Some highlights from dark matter physics

Rencontres de Physique des Particules 2017, Marseille

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LPTHE - Jussieu

Tuesday 25/4/2017

What I'll try to summarise

- WIMP searches

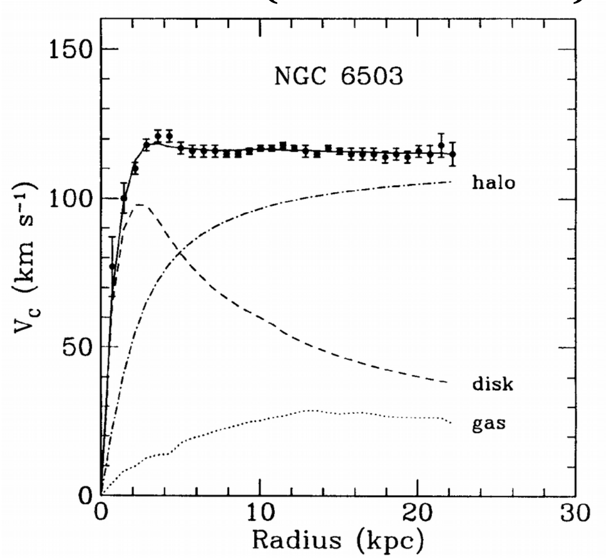
- (a few things on) Some non-WIMP candidates

First things first : why dark matter

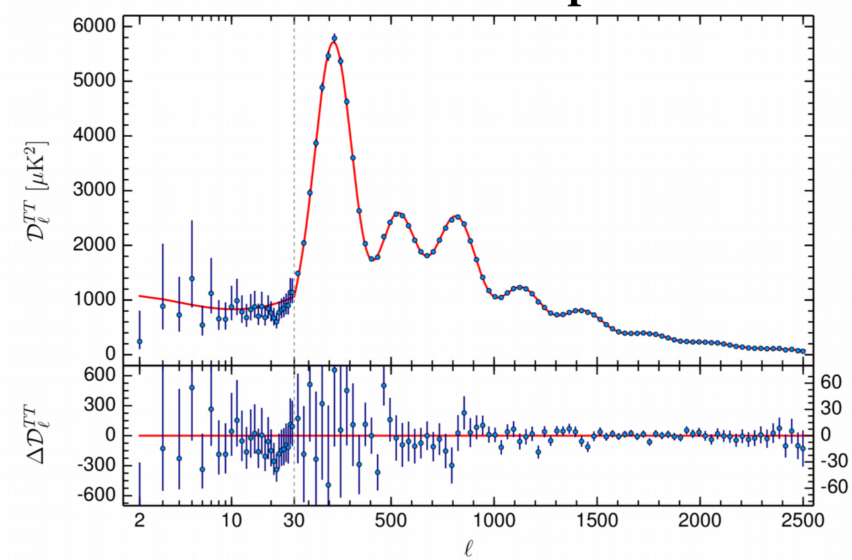
By now, the existence of Cold(-ish) Dark Matter (CDM) is pretty well-established.

Evidence at multiple scales

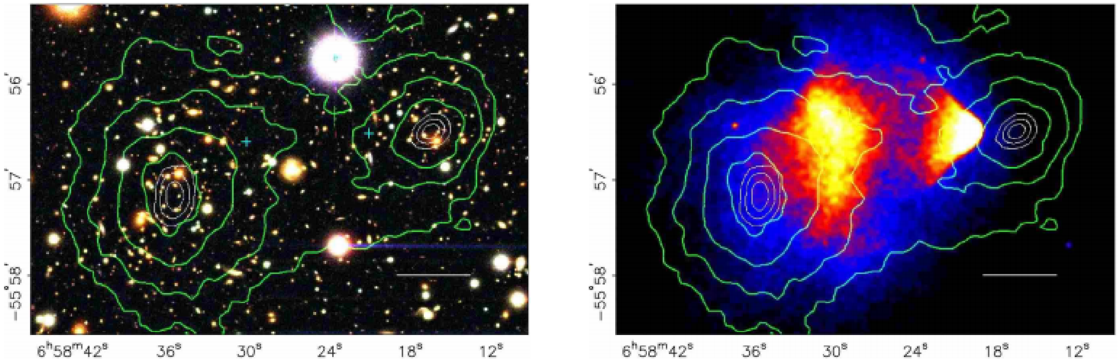
Galaxies (rotation curves)



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: Of course, this is not proof!

Dark matter and BSM physics

All pieces of evidence for the existence of dark matter rely on gravity...

No information about its (particle?) nature!

But :

- It cannot be baryons (not seen, BBN, microlensing).

- It cannot be neutrinos (too light – $m_\nu < 2$ eV, would require > 10 eV / too hot, since ν's freeze-out – spoils structure formation).

Cosmology points towards BSM physics

Candidates (strongly related to production mechanisms) :

- Axions (from coherent oscillations → CDM-like equation of state, $m_a < \mathcal{O}(\text{meV})$)

- Sterile neutrinos (from oscillations with ordinary ones, from freeze-in)

- Asymmetric (density depends on initial asymmetry + freeze-out)

- WIMPy (from freeze-out to the visible sector – minimal, SUSY, KK...) *Cf* talks by R. Ruffault, G. Robbins

- FIMPy (from freeze-in/dark freeze-out) *Cf* talks by M. Dutra, Y. Chen

- Super-heavy (from gravitational production) / Macroscopic (primordial black holes)

Searches VS candidates

Explaining the dark matter abundance is one thing, observing it non-gravitationally is another. Or is it?

$$\text{Dark matter models} \; \underset{\text{Constrain}}{\overset{\text{Motivate}}{\rightleftarrows}} \; \text{Dark matter searches}$$

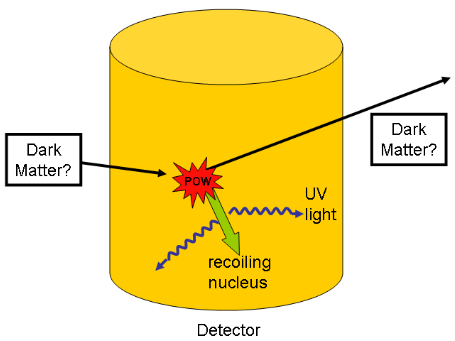
Searches VS candidates

Explaining the dark matter abundance is one thing, observing it non-gravitationally is another. Or is it?

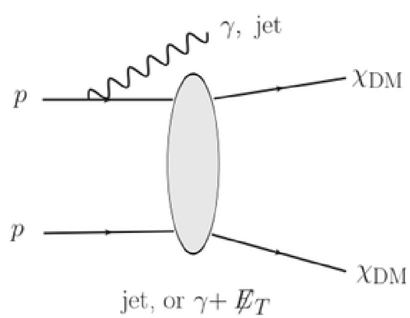
Dark matter models —Motivate→ **Dark matter searches**

Dark matter models ←Constrain— **Dark matter searches**

Direct detection



Collider searches



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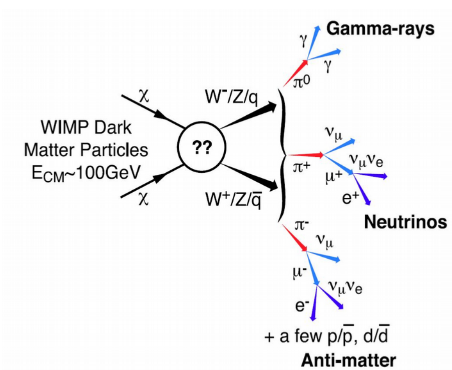

Require non-negligible interactions with the SM

→ Equilibrium

→ Freeze-out

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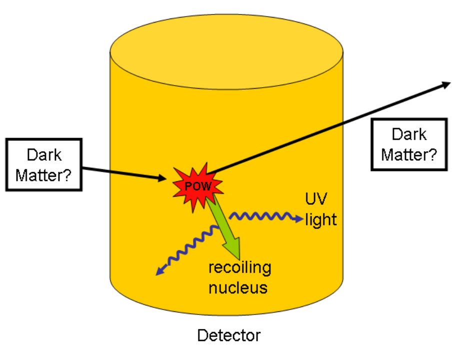

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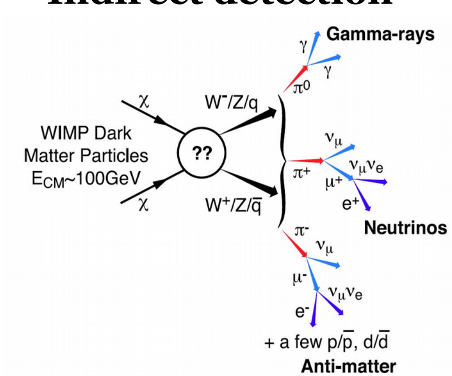

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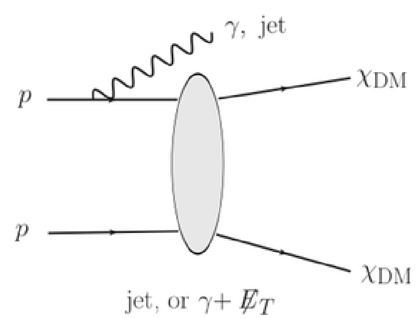


Require non-negligible interactions with the SM

→ Equilibrium

→ Freeze-out

Comparison with N-body simulations

Hints about DM non-gravitational interactions?

