Funny particles in the sky (astroparticles - theory)

GRASPA 2014

Annecy-le-Vieux, 21 - 25/08/2014

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Outline

Lecture 1 :

- Astroparticle physics : generalities
- Dark matter : why ?
- (one approach towards) Dark matter generation

Lecture 2 :

- WIMPs : an interesting coincidence
- (non-gravitational) Detection of dark matter
- Summary, omissions, conclusions and open questions

Part 0 : Generalities

Astro - particle physics ?

→ Kind of particle physics, but somehow related to astrophysics and cosmology

→ Kind of cosmology, but somehow related to particle physics and astrophysics

→ Kind of astrophysics, but somehow related to particle physics and cosmology

A relatively common theme :
study of particles in their “natural habitat”

(i.e. not through man-made accelerators.)

Astro - particle physics ?

→ Kind of particle physics, but somehow related to astrophysics and cosmology

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→ Kind of astrophysics, but somehow related to particle physics and cosmology

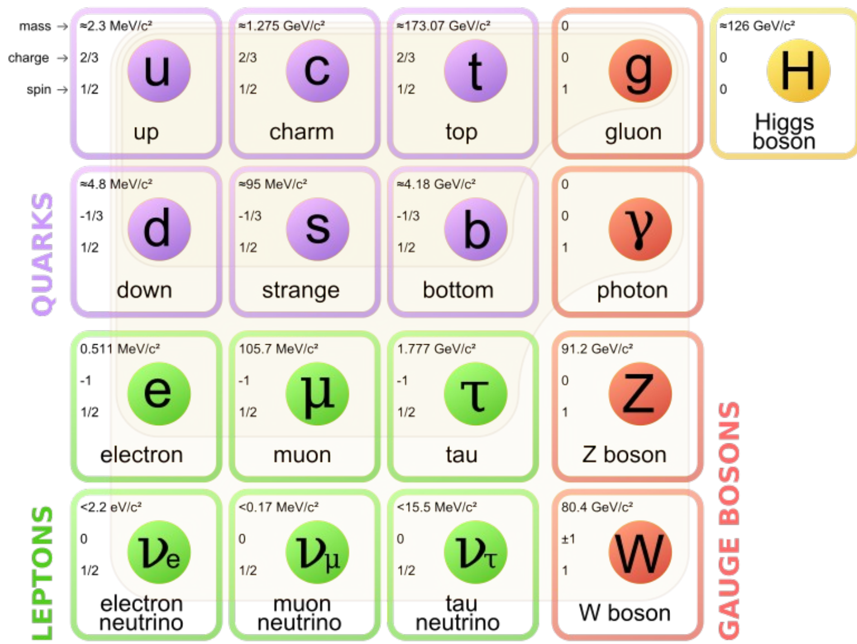
Some current research topics (taken from JCAP list):

- High-energy cosmic-ray physics and astrophysics
- Particle cosmology
- Particle astrophysics
- Related astrophysics: Supernova, Active Galactic Nuclei etc
- High-energy, VHE and UHE gamma-ray astronomy;
- High- and low-energy neutrino astronomy;
- Instrumentation and detector developments.

In these lectures : (mostly) Dark Matter

What particles do we encounter usually?

The only particles that are abundant in nature under “normal conditions” are : protons, neutrons (in nuclei), electrons, neutrinos, photons.



Why ?

One needs to consider two issues:

i) How easy is it to produce a particle?
(mass, production cross-section)

ii) For how long does it stay around?
(lifetime)

→ Well, most other particles decay extremely rapidly, with lifetimes much less than a sec.
→ So even if they were abundantly produced sometime in the early universe, they're long gone.

Btw: What happened to antimatter? Ask Cedric :-) !

Funny particles in the sky?

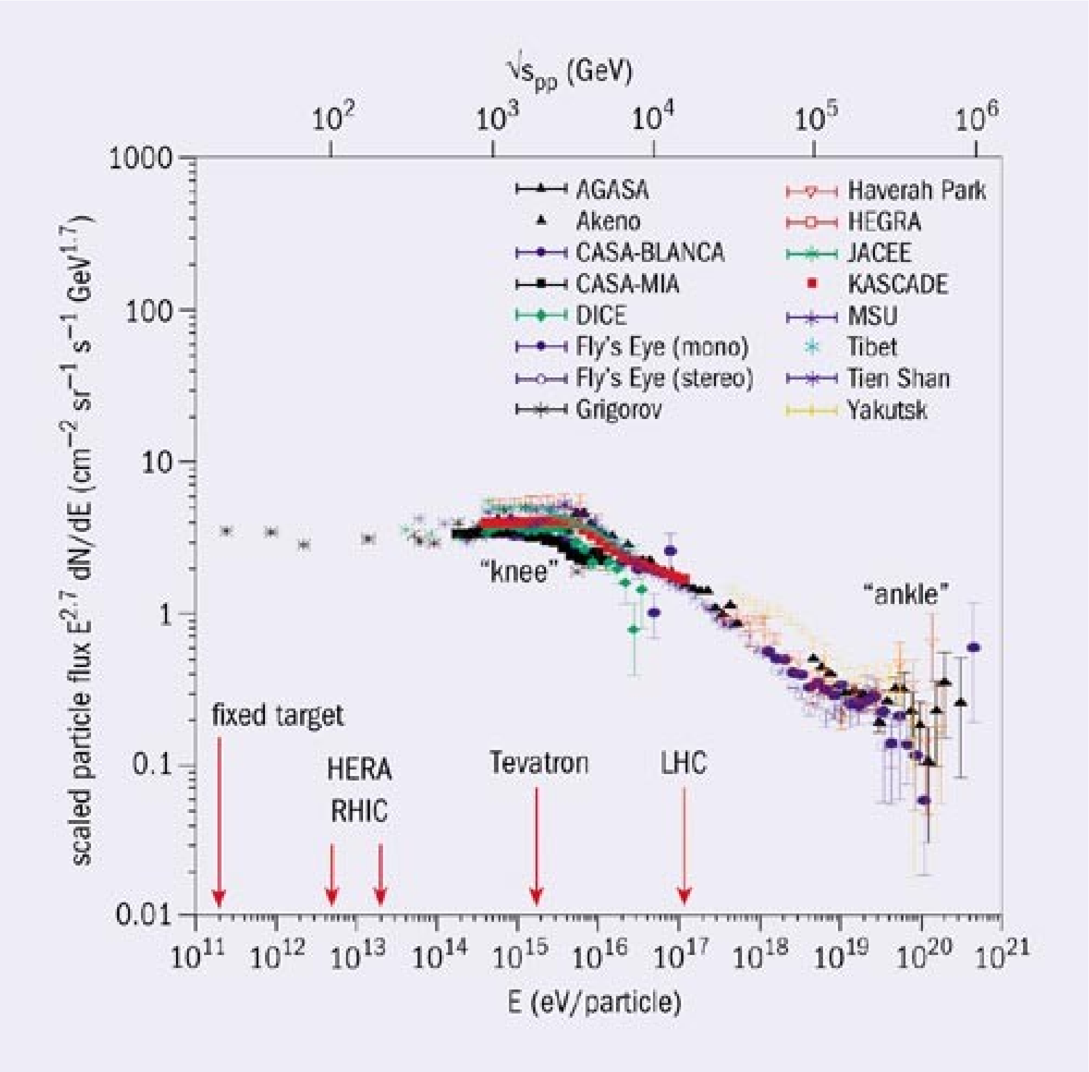
Some major particle discoveries
[L: LAB, CR: Cosmic Rays] :

- 1897: Electron [L]
- 1899: Alpha particle [L]
- 1900: Gamma ray [L]
- 1919: Proton [L]
- 1932: Neutron [L]

- 1932: Positron [CR]
- 1937: Muon [CR]
- 1947: Pion [CR]
- 1947: Kaon [CR]
- 1960's: ν oscillations [CR]

- 1955: Antiproton [L]
- 1956: Electron anti-ν [L]
- 1975: Tau [L]
- 1983: W and Z bosons [L]
- 1995: Top quark [L]
- 2012: Higgs (?) [L]

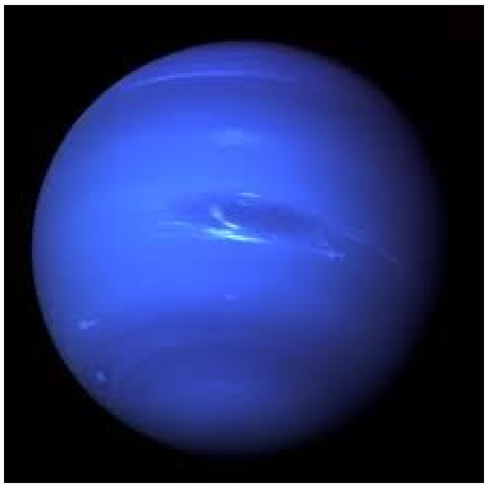
Available CM energies :



Part 1 : Dark matter – why?

Two crises in 19th century astronomy

What do physicists do when theory and observation don't agree?

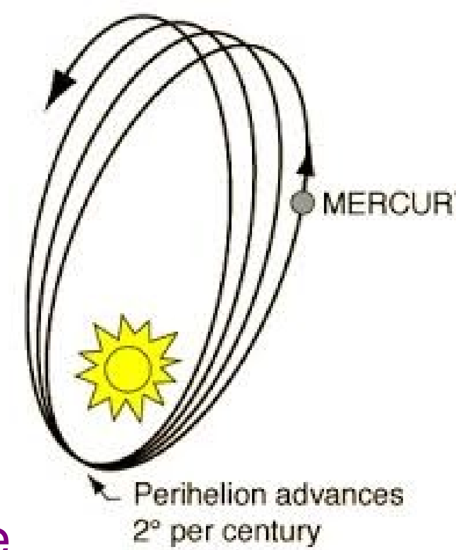


- Observations of anomalies in the orbit of Uranus led to the postulation of a new “dark” planet by Adams (1844-45) and Le Verrier (1845-46).

→ This new planet (Neptune) was discovered in 1846 by Galle.
(Dark matter!)

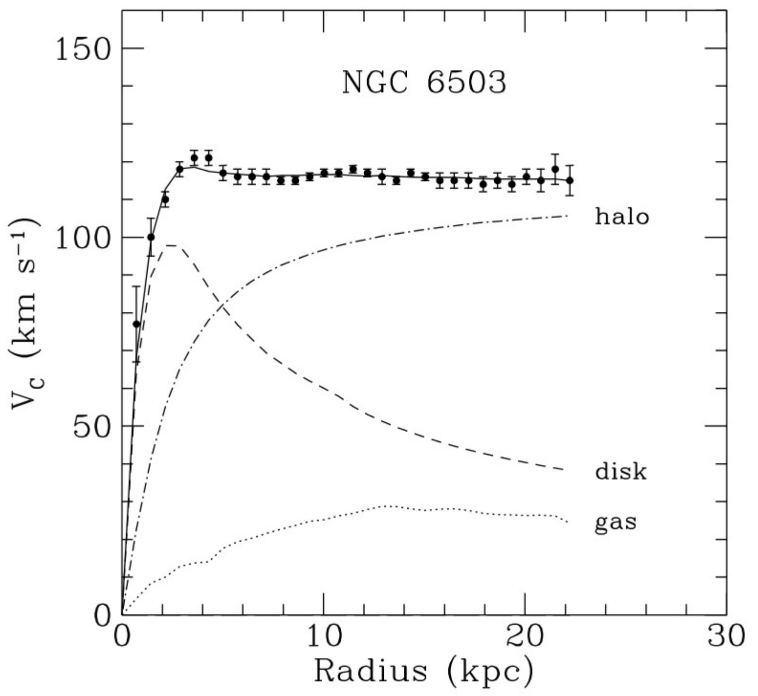
- Observations of anomalies in the orbit of Mercury led Le Verrier to introduce another dark planet, “Vulcan” (1859).

