Introduction to Dark Matter

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Valencia, May 21-31, 2018

Plan of lectures

- I Evidences and generalities

- II Non-gravitational searches

Disclaimer:

Not all experimental techniques will be discussed

Axion searches

Sterile neutrino signals

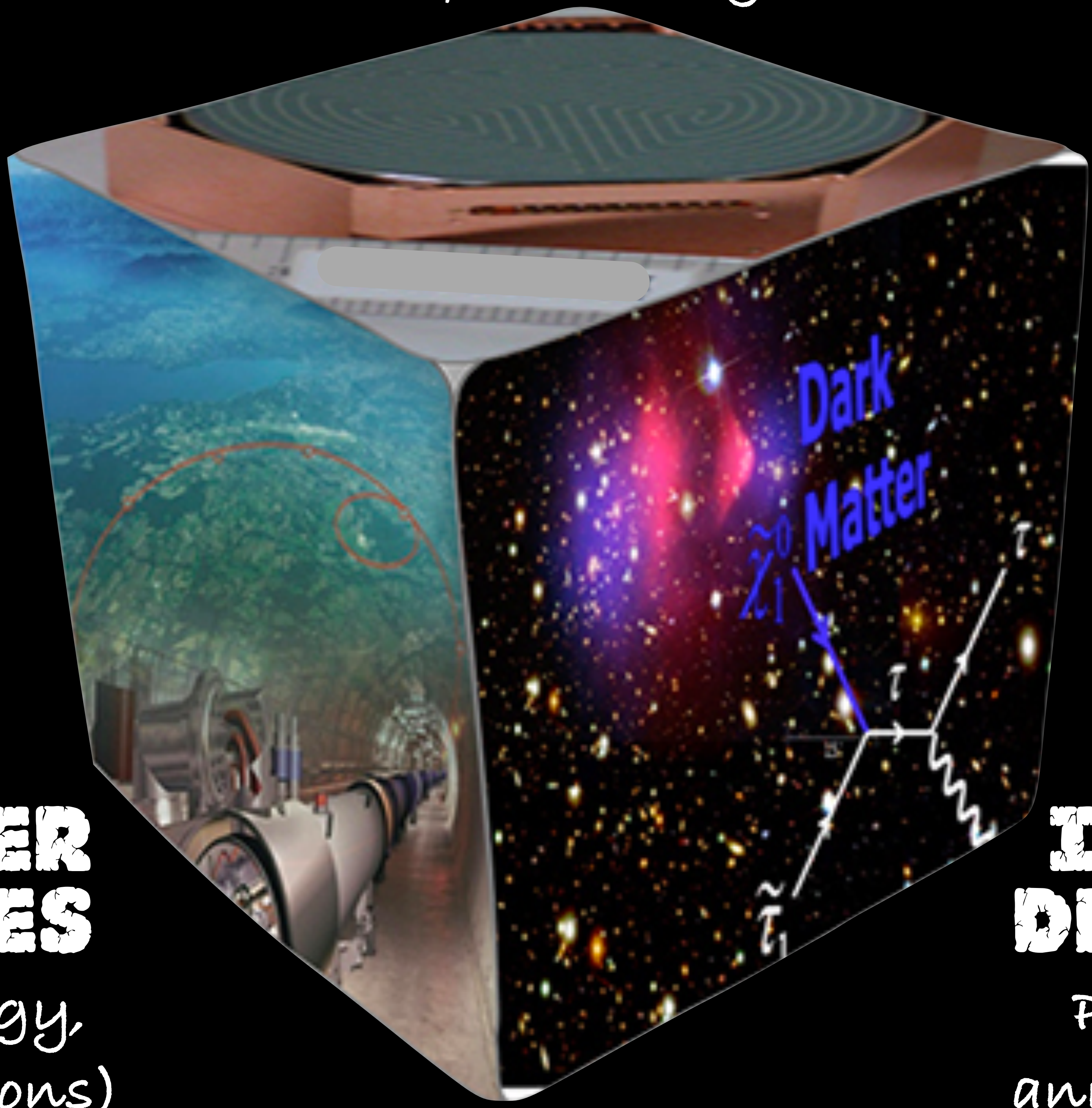
Primordial Black Holes

...

DM DETECTION

DIRECT DETECTION

Nuclear recoil produced by DM scattering



COLLIDER SEARCHES

Missing energy, mono-jets (bosons)

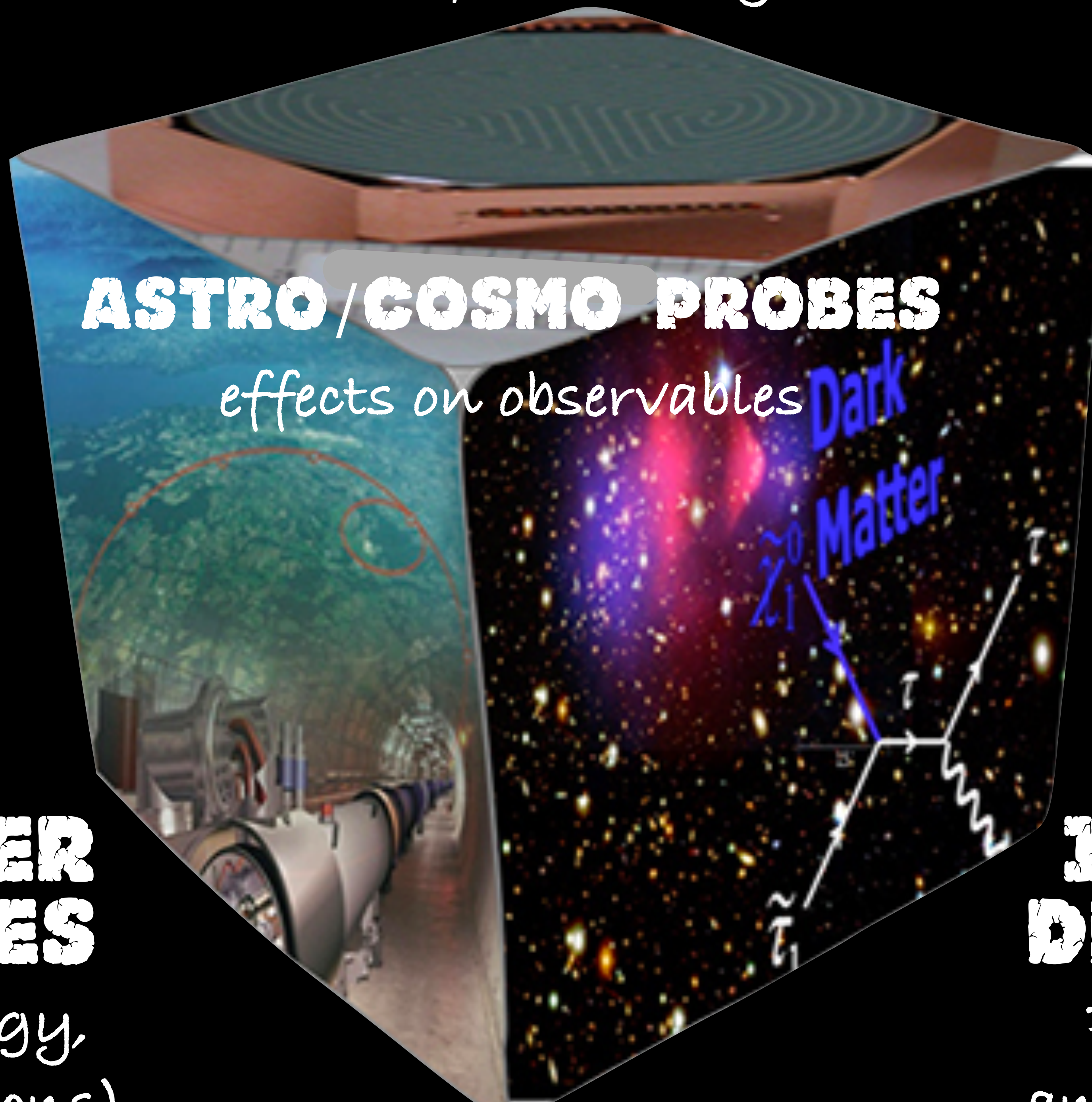
INDIRECT DETECTION

Products of DM annihilation/decay

DM DETECTION

DIRECT DETECTION

Nuclear recoil produced by DM scattering



ASTRO/COSMO PROBES

effects on observables

COLLIDER SEARCHES

Missing energy, mono-jets (bosons)

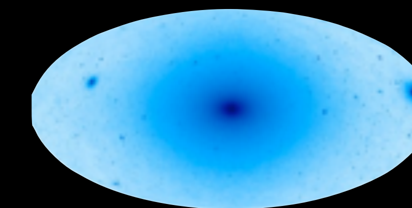
INDIRECT DETECTION

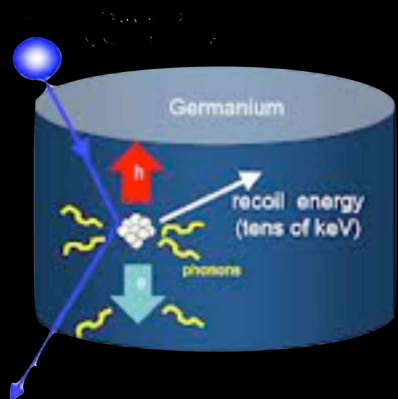
Products of DM annihilation/decay

Annihilation

thermal freeze-out (early Universe)

indirect detection (now)

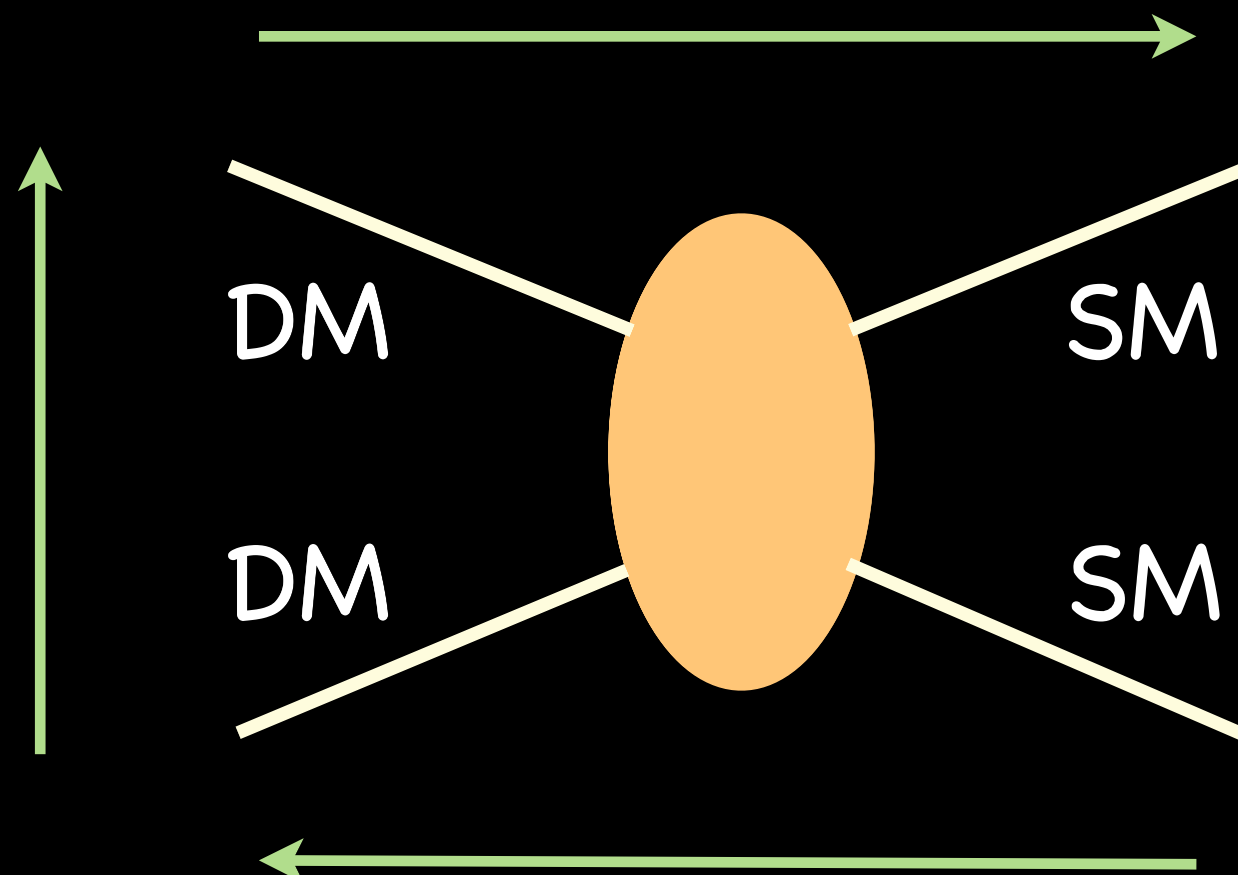




Scattering

direct detection

capture in Sun/Earth



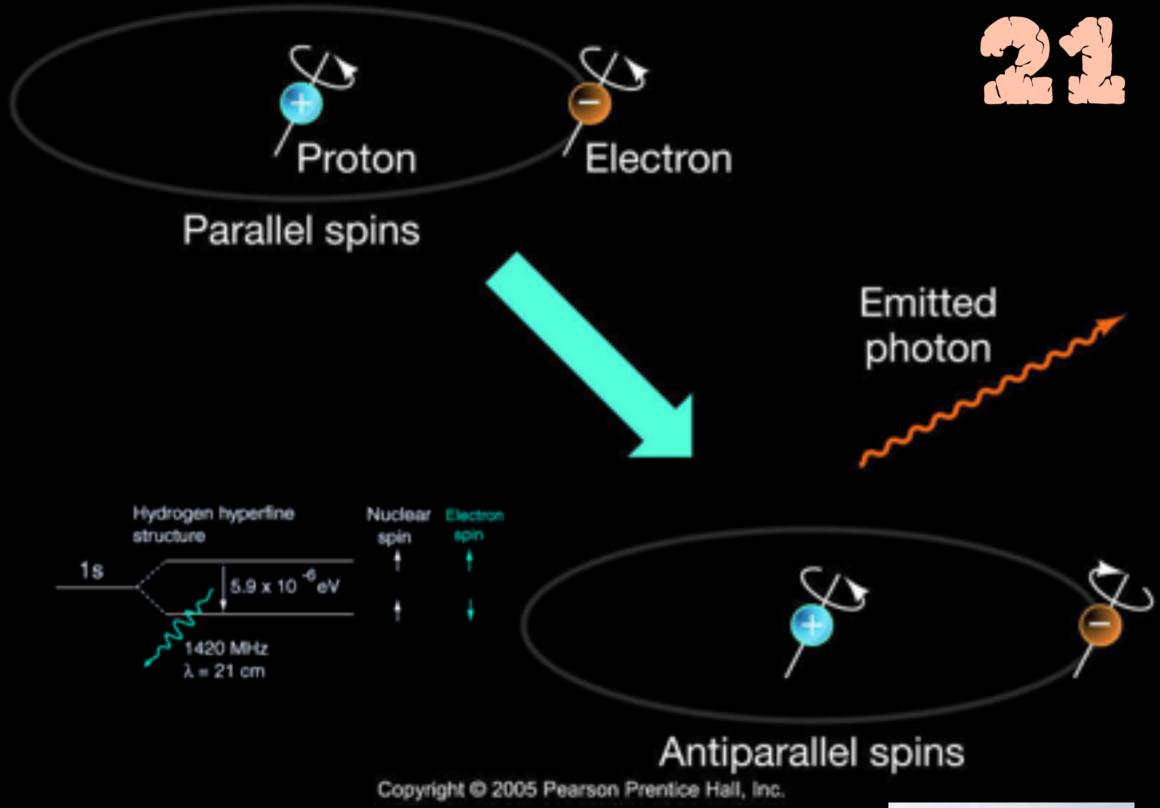
Production

colliders

ASTRO/COSMO PROBES

Effects on BBN
Changes in the ionization history (CMB)
21 cm signal
Modification of structure formation
Modification of stars dynamics
Planet warming
…

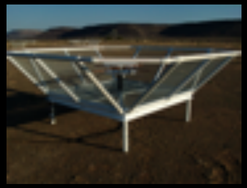
21 CM LINE



Hyperfine transition: ν = 1420 Mhz

21cm photon form HI clouds during the dark ages: ν ~ 100 Mhz



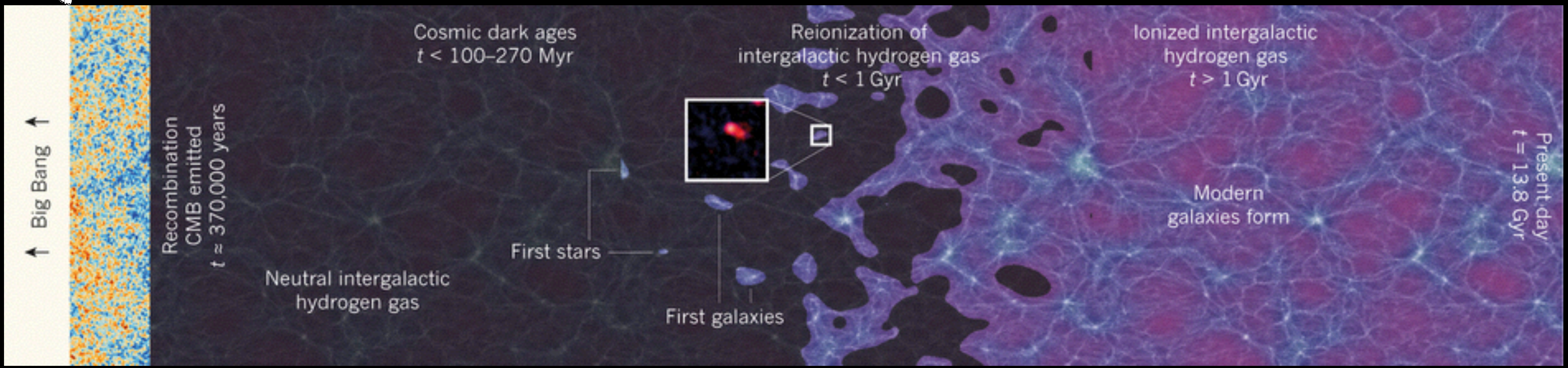
Interferometers
LOFAR, MWA, PAPER, GMRT
HERA, SKA

Galaxy Surveys


Redshift

$z \sim 5\text{-}30$

$z < 5$



$$\delta T_b(\nu) \propto x_{HI}\left(1-\frac{T_{CMB}}{T_S}\right)$$

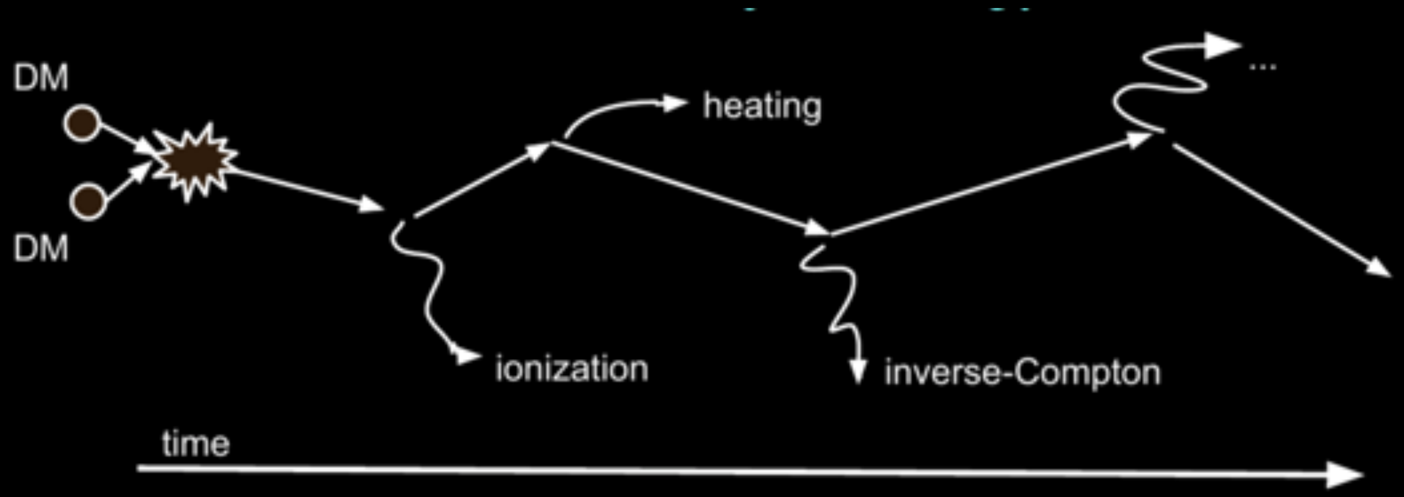
Fraction of neutral H

spin temperature: occupation of the two states

Astrophysical processes decouple T_S from T_{CMB}

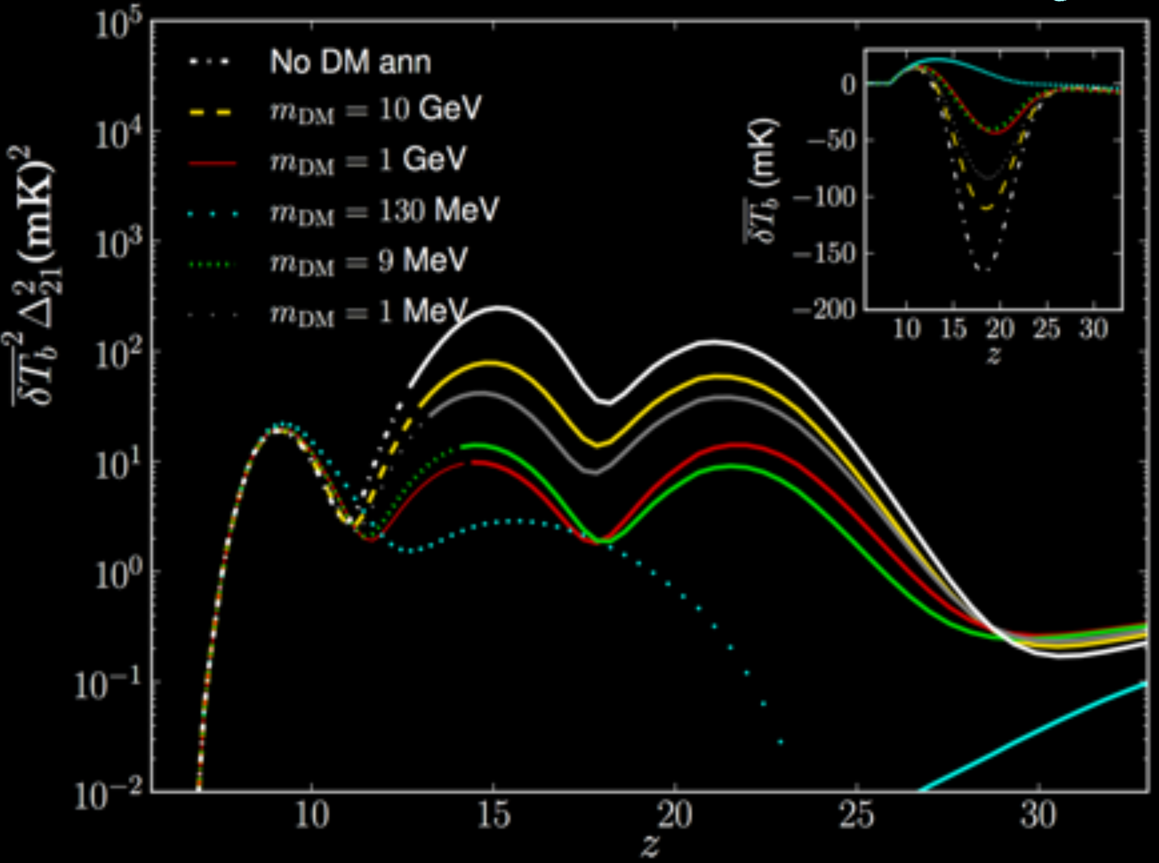
Dark matter annihilation:
injects energy into the IGM

Chen'03, Hansen'03, Pierpaoli'03, Padmanabhan'05, Shchenikov'06, Furlanetto'06, Valdes'07, Chuzhoy'07, Cumberbatch'08, Natarajan'09, Yuan'09, Valdes'12, Evoli'14



