Unraveling The Role of Cosmic Velocity Field in Dark Matter Halo Mass Function Using Deep Learning






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Introduction

Analytical models

Pros:

- Physical insight about the process of halo formation

Cons:

- Non accurate HMF for the smallest halos
- Simplified assumptions about the halos' shape

N-body Simulations

Pros:

- Accurate Halo Mass function
- Without any assumption about the halos' shape

Cons:

- Computationally expensive
- Lack of physical insight through the collapse process

Does the initial condition have enough information to capture all the properties of dark matter halos?

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- Si

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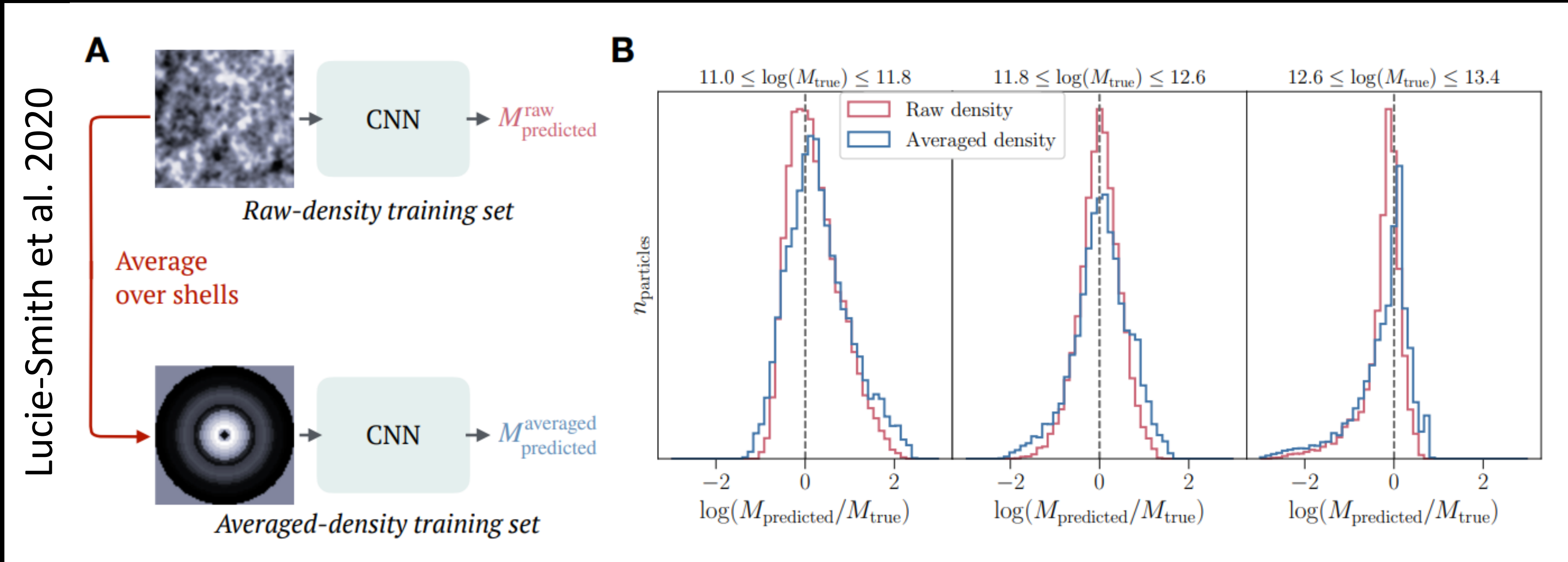
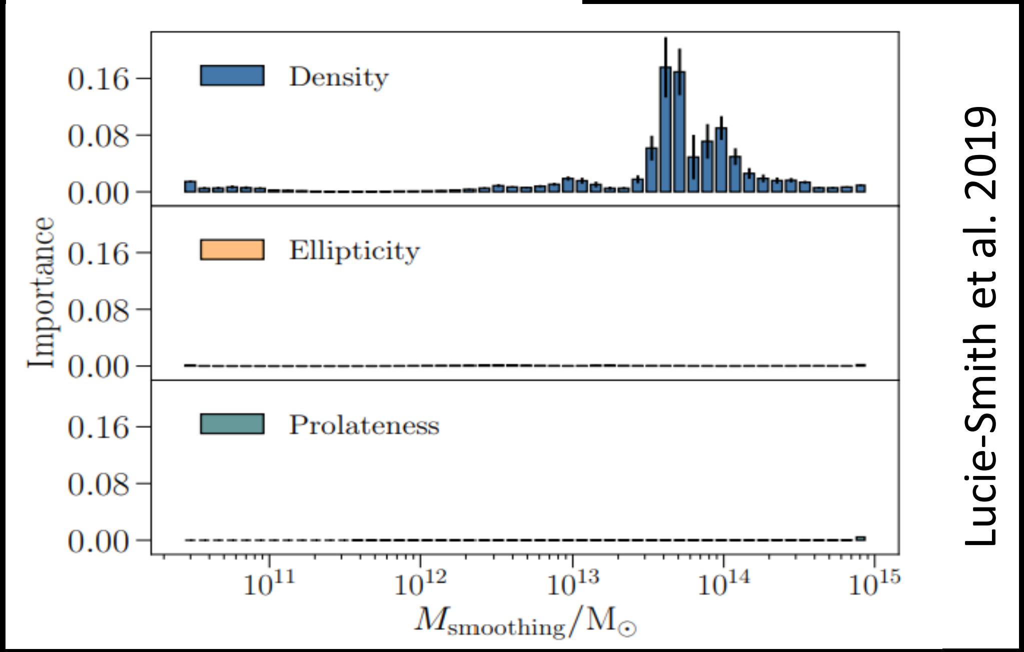
Suppose the initial condition is enough to capture the dark matter mass distribution.

Would initial density field information (isotropic or non-isotropic) be sufficient to predict the halo mass function accurately?



Classifier: Random Forest



Isotropic or anisotropic density field?

