On self-interacting dark matter:
Current status and perspectives

Kai Schmidt-Hoberg

Task:

kindly ask you to talk about (one of) the **following topics:**
Overview of SIDM including astroparticle probes, structure formation and laboratory probes.

With best regards,
Claudia and Mads
(local organizers of DAvCo)

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

HELMHOLTZ ASSOCIATION

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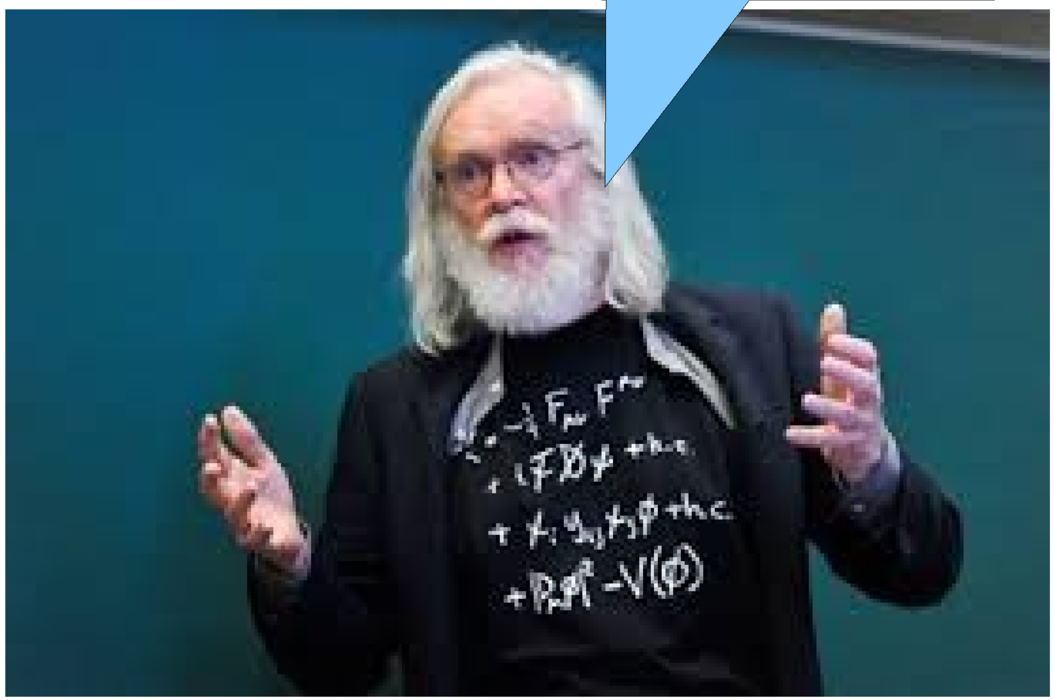
DESY

Prelude: Thoughts about the SUSY WIMP

but being in Odense...

“SUSY anywhere is better than SUSY nowhere!”



Why we like(d) SUSY

- Hierarchy problem: stabilizes the weak against the Planck scale
- Dark matter: If lightest SUSY particle stable → dark matter candidate
- Gauge coupling unification:
- A 125 GeV Higgs boson: Additional hint for SUSY?

...someone from Odense still owes me...

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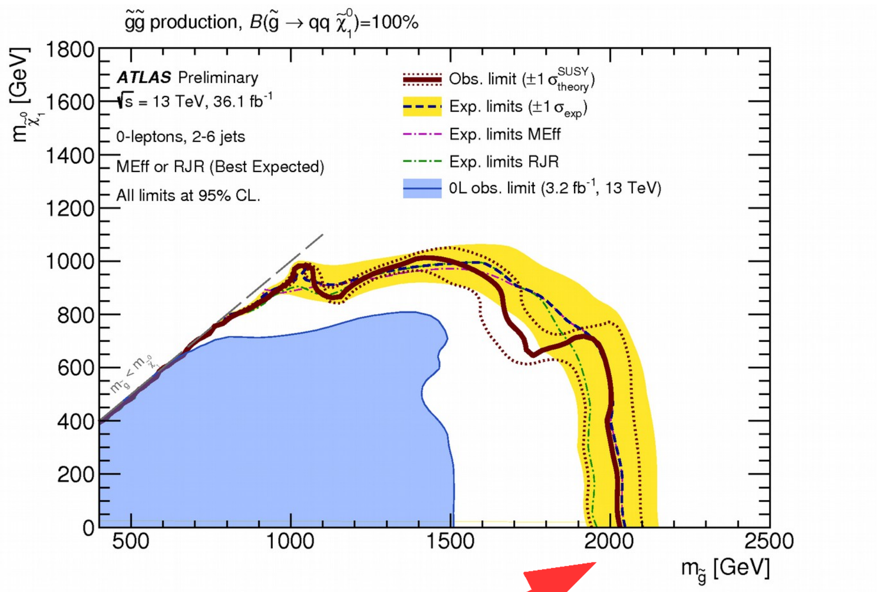
- **>** So why do people get worried?



~ 2 TeV

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NATURALNESS!

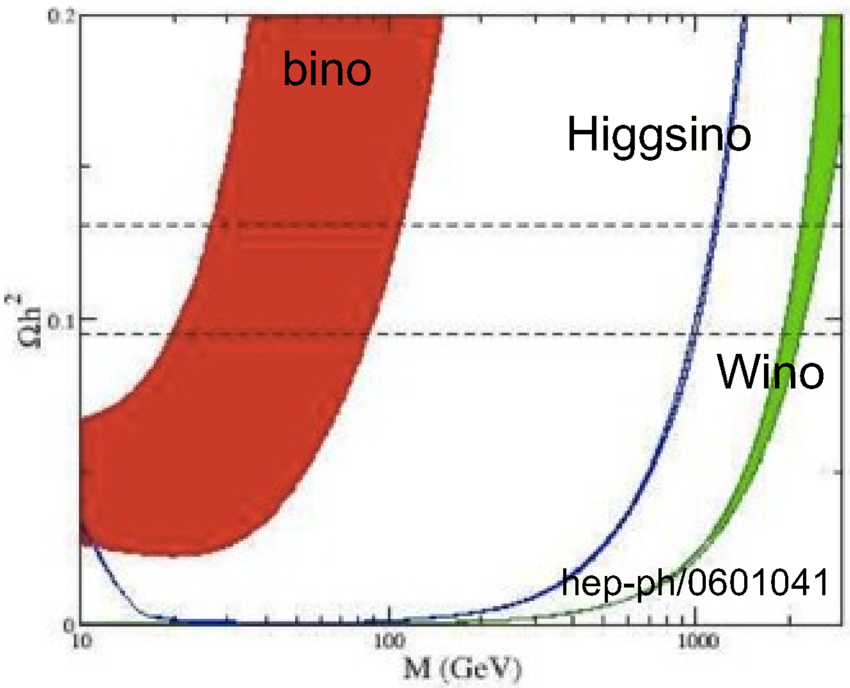
DM naturalness in the MSSM

- 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 :-)



EW naturalness in the MSSM

- Electroweak vev (or m_Z) determined by SUSY parameters

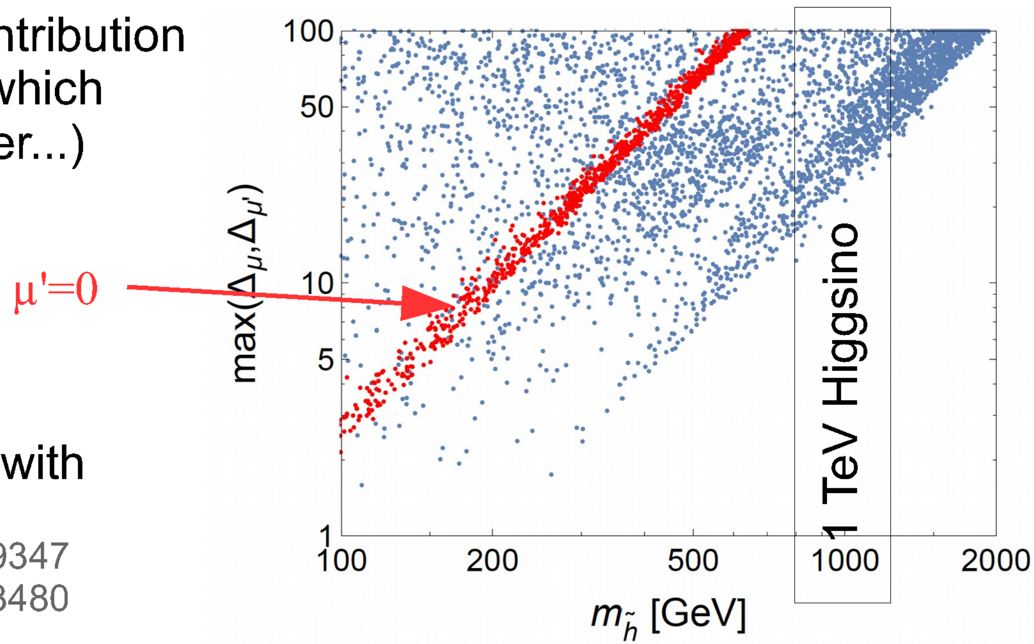
$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \ldots$$

- Cancellation (tuning) needed for large SUSY masses → $\Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p} = \frac{p}{v^2}\frac{\partial v^2}{\partial p}$

  Higgsino mass ~ $\mu \sim 1$ TeV → $\Delta_\mu \sim \frac{2\mu^2}{M_Z^2} \sim 250$

- However: possible soft contribution μ' to the Higgsino mass (which most people never consider...)

  $m_h \sim \mu + \mu'$



- Allows for 1 TeV Higgsino with moderate FT!

