

# Screened Forces in a QCD-Like Dark Sector on Galactic Scales

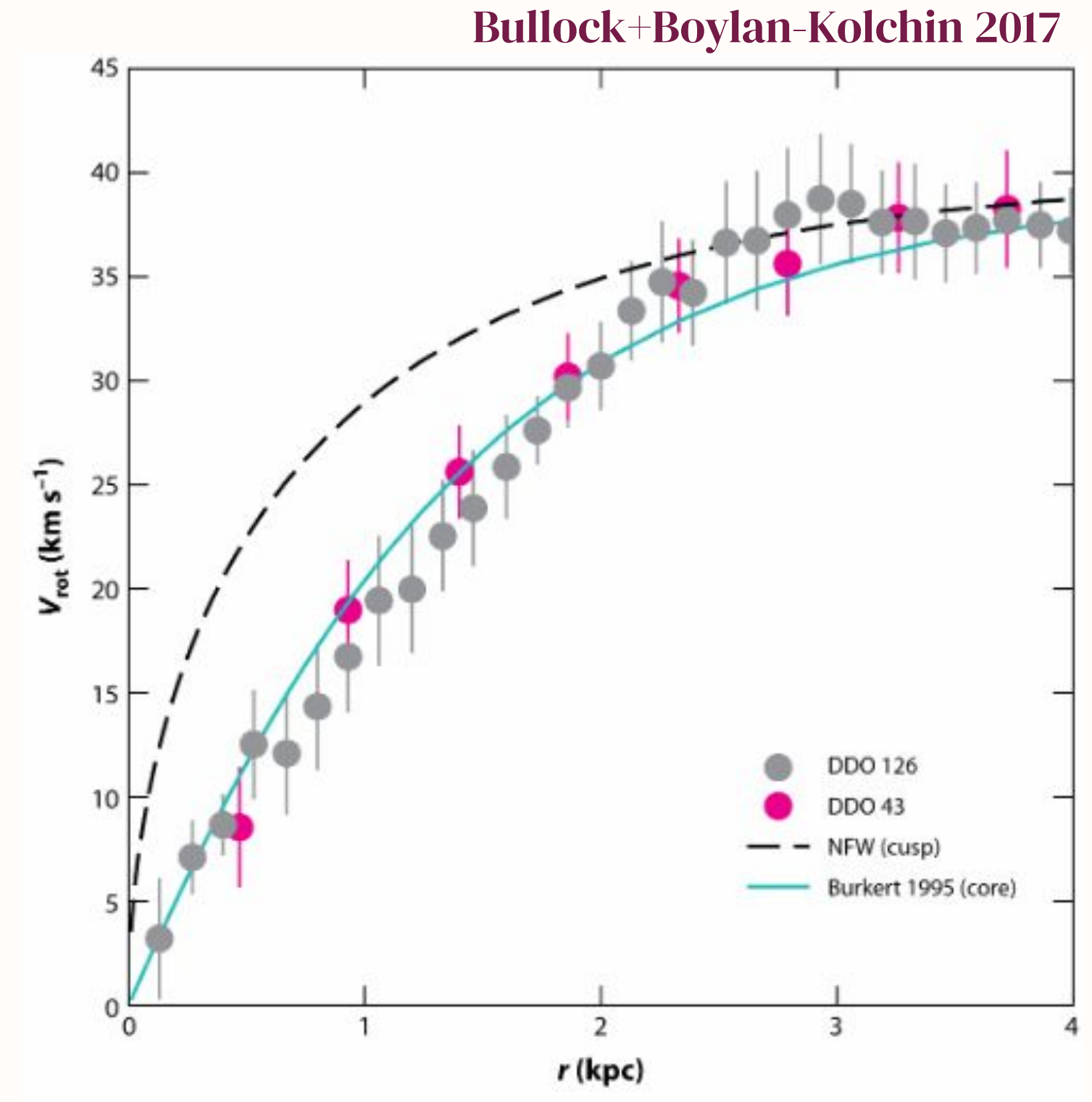
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**Justin Khoury, Robyn Sanderson**

**University of Pennsylvania**

# What's wrong with CDM?

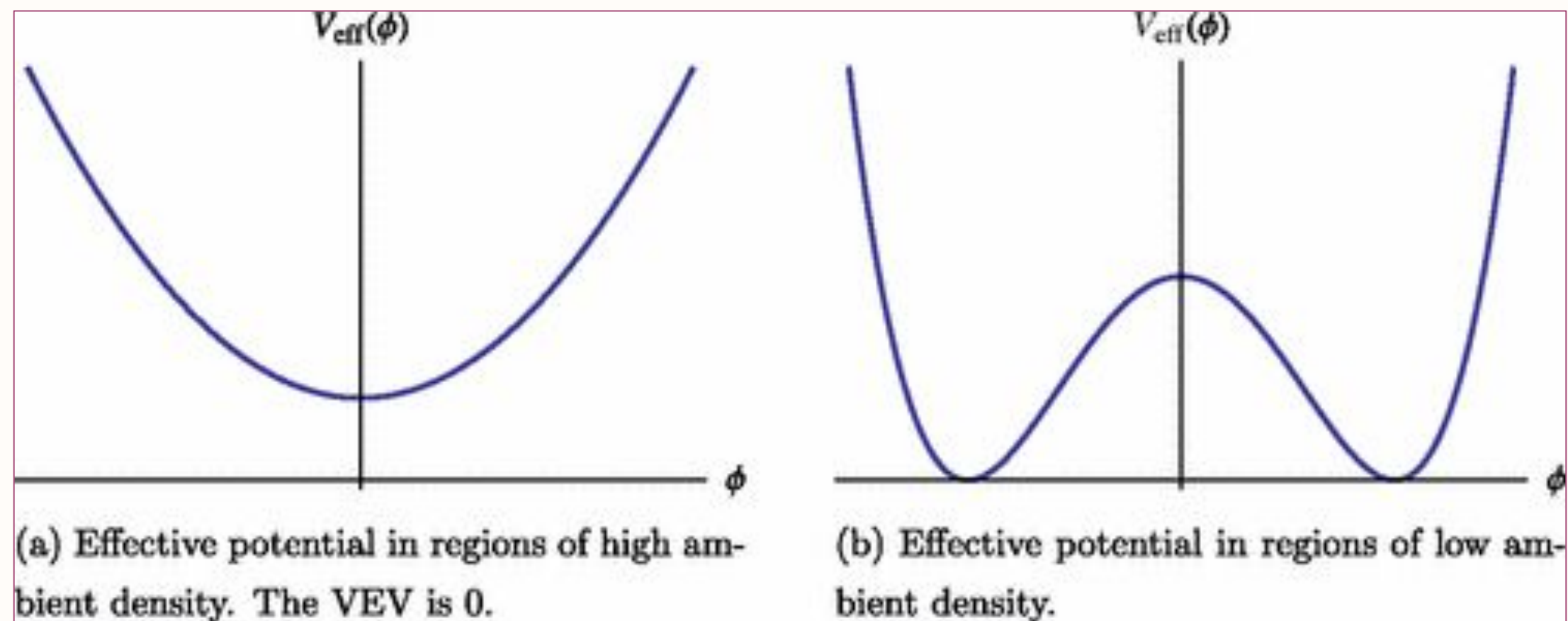
- **Small-Scale Structure Issues:**
  - Core-Cusp problem/diversity in rotation curves
  - Missing Satellites
  - Too-Big-To-Fail
- **Need a DM model with a built-in mass-scale.**



# Screened Forces and Dark QCD

# Density-Dependent Forces

- Screened fifth forces avoid local constraints in the Solar System and Milky Way.
- Density-dependent potentials give density-dependent forces.



Hinterbichler+ 2011

# Screened Forces in QCD

## Action

$$S = \int d^4x \sqrt{-g} \left[ -\frac{1}{2} (\partial\phi)^2 + i\bar{\psi} \not{\nabla} \psi - V(\phi) \right]$$

## Vacuum Potential

$$V(\phi) = \Lambda^4 \left[ 1 + \nu - \sqrt{1 - \xi \sin^2(\phi/2f)} \right]$$

Standard Model, Forces between Neutron Stars:

Hook+Huang, 2018

Dark QCD as dark energy: Khoury, Lin, +Trodden, 2025

## Model Parameters

- $\Lambda$  : energy scale of theory
- $\xi$  : ratio of quark masses
- $f$  : axion decay constant
- $\nu$  : constant shift

# Screened Forces in QCD

## Finite-Density Correction

$$V(\phi) = \Lambda^4 \left[ 1 + \nu - \left( 1 - \frac{2\sigma_N n}{\Lambda^4} \right) \sqrt{1 - \xi \sin^2 \left( \frac{\phi}{2f} \right)} \right]$$

