PIKIMO 12
University of Notre Dame, 30 April 2022

SIGNATURES OF HIDDEN DARK SECTORS

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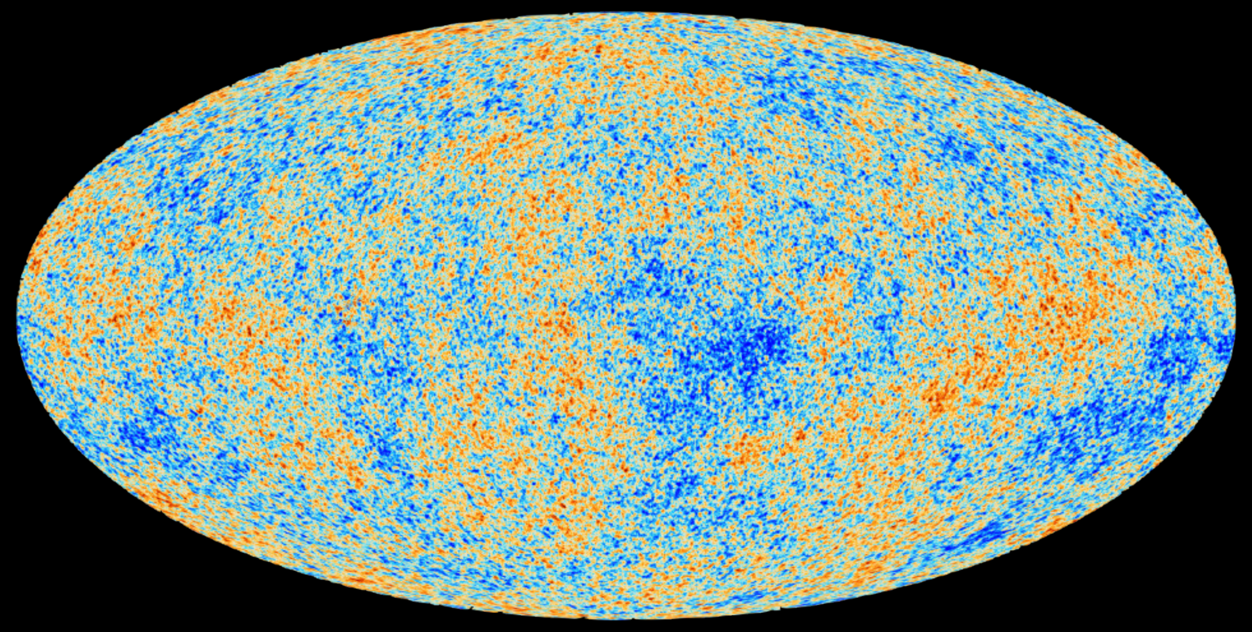
General Properties of Dark Matter

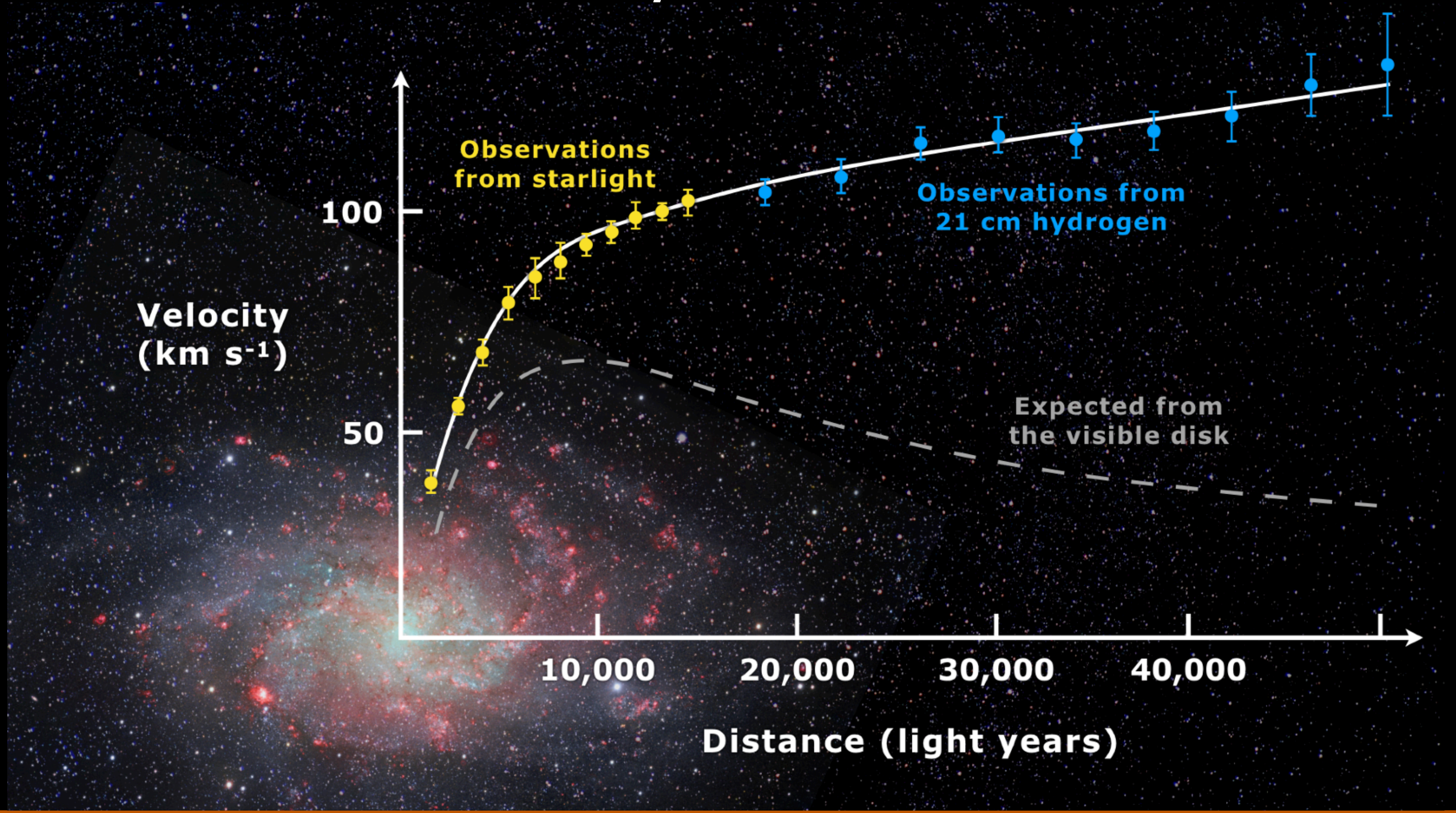
- From cosmic microwave background (CMB) anisotropies:



ΛCDM →

Universe today is about
- 68% dark energy
- 5% baryons
- 27% dark matter

- Dark matter is responsible for hierarchical structure formation, as seen in N-body simulations
- Dark matter forms halos that host galaxies
- Question on everyone's mind:
  What is the particle nature of dark matter?



Dark Sectors

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- "Nightmare scenario" in which dark matter has effectively no interactions with Standard Model can leave gravitational signatures!
- Consider dark matter that self-interacts through "light" mediator

Disclaimer: Various dark sector models considered here is not at all an exhaustive list and reference lists are incomplete!

Early-Universe Cosmology

- Light mediators contribute to N_{eff}

$$\rho_{\text{rad}} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]$$

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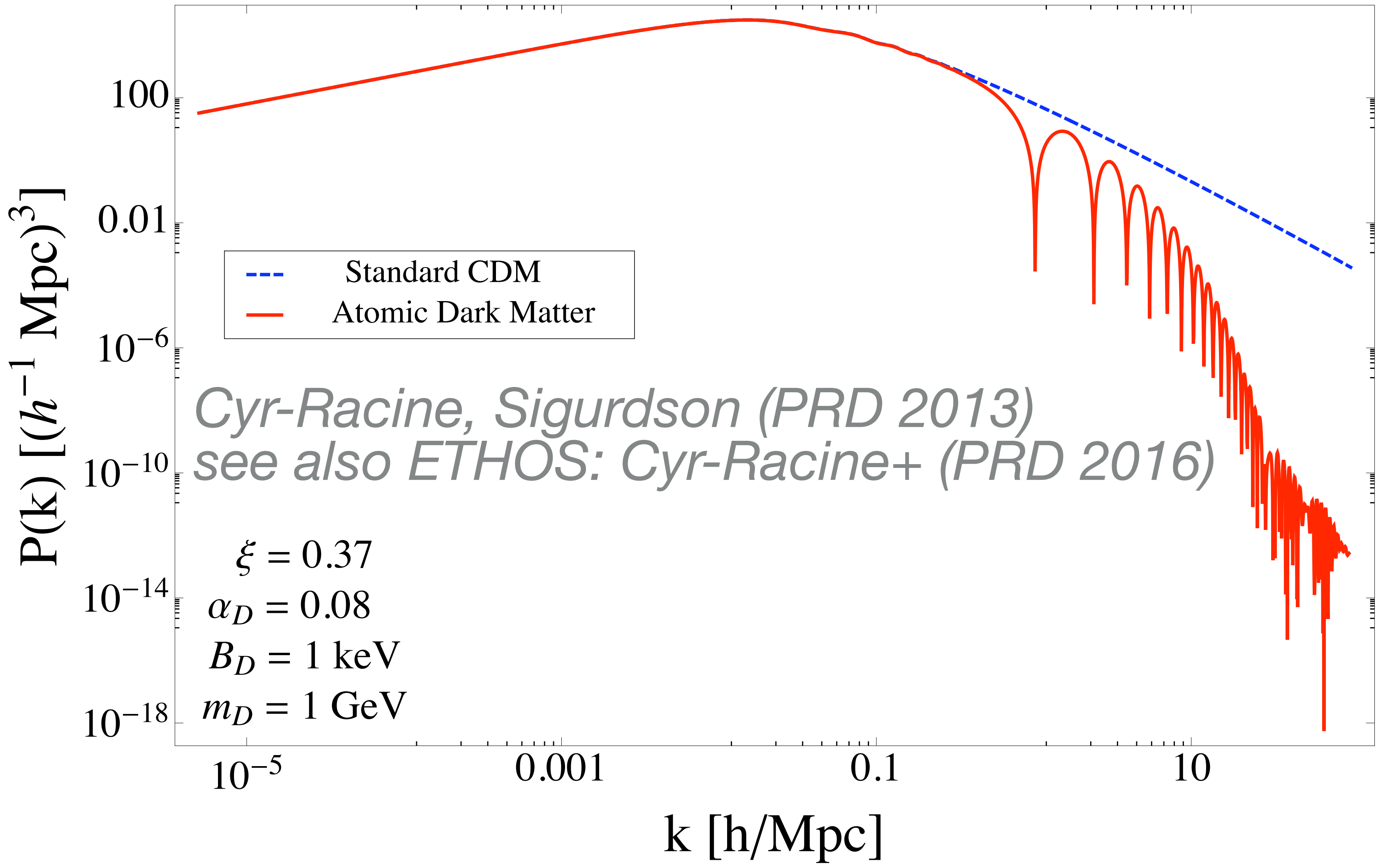

