Dark matter – theoretical overview.

Kai Schmidt-Hoberg

HELMHOLTZ ASSOCIATION

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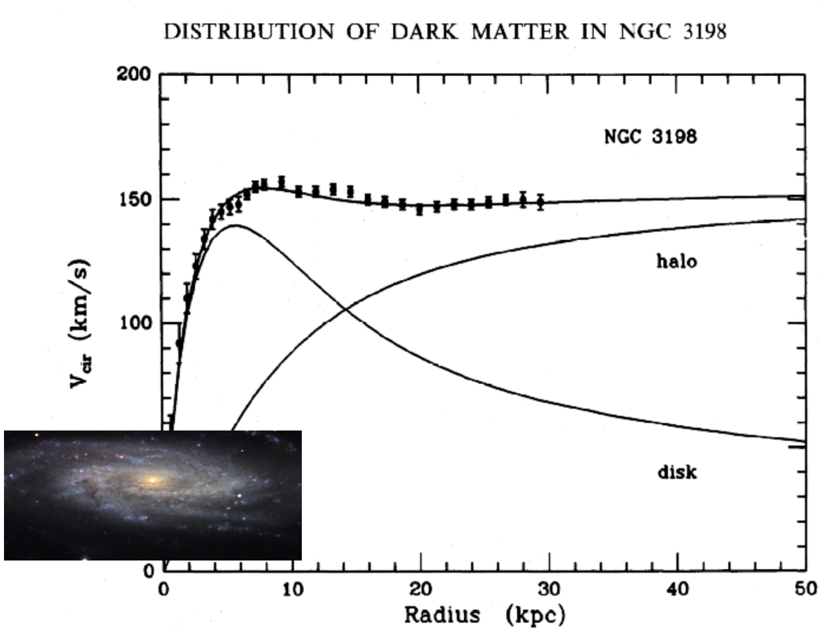
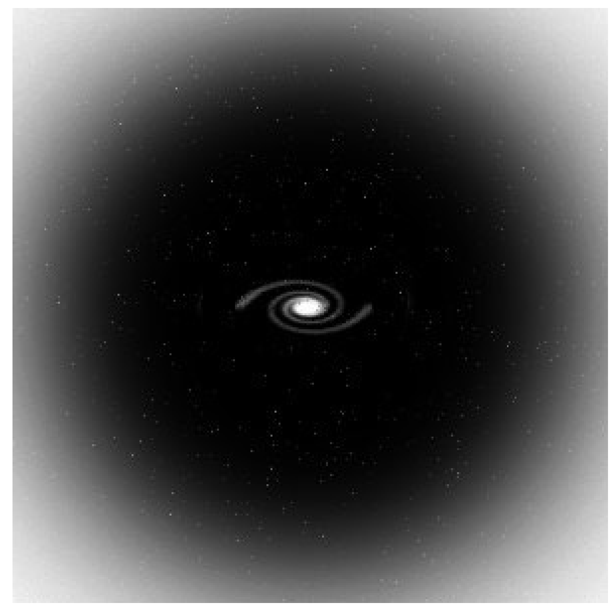
DESY

Evidence for dark matter.

Compelling evidence for dark matter on all astrophysical scales:

- Galactic scales: Rotation curves of Galaxies





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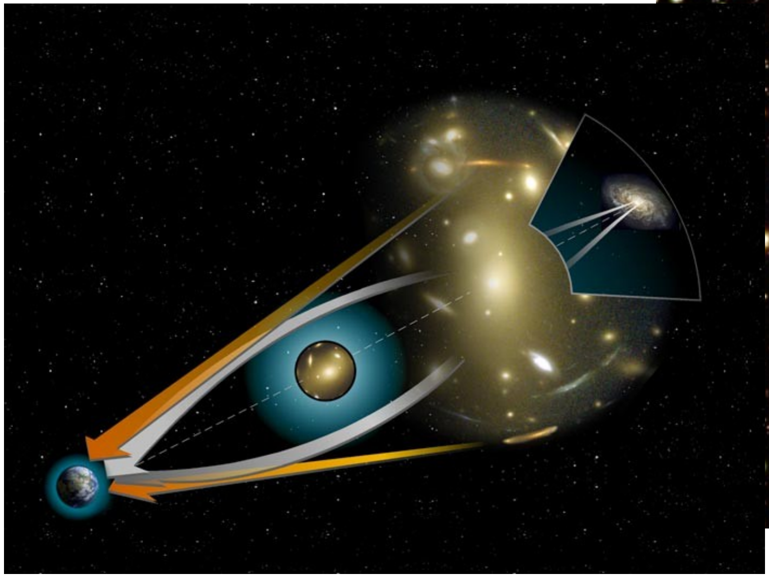
- Cluster scales: Gravitational lensing



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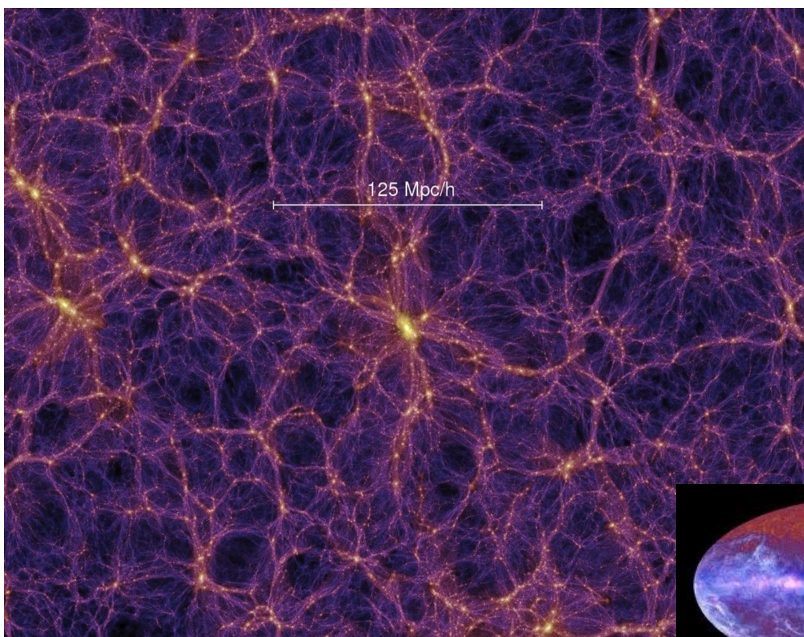
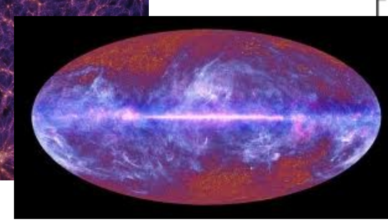
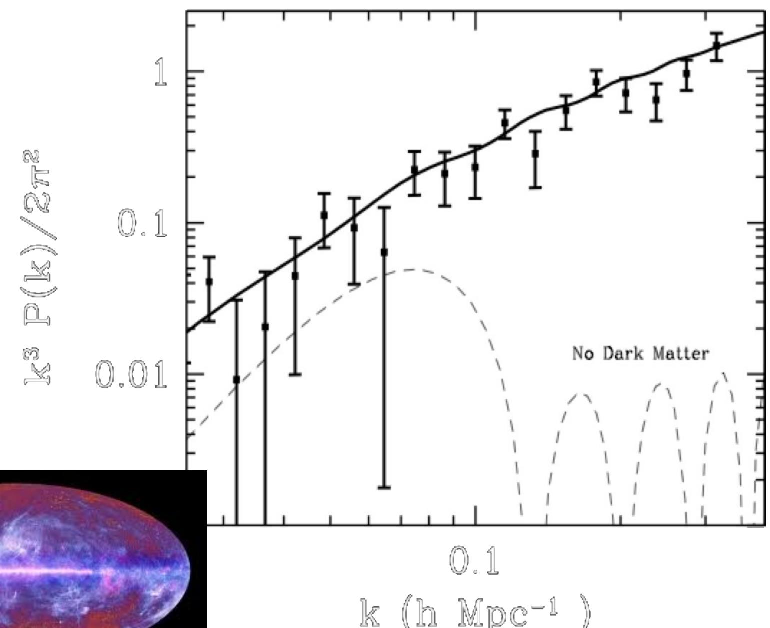
- Cosmological scales: Large scale structure (N body simulations) & CMB







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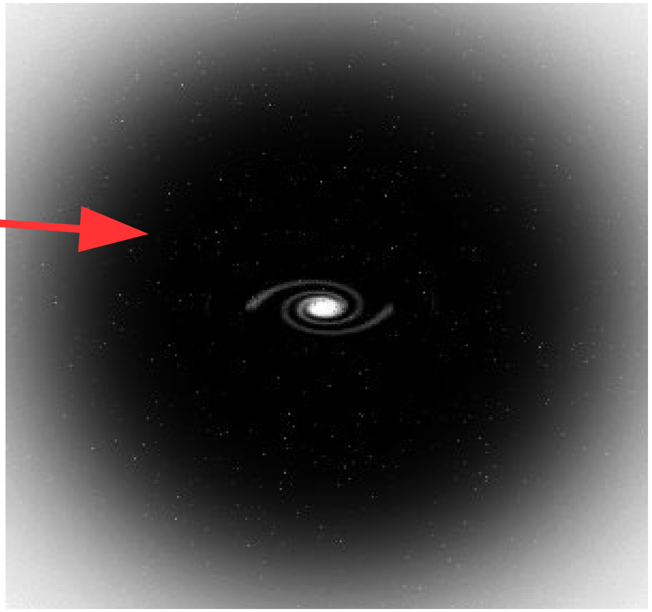
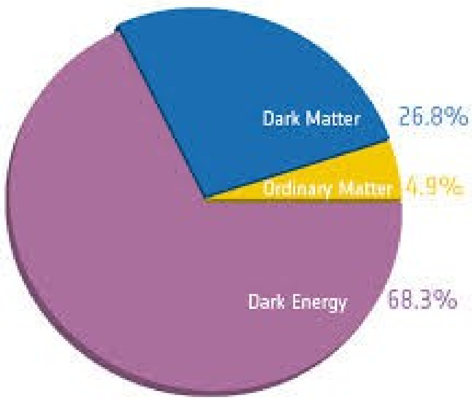
What is it ???

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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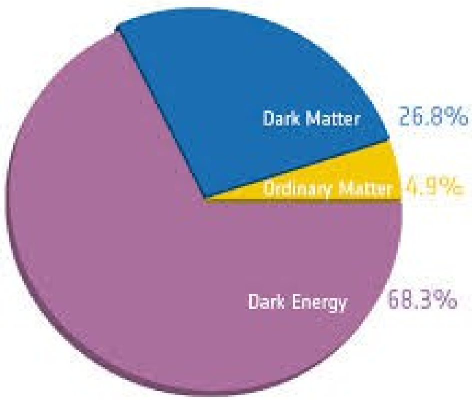


Candidate within the Standard Model of particle physics?

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

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

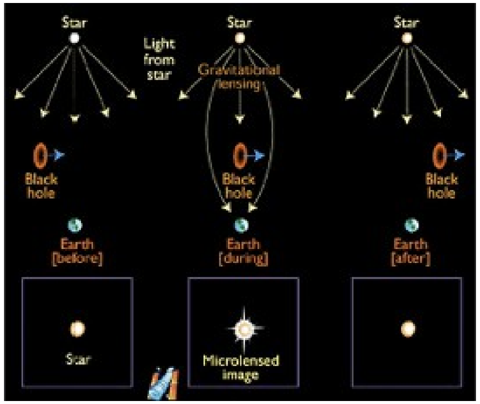
Physics beyond the Standard Model !

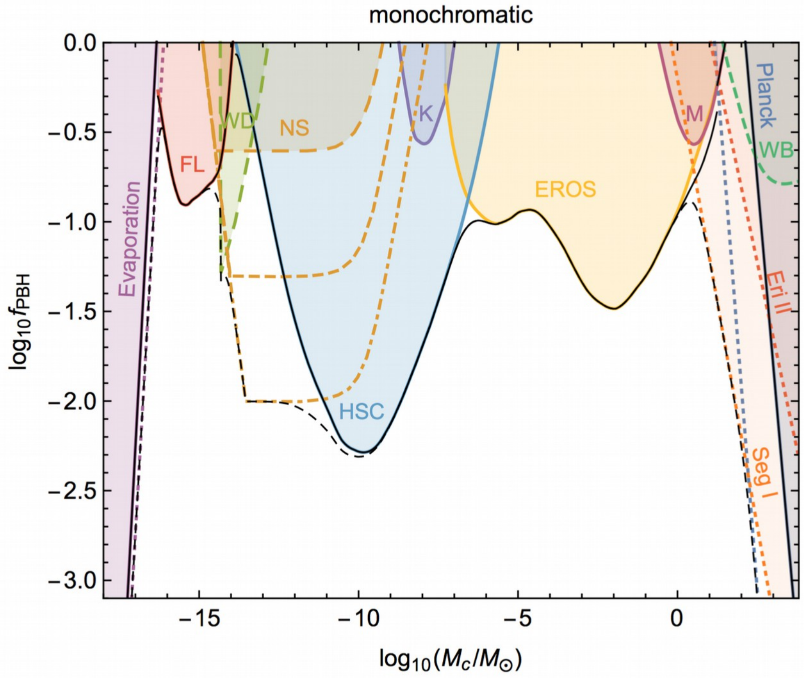
Many candidates (theorists are inventive...)

