Overview of Dark Matter models.

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HELMHOLTZ
ASSOCIATION

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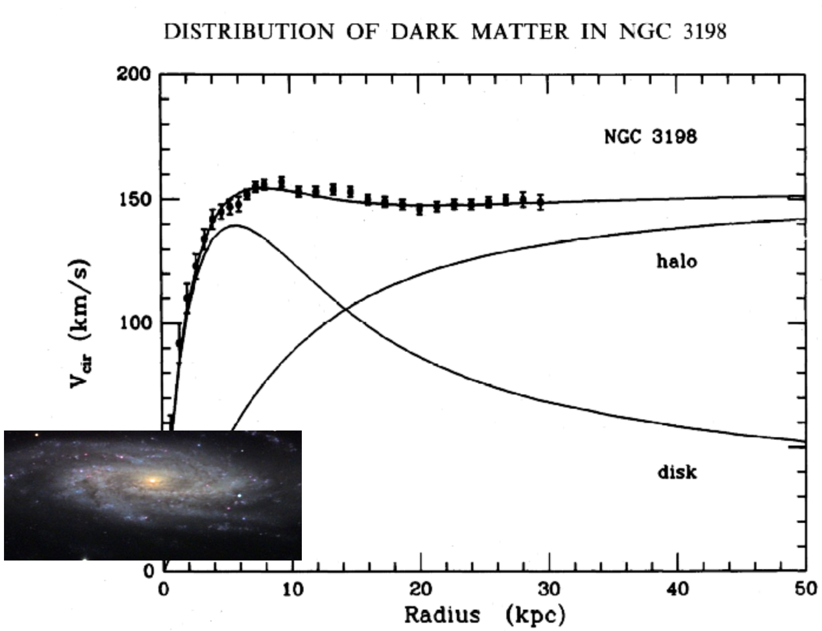
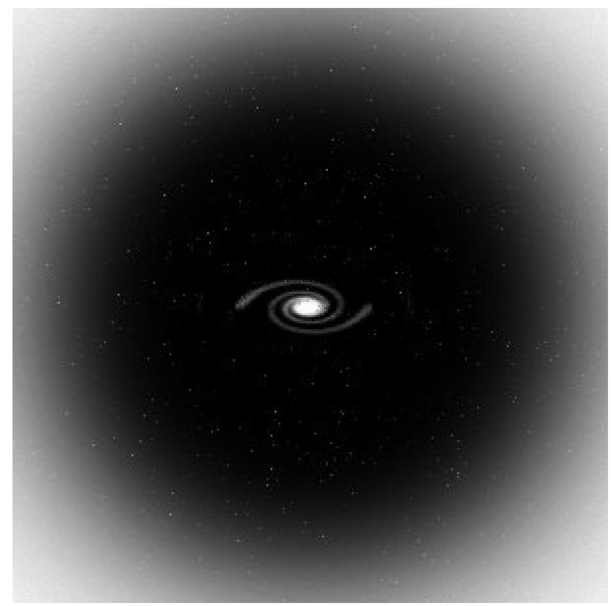
DESY

Evidence for dark matter.

Compelling evidence for dark matter on all astrophysical scales:

- Galactic scales: Rotation curves of Galaxies





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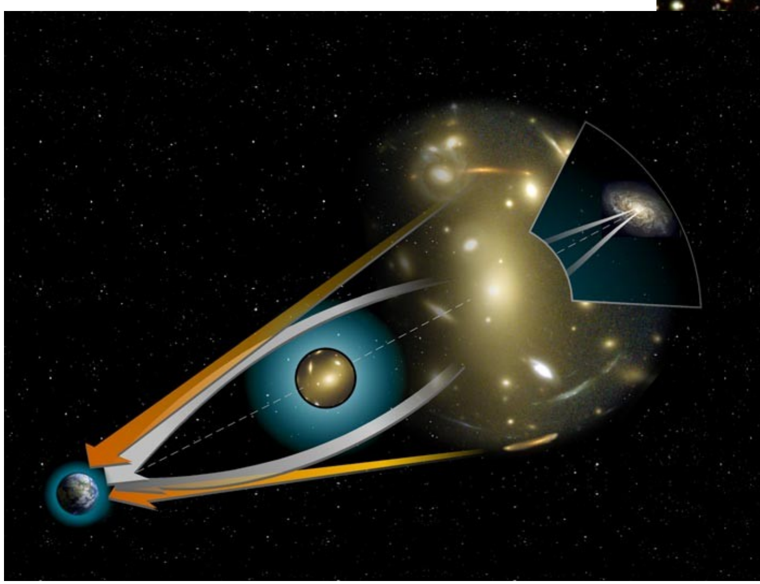
- Cluster scales: Gravitational lensing



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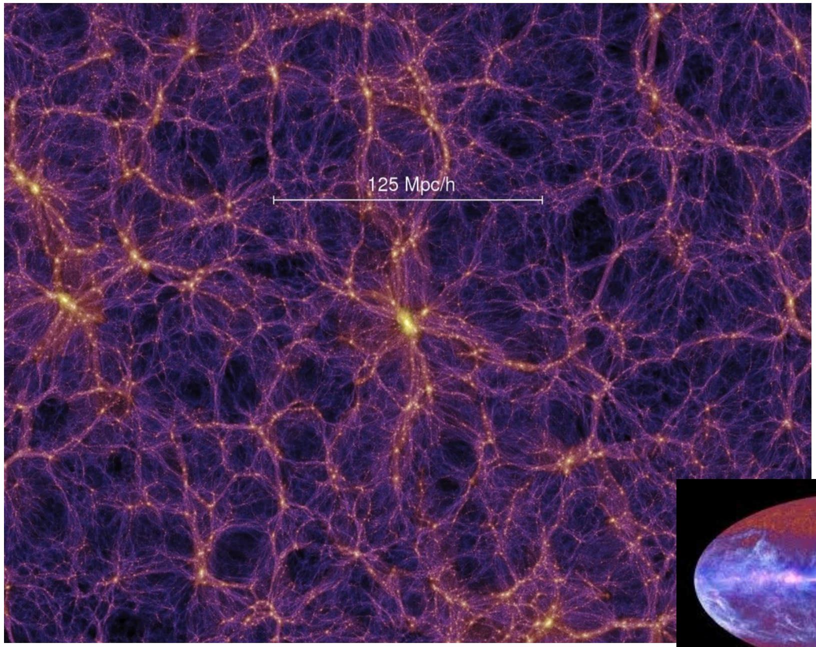
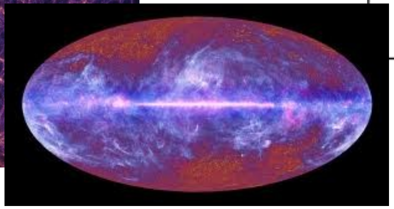
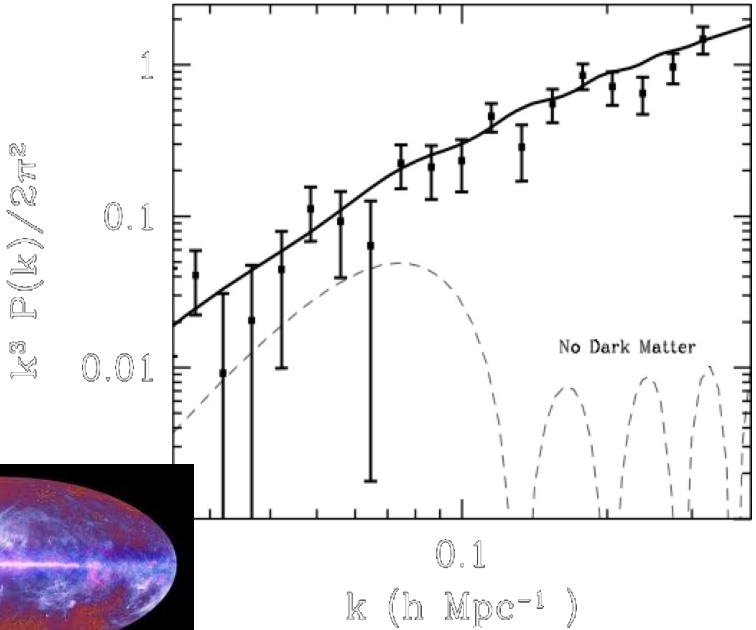
- Cosmological scales: Large scale structure (N body simulations) & CMB







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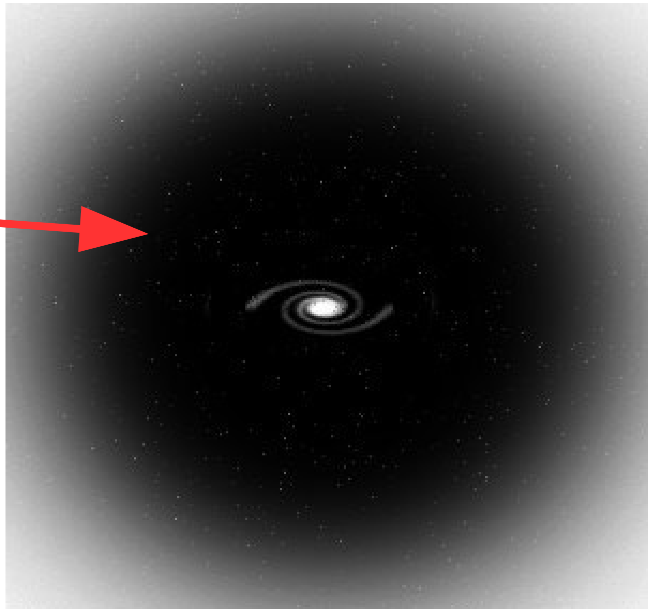
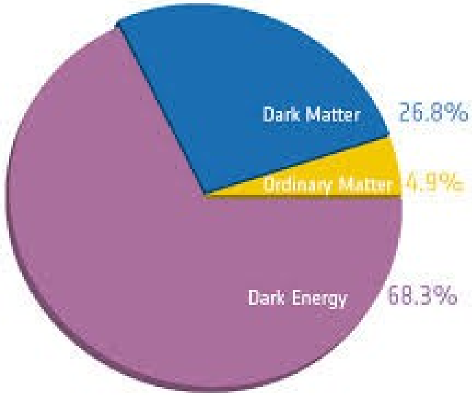
What is it ???

What do we know
to start with?



What do we know?

