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

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Based on Paper: Cosmological Zoom-In Simulations of Milky Way Host Mass Dark Matter Halos with a Blue-Tilted Primordial Power Spectrum
Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16072]

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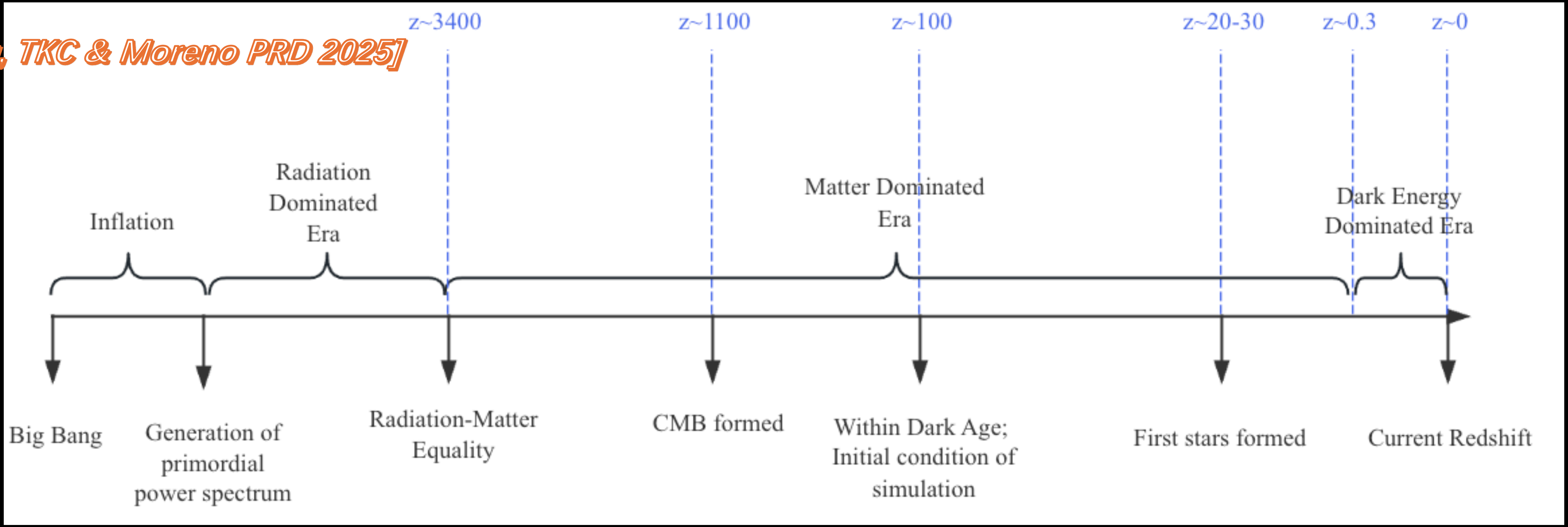
1. Background and Motivations

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

[Wu, TKC & Moreno PRD 2025]



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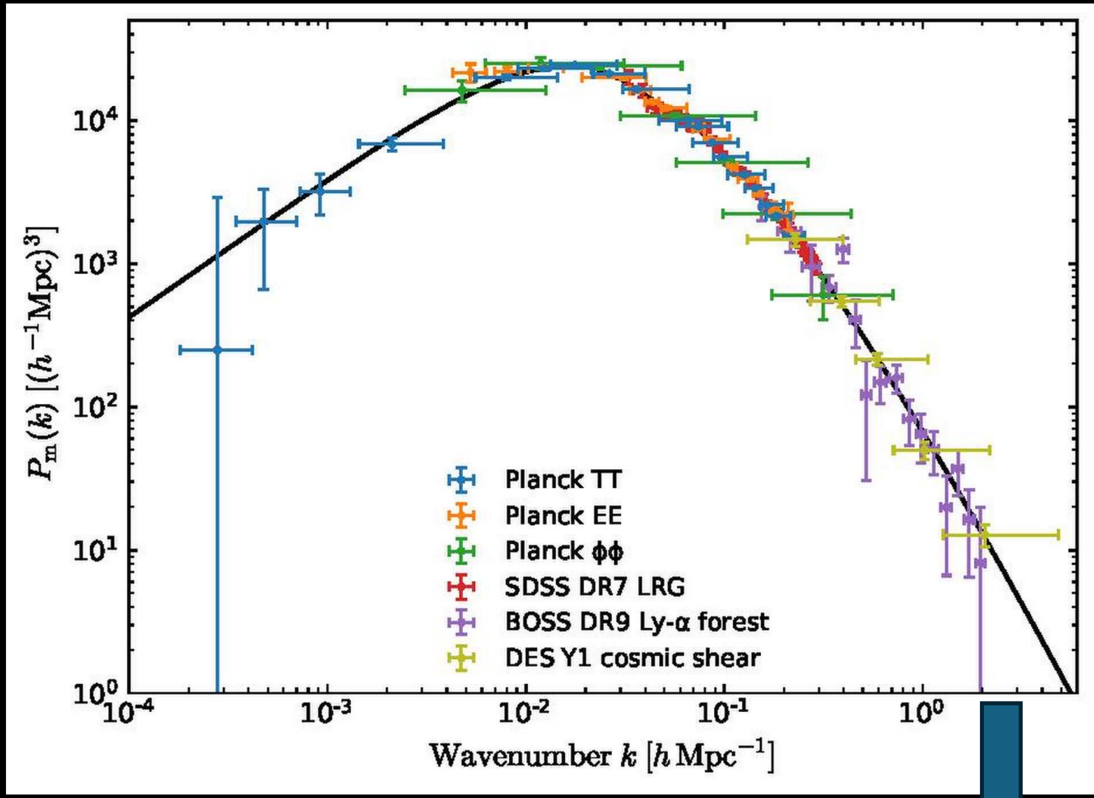
Uncertain at small scales

- 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

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A small-scale enhanced or suppressed?

- There is *already a paper* using a small scale enhanced primordial power spectrum to explain the ***early formed massive galaxies in JWST***
- **Besides**, several **other** observations are in favor of ***a small scale enhanced*** cosmological model—we are trying to address them!
    - 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])+ *over-concentrated subhalo event* is detected (SDSSJ0946+1006, i.e. "Jack Pot" lensing event)
    - A *too-many-satellite-galaxies* problem appeared in nearby galaxy observation (arxiv [1711.06267] [2403.08717])

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

[Shingo Hirano, Naoki Yoshida 2023]

