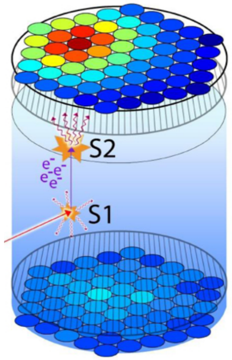
Self-interacting dark matter:
Current status and perspectives

Kai Schmidt-Hoberg

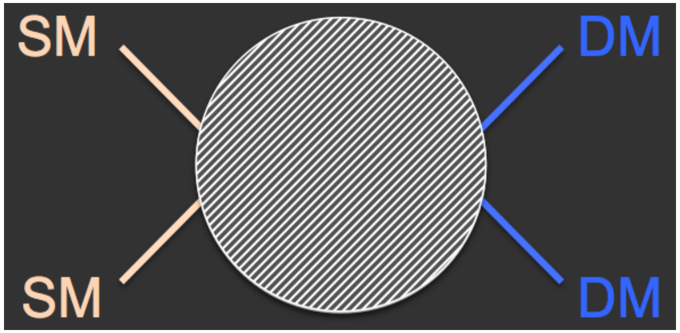
partially based on work with
T Bringmann, M Duerr, M Frandsen, F Kahlhoefer, J Kummer,
S Sarkar, P Walia, S Wild

A global view on dark matter interactions...

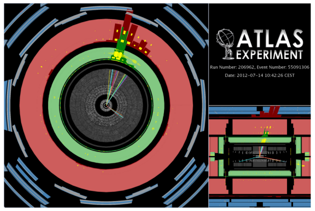
Indirect detection

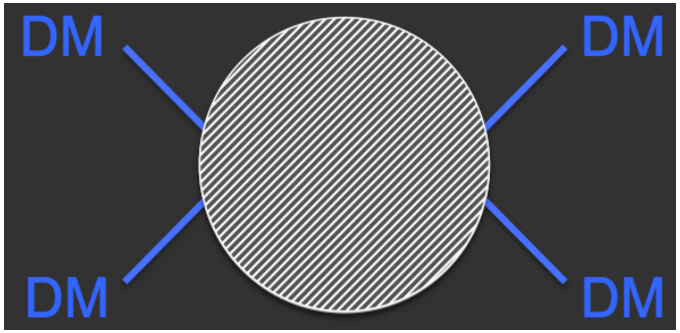


Direct detection



Collider searches



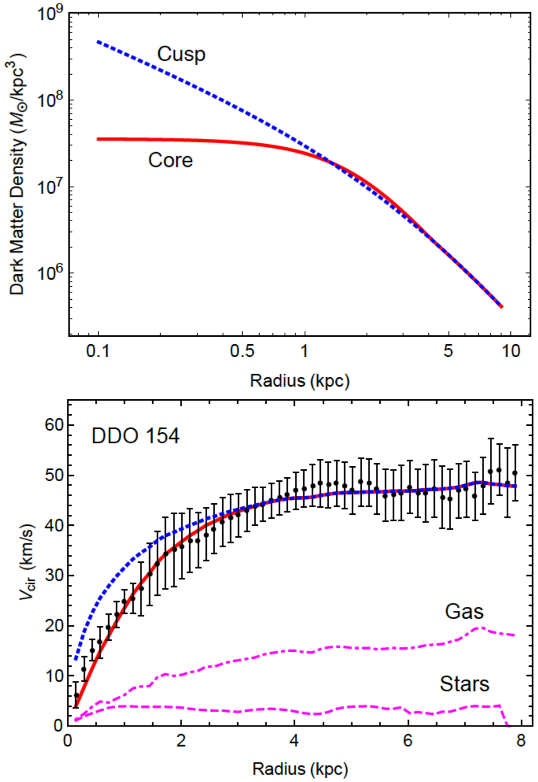


DM self-interactions

This talk

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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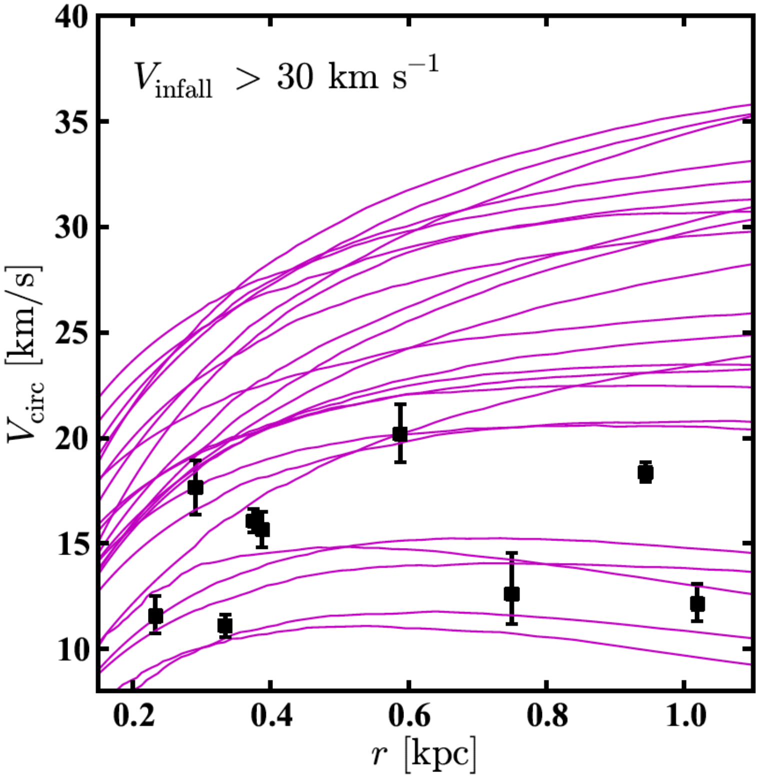

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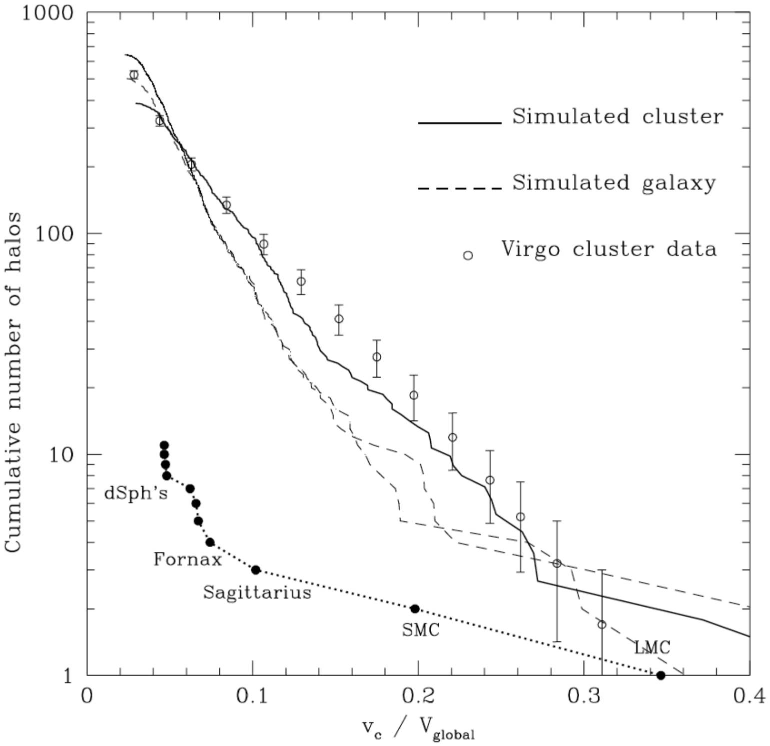
  - Missing-satellite problem

(or maybe not...)

Kim, Peter, Hargis, 1711.06267



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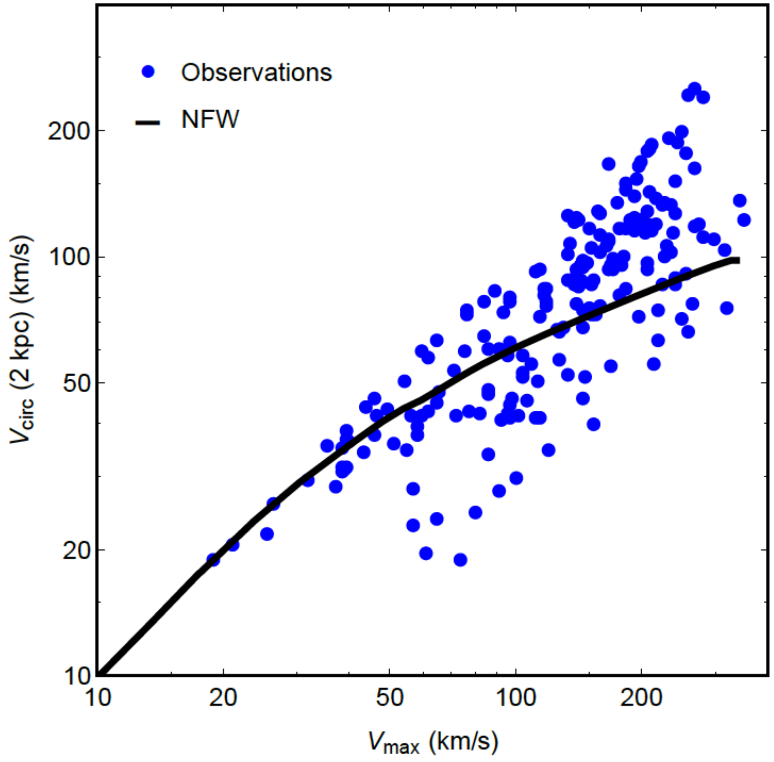
  - Diversity problem