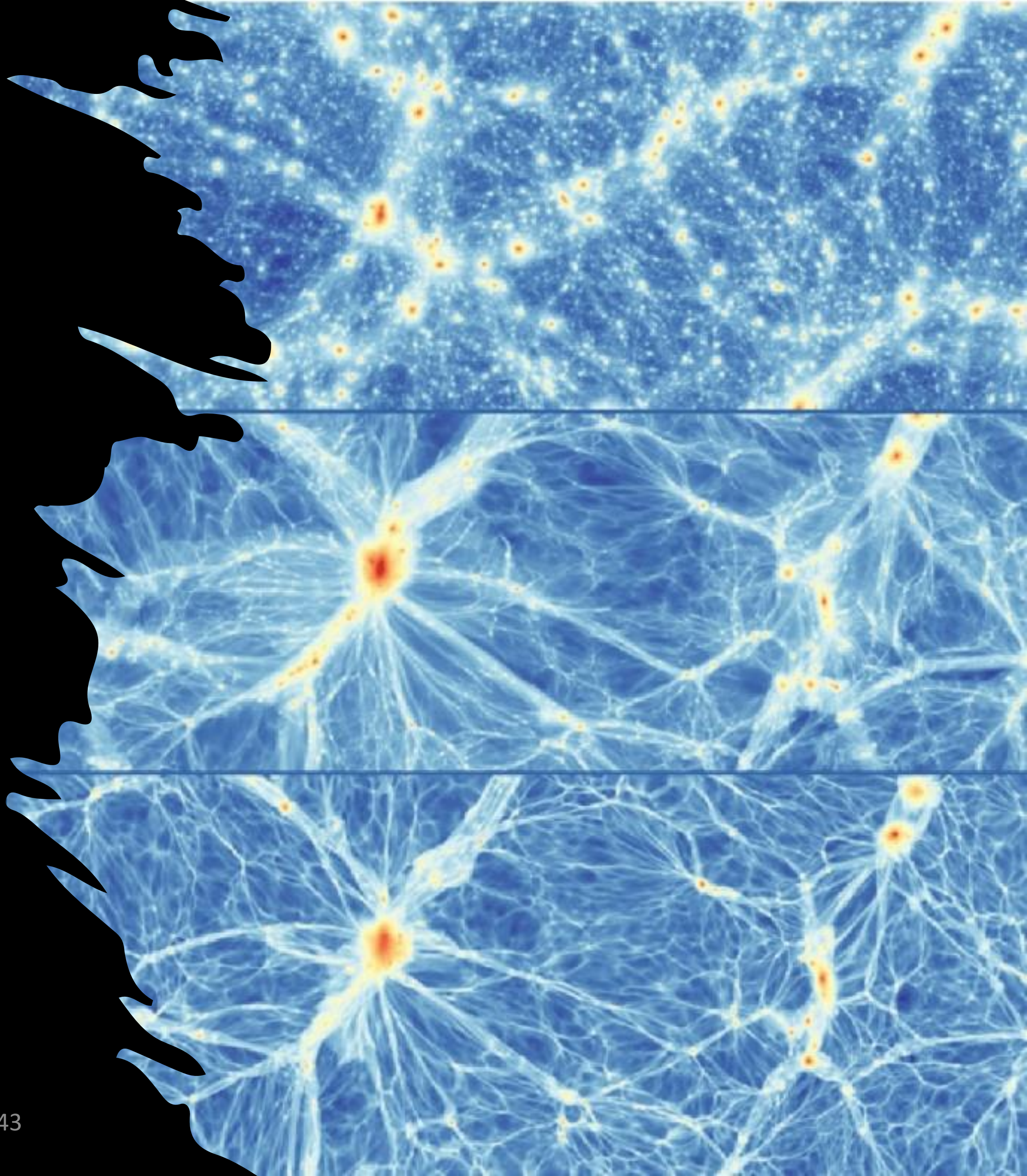
Method

Simulation + Halo finder

- gevolution relativistic simulation ([Adamek et al.]) – Dark Matter only N-body
- Box size = 50 Mpc/h
- #grids = 600^3
- #particles = 600^3

- Halo finder : Rockstar (Behroozi et al.) – grid independent and shape independent

- Fixed mesh grid: Reliable halo mass range is $10.5 \leq \log\left(\frac{M}{M_{sun}}\right) \leq 14$

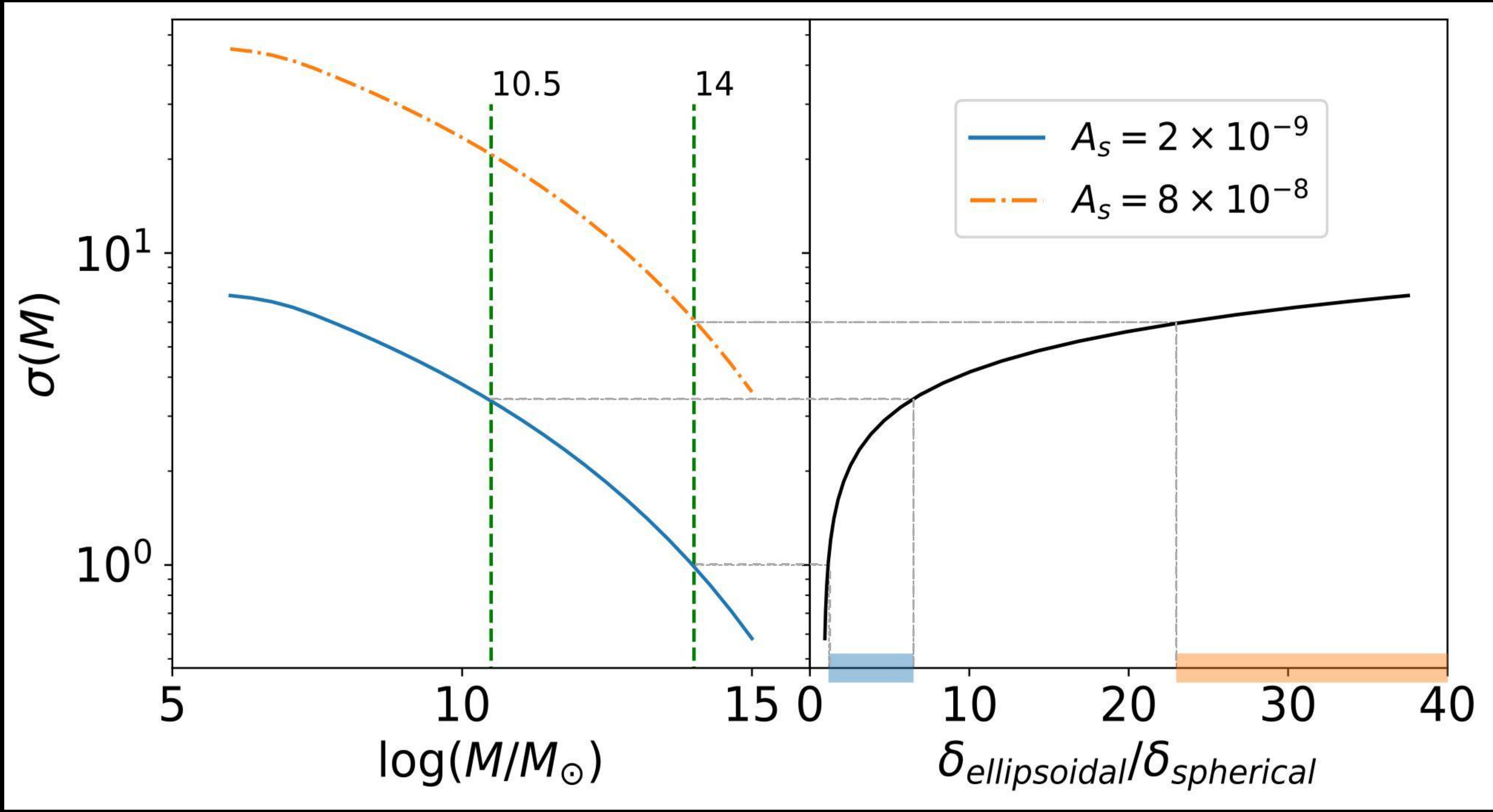


How to analyze the effects in the smaller mass scales?

- Effect of increasing the amplitude of initial curvature perturbations looks like moving to smaller mass scales in the standard cosmological model.

$$\sigma_M = \sigma_M(M_{halo}, A_s)$$

$$f \equiv \frac{\delta_{ellipsoidal}}{\delta_{spherical}} = f(\sigma_M)$$



Interpretable Deep Learning Frameworks → Learning the collapse process directly from N-Body sims

