Self-interacting dark matter: Current status and perspectives

Kai Schmidt-Hoberg

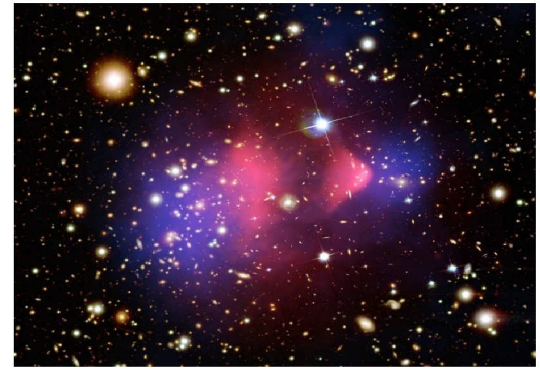
partially based on work with
T Bringmann, M Duerr, M Frandsen, F Kahlhoefer, J Kummer,
S Sarkar, P Walia, S Wild

HELMHOLTZ ASSOCIATION

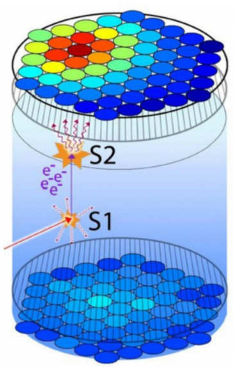
erc

DESY

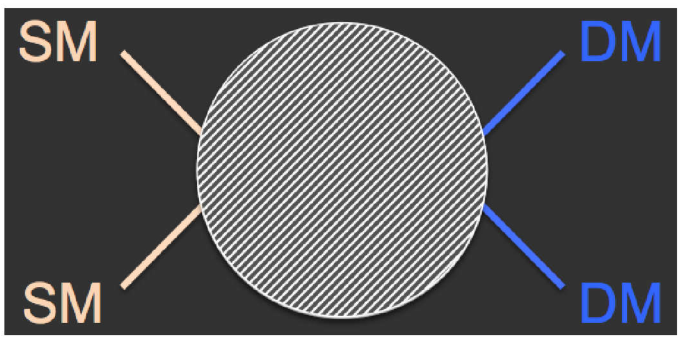
A global view on dark matter interactions...

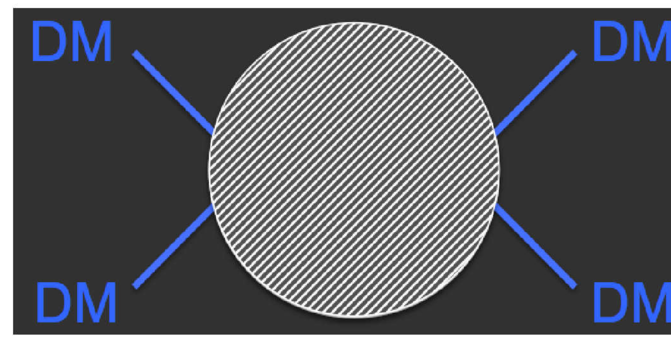


Indirect detection



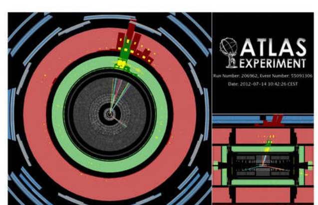
Direct detection





Collider searches

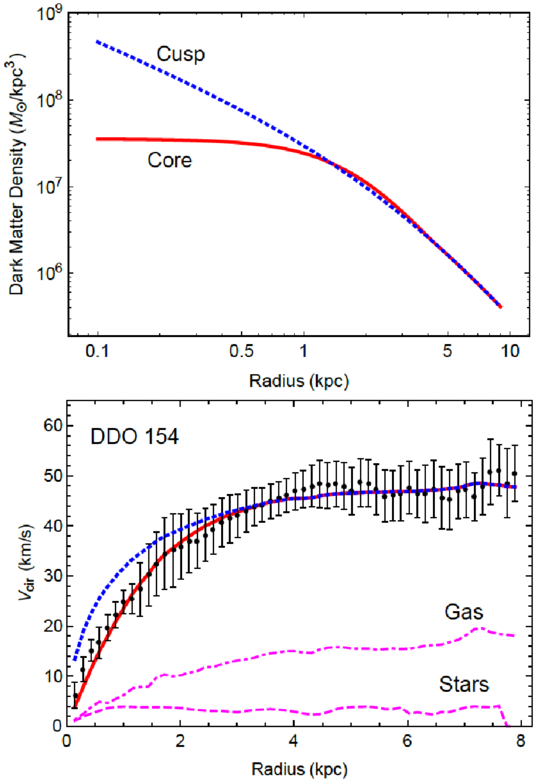
DM self-interactions



Motivation: Cosmology

Covered by JESUS

- 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

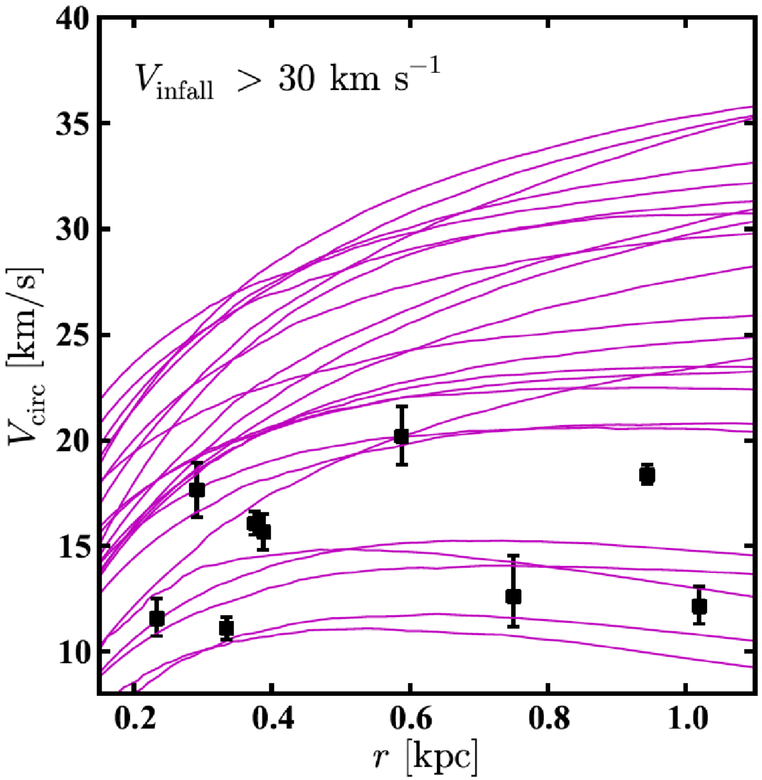


Tulin, Yu: 1705.02358

Motivation: Cosmology

Covered by JESUS

- 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

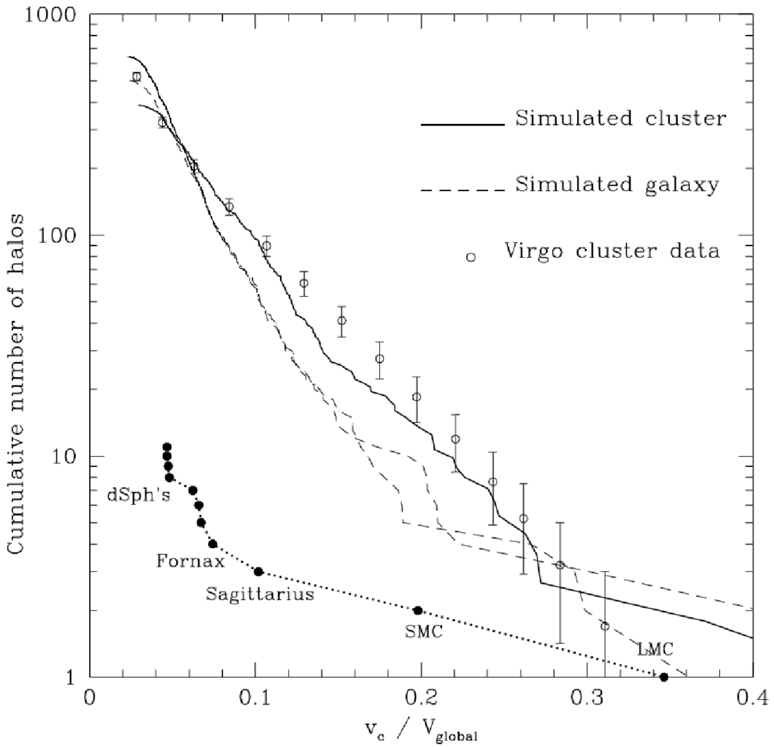


Tulin, Yu: 1705.02358

Motivation: Cosmology

Covered by JESUS

- 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

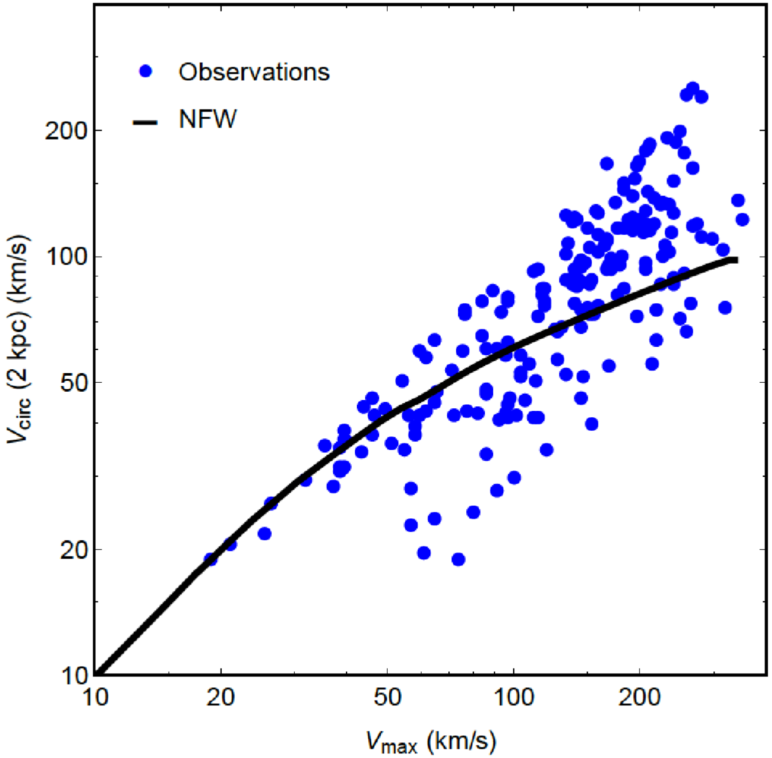


Tulin, Yu: 1705.02358

Motivation: Cosmology

Covered by JESUS

- 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
  - Diversity problem



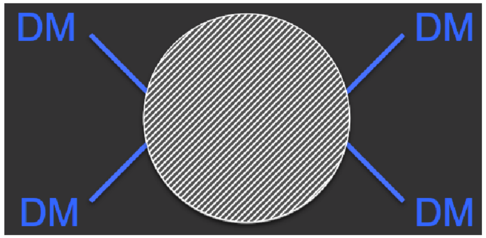
Tulin, Yu: 1705.02358

Motivation: Cosmology

Covered by JESUS

- 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
  - Diversity problem

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



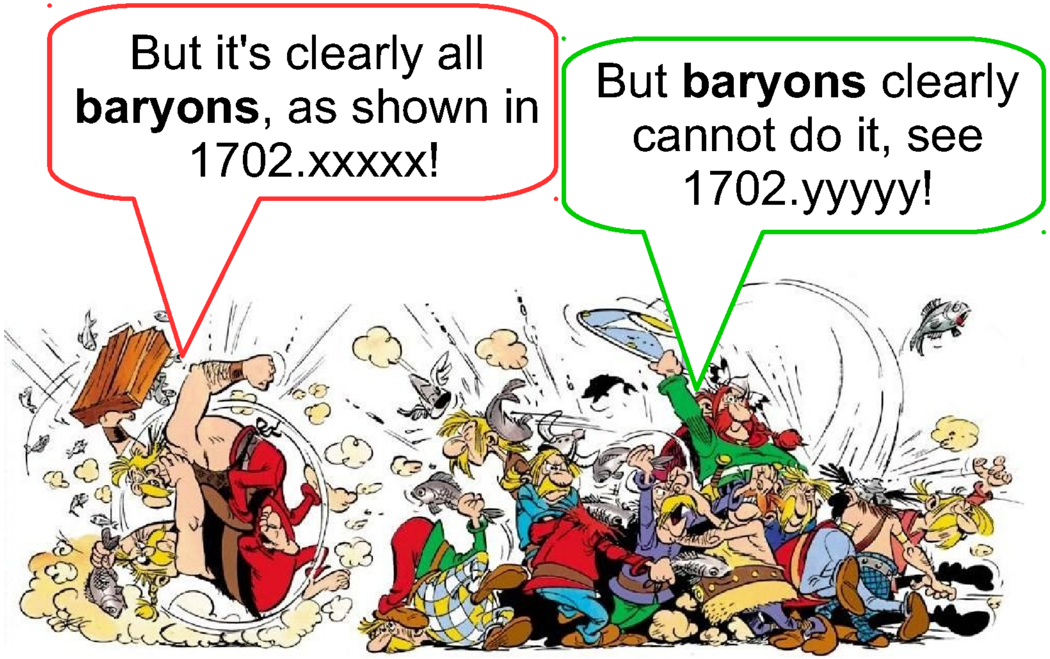
Spergel & Steinhard: astro-ph/9909386
Aarsen, Bringmann, Pfrommer, 1205.5809

