On self-interacting dark matter: Current status and perspectives

Kai Schmidt-Hoberg

HELMHOLTZ | ASSOCIATION

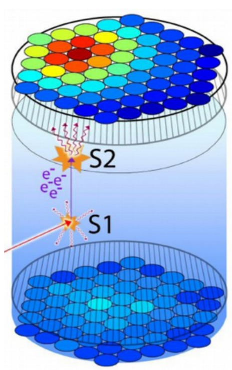
erc

DESY

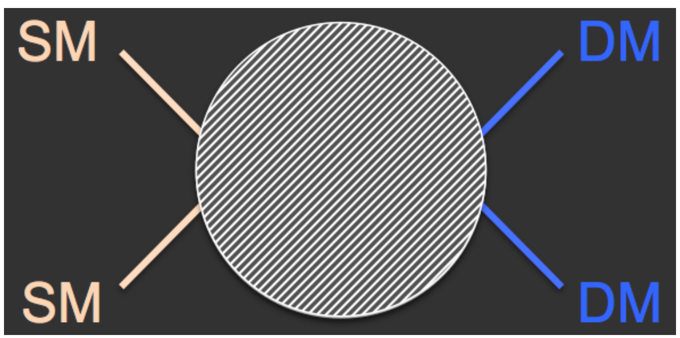
How to constrain the properties of dark matter?

- Our 'usual way' to search for dark matter

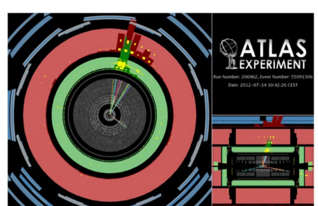
Indirect detection



Direct detection



Collider searches



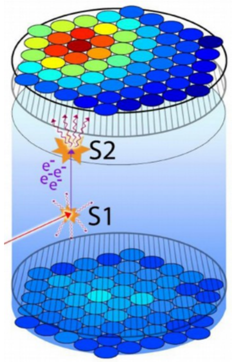
How to constrain the properties of dark matter?

- Our 'usual way' to search for dark matter

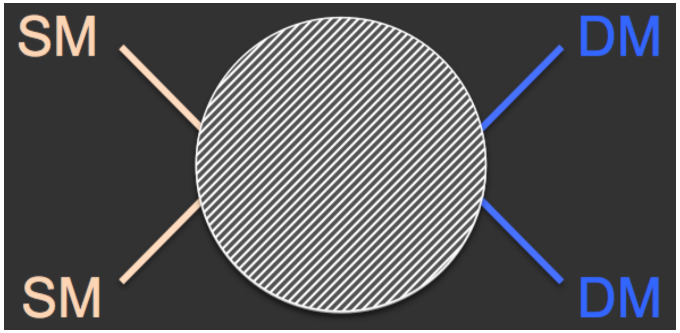
cf. Talks by
H M Lee, C Spethmann, D Huang

- A fourth way...

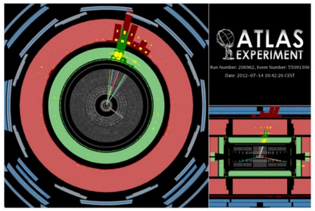
Indirect detection



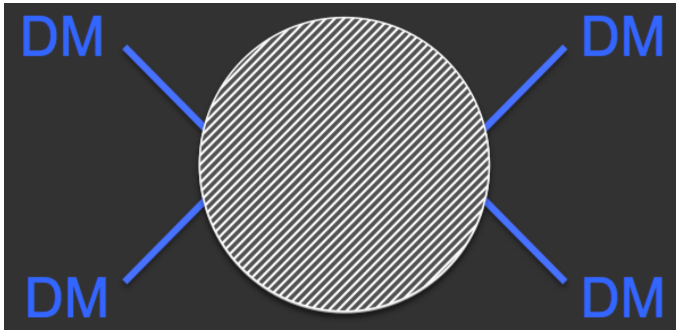
Direct detection



Collider searches



This Talk:



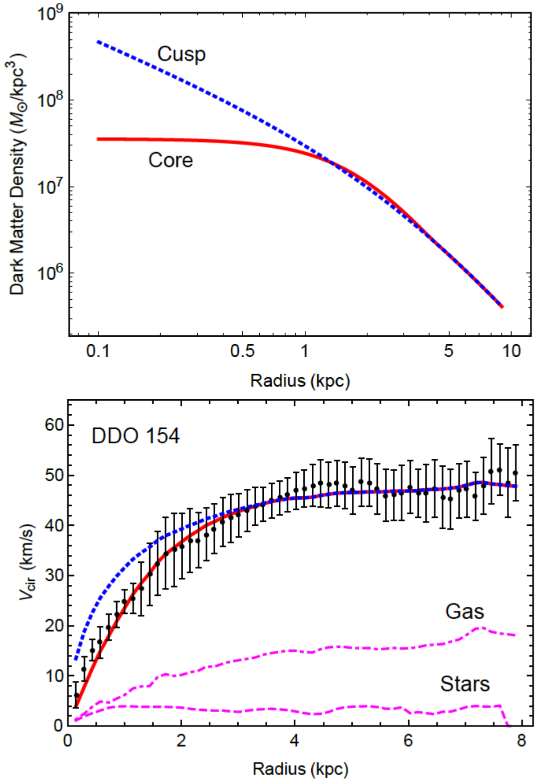
DM self-interactions

Motivation: Cosmology

cf. talk by Pran Nath

- 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



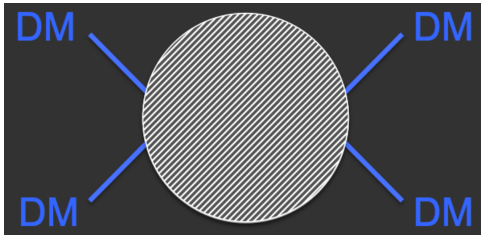
Tulin, Yu: 1705.02358

Motivation: Cosmology

cf. talk by Pran Nath

- 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
  - Too-big-to-fail problem
  - Missing-satellite problem

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



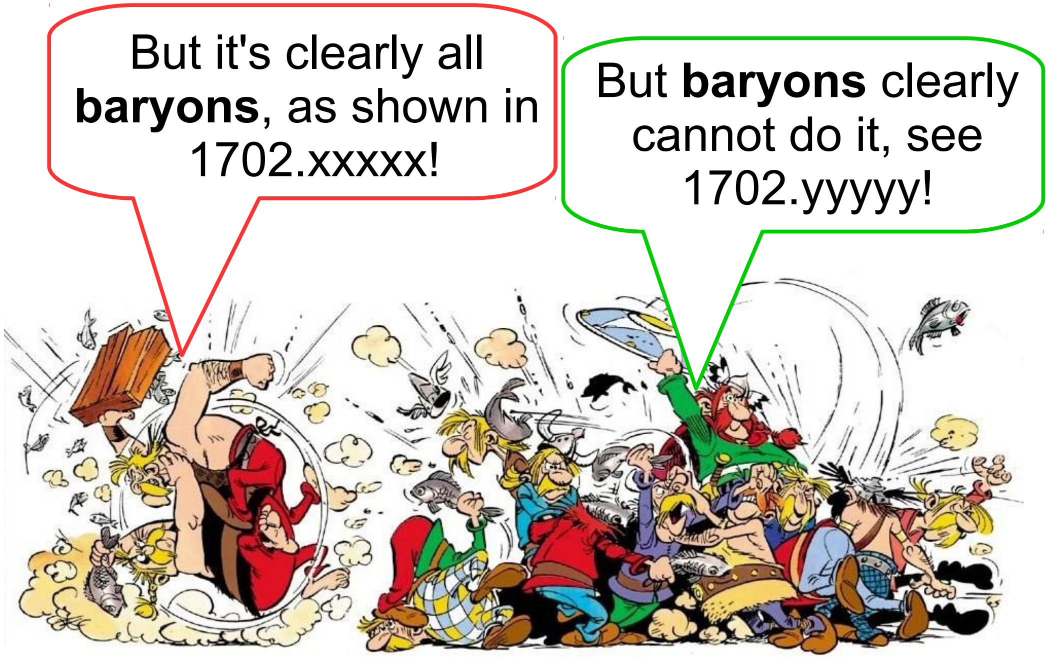
Spergel & Steinhard: astro-ph/9909386
Aarsen, Bringmann, Pfrommer, 1205.5809