- How much: $\Omega_{DM} \approx 0.26$
- Likely particle with non-gravitational interactions
- Dark:
  - Electrically neutral - probably
  - Colour neutral – (H-dibaryon...)
- Cold: nonrelativistic during structure formation
- Sufficiently long-lived
- Non-baryonic (from BBN – $\Omega_B \approx 0.04$)



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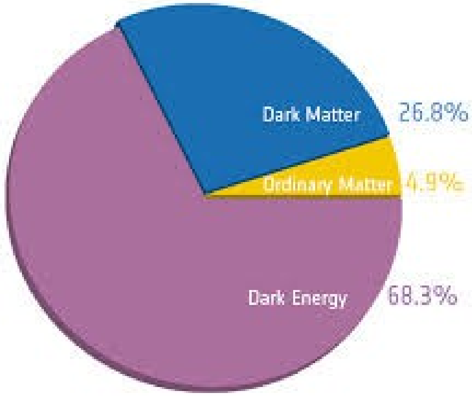


Candidate within the Standard Model of particle physics?

- Neutrinos
  - Correspond to hot DM
  - Cannot account for the observed dark matter density

$$\sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\mathrm{eV}$$

Physics beyond the Standard Model !

Many candidates (theorists are inventive...)

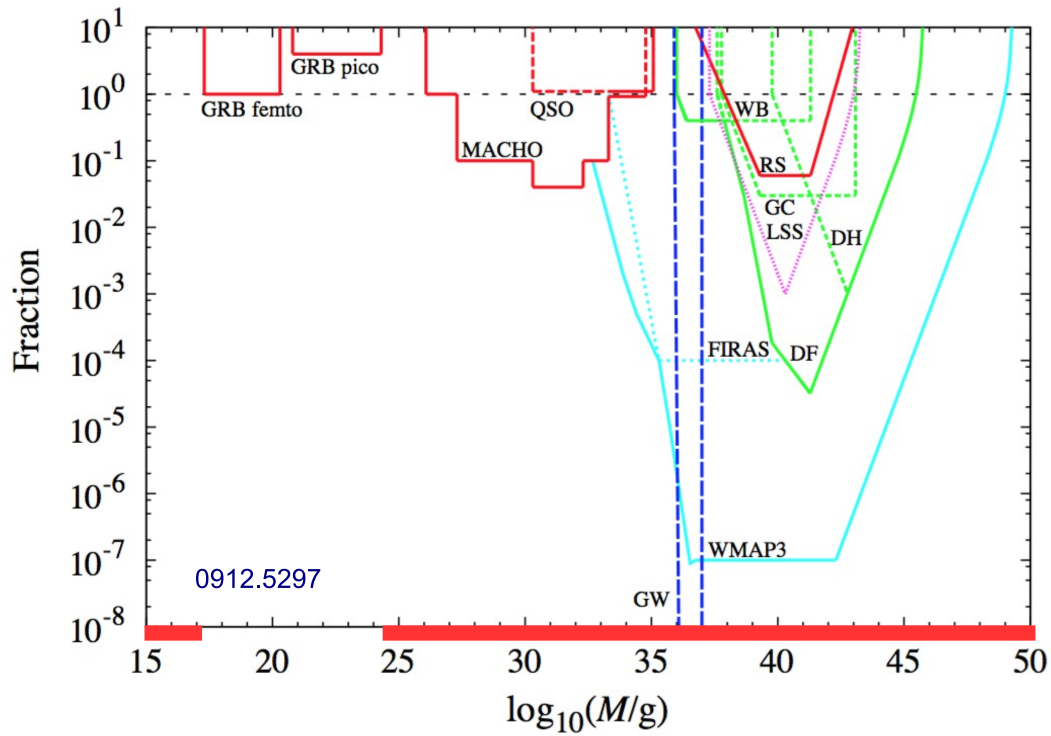
Really BSM?

Primordial black holes

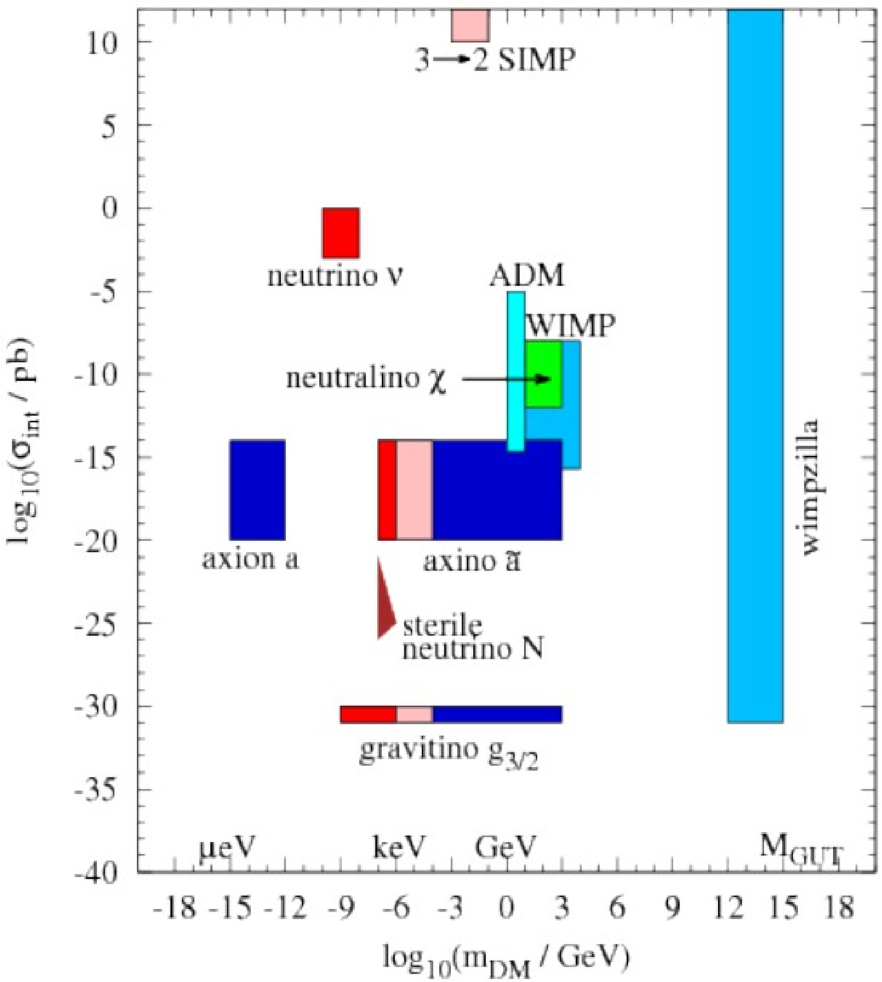
- Could form in early universe
- Too light black holes will have Hawking evaporated. Slightly heavier ones should give a signal in gamma rays, leading to $\mathbf{M_{bh} > 10^{17}\ g}$

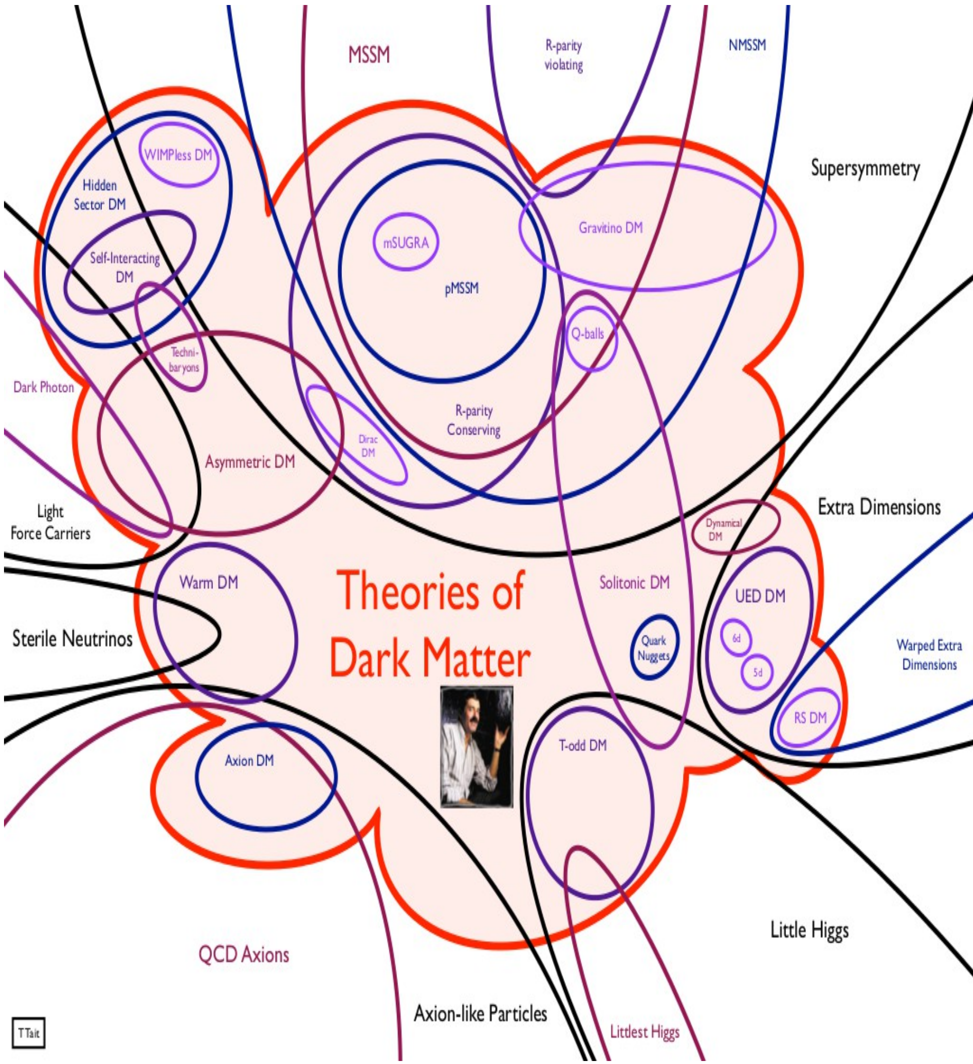
- MACHO (via microlensing) and other constraints give $\mathbf{M_{bh} < 10^{24}\ g}$

- Discussions about the remaining mass window (PBH capture and destruction of neutron stars)