Stellar evolution

Dark matter accretion in stars can modify their thermal evolution.

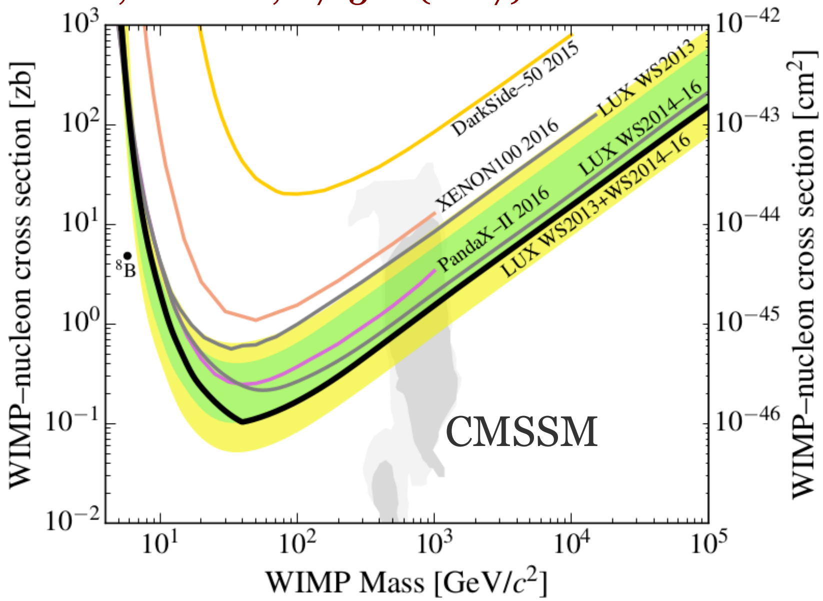
Primordial nucleosynthesis

E.g. when from decay of a parent particle.

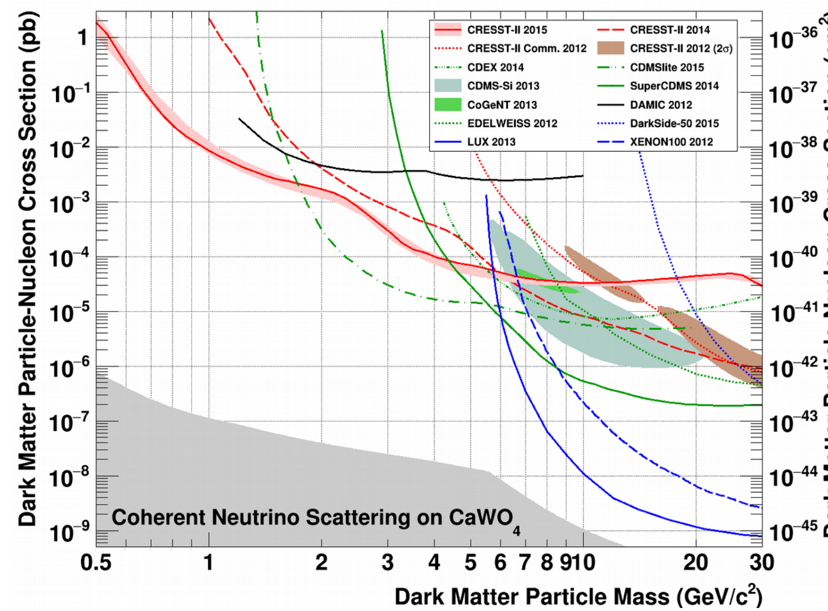
Direct detection

State-of-the-art of conventional searches (spin-independent scattering)

LUX, PRL 118, 021303 (2017)
PANDA-X, PRL 118, 071301 (2017)



CRESST-II, EPJC (2016) 76:25



Testing actual (“well-motivated”) dark matter models!

Direct detection starts probing the sub-GeV mass range!

Direct detection

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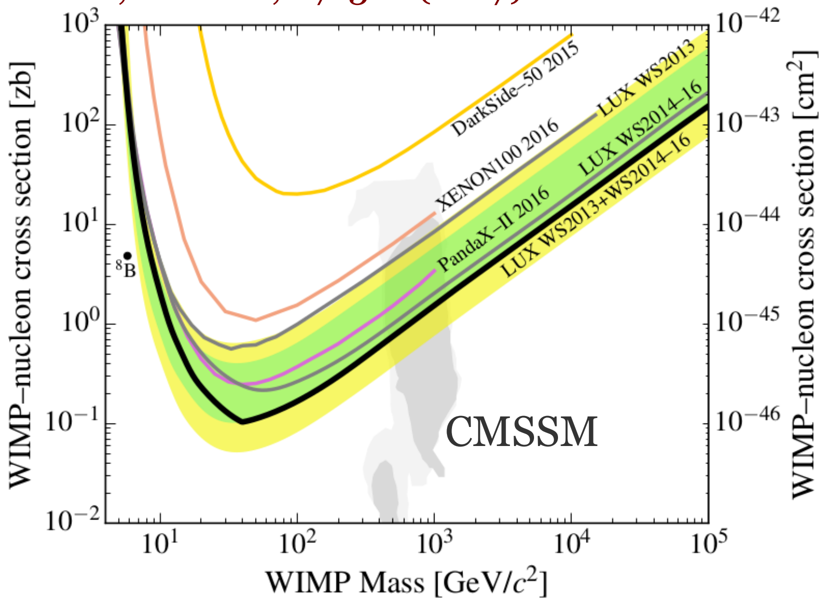

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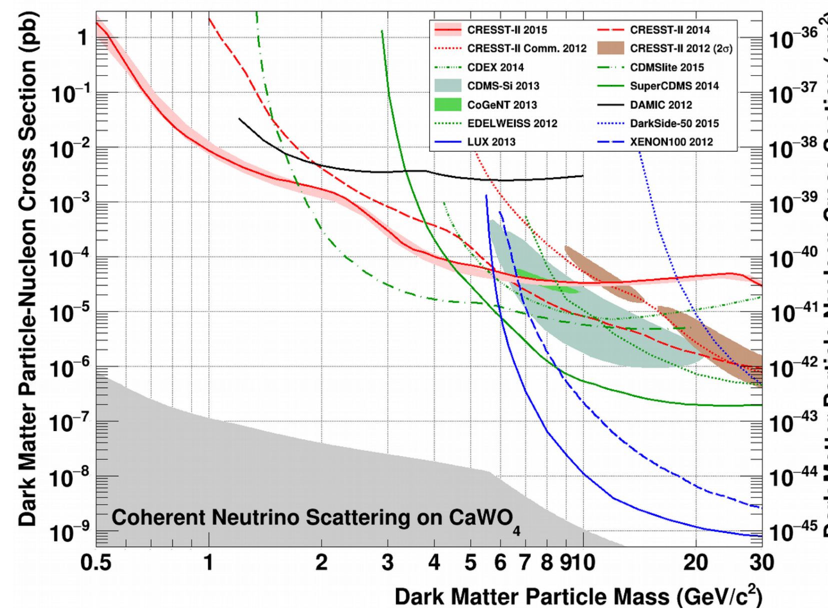

Assumptions :

- Velocity distribution: truncated Maxwellian
- Escape velocity: 544 km/s, circular velocity: 220 km/s
- Local density: ρ_{local} = 0.3 GeV/cm³

- In principle correlated!
Reviewed in: A. M. Green, arXiv:1703.10102 + references therein

- O(50%) uncertainty in limit
J. Lavalle, S. Magni, PRD 91, 023510 (2015)

- Same scattering strength on protons and neutrons: $f_p = f_n$

Isospin-violating effects?

