Dark matter and light mediators

Felix Kahlhoefer

Invisibles18 Workshop
Karlsruhe Institute of Technology
3-7 September 2018

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

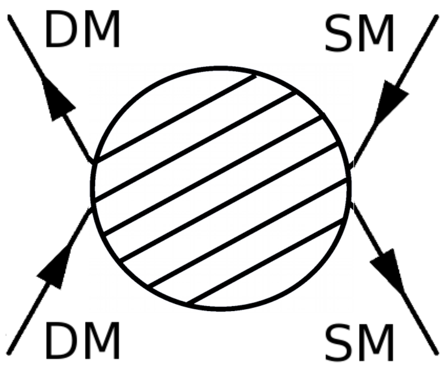
TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Outline

- Motivation for light mediators: Self-interacting WIMPs
- Light mediators in direct detection: Long-range interactions
- Light mediators in indirect detection: Sommerfeld enhancement
- Light mediators in cosmology: Late decays and annihilations
- Constraints on long-lived light mediators

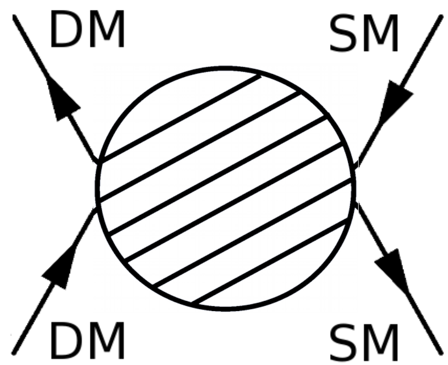
Introduction

- Heavy mediator ($m_{med} >> m_{DM}$)

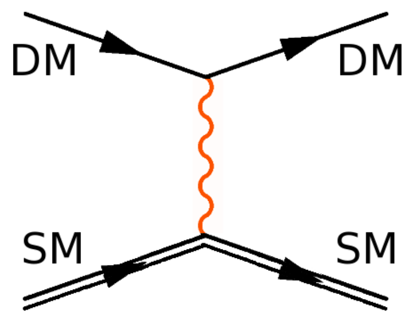


Introduction

- Heavy mediator ($m_{med} >> m_{DM}$)

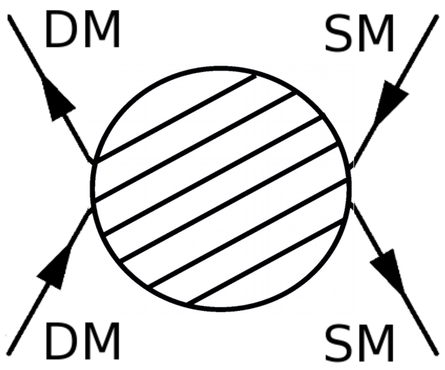


- Light mediator ($m_{med} << m_{DM}$)

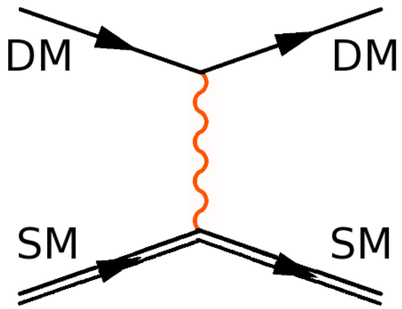


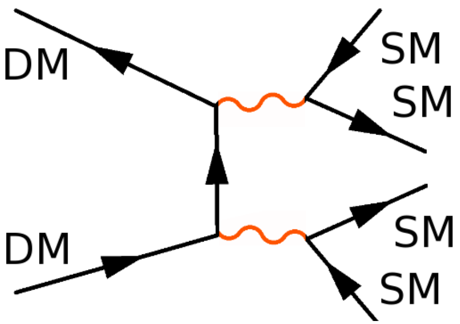
Introduction

- Heavy mediator ($m_{med} >> m_{DM}$)



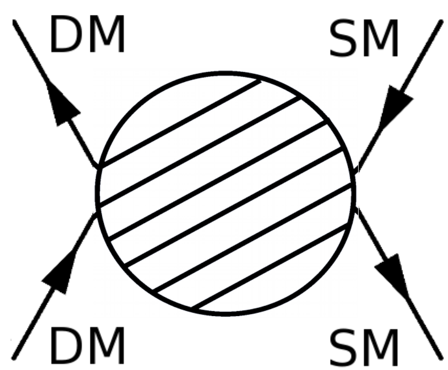
- Light mediator ($m_{med} << m_{DM}$)



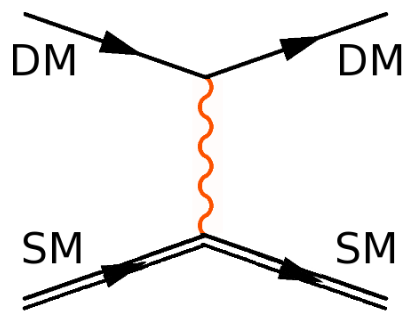


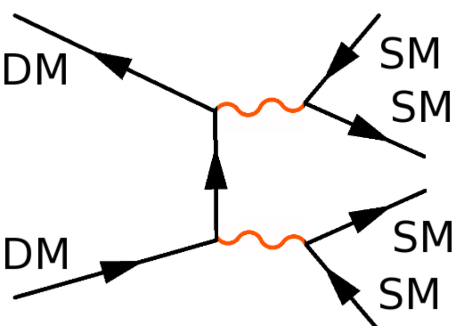
Introduction

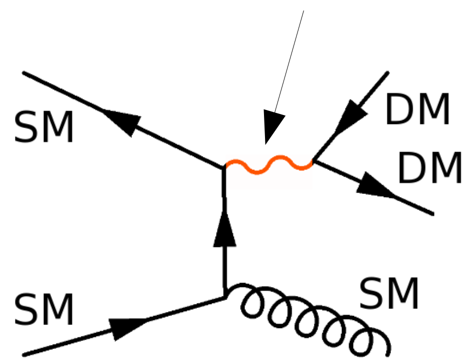
- Heavy mediator ($m_{med} >> m_{DM}$)



- Light mediator ($m_{med} << m_{DM}$)

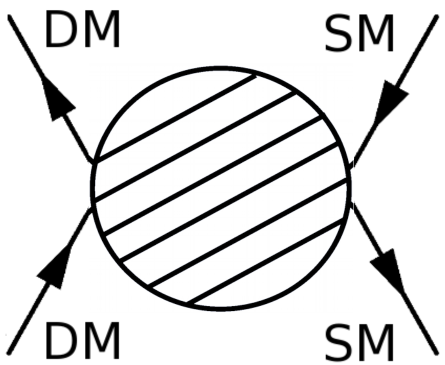




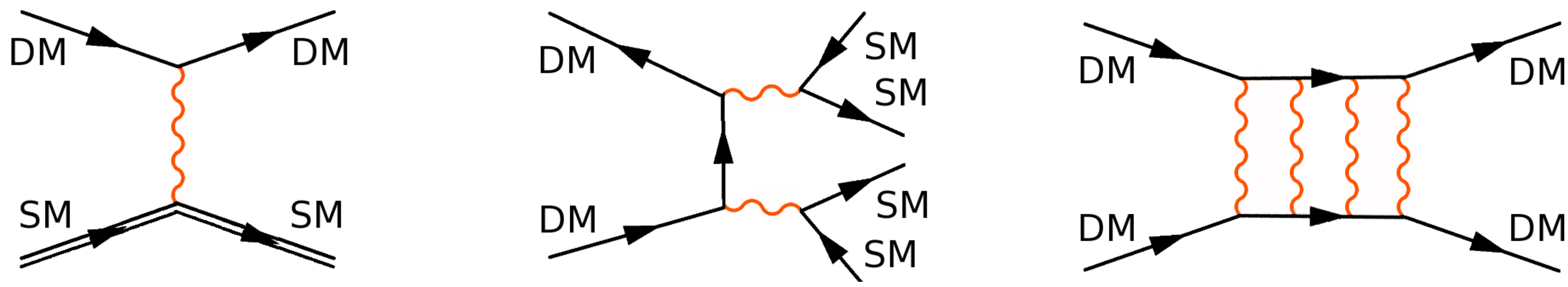


Introduction

- Heavy mediator ($m_{med} >> m_{DM}$)



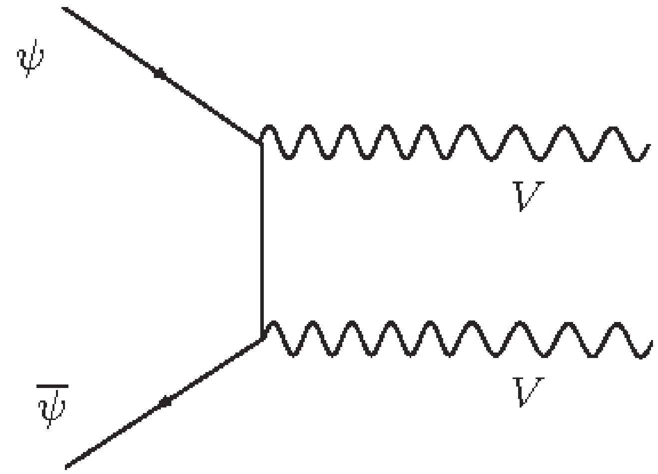
- Light mediator ($m_{med} << m_{DM}$)