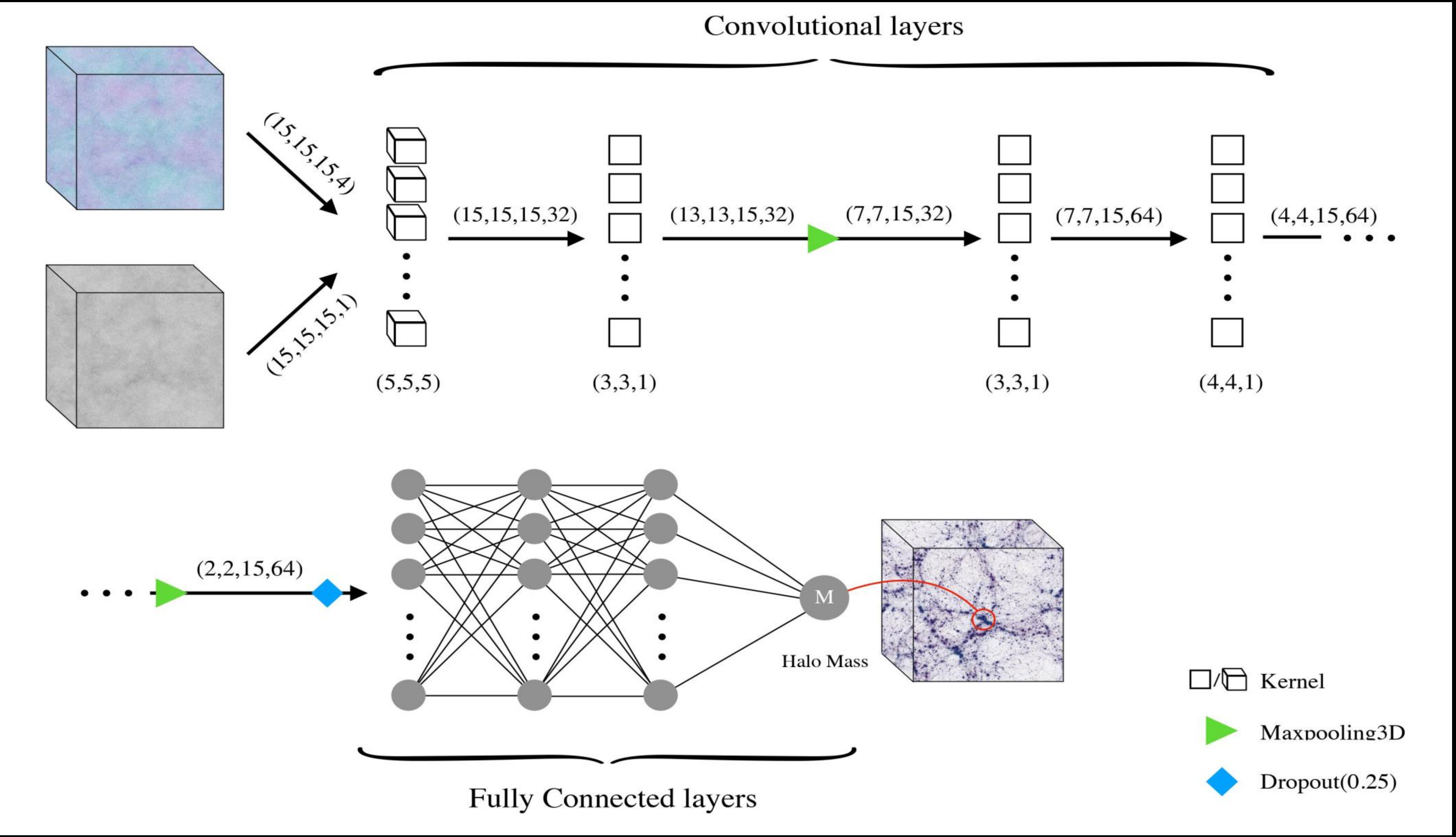


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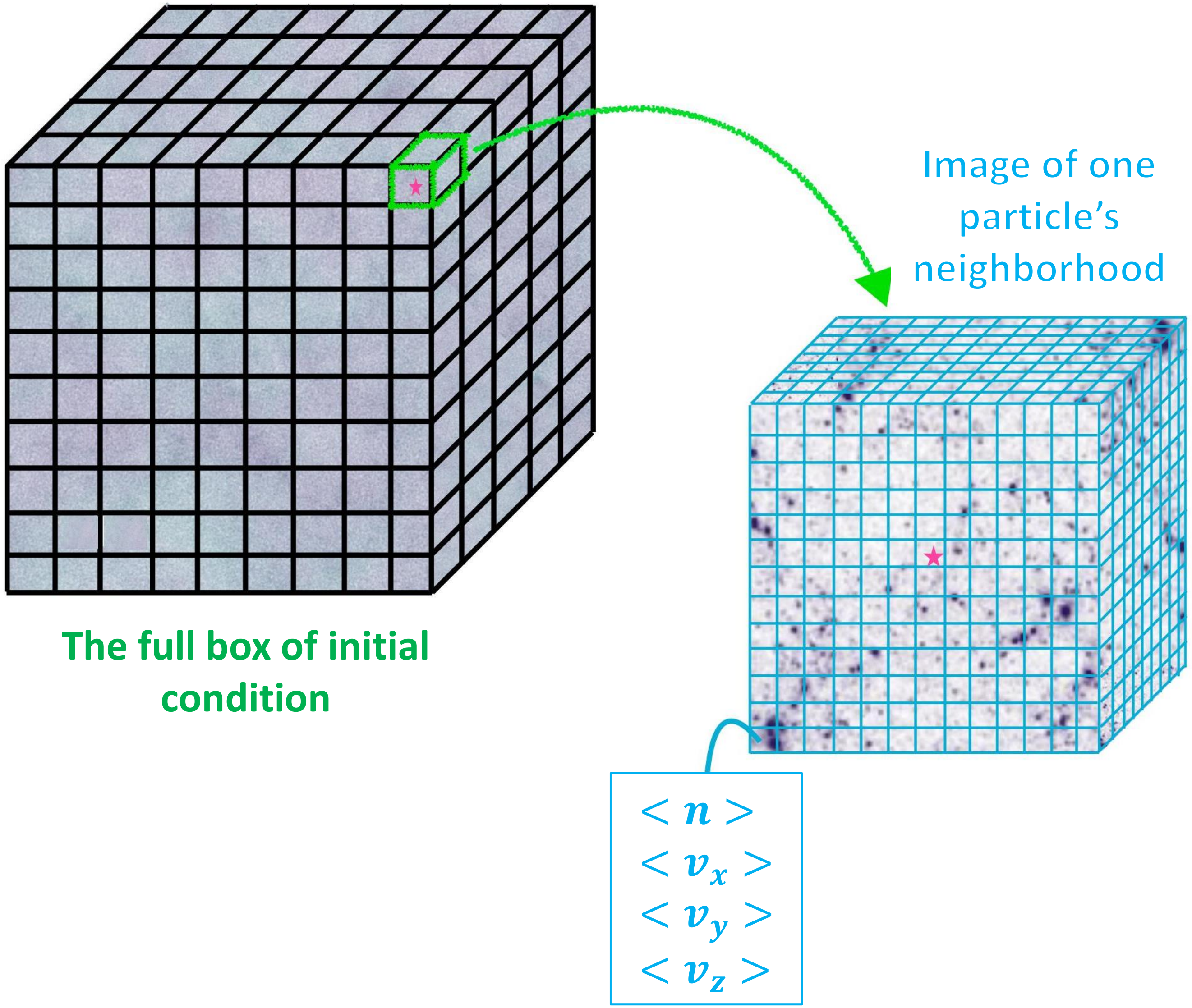
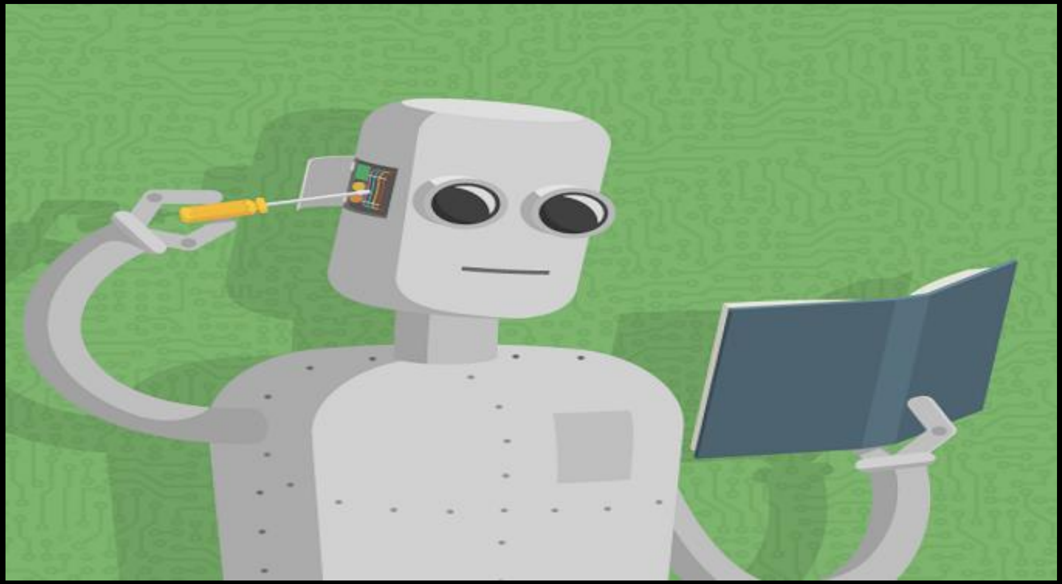
Image construction

- Physical size = 7.5 Mpc/h
- Physical resolution = 0.5 Mpc/h
- $Images\ shape: \begin{cases} (15,15,15,1) \\ or \\ (15,15,15,4) \end{cases}$





Things are not that simple!