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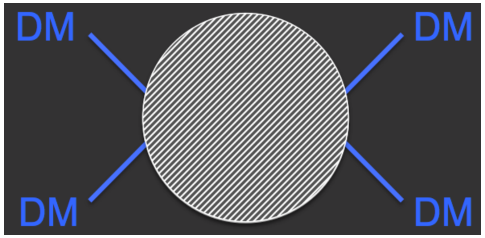

DM self-interactions may solve some (or all) of these problems

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

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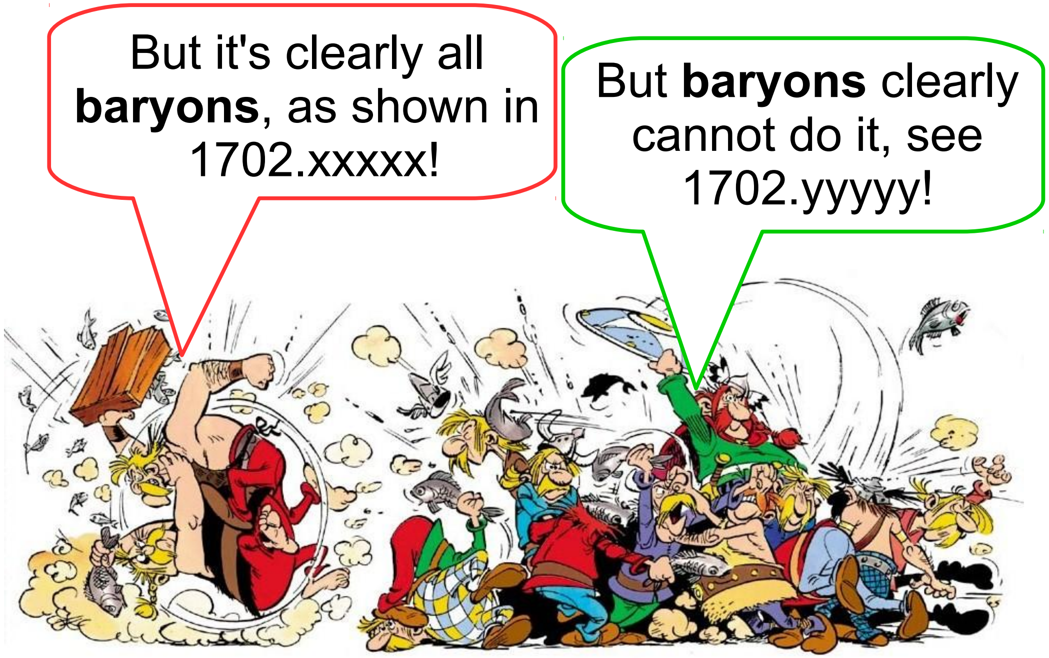


Spergel & Steinhard: astro-ph/9909386
Aarsen, Bringmann, Pfrommer, 1205.5809

How large a cross section?

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

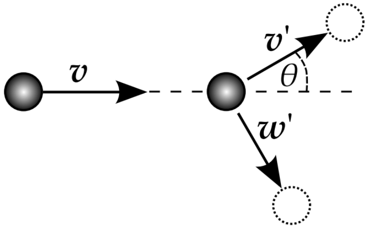
$$\sigma / m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns}/\mathrm{GeV}$$

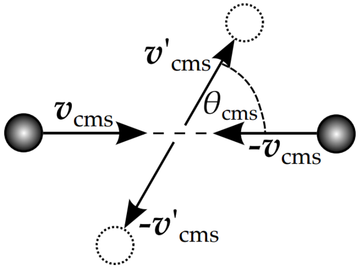
- The nucleon nucleon scattering cross section ~20 barns at low energies
- The typical cross section of a WIMP is 20 orders of magnitude smaller!

- **Potential impact:** Evidence for DM self-interactions on astrophysical scales would rule out many popular models for DM, such as supersymmetric WIMPs, gravitinos, axions…

The particle physics perspective

- Assume 2 → 2 elastic scattering





- The scattering cross-section can have an **angular** and a **velocity** dependence

- Effective momentum transfer is given by

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

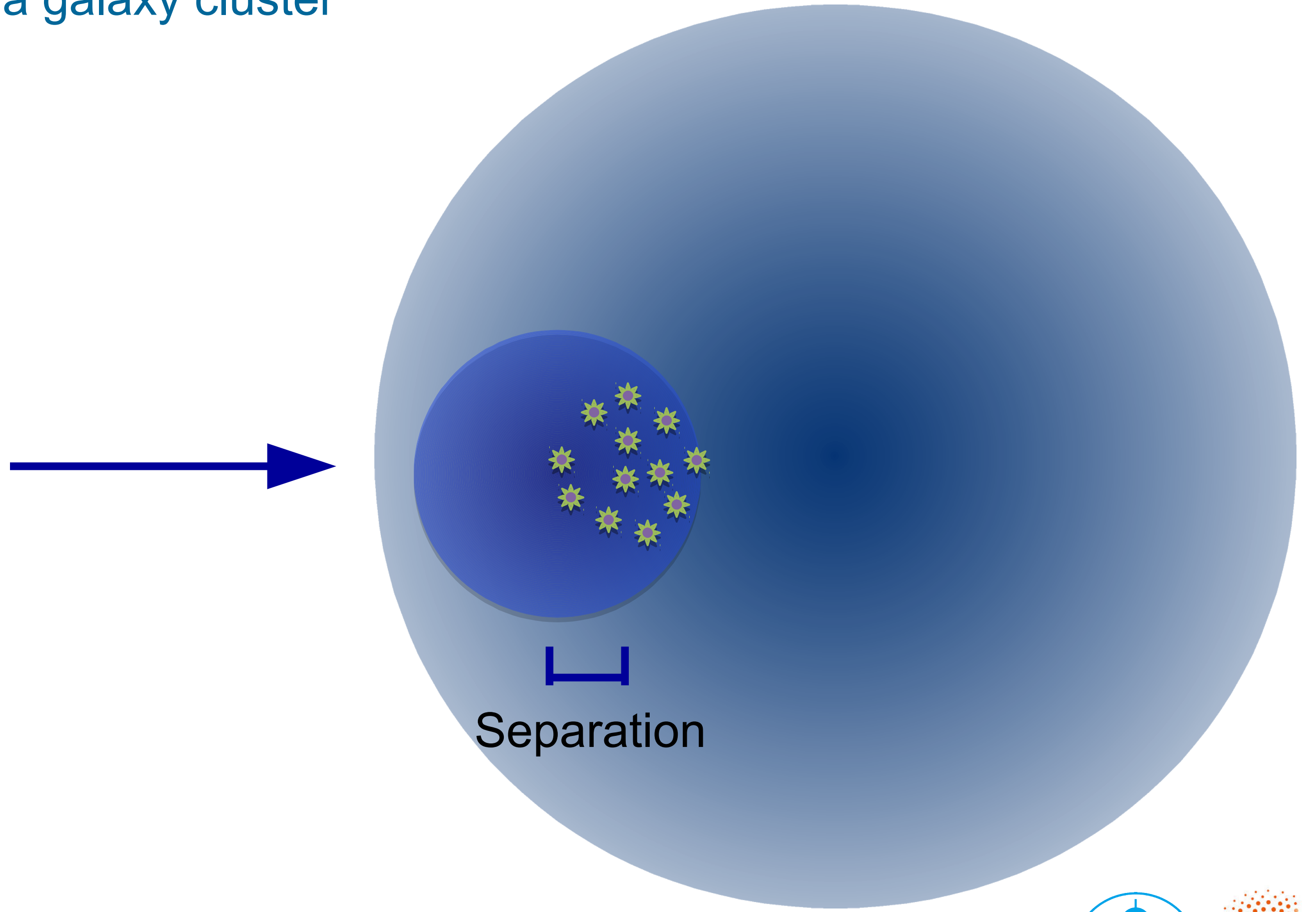
- This is the quantity typically studied (and implemented in N-body simulations)

- 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)

- Can result in different observable effects

A smoking gun observable

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



Smoking gun?