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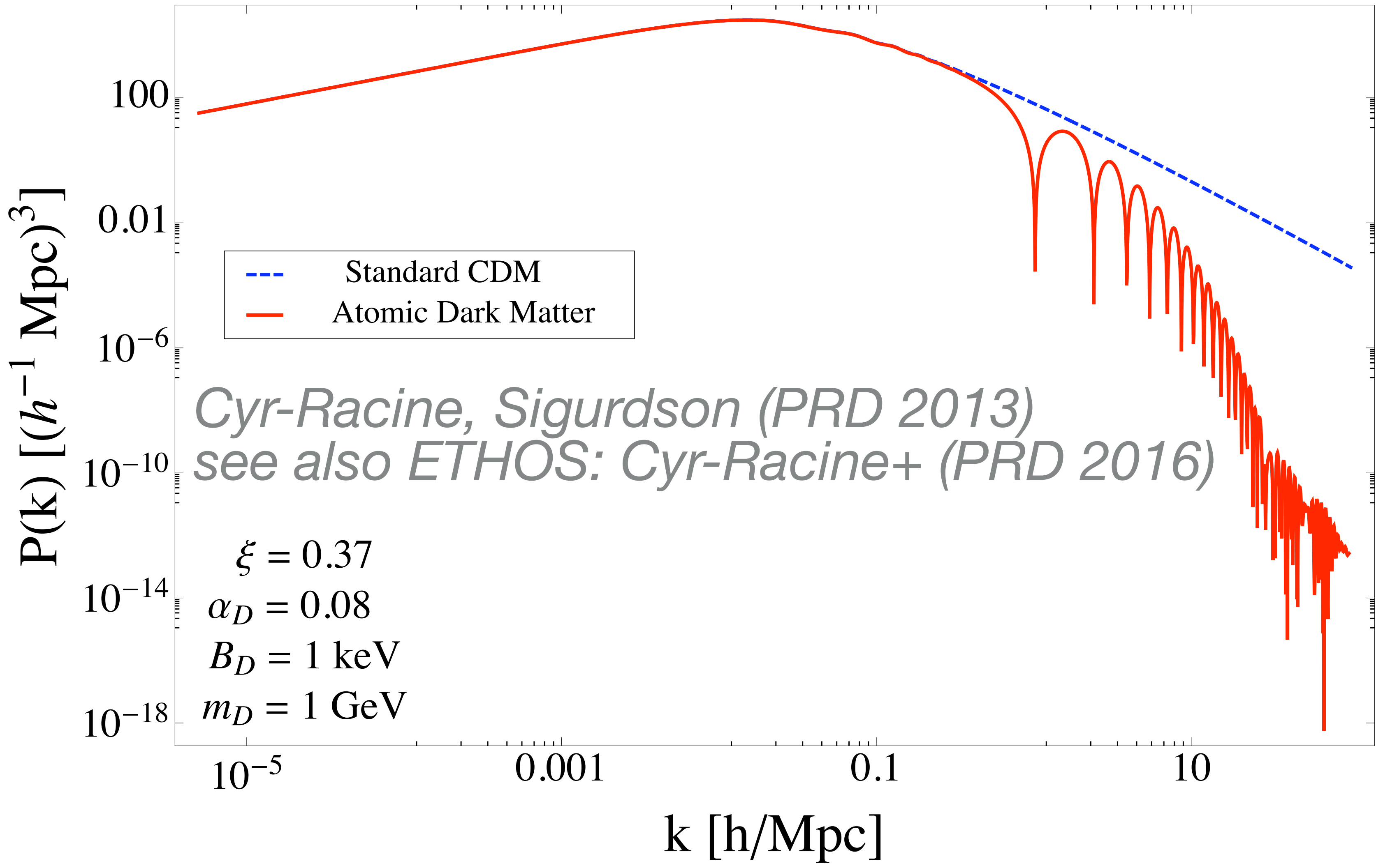
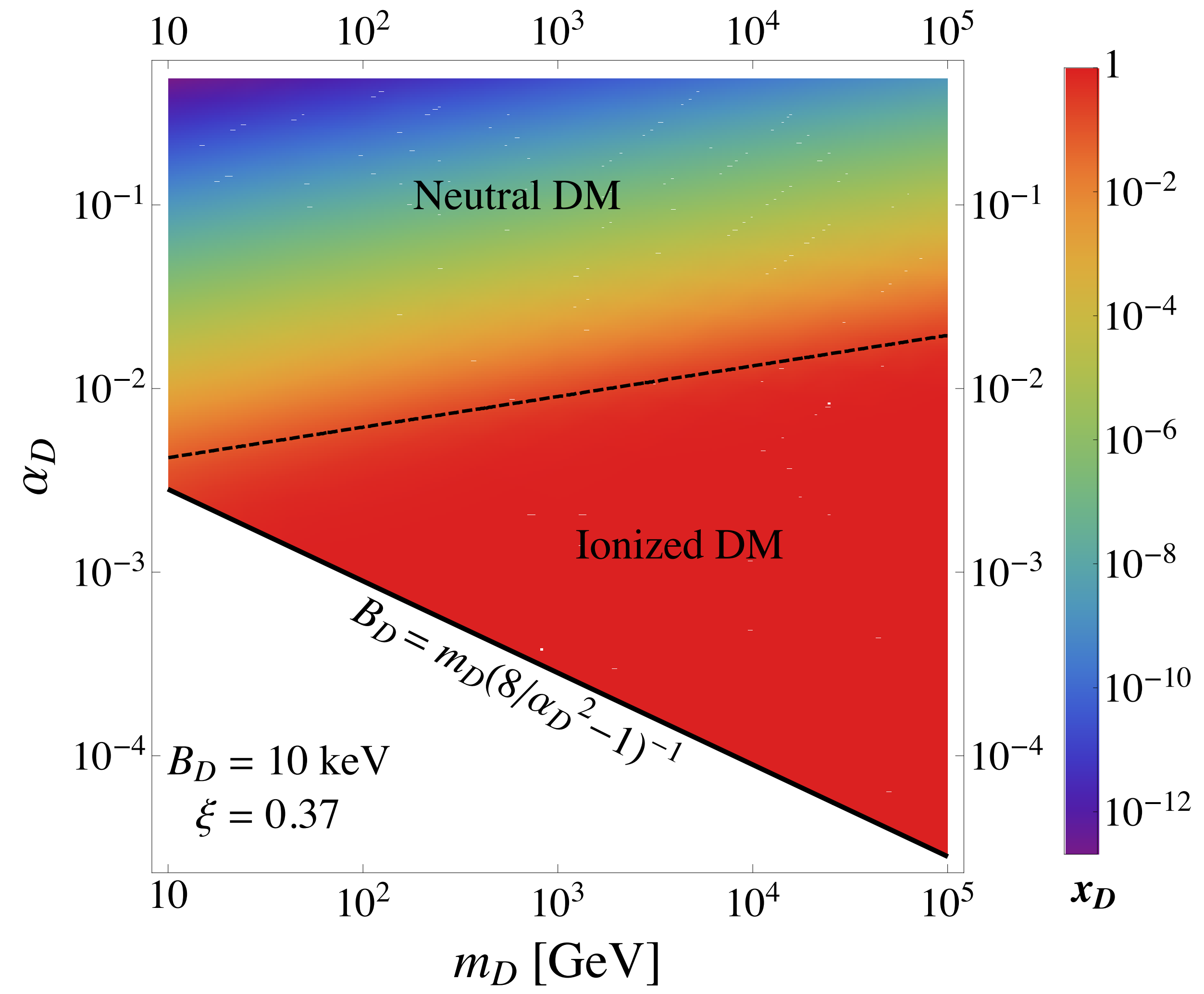


Cyr-Racine, Sigurdson (PRD 2013)
see also ETHOS: Cyr-Racine+ (PRD 2016)

- Composite dark matter (e.g. atomic, nuclear) permits different pheno in early & late Universe



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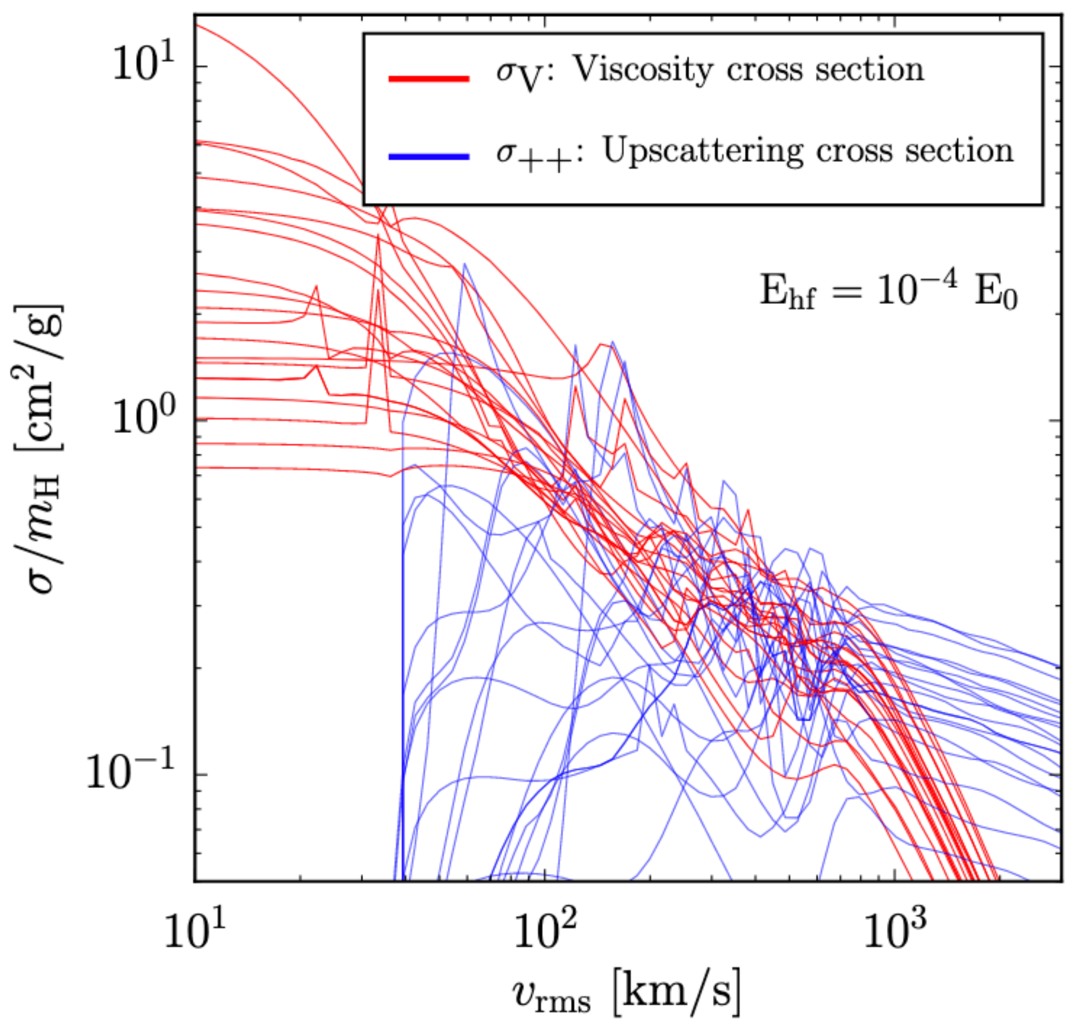

KB, Kaplinghat, Kwa, Peter (PRD 2016)

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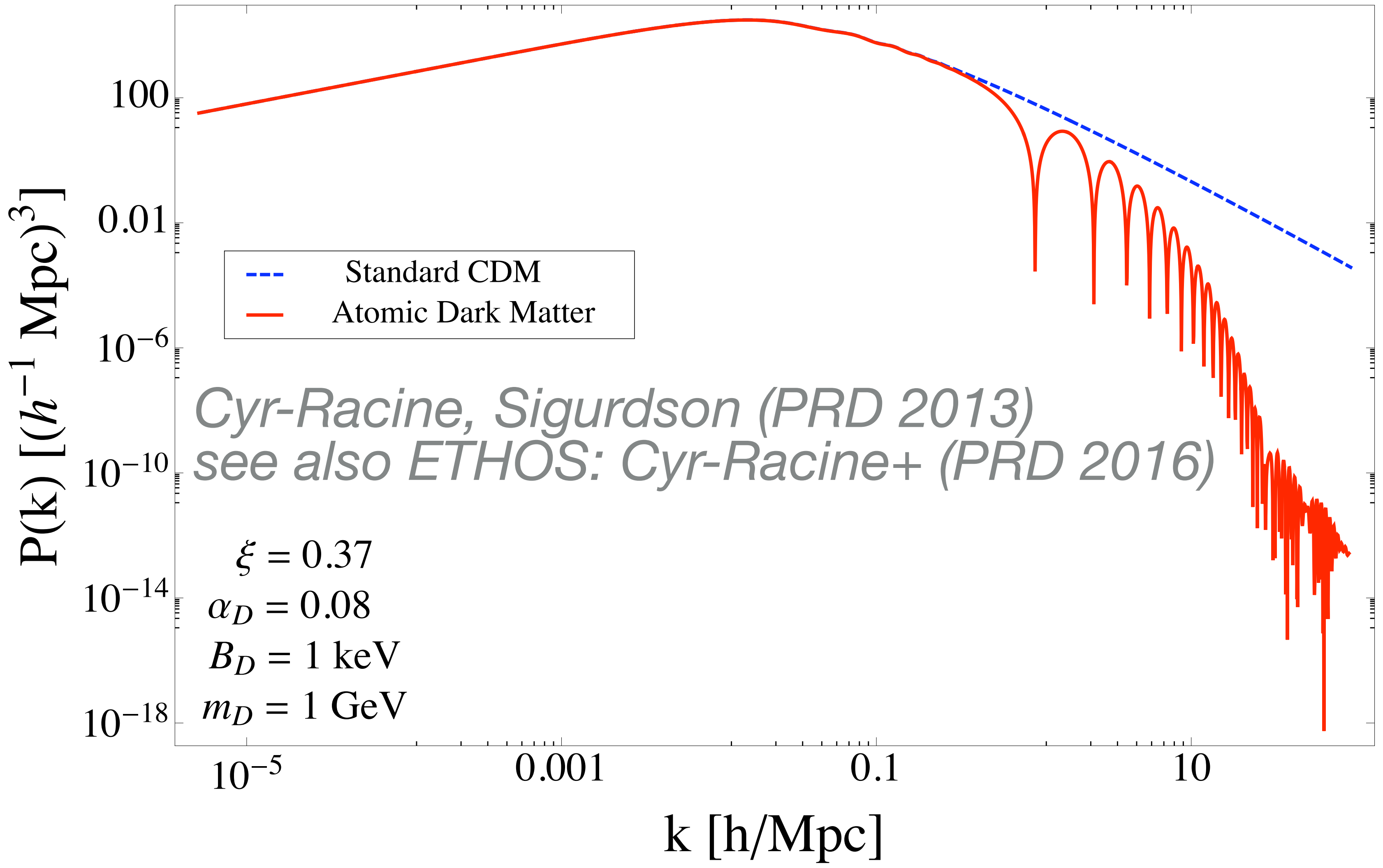

