# Dark matter 2017

Journée Théorie CPTGA 2017, Grenoble

Andreas Goudelis
LPTHE - Jussieu

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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# What I'll try to summarise

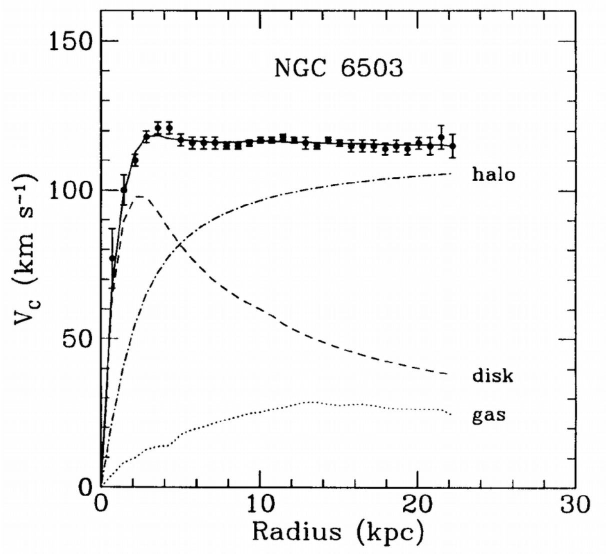
- Why we need dark matter and what we know about it
- The most popular ways to look for it
- What we learn from these searches about the way it came to be
- Some ideas which are a bit less "mainstream"

# First things first : why dark matter

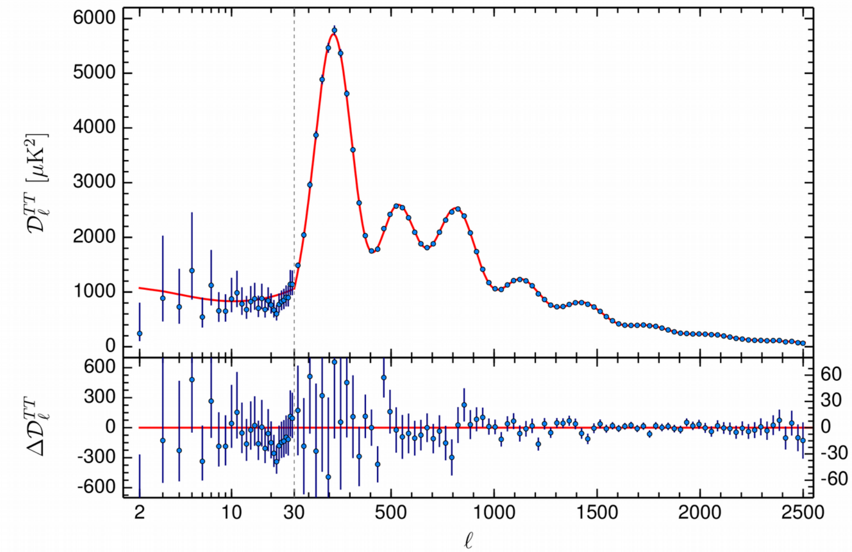
The key argument for the existence of dark matter :

**Evidence at multiple scales**

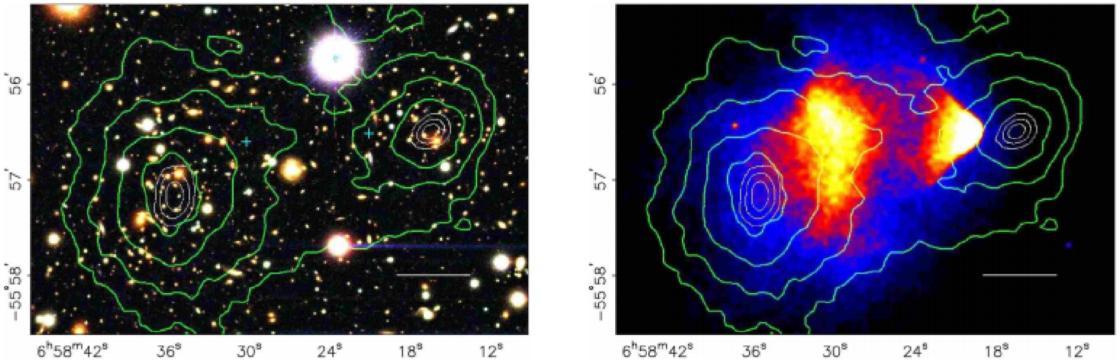
**Galaxies (rotation curves)**




**CMB anisotropies**




**Galaxy clusters (X-ray spectroscopy VS lensing)**




In a nutshell:

**No known cosmological model can explain all these observations simultaneously without introducing some amount of dark matter.**

NB: Strong argument, but not proof!

# Dark matter and particle physics

But all these pieces of evidence for the existence of dark matter rely on gravity…

No information about its (particle?) nature!

Some general things that we *do* know about dark matter :

· It constitutes ~85% of the matter content of the Universe (CMB: WMAP/Planck satellite missions).

$$\Omega_{\rm DM} = 0.1187 \pm 0.0012$$

Can we explain this number?

· It must be cold-ish (aka have a small free-streaming length for structure formation).

· It must be stable on cosmological timescales + E/M neutral.

· It cannot be baryons (Big Bang Nucleosynthesis constrains their abundance).

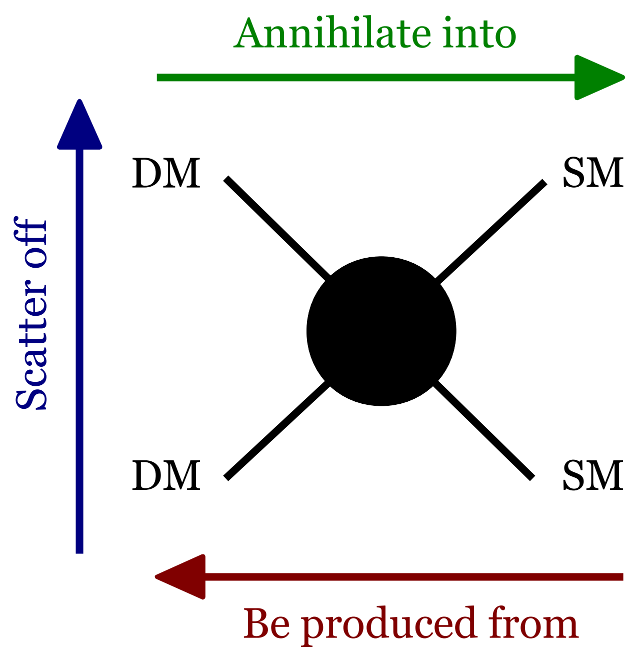
There's a caveat, I'll come back to that.

