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A physical and concise halo model based on the depletion radius

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Background

- Matter distribution

How is matter distribute in the universe?

Halo model

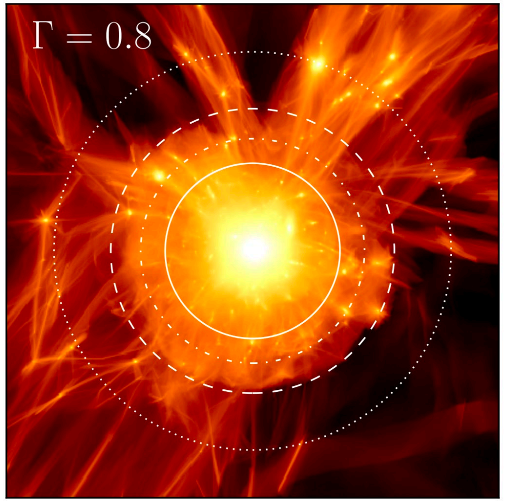
Small scales: The distribution of mass within each halo

Large scales: The spatial distribution of the haloes

Basic idea: **Density field = packed haloes**

More et al. (2015)

Cooray & Sheth (2002)



halo interior structure

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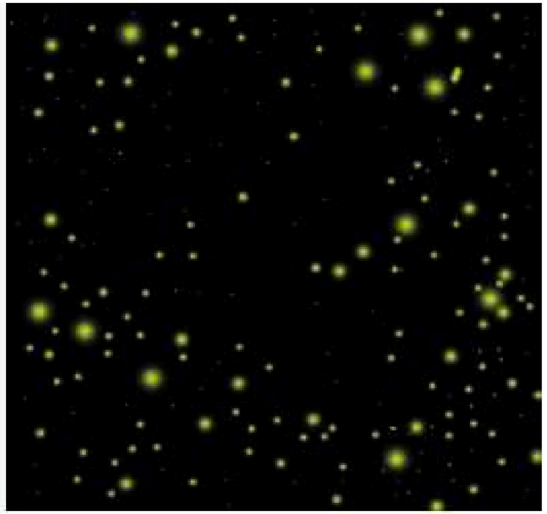

halo spatial distribution

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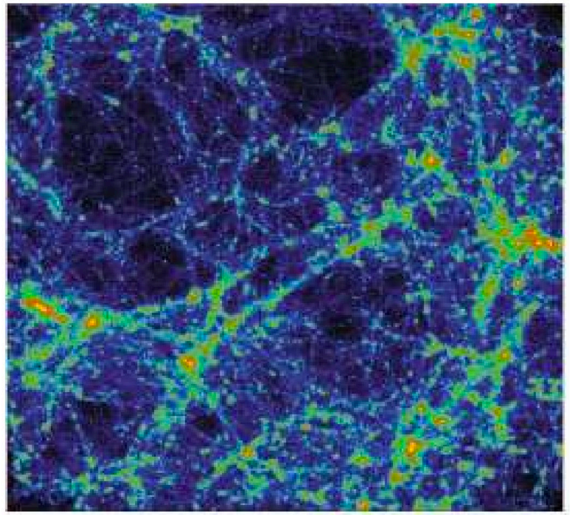
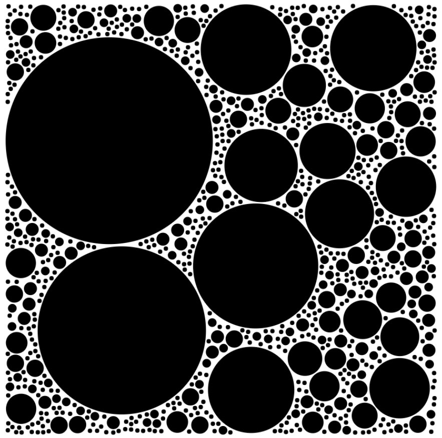