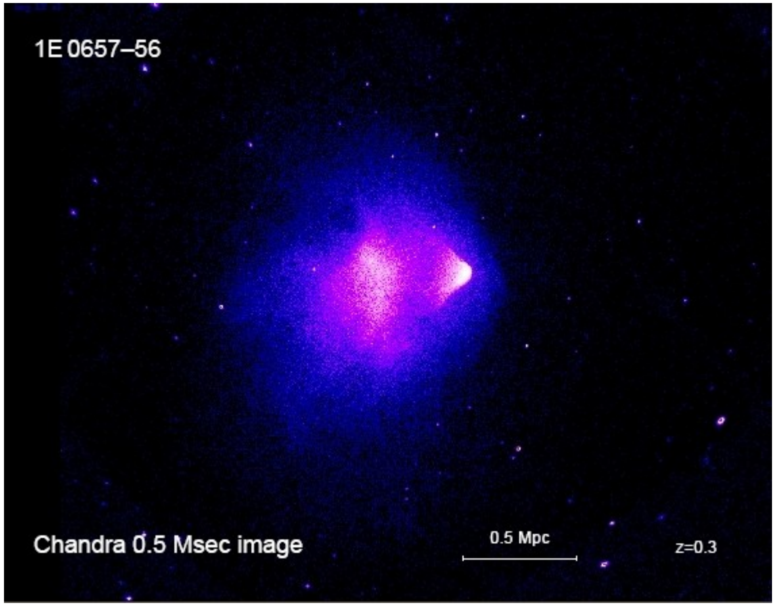
→ This time the trick didn't work out that well! What solved the problem was GR, half a century later.
(Modified gravity!)

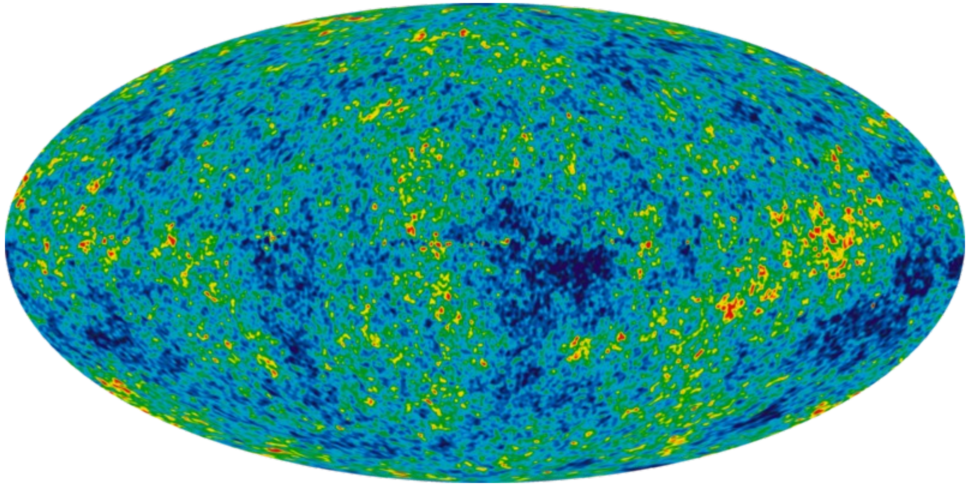


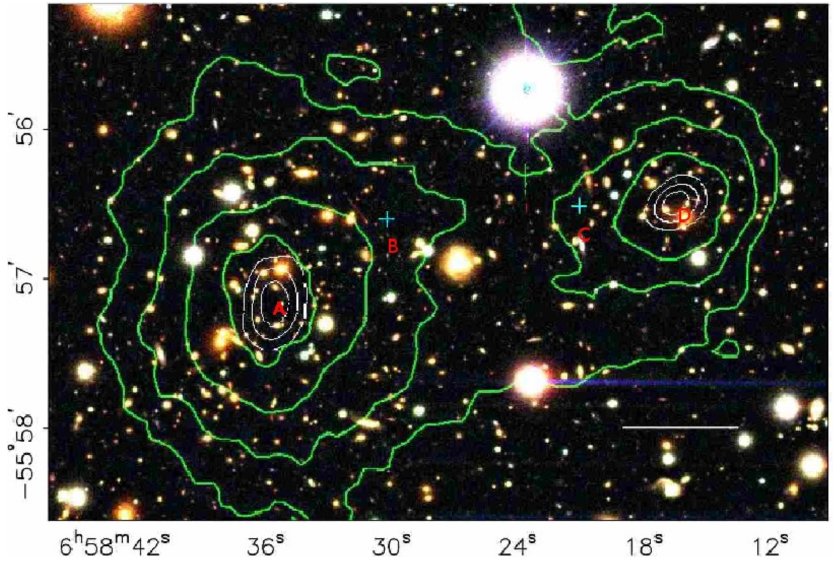
→ People have successfully modified both the form and the content of equations.

Contemporary issues in gravitation



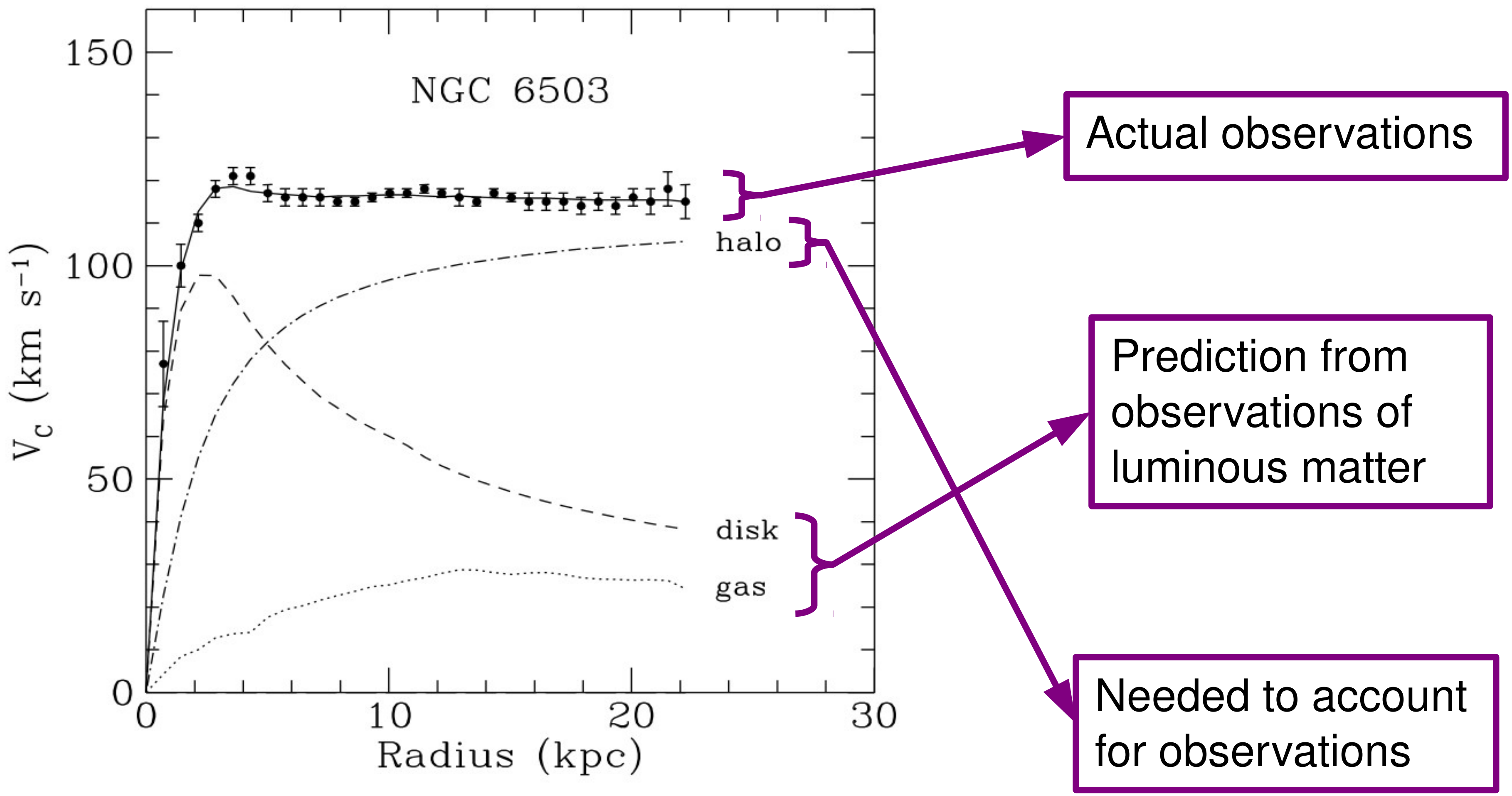




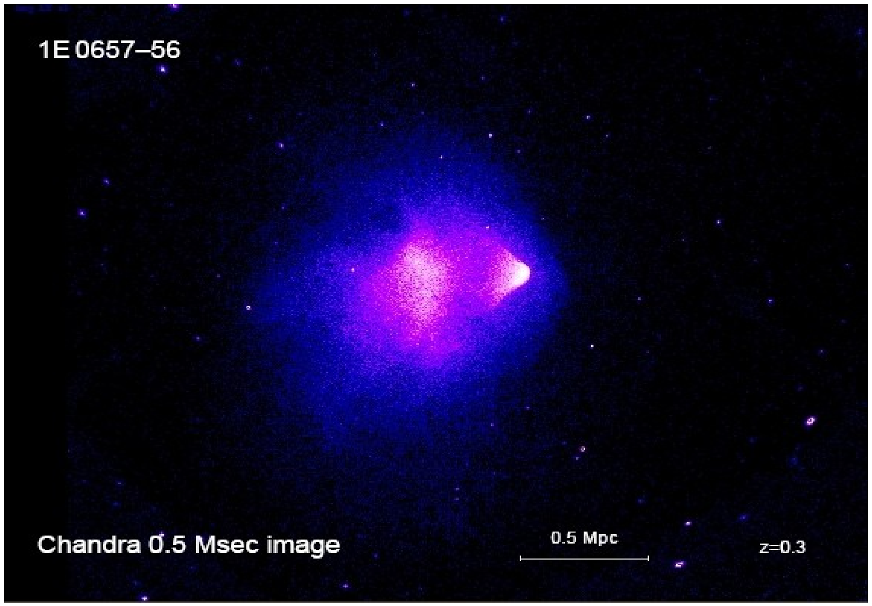


Galactic rotation curves

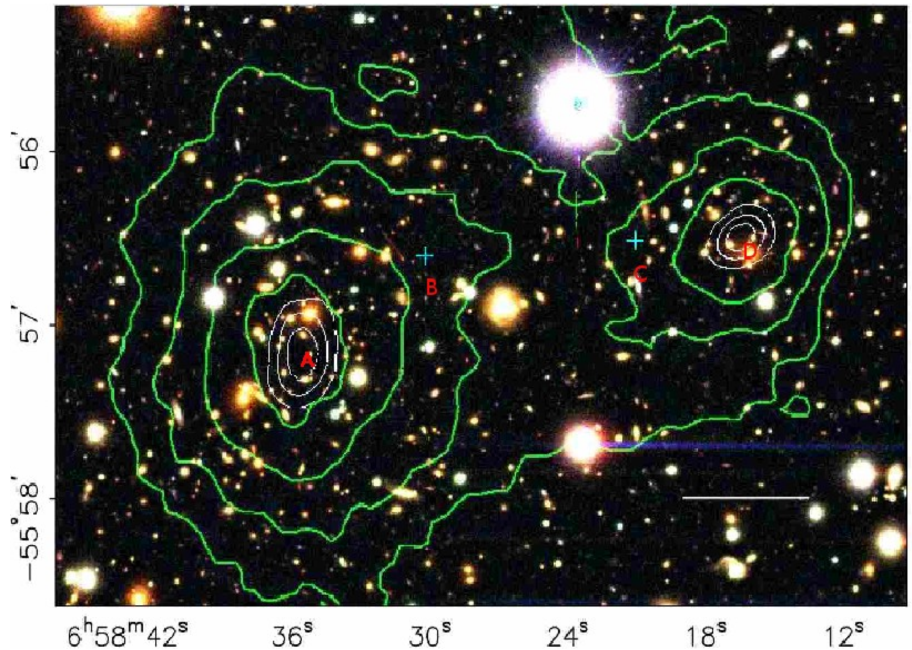
Galactic dynamics is more or less described by Newtonian mechanics. But...