Motivation: Cosmology

Covered by JESUS

- 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
  - Diversity problem

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



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

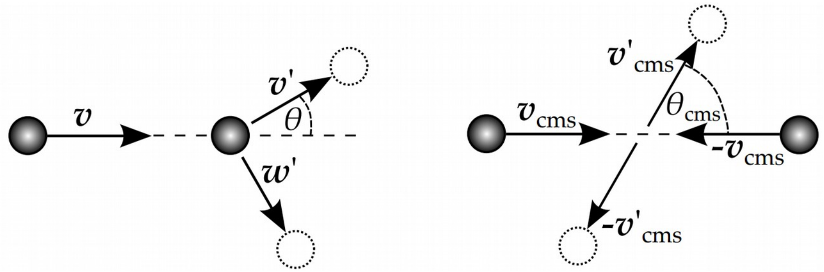
$$\sigma / m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns}/\mathrm{GeV}$$

- 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 (inelastic possible for multi-component DM with small mass splitting, collective effects possible if DM a plasma)



- The scattering cross-section can have an **angular** and a **velocity** dependence
- For single scatter momentum transfer completely fixed by the scattering angle.
- Effective momentum transfer is given by

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

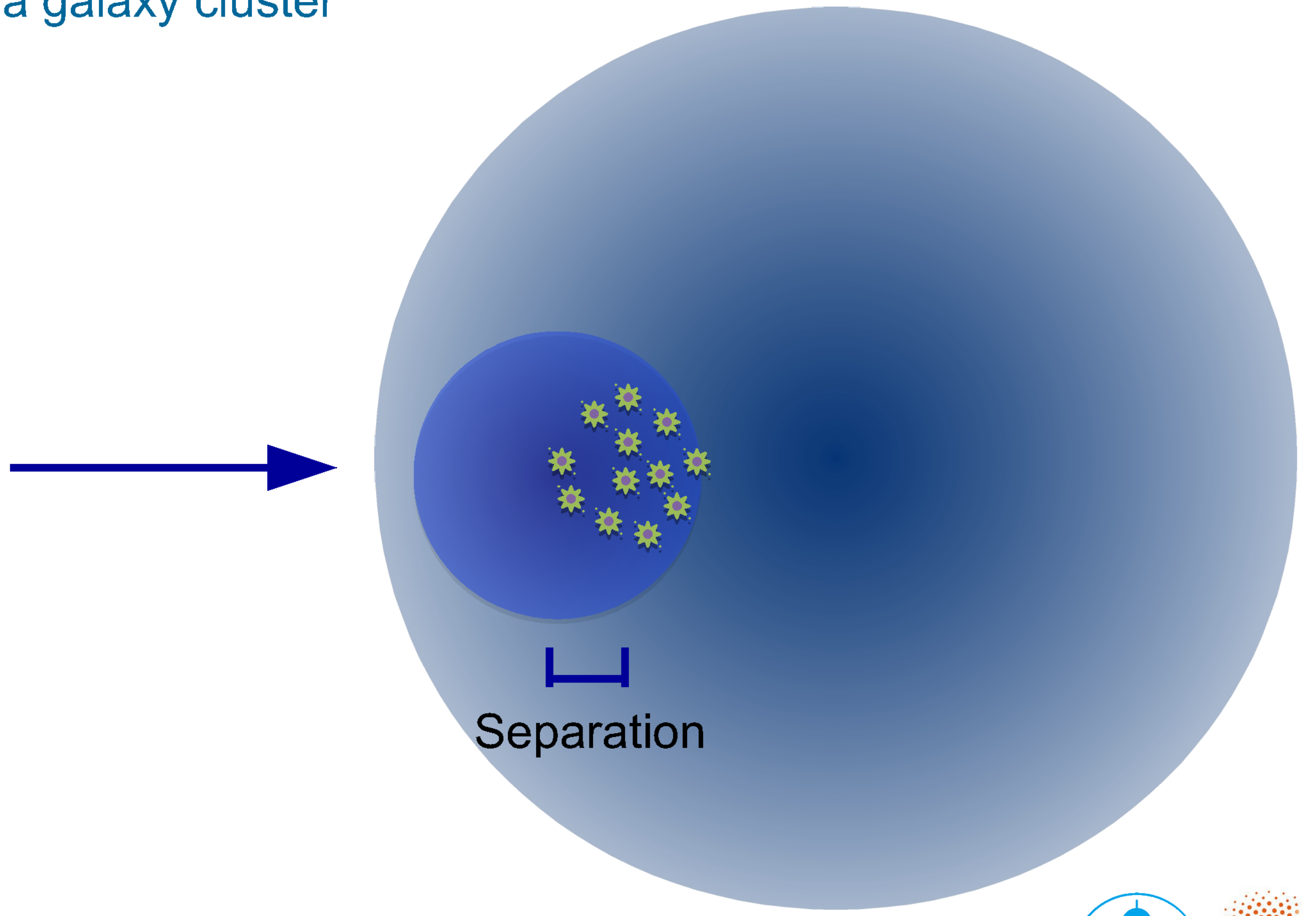
- This is the quantity typically studied (and implemented in N-body simulations)

The particle physics perspective

- 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)
- The different underlying physics can result in different observable effects

A smoking gun observable

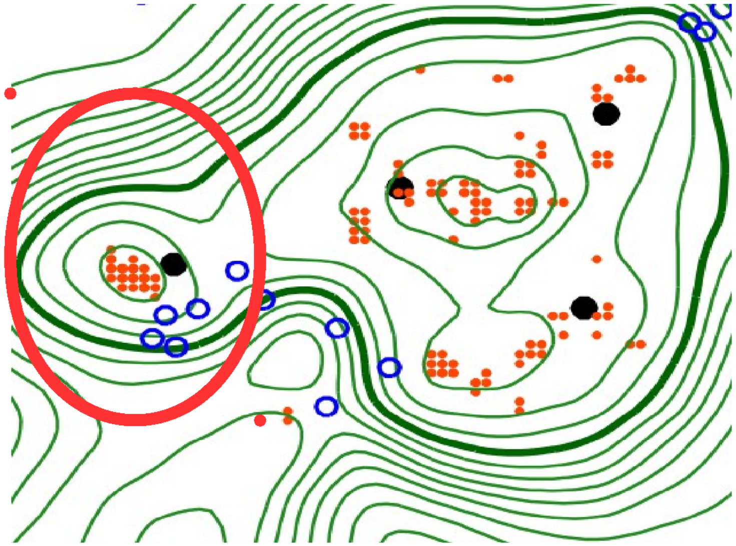
- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster

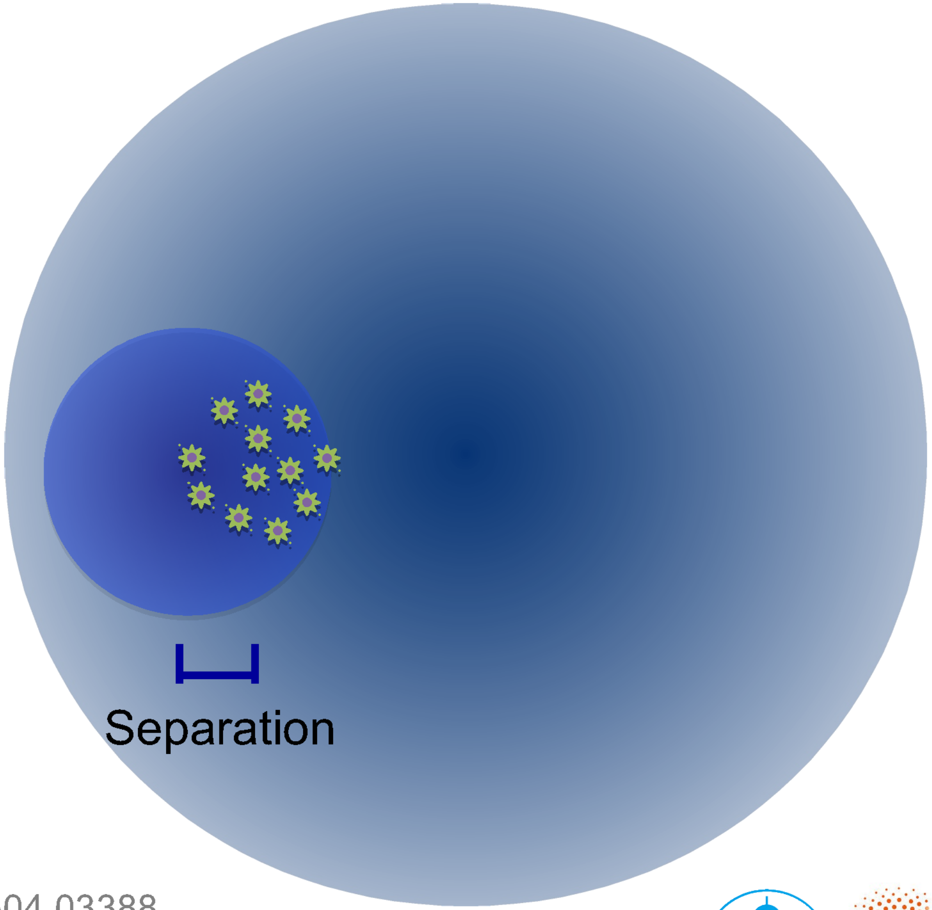


Smoking gun?

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

Observed offset: 1.62+/-0.48kpc





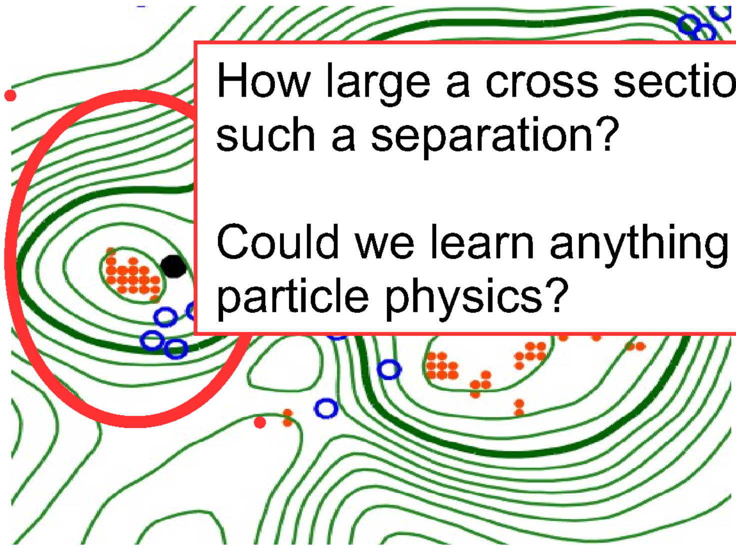
- Observed in 2015 in **A3827**

Massey et al., arXiv:1504.03388

Smoking gun?

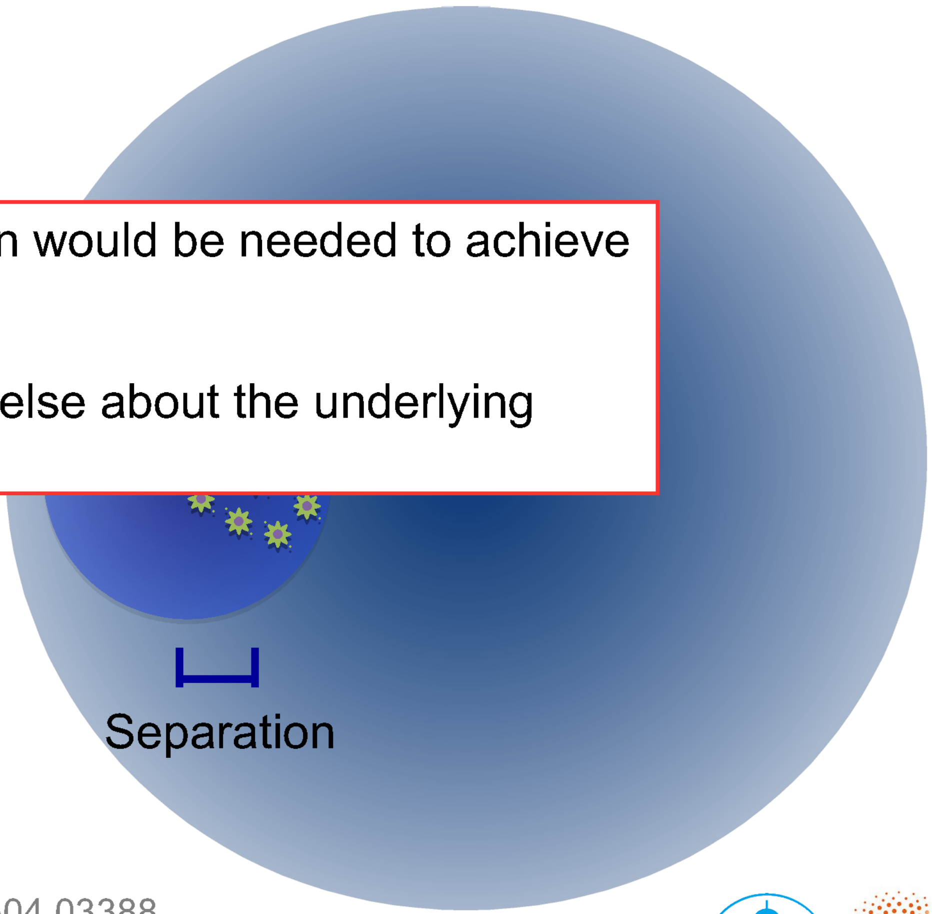
- Smoking gun signal? Separation between dark matter halo and stars of a galaxy falling into a galaxy cluster

Observed offset: 1.62+/-0.48kpc



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

Could we learn anything else about the underlying particle physics?