matter distribution

Background

- Halo exclusion

Haloes are independent objects that do not overlap with each other

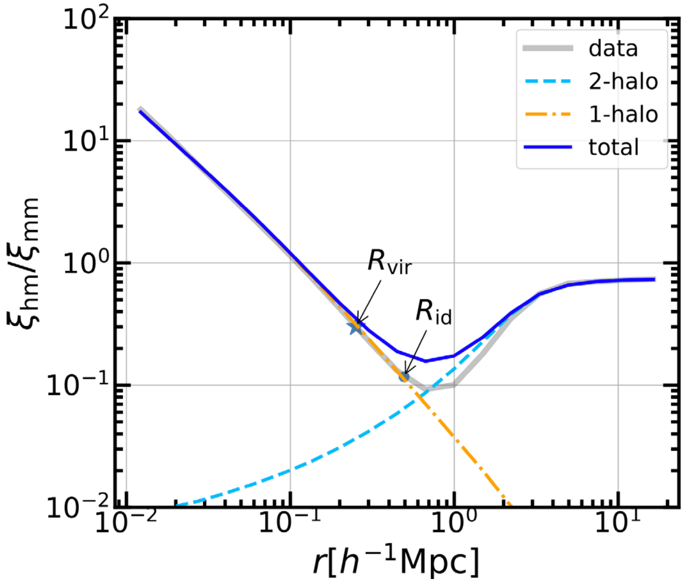


- **Standard halo model**

matter distribution around halo centre $\xi_{\rm hm}(r|M) = \langle \delta_{\rm h}(\boldsymbol{x}|M)\delta_{\rm m}(\boldsymbol{x}+\boldsymbol{r})\rangle$

1-halo term: $\xi^{\rm 1h}_{\rm hm}(r|m) = \dfrac{\rho(r|m)}{\bar{\rho}}$ (small scales)

2-halo term: $\xi^{\rm 2h}_{\rm hm}(r|m) = b(m)\xi_{\rm L}(r)$ (large scales)



- **Issues:**
  - Unphysical radius definition leads to the ambiguity in halo edges;
  - Conventional model is defective on transition scales due to halo exclusion;

A physical exclusion radius matching to the halo model is needed

Background

- Depletion radius

- **Mass flow rate:** $I_{\rm m}(r) \equiv 4\pi r^2 \rho(r) v_{\rm r}(r)$

- **Continuity equation of mass:**

$$\frac{\partial \rho(r)}{\partial t} + \frac{1}{4\pi r^2}\frac{\partial I_{\rm m}(r,t)}{\partial r} = 0$$

$$\text{Grow}: \ \partial I_{\rm m}/\partial r < 0, \ \partial\rho/\partial t > 0$$
$$\text{Deplete}: \ \partial I_{\rm m}/\partial r > 0, \ \partial\rho/\partial t < 0$$

- Maximum infall rate: **inner depletion radius $R_{\rm id}$**
  - Growth boundary: Grow vs. Deplete
  - **Exclusion boundary: Halo vs. Environment**

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***$R_{\rm id}$* as a natural choice for the halo boundary**

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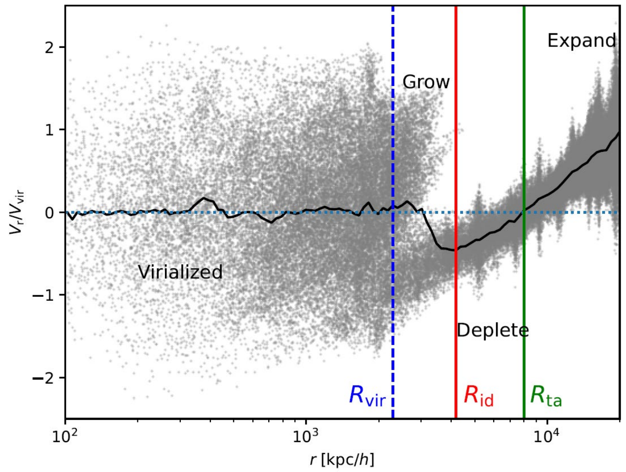
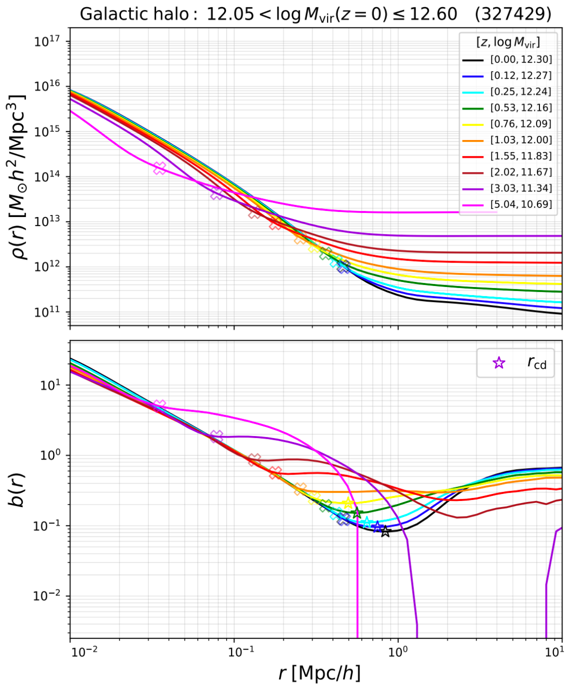
Build a physical halo model based on $R_{\rm id}$