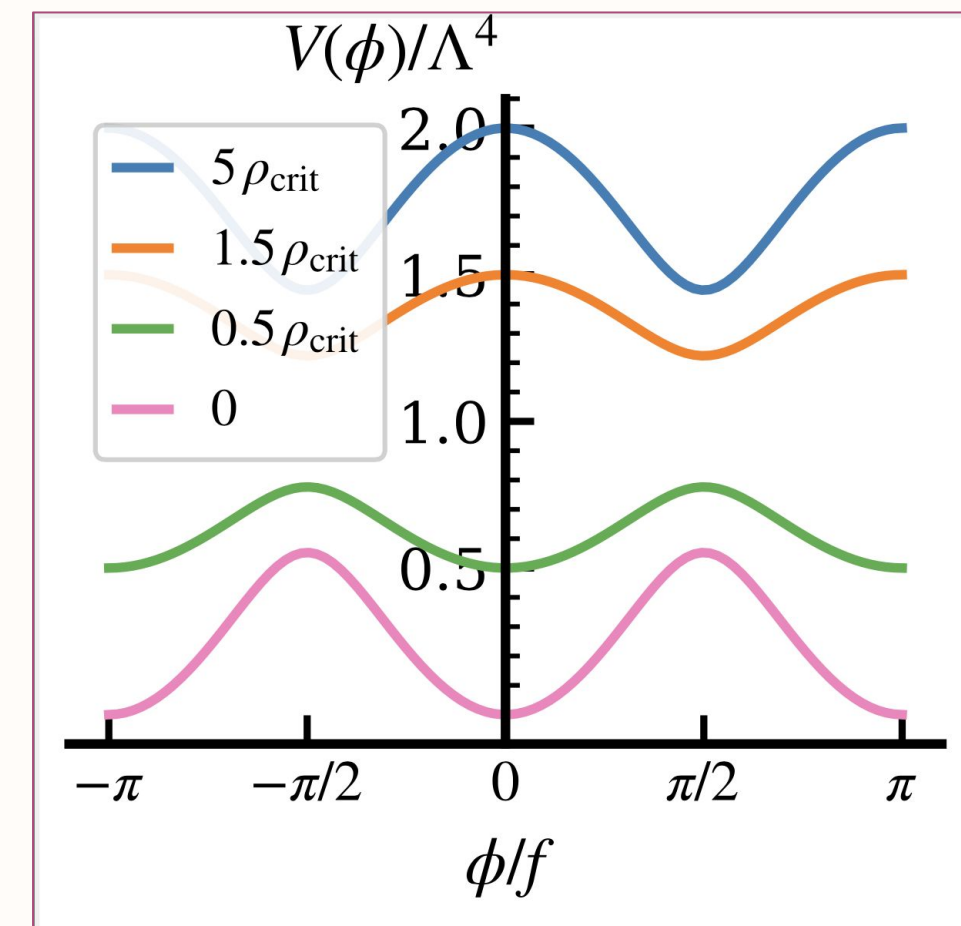
## New Model Parameter

$\sigma_N/m_0$  : dependence of baryon

masses on quark masses

## Potential flips sign at critical density!

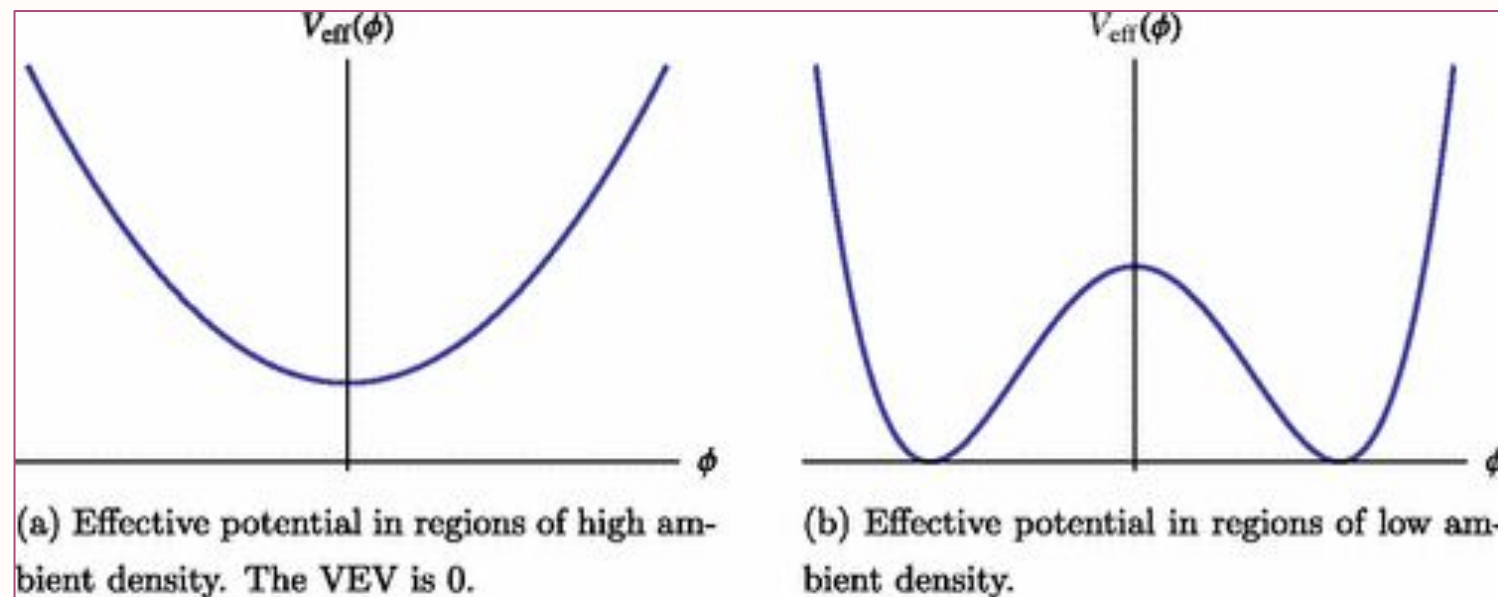
$$n_c = \frac{\Lambda^4}{2\sigma_N} \quad \rho_c = \frac{\Lambda^4}{2(\sigma_N/m_0)}$$



MD , Khoury, Sanderson; in prep.

# Symmetron

$$V_{\text{eff}}(\phi) = \frac{1}{2} \left( \frac{\rho}{M^2} - \mu^2 \right) \phi^2 + \frac{1}{4} \lambda \phi^4$$