Secluded dark matter: Dark sector freeze-out

- For concreteness consider a fermionic DM particle coupled to a light vector mediator:

$$\mathcal{L} \supset g_\chi \, \bar{\chi}\gamma^\mu \chi V_\mu$$



- Total annihilation cross section set by *s*-wave annihilations into pairs of mediators

- DM relic abundance depends only on DM-mediator coupling g_x

  → Dark sector freeze-out

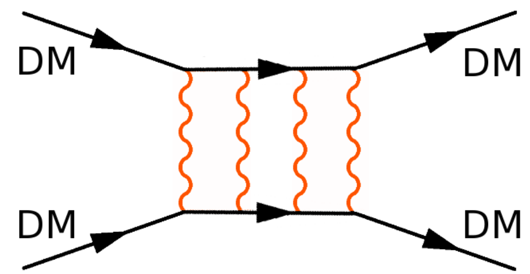
- Always possible to fix coupling g_x such that observed relic abundance is reproduced

- To avoid overclosing the Universe, the mediator should ultimately decay

  → Important cosmological constraints

Self-interactions from a light mediator

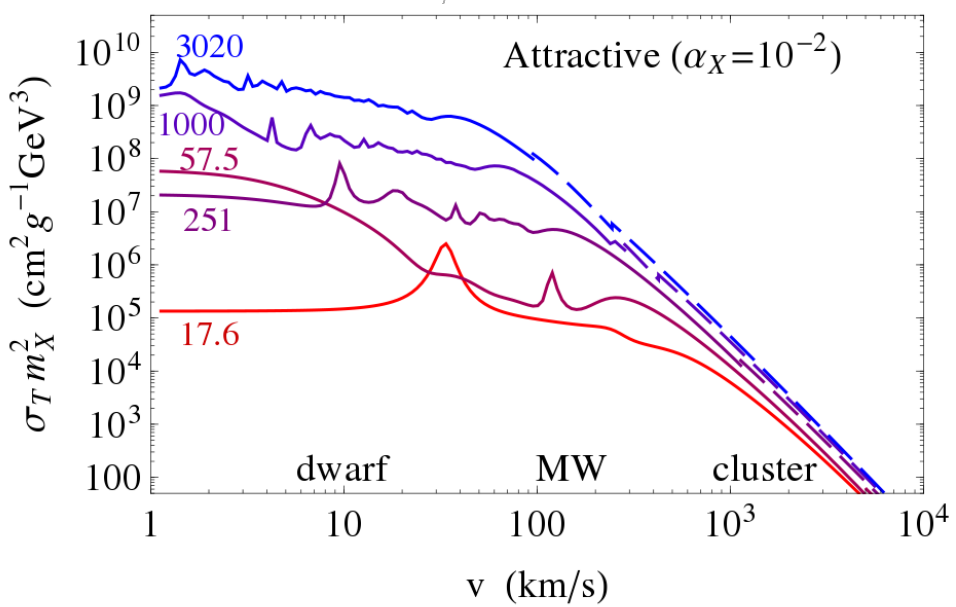
- Non-perturbative effects due to multiple mediator exchange enhance DM self-interactions
- Can be calculated by solving non-relativistic Schroedinger equation for Yukawa potential:



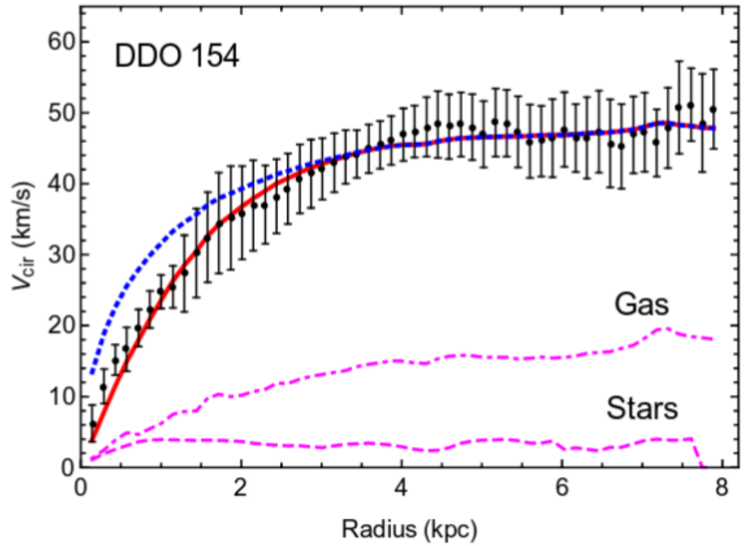
$$V(r) = \frac{\alpha \, e^{-r \, m_{\rm med}}}{r}$$

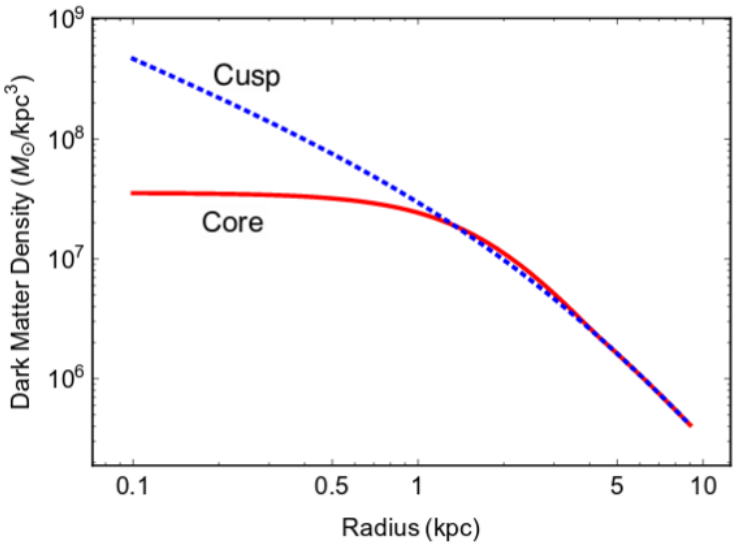
- For $\alpha_S m_\psi \gtrsim m_\phi$ resonances appear and modify results of tree-level calculation.
- Bonus: self-interactions depend on the relative velocity of the DM particles