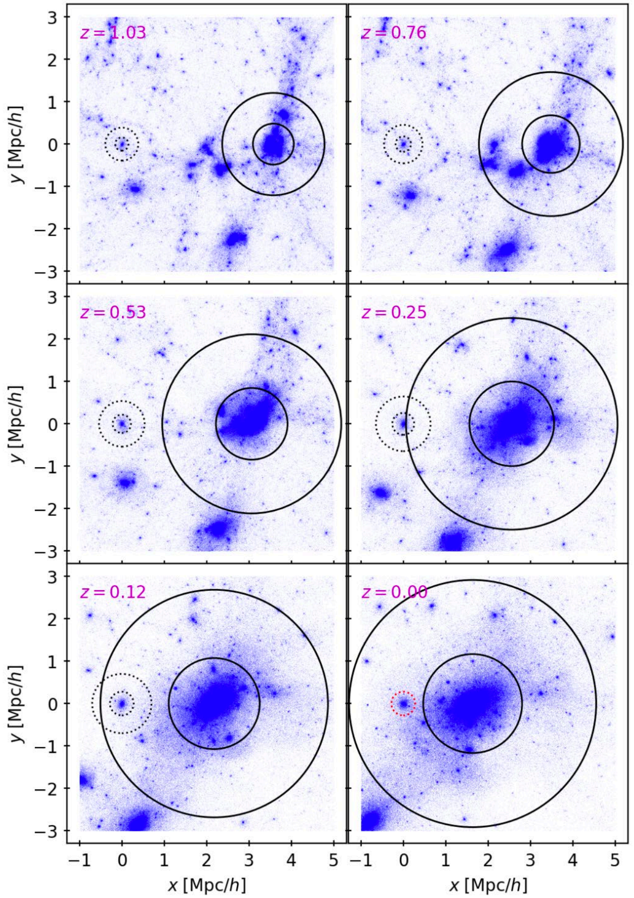
Fong & Han (2021)



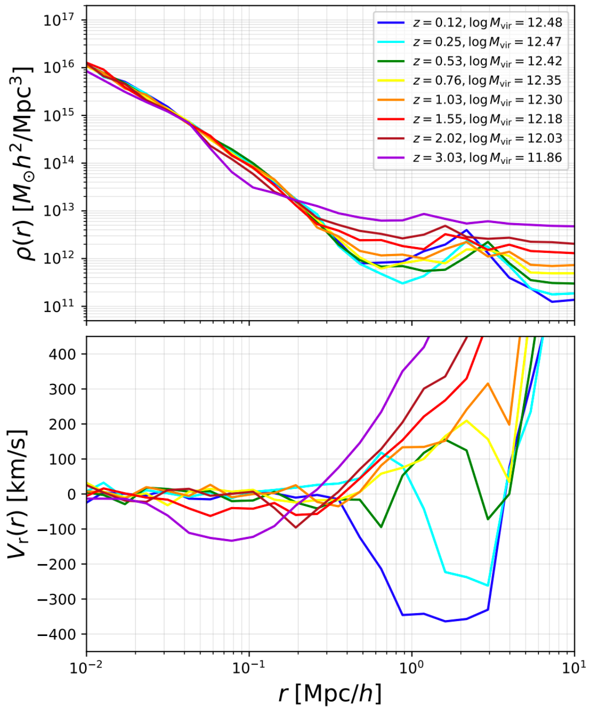
Gao et al. (2023)