Gravitational lensing

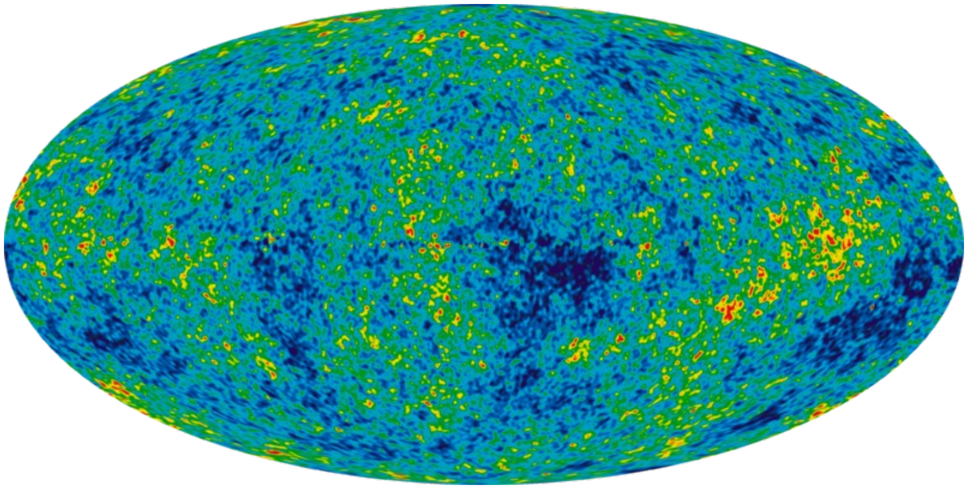


Distribution of gas
(bulk of luminous matter)



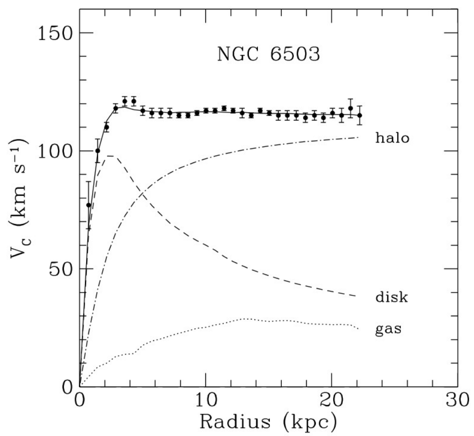
Total matter distribution
(gravitational lensing)

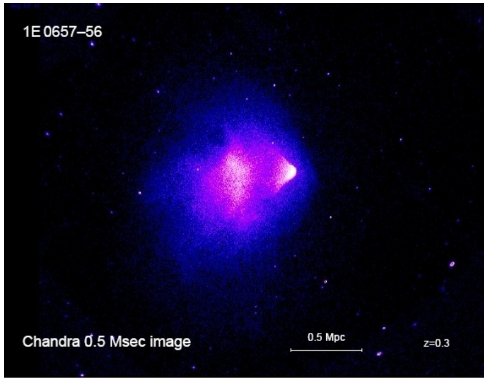
Cosmic Microwave Background (CMB)

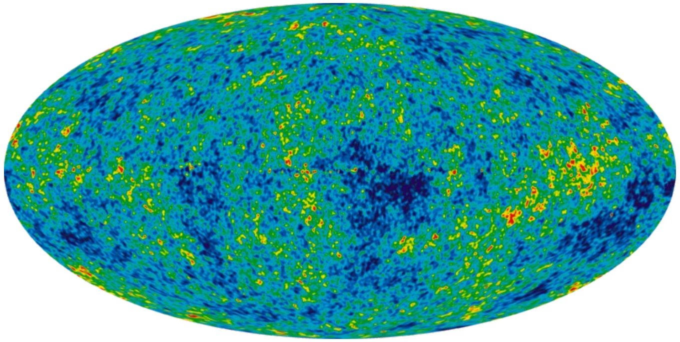


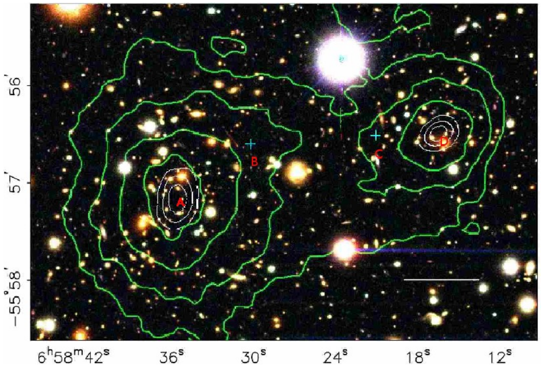
A *very* complicated topic, thankfully explained in the cosmology course :-) !

Very important clarification









→ The DM interpretation of these anomalies is *one of the possible solutions*. Researchers *also* work on efforts to modify the laws of gravity!

→ The DM option is more widely accepted, but *both are equally legitimate!*

→ In the following we'll go with DM, but keep this in mind...

Part 2 : Dark matter - how?

Some sort of starting point...

So dark matter is some kind of matter that we believe to exist in the universe.

→ And we basically don't have a clue about what it is...

It however seems to indeed possess a few characteristics :

- It is indeed matter, and fairly "cold" (or "warm").

- It is pretty "dark": It doesn't absorb or emit "light". But it does gravitate.

- It is "non-baryonic" → DM also becomes a problem of (BSM) particle physics.

But there are also a few things on which we know essentially nothing :

- Does it possess any non-gravitational interactions?

- What is its mass? *(for the moment DM physics has no mass scale – major issue!)*

The DM density today

The WMAP and Planck satellites gave us some valuable information on the total DM density of the universe

$$\Omega_{\mathrm{DM}} = 0.1187 \pm 0.0017$$

(valid within ΛCDM cosmology...)

Where *Ω* is defined through

$$\Omega_{\mathrm{DM}} = \frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{crit}}}$$

whereas the *critical density* is

$$\rho_{\mathrm{crit}} \approx 3 \times 10^{10} \frac{M_{\odot}}{\mathrm{Mpc}^3} \approx 10^{-6} \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Also note that : $\Omega_{\mathrm{DM}} \approx 5 \times \Omega_{\mathrm{BM}}$

The DM density today

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$$\Omega_{\mathrm{DM}} = 0.1187 \pm 0.0017$$

(valid within ΛCDM cosmology...)

→ Where does this number come from?
Can it be placed in a “historical” (i.e. thermodynamical) context?

There is a series of basic questions that we need to address :

i) Given some initial conditions, how does the DM system evolve over time?

ii) What could these initial conditions be?

iii) What is the interplay among the above?

iv) Could there be any other complication? (surprise-surprise, lots!)

The DM density today

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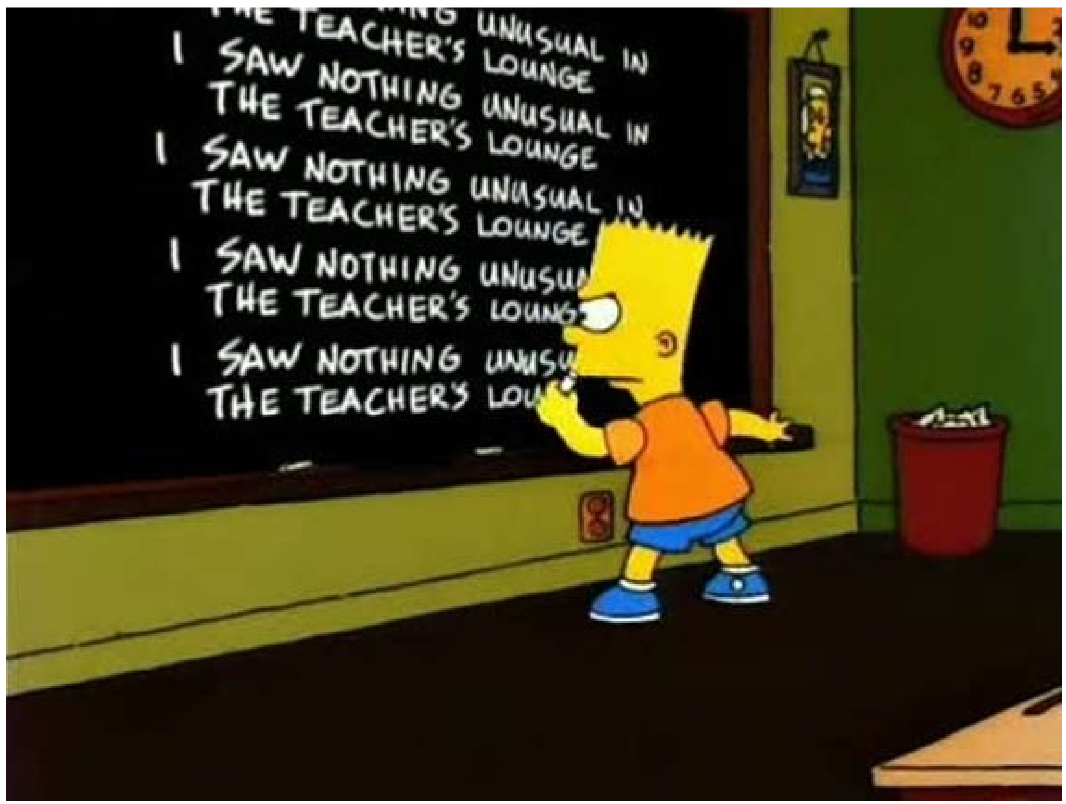


