1st Theoretical Astroparticle and Cosmology Symposium in Texas
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DARK MATTER HALO COLLAPSE WITH VELOCITY-DEPENDENT SELF-INTERACTING DARK MATTER

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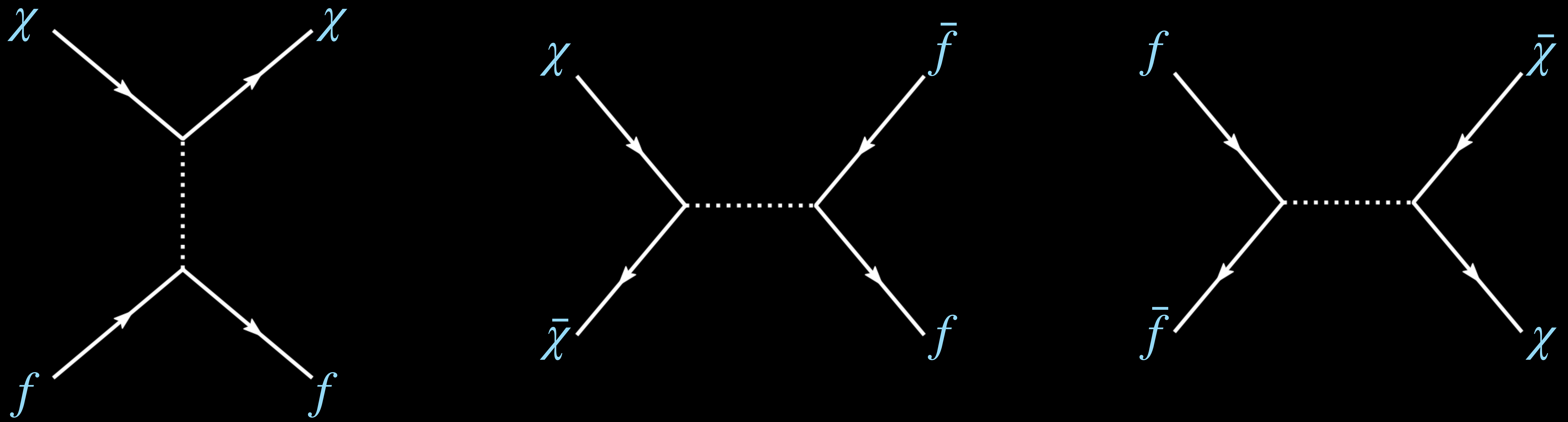
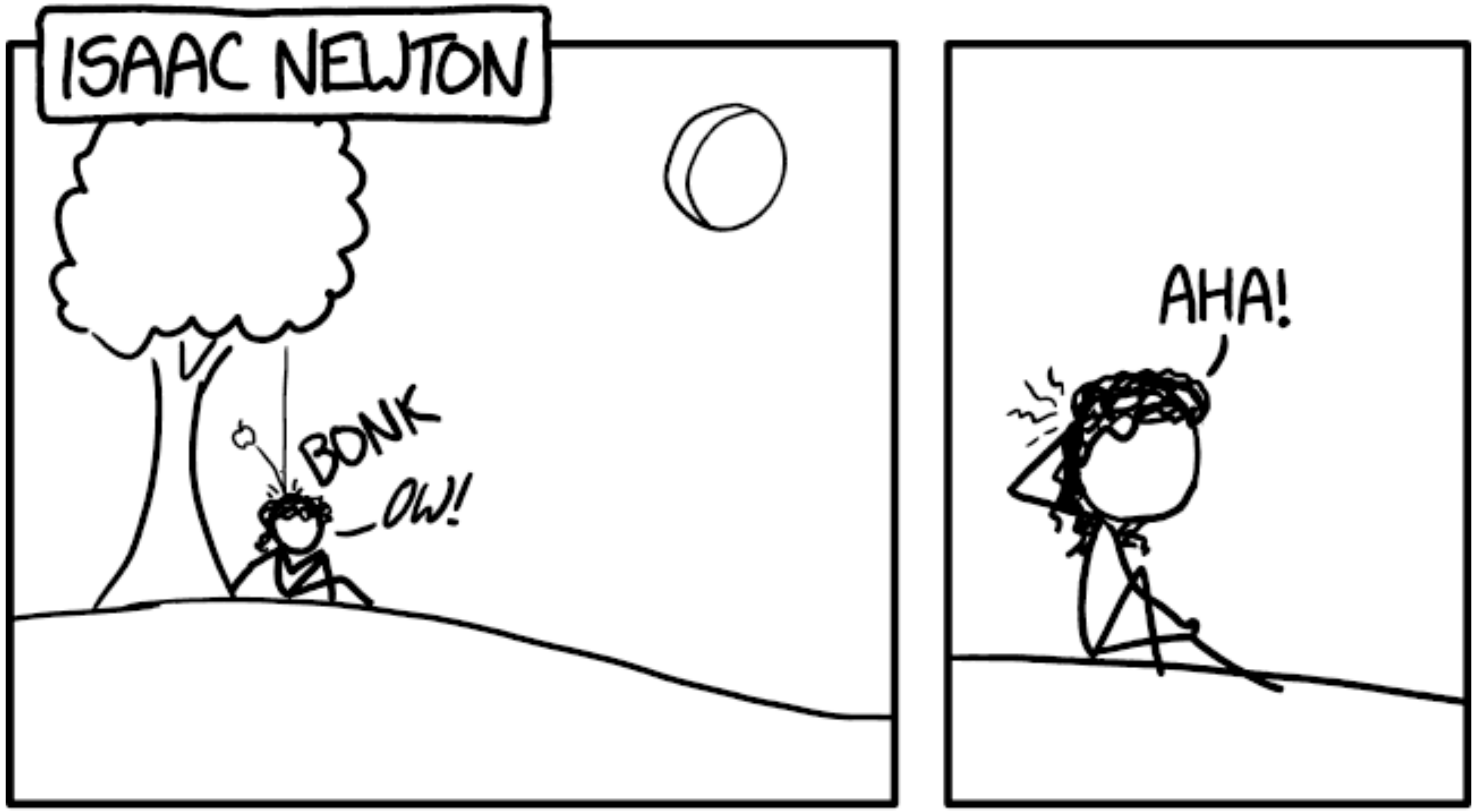
Dark Matter Searches

- Standard WIMPs: simple explanation of DM relic abundance that can arise from model-building efforts to address hierarchy problem
- Significant effort dedicated to searching for WIMPs through interactions with Standard Model (direct/indirect detection, collider searches)



- “Nightmare scenario”: DM has effectively no interactions with Standard Model

How do we proceed?



from "Moments of Inspiration" https://xkcd.com/1584/

- Secluded dark sectors can leave gravitational signatures!
- Rich phenomenology: multiple dark particles & new dark forces
- DM can easily have sizable self interactions (~1 cm^2/g)

