CERN-CKC Workshop on Physics beyond the Standard Model
Jeju Island, 7 June 2022

EVOLUTION OF SELF-INTERACTING DARK MATTER HALOS

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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

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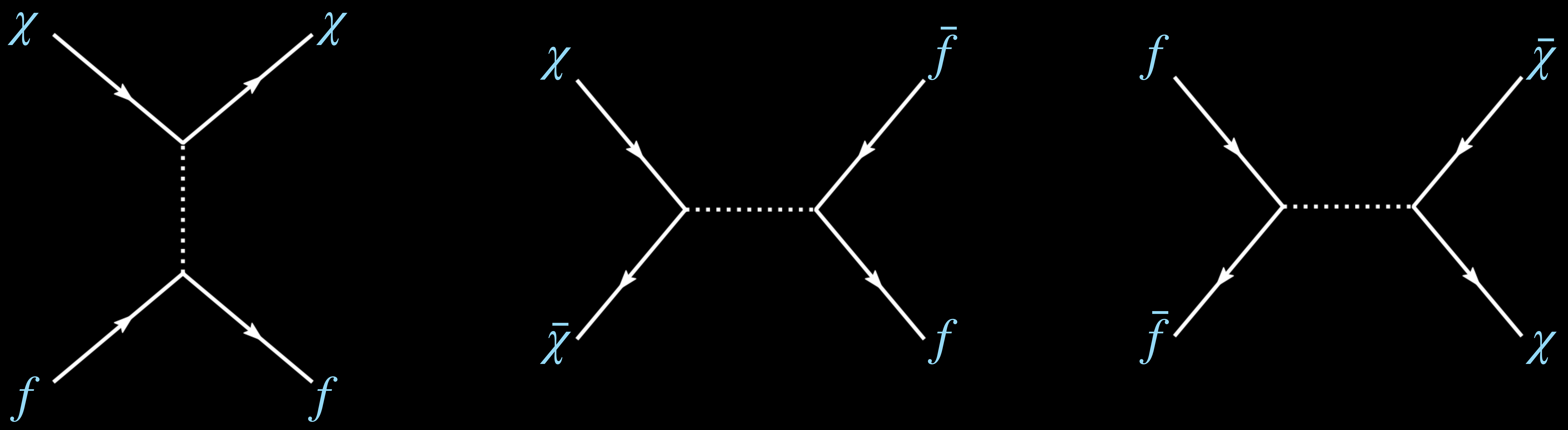
- Significant effort dedicated to searching for WIMPs through interactions with Standard Model (direct/indirect detection, collider searches)



Dark Matter Searches

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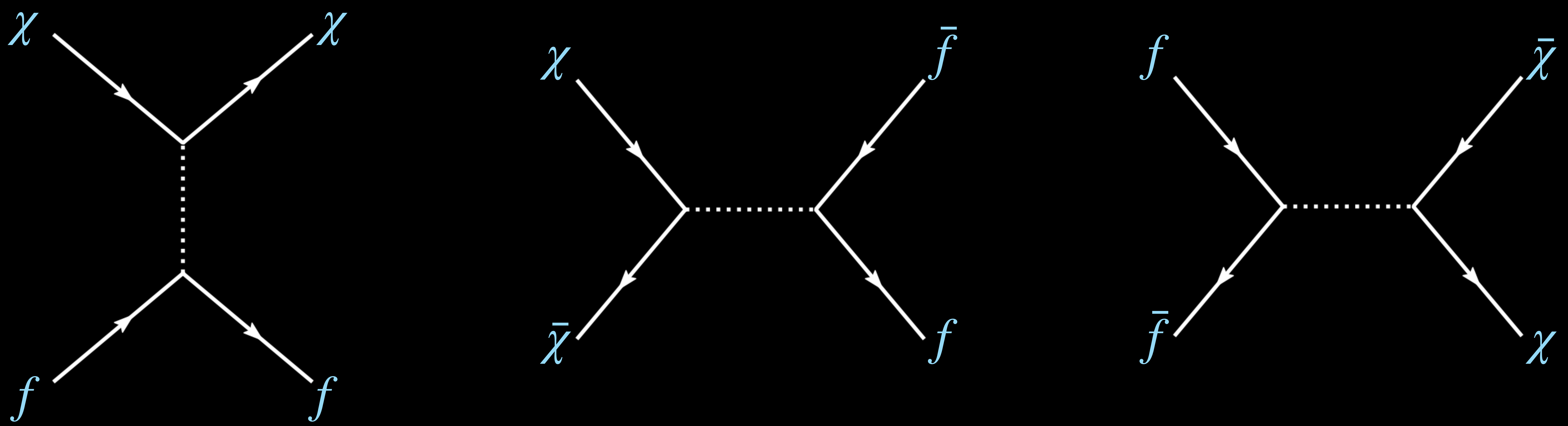
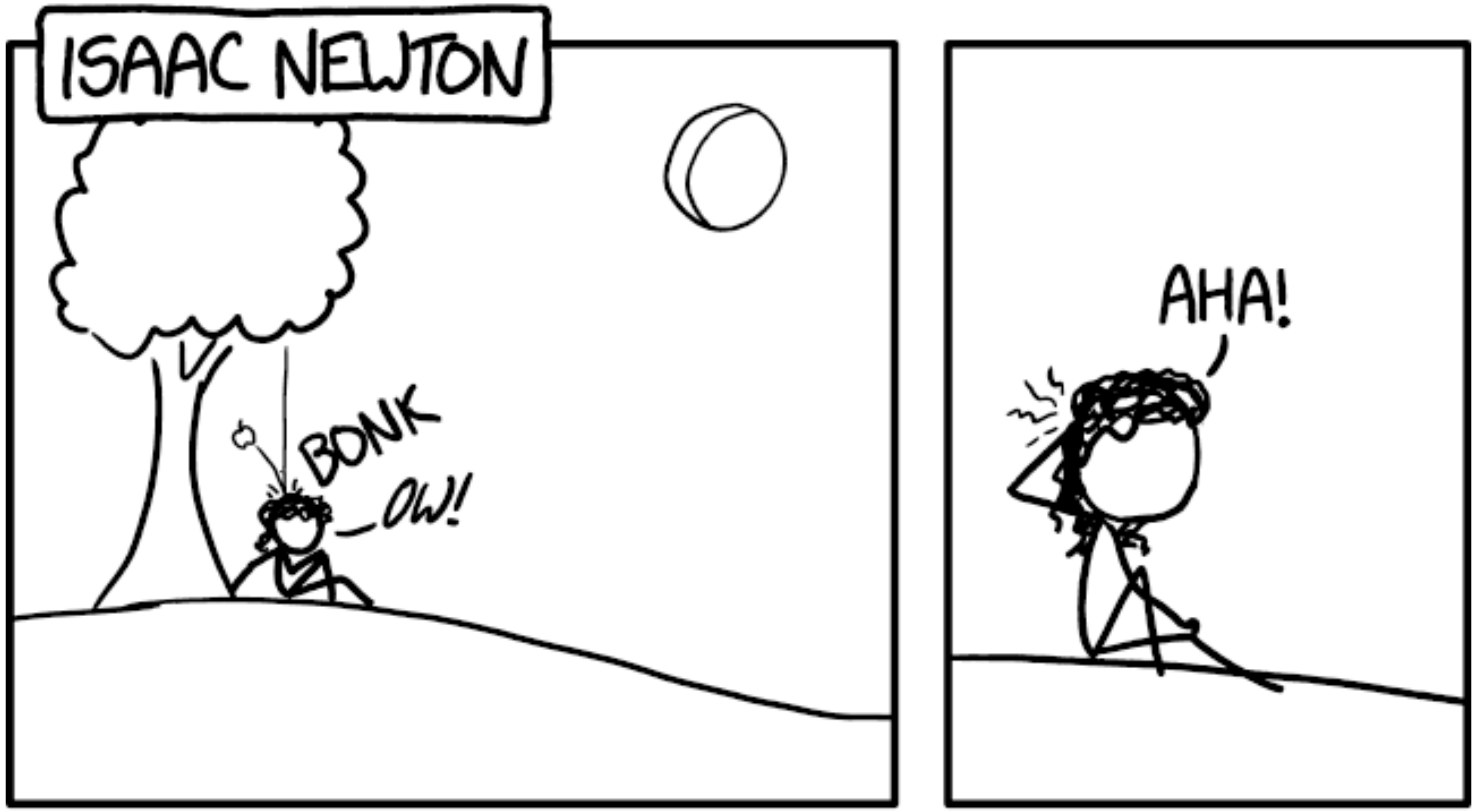


