Core formation from dark matter self-heating

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(1803.09762, JCAP)

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

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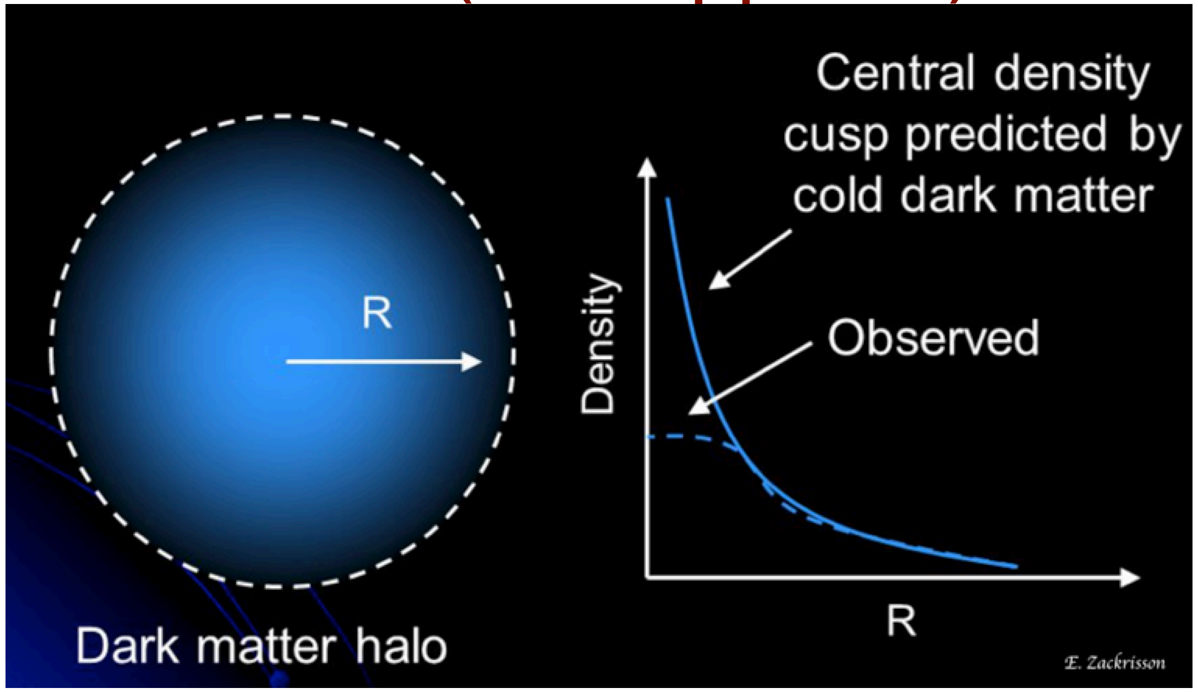
I. Introduction

Dark matter (DM) halo **mass deficit?**

1. **DM cores** are preferred by observed circular velocities in dwarf/LSB galaxies;

[Moore 1994; Burkert 1995, …]

(core/cusp problem)



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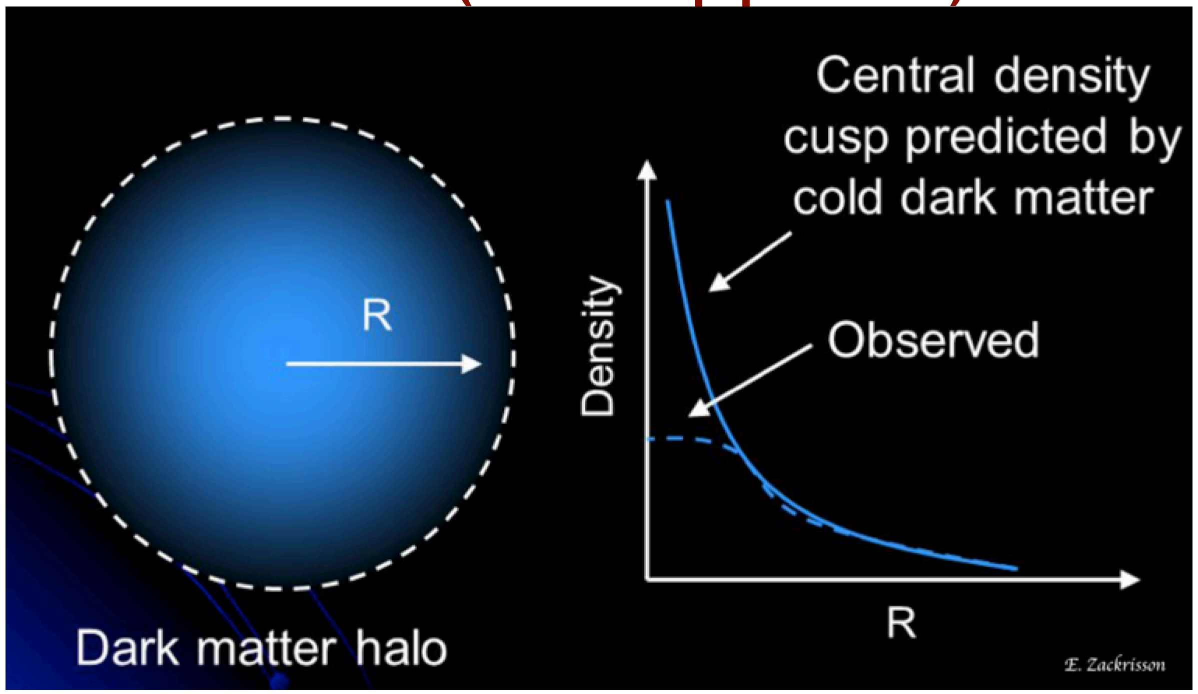
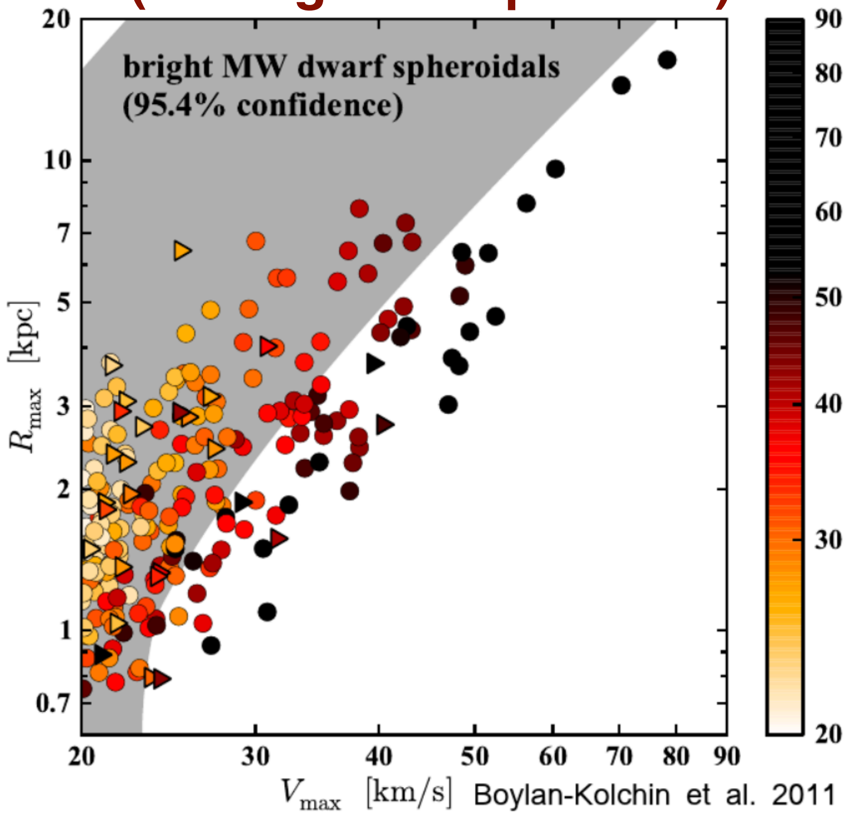


