May 2016

IDPASC School - Vipava, Slovenia

Dark Matter:

introduction, some theory and some phenomenology

Marco Cirelli

(LPTHE Jussieu CNRS Paris)

Reviews on Dark Matter:

Jungman, Kamionkowski, Griest, Phys.Rept. 267, 195-373, 1996
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Bergstrom 0903.4849, 1205.4882, 1202.1170
Cirelli, Strumia arXiv: yymm.nnnn (*upcoming*)

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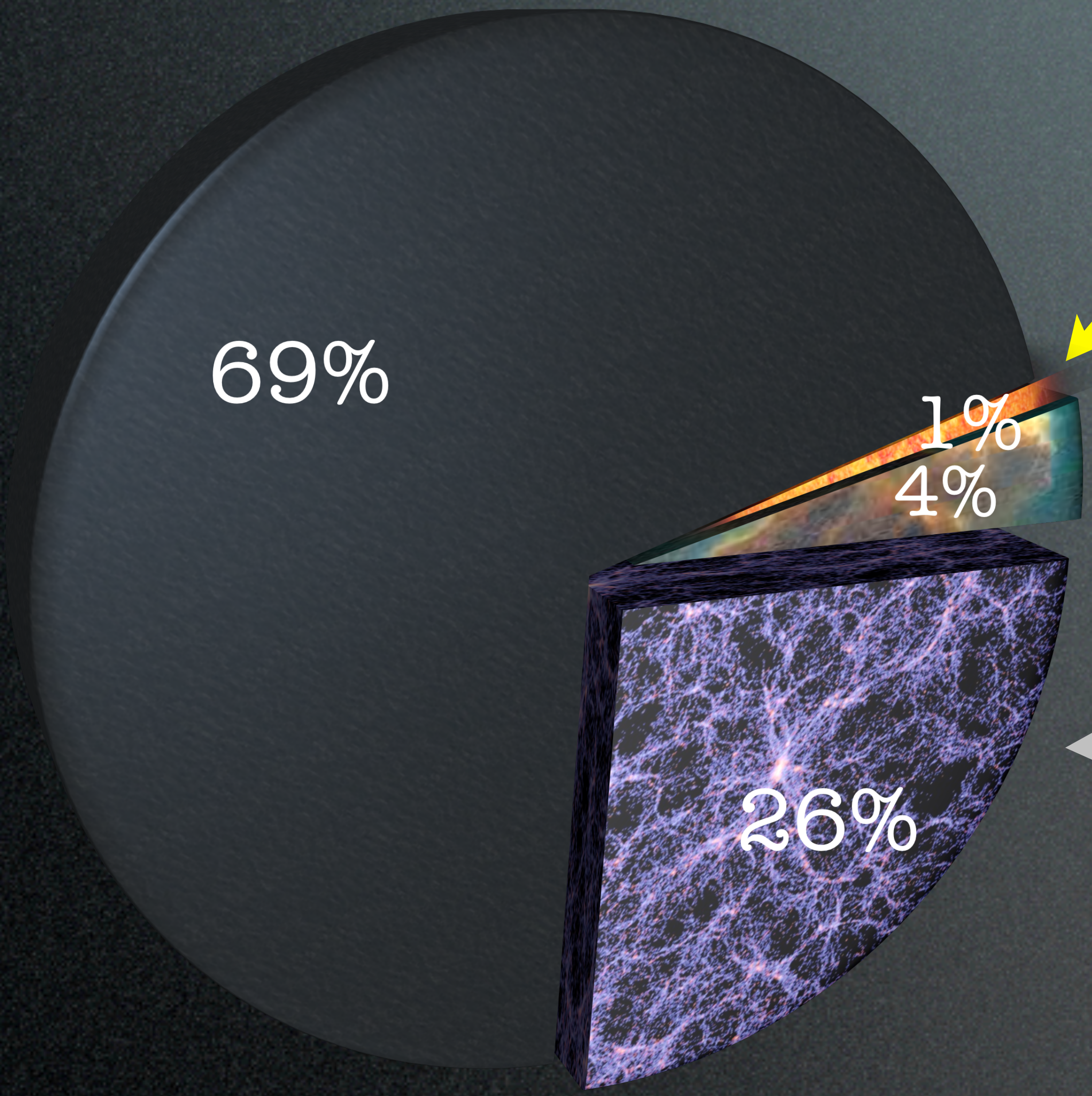
The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

-BBN
-CMB

$\Omega_{\rm DM} \sim 0.26$

$\Omega_{\rm de} \sim 0.69$

- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1\ (\text{flat});\ \text{HST}\ h = 0.71 \pm 0.07\right)$$

what's the difference
between DM and DE?

The cosmic inventory

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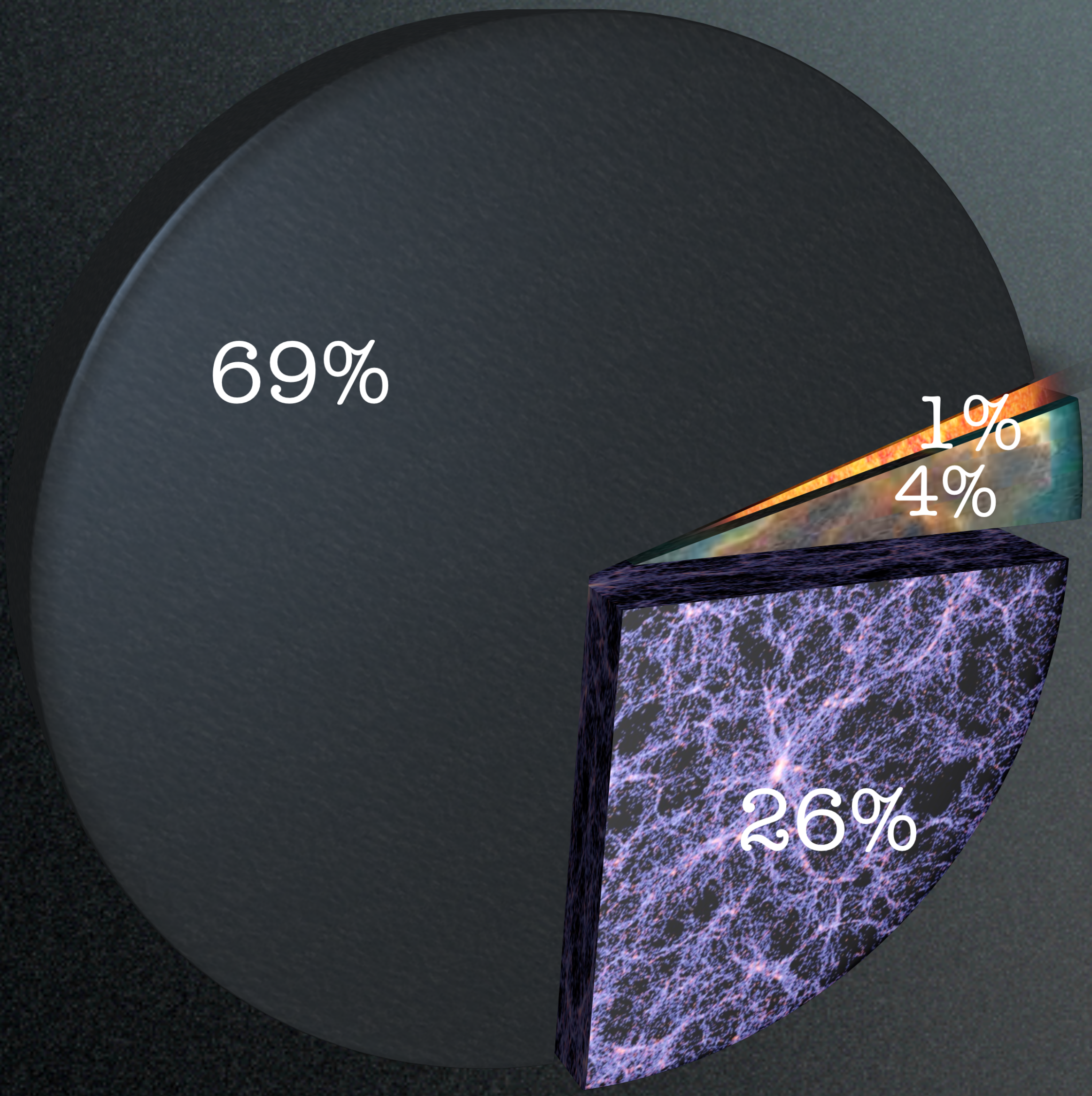

FAvgQ: what's the difference between DM and DE?

DM behaves like matter

- overall it dilutes as volume expands
- clusters gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
  (radiation has $w = -1/3$)

DE behaves like a constant

- it does not dilute
- does not cluster, it is prob homogeneous
- $w = P/\rho \simeq -1$
- pulls the acceleration, FRW eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_{\rm N}}{3}(1-3w)\rho$

The cosmic inventory

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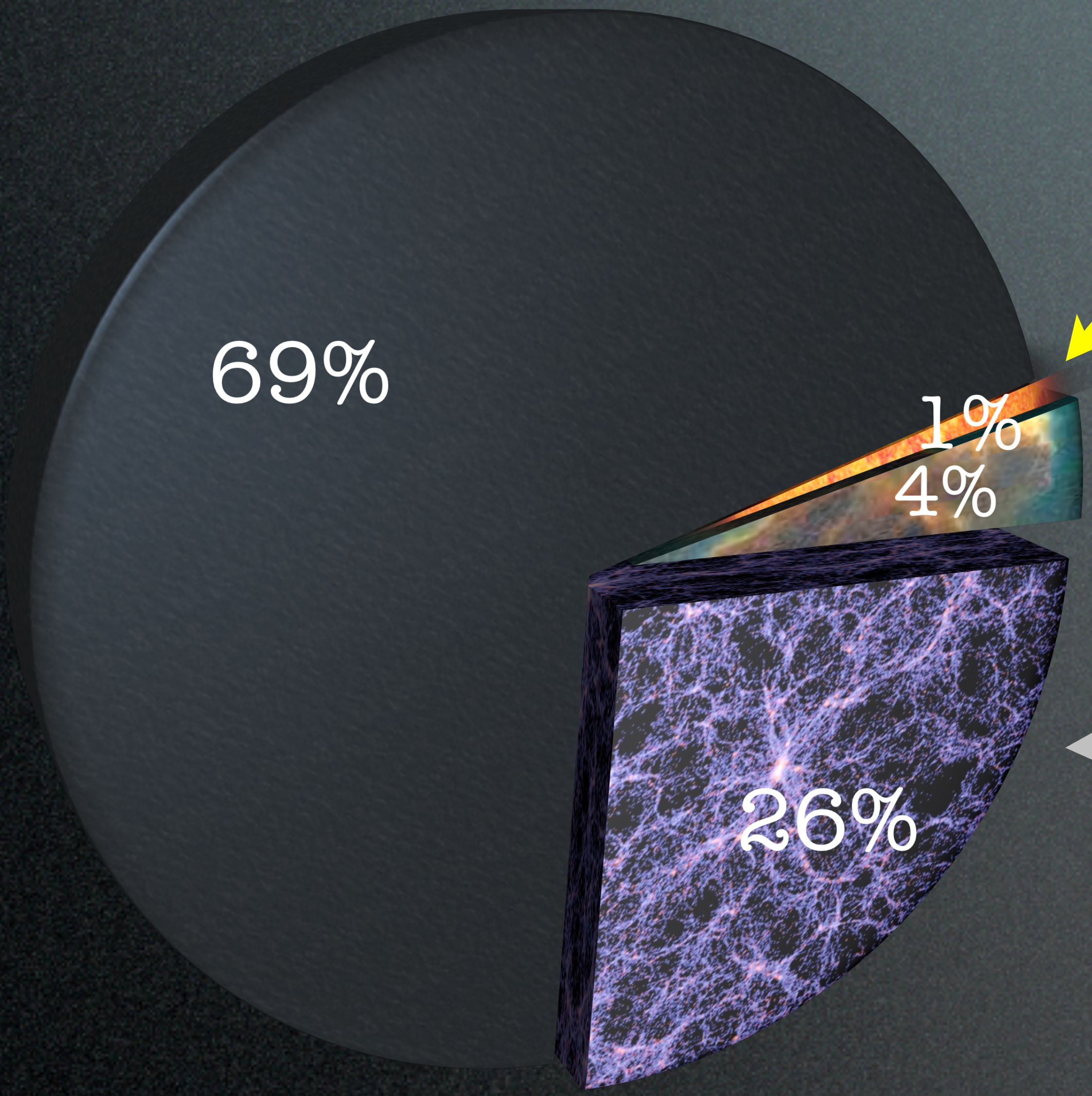

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particle physics $\bigcap$ cosmology

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How do we know that Dark Matter is out there?

The Evidence for DM

1) galaxy rotation curves

2) clusters of galaxies

3) ‘precision cosmology’

The Evidence for DM

1) galaxy rotation curves

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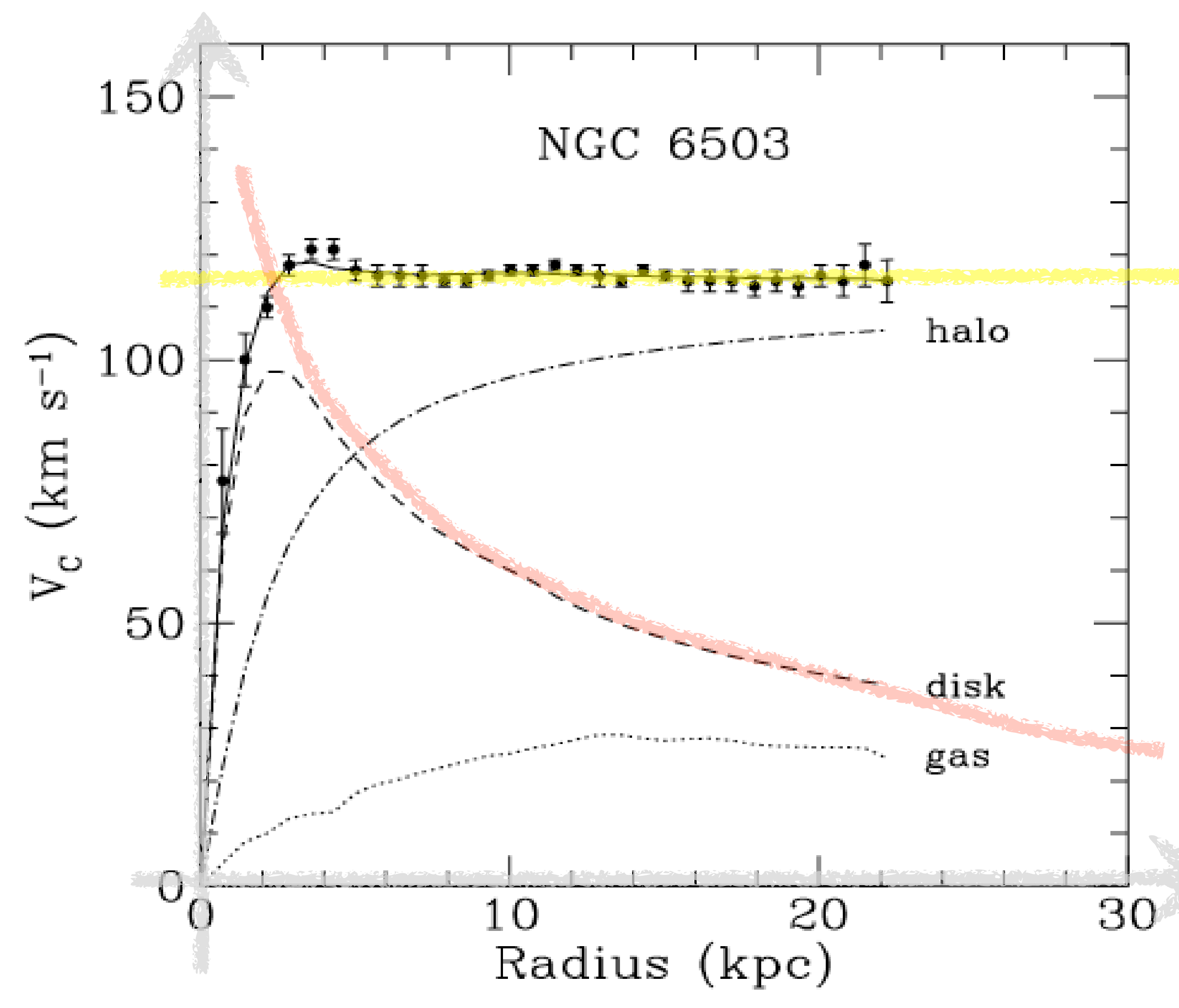
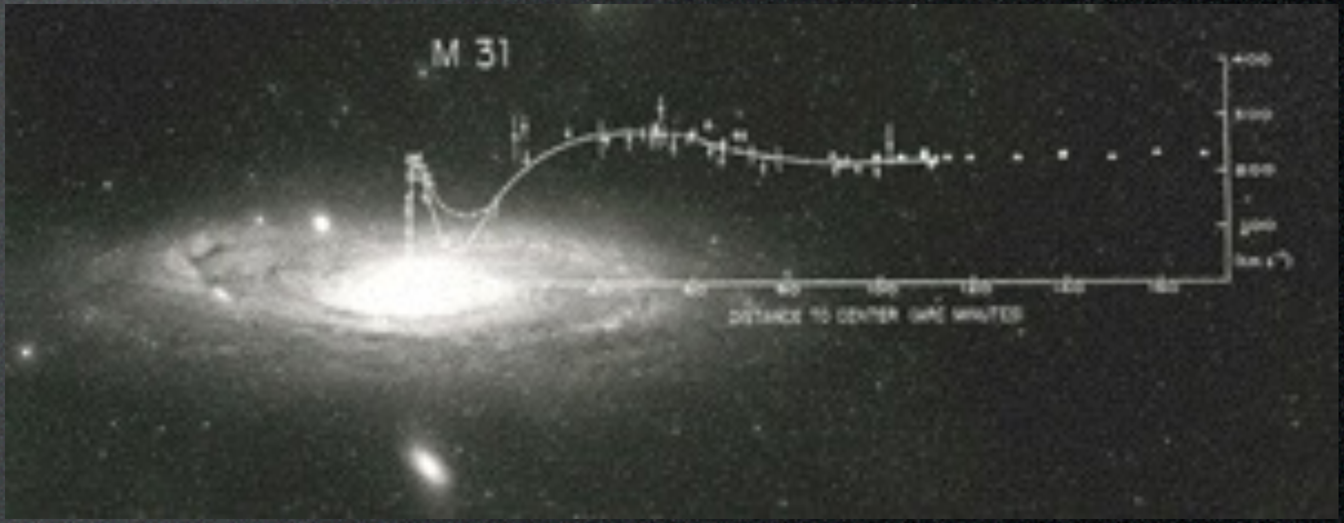
1) galaxy rotation curves



Begeman et al., MNRAS 249 (1991)

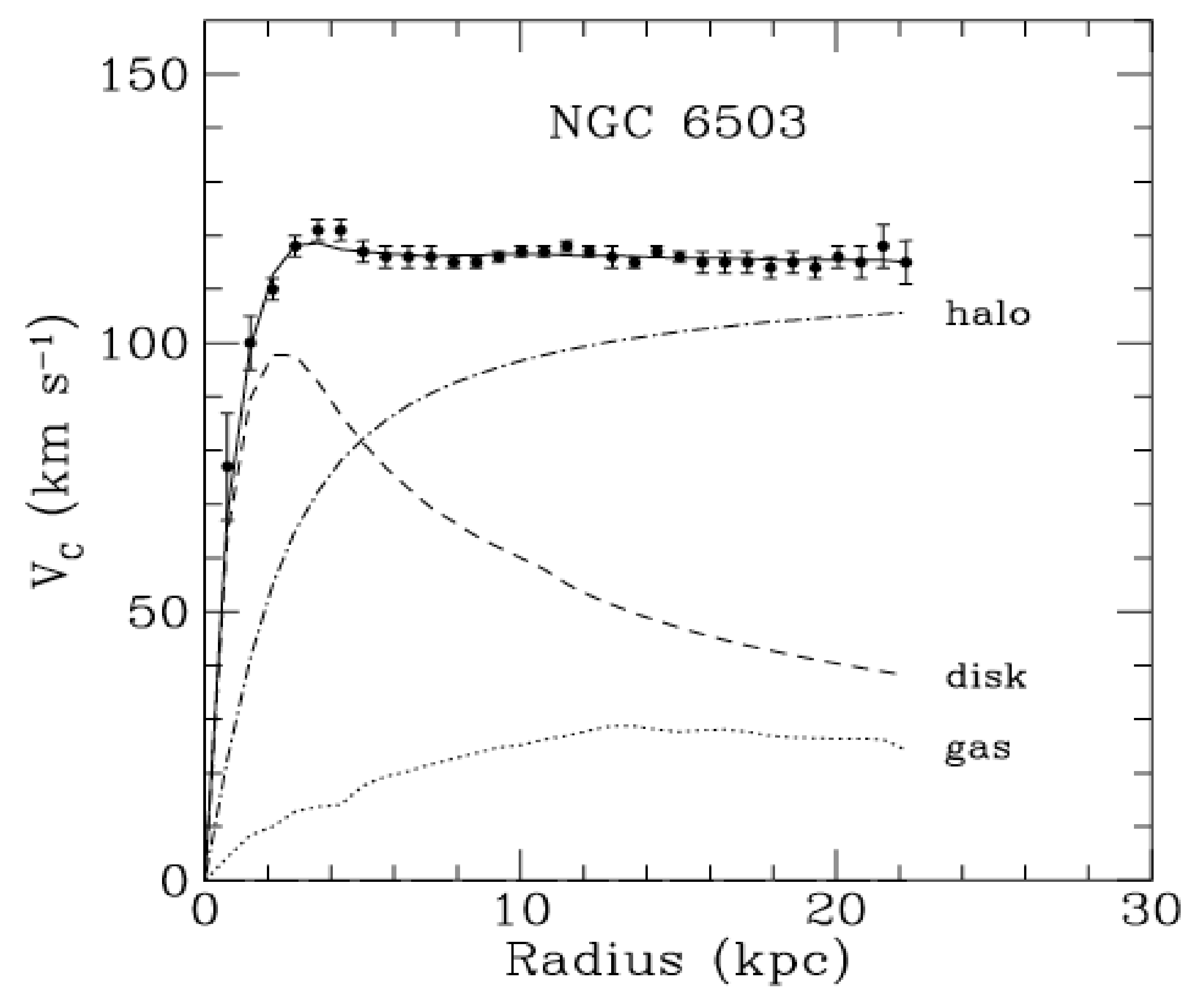


The Evidence for DM

1) galaxy rotation curves

$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

‘centrifugal’ ‘centripetal’



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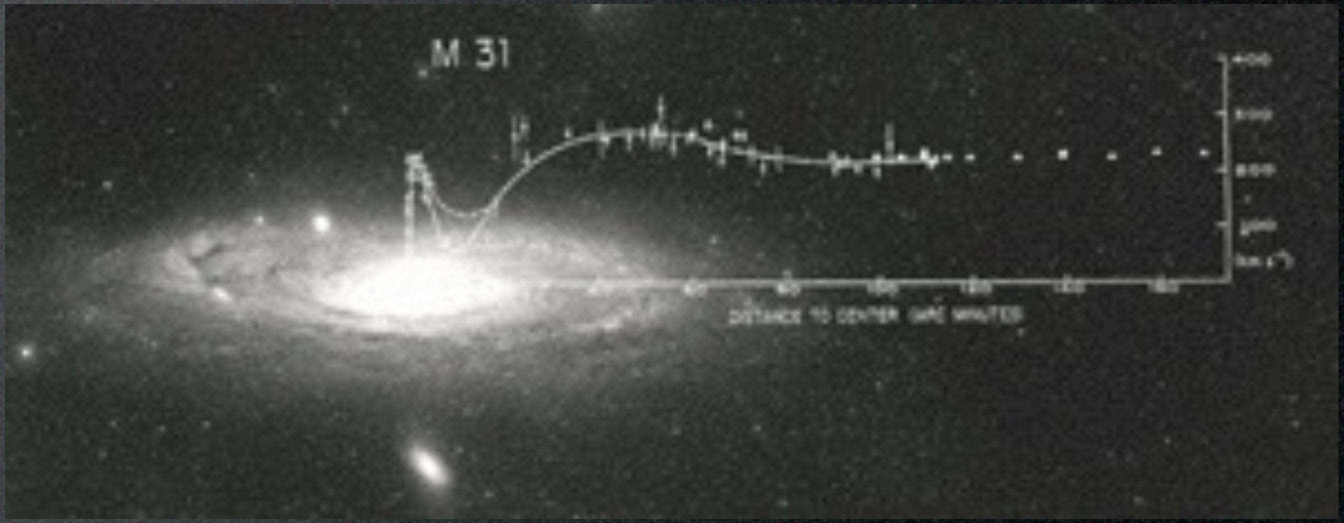

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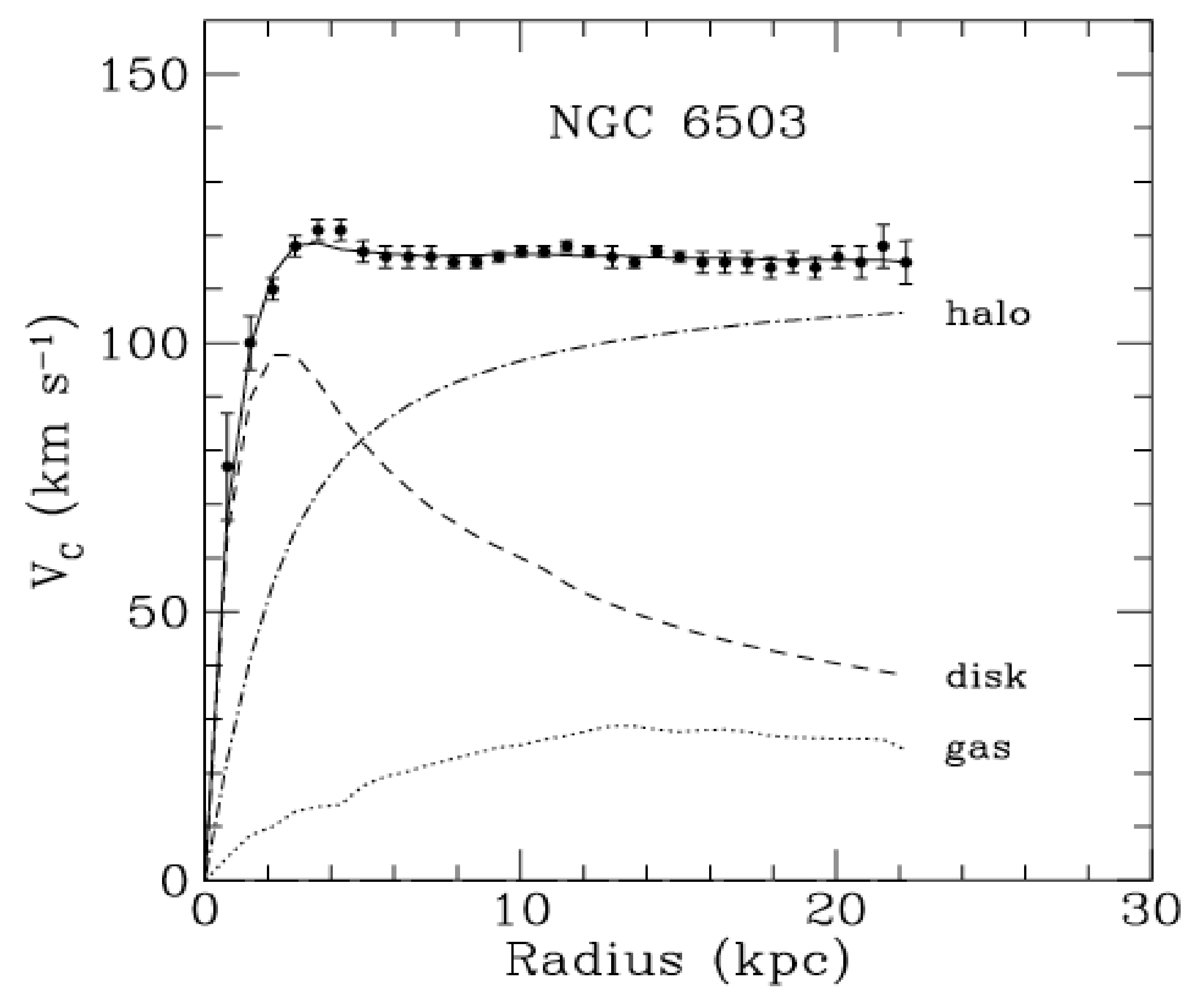

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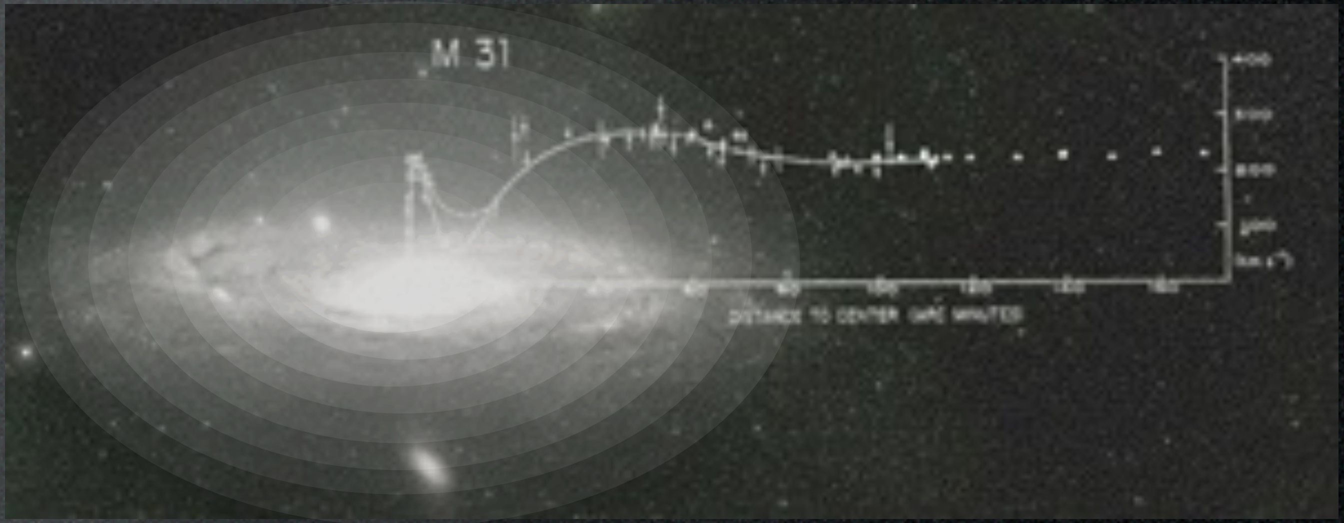

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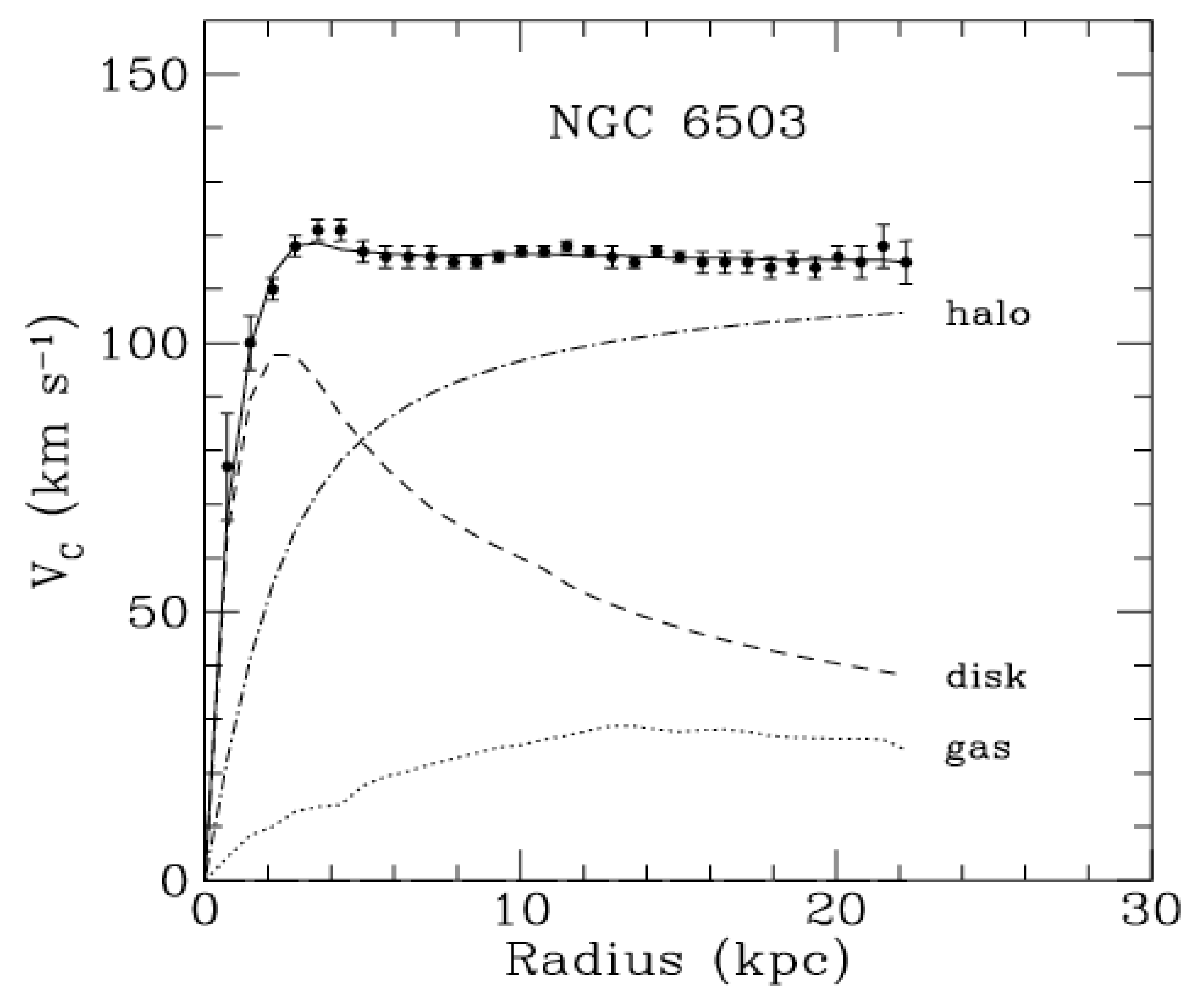

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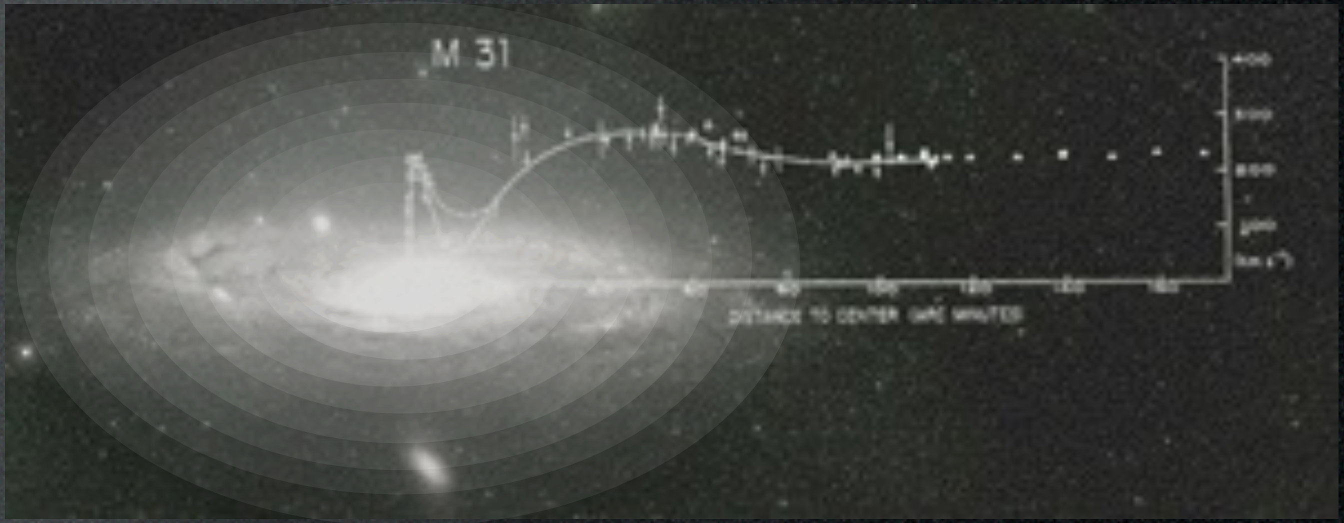
Fritz Zwicky
(1898-1974)



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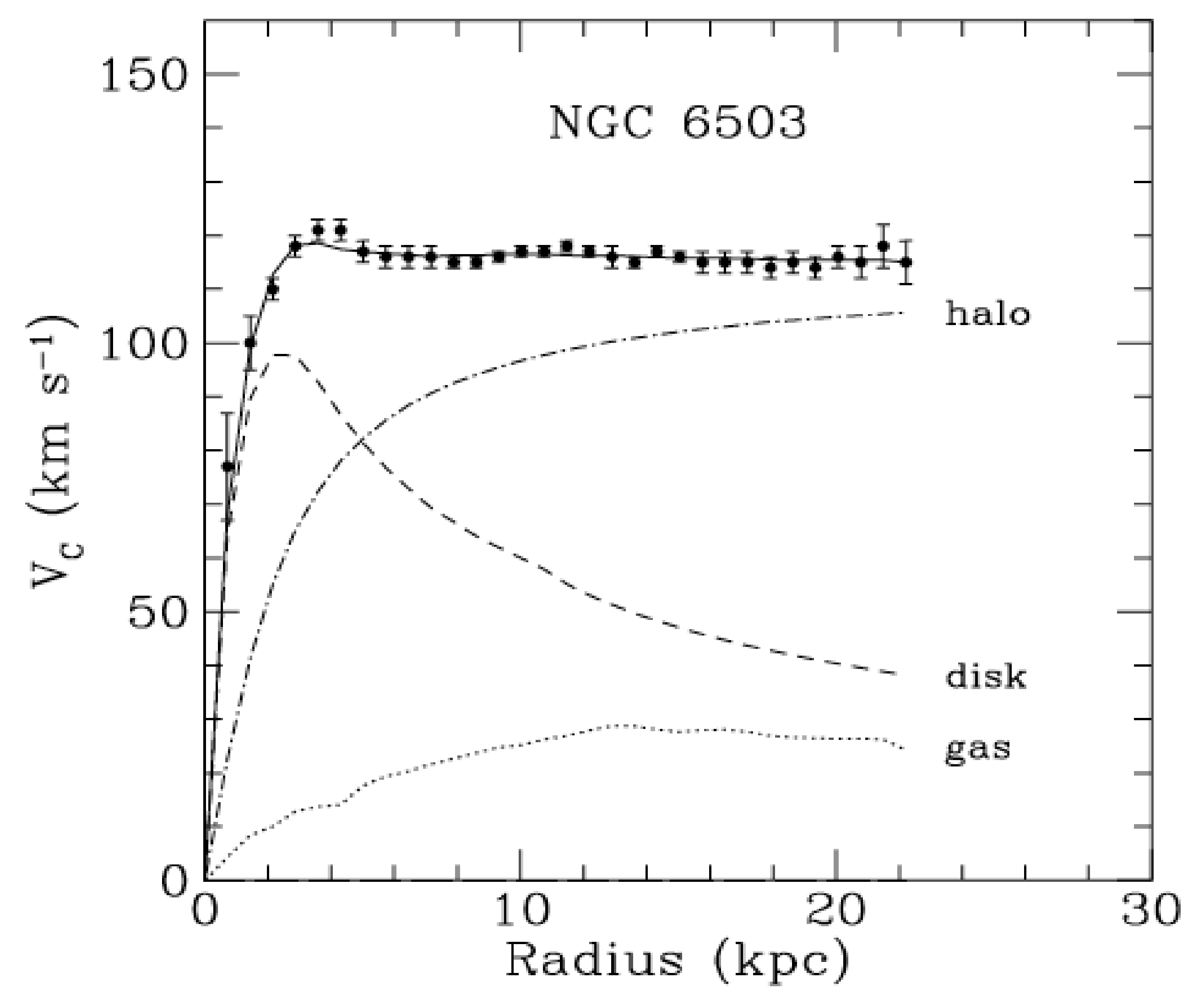

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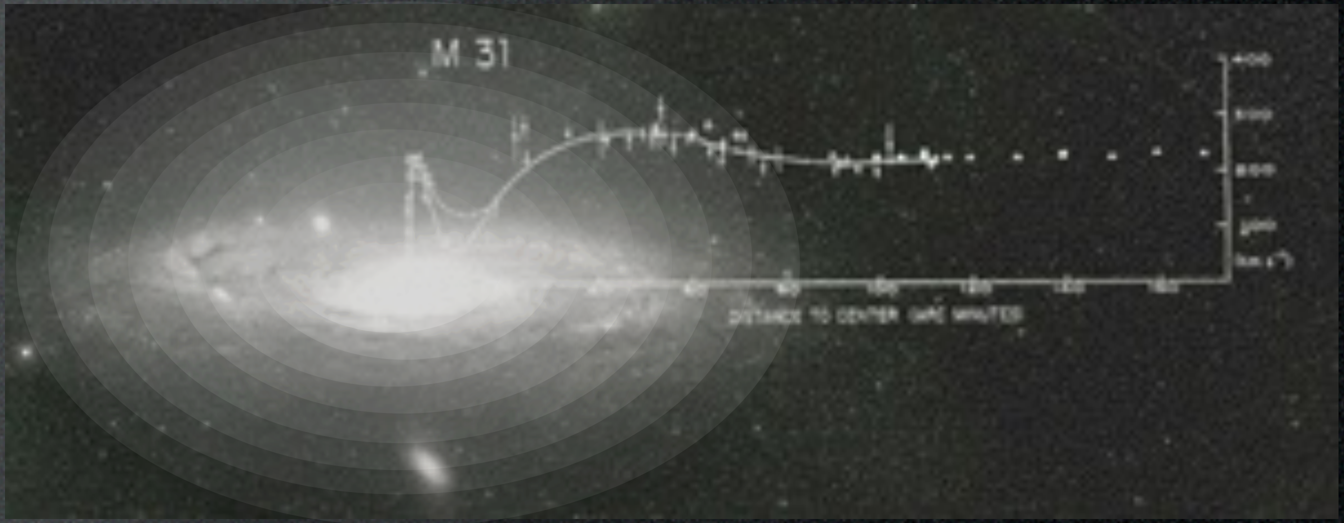

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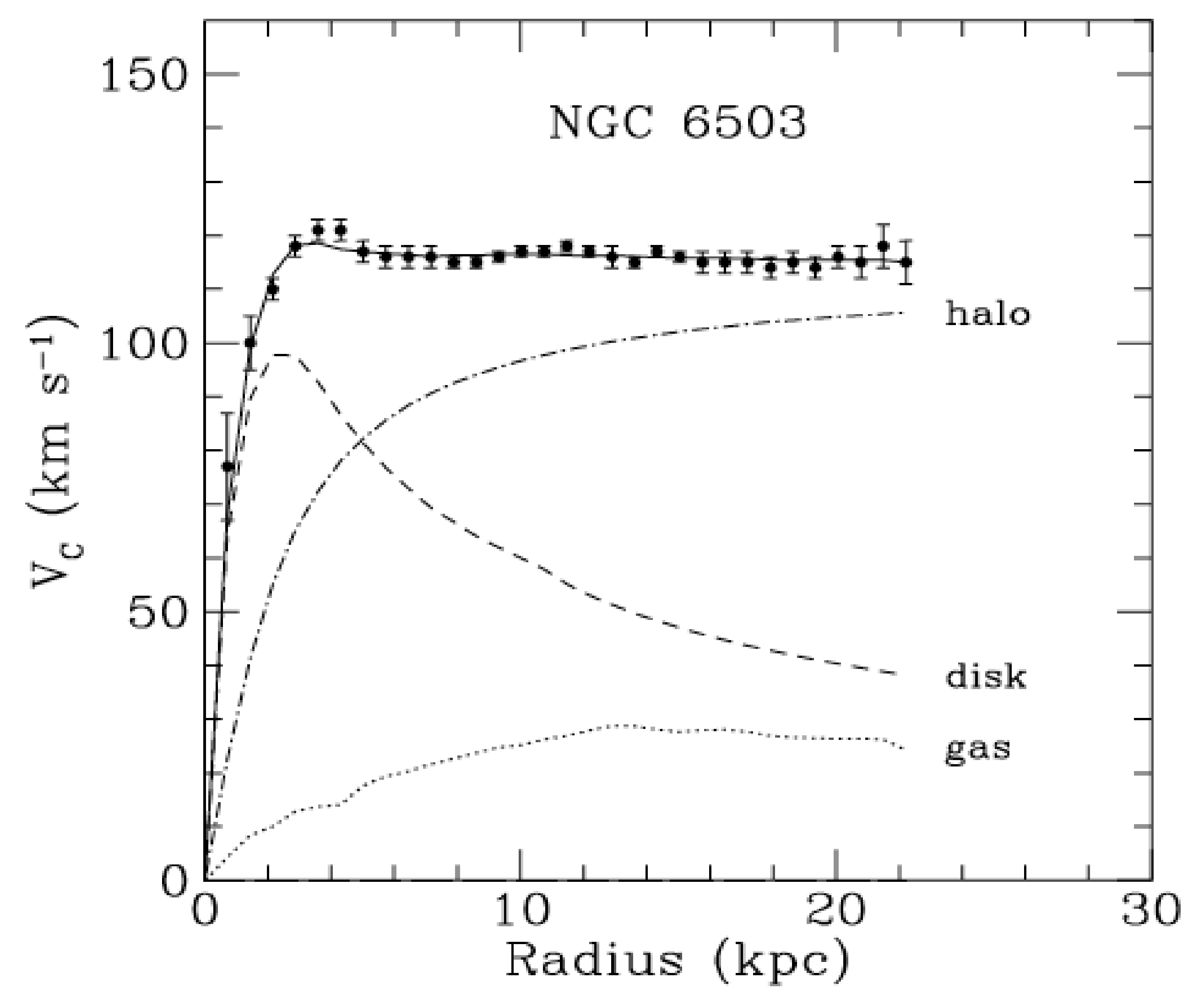

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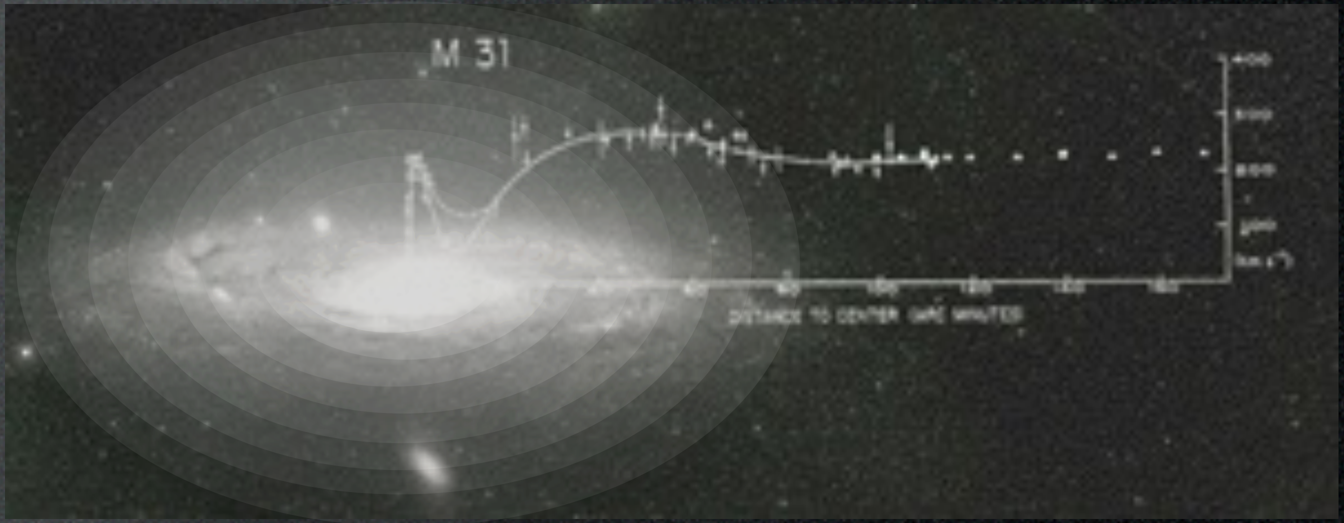

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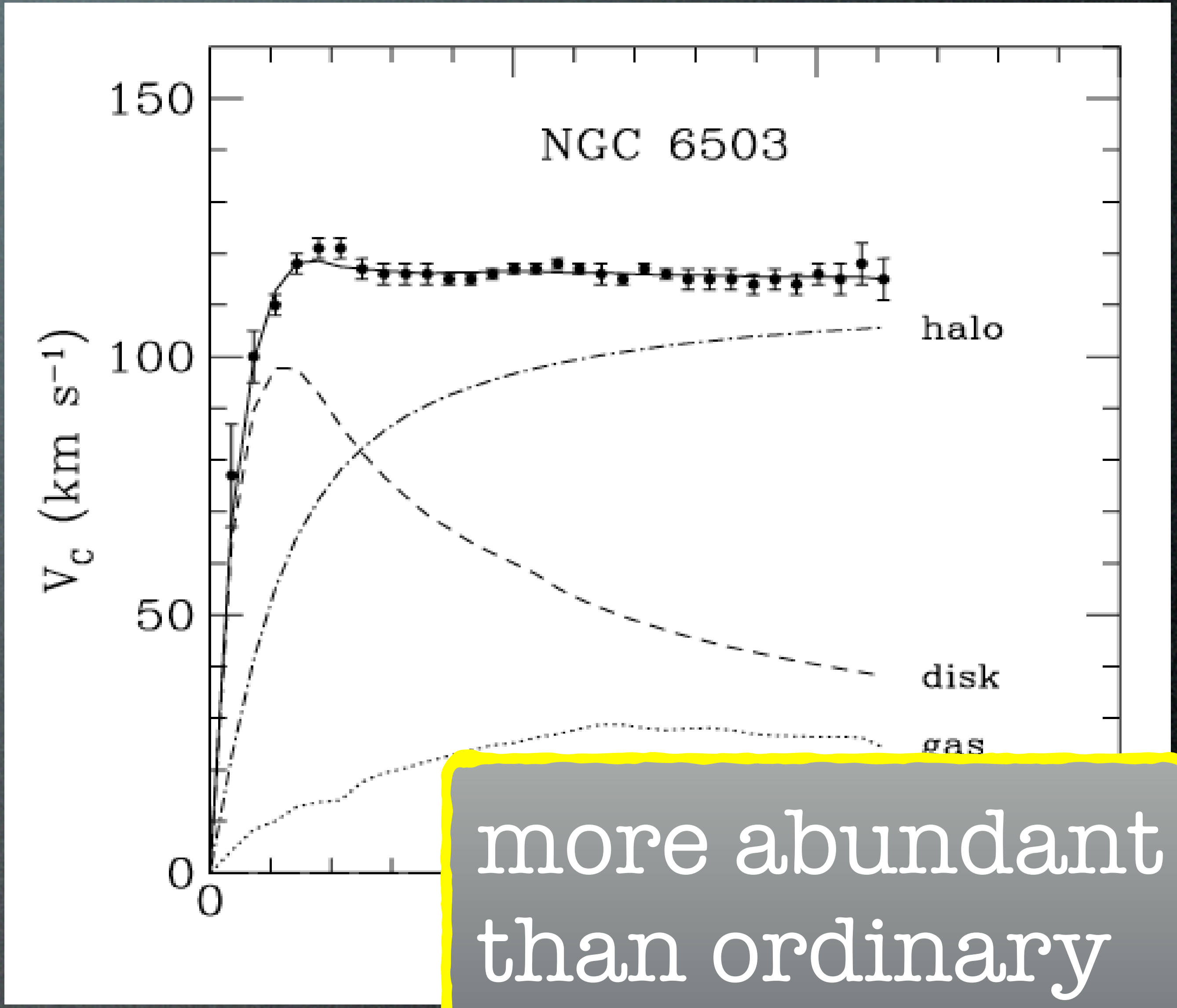

more abundant than ordinary matter!

Begeman et al., MNRAS 249 (1991)

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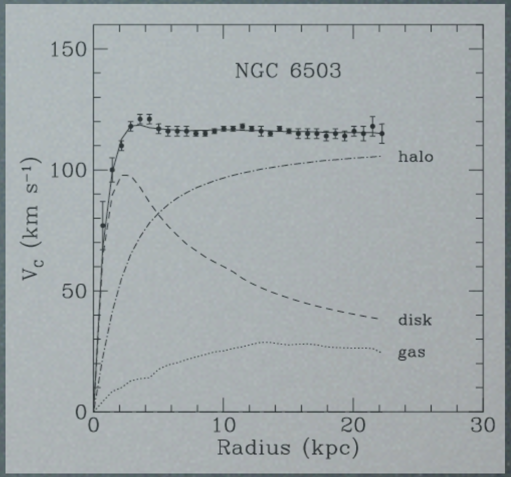

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- “rotation curves”
- gravitational lensing

“bullet cluster” - NASA
astro-ph/0608247

[further developments]

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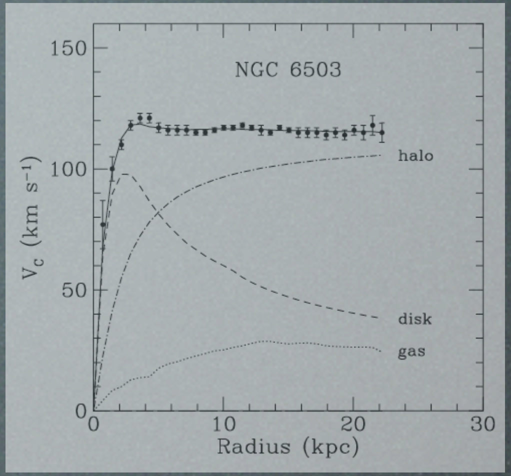

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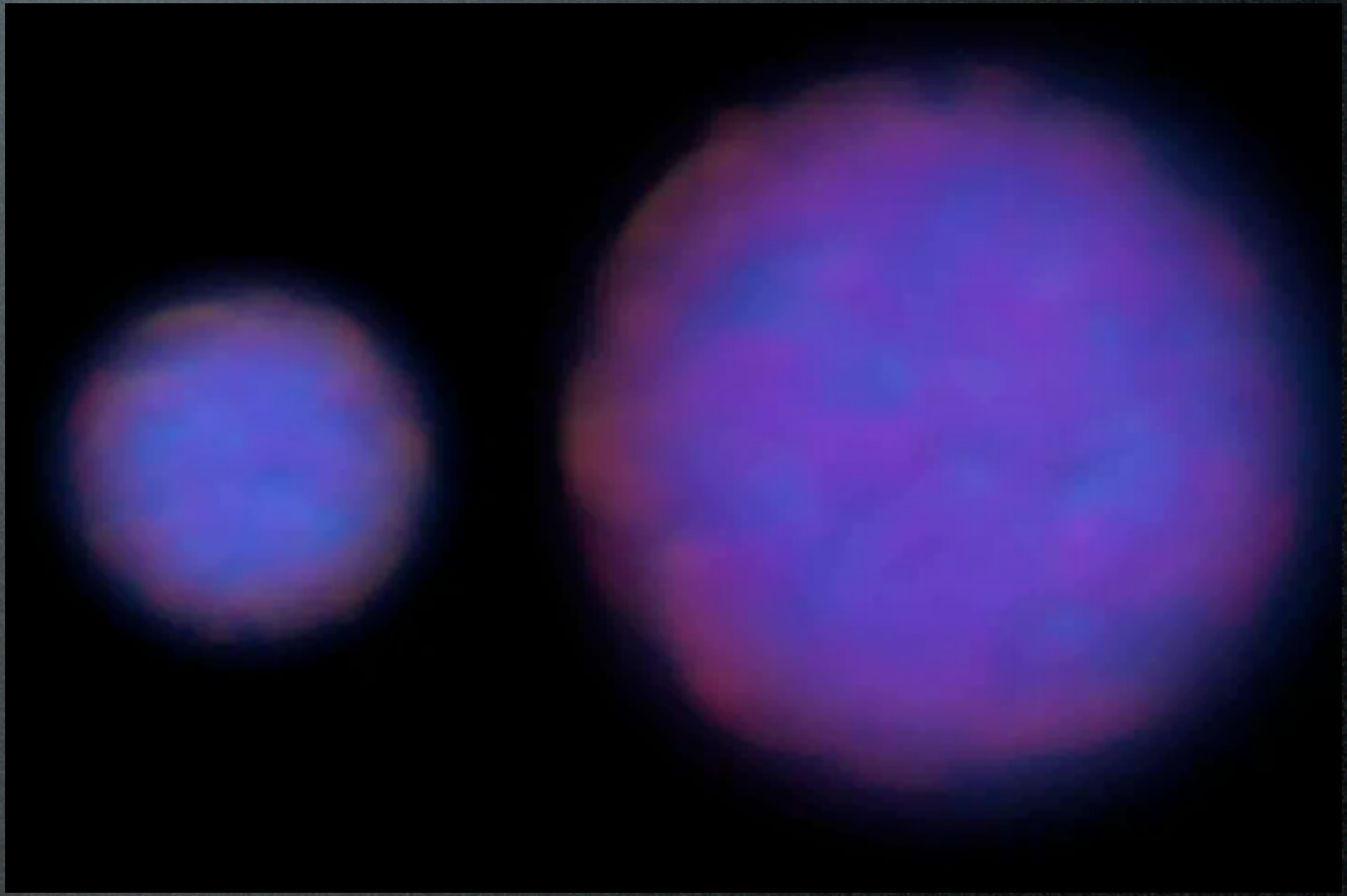

chandra.harvard.edu

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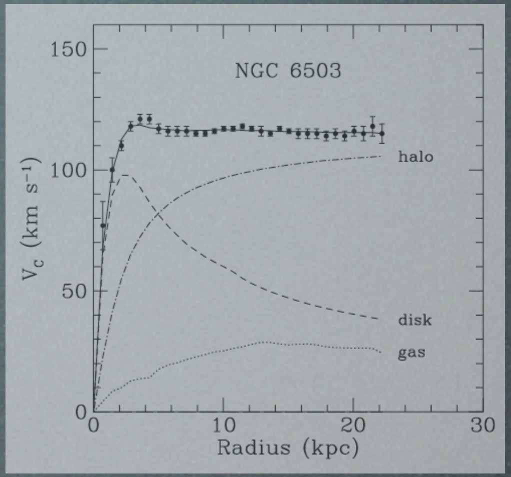

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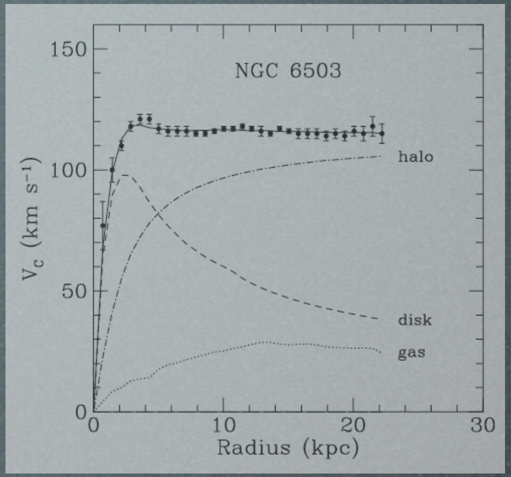

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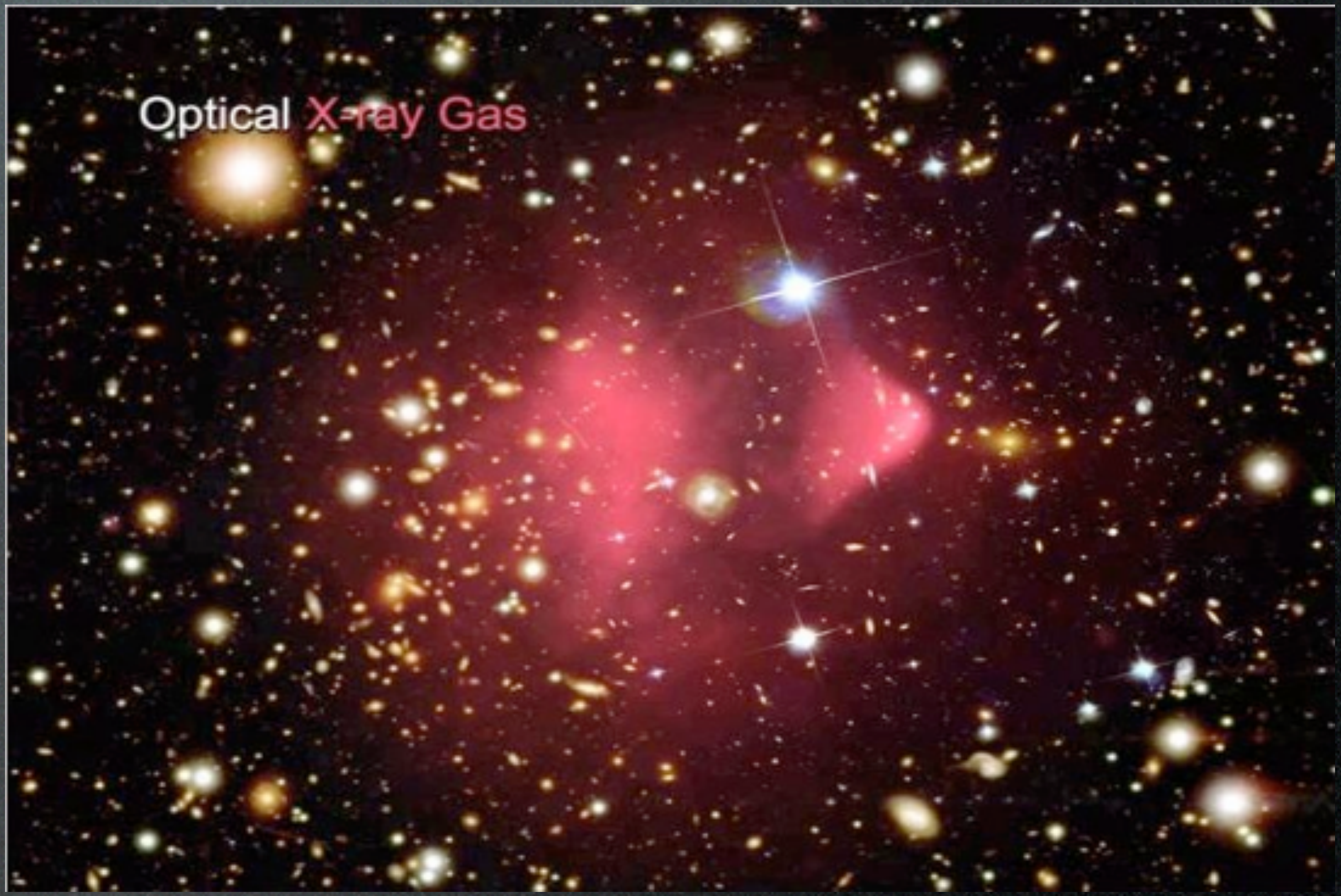

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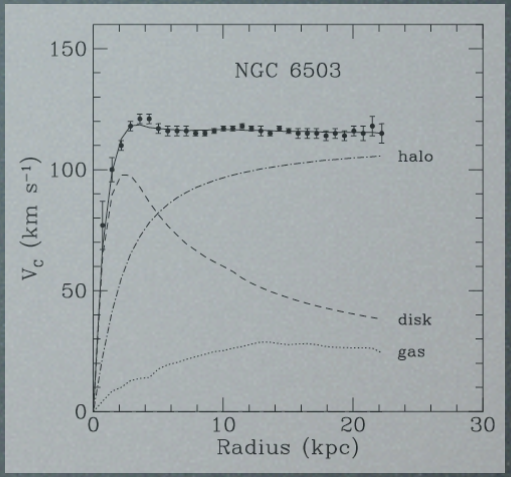

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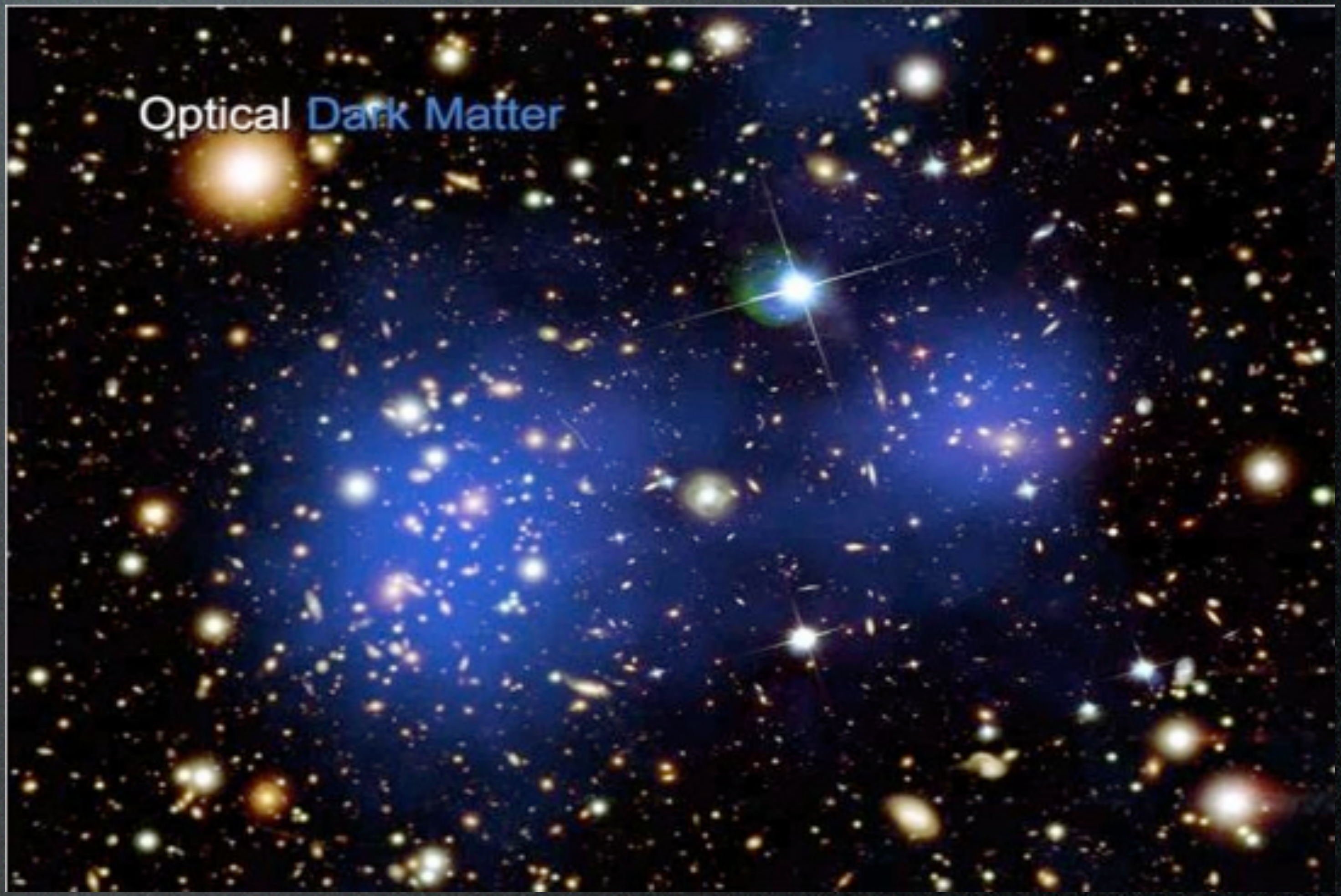

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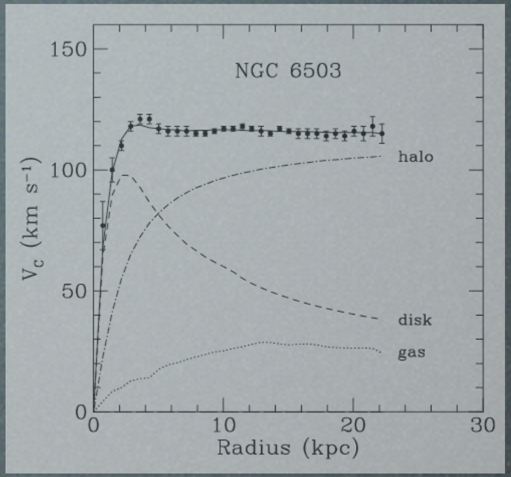

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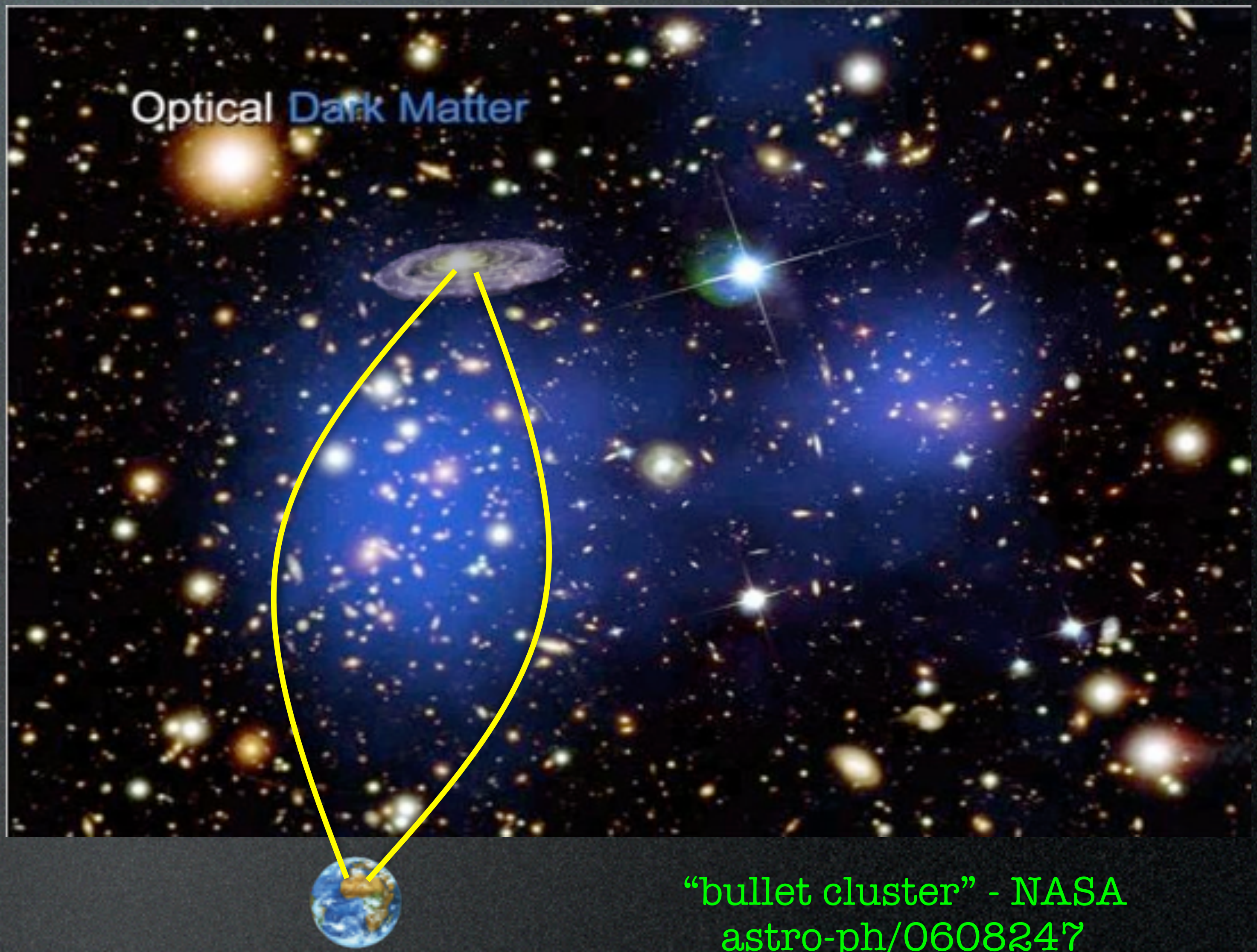

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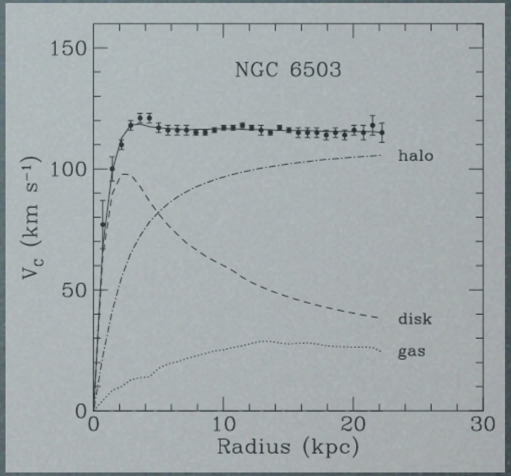

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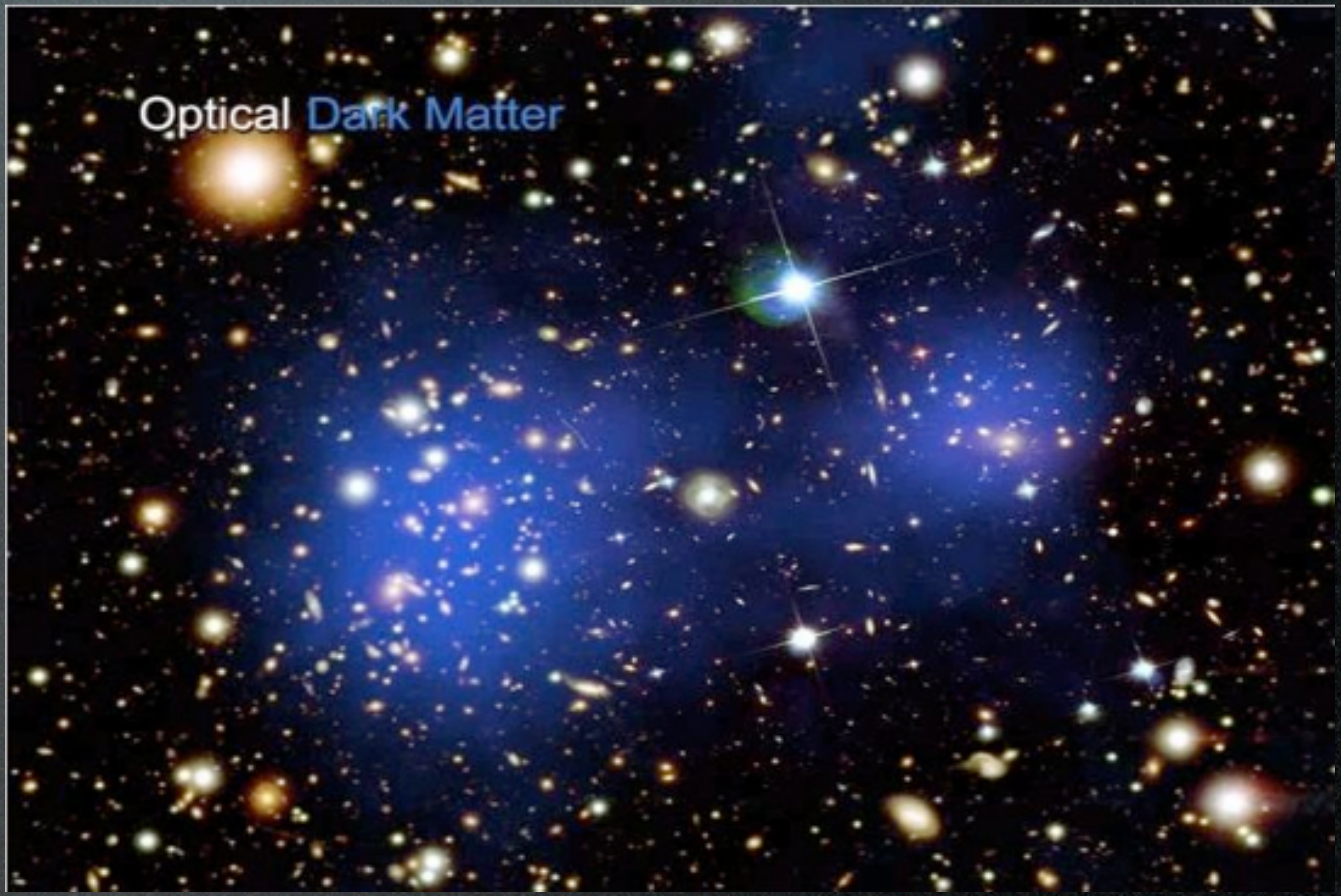

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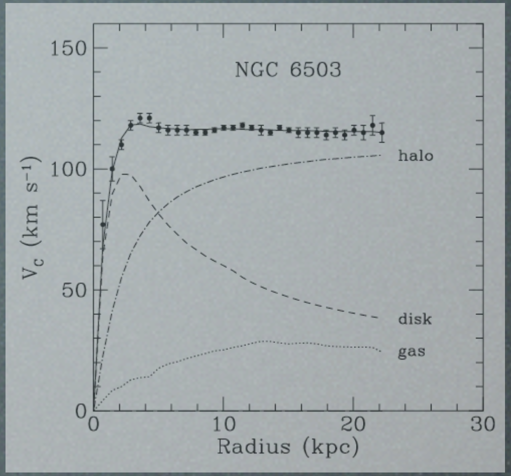

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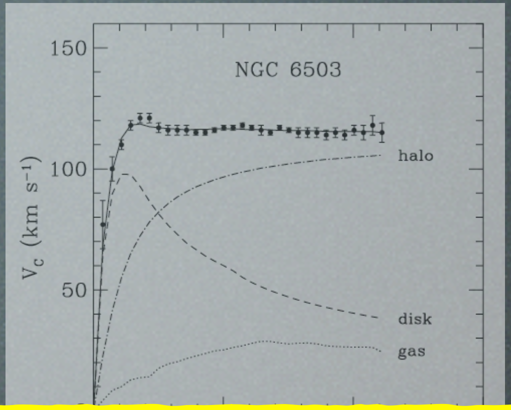

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does not emit light,
it is **neutral**

no or very feeble interaction

“bullet cluster” - NASA
astro-ph/0608247

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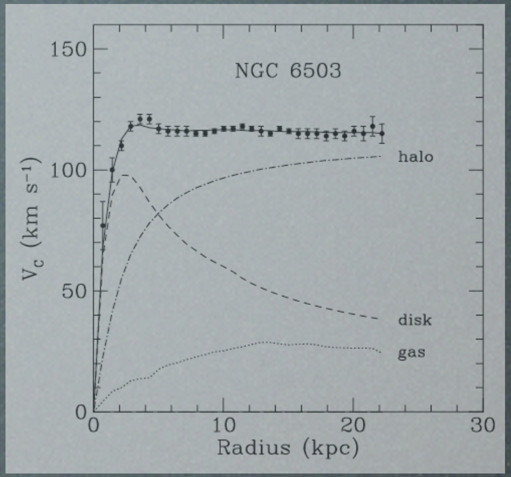

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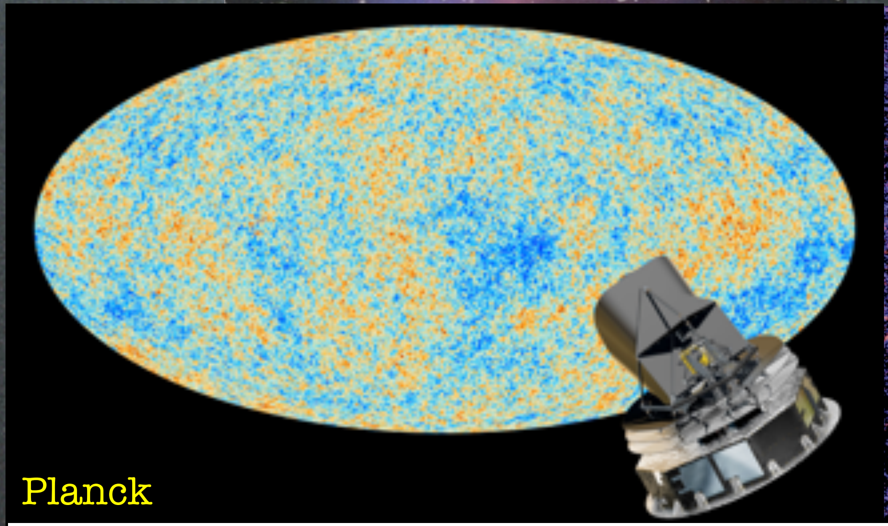
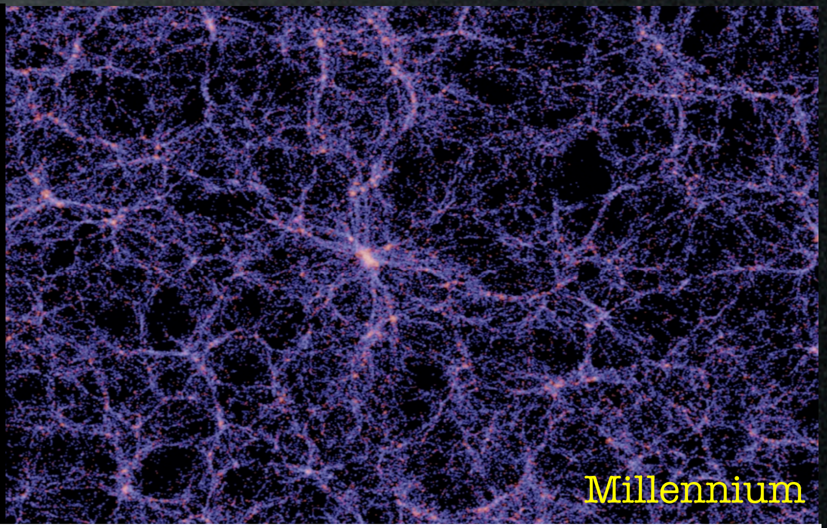
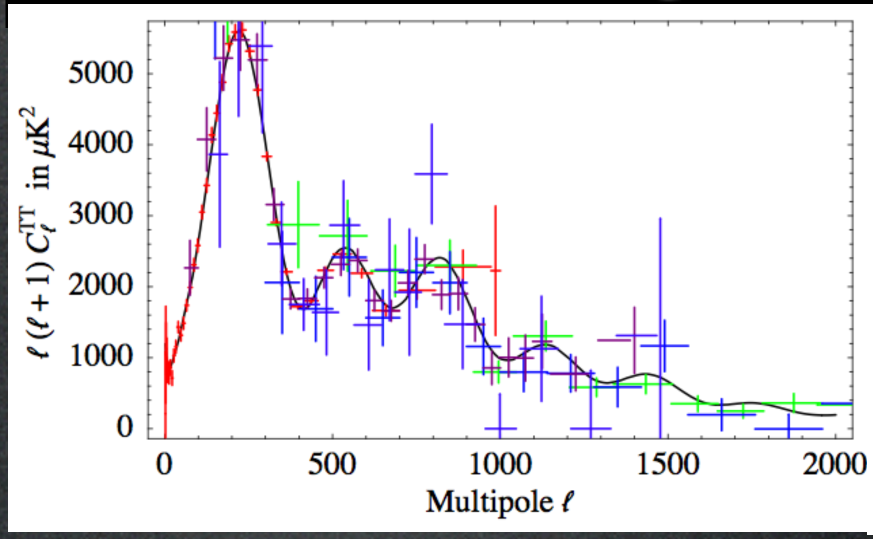
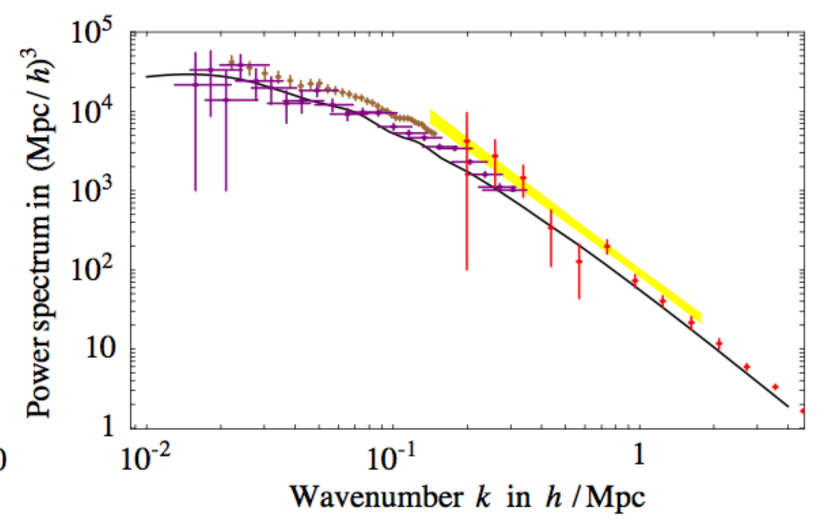


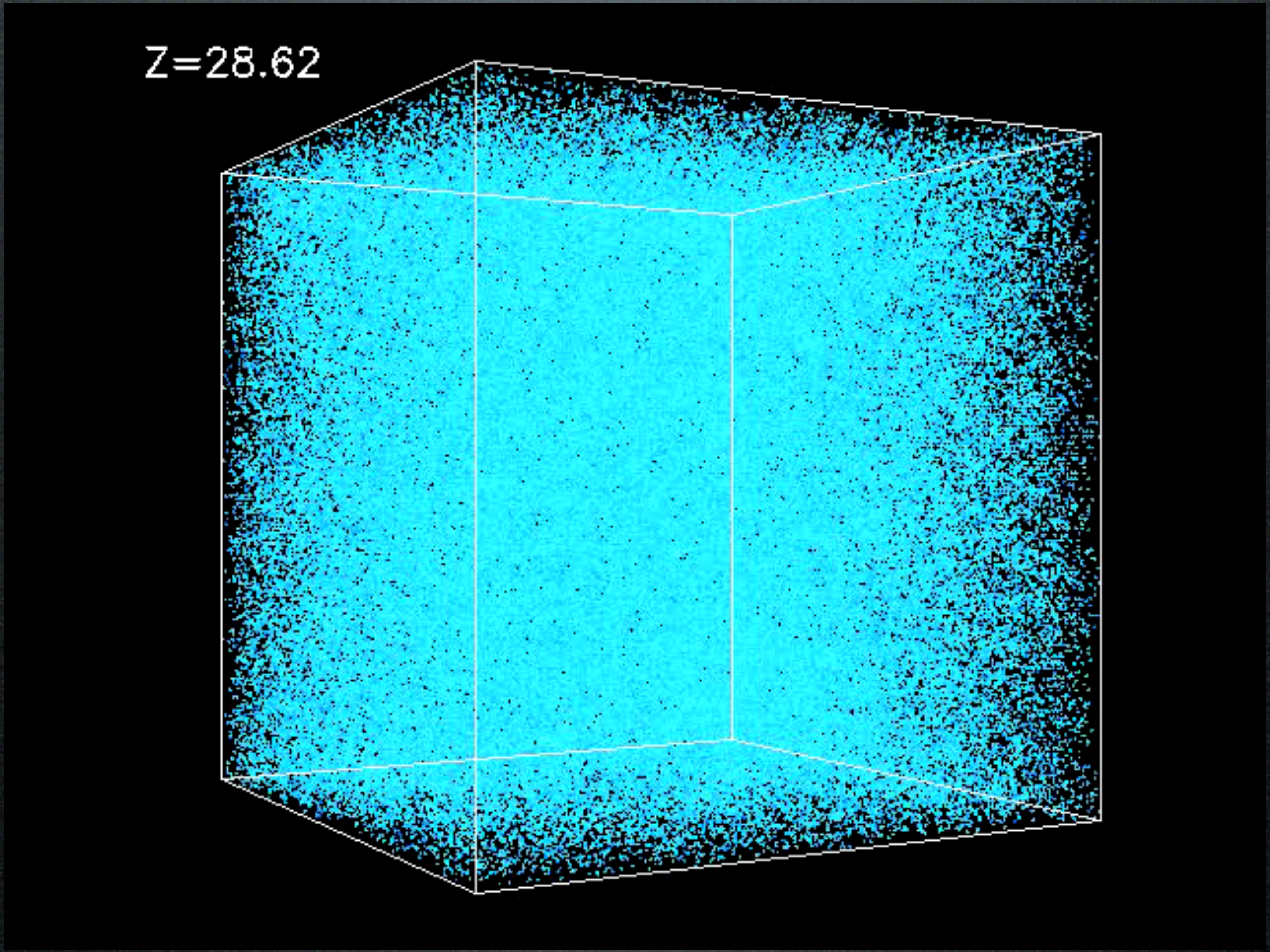






DM N-body simulations

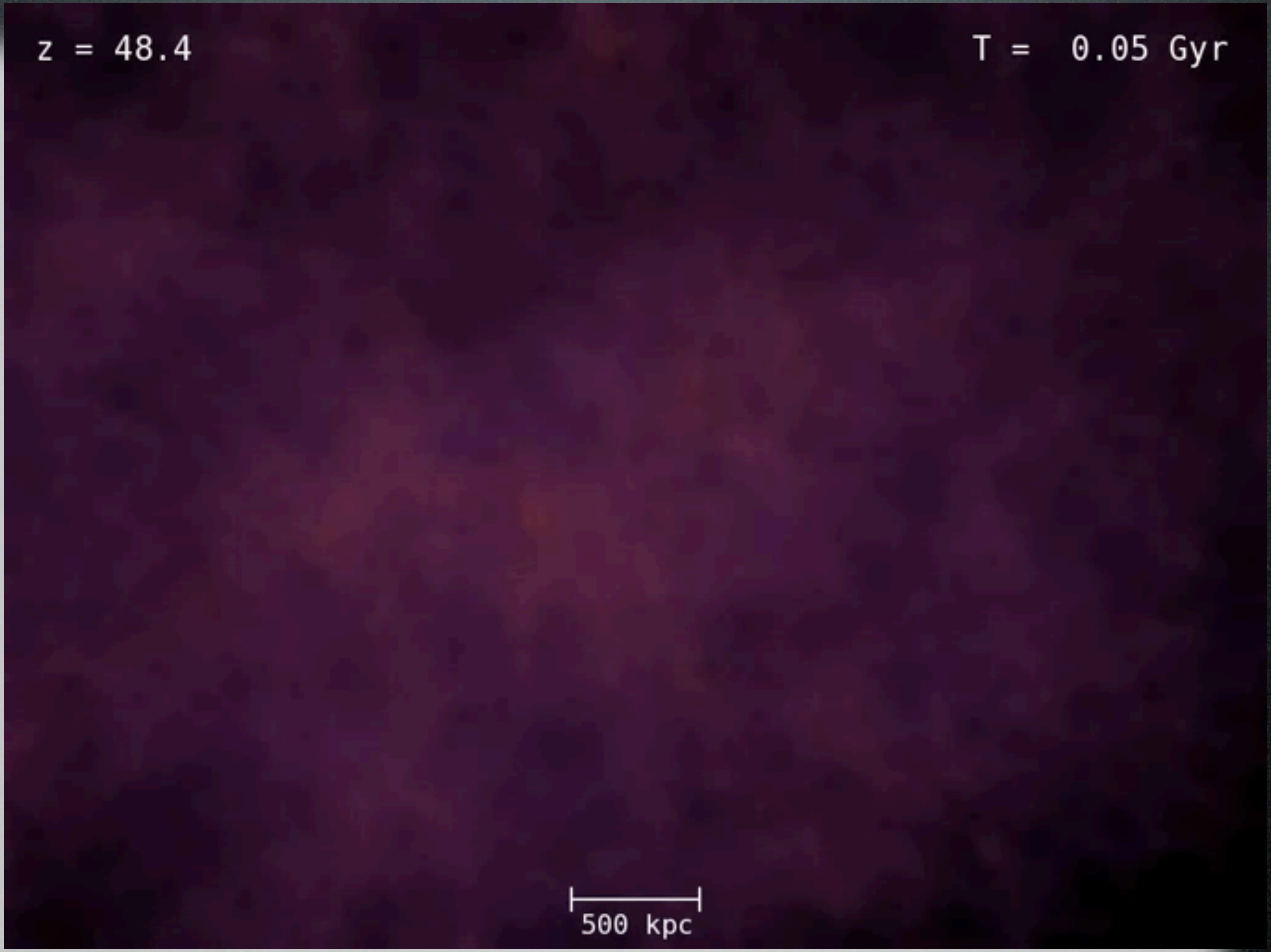
2 10^6 CDM particles, 43 Mpc cubic box



Andrey Kravtsov, cosmicweb.uchicago.edu

DM N-body simulations

Aquarius project of the VIRGO coll.:
1.5 10^9 CDM particles, single galactic halo

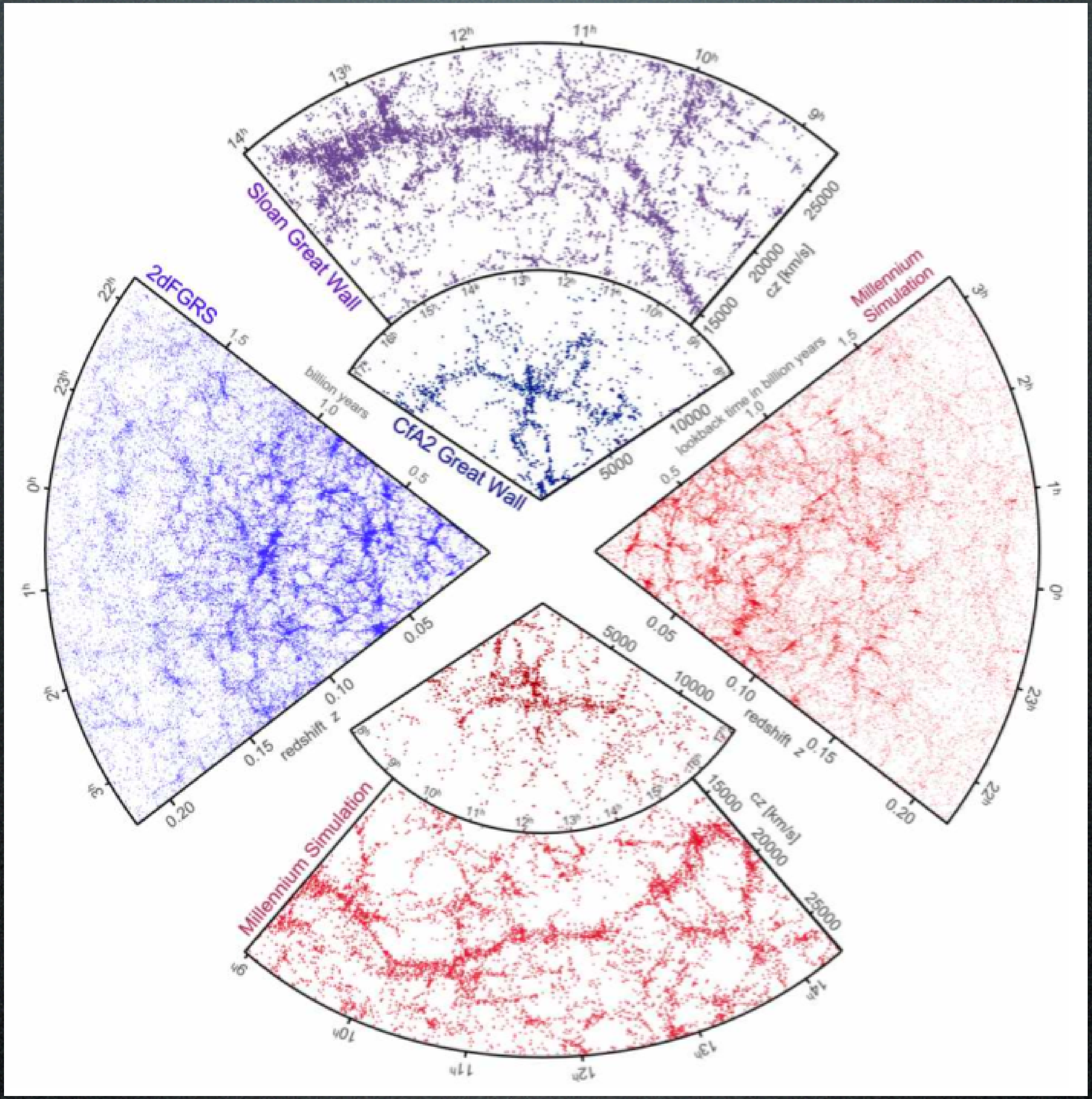


VIRGO coll., Aquarius project, www.mpa-garching.mpg.de/aquarius/

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

Of course, you have to
infer galaxies within the
DM simulation

Millennium:
10^{10} particles,
500 h^{-1} Mpc

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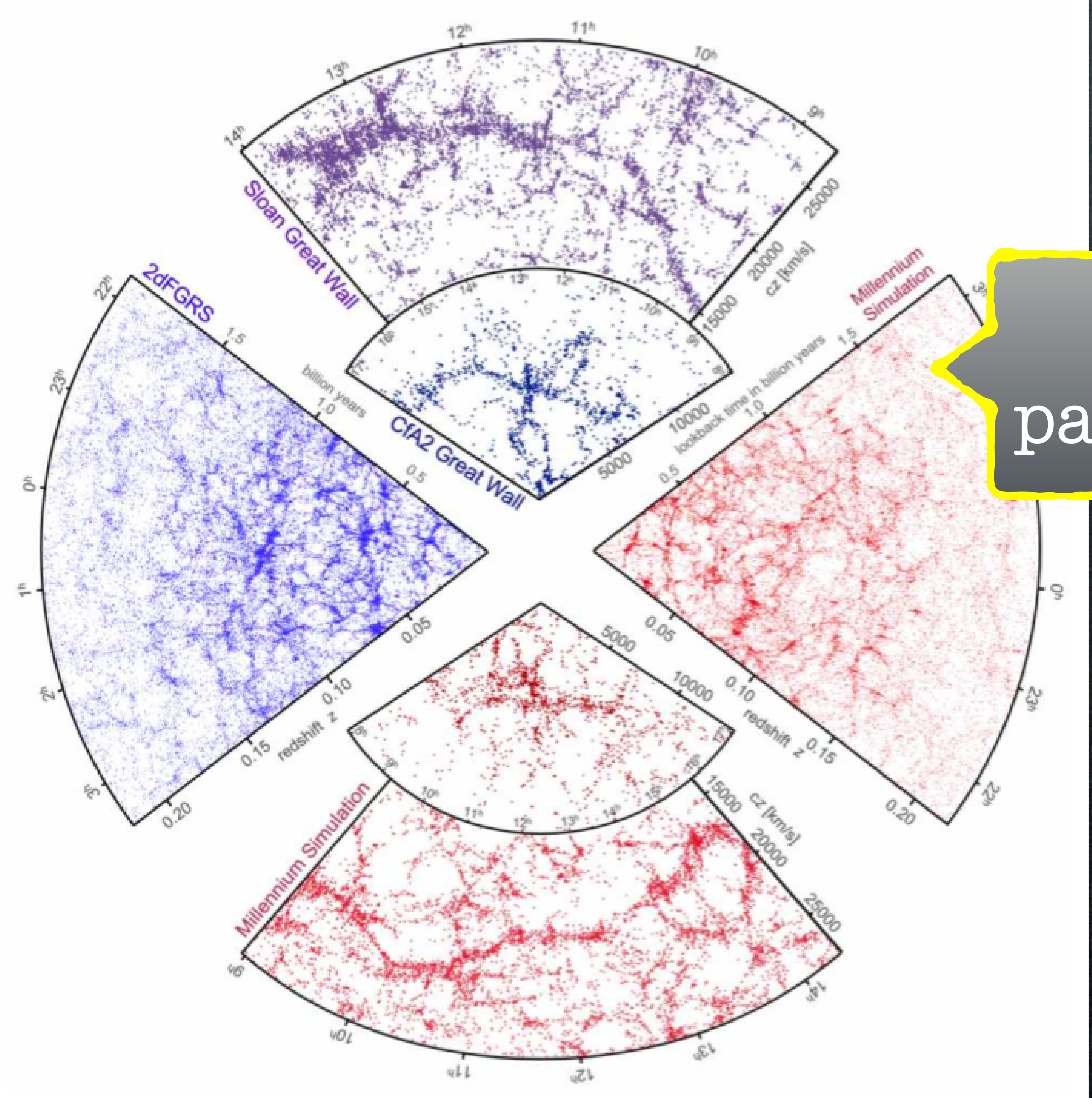

particles

Springel, Frenk, White, Nature 440 (2006)

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DETOUR

Modified gravity?

Modified gravity?

1846

Urbain Le Verrier

Modified gravity?

1846

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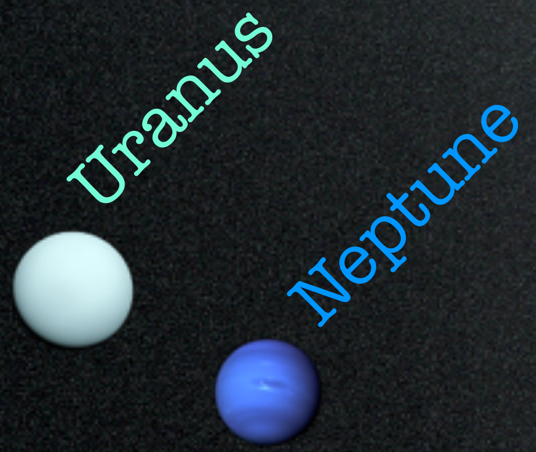

Modified gravity?

1846

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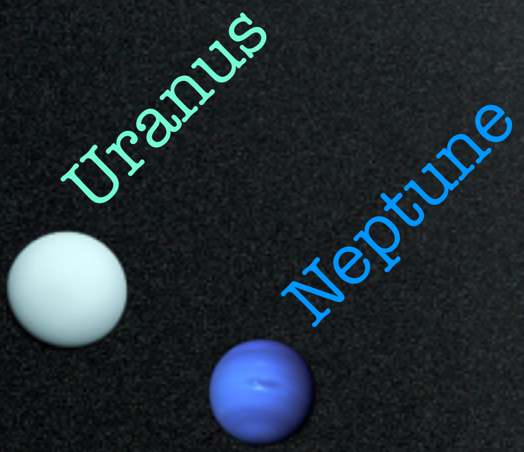

✓

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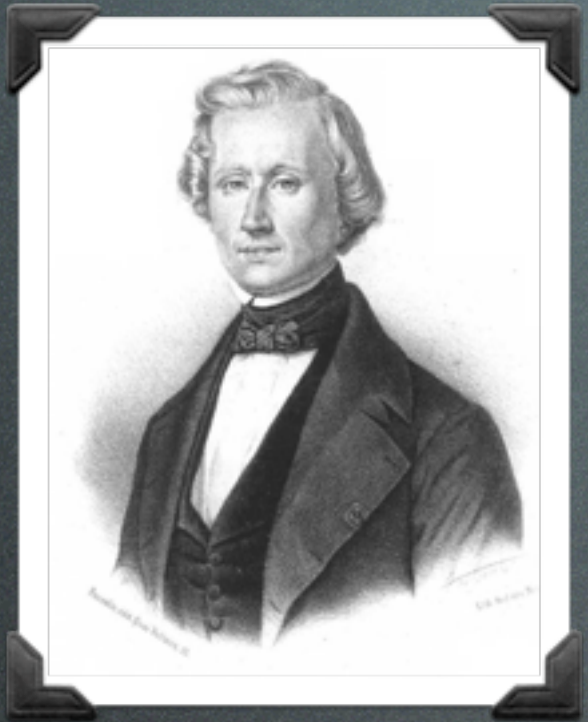
Urbain Le Verrier

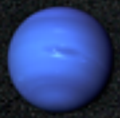
1859



Urbain Le Verrier

Uranus

Neptune



Mercury

✓

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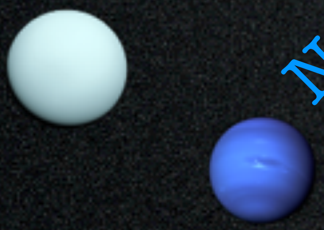

Uranus

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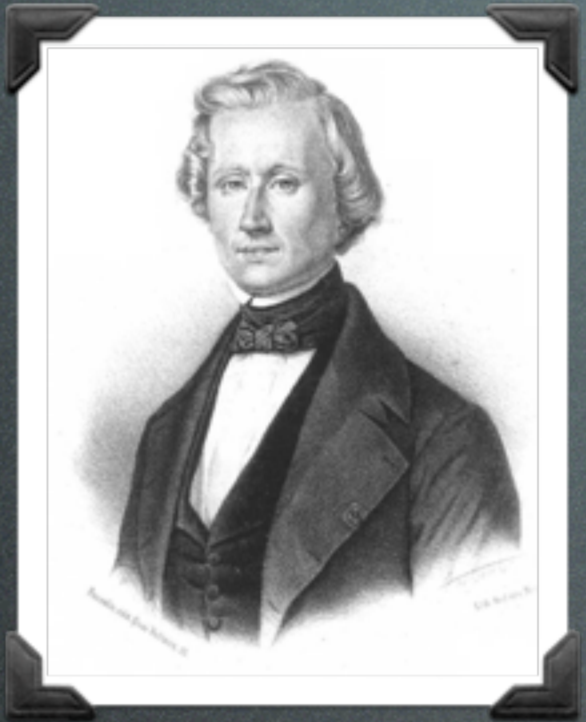
1859



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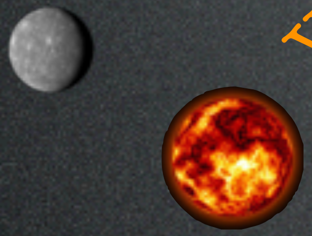

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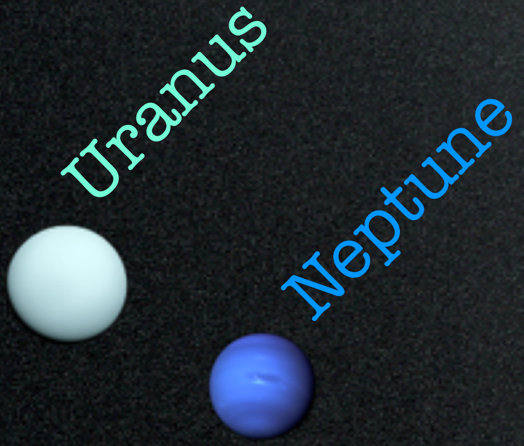

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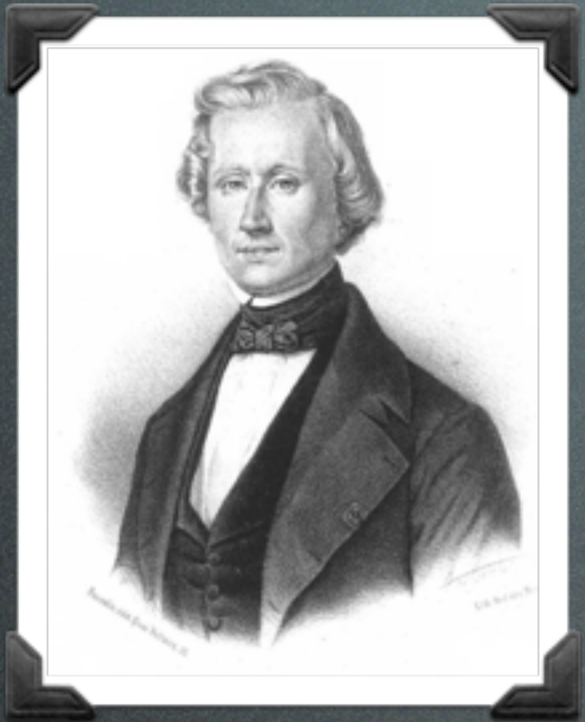

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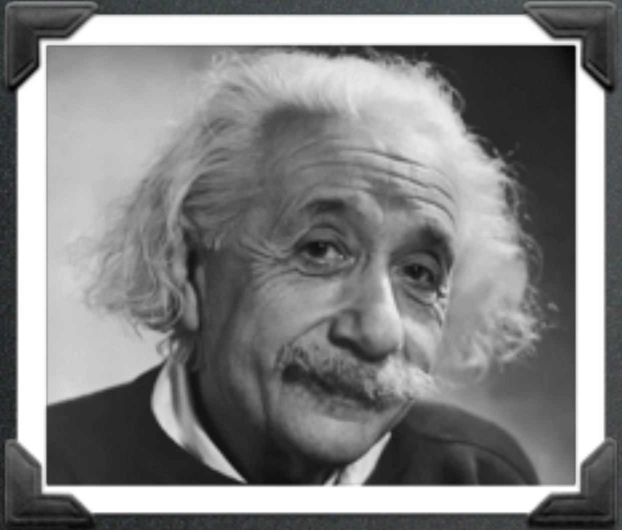

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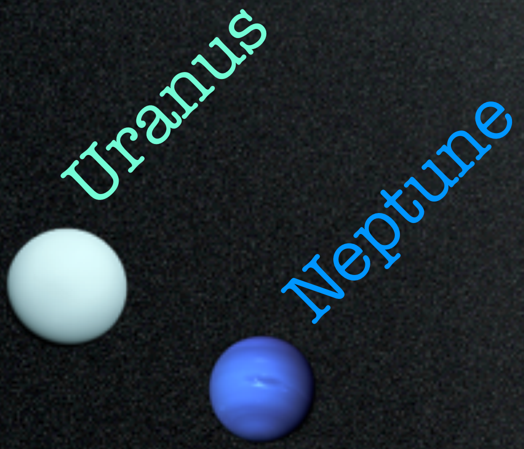

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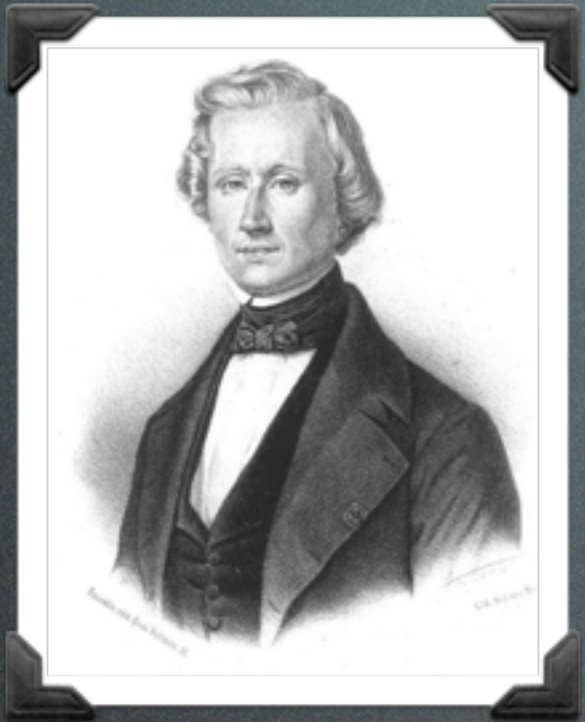

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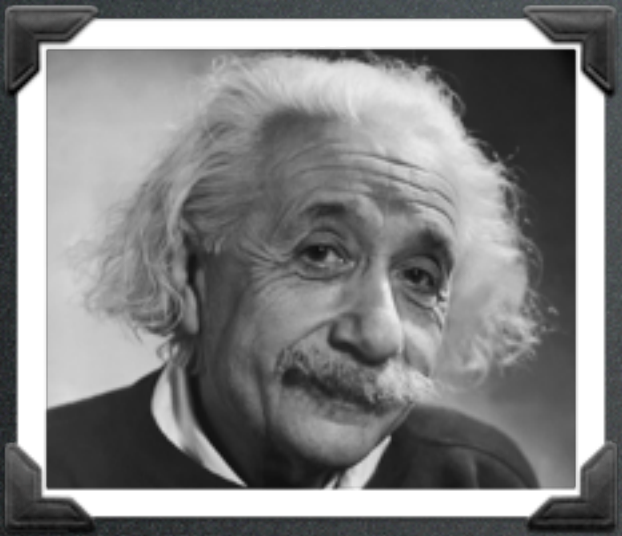

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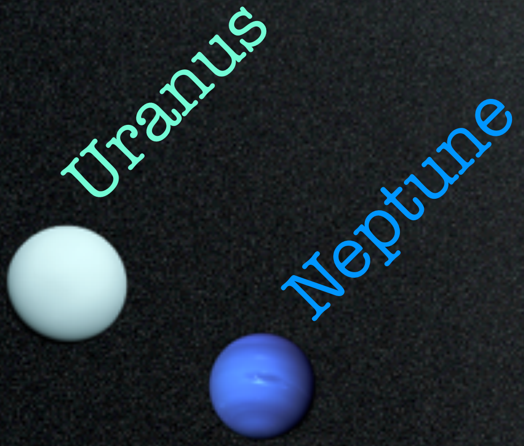
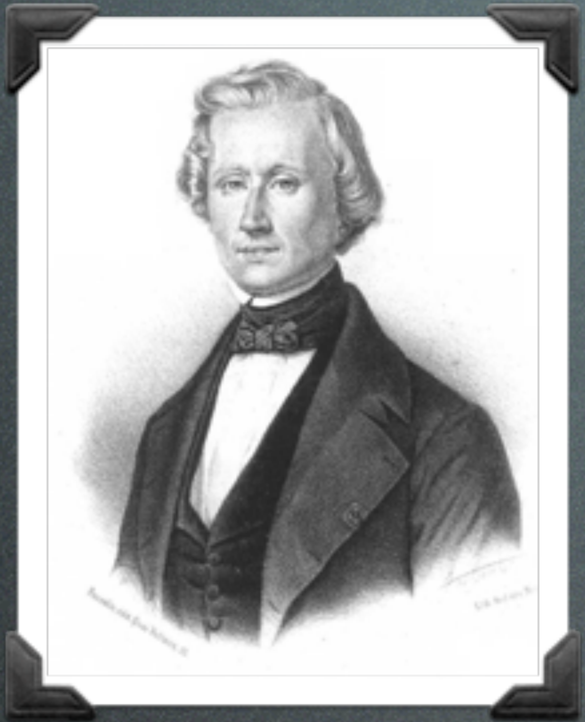
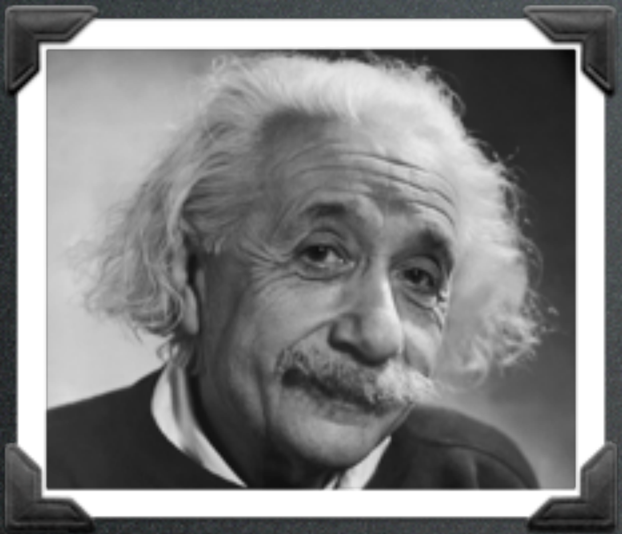


✓

1859



Urbain Le Verrier



✗

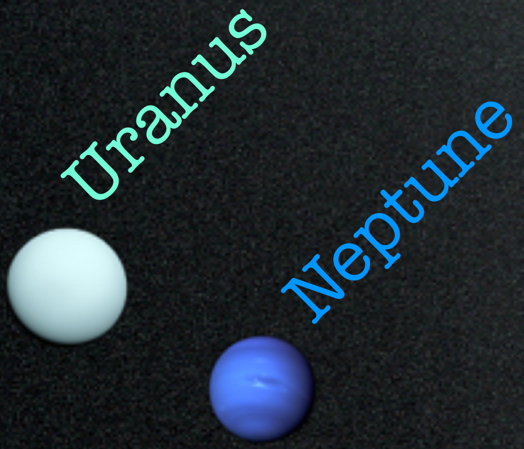
1981

Mordehai Milgrom

Modified gravity?