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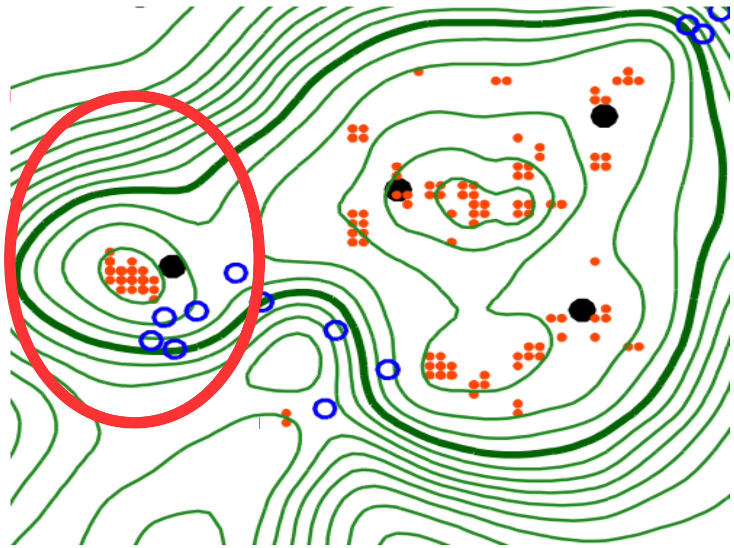
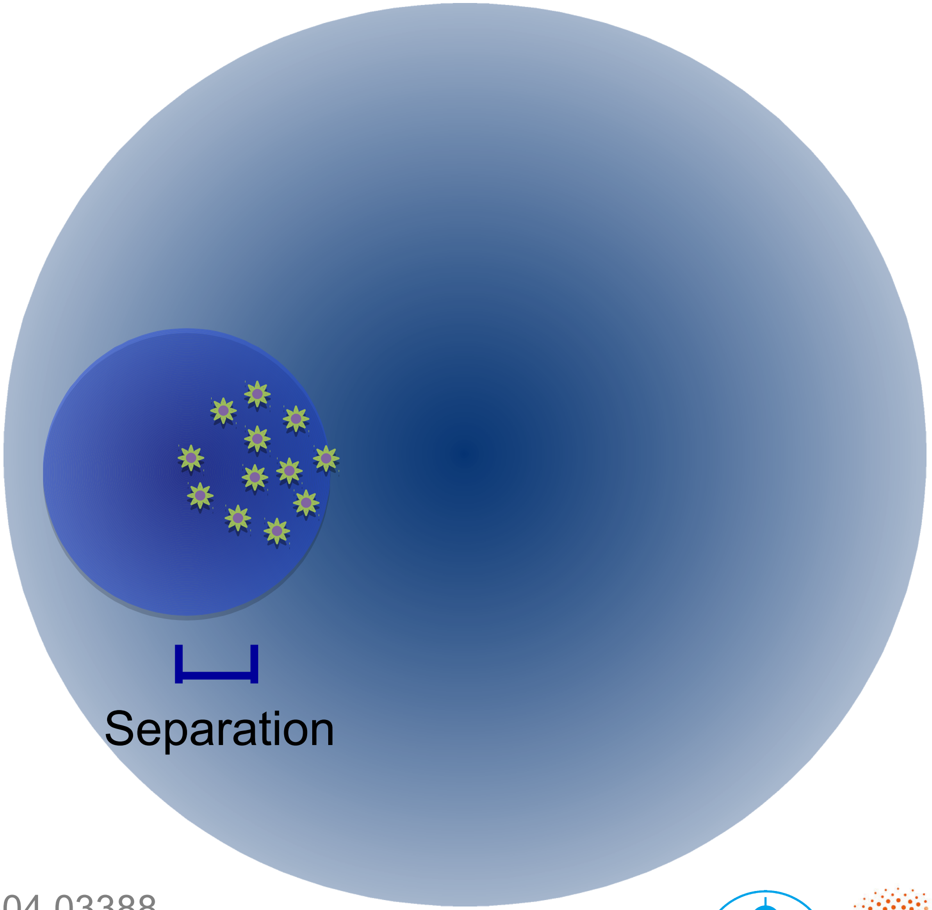
Observed offset: 1.62+/-0.48kpc





- Observed in 2015 in **A3827**

Massey et al., arXiv:1504.03388

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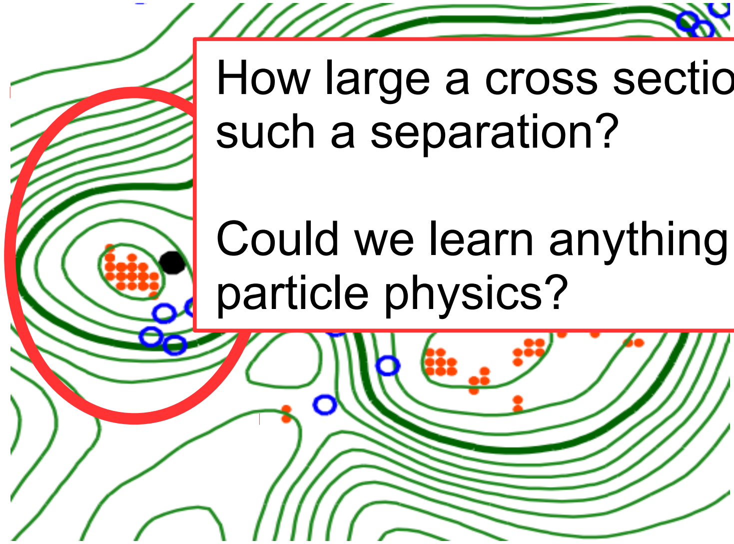
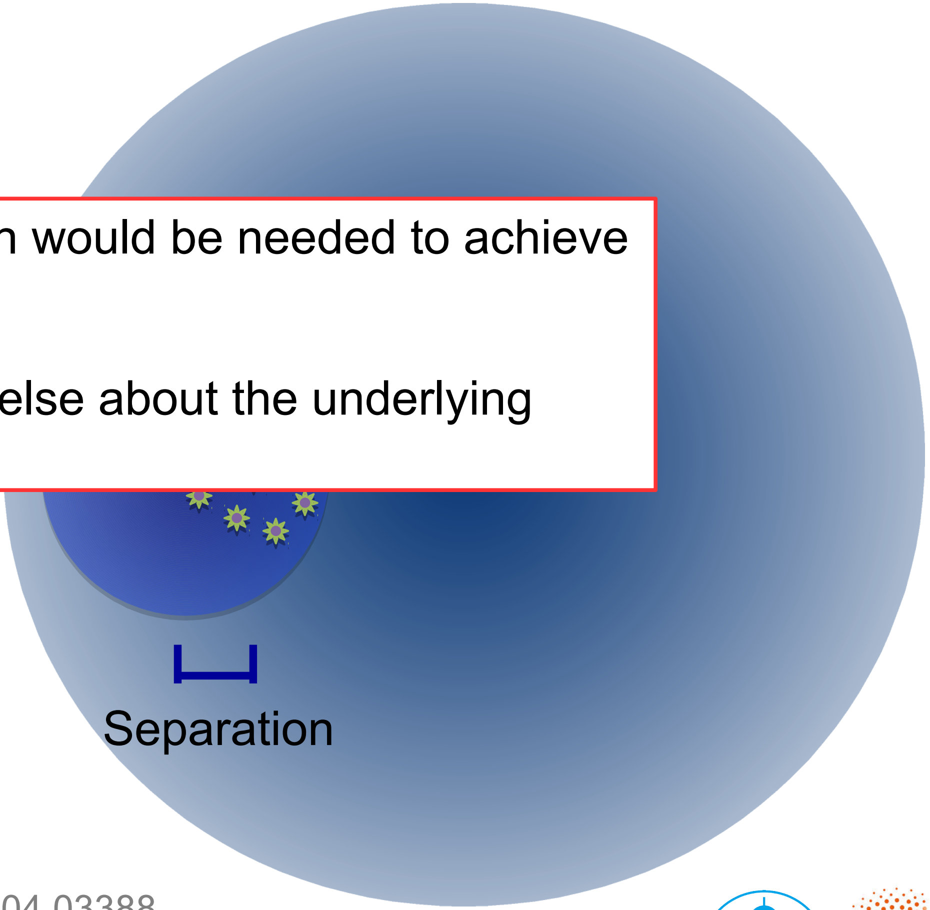


How large a cross section would be needed to achieve such a separation?

Could we learn anything else about the underlying particle physics?



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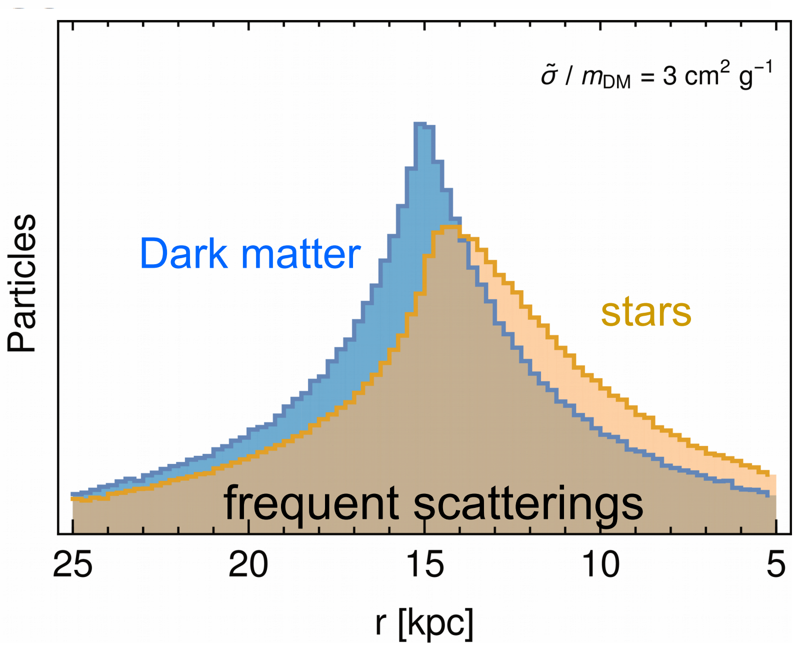
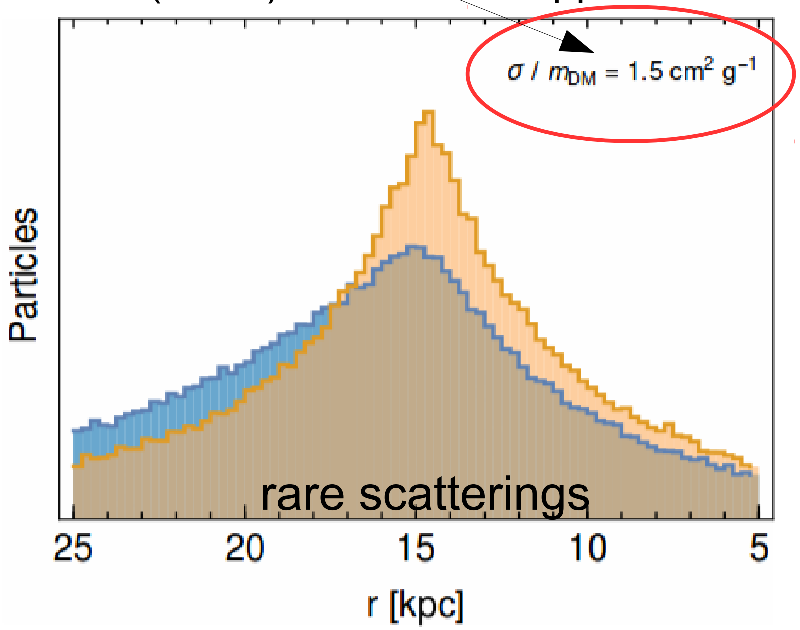
Infalling galaxy in A3827