Green region is from JWST

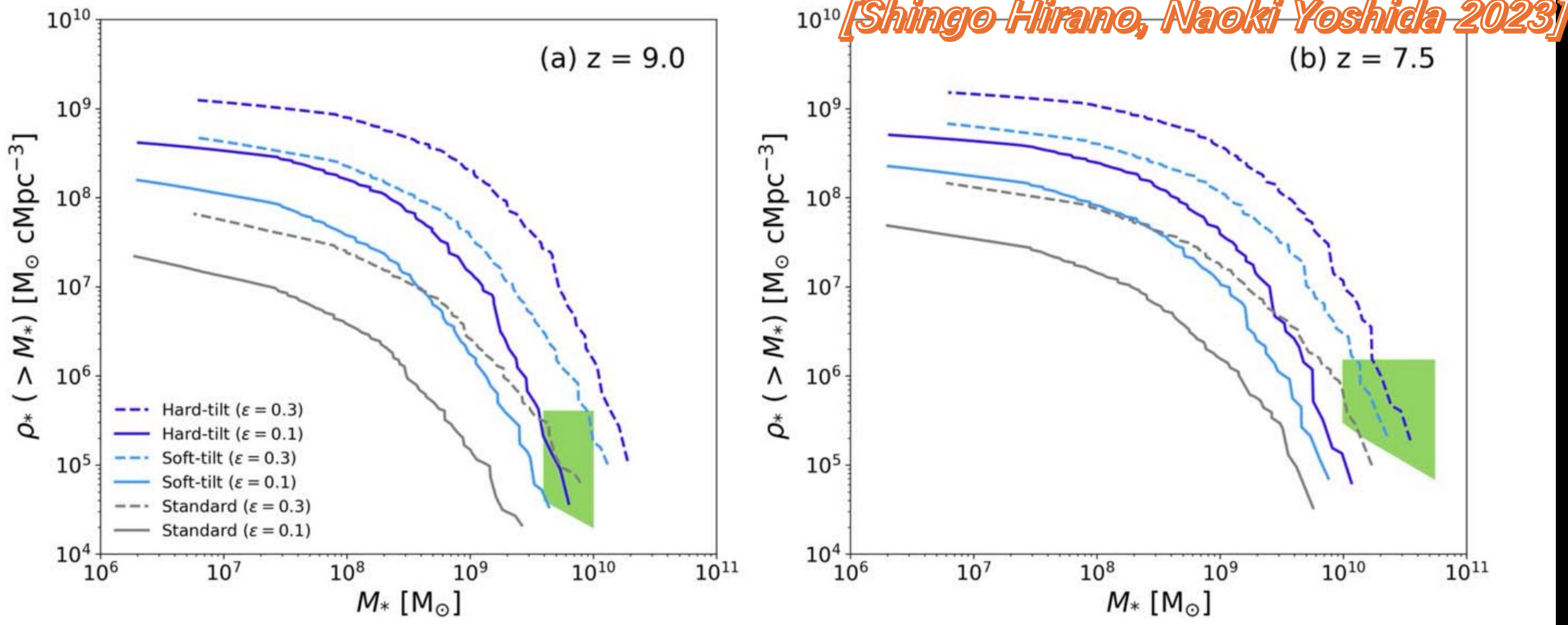

Figure 4. Cumulative comoving stellar mass density for the standard (gray), soft-tilt (light blue), and hard-tilt (blue) models at (a) $z = 9$ and (b) $z = 7.5$. We adopt a moderate star formation efficiency of $\epsilon = 0.1$ (solid lines) and 0.3 (dashed). The green regions are the CCSMD adopted from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

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

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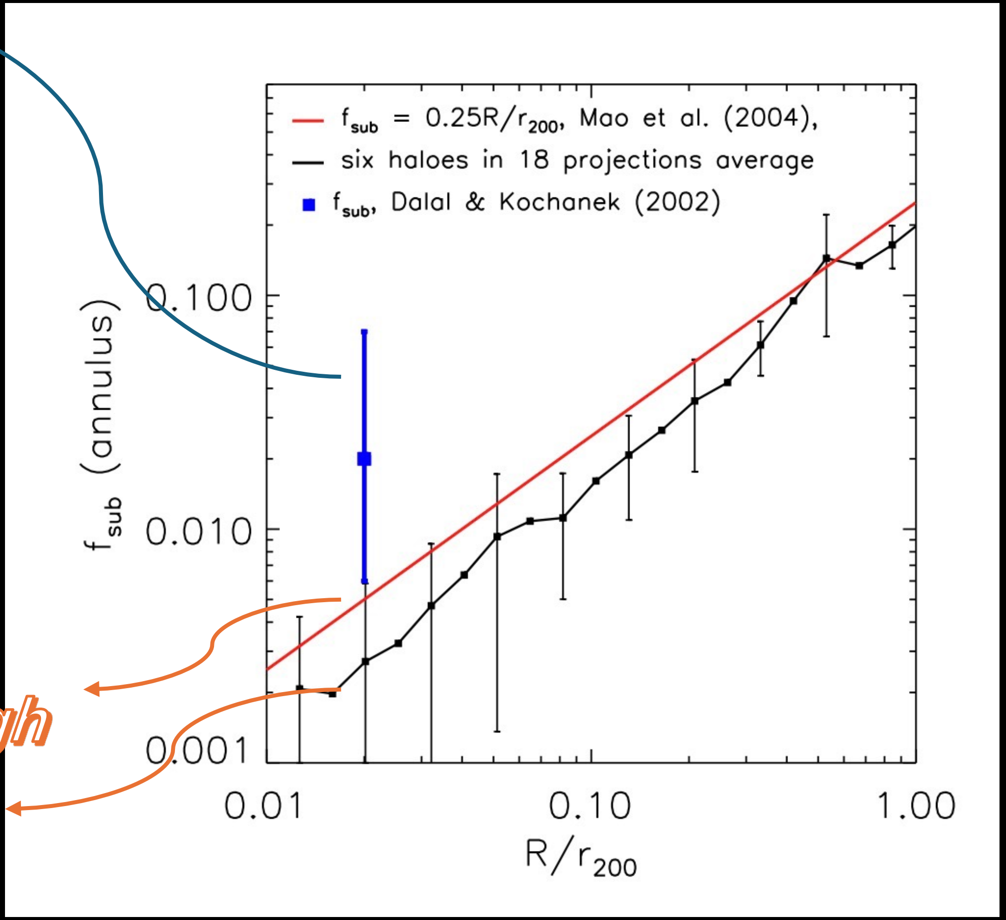
“anomalous” flux ratio problem

From strong lensing

The flux ratio anomalies in strong lensing was expected to be solved by high-resolution simulations for CDM halos, as the substructure would appear **if the resolution is high enough**

But it failed

[D. D. Xu , Shude Mao et al 2009]



From LCDM N-body high resolution simulation

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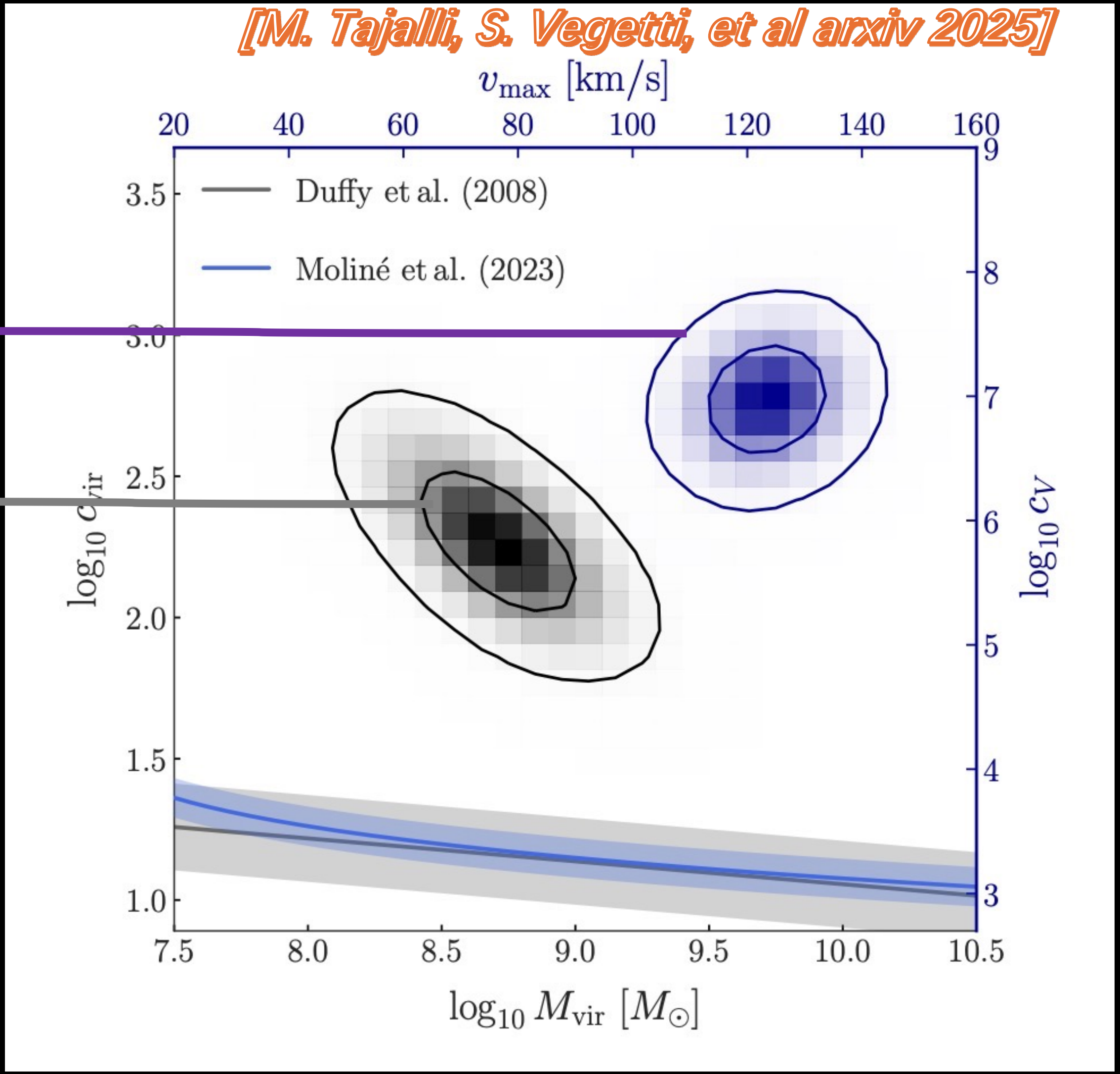
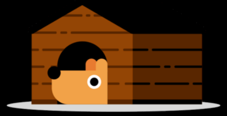
over-concentration event