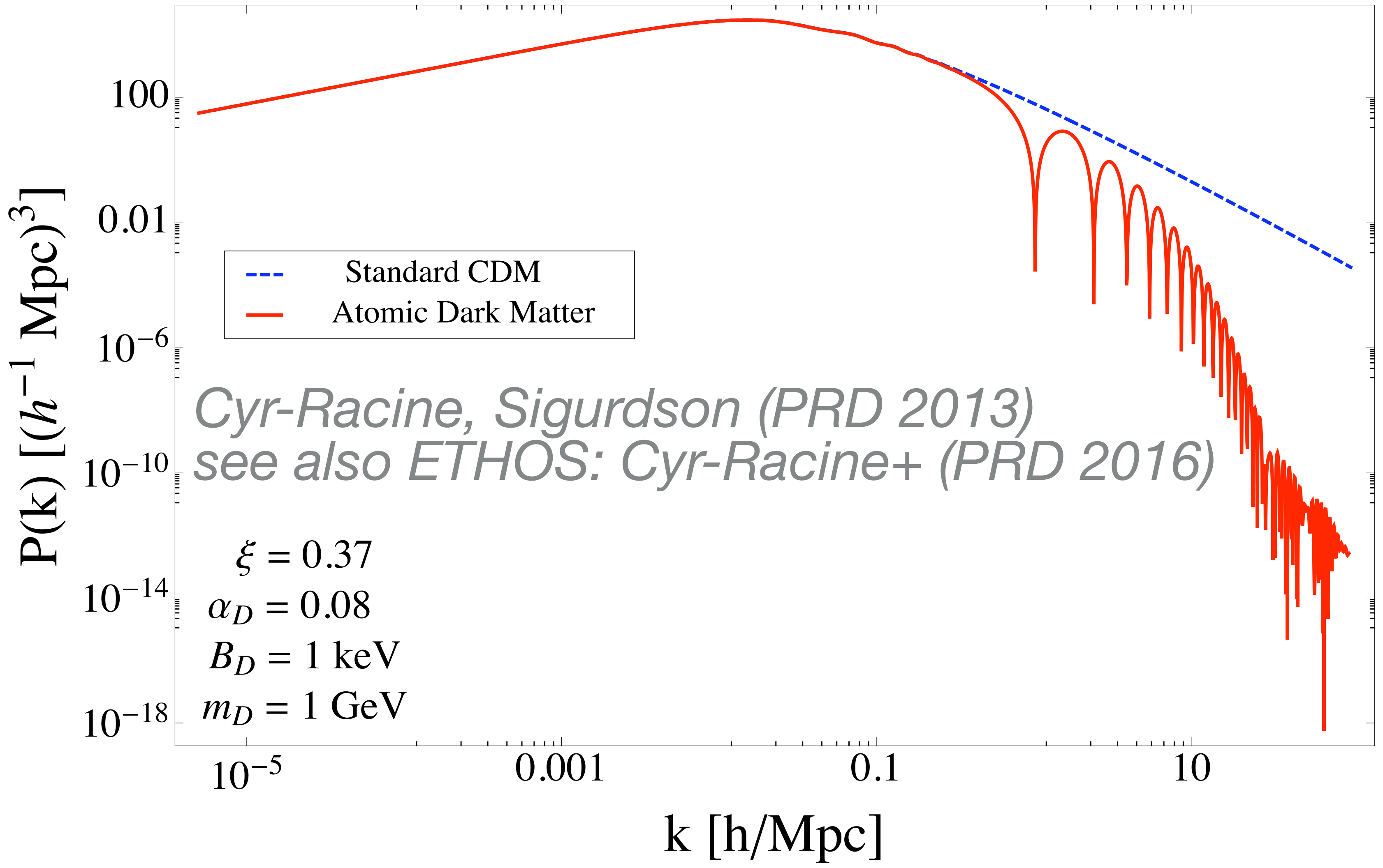
Consider self-interactions via light mediator

Early-Universe Cosmology

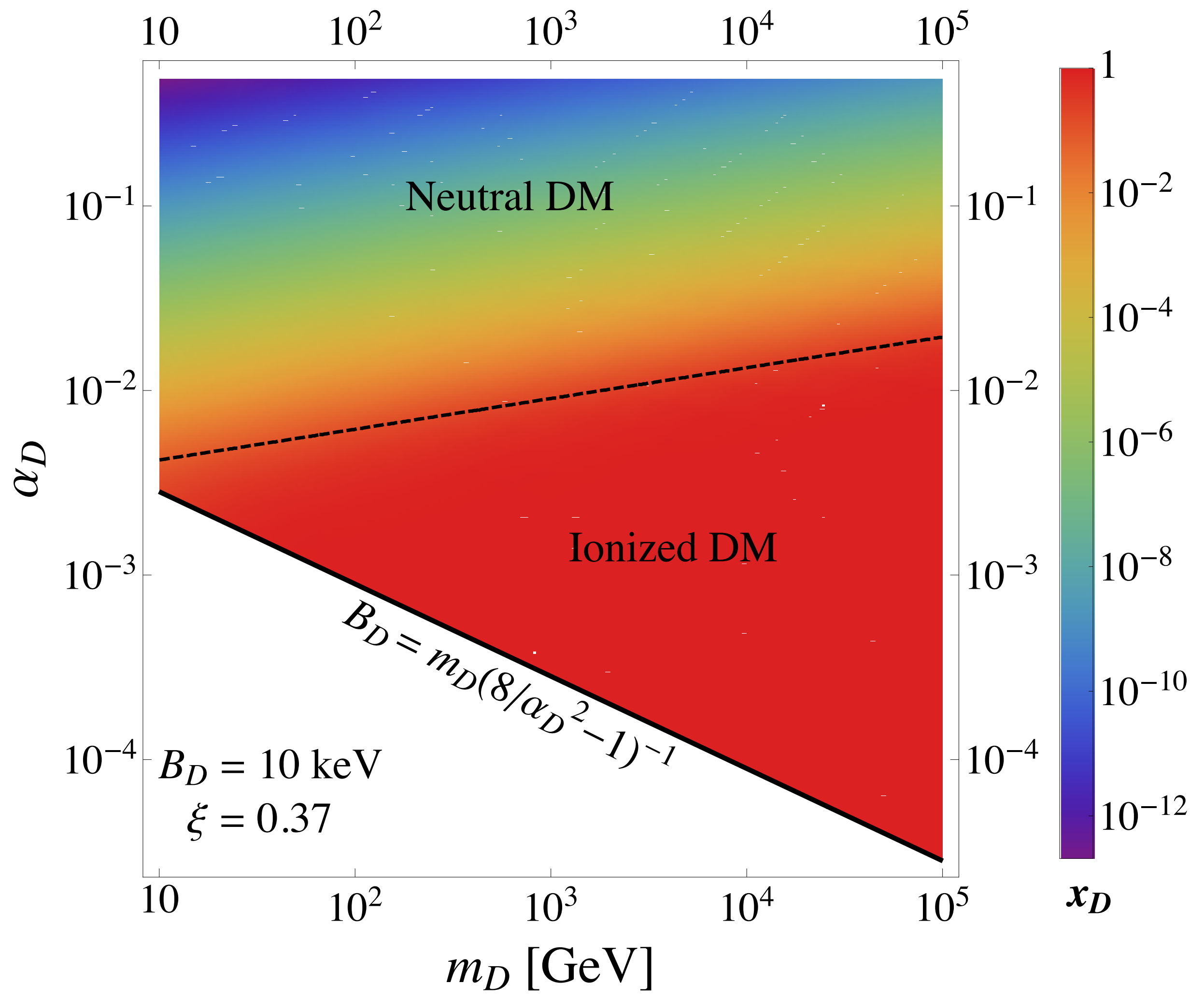
- Light mediators contribute to N_{eff}

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

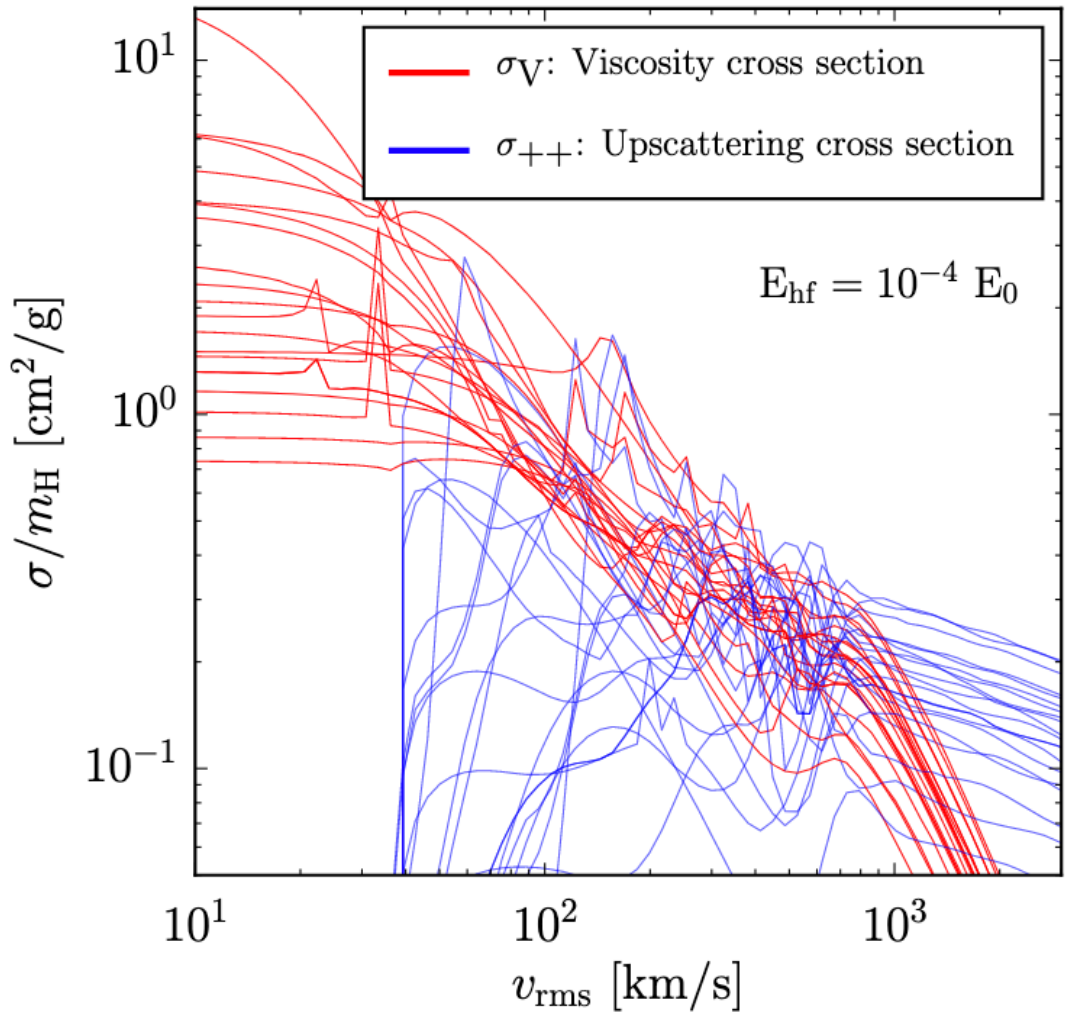
- Dark radiation induces dark acoustic oscillations
- Composite dark matter (e.g. atomic, nuclear) permits different pheno in early & late Universe