(too-big-to-fail problem)



Boylan-Kolchin et al. 2011

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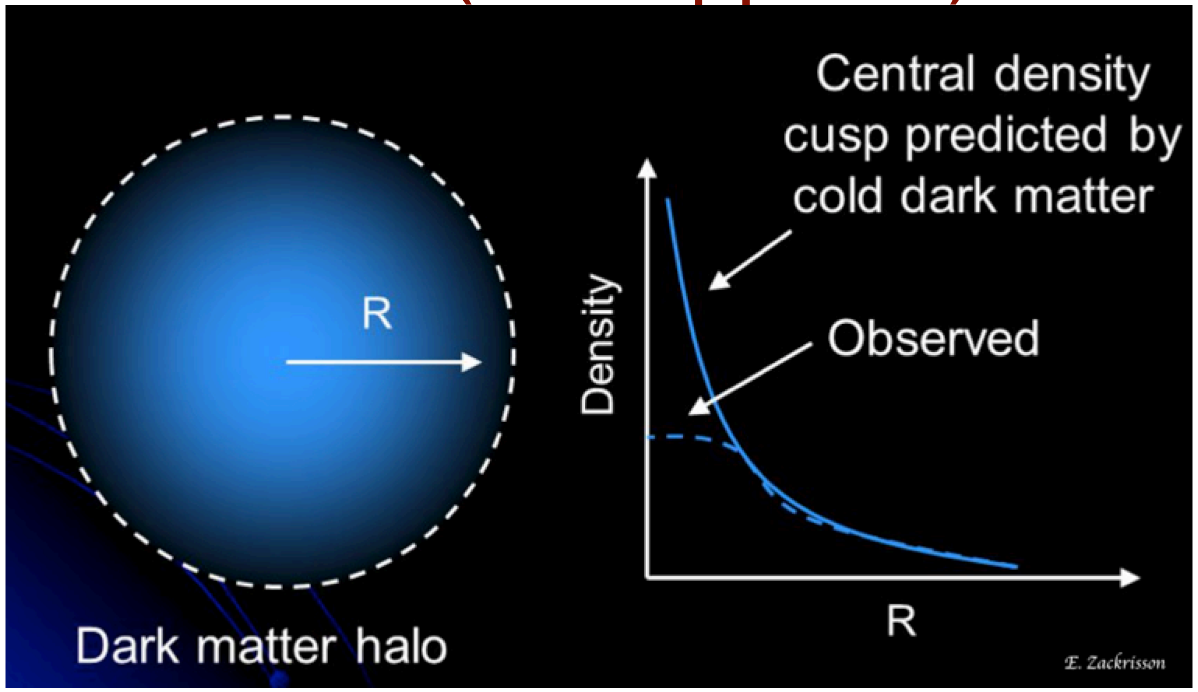

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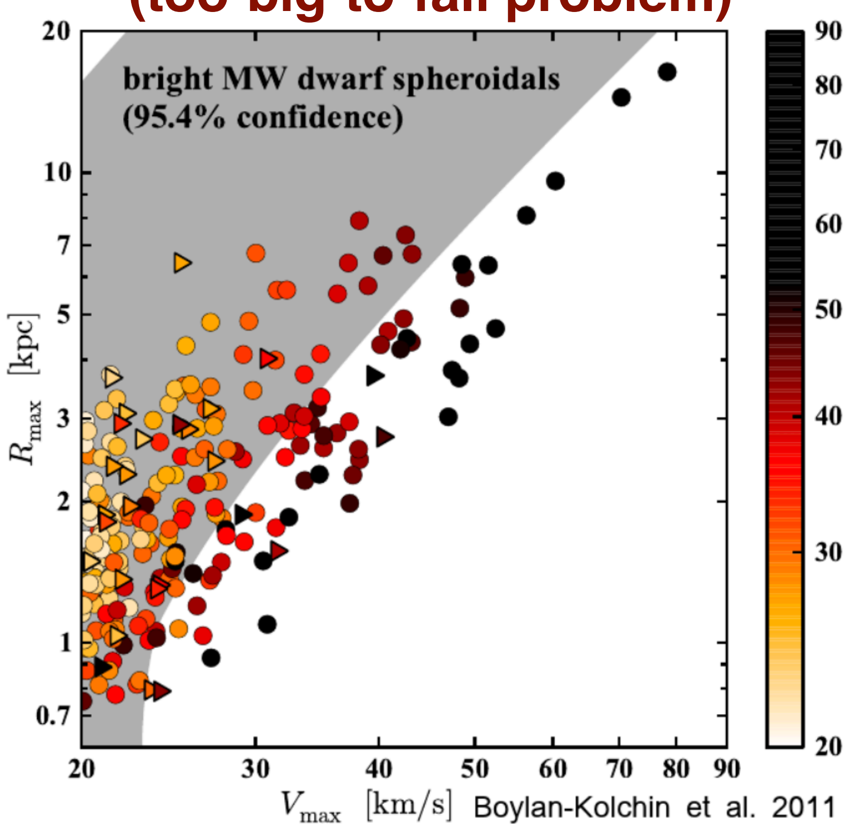
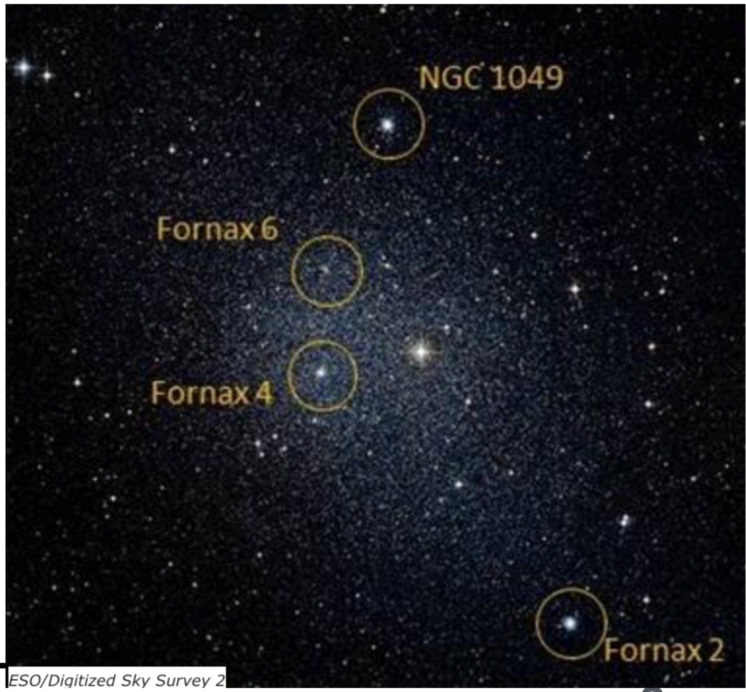