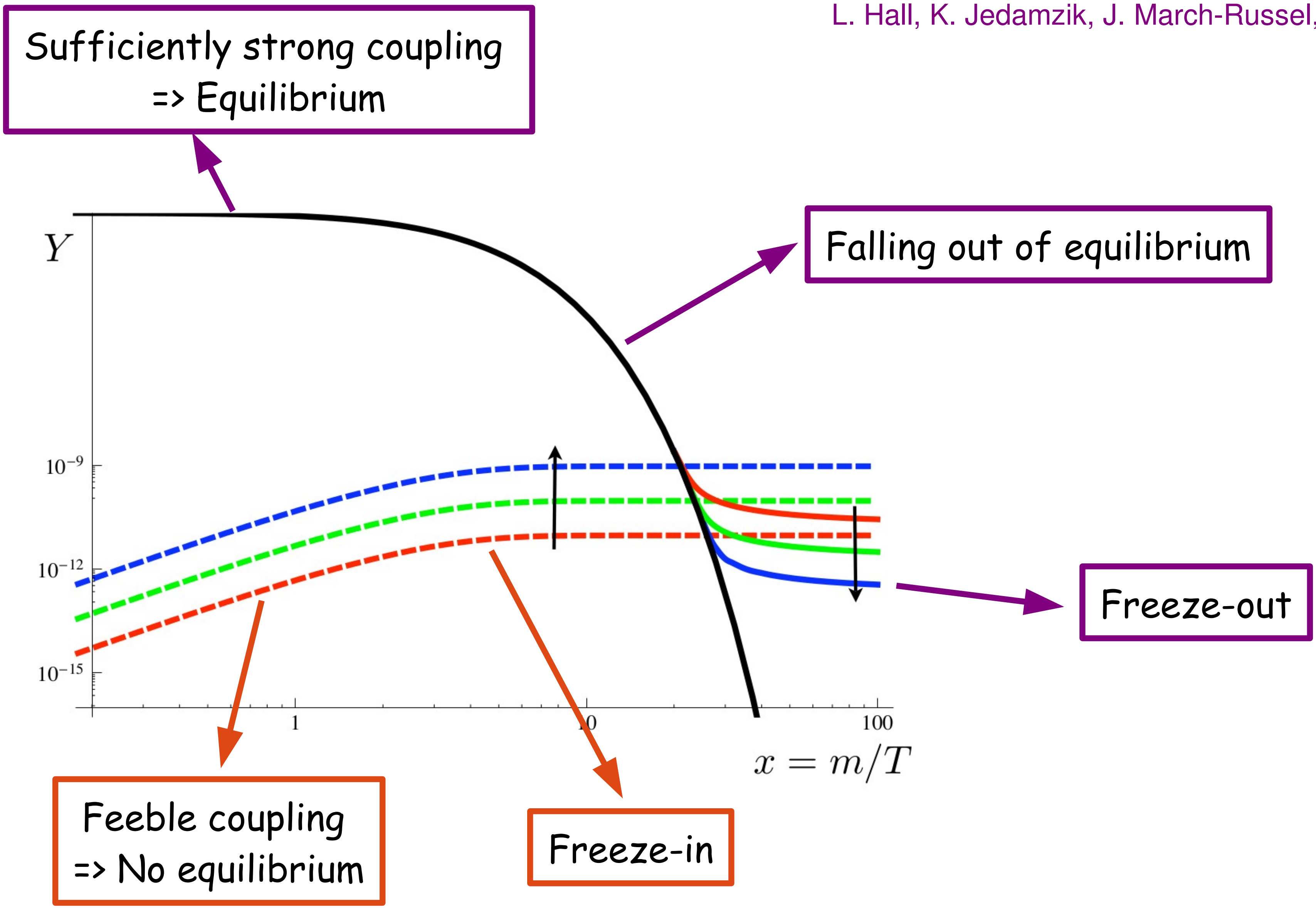
Blackboard time :-) !

(...blackboard time...)

The DM density evolution

Here's a nicer picture of potential outcomes of the DM number density evolution

L. Hall, K. Jedamzik, J. March-Russel, S.M. West (2009)



Part 3 : Dark matter - what?

Ingredients for a DM model

When constructing a DM model, there are a few things that we might want to consider :

- Can we explain the amount of DM in the universe?

→ Or at least some of it.

→ DM should be (quasi-)stable.

Q: the DM density today

- Can we "hide" dark matter well-enough?

→ We have only "seen" it through its gravitational effects.

- Can we nonetheless make our DM candidate observable in some non-gravitational experiment?

→ We would like to find out what it is, wouldn't we :-) ?

Q: dark matter detection

What does a DM model look like ?

Probably the simplest DM model: the Singlet Scalar Model

McDonald (1994)
Burgess, Pospelov, Rychkov (2006)
Davoudiasl, Kitano, Li, Murayama (2006)
...

- Gauge + spacetime symmetries : as in the SM.

- Particle content : SM + one real, SU(2) - singlet scalar field *S*.

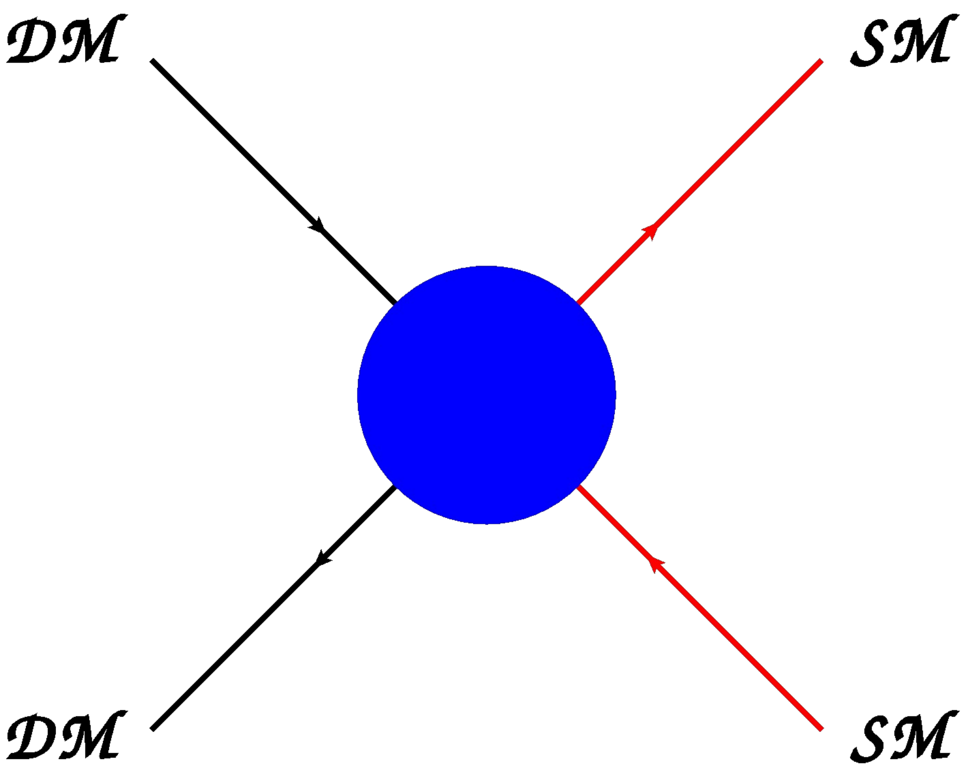
- An extra Z2 discrete symmetry that protects *S* from decaying.

So, here's what this simple dark matter model looks like :

$$\mathcal{L} \;=\; \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_0^2}{2} S^2 - \frac{\lambda_S}{4} S^4 - \lambda S^2 H^\dagger H$$

Detection of dark matter

Based on the freeze-out picture (and the “WIMP miracle”), 3 basic ways to detect dark matter have been pursued



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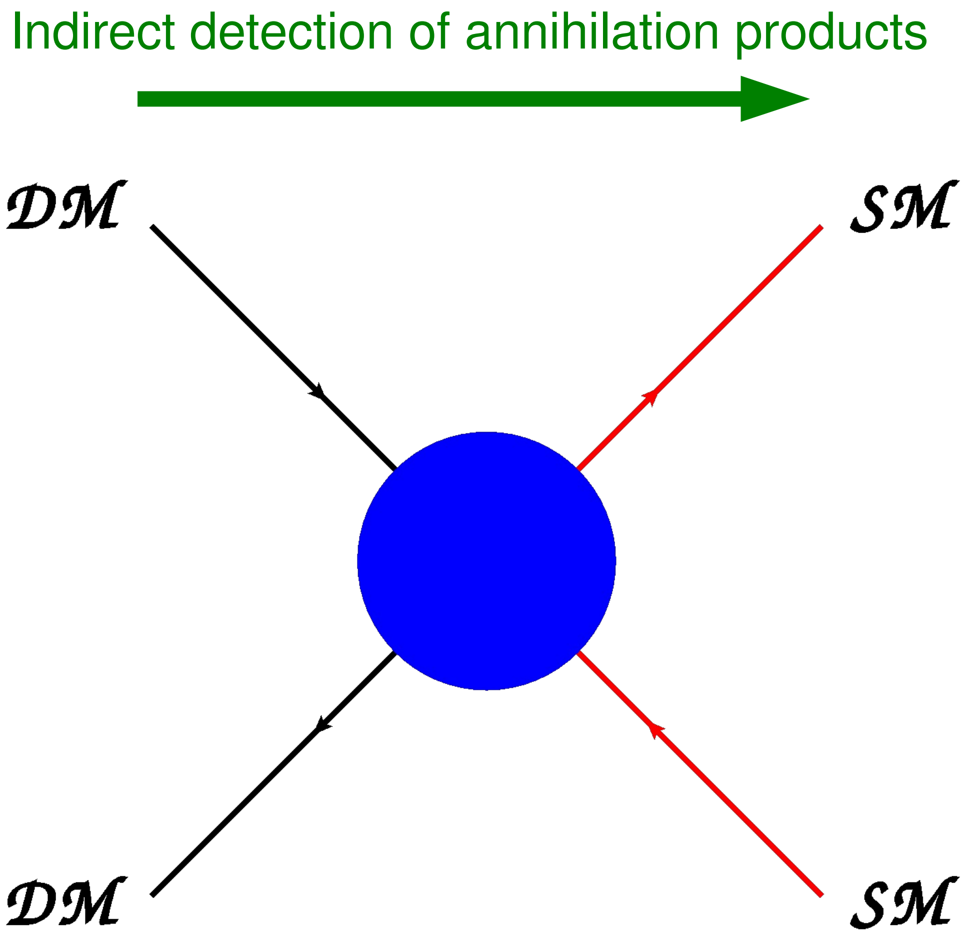

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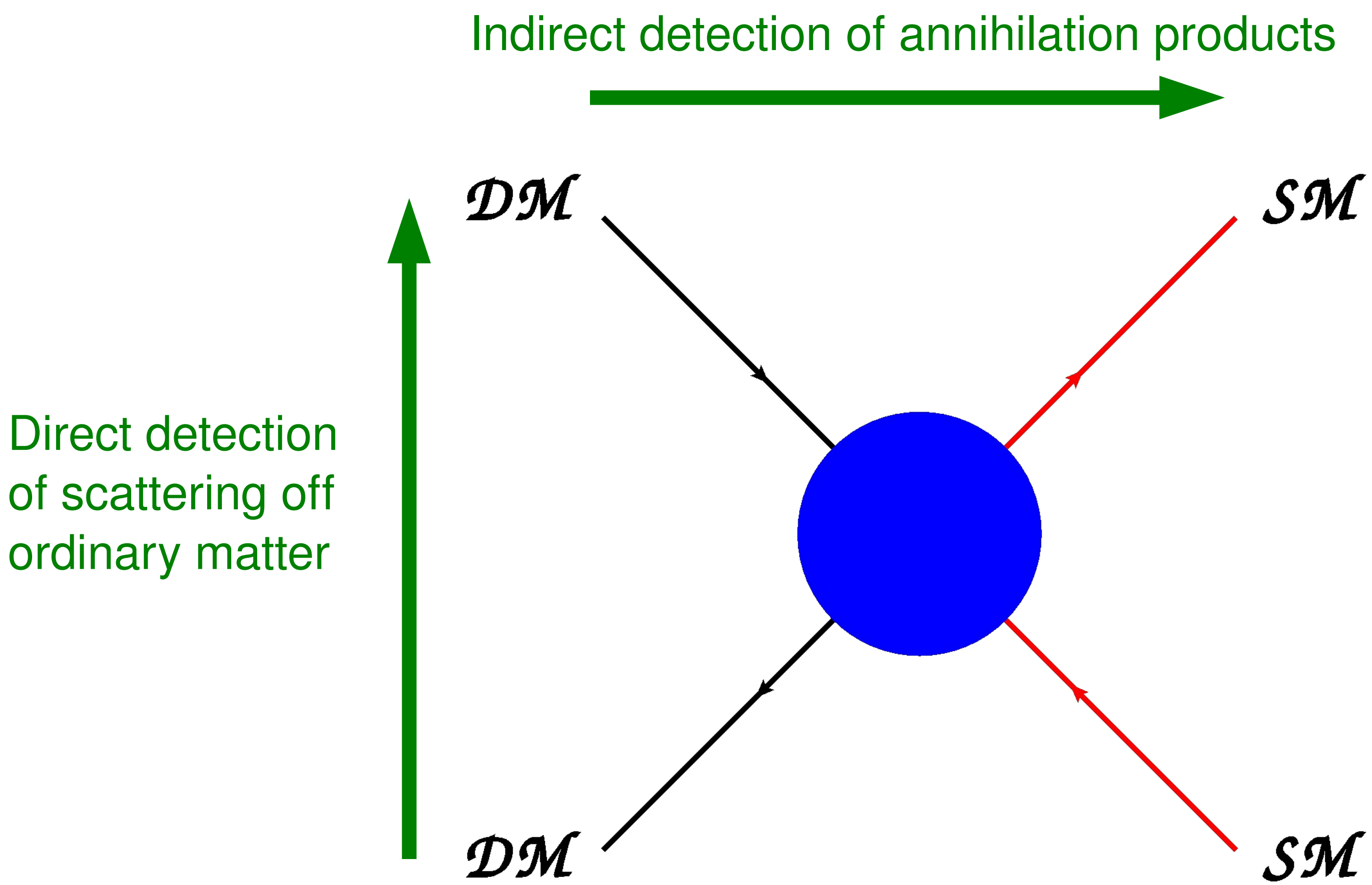

