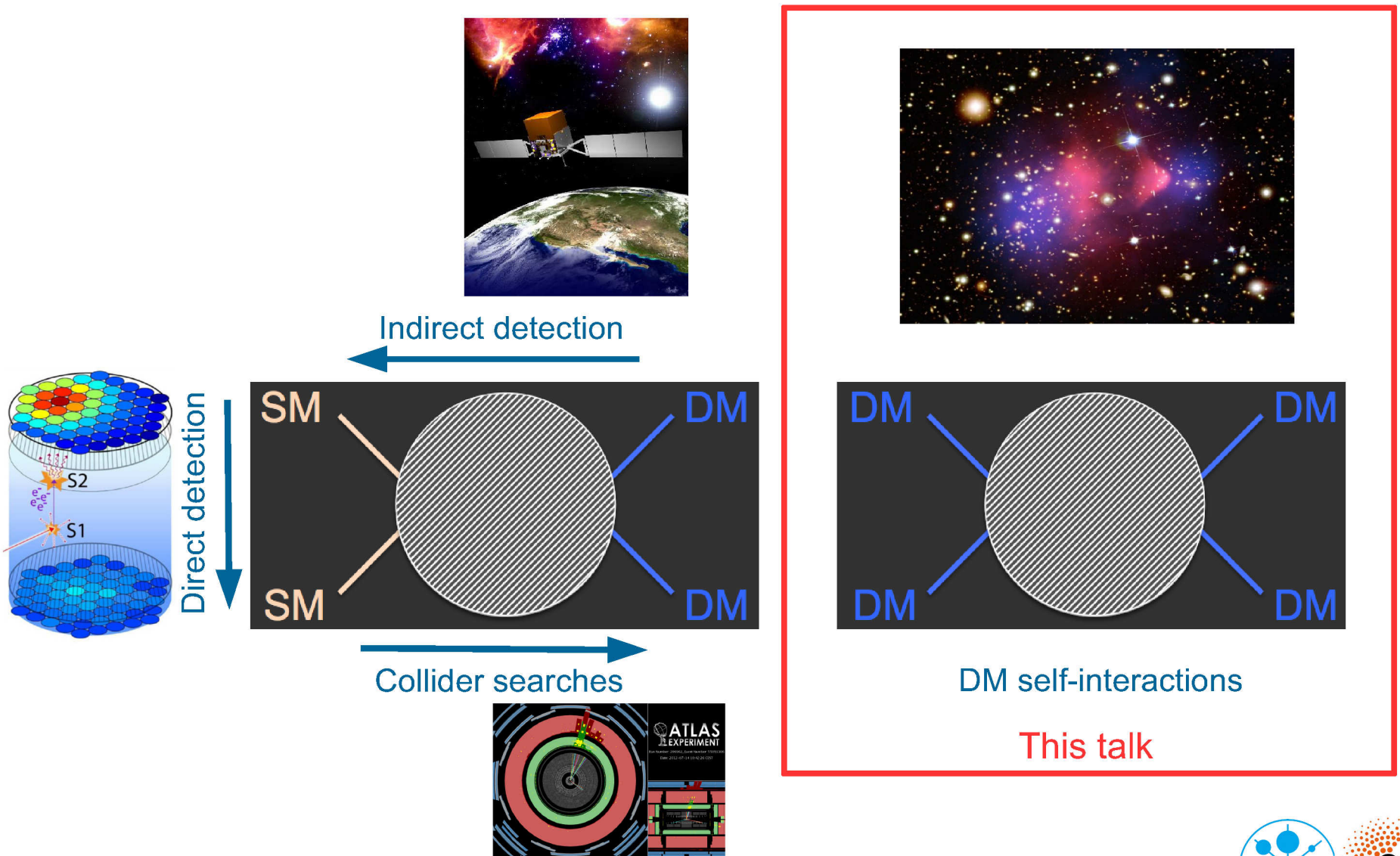


Self-interacting dark matter: Current status and perspectives

Kai Schmidt-Hoberg

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

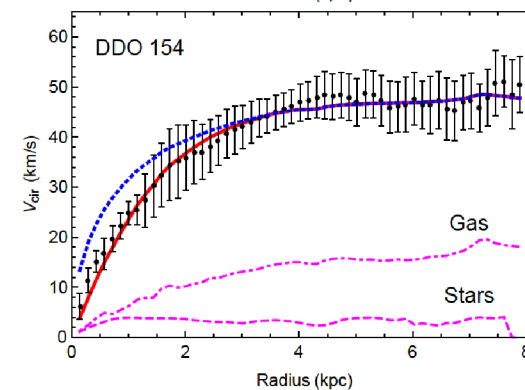
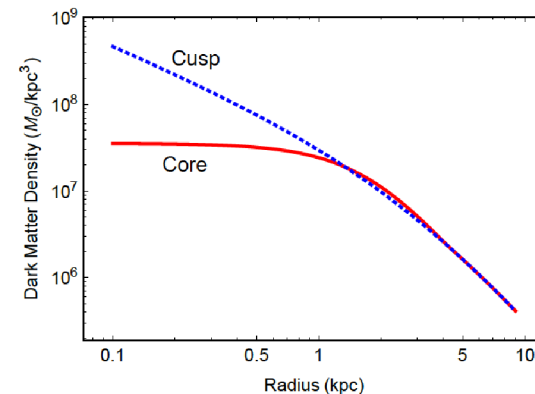
A global view on dark matter interactions...



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

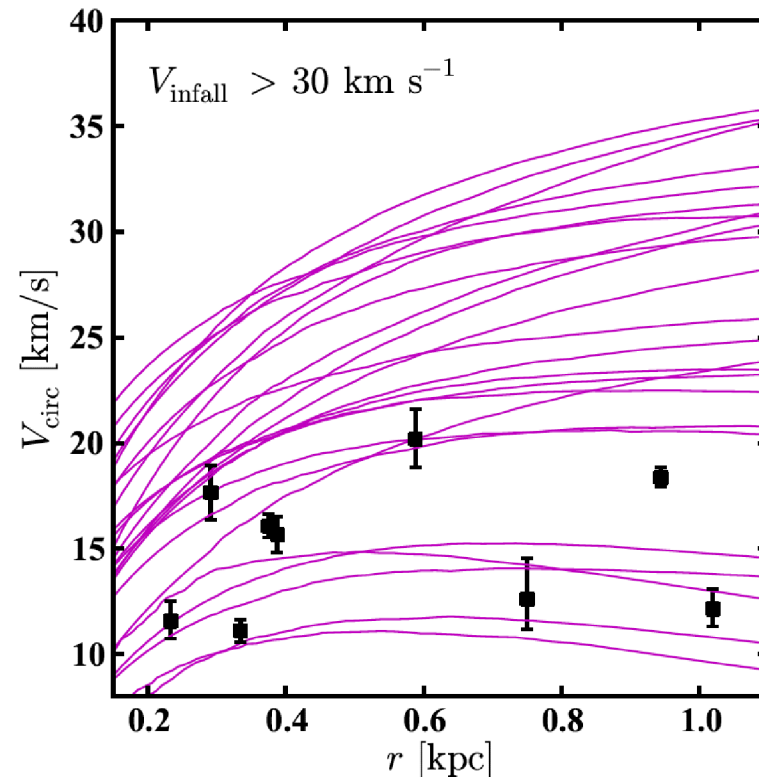


Tulin, Yu: 1705.02358

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Tulin, Yu: 1705.02358

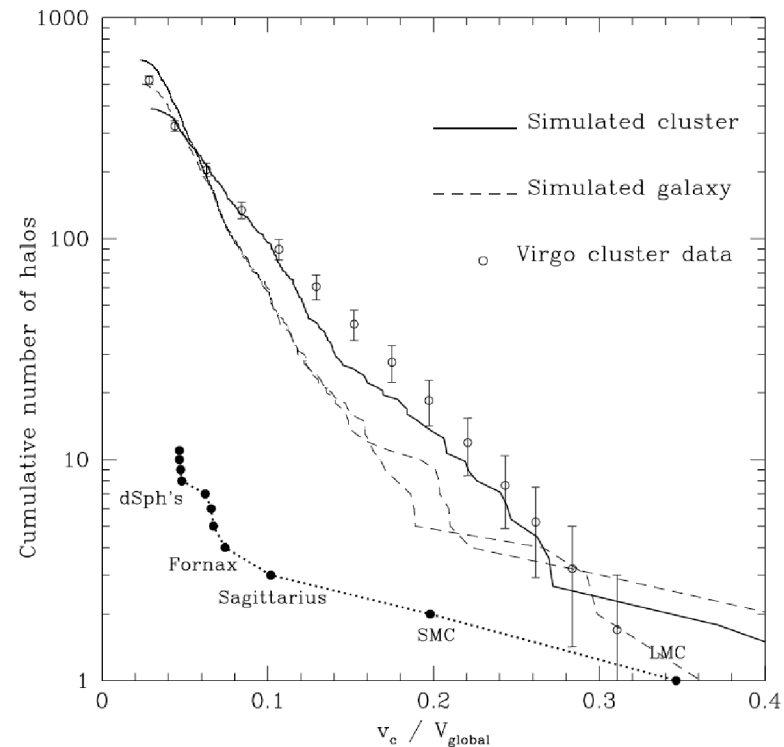
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- Too-big-to-fail problem
- Missing-satellite problem

(or maybe not...)