1603.09347
1701.03480

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...and now to the 'real' talk

- How
  μ' t
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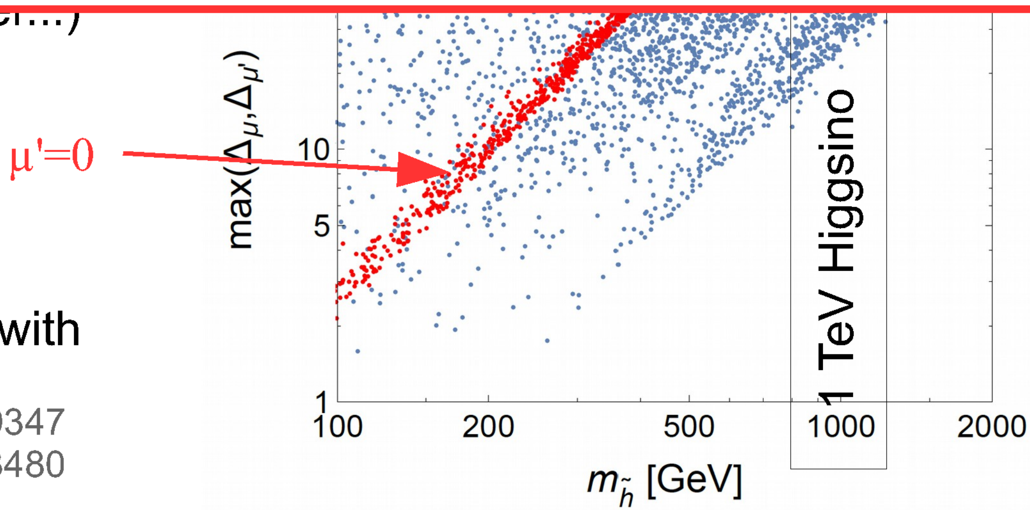

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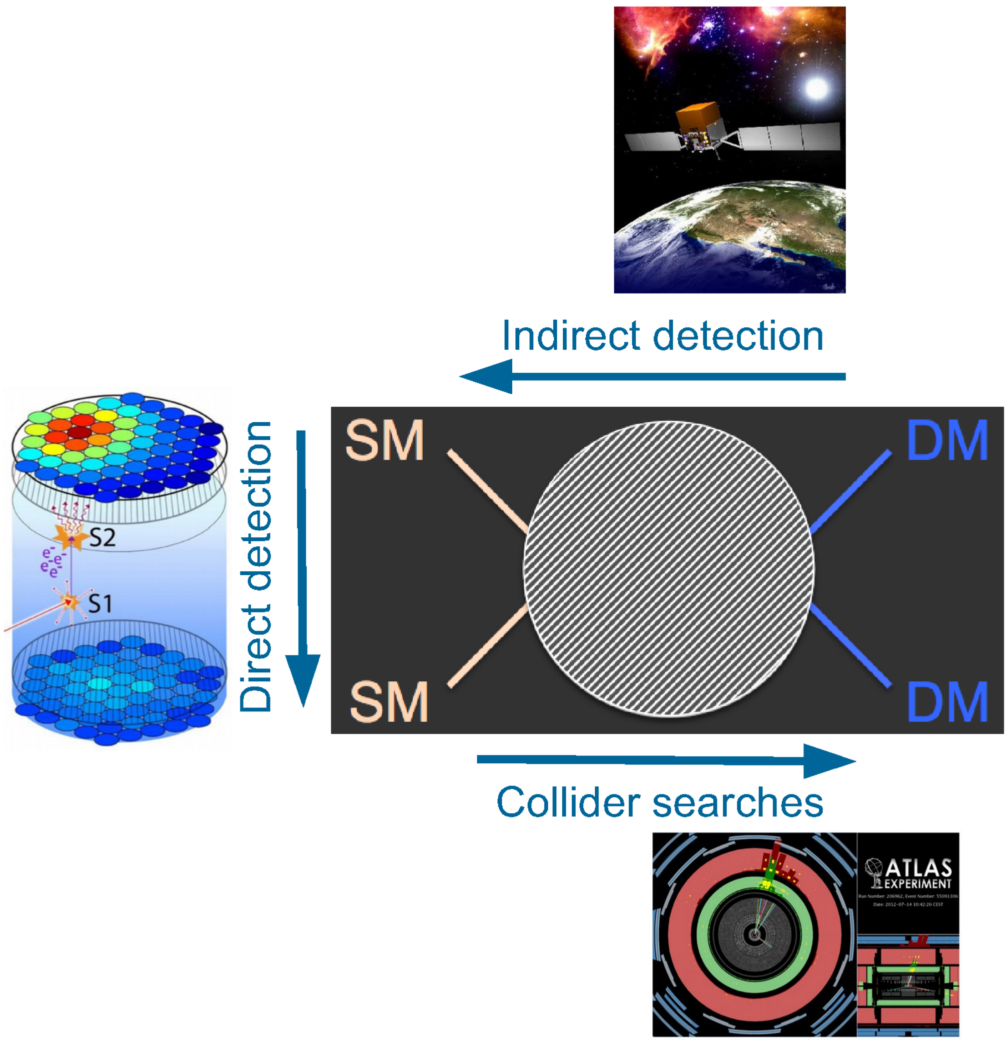
How to constrain the properties of dark matter?

- Our 'usual way' to search for dark matter

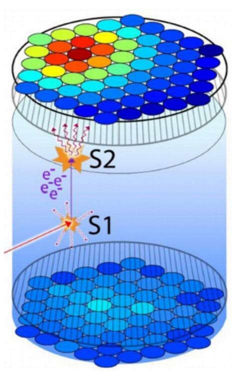


How to constrain the properties of dark matter?

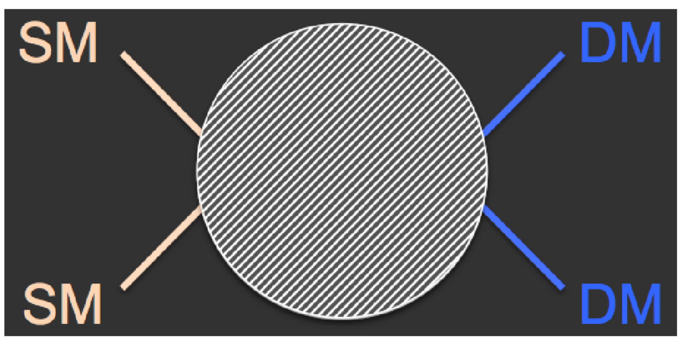
- Our 'usual way' to search for dark matter
- A fourth way...

See also talks by
T Bringmann and F Kahlhoefer

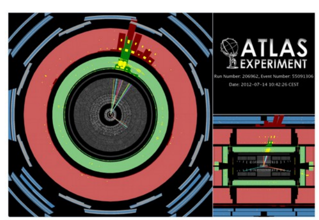
Indirect detection



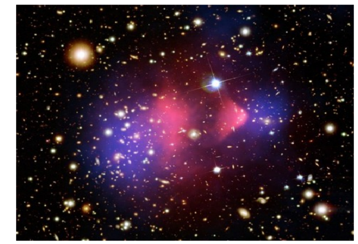
Direct detection

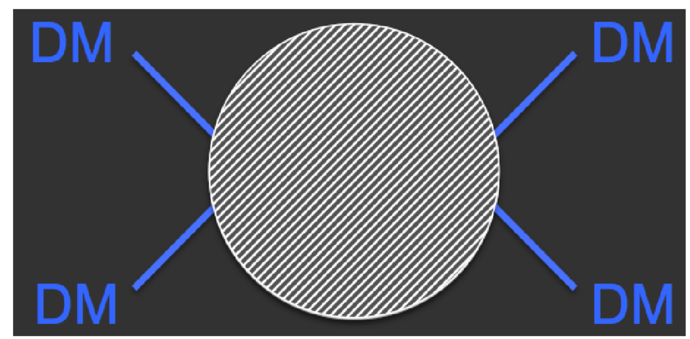


Collider searches



This Talk:

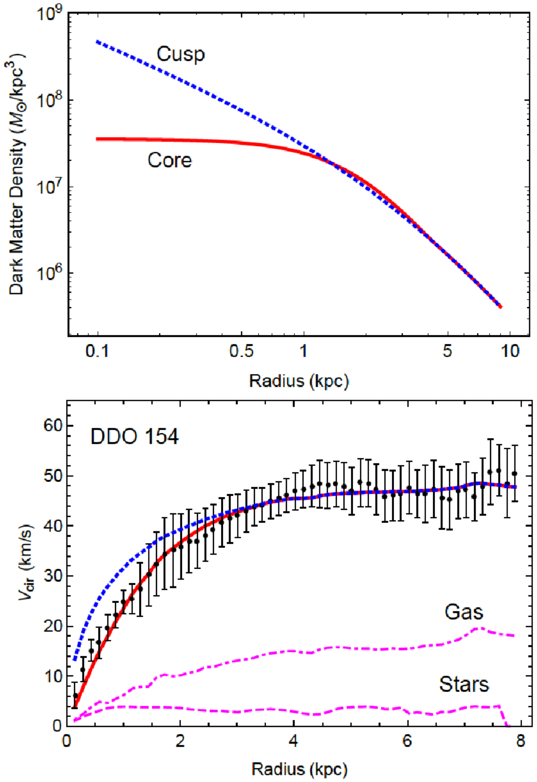




DM self-interactions

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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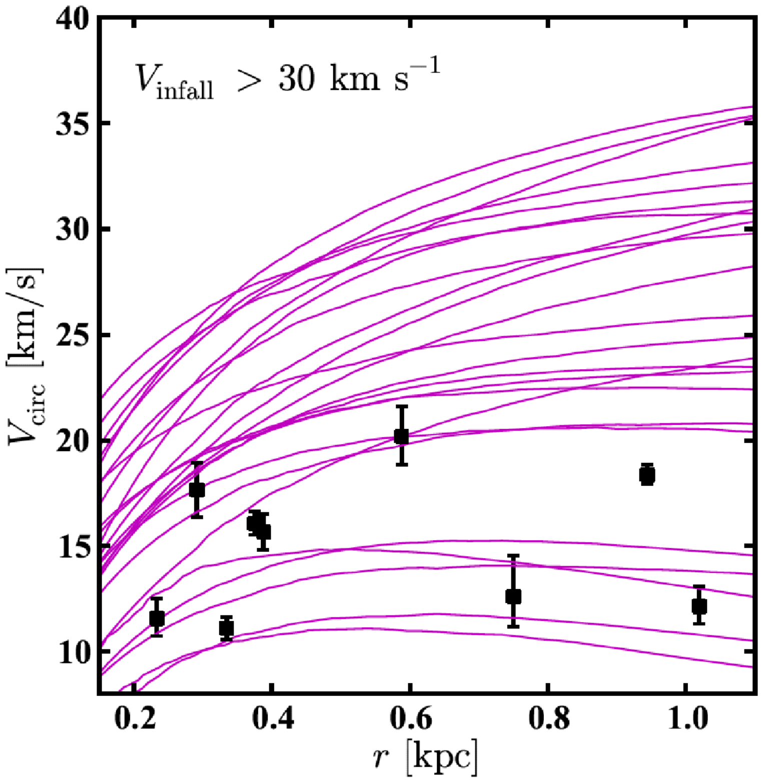

