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

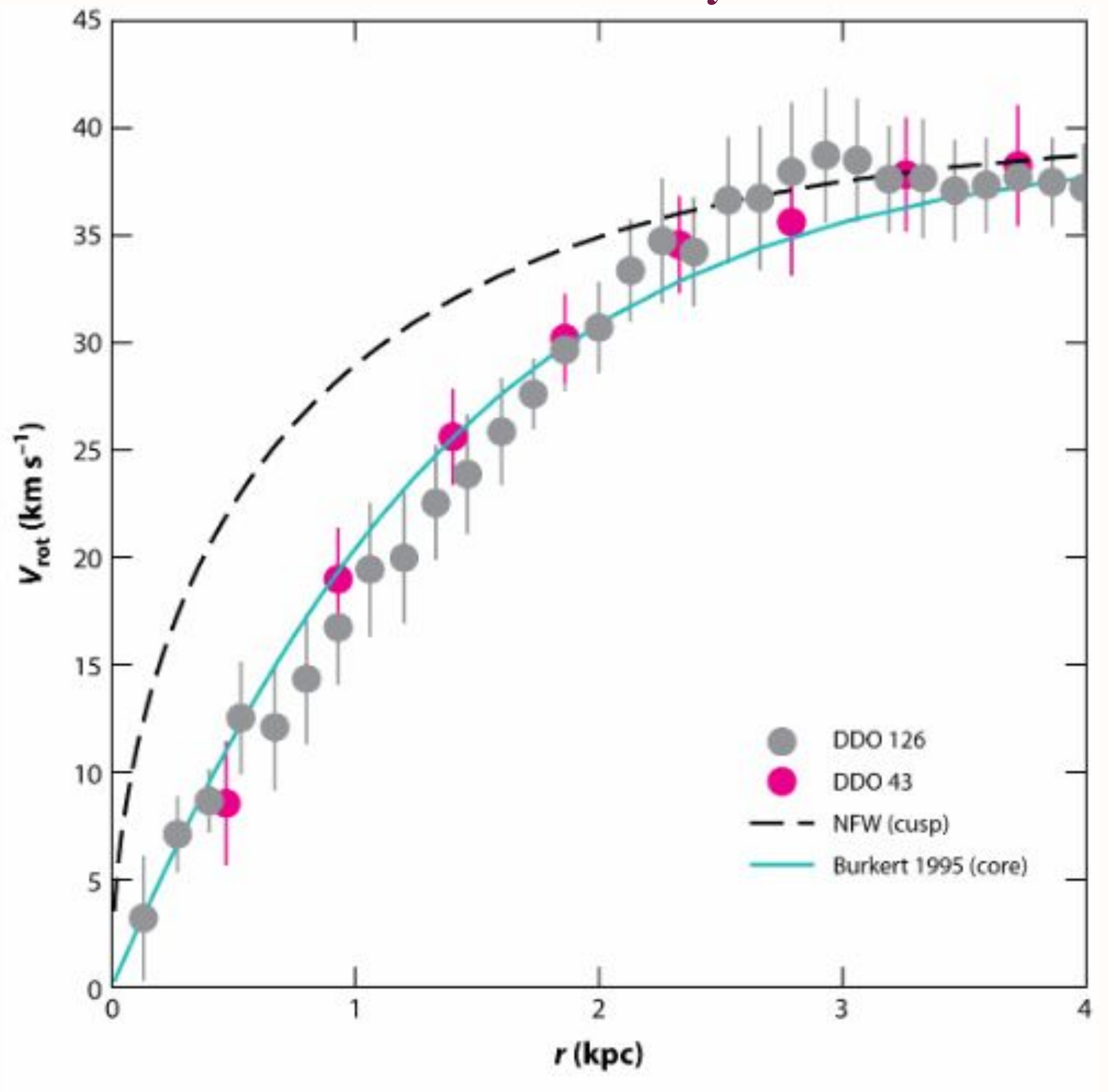
Mathilda Denison

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.**

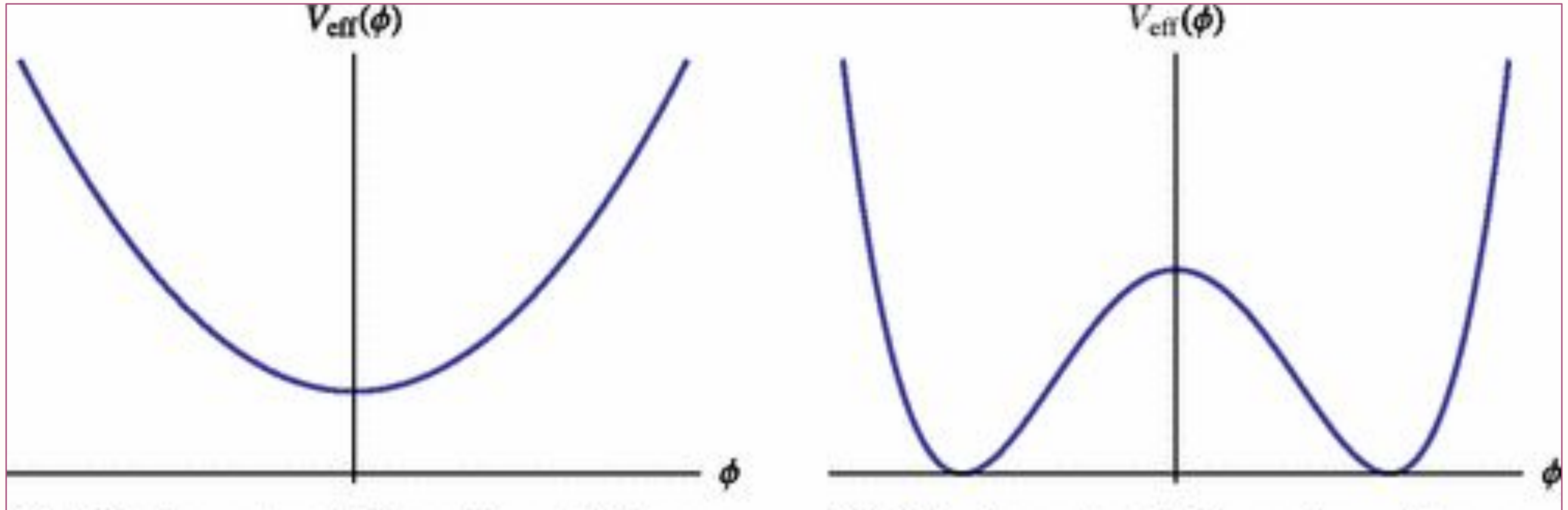
Bullock+Boylan-Kolchin 2017



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.



(a) Effective potential in regions of high ambient density. The VEV is 0.

(b) Effective potential in regions of low ambient density.

Hinterbichler+ 2011

Screened Forces in QCD

Action

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\partial\phi)^2 + i\bar{\psi}\nabla\!\!\!\!/\,\psi - V(\phi)\right]$$

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

- Λ : energy scale of theory
- ξ : ratio of quark masses
- f : axion decay constant
- ν : constant shift

Screened Forces in QCD

Finite-Density Correction

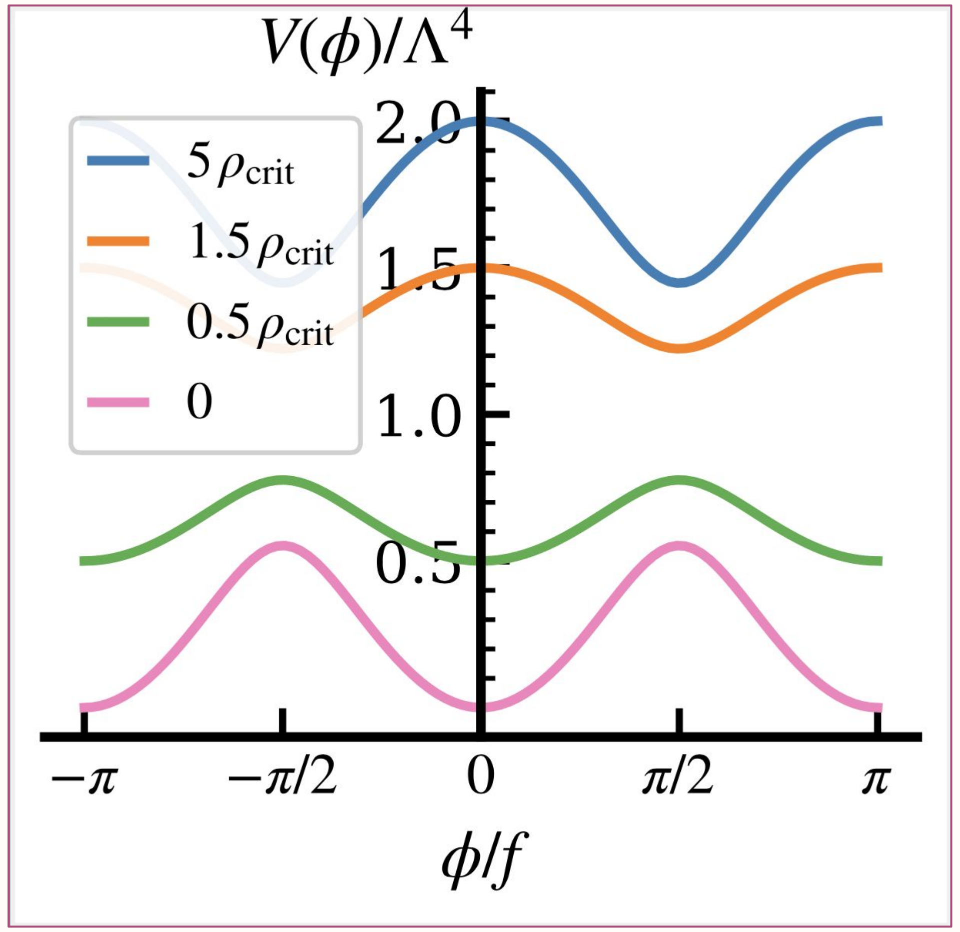
$$V(\phi) = \Lambda^4 \left[1 + \nu - \left(1 - \frac{2\sigma_N n}{\Lambda^4}\right) \sqrt{1 - \xi \sin^2\left(\frac{\phi}{2f}\right)} \right]$$

New Model Parameter

σ_N/m_0 : dependence of baryon masses on quark masses

Potential flips sign at critical density!