Tunning hyper-parameters

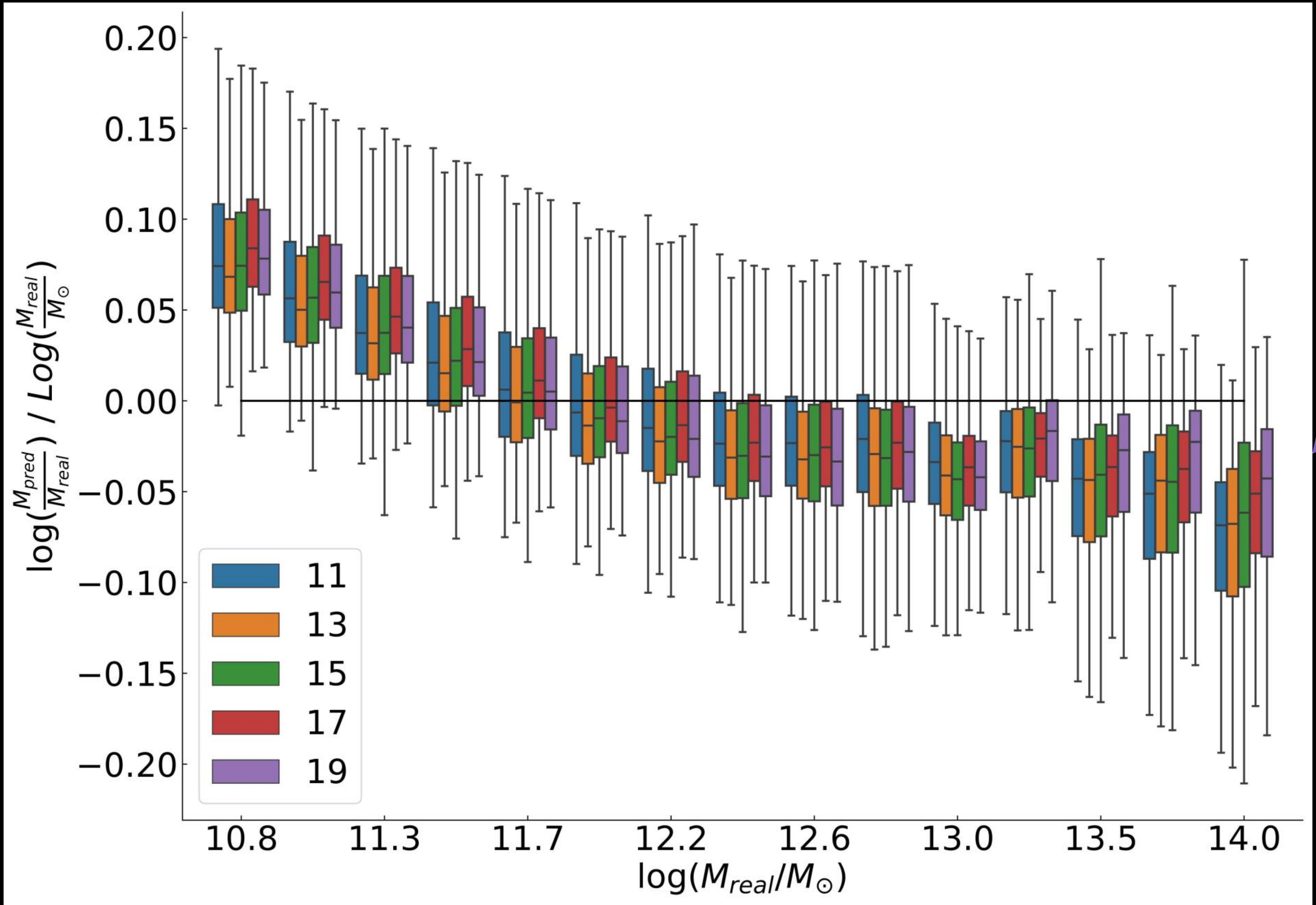


Image size

Image resolution

Minimum Halo Mass

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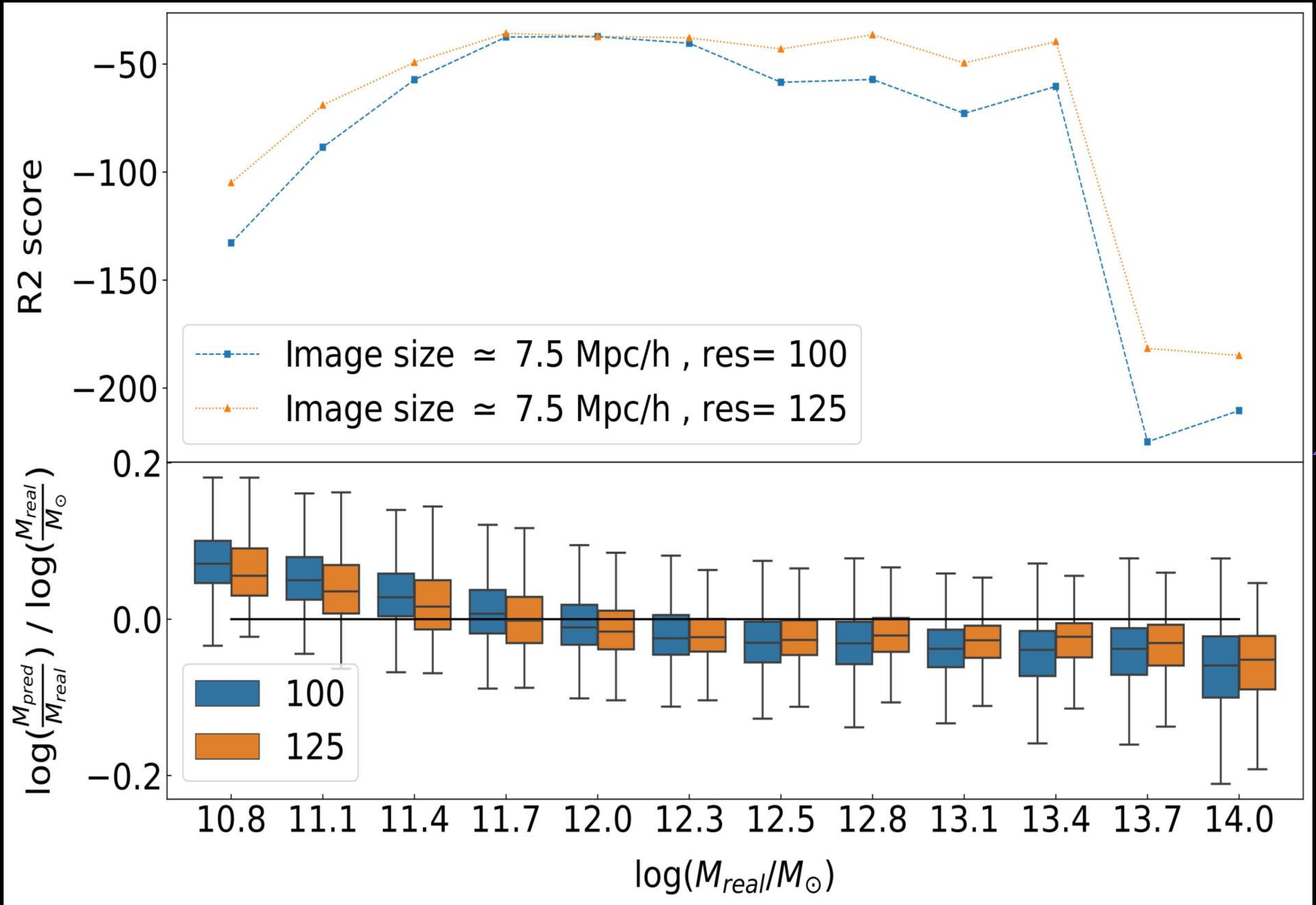
Tunning hyper-parameters