Depletion halo model

- A self-consistent halo catalog



small halo profiles



Gao et al. (2023)

- **Catalog cleaning:**

remove the haloes overlapping with more massive neighbours

- **Exclusion scale:** $R_{\rm ex}(m_1, m_2) = R_{\rm id}(m_1)+R_{\rm id}(m_2)$

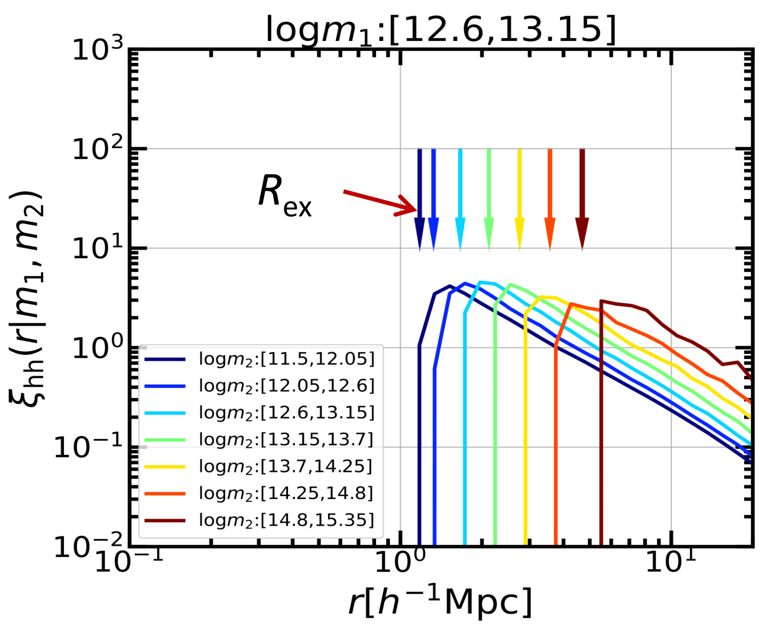
- **Isolated halo sample:** $d > R_{id}(m_1) + R_{id}(m_2)$

Depletion halo model

- Exclusion feature

- **Halo-halo correlation function** $$\xi_{\rm hh}(r|m,M)=\frac{\langle n(r,m)|M\rangle}{\bar{n}(m)}-1$$

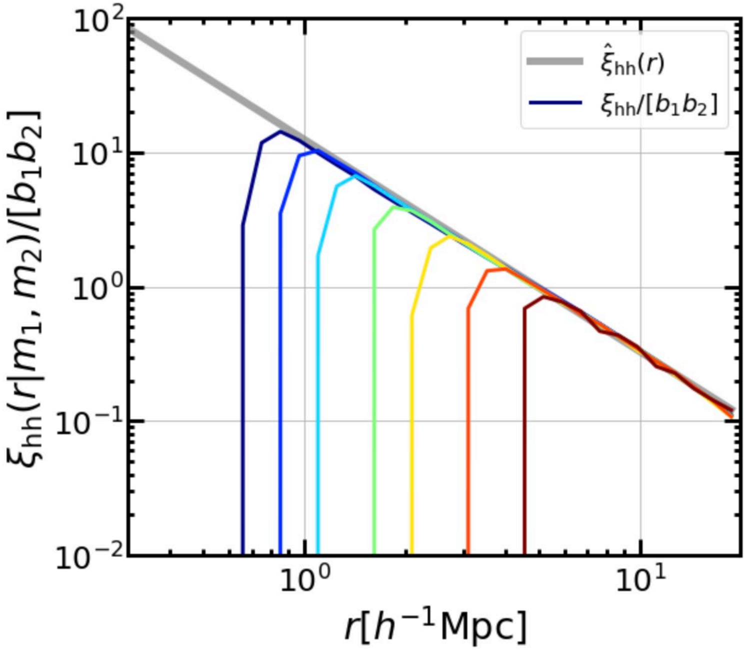
Exclusion scale: $R_{\rm ex}(m_1,m_2)=R_{\rm id}(m_1)+R_{\rm id}(m_2)$