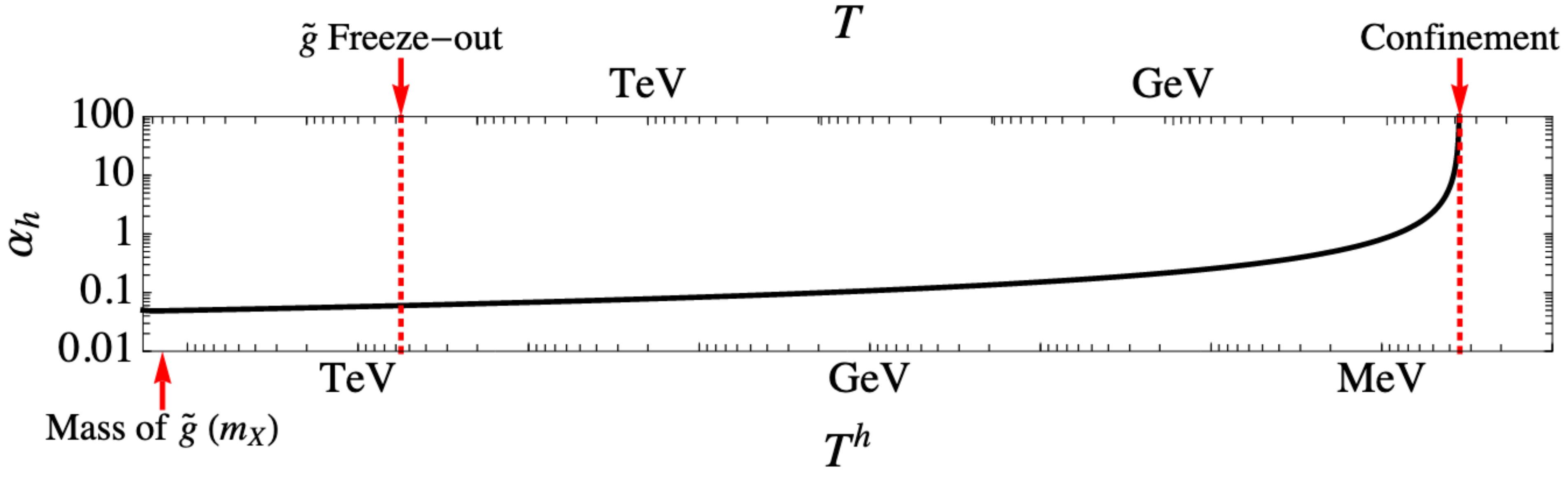
Cyr-Racine, Sigurdson (PRD 2013)
see also ETHOS: Cyr-Racine+ (PRD 2016)



Cyr-Racine, Sigurdson (PRD 2013)



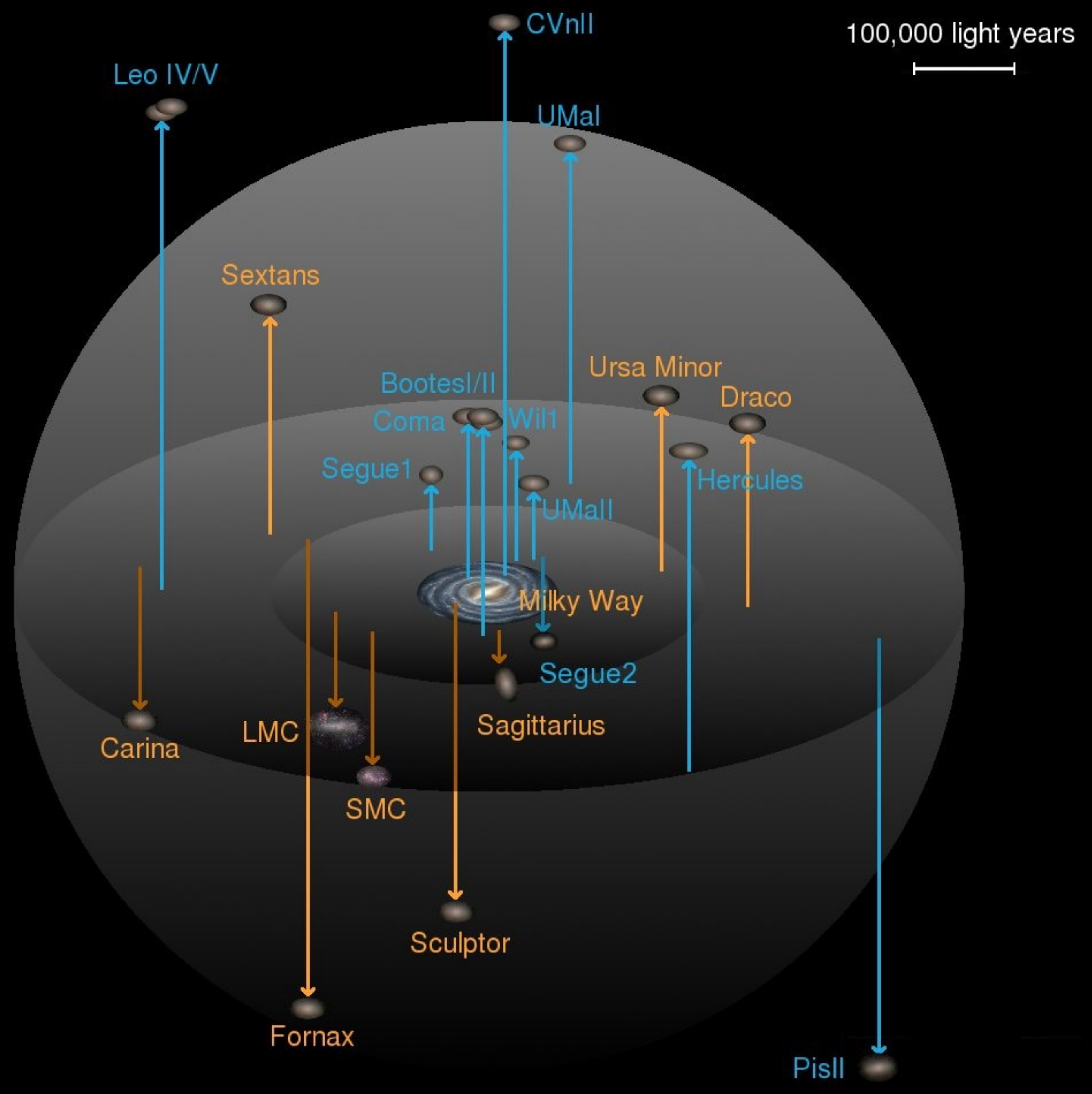
KB, Kaplinghat, Kwa, Peter (PRD 2016)



KB, Feng, Kaplinghat, Tait (PRD 2014)

Small-Scale Structure

Dwarf Spheroidals



Low-Surface Brightness (LSB)