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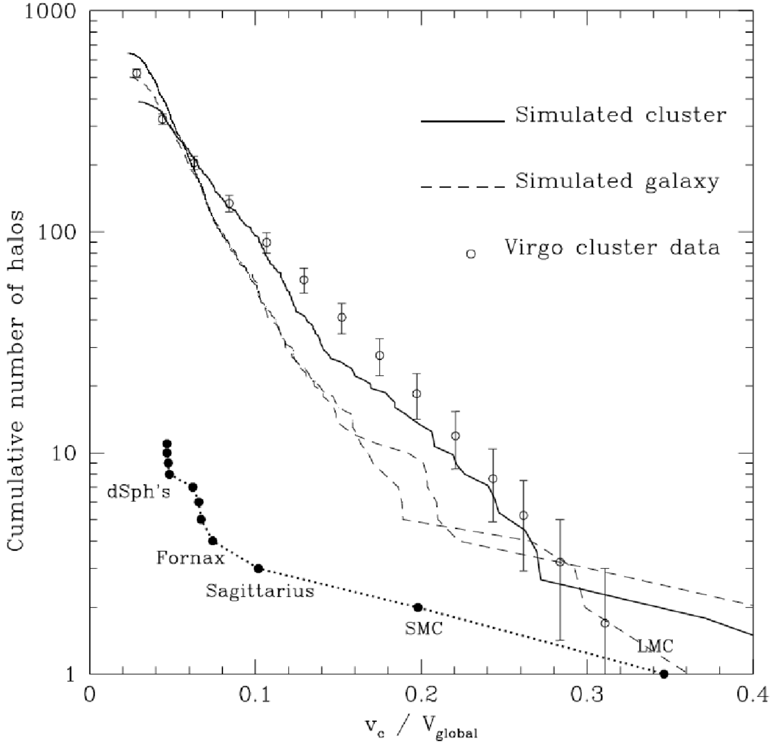

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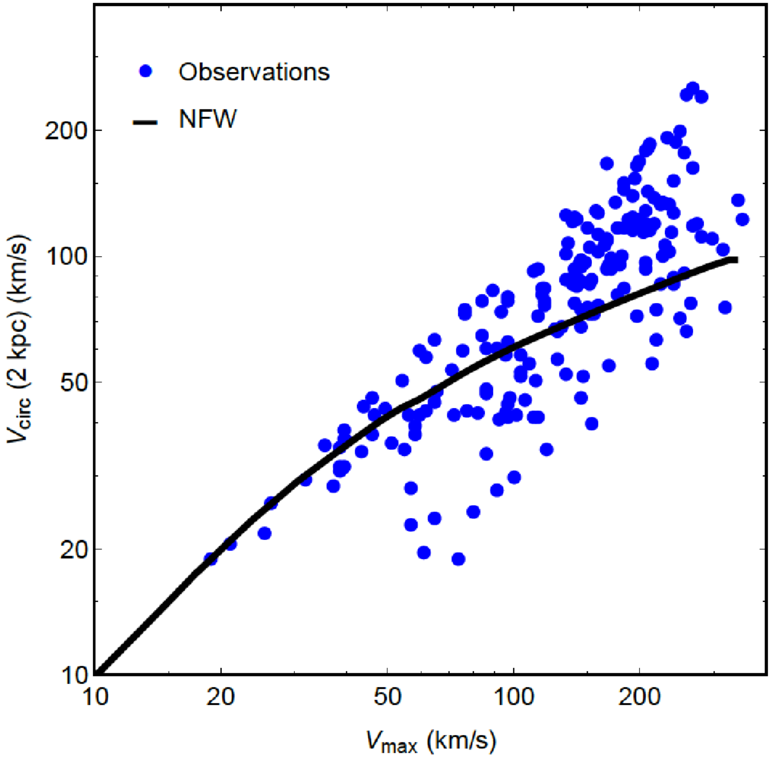

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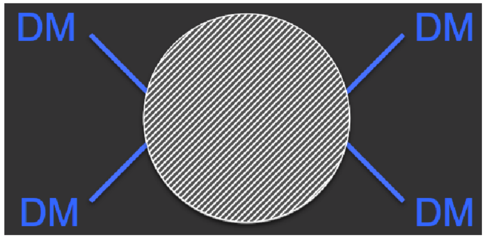
DM self-interactions may solve some (or all) of these problems



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

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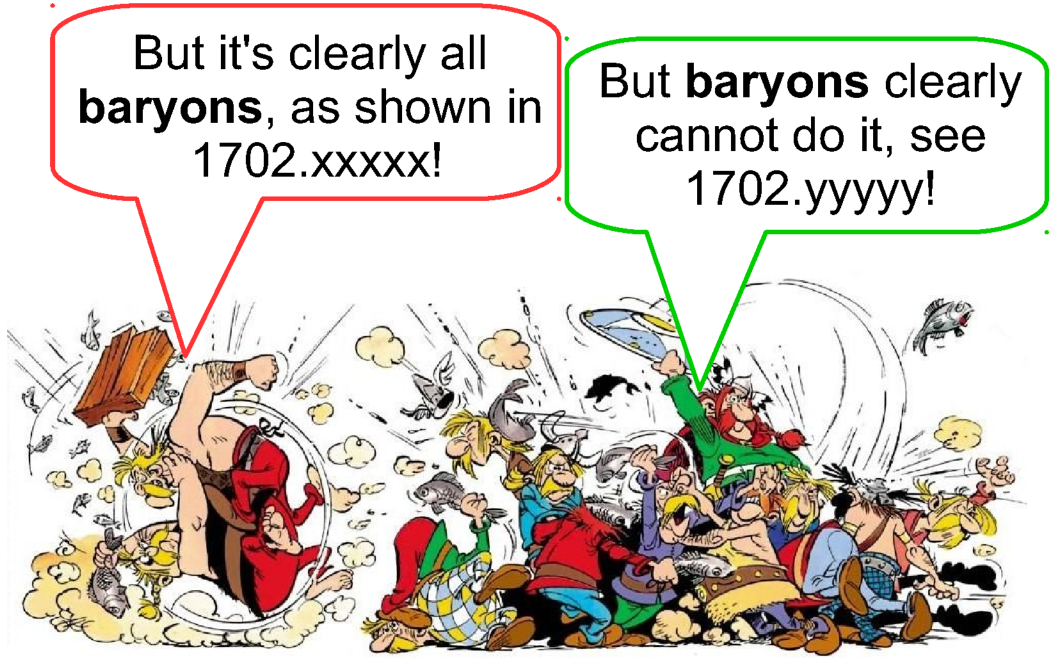

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Motivation: Particle physics

- 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

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

- 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

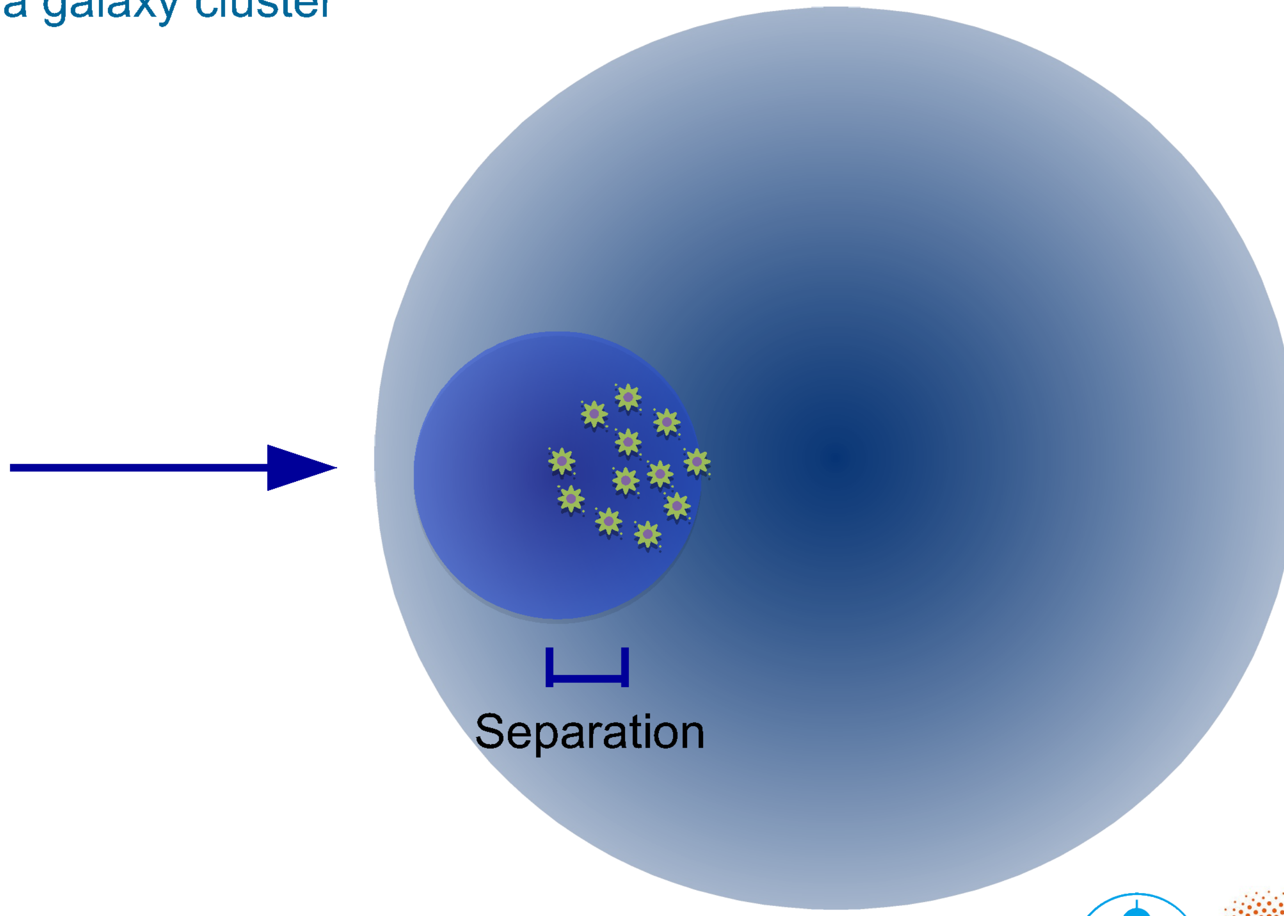
- Various astrophysical observations give constraints on SIDM:

  - 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!

