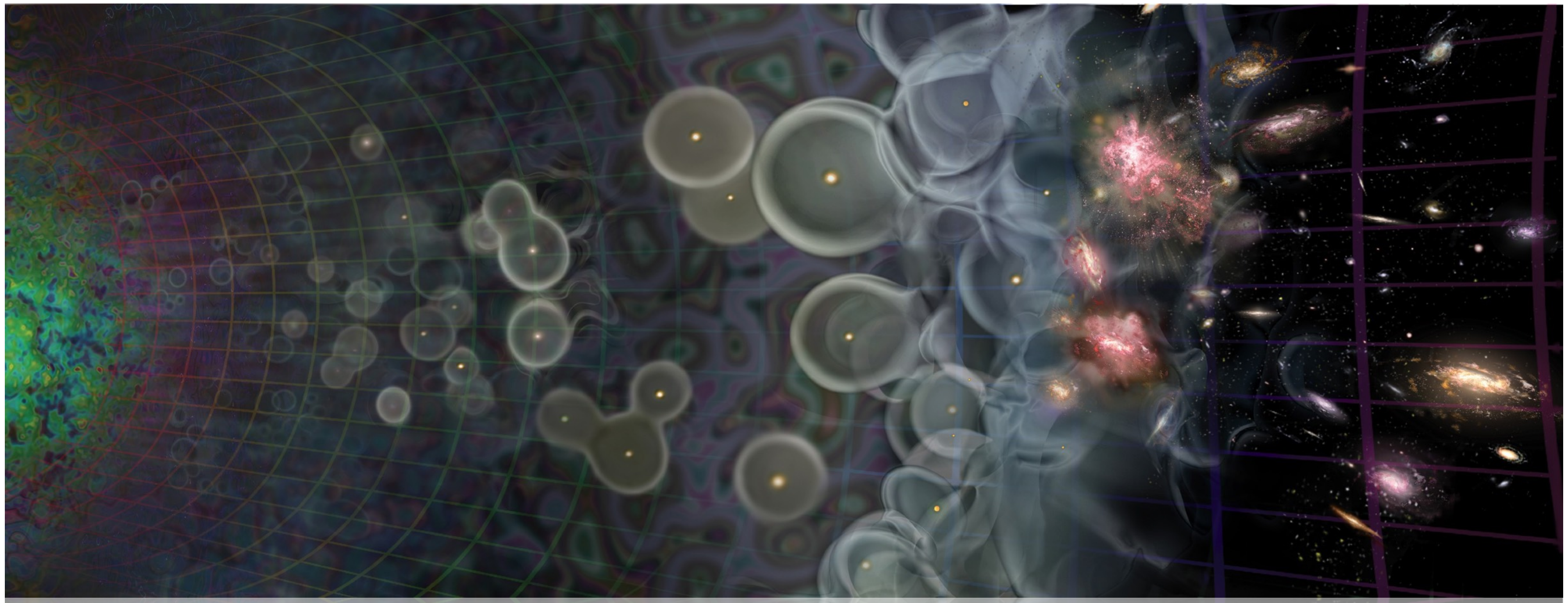


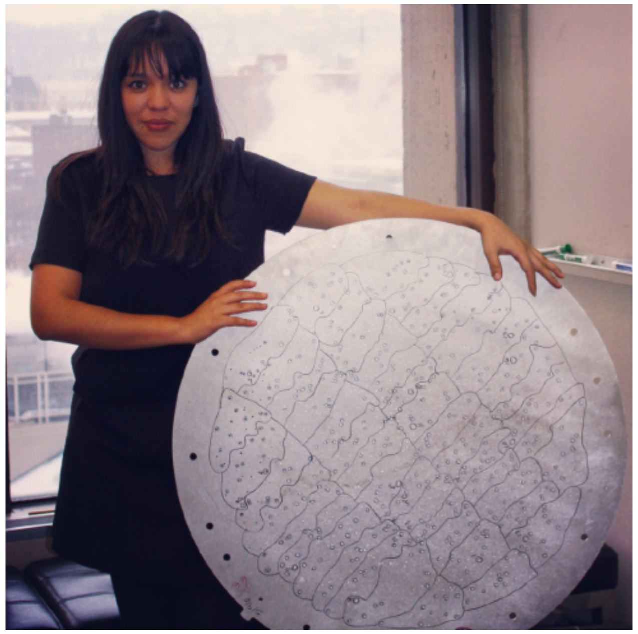
Proposal of local bias estimation for forward modeling Reconstruction in the BAO Peak analysis.

Sebastien Fromenteau
ICF-UNAM

INSTITUTO DE CIENCIAS FÍSICAS

Seminario de Fisíca de Altas Energias, ICN - Martes 2 de Mars 2022

Group participating on this work



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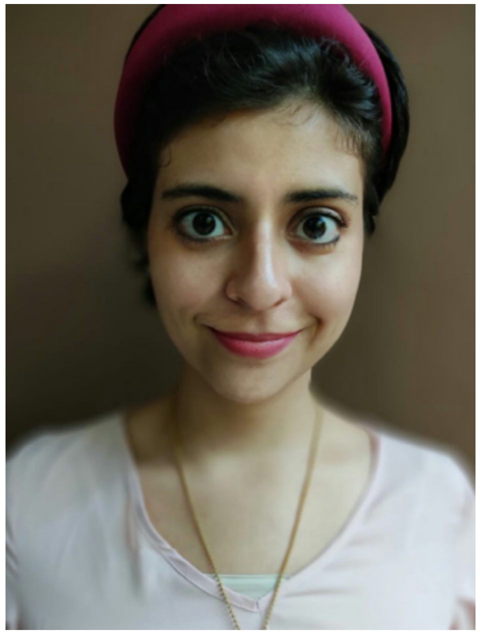

Miroslava Sandoval Ramos
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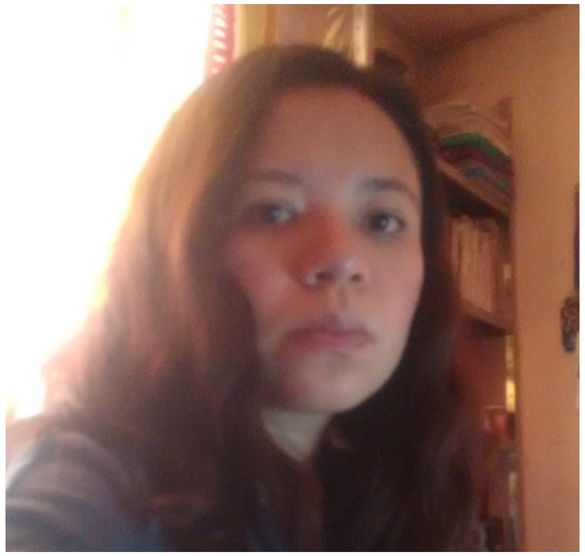


Brenda Tapia Benavides
UNAM

Matias
Rodriguez Otero
UNAM

Marcos
Toledo Ortiz
UAEM

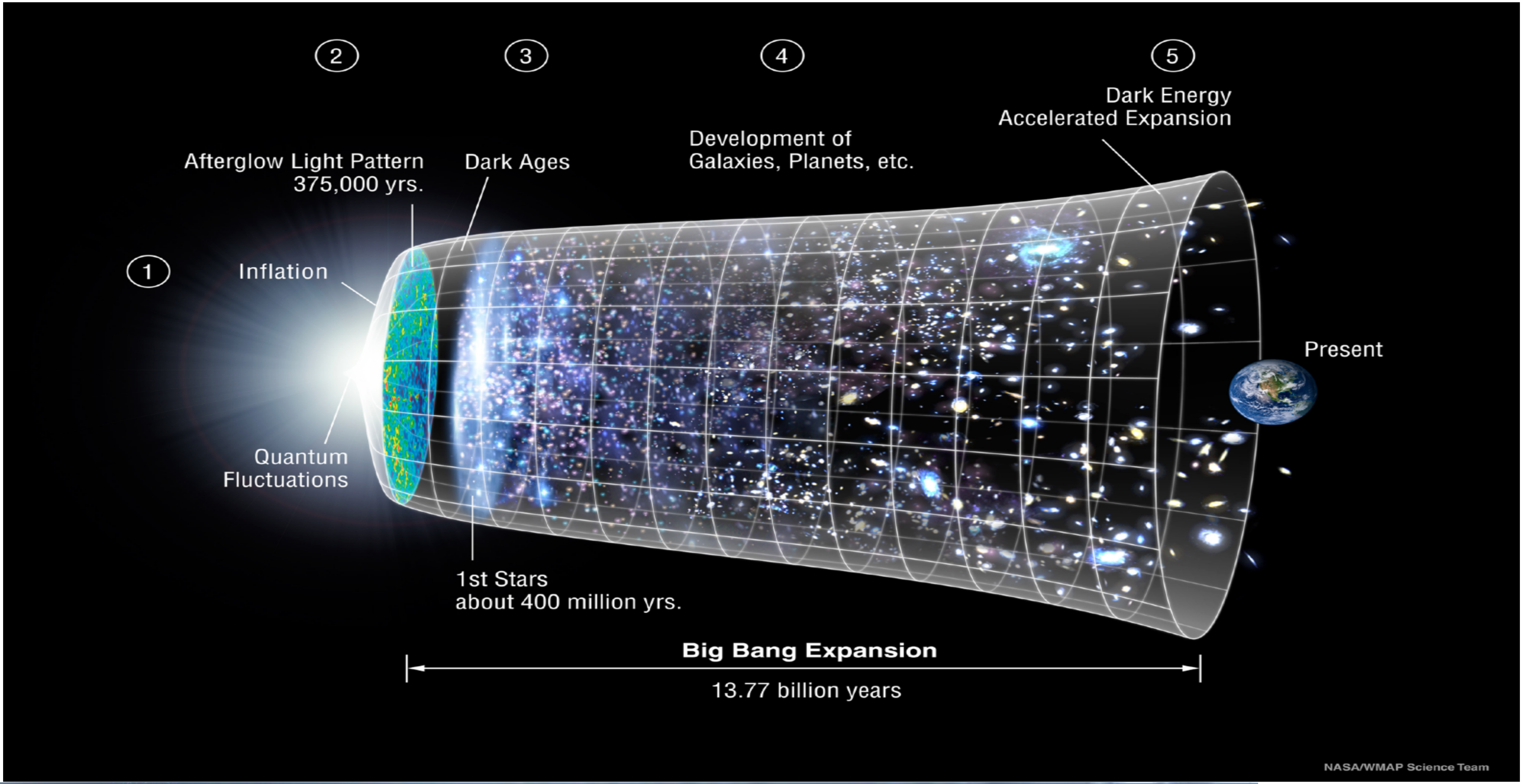
Summary

- **Cosmology**
  - Perturbations description and evolution
  - Halo bias and Galaxy bias

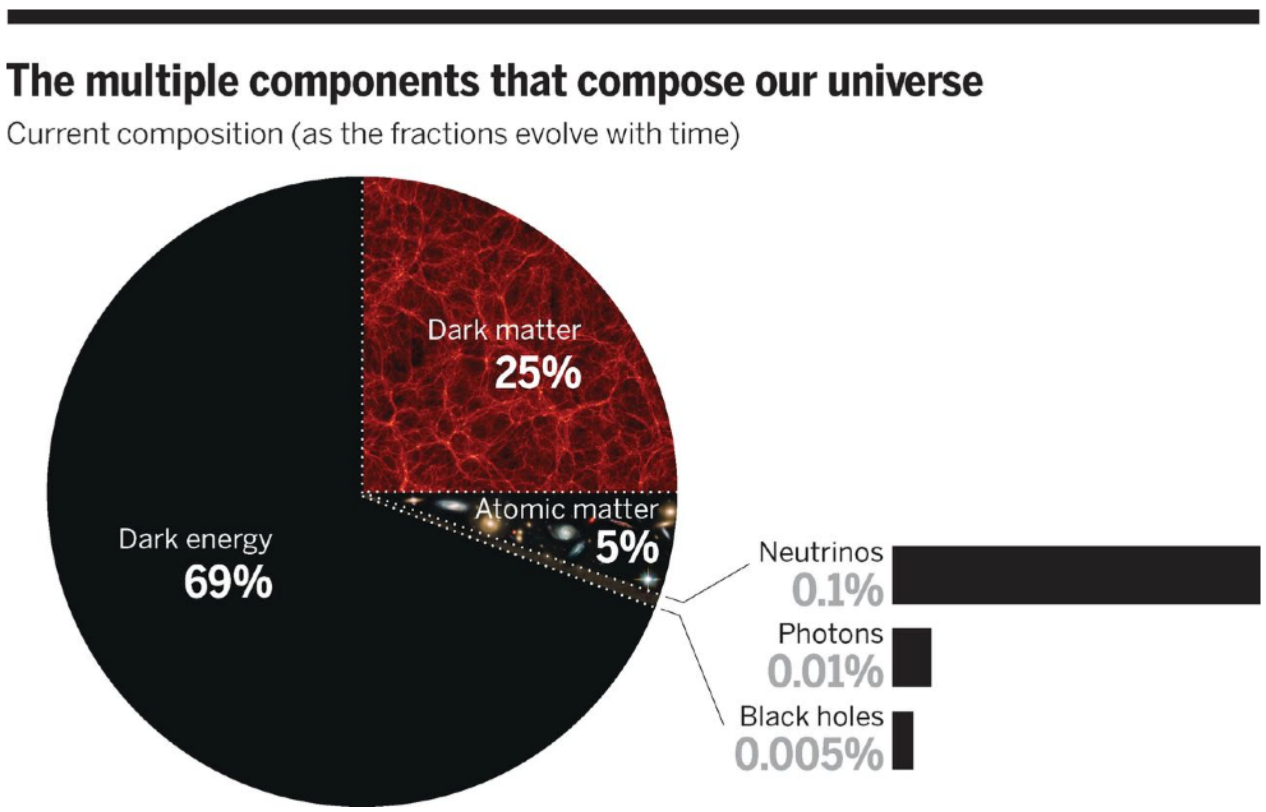
- **Use of astrophysical local properties to enhance bias determination**
  - Galaxy luminosity as a degeneracy break information
  - A direct use for the CDM mapping - BAO Reconstruction
  - Emission line galaxies

Cosmology Standard Model

$\Lambda - CDM$



Cosmological Parameters



$$\Omega_i, n_s, A_s, \tau, H_0$$

- 67.4 ± 0.5
- 73.9 ± 1.8

Perturbations (n_s, A_s)

EARLY ROUTE

Cosmic Microwave Background

Galaxy clustering:
BAO
RSD

Galaxy weak lensing

LATE ROUTE

Supernovae Ia and all other standardizable observable based on Cosmic Ladder

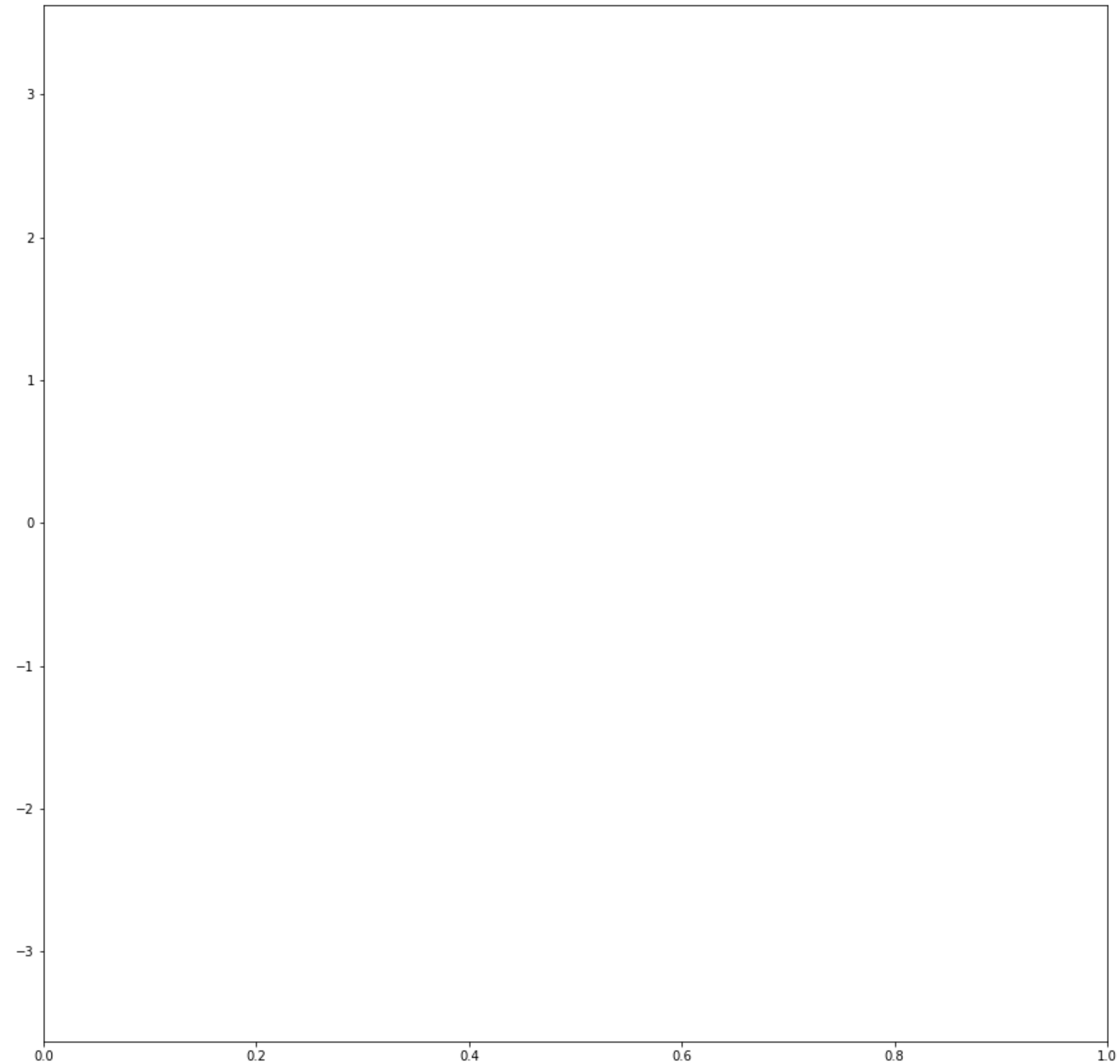
Quantum Fluctuations during inflation

Heisenberg incertitude

$$\Delta x \times \Delta p \geq \hbar$$

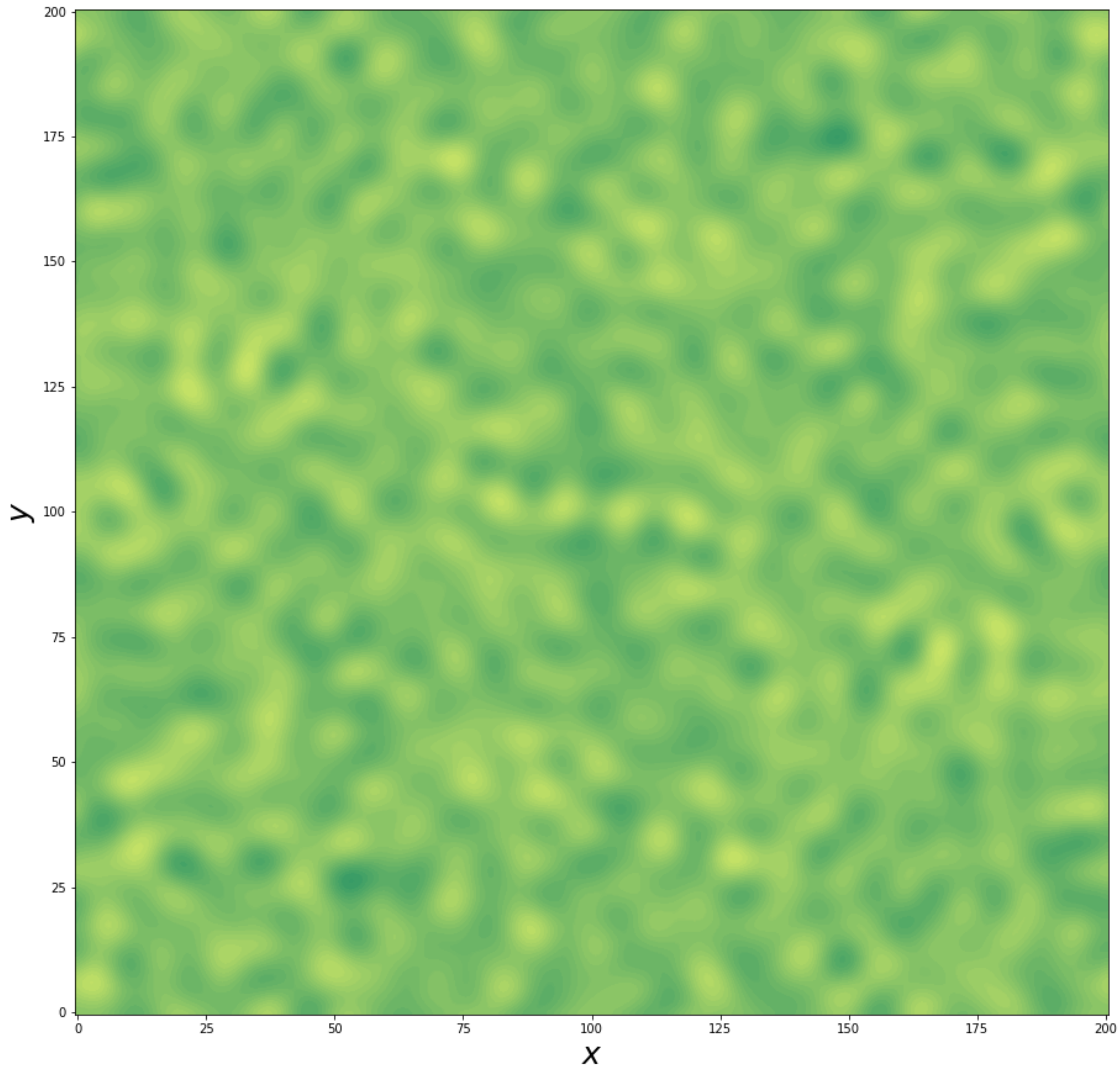
↓

$$\Delta T \times \Delta E \geq \hbar$$

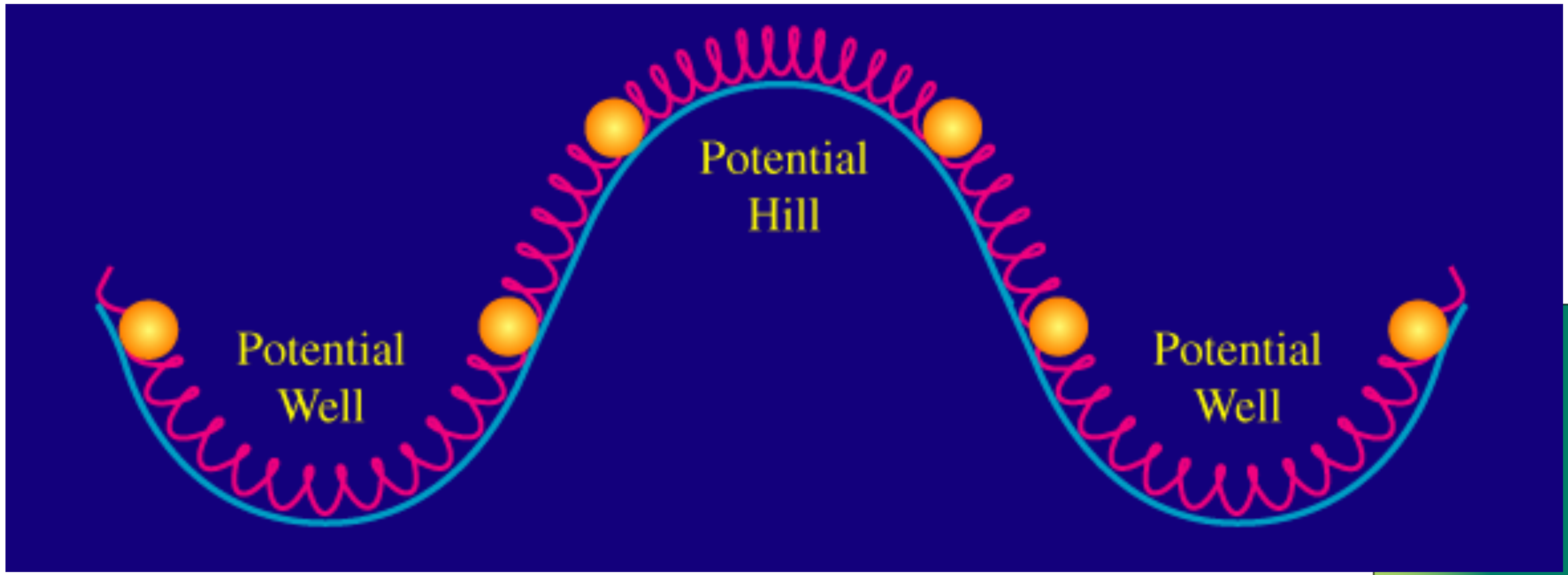


Freeze perturbations !!!!!