From A. C. Vincent

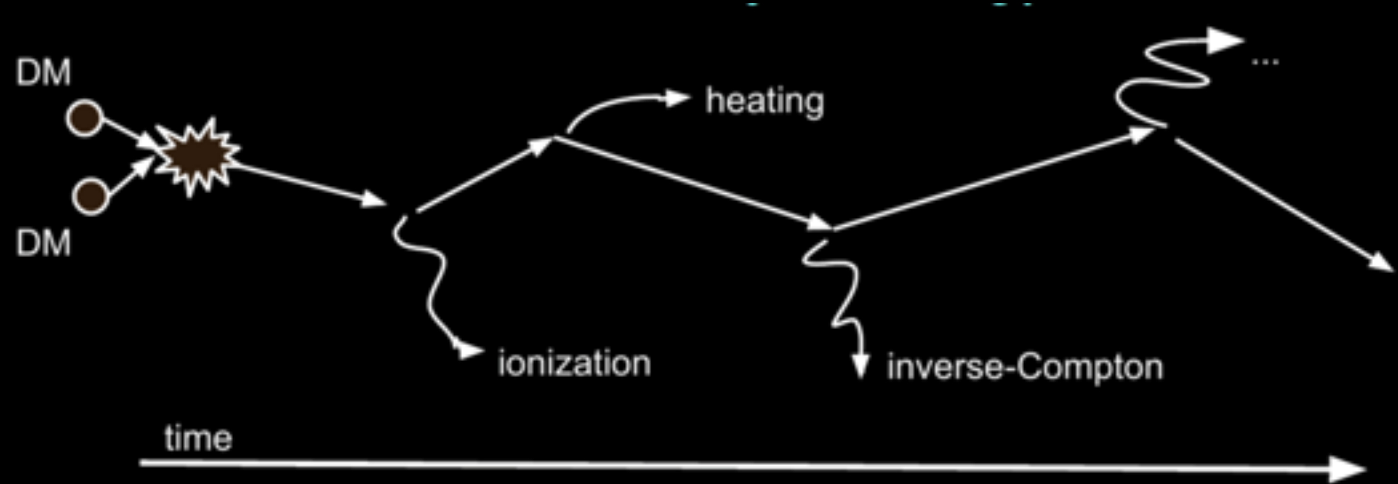
DM: suppress power
but effects degenerated with astrophysics



L. Lopez-Honorez, O. Mena, A. Moliné, SPR and A. C. Vincent, JCAP 1608:004, 2016

EFFECTS ON THE CMB

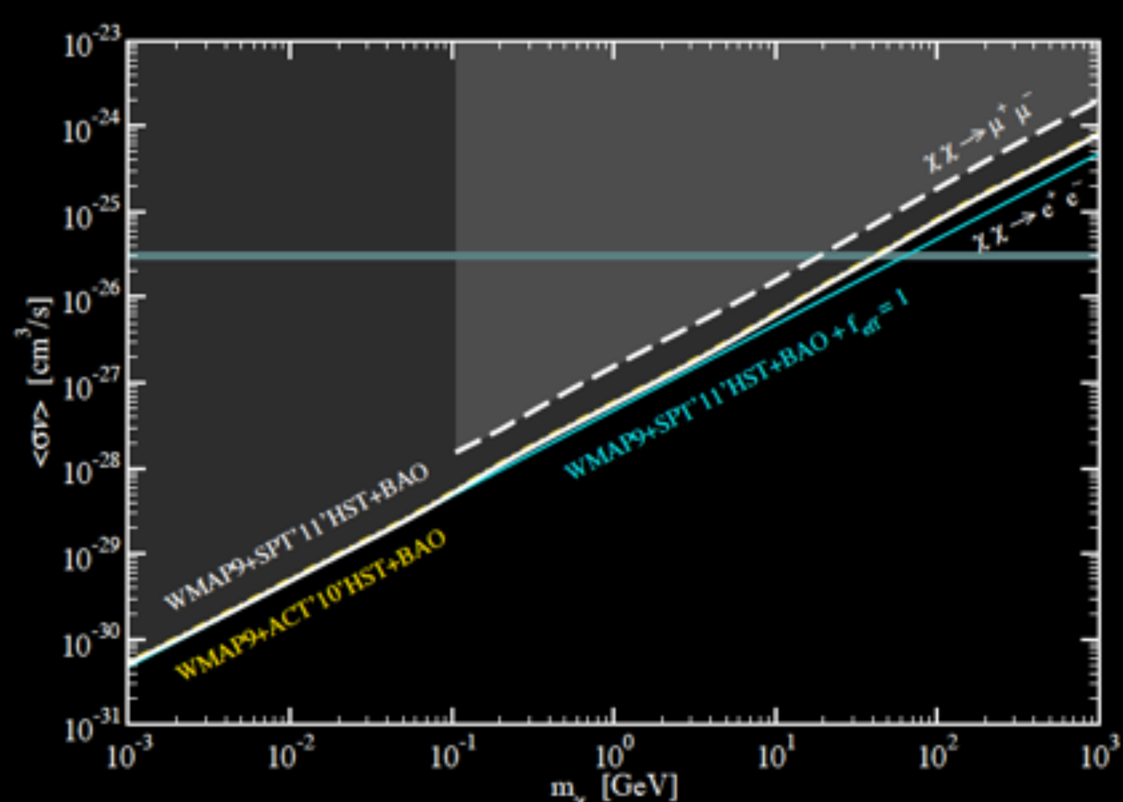
Dark matter annihilation:
injects energy in the IGM



From A. C. Vincent

Padmanabhan & Finkbeiner '05, Zhang et al.'06, Finkbeiner et al. '08, Galli et al. '09, Slatyer et al. '09, Kanzaki et al. '09, Galli et al. '11, Hutsi et al. '11, Evoli et al. '12, Giesen et al. '12, Evoli et al. '12, Slatyer '12, Fry & Reid '13, Cline & Scott '13, Weniger et al. '13, Lopez-Honorez et al. '13, Galli et al. '13, Diamanti et al. '14, Madhavacheril et al. '14, Slatyer '16, Poulin et al. '15, Kawasaki et al, '16, Slatyer & Wu '17

It modifies the propagation of photons from the LSS (reionization history) and affects CMB temperature and polarization anisotropies



Advantage over other DM annihilation probes:

do not suffer from astrophysics uncertainties

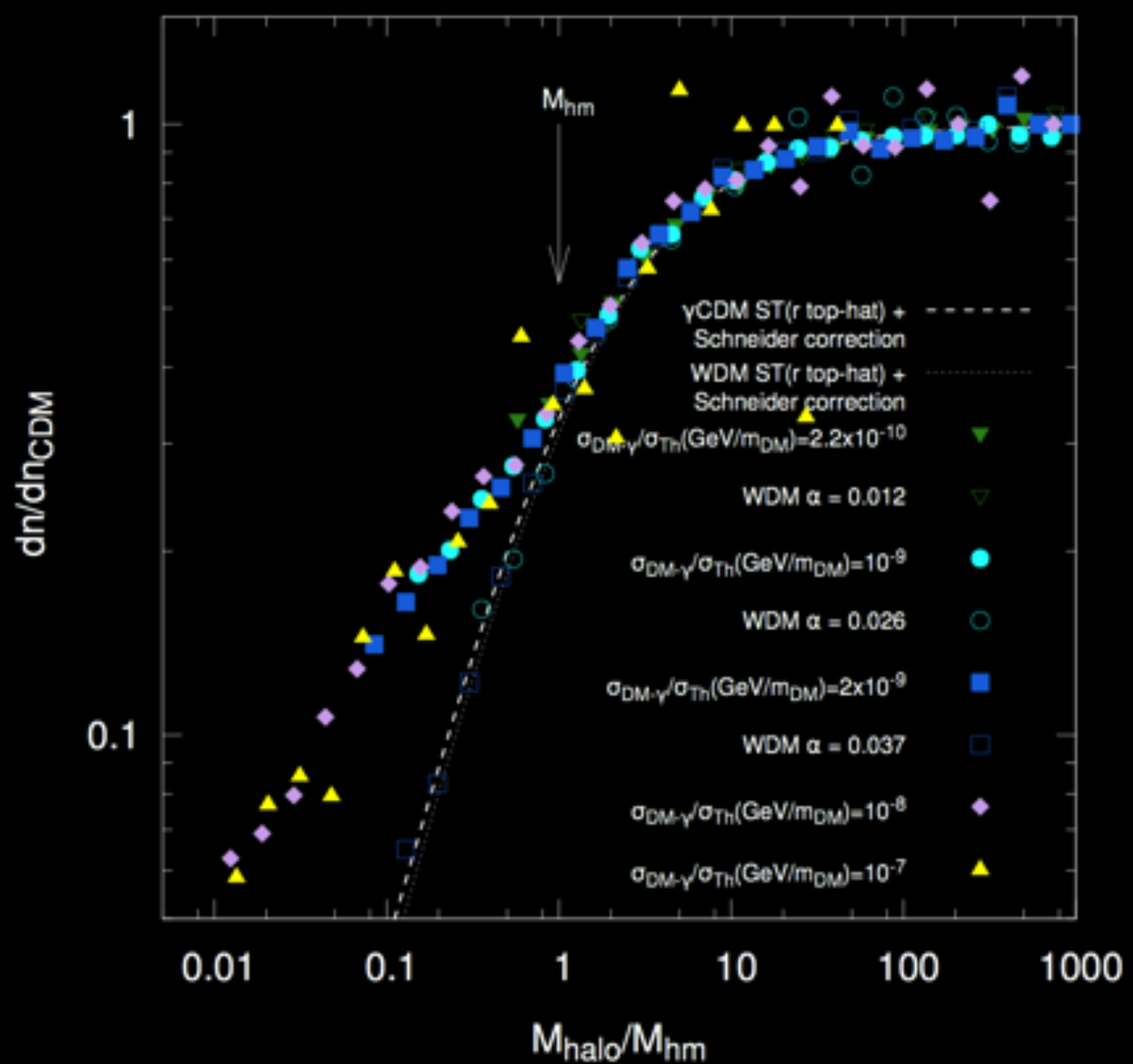
L. Lopez-Honorez, O. Mena, SPR and A. C. Vincent, JCAP 1307:046, 2013

DM-RADIATION INTERACTIONS

Collisional damping

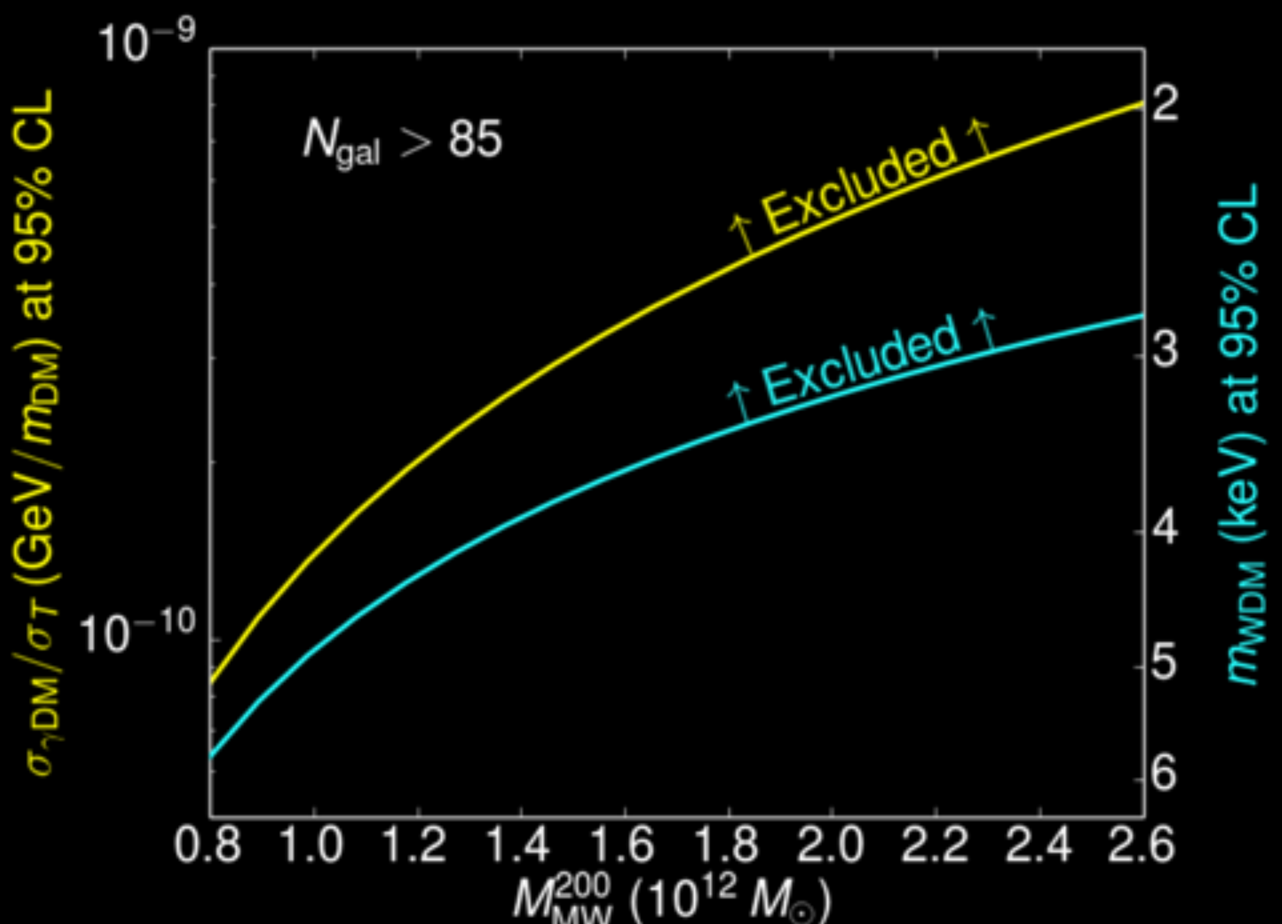
C. Boehm, P. Fayet and R. Schaeffer, Phys. Lett. B518:8, 2001

It suppresses structure formation at small scales



J. A. Schewtschenko et al.,
Mon. Mot. Roy. Astron. Soc. 449:3587, 2015

This can be used to set constraints on the largest allowed cross section from CMB and galaxy counts



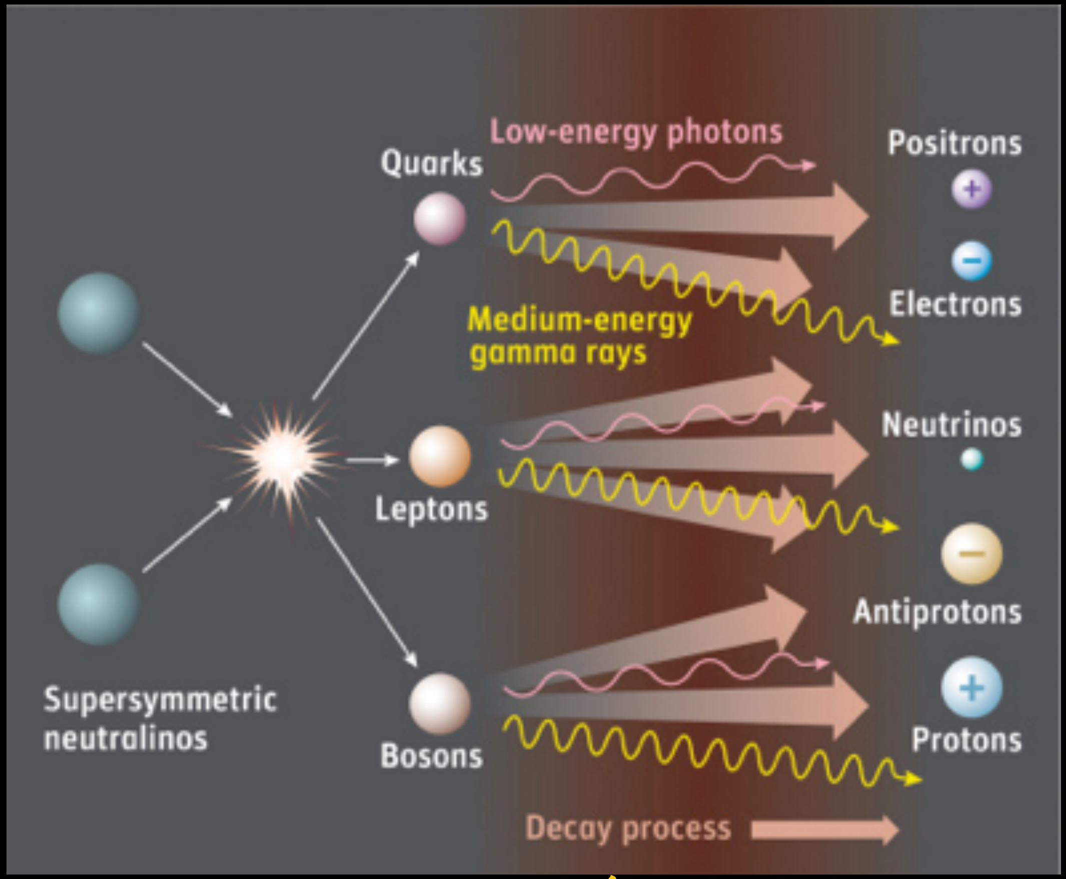
M. Escudero et al., arXiv:1803.08427 (accepted in JCAP)

See also: A. Moliné et al., JCAP 1608:069, 2016

INDIRECT DETECTION

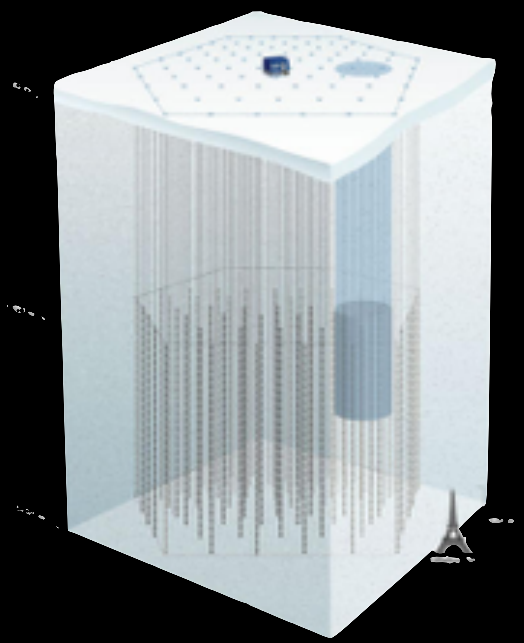
γ-rays

Fermi-LAT, MAGIC, VERITAS, HESS, radio telescopes...



Neutrinos

IceCube, SuperKamiokande...

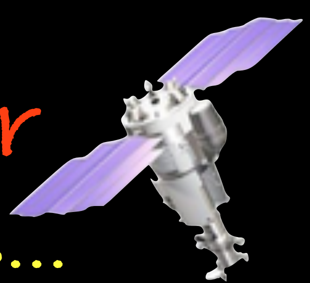


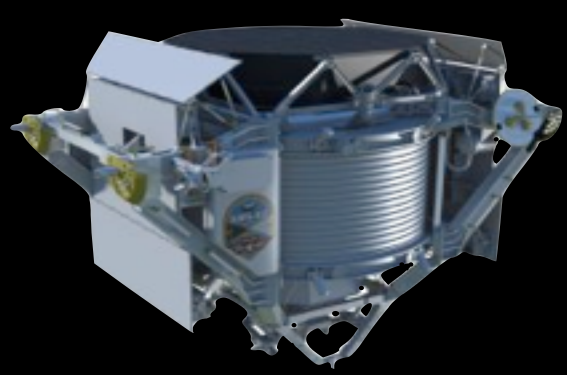
Expected signal:
annihilation (decay) products

Challenges:
absolute rates
discrimination against other sources

Antimatter

PAMELA, AMS...





Need to know:
local density, halo profile, amount of substructure...

Signal

(antimatter)

Flux x Propagation effects x

Effective area x Time

Effective area

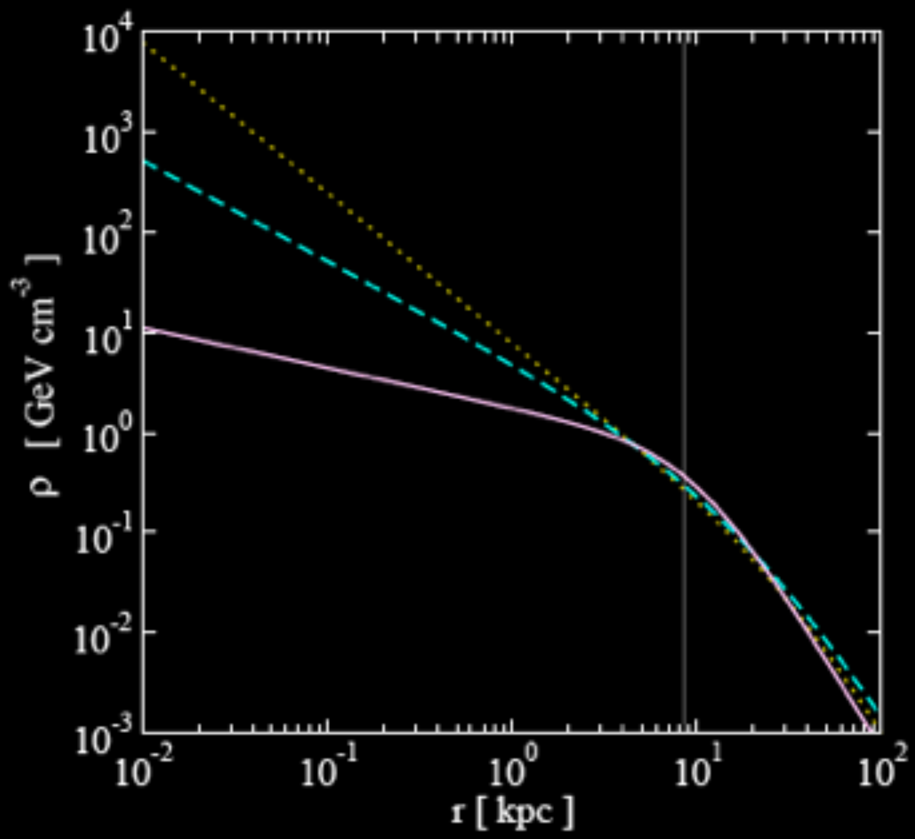
Cross section x Detector's size x Efficiency

$$\text{flux} \propto n^2 \langle \sigma v \rangle$$

particle physics

astro/cosmo

thermal value?
velocity-independent?

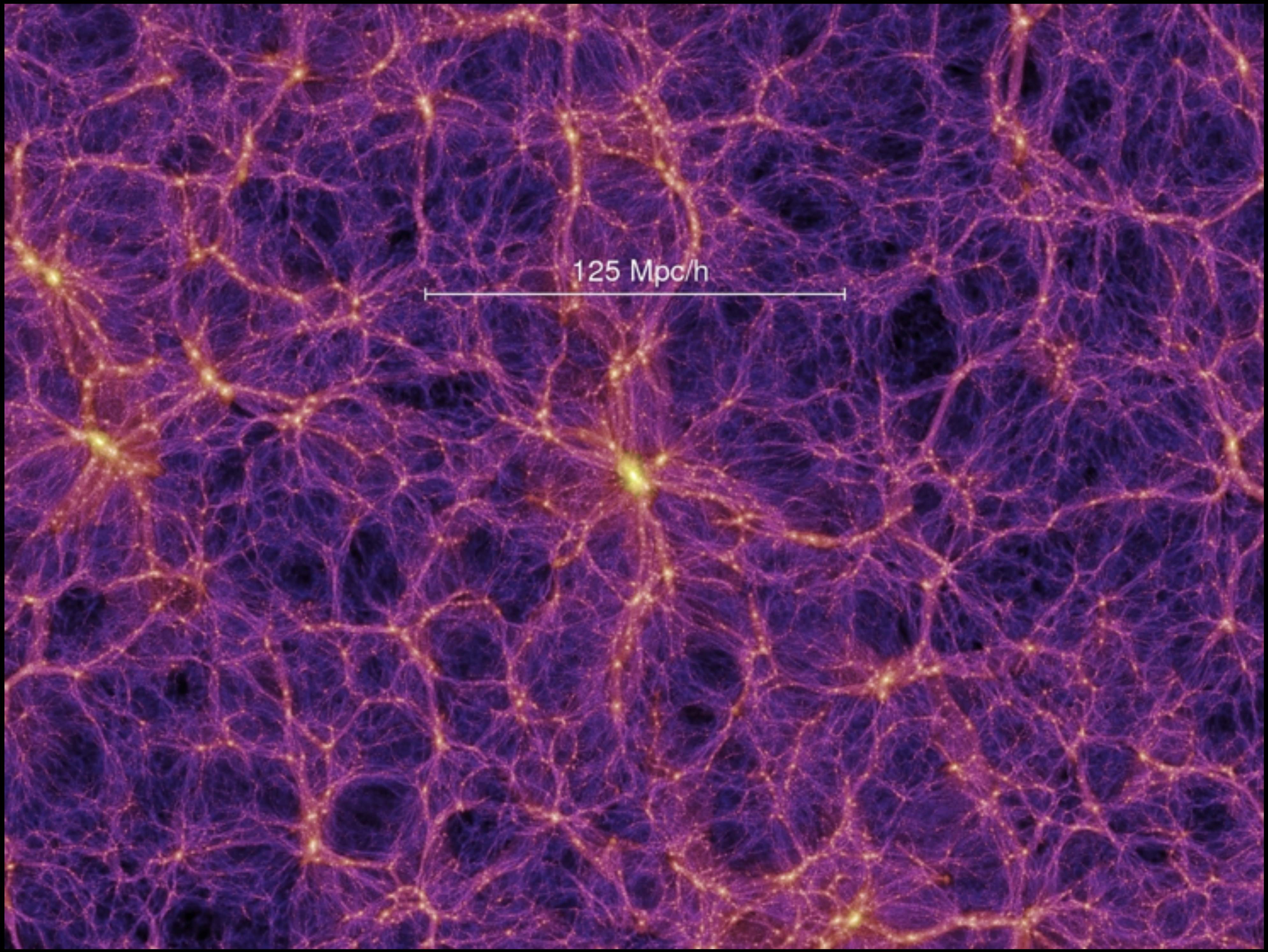


local density
presence of substructure
minimum halo mass
distribution in different systems
dependence with redshift