Kahlhoefer et al, 1504.06576

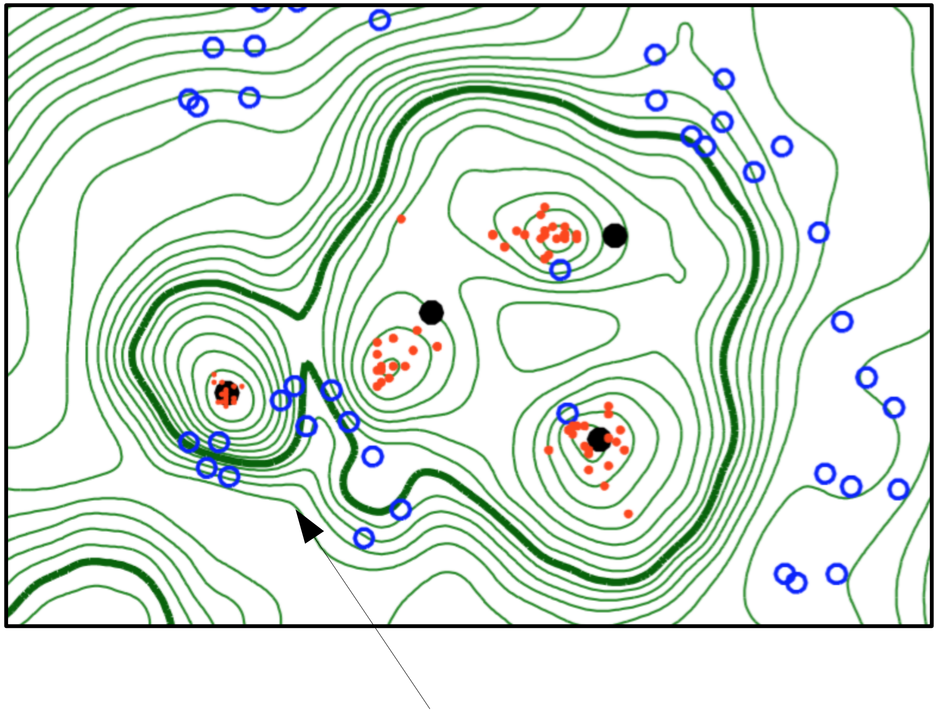


A3827: In (some) tension with upper bounds



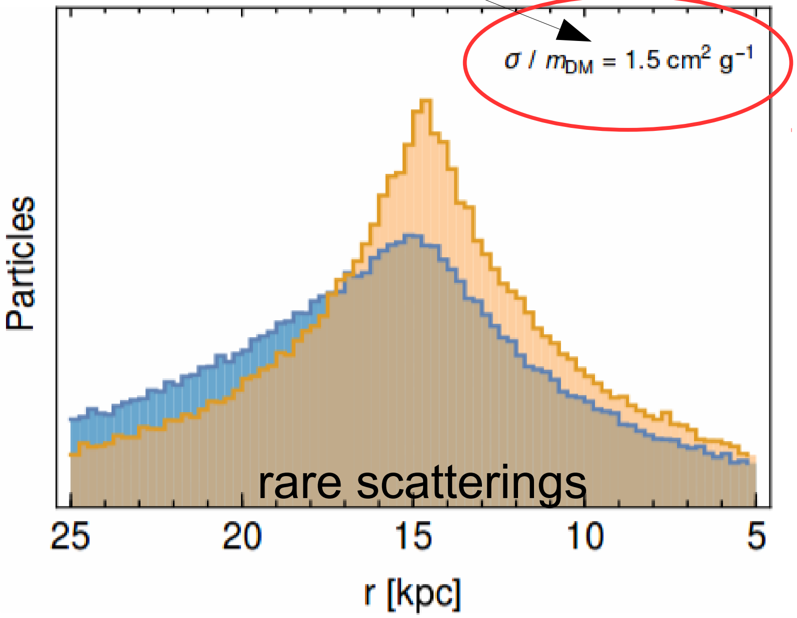
Infalling galaxy in A3827

R Massey, talk at SIDM17



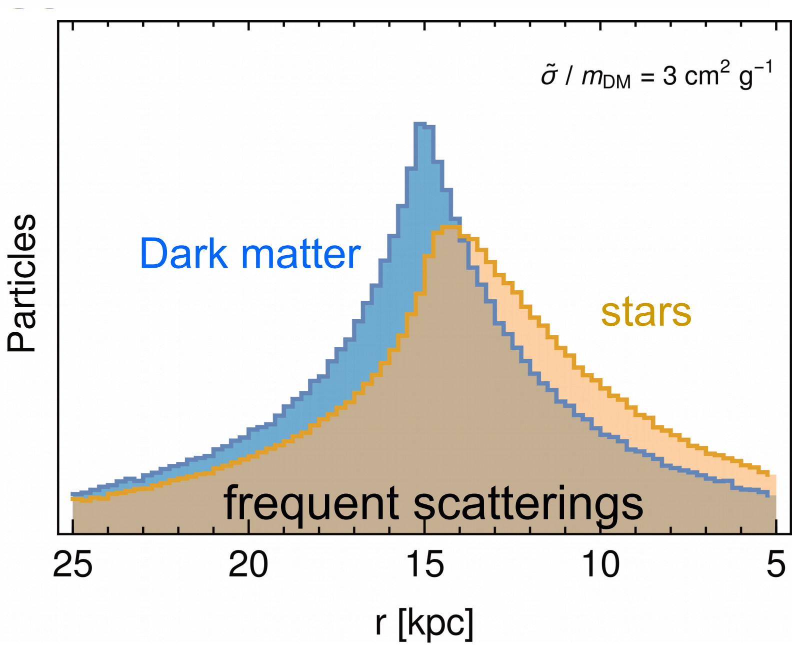
Reanalysis from 2017 – offset gone :-(

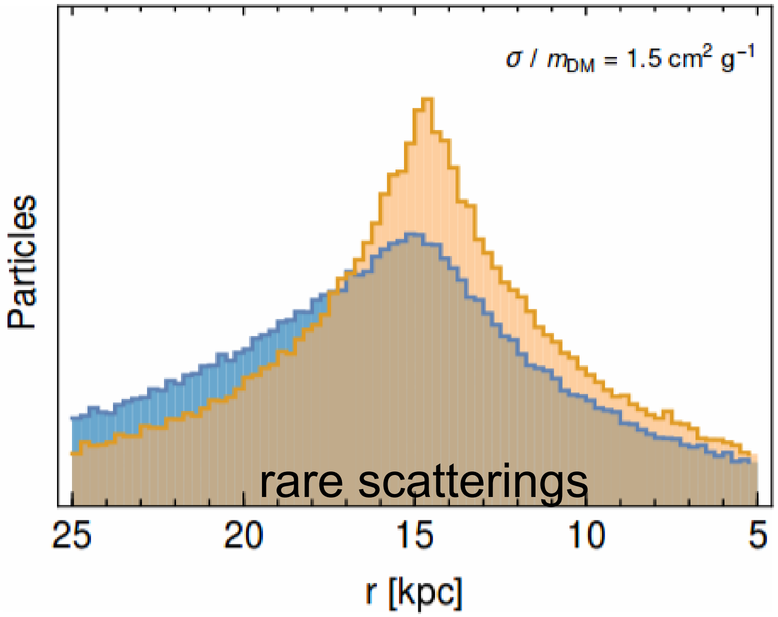
A3827: In (some) tension with upper bounds



More generally: Distinguishing different types of SIDM

Kahlhoefer et al, 1504.06576



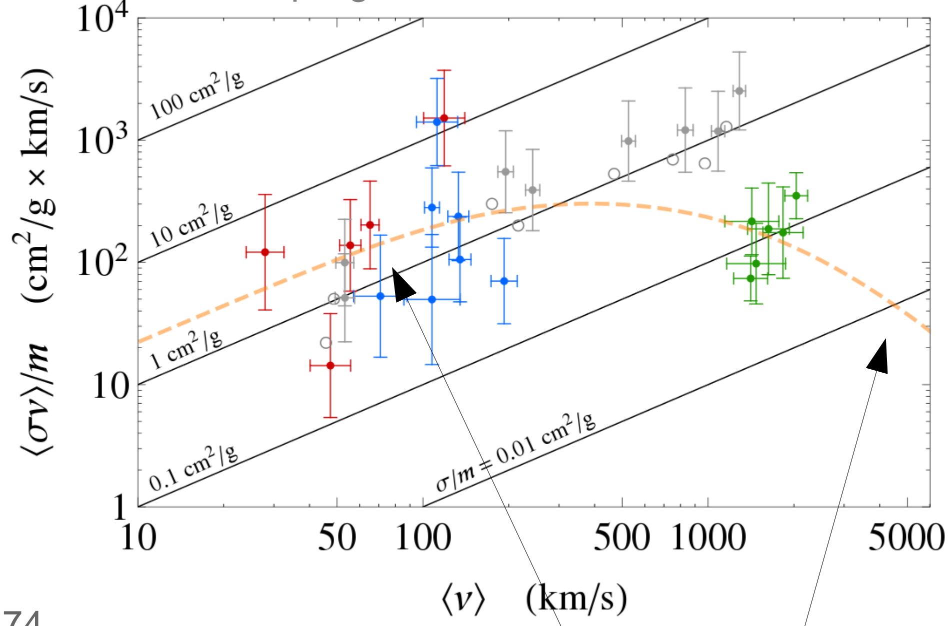


- **Effective drag force:** the DM subhalo retains its shape, while the distribution of stars are both shifted and deformed.
- **Contact interactions**: the DM subhalo is deformed due to the scattered DM particles leaving the subhalo in the backward direction.
- Potentially distinguishable (but very tough)!
- At this point no indication either way...what about the velocity dependence?