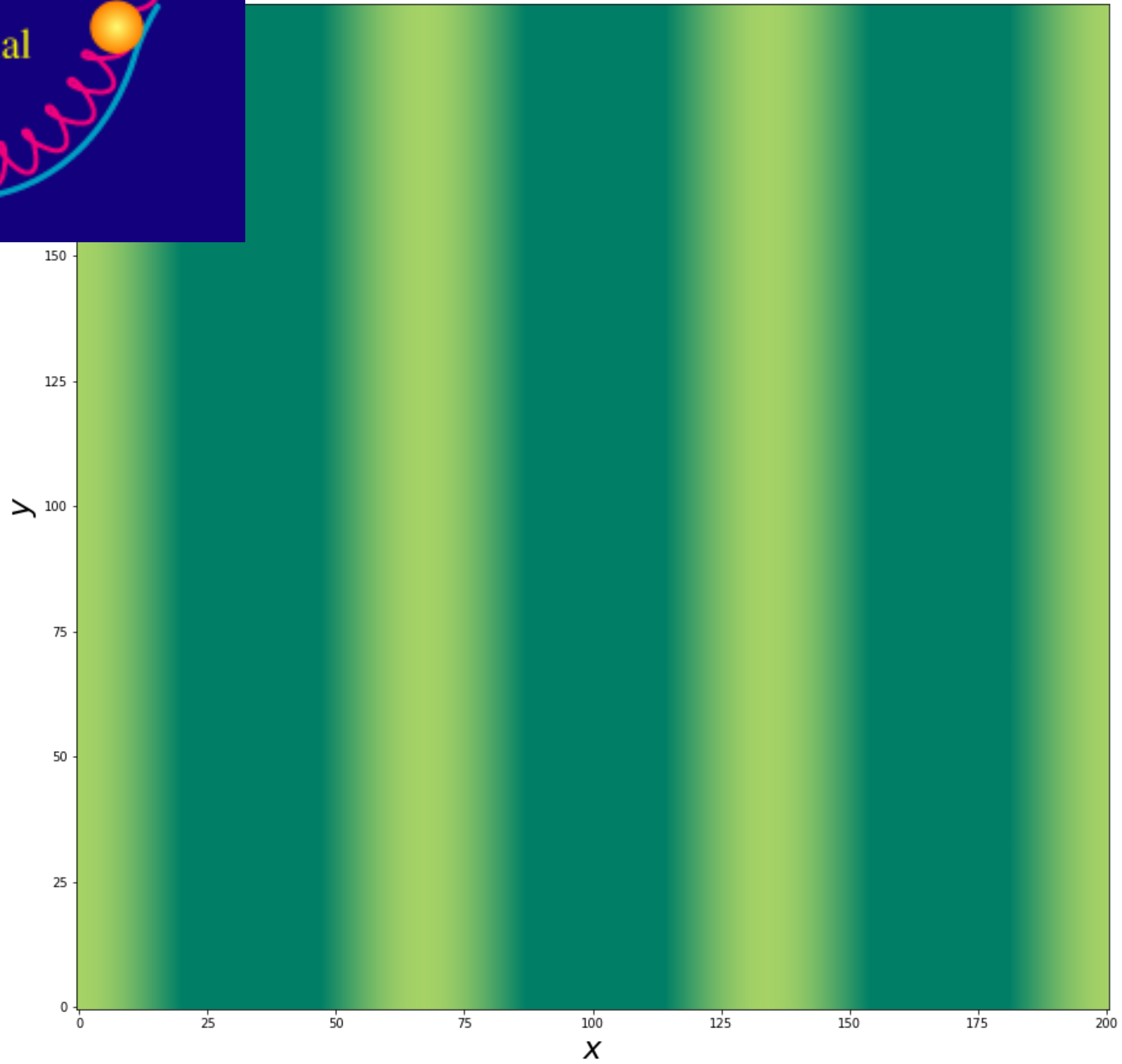
From Reheating to CMB

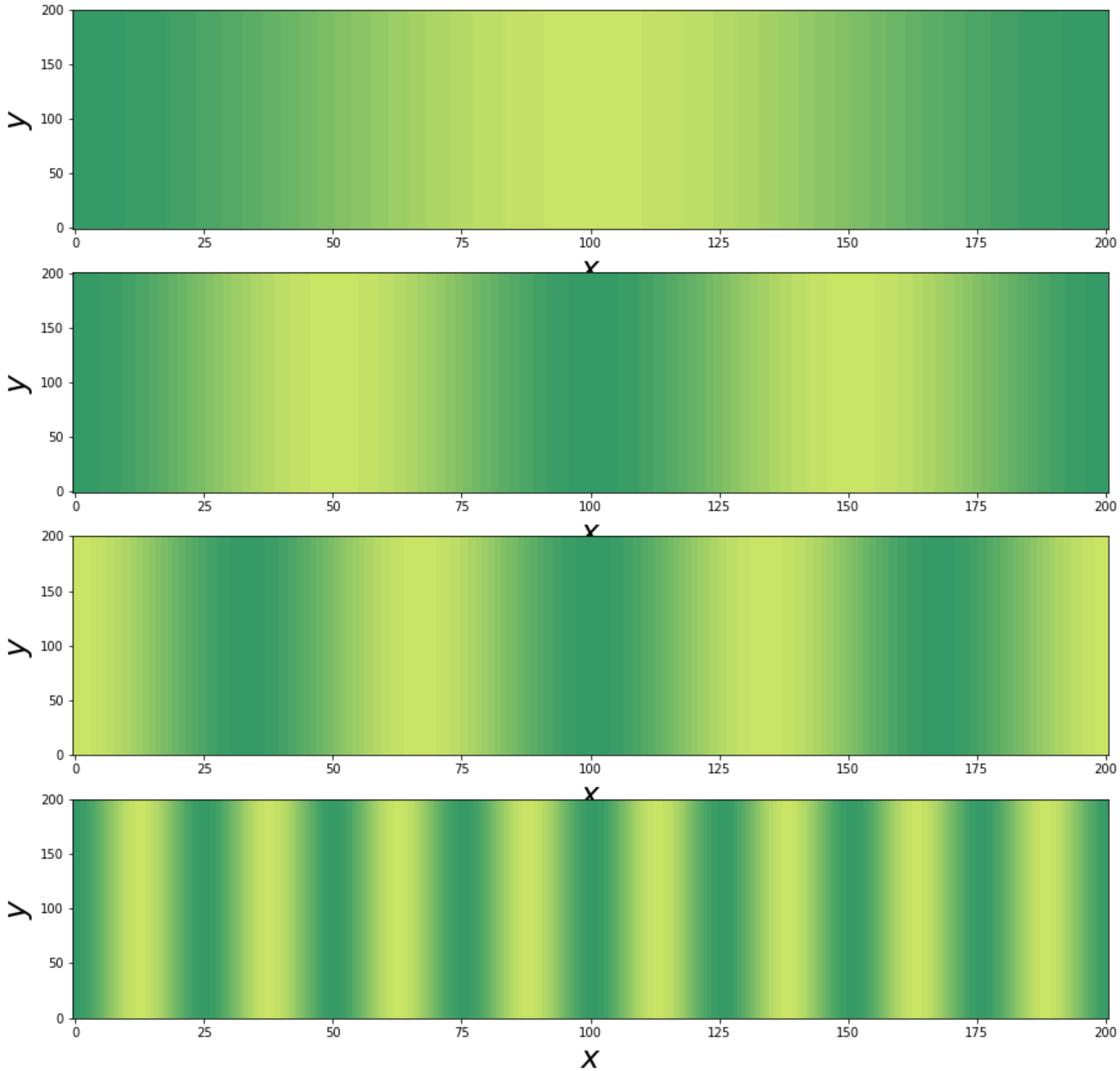


Baryon-photon oscillates



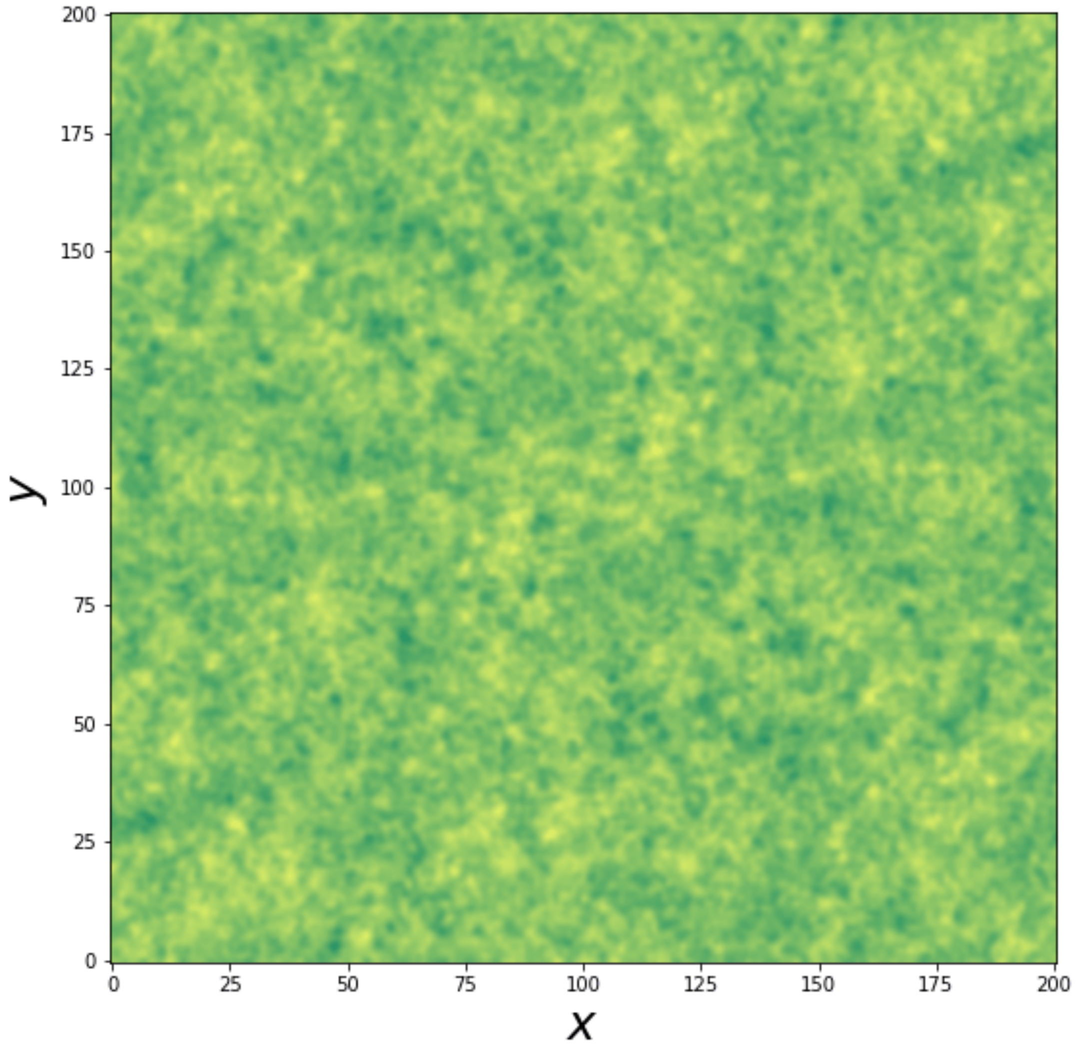
Wayne Hu's tutorial

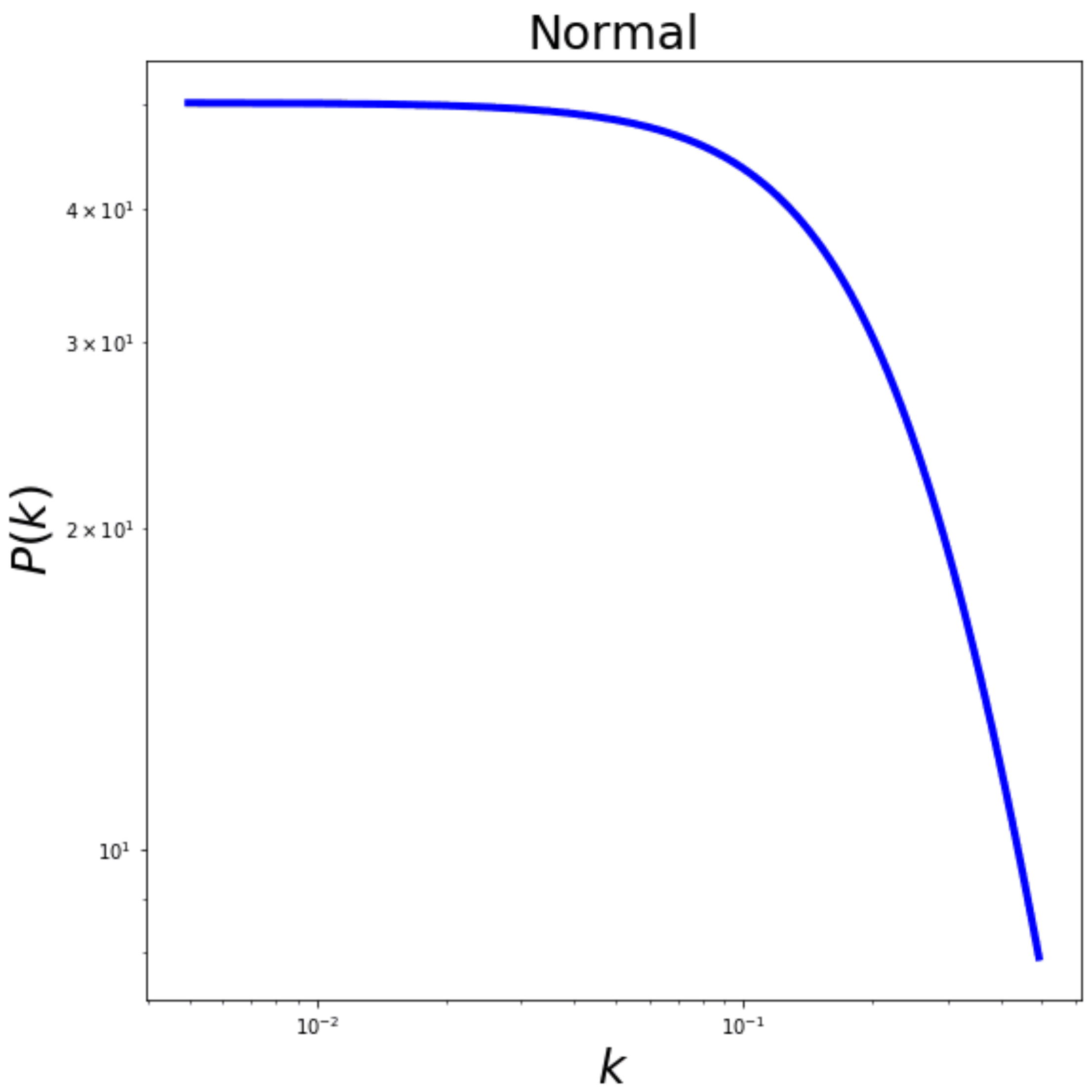




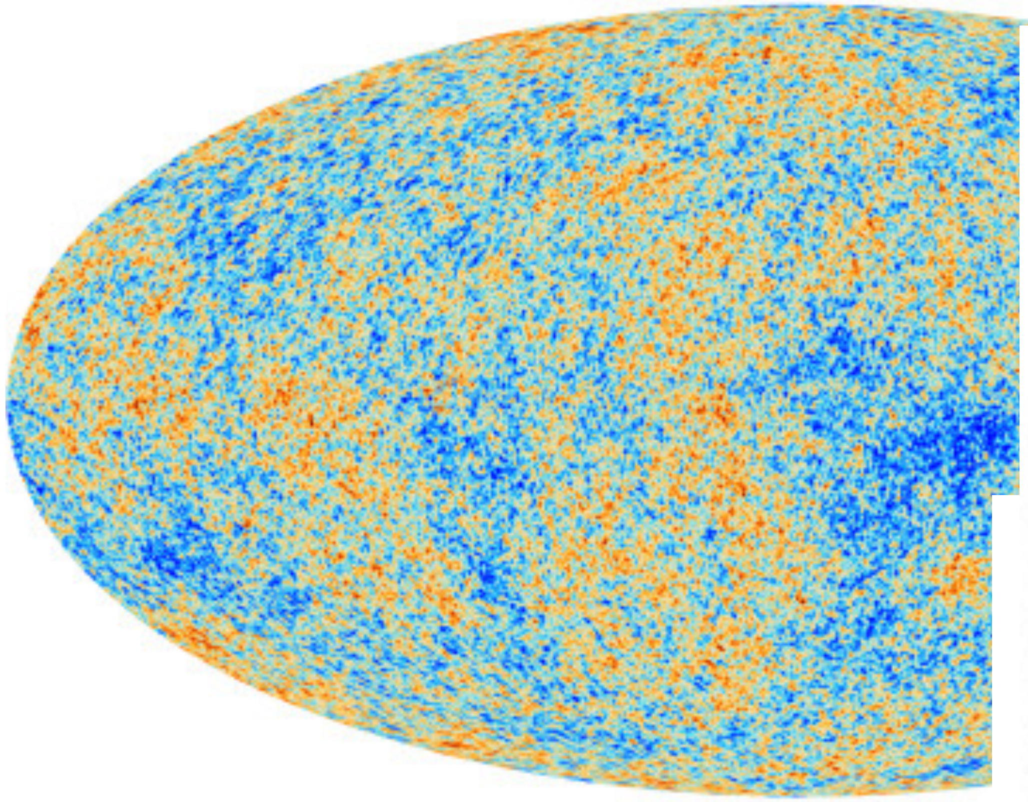
y
200
150
100
50
0
0
25
50
75
100
125
150
175
200
x

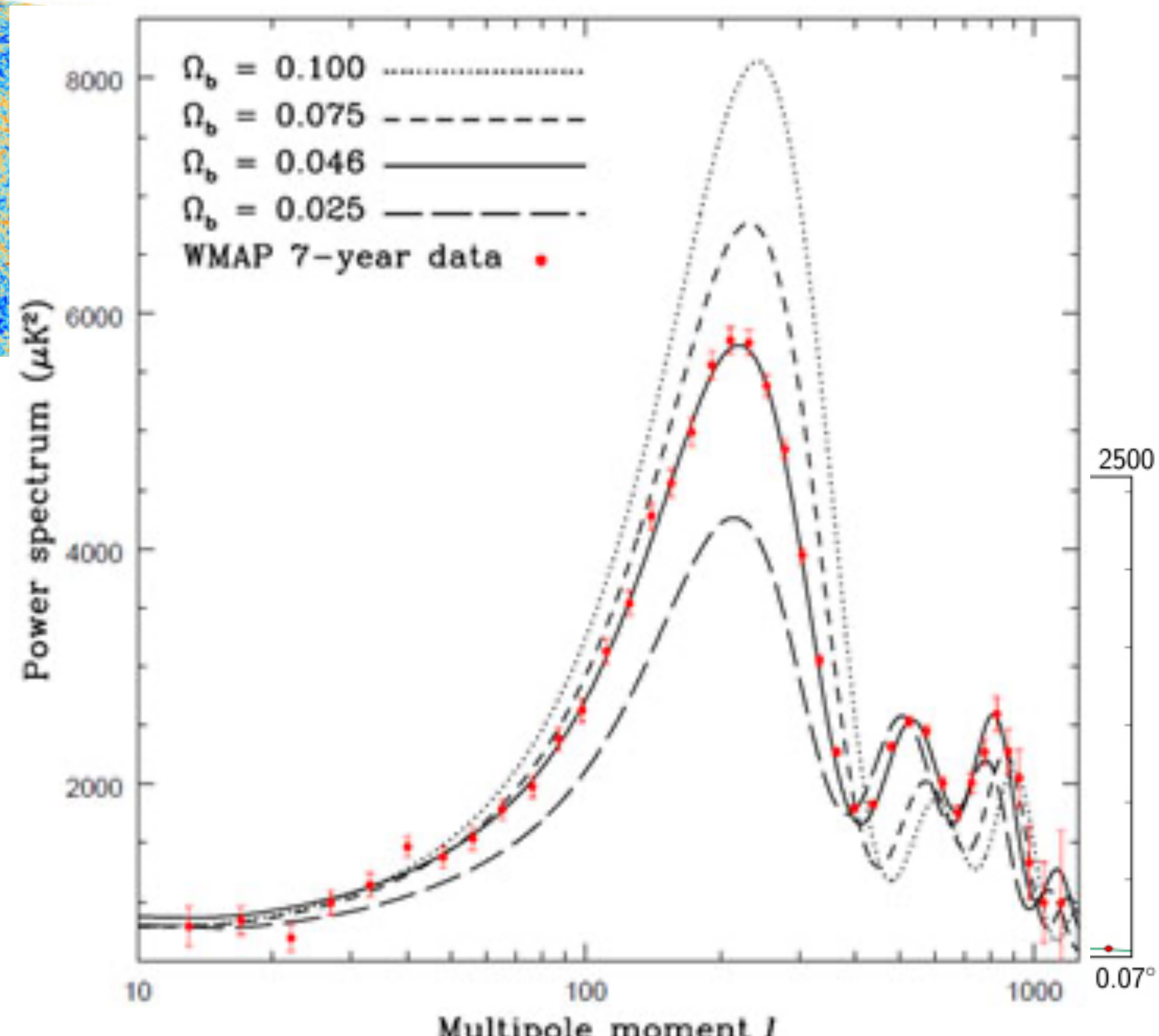
Fourier / Spherical Harmonics (CMB)





Cosmic Microwave Background (CMB)

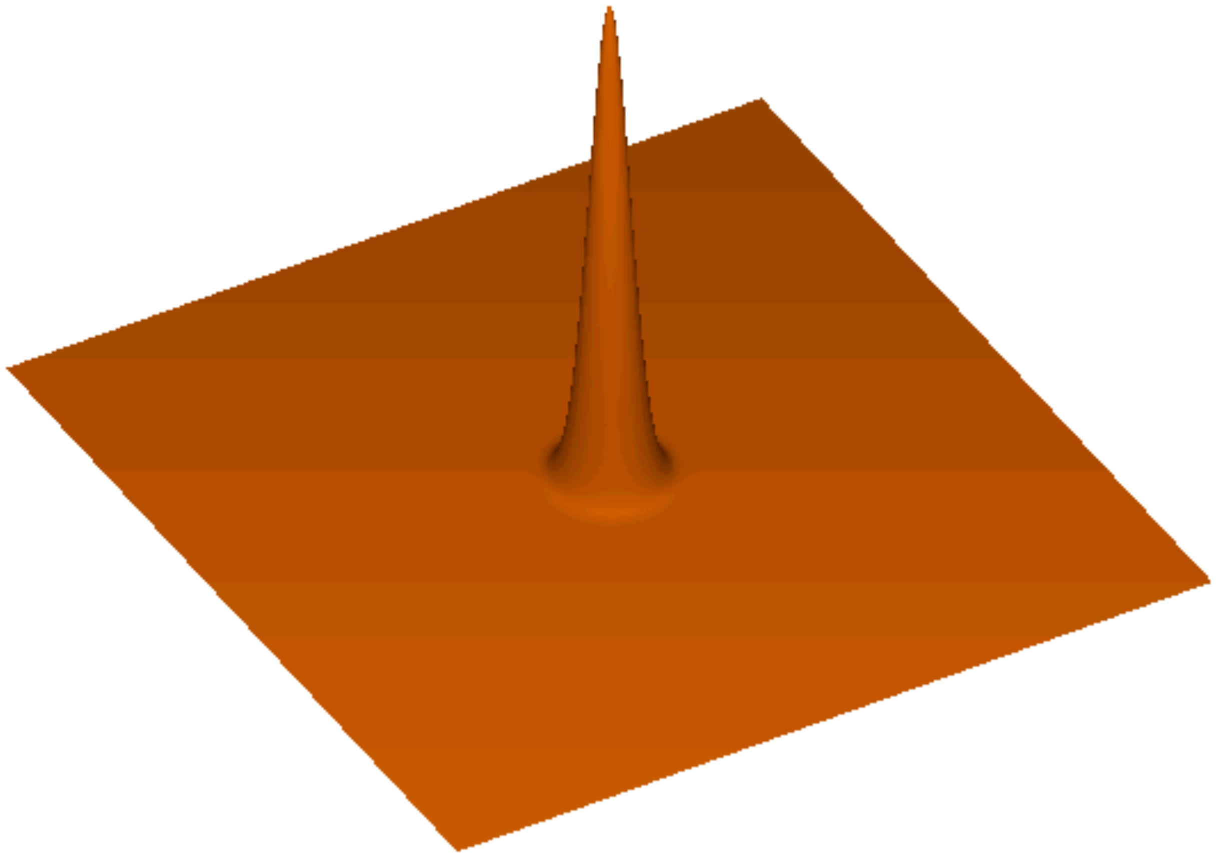




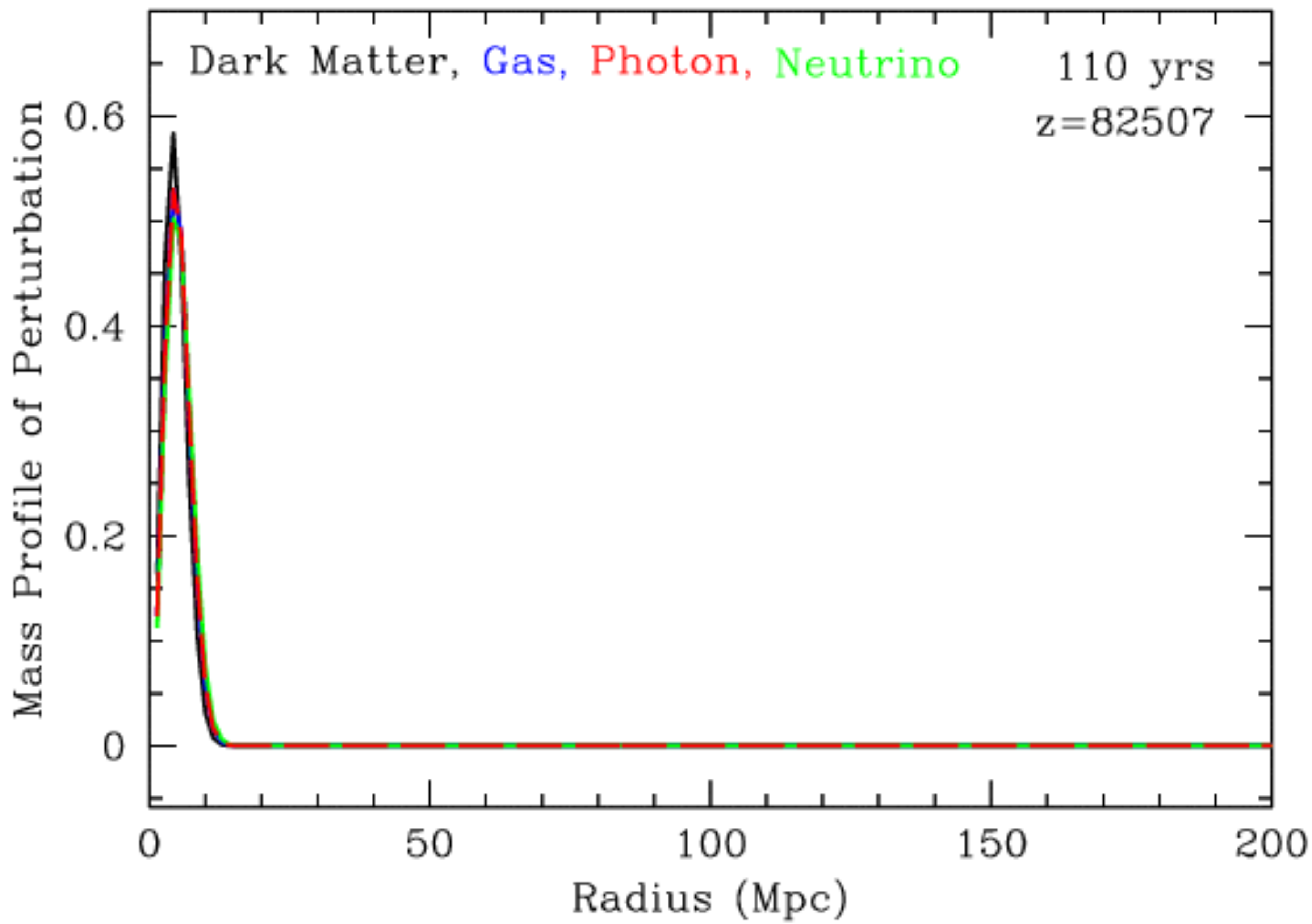
Baryonic Acoustic Oscillations (BAO) Real Space

Around all over-densities

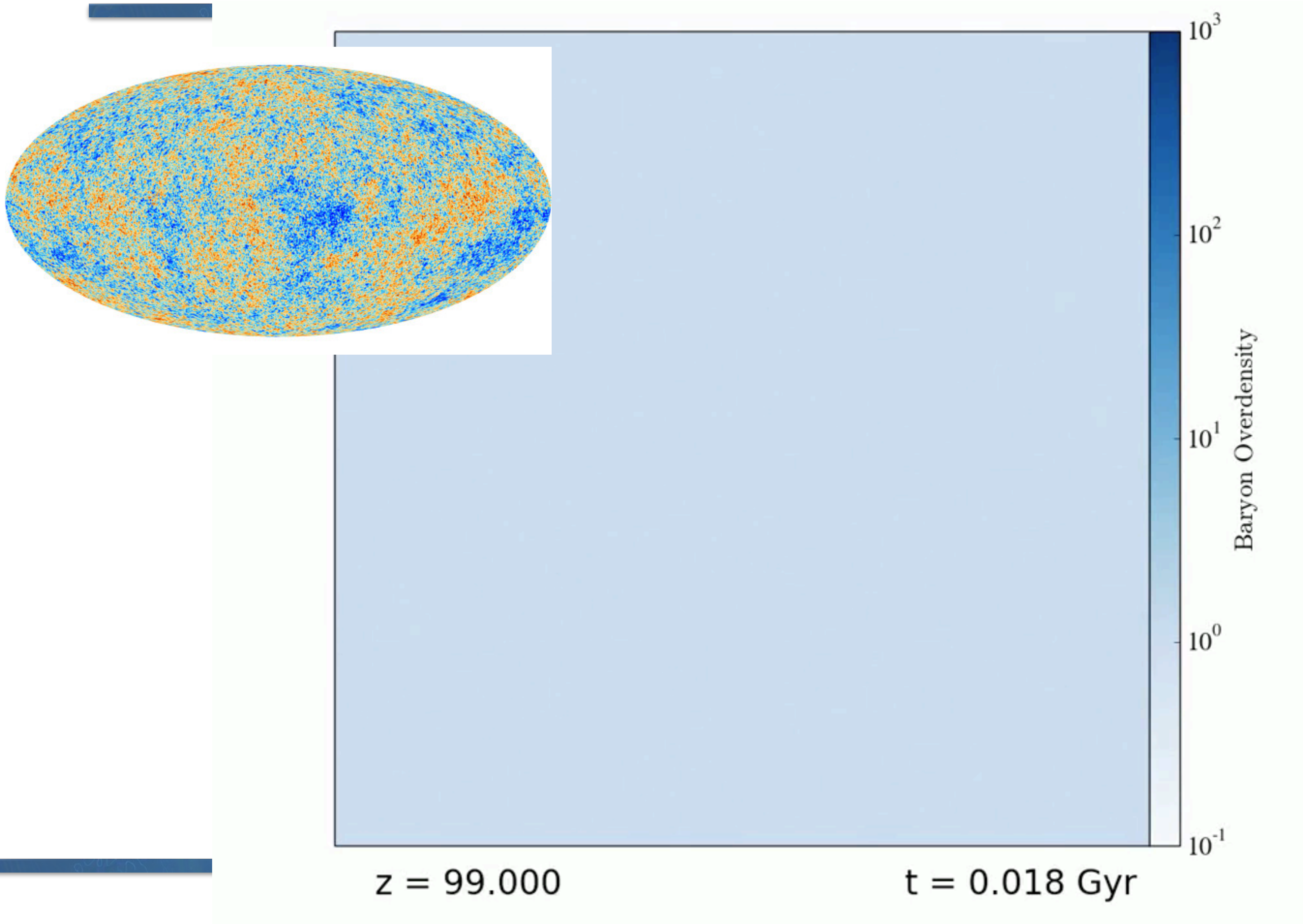
Stop to propagate when the plasma disappear



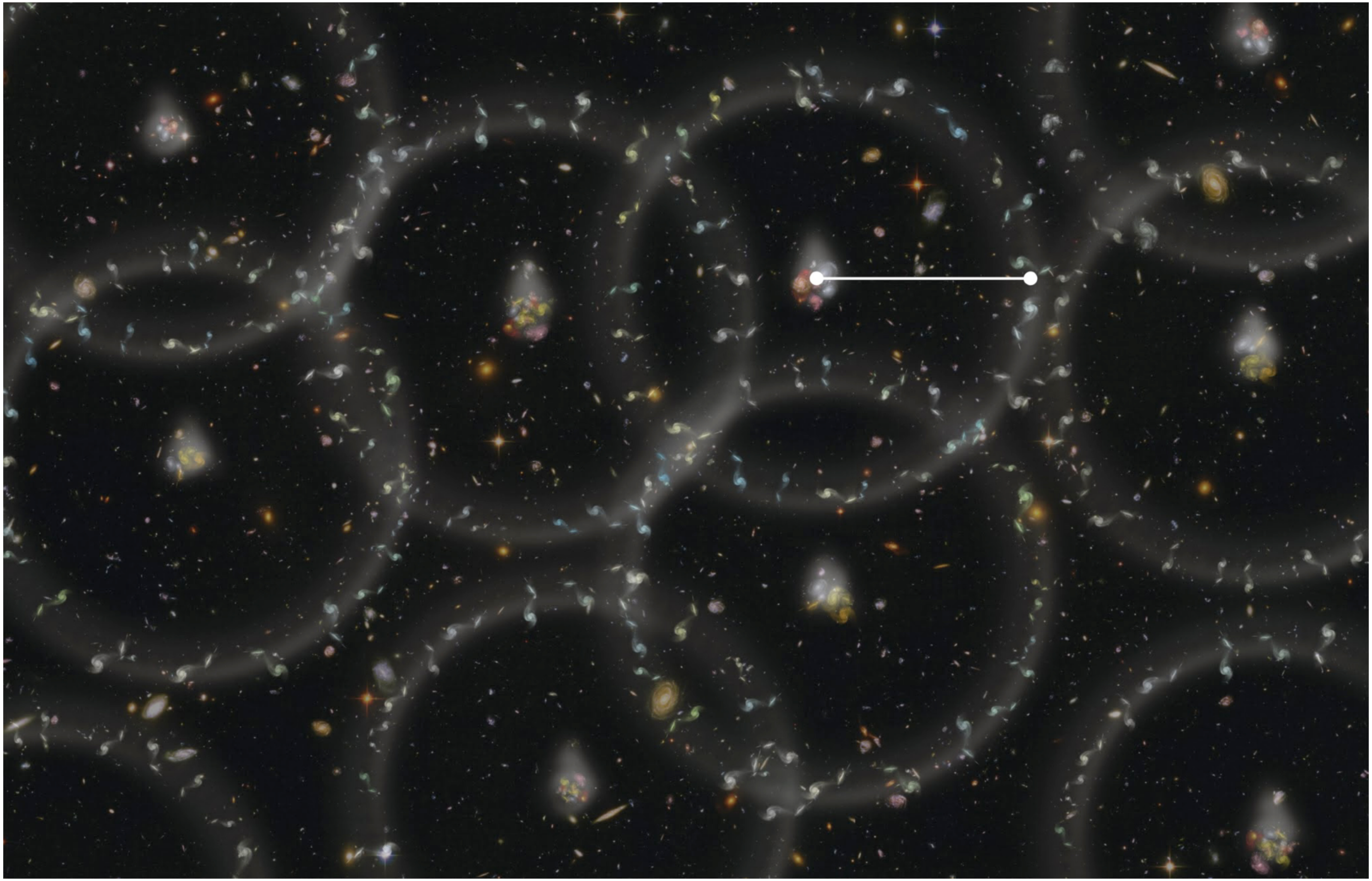
BAO in real space



Perturbations after CMB



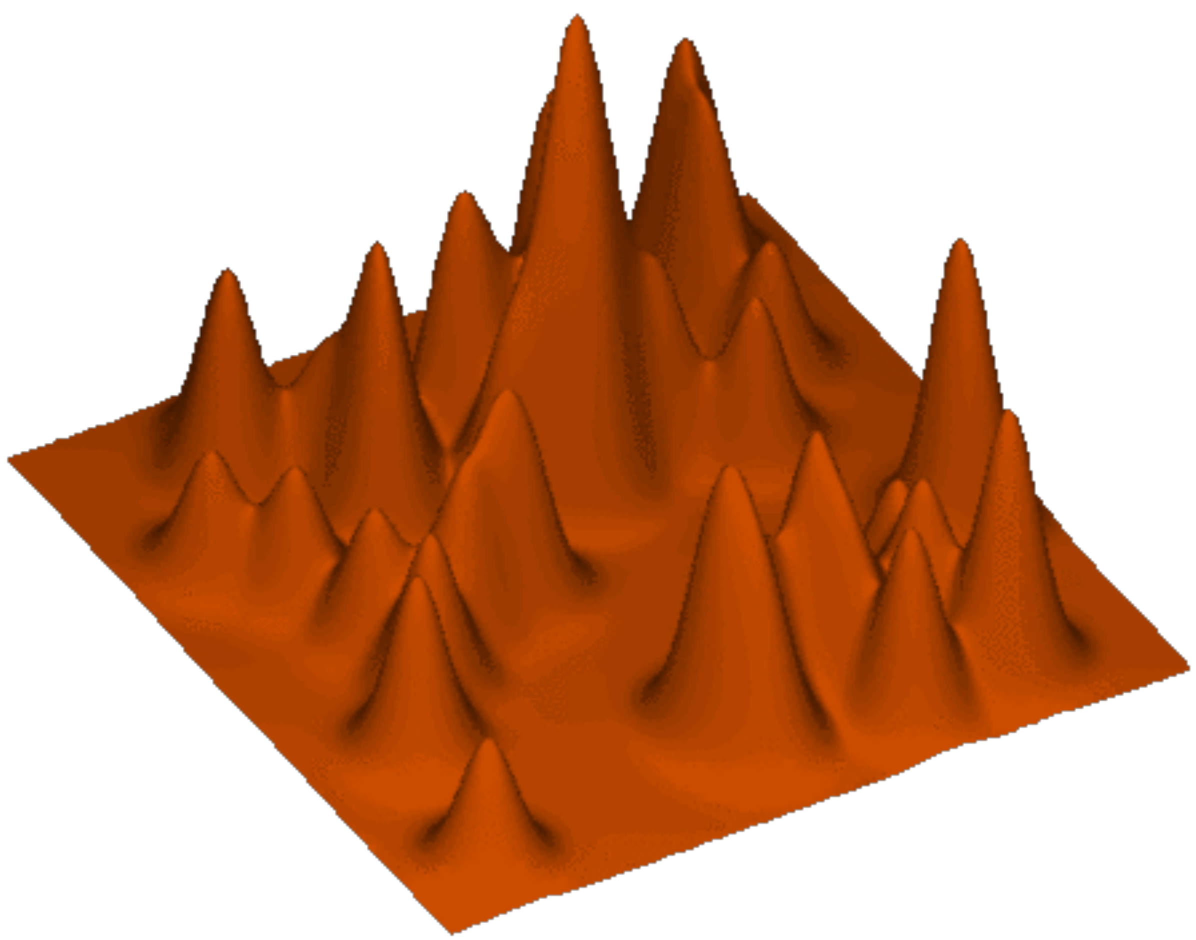
BAO in galaxies



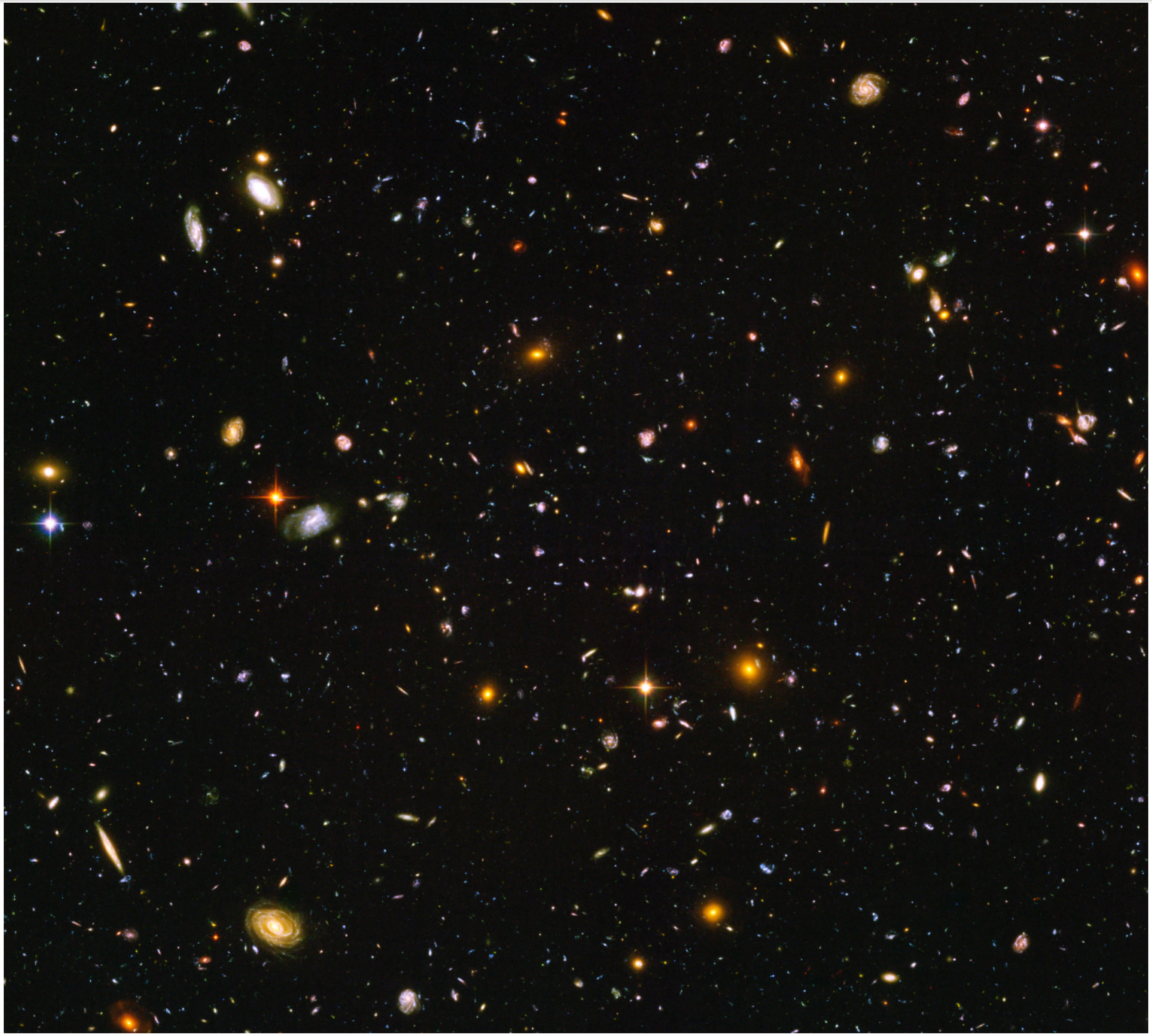
Baryonic Acoustic Oscillations (BAO)
Real Space