velocity distribution

H. Yuksel, S. Horiuchi, J. F. Beacom and S. Ando,
Phys. Rev. D76:123506, 2007

Numerical Simulations



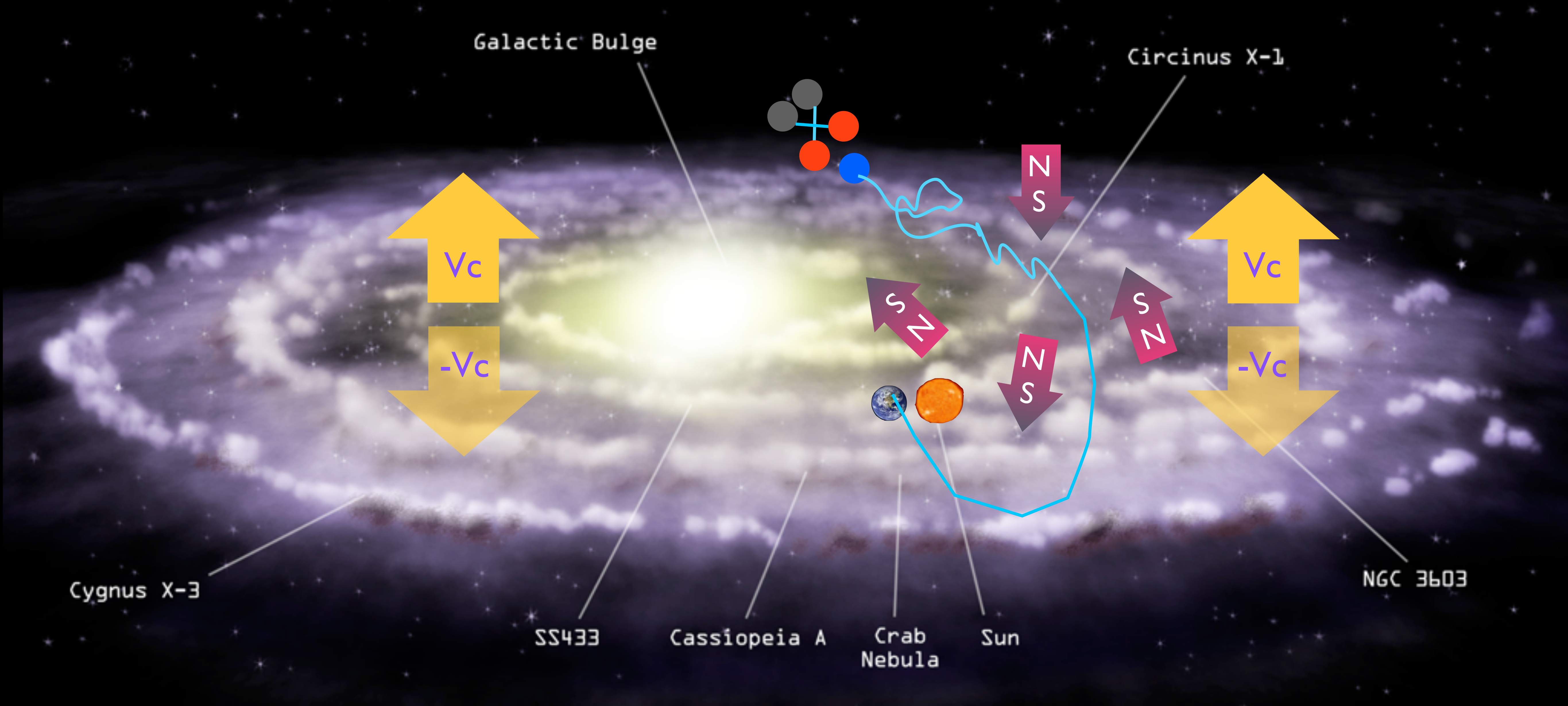
Credit: Aquarius simulation

NUMERICAL SIMULATIONS

Credit: Aquarius simulation

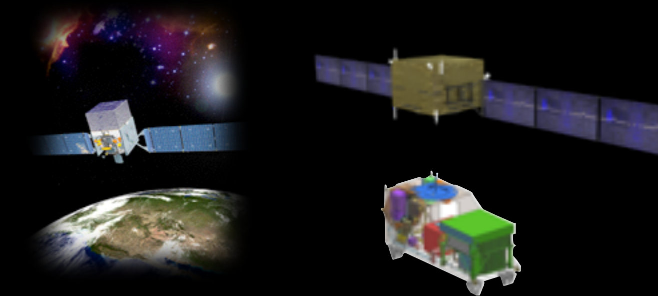
ANTIMATTER

we can only see the local neighborhood (few kpc):
diffusion, convection, energy losses, spallations...



propagation affects positrons mainly at low energies
the spectral shape for antiprotons does not change much

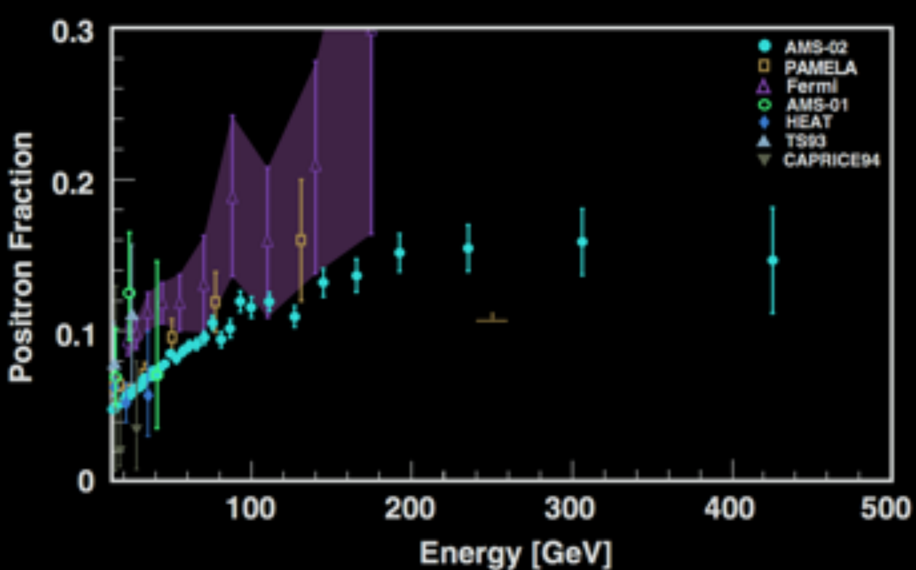
RESULTS

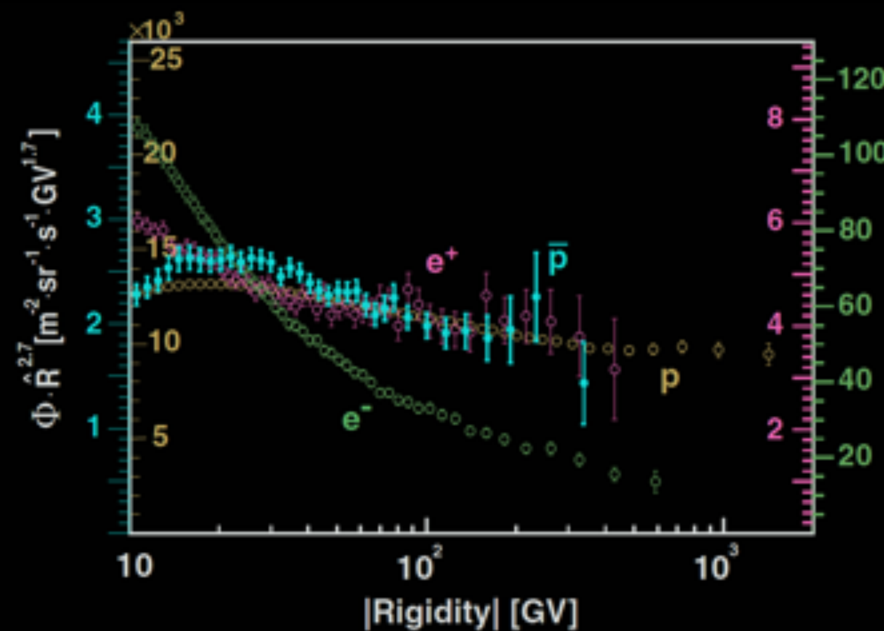


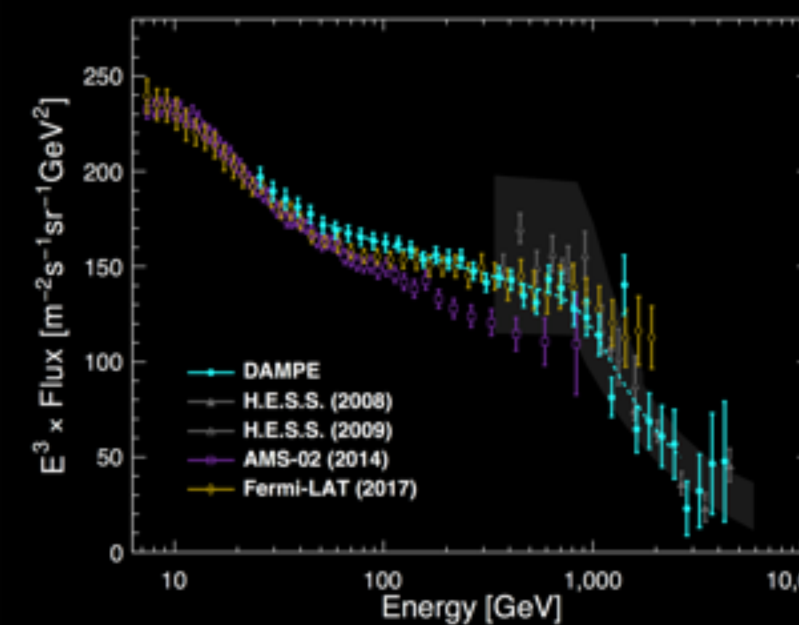
Positron fraction

Antiprotons

Electrons+positrons





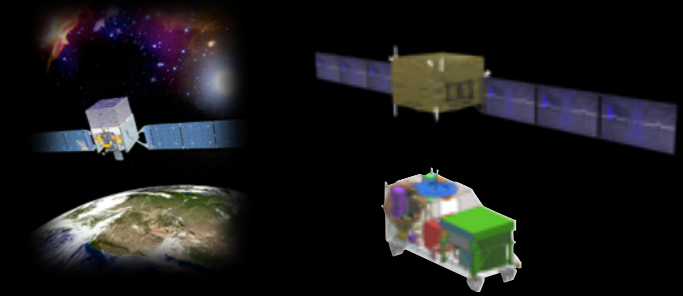


L. Accardo et al. [AMS Collaboration], Phys. Rev. Lett. 113:121101, 2014

M. Aguilaret al. [AMS Collaboration], Phys. Rev. Lett.117, no.9:091103, 2016

G. Ambrosiet al. [DAMPE Collaboration], Nature 552:63, 2017

RESULTS



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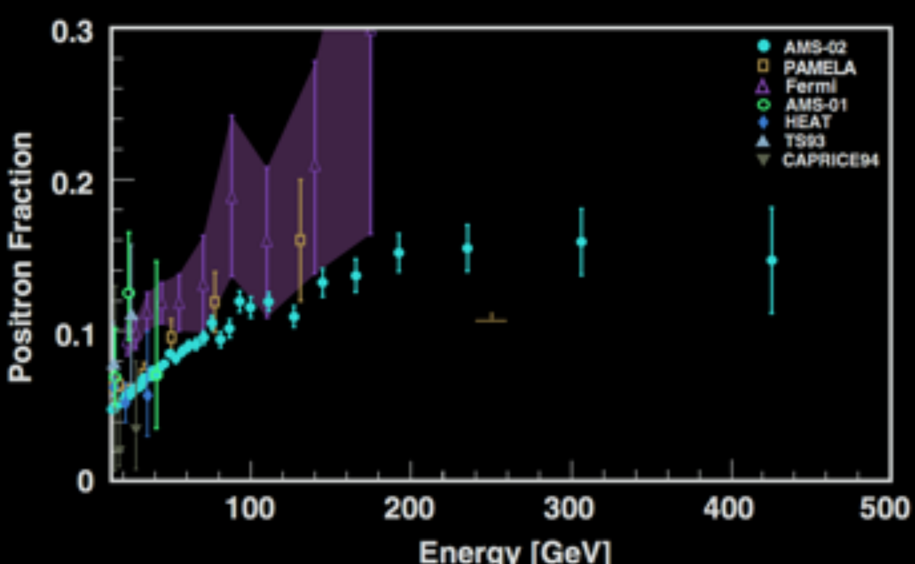

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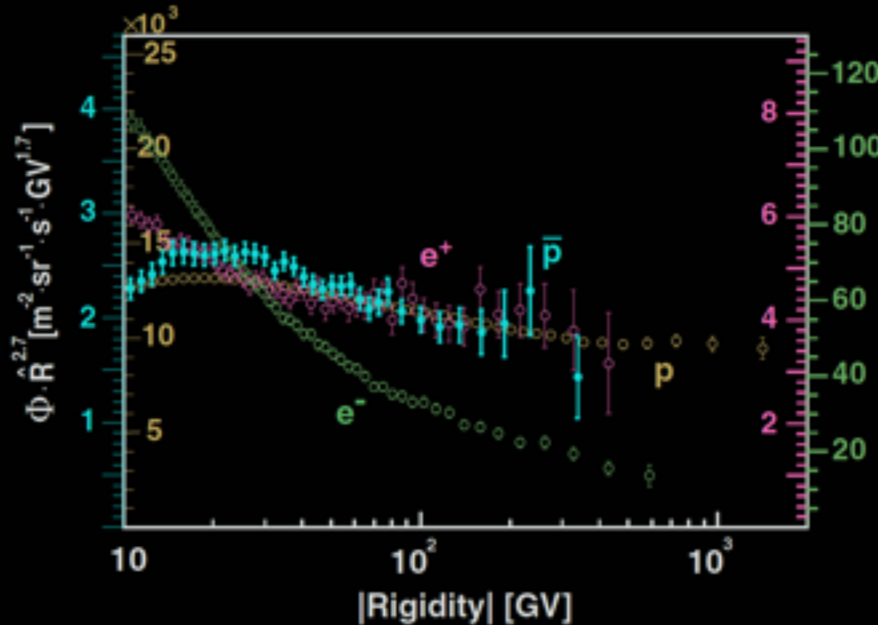

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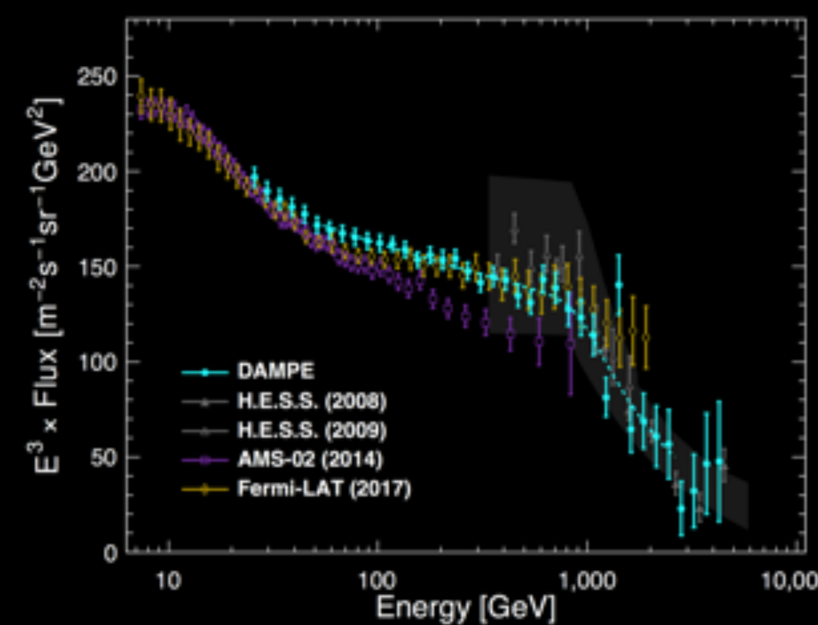


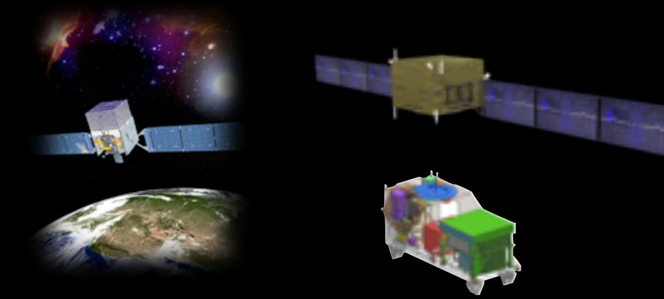
G. Ambrosiet al. [DAMPE Collaboration], Nature 552:63, 2017

positron excess can be interpreted as a DM signal...

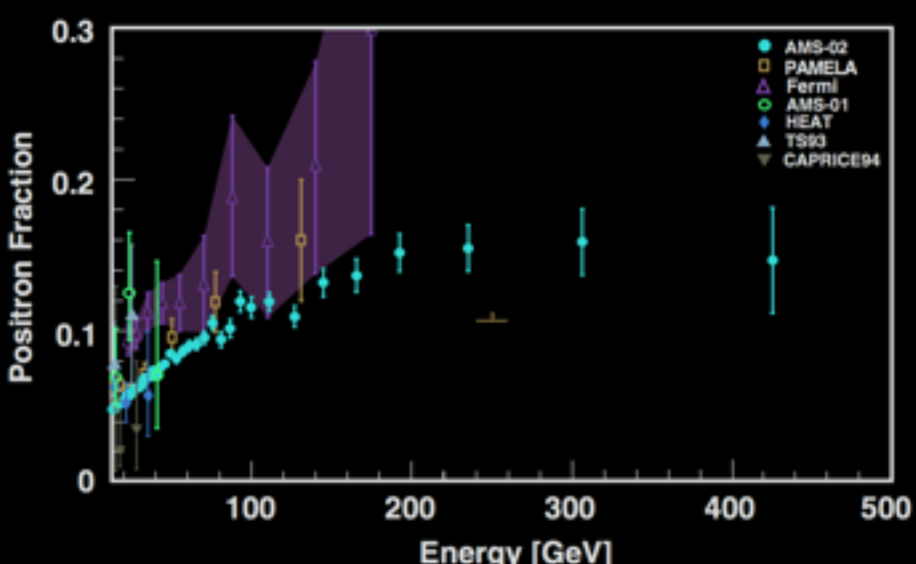
but it needs a very large annihilation cross section (or astrophysical boost factor) and suppressed hadronic channels

$$\langle \sigma v \rangle \approx 10^{-23} \mathrm{cm}^3/\mathrm{s}$$


RESULTS



Positron fraction



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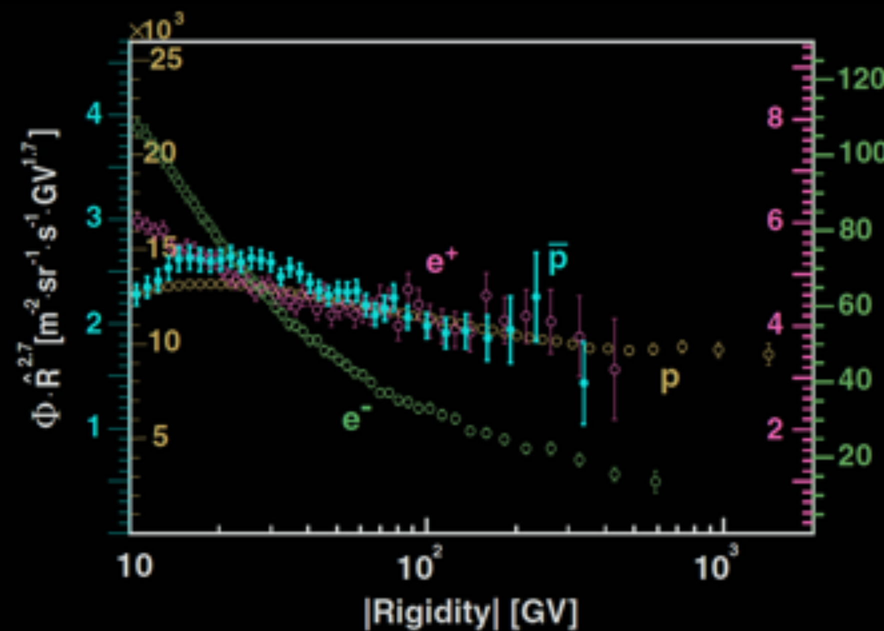
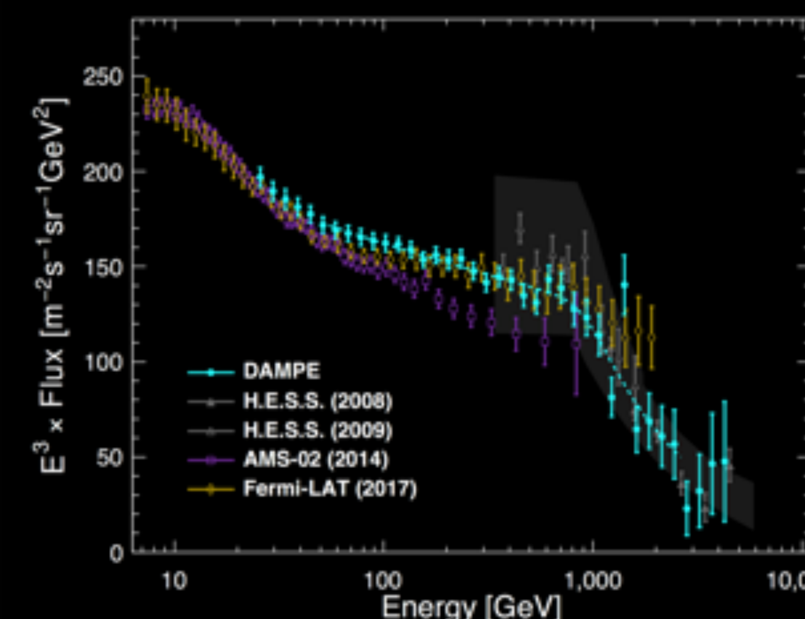


M. Aguilaret al. [AMS Collaboration], Phys. Rev. Lett.117, no.9:091103, 2016

Electrons+positrons



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positron excess can be interpreted as a DM signal...
but it needs a very large annihilation cross section (or astrophysical boost factor) and suppressed hadronic channels

$$\langle \sigma v \rangle \approx 10^{-23} \mathrm{cm}^3/\mathrm{s}$$

... and there are also astrophysical explanations: pulsars

Signal

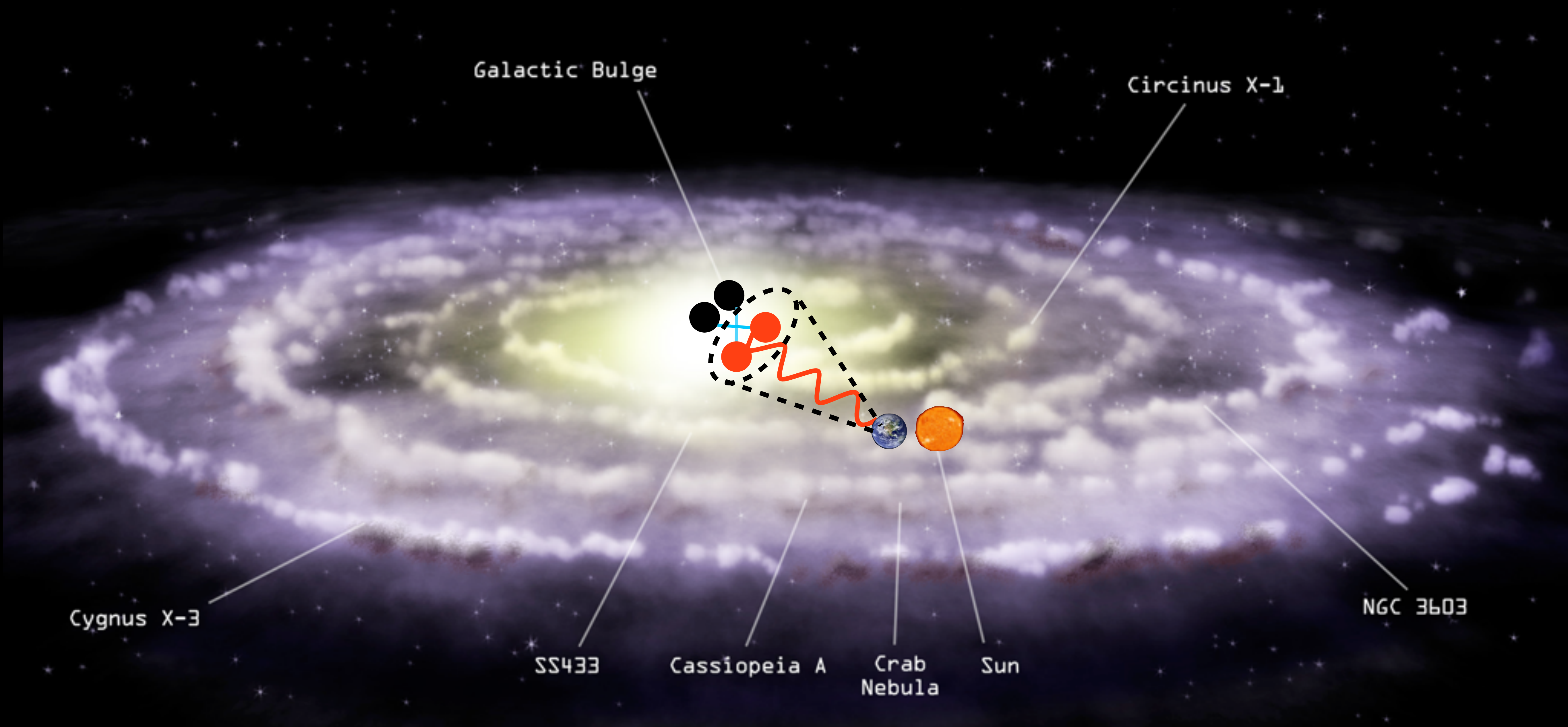
(gamma-rays and neutrinos)