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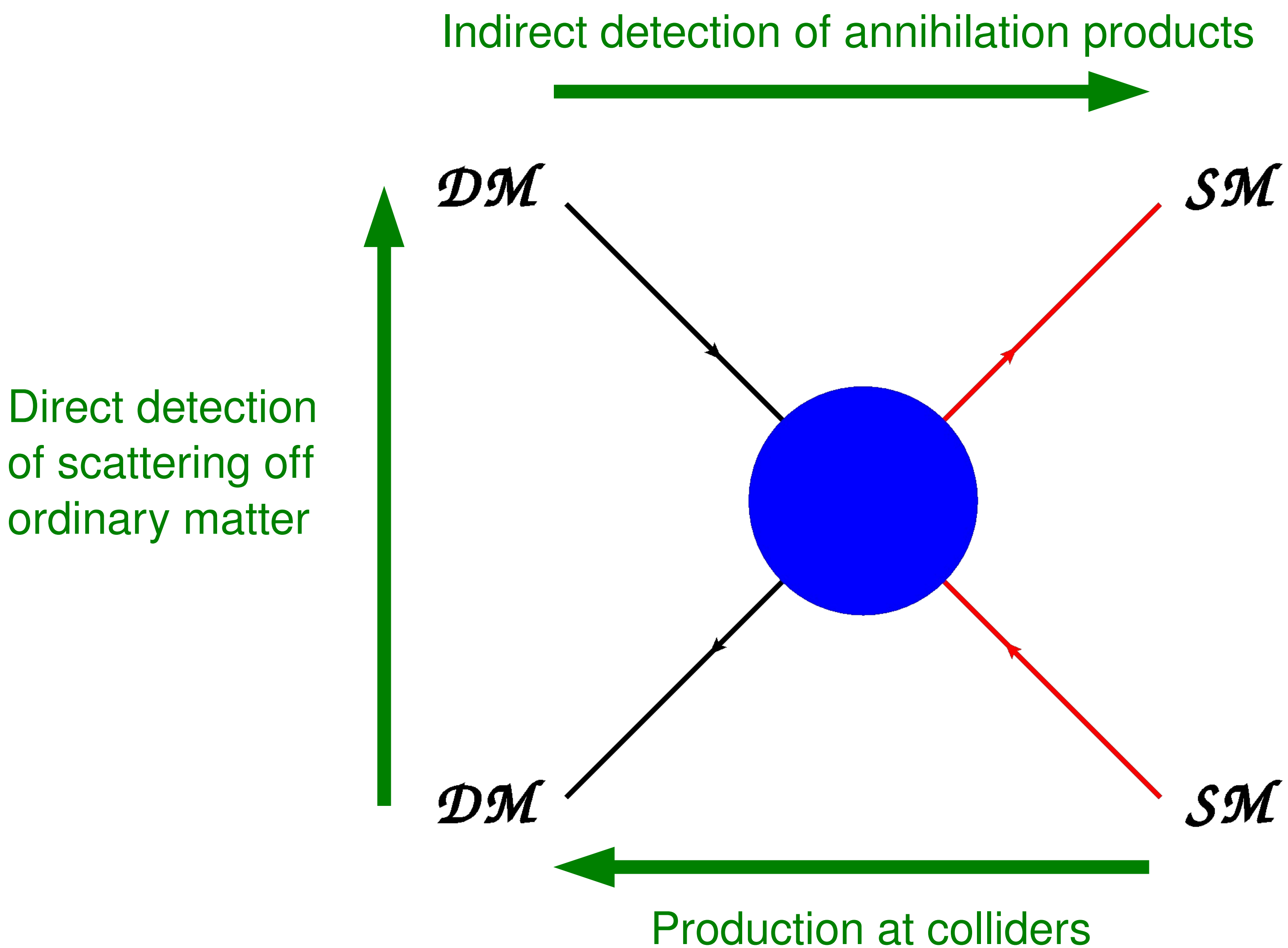
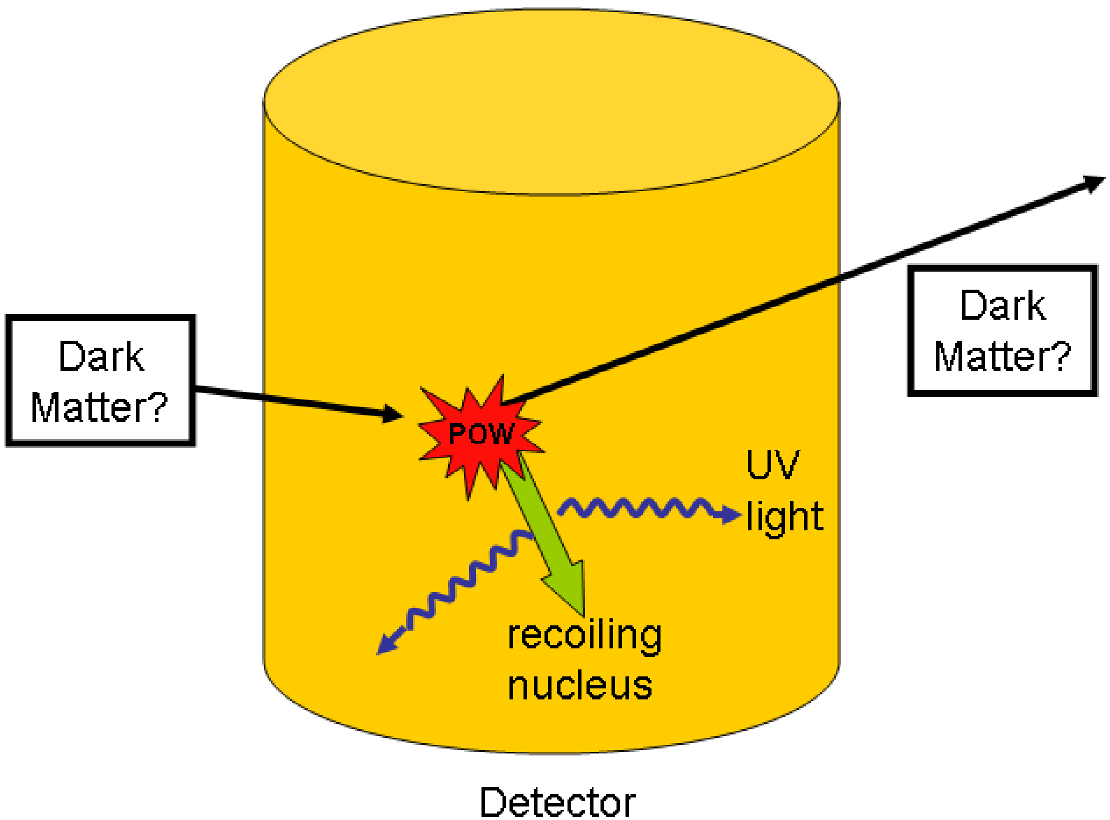


Direct detection – general idea

The idea:

- Dark matter is all around us.

- It might interact with ordinary matter (esp. based on the WIMP picture).



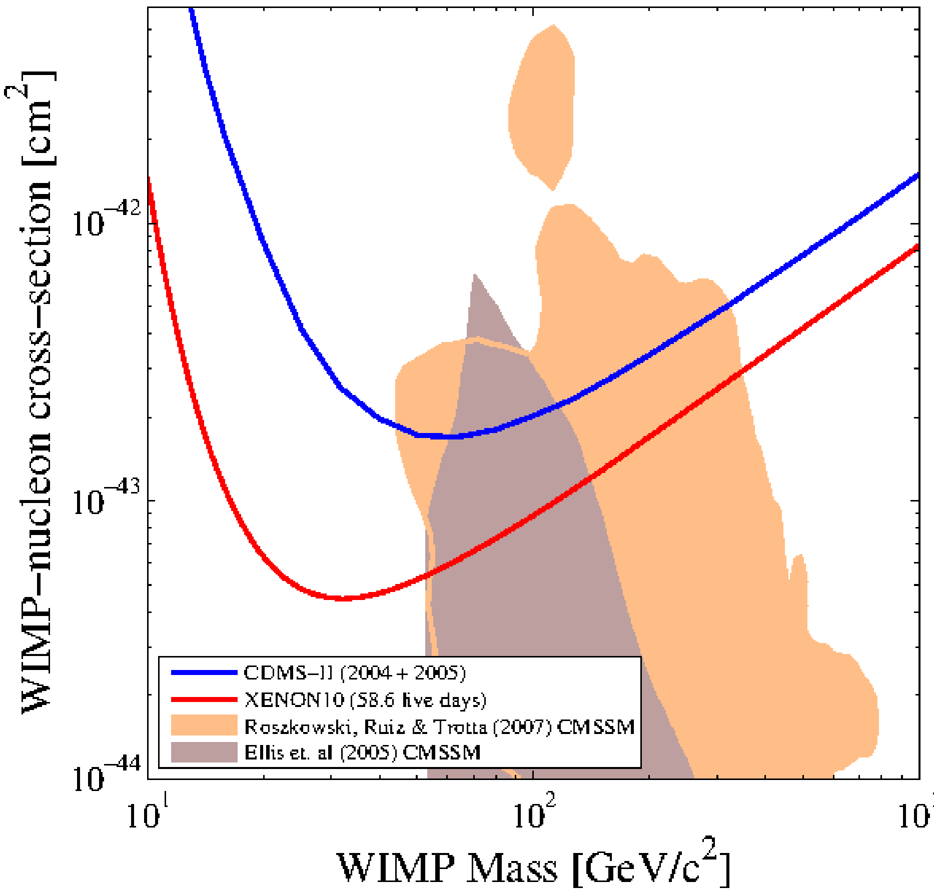
Typical even rate for WIMPs :

- Varies *a lot*, but we could keep in mind something of the order of 0.05 events per kg per day for a cross-section of 10^{-8} pb and m_X~100 GeV.