Direct detection

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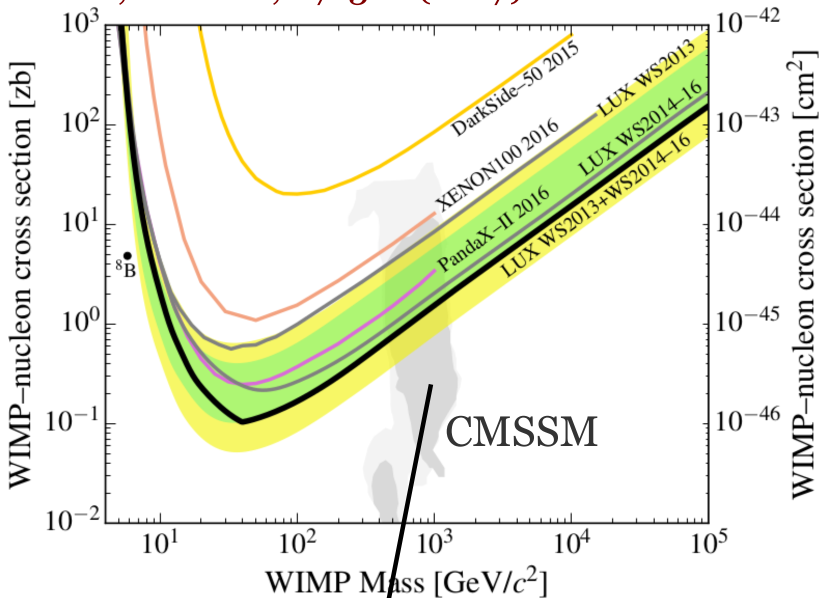

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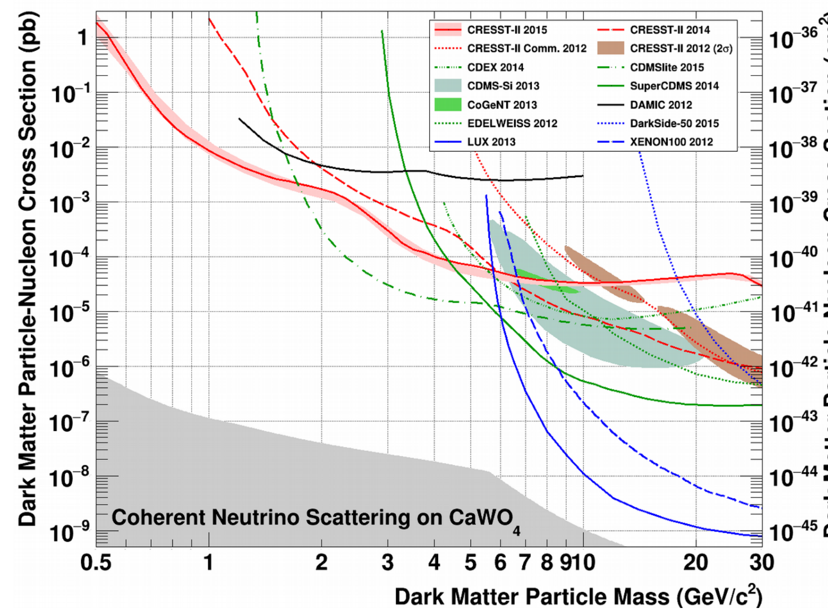


NB: This calculation also comes with assumptions, e.g. on p/n scalar quark content.

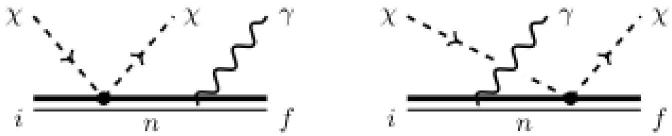
Cf talk by L. Lellouch

Direct detection

Limitations of current searches ?

Light dark matter

Nuclear recoil bremsstrahlung



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

“whereas, say, E_R = 0.5 keV, is experimentally easily missed,
a photon of energy ω = 0.5 keV is hardly ever missed”

Direct detection

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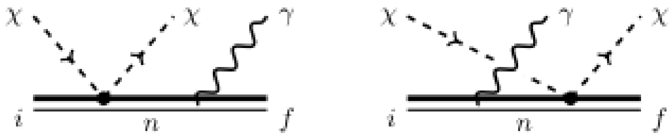
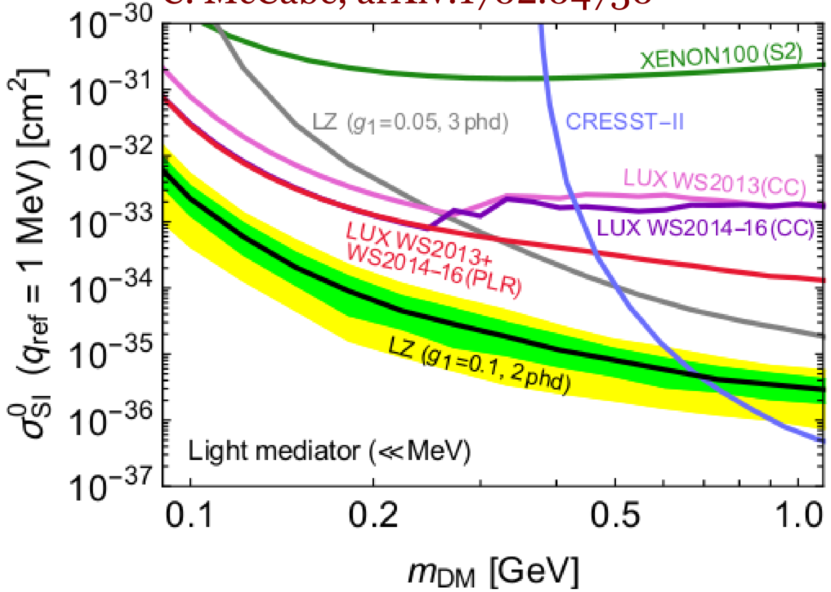
Nuclear recoil bremsstrahlung



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

Applied to XENON detectors

C. McCabe, arXiv:1702.04730



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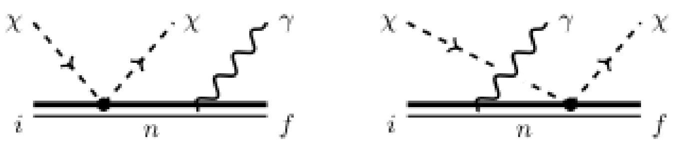

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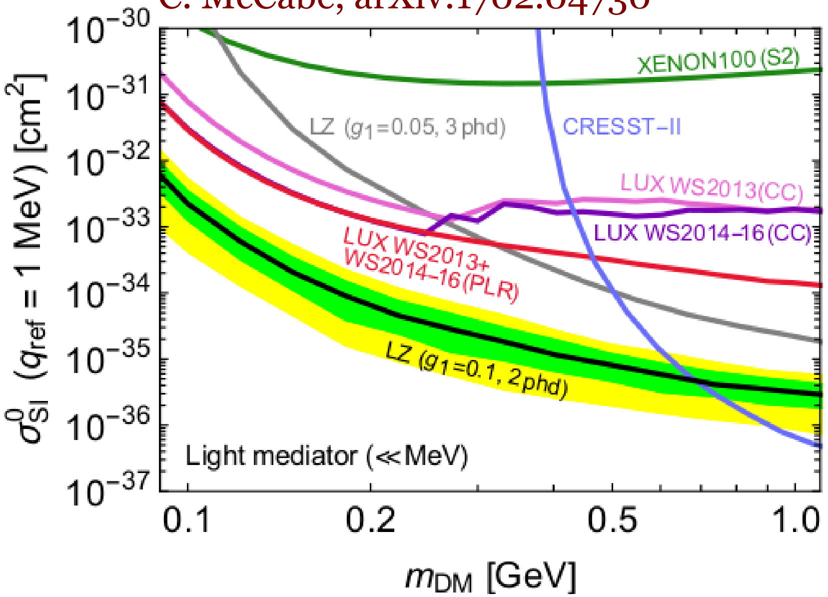