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

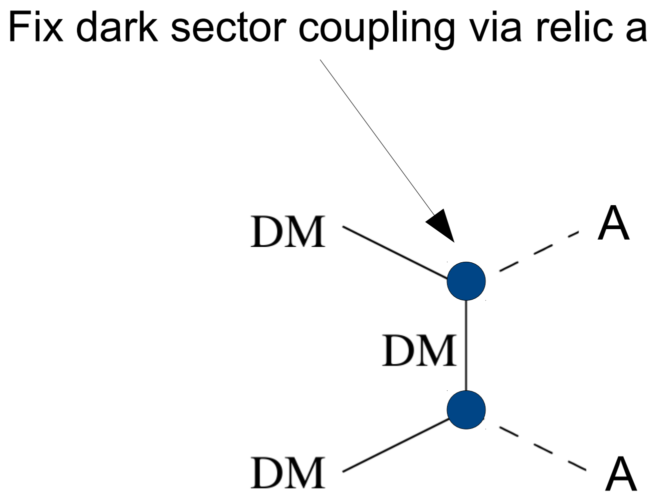


Kaplinghat et al., arXiv:1508.03339

- Scales as $1/(q^2 + m_{\text{med}}^2)^2$
  - 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):



Fix dark sector coupling via relic abundance

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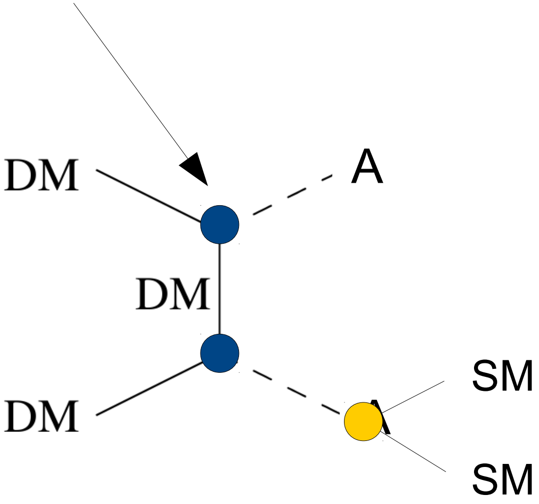
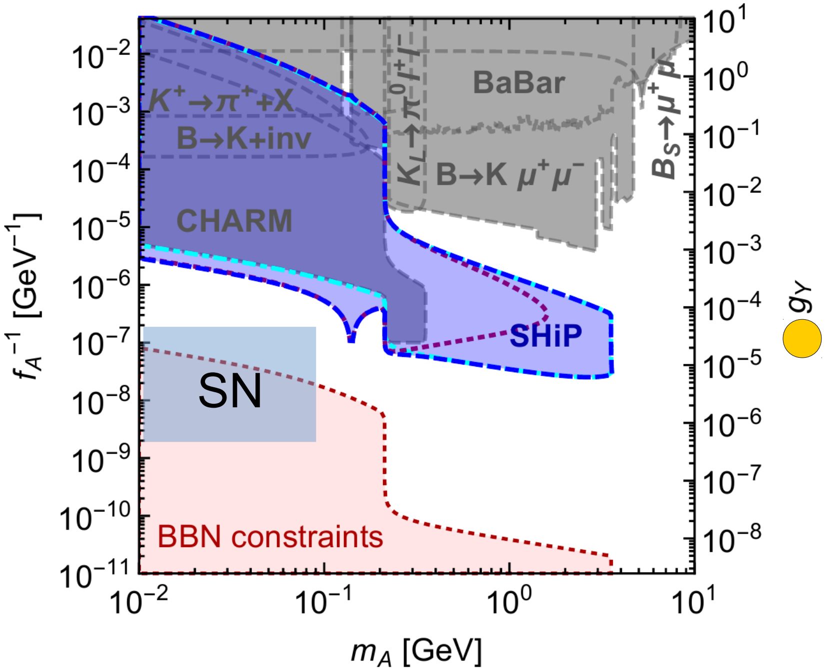




- To avoid overclosing the Universe, the mediator should ultimately disappear, so its couplings to SM states cannot be arbitrarily small – many constraints

DM annihilations – s-wave vs. p-wave

- At freeze out dark matter is semi-relativistic, in the later Universe it is non-relativistic.
- Annihilation cross section can depend on relative velocity
- Make expansion in velocity

$$\sigma\, v_{\rm rel} \;=\; \sigma_0 + \sigma_1\, v_{\rm rel}^2 + \mathcal{O}\left(v_{\rm rel}^4\right)$$

s-wave
(vector mediator)

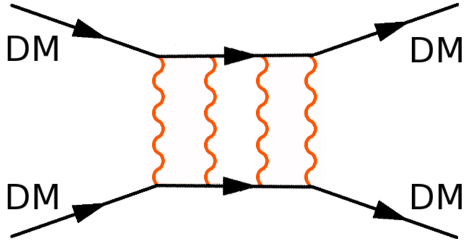
p-wave
(scalar mediator)

- Both terms contribute at freeze-out. Later p-wave is very suppressed...

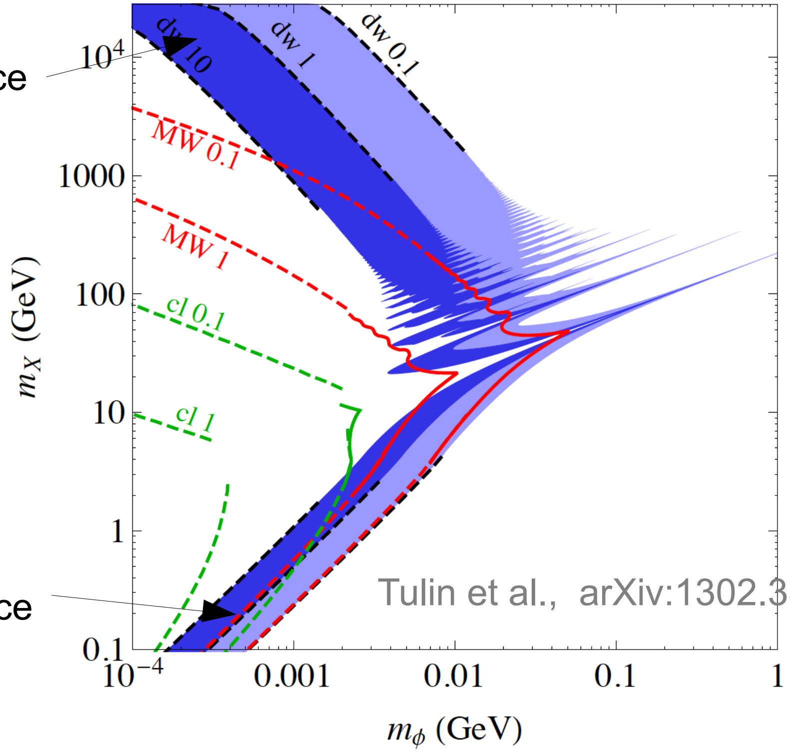
Enhancement of DM self-interactions

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

- Scalar and vector mediators
  → Yukawa potential



Dark matter with relic density (s−wave)



strong velocity dependence

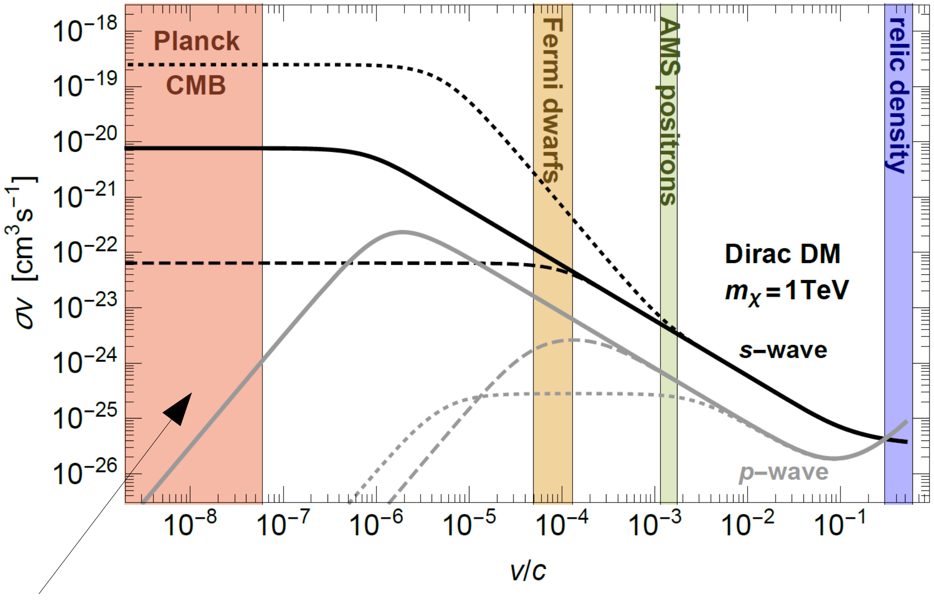
weak velocity dependence

Tulin et al., arXiv:1302.3898

Enhancement of DM annihilations

- Significant non-perturbative corrections to the tree-level annihilation rate (Sommerfeld enhancement).
- Effects small during freeze-out, but increase with decreasing DM velocity.

