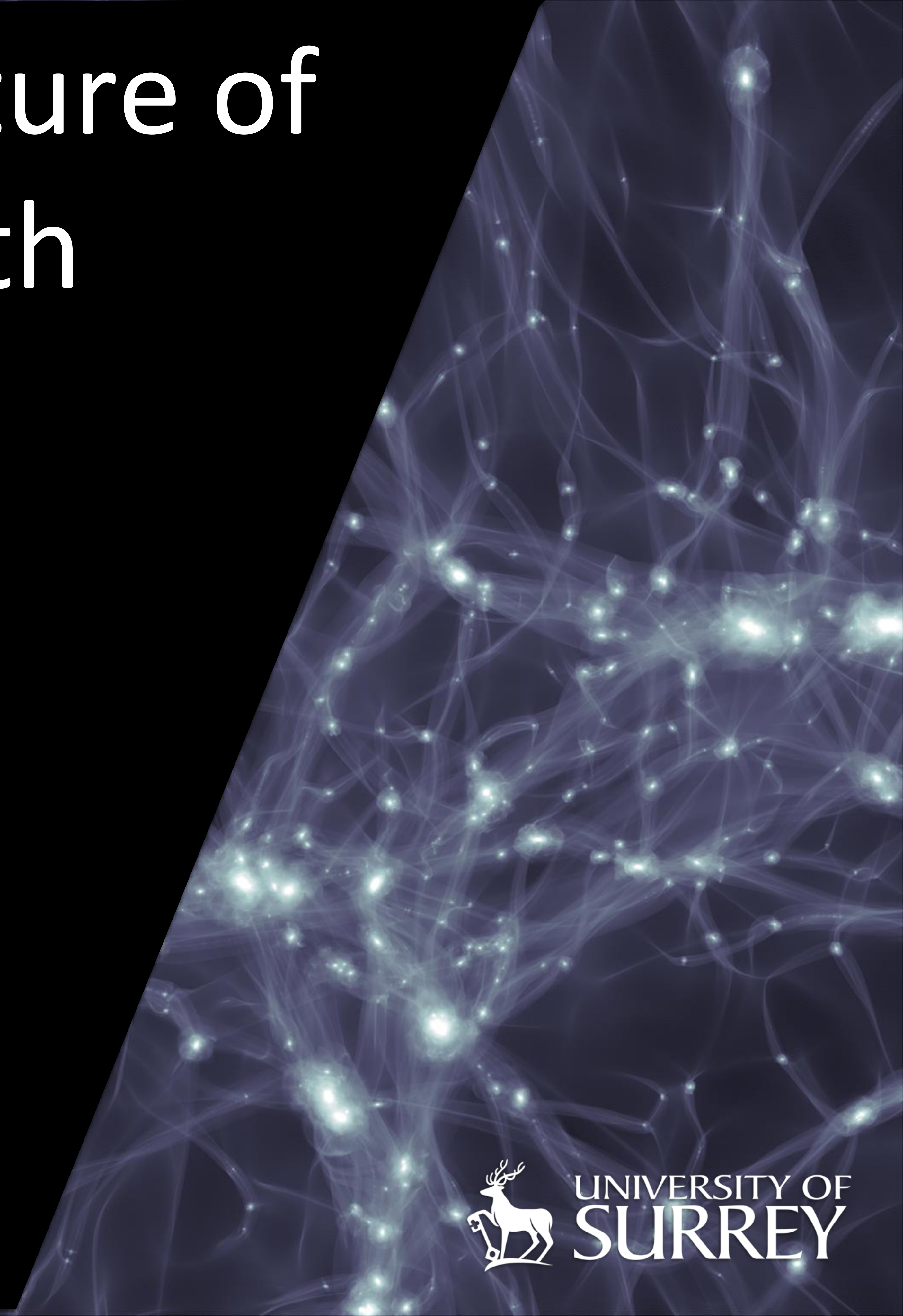
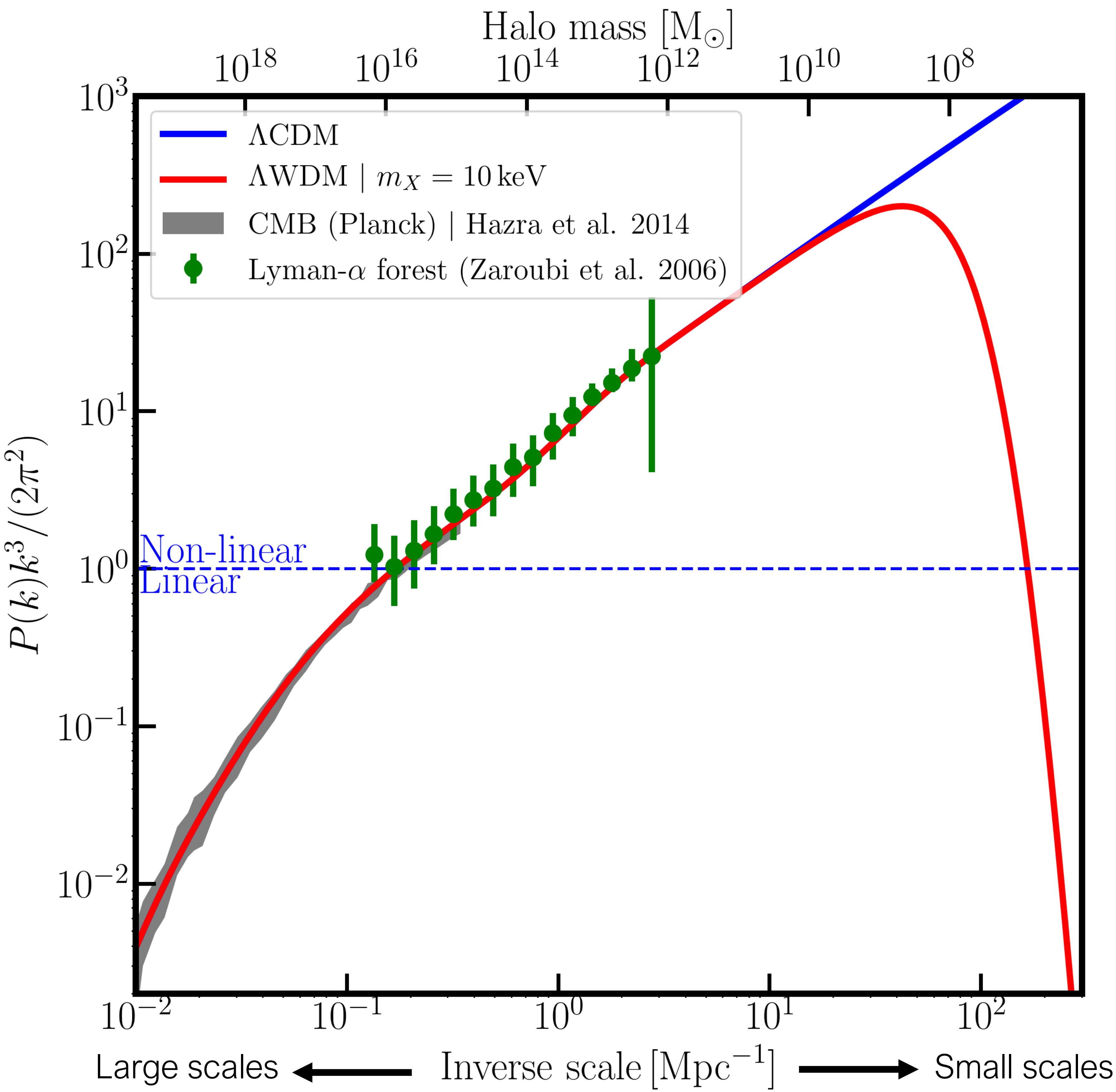
Probing the Nature of Dark Matter with Astrometry

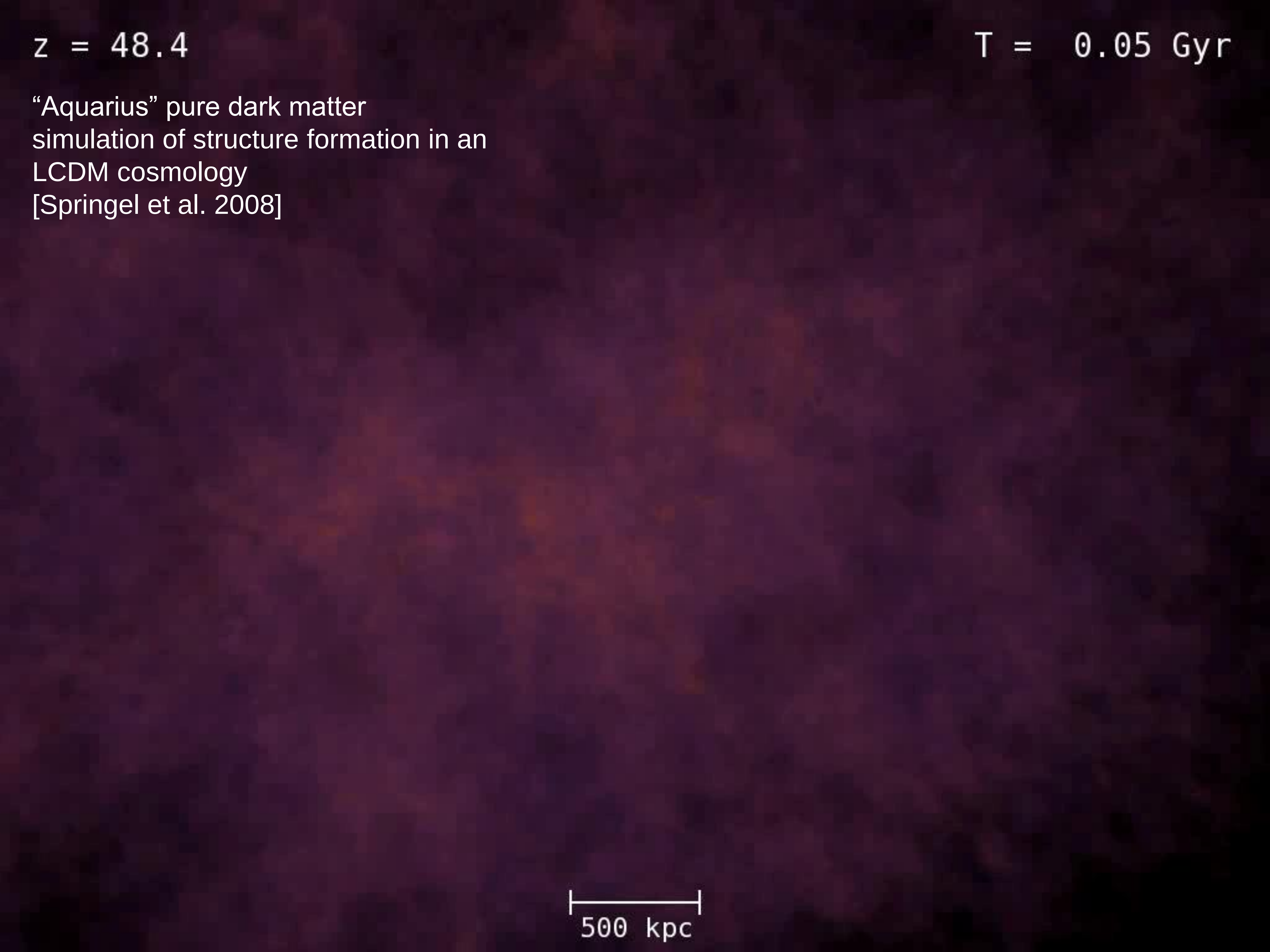


Prof. Justin I. Read

The Standard Cosmological Model

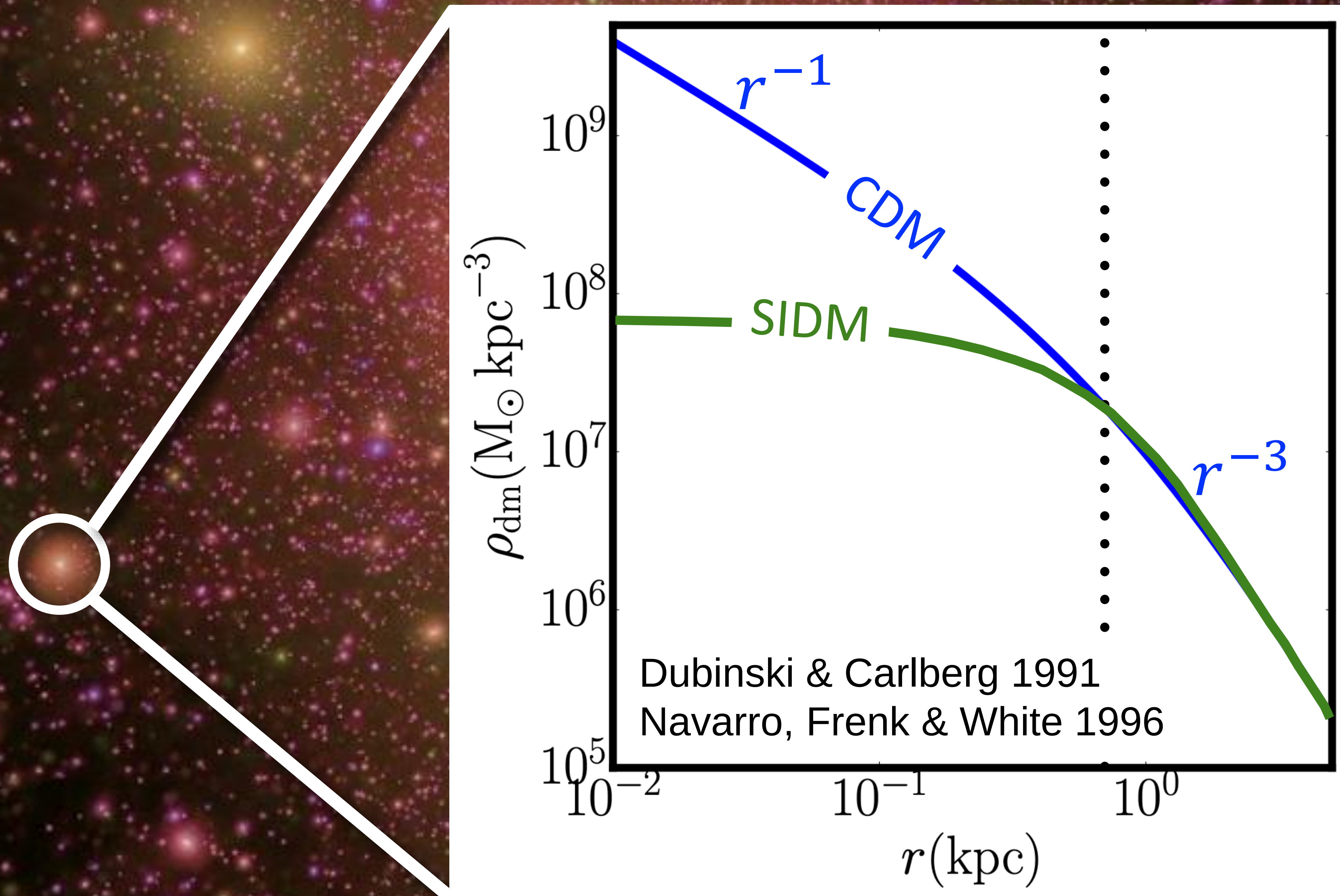
The Standard Cosmological Model





“Aquarius” pure dark matter simulation of structure formation in an LCDM cosmology [Springel et al. 2008]

