Can blue-tilted primordial power spectrum save the small scale crisis in MW?

From the perspective of Zoom-In simulation for MW host size dark matter halo

Jianhao WU Personal website: https://rushingfox.github.io/

2nd year MPhil student @ CUHK Physics, Prof. T. K. Chan's AstroSim Group

CUHK Cosmology Journal Club

Paper: Cosmological Zoom-In Simulations of Milky Way Host Size Dark Matter Halos with a Blue-Tilted Primordial Power Spectrum
https://arxiv.org/abs/2412.16072 Under Review by PRD

Jianhao Wu(CUHK), Tsang Keung Chan(CUHK), Victor J. Forouhar Moreno(Leiden).

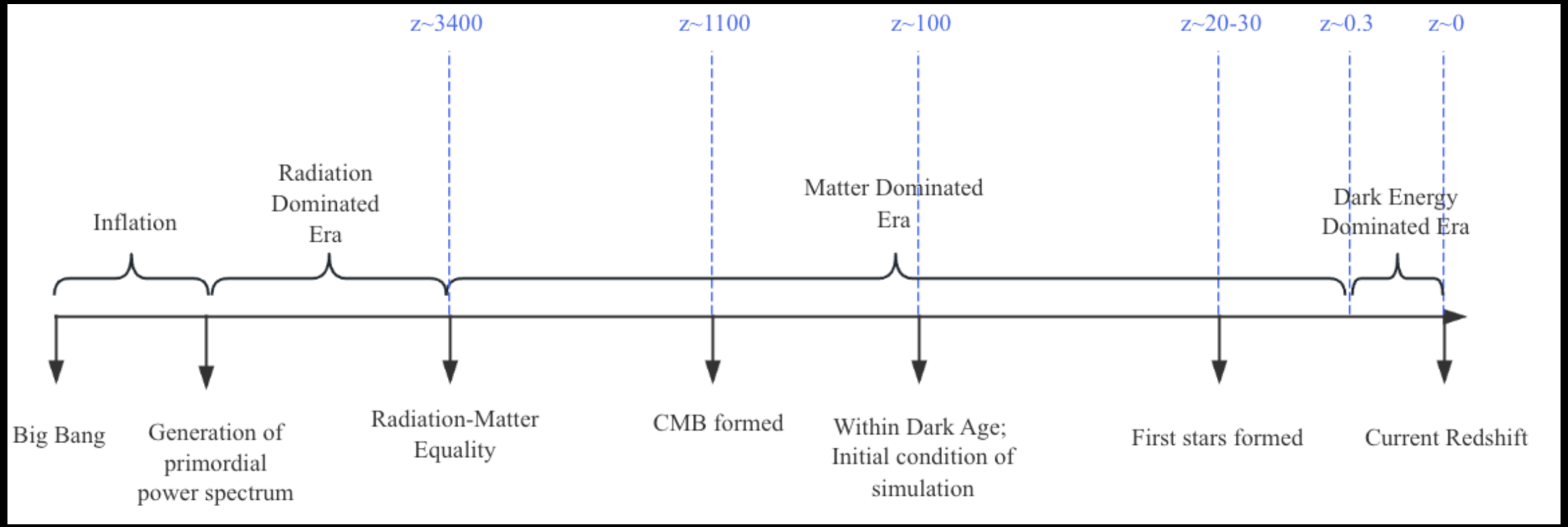
香港中文大學 CUHK

Universiteit Leiden Leiden Observatory

[arxiv:2412.16072]

Standard Cosmology Model

- The standard cosmology model consists of:
  - The single-field slow-roll inflationary model, which would generate a ***power law*** primordial power spectrum at very early universe
  - The LCDM model, which dominates the later evolution of the universe

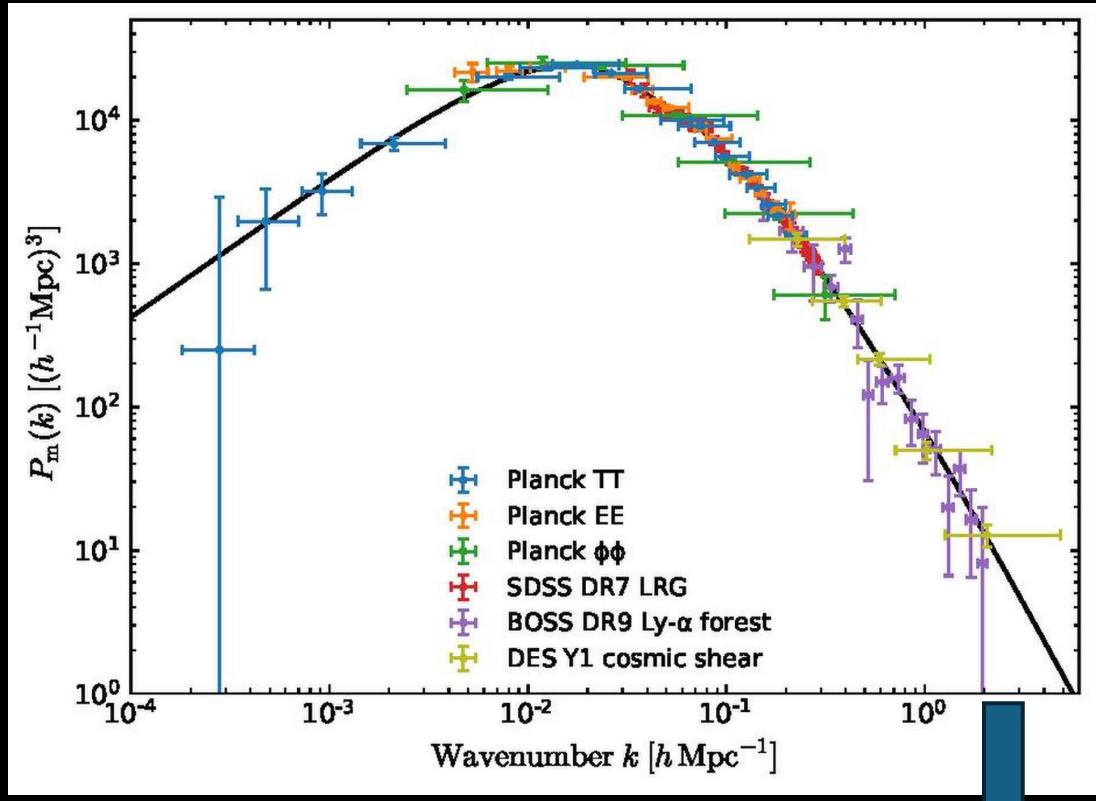


[arxiv:2412.16072]

Uncertain at small scales

- Standard cosmology model has achieved great success during the past several decades, on ***large scale of universe***

- However on ***small scales*** the primordial power spectrum is ***loosely constrained***



MW host dark matter halo's size corresponds to ~2.5 h/Mpc

[arxiv:2412.16072]

A small-scale enhanced or suppressed?

- Besides, multiple observations are in favor of ***a small scale enhanced*** cosmological model:
  - JWST has observed early formation of massive galaxies (arxiv [2306.11993])
  - Even CDM model could not solve the “anomalous” flux ratio problem in strong lensing: a larger fraction mass of substructure is required (arxiv [0903.4559])
  - A too-many-satellite-galaxies problem appeared in nearby galaxy observation (arxiv [1711.06267] [2403.08717])

[arxiv:2412.16072]

A small scale enhanced primordial power spectrum could explain JWST early structure formation!