Kim, Peter, Hargis, 1711.06267

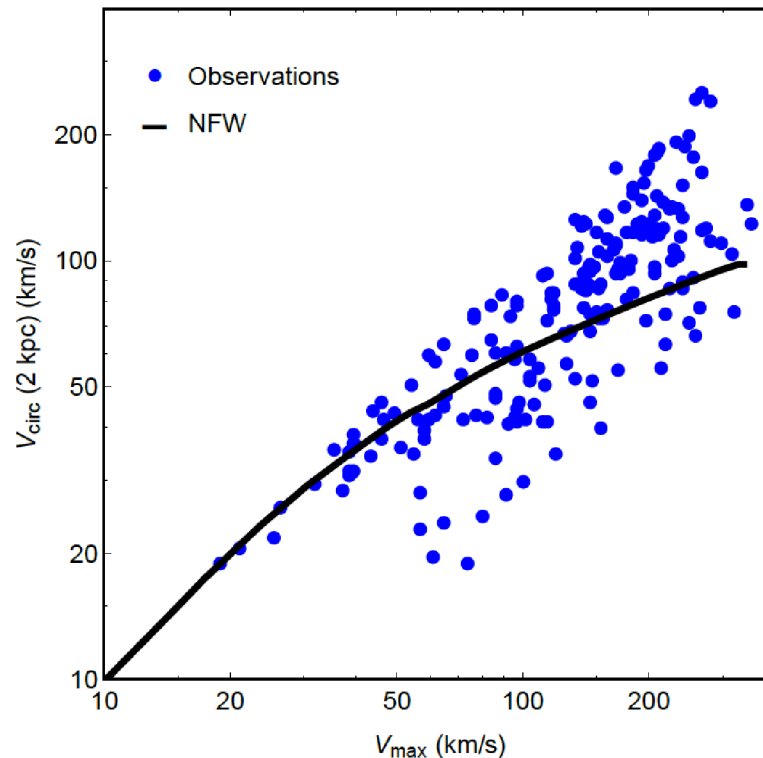


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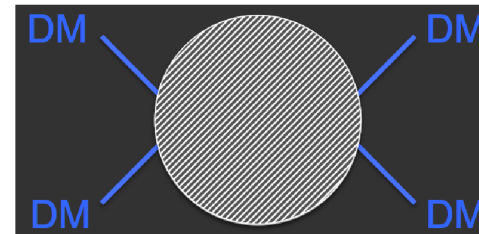


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DM self-interactions may solve some (or all) of these problems



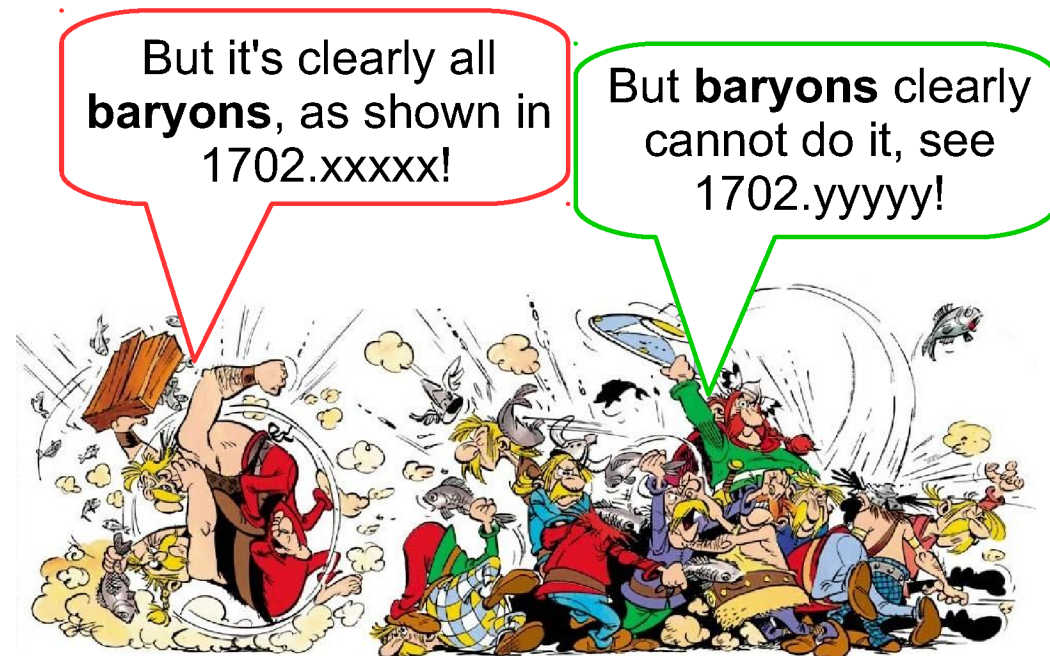
Spergel & Steinhard: astro-ph/9909386
Arsen, Bringmann, Pfrommer, 1205.5809

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How large a cross section?

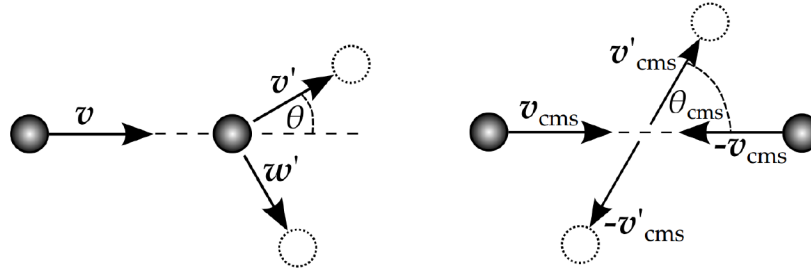
- To be observable on astrophysical scales, self-interaction cross sections have to be large, typically

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

- 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 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

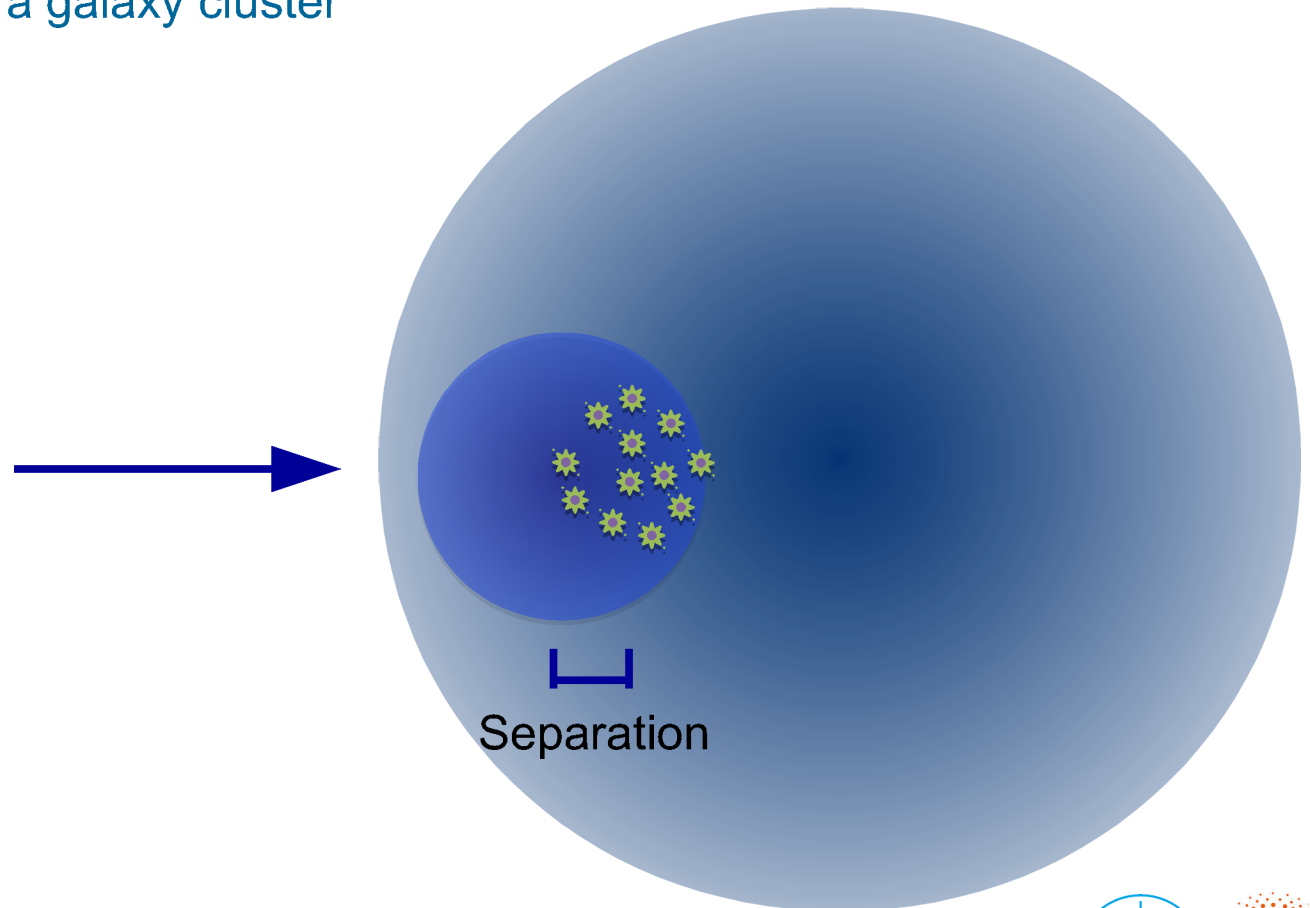
- Effective momentum transfer is given by