Really BSM?

Primordial black holes

- Could form in early universe (but not really SM…)
- Too light black holes will have Hawking evaporated. Slightly heavier ones should give a signal in gamma rays.
- MACHO searches (via microlensing) and CMB give **very strong constraints**
- **basically excluded** for monochromatic case.

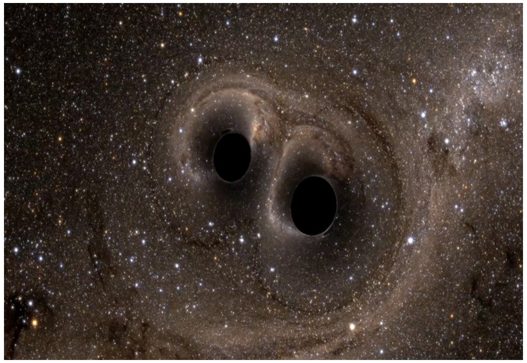


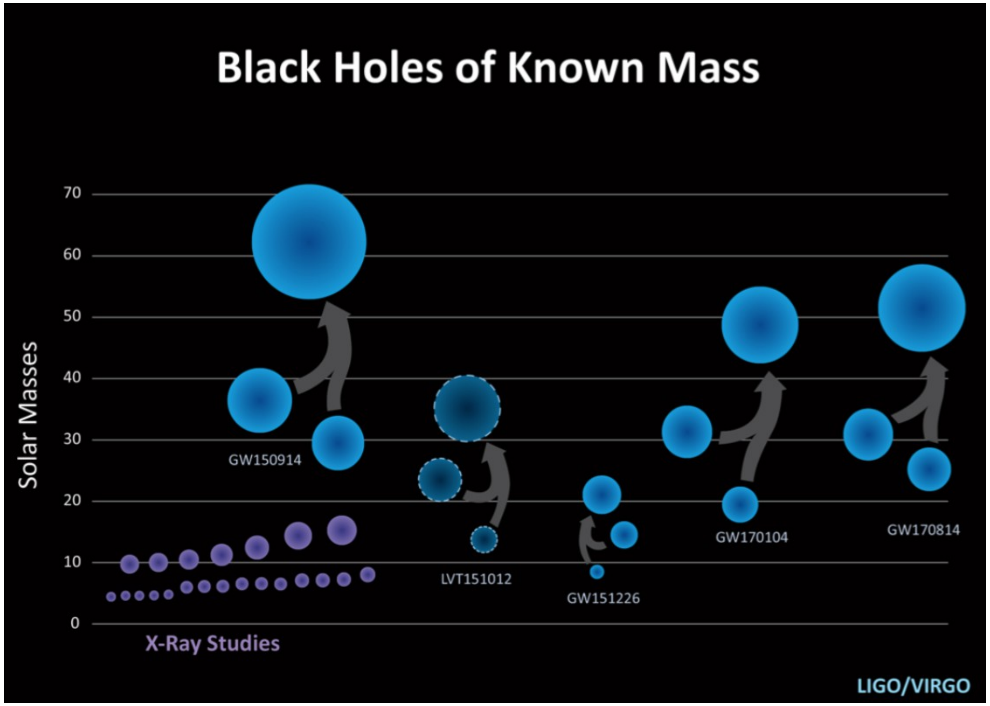


Really BSM?

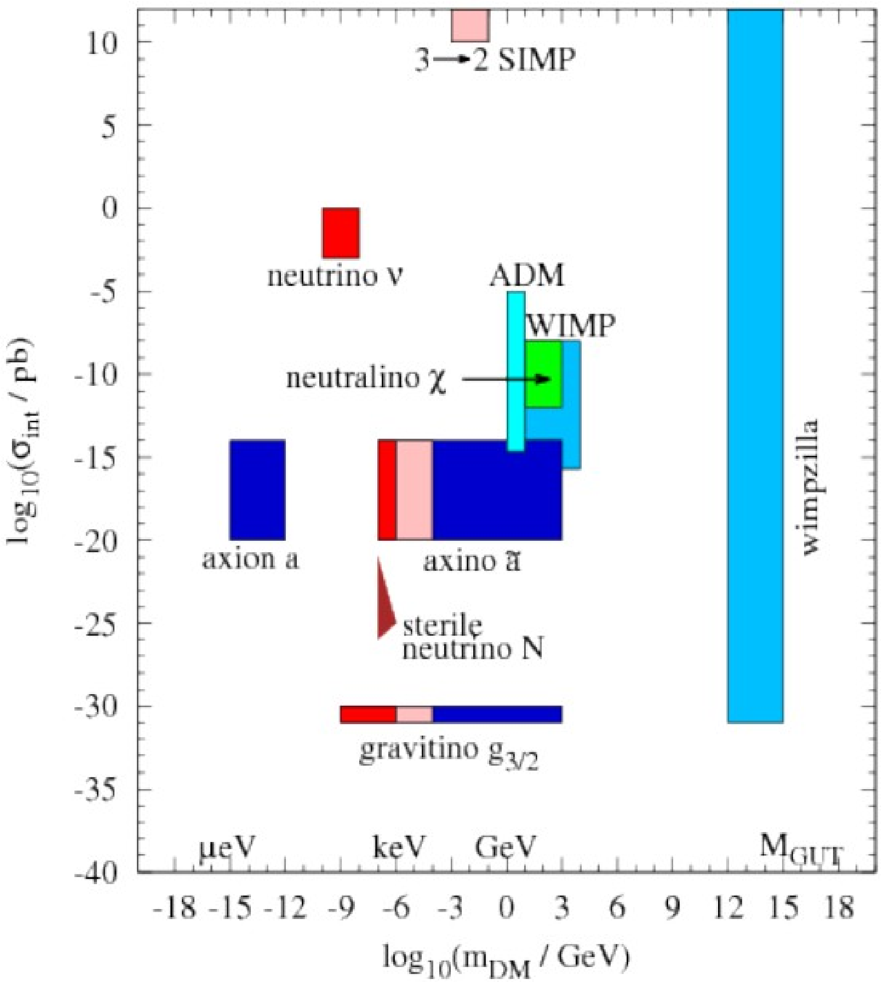
Primordial black holes

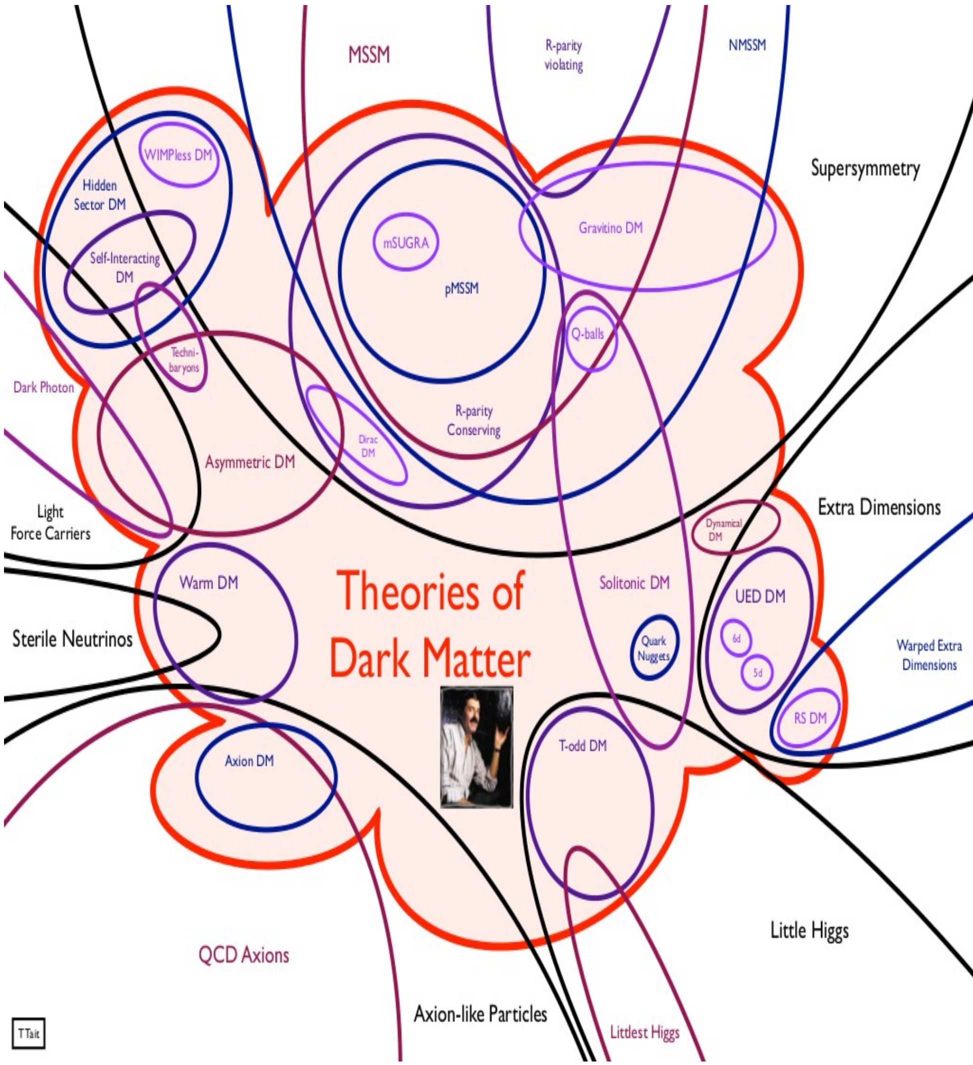
- Nevertheless **renewed interest** since **LIGO** results
- In fact still quite interesting...
- Constraints weaken for broad mass distribution (and clustering)
- Merger rate roughly consistent with DM abundance
- Measured spins rather low → spherical collapse?
- Could explain SMBHs in early universe
- Smoking gun? Merger with mass below the Chandrasekhar limit





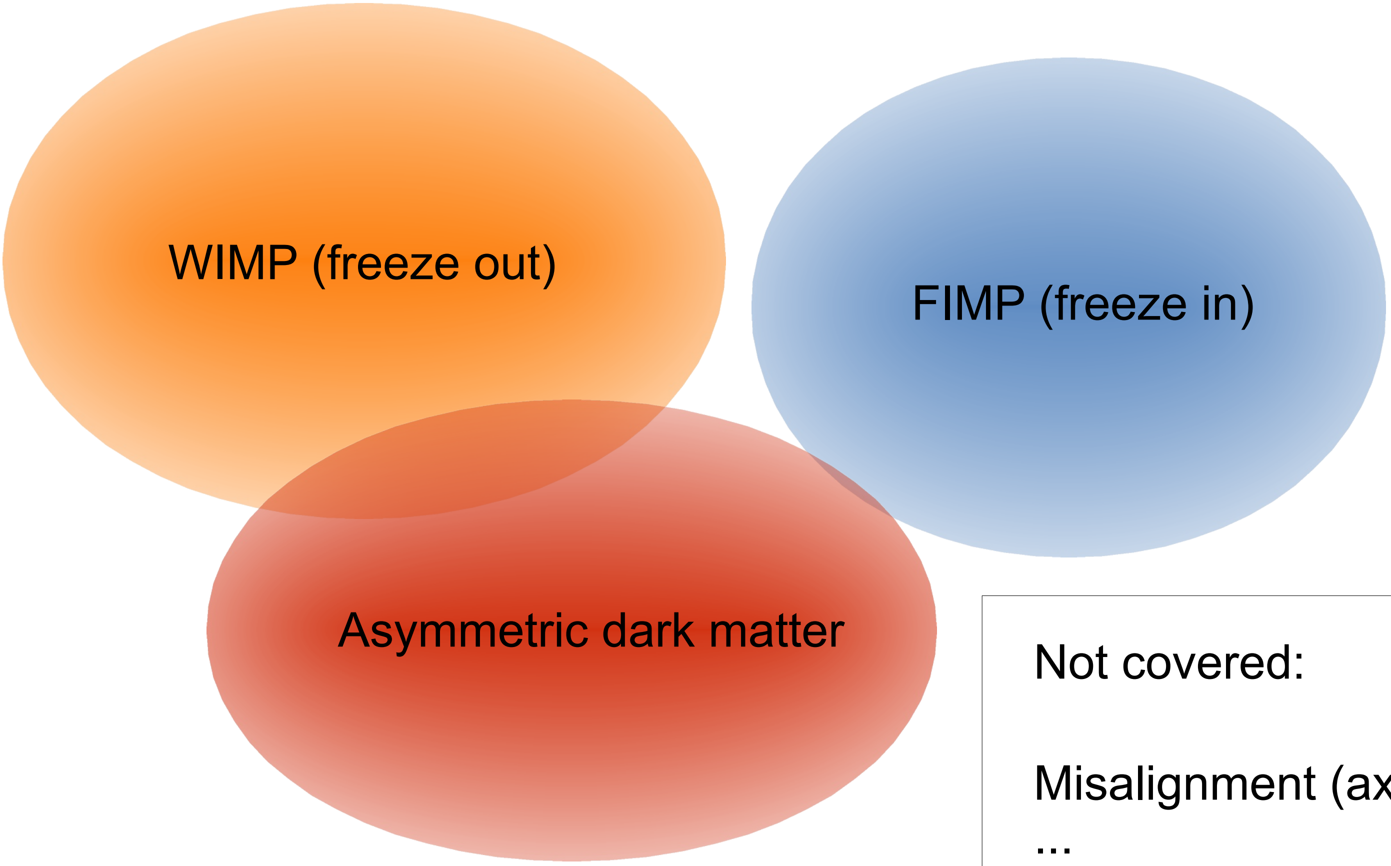
Particle physics candidates





Particle physics candidates

- Here: order by production mechanism



Not covered:

Misalignment (axion)
...