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
  - Too-big-to-fail problem
  - Missing-satellite problem

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



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

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

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

- 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…

Constraints on self-interactions

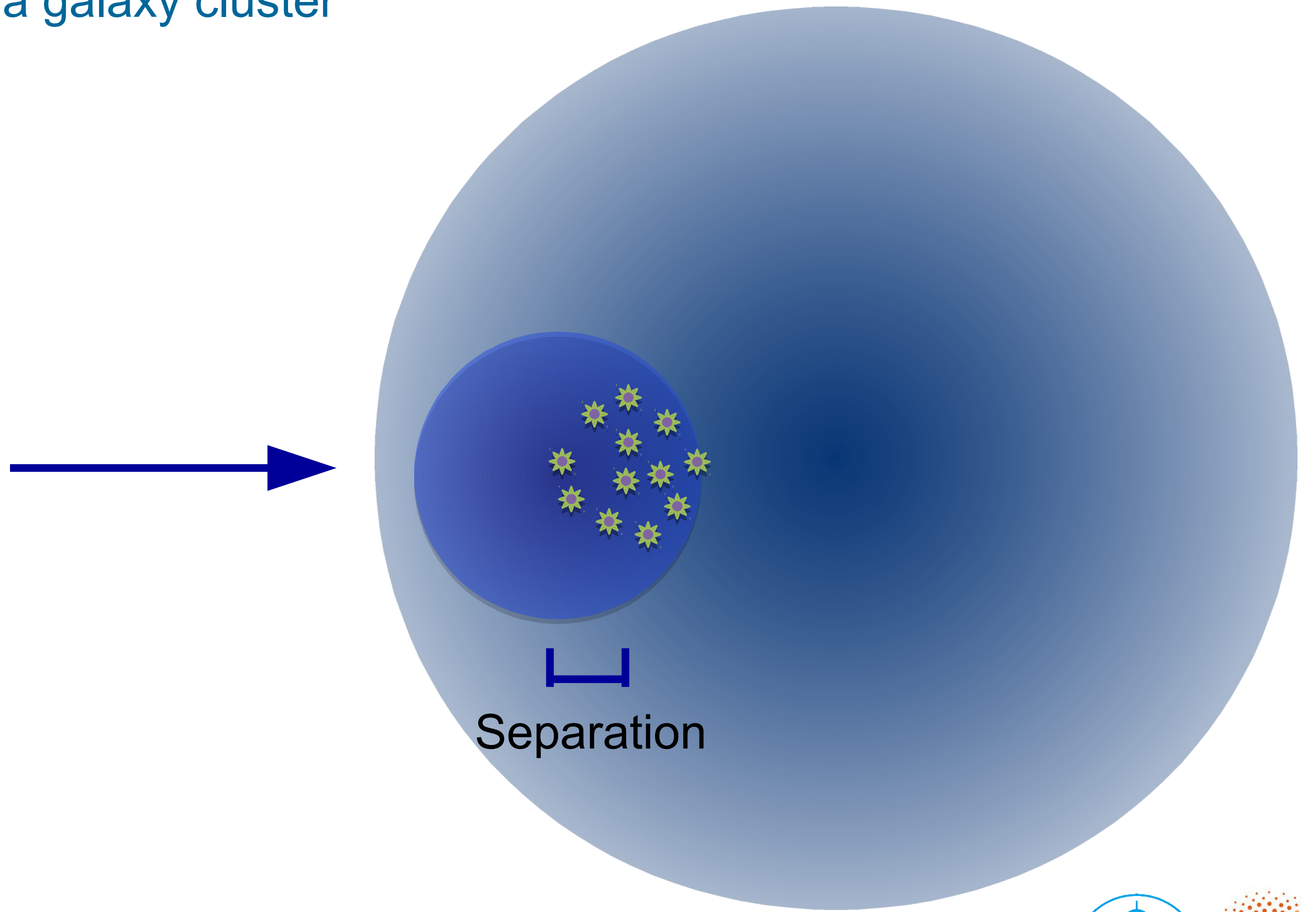
- Various astrophysical observations give constraints on SIDM:
  - Bullet cluster — Randall et al 0704.0261

  - Subhalo evaporation rate — Gnedin, Ostriker: astro-ph/0010436
  - Halo ellipticity — Miralda-Escude (2002)
  - Core density in clusters and dwarfs — Yoshida et al.: astro-ph/0006134; Dave at al.: astro-ph/0006218

- SIDM probed at different velocities in different systems
  → a handle on the velocity dependence of the self scattering cross section!

Smoking gun?

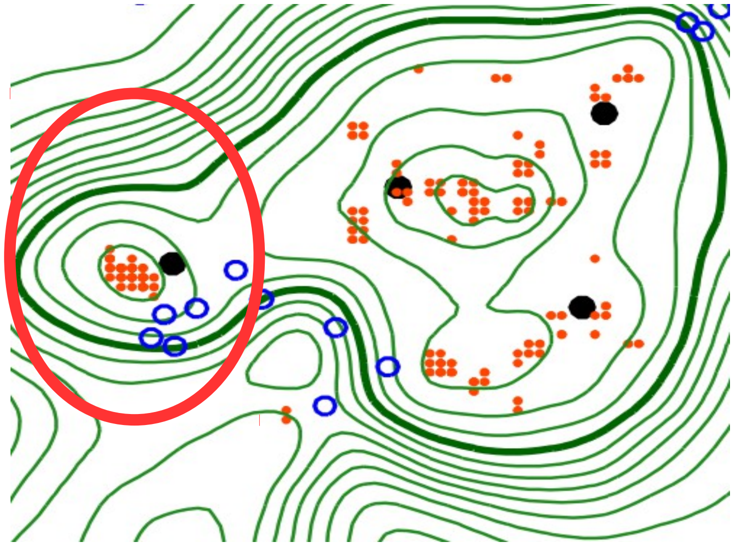
- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster

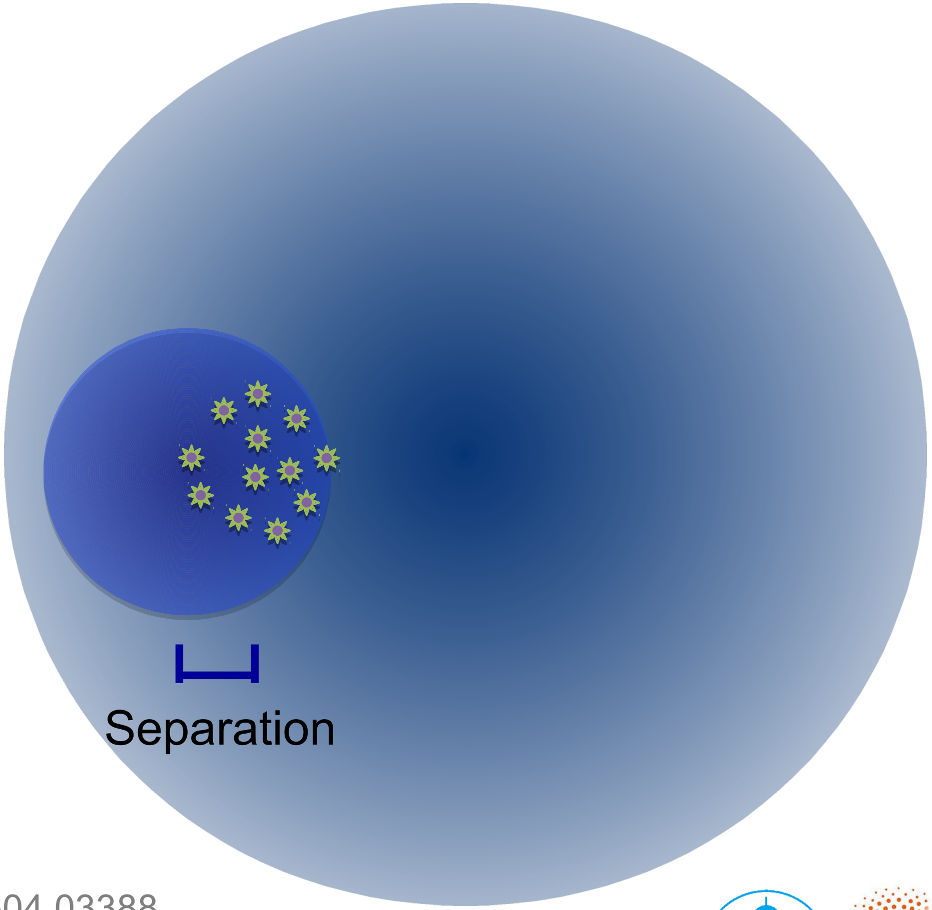


Smoking gun?

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

Observed offset: 1.62+/-0.48kpc





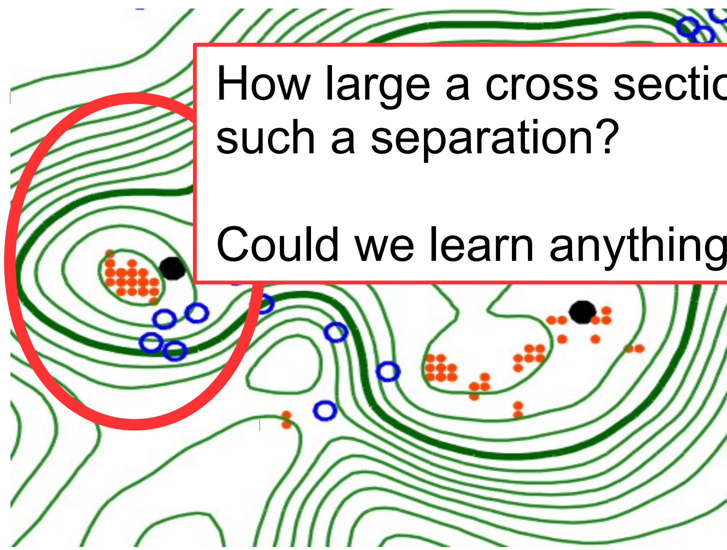
- Recently been **observed in A3827**

Massey et al., arXiv:1504.03388

Smoking gun?

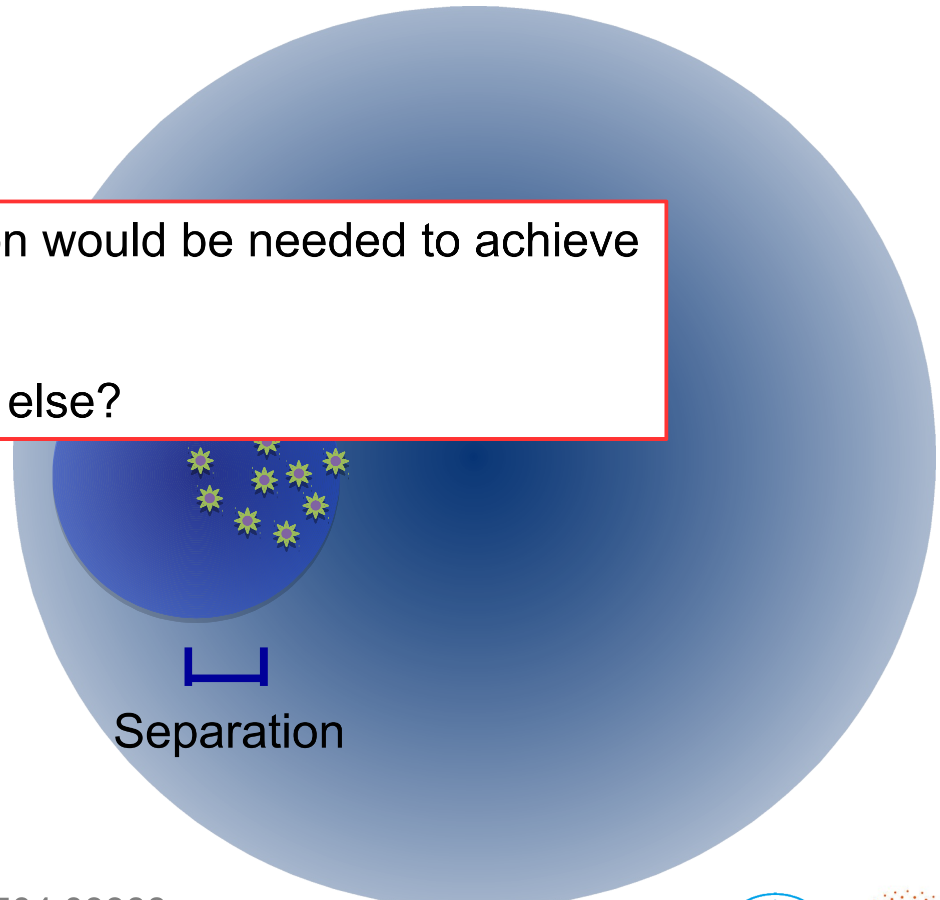
- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster

Observed offset: 1.62+/-0.48kpc



How large a cross section would be needed to achieve such a separation?