1846

Urbain Le Verrier



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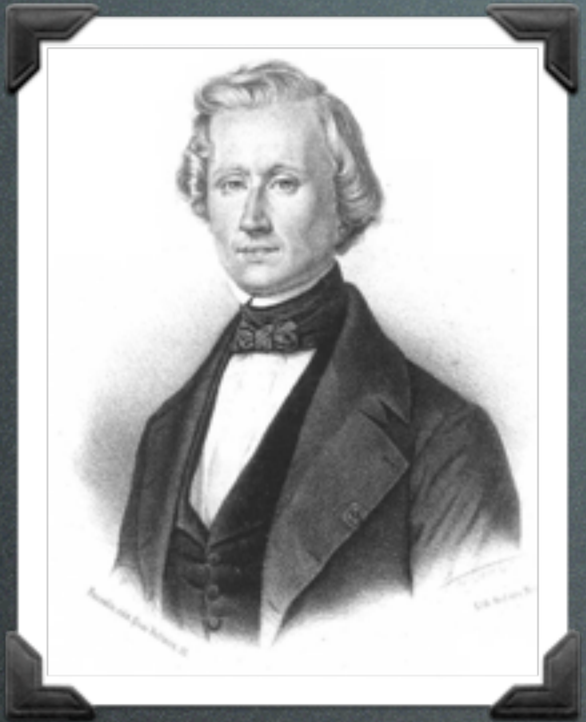

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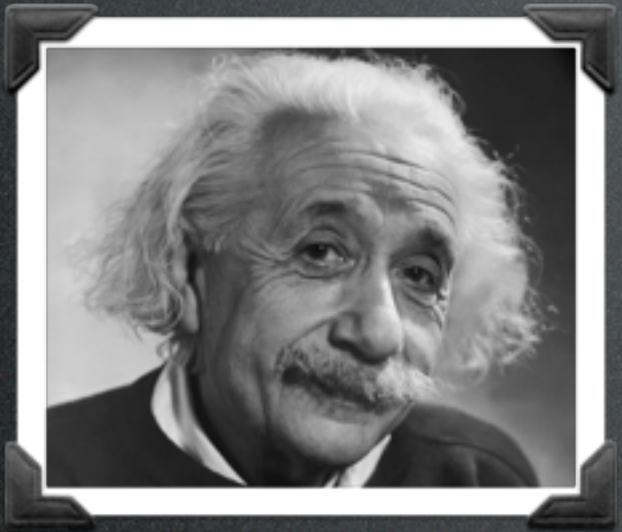


✗

1981

Mordehai Milgrom

$$F = m\,a \longrightarrow F = m\,a \cdot \mu(a)$$

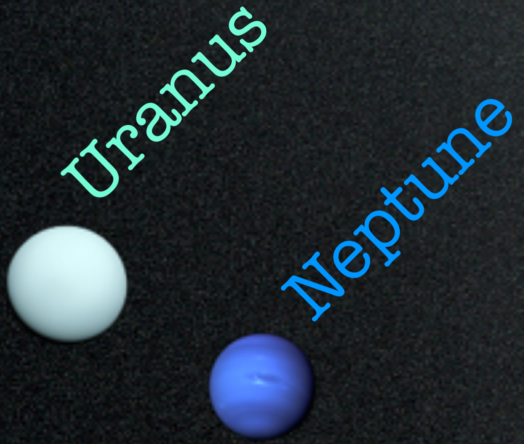
$$\mu(a) = \begin{cases} 1 & a > a_0 \\ a/a_0 & a \sim a_0 \end{cases}$$

$$a_0 = 1.2 \cdot 10^{-10} m/s^2$$

Modified gravity?

1846

Urbain Le Verrier



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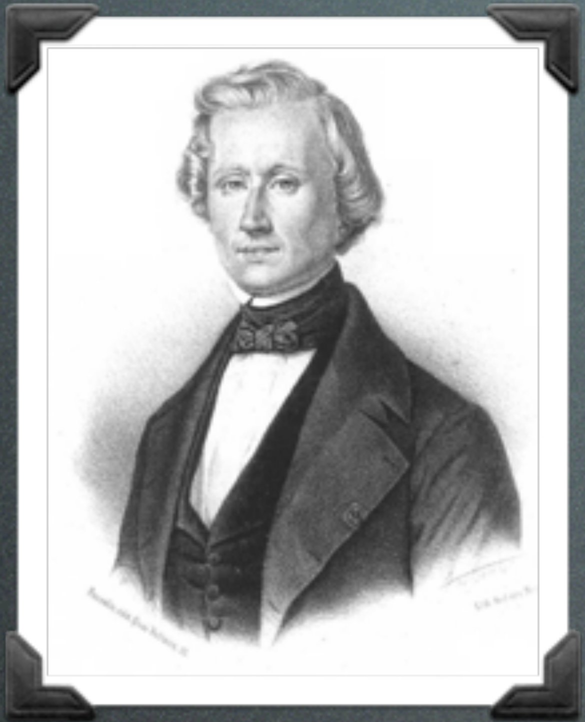

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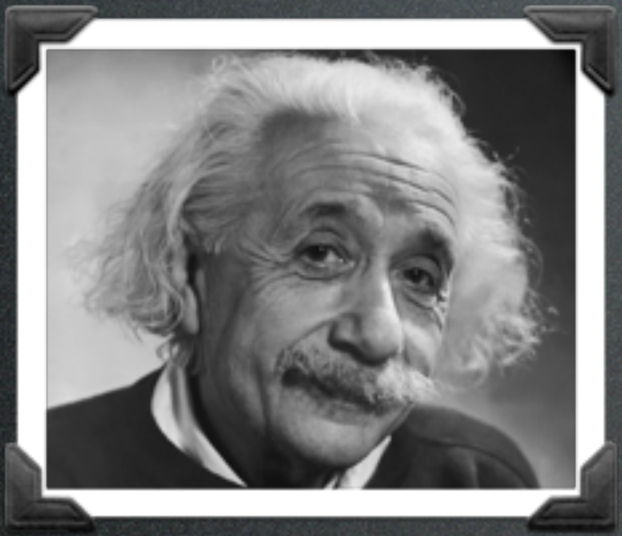

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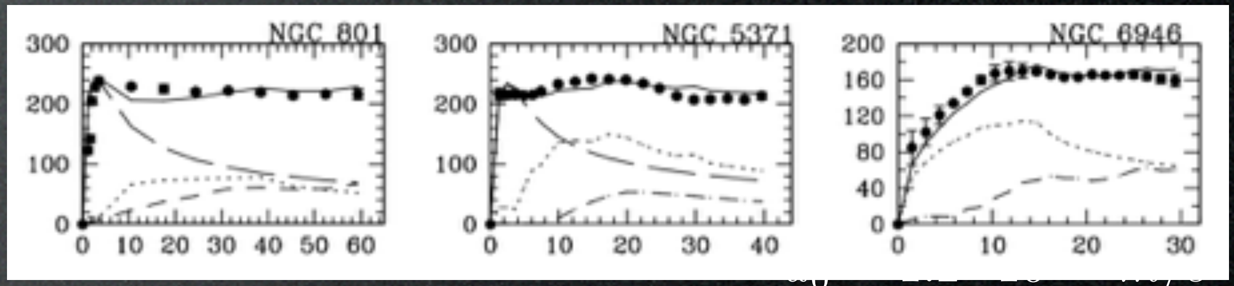

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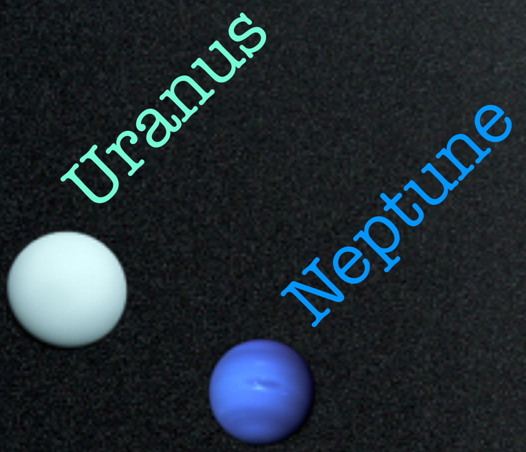

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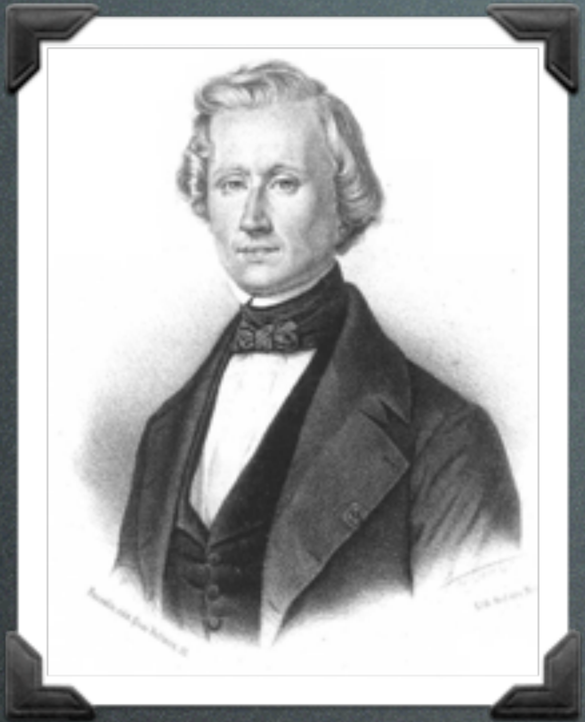

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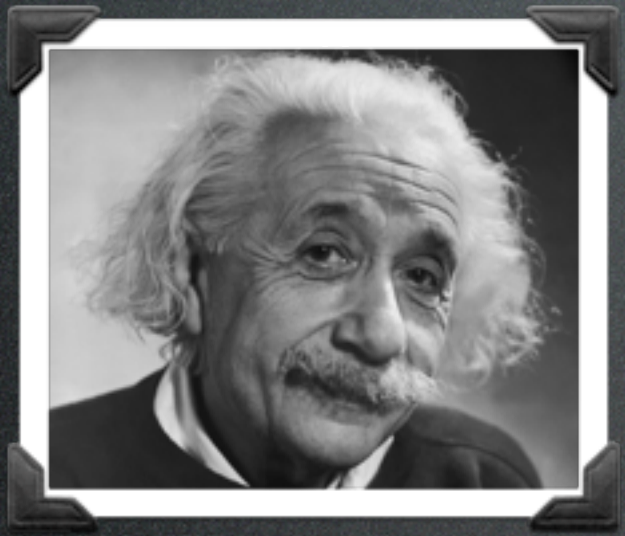

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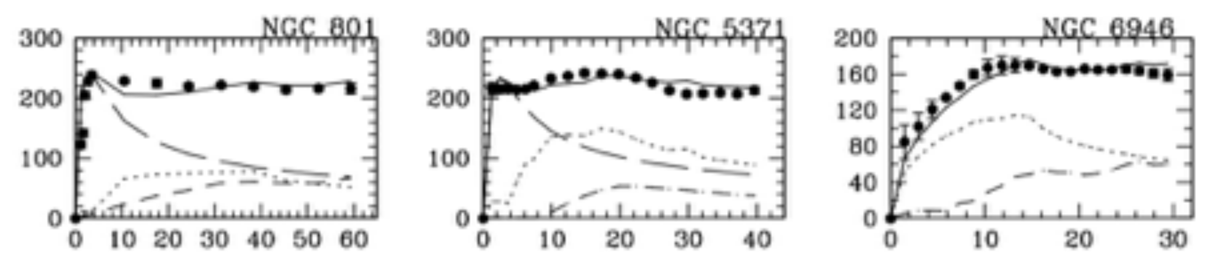


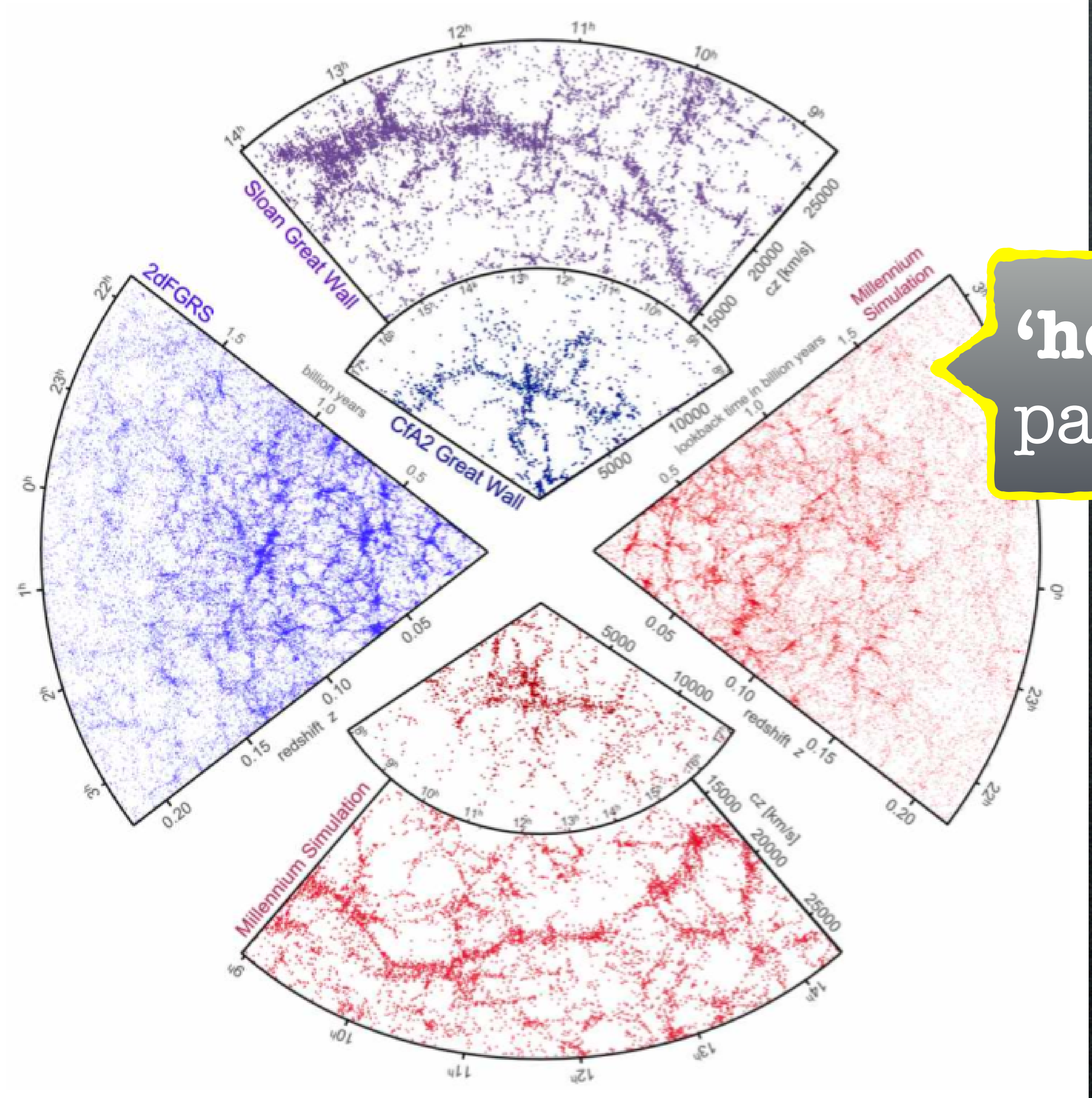
?


DETOUR

The Evidence for DM

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billions
d'années lumière



'**heavy**'
particles

Millennium:
10^{10} particules,
500 h^{-1} Mpc

Springel, Frenk, White, Nature 440 (2006)

The Evidence for DM

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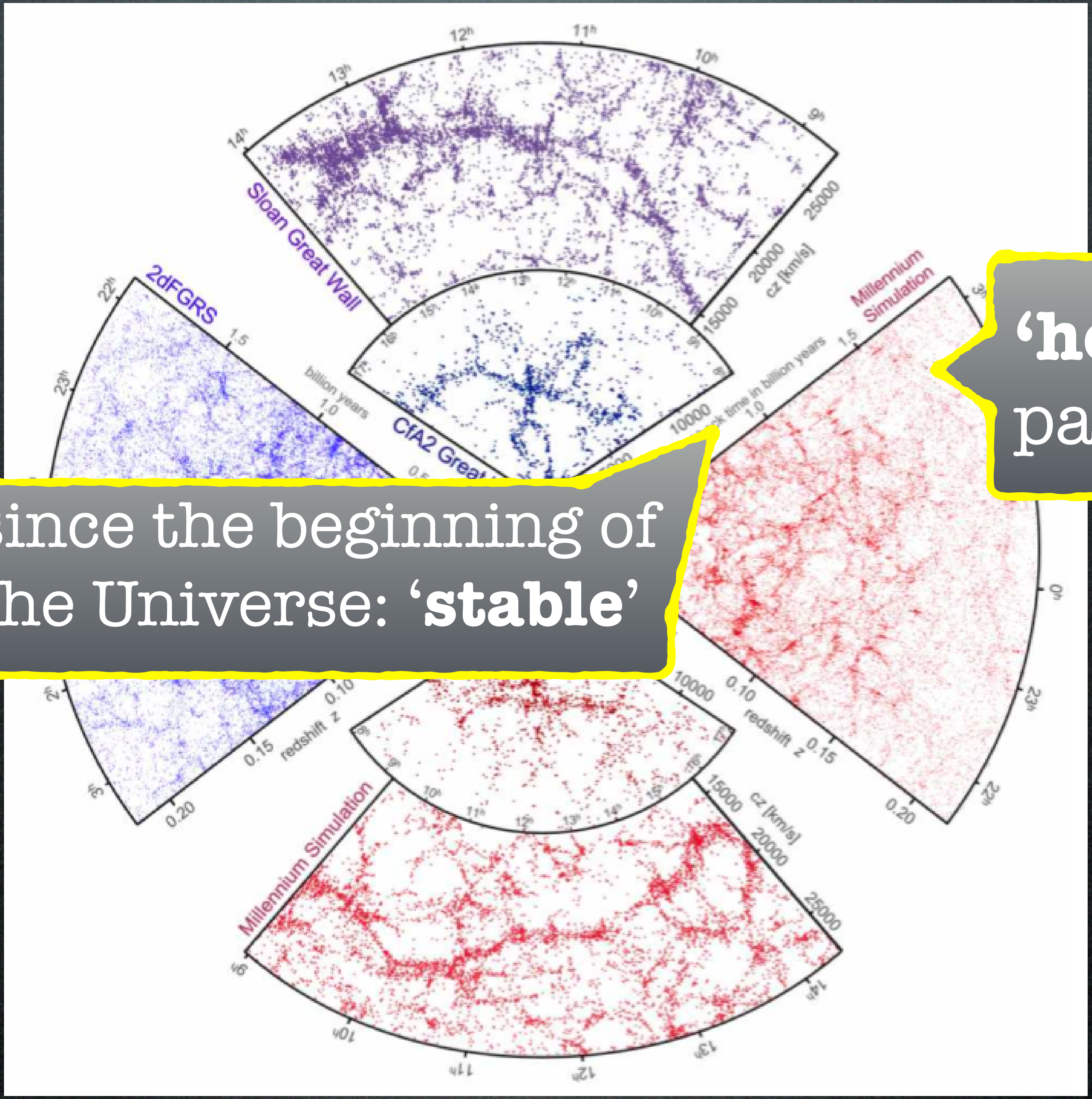

'**heavy**' particles

since the beginning of the Universe: '**stable**'

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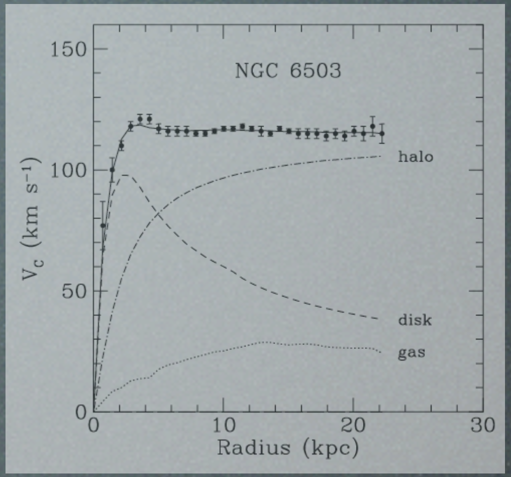
Springel, Frenk, White, Nature 440 (2006)

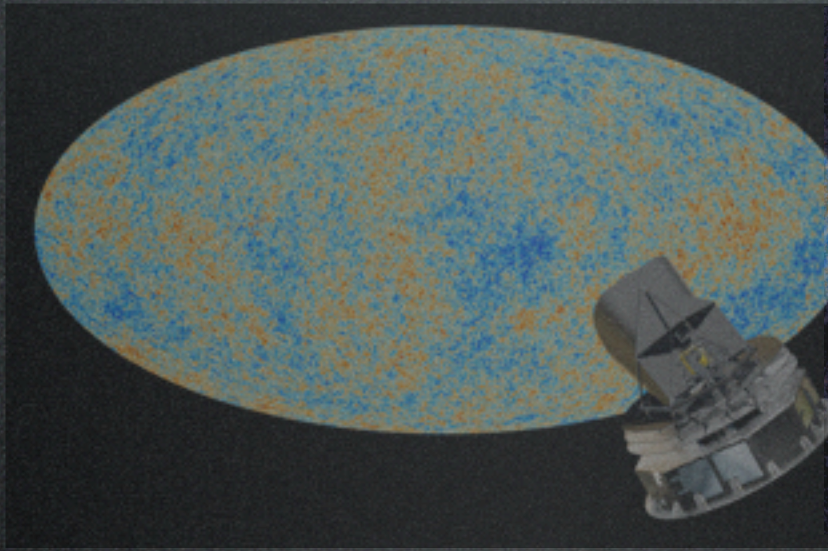
The Evidence for DM

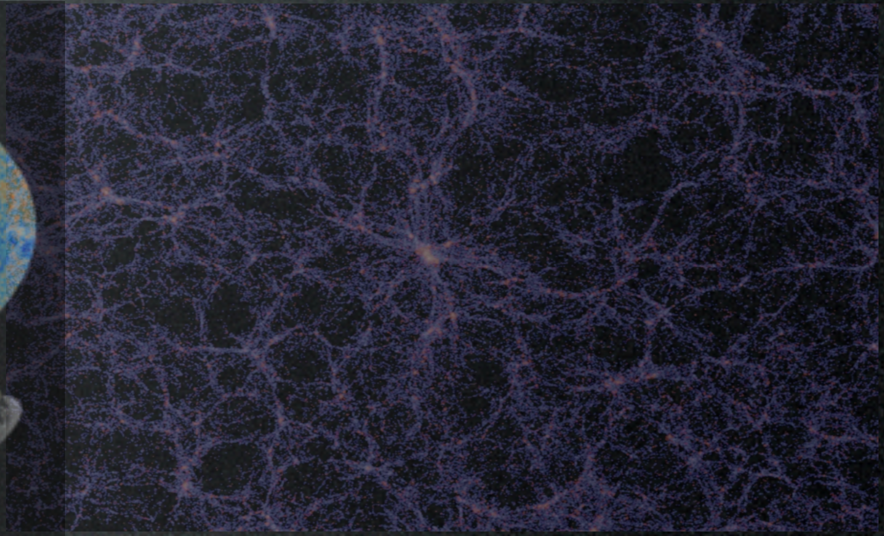
1) galaxy rotation curves



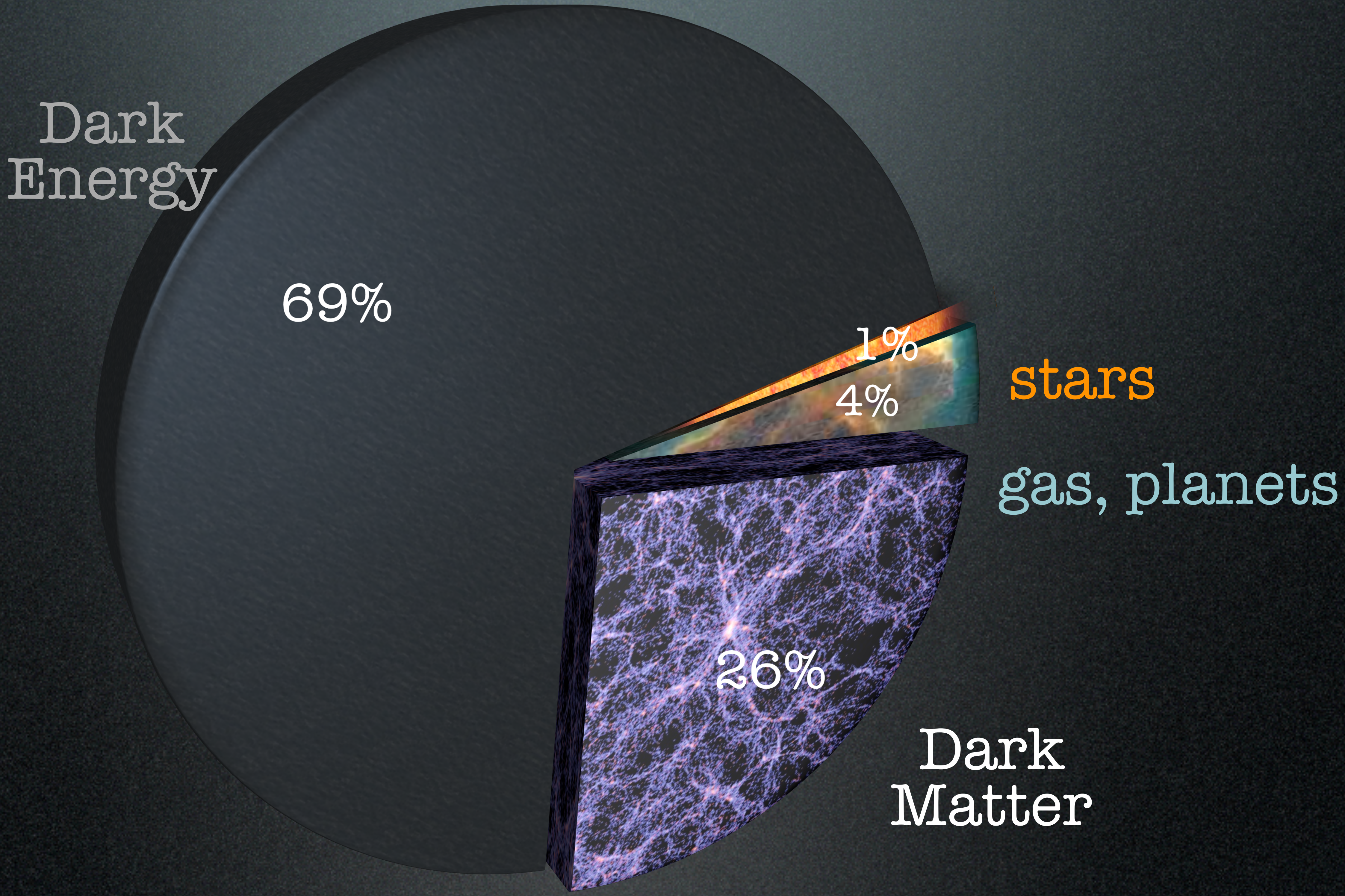
2) clusters of galaxies

3) ‘precision cosmology’

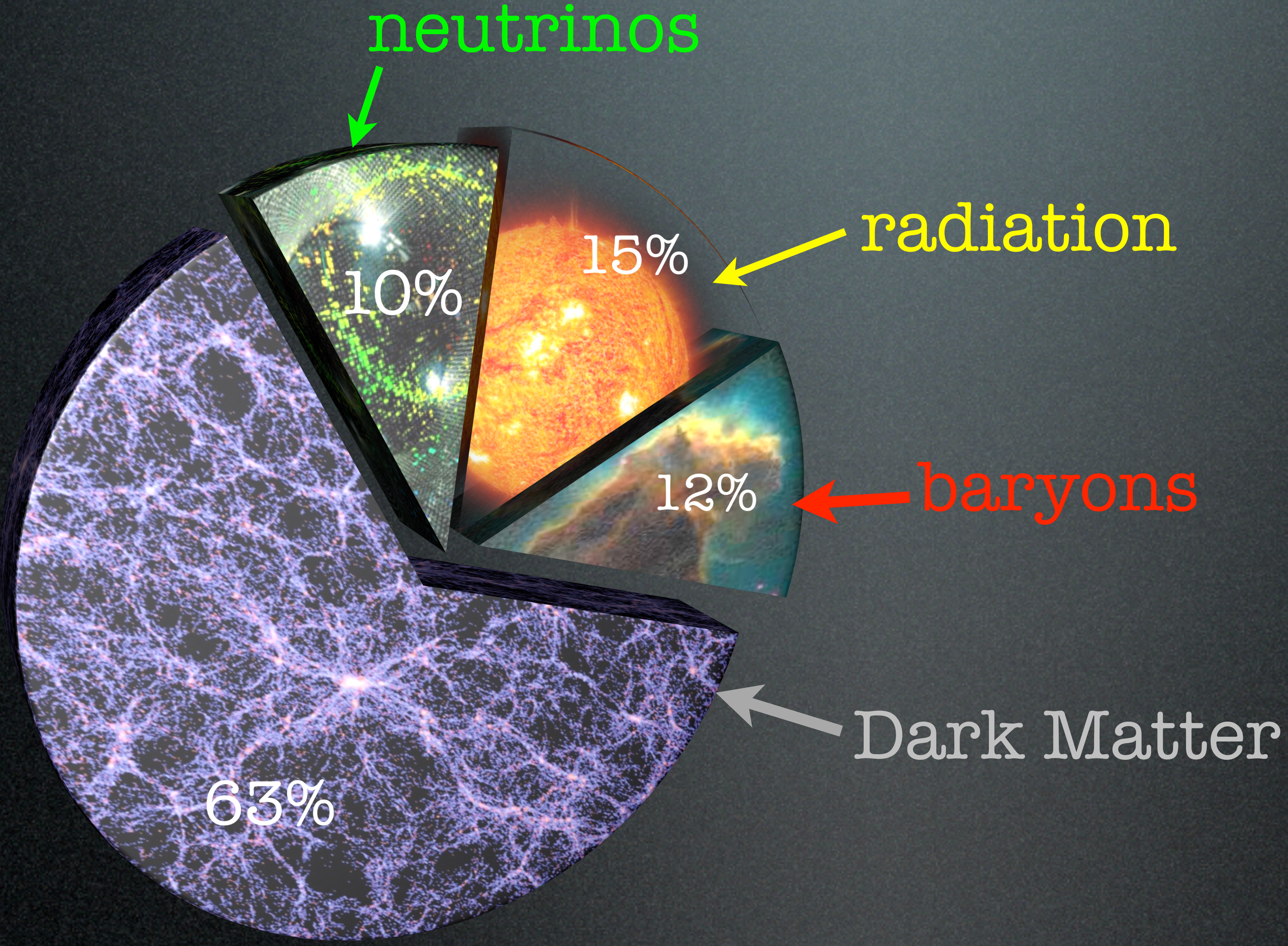




95% of the Universe is unknown, dark



The cosmic inventory



At the time of CMB formation (380 Ky)

What do we know of the particle physics properties of Dark Matter?

Nature and properties

does not emit light,
it is ‘**neutral**’

‘**heavy**’
particles

since the beginning of
the Universe: ‘**stable**’

more abundant
than ordinary
matter!

no or very feeble
interactions

Nature and properties

‘heavy’ particles

‘neutral’

‘stable’

almost no interactions

Nature and properties

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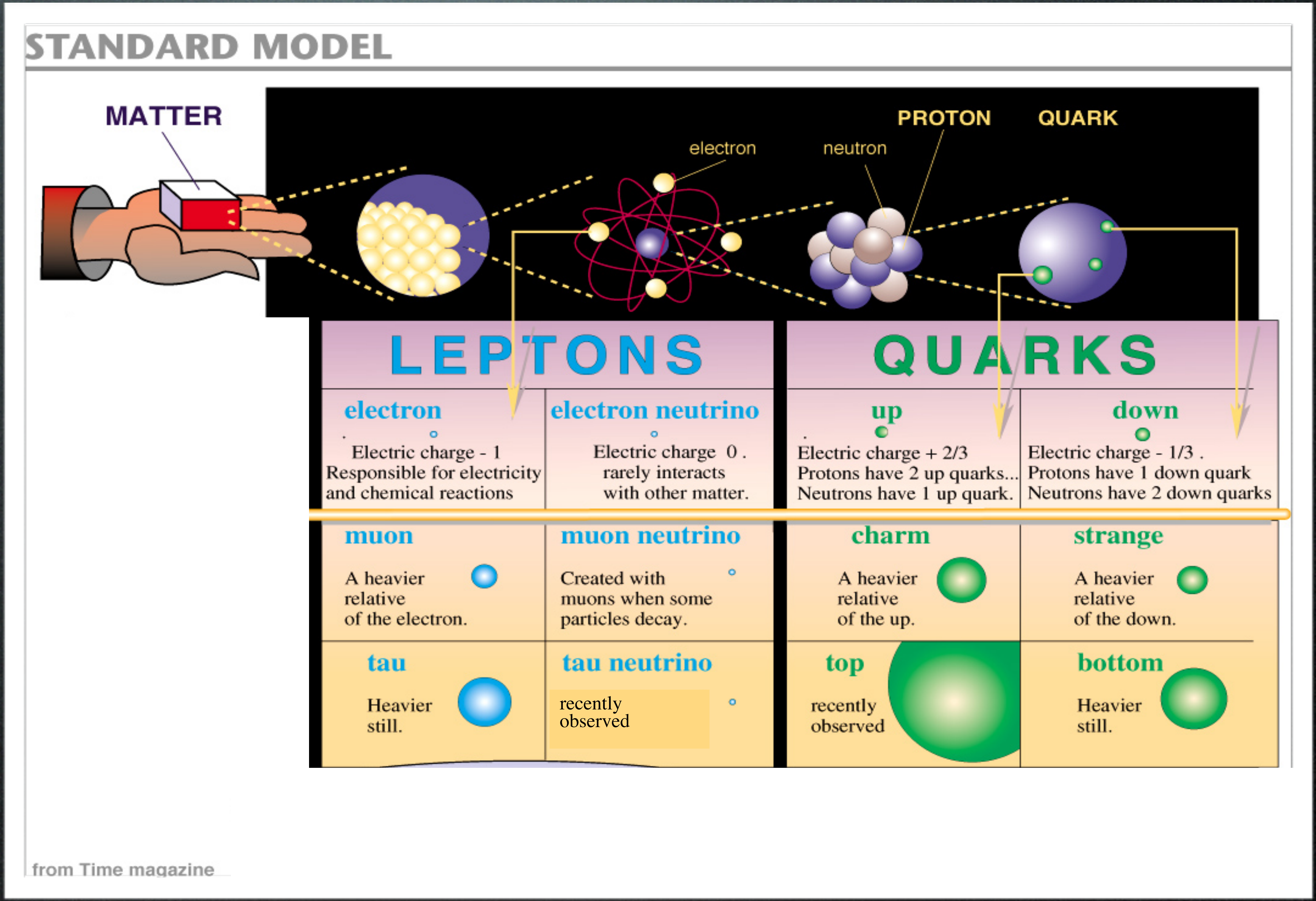

STANDARD MODEL

LEPTONS		QUARKS	
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from Time magazine

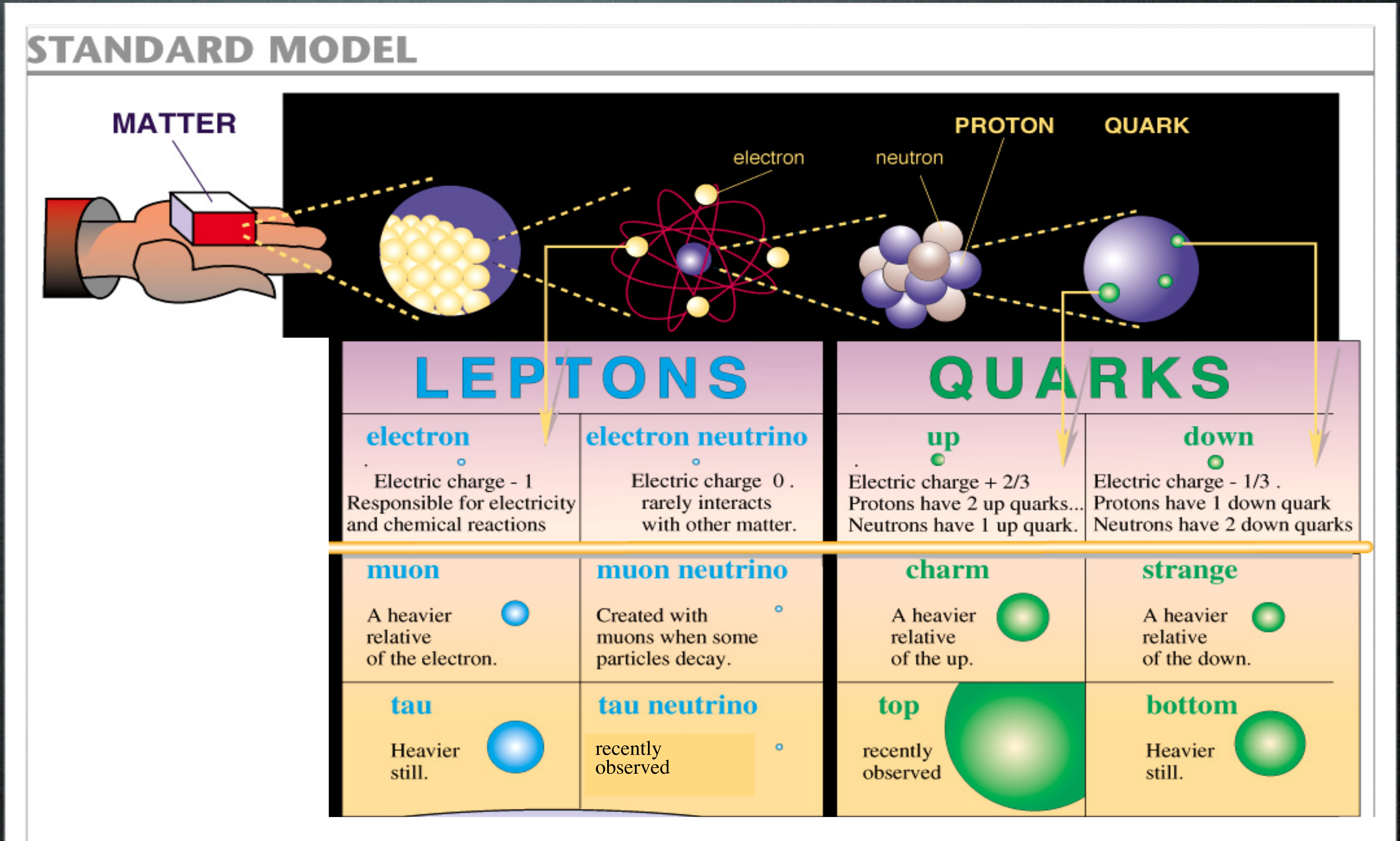
Nature and properties

‘heavy’ particles

‘neutral’

‘stable’

almost no interactions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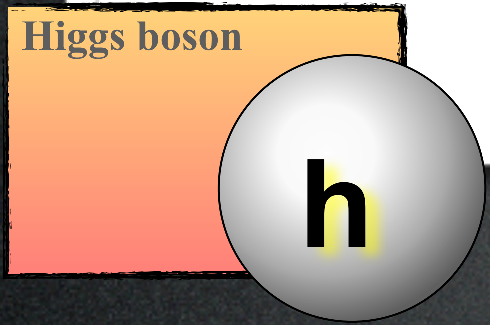
Higgs boson

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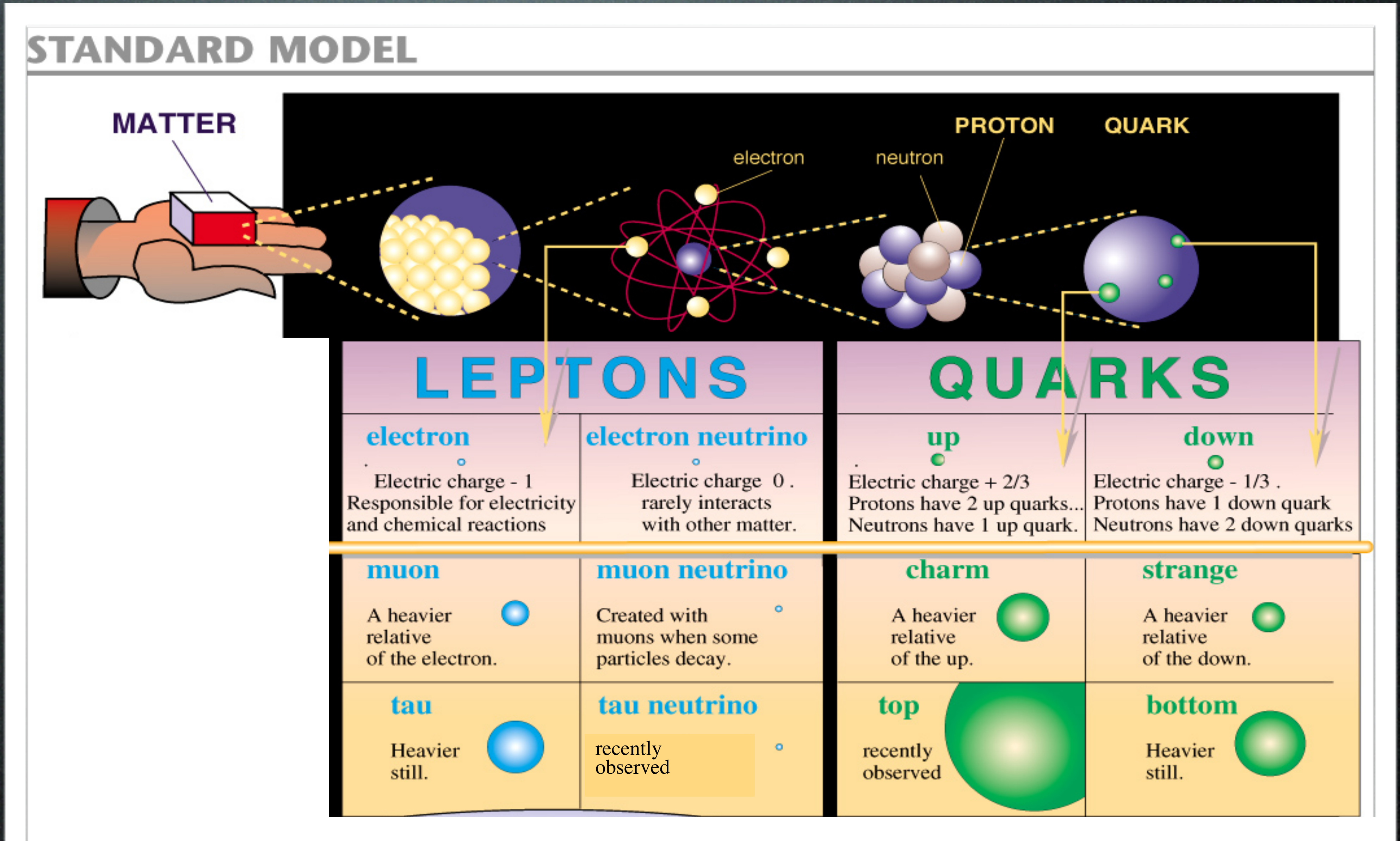

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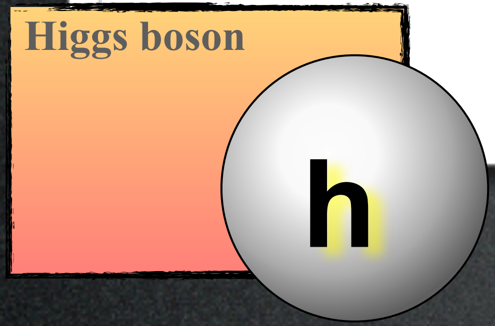

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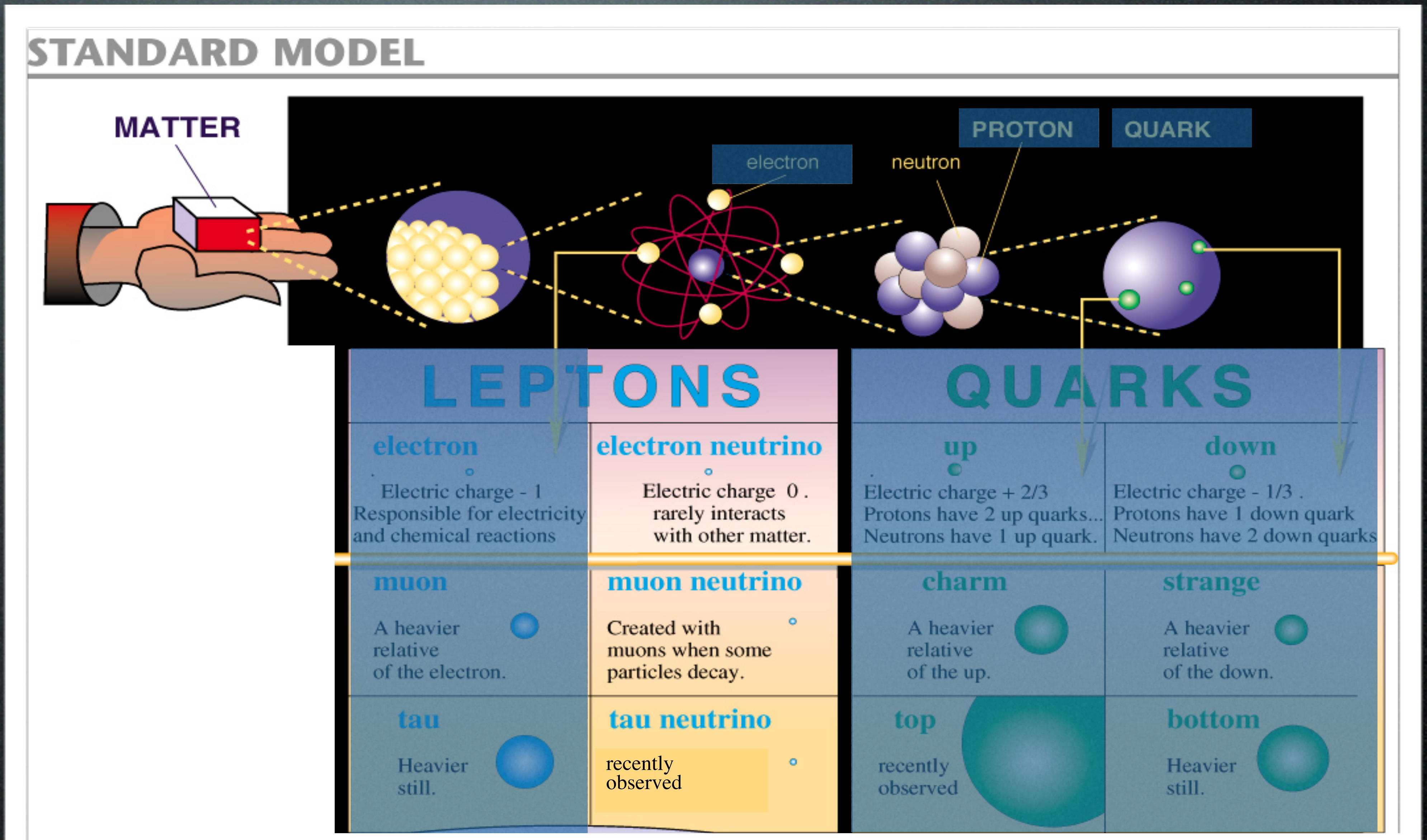

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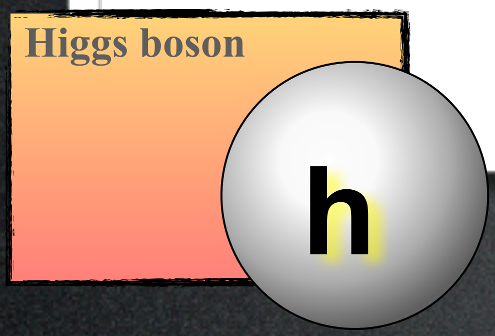

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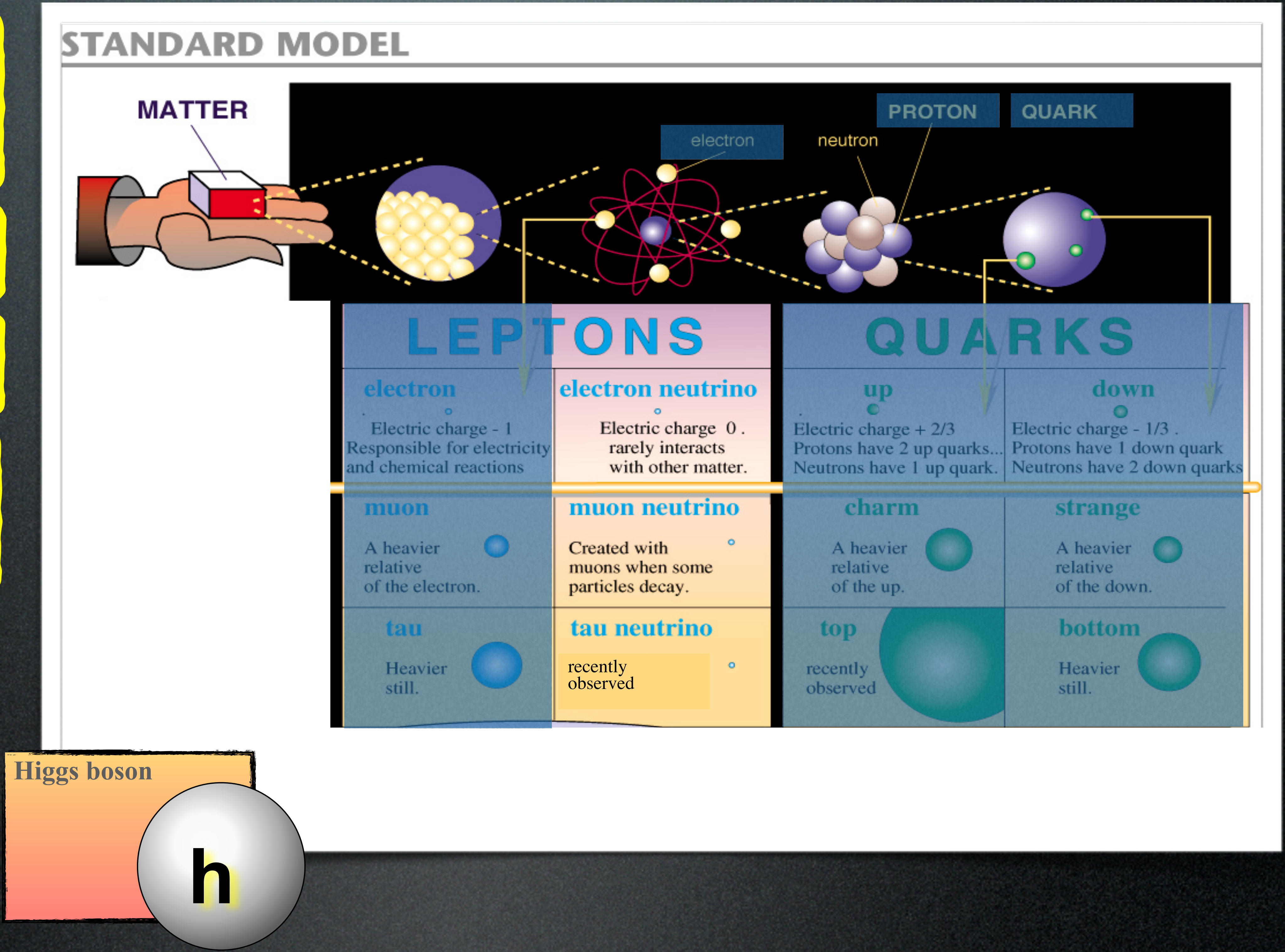

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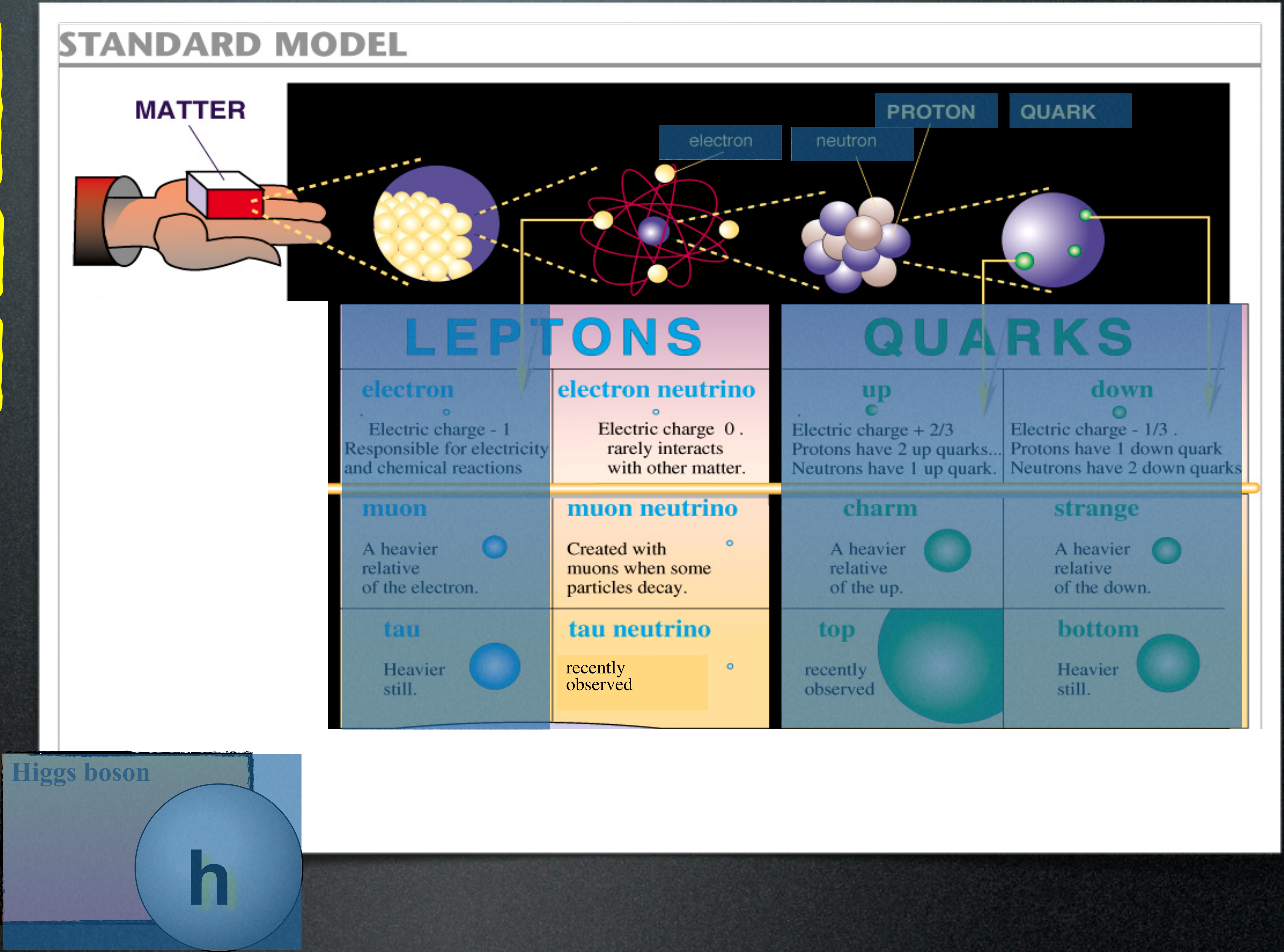

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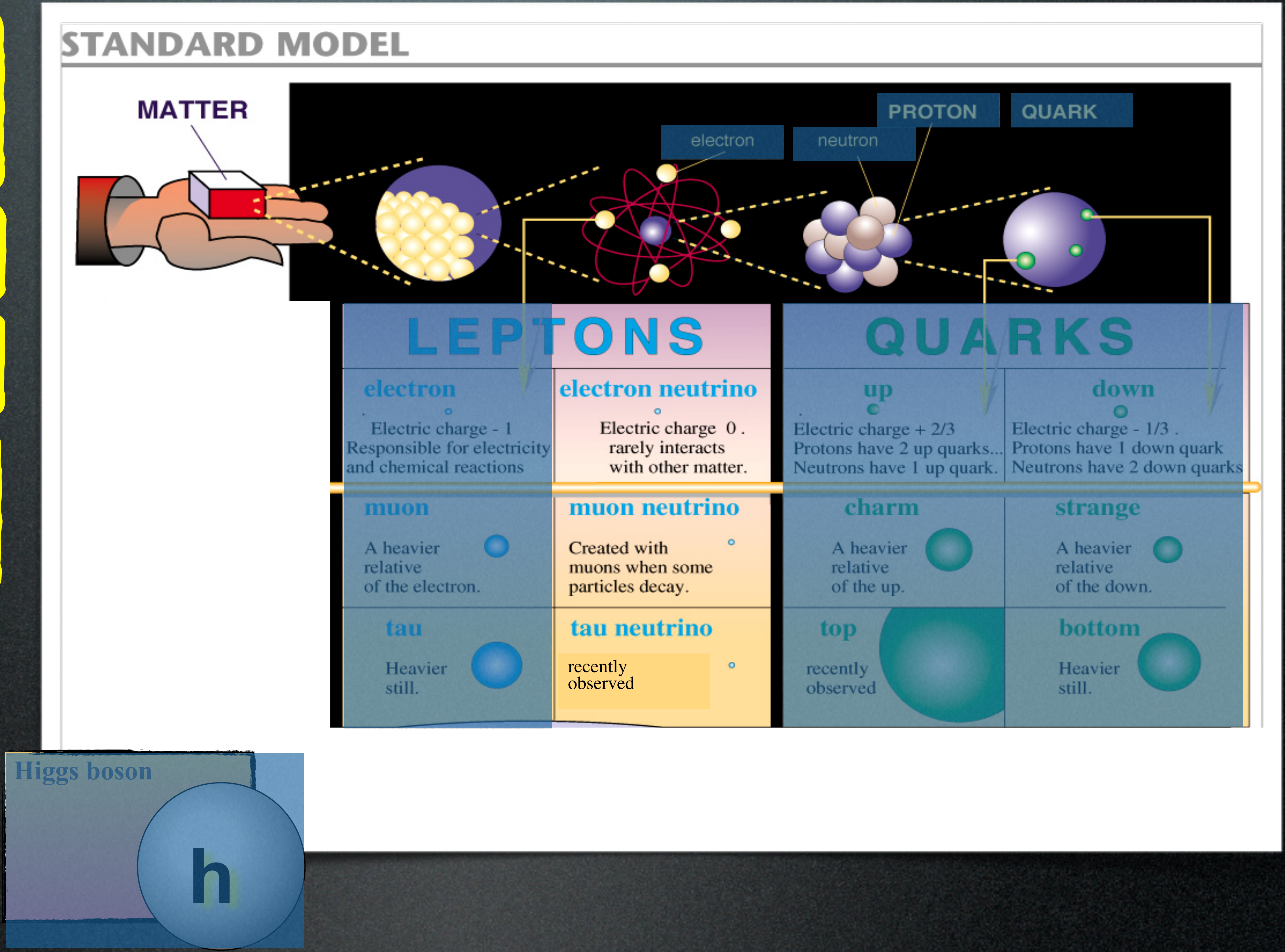

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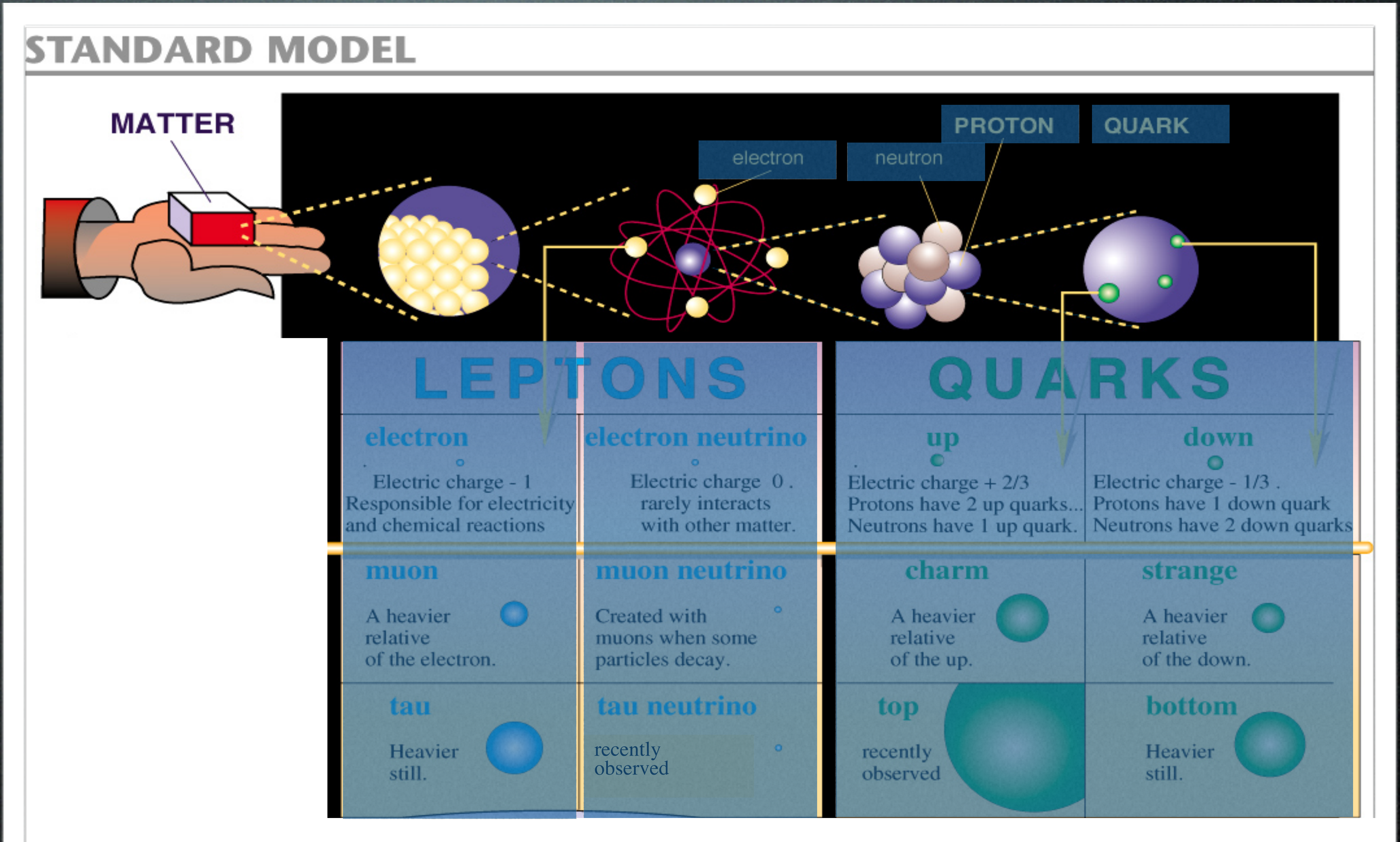

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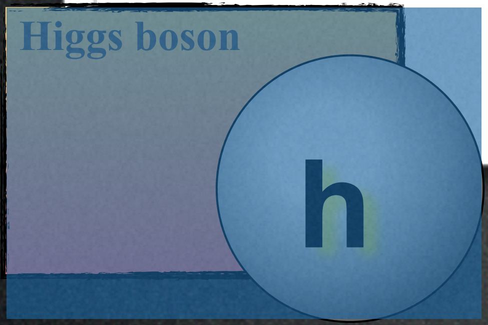
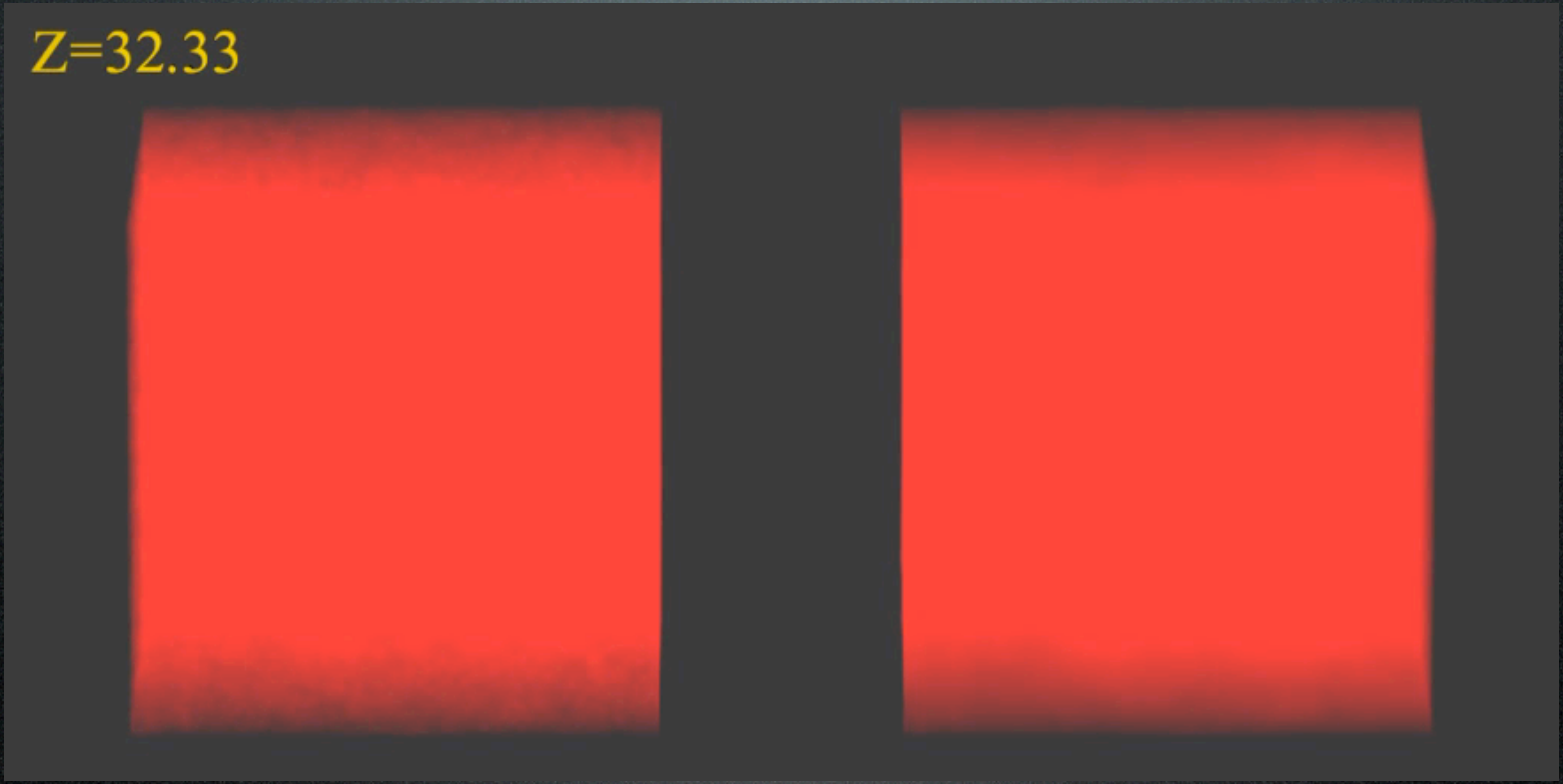


(Neutrino) DM



no HDM

$\sum m_\nu = 0$

some HDM

$\sum m_\nu = 6.9$ eV

ΛCDM - Gadget2 - 768 Mpc^3

T.Haugboelle, S.Hannestad, Aarhus University

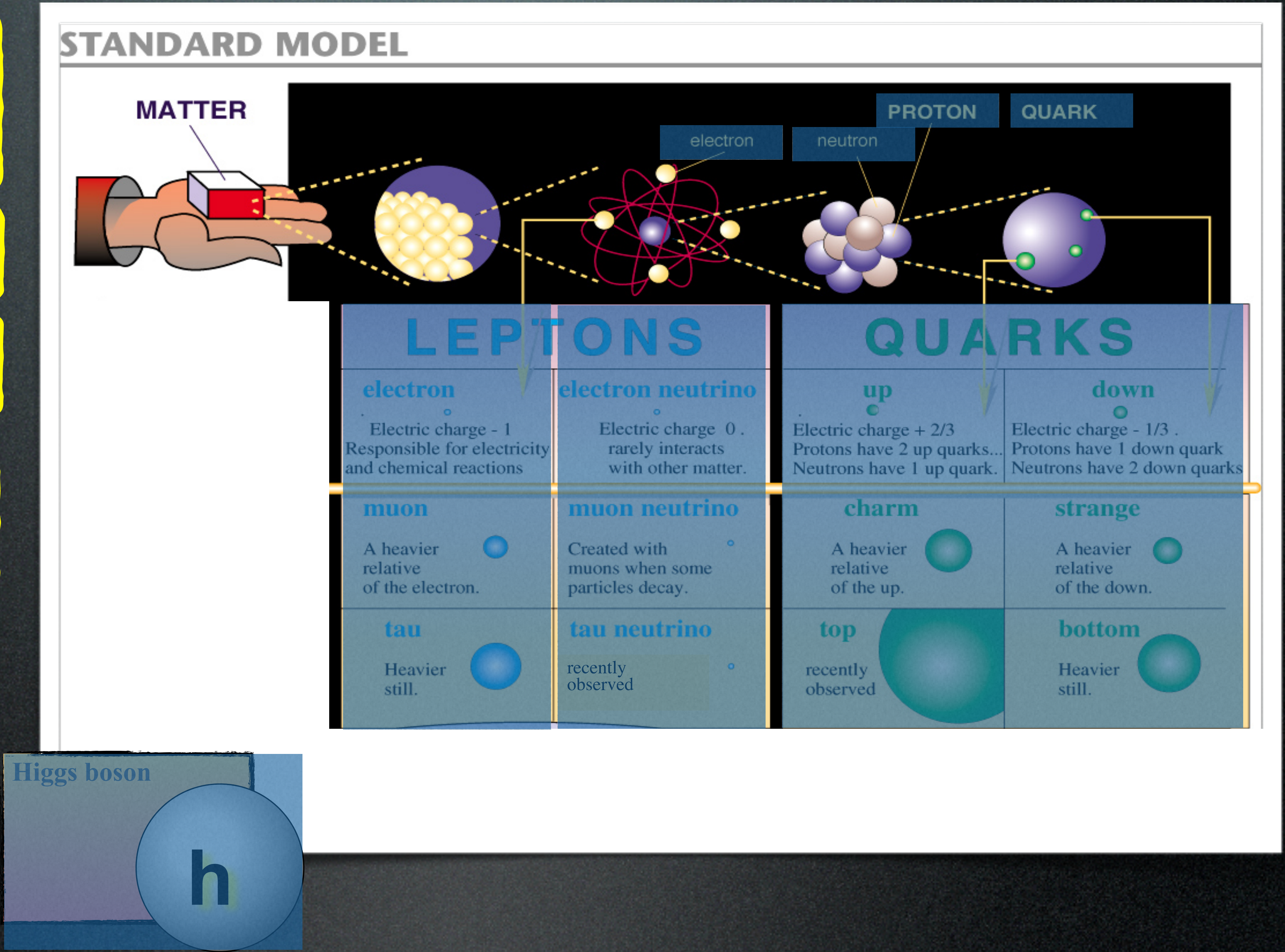
Nature and properties

'**heavy**' particles

'**neutral**'

'**stable**'

almost no interactions



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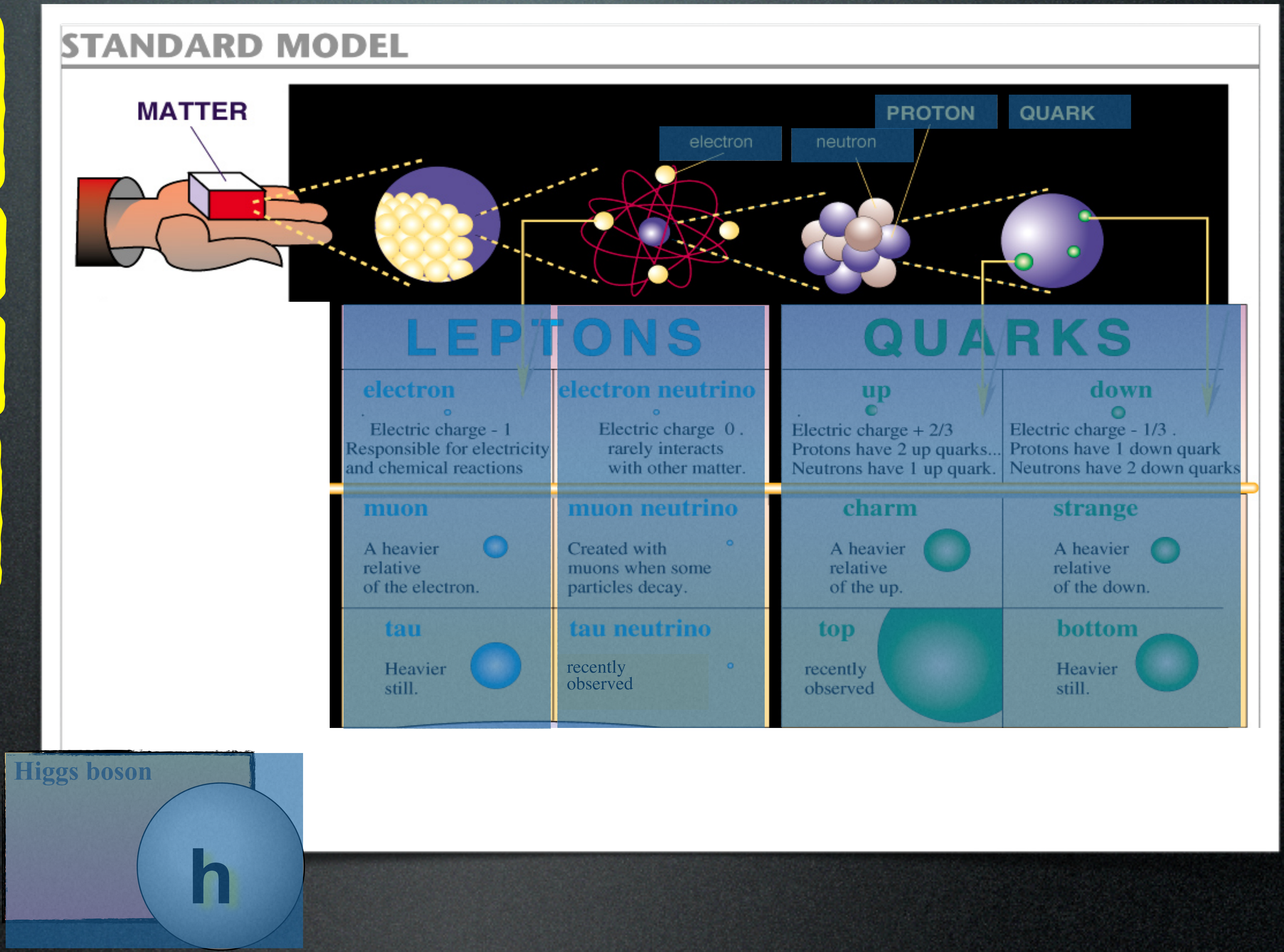
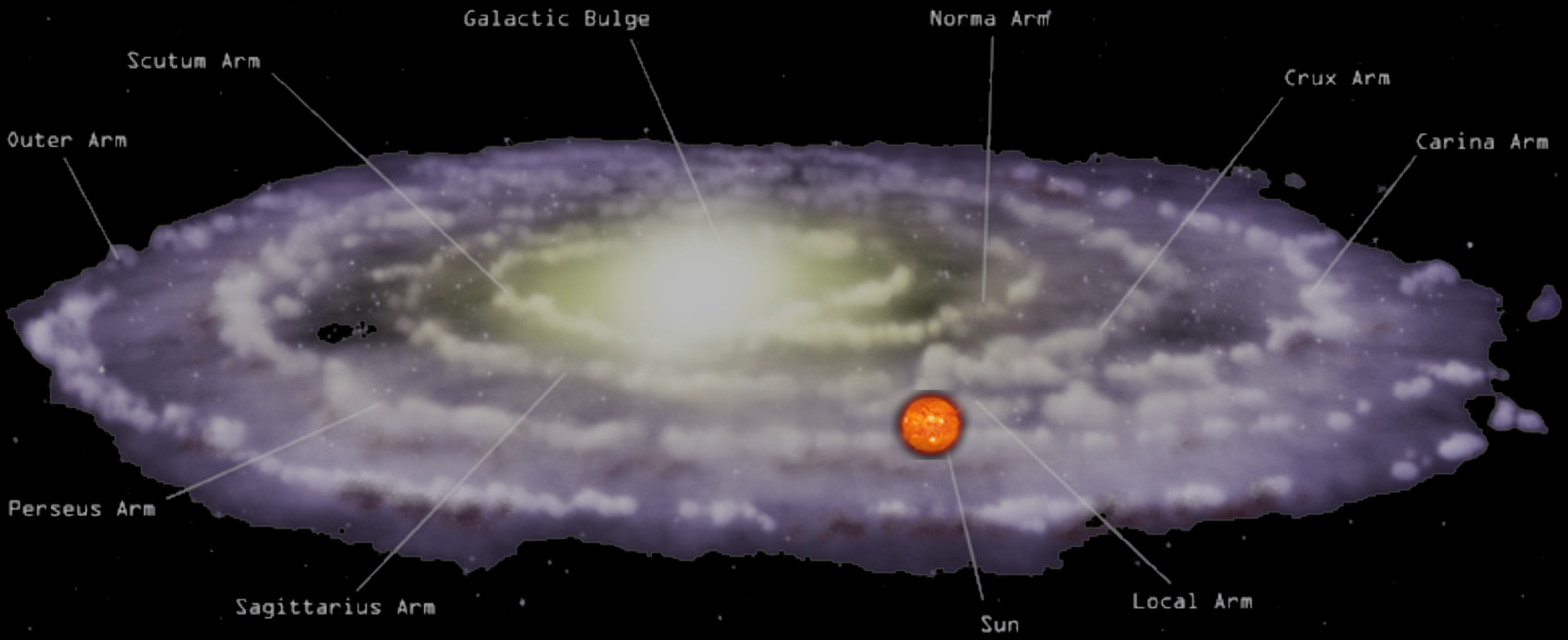


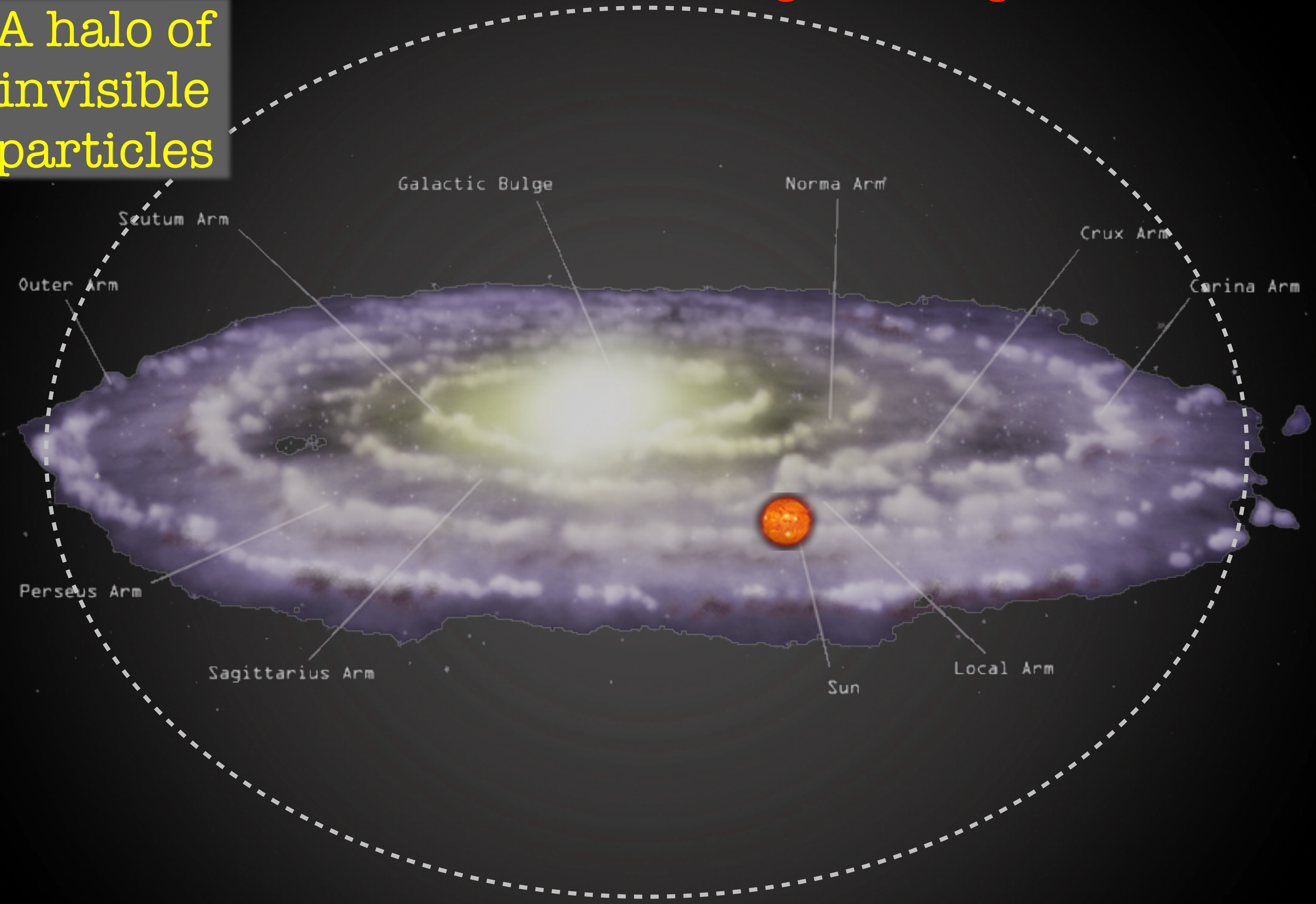
a **new** particle, still **unknown**

In the Milky Way



In the Milky Way

A halo of invisible particles



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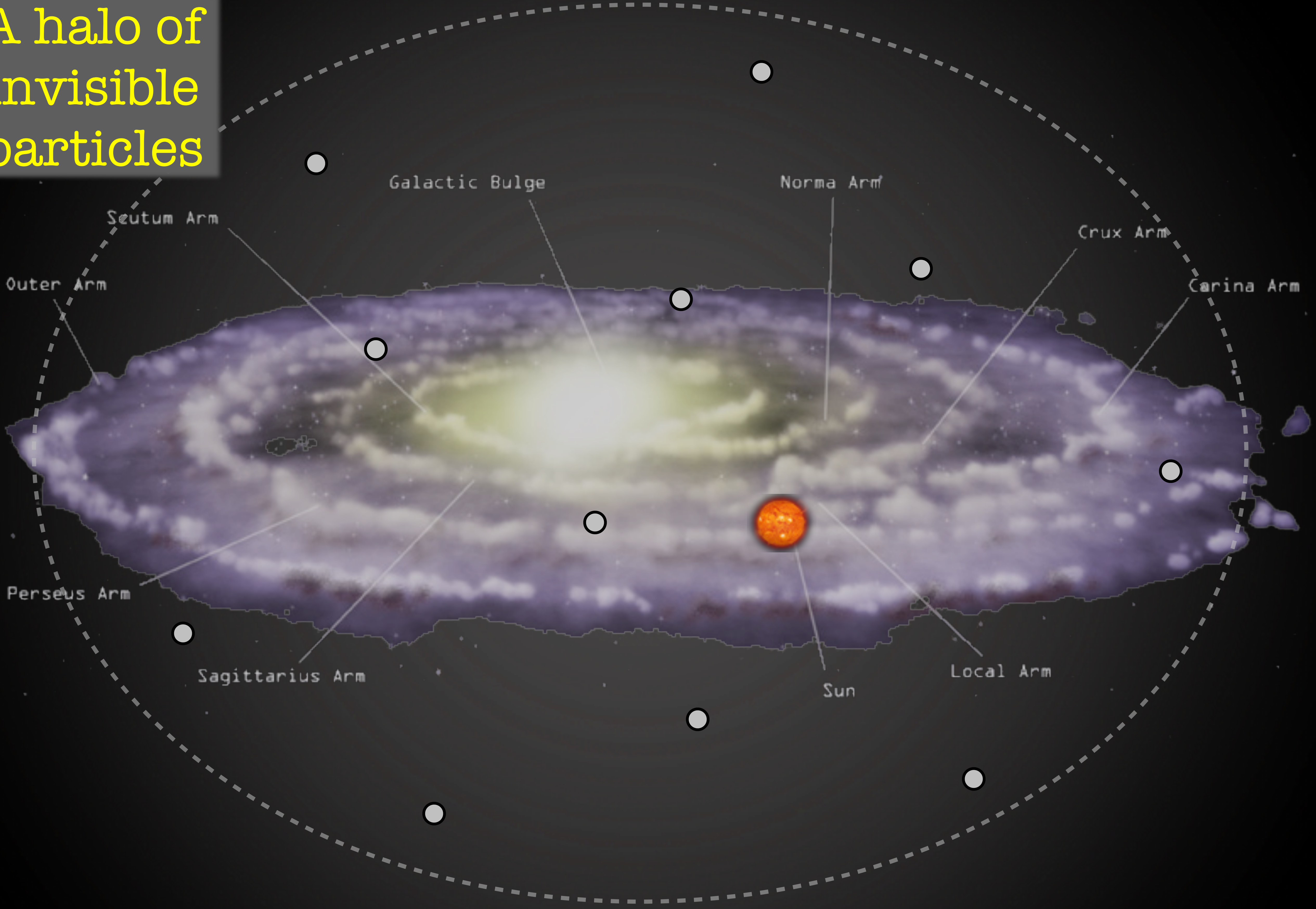

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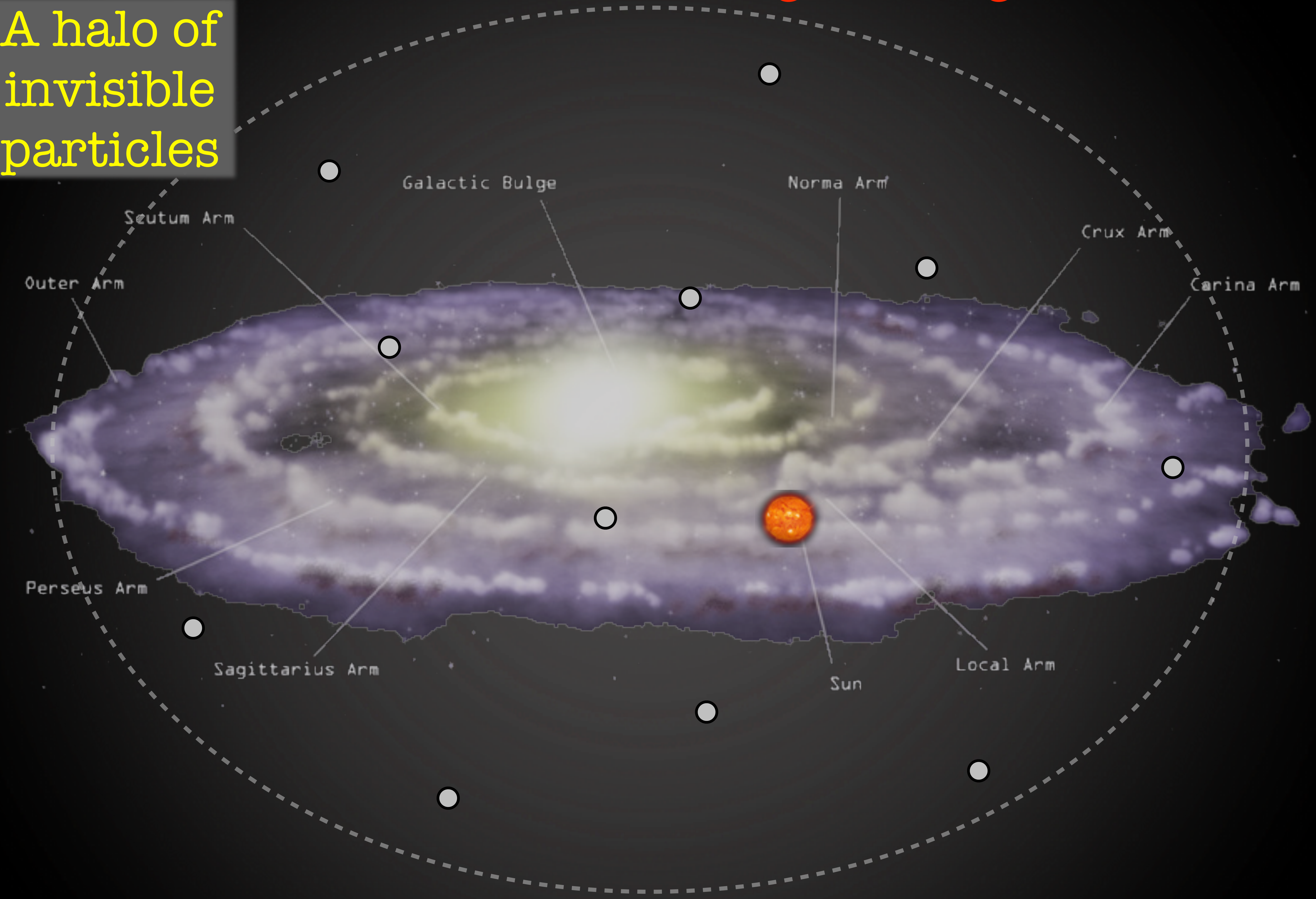

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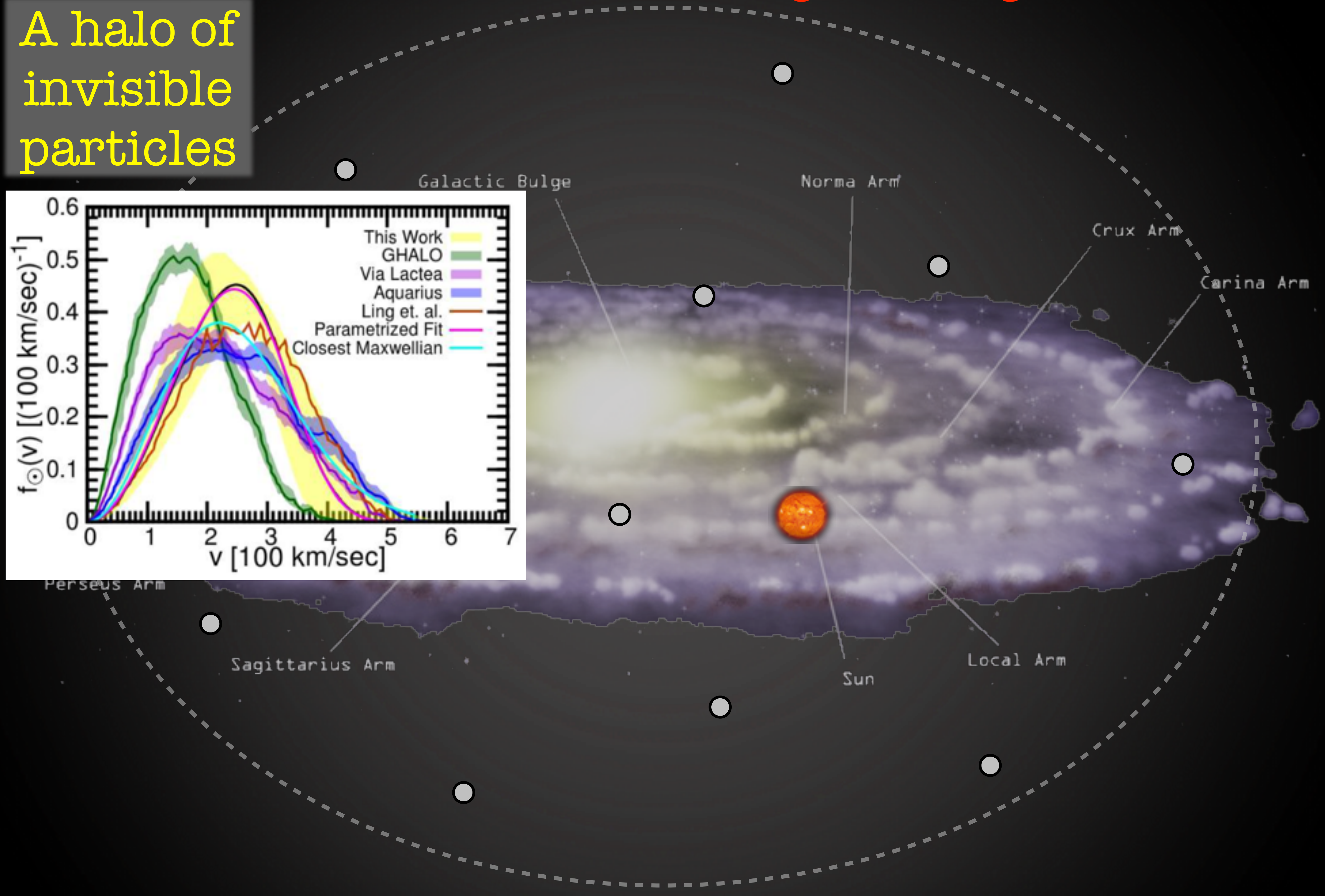

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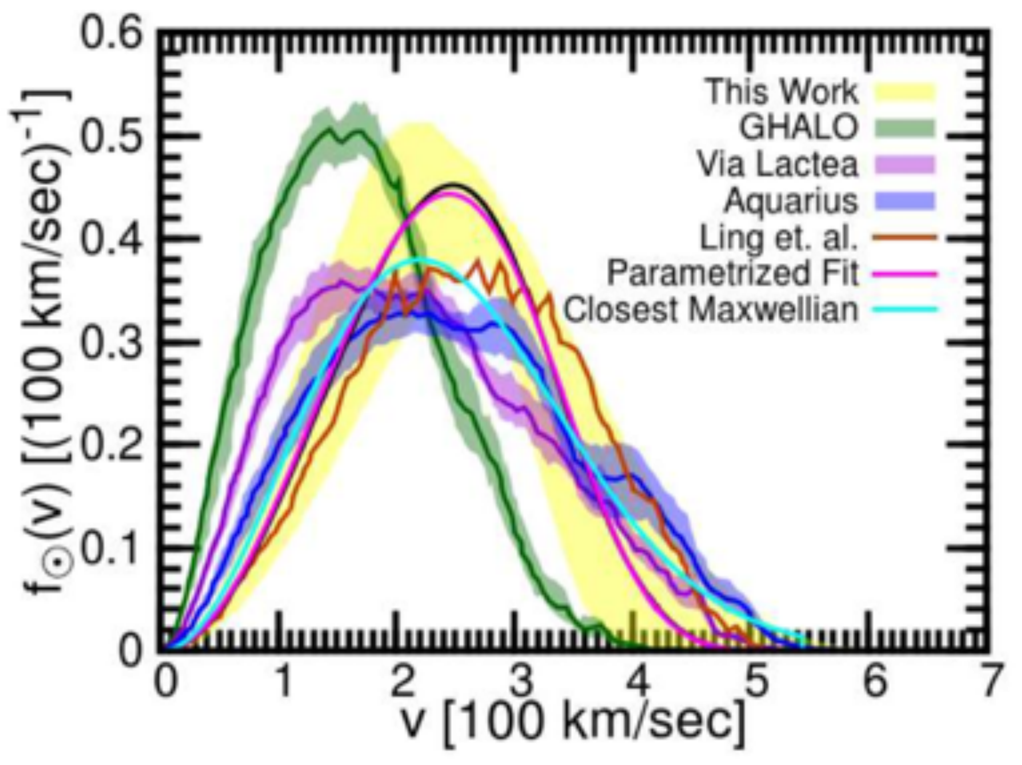
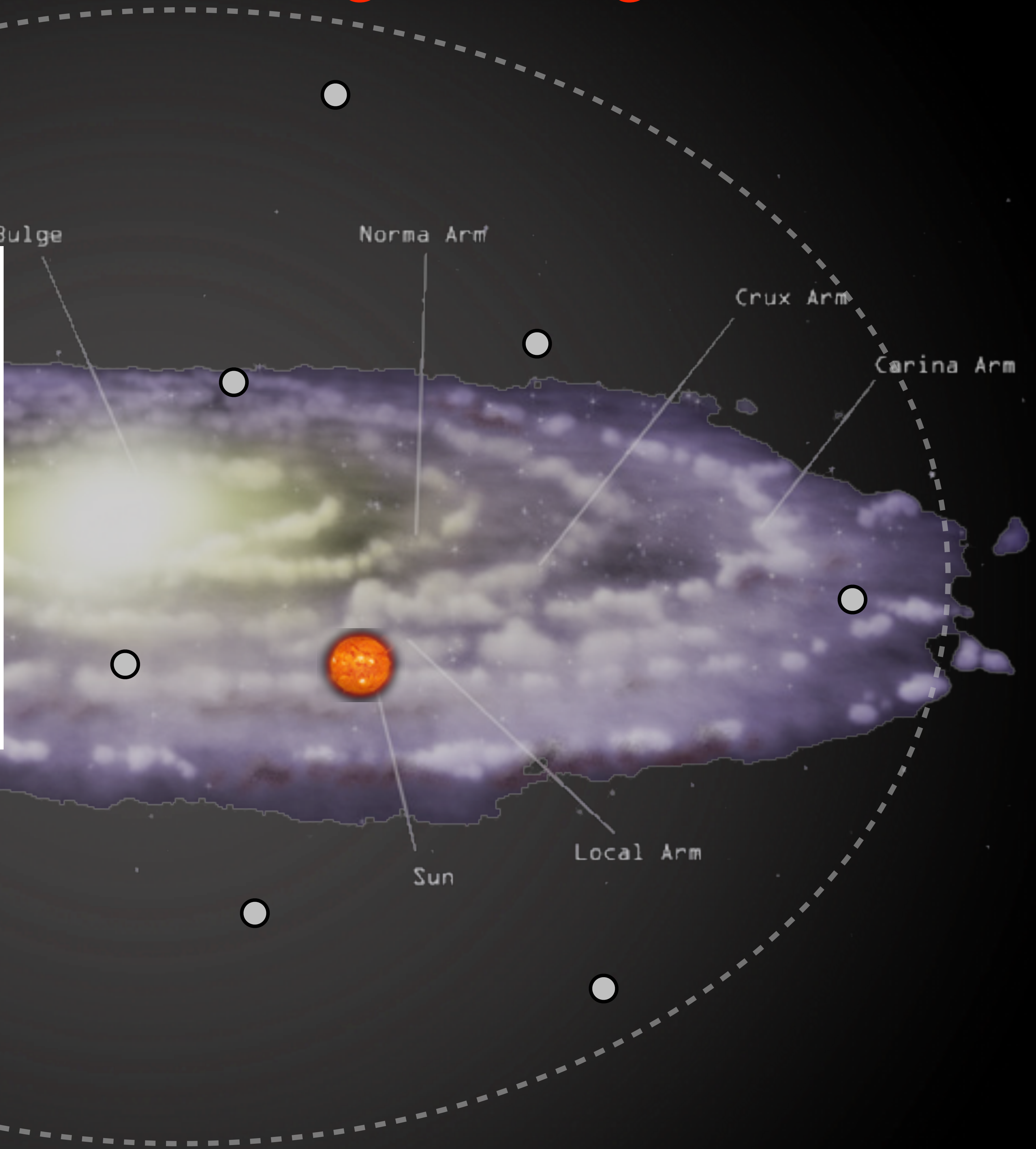
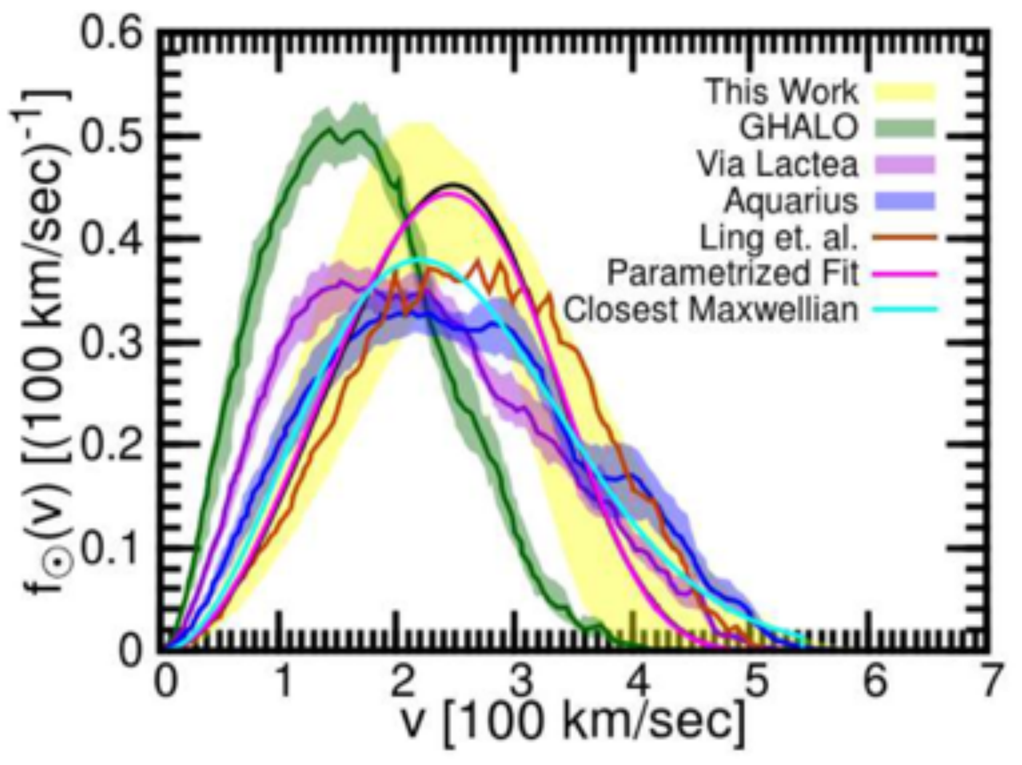


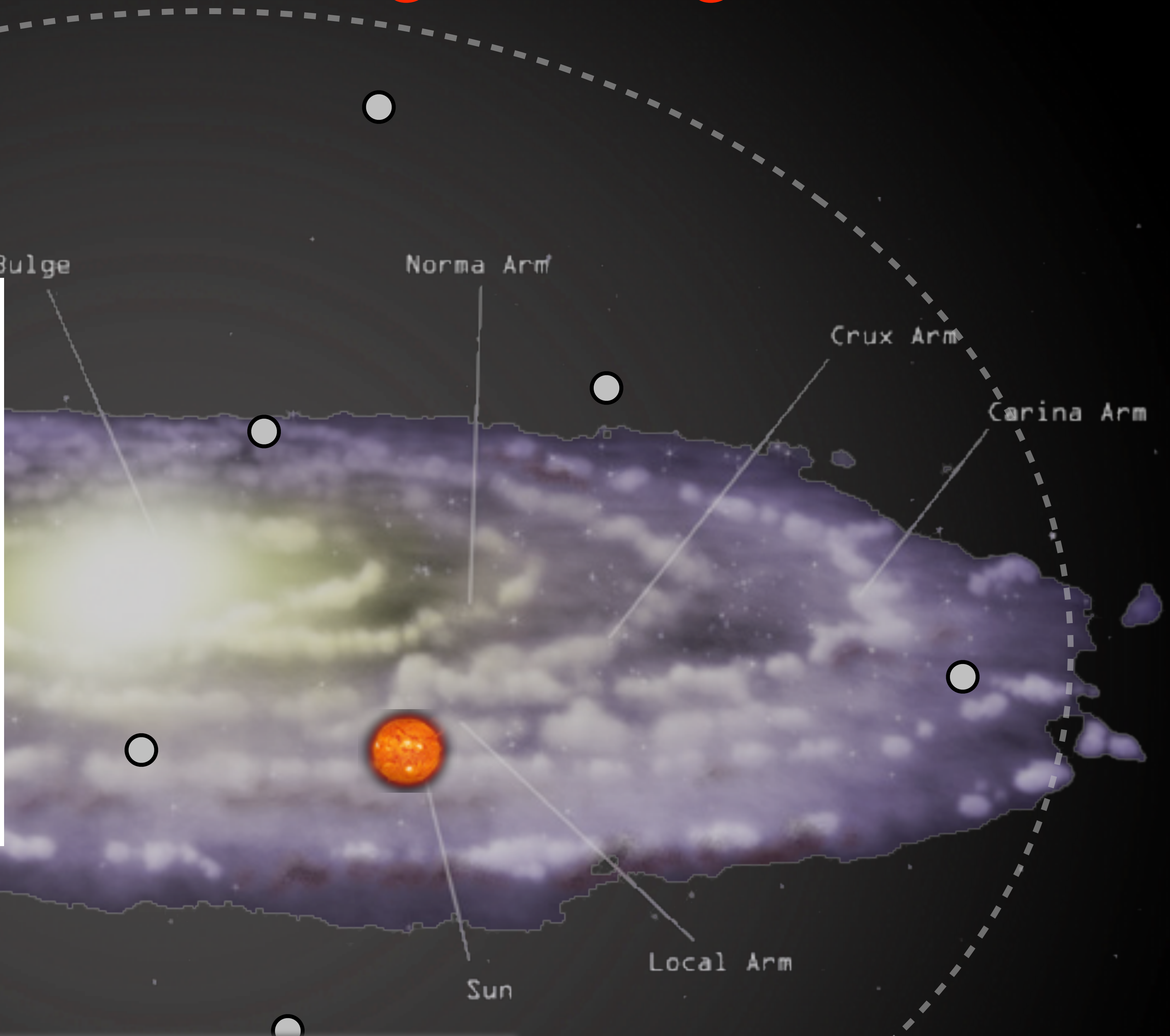


How heavy?

In the Milky Way

A halo of invisible particles





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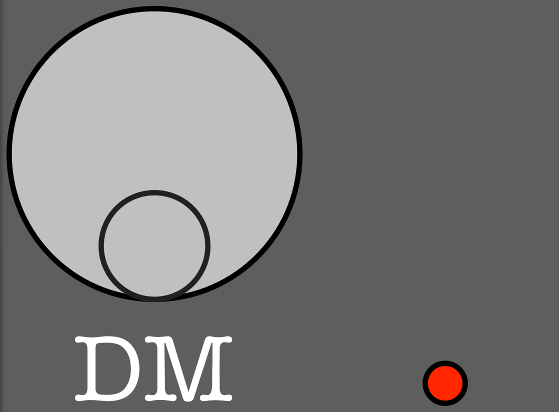


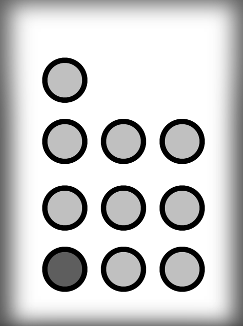
DM

10-1000 GeV

proton

1 GeV

How dense?



10 GeV

100 GeV

In the Milky Way

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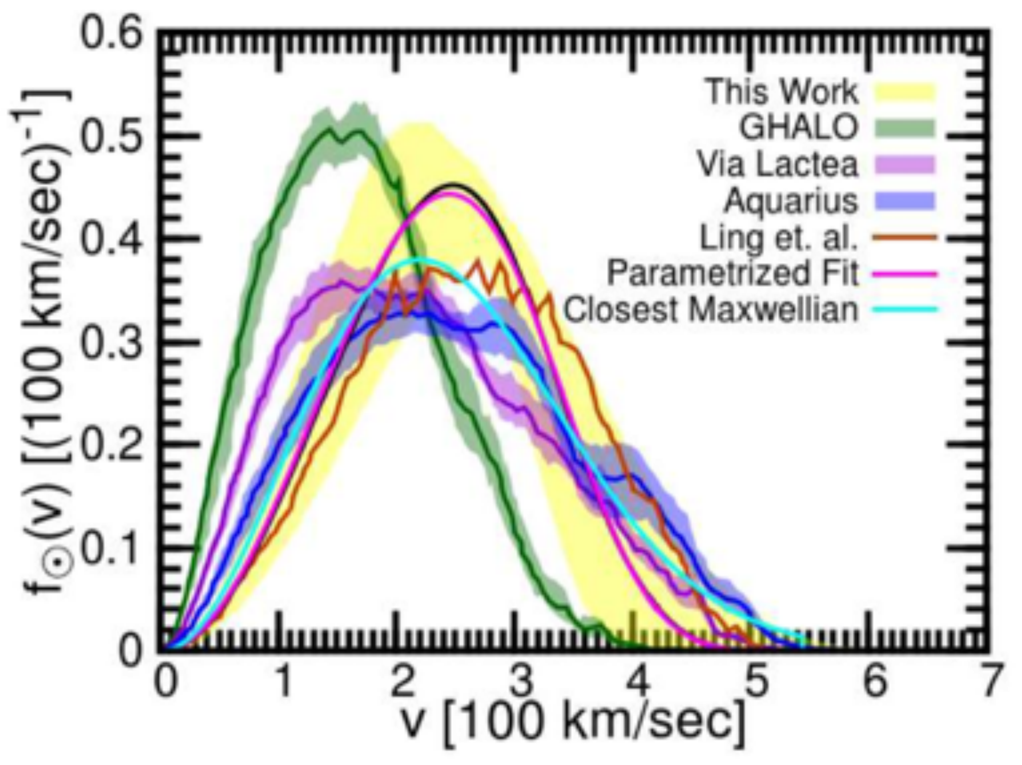
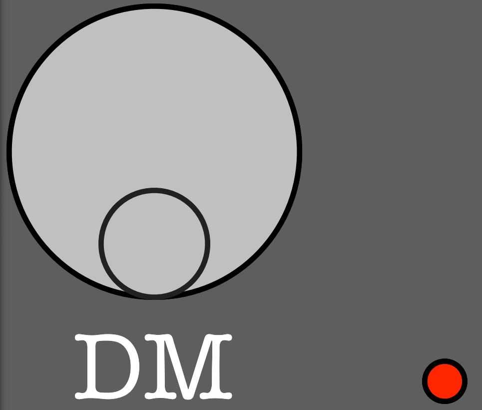


They do not interact with normal matter nor with themselves, they fly freely thru matter

How heavy?



