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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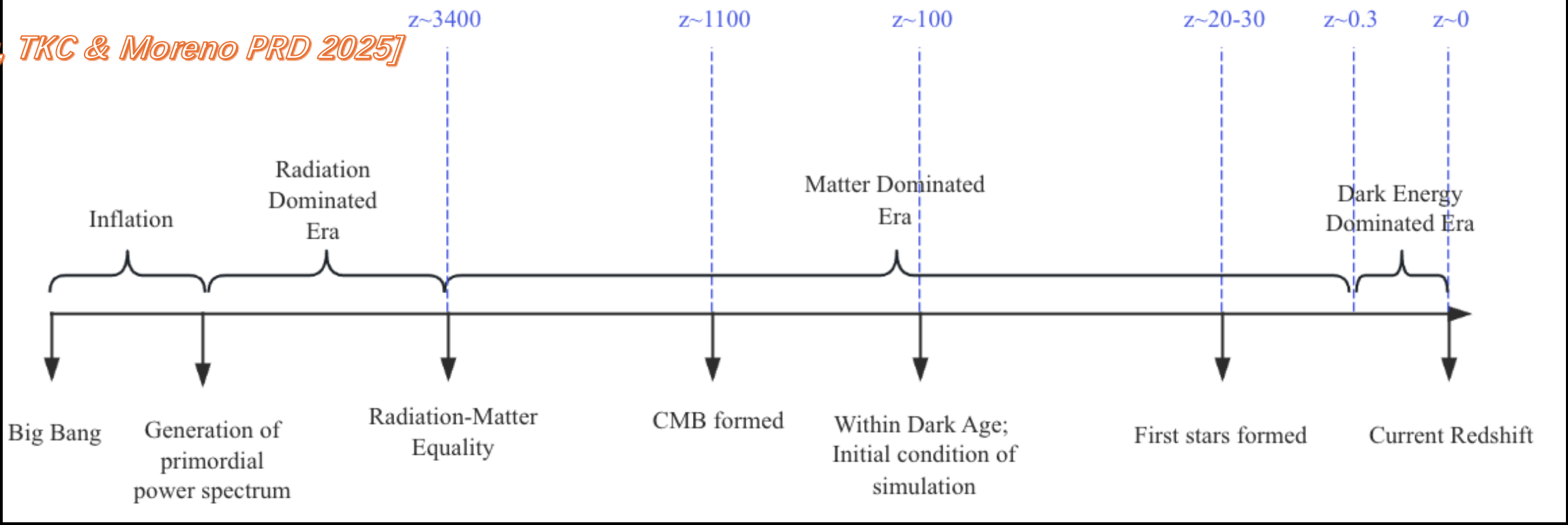
1. Background and Motivations

Phys. Rev. D 112 (2025) 023512 [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

[Wu, TKC & Moreno PRD 2025]



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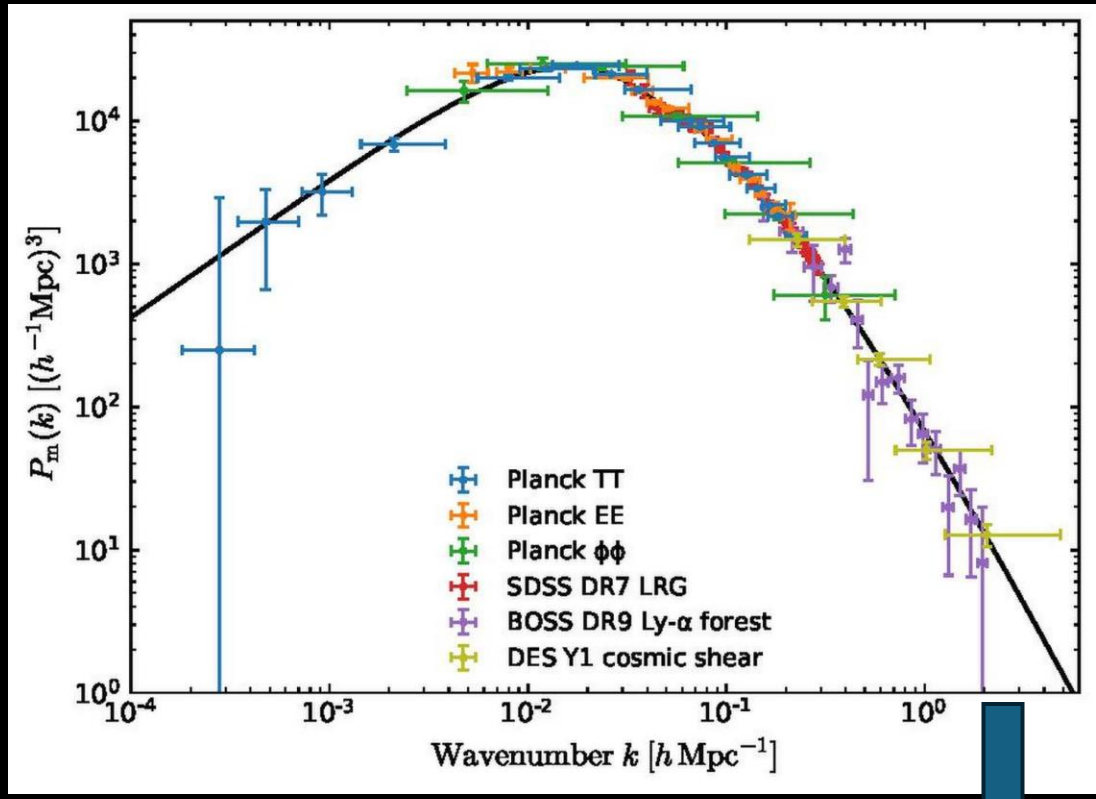
Uncertain at small scales

- 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?