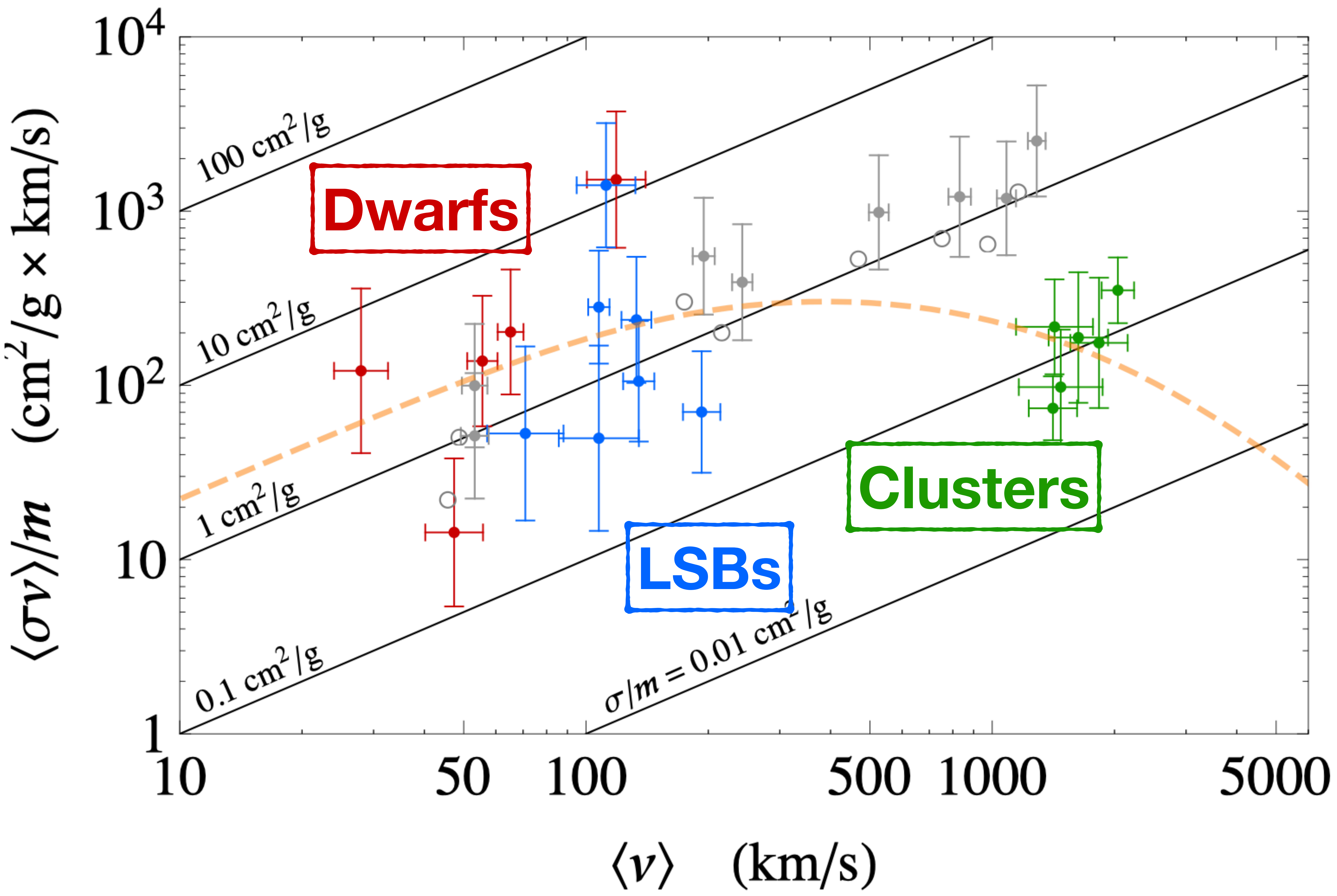
Clusters

X-ray: NASA/CXC/CfA/ M
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Ariz
Optical: NASA/STScI; Magellan/U.Ariz

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

Attempt to address with SIDM *Spergel, Steinhardt (PRL 2000)*

Revisit Particle Physics of SIDM



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

Kaplinghat, Tulin, Yu (PRL 2016)

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

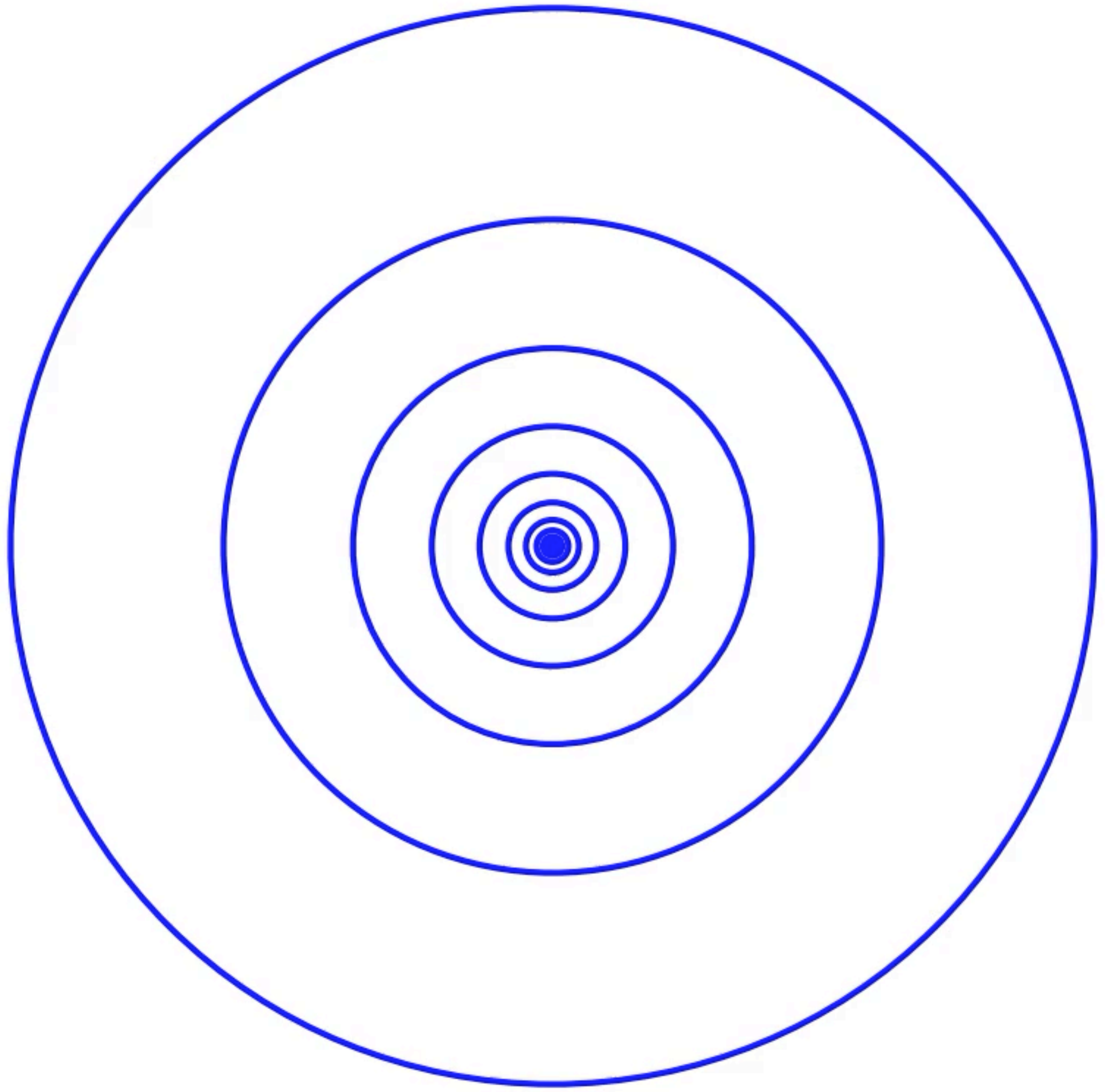
$$\frac{\partial(\rho\nu^2)}{\partial r} = -G\frac{M\rho}{r^2}$$

- 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

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



Self-gravitating systems have *negative* heat capacity

Unstable system → gravothermal catastrophe

Heat Conductivity (simple case: constant cross section)