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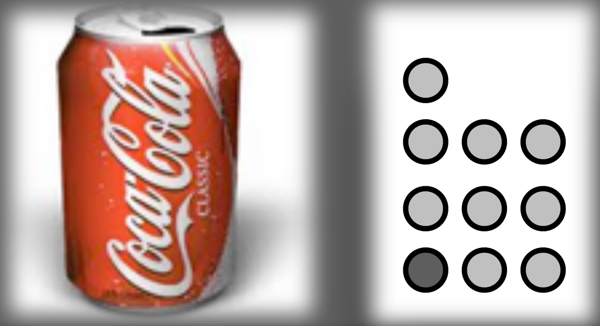

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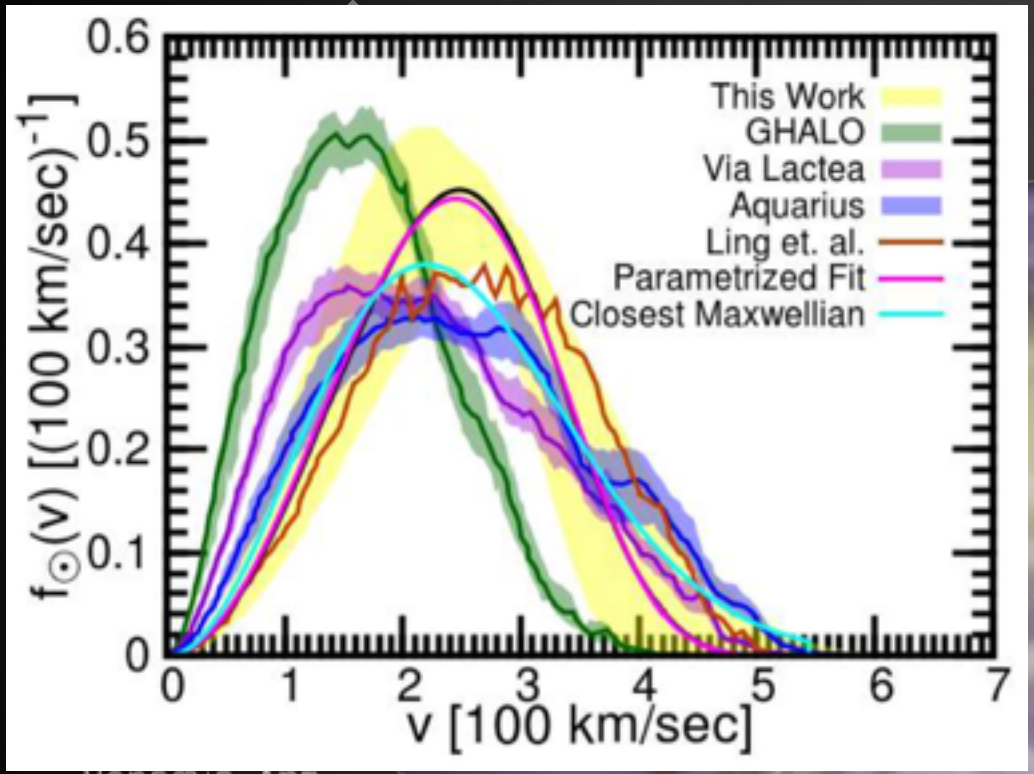
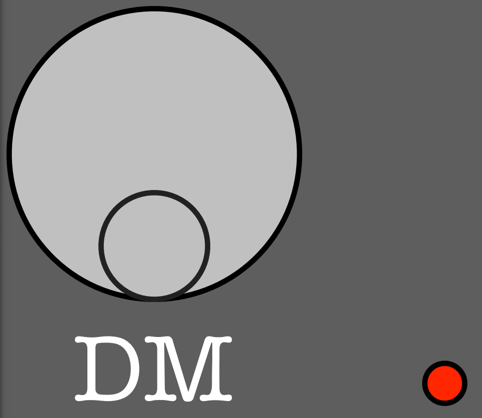


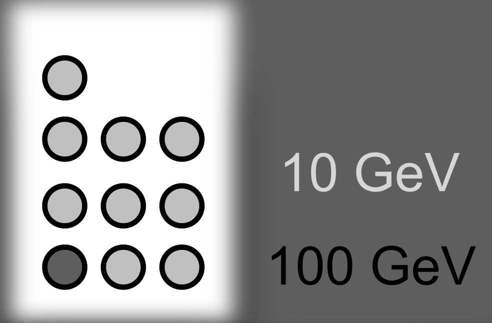
How heavy?



DM
10-1000 GeV

proton
1 GeV

How dense?



They interact a little little bit…

How was Dark Matter produced?

A thermal relic from the Early Universe

Consider a particle χ:

- subject to $\chi\bar{\chi} \rightarrow \ldots$
- ‘heavy’ (e.g. 100 GeV)
- ‘stable’
- in an expanding Universe
- symmetric abundance

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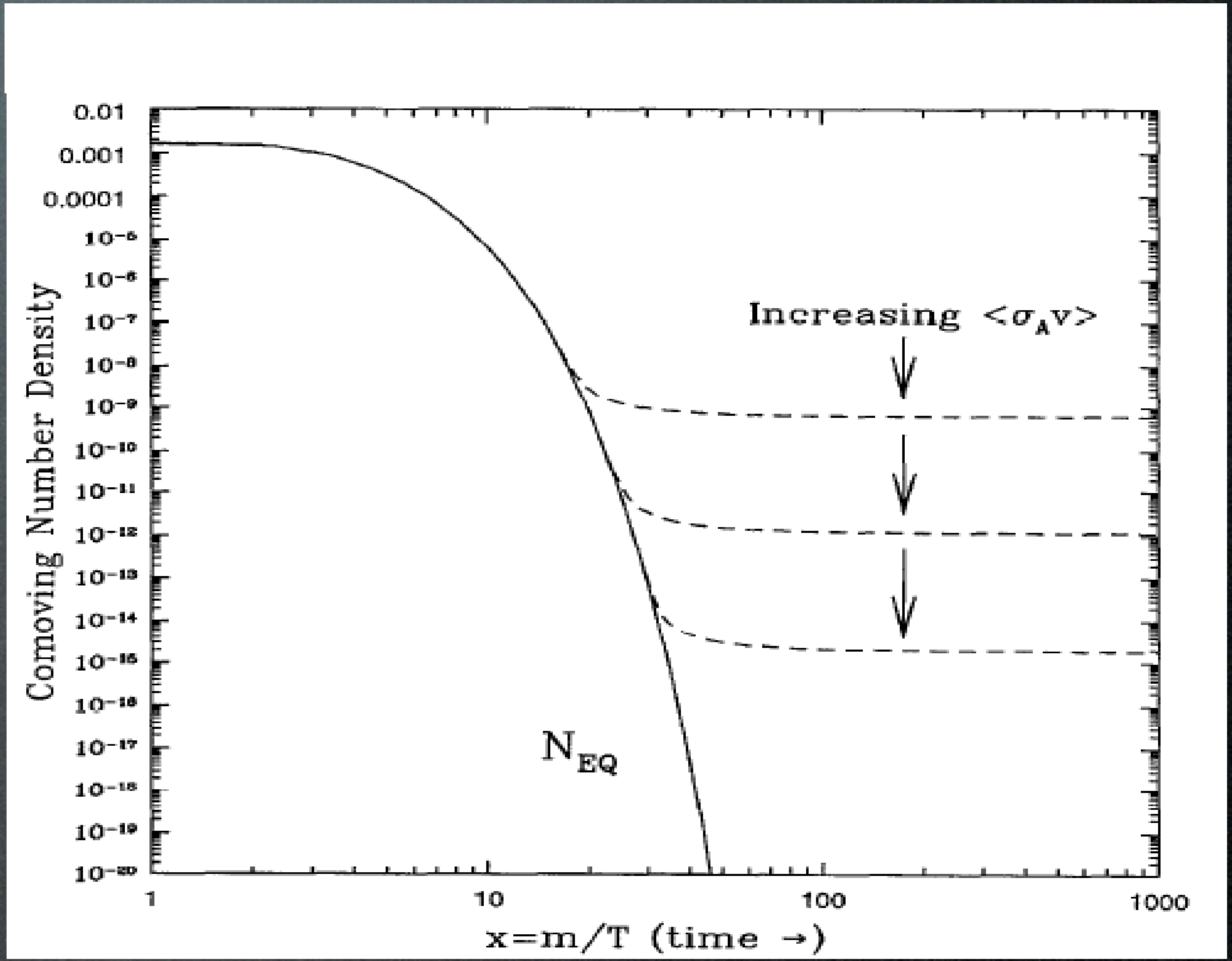

Kolb,Turner, The Early Universe, 1995

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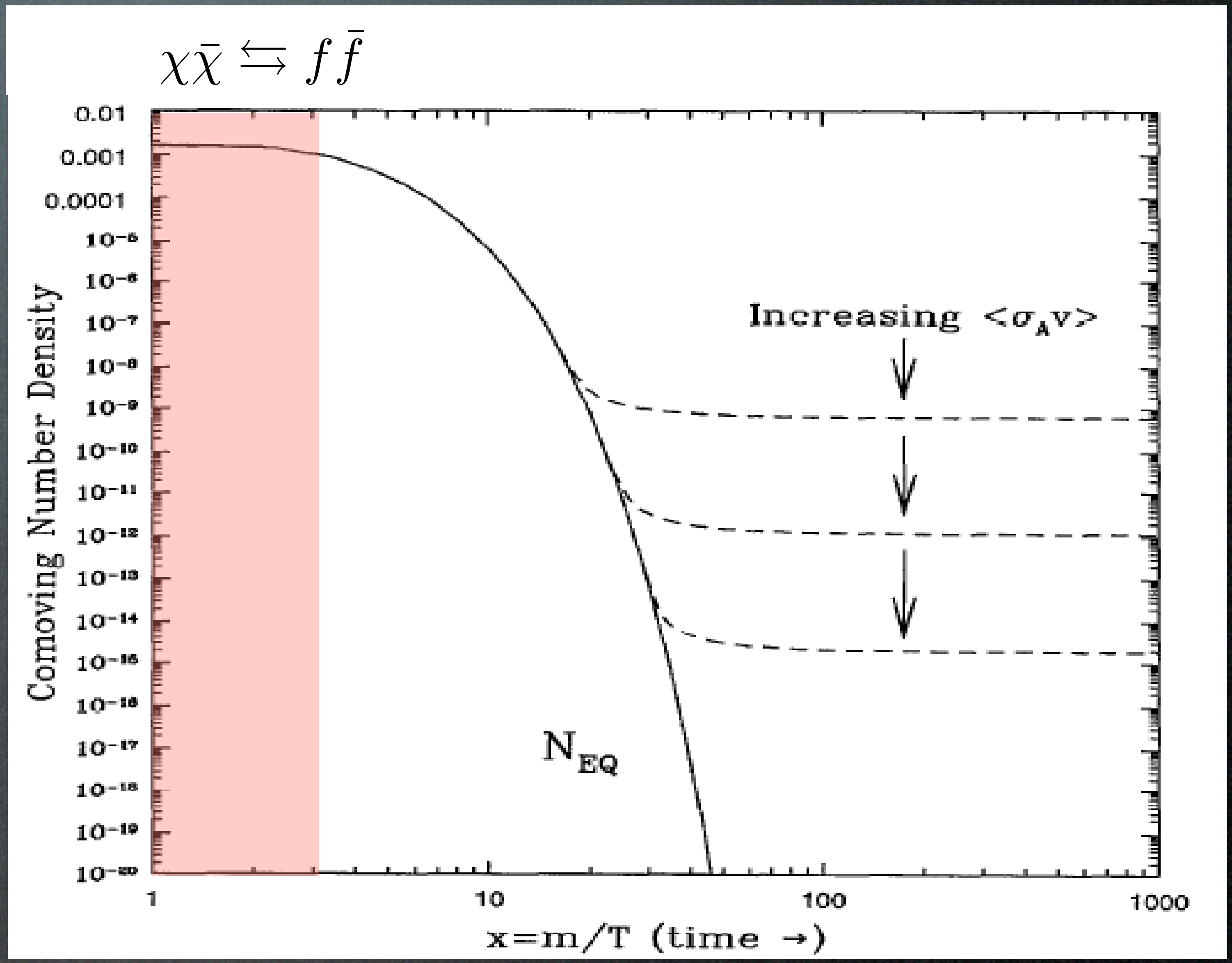

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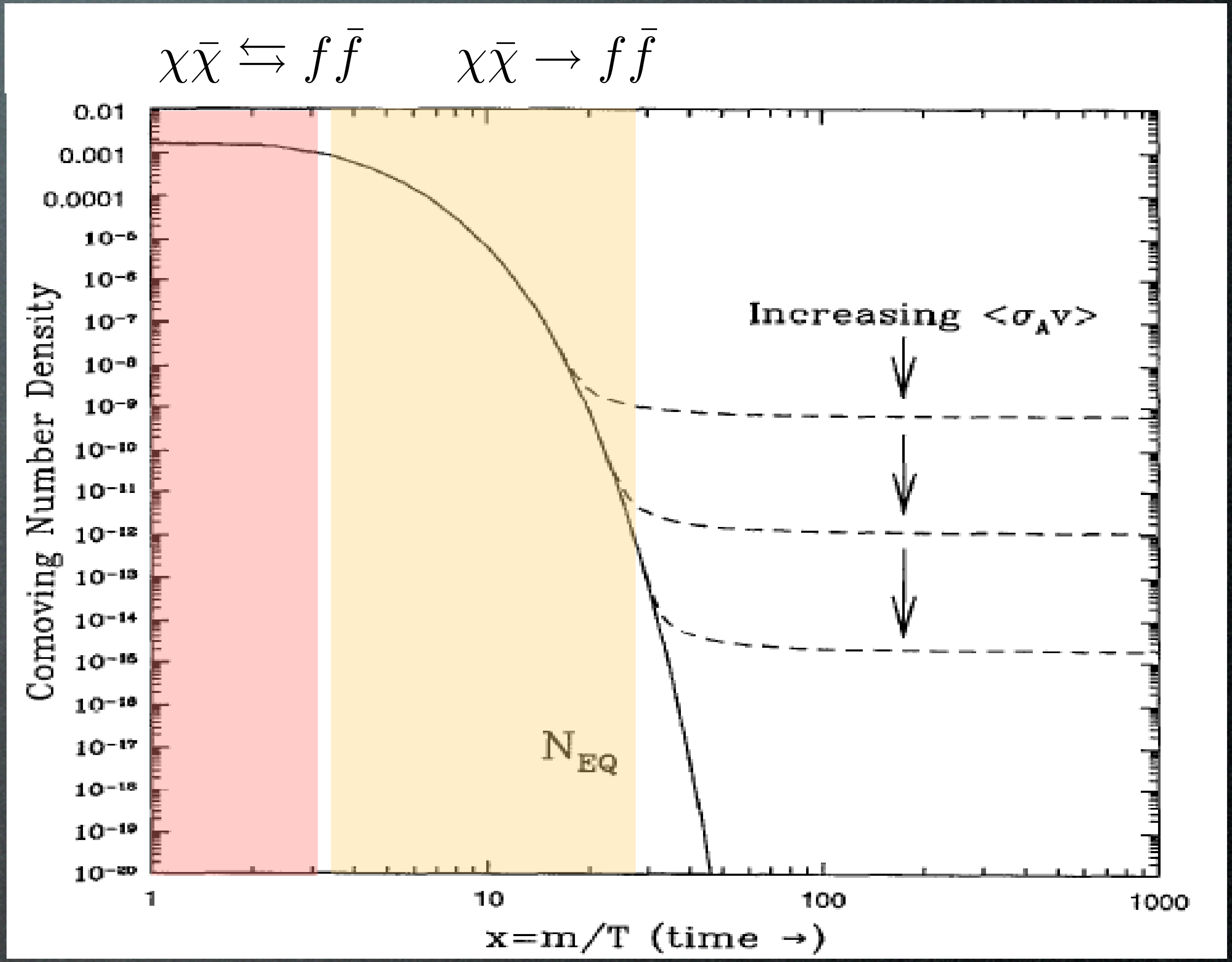

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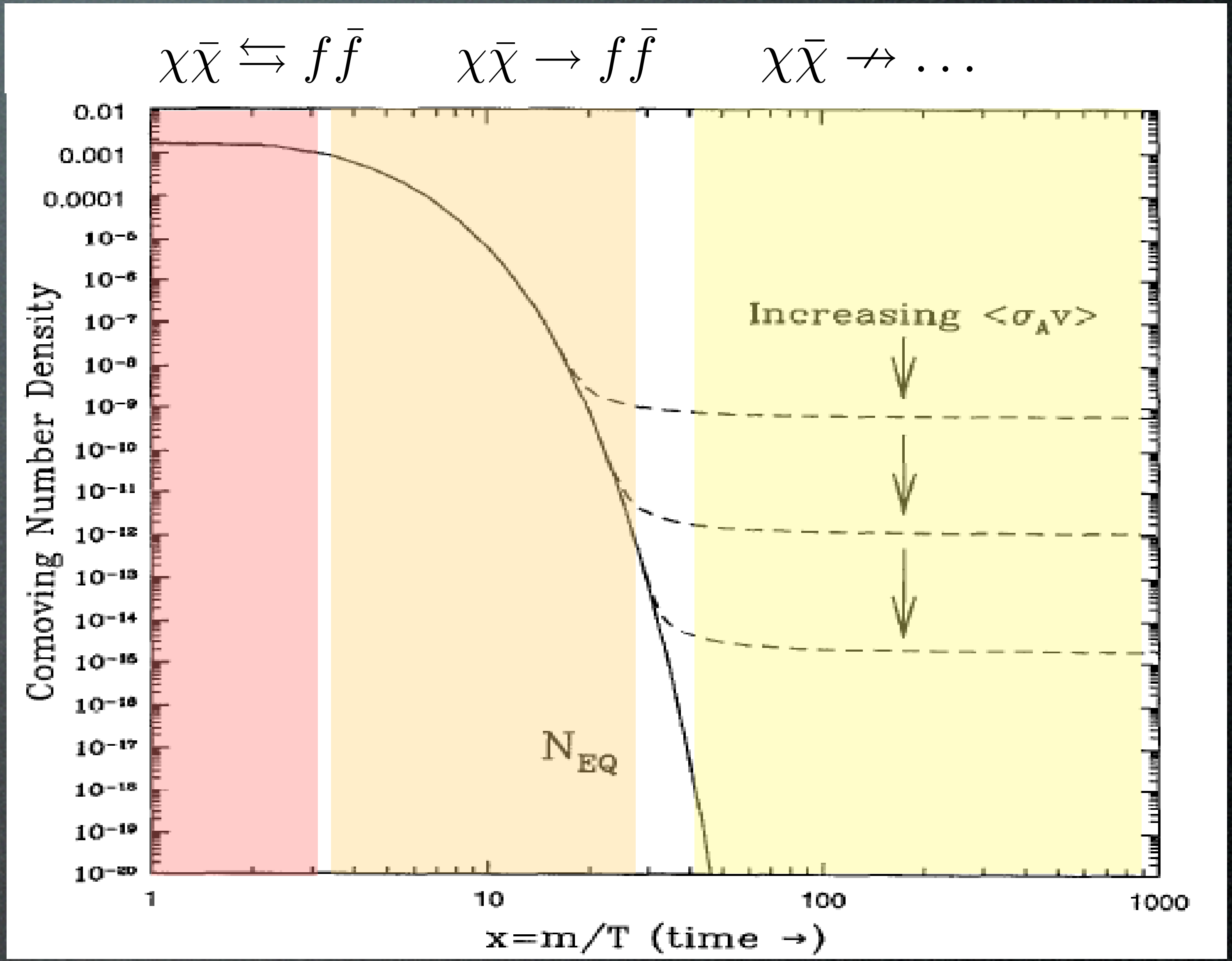

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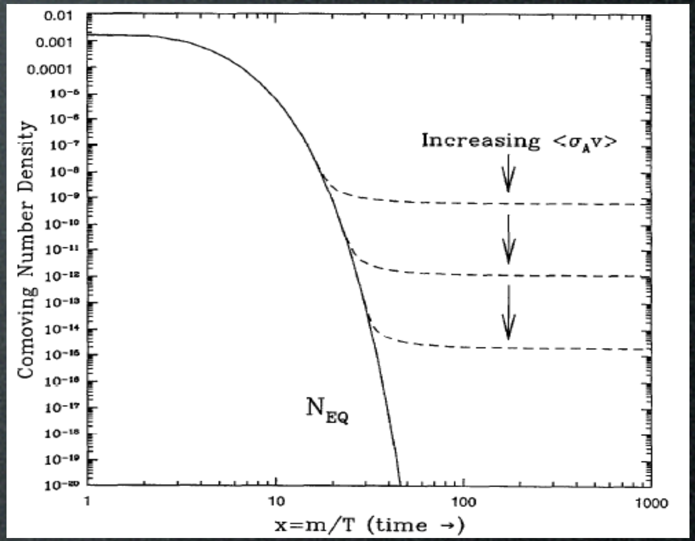


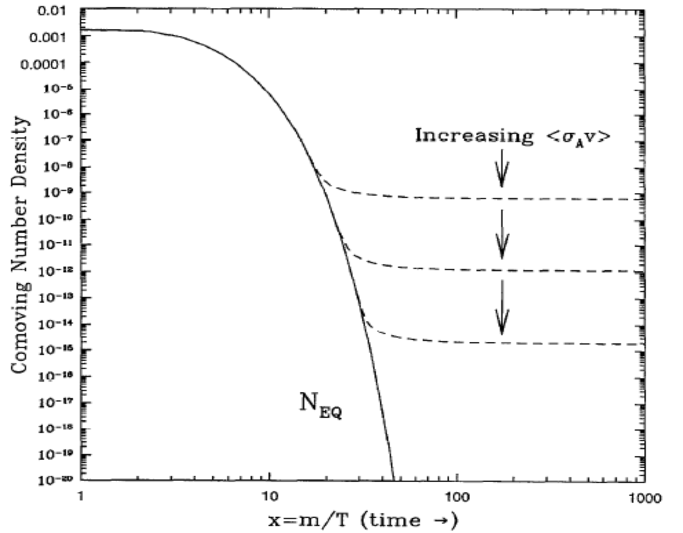
Boltzmann equation in the Early Universe:

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma_{\rm ann}v\rangle\left[n_X^2 - n_X^{\rm eq\,2}\right]$$

cosmology

particle physics

A thermal relic from the Early Universe



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the density of n_X...

...is decreased by the expansion...

...and is affected by the annihilations:

for $n_X > n_X^{\rm eq}$, $n_X \searrow$

for $n_X < n_X^{\rm eq}$, $n_X \nearrow$

i.e. n_X is driven to (sticks to) $n_X^{\rm eq}$

Look for the moment at which r.h.s. ‘cannot keep up’ with l.h.s. any longer (comoving n_X will stay constant afterwards)

NB: if one defines $Y_X = \frac{n_X}{s}$, Boltzmann equation is recast as $\frac{dY_X}{dt} = -\langle\sigma_{\rm ann} v\rangle \frac{1}{s} \left[Y_X^2 - Y_X^{\rm eq\,2}\right]$

when annihilations become inefficient, Y_X stays constant

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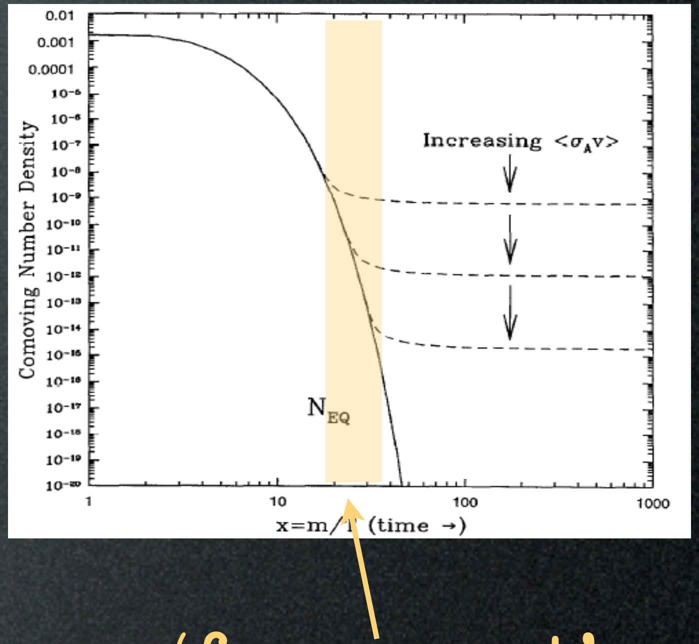
Shortcut (NB: includes cheating)

$$\Gamma \sim H$$



‘freeze-out’

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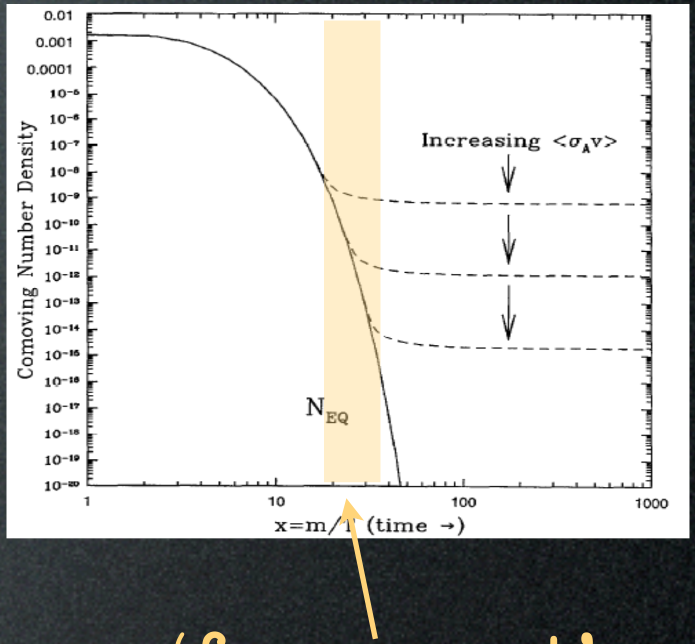
$$\rotatebox{-45}{=}\qquad\qquad\qquad\rotatebox{45}{=}$$

$$n_X\sigma_{\rm ann} \qquad\qquad \sqrt{\frac{8\pi}{3}G_N\,\rho_{\rm tot}}$$



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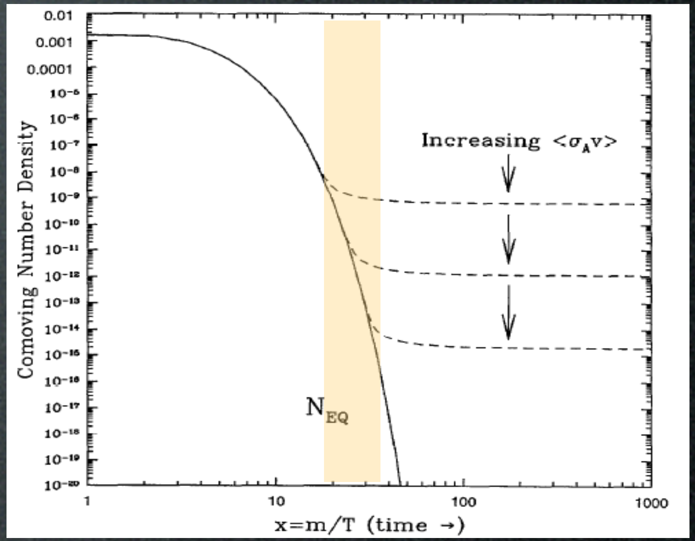

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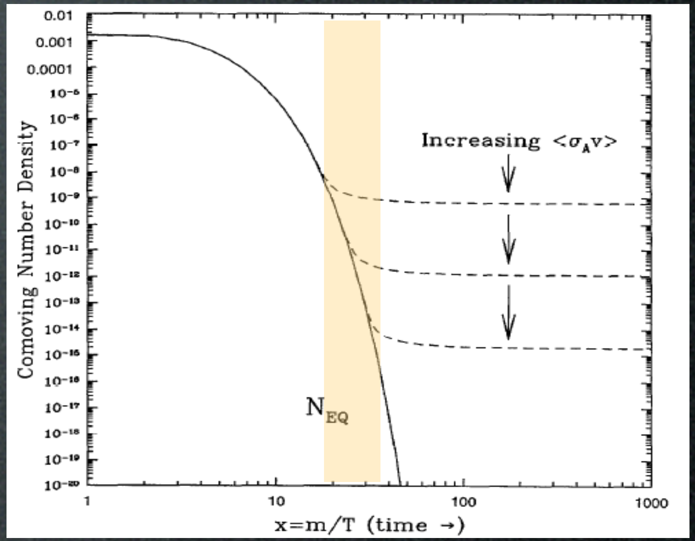
$$\begin{array}{lcl} & \Gamma \sim H & \\ \parallel & & \parallel \\ n_X\sigma_{\rm ann} & & \sqrt{\frac{8\pi}{3} G_N\, \rho_{\rm rad}} = \frac{1}{M_{\rm Pl}}\sqrt{\frac{8\pi^3}{90} g_*}\, T^2 \end{array}$$

$$\rho_{\rm rad} = \frac{\pi^2}{30} g_*\, T^4$$

$$g_* = \sum_{\rm bos} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8}\sum_{\rm fer} g_i \left(\frac{T_i}{T}\right)^4$$

A thermal relic
from the Early Universe



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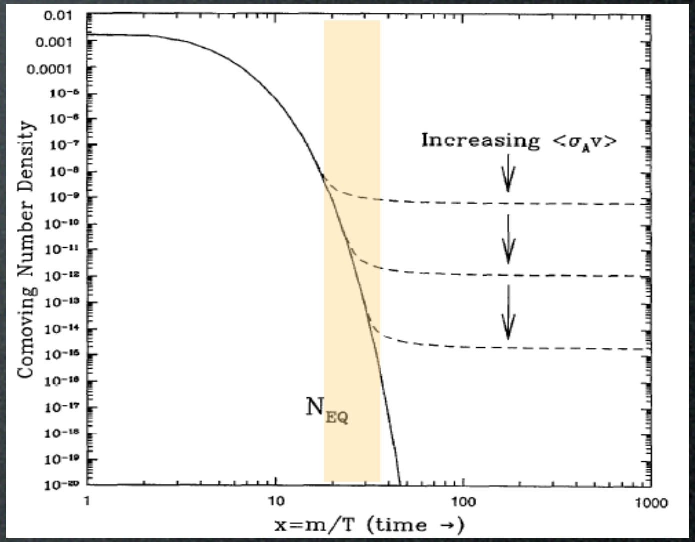

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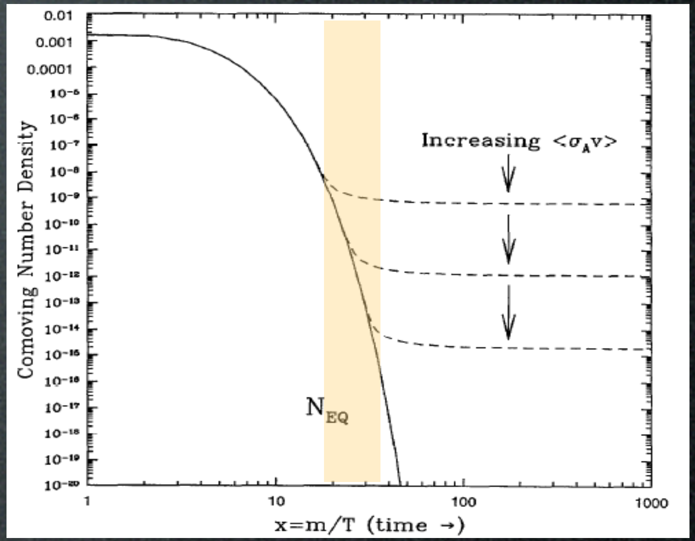
Define $Y_X = \dfrac{n_X}{s}$

$$s = \frac{2\pi^2}{45}g_{*s}T^3$$

A thermal relic from the Early Universe



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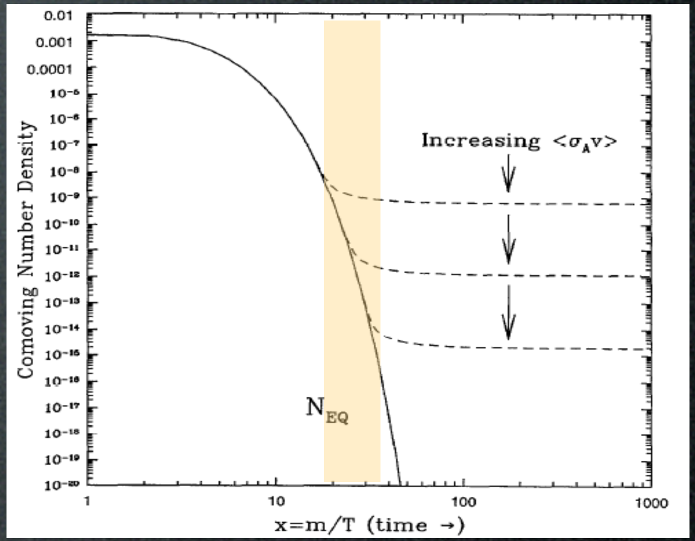

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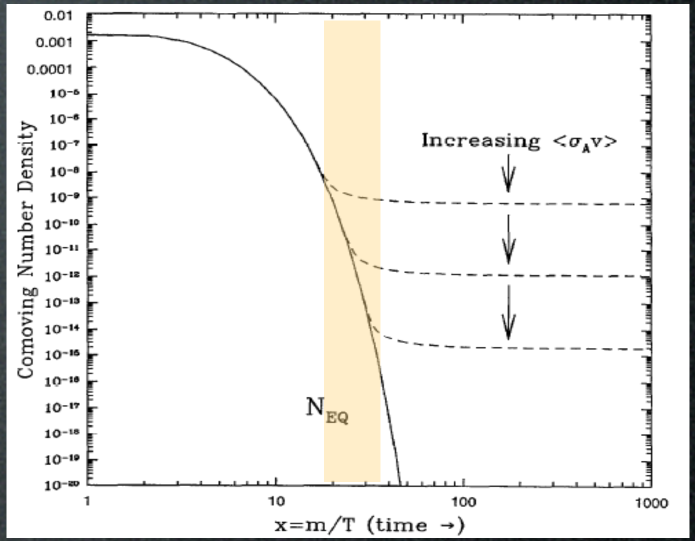
$$T_{\rm f.o.} \sim m_X/20$$
$$g_* \simeq g_{*s} \simeq 100$$

A thermal relic from the Early Universe



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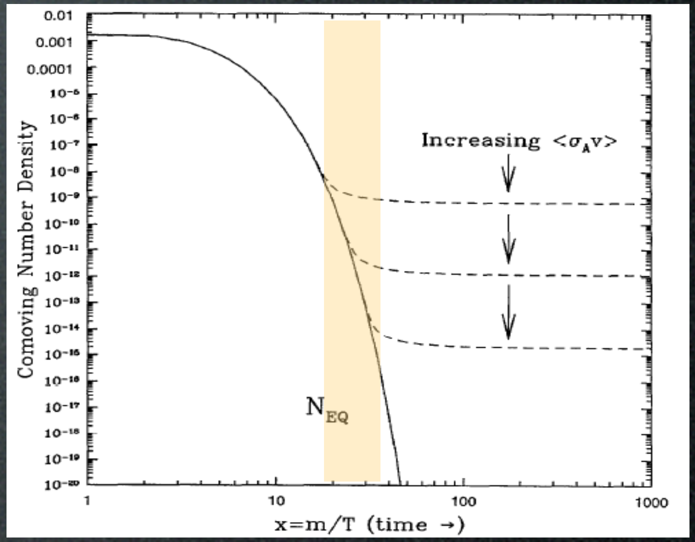
$$\Omega_X = \frac{\rho_X}{\rho_{\rm crit}} = \frac{m_X n_X}{\rho_{\rm crit}} = \frac{m_X Y_{\rm today}\,s_{\rm today}}{\rho_{\rm crit}} = \frac{m_X\,\frac{\#}{M_{\rm Pl}\,\sigma_{\rm ann}\,m_X}\,s_{\rm today}}{\rho_{\rm crit}}$$

A thermal relic from the Early Universe



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mx cancels out

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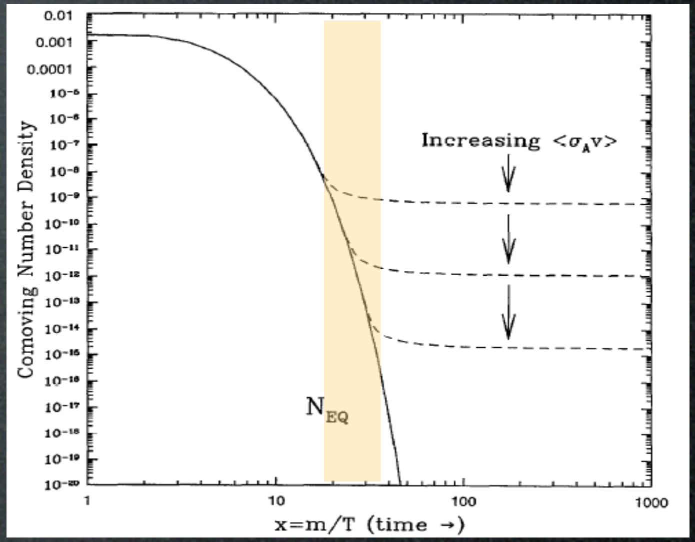

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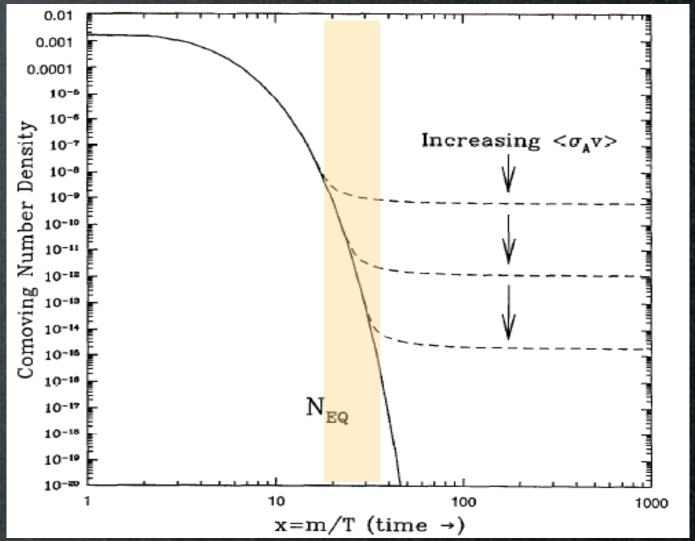

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or

$$\boxed{\Omega_X \approx \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma_{\rm ann}v\rangle}}$$

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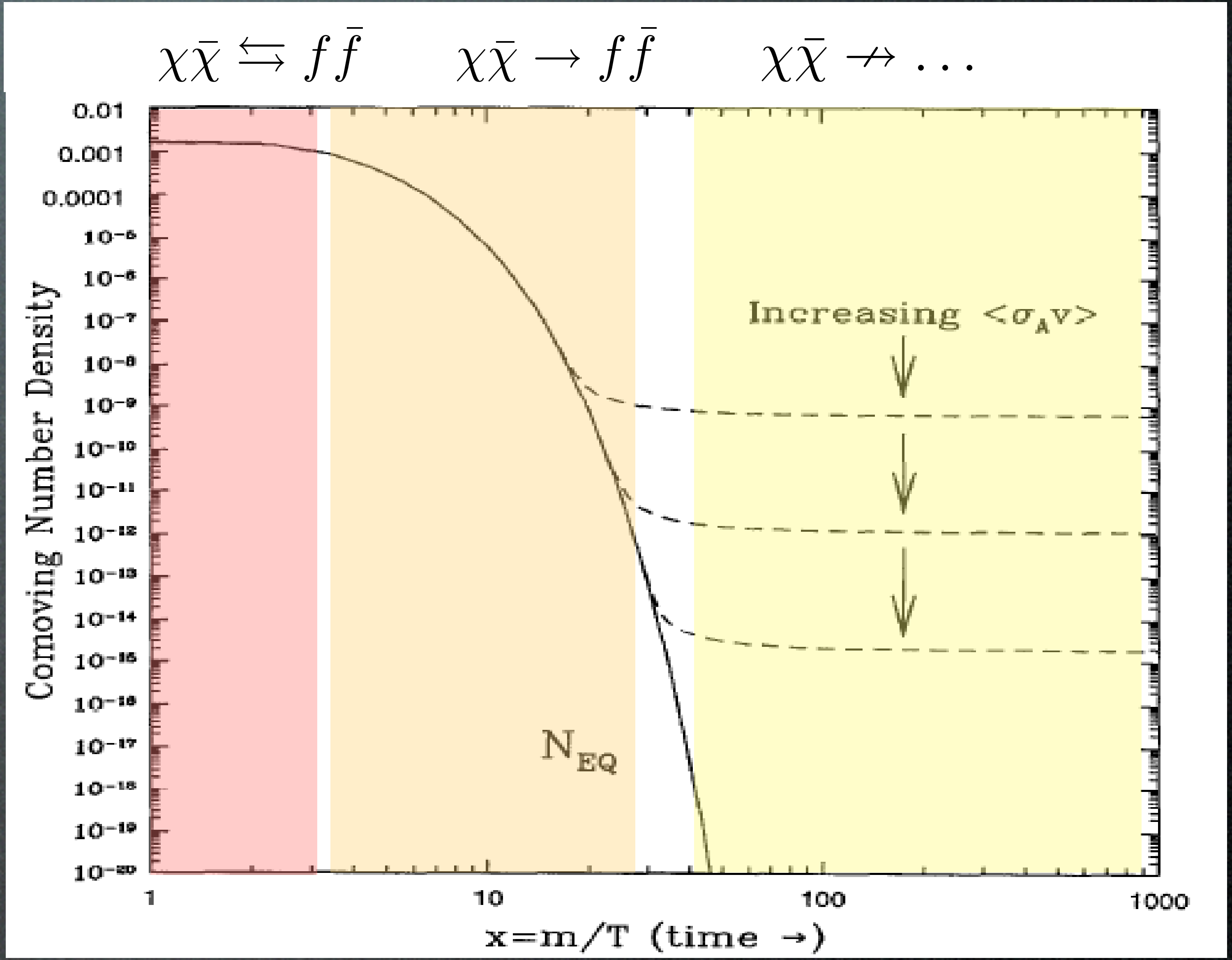
Boltzmann equation
in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle \sigma_{\mathrm{ann}} v \rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



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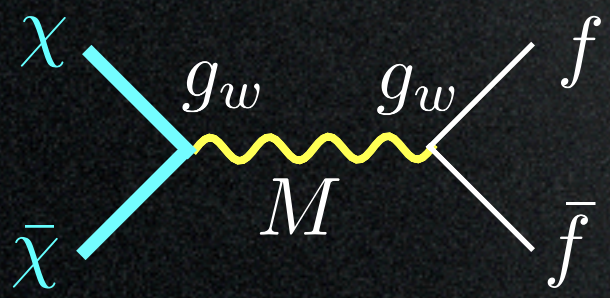
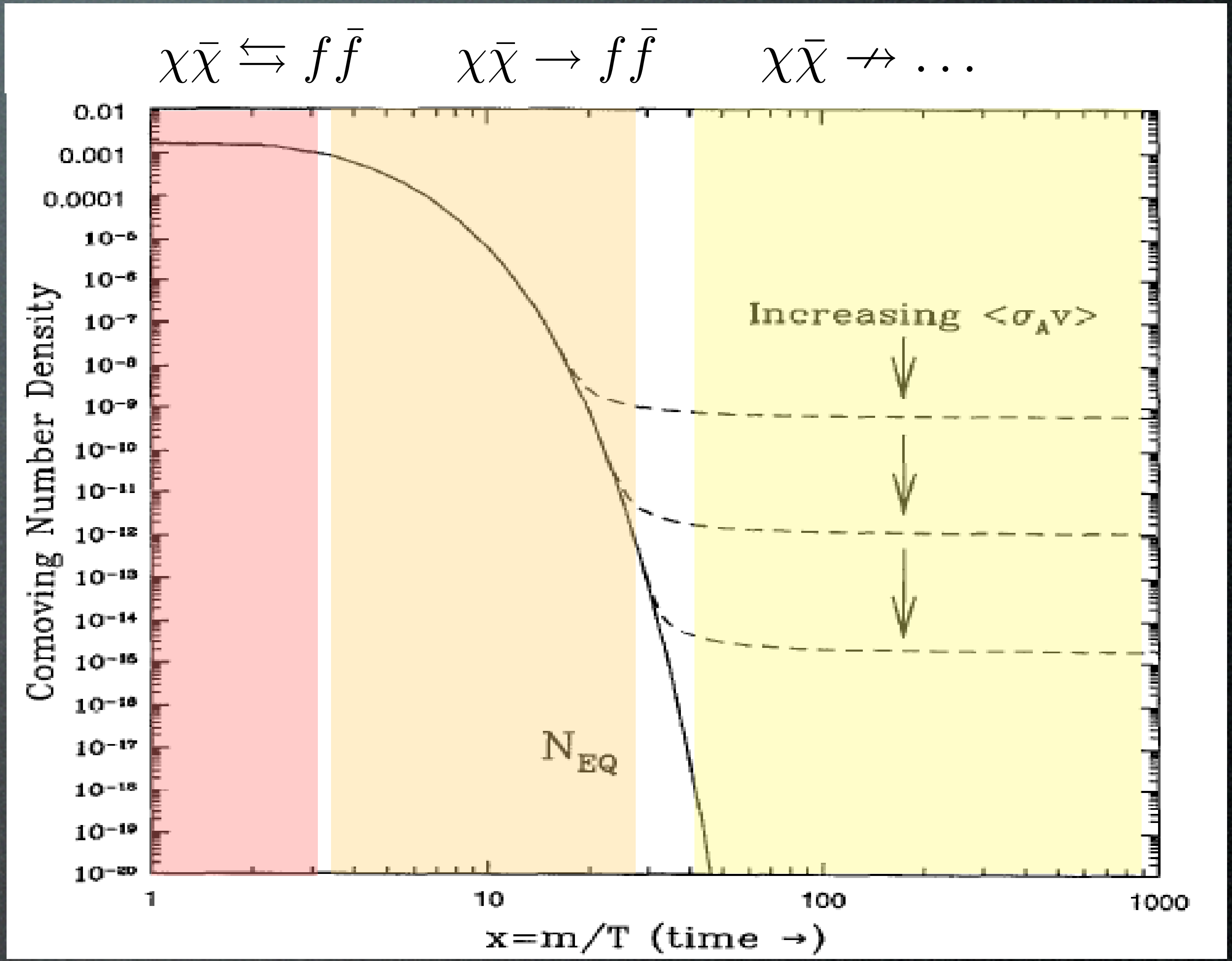
Weak cross section:





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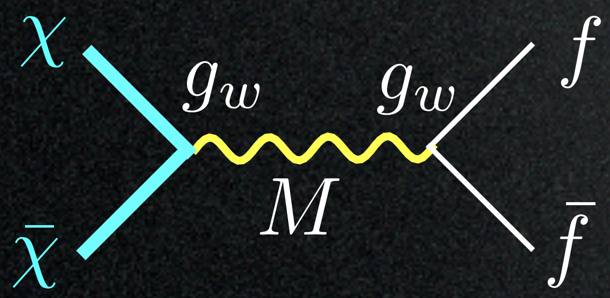
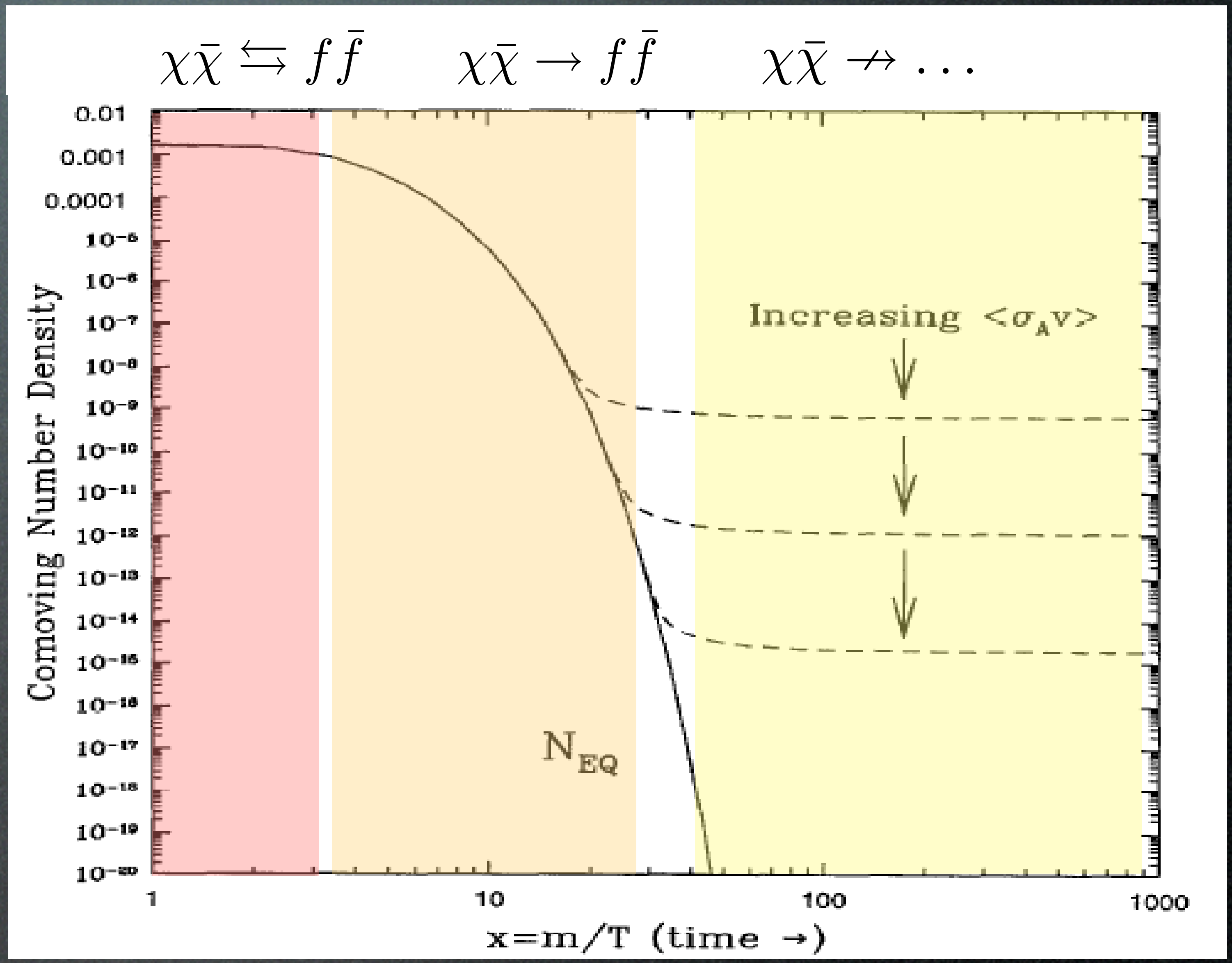


$$\langle\sigma_{\mathrm{ann}}v\rangle \approx \frac{(g_w^2/4\pi)^2}{M^2} \approx 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



WIMP *miracle!*

Asymmetric DM:
a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

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Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \overset{?}{=} \eta_{\rm B}$$

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$$\boxed{m_{\rm DM} \simeq 5\ {\rm GeV}}$$

Is this the DM of DAMA, CoGeNT, CRESST?!?

Asymmetric DM: a completely different relic

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'Darko'genesis:

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A variety of specific models/ideas:

transferring or co-genesis

cfr J. March-Russell

DM stores the anti-B number

via leptogenesis

connection to neutrino masses

Asymmetric DM:
a completely different relic

$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \rightarrow f\bar{f} \qquad \chi\,? \nrightarrow \ldots$

Consider a particle χ:

- subject to $\chi\bar{\chi} \rightarrow \ldots$
- ‘heavy’ (e.g. 100 GeV)
- ‘stable’
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- **A**symmetric abundance
- large annihilation cross sec

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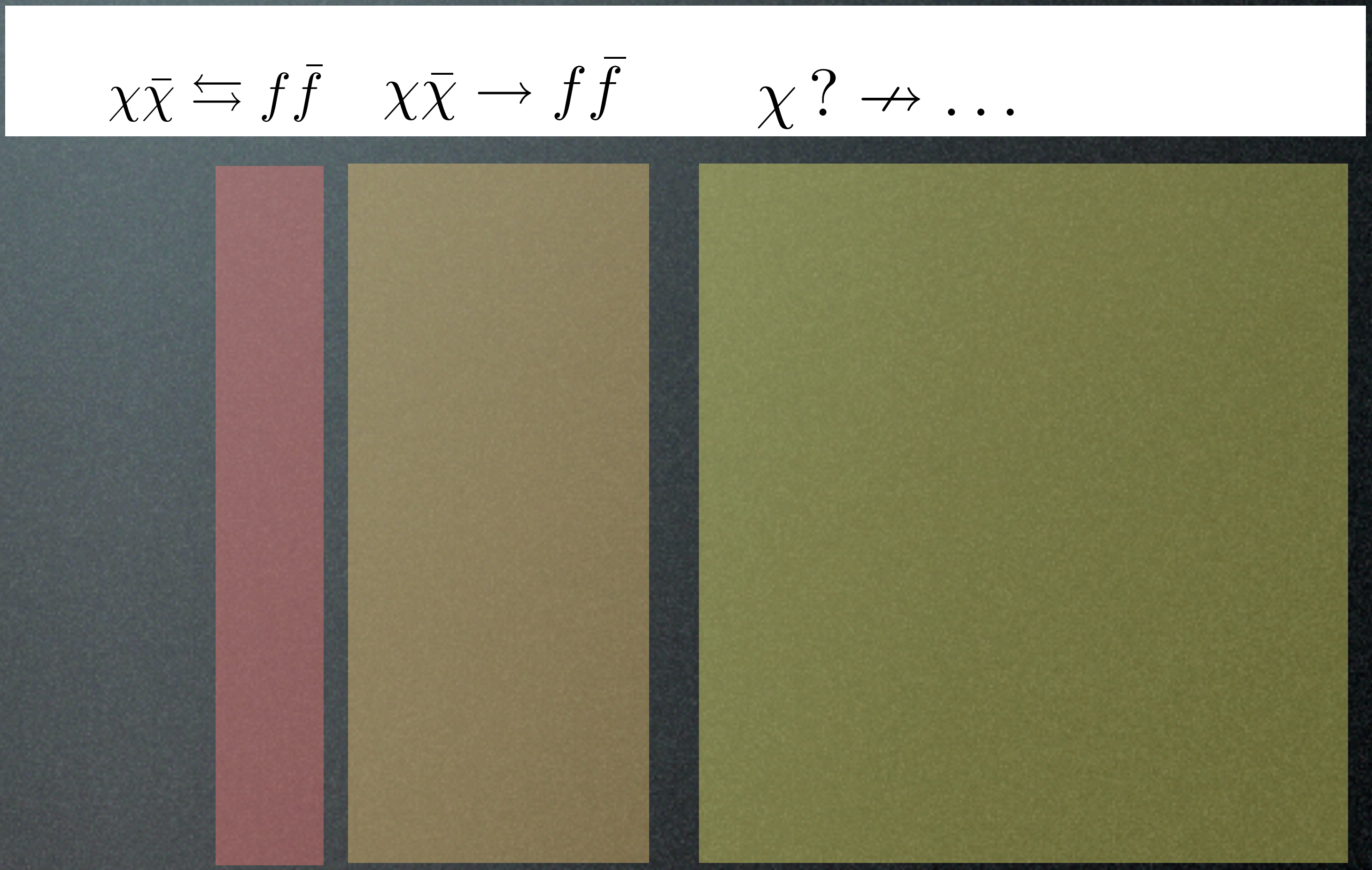
a completely different relic

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- ‘heavy’ (e.g. 100 GeV)
- ‘stable’
- in an expanding Universe
- Asymmetric abundance
- large annihilation cross sec



$$\Omega_X \simeq \frac{m_X\, s}{\rho_{\rm crit}}\eta_0$$

The relic abundance is determined by η_0 and m_X.

Freeze-in:
like rodents in the paleocene

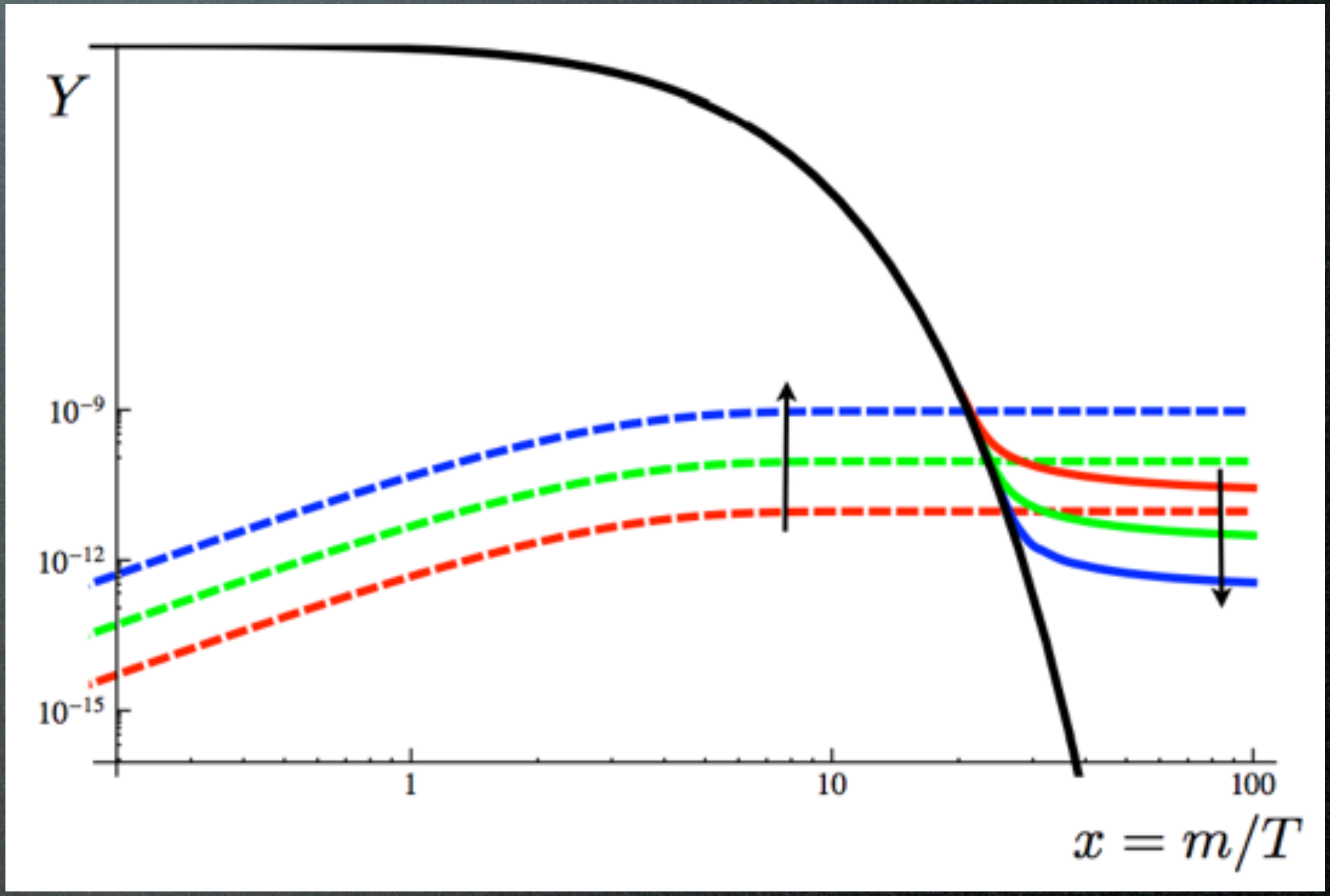
Hall, Jedamzik, March-Russell, West 2009

Freeze-in:
like rodents in the paleocene

Hall, Jedamzik, March-Russell, West 2009

Consider a particle χ:

- subject to $f\bar{f} \to \chi, \chi\bar{\chi}$ with a very small rate
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- zero initial abundance



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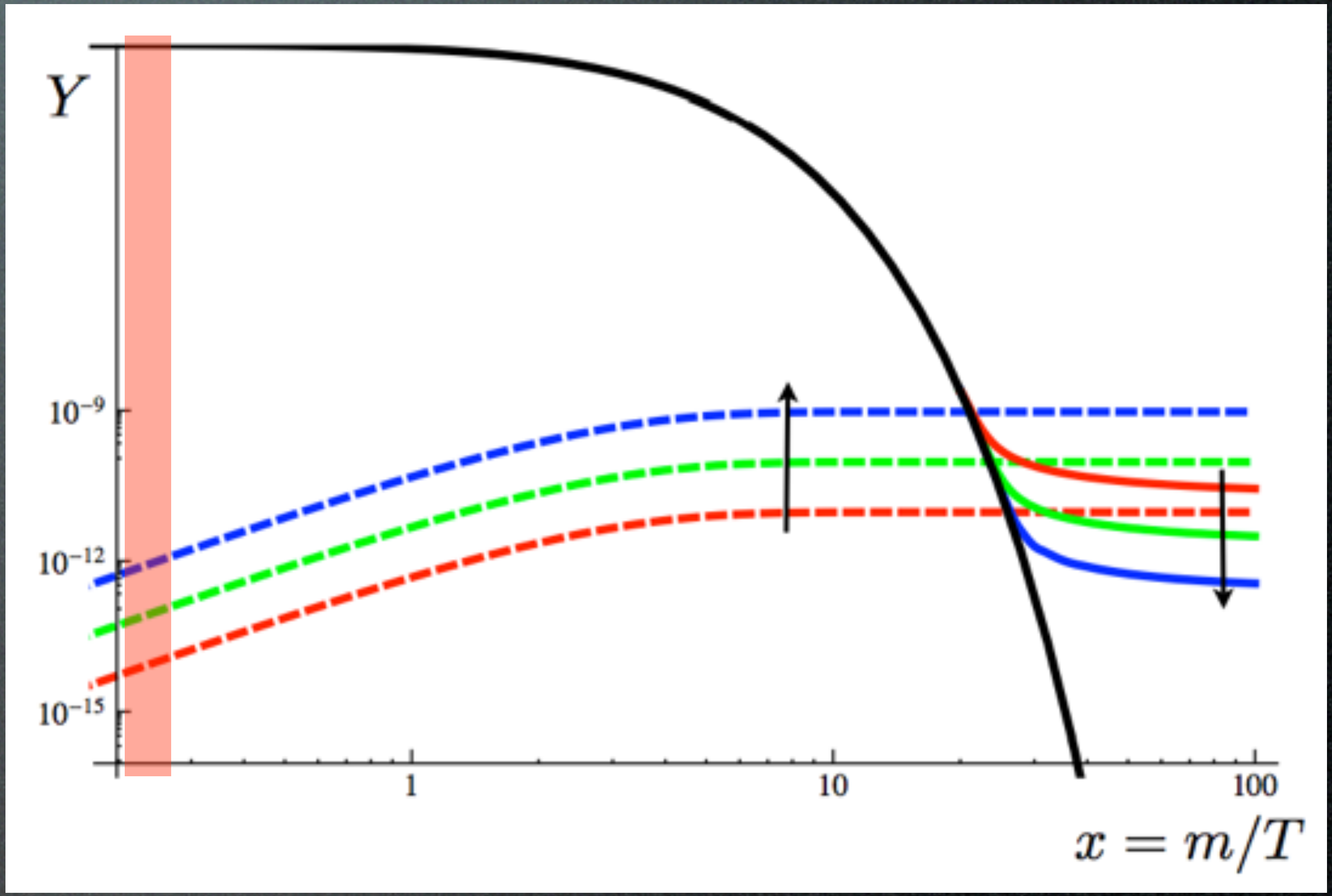

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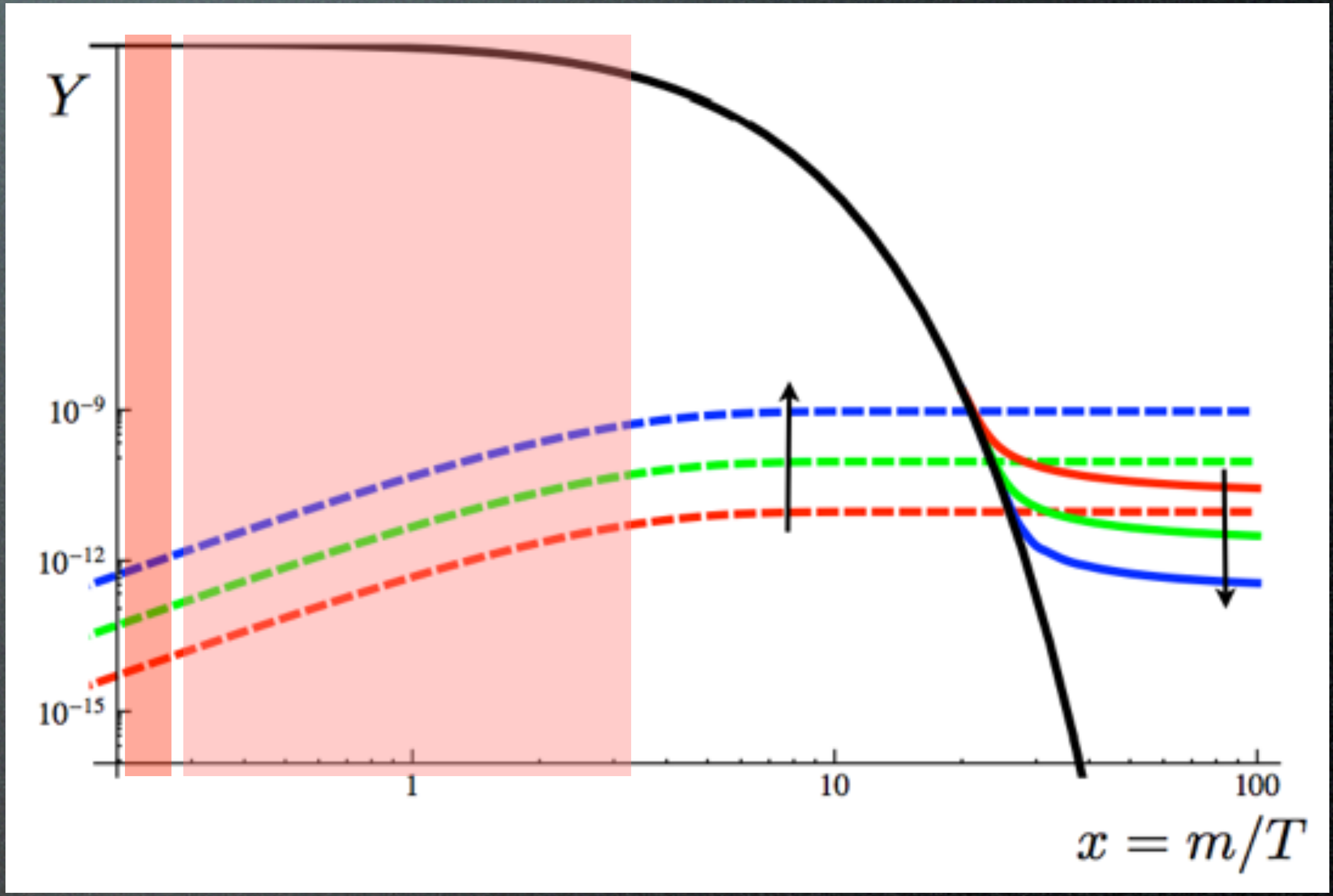

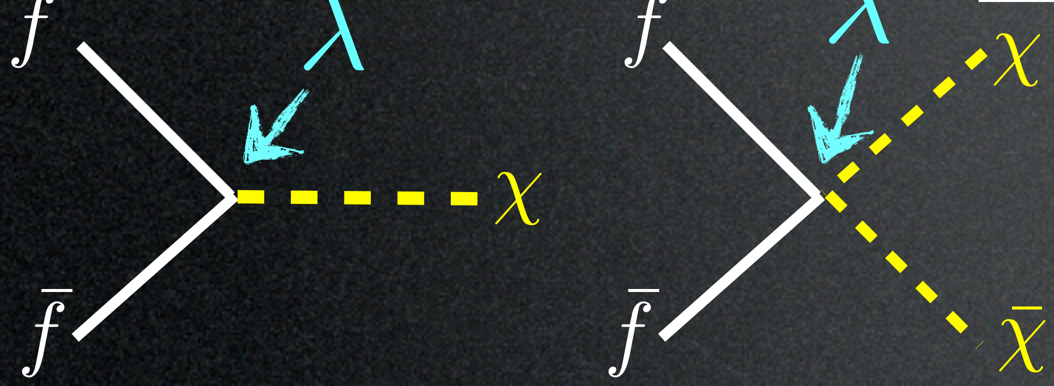

$\lambda \sim 10^{-12}$

very slowly but steadily produced

Freeze-in:
like rodents in the paleocene

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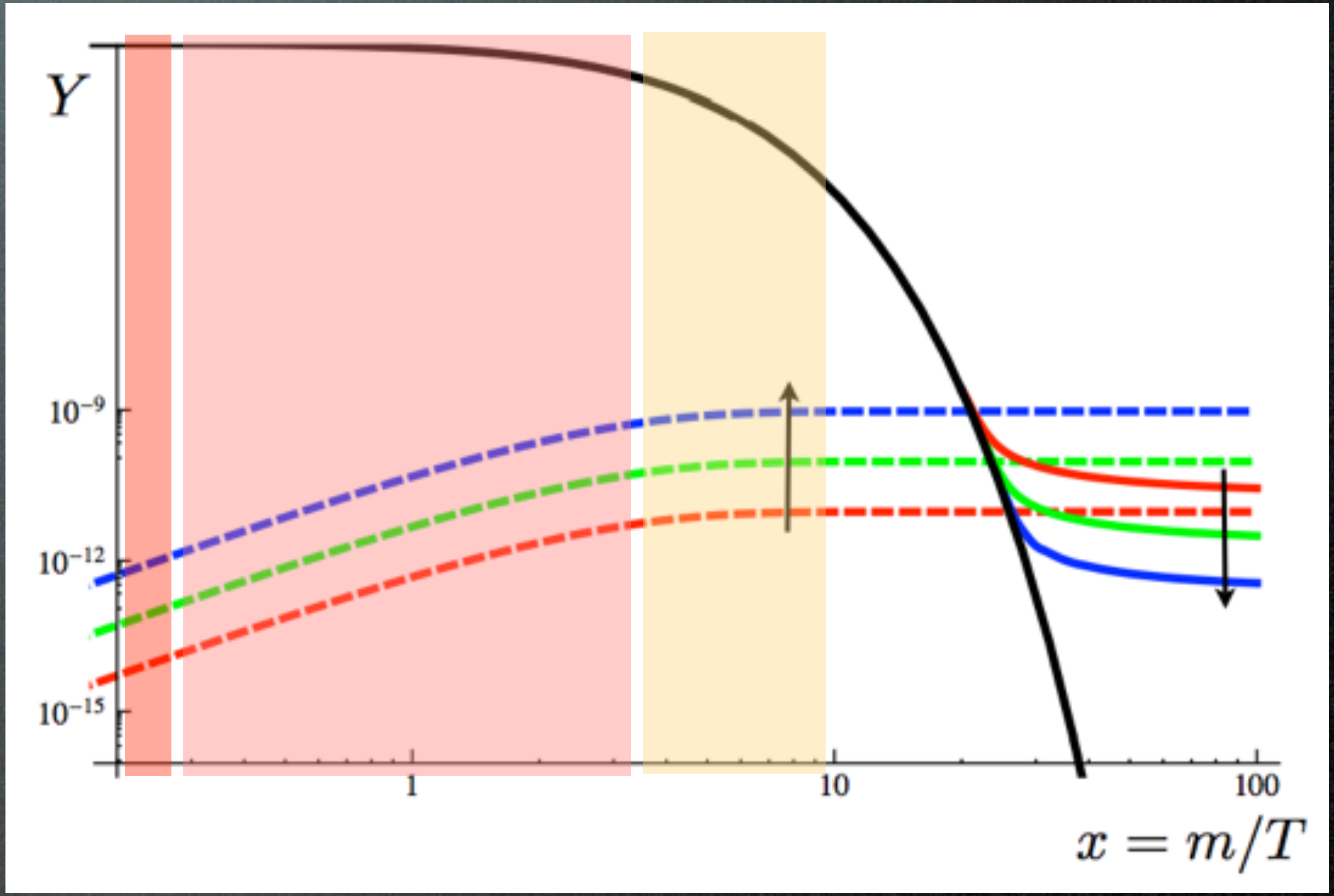

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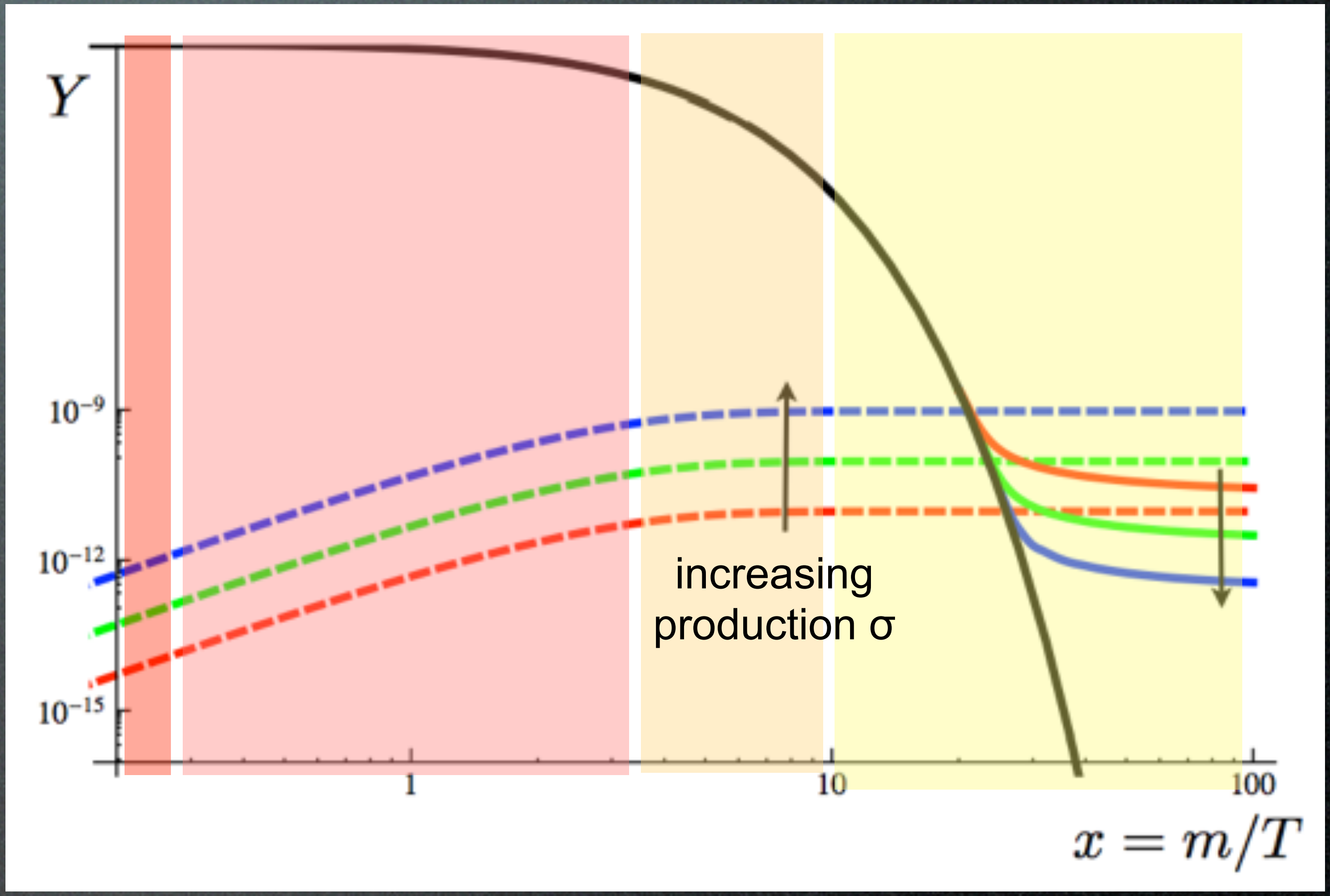


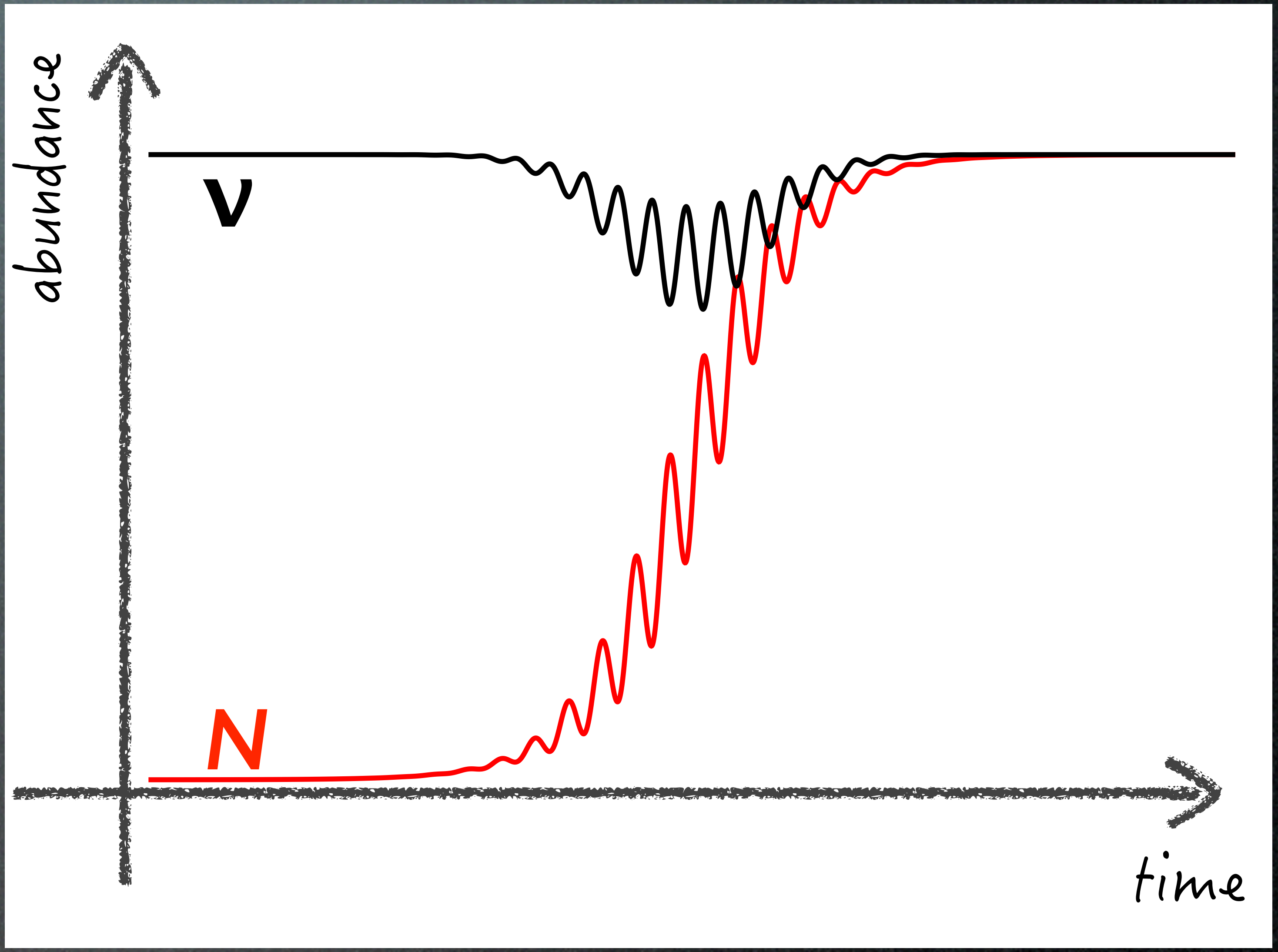
The final abundance is determined by σ (or rather λ).

Oscillations

Dodelson, Widrow 1994

Consider a particle ***N***:

- subject to $\nu \leftrightarrow N$ with a small mixing
- not too ‘heavy’ (few KeV)
- stable
- in an expanding Universe
- zero initial abundance



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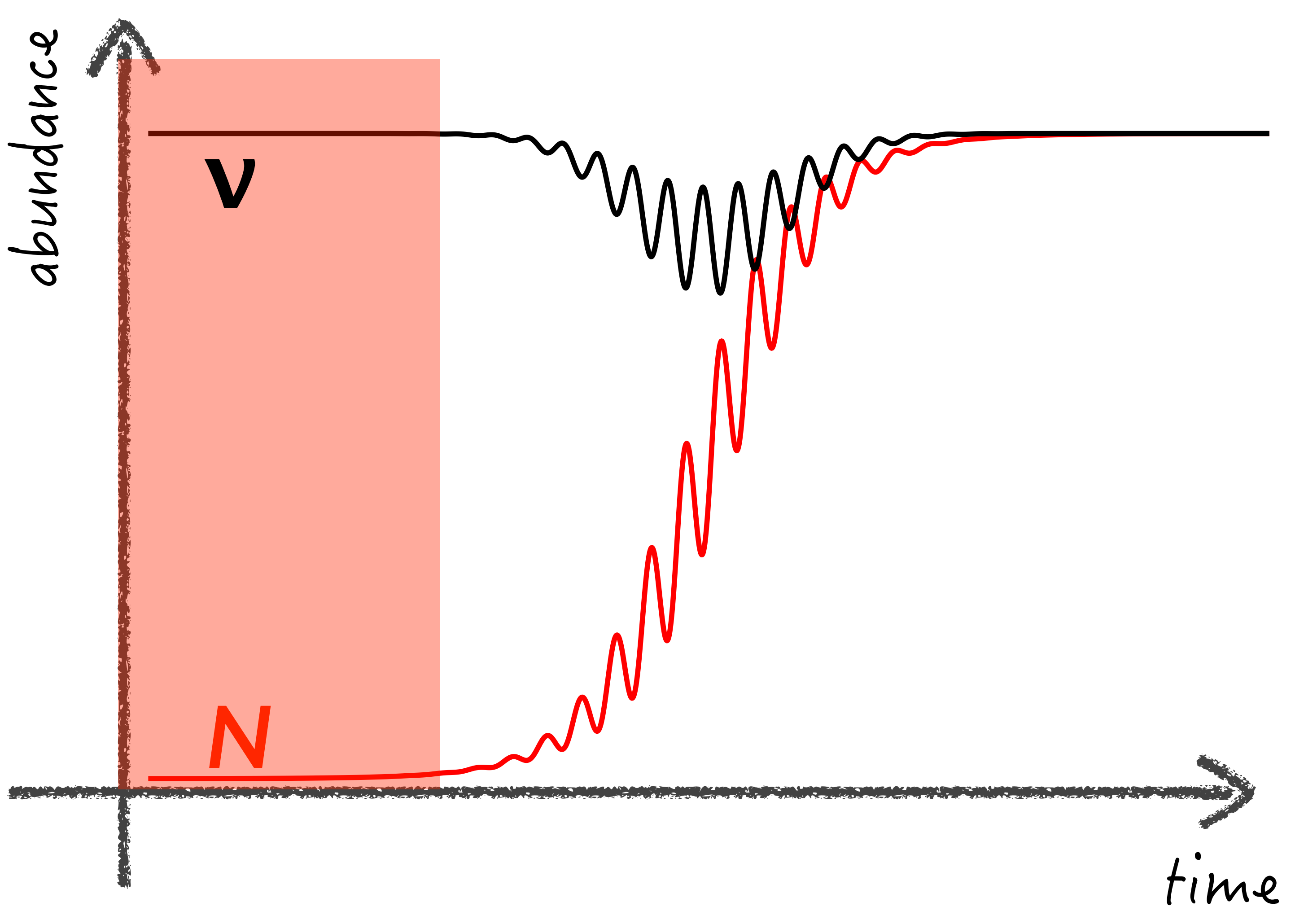

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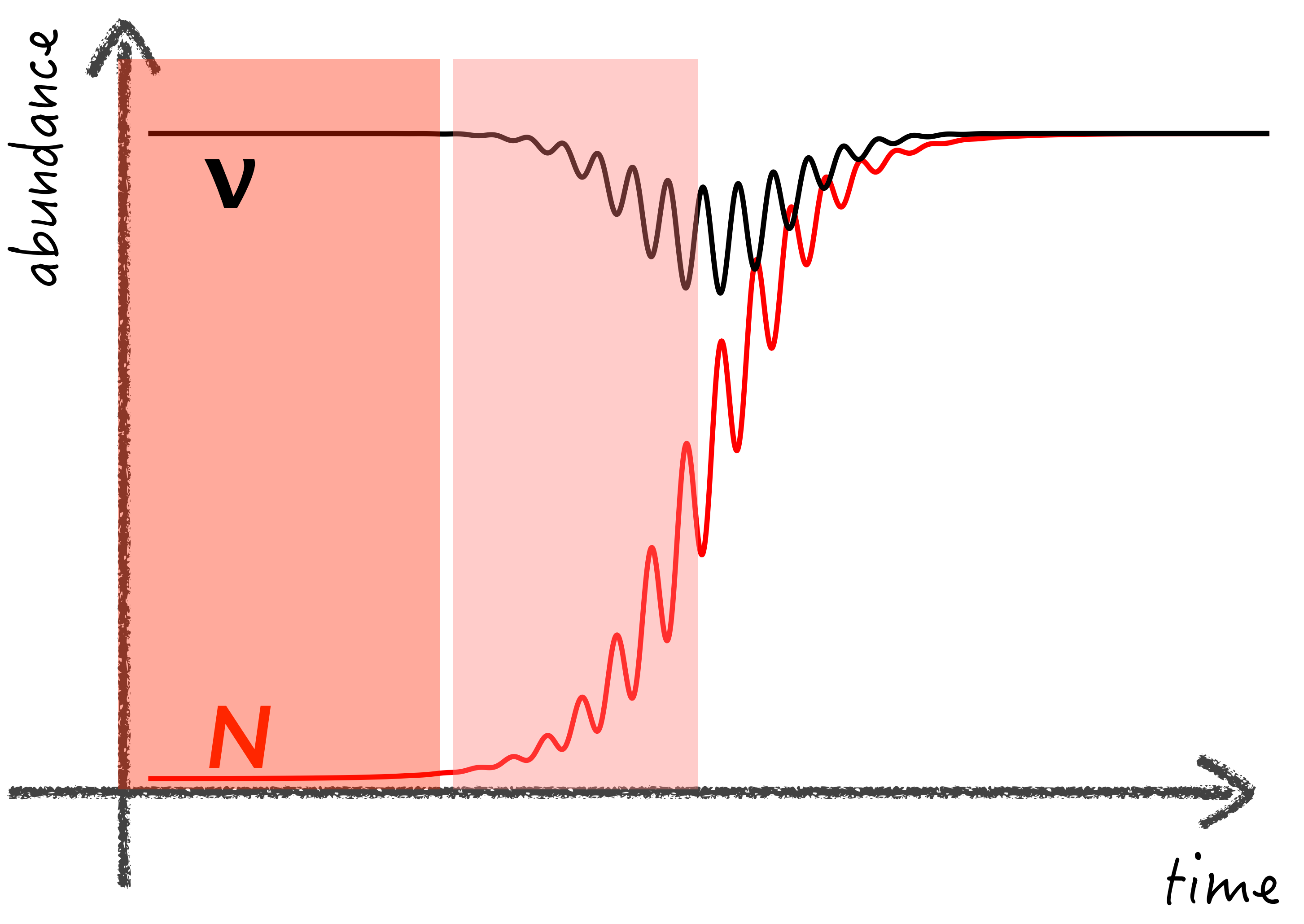

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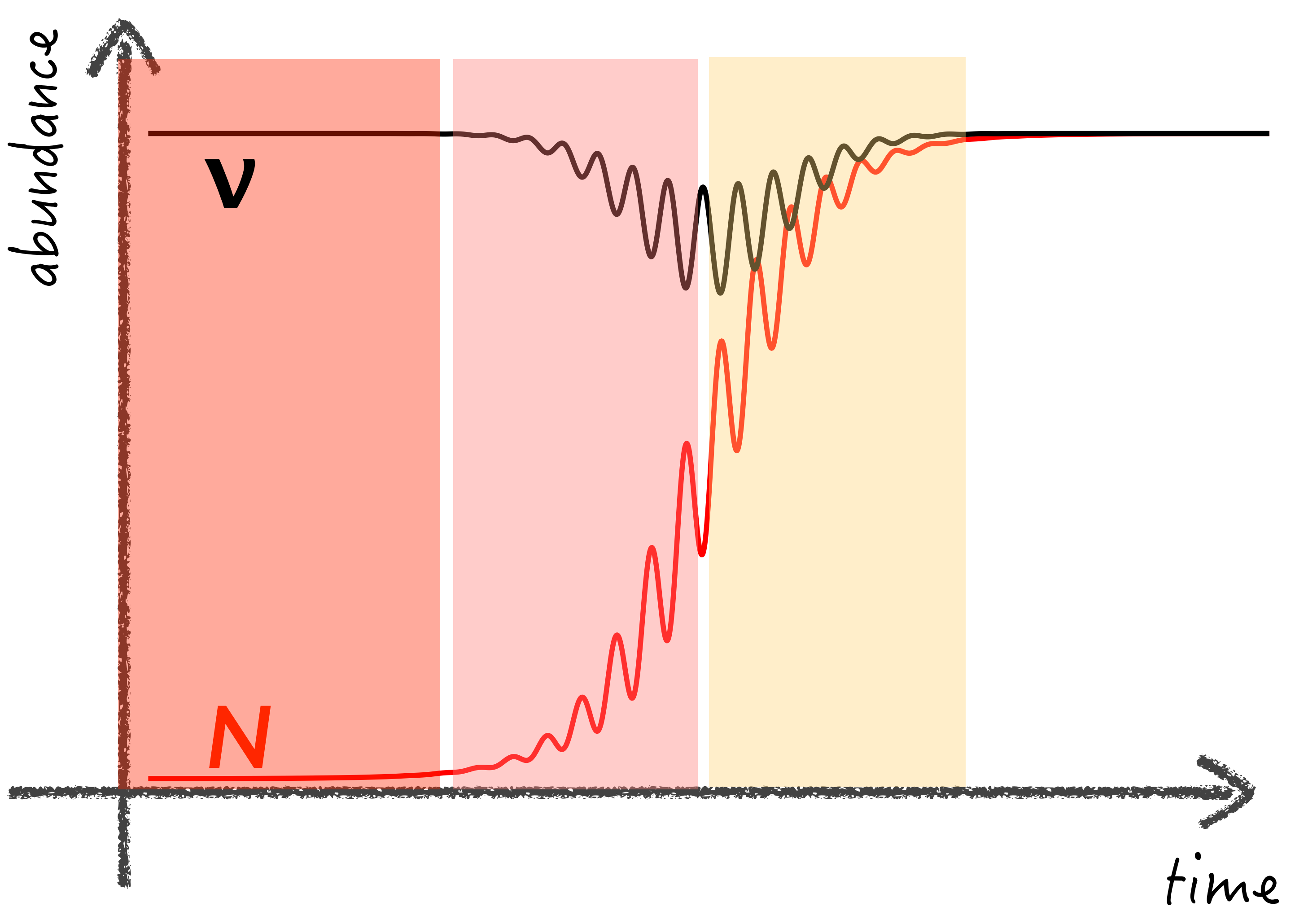

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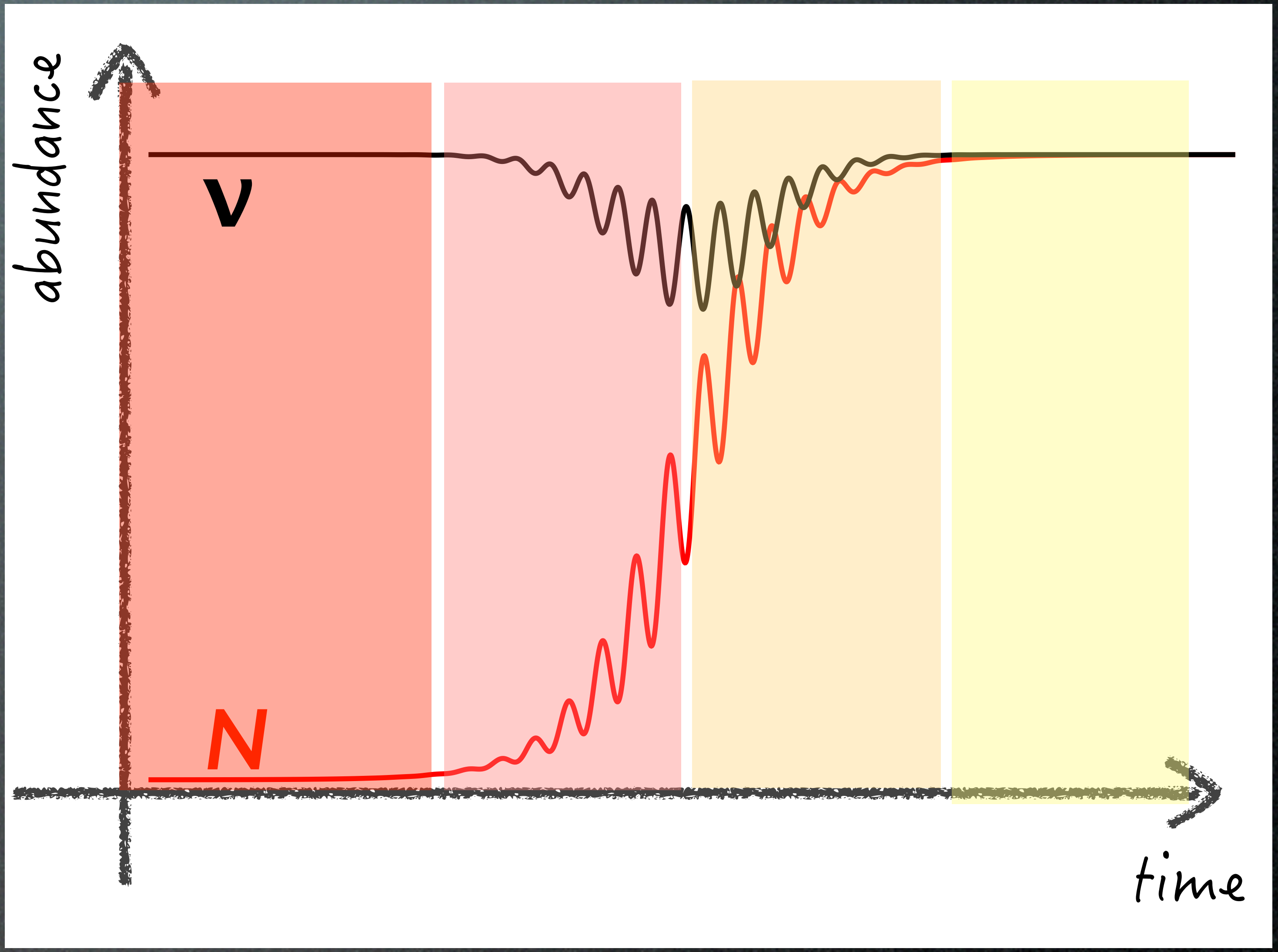


$$\Omega_N \simeq \left(\frac{\sin^2\theta}{3\cdot 10^{-9}}\right)\left(\frac{m_N}{3\,\mathrm{KeV}}\right)$$

The relic abundance is determined by θ and m_N.

Overview of Particle Physics candidates for Dark Matter

Candidates

A matter of perspective:

Candidates

A matter of perspective:

SuSy DM

Non SuSy DM

Candidates

A matter of perspective:

SuSy DM

Non SuSy DM

LA VERDADERA PIZZA Y PASTA ITALIANA
PLAZA P. CANA - BAVARO - 809 552 1547

?

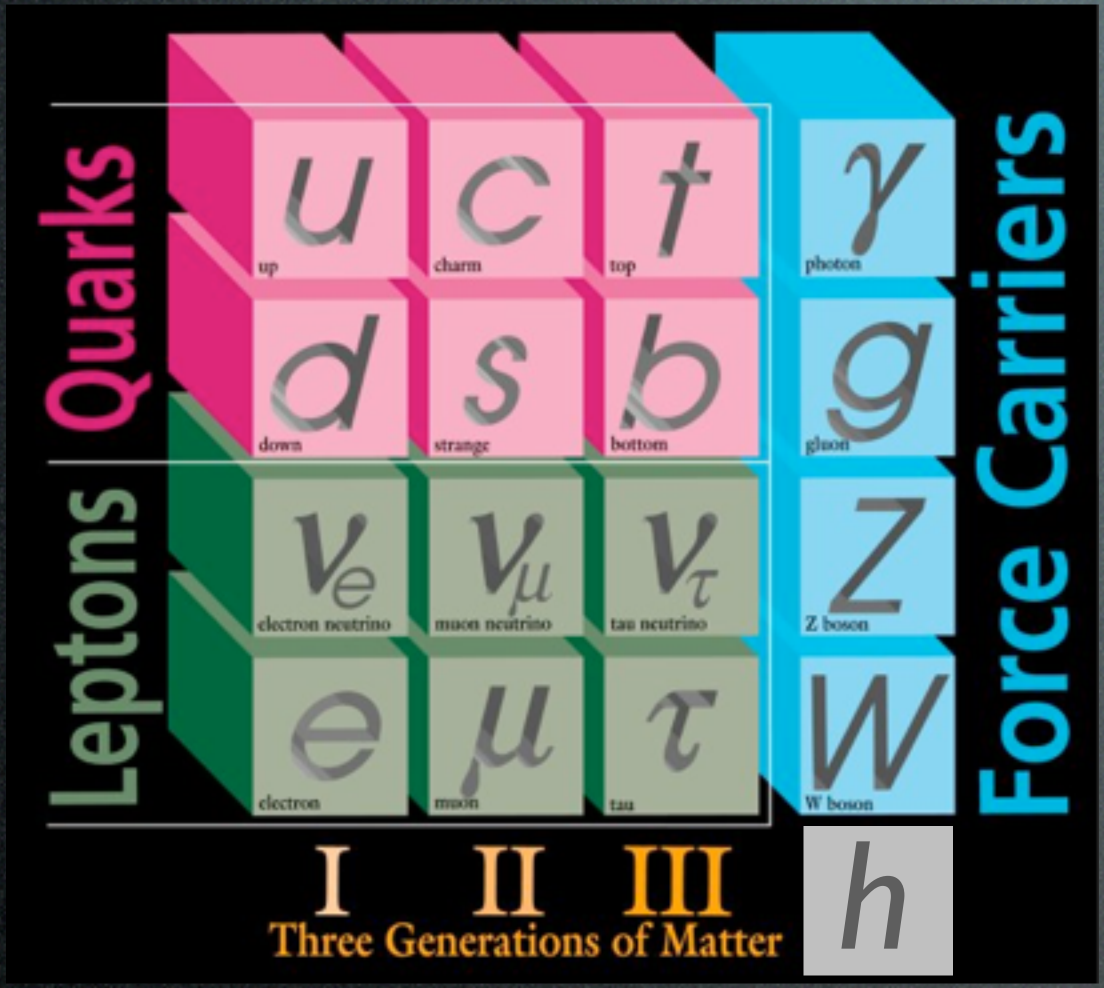
Candidates

A matter of perspective:

SuSy neutralino

other exotic candidates

SuSy DM in 2 minutes



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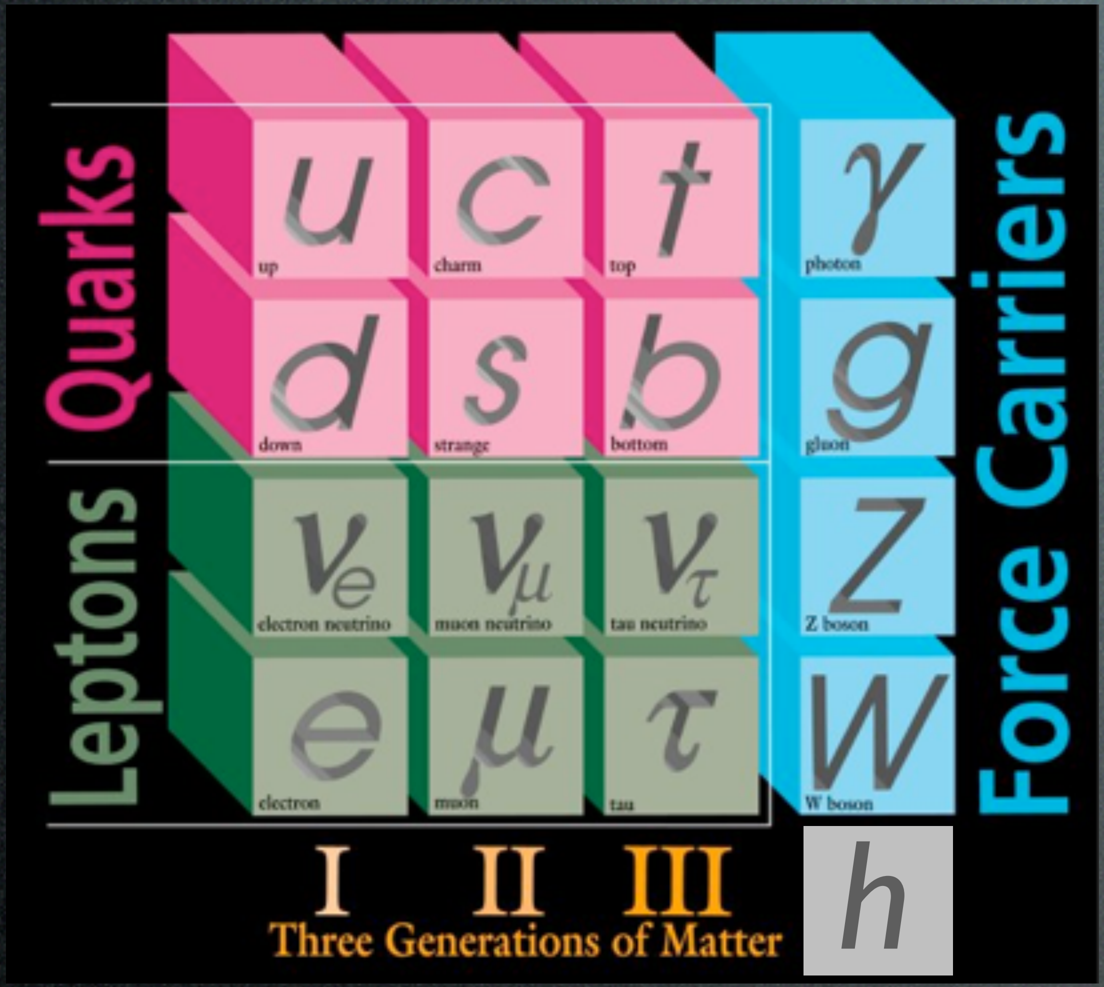

$m_{\mathrm{h}} \simeq 125~\mathrm{GeV}$

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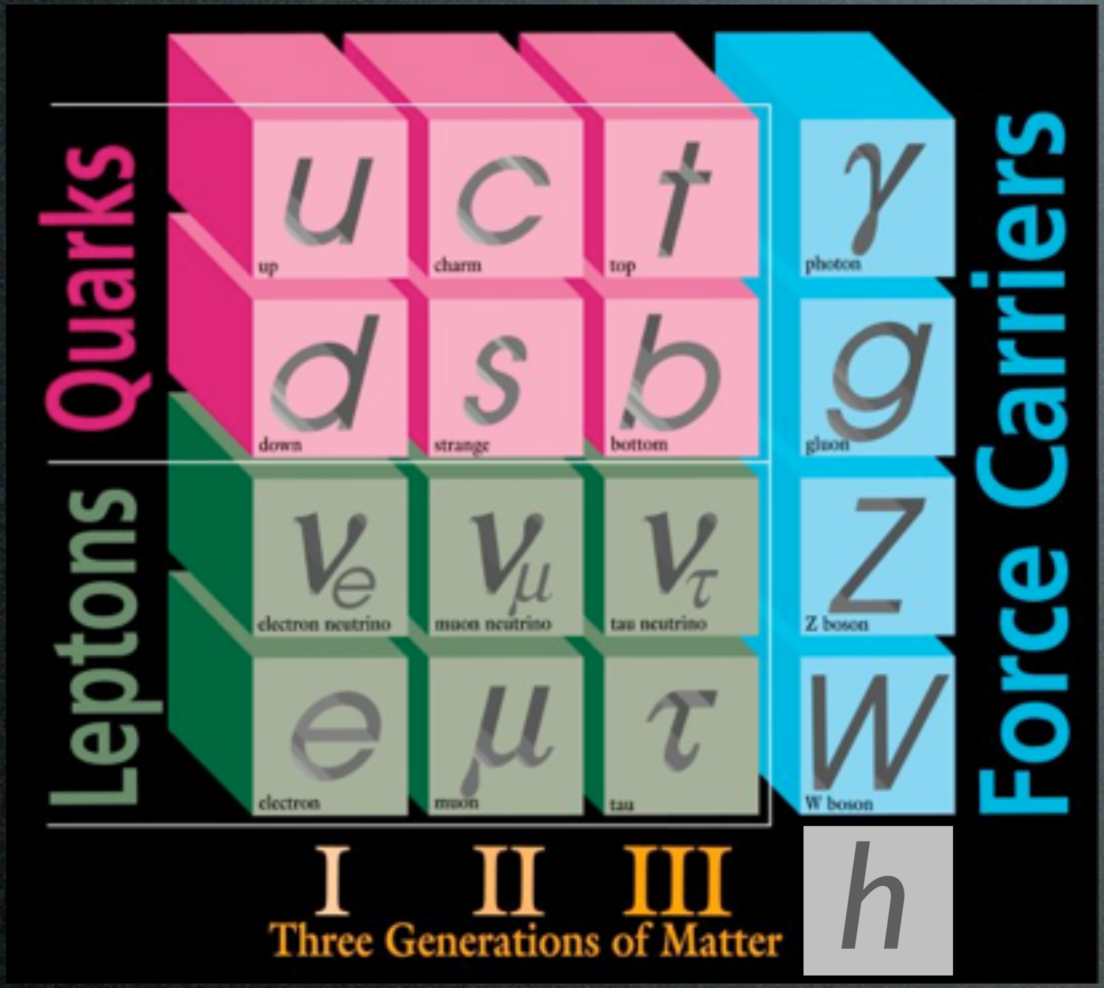

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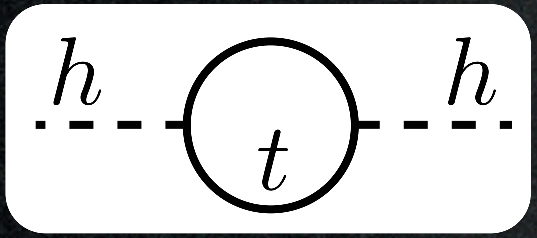

$\Delta m_{\rm h} \propto 10^{19}$ GeV

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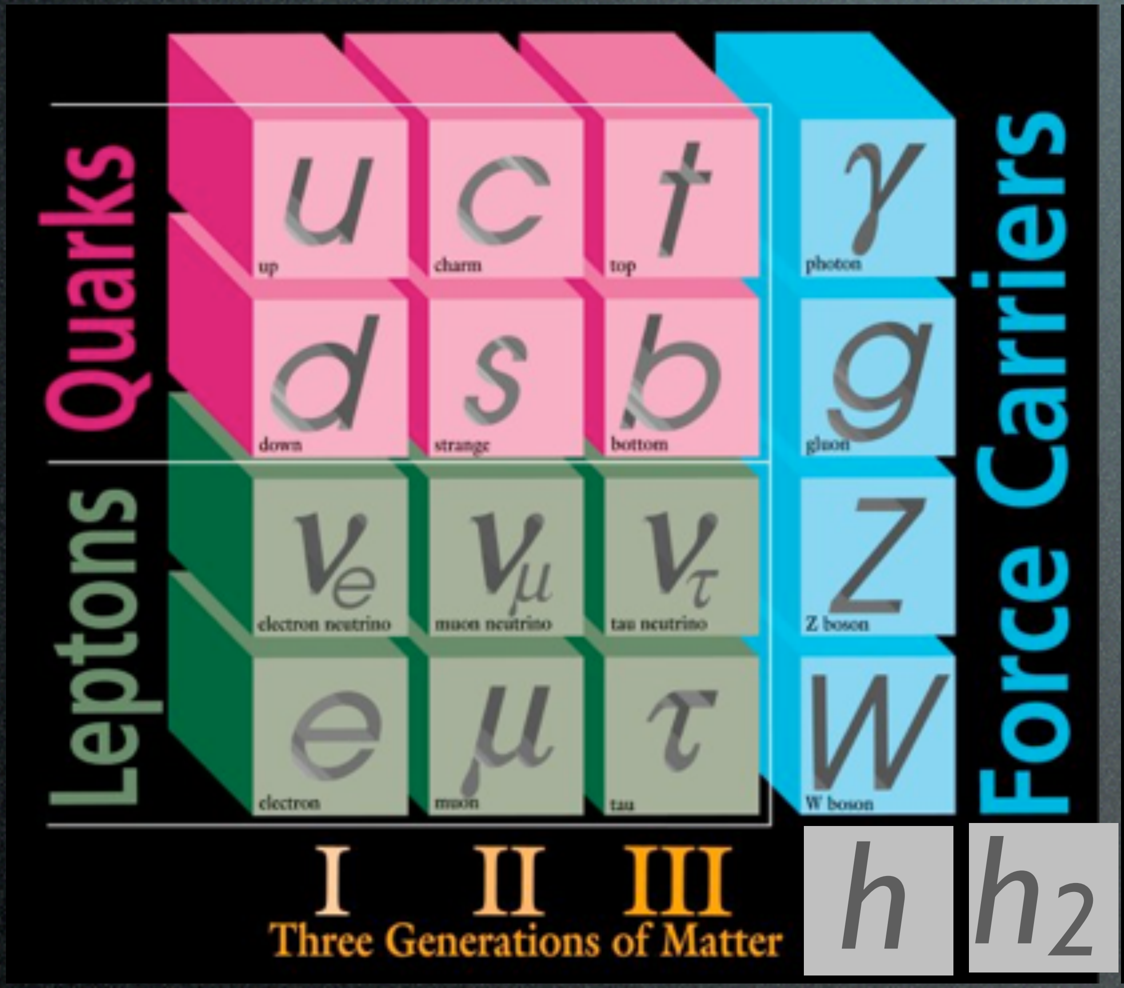

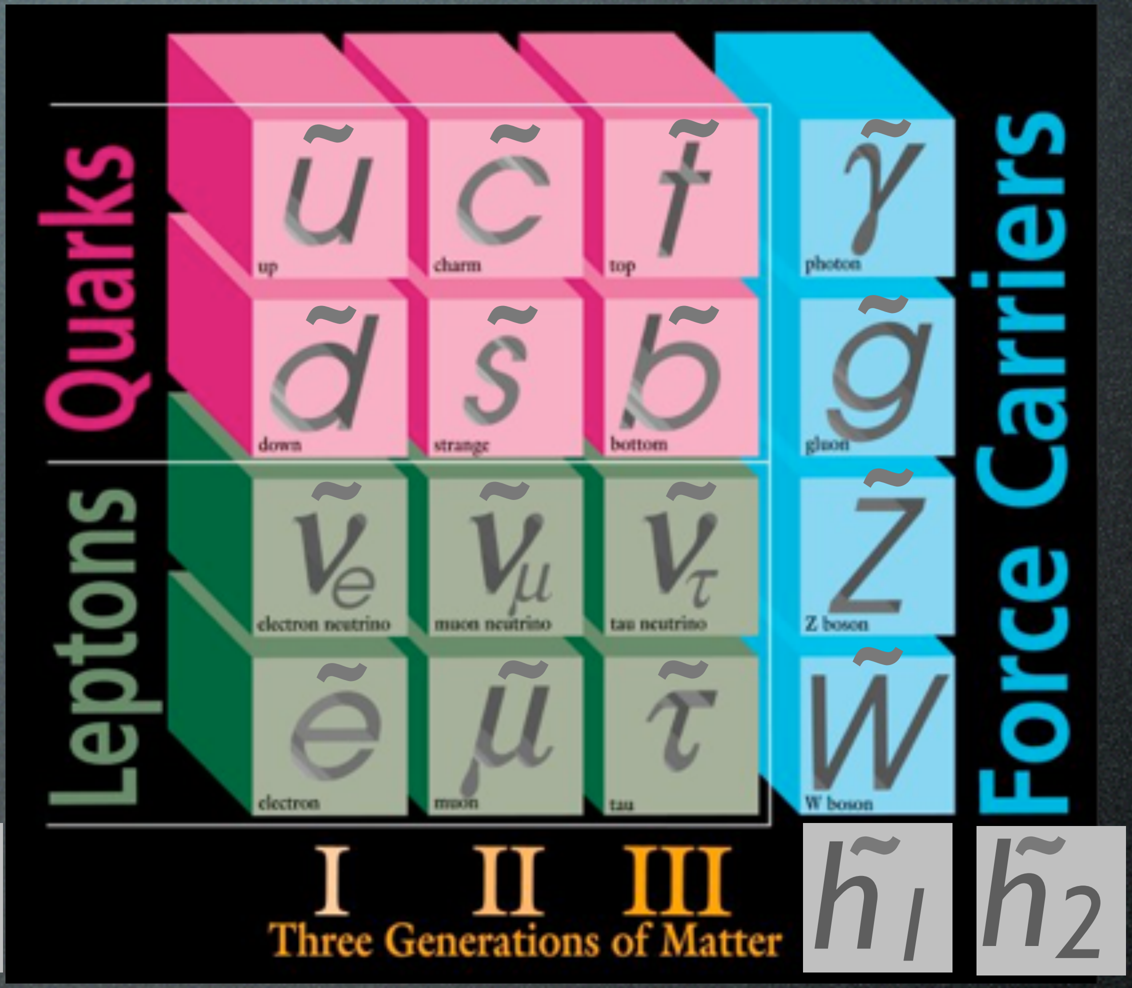

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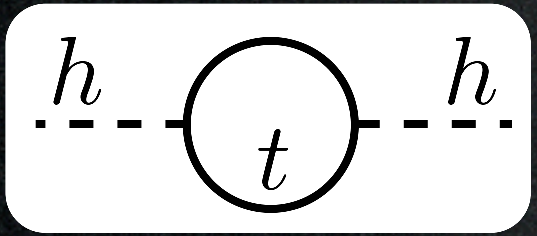

