Self-interacting dark matter

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Particle properties of dark matter

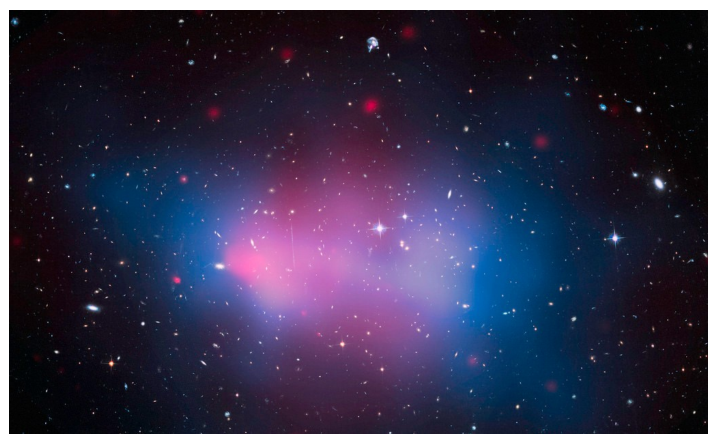
- One of the great successes of modern physics is the connection between microscopic and macroscopic phenomena
  - Nuclear reactions determine how stars evolve
  - Interactions between electrons, protons and photons determine how galaxies form
  - Fundamental properties of neutrinos determine structure formation in the early Universe
- If dark matter (DM) is composed of elementary particles, we can hope to determine their properties from astrophysical and cosmological data
- Almost all current data is compatible with the assumption of DM being a perfectly collisionless non-relativistic fluid
- However, for almost any particle physics model of DM this approximation is **predicted to break down** at some point
- As new (and more precise) observations become available, we can expect that **deviations** from the simplest predictions emerge

Can DM particles self-interact?

- The Bullet Cluster tells us that 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)

- Similar observations in other major mergers

Abel 520



El Gordo

Baby Bullet

Can DM particles self-interact?

- 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 $\Sigma \sim 0.3\ \mathrm{g/cm^2}$
- This implies $\Sigma\, \sigma / m_x \lesssim 0.5$, and thus $\sigma / m_x \lesssim 1.5\ \mathrm{cm^2/g}$
- **Not at all a small cross section** ($1.5\ \mathrm{cm^2/g} = 3$ barn/GeV) – comparable to nucleon-nucleon scattering!

Are DM particles expected to self-interact?

- We know from the Standard Model that two forms of strong self-interactions exist in Nature:
  - **Long-range interactions** with a massless mediator (electron-electron scattering)
  - **Short-range interactions** from strong interactions (nucleon-nucleon scattering)
- With the exception of neutrinos all fermions in the Standard Model experience at least one of the two
- Of course we know that DM cannot have electromagnetic or strong interactions, but there could very well be **analogous forces in the dark sector**
- Papers on DM particles with new strong interactions (e.g. technibaryons) go back to the 1980s

A back-of-the-envelope estimate

- In order to have observable effects on astrophysical scales, one needs

$$\sigma_{self}/m \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim (60\ \mathrm{MeV})^{-3}$$

→ Non-trivial connection between astrophysics and MeV scale

- Simplest example: Strongly interacting dark sector with stable dark pions

$$\frac{\sigma_{\rm self}}{m_\pi} = \frac{m_\pi}{4\pi\, f_\pi^4}$$

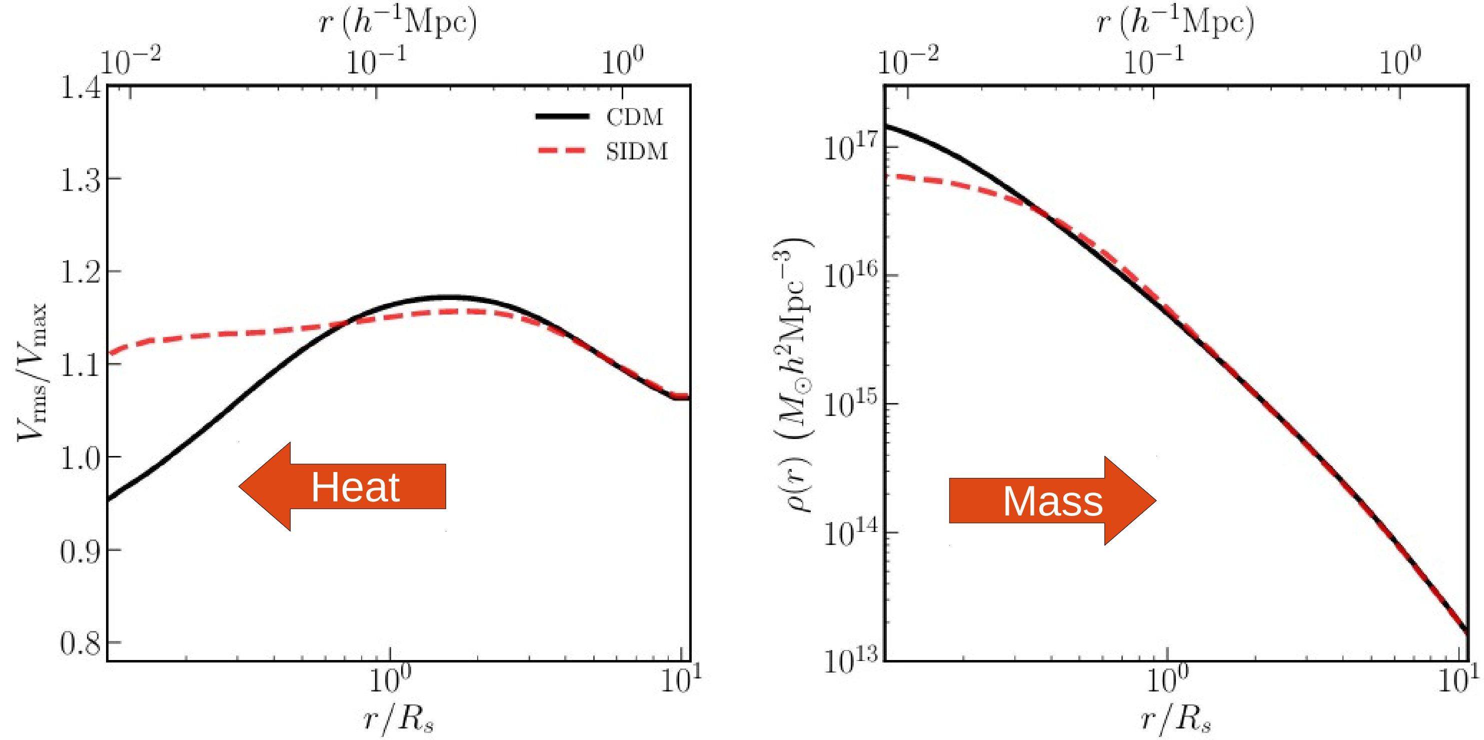
→ Bullet Cluster constraint places lower bound m_π > 50 MeV