- Particle physics contained in expression for κ
- Short mean free path regime: Calculate thermal conductivity perturbatively with Chapman-Enskog expansion

$$\kappa_{\mathrm{SMFP}} = \frac{3}{2}\frac{b\nu}{\sigma_0}$$

- Long mean free path regime: Thermal conductivity is sensitive to “size of box”, which is not well-defined for halos

$$\kappa_{\mathrm{LMFP}} = \frac{3aC}{8\pi G}\frac{\sigma_0}{m_\chi^2}\rho\nu^3$$

where C is order unity and must be determined via calibration to simulations

Parameters

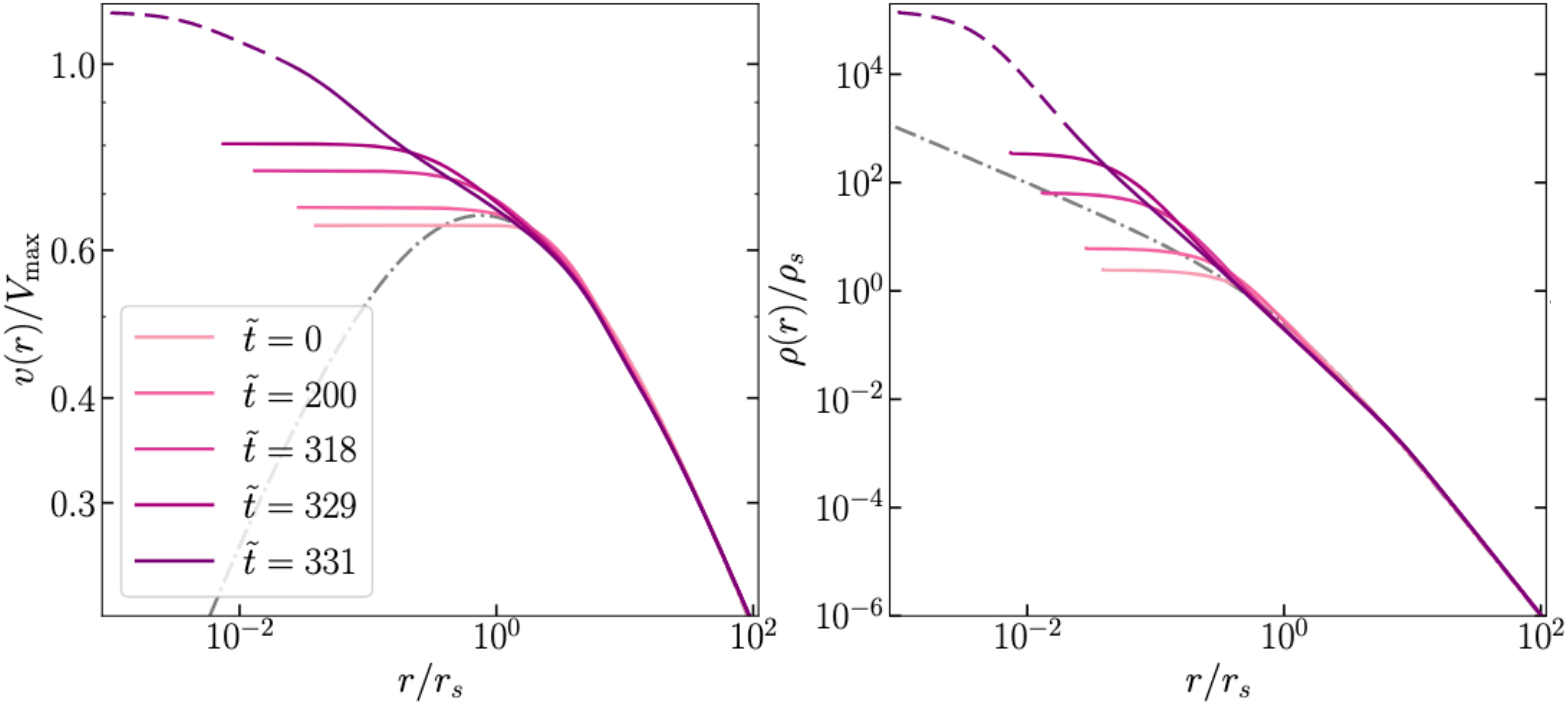
- Reduce all equations to dimensionless form

$$\frac{\partial \tilde{M}}{\partial \tilde{r}} = \tilde{r}^2\tilde{\rho}, \quad \frac{\partial(\tilde{\rho}\tilde{v}^2)}{\partial \tilde{r}} = -\frac{\tilde{M}\tilde{\rho}}{\tilde{r}^2}, \quad \frac{\partial \tilde{L}}{\partial \tilde{r}} = -\tilde{r}^2\tilde{\rho}\tilde{v}^2 \left(\frac{\partial}{\partial \tilde{t}}\right)_{\tilde{M}} \log\left(\frac{\tilde{v}^3}{\tilde{\rho}}\right), \quad \tilde{L} = -\tilde{r}^2\tilde{\kappa}\frac{\partial \tilde{v}^2}{\partial \tilde{r}}$$

where $\tilde{\kappa} = \tilde{\rho}\tilde{v}^3 \left[1 + \hat{\sigma}^2\tilde{\rho}\tilde{v}^2\right]^{-1}$

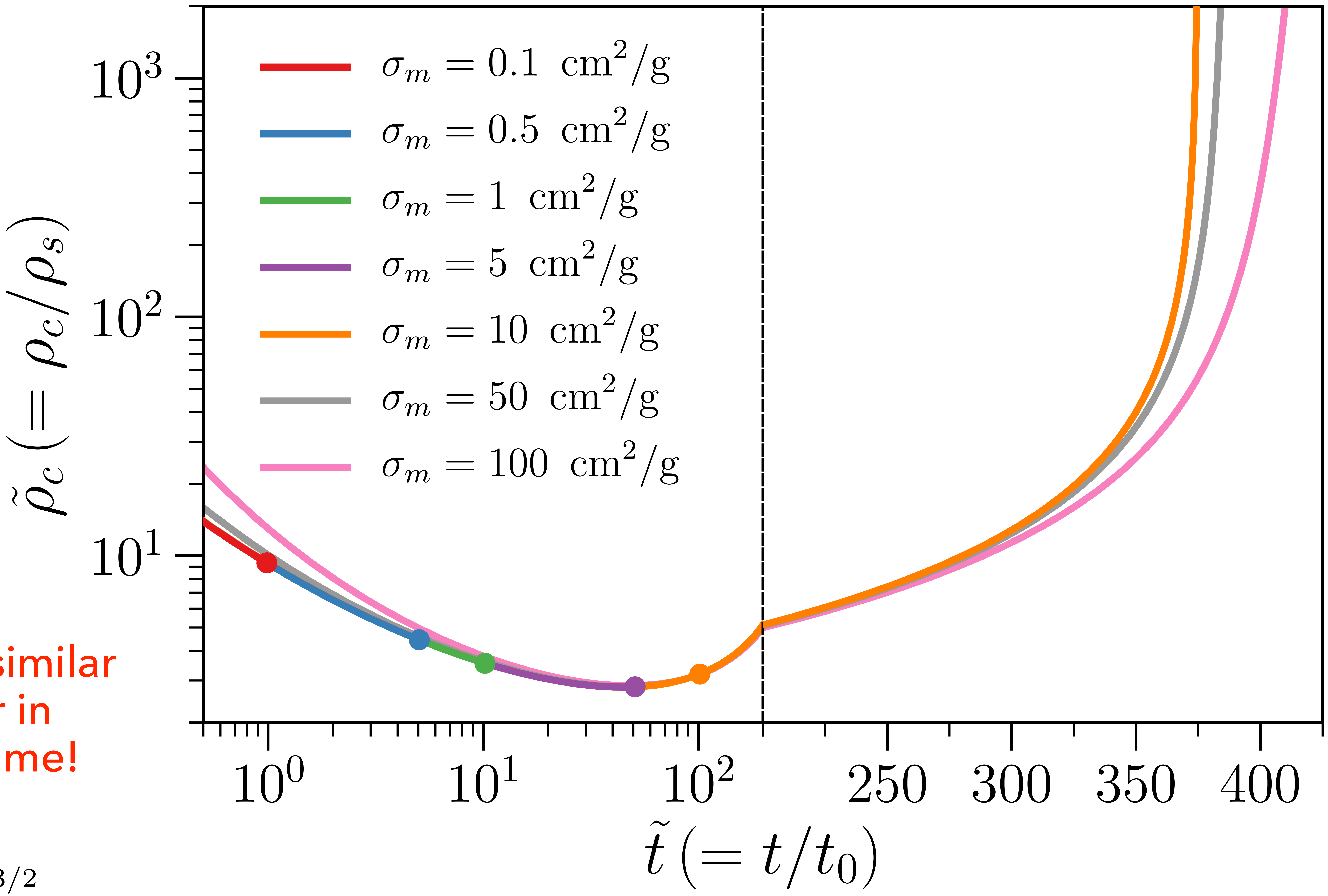
- Need to set 2 scales (e.g., r_s and ρ_s)
- Assume initial NFW profile: $\tilde{\rho}_{\text{initial}}(\tilde{r}) = \tilde{r}^{-1}(1+\tilde{r})^{-2}$
- Gravothermal equations fully specified by 1 parameter: $\hat{\sigma}$
- In LMFP regime, no free parameters – evolution is universal for all halos

Evolution of Density Profile



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

Central Density Evolution



Obtain self-similar behavior in LMFP regime!