· It cannot be neutrinos (too light → abundance issue / too hot → spoil structure formation).

Cosmology points towards physics Beyond the Standard Model

# How do we look for dark matter ?

Some basic ways through which DM could interact with the visible sector (*now*):



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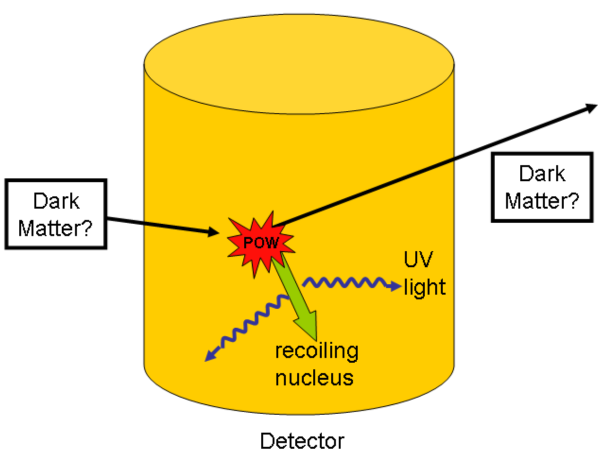
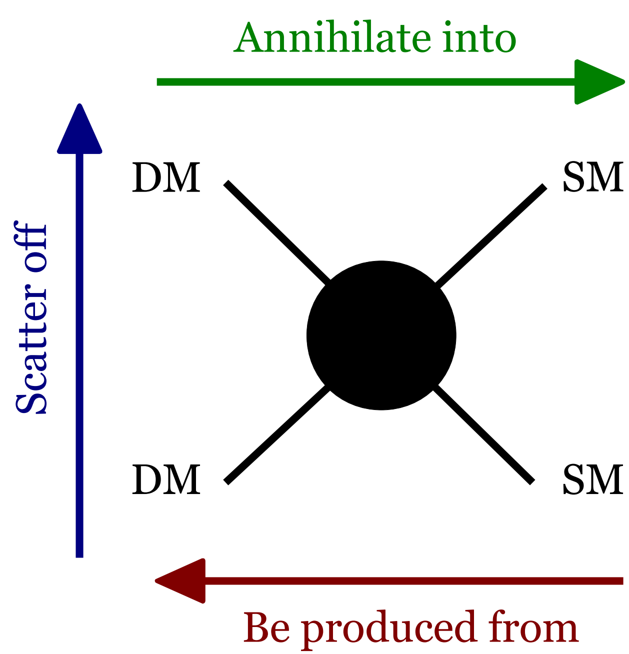
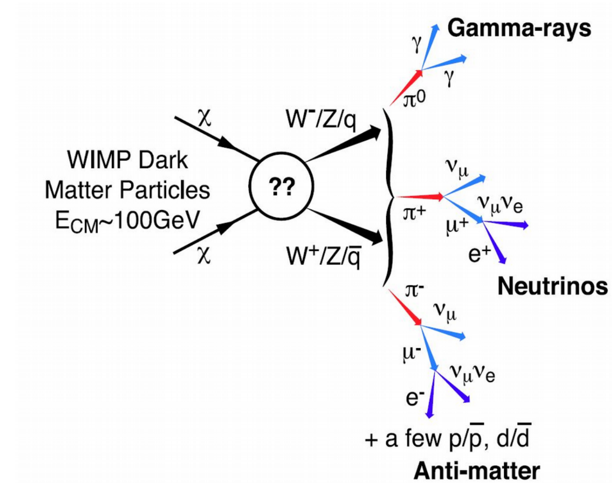
Some basic ways through which DM could interact with the visible sector (*now*):

**Direct detection**

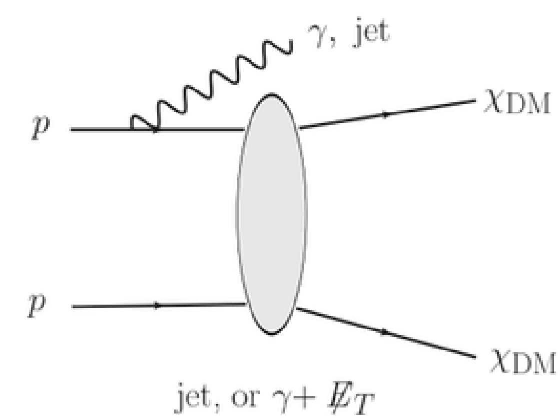



**Indirect detection**




**Collider searches**



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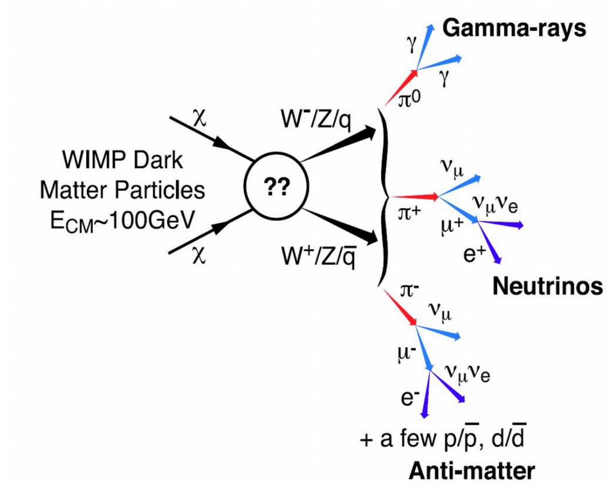
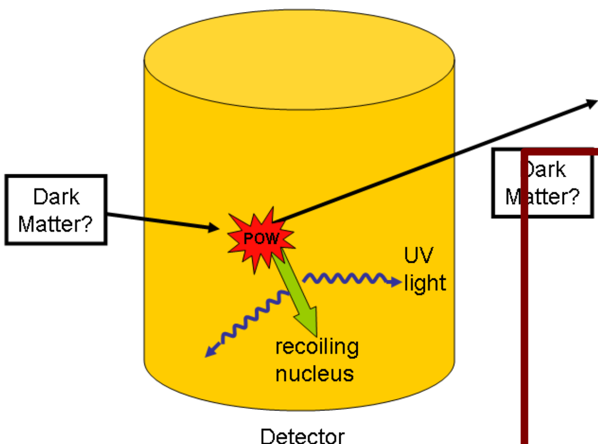
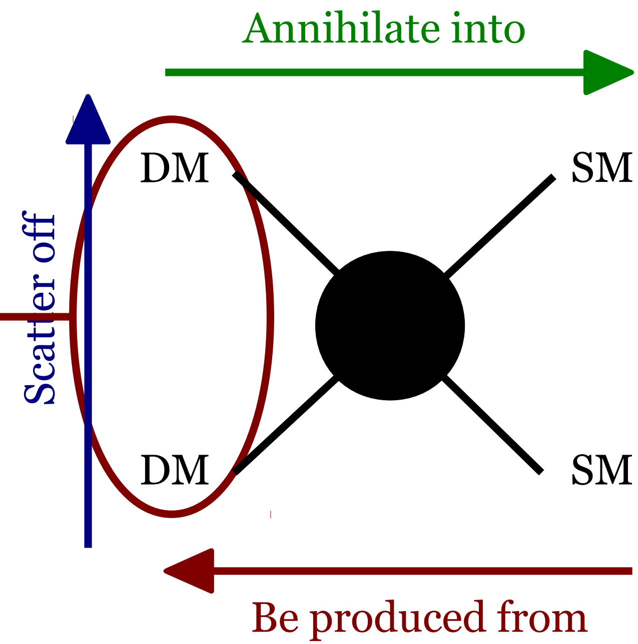
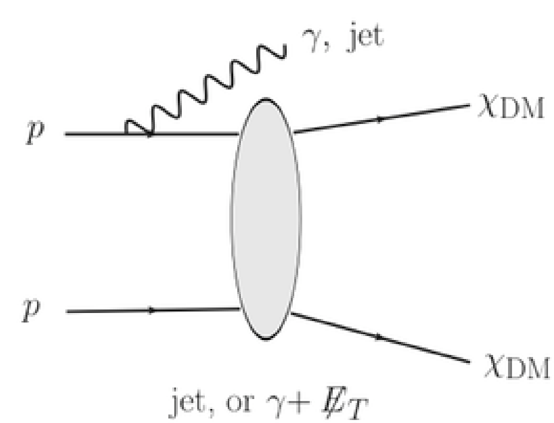