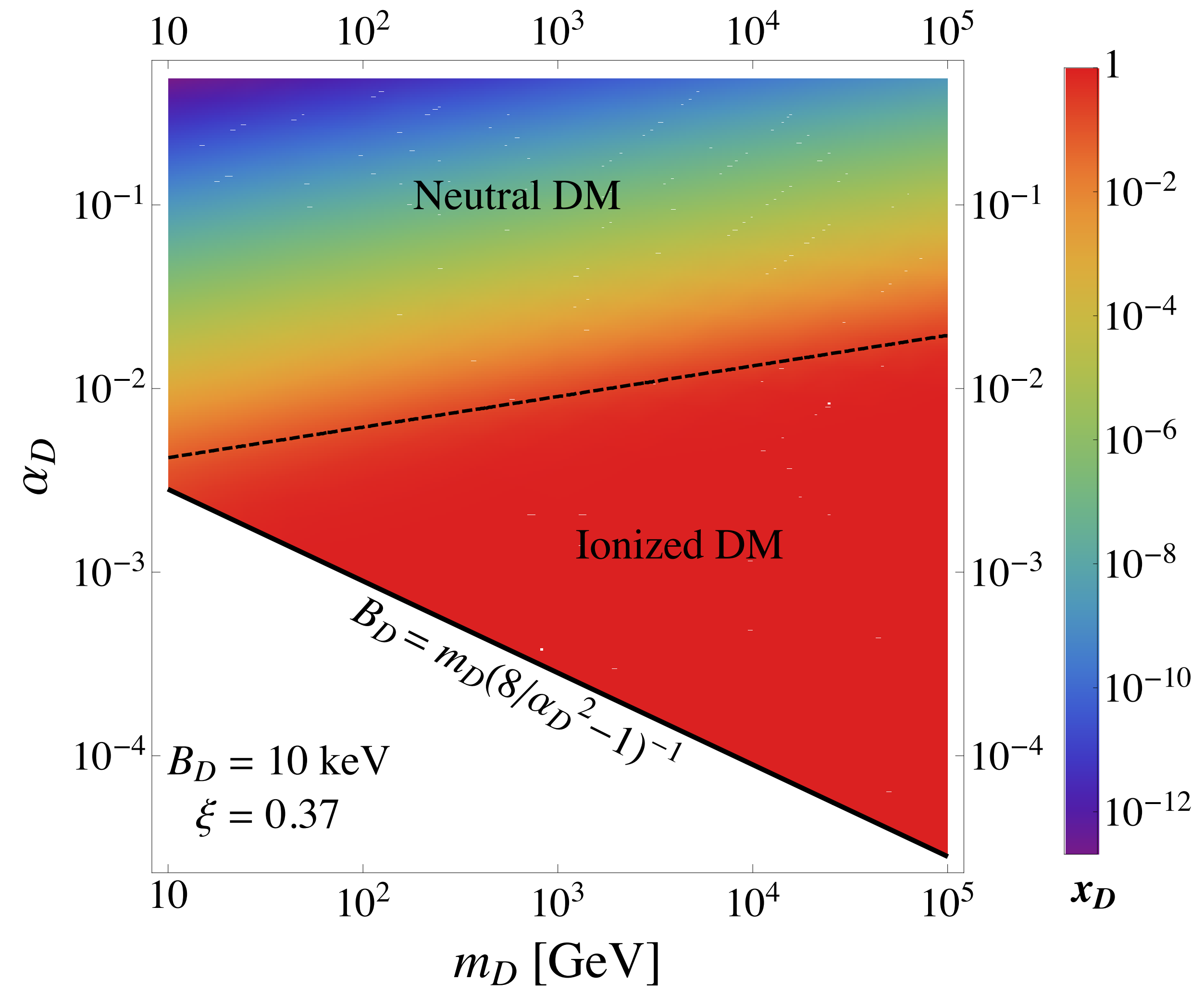

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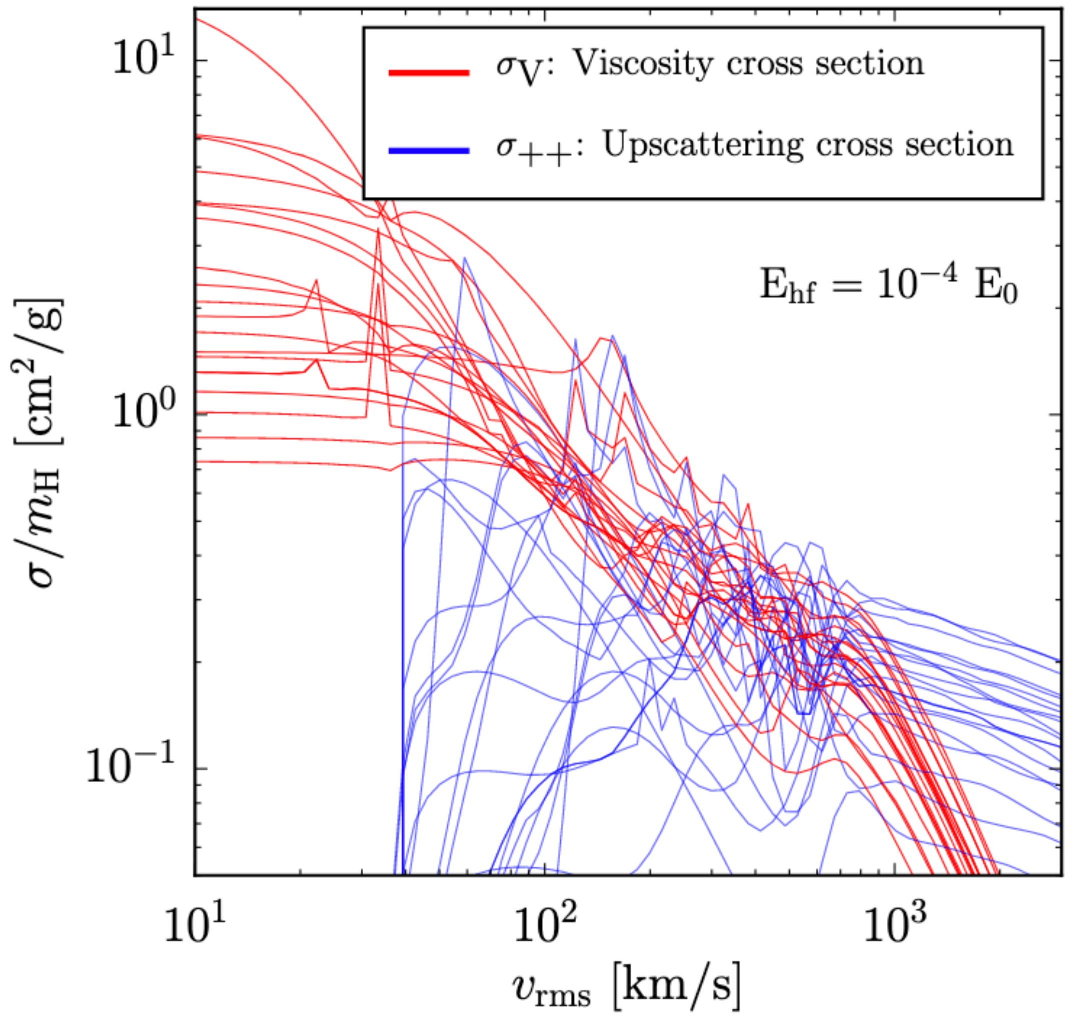