Green region is from JWST

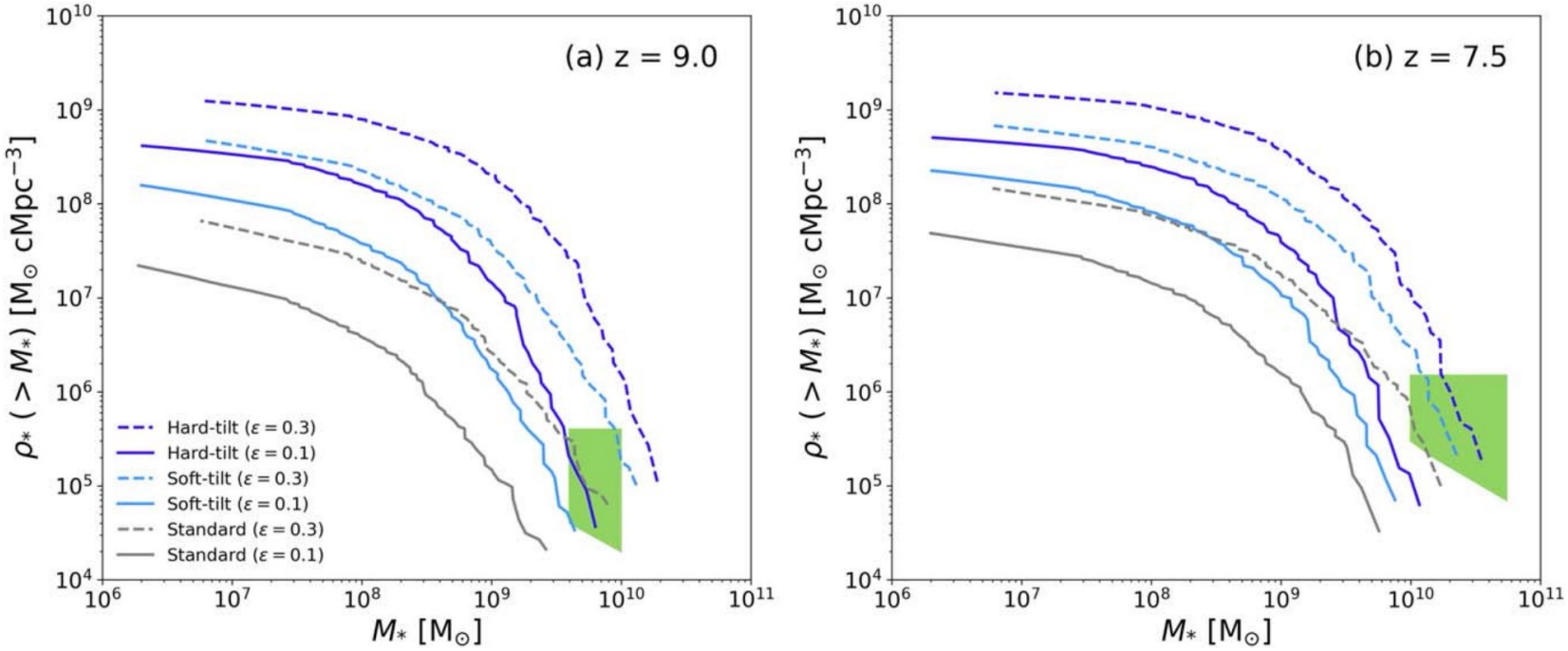


Figure 4. Cumulative comoving stellar mass density for the standard (gray), soft-tilt (light blue), and hard-tilt (blue) models at (a) $z = 9$ and (b) $z = 7.5$. We adopt a moderate star formation efficiency of $\epsilon = 0.1$ (solid lines) and 0.3 (dashed). The green regions are the CCSMD adopted from Parashari & Laha (2023) for the observations of Labbé et al. (2023).

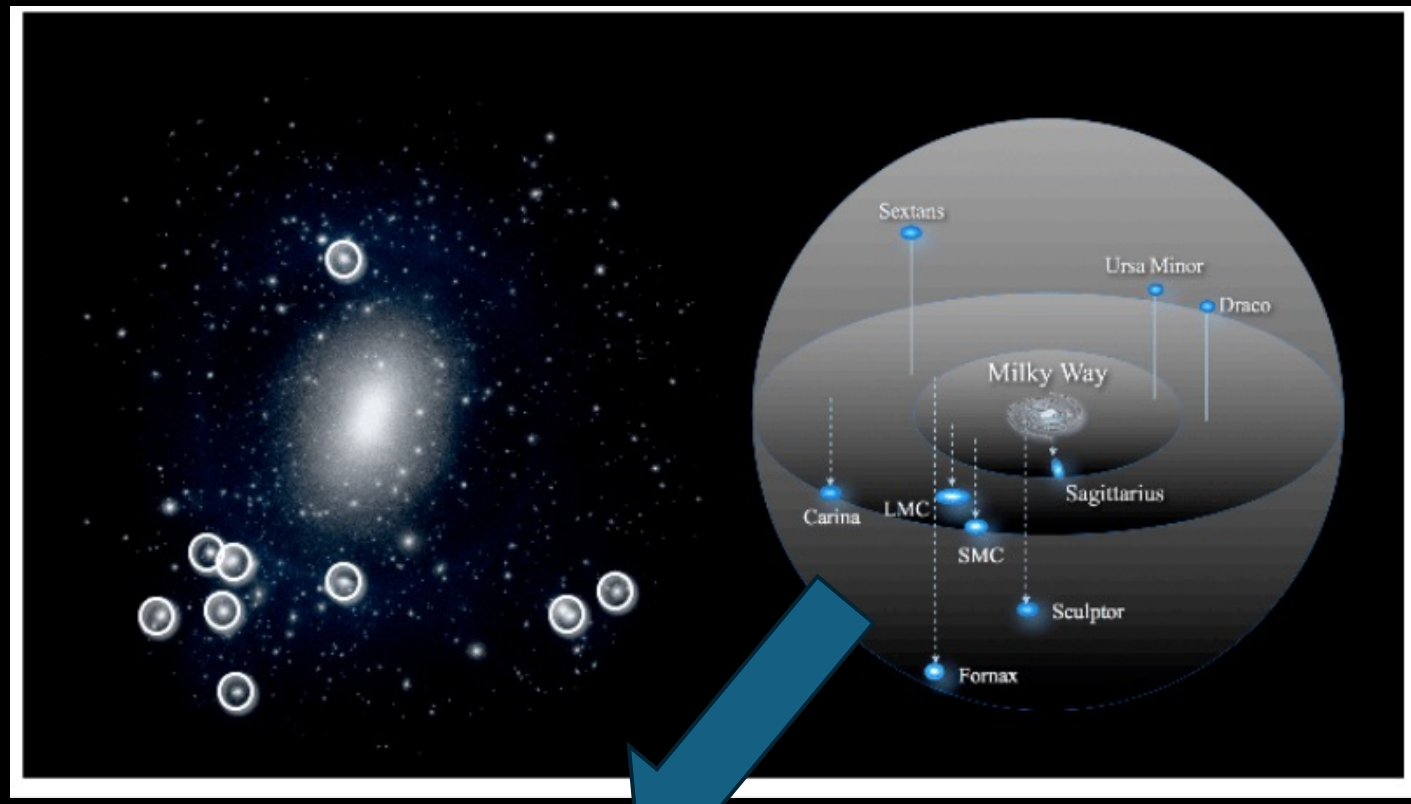
Could have more moderate star formation rate than standard cosmology model!

source: 2306.11993

[arxiv:2412.16072]

MW satellite galaxies can help constrain small scale !

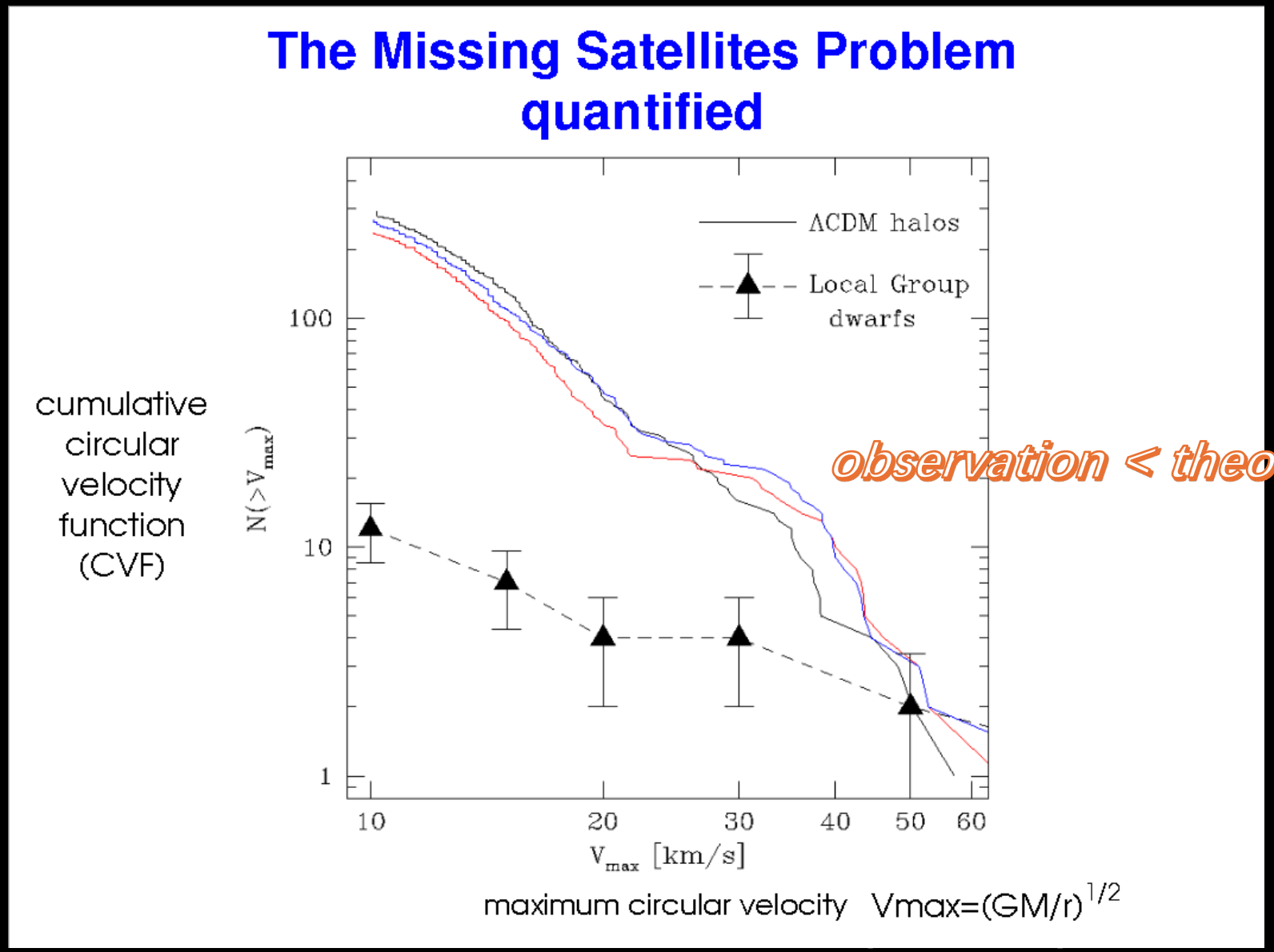
A **satellite galaxy** is a smaller galaxy that orbits around a larger galaxy due to gravitational forces



Milky-Way has $\gtrsim$50 satellite galaxies!