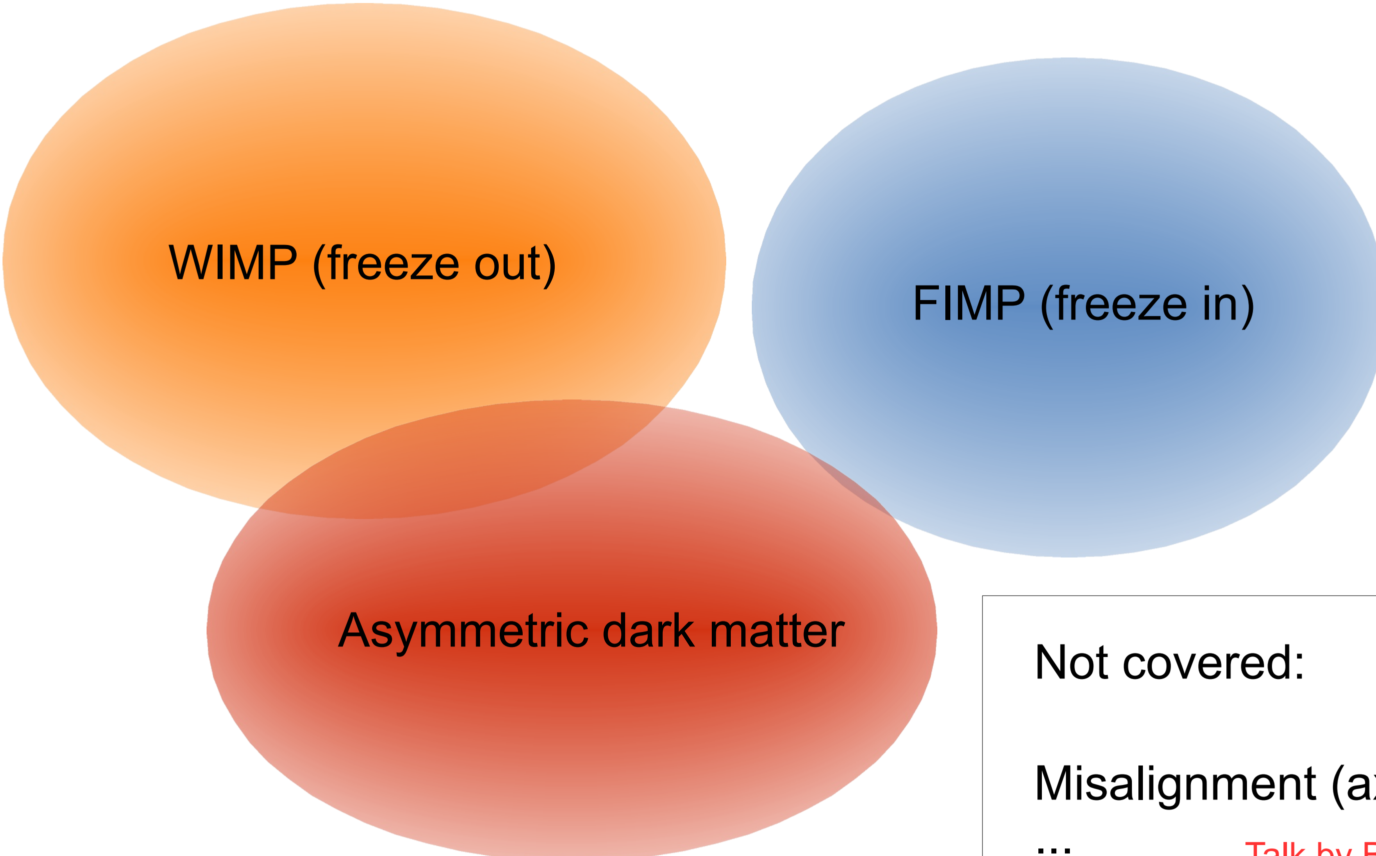
Particle physics candidates





Particle physics candidates

- Here: order by production mechanism



Not covered:

Misalignment (axion)

...

Talk by Brian SHUVE

Freeze out - WIMPs

(1) Assume dark matter X is initially in thermal equilibrium:

$$XX \longleftrightarrow SM\ SM$$

(2) Universe cools:

$$XX \longrightarrow SM\ SM$$

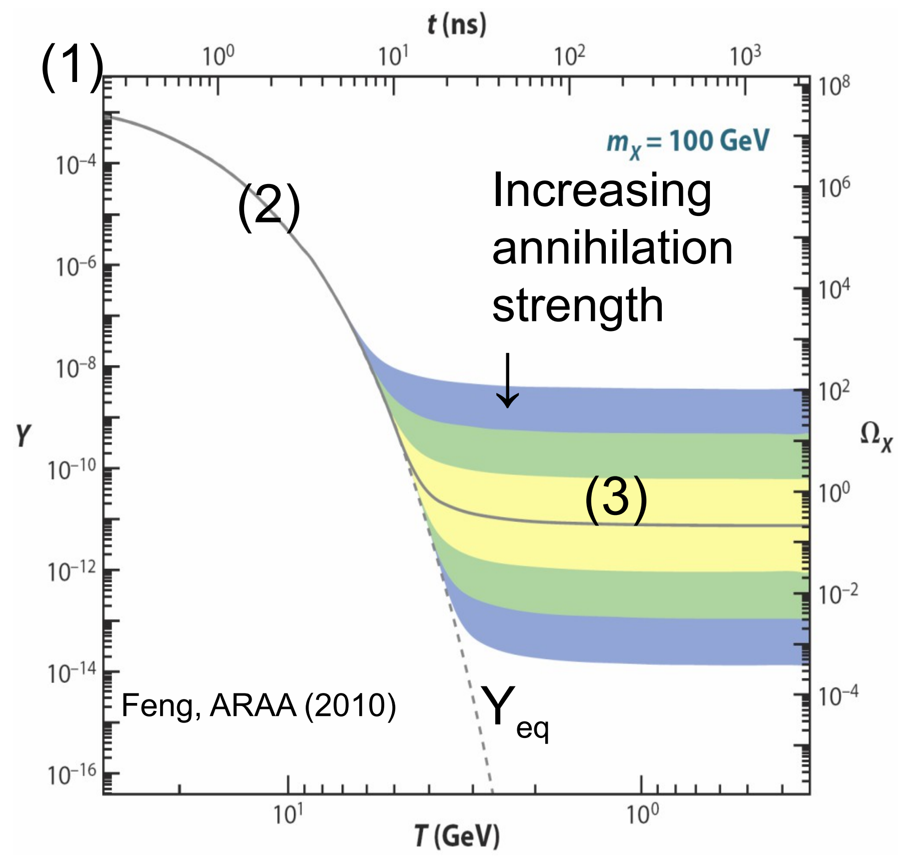
(3) Universe expands:

$$XX \qquad SM\ SM$$

The abundance is determined by the annihilation cross section!

Works just fine for weak scale masses and couplings → WIMP miracle

Unitarity bound: $m_{DM} \leq 100$ TeV



The prototypical WIMP – a neutralino

Weak scale is where we expect new physics for other reasons → SUSY

Needed: discrete symmetry → LSP stable and DM candidate

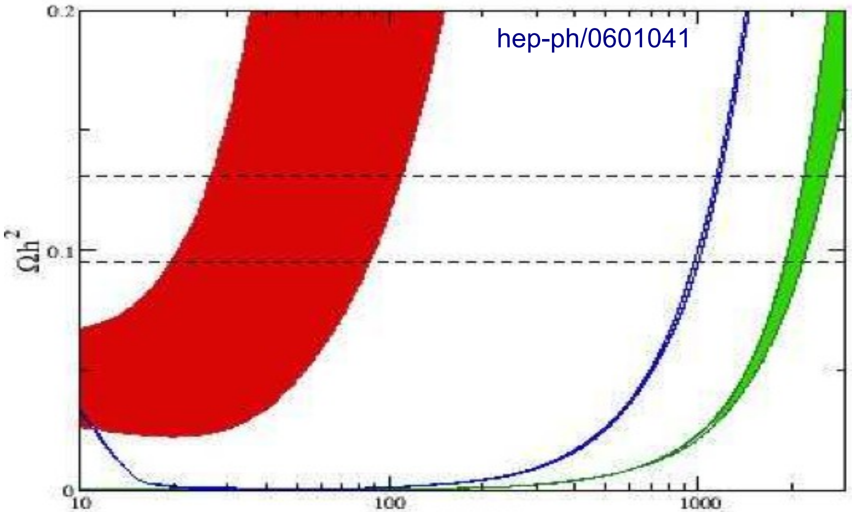
Spectrum depends on SUSY breaking

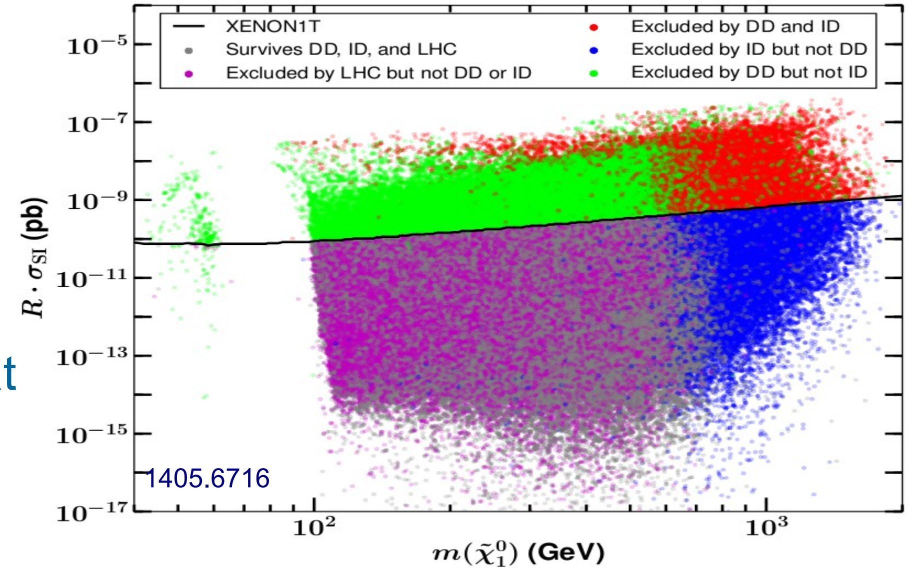
Often a neutralino LSP: spin ½ fermion (mixture of bino, wino and higgsino)

Relic abundance?