- There are several reports for over-concentrated halos/subhalos in strong lensing:
  - J0946+1006: a subhalo with 12 sigma deviation from subhalo C-M relation
  - B1938+666: a field halo with 4 sigma deviation from field halo C-M relation





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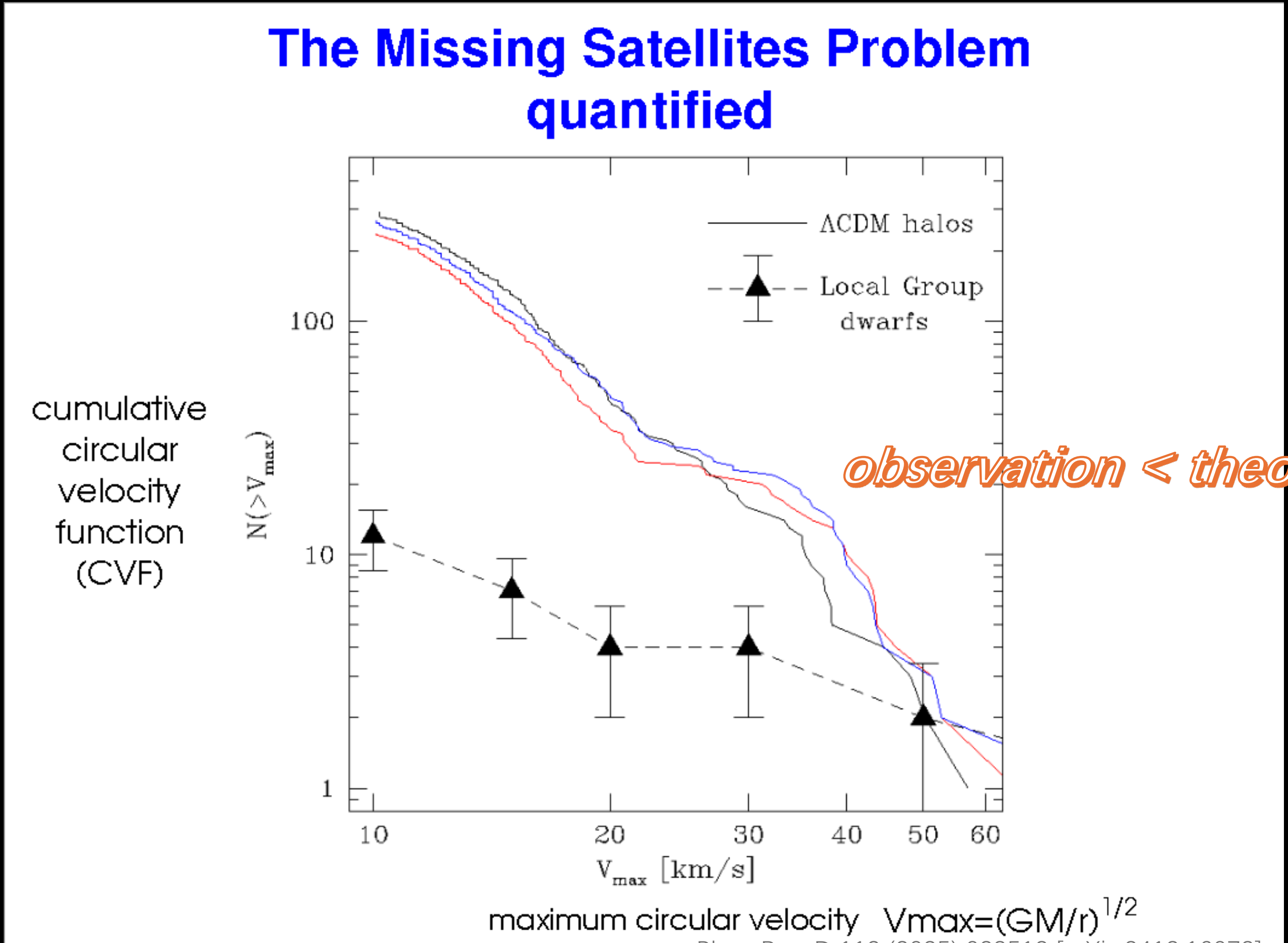
The old *Missing Satellite Problem* in standard cosmology model



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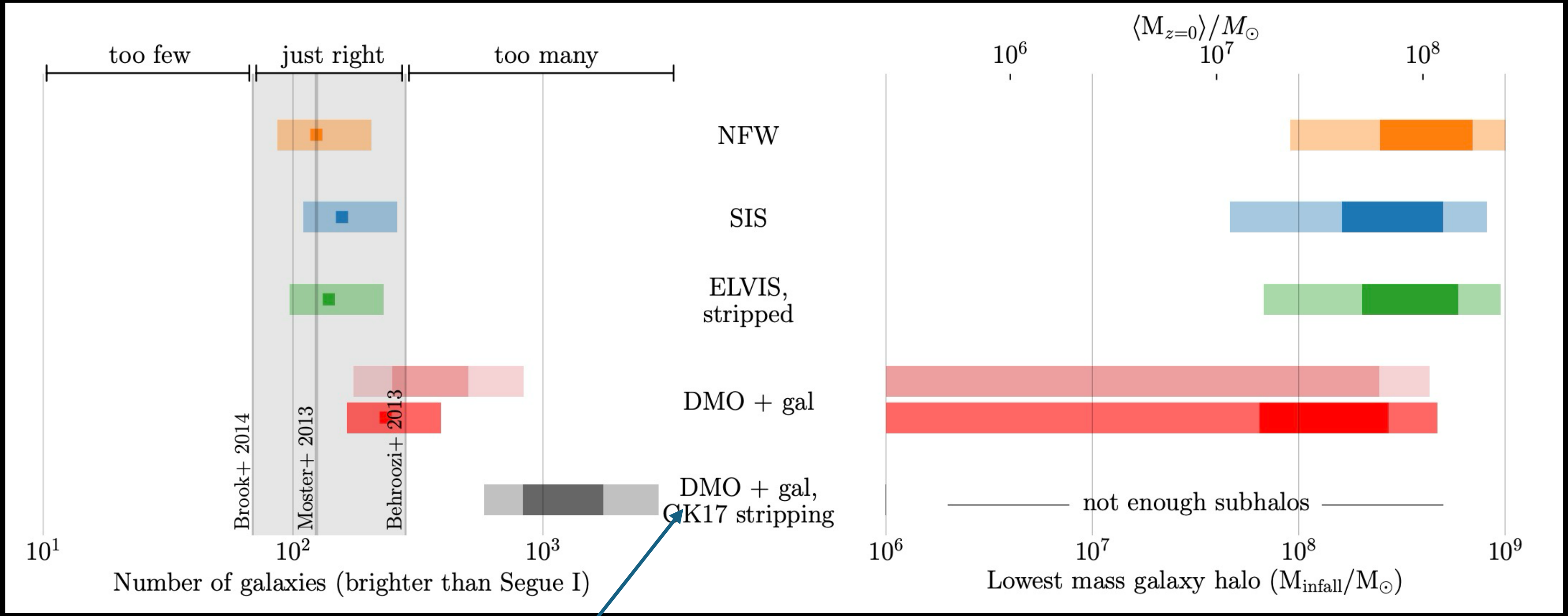
MSP:
observation < theoretical (simulation) prediction

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!