Bringmann et al., arXiv:1612.00845

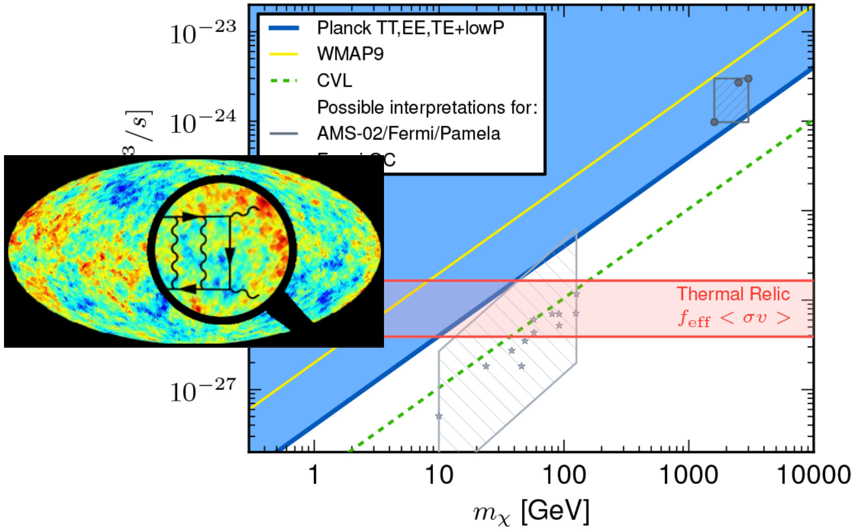


During recombination dark matter particles move at walking speed.

Constraints on DM self-interactions

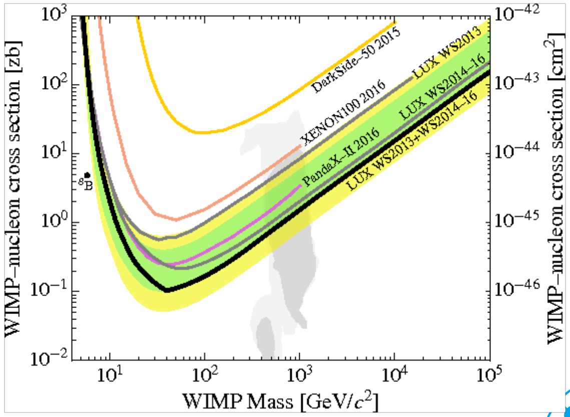
- DM annihilations during recombination, followed by mediator decays into SM particles, inject energetic electrons and photons into the plasma.

  → very strong constraints for s-wave annihilation



- DM-nucleon scattering cross section also scales as $1/(q^2 + m_{\rm med}{}^2)^2$

- strongly enhanced for light mediators!



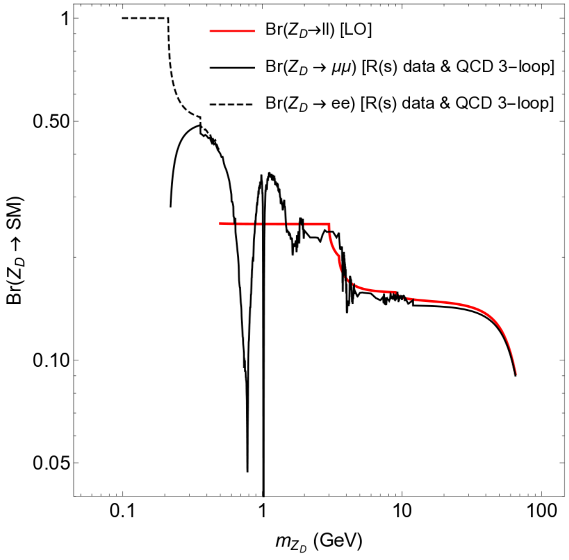
Vector mediators

- 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

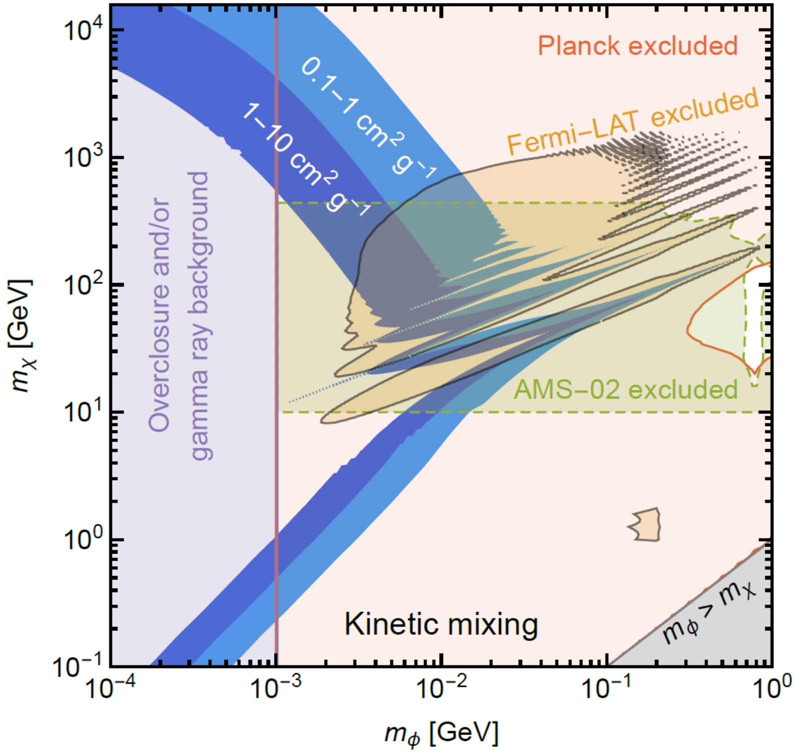


Curtin et al., arXiv:1412.0018

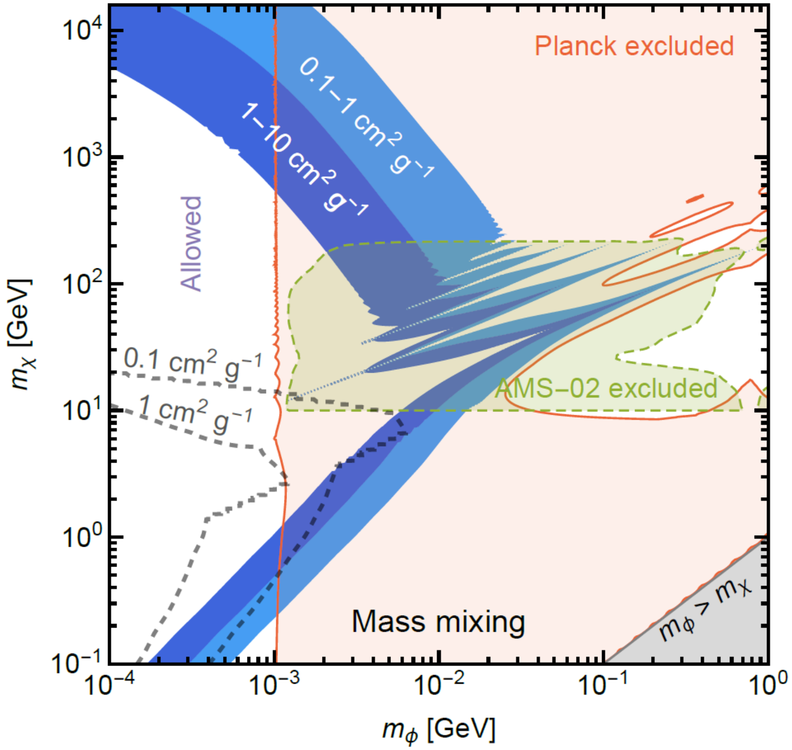
- Main difference:
  - A gauge boson with kinetic mixing is effectively stable below the electron threshold.
  - Mass mixing induces sizable decay rates into neutrinos

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



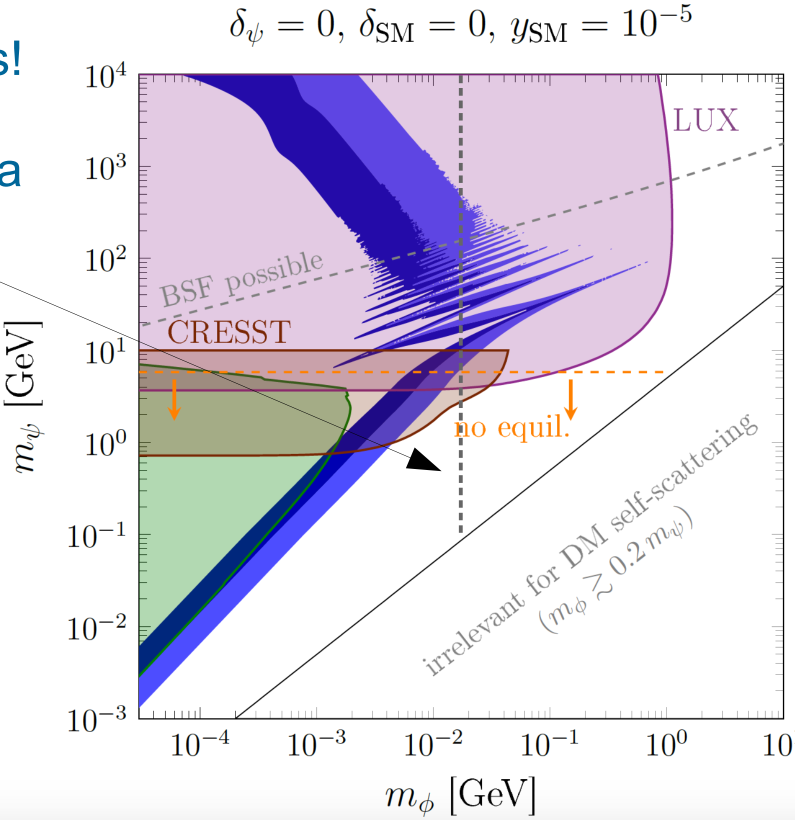
Bringmann et al., arXiv:1612.00845



Bringmann et al., arXiv:1612.00845

Constraints on scalar mediators

- Consider scalar mediator with Higgs mixing (→ Yukawa-like couplings)
- Annihilation proceeds via p-wave
- No constraints from indirect detection or the CMB.
- Strong direct detection constraints!
- Lifetime rather long due to Yukawa suppression
- Naive BBN bound: τ < 1 s
- How does this depend on ySM?