## Direct detection




## Collider searches




Why in pairs? DM stability issue: typically impose some Z2 – like symmetry to prevent it from decaying into lighter particles.

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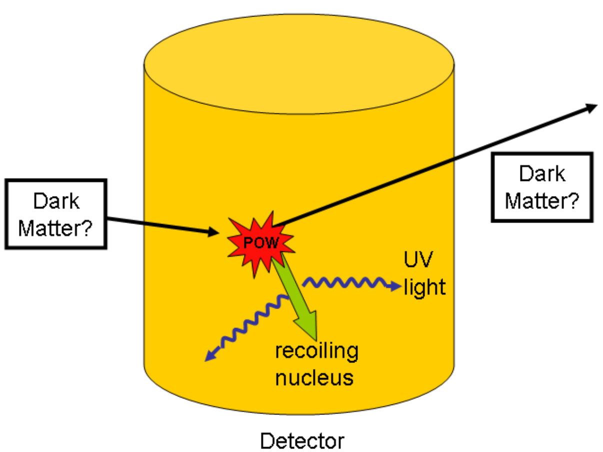
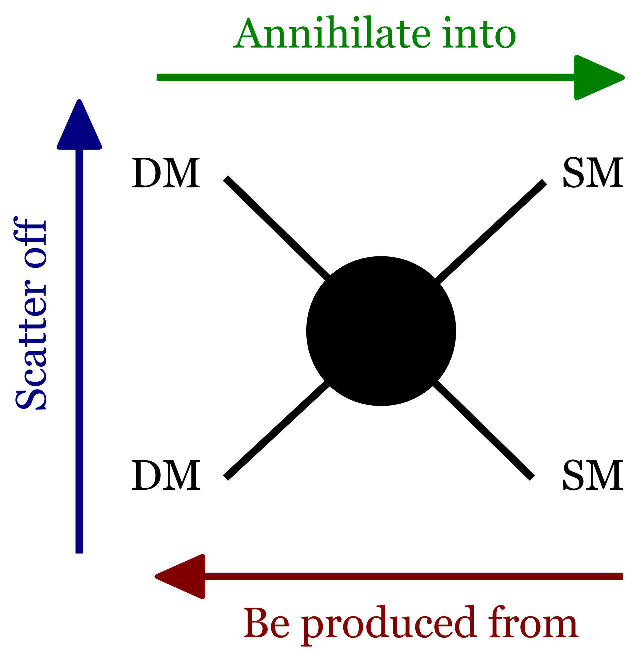
**Direct detection**

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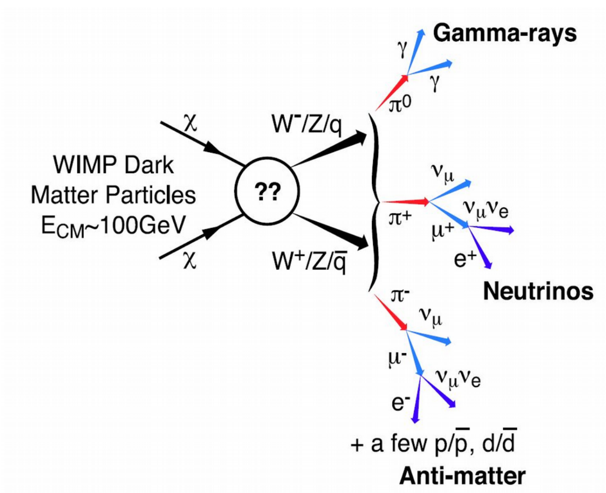


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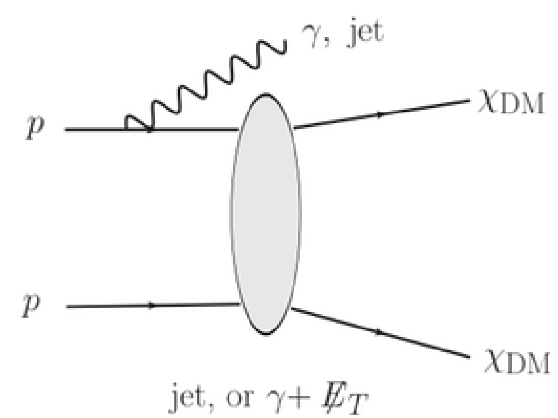
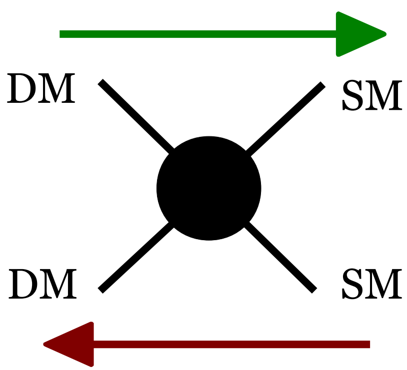



For all of this to make sense :

> Dark matter should interact not-too-feebly with the visible sector

# Detection vs abundance

Assume that, indeed, dark matter particles interact substantially with the Standard Model.