See e.g. Bernreuther, FK et al., arXiv:1907.04346

- Strong motivation to study MeV-scale strongly-interacting dark sectors

Predictions of SIDM: Core formation

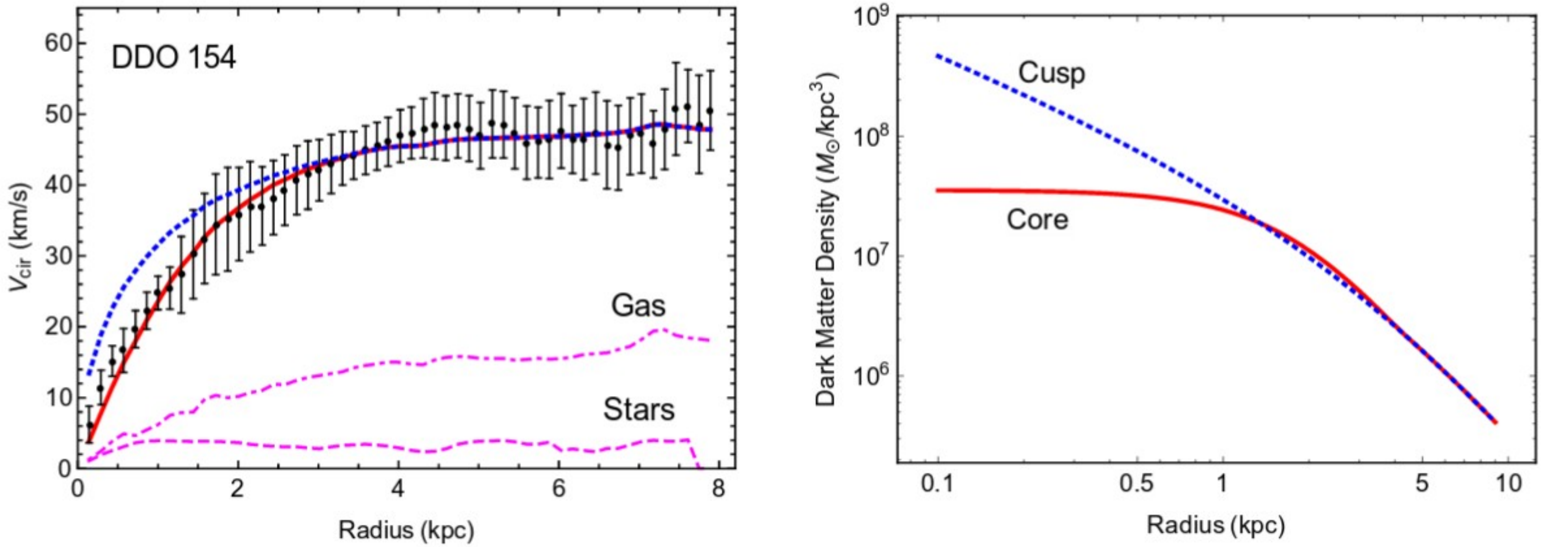
- Dark matter self-interactions transfer energy from hot regions of a DM halo (large velocity dispersion ↔ shallow gravitational potential) to cold regions (small velocity dispersion ↔ deep gravitational potential)
- As a result, they transform halos with cuspy profile ($\rho \sim r^{-1}$) into halos with central cores ($\rho \sim$ const)



Banerjee et al., arXiv:1906.12026

The cusp-core problem

- There are various observations that favour DM halos with contant-density cores, in apparent disagreement with the predictions of collisionless cold DM



Tulin & Yu: arXiv:1705.02358

- DM self-interactions may potentially resolve this discrepancy

Spergel & Steinhard: astro-ph/9909386

- Important caveat: Neither the observational situation nor the predictions from numerical simulations are fully robust, so there may be no cusp-core problem

See e.g. Read et al., arXiv:1808.06634

A simple semi-analytical model

- Assume that self-interactions leave the outer parts of DM halos unaffected, while the inner part reaches hydrostatic equilibrium (constant velocity dispersion)

  → Outer part: Can be described by NFW profile

  → Inner part: Profile given by solving Jeans equation

$$\boldsymbol{\nabla}\left(\sigma_0^2\,\rho_{\rm iso}(\mathbf{r})\right) = -\rho_{\rm iso}(\mathbf{r})\,\boldsymbol{\nabla}\Phi_{\rm tot}(\mathbf{r})$$

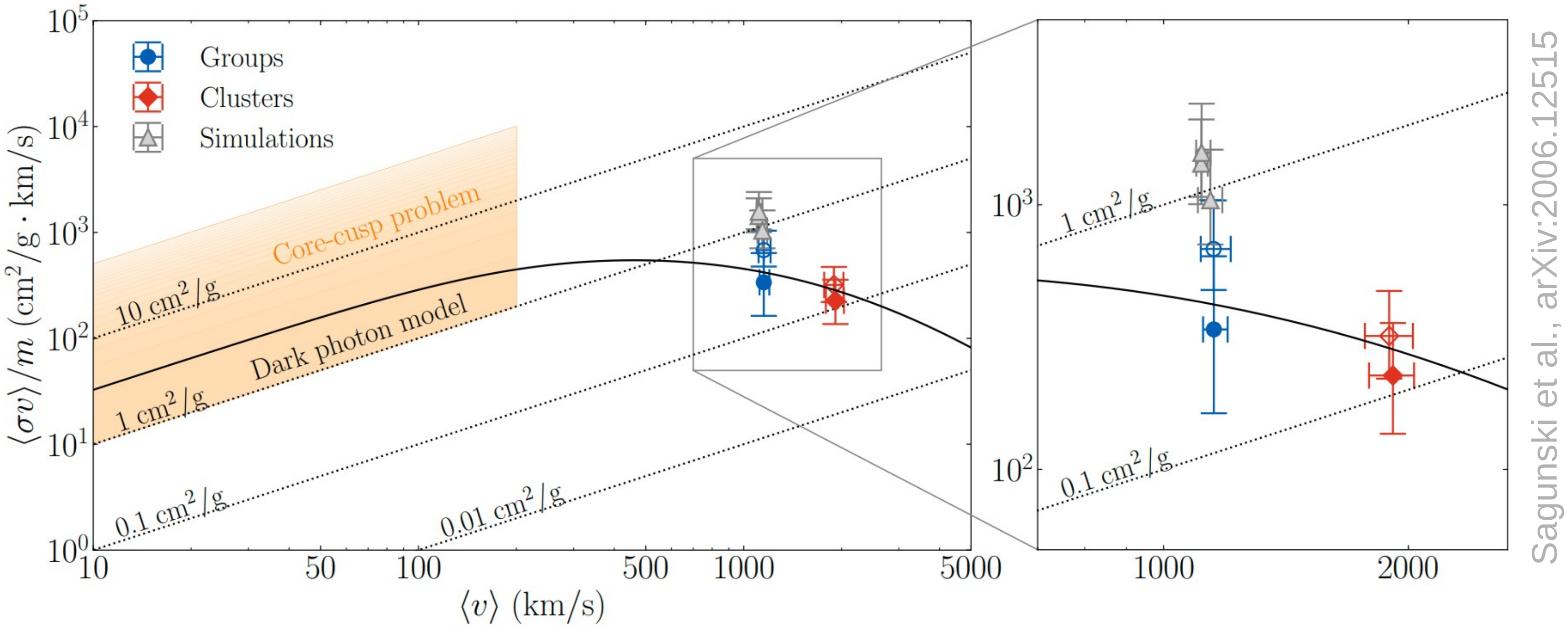
- The transition between the two regions is given by the requirement that at the boundary r_1 DM particles have experienced on average one scatter since the formation of the system:

$$\rho(r) = \begin{cases} \rho_{\rm iso}(r)\,, & r < r_1 \\ \rho_{\rm NFW}(r)\,, & r > r_1 \end{cases} \quad \text{with} \quad \rho_{\rm SIDM}(r_1)\,\frac{\langle\sigma v\rangle}{m}\,t_0 = 1$$