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source: arxiv [1711.06267]

2. To solve the Too-Many-Satellites Problem

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

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

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

old 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:

blue-tilted model

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

which is a broken power law modification of Equation 2.

[Wu, TKC & Moreno arxiv 2024]

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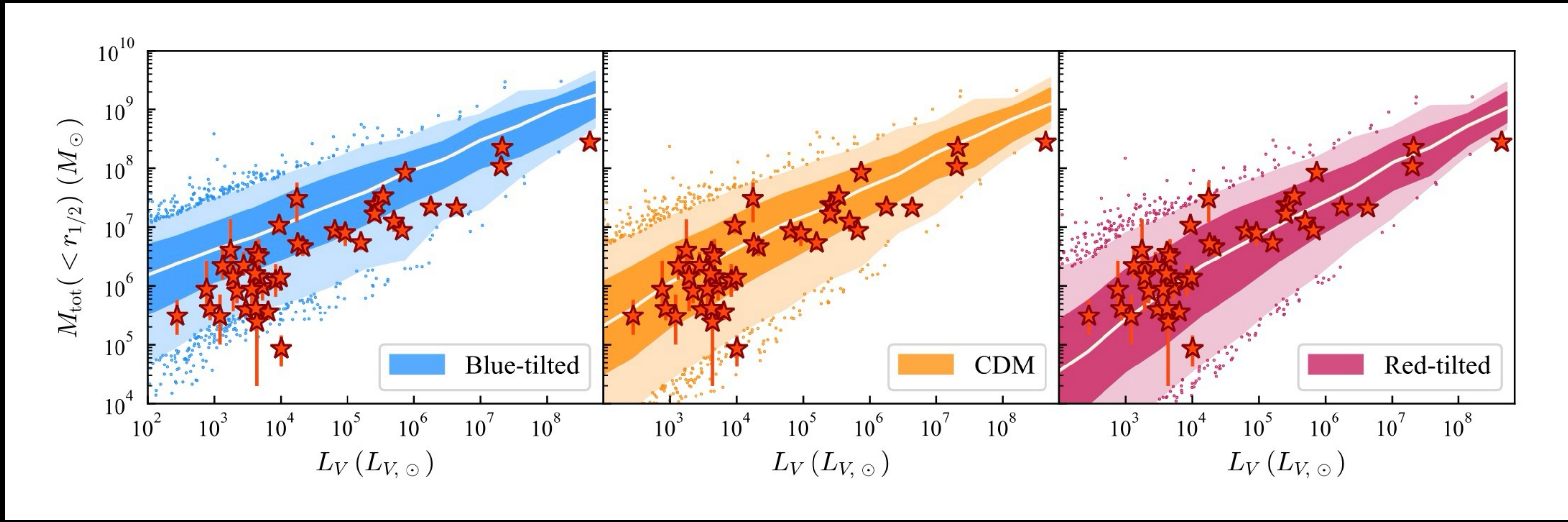
How to choose parameter sets?
Besides JWST, its hosting satellite galaxy's central density (concentration) could also constrain Primordial Power!

They assume:

"the main effect of the change is on the halo concentration, while galaxy evolution is assumed to be unaffected."



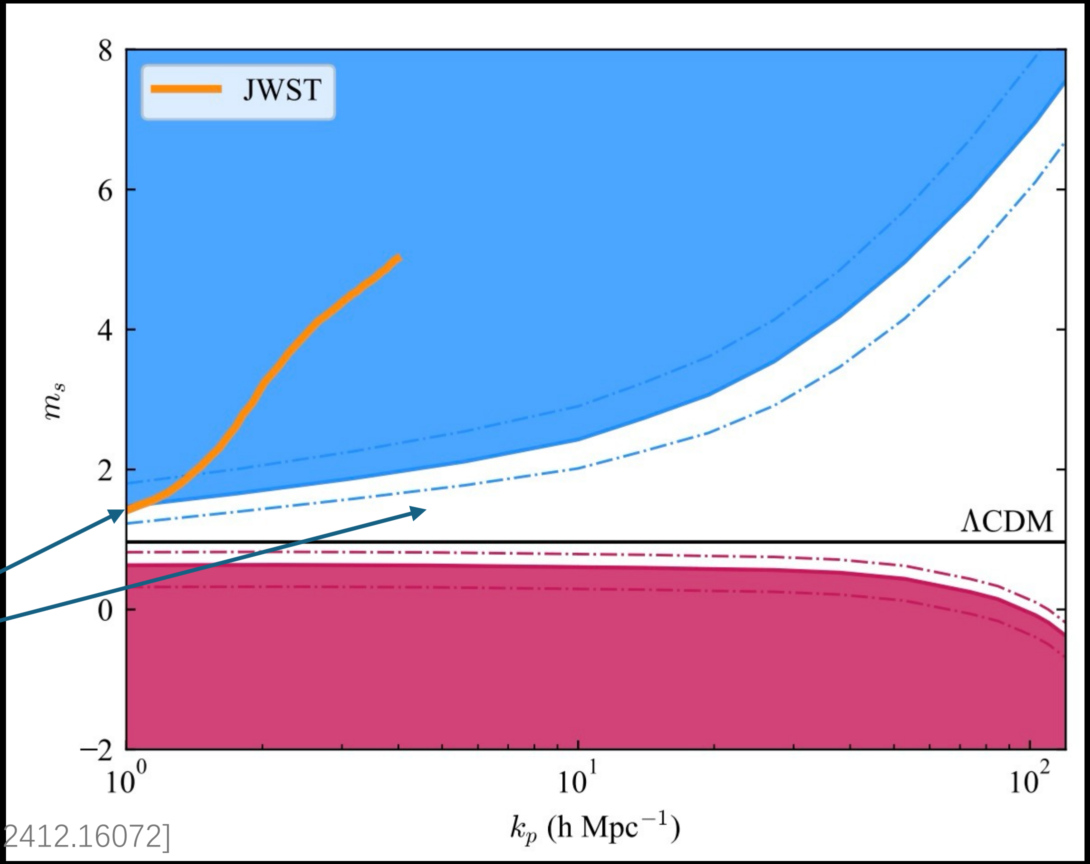
source: arxiv [2407.04198]

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!



