Phenomenology of self-interacting WIMPs

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Cosmology Seminar
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Based on
arXiv:1612.00845, **arXiv:1704.02149** and **arXiv:1707.08571**
in collaboration with Torsten Bringmann, Suchita Kulkarni,
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Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

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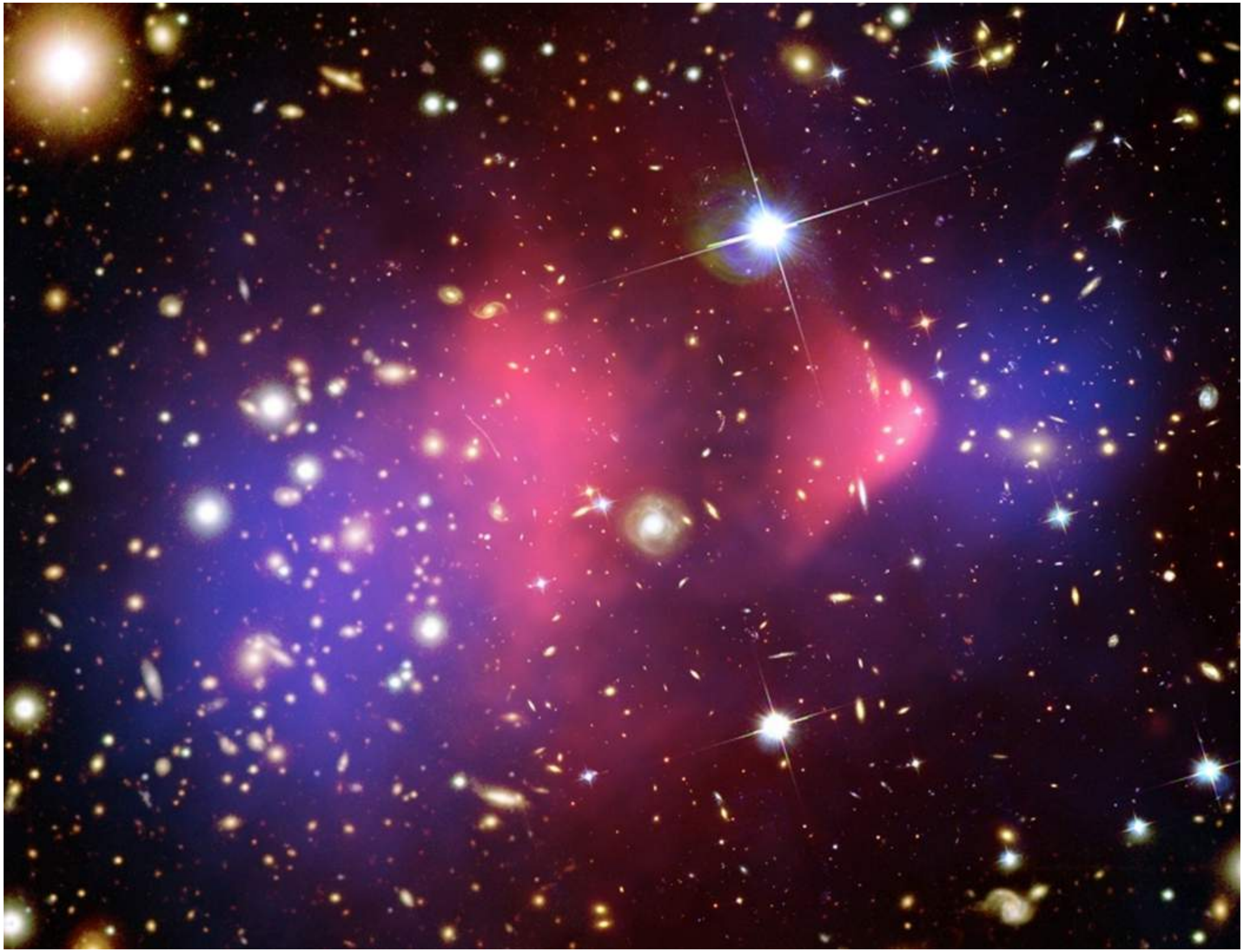
RWTH AACHEN UNIVERSITY

Outline

- Motivation for self-interacting dark matter
- Self-interacting WIMPs from thermal freeze-out
- Light mediator phenomenology
  - CMB constraints and indirect detection
  - Low-threshold direct detection experiments
- Reconstructing self-interacting WIMPs with future data
- Conclusions

The Bullet Cluster



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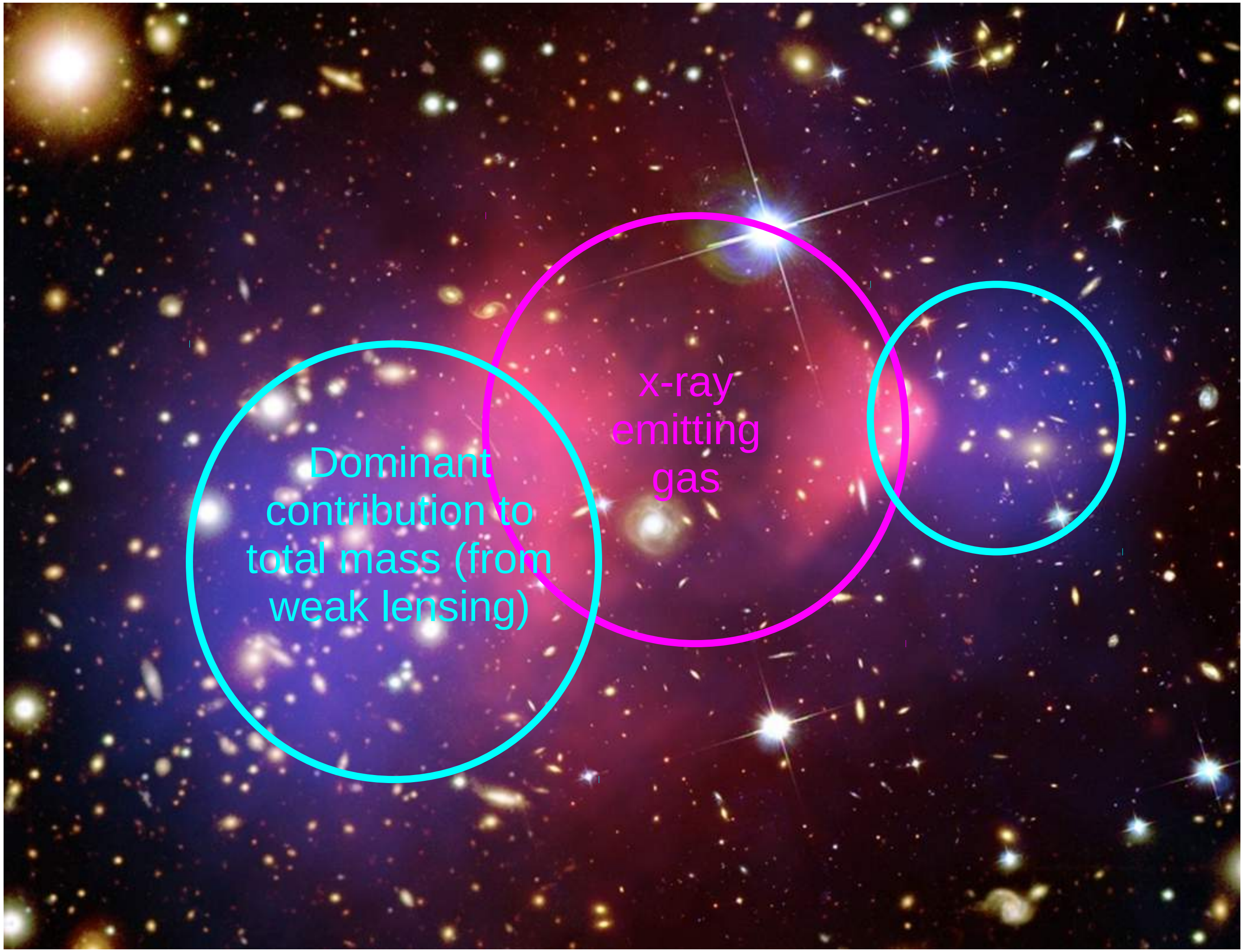


The Bullet Cluster

- The dominant form of matter in galaxy clusters behaves very differently from baryonic gas
  - No emission of x-ray radiation
  - No significant dissipation of energy (i.e. no inelastic scattering)
  - No loss of direction (i.e. no elastic scattering)
- Many similar observations in other major mergers

Abel 520

El Gordo

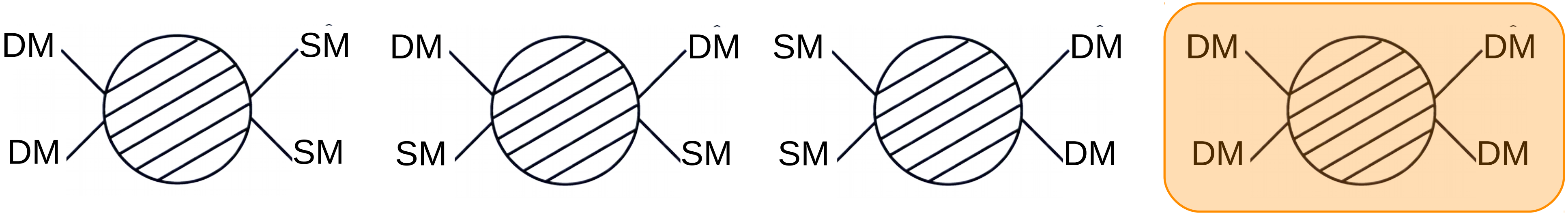
Baby Bullet

Collisionless dark matter?

- What do collisions of galaxy clusters tell us about the self-interactions of DM particles?
- Most DM particles travel from one end of the Bullet Cluster to the other without scattering
- The central region of the Bullet Cluster has a projected (surface) DM density of $\Sigma \sim 0.3 \text{ g/cm}^2$
- This implies $\Sigma\, \sigma / m_x \lesssim 0.5$, and thus $\sigma / m_x \lesssim 1.5 \text{ cm}^2\text{/g}$
- Not at all a small cross section ($1.5 \text{ cm}^2\text{/g} = 3$ barn/GeV) – comparable to nucleon-nucleon scattering!

Self-interacting dark matter

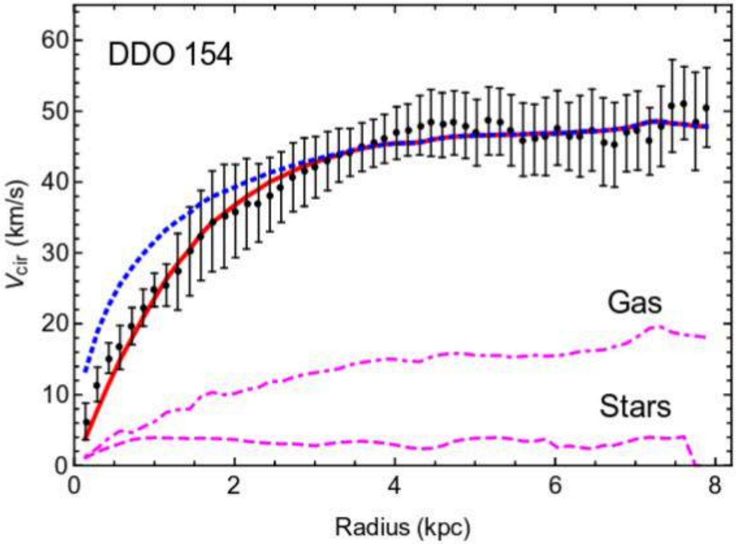
- In order to be observable on astrophysical scales, DM self-interactions have to be very large
- Even such large cross sections cannot be tested in the laboratory
- Astrophysics gives us a completely different window to study DM properties.