Tulin et al., arXiv:1302.3898



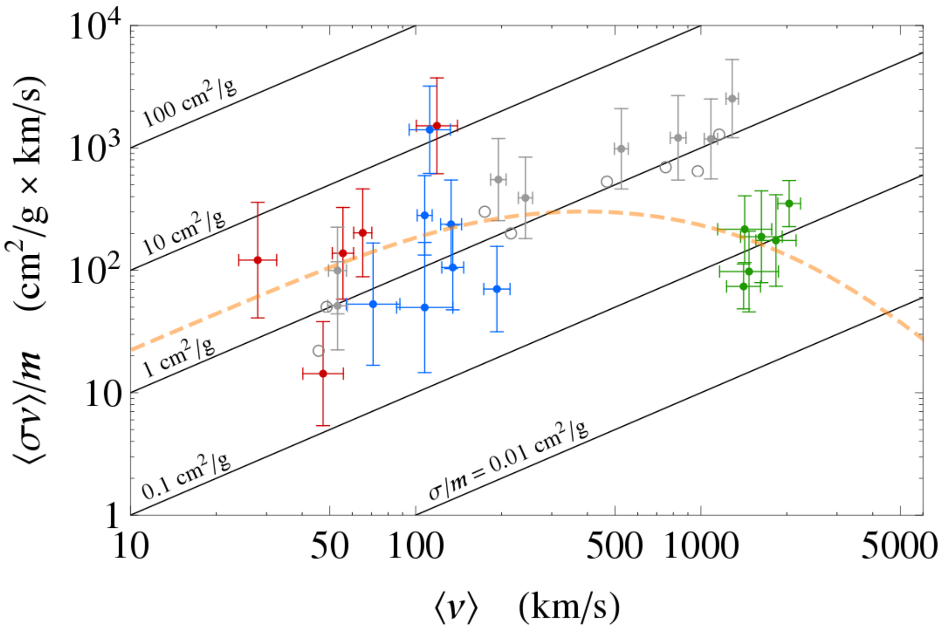
Velocity-dependent self-interactions





Tulin & Yu: arXiv:1705.02358

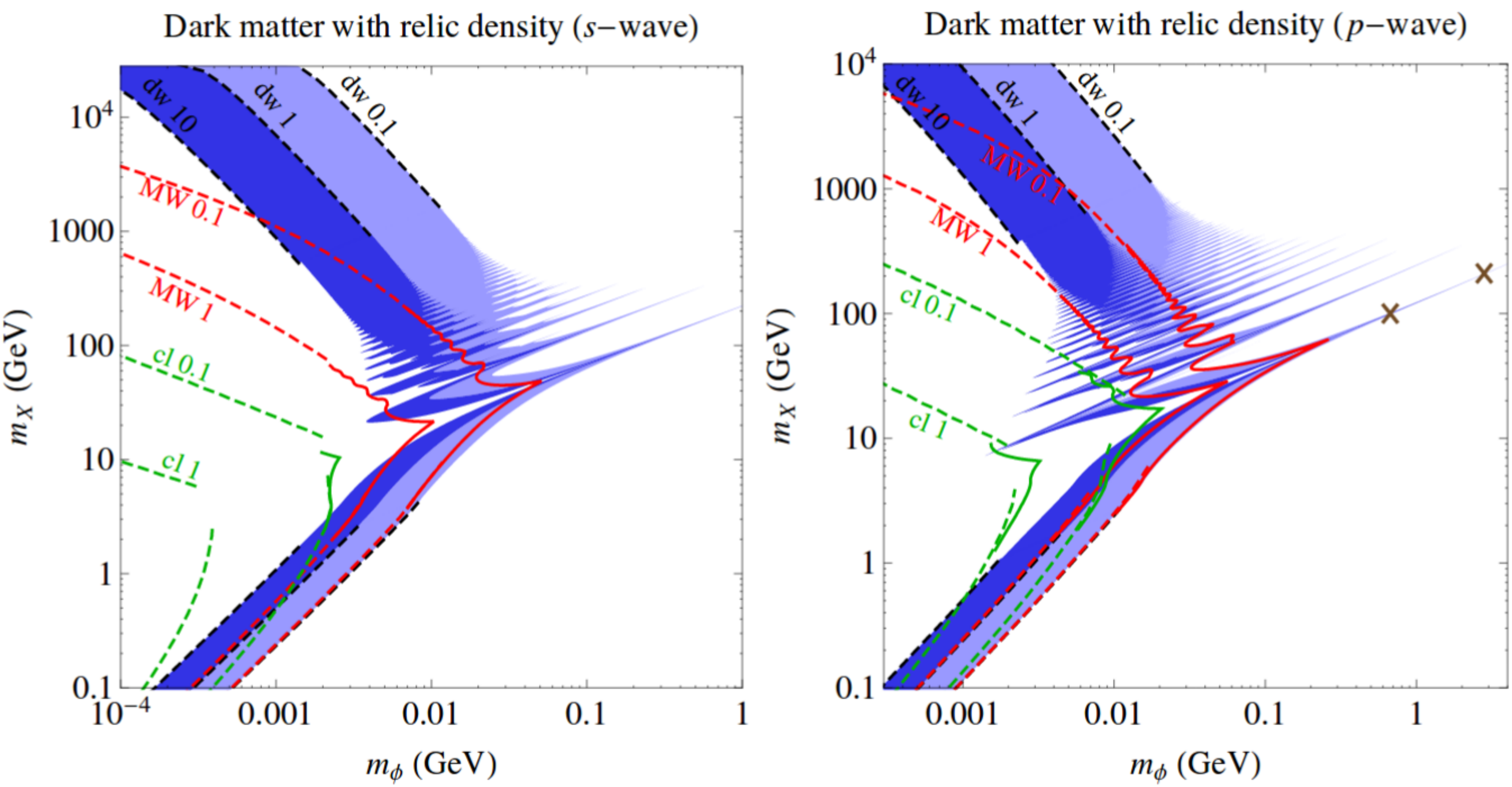
- DM self-interactions lead to energy transfer between DM particles
- Creation of an isothermal core
- Resolution of cusp-core problem
- Need velocity dependence to explain observations at different scales



Kaplinghat et al., arXiv:1508.03339

Benchmarks for self-interacting dark matter

- Combining relic density constraints and bounds on DM self-interactions, we can identify the preferred parameter regions in the $m_{\mathrm{DM}} - m_{\mathrm{med}}$ parameter plane



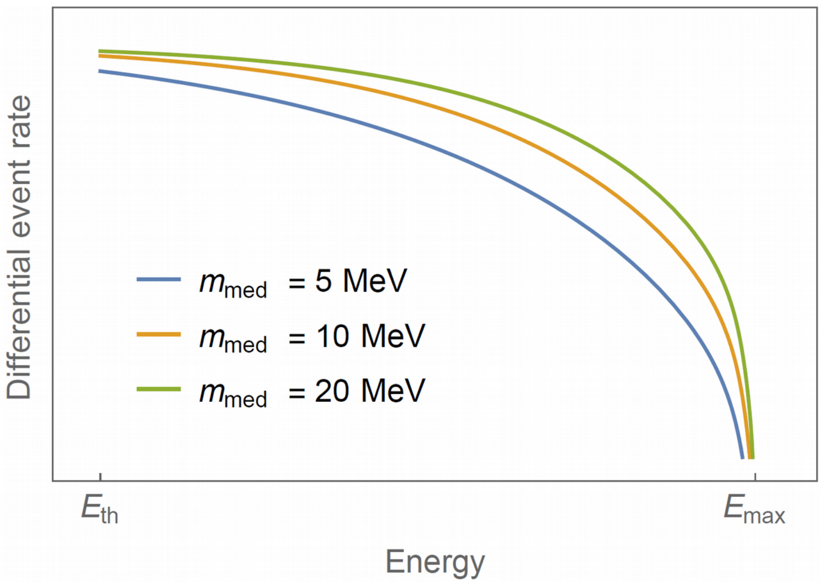
Tulin et al., arXiv:1302.3898

Direct detection with light mediators

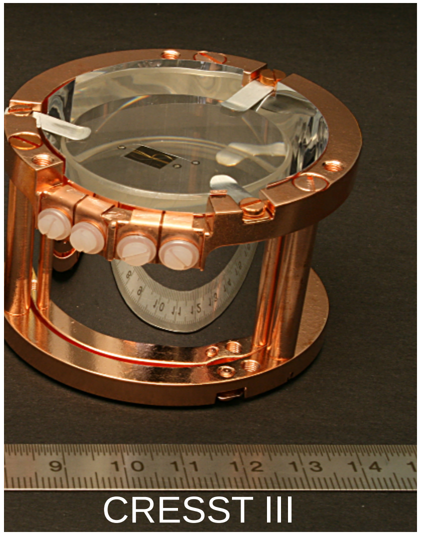
- Differential event rate:

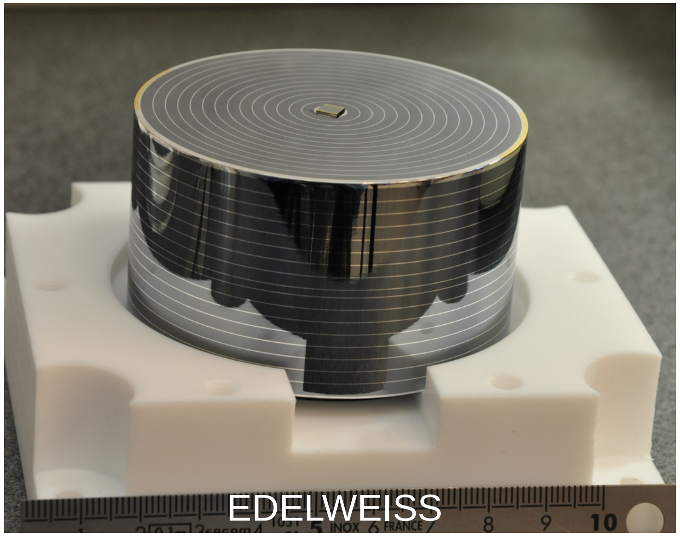
$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0}{m_\mathrm{DM}} \eta(v_\mathrm{min}(E_\mathrm{R})) \frac{g^2 F_T^2(E_\mathrm{R})}{2\pi \left(2\, m_T\, E_\mathrm{R} + m_\mathrm{med}^2\right)^2}$$

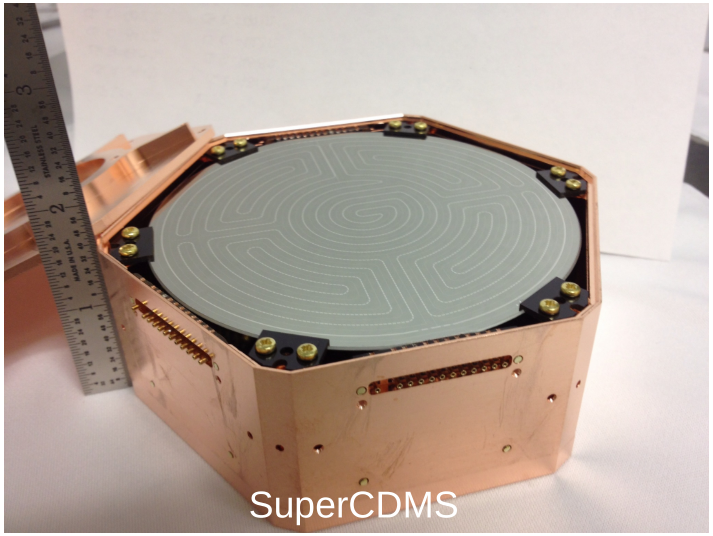
- **Observation 1:** For $m_\mathrm{med} > (2\ m_\mathrm{T}\ E_\mathrm{R})^{1/2}$ direct detection event rates grow rapidly with decreasing mediator mass → sensitivity to very small couplings
- **Observation 2:** For $m_\mathrm{med} > (2\ m_\mathrm{T}\ E_\mathrm{R})^{1/2}$ the shape of the differential event rate depends on m_med in non-trivial way
- With sufficient statistics and resolution, may be possible to *measure* mediator masses in the MeV range
- Exactly the mass range interesting for self-interacting WIMPs!