Flux x Effective area x Time

Effective area

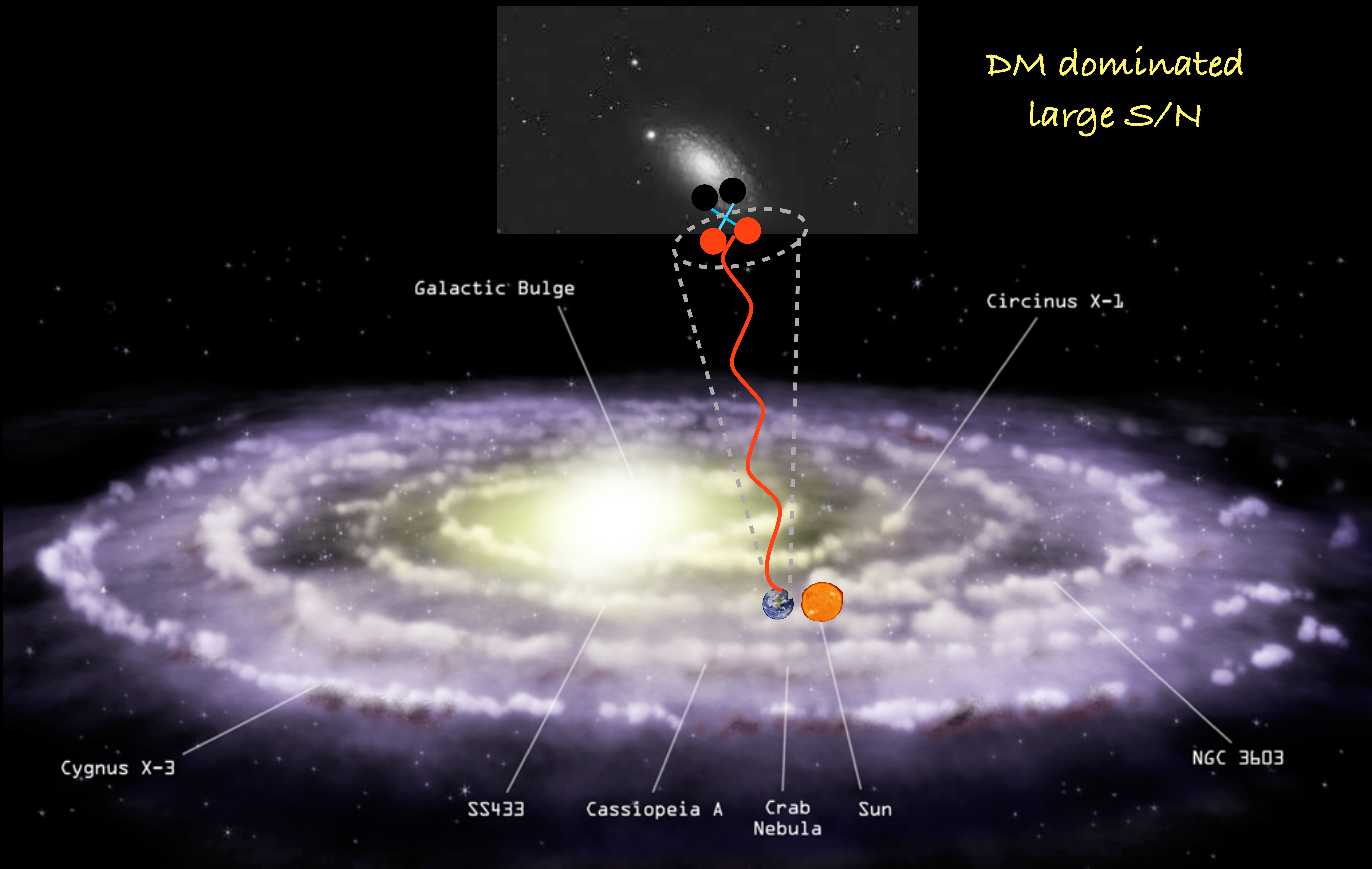
Cross section x Detector's size x Efficiency

GALACTIC CENTER

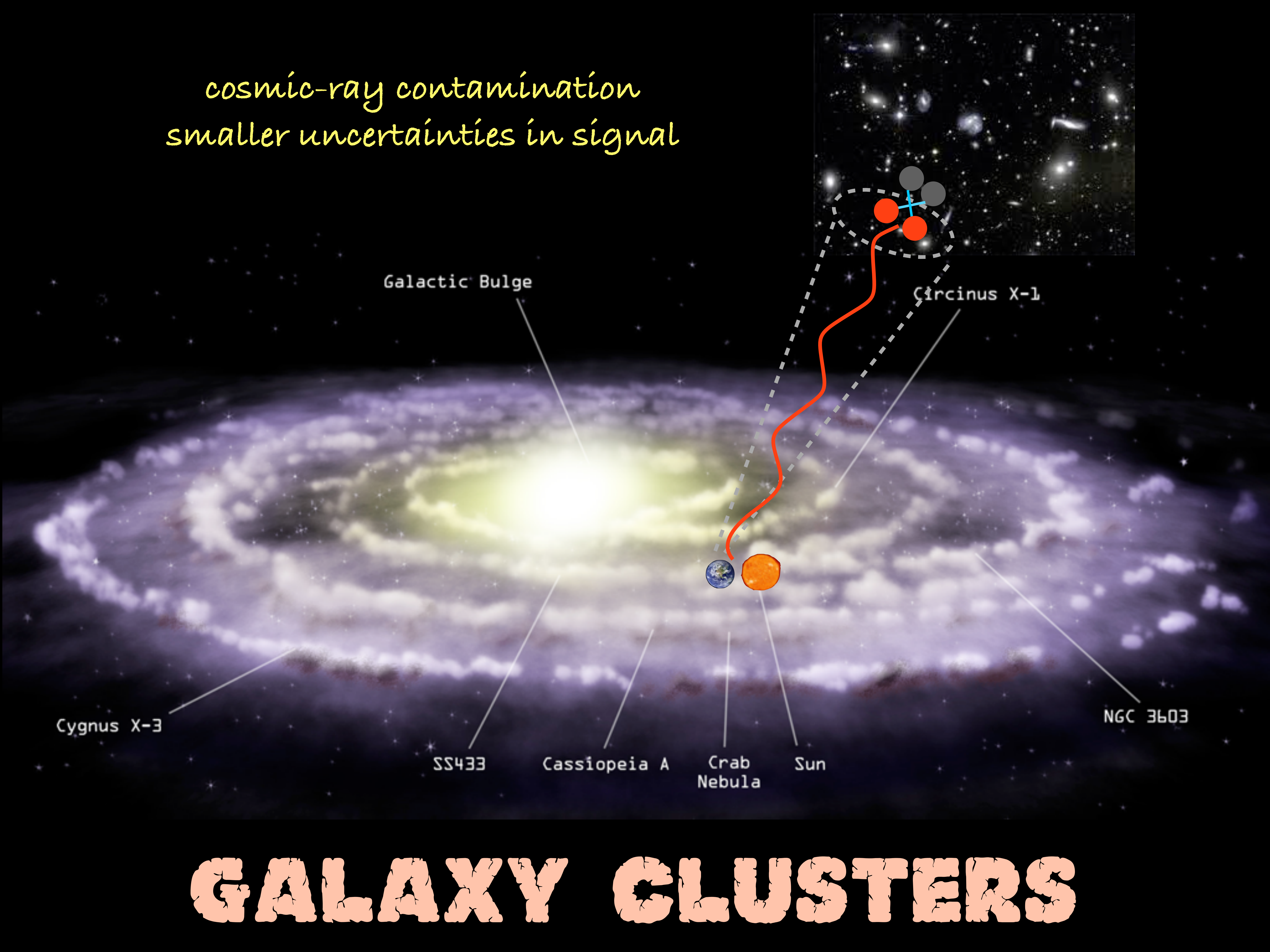


brightest DM source

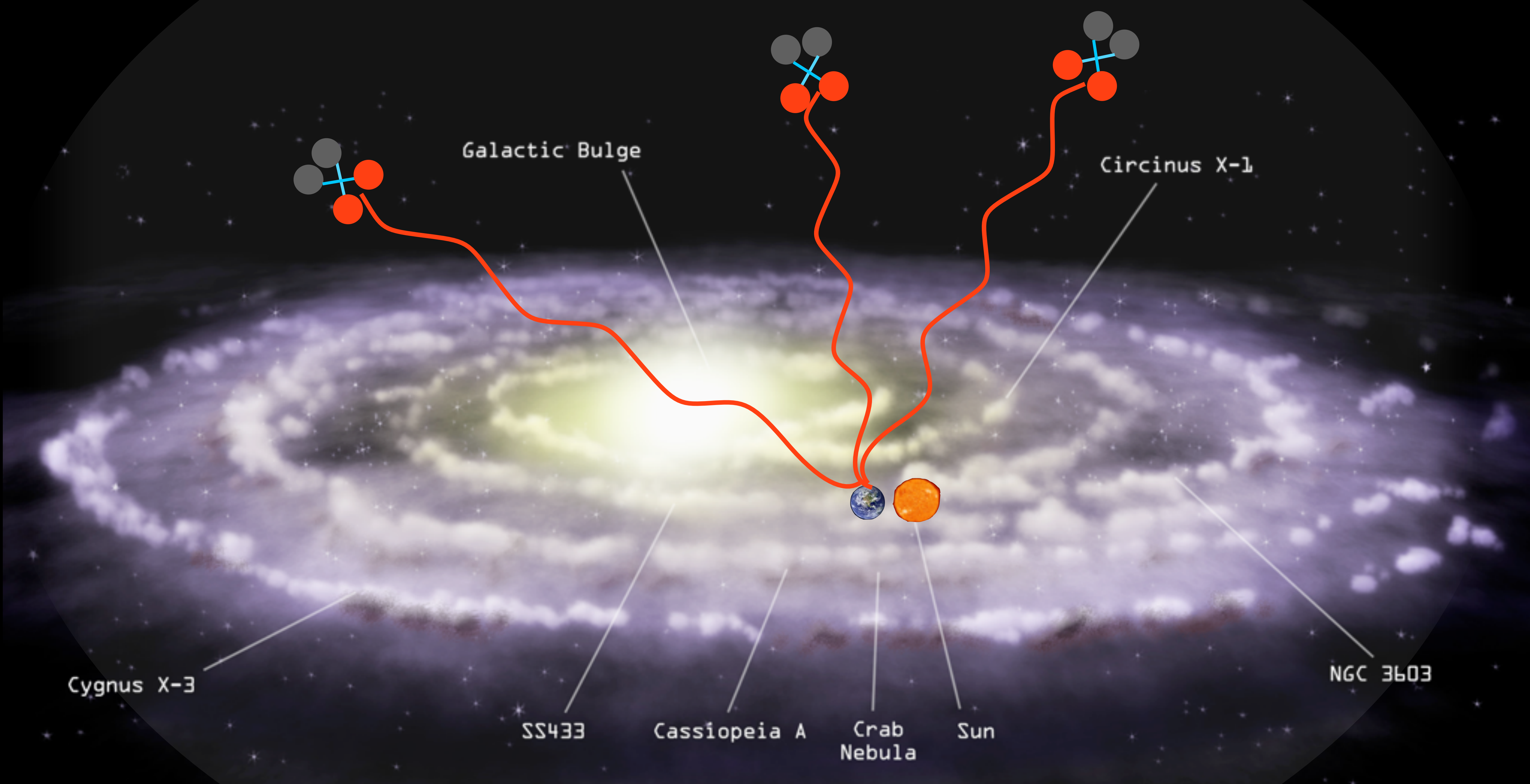
large backgrounds and uncertainties



SATELLITE GALLAXIES


cosmic-ray contamination
smaller uncertainties in signal
Galactic Bulge
Circinus X-1
Cygnus X-3
SS433
Cassiopeia A
Crab Nebula
Sun
NGC 3603
GALAXY CLUSTERS

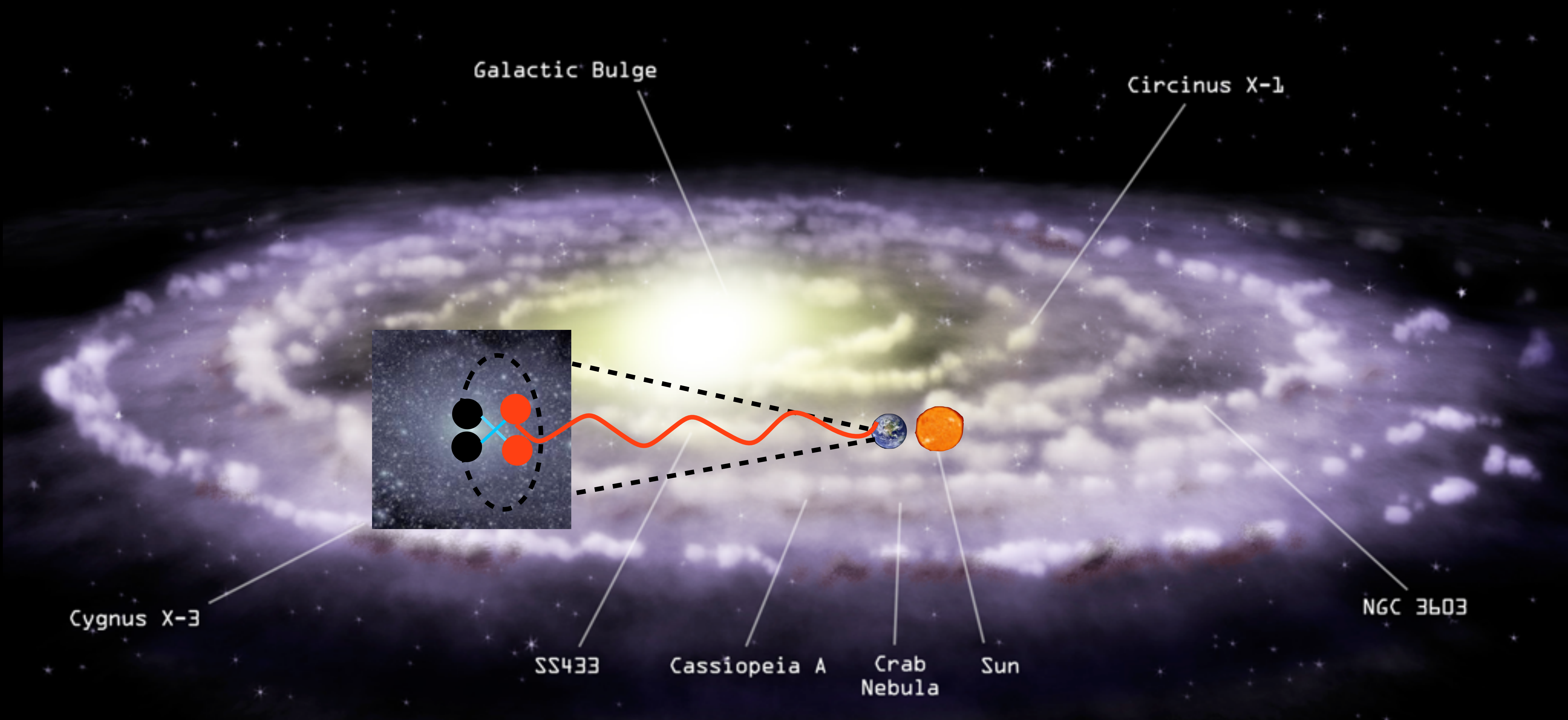
GALACTIC HALO



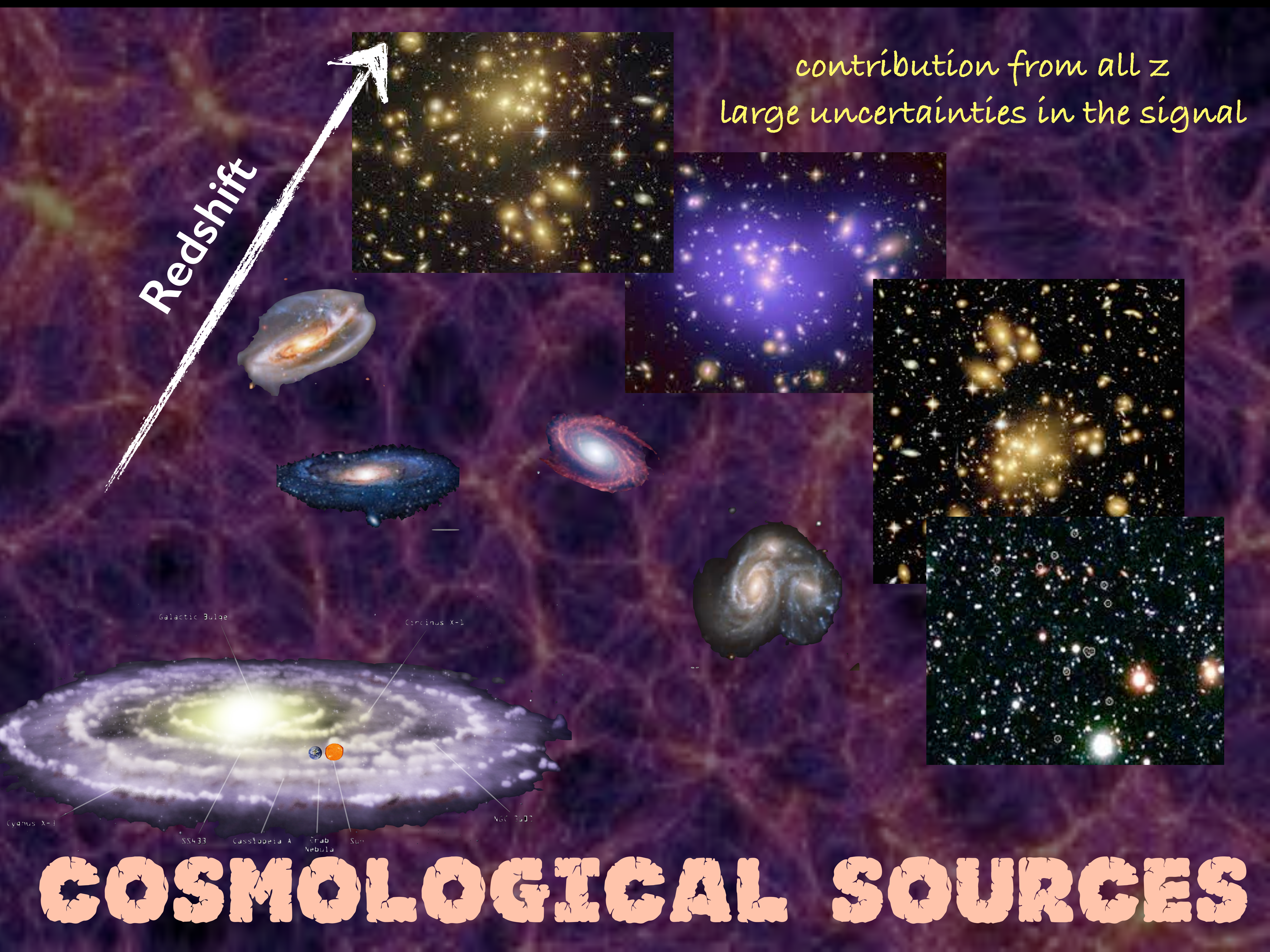
angular information

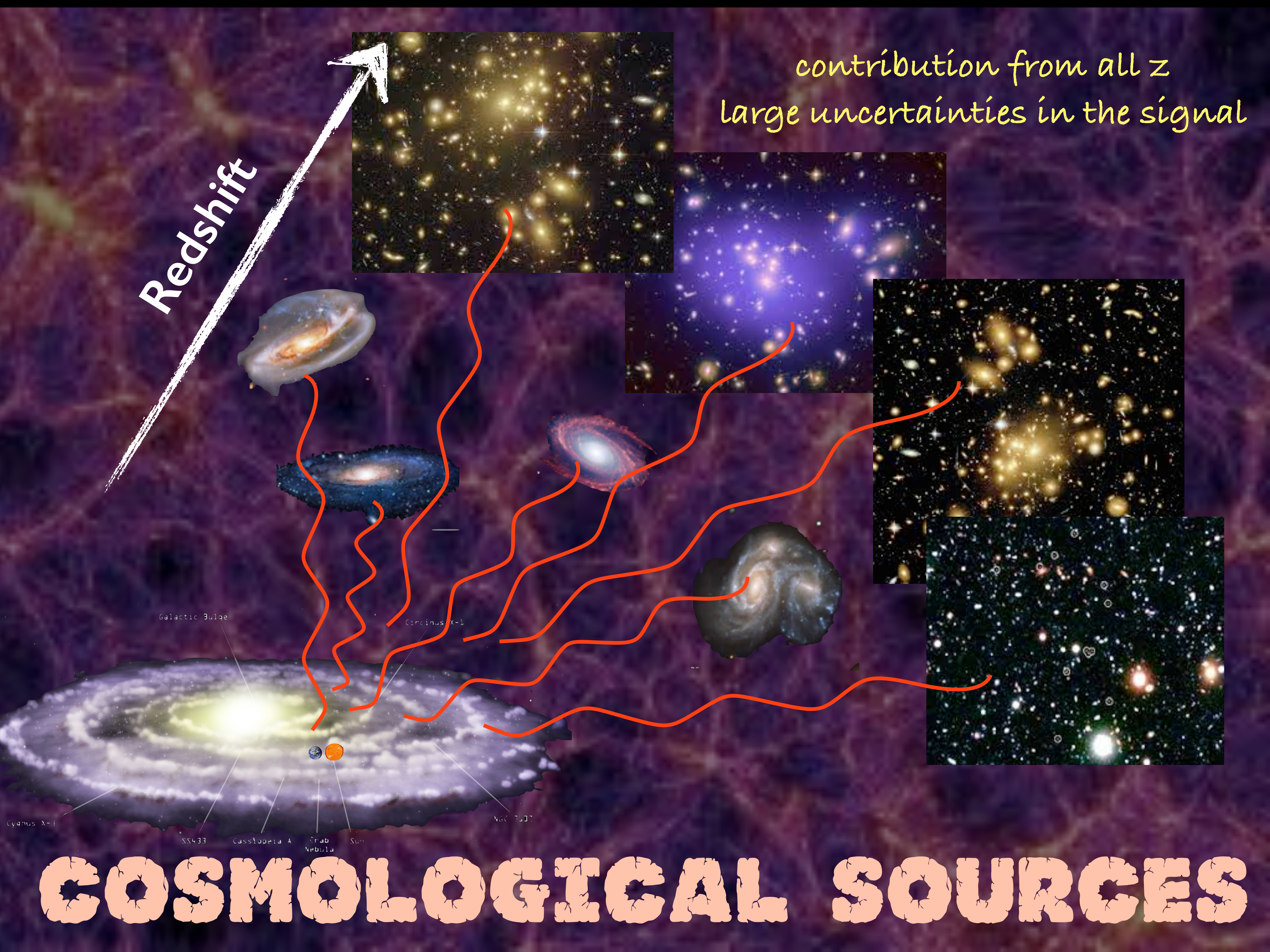
lower galactic backgrounds

GALACTIC SUBSTRUCTURE



relatively easy discrimination (if found)
bright enough?


contribution from all z
large uncertainties in the signal
Redshift
Galactic Bulge
Circinus X-1
Cygnus X-3
SS433
Cassiopeia A
Crab Nebula
Sun
COSMOLOGICAL SOURCES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Sun
COSMOLOGICAL SOURCES

GENERAL COMMENTS
EXAMPLE: GALACTIC SIGNALS

ANNIHILATION

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu,\Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_i \frac{dN_\nu^i}{dE_\nu} BR_i \; \frac{1}{4\pi}\int_{\Delta\Omega}\int_{los}\rho\left(r(s,\Omega)\right)^2 ds$$

Particle Physics — Astrophysics

DECAY

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu,\Delta\Omega) = \frac{1}{\tau_\chi m_\chi}\sum_i \frac{dN_\nu^i}{dE_\nu} BR_i \; \frac{1}{4\pi}\int_{\Delta\Omega}\int_{los}\rho\left(r(s,\Omega)\right) ds$$

$\langle\sigma v\rangle$: annihilation cross section

τ_χ : DM lifetime

m_χ : DM mass

BR_i : branching ratio into channel i

$\frac{dN_\nu^i}{dE_\nu}$: neutrino spectrum for channel i

$\Delta\Omega$: field of view

ρ : DM density profile

To stay as model-independent as possible, explore all possible annihilation/decay channels into SM particles

GAMMA-RAY SIGNAL

PROMPT EMISSION

Continuum

From the hadronization, fragmentation and decay of products of DM annihilations

Lines

DM annihilations into photon(s)