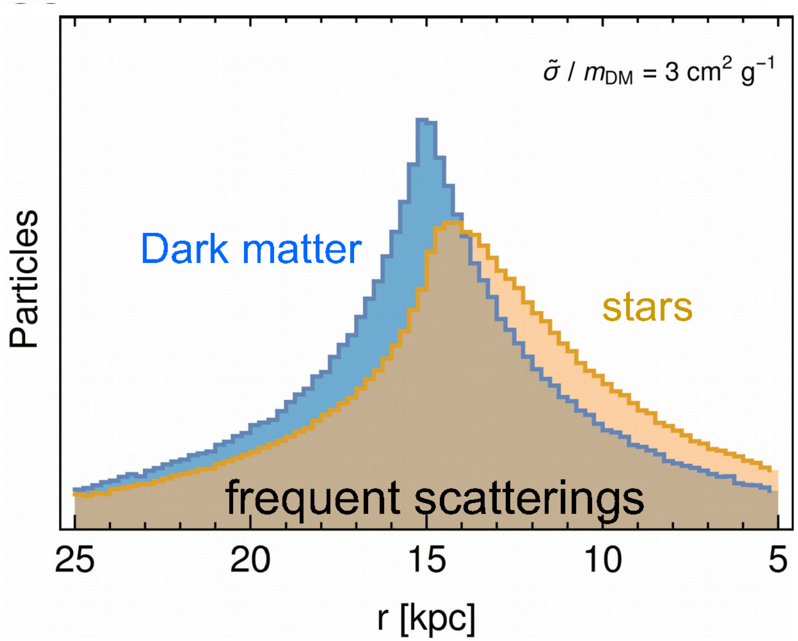


- Observed in 2015 in **A3827**

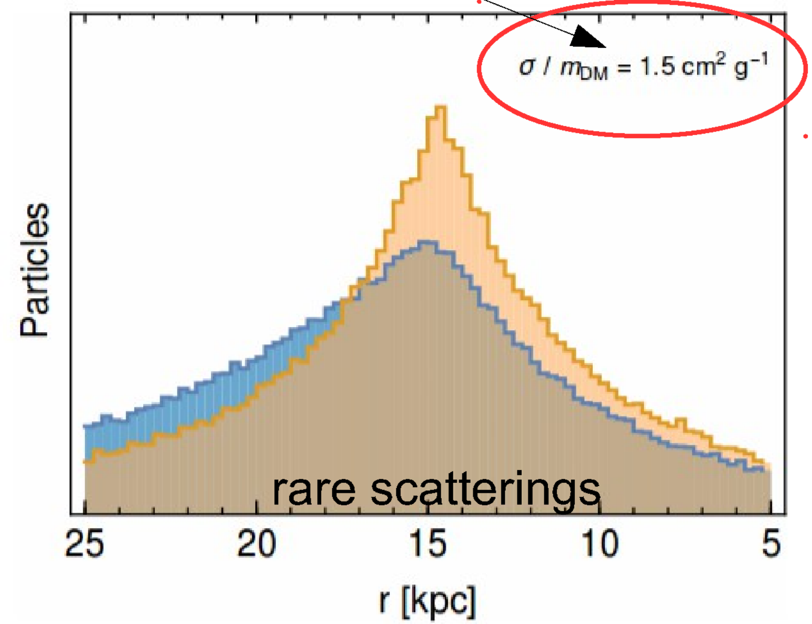
Massey et al., arXiv:1504.03388

Infalling galaxy in A3827

Kahlhoefer et al, 1504.06576

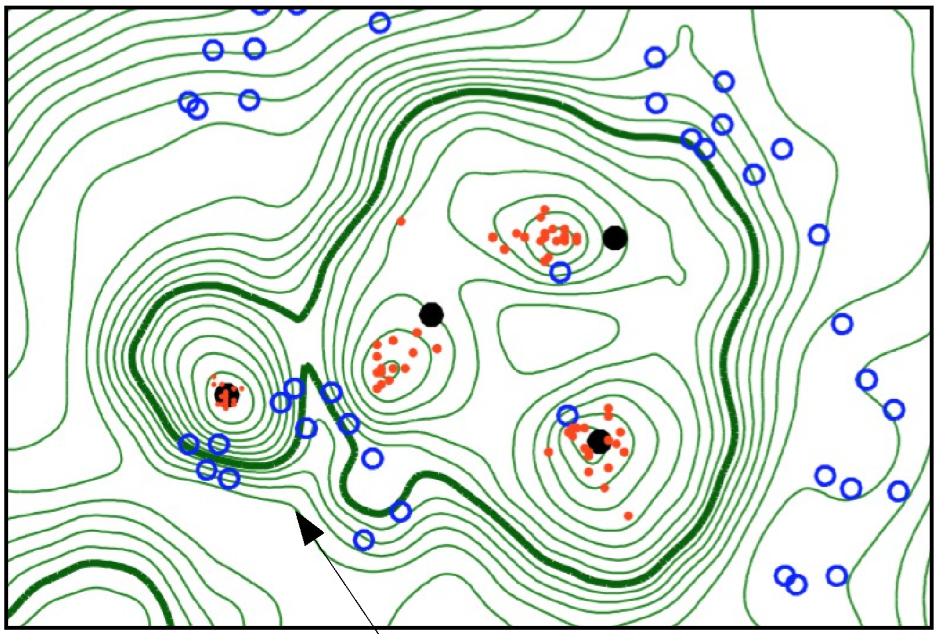


A3827: In (some) tension with upper bounds

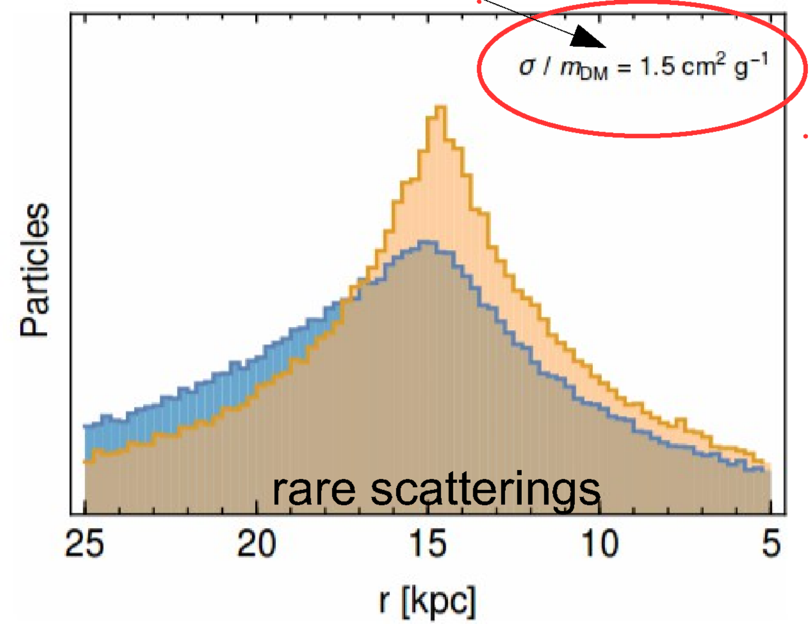


Infalling galaxy in A3827

R Massey, talk at SIDM17



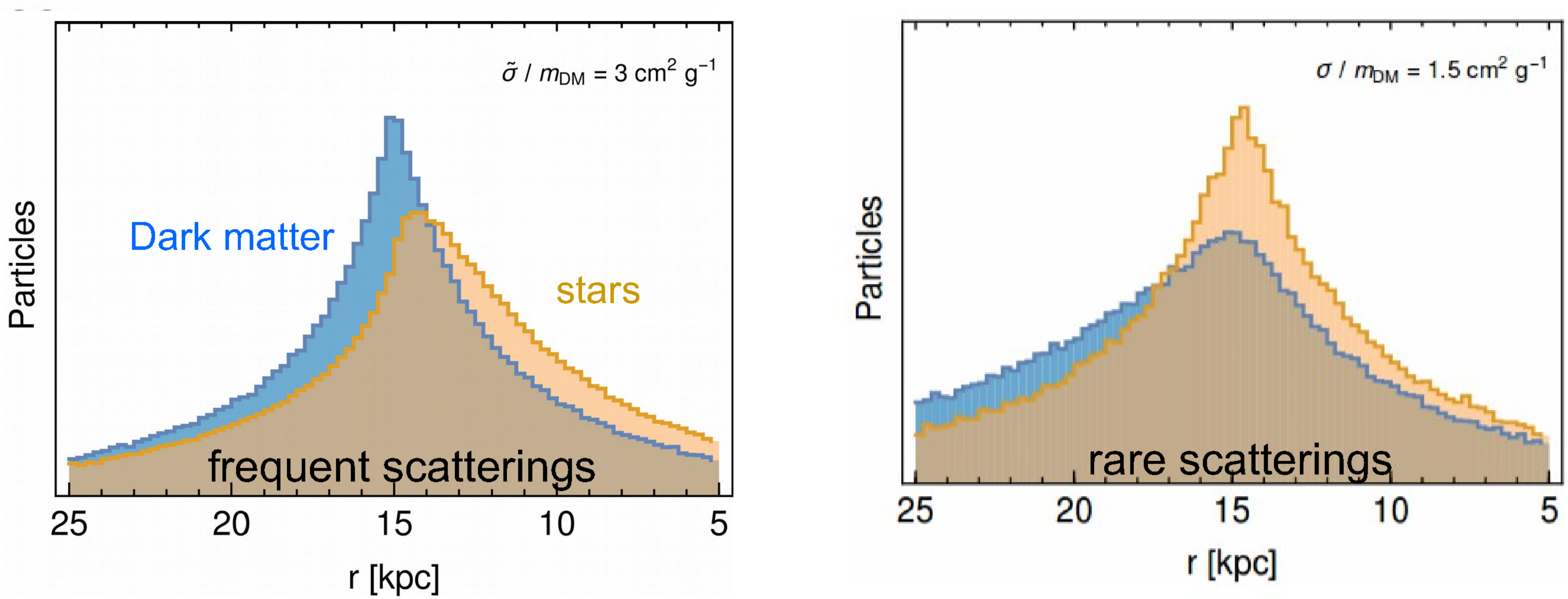
A3827: In (some) tension with upper bounds



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?

What about the velocity dependence?

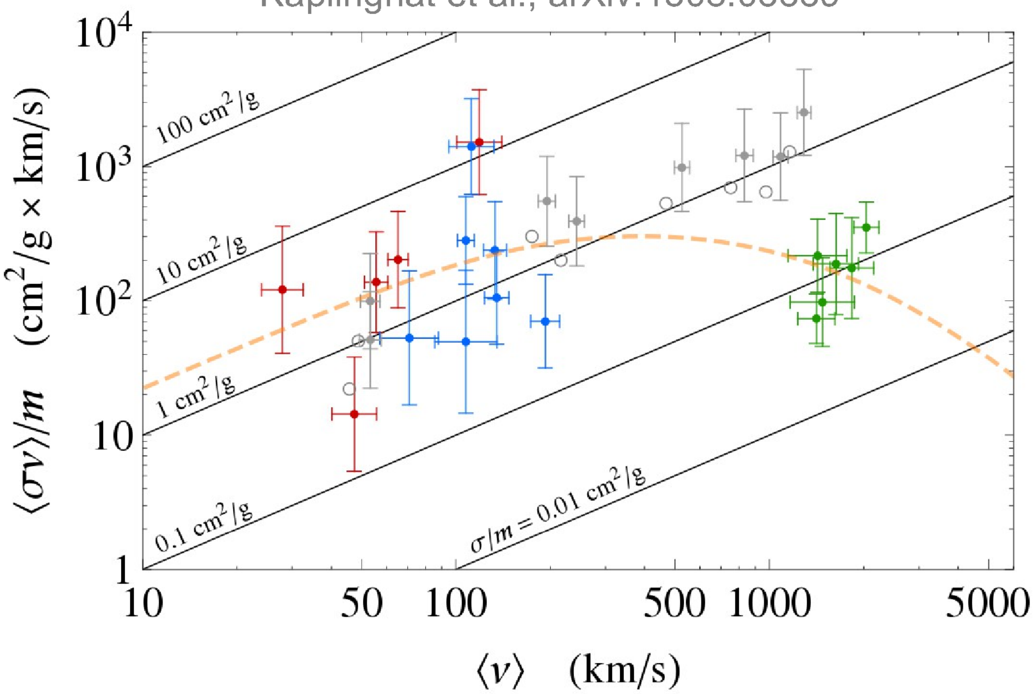
> Different astrophysical systems have different typical velocities!