Around all over-densities

Stop to propagate when the plasma disappear



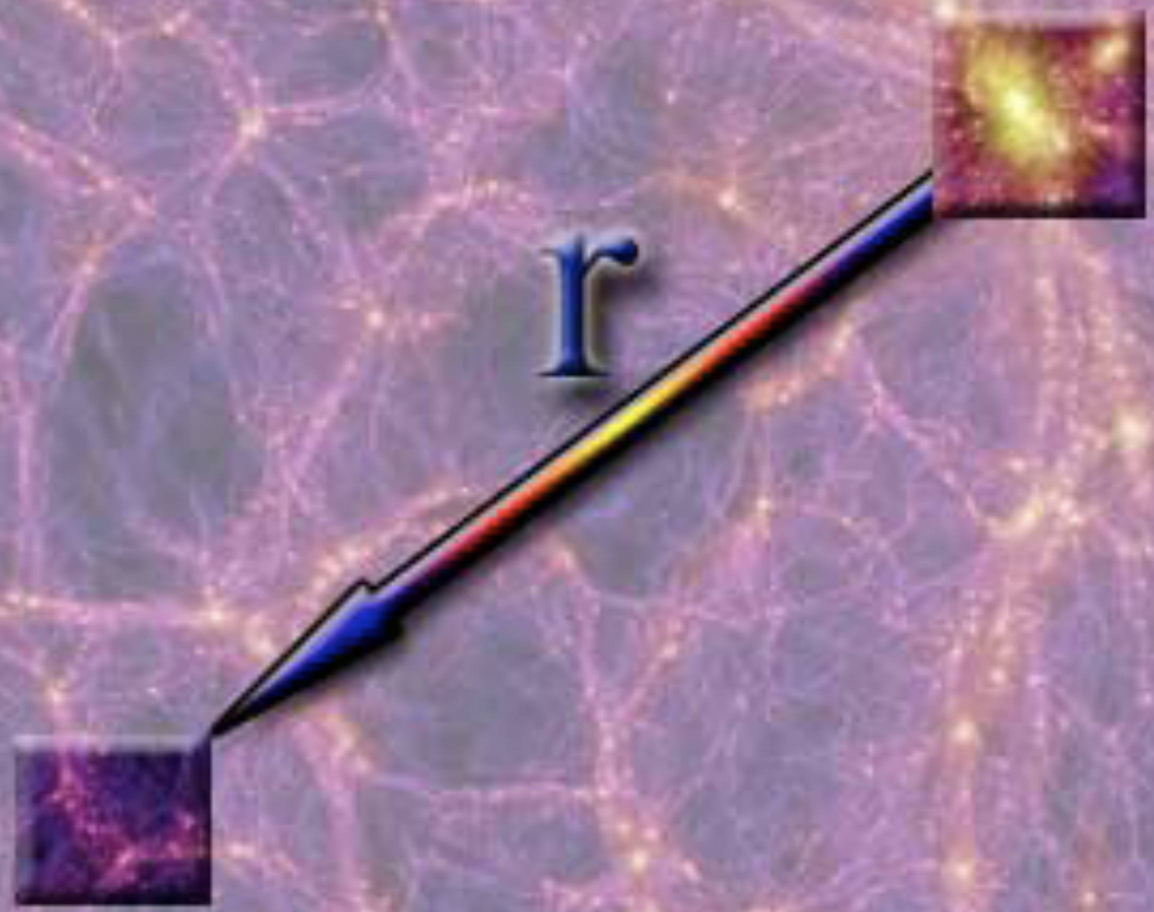
Reality



Measuring Clustering

$$dP_{12} = \bar{n}_g^2[1 + \xi(\vec{r}_{12})]dV_1 dV_2$$

We estimate it using galaxy pair counts



2-pt statistics

$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle_{volumen}$$

$\delta(x)$ is the contrast density

$$\delta(x) = \frac{\rho(x) - \langle \rho \rangle}{\langle \rho \rangle}$$

Power Spectrum $P(k)$ is the FT of $\xi(r)$:

$$P(k) = \int d^3 x e^{-ik\cdot r} \xi(r)$$

Power Spectrum and 2pt-correlation function

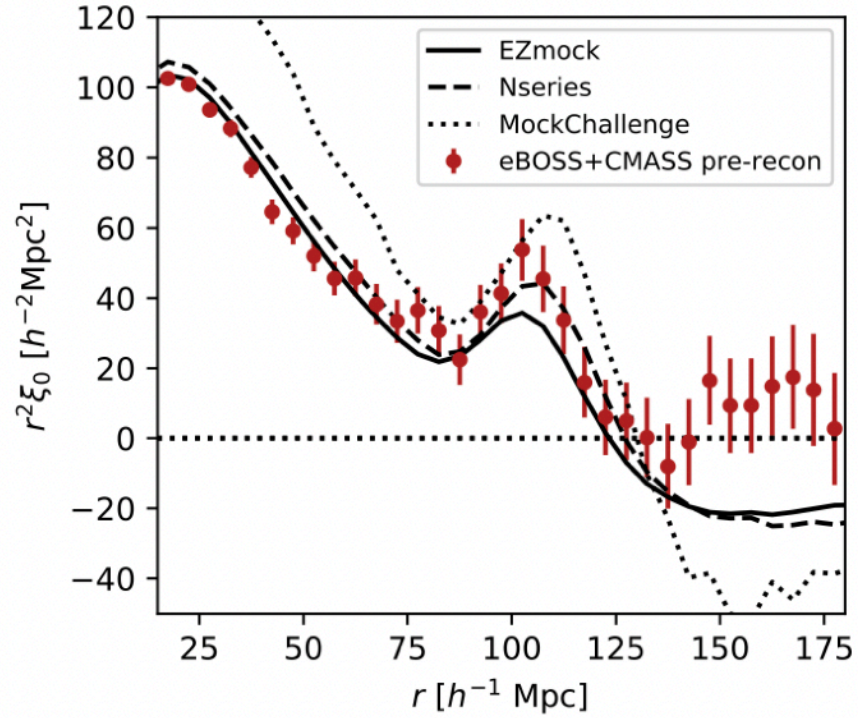
$$\xi(\vec{r}) = < \delta(\overrightarrow{x}) \, . \, \delta(\overrightarrow{x} + \vec{r}) >$$

$$P(\overrightarrow{k}) = \frac{1}{(2\pi)^3} \int d^3\vec{r} \xi(\vec{r}) e^{-i \overrightarrow{k} . \vec{r}}$$

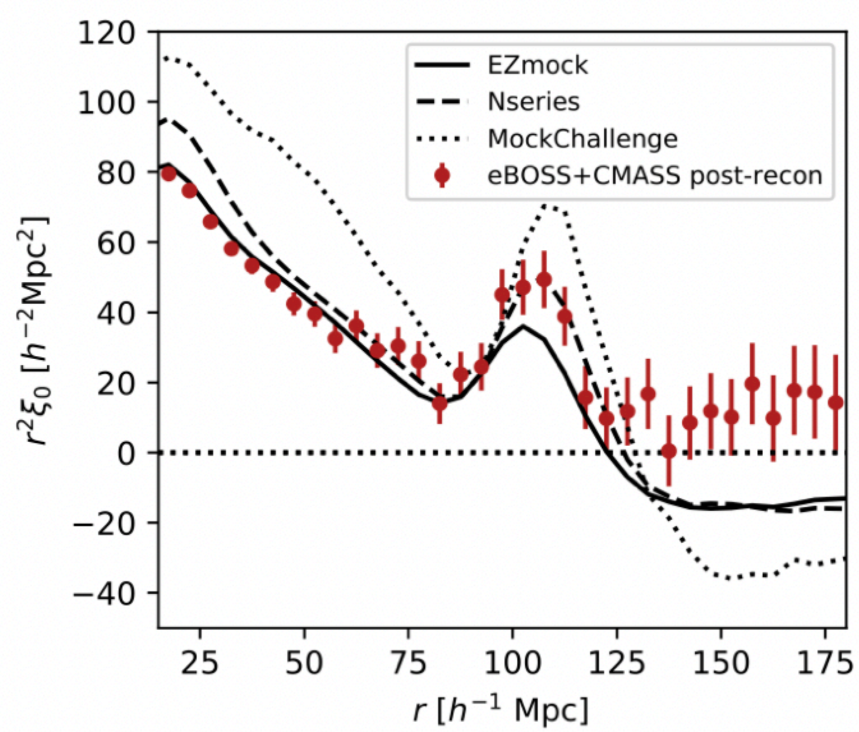
Real field condition : $\delta(-\overrightarrow{k}) = \delta^*(\overrightarrow{k})$

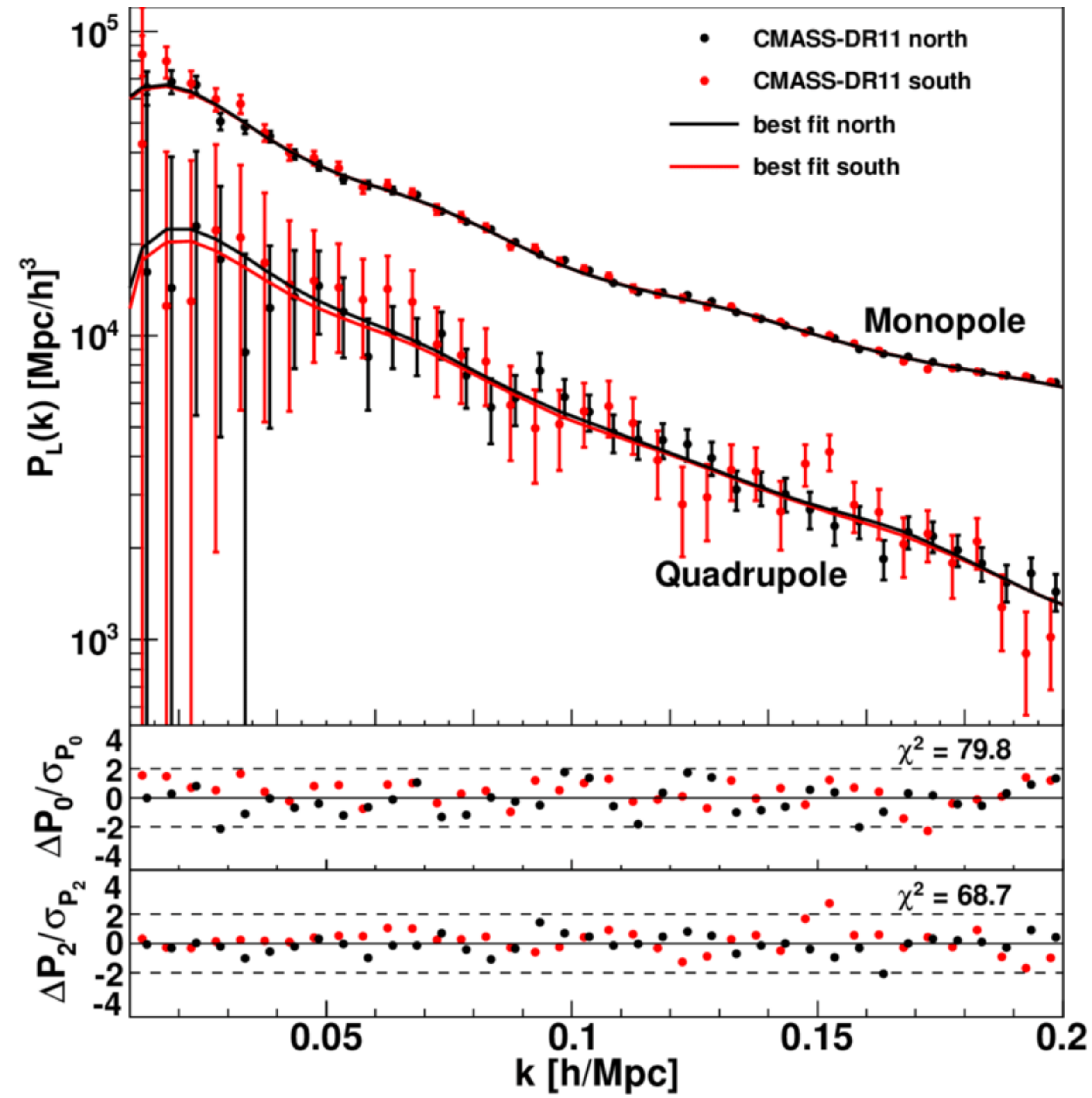
$$(2\pi)^3 P(\overrightarrow{k}) = < \delta(\overrightarrow{k}) \, . \, \delta^*(\overrightarrow{k}) > = < |\delta(\overrightarrow{k})|^2 >$$

Galaxy 2pt-statistics measurement



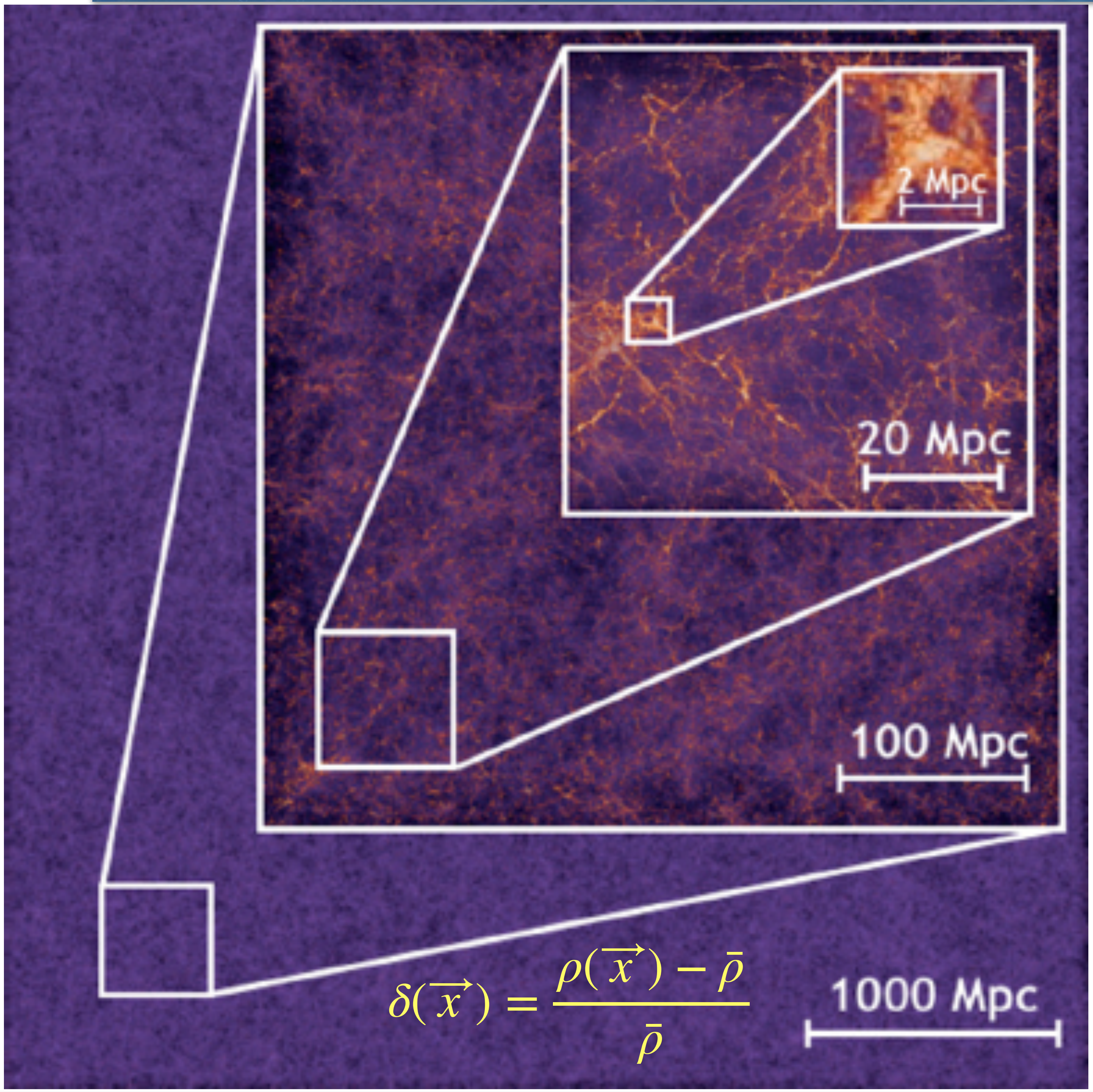
Bautista et al. 2021





Beutler et al. 2013

Scales in Cosmology



$\delta > 1$: Non-Linear

- **Simulations**

$\delta \sim 1$: Quasi-Linear

- **Simulations**
- **2-LPT**

$\delta \ll 1$: Linear

- **Simulations**
- **LPT** (Lagrangian Pert. Th)
- **Analytical approx.**

Millenium simulation

Linear evolution of Perturbations

$$\dot{\rho} + \nabla_{\vec{r}}.(\rho\vec{u}) = 0,$$

: Continuity equation

+

$$\rho\left[\dot{\vec{u}} + (\vec{u}.\nabla_{\vec{r}})\vec{u}\right] = -\nabla_{\vec{r}}p - \rho\nabla_{\vec{r}}\Phi,$$

: Euler's equation

+

$$\nabla^2_{\vec{r}}\Phi = 4\pi G(\rho + 3p) - \Lambda.$$

: Poisson's equation

+

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\rho_m\delta$$

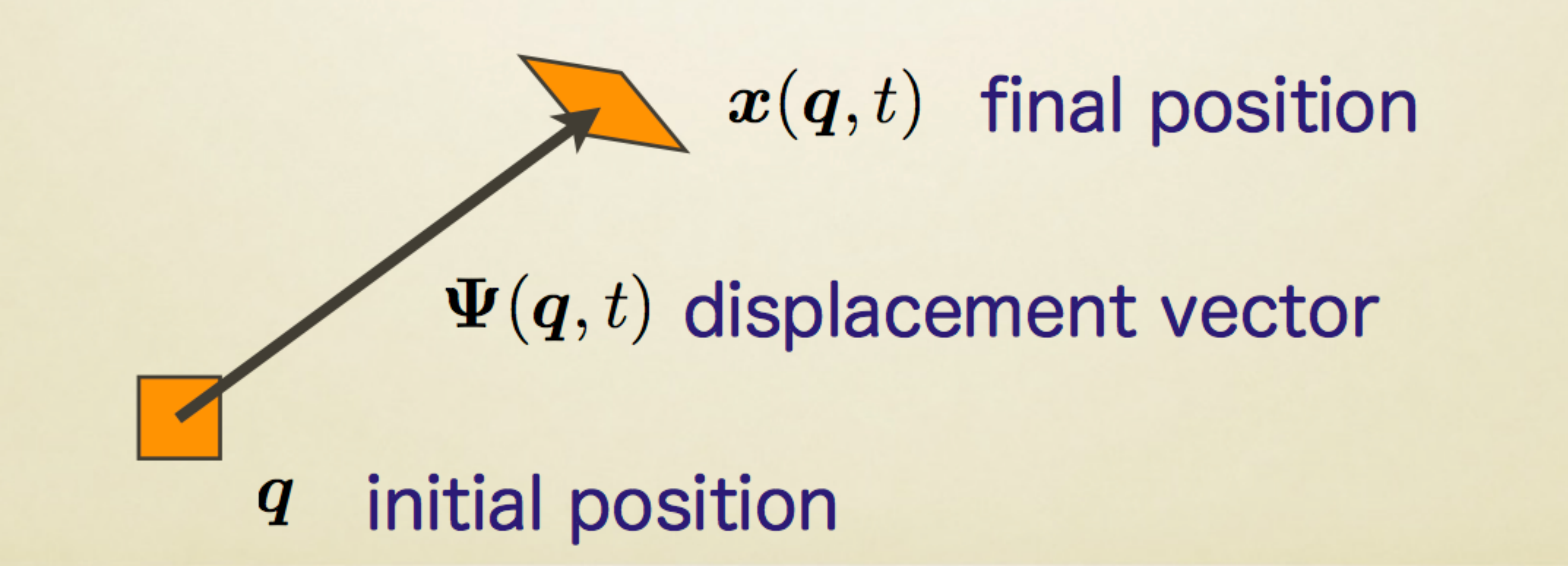
Solution for whole matter as Dark Matter

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} << 1$$

linearity condition

Lagrangian Perturbation Theory

$$\boldsymbol{\Psi}(\boldsymbol{q},t) = \boldsymbol{x}(\boldsymbol{q},t) - \boldsymbol{q}$$



Credit to Matsubara's presentation

Lagrangian Perturbation Theory

Equation of motion & Poisson's Equation

$$\ddot{\Psi} + \frac{\dot{a}}{a}\dot{\Psi} = -\frac{1}{a^2}\nabla_x \phi$$

$$\Delta_x \phi = 4\pi G\bar{\rho}a^2\delta(x,t)$$

Linearization & Zeldovich Approximation

$$\delta(x,t) = \left[\det\left(I + \frac{\partial \Psi}{\partial q}\right)\right]^{-1} - 1 \approx -\nabla_q . \Psi$$

$$\Psi \approx -D(t)\nabla_q \rho_0(q)$$

Credit to Lile Wang's presentation

Lagrangian Perturbation Theory

- **Taking into account the higher-order perturbations in the displacement**

$$\boldsymbol{\Psi} = \sum_{n=1}^{\infty} \boldsymbol{\Psi}^{(n)} = \boldsymbol{\Psi}^{(1)} + \boldsymbol{\Psi}^{(2)} + \boldsymbol{\Psi}^{(3)} + \cdots$$

$$\boldsymbol{\Psi}^{(1)} = -D(t)\nabla\varphi_0(\boldsymbol{q})$$

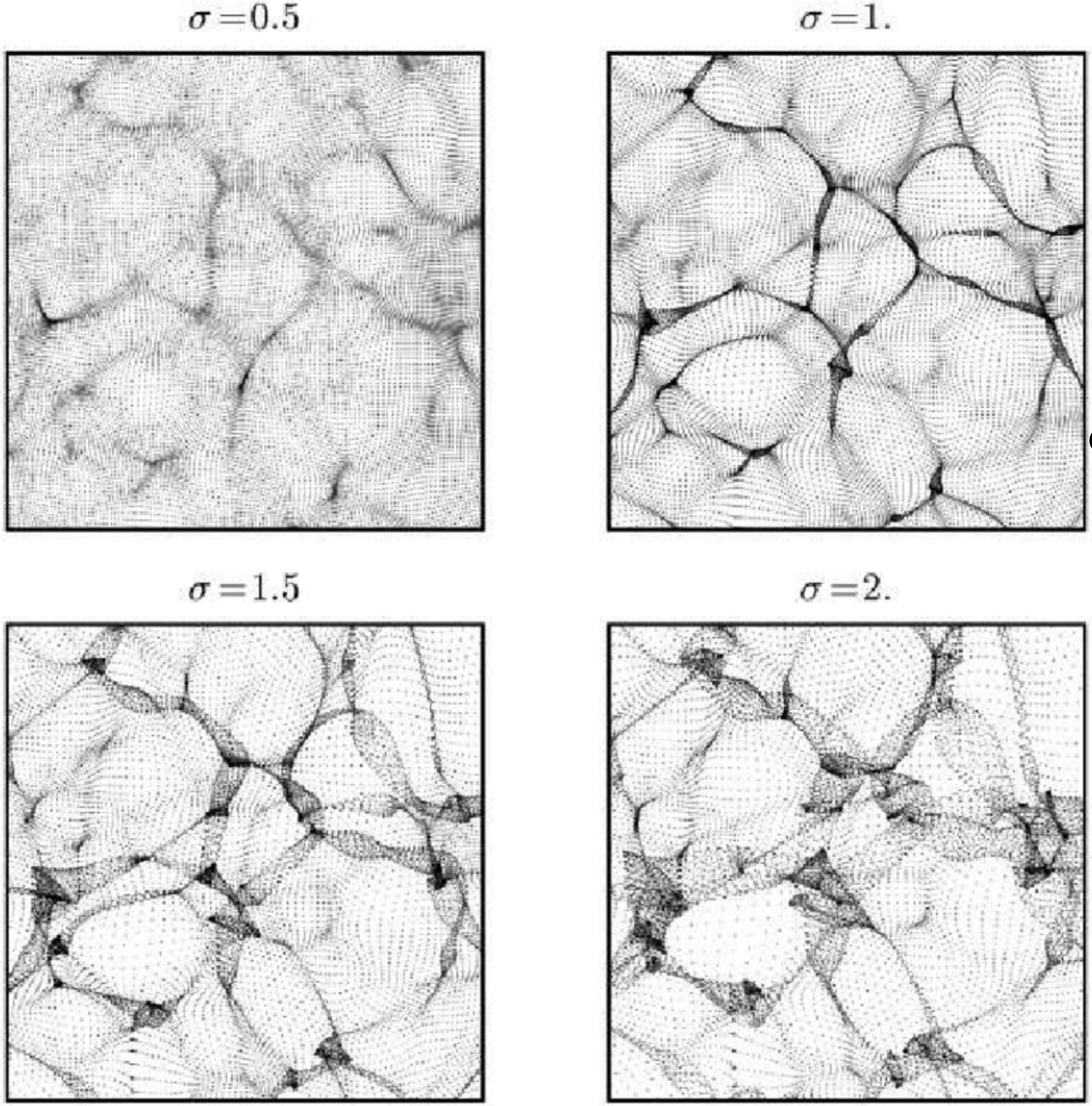
(First order: Zel'dovich approx.)

$$\boldsymbol{\Psi}^{(2)} = -\frac{1}{2}D_2(t)\nabla\triangle^{-1}\left[\Psi^{(1)}_{i,i}\Psi^{(1)}_{j,j} - \Psi^{(1)}_{i,j}\Psi^{(1)}_{i,j}\right]$$

$$\boldsymbol{\Psi}^{(3)} = -\frac{1}{3!}\Big[D_{3a}(t)\nabla\triangle^{-1}\left(\Psi^{(1)}_{i,i}\Psi^{(2)}_{j,j} - \Psi^{(1)}_{i,j}\Psi^{(2)}_{i,j}\right) + D_{3b}(t)\nabla\triangle^{-1}\det\left(\Psi^{(1)}_{i,j}\right)$$
$$+ D_{3c}(t)\triangle^{-1}\left(\boldsymbol{\Psi}^{(1)}_{,j}\Psi^{(2)}_{i,j} - \Psi^{(1)}_{i,j}\boldsymbol{\Psi}^{(2)}_{,j}\right)_{,i}\Big]$$

Recursive solutions

Credit to Matsubara's presentation



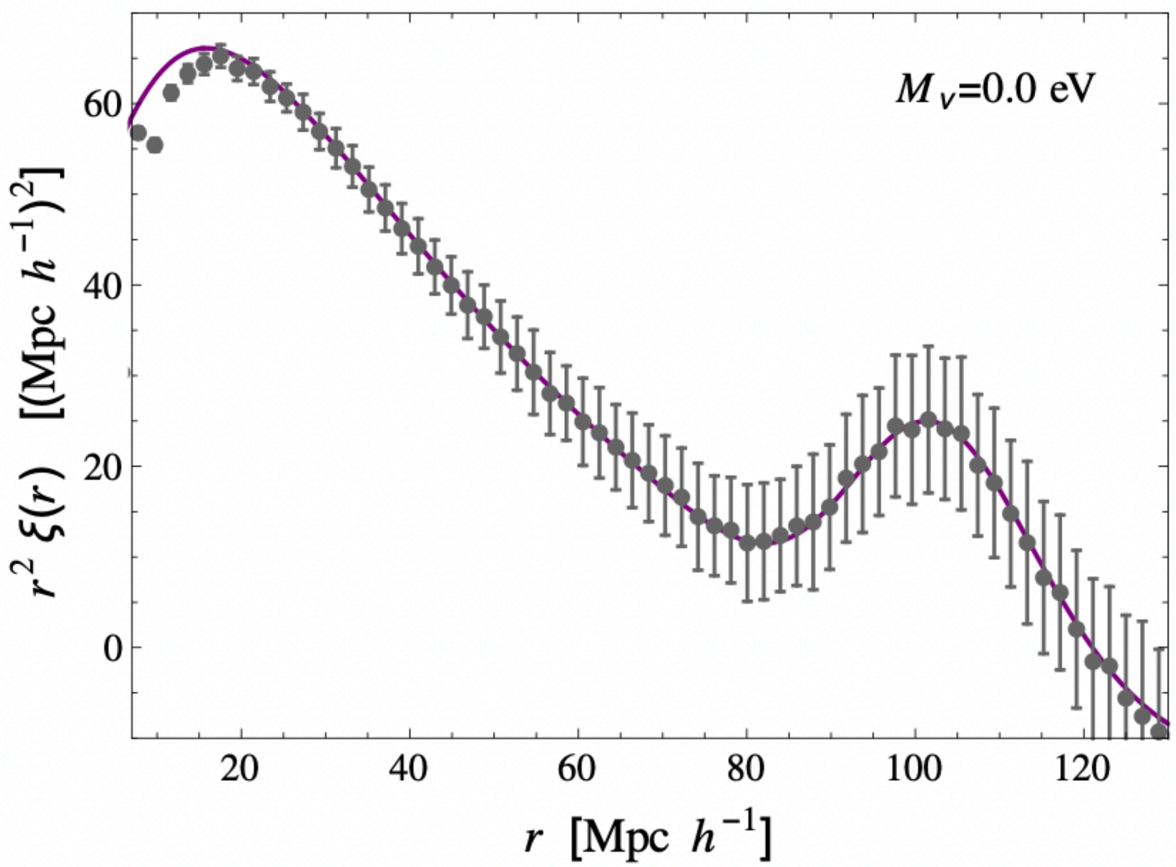
Applying the first order displacement field on initial particle positions.

Perturbtion theory can evaluate in average how these displacements modify the correlation function and Power Spectrum

Sergel 2009

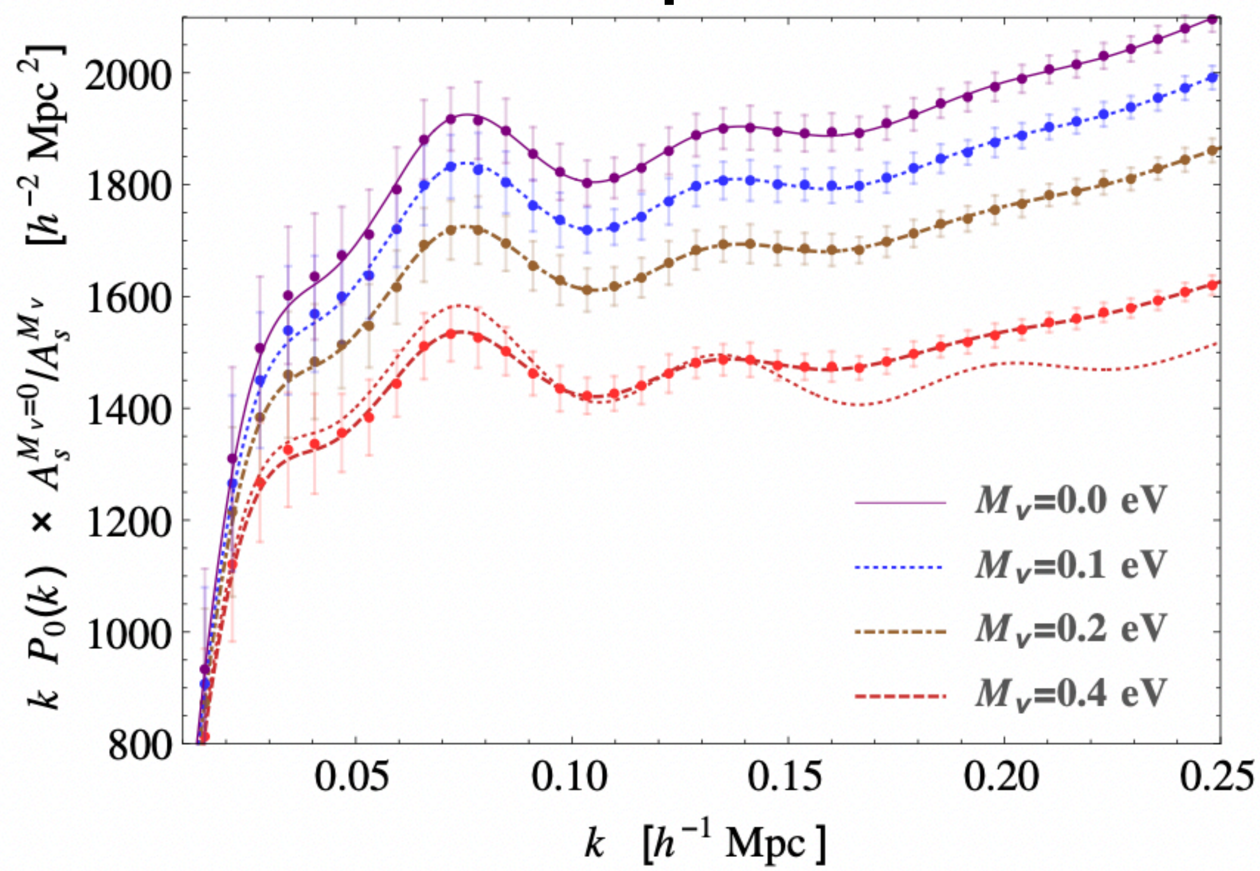
Perturbation Theory on stats Vs CDM simulations

2pt-corr function



A, Aviles & A, Banerjee 2020

Power spectrum

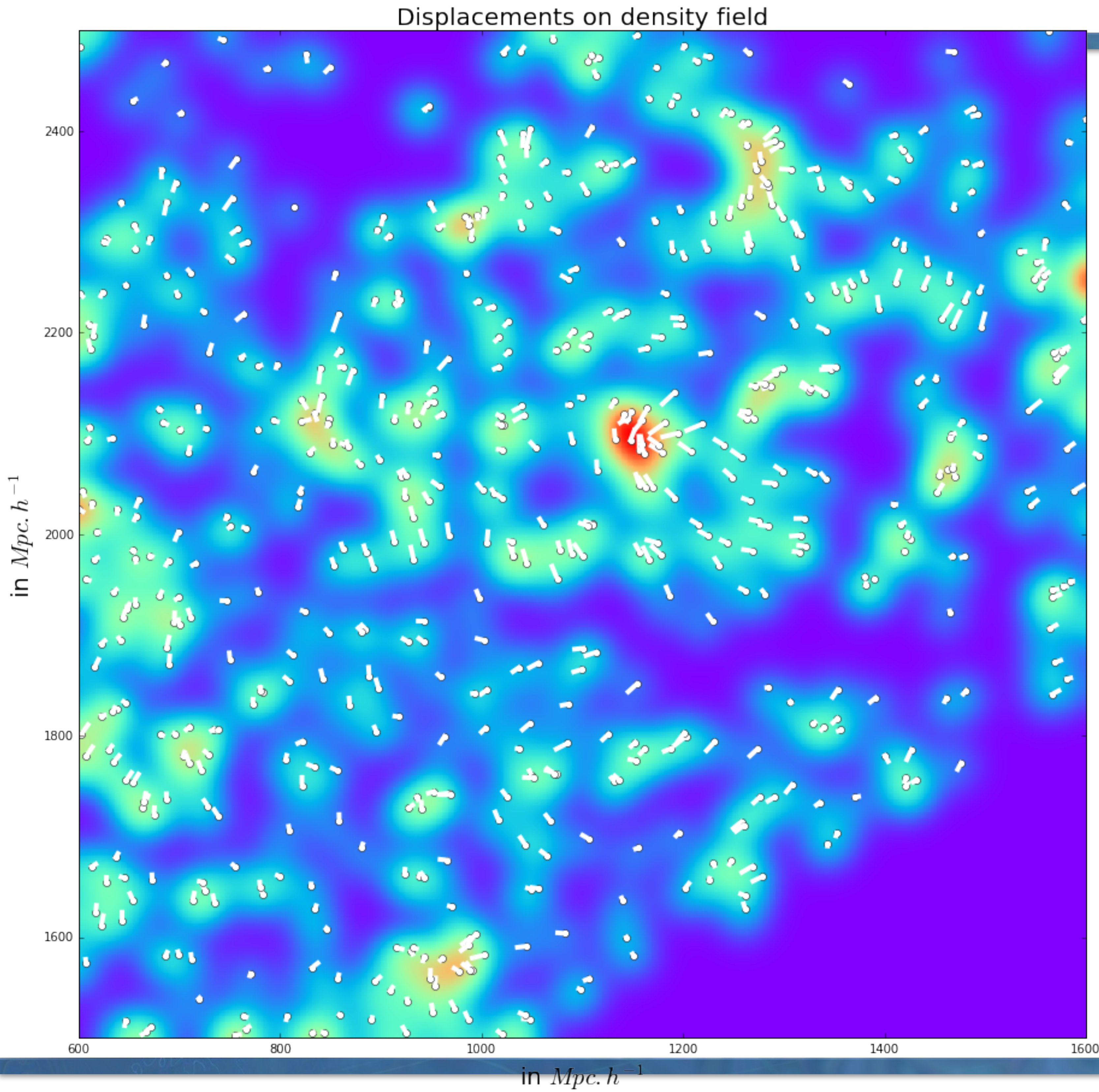


Alejandro Aviles et al 2021

Works very well up to :

$$r \sim 25\,Mpc/h$$
$$k \sim 0.3\,h/Mpc$$

Reconstruction to enhance BAO peak



Vargas, Ho, Fromenteau, Cuesta (2017)

