Numerical Cosmology

Lecture 2

Halo Finding and Mock Galaxy Catalogs

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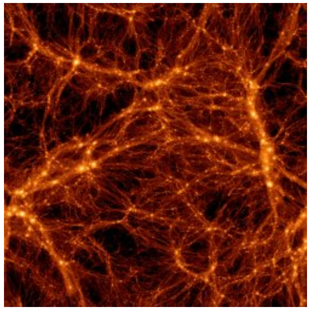
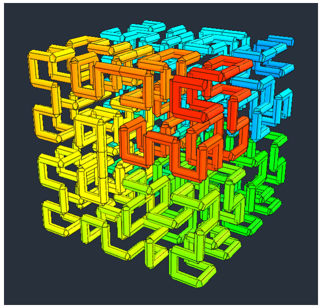
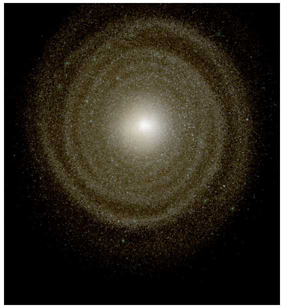
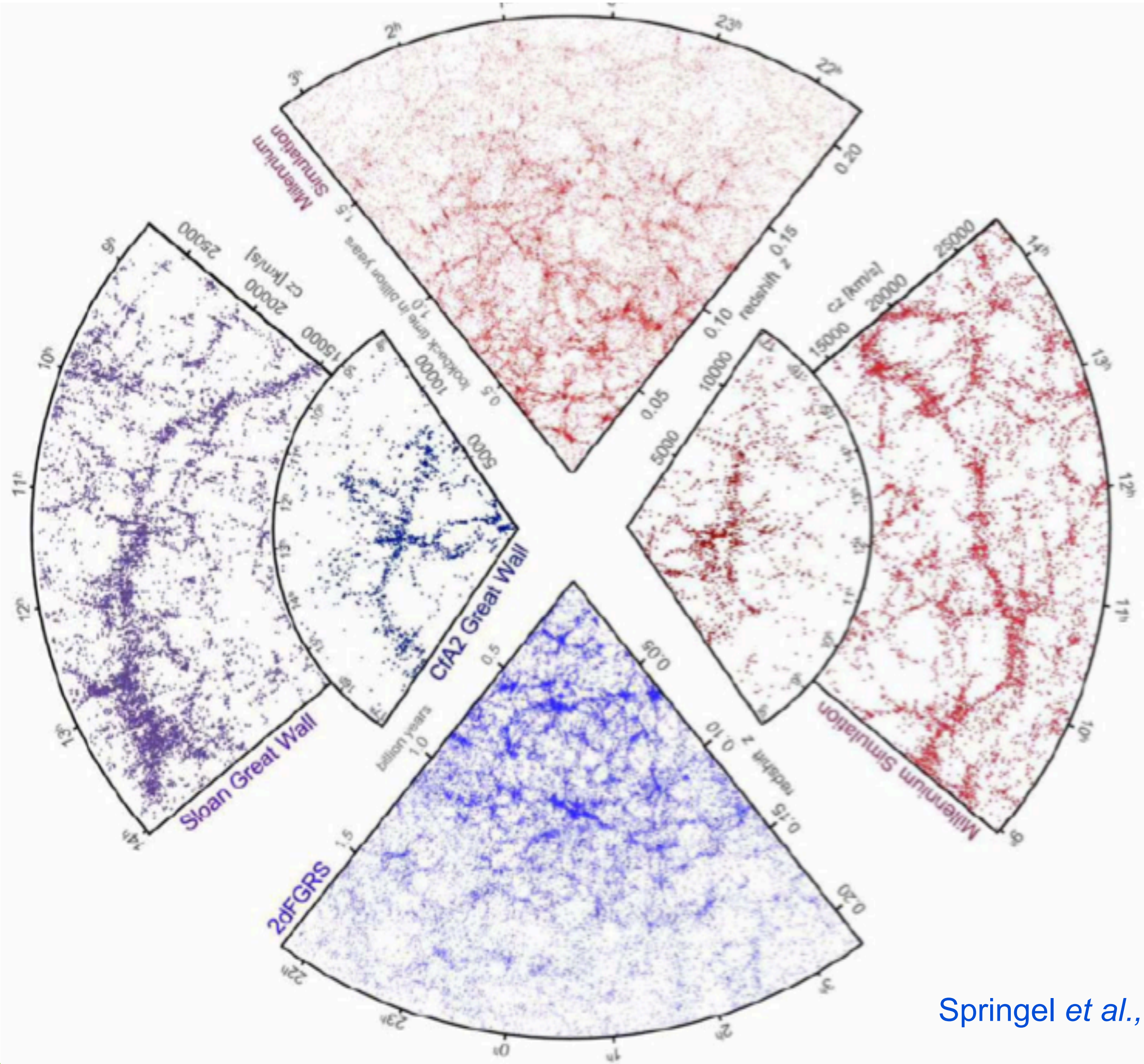




