Solving the core-cusp problem with Fermi pressure

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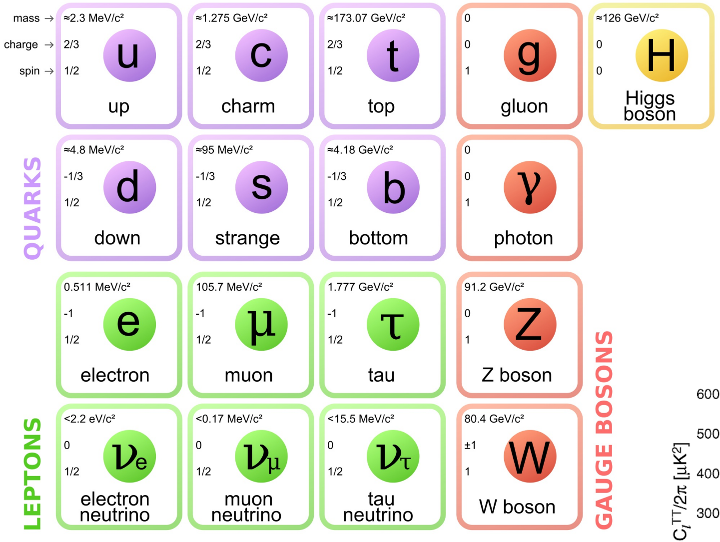
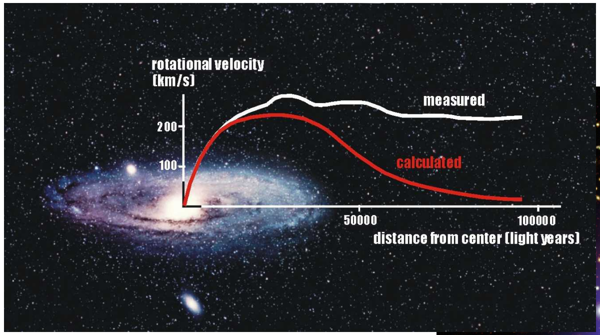
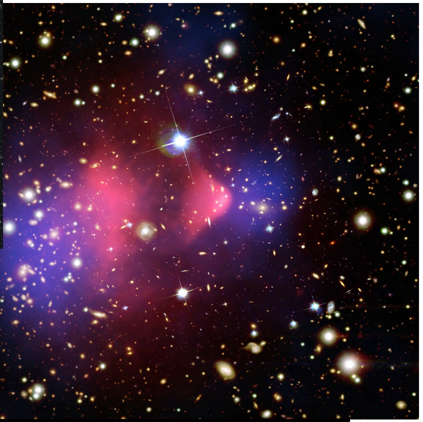
2019 TeV physics workshop

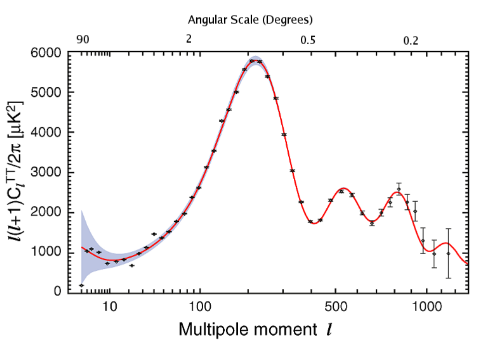
with Ran Huo and Wanqiang Liu, 1812.05699, 19XX,XXXXX

