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Small-scale enhanced primordial power spectrum can explain dense perturbers in strong lensing

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1. Motivation

The standard cosmology model includes a single-field slow-roll inflation model that specifies the initial condition of the very early universe, and the lambda cold dark matter model which governs the later evolution of our universe.

However, a crisis has emerged below Milky-Way dark matter halo scale, one recent problem of which is the **dense (sub)halo perturbers in strong lensing**. Subhalo H in strong lensing system J0946+1006 has been found to have a unusually high concentration with 15σ deviation from LCDM; halo A in strong lensing system B1938+666 also has a high concentration with 4σ compared to LCDM[1]. Besides, recently another halo V has also been identified in B1938+666 with ultra high concentration[2].

2. Theoretical Model

To explain the above over-concentrated (sub)halos in strong lensing, in this paper, we gave a small scale enhancement to the early universe model while keeping the LCDM model unchanged.

2.1 Blue tilted primordial power spectrum

Standard single-field slowroll inflationary model[3] is believed to generate a power-law form primordial power spectrum:

$$P_i(k) \propto k^{n_s} \tag{1}$$

where n_s is close to 1 from CMB measurements.

To get enhancement in small scale structure, a *blue tilted* primordial power spectrum[4, 5] for the early universe density perturbation has been proposed with m_s to be larger than n_s:

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

$$\propto k^{n_s} \cdot \left(\frac{k}{k_p}\right)^{m_s - n_s} (k > k_p) \tag{3}$$

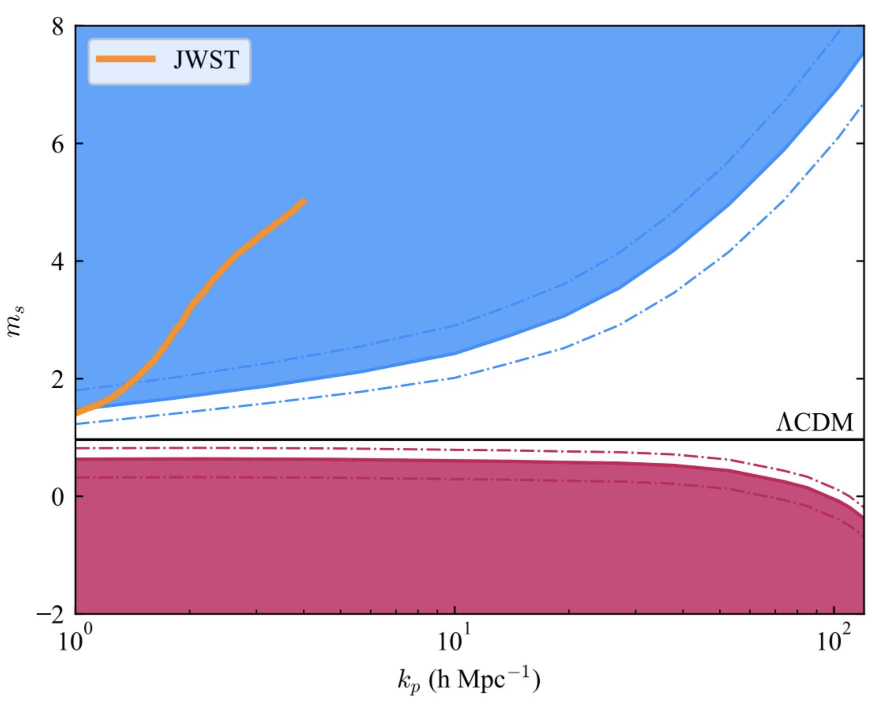

Figure 1: The constraint we adopted for blue tilted primordial power spectrum at scales smaller than $k \sim 1$ hMpc^{-1}, from [6].

[6] has used Milky Way dwarf galaxy central density observations to constrain the parameter space of blue tilted (see Figure 1), within which we selected the parameters for our chosen blue tilted model (Table 1):

Model	Related parameters
PL(power-law)	Standard Inflation, equivalent to $m_s = n_s$
BT(blue-tilted)	$k_p = 12$ Mpc^{-1}h, $m_s = 3.1$

Table 1: The parameters of chosen models.