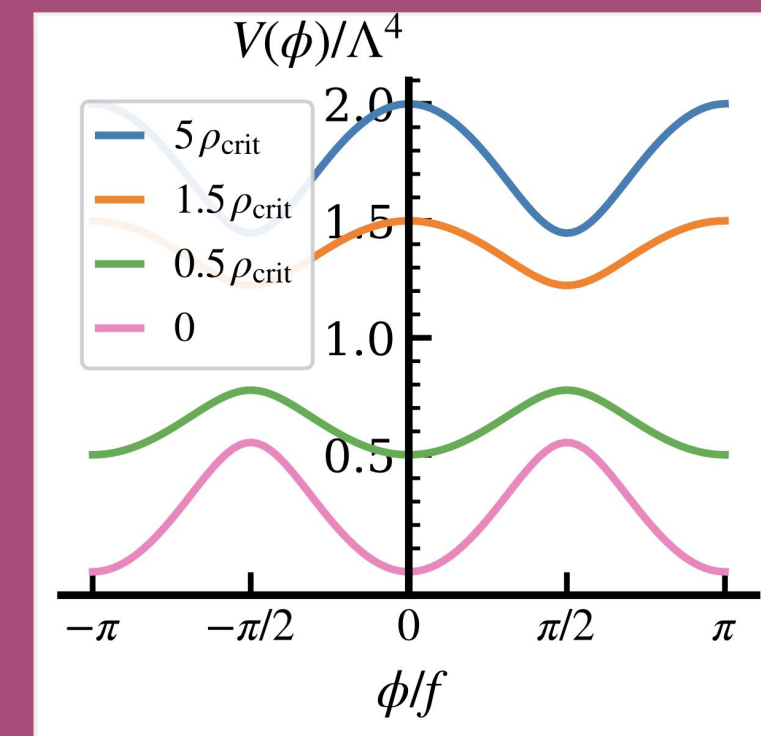


**In high densities,  $\phi \rightarrow 0 = \text{no force}$ .**

**In a vacuum,  $\phi \neq 0 = \text{force}$ .**

# QCD

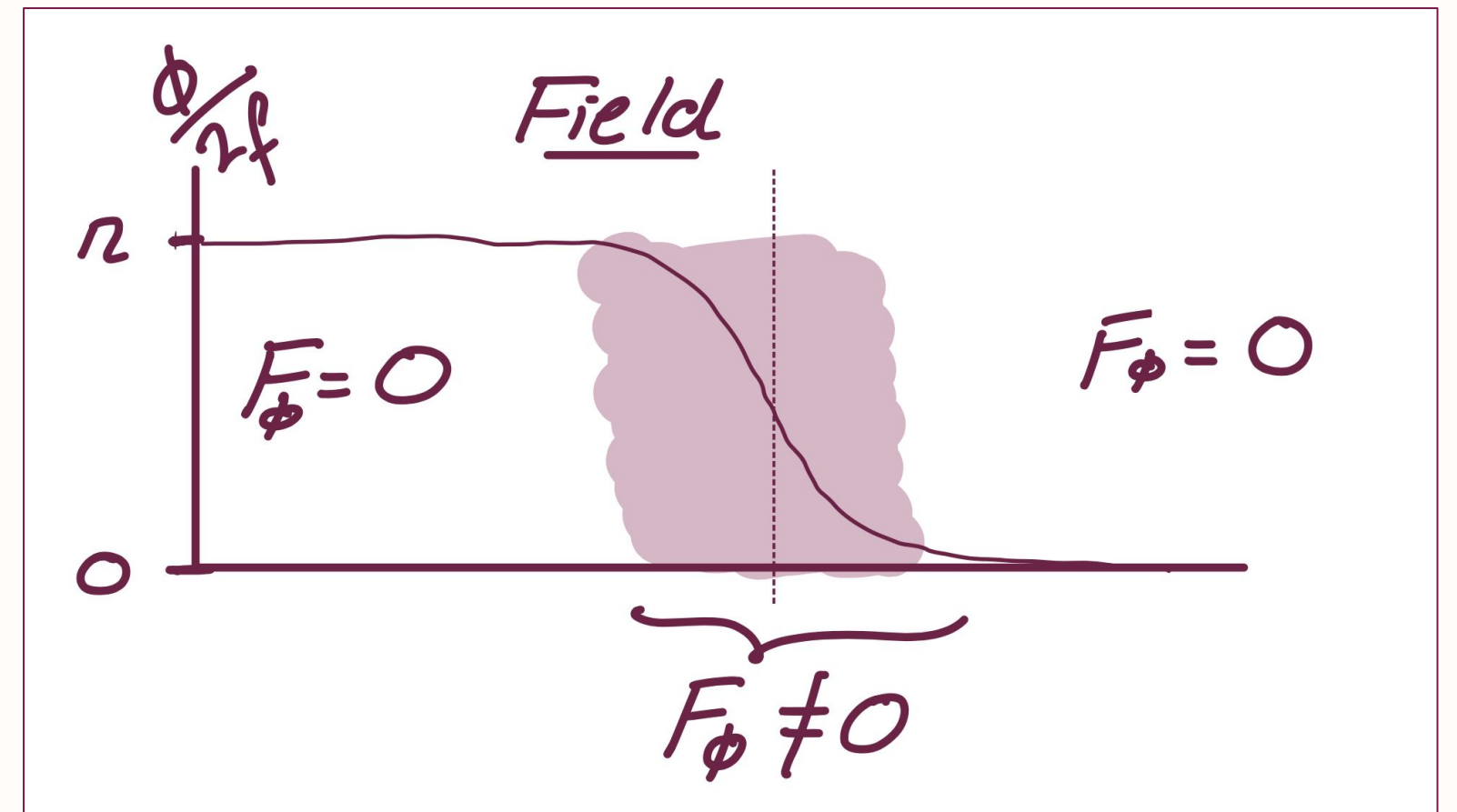
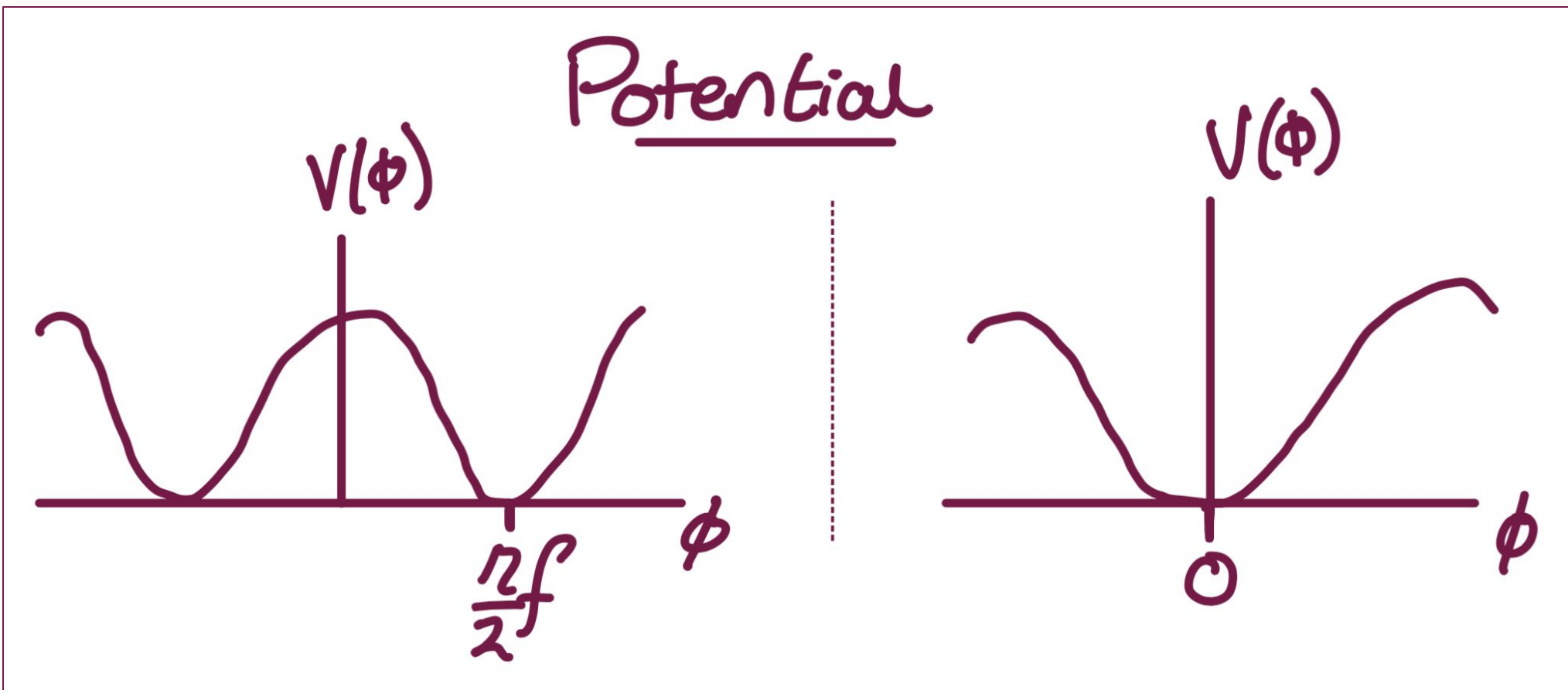
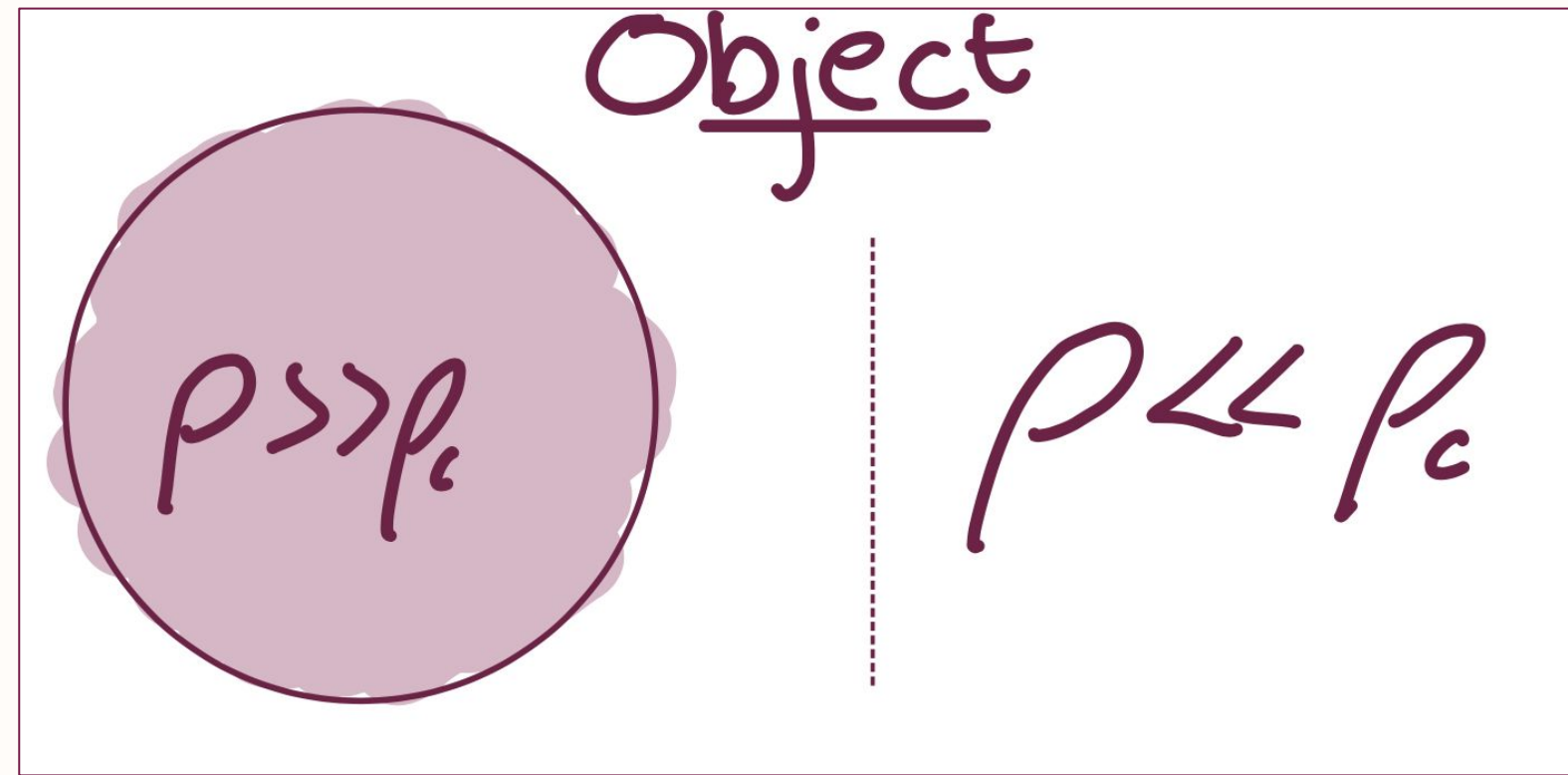
$$V(\phi) = \Lambda^4 \left[ 1 + \nu - \left( 1 - \frac{2\sigma_N n}{\Lambda^4} \right) \sqrt{1 - \xi \sin^2 \left( \frac{\phi}{2f} \right)} \right]$$