Exploit new technologies

- Semiconducting detectors (MeV dark matter)
  P. Graham *et al*, Phys. of the Dark Universe 1 (2012) 32-49
- Superconducting detectors (keV dark matter)
  Y. Hochberg *et al*, JHEP 1608 (2016) 057
- Superfluid He detectors (keV dark matter)
  W. Guo, D. McKinsey, PRD 87,115001 (2013)

Direct detection

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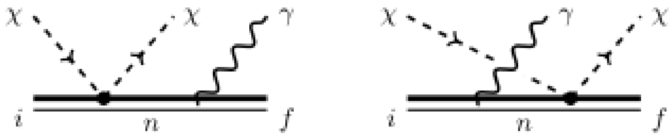

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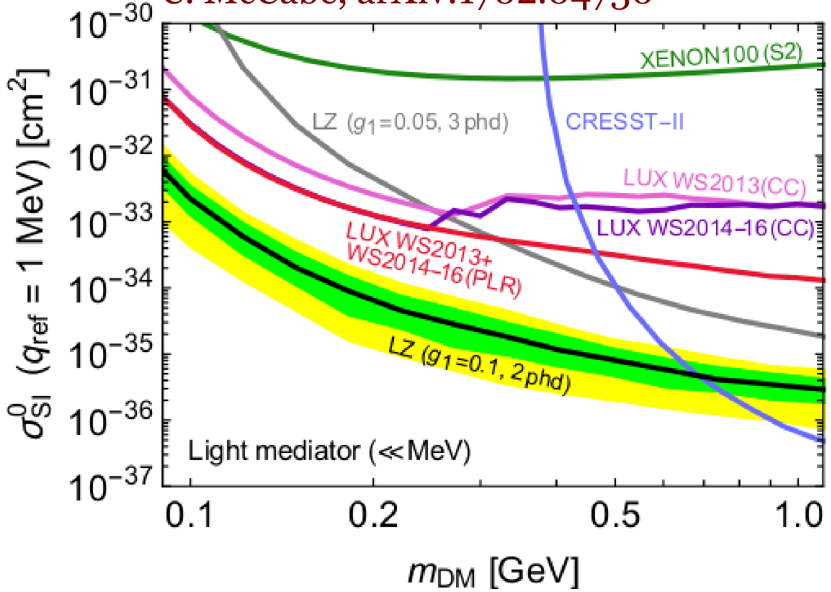

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W. Guo, D. McKinsey, PRD 87,115001 (2013)

Neutrino floor

- Tricky situation: can't distinguish between neutrino and dark matter scatterings...

- Directional detection: scalable?

F. Mayet et al, Phys. Rep. 627 (2016) 1

- Neutrino physics with DM detectors: dark matter becomes the background!

Indirect detection : gamma-rays

Expected gamma-ray flux

$$\Phi_\gamma(E\gamma,\Omega) = \underbrace{\left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\right]}_{\text{Particle physics}}\underbrace{\int_{\text{los}}\rho^2(l,\Omega)dl}_{\text{Astrophysics}}$$

NB: “Factorisation” holds if <σv> is velocity-independent

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What to look for

- Continuum (larger <σv> unless v-suppressed)
- Spectral features (easier to disentangle from background)

Where to look

- Galactic centre or around (large signal, large background, astro uncertain)
- Milky Way subhalos (smaller signal, smaller background, astro uncertain)
- Milky Way satellites (small signal, small background, astro more under control)
- Extragalactic (large signal, large background, astro uncertain)

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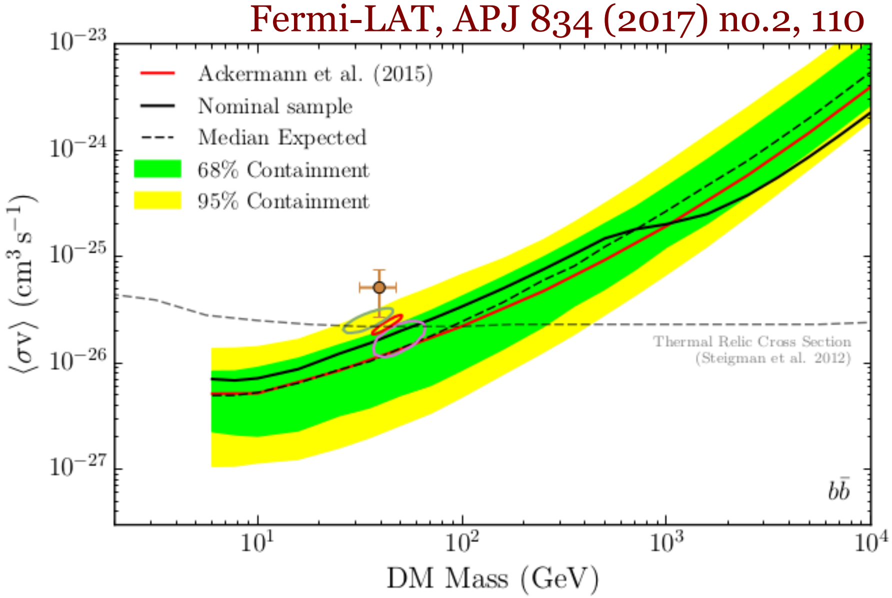
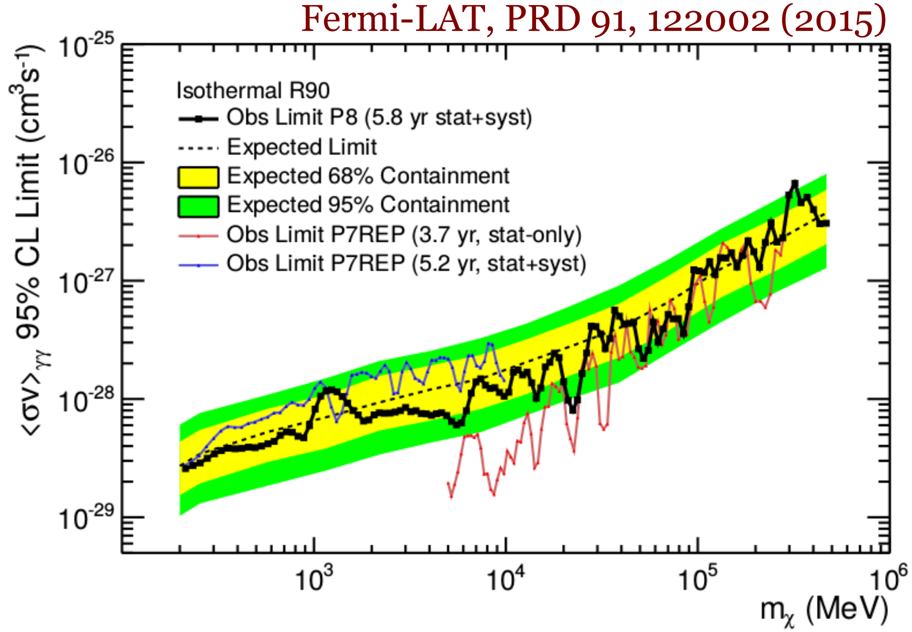
Continuum	**Spectral features**
Fermi-LAT limit from dSPhs	Fermi-LAT limit from Galactic Centre

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



Currently probing the WIMPy regime!