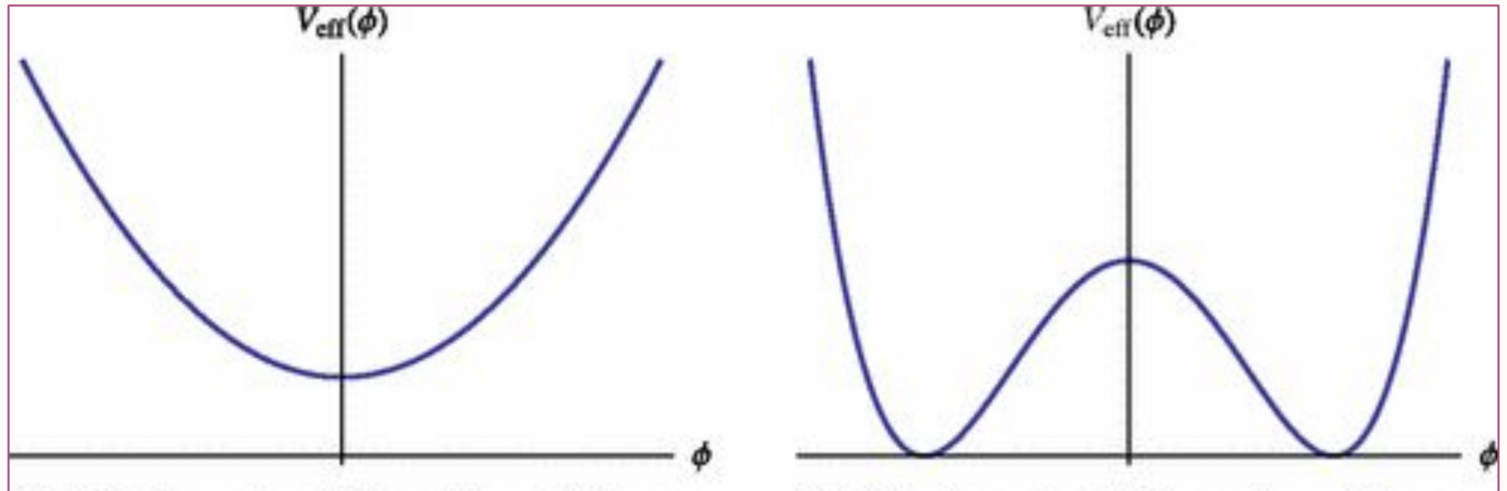
$$n_c = \frac{\Lambda^4}{2\sigma_N} \qquad \rho_c = \frac{\Lambda^4}{2\left(\sigma_N/m_0\right)}$$



MD , Khoury, Sanderson; in prep.

Symmetron

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



(a) Effective potential in regions of high ambient density. The VEV is 0.

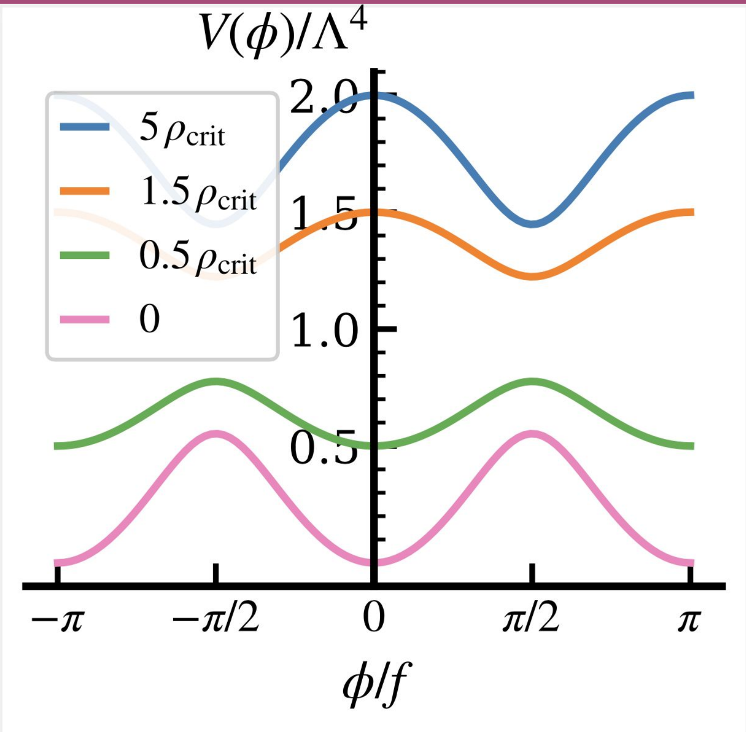
(b) Effective potential in regions of low ambient density.

In high densities, φ → 0 = no force.

In a vacuum, φ ≠ 0 = force.

QCD

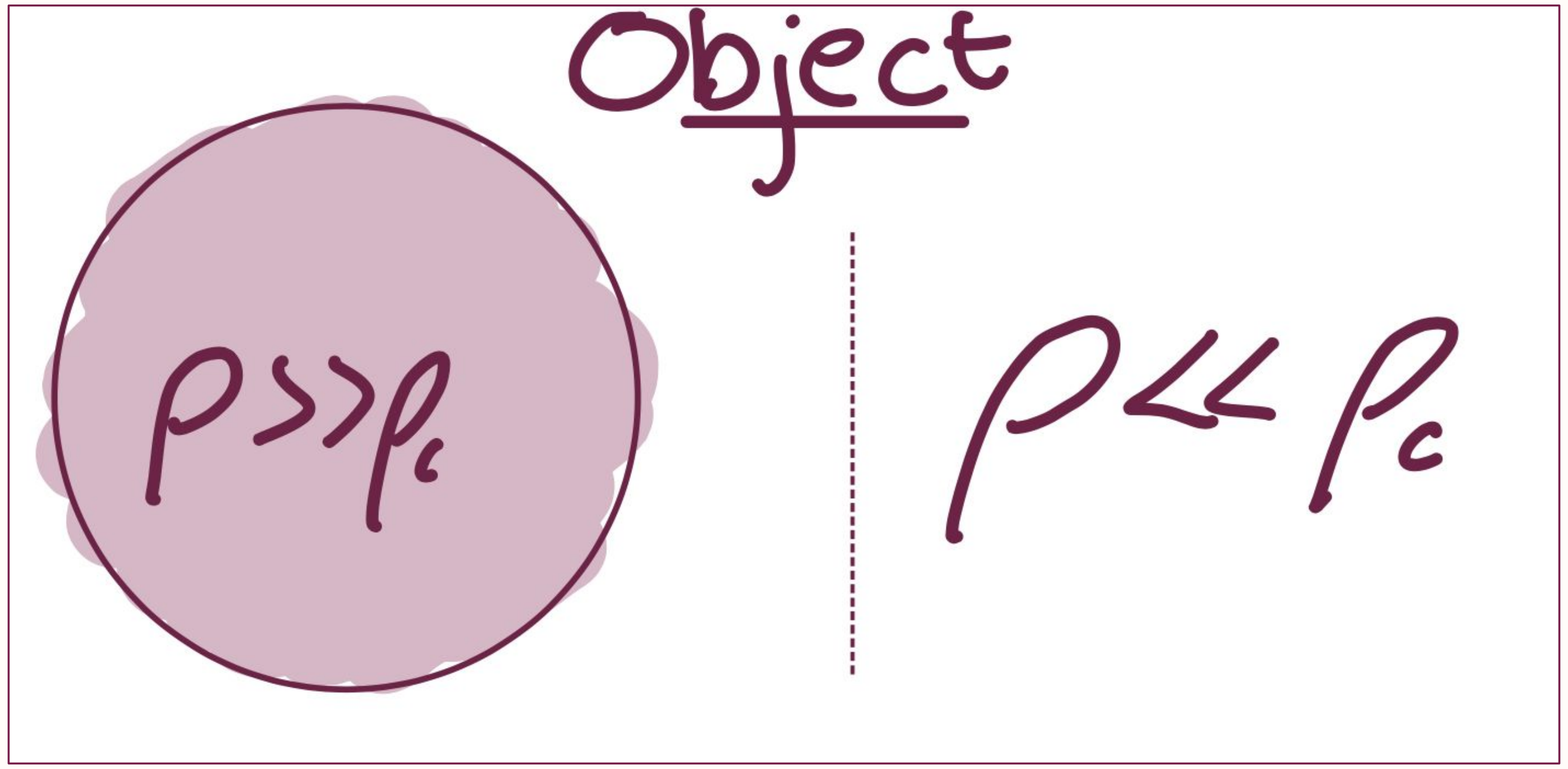
$$V(\phi) = \Lambda^4\left[1 + \nu - \left(1 - \frac{2\sigma_N n}{\Lambda^4}\right)\sqrt{1 - \xi\sin^2\left(\frac{\phi}{2f}\right)}\right]$$