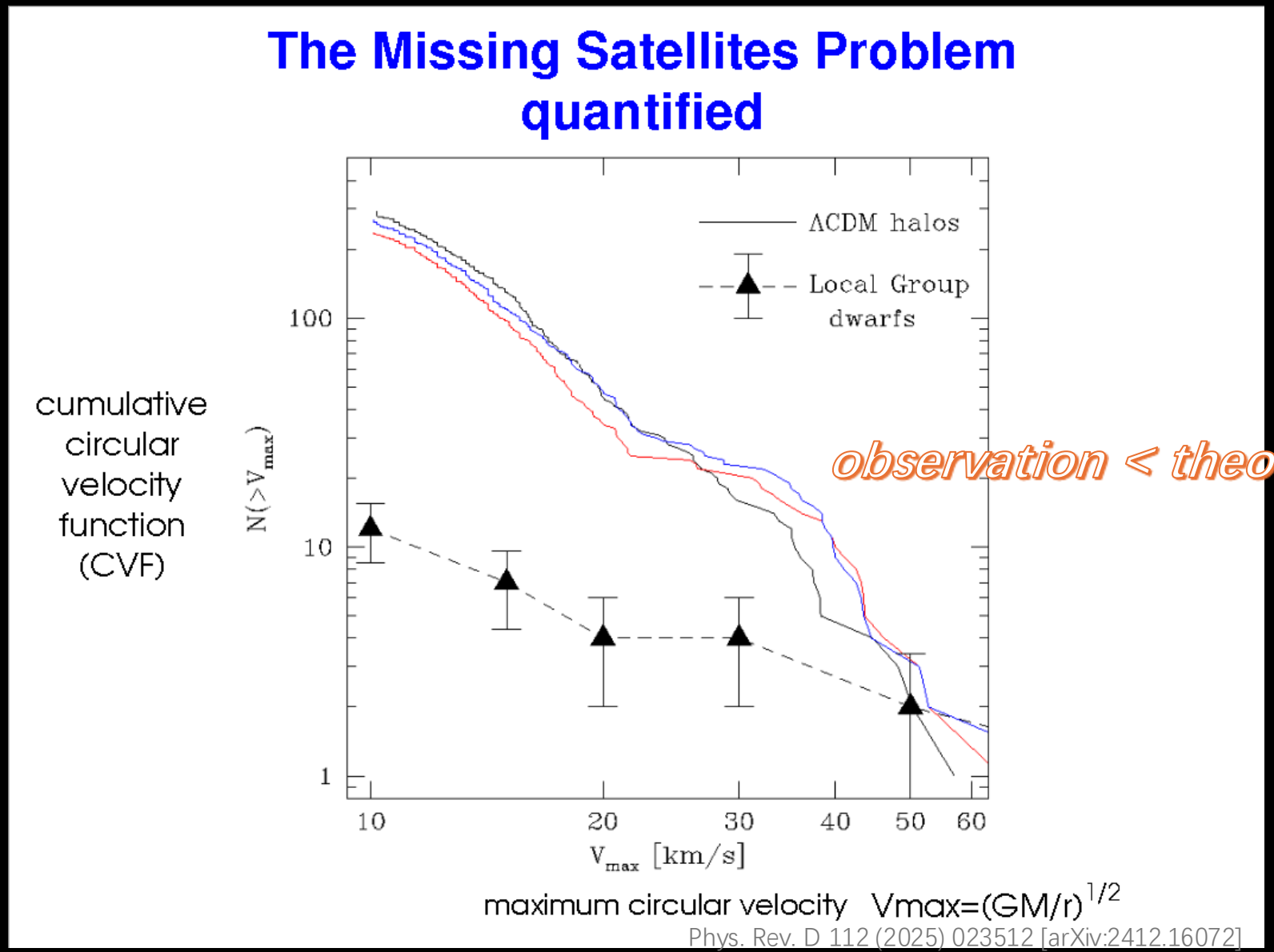
- There is ***already a paper*** using a small scale enhanced primordial power spectrum to explain the ***early formed massive galaxies in JWST***
- **Besides**, several **other** observations are in favor of ***a small scale enhanced*** cosmological model—we are trying to address them!

  - 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])

Phys. Rev. D 112 (2025) 023513 [arXiv:2412.16072]

The old *Missing Satellite Problem* in standard cosmology model

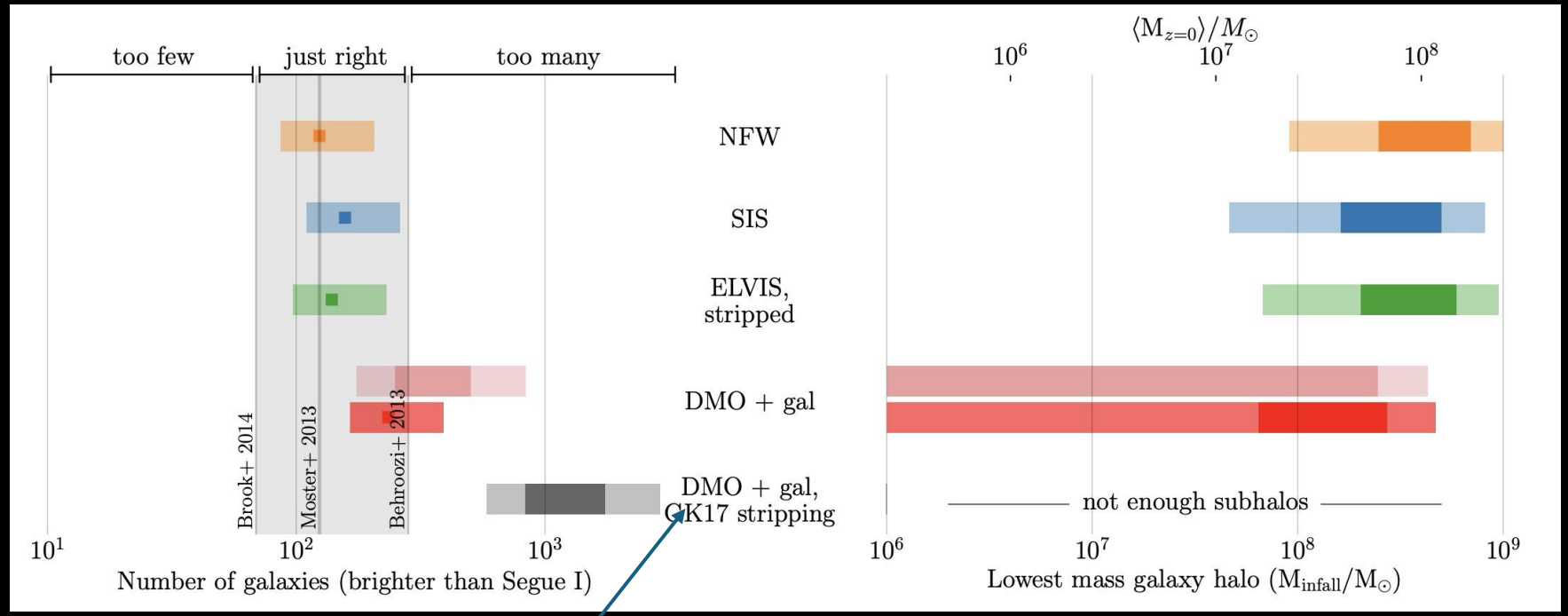


MSP:
observation < theoretical (simulation) prediction

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]

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!

old 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:

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.