If universal gaugino masses assumed at high scale, LSP bino like → need to go to special places (fine tuning)

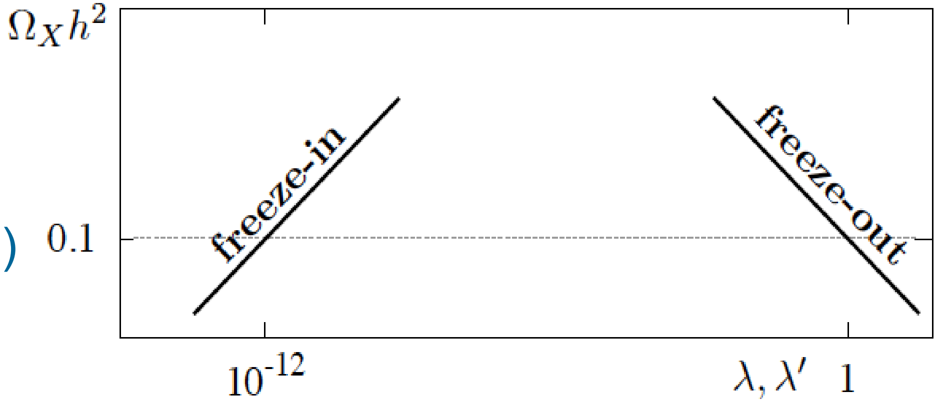
1 TeV Higgsino fine





FIMPs

- Another thermal production mechanism: **'freeze in'**
- A 'classic example': the gravitino (spin 3/2 superpartner of graviton)
- Also contribution from decay
- No chance in (in)direct detection.



NLSP long lived (s to months) - may be charged (often stau)

cf. Talk by Swagata MUKHERJEE

Collider signature: “stable”, charged, massive particles, not missing E_T

What could be learned?

$$\Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tau + \tilde{G}) = \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\mathrm{P}}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

Newton's constant and SUSY breaking scale!

Asymmetric dark matter

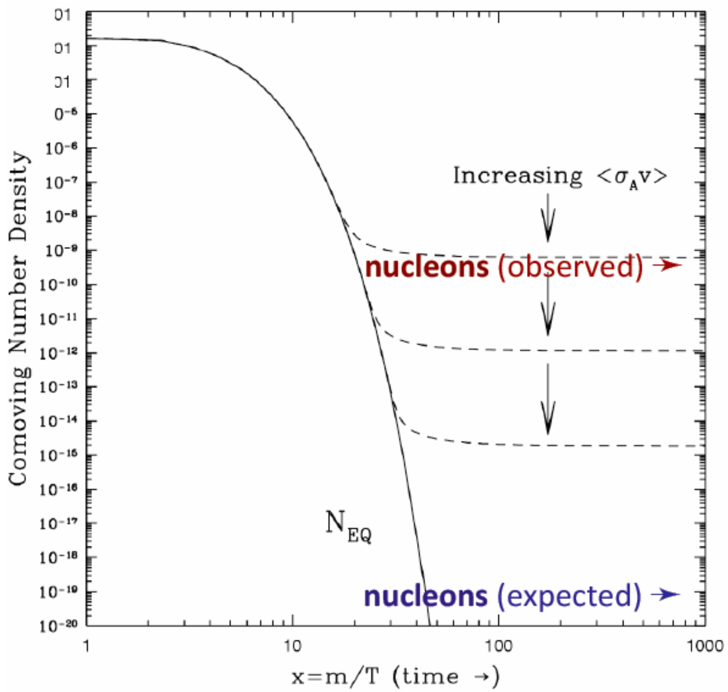
Why is the dark matter abundance so similar to that of baryons?
Do they have the same origin?

Apply our freeze out calculation to baryons:

$Y_B = Y_{\overline{B}} = 10^{-19}$

However, 10^{10} times more baryons and no antibaryons, so we must invoke an initial asymmetry

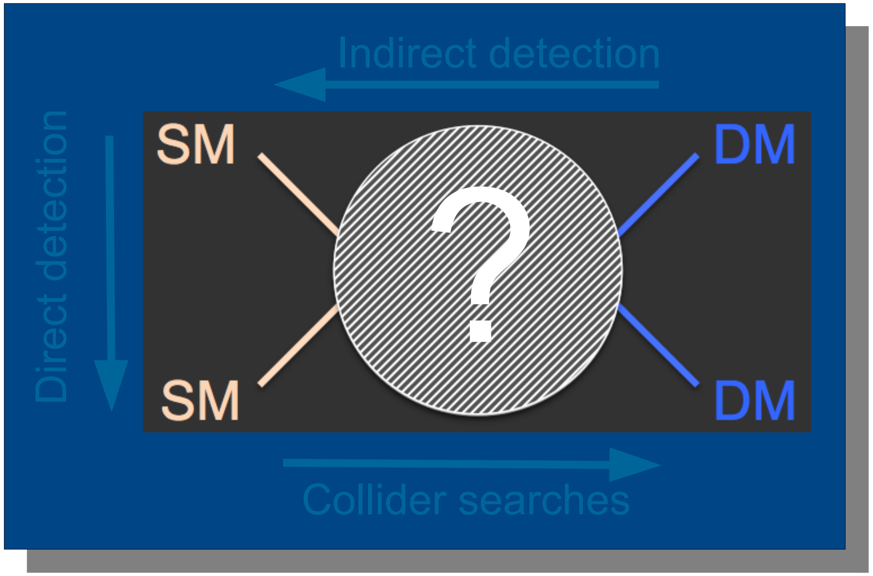
$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$



This requires baryogenesis, and there are ideas that the dark matter abundance could have the same origin

No classic indirect detection signals, but could accumulate in stars...

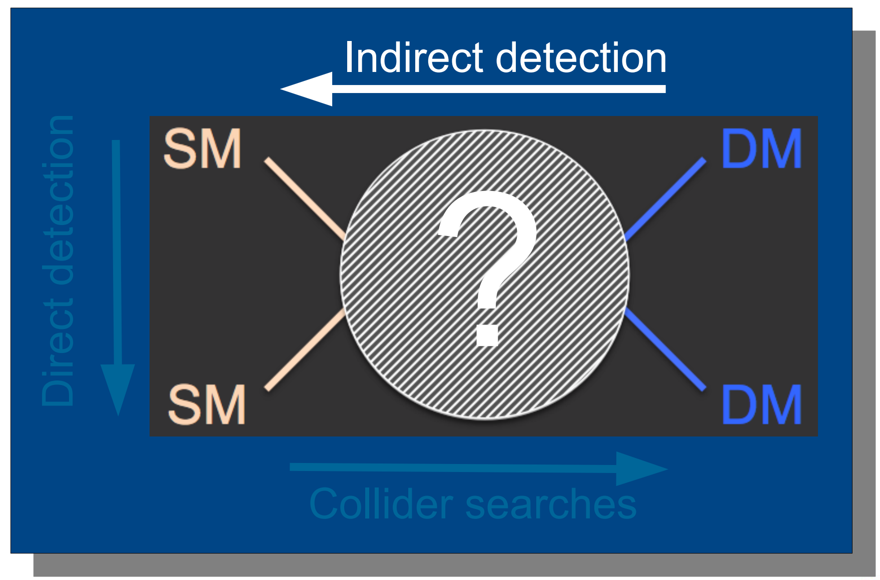
How to test it?



Dark matter annihilation

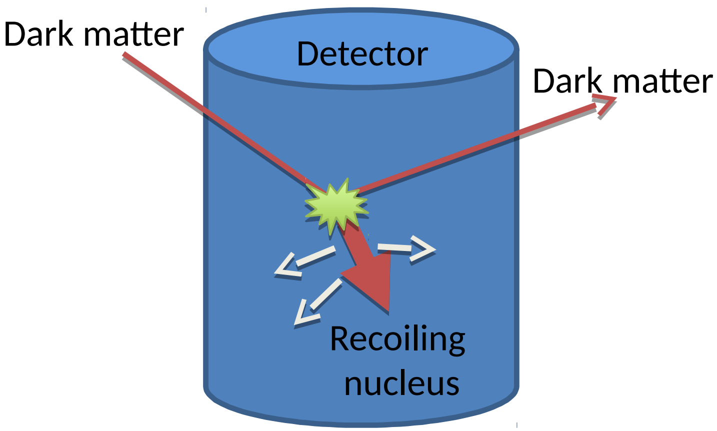
- In the early Universe, in many models DM annihilation sets the relic abundance

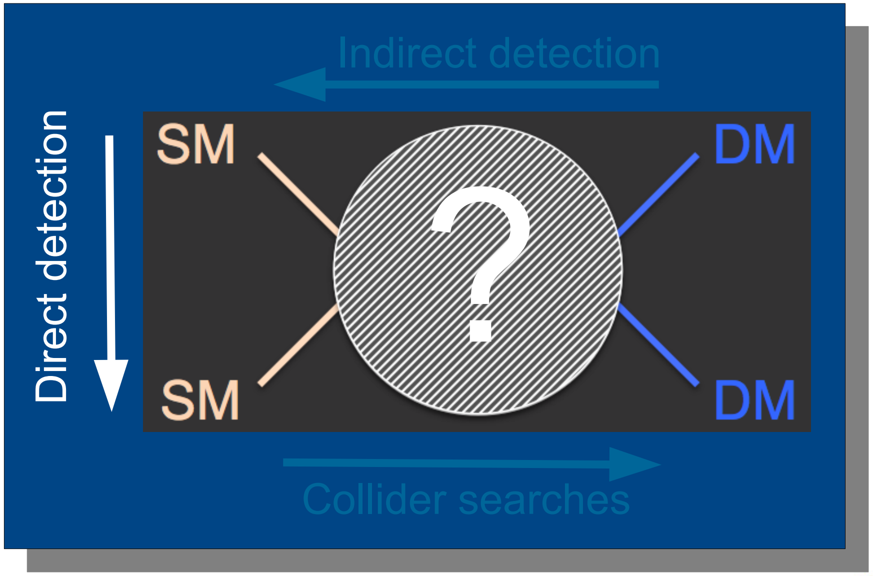
- Ongoing DM annihilations in regions of high DM density
- Indirect detection experiments look for the DM annihilation products



Direct detection

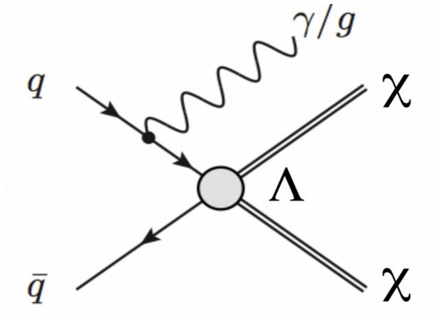
- Dark matter particles from the Galactic halo that pass through the Earth will occasionally scatter off nuclei.
- The resulting recoil energy of the nucleus can be measured in dedicated low background detectors.