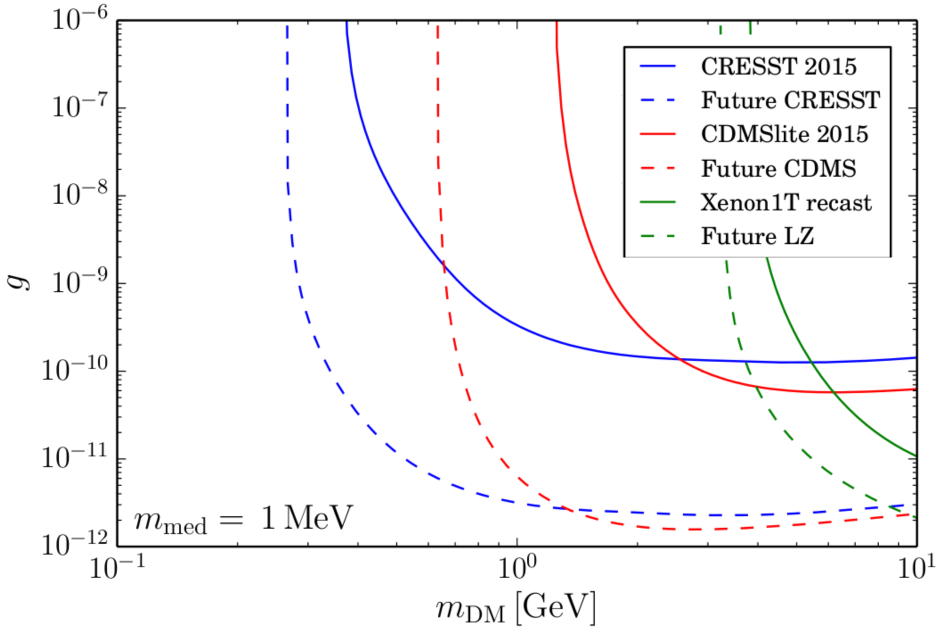
Low-threshold experiments







- Cryogenic direct detection experiments aim to significantly reduce the energy threshold (E_{th} < 20 eV feasible)
- Extended sensitivity of direct detection experiments to sub-GeV DM masses
- Detectors also achieve excellent energy resolution (σ_E ~ 10 eV feasible)



Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

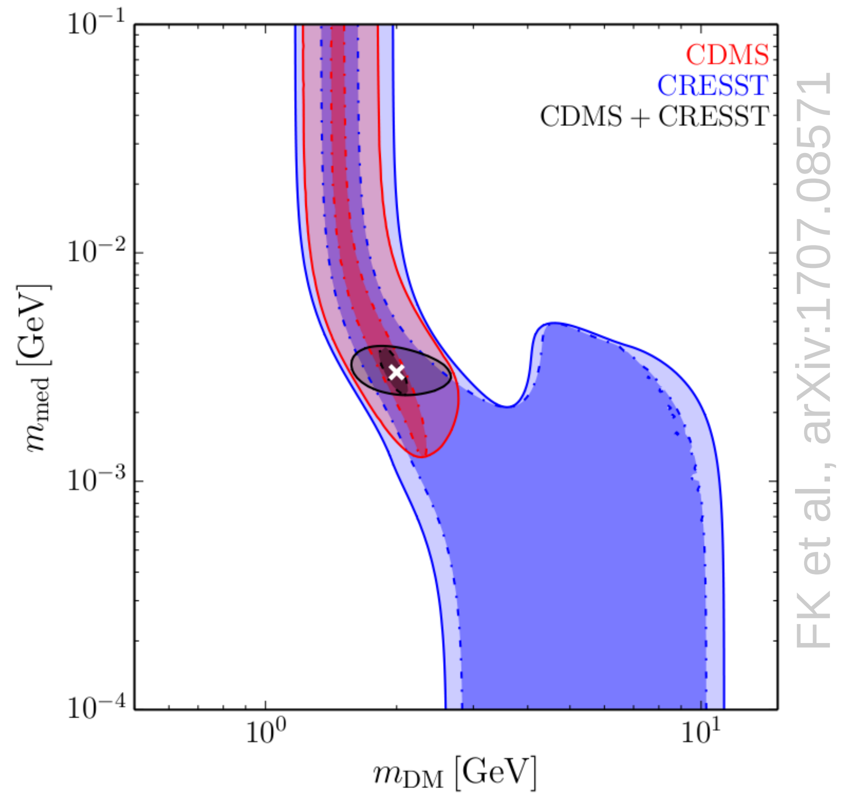
TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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

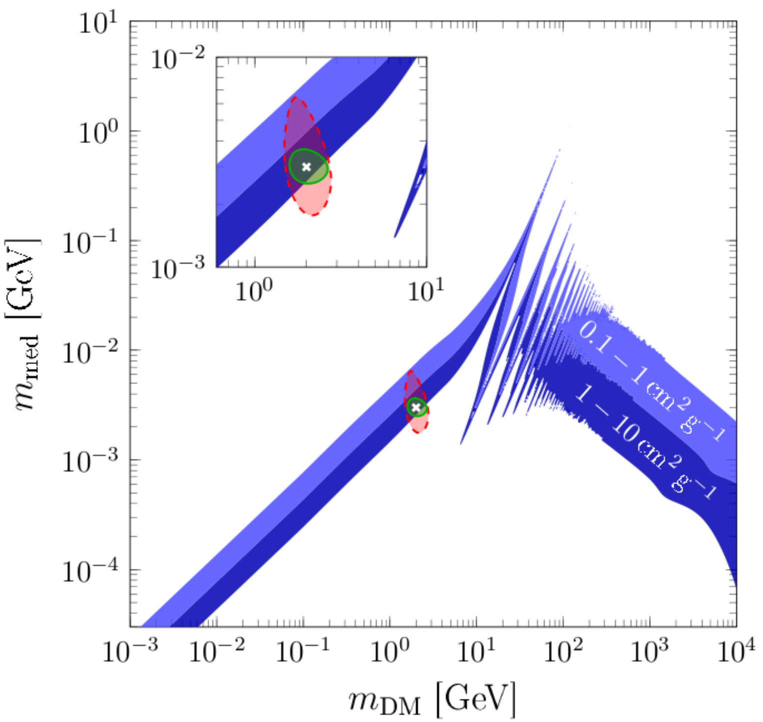
- Even with several nuisance parameters, an accurate reconstruction of the DM and mediator masses is possible given sufficient statistics.

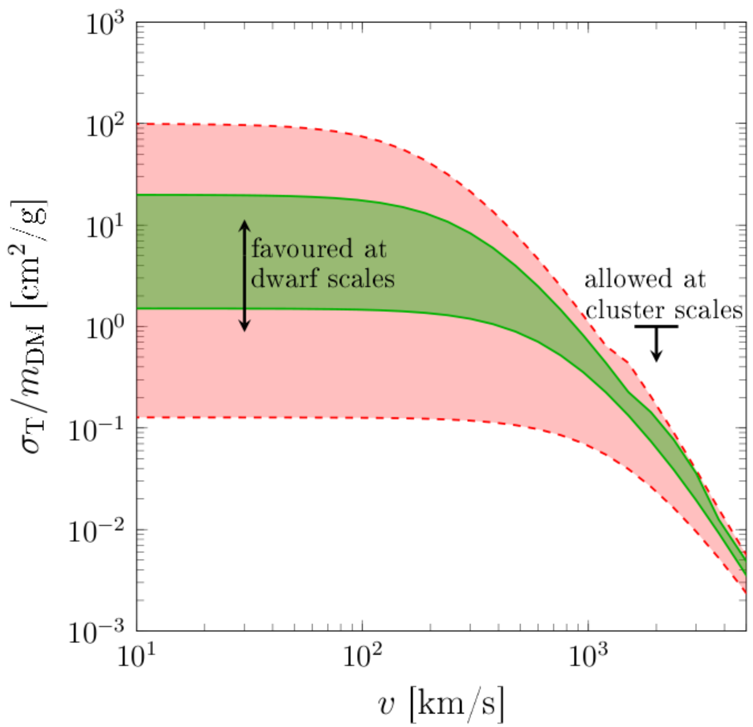
- Crucially, the combination of several different experiments breaks the degeneracies
  - between mediator mass and DM mass
  - between scattering off different elements in CRESST



Probing self-interacting WIMPs

- For specific models one can interpret direct detection signals in terms of self-interacting DM
- Example: fermionic DM, scalar mediator