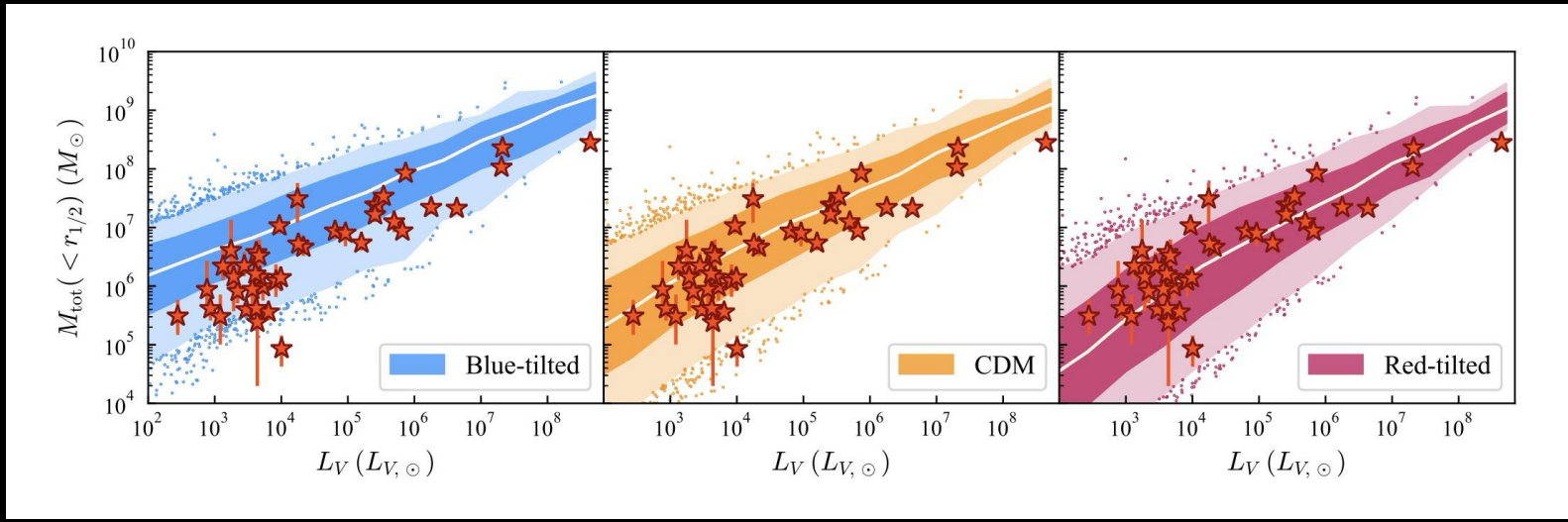
[Wu, TKC & Moreno arxiv 2024]

Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16072]

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."



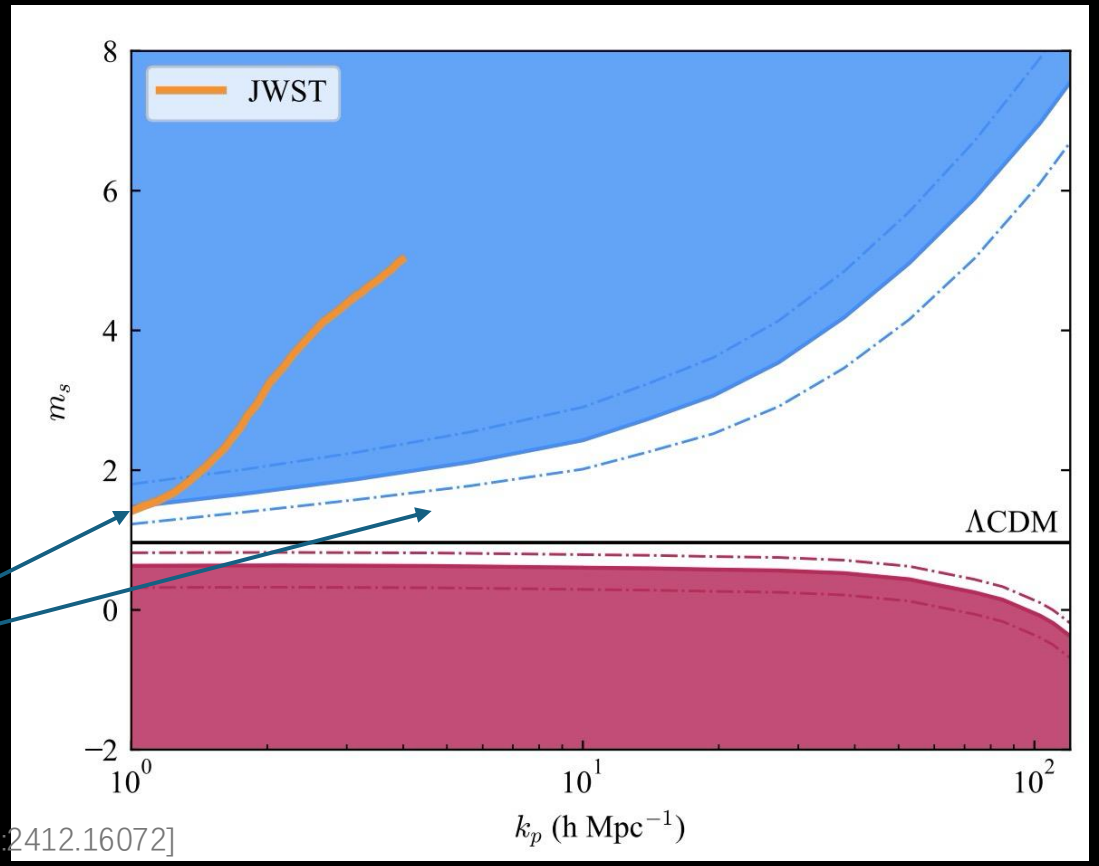
source: arxiv [2407.04198]

Phys. Rev. D 112 (2025) 023512 [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!

Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16072]

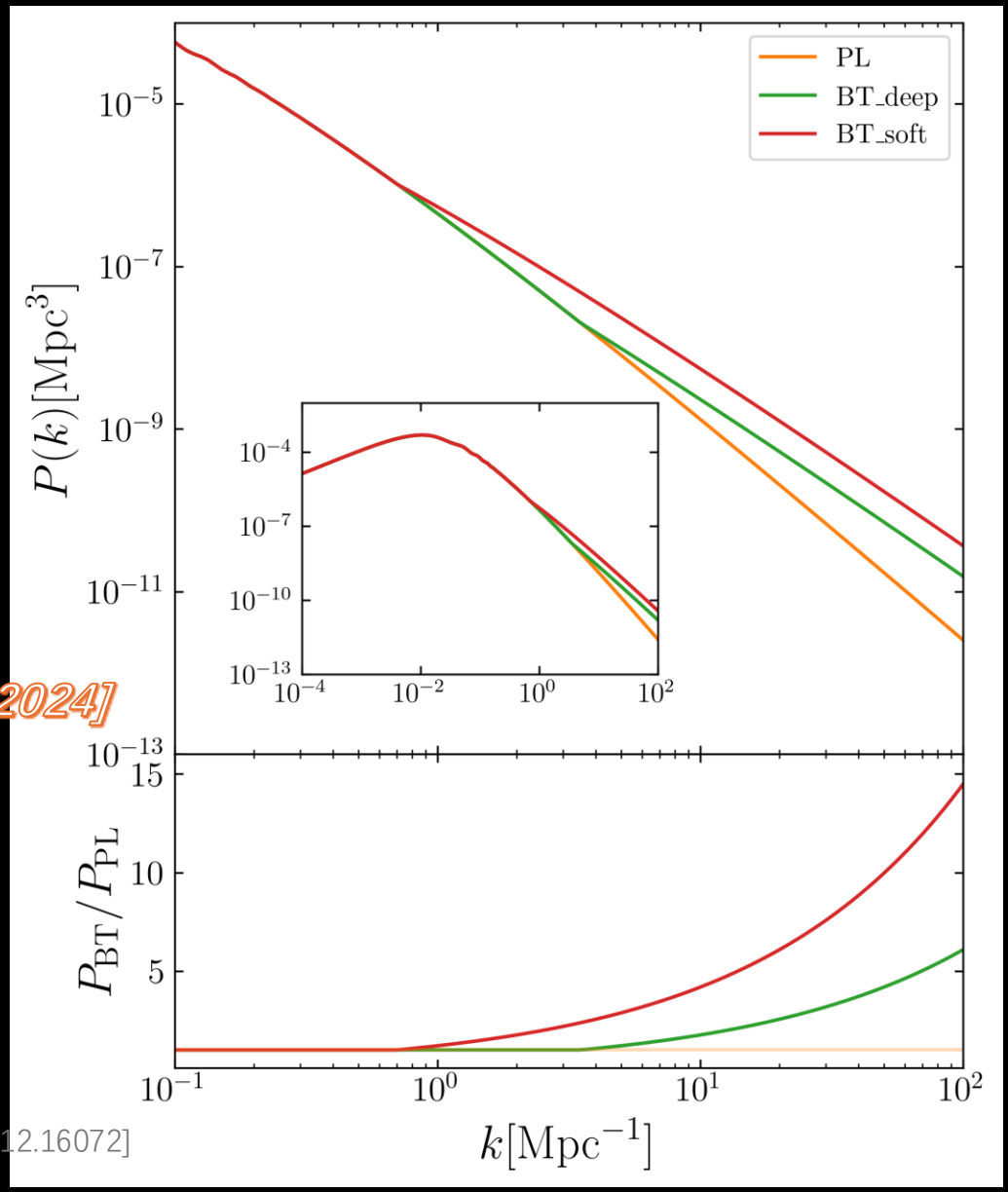
Two blue-tilted models

- 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.

[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 ($\mathbf{10^{12} M_\odot}$)!

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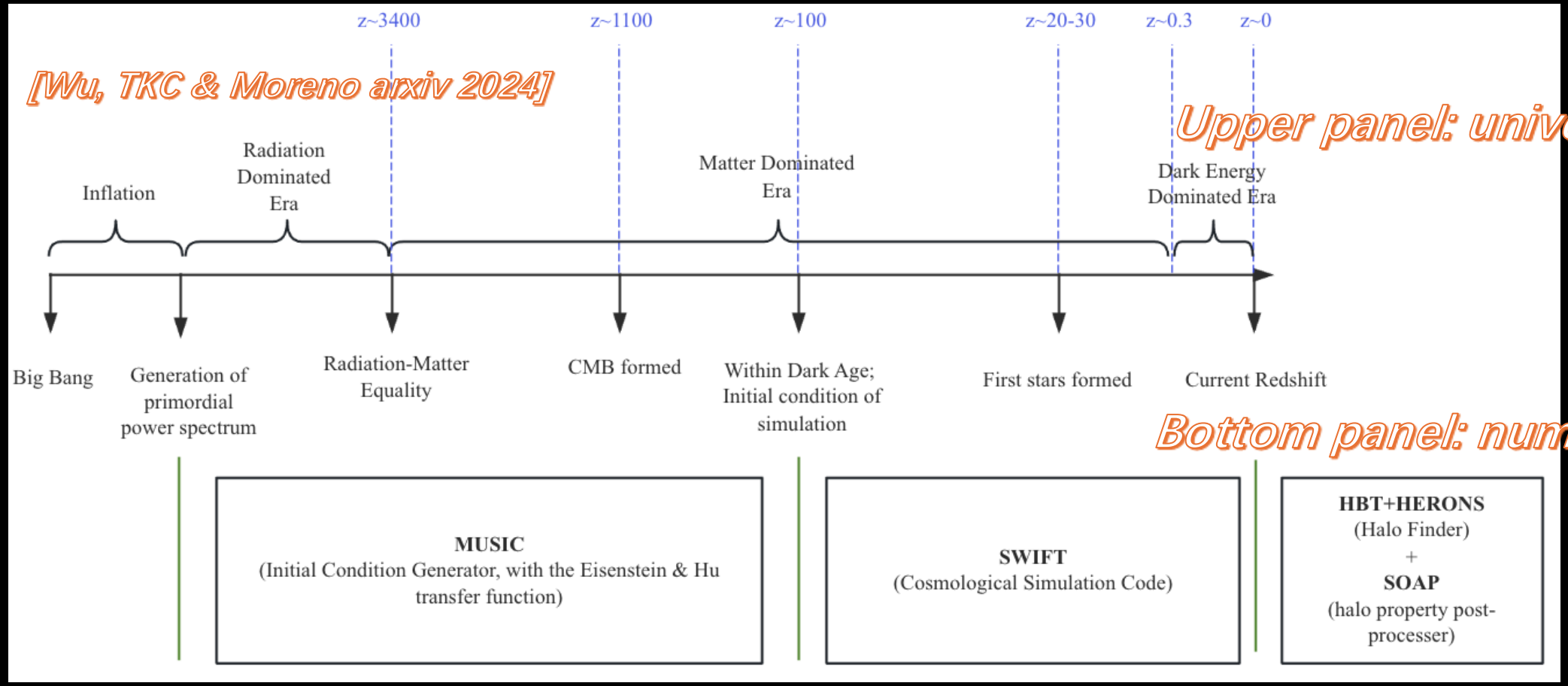
Numerical pipeline we used