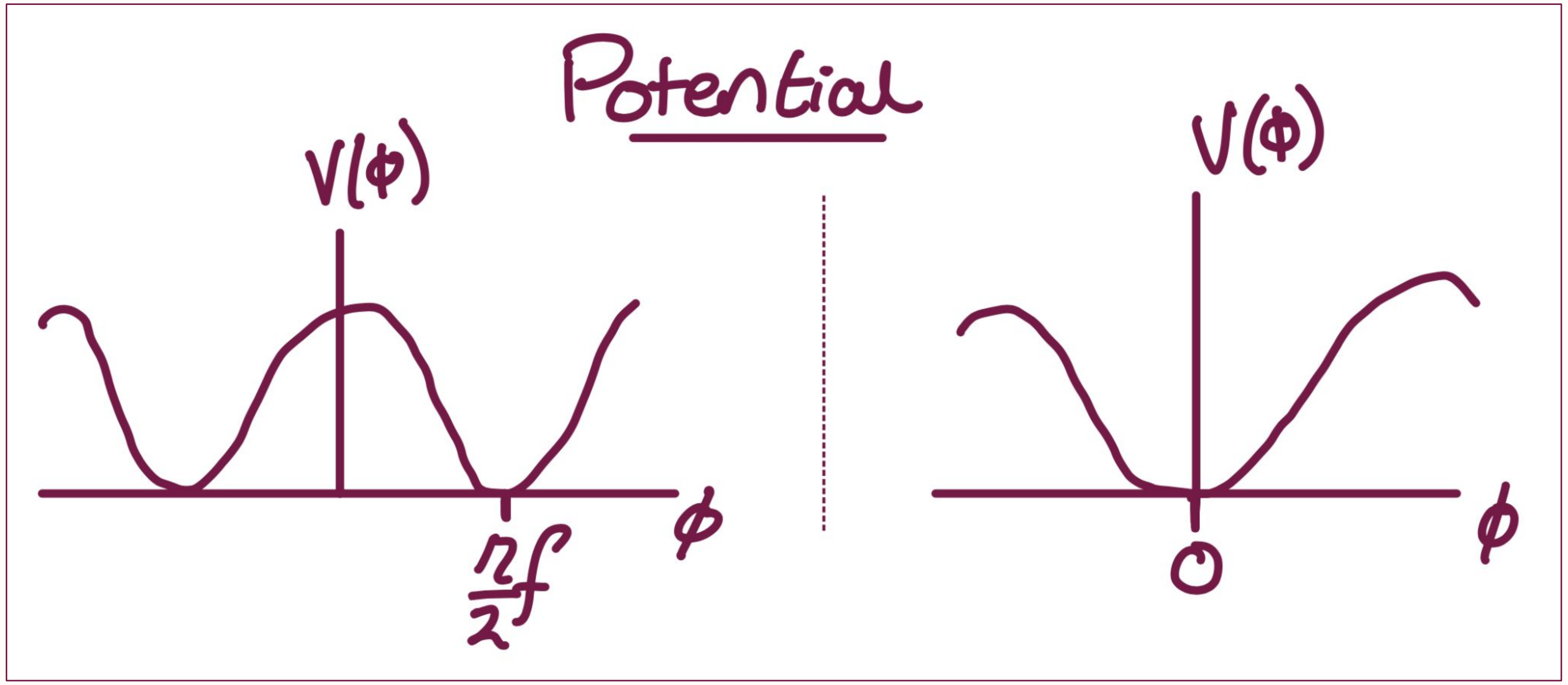


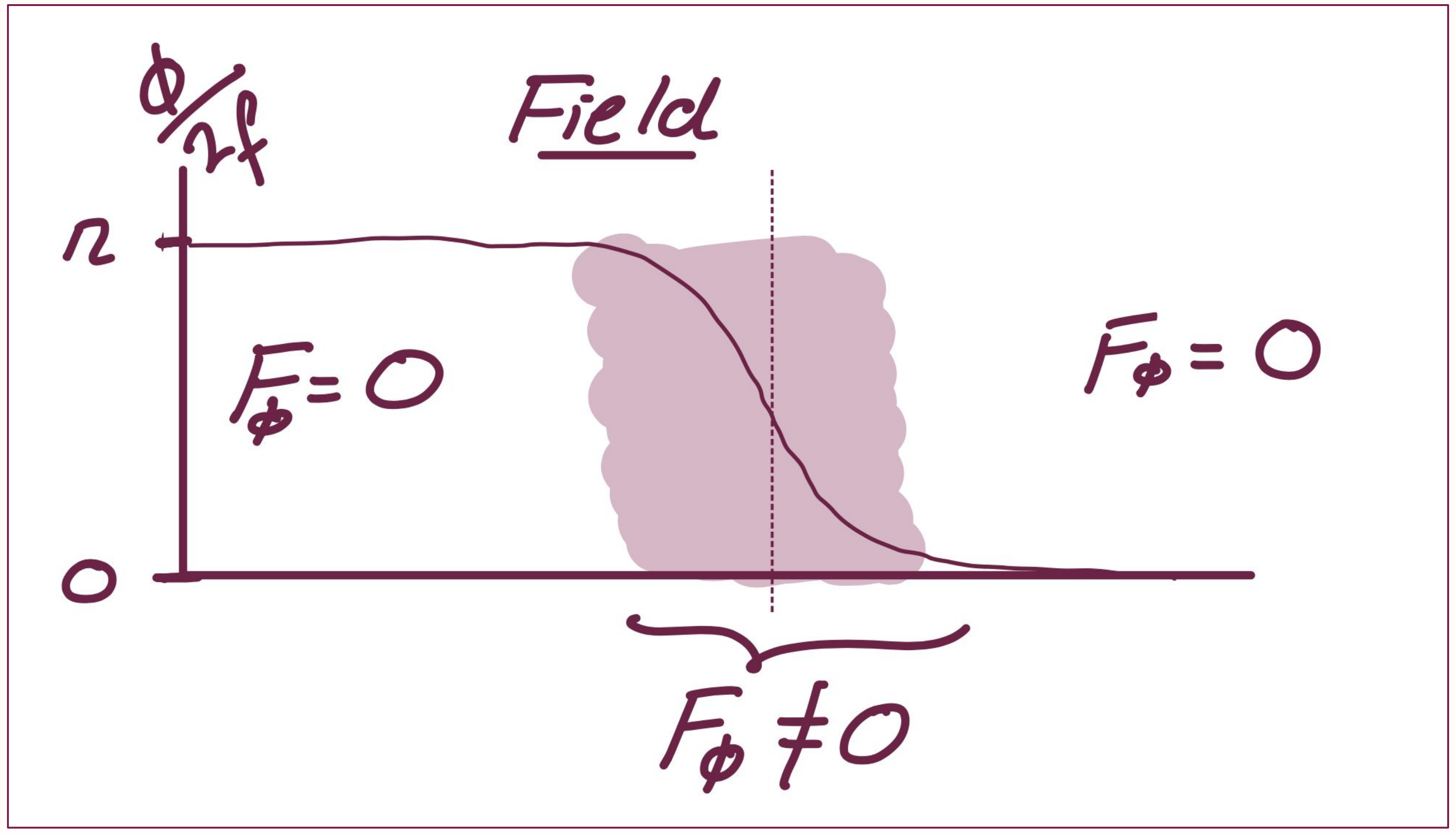
In high densities, φ → πf = no force.

In a vacuum, φ = 0 = no force.

In medium densities, 0 < φ < πf = force.