**In high densities,  $\phi \rightarrow \pi f = \text{no force}$ .**

**In a vacuum,  $\phi = 0 = \text{no force}$ .**

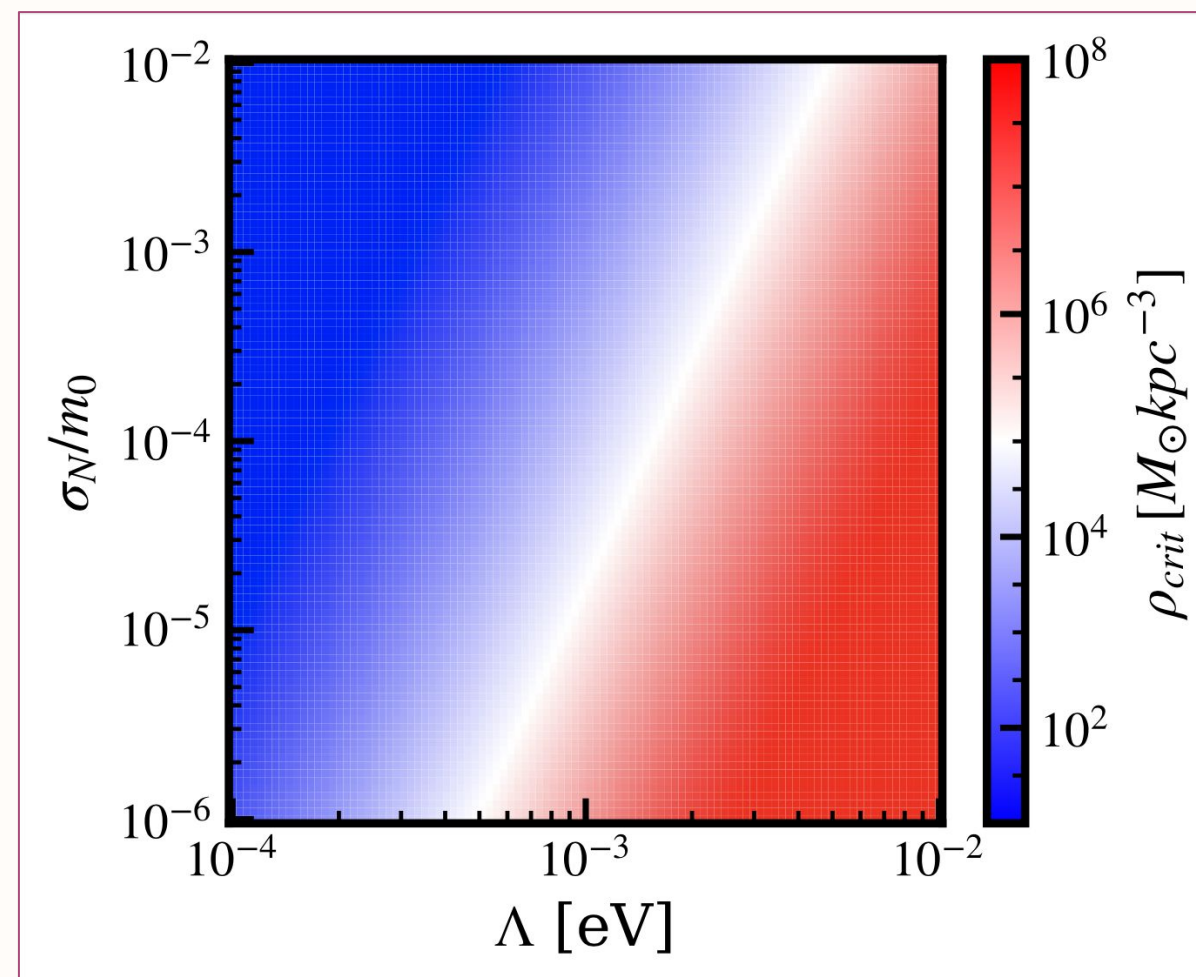
**In medium densities,  $0 < \phi < \pi f = \text{force}$ .**



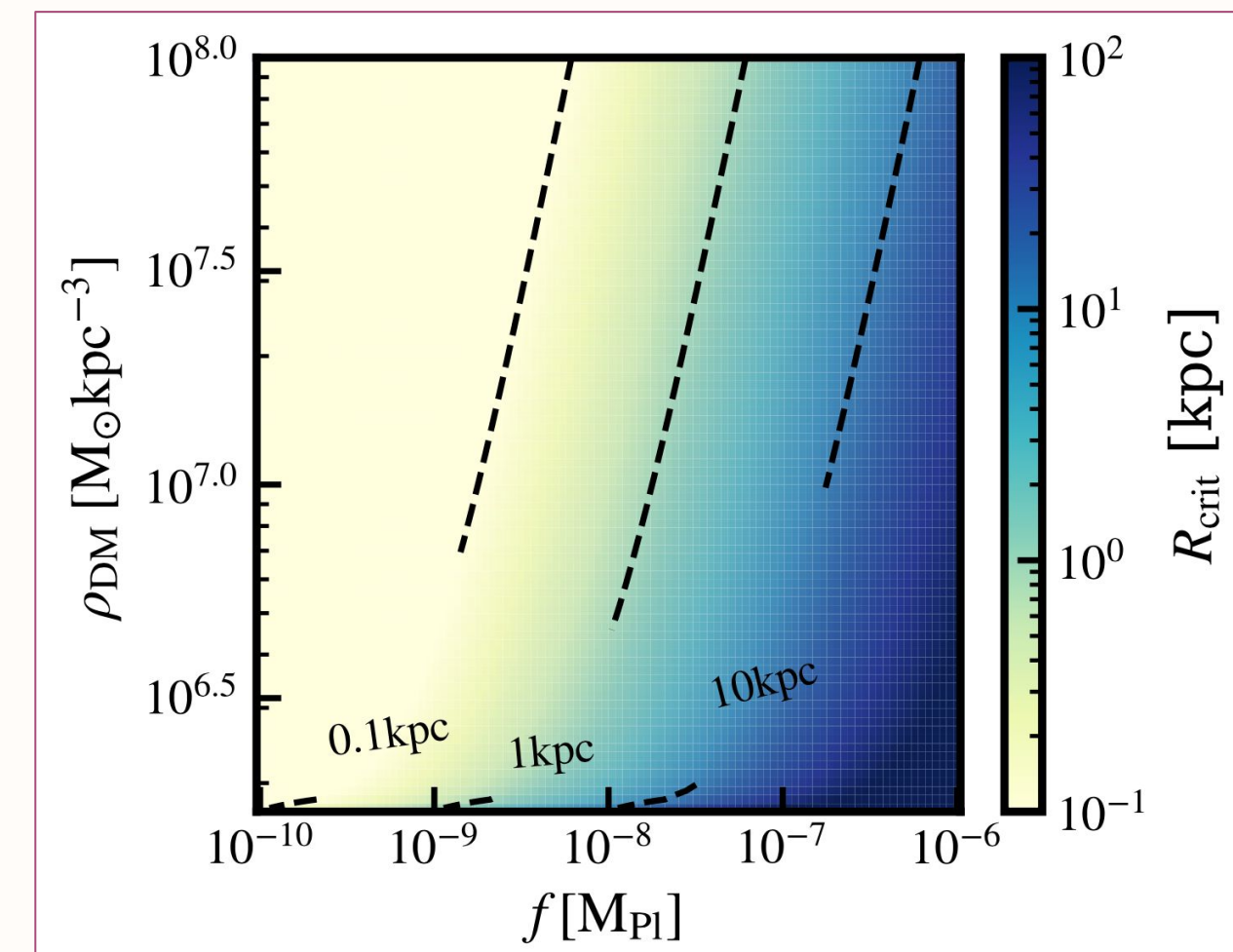
# The Parameter Space

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- We have a minimum density and radius to source the dark axion.
- For galactic scale density:  $10^{-6} < \sigma_N/m_0 < 10^{-2}$
- For galaxies to source the axion:  $f < 10^{-7}$



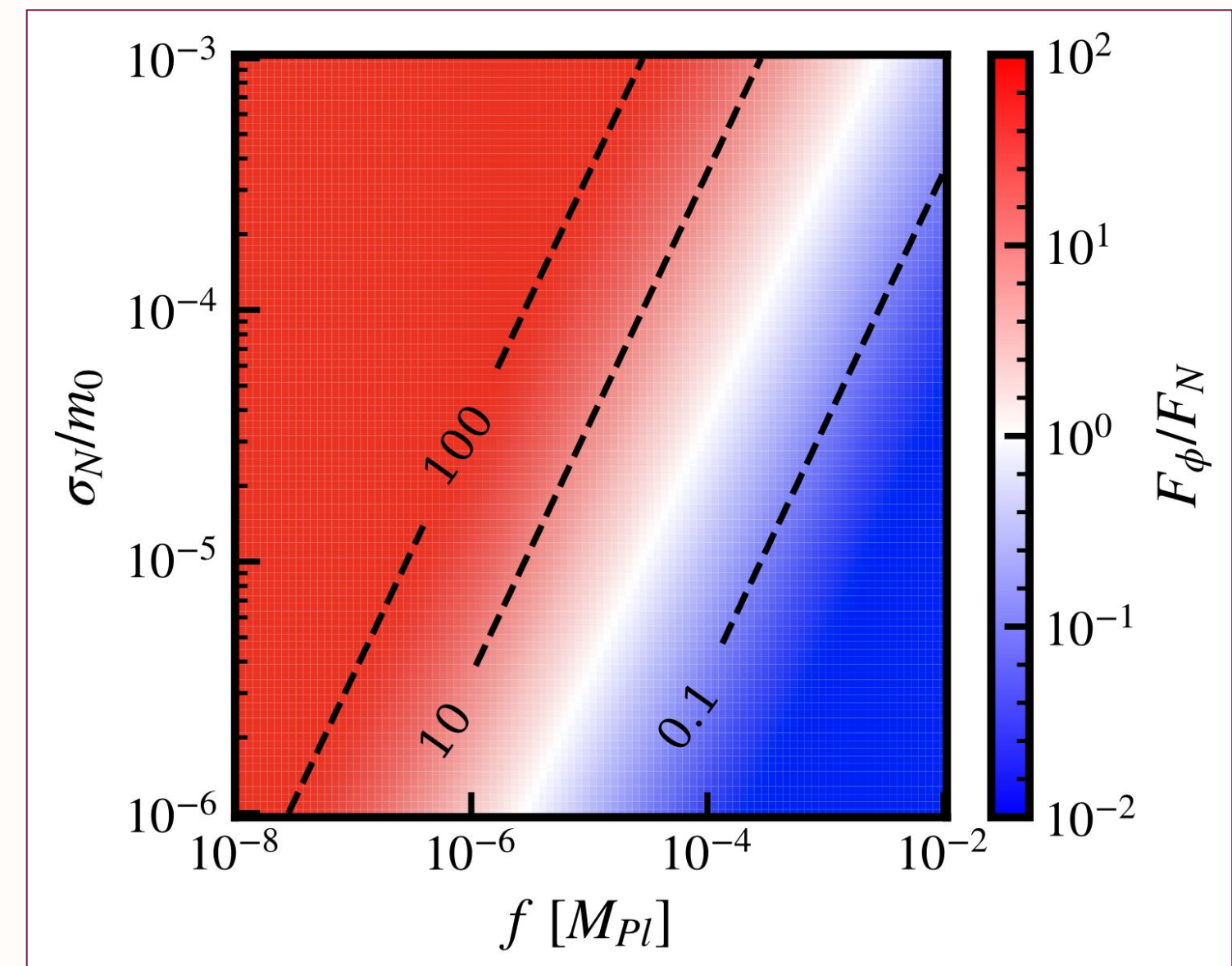
MD, Khoury, Sanderson; in prep.