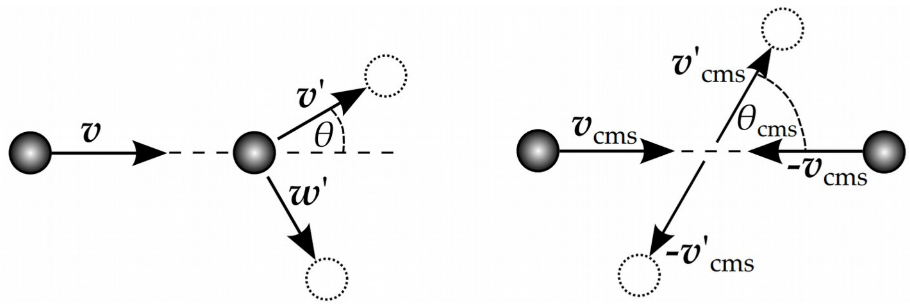
Could we learn anything else?



- Recently been **observed in A3827**

Massey et al., arXiv:1504.03388

Frequent vs. rare scatters



The momentum transfer in a collision of two DM particles is completely fixed by the scattering angle. The effective momentum transfer is given by

$$\sigma_{\mathrm{T}} = 2\pi \int_{-1}^{1} \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(1 - |\cos\theta|)\,\mathrm{d}\cos\theta$$

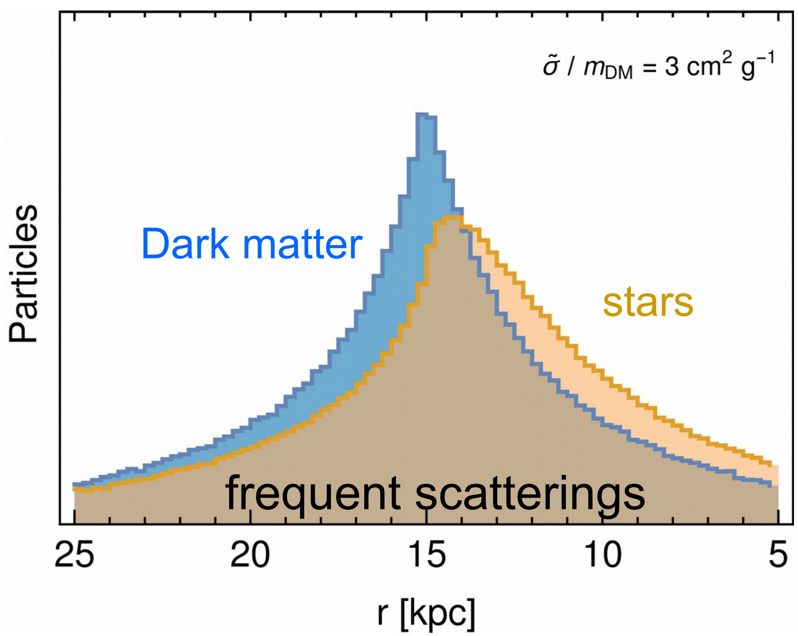
This is the quantity typically studied

Kahlhoefer et al, 1308.3419

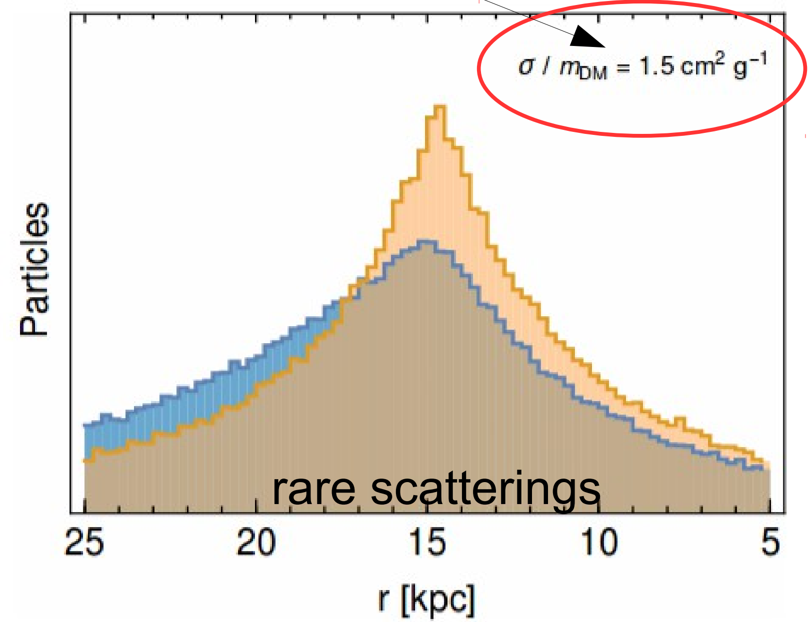
However, this is not all that matters…
Can be obtained with **rare scatters and large momentum transfer** (e.g. isotropic scattering) or **frequent scatters with small momentum transfer** (e.g. long range interactions)