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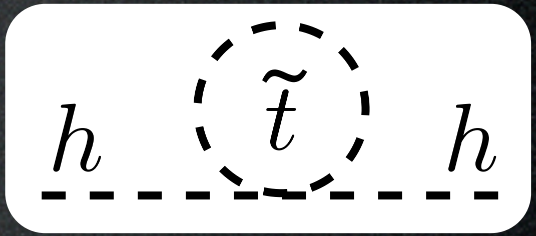

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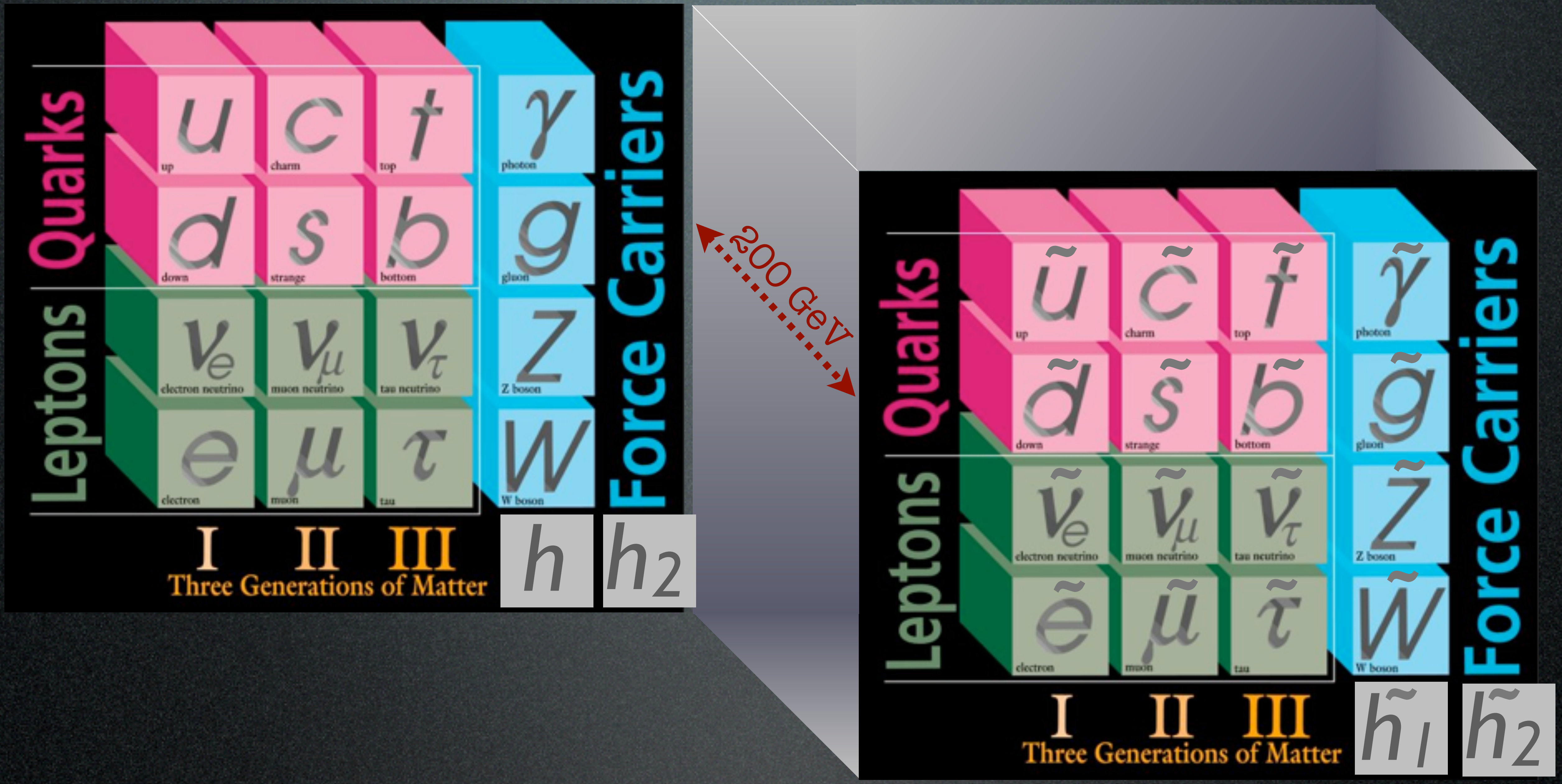

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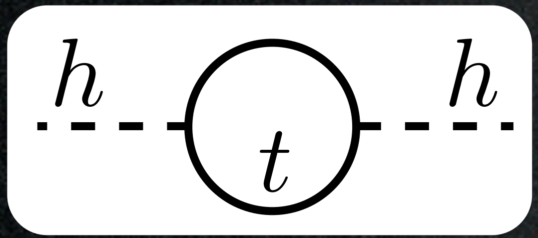

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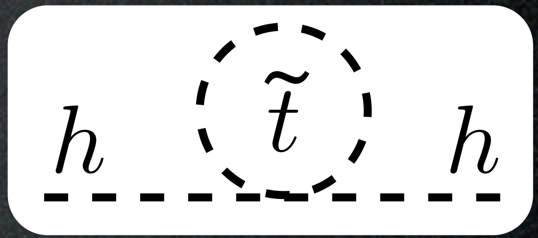

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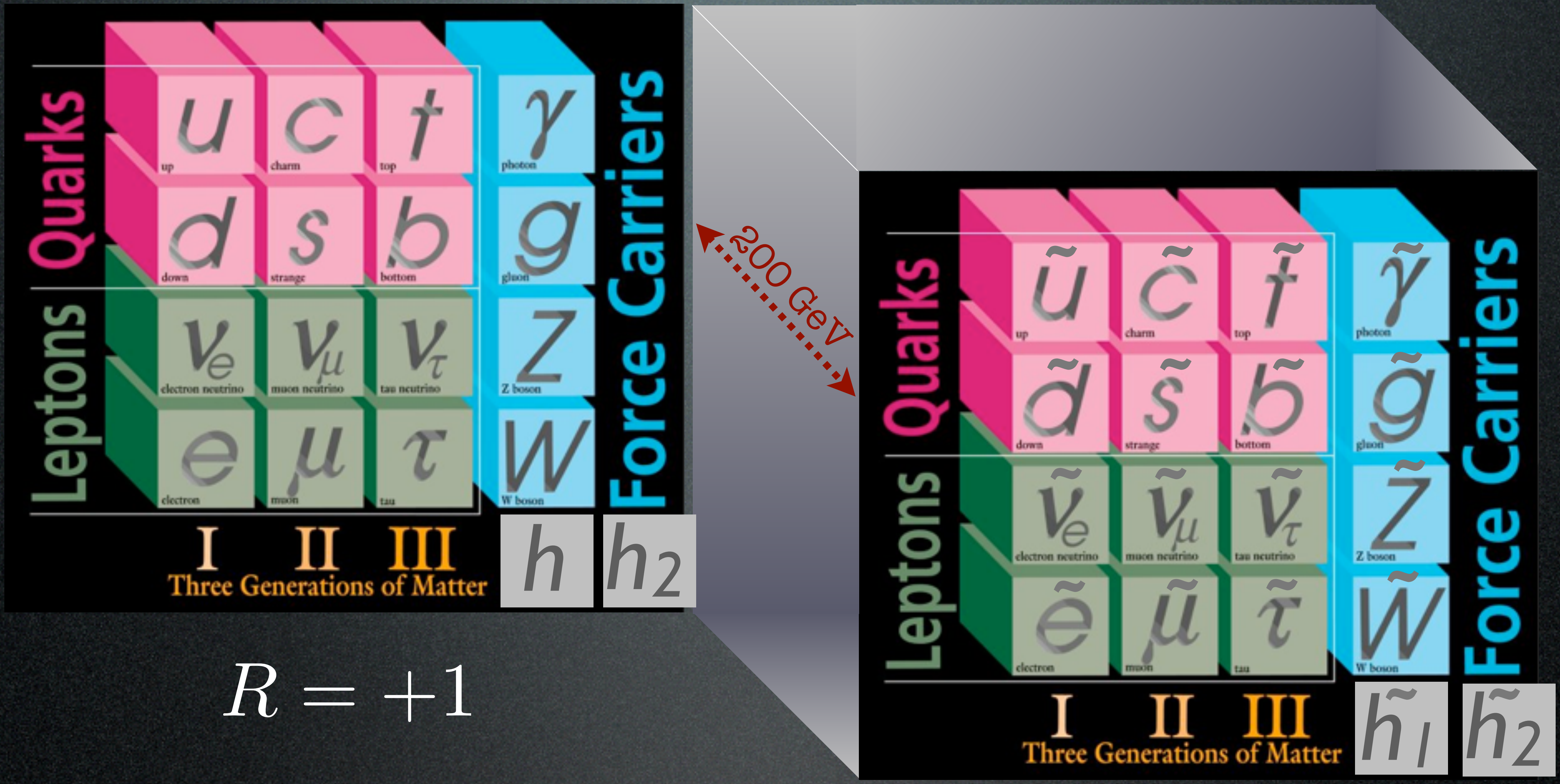
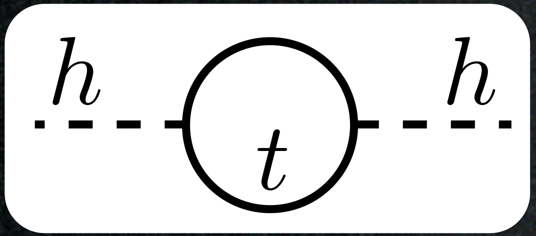


$$R = +1$$

$$m_{\rm h} \simeq 125 \text{ GeV}$$



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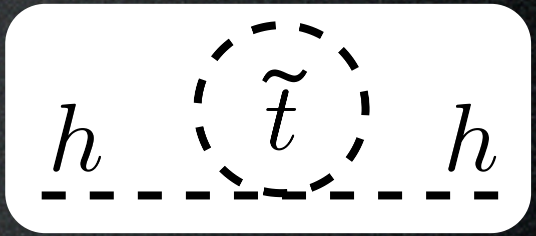

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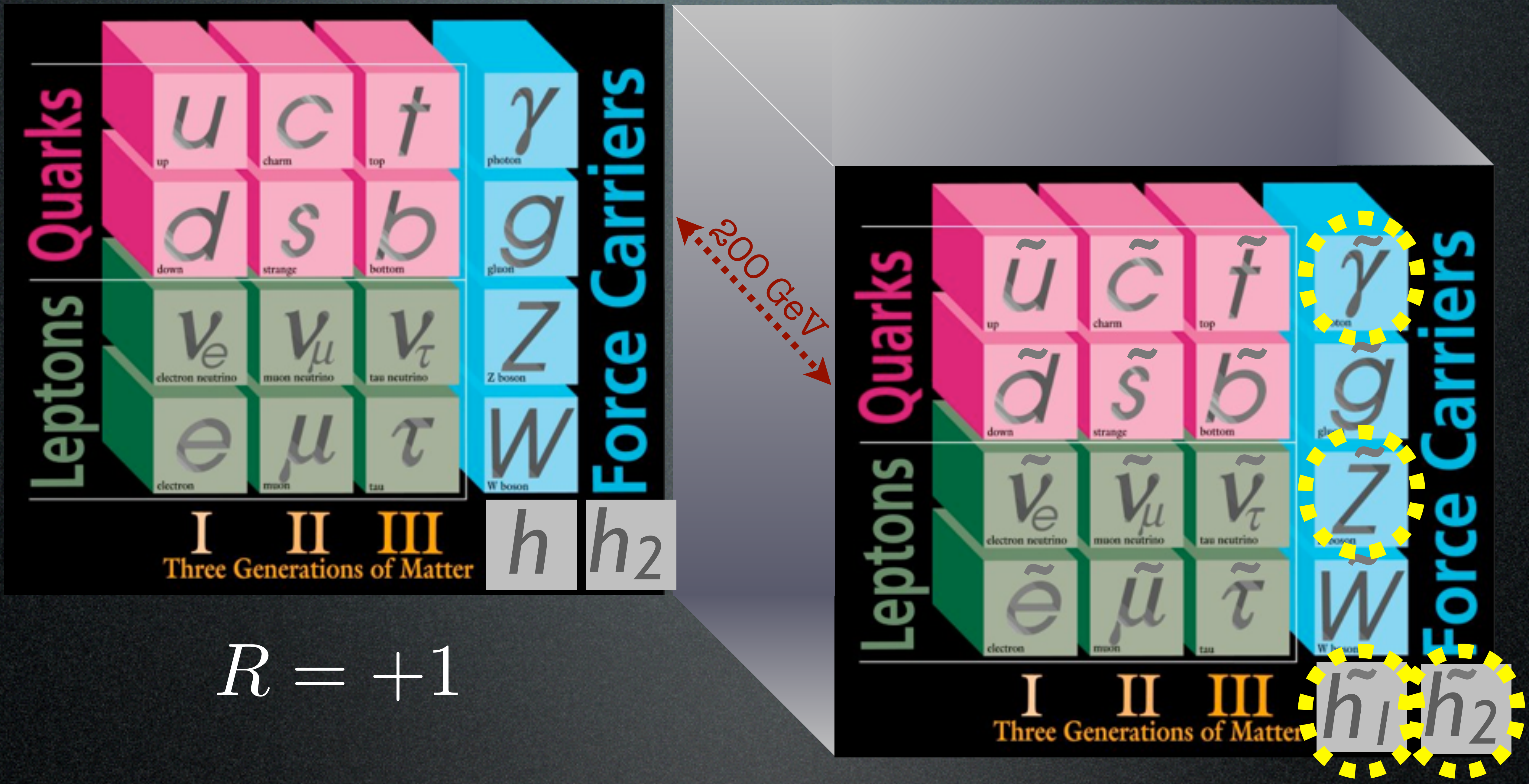

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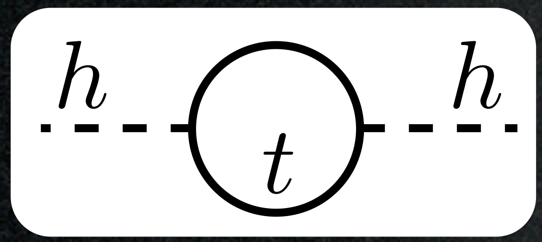

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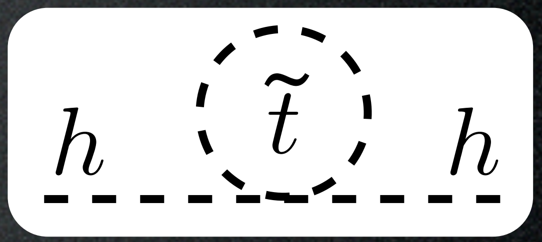

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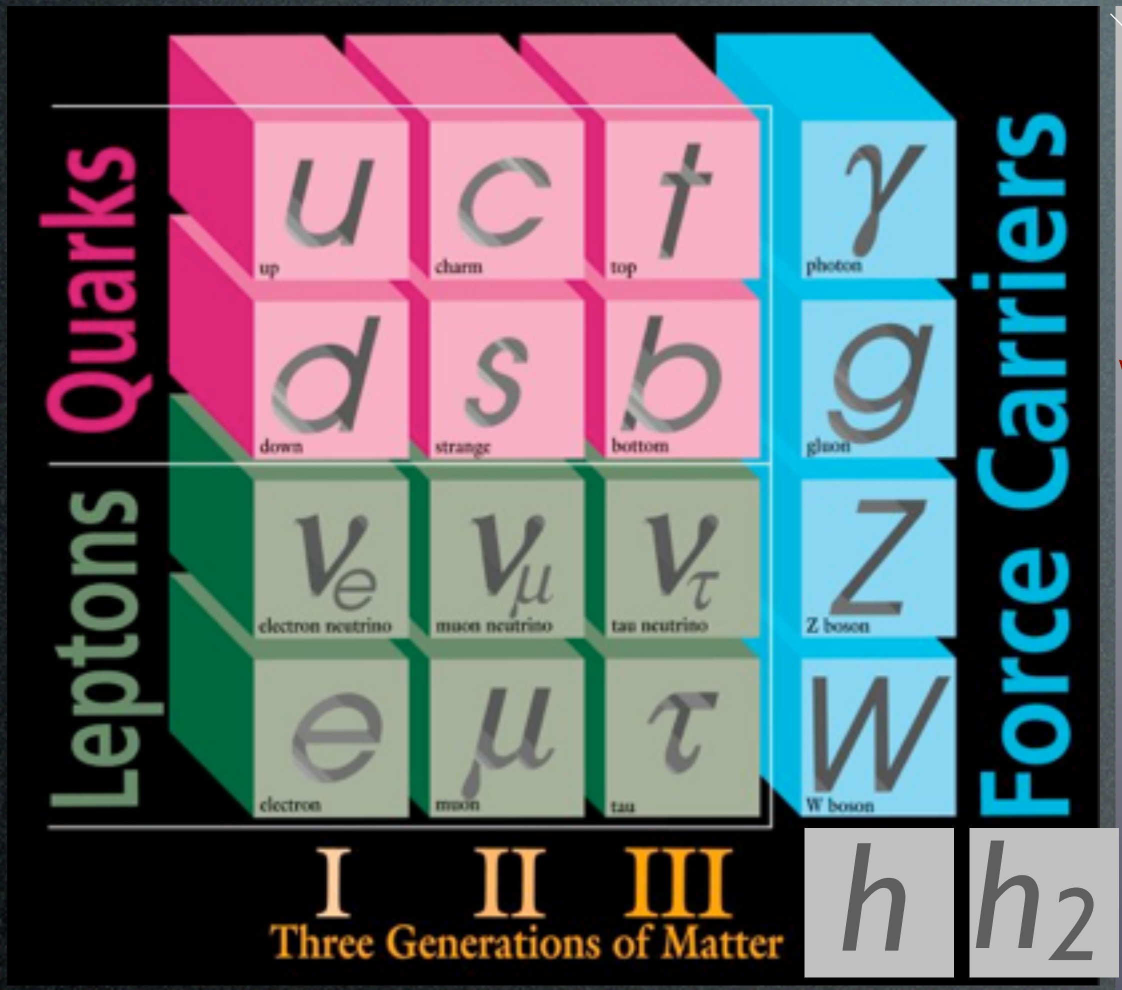

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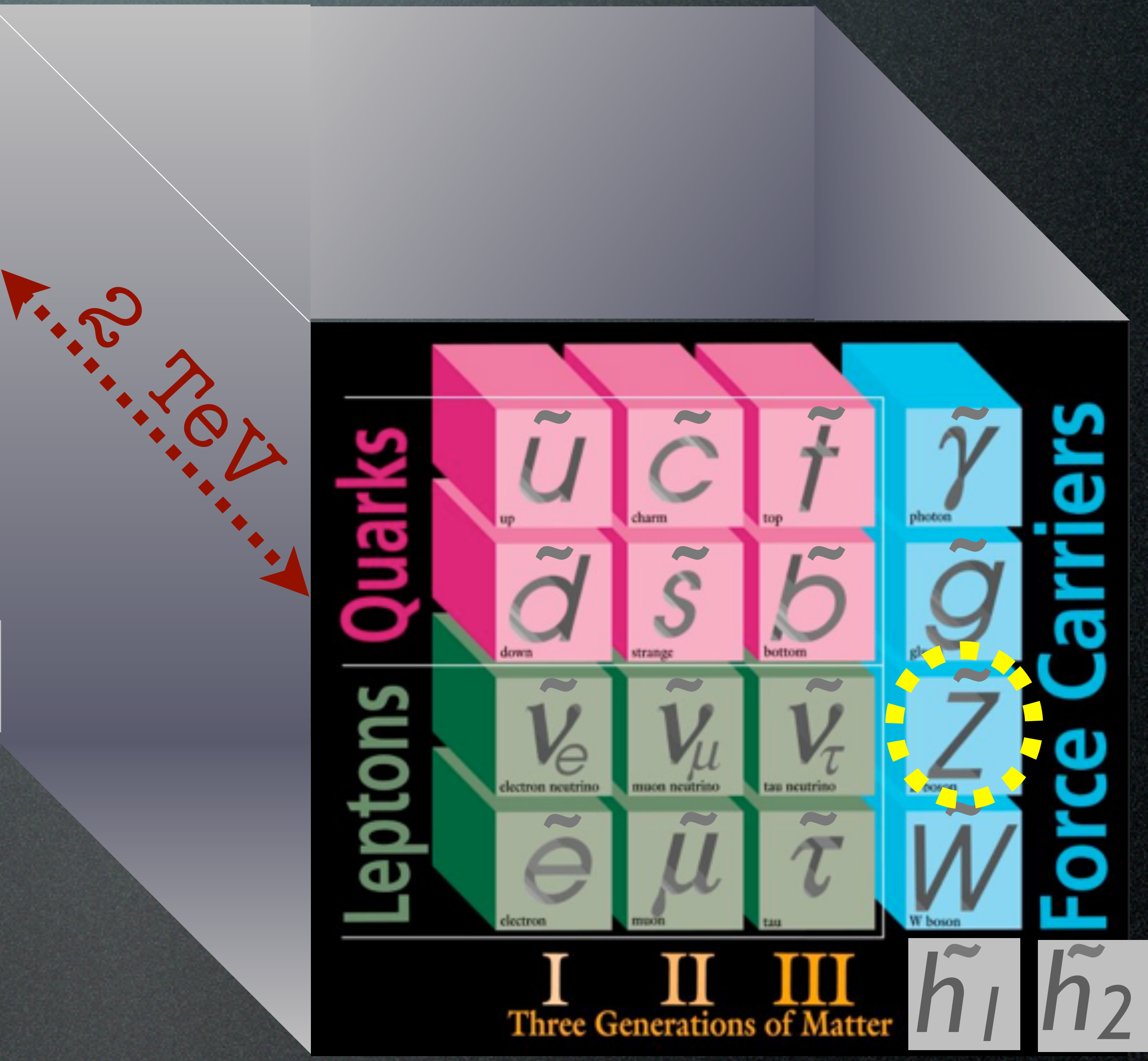

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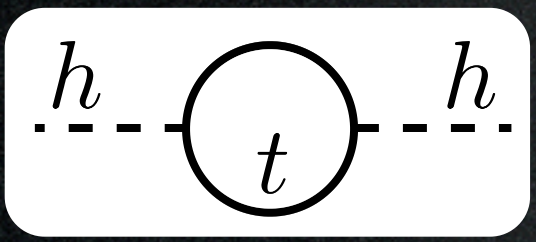

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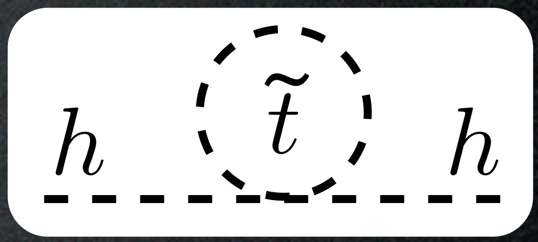

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Candidates

A matter of perspective:

SuSy neutralino

other exotic candidates

Candidates

A matter of perspective:

Minimal DM

cannibal DM

Anapole DM

Axino

dipolar DM

Little Higgs DM

Asym-metric DM

Scalar singlet

SIMPs

Rayleig DM

SuSy neutralino

Self-inter DM

WISPy DM

Techi-baryon

eXciting DM

inflatable DM

Dichromatic DM

Axions

vector DM

Forbidden DM

mirror matter

WIMPless DM

Secluded DM

heavy higgs DM

Sterile Neutrinos

Luminous DM

Kaluza-Klein DM

MeV DM

Q-balls

Gravitino

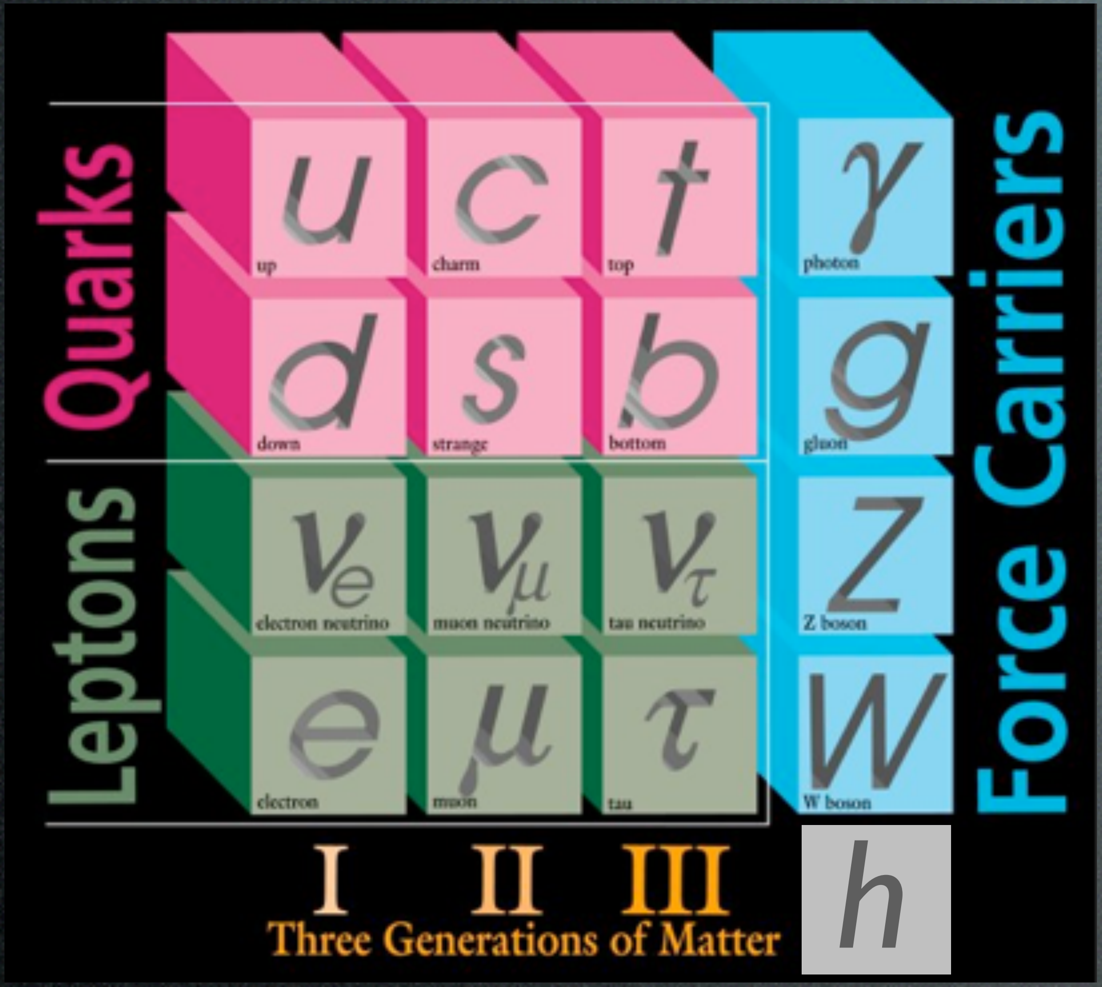
quark nuggets

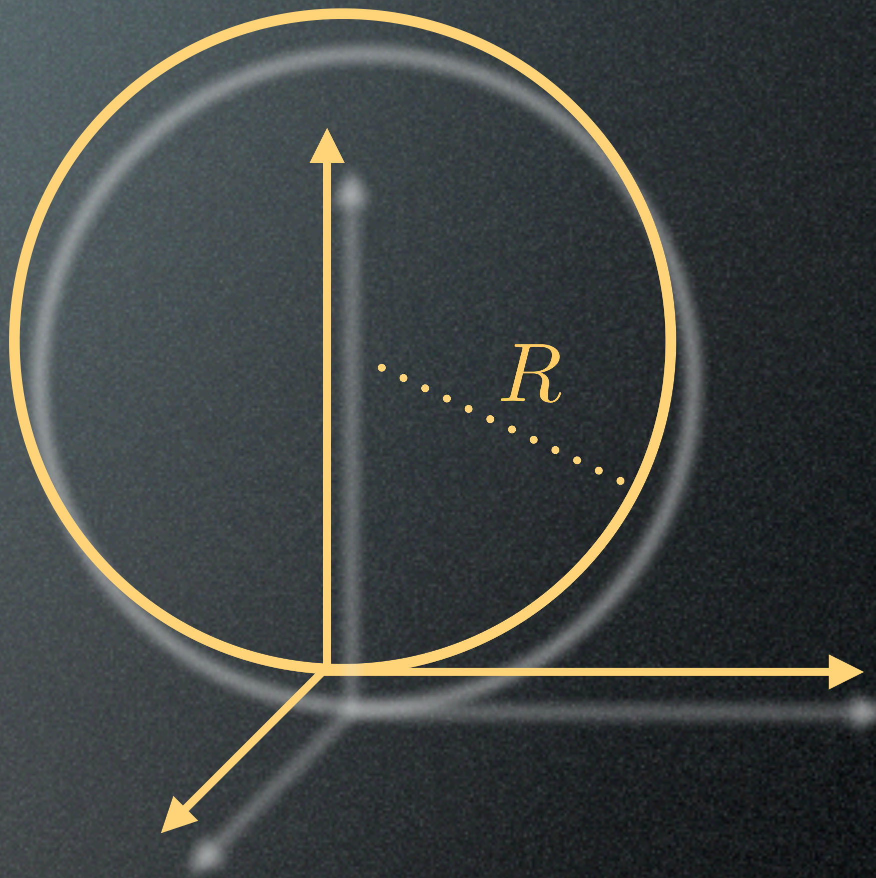
dark photon

Imperfect DM

Mimetic DM

ExDim DM in 2 minutes





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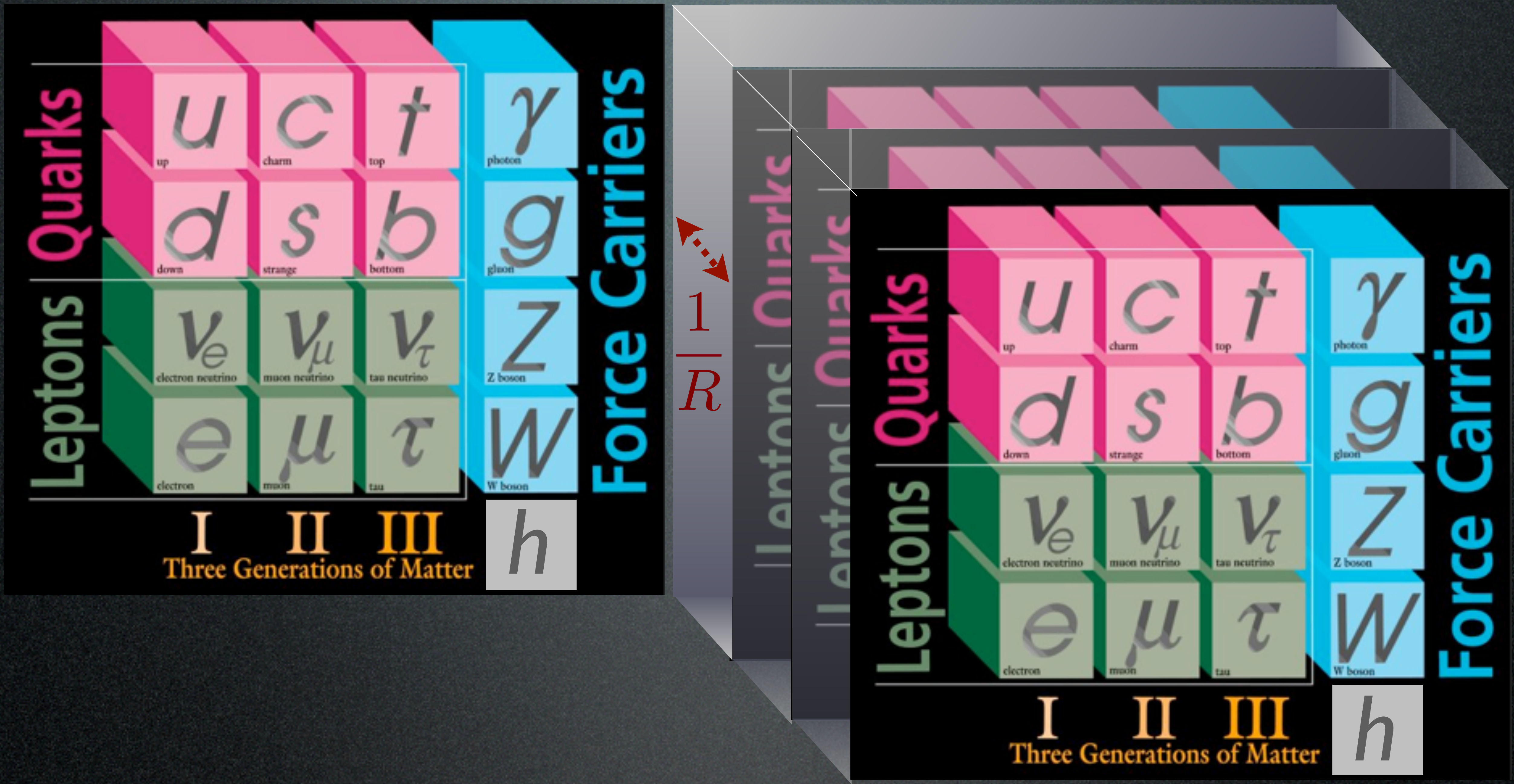

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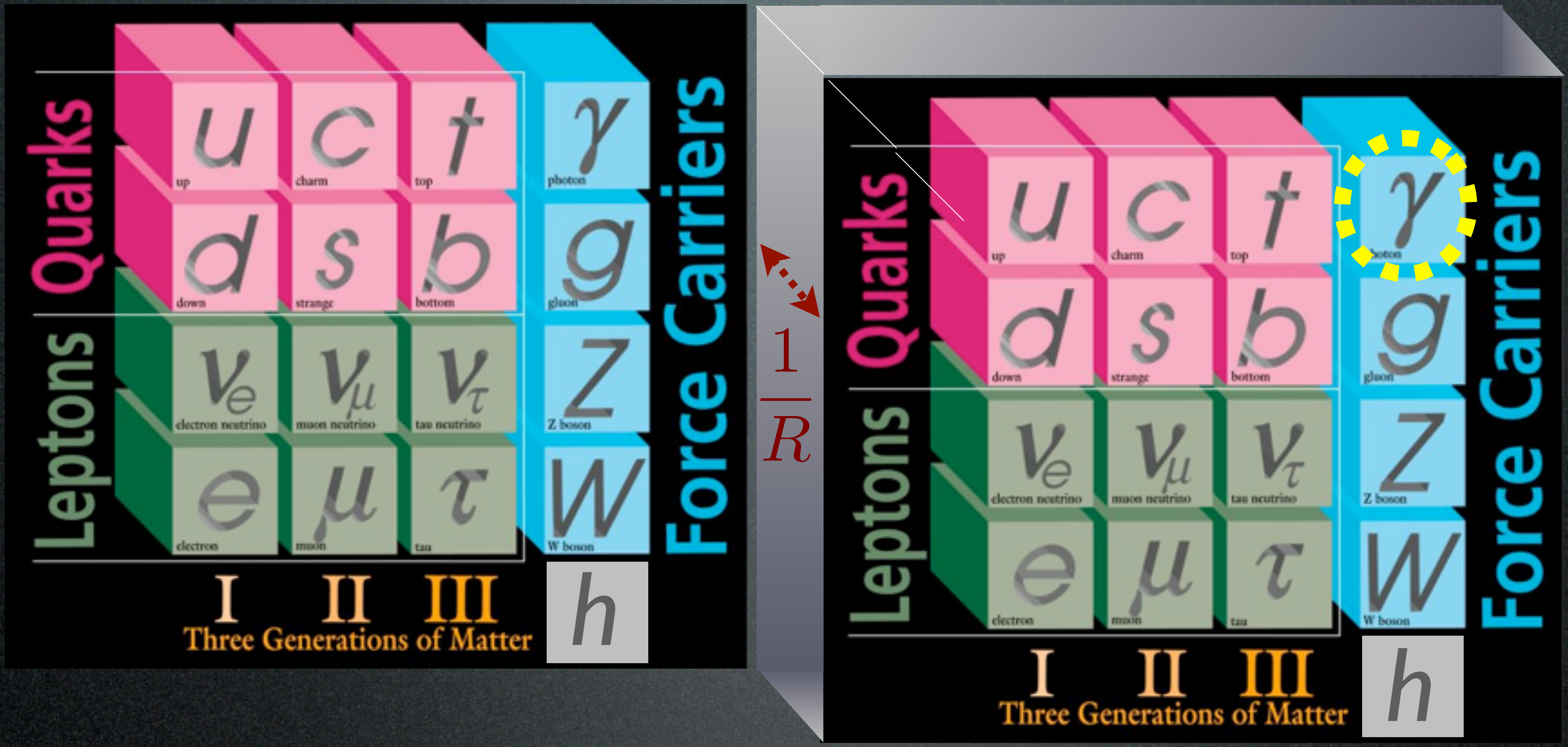

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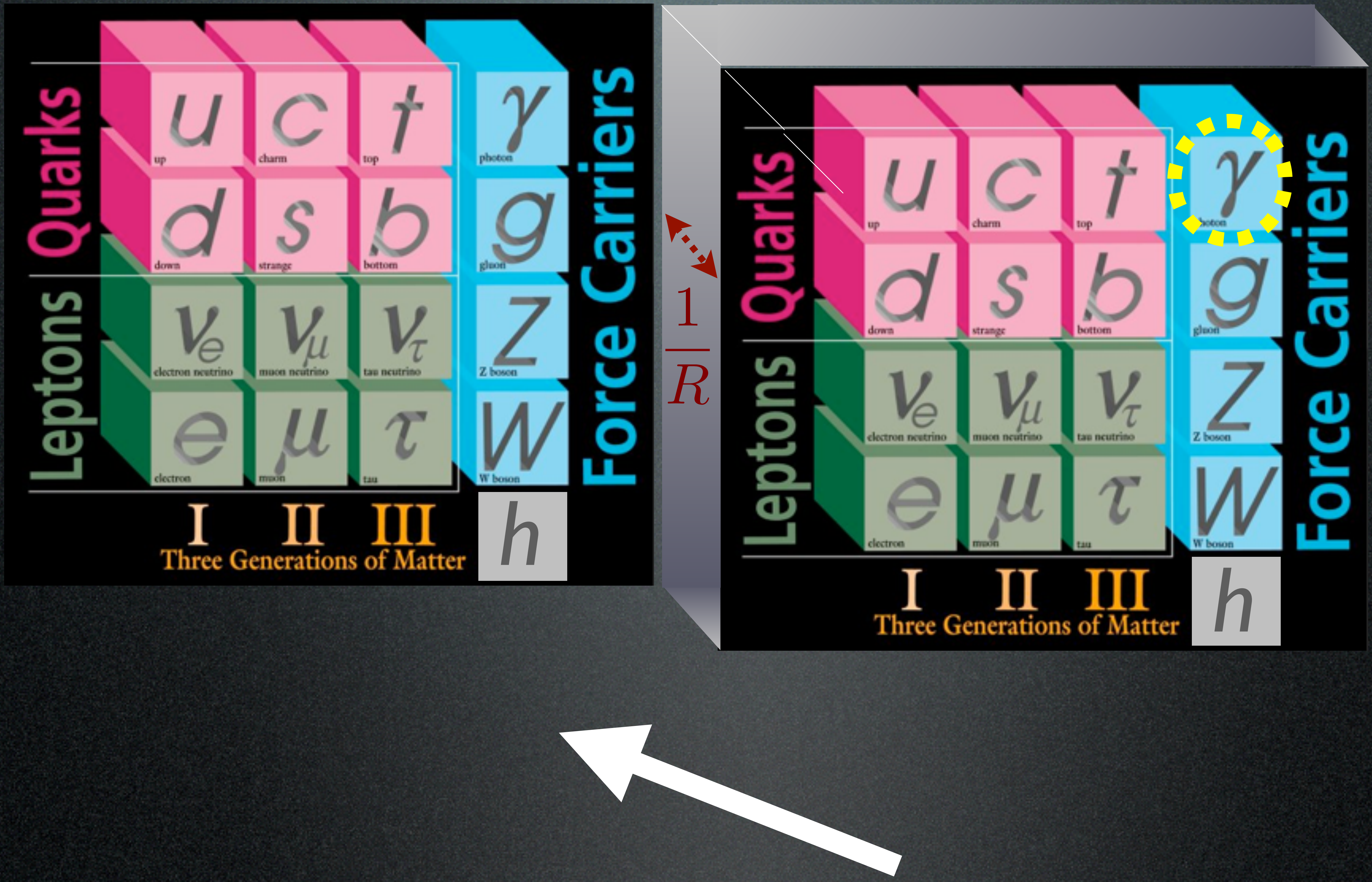

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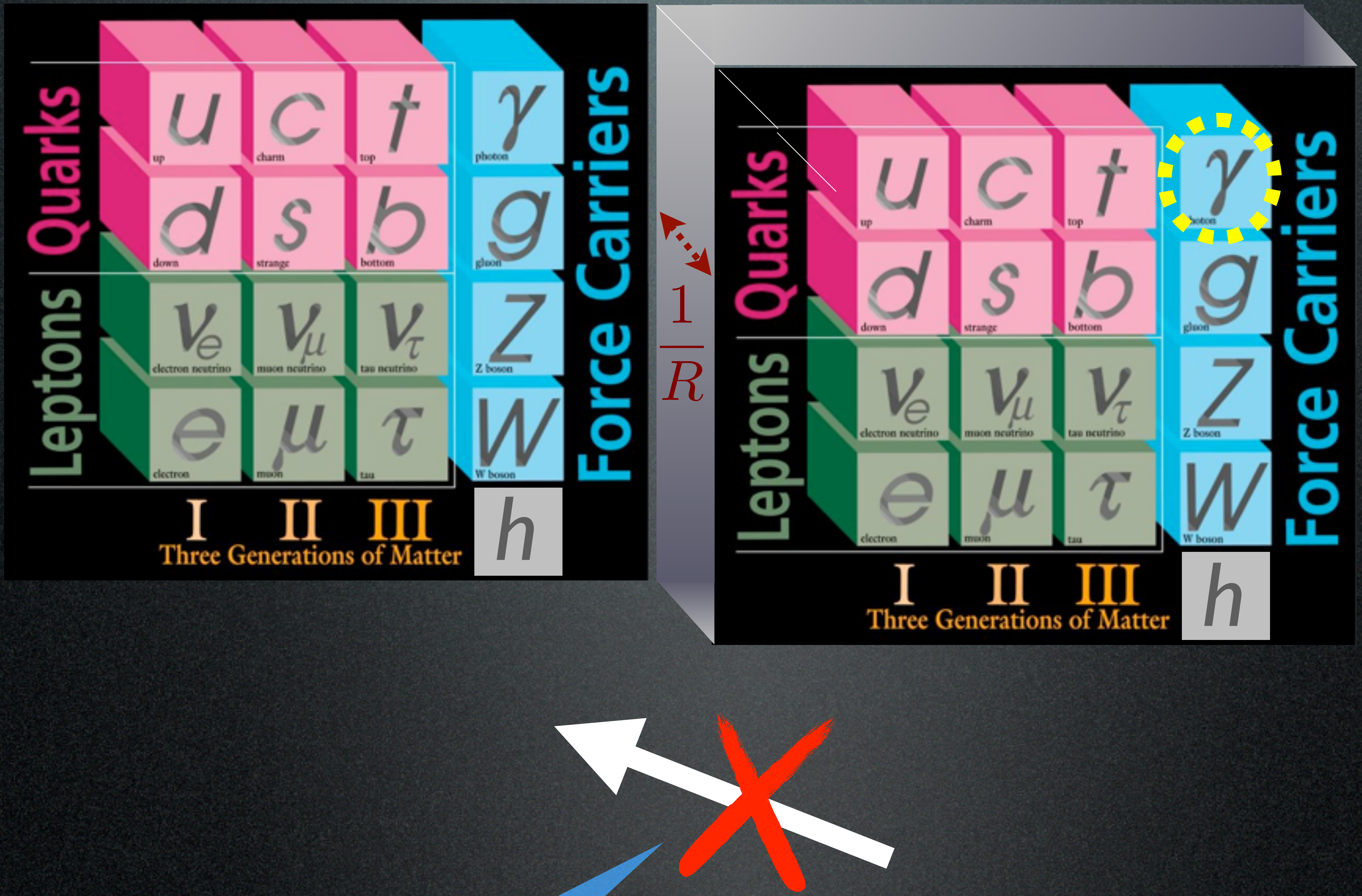

conservation of 5D momentum

(on orbifold boundary conditions, needed to have chiral SM fermions)

Theory space

The Dark Matter theory space:

Caveat: no categorization is perfect.

DM

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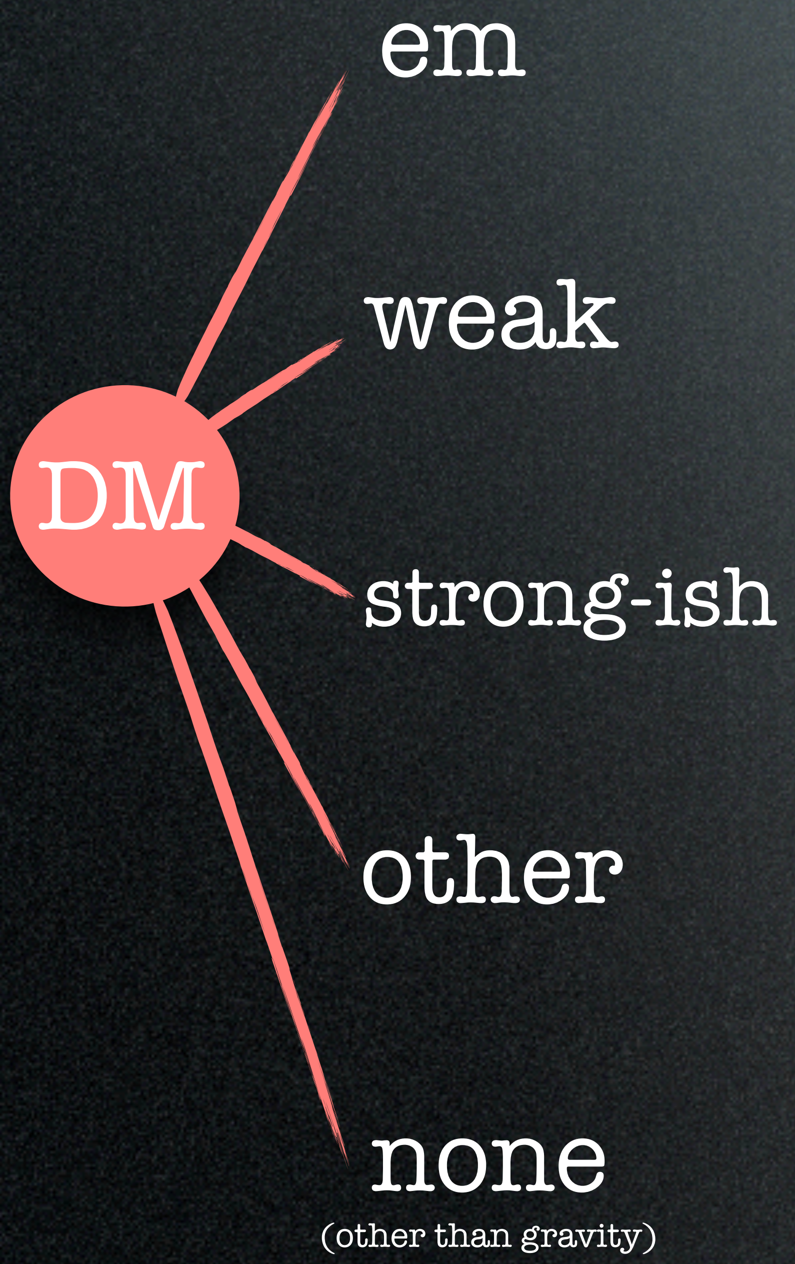
Interactions:



DM

- em
- weak
- strong-ish
- other
- none (other than gravity)

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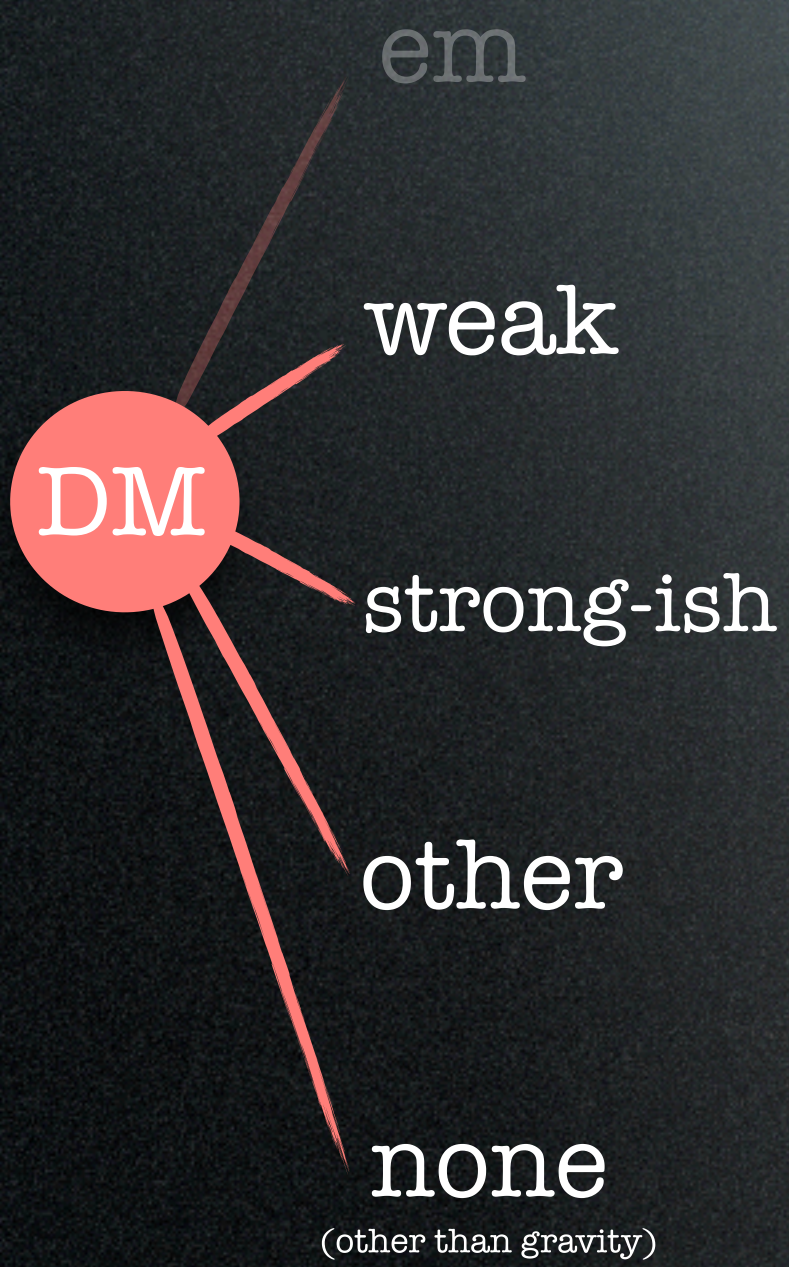

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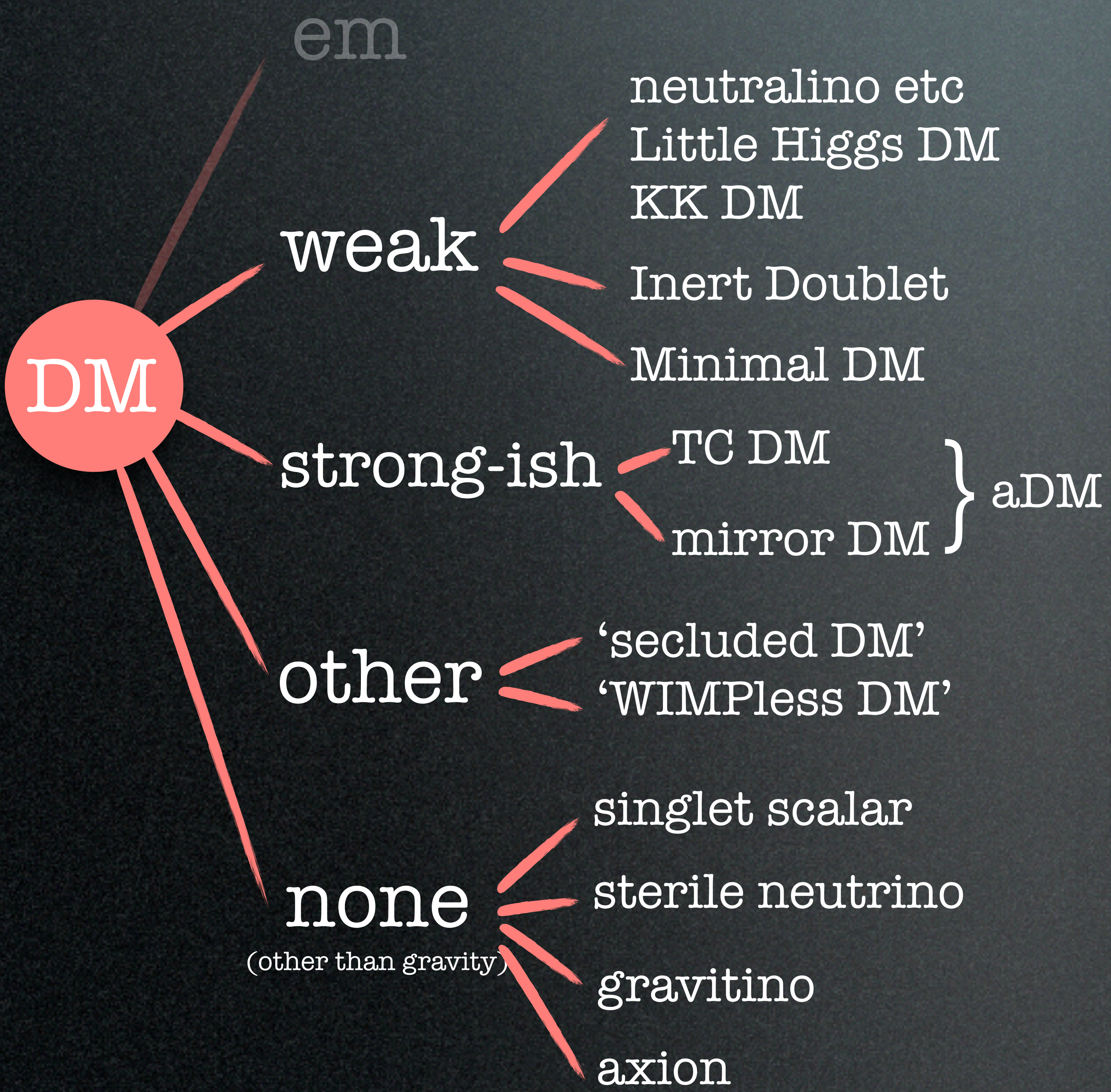

DM

- em
- weak
  - neutralino etc
  - Little Higgs DM
  - KK DM
  - Inert Doublet
  - Minimal DM
- strong-ish
  - TC DM
  - mirror DM
  - } aDM
- other
  - ‘secluded DM’
  - ‘WIMPless DM’
- none (other than gravity)
  - singlet scalar
  - sterile neutrino
  - gravitino
  - axion

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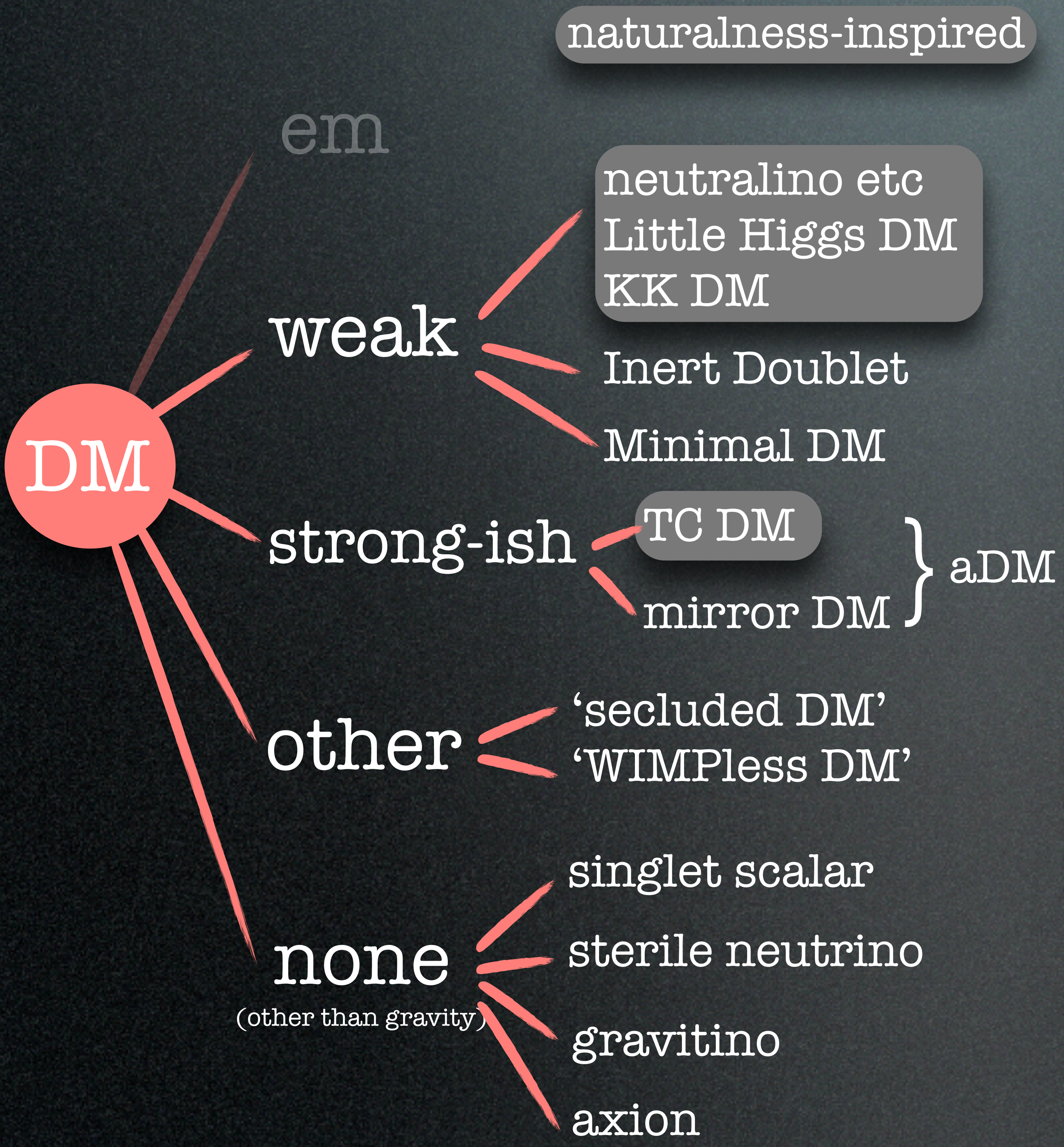

naturalness-inspired

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} aDM

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DM

naturalness-inspired: neutralino etc, Little Higgs DM, KK DM, TC DM

Interactions:		Production mechanism?	Stability?
em			
weak	neutralino etc	thermal freeze out	R parity
	Little Higgs DM	thermal freeze out	T parity
	KK DM	thermal freeze out	K parity
	Inert Doublet	thermal freeze out	Z_2 symmetry
	Minimal DM	thermal freeze out	gauge sym
strong-ish	TC DM } aDM	‘exhaustion’	Tbaryon #
	mirror DM } aDM	‘exhaustion’	Z_2 symmetry
other	‘secluded DM’	sort of freeze out	some symmetry
	‘WIMPless DM’	sort of freeze out	some symmetry
none (other than gravity)	singlet scalar	thermal freeze out	Z_2 symmetry
	sterile neutrino	mixing	just long lived
	gravitino	thermal or decay	R parity or just long lived
	axion	misalignment?	just long lived

Executive summary

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- it's a new, unknown particle

no SM particle can fulfil

dilutes as $1/a^3$ with universe expansion

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(notice error!)

[Planck 2015, 1502.01589]

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- very feebly interacting

  -with itself

  -with ordinary matter ('collisionless')

- stable or very long lived $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU

Executive summary

- DM exists
- it's a new, unknown particle — *no SM particle can fulfil* — *dilutes as 1/a^3 with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself* *-with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17} {\rm sec}$
- possibly a relic from the EU
- searched for by

Executive summary

- DM exists
- it's a new, unknown particle

  no SM particle can fulfil

  dilutes as $1/a^3$ with universe expansion
- makes up 26% of total energy
  82% of total matter

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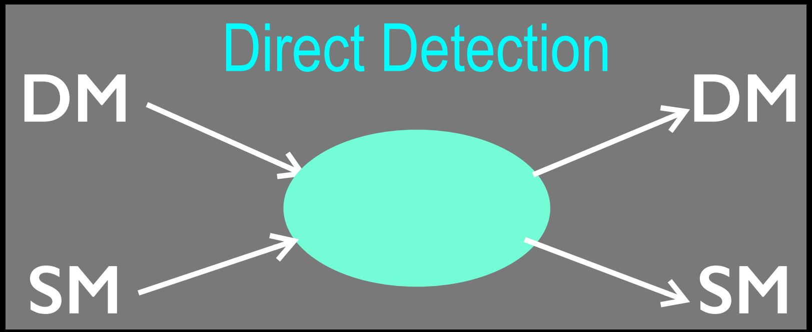

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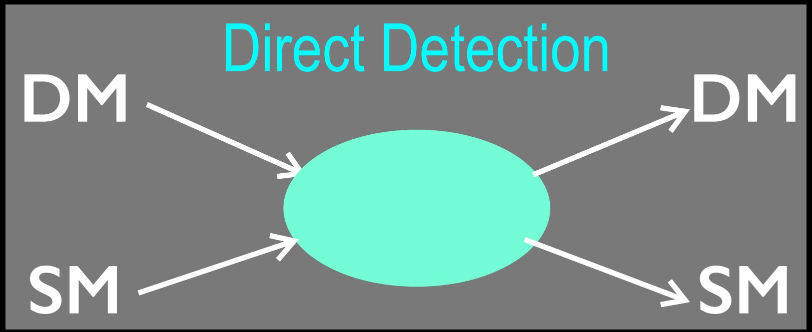

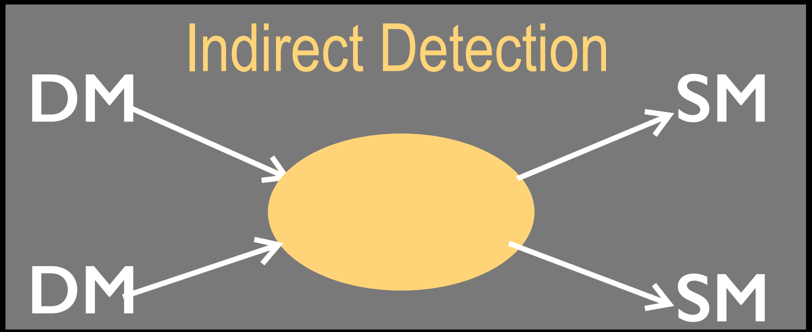

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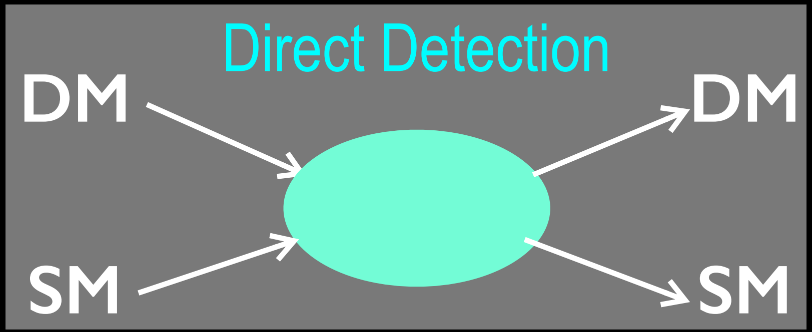
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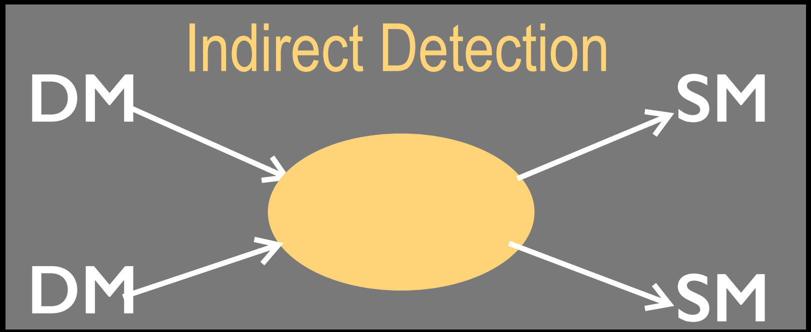
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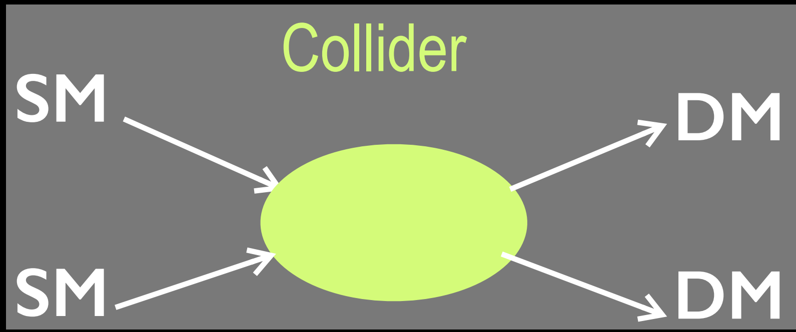

Collider

Detection

Detection

Dark
Matter

Underground physics

‘direct detection’

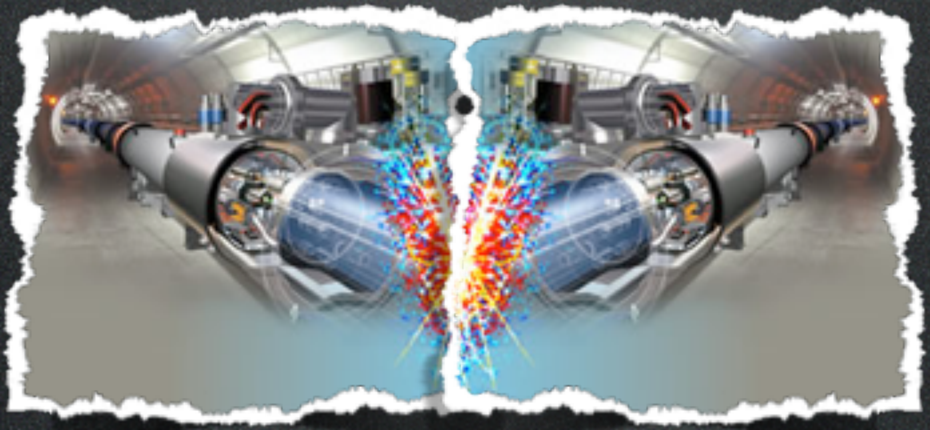
Dark Matter

Underground physics

‘direct detection’

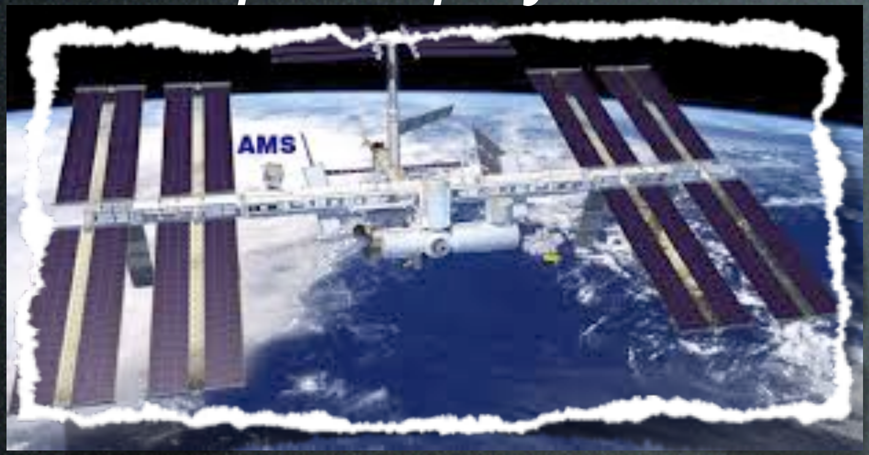
Dark
Matter

‘production’



Collider physics

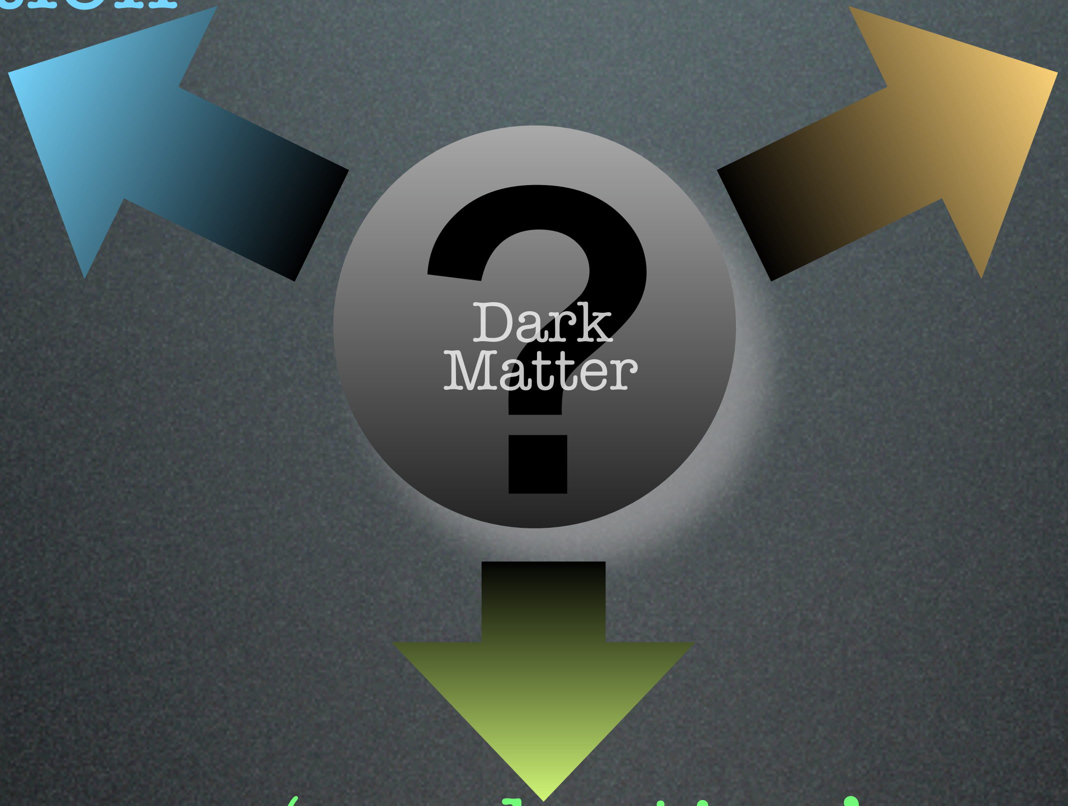
Space physics



‘indirect detection’

Underground physics

‘direct detection’



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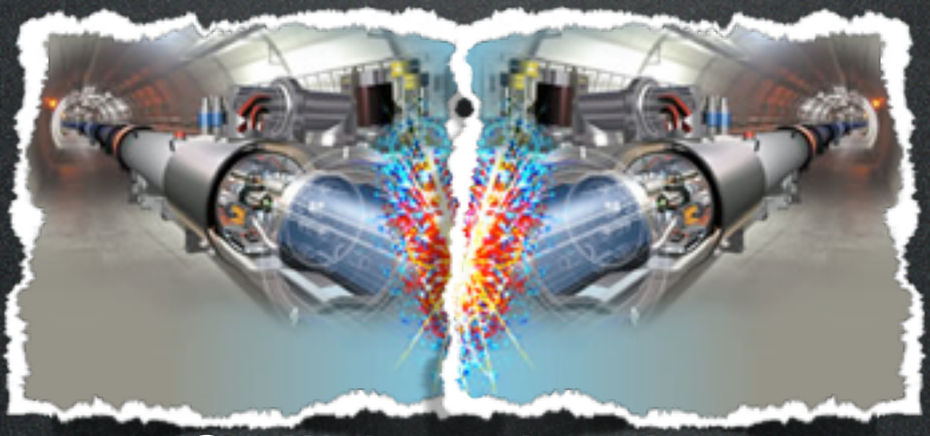

Collider physics

Direct Detection

Gran Sasso underground laboratories

Direct Detection

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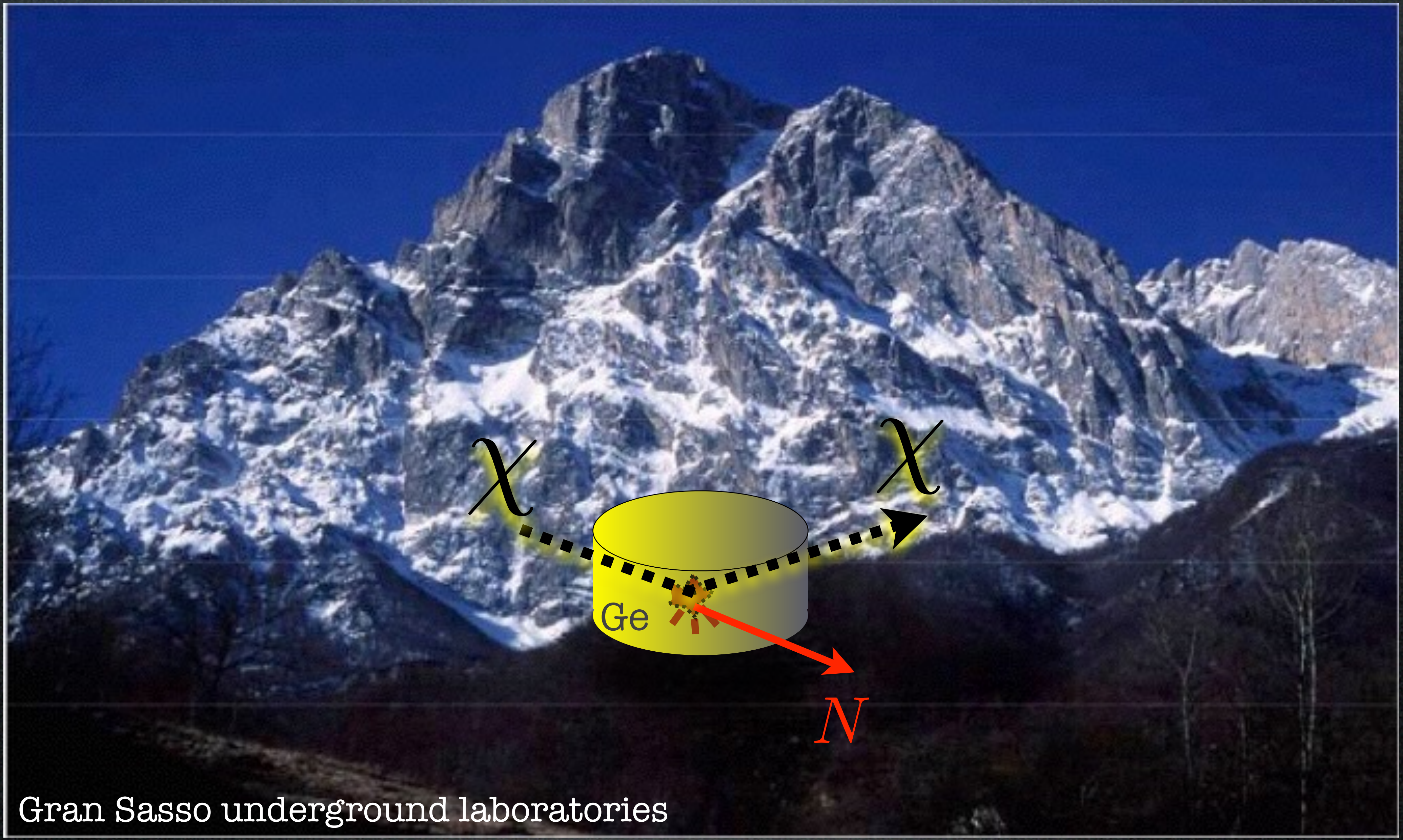
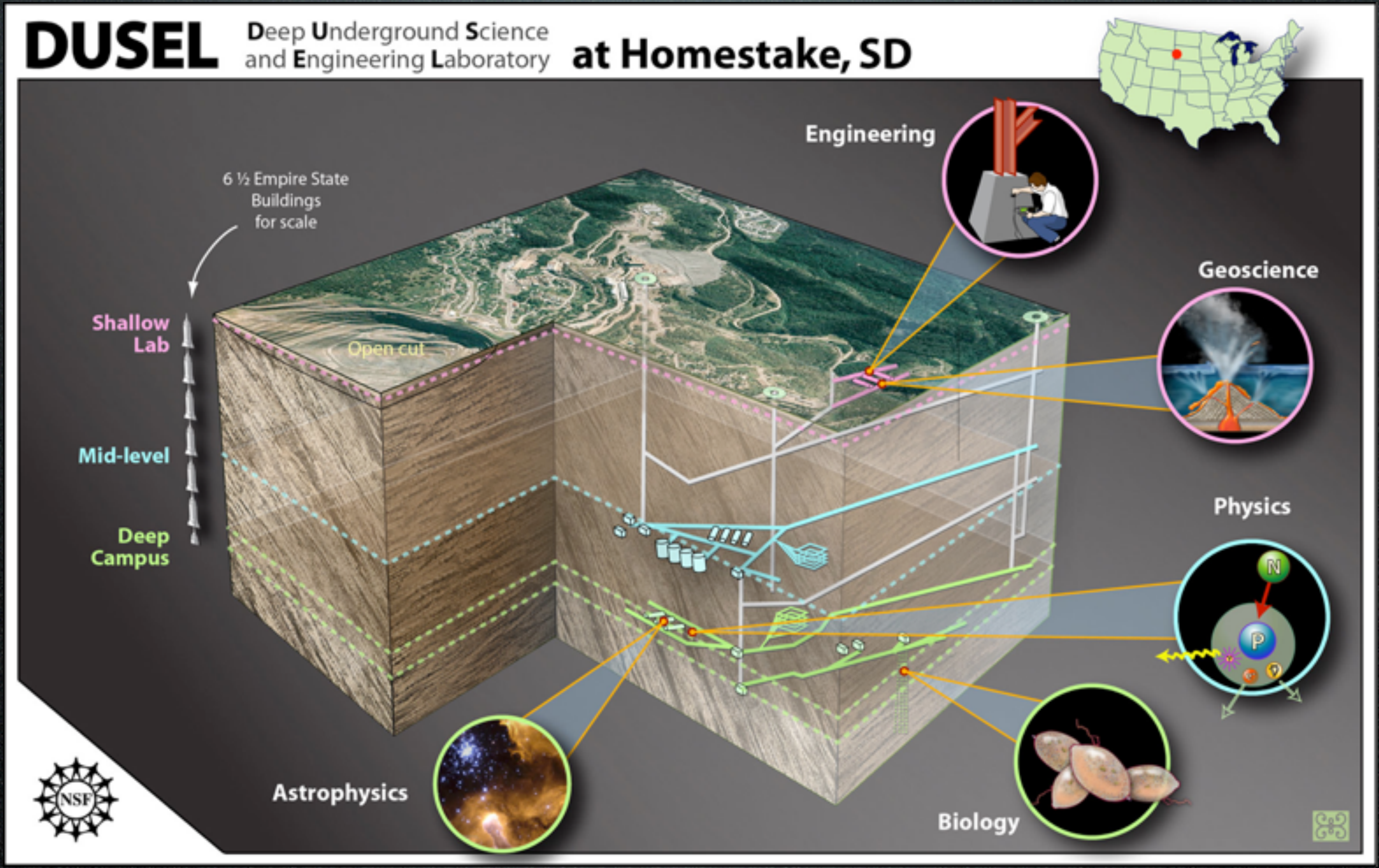


Gran Sasso underground laboratories

Direct Detection



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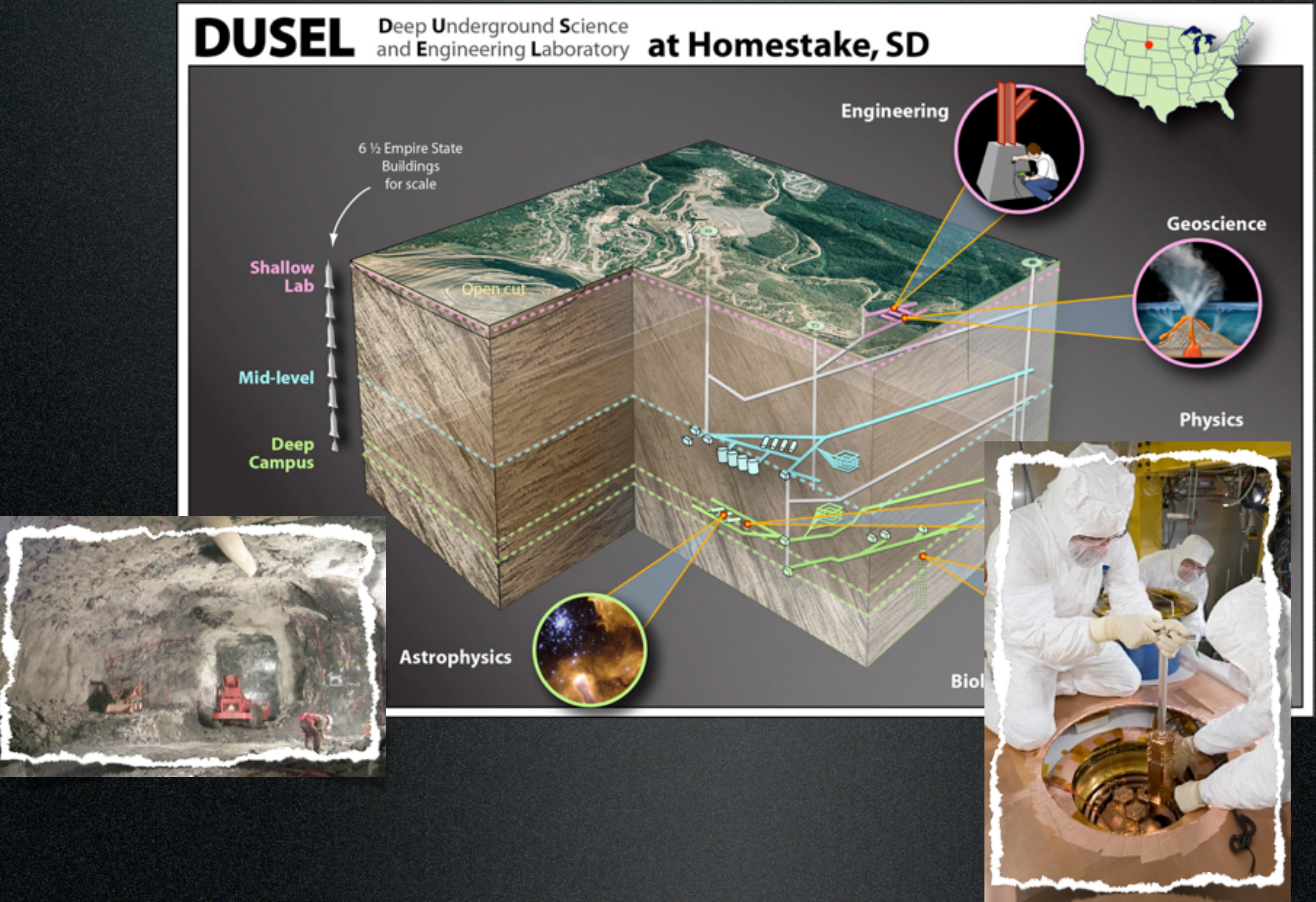
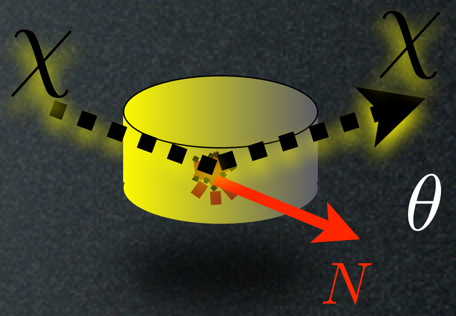


Direct Detection: basics

recoil energy $E_R = \frac{\mu_\chi^2 v^2}{m_N}(1 - \cos\theta)$



$$\mu_\chi = \frac{m_\chi m_N}{m_\chi + m_N} \rightarrow \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2} \frac{\rho_\odot}{m_\chi} \frac{\sigma}{\mu^2} \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v}) \, \mathrm{d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

$\sigma \approx \sigma_n^{\rm SI} A^4$ × nuclear form factors

number of events

$$N = \mathcal{E}\,\mathcal{T} \int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R} \, dE_R$$

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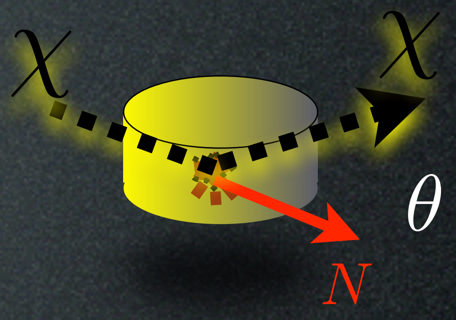

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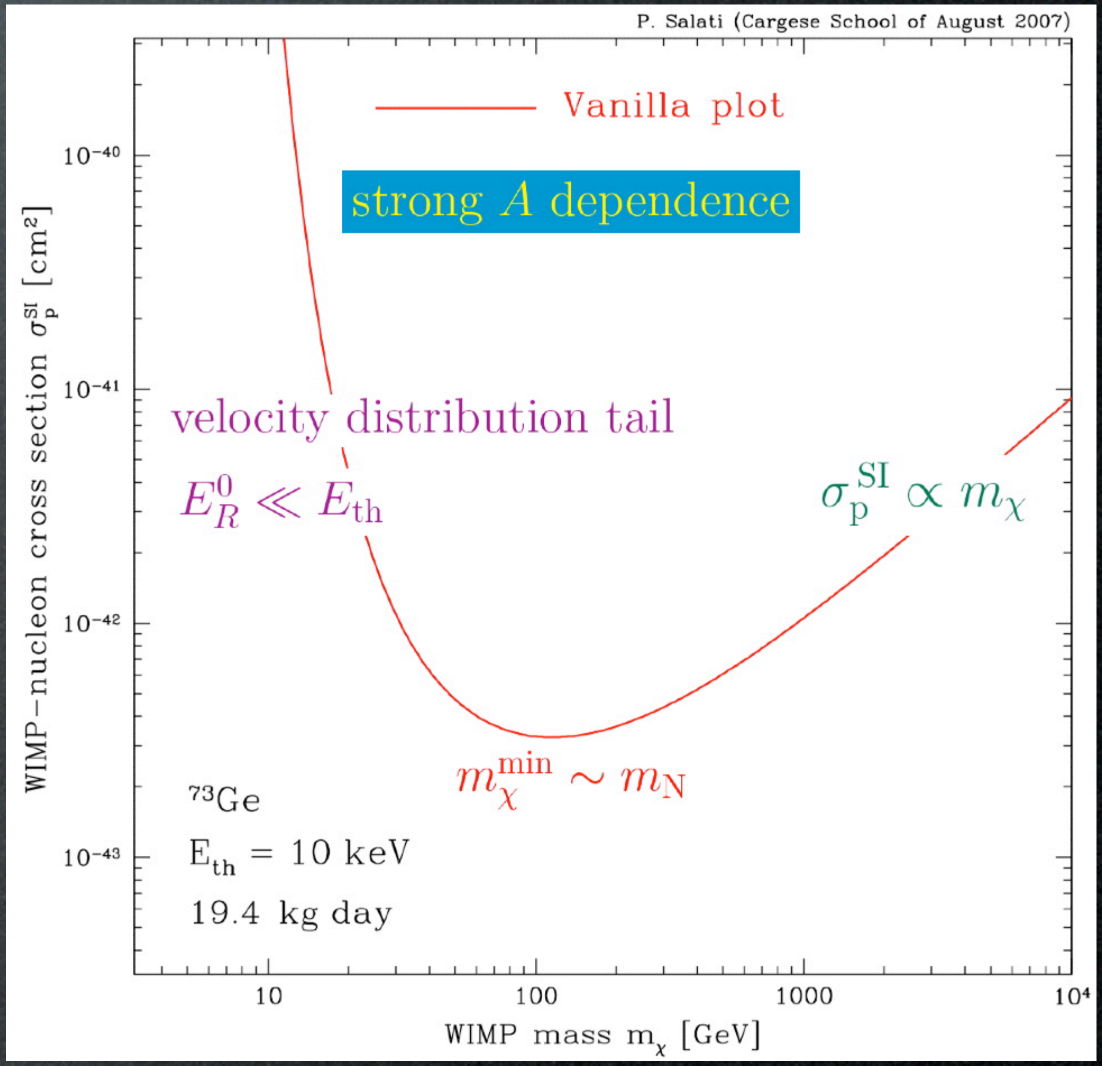

P.Salati, proceedings of Cargèse 2007

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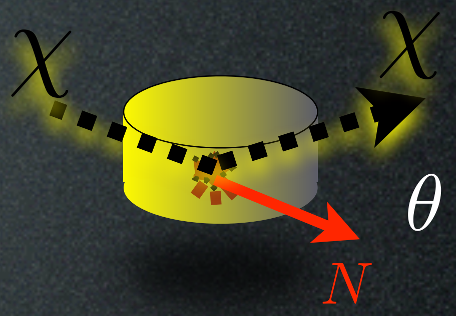

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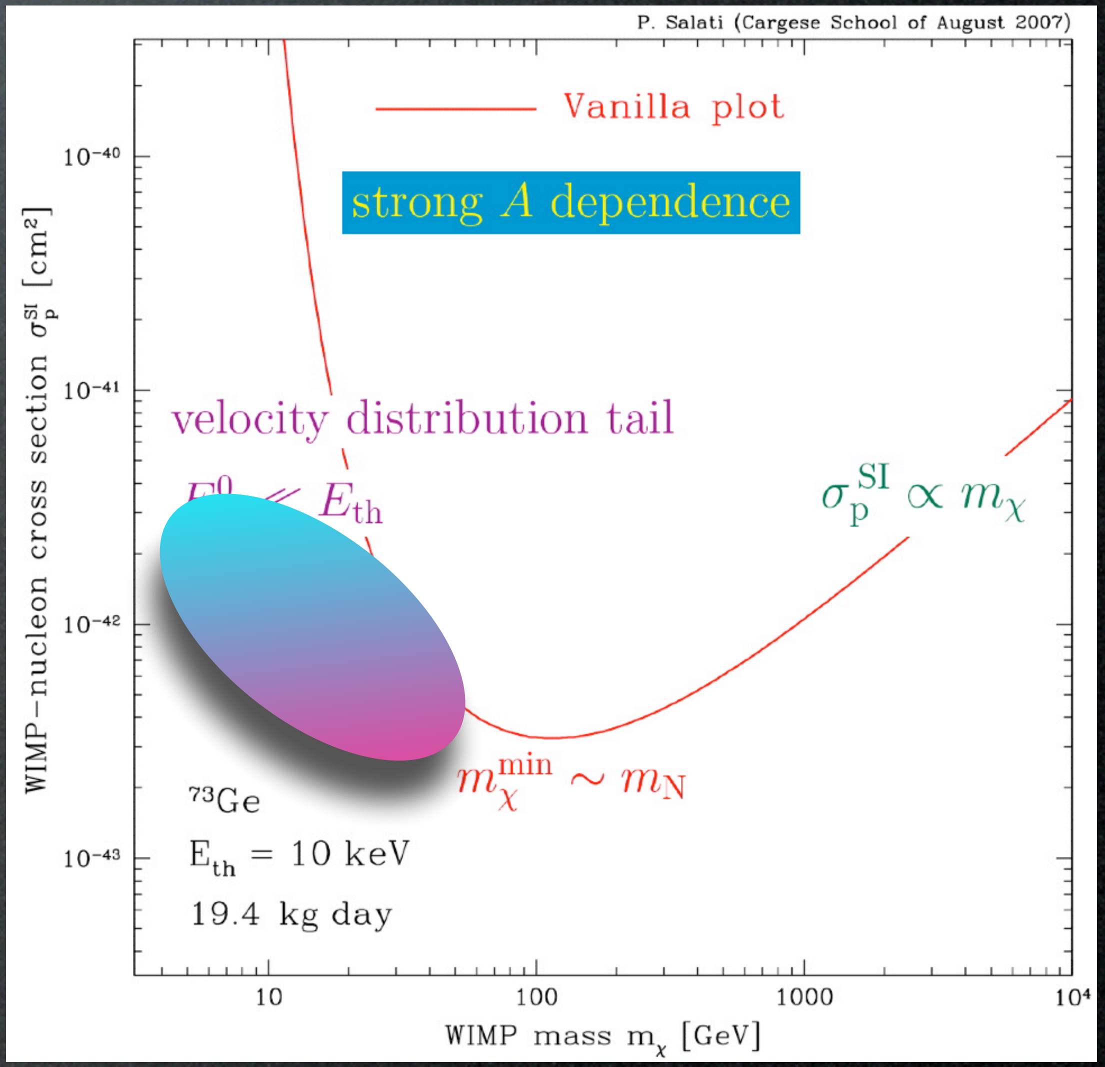

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Direct Detection

Strategy #1: silence the Universe

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measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

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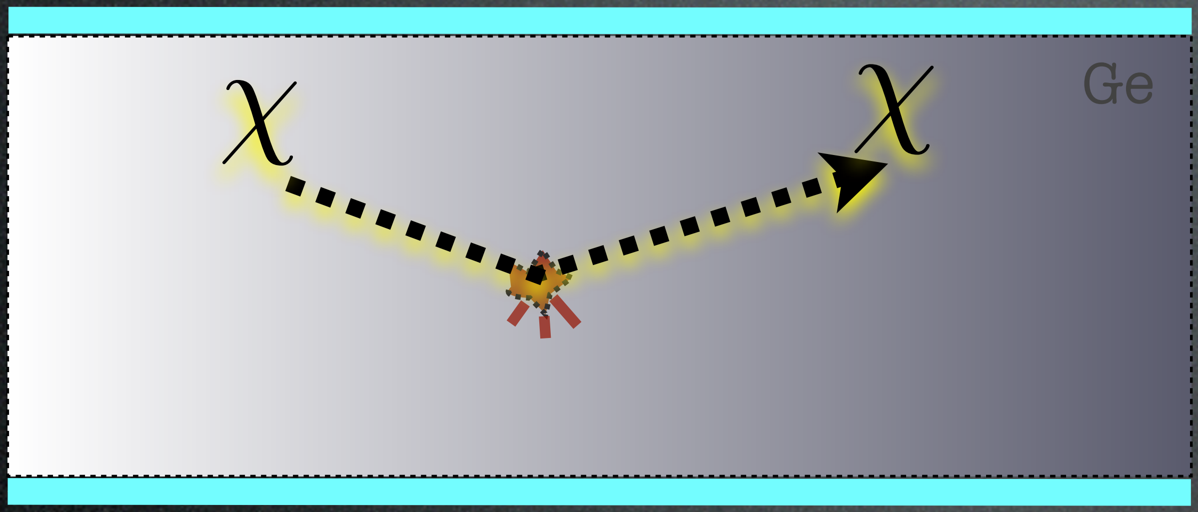

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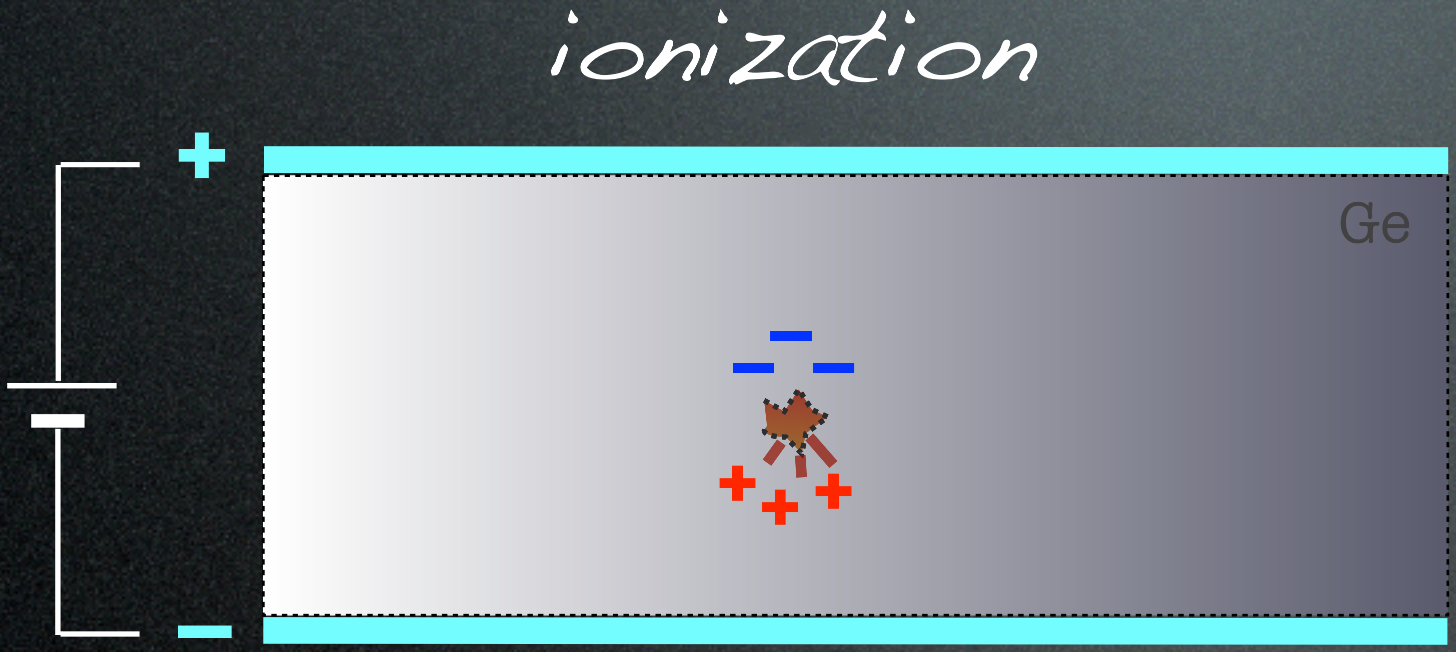

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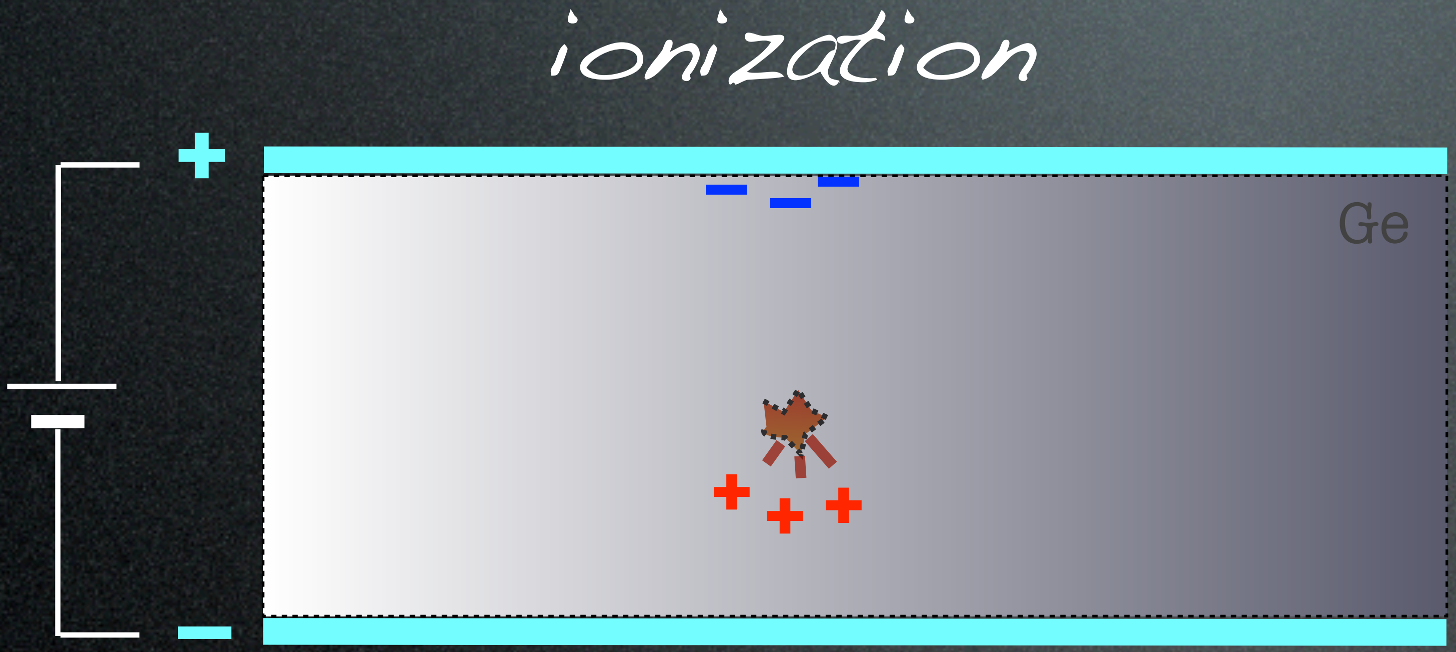

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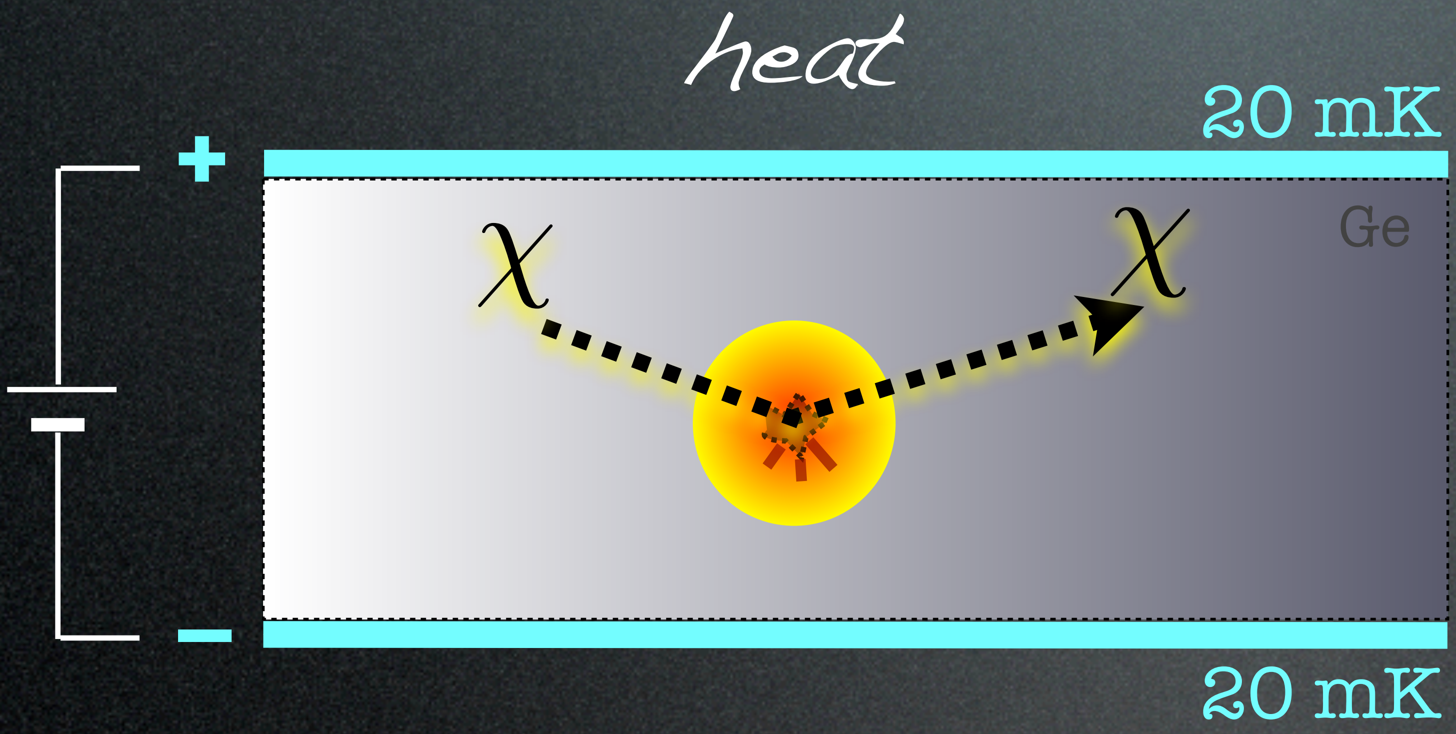

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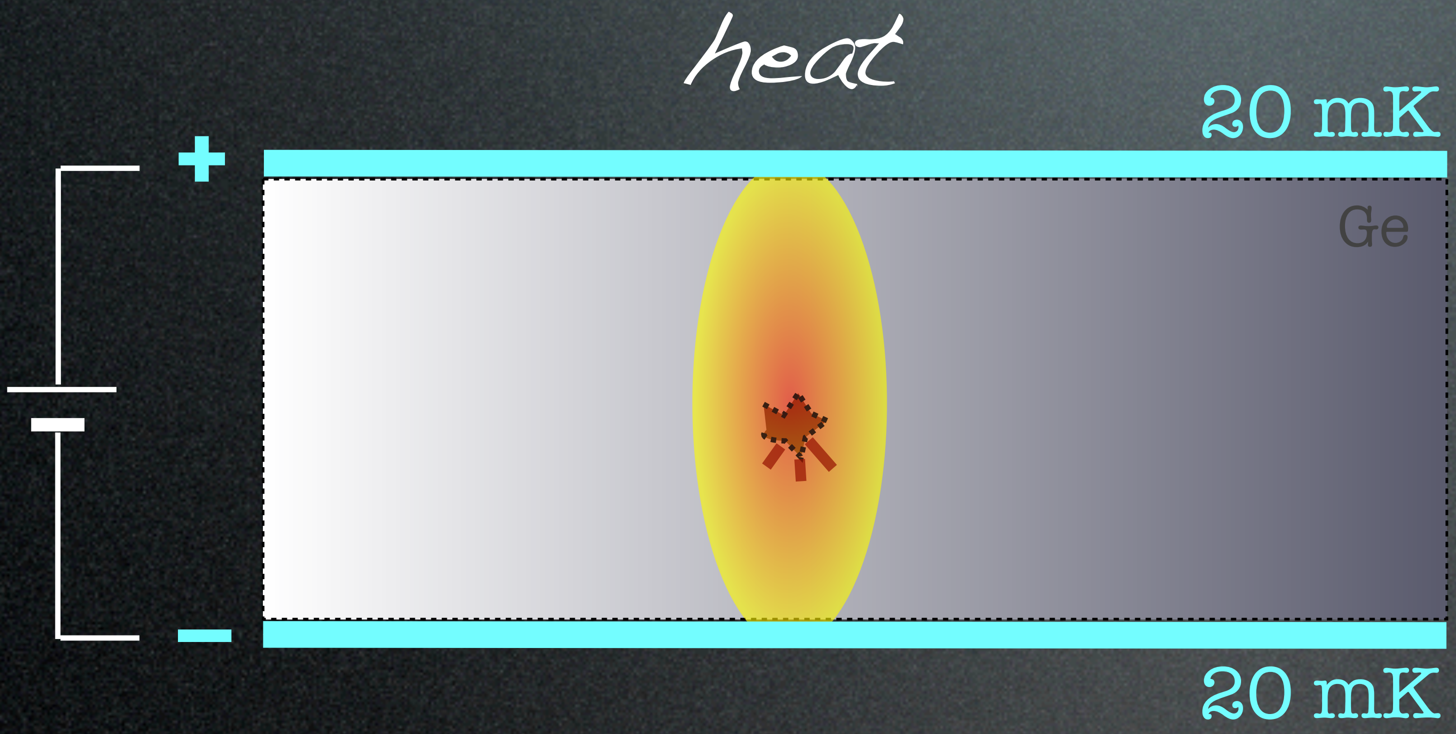

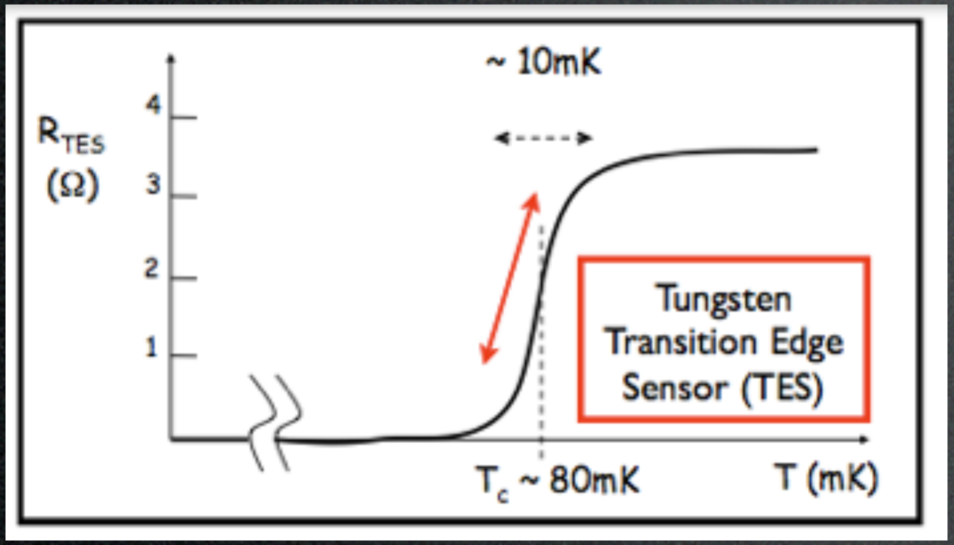

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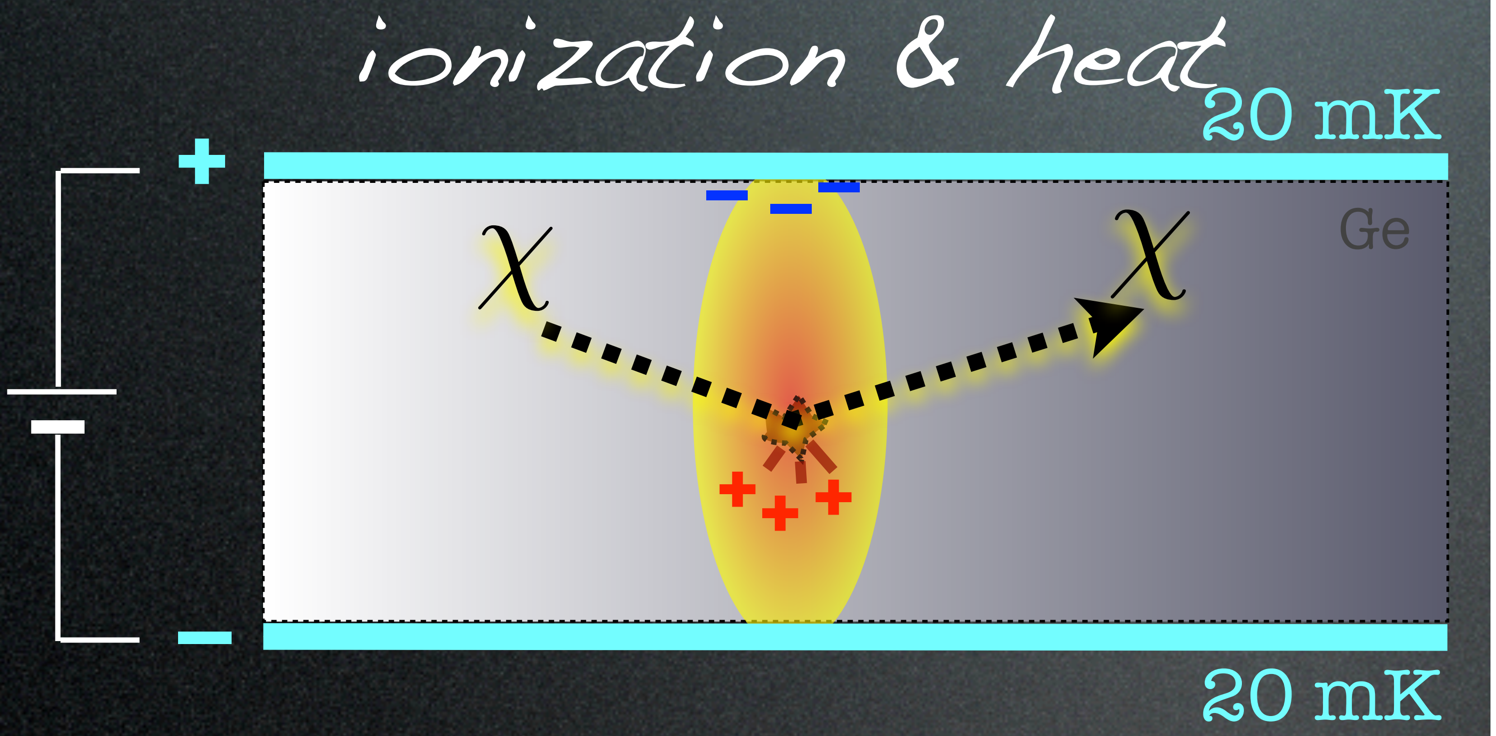

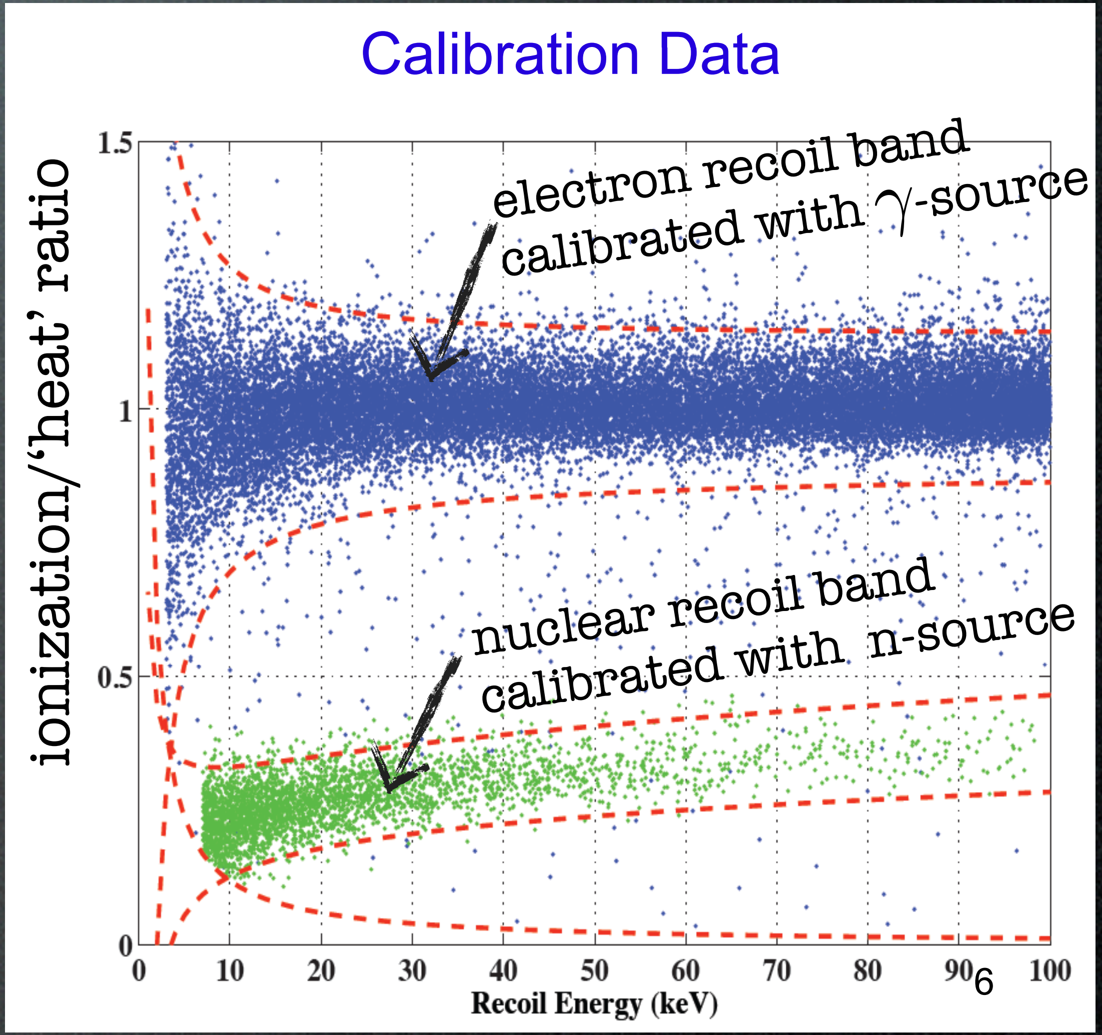

CDMS coll.