- "Nightmare scenario": DM has effectively no interactions with Standard Model

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

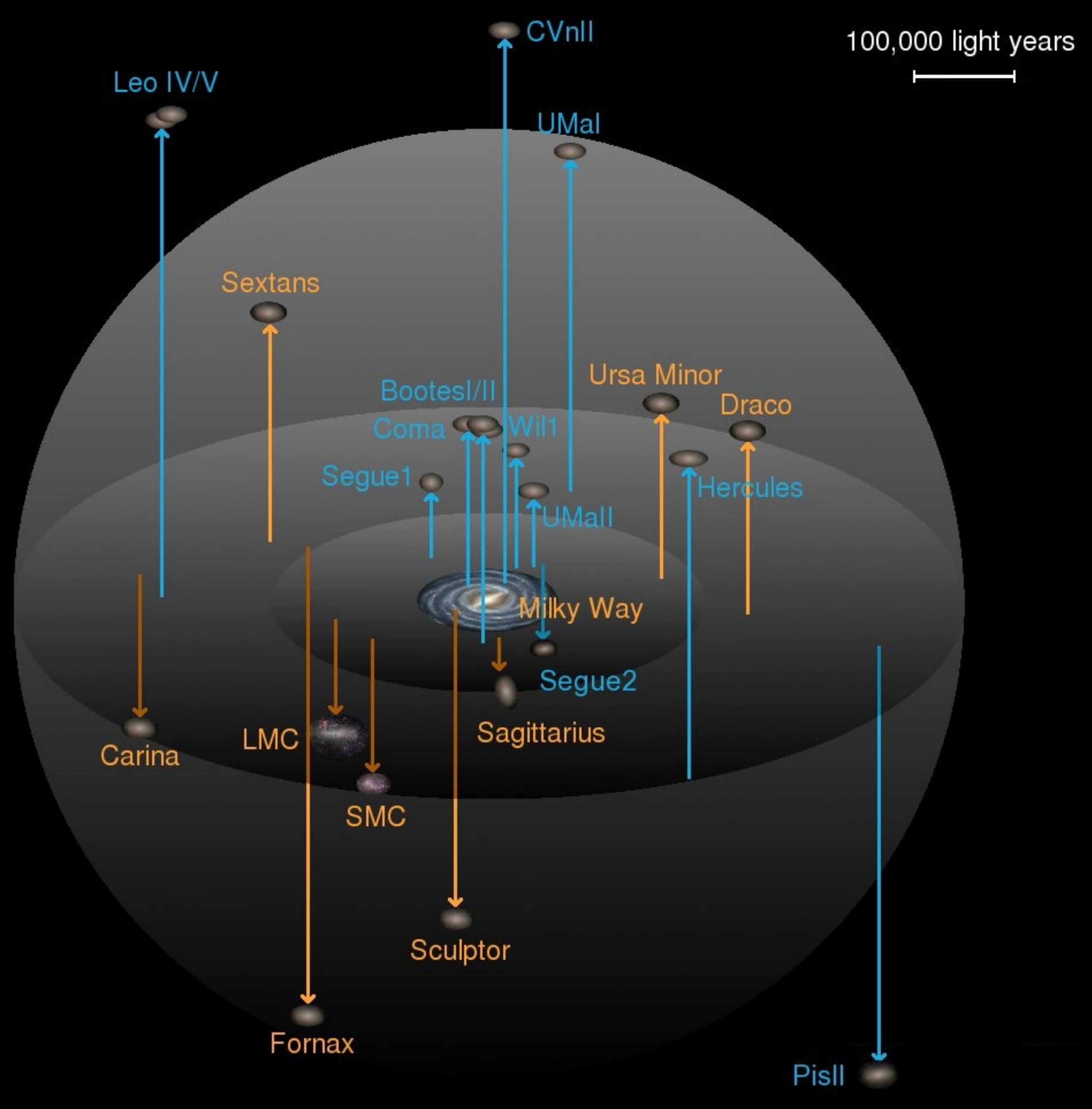
e.g., composite states
Khlopov, Kouvaris (PRD 2008); Kribs, Roy, Terning, Zurek (PRD 2010); Cline, Liu, Moore, Xue (PRD 2014); KB, Feng, Kaplinghat, Tait (PRD 2014); KB, Feng, Kaplinghat, Shadmi, Tait (PRD 2014); Antipin, Redi, Strumia, Vigiani (JHEP 2015); Kribs, Neil (IJMPA 2016); Ko, Nagata, Tang (PLB 2017); Tsai, McGehee, Murayama (2020)

e.g., atomic dark matter
Goldberg, Hall (PLB 1986), Kaplan, Krnjaic, Rehermann, Wells (JCAP 2010, 2011); Cline, Liu, Xue (PRD 1012); Cline, Liu, Moore, Xue (PRD 2014); Fan, Katz, Randall, Reece (PDU 2013, PRL 2013); Cyr-Racine, Sigurdson (PRD 2013); Cyr-Racine, dePutter, Raccanelli, Sigurdson (PRD 2014); KB, Kaplinghat, Kwa, Peter (PRD 2016); Gresham, Lou, Zurek (PRD 2018)

Focus on impact of self-interacting dark matter (SIDM)
on halo formation and evolution

Small-Scale Structure

Dwarf Spheroidals



Low-Surface Brightness (LSB)