[arxiv:2412.16072]

The old *Missing Satellite Problem* in standard cosmology model

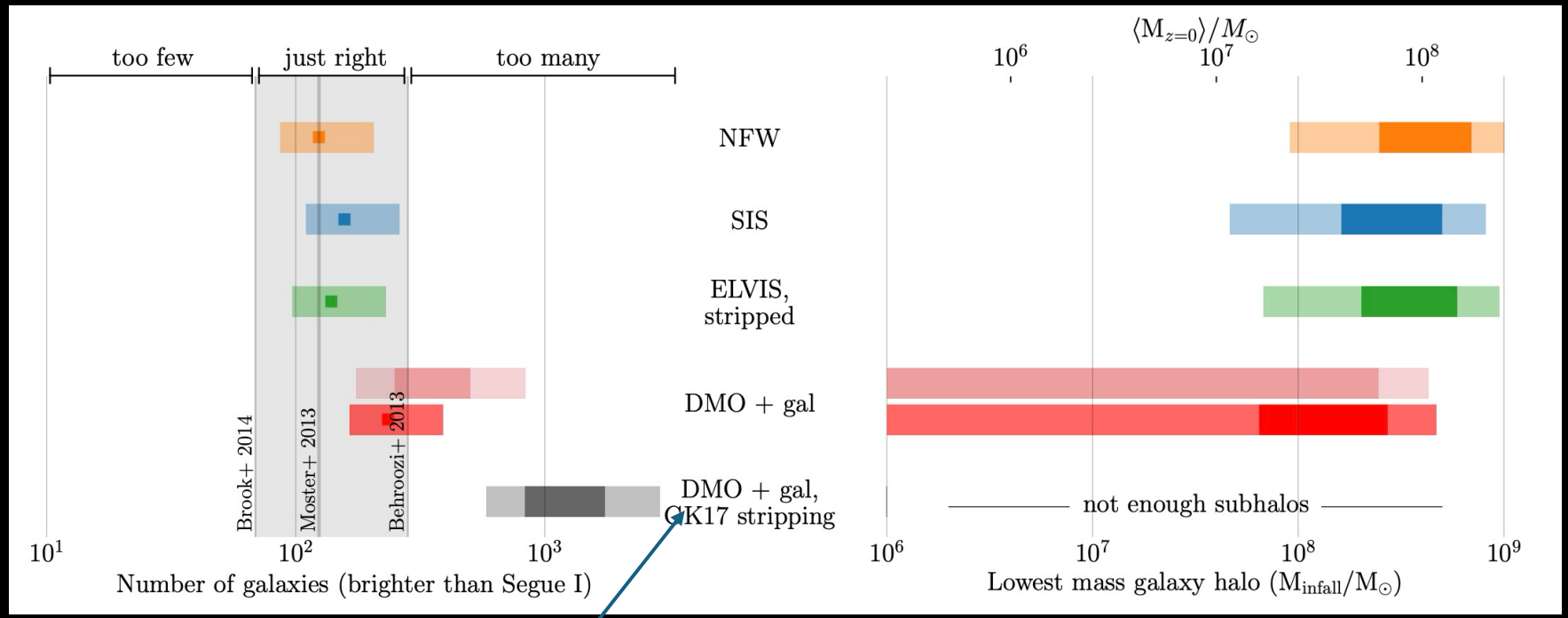


MSP:
observation < theoretical (simulation) prediction

source: astro-ph/0401088

Observation is underestimated!
Then Missing Satellite Problem->Too Many Satellites problem!

1. ***Reionization*** could prevent star formation
2. ***Completeness Check***: fainter satellite galaxy could only be observed within a much smaller radius/volume

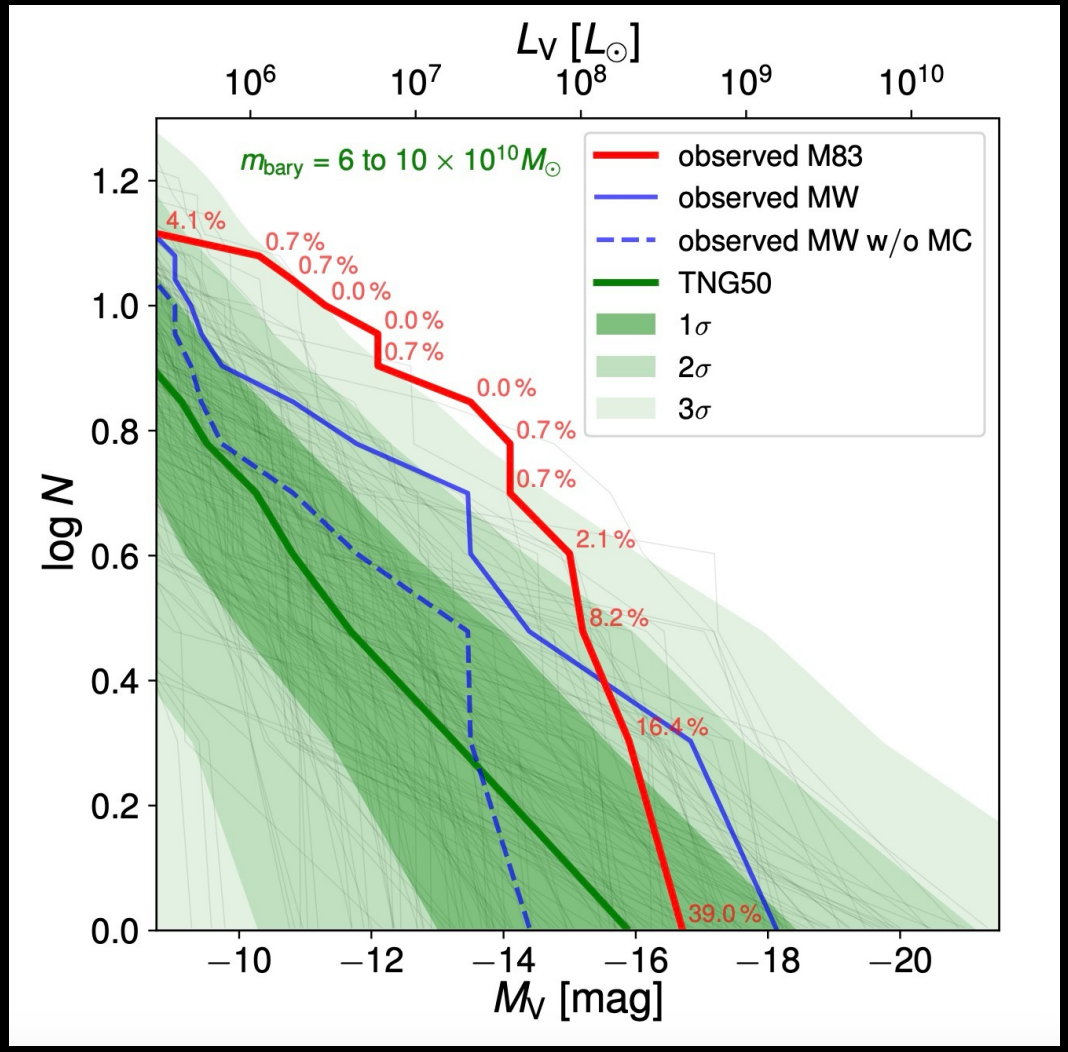


When considering the ***tidal stripping by central baryonic disk*** of MW, the satellites would be too many!

source: arxiv [1711.06267]

There are also direct observations for more satellite galaxies in nearby MW size galaxies!

Number of subhalos with luminosity higher than L



[arxiv:2412.16072]

M83 host dark matter halo is at the similar mass as MW's!

source: arxiv [2403.08717]

Change Power Law Primordial Power Spectrum->Broken Power Law!

- Larger spectral index at small scale end (large k), to give small scale enhancement!

old model

blue-tilted model

the growth factor. In the traditional single-field slow-roll inflation, the PPS follows the PL model:

$$P_i(k) \propto k^{n_s}, \tag{2}$$

with the spectral index $n_s \sim 0.96$ (see section III B 1).

Ref. [23] gave the following formalism for the BT models:

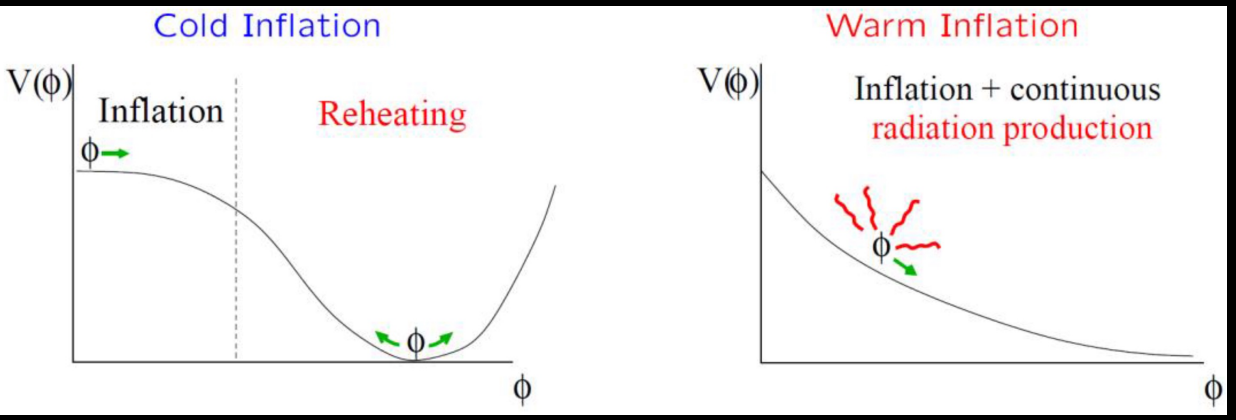
$$P_i(k) \propto \begin{cases} k^{n_s}, & (\text{for } k \leq k_p), \\ k^{n_s} \cdot \left(\frac{k}{k_p}\right)^{m_s - n_s}, & (\text{for } k > k_p), \end{cases} \tag{3}$$

which is a broken power law modification of Equation 2.