· The early Universe is *dense* and *hot*.

High interaction rate — All states kinematically accessible

↓

Thermal (kinetic + chemical) equilibrium.

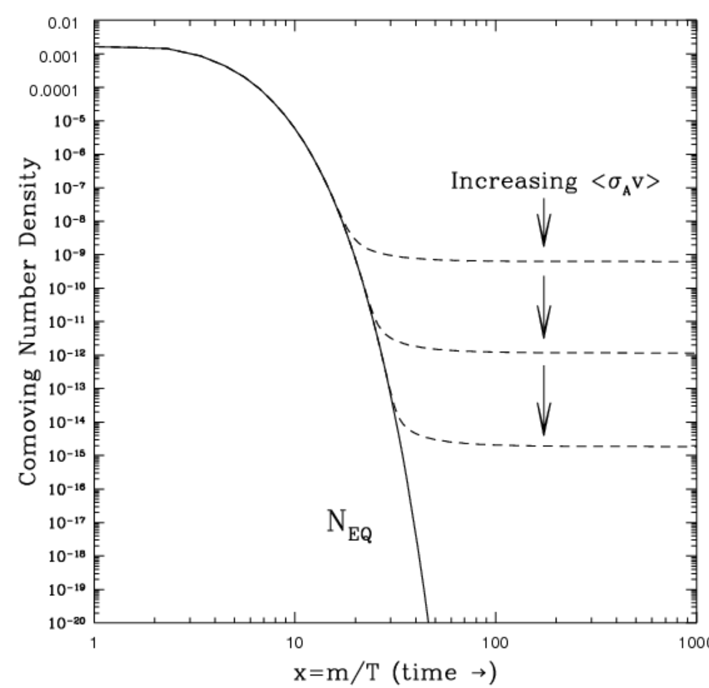
· As the expansion continues, the temperature drops below the dark matter mass.

↓

Dark matter particles can no longer be produced, only annihilate into SM ones.

· Eventually particles get so diluted that $H > \Gamma_{ann}$: "freeze-out".

**This picture dominated DM physics for decades and motivated the three main search modes.**

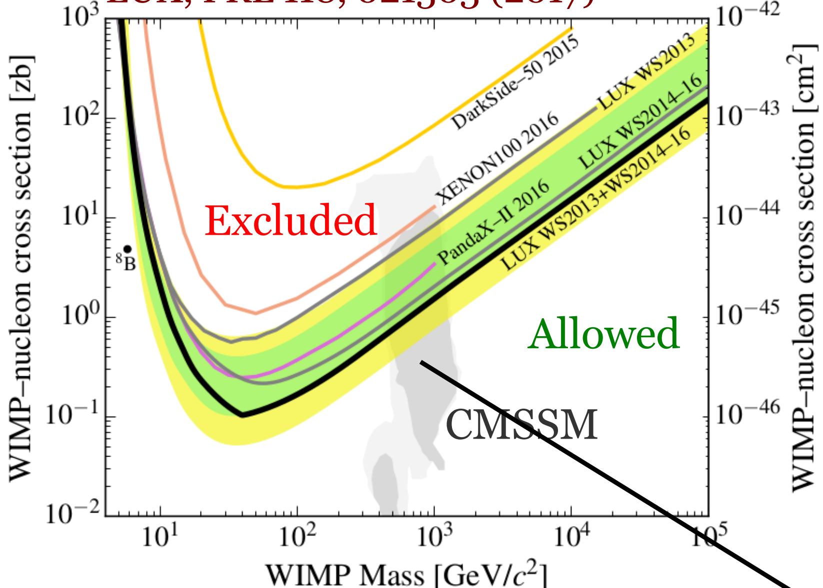



D. Hooper, arXiv:0901.4090

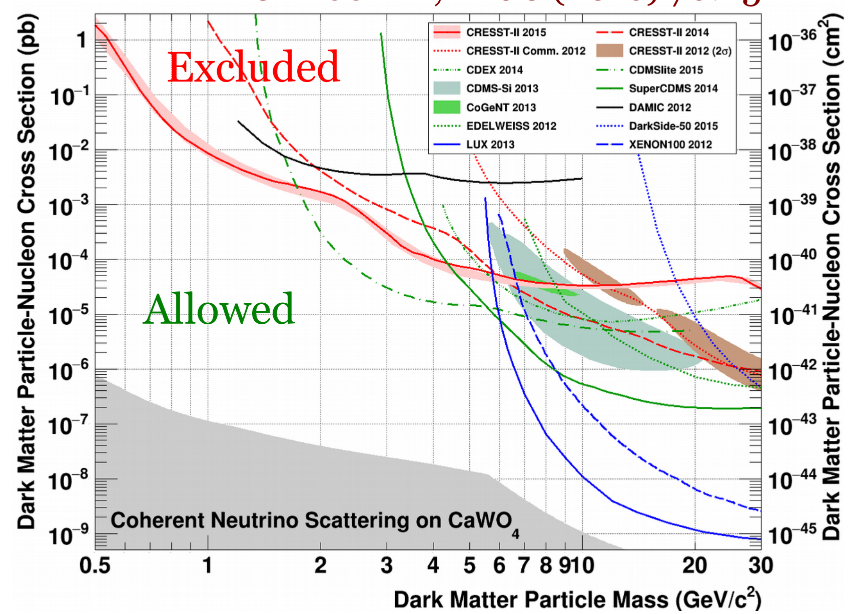
# Where we stand: Direct detection

State-of-the-art of conventional direct dark matter searches :

LUX, PRL 118, 021303 (2017)




CRESST-II, EPJC (2016) 76:25




· The most popular dark matter models are being probed *now*.