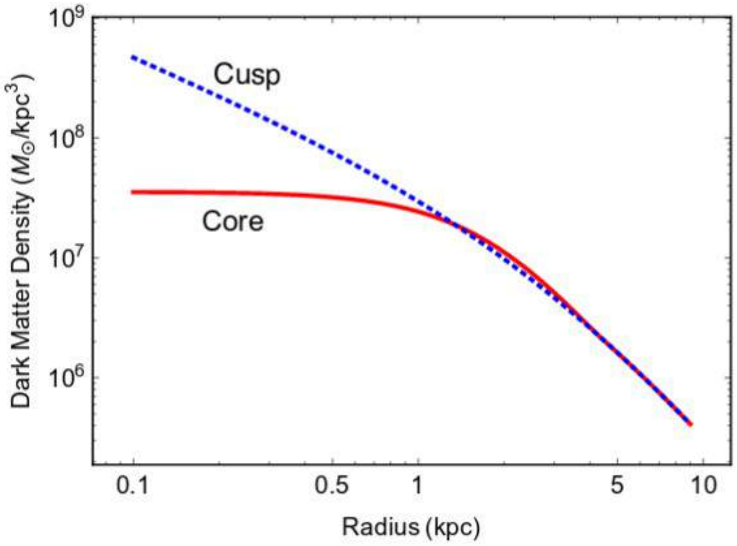


- Clear astrophysical evidence for DM self-scattering would rule out many popular DM models (neutralinos, axions, …)
- Instead: Point towards more complex dark sectors with additional structure

Hints for self-interacting dark matter?

- There are various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:
  - Too-big-to-fail problem — Boylan-Kolchin, Bullock, Kaplinghat: 1103.0007, 1111.2048
  - Missing-satellites problem — Klypin et al.: astro-ph/9901240; Moore et al.: astro-ph/9907411
  - Cusp-vs-core problem — Moore (1994); Flores, Primack: astro-ph/9402004
  - Diversity problem — Tulin & Yu: arXiv:1705.02358

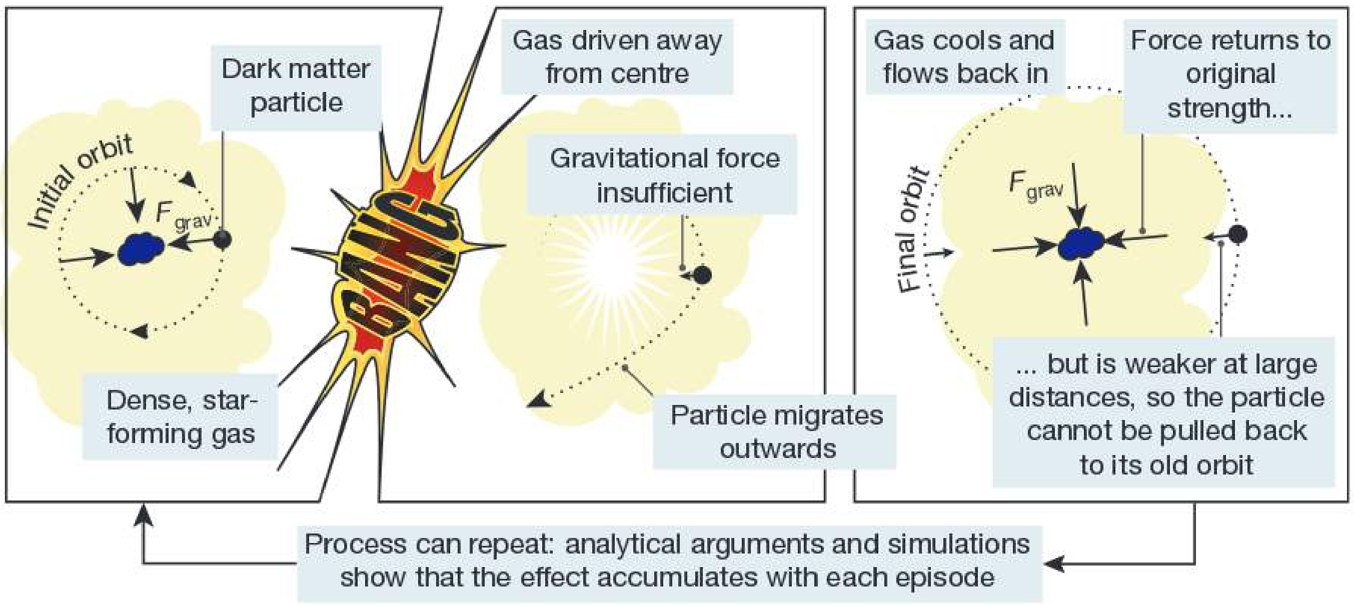




Tulin & Yu: arXiv:1705.02358

Hints for self-interacting dark matter?

- The observational situation concerning the “small-scale crisis” is not yet clear
- Maybe we just need to discover more Milky Way satellites
- Even if fully established, it remains unclear whether baryonic feedback can equally provide an explanation for missing satellites and cored dwarf galaxies



Dark matter particle

Dense, star-forming gas

Gas driven away from centre

Gravitational force insufficient

Particle migrates outwards

Gas cools and flows back in

Force returns to original strength...

... but is weaker at large distances, so the particle cannot be pulled back to its old orbit

Process can repeat: analytical arguments and simulations show that the effect accumulates with each episode

Pontzen & Governato,
Nature 506, 171–178 (2014)

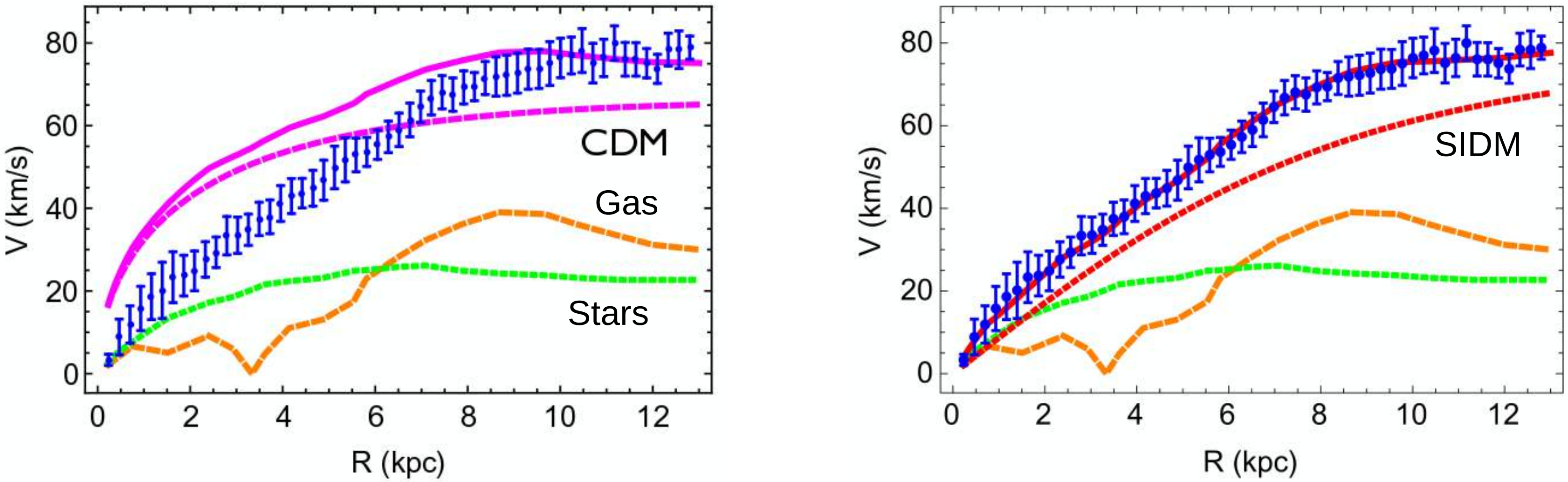
Hints for self-interacting dark matter?

- It is nevertheless intriguing that DM self-interactions may solve these problems

  Spergel & Steinhard: astro-ph/9909386

- Basic idea: In the central regions of DM halos, self-interactions can be sufficiently frequent to allow for energy transfer between DM particles

- This energy transfer will heat up DM particles that sit deep in the gravitational potential and create an isothermal core



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Constructing models of self-interacting DM

- Most widely studied paradigm for DM production in early Universe: thermal freeze-out
- Basic idea:

  Lee & Weinberg, 1977
  - At high temperatures: DM was in thermal equilibrium with the SM; annihilation and production processes happened frequently
  - As the temperature drops below the DM mass, interactions become less frequent
  - Finally, DM particles decouple from thermal equilibrium
- Successful predictions:
  - DM is non-relativistic (cold) during freeze-out, leading to successful formation of large-scale structures
  - Required interaction strength is comparable to weak interactions (for a particle with weak-scale mass): Weakly-interacting massive particles (WIMPs)

- Most typical WIMPs (neutralinos, Higgs portal DM, minimal DM) have only weak self-interactions

Is the WIMP idea incompatible with large self-interactions?

Three main avenues of model-building

1) Very light dark matter
   - Large DM number densities lead to large self-interaction rates
   - Relic density set e.g. by direct annihilation into SM states

Heikinheimo et al., arXiv:1604.02401; Chu et al., arXiv:1609.00399

2) Confinement in the dark sector
   - New strong dynamics leads to large self-scattering
   - Relic density set e.g. via 3 → 2 processes (*SIMP miracle*)

Hochberg et al., arXiv:1402.5143; arXiv:1512.07917; Kamada et al., arXiv:1606.01628

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

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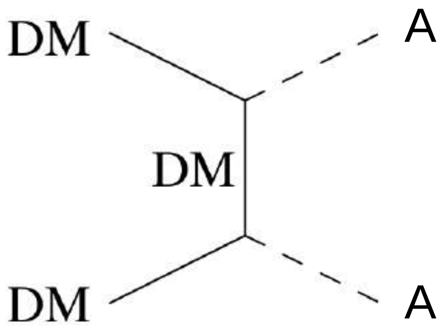
Focus of this talk

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

A new light mediator in the dark sector

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



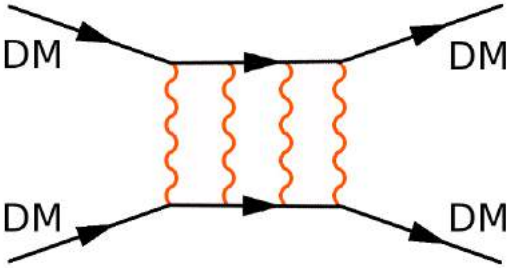
$$\Omega_\psi h^2 = 0.119 \times \frac{\langle \sigma v \rangle_\text{thermal}}{\langle \sigma v \rangle}$$

- It is always possible to fix the coupling in the dark sector in such a way that the observed DM relic abundance is reproduced

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

Self-interactions from a light mediator

- DM self-interactions are not just enhanced by the small mediator mass, but also by non-perturbative effects due to multiple mediator exchange.
- These effects can be calculated by solving the non-relativistic Schroedinger equation for the potential induced by the mediator.