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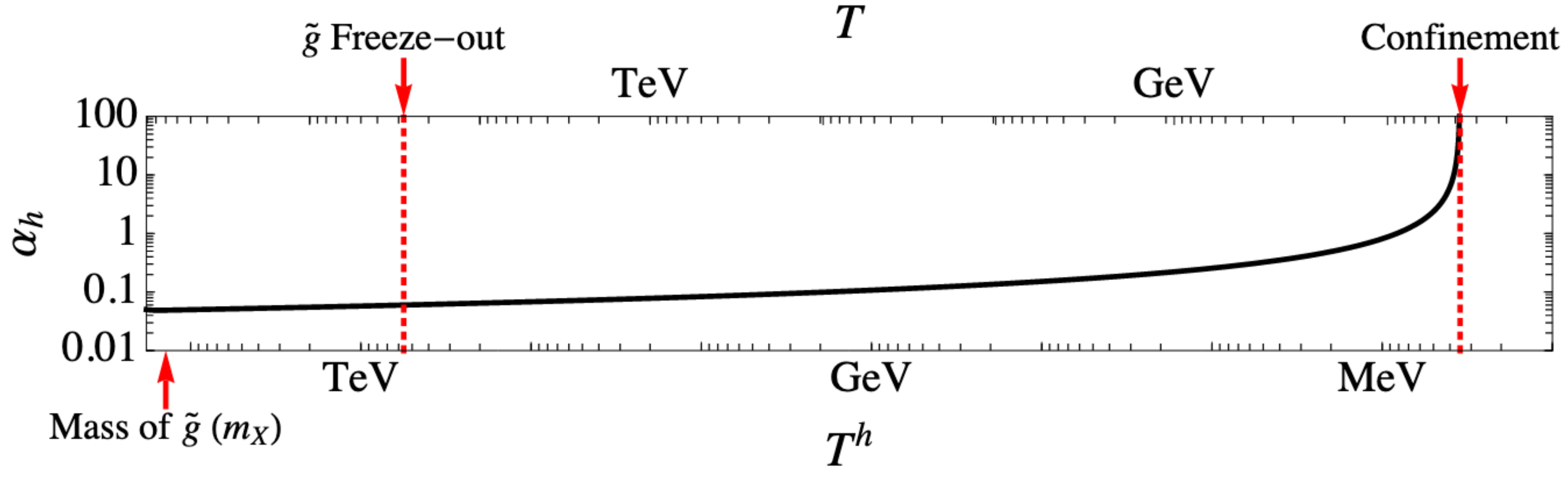
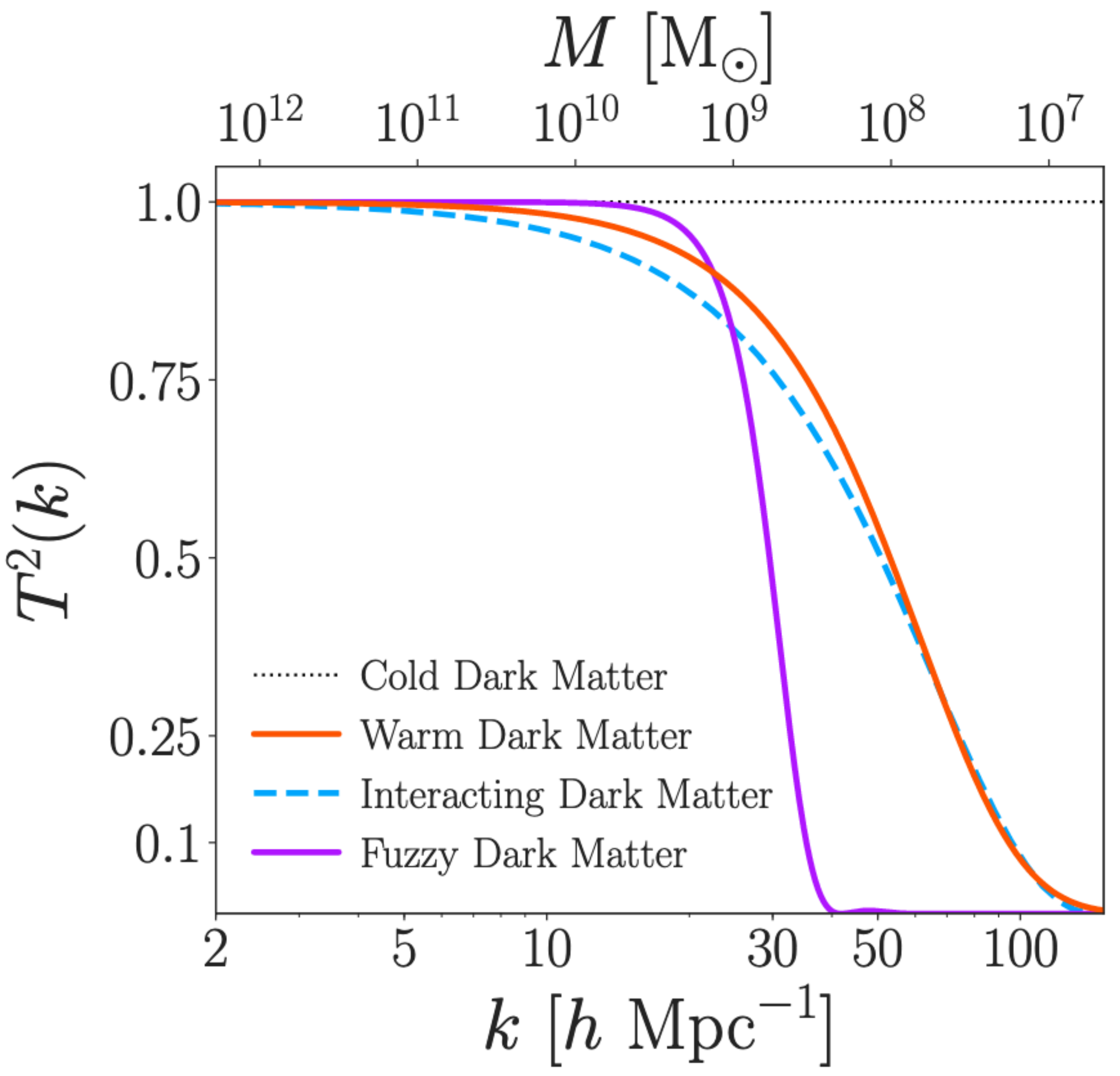
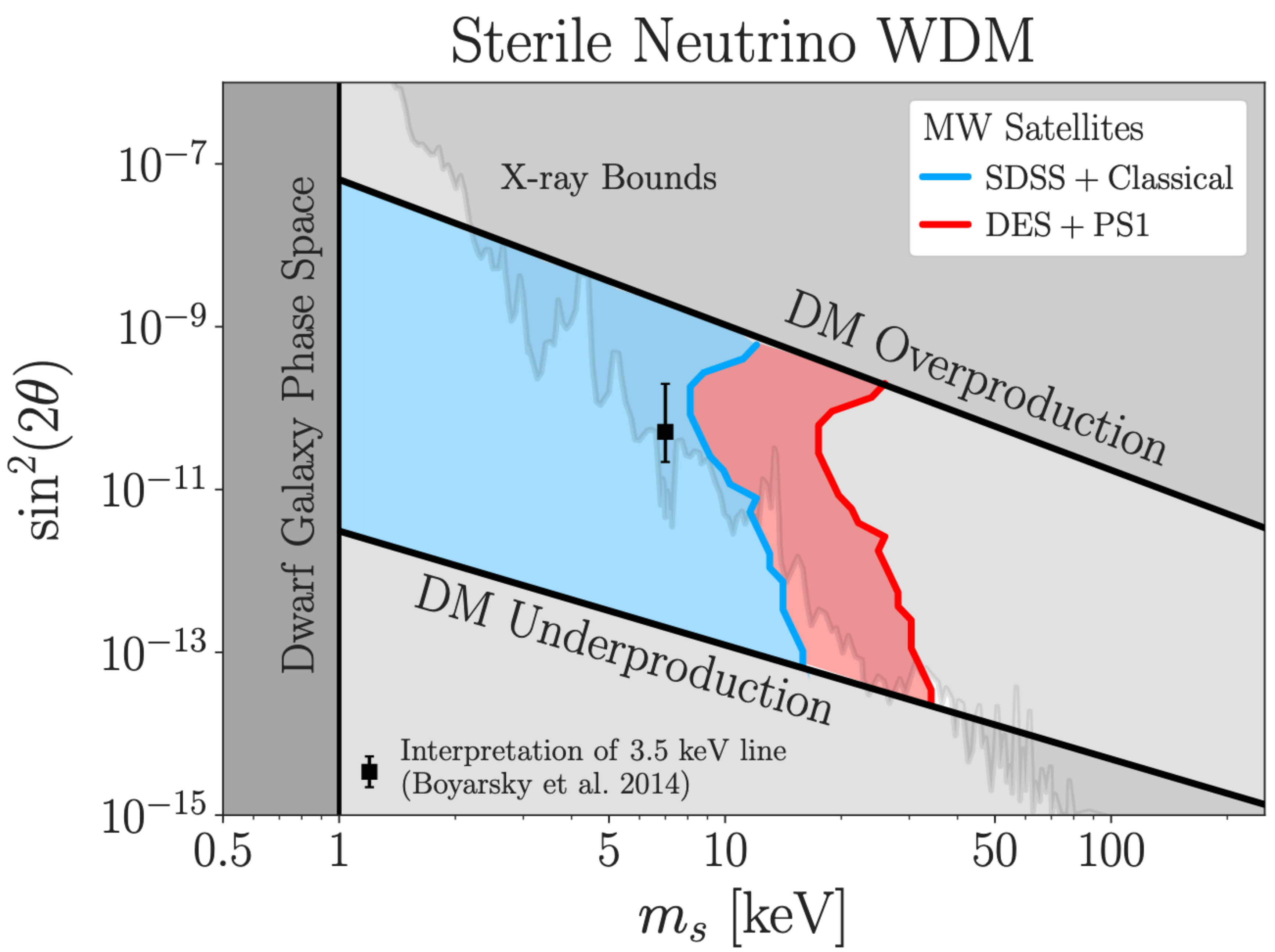
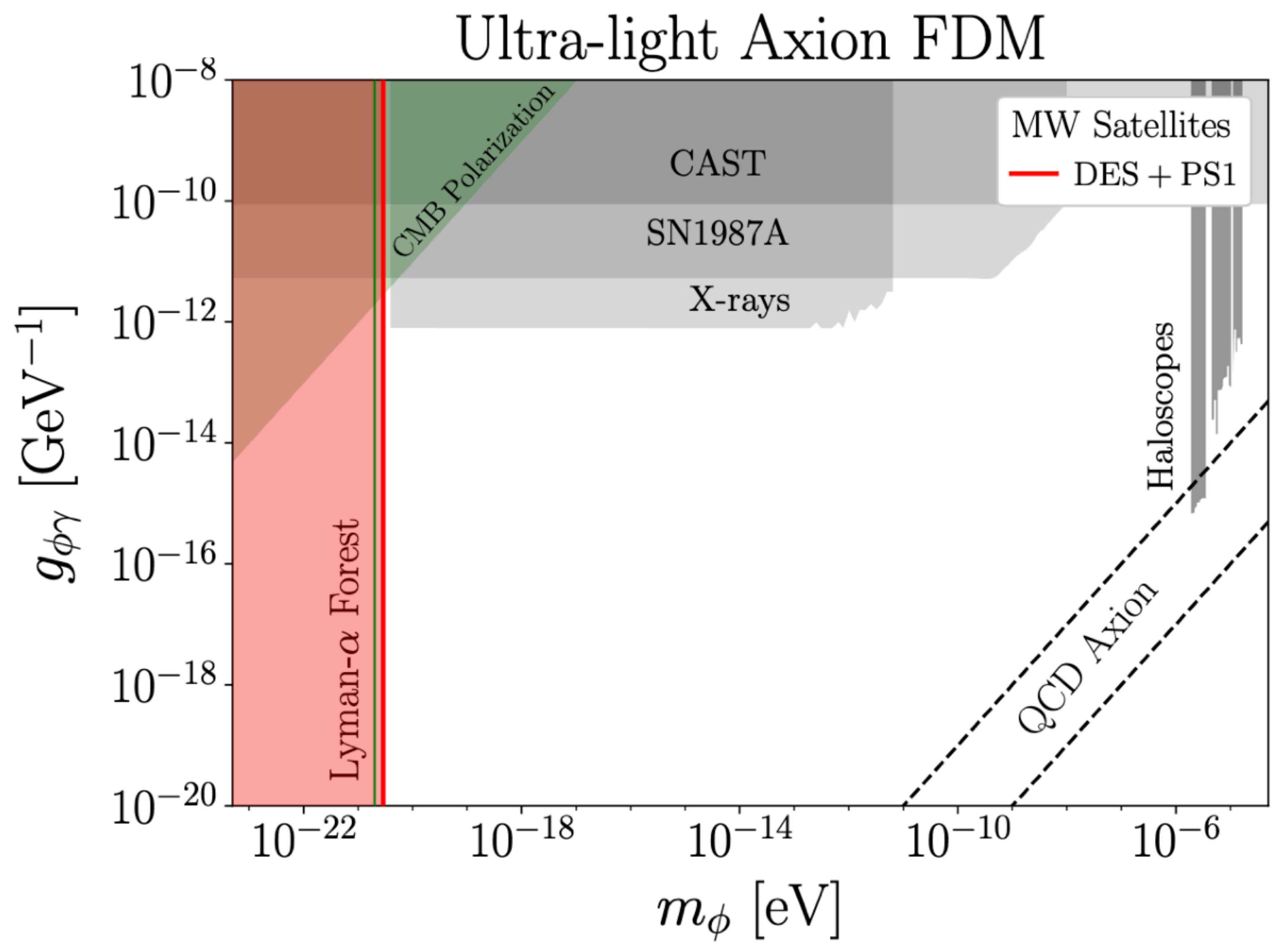


KB, Feng, Kaplinghat, Tait (PRD 2014)

Small-Scale Structure Suppression



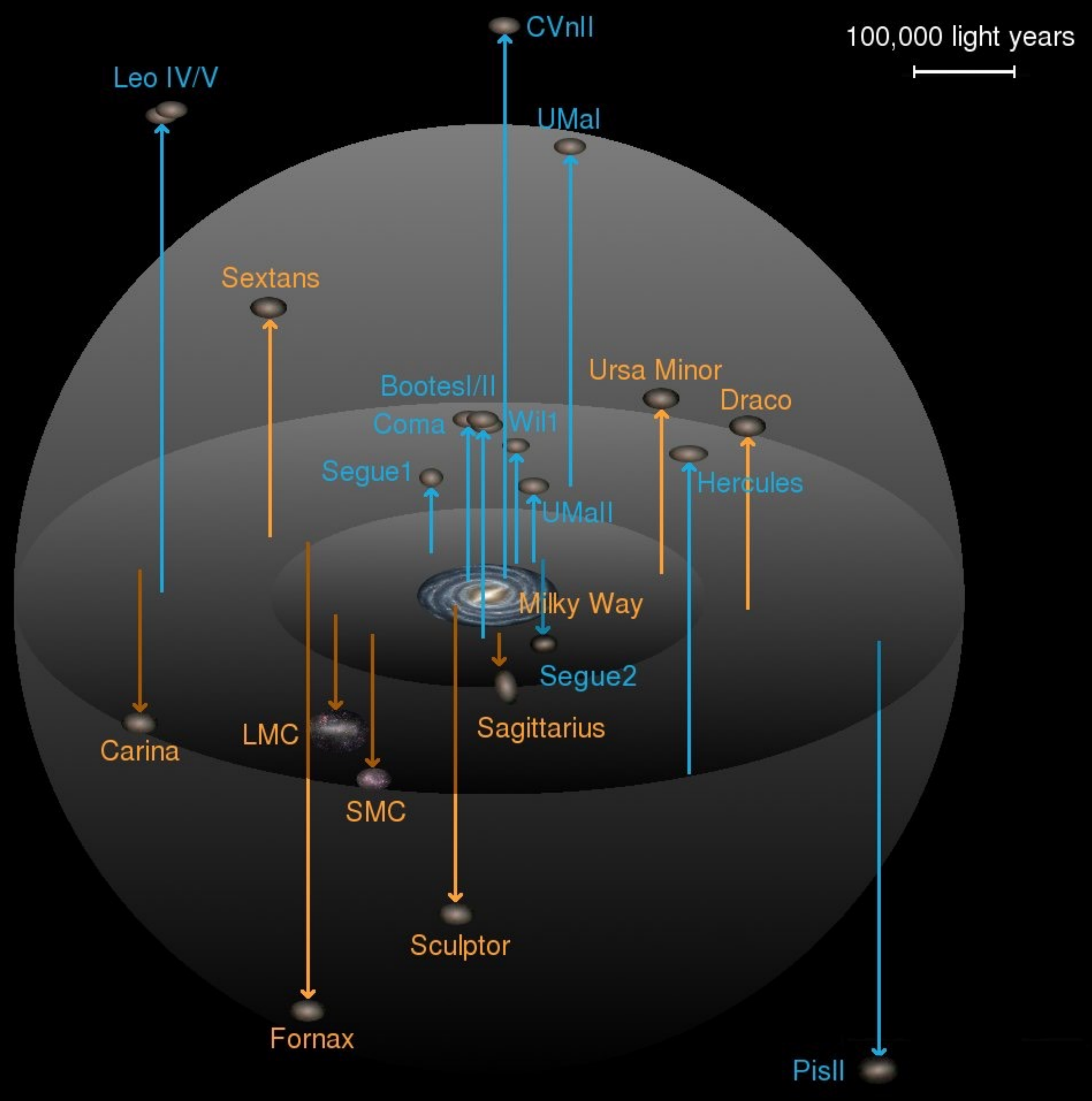




DES Collaboration, Nadler+ (PRL 2021)