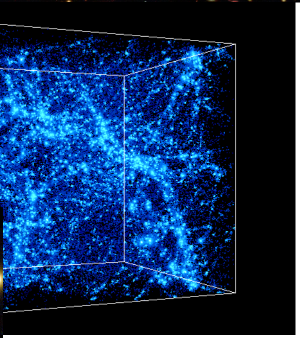
Evidences for dark matter

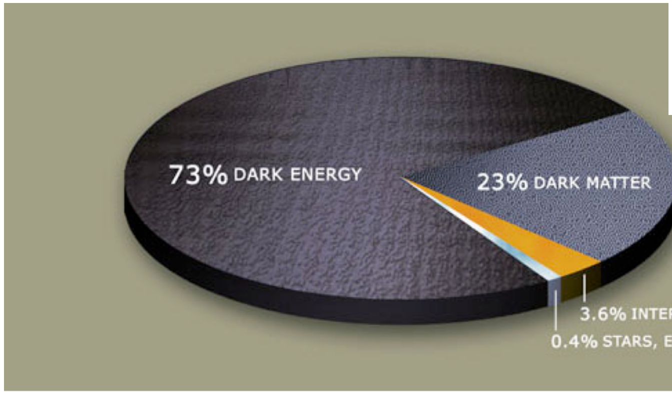


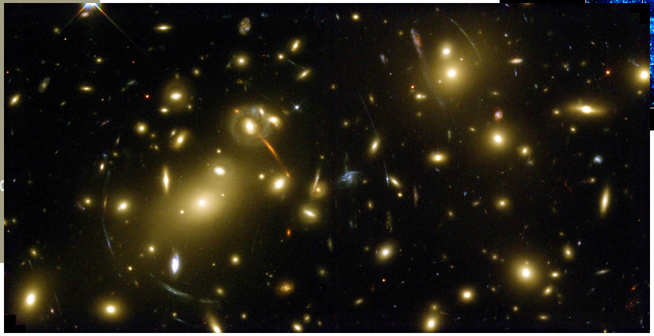




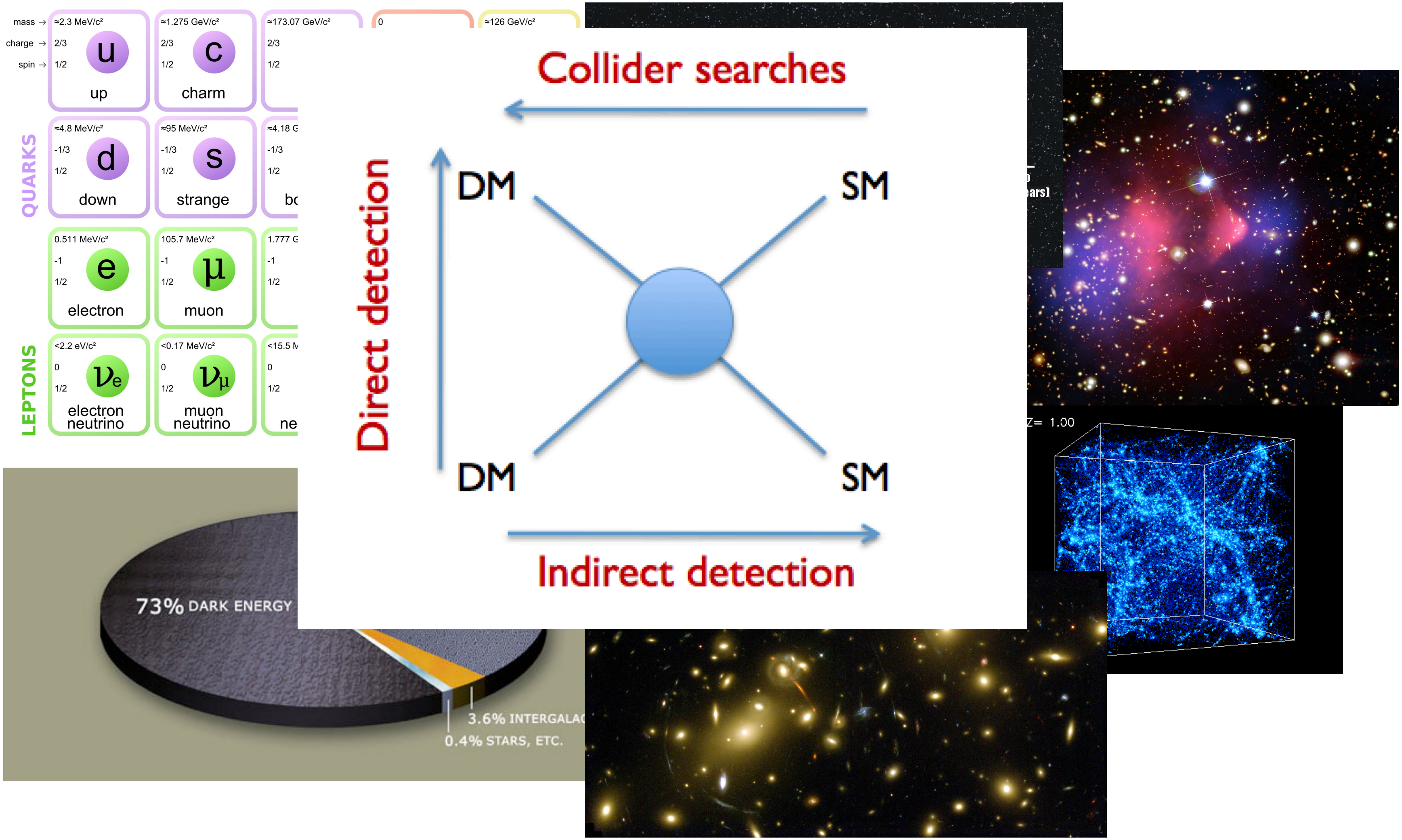






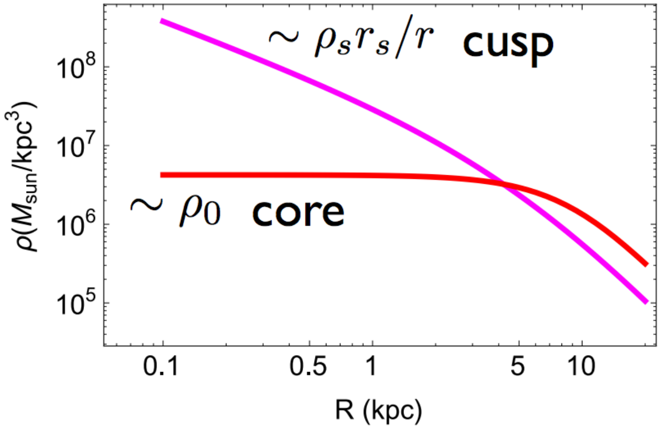


Evidences for dark matter



The core-cusp problem in dwarf galaxies

- DM only simulations show that the DM density at the center of dwarf galaxies are cusp like.
- What observed are core-like.



Dubinski, Carlberg, ApJ 378, 496 (1991)
Navarro, Frenk, White, ApJ 461, 563 (1996)
Navarro, Frenk, White, ApJ 490, 493 (1997)
Flores, Primack, ApJ 427, L1 (1994)
Moore, Nature 370, 629 (1994)
Moore et al., MNRAS 310, 1147 (1999)

- A chance to study the particle nature of DM.

Ideas of solving the core-cusp problem

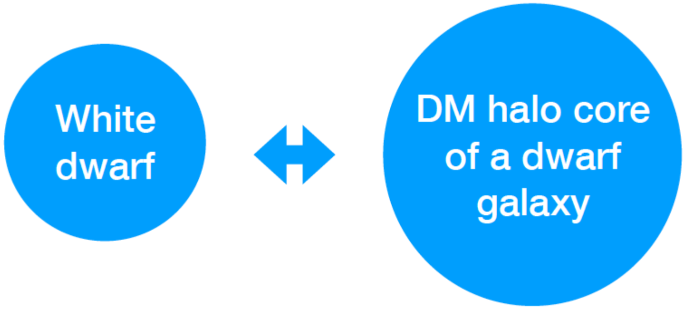
- Baryonic feed back
  - Supernova explosions can non adiabatically decrease the gravitational potential at the center of galaxies.

- Self-interaction DM
  - Kinetic energy from outside the center can be transferred into the center through self-interaction

- Fuzzy DM
  - Compton wavelength is comparable to the size of dwarf galaxies

With Fermi pressure

- Fermionic DM cannot be too light. (The Tremaine-Gunn bound) Tremain, Gunn, PRL 42, 407 (1979)



White dwarf

DM halo core of a dwarf galaxy

- If it is too heavy, we may have the core-cusp problem.
- At some mass range the core-cusp problem of cold DM can be solved.