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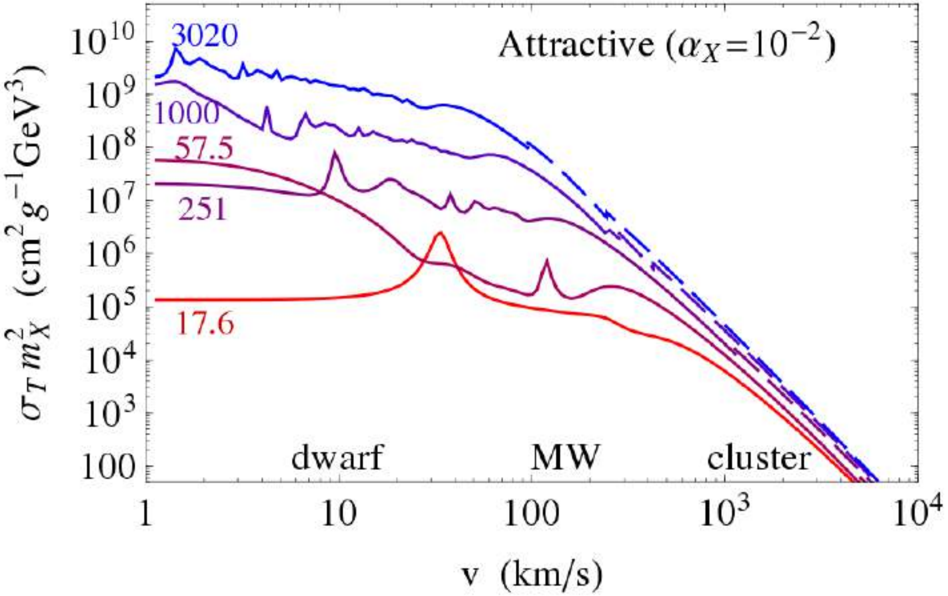


- In many relevant cases, mediator exchange gives rise to a Yukawa potential:

$$V_S(r) = \alpha_S\, e^{-m_\phi r}/r$$

- For $\alpha_S m_\psi \gtrsim m_\phi$ resonances appear and modify the results of the tree-level calculation.
- Bonus: self-interactions depend on the relative velocity of the DM particles

Phenomenology of self-interacting WIMPs

- Models with light mediators combine the ideas of thermal freeze-out and self-interacting dark matter
- The coupling between the mediator and DM can be eliminated by imposing the observed relic abundance
- The self-interaction cross section then depends only on the DM mass and the mediator mass → high predictivity!
- Mediator must decay → require additional couplings to SM particles
- These additional interactions may enable us to probe the parameter regions of sizeable self-interactions!

Annihilation of DM particles after thermal freeze-out

- CMB constraints
- Indirect detection experiments

Scattering of DM particles from the Galactic halo on SM particles

- Direct detection experiments

Mediator typology

- The relevant experimental signatures depend decisively on the quantum numbers of the light mediator

Mediator	Spin	Parity	CP	Annihilation	Scattering
Vector	1	–	–	s-wave	unsuppressed
Scalar	0	+	+	p-wave	unsuppressed
Pseudoscalar	0	–	–	p-wave	suppressed

- If annihilation proceeds via s-wave (no velocity dependence), we expect strong constraints from the CMB and indirect detection
- If annihilation proceeds via p-wave (v^2 suppression), the strongest constraints will come from direct detection experiments

Enhancement of DM annihilations

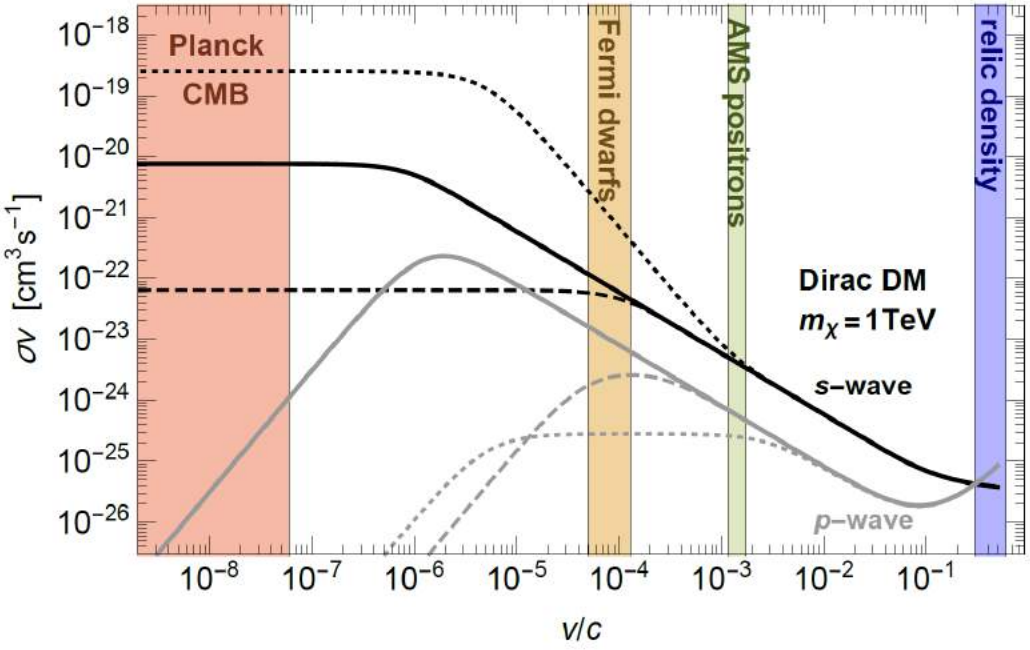
- The Yukawa potential from the light mediator exchange modifies the wave-function of the annihilating DM pair (so-called Sommerfeld enhancement).

- Significant non-perturbative corrections to the tree-level annihilation rate.

- Effects small during freeze-out, but increase with decreasing DM velocity.

- Very different behaviour for s-wave and p-wave annihilation.

Bringmann, FK et al., arXiv:1612.00845



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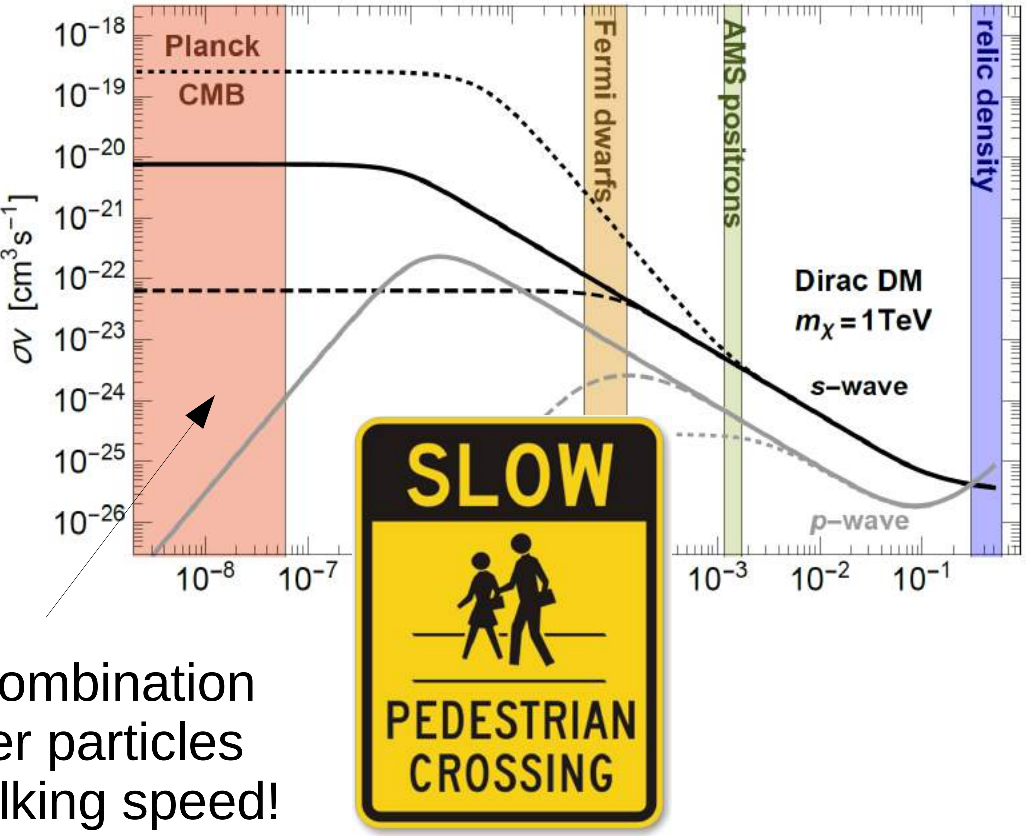
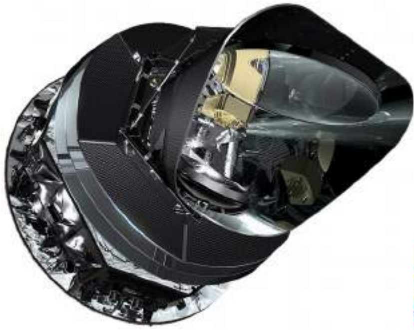
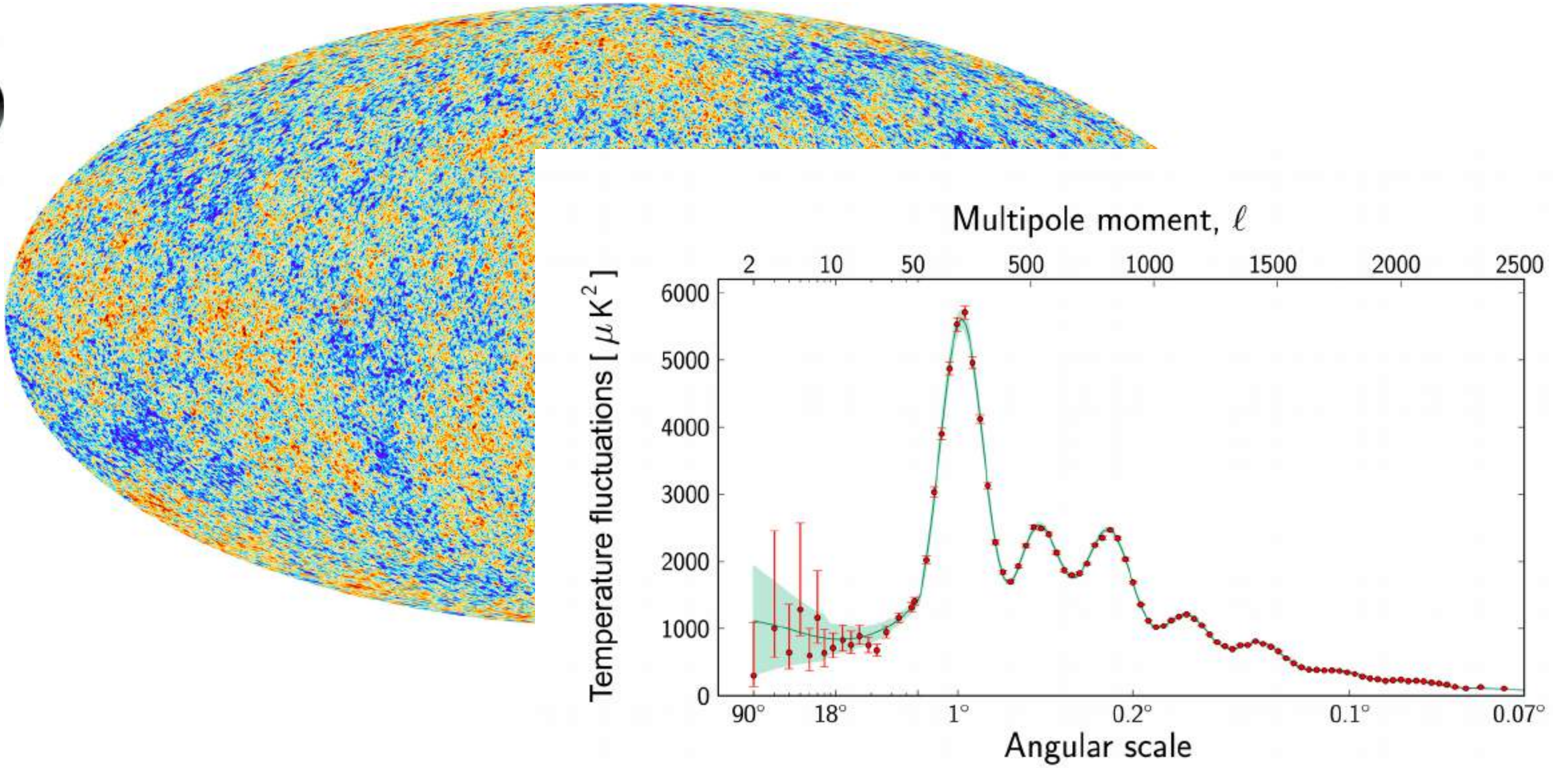