Small-Scale Structure

Dwarf Spheroidals



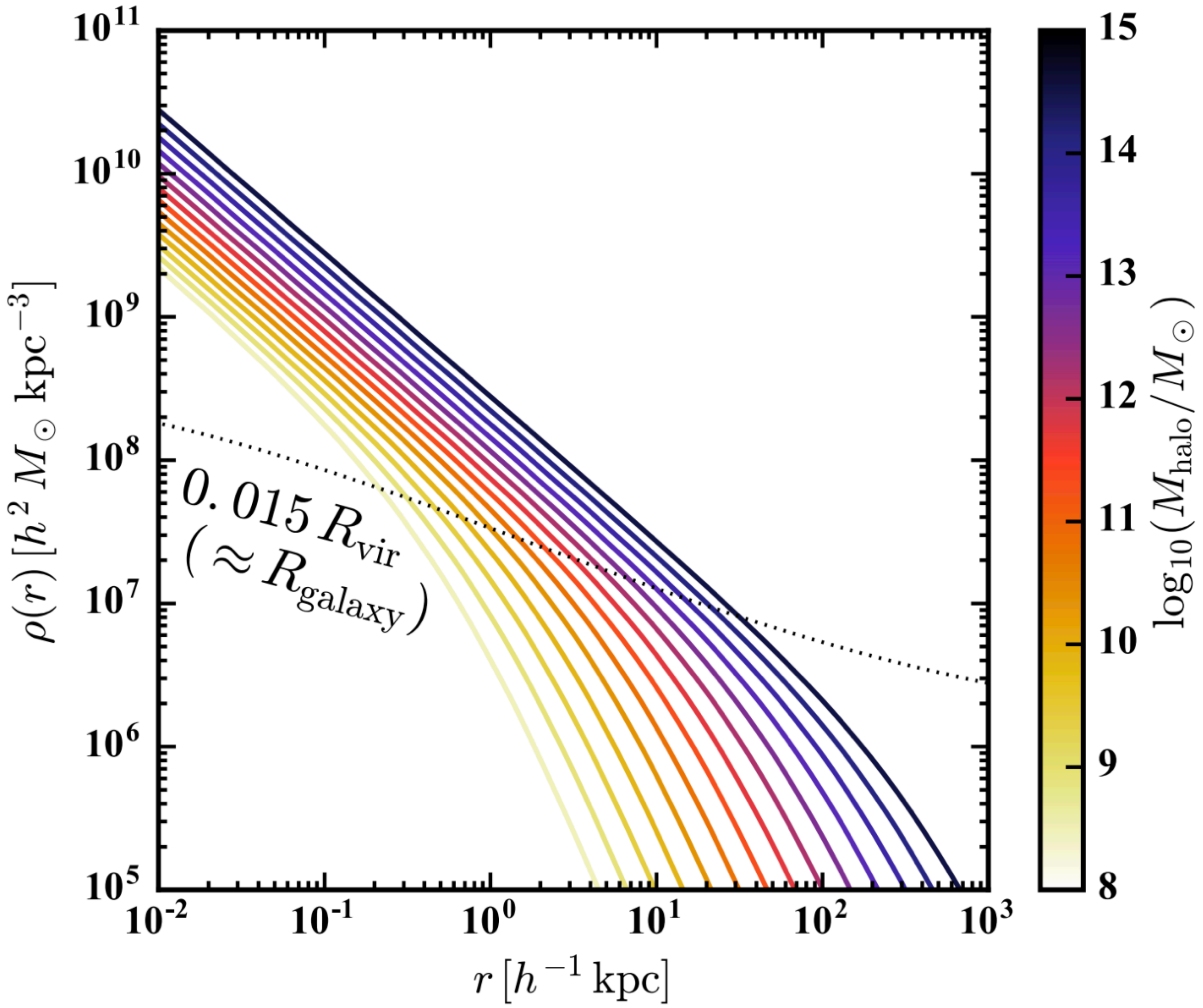
Low-Surface Brightness (LSB)

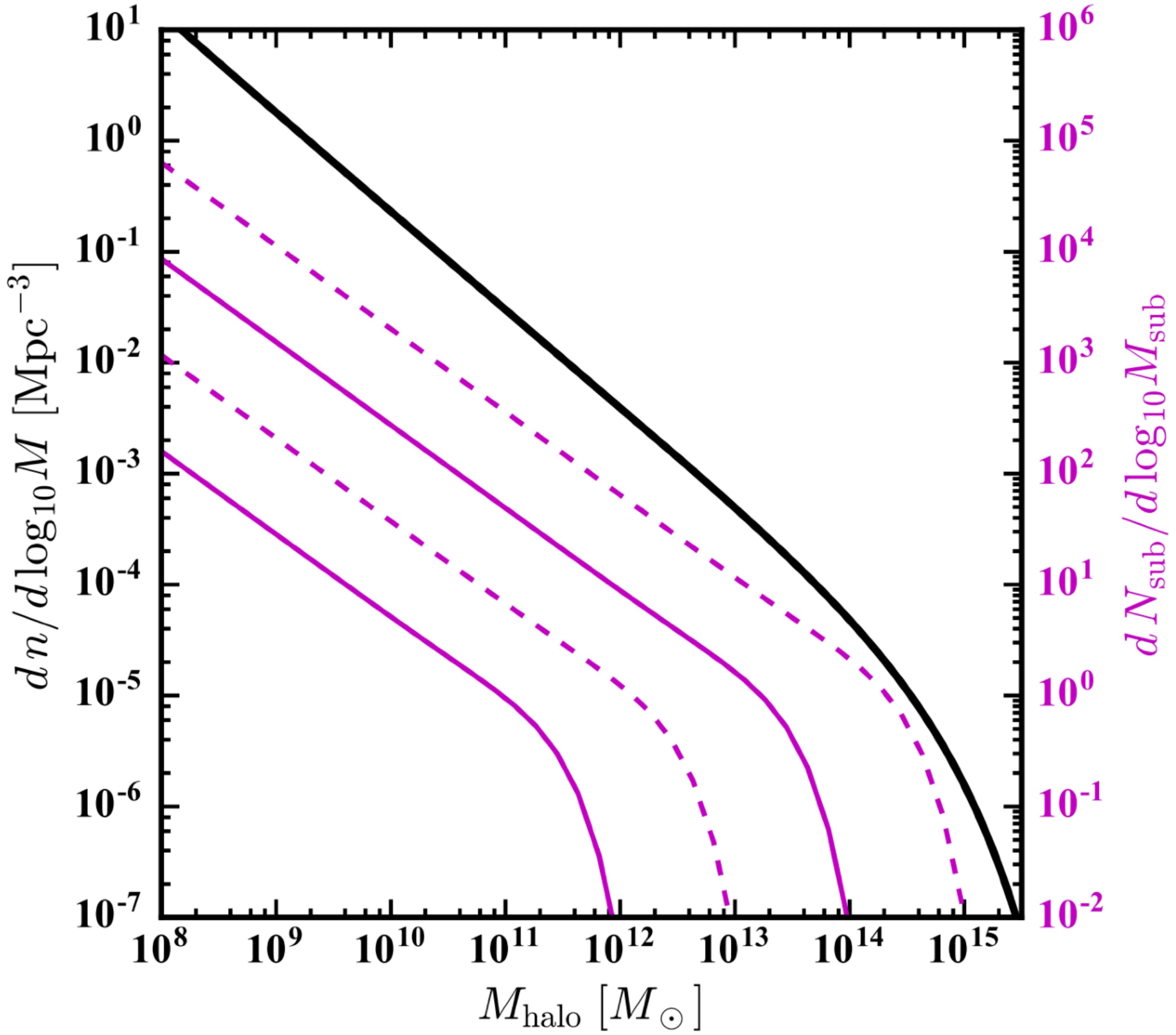
Clusters

N-body Simulations

- Density profiles of dark matter halos are dense and cuspy
- There are many more small halos than large ones
- Substructure is abundant and almost self-similar

CDM only!





Bullock & Boylan-Kolchin, Annu. Rev. Astron. Astrophys. (2017)

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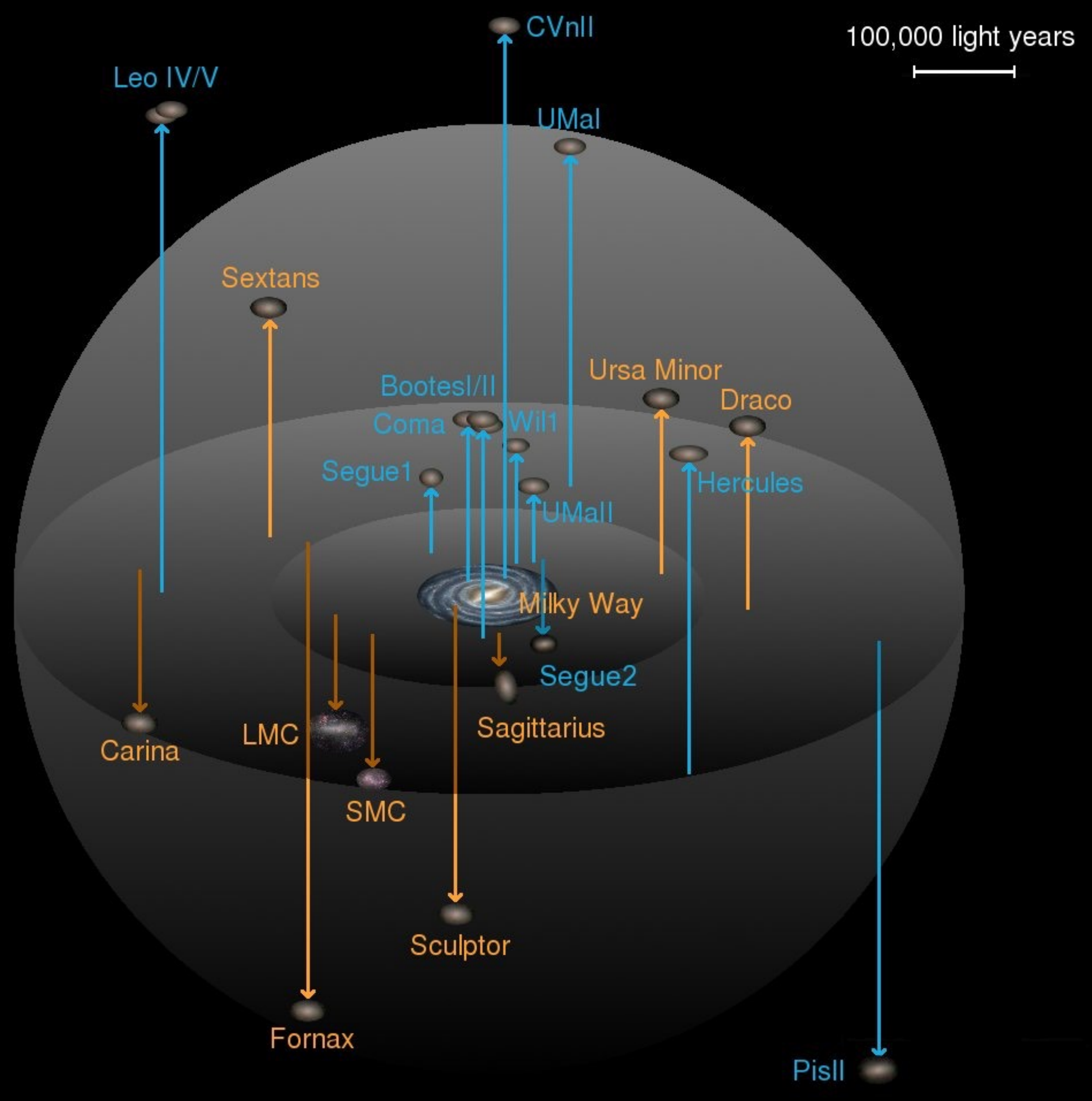