- Self-similar for different halo masses
- Truncate at the exclusion scale

scaled by halo biases

- **Unit halo correlation** $$\hat{\xi}_{\rm hh}(r)=\frac{\xi_{\rm hh}(r|m_1,m_2)}{b(m_1)b(m_2)}$$



1. a universal halo spatial distribution $\hat{\xi}_{\rm hh}(r)=\left(\frac{r}{r_0}\right)^{-\gamma}$
2. a truncation depending on the halo mass

$$1+\xi_{\rm hh}(r|m_1,m_2)=[1+b(m_1)b(m_2)\hat{\xi}_{\rm hh}(r)]{\rm H}(r-r_{\rm t}),$$

Depletion halo model

- Model framework

- **Improvements:**

$\xi_{\rm hm}(r|M)$

- 1-halo term → $\xi^{\rm 1h}_{\rm hm}$: Mass from the central halo
- 2-halo term
  - $\xi^{\rm res}_{\rm hm}$: Neighboring resolved haloes
  - $\xi^{\rm unr}_{\rm hm}$: Unresolved haloes and mass

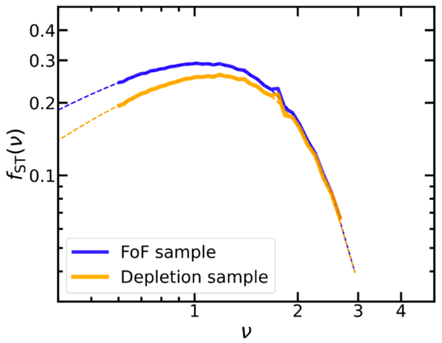
new free parameter →

Effective bias factor: b_{unr}

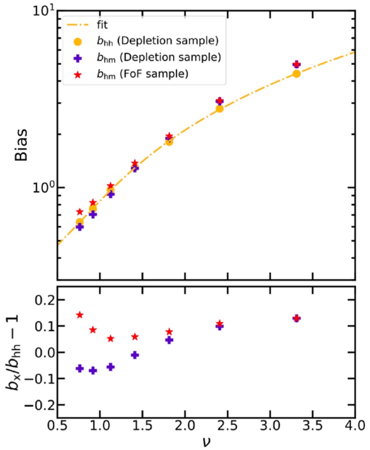
- Contribution of unresolved mass
- Obtained by fitting
- Mass conservation is maintained;