Freeze out - WIMPs

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

$$XX \leftrightarrow SM\ SM$$

(2) Universe cools:

$$XX \longrightarrow SM\ SM$$

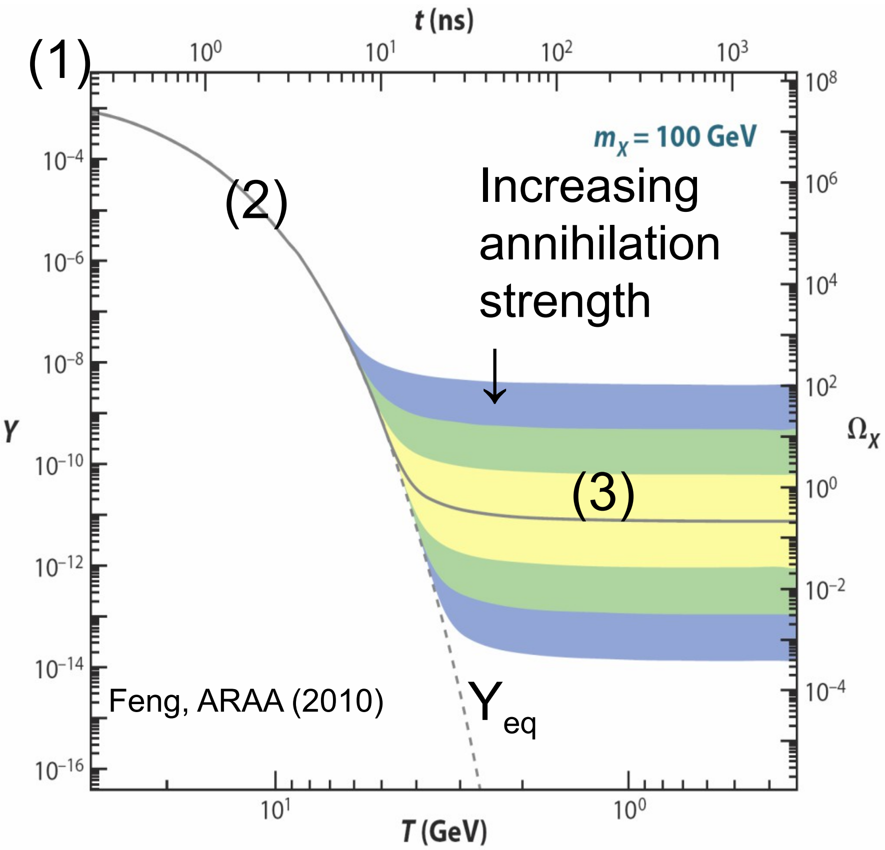
(3) Universe expands:

$$XX \qquad SM\ SM$$

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



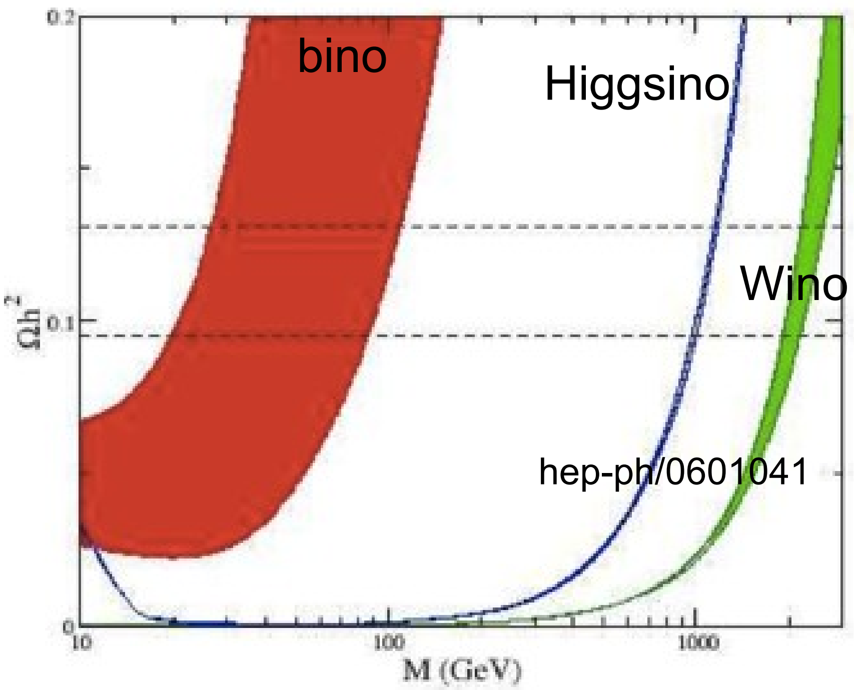
The prototypical WIMP – a neutralino

- Weak scale: expect new physics for other reasons → SUSY
- MSSM neutralino - the prototypical WIMP
- How naturally can the dark matter relic abundance be achieved?

Bino: Typically need to finely tune relic density via coannihilations or resonances :-(

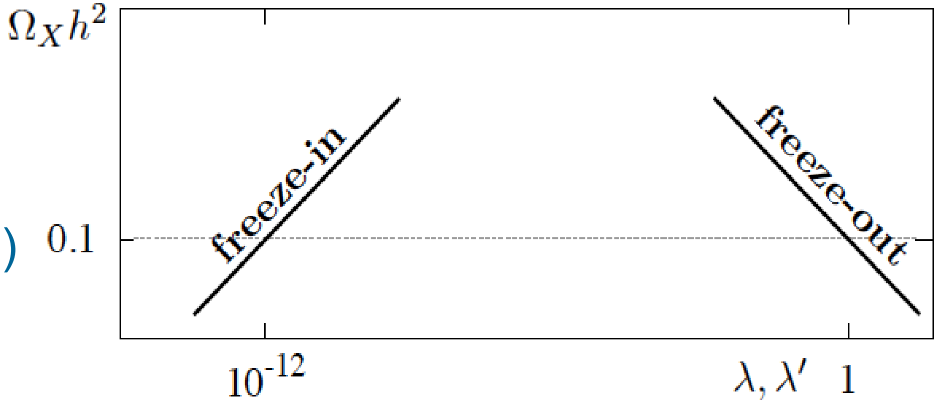
2-3 TeV Wino challenged by ID
Lisanti et al 1307.4082

1 TeV Higgsino looking good :-)



FIMPs and SuperWIMPs

- 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)

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

What could be learned?

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

Newton's constant and SUSY breaking scale!

Asymmetric dark matter

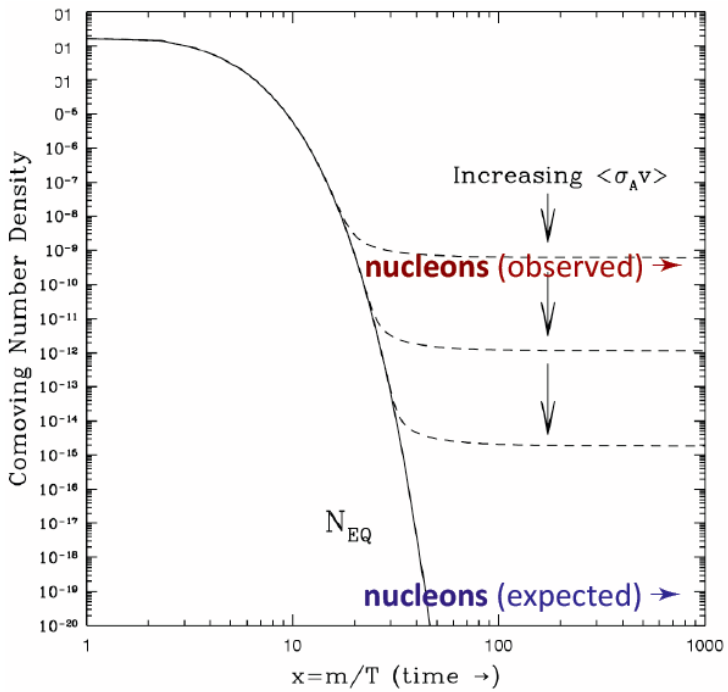
Why is the dark matter abundance so similar to that of baryons?
Do they have the same origin?

Apply our freeze out calculation to baryons:

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

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

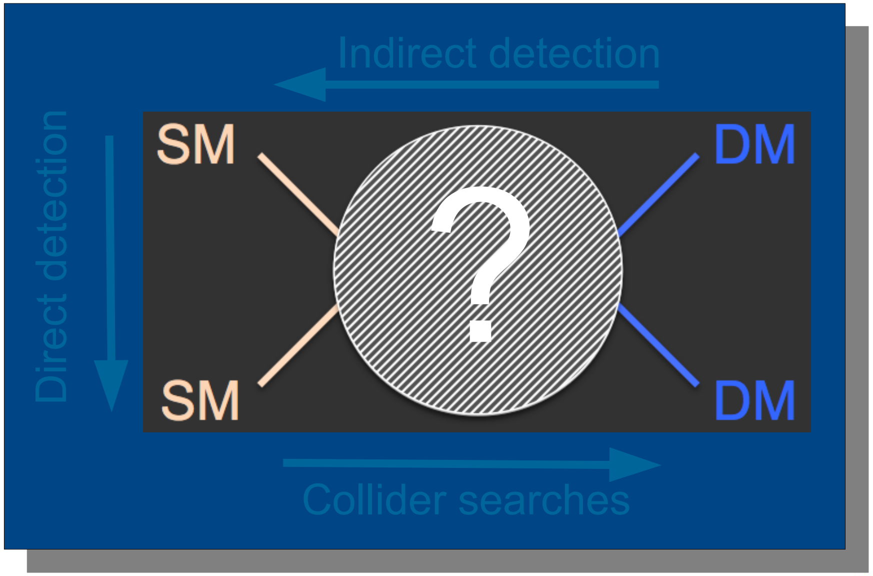
$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$



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...

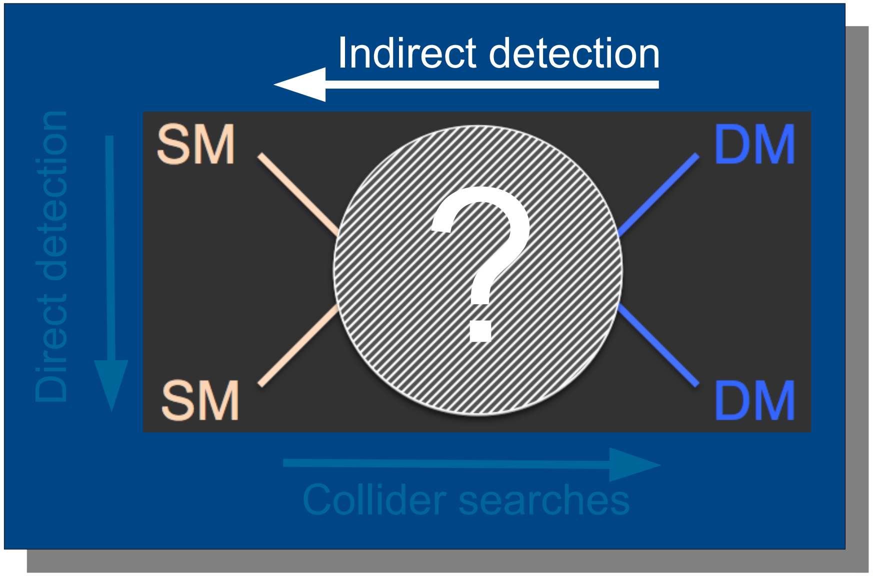
How to test it?