With Fermi pressure

- Dwarf galaxy:
  - 10^8 solar mass
  - Core size 500 pc
  - V ~ 10^{-4}
- $70 \text{ eV} < m_D < 400 \text{ eV}$

  L. Randall, J. Scholtz, J. Unwin, Mon. Not. Roy. Astron. Soc. 467, no. 2, 1515 (2017)
- $245 \text{ eV} < m_D < 305 \text{ eV}$

  B.G.Glimore, R. Peschanski, arXiv:1806.07283

Lyman-alpha bound

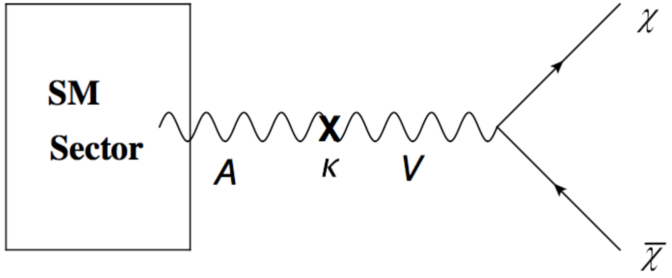
- Lyman-alpha observation measures the structure of the universe
  - The lower bound for sterile neutrino warm DM assuming thermal distribution is 5.1 keV (3.5 keV if assuming a non-standard thermal history).
  - It corresponding to a free-streaming length of about 0.02 Mpc.

- A successful model has to alleviate this bound

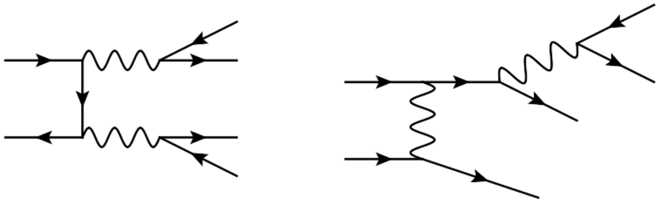
From 5.1 keV to 200~ 400 eV !!

A freeze-in model

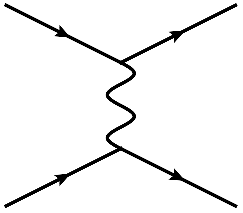
- Freeze-in through kinetic mixing



- Self-replication lowers the temperature

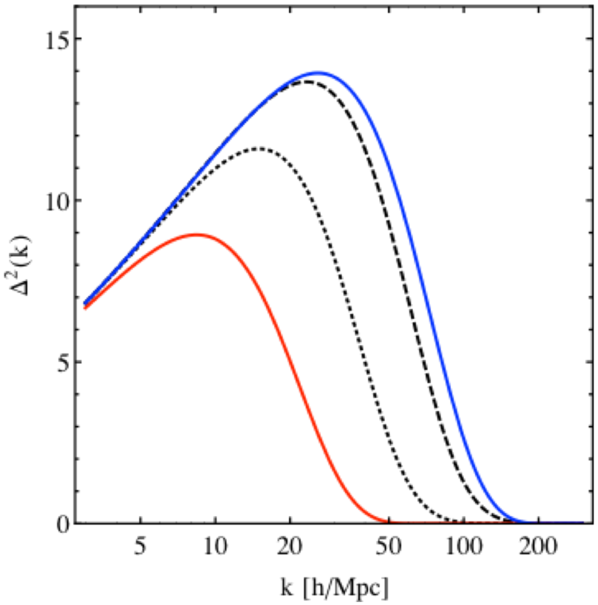


- Self-scattering turns free-streaming into Brownian motion



Alleviate the Lyman-alpha bound

- Scattering turns free-streaming into Brownian motion, migration distance much shorter.



CAMB simulation result

– – – – 5.1 keV WDM $\lambda_{\rm fs} \sim 0.02\ \text{Mpc}$

------- 3.5 keV WDM

🟥 $m_D = 1\ \text{keV},\ \sigma_T/m_D = 0.1\ \text{cm}^2/\text{gram}$

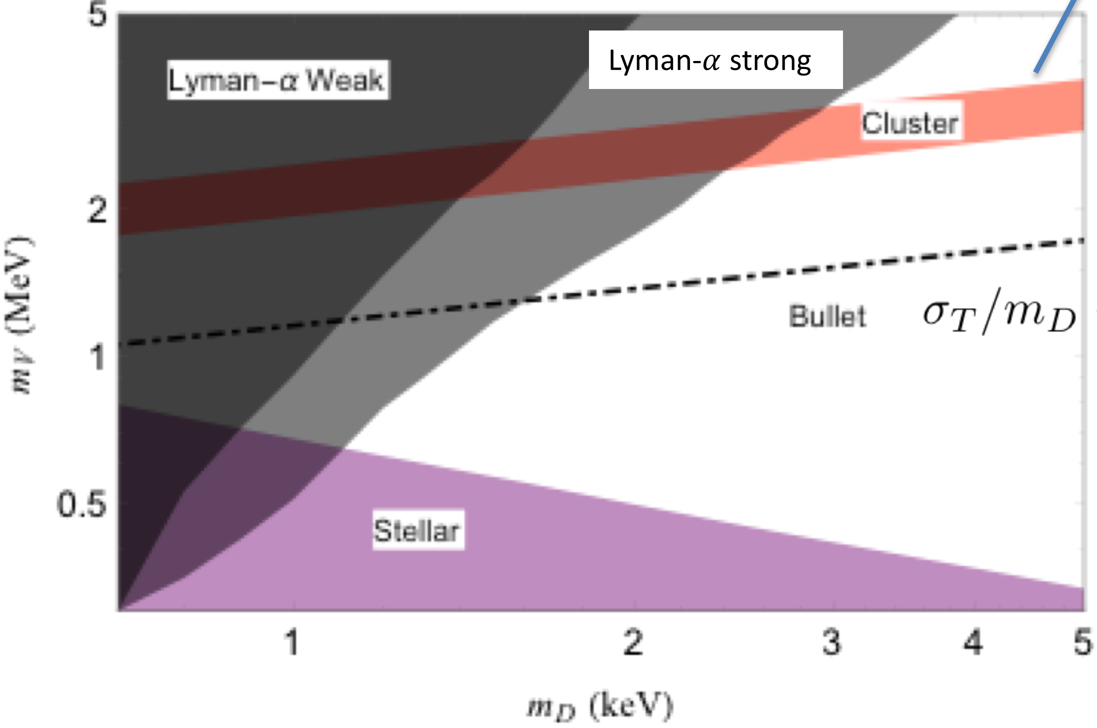
🟦 $m_D = 3\ \text{keV},\ \sigma_T/m_D = 0.1\ \text{cm}^2/\text{gram}$