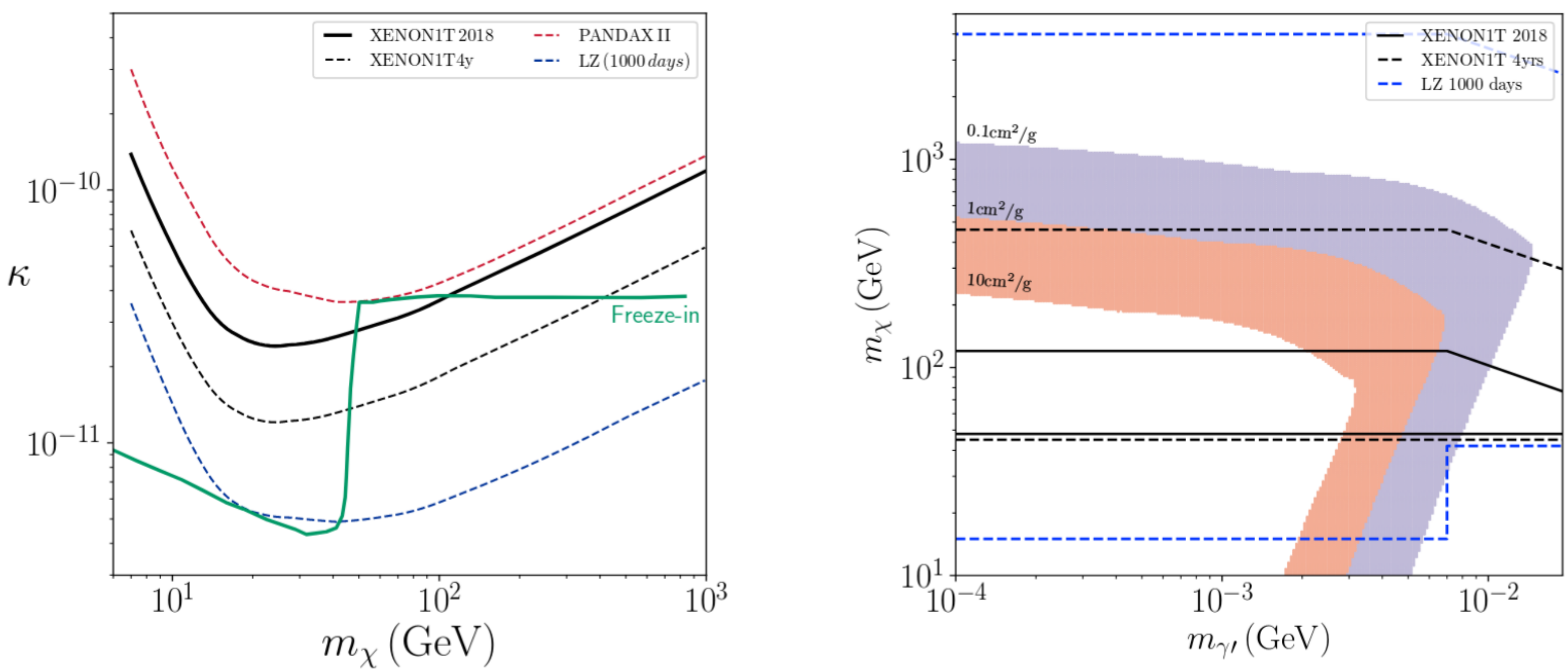


Testing freeze-in with direct detection

- Direct detection for light mediators is so sensitive that it may be possible to explore scenarios beyond thermal equilibrium

Direct Detection is testing Freeze-in

Thomas Hambye,[1,*] Michel H.G. Tytgat,[1,†] Jérôme Vandecasteele,[1,‡] and Laurent Vanderheyden[1,§]



Hambye et al., arXiv:1807.05022

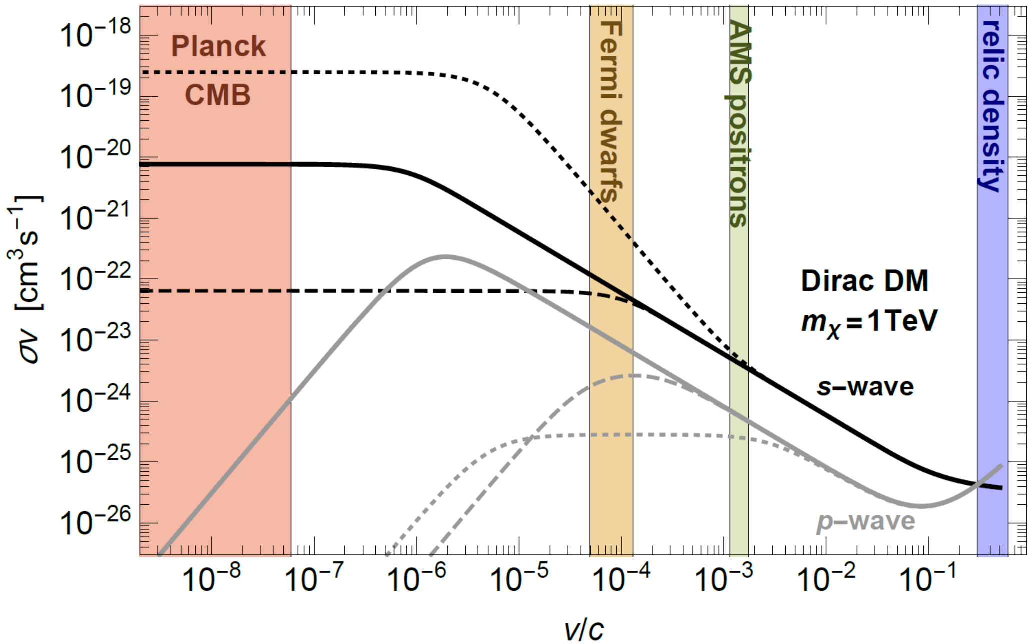
Indirect detection with light mediators

- The Yukawa potential from the light mediator exchange also 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

Bringmann, FK et al., arXiv:1612.00845



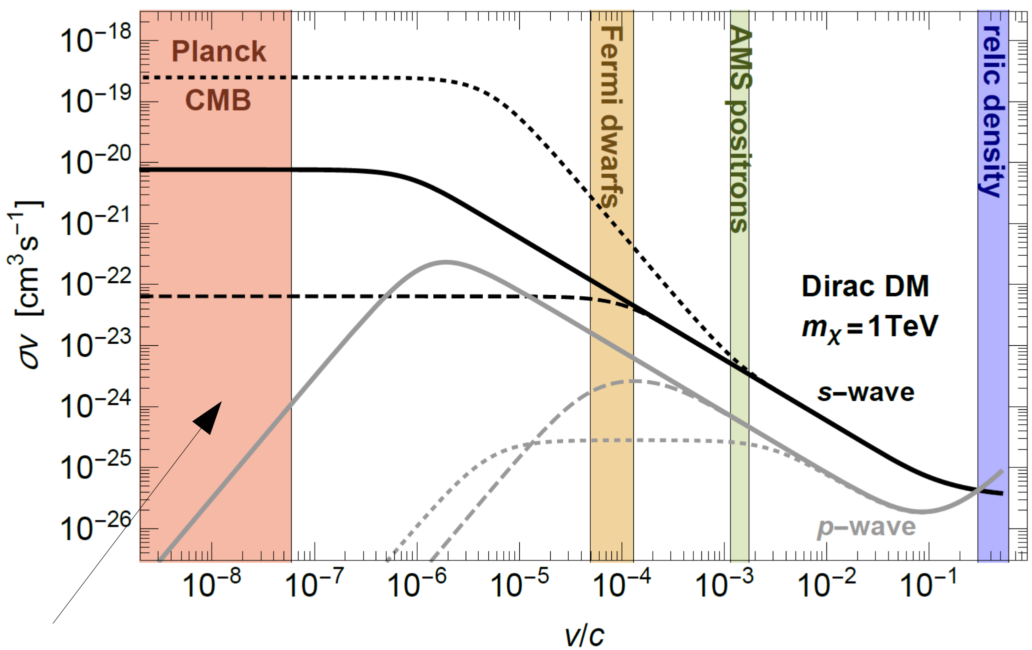
Indirect detection with light mediators

- The Yukawa potential from the light mediator exchange also 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

Bringmann, FK et al., arXiv:1612.00845

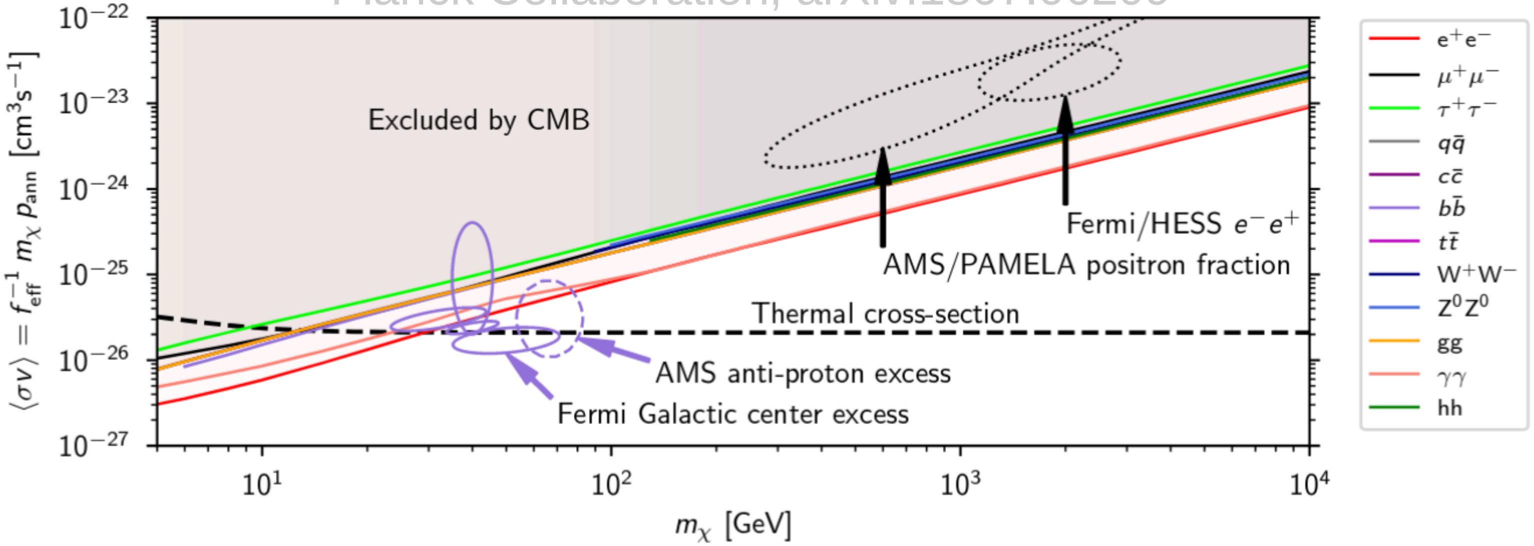


During recombination dark matter particles move at walking speed!