# The Parameter Space

- We have a minimum density and radius to source the dark axion.
- For galactic scale density:  $10^{-6} < \sigma_N/m_0 < 10^{-2}$
- For galaxies to source the axion:  $f < 10^{-7}$
- This leads to very high forces

MD, Khoury, Sanderson; in prep.

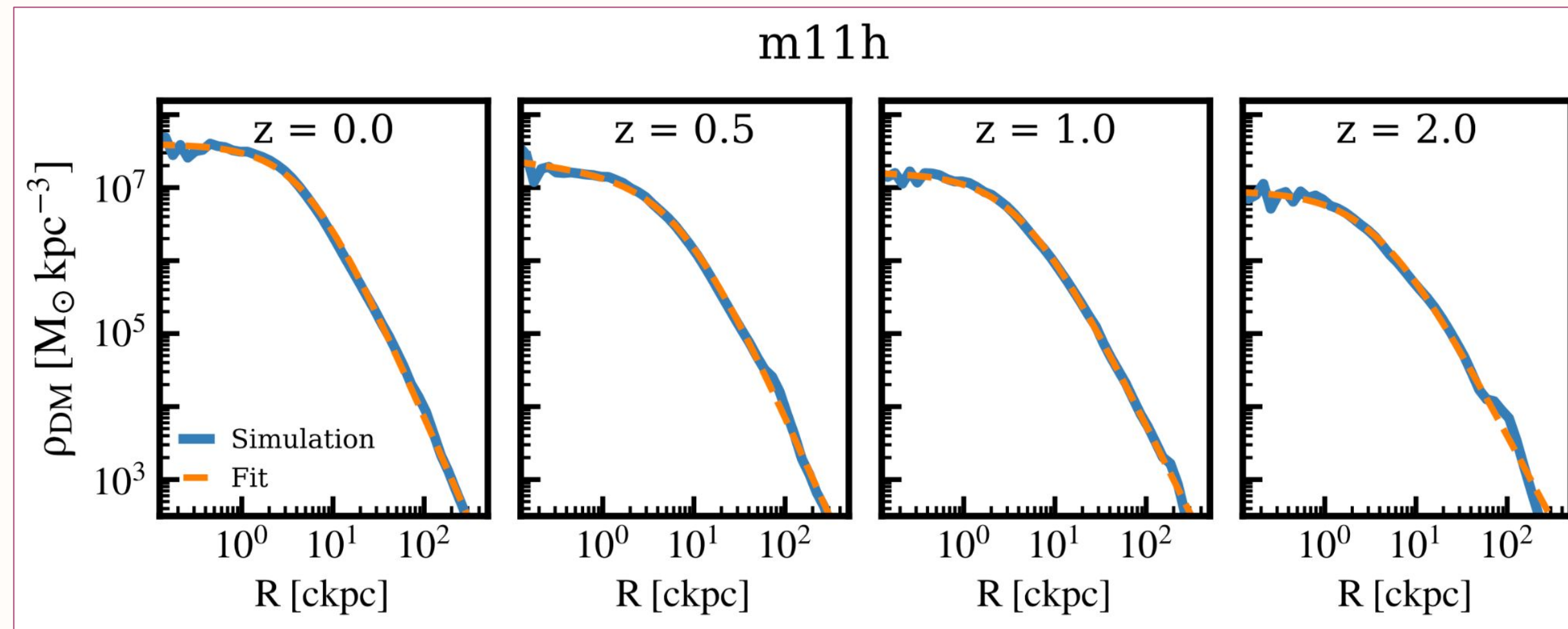


**Does it actually work?**

# Does it actually work?

- Do realistic halos source the dark axion?
- Do we get reasonable forces?

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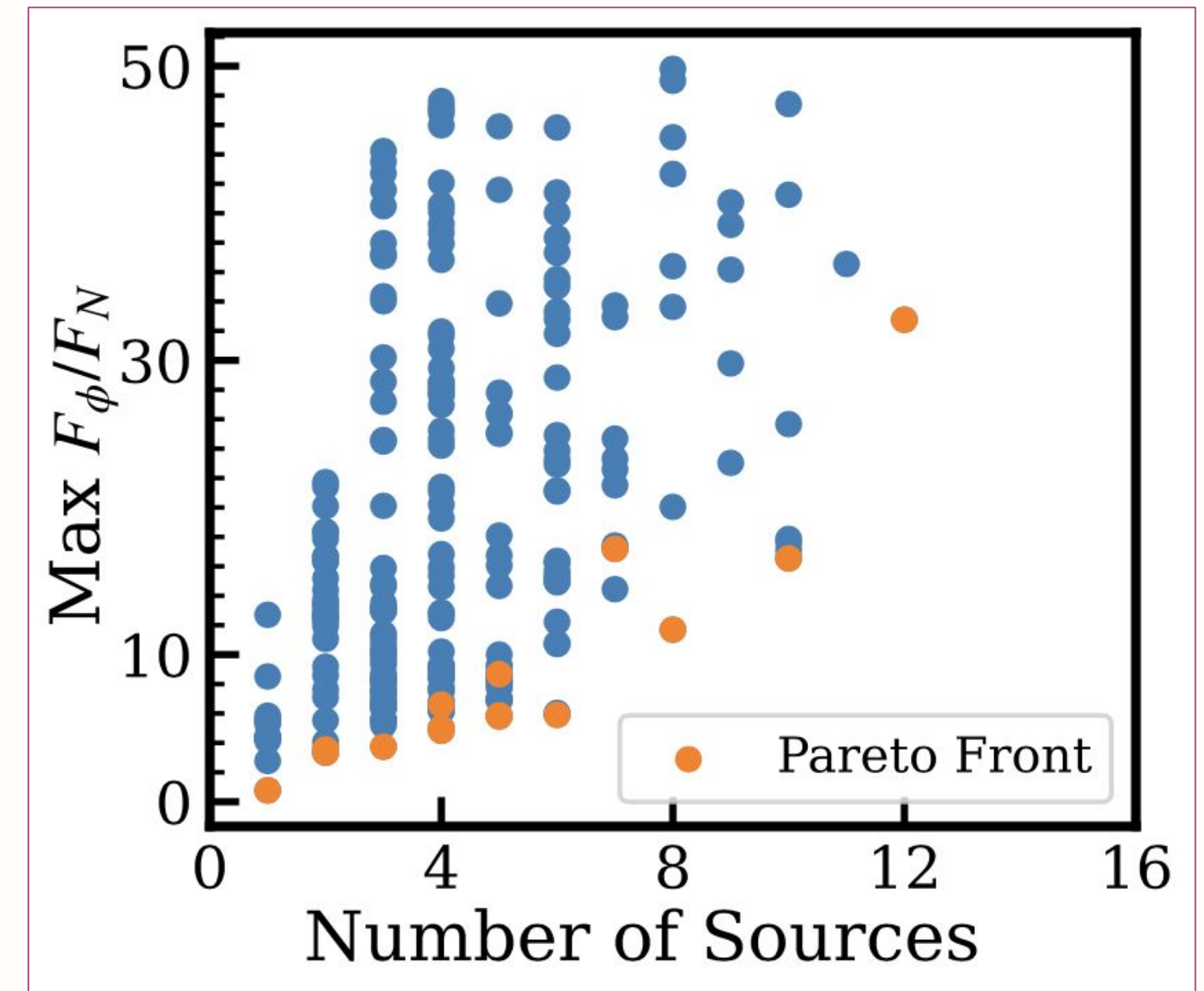


Fit of DM density profiles (using Zhao profile) of m11h from FIRE-2 cosmological zooms at different redshifts.

# Does it actually work?

MD, Khoury, Sanderson; in prep.

- Numerically solve for the dark axion radial profile.
- Find the force relative to gravity.
- Run a basin-hopping optimizer to find best parameters.
- Test best parameters over all halos at all redshifts.



**Note:** All results are instantaneous using CDM simulations. Self-consistent simulations are needed to see how these fields and galaxies evolve.

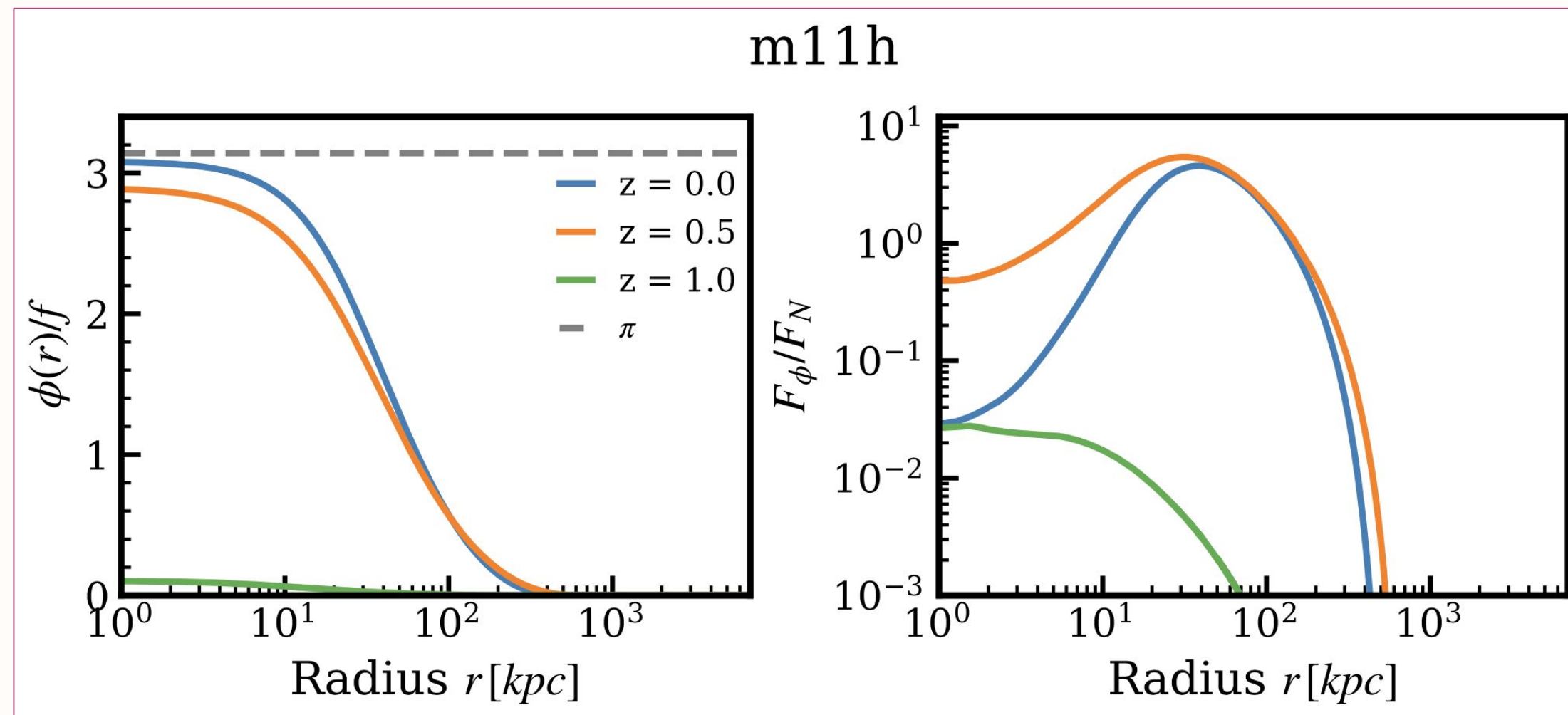
# Yes!