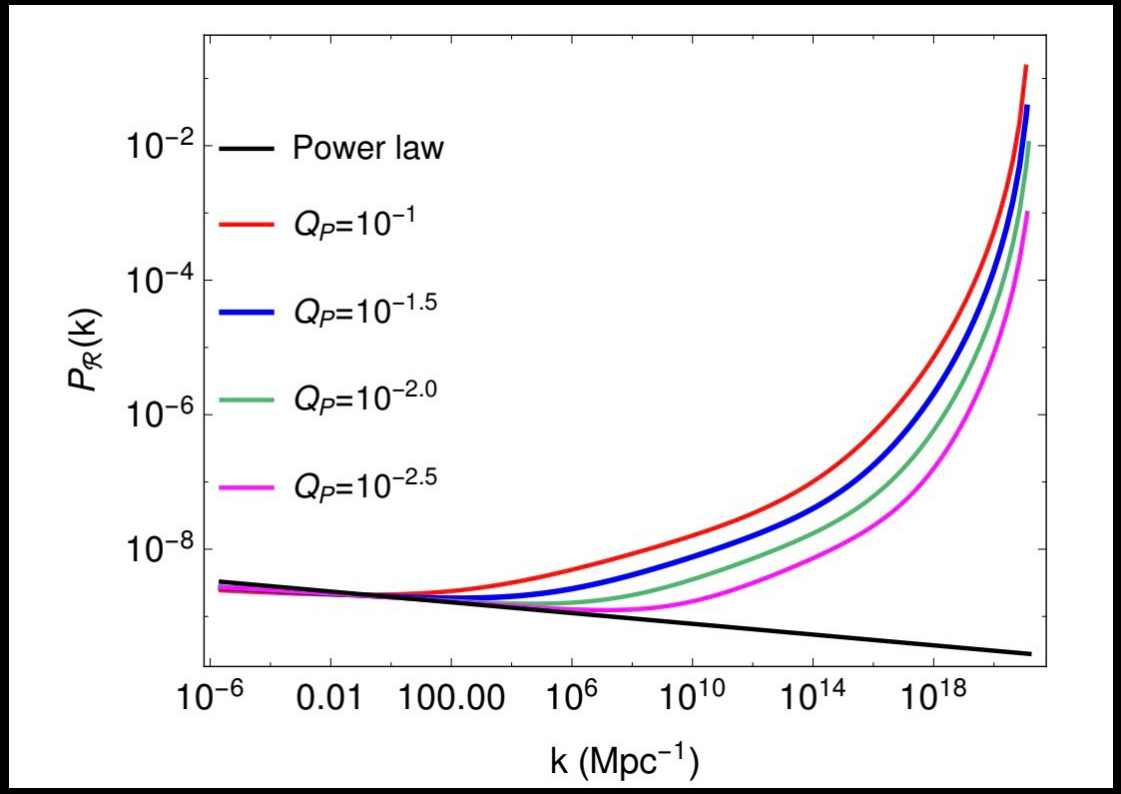
[arxiv:2412.16072]

There are already some inflationary scenarios producing small scale enhancement!

- ***Warm Inflation:***
  - There is a thermal bath which the scalar field could interact with
  - The power spectrum would have small scale enhancement!



(Berera et al. (2009)).



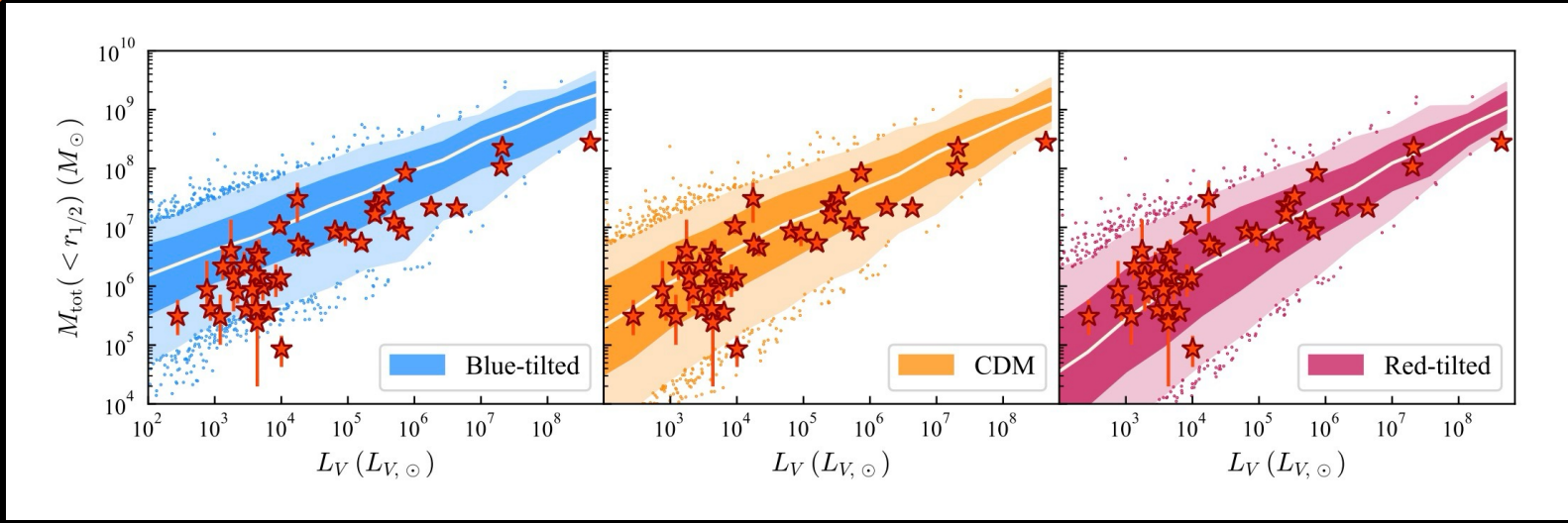
(Arya et al, JCAP02 (2018) 043)

[arxiv:2412.16072]

How to choose parameter sets?
Besides JWST, its hosting satellite galaxy's central density (concentration) could also constrain Primordial Power!

The mass within half-light radius

More power on small scale→
More concentrated subhalo→
Larger fraction of mass in inner region→
Larger Mtot(r<r1/2)!



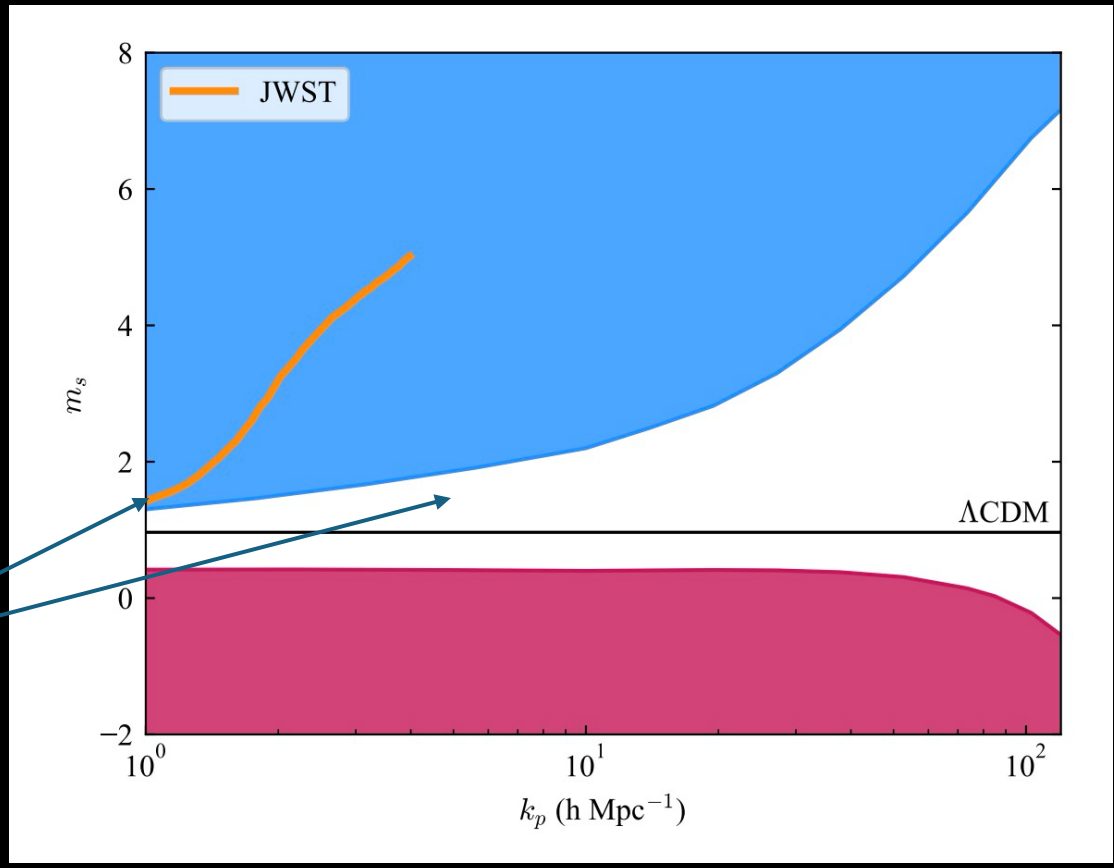
source: arxiv [2407.04198]
(similar approach as [2306.04674], but use blue-tilted formalism instead of lumpy dark matter one!)

[arxiv:2412.16072]

We chose two blue-tilted parameter sets within the allowable parameter space!

- One could ease the tension of high star formation rate brought by JWST, while another could not
- Both are within (or at least on the border of parameter space :))

source: arxiv [2407.04198]



Two BT models we chose!