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

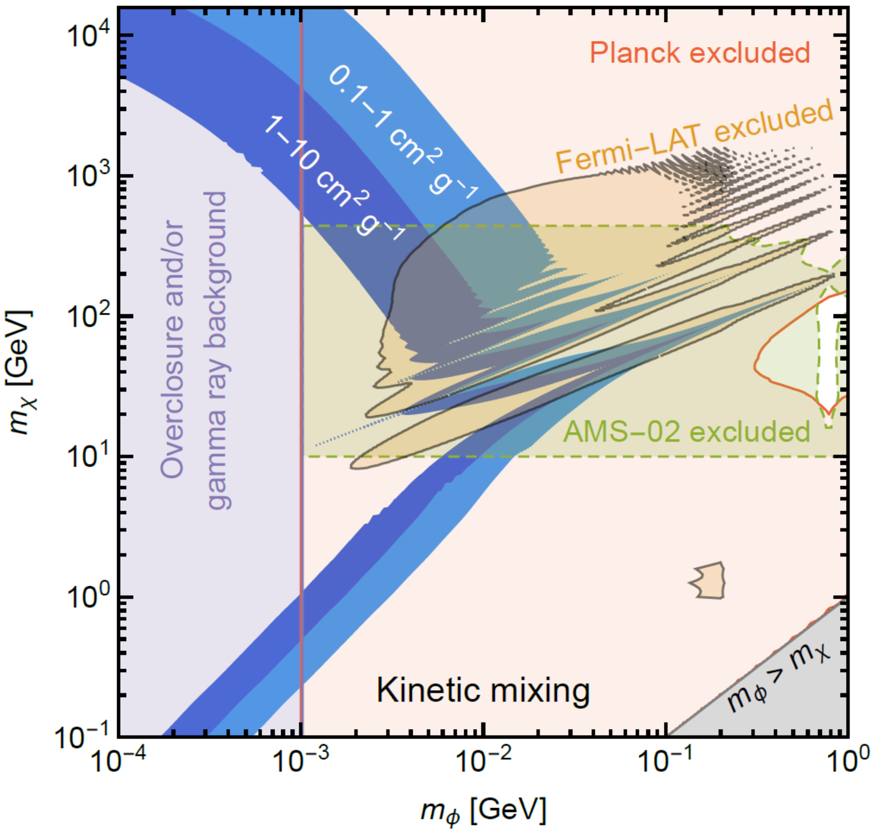
Planck Collaboration, arXiv:1807.06209



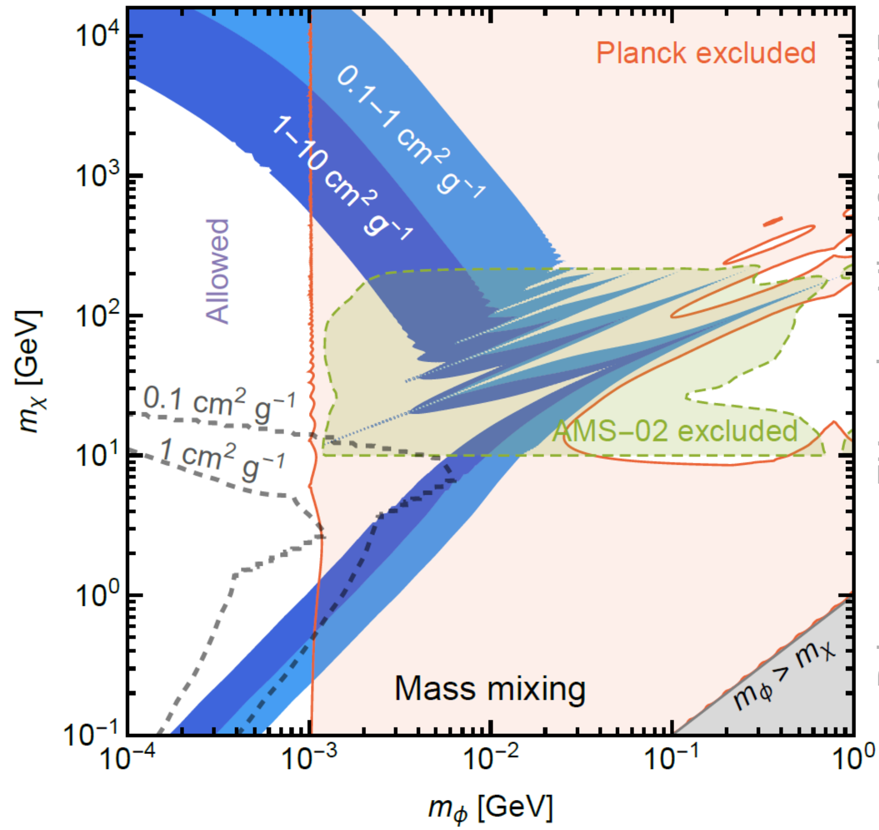
- Result: $$\frac{\langle\sigma v\rangle_{\rm rec}}{N_\chi} \lesssim 4\times10^{-25}\,{\rm cm}^3\,{\rm s}^{-1}\left(\frac{f_{\rm eff}}{0.1}\right)^{-1}\left(\frac{m_\chi}{100\,{\rm GeV}}\right)$$

CMB constraints on self-interacting DM

- CMB and indirect detection constraints basically exclude the case of *s*-wave annihilations under the assumption that the mediator decays into SM particles



Mediator with photon-like couplings



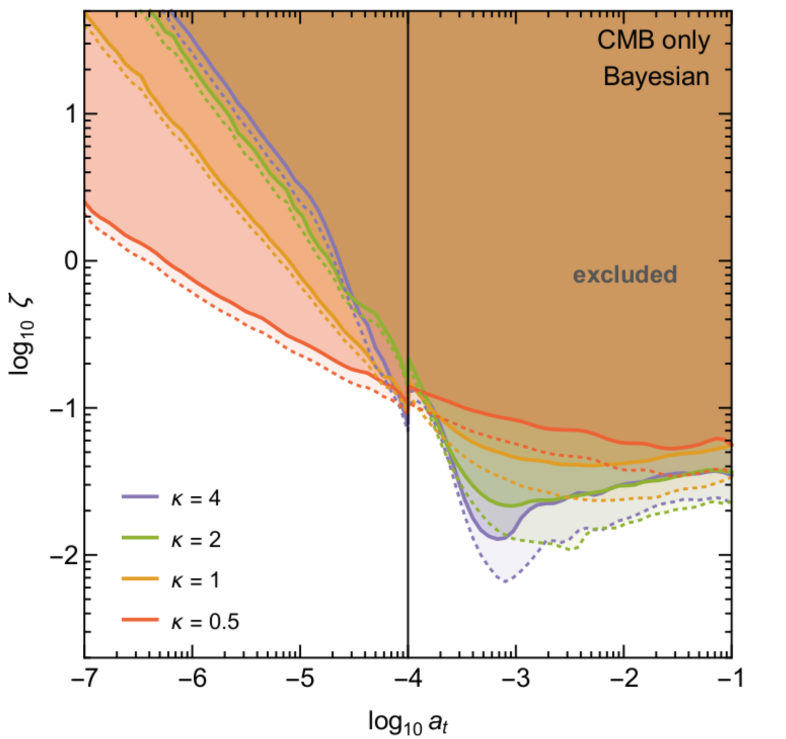
Mediator with Z-like couplings

Bringmann, FK et al., arXiv:1612.00845

What if the mediator decays invisibly?

- Assume the mediator couples to some form of dark radiation (e.g. sterile neutrinos)
- No injection of electromagnetic energy into plasma → much weaker CMB constraints
- Sommerfeld enhancement leads to the conversion of a fraction ζ of DM to dark radiation after the end of freeze-out
- If the conversion happens after recombination, CMB constraints require ζ < 5%
- This constraint is largely independent of when exactly and how quickly the conversion happens