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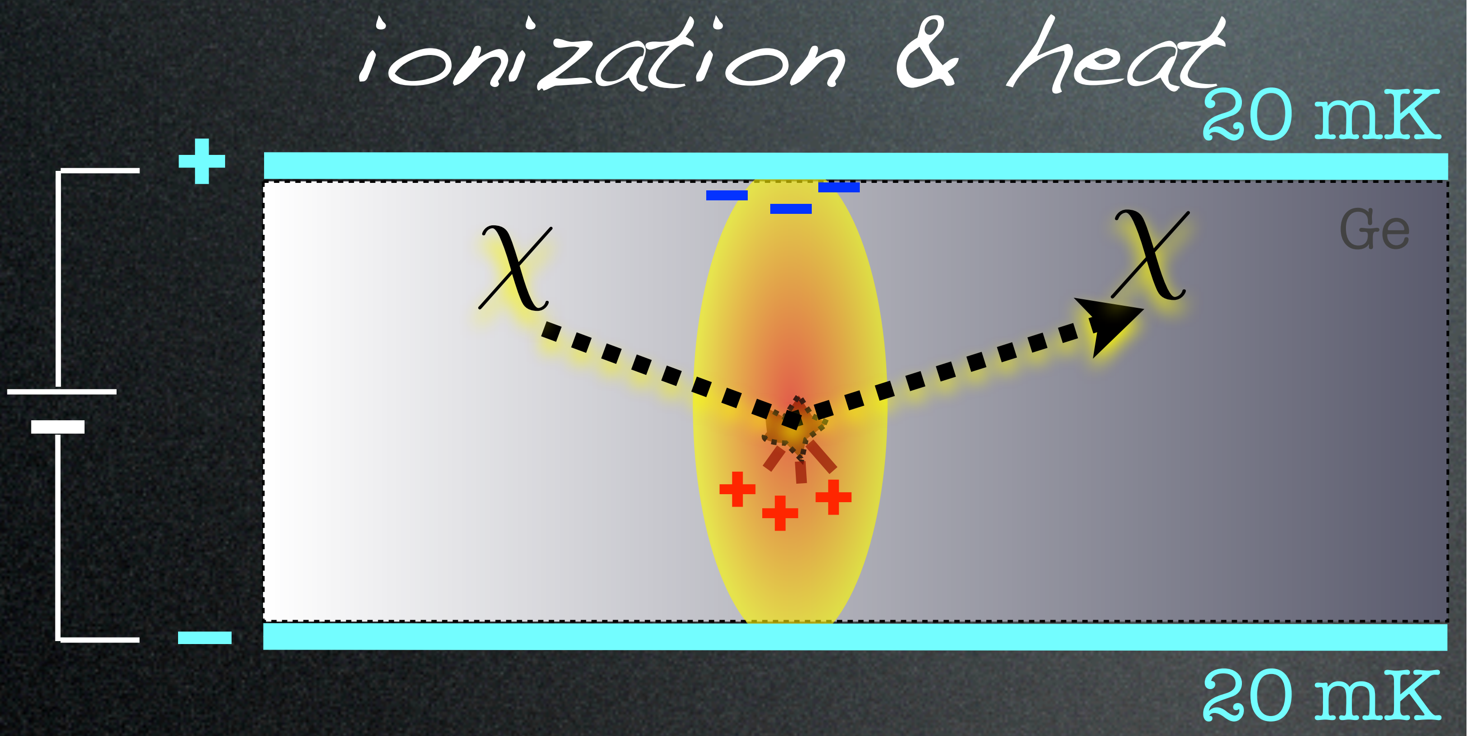

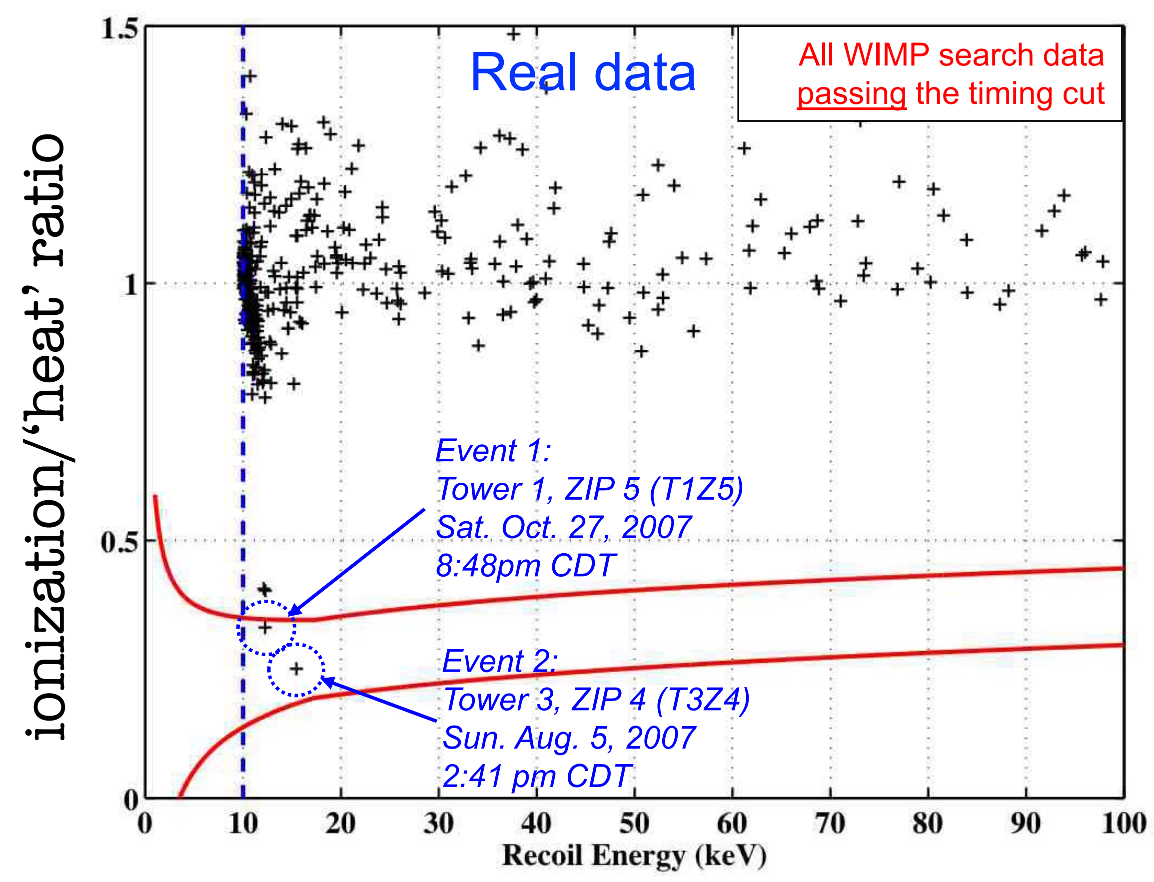

Event 1:
Tower 1, ZIP 5 (T1Z5)
Sat. Oct. 27, 2007
8:48pm CDT

Event 2:
Tower 3, ZIP 4 (T3Z4)
Sun. Aug. 5, 2007
2:41 pm CDT

CDMS coll., Science 327 (2010), 0912.3592

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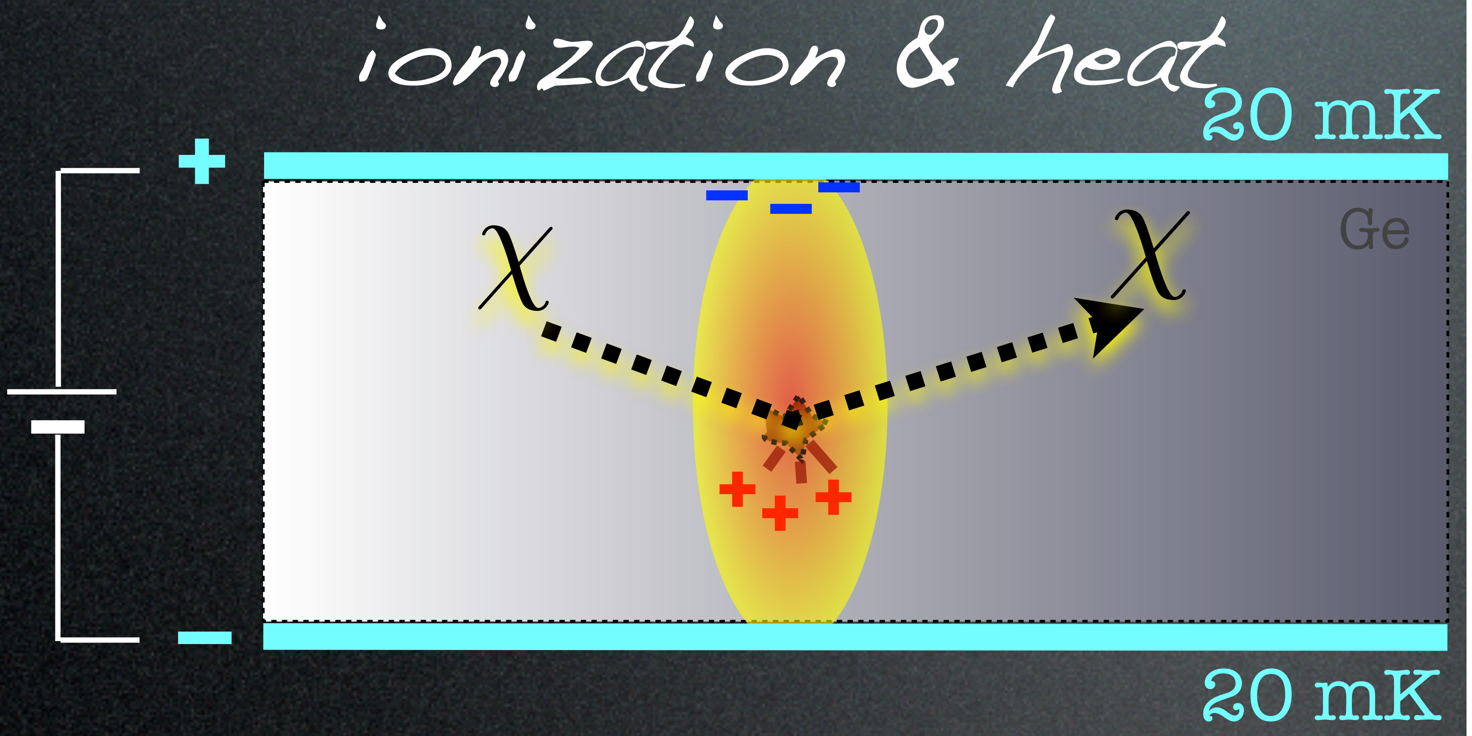

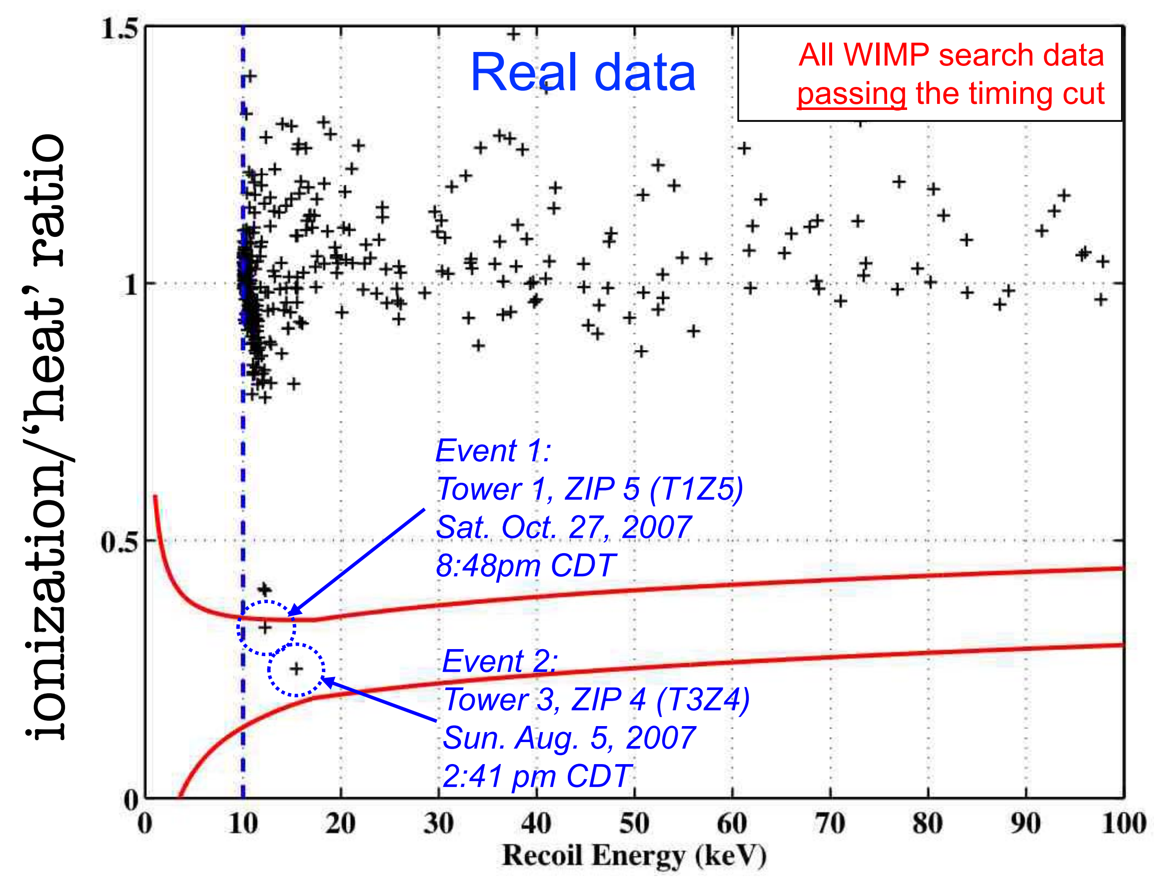

CDMS coll., Science 327 (2010), 0912.3592

NB: 10^{-44} cm^2 (=10^{-8} pb) $\longrightarrow$ 1 evt/kg/yr!

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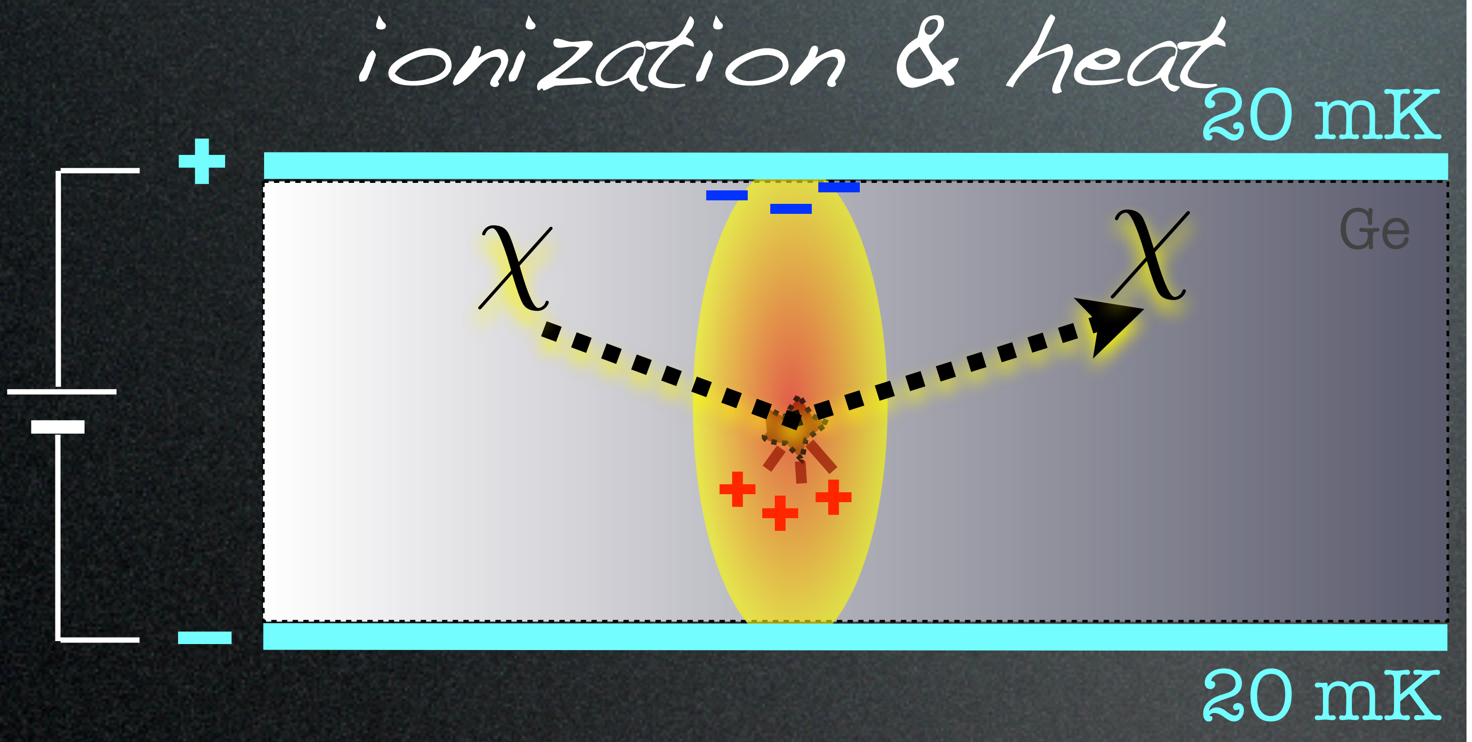

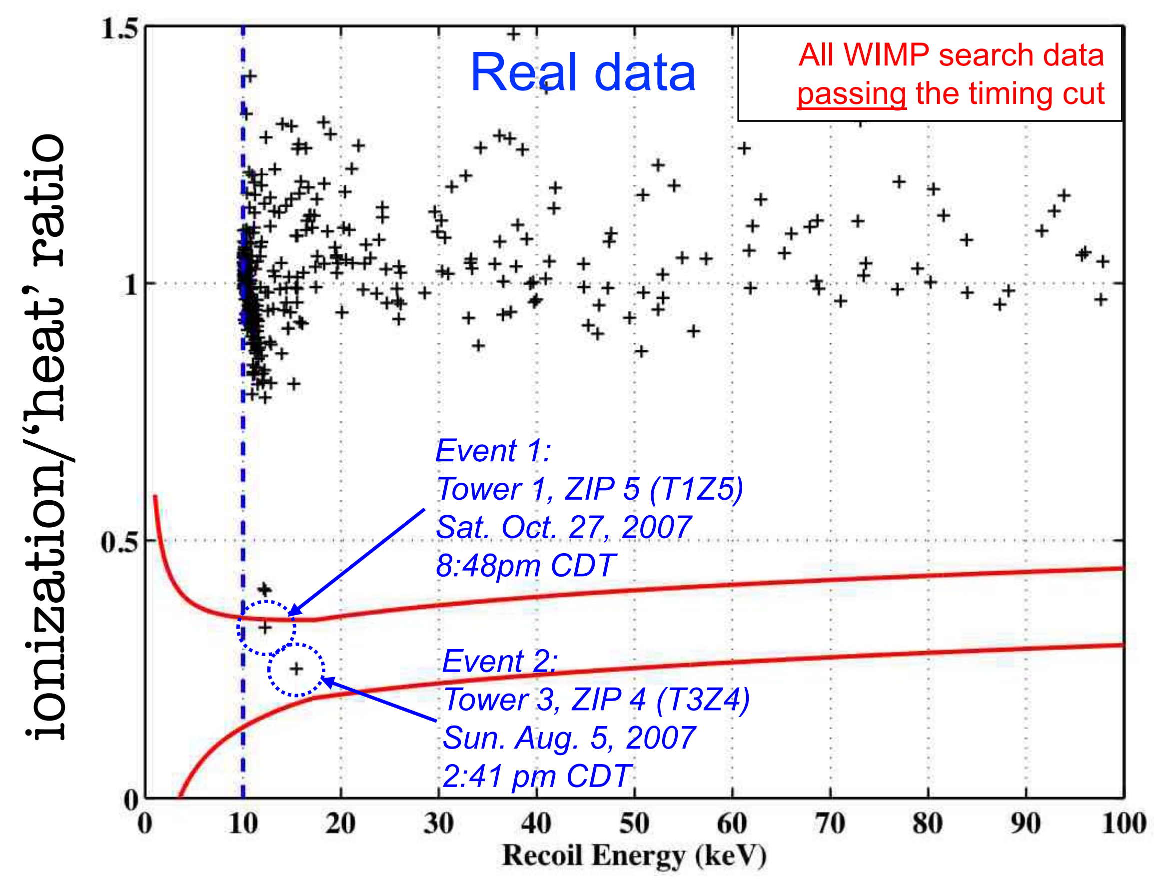

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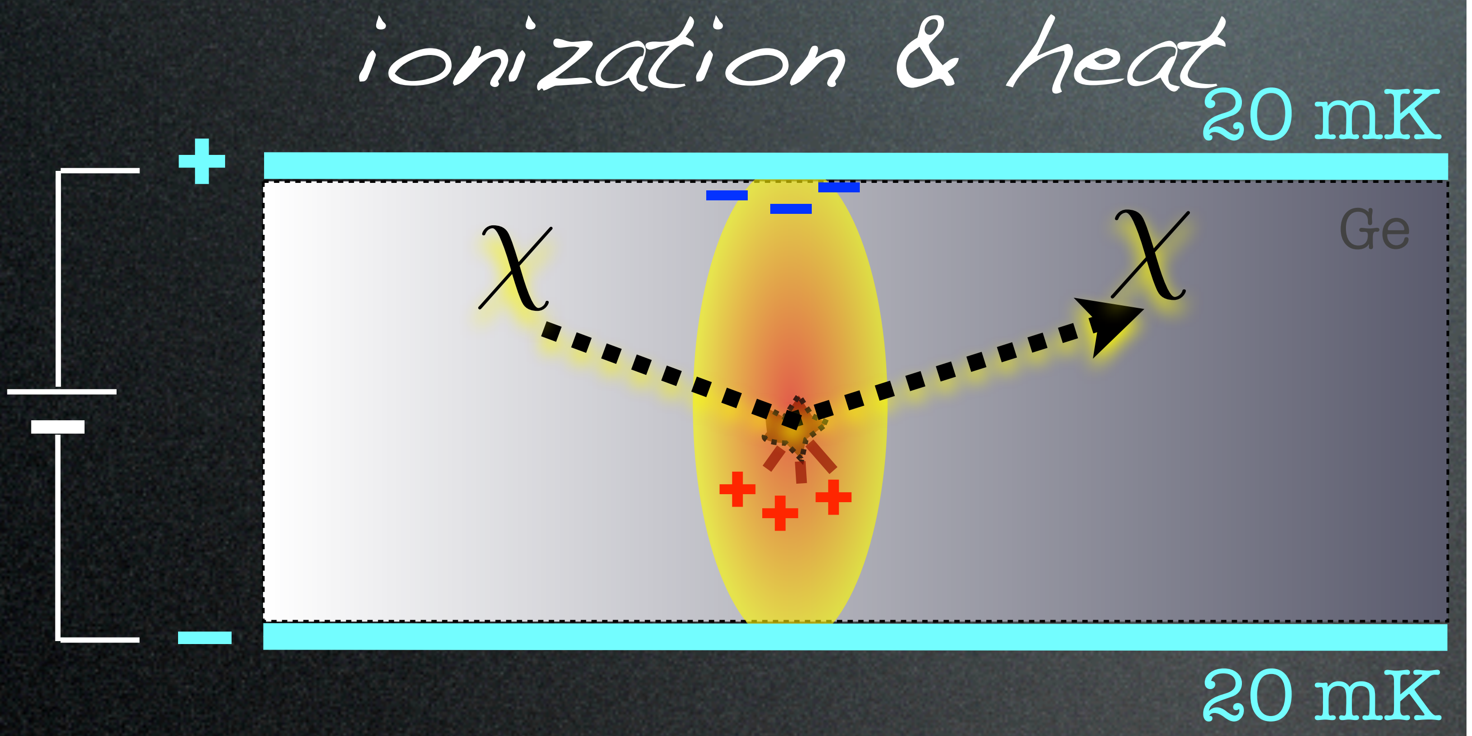

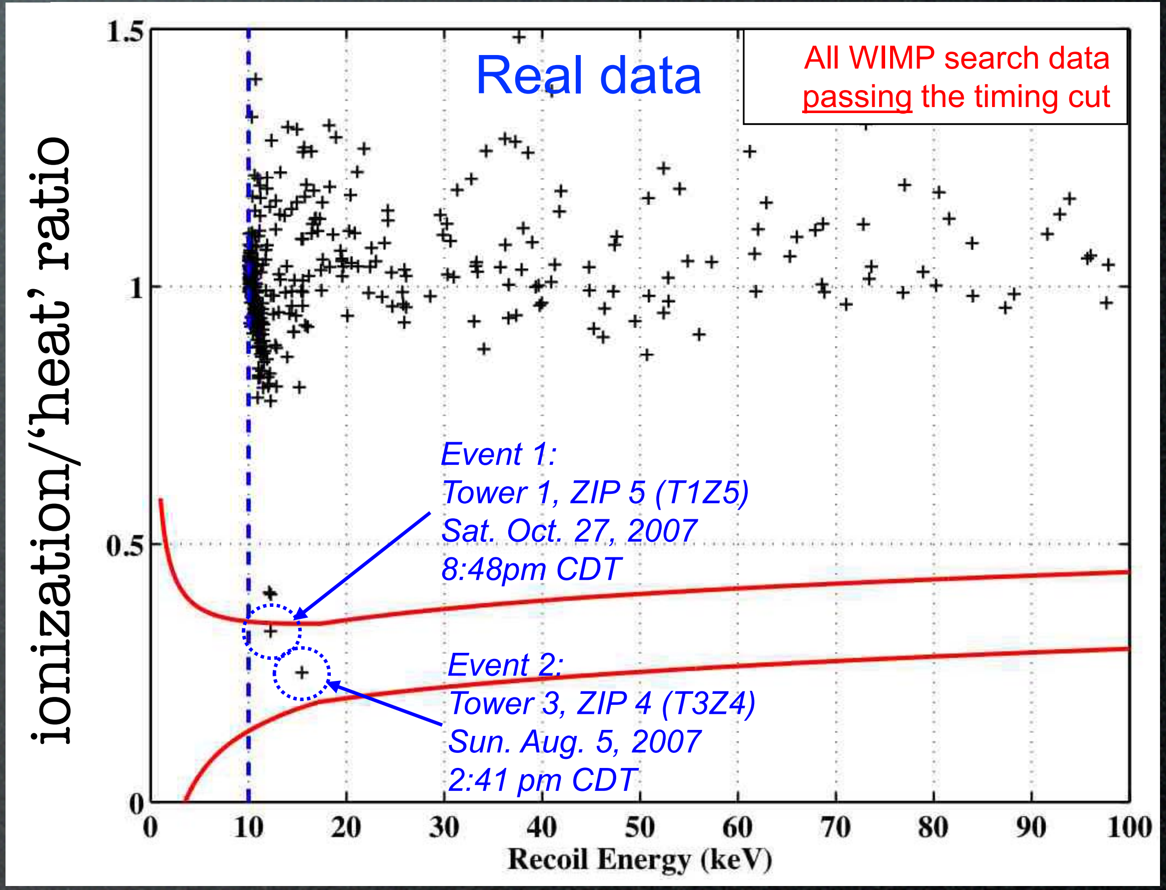

CDMS coll., Science 327 (2010), 0912.3592

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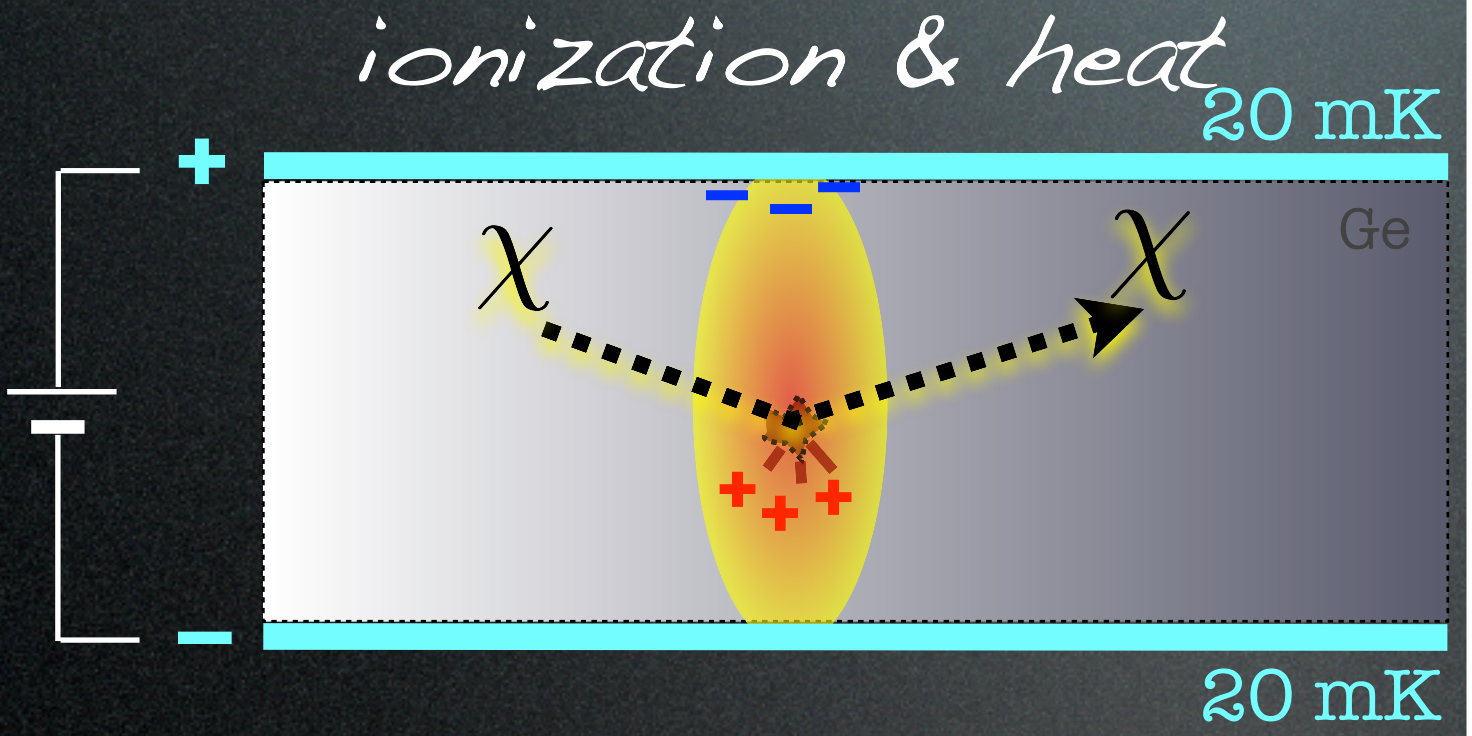

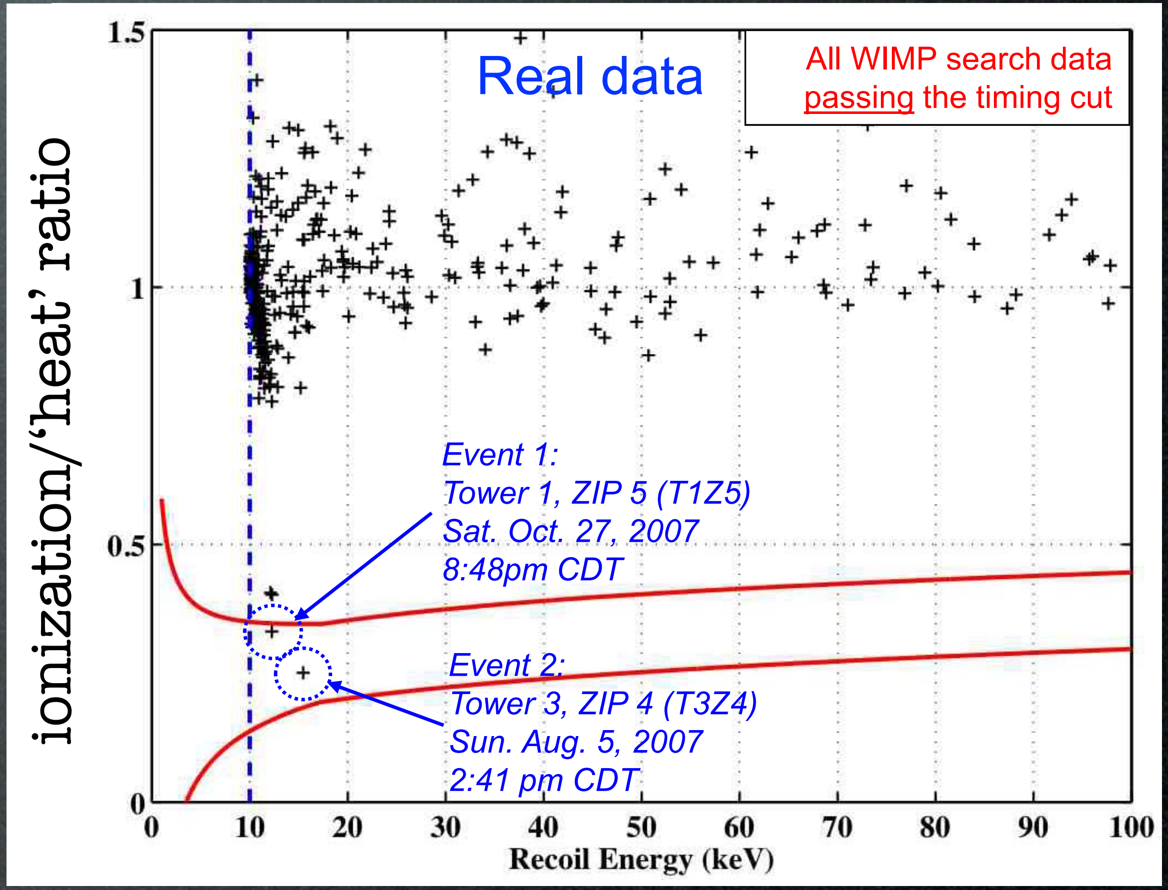

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Edelweiss

vs

10 billion tons

Direct Detection

Strategy #2: ride the dark wave

collect all events, and detect an annual modulation

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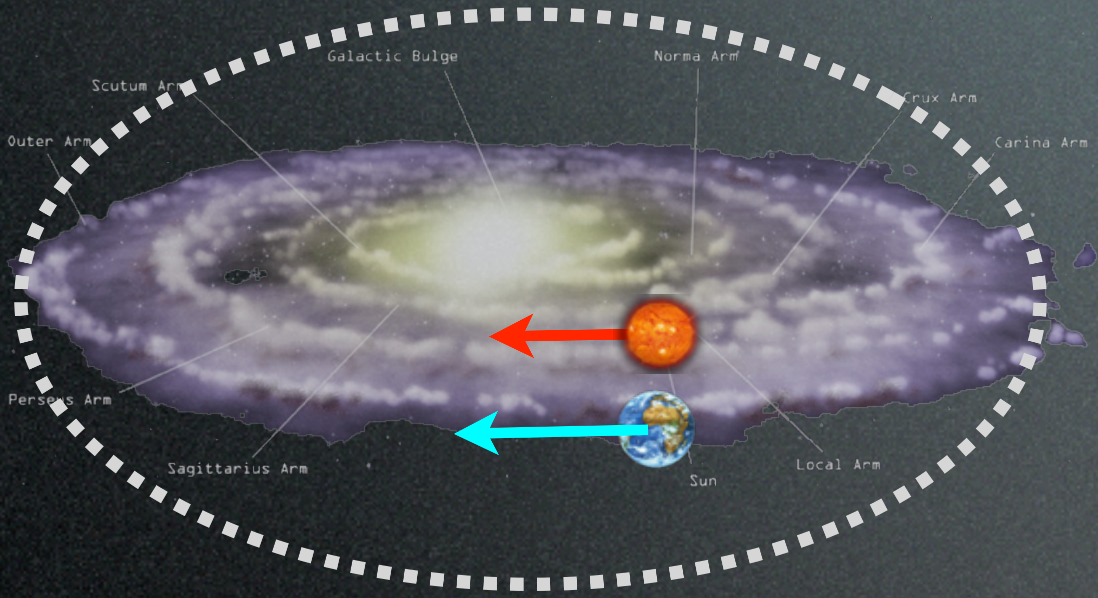

summer

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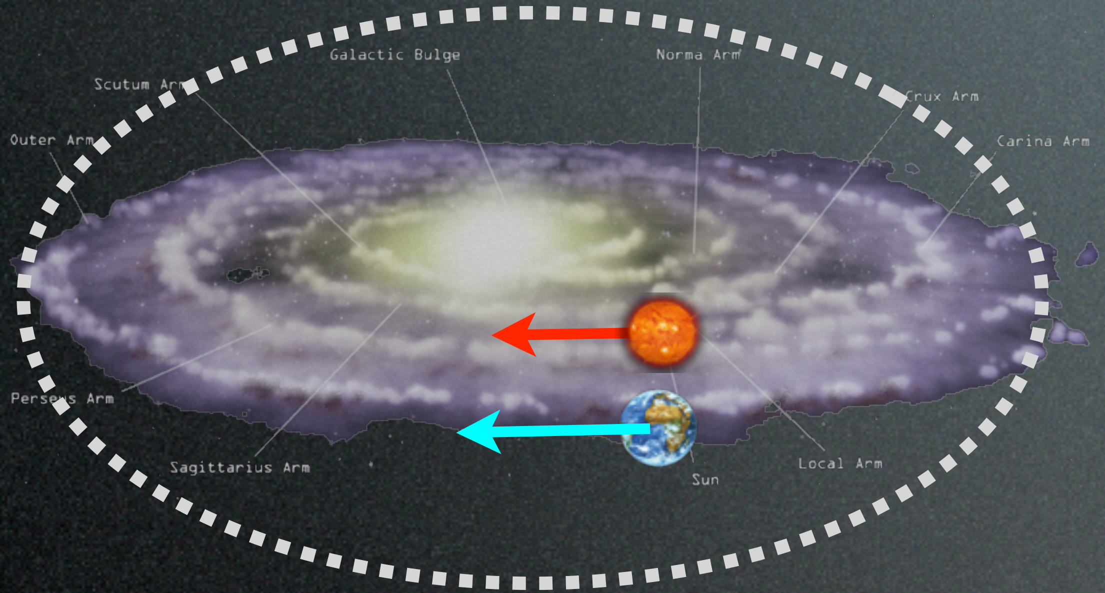
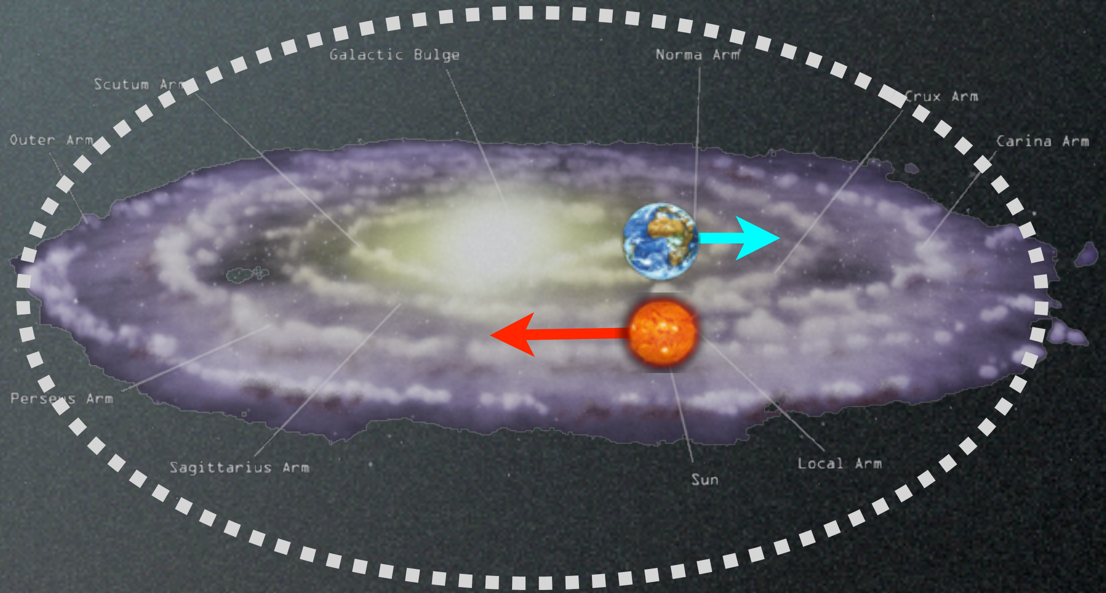


summer



winter

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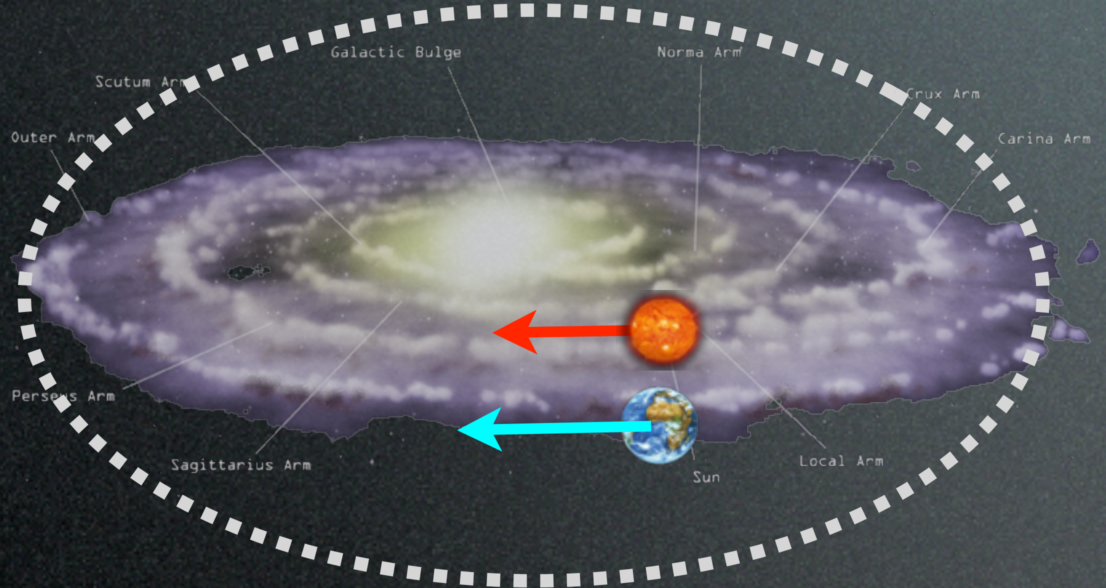
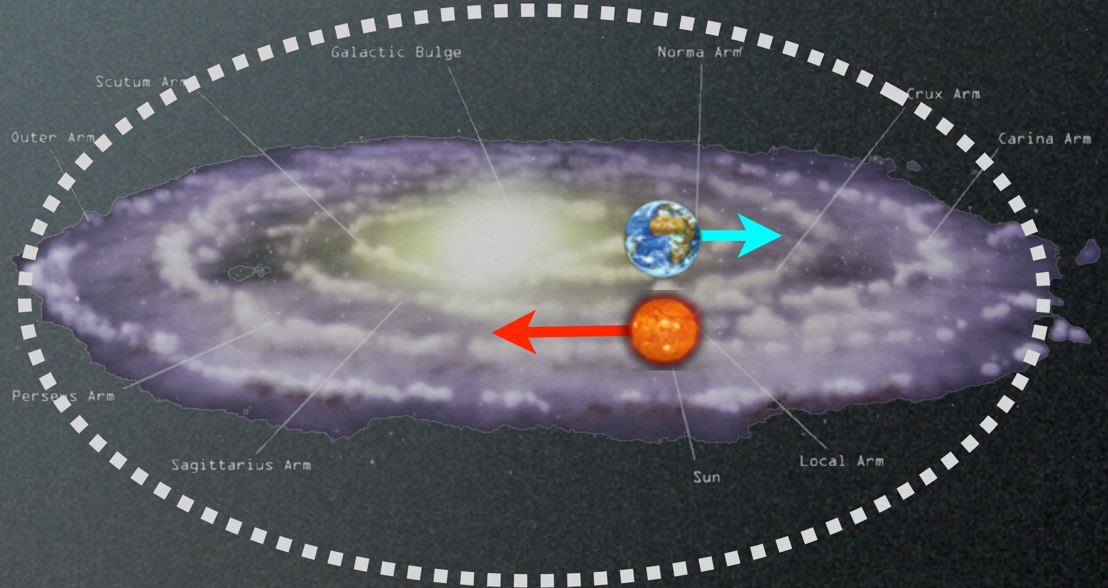
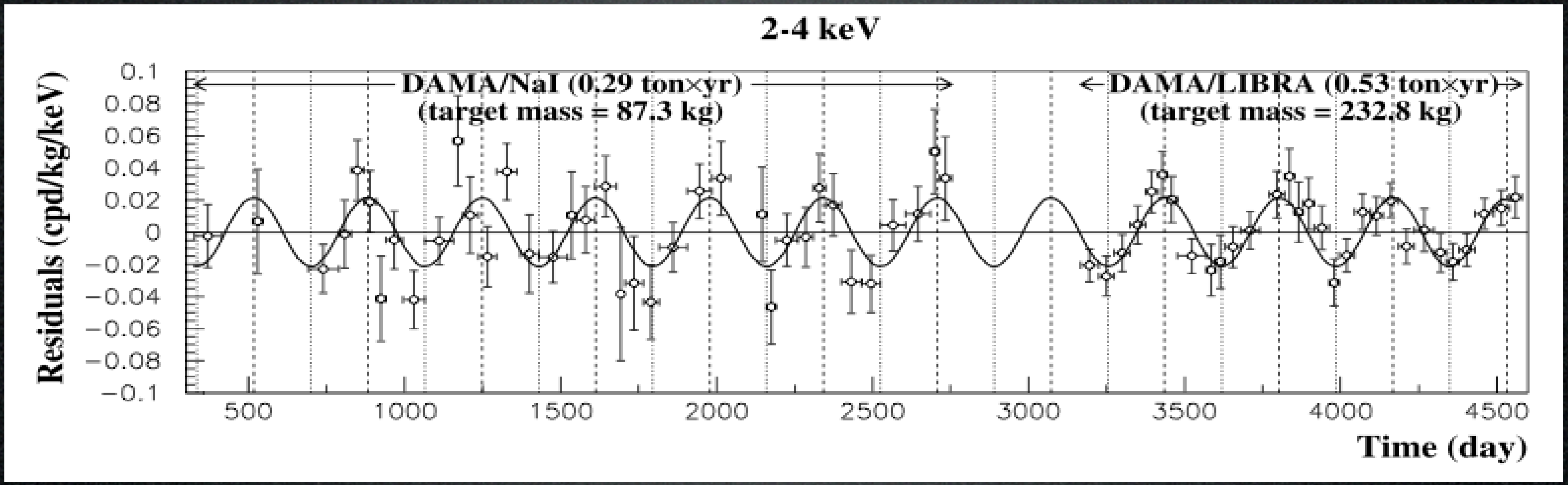


summer



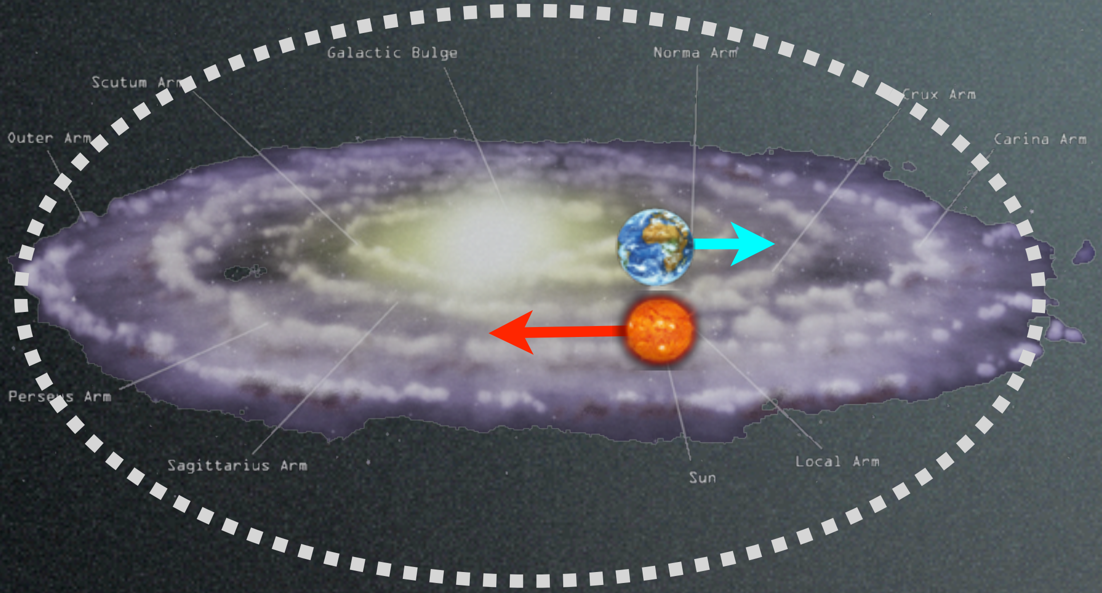
winter



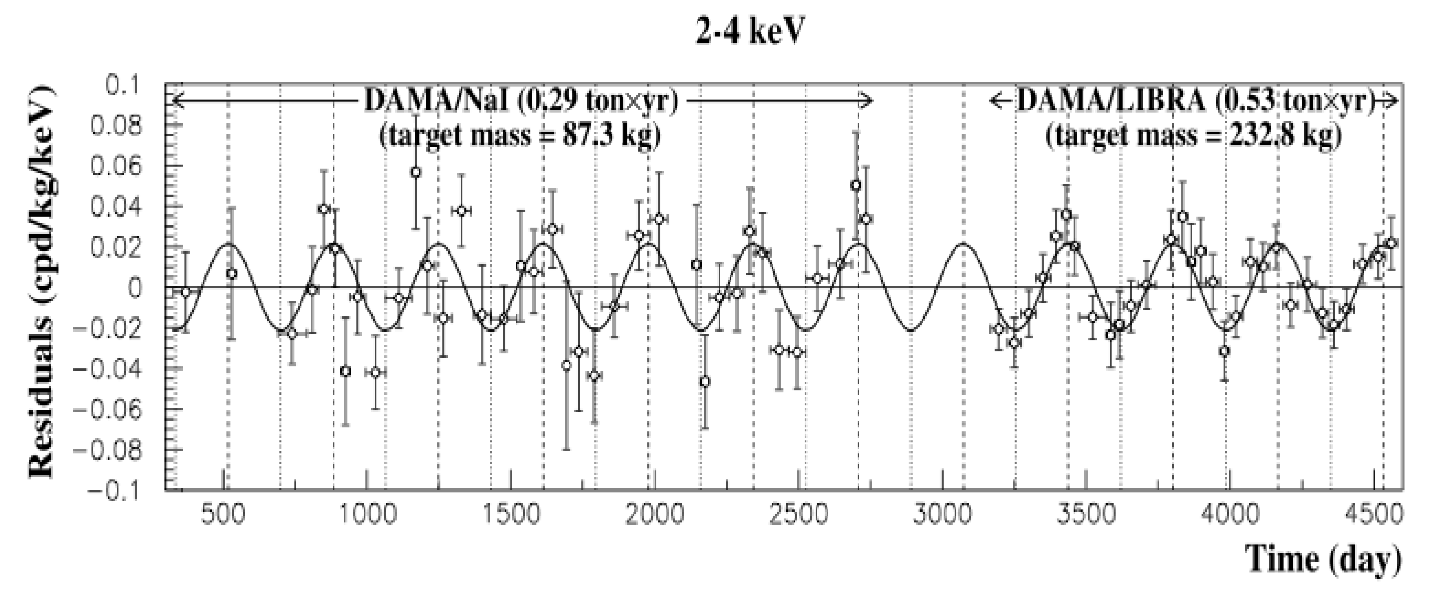
DAMA Coll., 0804.2741, 2008

Direct Detection: hint?

DAMA/Libra



Annual modulation seen (8σ):



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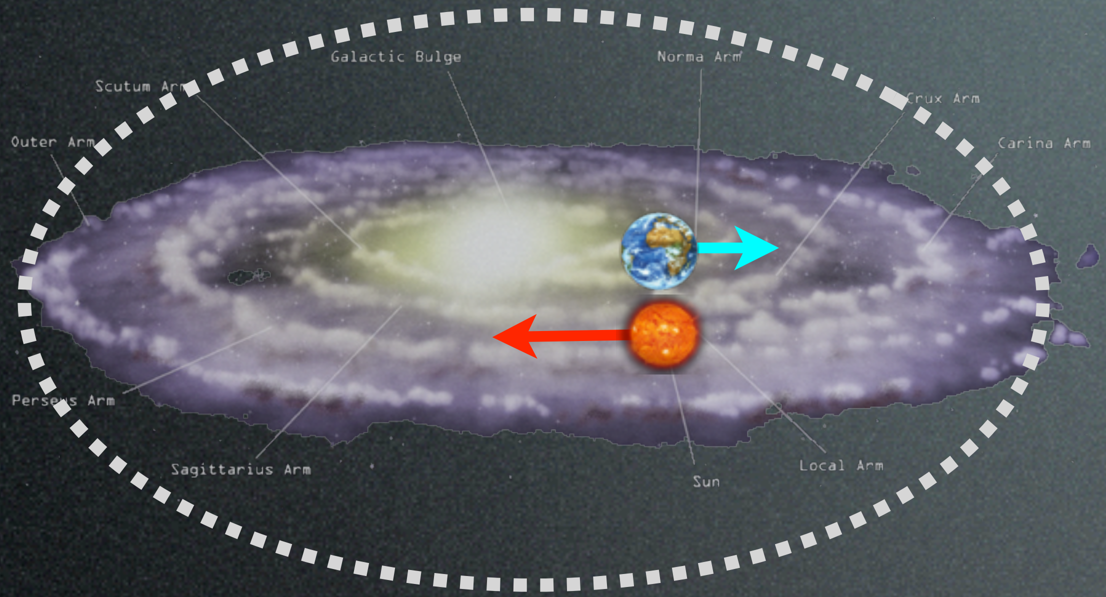

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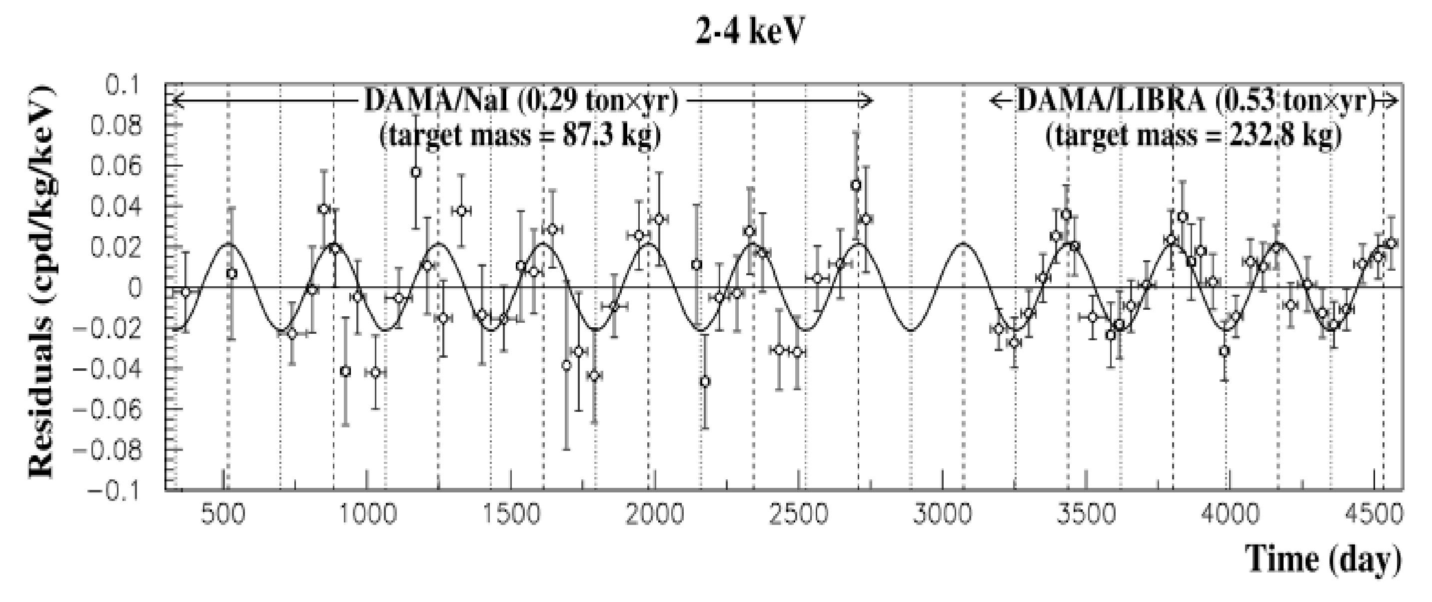
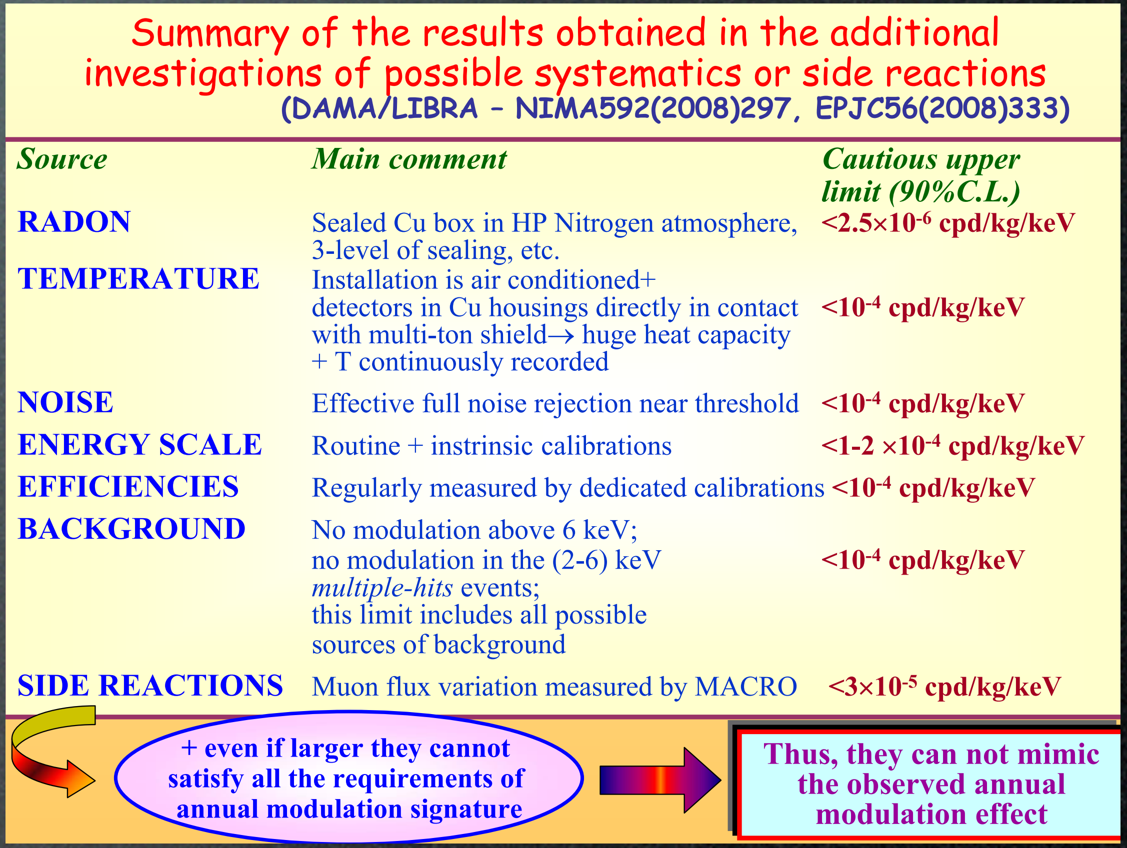


DAMA Coll., 0804.2741, 2008

An instrumental effect?



Summary of the results obtained in the additional investigations of possible systematics or side reactions

(DAMA/LIBRA – NIMA592(2008)297, EPJC56(2008)333)

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**<1-2 $\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<10^{-4} cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured by MACRO	**<3×10^{-5} cpd/kg/keV**

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect

'NO!' e.g. P.Belli, KITP workshop 12.2009

Direct Detection: status

Direct Detection: status


DAMA/Libra
(1998-2011)

CoGeNT
(2010-2011)

CRESST
(2011)

Dark Matter!
Dark Matter! DARK MATTER!

Seen an **excess** of events and/or annual **modulation**.
Light (few GeV) DM with large scattering.

Direct Detection: status

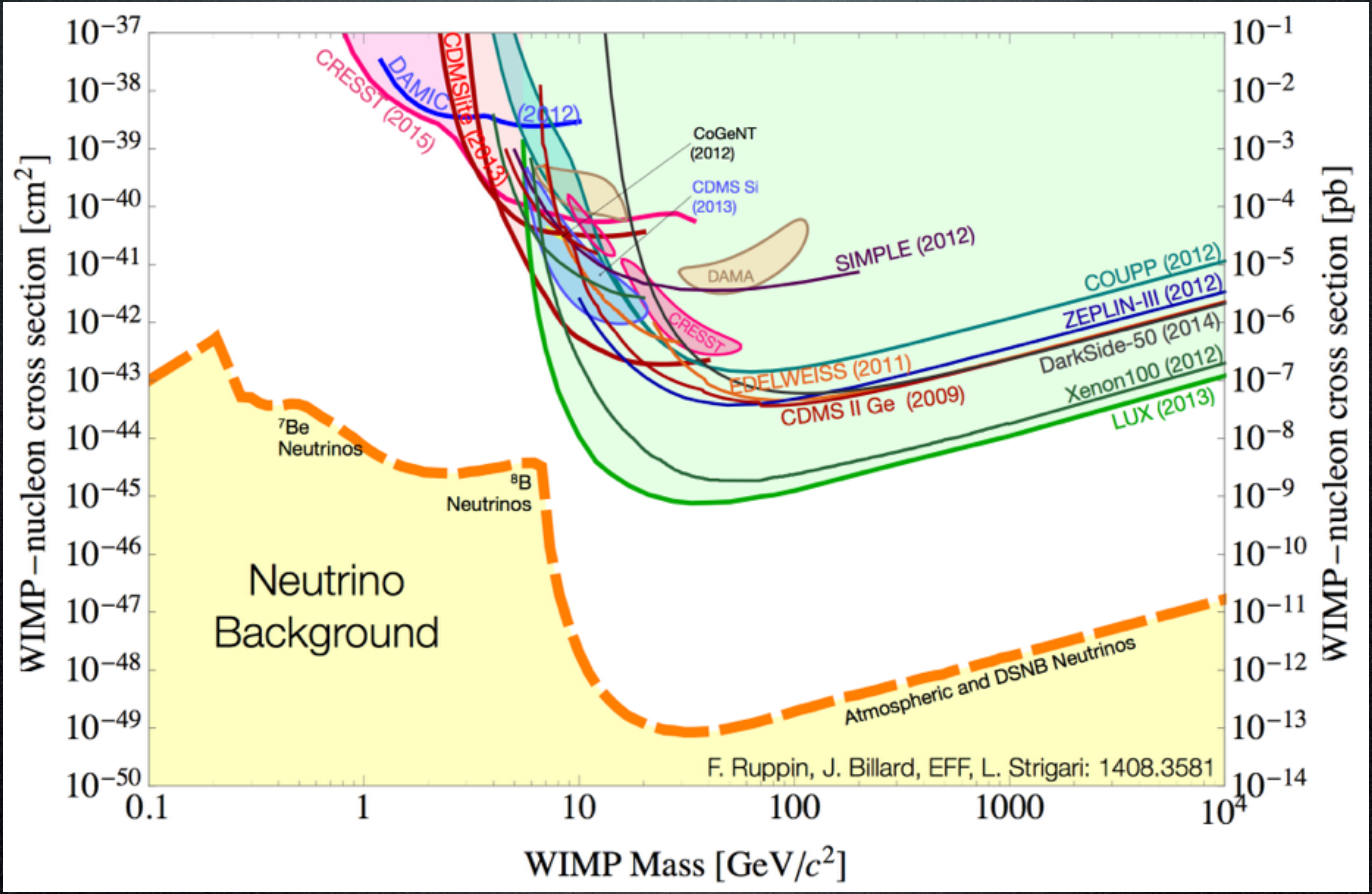
Dark Matter!
Dark Matter! DARK MATTER!

Seen an **excess** of events and/or annual **modulation**.
Light (few GeV) DM with large scattering.

No way.

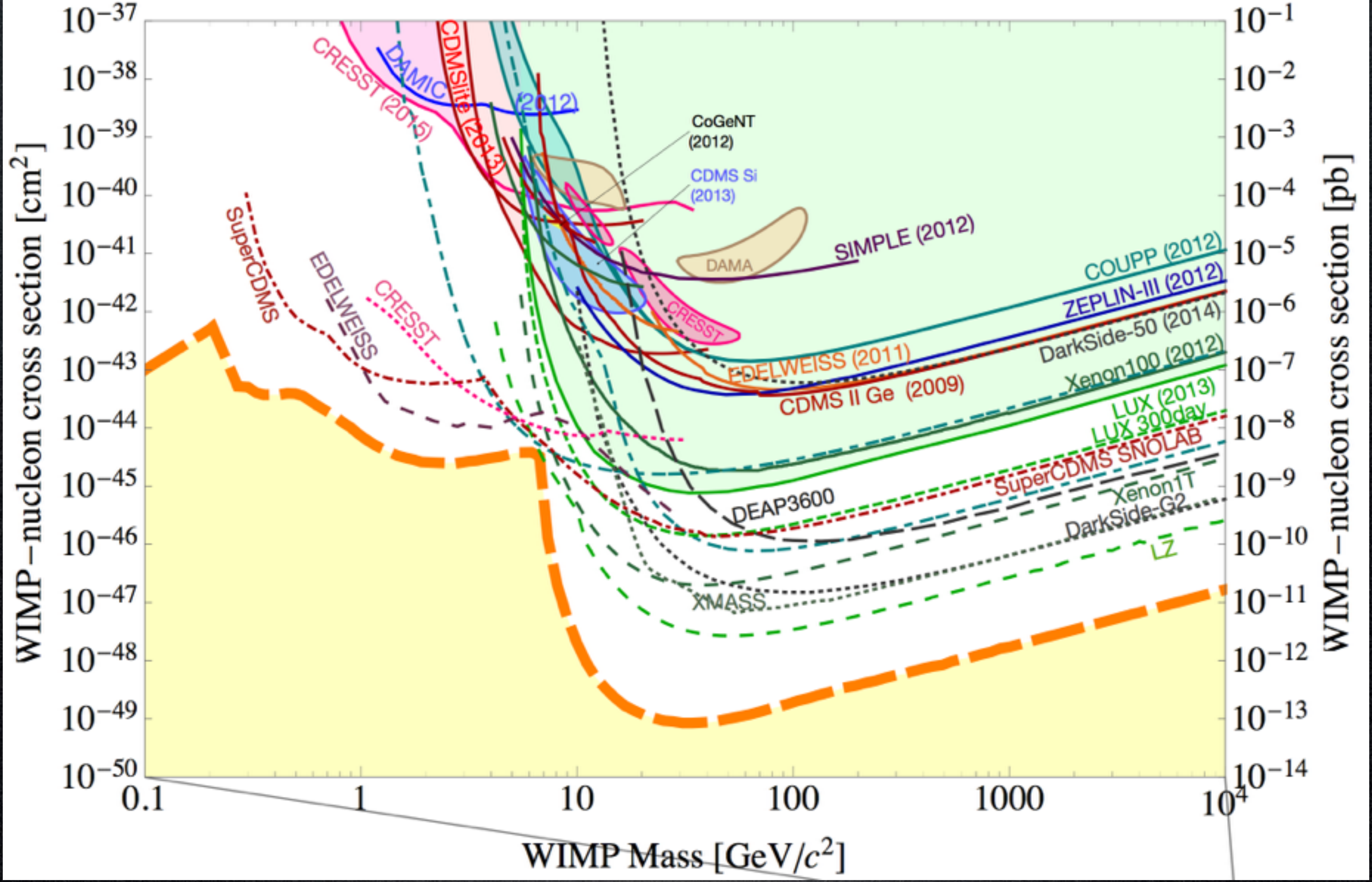
Absolute **cosmic silence** recorded,
limits are stronger than signal.

Direct Detection: results



E. Figueroa-Feliciano - ICRC 2015

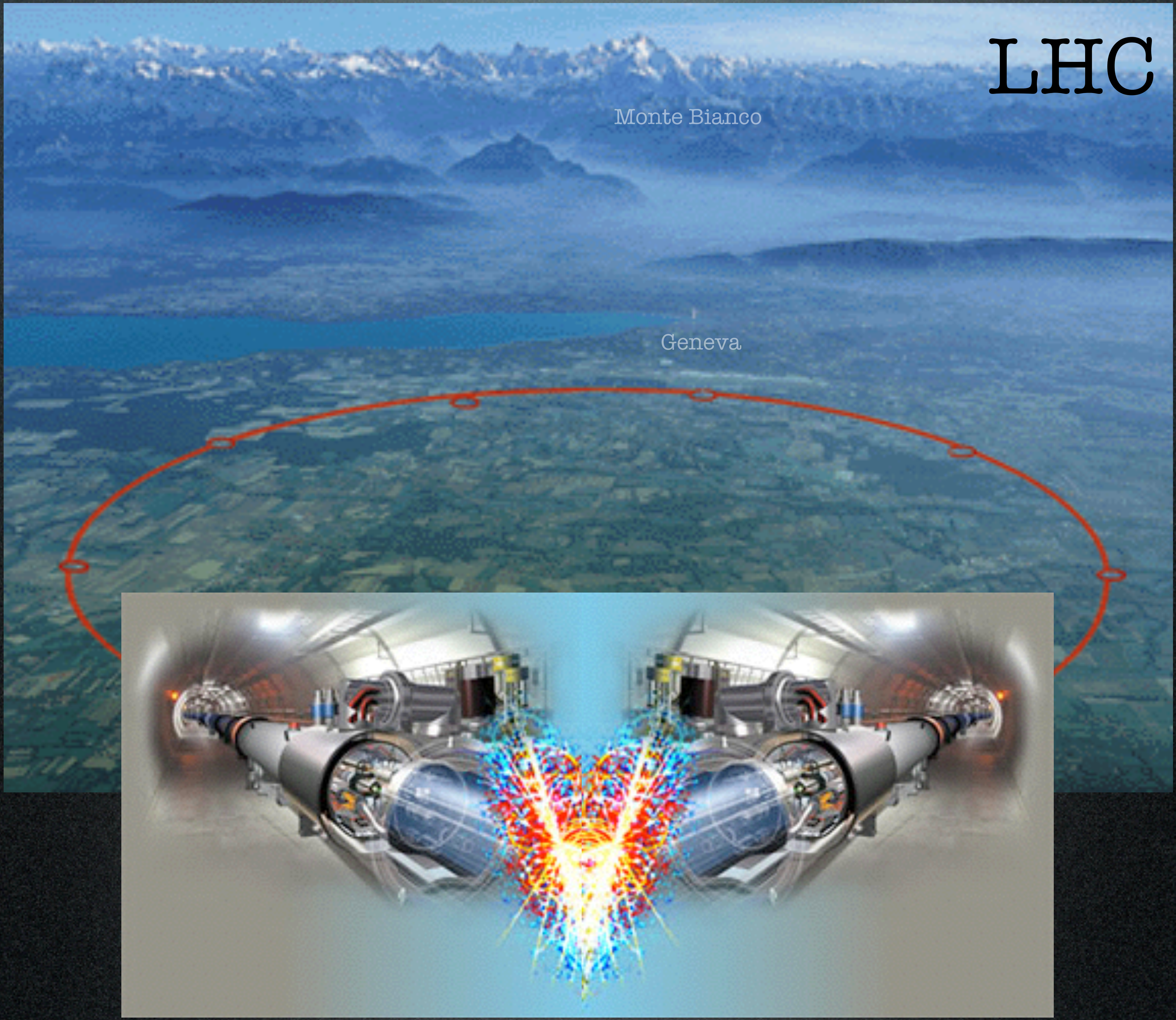
Direct Detection: future



E. Figueroa-Feliciano - ICRC 2015

Production at colliders

Production at colliders



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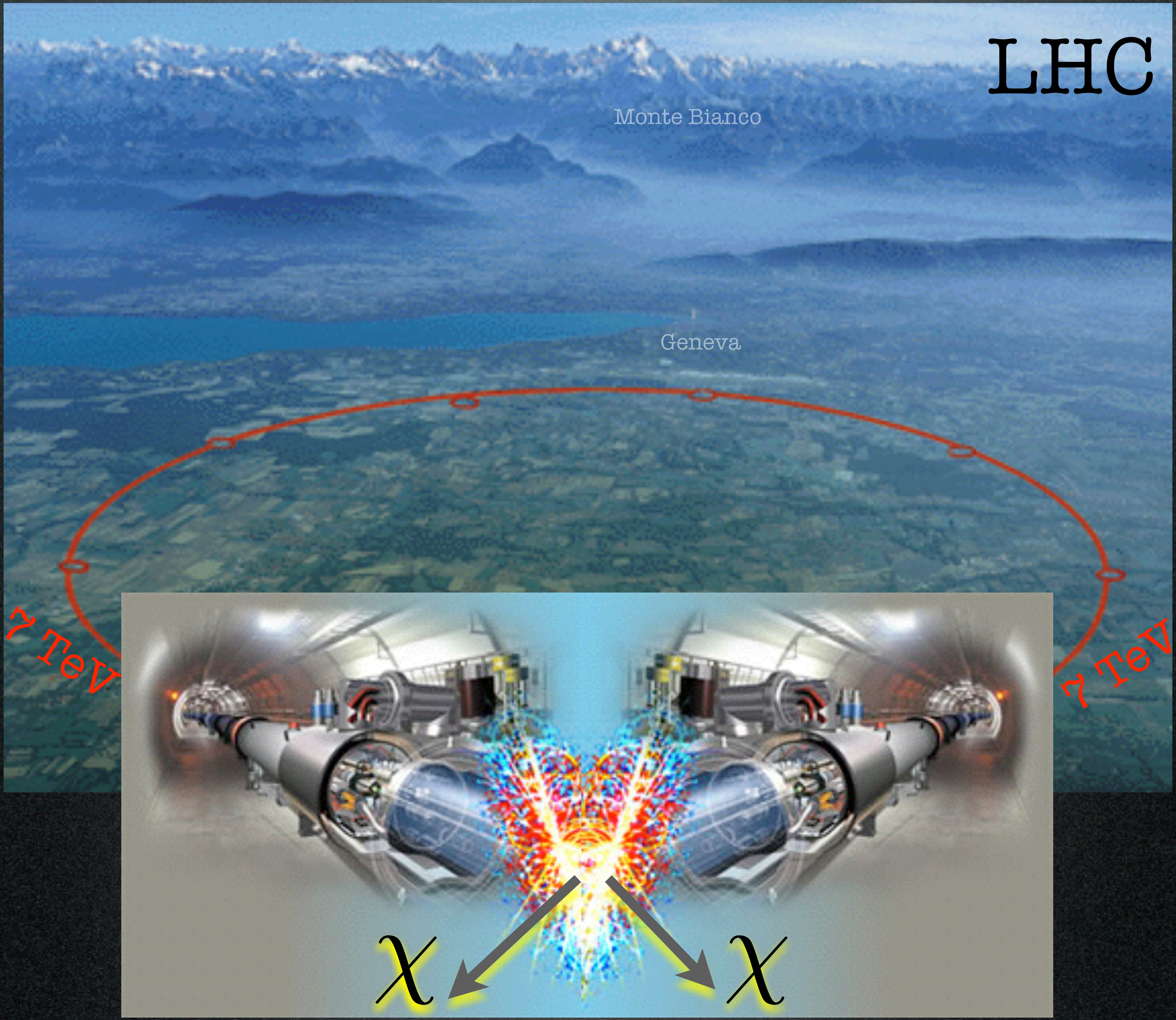

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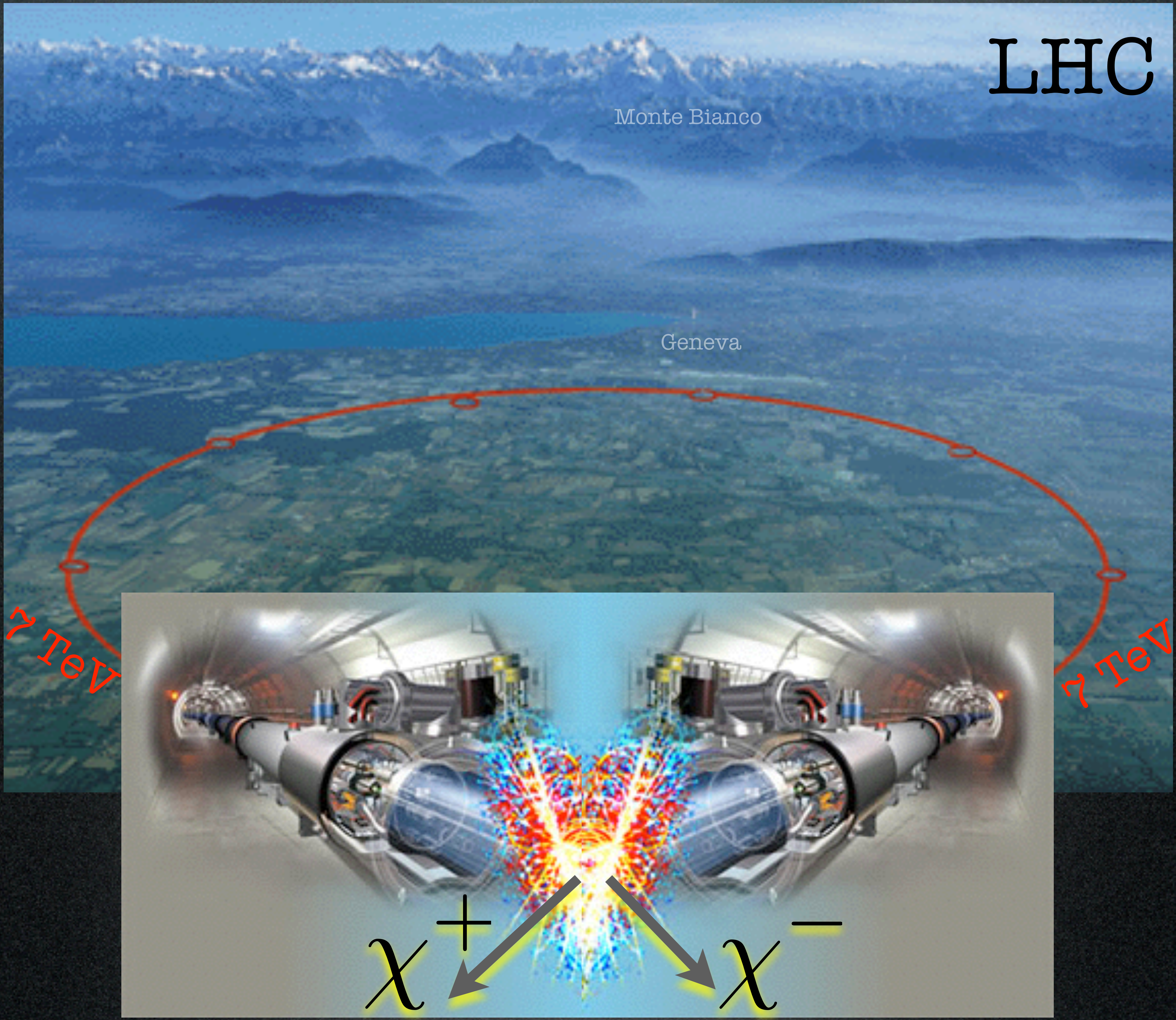

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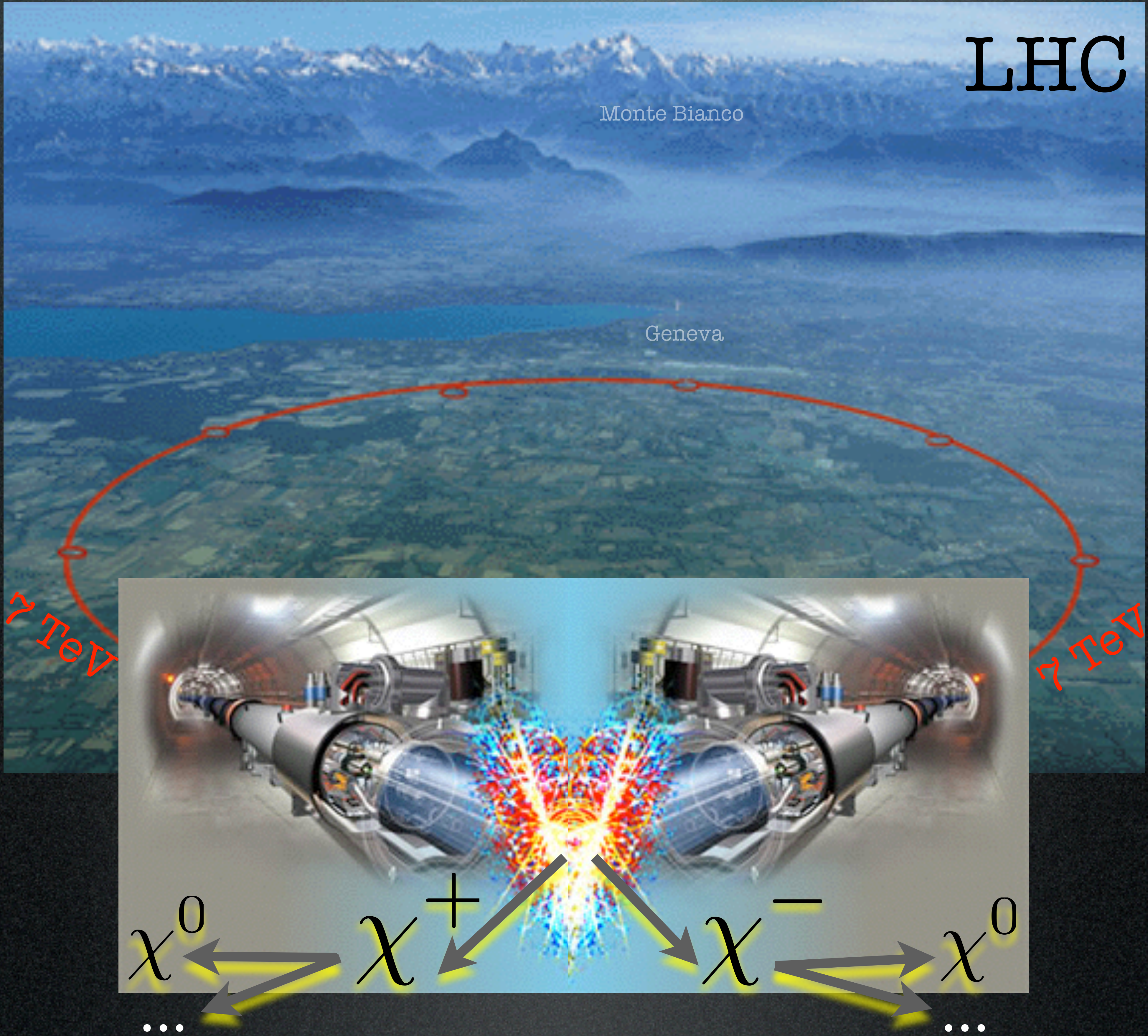

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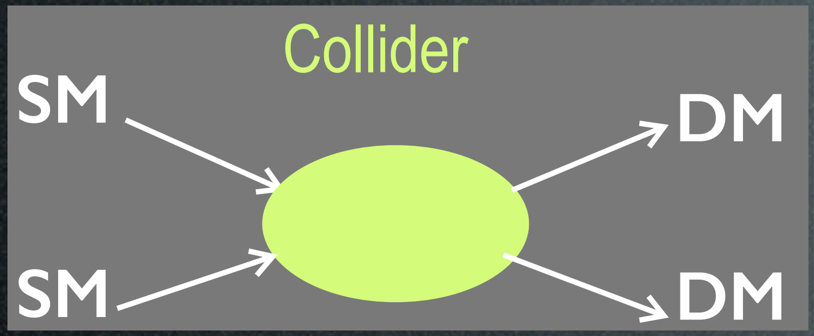
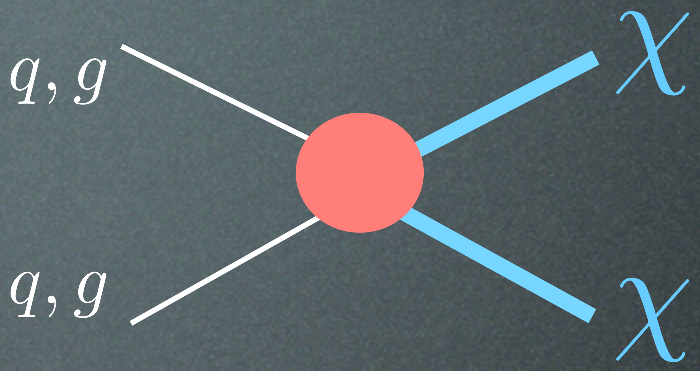


At LHC:



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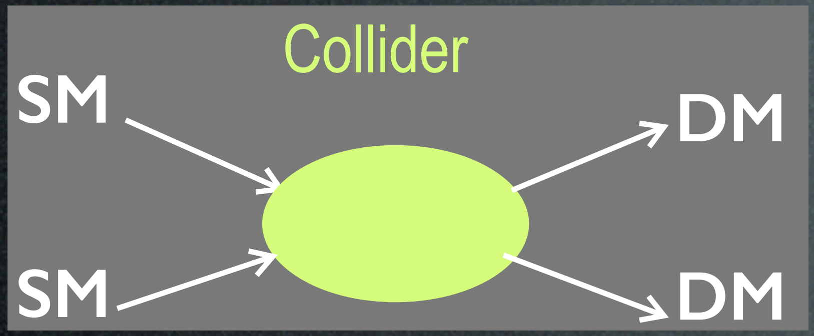

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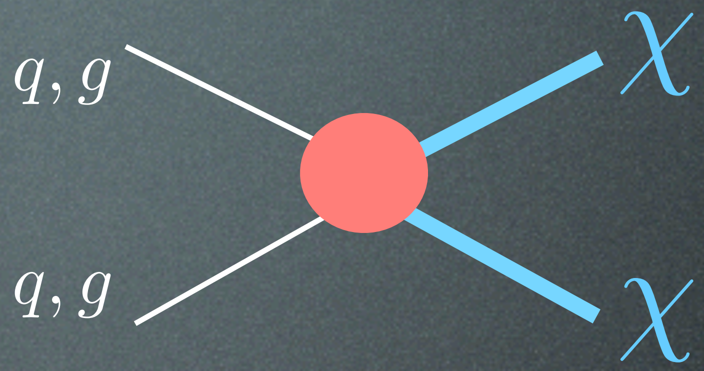
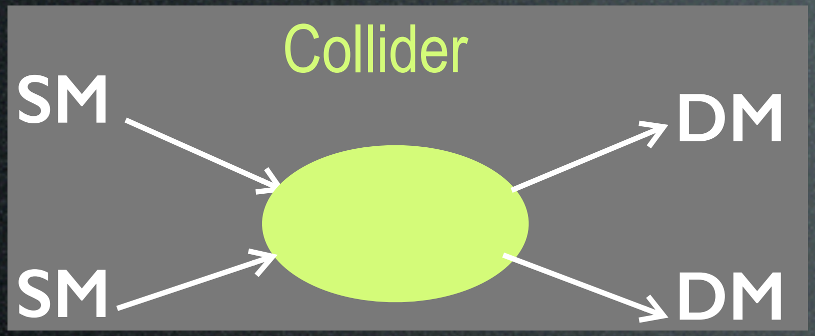


‘Problem’ is: DM flies away

Production at colliders



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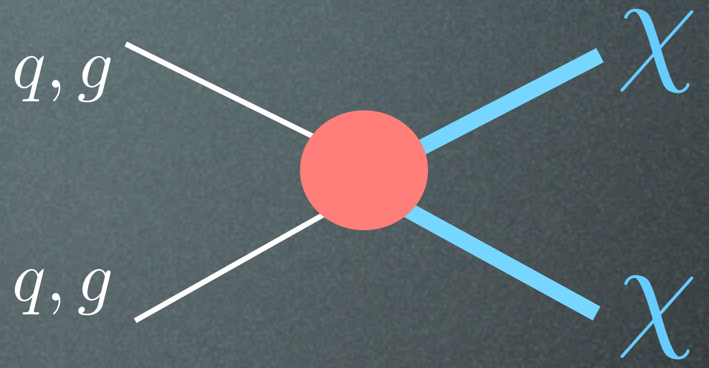
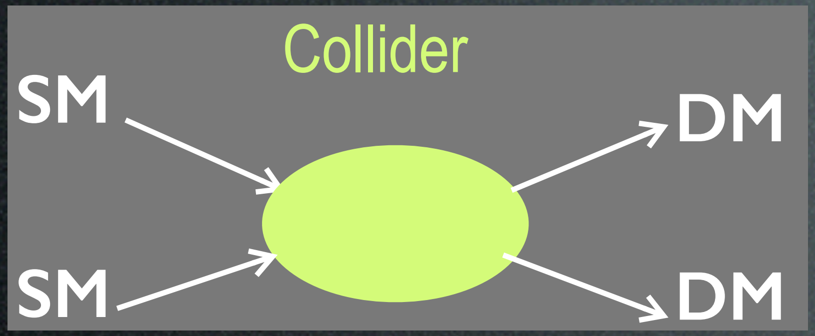


'Problem' is: DM flies away

Signature is: missing energy

Production at colliders



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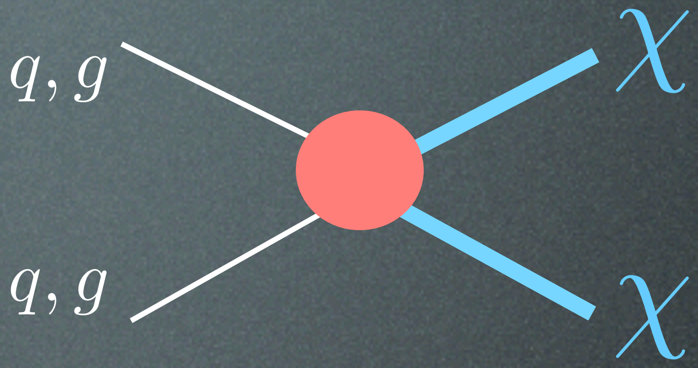
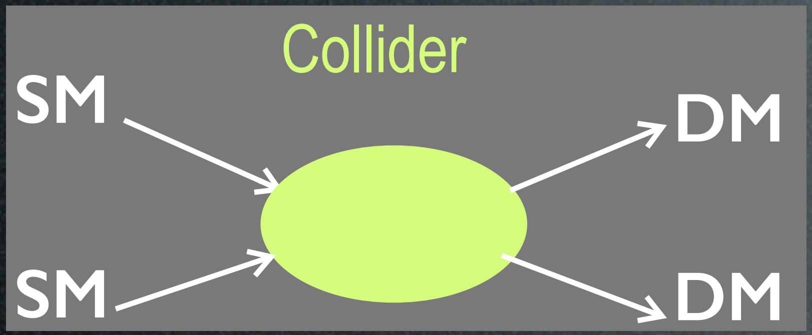


'Problem' is: DM flies away

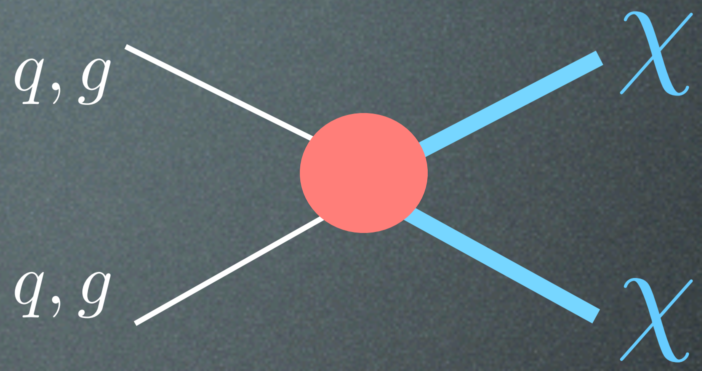
Signature is: missing energy

transverse

Production at colliders

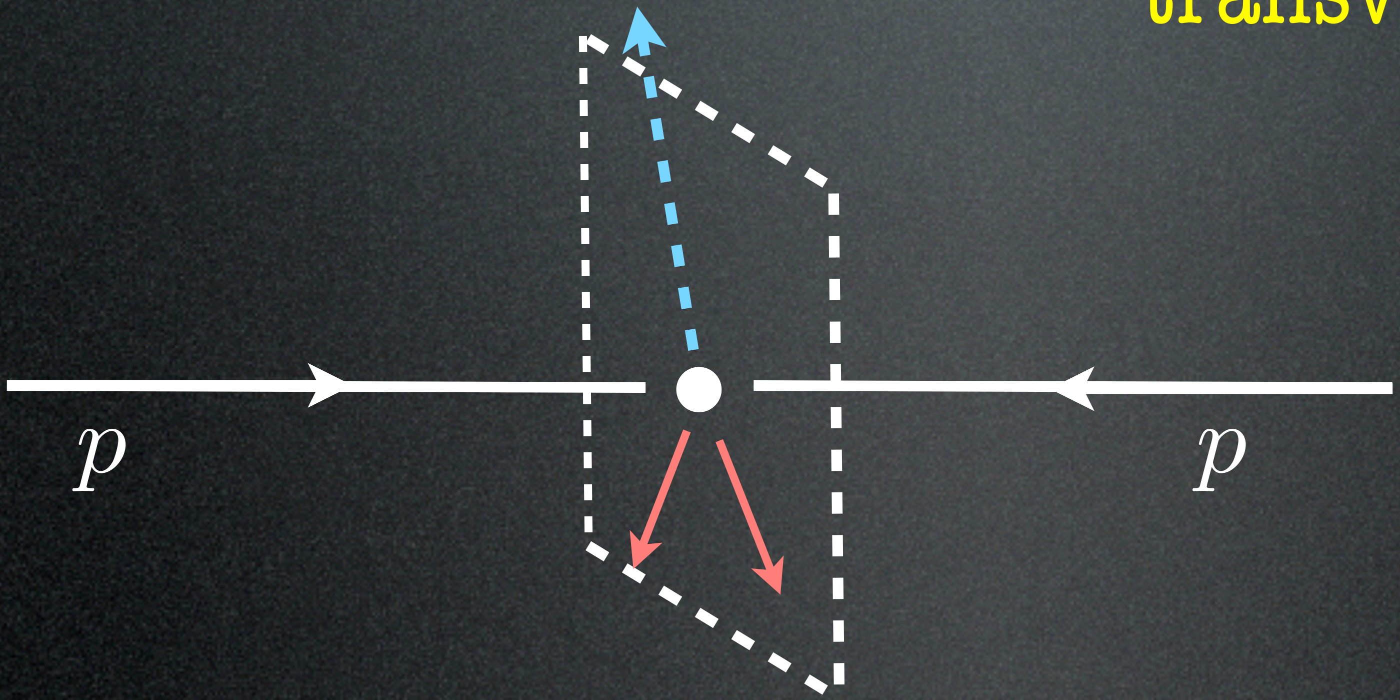


At LHC:



‘Problem’ is: DM flies away

Signature is: missing energy
transverse



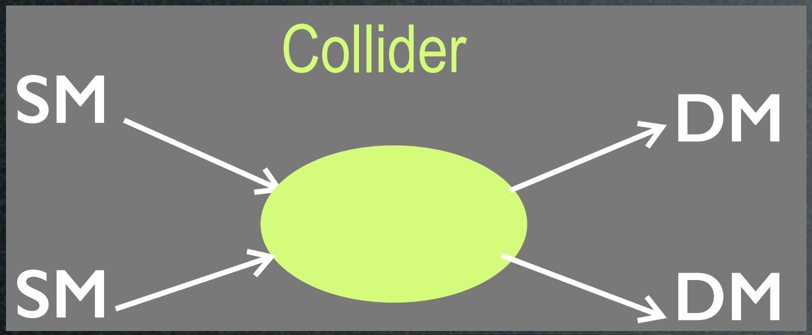
Before collision: $\vec{P}_T^{\mathrm{tot}} \equiv 0$

(NB: $\vec{P}_L^{\mathrm{tot}} \neq 0$ in general)

After collision: $\vec{P}_T^{\mathrm{vis}} \overset{?}{=} 0$

If ≠, then ‘MET’

Production at colliders



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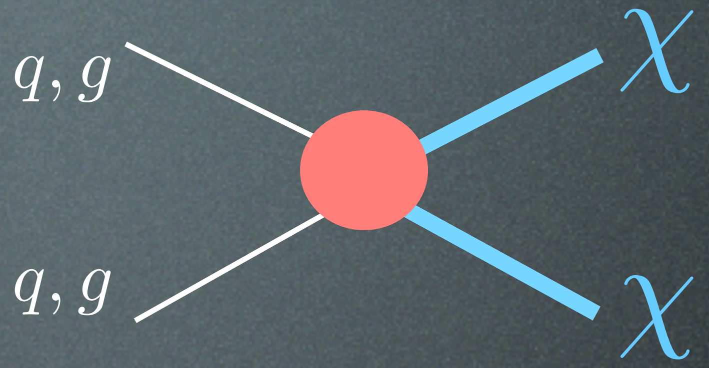

'Problem' is: DM flies away

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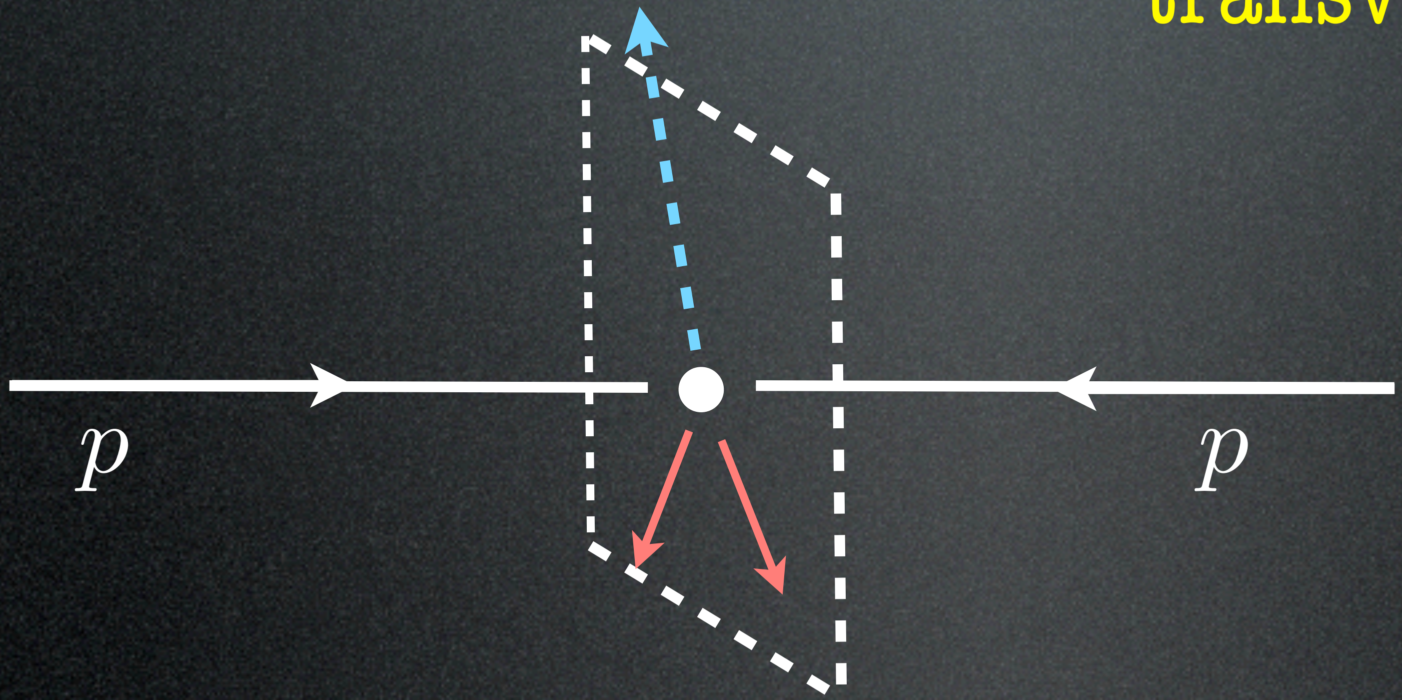
transverse



Before collision: $\vec{P}_T^{\rm tot} \equiv 0$

(NB: $\vec{P}_L^{\rm tot} \neq 0$ in general)

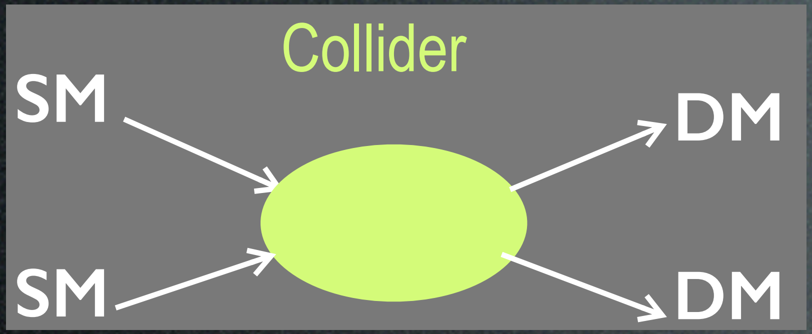
After collision: $\vec{P}_T^{\rm vis} \overset{?}{=} 0$

If ≠, then '**MET**'

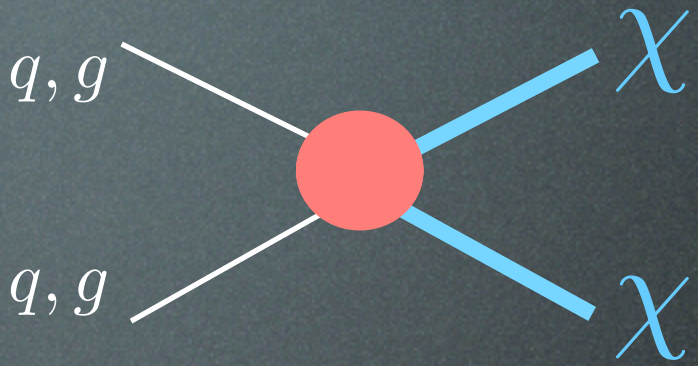
Background: neutrinos (e.g. W⟶eν)

- model your background and look for anomalies
- construct kinematic variables sensitive to χ mass

Production at colliders



At LHC:



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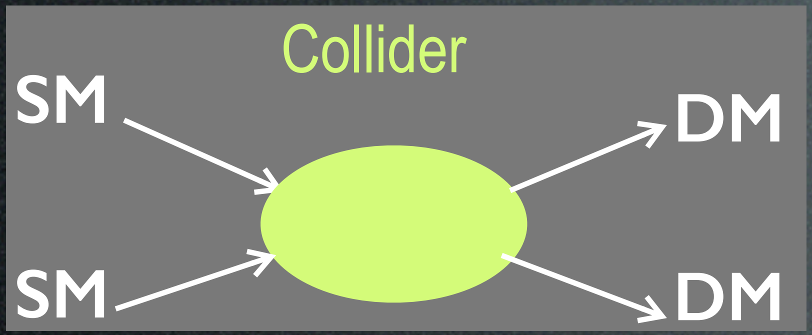
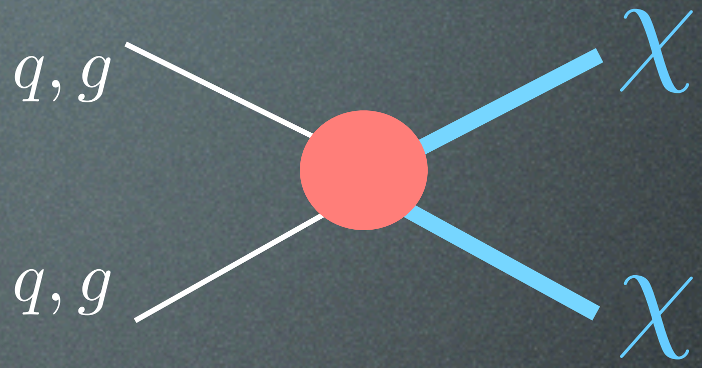


At LHC:



‘Problem’ is: DM flies away

Signature is: missing energy

transverse

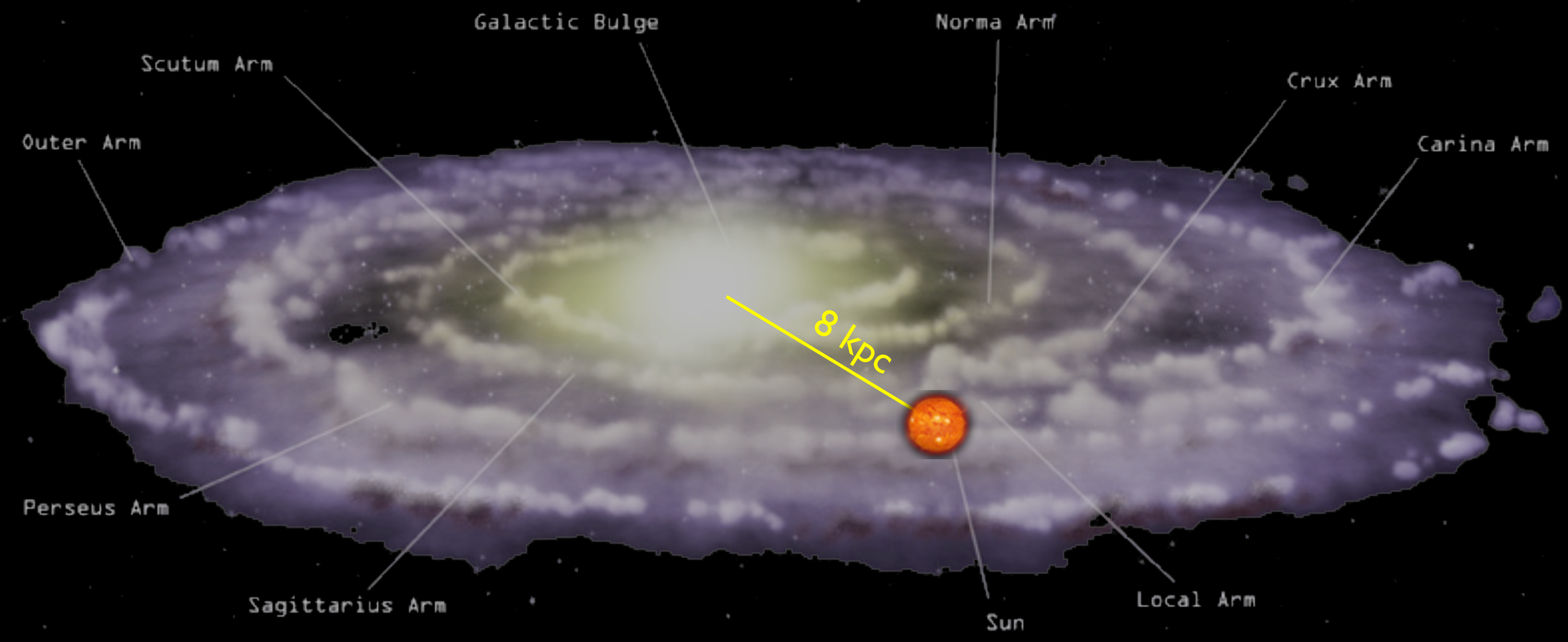
Status:

So far,
no missing energy
whatsoever.