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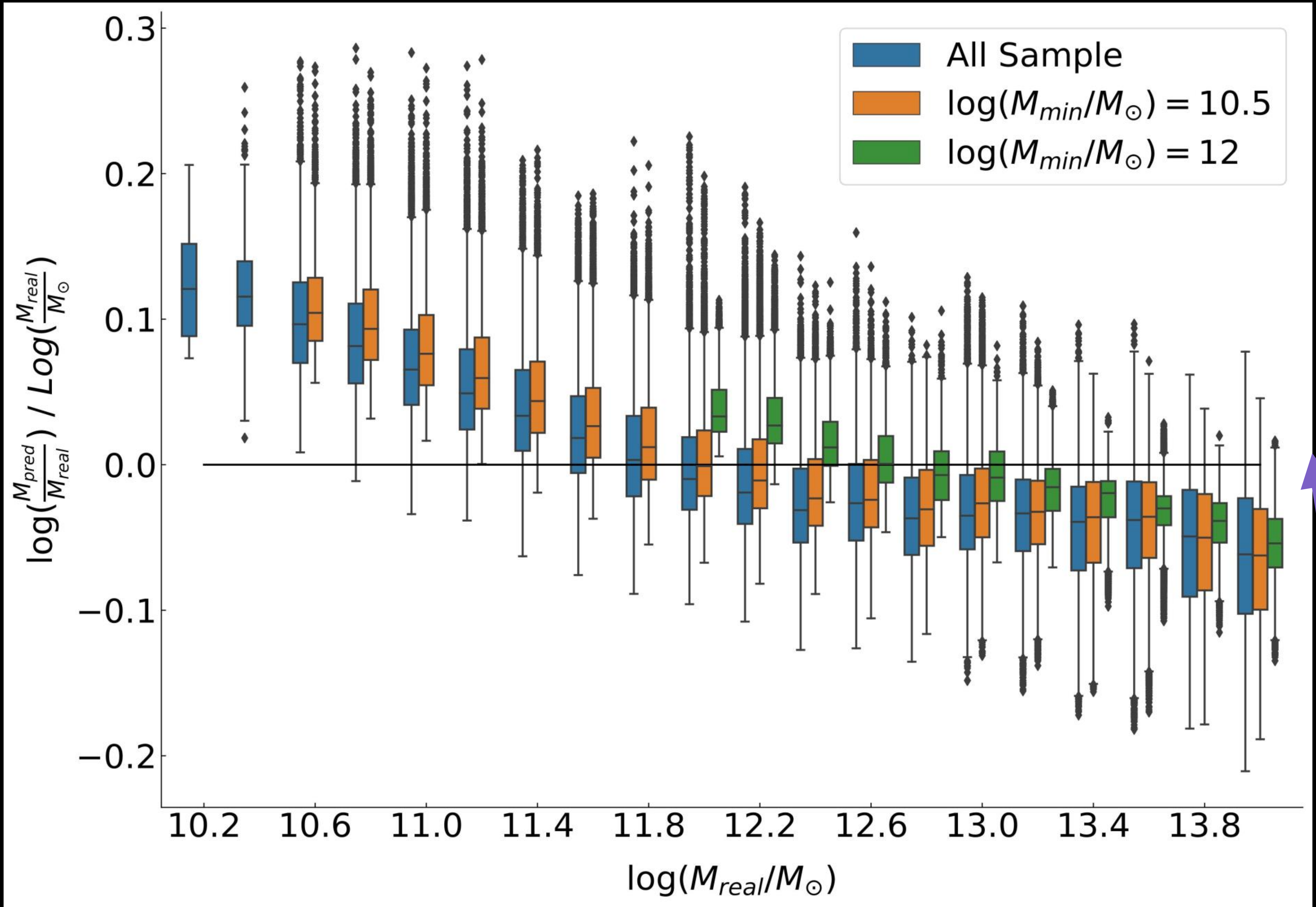

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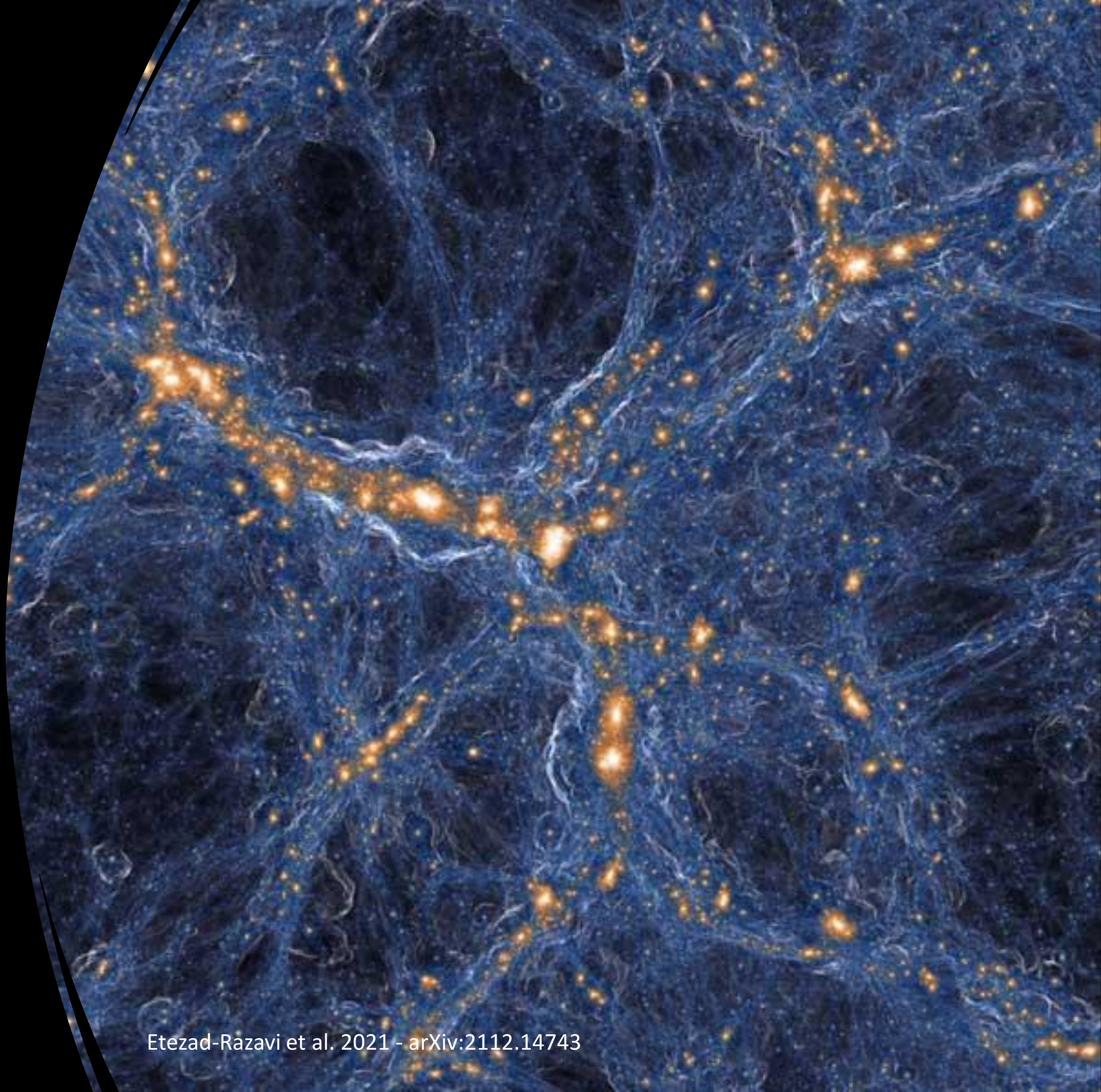
Minimum Halo Mass