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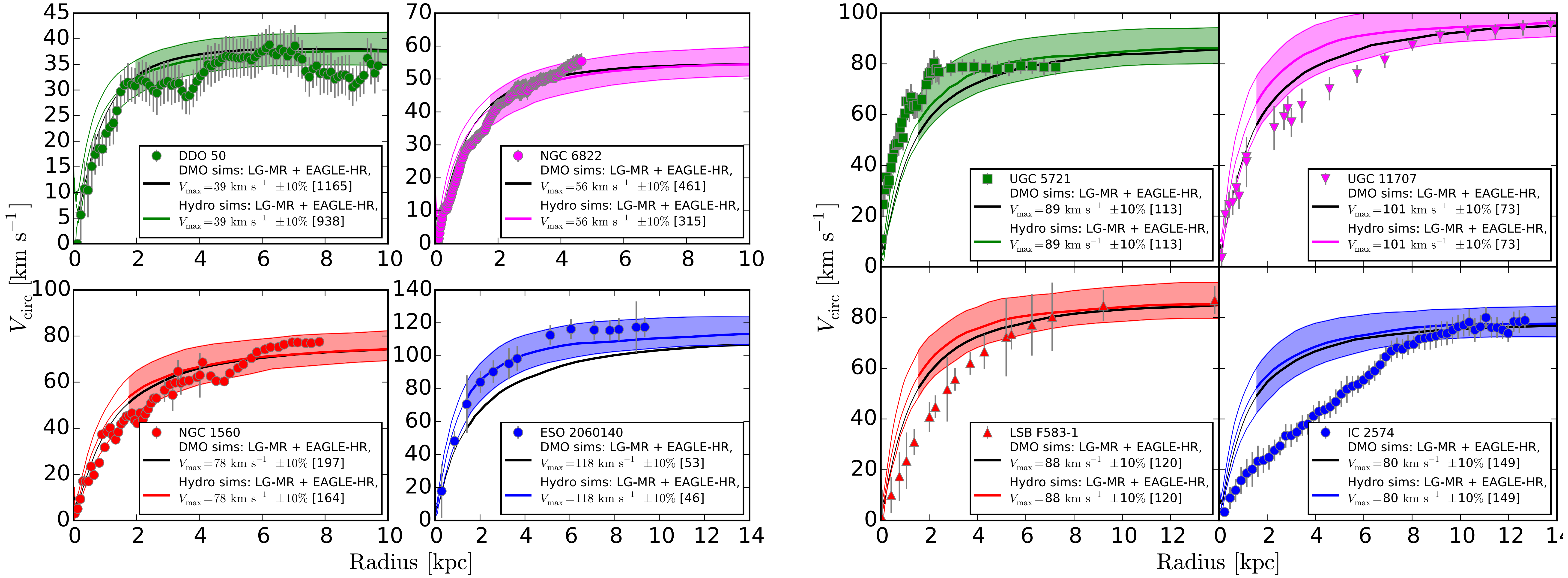
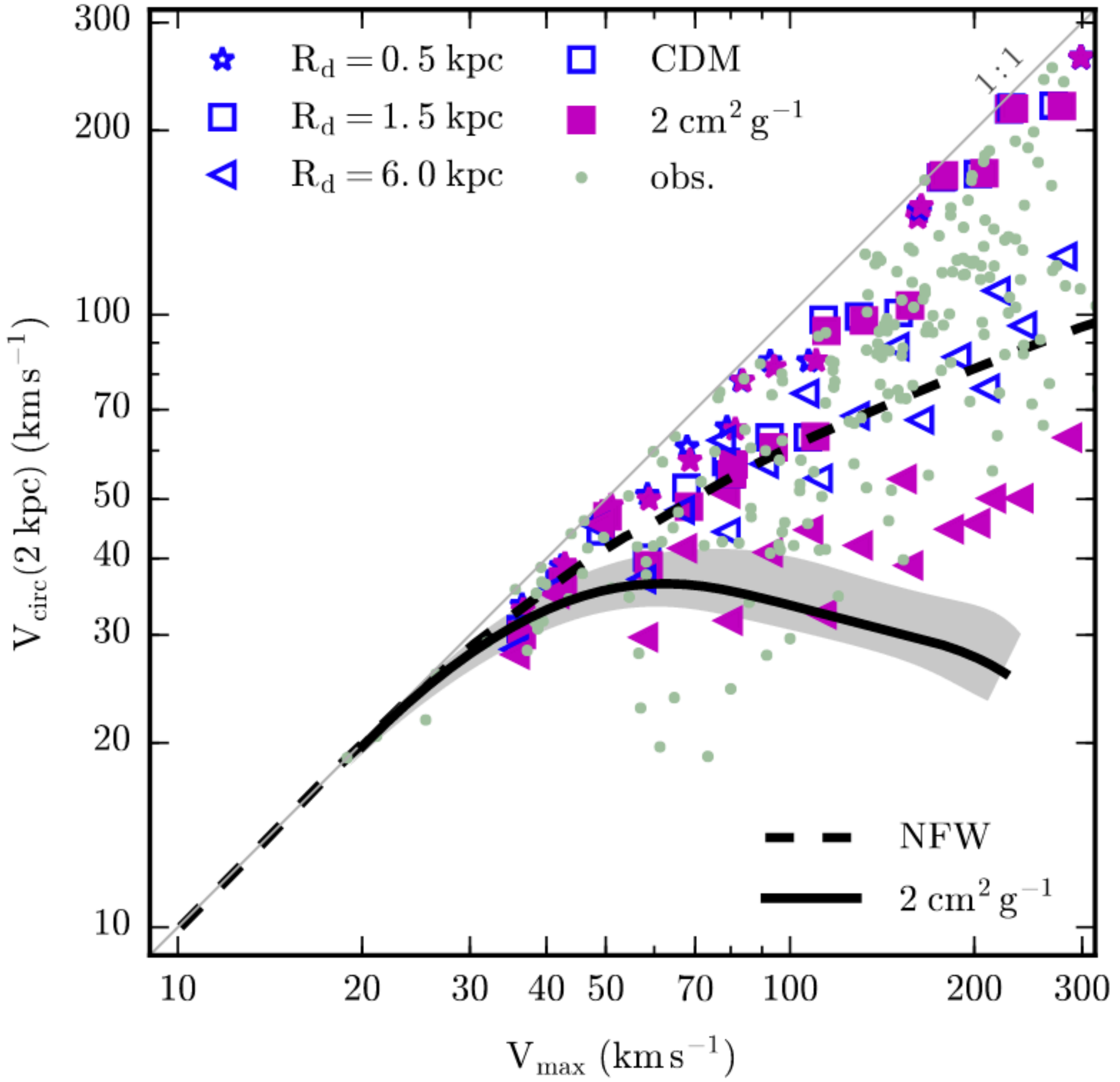
Small-scale structure puzzles arise in various systems:
~~missing satellites~~, core-cusp, too-big-to-fail, diversity

Diversity Problem

- Rotation curves of spiral galaxies exhibit large diversity for systems of similar halo mass and stellar content
- SIDM + baryonic feedback can help explain diversity





Oman+ (MNRAS 2015)

Creasey+ (MNRAS 2017)

Self-Interacting Dark Matter (SIDM)

Spergel, Steinhardt (PRL 2000)

Dwarfs

Clusters

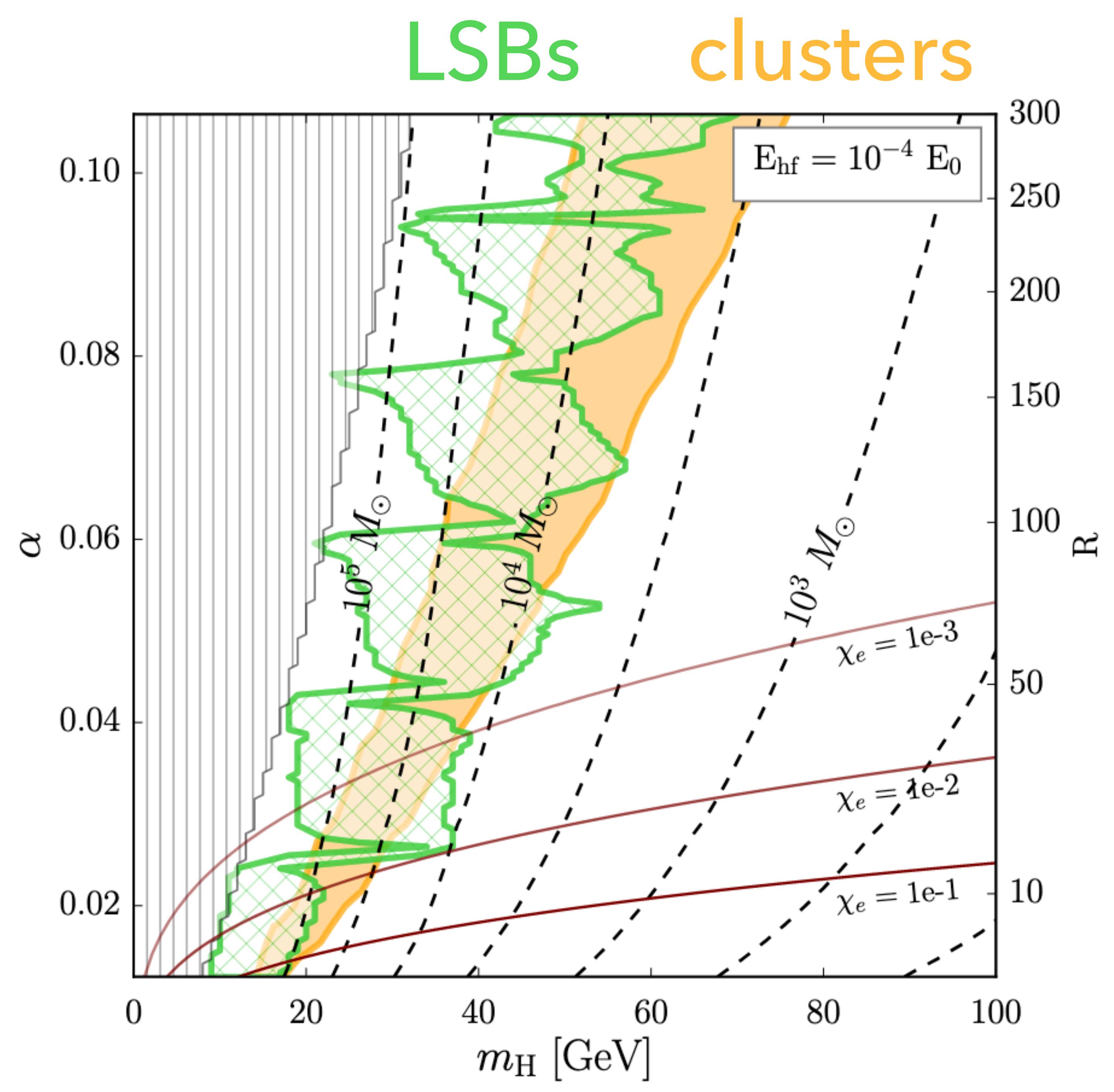
LSBs

Need to model halo formation and evolution
with velocity-dependent SIDM

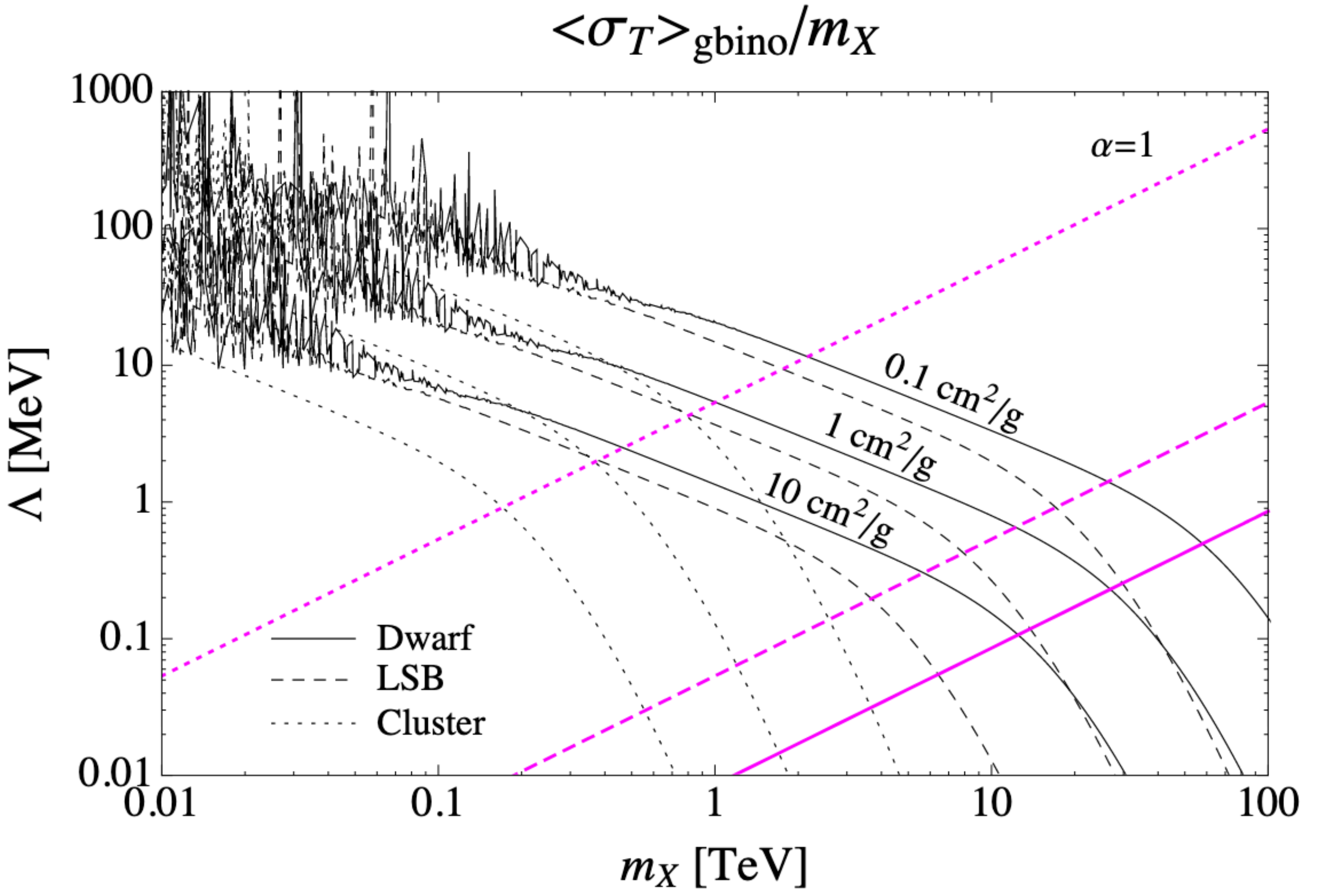
Kaplinghat, Tulin, Yu (PRL 2016)

Late-Universe Astrophysics

- Self interactions, inelastic collisions, dissipation, etc. can all affect structure of halos and their evolution
- Approximate treatment: assume fixed SIDM cross section, evaluated at characteristic velocity of dark matter particles in halo



KB, Kaplinghat, Kwa, Peter (PRD 2016)



KB, Feng, Kaplinghat, Tait (PRD 2014)

Millennium-II, Boylan-Kolchin+ (2009)

Can we understand SIDM halo evolution without needing to run N-body simulations?