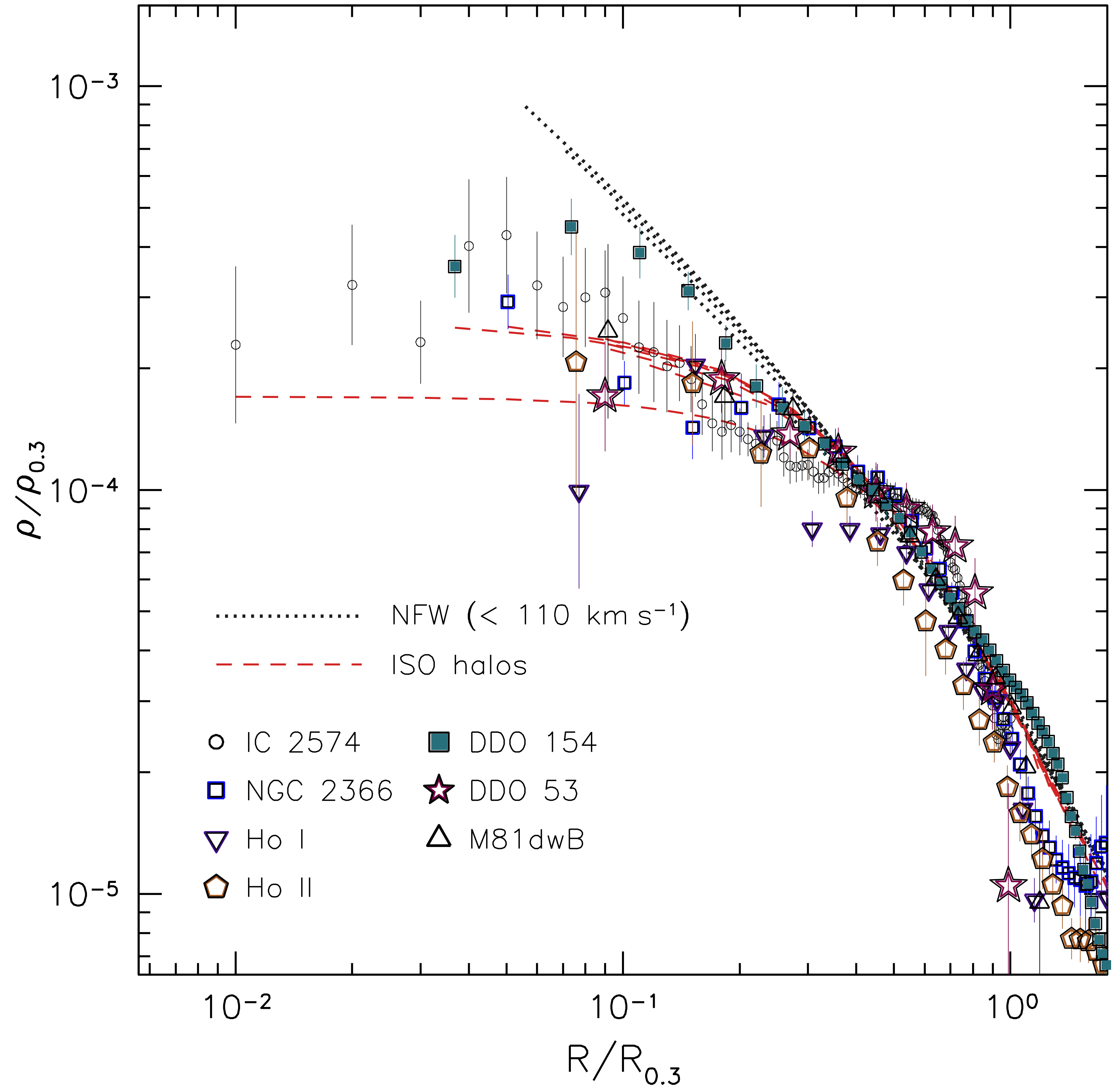
Clusters

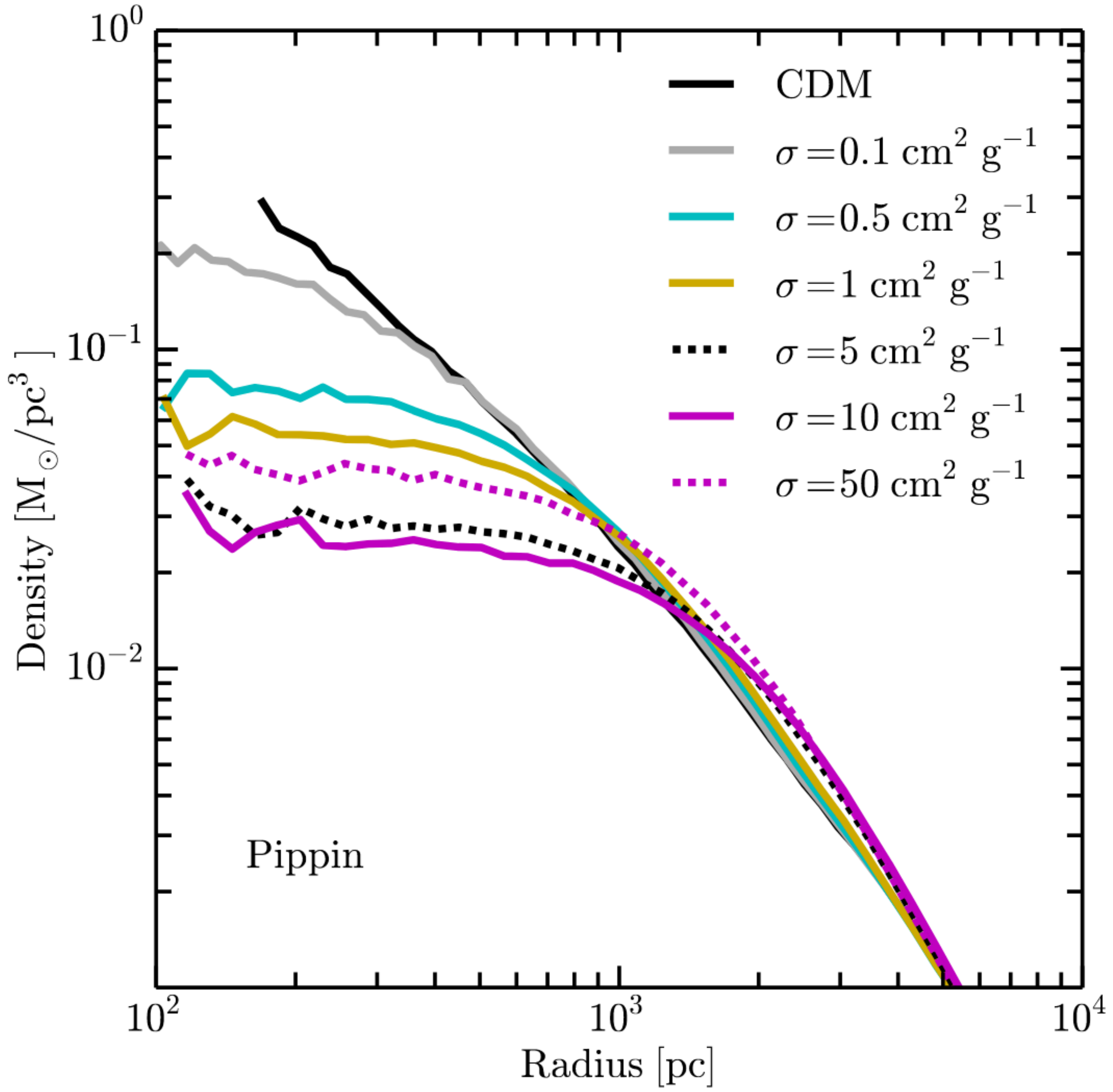
Small-scale structure puzzles arise in various systems:
~~missing satellites~~, core-cusp, too-big-to-fail, diversity

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

Core-Cusp & Too-Big-To-Fail

- DM-only simulations produce ~NFW profiles, which are cuspy
- Observe galaxies with lower-density cores
- Address issues with baryonic physics, SIDM