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



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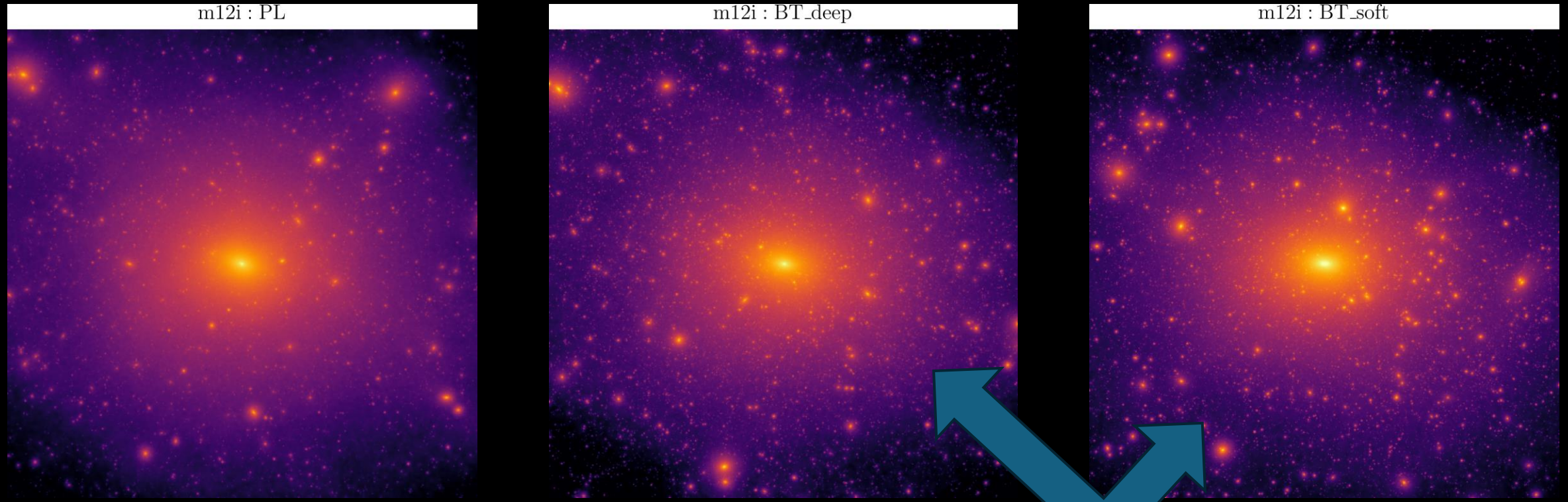
Intuitive look: projection map

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



[Wu, TKC & Moreno arxiv 2024]

Both BT models give more subhalos than power-law!

Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16078]

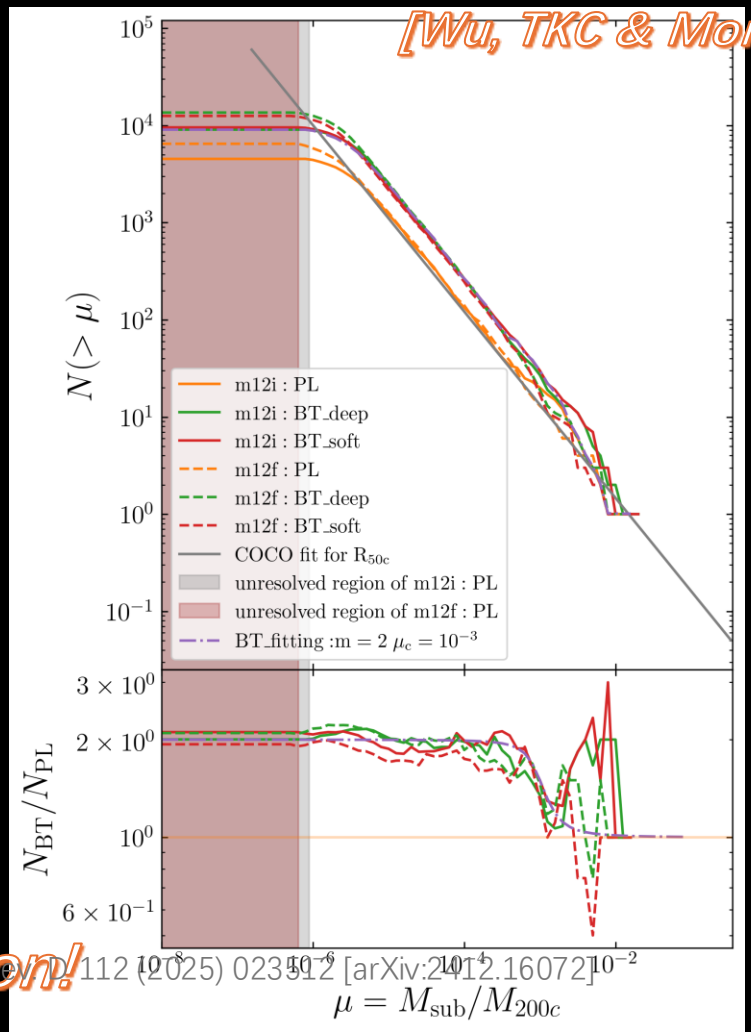
To help the Too-Many-Satellites (Mass/Vmax)