Kaplinghat et al., arXiv:1508.03339
Robertson et al., arXiv:2009.07844

Results

- In order to address the cusp-core problem, self-interaction cross sections need to be larger than 1 cm²/g on the scale of dwarf galaxies (v < 100 km/s)
- Such a cross section would give rise to unacceptably large cores in groups and galaxy clusters, which require cross sections smaller than 1 cm²/g for v > 1000 km/s

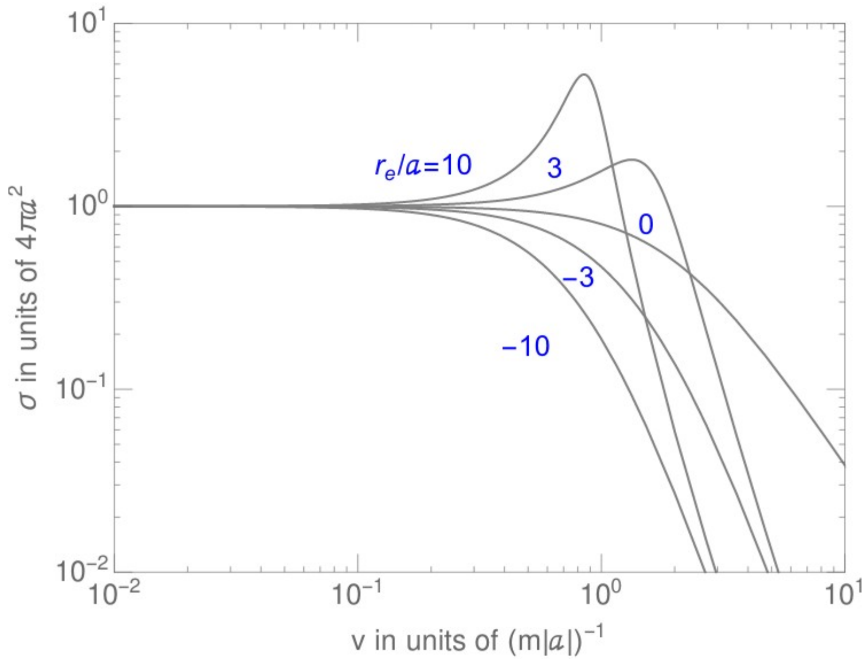


- Explanation of all observations requires velocity-dependent DM self-interactions → not easily achieved in confining dark sectors

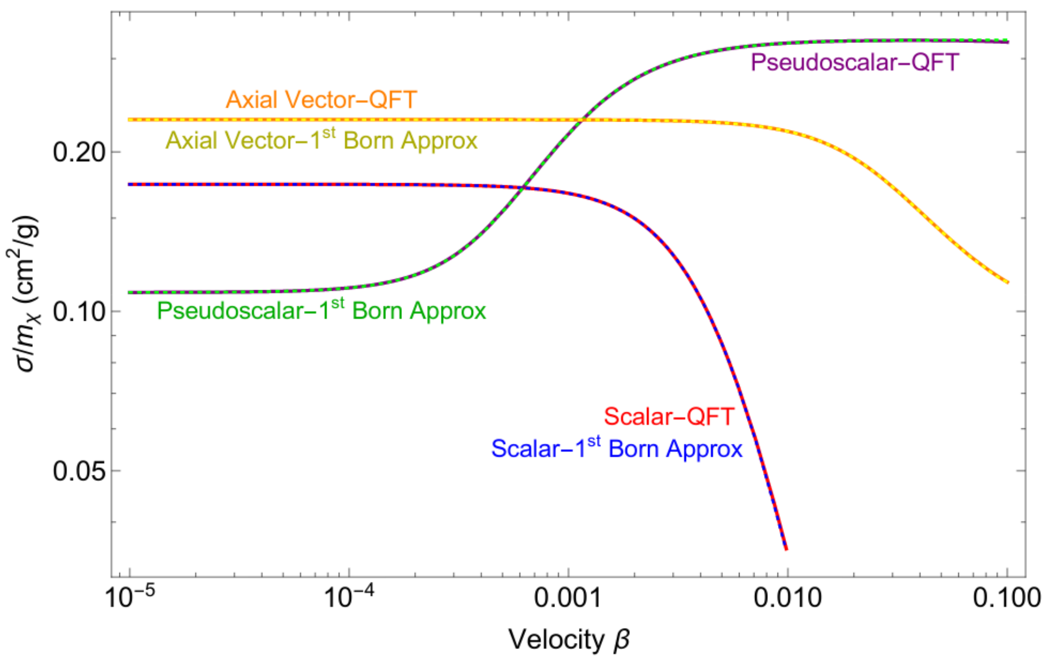
Velocity-dependent self-interactions

- Several recent studies classify DM self-interactions in terms of velocity dependence

Effective range formalism
Chu et al., arXiv:1908.06067



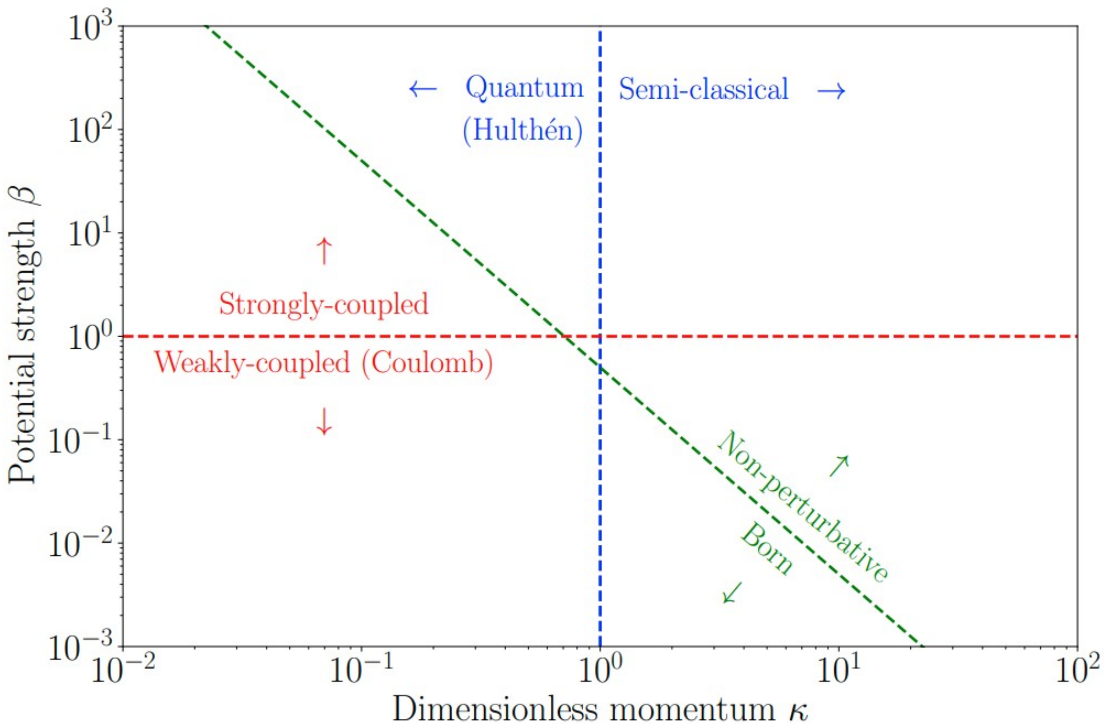
Effective Theory of SIDM
Agrawal et al., arXiv:2003.00021