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

- 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

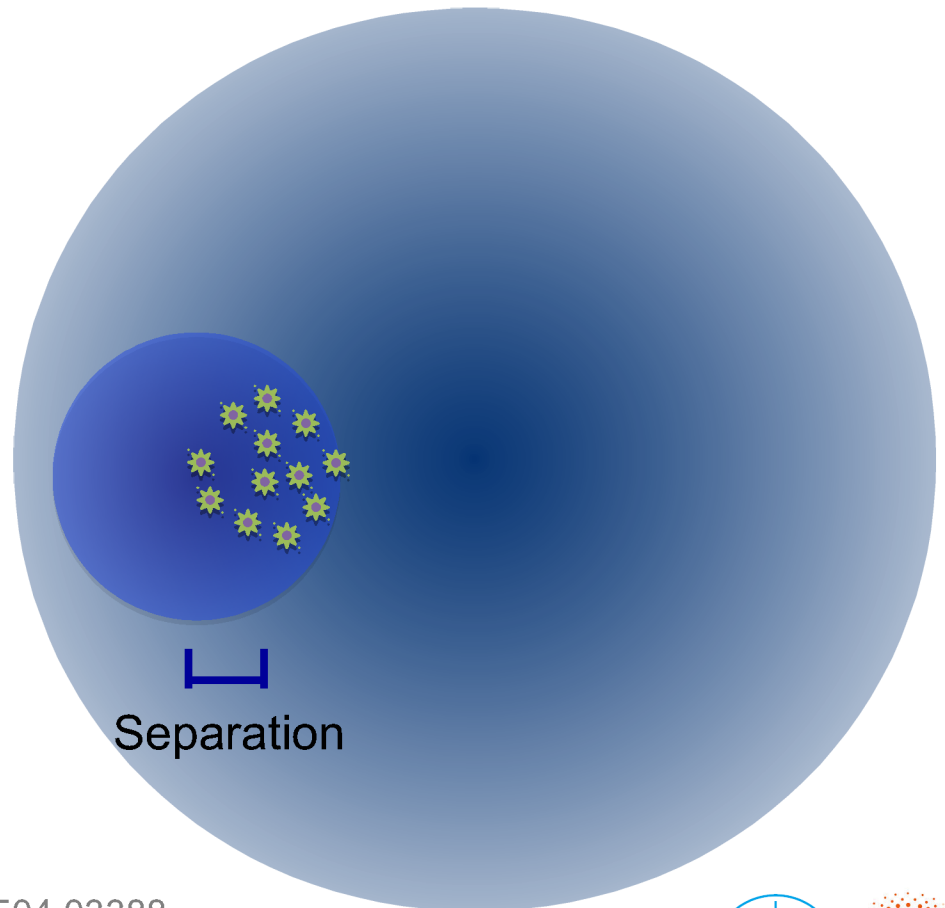
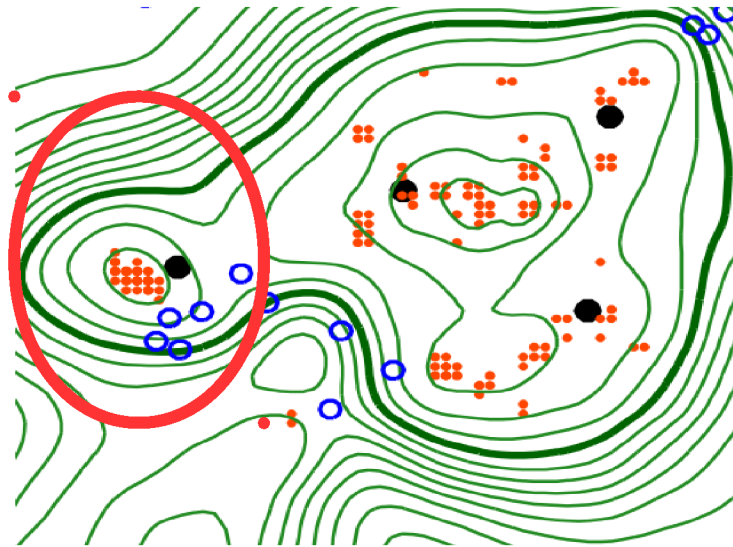
- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster



Smoking gun?

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Observed offset: $1.62 \pm 0.48 \text{ kpc}$



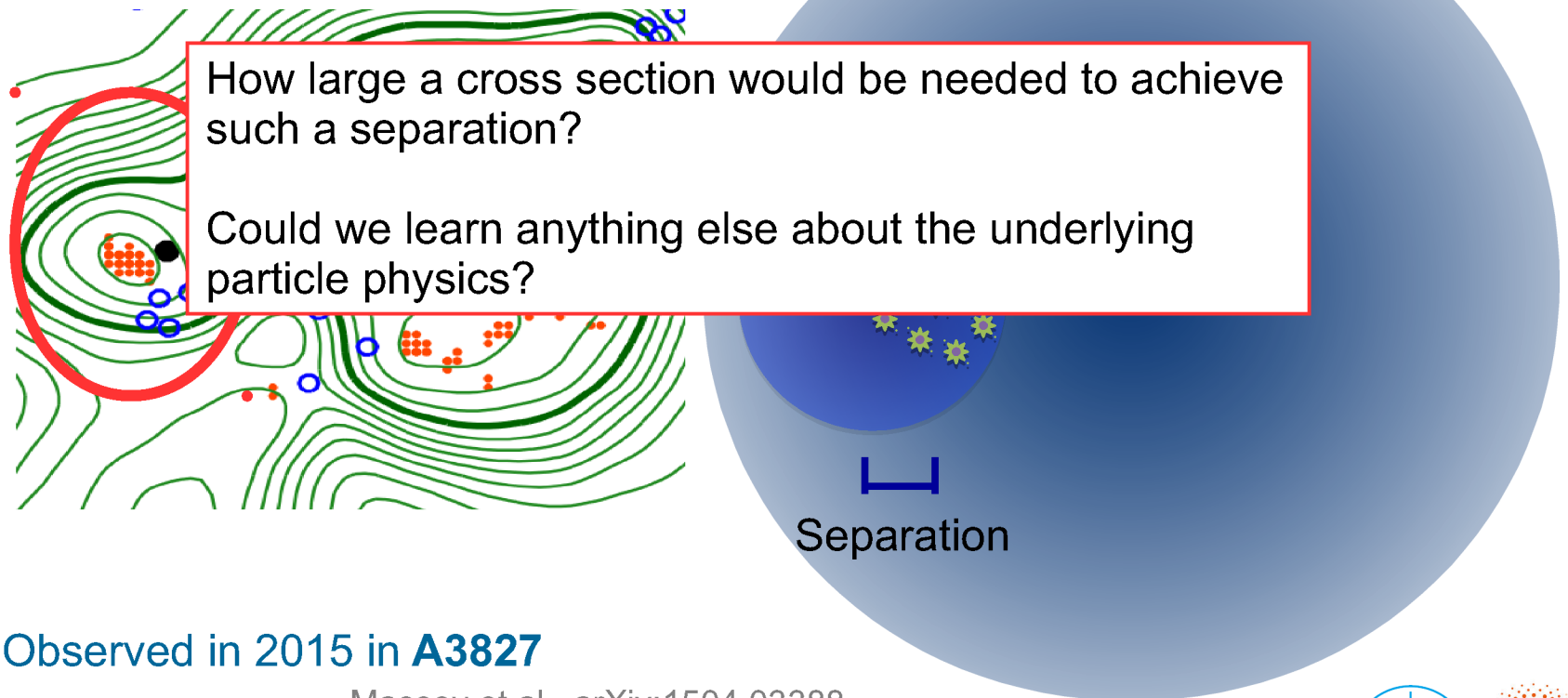
- Observed in 2015 in **A3827**

Massey et al., arXiv:1504.03388

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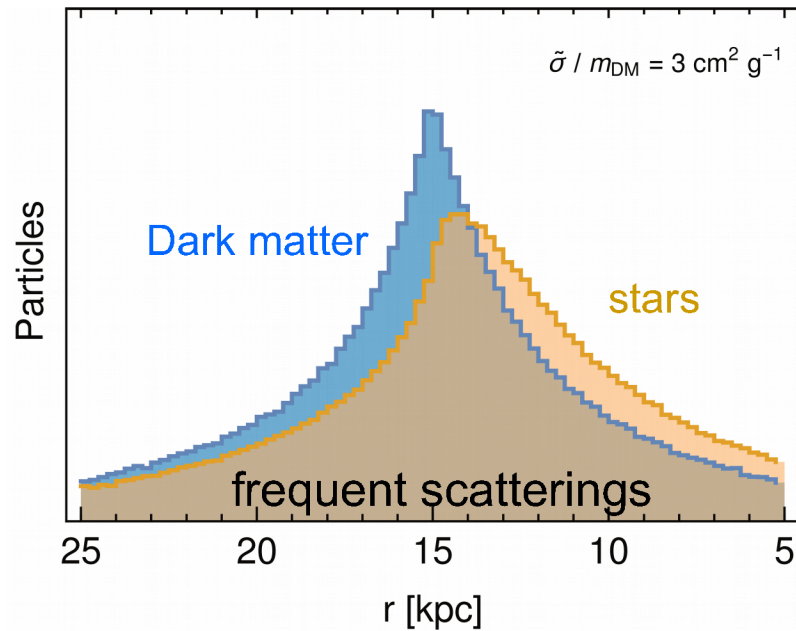