Bound from cluster DM distribution

Numerical result

HA, Ran Huo and Wanqiang Liu, 1812.05699

$$0.06\ \mathrm{cm}^2/\mathrm{gram} < \sigma_T/m_D < 0.16\ \mathrm{cm}^2/\mathrm{gram}$$



$$\sigma_T/m_D < 1.25\ \mathrm{cm}^2/\mathrm{gram}$$

$$\kappa = \tilde{\kappa}(\alpha_D, m_V) \times \left(\frac{m_D}{200\ \mathrm{eV}}\right)^{-2/3}$$

Numerical results

- With self-scattering

5.1 keV → 2.5 keV

3.5 keV → 1.5 keV

- The core is too small (about 10~20 parsec).

Can we avoid the Lyman-alpha constraints?

- Even $T_D = 0$, the fermions still propagate due to its non-degenerate nature.

- For 200~400 eV DM, we can show that even we assume $T_D = 0$ in the radiation dominated era, it is still in conflict with the Lyman-alpha constraint.

- If we want such light DM, in the early universe its energy must be carried by bosons, which later decay into fermions.

Scalar decay scenario

- The model:

Scalar field ϕ: a scalar field produced in the early universe through misalignment.

Fermionic field χ: the dark matter

Fermionic field ψ: the dark radiation

$$m_\phi \approx m_\chi \ , \quad m_\psi \approx 0$$

$\phi \rightarrow \chi + \psi$ during the structure formation

Scalar (moduli) decay scenario

- The model:

Scalar field ϕ: a scalar field produced in the early universe through misalignment.

Fermionic field χ: the dark matter

Fermionic field ψ: the dark radiation

$$m_\phi \approx m_\chi \ , \quad m_\psi \approx 0$$

$\phi \rightarrow \chi + \psi$ during the structure formation

$$m_\phi - m_\chi \ll m_\phi \approx m_\chi$$

- Supersymmetry can be used to make this scenario natural.

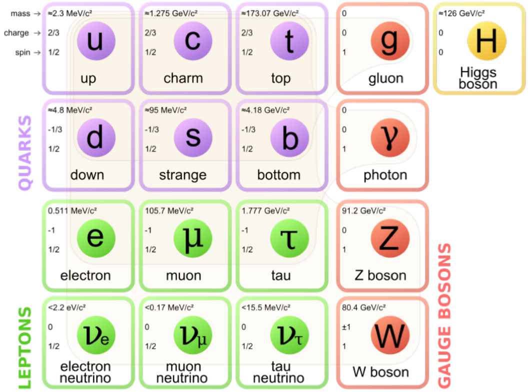
(work in progress)

Summary

- With self-scattering, we can alleviate the Lyman-alpha constraints on warm matter from 5.1 keV (3.5 keV) to 2.5 keV (1.5 keV).

- Scalar decay model may save the idea of using the Fermi pressure to solve the core-cusp problem.

The theory



QED

Dirac fermion, the DM candidate

$$\bar{\chi}(i\gamma^\mu D_\mu - m_D)\chi$$

Connecting the DM to the SM sector

$$-\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V^2$$

$$-\frac{\kappa'}{2}B^{\mu\nu}V_{\mu\nu}$$

Spontaneous symmetry breaking

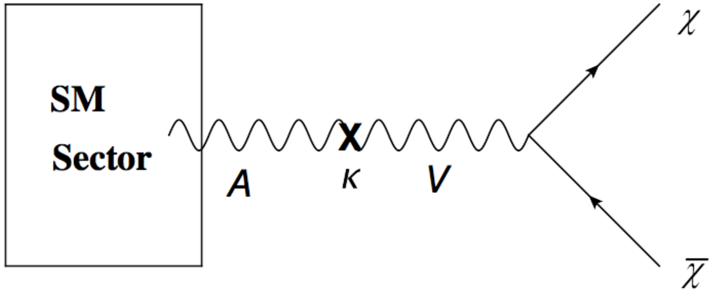
$$-\frac{\kappa}{2}F^{\mu\nu}V_{\mu\nu}$$

$$\mathcal{L} = \mathcal{L}_{\text{QED}} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \bar{\chi}(\gamma^\mu D_\mu - m_D)\chi$$

$$m_D \sim \ 1 \text{ keV} \ , \quad m_V \sim 1 \text{ MeV} \ , \quad \alpha_D \sim \alpha_{\text{EM}} \ , \quad \kappa \sim 10^{-11}$$

Freeze-in mechanism

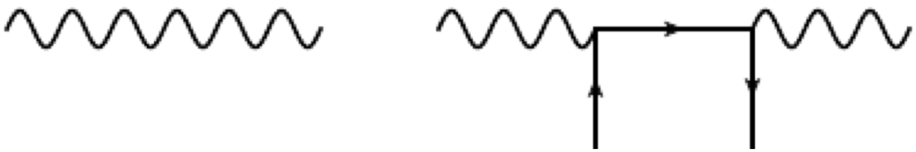
L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West,
JHEP 1003, 080 (2010) doi:10.1007/JHEP03(2010)080



1. $e^+e^- \rightarrow \chi\bar{\chi}$

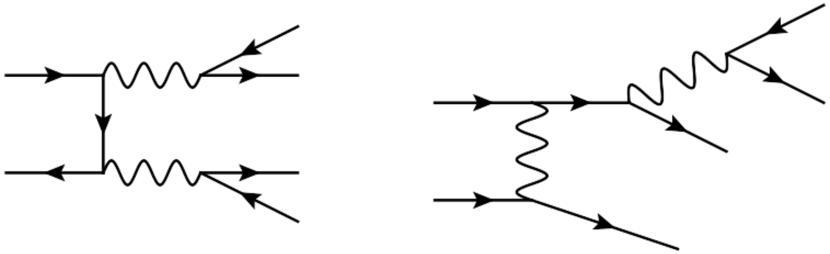
2. Plamson decay

Photon gets a “mass”