Bringmann, FK et al., arXiv:1612.00845

During recombination dark matter particles move at walking speed!

CMB constraints on self-interacting DM

- 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.





CMB constraints on self-interacting DM

- Recent Planck measurements imply

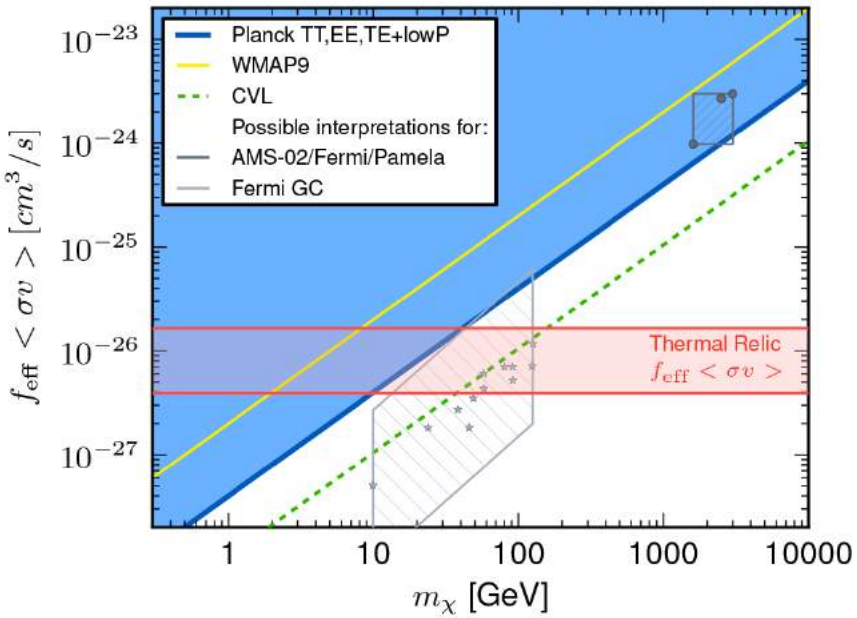
$$\frac{\langle \sigma v \rangle_{\rm rec}}{N_\chi} \lesssim 4 \times 10^{-25}\,{\rm cm}^3\,{\rm s}^{-1} \left(\frac{f_{\rm eff}}{0.1}\right)^{-1} \left(\frac{m_\chi}{100\,{\rm GeV}}\right)$$

where the efficiency factor $f_{\rm eff}$ depends slightly on the mediator decay mode.

- Without Sommerfeld enhancement $\langle\sigma v\rangle_{\rm rec} \sim 3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}$, so one can typically exclude $m_\chi < 10$ GeV.

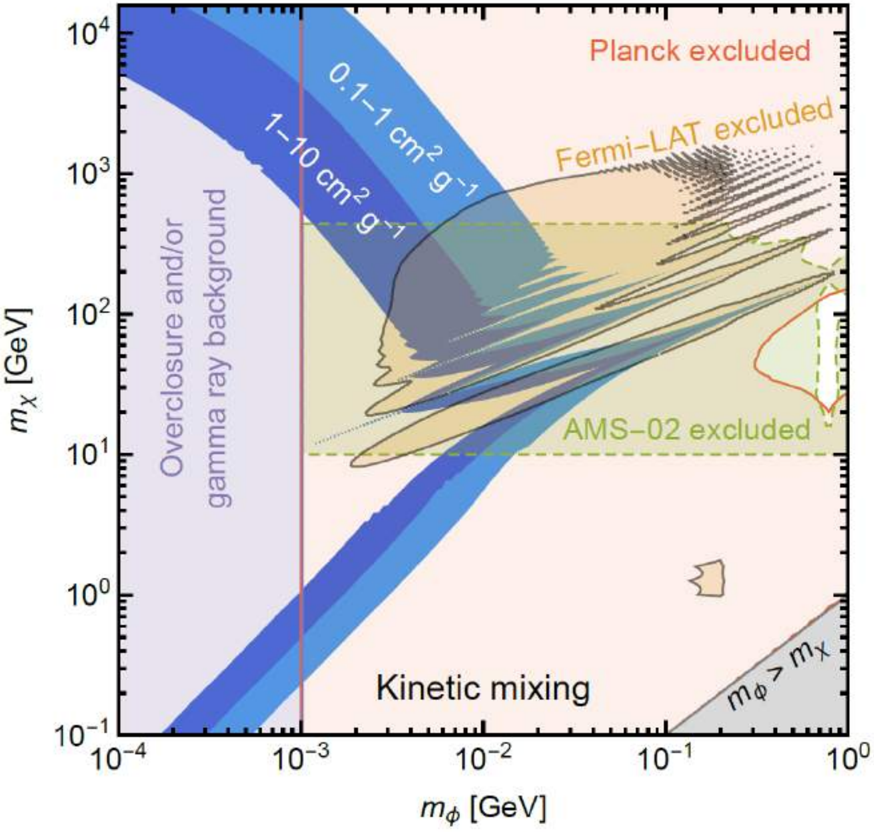
- With Sommerfeld enhancement $\langle\sigma v\rangle_{\rm rec}$ can be much larger and hence one can potentially probe much larger DM masses.

Planck Collaboration, arXiv:1502.01589

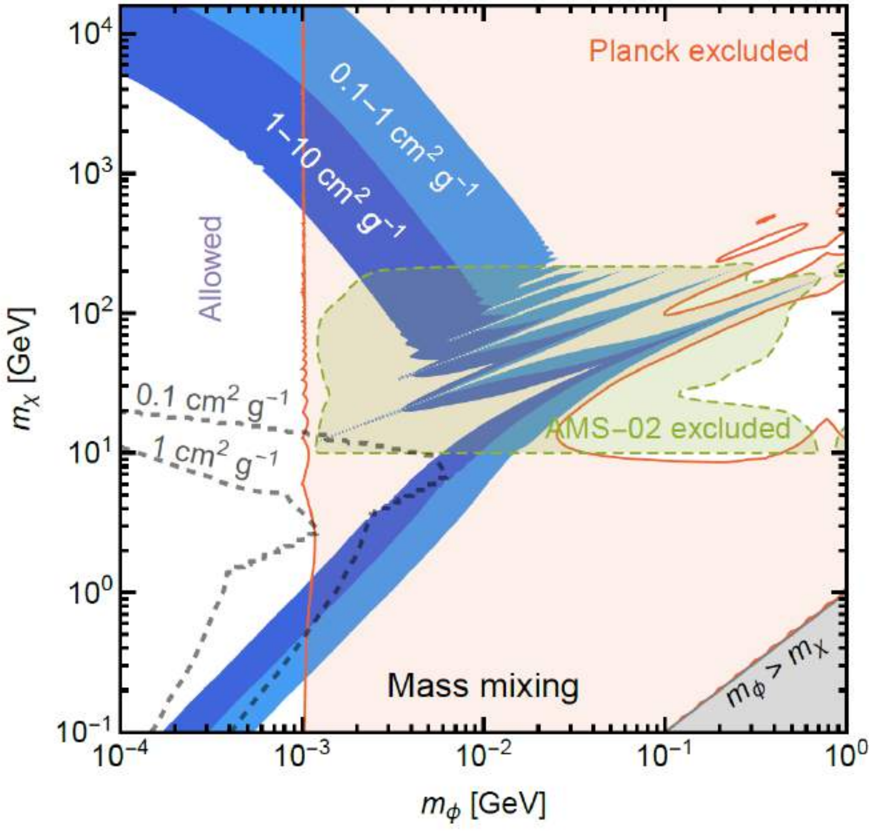


Constraints on vector mediators

- For vector mediators, DM annihilation proceeds via s-wave:
  - Large Sommerfeld enhancement for small velocities
  - Strong constraints from indirect detection and CMB measurements



Mediator with photon-like couplings



Mediator with Z-like couplings

Bringmann, FK et al., arXiv:1612.00845

Direct detection with light mediators

- Event rates in direct detection experiments:

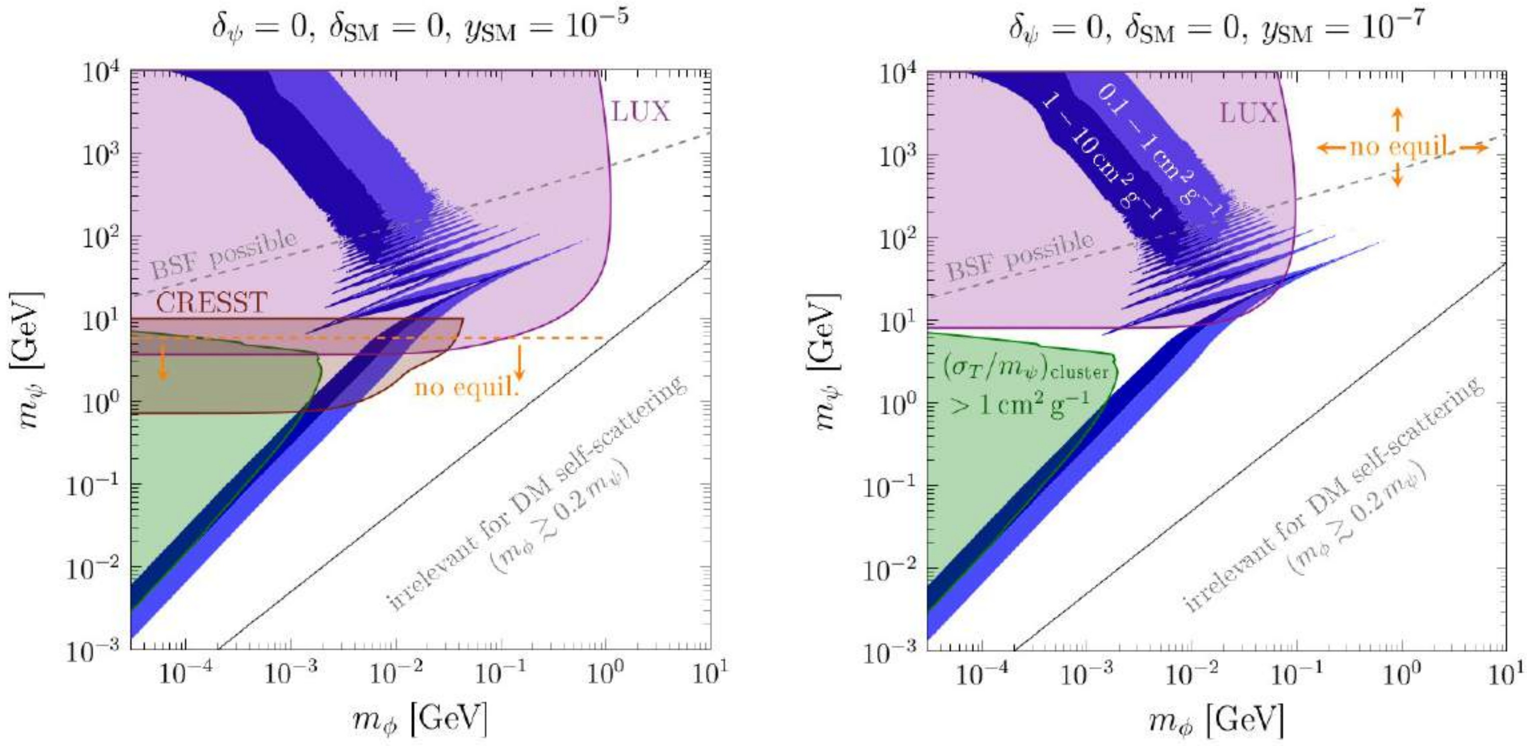
$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \underbrace{\underset{\substack{\uparrow \\ \text{Number} \\ \text{density}}}{\frac{\rho_0}{m_\mathrm{DM}}} \; \underset{\substack{\uparrow \\ \text{Velocity} \\ \text{integral}}}{\eta(v_\mathrm{min}(E_\mathrm{R}))}}_{\text{Integrated flux}} \; \underset{\substack{\uparrow \\ \text{Scattering} \\ \text{cross section}}}{\frac{g^2\, F_T^2(E_\mathrm{R})}{2\pi\, m_\mathrm{med}^4}}$$

- Scattering rates are strongly enhanced for light mediators

- Expect strong constraints from direct detection experiments

Constraints on scalar mediators

- For fermionic DM and scalar mediators annihilation is p-wave (velocity-suppressed)
- No constraints from indirect detection or the CMB.
- To study direct detection constraints, we need to specify the coupling y_{SM} of the mediator to SM states



FK, et al., arXiv:1704.02149

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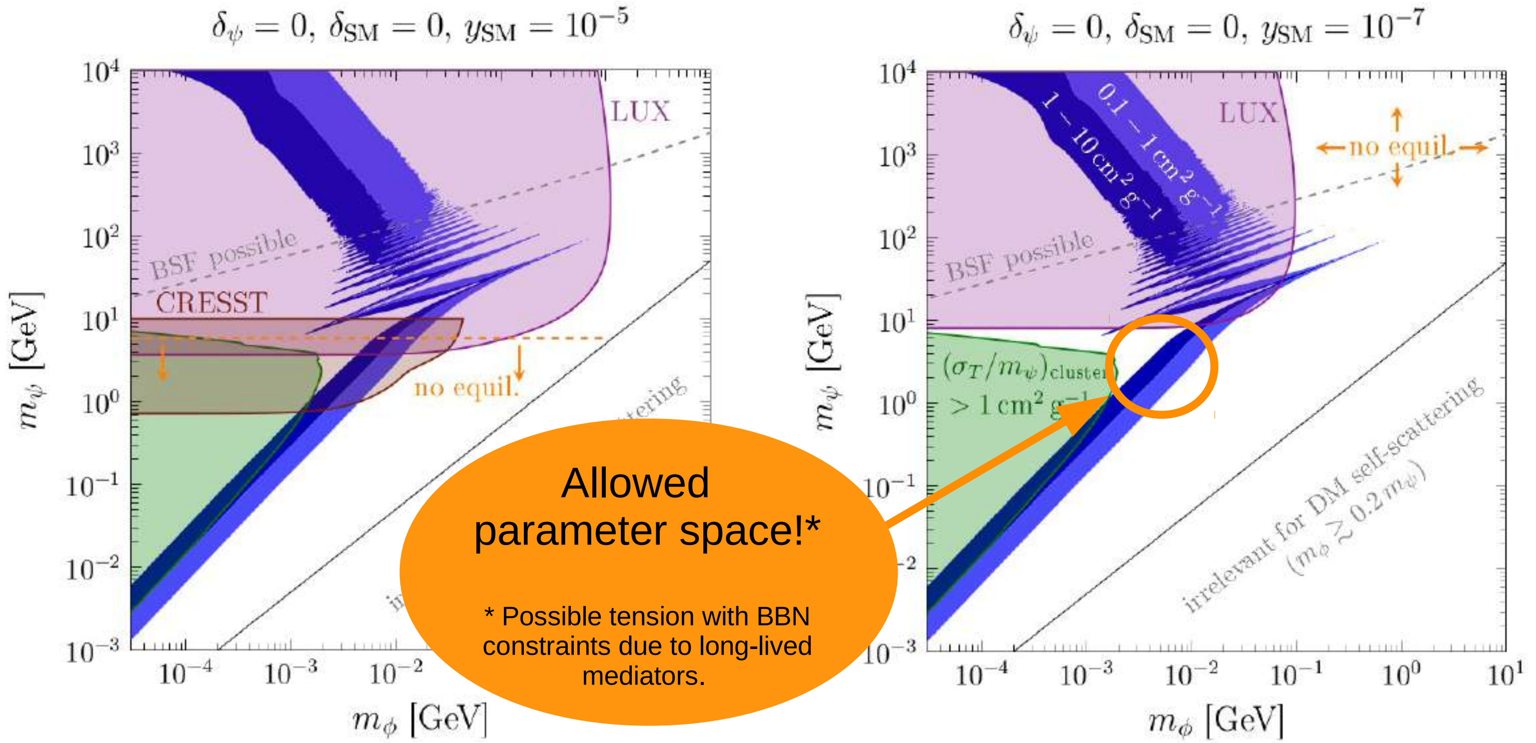


Allowed parameter space!*

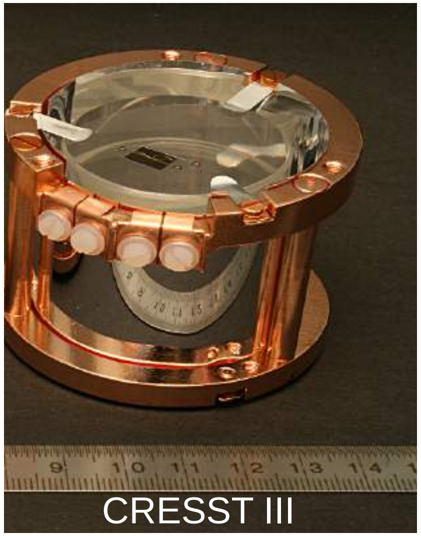
* Possible tension with BBN constraints due to long-lived mediators.

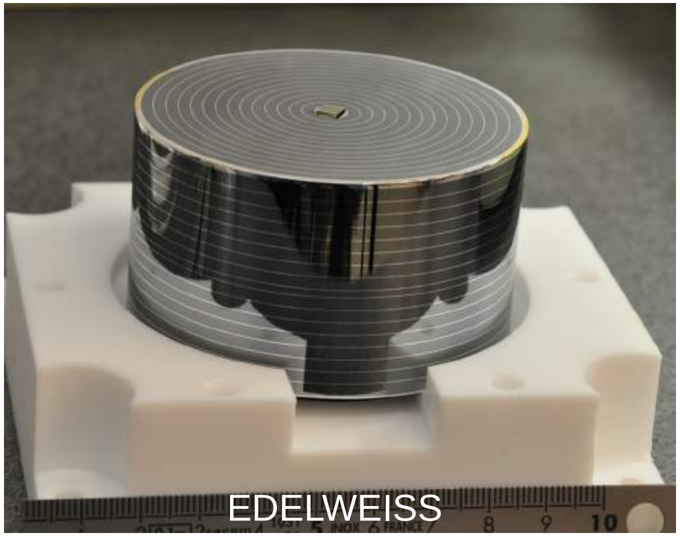
FK, et al., arXiv:1704.02149

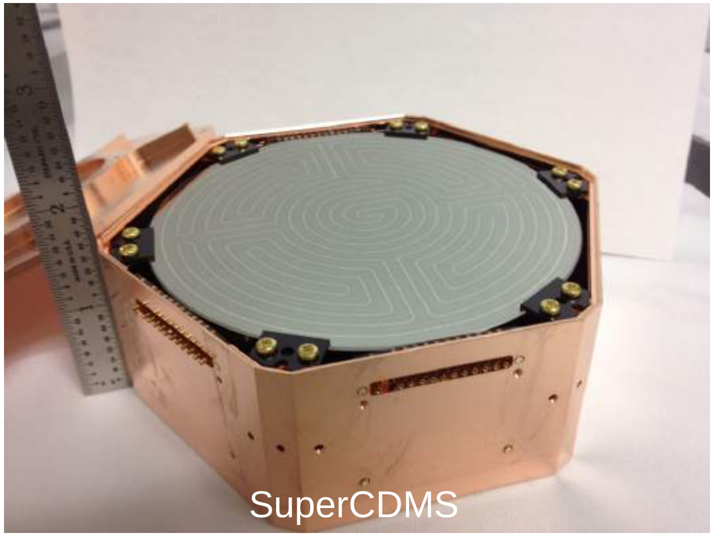
Low-threshold experiments

- Direct detection experiments rapidly lose sensitivity for DM masses below about 5 GeV, as these particles have insufficient energy to induce observable signals

- Cryogenic direct detection experiments aim to extend the sensitivity to lower DM masses by significantly reducing the energy threshold (E_{th} < 100 eV feasible)