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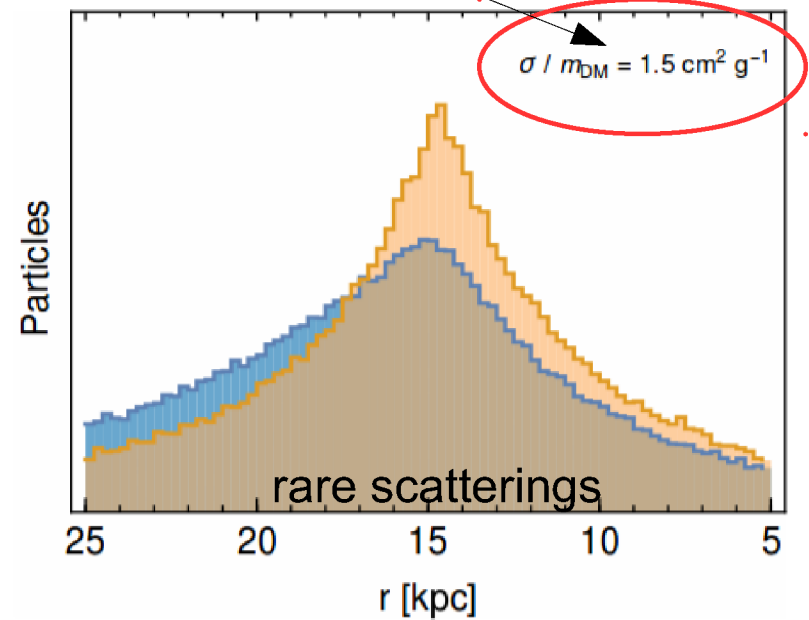
Massey et al., arXiv:1504.03388

Infalling galaxy in A3827

Kahlhoefer et al, 1504.06576



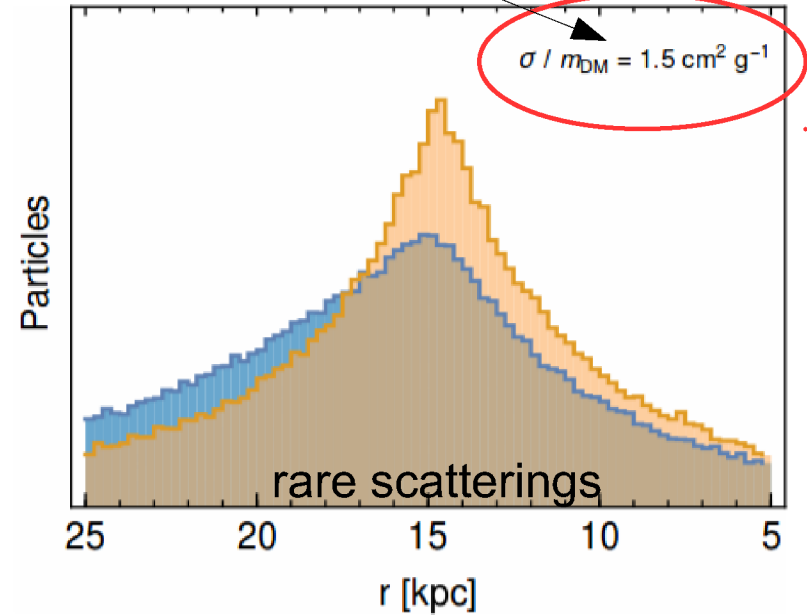
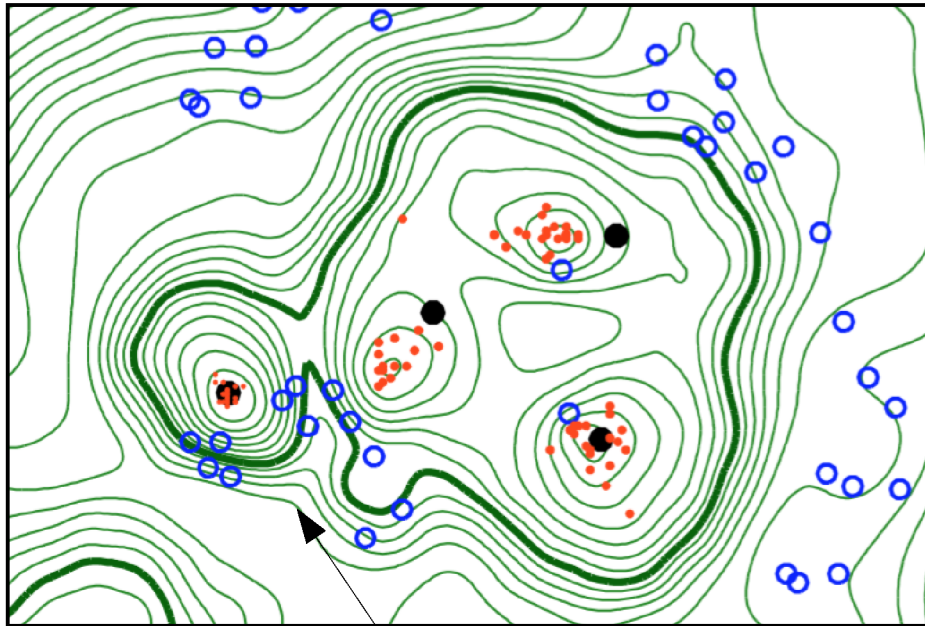
A3827: In (some) tension with upper bounds



Infalling galaxy in A3827

R Massey, talk at SIDM17

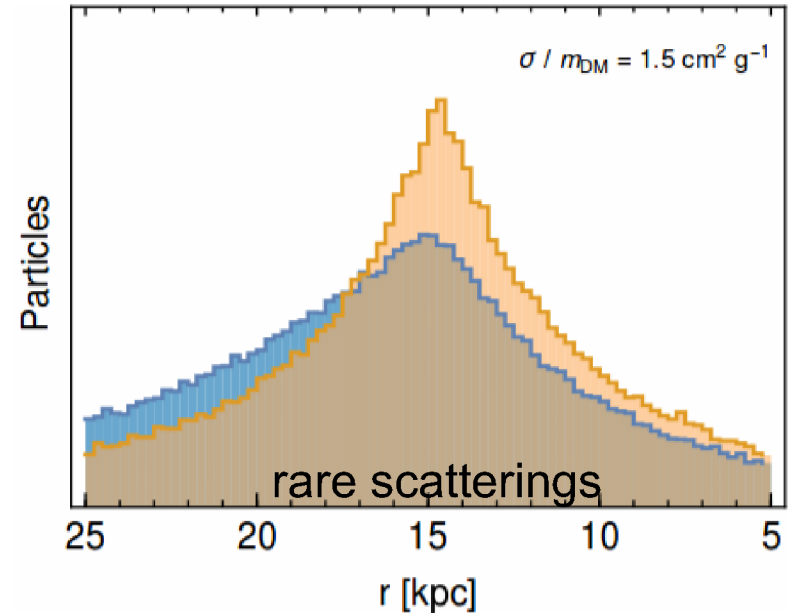
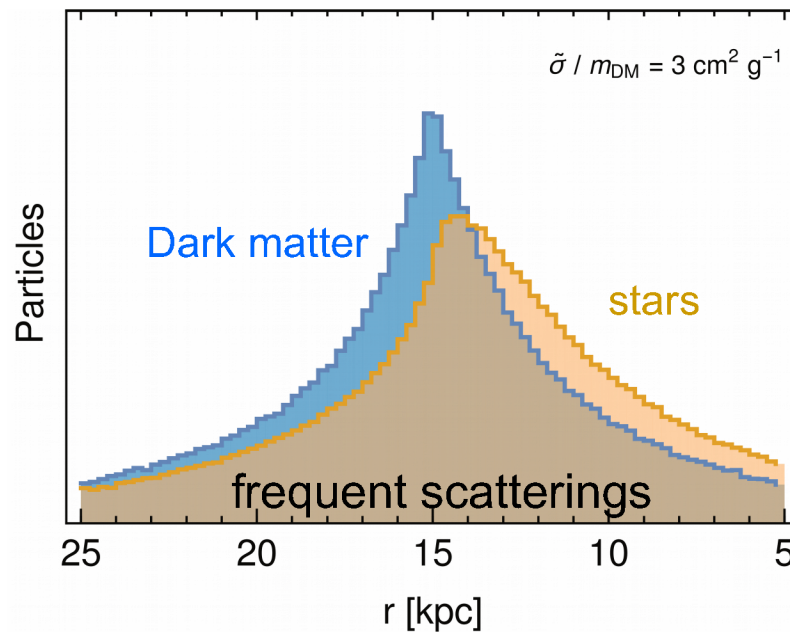
A3827: In (some) tension with upper bounds



Reanalysis from 2017 – offset gone :-(

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?