- At first sight, the number of possible DM models is overwhelmingly large
- In the non-relativistic limit only a few different types of interactions are possible

The semi-classical regime

- Particularly interesting: Strong potential with contribution from many partial waves
- Quantum effects are subdominant → semi-classical treatment possible
- Results from “dusty” plasmas can be adapted to the case of elementary particles
- New analytical treatment accurately reproduces numerical results



Colquhoun, FK et al., arXiv:2011.04679

$$\sigma_V^{\text{even}} m_\phi^2 \approx \frac{8\pi}{\kappa^2}\int_0^\infty d\ell \, \frac{(2\ell)(2\ell+1)}{4\ell+1}\sin^2 2\delta'(2\ell)$$

$$\approx \frac{2\pi}{\kappa^2}\int_{1/2}^\infty d\ell \, \ell \sin^2 2\delta'(\ell - 1/2)\,,$$

$$\sigma_V^{\text{odd}} m_\phi^2 \approx \frac{8\pi}{\kappa^2}\int_0^\infty d\ell \, \frac{(2\ell+1)(2\ell+2)}{4\ell+3}\sin^2 2\delta'(2\ell+1)$$

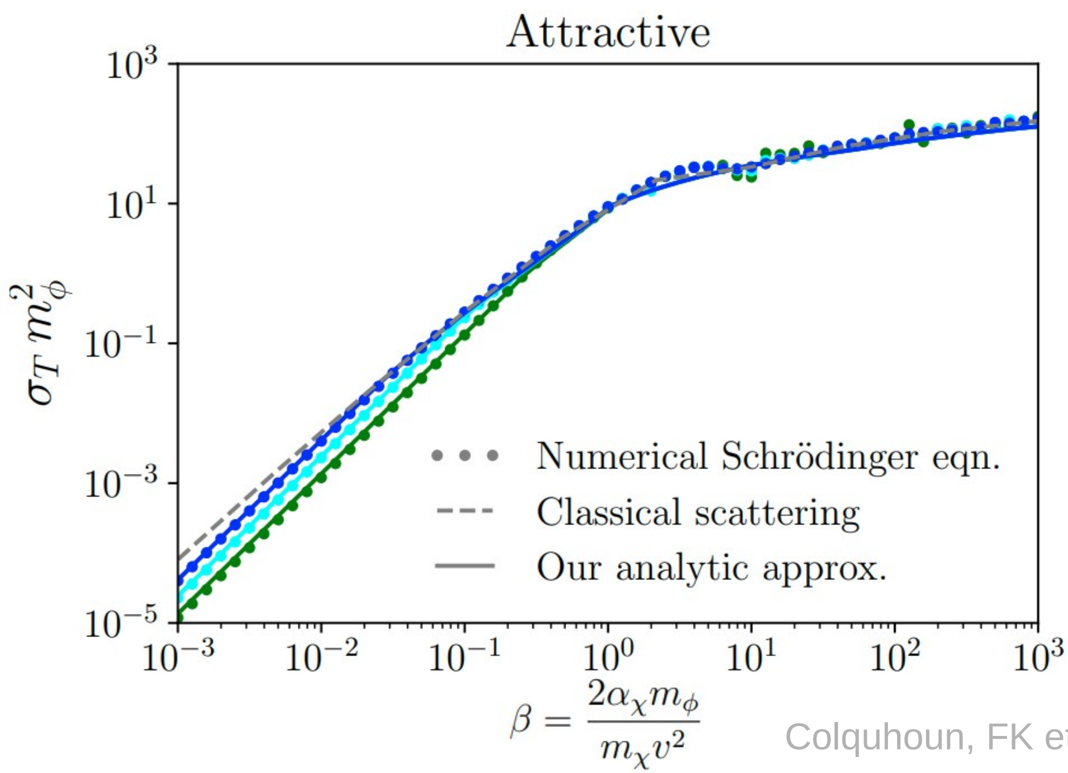
$$\approx \frac{2\pi}{\kappa^2}\int_{3/2}^\infty d\ell \, \ell \sin^2 2\delta'(\ell - 1/2)\,.$$