- **Ingredients:** adjust for isolated halo sample

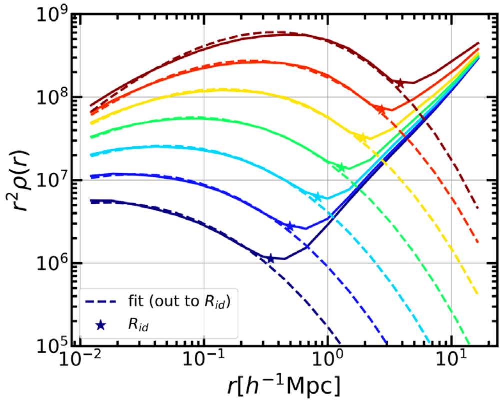
halo mass function



halo bias



halo density profile



Results

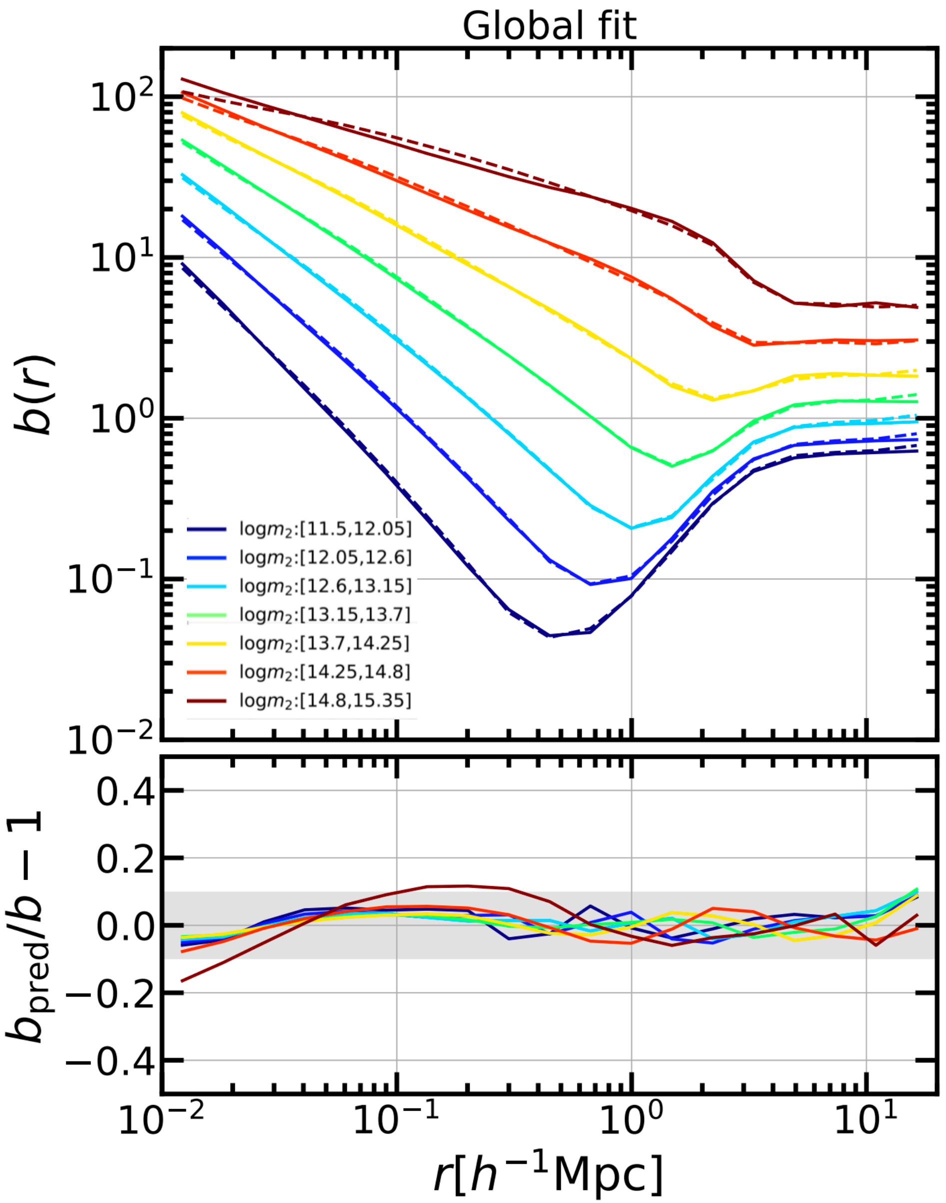
- Fits to bias profiles

Relative density profile: $$b(r) = \frac{\xi_{\rm hm}(r)}{\xi_{\rm mm}(r)} = \frac{\langle \delta(r) \rangle}{\xi_{\rm mm}(r)}$$

Mass range: $10^{11.5} h^{-1}{\rm M}_\odot < M_{\rm vir} < 10^{15.35} h^{-1}{\rm M}_\odot$

Radial range: $0.01 h^{-1}{\rm Mpc} < r < 20 h^{-1}{\rm Mpc}$

- Single free parameter: $b_{\rm unr}$
- $b(r)$ with accuracy $\lesssim 10\%$ across wide radial and mass range
- Deviations of the highest-mass haloes on small scales are caused by fixed parameter relation in the 1-halo term.