Bringmann, FK et al., arXiv:1803.03644

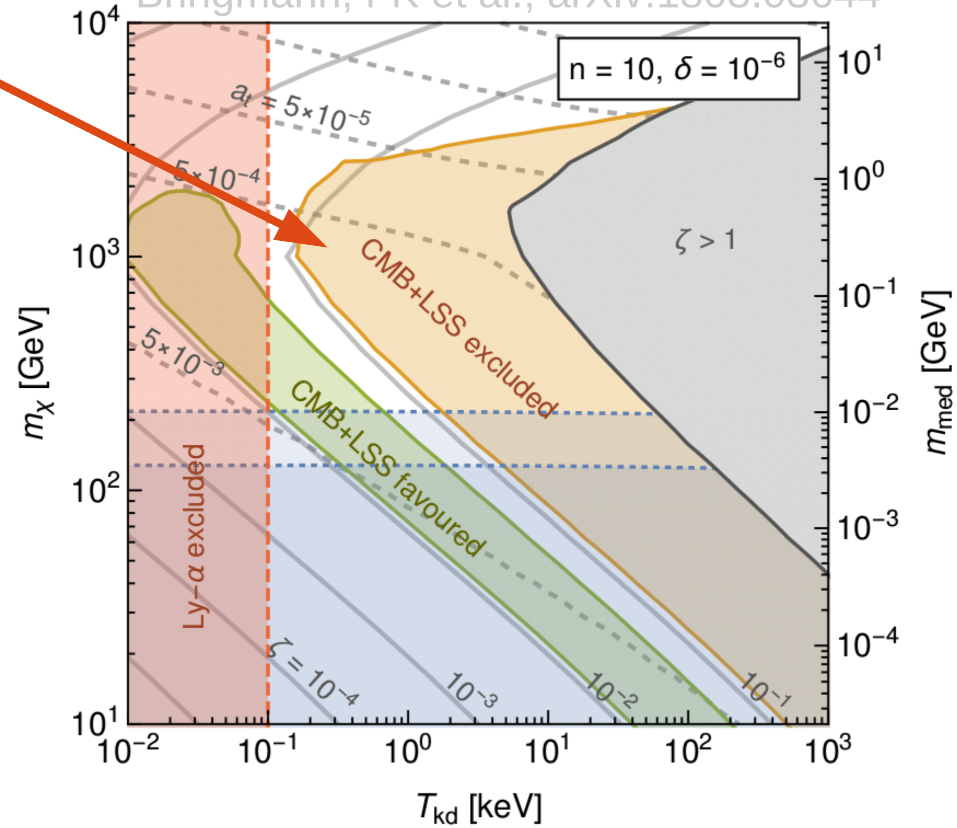


Constraints on light mediators

- Assume Sommerfeld enhancement close to resonance (fixed mass relation)
- 2nd relevant parameter: kinetic decoupling temperature
  → Determines when DM annihilations become important

Bringmann, FK et al., arXiv:1803.03644

Excluded by requirement ζ < 5%

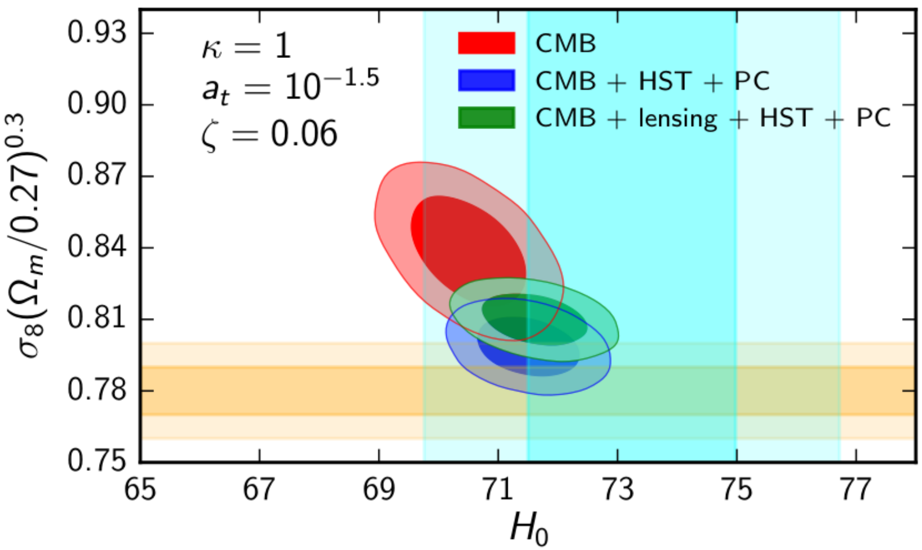


Constraints on light mediators

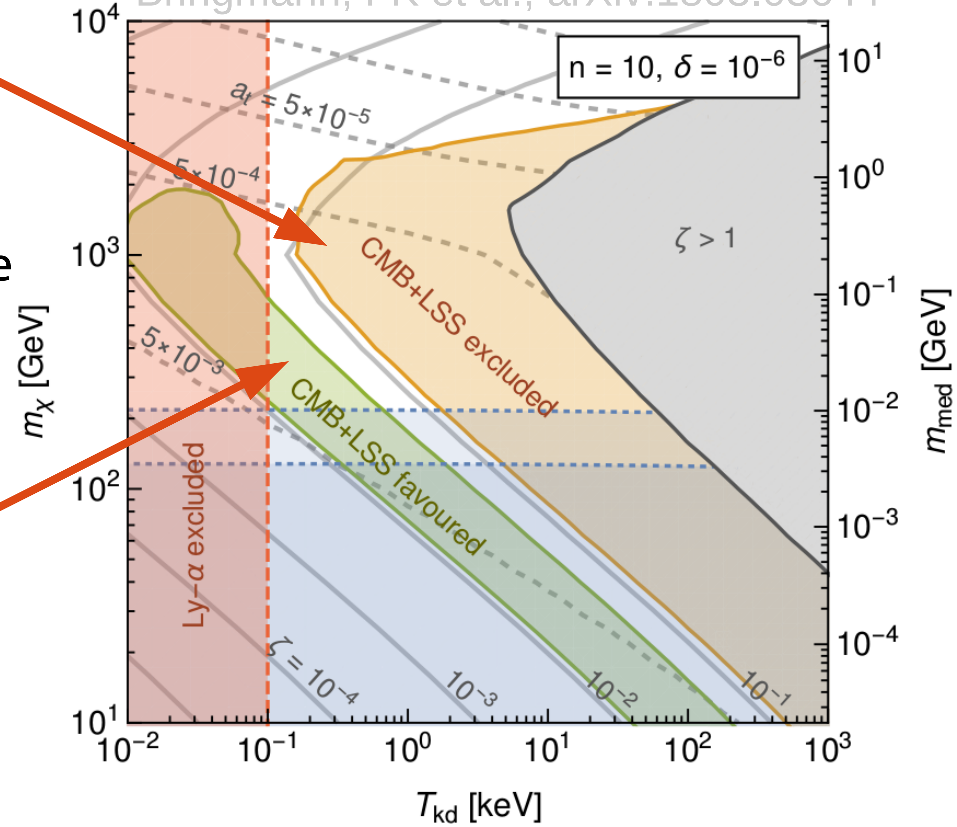
- Assume Sommerfeld enhancement close to resonance (fixed mass relation)
- 2nd relevant parameter: kinetic decoupling temperature
  → Determines when DM annihilations become important

Excluded by requirement ζ < 5%

For ζ ~ few % reduced tension between CMB and low-redshift observables → 2σ preference



Bringmann, FK et al., arXiv:1803.03644

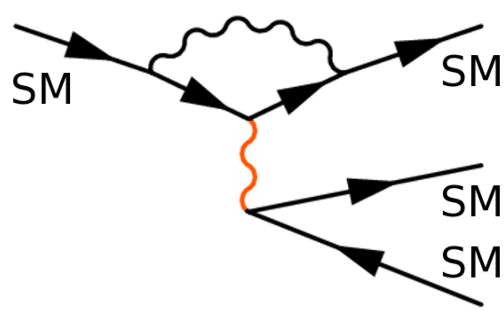


Long-lived mediators

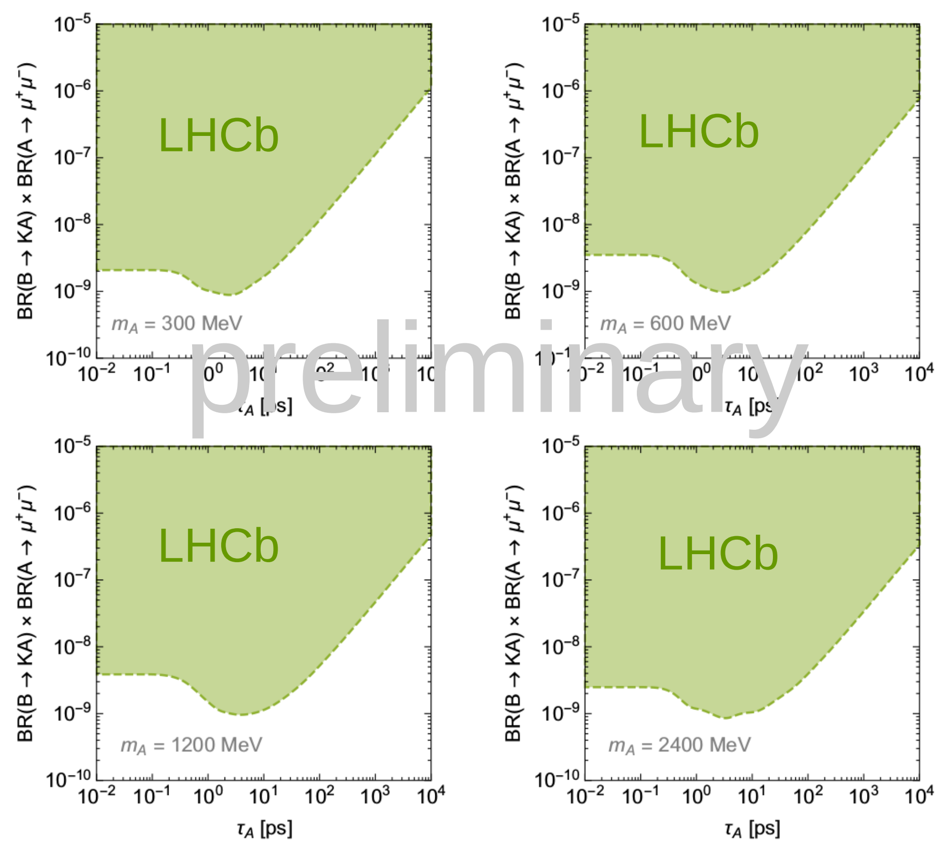
- For *p*-wave annihilations Sommerfeld enhancement is less important
- Nevertheless, strong constraints on mediators with long lifetimes