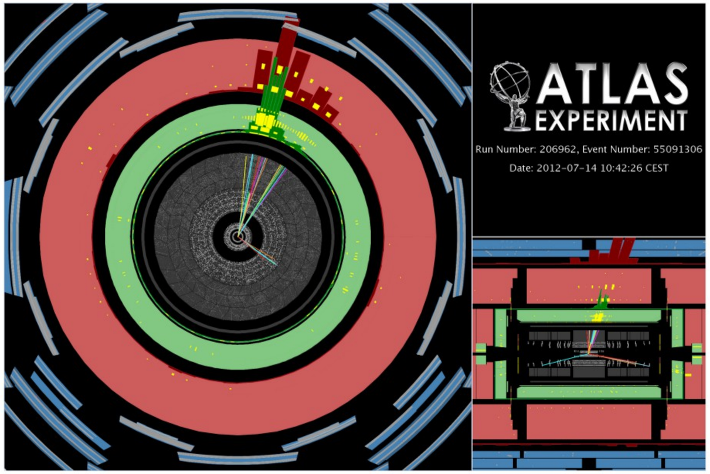


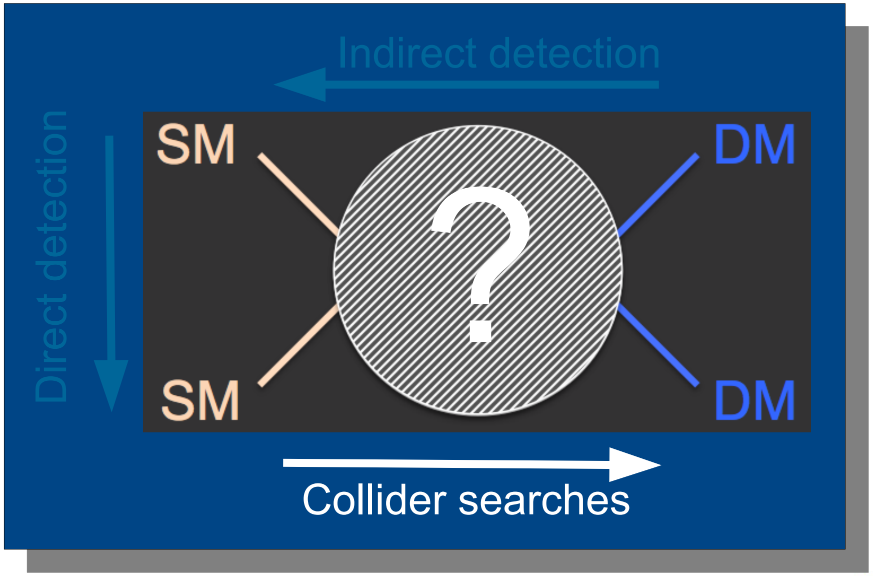


Collider searches

- DM particles produced at colliders can be inferred if other particles (such as jets) are produced in association



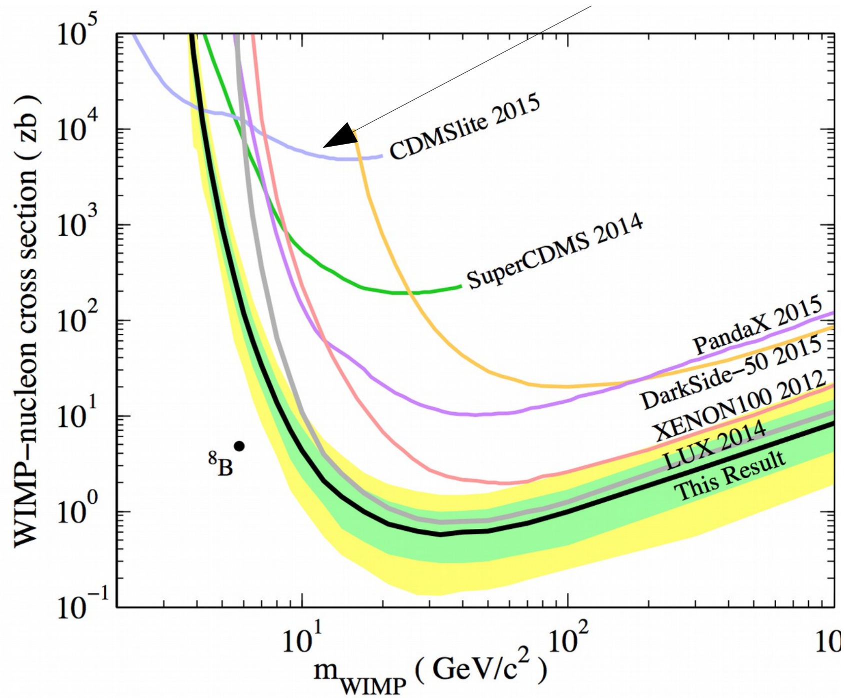




Current experimental status – direct detection

Spin independent

anomalies gone



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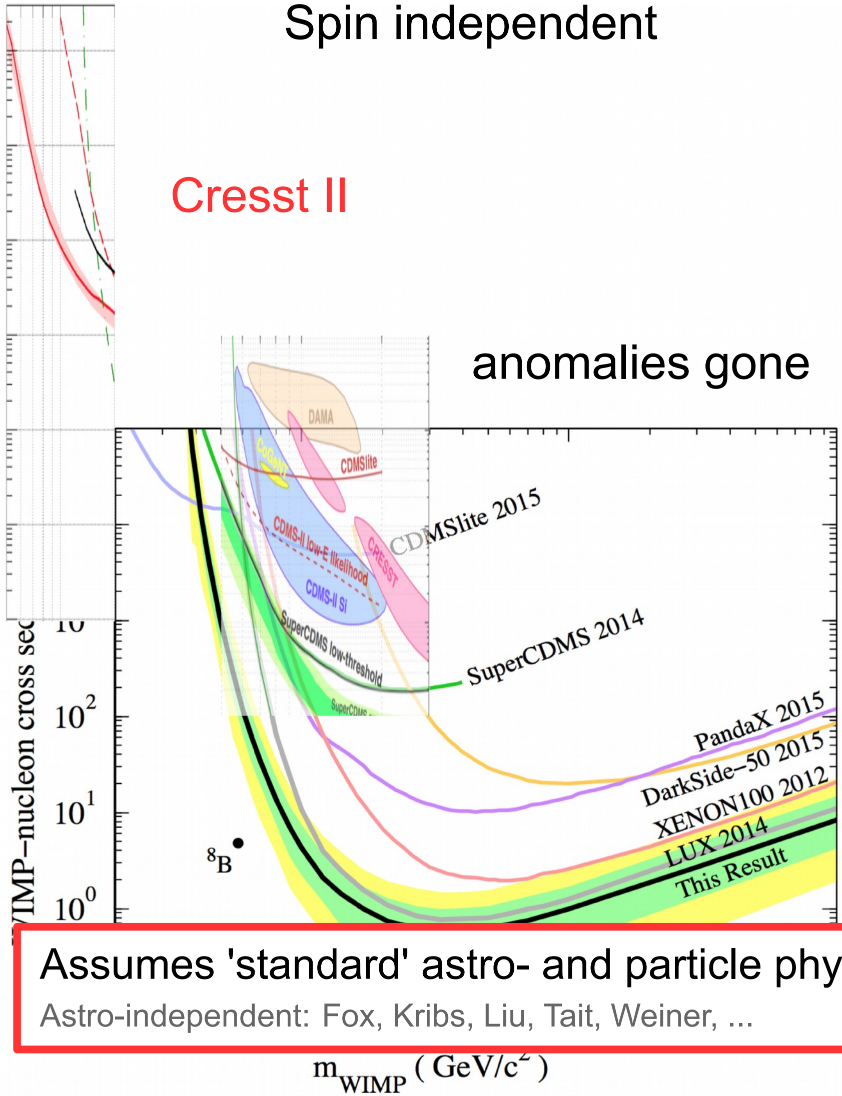
Cresst II

anomalies gone



Assumes 'standard' astro- and particle physics

Astro-independent: Fox, Kribs, Liu, Tait, Weiner, ...

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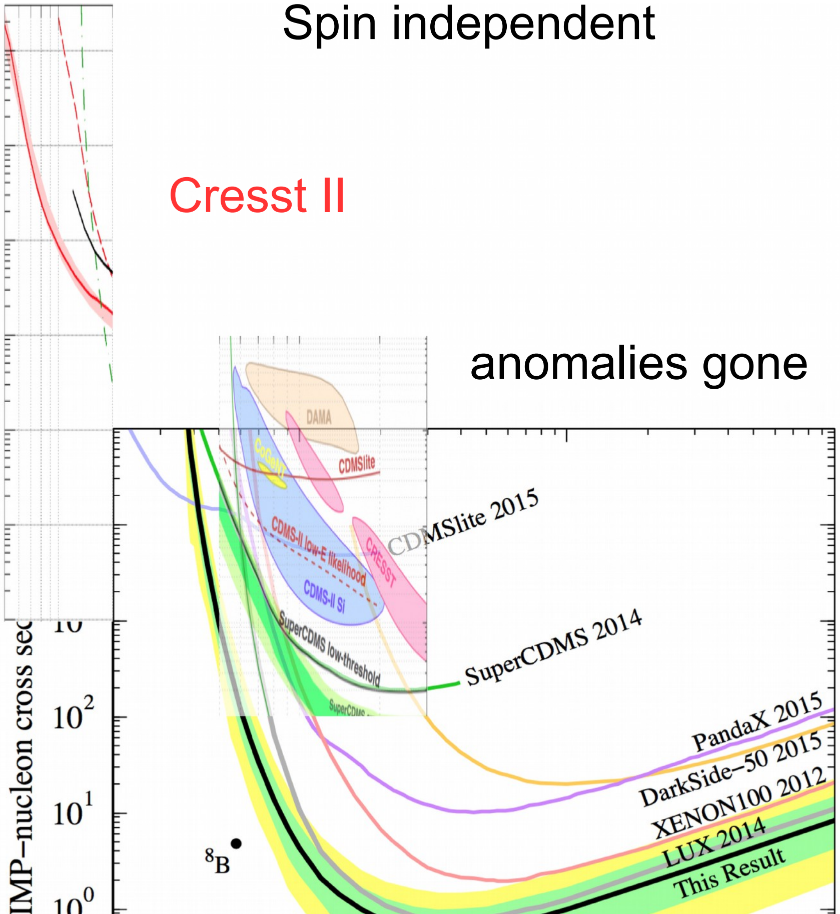