Results



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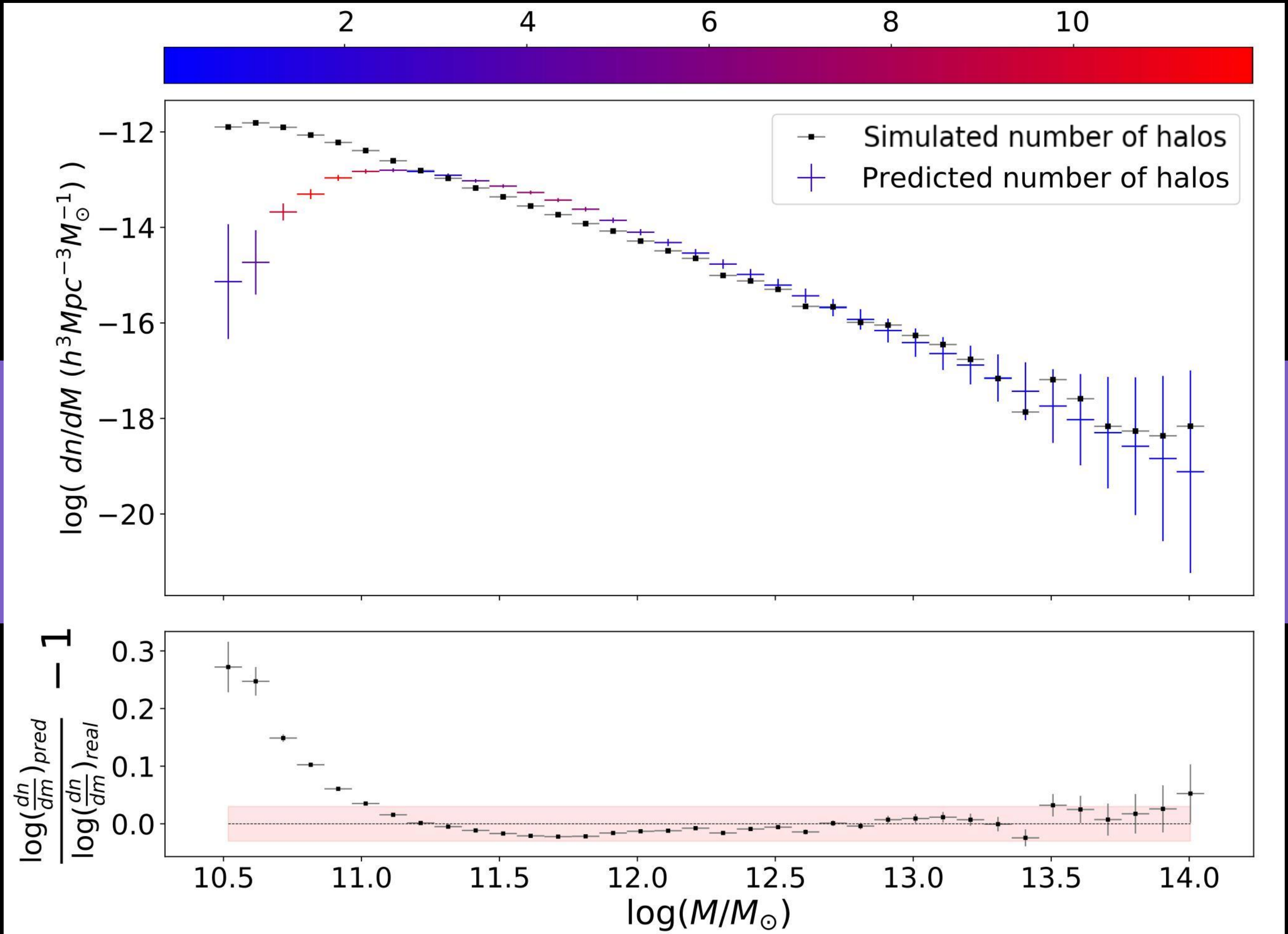