Indirect Detection

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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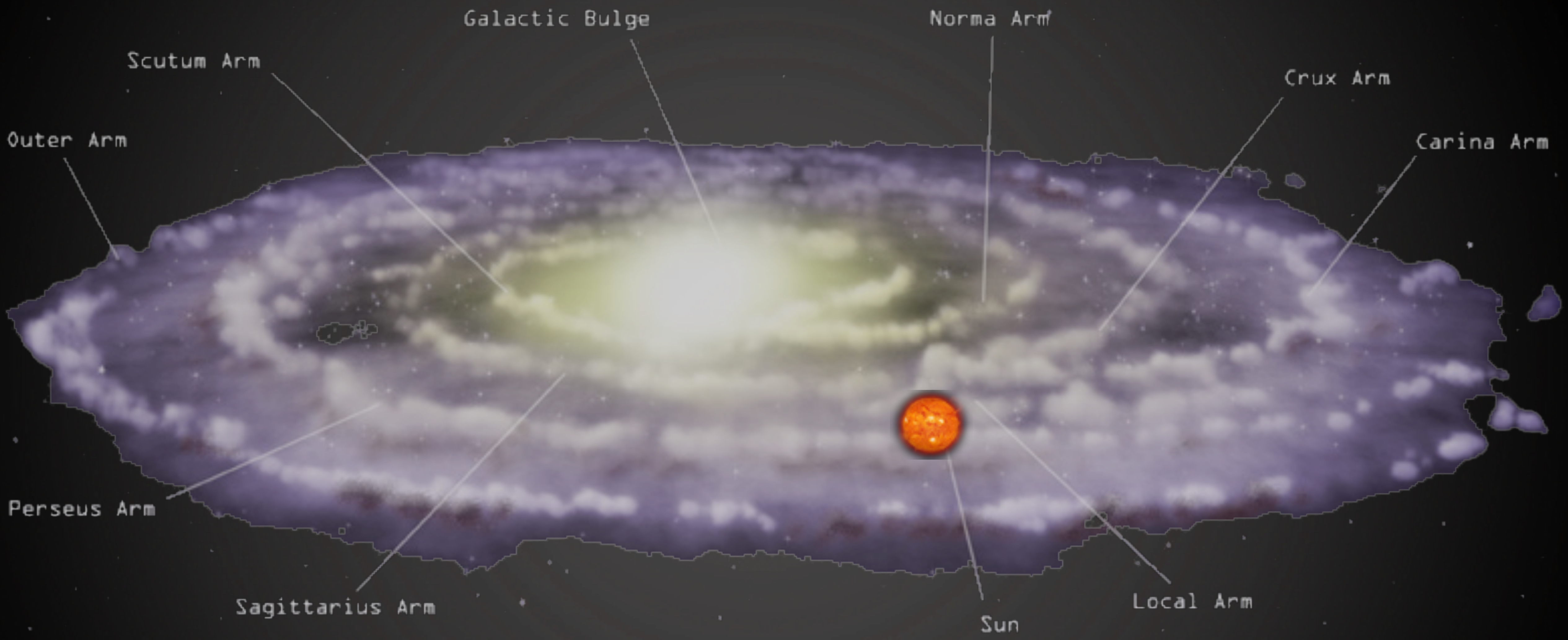

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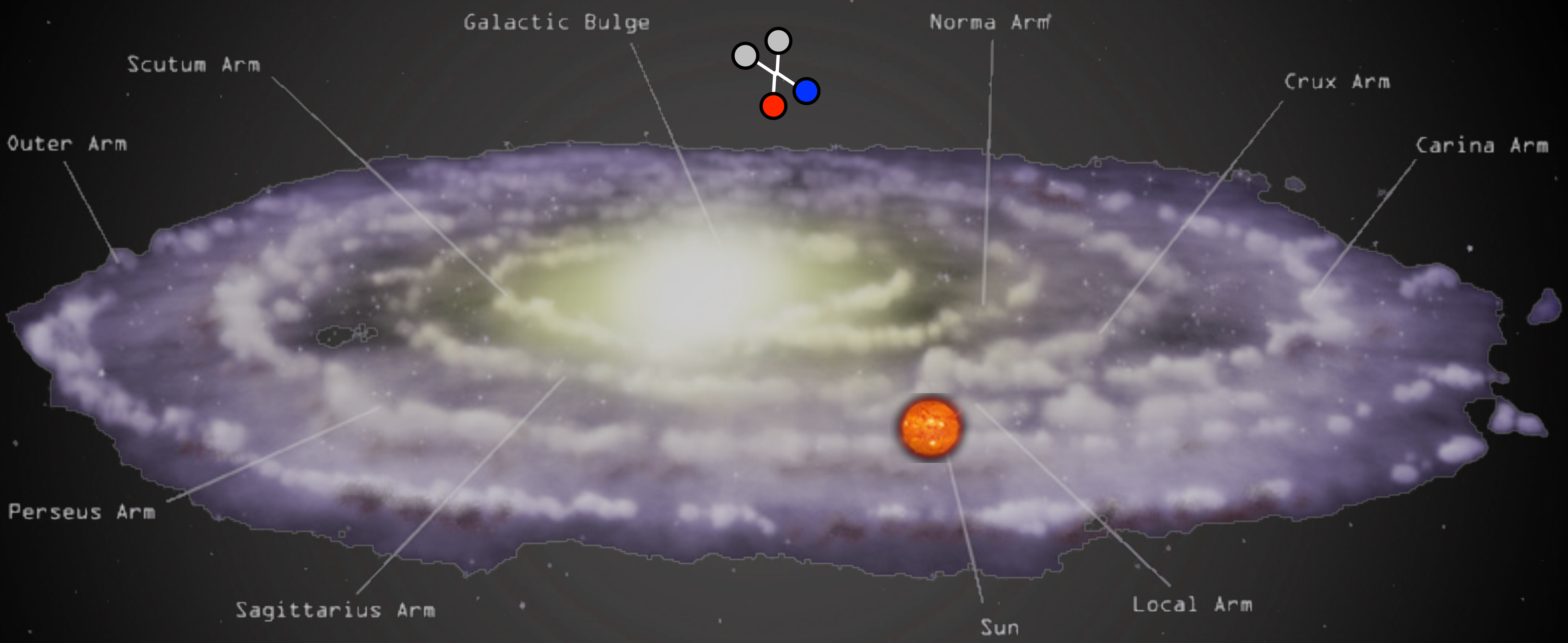
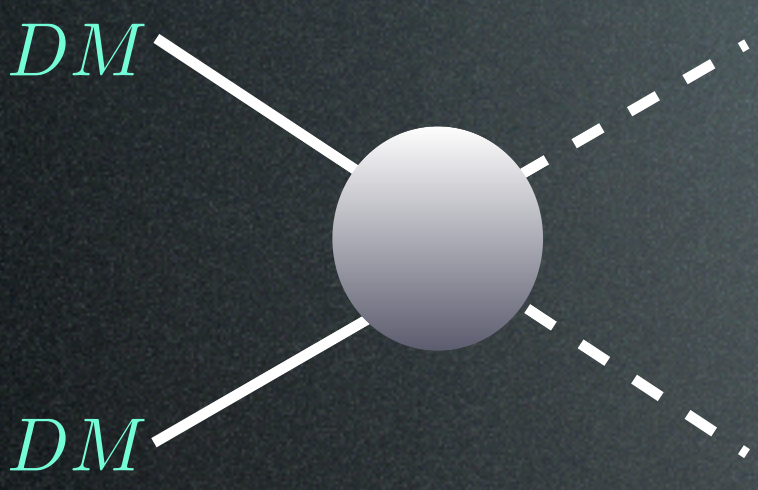


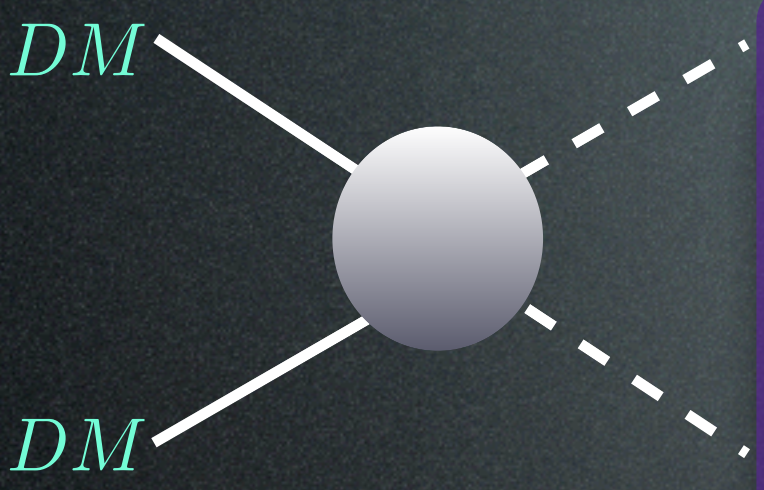
Fluxes at production



$$W^-, Z, b, \tau^-, t, h \ldots \leadsto e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \leadsto e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$$

Fluxes at production

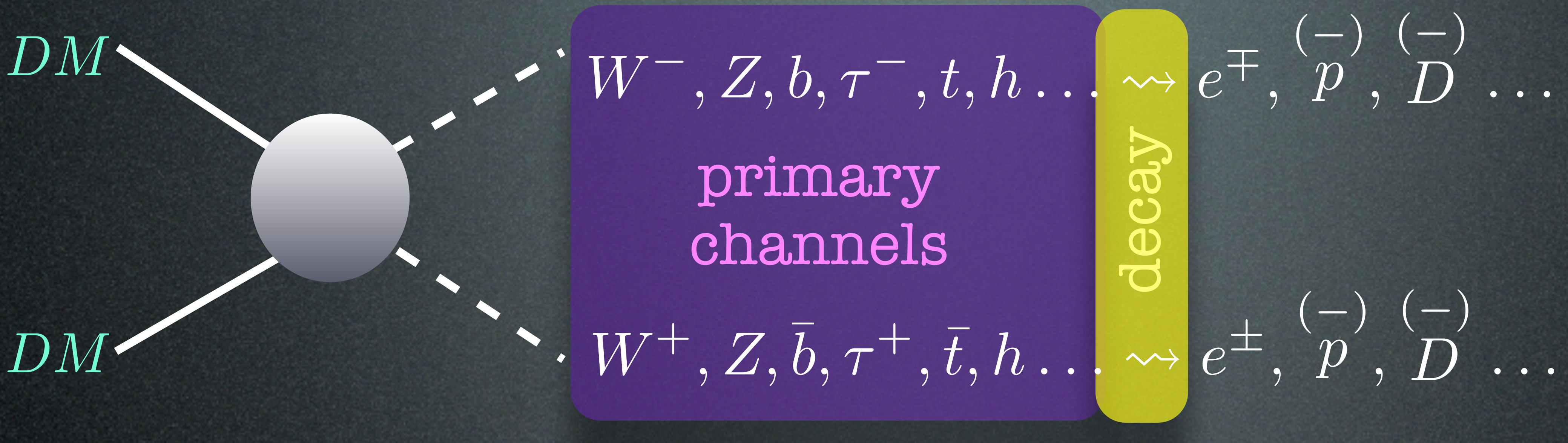


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary
channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

Fluxes at production



DM

DM

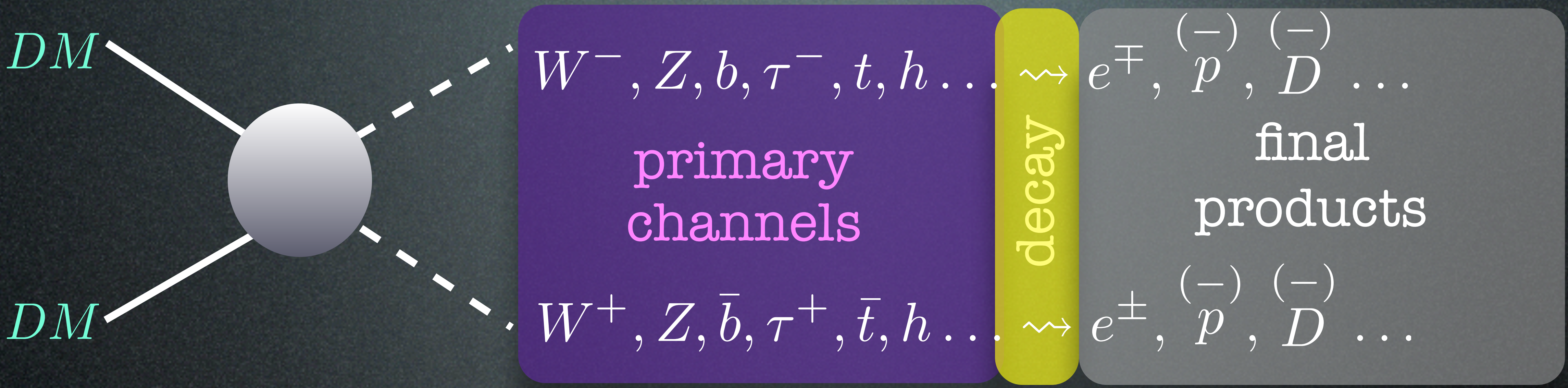
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary channels

decay

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

Fluxes at production



DM

DM

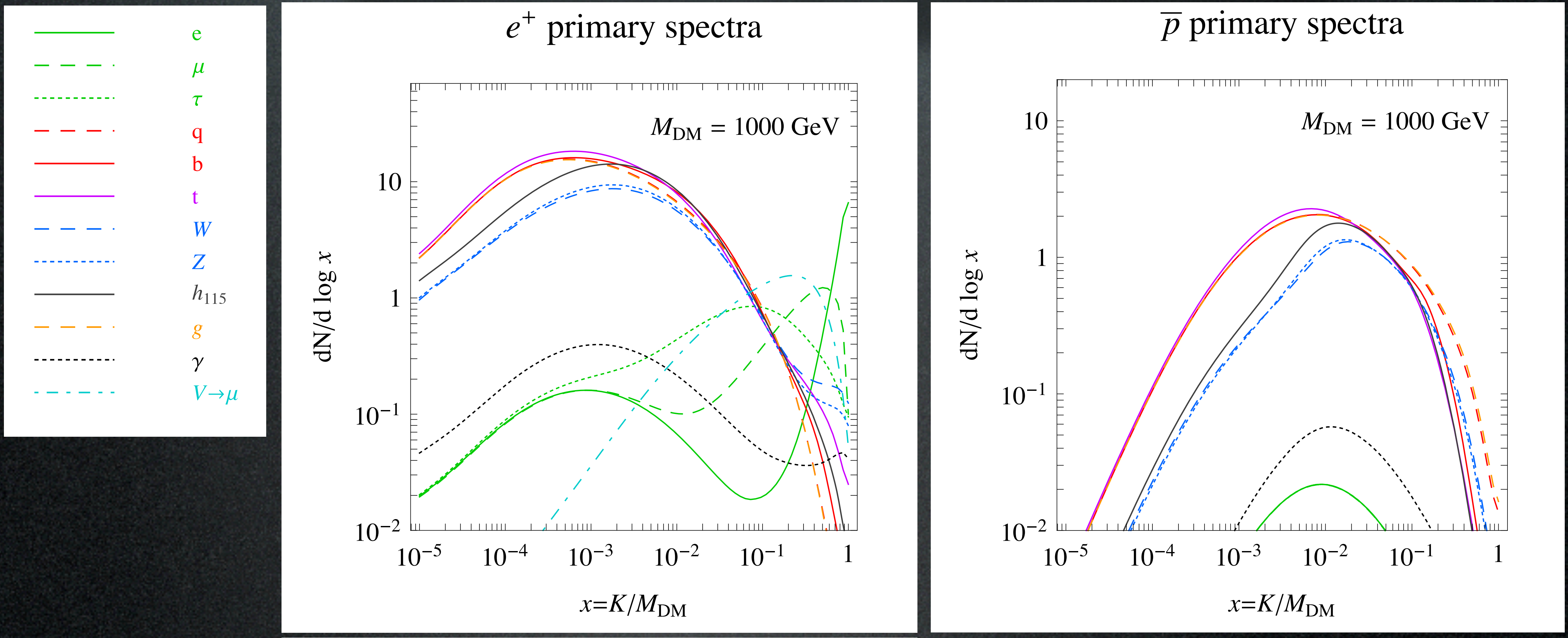
$W^-, Z, b, \tau^-, t, h \ldots$ $\rightsquigarrow$ $e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

primary channels

decay

final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$ $\rightsquigarrow$ $e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$



e^+ primary spectra

$\overline{p}$ primary spectra

Fluxes at production

ElectroWeak corrections are important!

Fluxes at production

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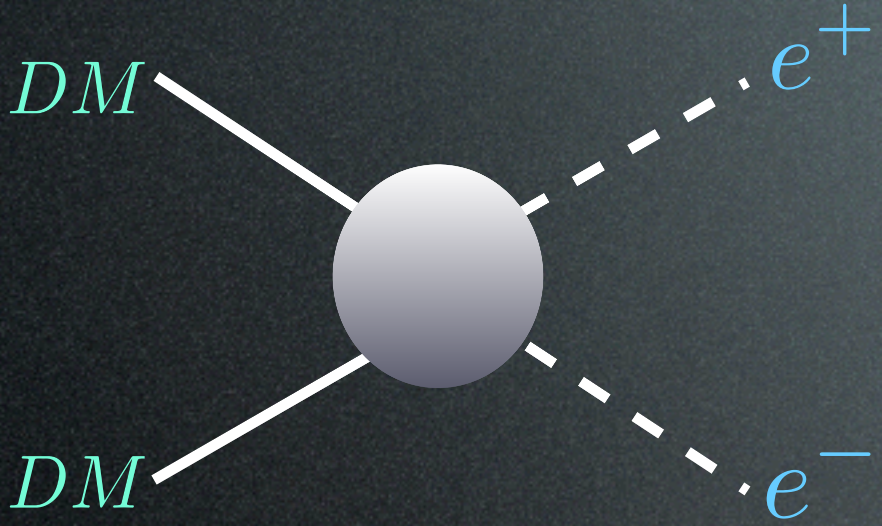

Fluxes at production

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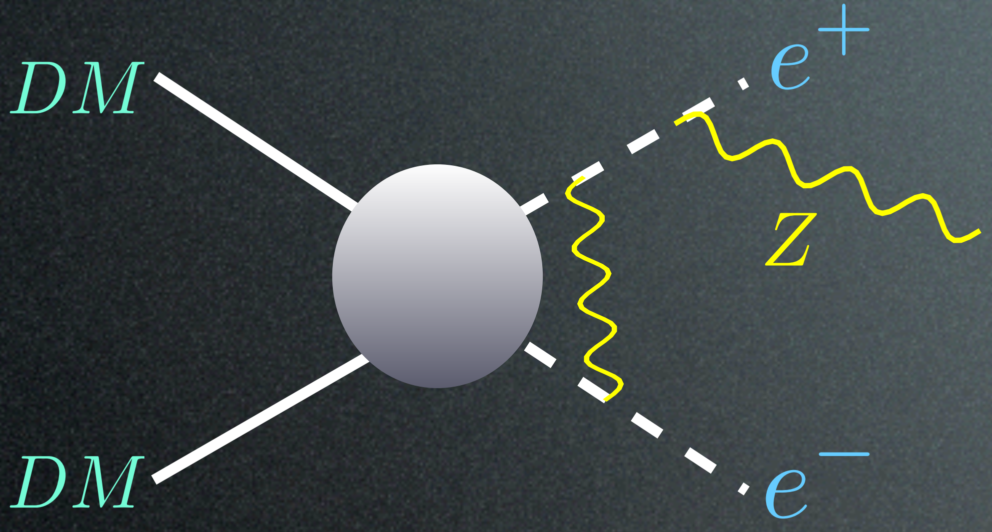

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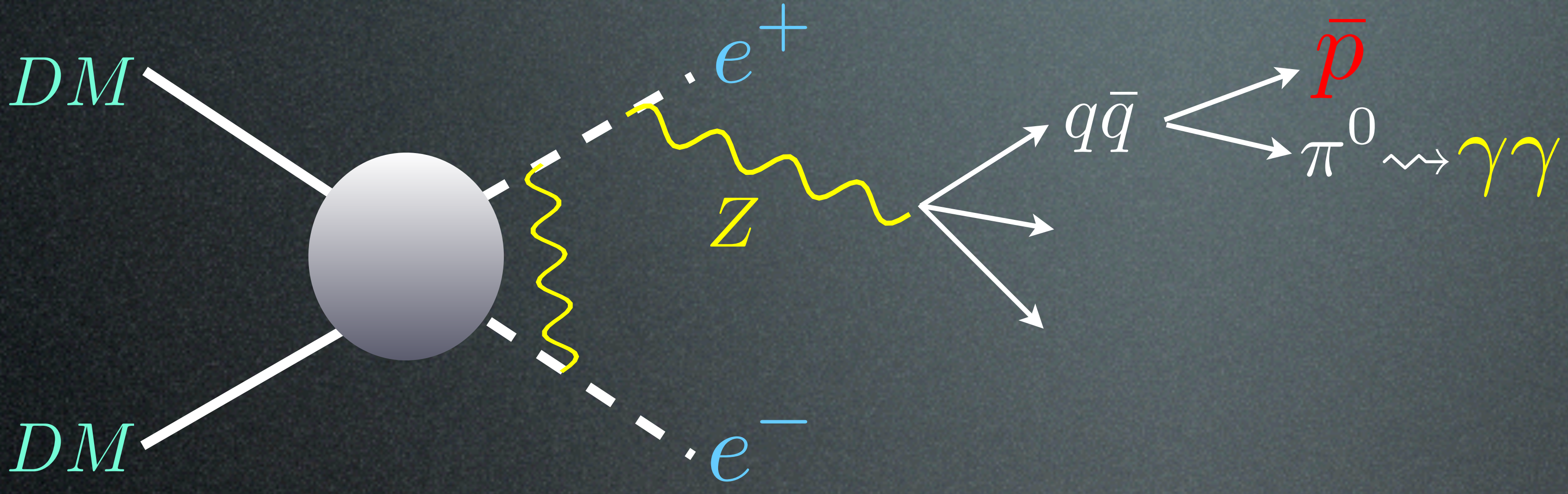

Fluxes at production

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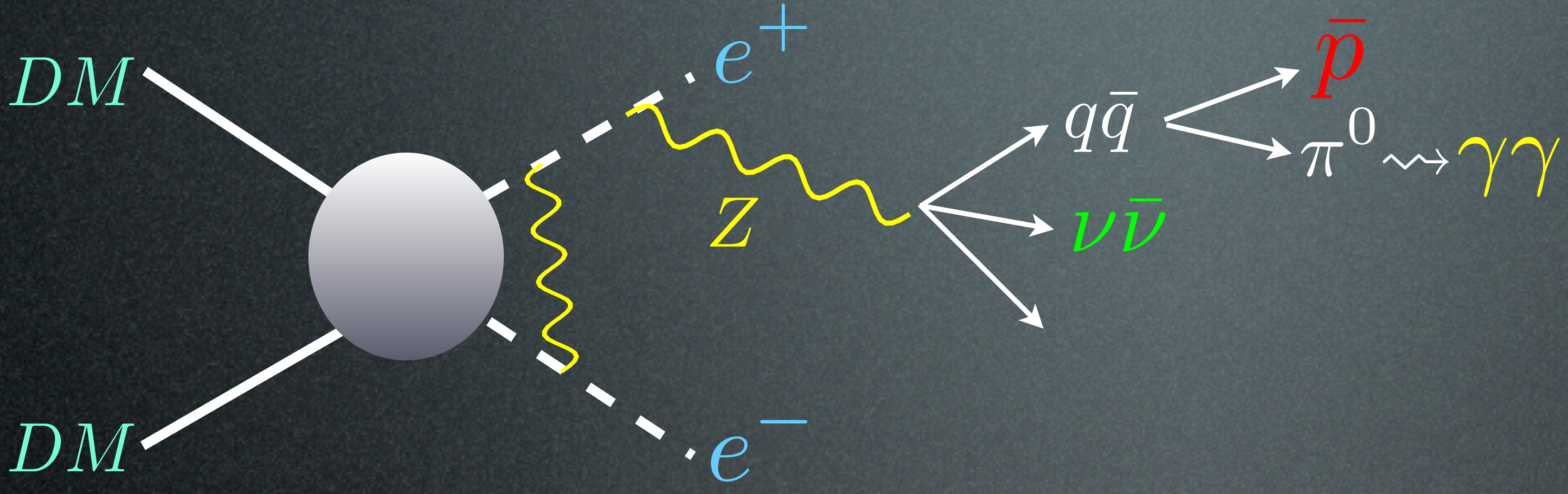

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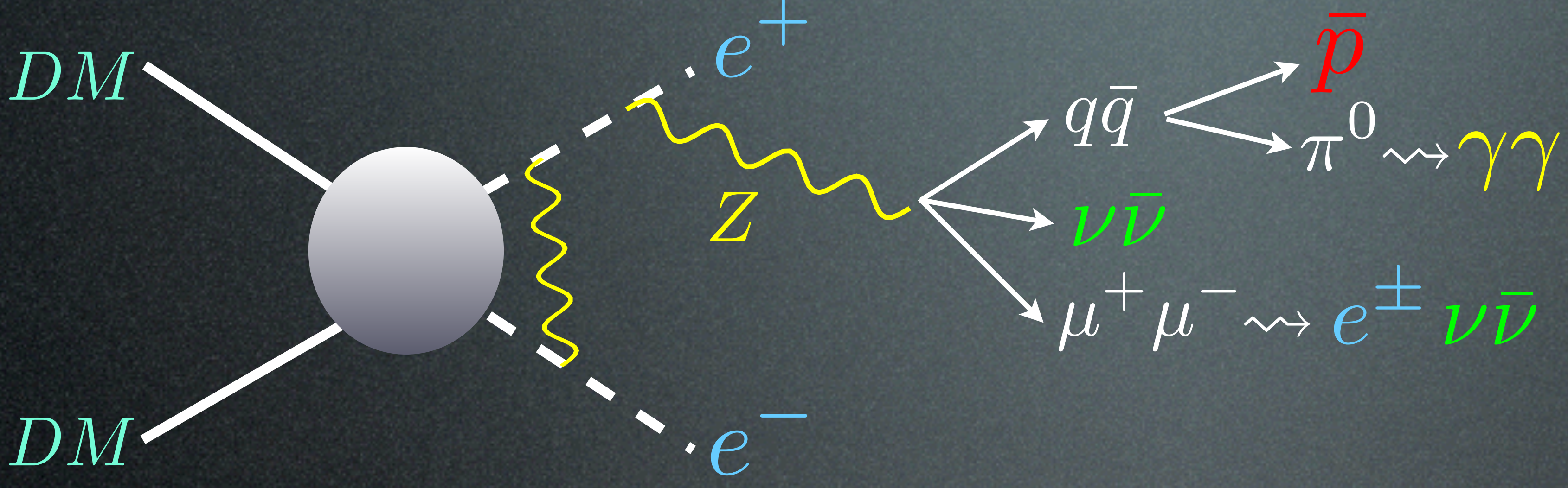

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

Fluxes at production

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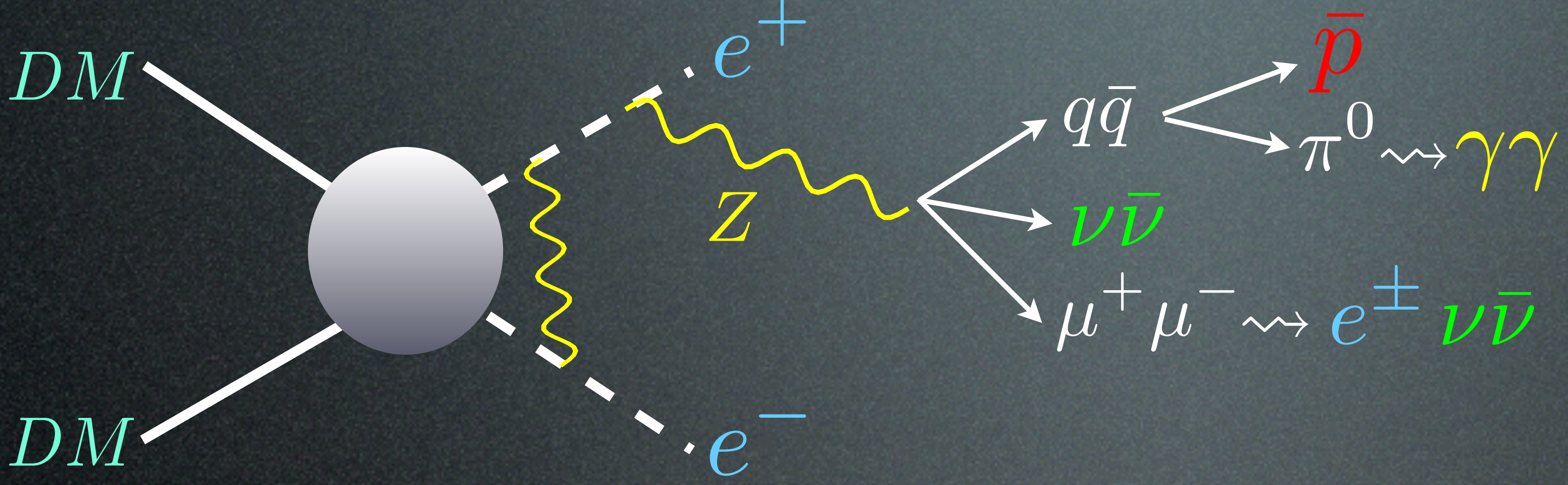
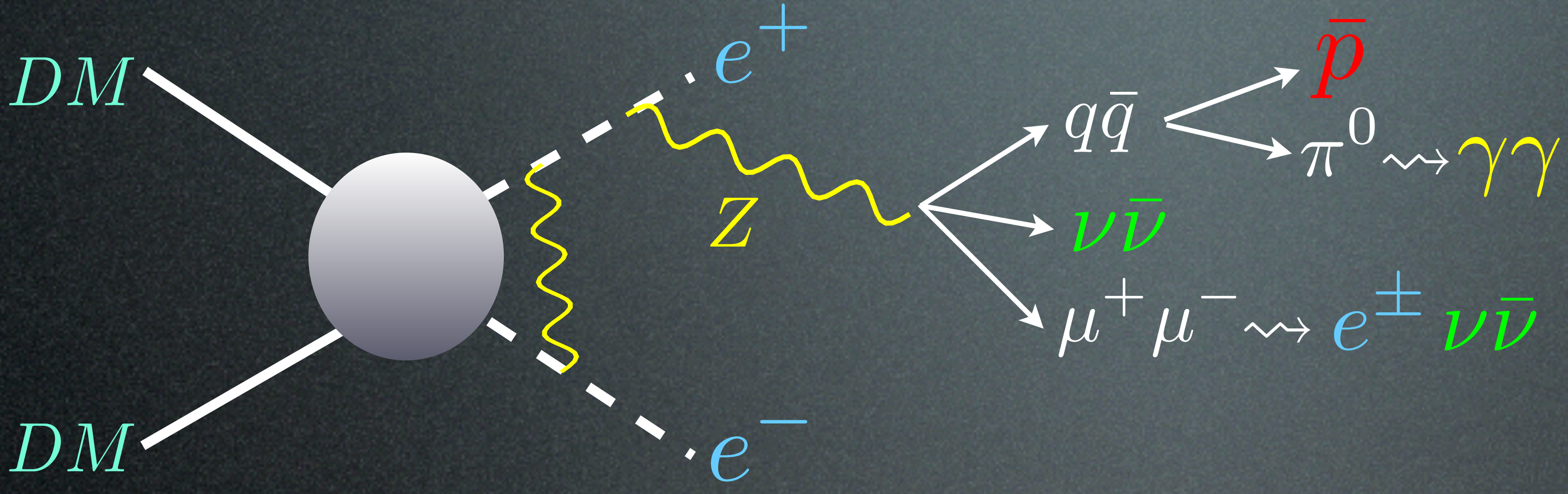


$$\frac{\Delta\sigma}{\sigma} \propto \alpha_{\rm weak} \ln^2\left(\frac{M^2_{\rm DM}}{M^2_{\rm Z}}\right)$$

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

Fluxes at production

ElectroWeak corrections are important!



$$\frac{\Delta\sigma}{\sigma} \propto \underbrace{\alpha_{\rm weak}}_{\sim 0.03} \underbrace{\ln^2\left(\frac{\overset{\sim \text{TeV}}{M_{\rm DM}^2}}{M_Z^2}\right)}_{\sim 25}$$

Ciafaloni et al., JCAP 1103 (2011)
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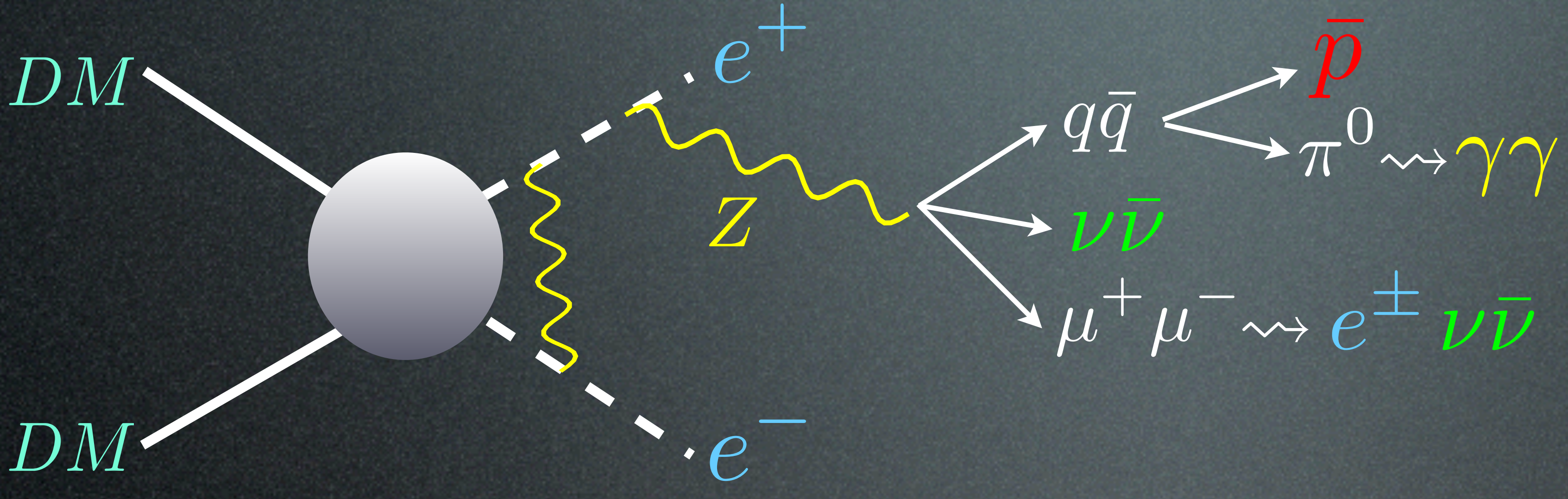
Fluxes at production

ElectroWeak corrections are important!



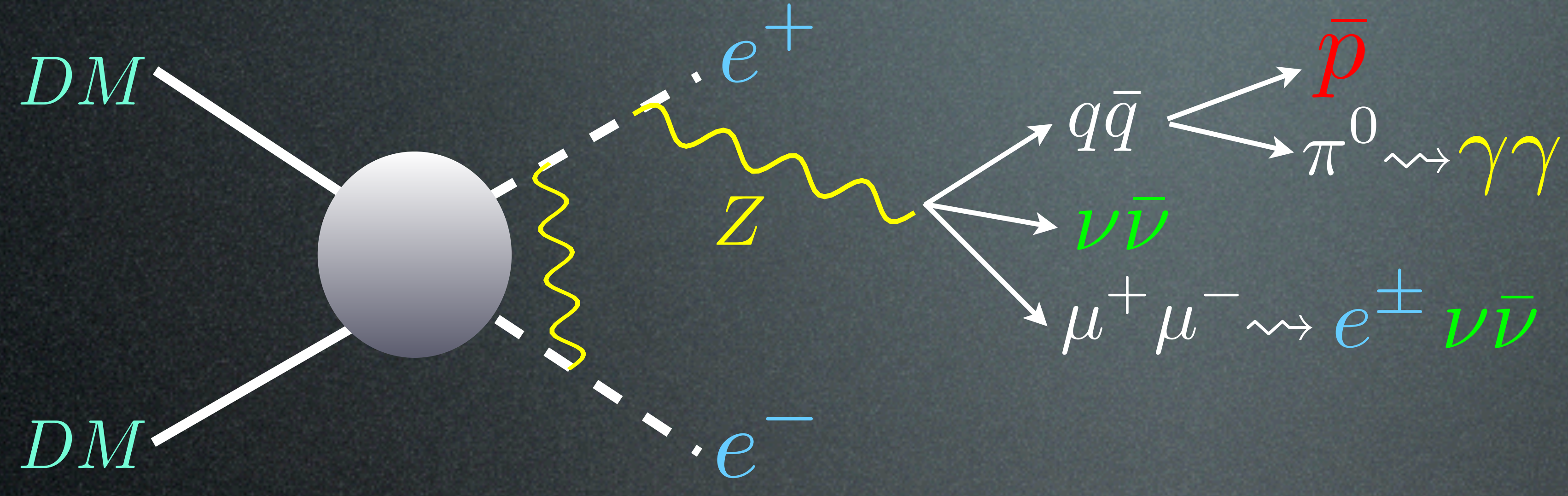
$$\frac{\Delta\sigma}{\sigma} \propto \underbrace{\underbrace{\alpha_{\rm weak}}_{\sim 0.03} \underbrace{\ln^2\left(\frac{\overset{\sim \text{TeV}}{M_{\rm DM}^2}}{M_{\rm Z}^2}\right)}_{\sim 25}}_{\sim 75\%}$$

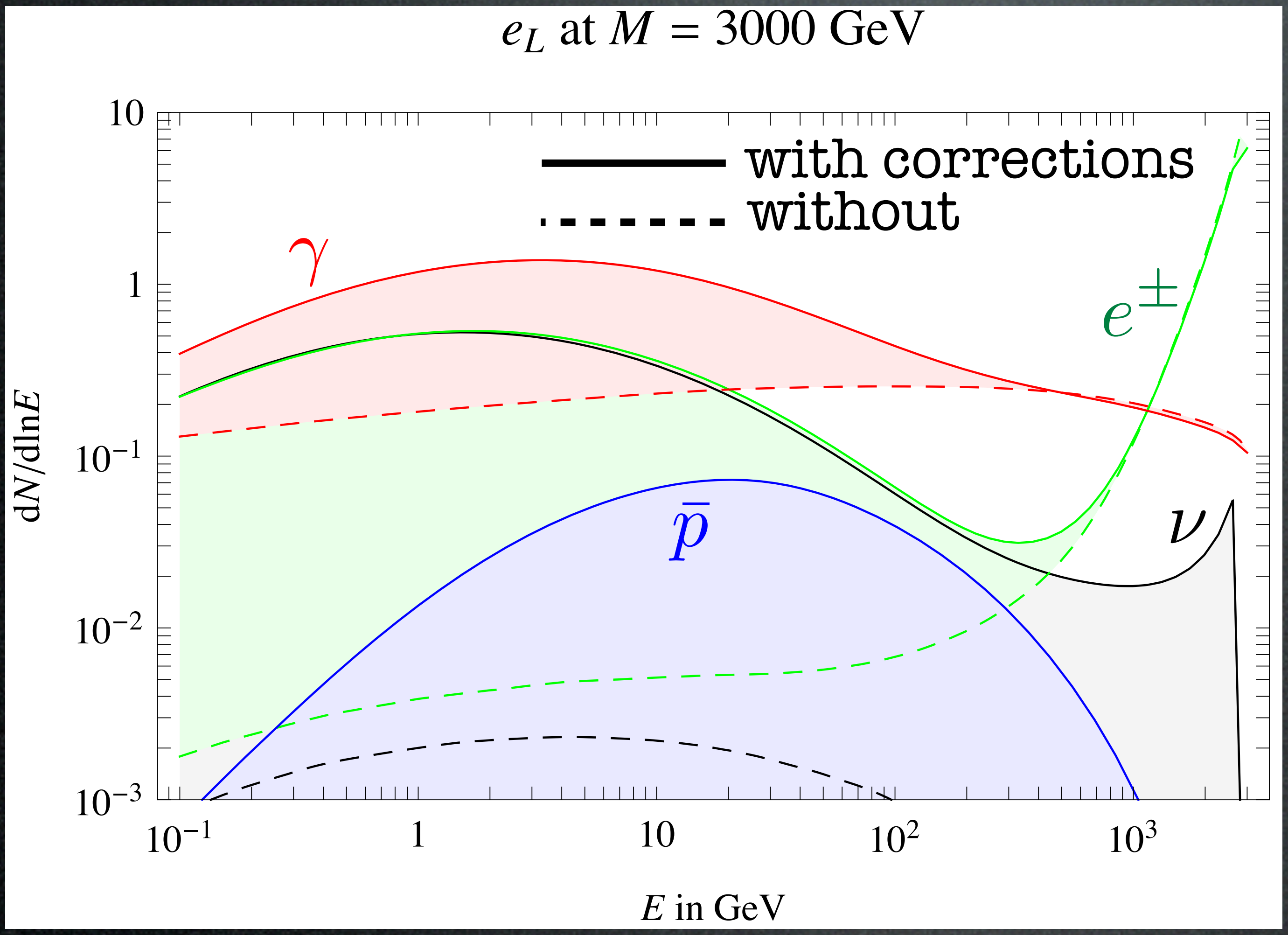
(NB the finite mass of Z, W regulates the divergencies, only log terms left)

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

Fluxes at production

ElectroWeak corrections are important!





- unexpected species
- different spectra

  (especially at low energy, but not only)

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

Fluxes at production

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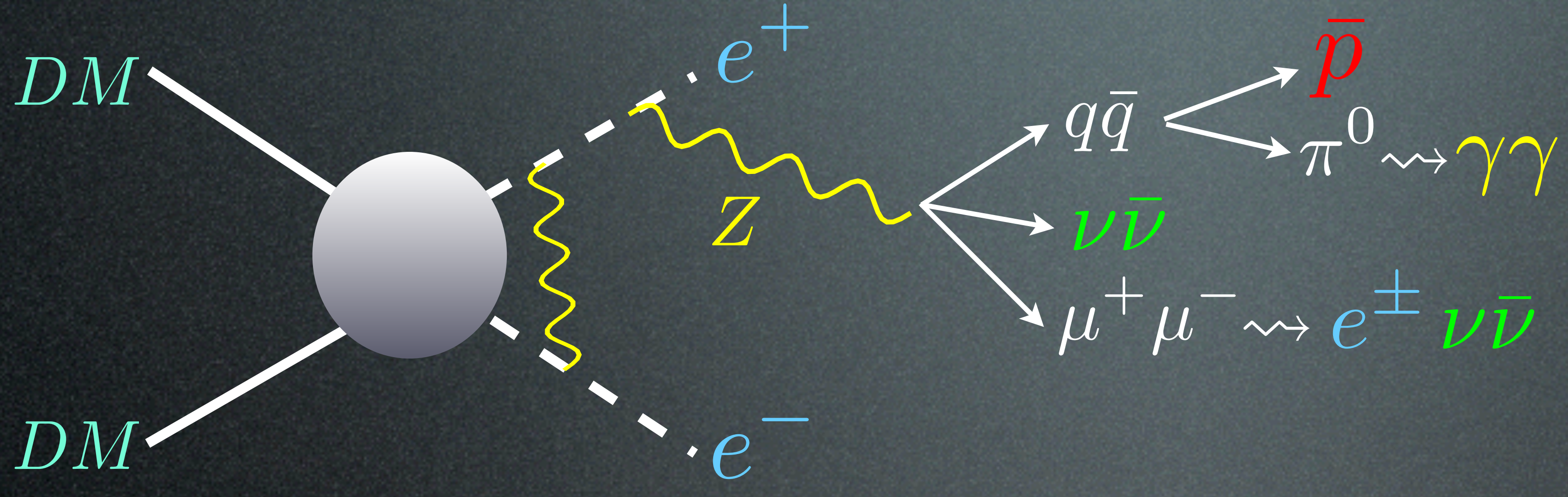

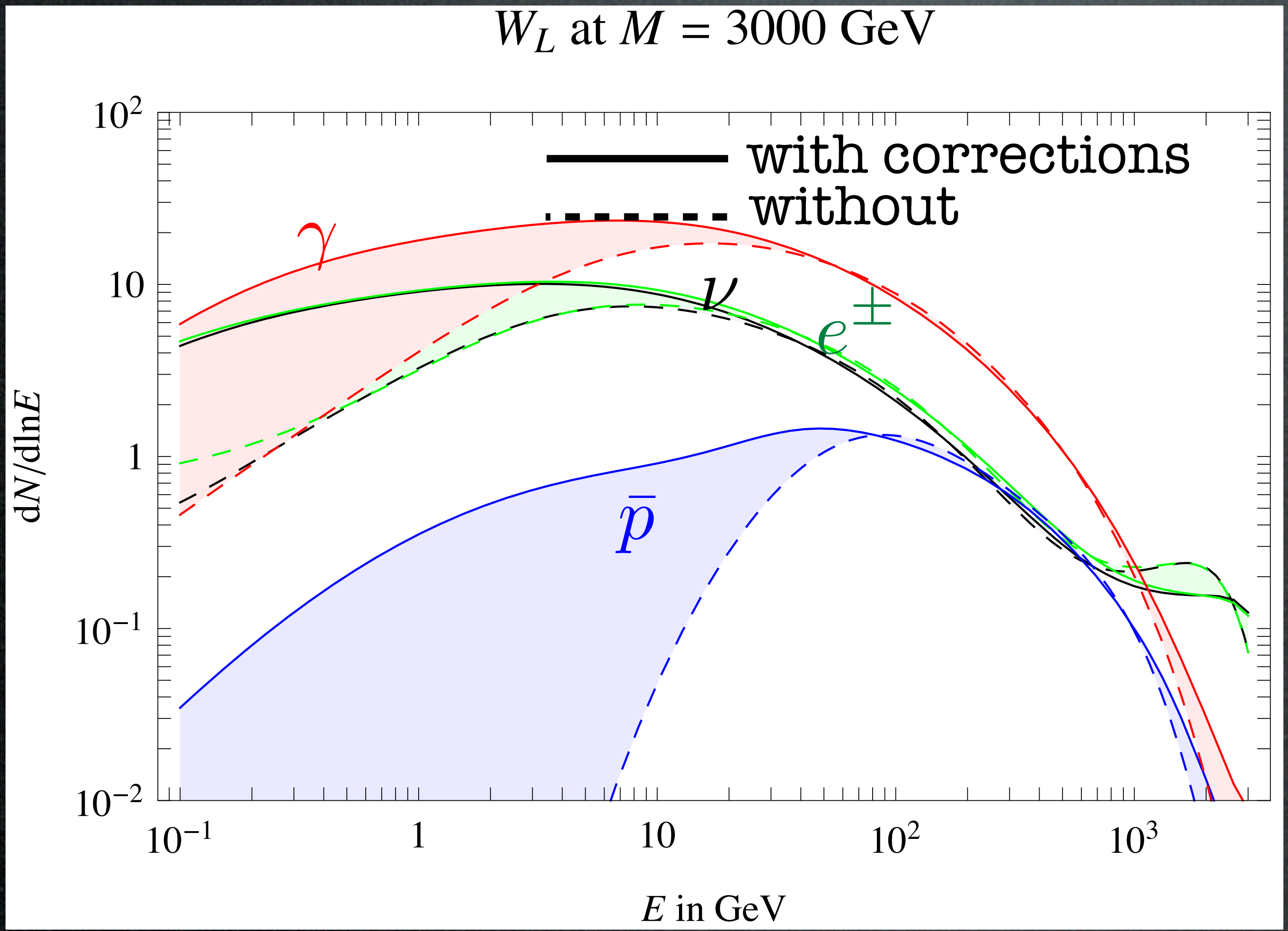

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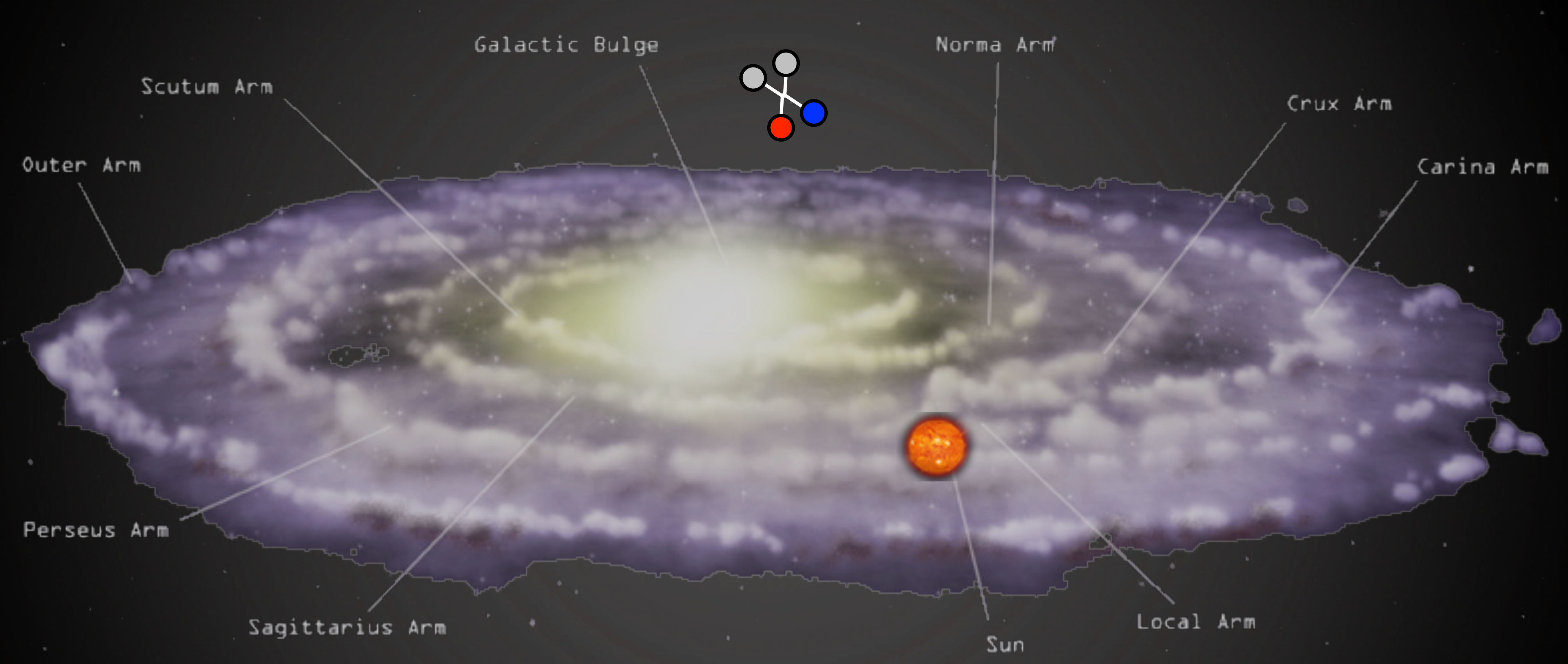
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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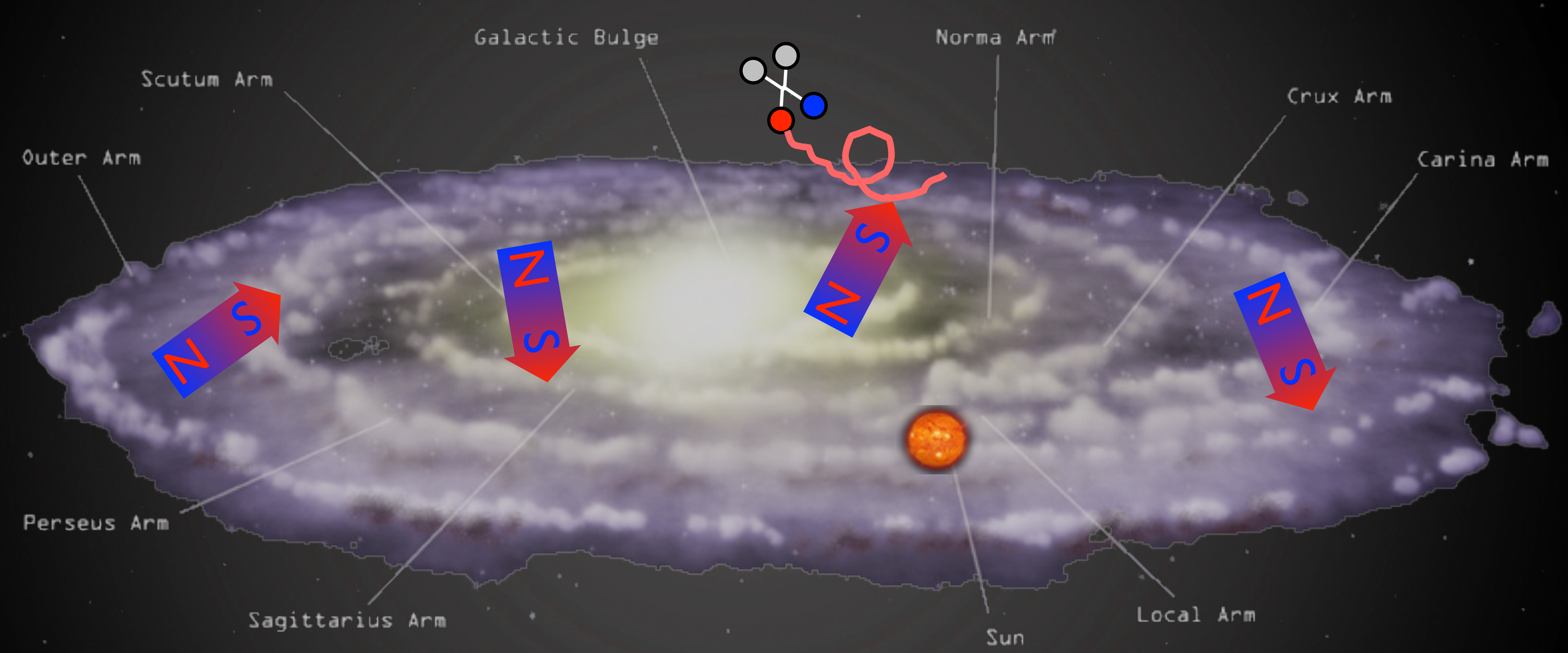

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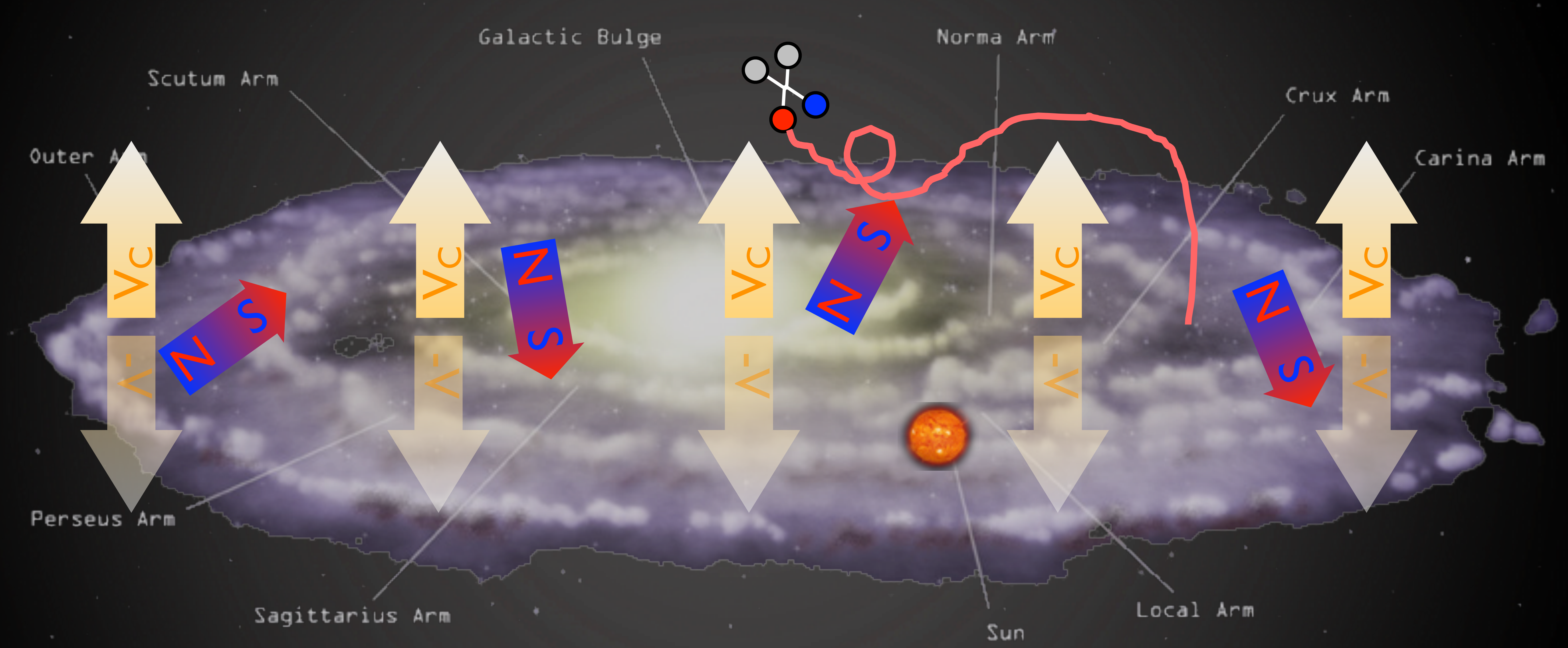

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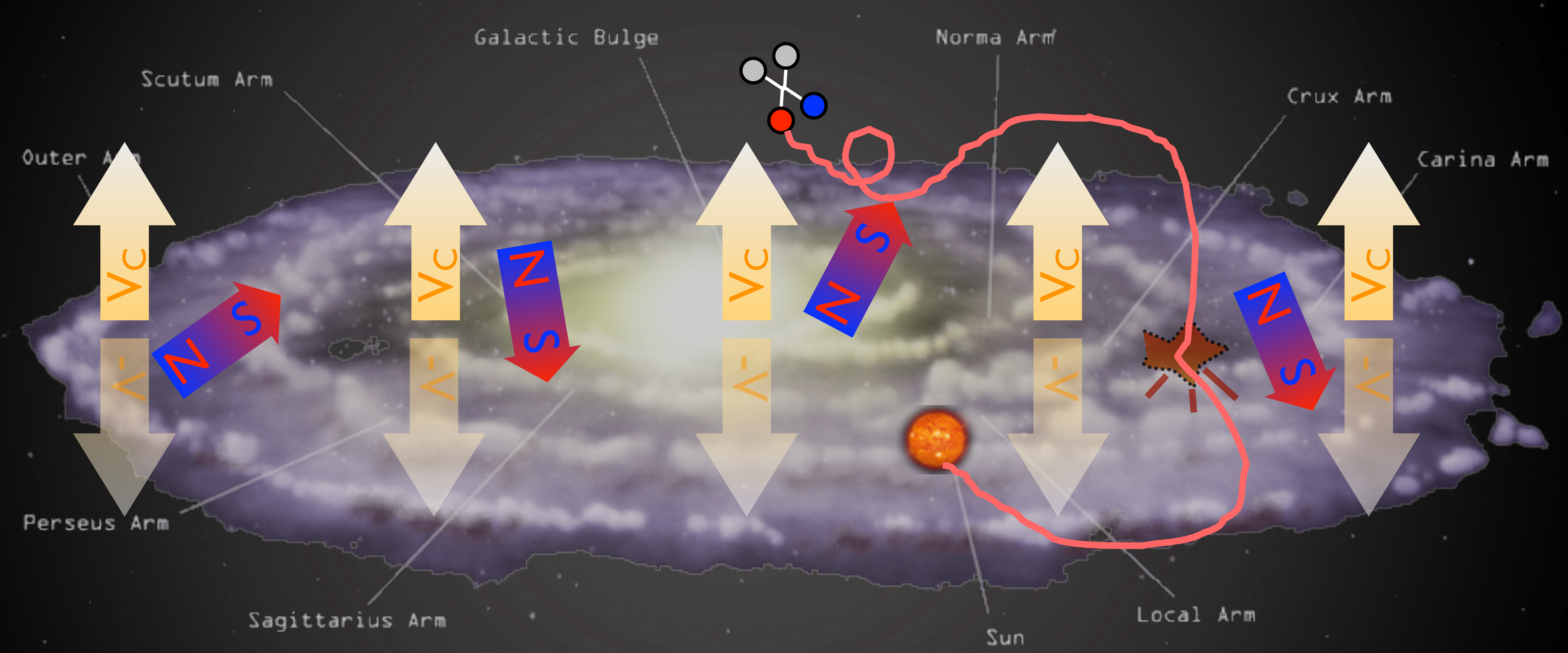

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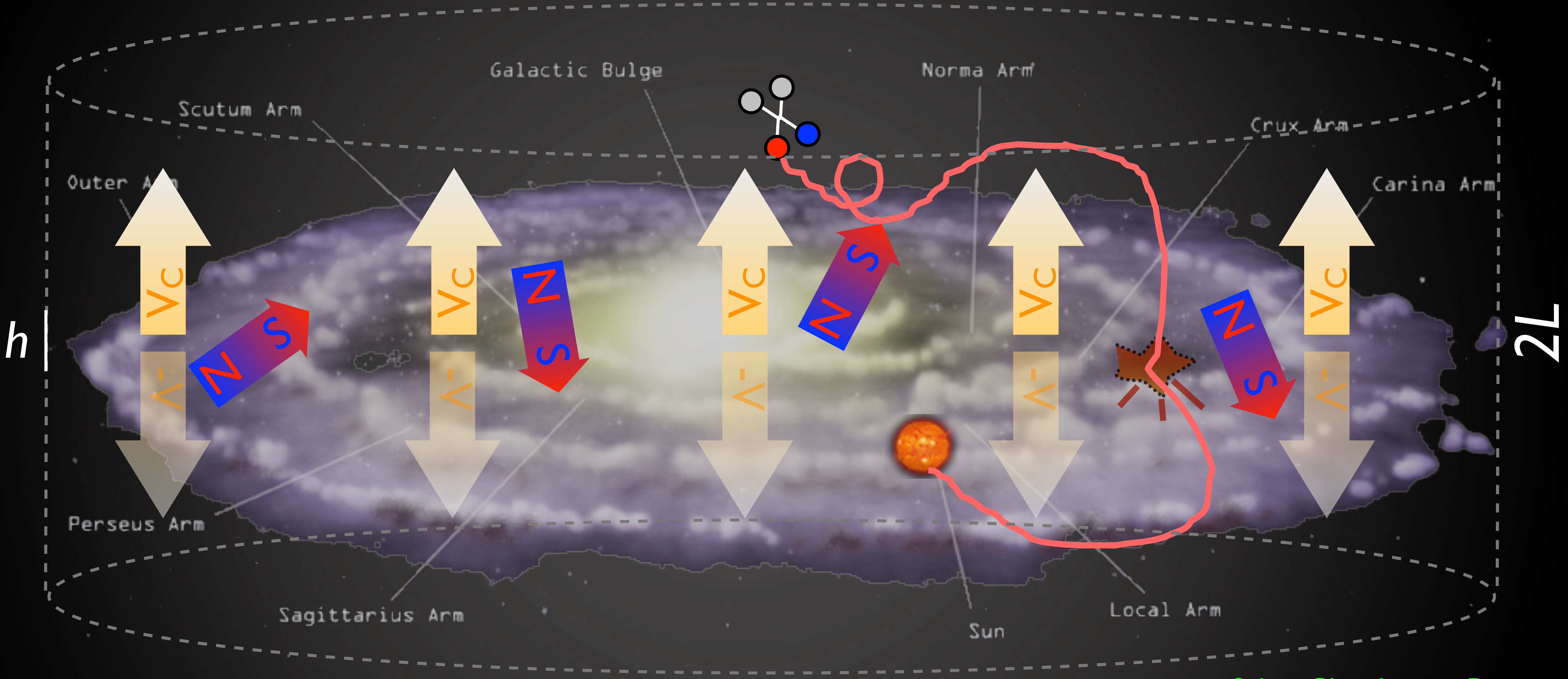


Salati, Chardonnay, Barrau,
Donato, Taillet, Fornengo, Maur
Brun... '90s, '00s

spectrum

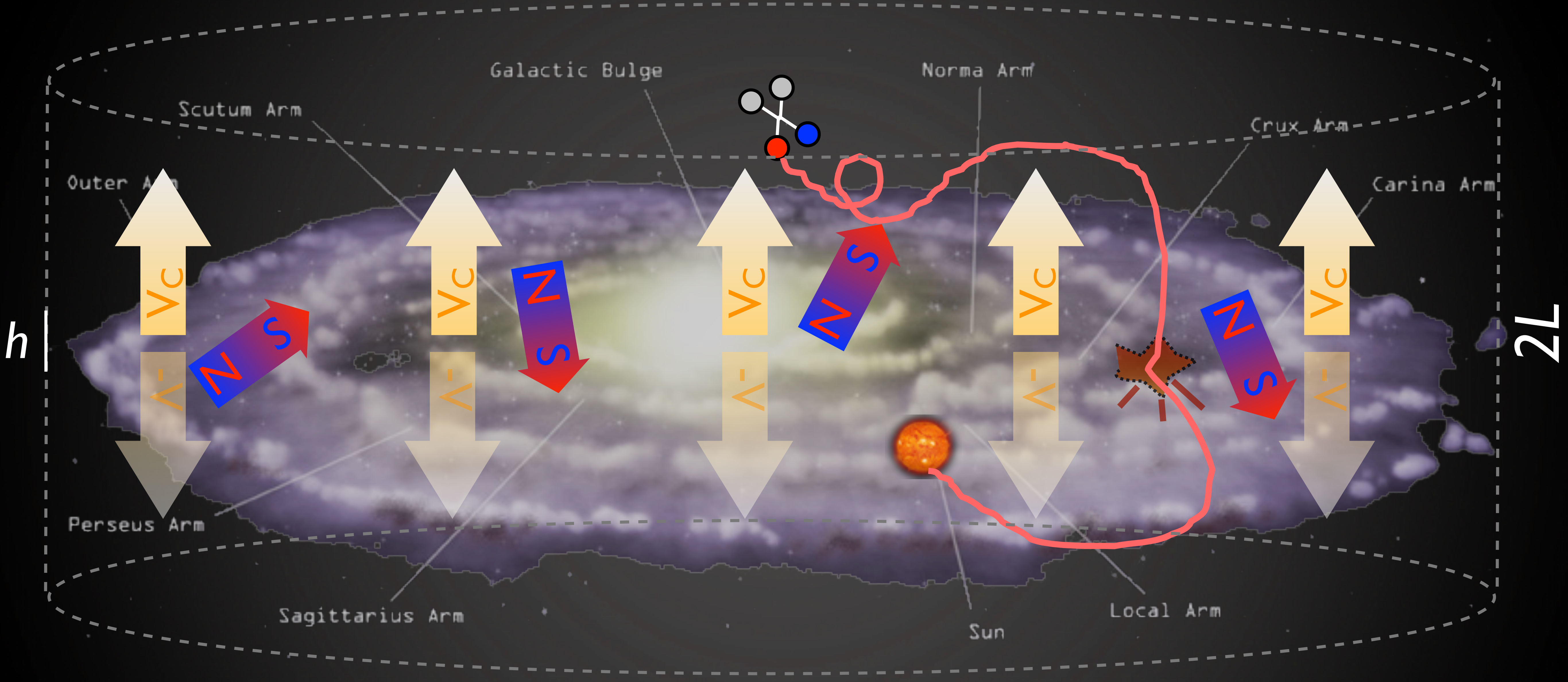
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

[uncert]

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo

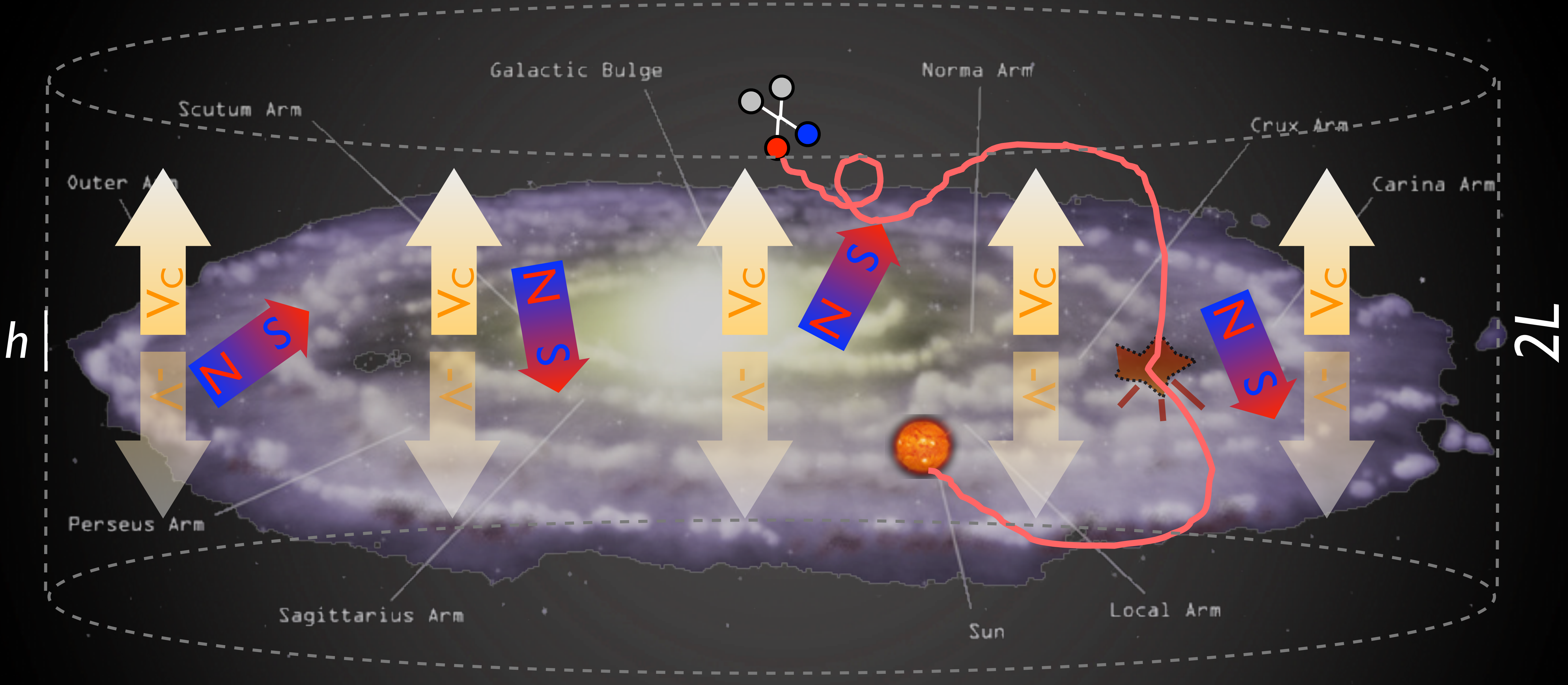


What sets the overall expected flux?

$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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astro& cosmo

particle

Indirect Detection: basics

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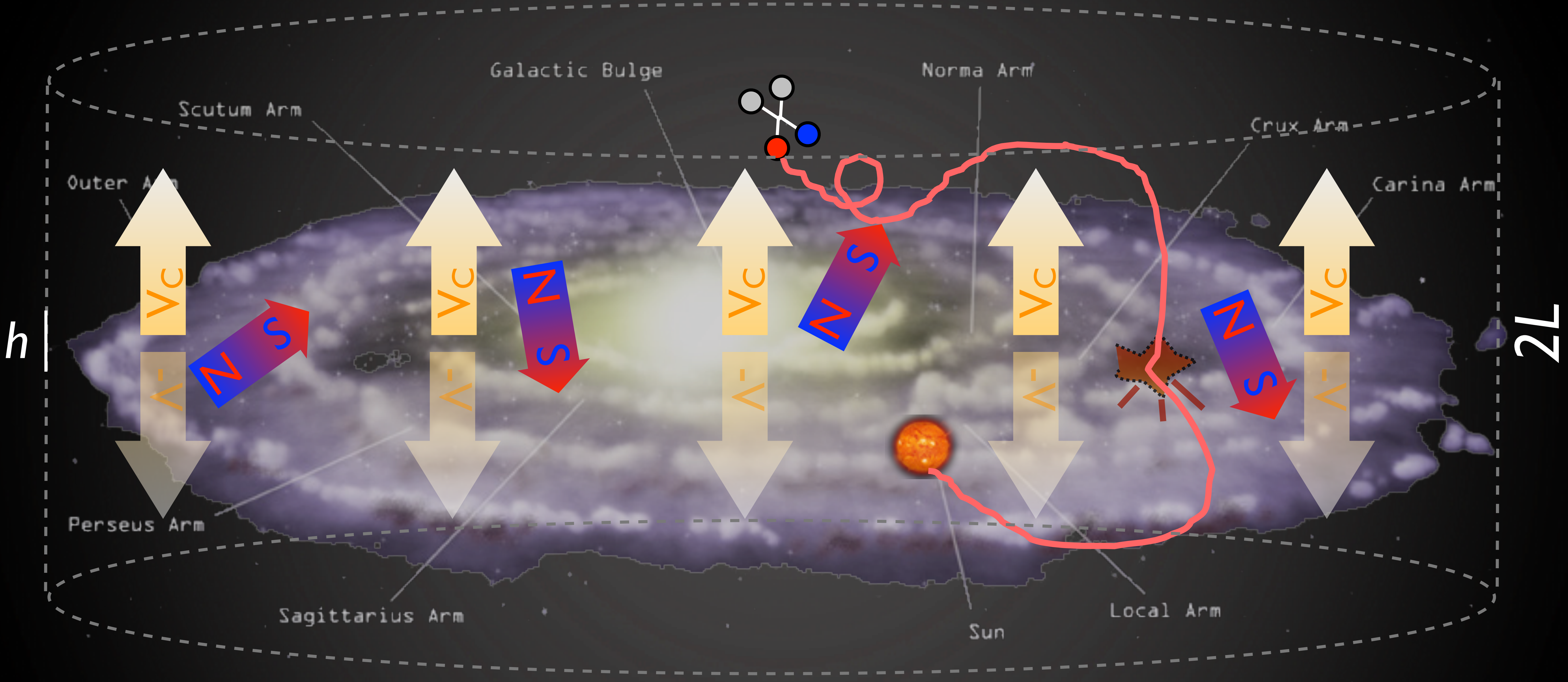


What sets the overall expected flux?

$$\text{flux} \propto n^2 \sigma_{\text{annihilation}}$$

astro& cosmo

particle

reference cross section:

$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$

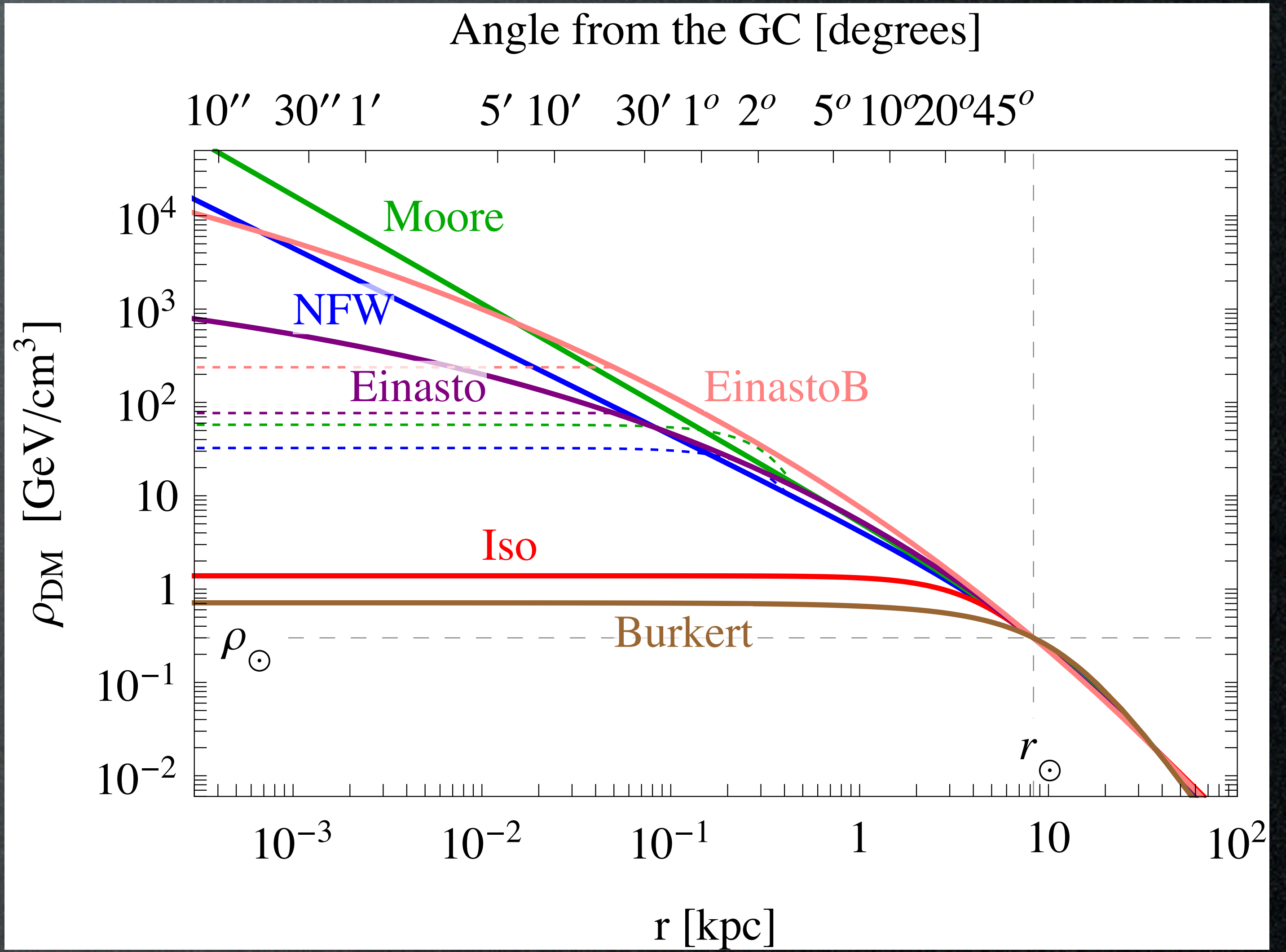
DM halo profiles

From N-body numerical simulations:

$$
\begin{aligned}
\text{NFW}: \quad \rho_{\rm NFW}(r) &= \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \\
\text{Einasto}: \quad \rho_{\rm Ein}(r) &= \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\} \\
\text{Isothermal}: \quad \rho_{\rm Iso}(r) &= \frac{\rho_s}{1+(r/r_s)^2} \\
\text{Burkert}: \quad \rho_{\rm Bur}(r) &= \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)} \\
\text{Moore}: \quad \rho_{\rm Moo}(r) &= \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}
\end{aligned}
$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

At small r: $\rho(r) \propto 1/r^\gamma$



6 profiles:

cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

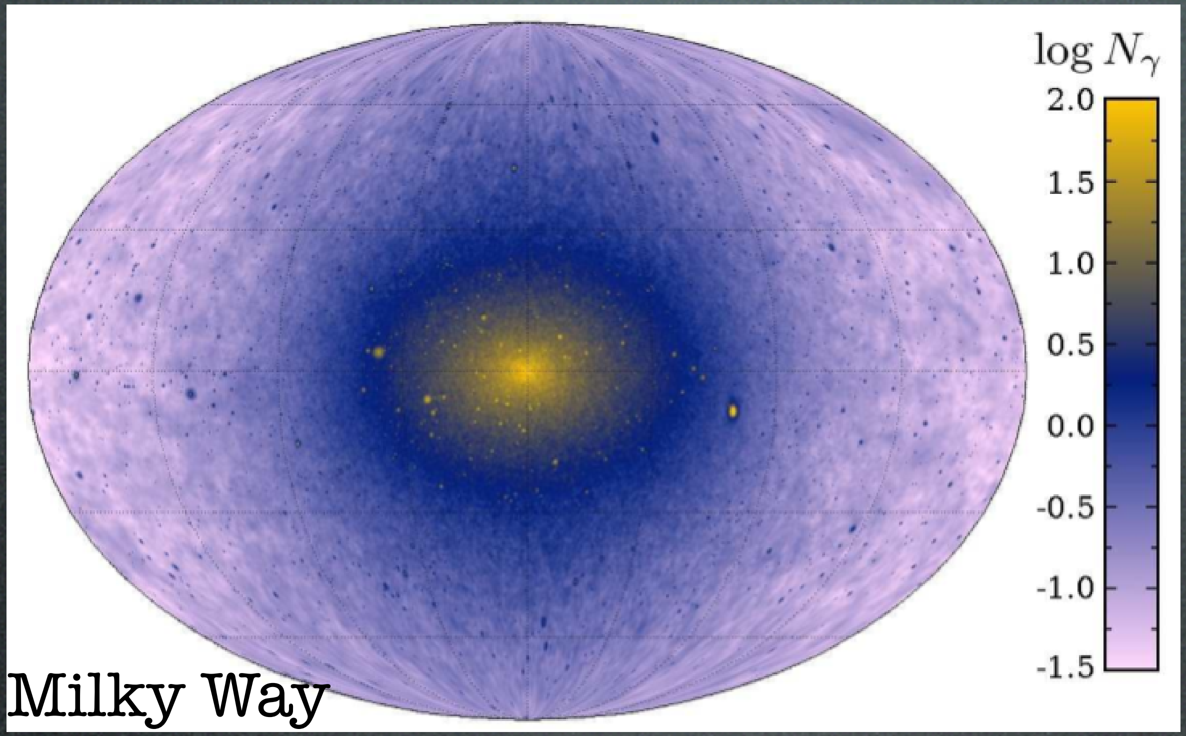
EinastoB = steepened Einasto

(effect of baryons?)

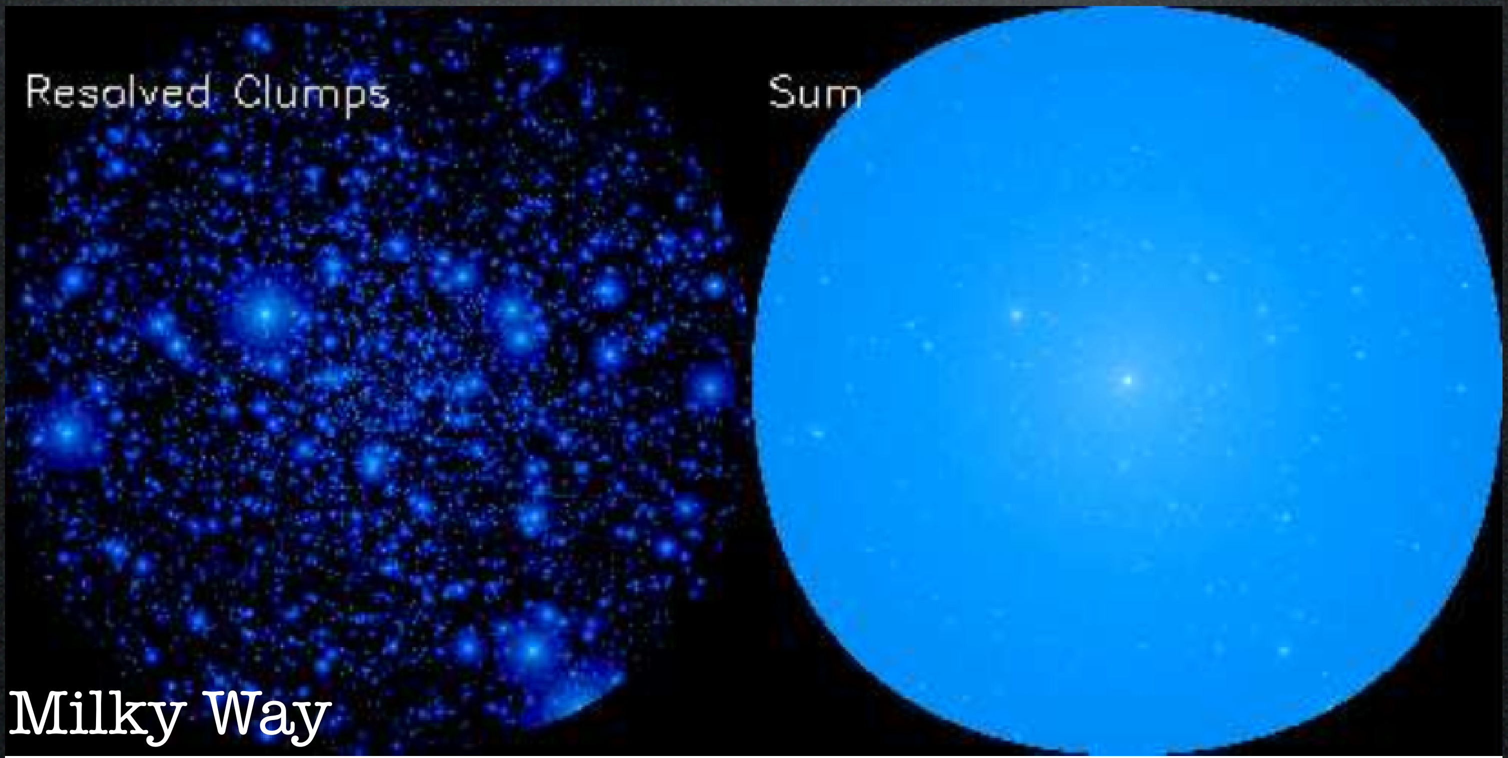
DM halo profiles

Boost Factor: local clumps in the DM halo enhance the density, boost the flux from annihilations.

For illustration:



Kuhlen, Diemand, Madau 2007



Pieri, Bertone, Branchini, MNRAS 384 (2008), 0706.2101

Propagation

Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T)\cdot\nabla^2 f + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, f\, V_{\mathrm{conv}}\right) = Q - 2h\,\delta(z)\,\Gamma_{\mathrm{ann}} f$$

diffusion

convective wind

spallations

$K(T) = K_0 \beta\,(p/\mathrm{GeV})^{\delta}$

T kinetic energy

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T kinetic energy

Model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

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Solution:

$$\Phi_{\bar p}(T,\vec r_\odot) = B\,\frac{v_{\bar p}}{4\pi}\left(\frac{\rho_\odot}{M_{\mathrm{DM}}}\right)^2 R(T)\sum_k \frac{1}{2}\langle\sigma v\rangle_k \frac{dN^k_{\bar p}}{dT}$$

Propagation

Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T)\cdot\nabla^2 f + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, f\, V_{\mathrm{conv}}\right) = Q - 2h\,\delta(z)\,\Gamma_{\mathrm{ann}}\, f$$

diffusion

convective wind

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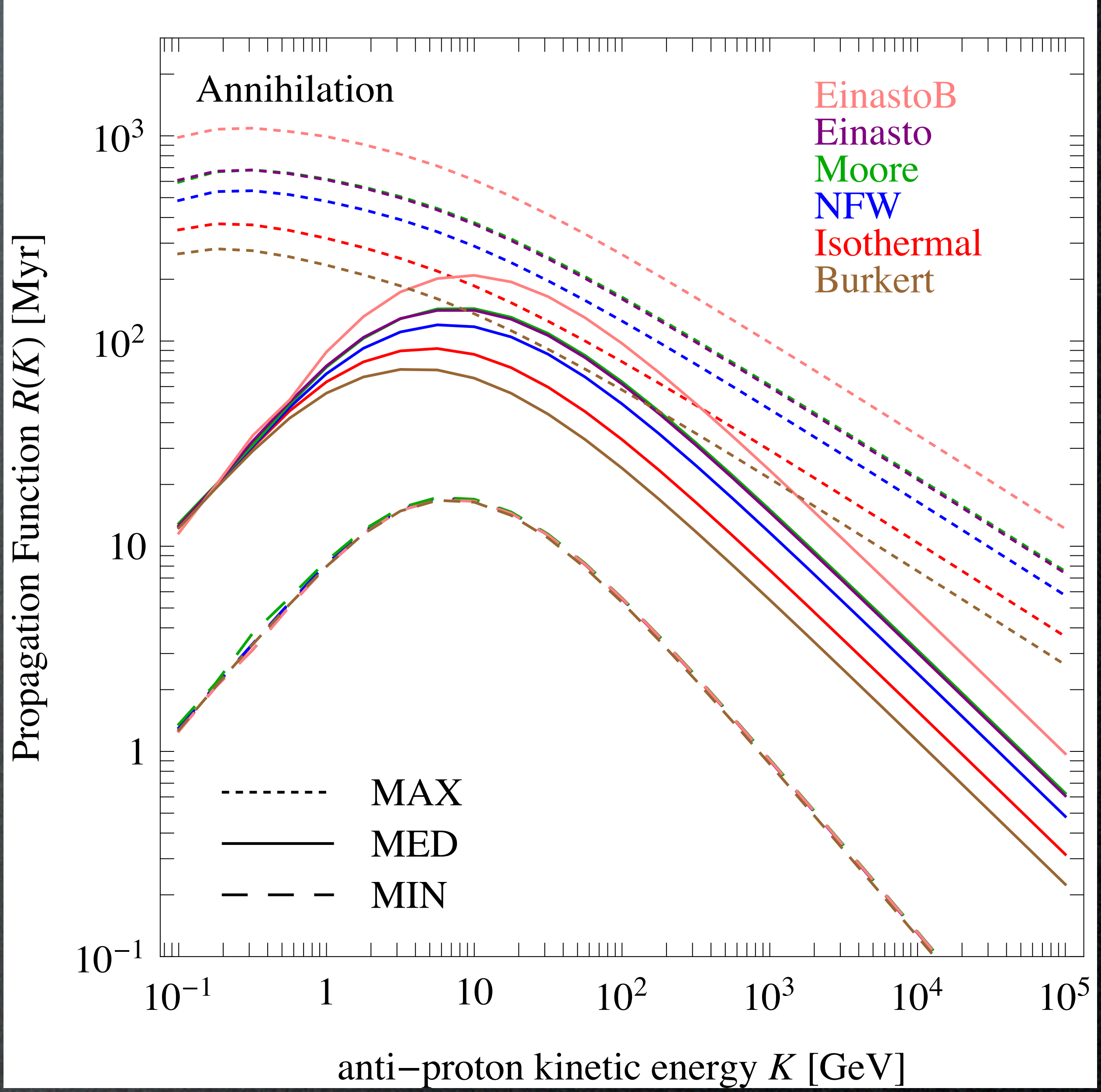
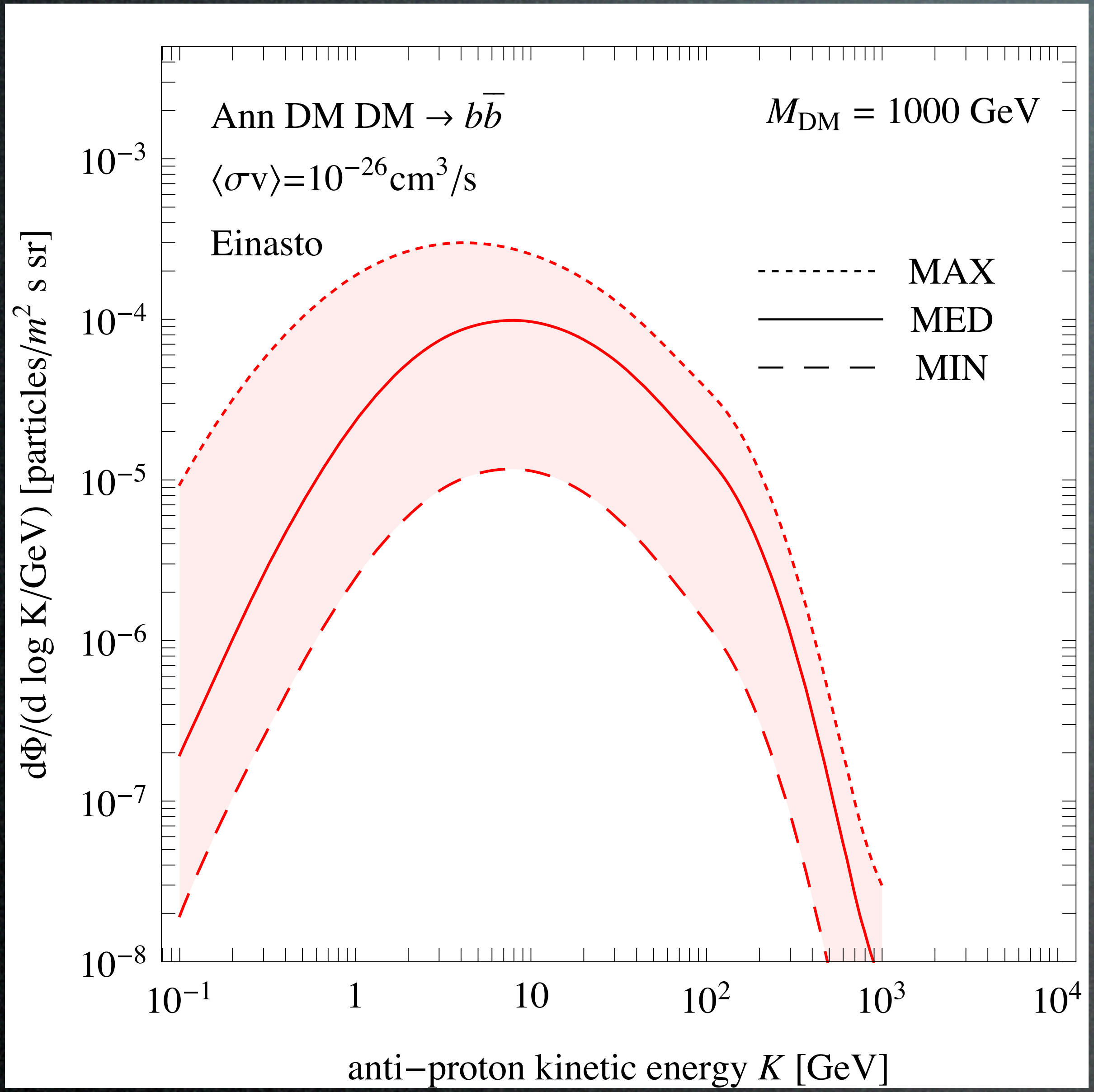


Propagated fluxes

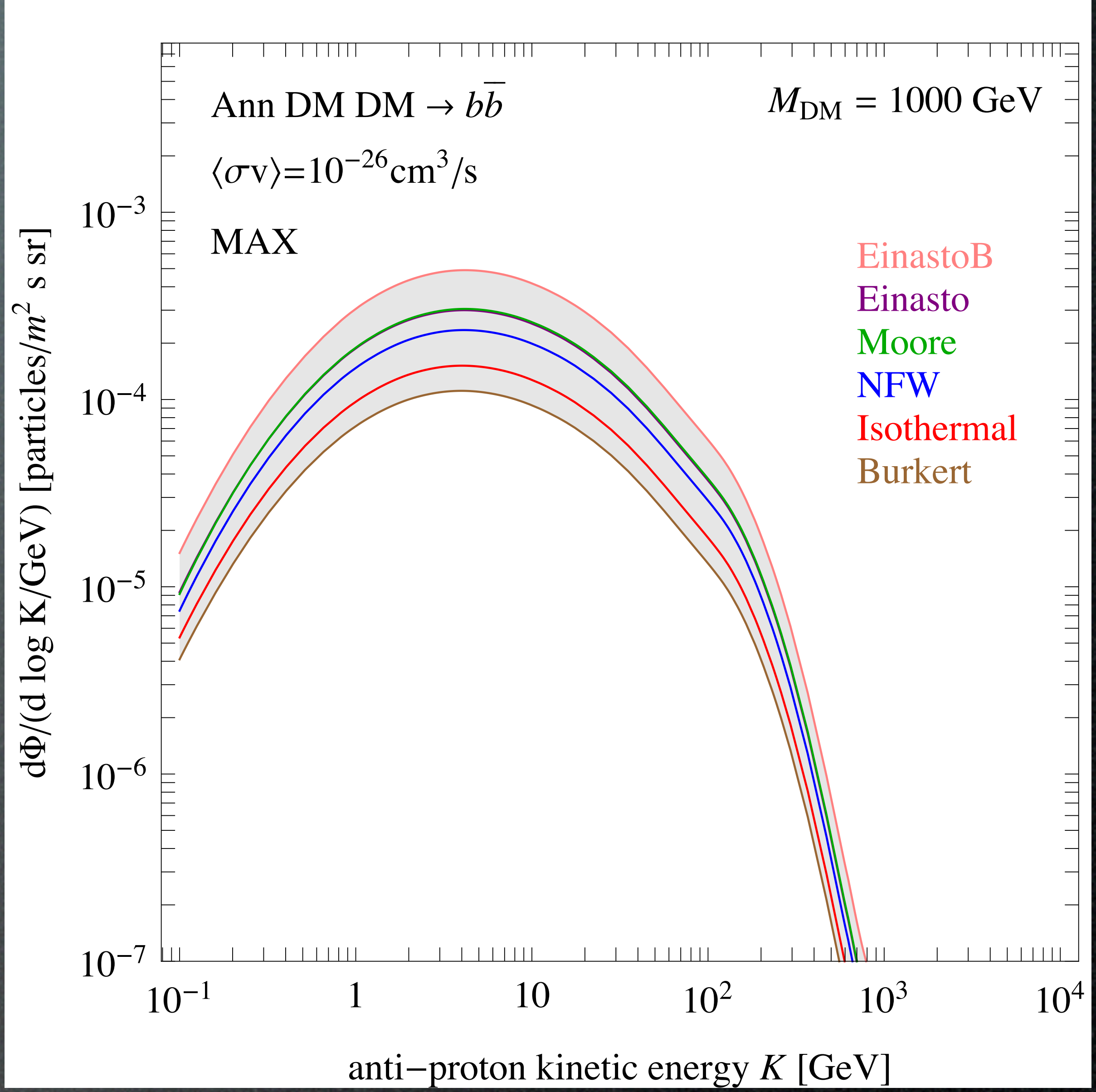
Antiprotons

Varying prop parameters



Almost 2 orders of magnitude

Varying halo profile

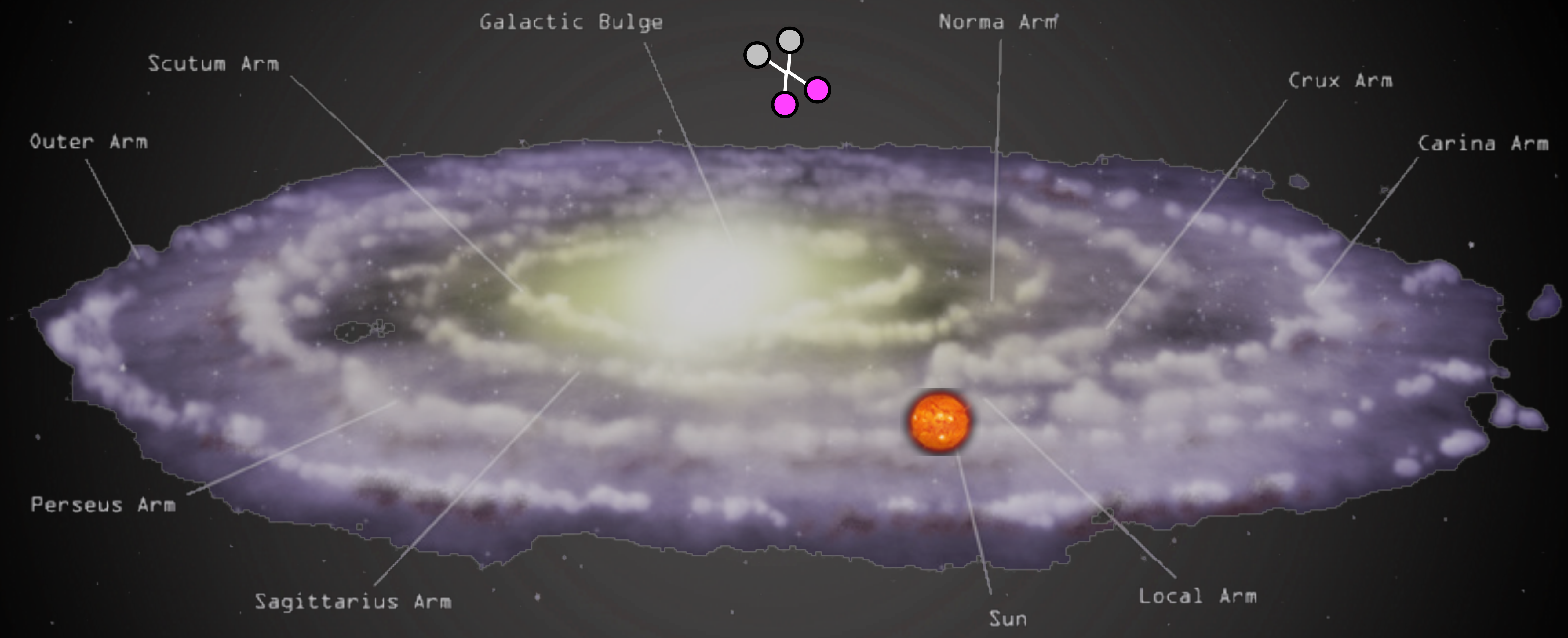


Almost 1 order of magnitude

Bottom line: Antiprotons are quite affected by propagation, but spectral shape somewhat preserved

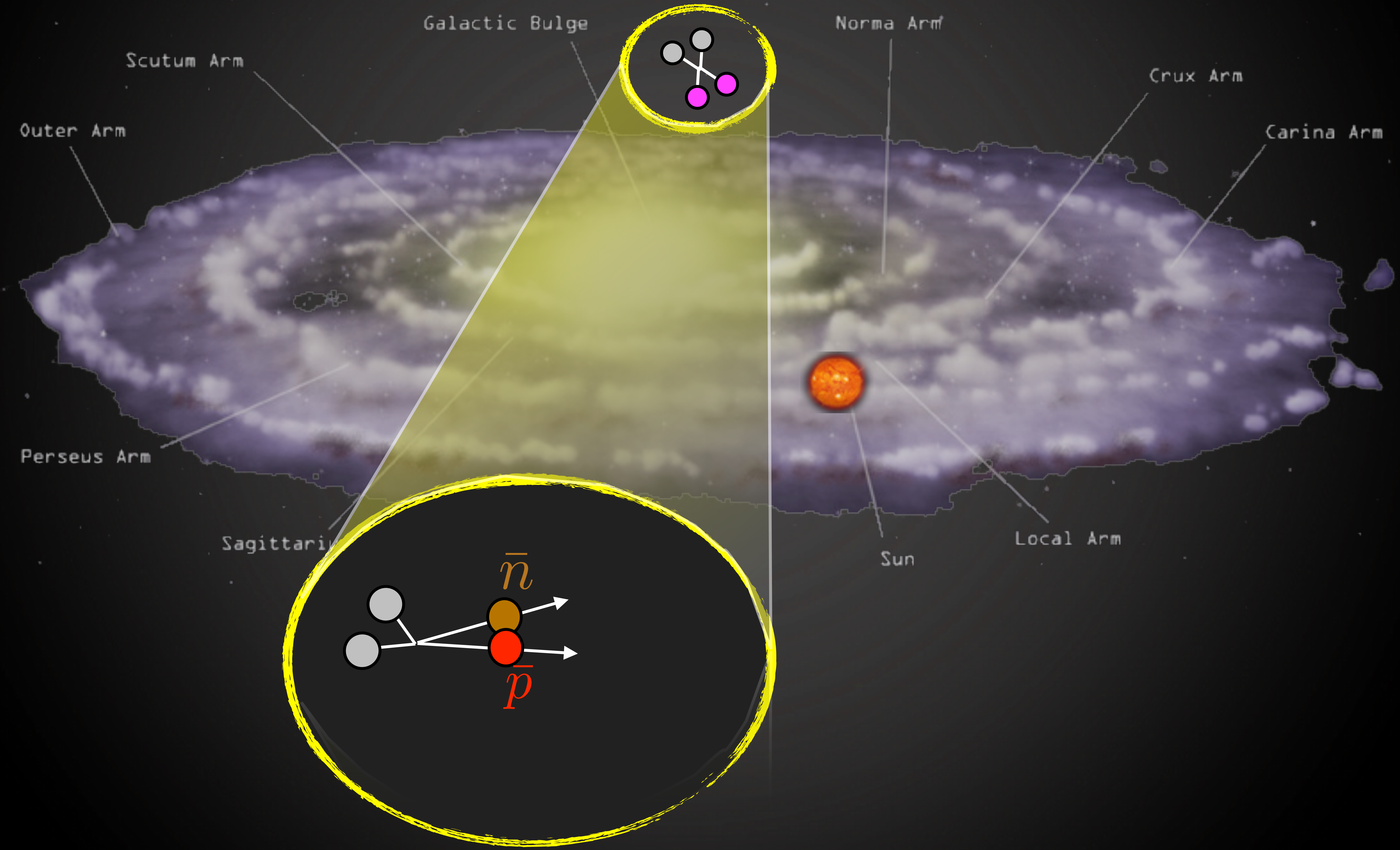
Indirect Detection

$\bar{d}$ from DM annihilations in halo



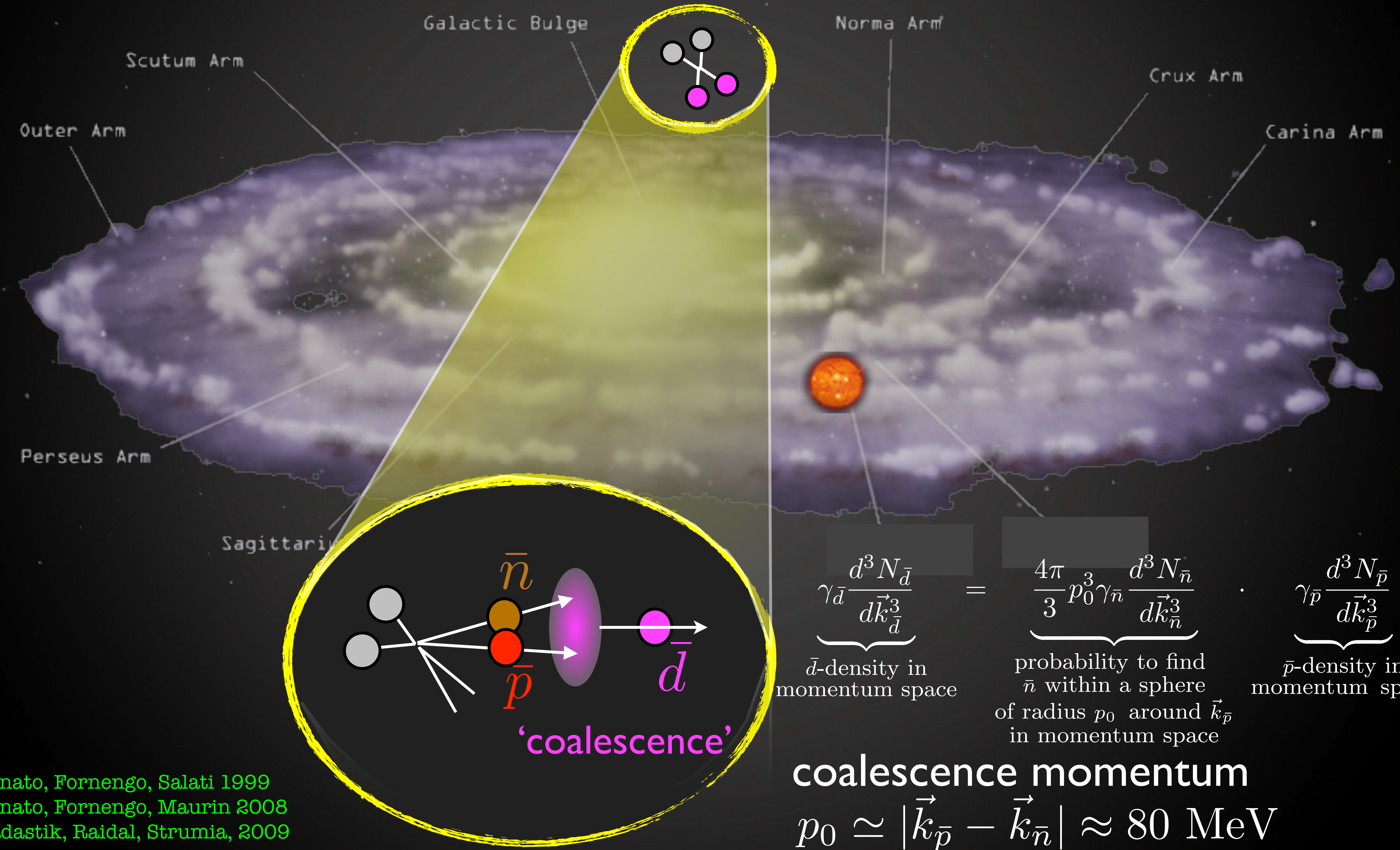
Indirect Detection

$\bar{d}$ from DM annihilations in halo



Indirect Detection

$\bar{d}$ from DM annihilations in halo



$$\underbrace{\gamma_{\bar{d}}\frac{d^3N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}}}_{\substack{\bar{d}\text{-density in}\\ \text{momentum space}}} = \underbrace{\frac{4\pi}{3}p_0^3\gamma_{\bar{n}}\frac{d^3N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}}}_{\substack{\text{probability to find}\\ \bar{n}\text{ within a sphere}\\ \text{of radius } p_0 \text{ around } \vec{k}_{\bar{p}}\\ \text{in momentum space}}} \cdot \underbrace{\gamma_{\bar{p}}\frac{d^3N_{\bar{p}}}{d\vec{k}^3_{\bar{p}}}}_{\substack{\bar{p}\text{-density in}\\ \text{momentum space}}}$$

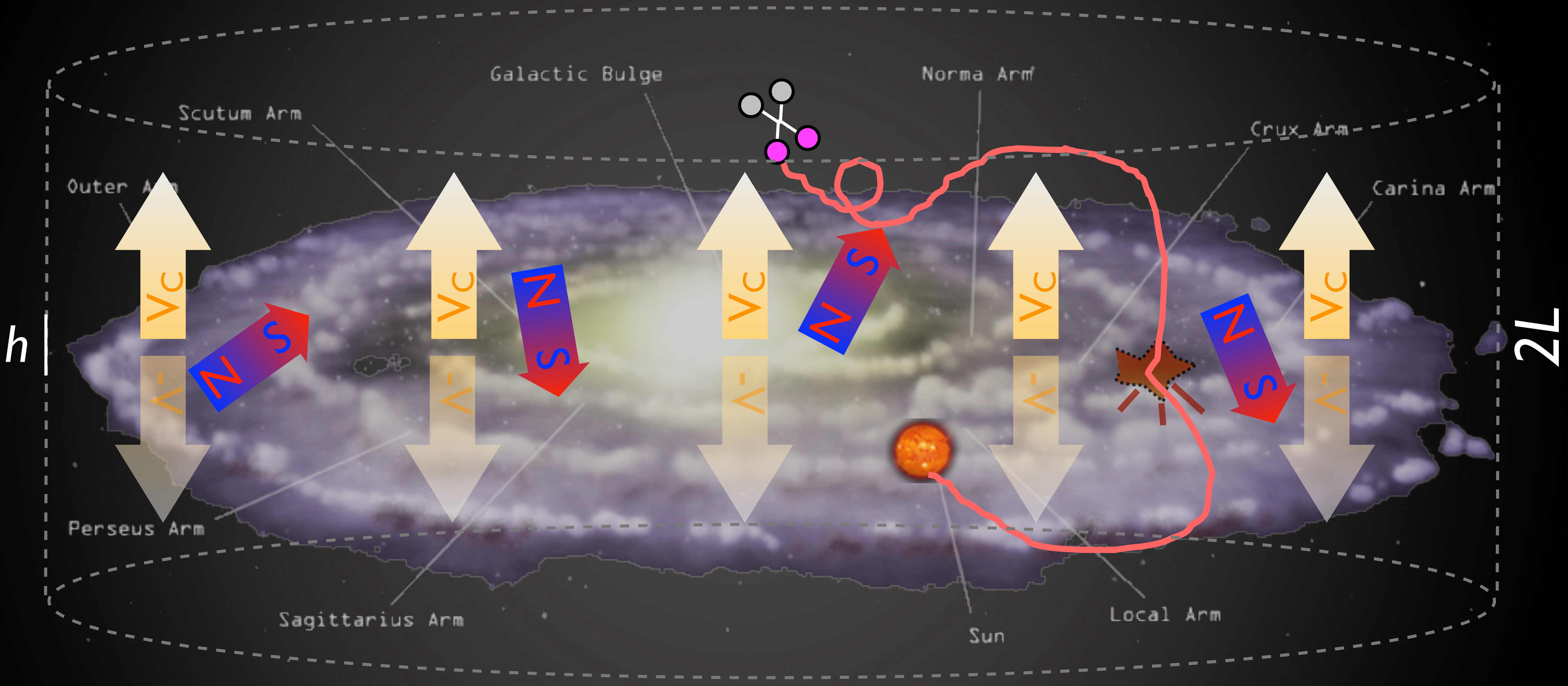
coalescence momentum

$$p_0 \simeq |\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}| \approx 80\ \text{MeV}$$

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Kadastik, Raidal, Strumia, 2009

Indirect Detection

$\bar{d}$ from DM annihilations in halo



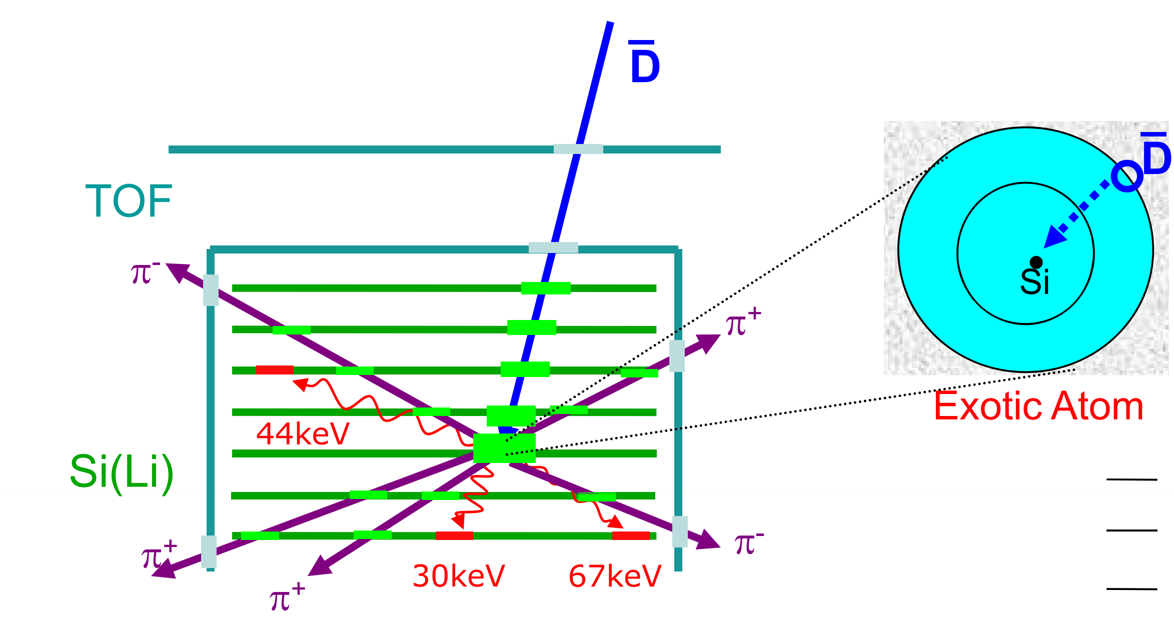
$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(V_c f) = Q_{\text{inj}} - 2h\delta(z)\Gamma_{\text{spall}} f$$

diffusion energy loss convective wind source spallations

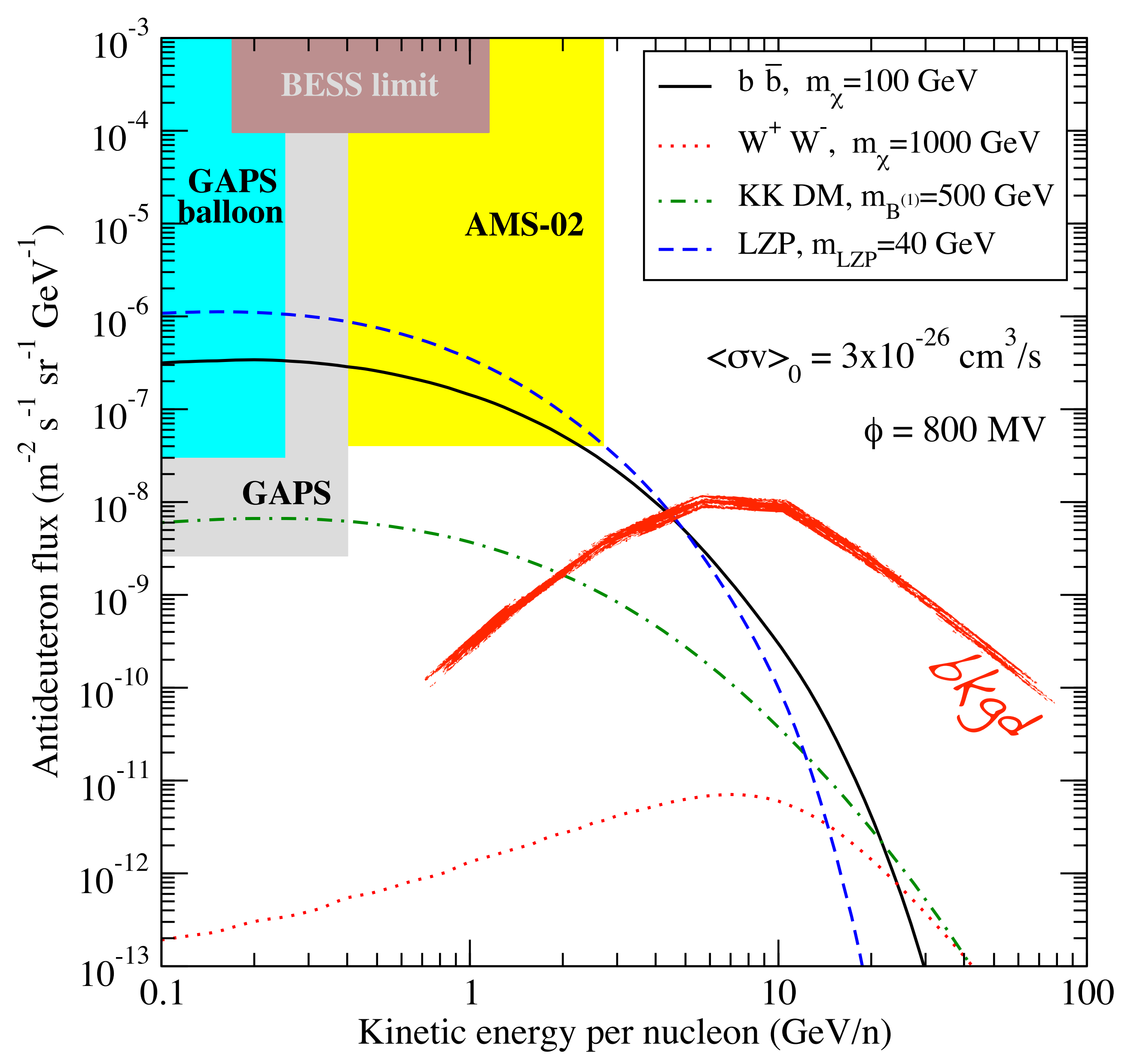
Indirect Detection

$\bar{d}$ from DM annihilations in halo

GAPS detection principle



$\bar{d}$ is slowed down,
captured (exotic atom),
annihilates w distinctive emissions



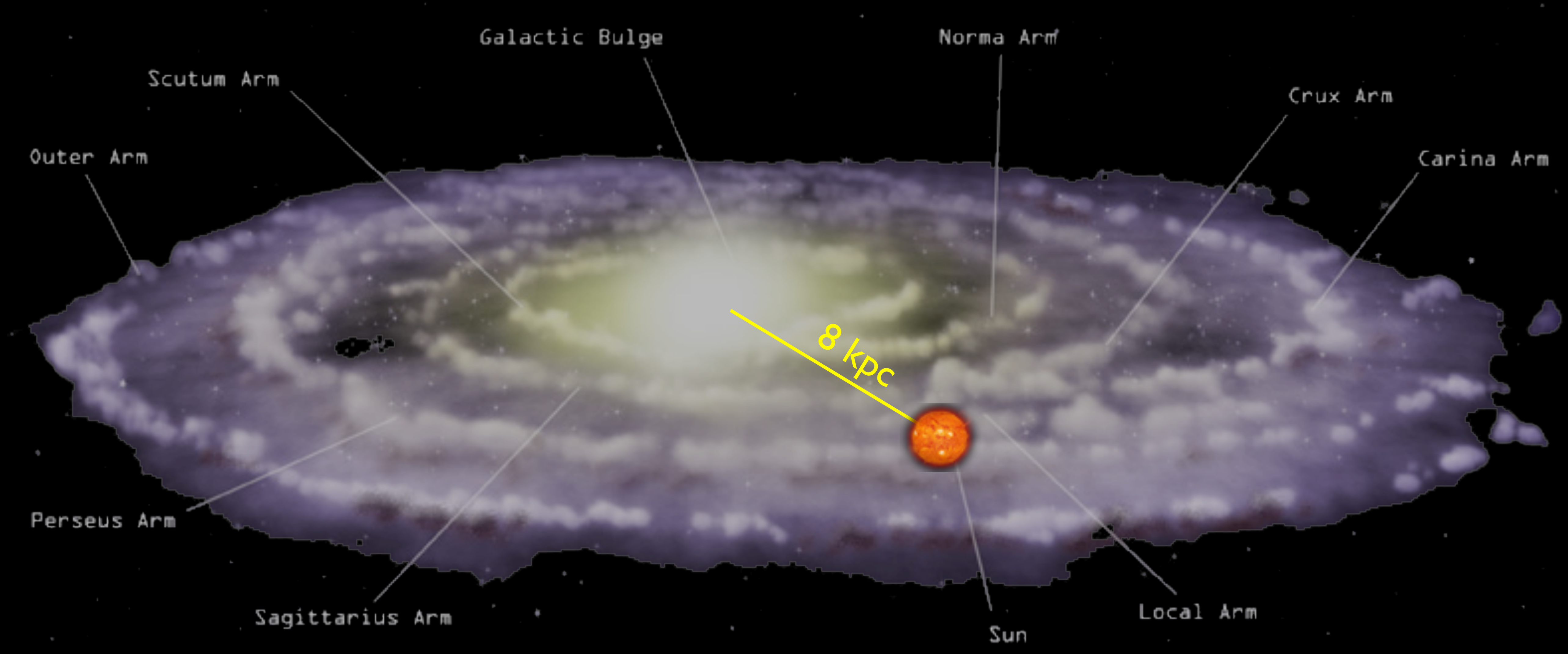
adapted from Bear, Profumo astro-ph/0510722

DM signal in the reach of GAPS and AMS-02

also: Bräuninger, Cirelli, PLB 678, 0904.1165 (for the case of large m_{DM})

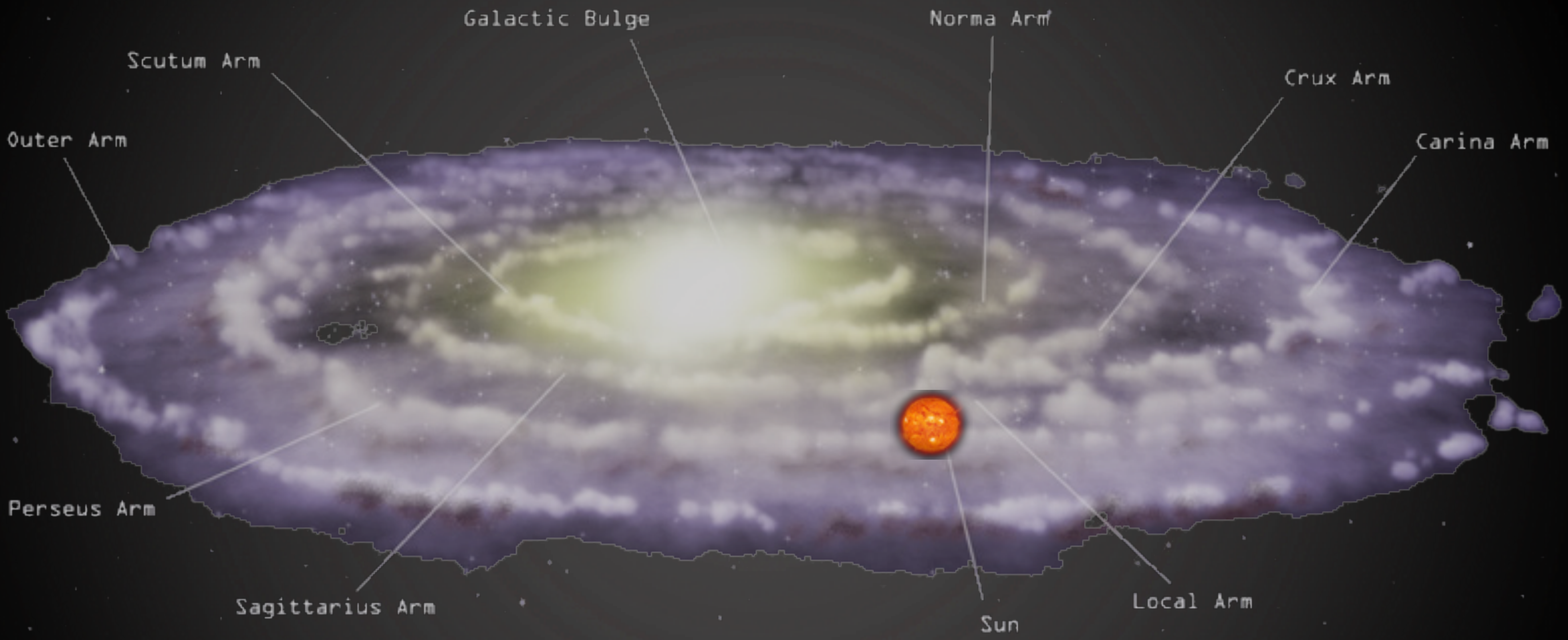
Basic picture

γ from DM annihilations in galactic center



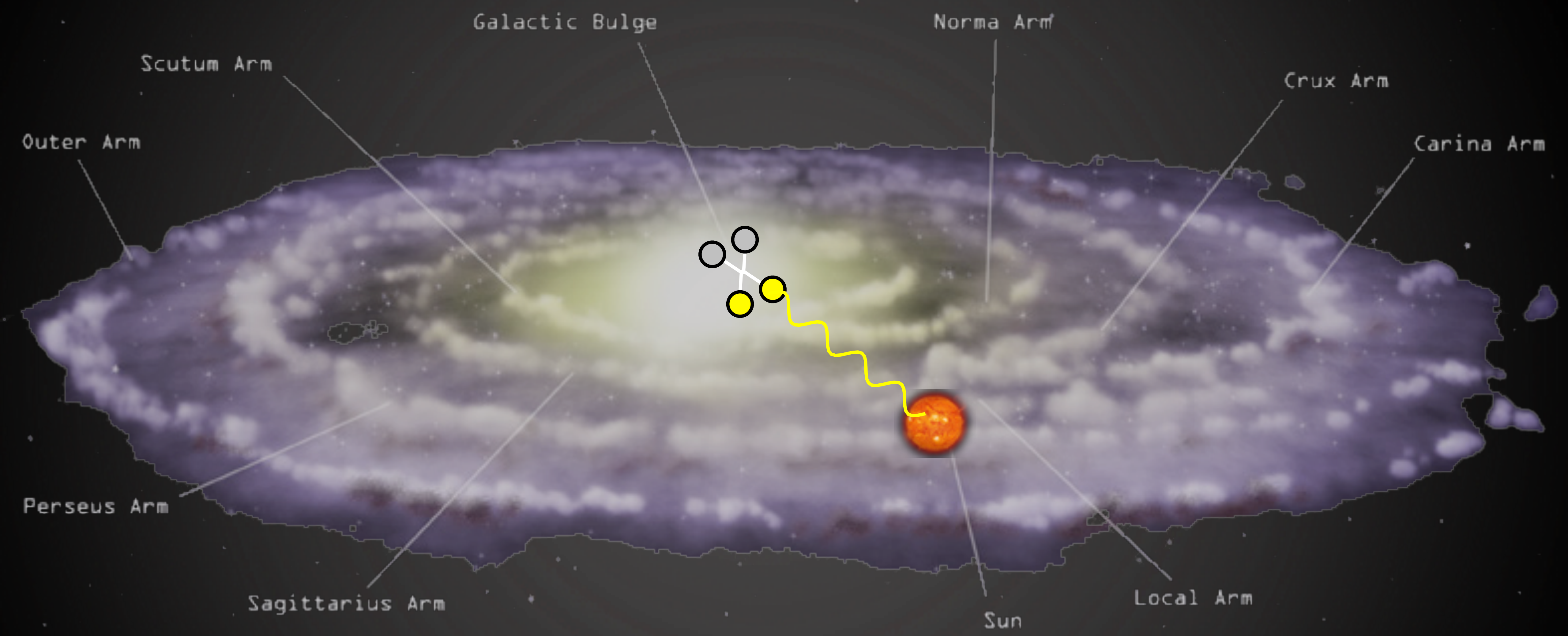
Basic picture

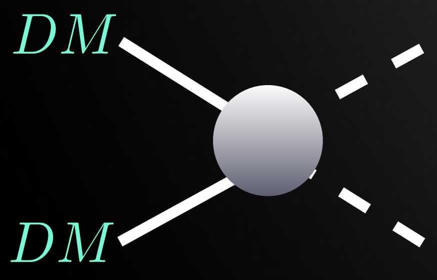
γ from DM annihilations in galactic center



Basic picture

γ from DM annihilations in galactic center





$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

How does DM produce γ-rays?