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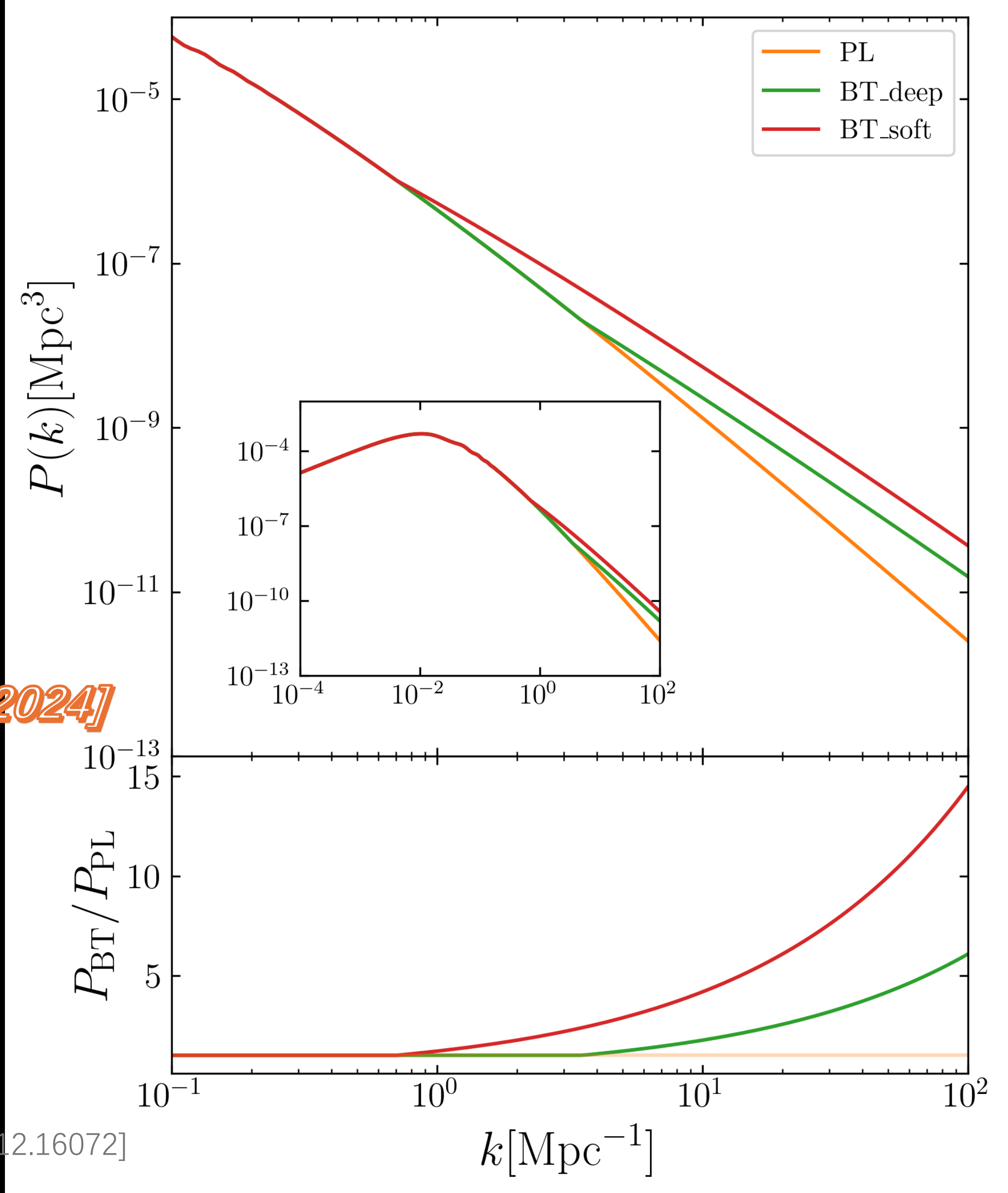
Two blue-tilted models

- 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.

[Wu, TKC & Moreno arxiv 2024]



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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 $r_l = \frac{1}{2}\lambda$

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

For BT_deep: $\mathbf{1.1 \times 10^{11} M_\odot}$

For BT_soft: $\mathbf{1.4 \times 10^{13} M_\odot}$

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

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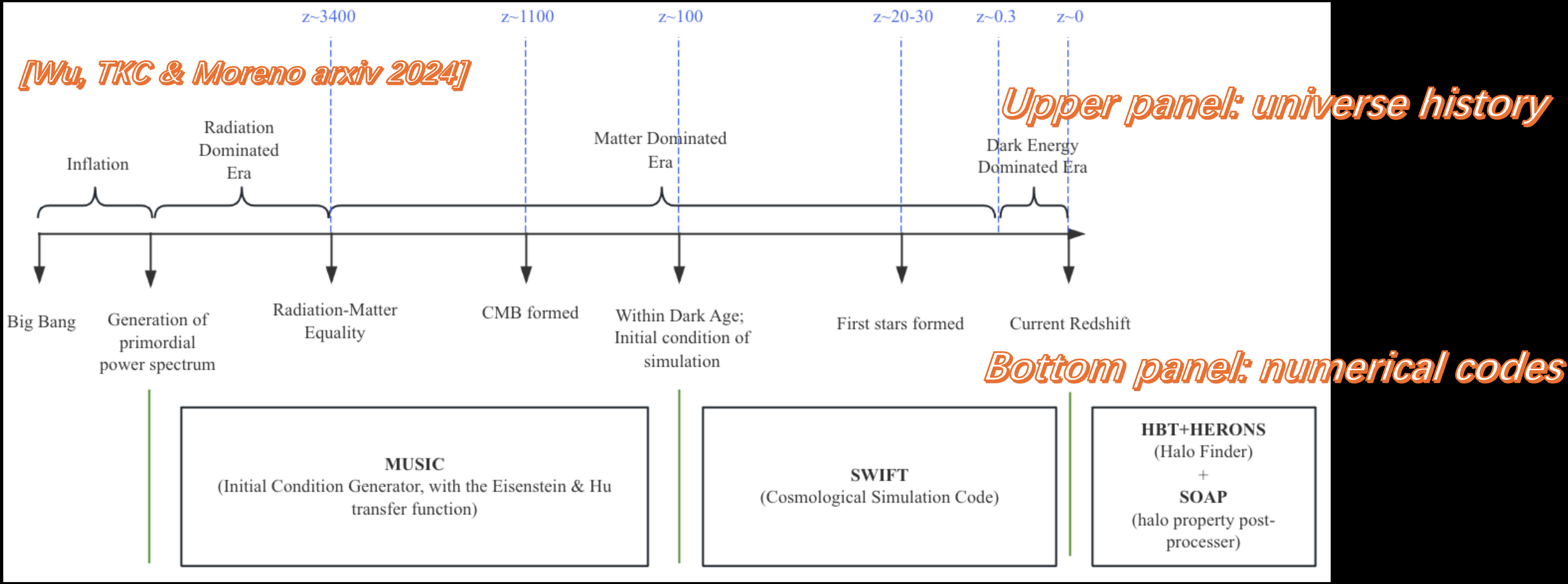
Numerical pipeline we used

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



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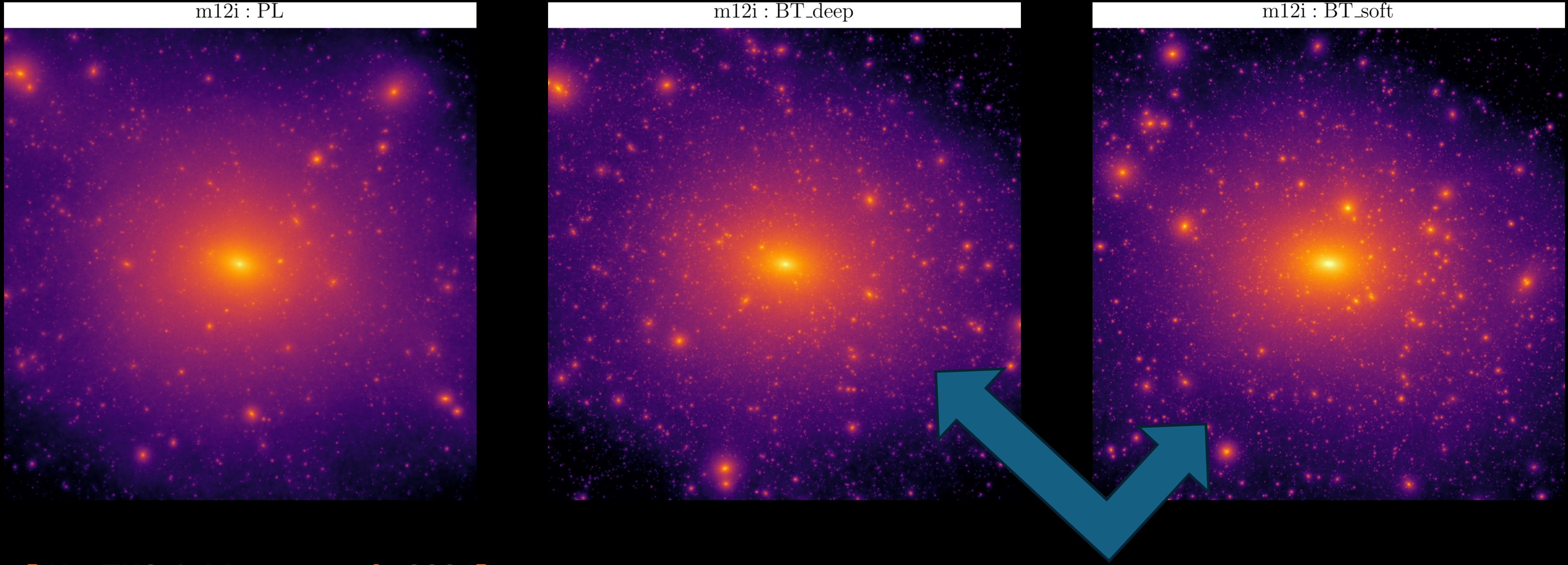
Intuitive look: projection map

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



[Wu, TKC & Moreno arxiv 2024]

Both BT models give more subhalos than power-law!