Positive observations	σ/m	$v_{\rm rel}$	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm^2/g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves	[64, 80]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[74]
Local Group	$\gtrsim 0.5\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[75]
Cores in clusters	$\sim 0.1\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing	[80, 90]
Abell 3827 subhalo merger	$\sim 1.5\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	DM-galaxy offset	[91]
Abell 520 cluster merger	$\sim 1\ \mathrm{cm^2/g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset	[92, 93, 94]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm^2/g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys	[73]
Substructure mergers	$\lesssim 2\ \mathrm{cm^2/g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset	[79, 95]
Merging clusters	$\lesssim$ few $\mathrm{cm^2/g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm^2/g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio	[68]

Velocity dependent self-interactions

- Idea: Relate core size of different systems to SIDM cross section
- Simple analytical model to do this fit
- DM self-interactions seem to depend on the typical relative velocity of DM particles.
- But taken with a grain of salt (baryonic effects again...)

Kaplinghat et al., arXiv:1508.03339



SIDM model building

1) Very light dark matter

- Large DM number densities lead to large self-interaction rates σ / m_χ
- Relic density set e.g. by direct annihilation into SM states

Chu, Garcia-Cely, Hambye, 1609.00399

SIDM model building

1) Very light dark matter

- Large DM number densities lead to large self-interaction rates σ / m_χ
- Relic density set e.g. by direct annihilation into SM states

Chu, Garcia-Cely, Hambye, 1609.00399

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

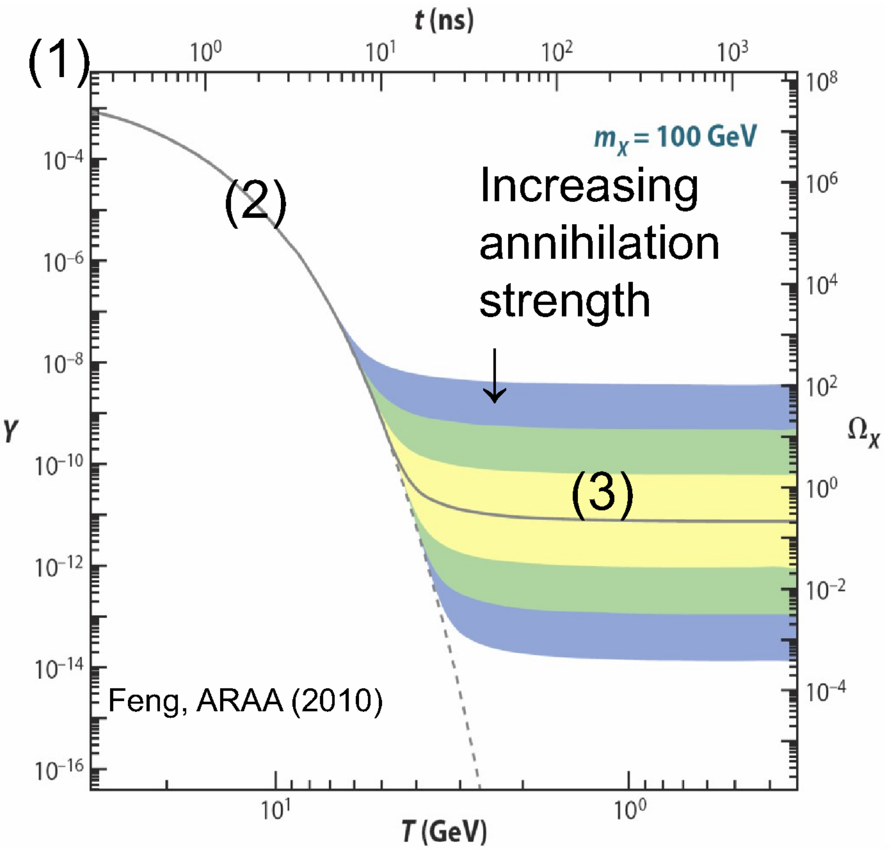
$$XX \leftrightarrow SM\ SM$$

(2) Universe cools:

$$XX \longrightarrow SM\ SM$$

(3) Universe expands:

$$XX \qquad SM\ SM$$



SIDM model building

1) Very light dark matter

- Large DM number densities lead to large self interaction rates σ / m_χ
- Relic density set e.g. by direct annihilation into SM states

Velocity independent scatterings

Chu, Garcia-Cely, Hambye, 1609.00399

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

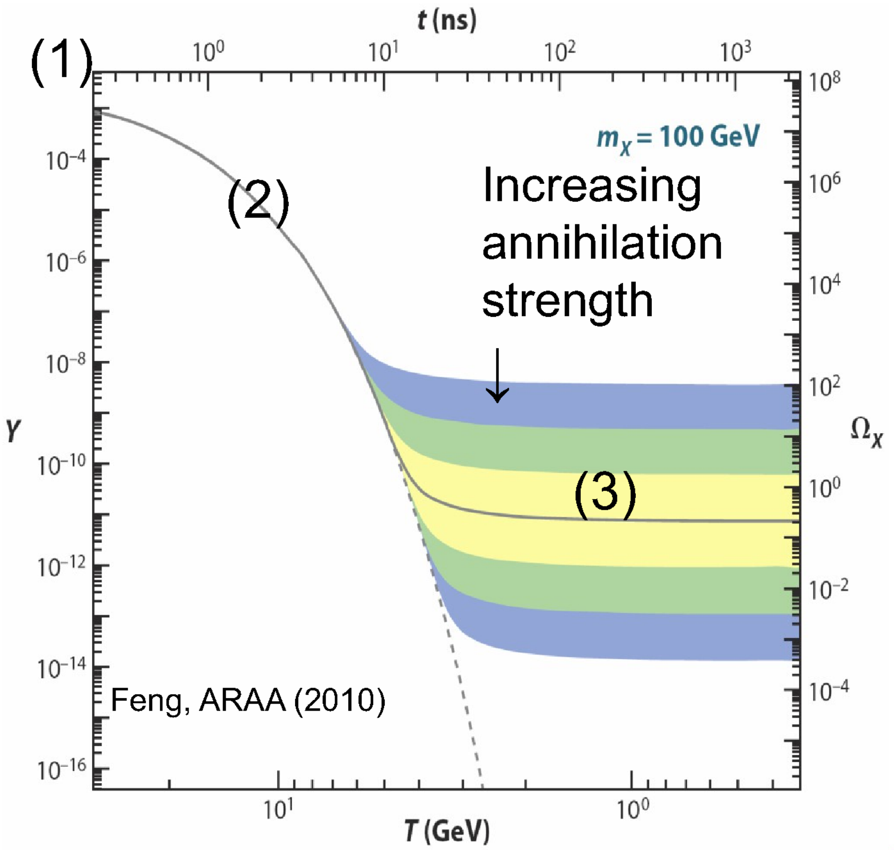
$$XX \leftrightarrow SM\ SM$$

(2) Universe cools:

$$XX \longrightarrow SM\ SM$$

(3) Universe expands:

$$XX \qquad SM\ SM$$



SIDM model building

1) Very light dark matter

- Large DM number densities lead to large self-interaction rates σ / m_χ
- Relic density set e.g. by direct annihilation into SM states

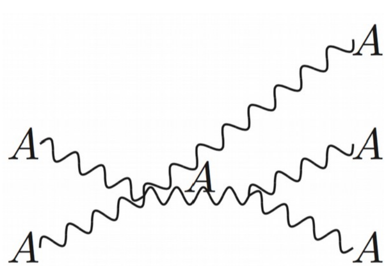
Velocity independent scatterings

Chu, Garcia-Cely, Hambye, 1609.00399

2) New strong dynamics in the dark sector

- large self-scattering (dark nuclei)
- Relic density set e.g. via 3 → 2 processes
- Asymmetric dark matter also natural possibility

Hochberg et al., 1402.5143; 1512.07917;
Bernal et al., arXiv:1510.08063



SIDM model building

1) Very light dark matter

- Large DM number densities lead to large self-interaction rates σ / m_χ
- Relic density set e.g. by direct annihilation into SM states

Velocity independent scatterings

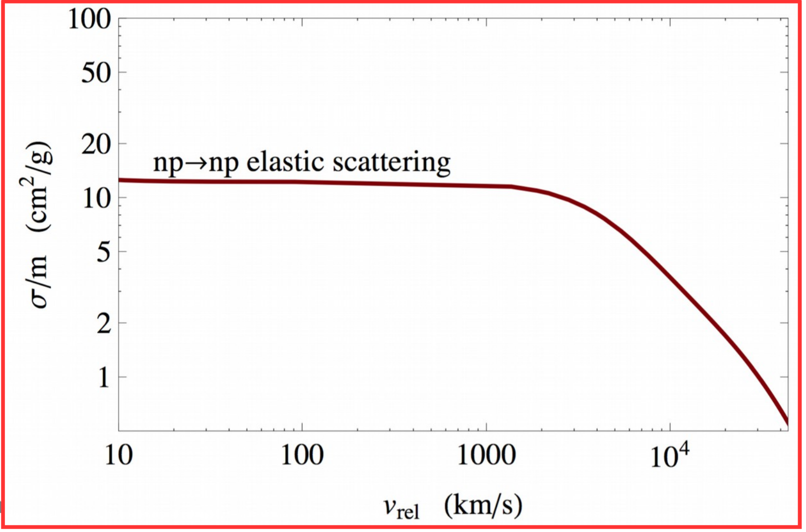
Chu, Garcia-Cely, Hambye, 1609.00399

2) New strong dynamics in the dark sector

- large self-scattering (dark nuclei)
- Relic density set e.g. via 3 → 2 processes
- Asymmetric dark matter also natural possibility

Velocity independent scatterings for the velocities of interest?

.07917;



SIDM model building

1) Very light dark matter

- Large DM numb… …tion rates σ / m_χ

Velocity independent scatterings

- Relic density set e.g. by direct annihilation into SM states

Chu, Garcia-Cely, Hambye, 1609.00399

2) New strong dynamics in the dark sector

- large self-scattering (dark nuclei)
- Reli…

Velocity independent scatterings for the velocities of interest?

.07917;

- Asymmetric dark matter also natural possibility

3) New light mediator in the dark sector

- Self-interactions are enhanced by the small mediator mass
- Relic density set by direct annihilation into pairs of mediators

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

SIDM model building

1) Very light dark matter

- Large DM numb… tion rates σ / m_χ
- Relic density set e.g. by direct annihilation into SM states

Velocity independent scatterings

Chu, Garcia-Cely, Hambye, 1609.00399

2) New strong dynamics in the dark sector

- large …
- Reli…
- Asymmetric dark matter also natural possibility

Velocity independent scatterings for the velocities of interest?

.07917;

3) New light mediator in the dark sector

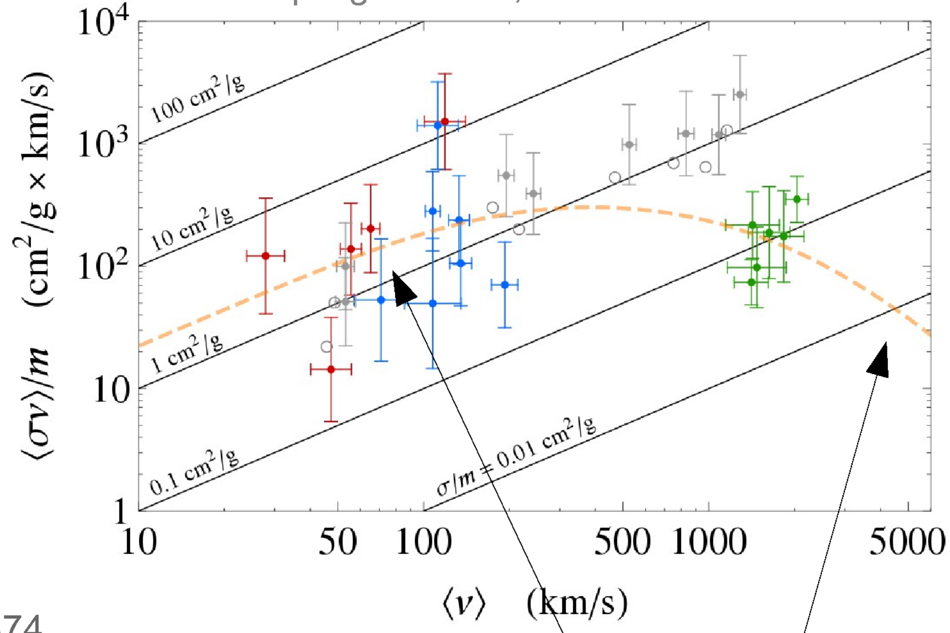
- Self-int…
- Relic d… pairs of mediators

Velocity dependent scatterings

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

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!