Fermi-LAT, PRD 91, 122002 (2015)

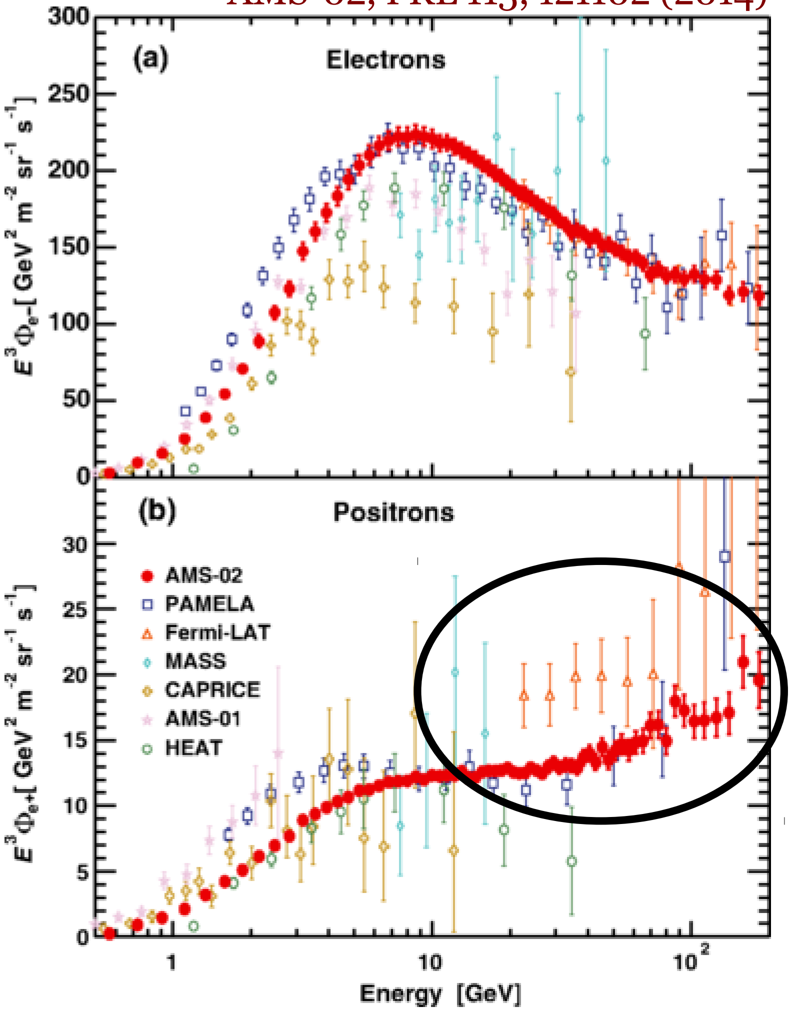


(Limit stronger by up to one OOM for cuspier halos.)

Indirect detection : positrons

The PAMELA legacy: positrons are not really under control...

AMS-02, PRL 113, 121102 (2014)



- Different spectral index for e+ / e-
- Astrophysical sources of primaries?
  D. Hooper, P. Blasi, P. Serpico, JCAP 0901 (2009) 025
- Acceleration of secondaries?
  M. Ahlers, P. Mertsch, S. Sarkar, PRD 80 (2009) 123017
- Dark matter?
  Comprehensive study in DiMauro *et al*, JCAP 1605 (2016) 031

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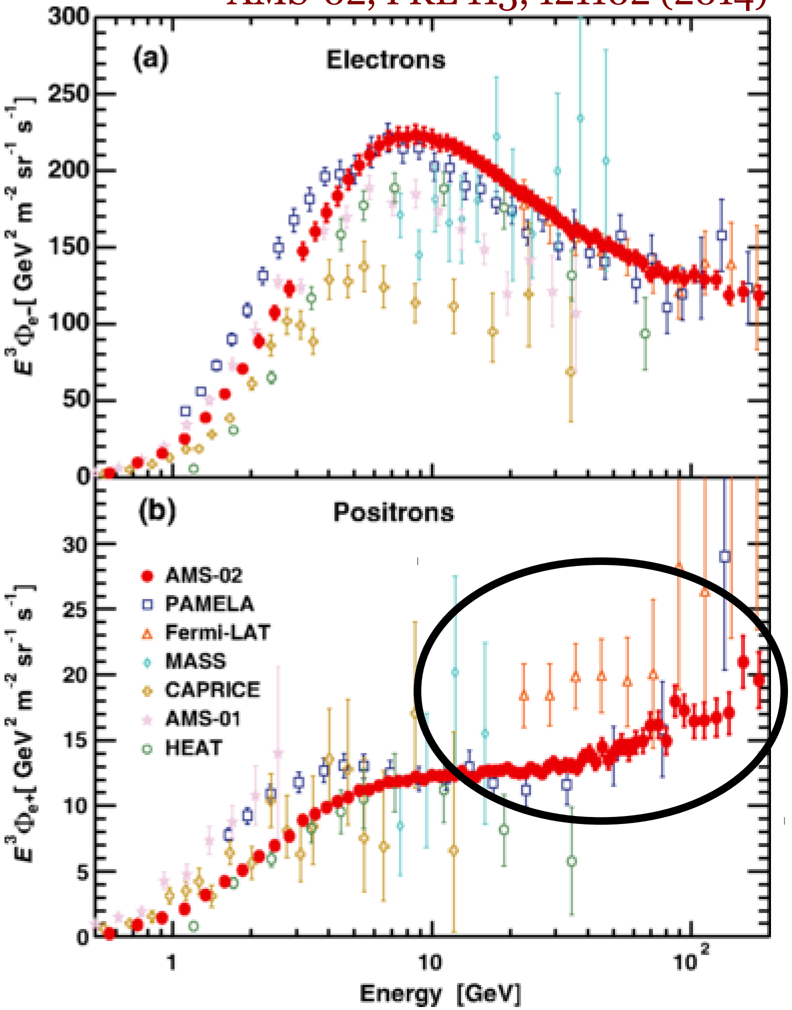

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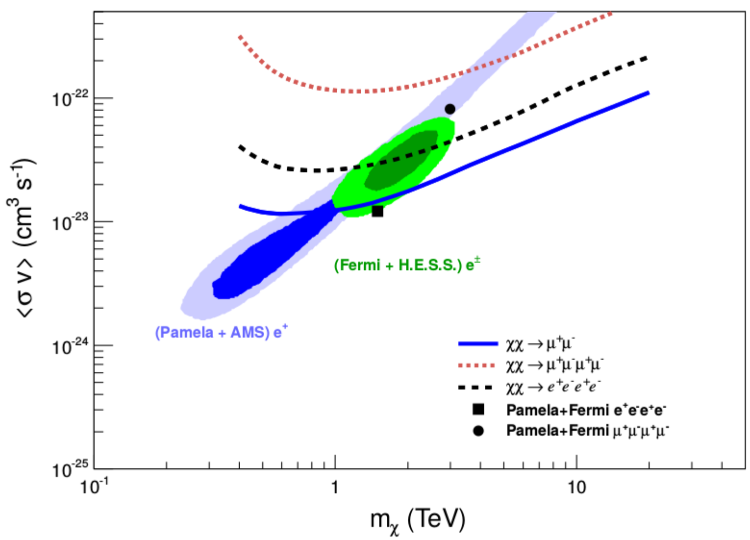

A.G., P. Serpico + HESS PRD 90 (2014) 112012

Another issue with DM explanations

Indirect detection : positrons

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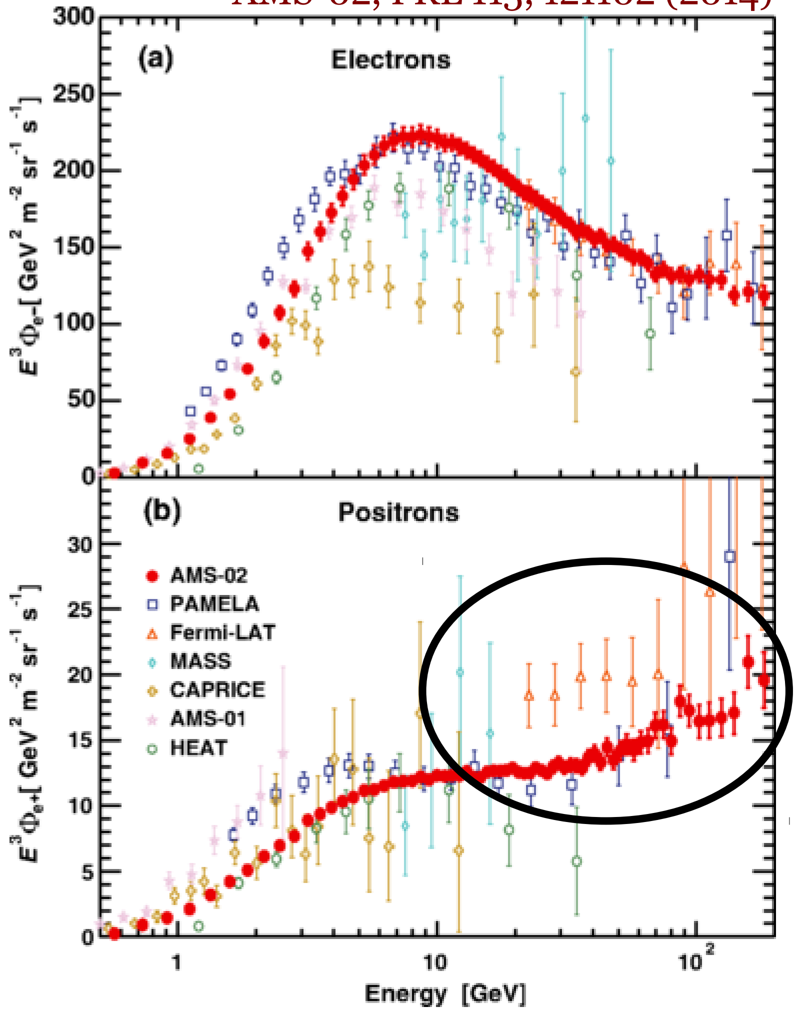