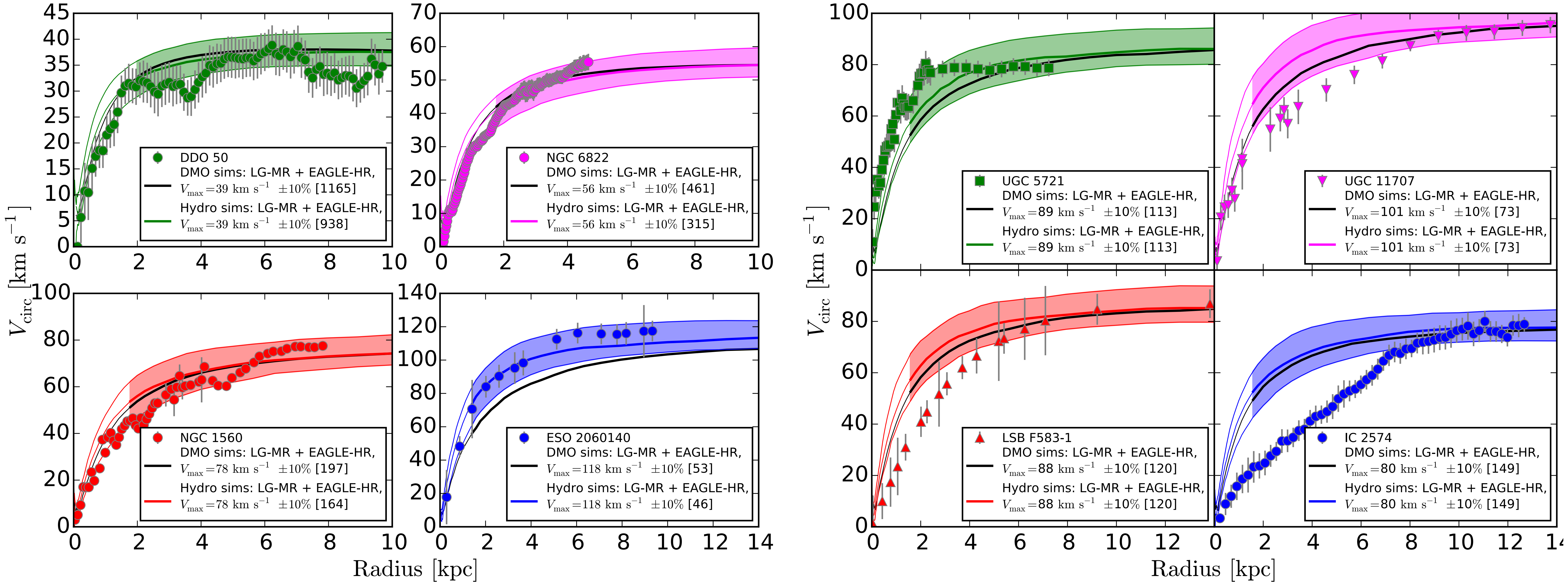


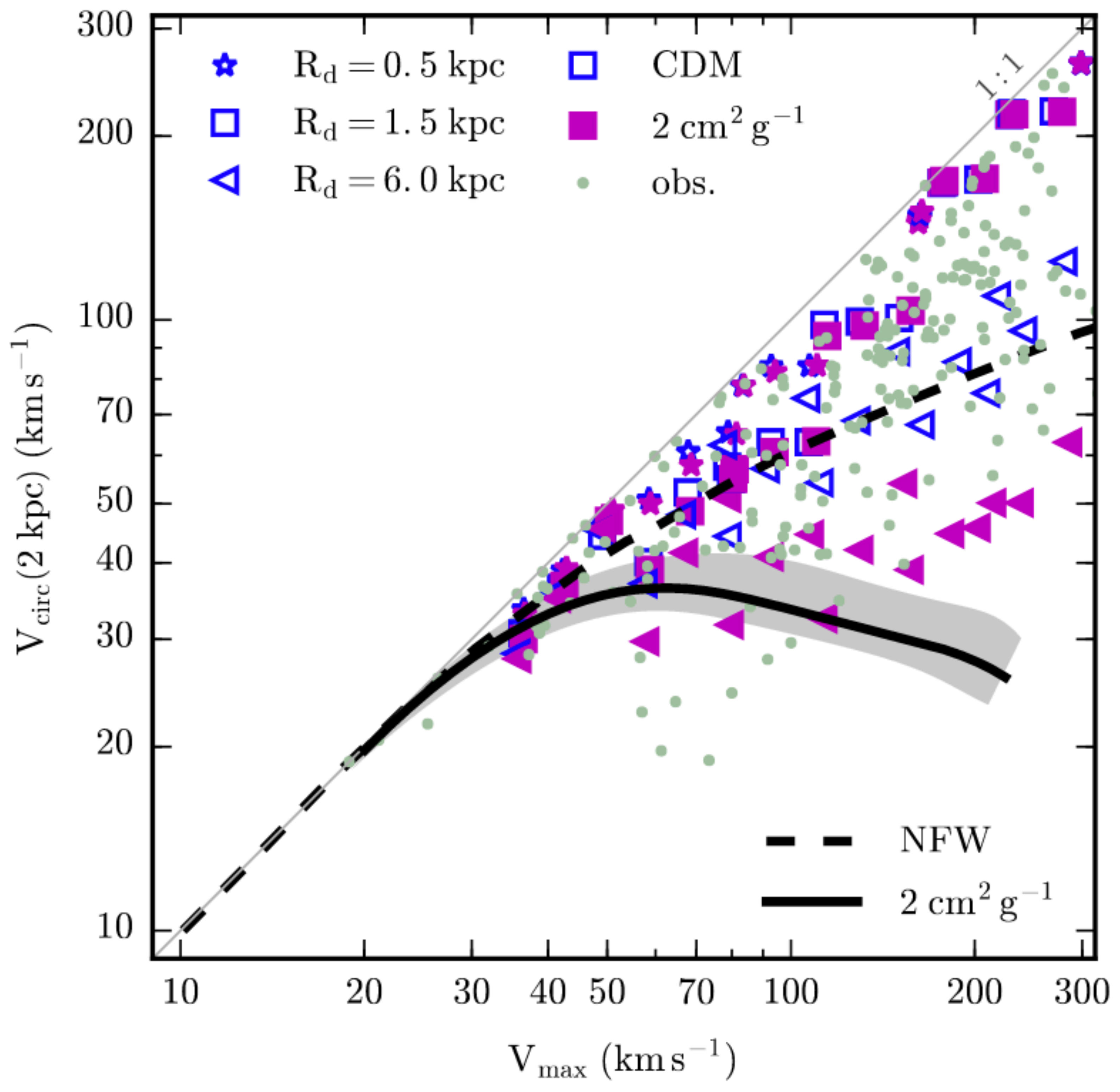
Oh+ (ApJ 2010)

Elbert+ (MNRAS 2015)

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)


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

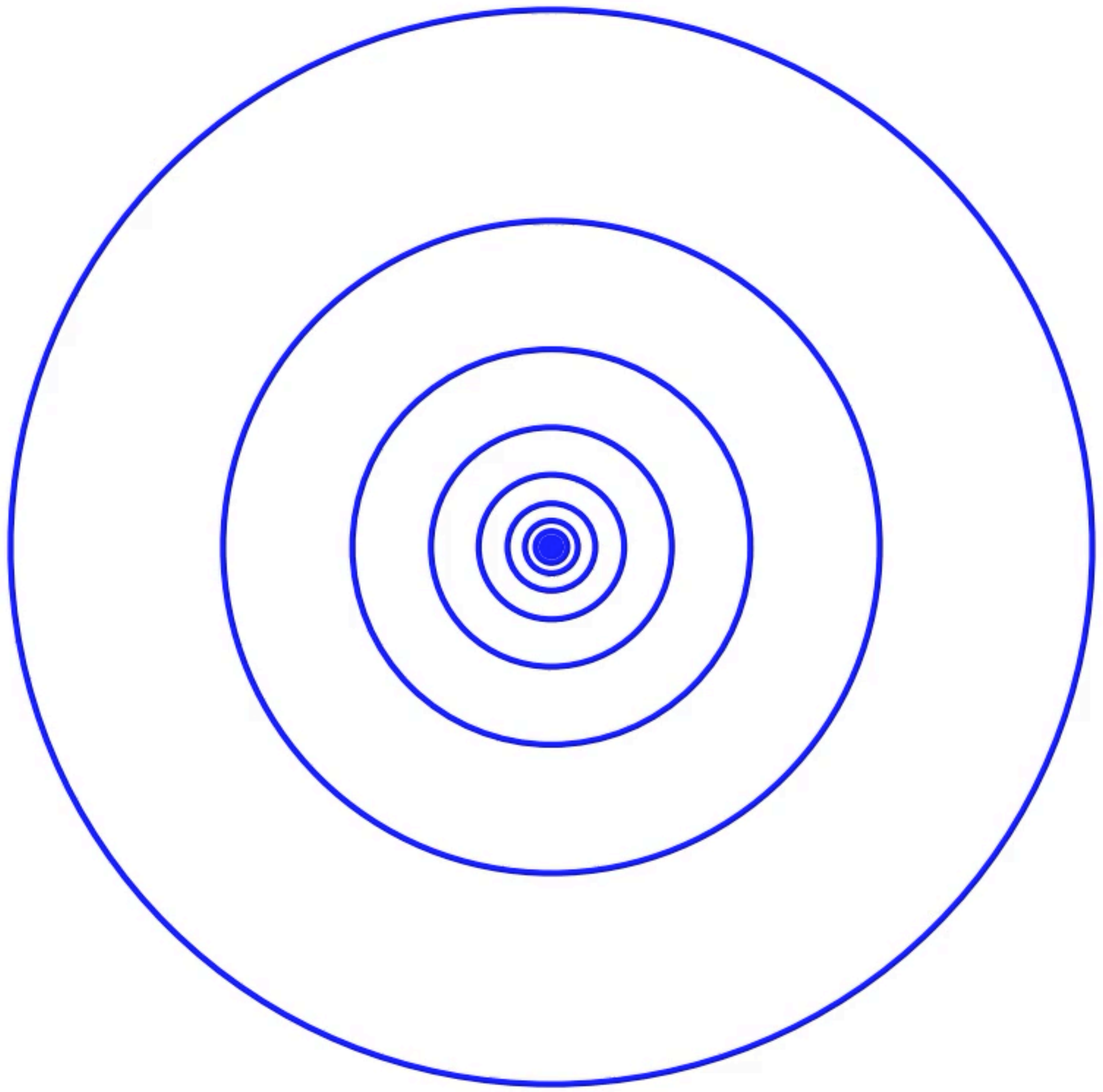
$$\frac{\partial(\rho\nu^2)}{\partial r} = -G\frac{M\rho}{r^2}$$

- 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

- Particle physics contained in expression for κ

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- Short mean free path regime: Calculate thermal conductivity perturbatively with Chapman-Enskog expansion