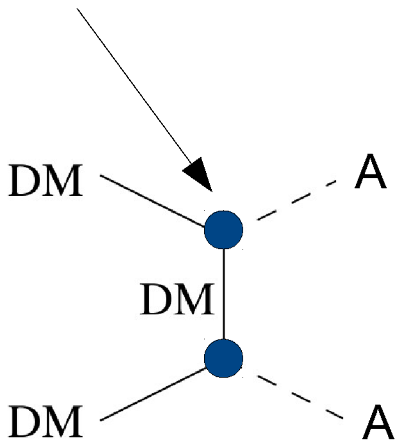
  Loeb & Weiner: arXiv:1011.6374

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

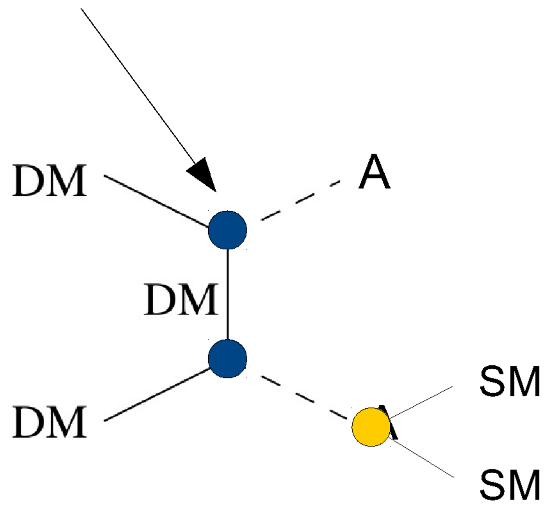
- The relic abundance is typically set by annihilations into pairs of mediators (so-called dark sector freeze-out):

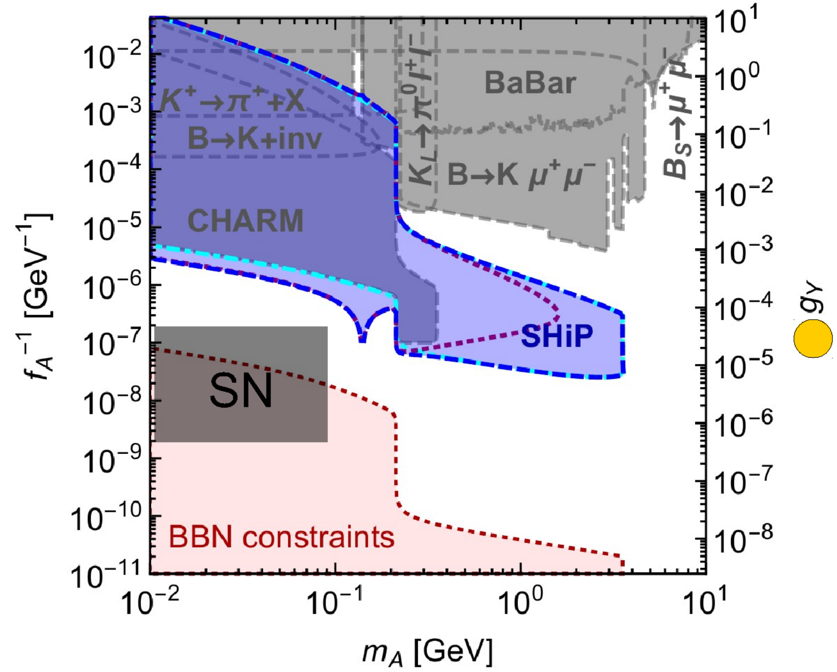
Fix dark sector coupling via relic abundance



A new light mediator

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

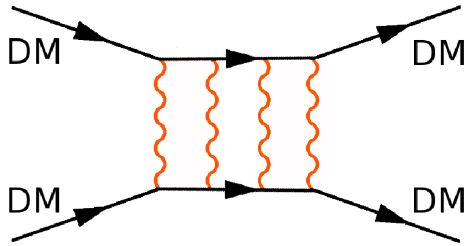




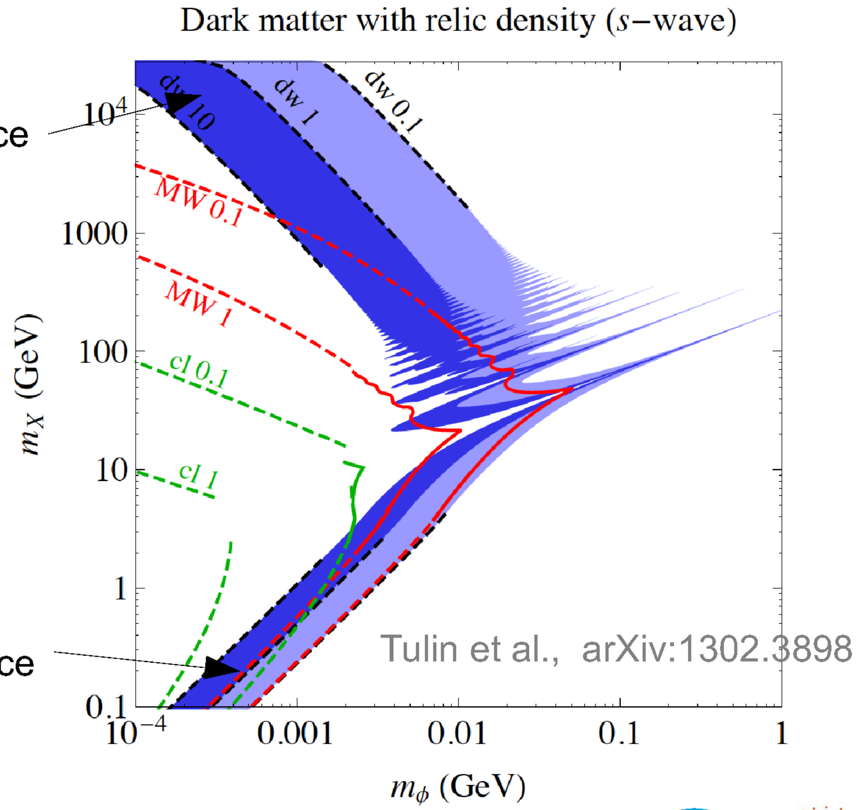
- To avoid overclosing the Universe, the mediator should ultimately disappear, so its couplings to SM states cannot be arbitrarily small – many constraints

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

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) → σ_0

p-wave (scalar mediator) → $\sigma_1\, v_{\rm rel}^2$

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

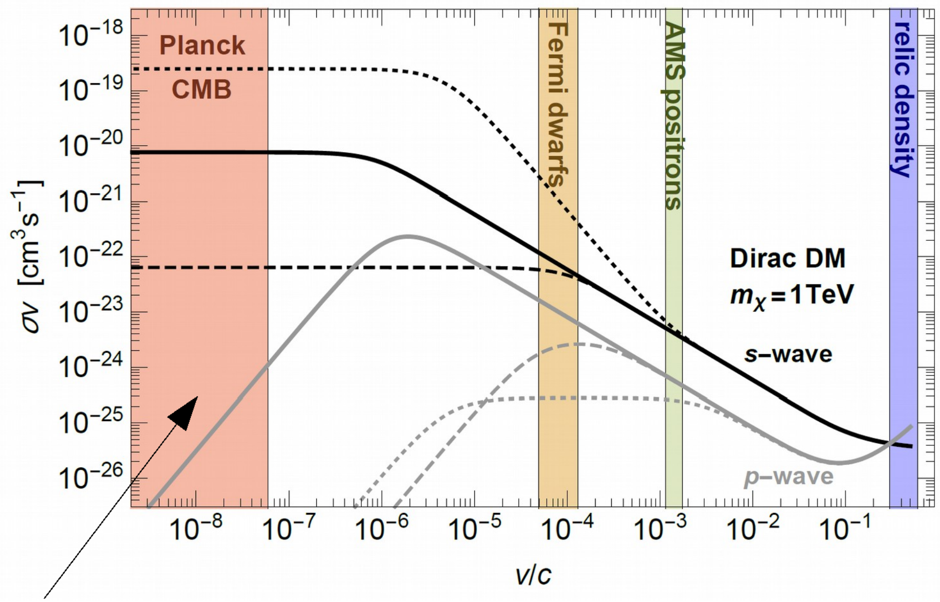
Enhancement of DM annihilations

- Significant non-perturbative corrections to the tree-level annihilation rate (Sommerfeld enhancement).

- Effects small during freeze-out, but increase with decreasing DM velocity as 1/v.

- Saturates when v~m/M

Bringmann et al., arXiv:1612.00845



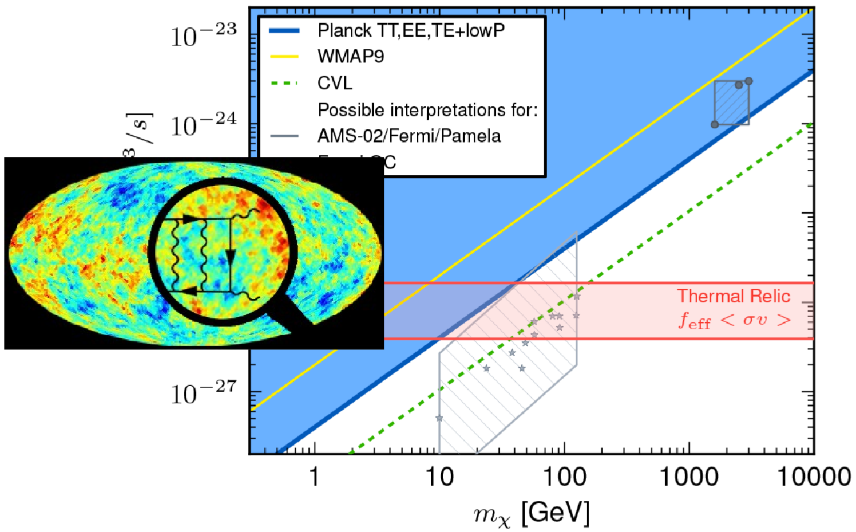
During recombination dark matter particles move at walking speed.

Constraints on DM self-interactions

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

- These energetic particles can re-ionize neutral atoms and thereby spoil the excellent agreement between predictions and measurements of the CMB

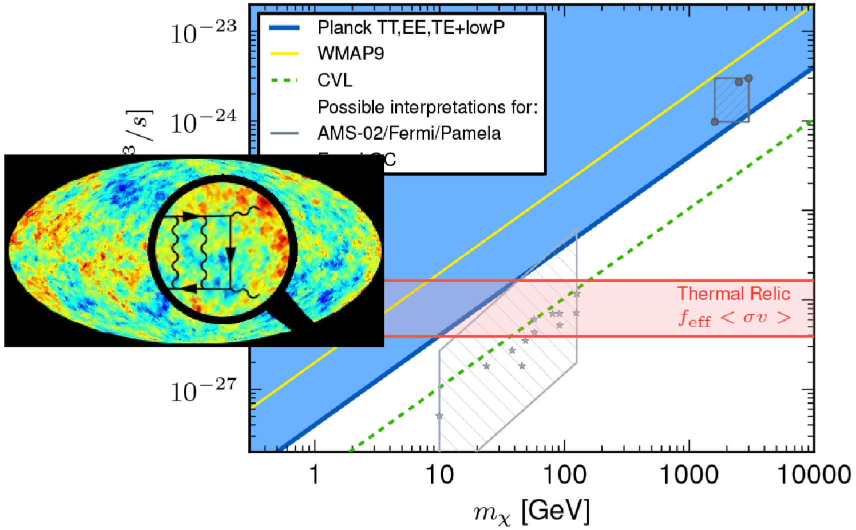
→ very strong constraints for s-wave annihilation



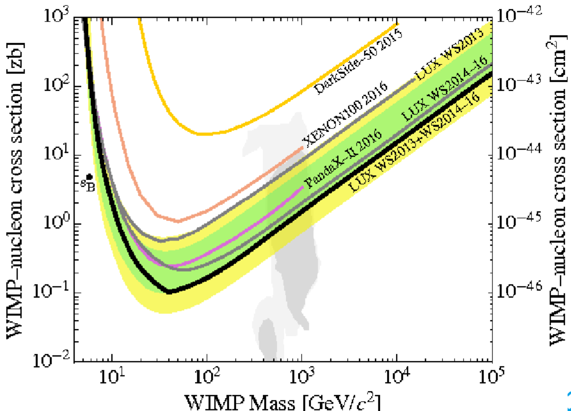
Constraints on DM self-interactions

- DM annihilations during recombination, followed by mediator decays into SM particles, inject energetic electrons and photons into the plasma.
- These energetic particles can re-ionize neutral atoms and thereby spoil the excellent agreement between predictions and measurements of the CMB

  → very strong constraints for s-wave annihilation



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



- strongly enhanced for light mediators!