[arxiv:2412.16072]

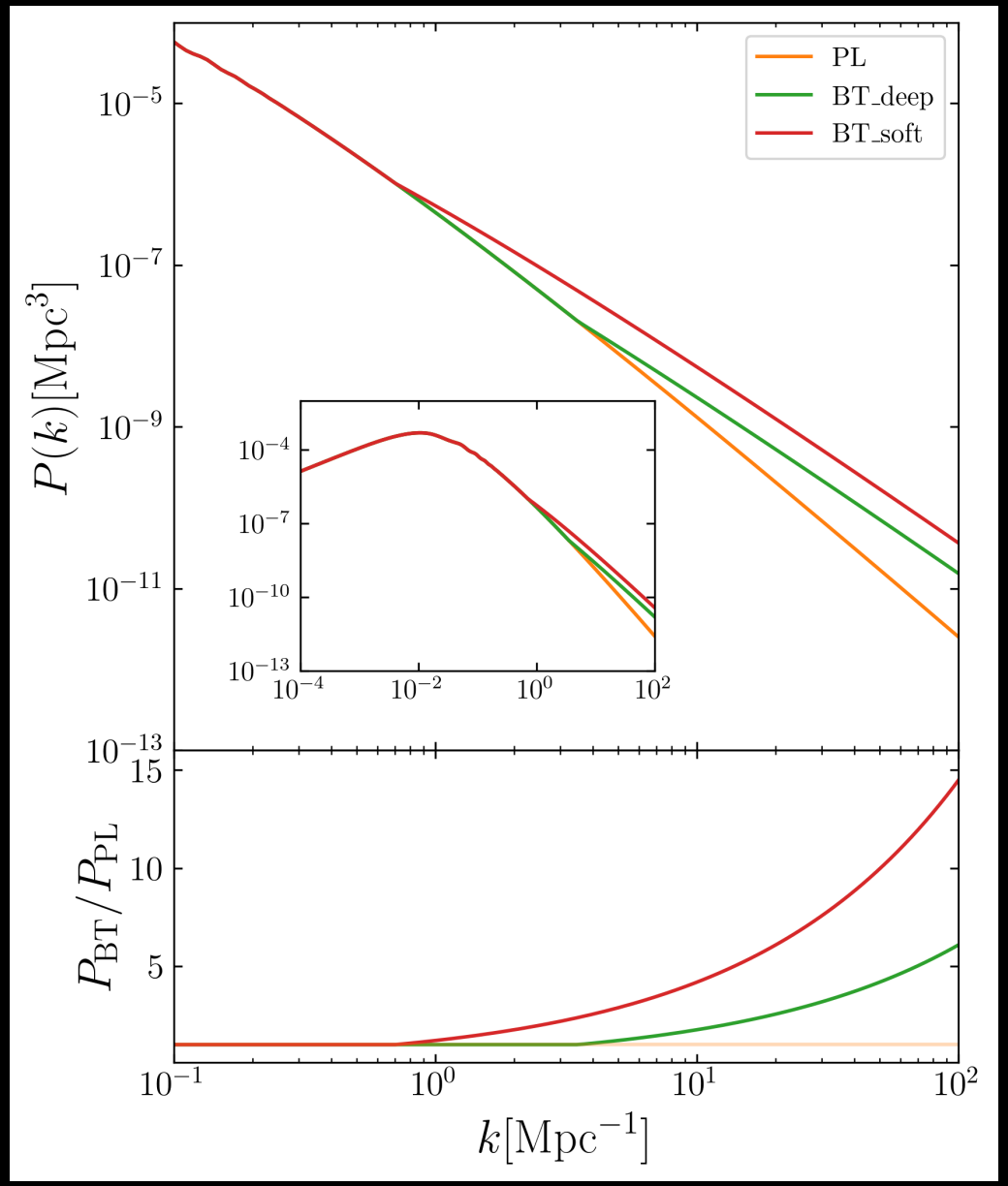
Two blue-tilted models

- We chose two sets of parameters for blue-tilted model (***BT model***), along with the standard model (power-law model aka ***PL model*** here)

Models	Related parameters
PL	Power Law Primordial Power Spectrum
	$n_s = 0.961$
BT_deep	$k_p = 3.51\ \mathrm{Mpc}^{-1}$ $m_s = 1.5$
BT_soft	$k_p = 0.702\ \mathrm{Mpc}^{-1}$ $m_s = 1.5$

TABLE I. The parameters of all the chosen models. k_p is the wave vector at which the BT PPS would deviate from the PL PPS. m_s is the enhanced spectral index for $k > k_p$, at the small scales. For other cosmological parameters, see section III B 1.

[arxiv:2412.16072]



Broken point's scale corresponds to a cosmic structure mass scale

- k_p should correspond to a mass scale for cosmic structure, only below which blue-tilted model could affect.
- How to get it?
  - wave number k_p ->
  - wave length λ->
  - A sphere whose radius $r_l = \frac{1}{2}\lambda$

$$M_l = \frac{4\pi}{3} r_l{}^3 \rho_m = \frac{\Omega_m H_0^2}{2G} r_l^3$$
$$= 1.71 \times 10^{11} \left(\frac{\Omega_m}{0.3}\right) \left(\frac{H_0}{70}\right)^2 \left(\frac{r_l}{1\ \mathrm{Mpc}}\right)^3 \ \mathrm{M}_\odot. \quad (4)$$

[arxiv:2412.16072]

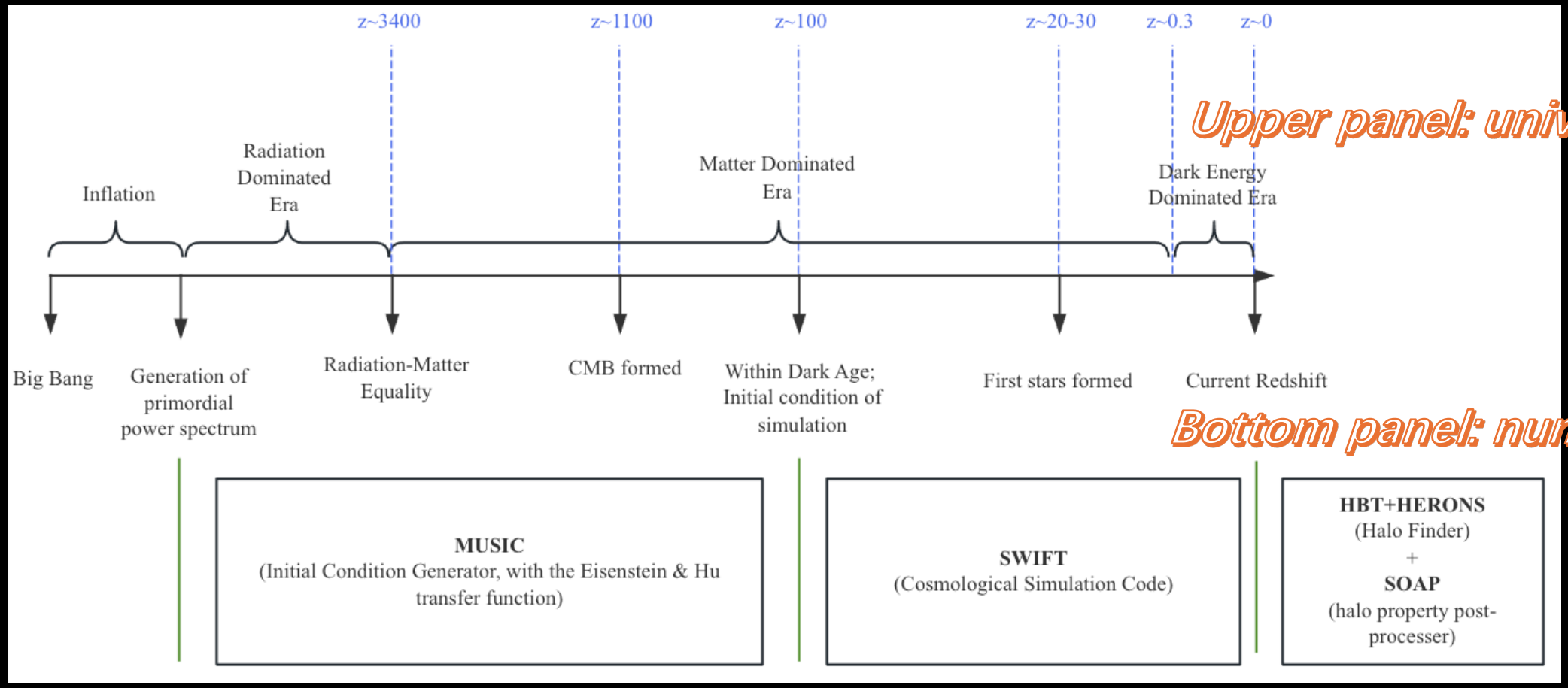
For BT_deep: $1.1\times10^{11} M_\odot$

For BT_soft: $1.4\times10^{13} M_\odot$

Both could cover the mass scale for most dark matter subhalos in MW host ($10^{12} M_\odot$)!

Numerical pipeline we used

- After changing the primordial power spectrum, then use cosmological simulation to evolve to current redshift!