Boylan-Kolchin et al. 2011

3. Some globular clusters are expected to sink to the center **if dwarf-sized halos are cuspy.** [J. Binney & S.Tremaine 2008, …]

(timing problem)

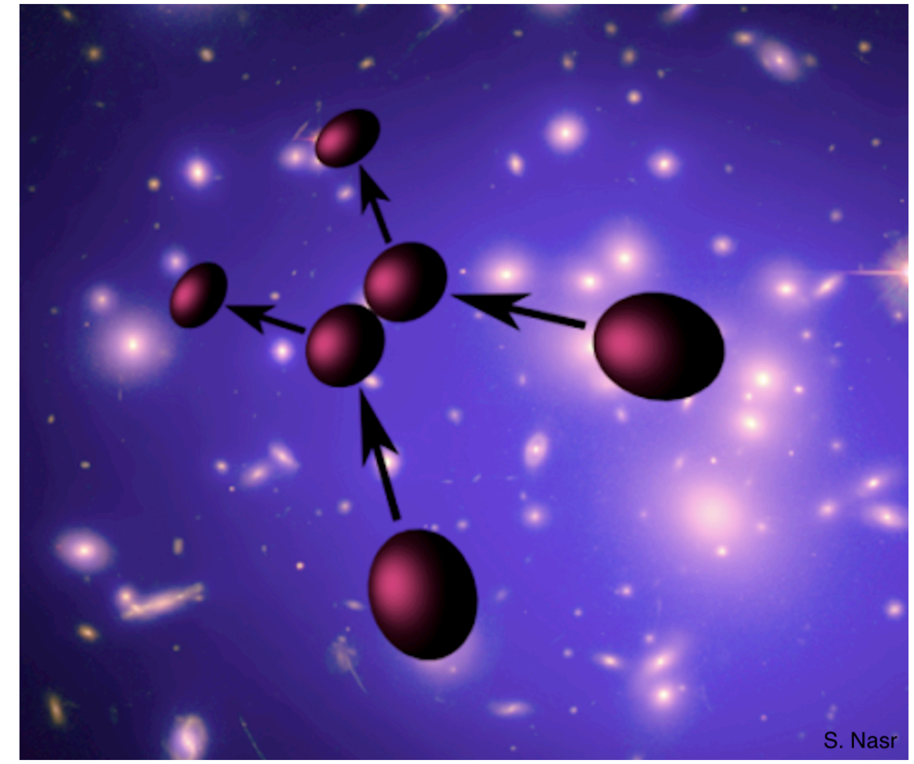


Baryonic effects? **Self-interacting dark matter?**

Observational evidence for self-interacting cold dark matter

D.N. Spergel and P J. Steinhardt [astro-ph/9909386]

Infalling dark matter is scattered before reaching the center of the galaxy so that the orbit distribution is isotropic rather than radial. These collisions increase the entropy of the dark matter phase space distribution and lead to a dark matter halo profile with a shallower density profile.



Strong DM self-scattering ➡ inner halo **DM self-thermalization**

(heating up the halo center)

$$\frac{\sigma_{\rm SI}}{m_{\rm DM}} \sim 0.1\text{–}10\,{\rm cm}^2/{\rm g}$$

$$\frac{\rho\,\langle \sigma v_{\rm SI}\rangle}{m_{\rm DM}} \simeq \frac{1}{t_{\rm age}}$$

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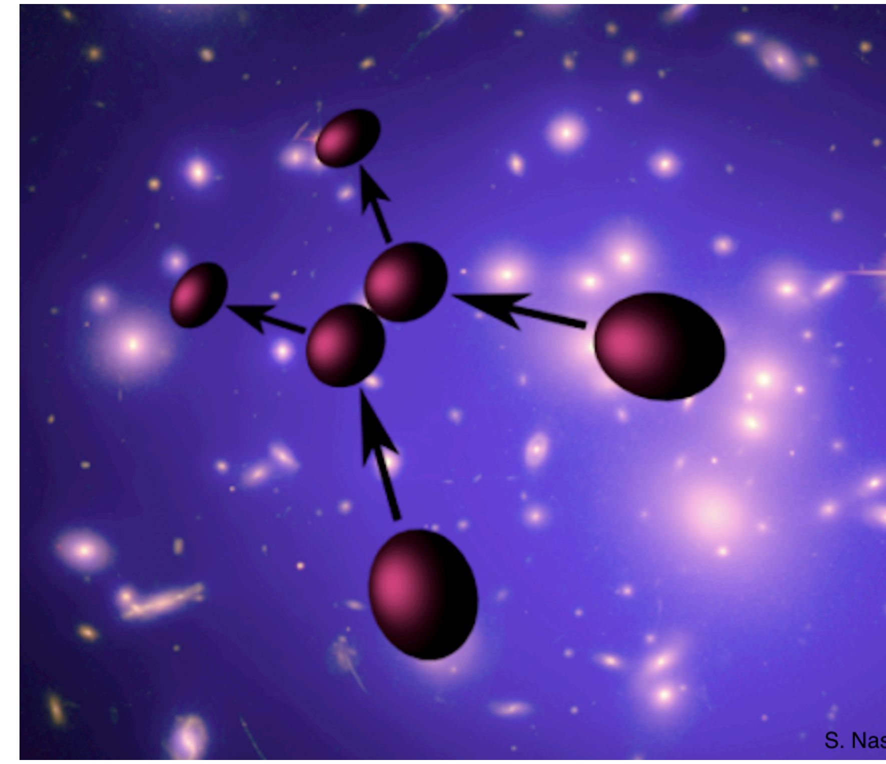