Infalling galaxy in A3827

Kahlhoefer et al, 1504.06576

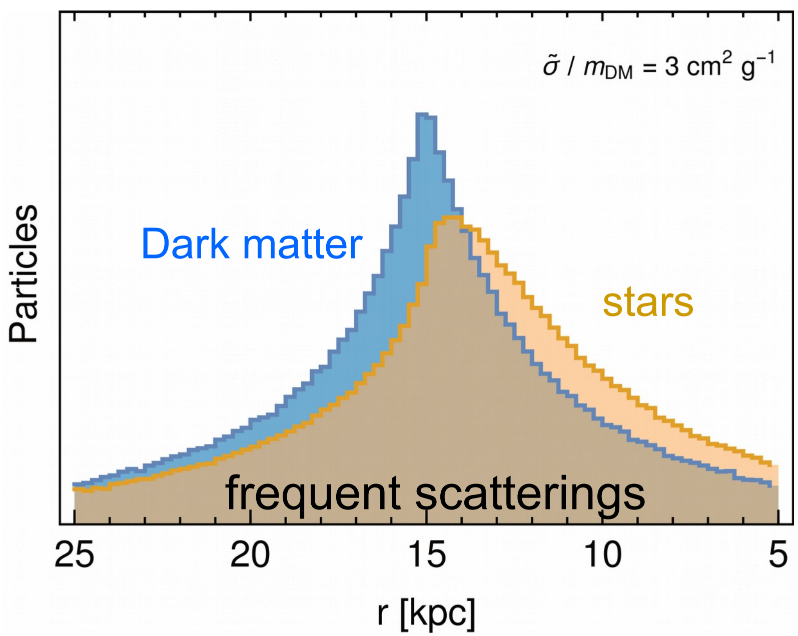


A3827: In (some) tension with upper bounds

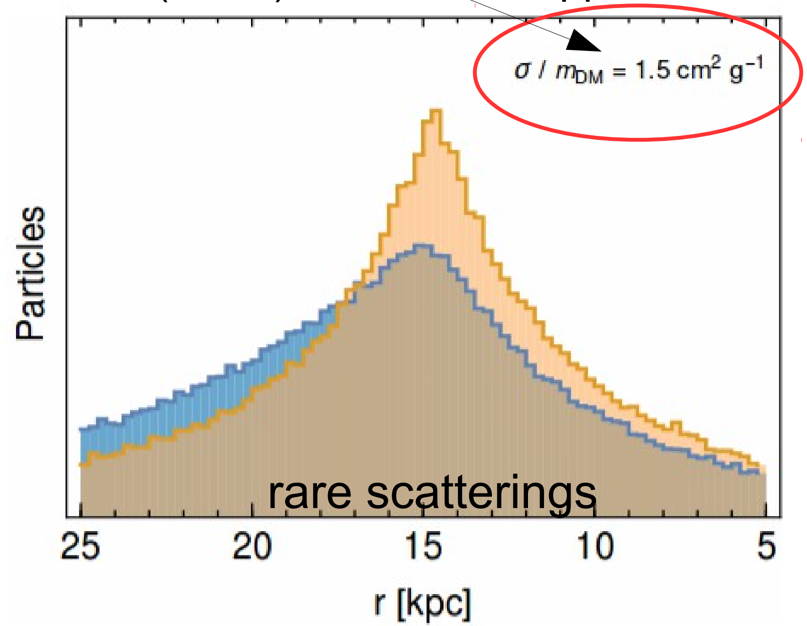


Distinguishing different types of SIDM

Kahlhoefer et al, 1504.06576



A3827: In (some) tension with upper bounds



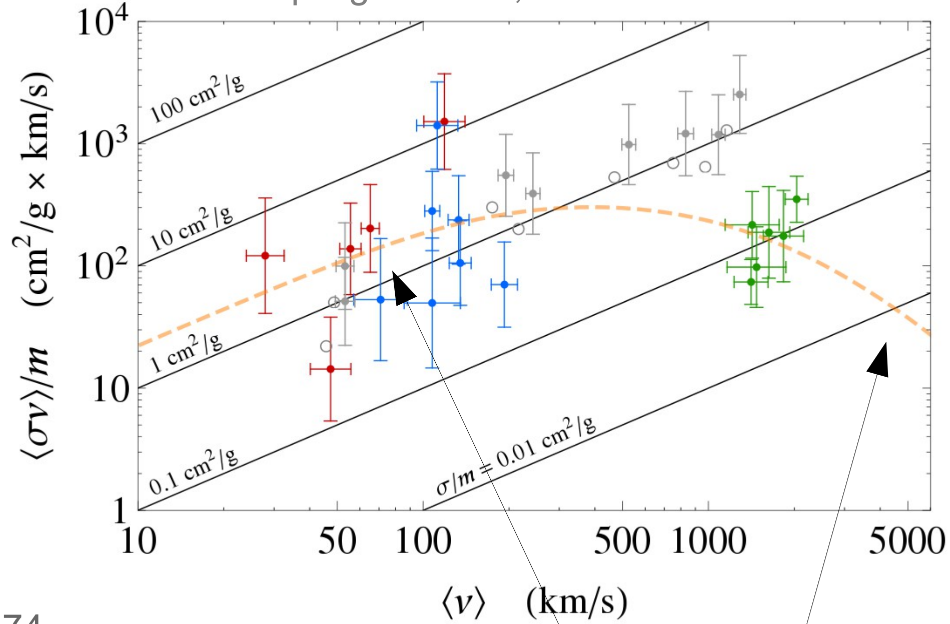
- **Effective drag force:** the DM subhalo retains its shape, while the distribution of stars are both shifted and deformed.
- **Contact interactions**: the DM subhalo is deformed due to the scattered DM particles leaving the subhalo in the backward direction.
- Potentially distinguishable!

Velocity dependent self-interactions

- 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

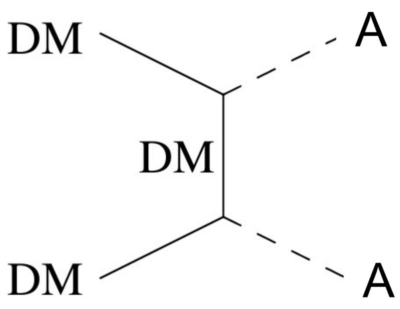
Kaplinghat et al., arXiv:1508.03339



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

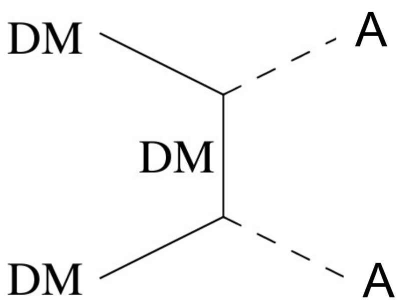
A new light mediator

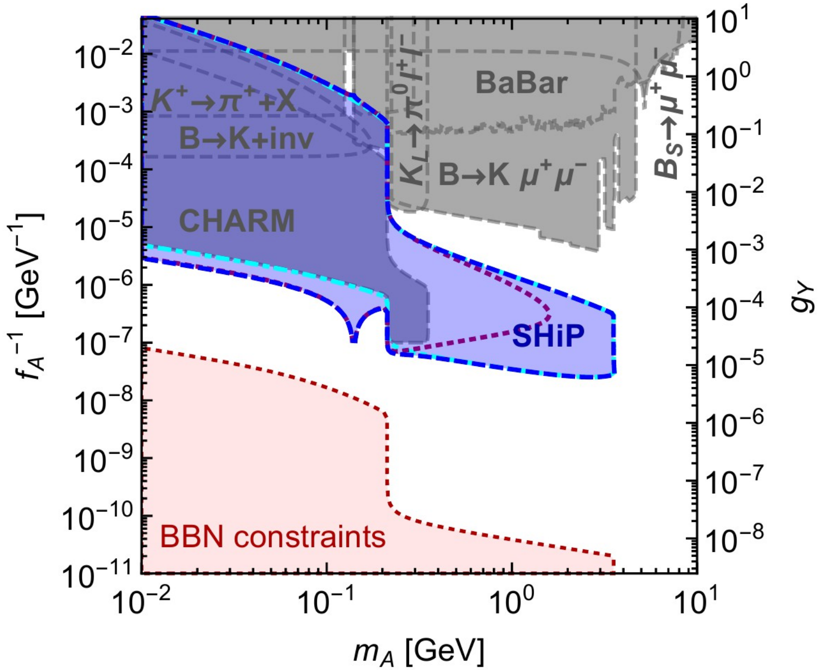
- The relic abundance is typically set by annihilations into pairs of mediators (so-called dark sector freeze-out):