Internal dark matter structure

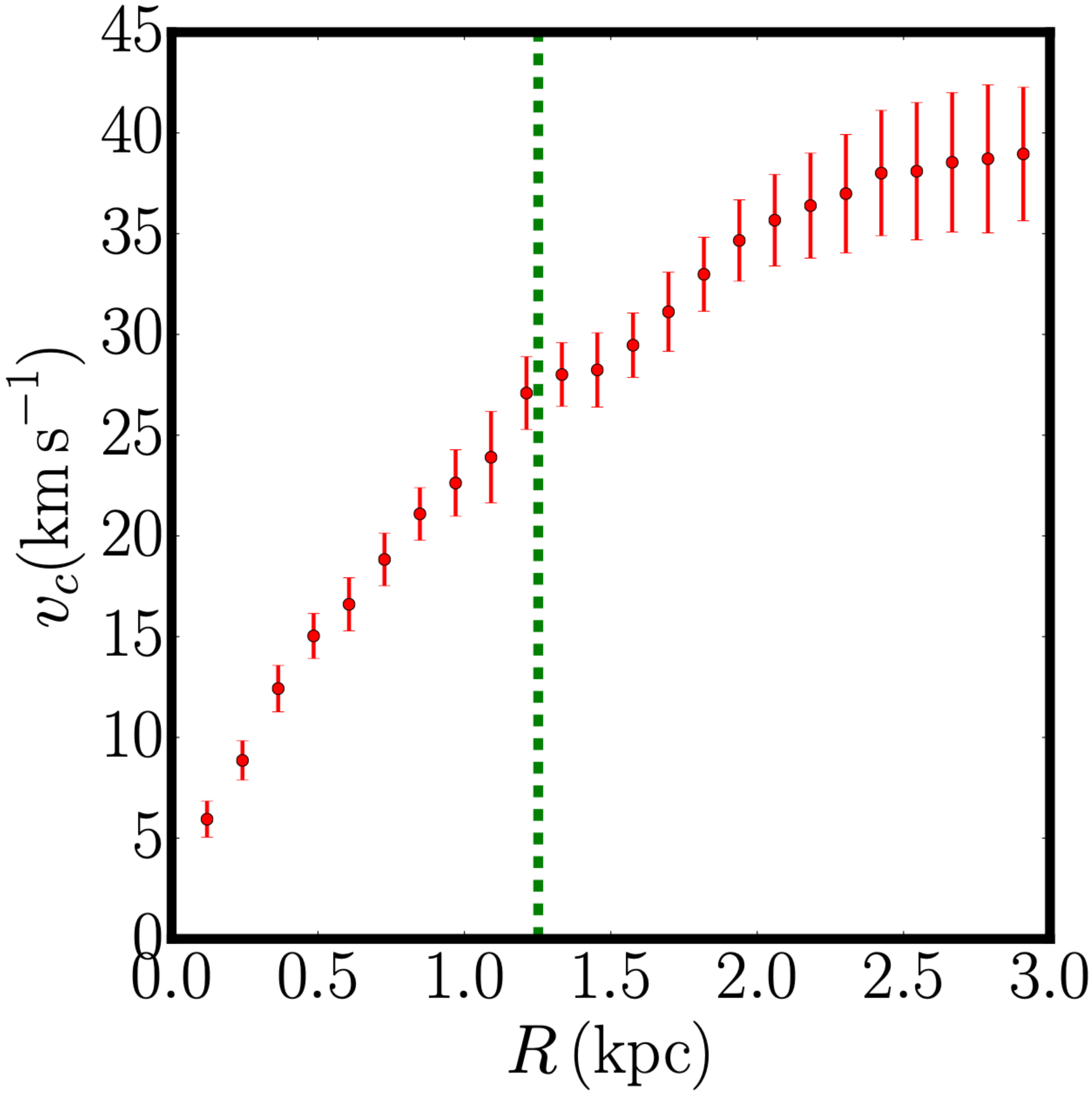


Volker Springel
Max-Planck-Institute
for Astrophysics

The Cusp-Core Problem

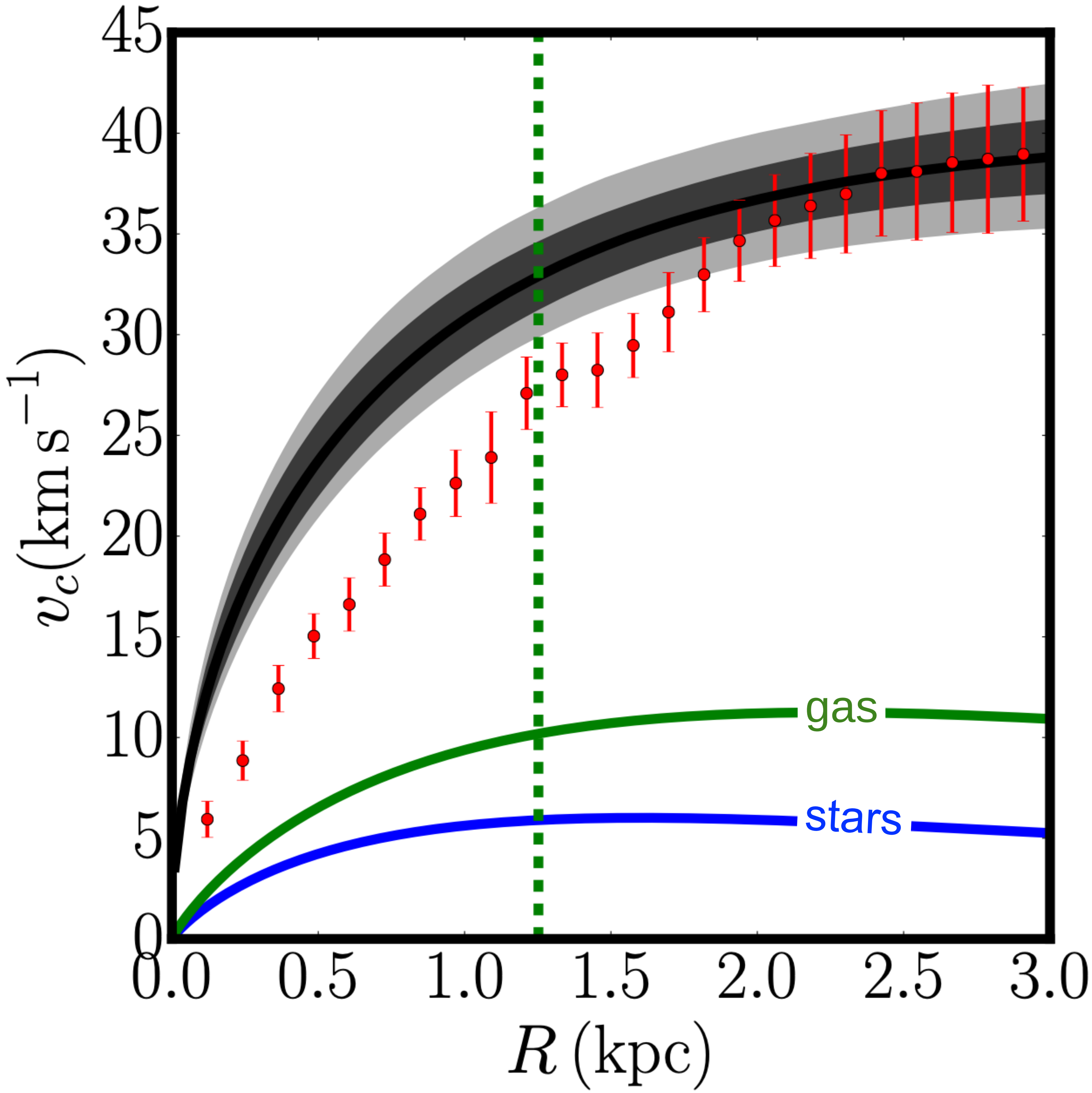
WLM; Leroy, Nature 2015

The Cusp-Core Problem



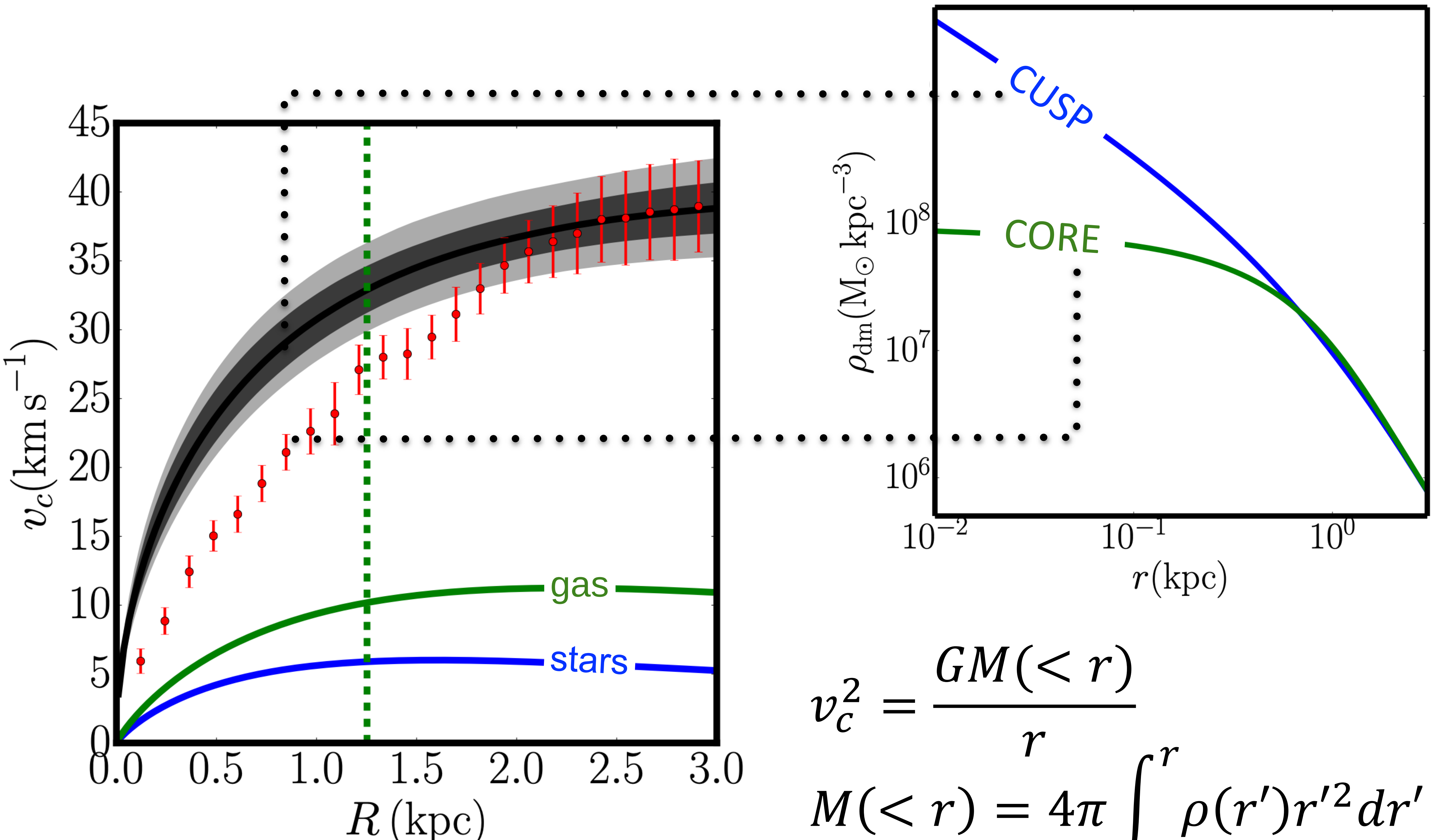
e.g. Flores & Primack 1994; Moore 1994; Read et al. 2017

The Cusp-Core Problem



e.g. Flores & Primack 1994; Moore 1994; Read et al. 2017

The Cusp-Core Problem



$$v_c^2 = \frac{GM(<r)}{r}$$

$$M(<r) = 4\pi \int_0^r \rho(r')r'^2 dr'$$

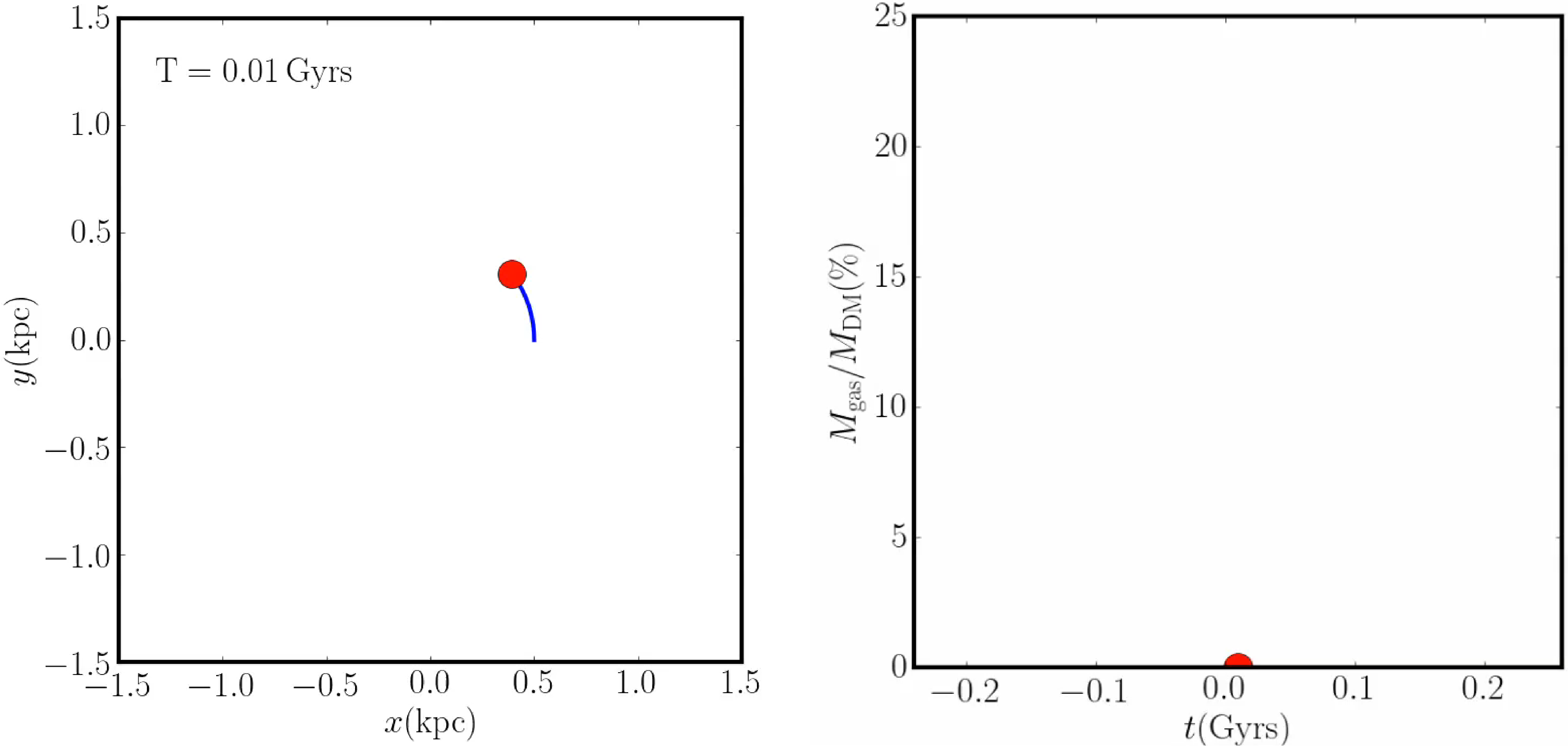
e.g. Flores & Primack 1994; Moore 1994; Read et al. 2017

Pure Dark Matter Simulations

Observed Universe

Dark Matter Heating

Dark matter “heating”



e.g. Navarro et al. 1996; Read & Gilmore 2005; Pontzen & Governato 2012; Read et al. 2016