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

Heat Conductivity

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

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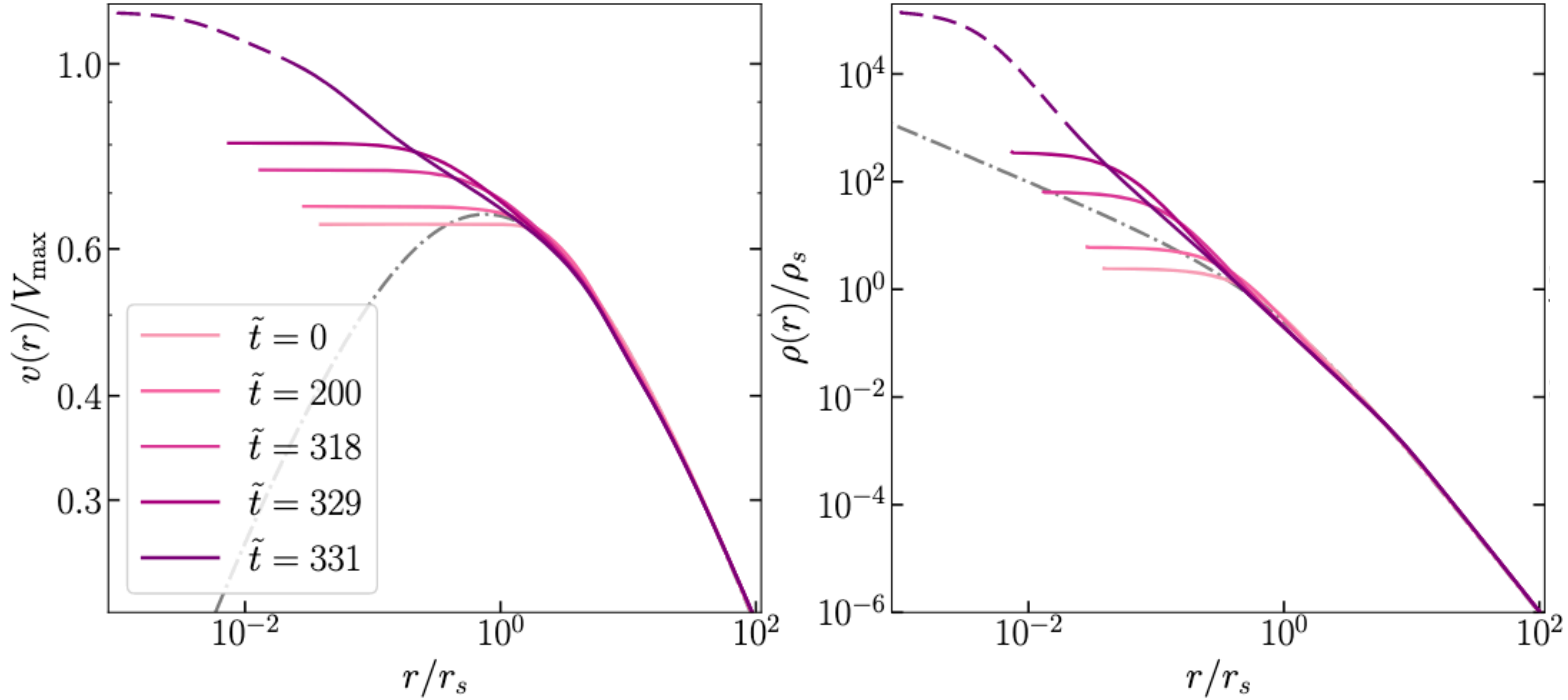
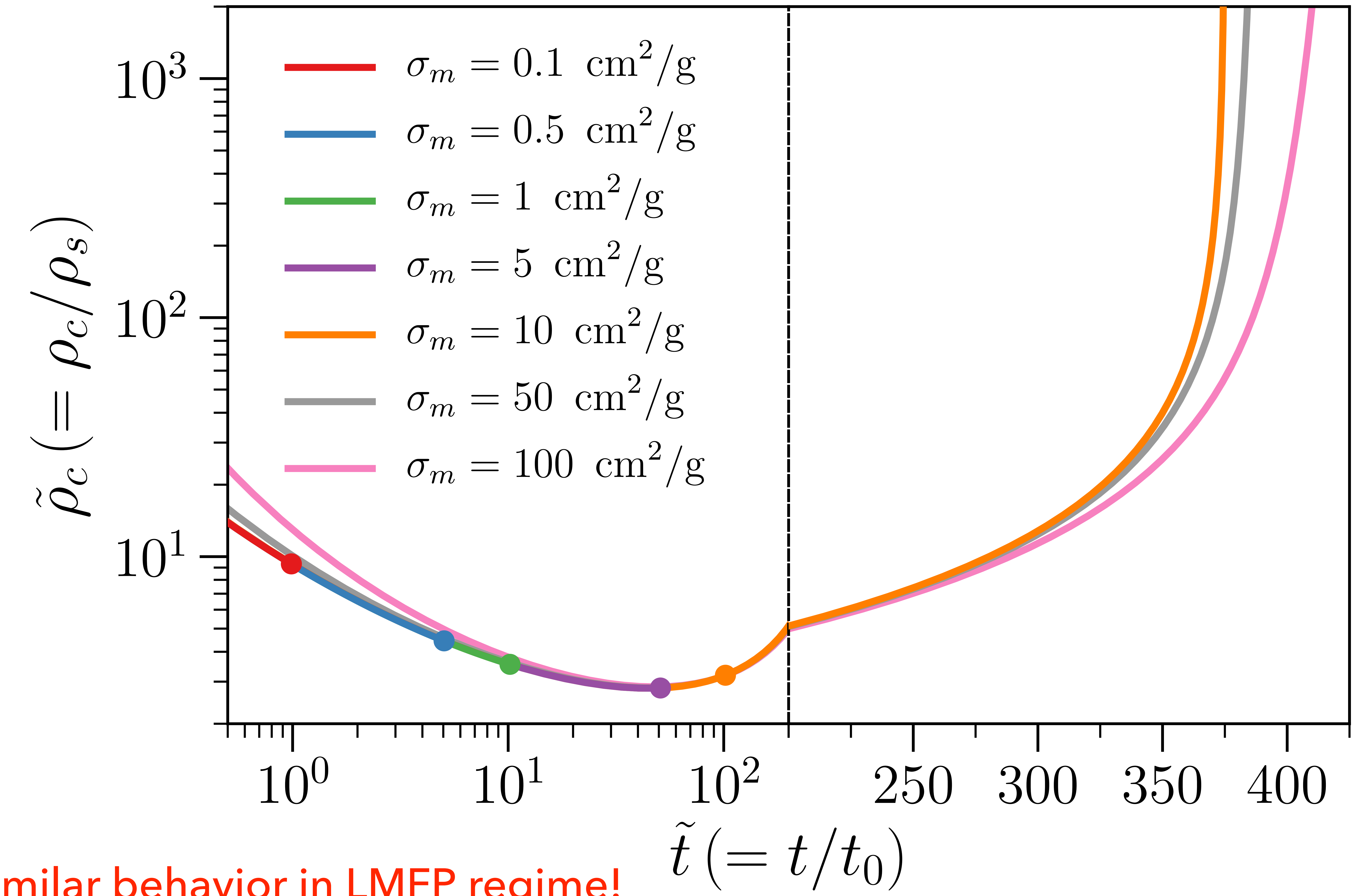
- Gravothermal equations fully specified by 1 parameter: $\hat{\sigma}$
- In LMFP regime, no free parameters – evolution is universal for all halos

Evolution of Density Profile



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

Central Density Evolution



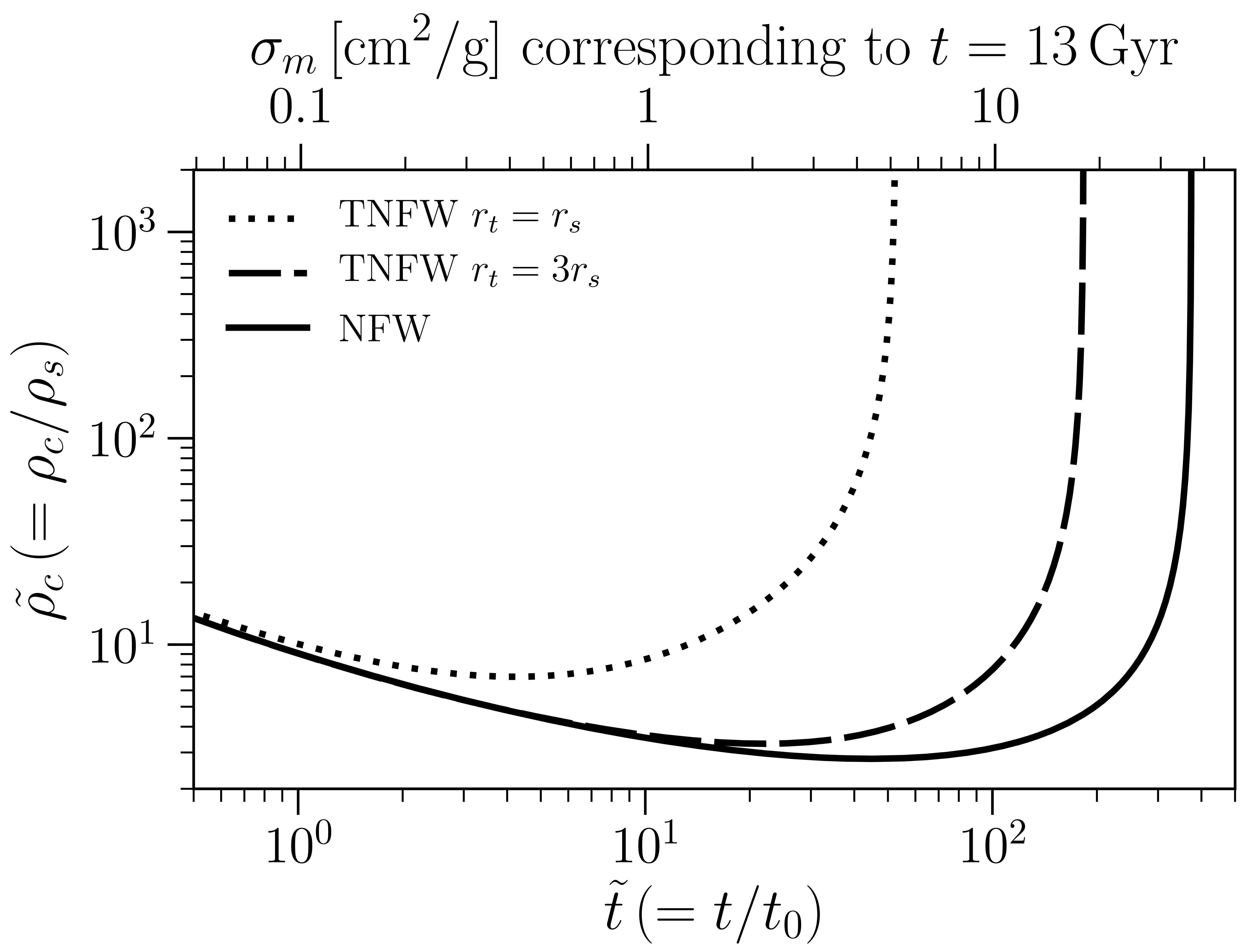
Obtain self-similar behavior in LMFP regime!