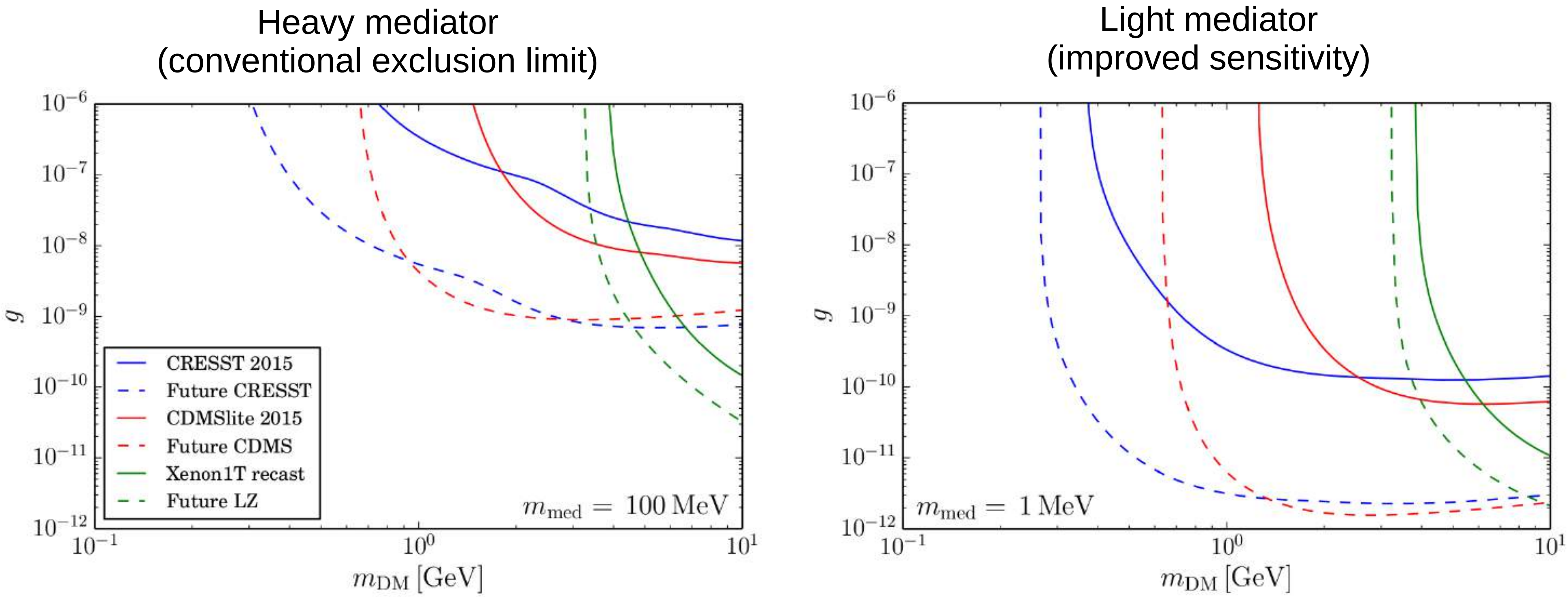

CRESST III


EDELWEISS


SuperCDMS

- Moreover these detectors achieve excellent energy resolution (σ_E ~ 20 eV feasible)

Sensitivity of cryogenic experiments



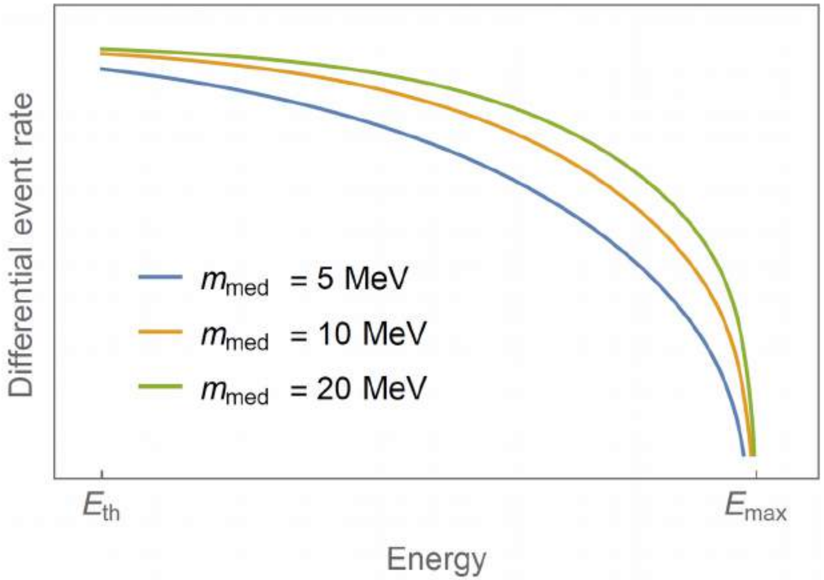
- Future upgrades of CRESST and SuperCDMS promise significant gain in sensitivity
- Two orders of magnitude in coupling → four orders of magnitude in event rates
- We can hope to see 1000s of events from DM scattering!

Learning from future direct detection signals

- Assume that the DM particle lies in the parameter region probed by future cryogenic experiments.
- What can we hope to learn from the observation of a signal in these experiments?
- Crucial observation: Event rates depend on the mediator mass in a non-trivial way!

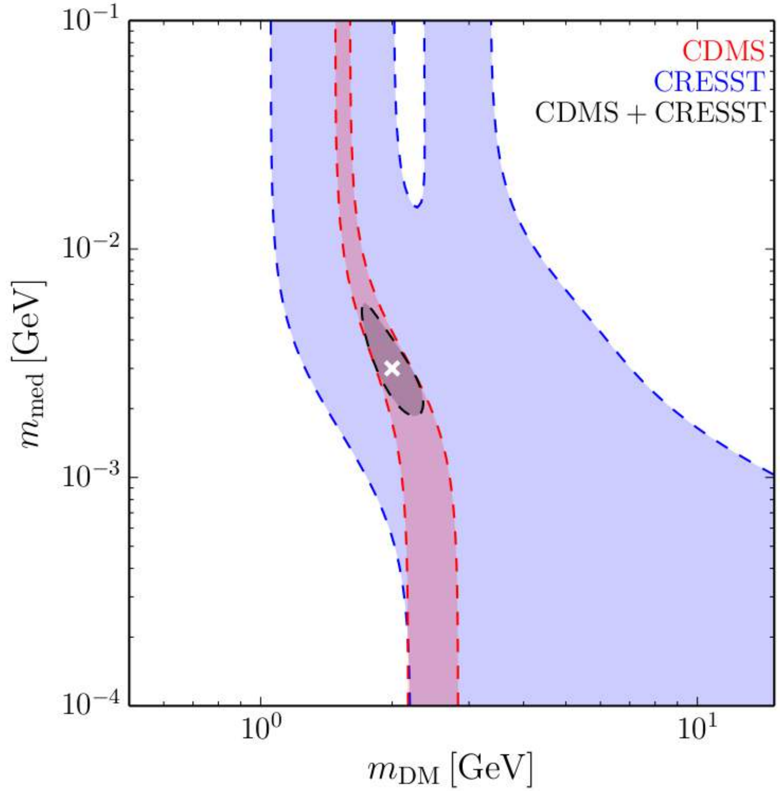
$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0}{m_\mathrm{DM}} \eta(v_\mathrm{min}(E_\mathrm{R})) \frac{g^2\, F_T^2(E_\mathrm{R})}{2\pi\, \left(2\, m_T\, E_\mathrm{R} + m_\mathrm{med}^2\right)^2}$$

- The shape of the differential event rate changes as soon as m_med is comparable to $(2\ m_T\ E_\mathrm{R})^{1/2} = q$ (the momentum transfer).
- This corresponds exactly to the mass range interesting for self-interacting WIMPs!

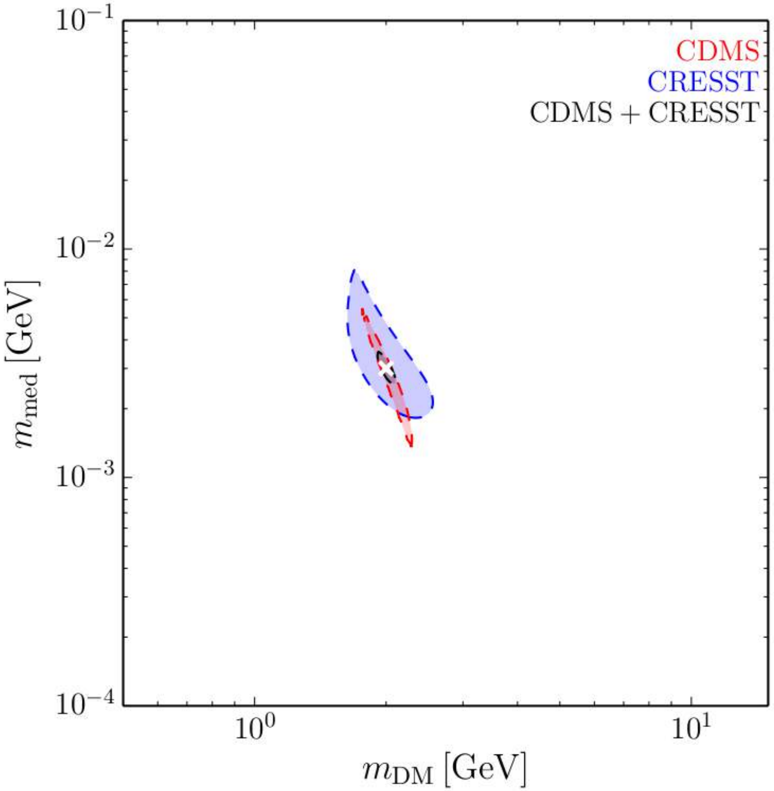


Parameter reconstruction

- Choose a benchmark point (compatible with current limits)
- Generate mock data for CRESST-III and SuperCDMS
- Determine parameter regions that give a good fit to the data



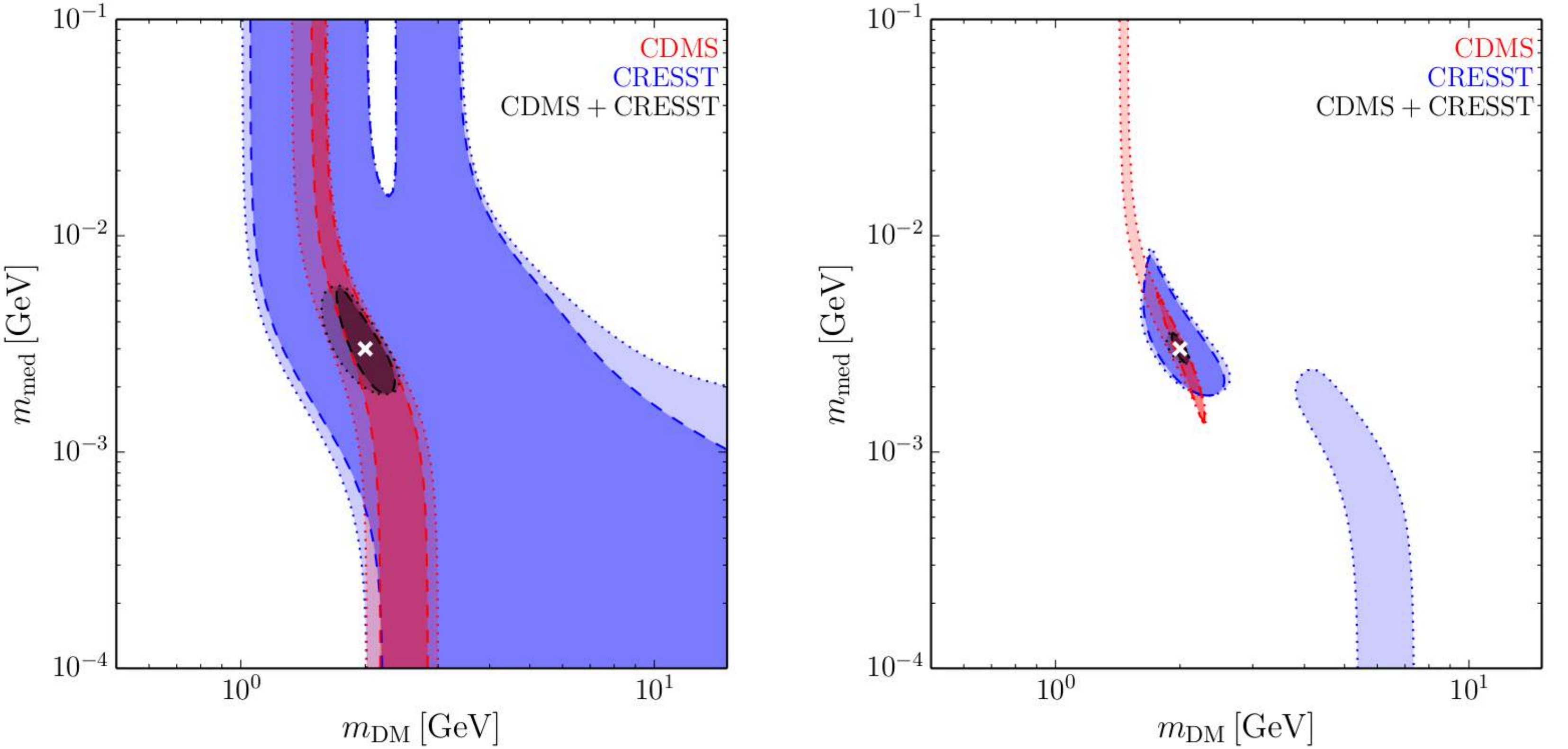
Low statistics case
(~900 events total)