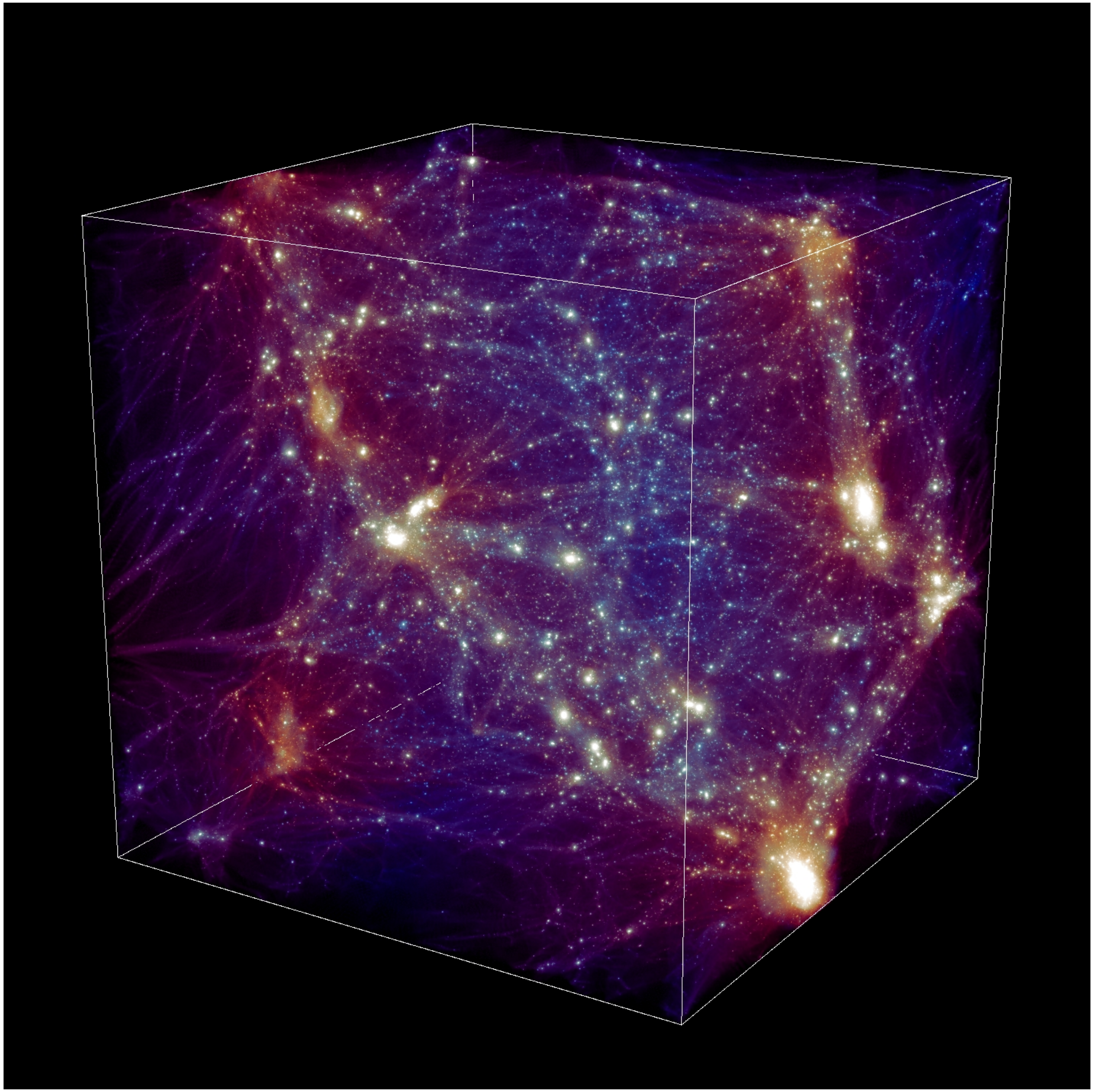


Cosmological simulations



Springel *et al.,* Nature, 2006

The Universe is made of dark matter halos



Press-Schechter Theory

PS theory defines a halo as a spherical Lagrangian region of mass $M = \frac{4\pi}{3}\rho_m R^3$.

The density fluctuations at the smoothing scale R are Gaussian with variance $\sigma^2(R) = \frac{1}{8\pi^3}\int_0^{+\infty} 4\pi k^2 P(k) W(kR) \mathrm{d}k$. The spherical collapse model says the spherical region will collapse if $\delta > \delta_c \simeq 1.686$ (weakly cosmology dependent).

The mass fraction in collapse region of mass M is given by:

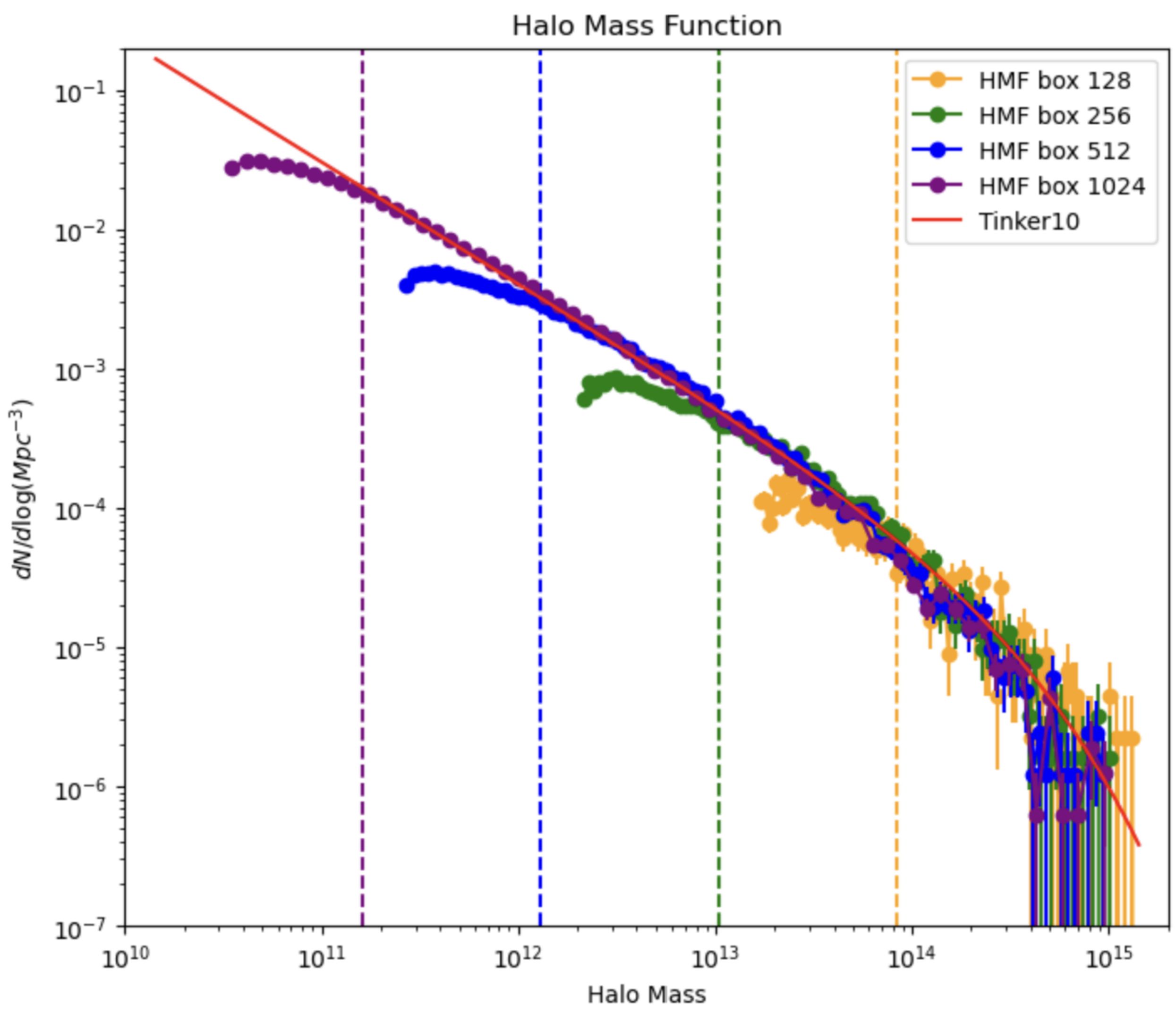
$$F(>M) = 2\int_{\frac{\delta_c}{\sigma(M)}}^{+\infty} \frac{1}{\sqrt{2\pi}} \exp(-\nu^2/2) \mathrm{d}\nu \quad \text{where} \quad \nu = \frac{\delta}{\sigma(M)}.$$