Object
$\rho \gg \rho_c$
$\rho \ll \rho_c$


Potential
$V(\phi)$
ϕ
$\frac{\pi}{2}f$
$V(\phi)$
ϕ
0

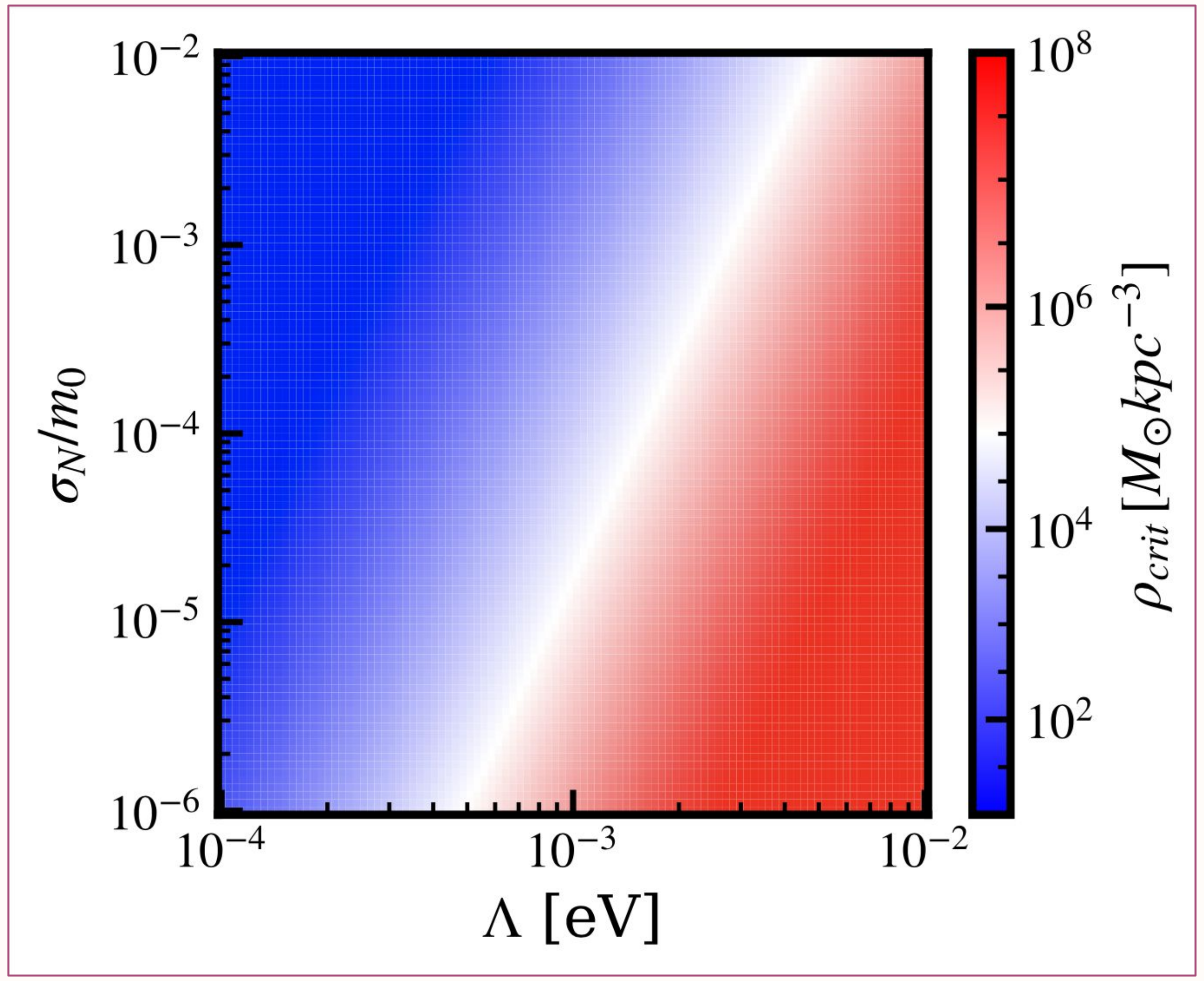

$\phi/2f$
Field
π
0
$F_\phi = 0$
$F_\phi = 0$
$F_\phi \neq 0$

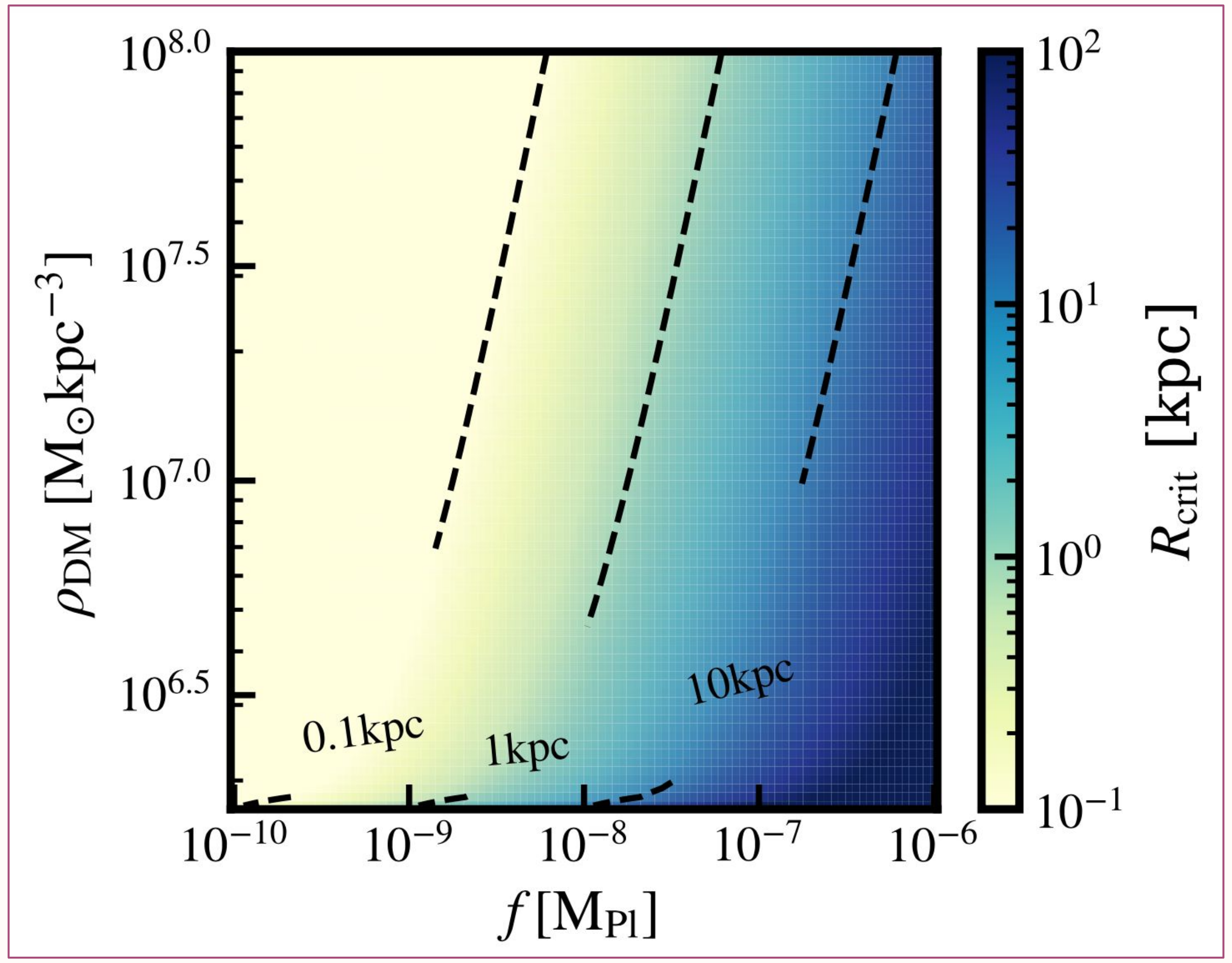
The Parameter Space

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: $f < 10^{-7}$

MD, Khoury, Sanderson; in prep.

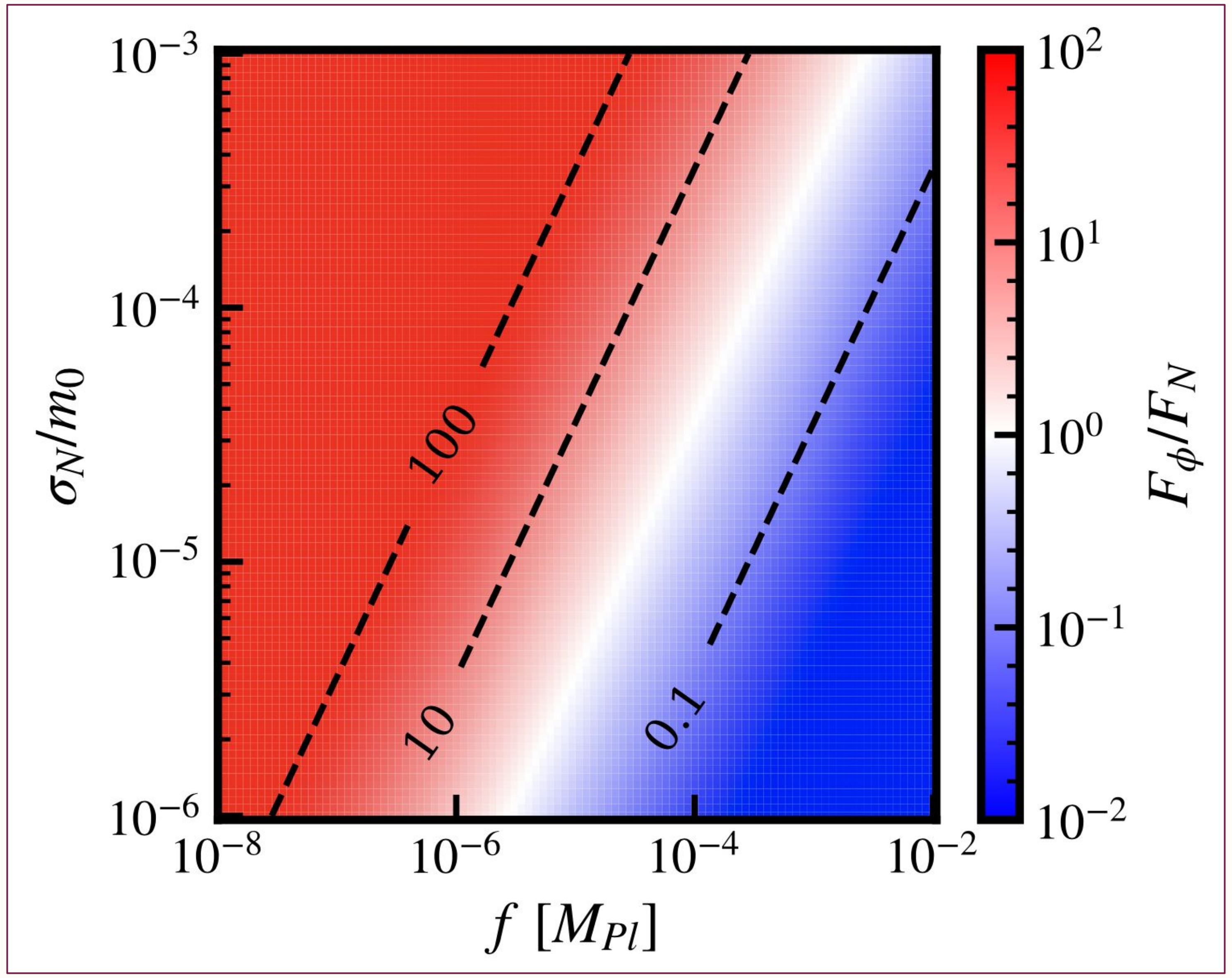




The Parameter Space

- 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.