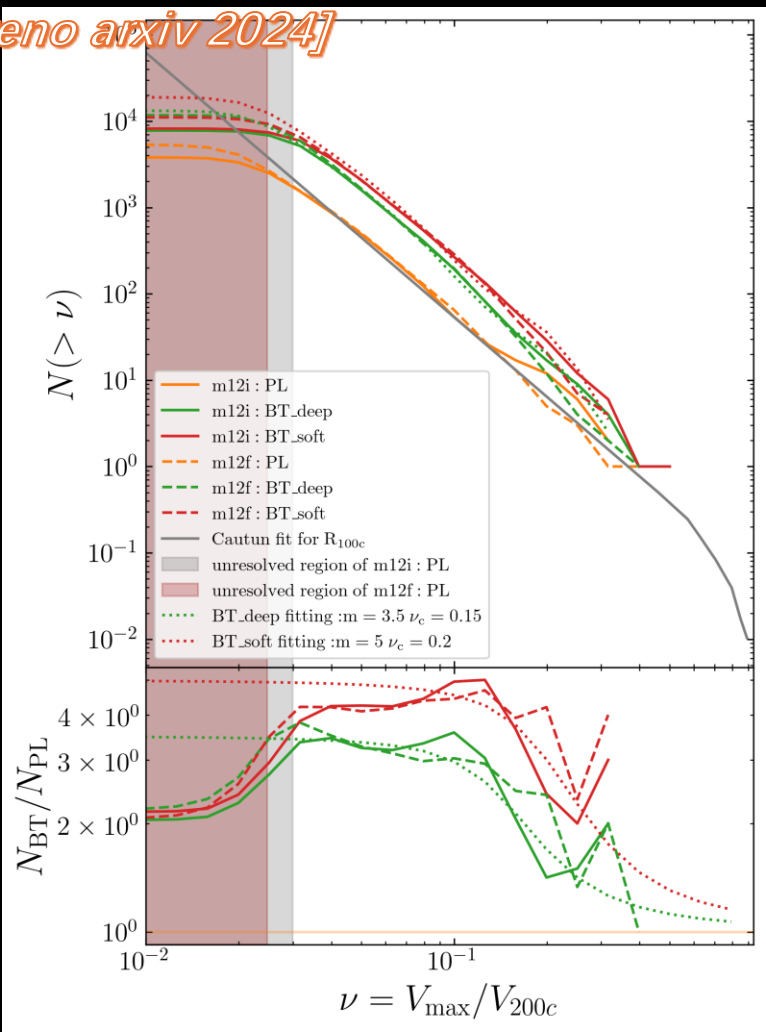
- **subhalo function(aka subhalo number distribution) by mass or Vmax**
  - **subhalo mass function could be enhanced by a factor of two at low mass end**
  - **subhalo Vmax function could be enhanced by more than 3 times at low Vmax end**

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!

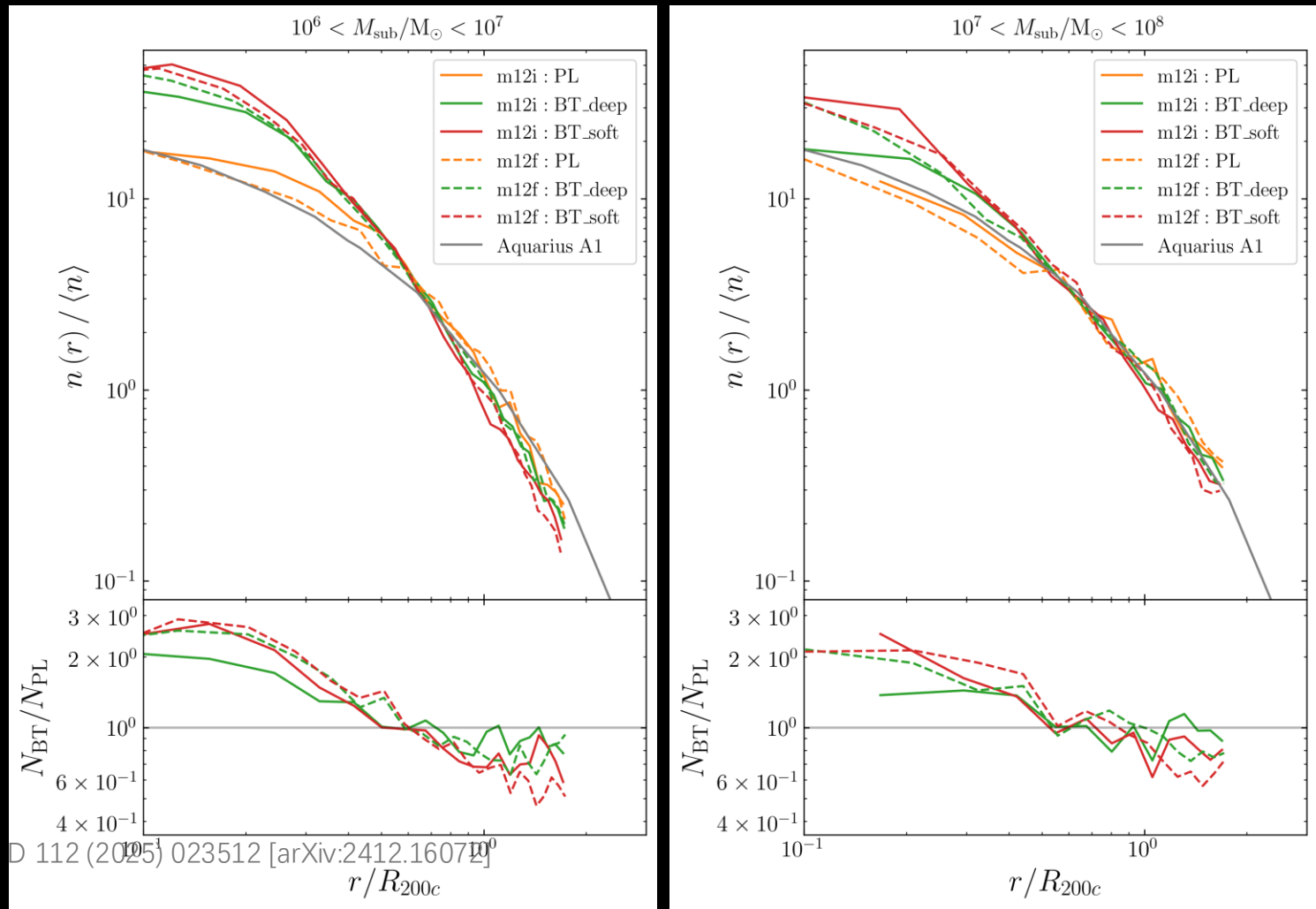
Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16072]

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

- radial distance ***from the center of main halo*** ***[Wu, TKC & Moreno arxiv 2024]***
  - At inner region of main halo, normalized number density nearly doubled

scaled radial distance

scaled radial distance



Normalized number density

Ratio(BT over PL)

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

Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16072]

