Is self-interacting dark matter with no light mediator viable?

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DESY, Hamburg
DESY theory workshop

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In collaboration with Xiaoyong Chu and Hitoshi Murayama
Based on JCAP 1807 (2018) no.07, 013 and arXiv:1910.xxxxx

Challenges to the ΛCDM model at small scales

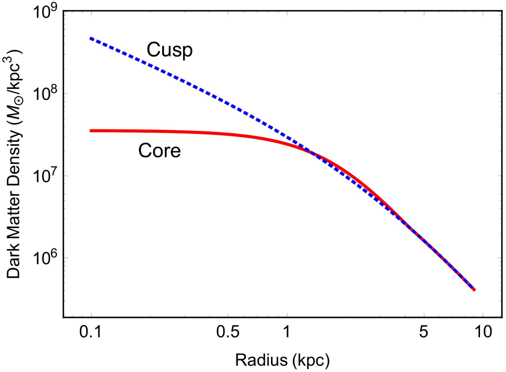
Core vs. cusp problem

dwarf galaxies exhibit a core while N-body simulations predict a cusp at their center

Moore (1994)

Flores et al. (1994)

Naray et al. (2011)



Tulin, Yu(2017)

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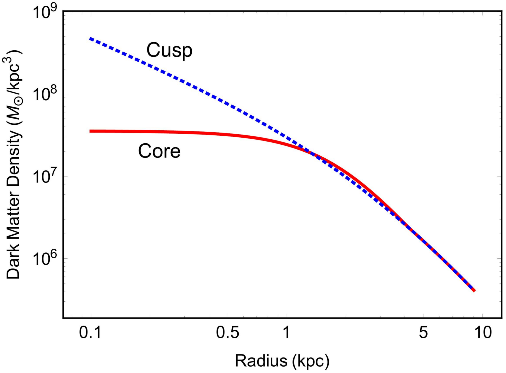
Too-big-to-fail problem

Boylan-Kolchin et al.(2011)



Tulin, Yu(2017)

See Kai Schmidt-Hoberg's talk (yesterday)

SIDM as a plausible solution

Astrophysical possible solutions:

- Including baryons on the simulations
- Supernova feedback
- Tidal effects
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- postulate dark matter interactions that become relevant at small scales, without modifying the physics at large scales.

$$\text{Mean Free Path} \sim \left(\frac{\rho}{m_{\text{DM}}}\sigma_{\text{scattering}}\right)^{-1}$$

$$\frac{\sigma_{\text{scattering}}}{m_{\text{DM}}} \sim 1\text{cm}^2/g \quad \text{at the scale of galaxies } (v \sim 10 \text{ - } 100 \text{ km/s})$$

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"..To be more specific, we suggest that the dark matter particles should have a mean free path between 1 kpc to 1 Mpc at the solar radius in a typical galaxy." Spergel, Steinhardt (1999)

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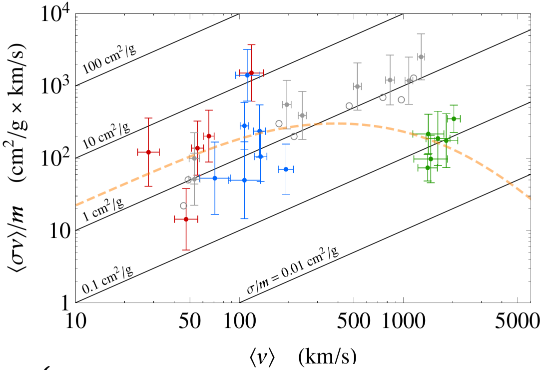
Simulations show that this is indeed a solution

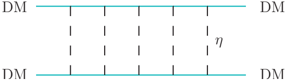
Wandelt, et.al (2000), Vogelsberger et.al (2012)
Peter et.al (2012), Rocha et.al (2013),Zavala et.al (2012)
Elbert et.al (2014), Kaplinghat (2015), Vogelsberger et.al (2015)
Francis-Yan Cyr-Racine (2015)

How can we obtain this cross section?

The cross section seemingly depends on the velocity Kaplinghat, Tulin, Yu (2015)



Light mediator η { Long-range forces



Kai Schmidt Hoberg's talk yesterday

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Is this the only possibility? If that is true, many SIDM models are strongly disfavored.

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  $\rightarrow$ pions act as light mediators.