- Different halo mass scales, prefer different energy scales.

- In all cases,  $\sigma_N/m_0 = 10^{-6}$

- For the dwarf galaxies:

$$\Lambda = 0.1 \text{ meV} \quad f = 7 \times 10^{-8} M_{\text{Pl}} \quad \xi = 0.72$$

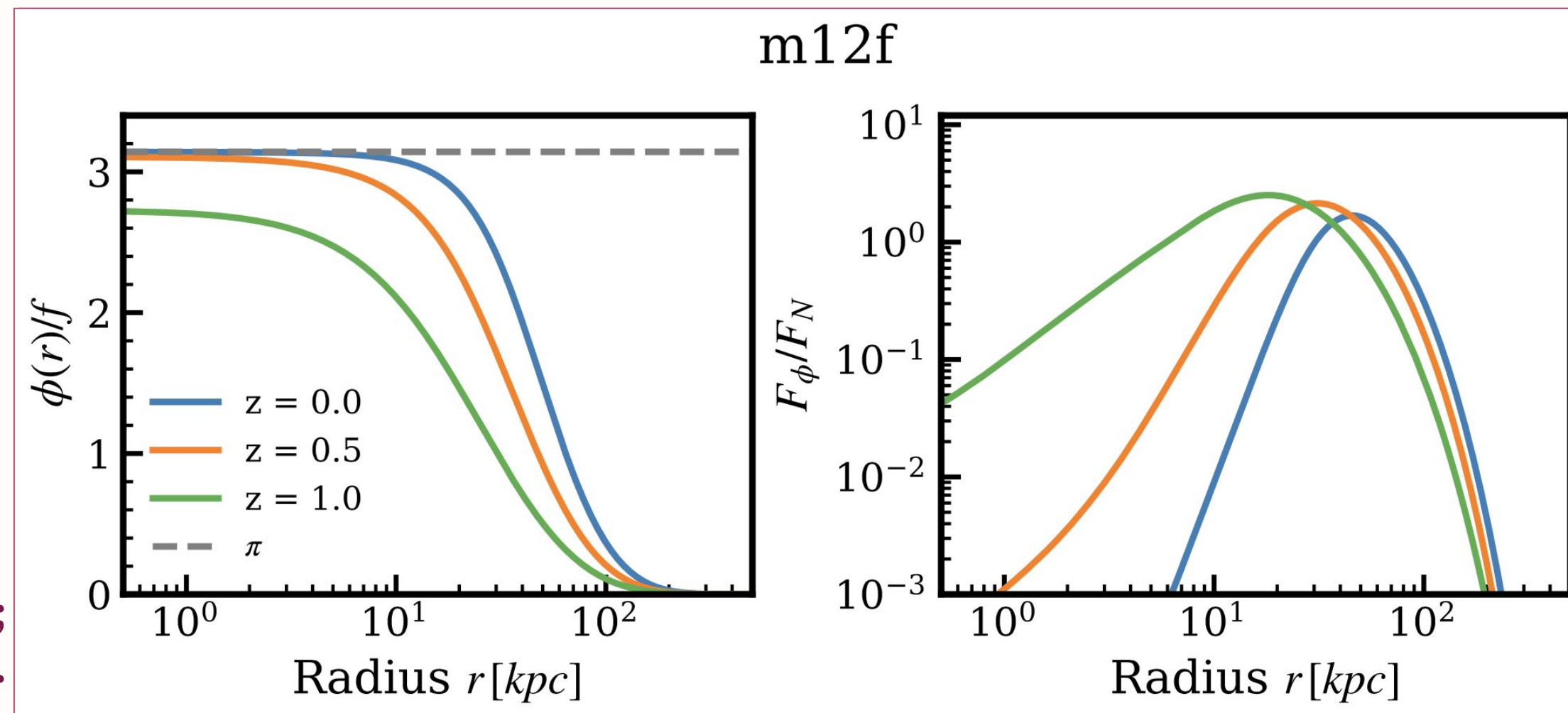


MD, Khoury, Sanderson;  
in prep.

# Yes!

- Different halo mass scales, prefer different energy scales.
- In all cases,  $\sigma_N/m_0 = 10^{-6}$
- For the Milky Ways:

$$\Lambda = 0.5 \text{ meV} \quad f = 10^{-7} M_{\text{Pl}} \quad \xi = 0.8$$



MD, Khoury, Sanderson;  
in prep.

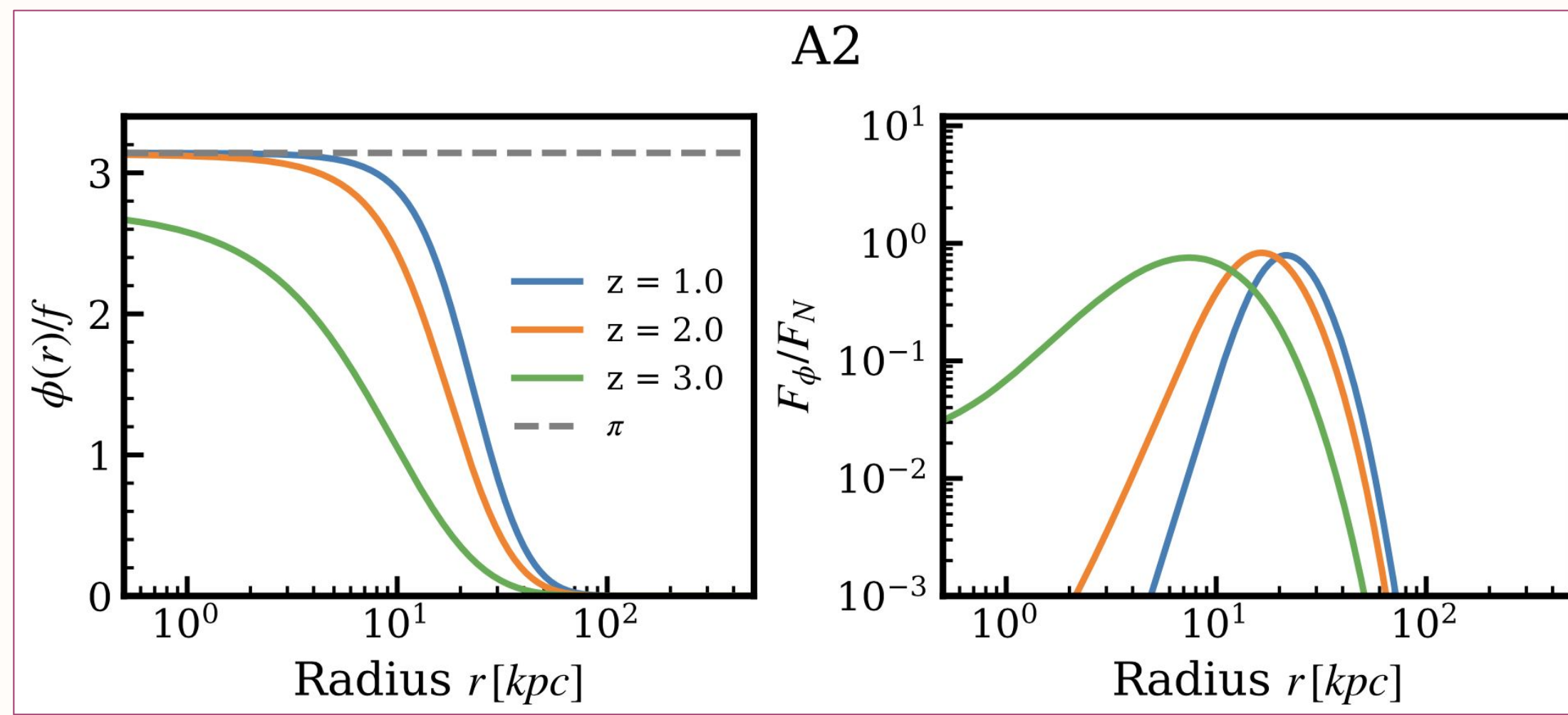
# Yes!

- Different halo mass scales, prefer different energy scales.