2.2 Semi-Analytical Model for calculating (sub)halo structure under Blue Tilted

[7] has proposed a semi-analytical model able to calculate (sub)halo structure properties like NFW concentration parameter, and it has been implemented in the python package COLOSSUS [8] as so-called *Diemer19 model*. This model made the concentration-mass relationship to be a function of physical parameters peak height ν and effective power spectrum slope n_{eff}, thus this model can capture the effects brought by different primordial power spectrum.

3. Simulation Validation

We used numerical simulation to validate the above semi-analytical model's effectiveness under blue tilted primordial power spectrum.

In the $z = 0$ snapshot, we chose several halos with masses spanning from $10^{6.5} \sim 10^9 M_\odot$, and plot their density profiles in Figure 6. Along with simulation outputs (in blue), we also plotted the NFW profiles with concentration calculated by the Diemer19 semi-analytical model for both PL (in green) and BT (in yellow); the numbers in the legend are the NFW concentration parameters given by Diemer19.

From Figure 6 we can find that our BT simulation results fit quite well with the Diemer19 prediction for BT, thus as a good enough validation for Diemer19 model applied in blue tilted.

4. Result

We used the above validated model to explain the dense perturbers A, H, and V's unusual concentration-mass relation (see Figure 2) and $\gamma_{2D} - M_{2D}$ relation (see Figure 3, Figure 5, Figure 4). In those figures, orange lines are Diemer19 model's prediction for BT, grey lines are Diemer19 model's prediction for PL, while markers are the observation points from strong lensing studies [9, 1]; dashed lines indicate the (sub)halos with 1σ higher concentration than the median values(solid lines).

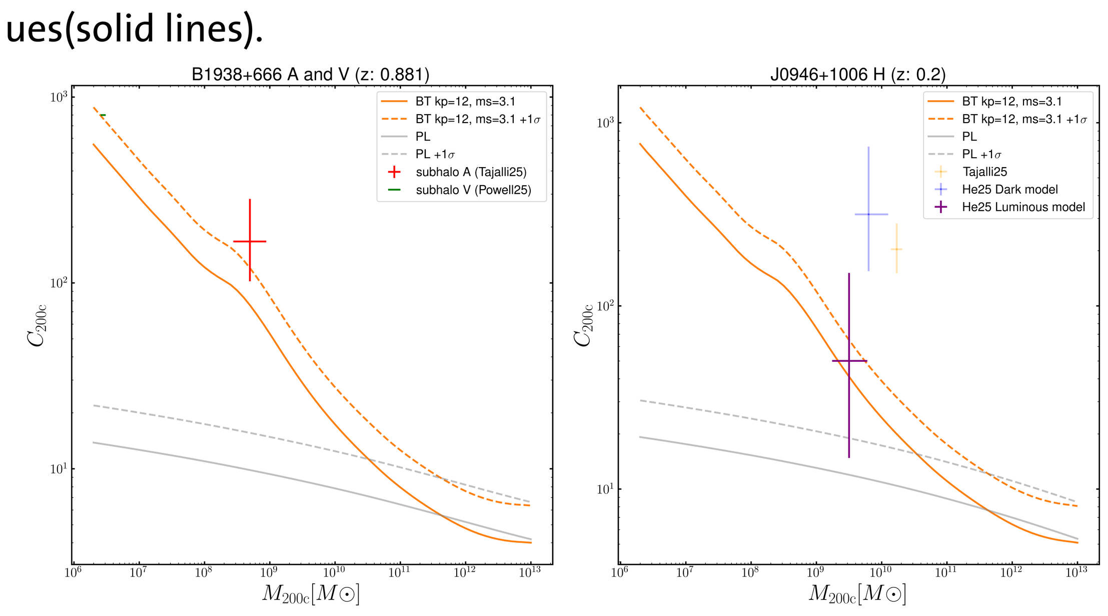

Figure 2: The Concentration-Mass relationship for halo A and V in lensing system B1938+666 (left panel, $z = 0.881$) and subhalo H in lensing system J0946+1006 (right panel, $z = 0.2$).