We estimate the smoothed galaxy density field

↓

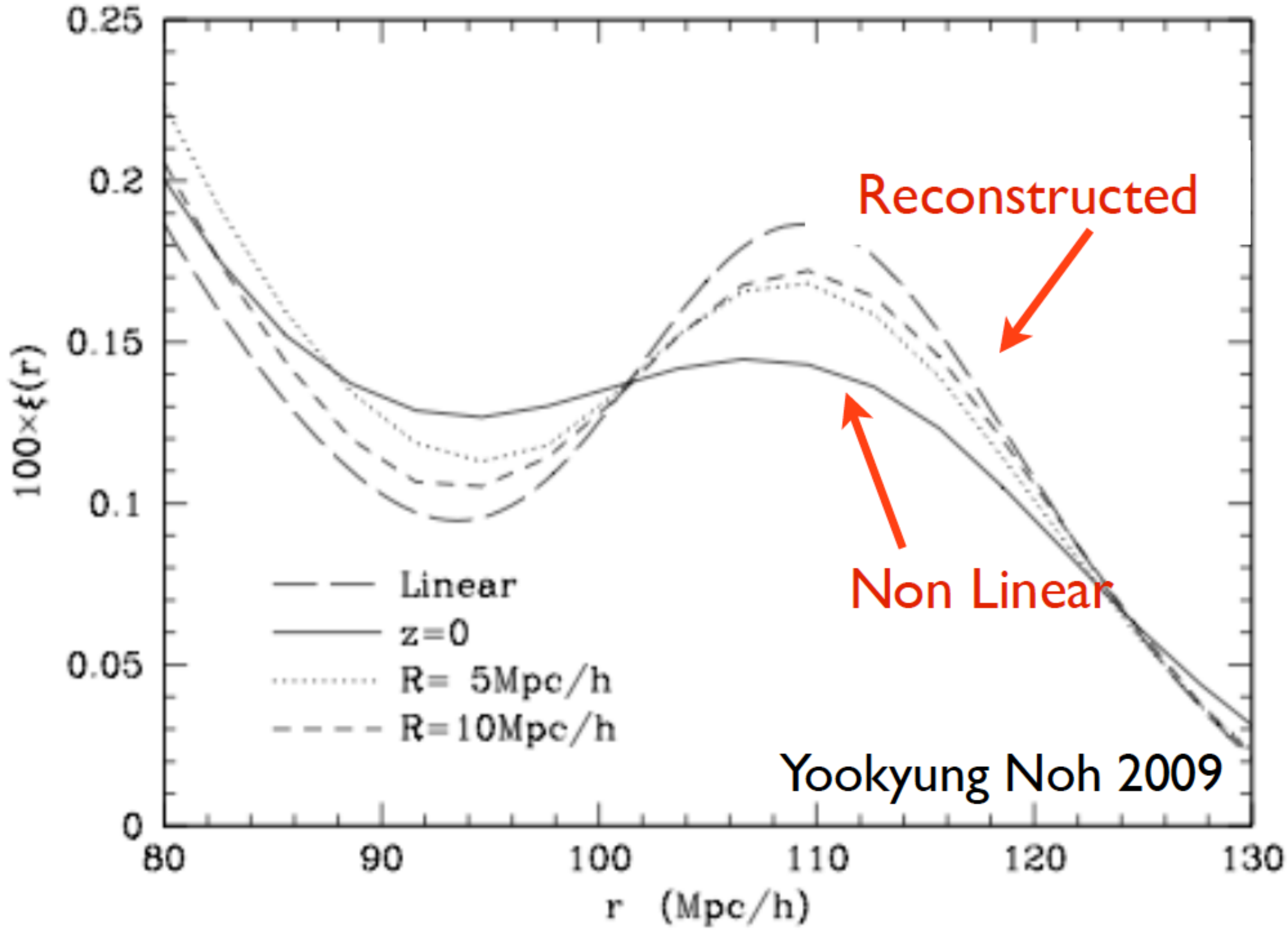
Using linear bias, we derive the matter density field

↓

We move back the galaxies to their original position

$$\vec{\psi}(\vec{k}) = \frac{-i\vec{k}}{k^2}\frac{\delta_g(\vec{k})}{b_g}$$

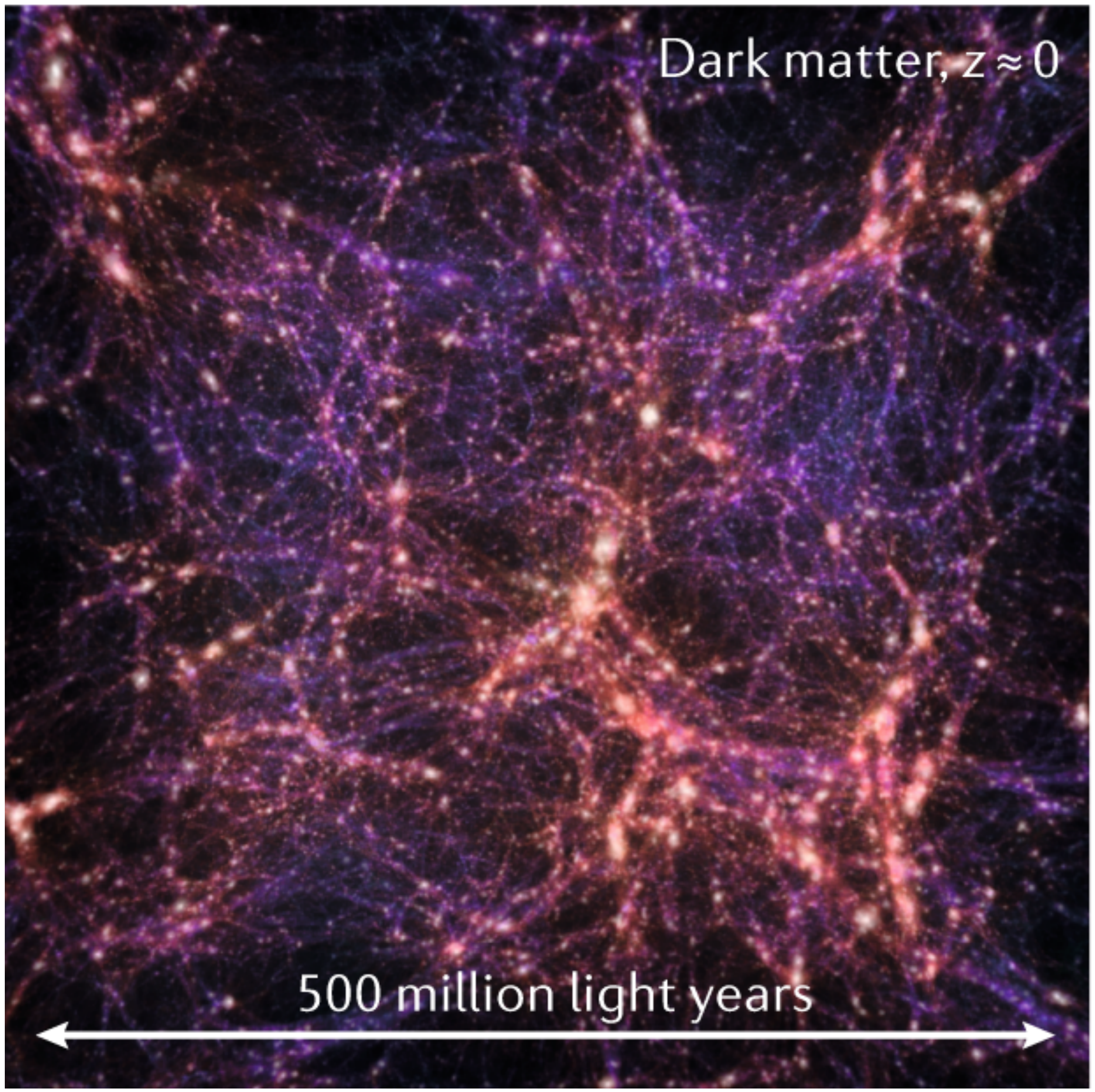
Reconstruction to enhance BAO peak



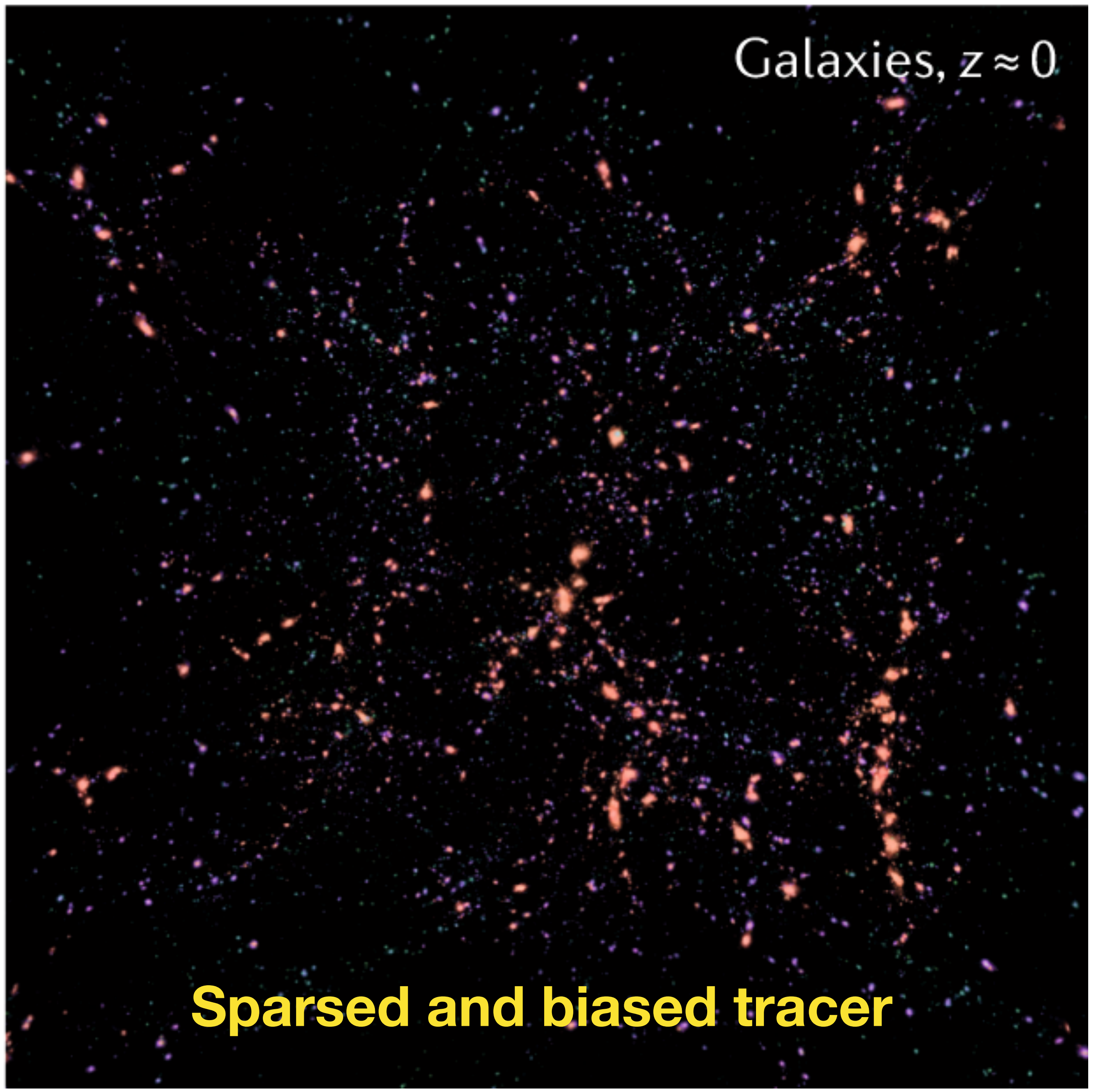
Is part of the standard BAO analysis

What we do observe?

a **That's what we need**

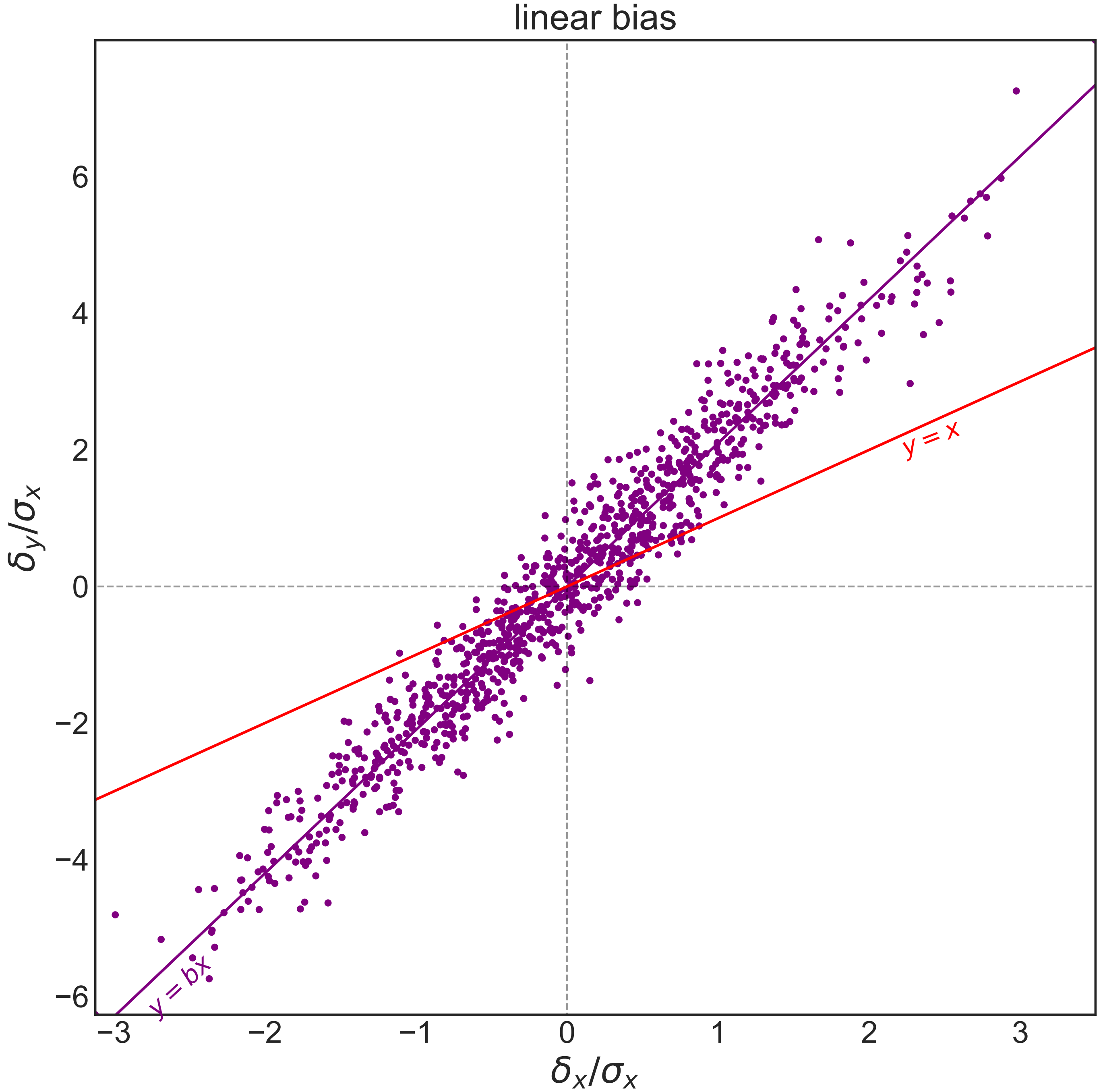


b **That's what we have**



(Image from Robertson et al. 2019)

Global bias (linear)



$$\delta_y = b_1(\delta_x - \bar{\delta}_x)$$

2pt-statistics and linear bias

$$\xi_{mm}(\vec{r}) = \langle \delta_m(\vec{x} + \vec{r}) \,.\, \delta_m(\vec{x}) \rangle_{\vec{x}}$$

$$\delta_x = \frac{\rho_x - \bar{\rho}_x}{\bar{\rho}_x}$$

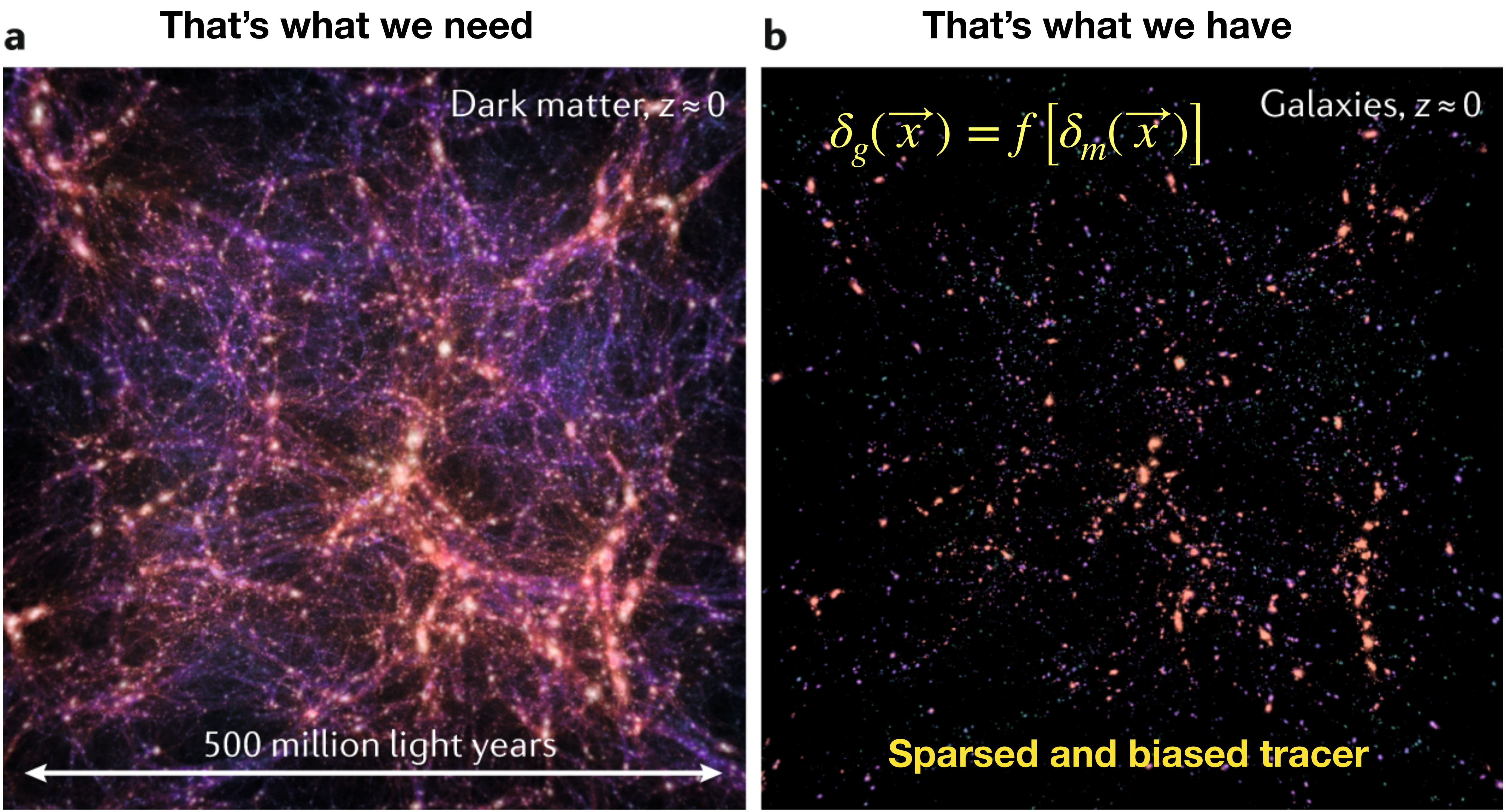
$$\xi_{gg}(\vec{r}) = \left\langle \delta_g(\vec{x} + \vec{r}) \,.\, \delta_g(\vec{x}) \right\rangle_{\vec{x}}$$

$$\xi_{gg}(\vec{r}) = \left\langle b_g \delta_m(\vec{x} + \vec{r}) \,.\, b_g \delta_m(\vec{x}) \right\rangle_{\vec{x}}$$

b = linear bias

$$\xi_{gg}(\vec{r}) = b_g^2 \xi_{mm}(\vec{r})$$

Complicated because bias can be complex



(Image from Robertson et al. 2019)

But what to do?

$$\xi_{mm}(\vec{r}) = \left\langle \delta_m(\overrightarrow{x} + \vec{r}) \,.\, \delta_m(\overrightarrow{x}) \right\rangle_{\overrightarrow{x}}$$

$$\delta_x = \frac{\rho_x - \bar{\rho}_x}{\bar{\rho}_x}$$

$$\xi_{gg}(\vec{r}) = \left\langle \delta_g(\overrightarrow{x} + \vec{r}) \,.\, \delta_g(\overrightarrow{x}) \right\rangle_{\overrightarrow{x}}$$

$$\xi_{gg}(\vec{r}) = \left\langle f\left[\delta_m(\overrightarrow{x} + \vec{r})\right] .f\left[\delta_m(\overrightarrow{x})\right] \right\rangle_{\overrightarrow{x}}$$

???

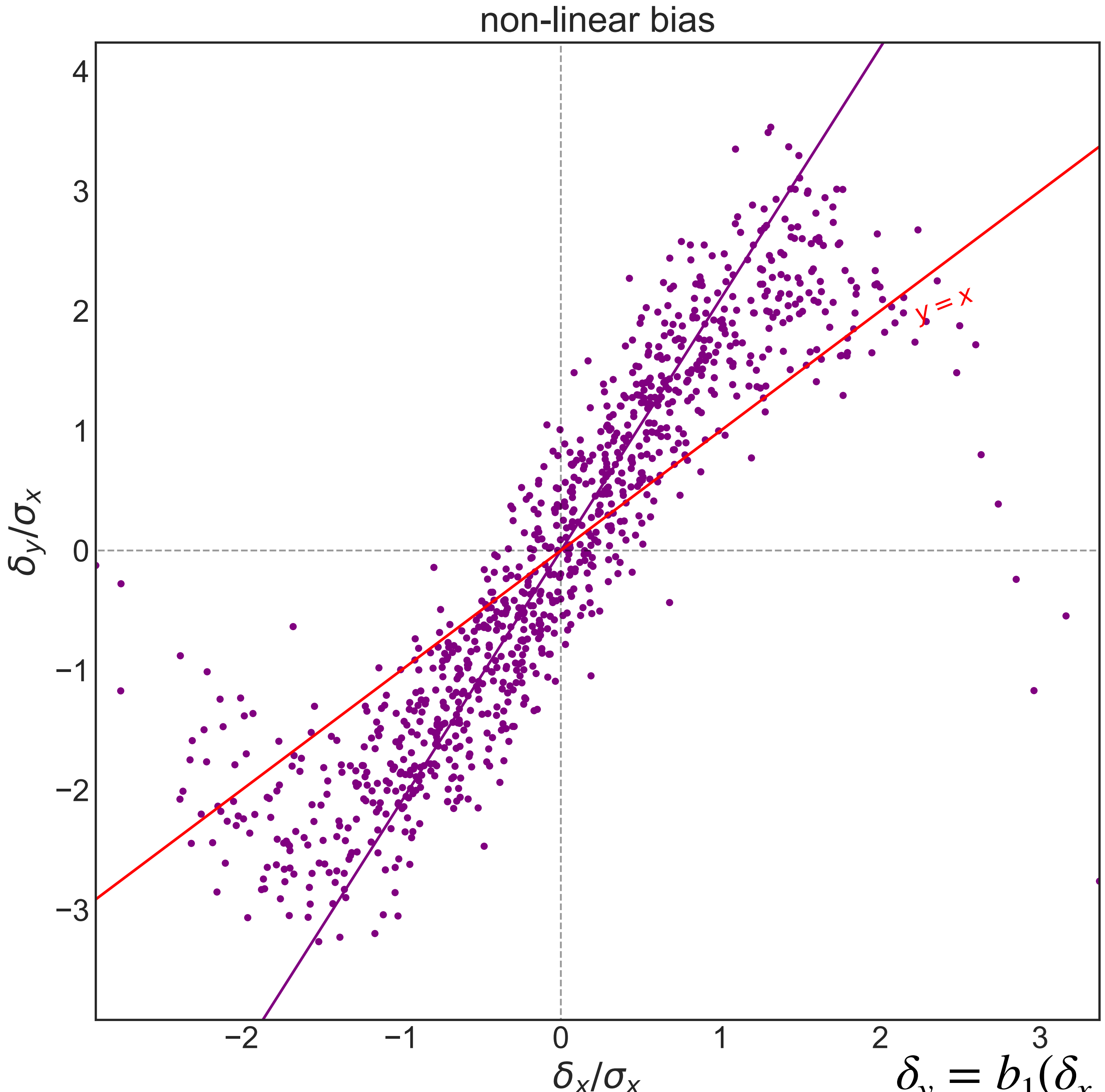
Standard bias scheme

$$\delta_g(\overrightarrow{x}) = f\left[\delta_m(\overrightarrow{x})\right] \longrightarrow \delta_g(\overrightarrow{x}) = \sum_{i=0}^{\infty} \frac{b_i}{i!}\delta_m^i(\overrightarrow{x})$$

Local
No specific form

non-Local
Taylor expansion

Non-local bias orden 2



$$\delta_y = b_1(\delta_x - \bar{\delta}_x) + \frac{b_2}{2}(\delta_x^2 - <\delta_x^2>)$$

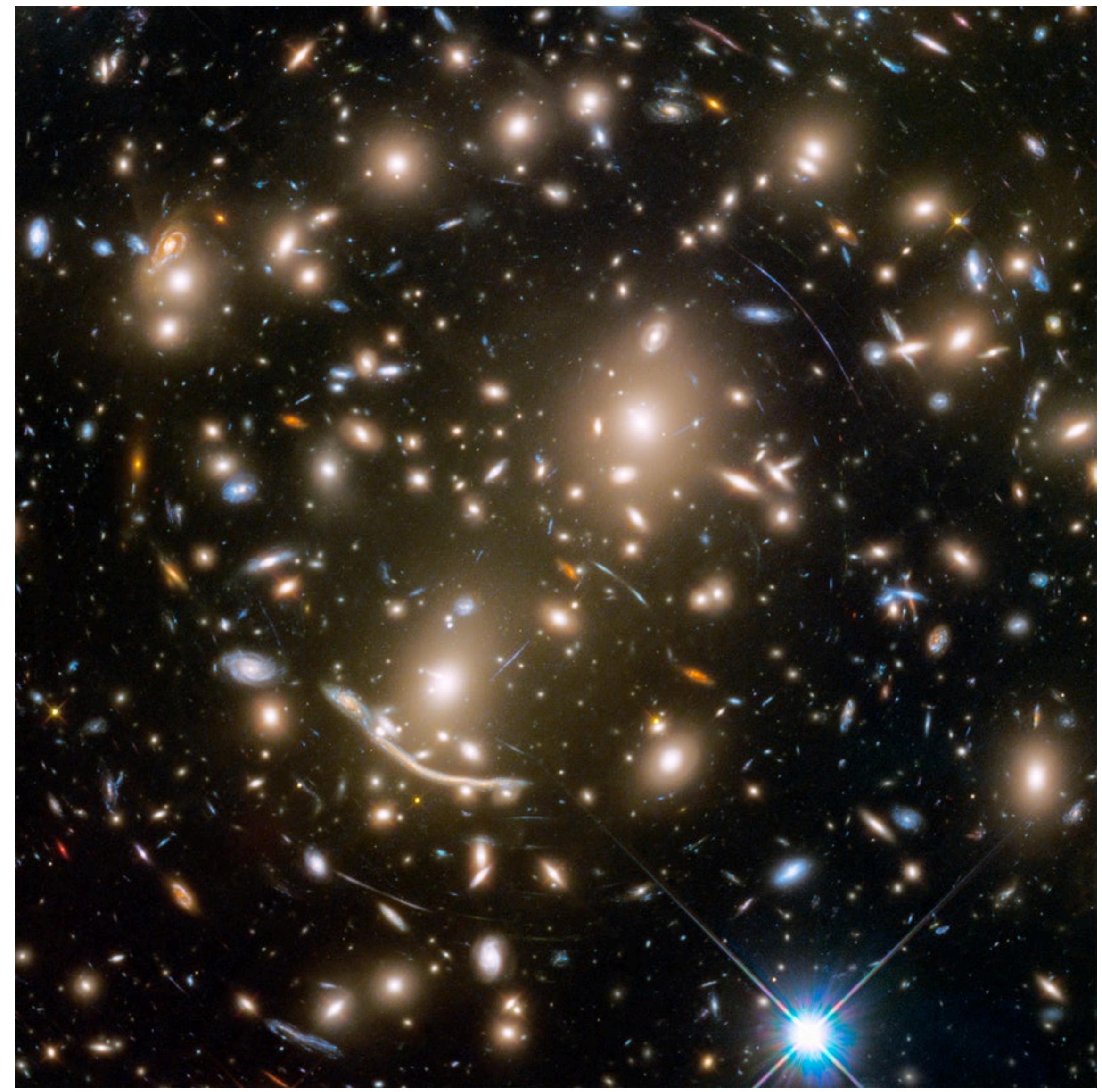
Real application : Hard!!

$$\delta_g = c_\delta\, \delta + \frac{1}{2}\, c_{\delta^2}\, \left(\delta^2 - \sigma^2\right) + \frac{1}{2} c_{s^2} \left(s^2 - \frac{2}{3}\sigma^2\right) + \frac{1}{3!}\, c_{\delta^3}\, \delta^3 + \frac{1}{2} c_{\delta s^2}\, \delta\, s^2 + c_\psi\, \psi + c_{st}\, st + \frac{1}{3!}\, c_{s^3}\, s^3$$
$$+ c_\epsilon\, \epsilon + c_{\delta\epsilon}\, \delta\epsilon + \frac{1}{2}\, c_{\delta^2\epsilon}\, \delta^2\epsilon + \frac{1}{2} c_{s^2\epsilon}\, s^2\epsilon + \frac{1}{2} c_{\epsilon^2}\, \left(\epsilon^2 - \sigma_\epsilon^2\right) + \frac{1}{2} c_{\delta\epsilon^2}\, \delta\epsilon^2 + \frac{1}{3!} c_{\epsilon^3}\, \epsilon^3 + \ldots$$

$$\begin{aligned}
P_{mg}(k) &= c_\delta\, P_{\rm NL}(k) \\
&+ c_{\delta^2} \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q)\, P(|\mathbf{k}-\mathbf{q}|)\, F_S^{(2)}(\mathbf{q}, \mathbf{k}-\mathbf{q}) + \frac{34}{21}\, c_{\delta^2}\, \sigma^2\, P(k) \\
&+ c_{s^2} \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q)\, P(|\mathbf{k}-\mathbf{q}|)\, F_S^{(2)}(\mathbf{q}, \mathbf{k}-\mathbf{q})\, S(\mathbf{q}, \mathbf{k}-\mathbf{q}) \\
&+ 2\, c_{s^2}\, P(k) \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q)\, F_S^{(2)}(-\mathbf{q}, \mathbf{k})\, S(\mathbf{q}, \mathbf{k}-\mathbf{q}) \\
&+ \frac{1}{2}\, c_{\delta^3}\, \sigma^2\, P(k) + \frac{1}{3}\, c_{\delta s^2}\, \sigma^2\, P(k) \\
&+ 2\, c_\psi\, P(k) \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q) \left[\frac{3}{2} D_S^{(3)}(\mathbf{q}, -\mathbf{q}, -\mathbf{k}) - 2\, F_S^{(2)}(-\mathbf{q}, \mathbf{k})\, D_S^{(2)}(\mathbf{q}, \mathbf{k}-\mathbf{q})\right] \\
&+ 2\, c_{st}\, P(k) \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q)\, D_S^{(2)}(-\mathbf{q}, \mathbf{k})\, S(\mathbf{q}, \mathbf{k}-\mathbf{q}) \\
&+ \frac{1}{2}\, c_{\delta\epsilon^2}\, \sigma_\epsilon^2\, P(k)\,.
\end{aligned}$$