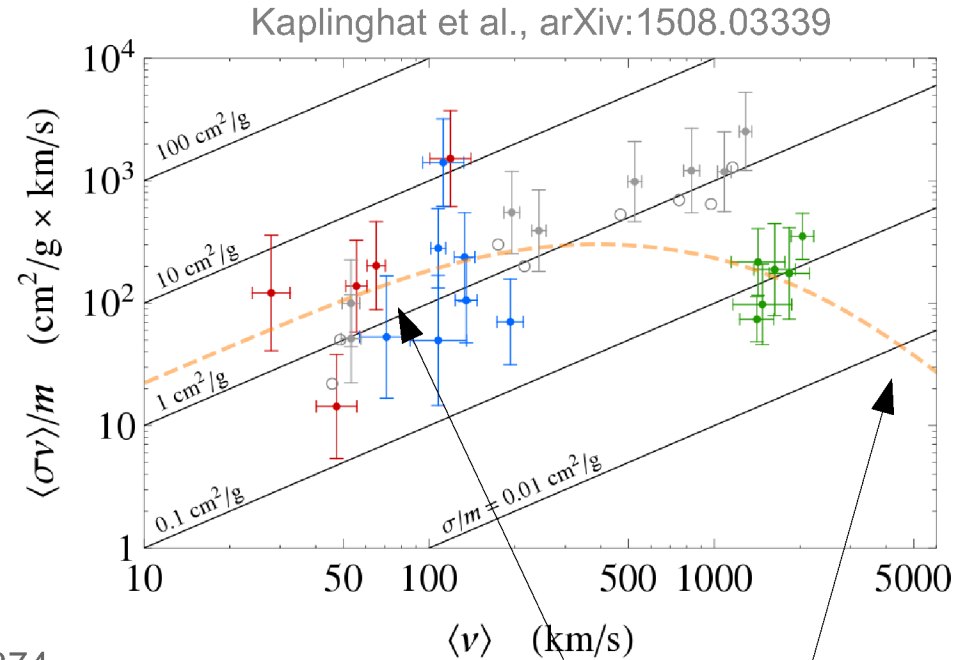
Velocity dependent self-interactions

- 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

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

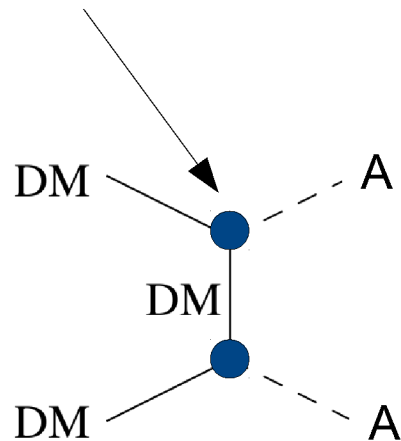
- Scattering for small momentum transfer ($q < m_{\text{med}}$) proportional to $1/m_{\text{med}}^4$
- Scattering for large momentum transfer ($q > m_{\text{med}}$) proportional to $1/q^4$



A new light mediator

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

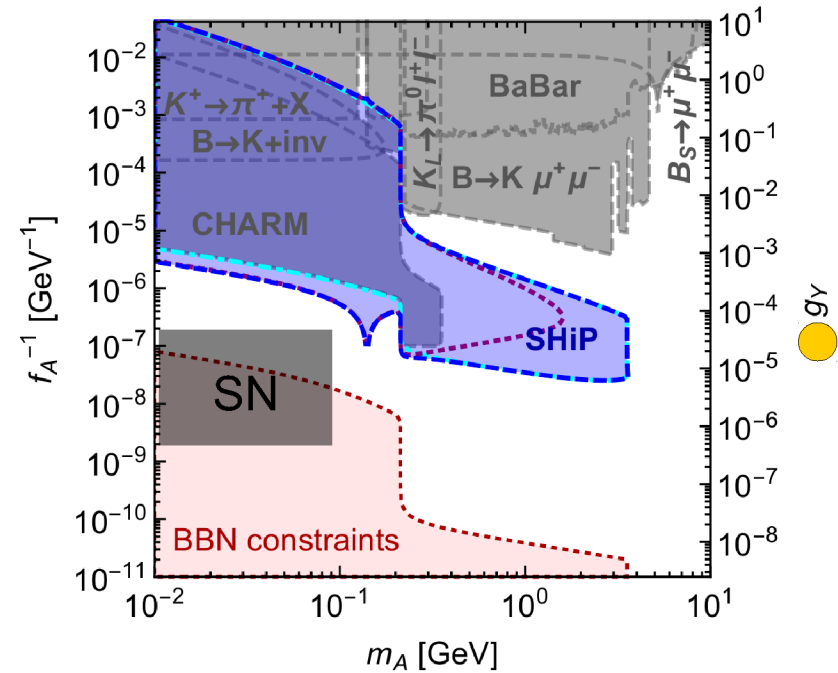
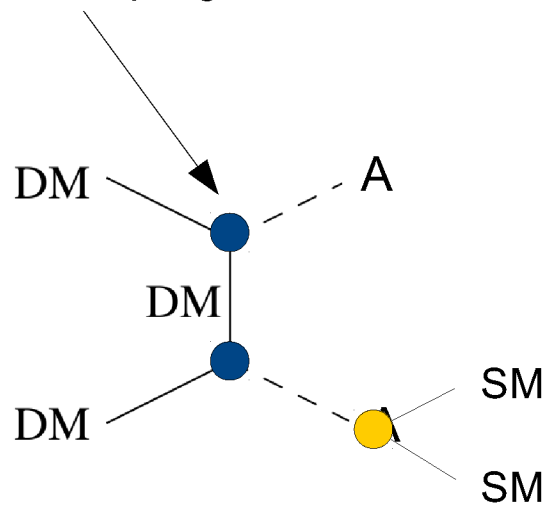
Fix dark sector coupling via relic abundance



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Fix dark sector coupling via relic abundance

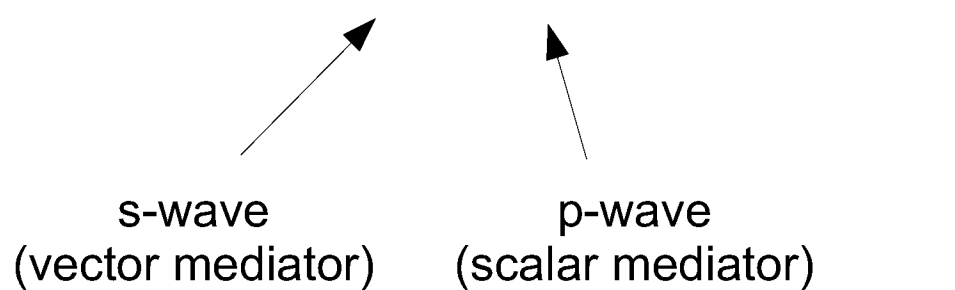


- To avoid overclosing the Universe, the mediator should ultimately disappear, so its couplings to SM states cannot be arbitrarily small – many constraints

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

$$\sigma v_{\text{rel}} = \sigma_0 + \sigma_1 v_{\text{rel}}^2 + \mathcal{O}(v_{\text{rel}}^4)$$

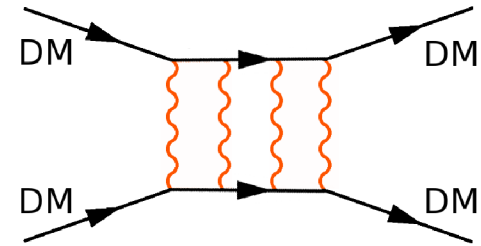


s-wave
(vector mediator) p-wave
(scalar mediator)

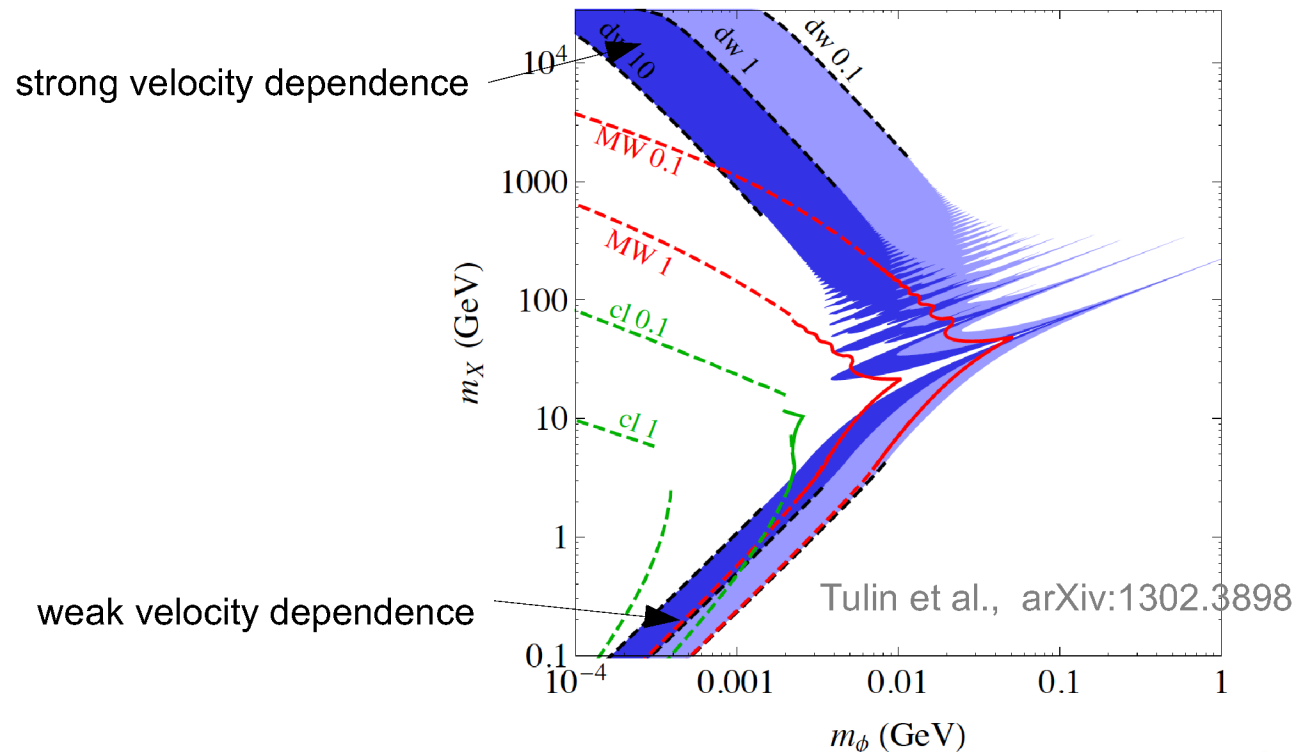
- > Both terms contribute at freeze-out. Later p-wave is very suppressed...