(or have been already excluded)

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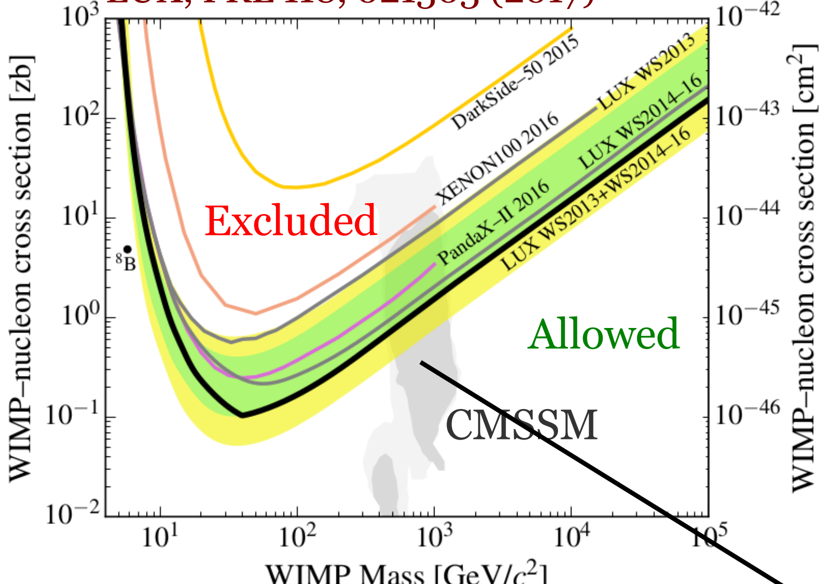


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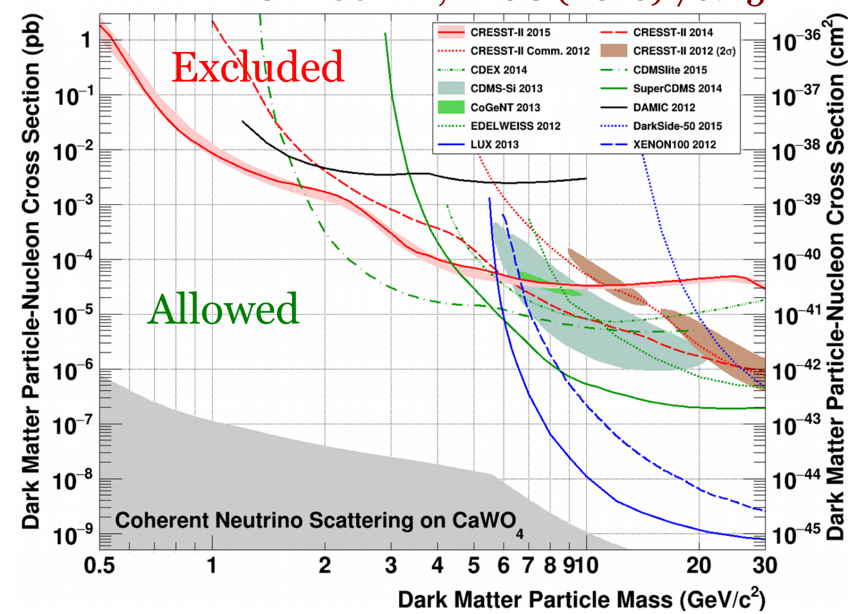
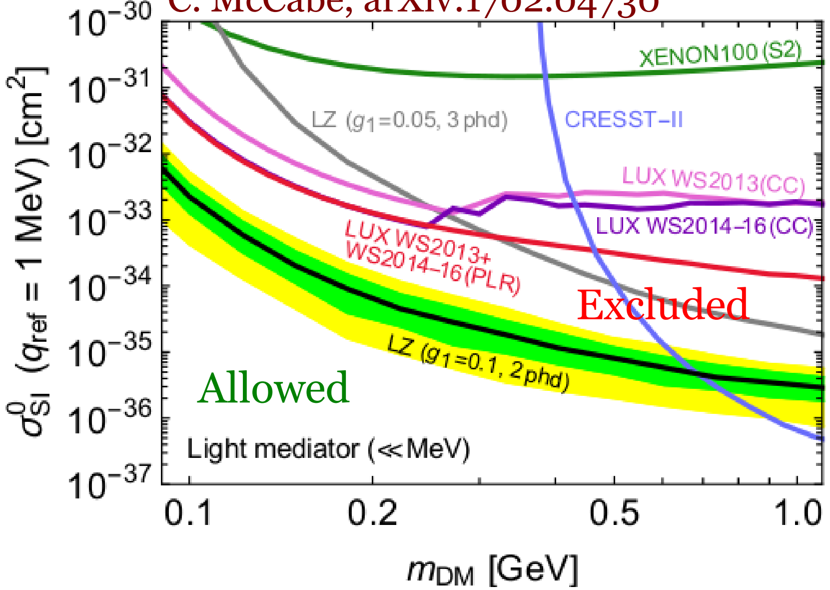


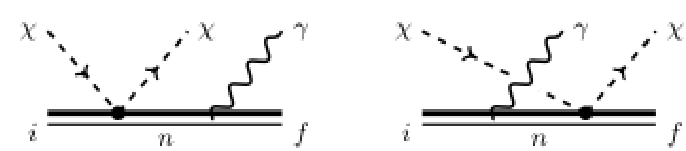

C. McCabe, arXiv:1702.04730




· The most popular dark matter models are being probed *now*.

(or have been already excluded)

· Based on new proposal using instead



C. Kouvaris, J. Pradler, PRL 118, 031803 (2017)

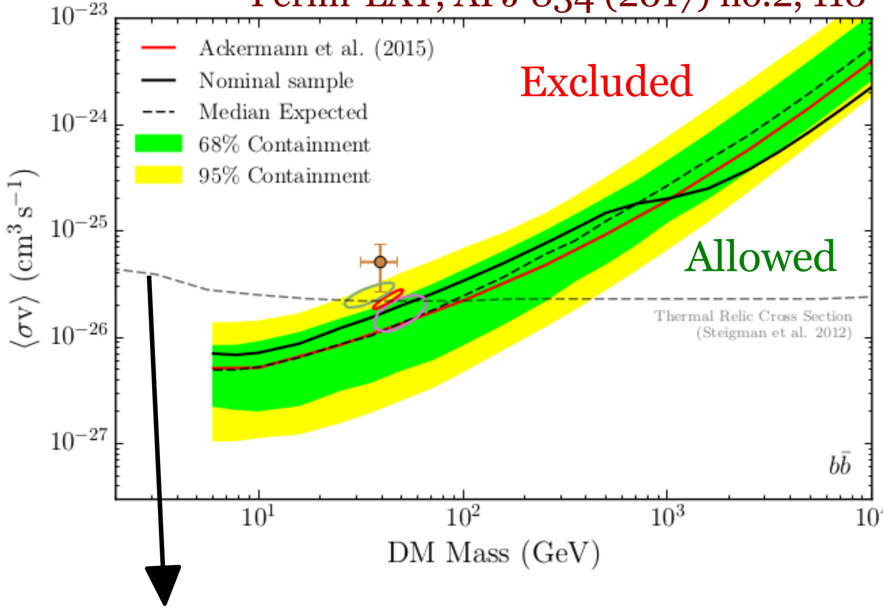
· There's a limit: the neutrino floor.