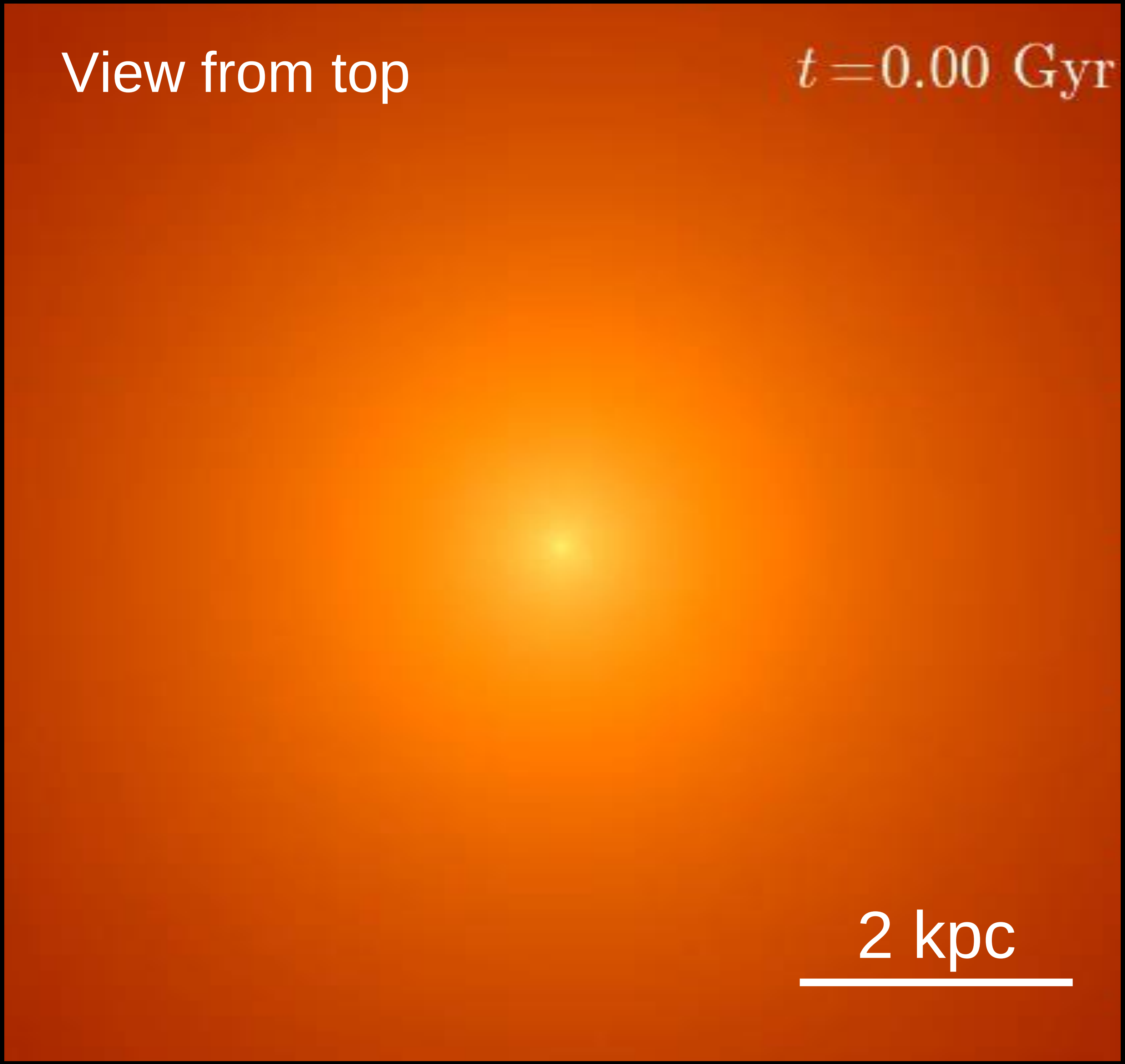
Dark matter heating

$\Delta x = 4\text{pc}$

$M_{\text{res}} = 300\text{M}_{\odot}$

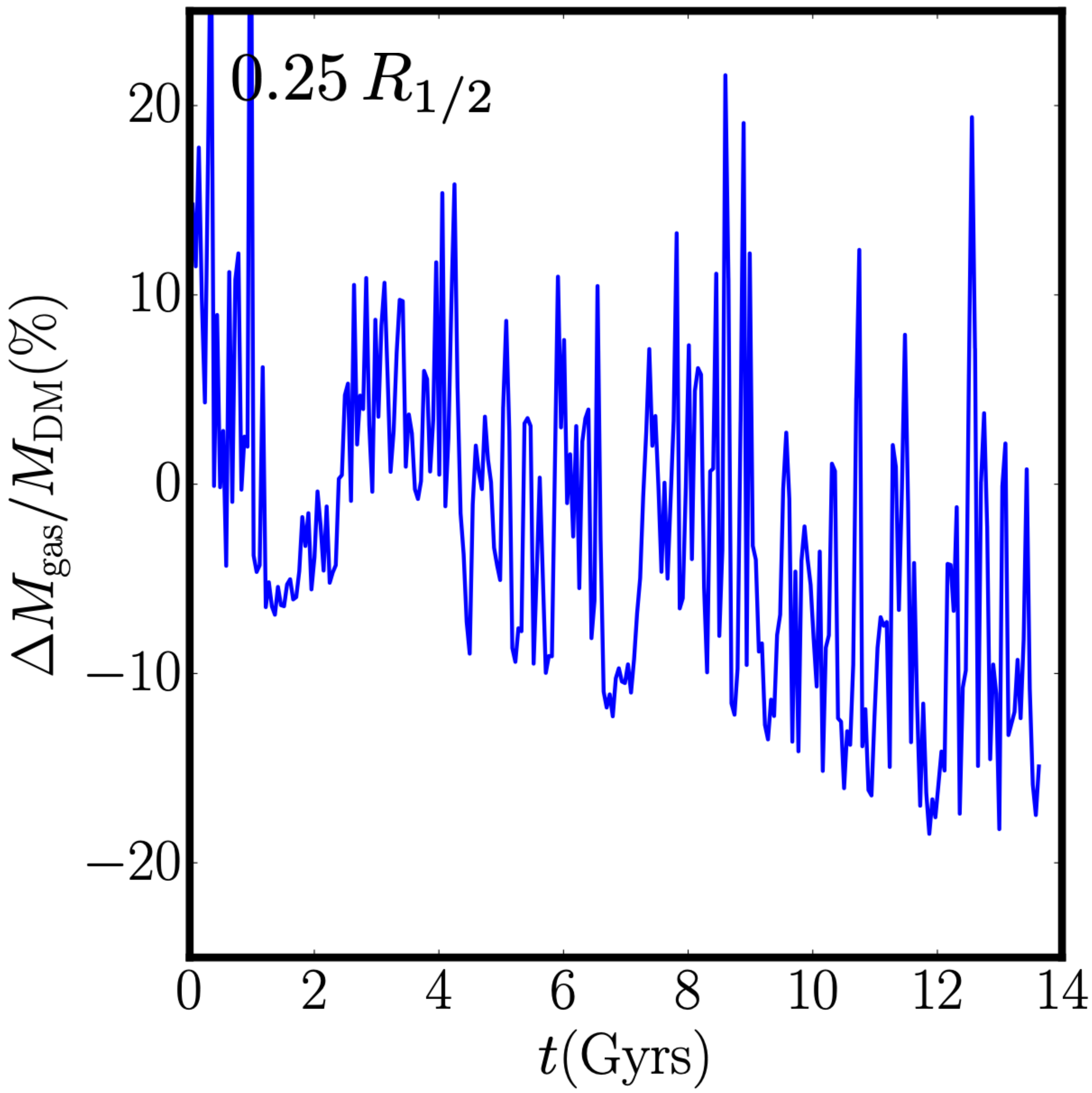
$\rho_{\text{th}} = 300\ \text{atoms/cc}$

$T_{\text{gas,min}} = 10\text{K}$



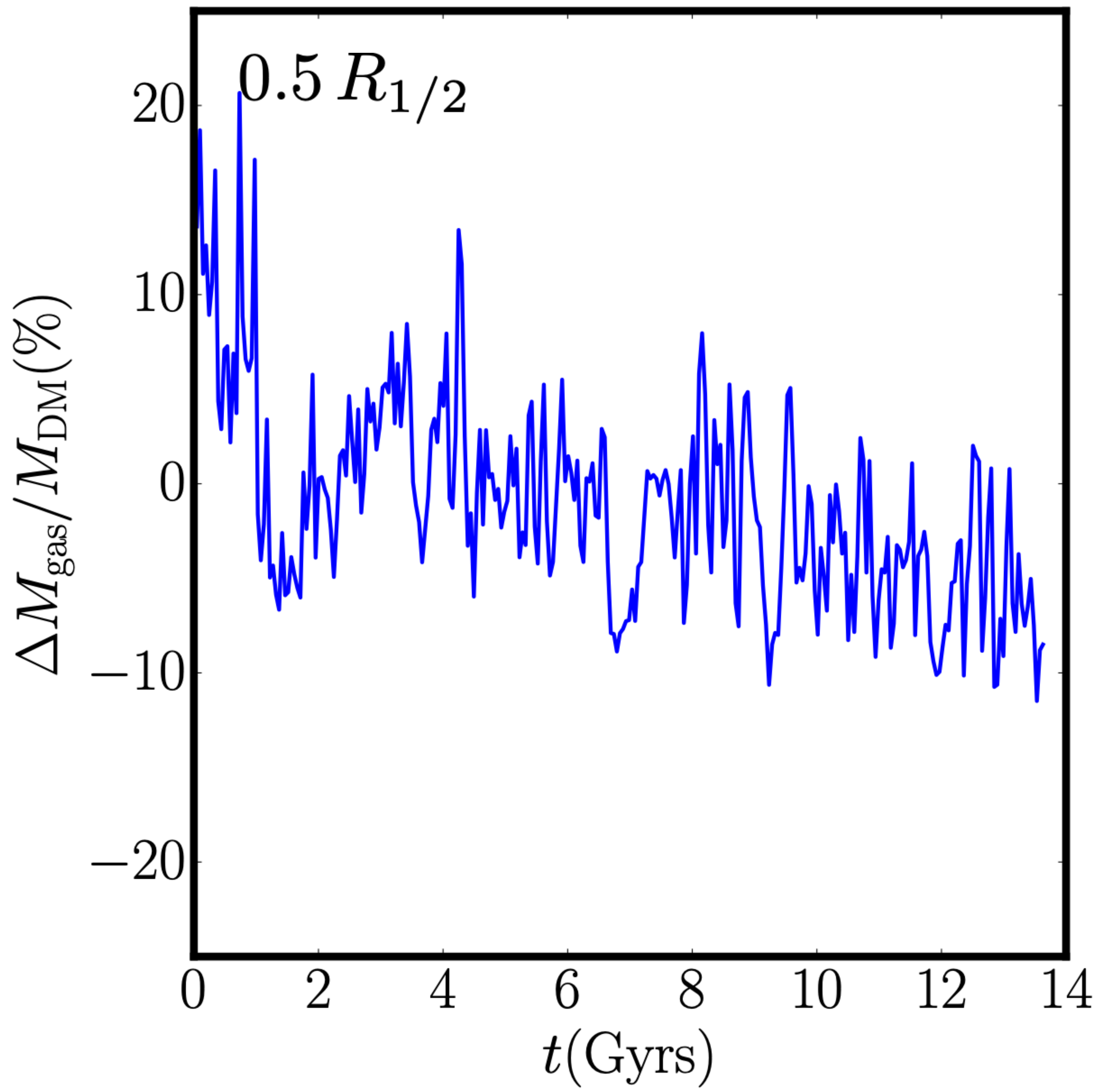
Navarro et al. 1996; Read & Gilmore 2005; Pontzen & Governato 2012; Read et al. 2016