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

Central Density Evolution with Truncation



Nishikawa, KB, Kaplinghat (PRD 2020)

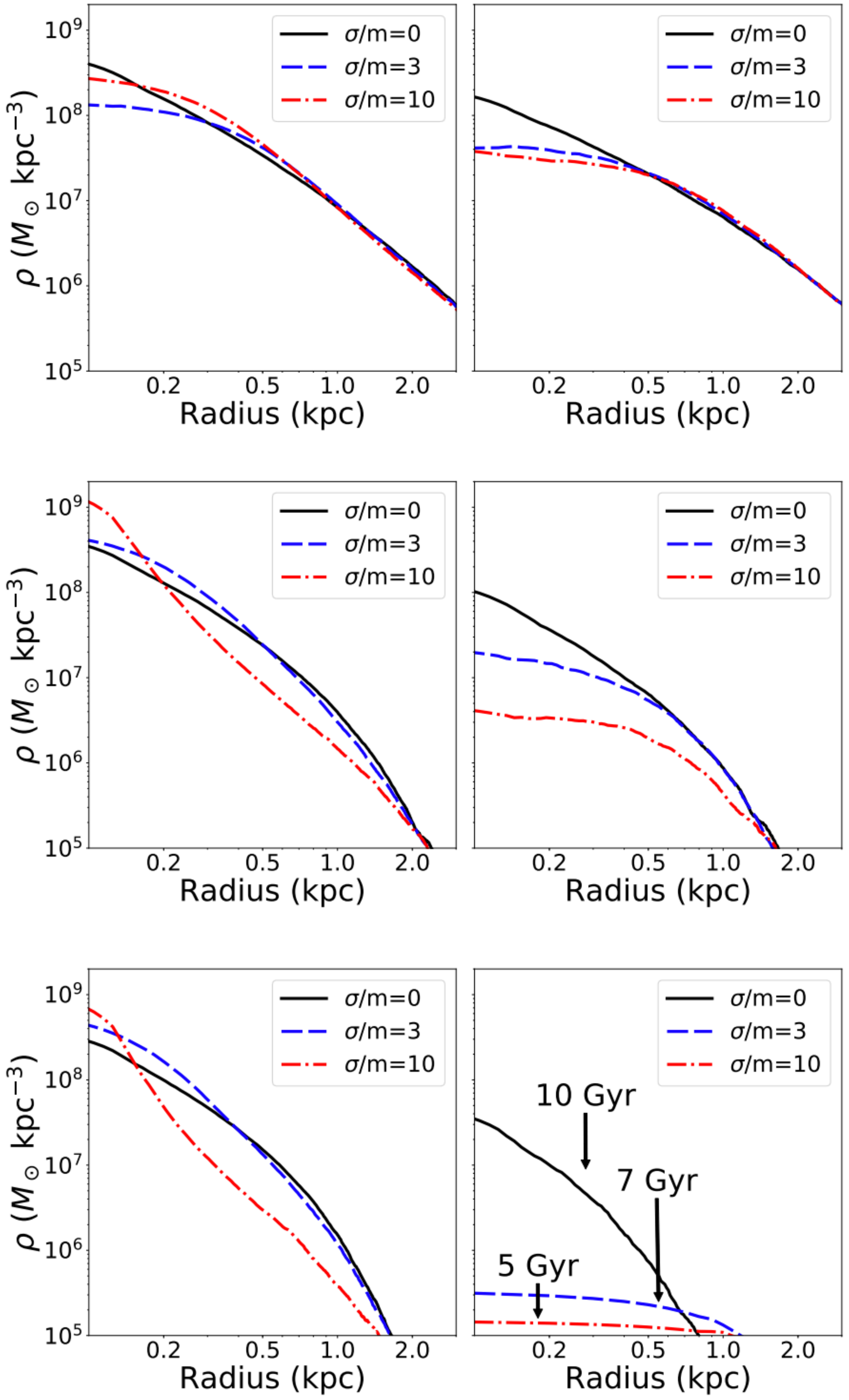
Simulations with Infall

Field halos

Satellites
(long period orbit)

Satellites
(short period orbit)

high concentration



low concentration

Kahlhoefer, Kaplinghat, Slatyer, Wu (JCAP 2019)
see also Sameie+ (PRL 2020)

Revisit Particle Physics of SIDM

Dwarfs

Clusters

LSBs

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

Kaplinghat, Tulin, Yu (PRL 2016)