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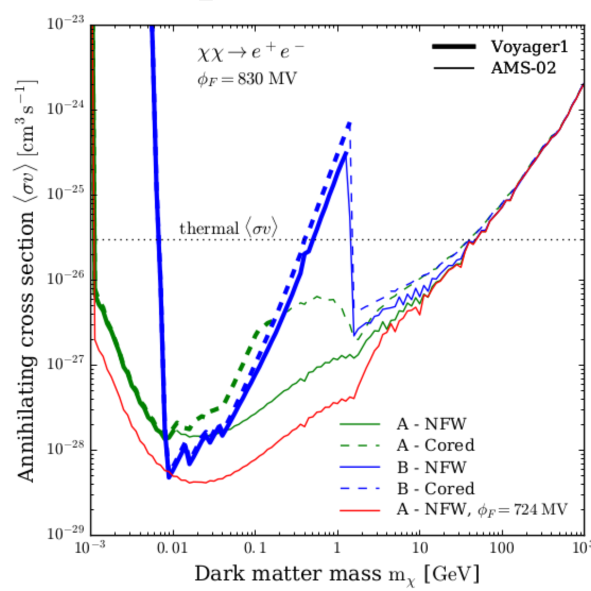
An unexpected one (at least for me!)



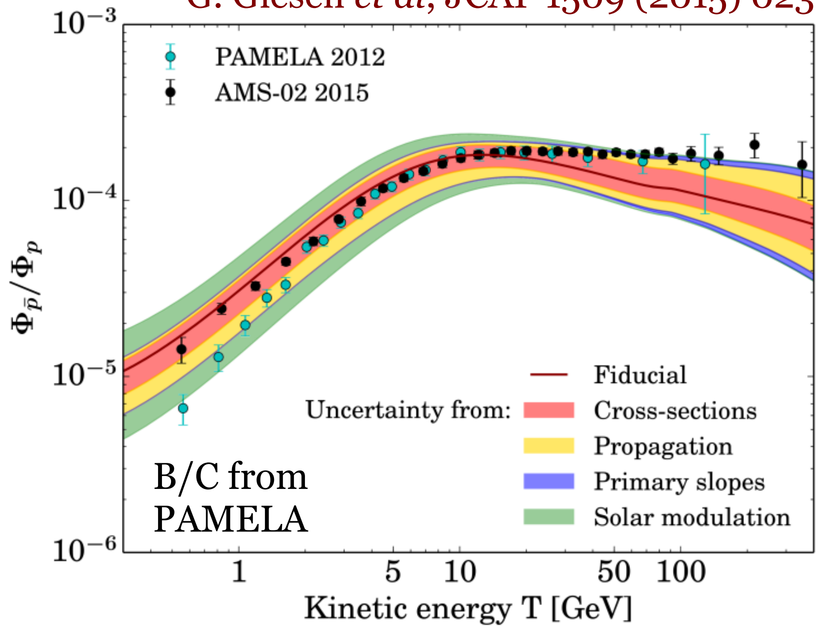
Constraints on light DM from combination of AMS-02 with Voyager I

M. Boudaud, J. Lavalle, P. Salati, arXiv:1612.07698

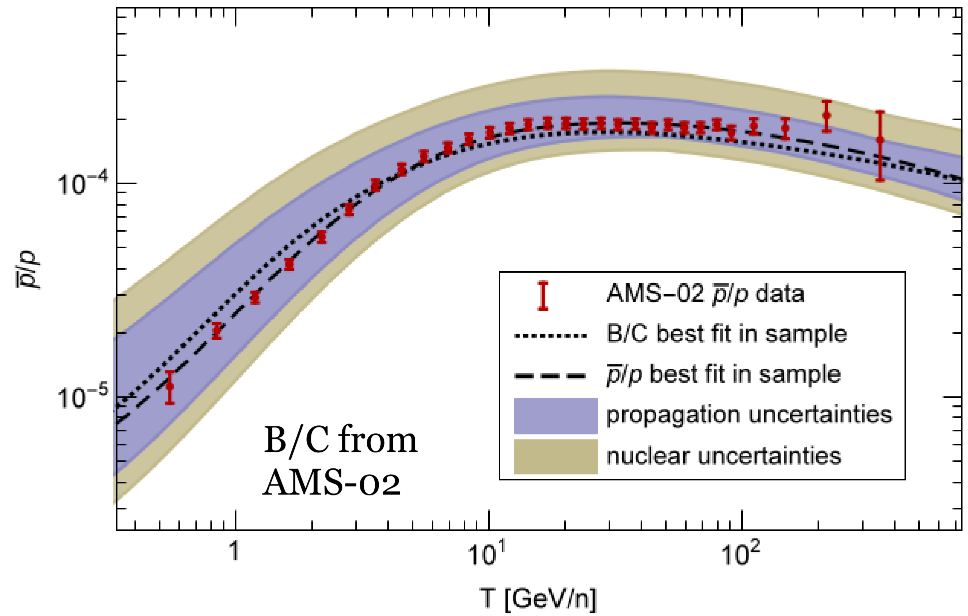
Indirect detection : antiprotons

Things more under control, but uncertainties had been underestimated

G. Giesen *et al*, JCAP 1509 (2015) 023



R. Kappl *et al*, JCAP 1510 (2015) 034



Cf also update in Winkler, JCAP 1702 (2017) 048 (although no astro uncertainties)