$\delta_\psi = 0,\ \delta_{\rm SM} = 0,\ y_{\rm SM} = 10^{-5}$

1704.02149

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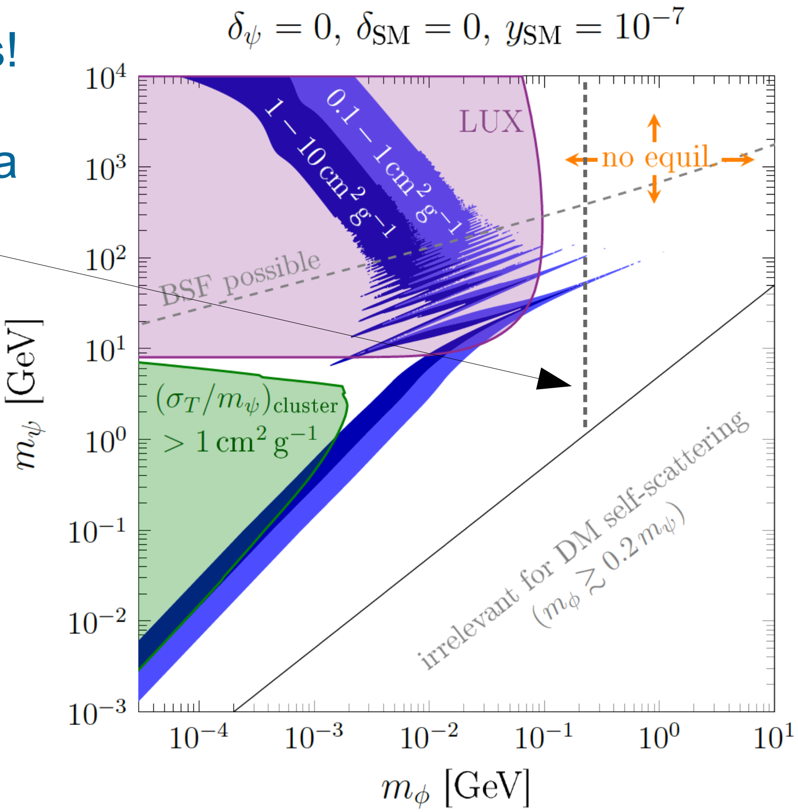
- Requires dedicated BBN study!



$\delta_\psi = 0,\ \delta_{\mathrm{SM}} = 0,\ y_{\mathrm{SM}} = 10^{-7}$

1704.02149

Ways out for light mediators

- There are a number of ways to evade the various constraints
  - Mixed scalar/pseudoscalar couplings (CP violation)
    Kahlhoefer, KSH, Wild; 1704.02149
  - Inert decays of the mediator, for example into (sterile) neutrinos
    Hufnagel, KSH, Wild; 1712.03972
  - Stable mediator (which largely annihilates away)
    Ma, 1704.04666
  - 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
  - Asymmetric dark matter
    Baldes et al., 1712.07489
- 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
- Some preference for a velocity dependence of the cross section.
- The simplest possibilities (scalar or vector mediator with no additional new states) are in strong tension with direct and indirect detection experiments.
- A couple of ways around this conclusion, interesting model building
- Huge possible impact, ruling out WIMPs, axions, gravitinos,...

Thank you!

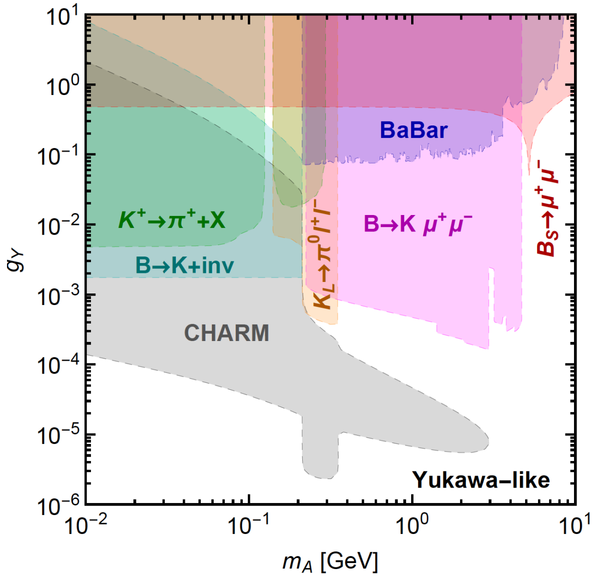
Pseudoscalar mediators

$$\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar\chi \gamma^5 \chi \qquad\qquad \mathcal{L}_{\rm SM}^{(Y)} = i\, g_Y \sum_{f=q,\ell} \frac{\sqrt{2}\, m_f}{v} A\, \bar f \gamma^5 f$$

- In the non-relativistic limit, scattering via the exchange of pseudoscalar mediators is strongly suppressed by powers of the momentum transfer.

- Direct detection constraints are therefore effectively absent 🤗

- The same effect suppresses DM self-scattering 😥



Dolan et al., arXiv:1412.5174

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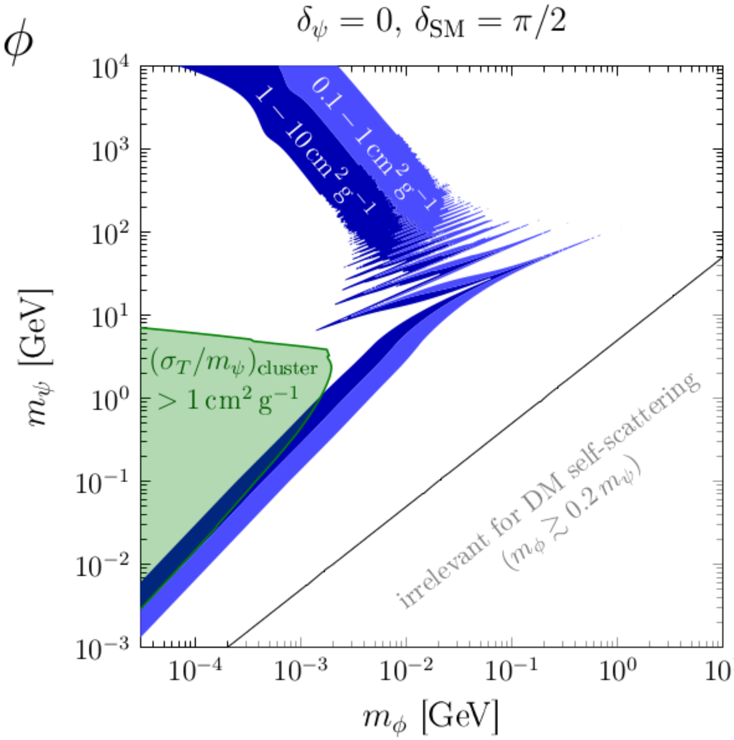
Idea: A mixed mediator (CP violation)

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

- For $\delta_\psi \sim 0$ (like a scalar) DM self-interactions can be large.
- For $\delta_{\mathrm{SM}} \sim \pi/2$ (like a pseudoscalar) direct detection constraints are strongly suppressed.
- Large allowed parameter space!