Halo Mass Function Prediction

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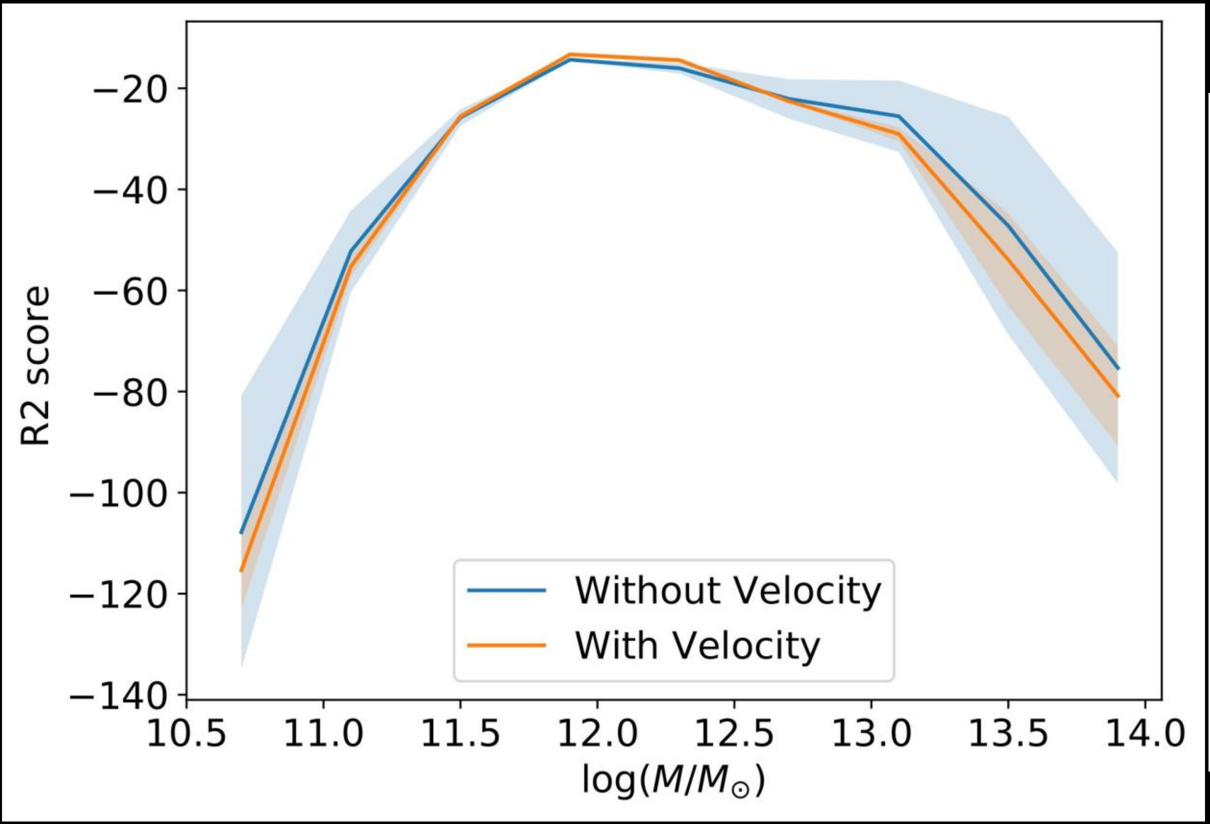
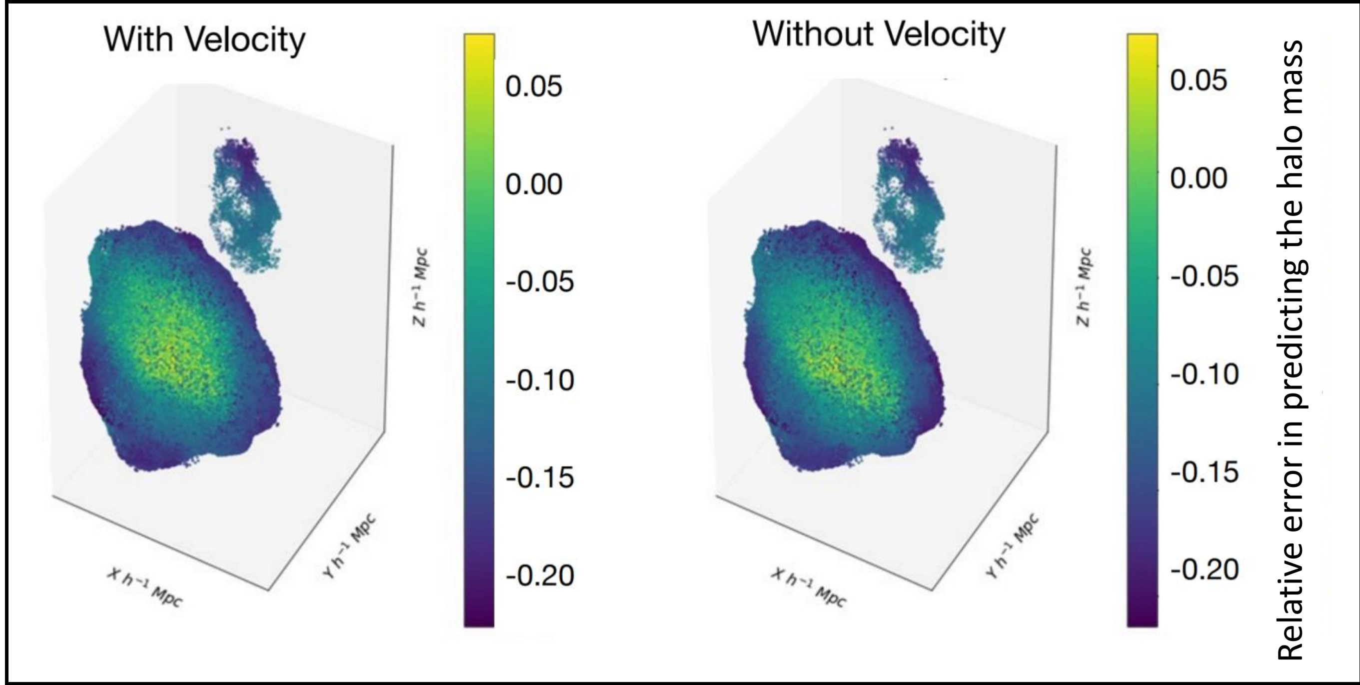
Standard Model of Cosmology

$$A_s = 2 \times 10^{-9}, \quad 10.5 \leq \log\left(\frac{M}{M_{sun}}\right) \leq 14$$

Adding velocity field information does not improve the performance of the model.





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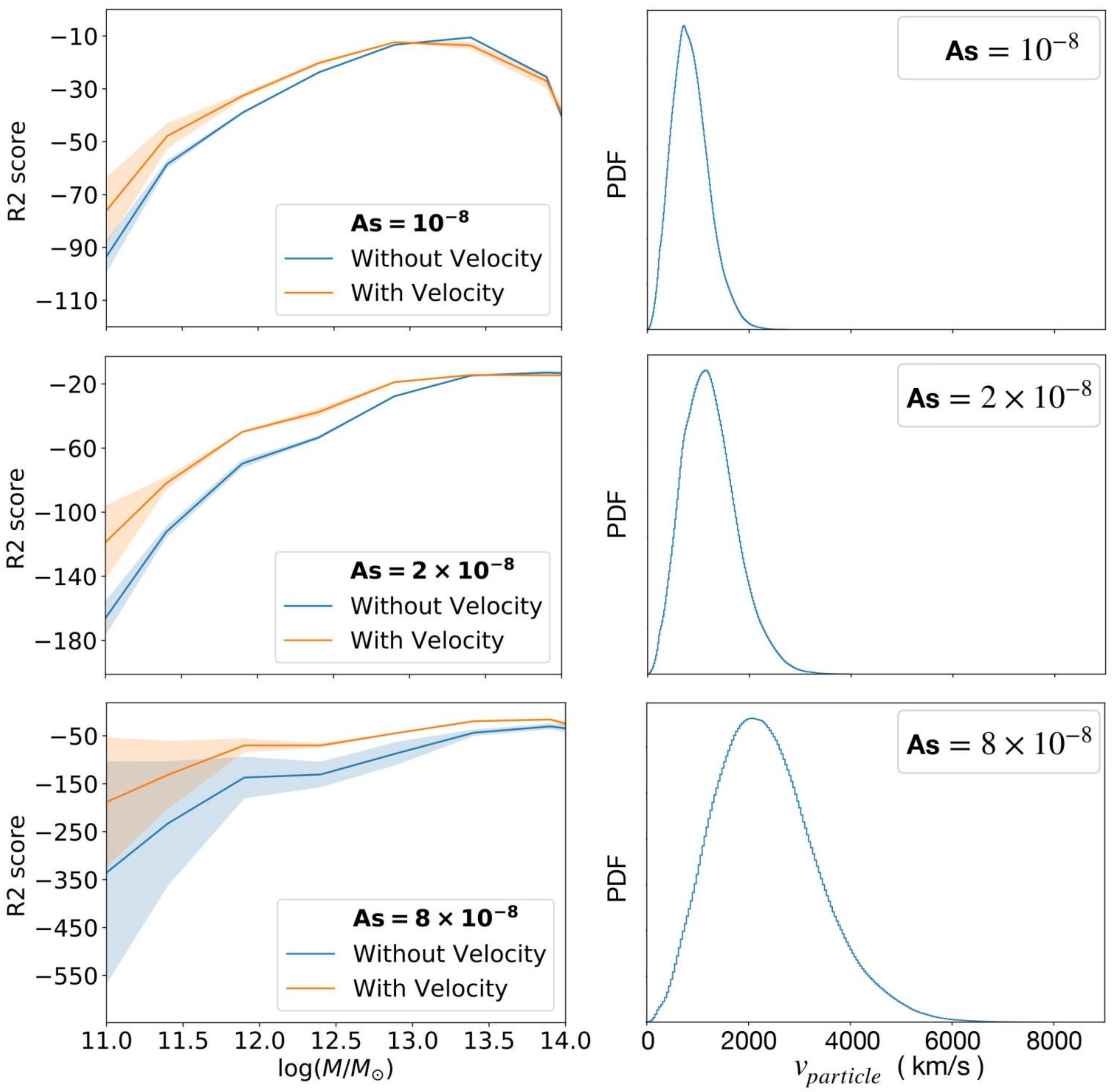
Effect of the velocity field information while increasing As