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Problems: **strong bounds exist** & **difficult to achieve such large interactions**

II. Heating via DM self-annihilation

DM self-heating mechanism

Semi-annihilation $\mathrm{DM} + \mathrm{DM} \to \mathrm{DM} + \phi_{\mathrm{light}}$

↓

kinetic energy gain: δE~ DM mass

A **fraction of its kinetic energy,** $\xi \cdot \delta E$**,** is absorbed by the halo via

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Such semi-annihilation increases **the halo entropy** with a rate (per DM particle) :

$$ds \equiv \frac{dU}{T} \sim \frac{\xi \cdot \delta E}{T} \underline{\frac{\rho}{m_{\mathrm{DM}}} \langle \sigma v_{\mathrm{semi}} \rangle}$$

$T \simeq m_{\mathrm{DM}} v_0^2$

annihilation rate per particle

Heat absorption

$$ds \equiv \frac{dU}{T} \sim \frac{\xi \cdot \delta E}{T} \frac{\rho}{m_{\rm DM}} \langle \sigma v_{\rm semi} \rangle$$

Two important quantities:

1. The energy absorption efficiency ξ (from scattering) **:**

can be estimated by the ratio of halo radius to DM mean-free-path

$$\xi \sim \frac{r_s}{m_{\rm DM}/(\rho_{\rm DM}\sigma_{\rm SI})} \simeq 10^{-3} \left(\frac{r_s}{5\,{\rm kpc}}\right) \left(\frac{\rho_{\rm DM}}{M_\odot/{\rm pc}^3}\right) \left(\frac{\sigma_{\rm SI}/m_{\rm DM}}{10^{-3}\,{\rm cm}^2/g}\right)$$

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2. The effective ratio $\mathcal{J}$:

$$\frac{\xi \delta E}{T} \sim \mathcal{O}(10^6) \cdot \frac{\xi}{10^{-3}} \cdot \left(\frac{10\,{\rm km/s}}{v_{\rm DM}}\right)^2$$

a) It leads to significant enhancements.

b) The effect is **larger at lower velocities** (e.g. in dwarf-sized halos), being similar to velocity-dependent SIDM (so less constrained).

Comparison with SIDM

self-heating	self-interacting $\frac{\sigma_{\rm SI}}{m_{\rm DM}} \sim 0.1\text{–}10\,{\rm cm}^2/{\rm g}$
$ds \equiv \frac{dU}{T} \sim \frac{\xi \cdot \delta E}{T} \frac{\rho}{m_{\rm DM}} \langle \sigma v_{\rm semi} \rangle$	$ds \sim \frac{\rho}{m_{\rm DM}} \langle \sigma v_{\rm SI} \rangle$

Note: **annihilation** $\langle \sigma v_{\rm semi} \rangle$ is velocity-independent, while for **scattering,** $\sigma_{\rm SI}$ is.

In order to achieve **similar effects with semi-annihilation**, one needs:

$$\langle \sigma v_{\rm semi} \rangle \sim \frac{T}{\xi \delta E} \times {\rm cm}^2/{\rm g} \times v \sim \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{0.1\,{\rm GeV}}$$

$$\mathcal{J}^{-1} \sim 10^{-6} \qquad 10^{-5} c - 10^{-4} c$$

leading to the observed abundance for sub-GeV thermal DM.

Numerical results (with simplifications)

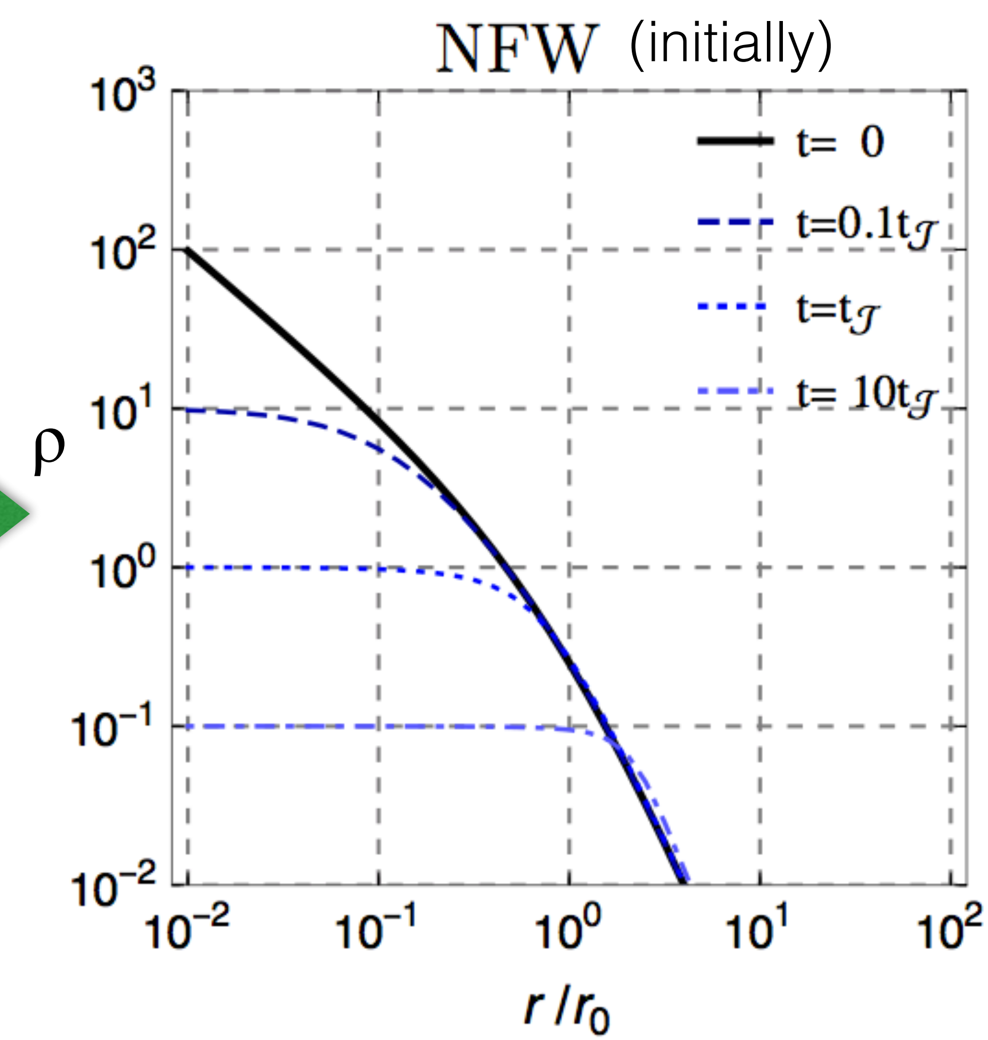
The halo is numerically modelled as a **gravo-thermal fluid** **[K.-J. Ahn & P. R. Shapiro, 2005] :**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = -\frac{\rho^2}{m} \langle \sigma v_{\rm semi} \rangle \,, \qquad \text{(density)}$$