Dark matter heating



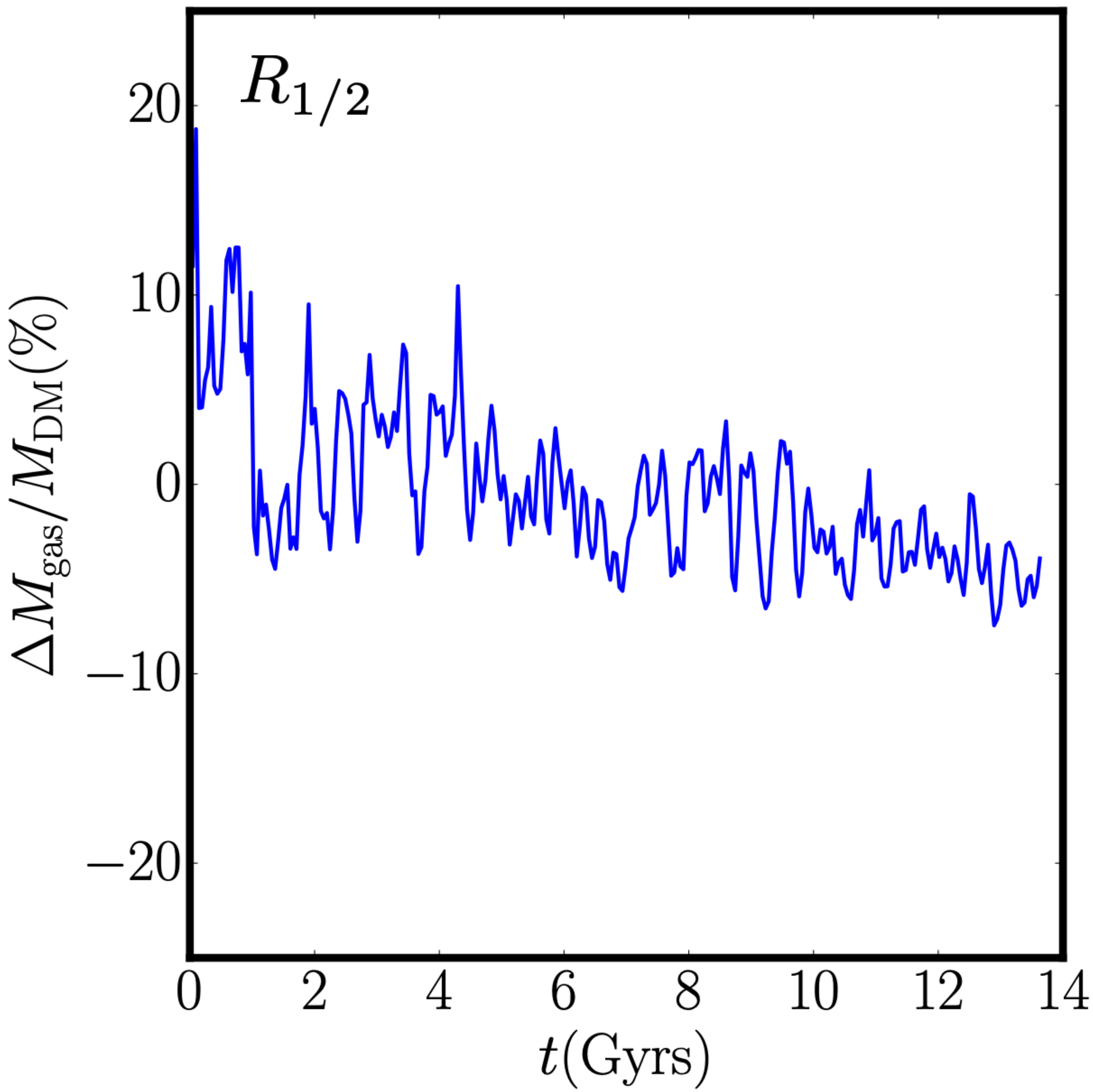
Read et al. 2016

Dark matter heating



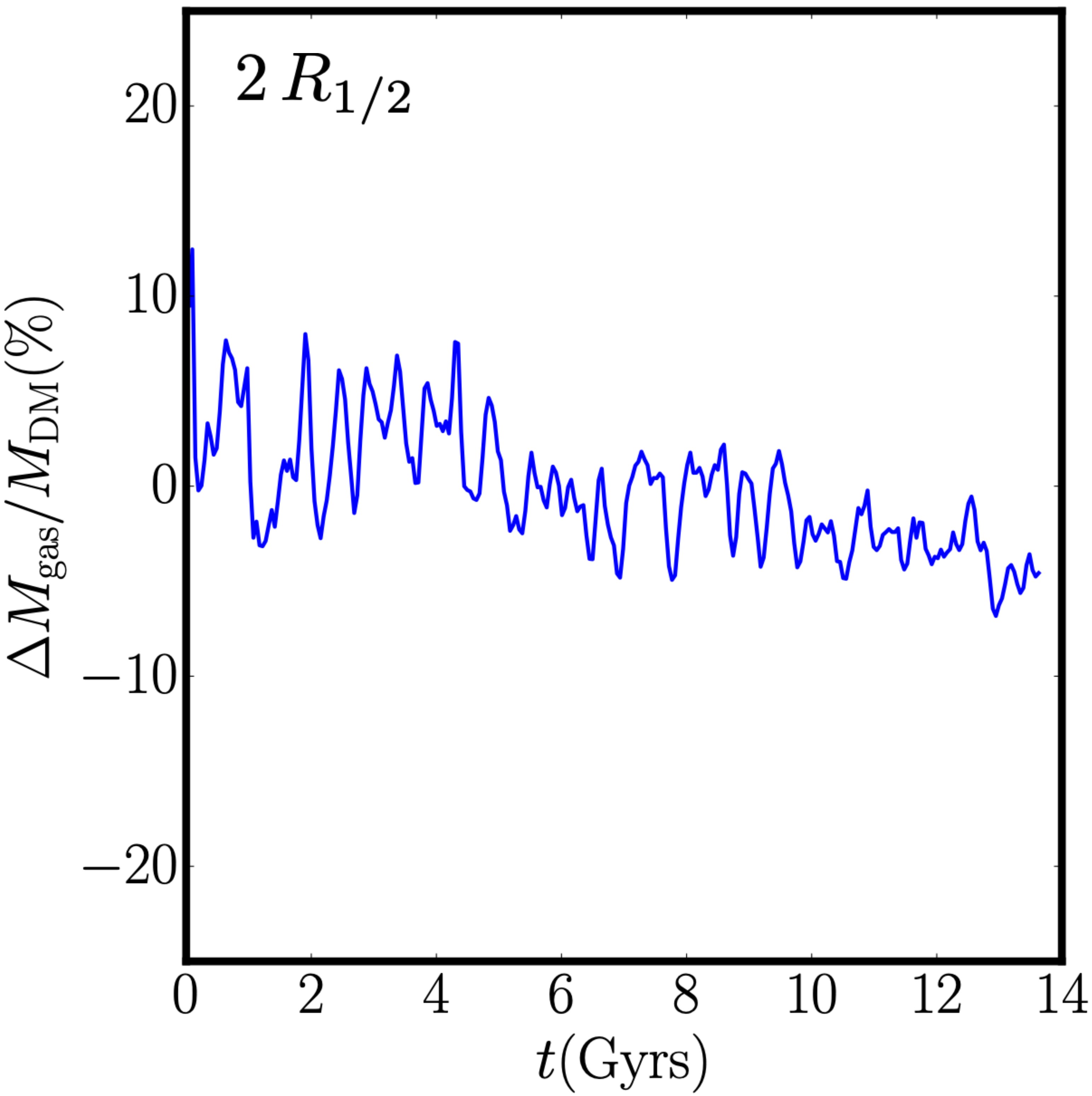
Read et al. 2016

Dark matter heating



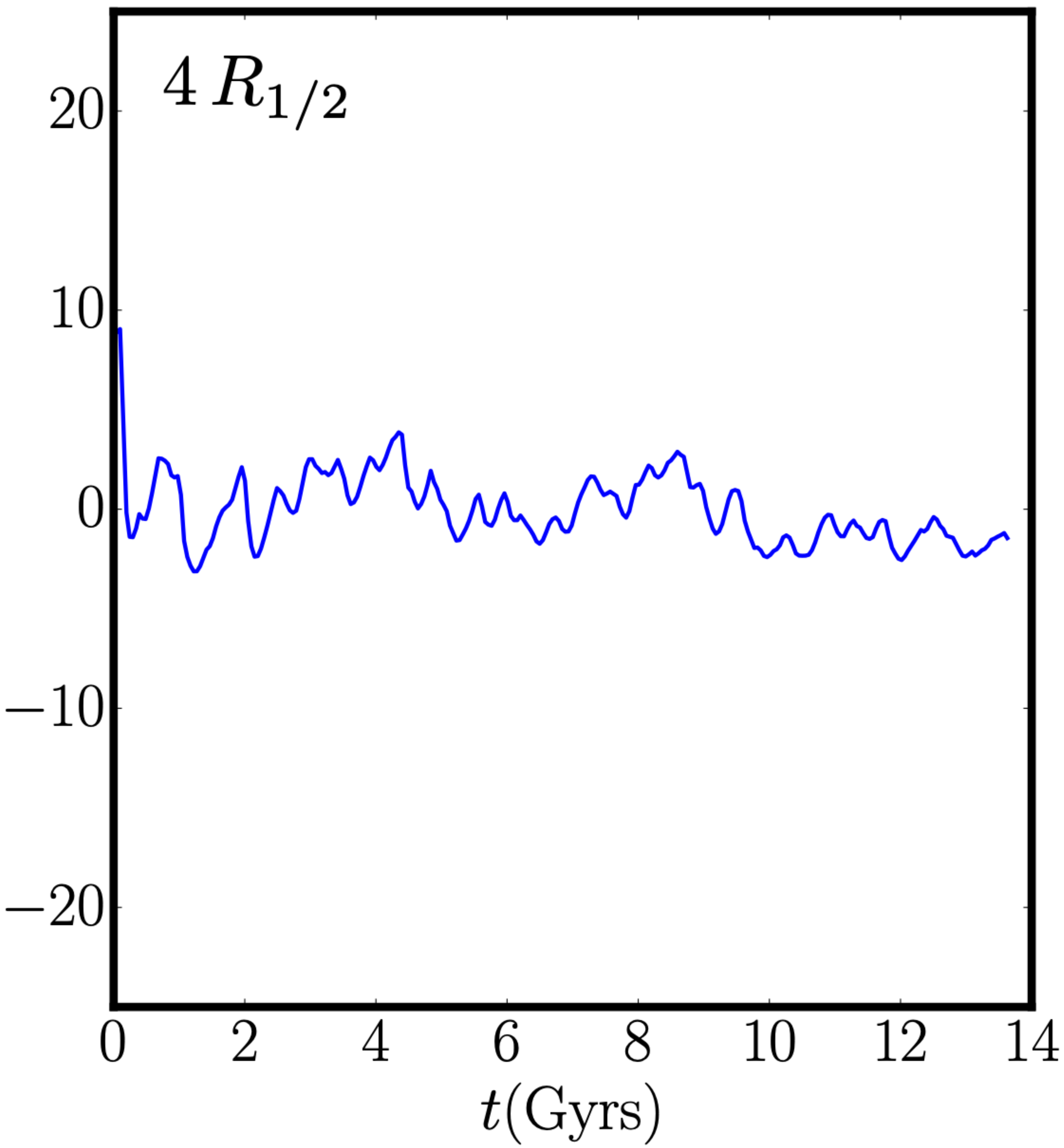
Read et al. 2016

Dark matter heating



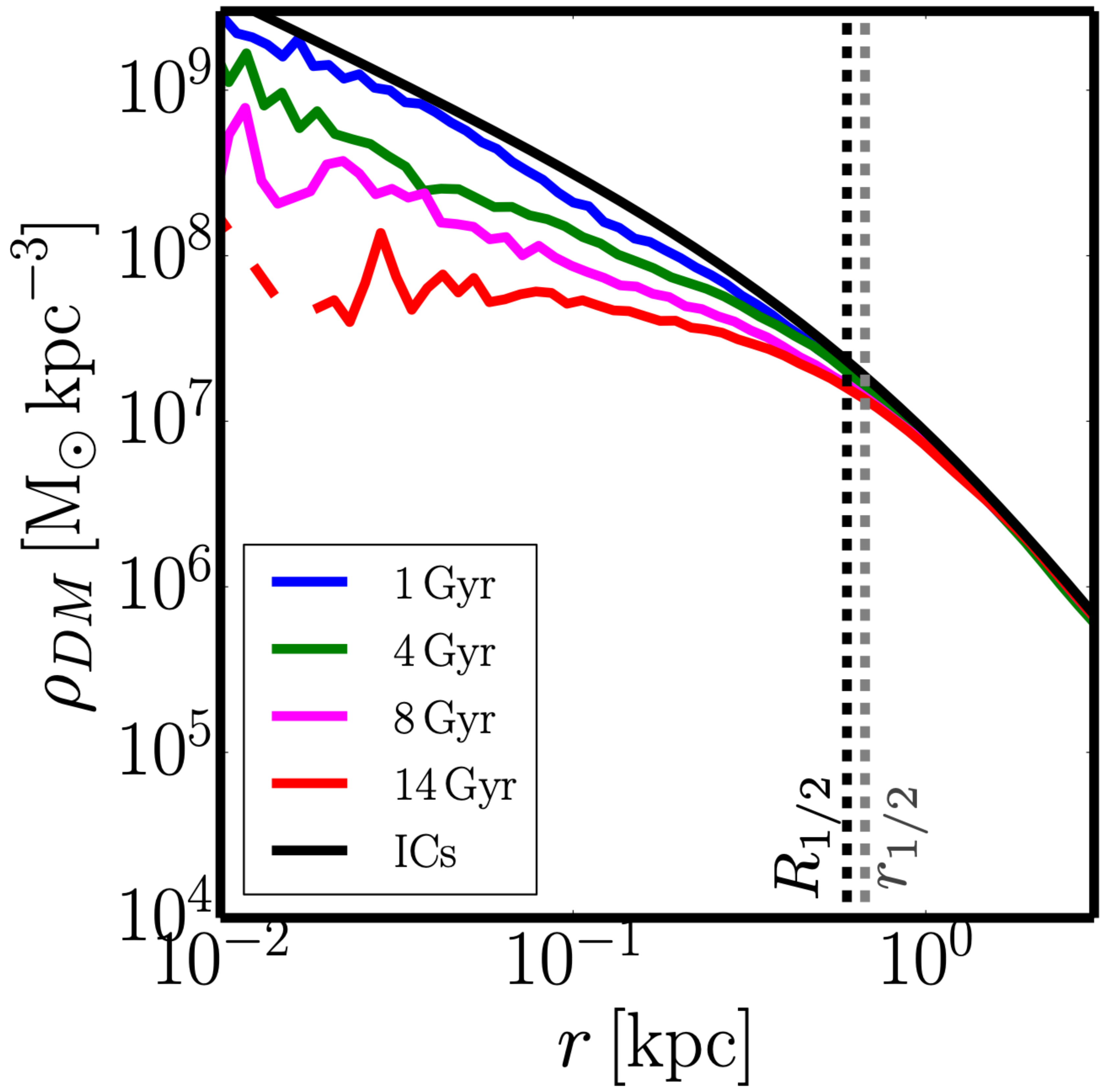
Read et al. 2016

Dark matter heating



Read et al. 2016

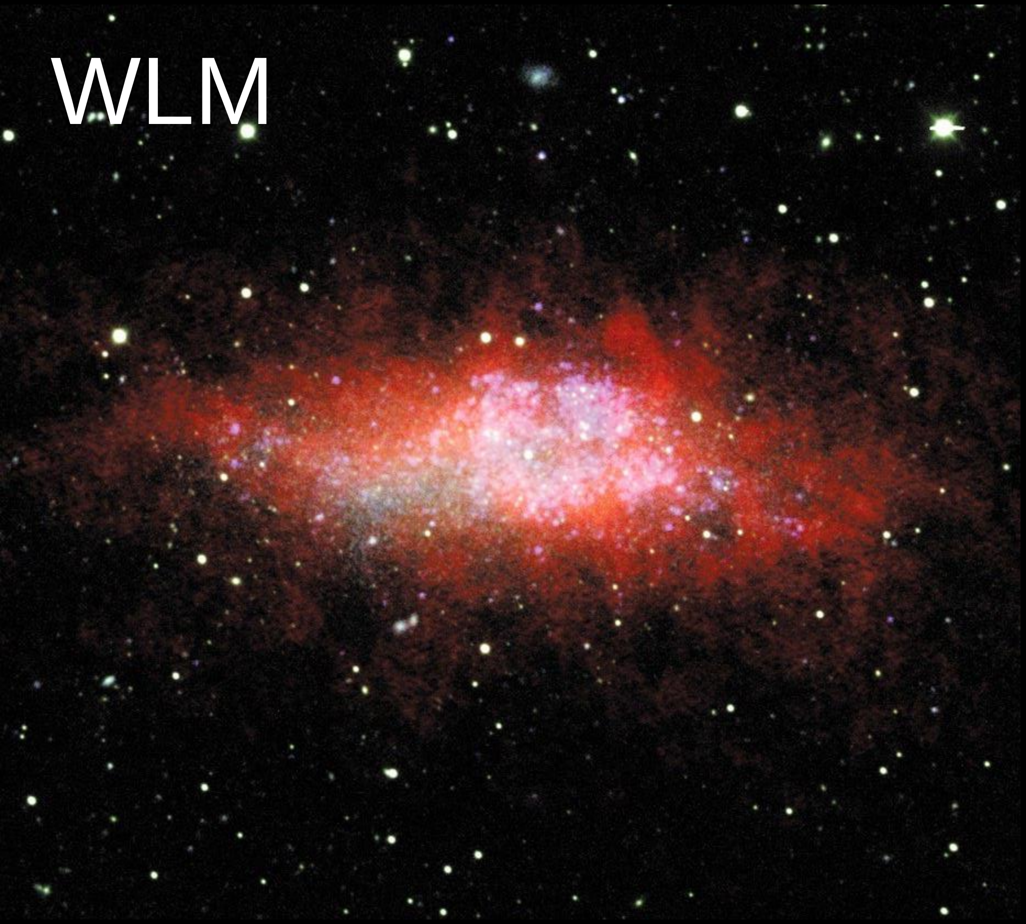
Dark matter heating



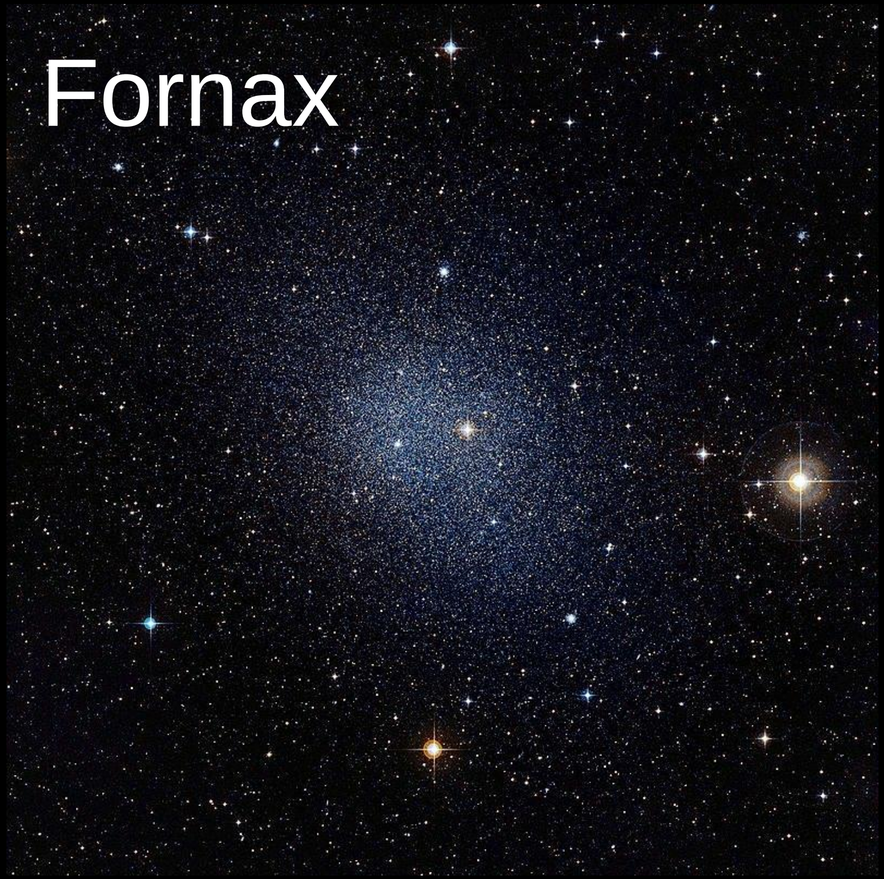
Read et al. 2016

“Smoking gun” evidence for DM heating

Dark matter heating | Evidence



Leroy, Nature 2015



ESO/Digitized Sky Survey 2

Robert Lupton & SDSS

Decreasing star formation
⇒
More DM cusp!

Dark matter heating | Evidence

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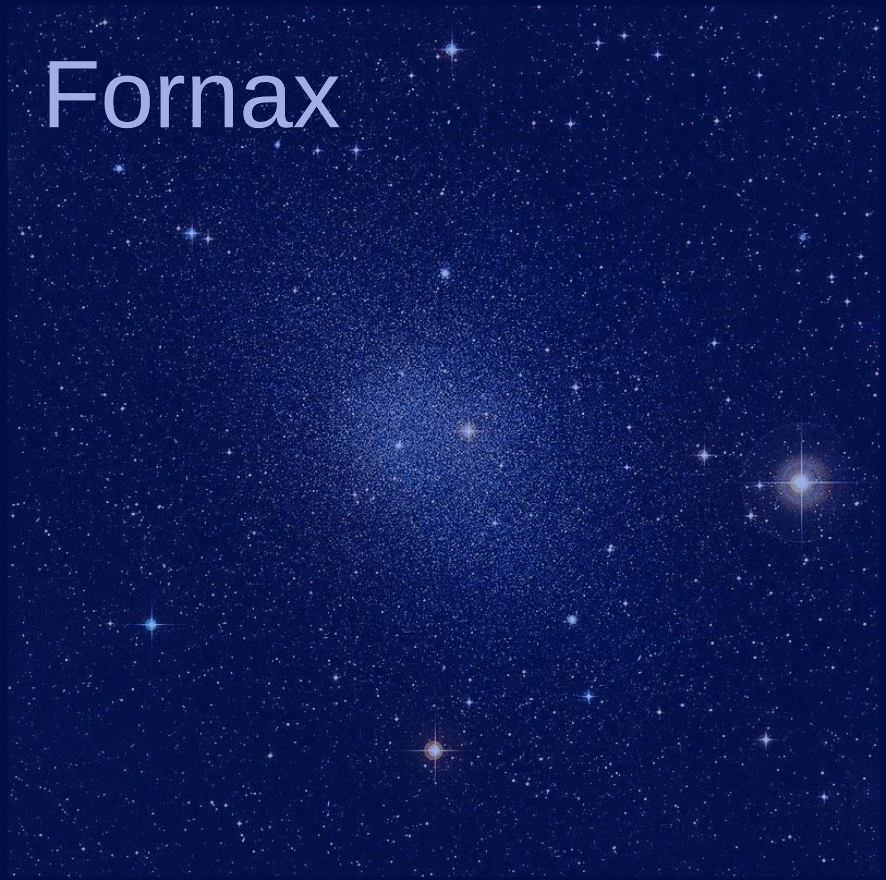
Leroy, Nature 2015



ESO/Digitized Sky Survey 2

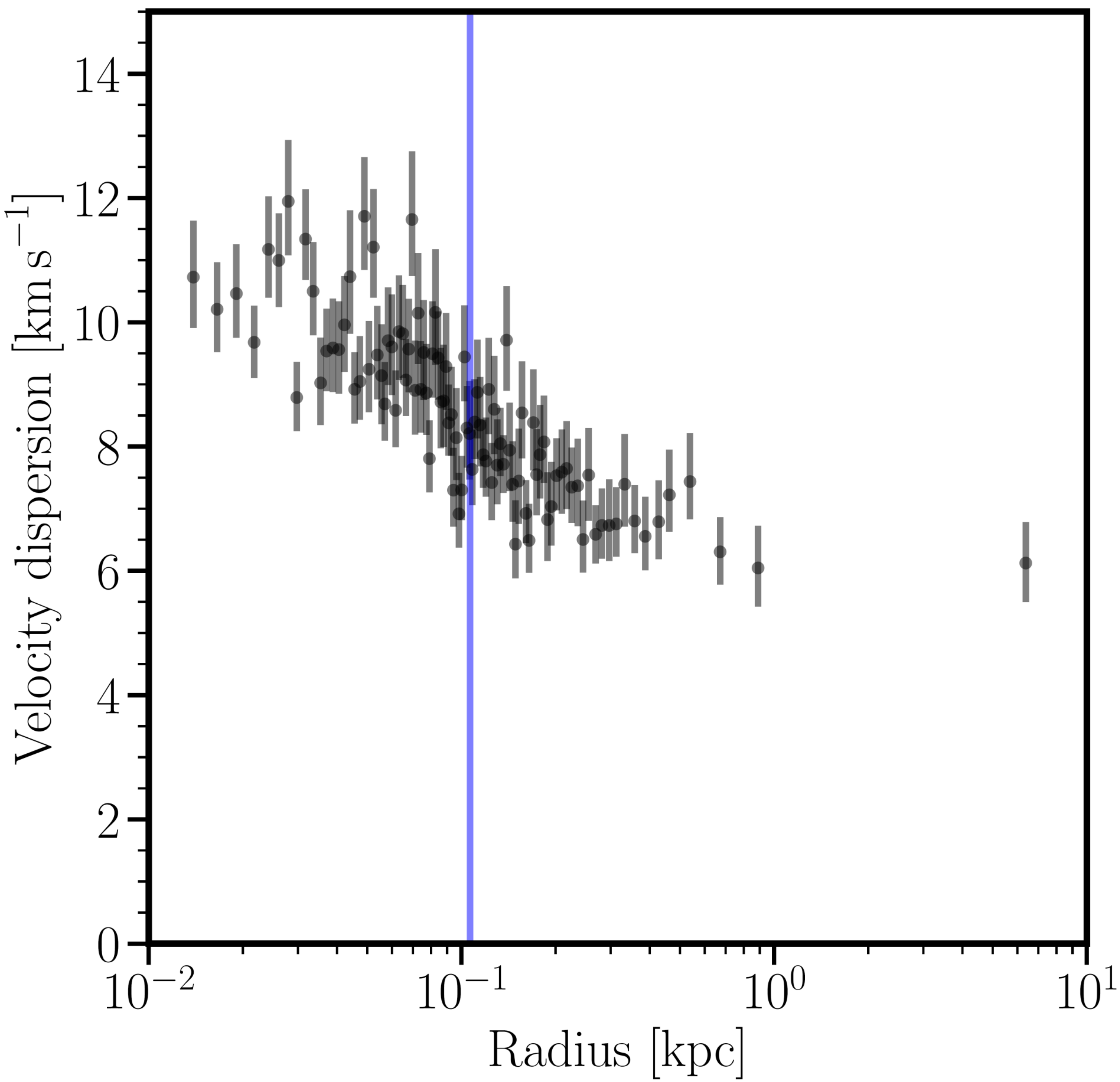
Robert Lupton & SDSS

Rotation curves

Stellar kinematics

Breaking the mass-anisotropy degeneracy

Breaking the mass-anisotropy degeneracy



Breaking the mass-anisotropy degeneracy

$$\sigma_{\rm LOS}^2(R) = \frac{2}{\Sigma_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} \mathrm{d}r,$$