The PS halo mass function(HMF) is therefore ($N_{\rm halo} = \frac{dn}{dM}\mathrm{d}M\mathrm{d}V$):

$$\frac{dn}{dM} = -\frac{\rho_m}{M}\frac{dF}{dM} = -\sqrt{\frac{2}{\pi}}\frac{\rho_m}{M}\frac{\delta_c}{M^2}\frac{d\sigma}{dM}\exp\left(-\frac{\delta_c^2}{2\sigma^2}\right).$$

Key property: self-similarity via $\sigma(M, z)$. Good fit for N-body simulations.

The Halo Mass Function (HMF)



Halo Definitions

Spherical collapse model:

$\overline{\rho}_{\rm vir} = 178\rho_m$ for Einstein-de Sitter

$\overline{\rho}_{\rm vir} = 337\rho_m$ for LCDM

Virialized region:

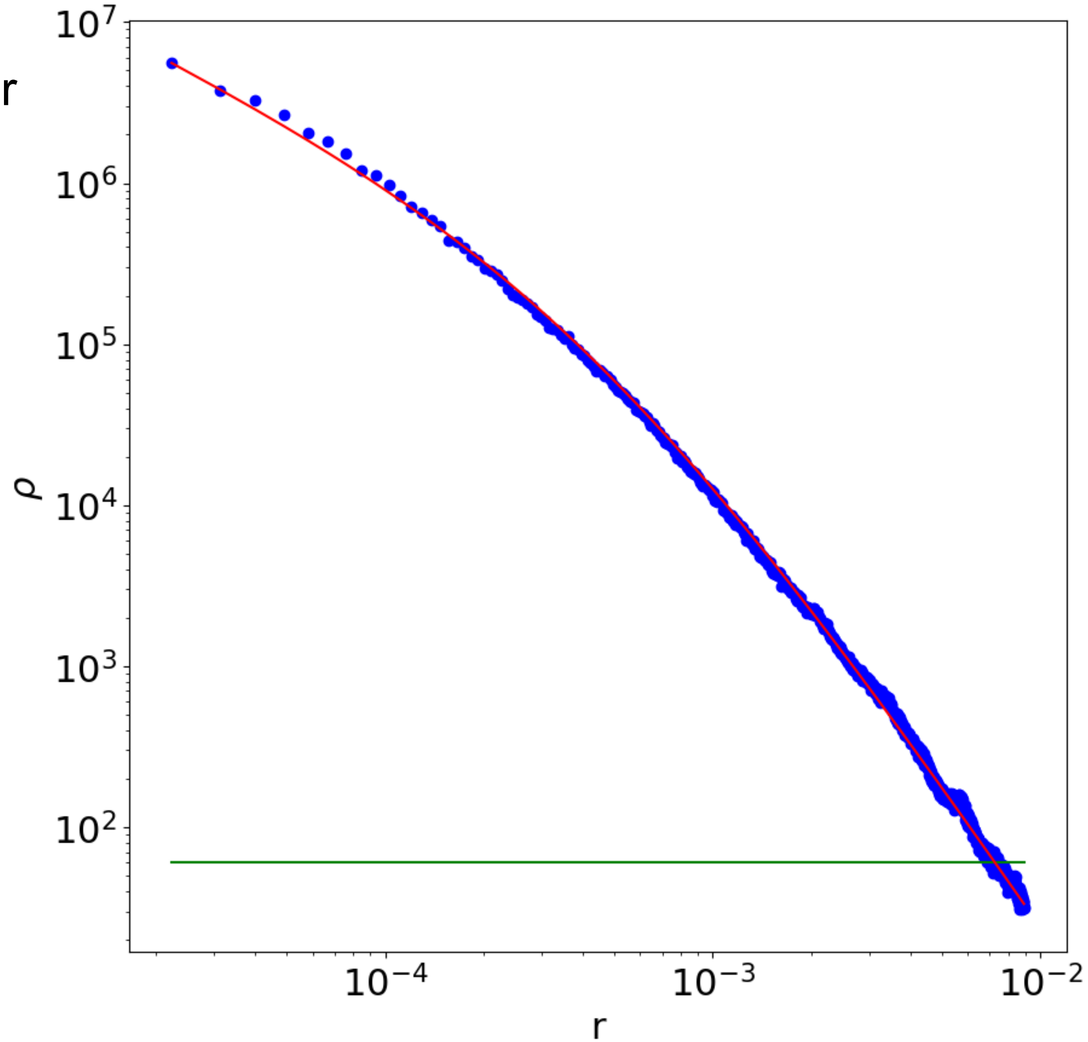
$\overline{\rho}_{\rm vir} = 200\rho_c = 666\rho_m$

Press-Schechter statistics:

$\overline{\rho}_{\rm vir} = 200\rho_m$

Conclusion: $\overline{\rho}_{\rm vir} = \Delta_{\rm vir}\rho_m$

$\Delta_{\rm vir} = 178,\ 200,\ 337,\ 666$?