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + (\nabla \mathbf{V} \cdot \nabla) \mathbf{V} \right) = -\rho \nabla \Phi - \nabla p \,, \qquad \text{(pressure)}$$

$$\nabla^2 \Phi = 4\pi G (\rho_h + \rho) \,, \qquad \text{(gravity)}$$

$$T \left(\frac{\partial s}{\partial t} + \mathbf{V} \cdot \nabla s \right) = \left.\frac{\delta q}{\delta t}\right|_{\rm conduction} + \left.\frac{\delta q}{\delta t}\right|_{\rm absorption} . \qquad \text{(entropy)}$$



Numerical results (with simplifications)

1. Heat/entropy ejection creates a radial DM outflow:

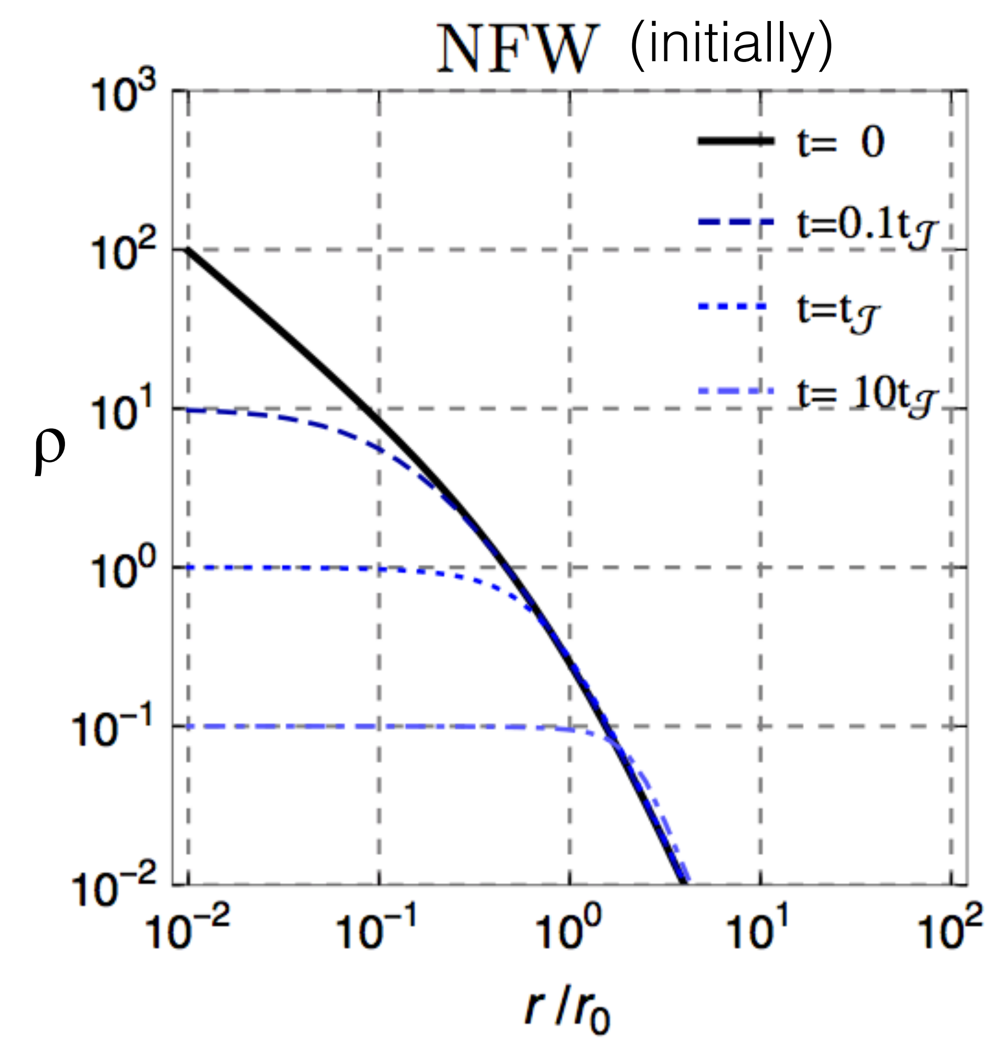
$$\mathbf{V} = \frac{\bar{\rho}}{3m}\langle \sigma v_{\rm semi}\rangle \mathcal{J}\mathbf{r}$$

(here heat conduction is only sub-leading)

2. For self-heating DM, the dynamical time-scale

$$t_{\mathcal{J}} \equiv \frac{m}{\rho_0 \langle \sigma v_{\rm semi}\rangle \mathcal{J}} \,.$$

should be close to the age of Universe.