Dark sector cools down through self-replication

- 2 to 4 self-replication processes



- If self-replication is fast enough, the DM can be seen as a thermal relic. (warm dark matter)

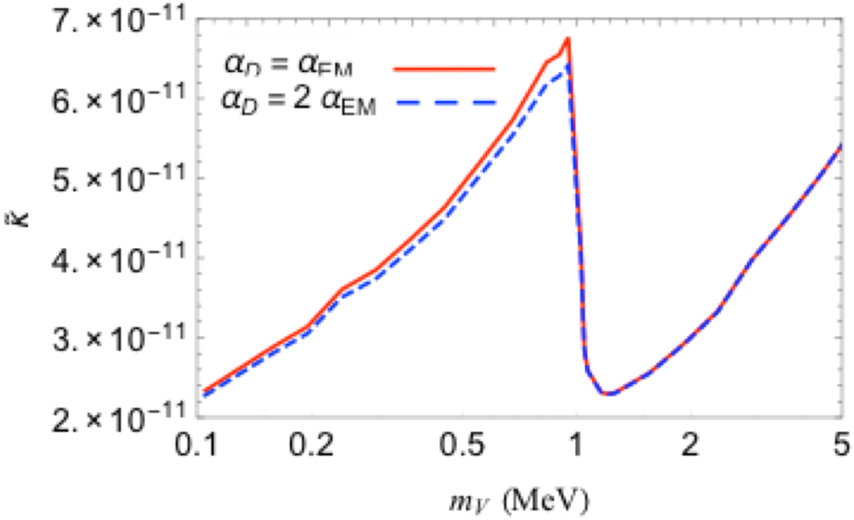
$$f(E) = \frac{g_D}{1 + \exp(E/T_D)}$$

$$\frac{T_D}{T} \sim \left(\frac{10\eta_\gamma m_p}{3m_D}\right)^{-1/3} \approx 0.3 \times \left(\frac{m_D}{1\ \mathrm{keV}}\right)^{-1/3}$$

Relic abundance

- Boltzmann equation $$\frac{d\rho_\chi}{dt} + 4H\rho_\chi = \Gamma^{\rho\chi}_{e^\pm} + \Gamma^{\rho\chi}_R$$

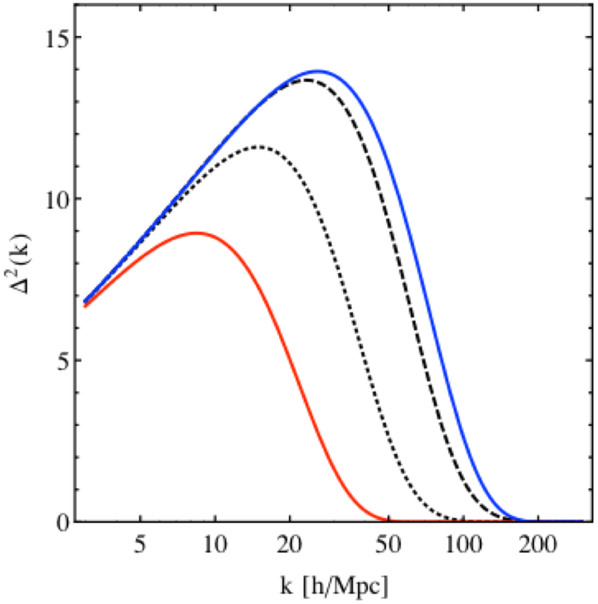
$$\kappa = \tilde{\kappa}(\alpha_D, m_V) \times \left(\frac{m_D}{200\ \mathrm{eV}}\right)^{-2/3}$$



Self scattering and Lyman-alpha bound

- Scattering turns free-streaming into Brownian motion, migration distance much shorter.

$$T_{\rm fs} \approx 1~{\rm eV} \times \left(\frac{\alpha_D}{\alpha_{\rm EM}}\right)^{-1} \left(\frac{T_D/T_{\rm SM}}{0.1}\right)^{-1/2} \left(\frac{m_V}{1~{\rm MeV}}\right)^{2}$$



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Cluster mass
deficit problem

Stellar constraints

- Red giant stars:
  - $T_C \approx 8.6\ \mathrm{keV}\ ,\ \ \omega_p \approx 20\ \mathrm{keV}$
  - Dark radiation < 10% of the luminosity