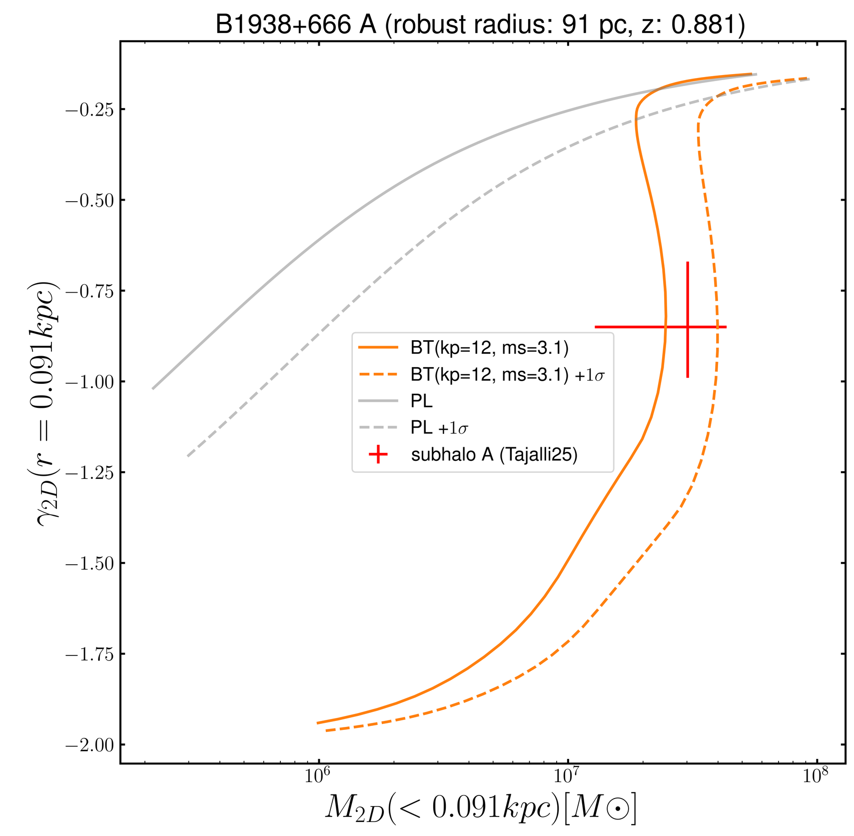

Figure 3: $\gamma_{2D} - M_{2D}$ for halo A.

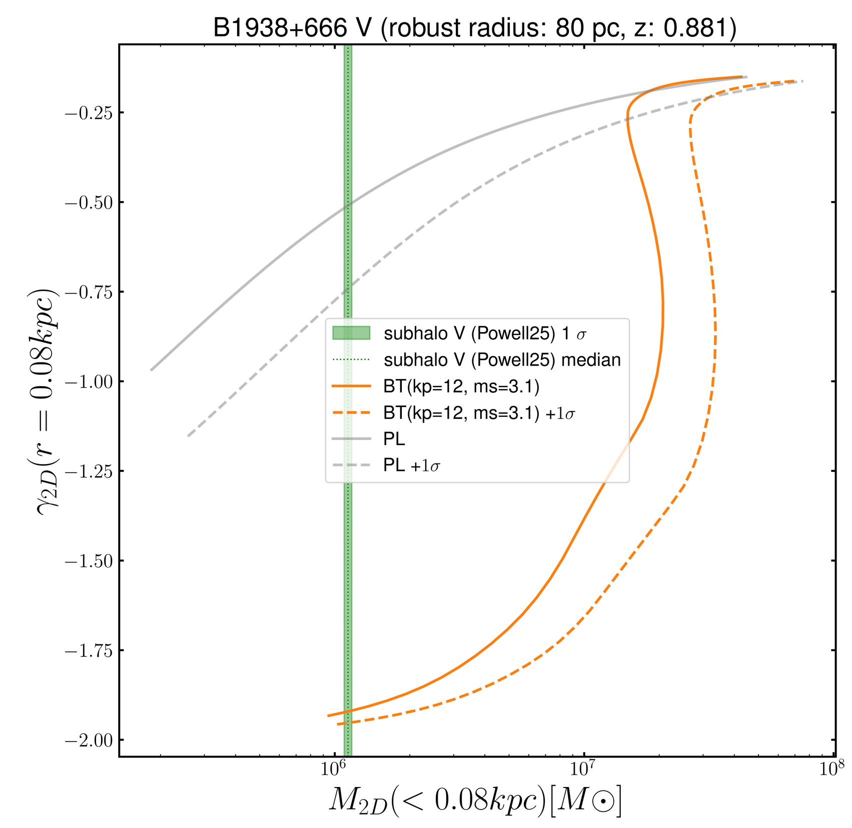

Figure 4: $\gamma_{2D} - M_{2D}$ for halo V.