$$\sigma_r^2(r) = \frac{1}{\nu(r)g(r)} \int_r^\infty \frac{GM(\tilde{r})\nu(\tilde{r})}{\tilde{r}^2} g(\tilde{r}) \mathrm{d}\tilde{r}$$

$$g(r) = \exp\left(2\int \frac{\beta(r)}{r} \mathrm{d}r\right)$$

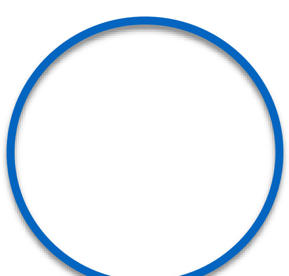
Read & Steger 2017

Breaking the mass-anisotropy degeneracy

$$\sigma_{\rm LOS}^2(R) = \frac{2}{\Sigma_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu(r)\sigma_r^2(r) r}{\sqrt{r^2 - R^2}} \mathrm{d}r,$$

$$\sigma_r^2(r) = \frac{1}{\nu(r) g(r)} \int_r^\infty \frac{GM(\tilde{r})\nu(\tilde{r})}{\tilde{r}^2} g(\tilde{r}) \mathrm{d}\tilde{r}$$

$$g(r) = \exp\left(2 \int \frac{\beta(r)}{r} \mathrm{d}r\right)$$



$\beta = 0$

Read & Steger 2017

Breaking the mass-anisotropy degeneracy

$$\sigma_{\rm LOS}^2(R) = \frac{2}{\Sigma_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu(r)\sigma_r^2(r) r}{\sqrt{r^2 - R^2}} \mathrm{d}r,$$

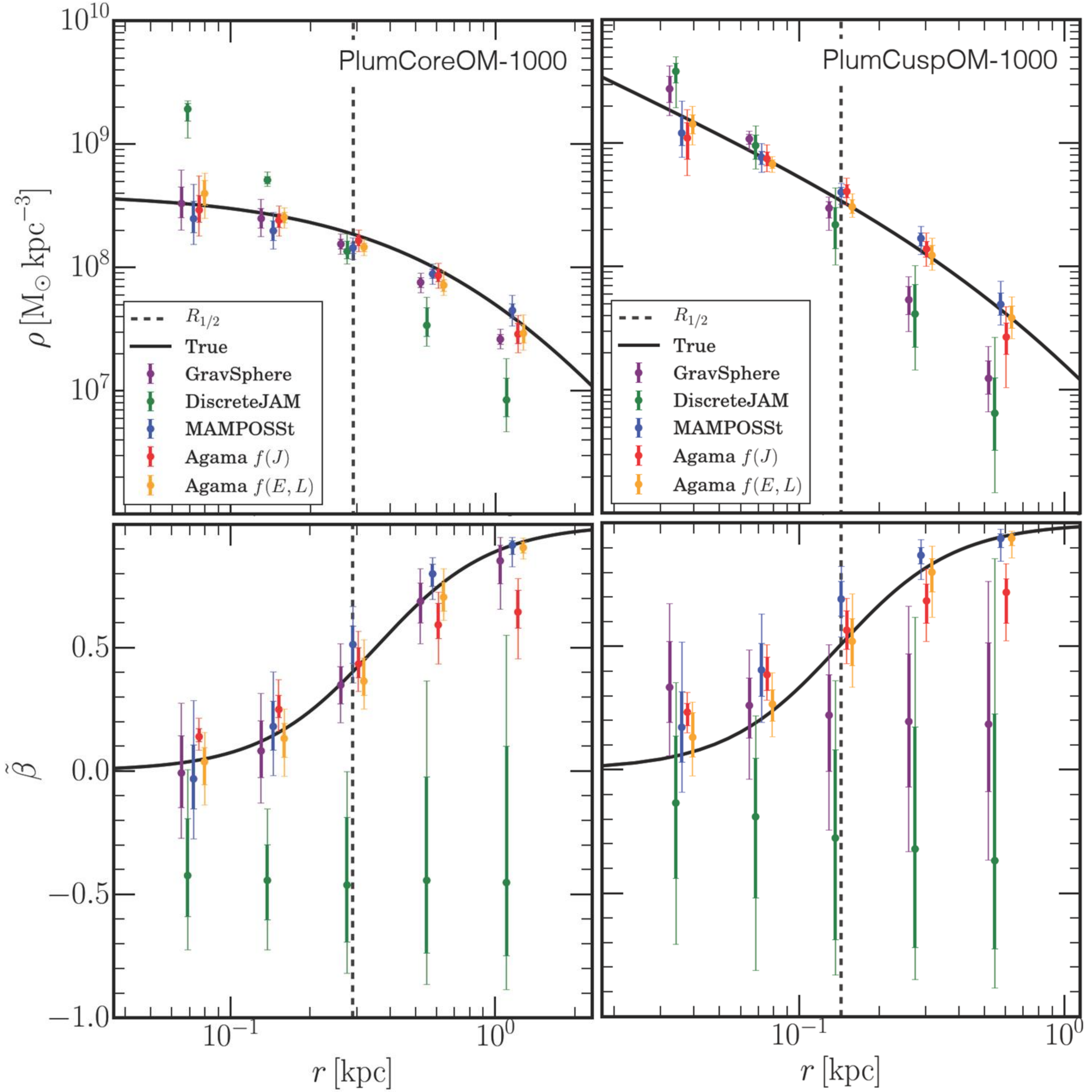
$$\sigma_r^2(r) = \frac{1}{\nu(r) g(r)} \int_r^\infty \frac{G M(\tilde{r}) \nu(\tilde{r})}{\tilde{r}^2} g(\tilde{r}) \mathrm{d}\tilde{r}$$