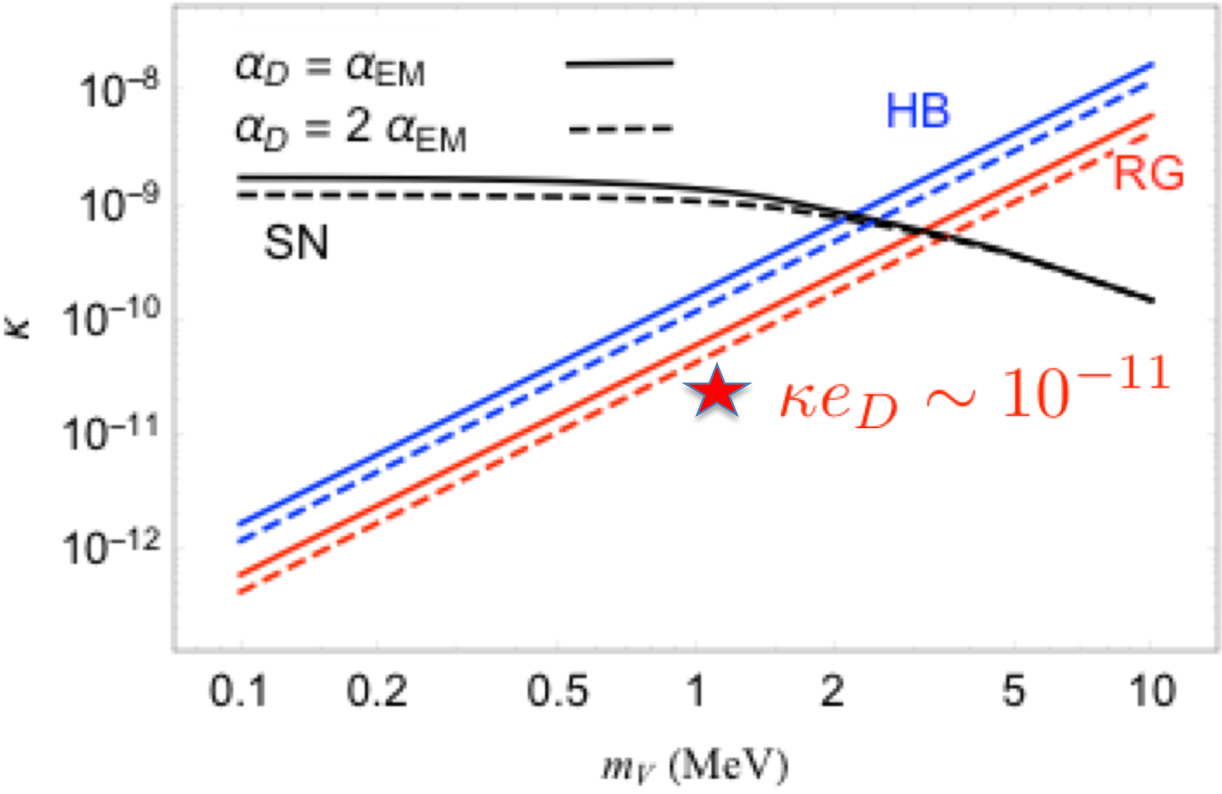
$$\Gamma_\chi \propto \left(\frac{\omega_p}{m_V}\right)^4$$

J. Redondo and G. Raffelt, JCAP 1308, 034 (2013)

- Supernovae
  - $T_C \approx 20\ \mathrm{MeV}\ ,\ \ \omega_p \approx 10\ \mathrm{MeV}$
  - Stronger constraint in large m_V region
  - We reinterpret the constraints on dark photon and milli-charged particles.

J. H. Chang, R. Essig, S. D. McDermott, arXiv:1803.00993

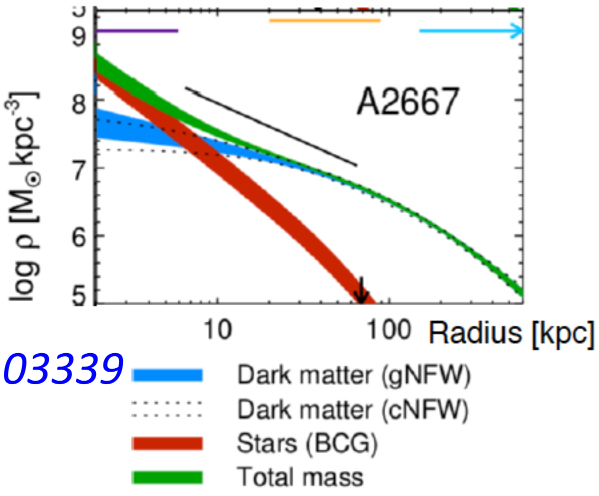
Stellar constraints



Cluster mass deficit

- Clusters (~ 100 kpc) has mass deficit in the inner 3 kpc compared to NFW.
  Newman et al. APJ 765, 25 (2013)

- Can be solved if DM has a self-interaction $\sigma_T/m_D \sim 0.1\ \mathrm{cm}^2/\mathrm{gram}$
  Kaplinghat et al.PRL 116, no.4 041302 (2016), 1508.03339

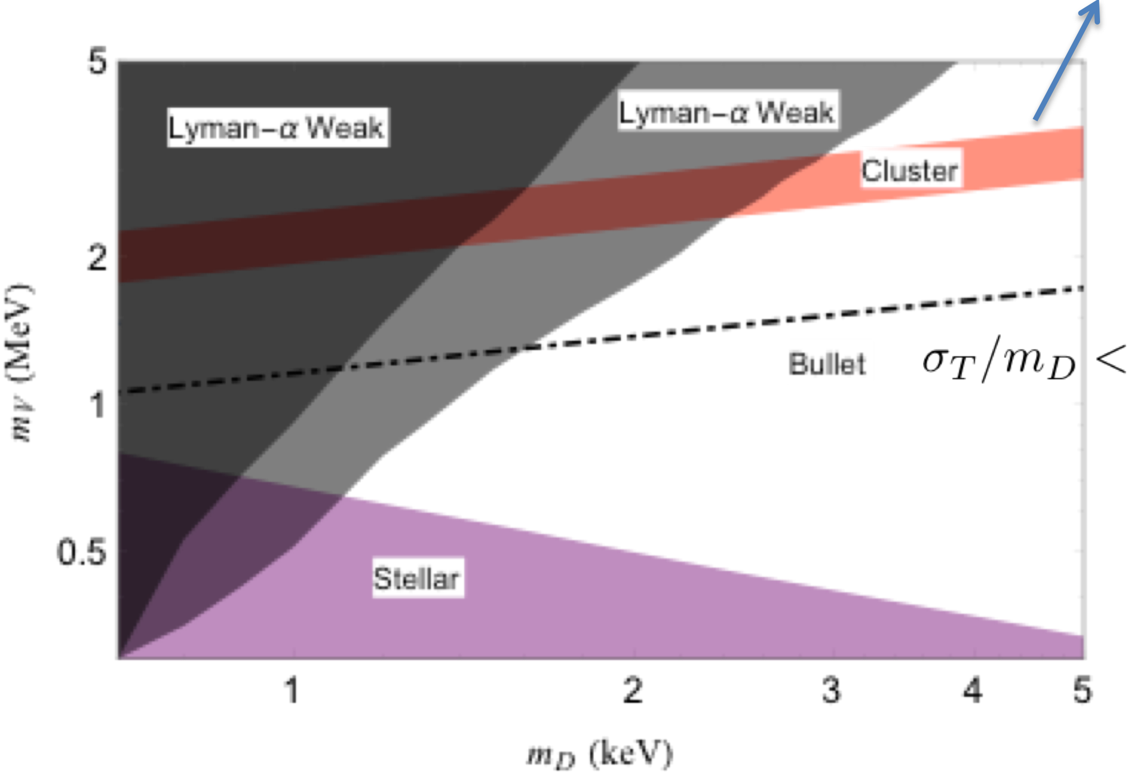


- Because of the effect of baryonic processes, observations of clusters alone cannot provide unambiguous support for DM theories. *Newman et al. APJ 765, 25 (2013)*