Dark matter annihilation

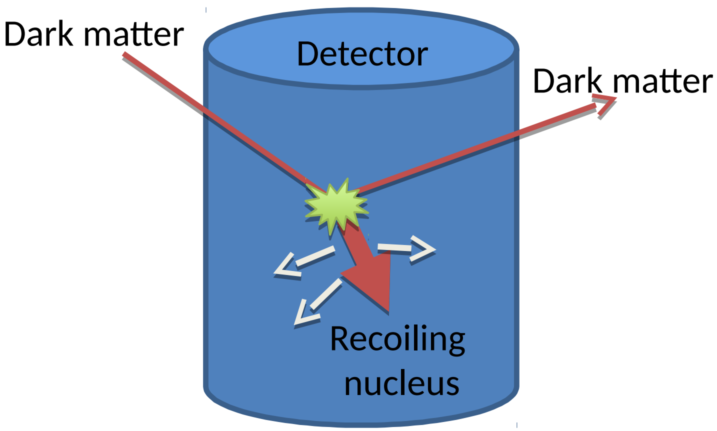
- In the early Universe, in many models DM annihilation sets the relic abundance

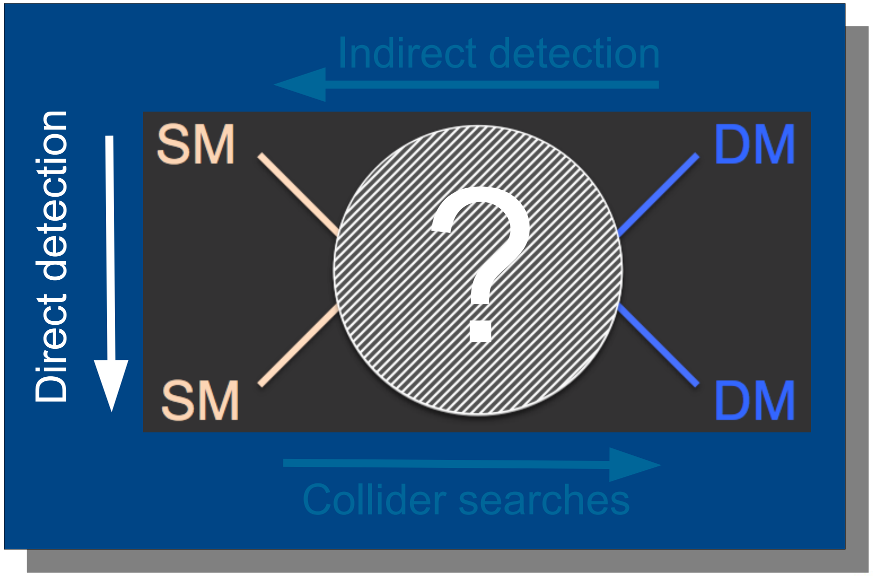
- Ongoing DM annihilations in regions of high DM density
- Indirect detection experiments look for the DM annihilation products



Direct detection

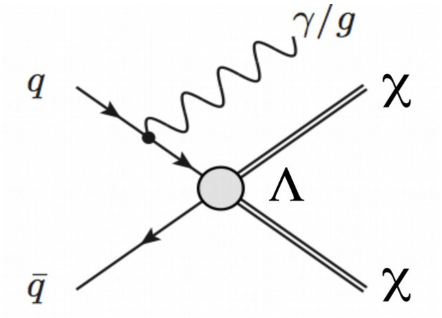
- Dark matter particles from the Galactic halo that pass through the Earth will occasionally scatter off nuclei.
- The resulting recoil energy of the nucleus can be measured in dedicated low background detectors.

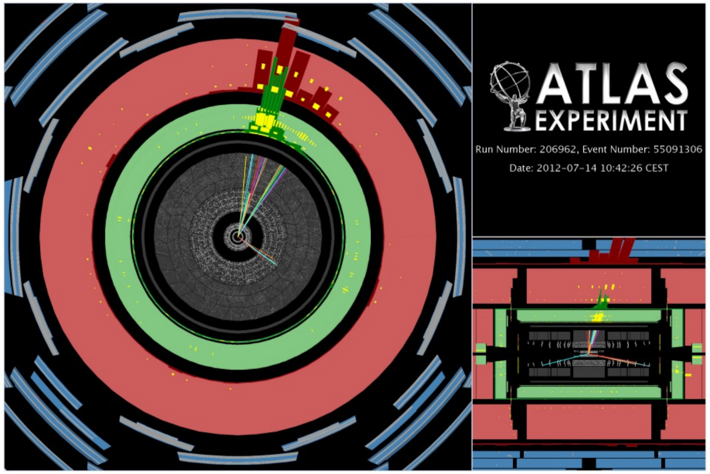


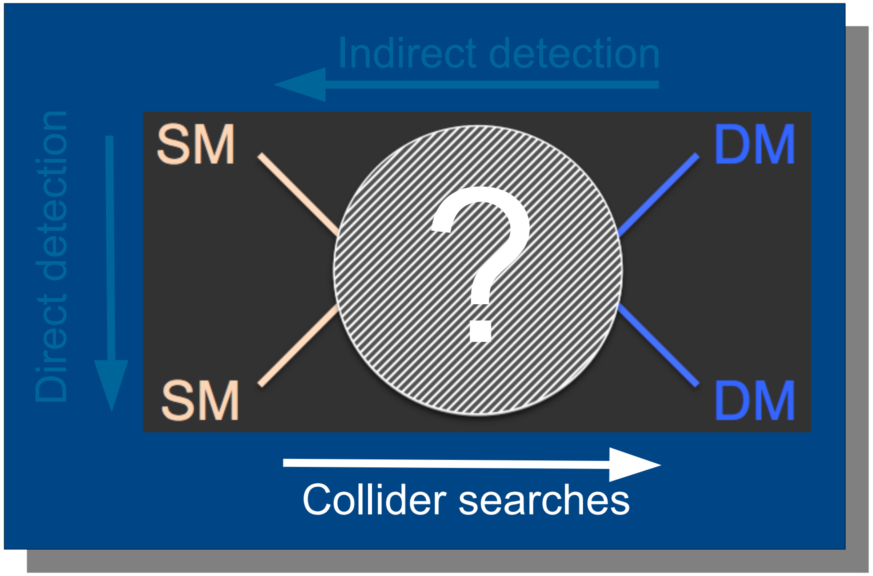


Collider searches

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



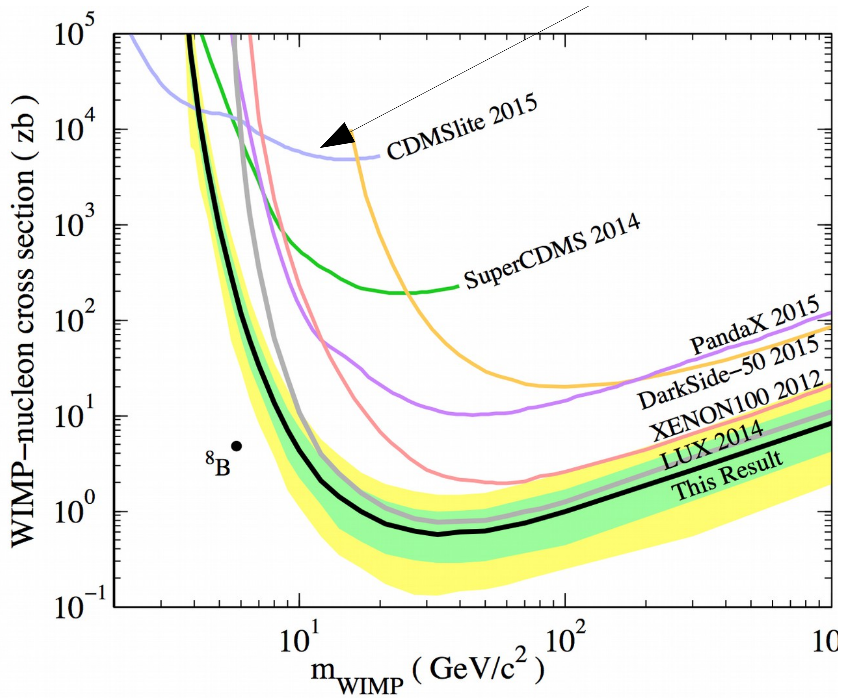


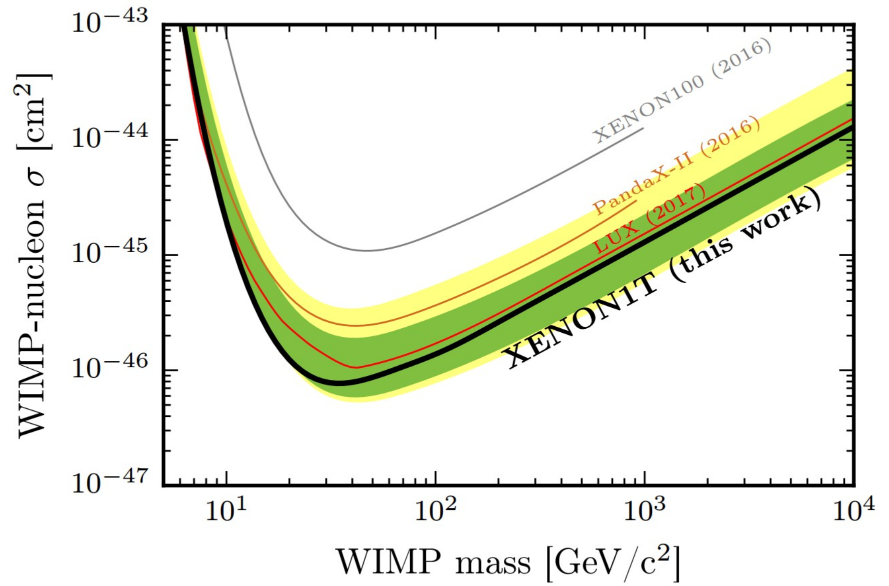


Current experimental status – direct detection

Spin independent

anomalies gone





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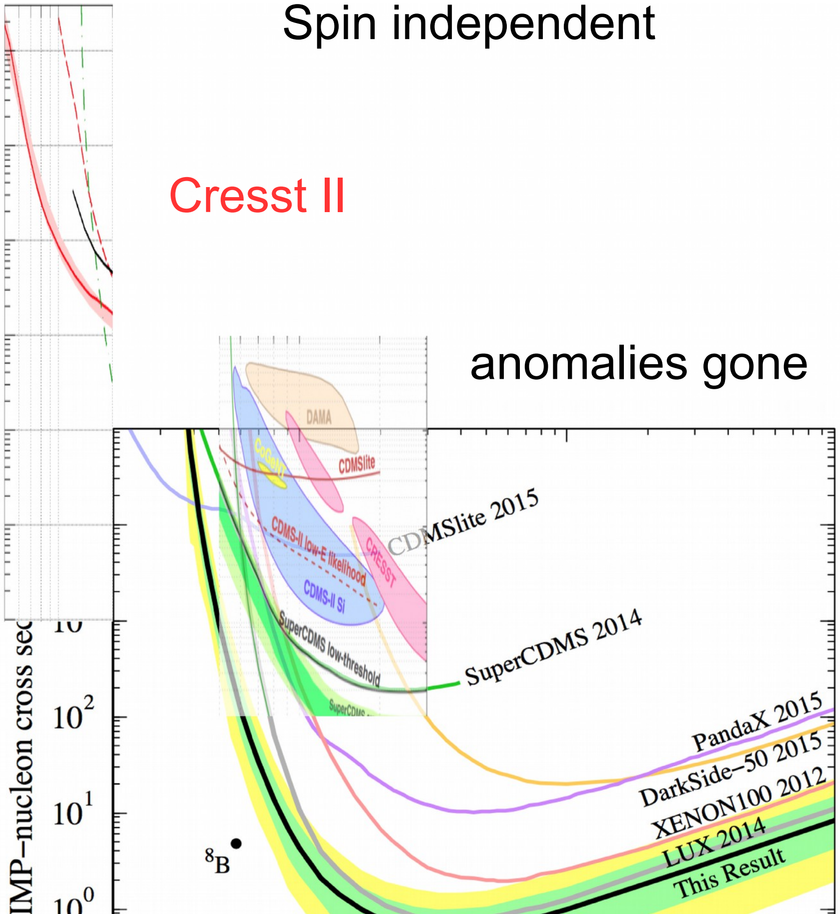
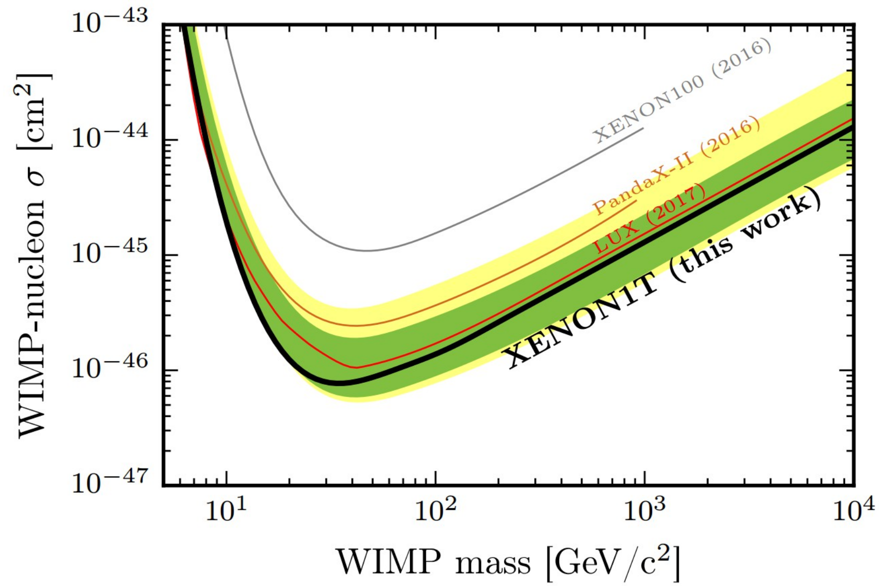