A new light mediator

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

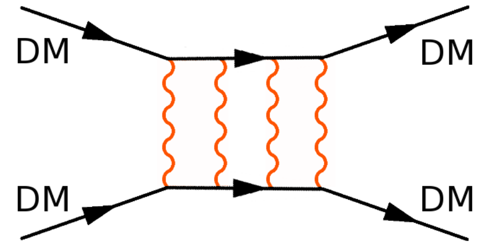




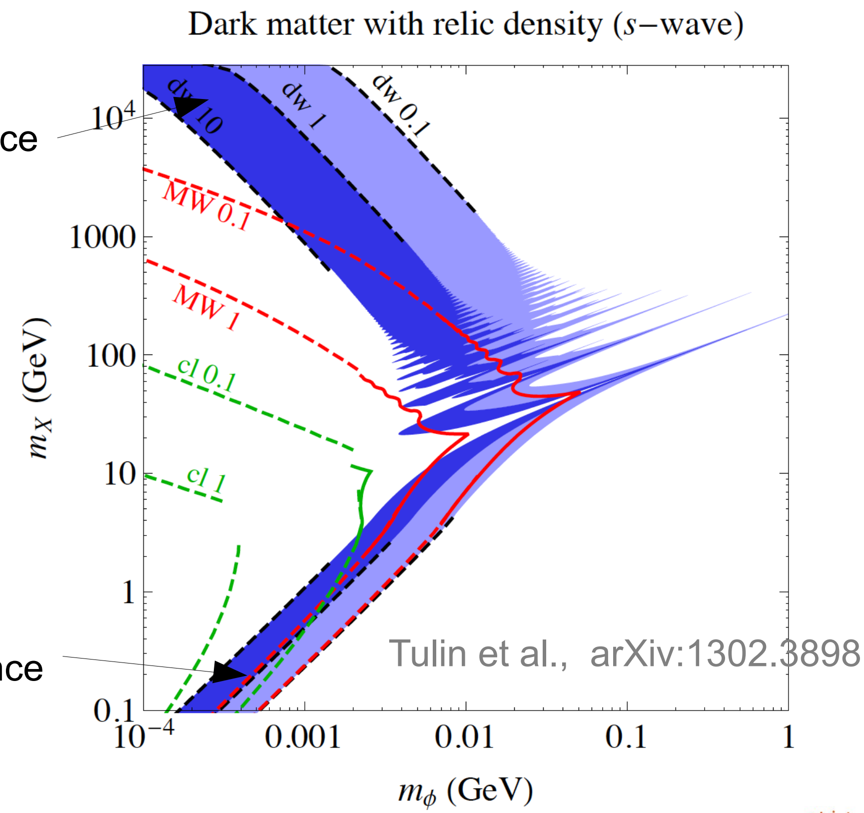
- To avoid overclosing the Universe, the mediator should ultimately decay, so its couplings to SM states cannot be arbitrarily small

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



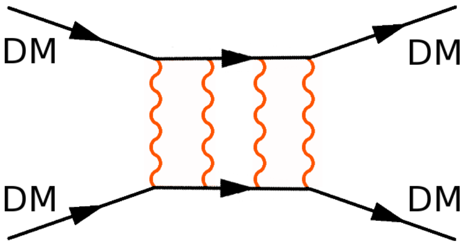
strong velocity dependence



weak velocity dependence

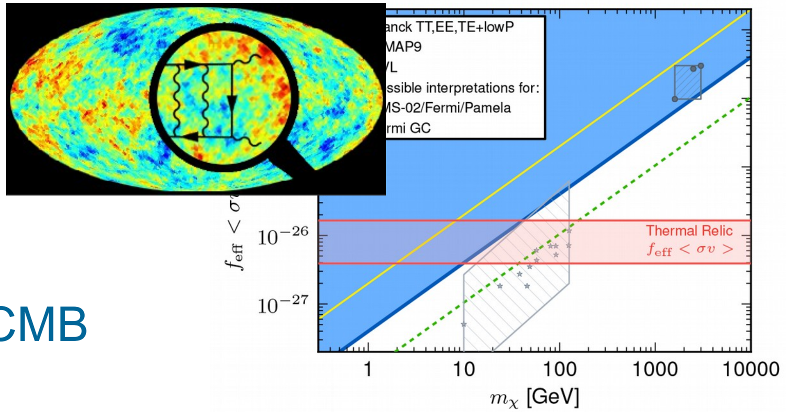
Enhancement of DM self-interactions

> DM self-interactions are enhanced also by non-perturbative effects due to multiple mediator exchange.



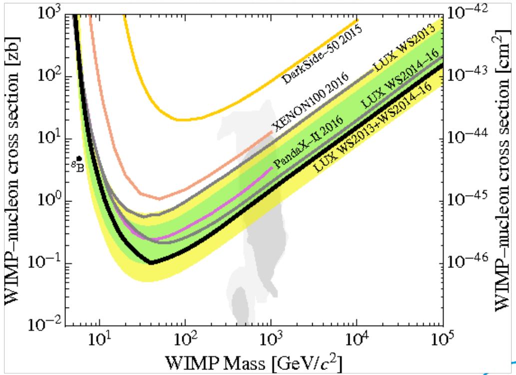
> Scalar and vector mediators particularly interesting

> 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



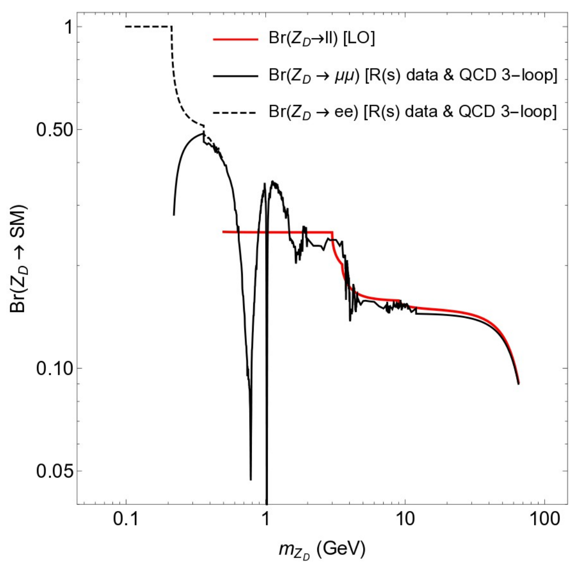
Vector mediators

- Example: A new gauge boson from a spontaneously broken U(1)' gauge group that mixes with the neutral gauge bosons of the Standard Model.

$$\mathcal{L} \supset -g_\chi^V \phi^\mu \bar{\chi}\gamma_\mu \chi - \frac{1}{2}\sin\epsilon\, B_{\mu\nu}\phi^{\mu\nu} - \delta m^2 \phi^\mu Z_\mu$$

Kinetic mixing:
Mediator obtains photon-like couplings

Mass mixing:
Mediator obtains Z-like couplings



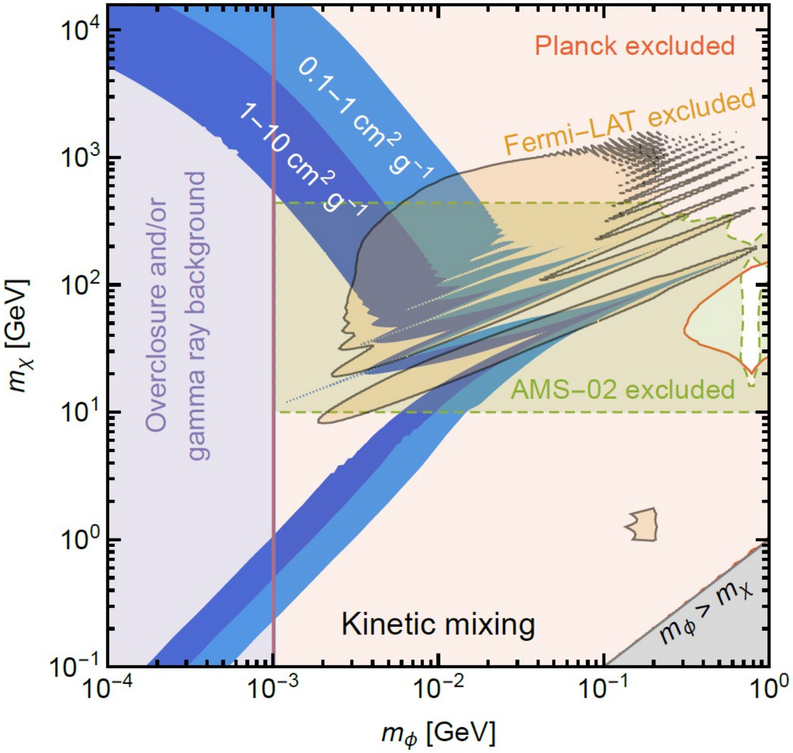
Curtin et al., arXiv:1412.0018

- Main difference:
  - A gauge boson with kinetic mixing is effectively stable below the electron threshold.
  - Mass mixing induces sizeable decay rates into neutrinos