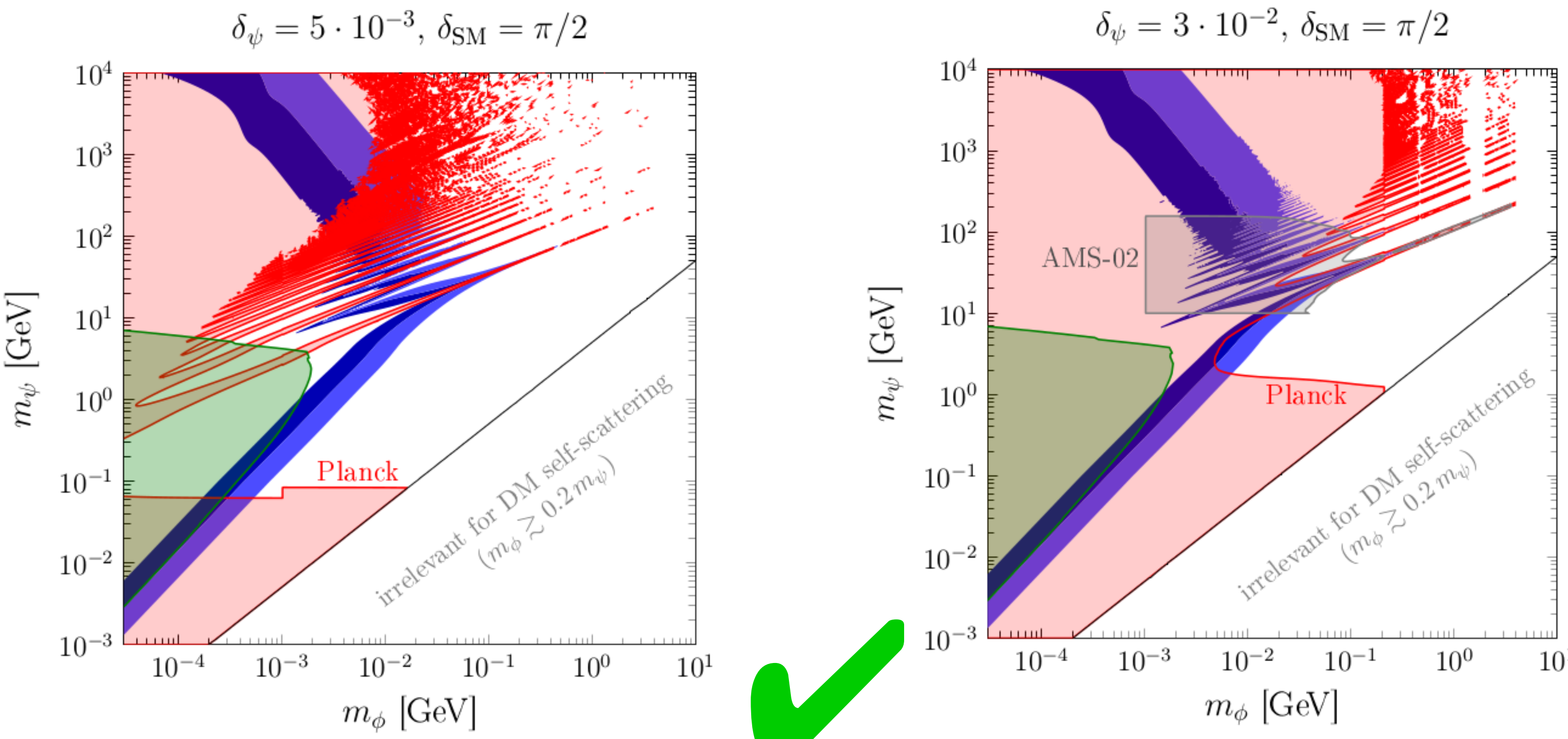
Kahlhoefer, KSH, Wild; 1704.02149

- Constraints on the CP-violating phase δ_{SM} (e.g. from electron EDMs) can be satisfied even for very light mediators as long as y_{SM} is sufficiently small ($y_{\mathrm{SM}} \ll 10^{-2}$).

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.

Kahlhoefer, KSH, Wild; 1704.02149



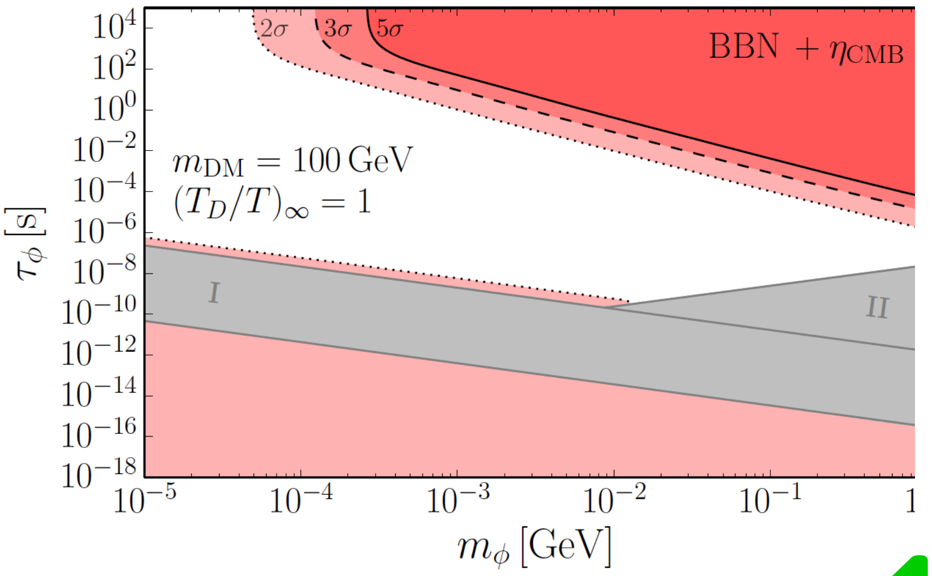
$\delta_\psi = 5 \cdot 10^{-3}$, $\delta_{\mathrm{SM}} = \pi/2$

$\delta_\psi = 3 \cdot 10^{-2}$, $\delta_{\mathrm{SM}} = \pi/2$

✓

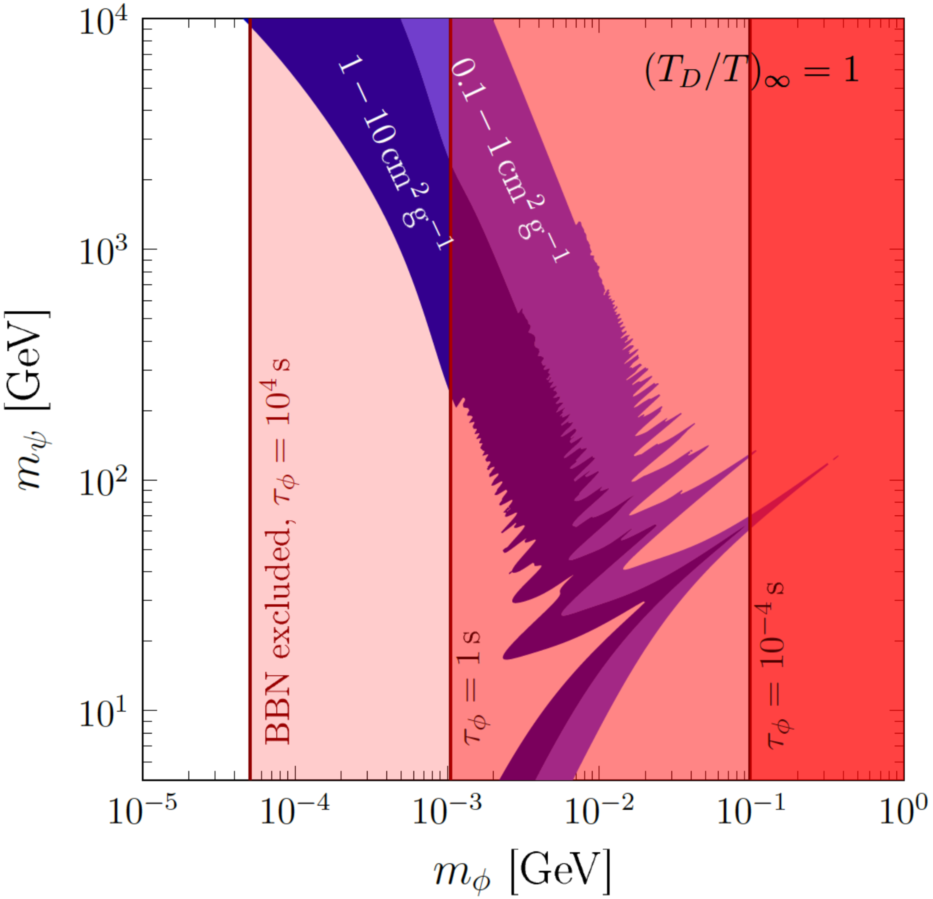
Inert decays of the mediator

- Assume vector mediator couples mainly to sterile neutrinos
- Extra energy contribution which affects the expansion rate H
- Changes predictions for BBN



Hufnagel, KSH, Wild; 1712.03972

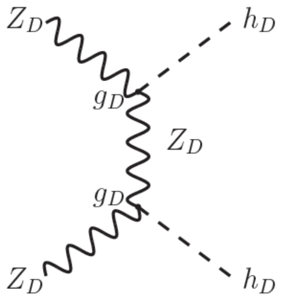
✓

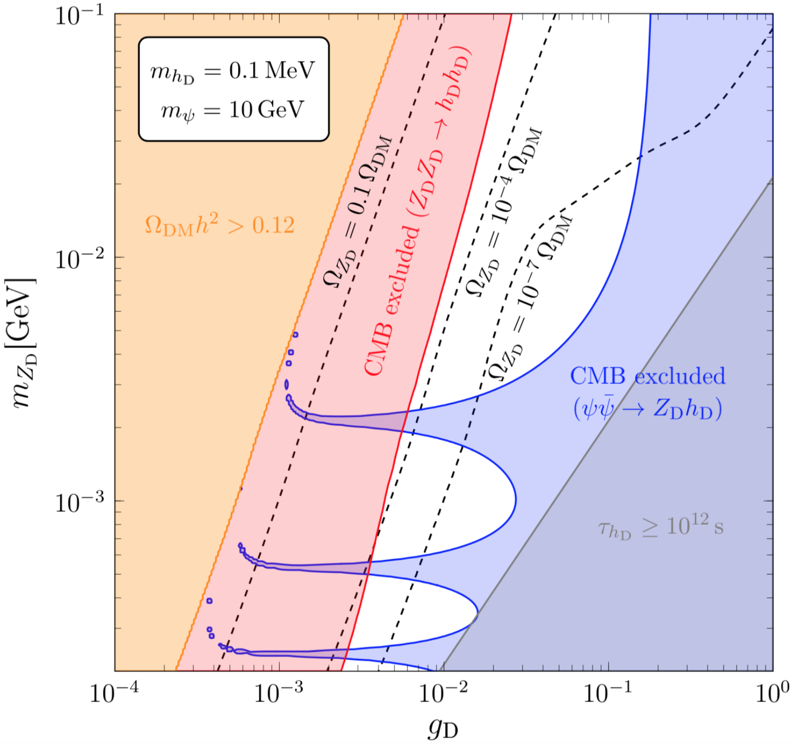


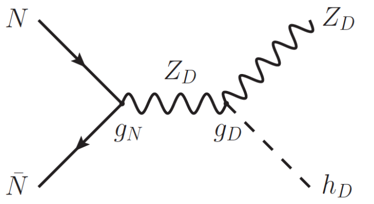
Stable mediator

Ma, 1704.04666

- Assume vector mediator Z_D is stable
- Introduce dark Higgs h_D to give mass, decays via mixing with SM Higgs
- Still constraints from CMB due to Higgs decays, but not ruled out







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[in preparation with M Duerr, S Wild]