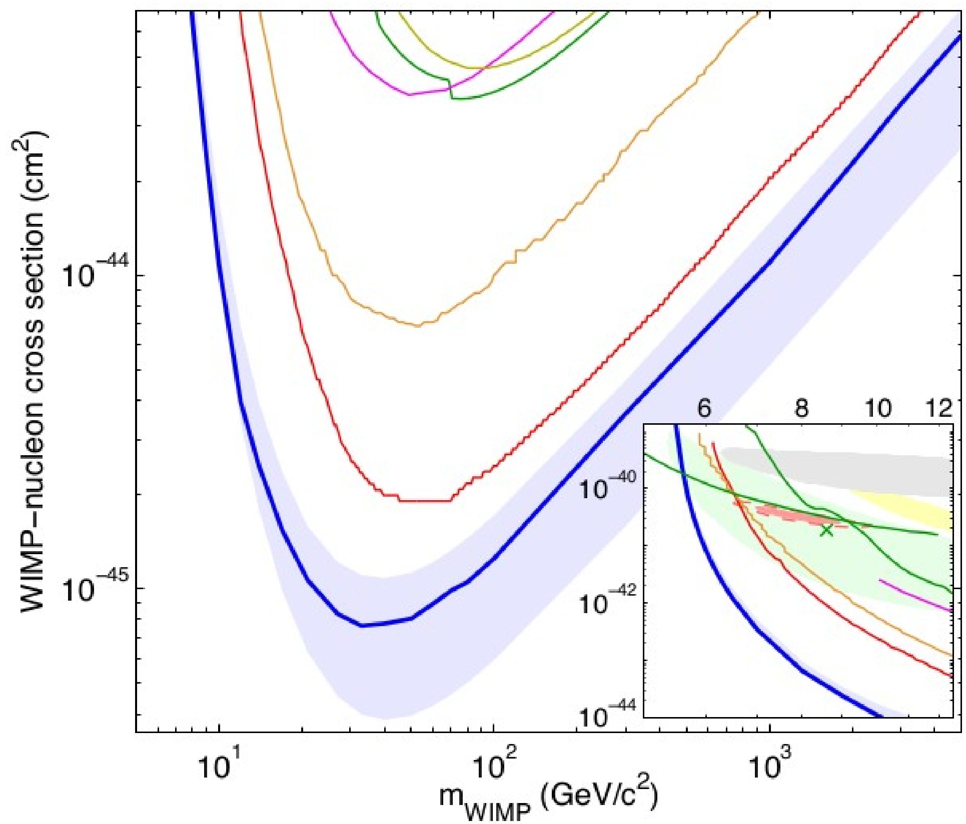
- Typical variations : lots of orders of magnitude!

→ Need large (underground) detectors!

Direct detection – results



Xenon 10 (~10 kg), 06/2007



LUX (~370 kg), 10/2013

Reminder : 0.05 events /kg/day for a cross-section of 10^{-8} pb (10^{-44} cm^2) and m_X~100 GeV.

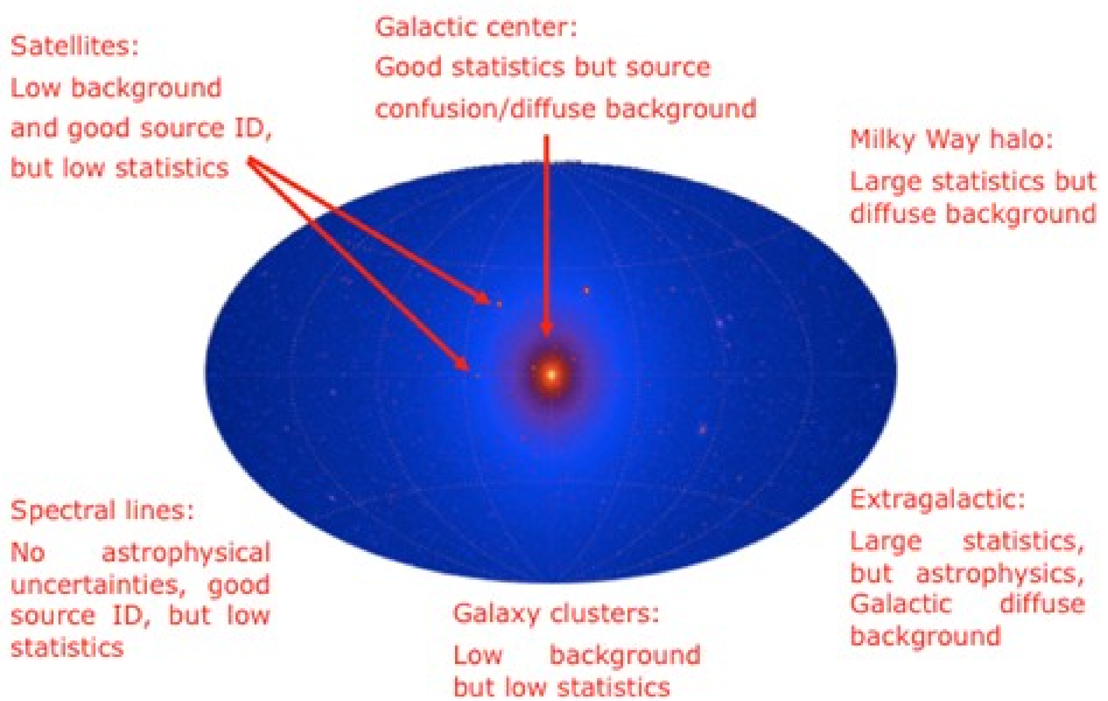
→ *Very* small even rates expected!

Indirect detection – general idea

The idea:

- Dark matter used to annihilate in the early universe.

- It might do so today (Rq.: it might also decay!!!).



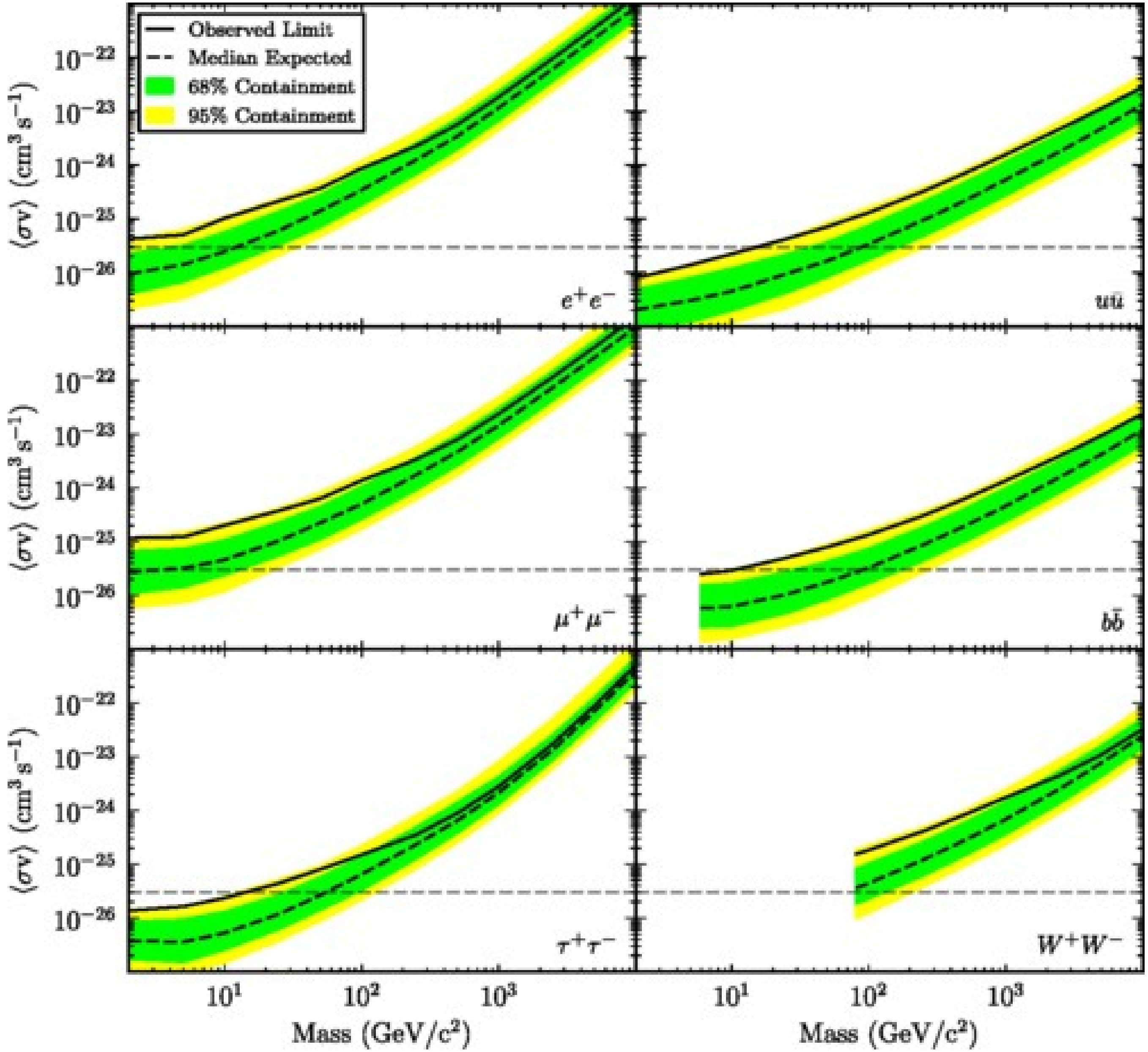
Typical even rate for WIMPs :

- Varies *a lot*, and depends on where we look!

- Take note of the fact that what counts is not only the signal, but also the *background* !

→ Need to combine different strategies and different *messengers*.

Indirect detection – results



- Recent result from the Fermi satellite, looking for gamma-rays in dwarf spheroidal galaxies.

- Note that situation is even more complicated because the limits depend on what DM annihilates into!

- The situation is yet more complicated once we look for charged particles : they actually propagate throughout the galaxy!

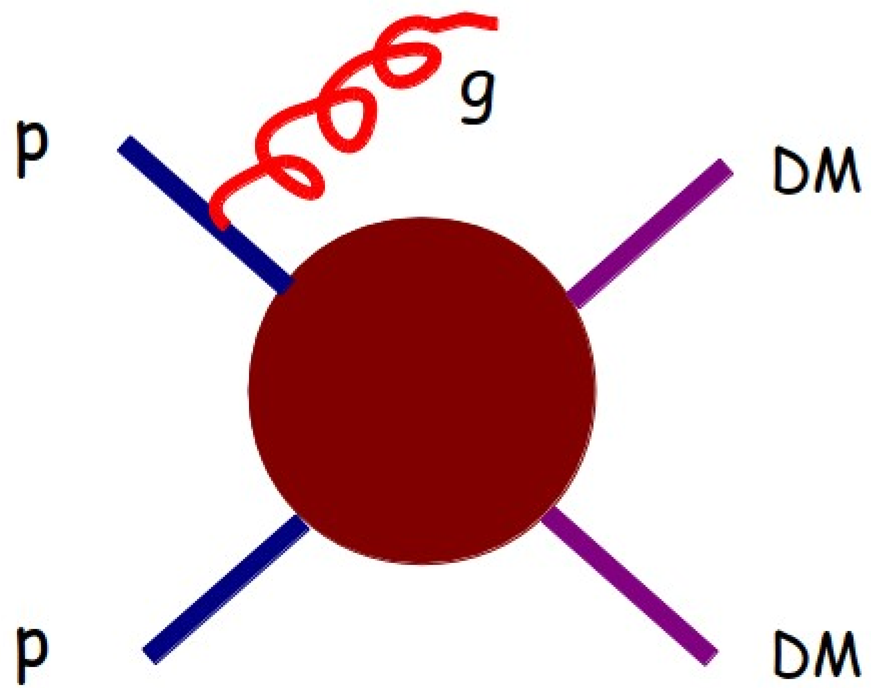
Fermi dSphs, 10/2013

Production in colliders – general idea

The idea:

- Dark matter used to be produced from SM annihilations in the early universe.

- It could be produced in SM annihilations at the LHC!