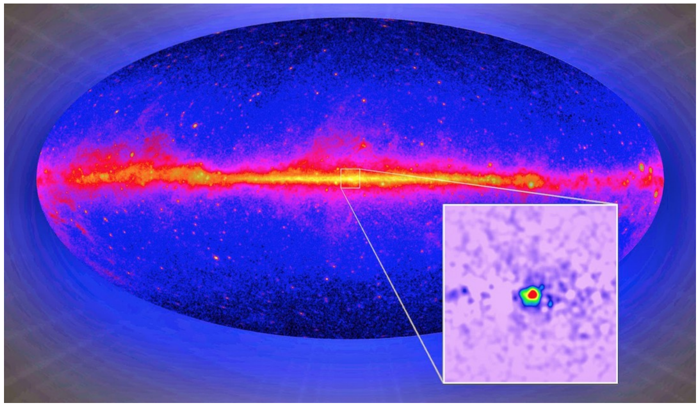
Assumes 'standard' astro- and particle physics

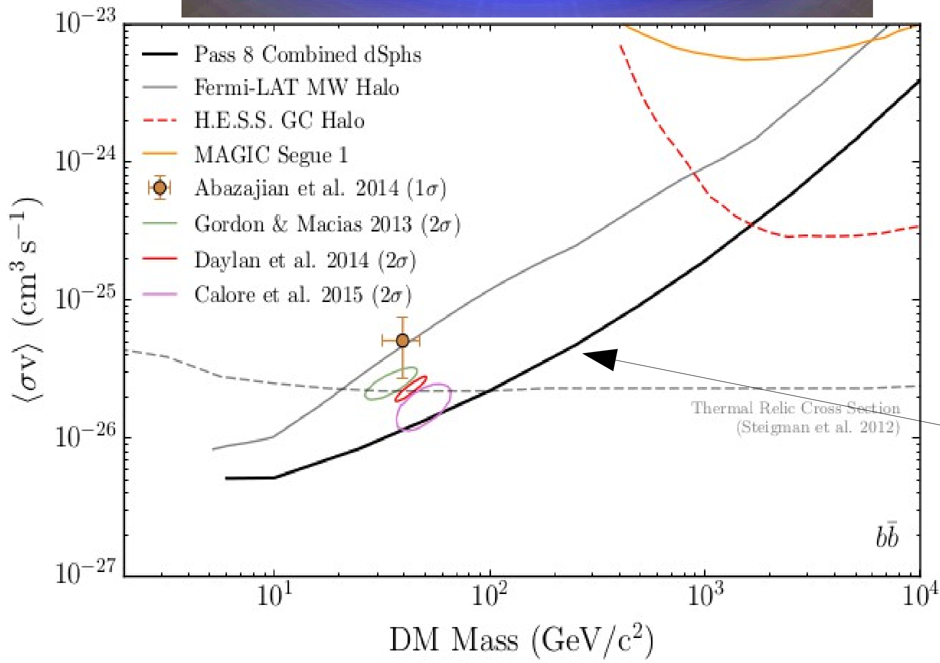
Astro-independent: Fox, Kribs, Liu, Tait, Weiner, ...

m_{WIMP} (GeV/c^2)

Current experimental status – indirect detection

Galactic centre excess





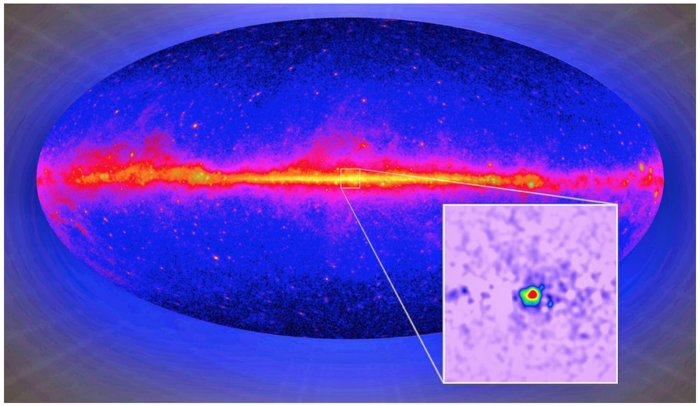
Morphology and spectrum as expected for 'vanilla WIMP'

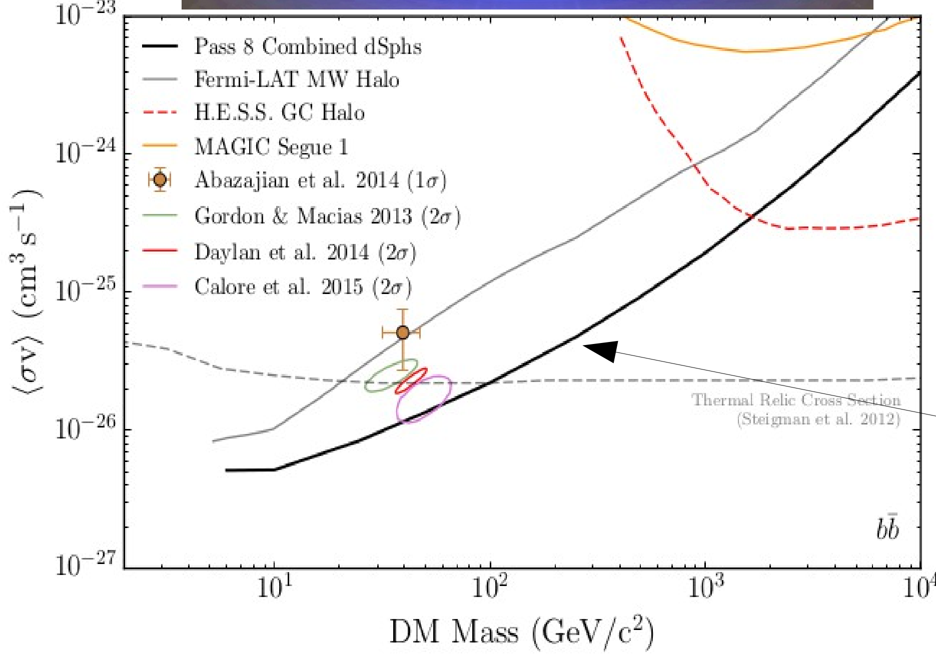
Challenged by limits from dwarf spheroidals

Also hints for non-resolved point sources

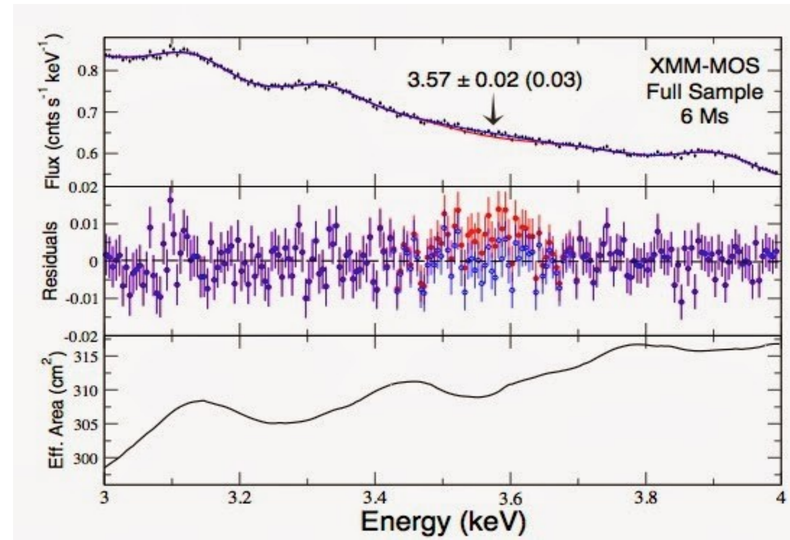
Current experimental status – indirect detection

Galactic centre excess





3.5 keV line



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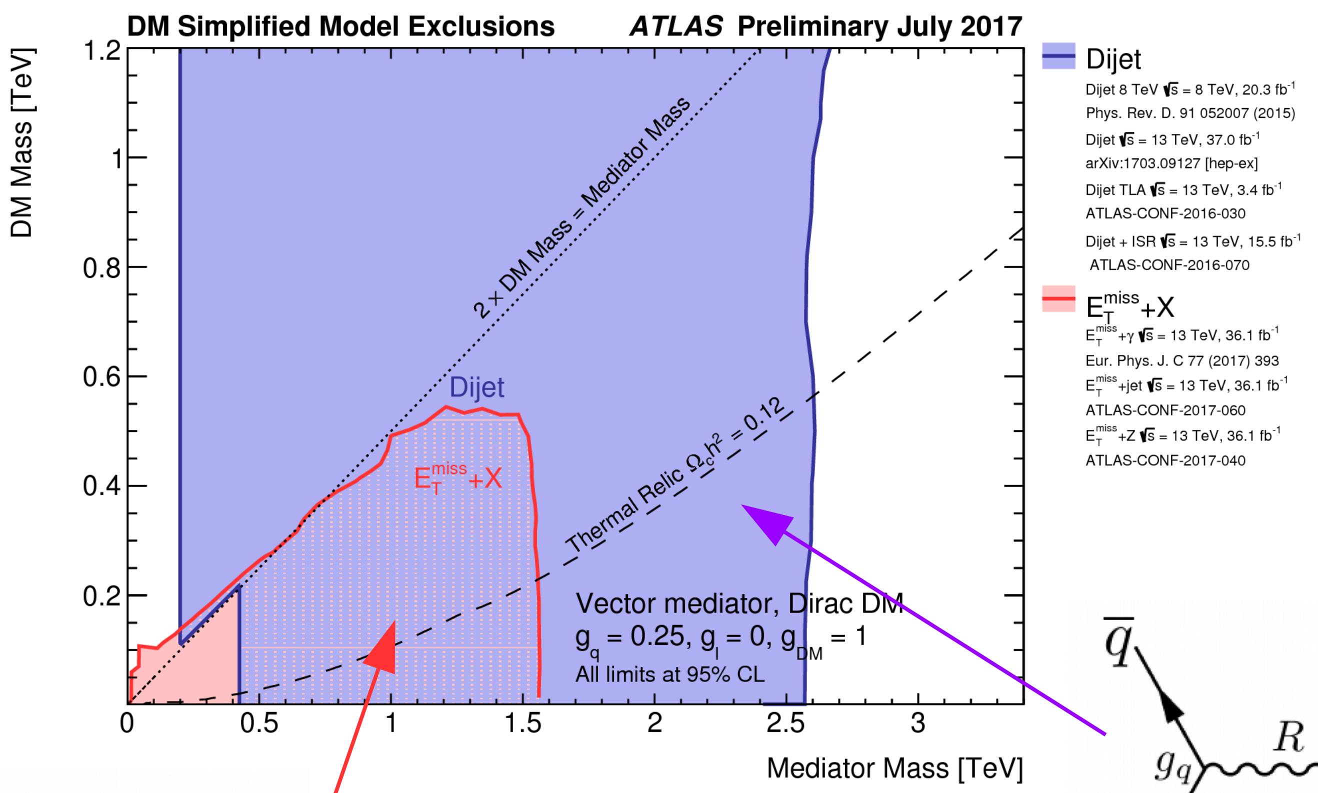
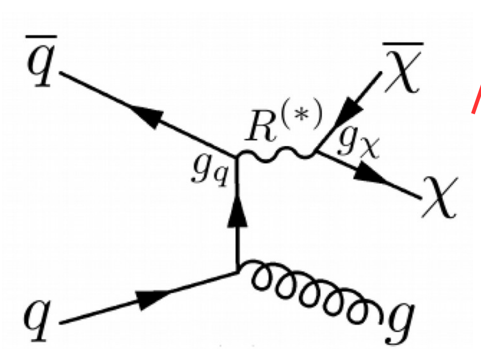
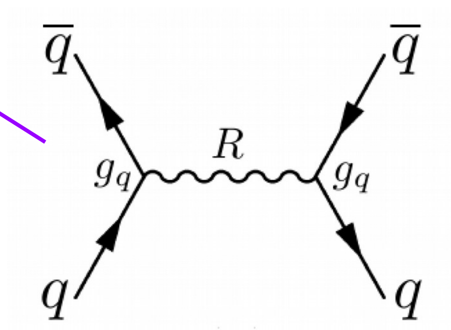
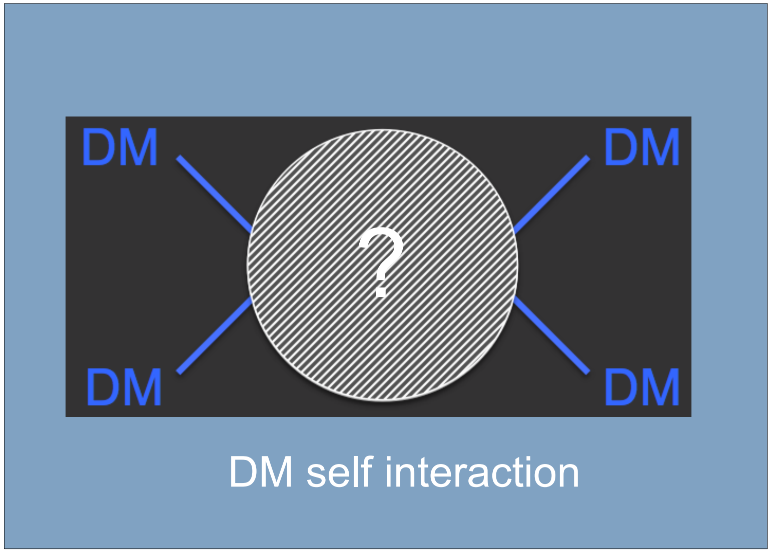