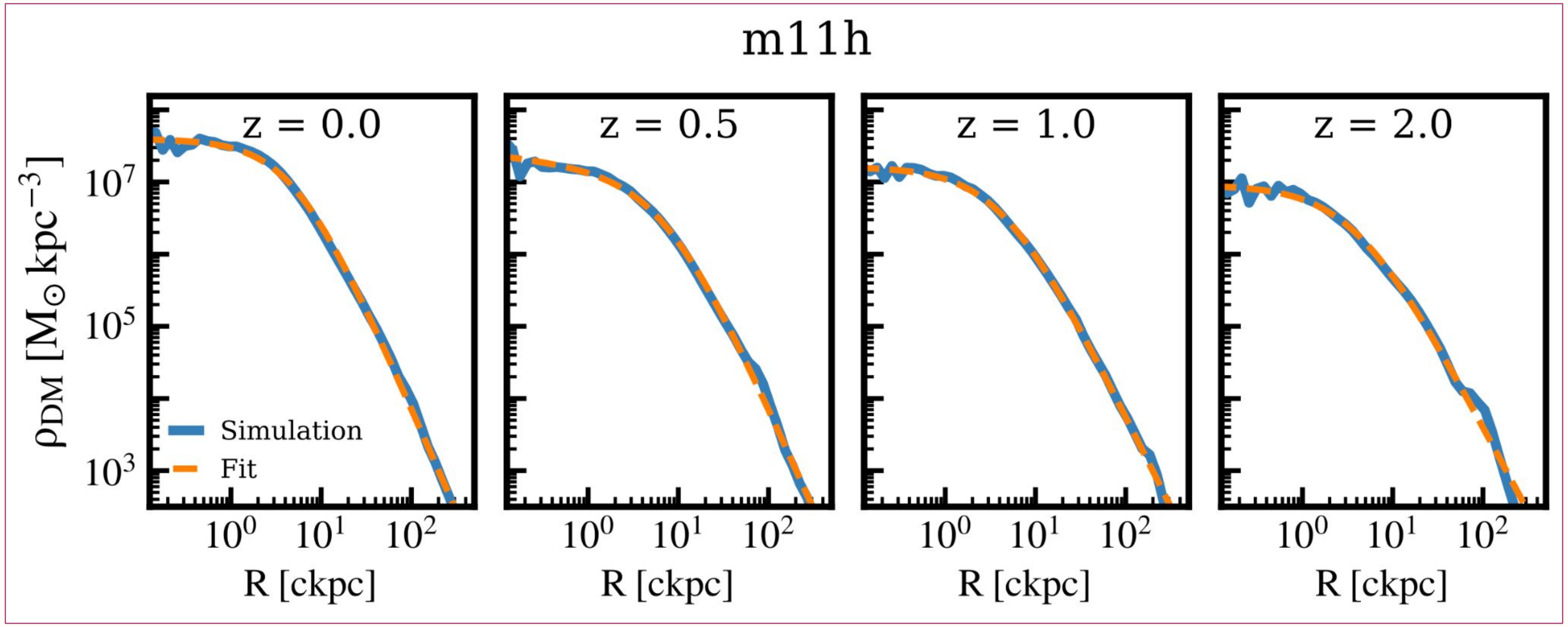


Does it actually work?

Does it actually work?

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

MD, Khoury, Sanderson; in prep.

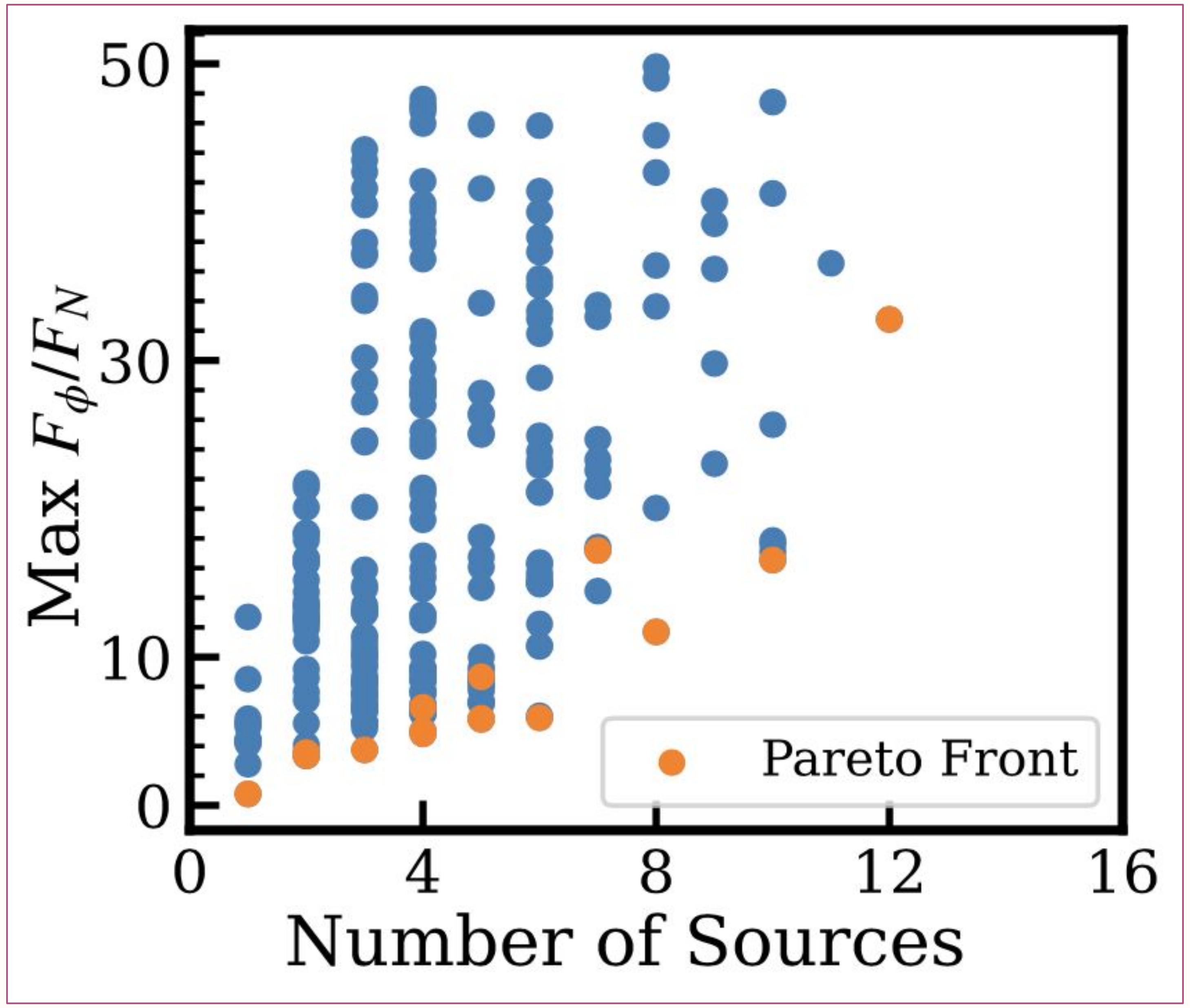


Fit of DM density profiles (using Zhao profile) of m11h from FIRE-2 cosmological zooms at different redshifts.

Does it actually work?

MD, Khoury, Sanderson; in prep.

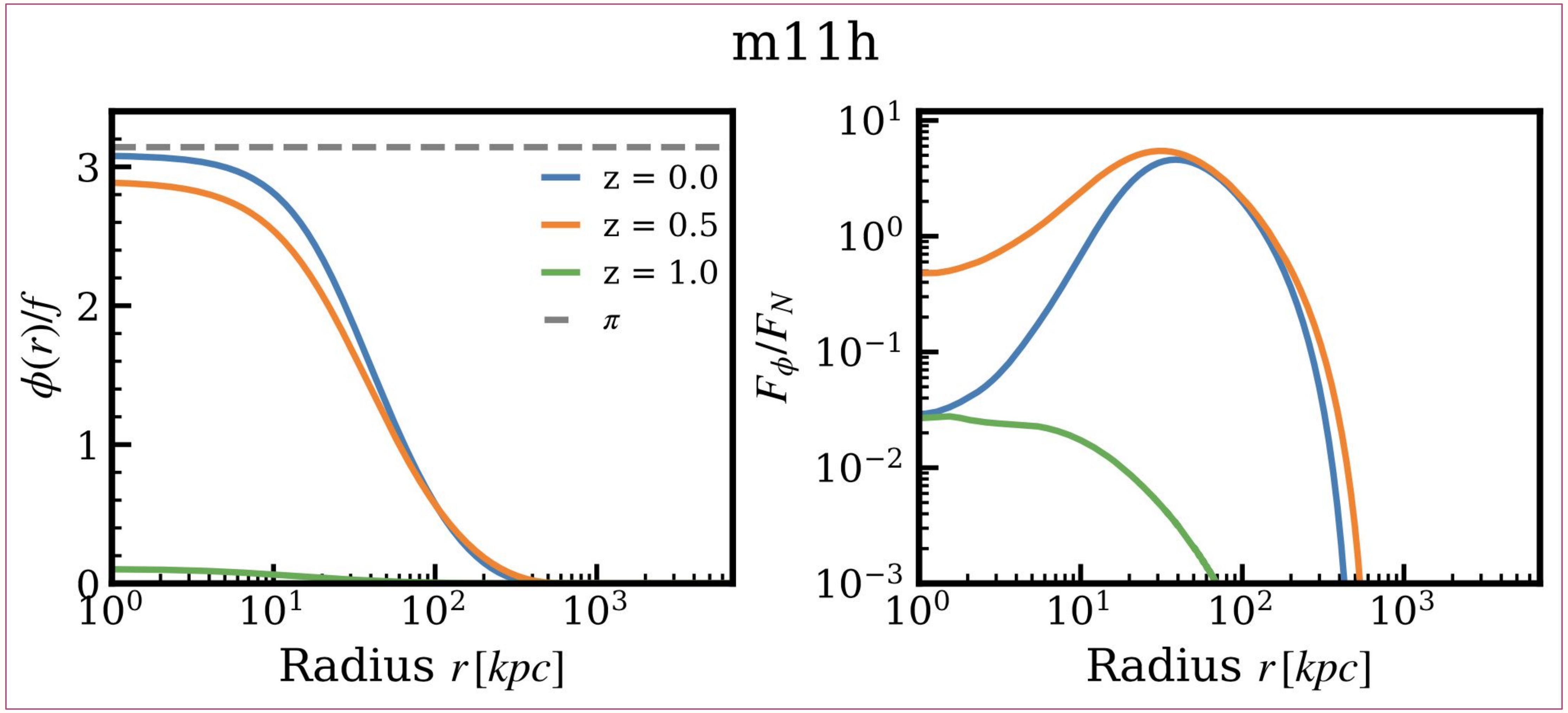
- Numerically solve for the dark axion radial profile.
- Find the force relative to gravity.
- Run a basin-hopping optimizer to find best parameters.
- Test best parameters over all halos at all redshifts.