$$g(r) = \exp\left(2 \int \frac{\beta(r)}{r} \mathrm{d}r\right)$$

$\beta = 1$

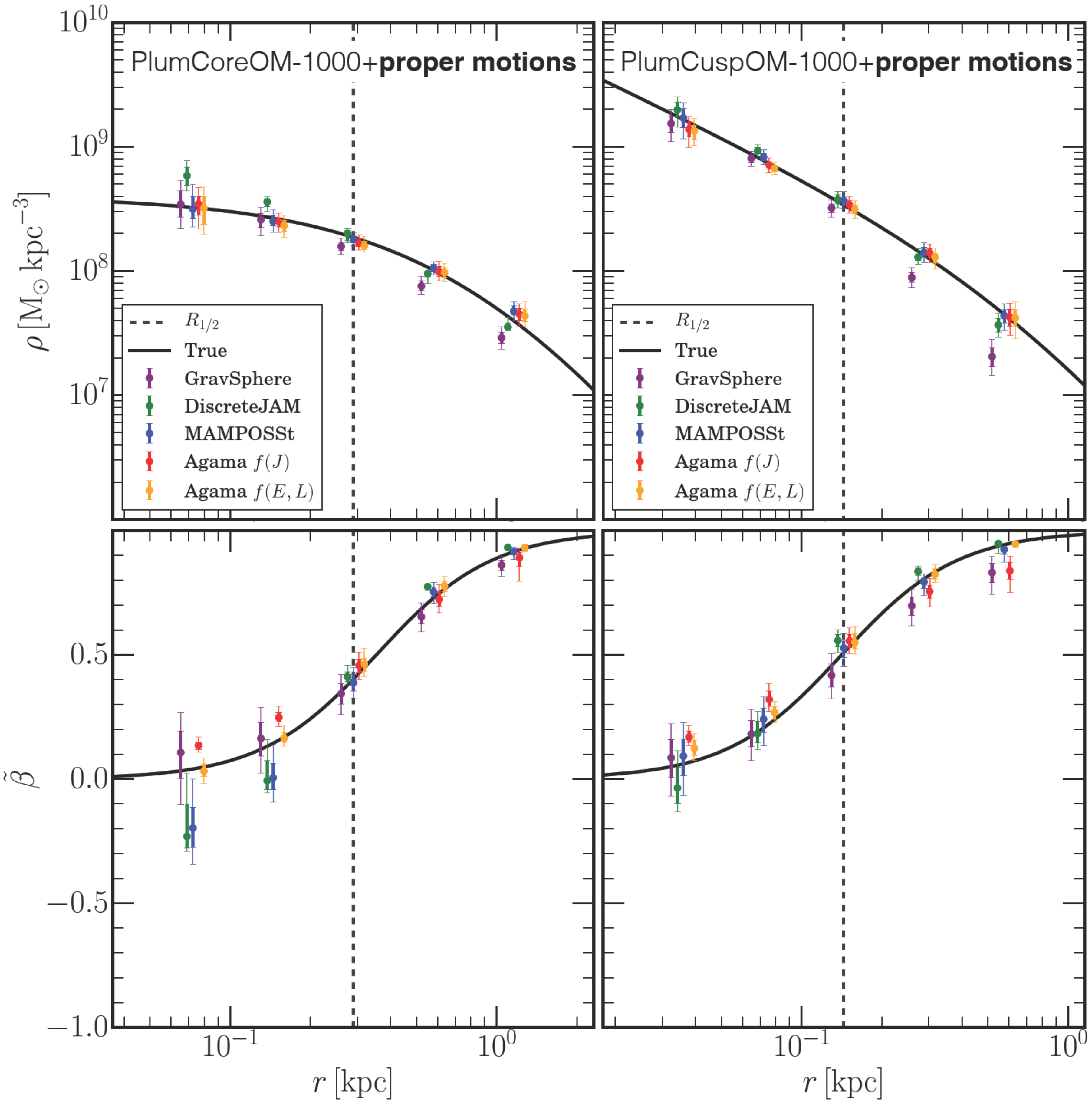
Read & Steger 2017

Breaking the mass-anisotropy degeneracy



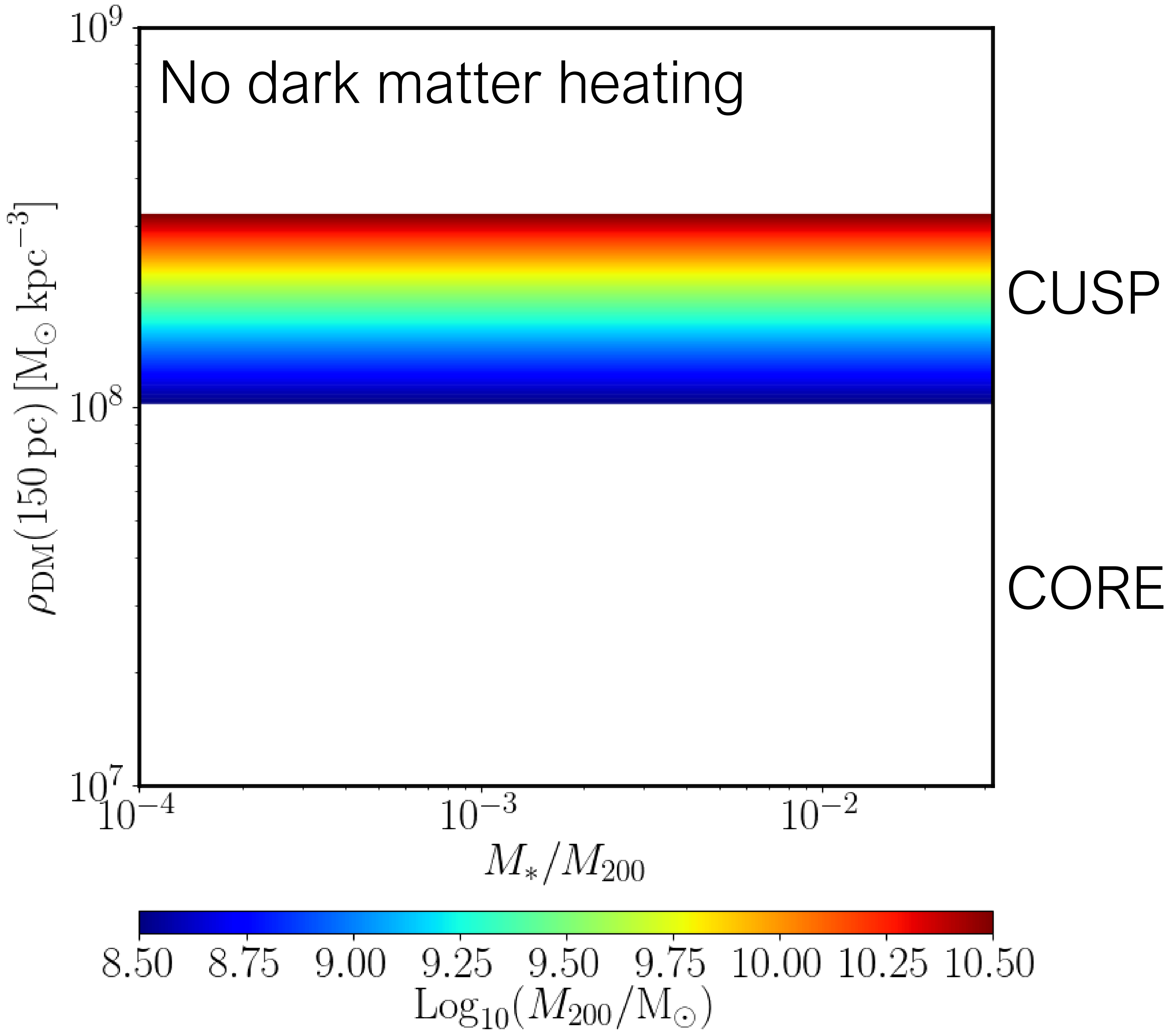
Read et al. 2021

Breaking the mass-anisotropy degeneracy

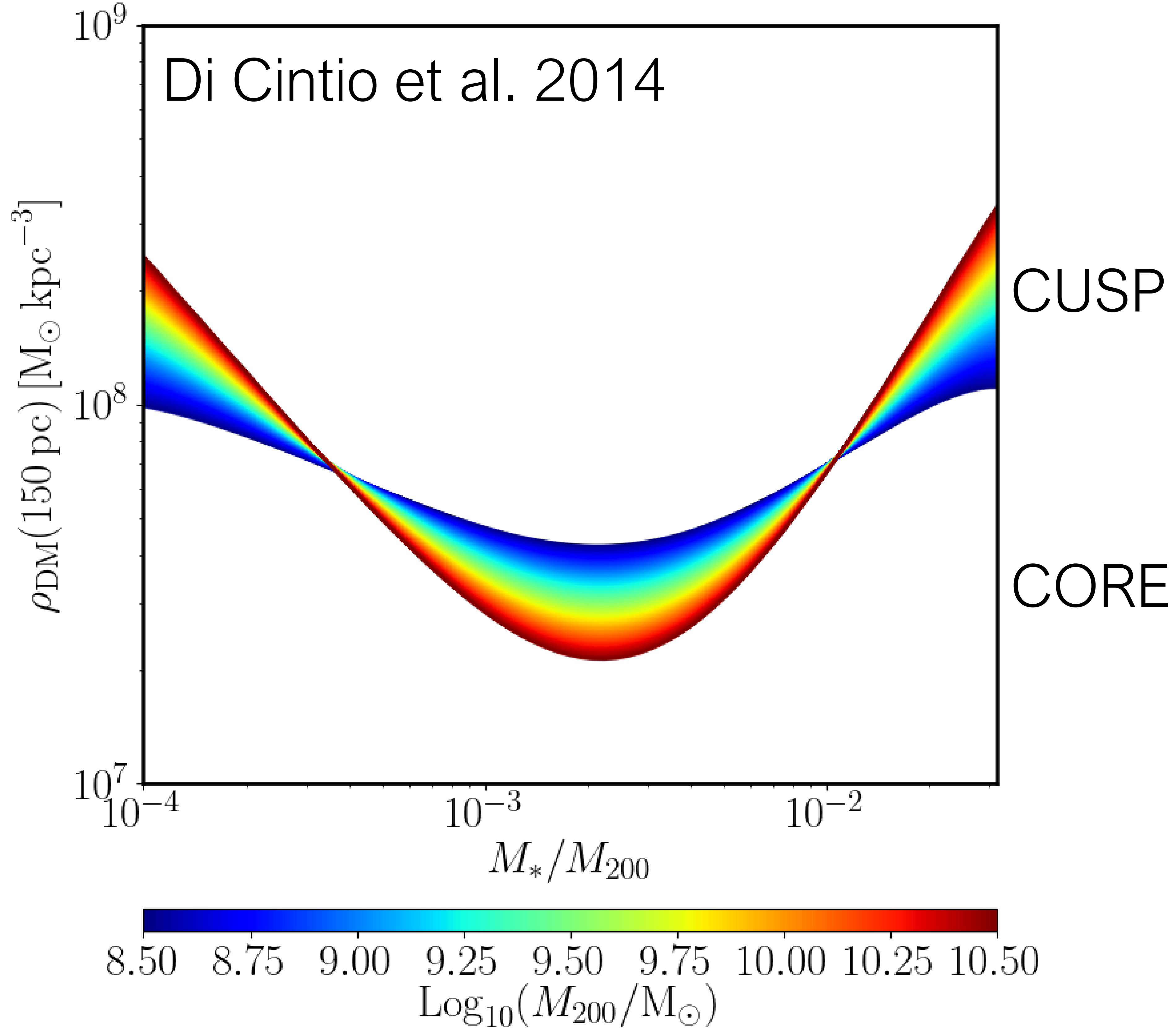


Read et al. 2021

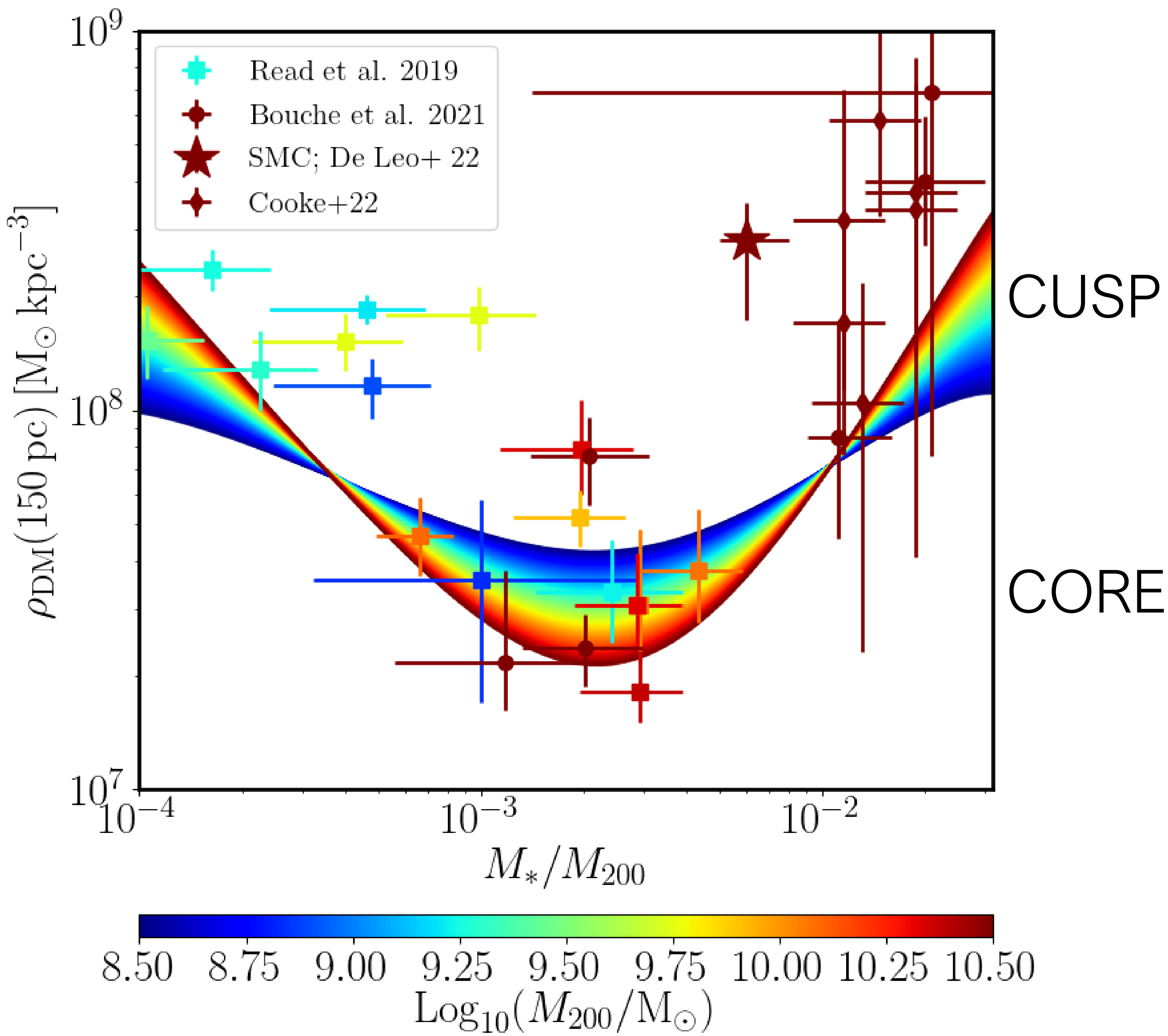
Dark matter heating | Evidence



Dark matter heating | Evidence



Dark matter heating | Evidence



Read et al. 2019, De Leo et al. 2023

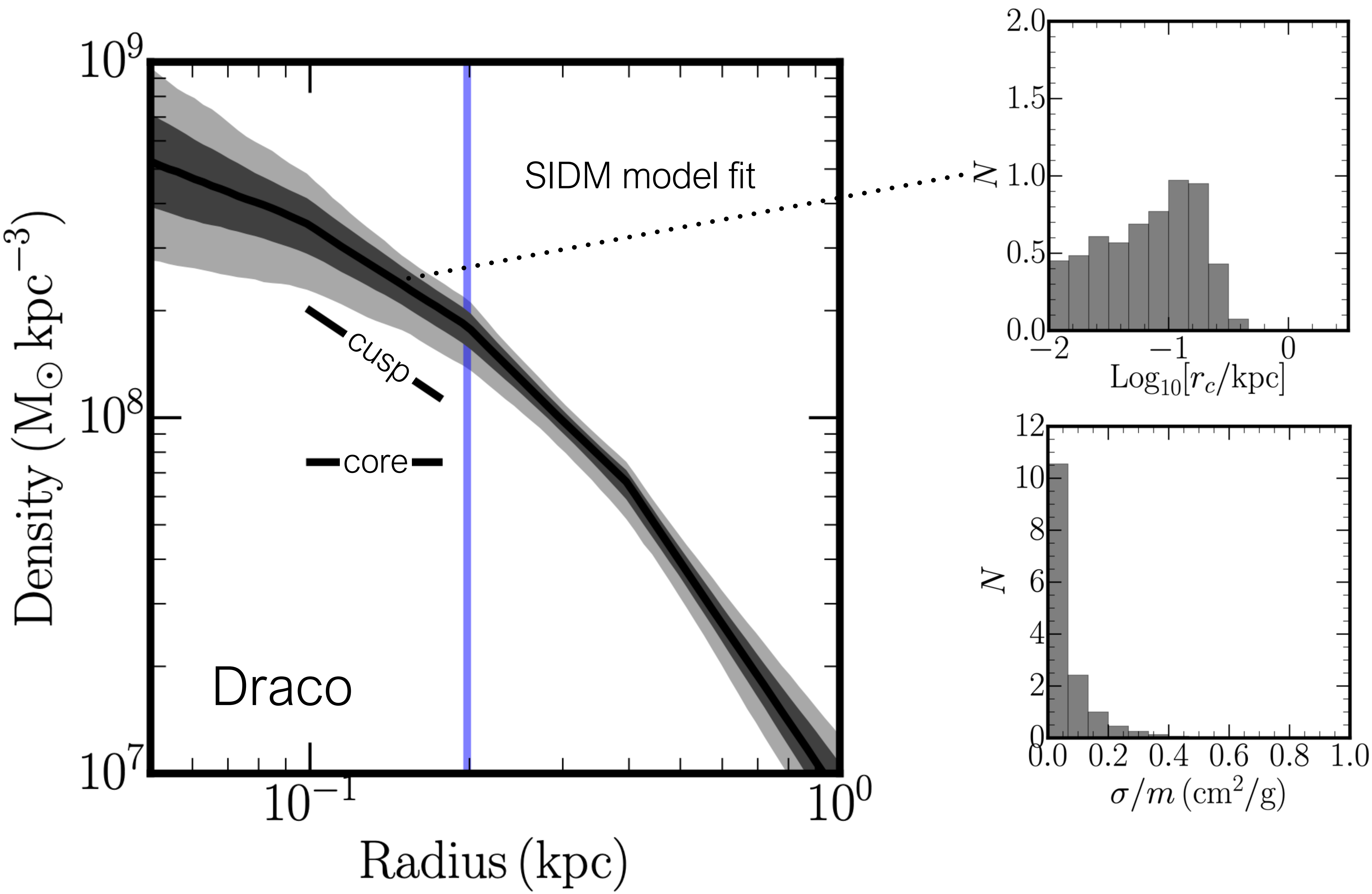
Dark matter heating | Evidence

#1 Dark matter is (most likely) a particle

#2 Use densest dwarfs to test models

Read et al. 2019, De Leo et al. 2023

Self interacting dark matter

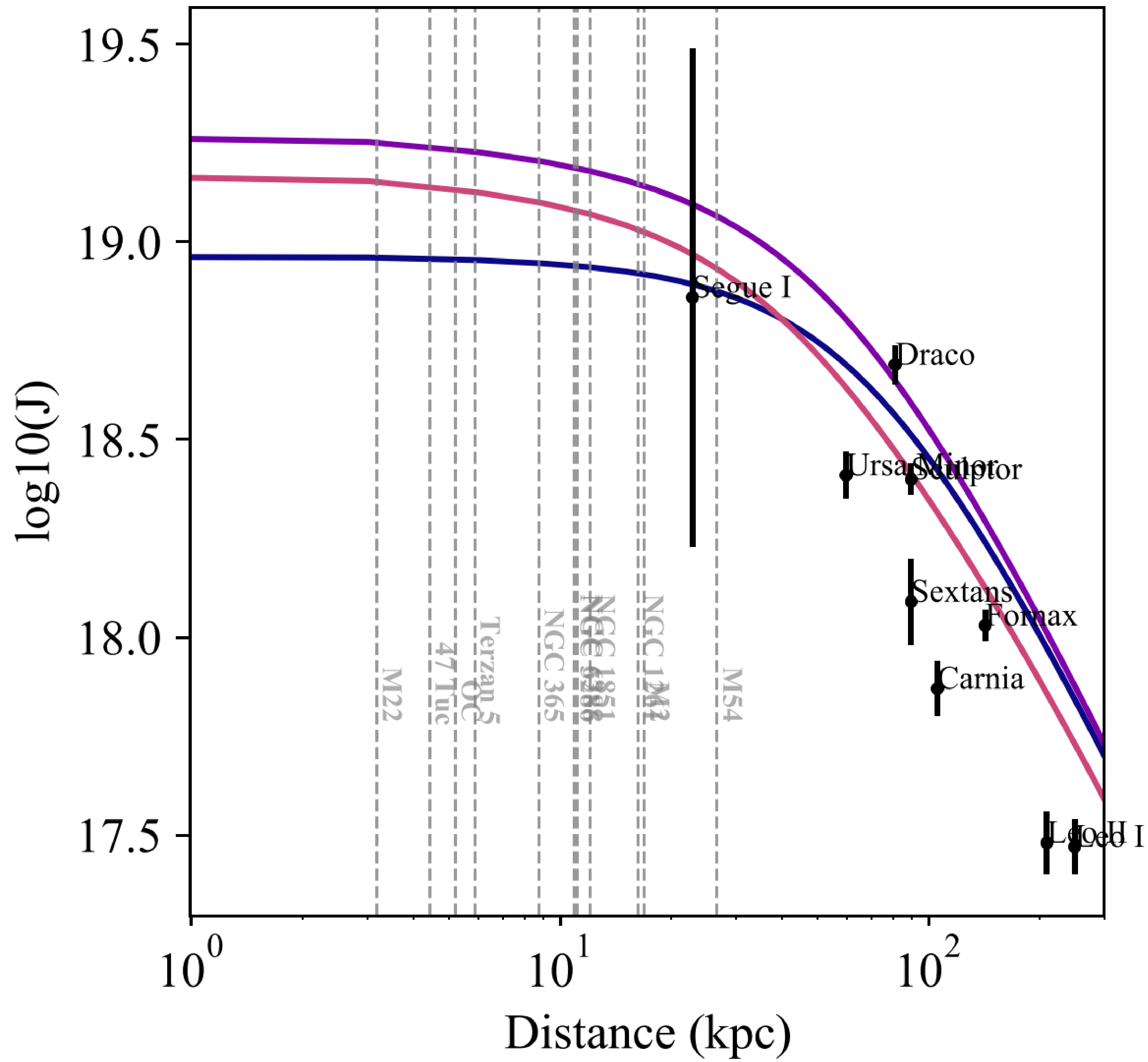


$$\sigma/m \ < \ 0.57\,\mathrm{cm}^2\,\mathrm{g}^{-1} \ \text{ at } \ 99\% \ \text{ confidence.}$$

Read et al. 2018 (arXiv:1805.06934) | But see Kaplinghat et al. 2019 & Omid et al. 2019

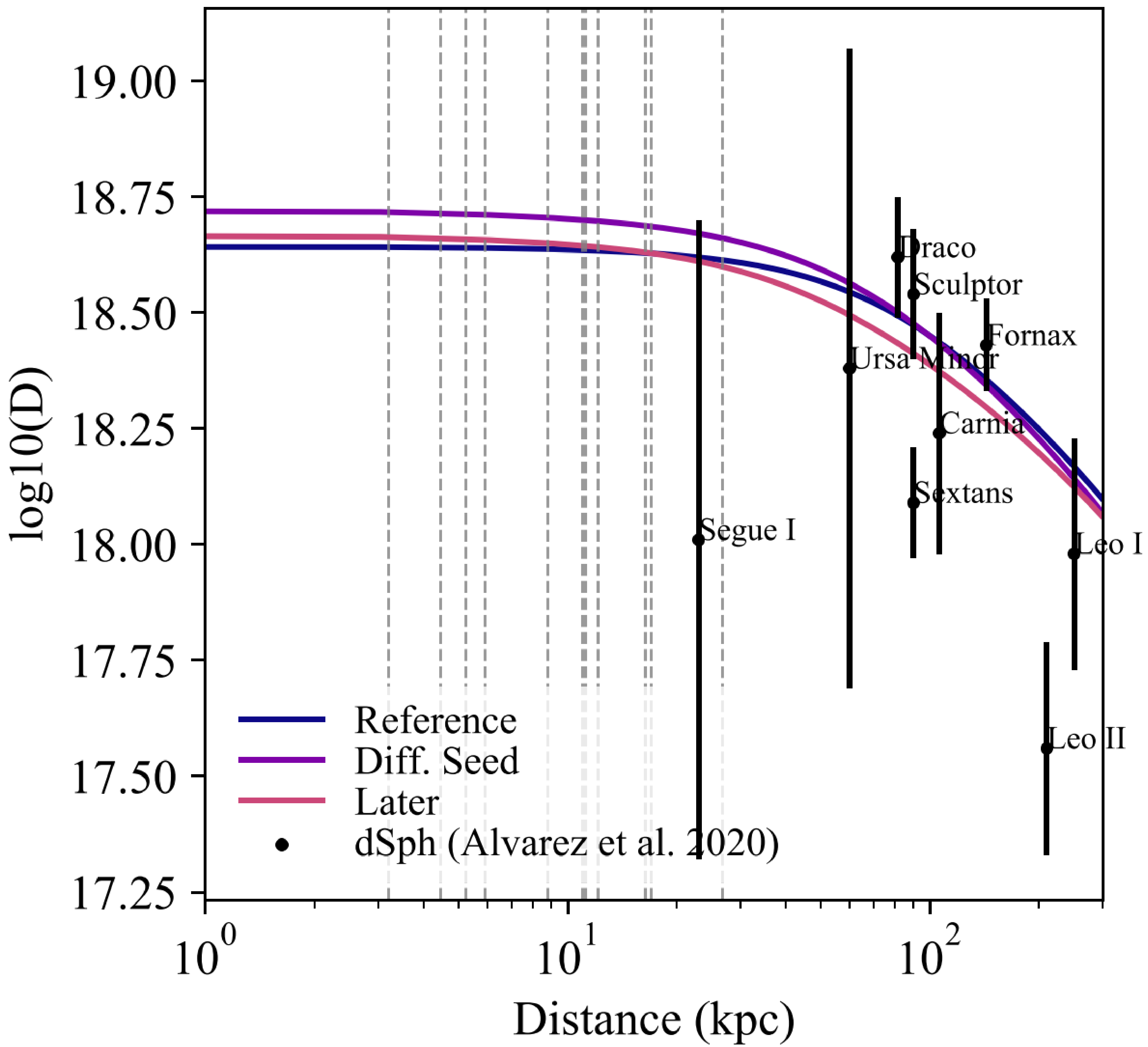
Annihilation & Decay of Dark Matter Particles

Annihilation & Decay | Where to look?



Alvarez et al. 2020; Gray et al. 2024; Gray et al. in prep.