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To help the Too-Many-Satellites (Mass/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

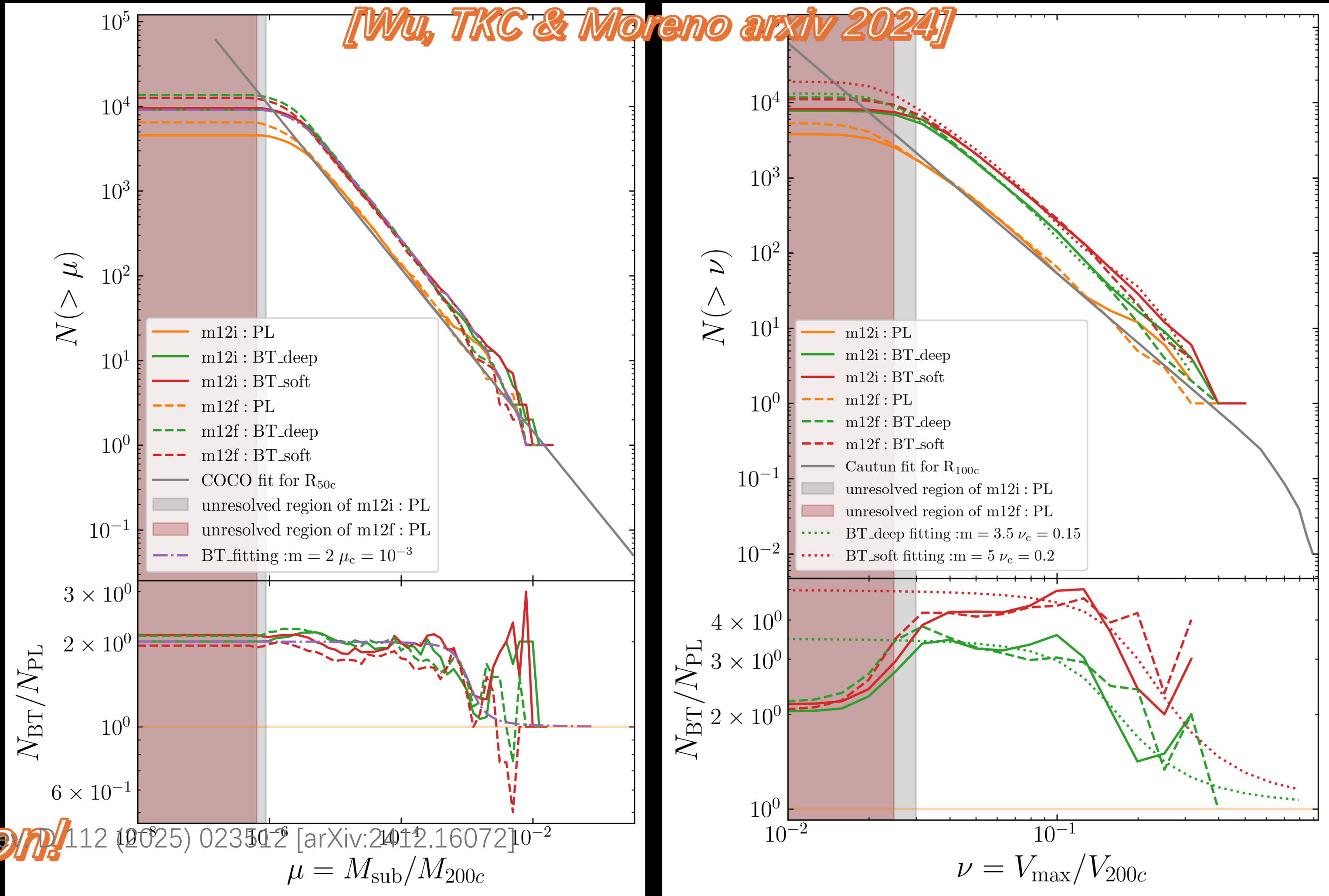
scaled mass

scaled Vmax

[Wu, TKC & Moreno arxiv 2024]

Number of subhalos

Ratios between numbers



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

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To help the Too-Many-Satellites (radial distance)

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

[Wu, TKC & Moreno arxiv 2024]