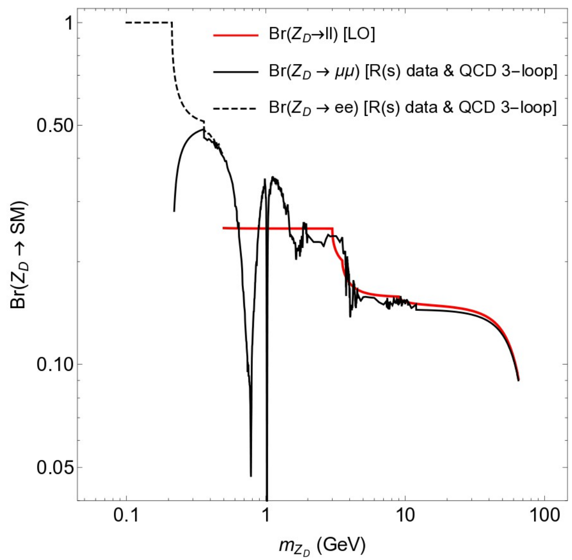
Vector mediators

- 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



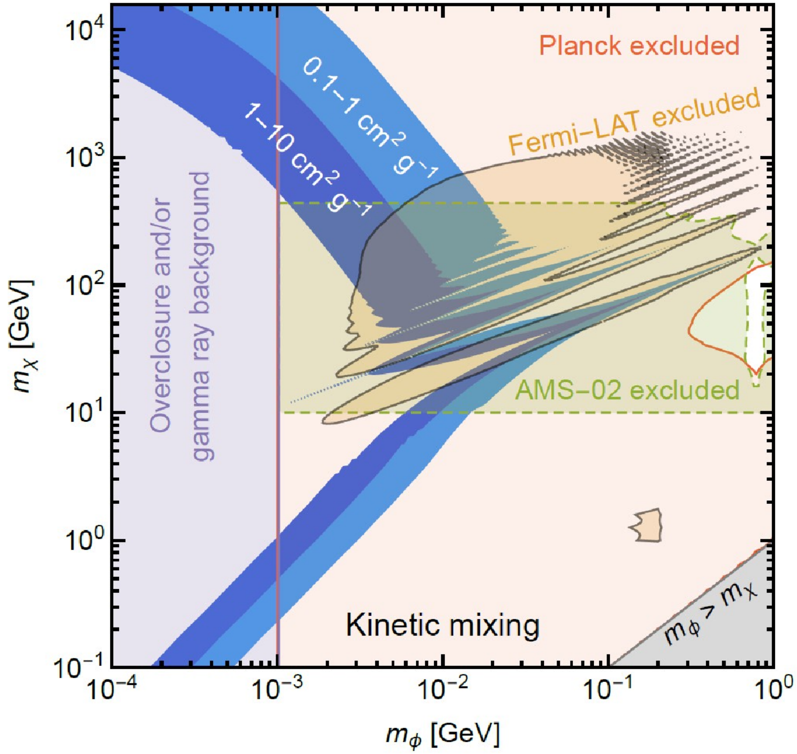
Curtin et al., arXiv:1412.0018

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

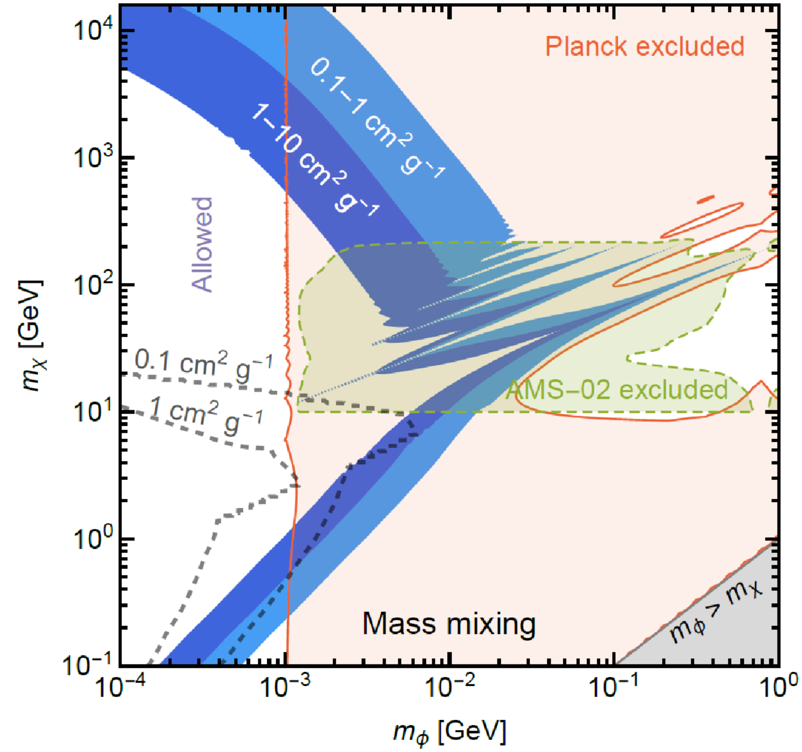
Constraints on vector mediators

- 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



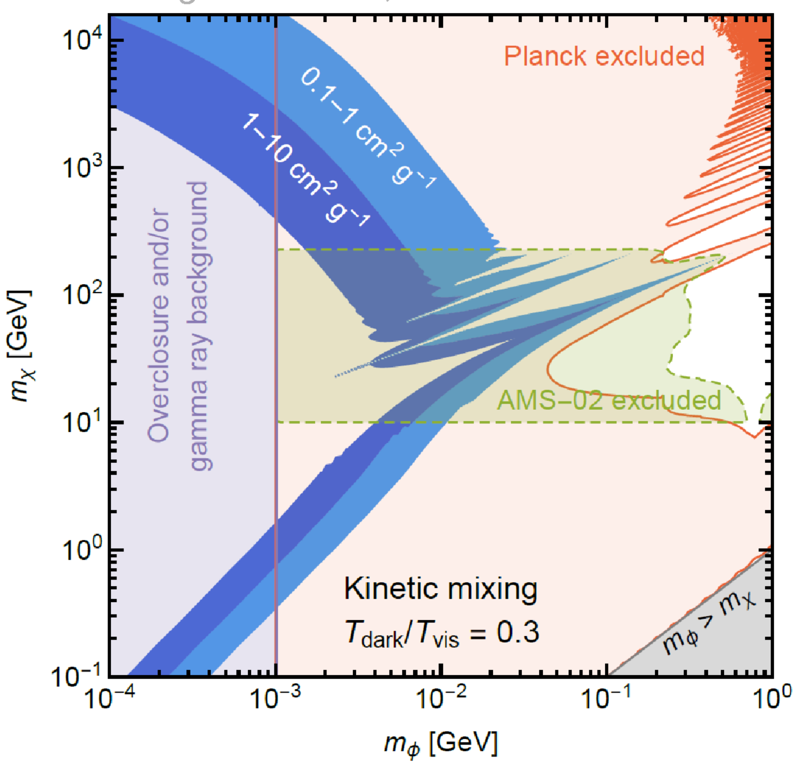
Bringmann et al., arXiv:1612.00845



Constraints on vector mediators

- Only assumption: The two sectors have the same temperature during freeze out.
- Kinetic mixing often required to be too small to bring into thermal equilibrium due to DD constraints
- 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.

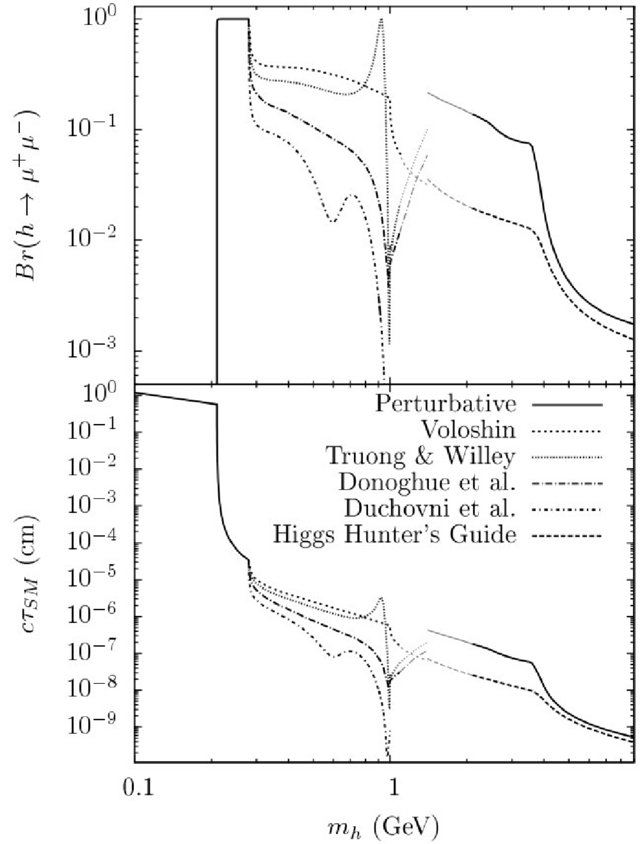
- This mixing induces Yukawa-like couplings to SM fermions consistent with minimal flavour violation:

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

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

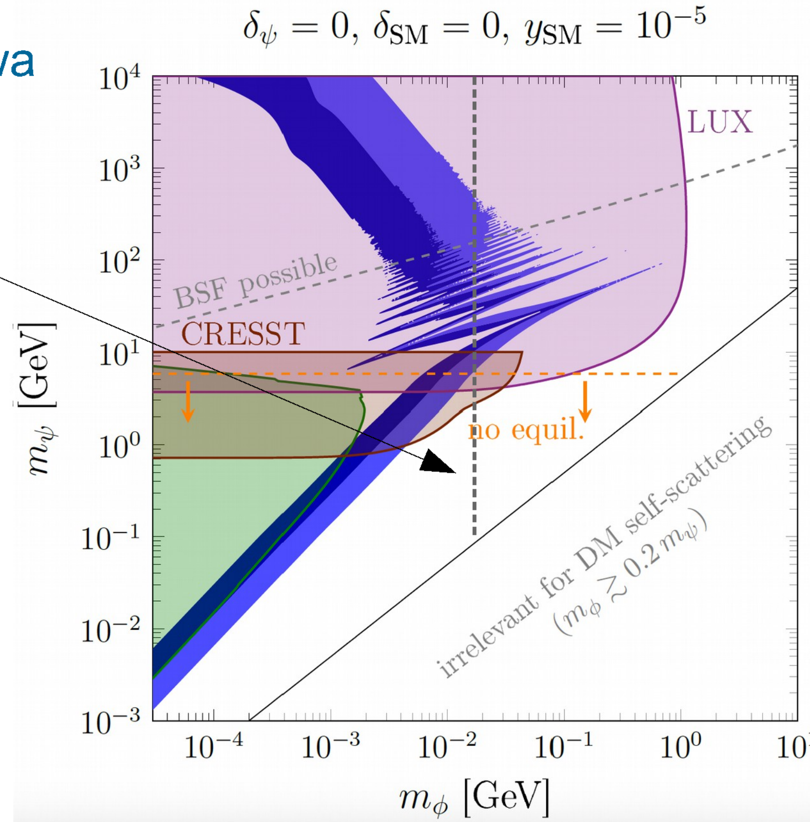
- We are interested in smaller masses where uncertainties are small

Clarke et al., arXiv:1310.8042



Constraints on scalar mediators

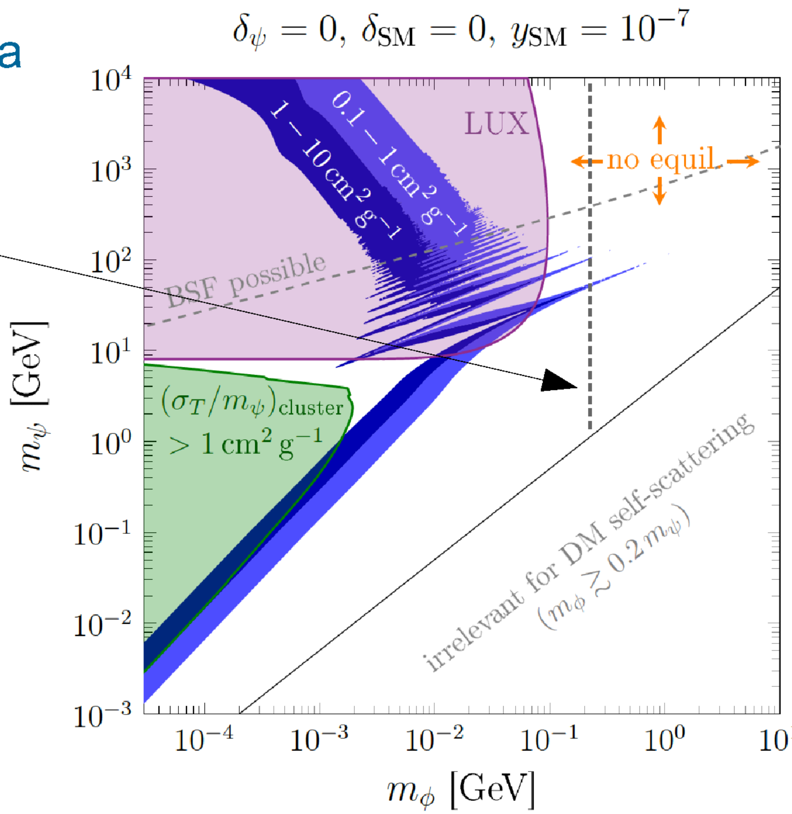
- For fermionic DM and scalar mediators annihilation proceeds via p-wave
- No constraints from indirect detection or the CMB.
- Direct detection constraints are very strong for scalar mediators.
- Lifetime rather long due to Yukawa suppression
- Naive BBN bound: τ < 1 s
- How does this depend on ySM?