High statistics case
(~8000 events total)

Including nuisance parameters

- Allowing for unknown background normalization



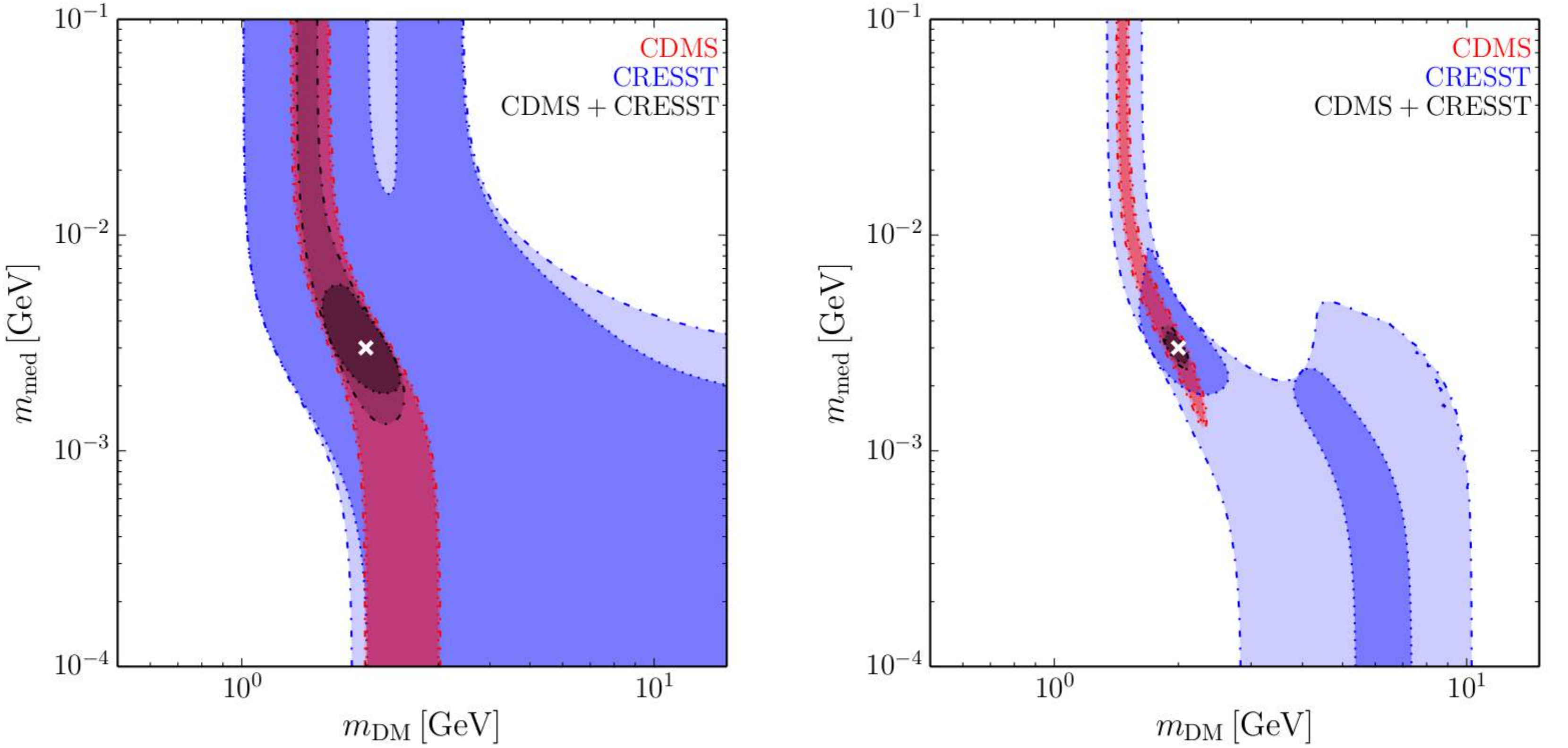
Low statistics case
(~900 events total)

High statistics case
(~8000 events total)

Including more nuisance parameters

- Profiling out the unknown coupling ratio f_p/f_n.

See also Frandsen et al., arXiv:1107.2118



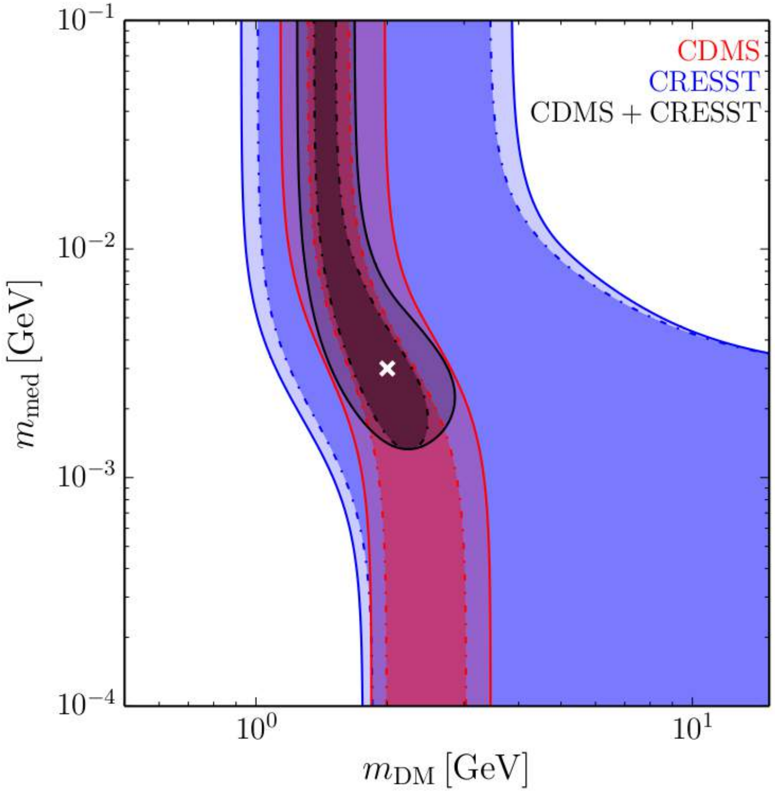
Low statistics case
(~900 events total)

High statistics case
(~8000 events total)

Including even more nuisance parameters

- Taking into account astrophysical uncertainties (by implementing a common rescaling factor for v_0 and v_{esc}).

See also Cherry et al., arXiv:1405.1420



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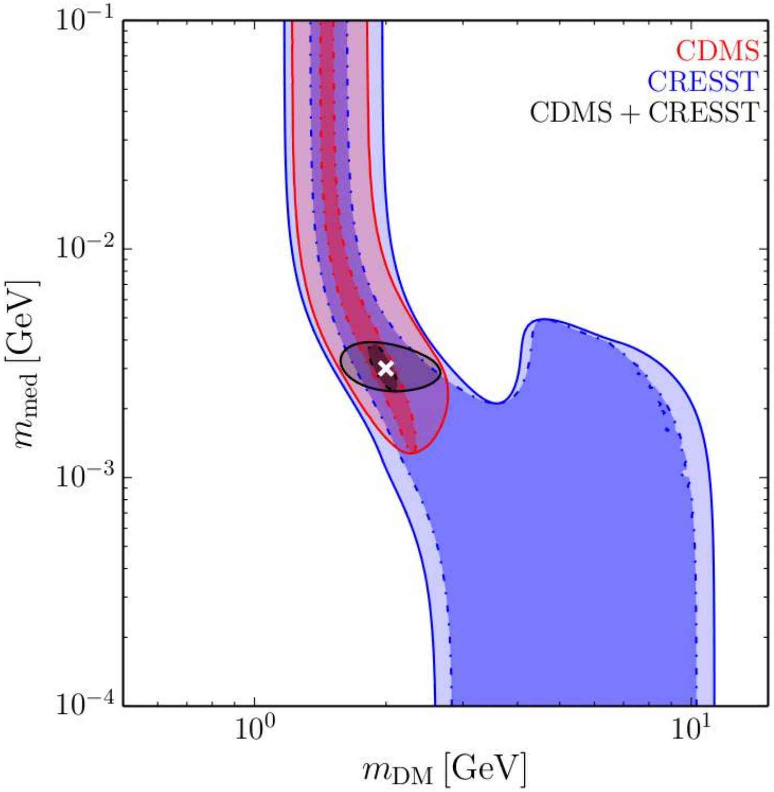
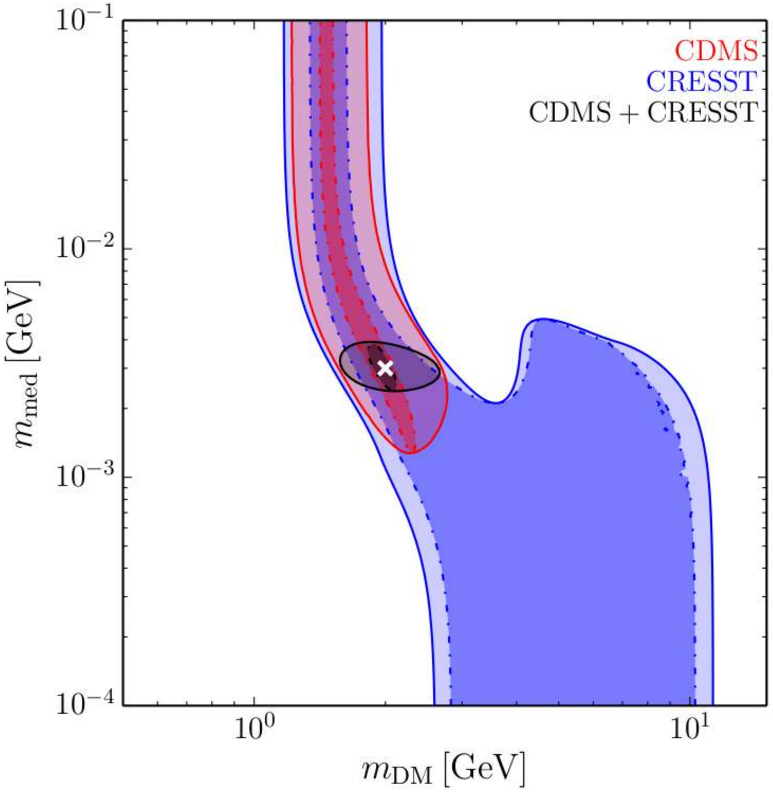