- $\sigma_T/m_D > 0.1\ \mathrm{cm}^2/\mathrm{gram}$ is disfavored.
  Elbert et al. 1609.08626

Numerical result

$0.06\ \mathrm{cm}^2/\mathrm{gram} < \sigma_T/m_D < 0.16\ \mathrm{cm}^2/\mathrm{gram}$



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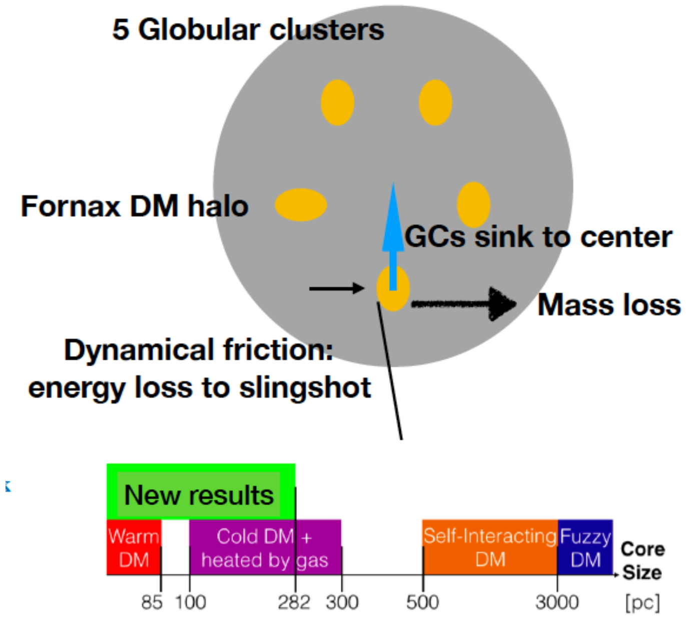
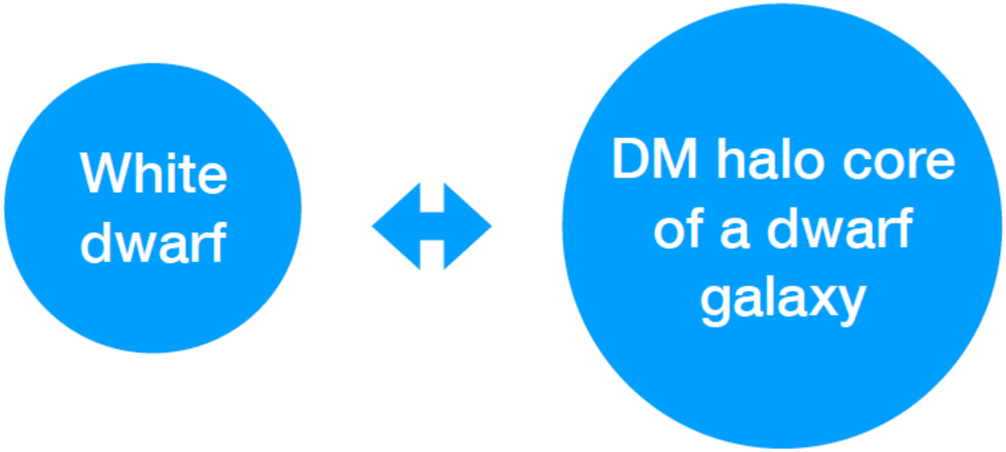
Recent debates on core-cusp problem

- Analysis of multi-tracers in the Fornax dSph: at 2sigma $0.2\ \mathrm{kpc} < r_c < 2.6\ \mathrm{kpc}$ *Amorisco et al. MNRAS 429 (2013) 89.*
- Study of the dynamical friction of the five globular clusters of Fornax shows $r_c < 0.282\ \mathrm{kpc}$ *Boldrini, Mohayaee and Silk, 1806.09591*
- There is a problem in the previous multi-tracer analysis that NFW like dwarfs can be mis-identified as cored.

Genina et al. 1707.06303



Fermionic core



White dwarf

↔

DM halo core of a dwarf galaxy

$$r_c \sim 40 \text{ pc} \times \left(\frac{m_D}{1.2 \text{ keV}}\right)^{-4/3} \left(\frac{\rho_c}{10^{-19} \text{kg}/\text{cm}^3}\right)^{-1/6}$$