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

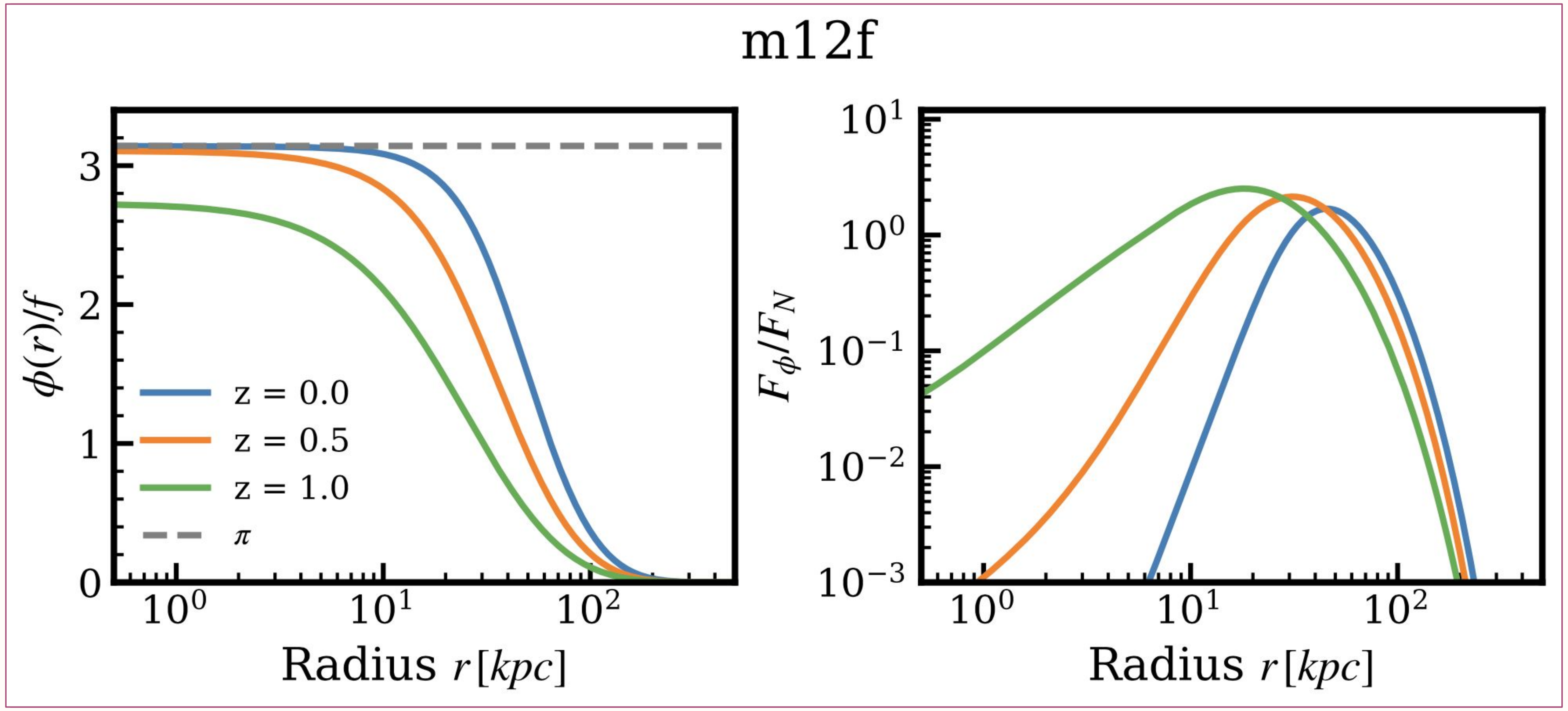


MD, Khoury, Sanderson; in prep.

Yes!

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

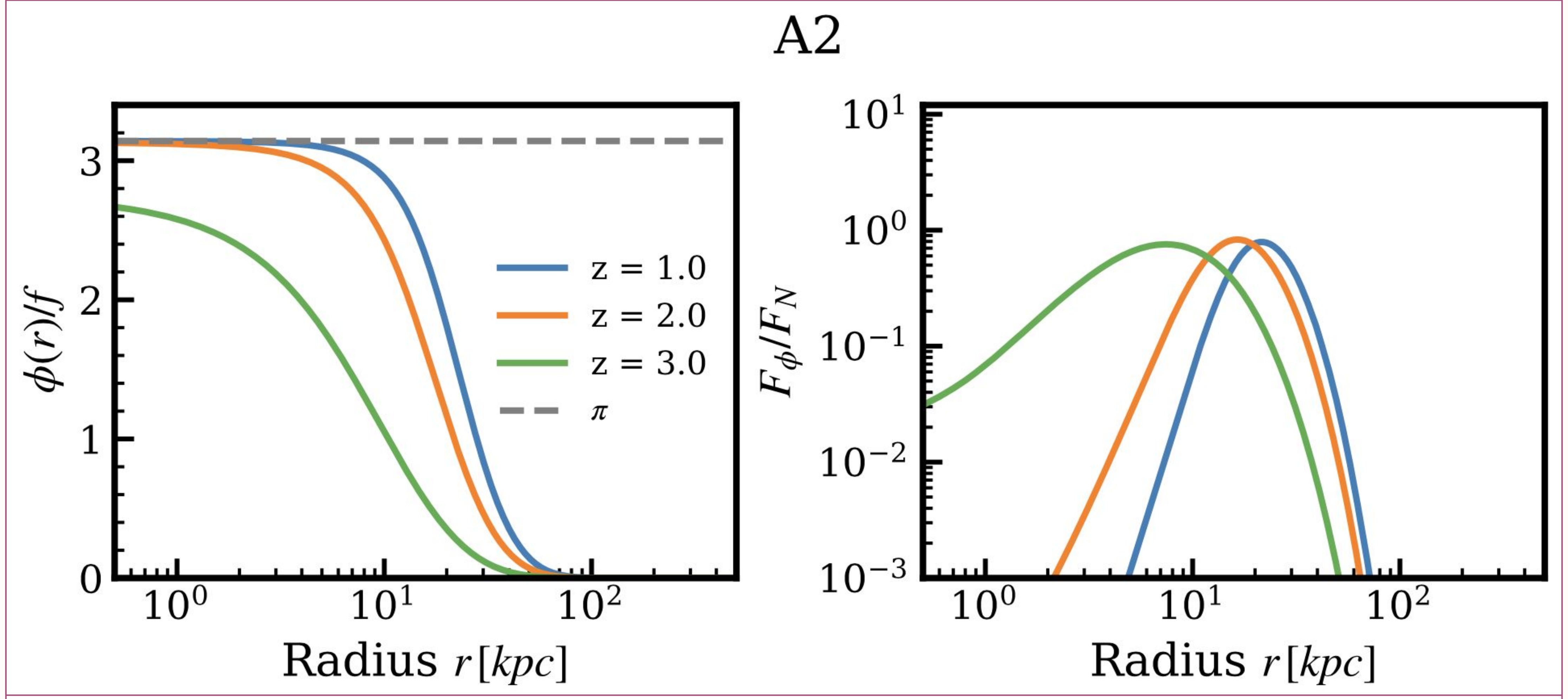
$$\Lambda = 0.5 \text{ meV} \qquad f = 10^{-7}\ \mathrm{M_{Pl}} \qquad \xi = 0.8$$



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:** $\Lambda = 1\ \mathrm{meV} \qquad f = 10^{-7}\ \mathrm{M_{Pl}} \qquad \xi = 0.8$