McDonald & Roy 2009

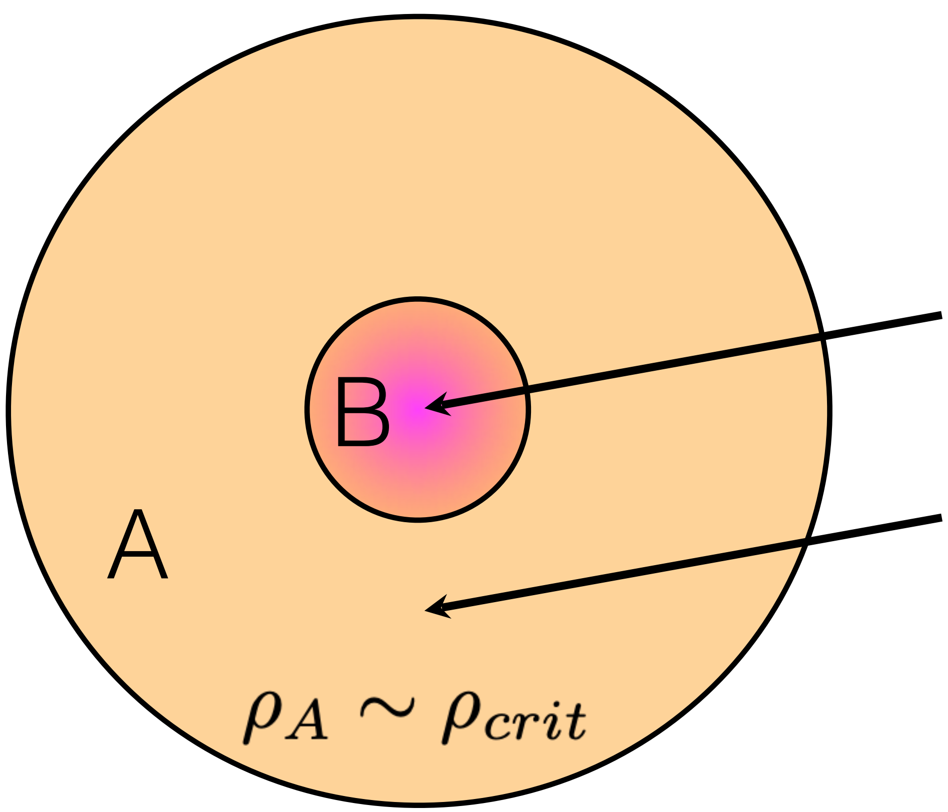
All galaxies are leaving in halos



Spherical halo model

The 2 areas A & B are considered as local universe with proper scale factor evolution

(Gunn & Gott 1972)

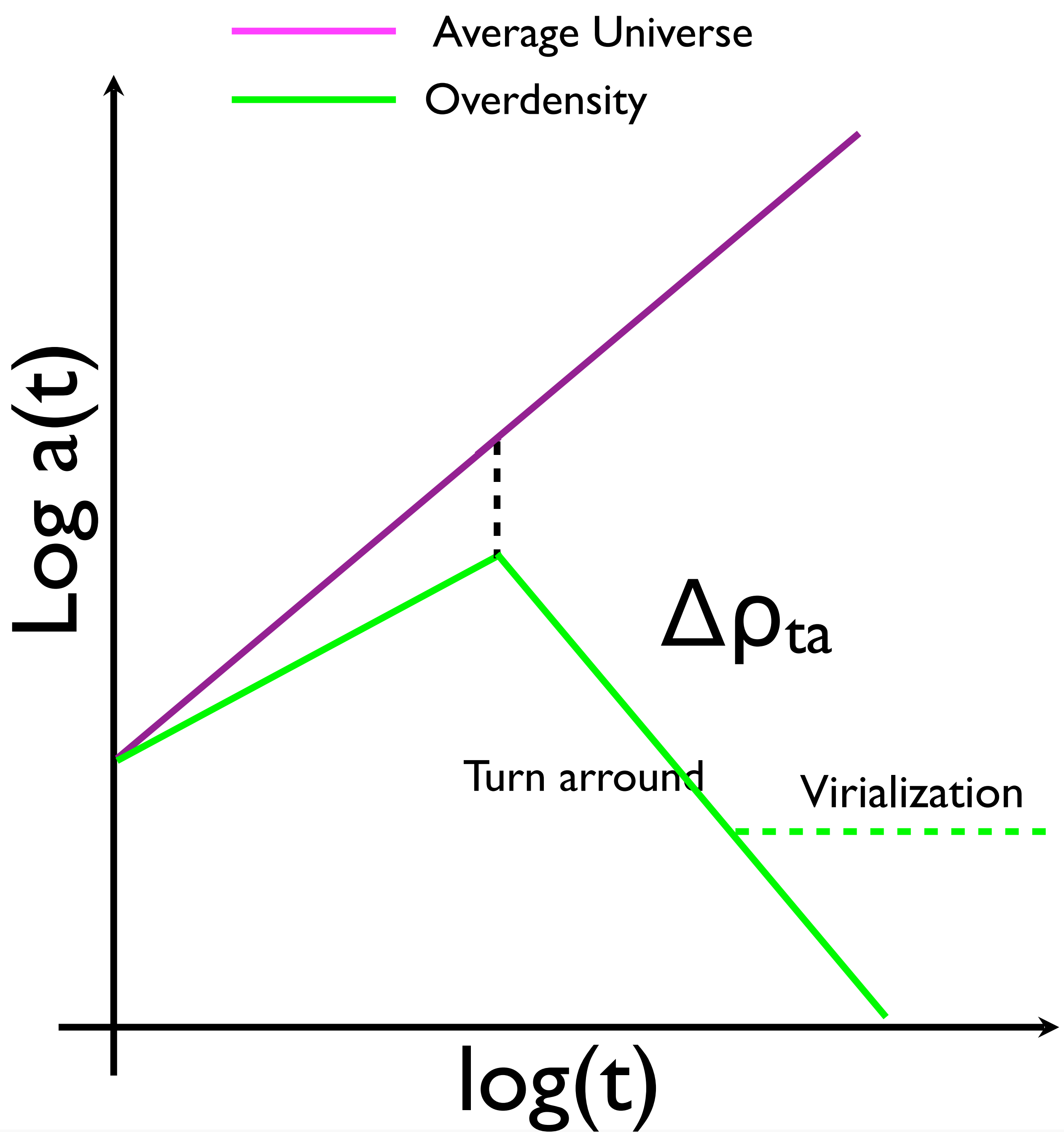


Curvature

$$H_B^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_B + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$H_A^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_A + \frac{\Lambda}{3}$$

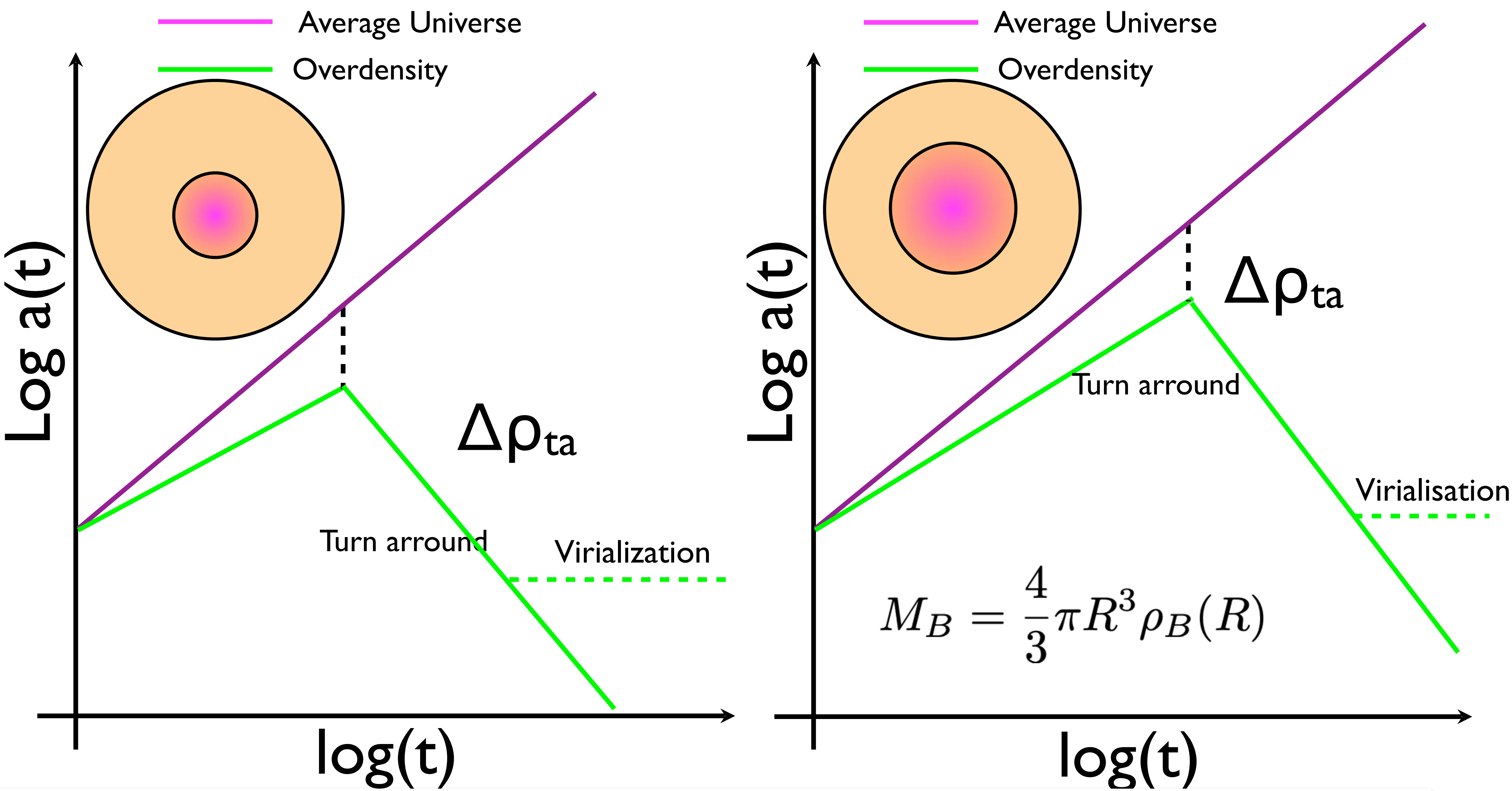
Galaxy clusters



$$M_B = \frac{4}{3}\pi R^3 \rho_B(R)$$

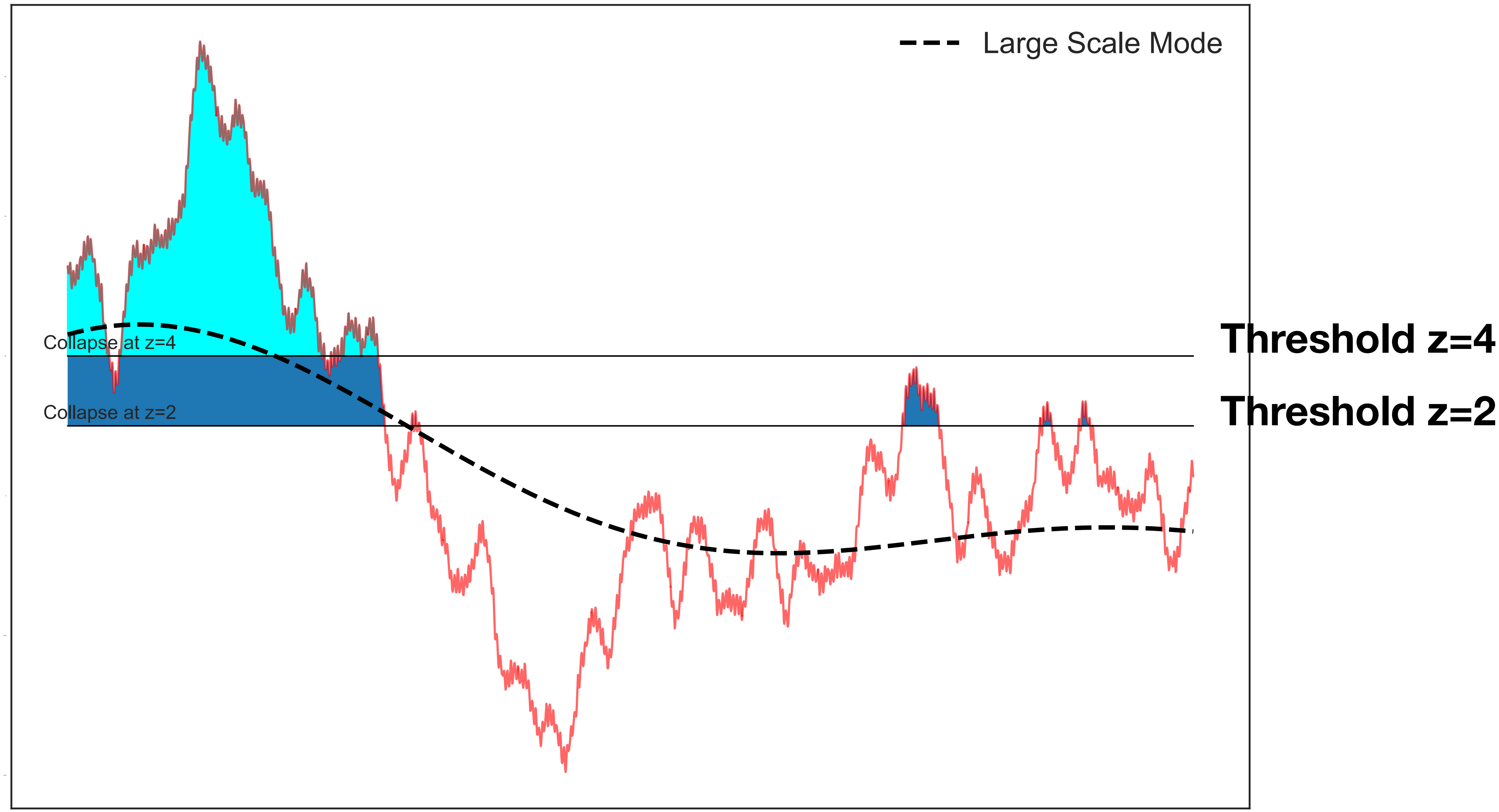
The number of virialized halos of a given mass at a given redshift

Galaxy clusters



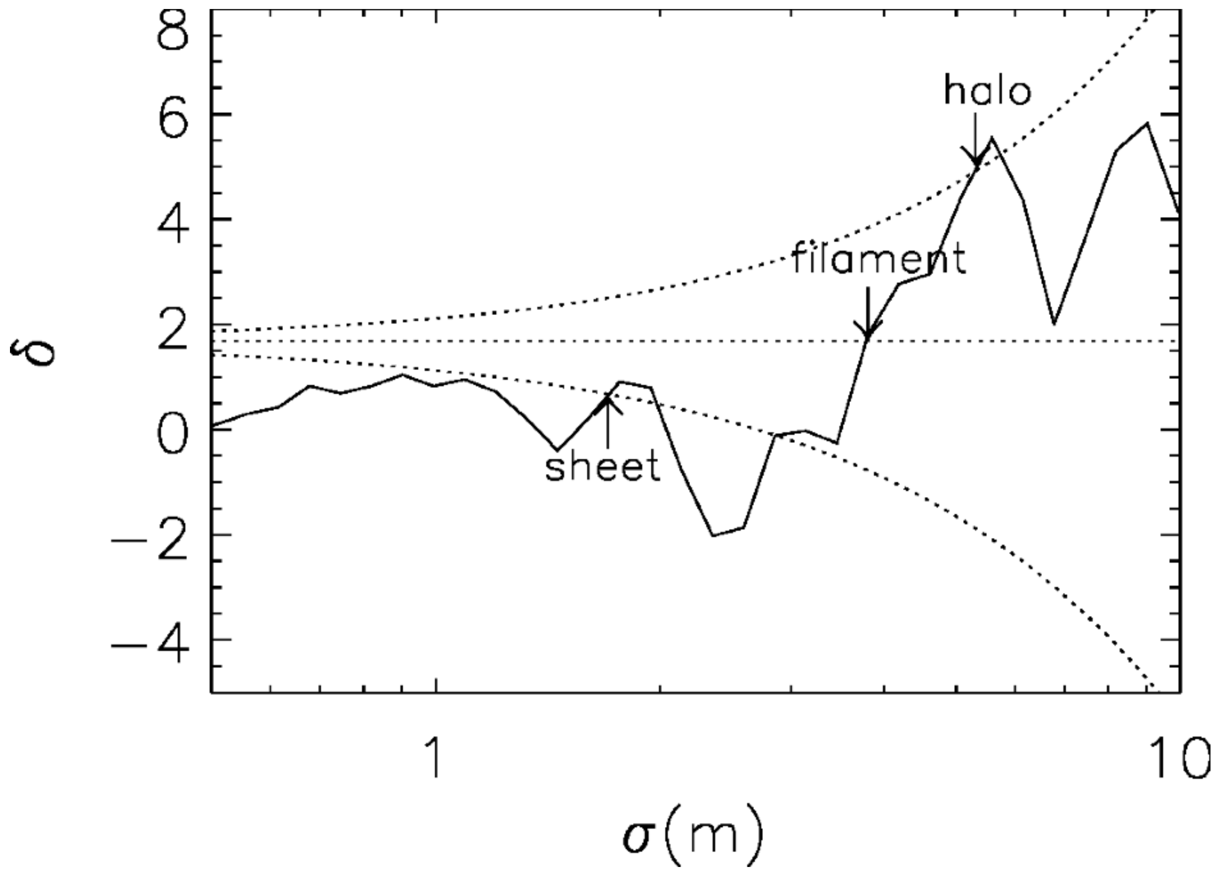
The number of virialized halos of a given mass at a given redshift

More massive halos formed in large scale over densities



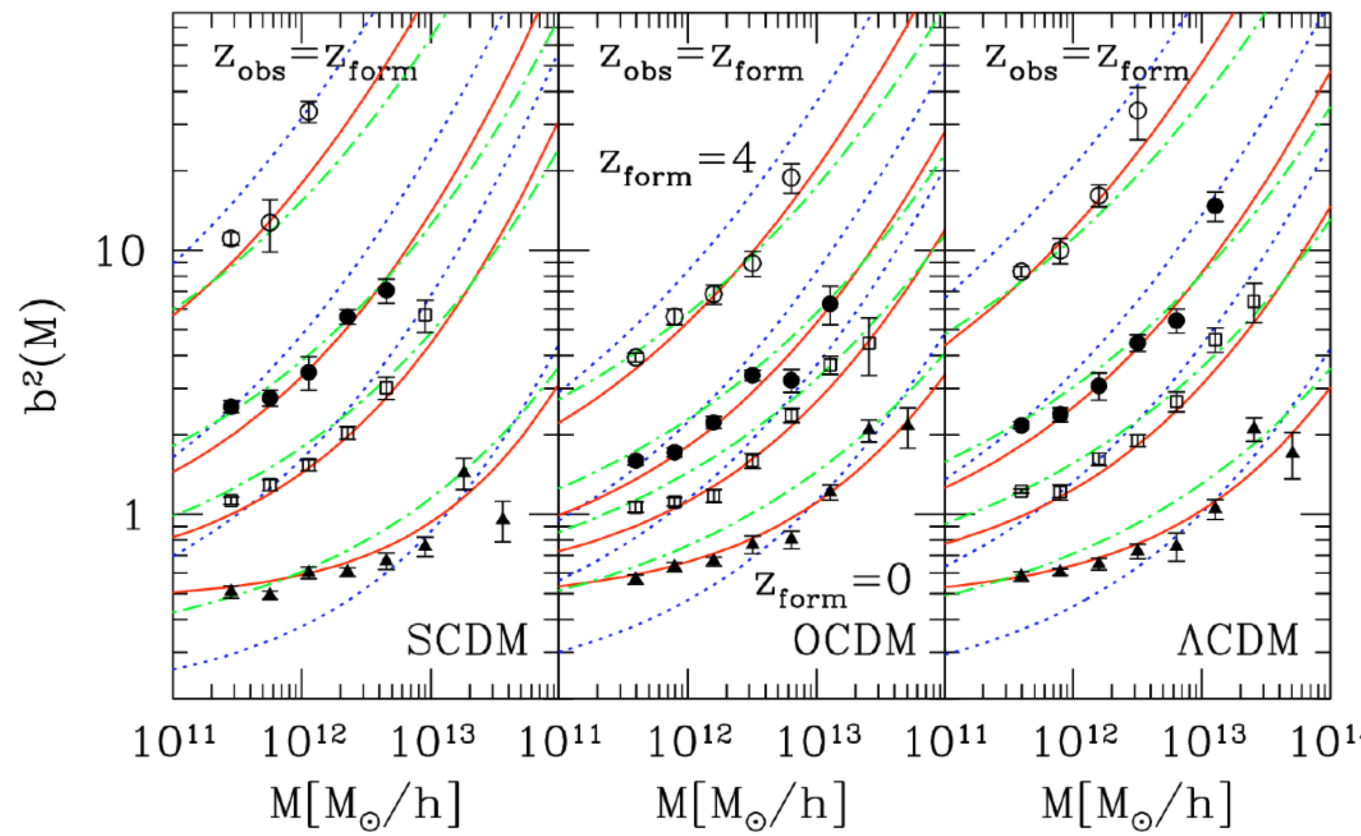
Conexión halo - materia

Excursion Set



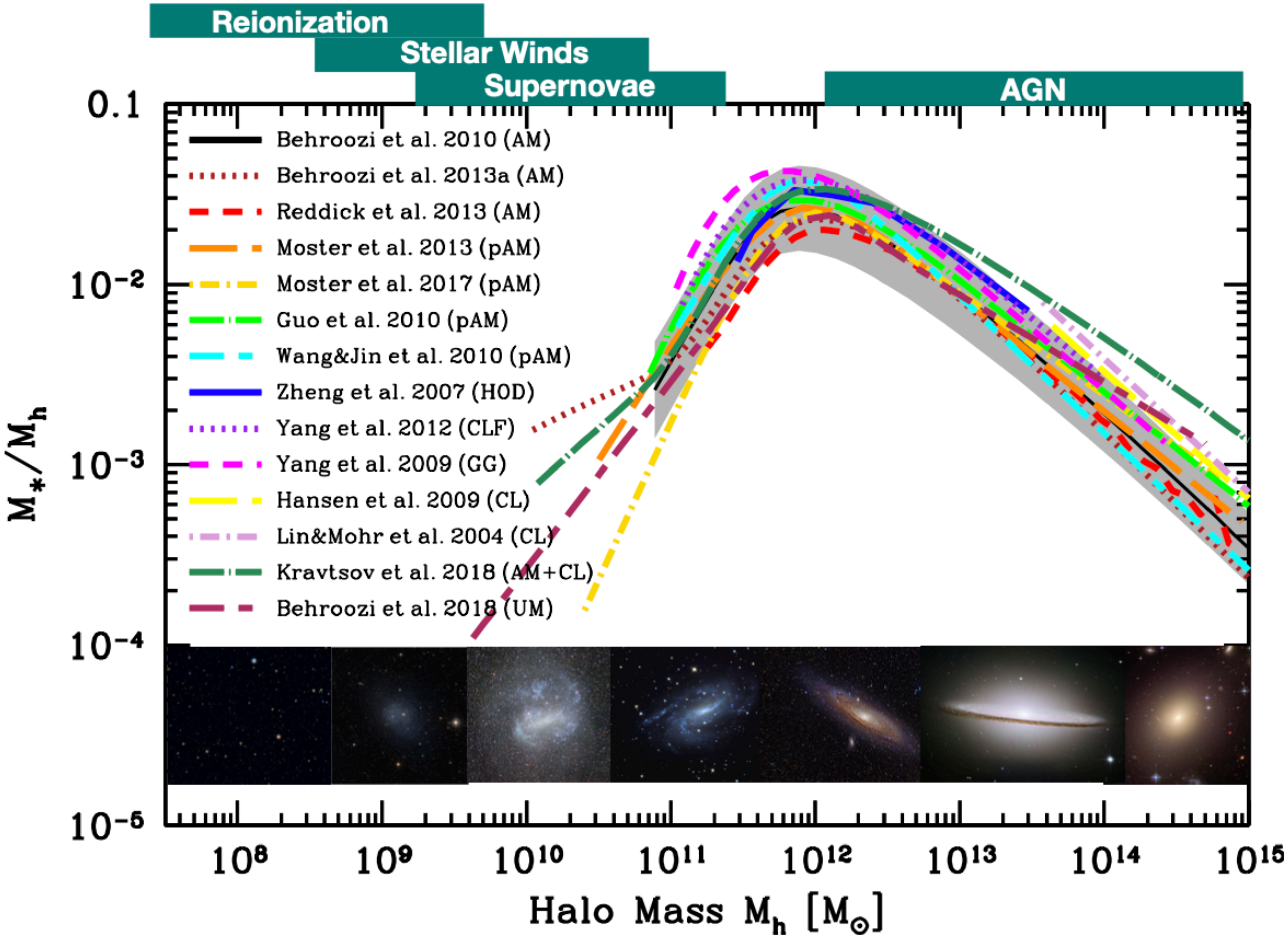
Bond el. 1991

Peak Background Split



Sheth & Tormen 1999

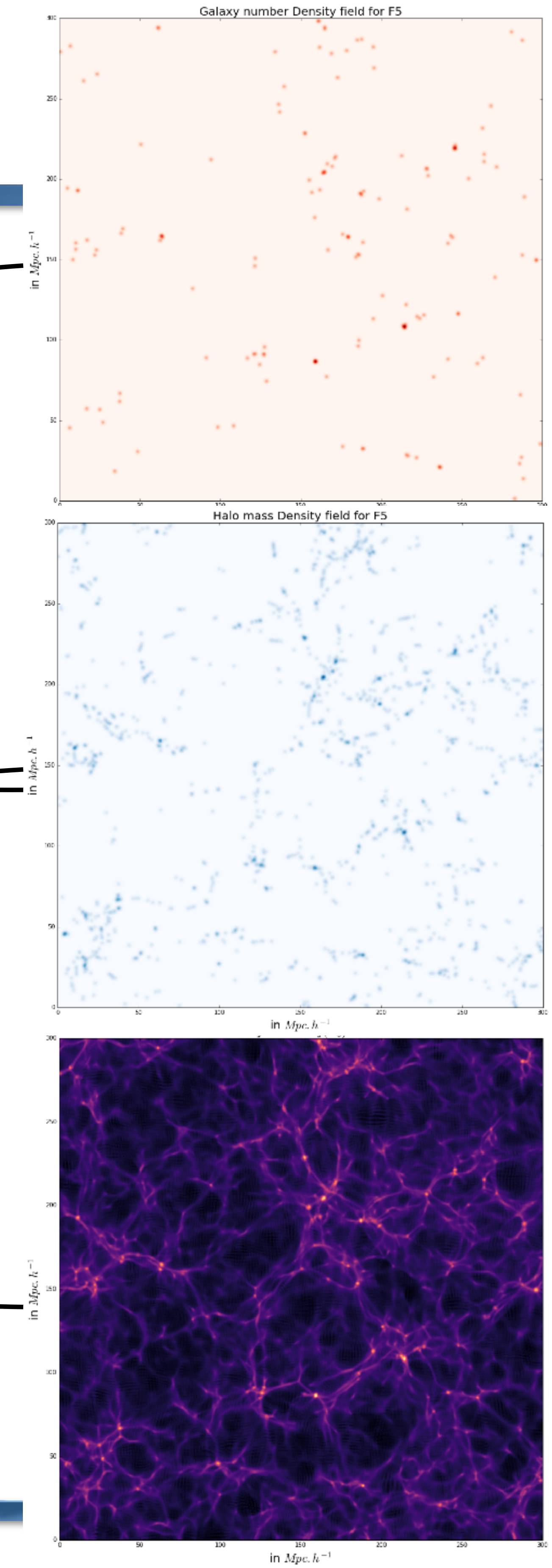
Stellar formation and galaxy evolution is much more complex

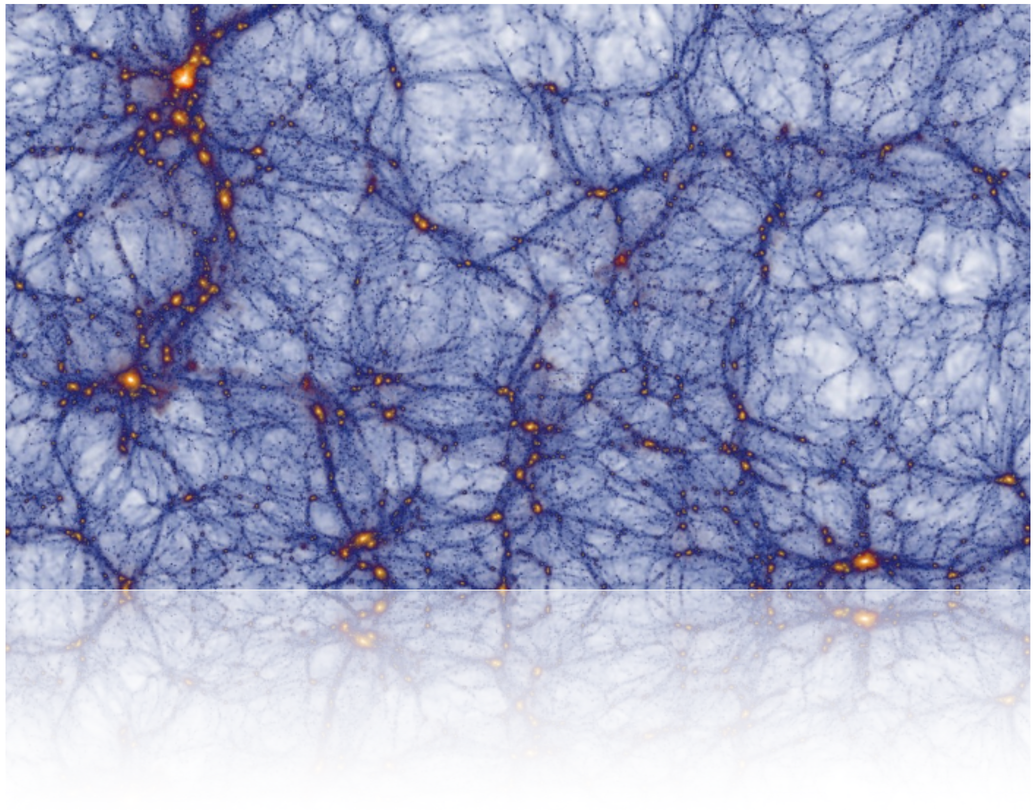


Idea

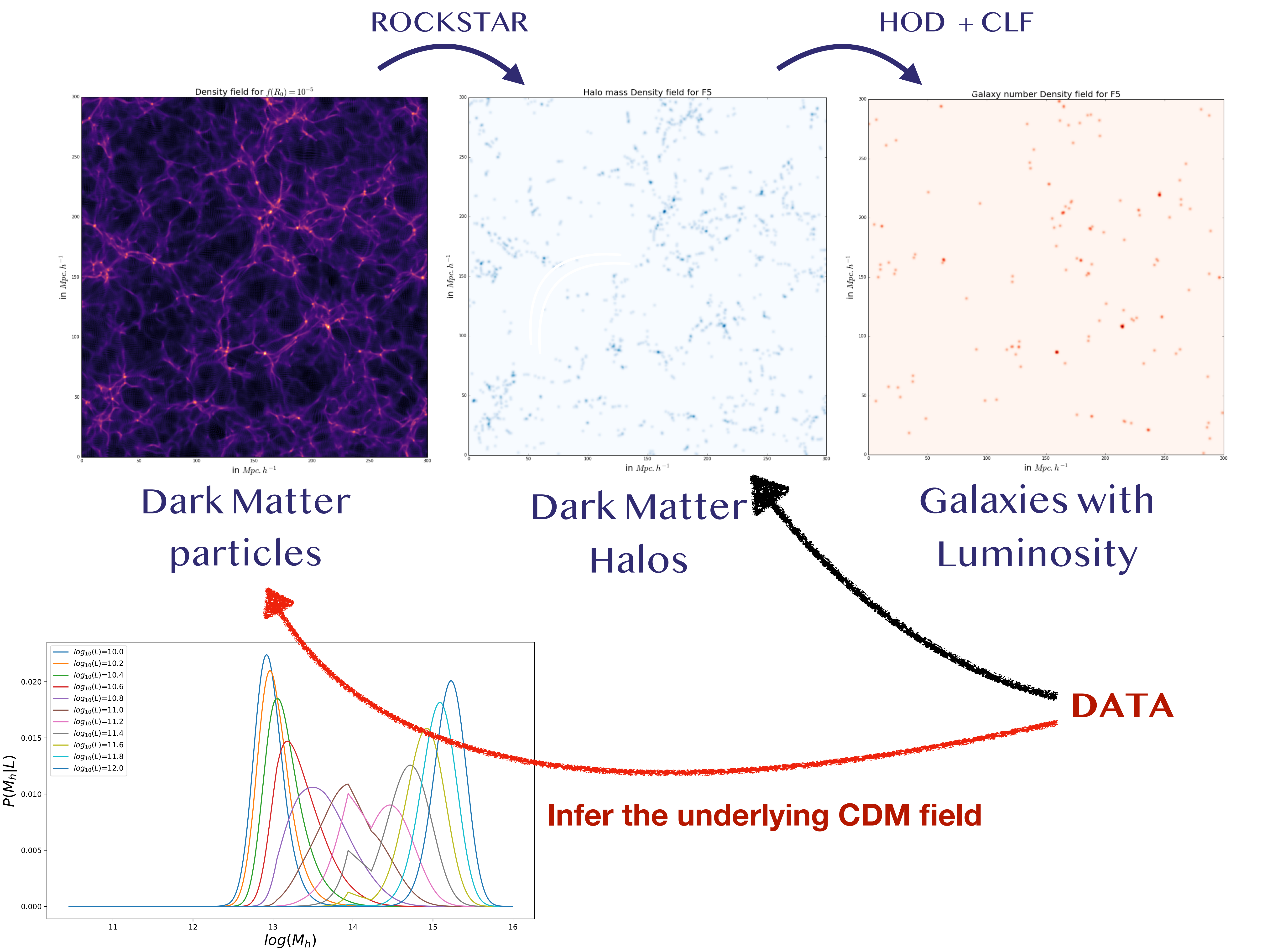
Use local astrophysical information to infer the hosting halo mass

Use the halo mass bias to connect with the matter density field





Invert HOD statistics



ROCKSTAR
HOD + CLF
Density field for $f(R_0) = 10^{-5}$
Halo mass Density field for F5
Galaxy number Density field for F5
in $Mpc.h^{-1}$
Dark Matter particles
Dark Matter Halos
Galaxies with Luminosity
DATA
Infer the underlying CDM field
$log_{10}(L)$=10.0
$log_{10}(L)$=10.2
$log_{10}(L)$=10.4
$log_{10}(L)$=10.6
$log_{10}(L)$=10.8
$log_{10}(L)$=11.0
$log_{10}(L)$=11.2
$log_{10}(L)$=11.4
$log_{10}(L)$=11.6
$log_{10}(L)$=11.8
$log_{10}(L)$=12.0
$P(M_h|L)$
$log(M_h)$

Reverting the information

$$\mathscr{P}(M_h|L) = \frac{\mathscr{P}(L|M_h) \cdot \mathscr{P}(M_h)}{\mathscr{P}(L)}$$