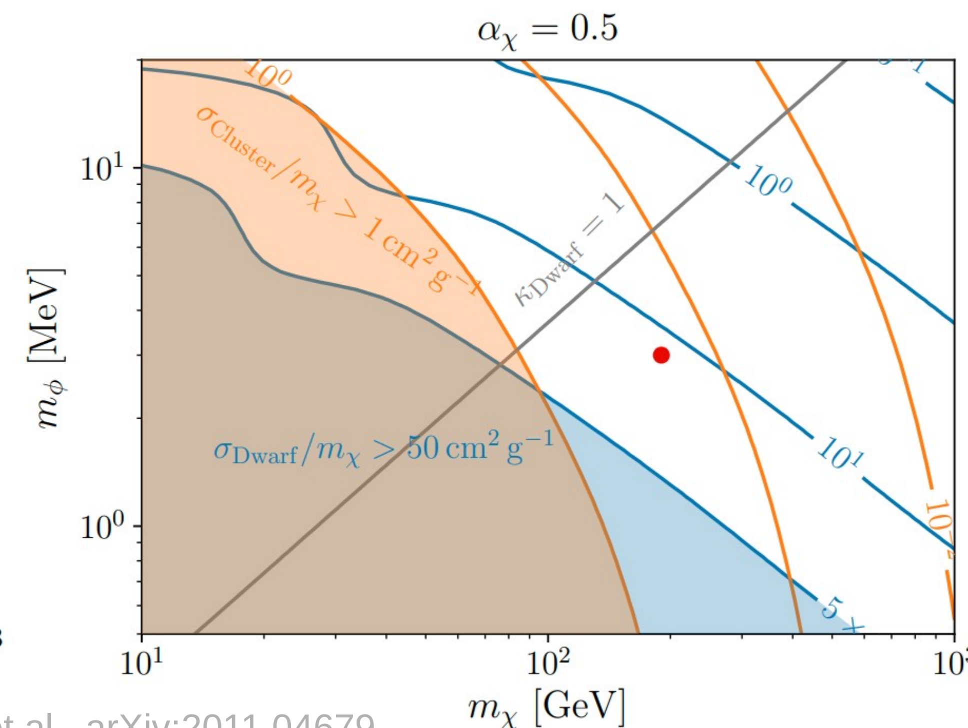
Example: Yukawa potential

- Simplest case: Yukawa potential arising from the exchange of a light mediator

$$U(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

- Required velocity dependence achieved for MeV-scale mediator mass





Colquhoun, FK et al., arXiv:2011.04679

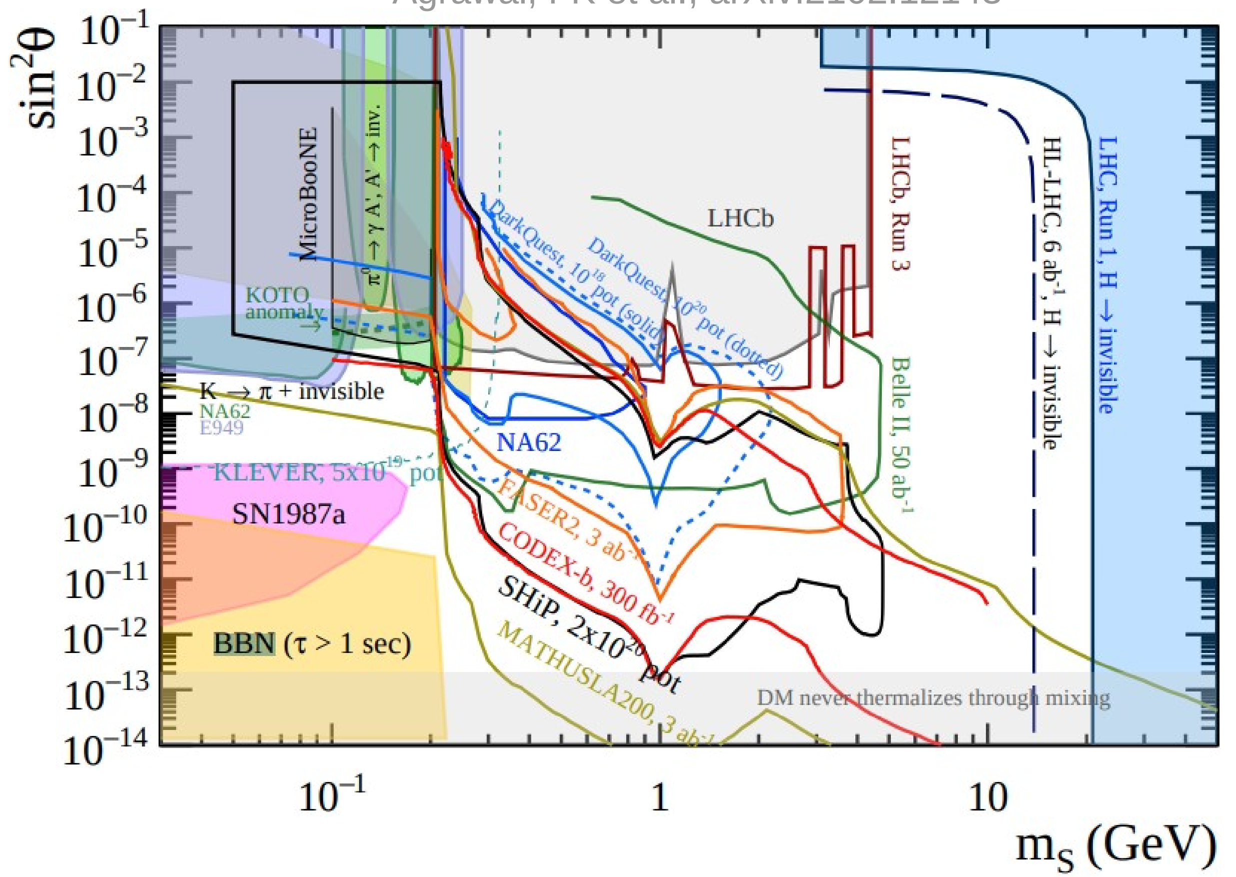
Experimental implications: Intensity frontier

- An MeV-scale mediator should have sizeable SM couplings to ensure decays before the beginning of BBN (~1s after Big Bang)

- Great wealth of possible search strategies!
  - B factories
  - Beam dumps
  - Rare decays

- Relevant constraints also from astrophysics
  - Cooling of horizontal branch stars
  - Supernova 1987a