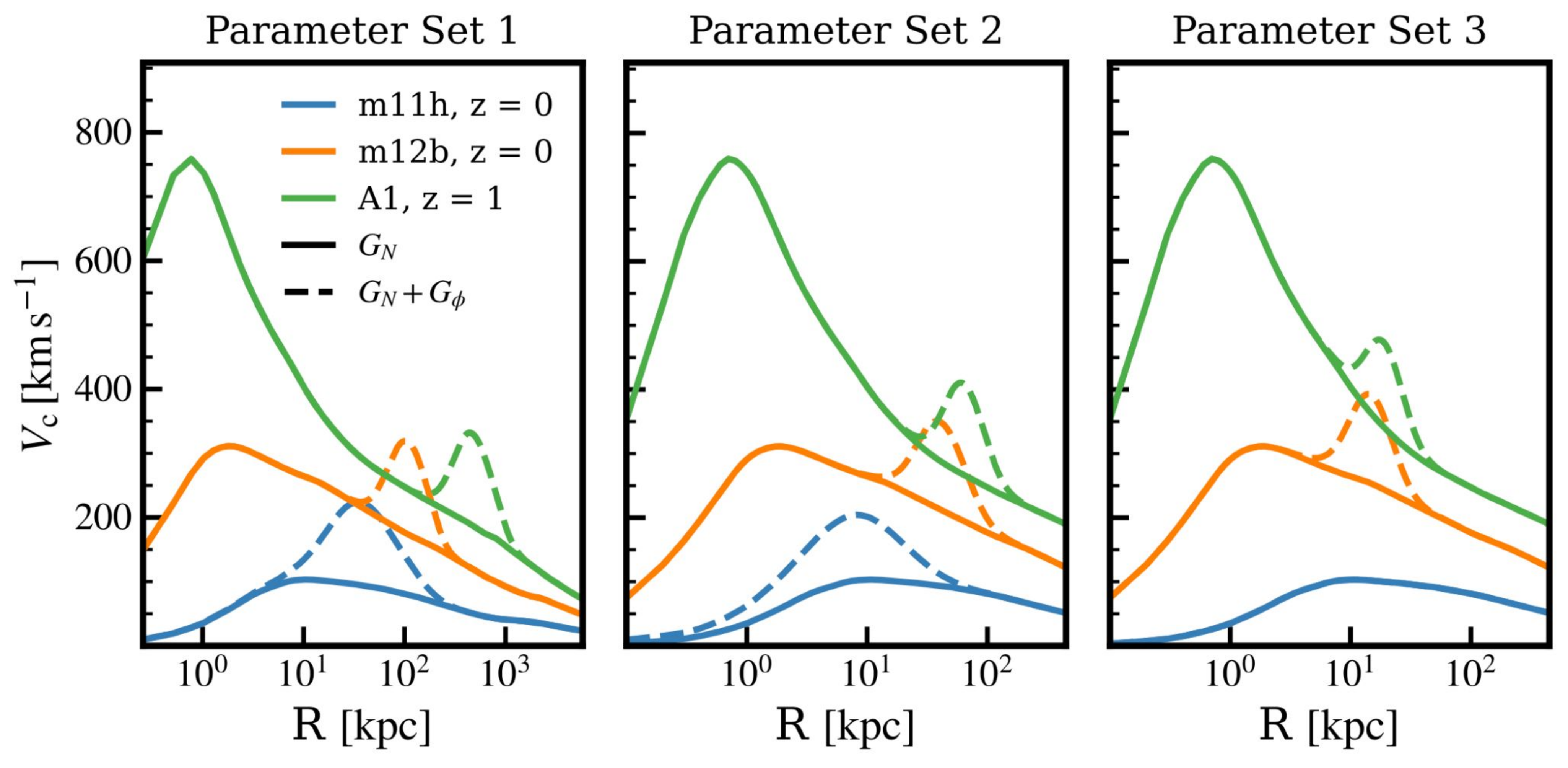


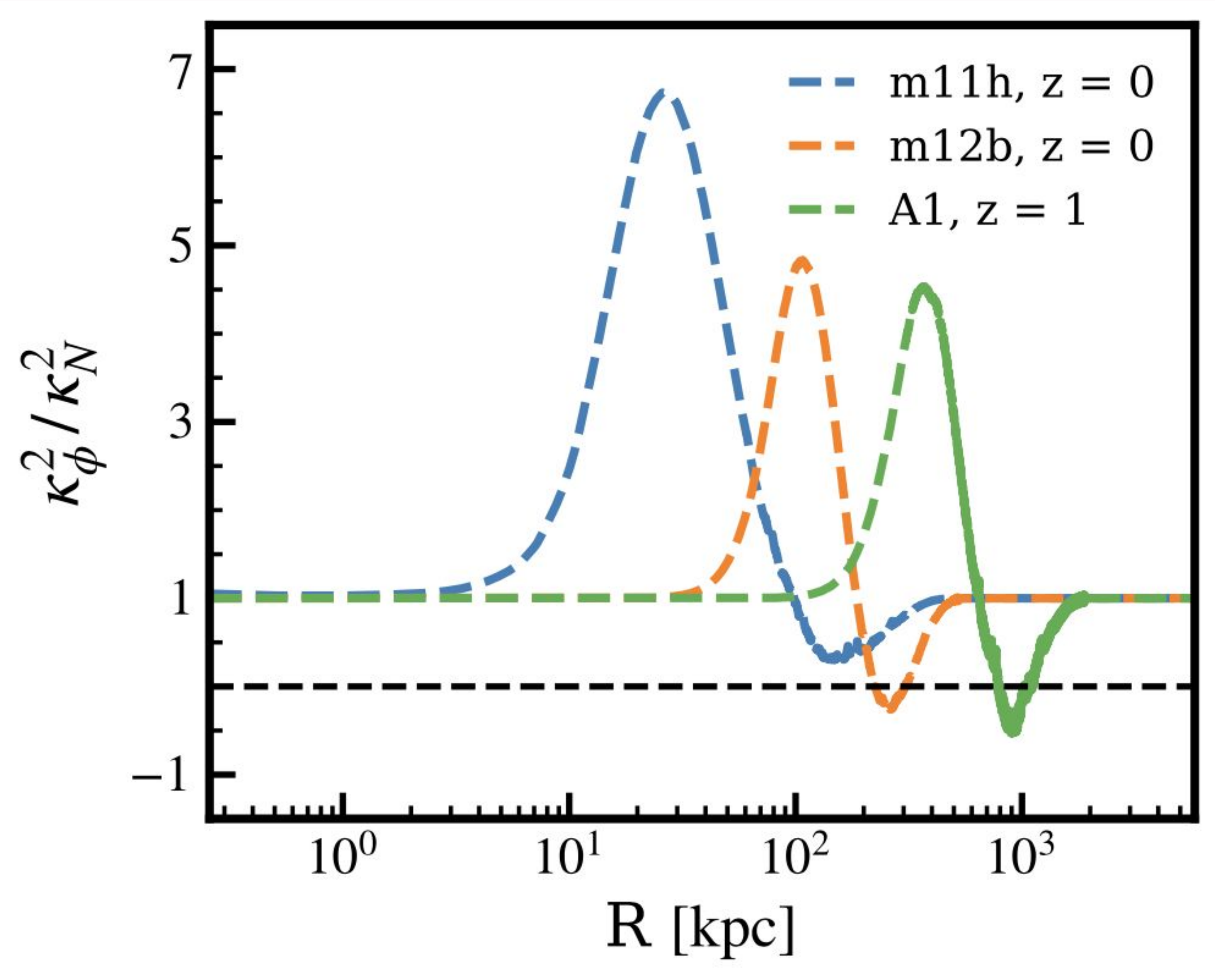
MD, Khoury, Sanderson; in prep.

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!