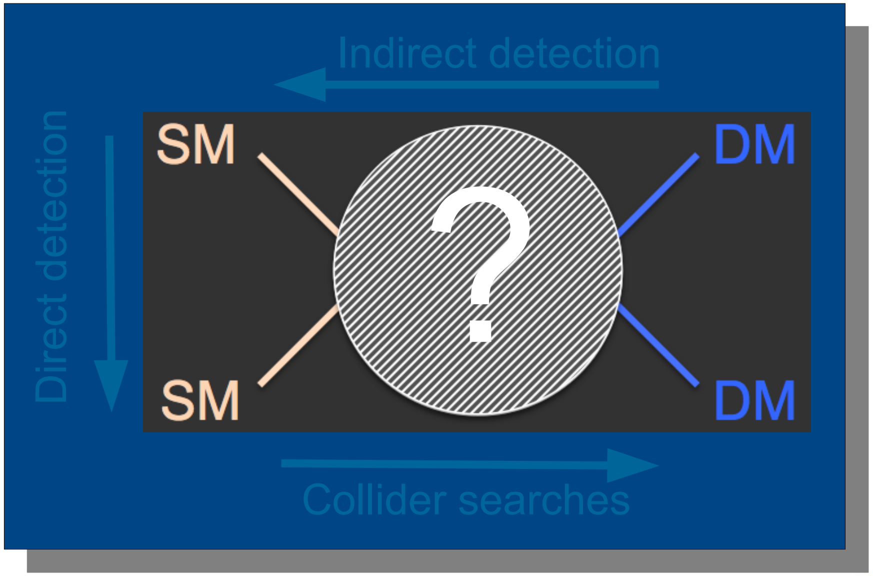




DM self interactions

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

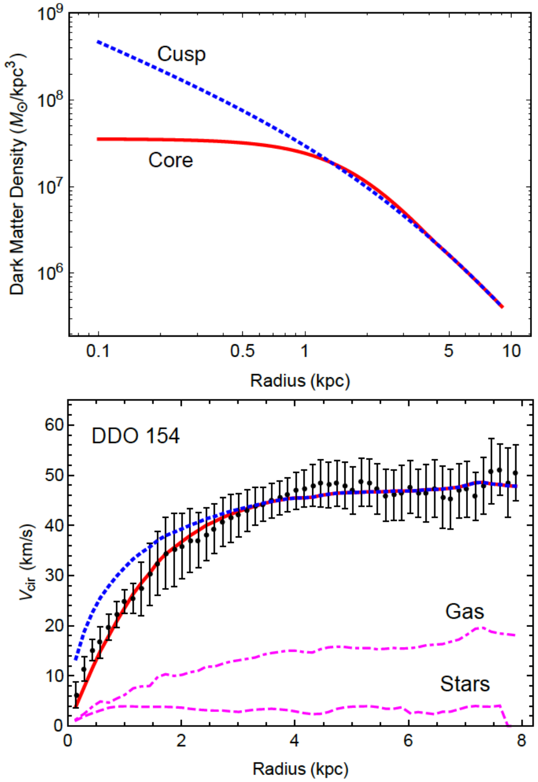




Motivation: Cosmology

- 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:

  - Cusp-vs-core problem



Tulin, Yu: 1705.02358

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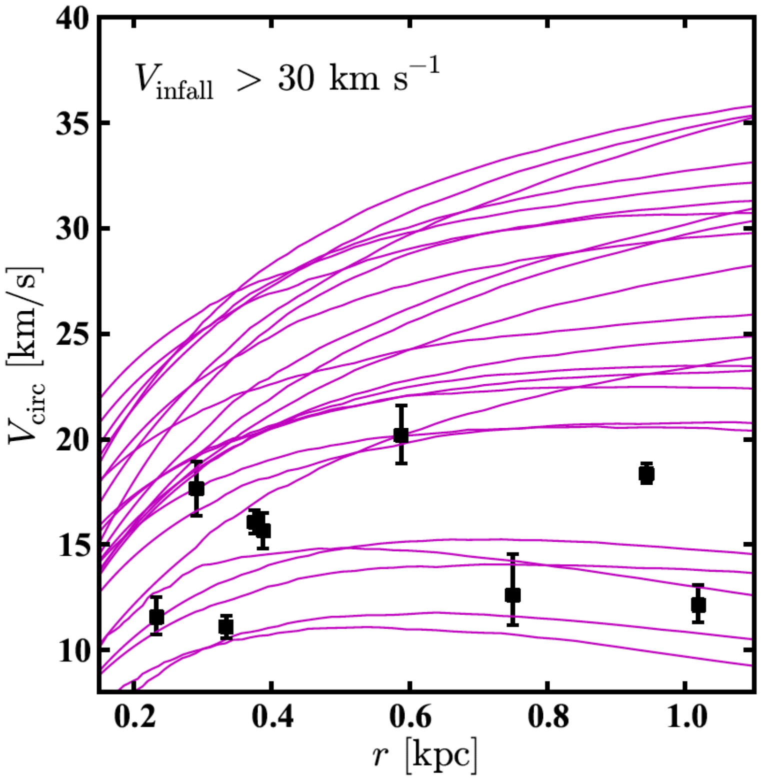

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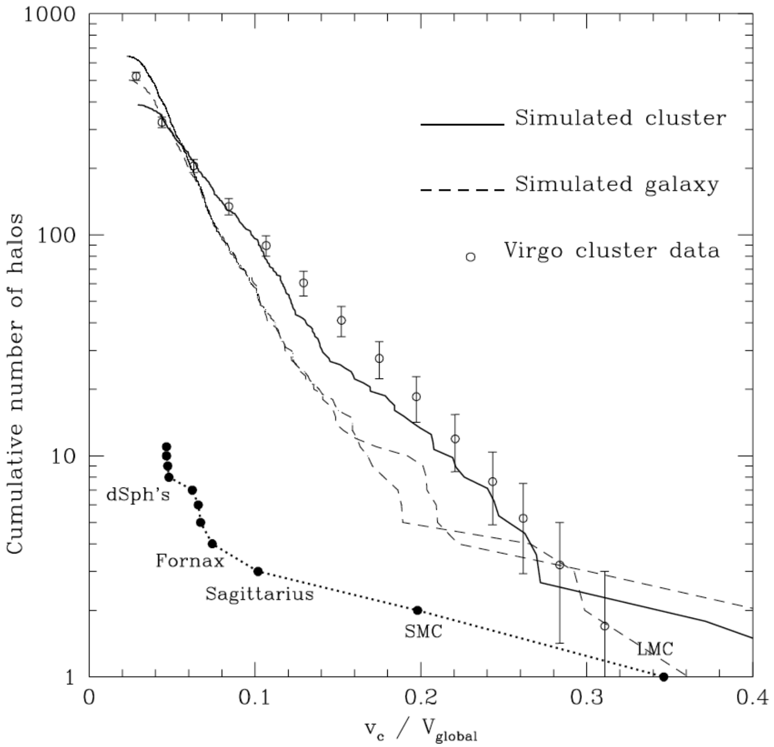

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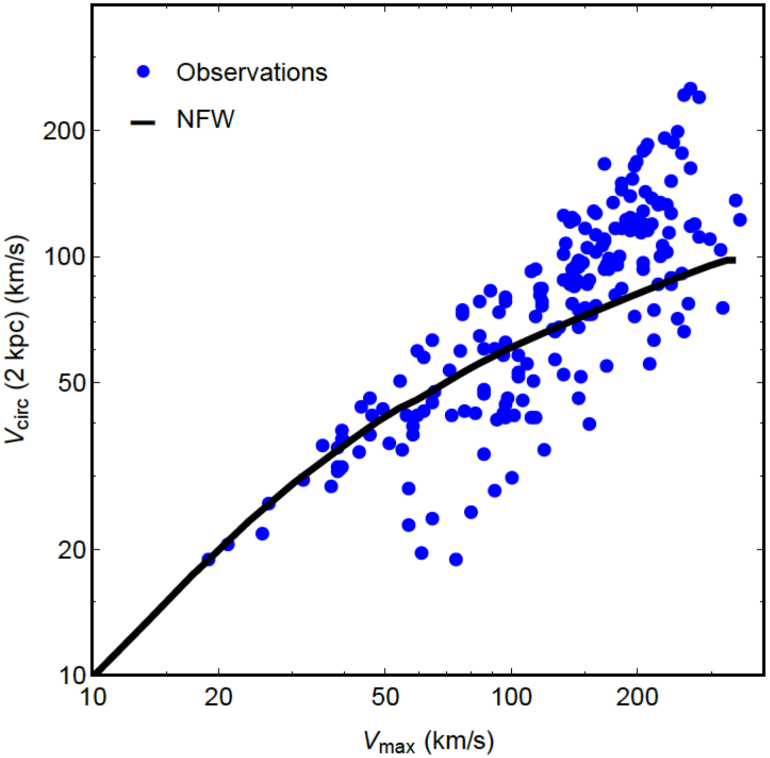

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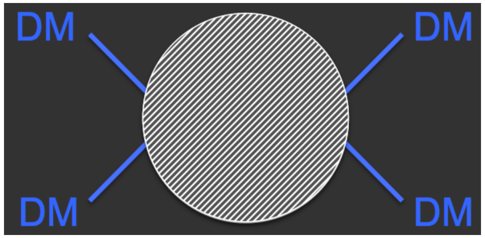

DM self-interactions may solve some (or all) of these problems

Spergel & Steinhard: astro-ph/9909386
Aarsen, Bringmann, Pfrommer, 1205.5809

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Motivation: 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 more complex dark sector (e.g. with a new gauge group)
  - Strongly interacting DM

    Carlson, Machacek, Hall (1992)
    Kusenko, Steinhardt: astro-ph/0106008
  - New light mediator in the dark sector

    Feng, Kaplinghat, Yu: arXiv:0905.3039
    Buckley & Fox: arXiv:0911.3898
    Loeb & Weiner: arXiv:1011.6374
- 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

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

- The nucleon nucleon scattering cross section ~20 barns 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