$t_0^{-1} \sim (\sigma/m) r_s \rho_s^{3/2}$

Nishikawa, KB, Kaplinghat (PRD 2020)

Accelerate Core Collapse

- Collapsed cores produce high central densities: bug or feature?
- Observe some systems with larger central densities than expected from CDM
- Various ways of accelerating collapse:
  - Tidal stripping of subhalos

    Nishikawa, KB, Kaplinghat (PRD 2020)
  - Dark matter dissipation

    Essig, Yu, Zhong, McDermott (PRL 2019)
  - Baryonic potential

    ongoing with Kaplinghat and Necib
- Semianalytic methods can inform simulators and explore new regimes
- Simulations are needed for calibration

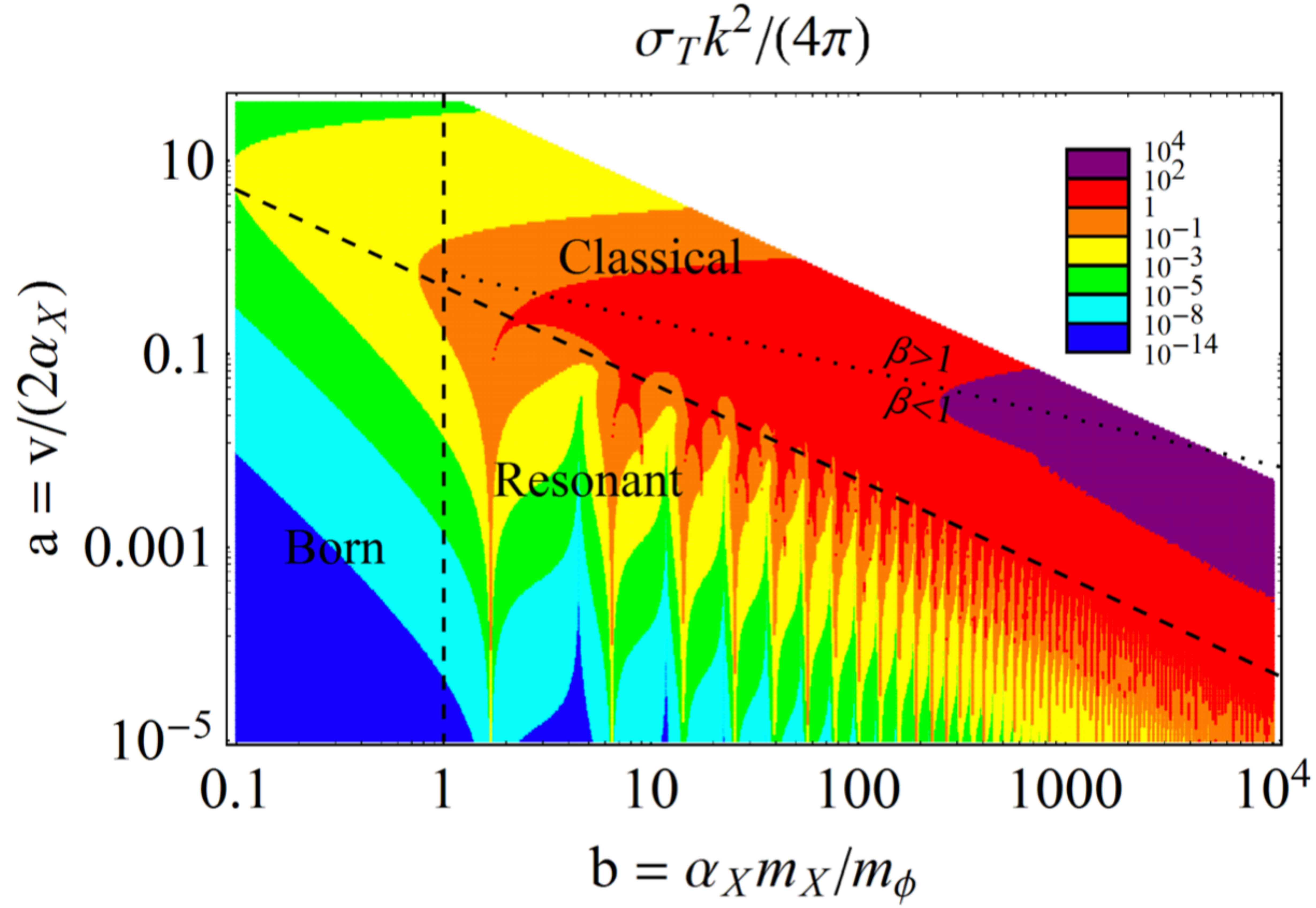
Yukawa Scattering

- Vector or scalar mediator gives rise to Yukawa potential

  $V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$ (attractive for scalar; attractive or repulsive for vector)
- Consider Born regime only for this talk
- Differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi} \left(1 + \frac{v_{\rm rel}^2}{w^2} \sin^2 \frac{\theta}{2} \right)^{-2}$$

  where $w = m_\phi / m_\chi$
- Isotropic, hard-sphere scattering for $w \to \infty$



Tulin, Yu, Zurek (PRD 2013)

Heat Conductivity (revisited)

- Particle physics contained in expression for κ
- Short mean free path regime: Calculate thermal conductivity perturbatively with Chapman-Enskog expansion

$$\kappa_{\text{SMFP}} = \frac{3}{2}\frac{b\nu}{\sigma_0}\boxed{\frac{1}{K_5}}$$

- Long mean free path regime: Thermal conductivity is sensitive to “size of box”, which is not well-defined for halos

$$\kappa_{\text{LMFP}} = \frac{3aC}{8\pi G}\frac{\sigma_0}{m_\chi^2}\rho\nu^3\boxed{K_3}$$

where C is order unity and must be determined via calibration to simulations

- Define K_p to easily recover hard-sphere scattering limit

$$K_p\left(\frac{\nu}{w}\right) = \frac{\langle\sigma_v v_{\text{rel}}^p\rangle}{\lim_{w\to\infty}\langle\sigma_v v_{\text{rel}}^p\rangle}$$

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

Parameters (revisited)

- Reduce all equations to dimensionless form

$$\frac{\partial \tilde{M}}{\partial \tilde{r}} = \tilde{r}^2 \tilde{\rho}, \quad \frac{\partial(\tilde{\rho}\tilde{v}^2)}{\partial \tilde{r}} = -\frac{\tilde{M}\tilde{\rho}}{\tilde{r}^2}, \quad \frac{\partial \tilde{L}}{\partial \tilde{r}} = -\tilde{r}^2\tilde{\rho}\tilde{v}^2 \left(\frac{\partial}{\partial \tilde{t}}\right)_{\tilde{M}} \log\left(\frac{\tilde{v}^3}{\tilde{\rho}}\right), \quad \tilde{L} = -\tilde{r}^2\tilde{\kappa}\frac{\partial \tilde{v}^2}{\partial \tilde{r}}$$