scaled radial distance

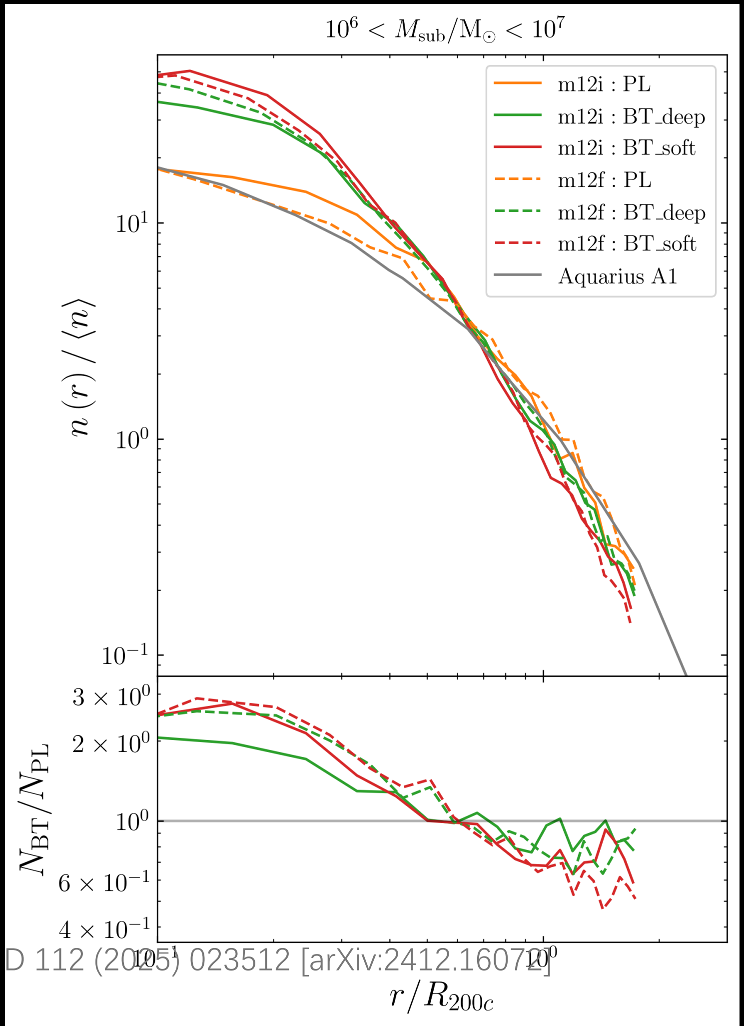
scaled radial distance

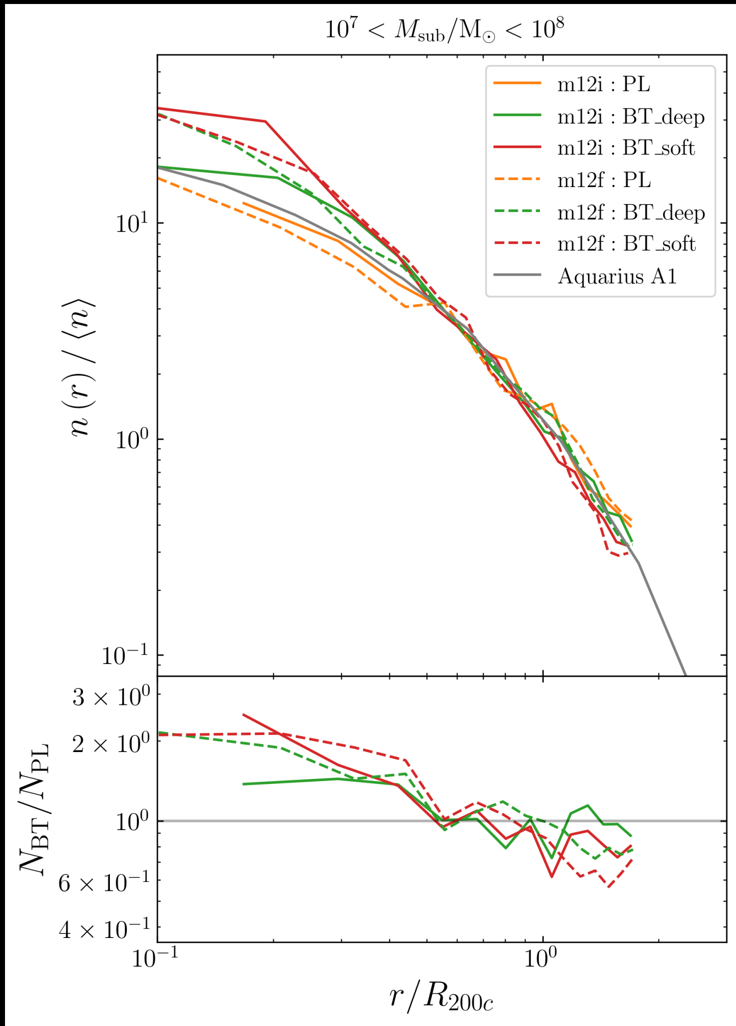
  - At inner region of main halo, normalized number density nearly doubled

Normalized number density

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

Ratio(BT over PL)





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3. To explain the Strong Lensing Anomalies

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To help Strong Lensing (flux ratio anamolies)

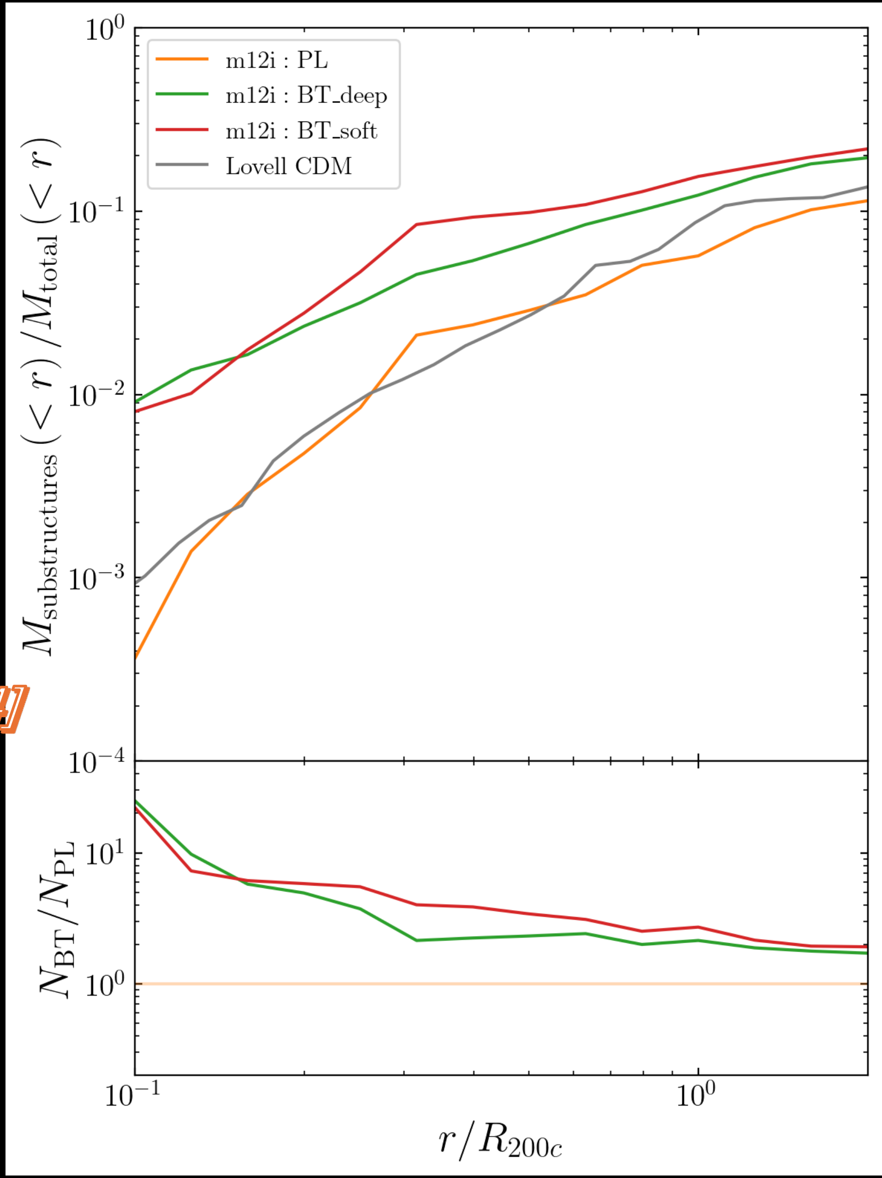
- substructure mass fraction:
  - Defined as *mass of particles belonging to substructures(within radius r)/total mass(within radius r)*
  - Blue-tilted model could reach an order of magnitude enhancement compared to traditional model

Substructure Mass Fraction

[Wu, TKC & Moreno arxiv 2024]

Ratio(BT over PL)

scaled radial distance



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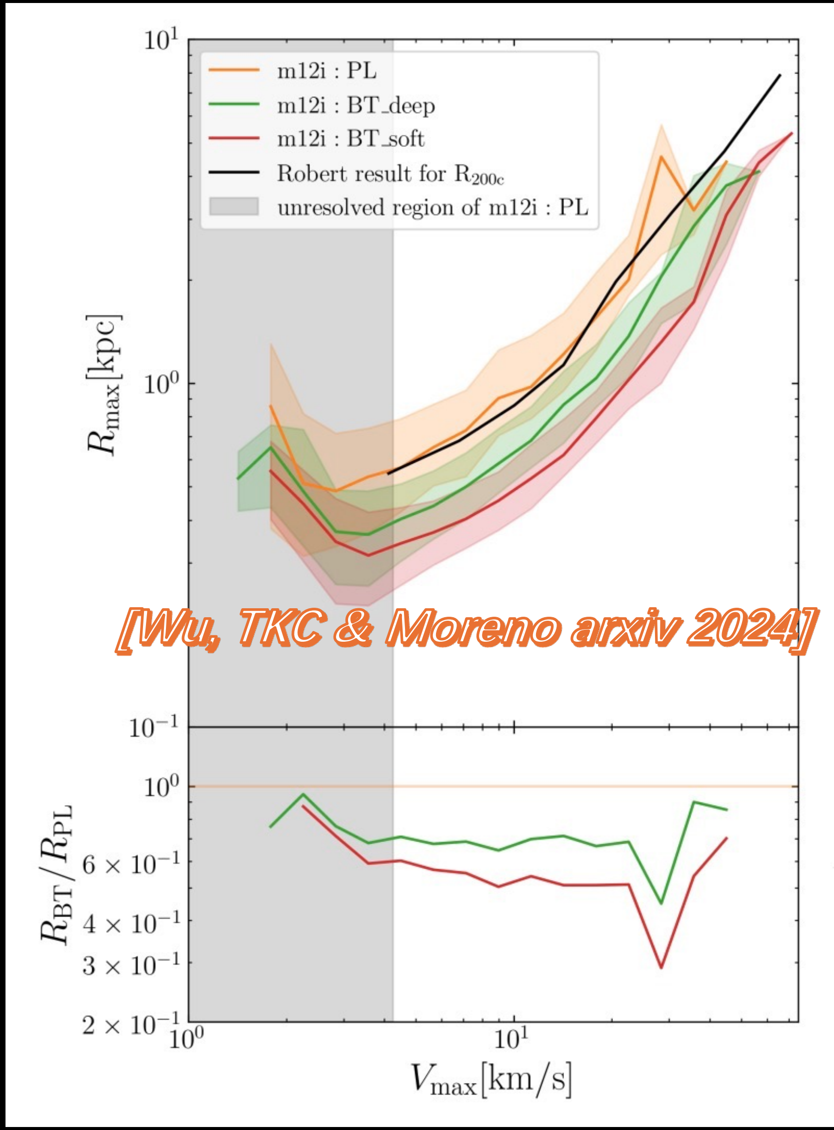
To help Strong Lensing (more concentrated subhalo)