Halo Profiles

Singular Isothermal Sphere model:

$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-2} \quad \overline{\rho}_{\rm vir} = 3\rho_{\rm min}$$

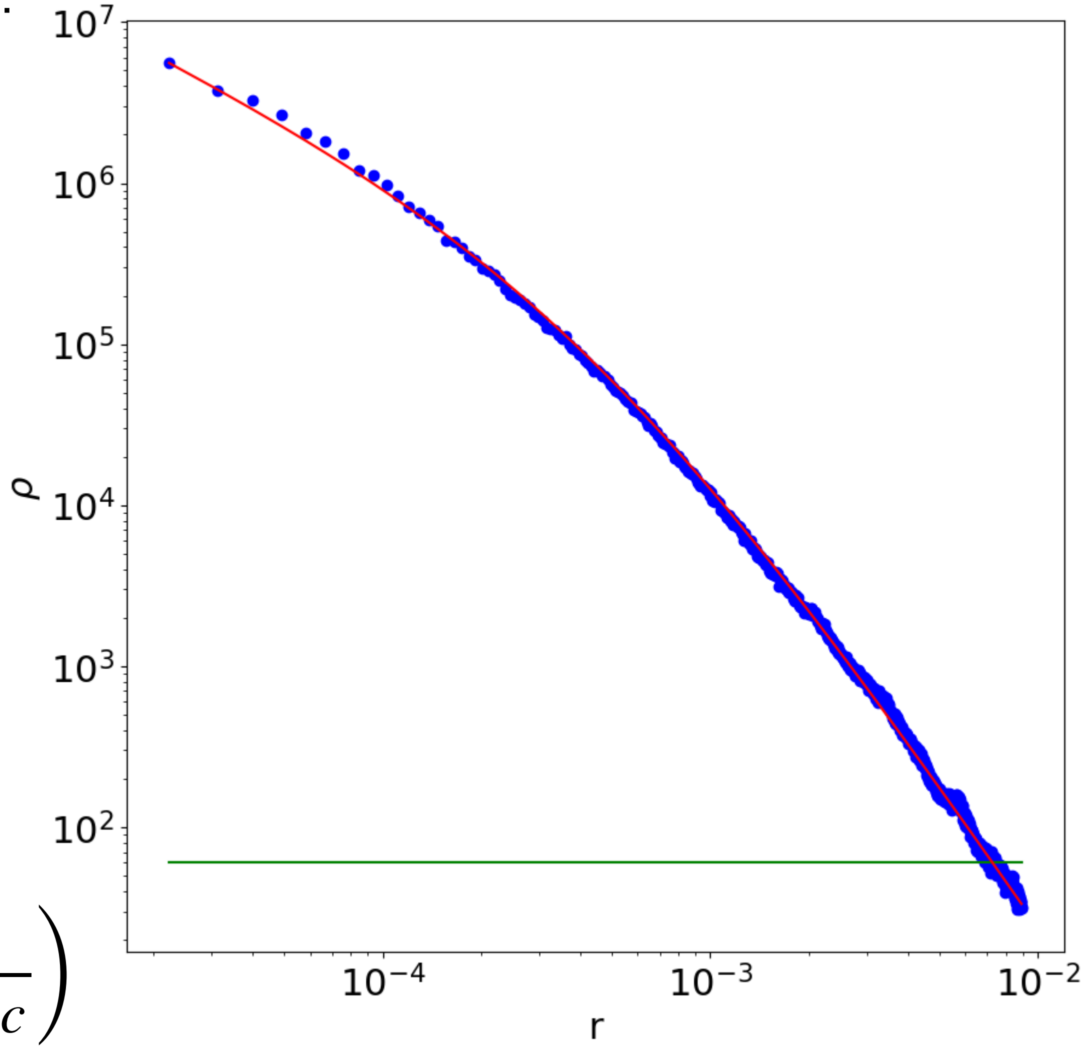
$$M_{\rm vir} = 4\pi\rho_s r_s^2 R_{\rm vir}$$

Navarro-Frenk-White model:

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

$$c = \frac{R_{\rm vir}}{r_s} \qquad \overline{\rho}_{\rm vir} = f(c)\rho_{\rm min}$$

$$M_{\rm vir} = 4\pi\rho_s r_s^3 \left(\ln(1+c) - \frac{c}{1+c}\right)$$



Halo Finding

Friends-Of-Friends: group particles within linking length $h = 0.2\Delta x$ which corresponds to $\rho_{\rm min} = \dfrac{6m}{4\pi h^3} \simeq 60\rho_m$ or $\overline{\rho}_{\rm vir} = 3\rho_{\rm min} \simeq 180\rho_m$.

This definition gives almost perfect Press-Schechter-like halo statistics.

Problem: what about the halo center?

Spherical Over-Density: detect peaks using $\rho_{\rm min}$ and compute the mass within $R_{\rm vir}$.

Problem: what about merging halos and what about sub-halos?

Peak-patch segmentation using saddle surfaces (Morse theory).