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  $\rightarrow$ Resonant scattering.
- Inelastic scatterings

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- Inelastic scatterings

  $\rightarrow$ Exothermic reactions

Resonant scattering of Dark Matter

Model independent study: Preliminary.

$$\sigma = \sigma_0 + \frac{2J_R + 1}{(2J_{\rm DM} + 1)^2} \frac{4\pi}{mE} \cdot \frac{\Gamma^2/4}{(E - E_R)^2 + \Gamma^2/4}, \quad \Gamma = m_R \gamma v^{2L+1}$$

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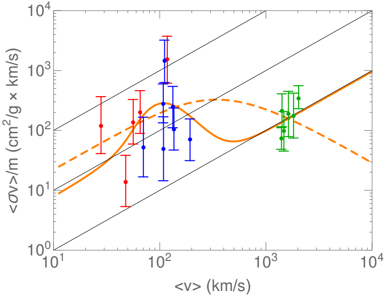

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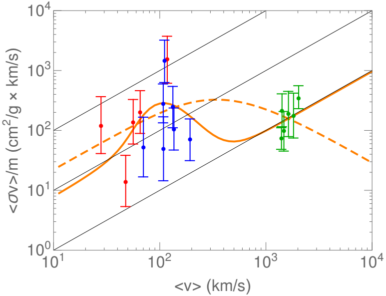
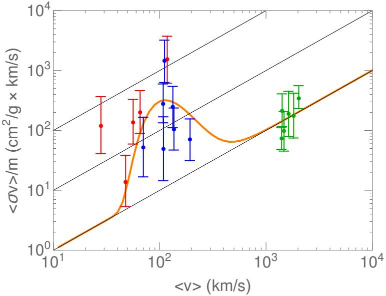
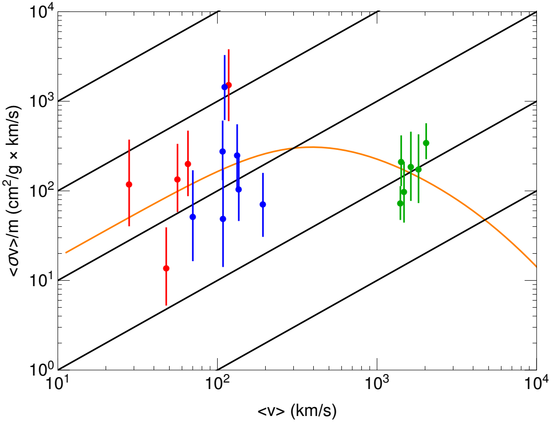


$L = 1$



$$\mathcal{L} = g\, R\overline{\mathrm{DM}}\gamma^5\mathrm{DM}\,. \qquad \text{(Pseudoscalar exchange)}$$ Preliminary.

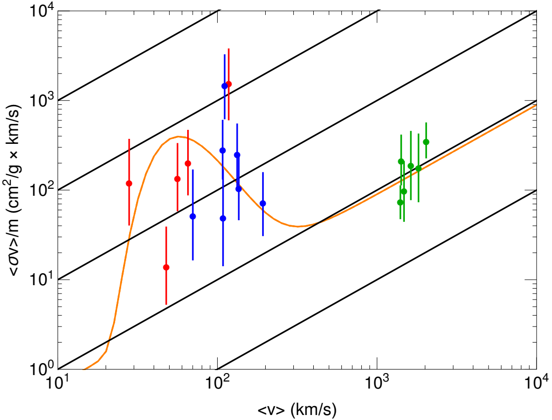
L	Γ_R/m_R	v_R (km/s)	m_{DM} (GeV)
0	$10^{-4.6}$	1506	10



$$\mathcal{L} = g\, R_\mu\, (\mathrm{DM}_1 \partial^\mu \mathrm{DM}_2 - \mathrm{DM}_2 \partial^\mu \mathrm{DM}_1) \qquad \text{(Dark pions)}$$

Preliminary.

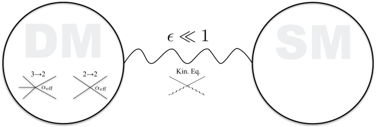
L	Γ_R/m_R	v_R (km/s)	m_{DM} (GeV)
1	$10^{-10.3}$	62	5



Example of a production mechanism

Consider annihilations of three DM particles into two of them.

SIMPs (Strongly Interacting Massive Particles)



Hochberg et al 2014

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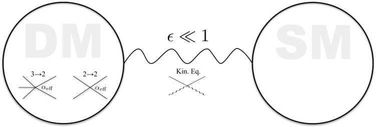


Hochberg et al 2014

Concrete models:

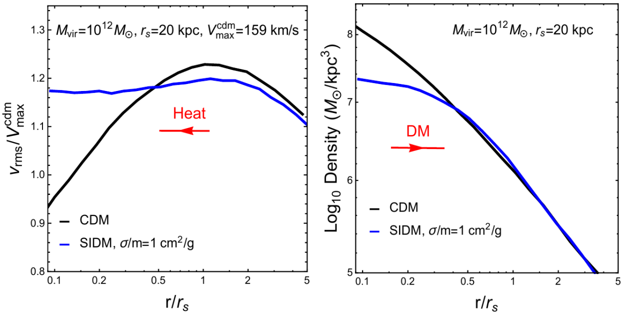
- Dark pions. Dark α particles. PRELIMINARY
- QCD-like theories of dynamical chiral symmetry breaking Hochberg et al, 2014
- Vector DM Bernal, Chu, GGC, Hambye, Zaldivar,2016

⋮

Self-heating Dark Matter

How does SIDM work?