But :

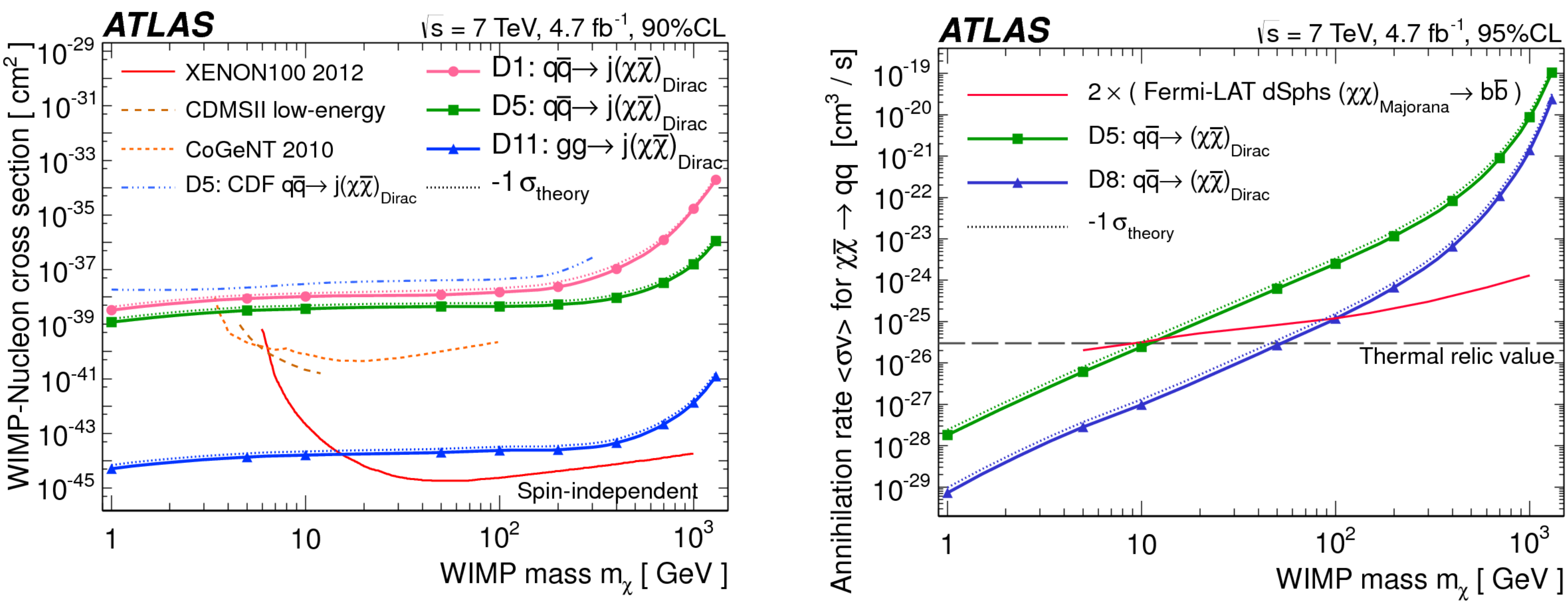
- DM interacts *very* weakly

→ If DM particles are produced, they are not seen (*missing energy*).

→ Need something extra to trigger on.

→ Look for events with one visible object and missing energy.

Production in colliders – (one type of) results



ATLAS collaboration, 10/2012

→ Experiments try to compare results amongst them. Interesting approach...

NB: But these plots come with *huge* assumptions!

Summary

- The introduction of dark matter was motivated (and still is!) by actual experimental problems in contemporary gravitational physics.

- It is one of the only experimental pieces of evidence for BSM physics.

- To this day, we basically don't know what dark matter is. We kind of know what it is *not*, but that's not enough :-) !

- One of the fundamental problems in DM physics: the *absence of a mass scale*.

- We have ideas about how dark matter was generated, and plenty of them! The basic question: how to test them!

→ Dark matter physics is an extremely active field of research in HEP. These small lectures aimed at giving a small glimpse of some of its aspects. There are many more!

→ When something is unknown, we can play around :) !

Not covered in this talk

Dark matter (incomplete list):

- Dark matter distribution in the galaxy and beyond (gravitational aspects).
- Alternative mechanisms for dark matter generation (there are *lots*!).
- Alternative search strategies for ultra-weakly coupled dark matter, superheavy dark matter etc.
- Warm DM candidates.
- Mediators of dark matter interactions.

Astroparticle physics (incomplete list):

- Cosmic rays : origin, propagation, role.
- Baryon asymmetry of the universe.
- Primordial nucleosynthesis.

Open questions

What the %$@#*&$ is dark matter ???

Thank you!

Freeze out : general picture

Key idea: at some point, DM particles reach equilibrium with the SM particles.

$$\frac{1}{R^3}\frac{dn_\chi R^3}{dt} = \langle\sigma v\rangle_{\mathrm{SM}\to\chi} n_{\mathrm{SM}}^2 - \langle\sigma v\rangle_{\chi\to\mathrm{SM}} n_\chi^2$$

$$H = \frac{1}{R}\frac{dR}{dt}$$

If χ in equilibrium its # density per comoving colume is constant

$$\frac{dR}{R} = -\frac{dT}{T}$$

$\longrightarrow$

$$\frac{d}{dt} = -HT\frac{d}{dT}$$

$\longrightarrow$

$$-\frac{dn_\chi}{dT} = -3\frac{n_\chi}{T} + \frac{\langle\sigma v\rangle}{HT}(n_{eq}^2 - n_\chi^2)$$

Freeze out : phases

$$-\frac{dn_\chi}{dT} = -3\frac{n_\chi}{T} + \frac{\langle \sigma v \rangle}{HT}(n_{eq}^2 - n_\chi^2)$$

We can distinguish 3 phases:

- $T \gg m_\chi$: χ is relativistic and in equilibrium, Hubble expansion negligible

- T a bit below m_χ : $n_{eq} \sim e^{-m/T}$, steep decrease, almost no production (decoupling)

- $T \ll m_\chi$: Hubble expansion dominance

NB: In the case of WIMPs, it's not really important if DM particles were produced upon reheating or not. The density evolution is pretty fast and equilibrium can be reached quite early.

Freeze in : general picture

Crucial assumption: DM particles are *not* produced upon reheating

“Direct” freeze-in:

- DM never reaches equilibrium because it is too feebly coupled.

- It is nevertheless produced by scarce SM particle annihilations.

- However the feebleness of its interactions make it that it does not annihilate back into SM particles.

- When the temperature reaches (roughly) the DM mass, the interaction gets frozen.

“Indirect” freeze-in:

- Similar mechanism as before, only that it involves both a FIMP and the LOSP.

→ Striking feature: the abundance can be independent of the DM mass!

NB: This is the original freeze-in scenario, where we demand that the whole process does not depend on the reheating temperature. Relaxing this assumption opens up further possibilities!

Another DM model : the IDM

One of the most "archetypical" DM models, the Inert Doublet Model

Desphande, Ma (1978)
Barbieri, Hall, Rychkov(2006)
Honorez, Nezri, Oliver, Tytgat (2006)
...

- Gauge + spacetime symmetries : as in the SM.

- Particle content : SM + one SU(2) doublet of complex (Lorentz) scalar fields.

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + \mathrm{i}G^0\right) \end{pmatrix}, \quad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + \mathrm{i}A^0\right) \end{pmatrix}$$

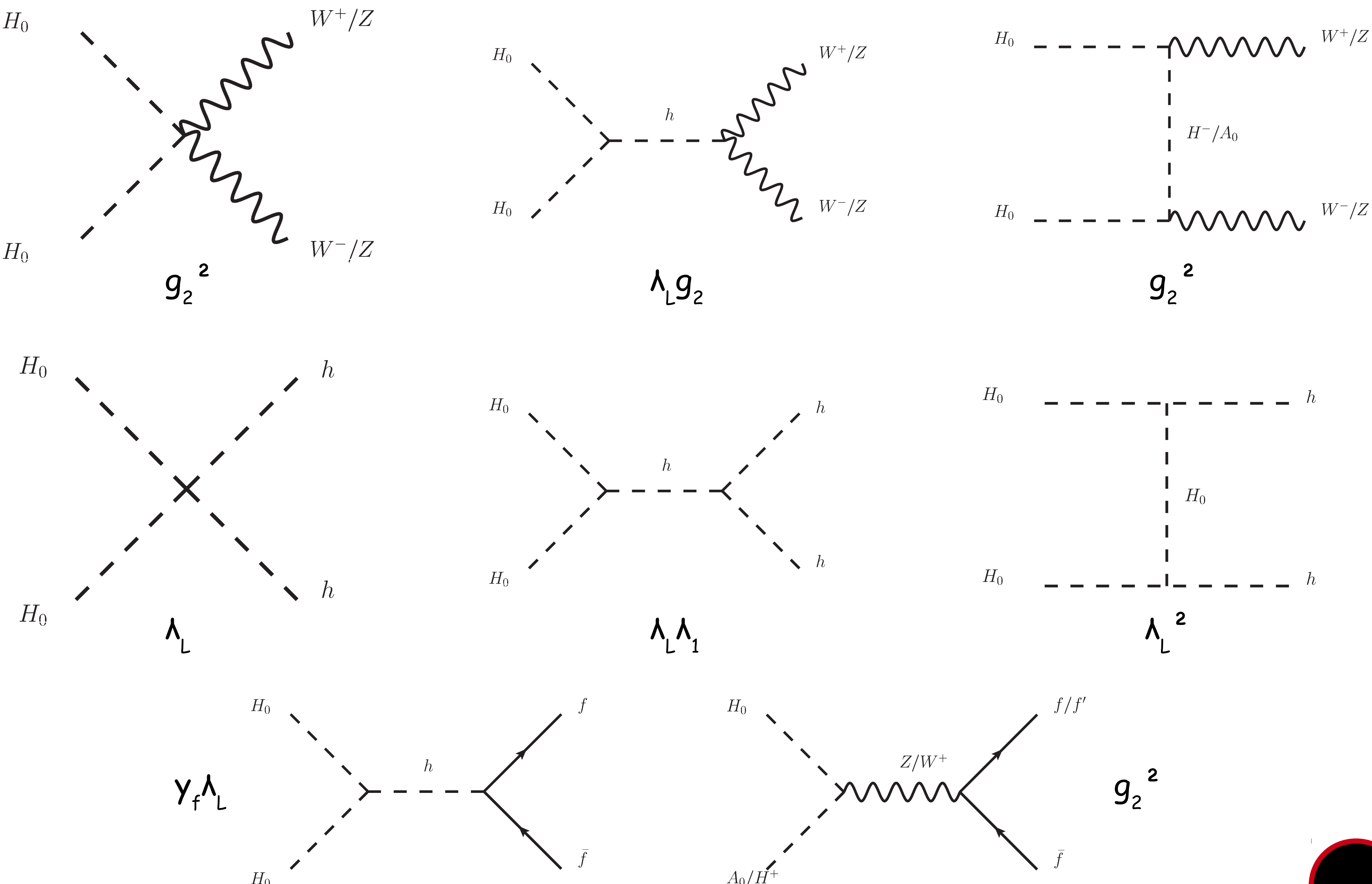
- An extra Z2 discrete symmetry that protects the lightest component of the extra doublet from decaying.