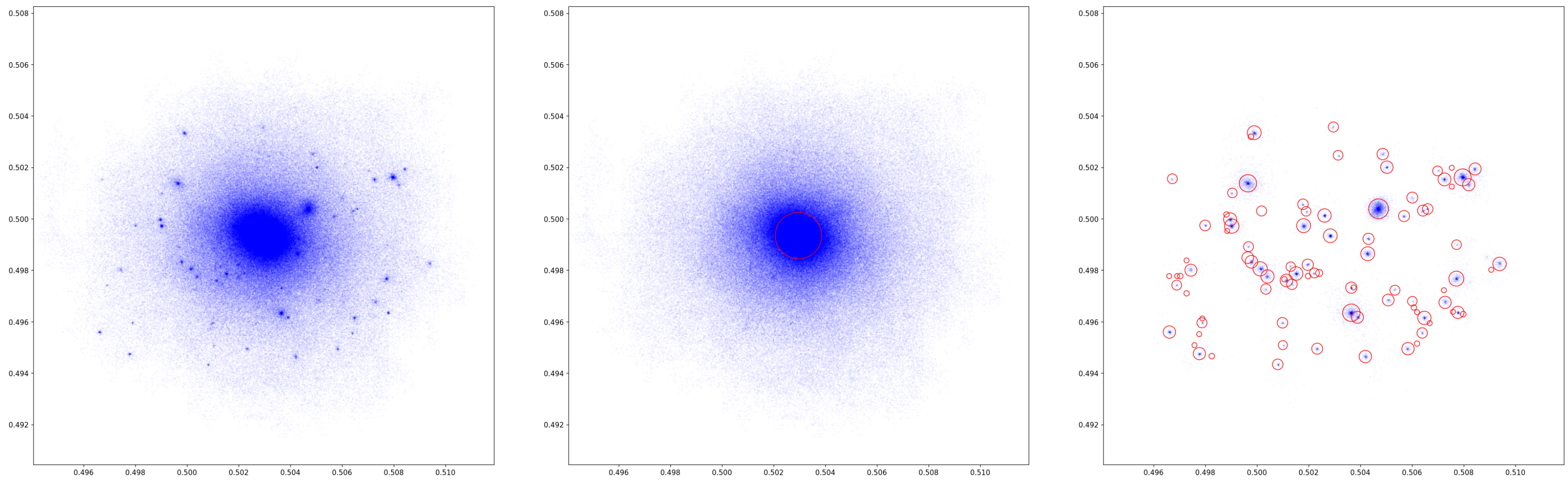
Halo/sub-halos decomposition using binding energy criterion.

Main halo (central) definition using most massive peak patches within halo region.

Various algorithms: HOP, AdaptaHOP, Subfind, PHEW, AHF, Rockstar…

Satellites and Centrals

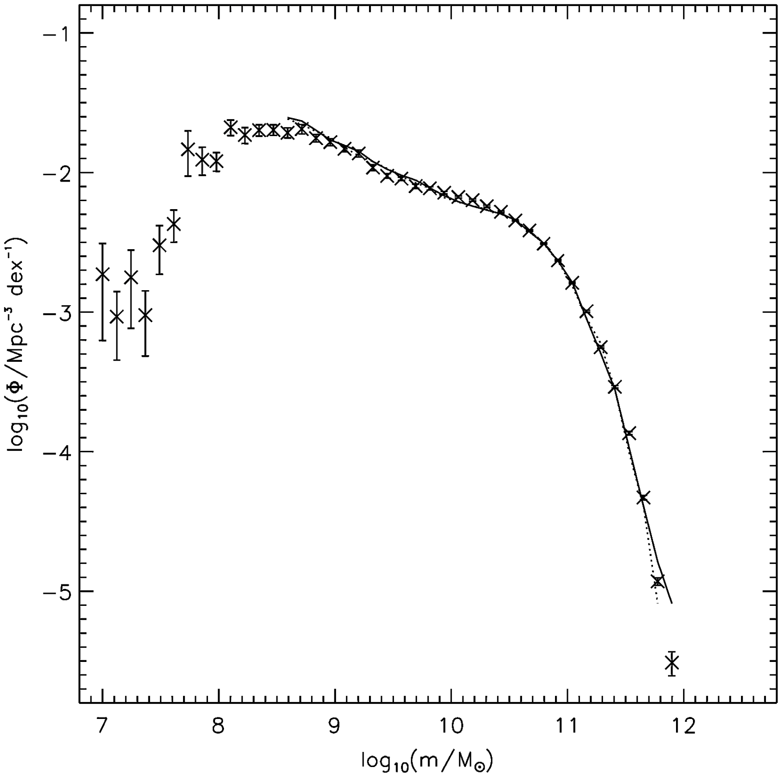
Example of main halo and sub-halos decomposition using PHEW in the RAMSES code.