# Where we stand: Indirect detection

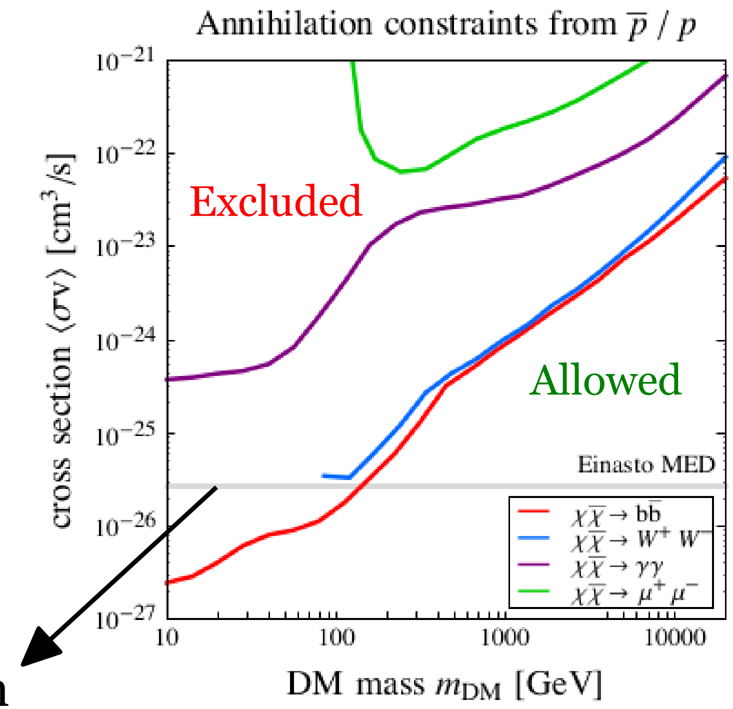
State-of-the-art of conventional indirect dark matter searches :

**Gamma-rays**

Fermi-LAT, APJ 834 (2017) no.2, 110




**Antiprotons**




G. Giesen *et al*, JCAP 1509 (2017)
Based on data from AMS-02

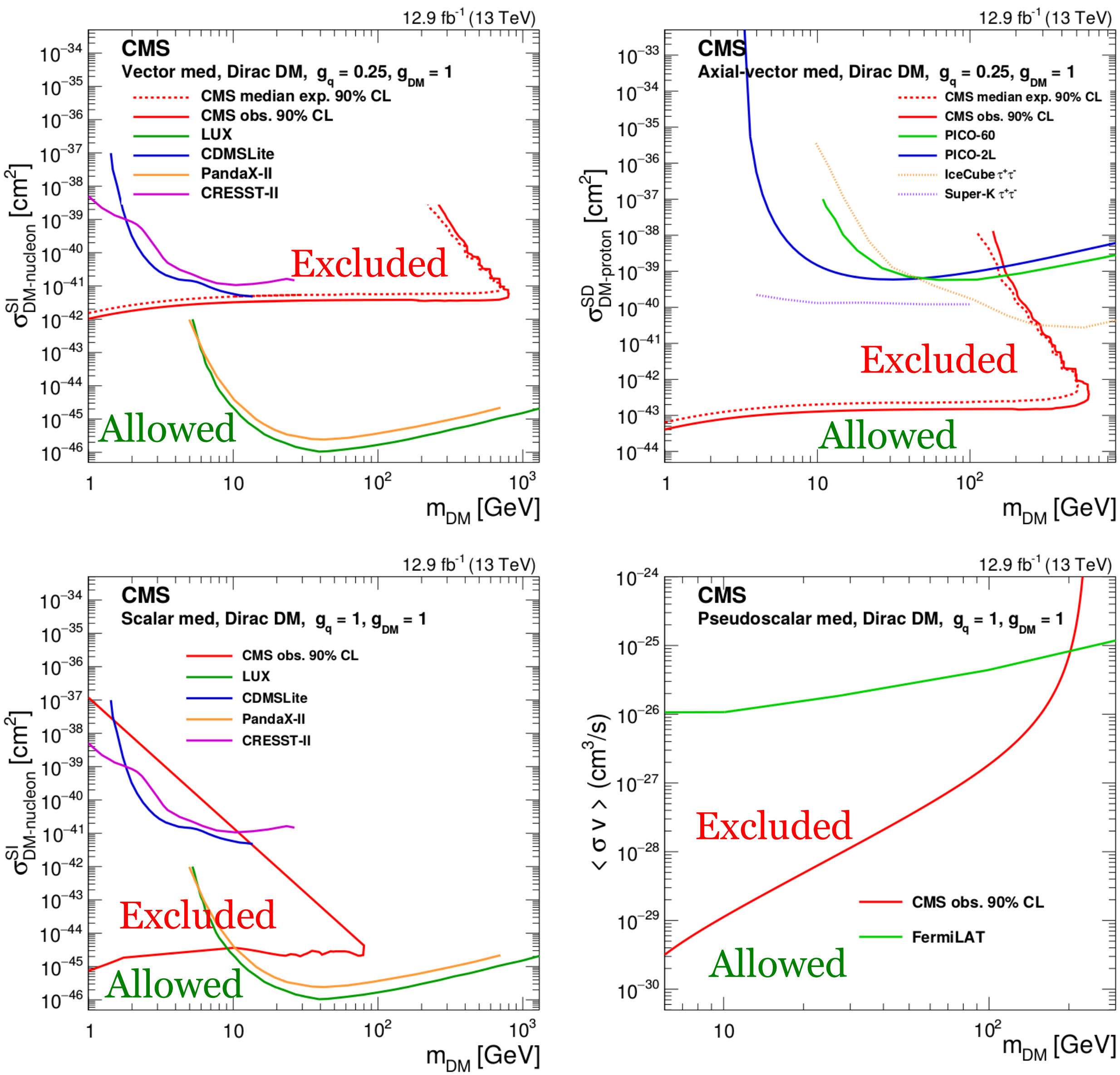
· This is the dark matter annihilation cross-section that's needed (*at freeze-out*) to reproduce the Planck measurement.

· Sensitivity drops for higher masses (CTA region).

· Main limitation: astrophysical uncertainties (unknown background).

# Where we stand: Collider searches

State-of-the-art of conventional collider dark matter searches :




CMS, arXiv:1703.01651

· Robust handle on light DM *as long as* $m_{DM} < m_{Med}/2$.

Otherwise limits vanish

· Relatively insensitive to the underlying Lorentz structure.

Very strong point!

· When direct detection works, it dominates.

The LHC offers *multiple handles* on dark matter models (*e.g.* searches for the mediator particles).