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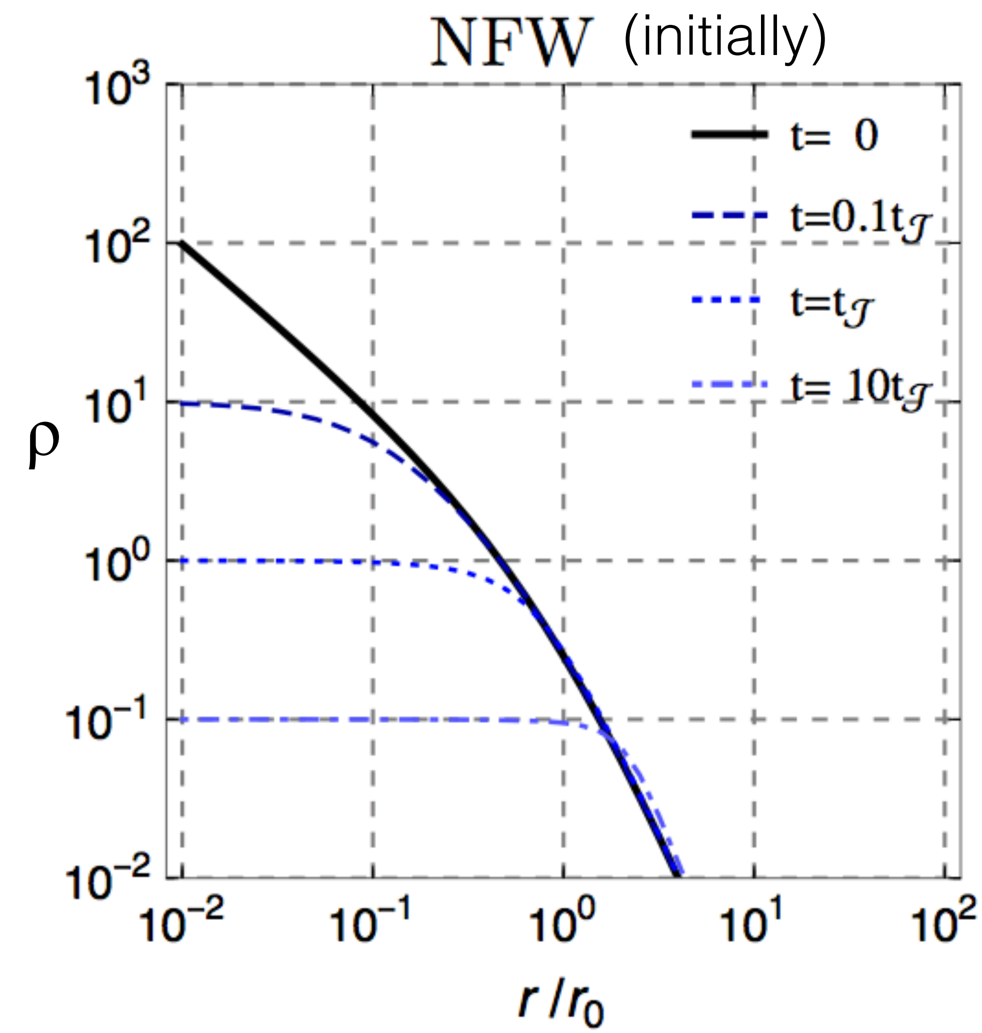
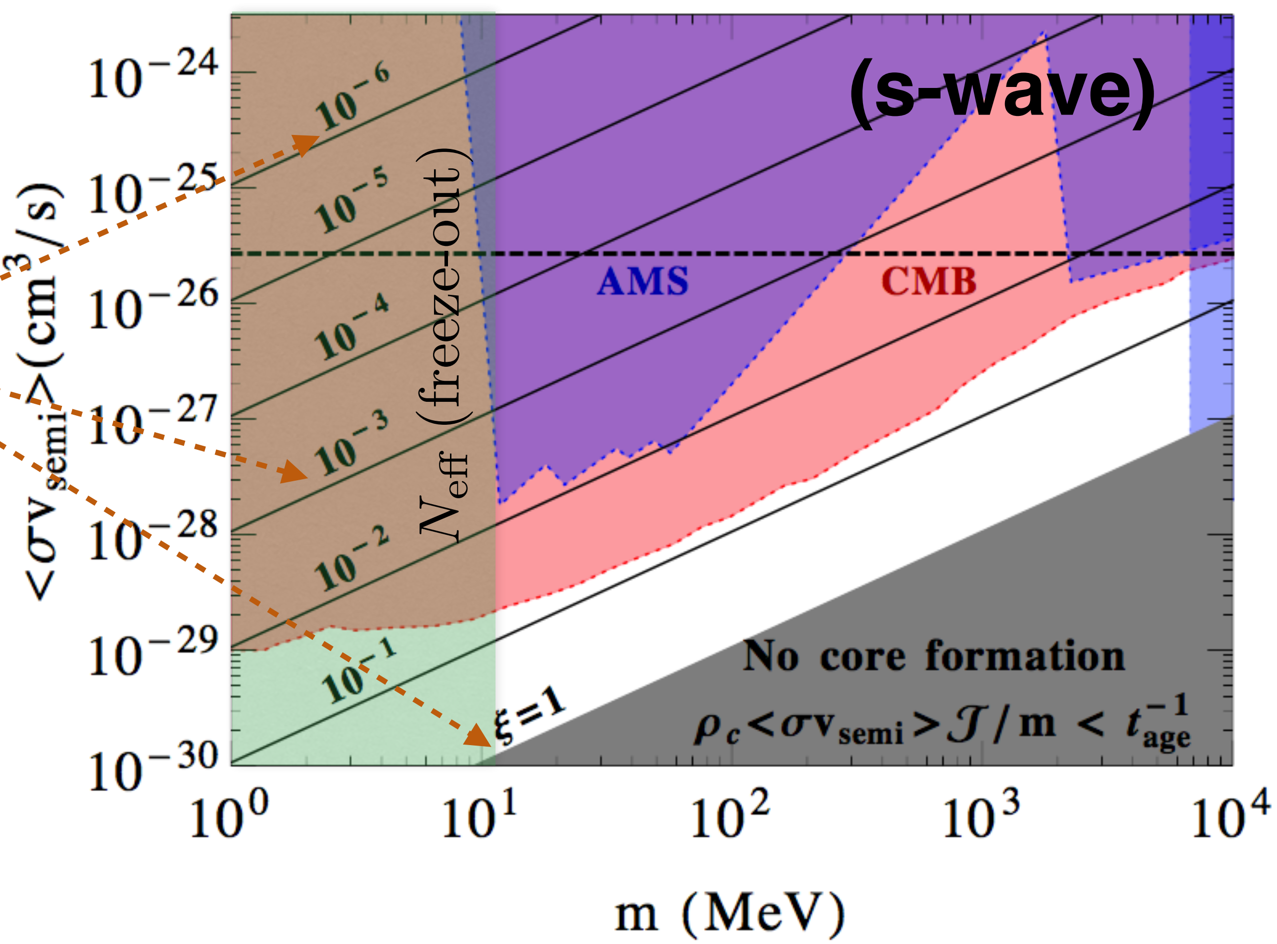


1. Entropy needed agrees with existing **simulations of slowly-decaying DM** [M. V. Medvedev 2013, M.-Y. Wang et al. 2014] and **gravitational energy argument** [T.K. Chan et al. 2014] .

2. **Cosmological simulations** are required to verify this simplified picture.

Experimental constraints:

<u>Black solid lines</u> for various **energy absorption efficiencies** give parameters that address the **mass-deficit problem** in DM sub-halos.