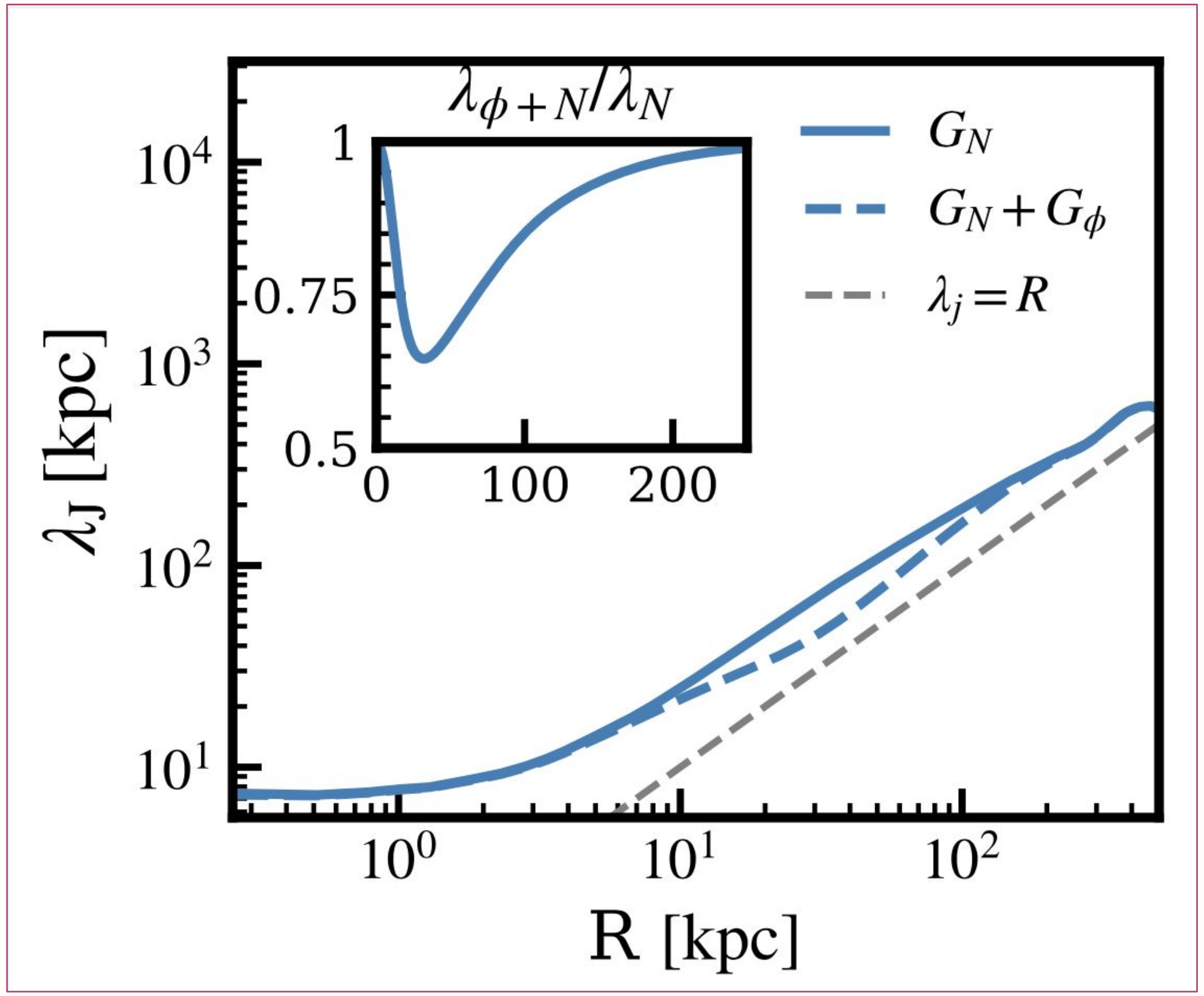


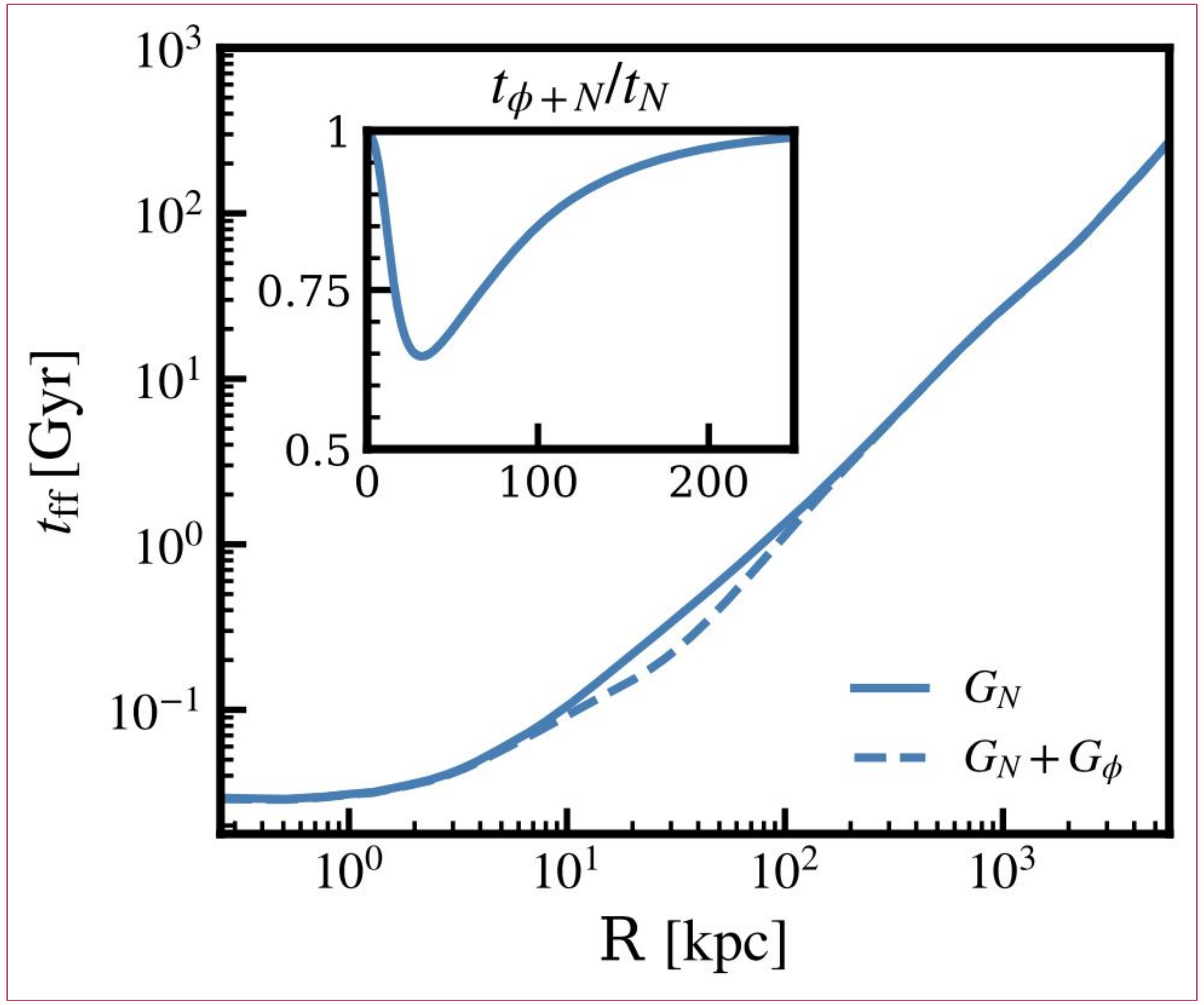
MD, Khoury, Sanderson; in prep.

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.





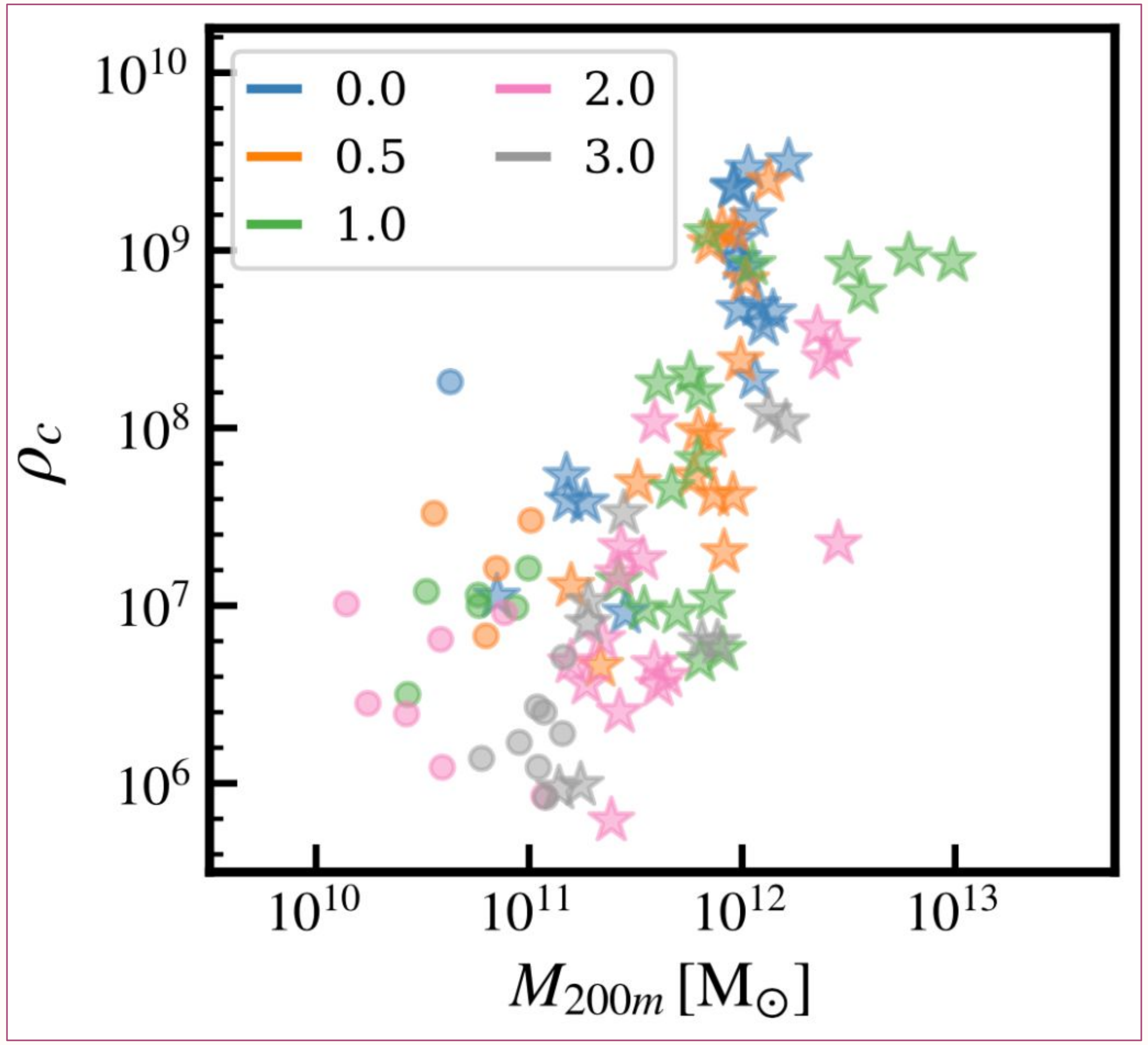
Does it destroy everything?

... hopefully not!

Summary

MD, Khoury, Sanderson; in prep.

- 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.



Future Work

- 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.