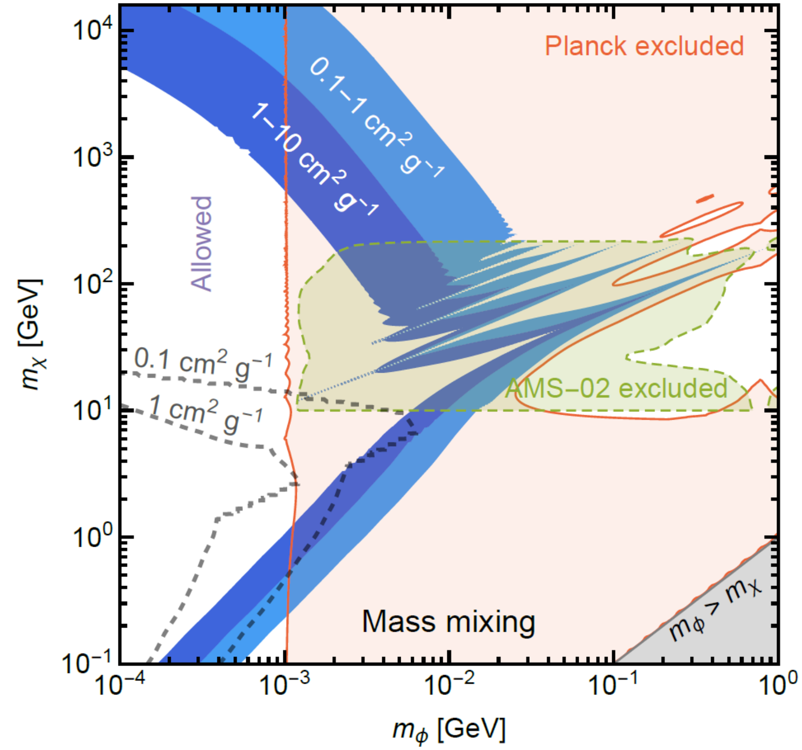
Constraints on vector mediators

- 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



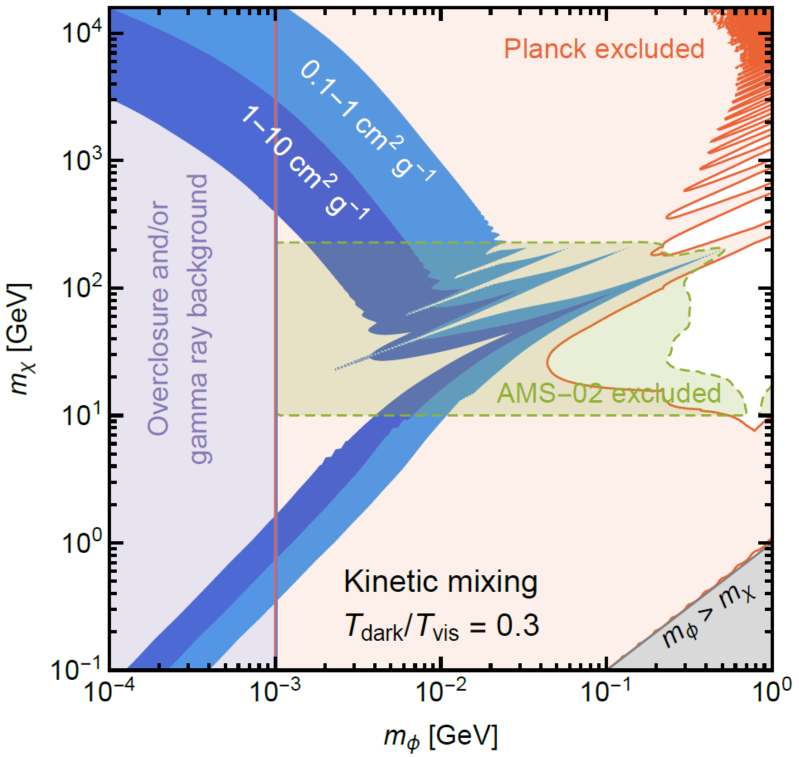
Bringmann et al., arXiv:1612.00845



Constraints on vector mediators

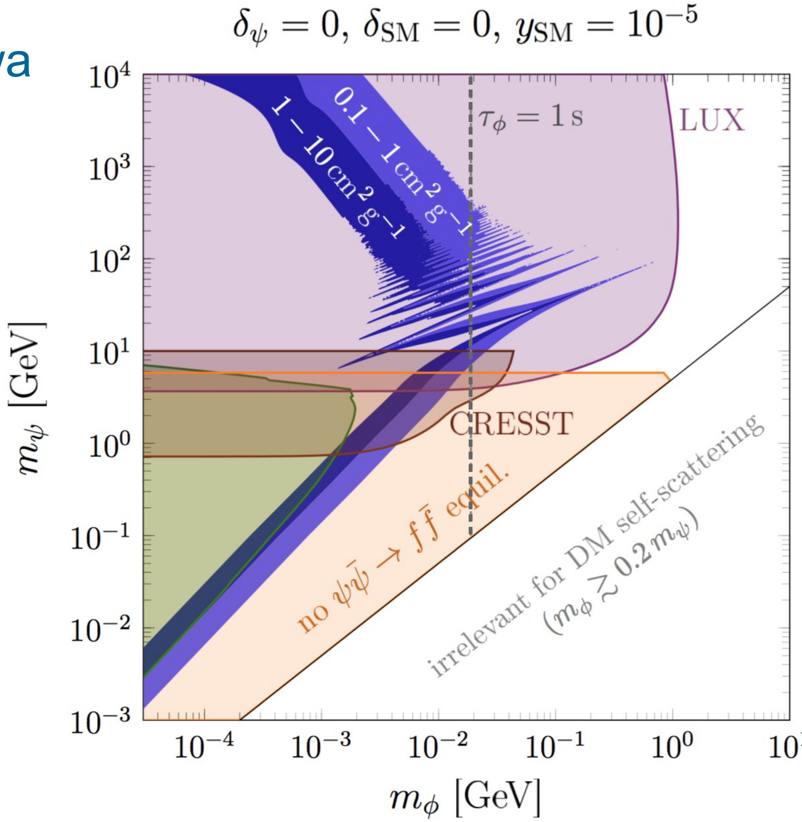
- Only assumption: The two sectors have the same temperature during freeze out.
- But even for different temperatures in the two sectors there are very strong constraints.