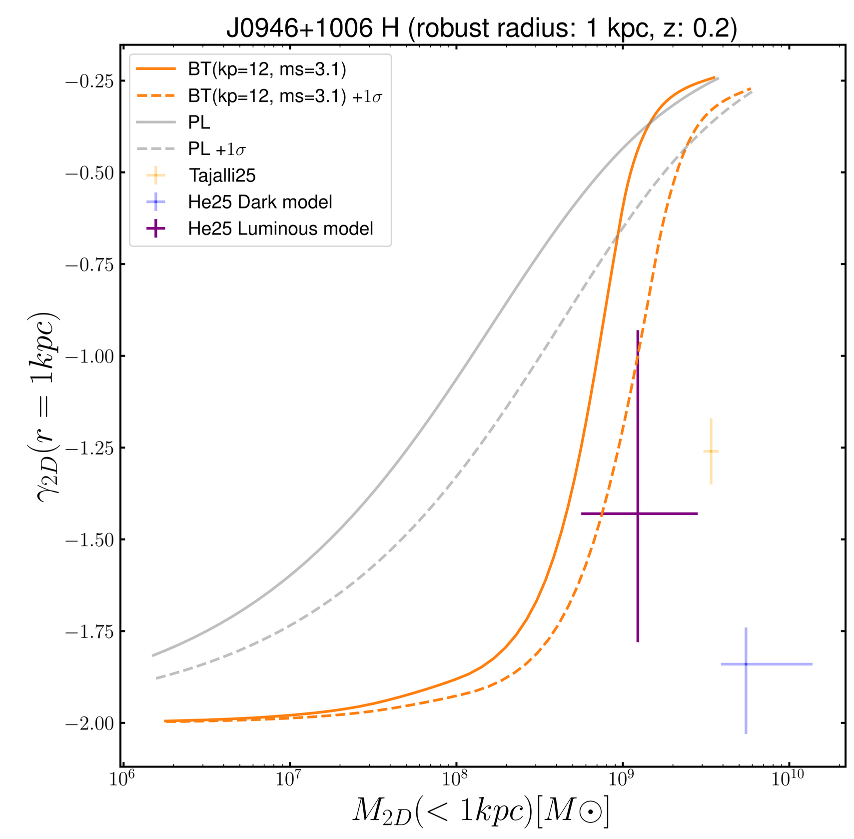

Figure 5: $\gamma_{2D} - M_{2D}$ for halo H.