1704.02149

Constraints on scalar mediators

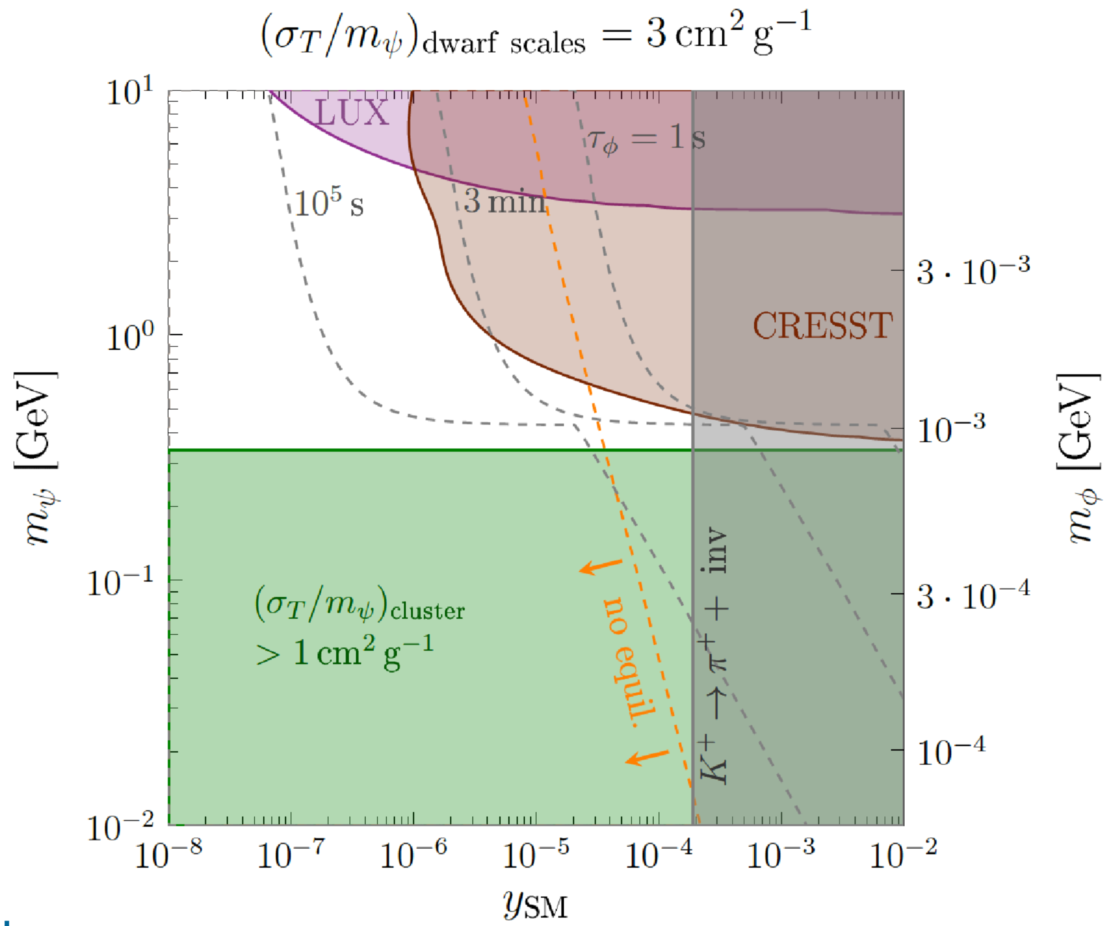
- For fermionic DM and scalar mediators annihilation proceeds via p-wave
- No constraints from indirect detection or the CMB.
- Direct detection constraints are very strong for scalar mediators.
- Lifetime rather long due to Yukawa suppression
- Naive BBN bound: τ < 1 s
- How does this depend on ySM?



1704.02149

Constraints on scalar mediators

- In a different plane, fixing the cross section at dwarf scales



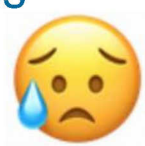
- Requires dedicated BBN study (ongoing)

Pseudoscalar mediators

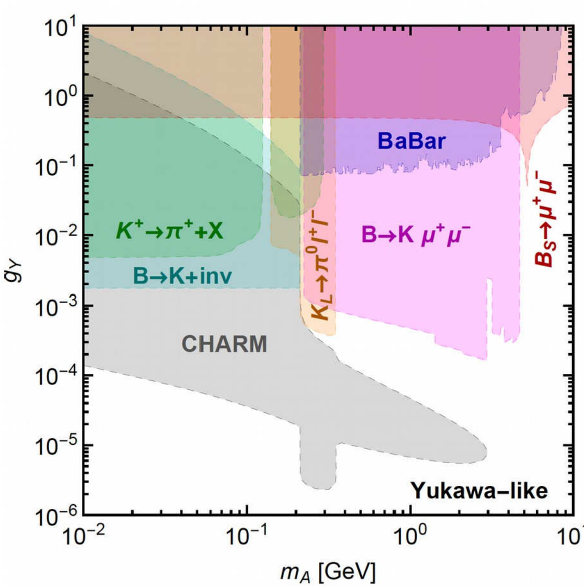
$$\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi \qquad \mathcal{L}_{\rm SM}^{(Y)} = i\, g_Y \sum_{f=q,\ell} \frac{\sqrt{2}\, m_f}{v} A\, \bar{f}\gamma^5 f$$

- 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 

- Strongest bounds come from direct searches for light pseudoscalars.



Dolan et al., arXiv:1412.5174

.

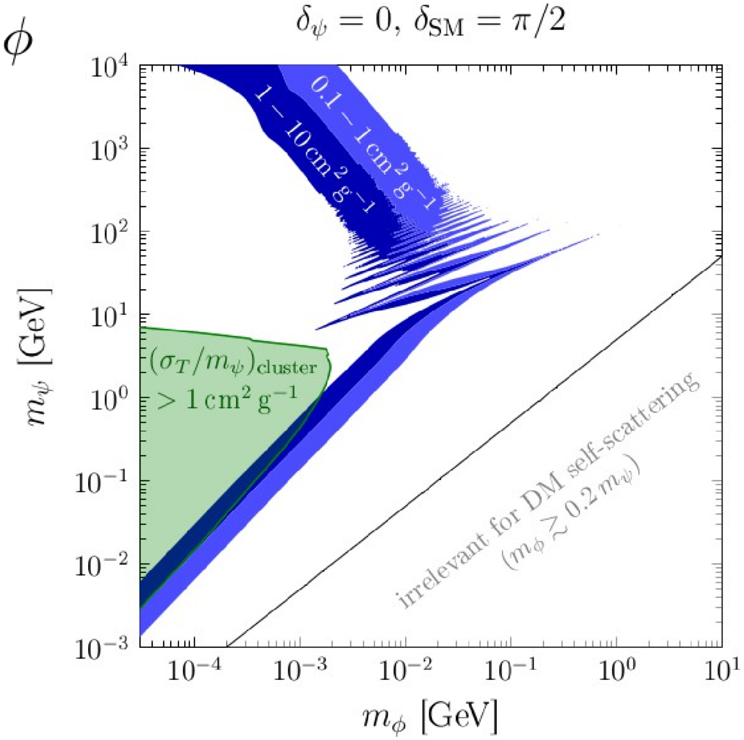
Ways out for light mediators

- There are a number of ways to evade the various constraints
  - Mixed scalar/pseudoscalar couplings (CP violation) Kahlhoefer et al; 1704.02149
  - 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
  - Stable mediator (which largely annihilates away) Ma, 1704.04666
  - Suppressed couplings to quarks (to evade direct detection constraints)
  - Small mass splitting (inelastic scattering) Blennow et al., 1612.06681

- Exciting phenomenology and interesting model-building challenges!

Idea: A mixed mediator (CP violation)

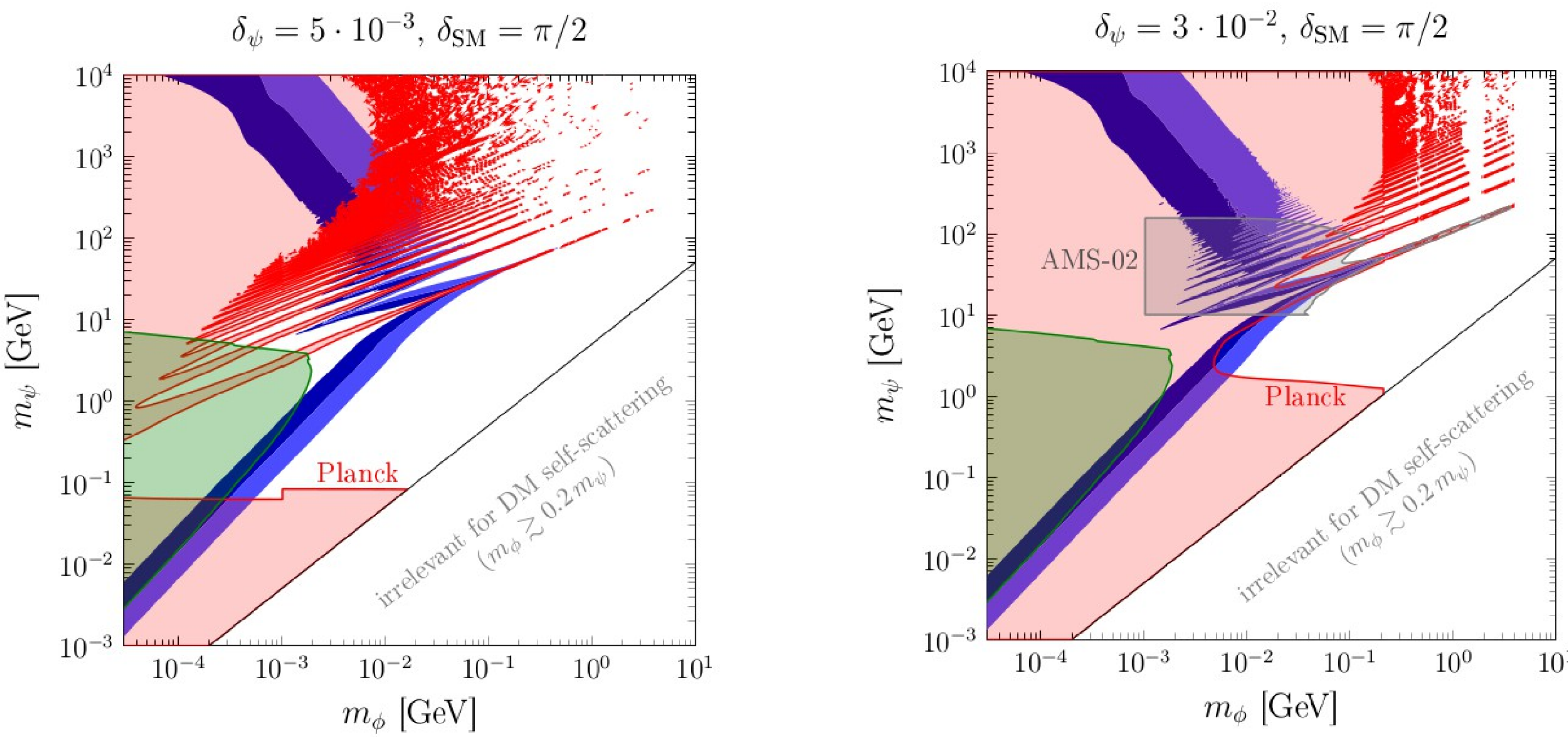
$$\mathcal{L}_{\rm DM} \supset y_\psi \cos\delta_\psi \; \bar\psi\psi\phi \; + \; y_\psi \sin\delta_\psi \; i\bar\psi\gamma^5\psi\phi$$



- 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 ($y_{SM} \ll 10^{-2}$).