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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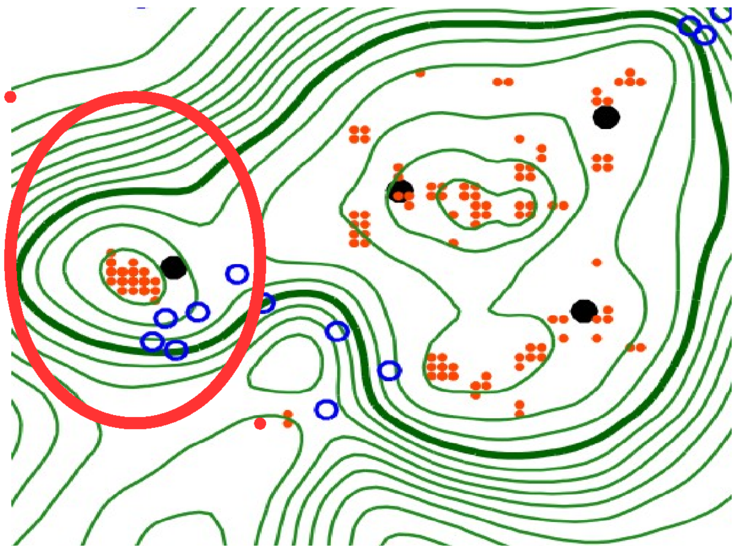
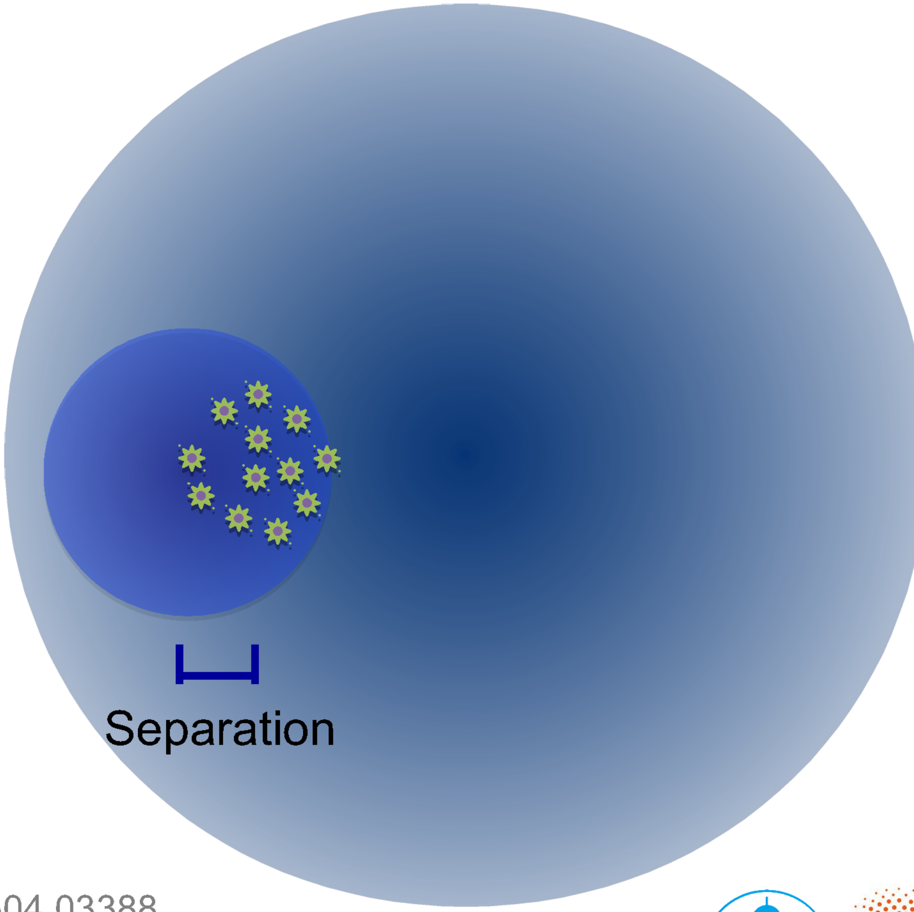
Observed offset: 1.62+/-0.48kpc





- Observed in 2015 in **A3827**

Massey et al., arXiv:1504.03388

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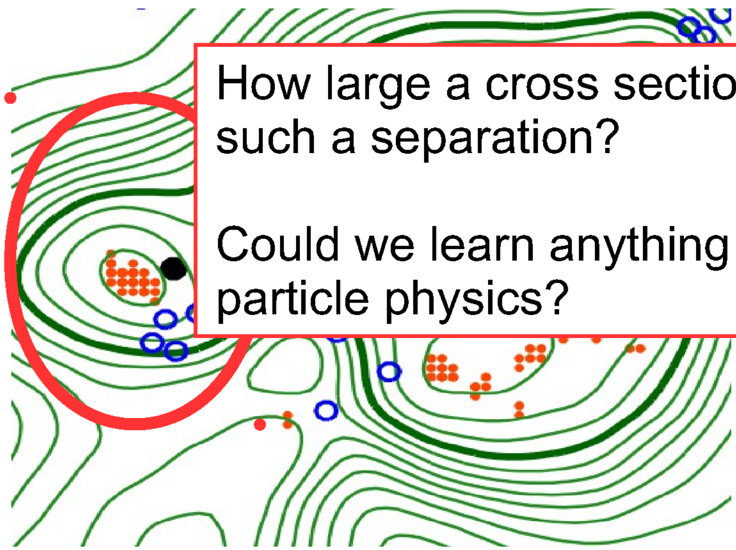


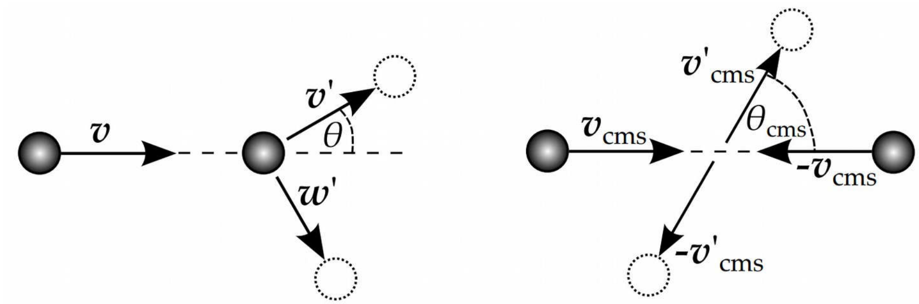
How large a cross section would be needed to achieve such a separation?

Could we learn anything else about the underlying particle physics?

- Observed in 2015 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

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

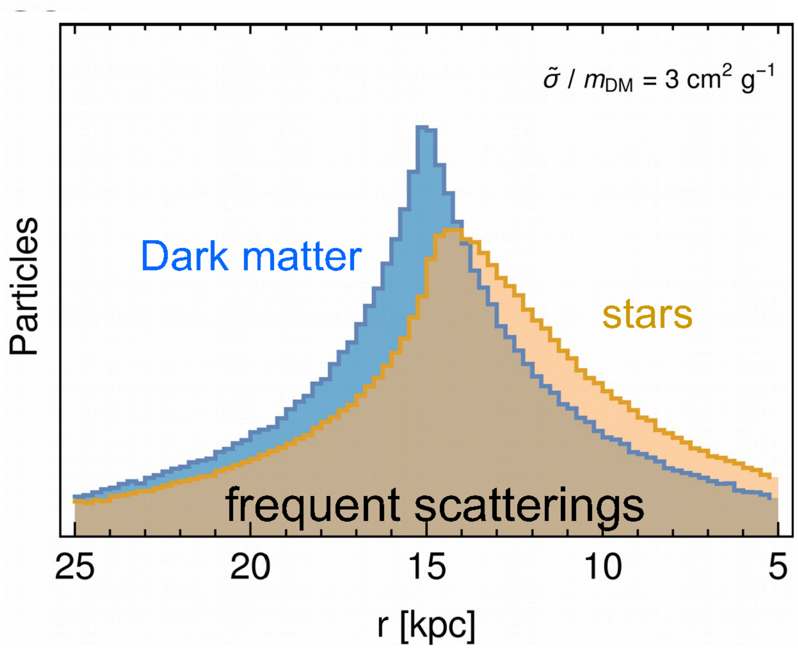
This is the quantity typically studied

Kahlhoefer et al, 1308.3419

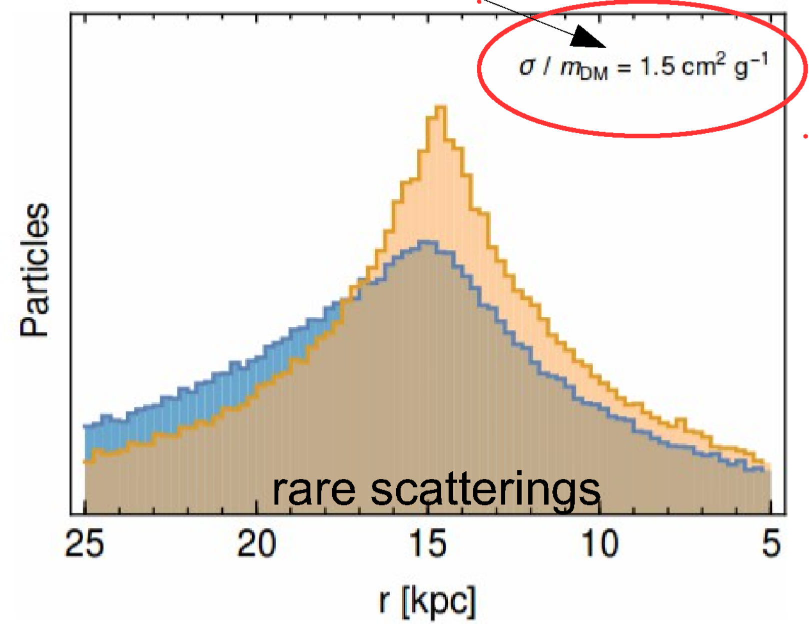
However, this is not all that matters…
Can be obtained with **rare scatters and large momentum transfer** (e.g. isotropic scattering) or **frequent scatters with small momentum transfer** (e.g. long range interactions)