Yes! Use semianalytic methods.

e.g., in globular clusters: Lynden-Bell, Eggleton (1980)
e.g., in SIDM halos: Balberg, S. Shapiro, Inagaki (2002); Koda, P. Shapiro (2011); Pollack, Spergel, Steinhardt (2015)

Gravothermal Evolution

- Mass conservation

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

- Hydrostatic equilibrium

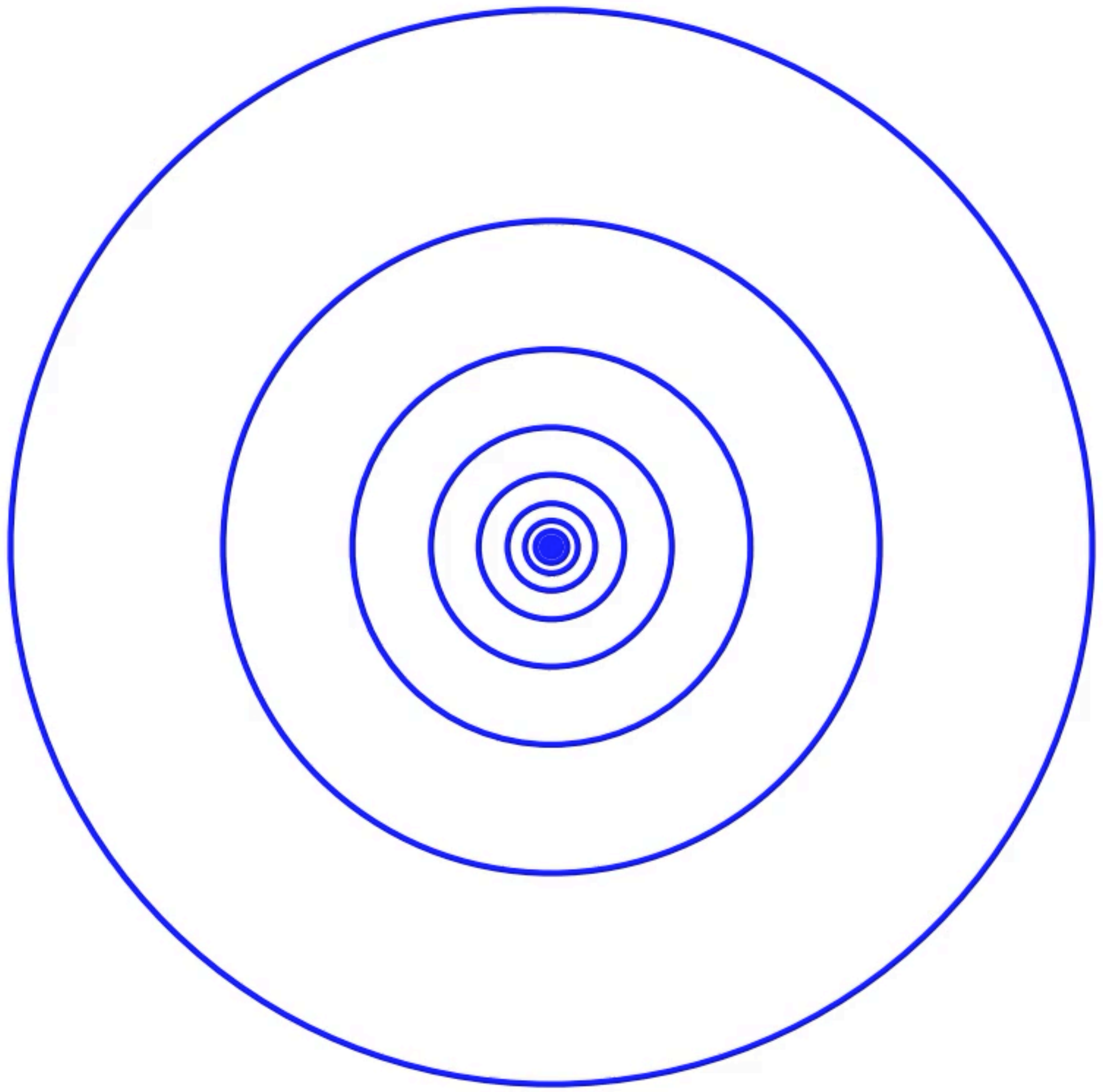
$$\frac{\partial(\rho \nu^2)}{\partial r} = -G\frac{M\rho}{r^2}$$

- Laws of thermodynamics

$$\frac{\partial L}{\partial r} = -4\pi r^2 \rho \nu^2 \left(\frac{\partial}{\partial t}\right)_M \ln\left(\frac{\nu^3}{\rho}\right)$$

- Heat conduction

$$\frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r} \quad \text{with} \quad \kappa^{-1} = \kappa_{\rm LMFP}^{-1} + \kappa_{\rm SMFP}^{-1}$$



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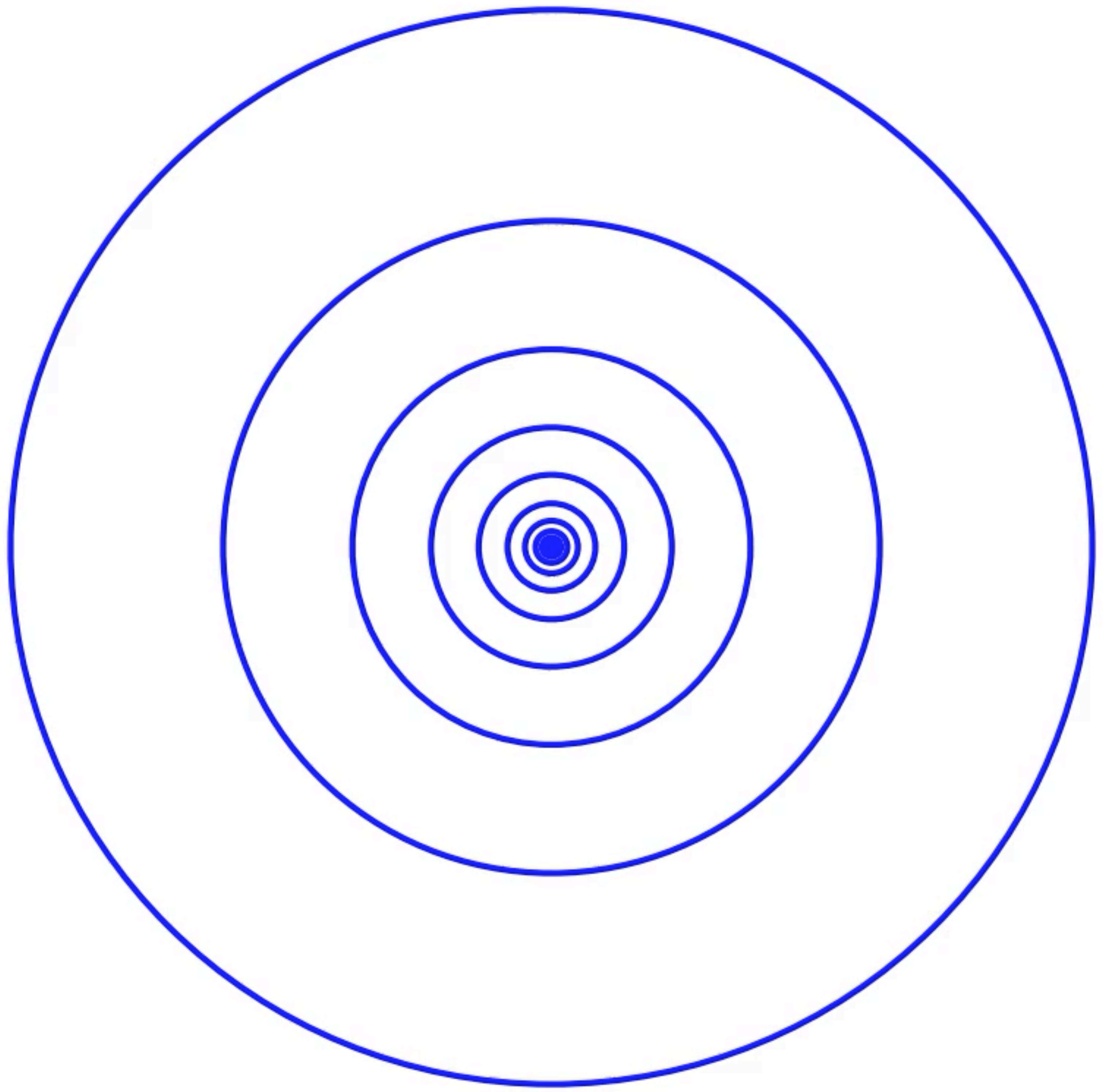
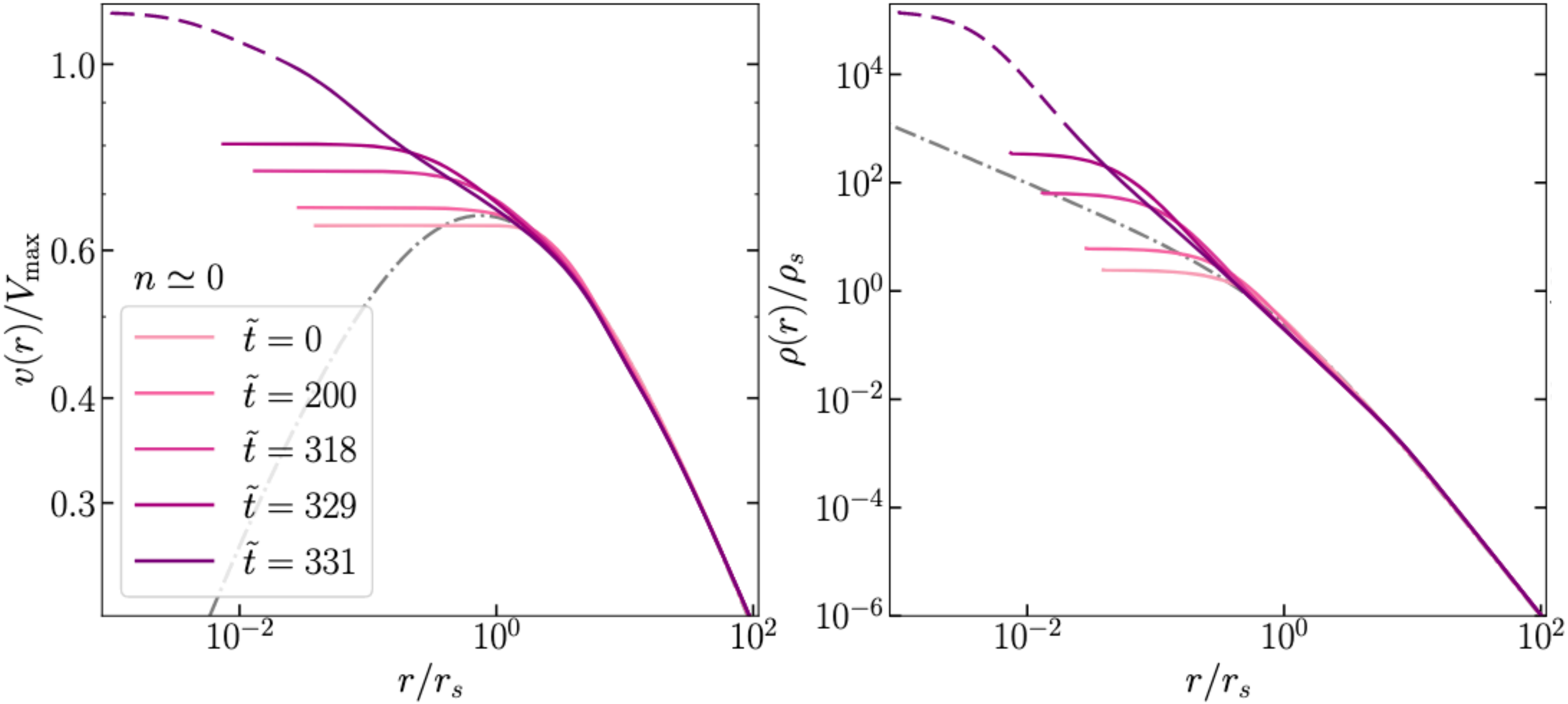


Self-gravitating systems have *negative* heat capacity

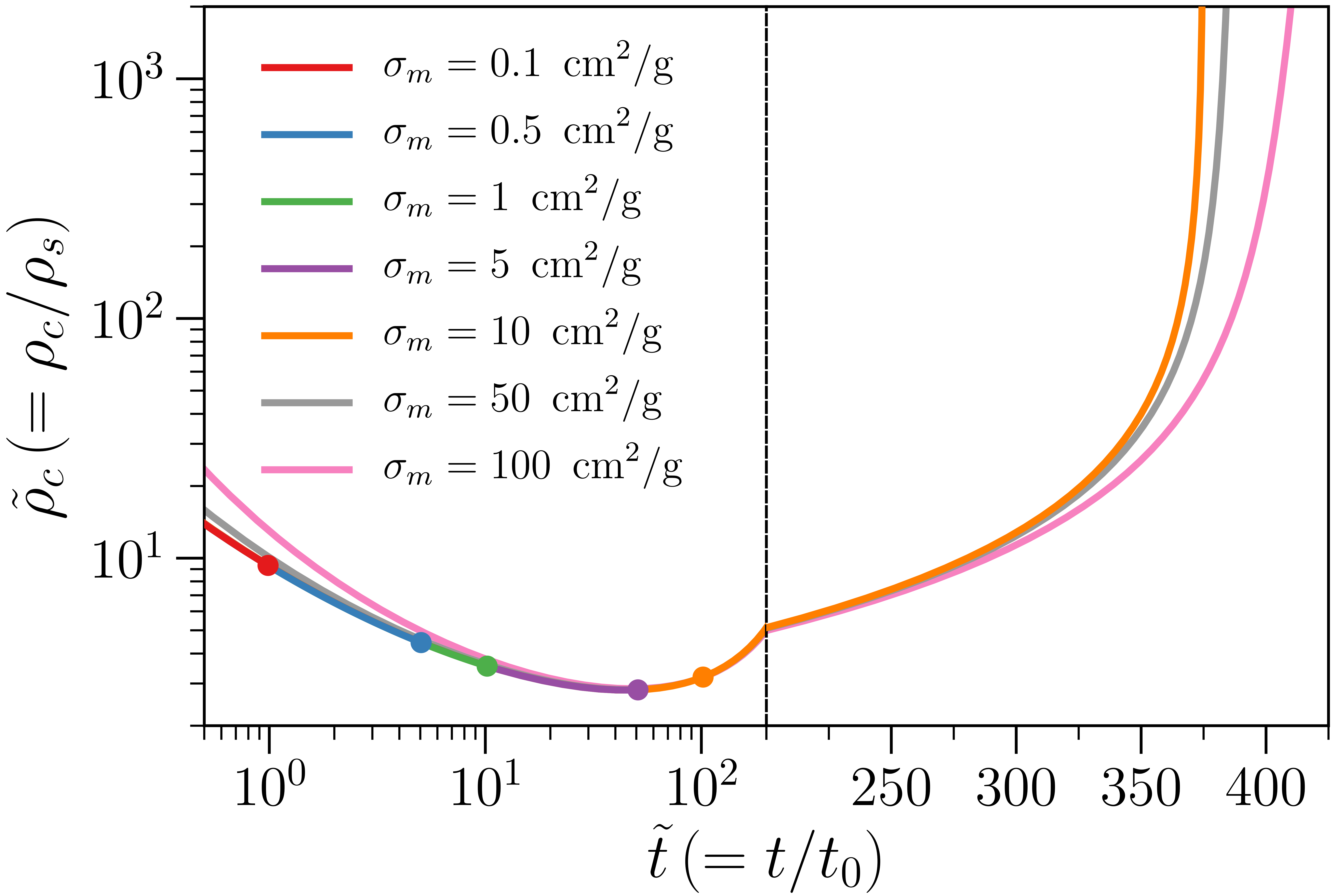
Unstable system → gravothermal catastrophe