High statistics case
(~8000 events total)

Parameter reconstruction: Results

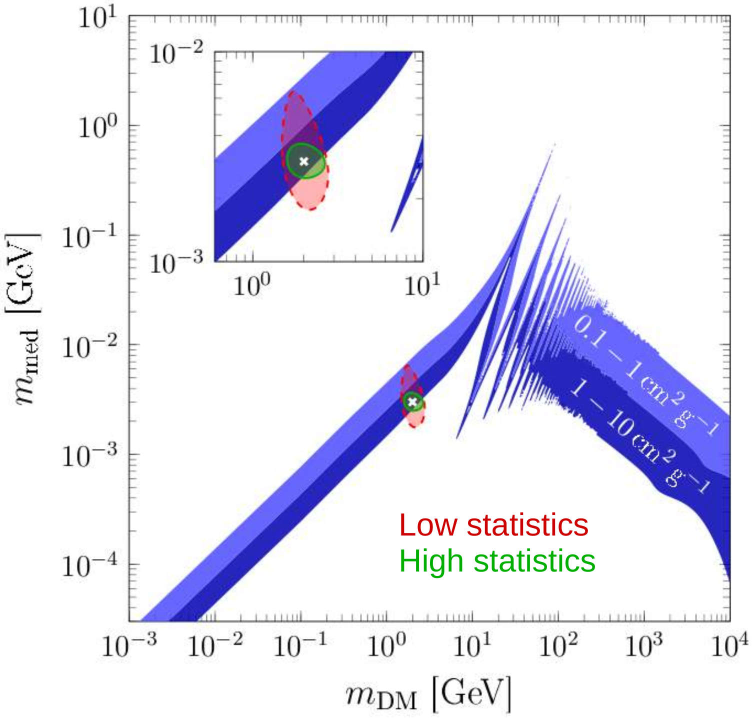
- Even with several nuisance parameters, an accurate reconstruction of the DM and mediator masses is possible given sufficient statistics.

- Crucially, the combination of several different experiments breaks the degeneracies
  - between mediator mass and DM mass
  - between scattering off different elements in CRESST



Probing self-interacting WIMPs

- Within specific model assumptions we can interpret a direct detection signal in terms of self-interacting DM.
- Example: fermionic DM, scalar mediator



- Compare the inferred DM and mediator mass to values compatible with large self-interactions
- Measure the DM self-interaction cross section with direct detection experiments

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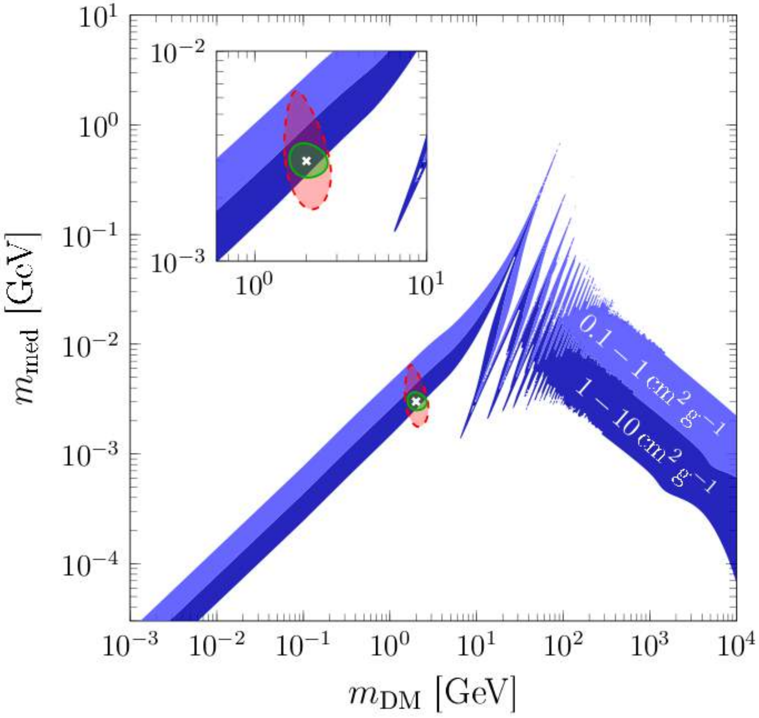
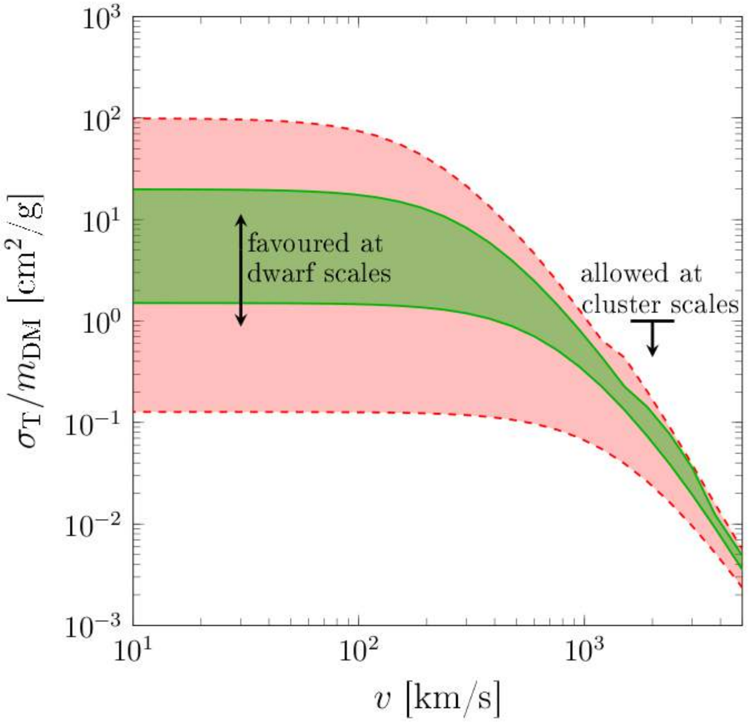




Conclusions

- Astrophysical probes of dark matter self-interactions offer a promising new window for exploring the dark sector
- Light mediators offer an attractive way for obtaining dark matter with velocity-dependent self-interactions from thermal freeze-out
- The two simplest possibilities are scalar and vector mediators , but there are strong constraints from direct and indirect detection experiments, respectively
- Cryogenic direct detection experiments are particularly well-suited for exploring this scenario
- There is remarkable potential to reconstruct the properties of the mediator, even when including experimental and theoretical uncertainties
- Within model assumptions it is possible to translate between signals in direct detection experiments and astrophysical observables
- We can hope to construct a coherent picture of the microscopic and macroscopic properties of DM

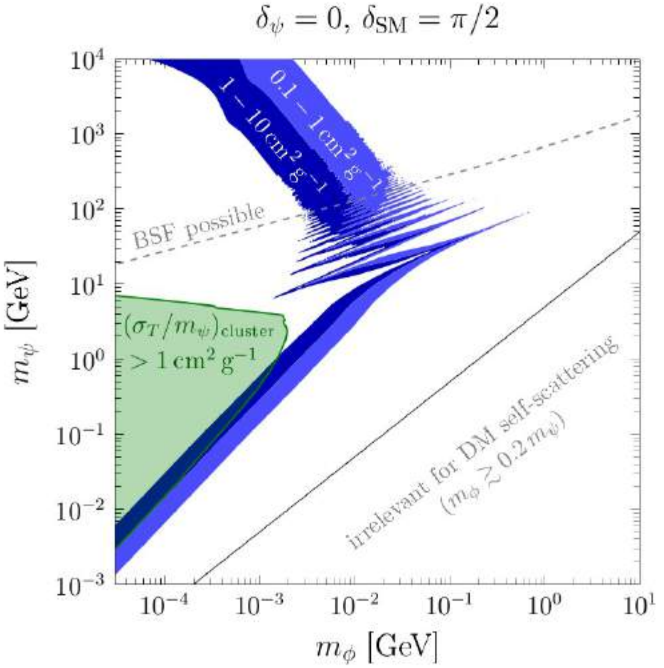
Backup

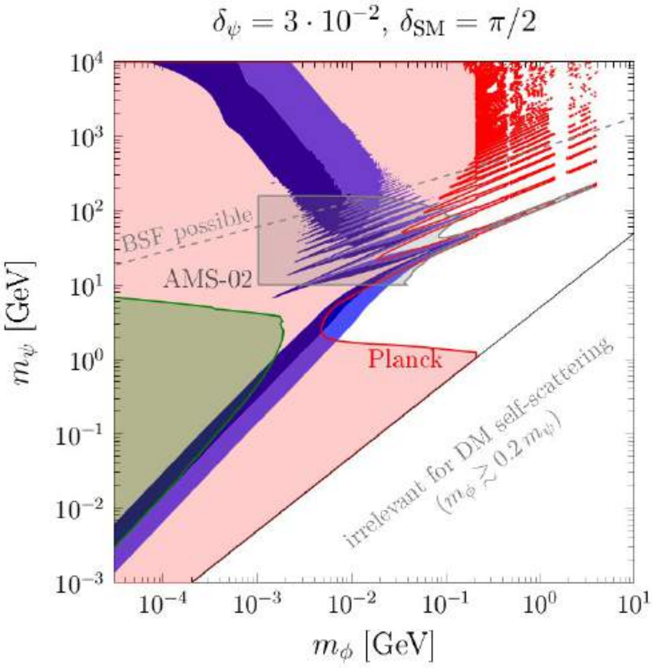
What about pseudoscalar mediators?

- Annihilation into pseudoscalar mediators is p-wave suppressed, so there are no indirect detection or CMB constraints
- In the non-relativistic limit, scattering via the exchange of pseudoscalar mediators is also strongly suppressed by powers of the momentum transfer
- Direct detection constraints are therefore effectively absent
- Unfortunately, the same effect also suppresses DM self-scattering
- It is impossible to obtain large self-interaction cross sections from pseudoscalar exchange
- This conclusion still holds when including loop-induced processes and Sommerfeld enhancement

Mixed scalar-pseudoscalar interactions

- An interesting possibility are mediators that couple to DM like a scalar but to the SM like a pseudoscalar (e.g. due to spontaneous CP violation)
- In this case, self-interactions can be large, but direct detection remains suppressed
- Large allowed parameter space!





FK, et al., arXiv:1704.02149

- Caveat: Once CP symmetry is broken, nothing forbids s-wave annihilation
- Need to worry about CMB constraints and indirect detection
- Potential fine-tuning problem…