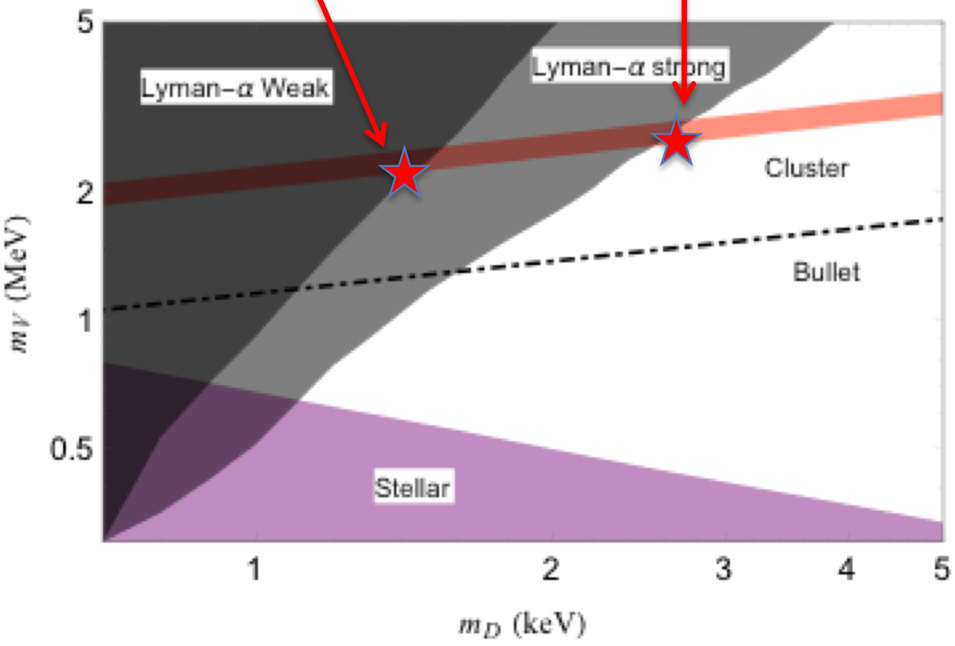
Numerical results

$m_D = 1.4$ keV

$r_c > 30 \sim 40$pc

$m_D = 2.2$keV

$r_c > 15 \sim 20$ pc



Summary

- We propose a freeze-in self-scattering warm dark matter model, which can generate the observed relic abundance.

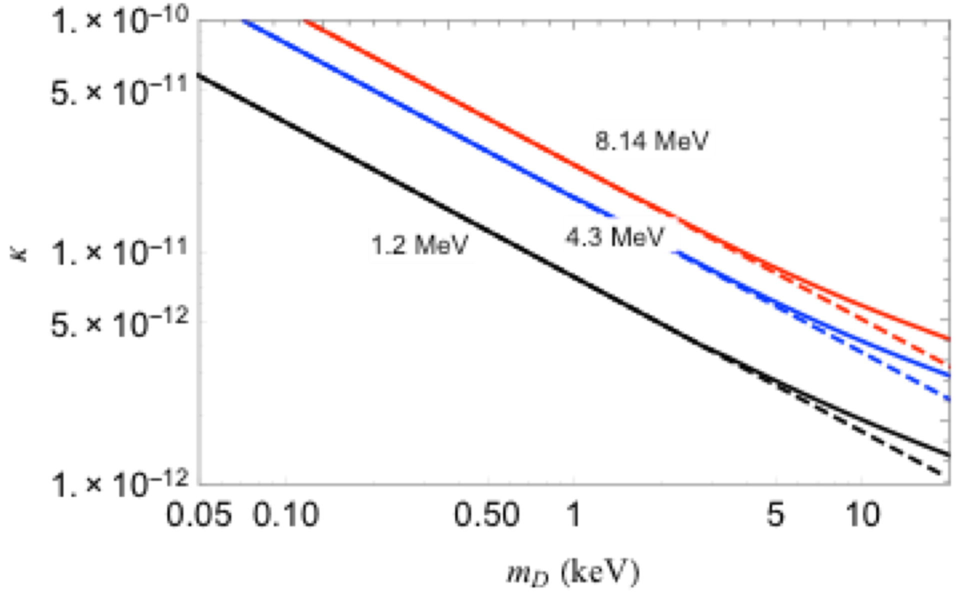
$$m_D \sim \ 1 \text{ keV} \ , \quad m_V \sim 1 \text{ MeV} \ , \ \ \alpha_D \sim \alpha_{\text{EM}}$$

- The self-scattering alleviates the Lyman-alpha constraints.

$$m_{\text{WDM}} > 5.1 \text{ keV} \ (3.5 \text{ keV}) \quad \Longrightarrow \quad m_D > 1.4 \text{ keV} \ (2.2 \text{ keV})$$

- At the region $m_D \sim 2 \text{ keV}$ and $\sigma_T / m_D = 0.1 \text{ cm}^2/\text{gram}$ this model predicts
  - A tiny core (~ 20 to 40 pc)
  - The matter power spectrum starts to drop at about 0.02 Mpc.

backups


1. × 10⁻¹⁰
5. × 10⁻¹¹
1. × 10⁻¹¹
5. × 10⁻¹²
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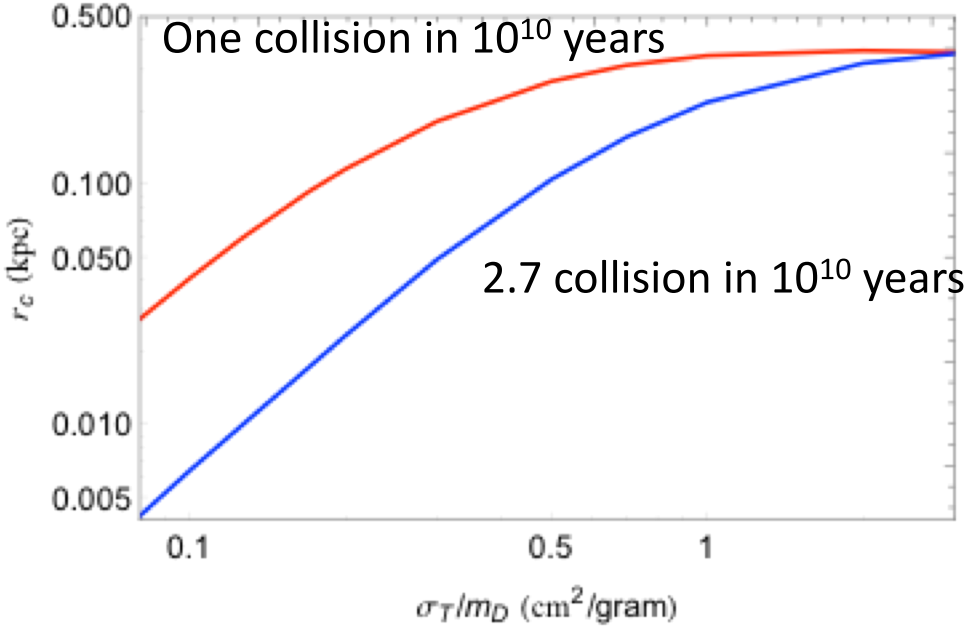
κ
0.05
0.10
0.50
1
5
10
m_D (keV)
8.14 MeV
4.3 MeV
1.2 MeV

Core size SIDM


One collision in 10^{10} years

2.7 collision in 10^{10} years

Core size SIDM

Zavala, Vogelsberger, Walker 1211.6426