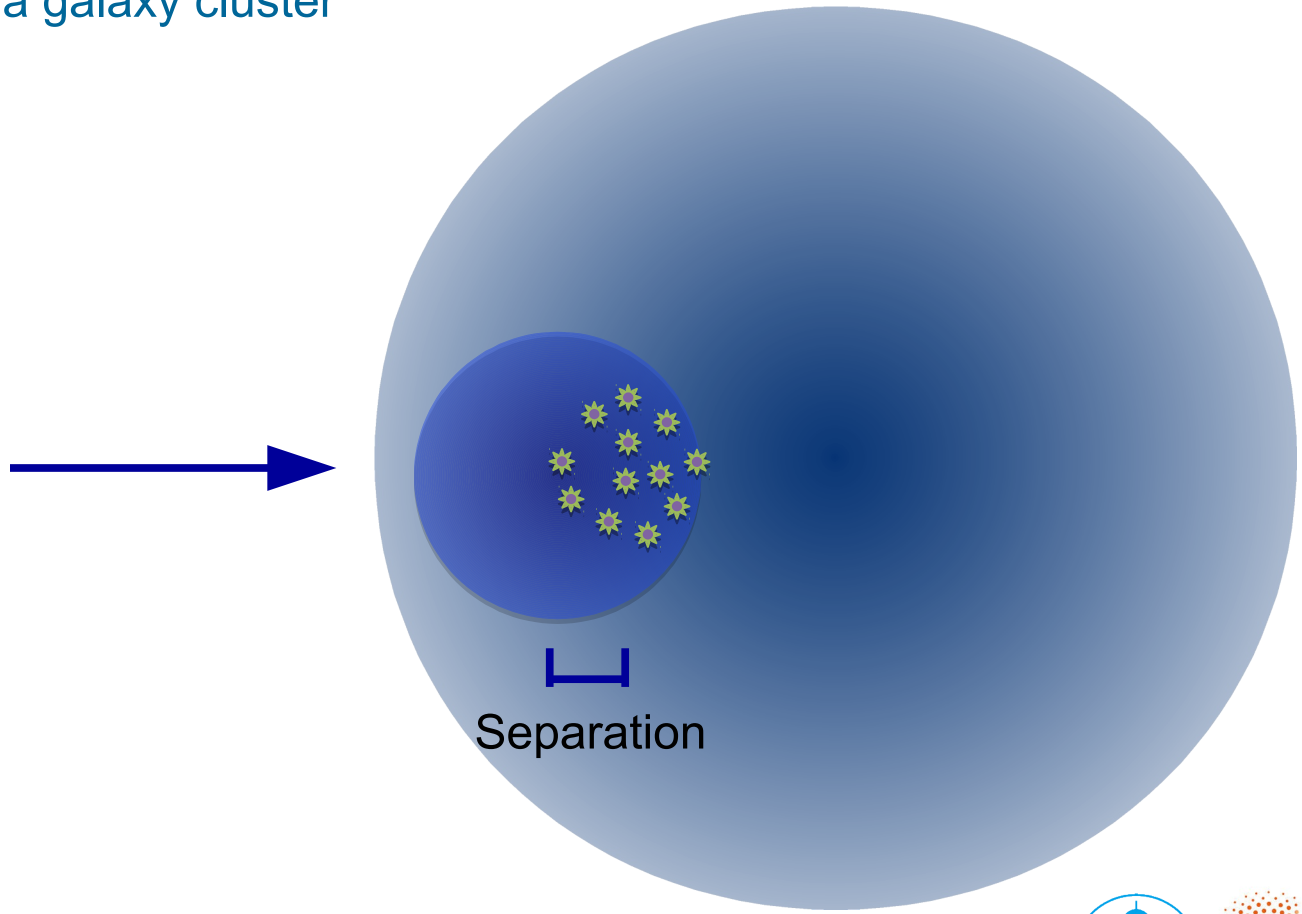
Rough bound: σ/m_χ < 1 cm²/g

New approach using halo surface densities may give slightly stronger constraints

Bondarenko et al.: 1712.06602

A smoking gun observable

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



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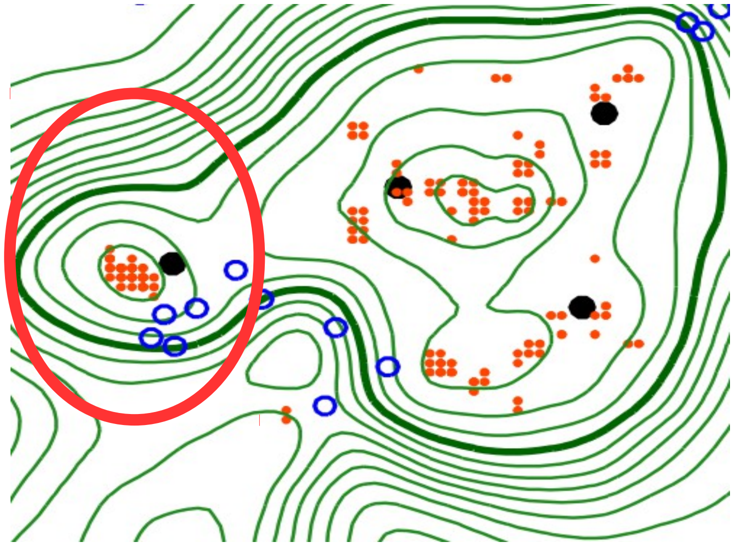
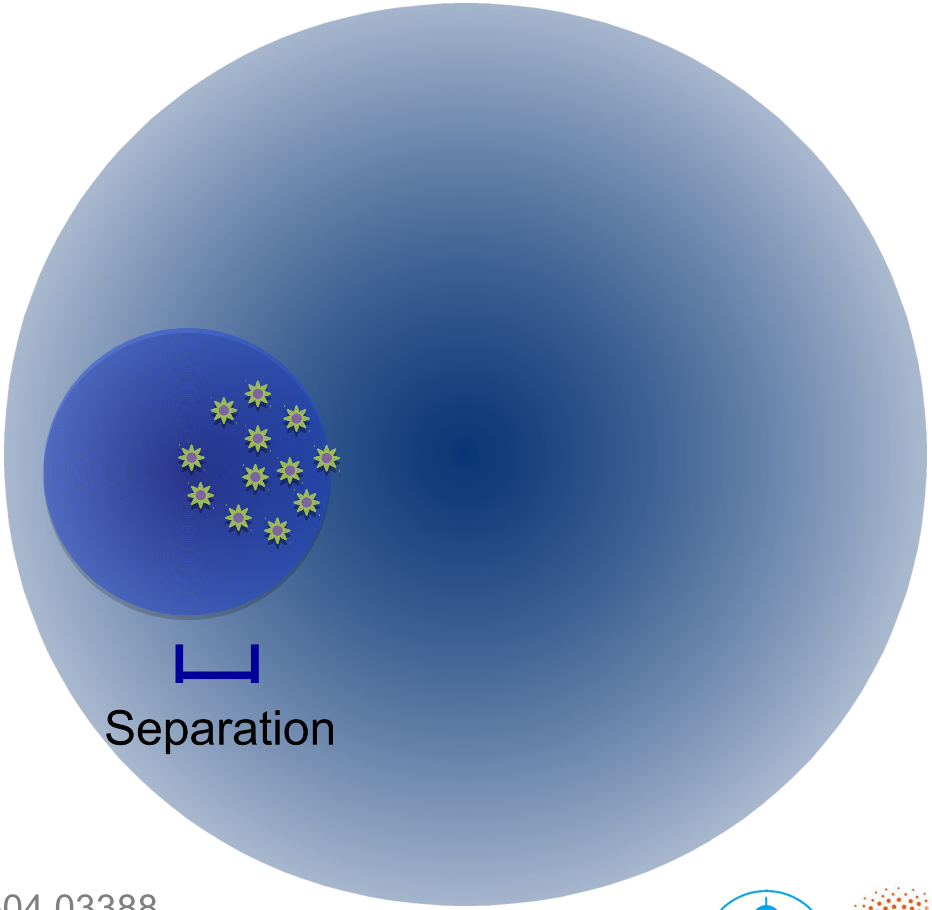
Observed offset: 1.62+/-0.48kpc





- Observed in 2015 in **A3827**

Massey et al., arXiv:1504.03388

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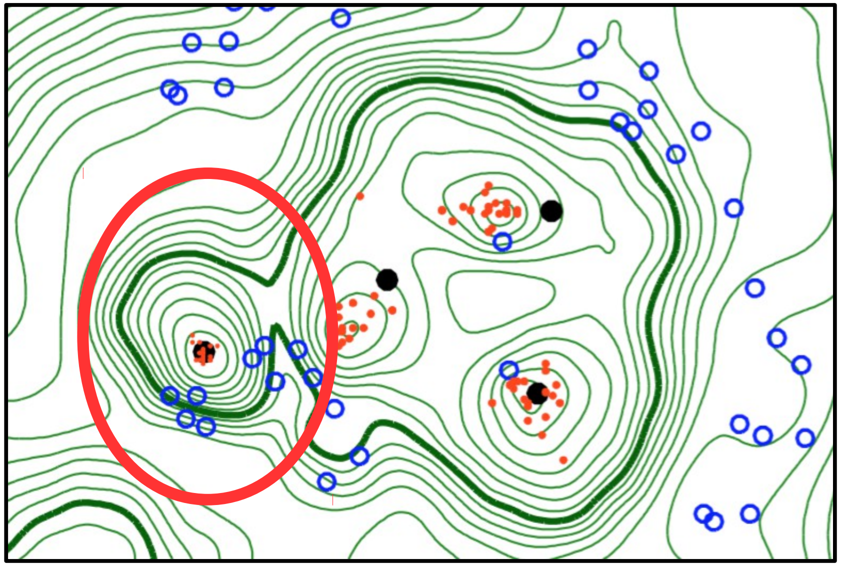
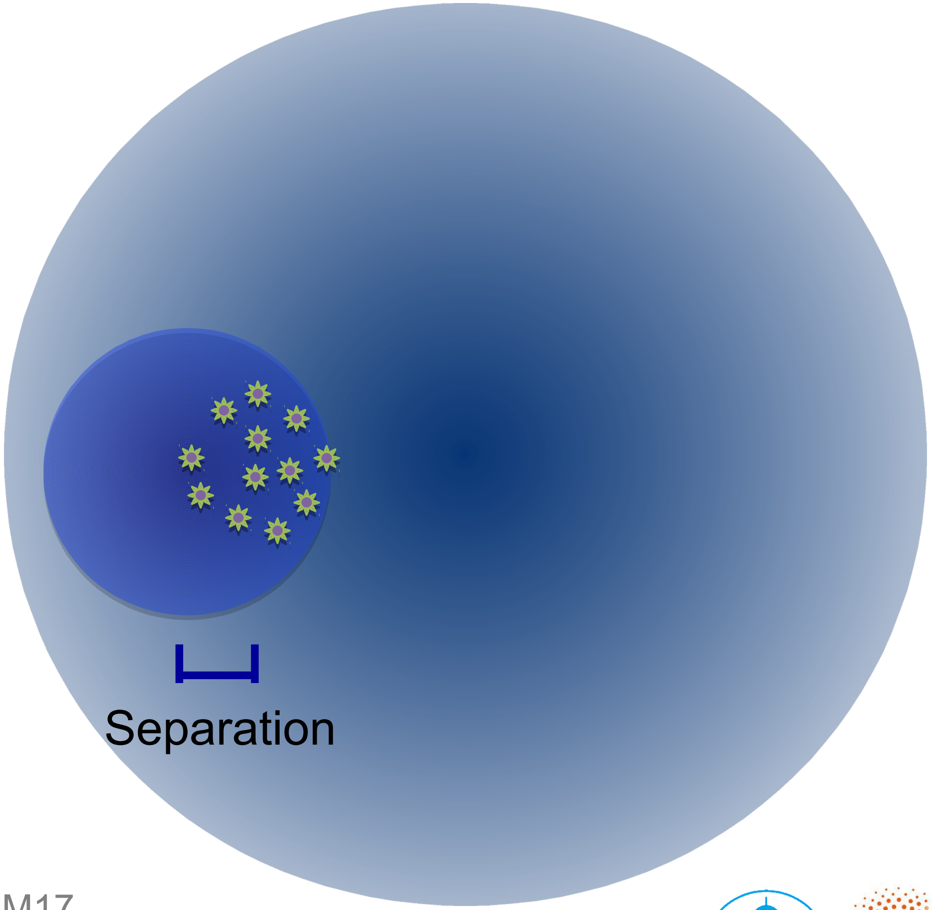
- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster





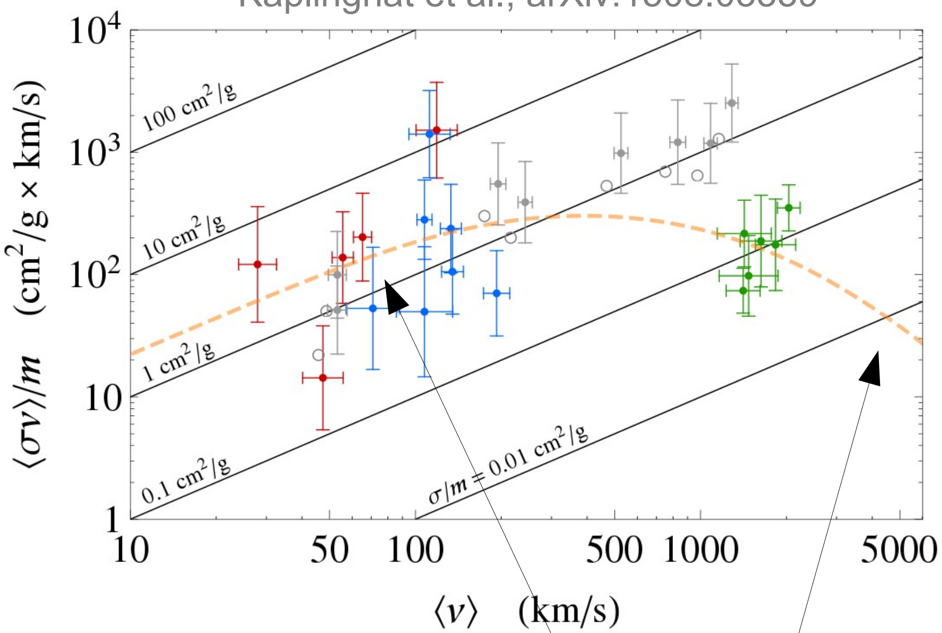
- Update 2017: offset gone

R Massey, talk at SIDM17

Velocity dependent self-interactions

- Maybe SI suppressed at cluster scales?
- Idea: Relate core size of different systems to SIDM cross section
- DM self-interactions seem to depend on the typical relative velocity of DM particles.
- Simplest realisation
  → light mediator!
  Loeb & Weiner: arXiv:1011.6374