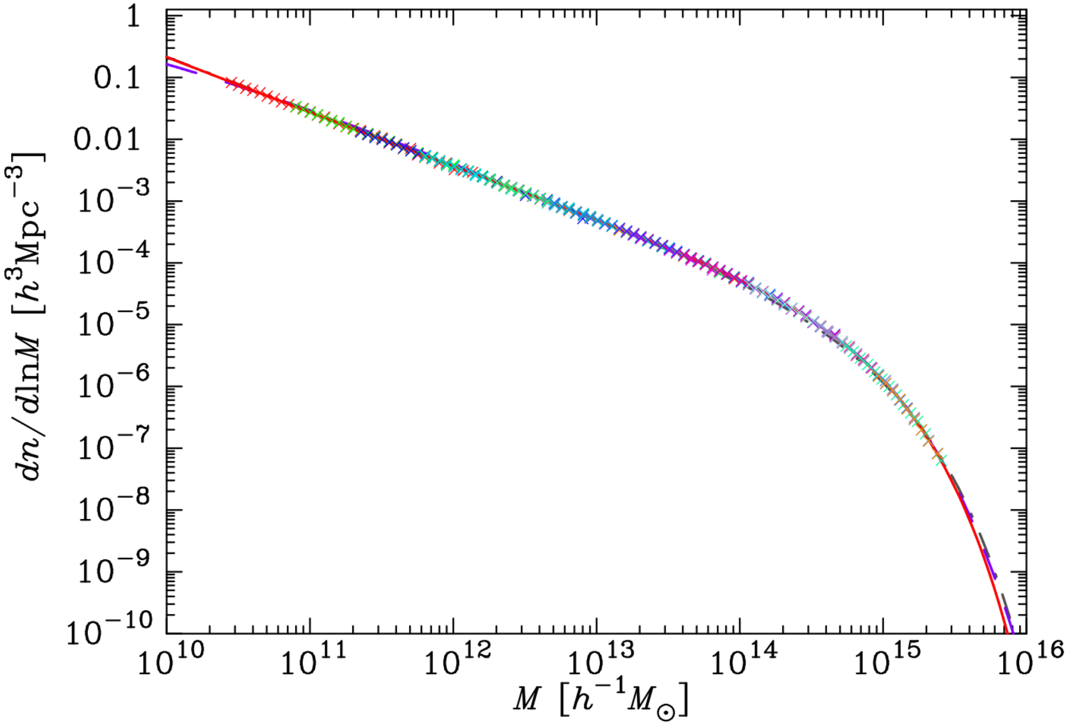
Binding energy: $\frac{1}{2}\left(\mathbf{v}_p - \mathbf{v}_0\right)^2 + \phi\left(\mathbf{x}_p - \mathbf{x}_0\right) < \phi\left(\mathbf{x}_{\mathrm{saddle}} - \mathbf{x}_0\right)$

Matching Main Halos with Central Galaxies

Moster et al. 2010



Warren et al. 2018



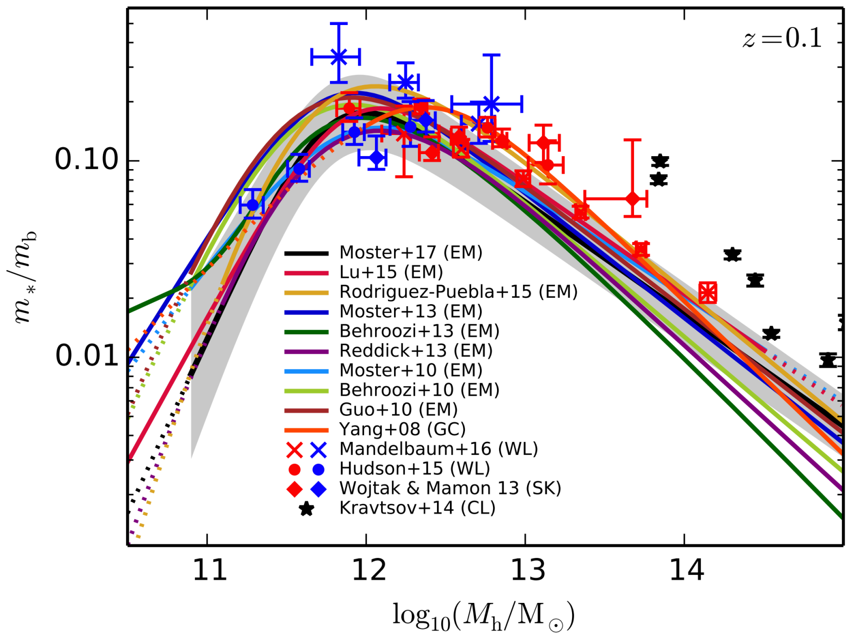
Galaxy stellar mass function

Dark matter halos mass function

Conroy & Wechsler 2009, Guo et al. 2010

Stellar Mass to Halo Mass Relation

Moster et al. (2018)



Conversion of baryons into stars is remarkably inefficient at all masses.

Stellar feedback regulates SF at low halo masses.

AGN feedback quenches star formation at high halo masses.

Abundance Matching Model for Galaxies

We use the SMHM relation to compute the stellar mass of the central galaxy inside each dark matter halo with $M_1 \simeq 10^{12} \mathrm{M}_\odot$, $\beta = 1.4$, $\gamma = 0.6$ and $F = 0.035$

$$\frac{M_*}{M_h} = 2F \left[\left(\frac{M_{\rm vir}}{M_1} \right)^{-\beta} + \left(\frac{M_{\rm vir}}{M_1} \right)^{\gamma} \right]^{-1}$$

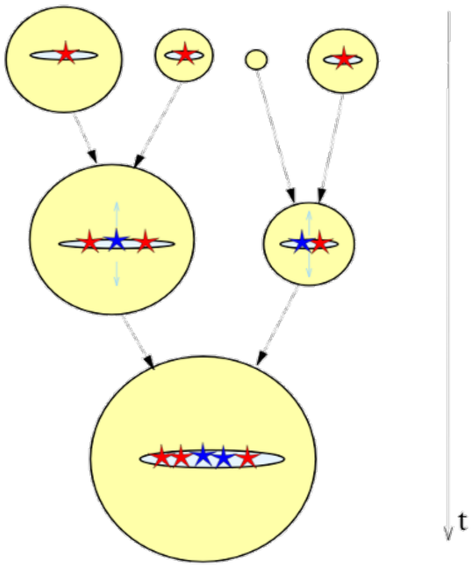
(Berhoozi *et al.* 2013)

We need also to predict the stellar mass for satellite halos. For this we need a merger tree.