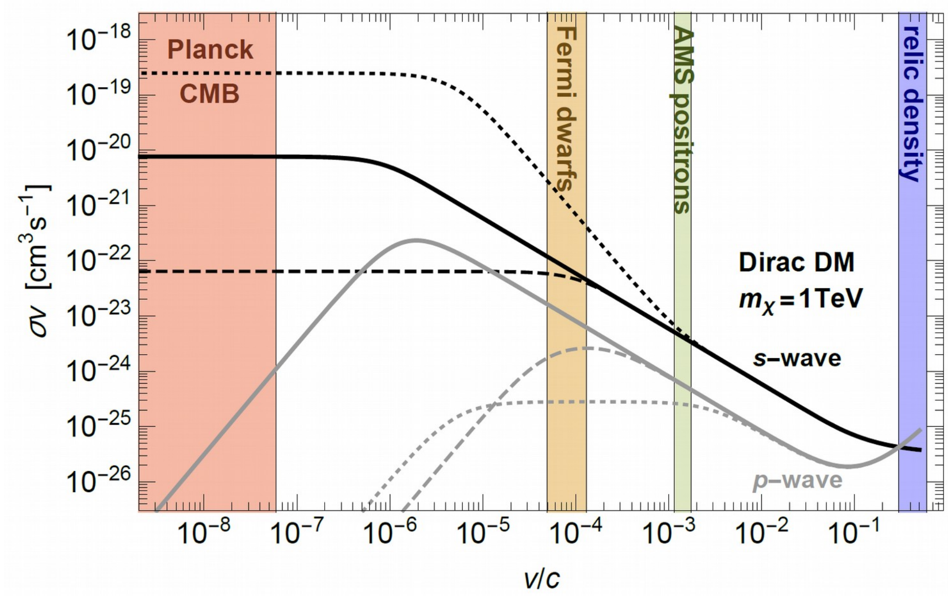
Agrawal, FK et al., arXiv:2102.12143

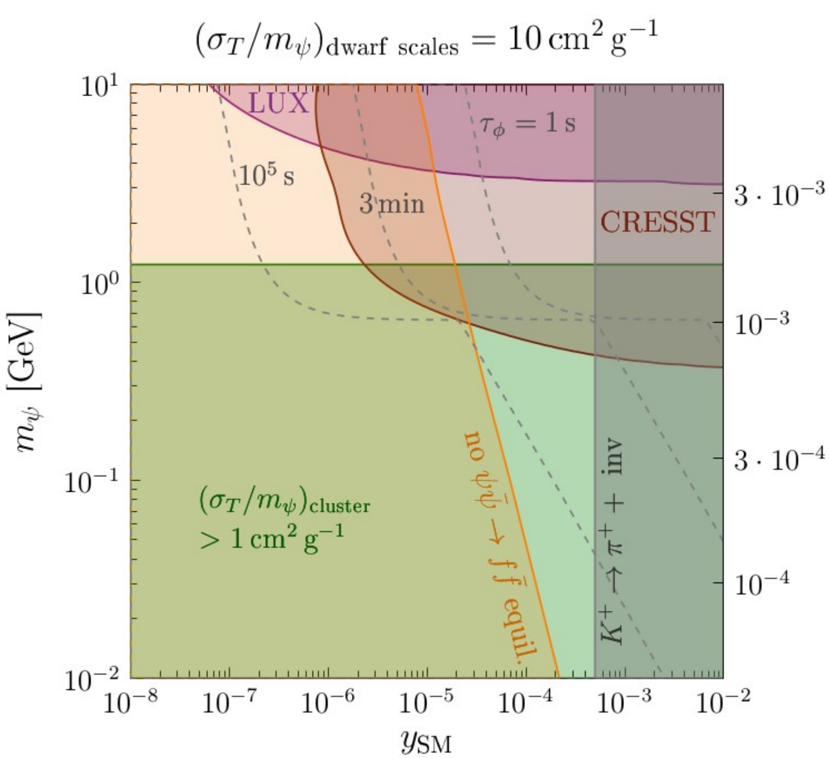


Challenges for self-interacting dark matter

- The simplest models of light mediators don't work!
  - For vector mediators DM annihilations receive strong Sommerfeld enhancement
    - → Late-time energy injection spoils the excellent agreement between predicted and measured CMB

Bringmann, FK et al., arXiv:1612.00845





  - For scalar mediators it is very challenging to achieve short lifetimes
    - → Tension between direct detection and BBN constraints

FK, et al., arXiv:1704.02149

New avenues

- The simplest picture of DM self-interactions can be modified in many ways:
  - Mediator of DM self-interactions violates CP

    FK, et al., arXiv:1704.02149

    → Interesting implications for for flavour physics and electric dipole moments
  - DM self-interactions proceed via inelastic excitations (Pseudo-Dirac DM)

    Blennow et al., arXiv:1612.06681

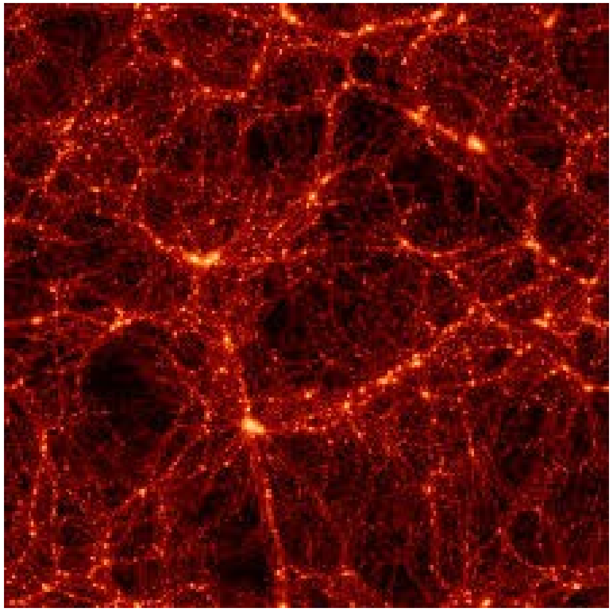
    → Deexcitations can lead to displaced vertices in searches for long-lived particles
  - Mediators can decay into additional invisible particles (dark radiation)

    Bringmann, FK et al., arXiv:1803.03644

    → Exciting signatures in missing-energy searches and neutrino factories
- Alternatively, constraints can be evaded by assuming that the DM particles never enter into thermal equilibrium (freeze-in mechanism)

  March-Russell et al., arXiv:2007.14688

A closer look: N-body simulations



- Analytical approximations insufficient to study systems far away from equilibrium, e.g. merging galaxy clusters

  → require N-body simulations

- **Problem:** Typical simulation "particles" are about 60 orders of magnitude heavier than elementary particles

- For a cold and collisionless fluid, it is sufficient to simulate a representative phase space sample

- For baryons, there is an enormous wealth of sub-grid physics, which can only be captured in an effective description (smoothed particle hydrodynamics)

- Similar approach needed for SIDM, but model-dependent implementation required

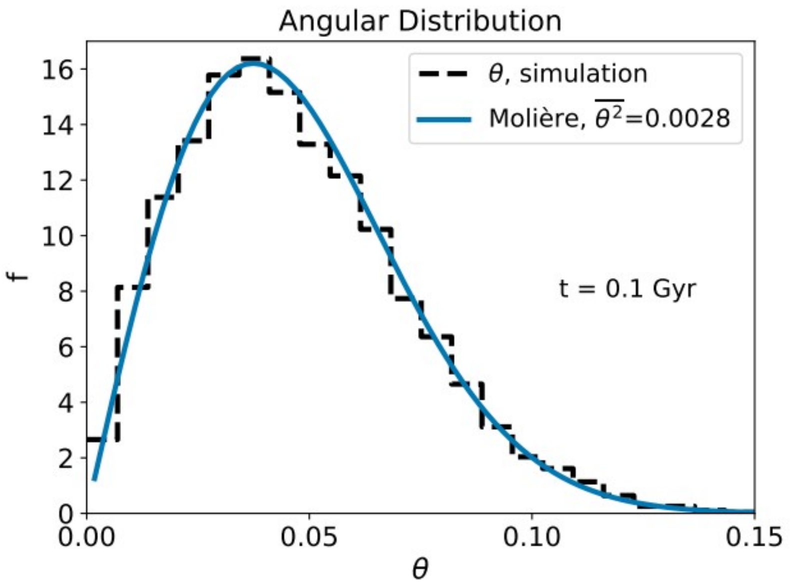
Frequent self-interactions

- If DM self-interactions are very frequent, they result in an effective drag force

$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{\tilde{\sigma}}{4\, m_{\rm DM}} \rho\, v_0^{2m}$$

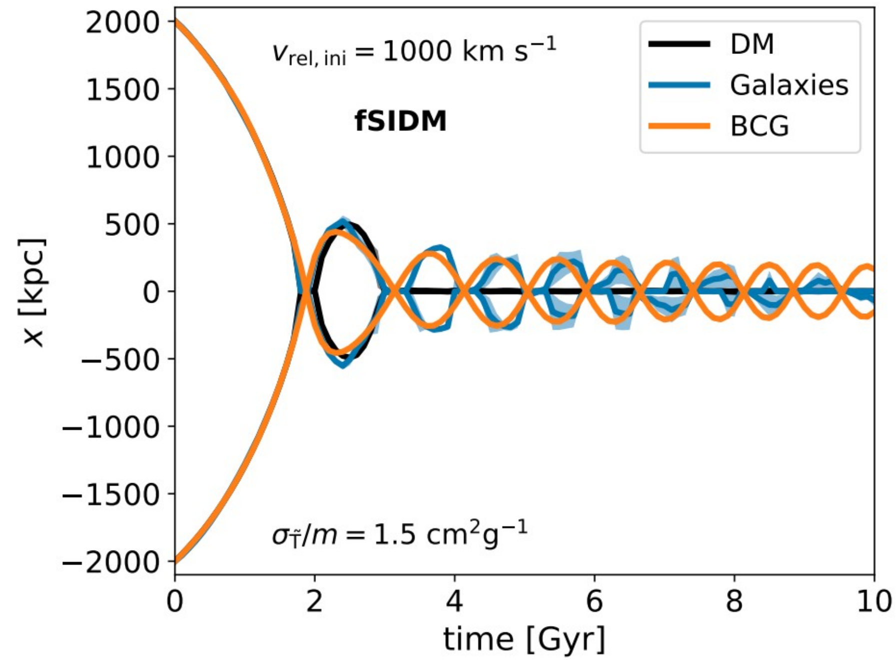
- Well motivated examples are $m = 1$ (like ram pressure) and $m = -1$ (like dynamical friction)
- Naive inclusion of drag force in numerical simulations leads to energy loss and halo collapse
- Need to re-inject energy in the form of random motion
- This approach can be consistently implemented in N-body simulations