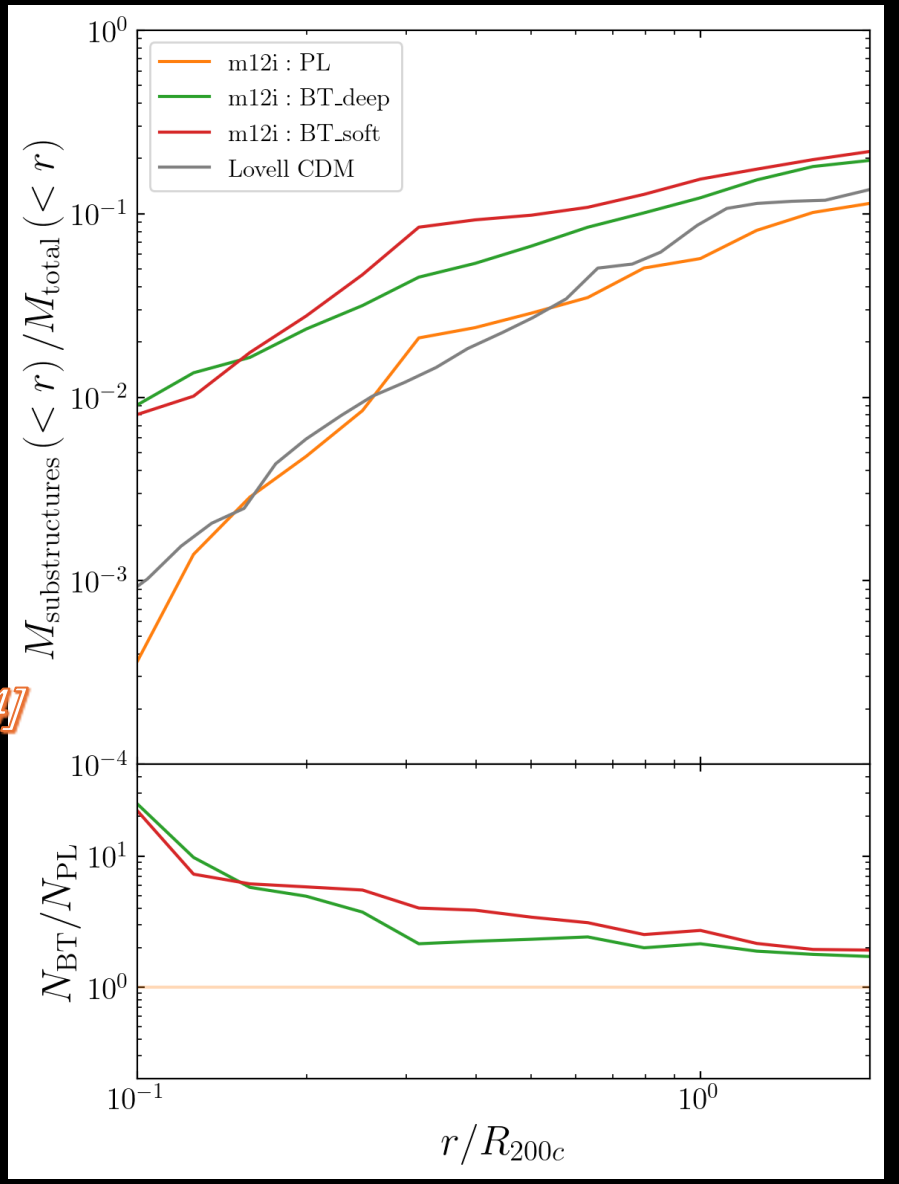
3. To explain the Strong Lensing Anomalies

Phys. Rev. D 112 (2025) 023512 [arXiv:2412.16072]

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

scaled radial distance



Substructure Mass Fraction

[Wu, TKC & Moreno arxiv 2024]

Ratio(BT over PL)

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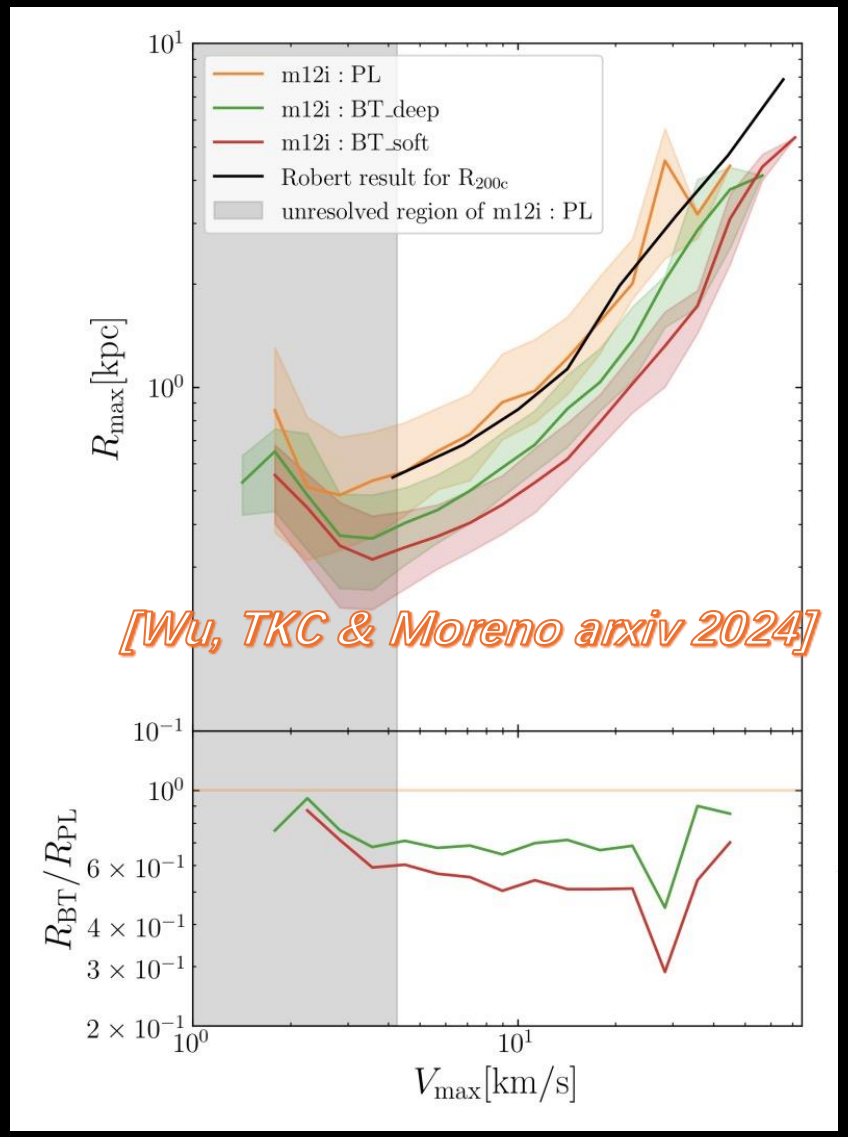
To help Strong Lensing (more concentrated subhalo)