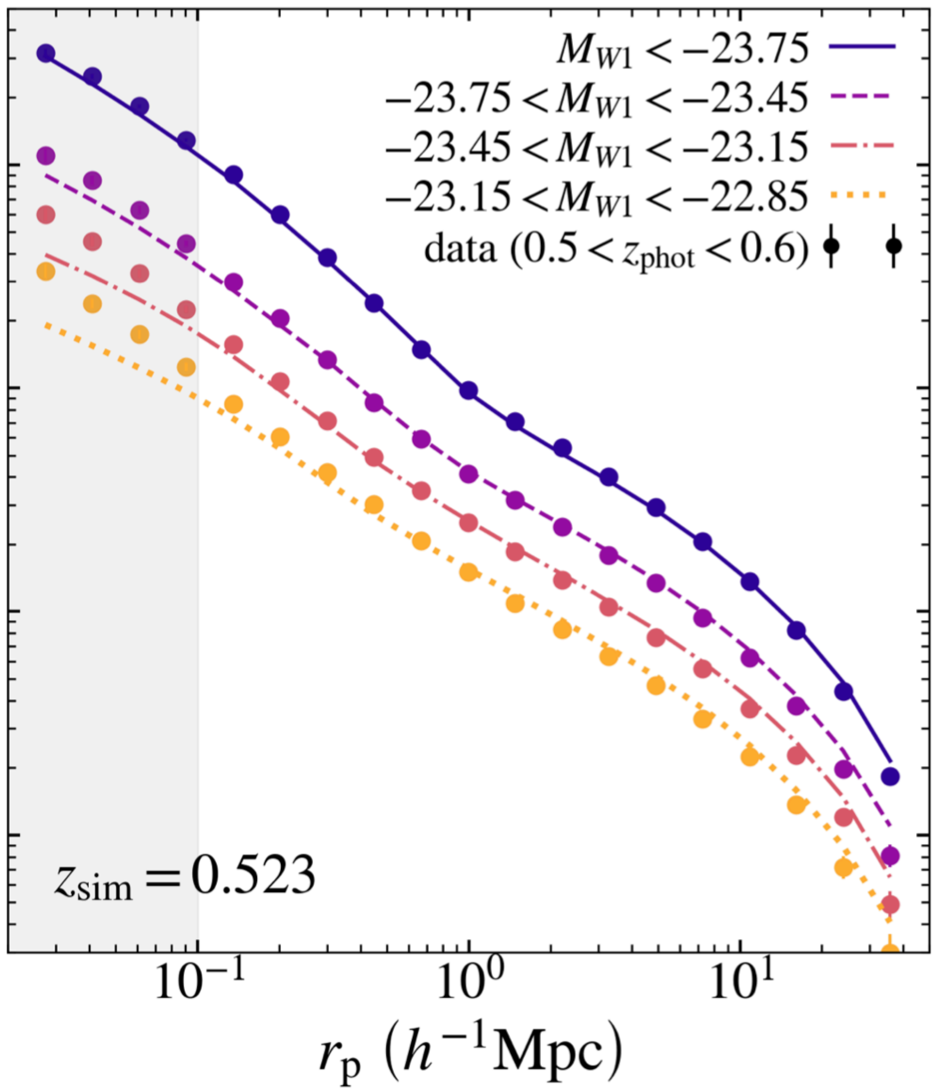
A merger tree follows individual peaks across snapshots. The stellar mass is computed using the SMHM relation with:

1- $M_{\rm vir} = \max_z (M_{\rm vir}(z))$

2- $M_{\rm vir} = \max_r (V_{\rm circ}(r))$.



Correlation Function for DESI



(Berti *et al.* 2023)

Regulator Models for Galaxies

In a regulator model, we describe each galaxy using a simple ODE:

$$\dot{M}_{\rm gas} = f_b \dot{M}_{\rm acc} - \dot{M}_* - \dot{M}_{\rm wind}$$

$$\dot{M}_{\rm wind} = \eta_{\rm wind} \dot{M}_*$$

Assuming steady state, we get: $$\dot{M}_* = \frac{f_b \dot{M}_{\rm acc}}{1+\eta_{\rm wind}}$$

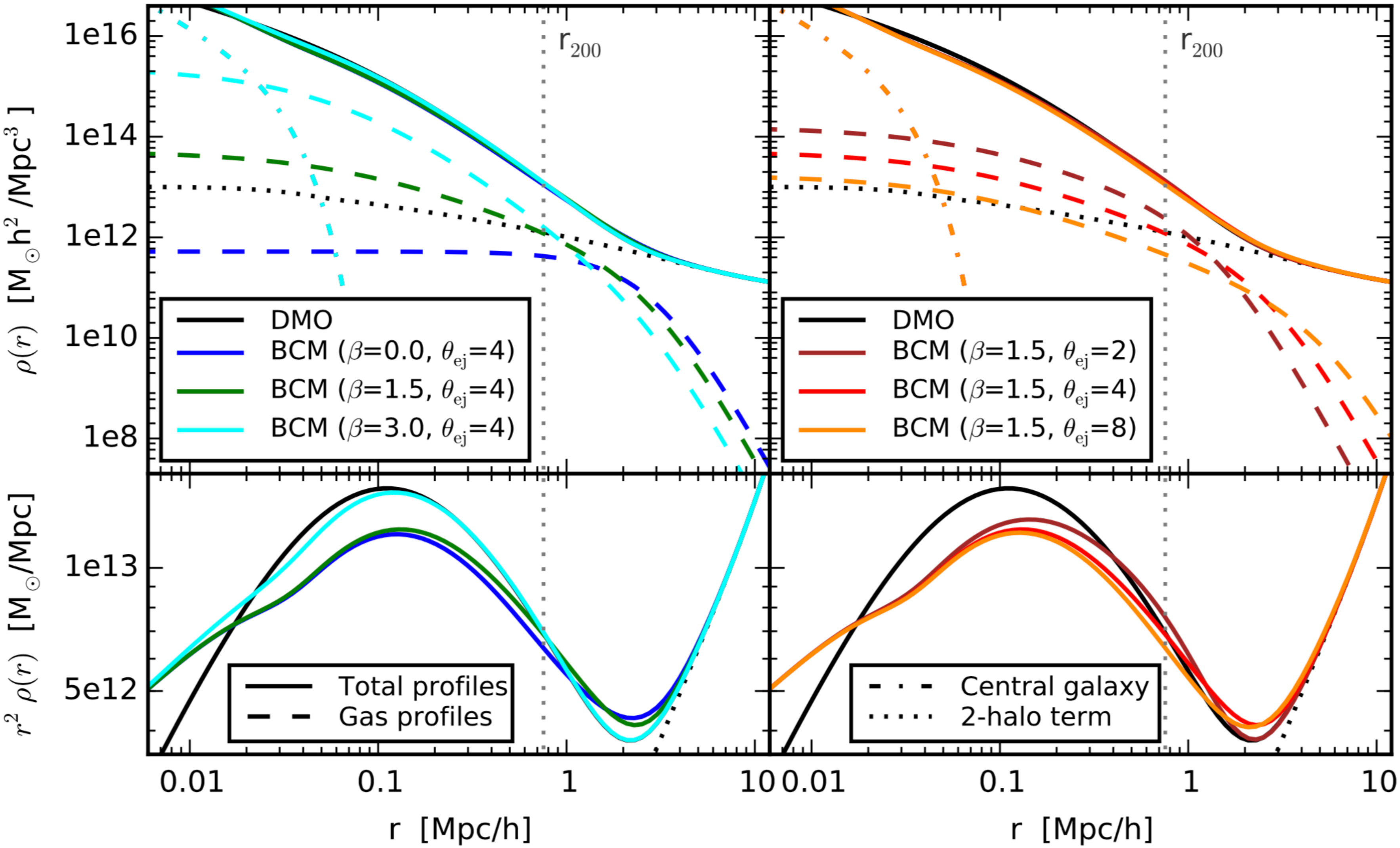
We need to adjust $\eta_{\rm wind}(M_{\rm vir})$ to reproduce observed galaxy properties.