- In all cases,  $\sigma_N/m_0 = 10^{-6}$

- For the galaxy groups:

$$\Lambda = 1 \text{ meV} \quad f = 10^{-7} M_{\text{Pl}} \quad \xi = 0.8$$

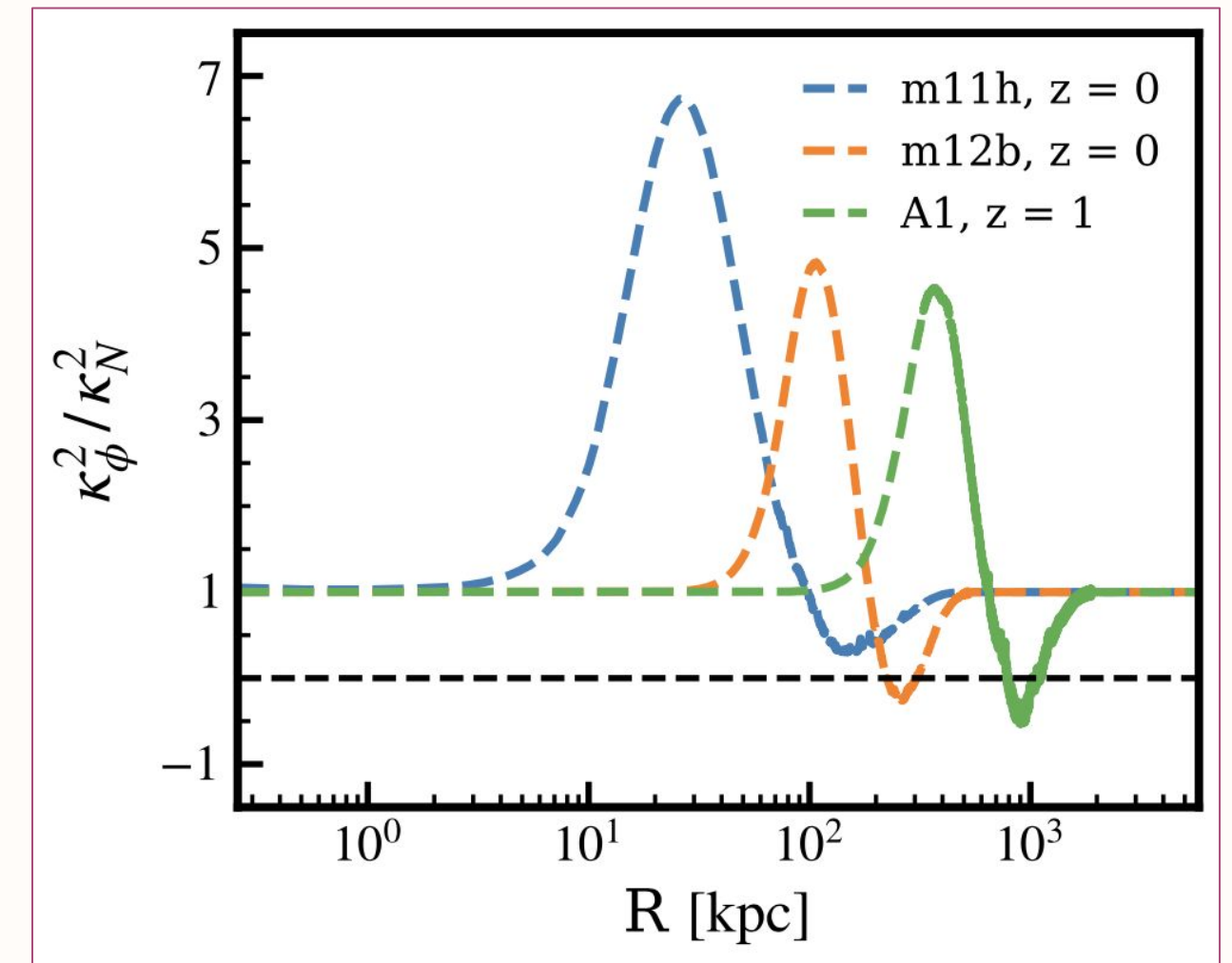
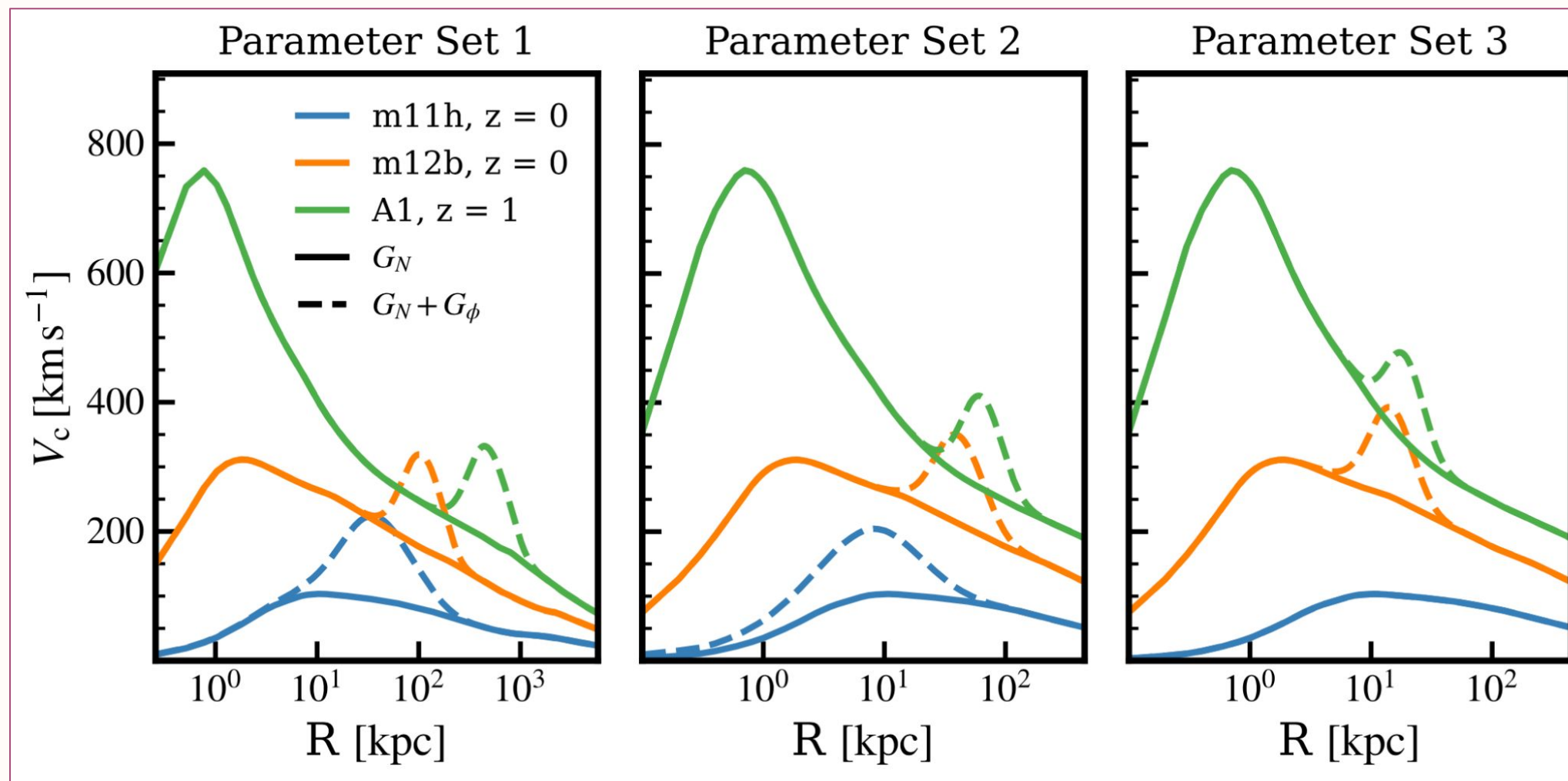


MD, Khoury, Sanderson;  
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Does it destroy  
everything?

# How does it change the halo?

- Circular velocities experience a boost.
- Circular orbits may become unstable.
- But only for dark baryons!