Infalling galaxy in A3827

Kahlhoefer et al, 1504.06576

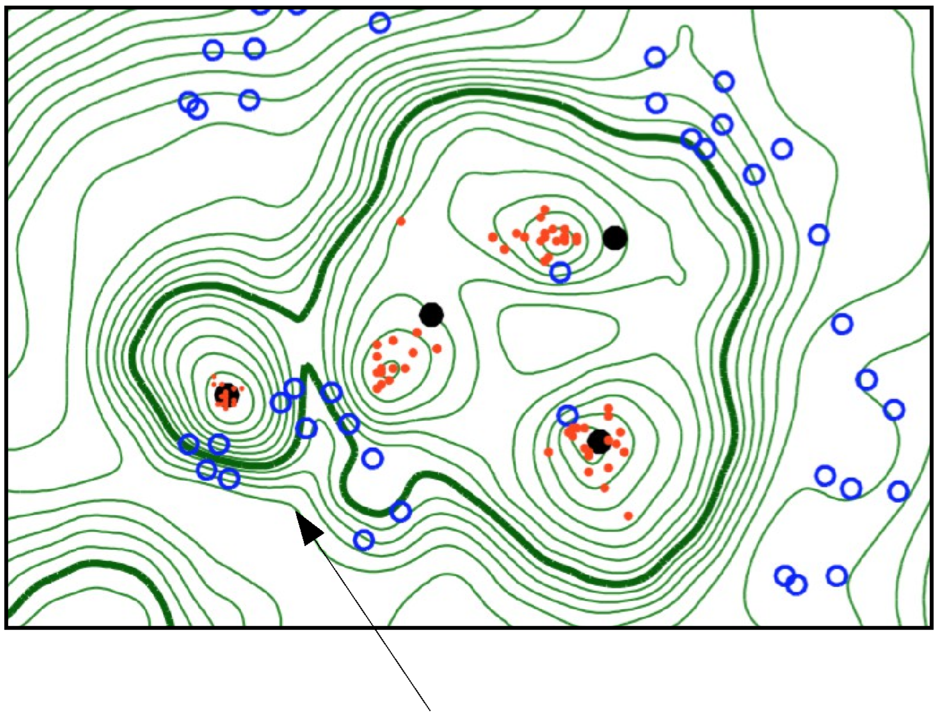


A3827: In (some) tension with upper bounds



Infalling galaxy in A3827

R Massey, talk at SIDM17



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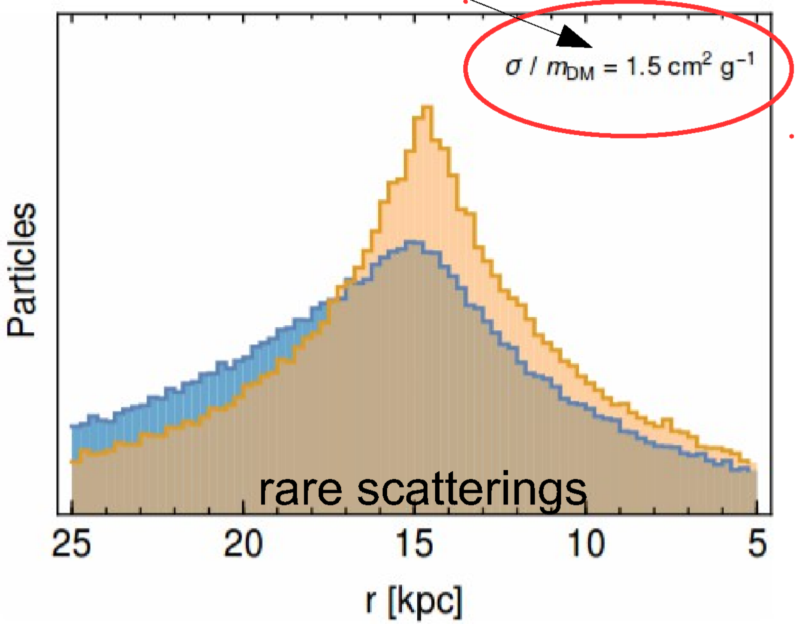
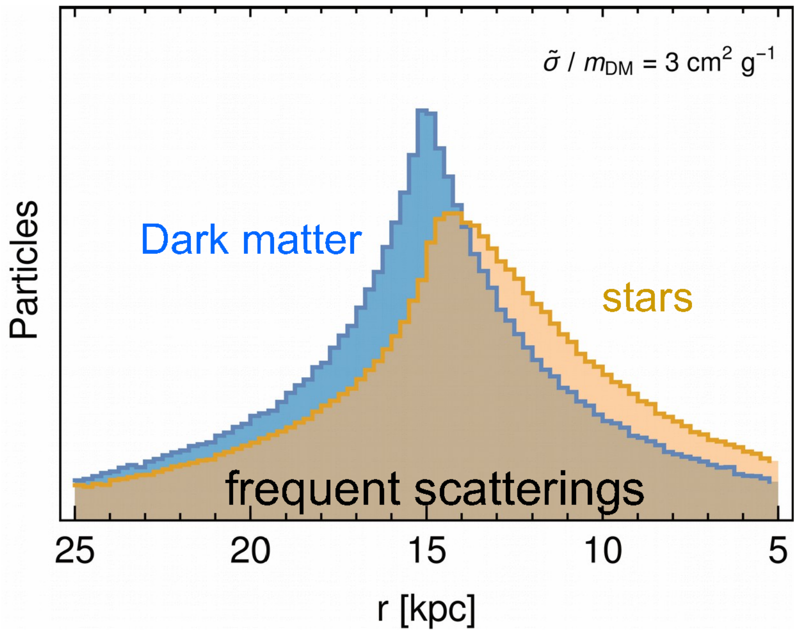
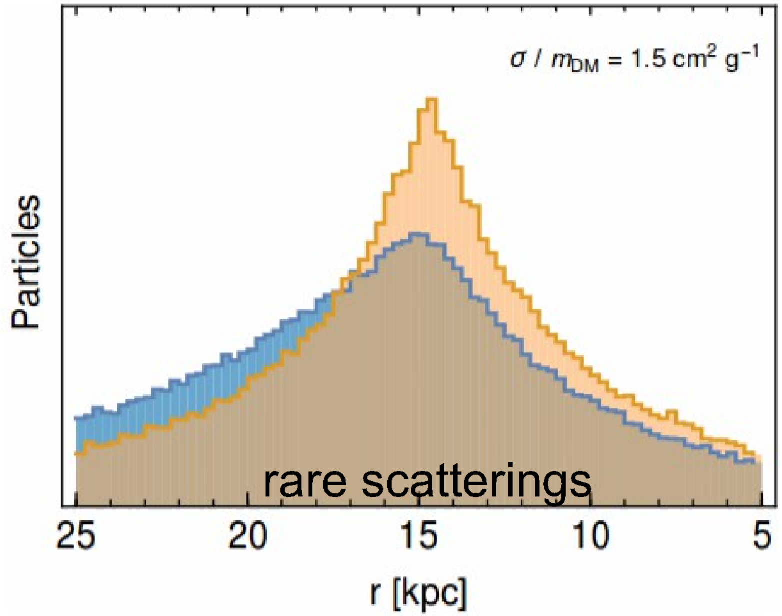


Reanalysis from 2017 – offset gone :-(

More generally: Distinguishing different types of SIDM

Kahlhoefer et al, 1504.06576

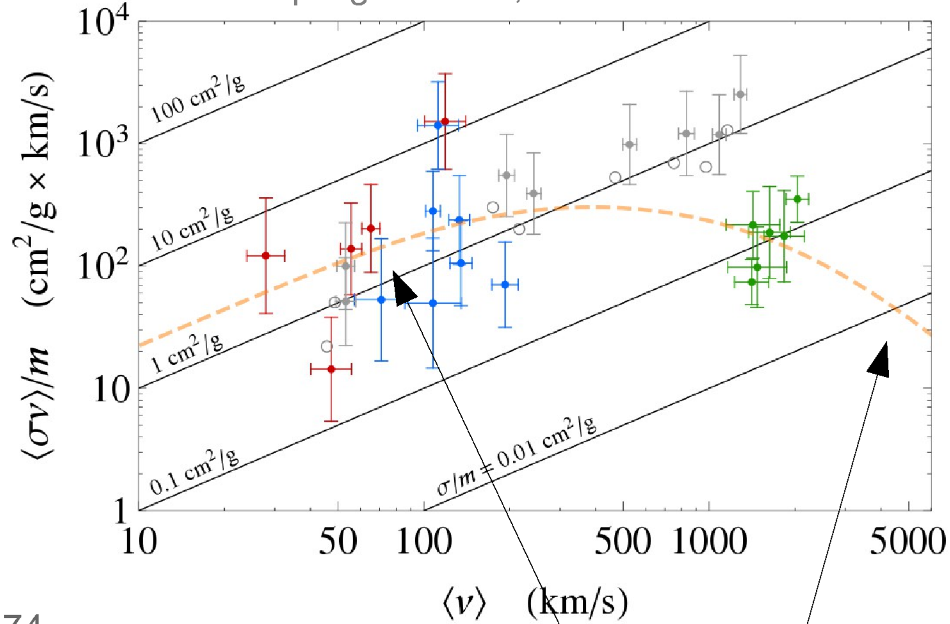




- **Effective drag force:** the DM subhalo retains its shape, while the distribution of stars are both shifted and deformed.
- **Contact interactions**: the DM subhalo is deformed due to the scattered DM particles leaving the subhalo in the backward direction.
- Potentially distinguishable (but very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

Velocity dependent self-interactions

Kaplinghat et al., arXiv:1508.03339



- 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!