Results

- Compare with other works

- **Hayashi & White (HW08):**

$$\xi_{\rm model}(r;M) = \begin{cases} \xi_{\rm 1h}(r) & \text{if } \xi_{\rm 1h}(r) \geq \xi_{\rm 2h}(r), \\ \xi_{\rm 2h}(r) & \text{if } \xi_{\rm 1h}(r) < \xi_{\rm 2h}(r), \end{cases}$$

$$\xi_{\rm 1h}(r) = \frac{\rho_{\rm halo}(r;M) - \overline{\rho}_{\rm m}}{\overline{\rho}_{\rm m}}$$

$$\xi_{\rm 2h}(r) = b(M)\xi_{\rm lin}(r),$$

- **Diemer & Kravtsov (DK14):**

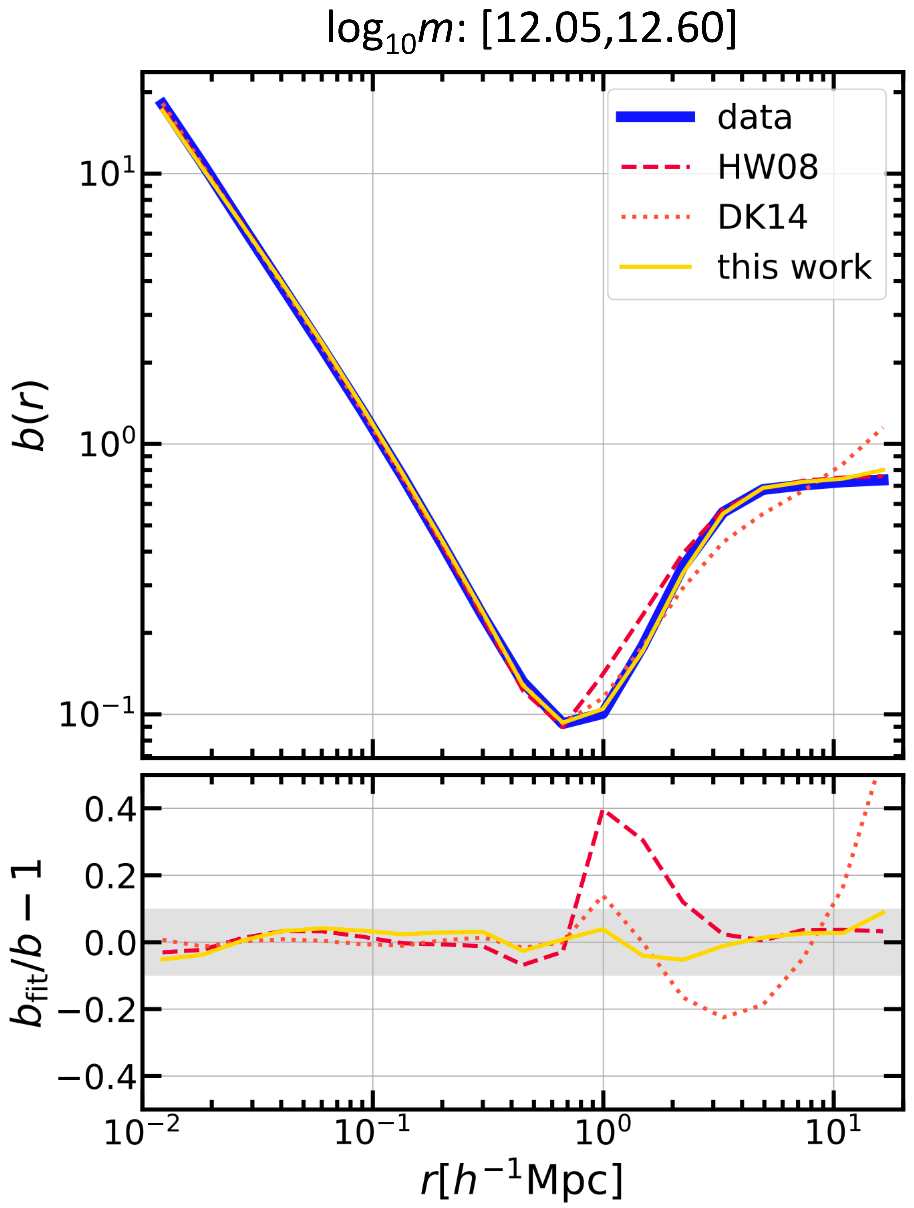
$$\rho(r) = \rho_{\rm inner} \times f_{\rm trans} + \rho_{\rm outer}$$

$$\rho_{\rm inner} = \rho_{\rm Einasto} = \rho_{\rm s} \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_{\rm s}}\right)^{\alpha} - 1\right]\right)$$