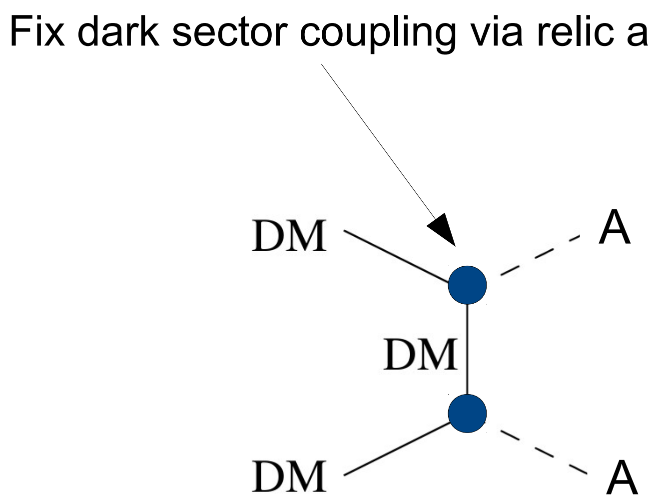
Kaplinghat et al., arXiv:1508.03339



- Consider a mediator with mass $m_{med} \sim m_{DM}\, v_{DM}$:
  - Scattering for small momentum transfer ($q < m_{med}$) proportional to $1/m_{med}^4$
  - Scattering for large momentum transfer ($q > m_{med}$) proportional to $1/q^4$

A new light mediator

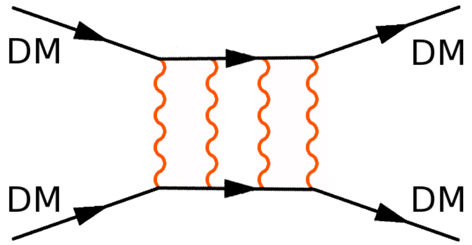
- The relic abundance is typically set by annihilations into pairs of mediators (so-called dark sector freeze-out):

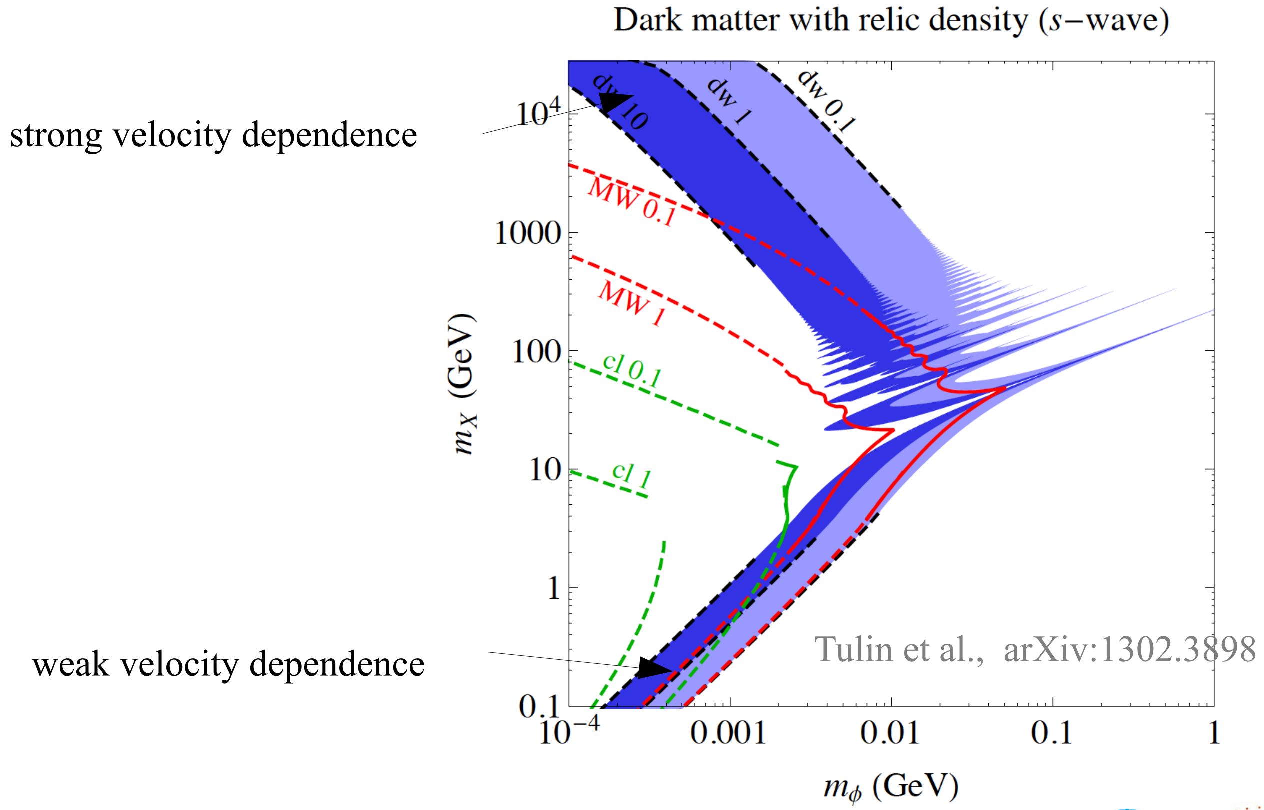


- To avoid overclosing the Universe, the mediator should ultimately decay, so its couplings to SM states cannot be arbitrarily small

Enhancement of DM self-interactions

- DM self-interactions are enhanced also by non-perturbative effects due to multiple mediator exchange.
- Scalar and vector mediators particularly interesting





Enhancement of DM self-interactions

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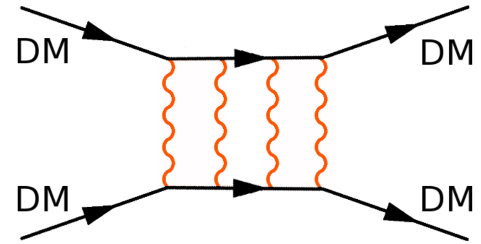
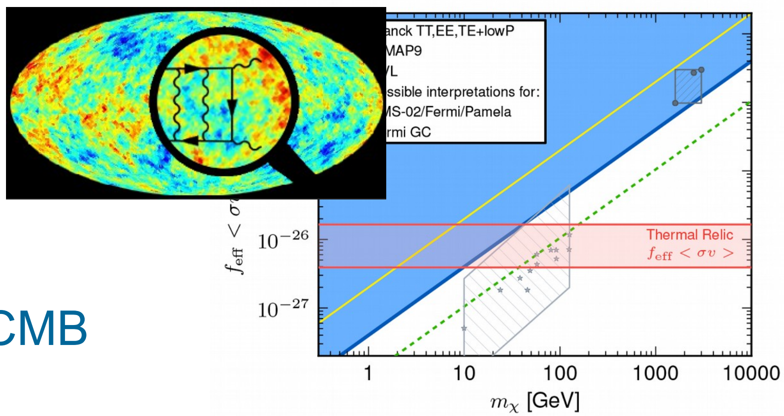


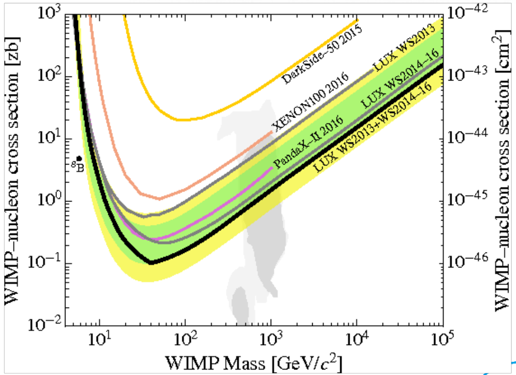
> Scalar and vector mediators particularly interesting

> In this case also Sommerfeld enhancement of annihilations



→ very strong reionisation bounds from the CMB for s-wave annihilation

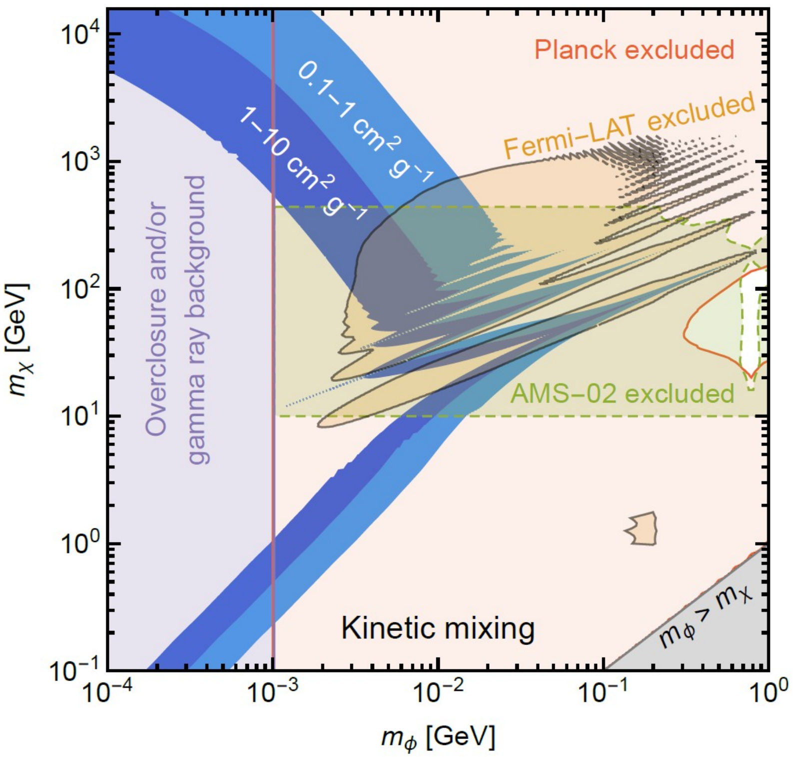
> DM-nucleon scattering cross section also strongly enhanced for light mediators



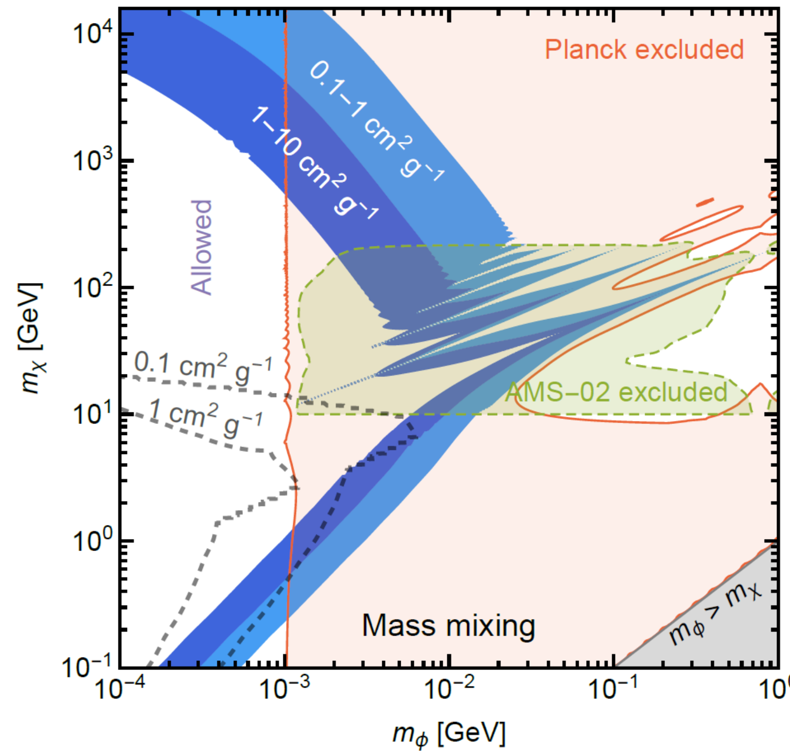
Example: vector mediators

- For vector mediators, DM annihilation proceeds via s-wave:
  - Large Sommerfeld enhancement for small velocities
  - g_χ fixed by relic density – essentially independent of coupling to SM

Bringmann et al., arXiv:1612.00845



Bringmann et al., arXiv:1612.00845



Future directions for light mediators

- There are a number of other ways to evade the various constraints
  - Inert decays of the mediator, for example into (sterile) neutrinos
  - No thermalization (DM production via the freeze-in mechanism)
    Bernal et al., arXiv:1510.08063
  - Suppressed couplings to quarks (to evade direct detection constraints)
  - Small mass splitting (inelastic scattering)
    Blennow et al., 1612.06681

- Nevertheless, constraints from BBN, direct detection and the CMB are very generic and will generally be relevant to any model of DM interacting via a new light mediator.

- Exciting phenomenology and interesting model-building challenges!

The coming years

- Lots of data to come the next couple of years!!!
- LHC just at the beginning of its 13 TeV run
- Xenon1T started, 2-3 orders of magnitude in the next two decades
- New indirect detection experiments (e.g. CTA) will probe the thermal WIMP paradigm
- Many more astrophysical observations (merging clusters etc.)

Exciting times ahead of us!