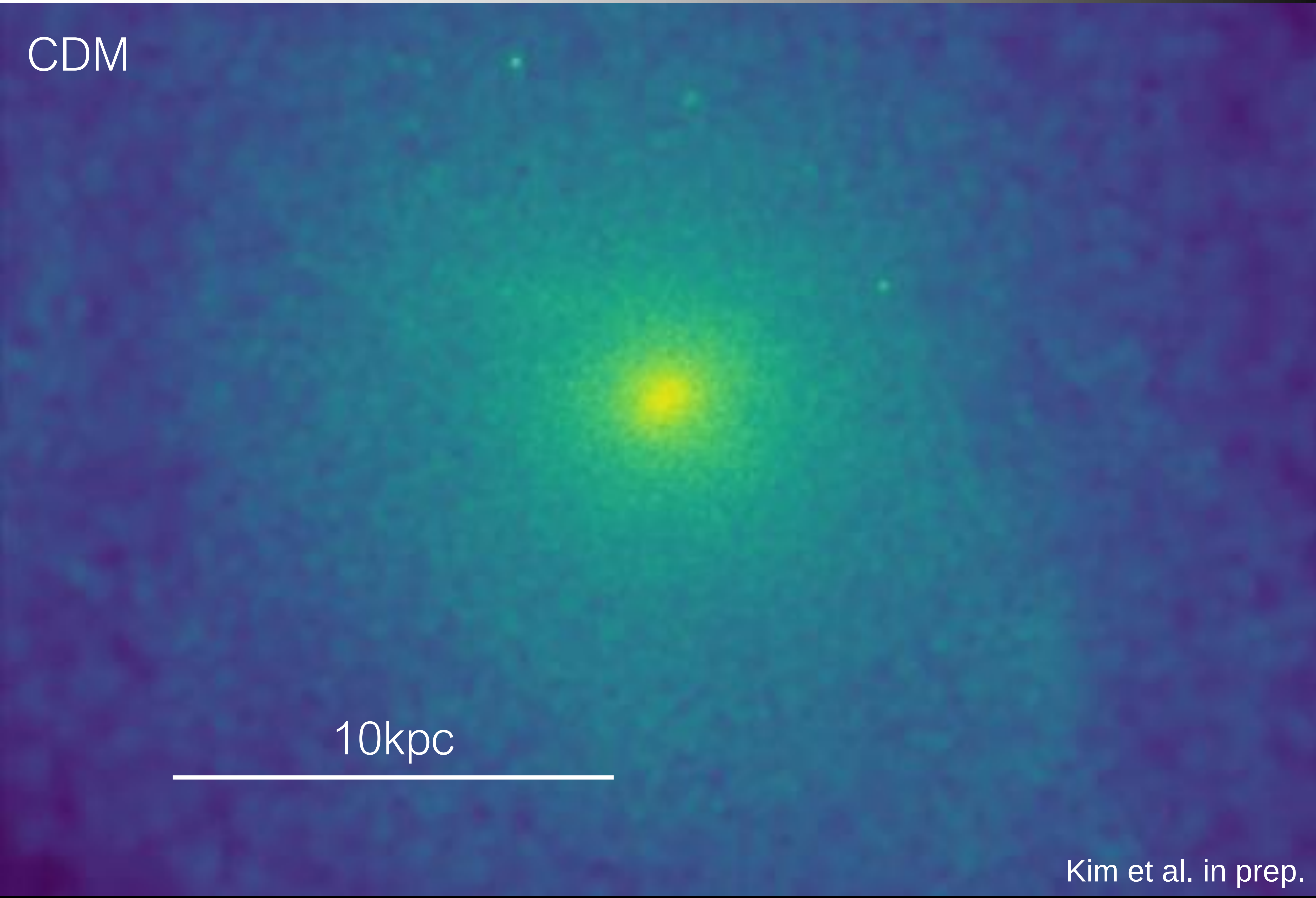
Annihilation & Decay | Where to look?



Alvarez et al. 2020; Gray et al. 2024; Gray et al. in prep.

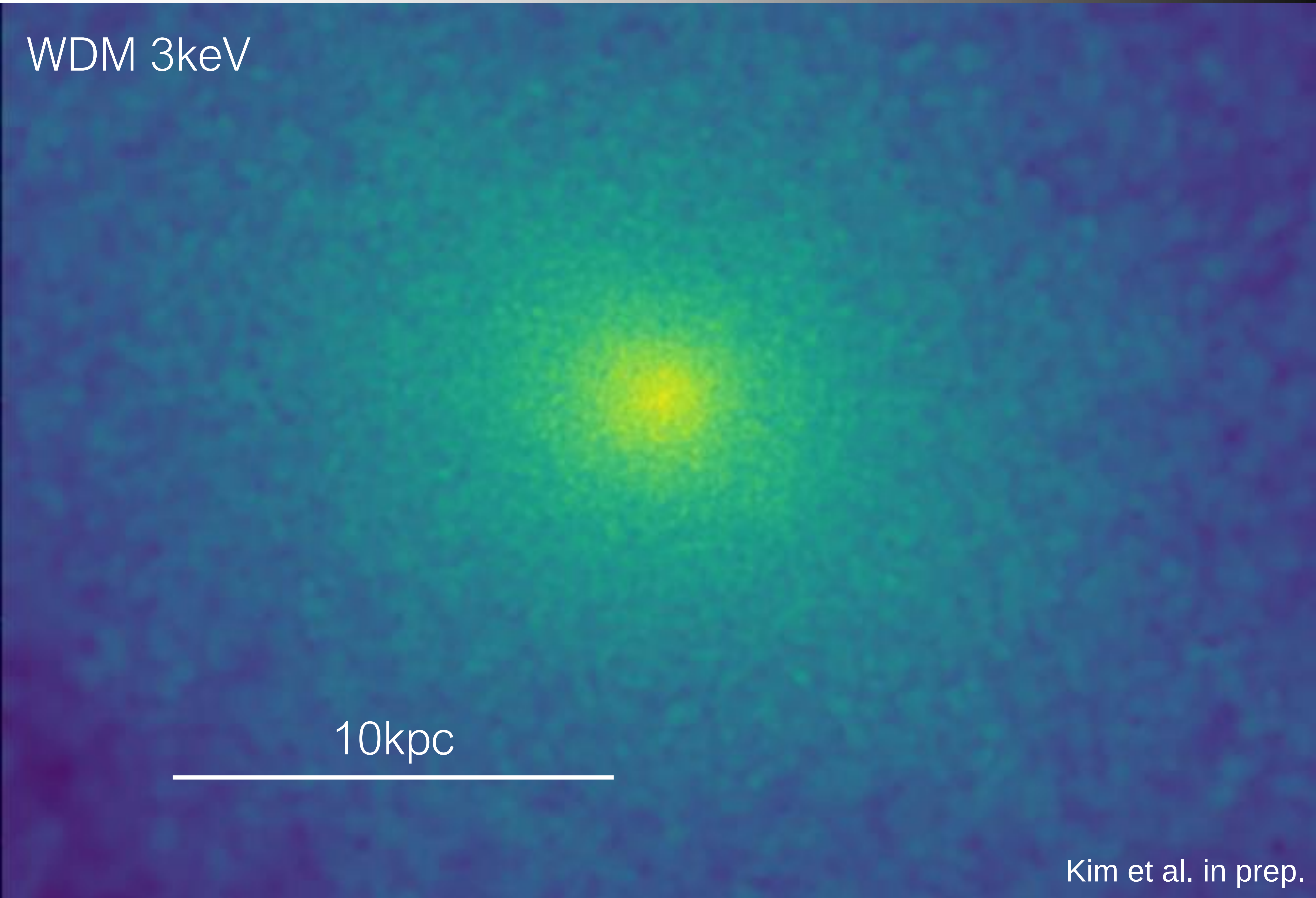
New Ideas

New ideas | Dwarf stellar halos



Kim et al. in prep.

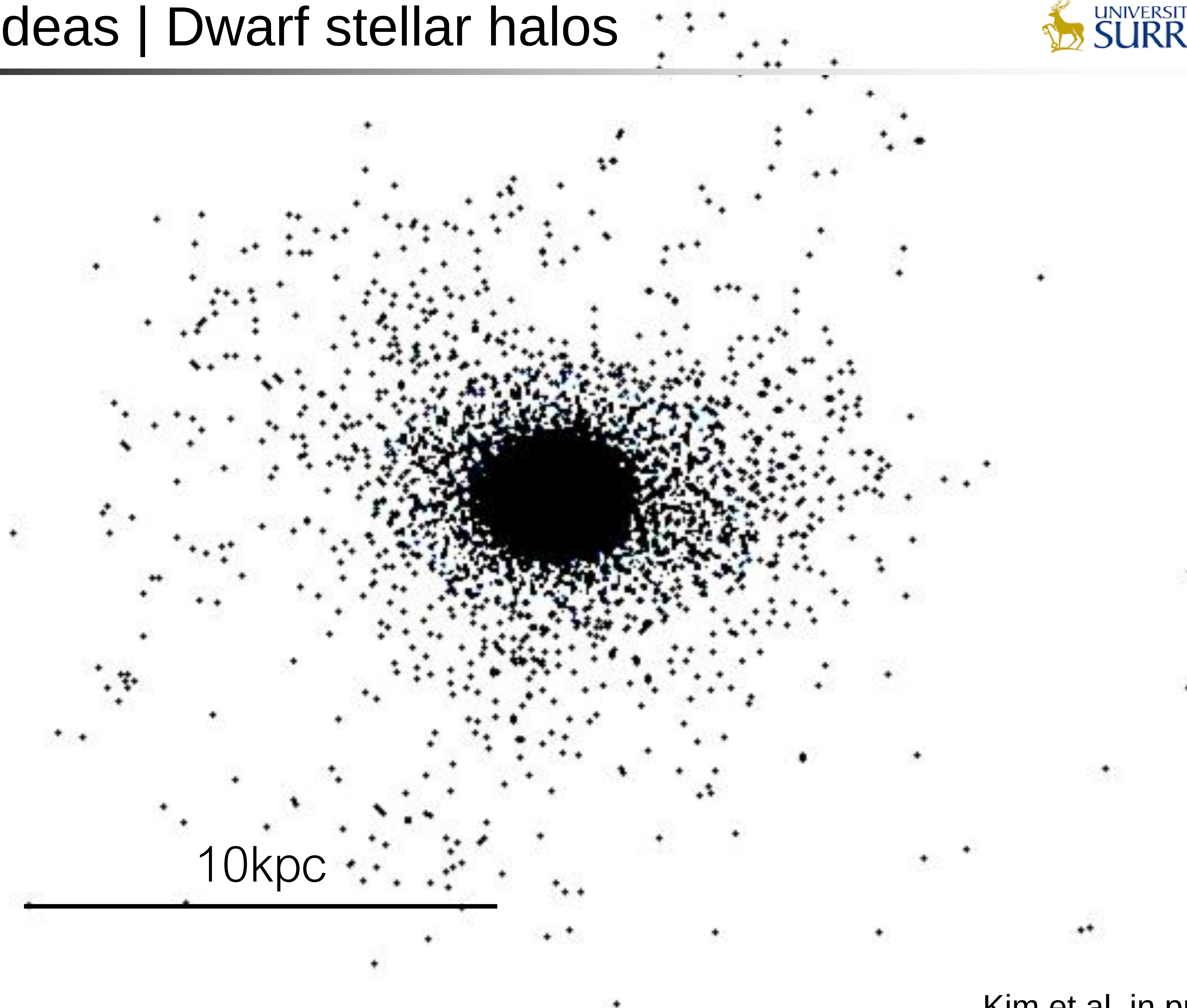
New ideas | Dwarf stellar halos



Kim et al. in prep.

New ideas | Dwarf stellar halos

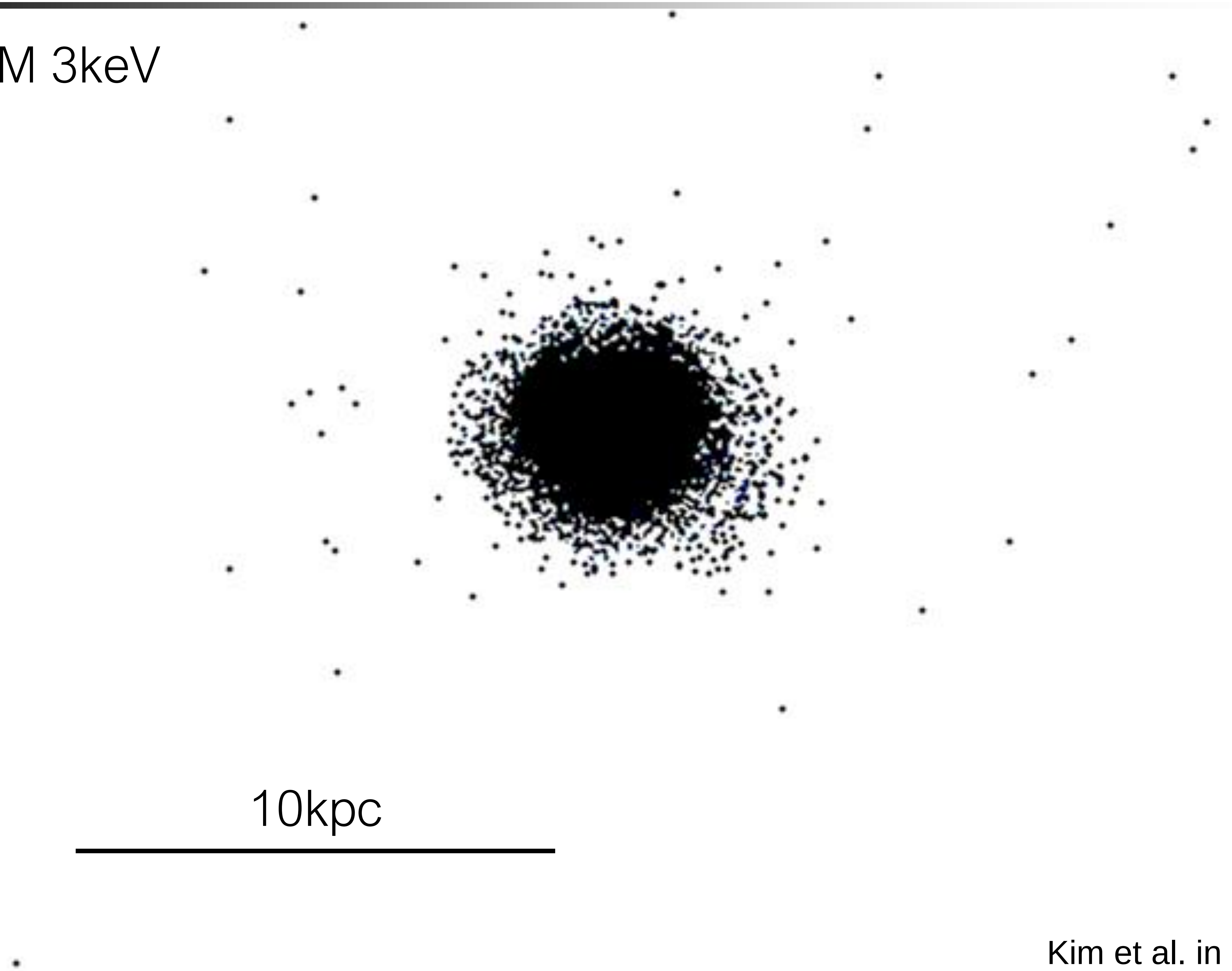
CDM



Kim et al. in prep.