The (BSM) Lagrangian reads :

$$\mathcal{L}_{\rm cov} = (D_\mu H)^\dagger (D^\mu H) + (D_\mu \Phi)^\dagger (D^\mu \Phi)$$

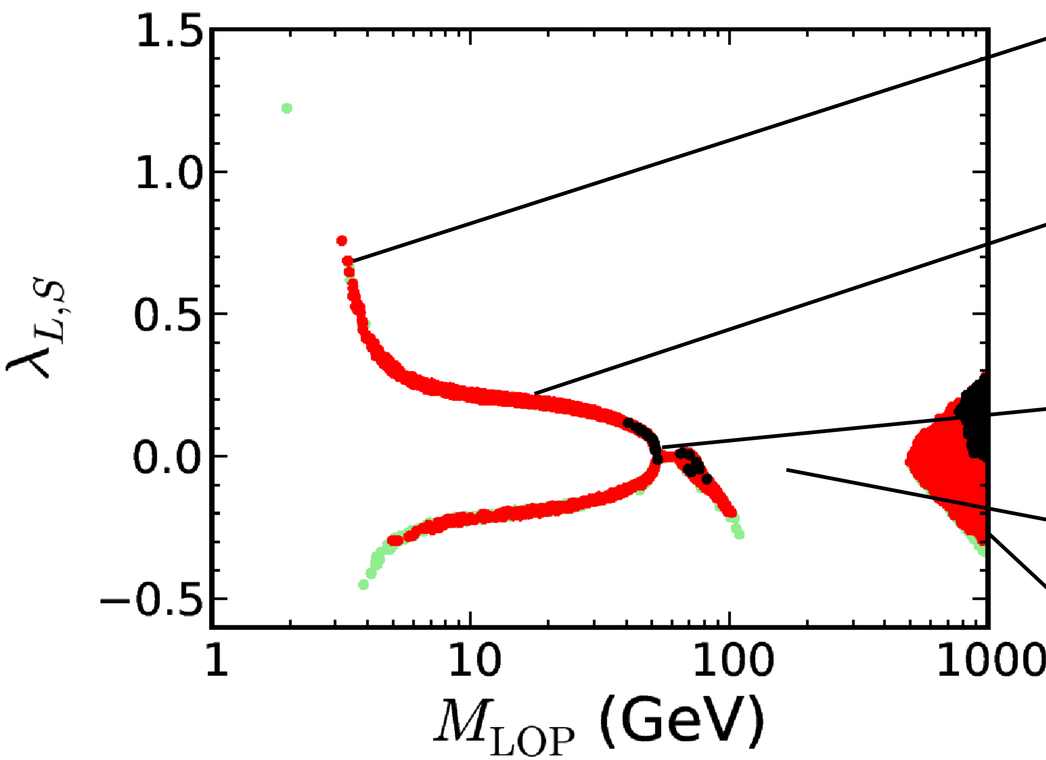
$$V_0 = \mu_1^2 |H|^2 + \mu_2^2 |\Phi|^2 + \lambda_1 |H|^4 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \lambda_4 |H^\dagger \Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger \Phi)^2 + \mathrm{h.c.}\right]$$

Another DM model : the IDM



Understanding a DM model

One of the neat things with simple models is that we can actually understand all of the underlying physics.



Annihilation primarily into τ's : small-ish Yukawa, large-ish λ_L needed

Annihilation primarily into b's : $O(3)$ smaller Yukawa, $O(3)$ larger λ_L

Resonant Higgs/WW^* (gauge) contributions : tiny λ_L

WW channel open for good, relic density too small

A bit more complicated : destructive interference

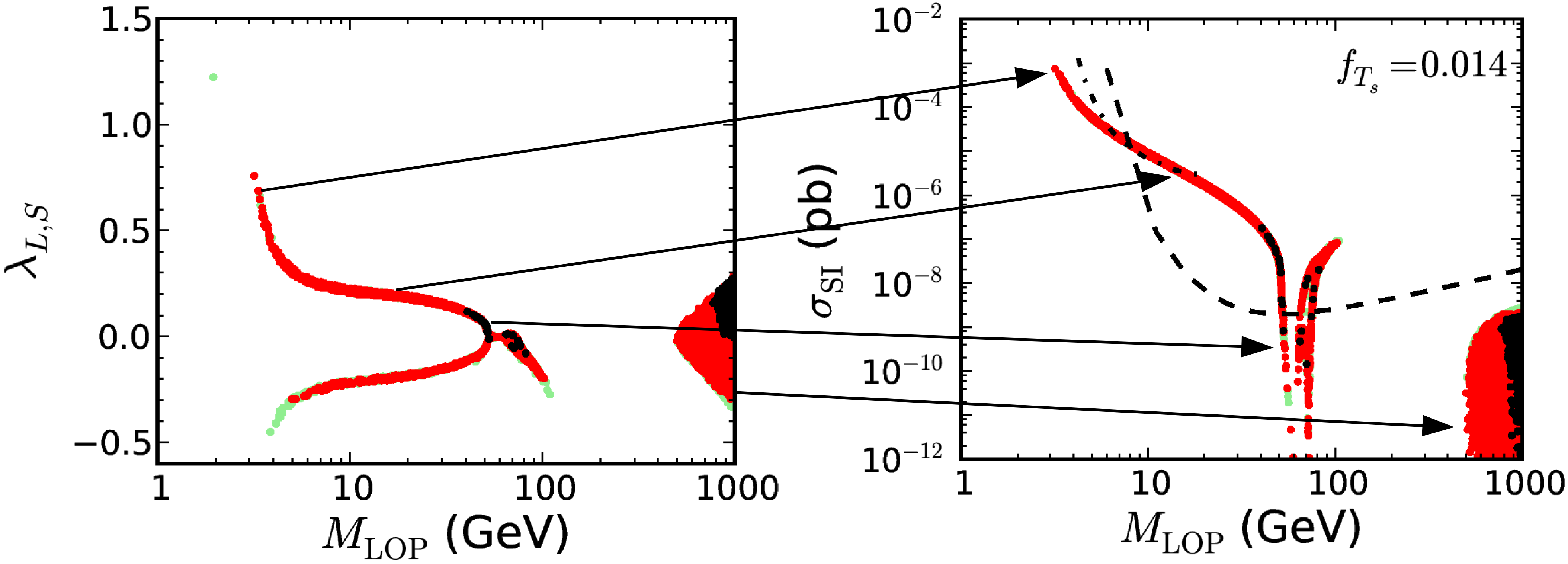
A.G., B. Herrmann, O. Stal (2013)
(see also Honorez, Nezri, Oliver, Tytgat (2006))

Connections...

We can easily establish a correspondence between the mechanisms producing the relic density and direct detection

A.G., B. Herrmann, O. Stal (2013)

A.G., B. Herrmann, O. Stal (2013)

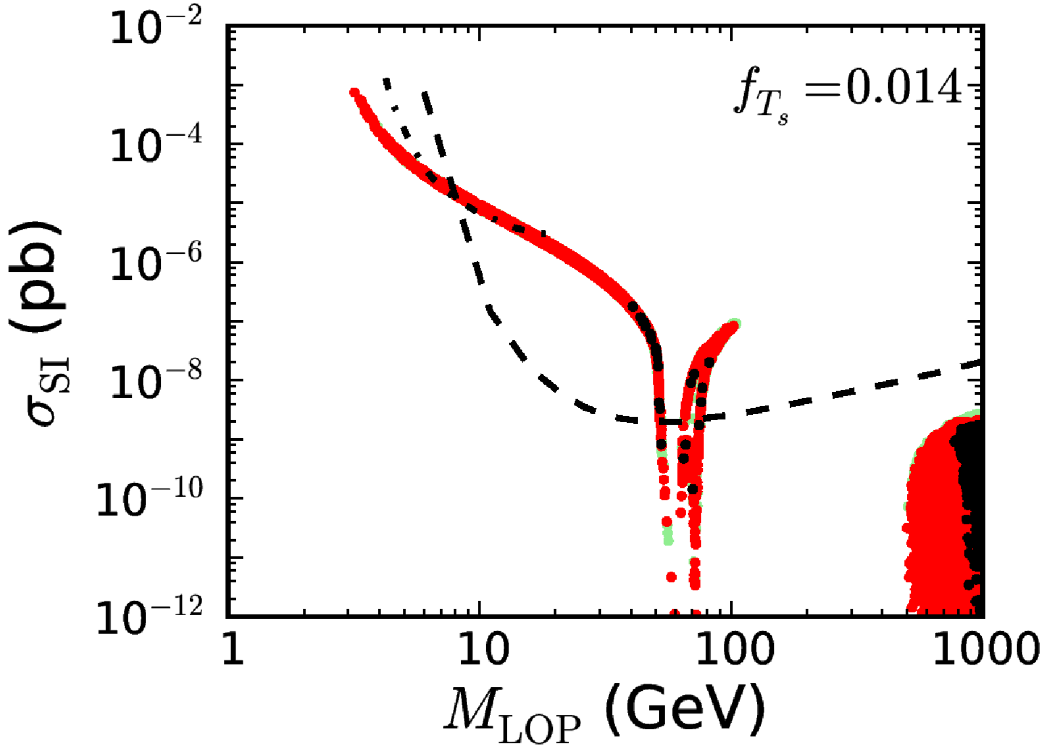


NB: this clear picture was made possible by the Higgs boson discovery!

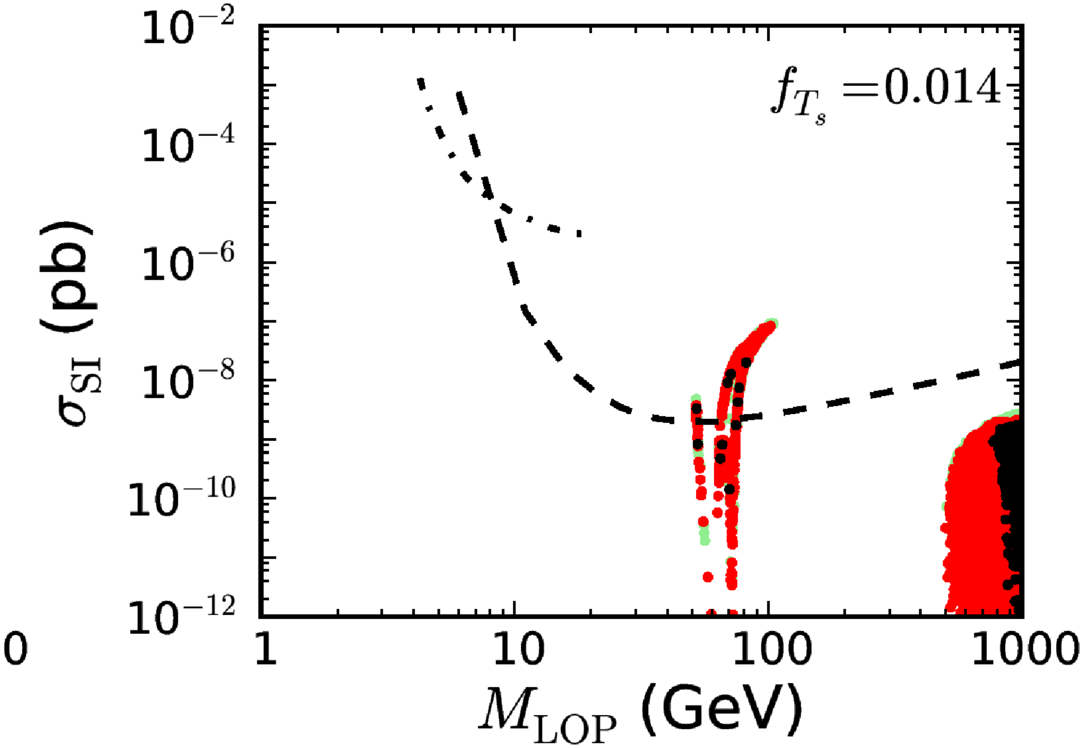
More connections...

What's more, the Higgs boson properties *also* constrain the IDM

A.G., B. Herrmann, O. Stal (2013)



A.G., B. Herrmann, O. Stal (2013)



A constraint that's clear from uncertainties, based on the *mediator* properties.