Maximum circular velocity

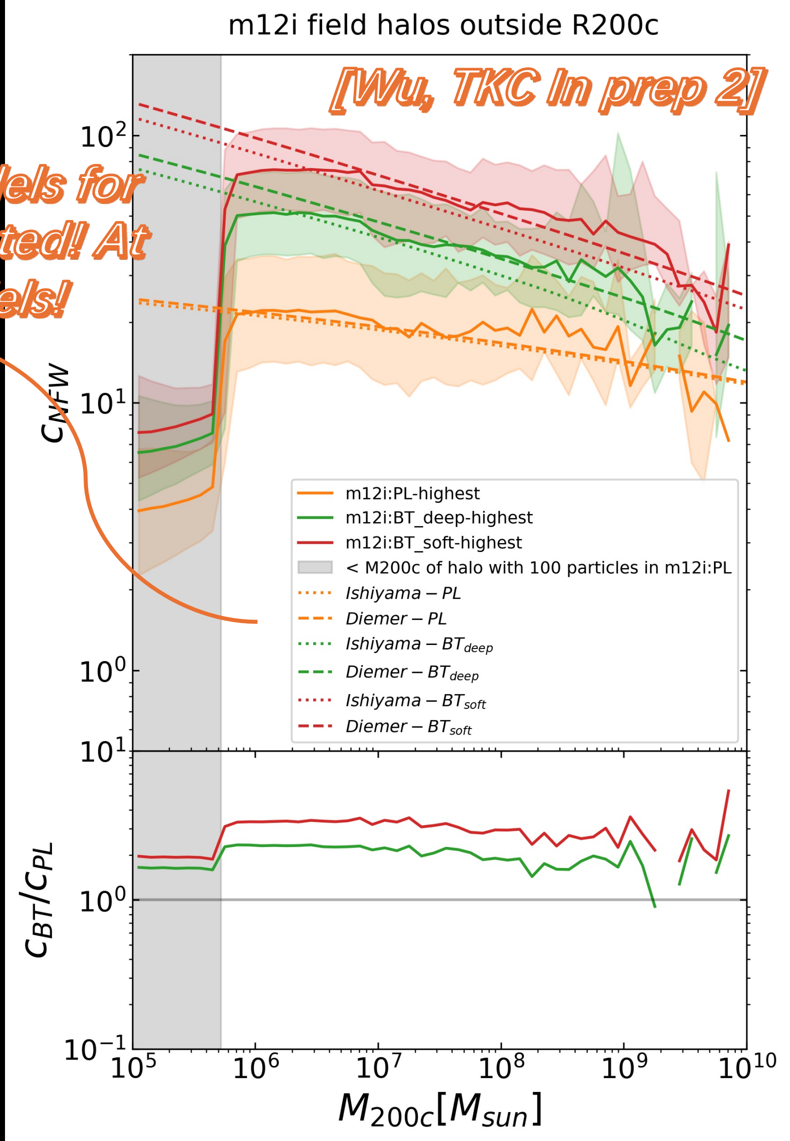


The Diemer19 and Ishiyama21 models for C-M-Z relationships are thus validated! At least for the soft and deep models!

The median Rmax/Cnfw within one Vmax bin

Ratio(BT over PL)

M200c



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By-Product: Main halo (could) be more concentrated

[Wu, TKC & Moreno arxiv 2024]

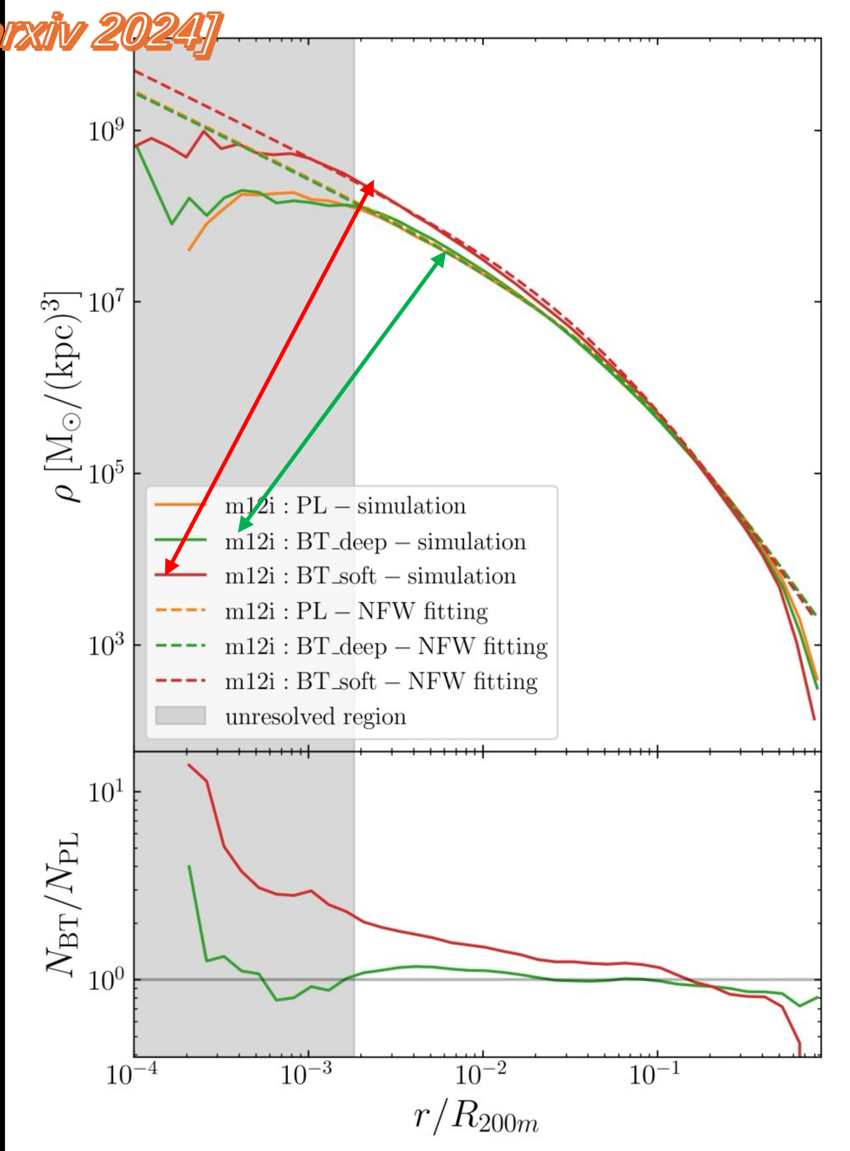
But only in BT_soft, BT_deep is very close to standard model!

And That fits well with our prediction!

scaled radial distance

radial density

Ratio(BT over PL)



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Summary

1. Background and Motivations:

- what is the standard cosmology model*(PL+LCDM)*
- which part we want to modify*(PL->BT)* and what motivates us to do so *(JWST)*
- what problems we want to solve with the new model

2. To solve the too-many-satellites problem

- DMO simulation *[Wu, TKC & Moreno 2024]+*DMO-BD potential simulation *[Wu & TKC, in prep 1]*

3. To explain the strong lensing anomalies

- Over-concentration events *[Wu, TKC & Moreno 2024]+[Wu & TKC, in prep 2]*
- Flux Ratio Anomalies *[Wu, TKC & Moreno 2024]+some future works?*

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