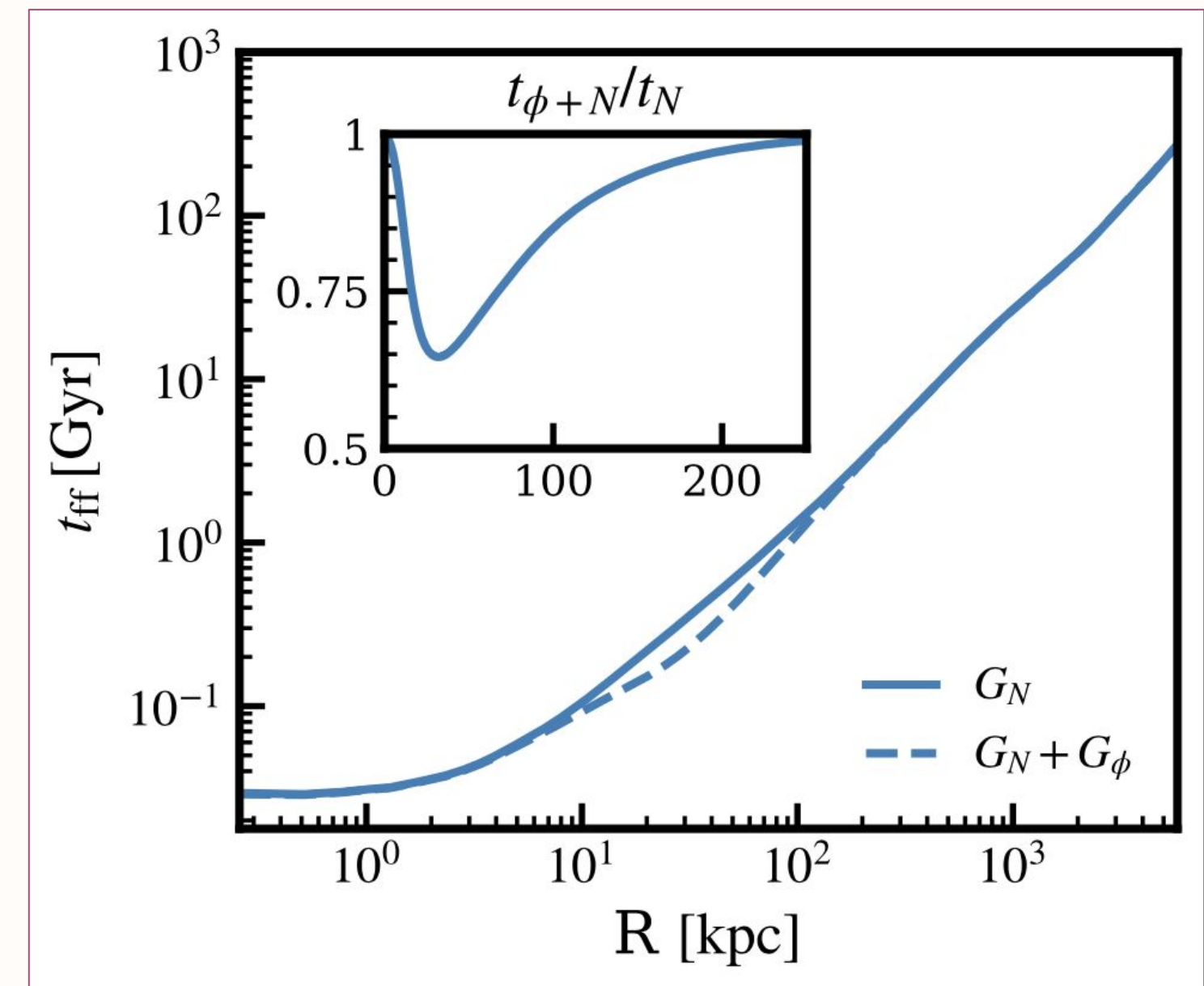
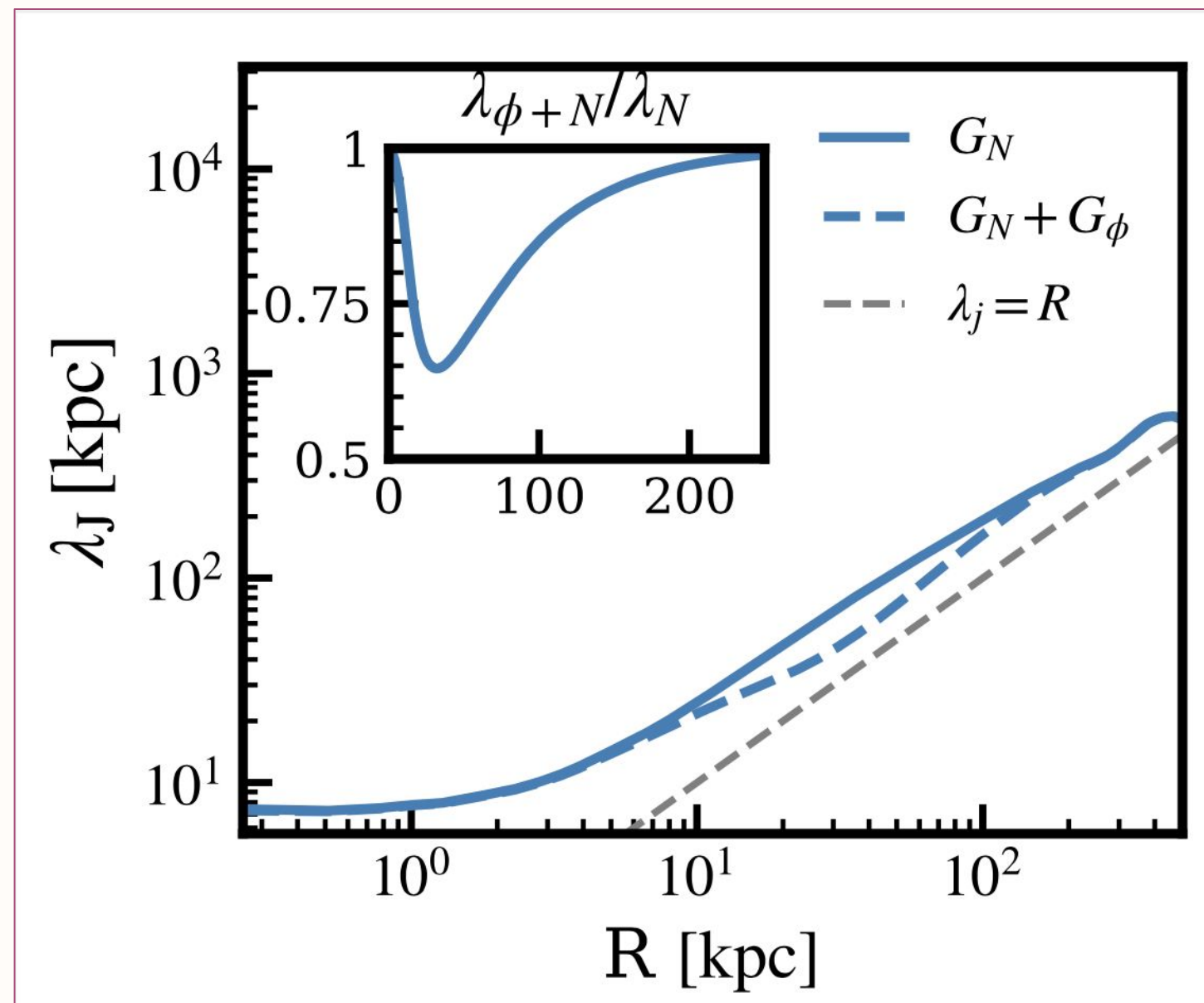


MD, Khoury, Sanderson; in prep.

# How does it change the halo?

- Enhanced instability around the peak of the force.
- Halo responds faster to changes in the DM distribution.

MD, Khoury, Sanderson;  
in prep.



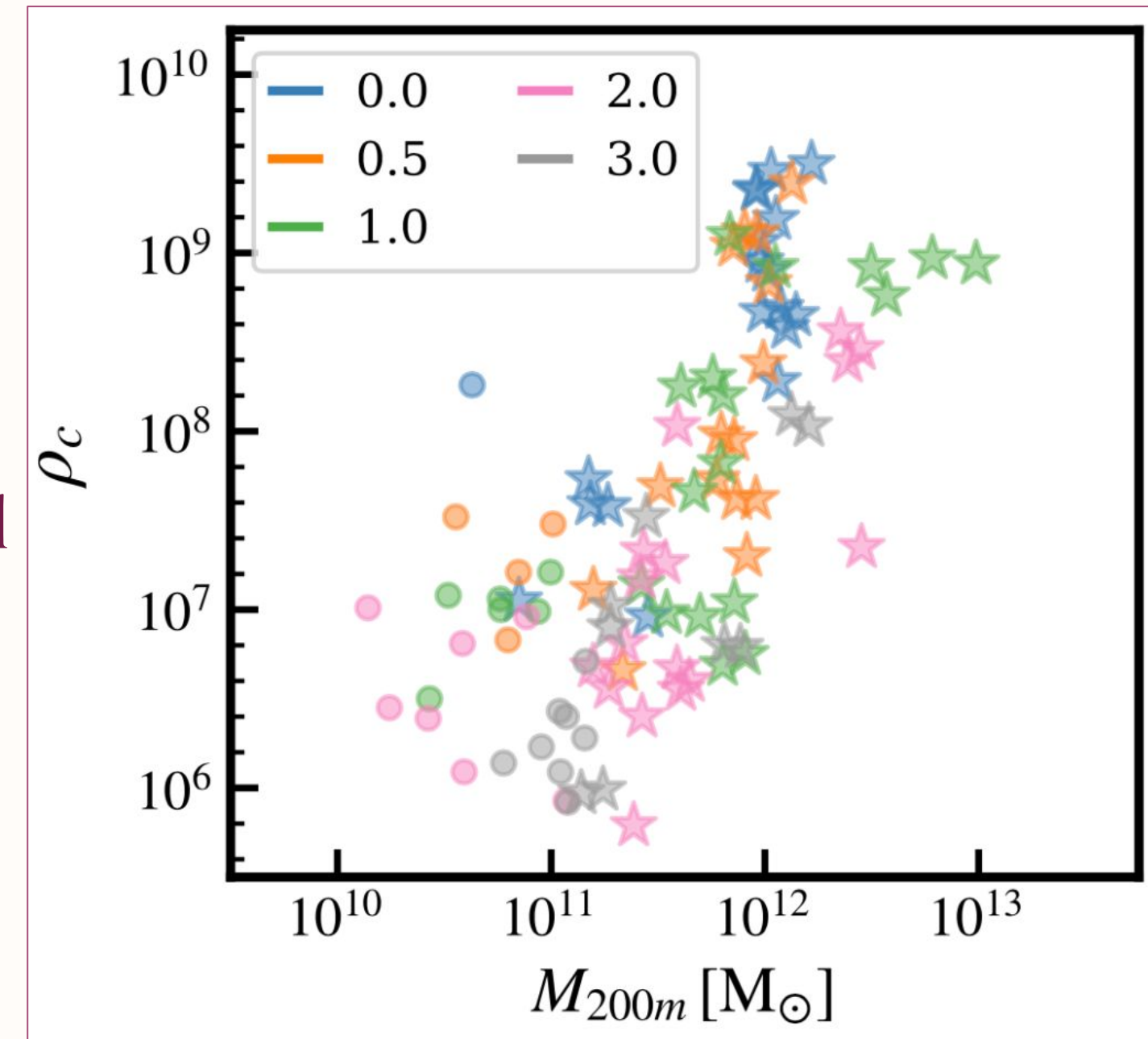
**Does it destroy  
everything?**

**... hopefully not!**

# Summary

- **Dark-QCD could provide a mass-scale dependent DM phenomenology.**
- **Realistic galaxies can source a dark axion field.**
- **Force profiles follow same structure: screened centre, force peak in transition region, and a fall to zero outside the galaxy.**
- **This force would enhance the gravity for exclusively the DM, leading to potential instabilities.**

MD, Khoury, Sanderson;  
in prep.



# Future Work

- **Early Universe: Can the dark axion be dark energy? With phantom crossing?**
- **Including more extensive QCD phenomenology: When does dQCD confinement occur? Ultra-light pions?**
- **Interactions between halos:**
  - **Force can be repulsive between two sourcing halos.**
  - **A subhalo in an existing axion field may source earlier than an isolated subhalo.**
- **Simulations: These are all instantaneous results, simulations needed to see evolution of the field and galaxies.**