Sharp features

Internal bremsstrahlung DM annihilations into a metastable state

SECONDARY EMISSION

ICS

Upscattering of ambient photons

Bremsstrahlung

soft gammas from bremsstrahlung

Synchrotron

radio-waves from synchrotron emission

Pion decays

soft γ-rays from CR interactions

GAMMA-RAY SIGNAL

PROMPT EMISSION

not affected by the ISM

Continuum

From the hadronization, fragmentation and decay of products of DM annihilations

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DM annihilations into photon(s)

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Internal bremsstrahlung
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SECONDARY EMISSION

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upscattering of ambient photons

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GAMMA-RAY SIGNAL

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not affected by the ISM

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From the hadronization, fragmentation and decay of products of DM annihilations

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DM annihilations into photon(s)

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Internal bremsstrahlung DM annihilations into a metastable state

SECONDARY EMISSION

depend on the ISM

ICS

upscattering of ambient photons

Bremsstrahlung

soft gammas from bremsstrahlung

Synchrotron

radio-waves from synchrotron emission

Pion decays

soft γ-rays from CR interactions

TELESCOPES

Space-borne

small effective area

large field of view

upper threshold <300 GeV

Ground-based

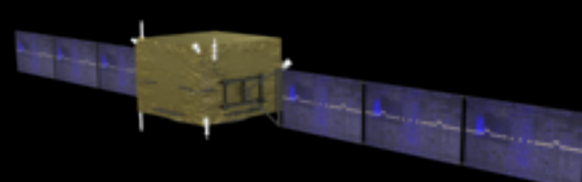
large effective area

small field of view

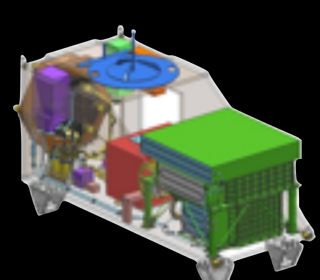
lower thresold >40 GeV

FERMI-LAT

DAMPE



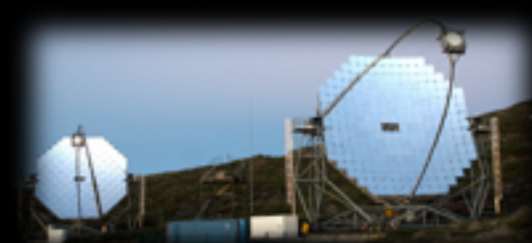
CALET



H.E.S.S

VERITAS

MAGIC

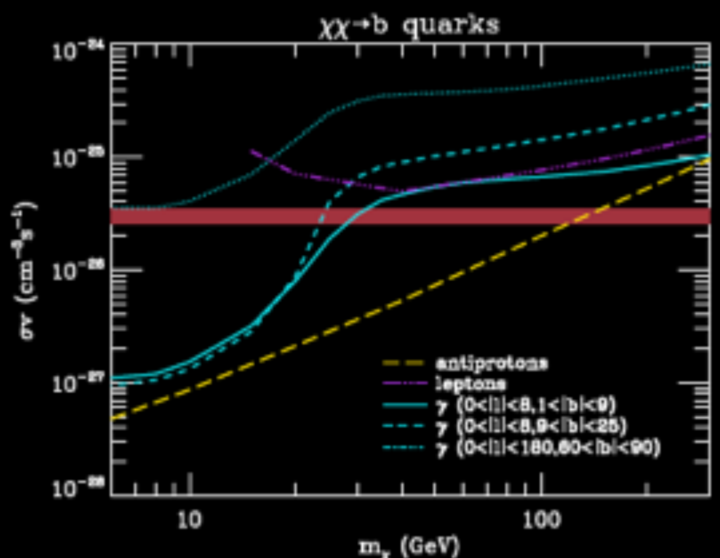


CTA

HAWC

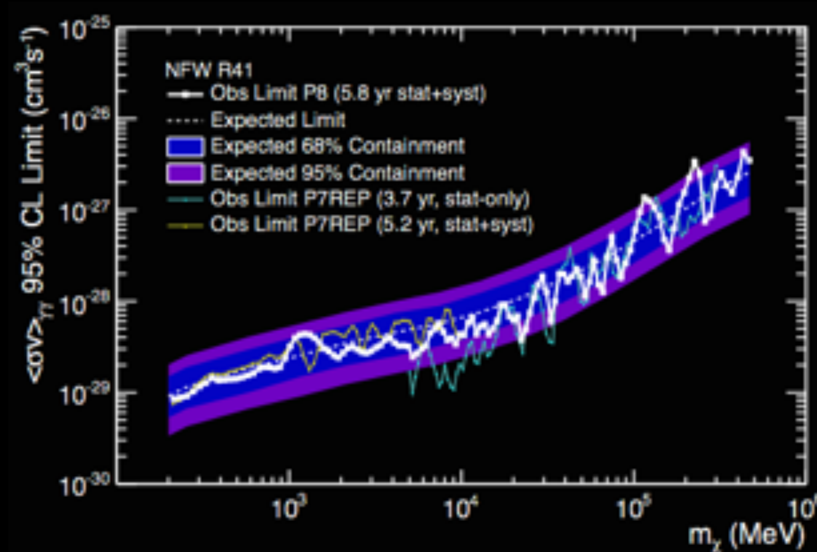
CONSTRAINTS

Milky Way halo



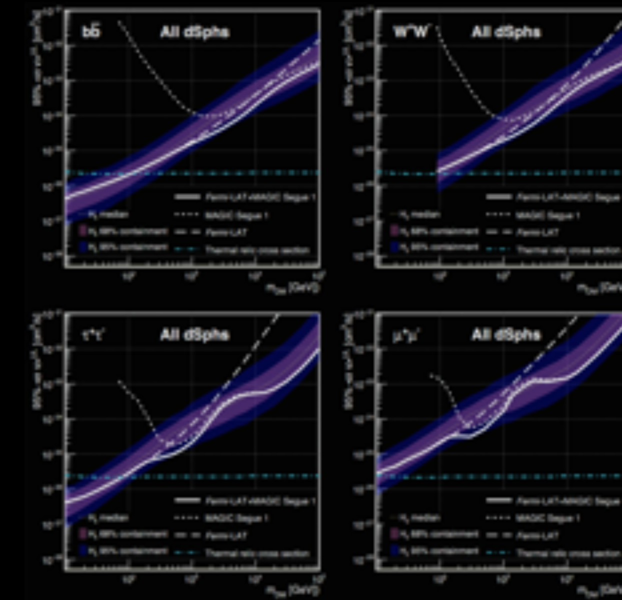
M. Tavakoli et al., JCAP 1401:017, 2014

Lines from GC



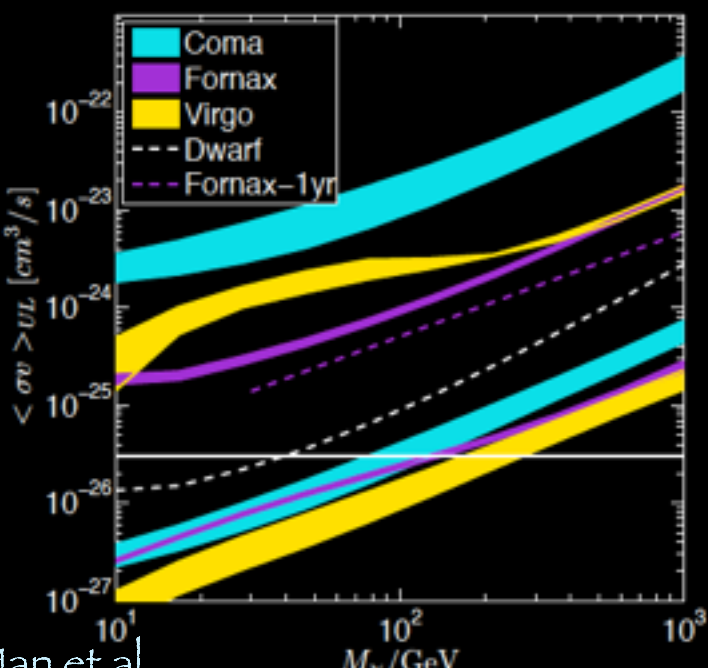
M. Ackermann et al. [Fermi-LAT Collaboration], Phys. Rev. D91:122002, 2015

Dwarf gallaxies



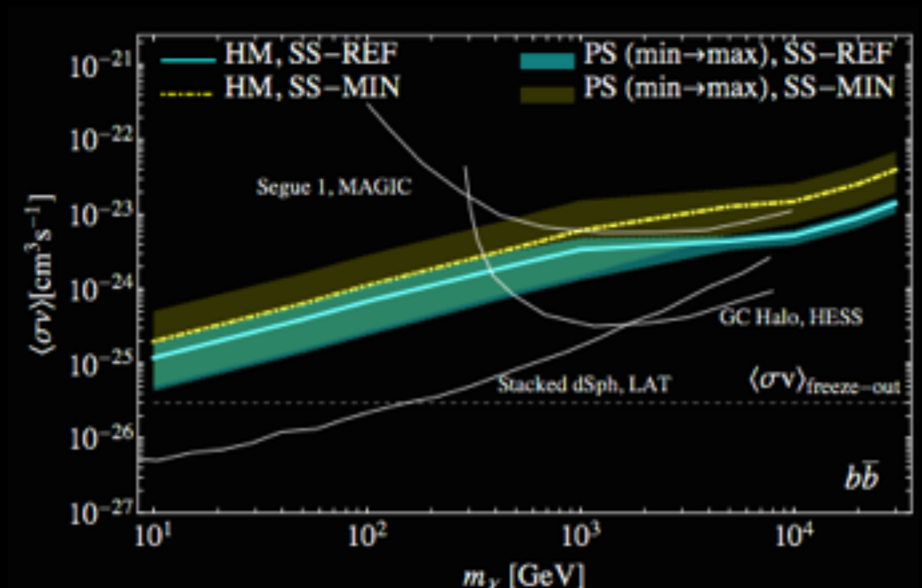
M. L. Ahnen et al. [Fermi-LAT and MAGIC Collaborations], JCAP 1602:039, 2016

Galaxy clusters



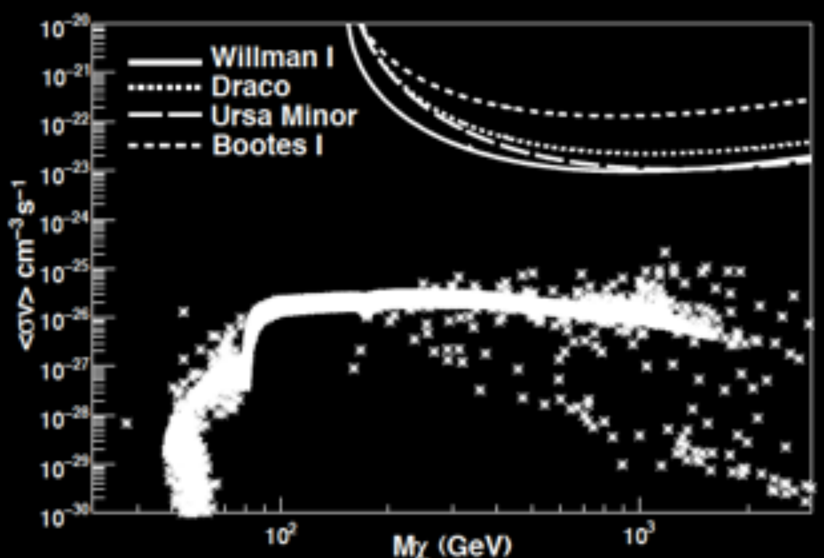
J. Han et al.,
Mon. Not. Roy. Astron. Soc. 427:1651, 2012

All halos



M. Ackermann et al.[Fermi-LAT Collaboration], JCAP 1509:008, 2015

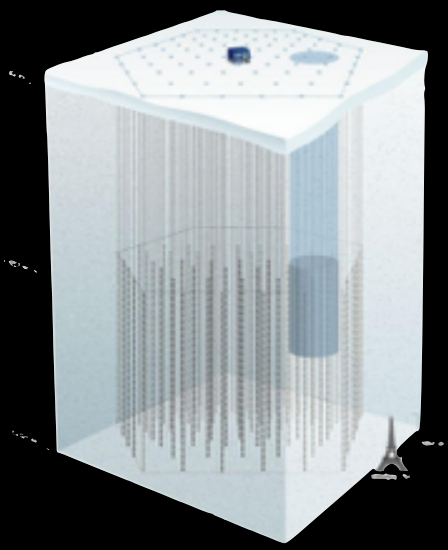
Dwarf gallaxies



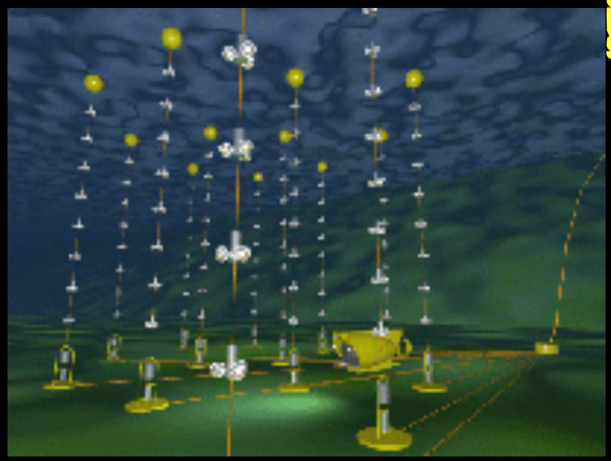
V. A. Acciari et al. [VERITAS Collaboration], Astrophys. J. 720:1174, 2010

NEUTRINO DETECTION

ICECUBE



ANTARES



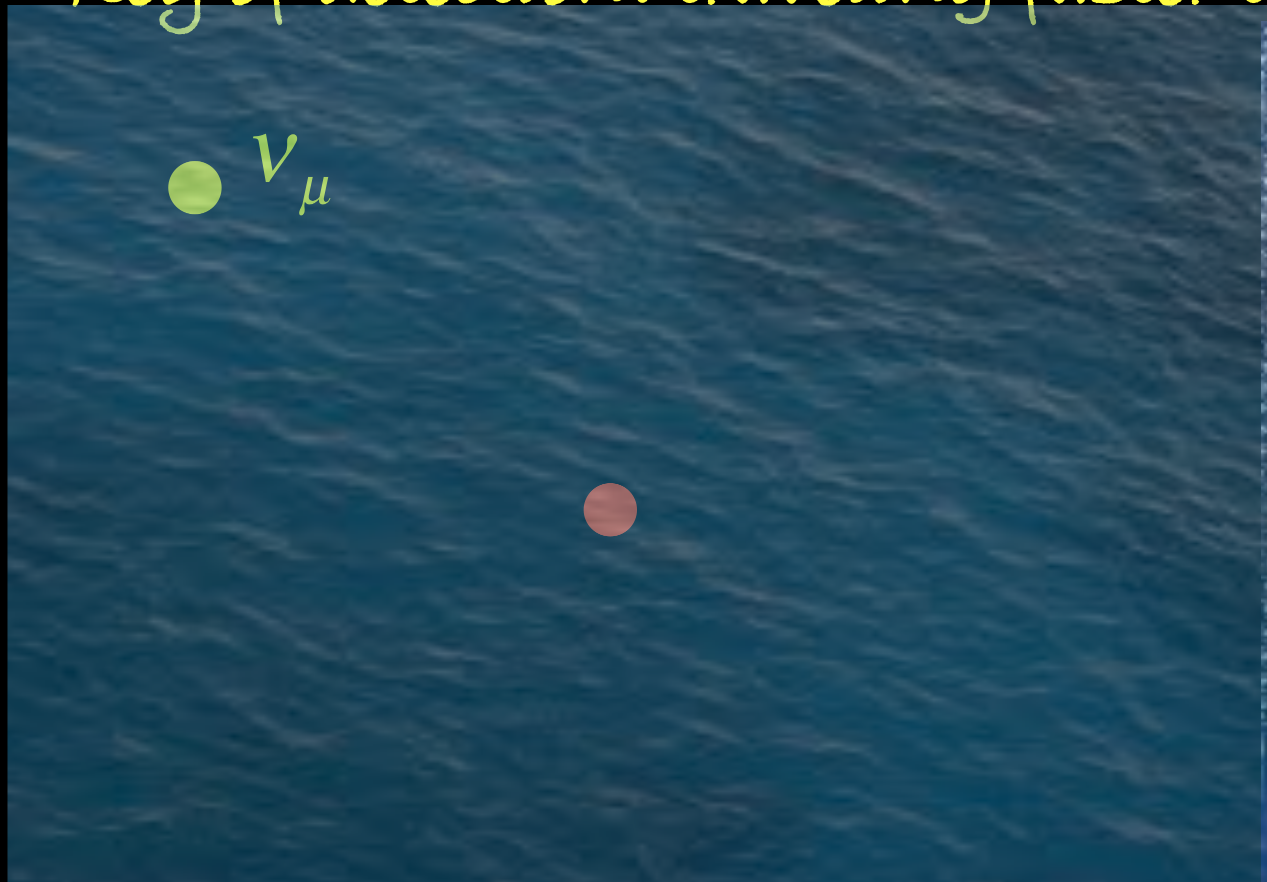
SUPER-KAMIOKANDE

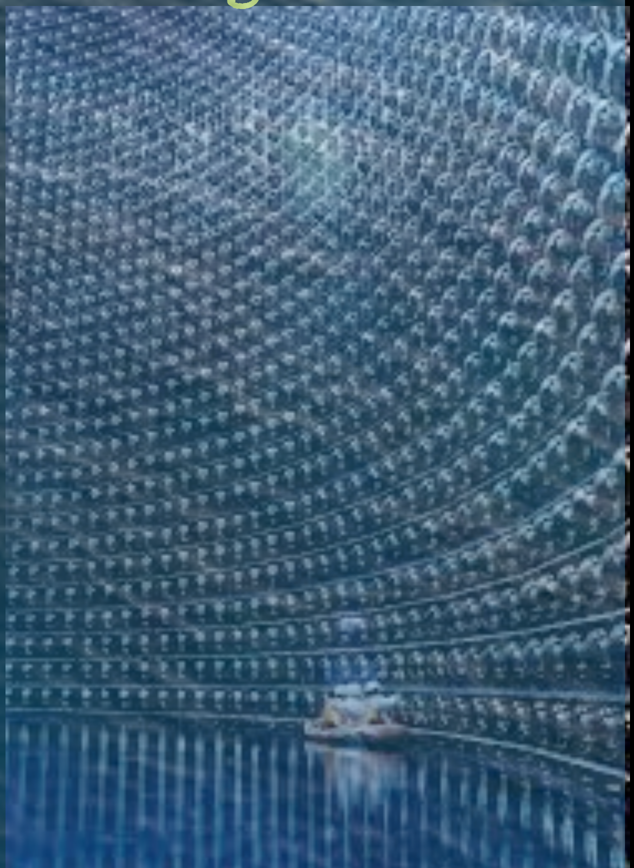
Cherenkov detectors

BAKSAN

scintillator detector

Key of detection: traveling faster than light



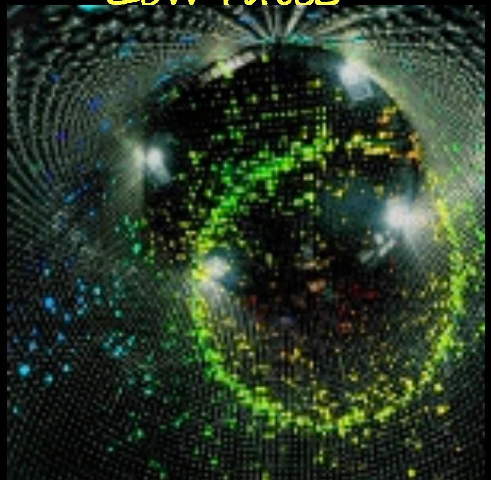


Main signal:

Cherenkov light from muons and electrons

Well-known background: atmospheric neutrinos

Low rates



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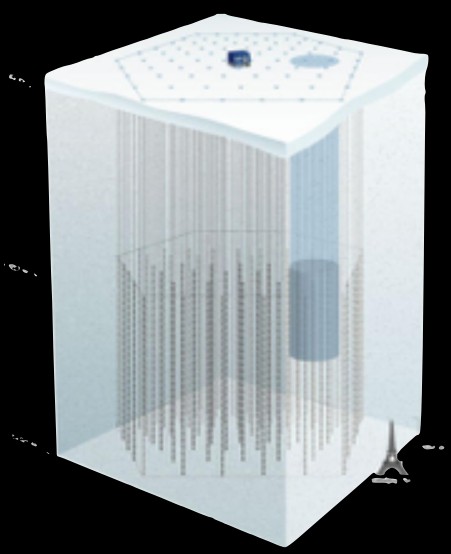
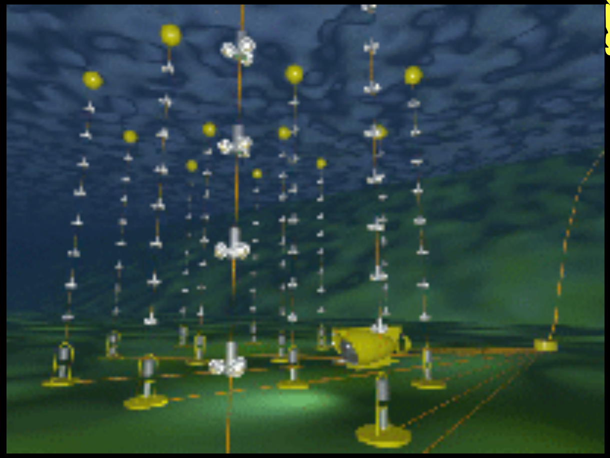
ICECUBE



ANTARES



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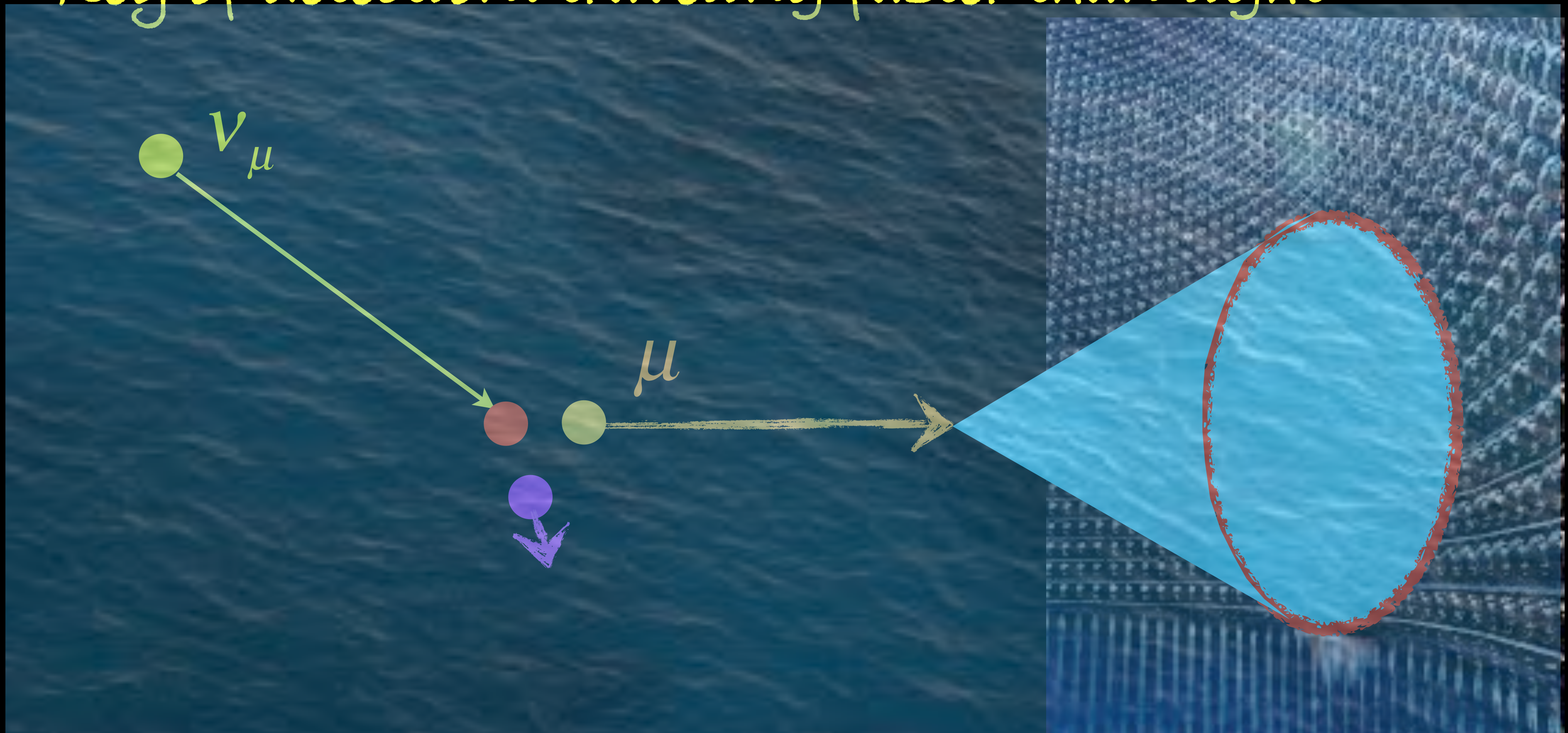