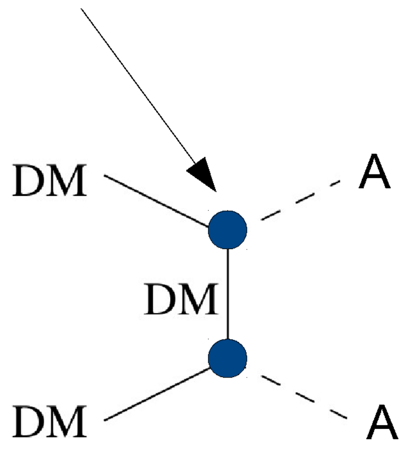
  Loeb & Weiner: arXiv:1011.6374

- 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):

Fix dark sector coupling via relic abundance



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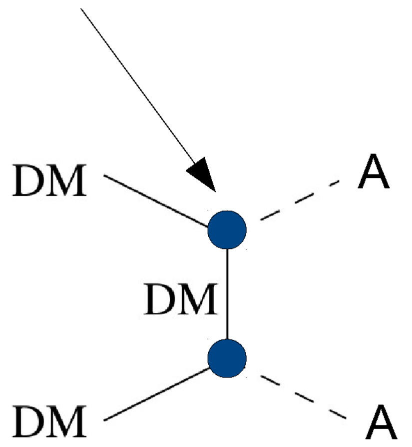
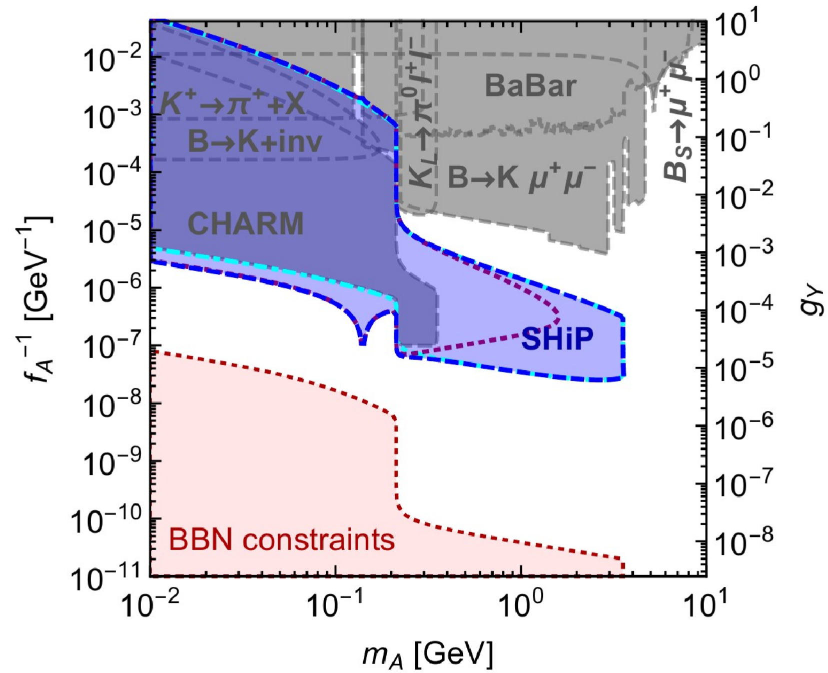
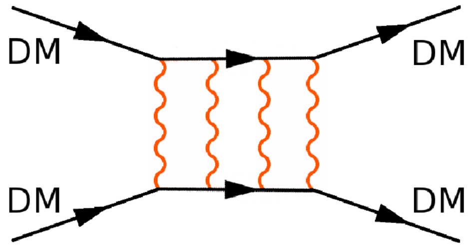




- To avoid overclosing the Universe, the mediator should ultimately decay, so its couplings to SM states cannot be arbitrarily small

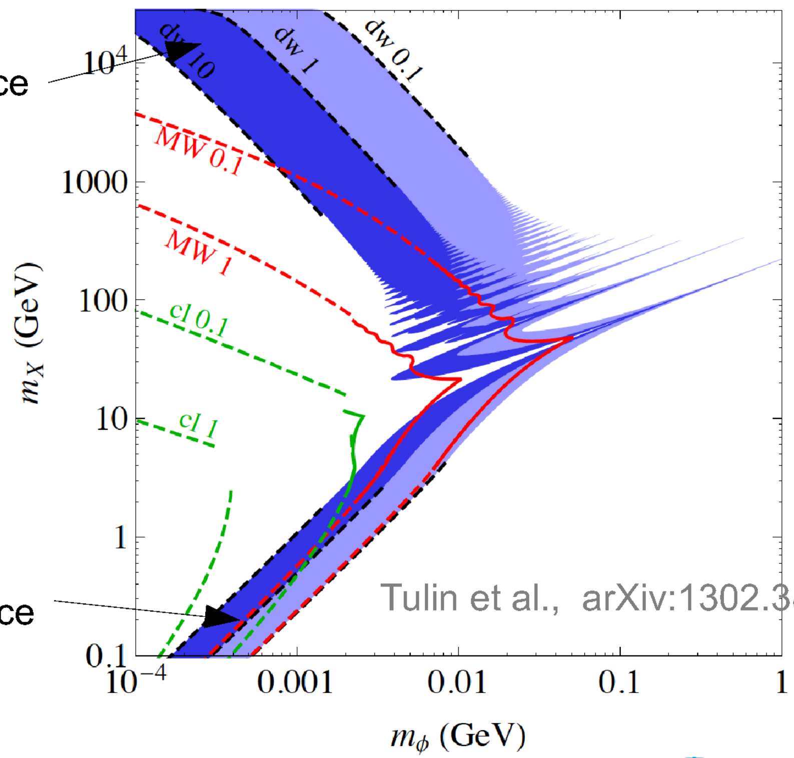
Enhancement of DM self-interactions

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



Dark matter with relic density (s−wave)

strong velocity dependence



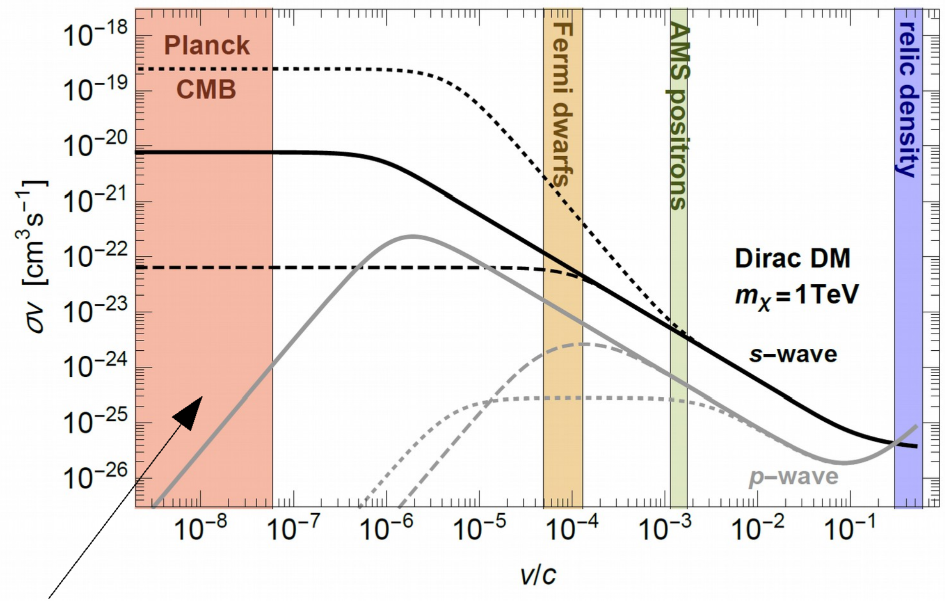
weak velocity dependence

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

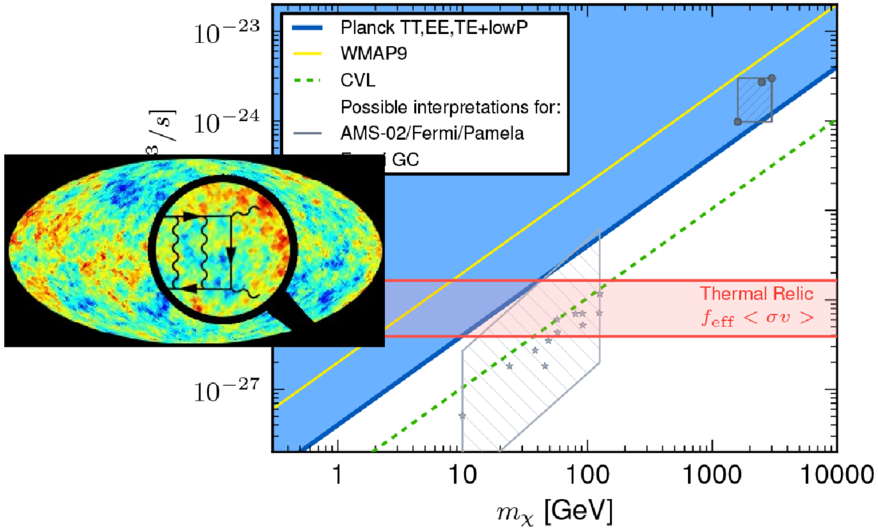


During recombination dark matter particles move at walking speed.

Constraints on DM self-interactions

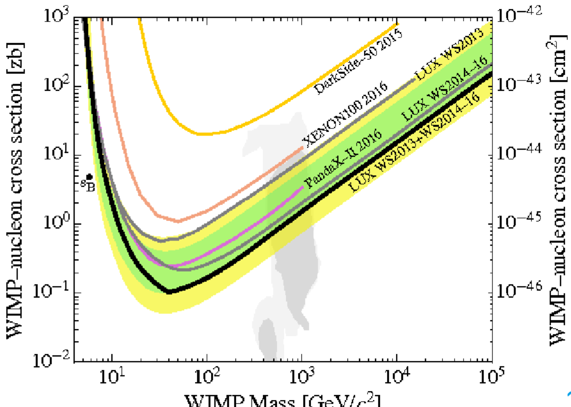
- DM annihilations during recombination, followed by mediator decays into SM particles, inject energetic electrons and photons into the plasma.