Posterior we want to evaluate

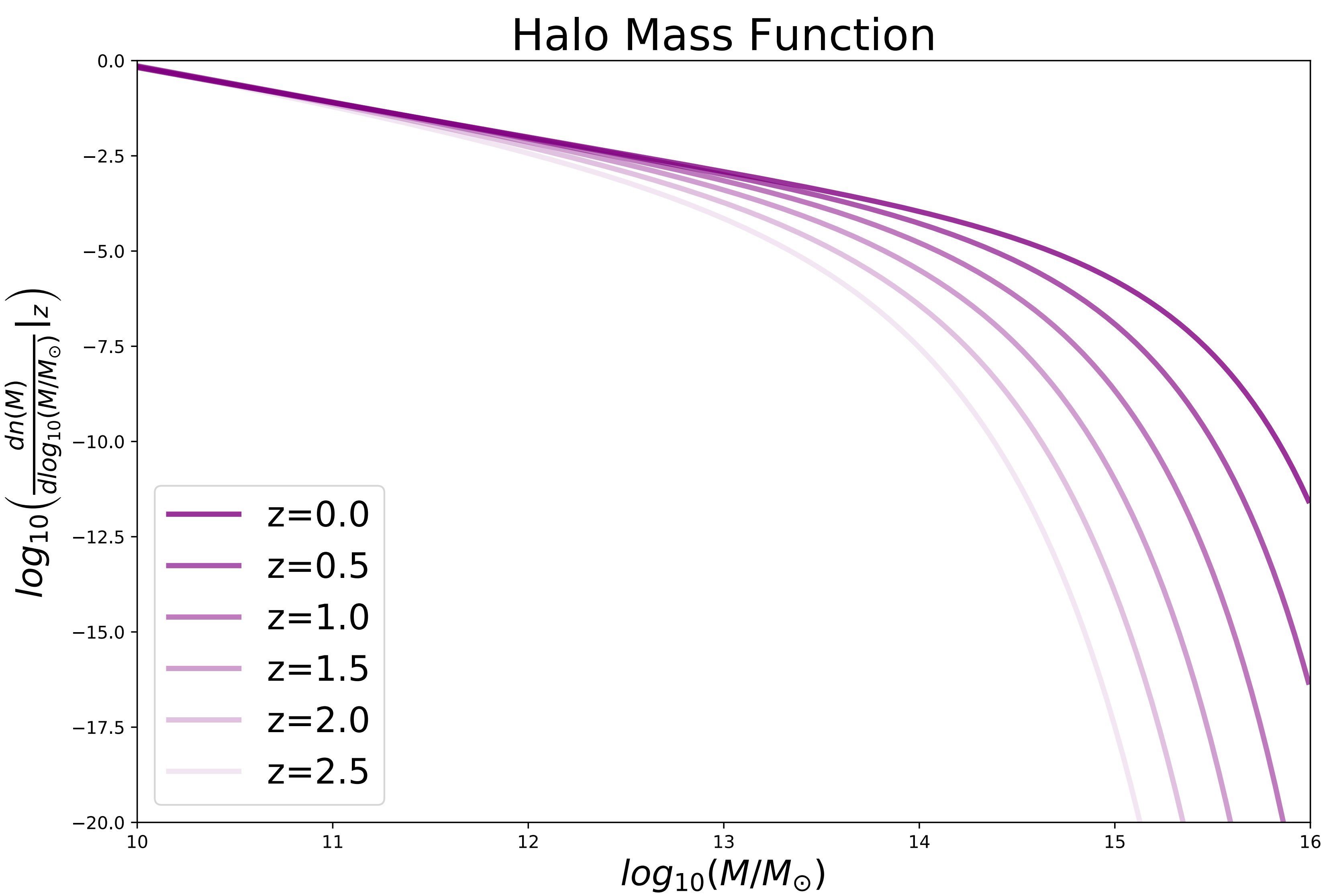
Conditional Luminosity Function

Convolution of HOD and HMF

Normalization which have not impact here

Halo Mass Function

1pt-statistics based on Press-Schechter and spherical collapse (Gunn & Gott) formalisms
+ Semi-analitical corrections



Halo Occupation Distribution

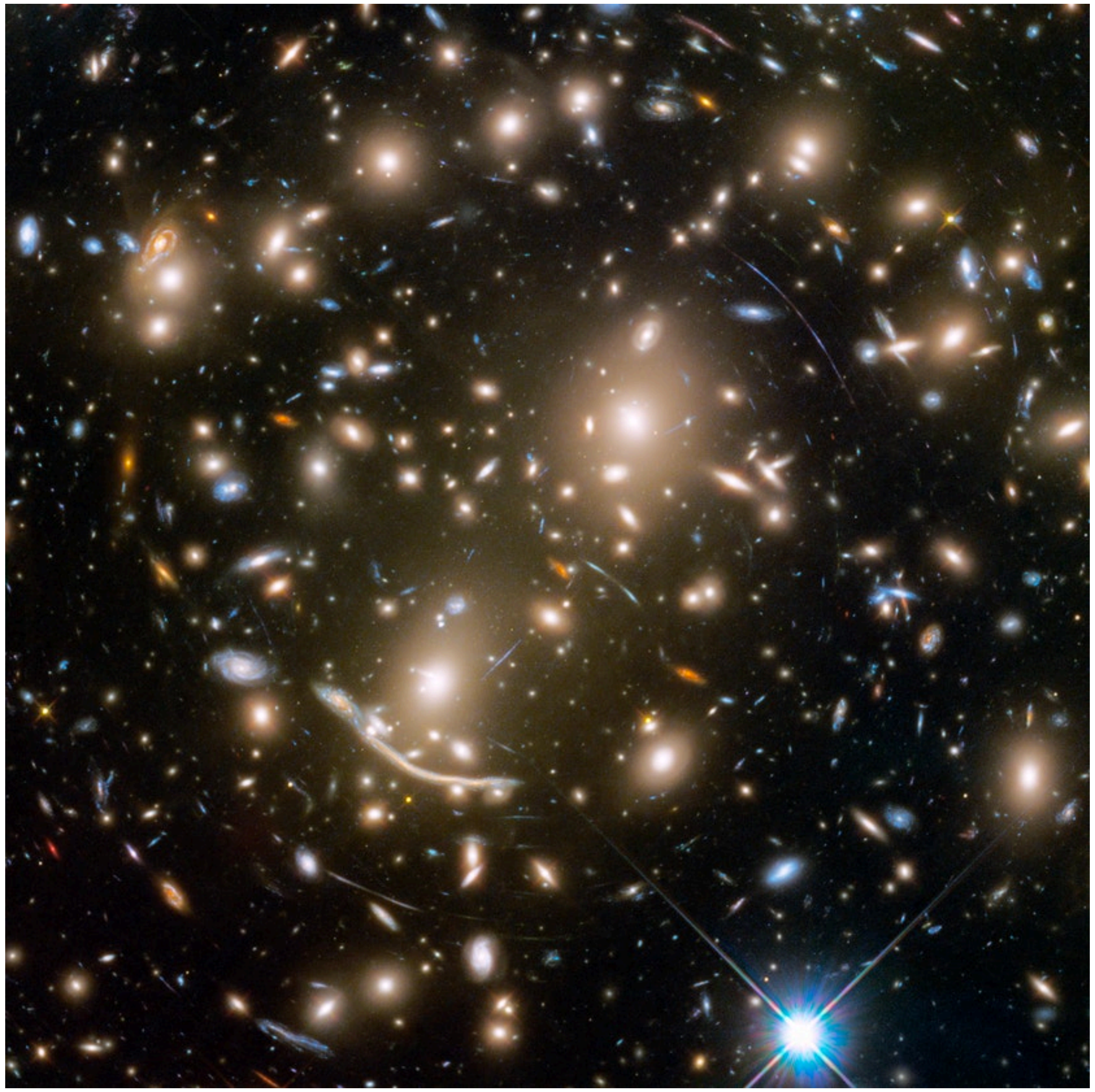
Link between the clustering of observed galaxies and the theoretical correlation function and the Halo profile

Associate a mean number of galaxies at a given halo mass

Each sample of galaxies has is proper HOD

$$\langle N(M) \rangle = \left\langle N_{cen}(M) \right\rangle + \left\langle N_{sat}(M) \right\rangle$$

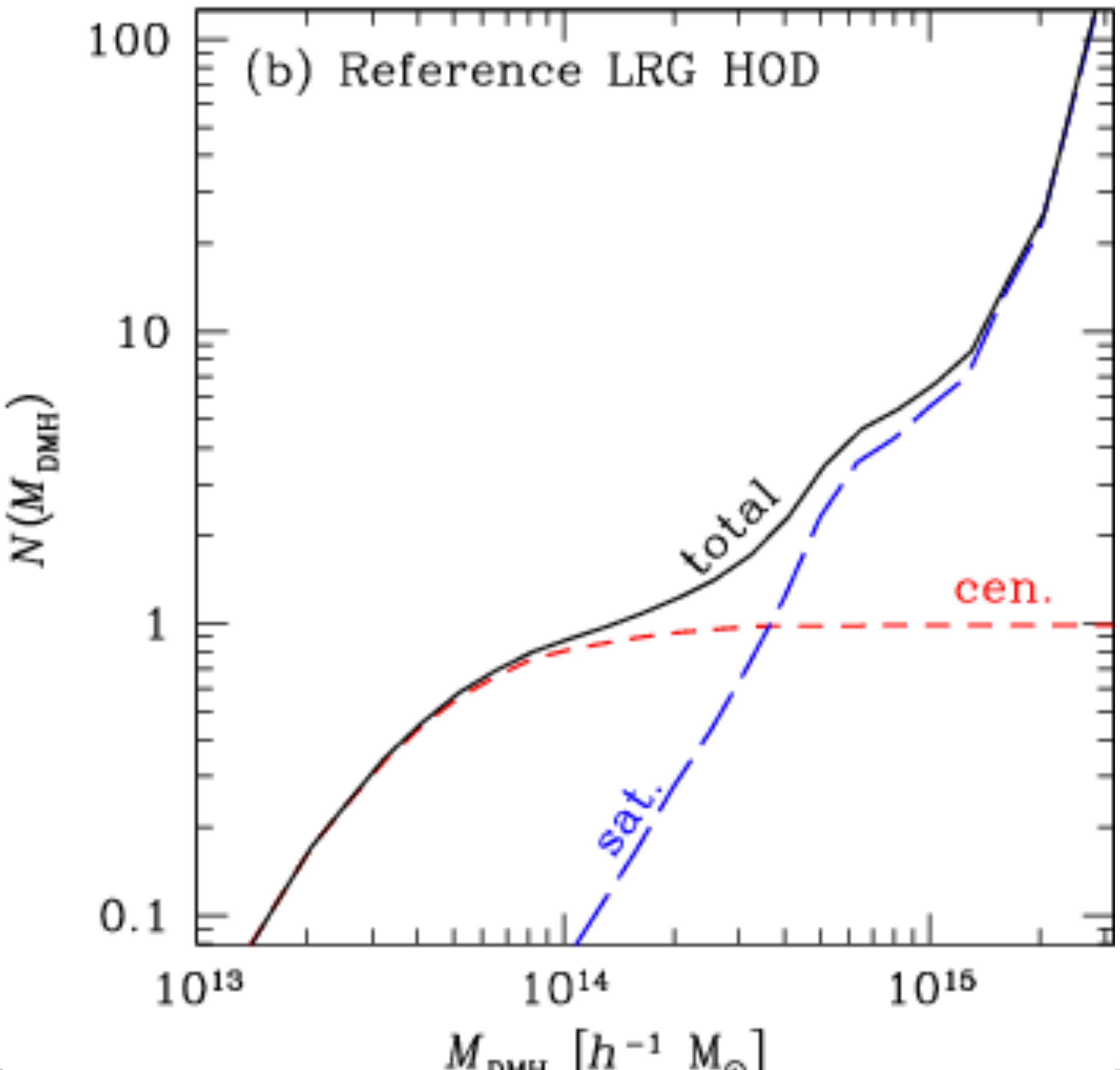
Halo Occupation Distribution

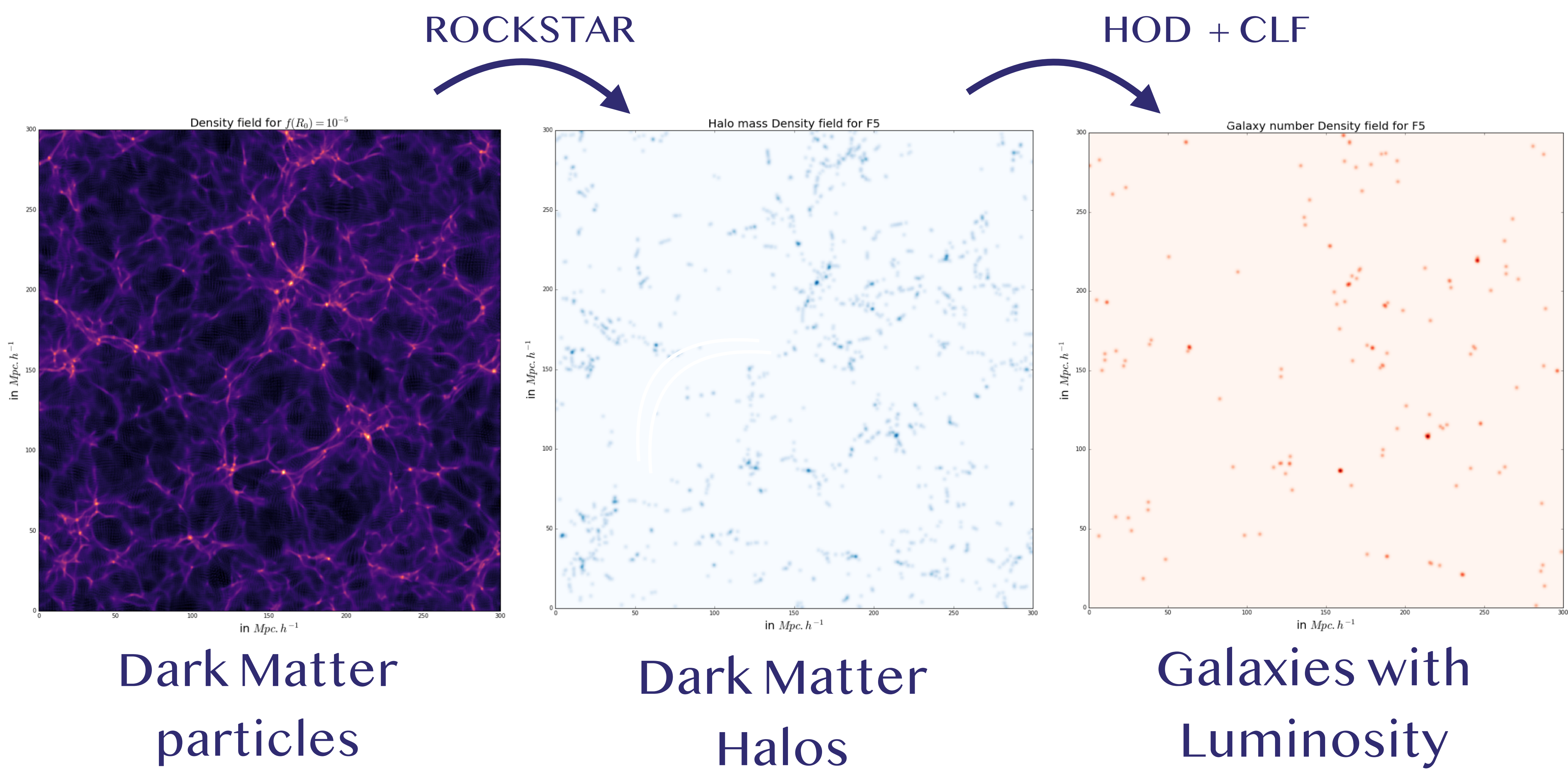


Example of HOD parametrization

$$\langle N_{cen}(M)\rangle = \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{\log M - \log M_{min}}{\sigma_{\log M}}\right)\right]$$

$$\langle N_{sat}(M)\rangle = \left(\frac{M - M_0}{M_1}\right)^{\alpha}$$

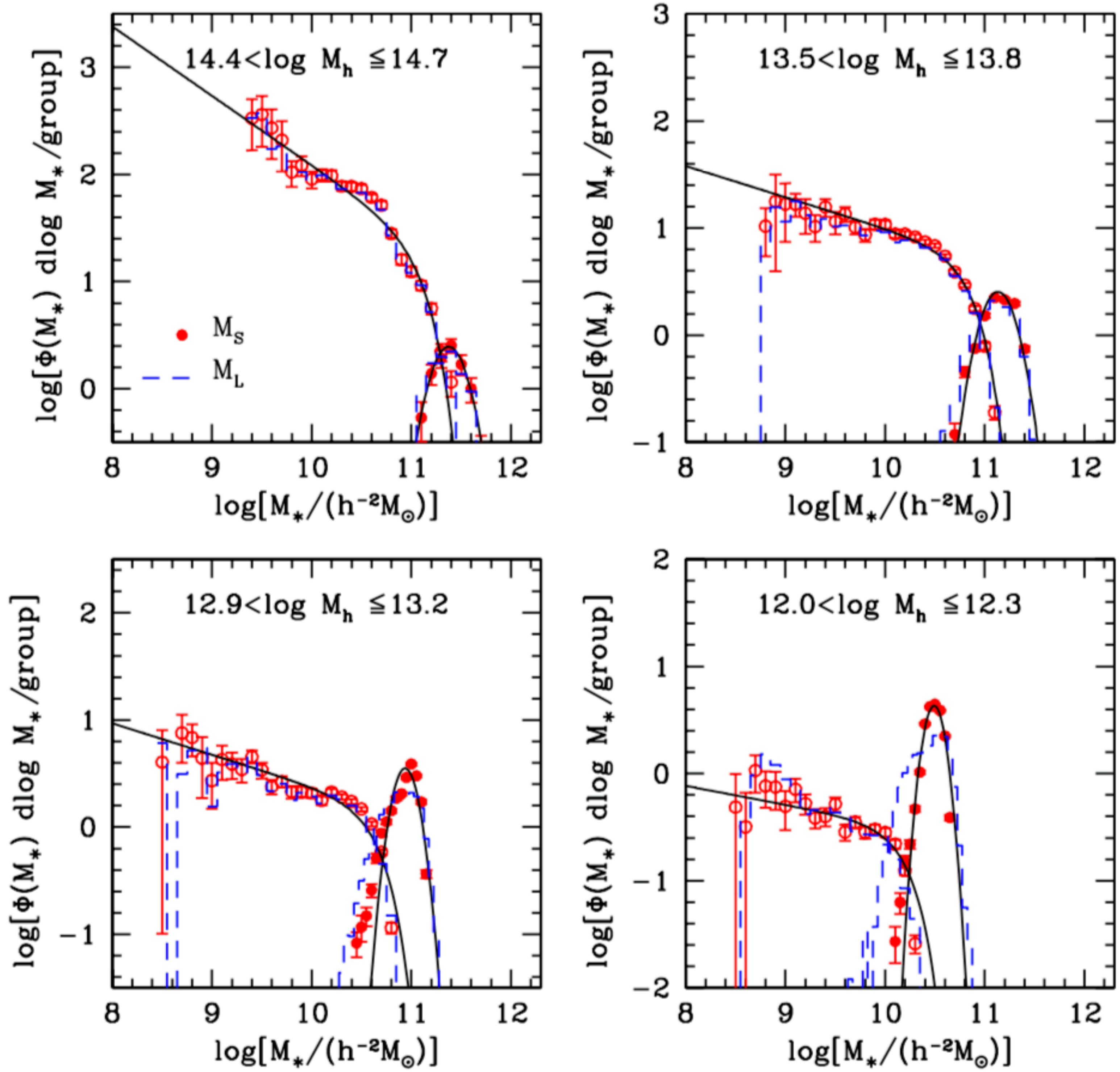




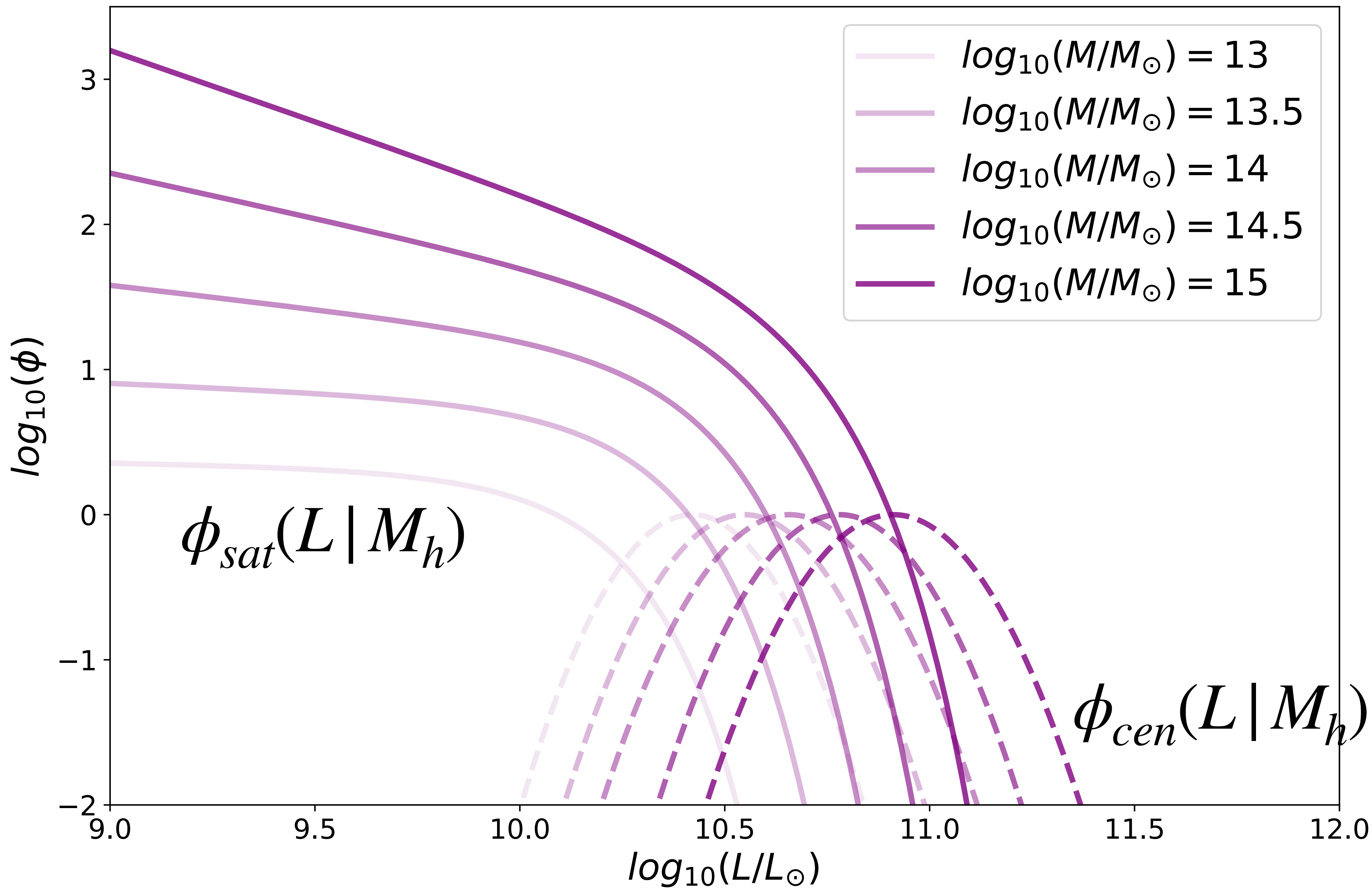
ROCKSTAR
HOD + CLF
Density field for $f(R_0) = 10^{-5}$
Halo mass Density field for F5
Galaxy number Density field for F5
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
in $Mpc.h^{-1}$
Dark Matter particles
Dark Matter Halos
Galaxies with Luminosity

Conditional Luminosity Function

(Yang, Mo, Van den Bosch 2009)



Conditional Luminosity Function



Conditional Luminosity Function

Satellite density as modified Schechter function:

$$\phi_{sat}(L|M_h) = \phi_s^* \left(\frac{L}{L_s^*}\right)^{(\alpha_s^*)} \exp\left\{-\left(\frac{L}{L_s^*}\right)^2\right\}$$

Follow the sub-halo mass function

Central density as modified log-normal function:

$$\phi_{cen}(L|M_h) = \frac{1}{\sqrt{2\pi}\sigma_c} \exp\left\{-\frac{(\log L - \log L_c)^2}{2\sigma_c^2}\right\}$$

Canibal evol. Can be at the most one.

Reverting the information

$$\mathscr{P}(M_h \,|\, L) = \frac{\mathscr{P}(L \,|\, M_h) \cdot \mathscr{P}(M_h)}{\mathscr{P}(L)}$$

Posterior we want to evaluate

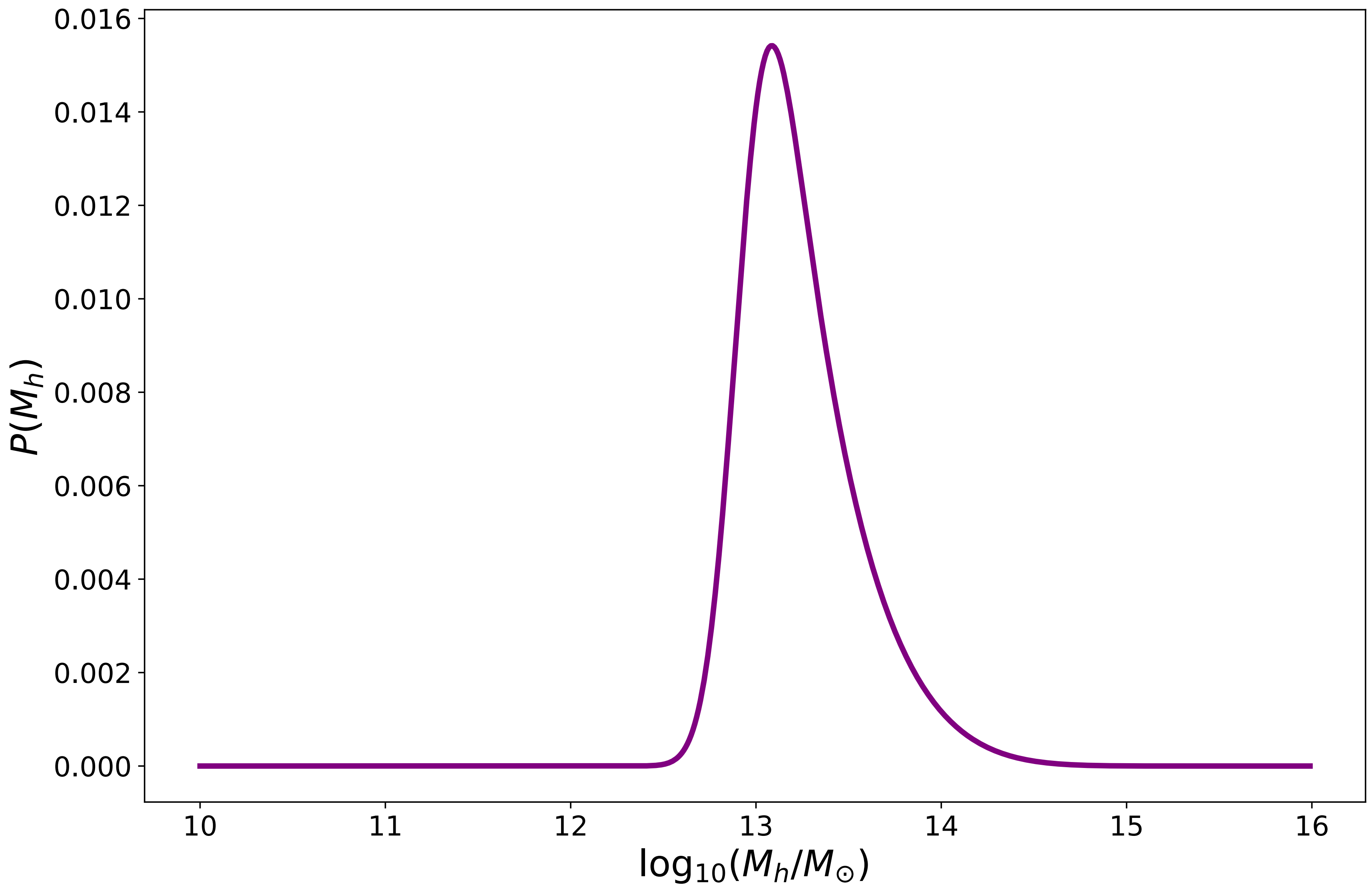
Conditional Luminosity Function

Convolution of HOD and HMF

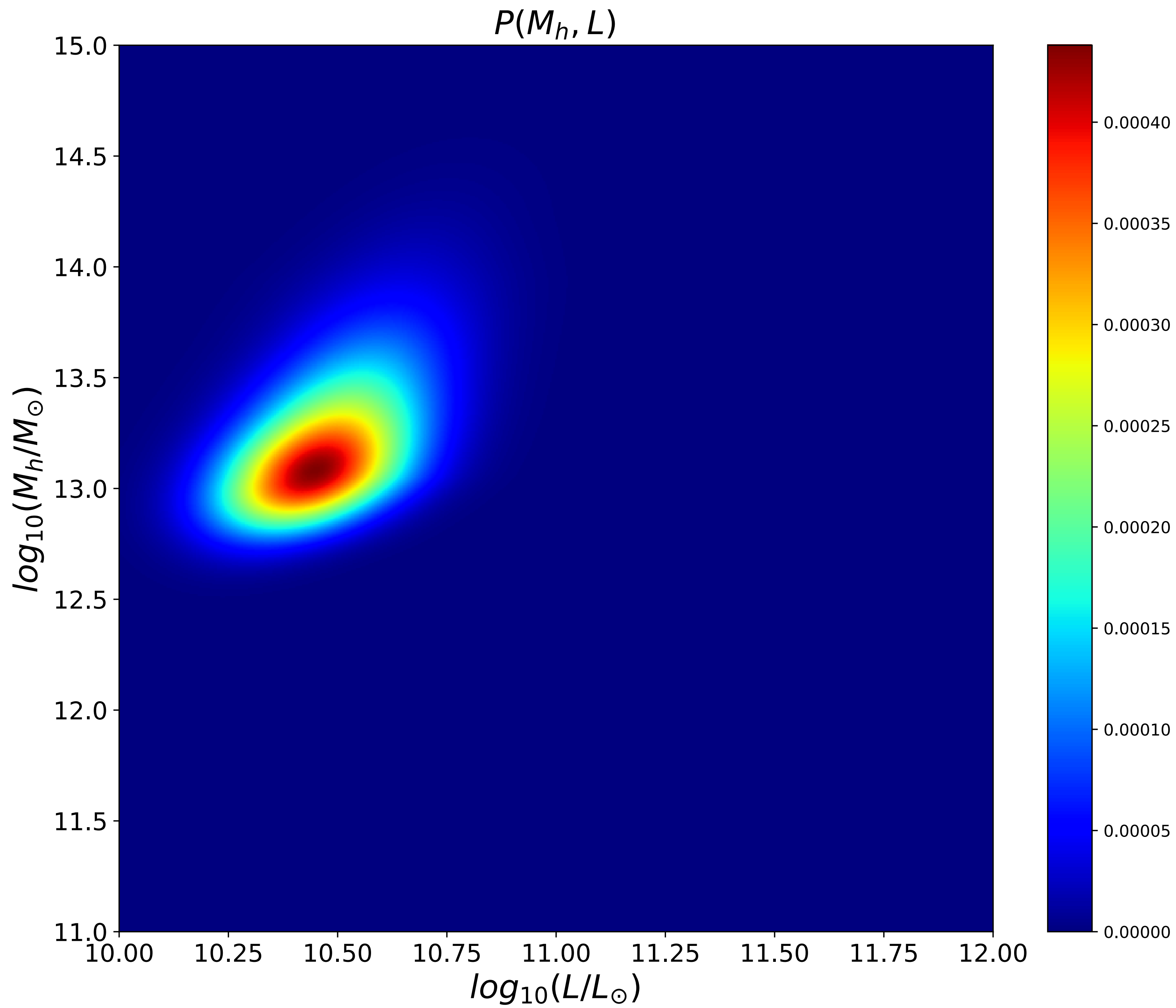
Normalization which have not impact here

Prior estimation

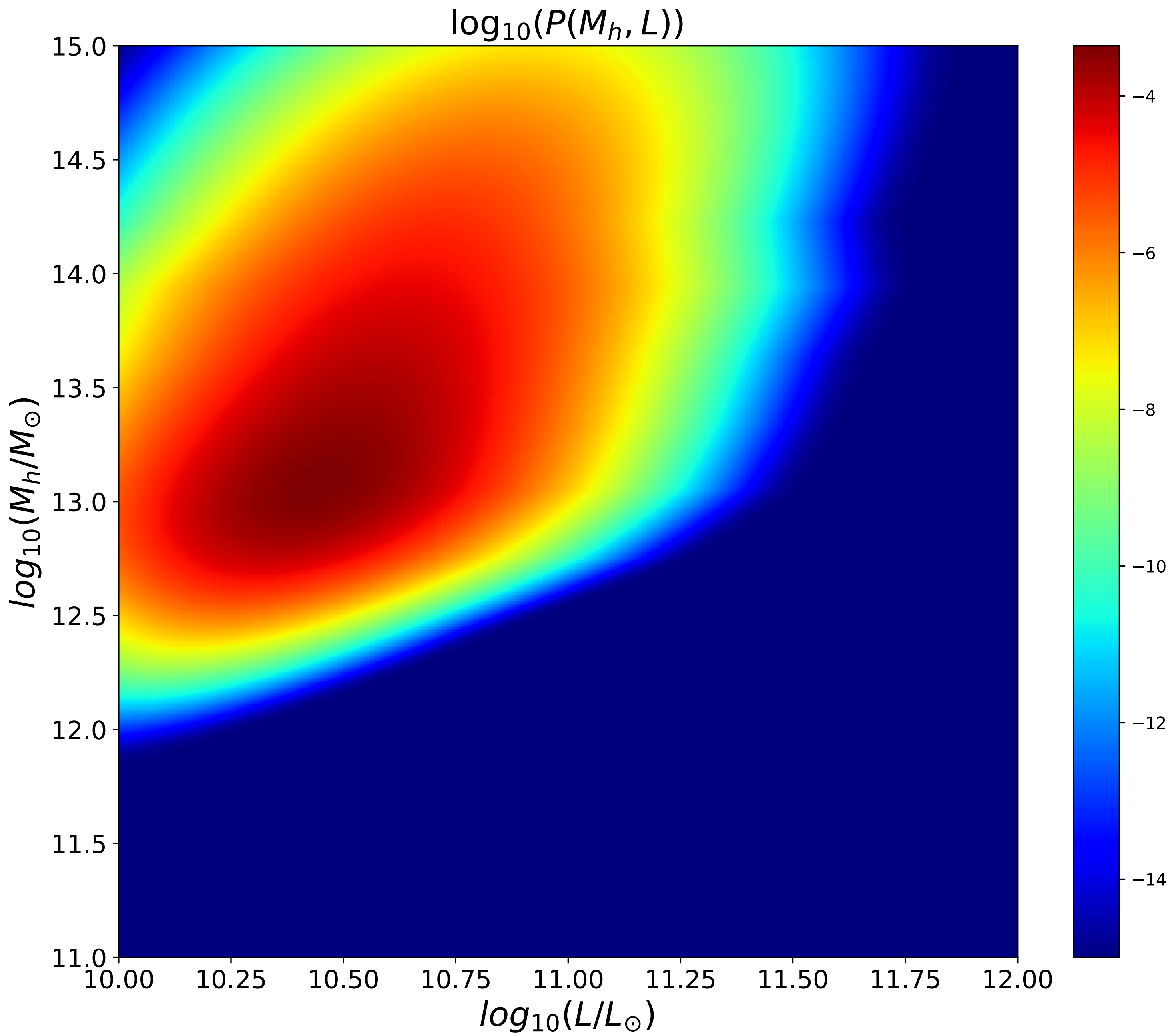
$$\mathscr{P}(M_h) = \frac{\mathscr{P}(N_{gal} \geq 1 \,|\, M_h) \times \frac{dn(M_h)}{d\log M}}{\int_0^\infty d\log M \mathscr{P}(N_{gal} \geq 1 \,|\, M_h) \times \frac{dn(M)}{d\log M}},$$