Bringmann et al., arXiv:1612.00845



Constraints on scalar mediators

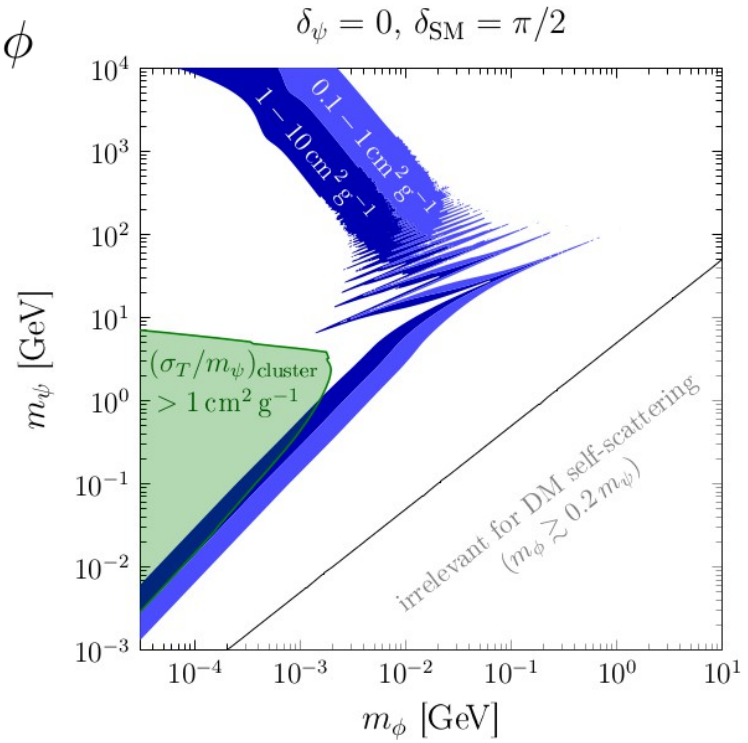
- For fermionic DM and scalar mediators annihilation proceeds via p-wave
- No constraints from indirect detection or the CMB.
- Direct detection constraints are very strong for scalar mediators.
- Lifetime rather long due to Yukawa suppression
- Naive BBN bound: τ < 1 s
- Impossible to satisfy all requirements and have large self-interaction cross sections.



1704.02149

A mixed mediator (CP violation)

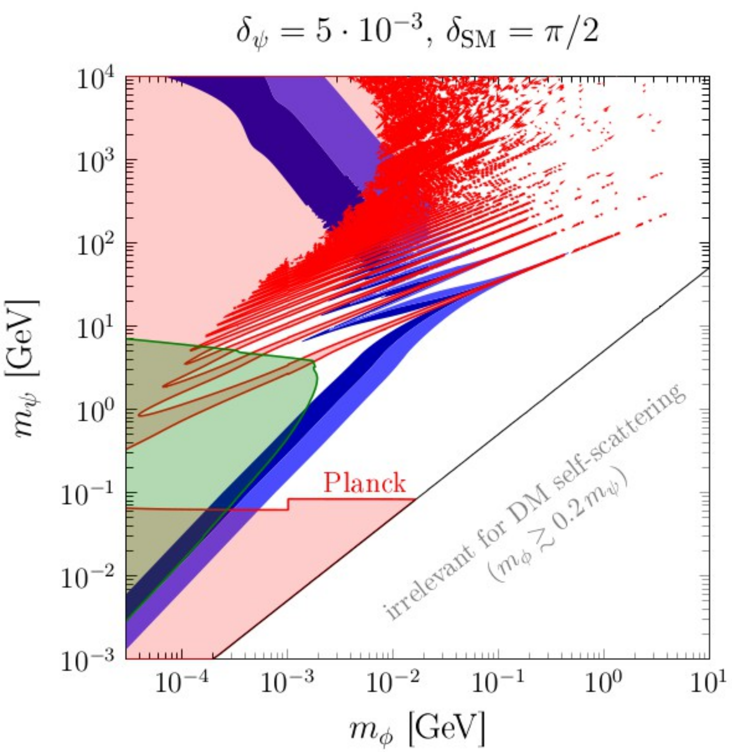
$$\mathcal{L}_{\rm DM} \supset y_\psi \cos\delta_\psi \; \bar\psi\psi\phi \; + \; y_\psi \sin\delta_\psi \; i\bar\psi\gamma^5\psi\phi$$

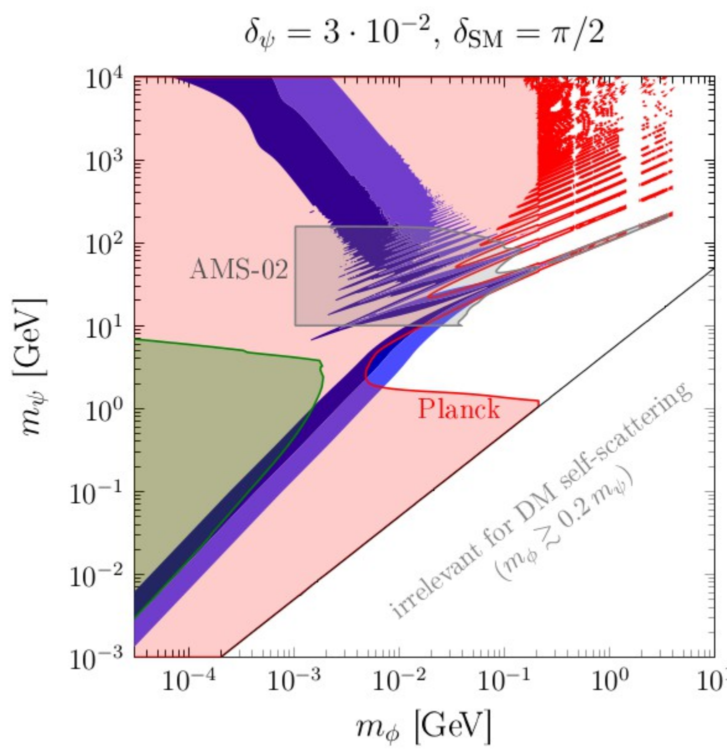


- For $\delta_\psi \sim 0$ (like a scalar) DM self-interactions can be large.
- For $\delta_{\rm SM} \sim \pi/2$ (like a pseudoscalar) direct detection constraints are strongly suppressed.
- Large allowed parameter space!
- Constraints on the CP-violating phase $\delta_{\rm SM}$ (e.g. from electron EDMs) can be satisfied even for very light mediators as long as $y_{\rm SM}$ is sufficiently small ($y_{\rm SM} \ll 10^{-2}$).

The return of CMB constraints

- Central problem: The fact that annihilation can only proceed via p-wave was a consequence of CP conservation.
- As soon as δ_ψ is not exactly zero, s-wave annihilation is again possible and will receive large Sommerfeld enhancement.





Future directions for light mediators

- There are a number of ways to evade the various constraints
  - Inert decays of the mediator, for example into (sterile) neutrinos
  - Thermalization via a different mechanism (possibly leading to different temperatures during freeze-out)
  - No thermalization (DM production via the freeze-in mechanism)

Bernal et al., arXiv:1510.08063

  - Suppressed couplings to quarks (to evade direct detection constraints)
- 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!

Summary

- Self interacting dark matter could solve some problems of the collisionless cold dark matter paradigm and can arise naturally in more complex dark sectors
- Orthogonal handle on properties of DM: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.
- Can potentially distinguish effective drag forces (from frequent self-interactions) and rare self-interactions
- Also could infer the velocity dependence of the cross section.
- The simplest possibilities (scalar or vector mediator coupling to fermionic dark matter with no additional new states) are in strong tension with direct and indirect detection experiments.
- One simple way out is spontaneous CP violation in the dark sector
- Huge possible impact, ruling out WIMPs, axions, gravitinos,...

Thank you!