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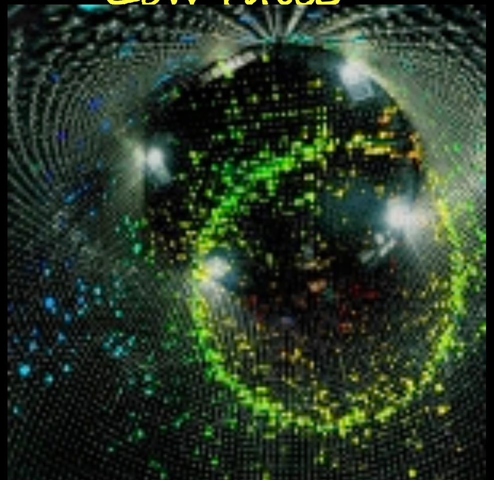
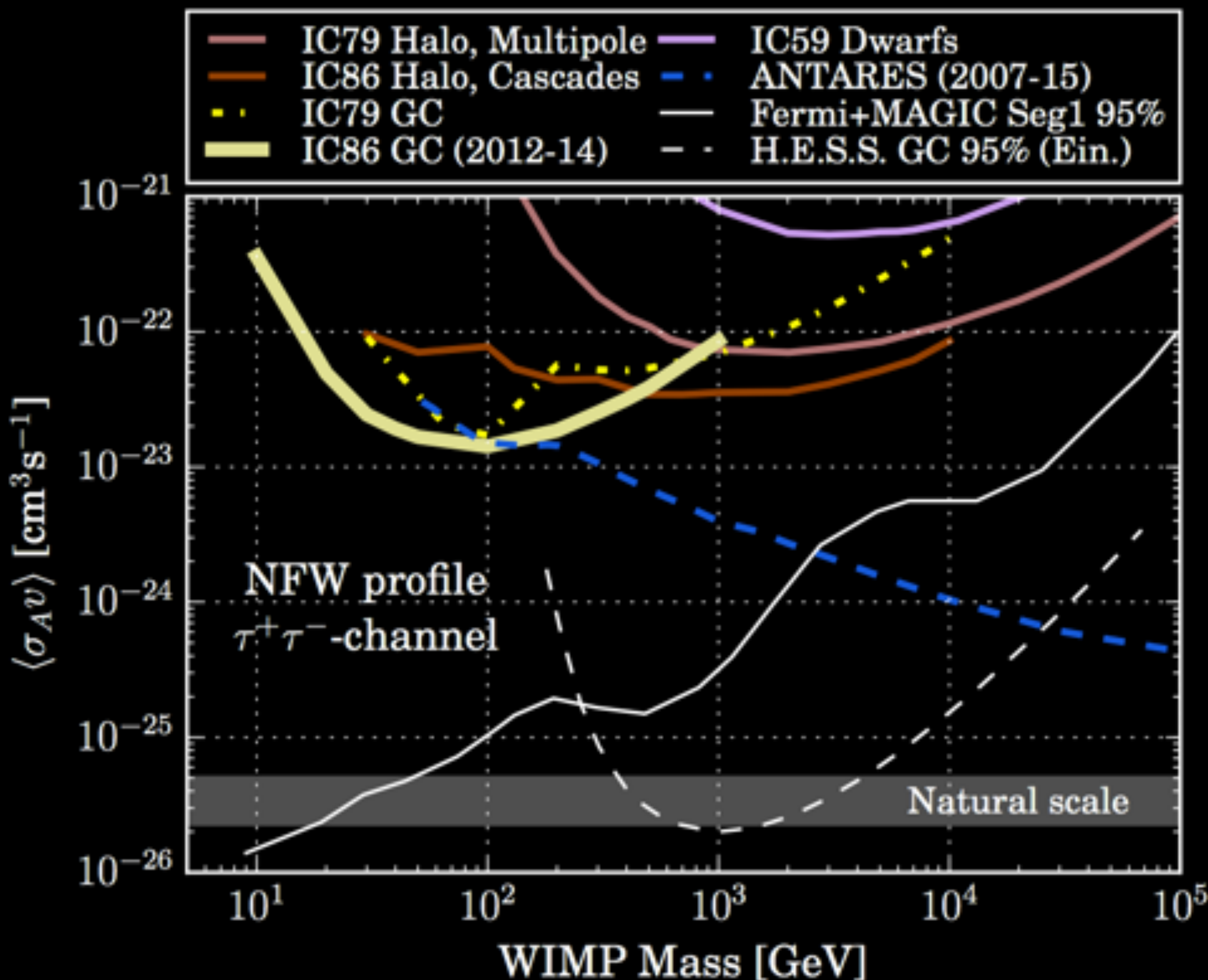


CONSTRAINTS

Galactic Center & Milky Way halo

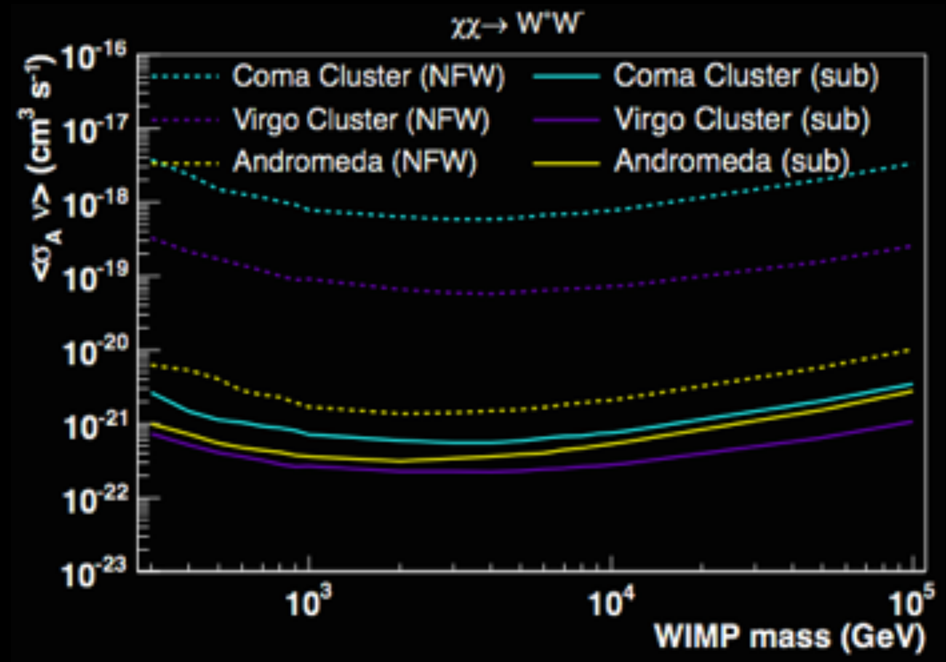


M. G. Aartsen et al [IceCube Collaboration], Eur. Phys. J. C77, no.9:627, 2017

S. Adrian-Martinez et al. [ANTARES Collaboration], JCAP 1510:068, 2015

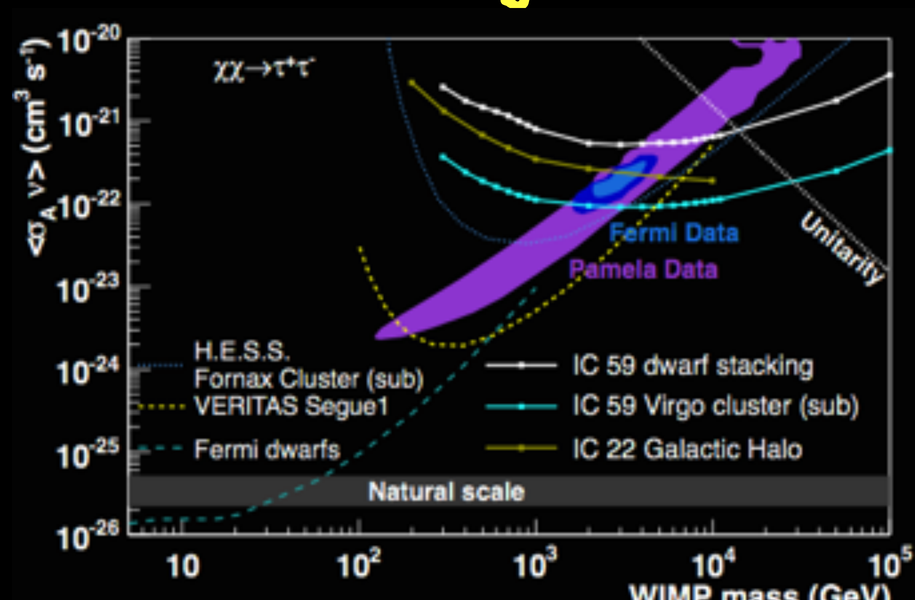
M. G. Aartsen et al [IceCube Collaboration], Eur. Phys. J. C75:20, 2015

Galaxy clusters



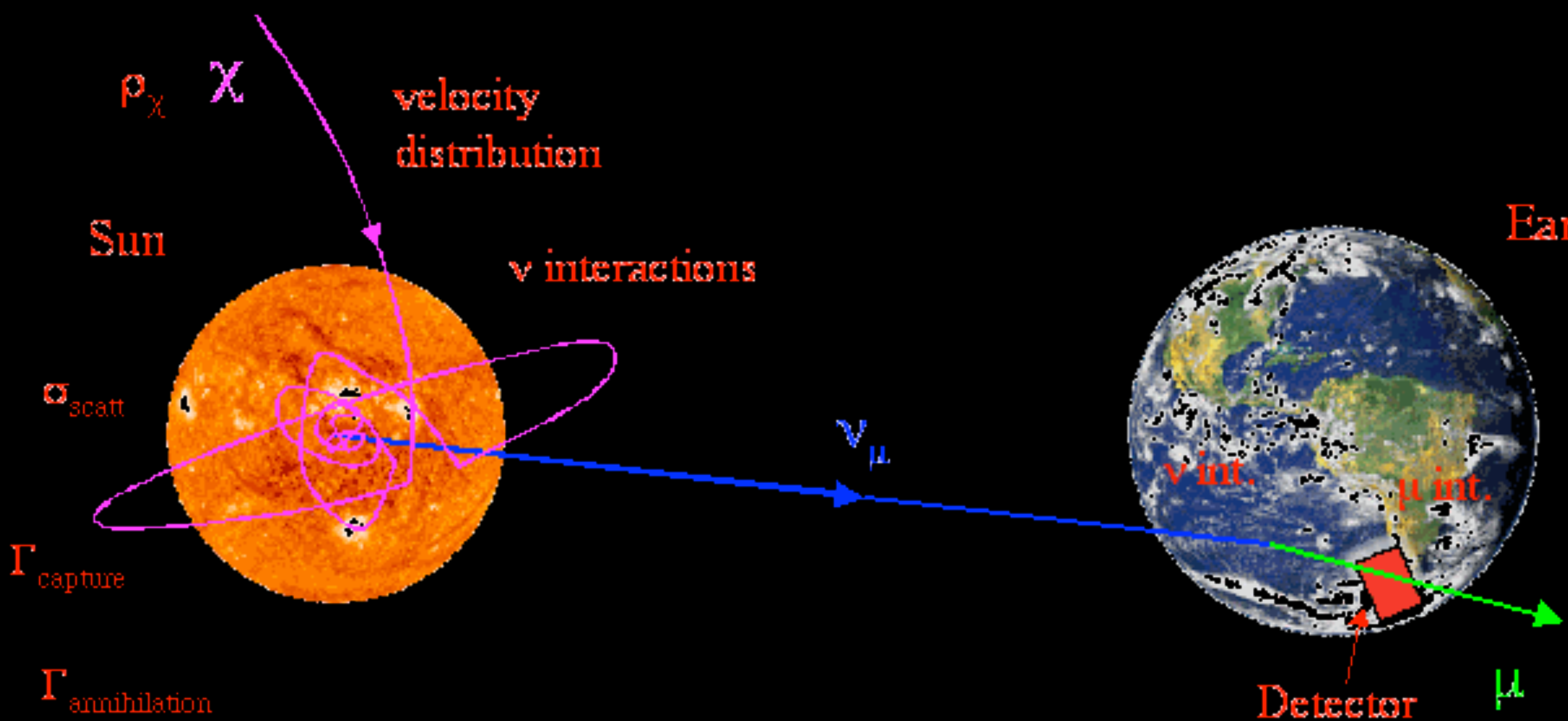
M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. D88:122001, 2013

Dwarf galaxies



M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. D88:122001, 2013

NEUTRINOS FROM THE SUN



J. Silk, K. A. Olive and M. Srednicki, Phys. Rev. Lett. 55:257, 1985

T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986

M. Srednicki, K. A. Olive and J. Silk, Phys. B279:804, 1987

K. Griest and D. Seckel, Nucl. Phys. B283:681, 1987

NEUTRINOS FROM THE SUN

- WIMPs elastically scatter with the nuclei of the Sun to a velocity smaller than the escape velocity, so they remain trapped inside

Additional scattering give rise to an isothermal distribution

$$C_\odot \simeq 9\times 10^{23}\,\mathrm{s}^{-1}\left(\frac{\rho_\odot}{0.3\ \mathrm{GeV/cm}^3}\right)\left(\frac{270\ \mathrm{km/s}}{\bar{\upsilon}_{\mathrm{local}}}\right)^3\left(\frac{\sigma_{SD}}{10^{-3}\ \mathrm{pb}}\right)\left(\frac{50\ \mathrm{GeV}}{m_\chi}\right)^2$$

- Trapped WIMPs can annihilate into SM particles

- After some time, annihilation and capture rates equilibrate

$$\Gamma(t_\odot)=\frac{1}{2}C_\odot \tanh^2\left(\frac{t_\odot}{\tau_\odot}\right)\simeq\frac{1}{2}C_\odot$$

- Only neutrinos can escape

J. Silk, K. A. Olive and M. Srednicki, Phys. Rev. Lett. 55:257, 1985
T. K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34:2206, 1986
M. Srednicki, K. A. Olive and J. Silk, Phys. B279:804, 1987
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STEPS IN THE CALCULATION

Use local DM density and velocity distribution

Compute capture and annihilation rates

Determine neutrino fluxes at production
for different annihilation channels

Oscillate neutrinos from the Sun to the Earth

Compute the event spectra at neutrino detectors

Compare with data

SENSITIVE TO SCATTERING CROSS SECTIONS

Spin-independent cross section (coherent interaction)

Scattering amplitudes (same for neutrons and protons) add coherently

$$\sigma_{SI} \propto \mu_A^2 \left(Z f_p + (A - Z) f_n \right)^2 \propto A^4$$

Spin-dependent cross section

Scattering amplitude changes sign with spin direction, so paired nucleons do not contribute: only the residual unpaired nucleons

$$\sigma_{SD} \propto \mu_A^2 J(J+1) \propto A^2$$

CONSTRAINTS

IceCube analysis: 317 days

M. G. Aartsen et al. [IceCube Collaboration], JCAP 1604:022, 2016

SK analysis: 3903 days

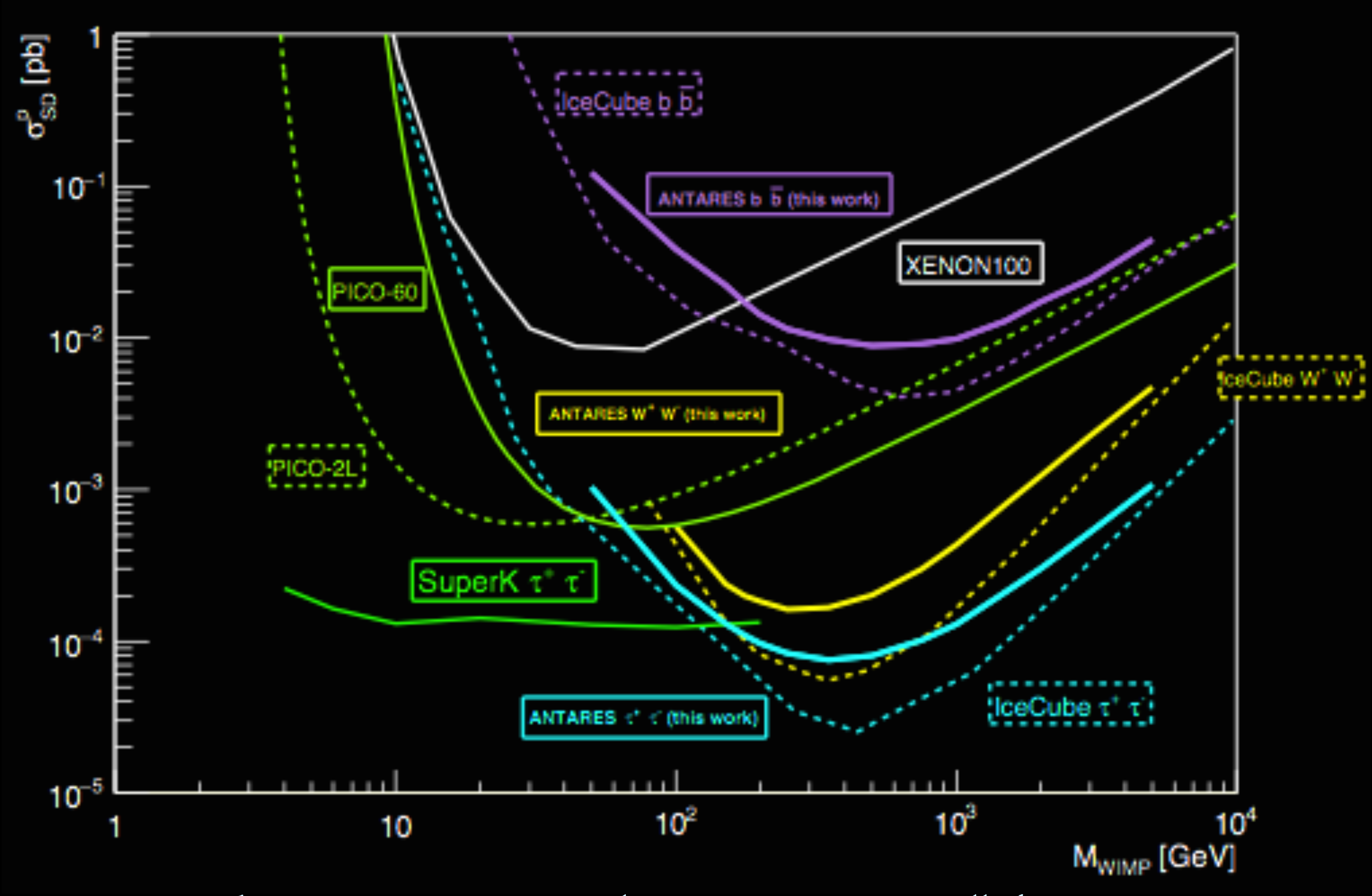
K. Choi et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 114:141301, 2015

ANTARES analysis: 5 years

S. Adrián-Martínez et al. [ANTARES Collaboration], Phys. Lett. B759:69, 2016

Baksan analysis: 24.12 years

M. M. Boliev, S. V. Demidov, S. P. Mikheyev and O. V. Suvorova, JCAP 1309:019, 2013



S. Adrián-Martínez et al. [ANTARES Collaboration], Phys. Lett. B759:69, 2016

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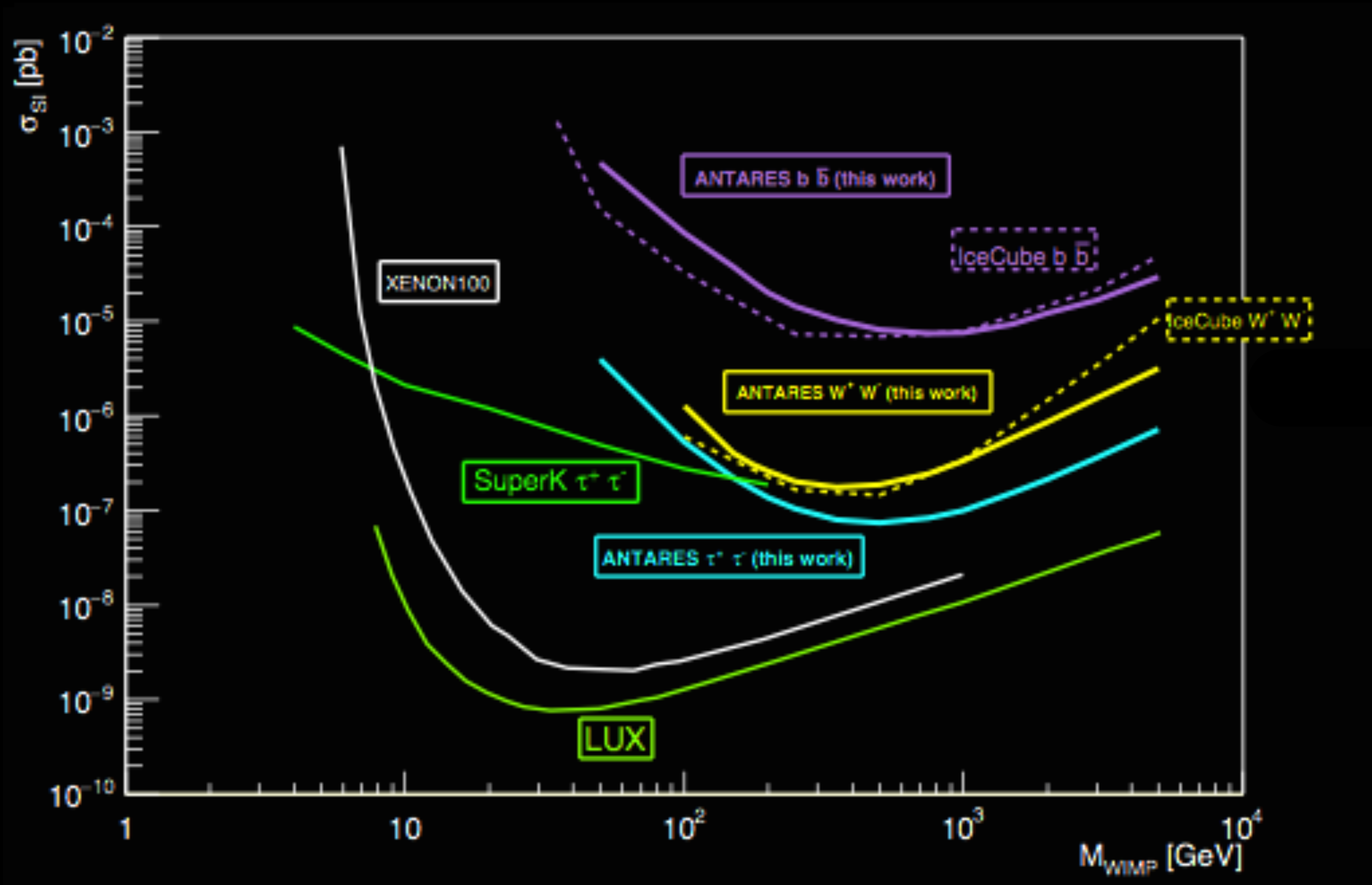