*e.g.* S. Banerjee, D. Barducci, G. Bélanger, B. Fuks, A. G., B. Zaldivar, arXiv:1705.02327

# Going to darker places: freeze-in

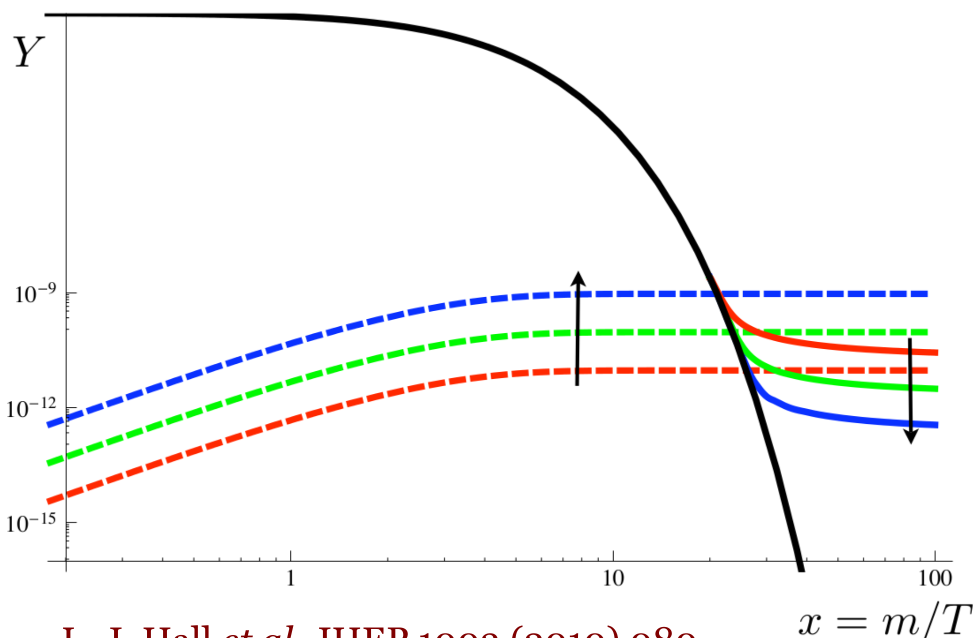
How weak can the DM interactions with the visible sector be?

Common freeze-out lore: weak enough so as not to overclose the Universe.

NB: Although even then solutions do exist, *cf e.g.*
G. Gelmini, P. Gondolo, A. Soldatenko, C. E. Yaguna, PRD 74 (2006) 083514

Crucial assumption in the previous statement: thermal equilibrium in the early Universe.
What if this never existed?

**Freeze-out vs freeze-in**




L. J. Hall *et al*, JHEP 1003 (2010) 080

· In thermal freeze-out, the initial conditions are provided by equilibrium itself.

NB: Which is, arguably, an attractive point!

· For feeble couplings, makes sense to assume initial density = 0.

· Produce DM through scatterings/decays.

# Going to darker places: freeze-in

The big question with freeze-in: how to test it?

· Freeze-in through scattering: very difficult in the general case.

· Freeze-in through decays: more promising! Strategy depends on lifetime of parent particle.

Some ideas:

**Primordial nucleosynthesis**

Probed lifetimes depend strongly on nature of decay products.

**Mono-X searches @ LHC**

If parent particle neutral and detector-stable.

**Charged track searches @ LHC**

If parent particle charged and detector-stable.

**Long-lived particle searches**

J. P. Chou, D. Curtin, H. J. Lubatti, PLB 767 (2017) 29-36

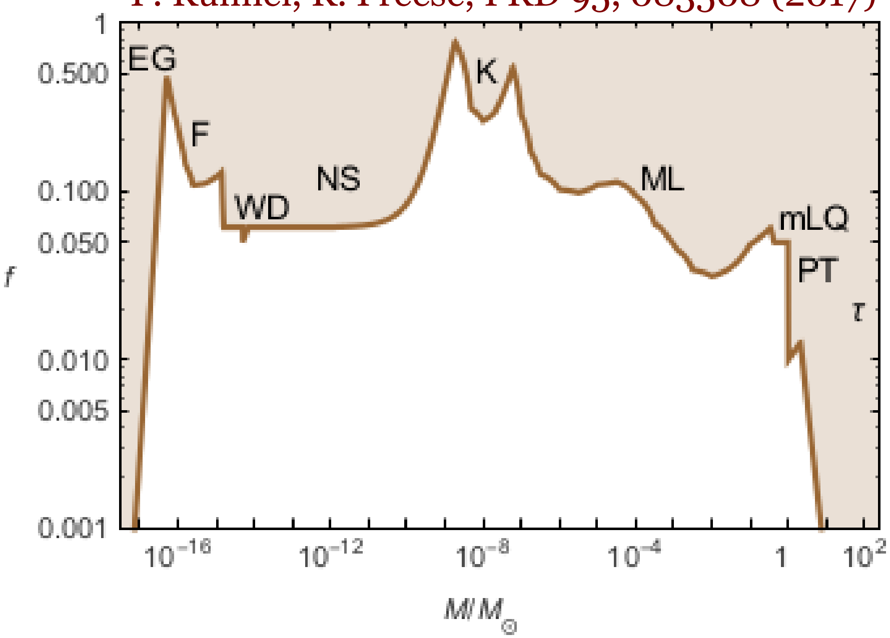
# Primordial black holes as dark matter

We mentioned that BBN constrains the total amount of baryons in the Universe. But what if some ordinary matter collapsed gravitationally *before* BBN?

Thought to be excluded, until the importance of one major simplification was pointed out.

Assuming monochromatic mass function

F. Kühnel, K. Freese, PRD 95, 083508 (2017)

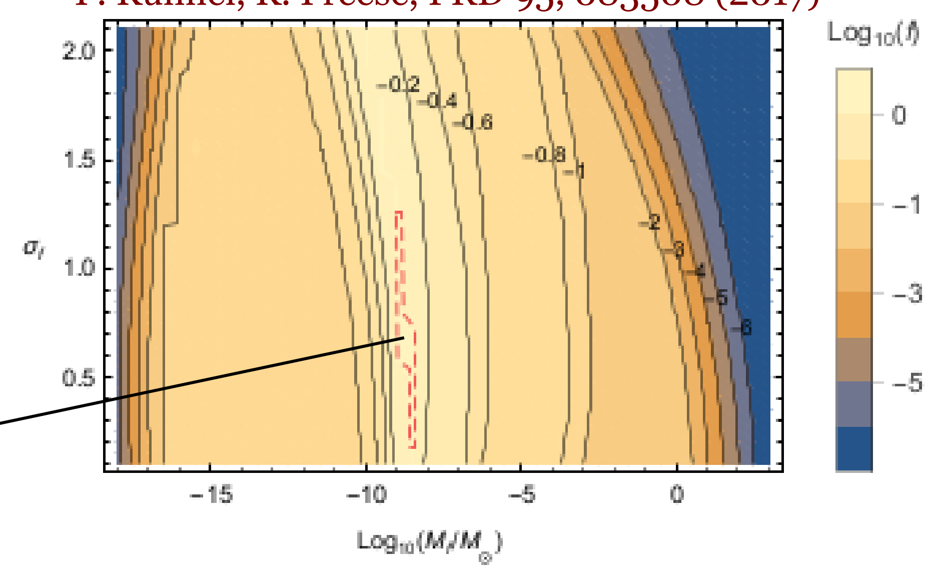



Assuming extended mass function as

$$\frac{dn}{dM} \equiv N \exp\left[-\frac{(\log M/M_f)^2}{2\sigma_f^2}\right]$$

A.M. Green, PRD 94, 063530 (2016)