Evolution of Density Profile



Outmezguine, KB, Gad-Nasr, Kaplinghat, Sagunski (2204.06568)

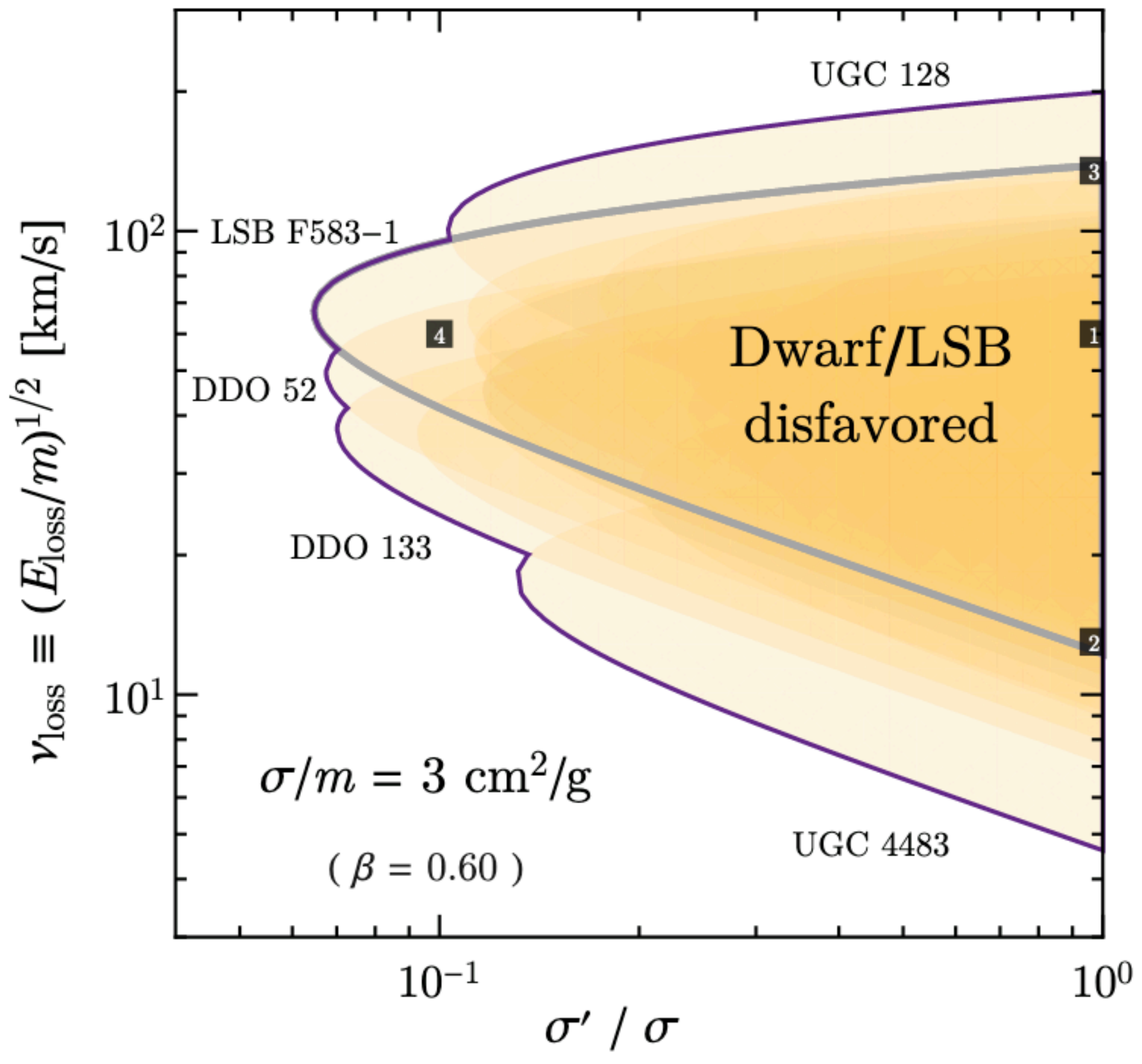
Central Density Evolution



Nishikawa, KB, Kaplinghat (PRD 2020)

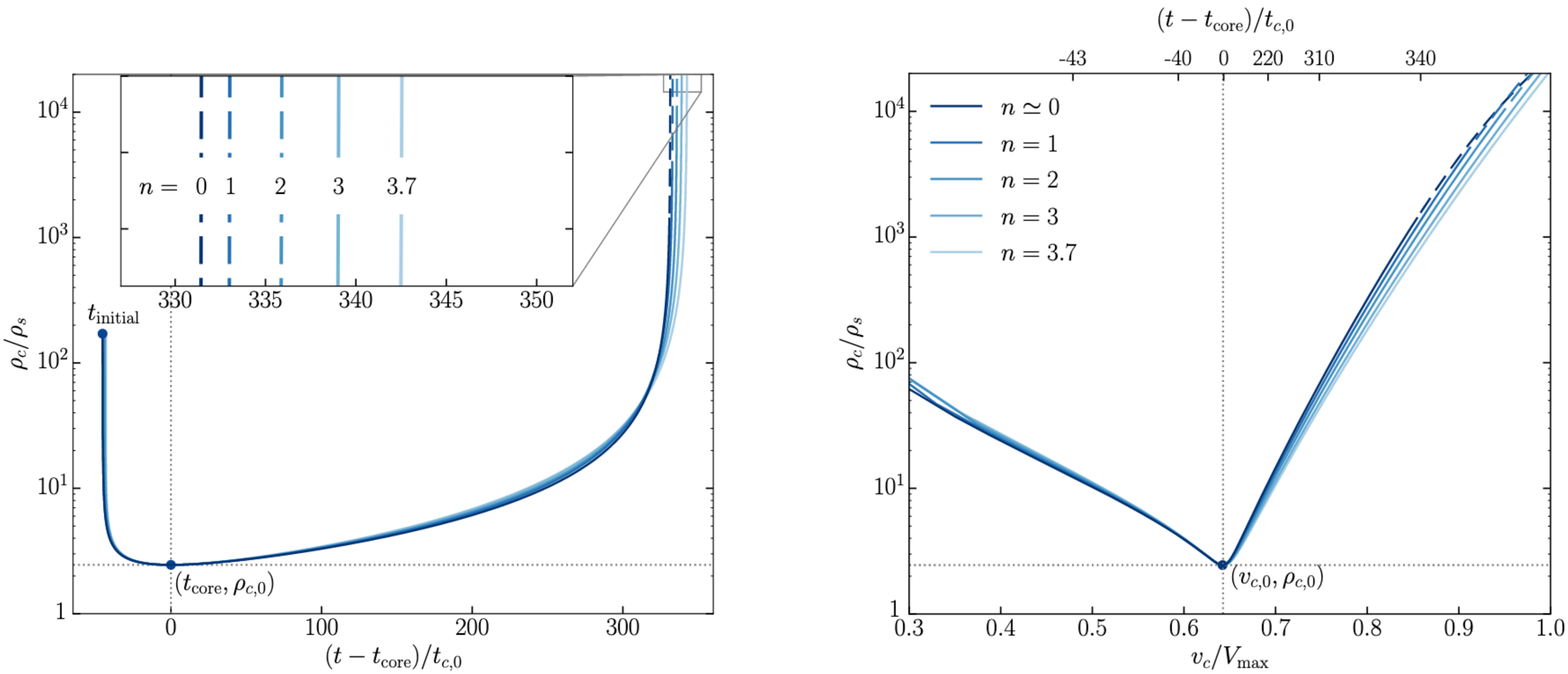
Accelerate Core Collapse

- Tidal stripping of subhalos
- Dark matter dissipation
- Baryonic potential
- Simulations are key to calibrating semianalytic equations (subsequent simulation studies have seen accelerated collapse)
- Collapsed cores produce high central densities



Essig, Yu, Zhong, McDermott (PRL 2019)

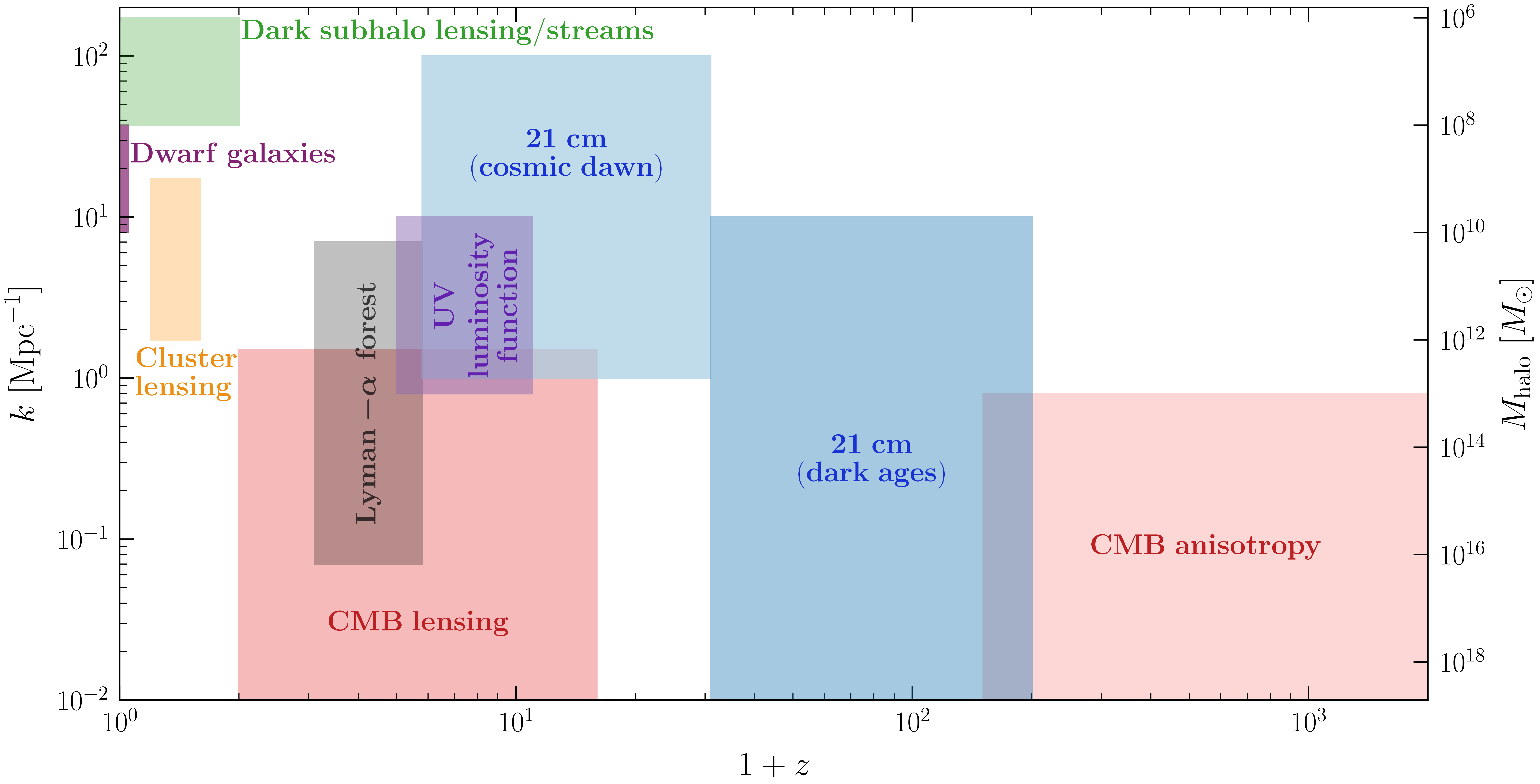
Incorporate Velocity Dependence



Obtain self-similar behavior in LMFP regime!

Outmezguine, KB, Gad-Nasr, Kaplinghat, Sagunski (2204.06568)

Complementarity



Snowmass 2021 Theory Frontier: Astrophysical and Cosmological Probes of Dark Matter (2203.06380)