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



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

  → see talk by Felix



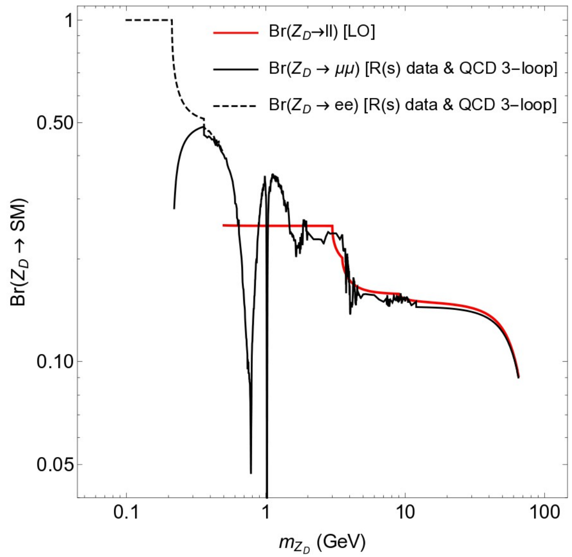
Vector mediators

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

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

Kinetic mixing:
Mediator obtains photon-like couplings

Mass mixing:
Mediator obtains Z-like couplings



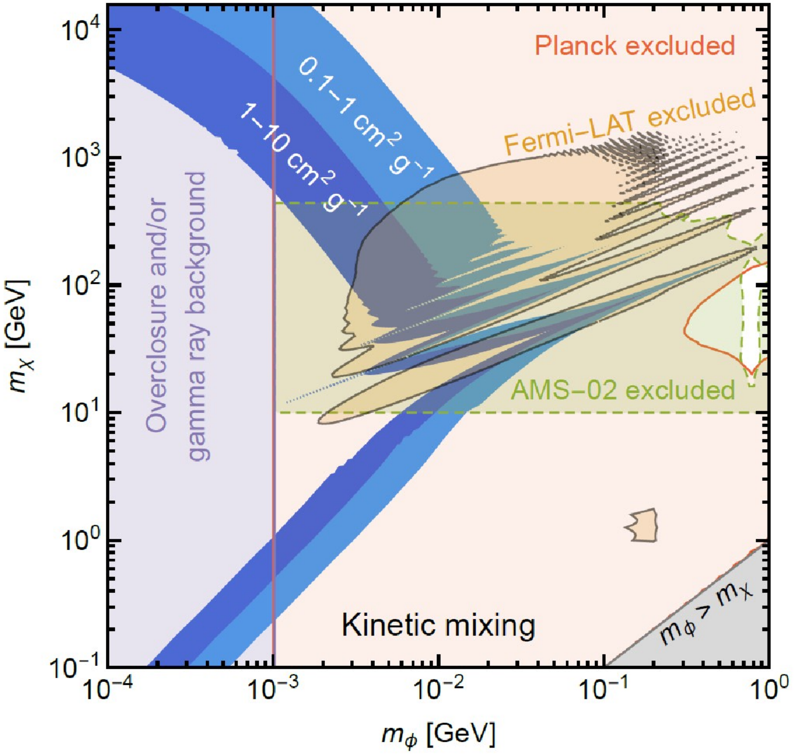
Curtin et al., arXiv:1412.0018

- 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



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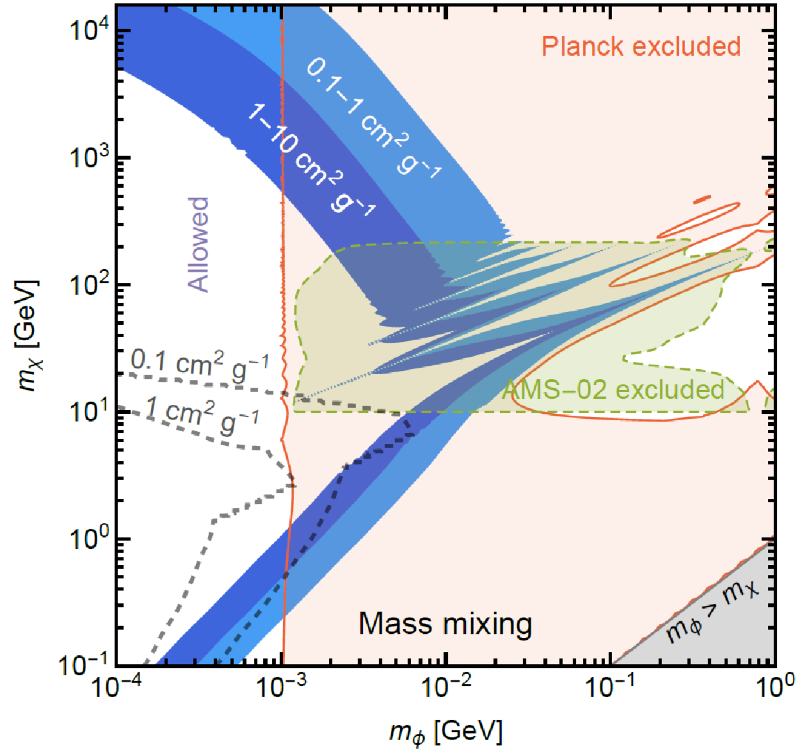
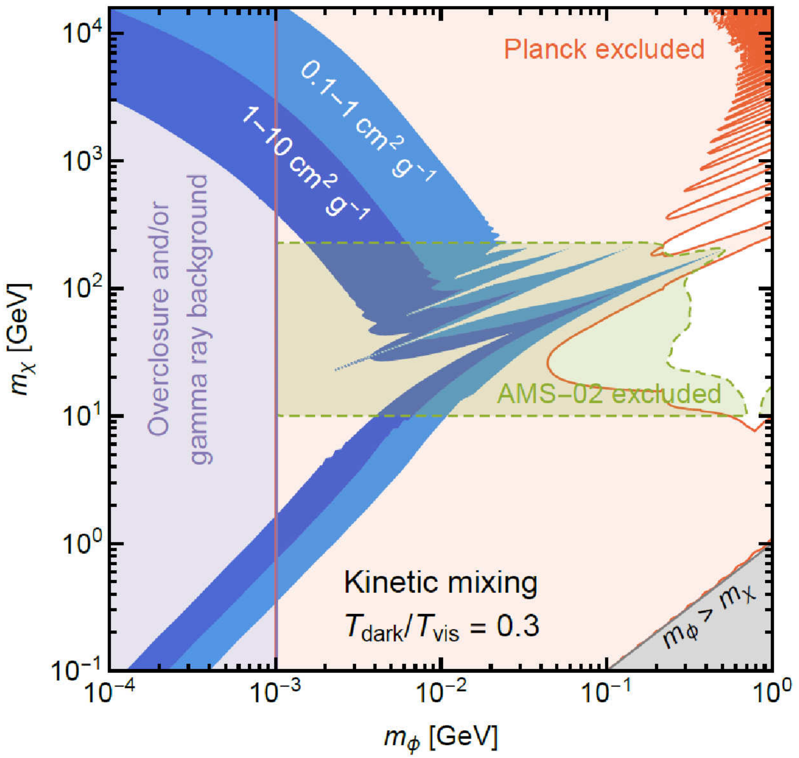


Constraints on vector mediators

- 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



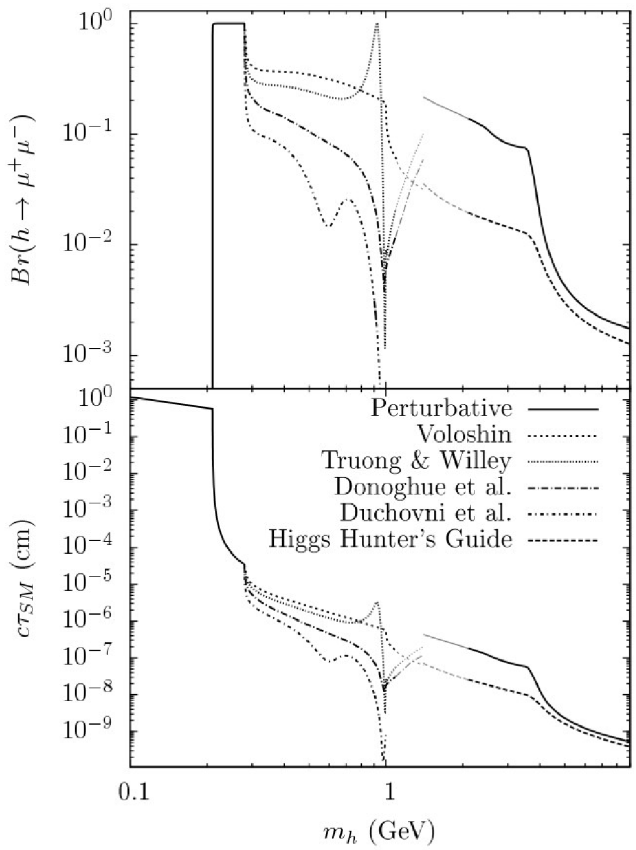
Scalar mediators

- Example: A real scalar singlet that obtains a vacuum expectation value and mixes with the SM Higgs boson.

- This mixing induces Yukawa-like couplings to SM fermions consistent with minimal flavour violation:

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{g_y\, m_f}{v}\,\phi\,\bar{f}f \;-\frac{1}{2}\kappa\phi\bar{\chi}\chi$$

Clarke et al., arXiv:1310.8042



- Branching ratios in the GeV region are difficult to calculate due to hadronic resonances

- Below the pion threshold the leptonic and photonic decay modes are well understood.