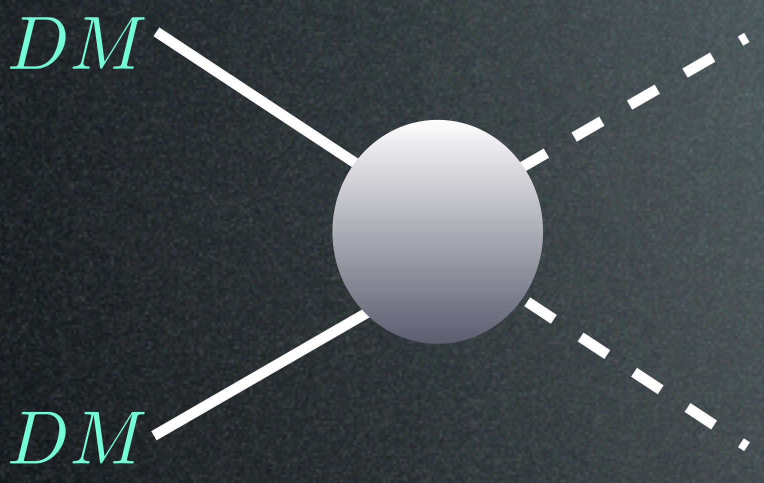
1. prompt emission

1a. continuum **1b.** line(s) **1c.** sharp features

2. secondary emission

2a. ICS **2b.** bremsstrahlung **2c.** synchrotron

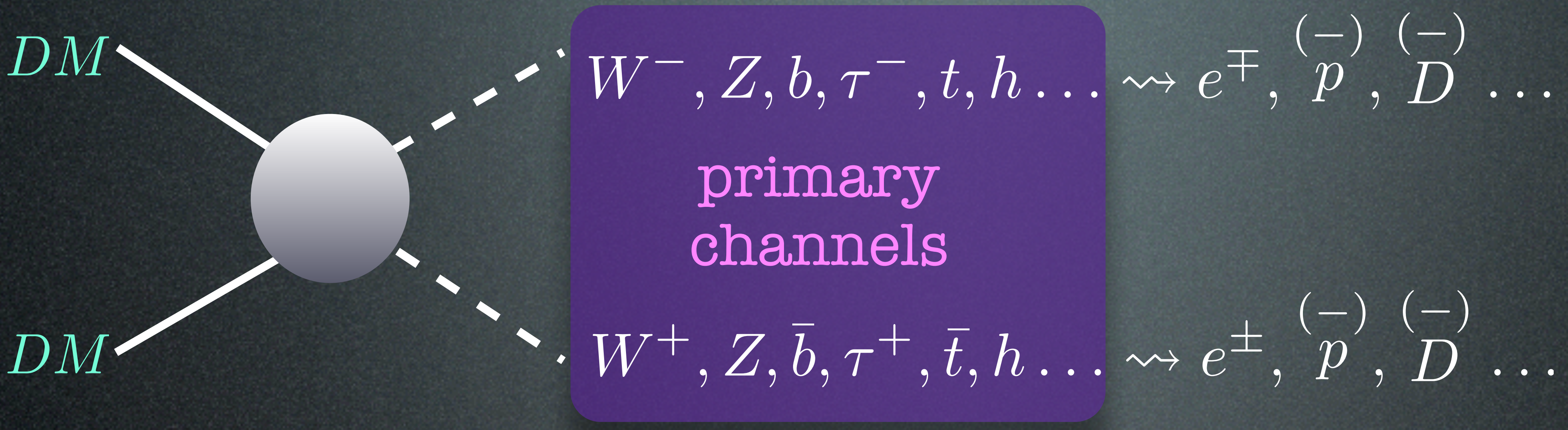
Prompt emission: continuum



$$W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \dots$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \dots$$

Prompt emission: continuum



DM

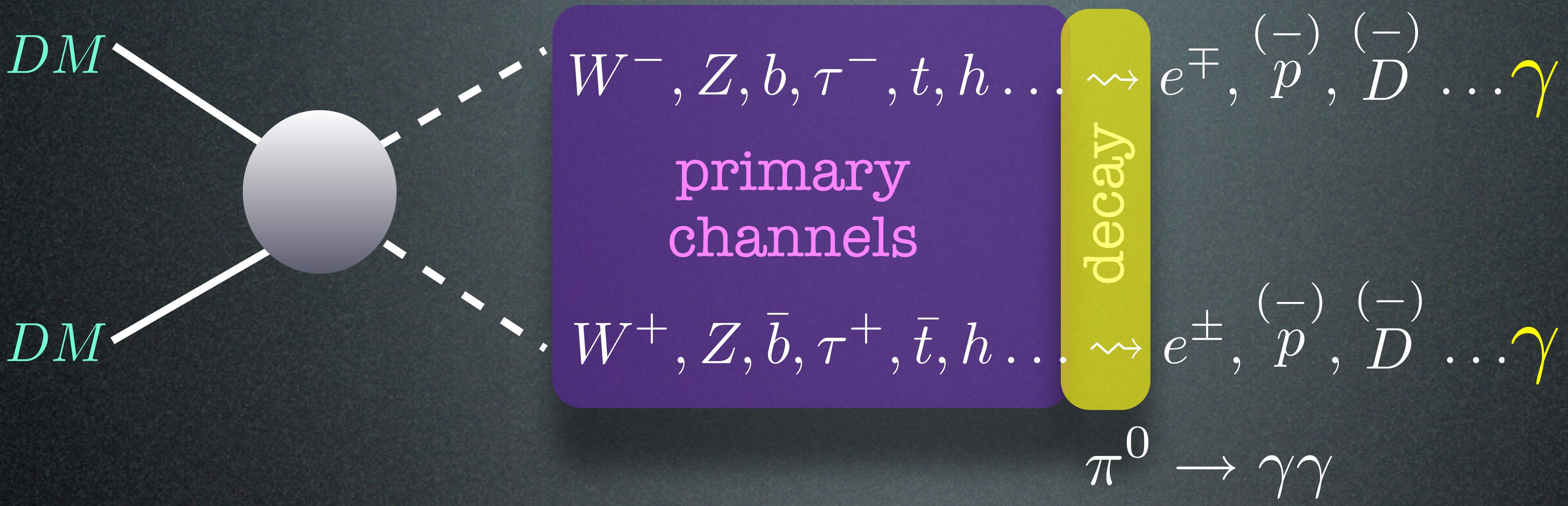
DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

primary
channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

Prompt emission: continuum



DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$

primary channels

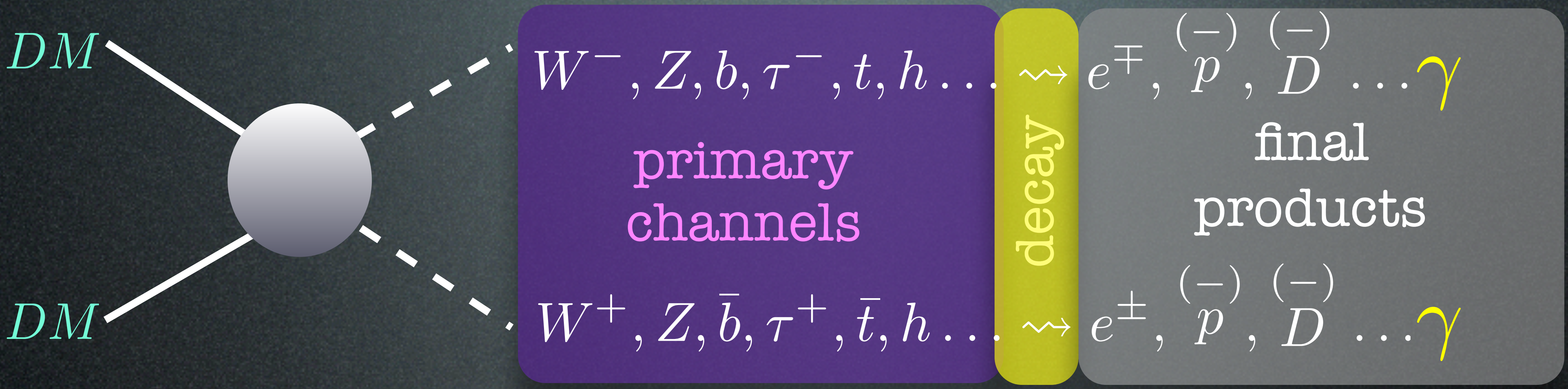
decay

DM

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$

$\pi^0 \longrightarrow \gamma\gamma$

Prompt emission: continuum



DM

DM

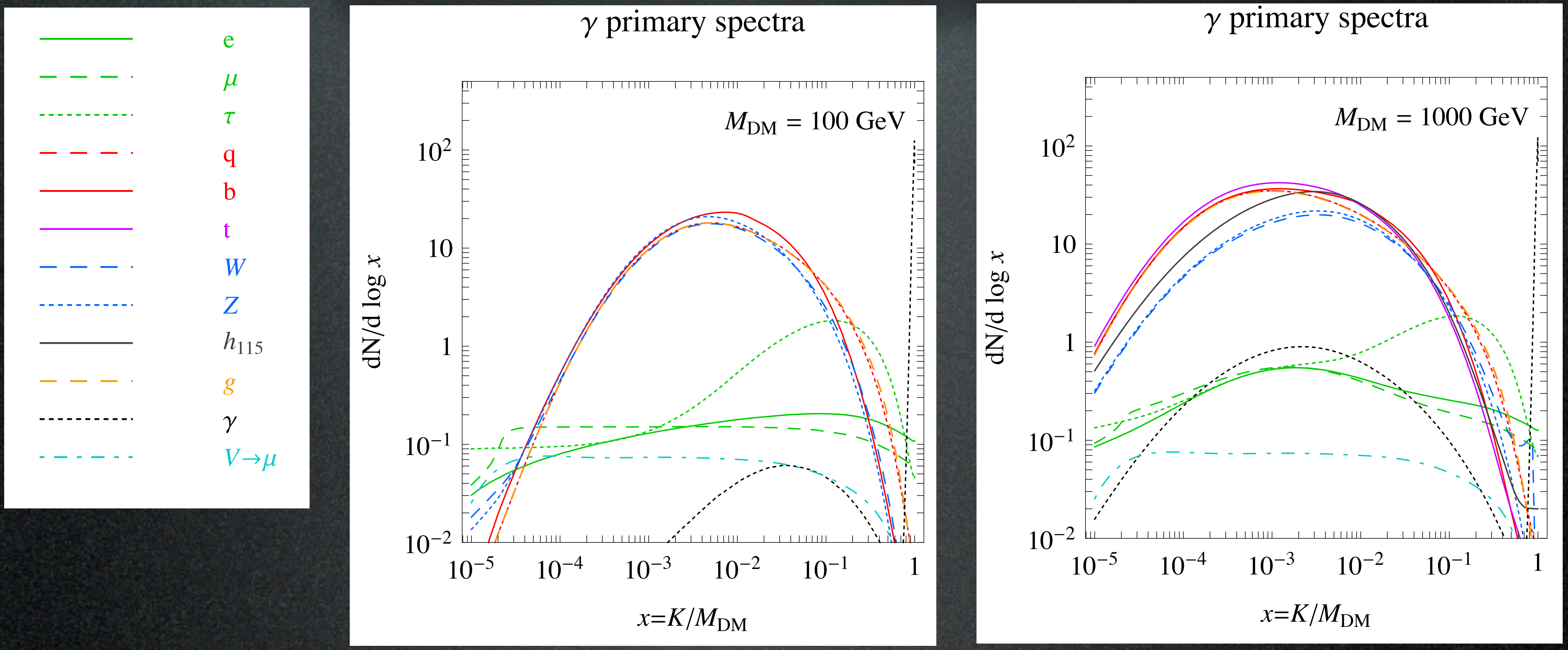
$W^-, Z, b, \tau^-, t, h\ldots$ $\rightsquigarrow$ $e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$

primary channels

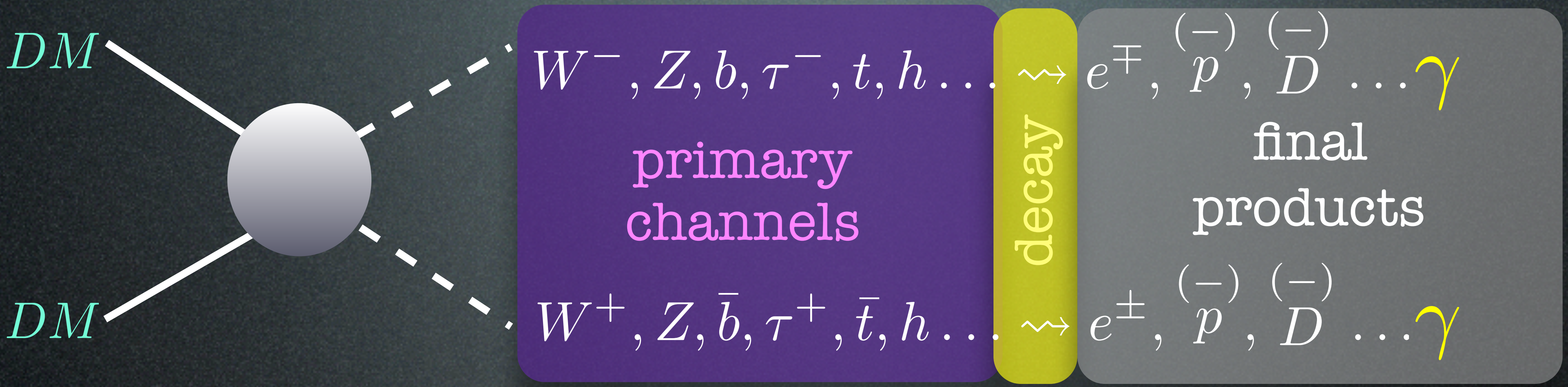
decay

final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h\ldots$ $\rightsquigarrow$ $e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$



Prompt emission: continuum



DM

DM

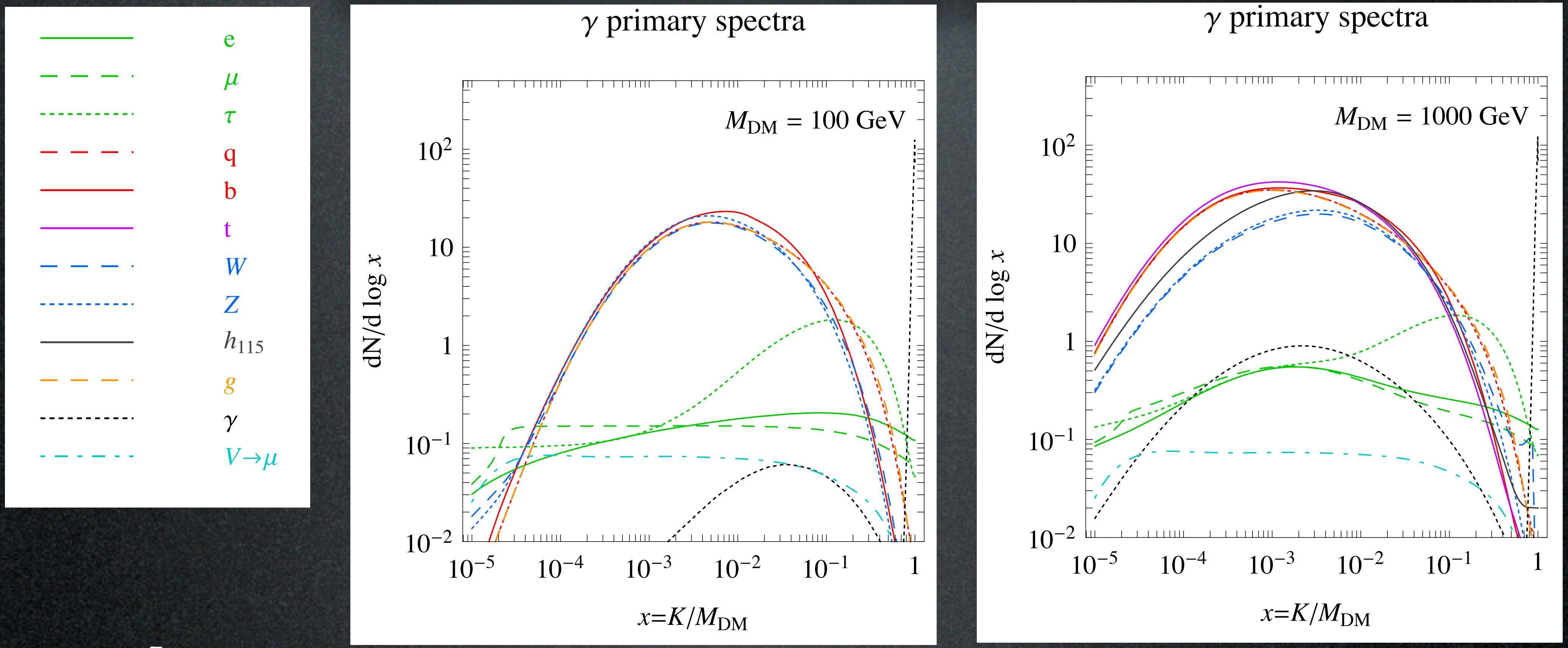
$W^-, Z, b, \tau^-, t, h \ldots$ $\rightsquigarrow$ $e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$

primary channels

decay

final products

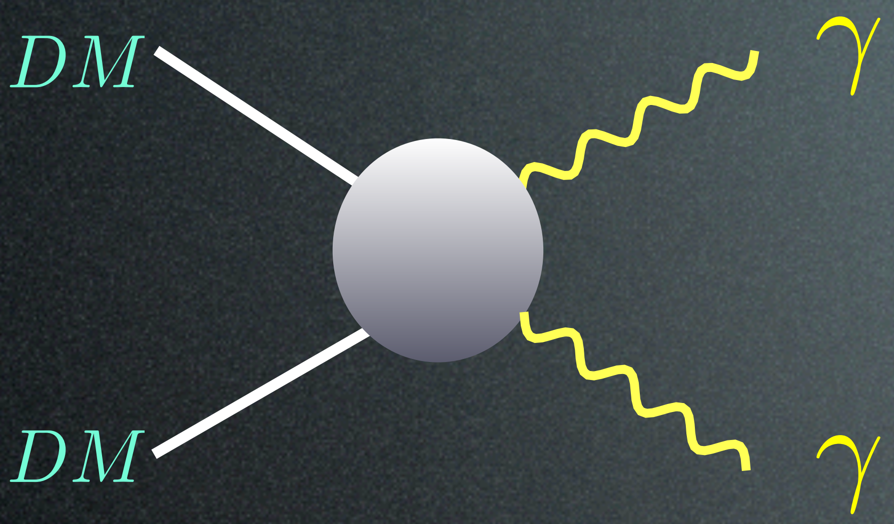
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$ $\rightsquigarrow$ $e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$



So what are the particle physics parameters?

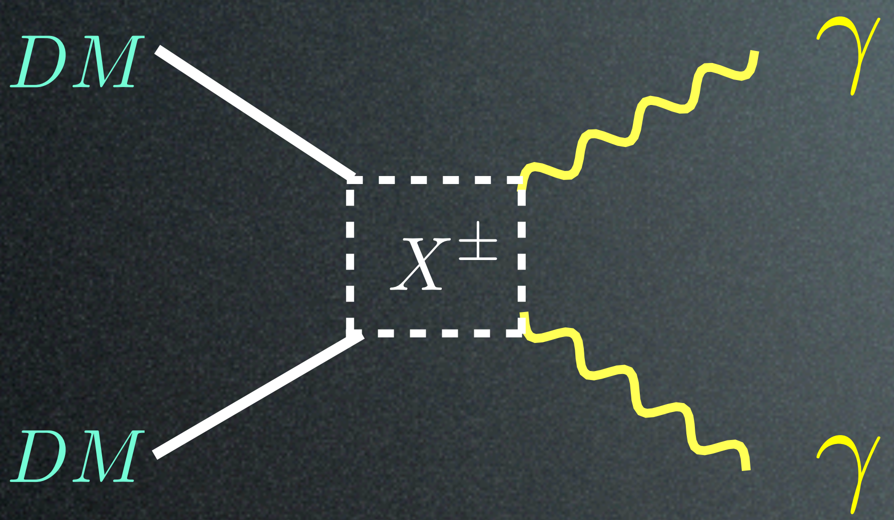
1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section $\sigma_{\rm ann}$

Prompt emission: line(s)



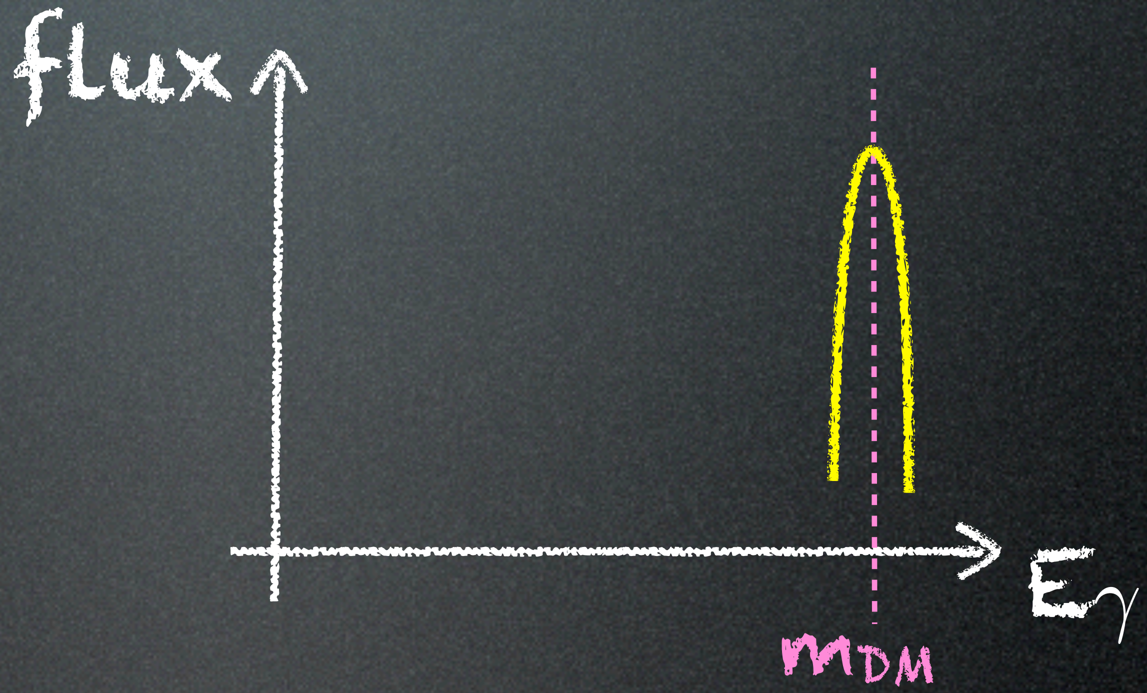
primary
channels

Prompt emission: line(s)



primary channels

$$E_\gamma = m_{\rm DM}$$



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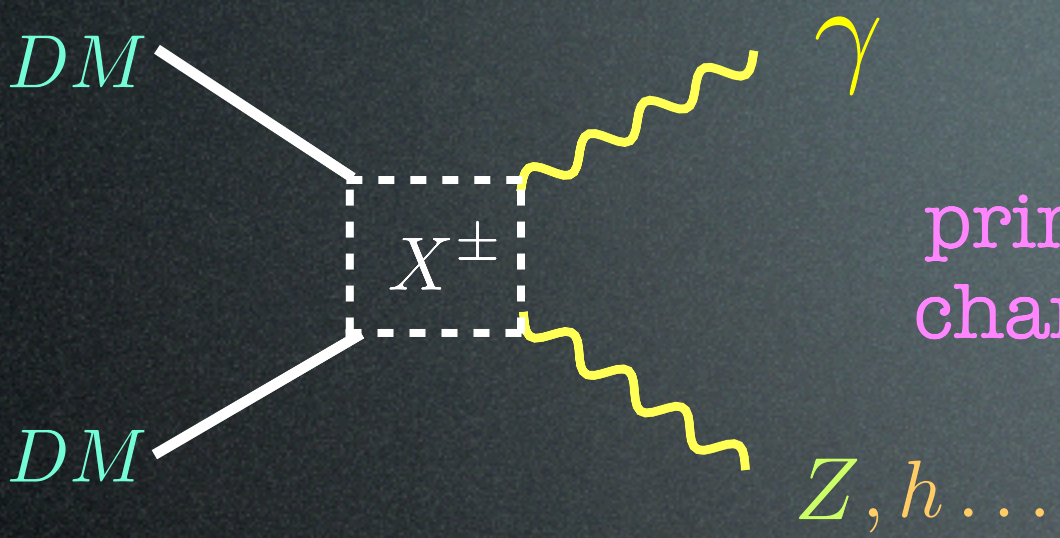
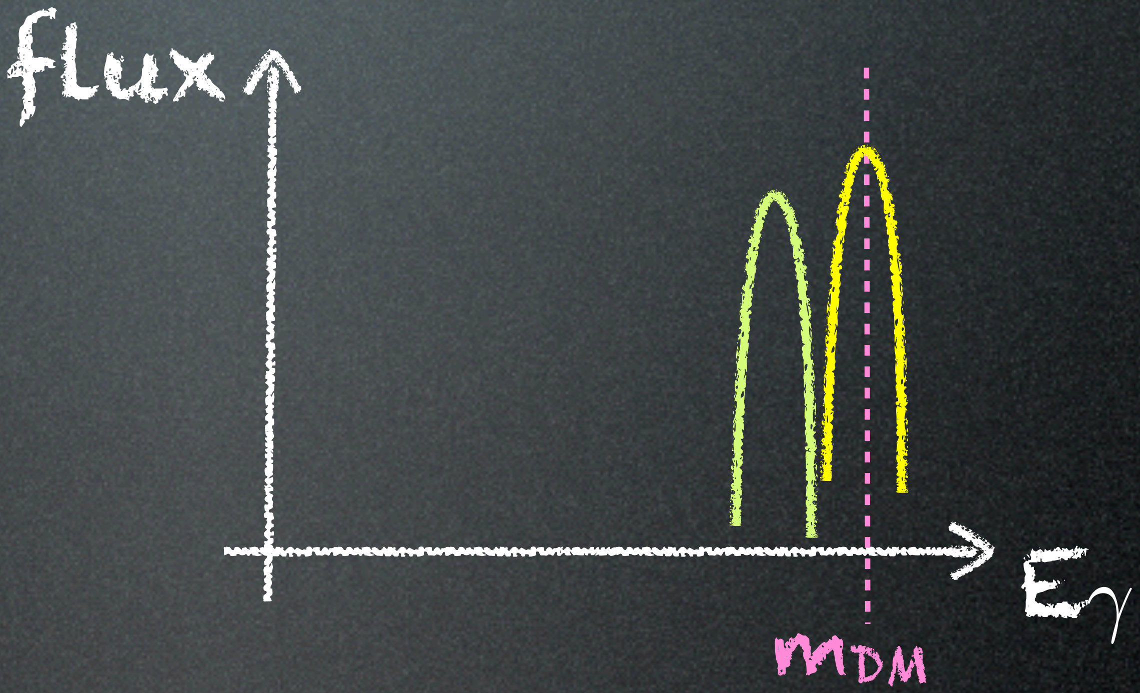


primary channels

$$E_\gamma = m_{\rm DM}$$

$$E_\gamma = m_{\rm DM}\left(1 - \frac{m_Z^2}{4\, m_{\rm DM}^2}\right)$$



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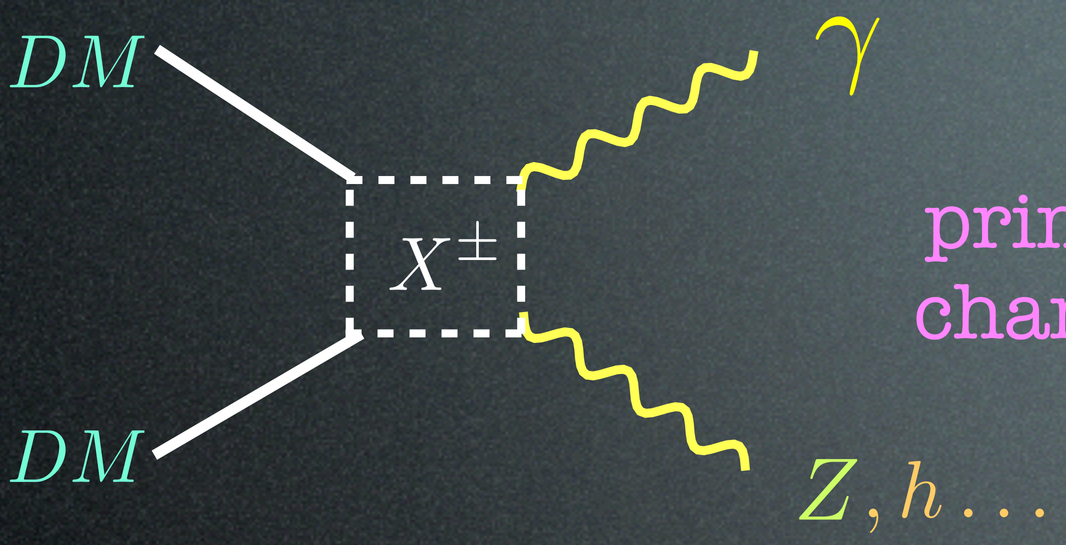

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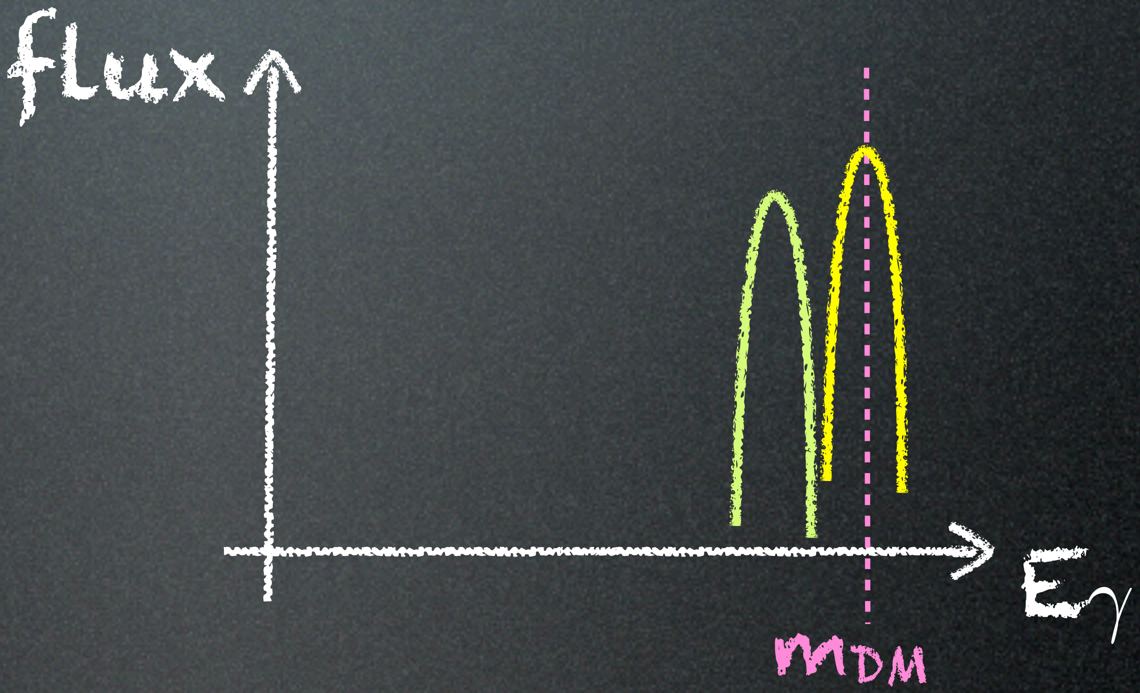

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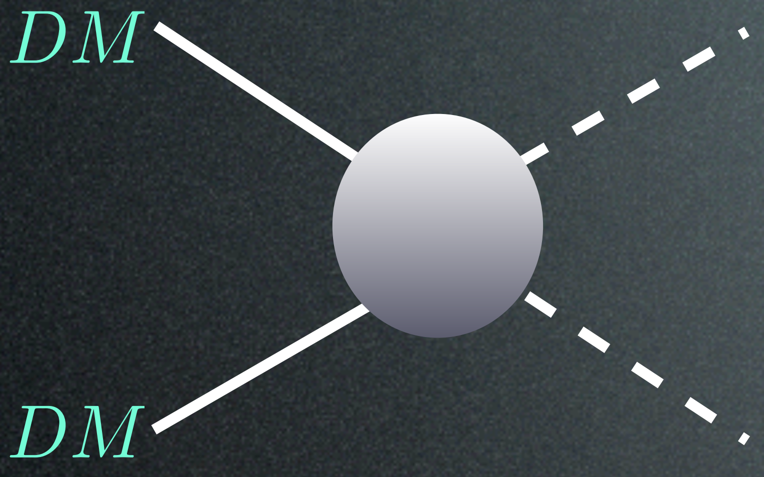
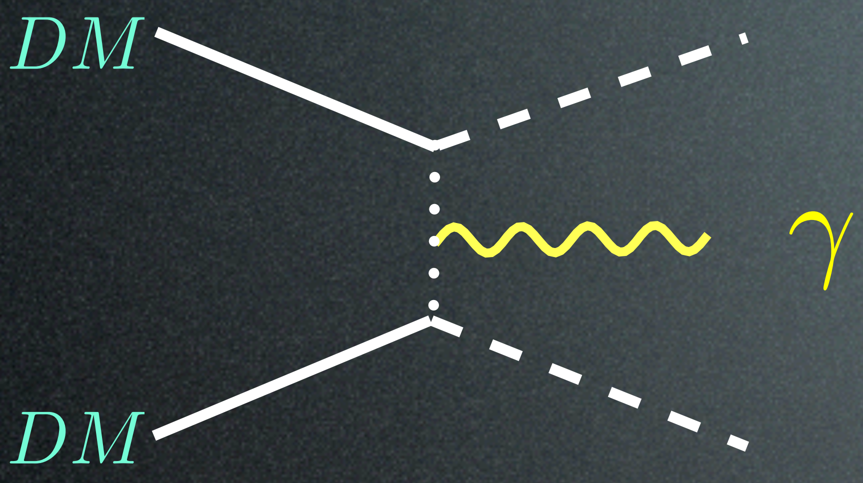
Prompt emission: sharp features



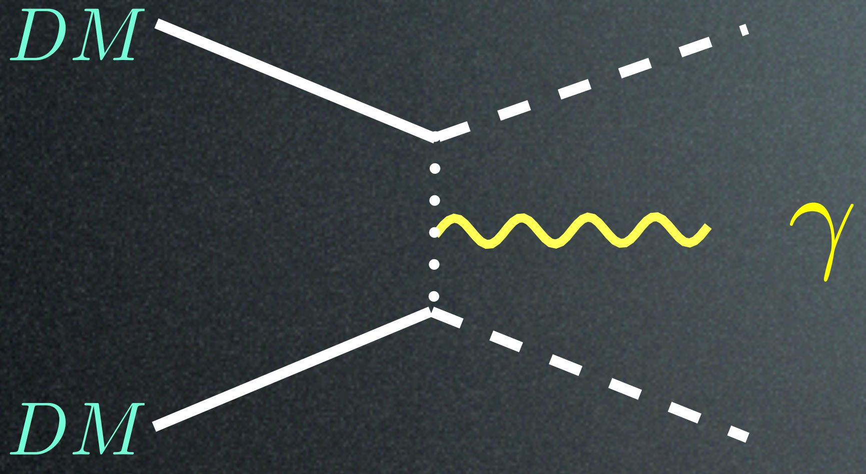
Prompt emission: sharp features



Internal Bremsstrahlung

Bergström 1989

Prompt emission: sharp features



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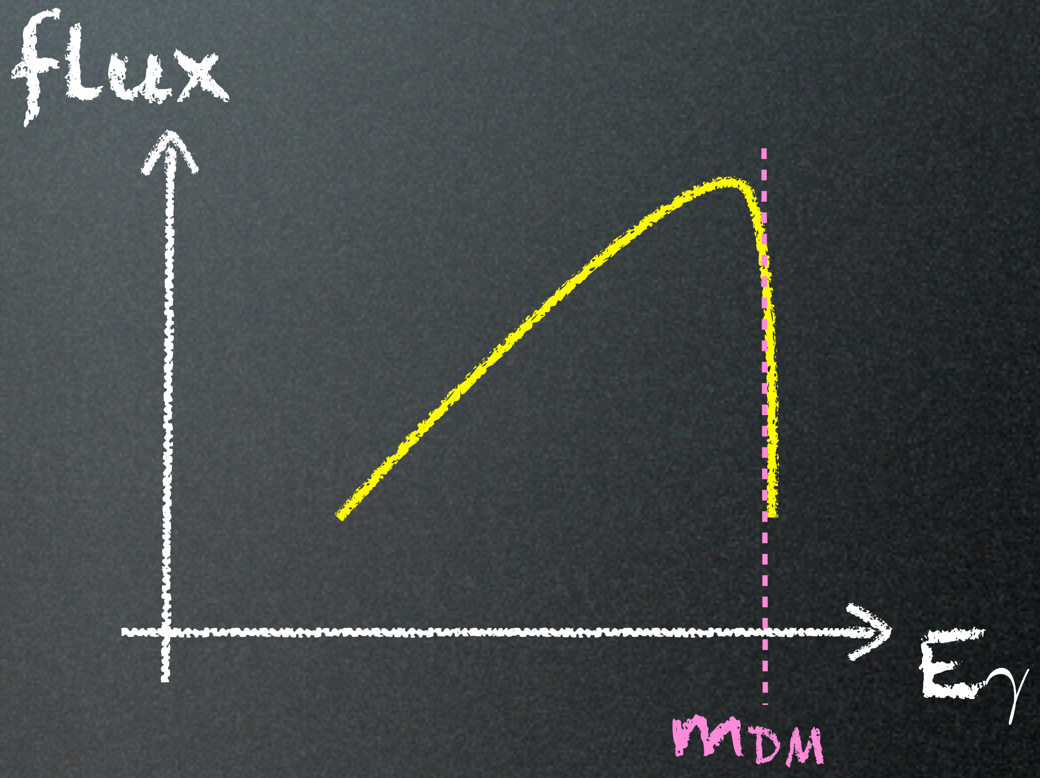
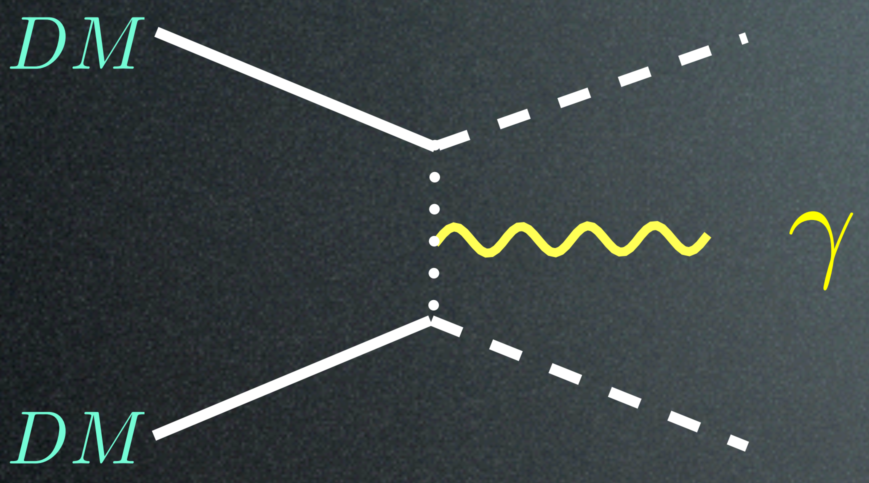


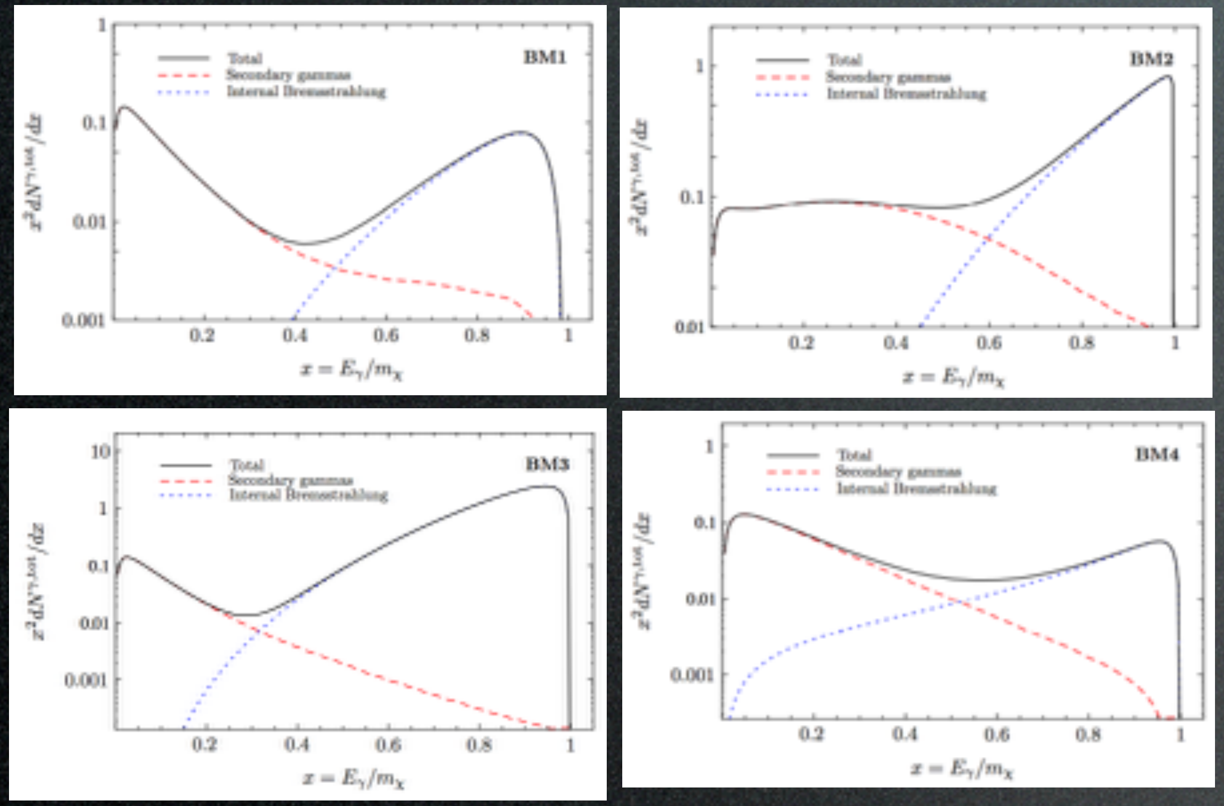
Prompt emission: sharp features

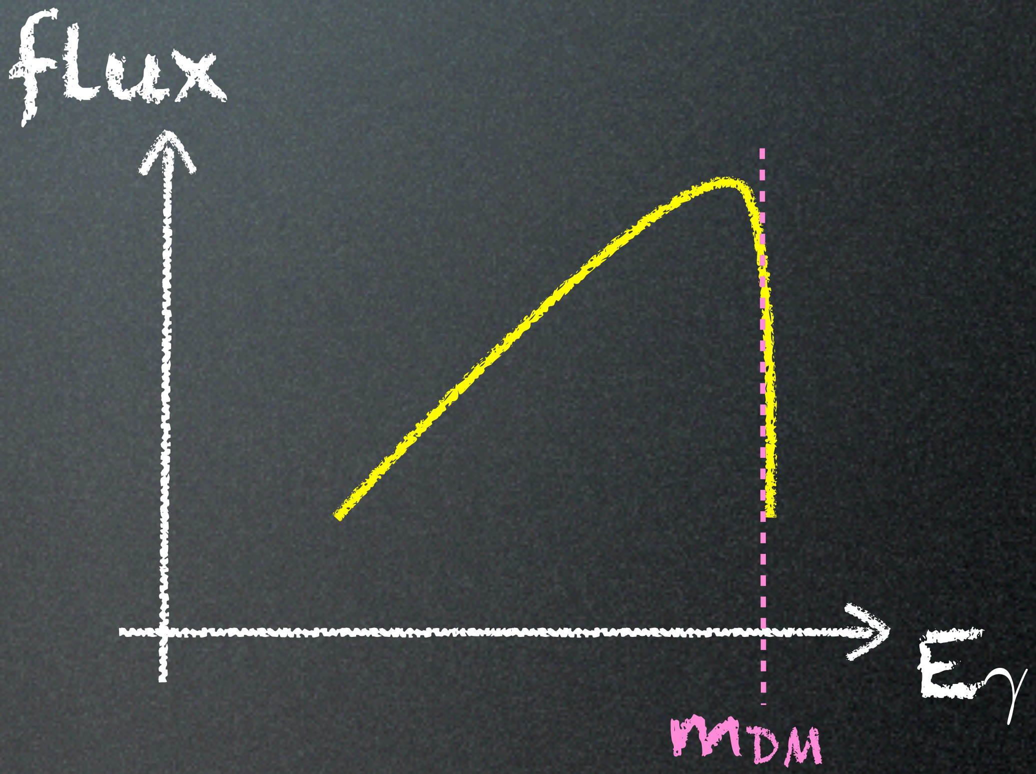


Internal Bremsstrahlung

Bergström 1989

Bringmann, Bergstrom, Edsjo 0710.3169



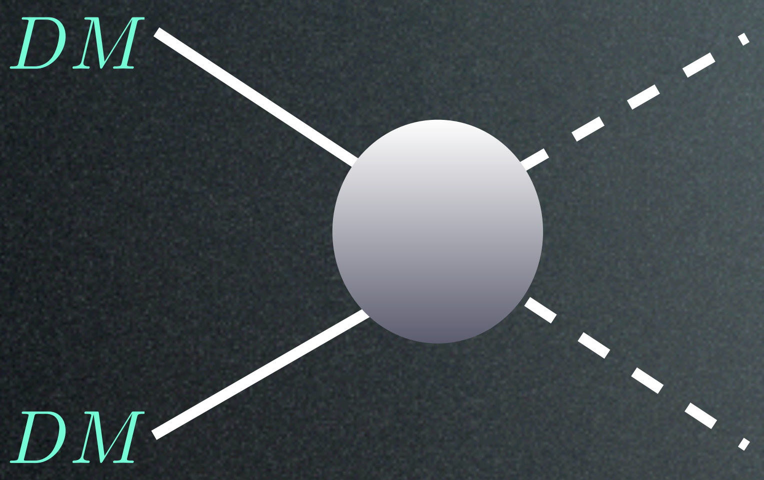


So what are the particle physics parameters?

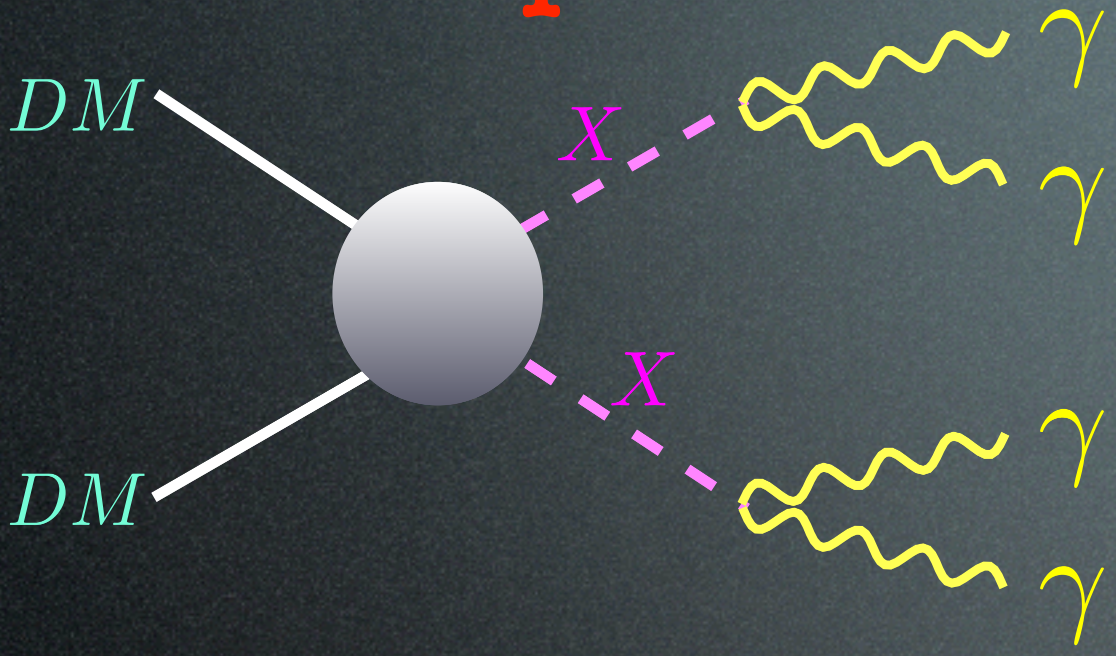
1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



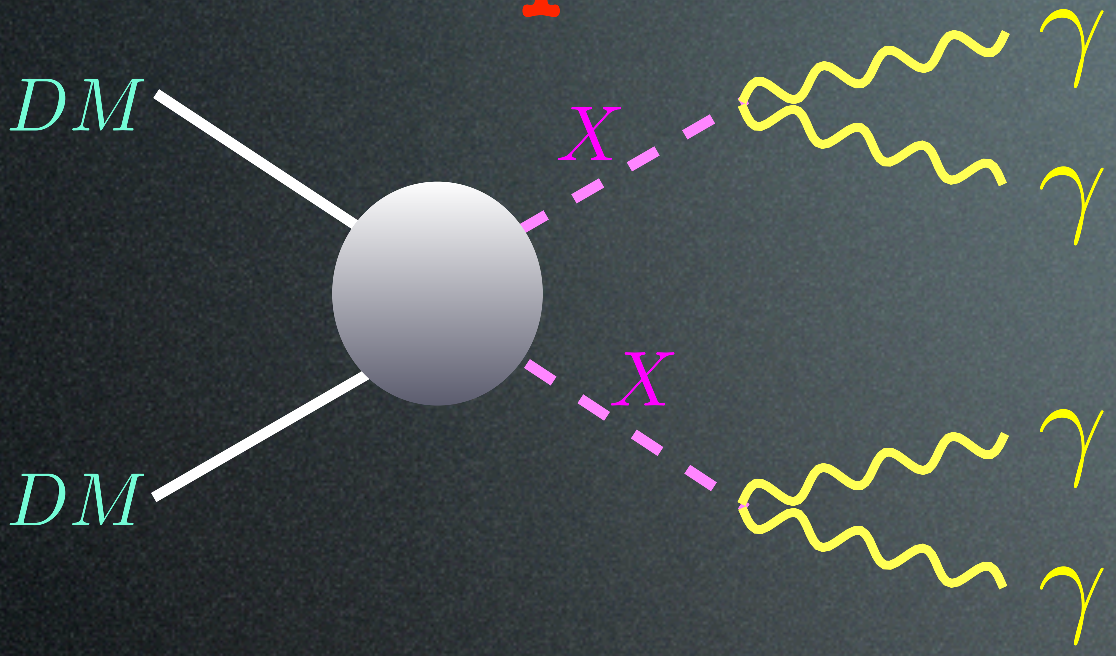
Prompt emission: sharp features



Metastable intermediate states

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Prompt emission: sharp features

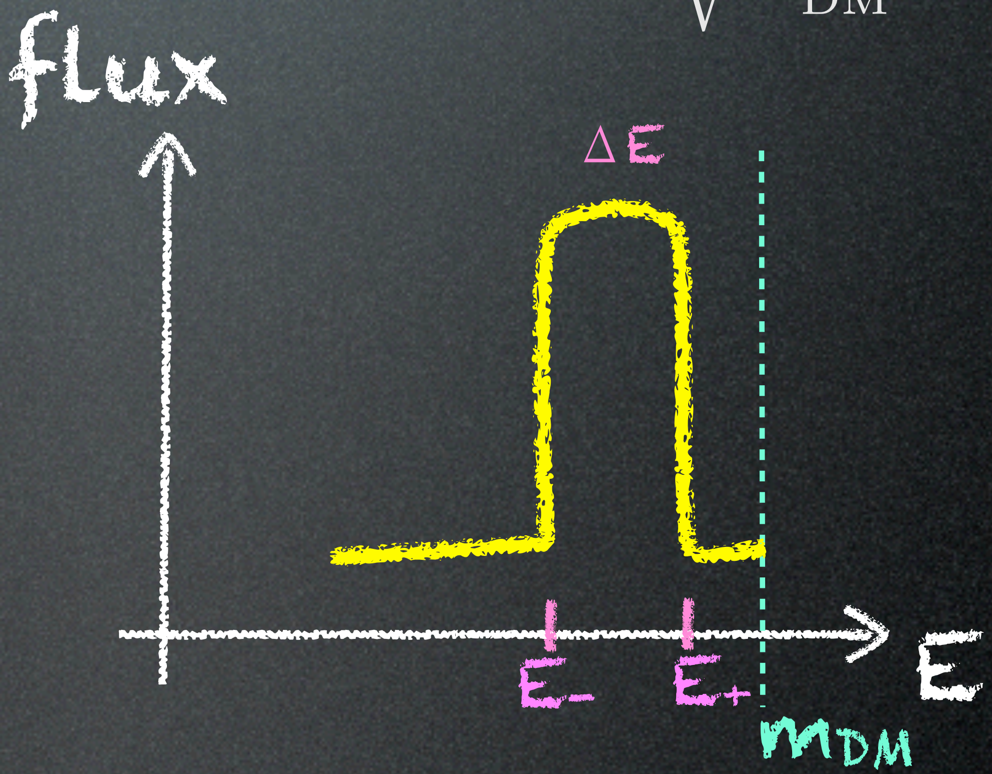


Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

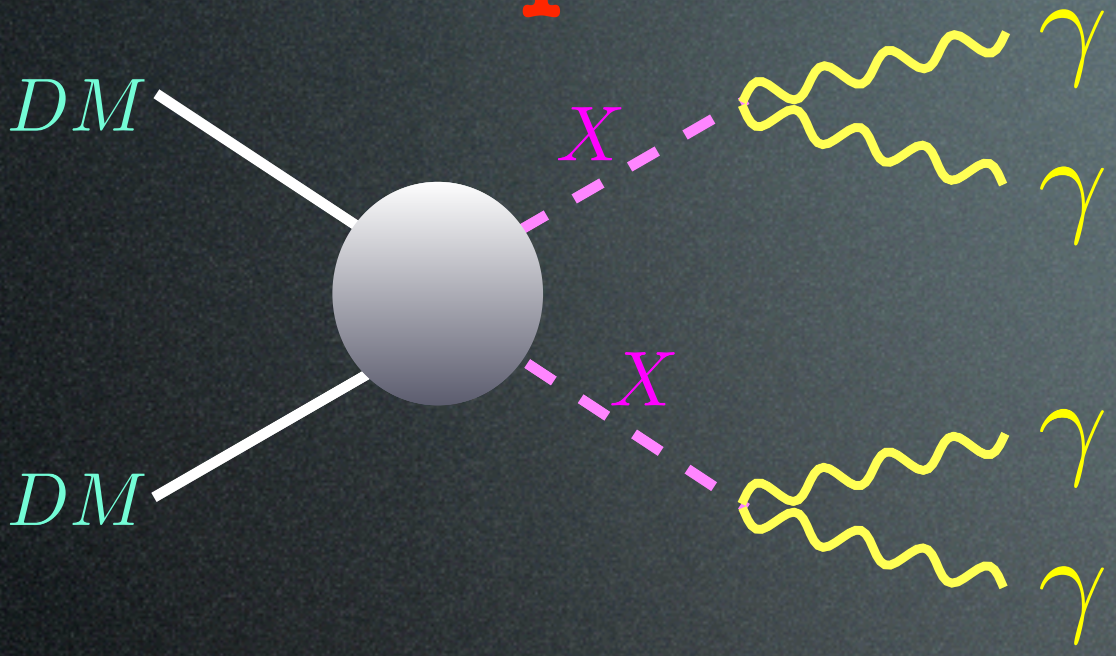
Metastable intermediate states

$$E_{\pm} = \frac{m_{\rm DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_X^2}{m_{\rm DM}^2}}\right)$$

$$\Delta E = \sqrt{m_{\rm DM}^2 - m_X^2}$$



Prompt emission: sharp features



Ibarra, Lopez Gehler, Pato 1205.0007
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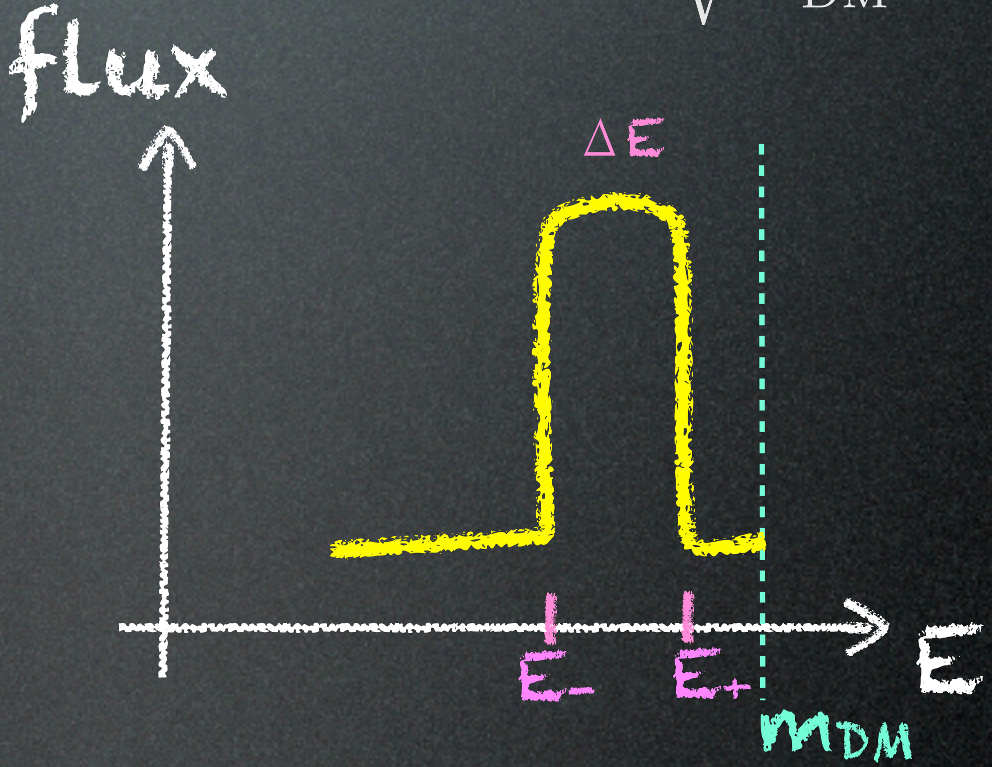
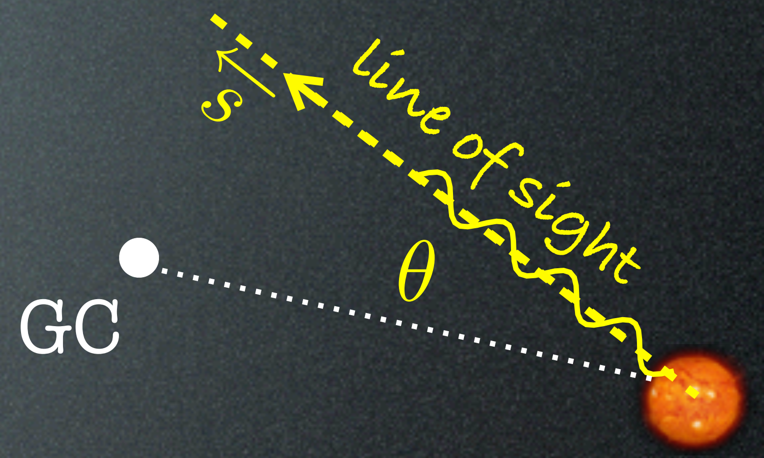


So what are the particle physics parameters?

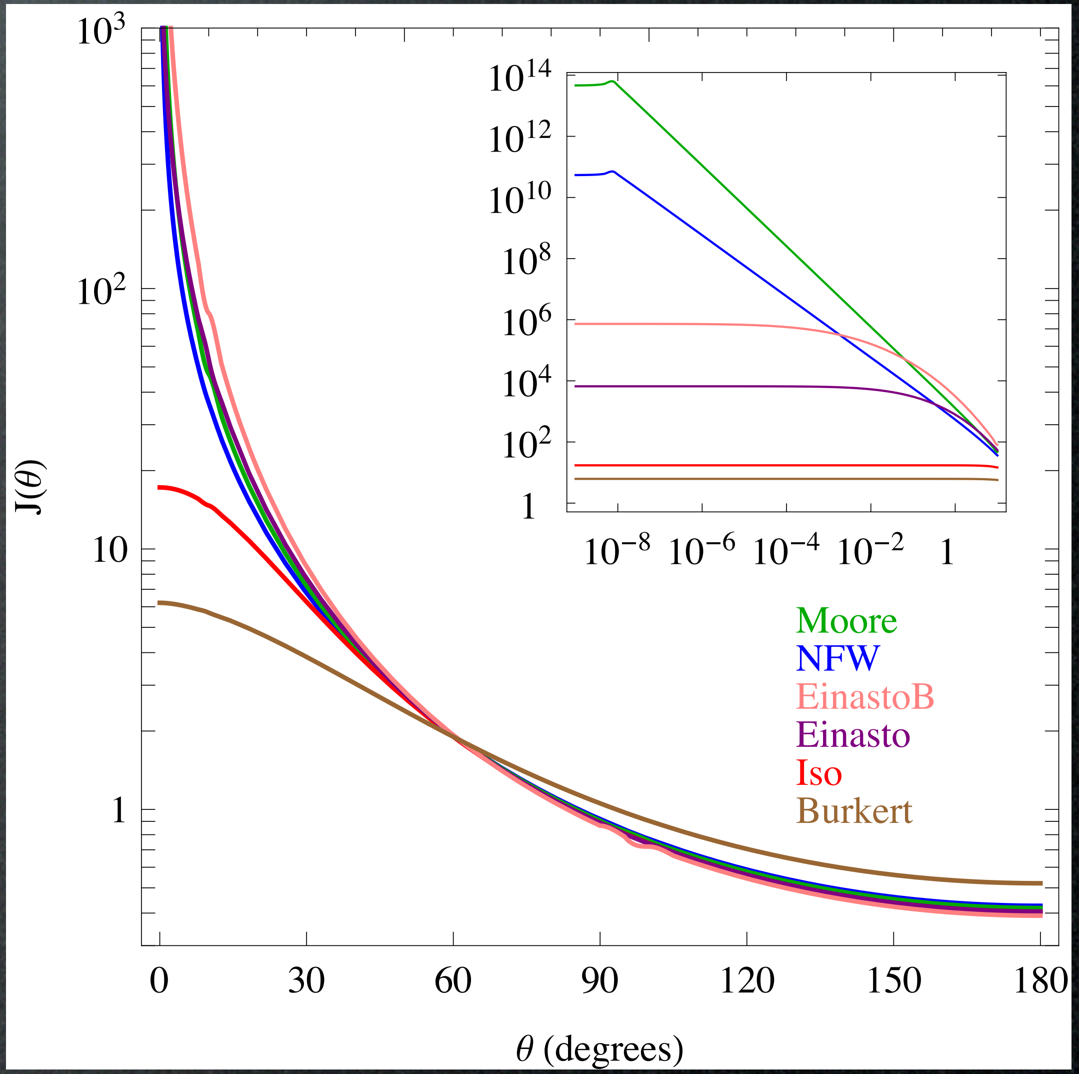
1. Dark Matter mass
2. The mediator mass

‘Prompt’ gamma rays

$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 J \sum_f \langle\sigma v\rangle_f \boxed{\frac{dN_\gamma^f}{dE}}$$

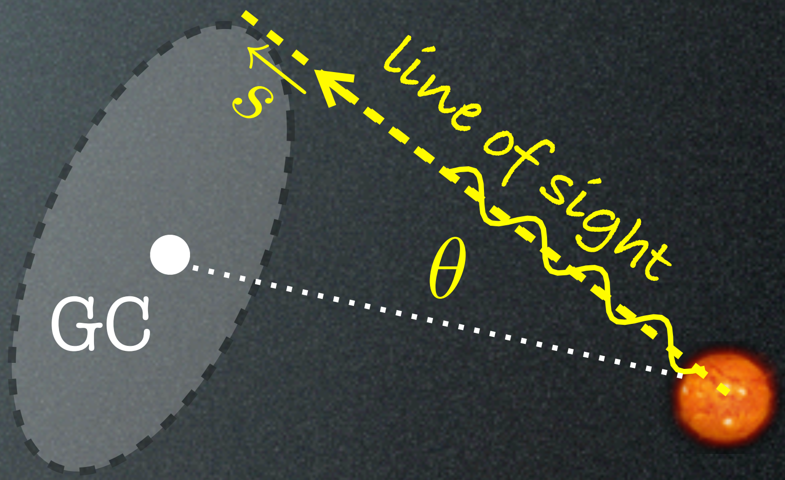


$$J = \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2$$

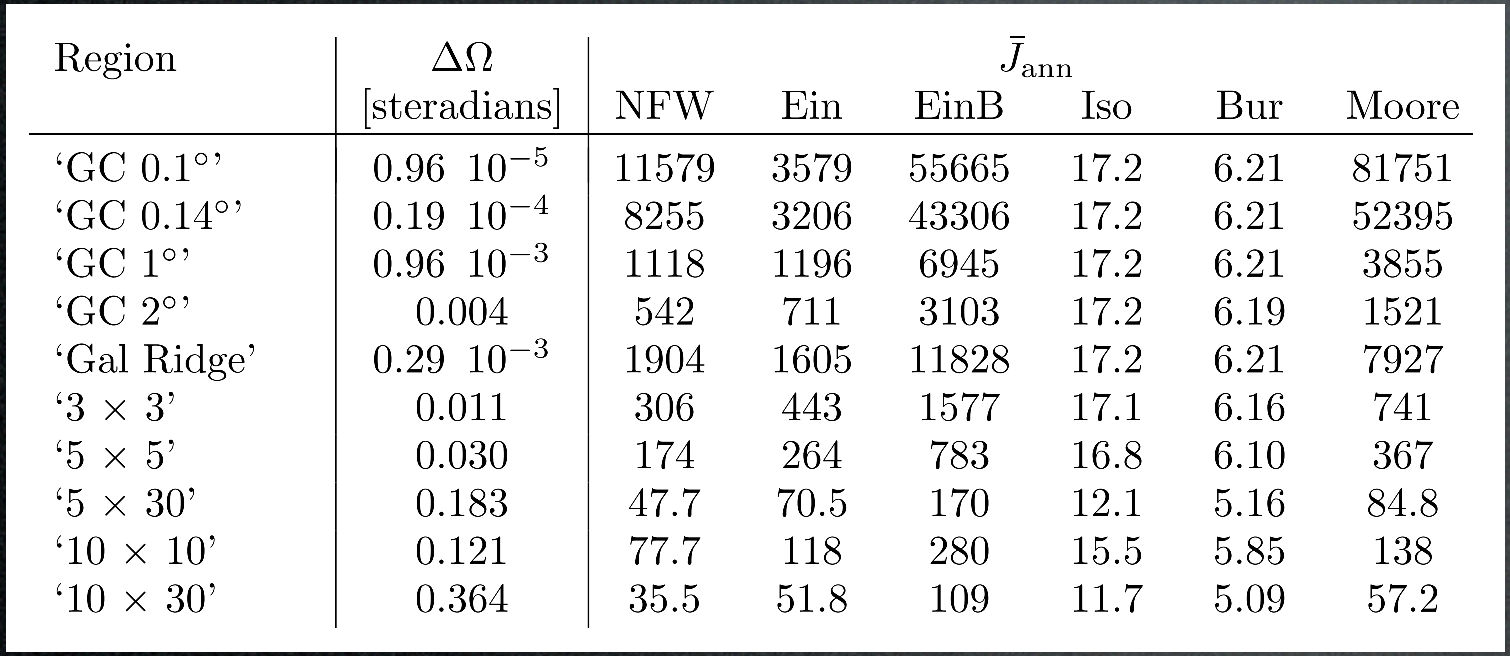


‘Prompt’ gamma rays

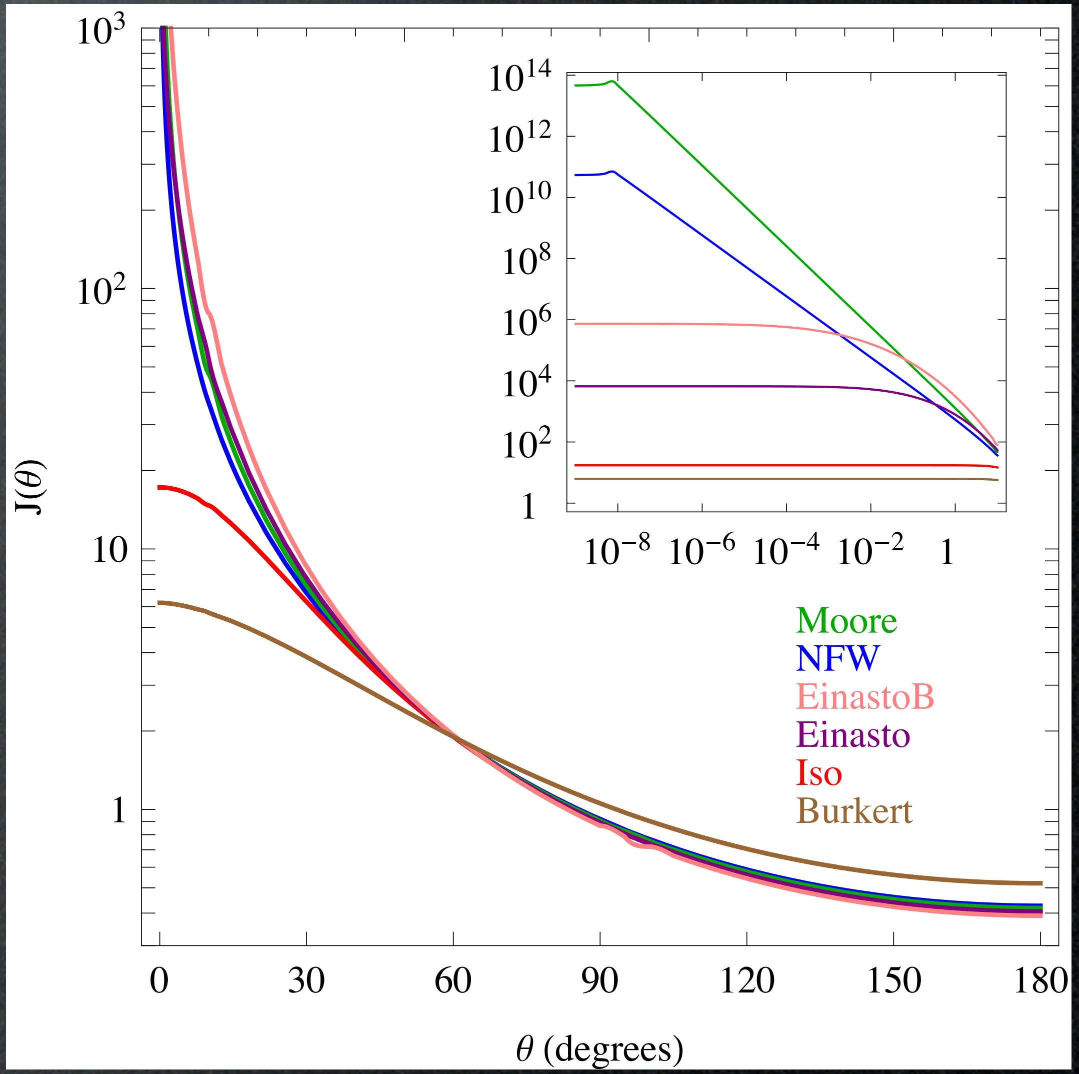
$$\frac{d\Phi_\gamma}{dE} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 \bar{J}\,\Delta\Omega \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE_\gamma}$$



$$\bar{J} = \frac{1}{\Delta\Omega}\int\int_{\rm l.o.s.}\frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2$$



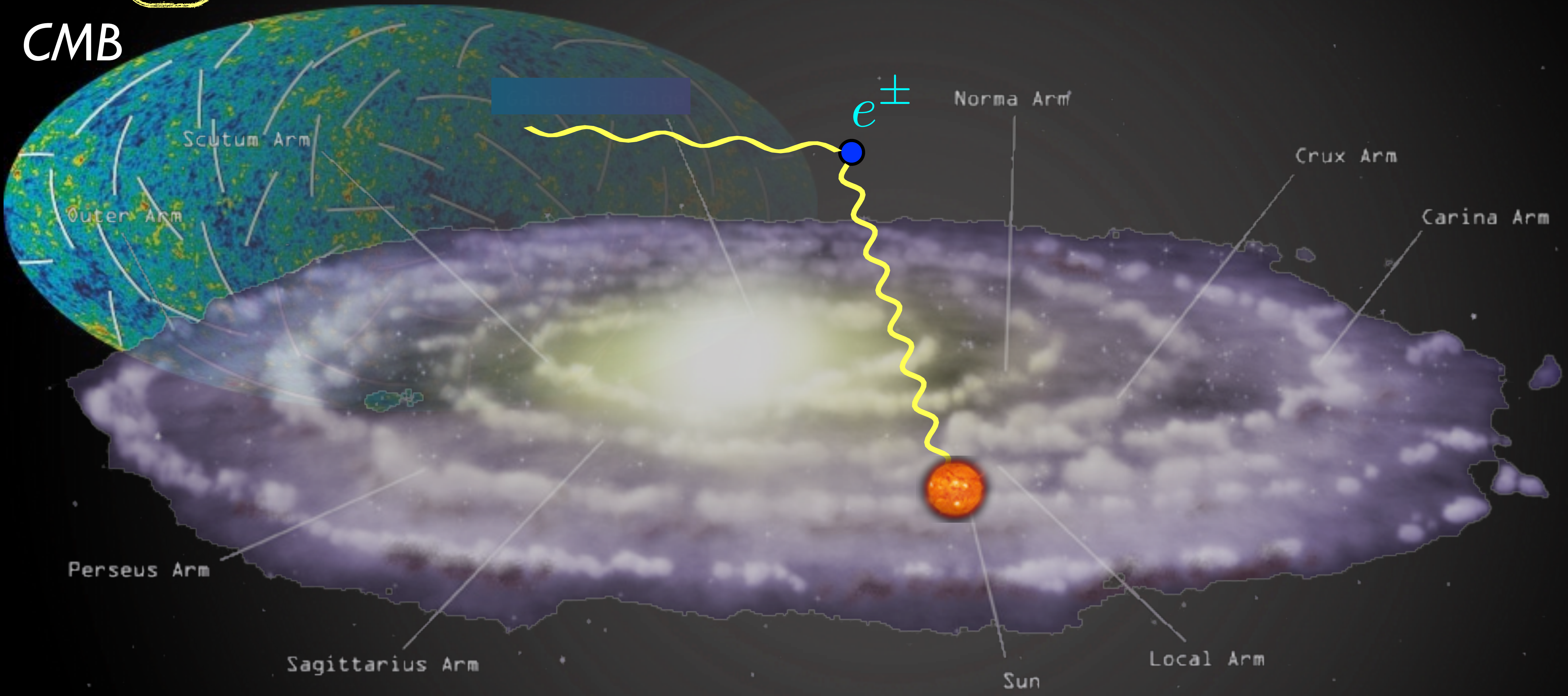
Region	$\Delta\Omega$ [steradians]	NFW	Ein	EinB	Iso	Bur	Moore
		$\bar{J}_{\rm ann}$					
‘GC 0.1°’	$0.96\ 10^{-5}$	11579	3579	55665	17.2	6.21	81751
‘GC 0.14°’	$0.19\ 10^{-4}$	8255	3206	43306	17.2	6.21	52395
‘GC 1°’	$0.96\ 10^{-3}$	1118	1196	6945	17.2	6.21	3855
‘GC 2°’	0.004	542	711	3103	17.2	6.19	1521
‘Gal Ridge’	$0.29\ 10^{-3}$	1904	1605	11828	17.2	6.21	7927
‘3 × 3’	0.011	306	443	1577	17.1	6.16	741
‘5 × 5’	0.030	174	264	783	16.8	6.10	367
‘5 × 30’	0.183	47.7	70.5	170	12.1	5.16	84.8
‘10 × 10’	0.121	77.7	118	280	15.5	5.85	138
‘10 × 30’	0.364	35.5	51.8	109	11.7	5.09	57.2



Spread is very large
for small regions close to GC

Secondary emission

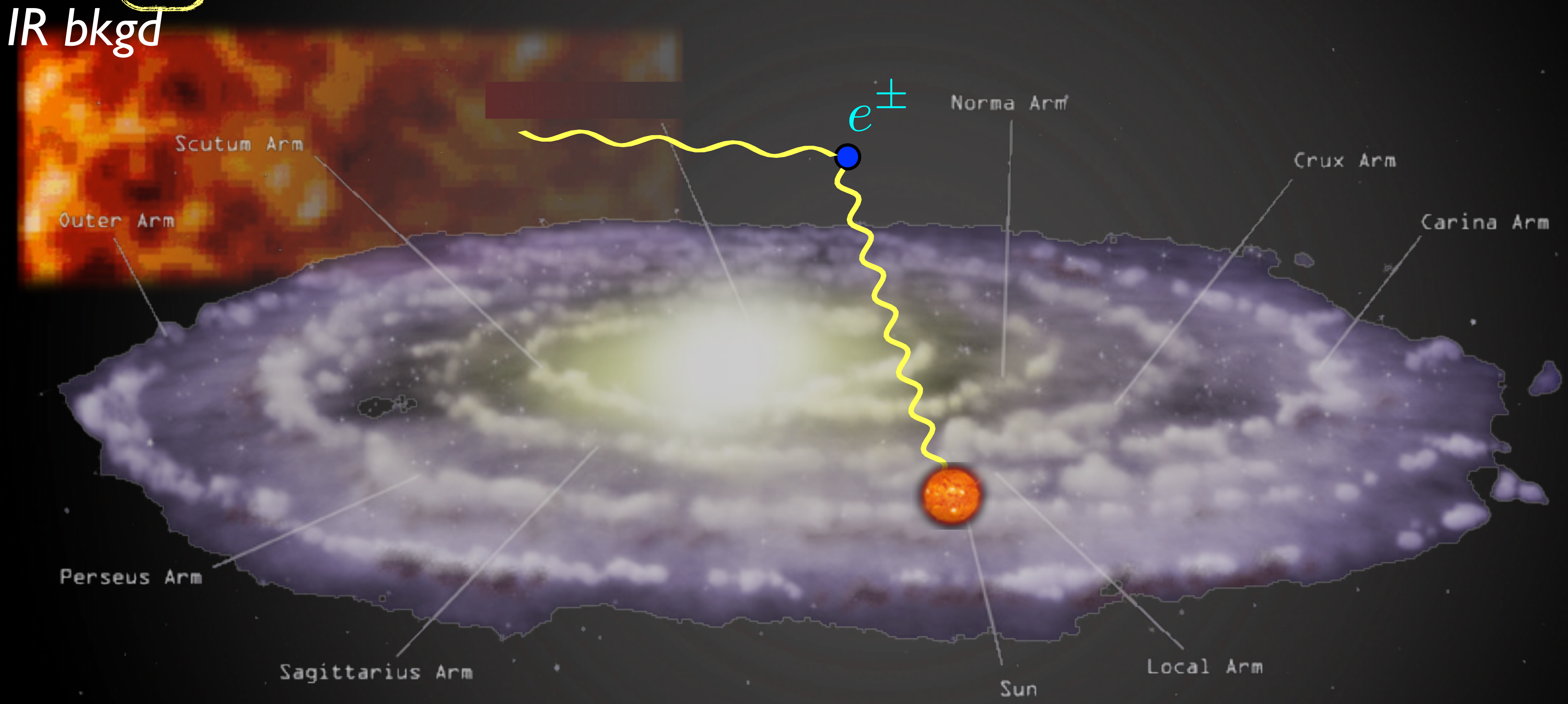
a. γ from Inverse Compton on $e^{\pm}$ in halo



- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Secondary emission

a. γ from Inverse Compton on $e^{\pm}$ in halo



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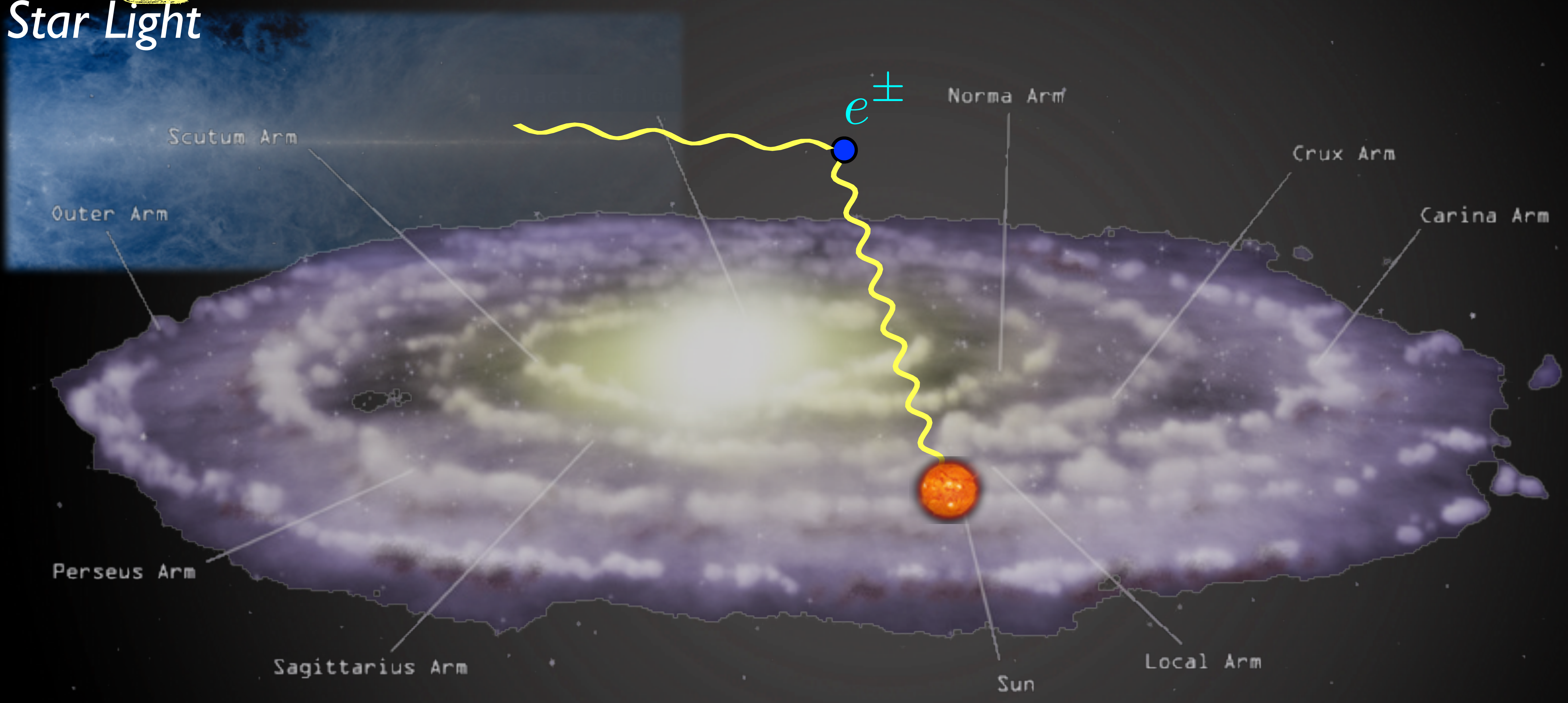

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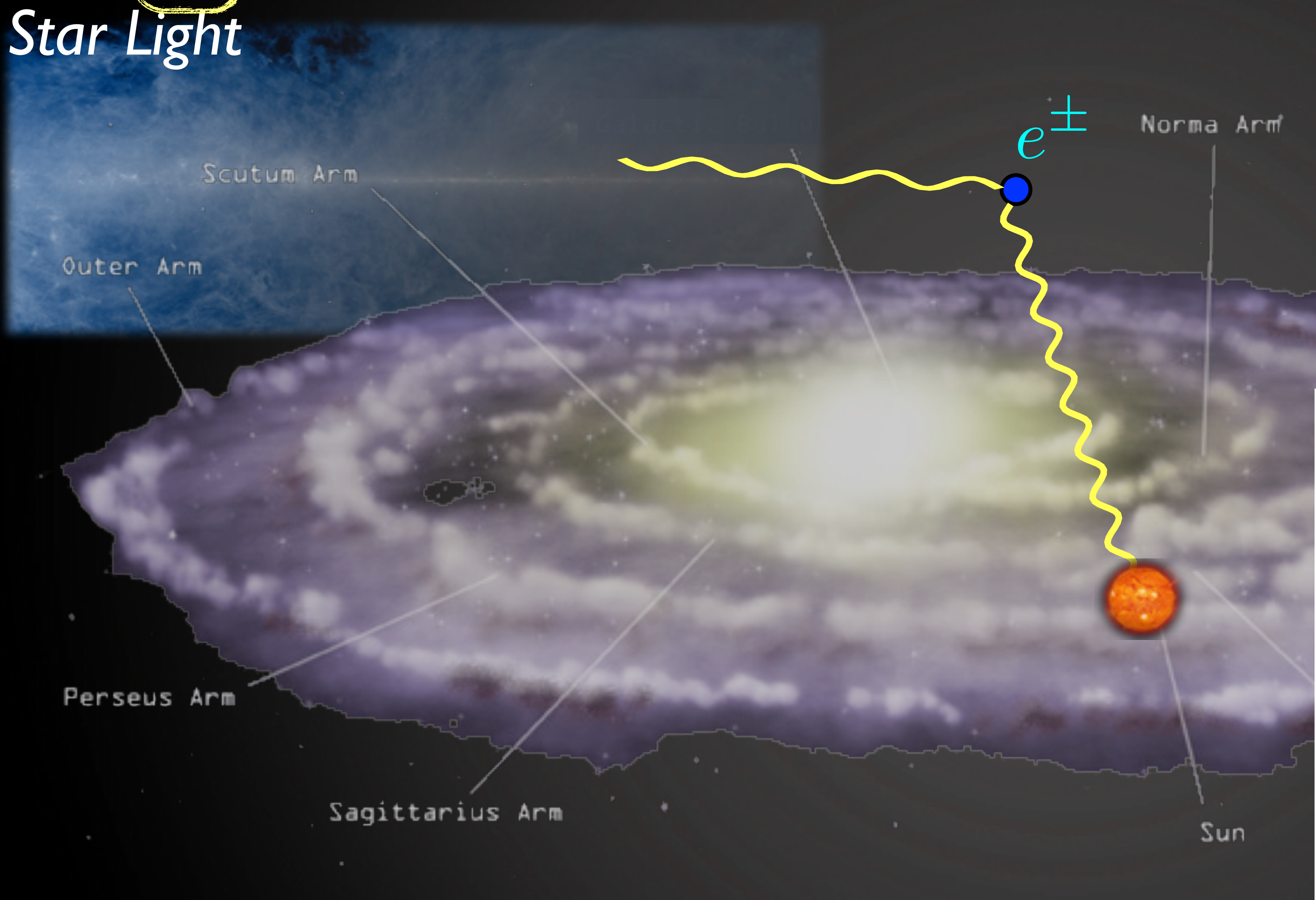
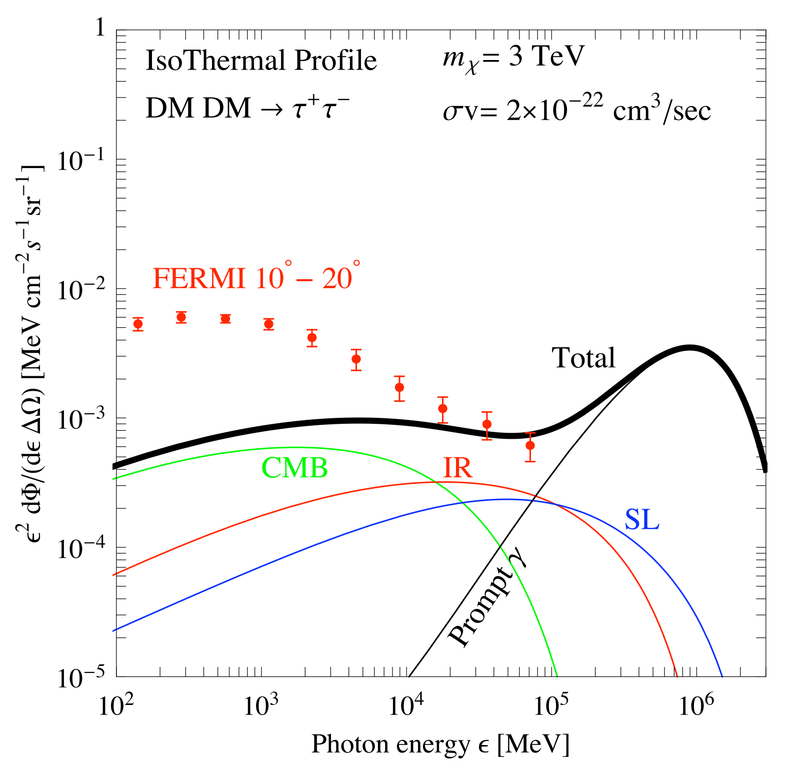


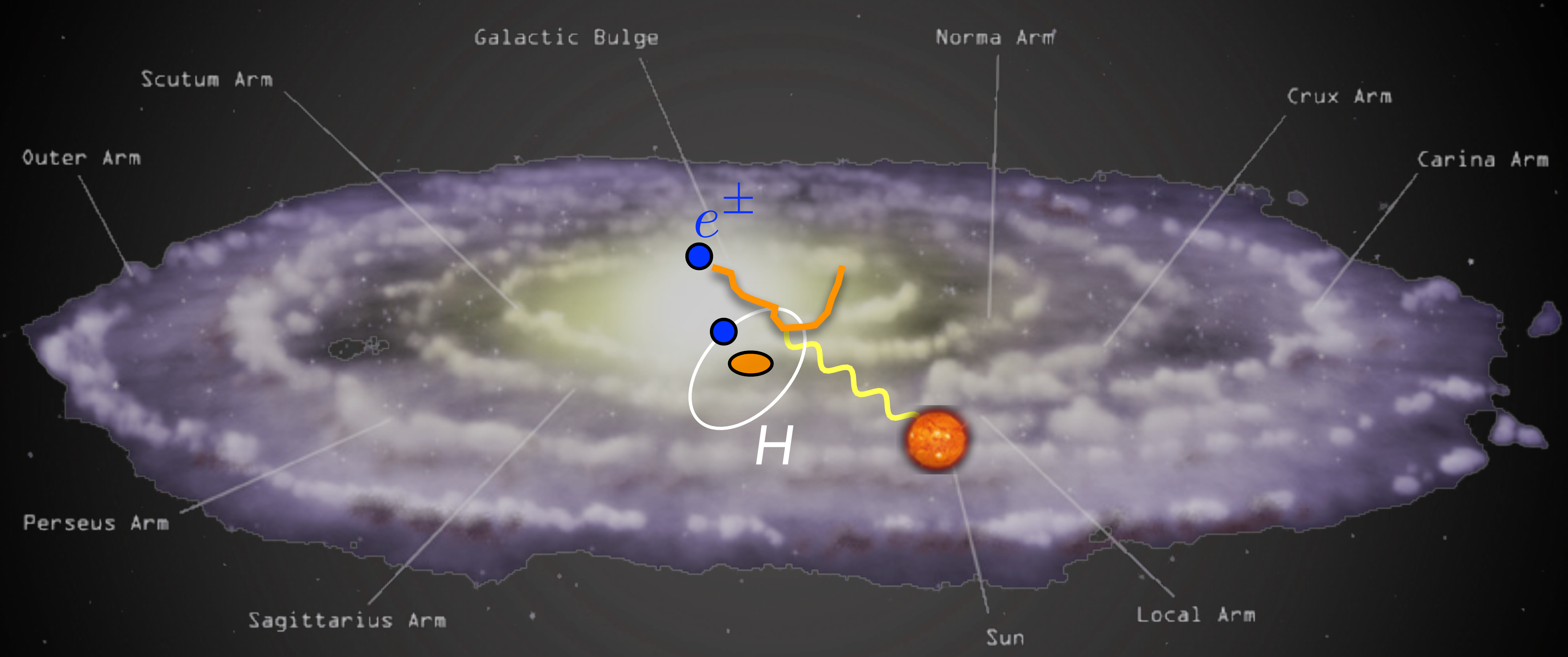


Cirelli, Panci, Serpico 0912.0663

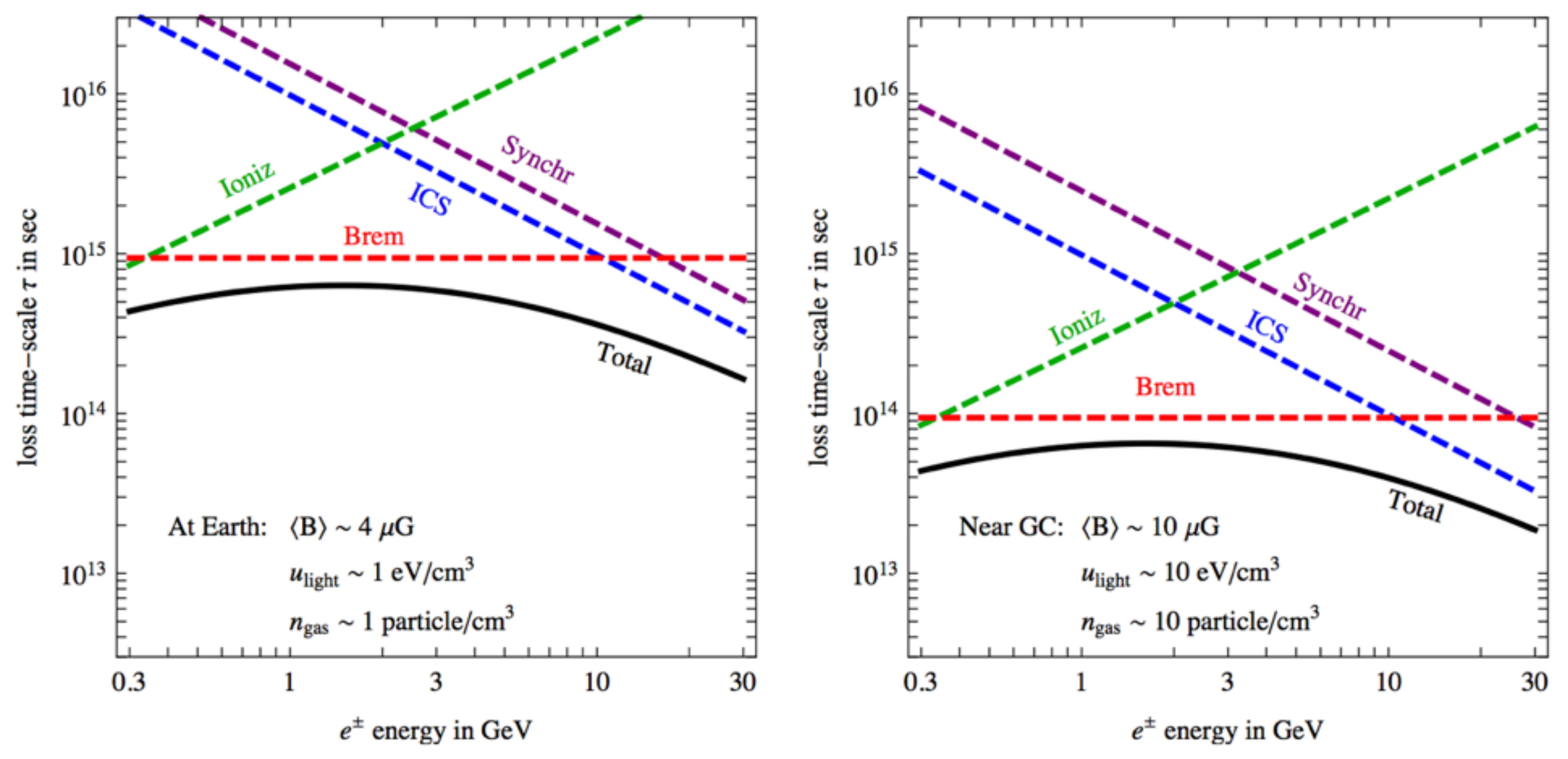
- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Secondary emission

b. soft gammas from bremsstrahlung of $e^{\pm}$ on ISM



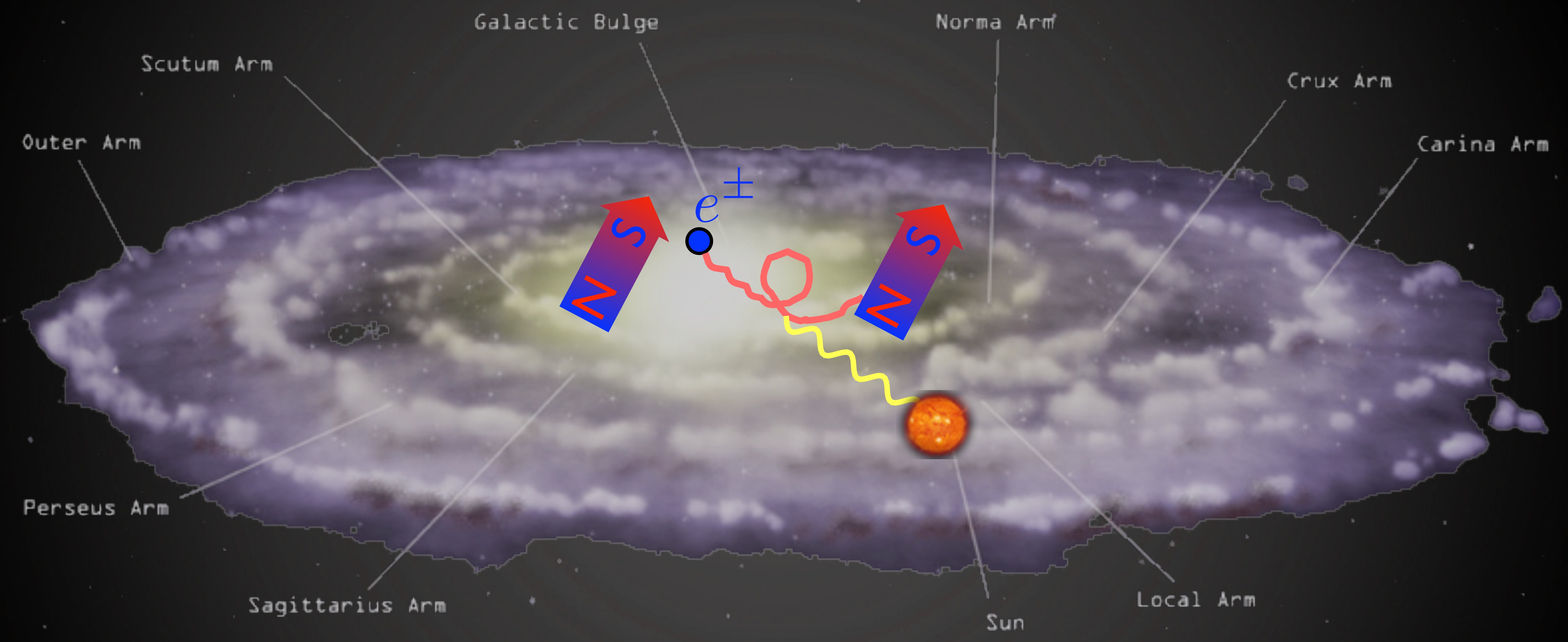
Relative importance of secondary emissions



=> brem is the dominant energy loss for low energy $e^{\pm}$!