Fischer, FK et al., arXiv:2012.10277

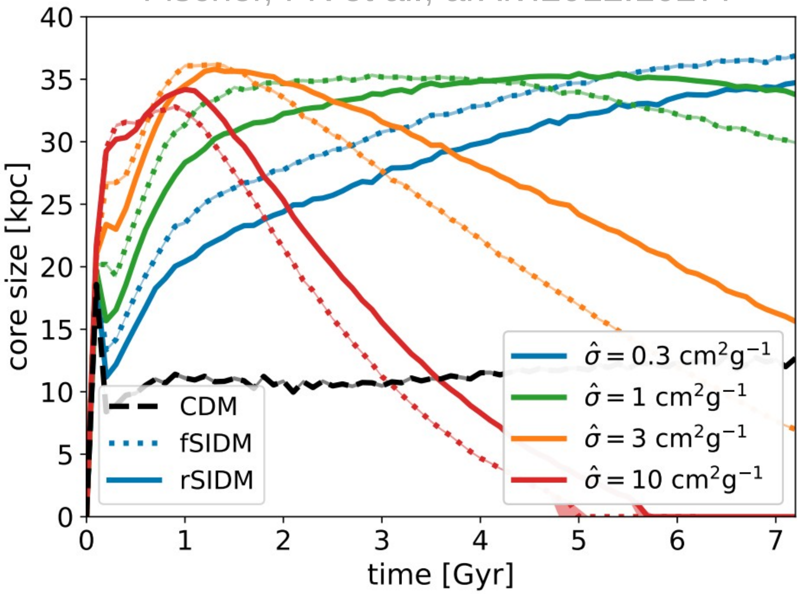


Many interesting applications

- Evolution of merging galaxy clusters
  - Separation between DM and galaxies
  - Deformation of DM haloes
  - “Wobbling” of the Brightest Cluster Galaxy



Fischer, FK et al., arXiv:2012.10277



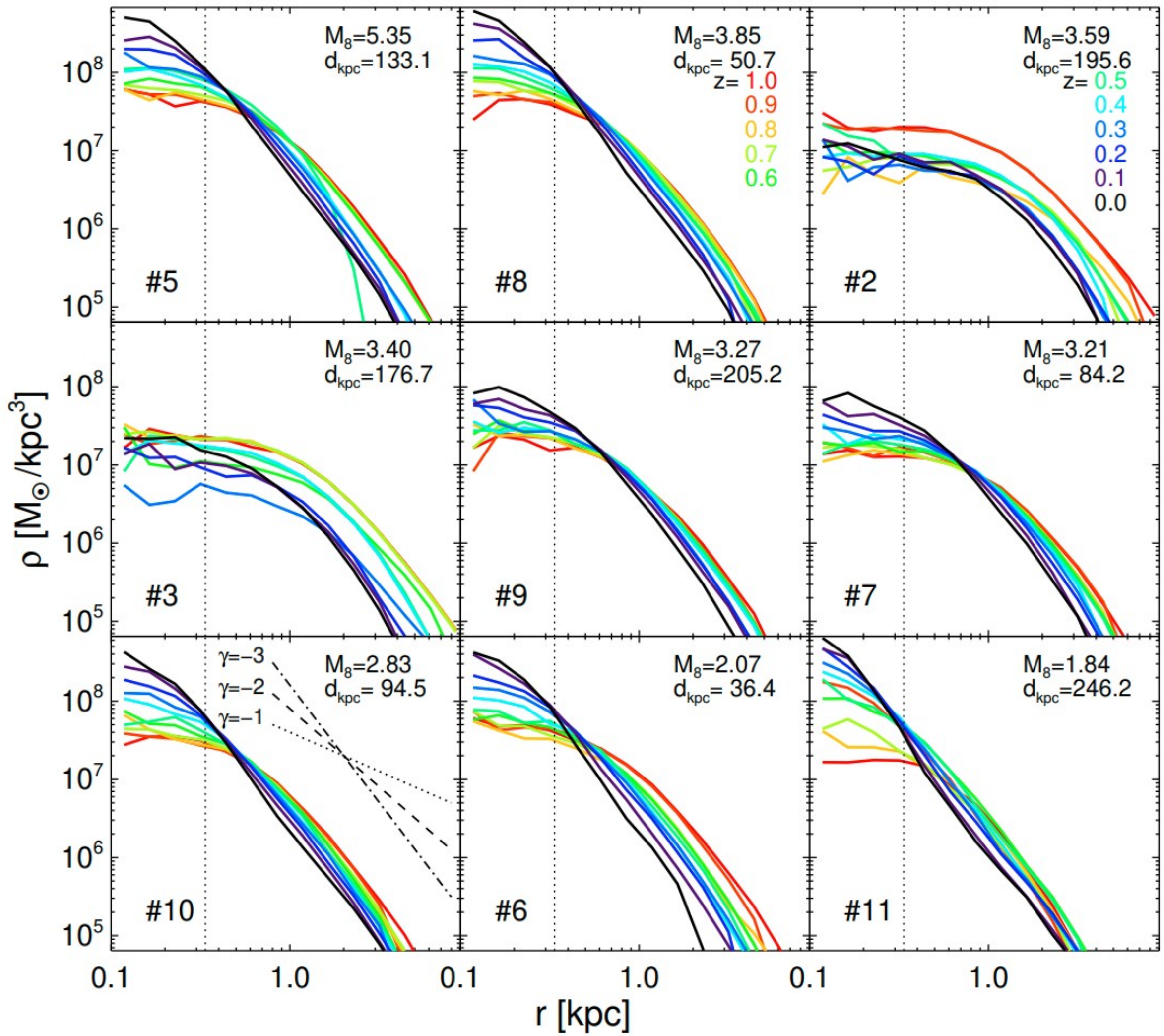
- Evolution of constant-density cores
  - Time dependence of core size
  - Core stability

Core collapse

- Cores created by DM self-interactions are not stable
- Once the inner region is fully thermalised, the direction of the heat flow reverses and the central region starts cooling down
- At late times (or for very large cross sections) cores experience gravitational collapse and cusps reappear