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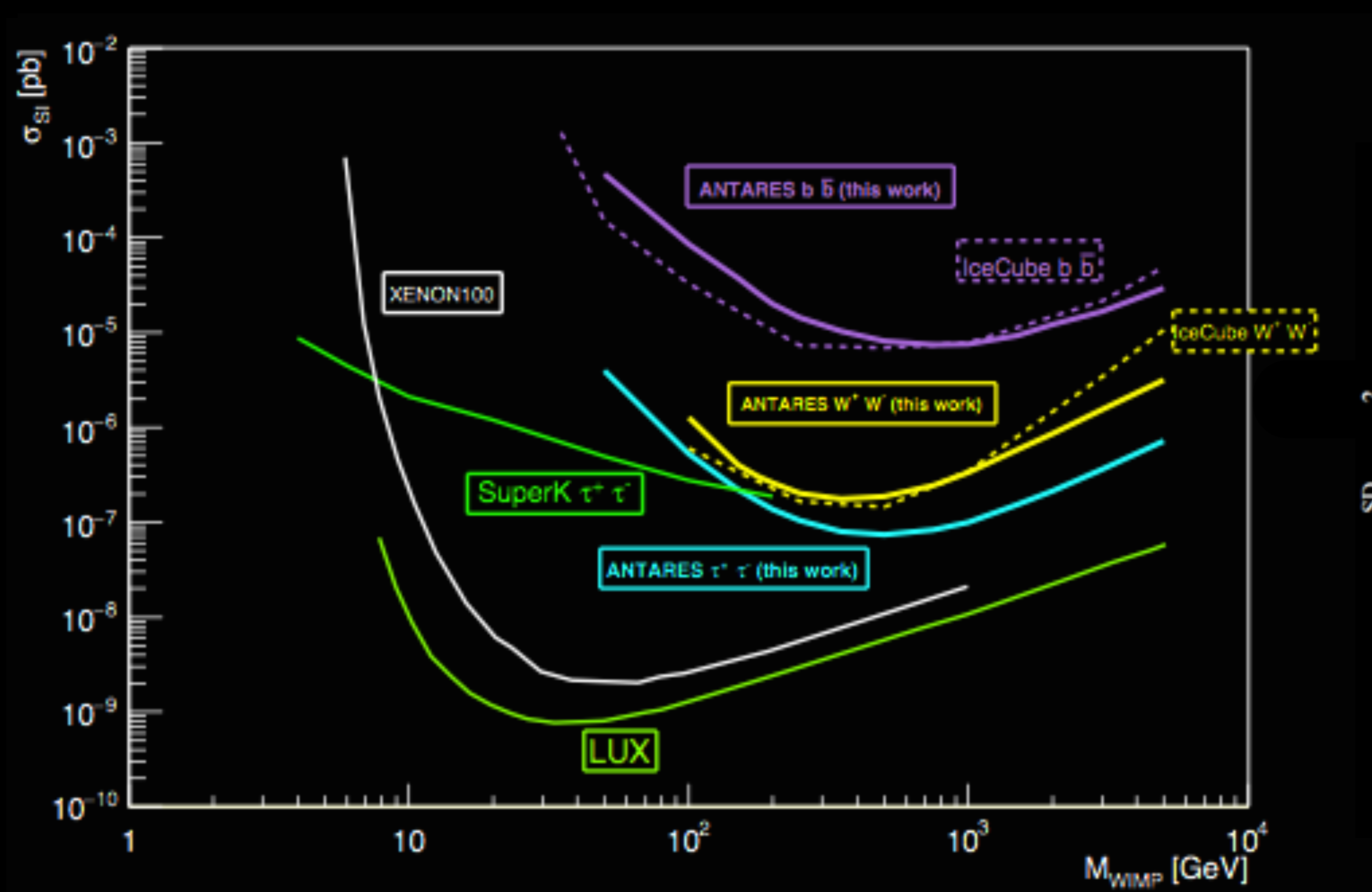
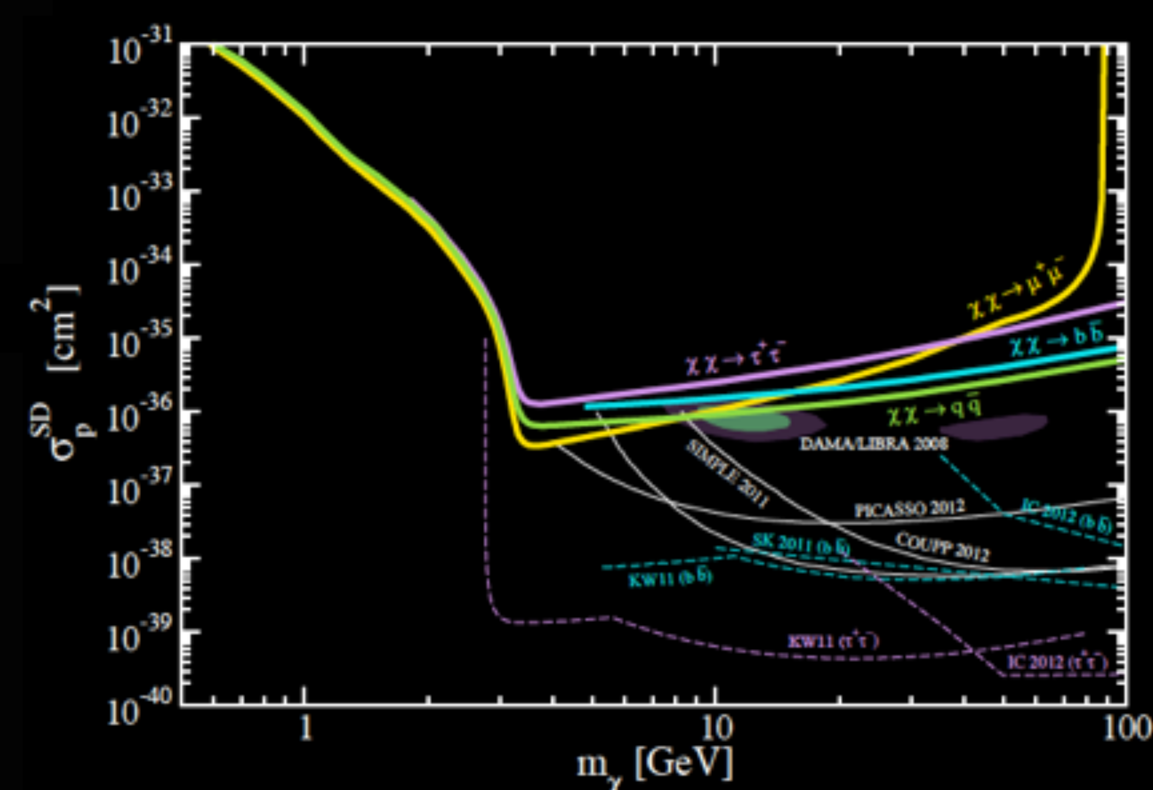


S. Adrián-Martínez et al. [ANTARES Collaboration], Phys. Lett. B759:69, 2016

Novel technique
use MeV neutrinos



N. Bernal, J. Martín-Albo, SPR, JCAP 1308:011, 2013

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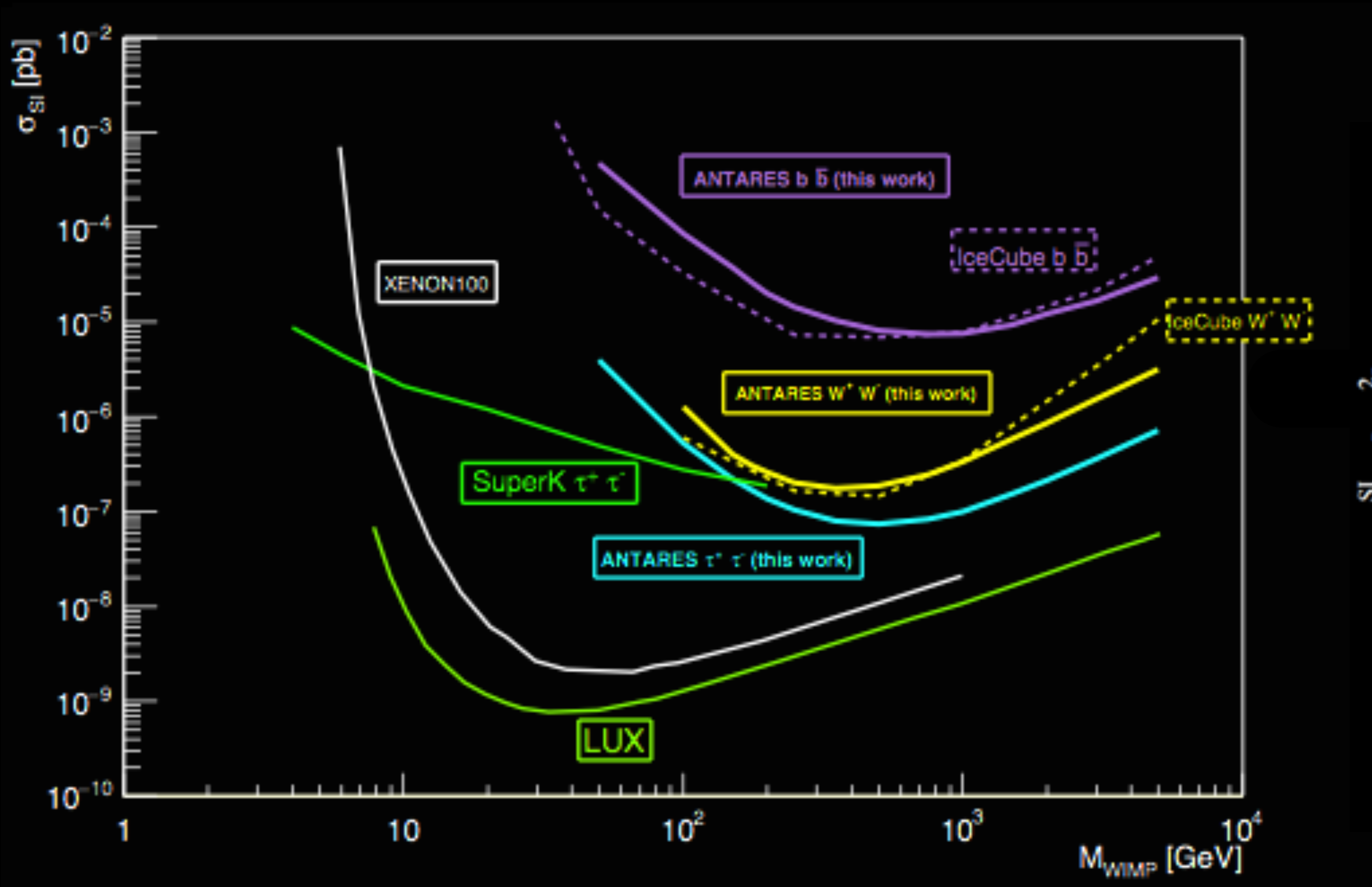

S. Adrián-Martínez et al. [ANTARES Collaboration], Phys. Lett. B759:69, 2016

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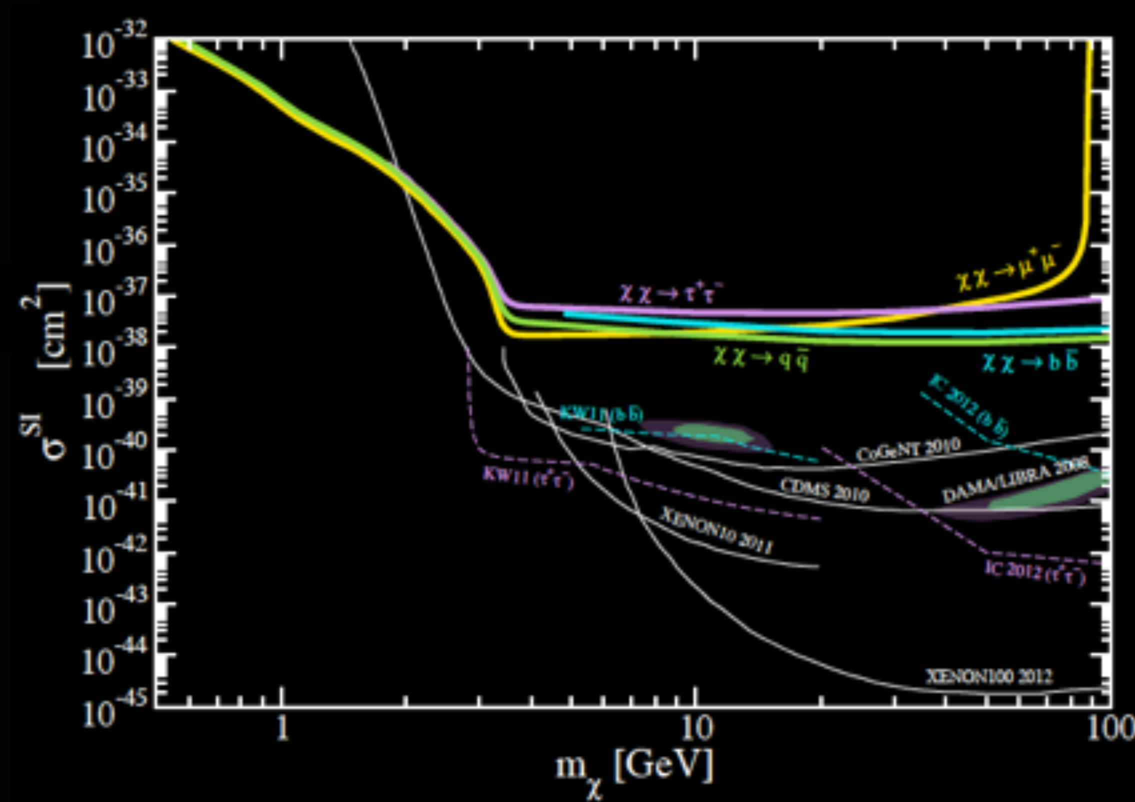
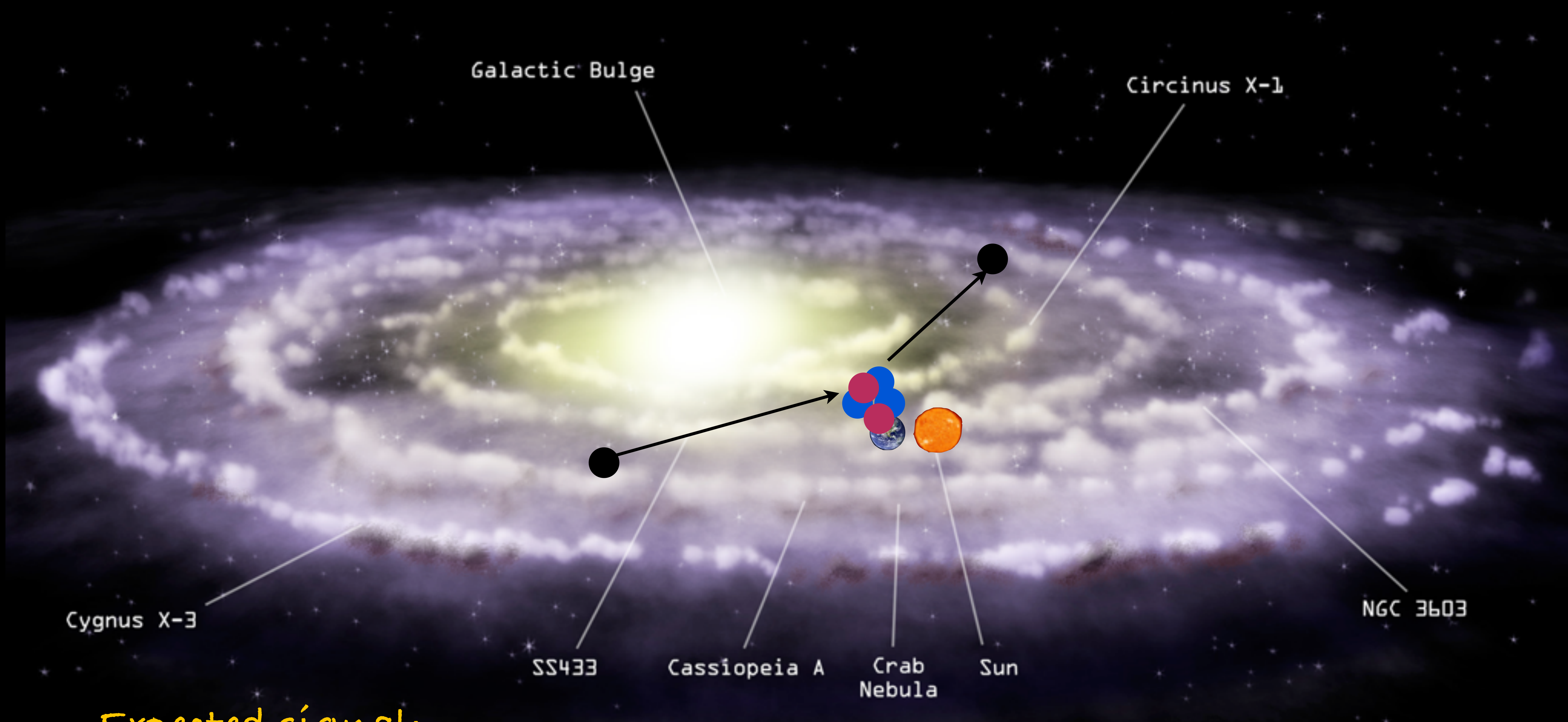


N. Bernal, J. Martín-Albo, SPR, JCAP 1308:011, 2013

DIRECT DETECTION



Expected signal:

nuclear recoil: 10's keV
featureless exponential
low rates < 0.1/kg/day

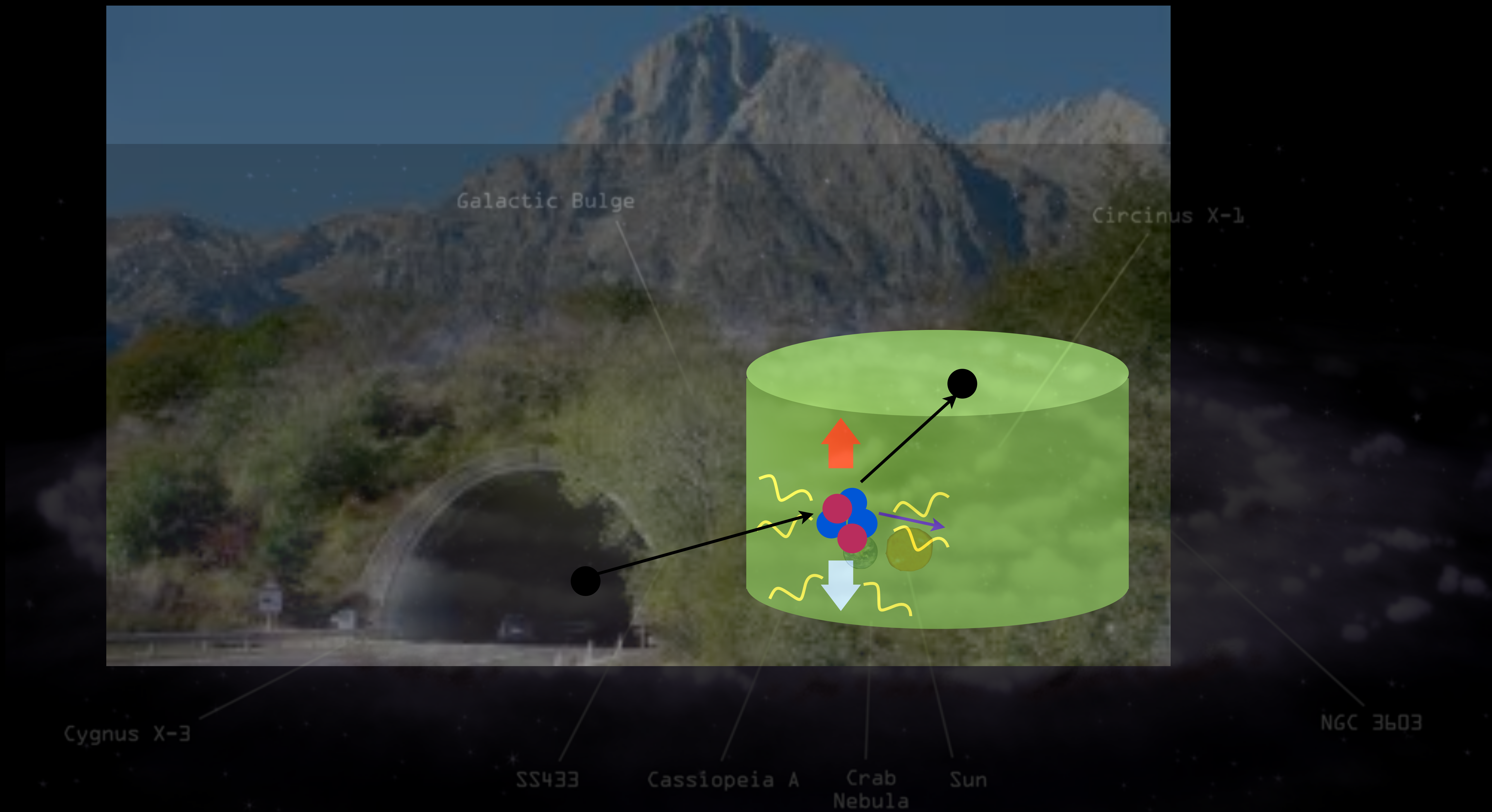
Challenges:

low energy threshold
large radioactive backgrounds

Need to know:

local density, velocity distribution...

DIRECT DETECTION



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nuclear recoil: 10's keV
featureless exponential
low rates < 0.1/kg/day

Challenges:
low energy threshold
large radioactive backgrounds

Need to know:
local density, velocity distribution...

EXCLUSION PLOT

recoil energy spectrum depends on:

local DM density

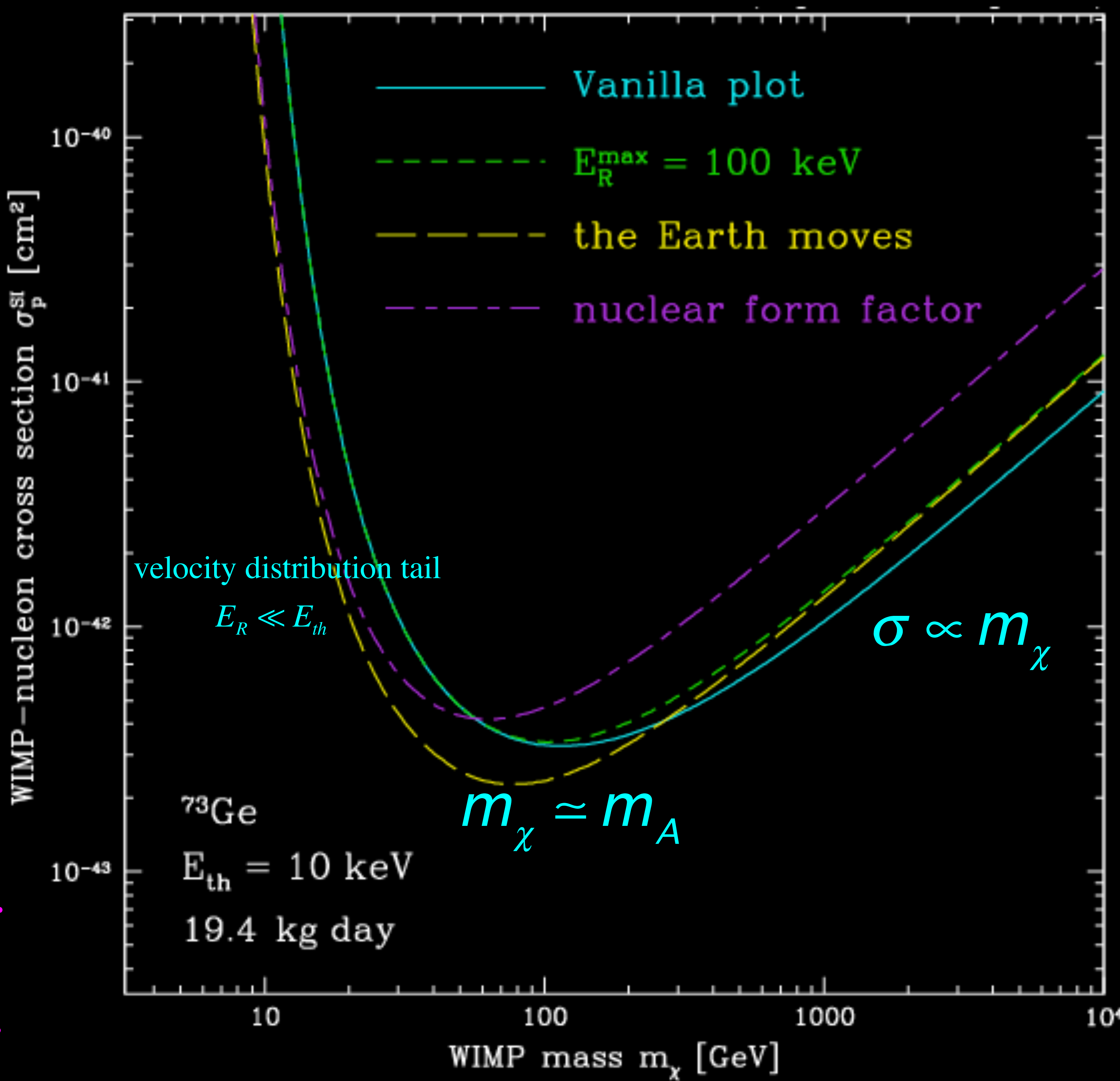
DM velocity distribution

Earth movement wrt halo

scattering cross section

$\sigma \propto \sigma_N^{SI} A^4 \times$ nuclear form factor

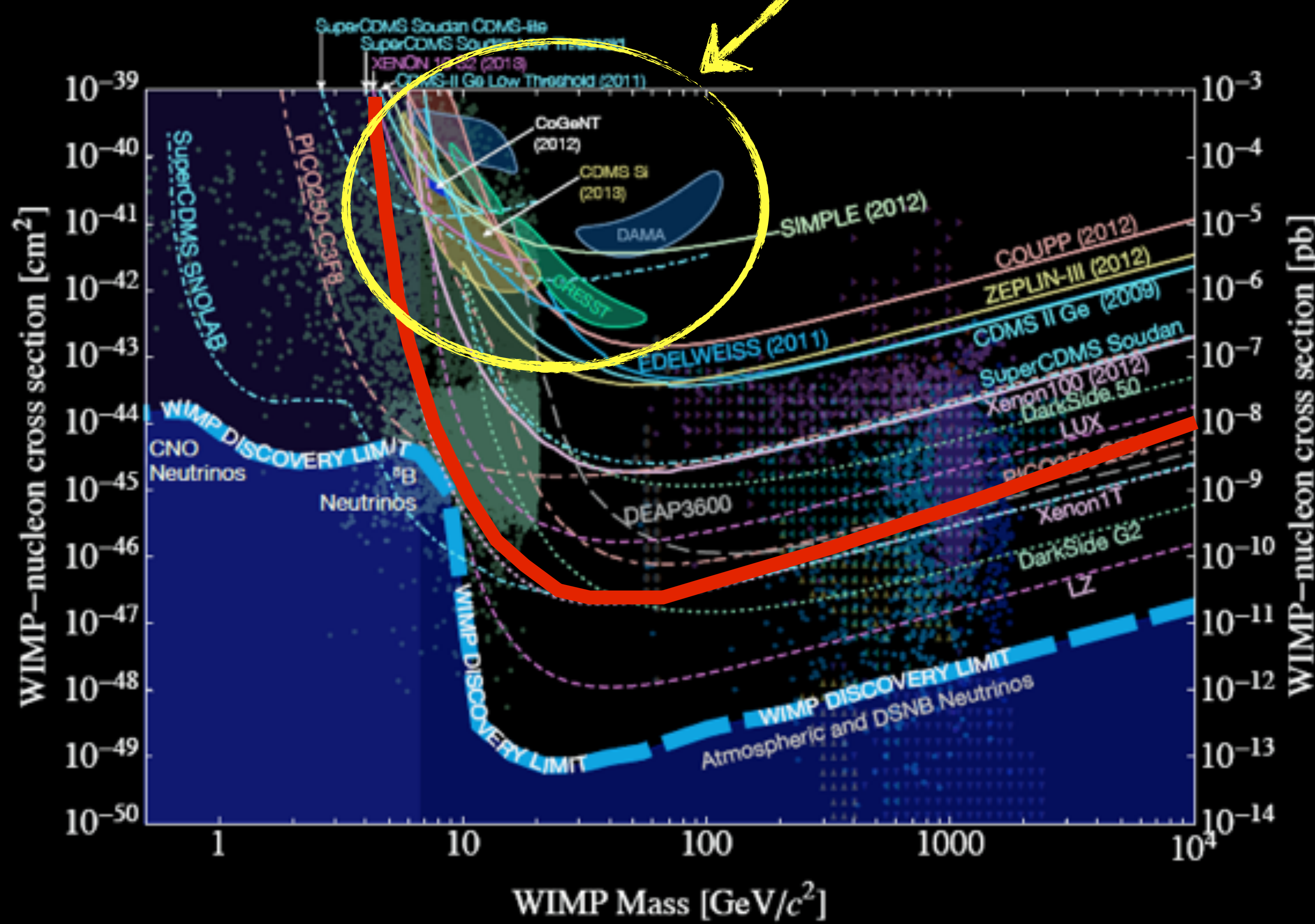
$\sigma \propto \sigma_N^{SD} A^2 \times$ nuclear form factor