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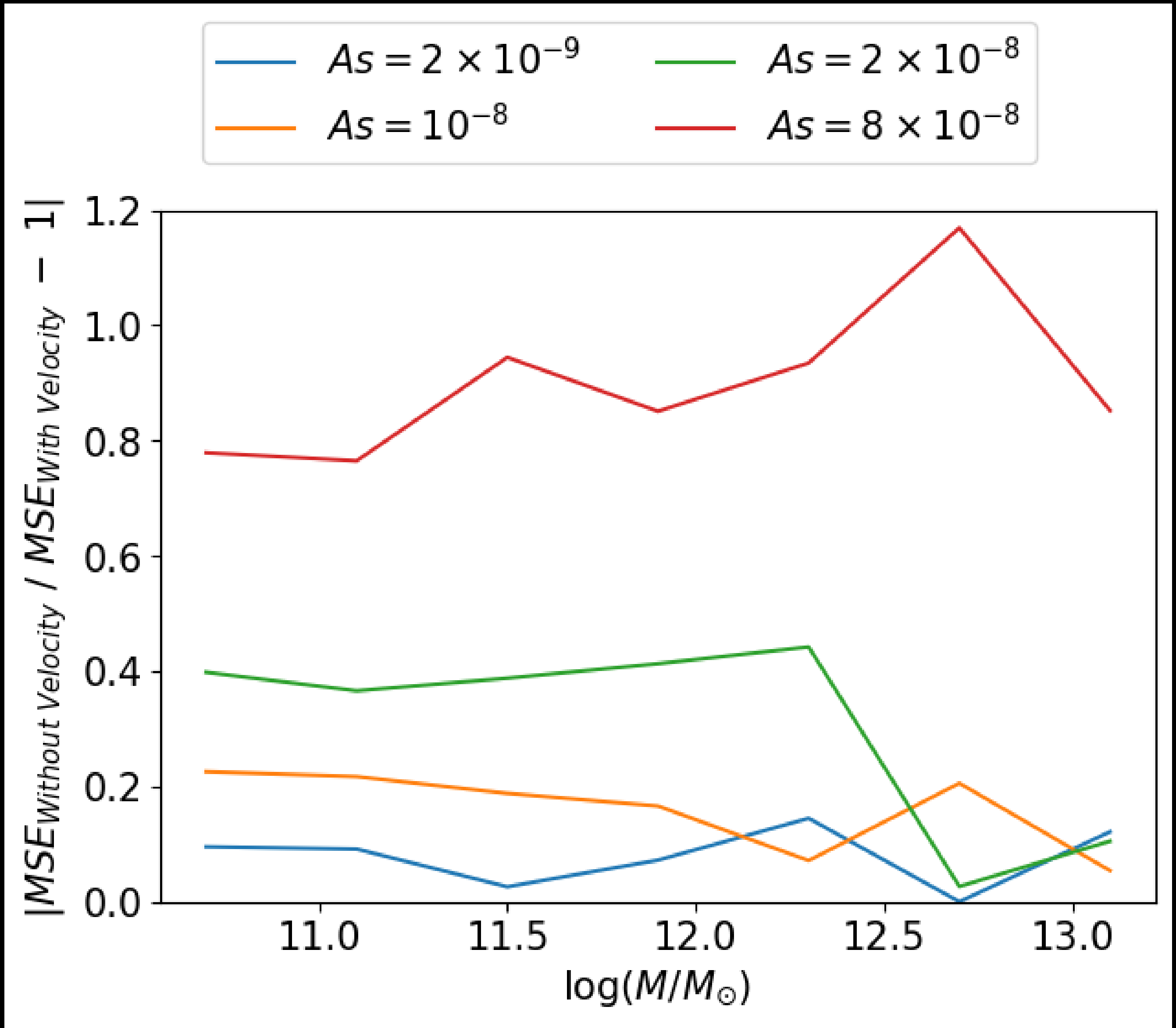
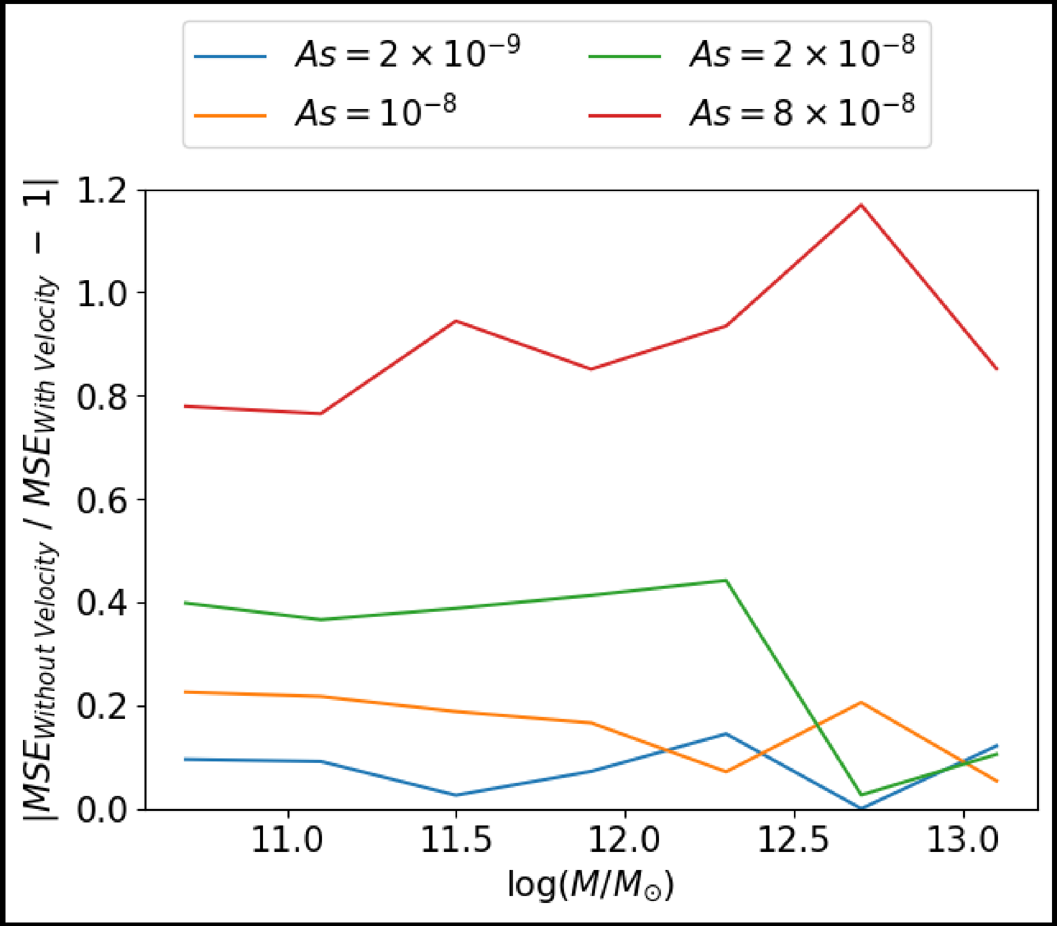


Model without velocity field information seems to fail to predict the Dark Matter halo mass for larger A_s values



Conclusion and future remarks

Interpretable CNN → **Insight into the process of halo collapse**

for ΛCDM *with* $A_s = 2 \times 10^{-9}$

$$10.5 \leq \log \frac{M}{M_\odot} \leq 14$$

Adding initial velocity field info doesn't change the accuracy of HMF prediction.

for $A_s > 2 \times 10^{-9}$

$$10.5 \leq \log \frac{M}{M_\odot} \leq 14$$

Neglecting initial velocity field info causes considerable inaccuracy compared to the model with velocity info.

Our result suggests that the effect of the velocity field on the halo formation is scale-dependent.

We can use this machinery to study structure formation in non-standard cosmologies.