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

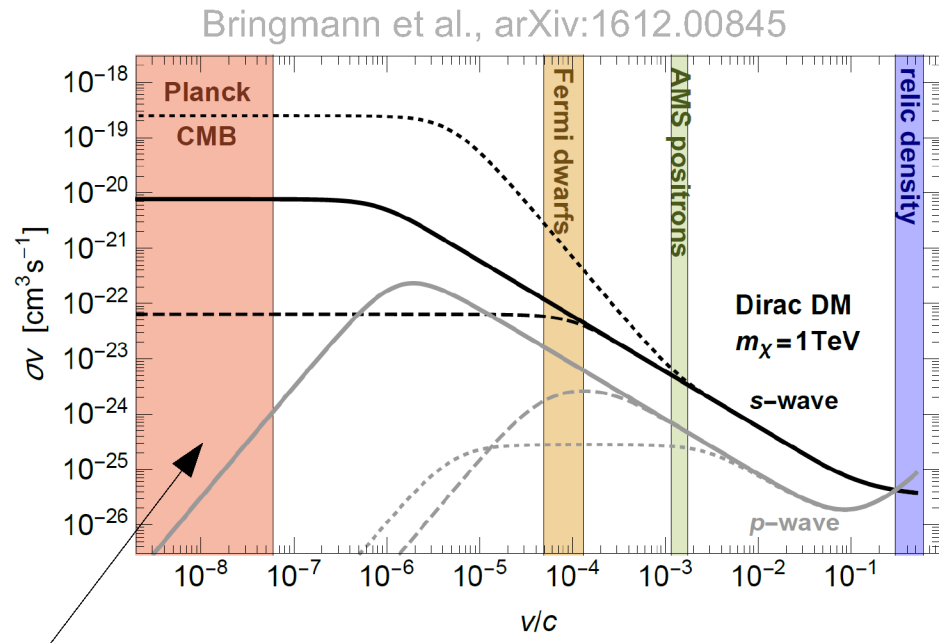


Dark matter with relic density (s -wave)



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.



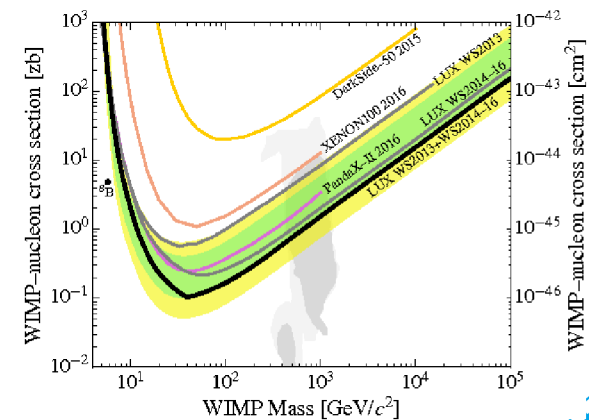
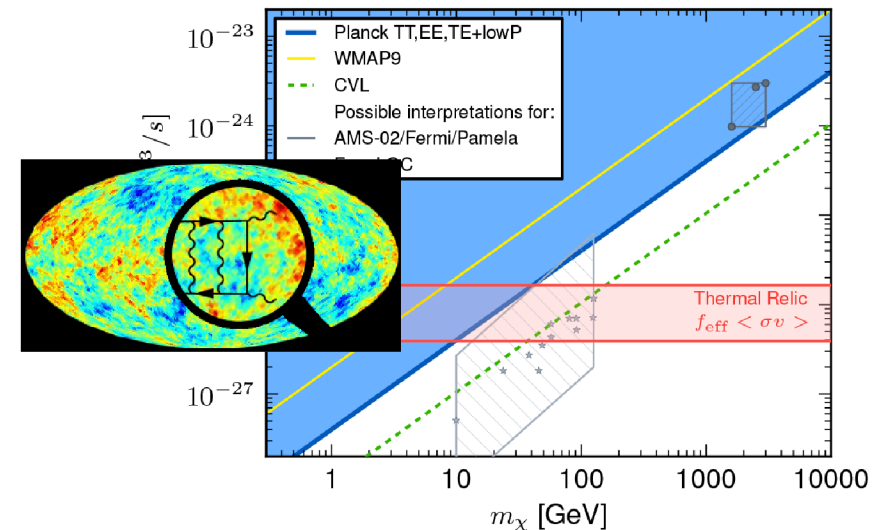
During recombination
dark matter particles
move at walking speed.

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 $1/(q^2 + m_{\text{med}}^2)^2$
- strongly enhanced for light mediators!



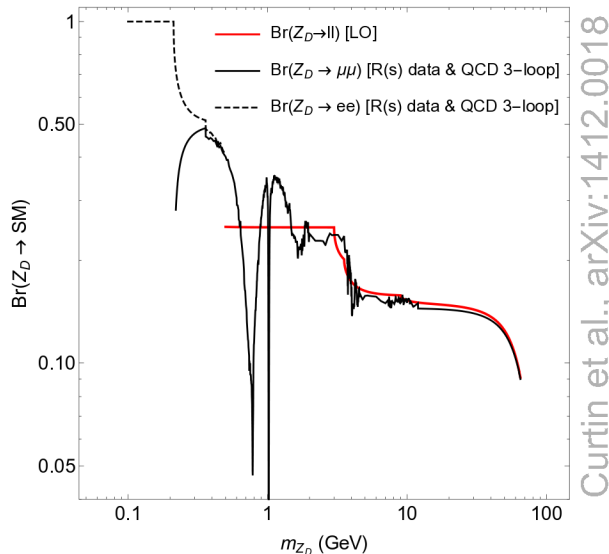
Vector mediators

- 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



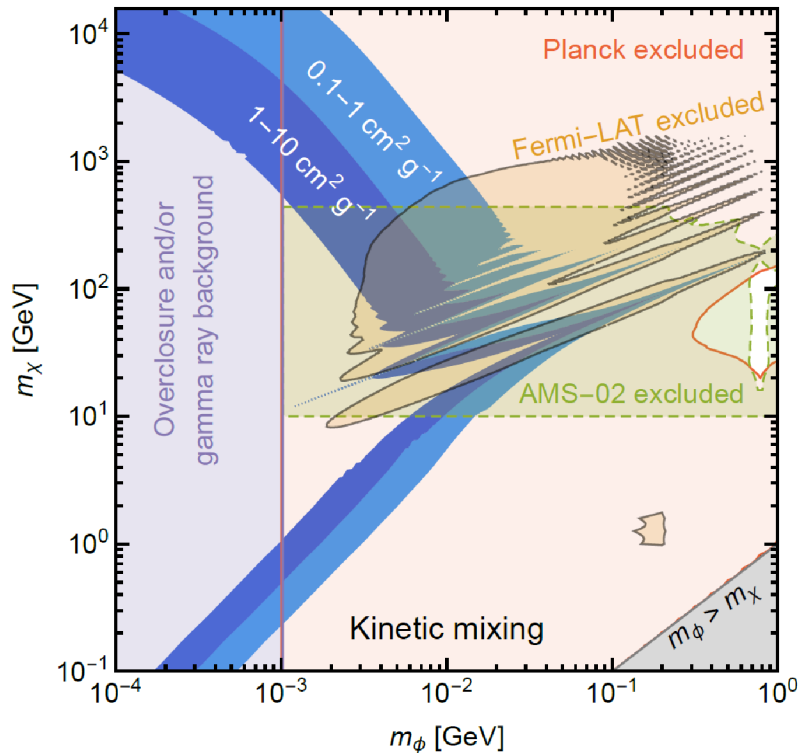
➤ Main difference:

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

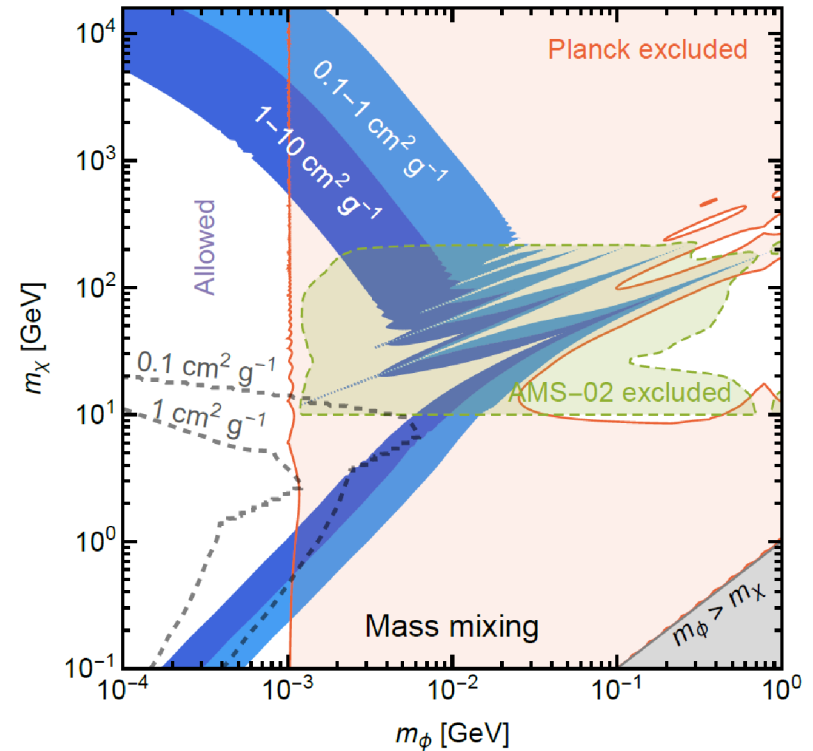
Constraints on vector mediators

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

Bringmann et al., arXiv:1612.00845

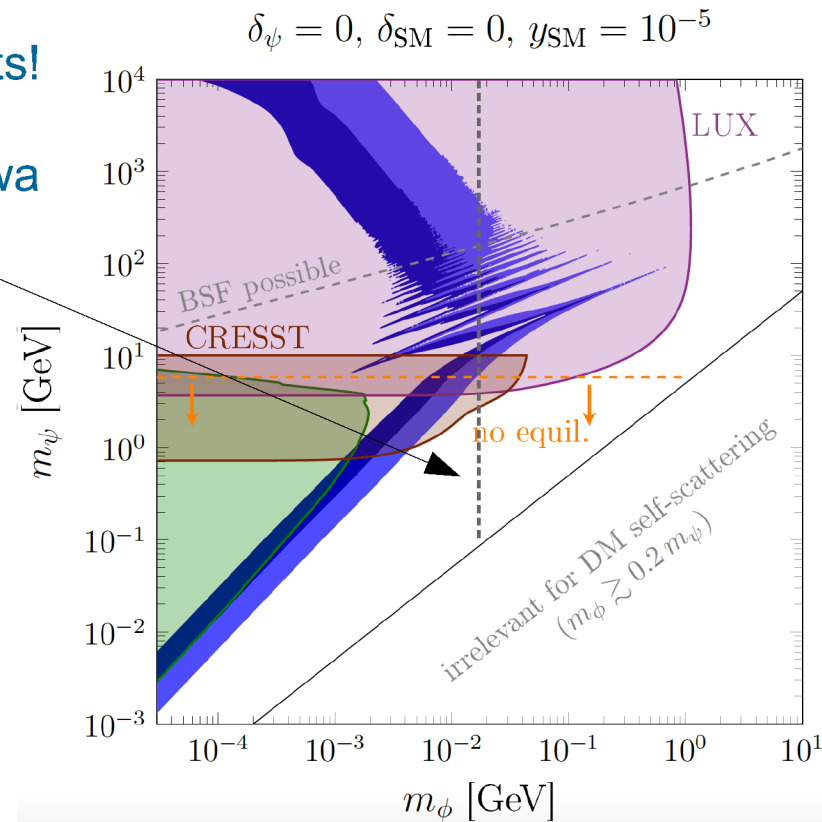


Bringmann et al., arXiv:1612.00845



Constraints on scalar mediators

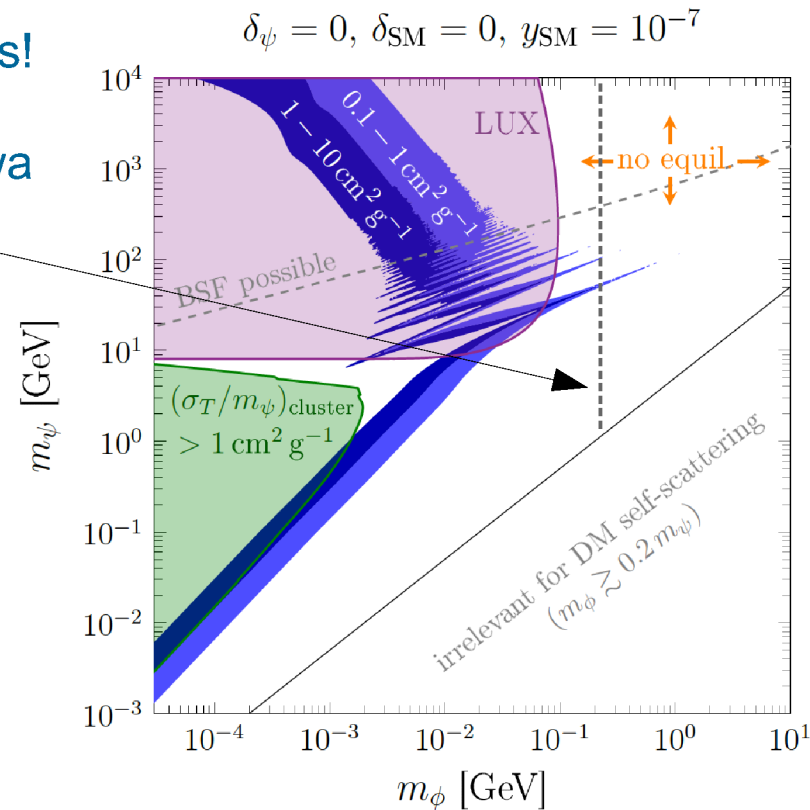
- Consider scalar mediator with Higgs mixing (\rightarrow Yukawa-like couplings)
- Annihilation proceeds via p-wave
- No constraints from indirect detection or the CMB.
- Strong direct detection constraints!
- Lifetime rather long due to Yukawa suppression
- Naive BBN bound: $\tau < 1$ s
- How does this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



1704.02149

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- Naive BBN bound: $\tau < 1$ s
- How does this depend on y_{SM} ?
- Requires dedicated BBN study!



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,...

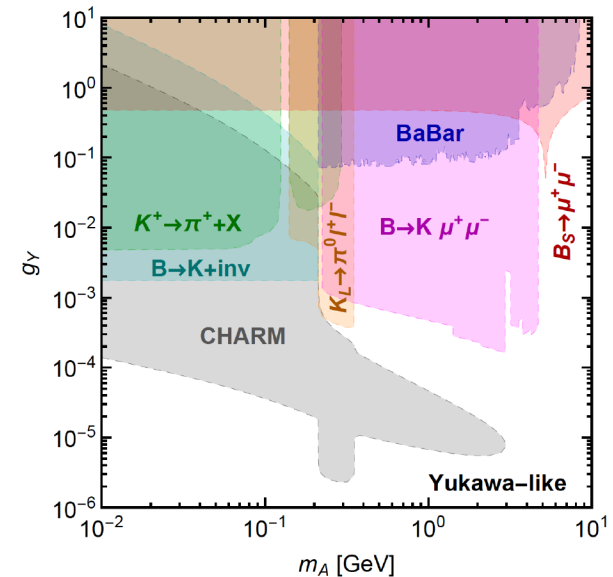
Thank you!

Pseudoscalar mediators

$$\mathcal{L}_{\text{DM}} = i g_\chi A \bar{\chi} \gamma^5 \chi$$

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

- 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

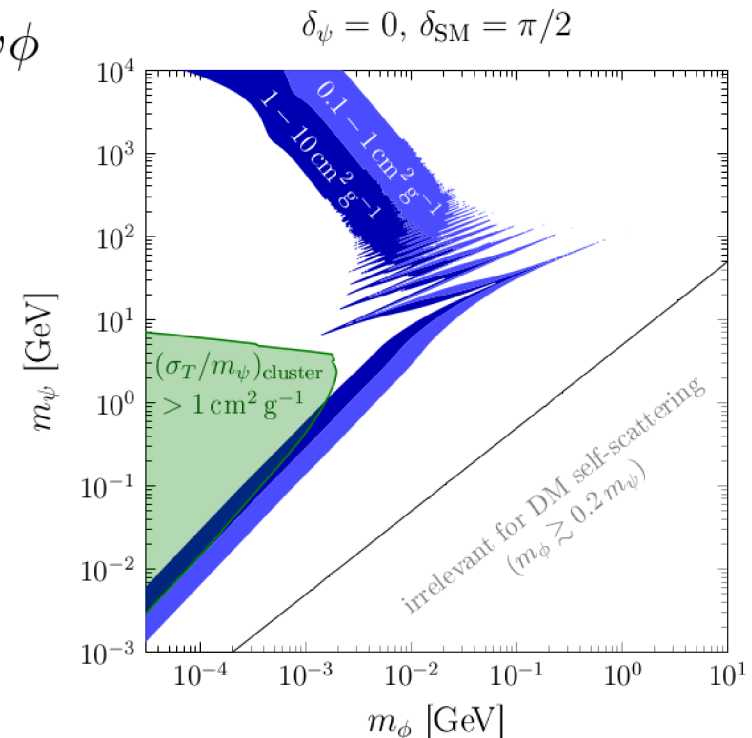


Dolan et al., arXiv:1412.5174

Idea: A mixed mediator (CP violation)