- Pretty good agreement with astrophysical predictions

- Major sources of uncertainty: propagation parameters + nuclear cross sections

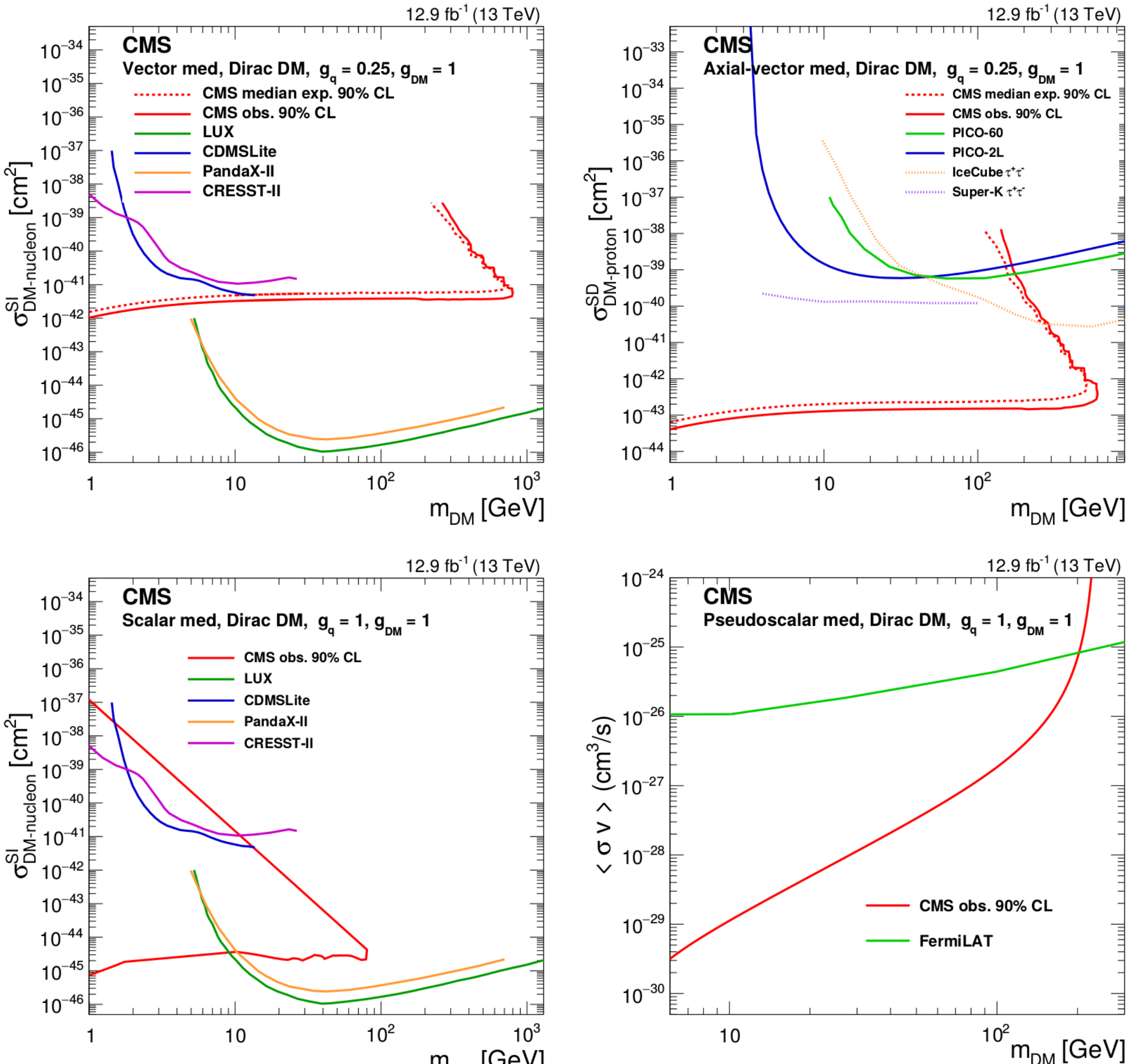
- When will we actually start probing the propagation models themselves?

- What is the ultimate limit?

Improvement is possible, *cf* discussion during XSCRC 2017 meeting

Large Hadron Collider

Most celebrated LHC dark matter searches: mono-X



CMS, arXiv:1703.01651

- Complete shift from EFTs.

- Four benchmark models: Dirac DM with vector, axial-vector, scalar and pseudoscalar mediator coupling to quarks.

- Robust handle on light DM.

- Relatively insensitive to the underlying Lorentz structure.

Very strong point!

- When direct detection works, it dominates.

- Heavy DM: indirect detection.

- Crucial assumption: $m_{DM} < m_{Med}/2$.

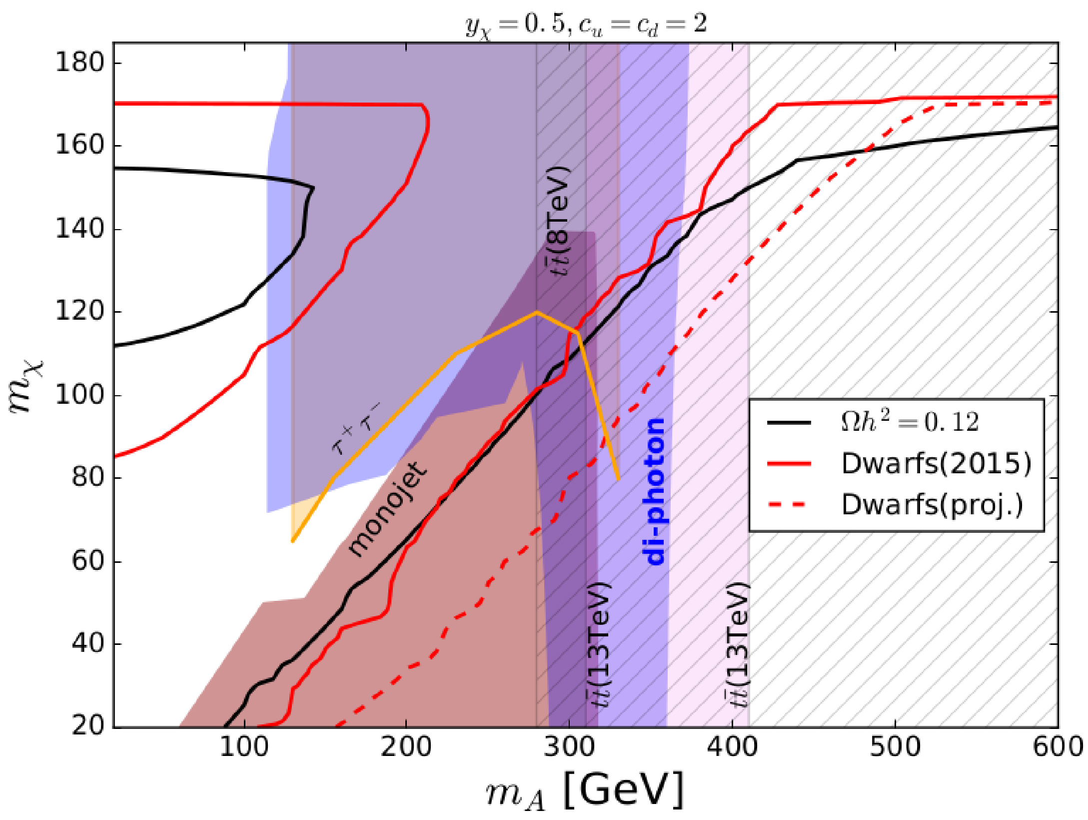
Otherwise limits vanish

Large Hadron Collider

What about the off-shell regime (aka $m_{DM} > m_{Med}/2$)?

Look for the mediator!

LHC searches complementary with direct/indirect detection but also amongst *themselves*!



S. Banerjee, D. Barducci, G. Bélanger, B. Fuks, A. G., B. Zaldivar, *to appear*

- Consider simple model of Majorana dark matter χ + Higgs-like pseudoscalar mediator *A*.

- Limits from: monojets, di-t/b + MET, di-t, di-τ, γγ, indirect detection.

- To keep in mind: light mediators are the trickiest ones.

Cf talk by B. Zaldivar

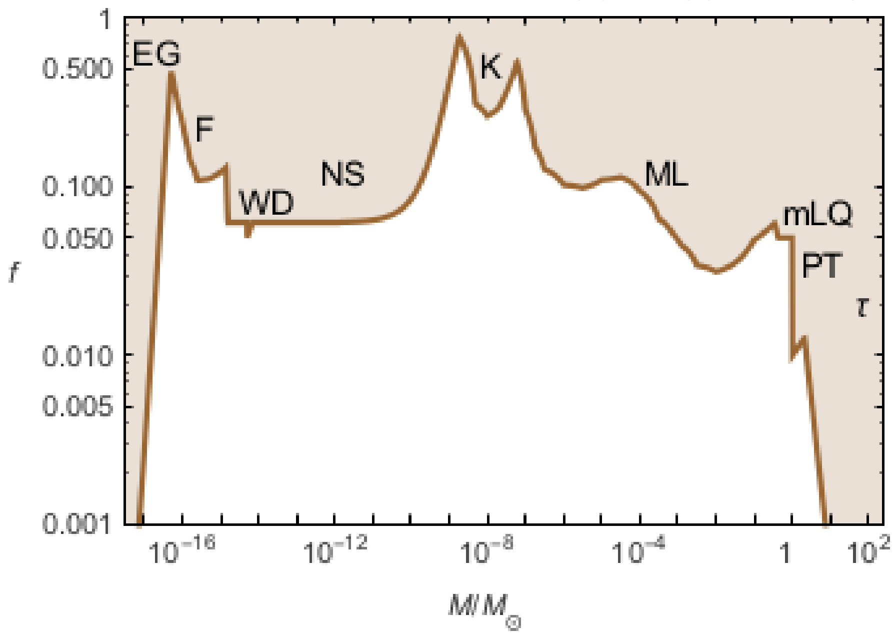
Primordial black holes as dark matter

Revived interest after the LIGO gravitational wave detection: could it be due to a merger of primordial black holes?