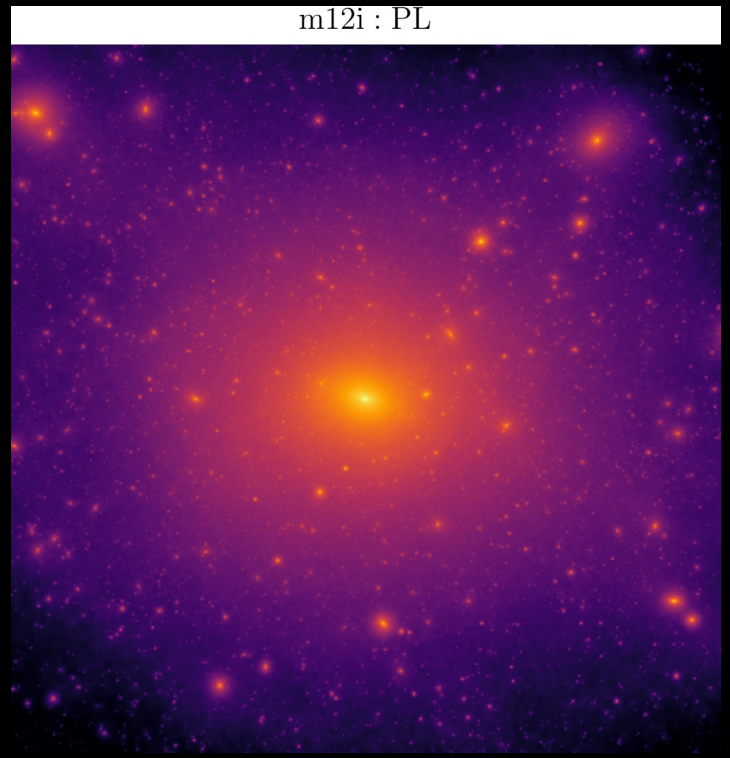
Upper panel: universe history

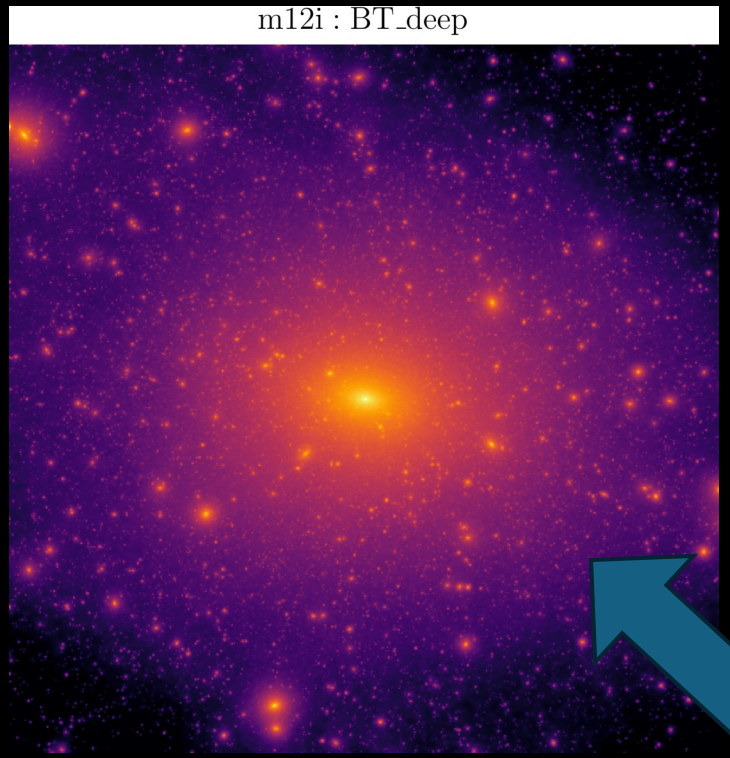
Bottom panel: numerical codes

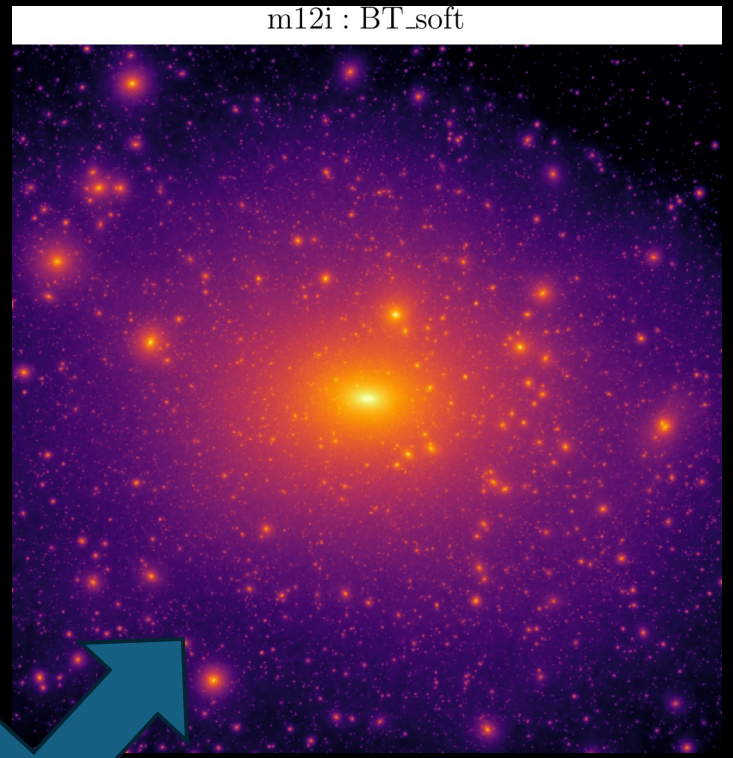
[arxiv:2412.16072]

Intuitive way: projection map showing more subhalos

- **dark matter 2D projection map, with side length 400 kpc**







[arxiv:2412.16072]

Both BT models give more subhalos than power-law!

In terms of mass and maximum circular velocity(Vmax)

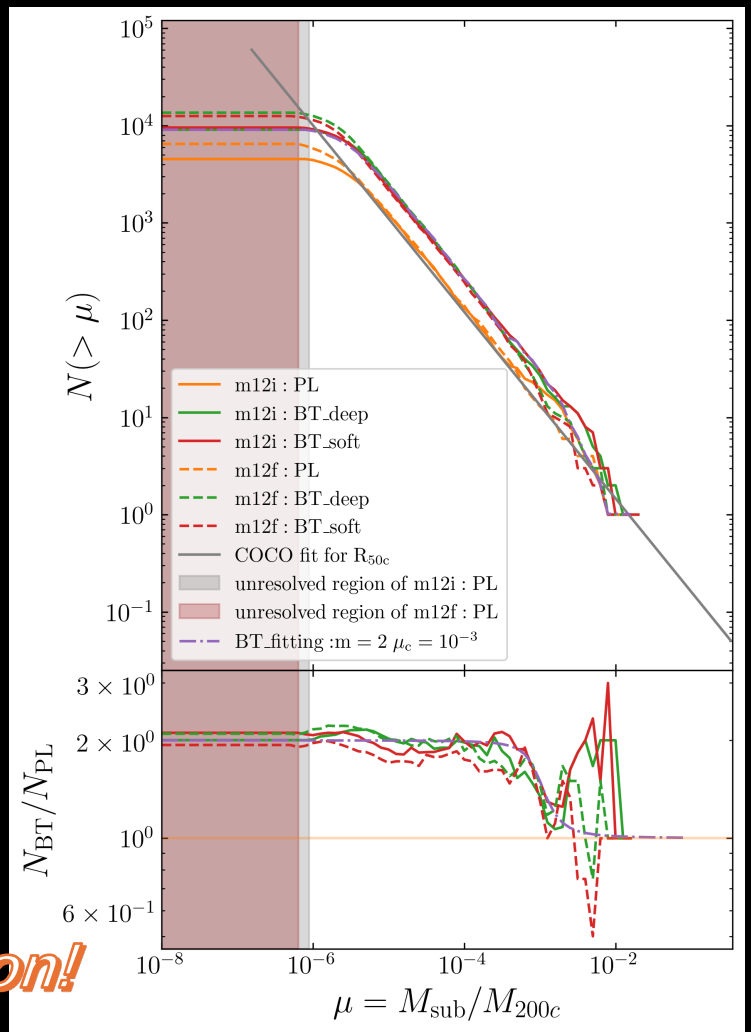
- **subhalo function(aka subhalo number distribution) by mass or Vmax**
  - **subhalo mass function could be enhanced by a factor of two at low mass end**
  - **subhalo Vmax function could be enhanced by more than 3 times at low Vmax end**

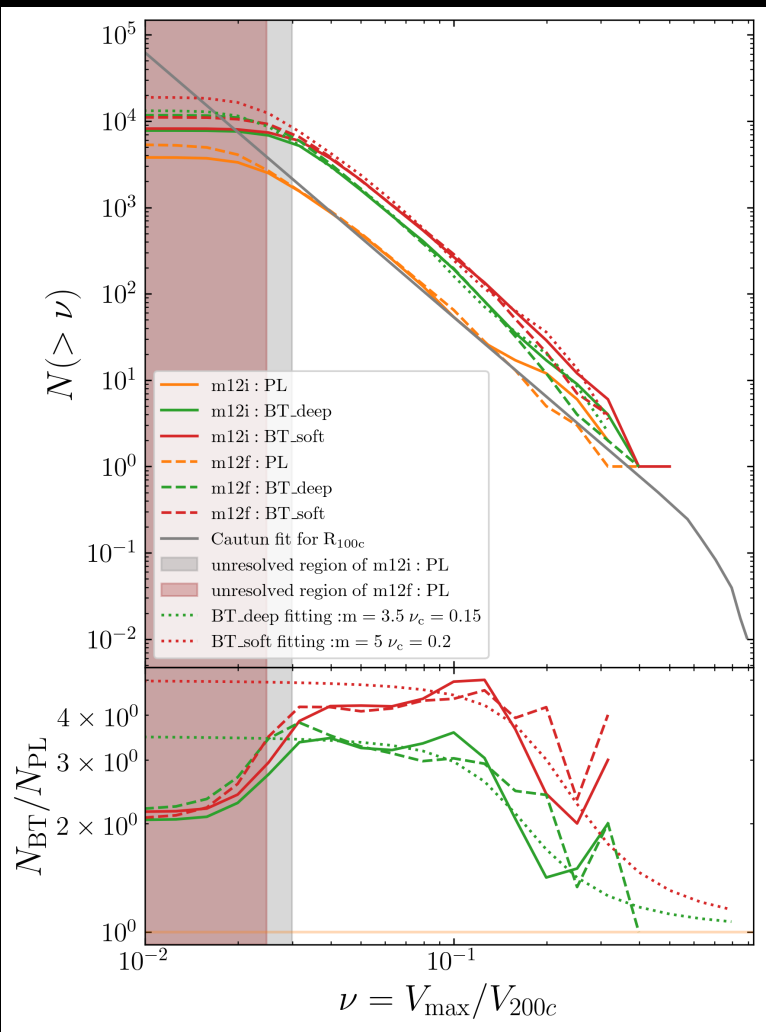
scaled mass

scaled Vmax

Number of subhalos

Ratios between numbers





The ratio for both functions, observes an inverse S shape function!