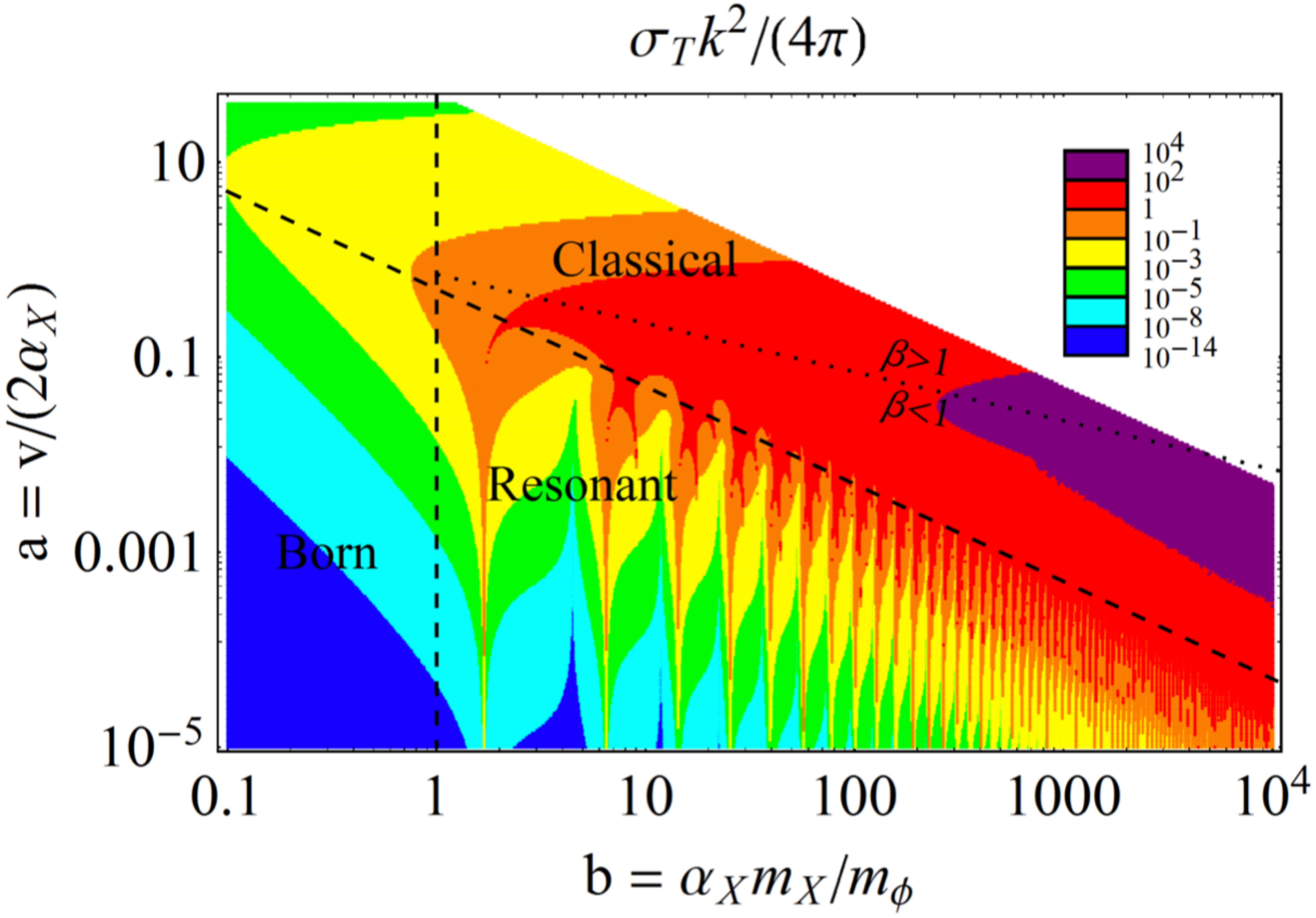
Yukawa Scattering

- 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

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

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

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

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)

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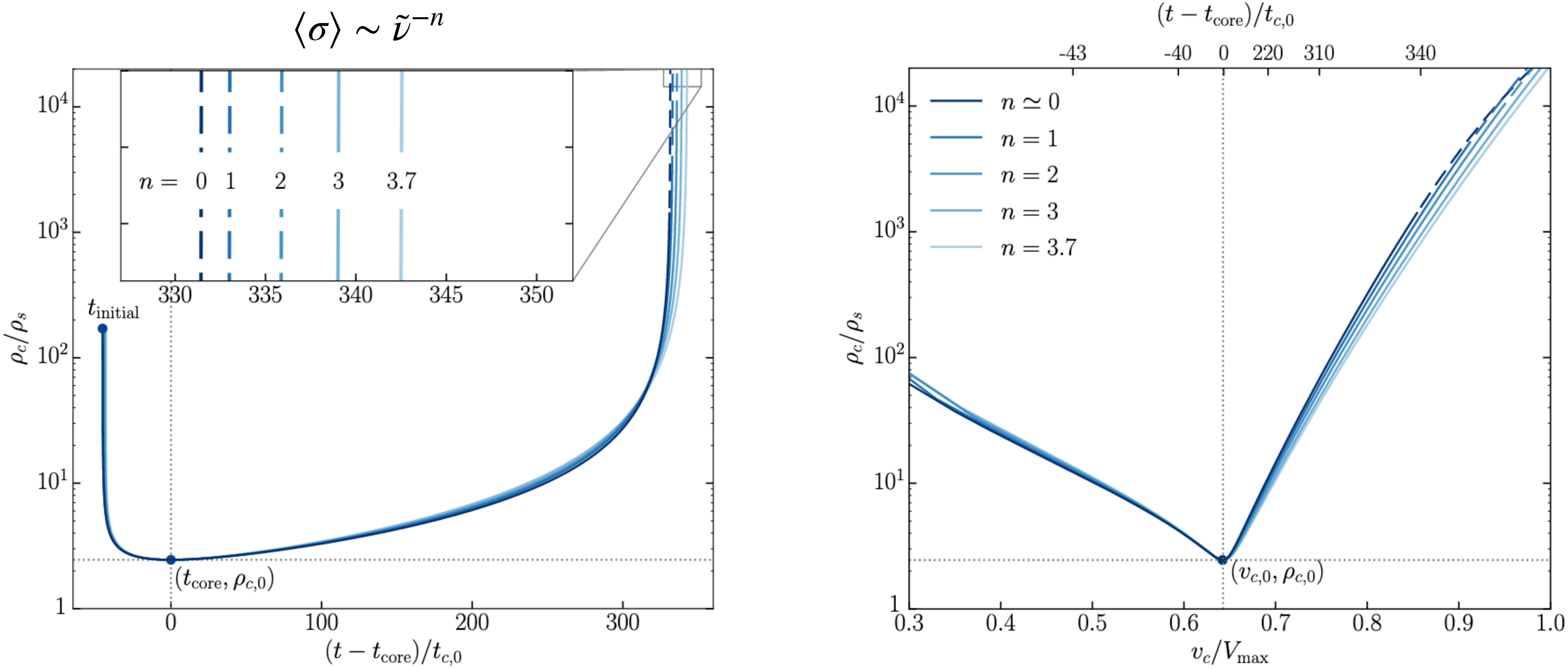
where $\tilde{\kappa} = \tilde{\rho}\tilde{v}^3 \tilde{K}_3 \left[1 + \hat{\sigma}^2 \tilde{\rho}\tilde{v}^2 \tilde{K}_3 \tilde{K}_5\right]^{-1}$ and $\tilde{K}_p = K_p(\tilde{v}/\tilde{w})/K_p(1/\tilde{w})$

- Need to set 2 scales (e.g., r_s and ρ_s)
- Assume initial NFW profile: $\tilde{\rho}_{\mathrm{initial}}(\tilde{r}) = \tilde{r}^{-1}(1+\tilde{r})^{-2}$
- 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

$$\langle \sigma \rangle \sim \tilde{\nu}^{-n}$$

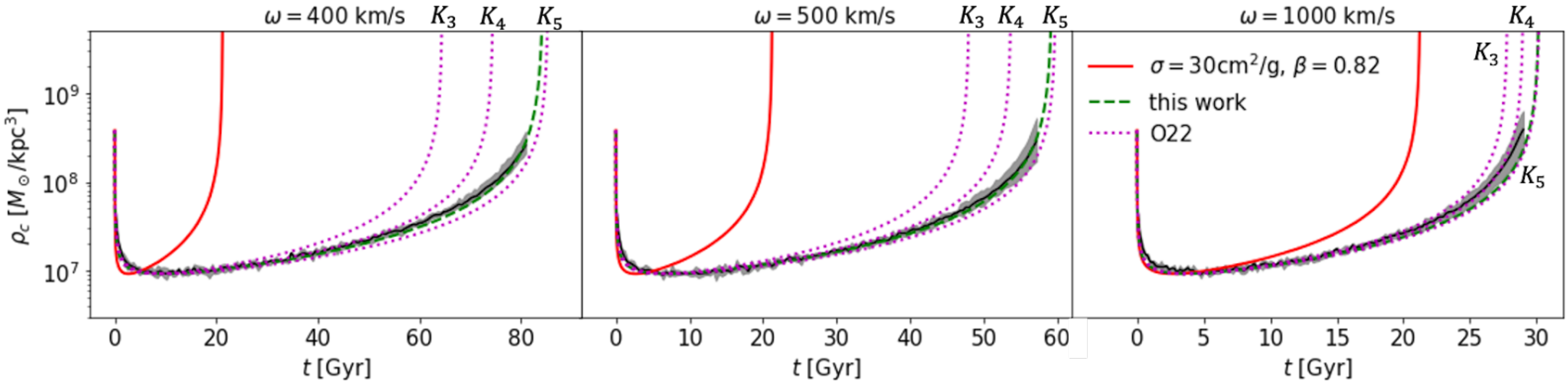


Obtain ~self-similar behavior in LMFP regime!
(dependence on n is mild)

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



modified from Yang+ (2205.02957)

Food for Thought

Generate Initial Conditions + Evolve Simulation (✓✓✓)

↓

Analyze Simulation Output (✓✓✓)

↓

Translate to Observable Parameter Space (✓✓✓)