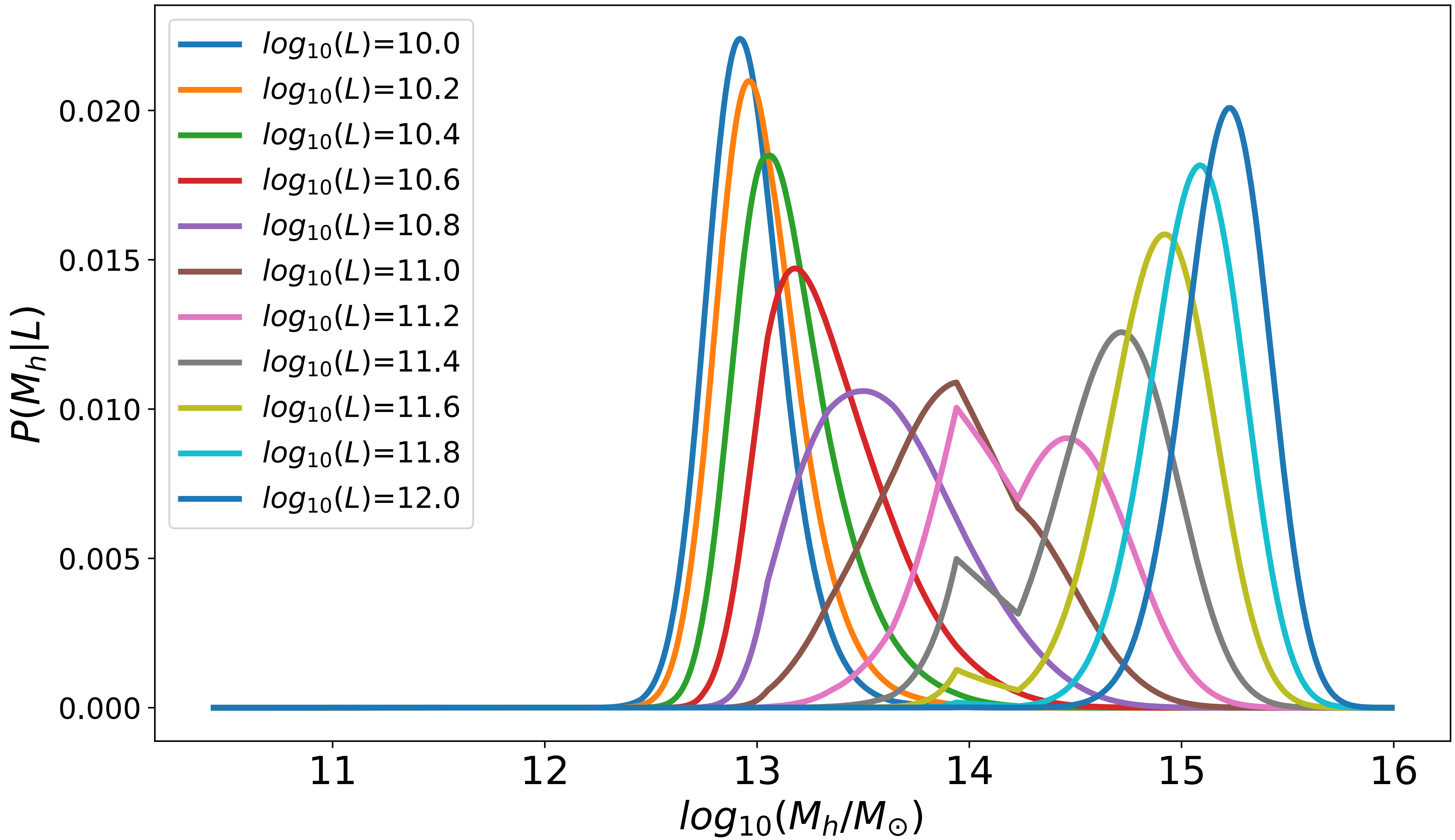
Joint Probability



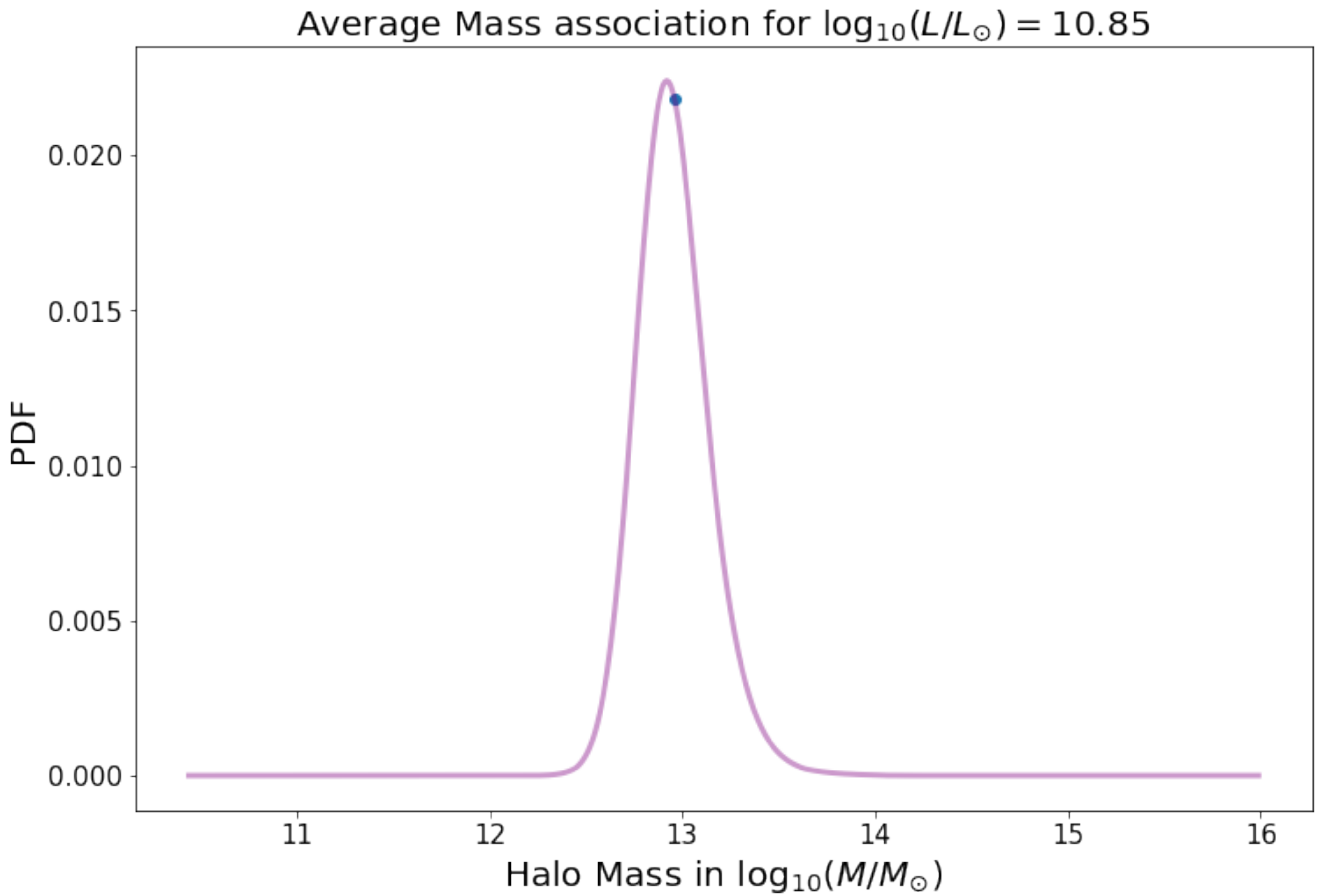
Joint Probability



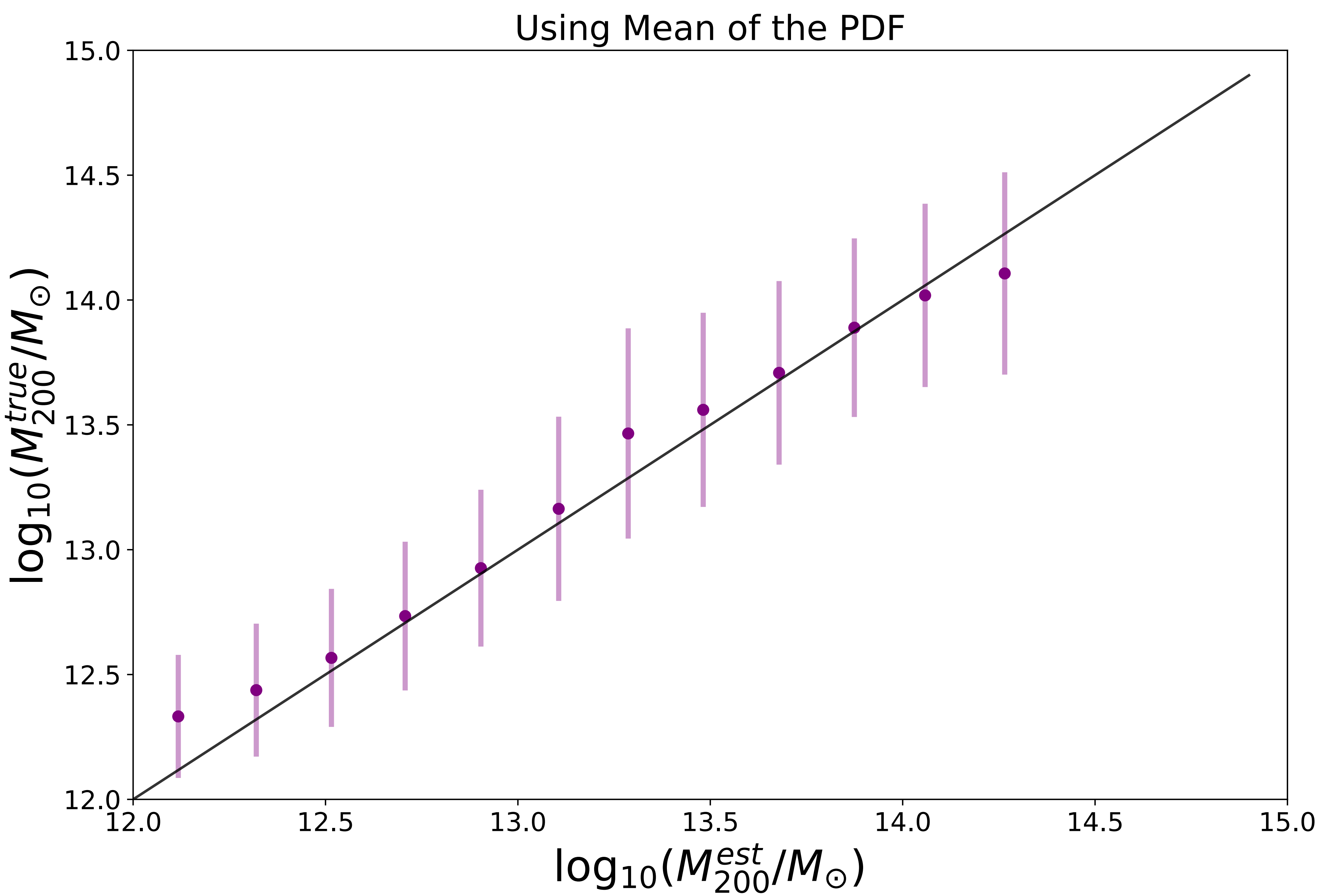
Posterior Results

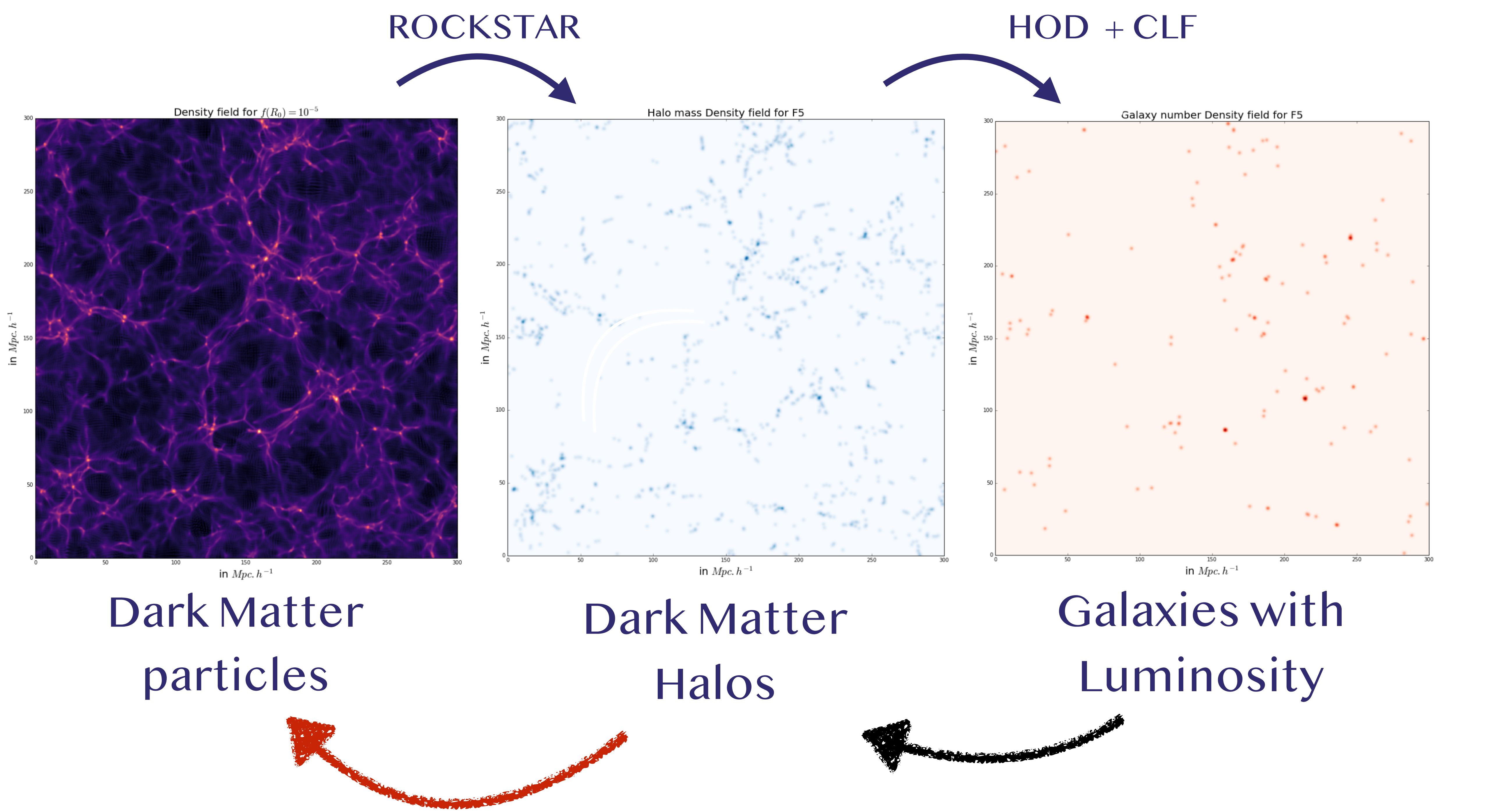


Average Mass



Estimation of the mass using L
In simulation

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Dark Matter Halos
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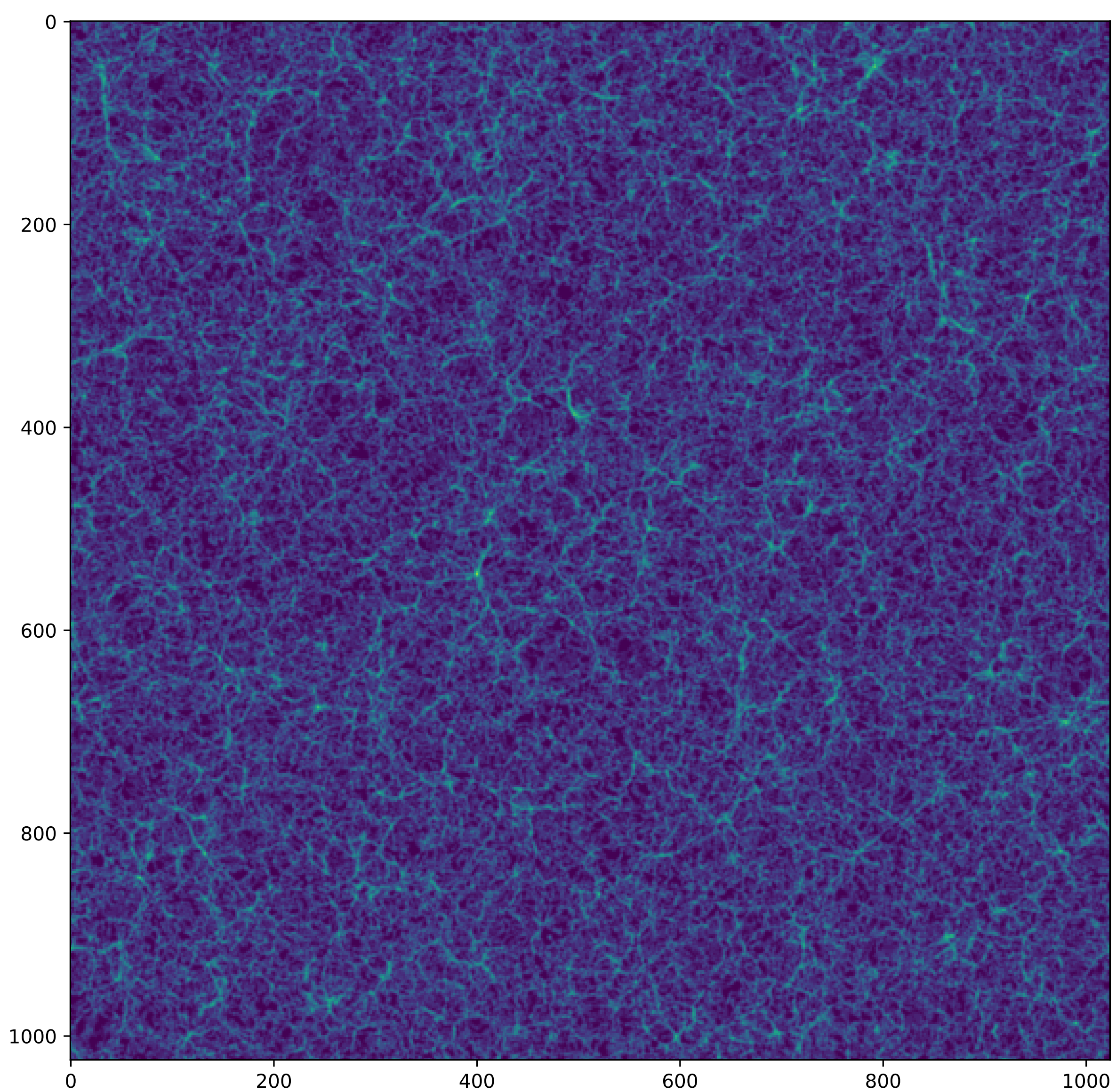
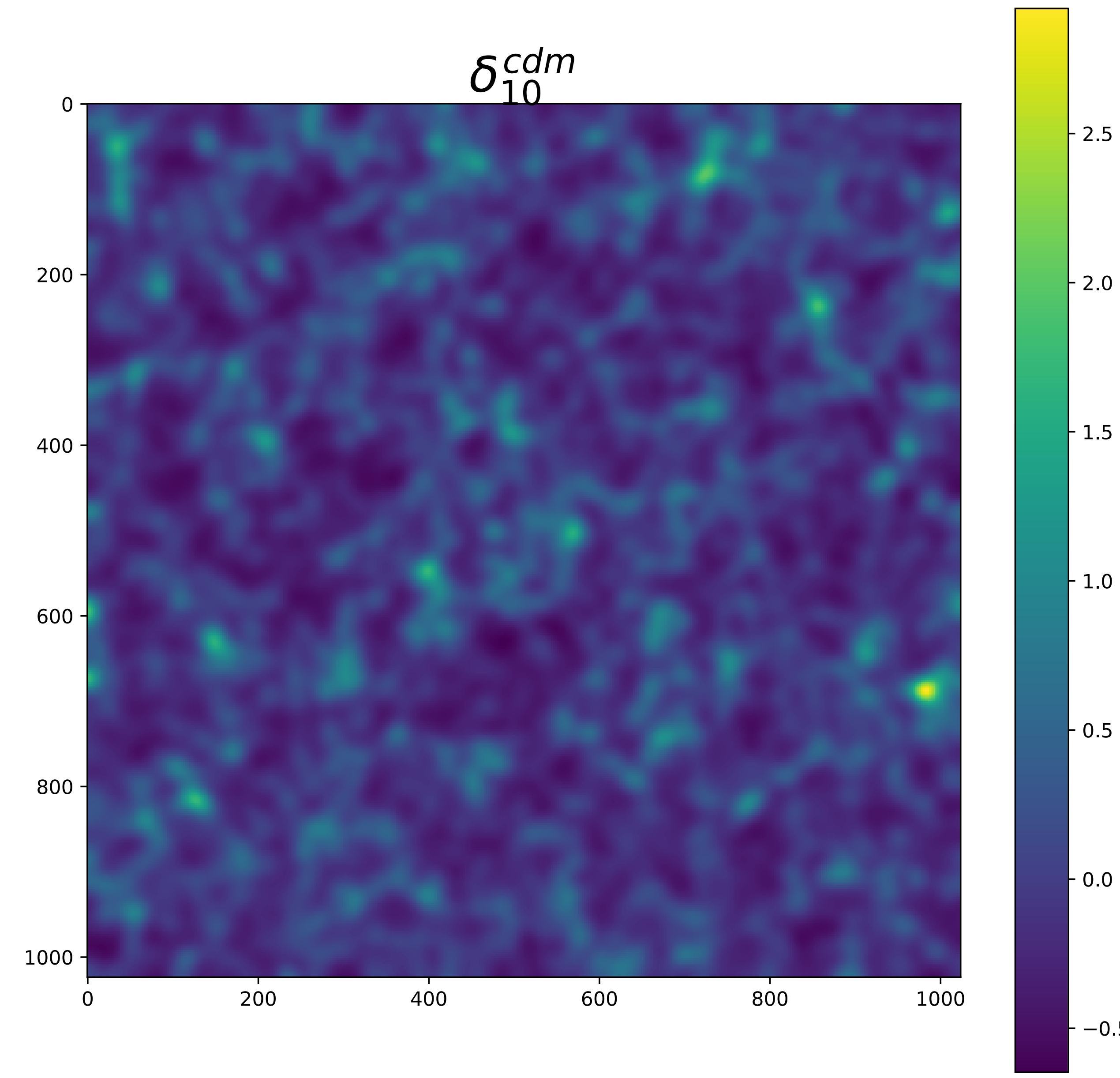
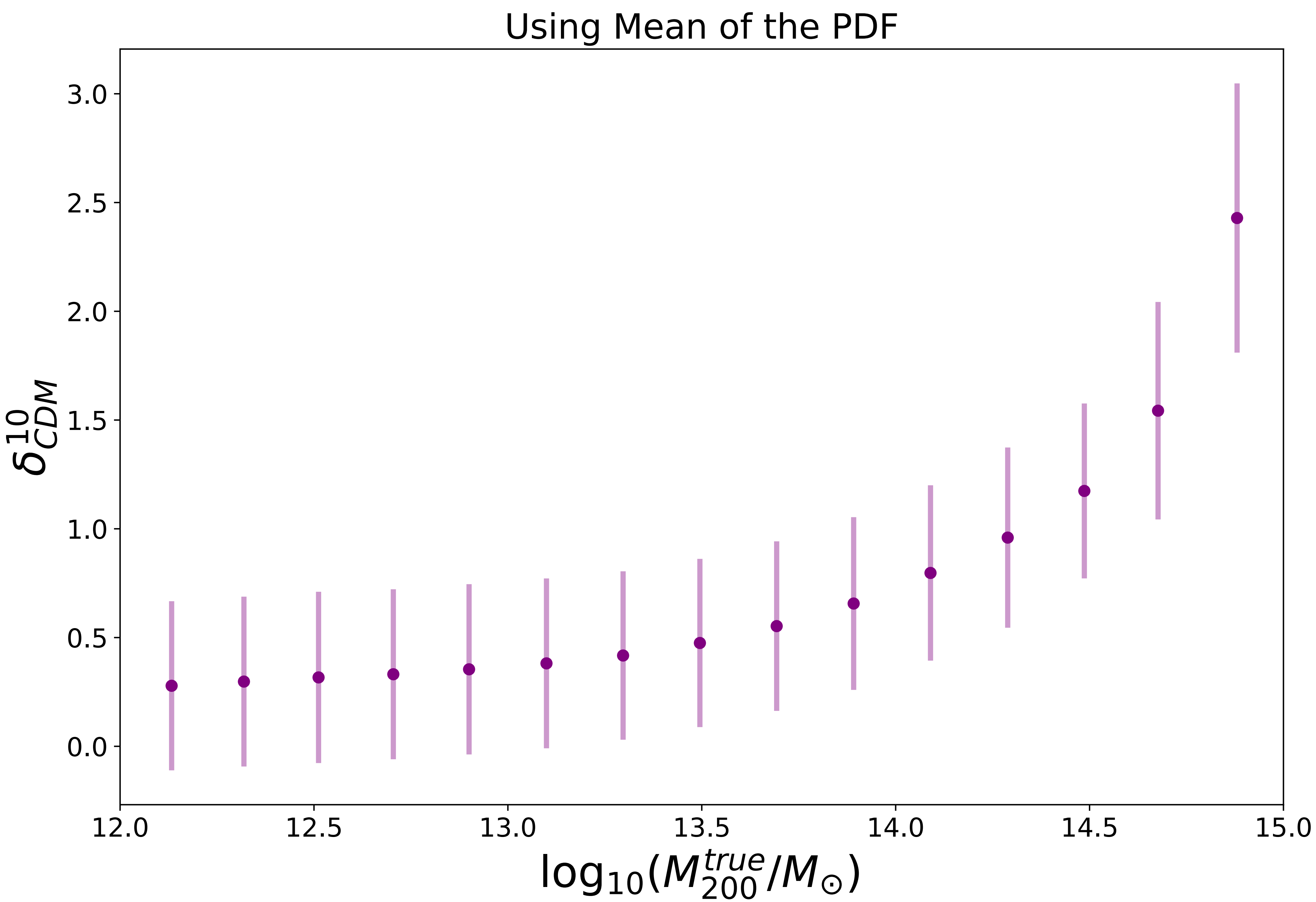
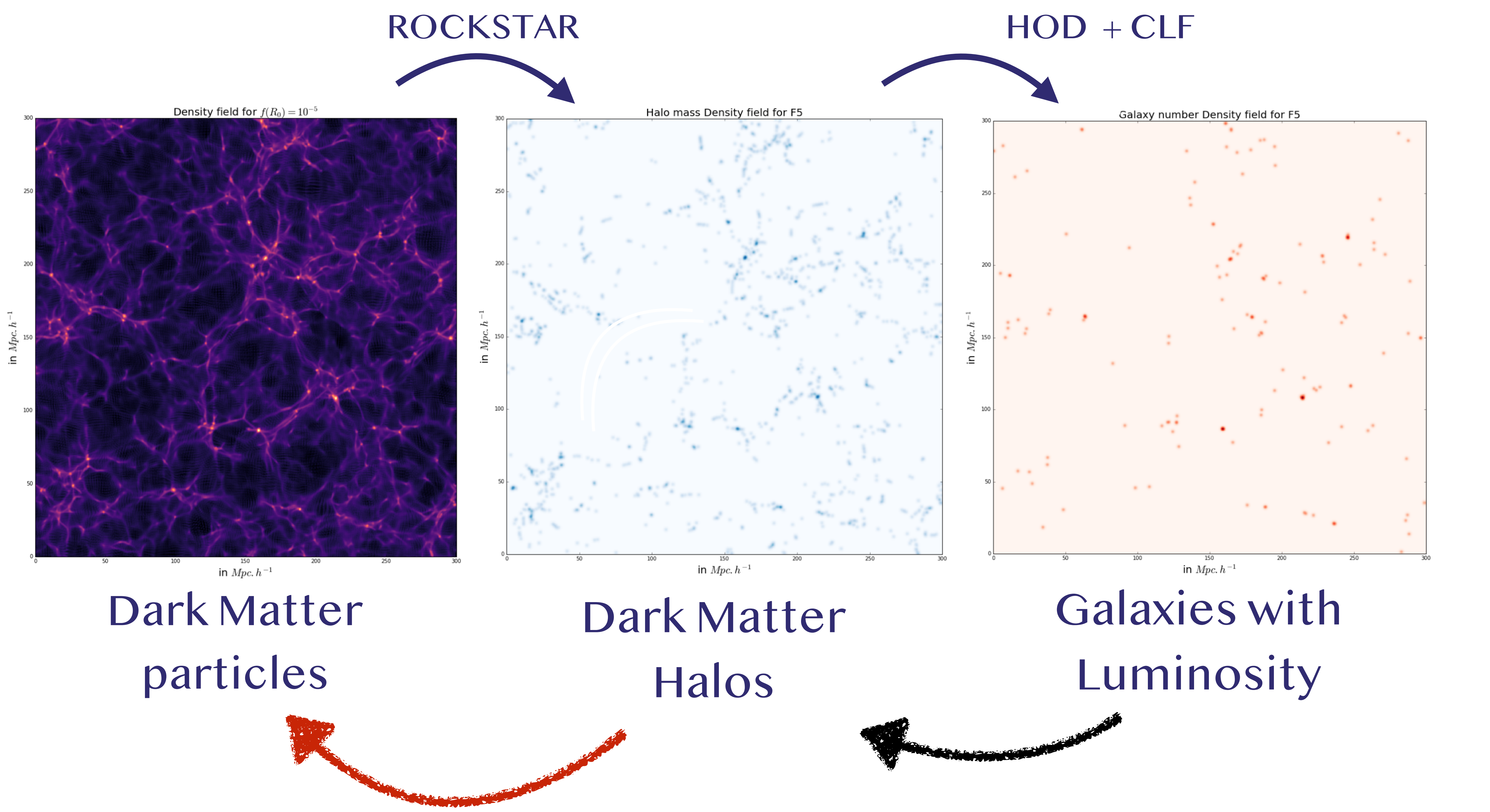
Gaussian filter at 10 Mpc