I. Cholis *et al*, PRL 116, 201301 (2016)

Assuming monochromatic mass function

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



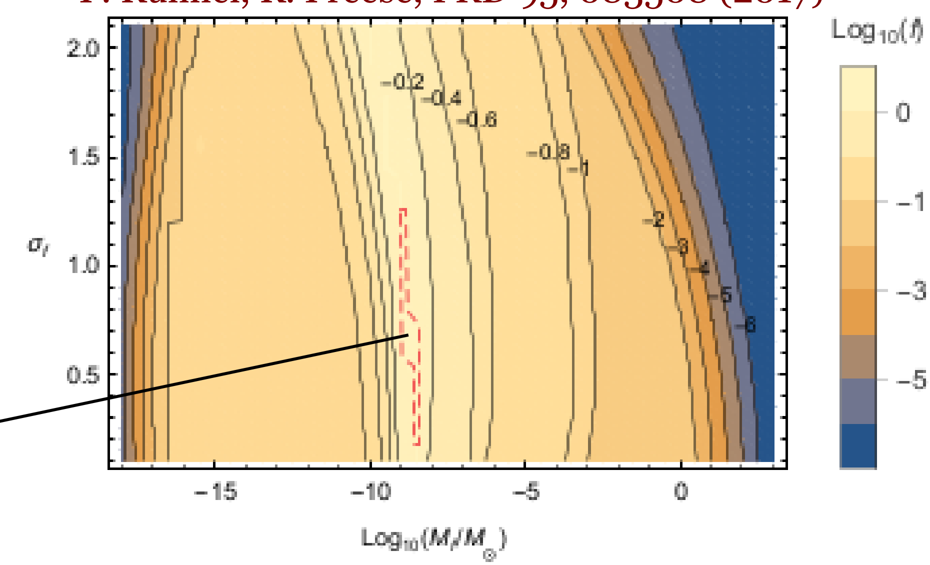
In this region PBHs could make up for the entire dark matter content in the Universe.

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 2016) PRD 94, 063530 (2016)

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



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 $O(10^2)$ satellite galaxies orbiting the MW.

but

Only $O(10)$ have been observed.

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 $\sigma_{SI} \sim 10^{10}\, \sigma_{weak}$!

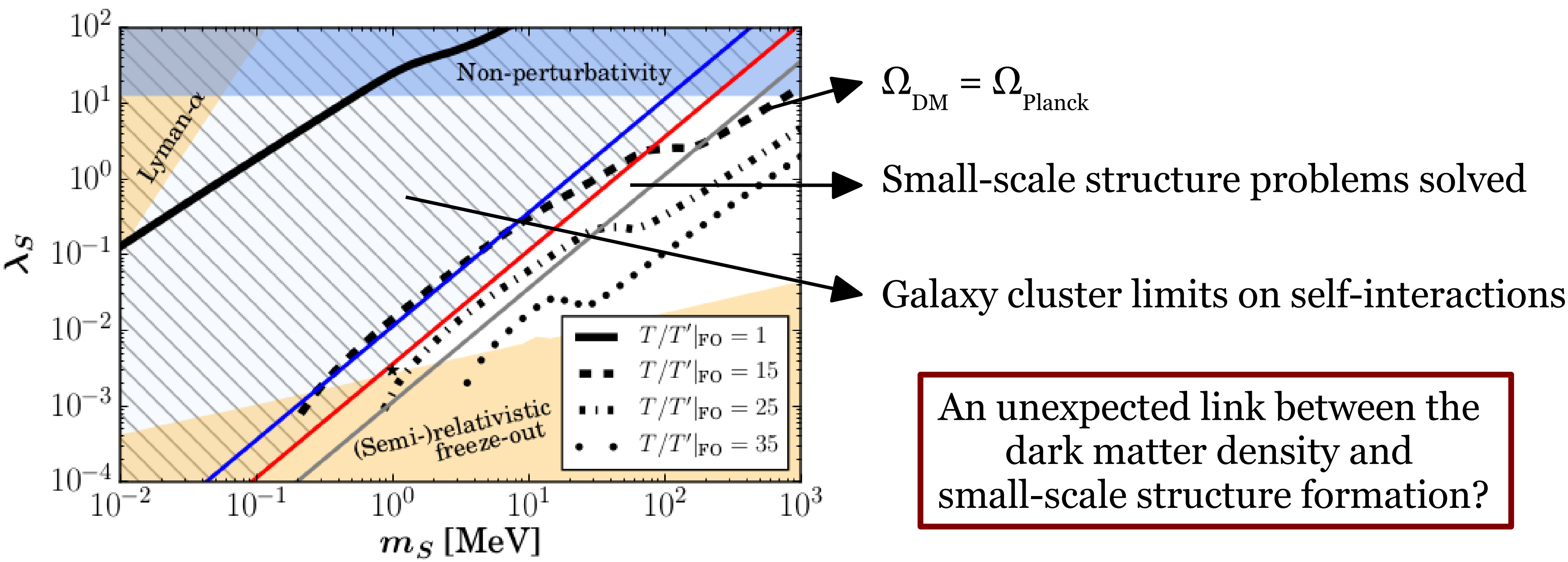
Possible corollary of self-interactions

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: $V = V_{\rm SM} + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} \left|H\right|^2 S^2$

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?

Going to darker places: freeze-in

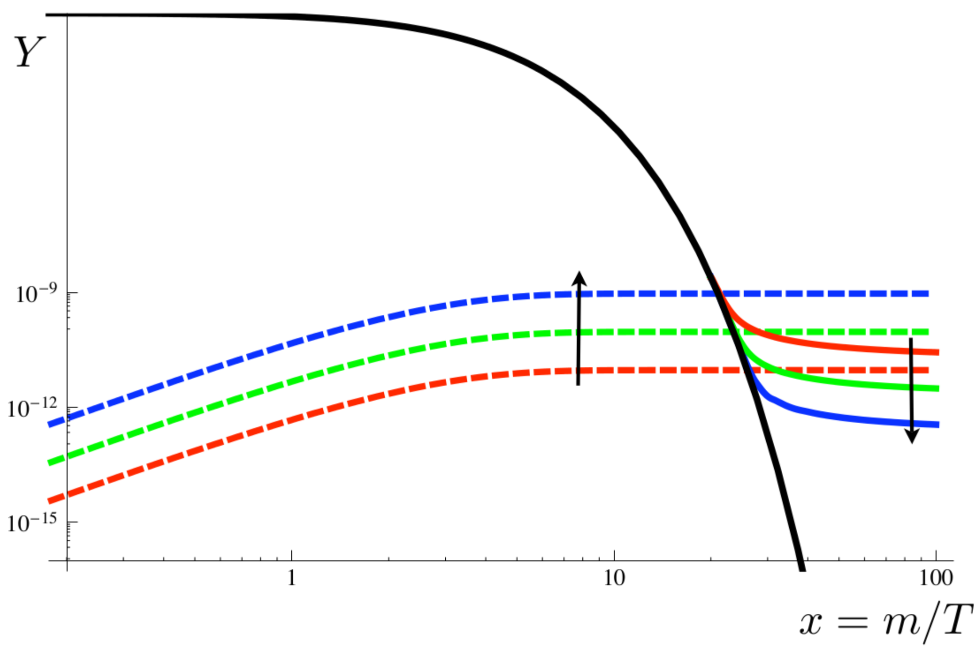
How weak can the DM interactions with the visible sector be?

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



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

NB: Which is, arguably, an attractive point: no dependence on initial conditions.

- 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

Outlook

- Traditional approaches towards dark matter physics are currently being probed.

Since ~ a decade actually, but things are getting tighter and tighter

Can we exclude thermal freeze-out?

→ Not in the general case, but we can test most "well-motivated" possibilities.

- Hardest regions to probe:
  - **Low (sub-GeV) masses**
    - Direct detection
    - Intensity frontier

    Eventually need new technologies
  - **High(multi-TeV) masses**
    - Indirect detection

    How to overcome astrophysical uncertainties?

    How to treat non-perturbative effects?

Outlook

- What are small-scale anomalies telling us?

Self-interacting dark matter?

→ Many theoretical subtleties appearing (e.g. modified phase space distributions), need to develop corresponding theoretical description.

- Is dark matter model-building just a BSM theorists' oddity? No!!!

No experimental search is performed blindly!

→ What could we be missing ("bottom-up")?

→ Where can we find motivation?

Experimental excesses, Naturalness, Flavour, Strong CP…

→ What kind of new searches?