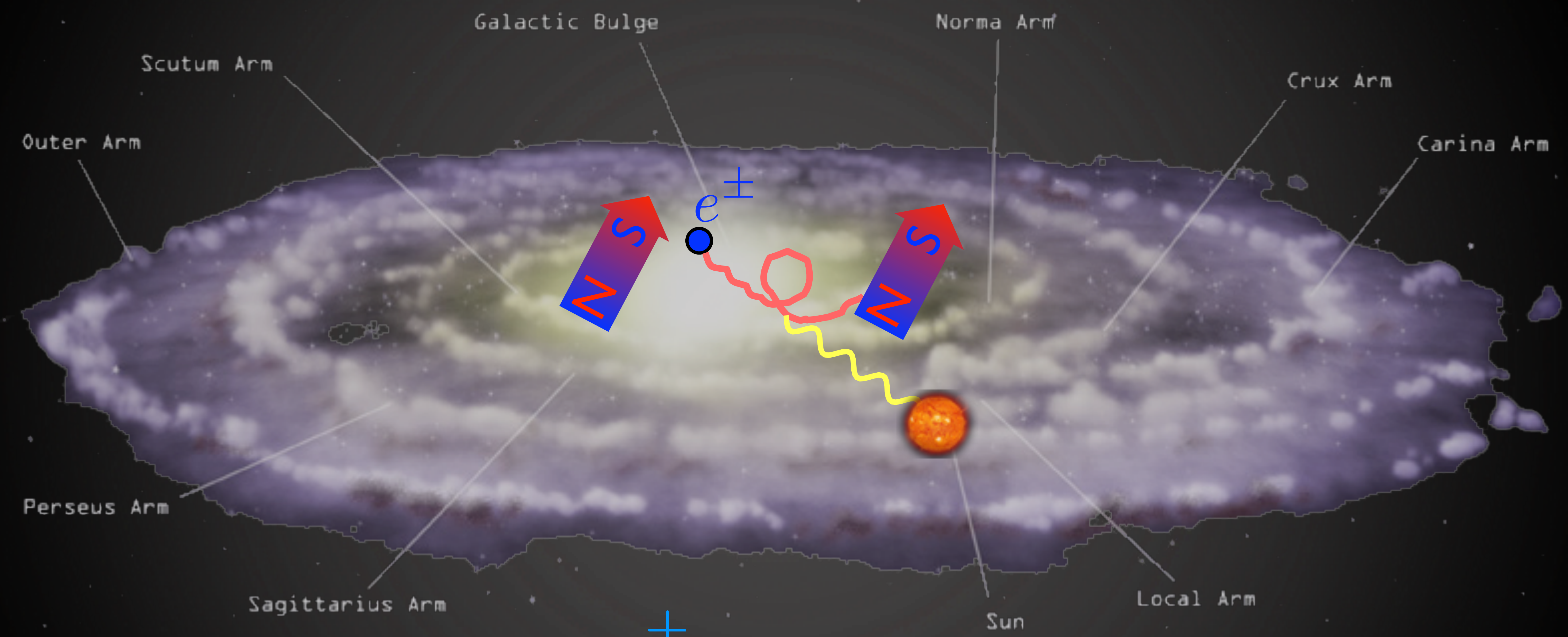
Secondary emission

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



Secondary emission

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



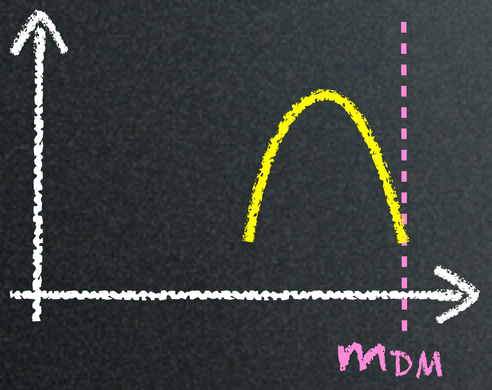
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

(assuming 'scrambled' B; in principle, directionality could focus emission, lift bounds by O(some))

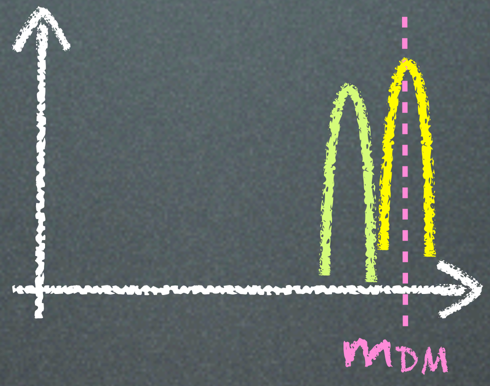
How does DM produce γ-rays?

1. prompt emission

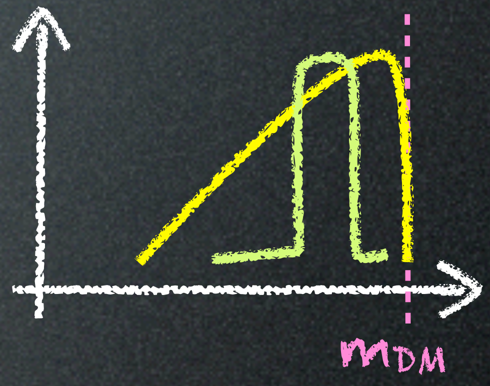
1a. continuum



1b. line(s)

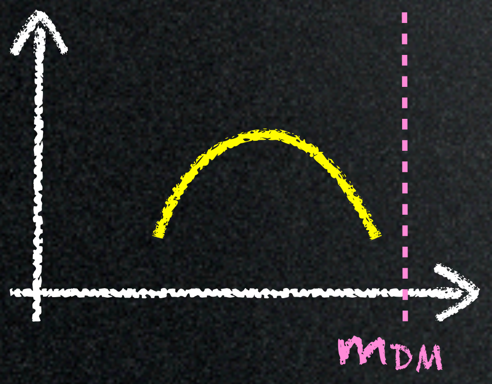


1c. sharp features

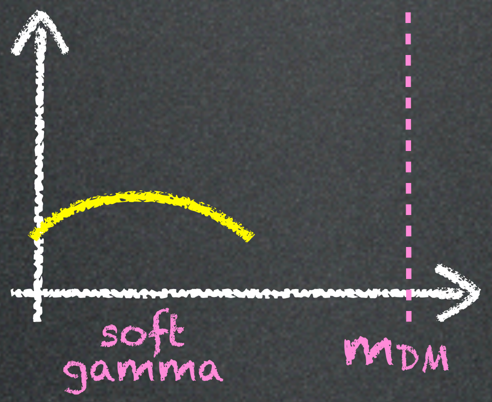


2. secondary emission

2a. ICS



2b. bremsstrahlung



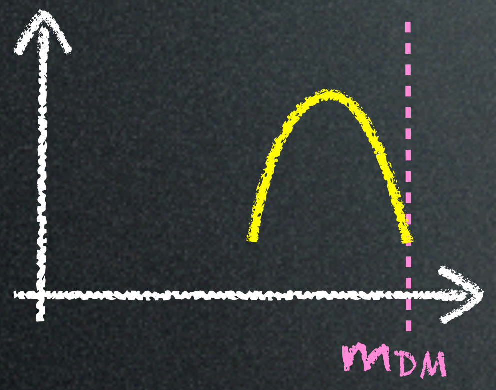
2c. synchrotron

How does DM produce γ-rays?

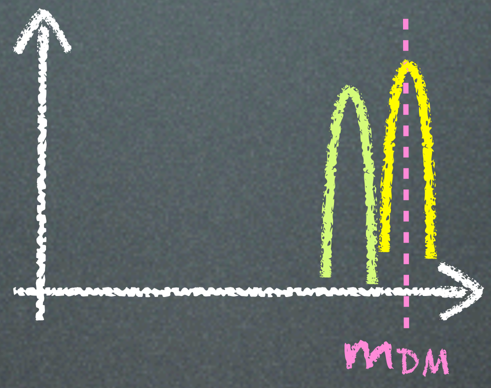
environment-independent

1. prompt emission

1a. continuum



1b. line(s)

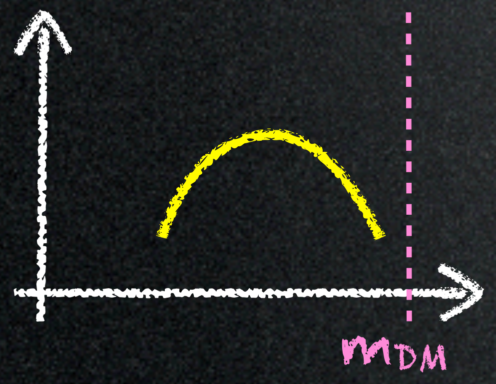


1c. sharp features

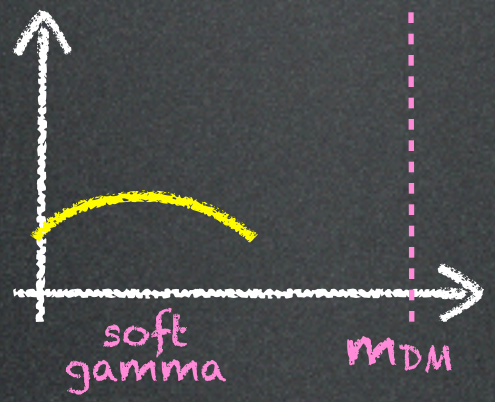
environment-dependent

2. secondary emission

2a. ICS



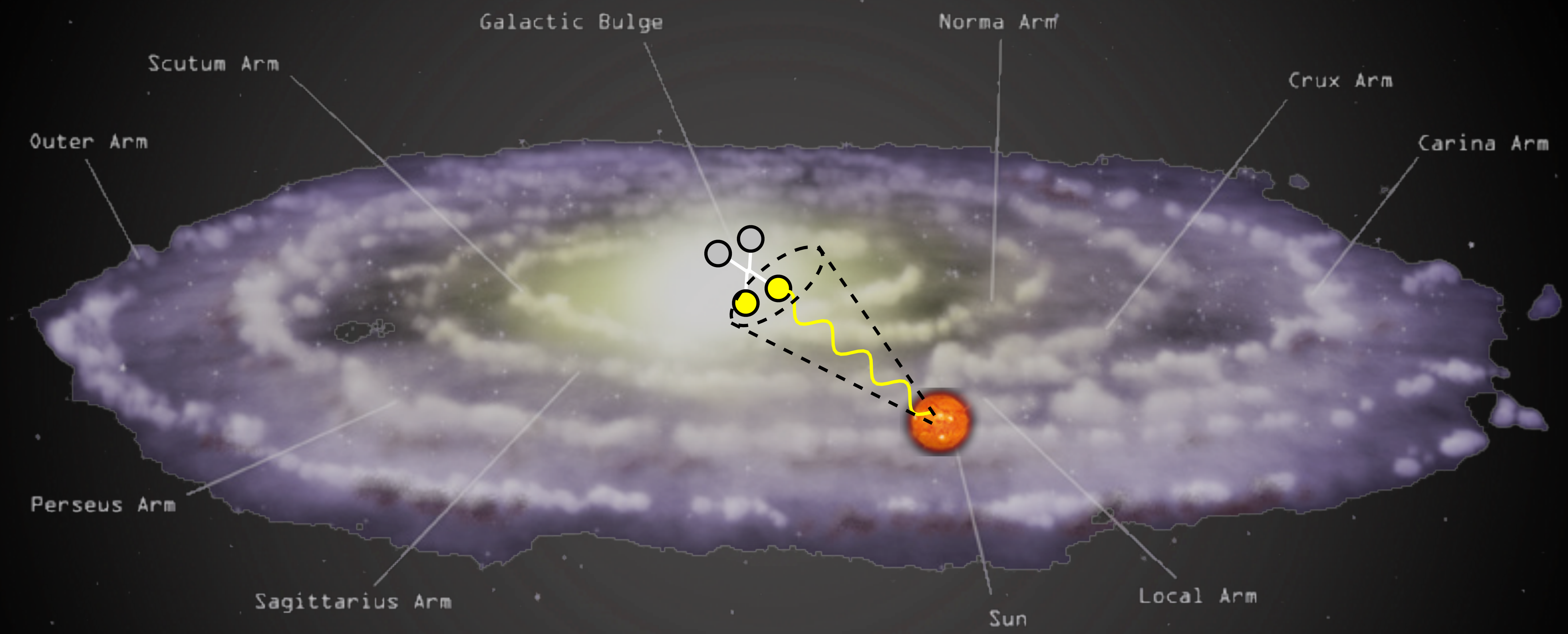
2b. bremsstrahlung

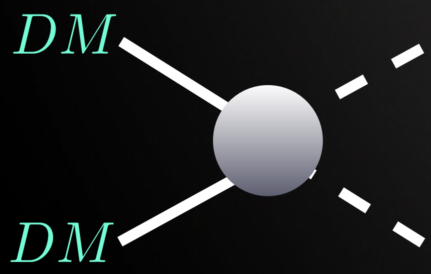


2c. synchrotron

Basic picture: targets

γ from DM annihilations in galactic center



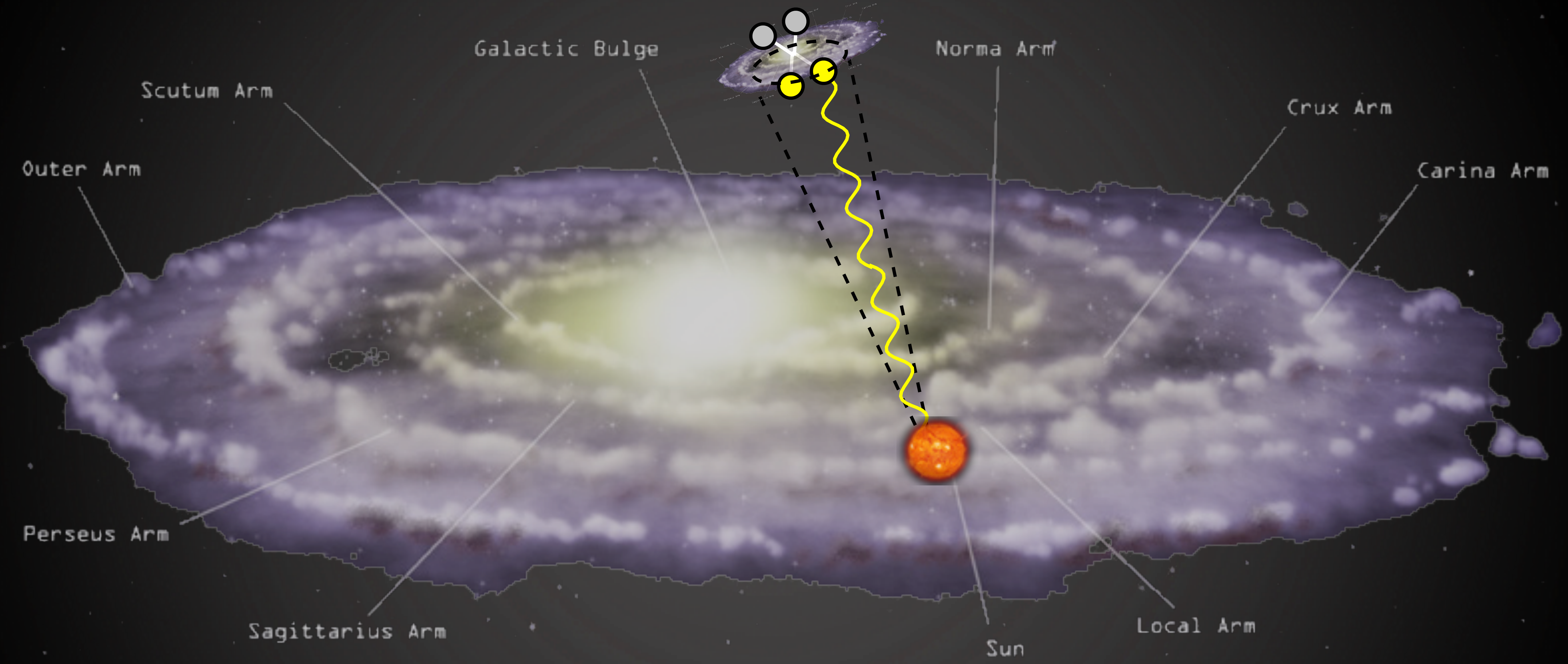


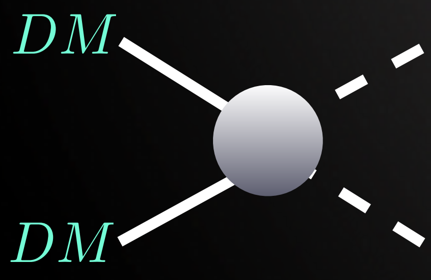
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

Basic picture: targets

γ from DM annihilations in dwarf galaxies



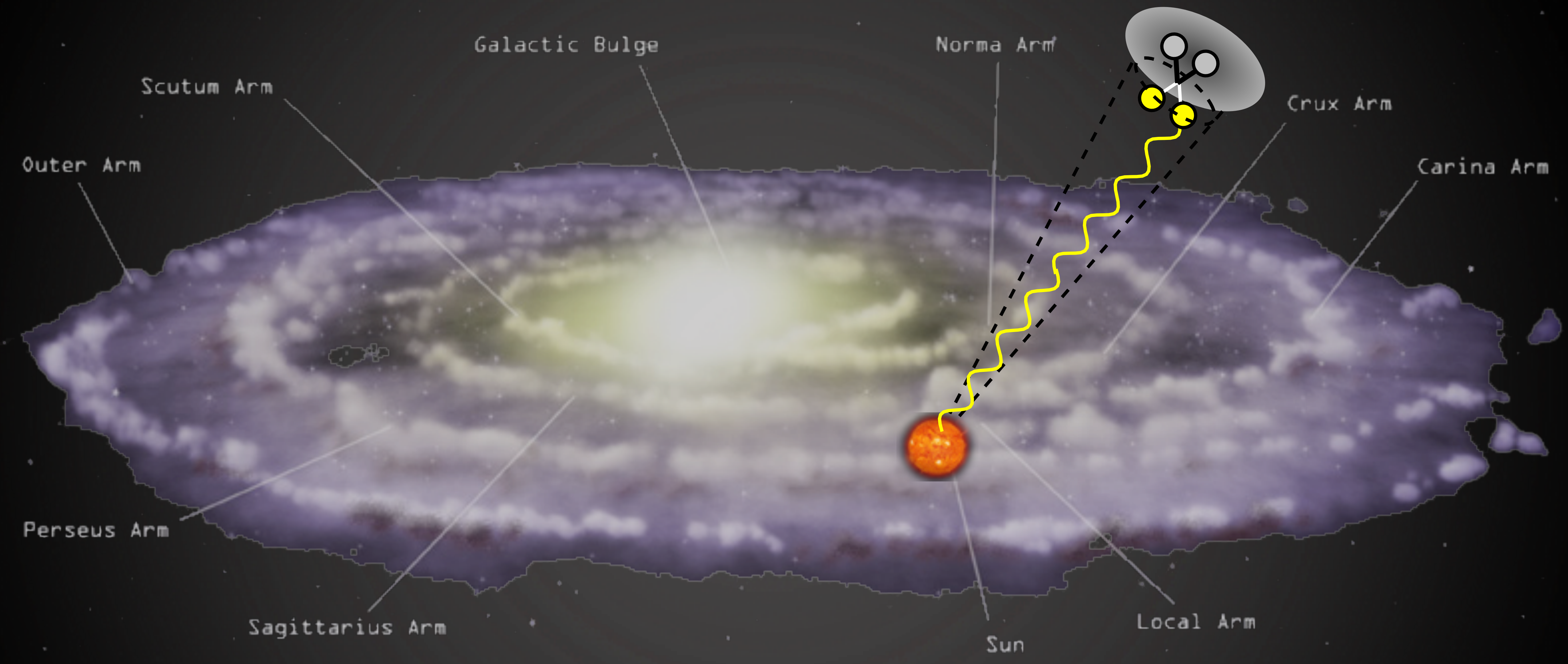


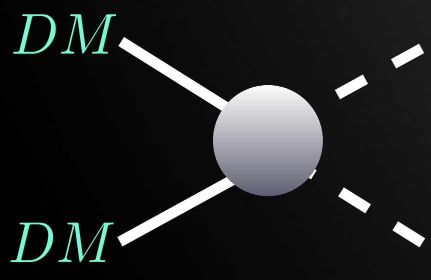
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \text{ and } \gamma$$

Basic picture: targets

γ from DM annihilations in subhaloes



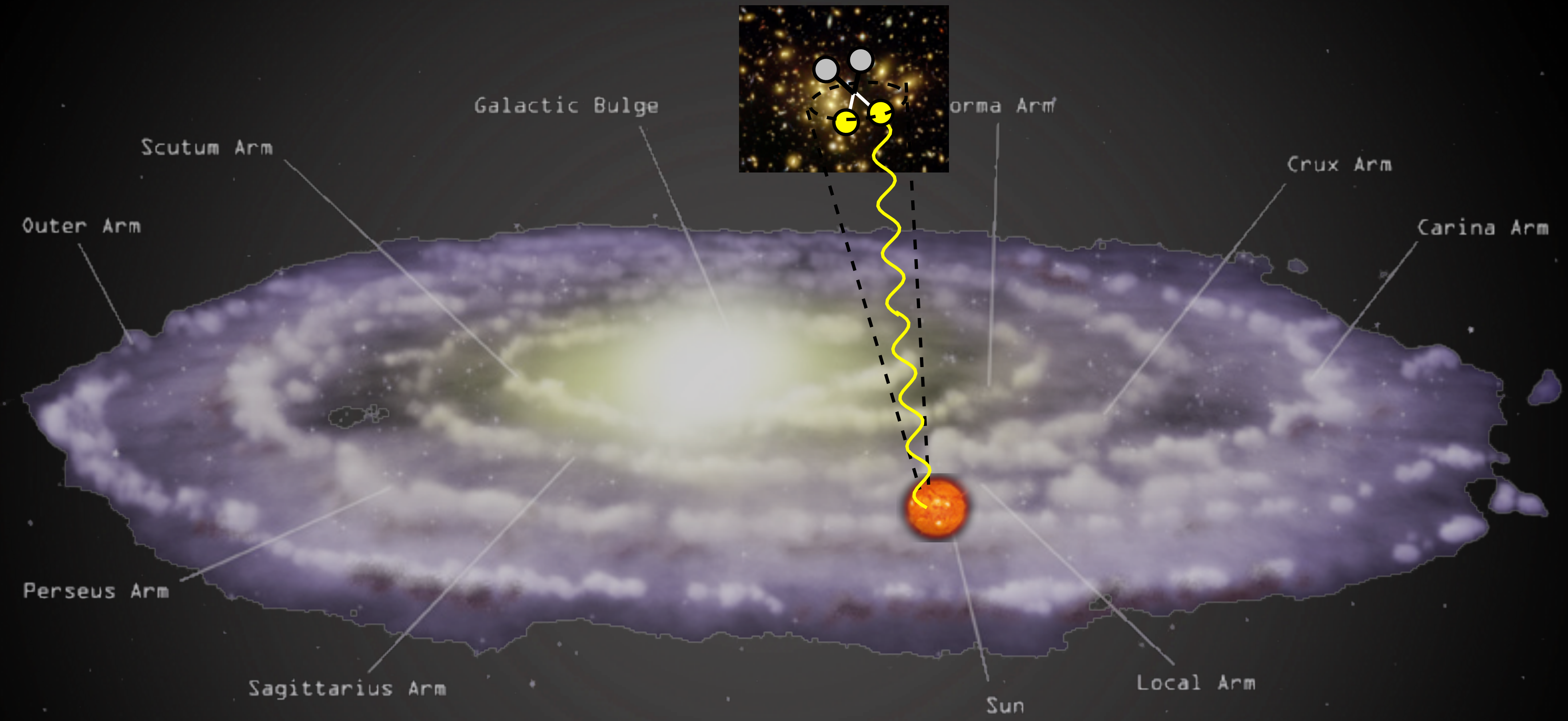


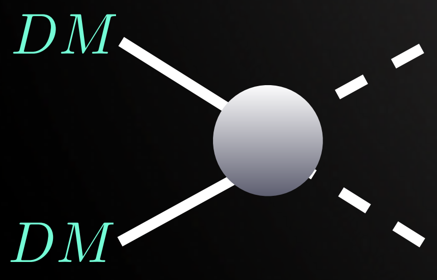
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and} \ \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and} \ \gamma$$

Basic picture: targets

γ from DM annihilations in galaxy clusters



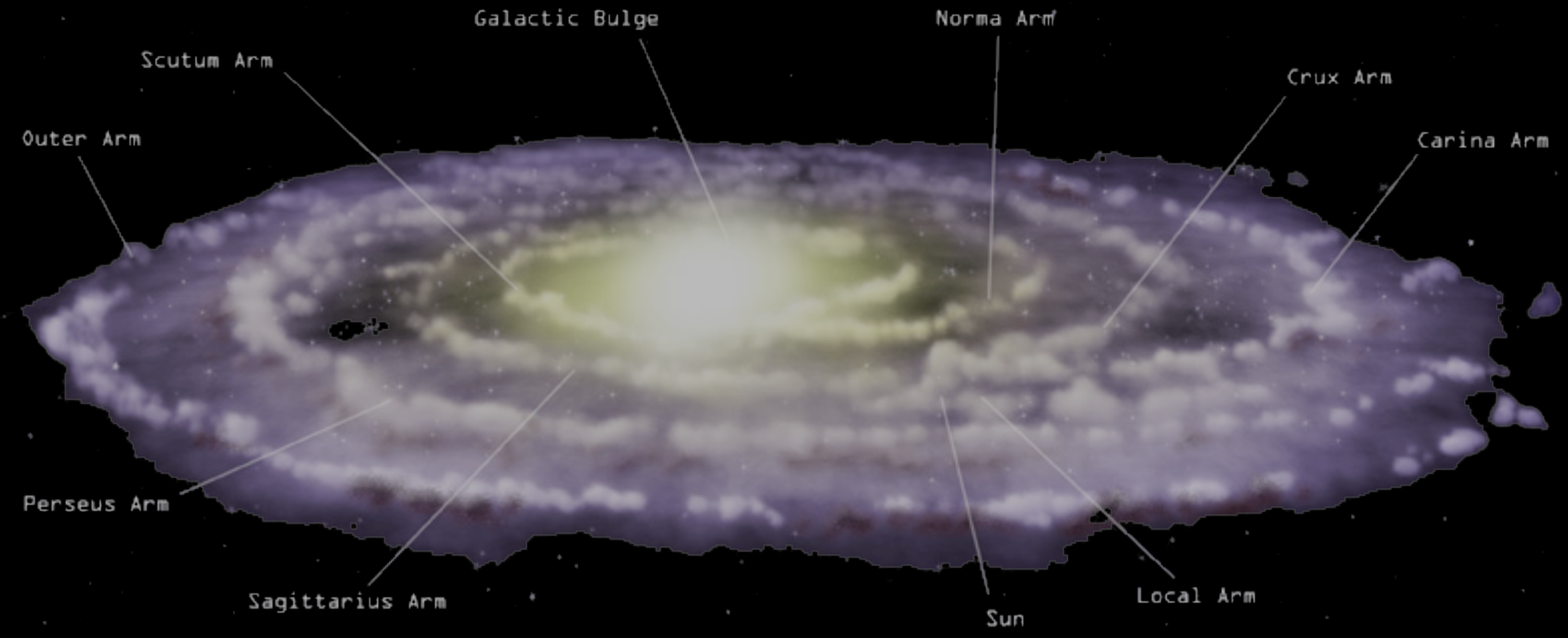


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and } \gamma$$

Basic picture: targets

γ from outside the Galaxy

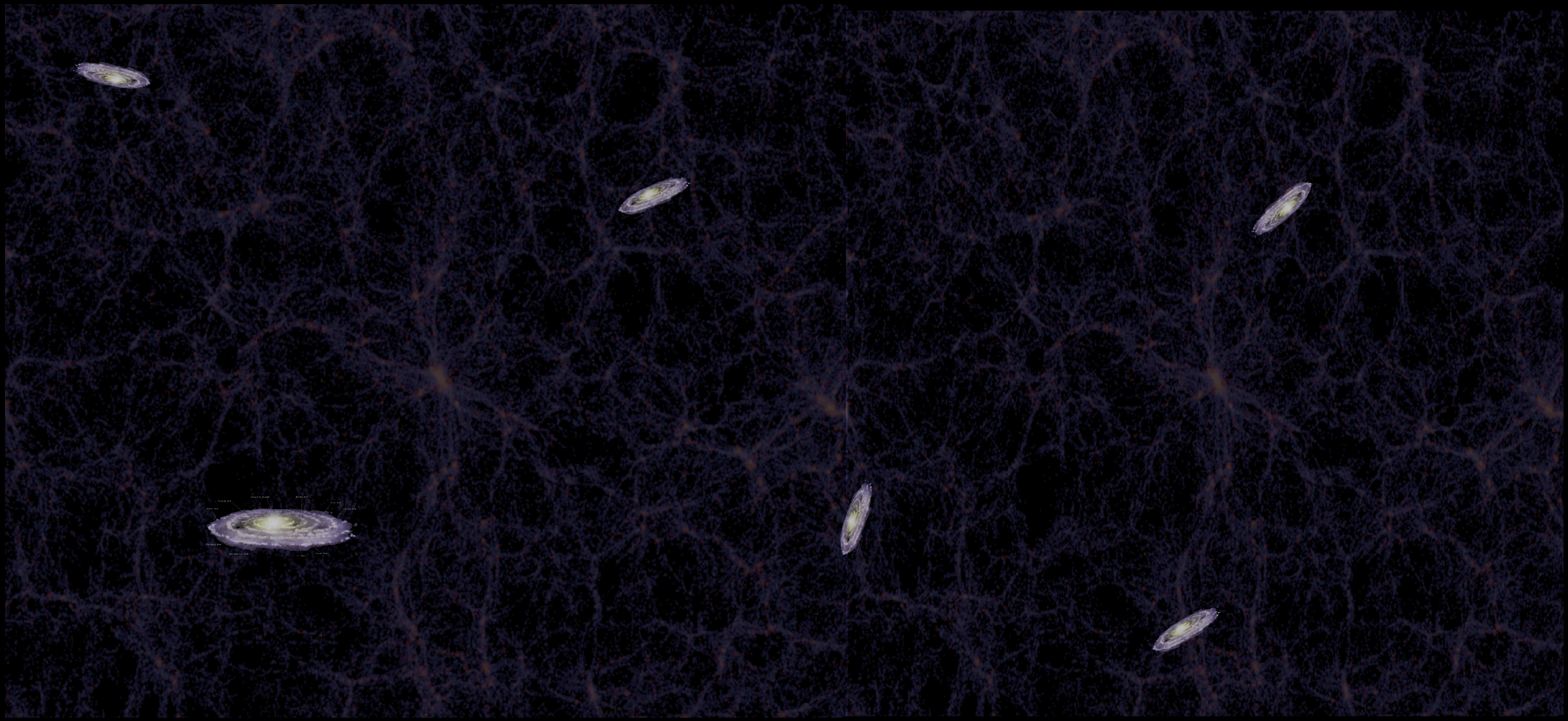


Basic picture: targets

γ from outside the Galaxy

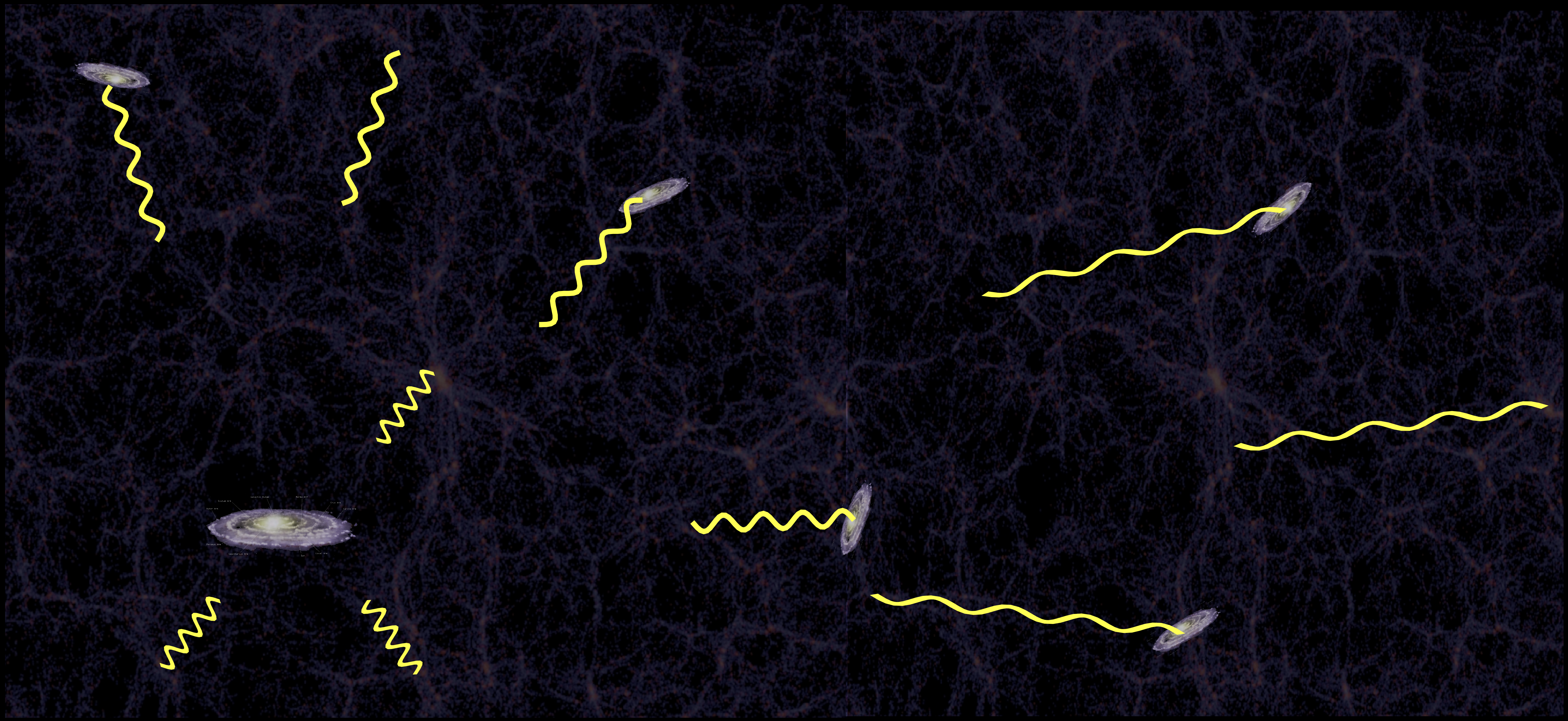
Basic picture: targets

γ from outside the Galaxy



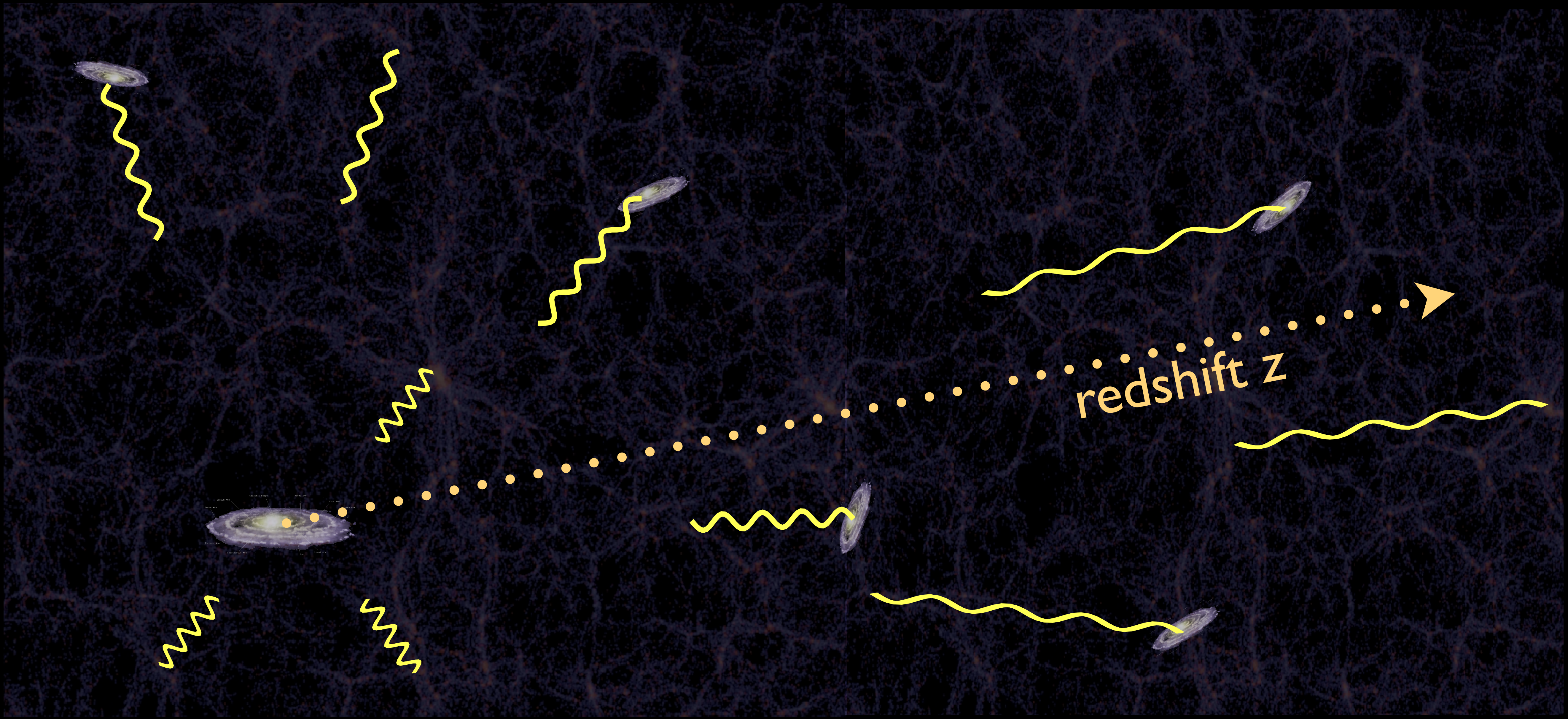
Basic picture: targets

γ from outside the Galaxy



Basic picture: targets

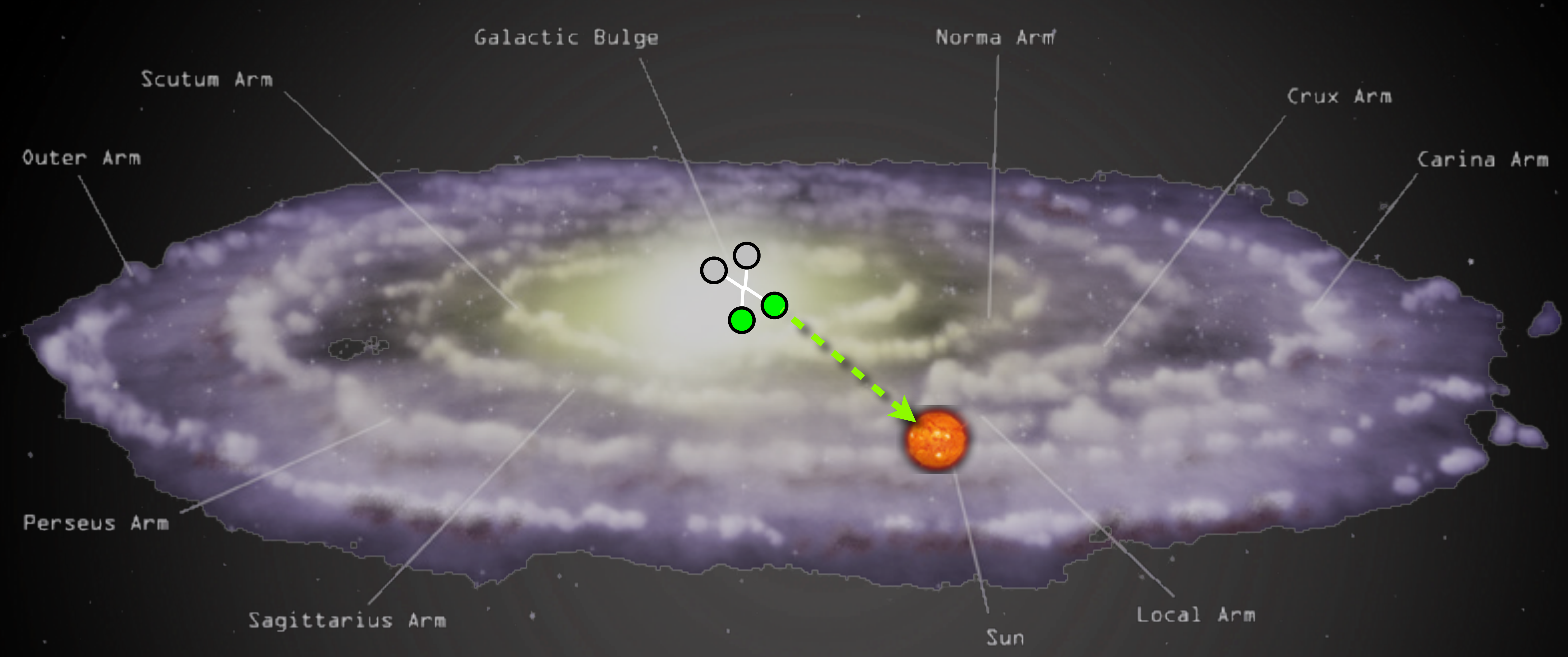
γ from outside the Galaxy

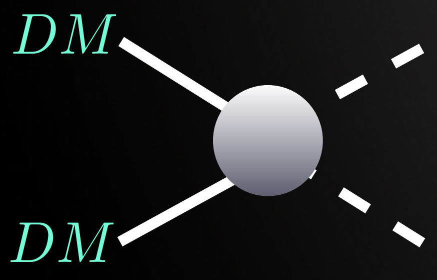


- isotropic flux of prompt and ICS gamma rays, integrated over *z* and *r*
- depends strongly on halo formation details and history

ID with neutrinos

ν from DM annihilations in galactic center

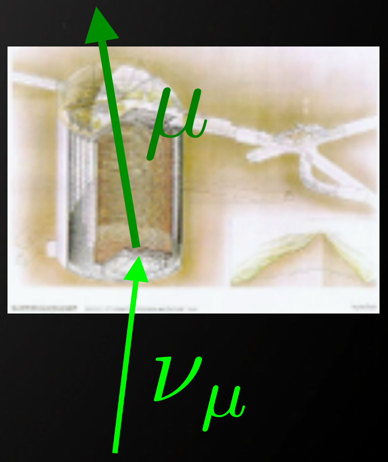




$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and ν

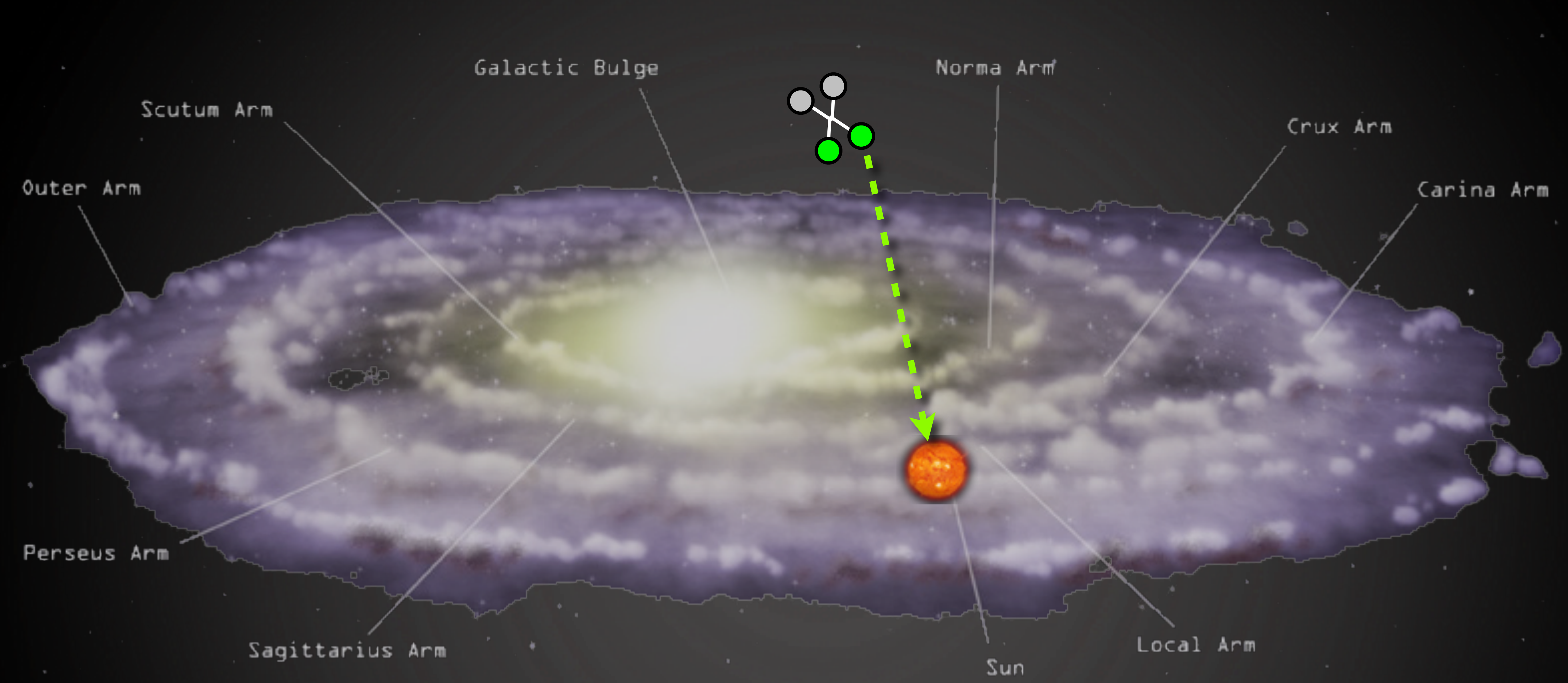
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and ν

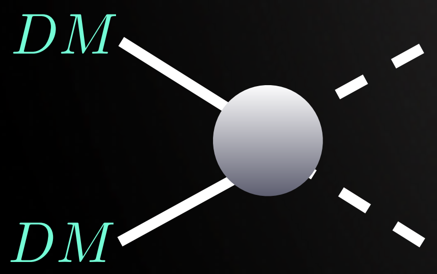
up-going muons:



ID with neutrinos

ν from DM annihilations in galactic halo

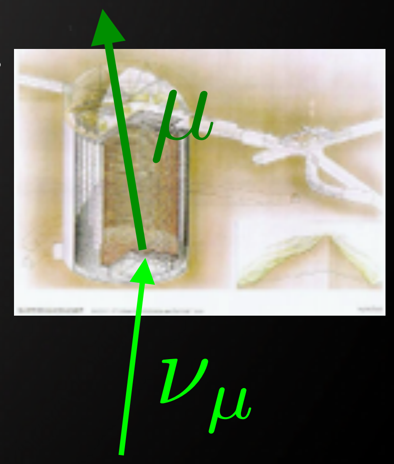




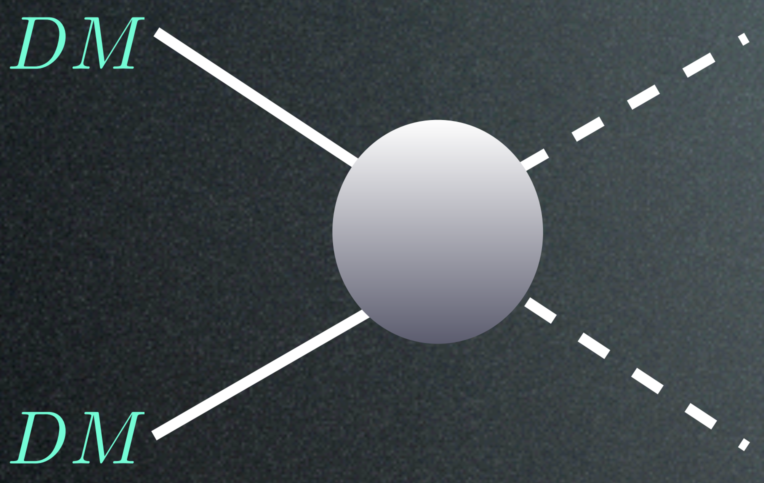
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \nu$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \nu$$

up-going muons:



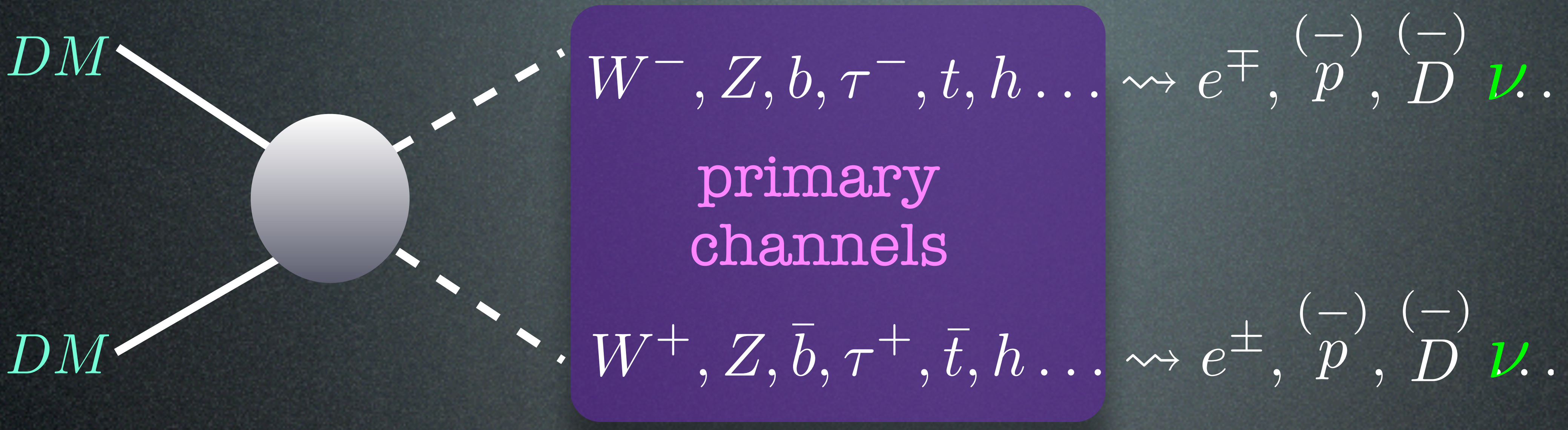
ID with neutrinos



$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu \ldots$

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D}\ \nu \ldots$

ID with neutrinos



DM

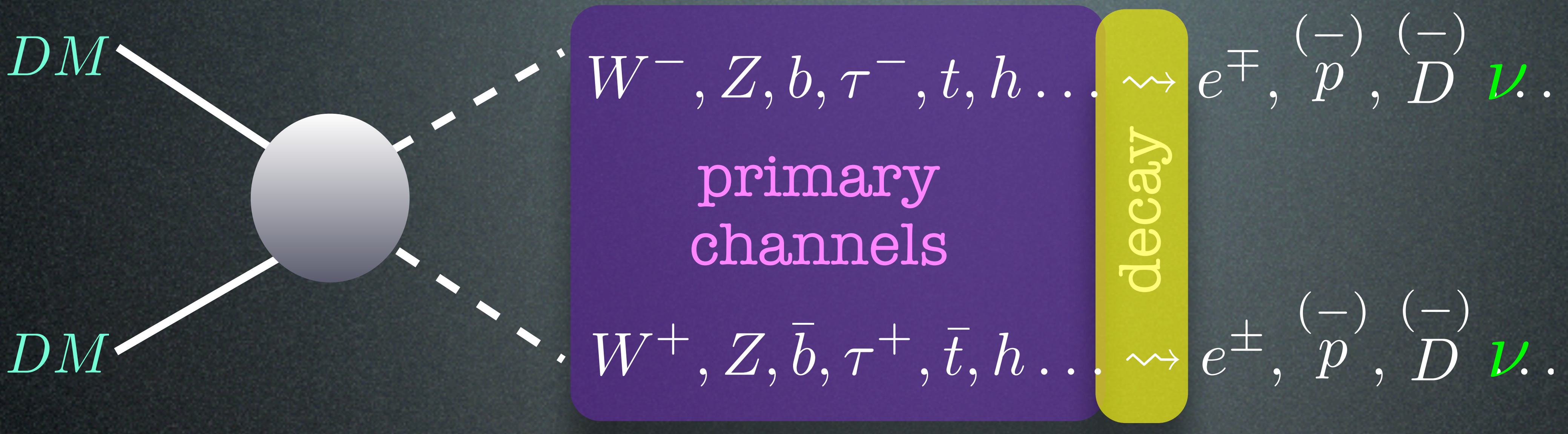
DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu\ldots$

primary channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D}\ \nu\ldots$

ID with neutrinos



DM

DM

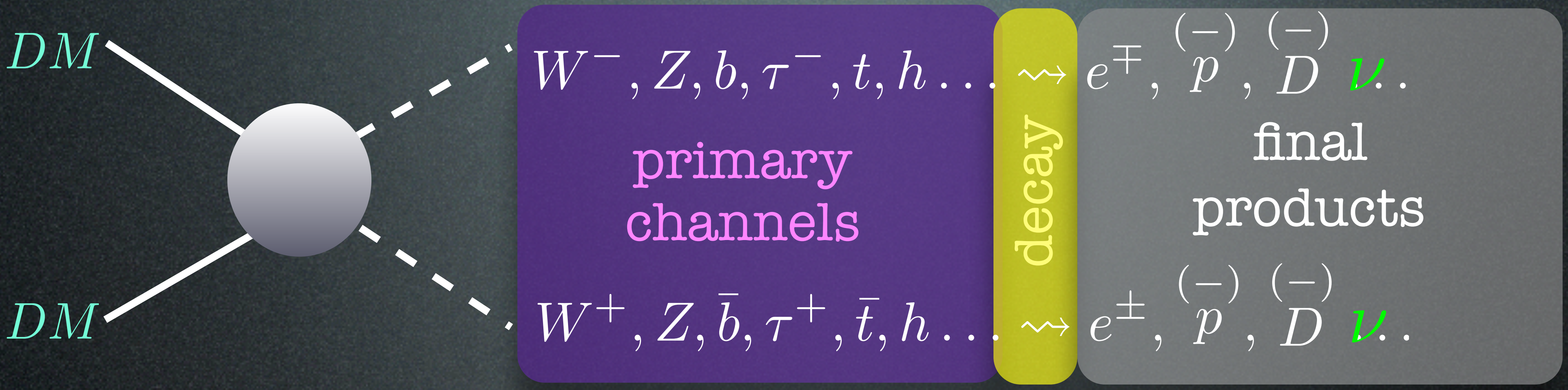
$W^-, Z, b, \tau^-, t, h\ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu\ldots$

primary
channels

decay

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h\ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D}\ \nu\ldots$

ID with neutrinos



DM

DM

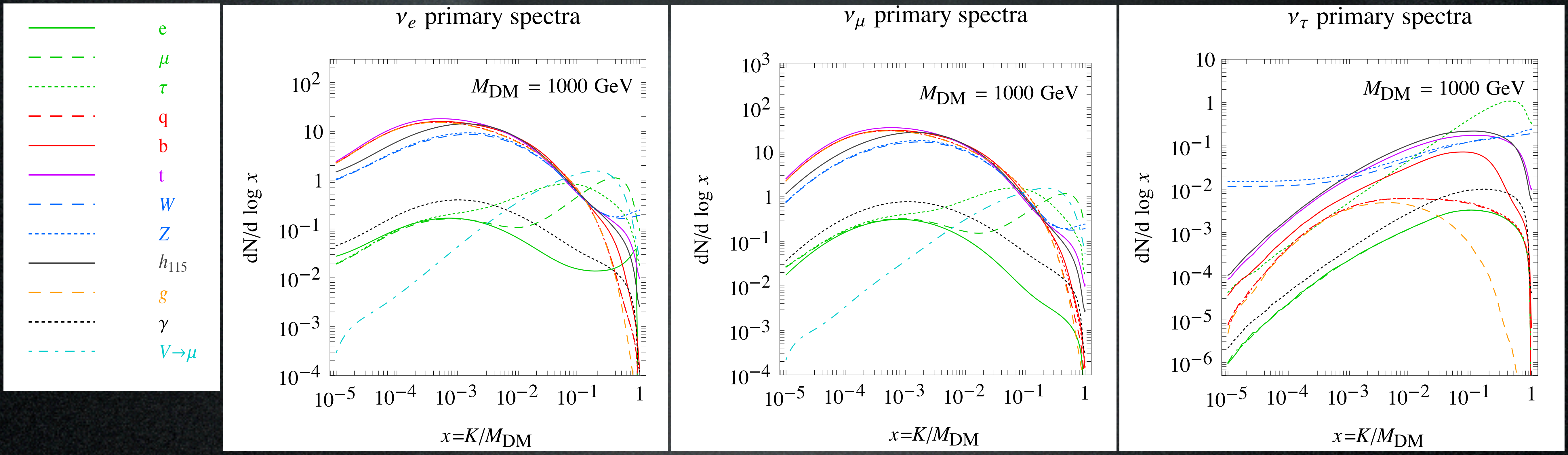
$W^-, Z, b, \tau^-, t, h\ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu\ldots$

primary channels

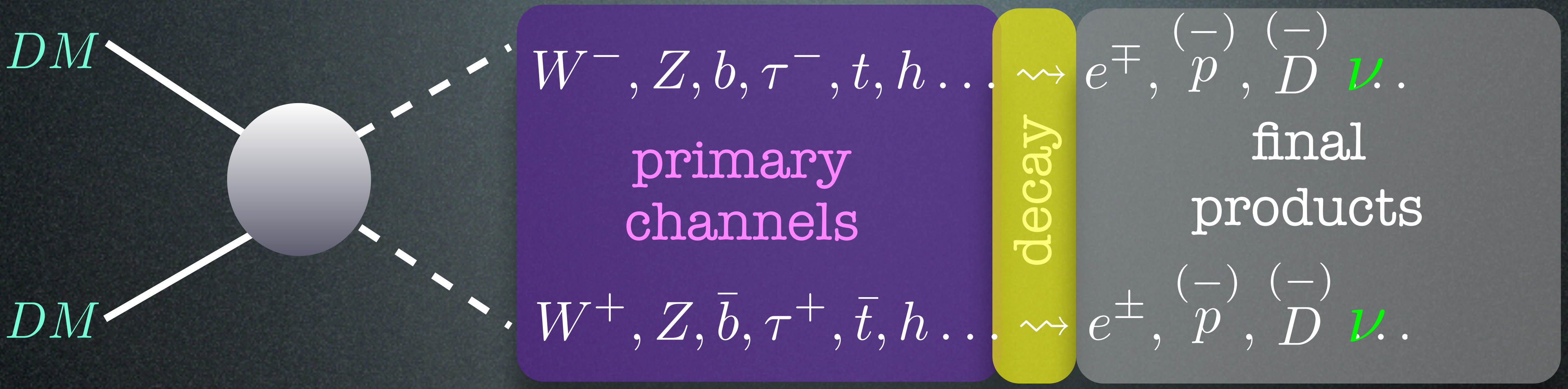
decay

final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h\ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D}\ \nu\ldots$



ID with neutrinos



DM

DM

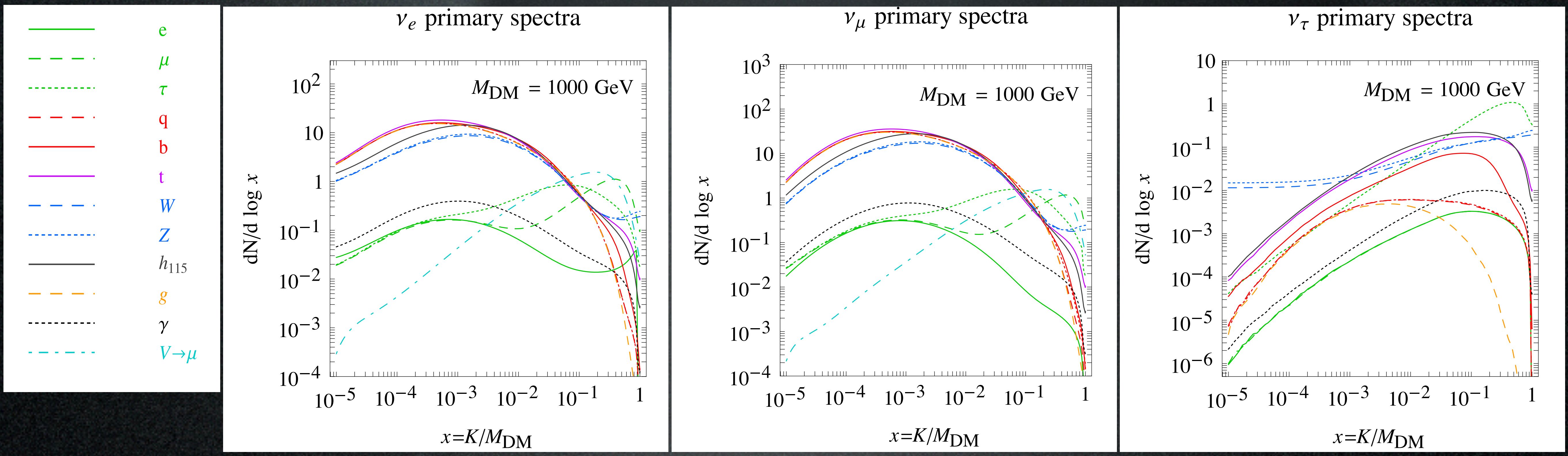
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu \ldots$

primary channels

decay

final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D}\ \nu \ldots$

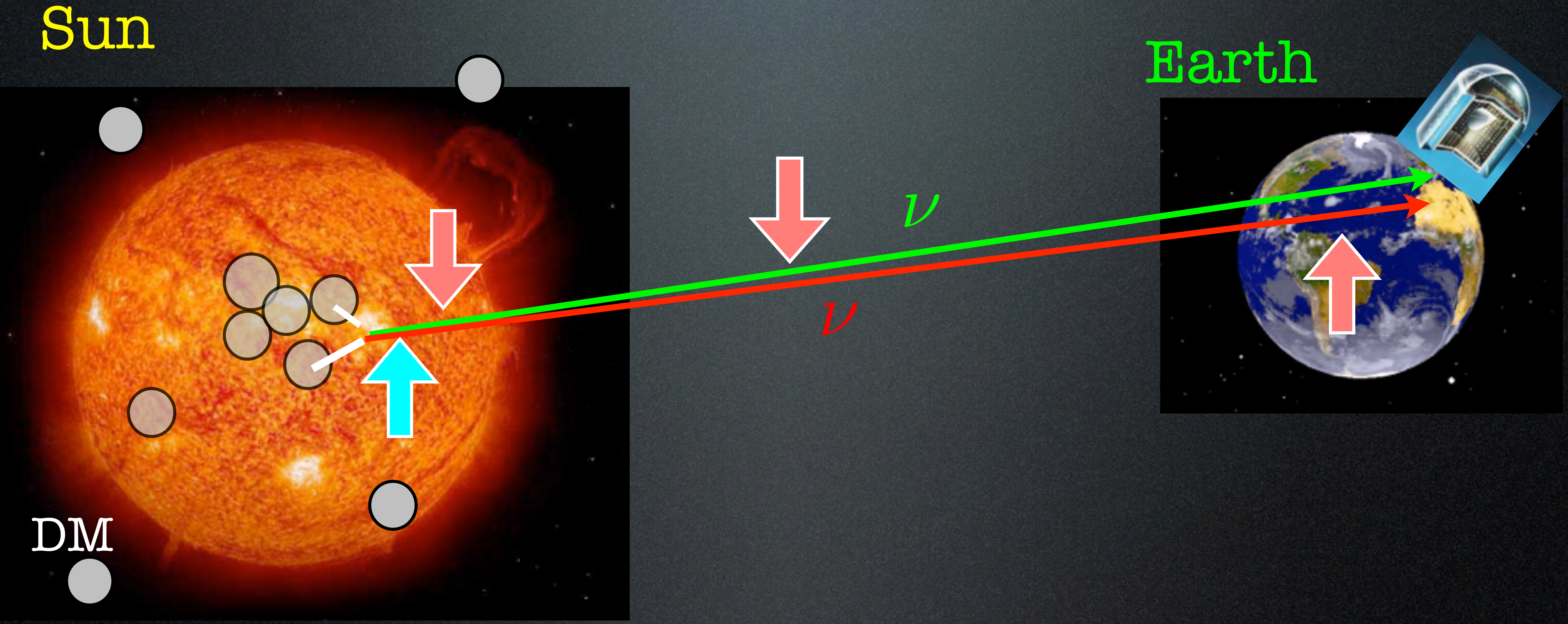


So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section σ_{ann}

ID with neutrinos

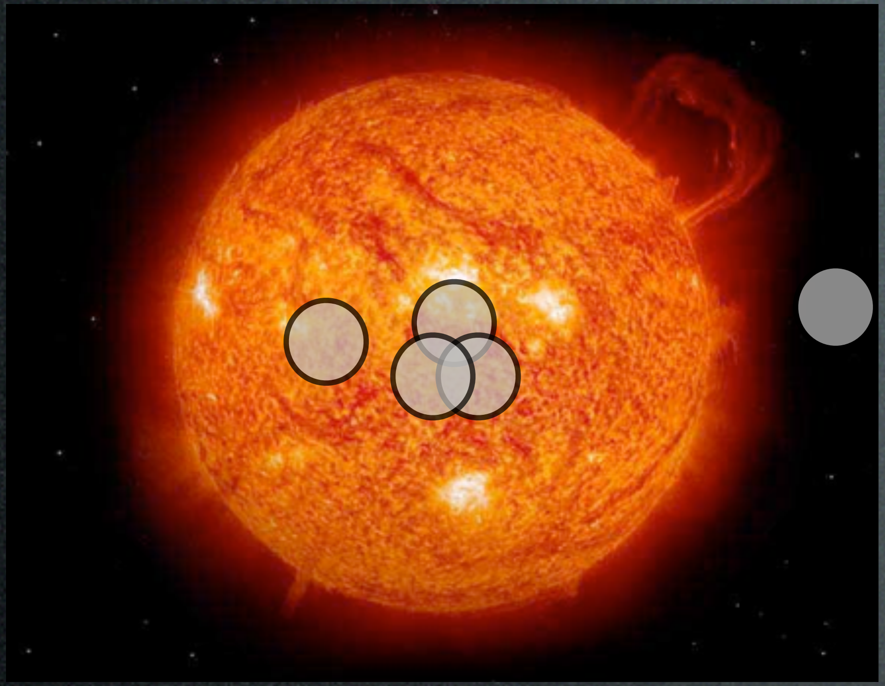
ν from DM annihilations in the Sun



Include oscillations + interactions:

- reshuffling of the 3 flavors
- distortions the spectra
- attenuations of the fluxes

1. Capture & annihilation



basics: DM particle scatters with nuclei and loses energy

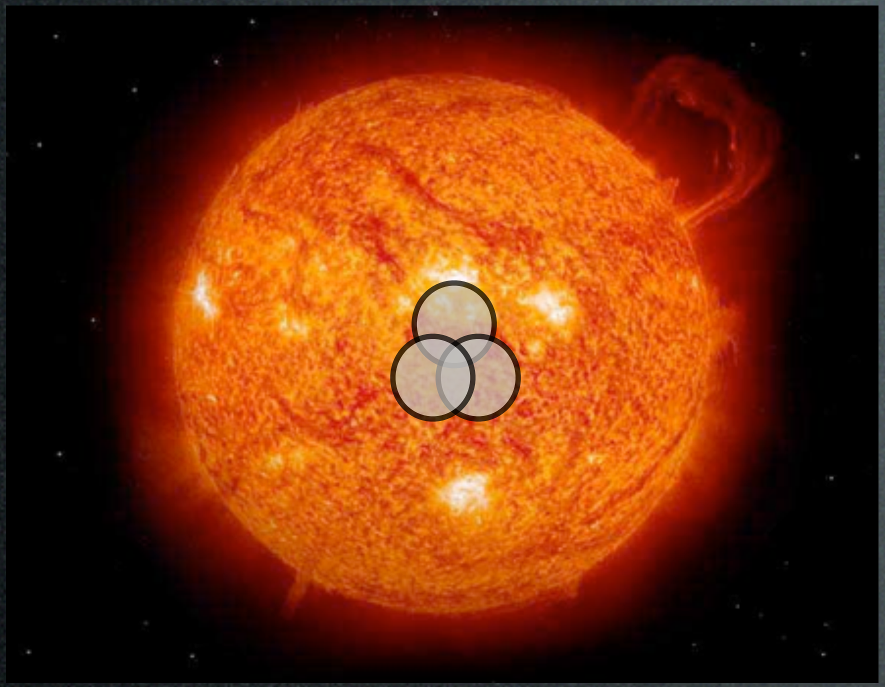
if $v_f < v_{\rm esc}$ particle is gravitationally trapped

it spirals to center of body and accumulates

annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
$$v_{{\rm esc},\odot} \simeq 620 \text{ km/s}$$
$$v_{{\rm esc},\oplus} \simeq 12 \text{ km/s}$$

1. Capture & annihilation



basics: DM particle scatters with nuclei and loses energy

if $v_f < v_{\rm esc}$ particle is gravitationally trapped

it spirals to center of body and accumulates

annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
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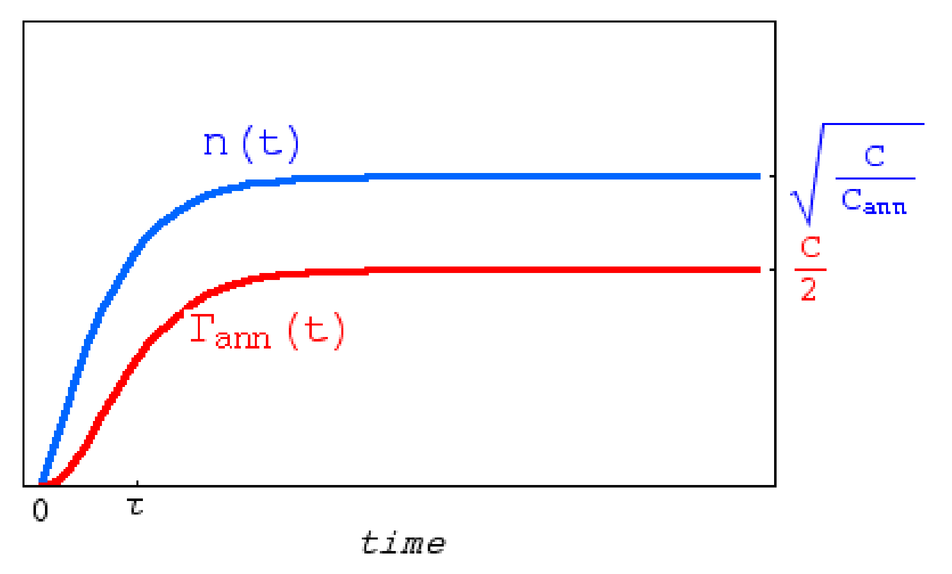
equilibrium attained:



$$\dot n = \overset{\sigma_N}{\Gamma_{\rm capt}} - \overset{\langle \sigma_{\rm ann} v \rangle}{C_{\rm ann}}\; n^2$$

$$C_{\rm ann} = \langle \sigma v \rangle \left(\frac{G_N\, M_{\rm DM}\, \rho_\odot}{3\,T_\odot} \right)^{3/2}$$

$$n(t) = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \tanh\left(\frac{t}{\tau}\right)$$

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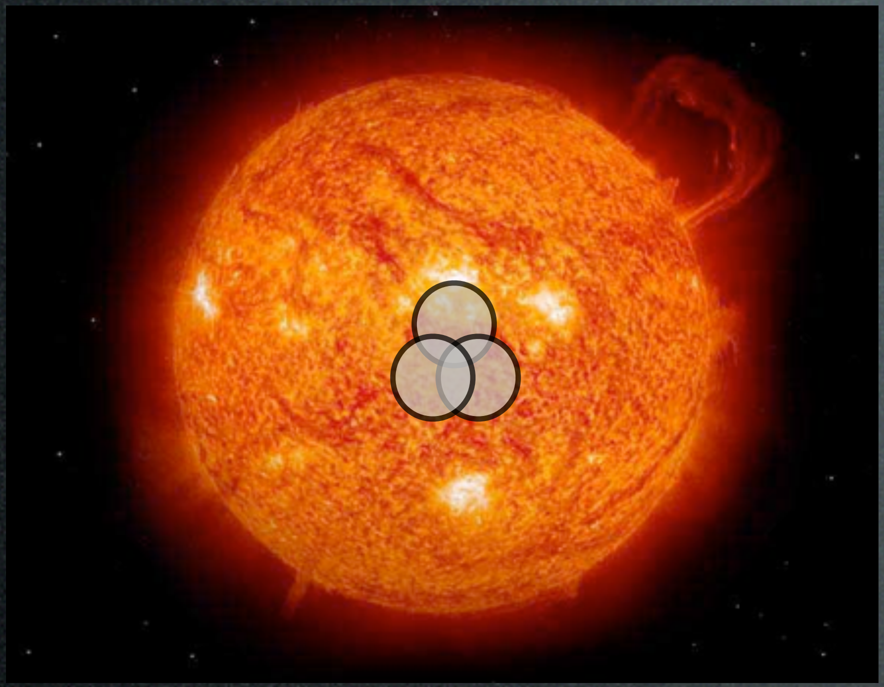

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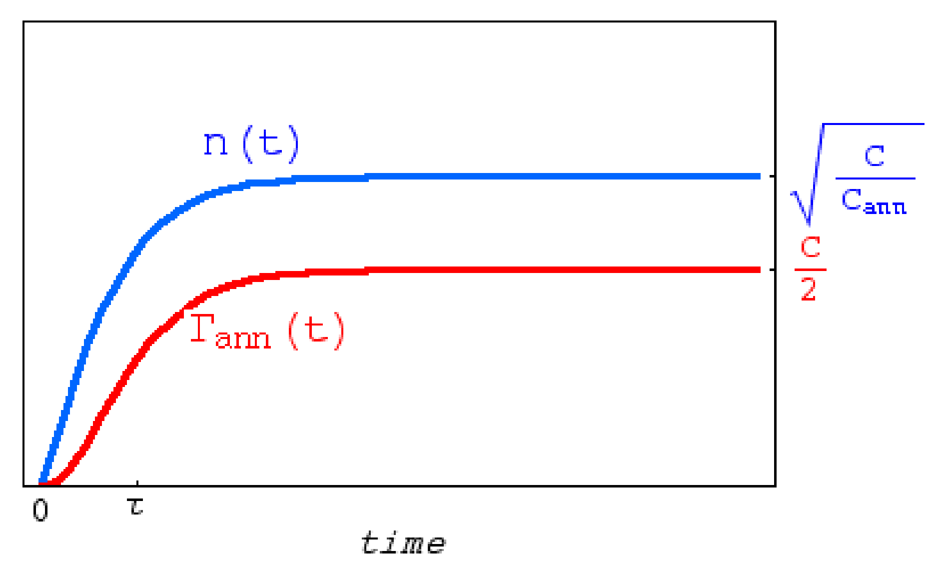

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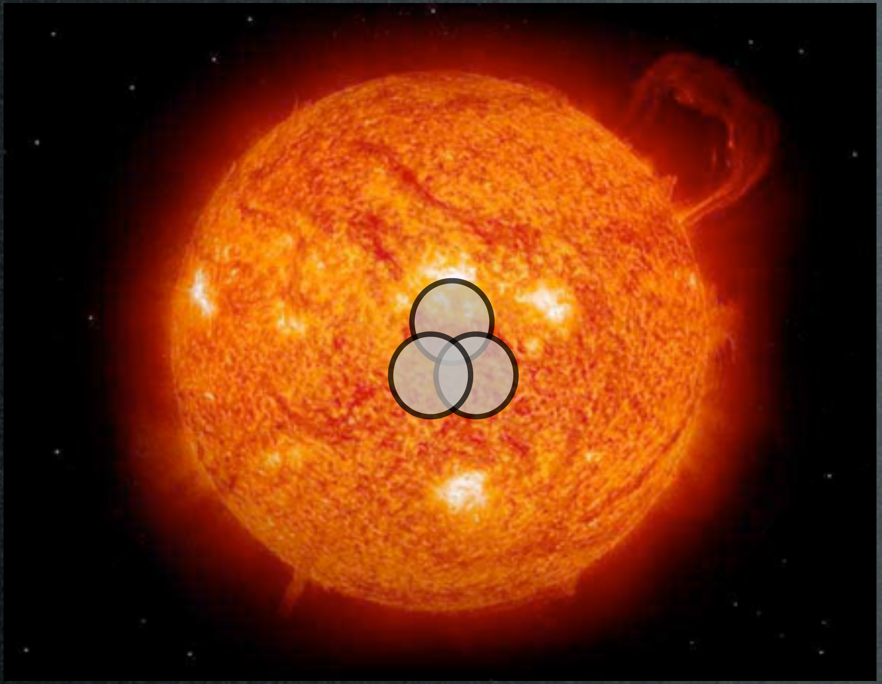

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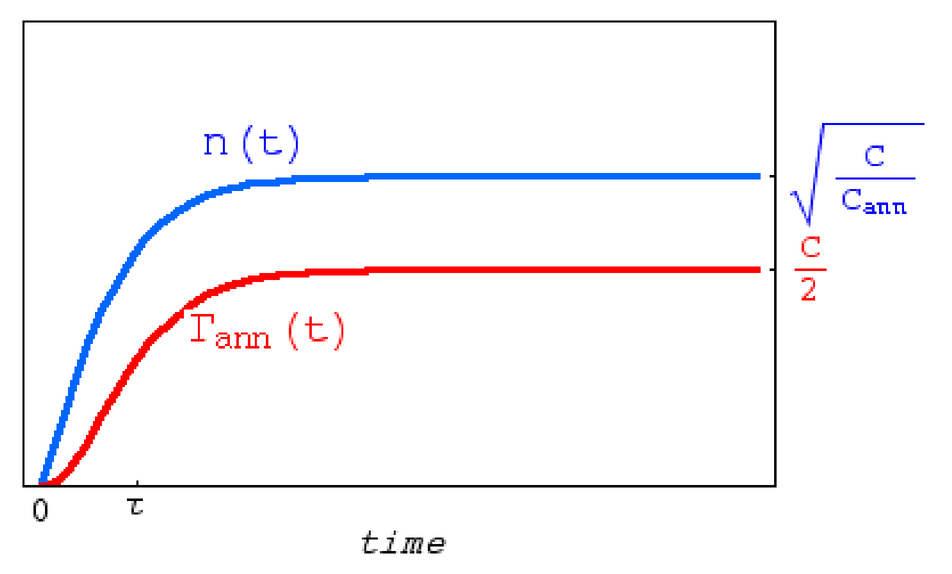

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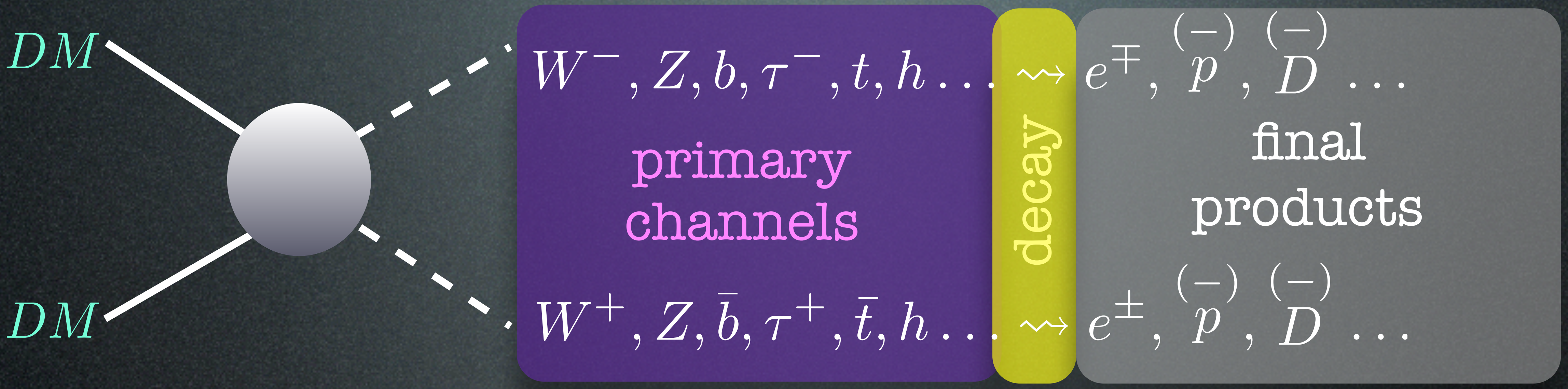

DM

DM

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

primary channels

decay

final products

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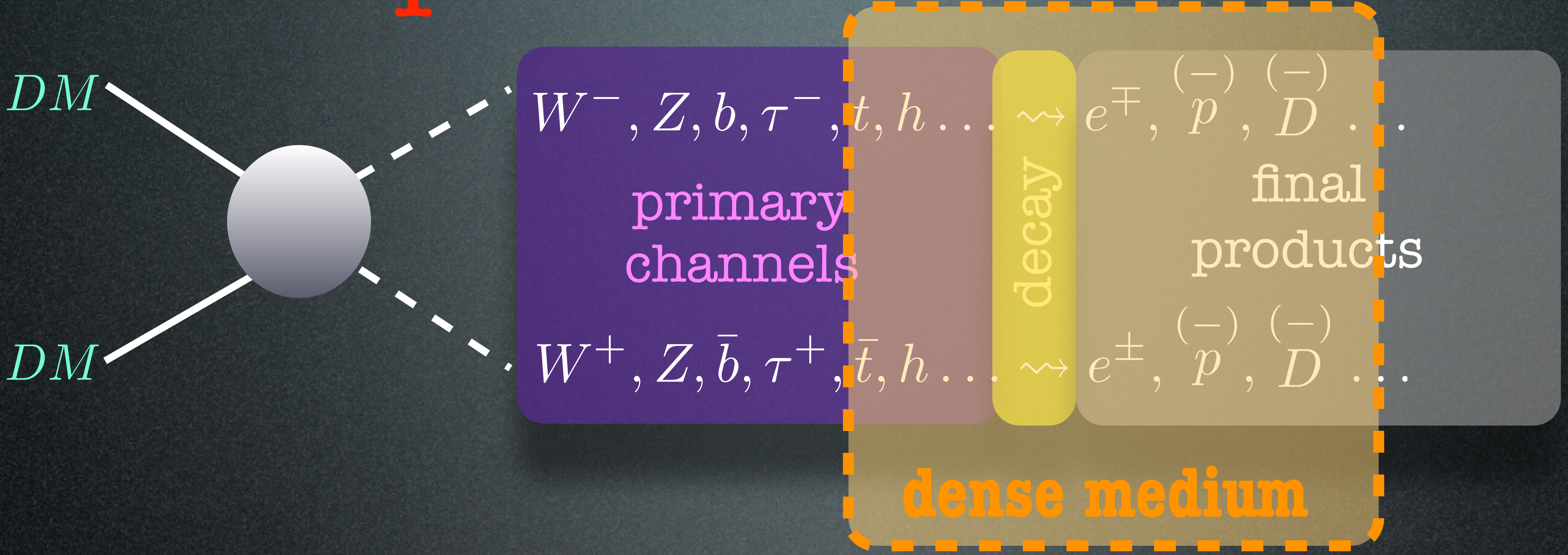

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dense medium

Effects of the medium:

1) light hadrons (π, K...) and leptons (μ) are stopped and decay at rest

2) heavy hadrons/leptons lose some energy before decaying

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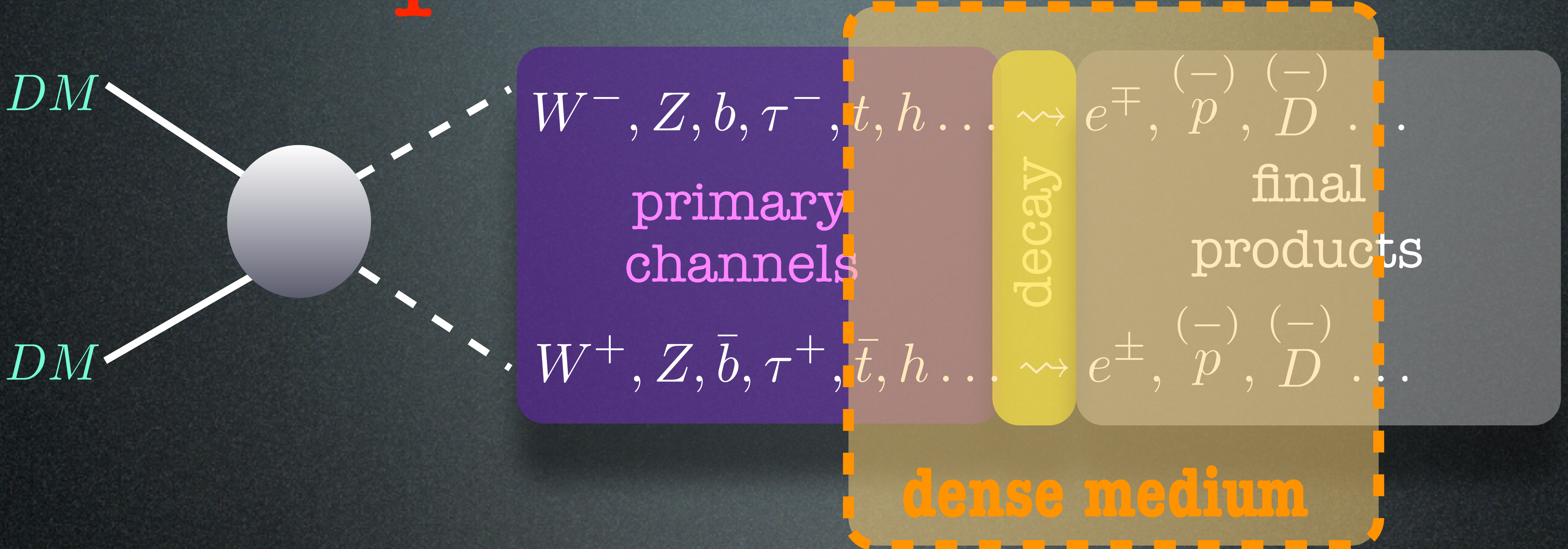

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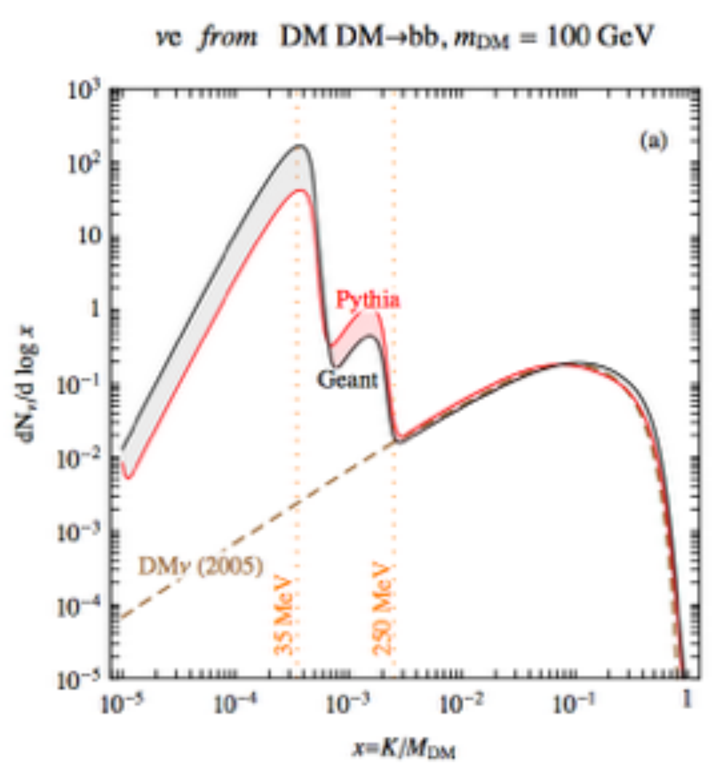

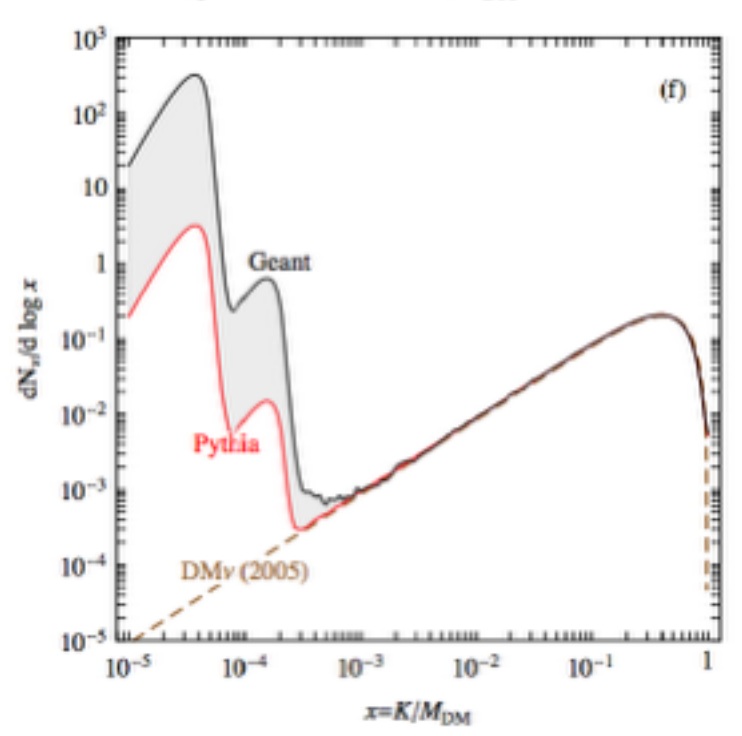

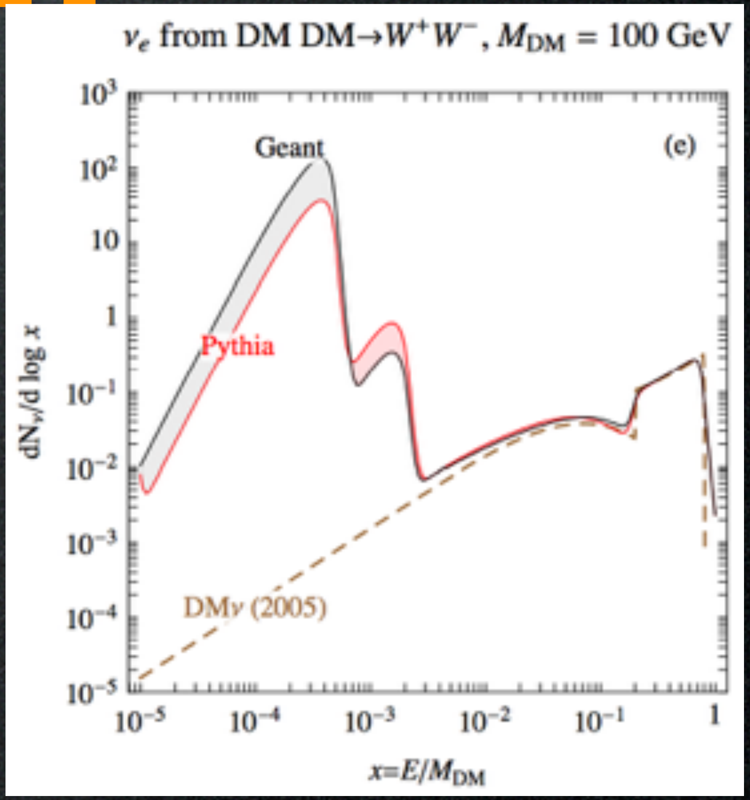

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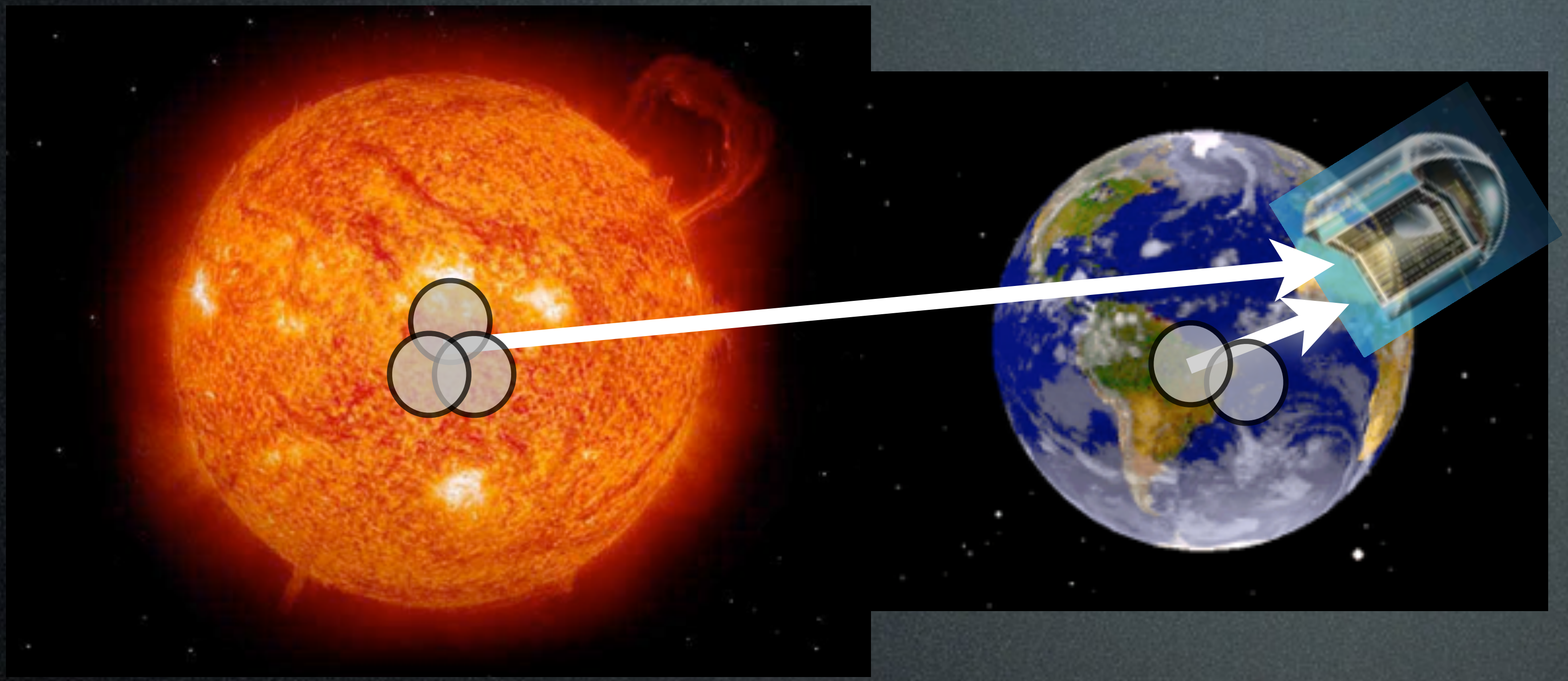

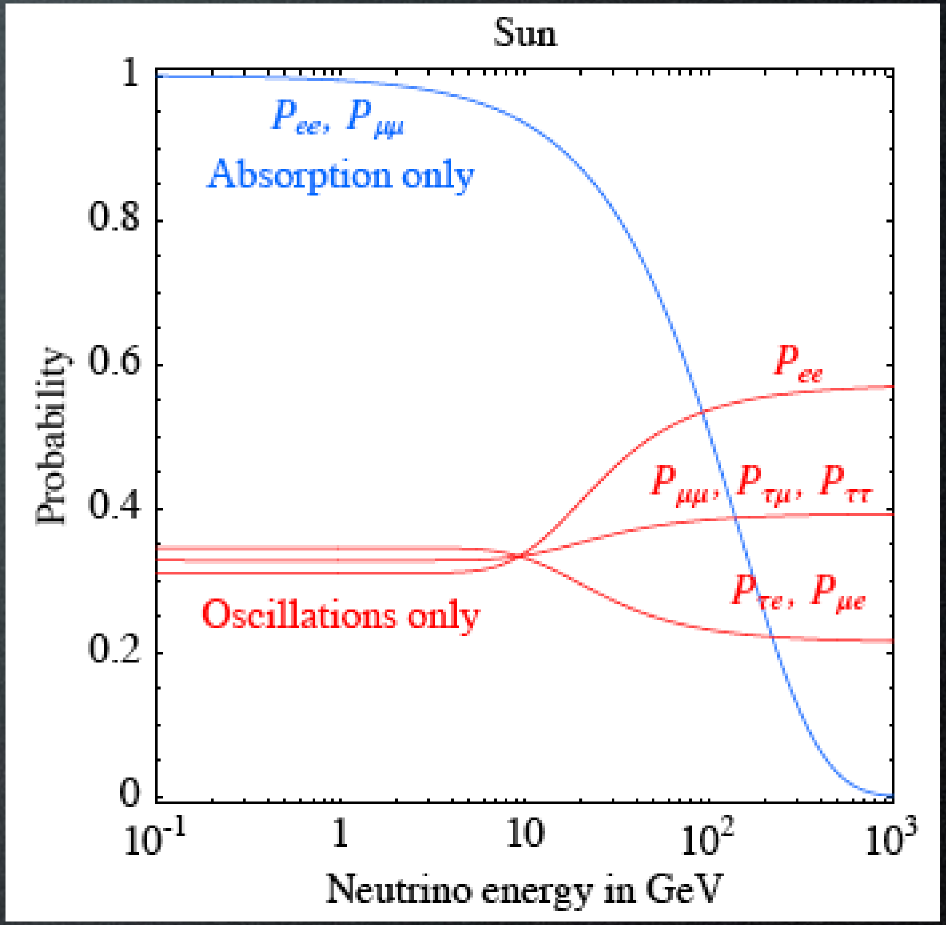

oscillations + interactions

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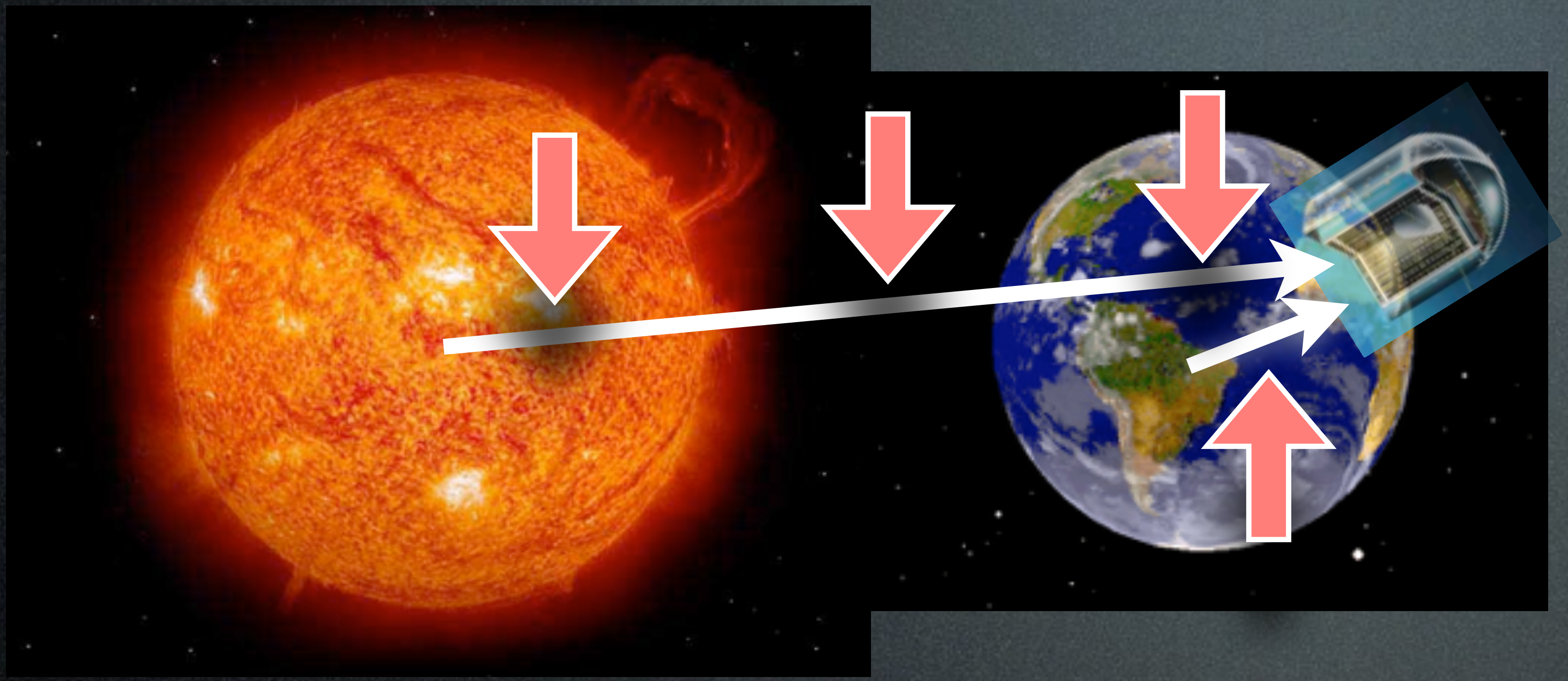

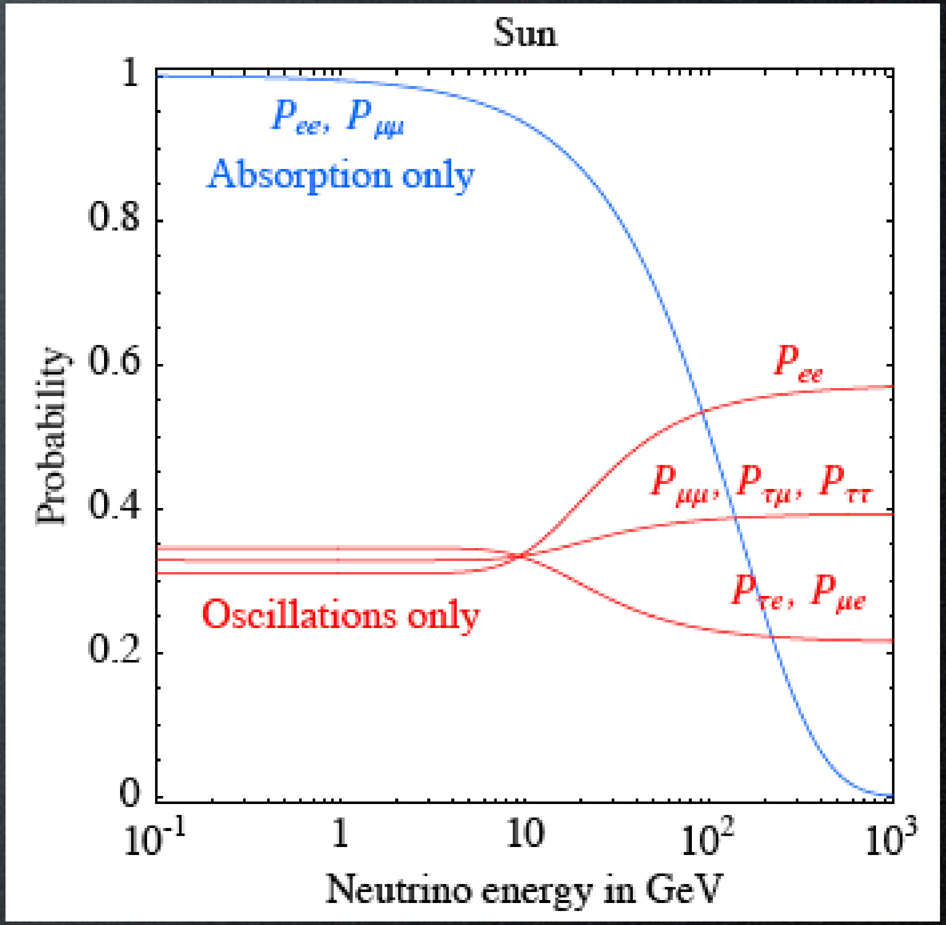

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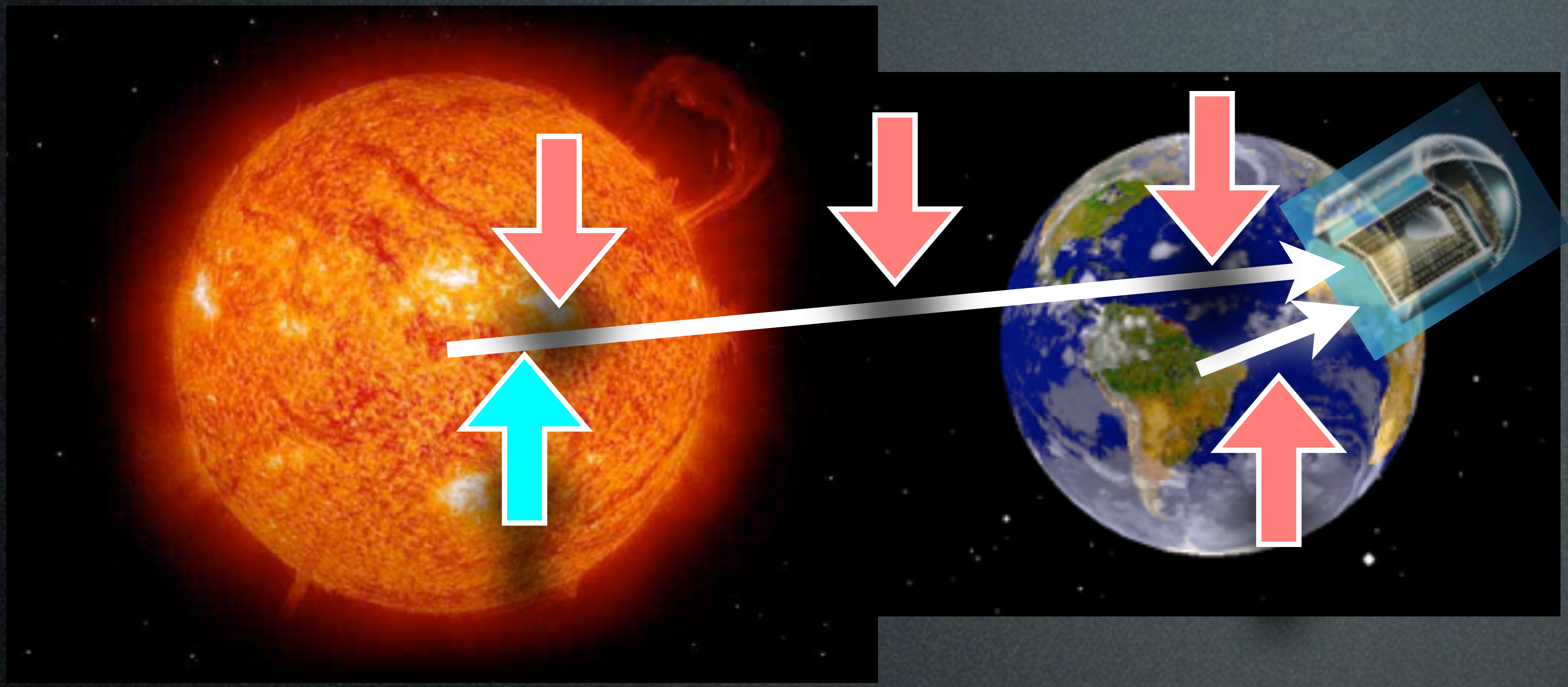

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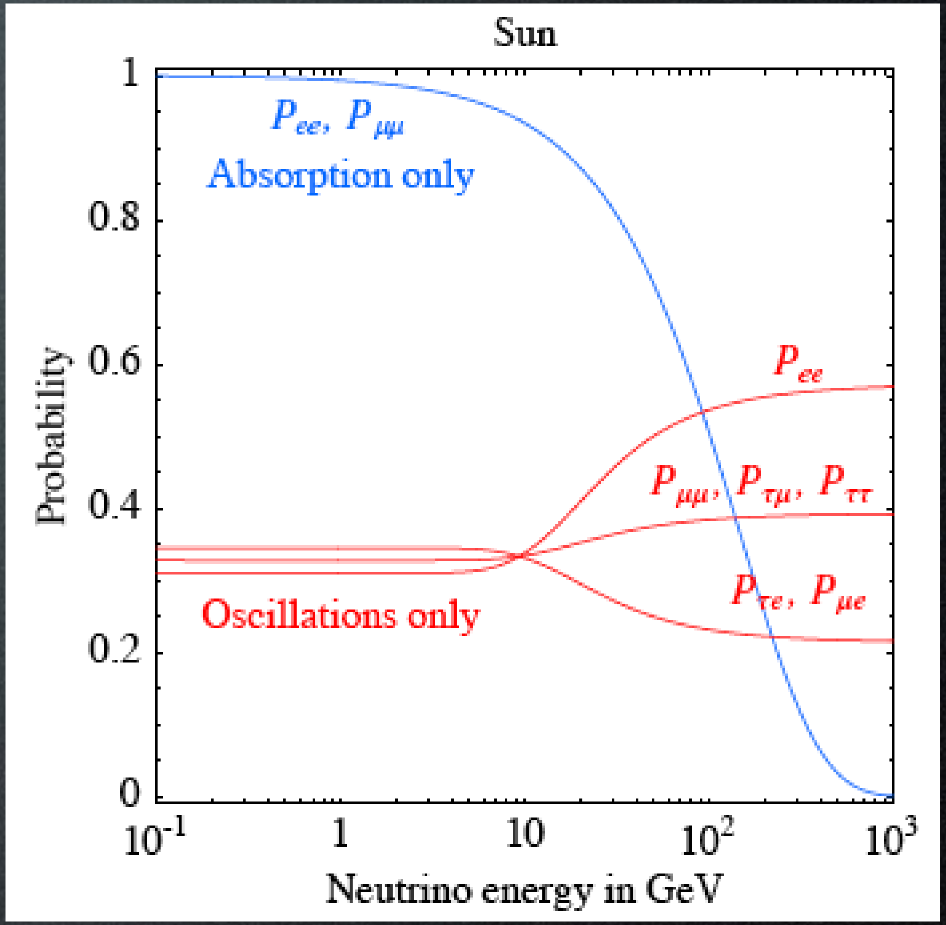

Summary

	Pro	**Contra**
e^+	local, info in spectral shape	propagation
e^-	local	propagation, larger background
$e^+ + e^-$	higher energy	propagation, larger background
$\bar{p}$	astro bkgd under control	propagation, largish volume, little info in spectral shape
prompt γ	straight line, no absorption (in galaxy), 'smoking gun'	suppressed, model dependent
secondary γ	large volumes	environment dependent (in intensity and spectrum)
radio	angular resolution	environment dependent (in intensity and spectrum)
$\bar{d}$	'unique'	very small flux (+ see antiprotons)
$\nu, \bar{\nu}$	straight line, cross section increases with energy	challenging detection