→ gravothermal catastrophe

Turner et al., arXiv:2010.02924



Gravothermal fluid formalism

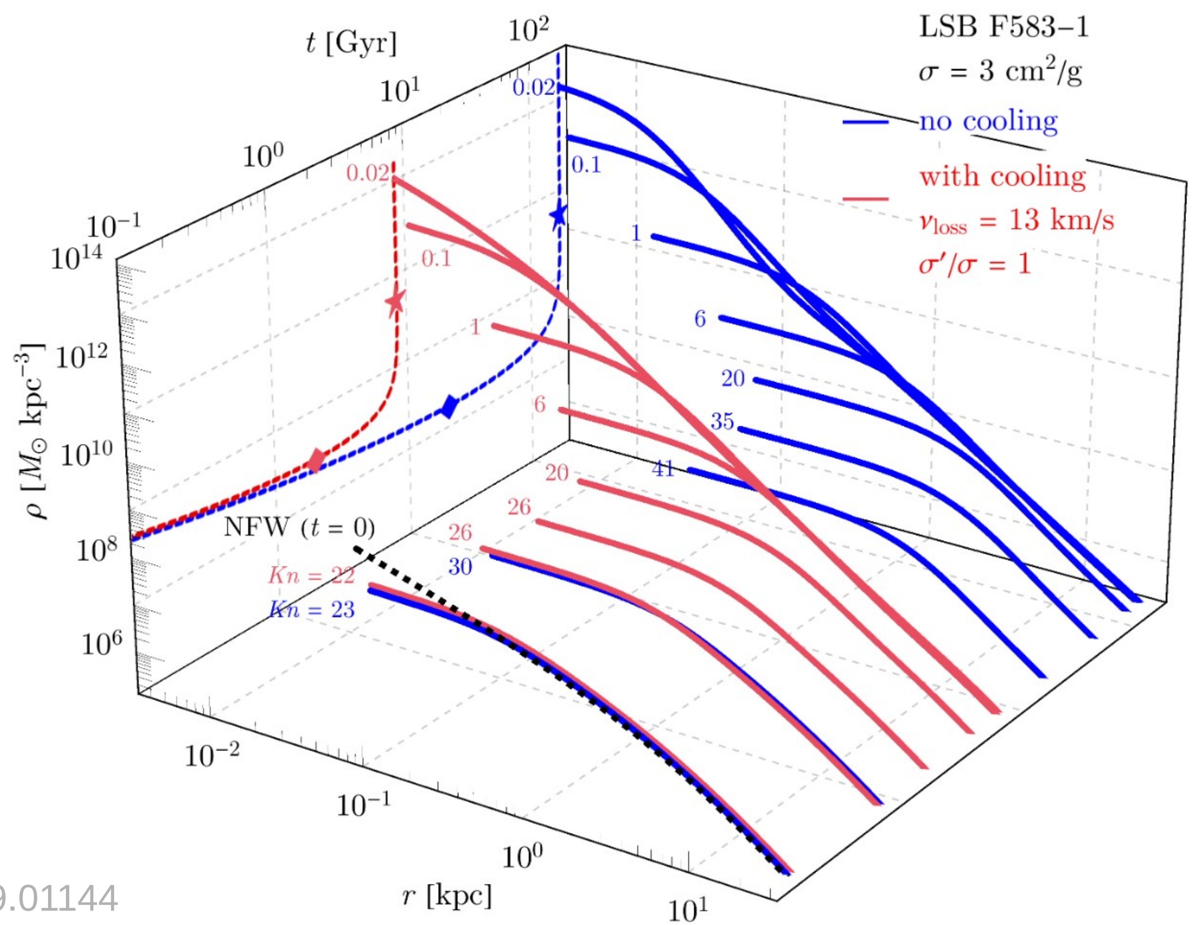
- In the central region DM self-interactions become so frequent that they are difficult to resolve with numerical simulations
- Alternative approach: Describe DM as self-gravitating fluid with conductivity κ

$$\frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r} = -\kappa' \frac{\partial \nu^2}{\partial r}$$

and solve resulting system of partial differential equations

Balberg et al., 2002

- Conclusion: For isolated DM halos core collapse does not occur within the age of the universe



Essig et al., arXiv:1809.01144

The impact of tidal forces

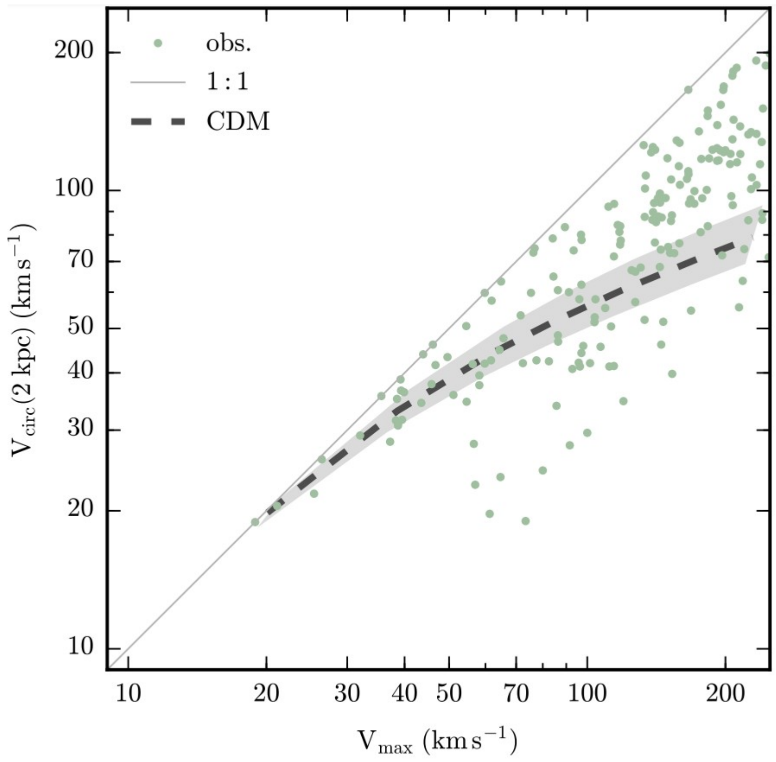
- Tidal forces (e.g. from a nearby galaxy) can strip the outer parts of a DM halo
- Such a stripping increases the heat loss and accelerates core collapse

Nishikawa et al., arXiv:1901.00499

- High-density halos become even denser, while low-density halos are disrupted
- Milky Way satellites that come closer to the Galactic centre experience stronger tidal forces
- Density of a halo depends on its trajectory
- Possible explanation of the observed diversity of MW satellites

Sameie et al., arXiv:1904.07872; FK et al., arXiv: 1904.10539

- Many predictions can be tested with Gaia data!



Conclusions

- Dark matter may be quite different from a perfectly cold and collisionless fluid
- Self-interactions lead to a range of astrophysical effects that may resolve (part of) the small scale crisis of the CDM paradigm
- Relevant cross section scale points towards new physics at the MeV scale
- Detailed observations of core sizes point to velocity-dependent self-interactions
- Possible explanation in the semi-classical regime: MeV-scale mediator
- N-body simulations including DM self-interactions enable more detailed studies
  - Major mergers
  - Core collapse
  - Tidal forces