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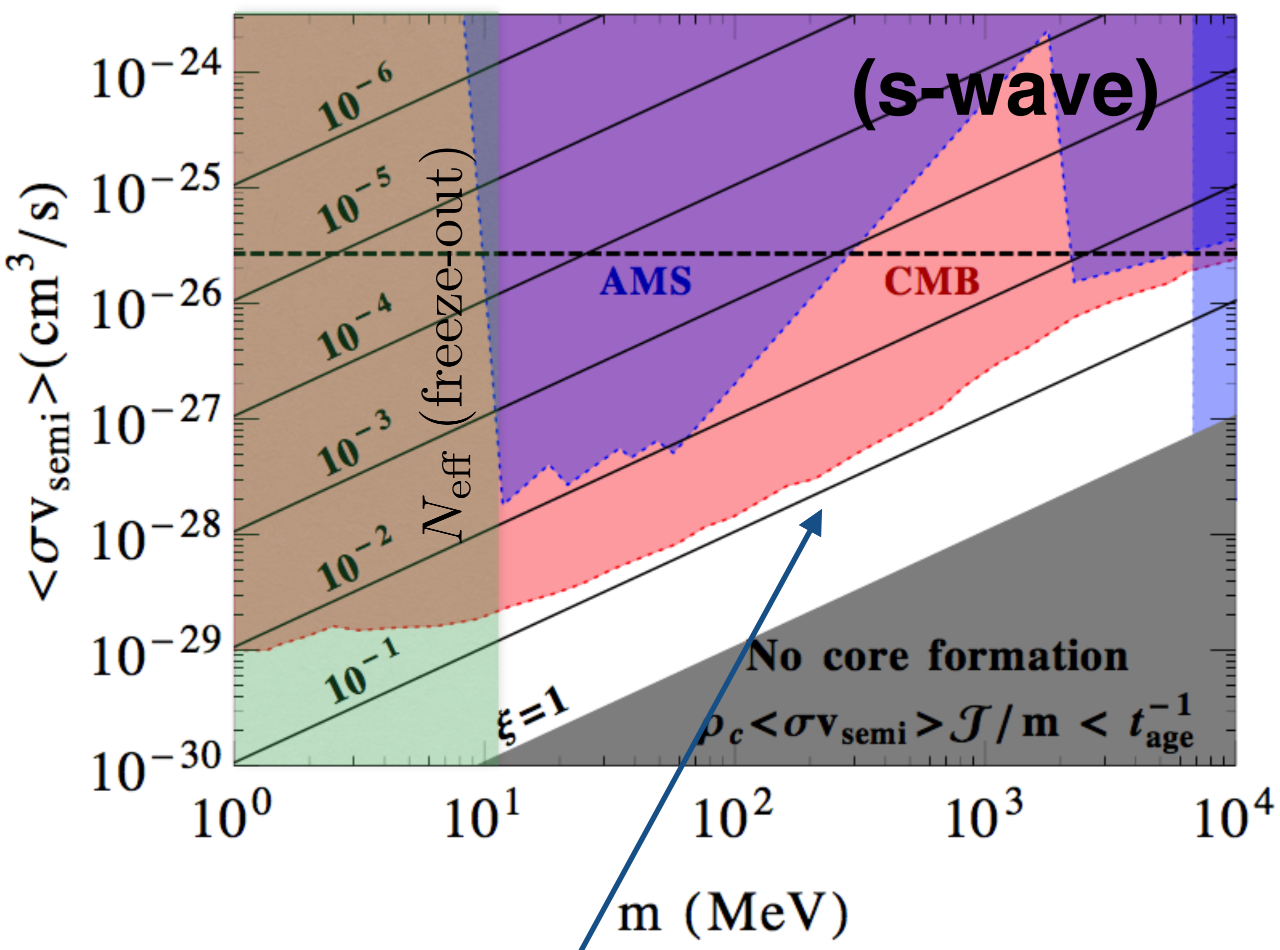


Black solid lines for various **energy absorption efficiencies** give parameters that address the **mass-deficit problem** in DM sub-halos.

a) If $\phi_{\rm light}$ results in **electromagnetic particles:**

Mildly strong self-scattering is required: $\frac{\sigma_{SI}}{m_{\rm DM}} \sim \mathcal{O}(10^{-2})\ \ {\rm cm}^2/{\rm g}$

b) If $\phi_{\rm light}$ only decays invisibly, **no CMB/AMS-02 constraints.**

Further issues:

1. Halo merging history may lead to **more massive halos with shallower cores.** [M. Boylan-Kolchin & C-P. Ma 2003, …]

2. Small halos are unstable since its gravitational binding energy may be smaller than the energy absorbed. [S. Schon et al. 2014, …]

$$M_{\rm halo} \geq \mathcal{O}(10^5)\, M_\odot$$

3. Baryonic contraction/feedback need to be taken into account, just like the case of self-scattering DM. [A. Kamada et al. 2016, O. Sameie et al. 2018, …]

III. Conclusions

Conclusions

- **Halo mass deficit may be hint of non-conventional DM;**

- **DM can heat up itself via semi-annihilation** (by adding certain self-scattering)

    - Much smaller interaction strength is needed;

    - Velocity-dependence can be achieved naturally.

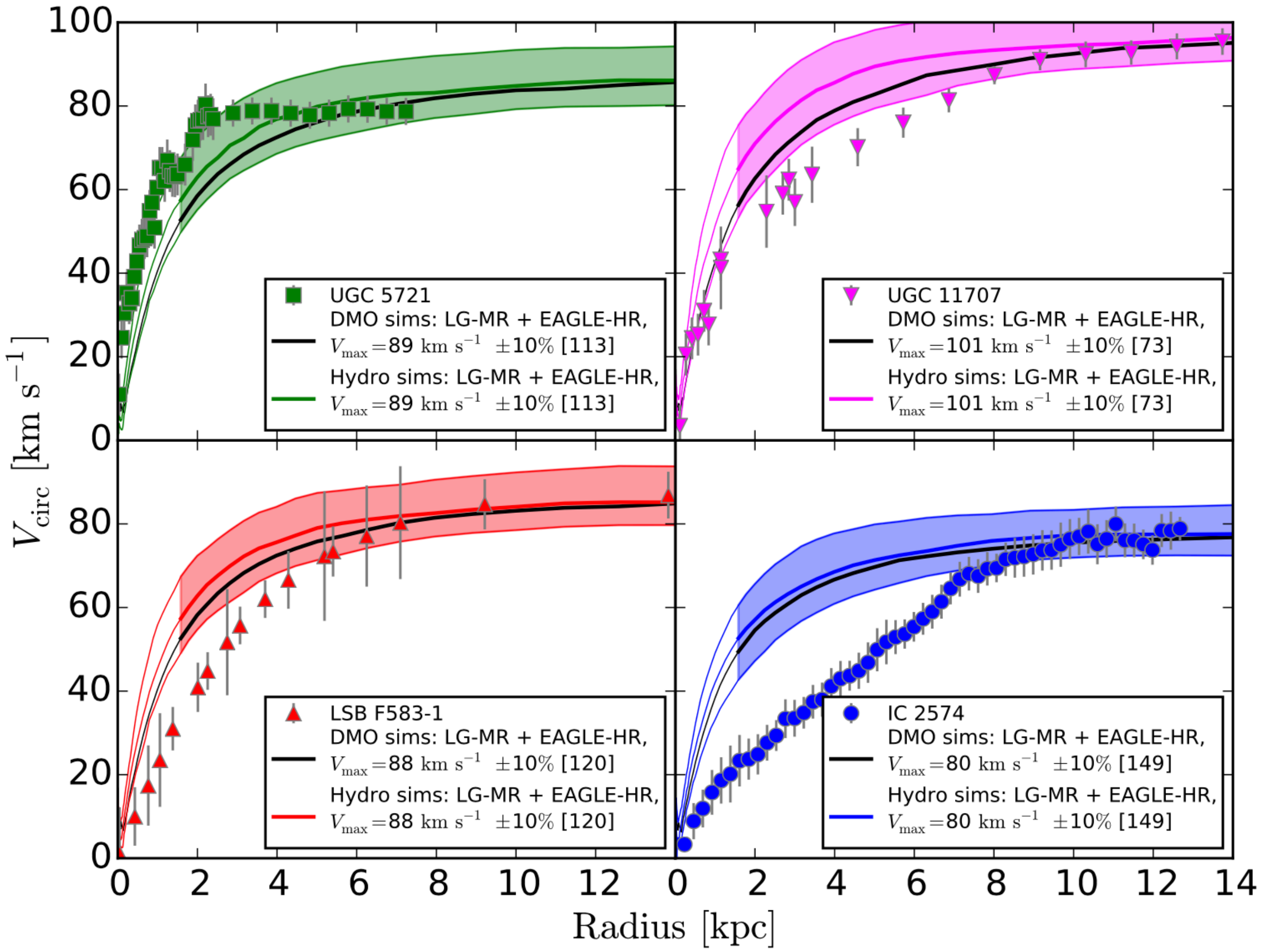
- The mechanism suggests **relations between DM mass deficit and (sub-)halo size/age.**