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

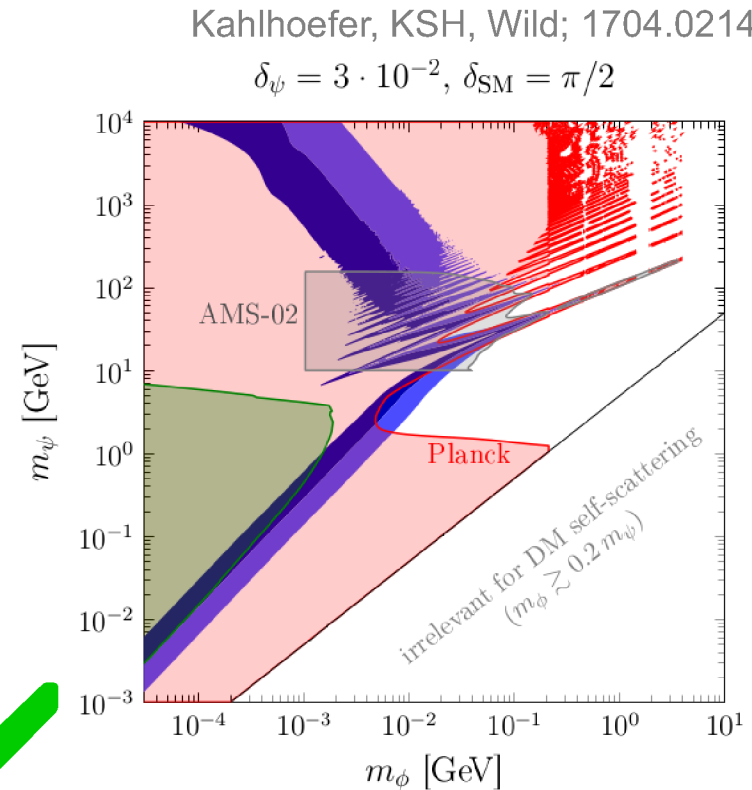
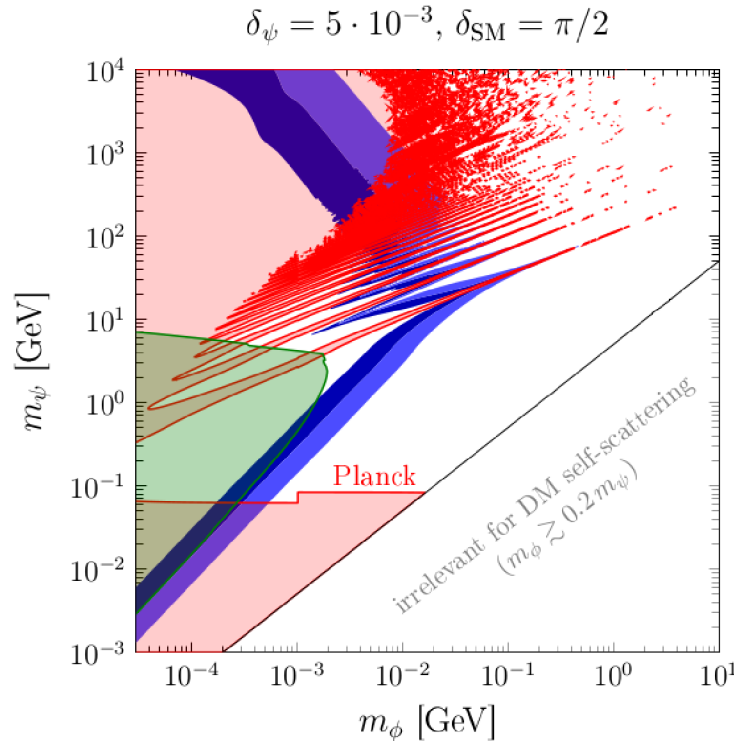
- For $\delta_\psi \sim 0$ (like a scalar) DM self-interactions can be large.
- For $\delta_{\text{SM}} \sim \pi/2$ (like a pseudoscalar) direct detection constraints are strongly suppressed.
- Large allowed parameter space!
- Constraints on the CP-violating phase δ_{SM} (e.g. from electron EDMs) can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



Kahlhoefer, KSH, Wild; 1704.02149

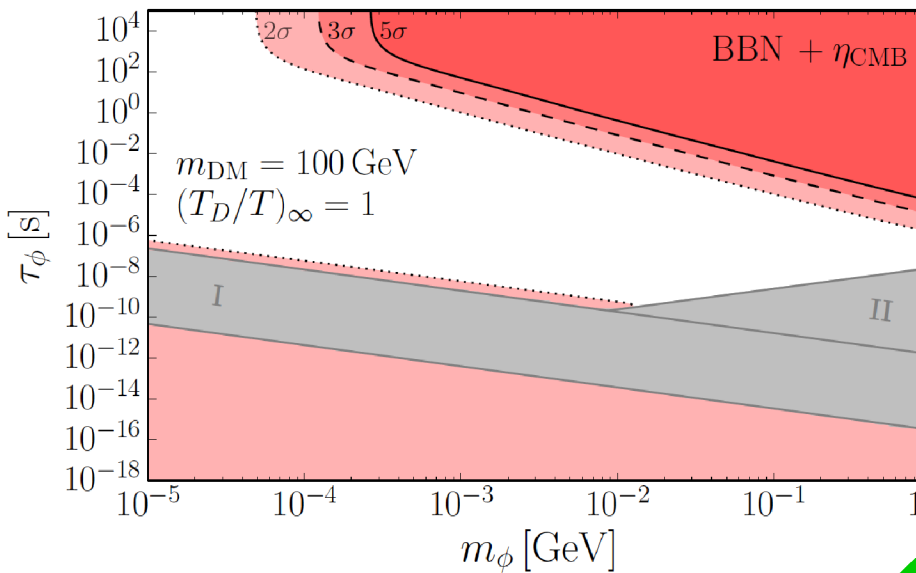
The return of CMB constraints

- 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.

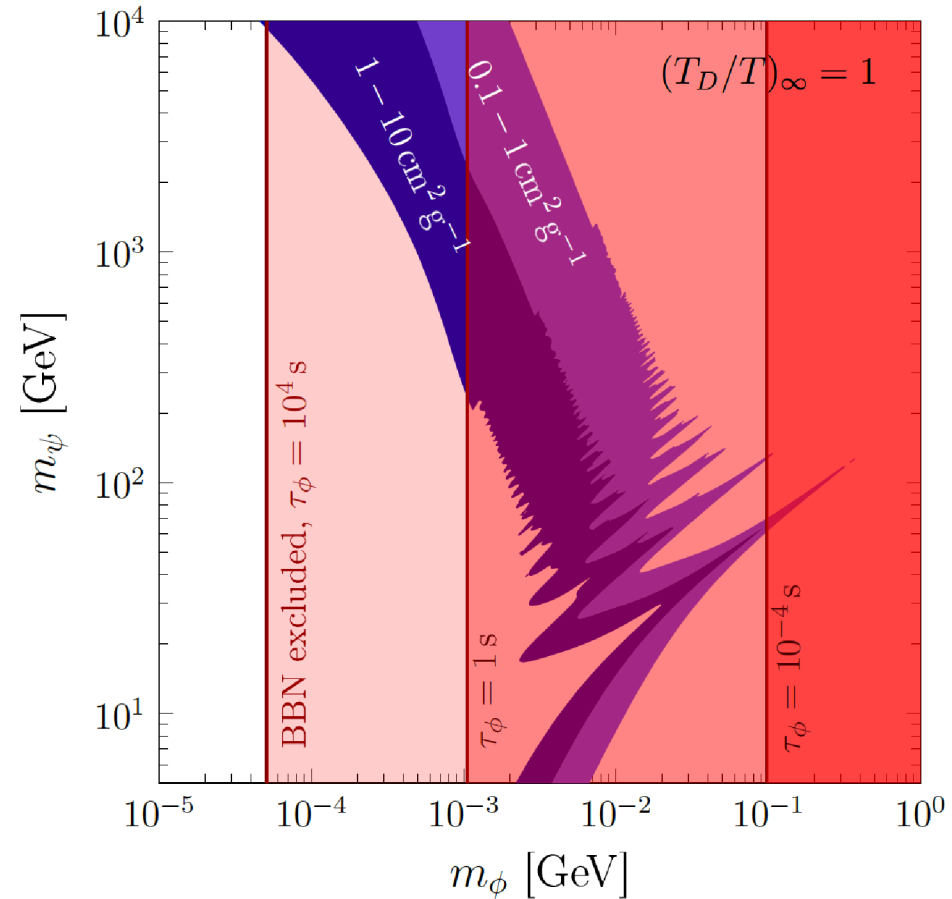


Inert decays of the mediator

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



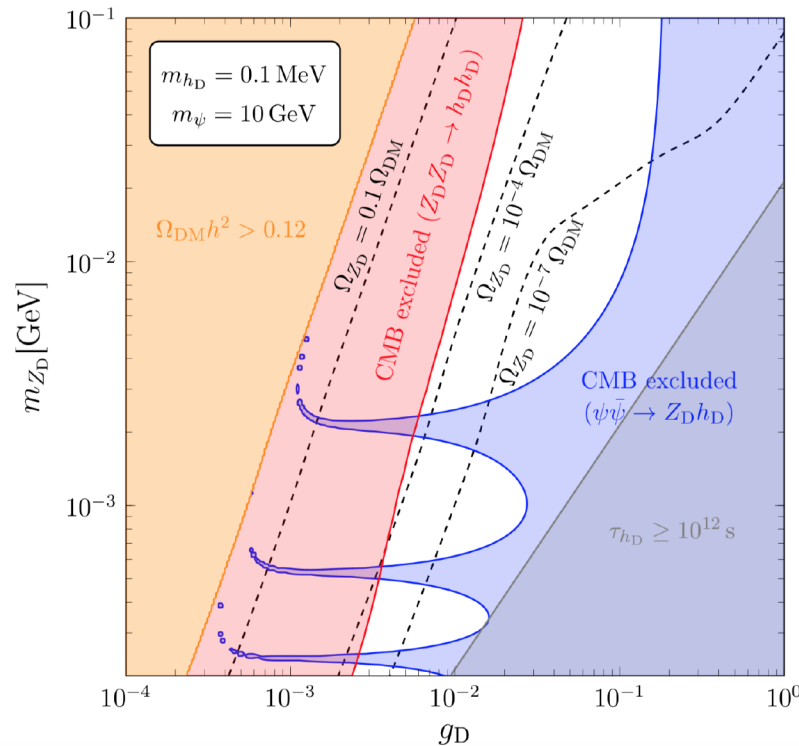
Hufnagel, KSH, Wild; 1712.03972



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



[in preparation with M Duerr, S Wild]