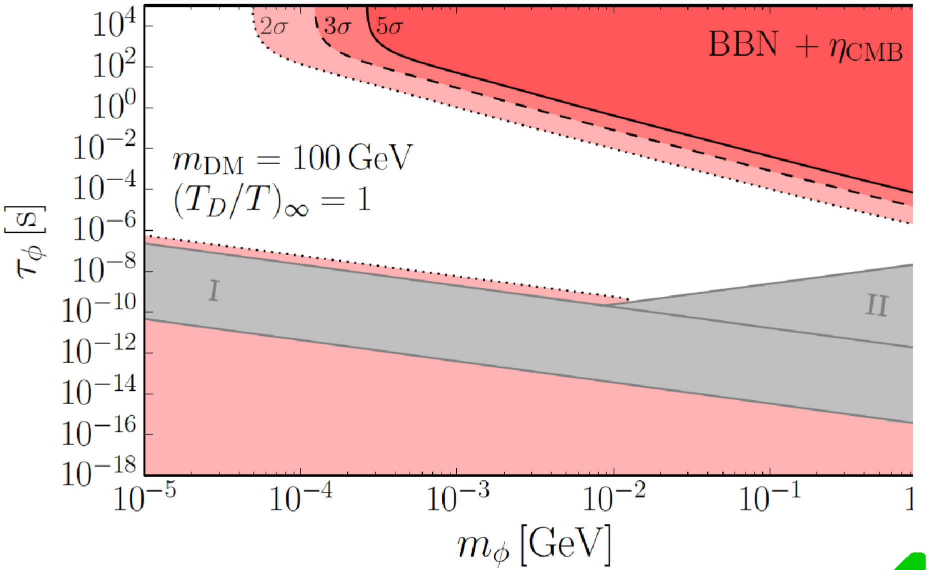
The return of CMB constraints

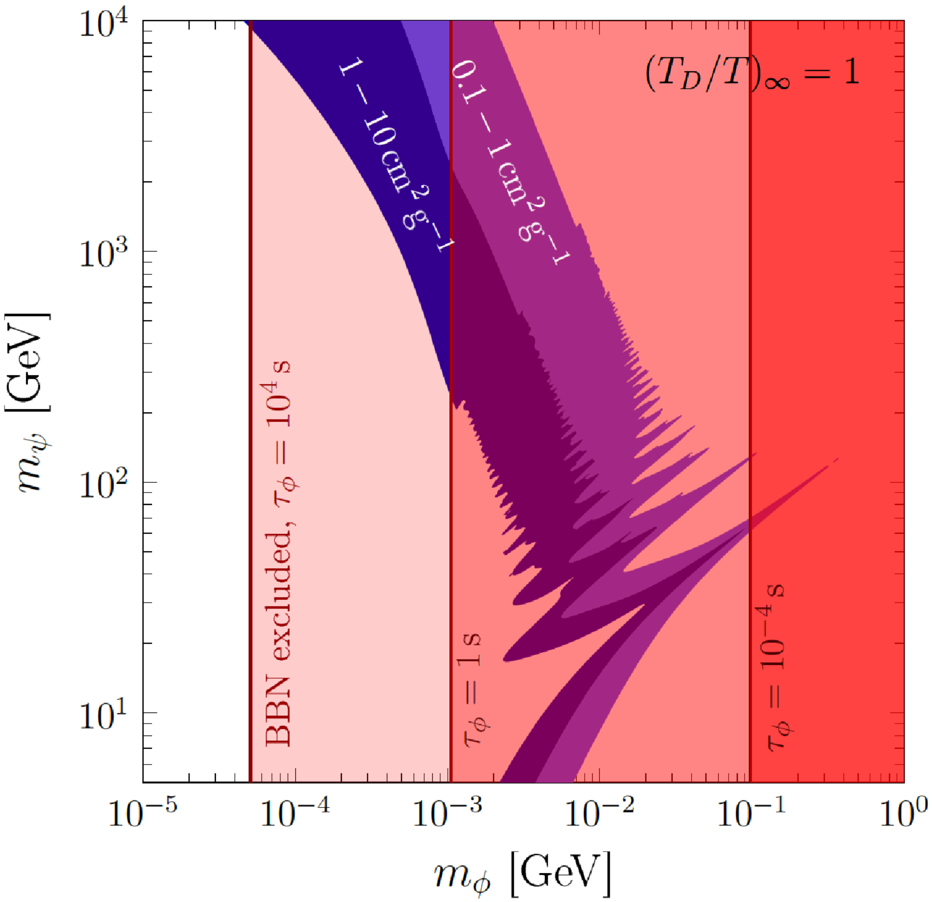
- Central problem: The fact that annihilation can only proceed via p-wave was a consequence of CP conservation.
- As soon as δ_ψ is not exactly zero, s-wave annihilation is again possible and will receive large Sommerfeld enhancement.



Inert decays of the mediator

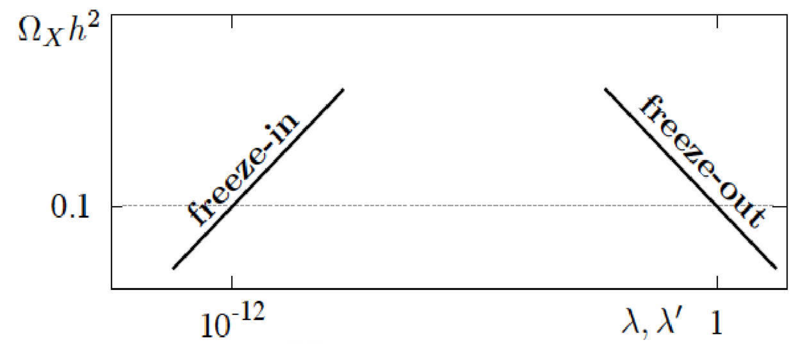
- Assume vector mediator couples mainly to sterile neutrinos
- Extra energy contribution which affects the expansion rate H
- Changes predictions for BBN

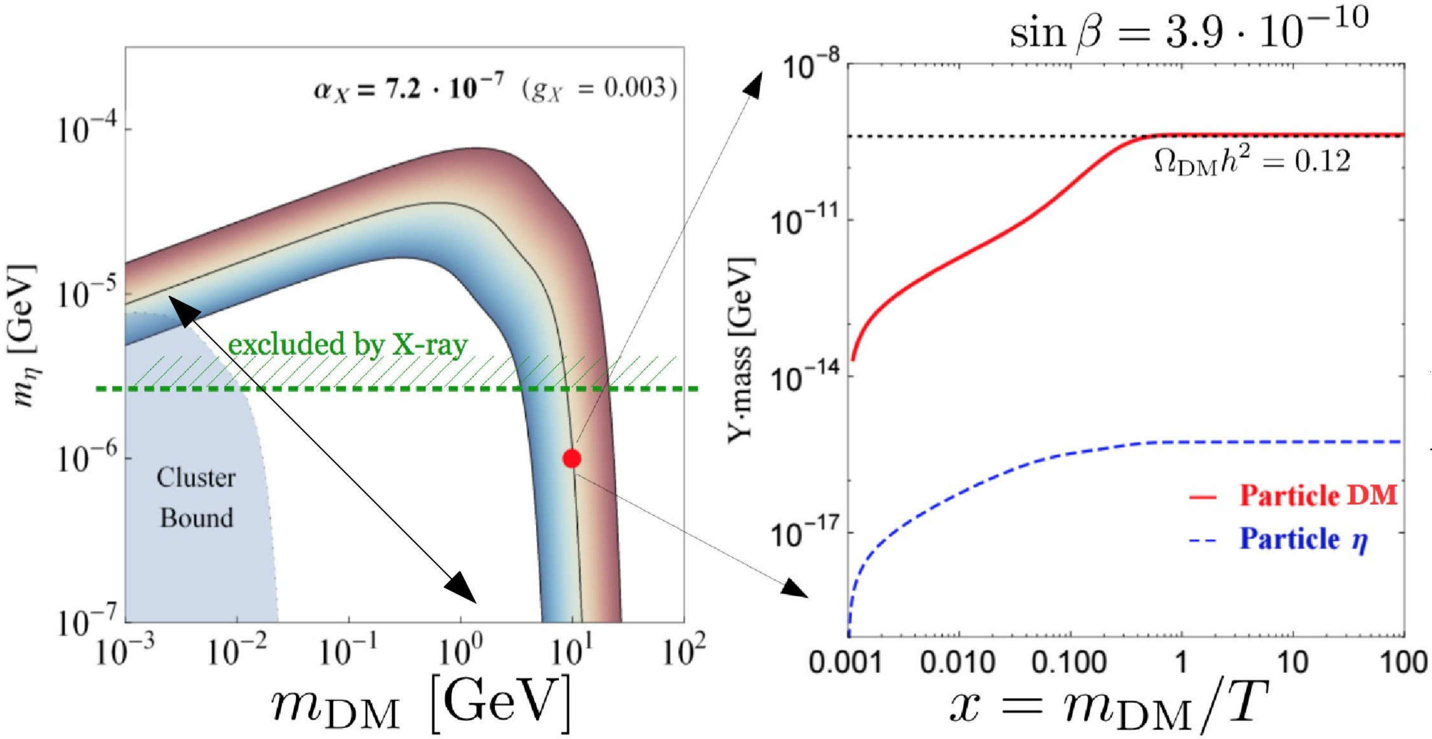




Freeze in

- Thermal production via freeze in
- General analysis of parameter space ('phase diagram') Chu, Hambye, Tytgat; 1112.0493





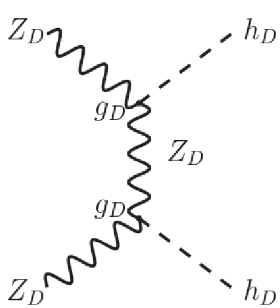
A lot less mediators!

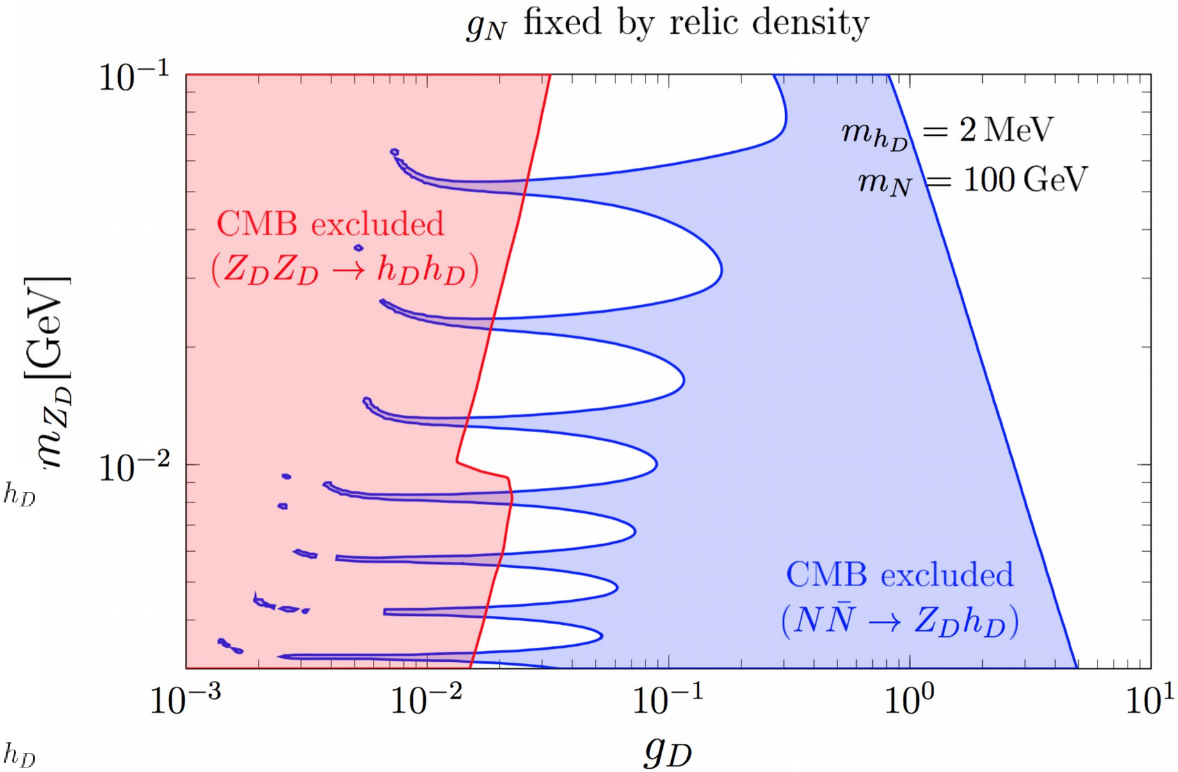
[Bernal, Chu, Garcia-Cely, Hambye & Zaldivar, 1510.08063]

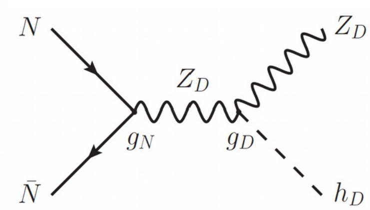
Stable mediator

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]

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!