- **Cosmological simulations are required** (dependence of the absorption rate on SIDM, halo evolution with time, baryons …).

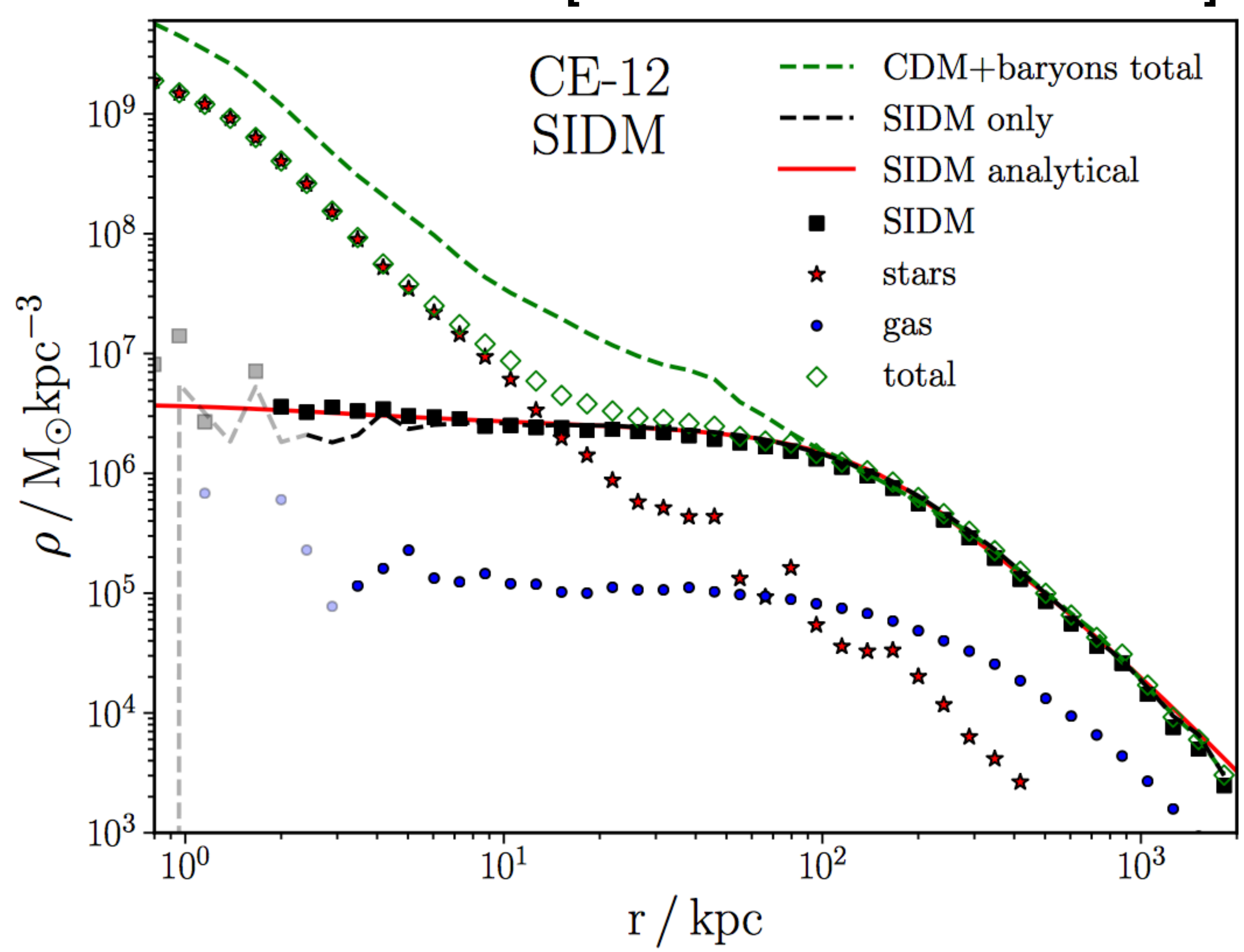
Thanks!

Solving diversity problem in SIDM

K. A. Oman et al. **[1504.01437]**



[A. Robertson et al. 1711.09096]



DM heating up visible astrophysics

A few previous studies for baryonic astrophysics:

Dark matter and the first stars: a new phase of stellar evolution

Arxiv: 0705.0521

Douglas Spolyar[1], Katherine Freese[2,3], and Paolo Gondolo[4]

Giant stars that are powered by DM annihilation…

The impact of dark matter decays and annihilations on the formation of the first structures

Arxiv: astro-ph/0606483

E. Ripamonti[1], M. Mapelli[2], A. Ferrara[2]

Evacuating gas and increasing the gas temperature…

Dark Matter Annihilation in the First Galaxy Halos

Arxiv: 1411.3783

S. Schön[1⋆], K. J. Mack[1,2,3], C. A. Avram[1,3], J. S. B. Wyithe[1,2] and E. Barberio[1,3]

Delaying the formation of first galaxies…

Semi-annihilating DM + SIDM in early Universe

It heats up dark matter particles, leading to larger DM free-steaming length.

[A. Kamada, H. J. Kim, and H. Kim, (2018)]