Long-lived mediators

- For *p*-wave annihilations Sommerfeld enhancement is less important
- Nevertheless, strong constraints on mediators with long lifetimes
- **Mediator lifetime ~ 10^{-14} – 10^{-8} s:** Constraints from precision measurements
- *Example:* Light mediators produced in rare SM decays (e.g. B → K + X)



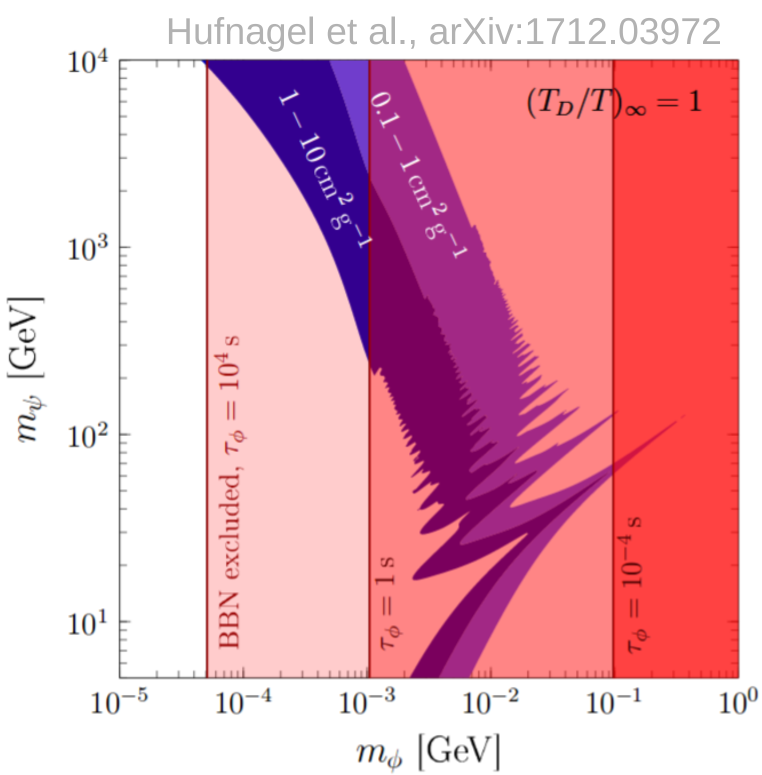
- Mediator decay length can be macroscopic → displaced decays

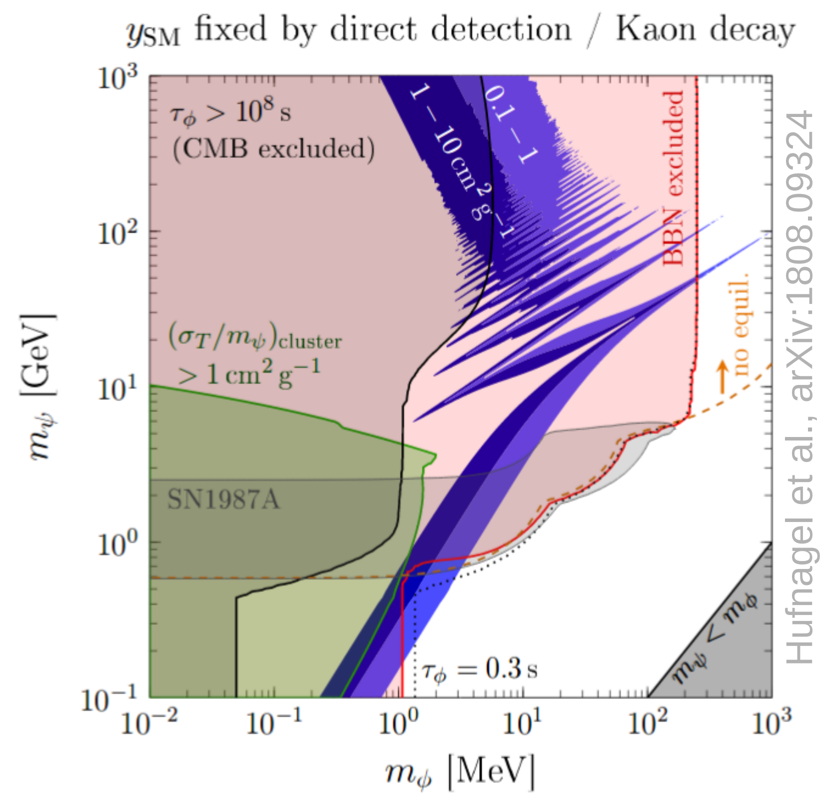


Döbrich, Ertas, FK & Spadaro, in preparation

Long-lived mediators

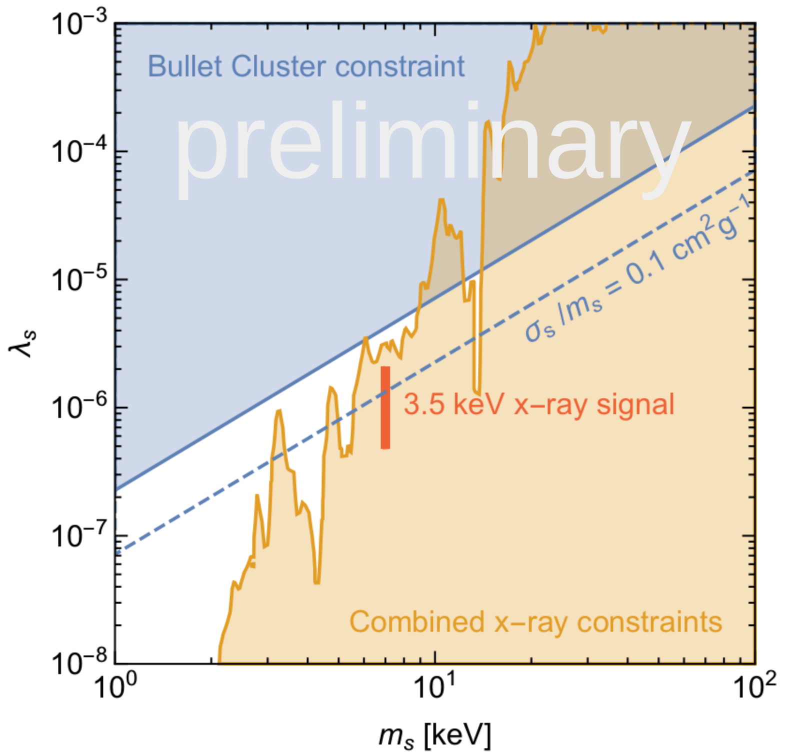
- For *p*-wave annihilations Sommerfeld enhancement is less important
- Nevertheless, strong constraints on mediators with long lifetimes
- **Mediator lifetime ~ 10^{-4} – 10^{4} s:** Constraints from BBN





Long-lived mediators

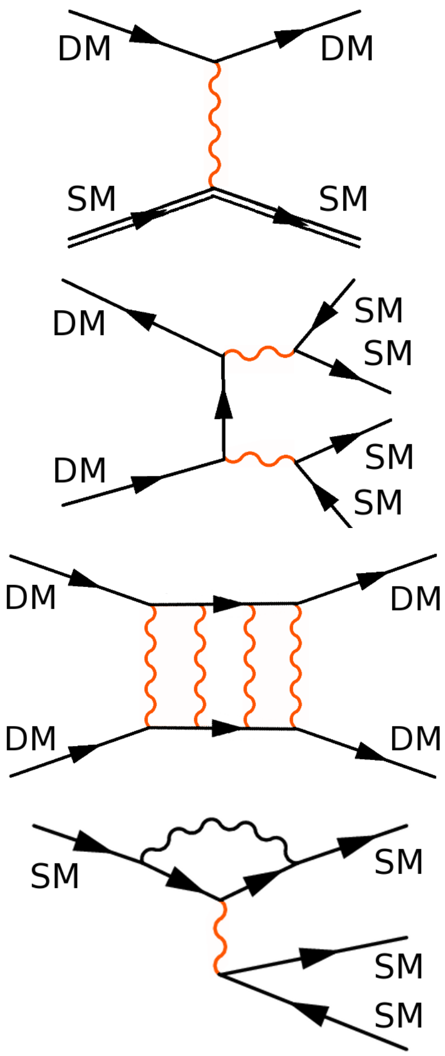
- For *p*-wave annihilations Sommerfeld enhancement is less important
- Nevertheless, strong constraints on mediators with long lifetimes
- **Mediator lifetime >> age of the Universe:** Constraints from indirect detection



- *Example:* keV scalar mediator produced via freeze-in mechanism
  - Can potentially explain X-ray line at 3.5 keV
  - Self-interactions prevent free-streaming → no suppression of small-scale structure

Heeba, FK, Stöcker, in preparation

Conclusions



- DM models with light mediators have exciting phenomenology
- **Direct detection:** Light mediators lead to enhanced sensitivity and modified recoil spectra
- **Indirect detection:** Sommerfeld enhancement leads to strong constraints on mediators decaying into SM particles
- **Cosmology:** Light mediators may faciliate the conversion of dark matter to dark radiation and reduce large-scale tension
- **Self-interactions:** Velocity-dependent scattering may lead to core formation in small DM halos (+resolve small-scale crisis?)
- **Late decays:** Strong constraints from searches for displaced decays, Big Bang nucleosynthesis and indirect detection