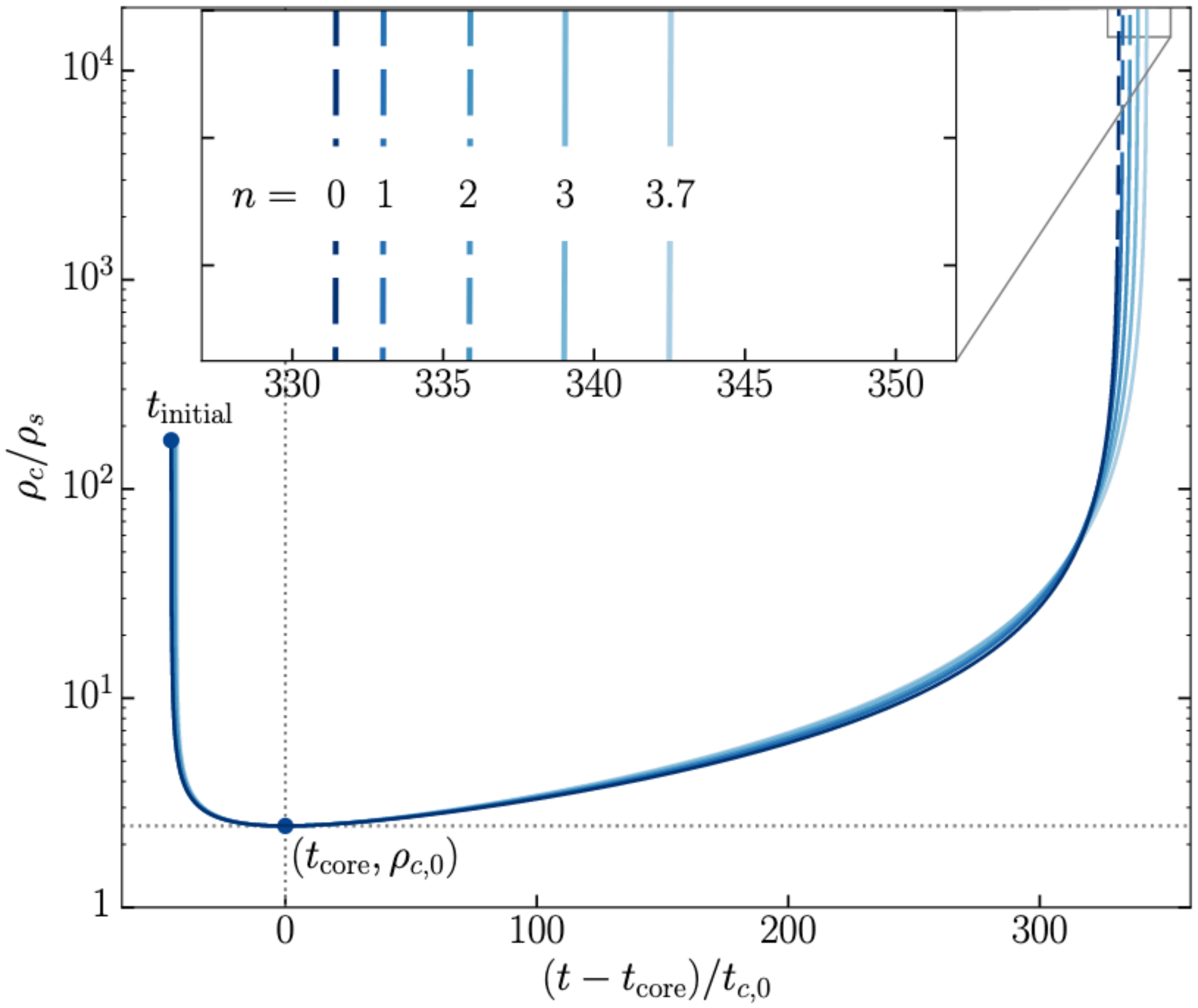
where $\tilde{\kappa} = \tilde{\rho}\tilde{v}^3\tilde{K}_3\left[1 + \hat{\sigma}^2\tilde{\rho}\tilde{v}^2\tilde{K}_3\tilde{K}_5\right]^{-1}$ and $\tilde{K}_p = K_p(\tilde{v}/\tilde{w})/K_p(1/\tilde{w})$

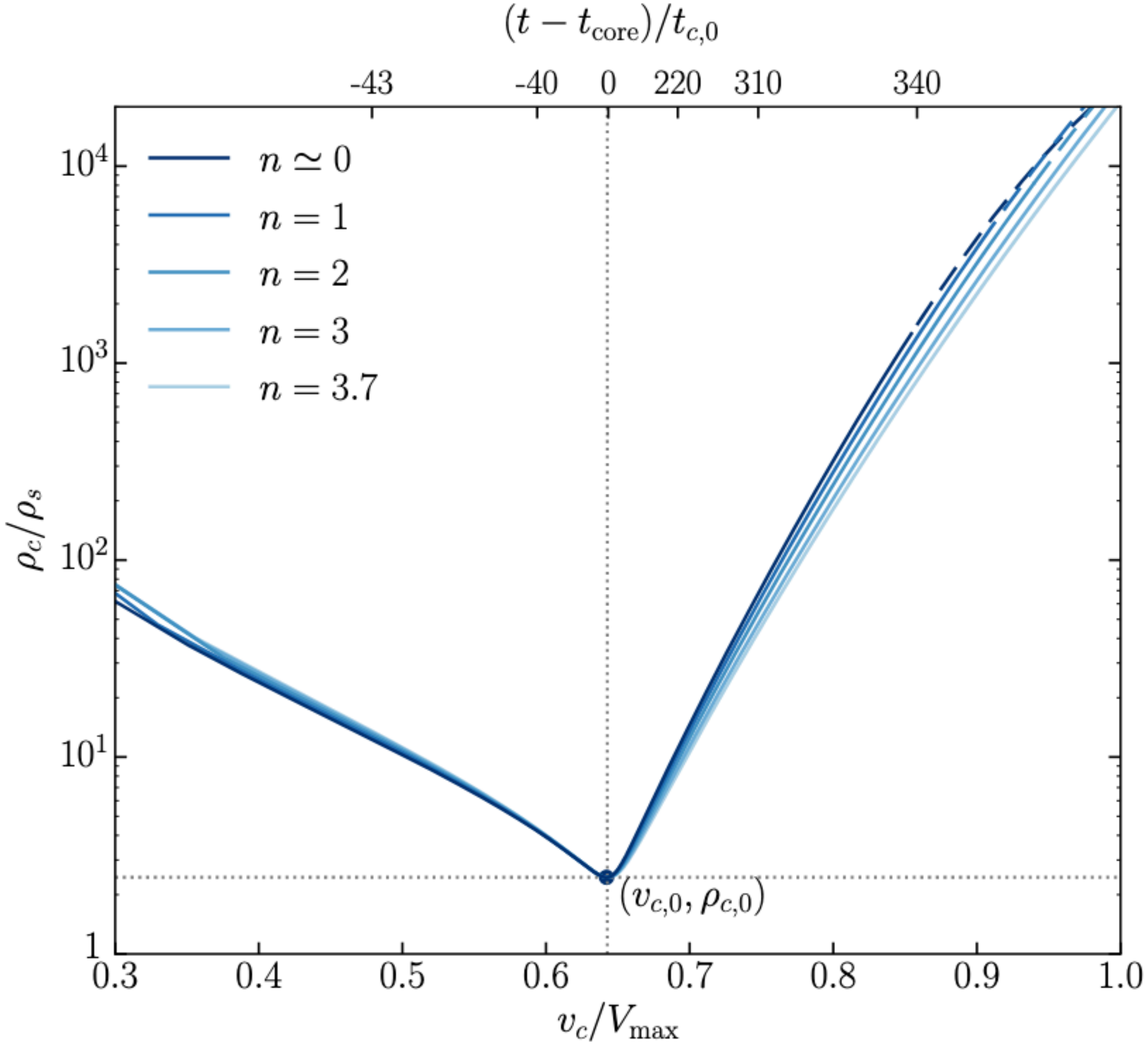
- Need to set 2 scales (e.g., r_s and ρ_s)
- Assume initial NFW profile: $\tilde{\rho}_{\text{initial}}(\tilde{r}) = \tilde{r}^{-1}(1+\tilde{r})^{-2}$
- Gravothermal equations fully specified by 2 parameters: $\hat{\sigma}$ and $\hat{w}$
- For hard-sphere scattering in LMFP regime, no free parameters – evolution is universal for all halos
- But for Yukawa scattering, there is dependence on $\hat{w}$ in LMFP regime