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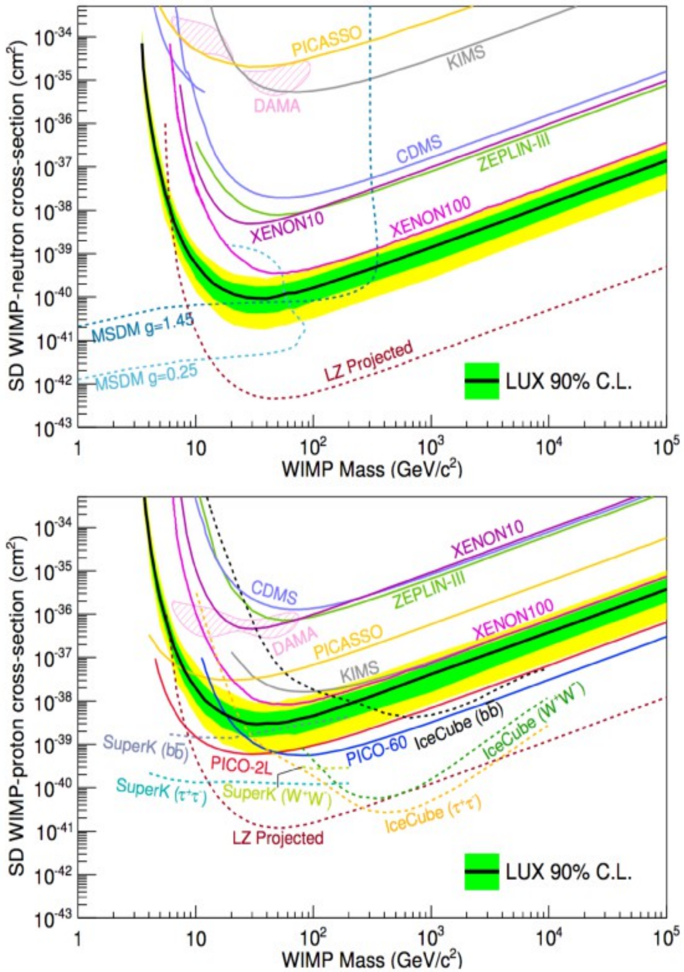

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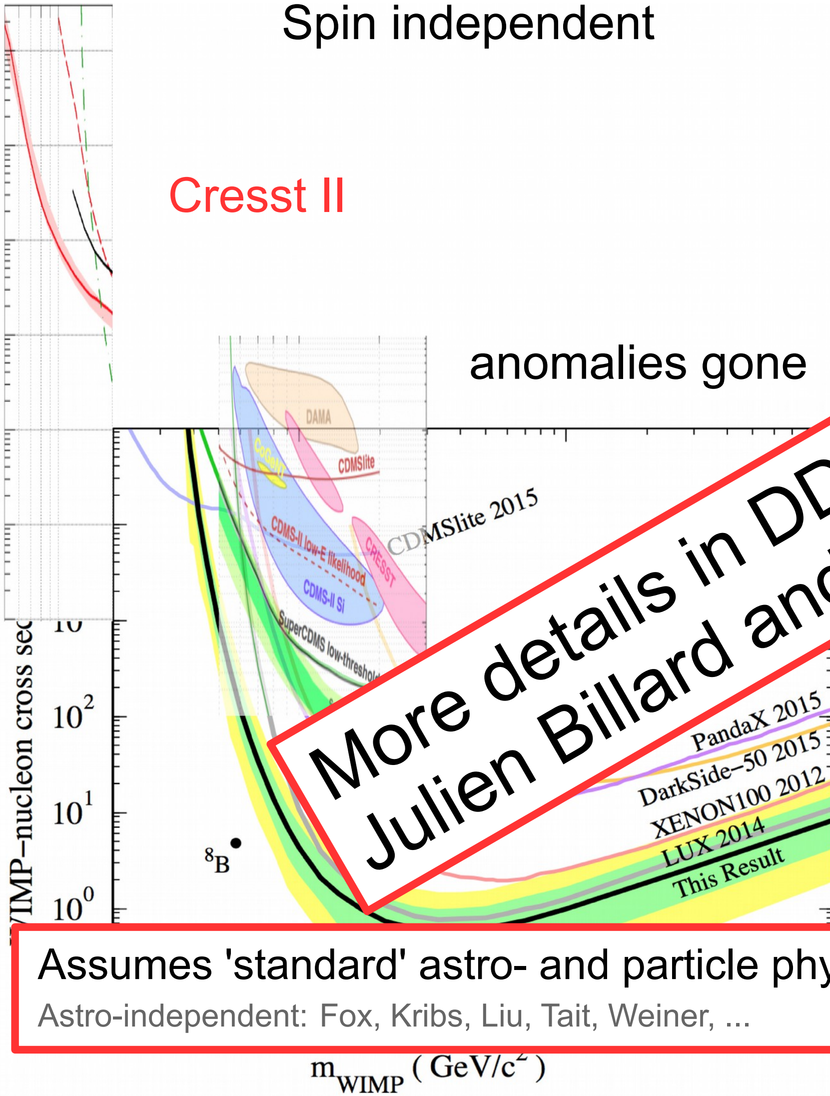

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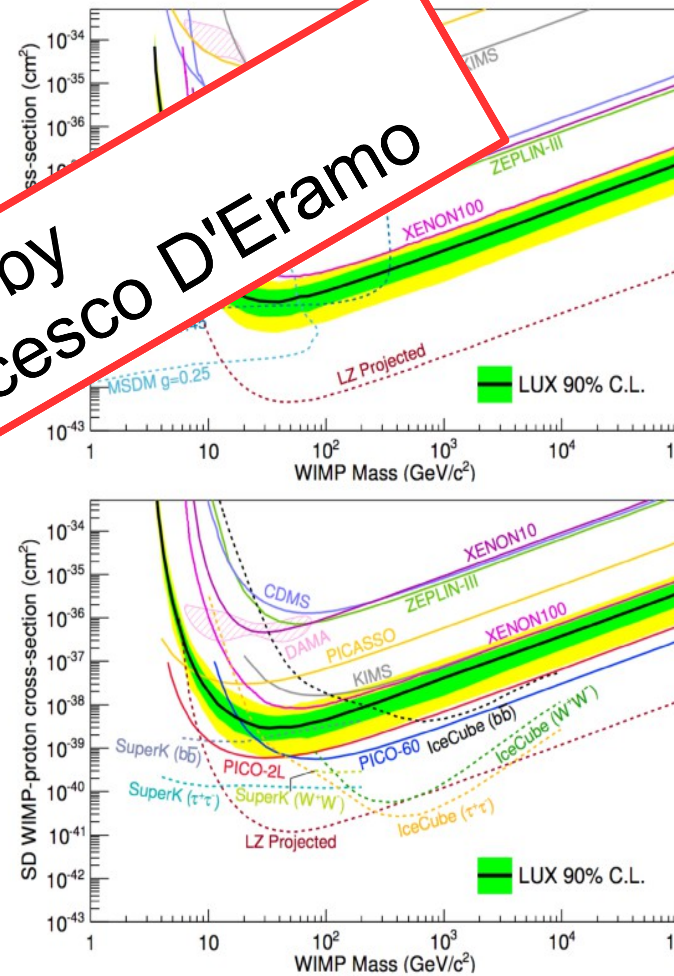
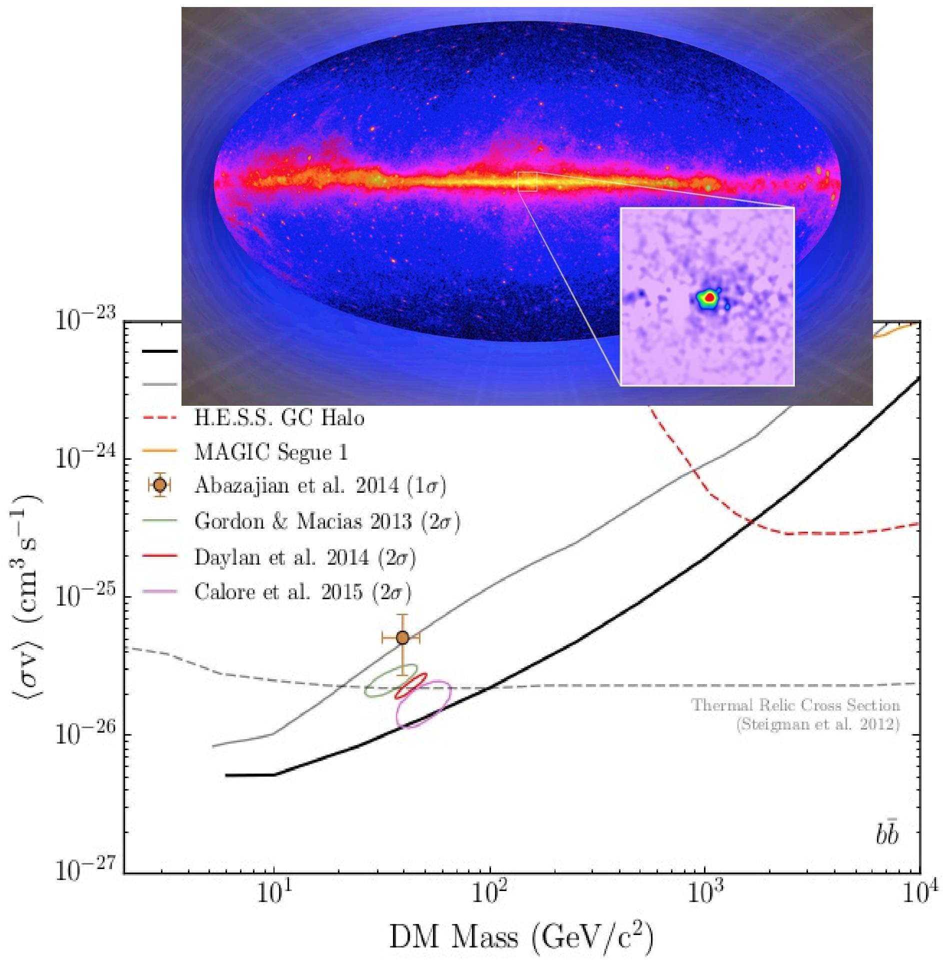