In terms of radial distance

- radial distance ***from the center of main halo***

  - At inner region of main halo, normalized number density nearly doubled

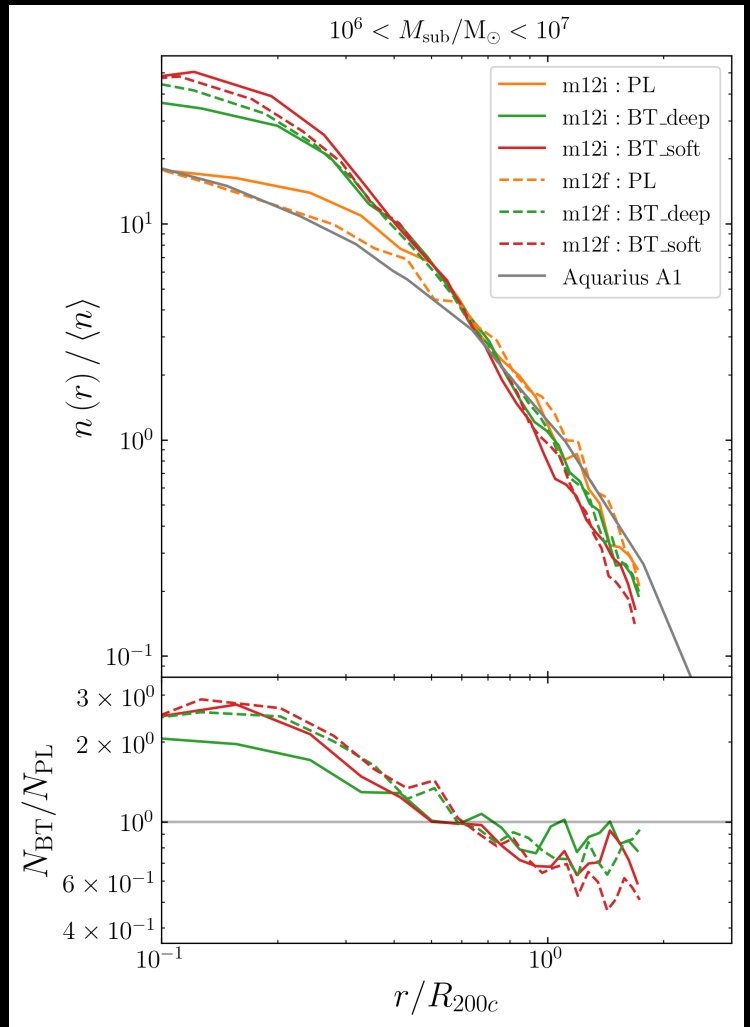
Grey lines are the same for different mass! (Found by Aquarius simulation [arxiv0809.0898])

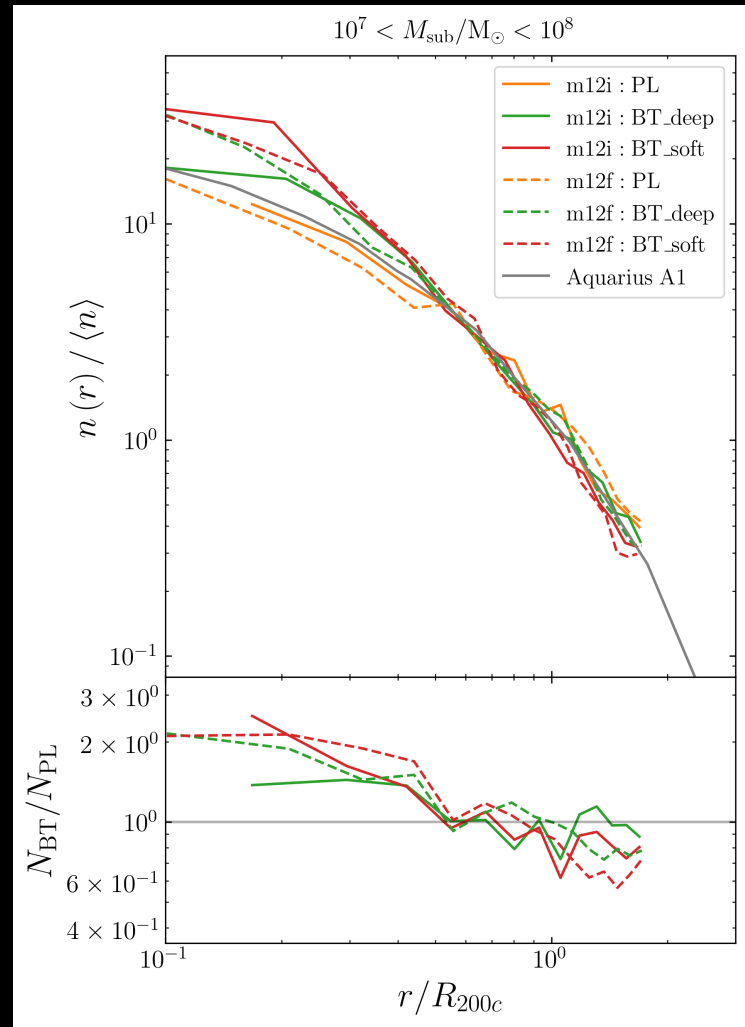
scaled radial distance

scaled radial distance

Normalized number density

Ratio(BT over PL)

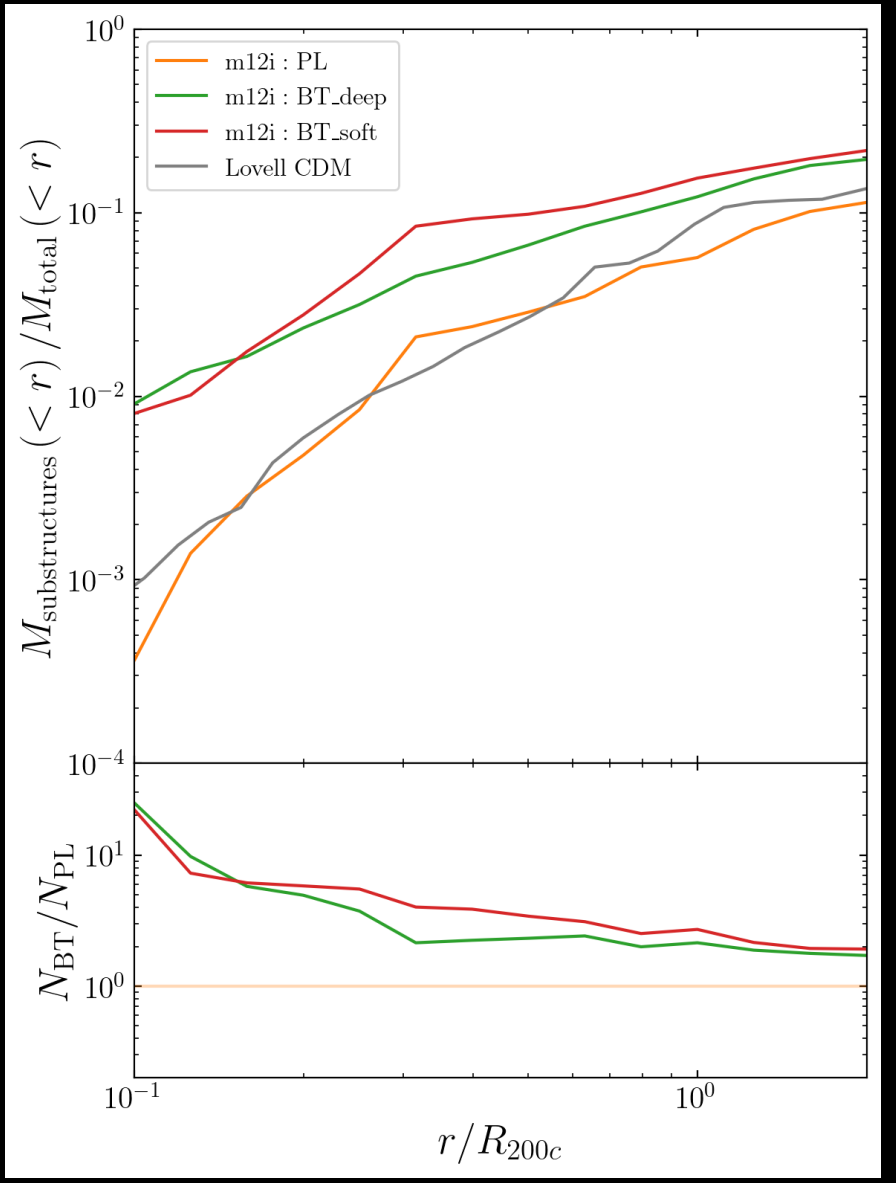




Larger substructure mass fraction!