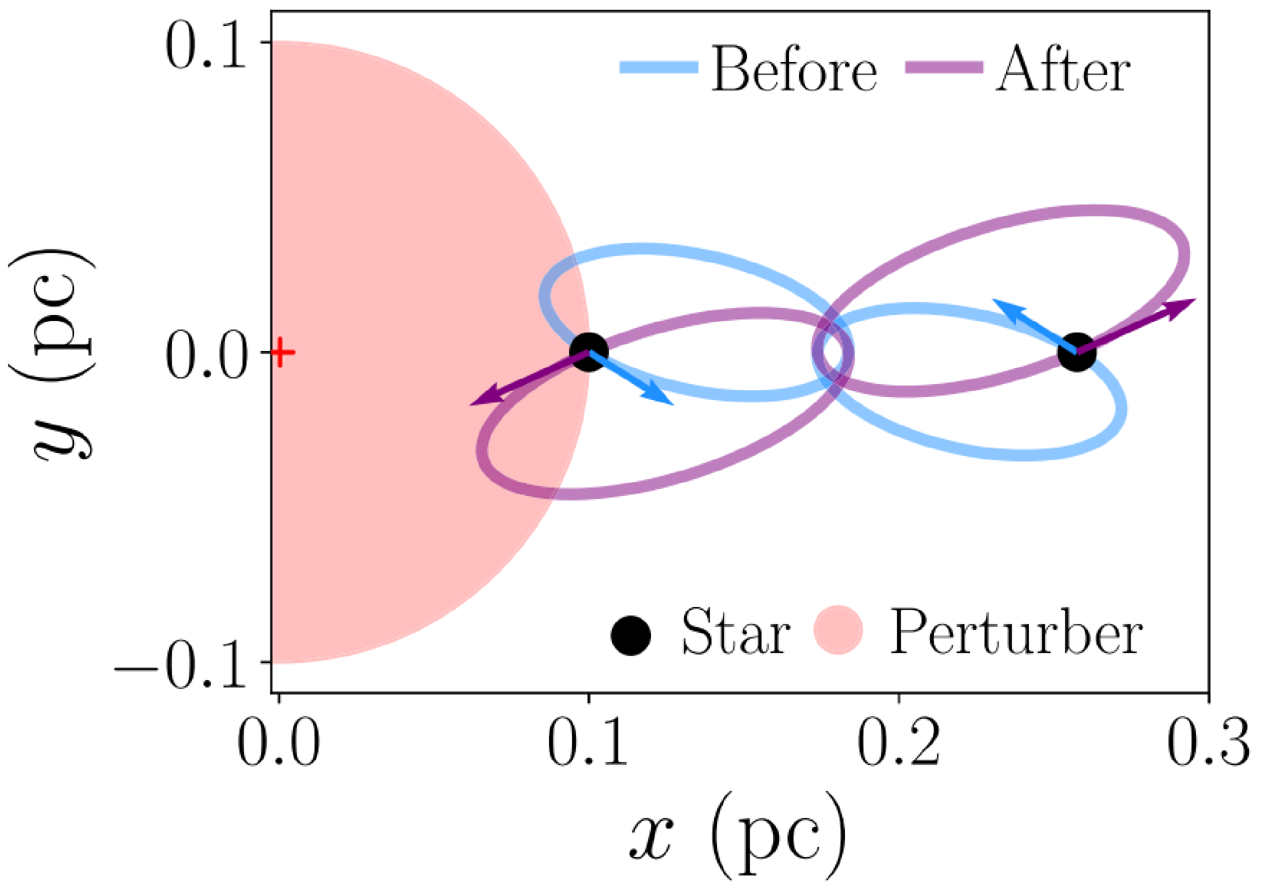
New ideas | Dwarf stellar halos

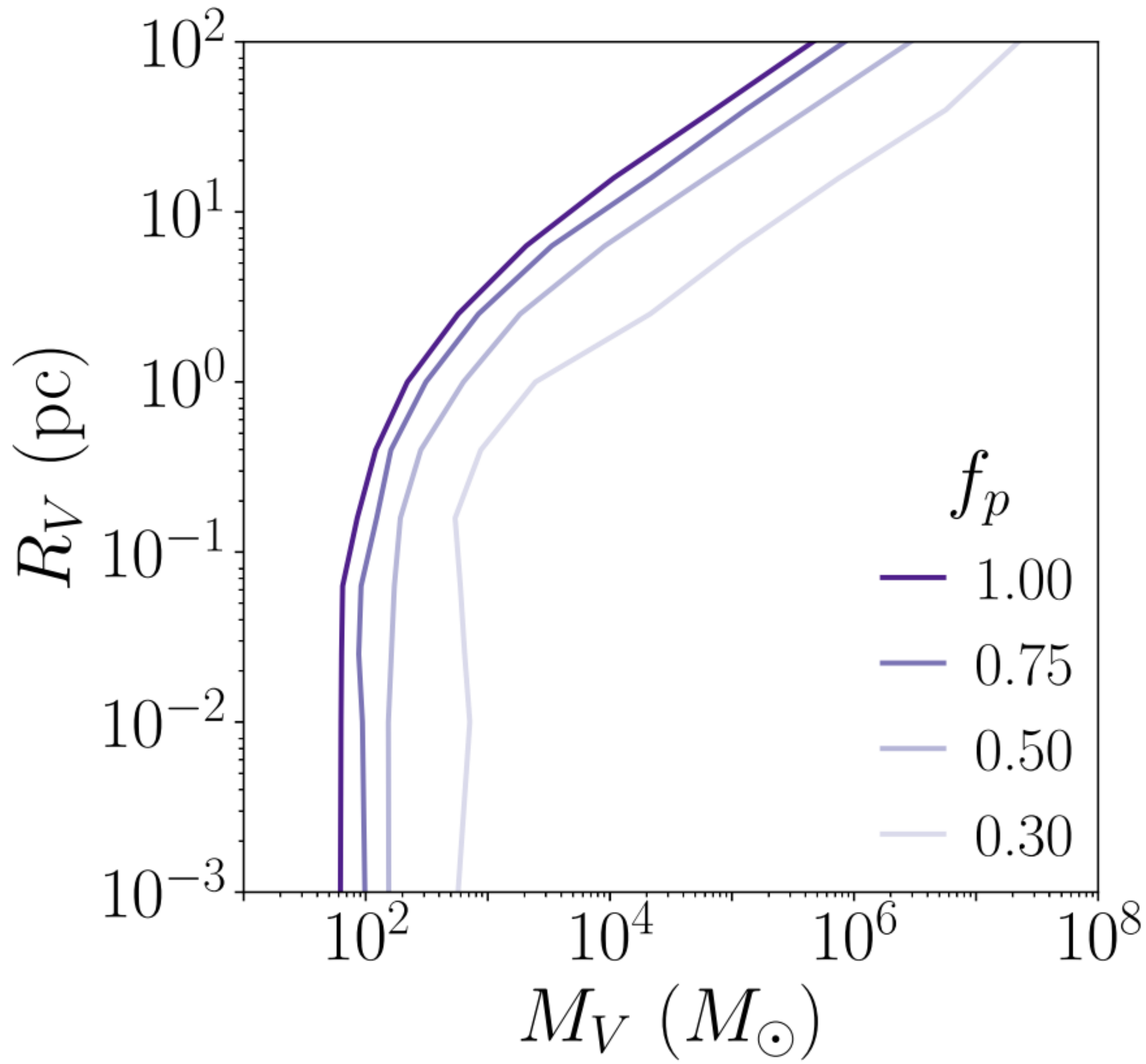
WDM 3keV



Kim et al. in prep.

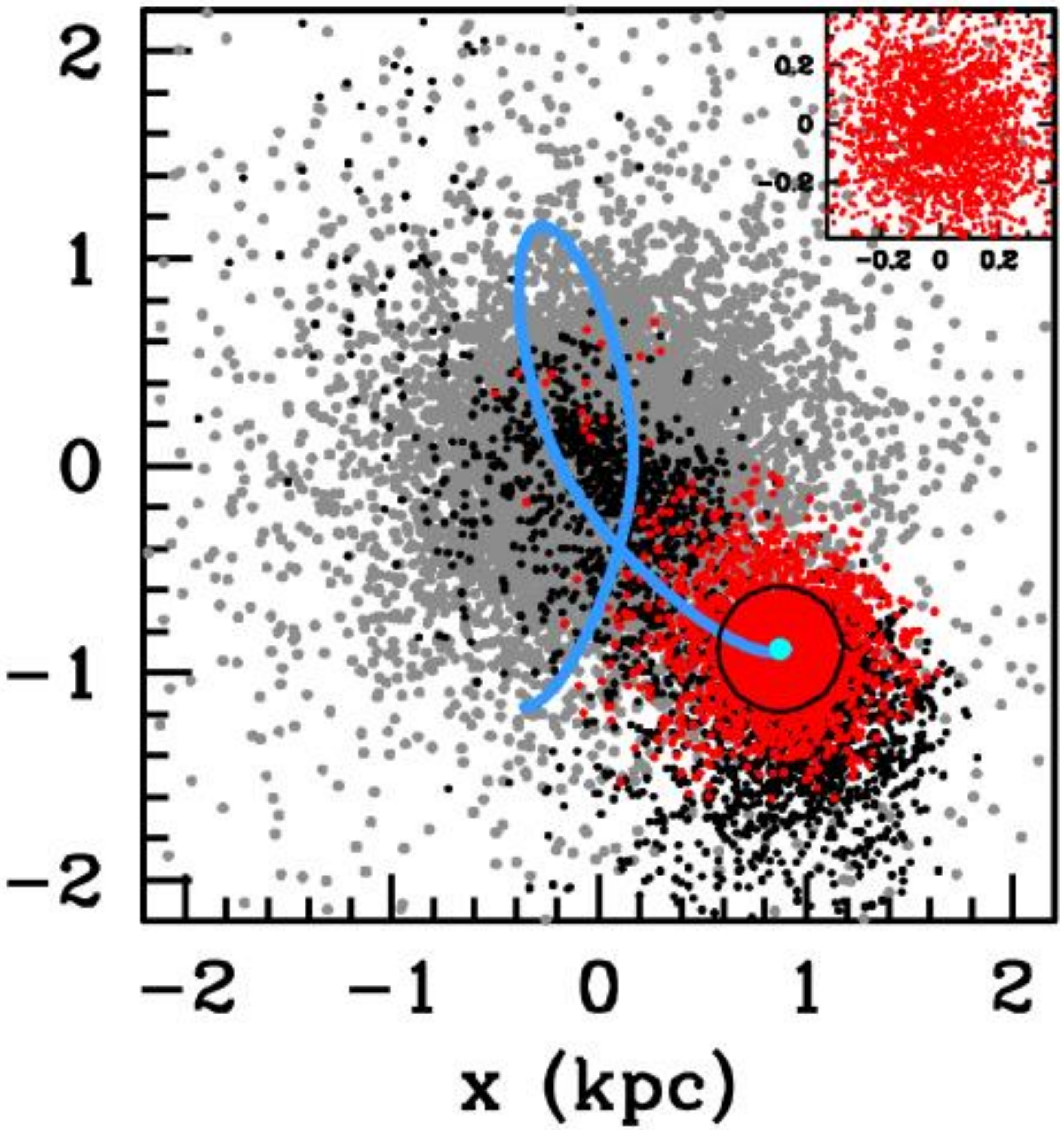
New ideas | Wide binaries





Peñarrubia et al. 2016; Kervick et al. 2021; Safarzadeh et al. 2022; Ramirez & Buckley 2023

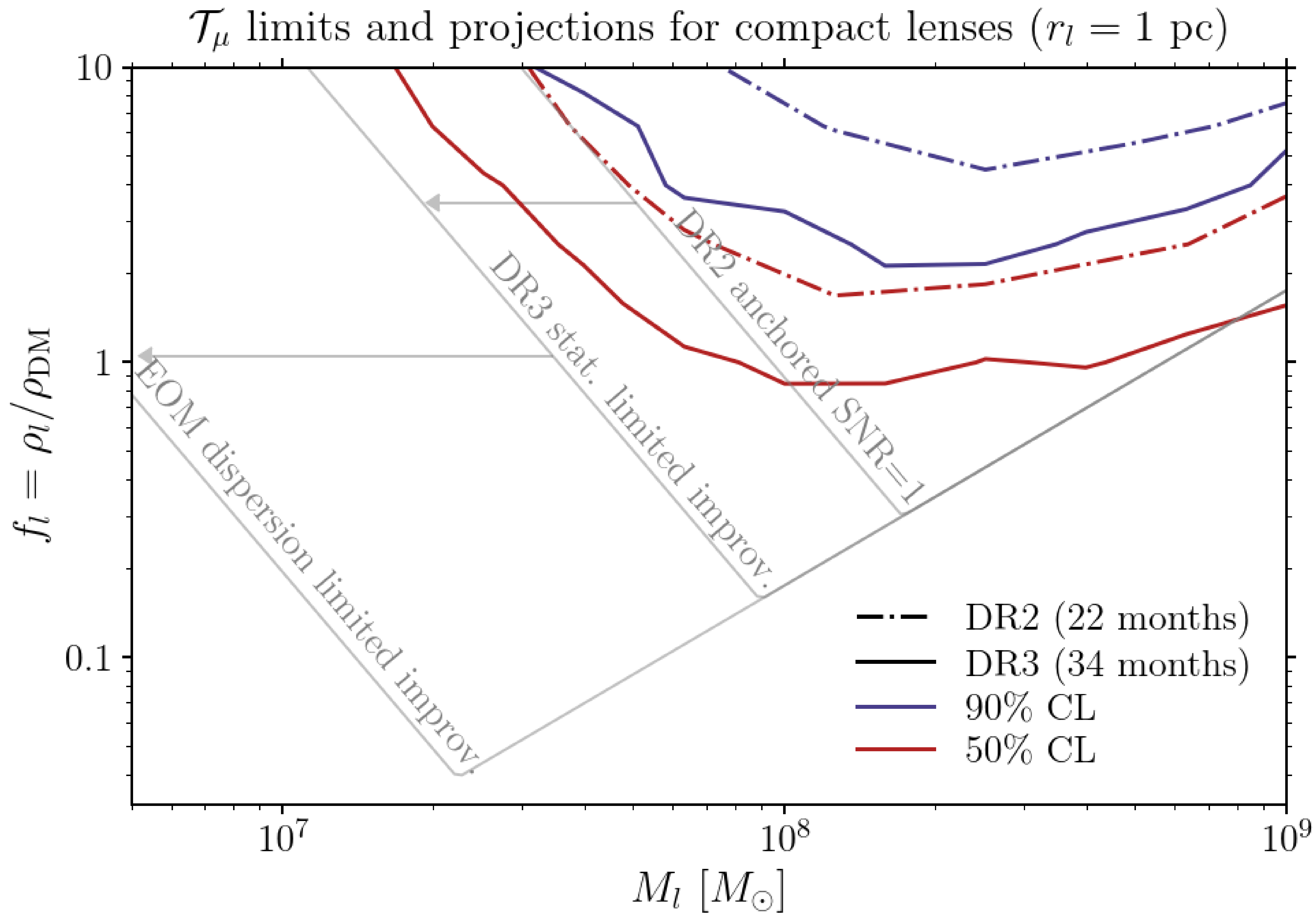
New ideas | Subhalo star-capture



- Can probe dark subhalos down to $10^{4-5} M_{\odot}$.
- May have found some already (e.g. GC-6 in Fornax).

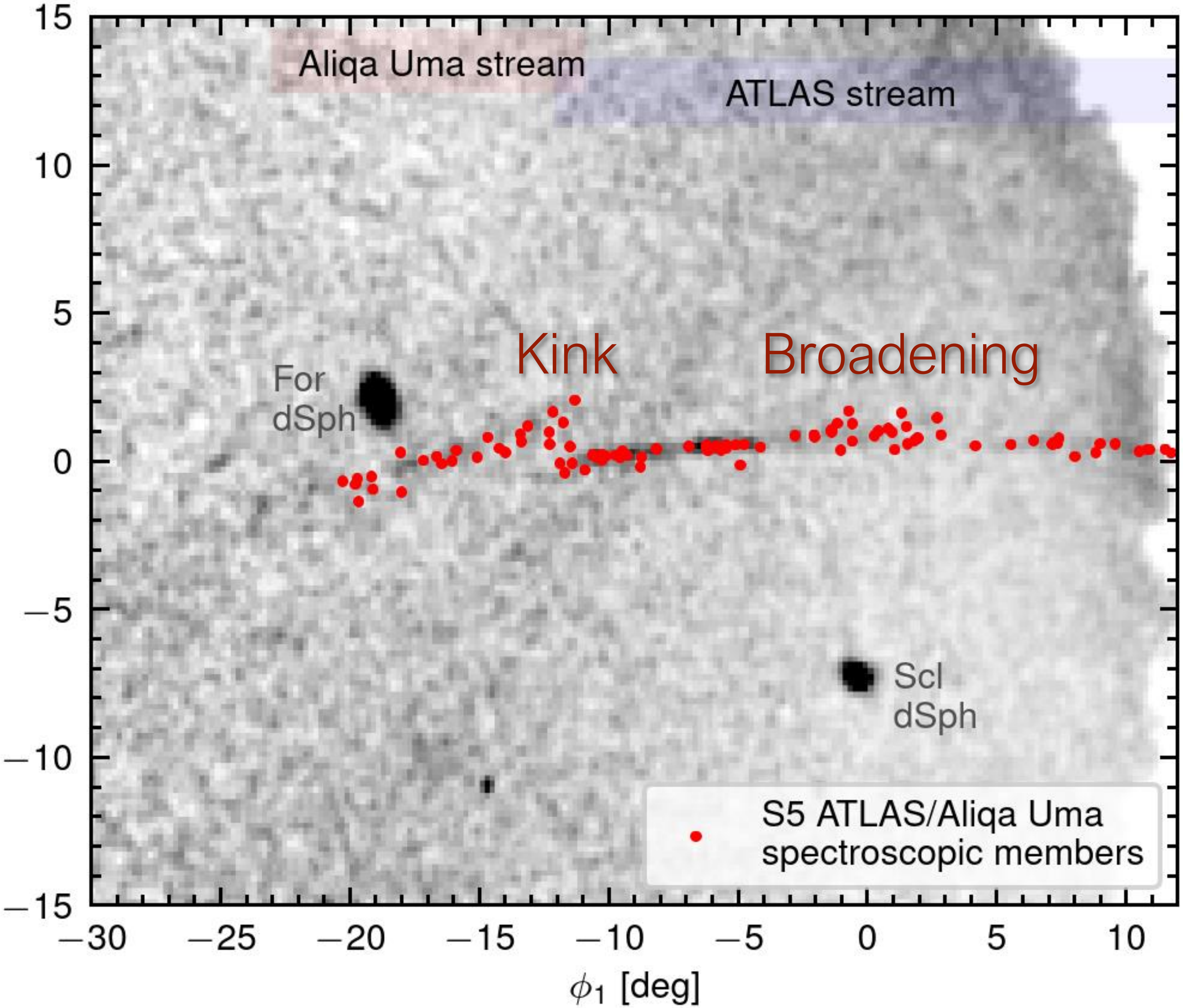
Peñarrubia et al. 2024

New ideas | Astrometric mircolensing



Mondino et al. 2024

New ideas | Stellar stream bumps



Li et al. 2021

Conclusions

Conclusions

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- We have found smoking gun evidence for "dark matter heating" in dwarf galaxies.
  [⇒ *no cusp-core problem; dark matter is probably a particle*]
- Densest dwarfs constrain dark matter models!
- Nearest + densest dwarfs are the best place to look for non-gravitational signatures of dark matter.
- A dedicated astrometric mission pointing at nearby dwarfs / globulars promises even tighter constraints on dark matter models.
- Lots of new ideas for how astrometry can be used to constrain dark matter. Which are most promising?

Justin I. Read