GRUMPY model: $\eta_{\rm wind}(M_{\rm vir}) \simeq \left(\frac{M_{\rm vir}}{10^{12} M_\odot}\right)^{-1.5}$ (Kravstov & Manwadkar 2022)

More sophisticated regulator models are so-called Semi-Analytical Models (SAMs) (see e.g. Somerville & Dave 2015) also based on merger trees.

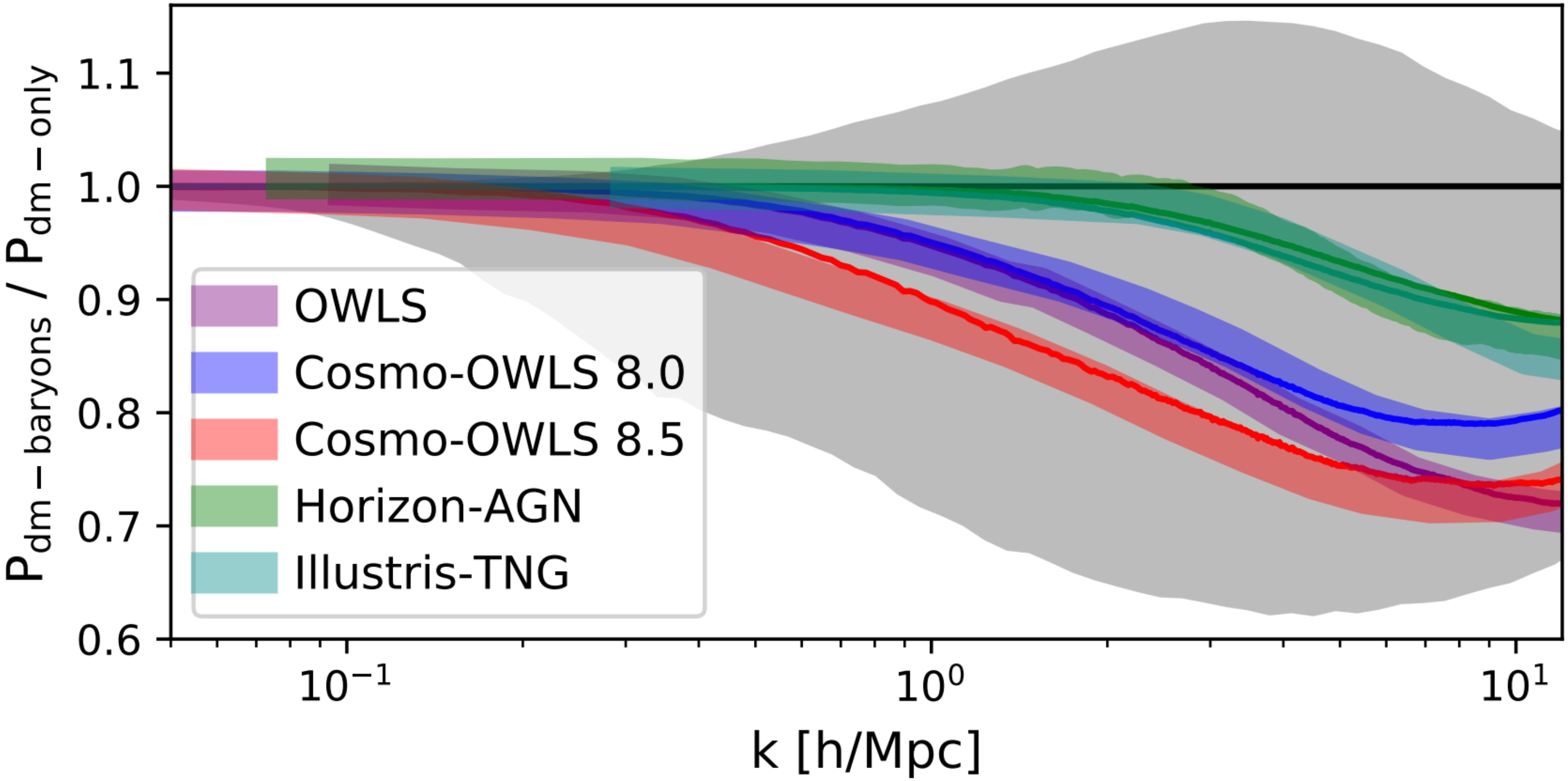
Baryonification

Schneider *et al.* (2018)



Baryonification

Schneider *et al.* (2018)



Light Cones