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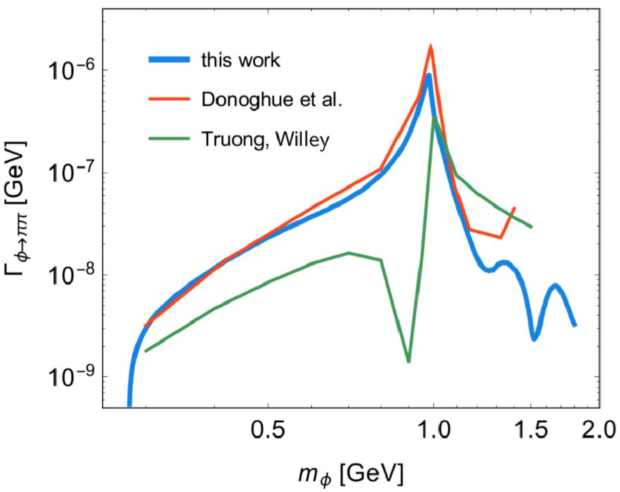
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{g_y\, m_f}{v}\, \phi\, \bar{f} f \; - \frac{1}{2}\kappa\phi\bar{\chi}\chi$$

M Winkler at Planck17

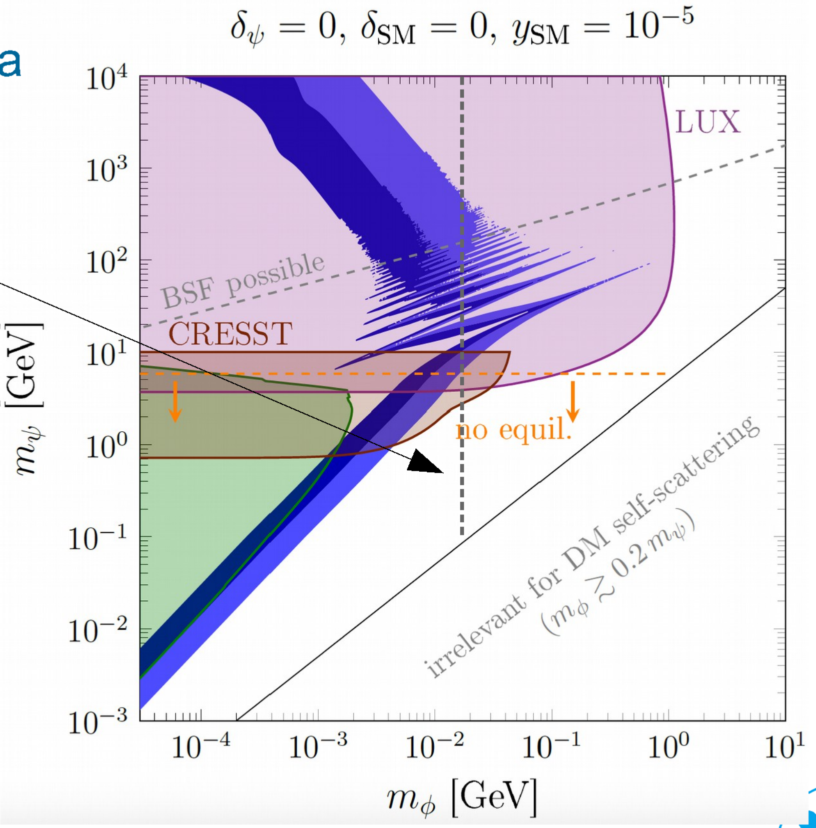


- Branching ratios in the GeV region are difficult to calculate due to hadronic resonances

- Below the pion threshold the leptonic and photonic decay modes are well understood.

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: $\tau < 1$ s
- Only velocity independent scattering allowed (if at all)



1704.02149

Pseudoscalar mediators

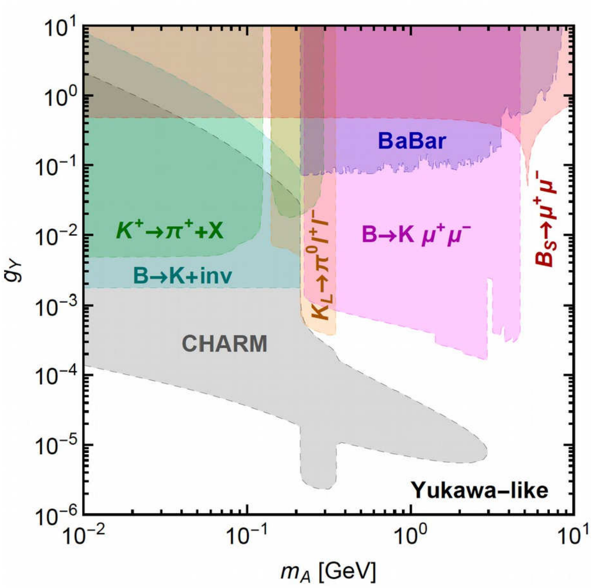
$$\mathcal{L}_{\mathrm{DM}} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi \qquad \mathcal{L}_{\mathrm{SM}}^{(Y)} = i\, g_Y \sum_{f=q,\ell} \frac{\sqrt{2}\, m_f}{v} A\, \bar{f}\gamma^5 f$$

> 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

> Strongest bounds come from direct searches for light pseudoscalars.



Dolan et al., arXiv:1412.5174

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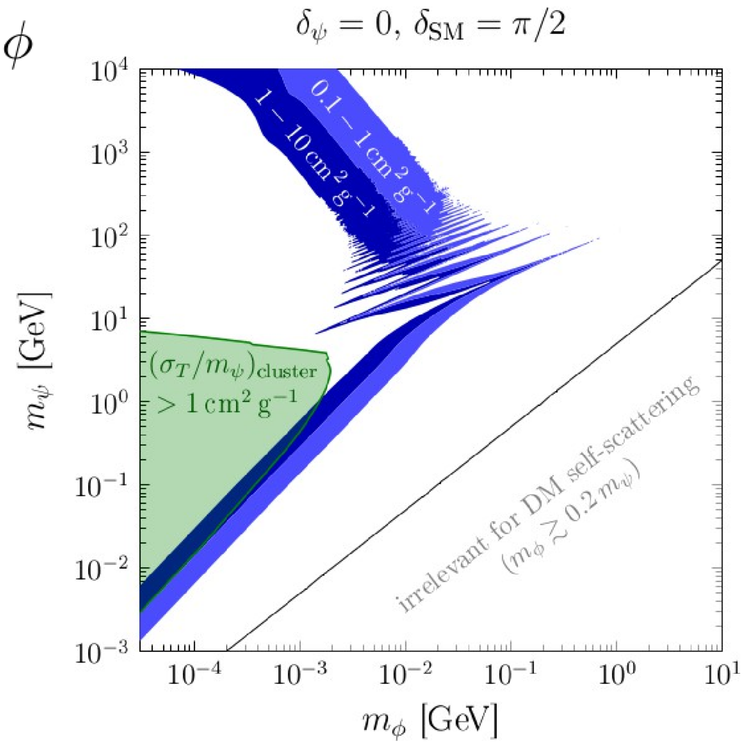
Idea: A mixed mediator (CP violation)

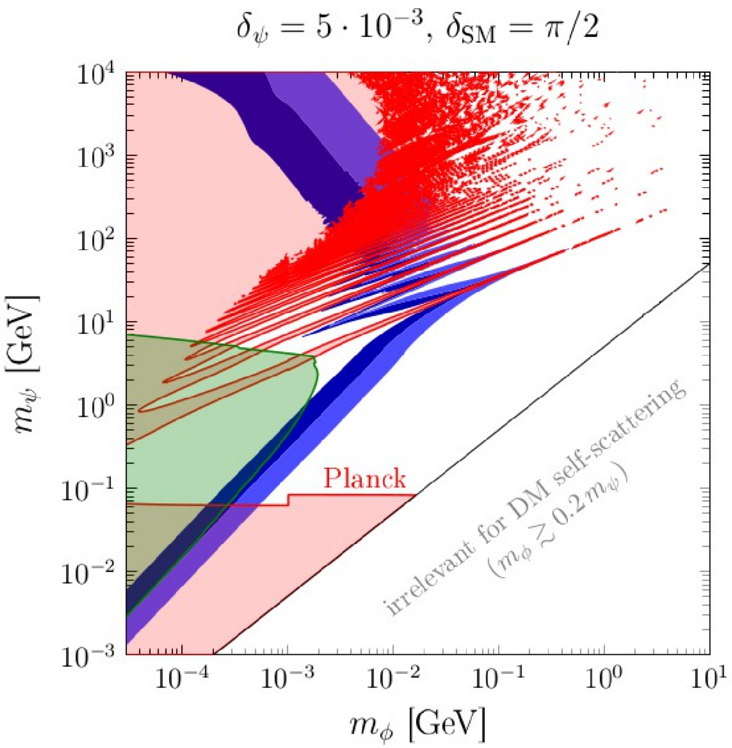
$$\mathcal{L}_{\rm DM} \supset y_\psi \cos\delta_\psi \; \bar\psi\psi\phi + y_\psi \sin\delta_\psi \; i\bar\psi\gamma^5\psi\phi$$

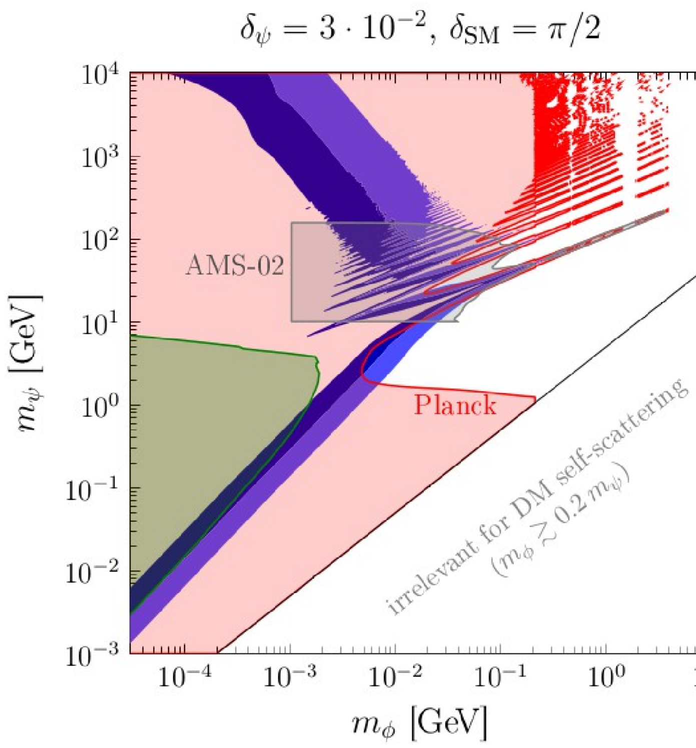


- For $\delta_\psi \sim 0$ (like a scalar) DM self-interactions can be large.
- For $\delta_{SM} \sim \pi/2$ (like a pseudoscalar) direct detection constraints are strongly suppressed.
- Large allowed parameter space!
- Constraints on the CP-violating phase δ_{SM} (e.g. from electron EDMs) can be satisfied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

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 other ways to evade the various constraints
  - Inert decays of the mediator, for example into (sterile) neutrinos $\rightarrow$ Torsten!
  - 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!

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!