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

Incorporate Velocity Dependence

$$\kappa_{\rm LMFP} \sim \tilde{\nu}^{3-n}$$



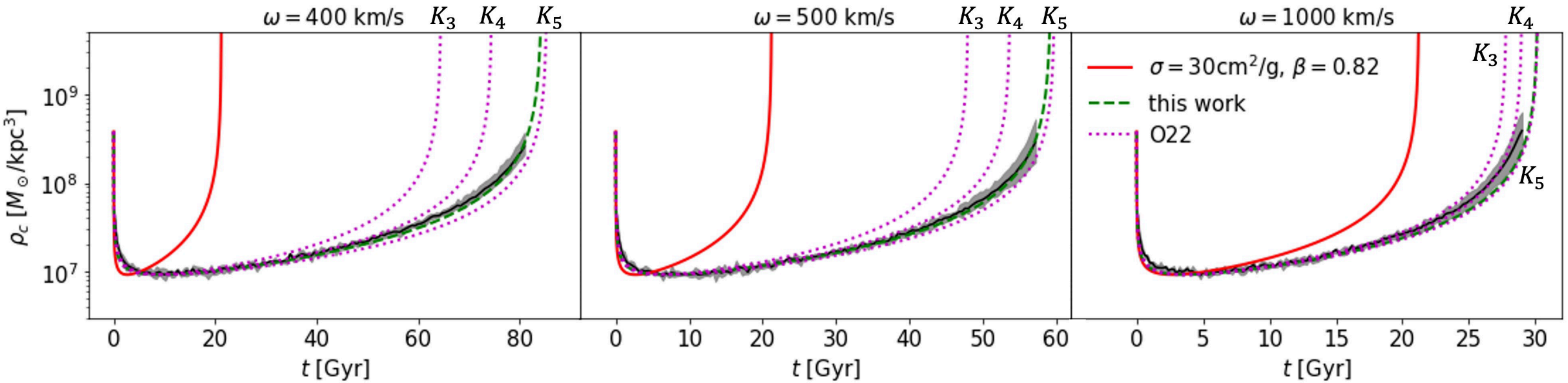


Obtain ~self-similar behavior in LMFP regime!
(dependence on *n* is mild)

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

Universality Permits Mapping

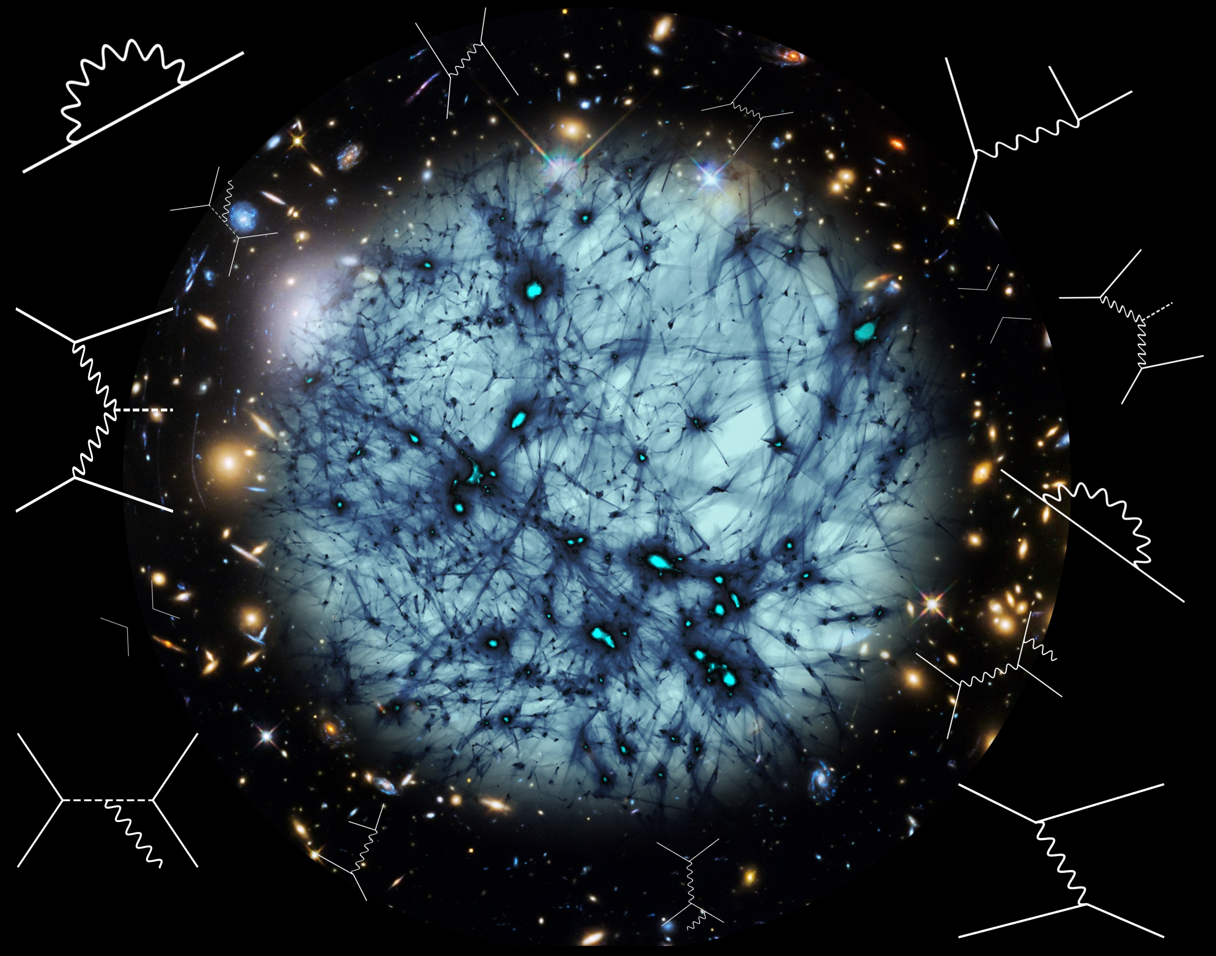
- We can systematically map constant-cross-section simulations to velocity-dependent cases
- Recent simulations support this idea, with proper calibration



Yang+ (2205.02957)

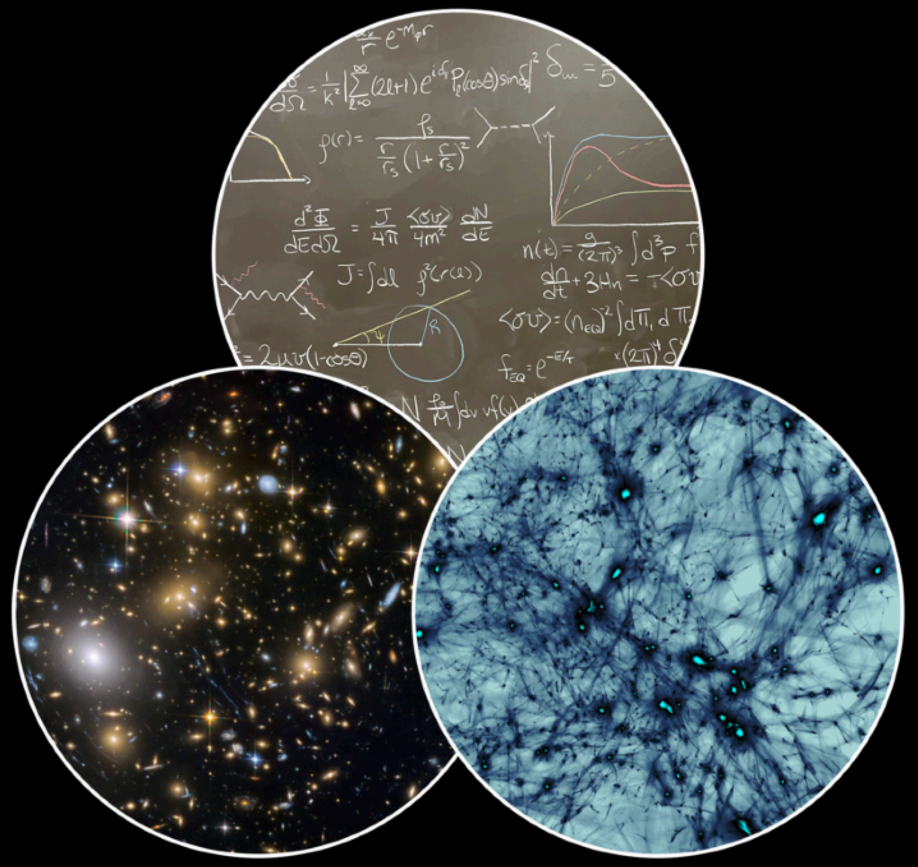
KITP 2024 Program Plug

Dark Matter Theory, Simulation, and Analysis in the Era of Large Surveys



- Coordinators:
  KB, Vera Gluscevic, Ferah Munshi, Annika Peter
- Scientific advisors:
  Jo Dunkley, Tim Tait, Risa Wechsler
- May 20 – July 12, 2024
  [Application deadline: February 12, 2023]

Cosmic Signals of Dark Matter Physics: New Synergies



- Coordinators:
  KB, Ferah Munshi, Ethan Nadler, Annika Peter
- June 3 – 6, 2024
  [Registration deadline: May 5, 2024]