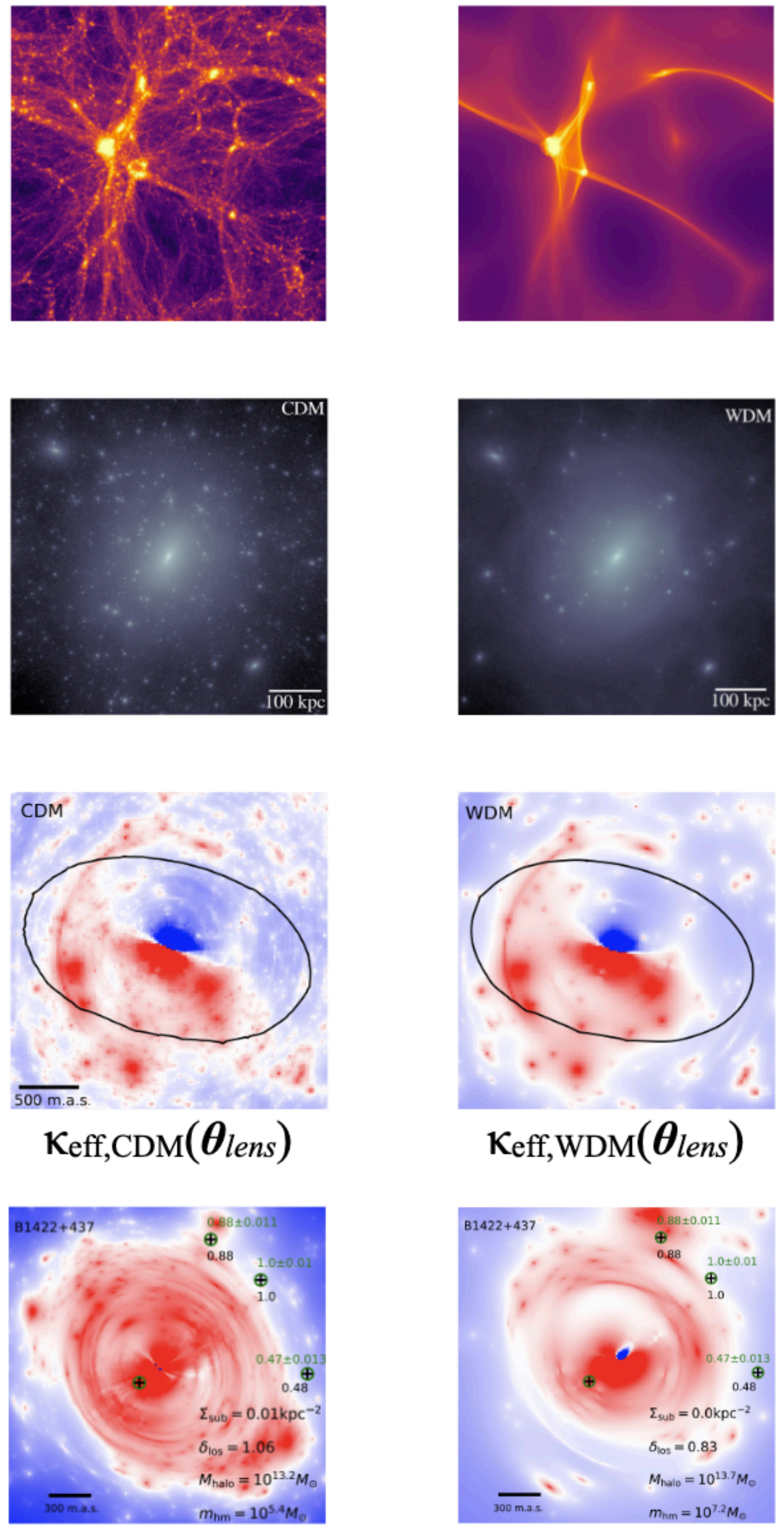
↓

Efficiently Model Observables (✓✓✓)

↓

Compare to Data (✓✓✓)

CDM **WDM**



$\kappa_{\mathrm{eff,CDM}}(\boldsymbol{\theta}_{lens})$ $\kappa_{\mathrm{eff,WDM}}(\boldsymbol{\theta}_{lens})$

$\kappa_{\mathrm{eff,obs}}(\boldsymbol{\theta}_{lens})$ $\kappa_{\mathrm{eff,obs}}(\boldsymbol{\theta}_{lens})$

↓ ↓

$P(\mathrm{CDM},\boldsymbol{\theta}_{lens}|\kappa_{\mathrm{eff,obs}})$ $P(\mathrm{WDM},\boldsymbol{\theta}_{lens}|\kappa_{\mathrm{eff,obs}})$

Need #1: Collaboration between simulators and particle theorists
Need #2: Algorithm development and code comparison tests
Need #3: Hydrodynamic simulations for observational targets
Need #4: Compare simulations to data in observable parameter space
Need #5: Fast realizations of observed systems to constrain dark matter
Need #6: Provide guidance to observers about dark matter signatures

Snowmass 2021 Cosmic Frontier White Paper: Cosmological Simulations for Dark Matter Physics (2203.07049)

Food for Thought

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Analyze Simulation Output (✓✓✓)

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Translate to Observable Parameter Space (✓✓✓)

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Efficiently Model Observables (✓✓✓)

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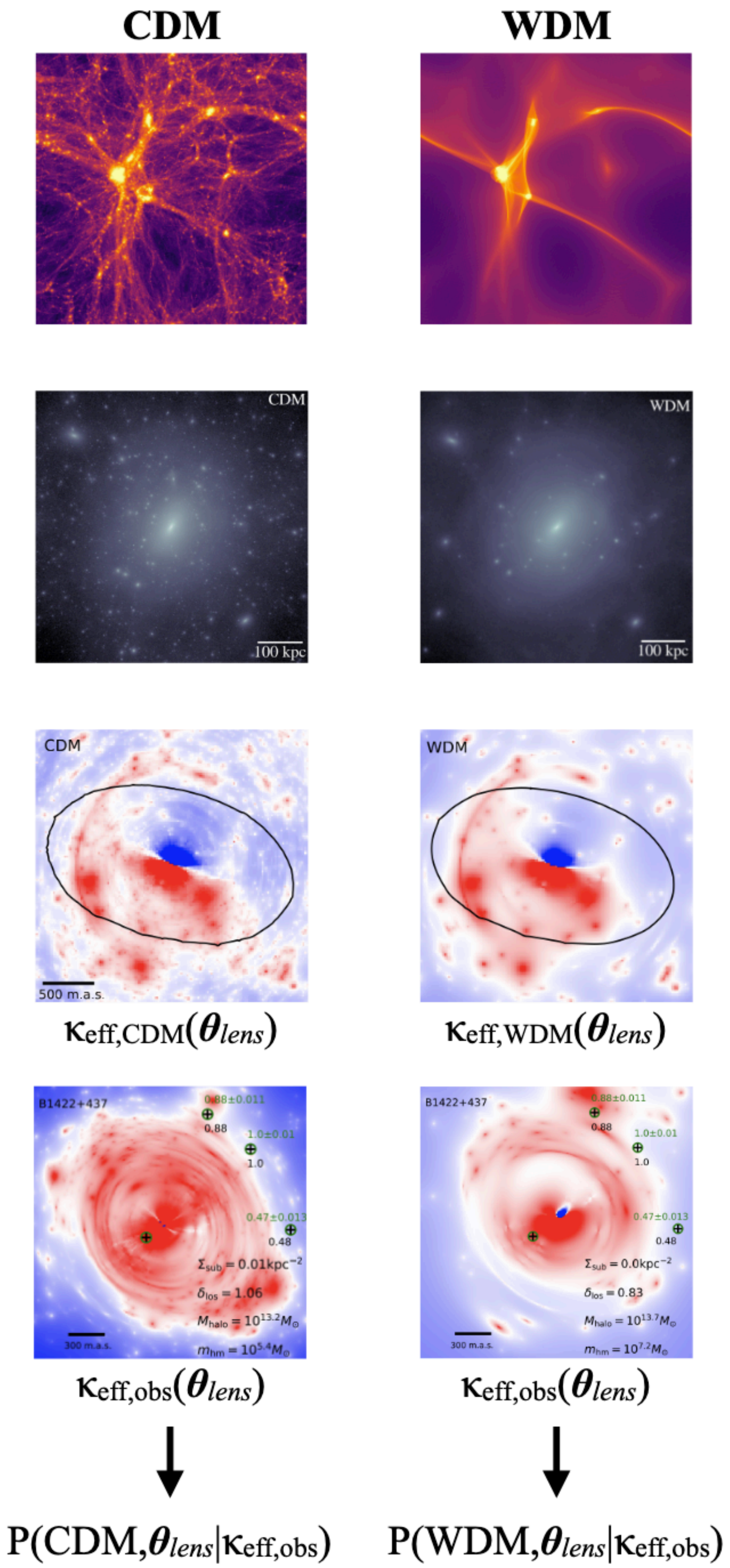
Compare to Data (✓✓✓)



Talk to your friendly neighborhood simulator!

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