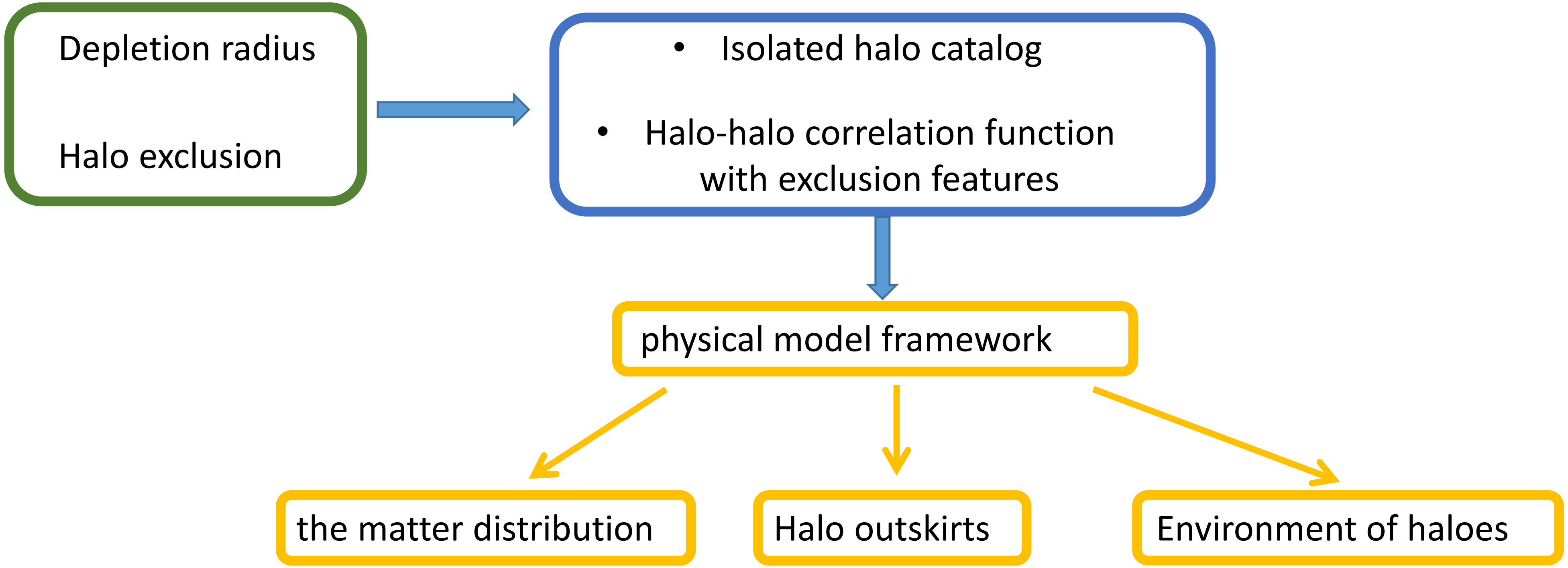
$$f_{\rm trans} = \left[1 + \left(\frac{r}{r_{\rm t}}\right)^{\beta}\right]^{-\frac{\gamma}{\beta}}$$

$$\rho_{\rm outer} = \rho_{\rm m}\left[b_{\rm e}\left(\frac{r}{5\,R_{\rm 200m}}\right)^{-s_{\rm e}} + 1\right].$$

- **Our model:** performs well on both intermediate and large scales



Summary



- Our model reproduces $b(r)$ with accuracy $\lesssim 10\%$ across wide radial and mass ranges;
- Mass conservation is automatically maintained in our model after considering the unresolved mass;
- Our model performs well in both linear and non-linear scales compared with previous work.