- substructure mass fraction:
  - Defined as *mass of particles belonging to substructures(within radius r)/total mass(within radius r)*
  - CDMO simulation is insufficient to explain strong lensing result (arxiv [0903.4559])
  - Blue-tilted model could reach an order of magnitude enhancement compared to traditional model

scaled radial distance



Substructure Mass Fraction

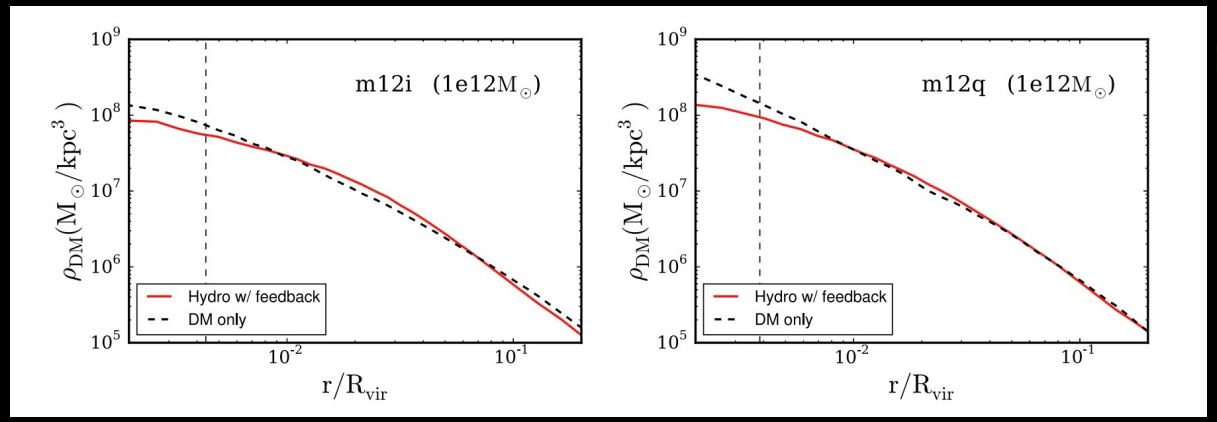
Ratio(BT over PL)

[arxiv:2412.16072]

Main halo becomes more concentrated…

But it doesn't matter!

That is because we are doing dark-matter-only simulation. The core-cuspy problem could be solved by baryonic physics under full hydro simulation!

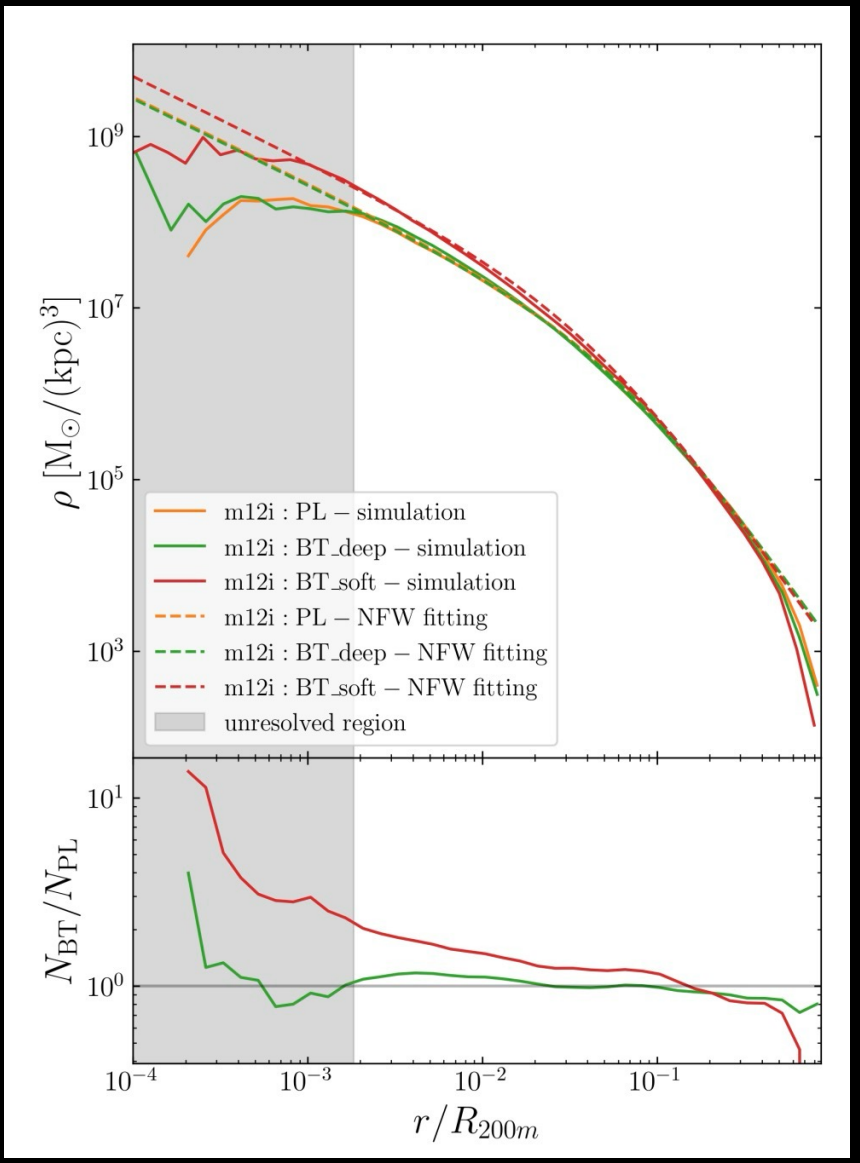


source: arxiv [1507.02282]

radial density

Ratio(BT over PL)

scaled radial distance



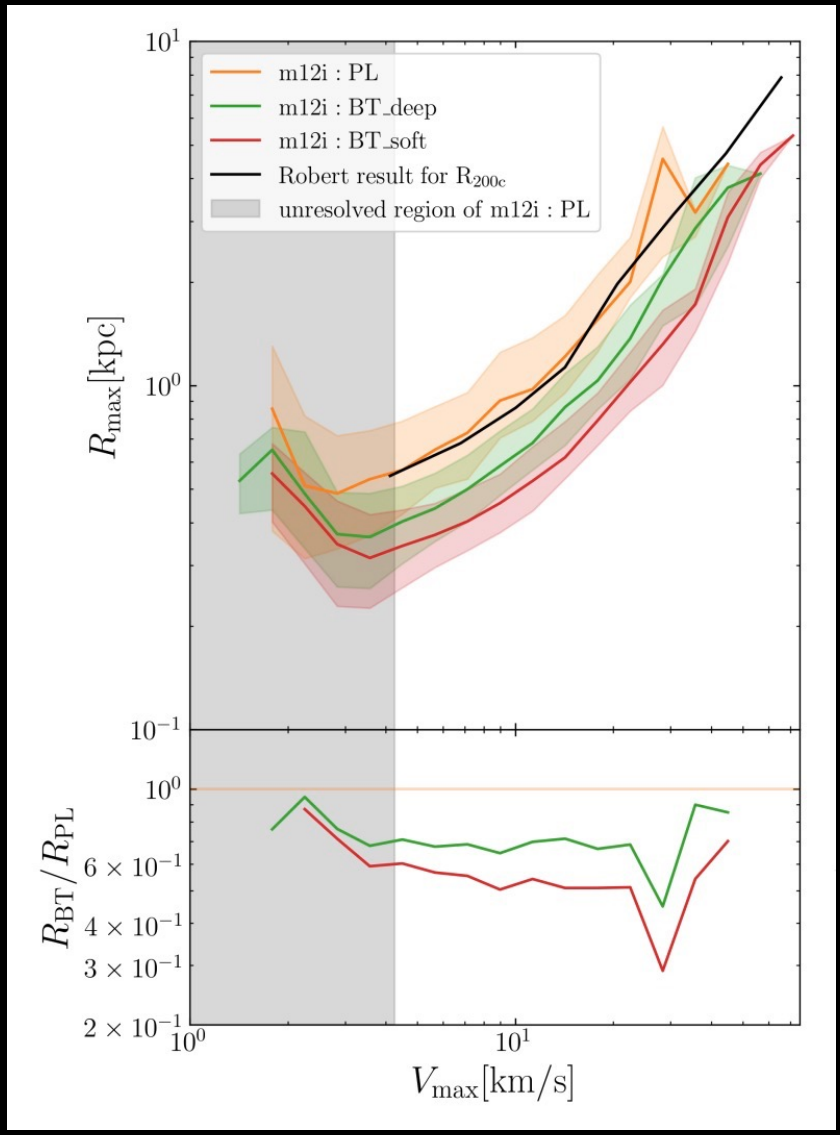
[arxiv:2412.16072]

subhalo also becomes more concentrated

But it should be fine!

Since our parameter choices are permitted by arxiv [2407.04198], that is the constraint from *central density/concentration/central mass*!

Maximum circular velocity



The median Rmax within this Vmax bin

Ratio(BT over PL)

[arxiv:2412.16072]

Conclusion

- We use cosmological simulation to show that a small scale enhanced early universe model could indeed generate more substructure, potentially help to the small scale debate in cosmology:
  - More subhalos in terms of mass, Vmax and distance
  - Larger fraction of substructure mass

- Now we are working on a follow-up project of the first: introducing baryonic disk potential, and then use observed satellite galaxies to constrain the early universe cosmology.

[arxiv:2412.16072]