F. Kühnel, K. Freese, PRD 95, 083508 (2017)




In this region PBHs could make up for the entire dark matter content in the Universe.

# Elements of summary - 1

· The nature of dark matter is one of the most important puzzles in contemporary fundamental physics.

Again, it's ~85% of the total matter content of the Universe!

· We don't know what it is. So far we gain more and more knowledge about what it's not.

· One of the main questions : can we explain its abundance in the Universe? We have ideas, in fact quite a few! Freeze-out, freeze-in, dark freeze-out, "gravitational" production, asymmetric dark matter…

· All these ideas motivate searches: there is no model-independent, fully generic dark matter detection technique!

· Thermal freeze-out is an attractive scenario.

**Can we fully exclude it ?**

→ Most likely not, but at least it can be rendered much less attractive.

This has actually partly happened

# Elements of summary - 2

· Hardest regions to probe:

- Low (sub-GeV) masses → Direct detection; Intensity frontier

  Eventually need new technologies

- High(multi-TeV) masses → Indirect detection

  How to tackle astrophysical uncertainties?

· A lot of effort is currently being dedicated to pinpoint the signatures of alternative dark matter generation mechanisms : LHC, astrophysics, cosmology, intensity frontier.

· On the model-building side : the traditional problem in dark matter physics is that we have no argument for some relevant mass scale.

**Where can we find motivation?**

Ideas include: experimental excesses, Naturalness, Flavour, Strong CP...

**A very active field at the crossroads of cosmology, astrophysics and particle physics!**

Thank you!

# Small-scale problems with CDM

The picture of collisionless CDM has had a massive success, but might only be providing part of the picture.

Some disagreement appears when comparing CDM halo simulations with actual observations…

**Cusp vs core problem**

CDM simulations strongly favour cusped DM halo profiles like NFW.

**but**

Actual observations in many galaxies rather suggest cored ones.

**Missing satellite problem**

CDM simulations predict $\mathcal{O}(10^2)$ satellite galaxies orbiting the MW.

**but**

Only $\mathcal{O}(10)$ have been observed.

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Solutions include:

- Baryonic effects → Can flatten out cusps (depending on $m_B/m_{DM}$), difficult to simulate!

- Warm dark matter → Larger free-streaming length, doesn't settle as much in gravitational wells.

- Self-interacting dark matter → Works for both, need $\sigma_{SI} \sim 10^{10}\, \sigma_{weak}$!

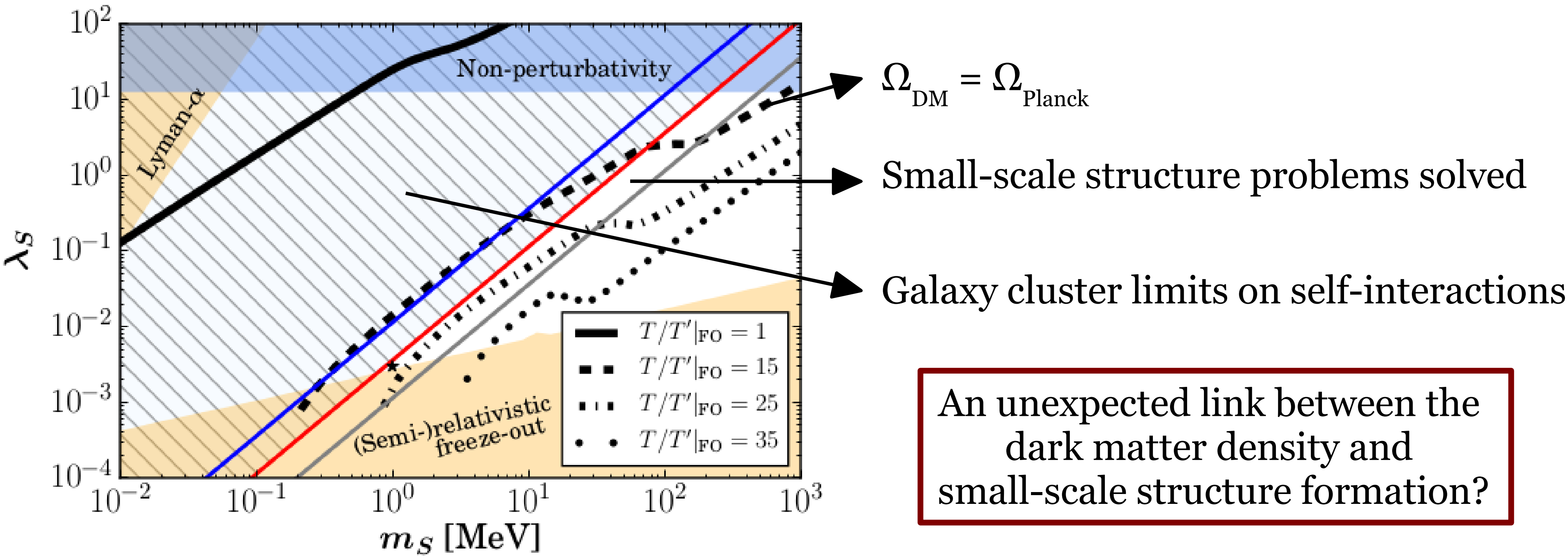
# Possible corollary of self-interactions

Usually, when computing the dark matter abundance, only $2 \leftrightarrow 2$ processes are taken into account.

But what if the self-interactions are so strong that number-changing processes *within* the dark sector dominate?

One example from the Singlet Scalar Model: $V = V_{\rm SM} + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} |H|^2 S^2$

N. Bernal, X. Chu, JCAP 1601 (2016) 006
*Cf* also N. Bernal *et al*, JCAP 1603 (2016) 018




An unexpected link between the dark matter density and small-scale structure formation?