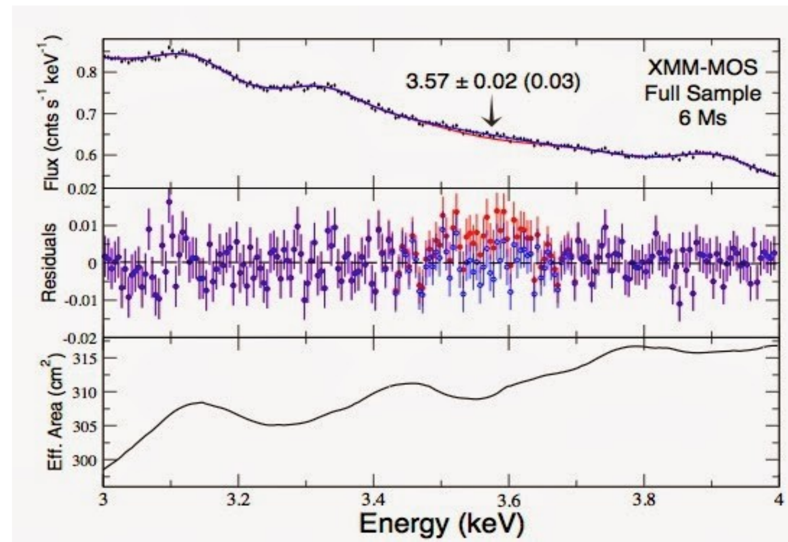
More details in DD talks by Julien Billard and Francesco D'Eramo

Current experimental status – indirect detection

Galactic centre excess



3.5 keV line



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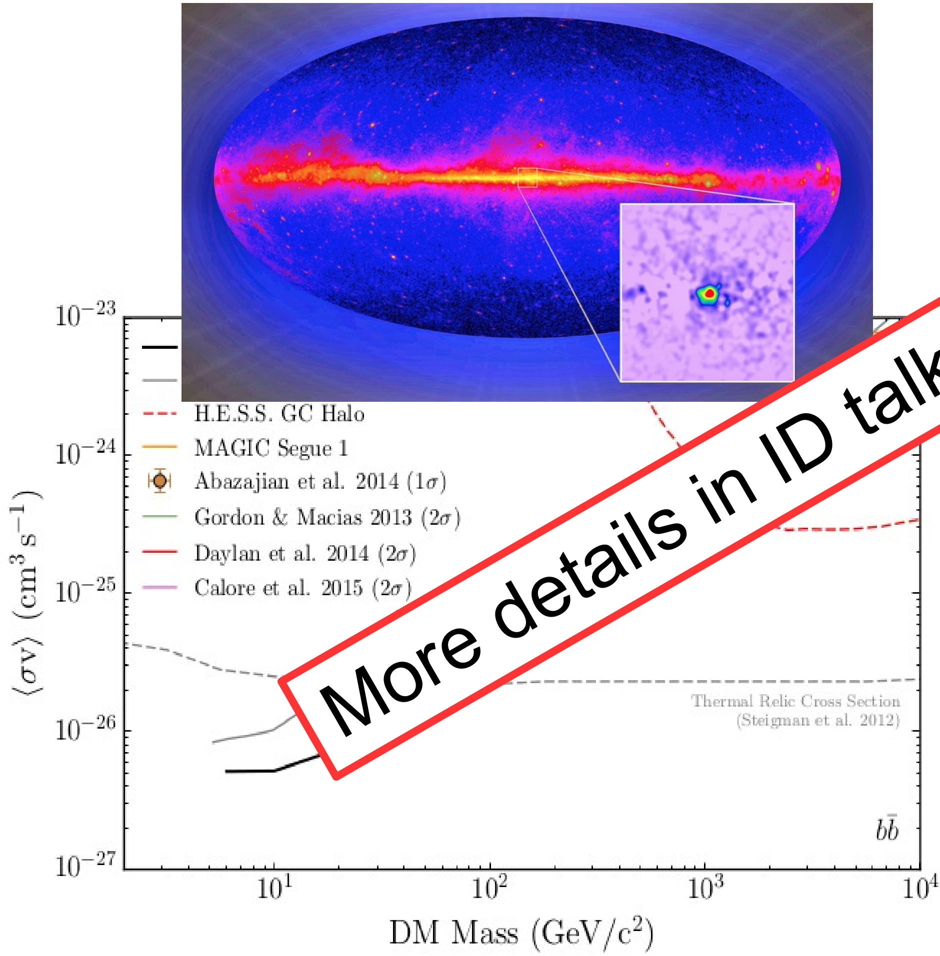

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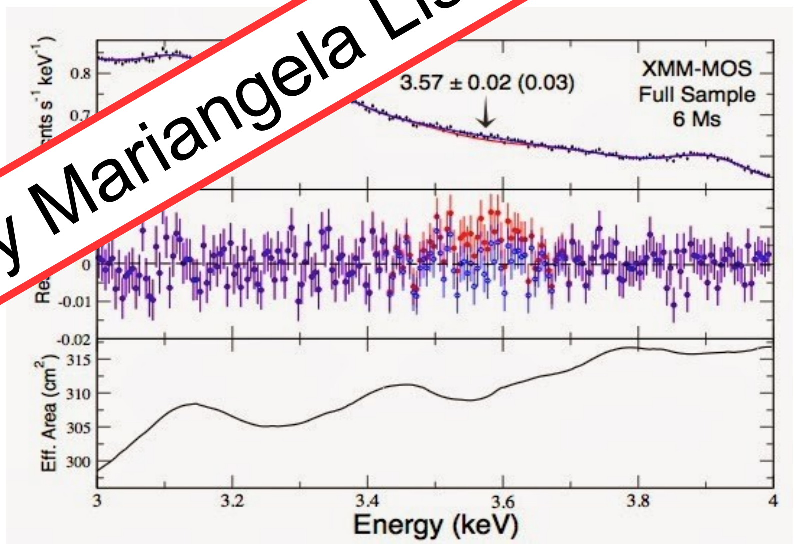


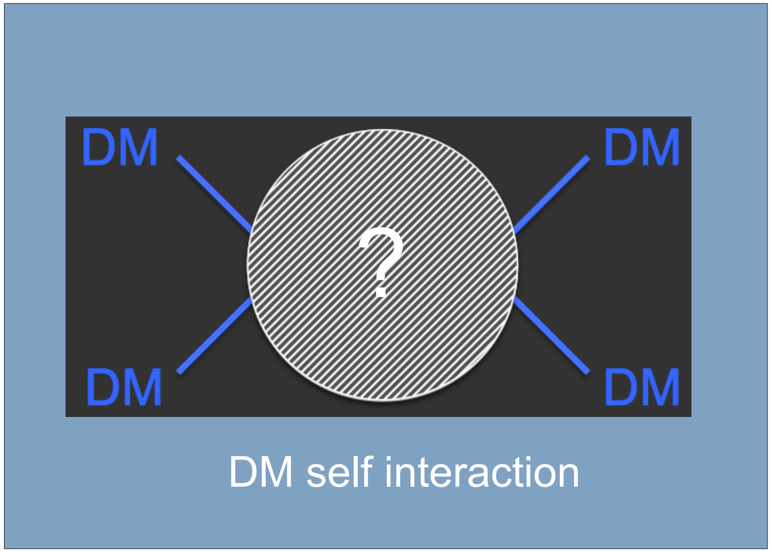
More details in ID talk by Mariangela Lisanti

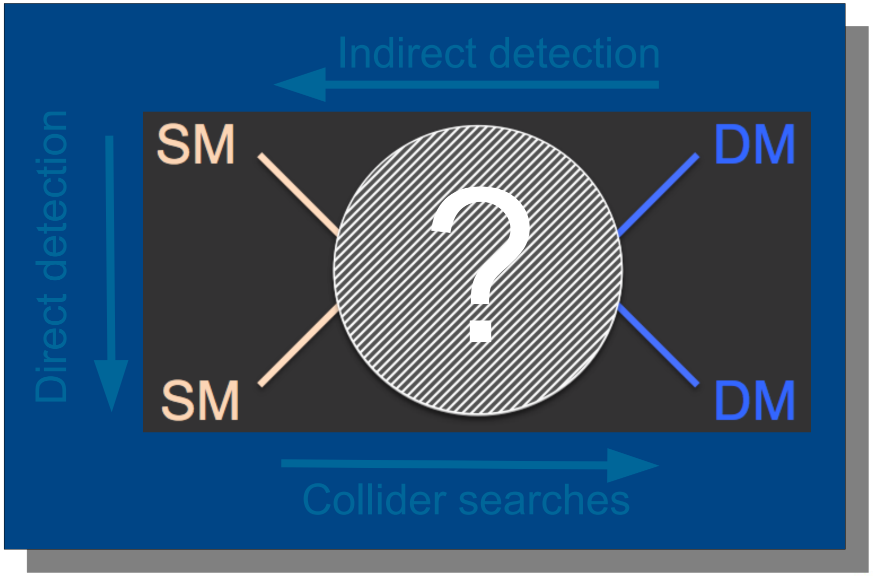
Current experimental status – colliders

Rest of the conference, starting in 5 minutes ;)

DM self interactions

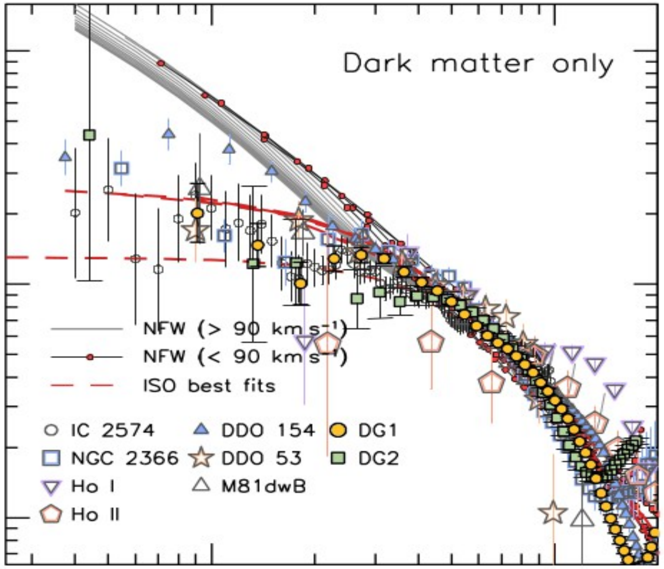
- A fourth way to look for dark matter...