Maximum circular velocity

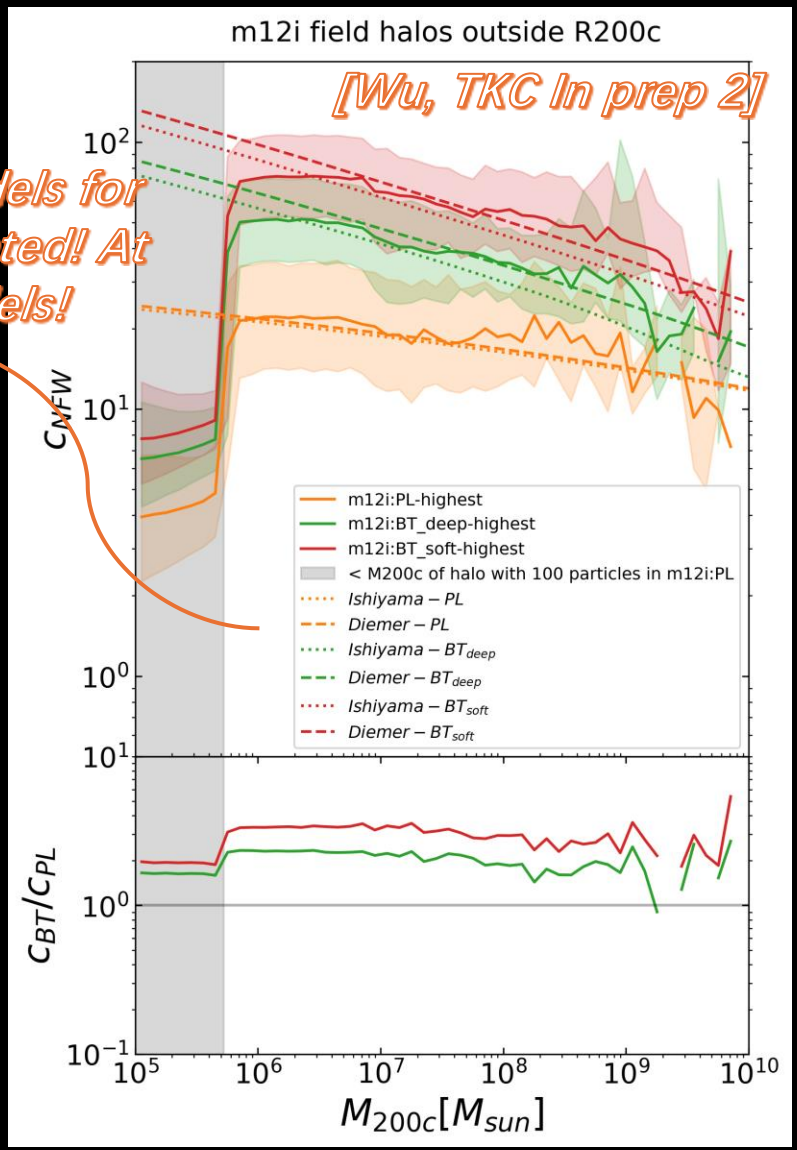


[Wu, TKC & Moreno arxiv 2024]

The median Rmax/Cnfw within one Vmax bin

Ratio(BT over PL)

M200c



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

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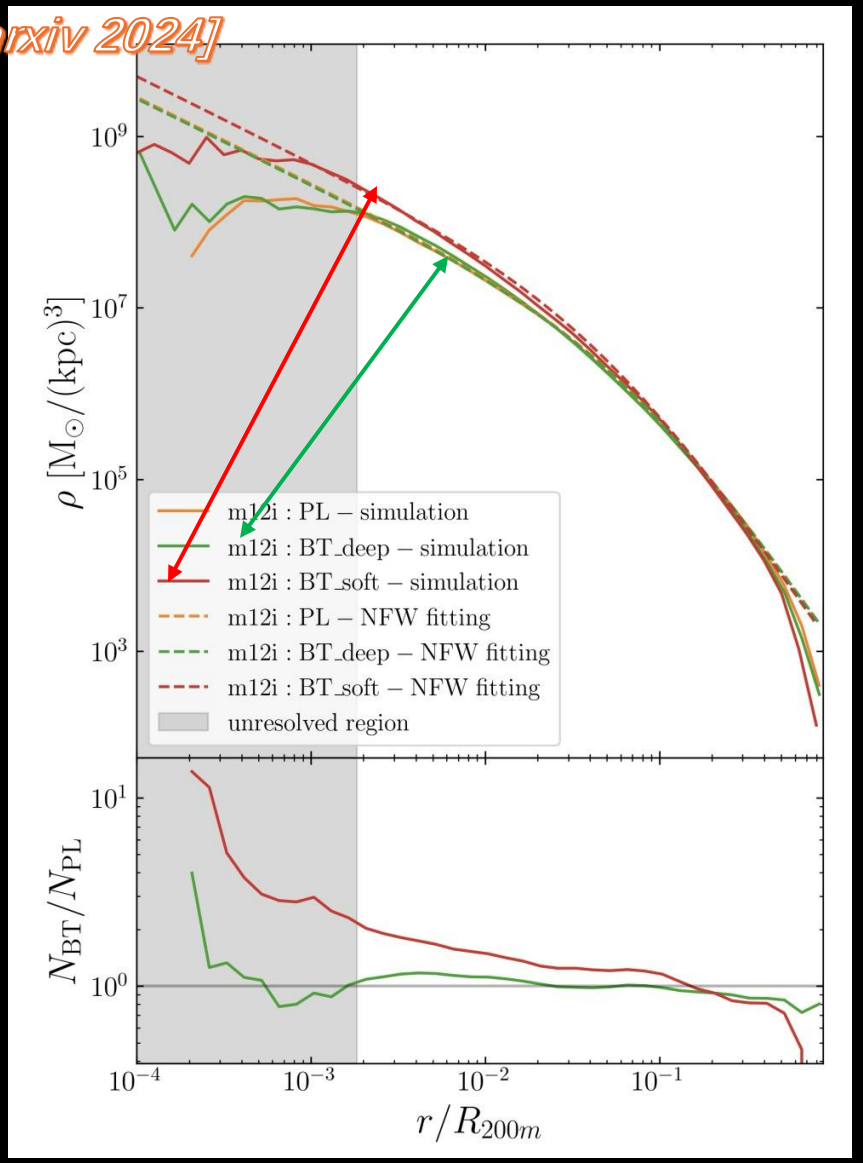
By-Product: Main halo (could) be more concentrated

[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!



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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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