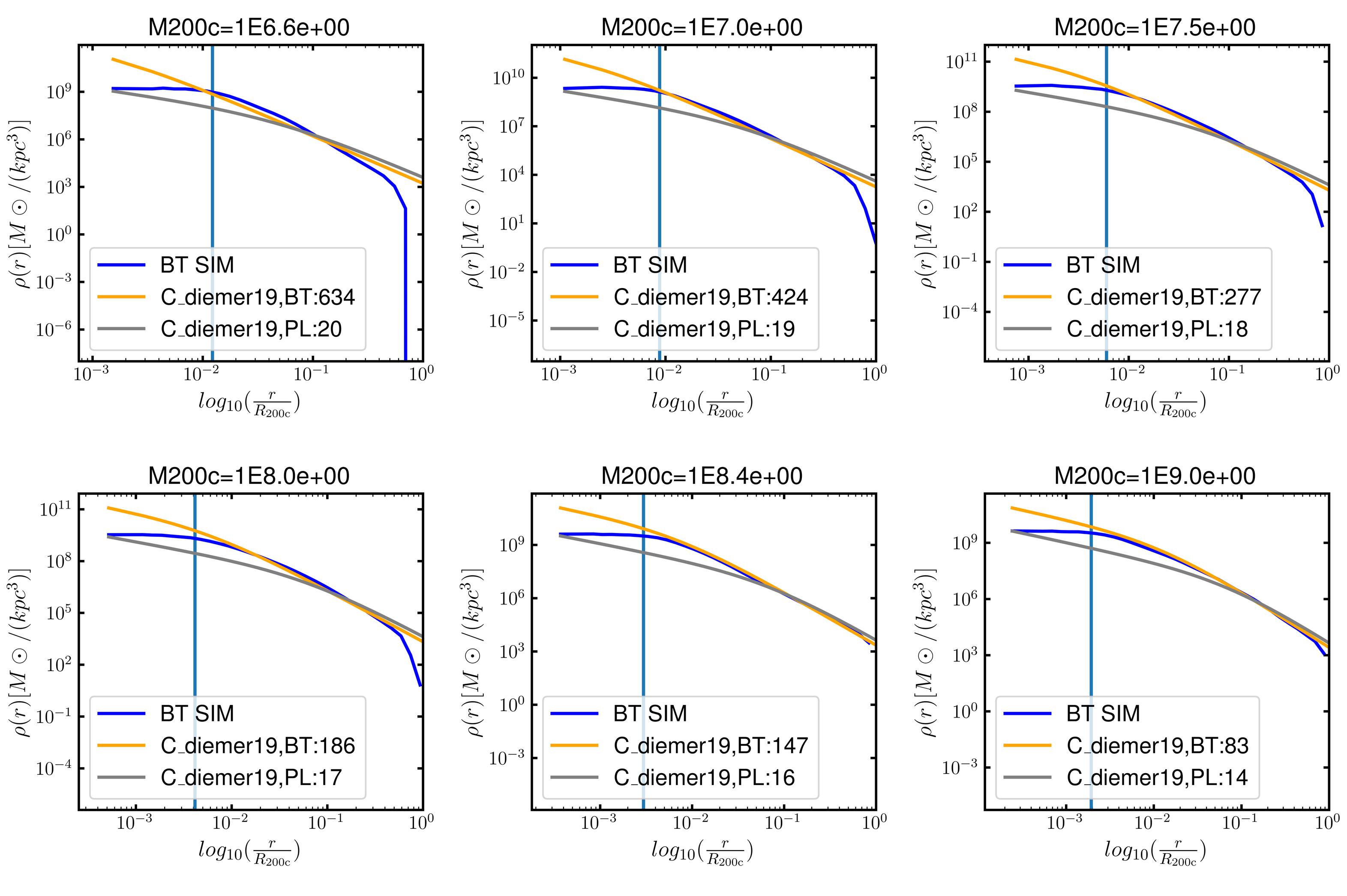

Figure 6: The density profiles for several halos in our Blue Tilted N-body simulation($k_p = 12$ Mpc^{-1}h, $m_s = 3.1$)

References

[1] Maryam Tajalli et al. In: *arXiv e-prints*, arXiv:2505.07944 (May 2025), arXiv:2505.07944.
[2] D. M. Powell et al. In: *Nature Astronomy* (Oct. 2025).
[3] E. R. Harrison. In: *Phys. Rev. D* 1 (10 May 1970), pp. 2726–2730.
[4] Laura Covi and David H. Lyth. In: *Phys. Rev. D* 59.6, 063515 (Mar. 1999), p. 063515.
[5] Jérôme Martin and Robert H. Brandenberger. In: *Phys. Rev. D* 63.12, 123501 (June 2001), p. 123501.
[6] Ariane Dekker and Andrey Kravtsov. In: *arXiv e-prints*, arXiv:2407.04198 (July 2024), arXiv:2407.04198.
[7] Benedikt Diemer and Michael Joyce. In: *ApJ* 871.2, 168 (Feb. 2019), p. 168.
[8] Benedikt Diemer. In: *ApJS* 239.2, 35 (Dec. 2018), p. 35.
[9] Qiuhan He et al. In: *ApJL* 991.2, L53 (Oct. 2025), p. L53.