Self interacting dark matter - cosmology

- The collisionless cold dark matter paradigm fits perfectly at large scales
- There are however various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales
- Example
  - Cusp-vs-core problem



- DM self-interactions may solve these problems (but baryons...)

Self interacting dark matter – particle physics

- Dark sector often assumed to be simple, mainly because we don't know much…
- Large self-interactions are natural in models with a complex dark sector (e.g. dark SU(N)), or light mediators

- Bonus: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.

How large a cross section?

- To be observable on astrophysical scales, self-interaction cross sections have to be large, typically

$$\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns/GeV}$$

- The nucleon nucleon scattering cross section ~20b at low energies
- The typical cross section of a WIMP is 20 orders of magnitude smaller!

- Potential impact:

  Evidence for DM self-interactions on astrophysical scales would rule out most popular models for DM, such as supersymmetric WIMPs, gravitinos, axions…

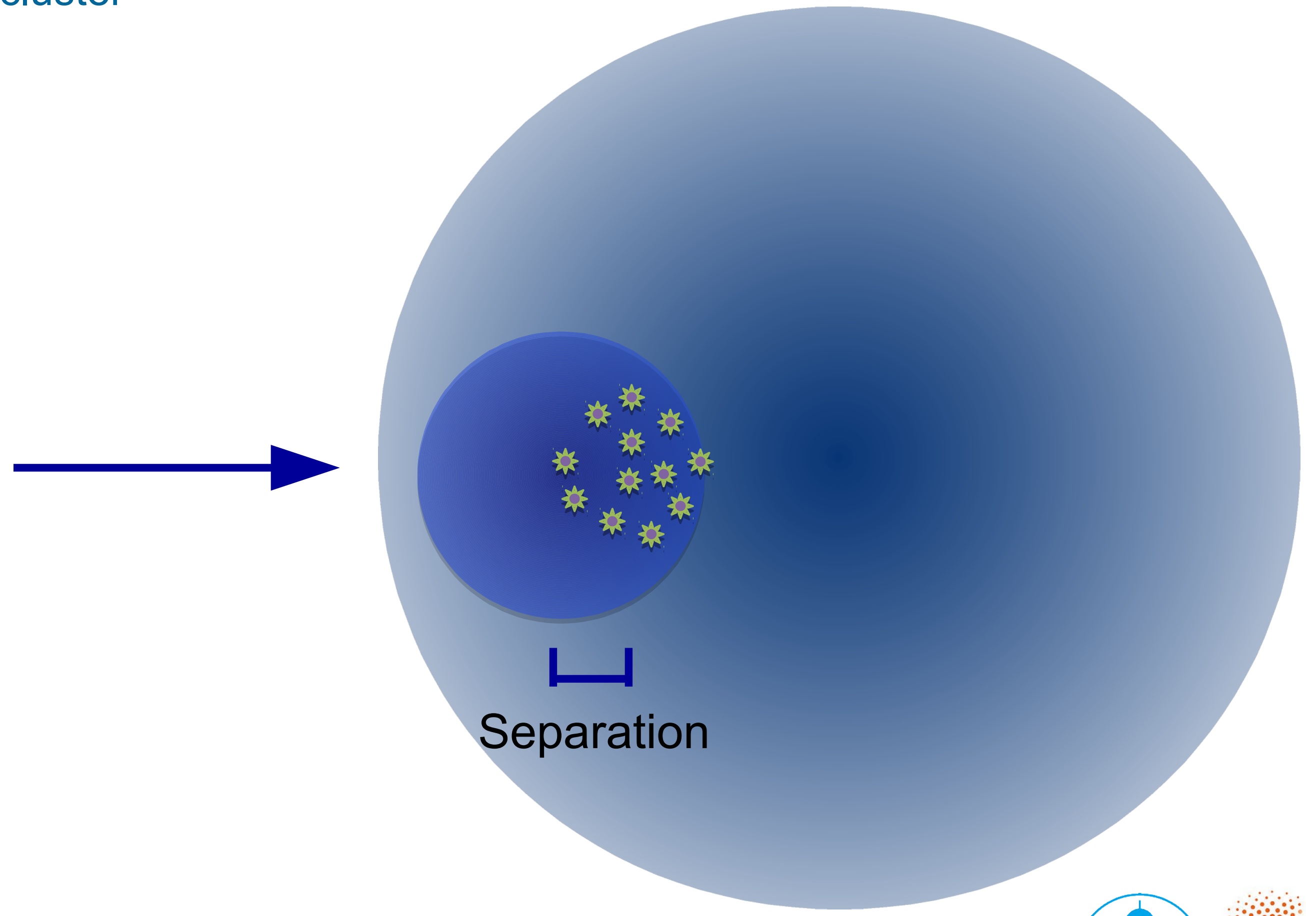
Astrophysical constraints

- Various astrophysical observations give constraints on the DM self-interaction cross section, e.g.
  - Subhalo evaporation rate
  - Merging galaxy clusters

- Rough bound: σ/m_χ < 1 cm^2/g

Smoking gun?

- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster



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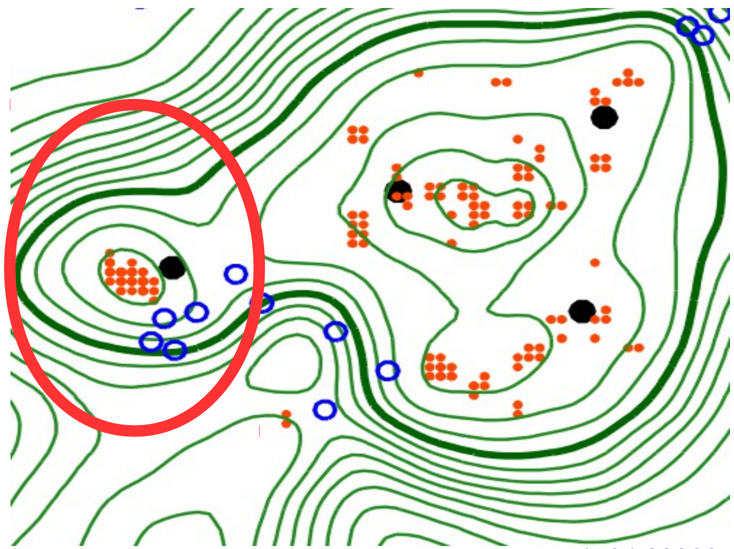
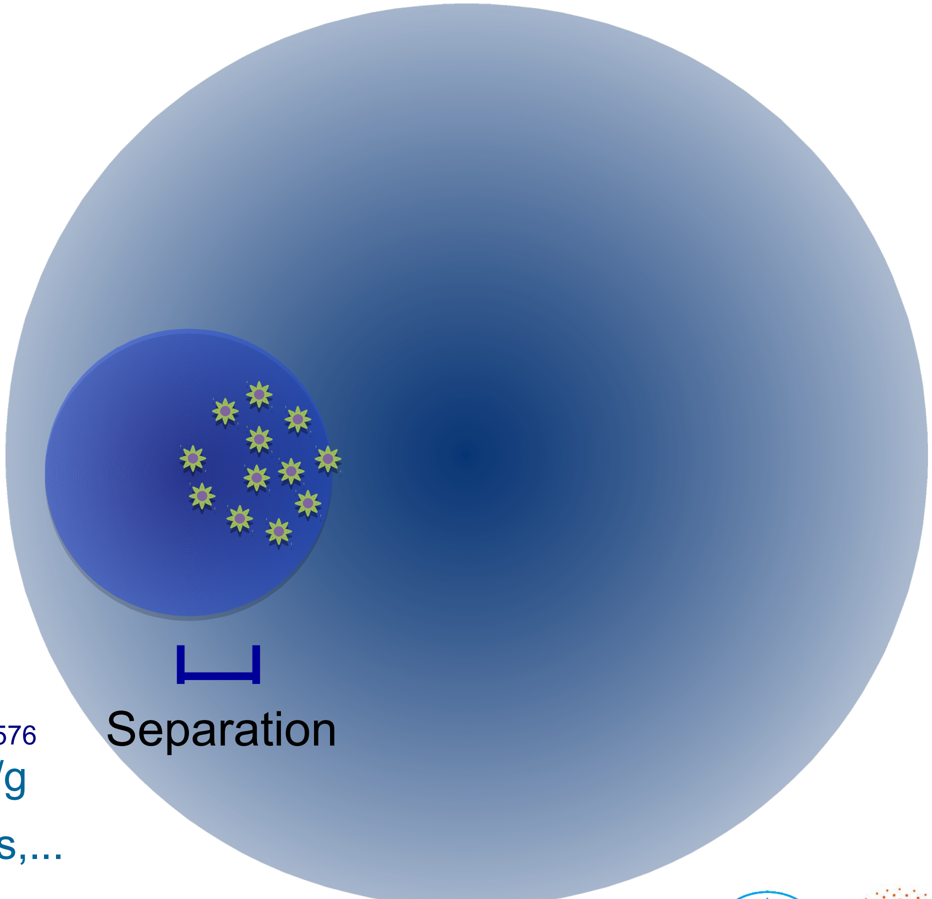


1504.03388



- Recently been **observed in A3827** (offset ~1.6 kpc at ~ 3σ) 1504.06576
- Required cross section: $\sigma/m_\chi \sim 1.5$ cm²/g
- If true would rule out neutralinos, axions,...

Summary and overview

Tentative signals	
Collider searches	✘
Direct detection	✘
Indirect detection	✔
Self-interactions	✔

WIMPs	
Collider searches	✔
Direct detection	✔
Indirect detection	✔
Self-interactions	✘

FIMPs	
Collider searches	✔
Direct detection	✘
Indirect detection	✘
Self-interactions	✘

ADM	
Collider searches	✔
Direct detection	✔
Indirect detection	✘
Self-interactions	✔

Axions
✔
✔
✘
✘

Summary and overview

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Axions
✔
✔
✘
✘

Exciting times ahead of us!