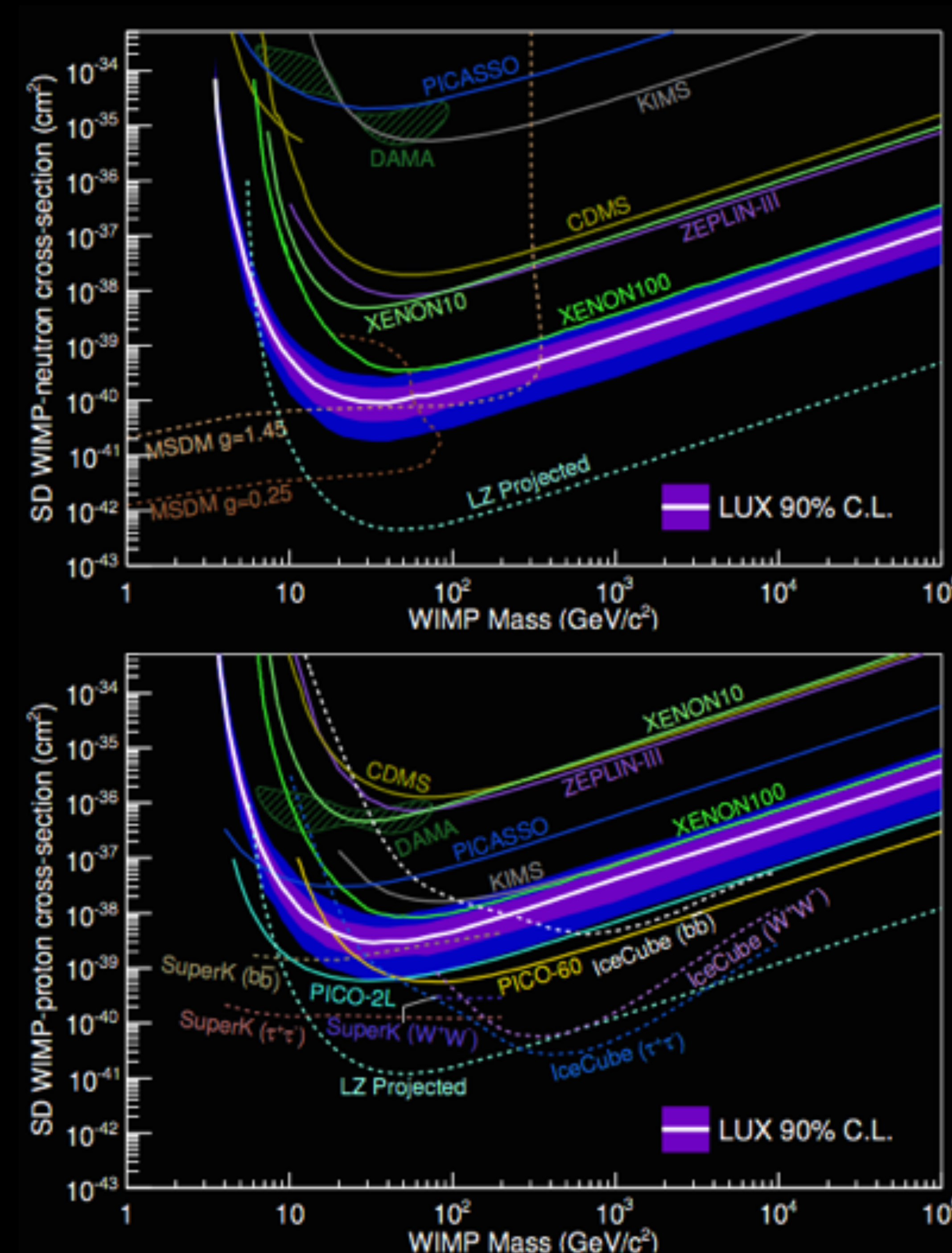
P. Salati, PoS Cargese 009, 2007

RESULTS

positive signals

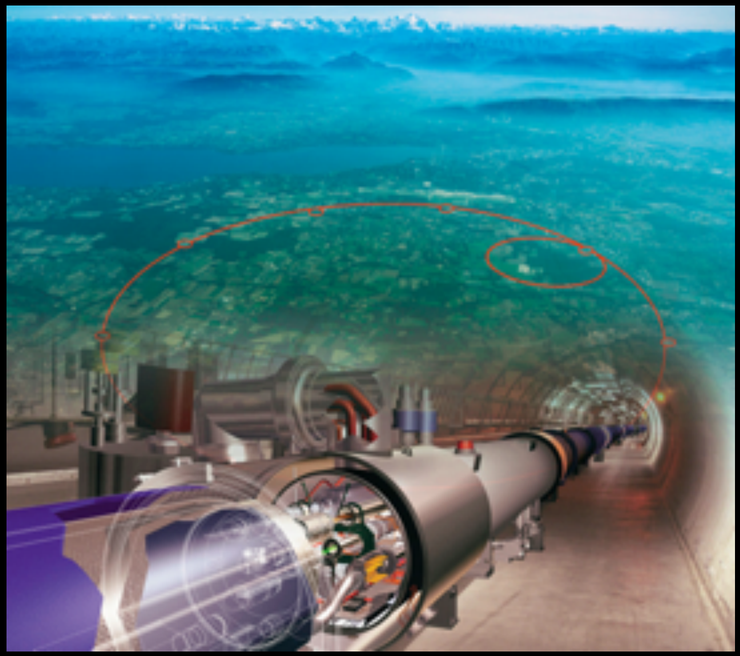


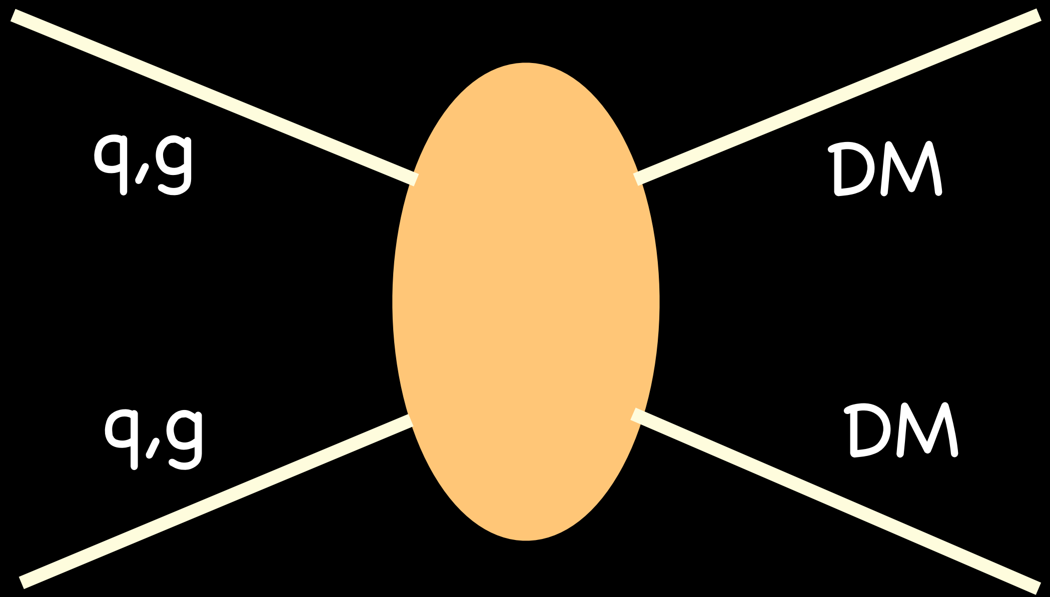
J. Billard, L. Strigari and E. Figueroa-Feliciano,
Phys. Rev. D89:023524, 2014



D. S. Akerib et al. [LUX Collaboration],
Phys. Rev. Lett. 116:161302, 2016

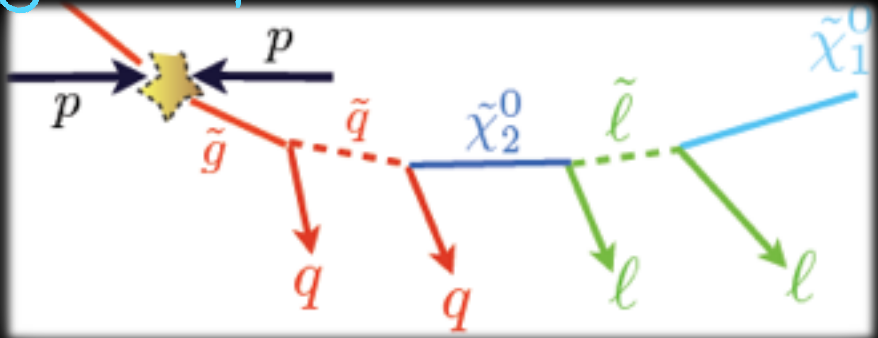
COLLIDERS



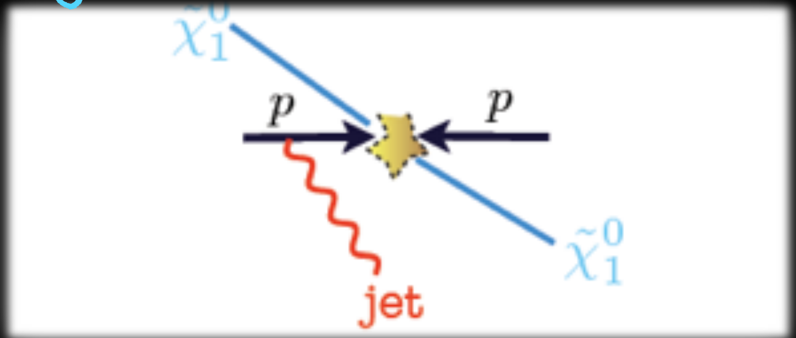


Very model/operator dependent

decays subproducts + missing energy

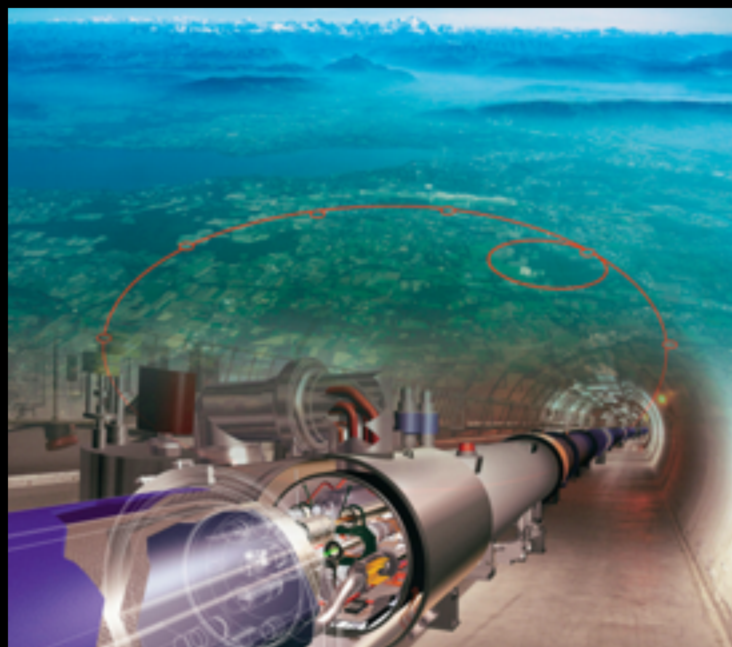


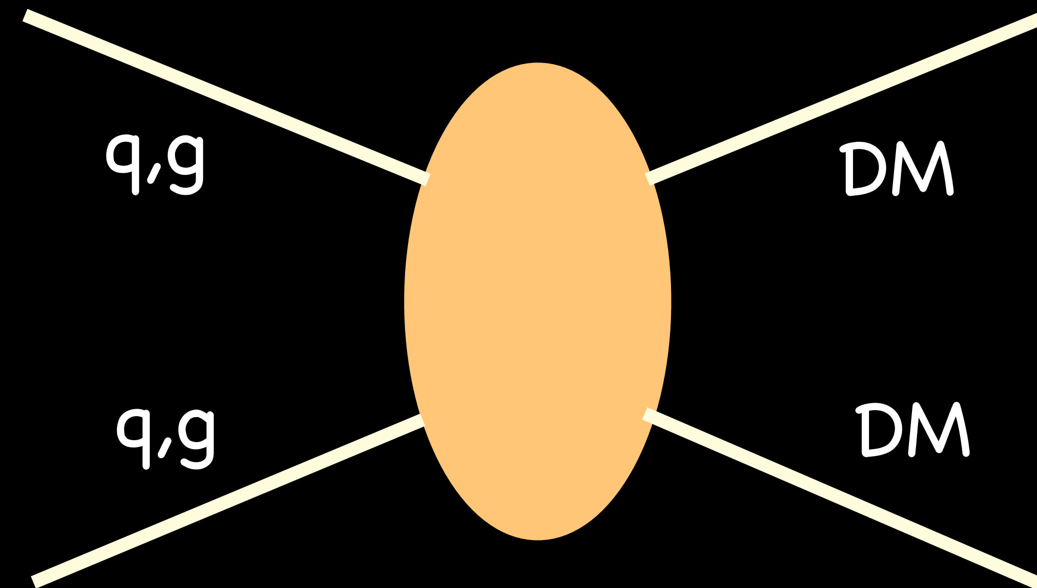
monojets or monoboson events



but also invisible decays, dileptons...

COLLIDERS





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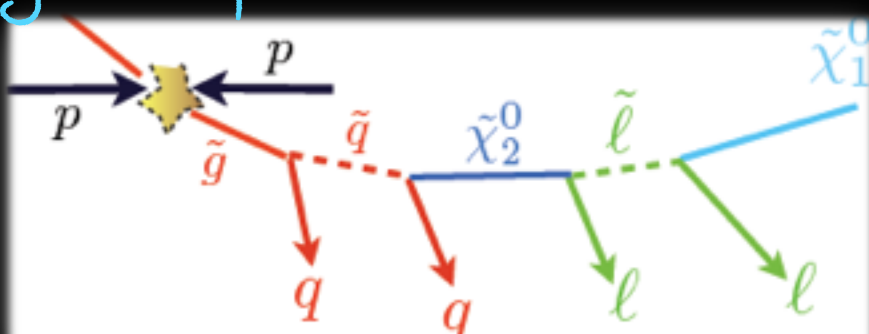

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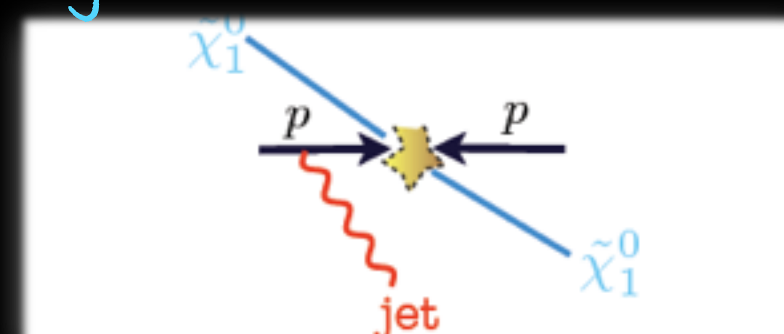
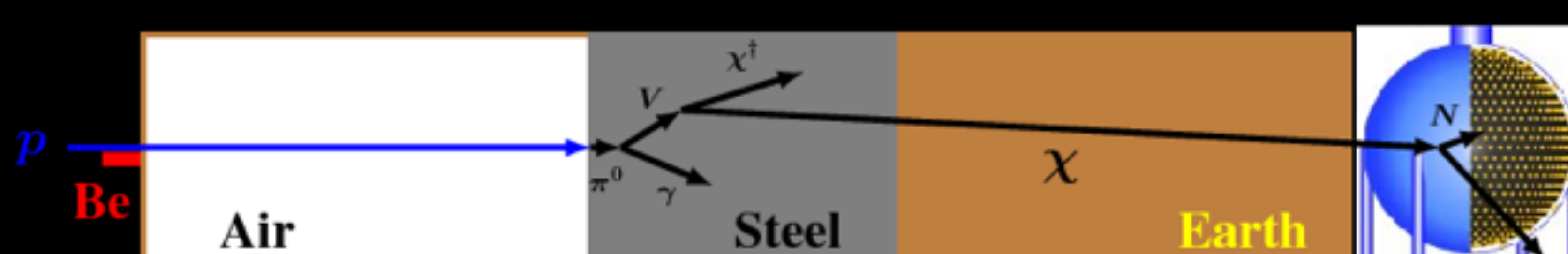


but also invisible decays, dileptons...

BUT ALSO FIXED TARGET BEAMS



EXAMPLE: SCALAR MEDIATOR

SCALAR DM (HIGGS MEDIATOR)

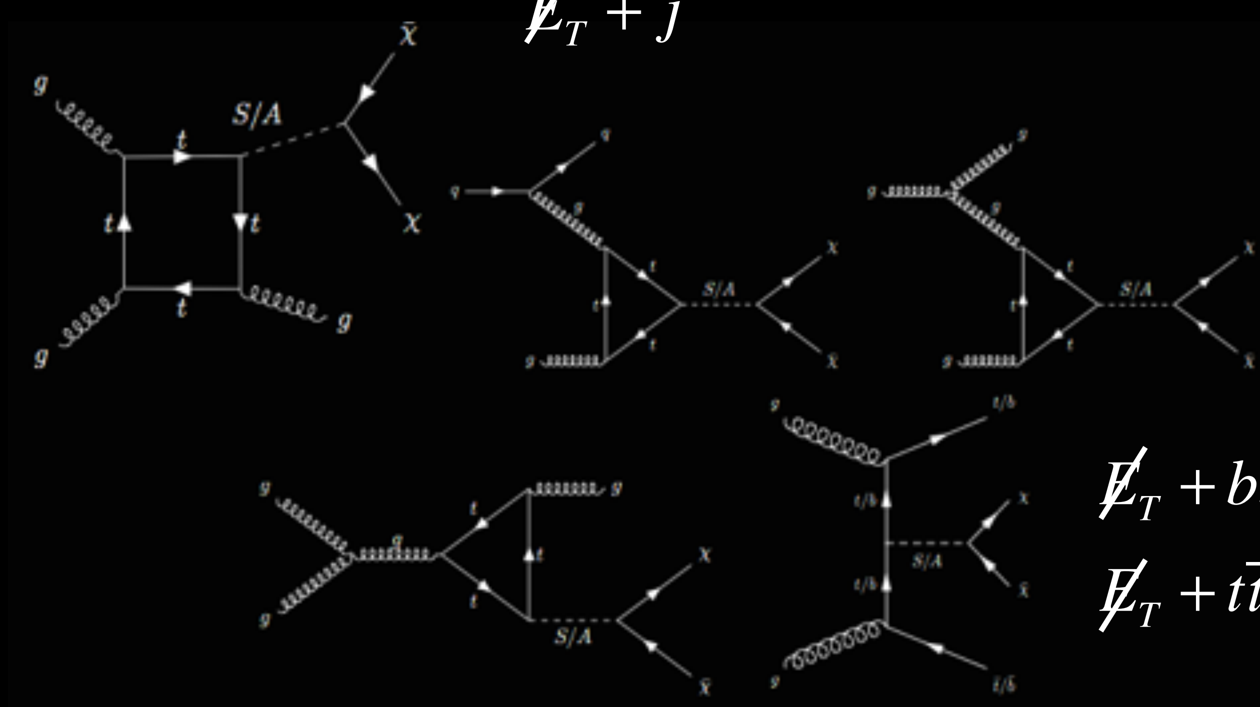
$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{\lambda_\phi}{4}\phi^2 H^\dagger H$$

A discrete Z_2 symmetry under which H is even and ϕ is odd would prevent $\phi - H$ mixing and make ϕ stable

Limits from invisible Higgs decays, if $m_H > 2\, m_\phi$
direct detection experiments (spin-independent), if $m_H < 2\, m_\phi$
s-wave annihilations

FERMION DM

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{1}{2} m_\phi^2 \phi^2 + \bar{\chi}\left(i\not{\partial} - m_\chi\right)\chi - g_\chi \phi \bar{\chi}\chi - g_{SM}\phi \sum_f \frac{y_f}{\sqrt{2}} \bar{f} f$$



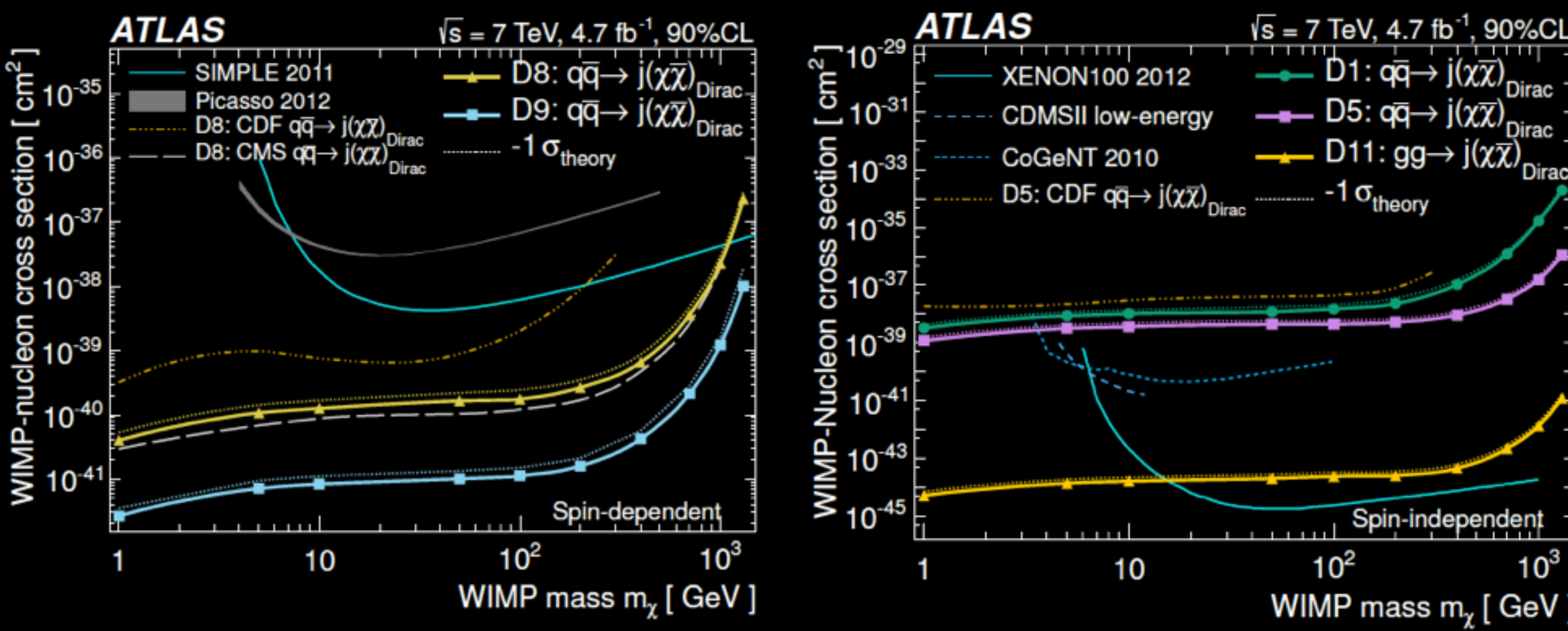
spin-independent interactions
p-wave annihilations

If the Higgs is the mediator,
LUX limits rule out this case
for masses < 1 TeV

A. De Simone and T. Jacques, Eur. Phys. J. C76:367, 2016

OPERATOR-DEPENDENT LIMITS

within EFT: jet+missing transverse momentum



ATLAS Collaboration, JHEP 04:075, 2013
T. Aaltonen et al [CDF Collaboration], Phys. Rev. Lett. 108:211804, 2012
CMS Collaboration, JHEP 09:094, 2012

CONCLUSIONS

Dark matter exists

We know how much there is

We know it is not baryonic and not within the SM

We live in the golden era of dark matter: a lot of theoretical developments and data, some hints... and hopefully soon a convincing discovery