Heat flows to the inner region



Tulin, Yu(2017)

Self-heating Dark Matter

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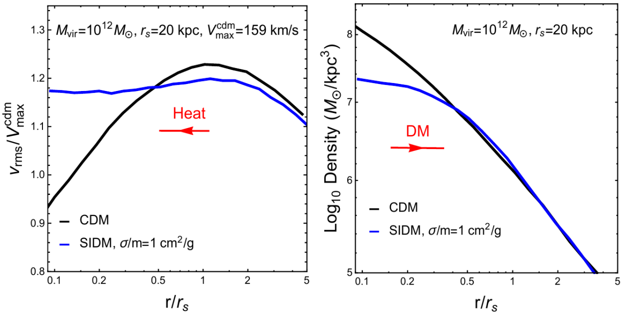
What if DM itself provides the heat?

Exothermic Inelastic scatterings

Chu and CGC (JCAP 2018)



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Gravothermal fluid approximation

Done for SIDM.

Gravothermal fluid approximation

Done for SIDM. For self-heating DM: Chu and CGC (JCAP 2018)

$$\begin{aligned}
\frac{ds}{dt} = \frac{\partial s}{\partial t} + \mathbf{V}\cdot\nabla s &= \frac{\rho}{m^2}\langle\sigma v\rangle\mathcal{J} \\
\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{V}) &= -\rho\frac{\delta N}{\delta t}\,. \\
\sigma_0^2\nabla\rho + \rho\left(\partial\mathbf{V}/\partial t + (\mathbf{V}\cdot\nabla)\mathbf{V}\right) &= -\rho\nabla\Phi
\end{aligned}$$

$$\mathcal{J} = \xi \;\times\; \frac{\text{Released energy per collision}}{\text{Average kinetic energy}}$$

Gravothermal fluid approximation

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$$\mathcal{J} = \xi \times \frac{\text{Released energy per collision}}{\text{Average kinetic energy}}$$

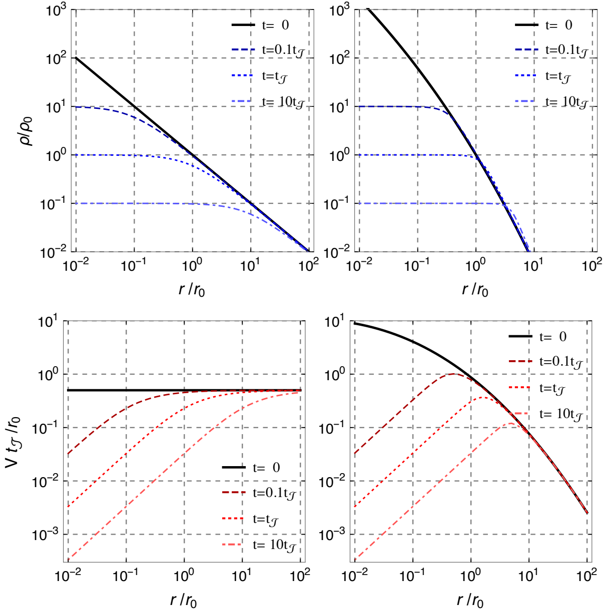
- The effect is bigger in small objects.
- A core is formed

$$\frac{\rho_c \langle \sigma v \rangle \mathcal{J} t_{\text{age}}}{m} \simeq 1 \, .$$

(analogous to SIDM, except for $\mathcal{J}$. Expect $\sigma \mathcal{J} \sim 1 \text{cm}^2/\text{g}$)

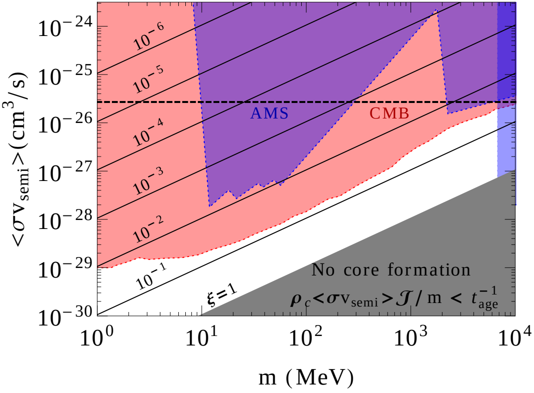
NFW

Einasto


t= 0
t=0.1t$_{\mathcal{J}}$
t=t$_{\mathcal{J}}$
t= 10t$_{\mathcal{J}}$
ρ/ρ_0
r/r_0
V $t_{\mathcal{J}}/r_0$

Phenomenology

Consider semi-annihilations DM DM $\to$ DM ϕ.
ϕ is the mediator. $\mathcal{J}$ is known up to the efficiency ξ.



Chu and CGC (JCAP 2018)

Conclusions

- Self-interacting dark matter (SIDM) is a well-motivated solution to the problems encountered at small scales.
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- Self-heating DM is a similar scenario. In this case, DM inelastically scatters releasing heat. Significant effects in dwarf galaxies but small effects in clusters. Chu and CGC (JCAP 2018)

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Thanks for your attention!