Gaussian filter at 10 Mpc

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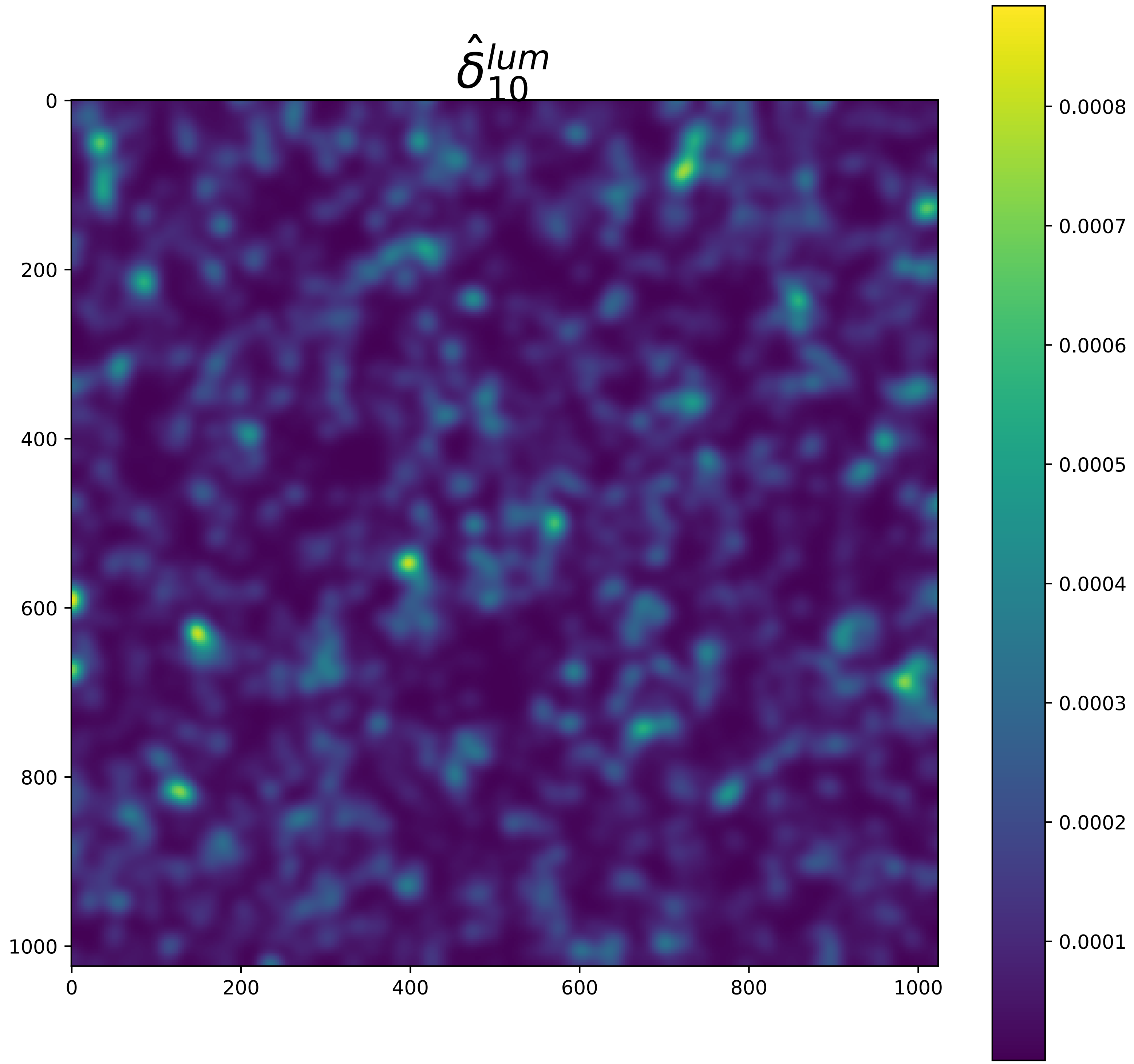
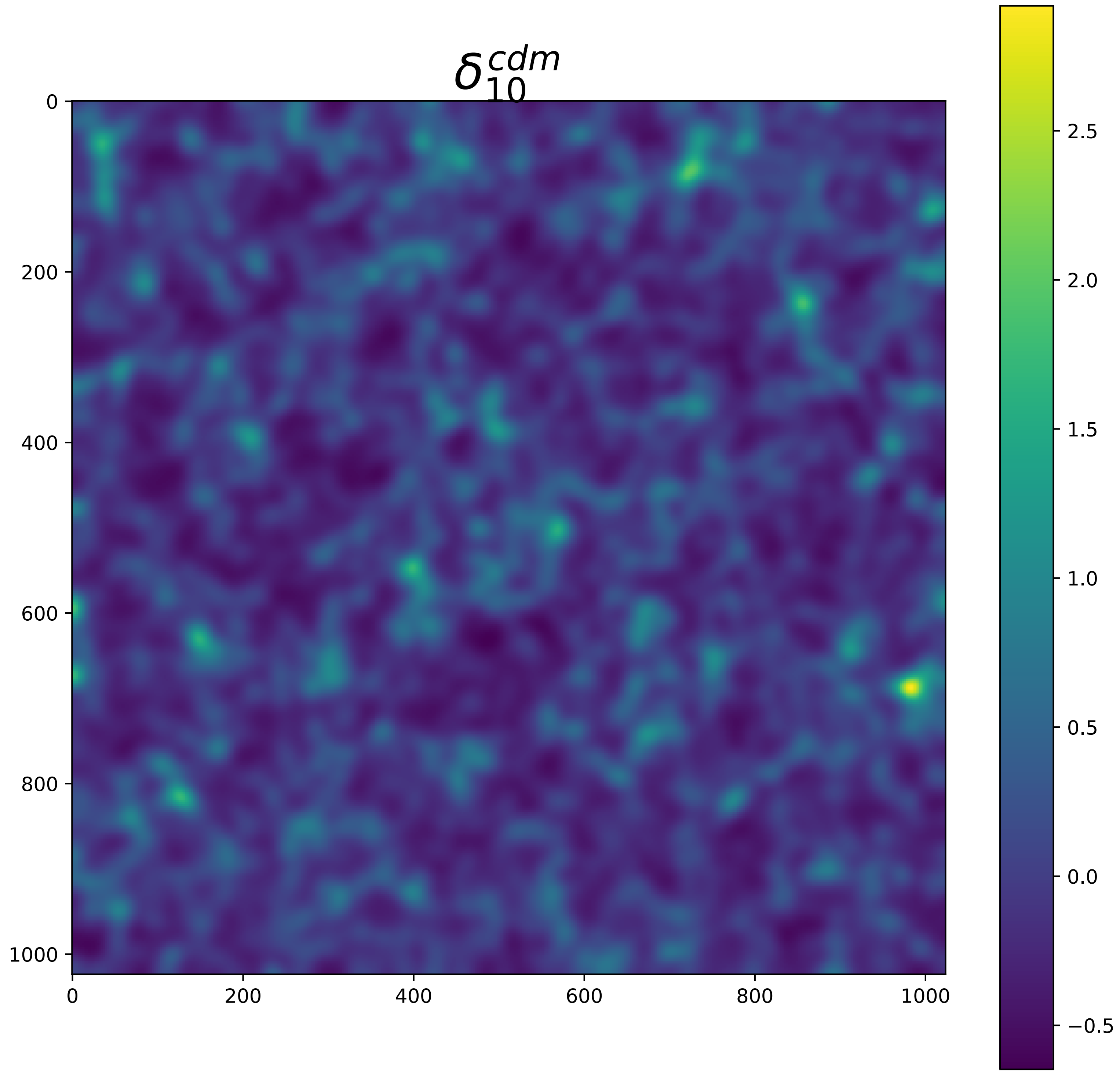
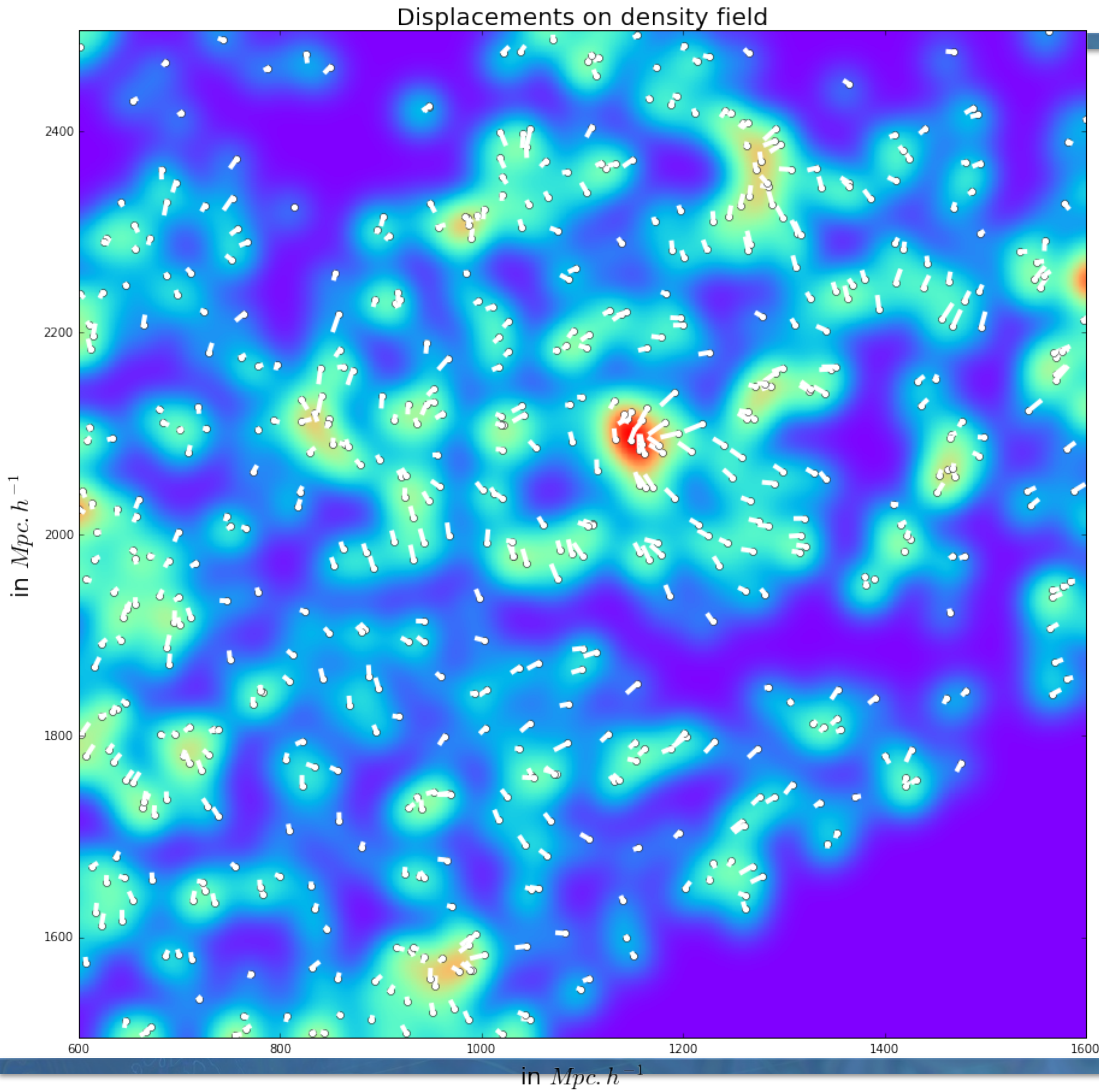

$\hat{\delta}_{10}^{lum}$
0
200
400
600
800
1000
0
200
400
600
800
1000
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001



δ_{10}^{cdm}
0
200
400
600
800
1000
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

Reconstruction to enhance BAO peak



Vargas, Ho, Fromenteau, Cuesta (2017)

We estimate the smoothed galaxy density field

↓

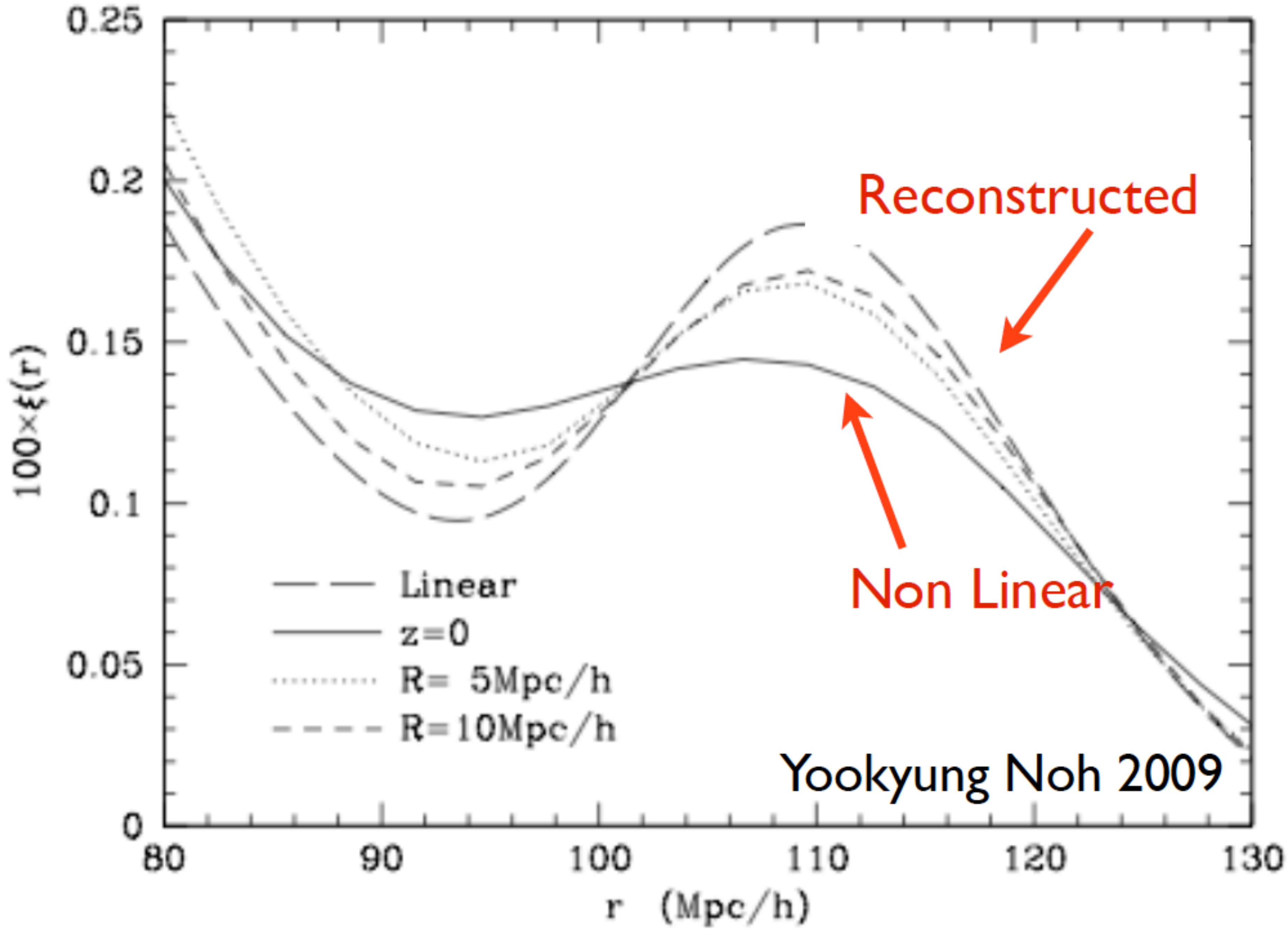
Using linear bias, we derive the matter density field

↓

We move back the galaxies to their original position

$$\vec{\psi}(\vec{k}) = \frac{-i\vec{k}}{k^2}\frac{\delta_g(\vec{k})}{b_g}$$

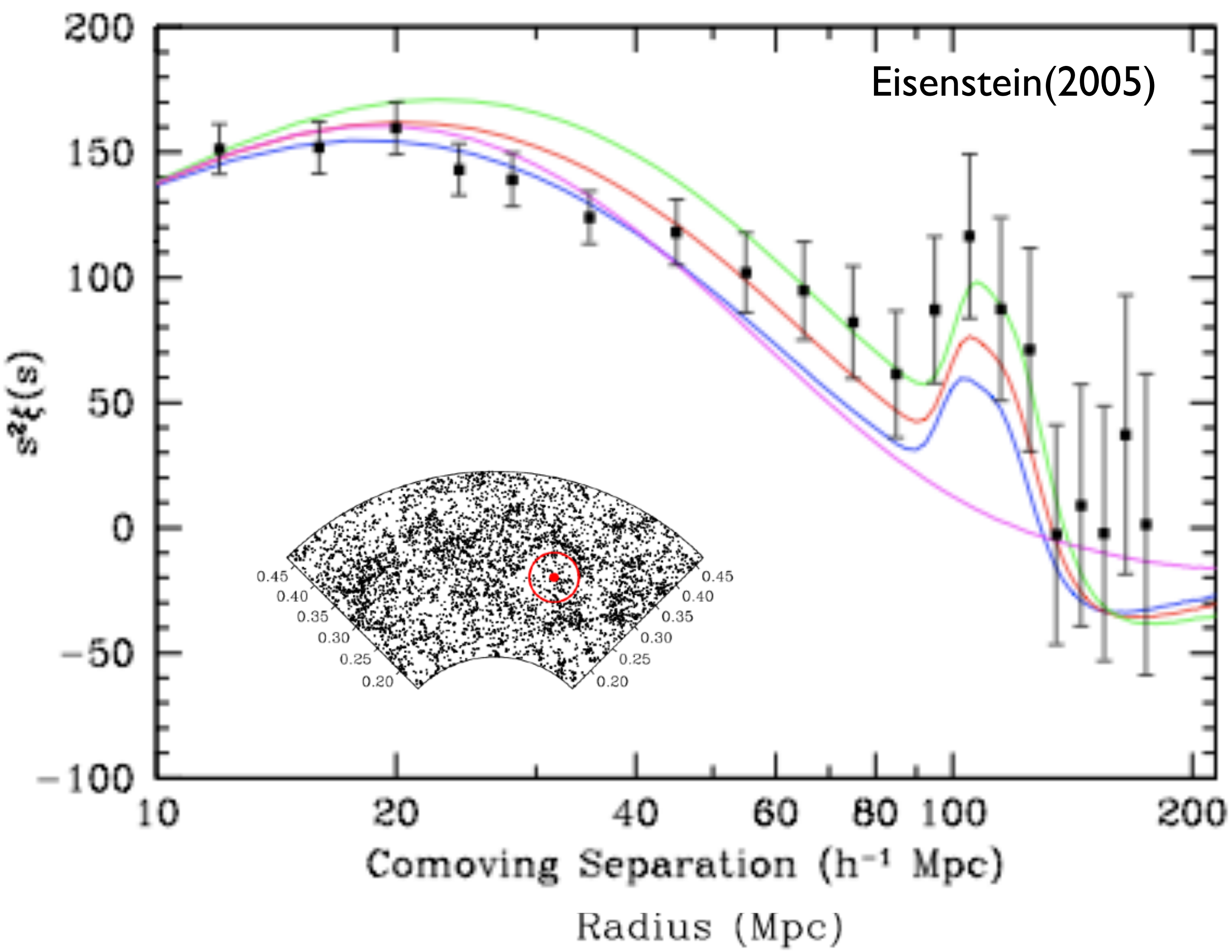
Reconstruction to enhance BAO peak

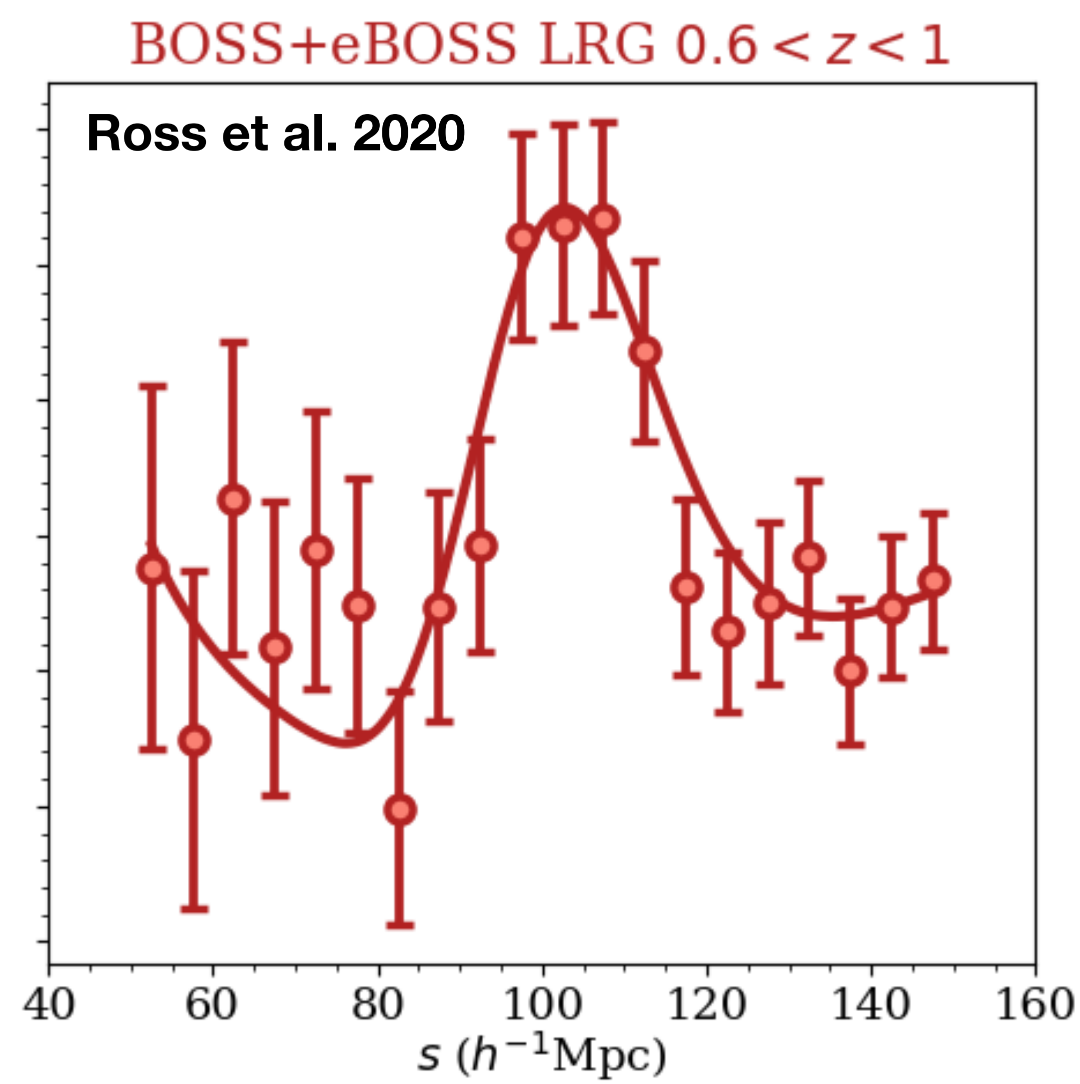


Is part of the standard BAO analysis

Baryonic Acoustic Oscillations Peak

BAO Detection in the correlation function of Luminous Red Galaxies





Mariana's talk on Saturday

Conclusions

Obtain non-linear local bias information using luminosity information in a probabilistic way

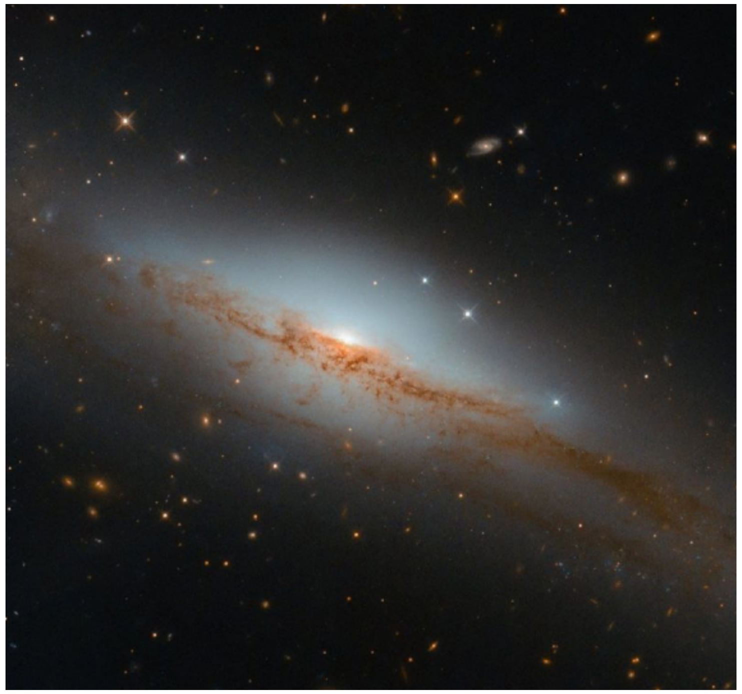
This method can be generalized to any statistical information connecting the tracer to the halo mass (for example density)

We can use this method in order to implement a redshift dependent reconstruction inside the large surveys

Different tracers

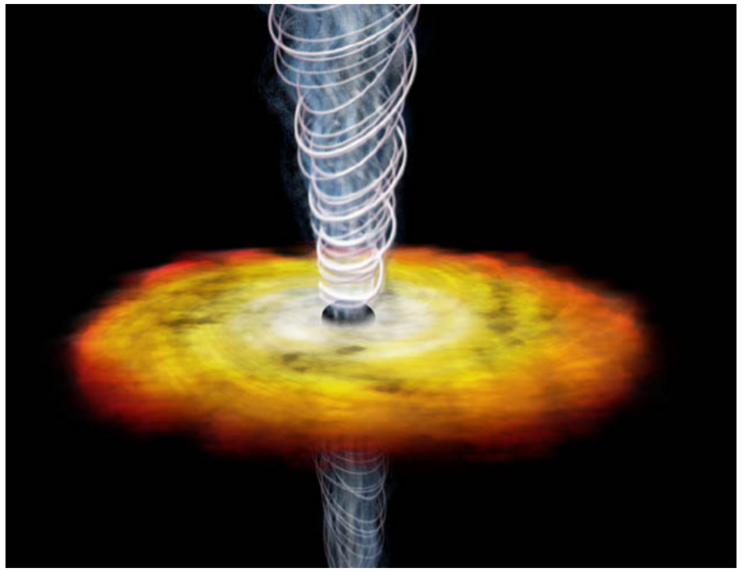
Luminous Red Galaxy

LRG



Emission Line Galaxy

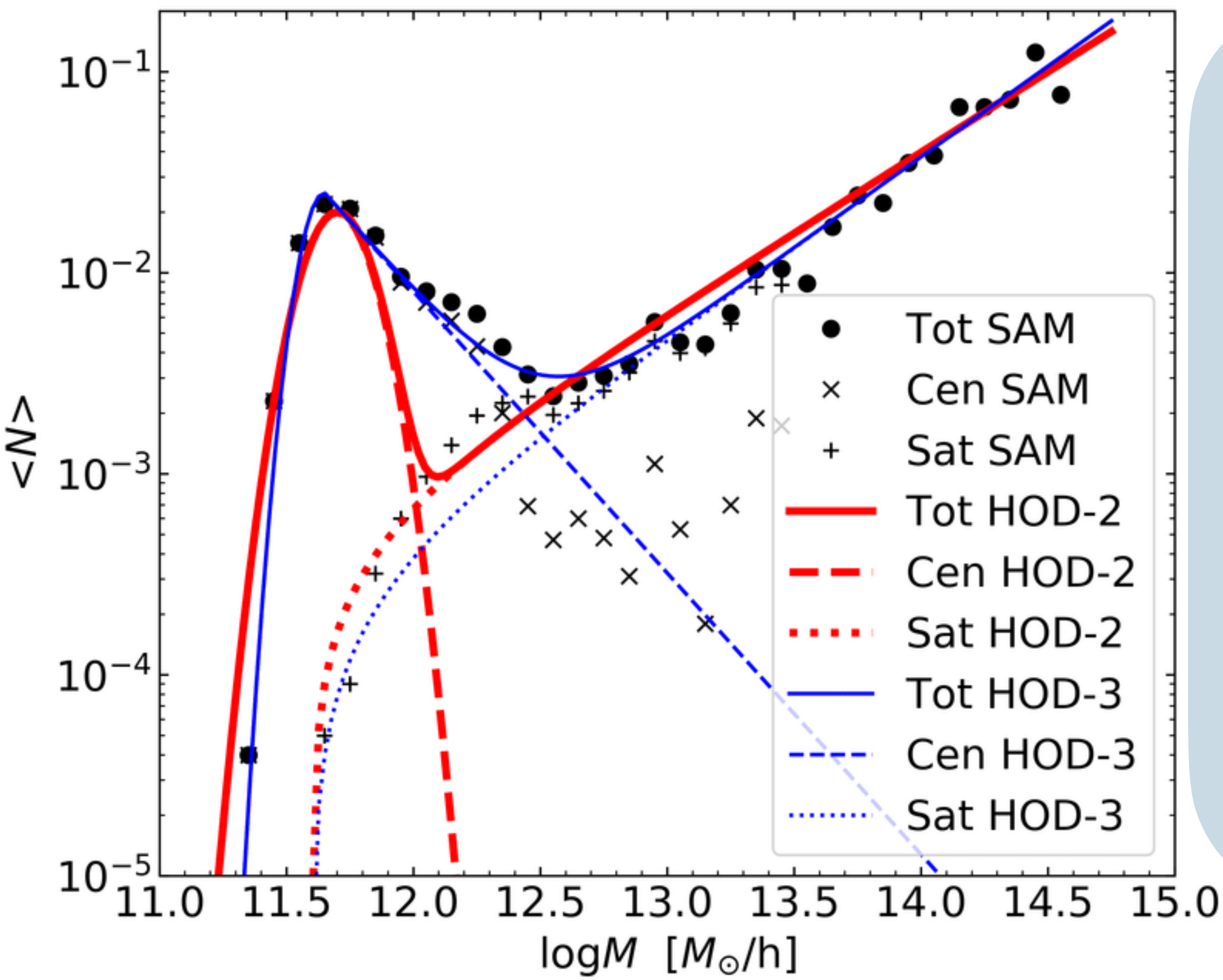
ELG



Quasar

QSO/AGN

Emission Line galaxies

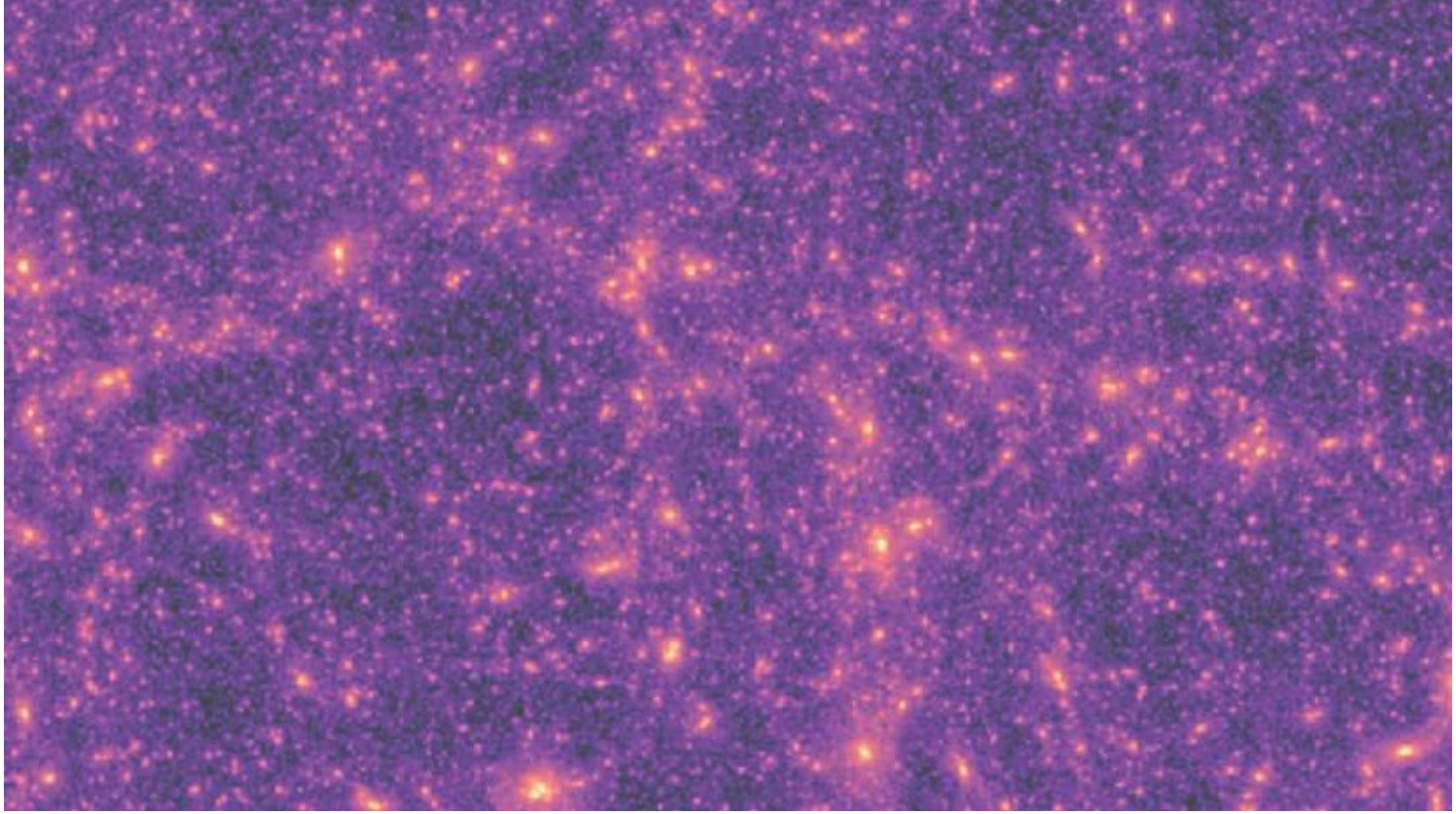


Avila et al 2020

Important new tracer for high redshift

The galaxy Halo connection is very complex

So galaxy bias is highly non-trivial



Thanks !

Halo Occupation Distribution

1 HALO TERM

$$\xi_{gg}(r) \propto \int d\log(M)\frac{dn}{d\log(M)} < N(M) > (< N(M) > -1) P_{NFW}(r|M)$$

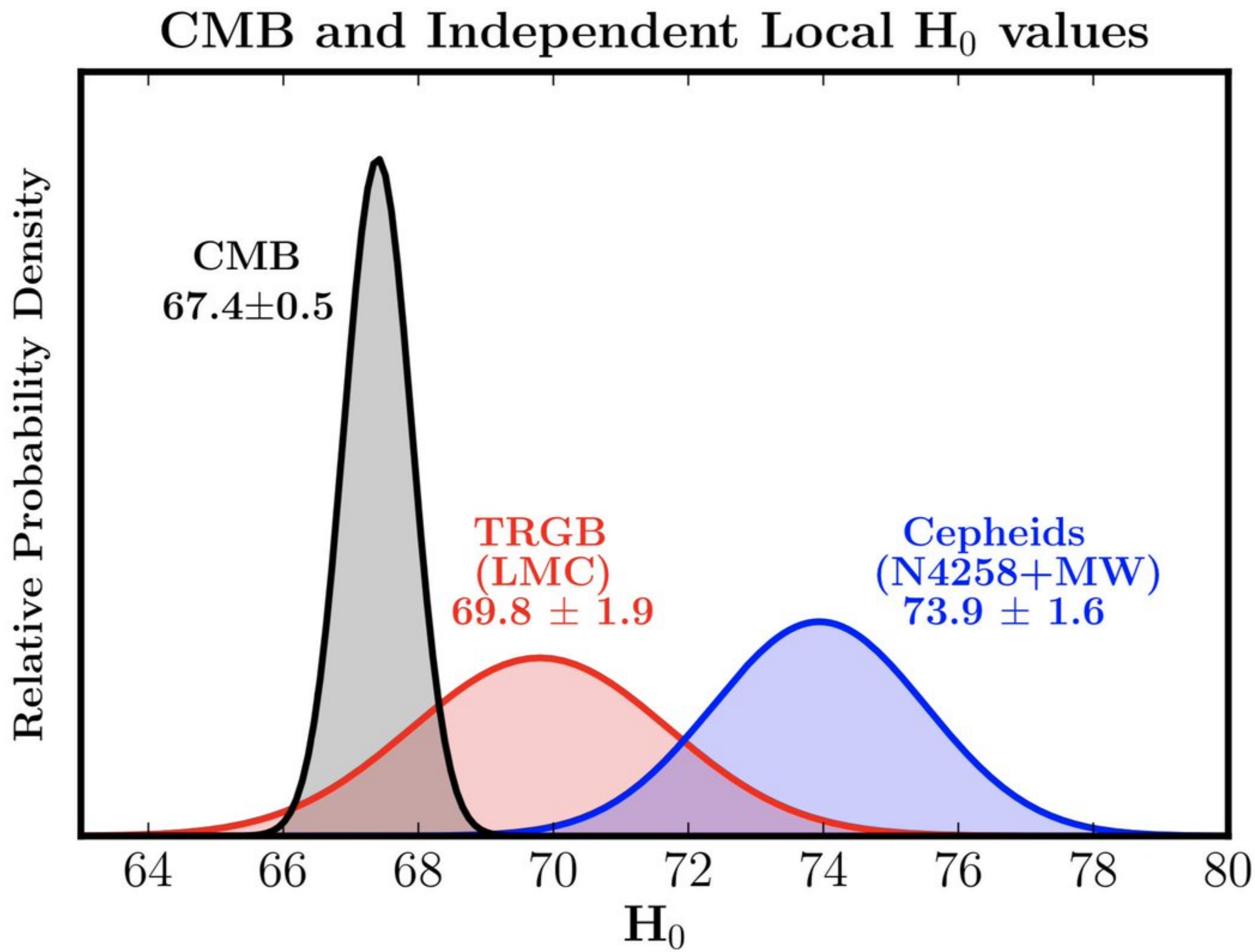
$$+ \int d\log(M_1) \int d\log(M_2) < N(M_1) > . < N(M_2) > b^2 \xi_{mm}(r) \times$$

$$\times \frac{P_{NFW}(r_1|M_1)dn}{d\log(M_1)} \frac{P_{NFW}(r_2|M_2)dn}{d\log(M_2)}$$

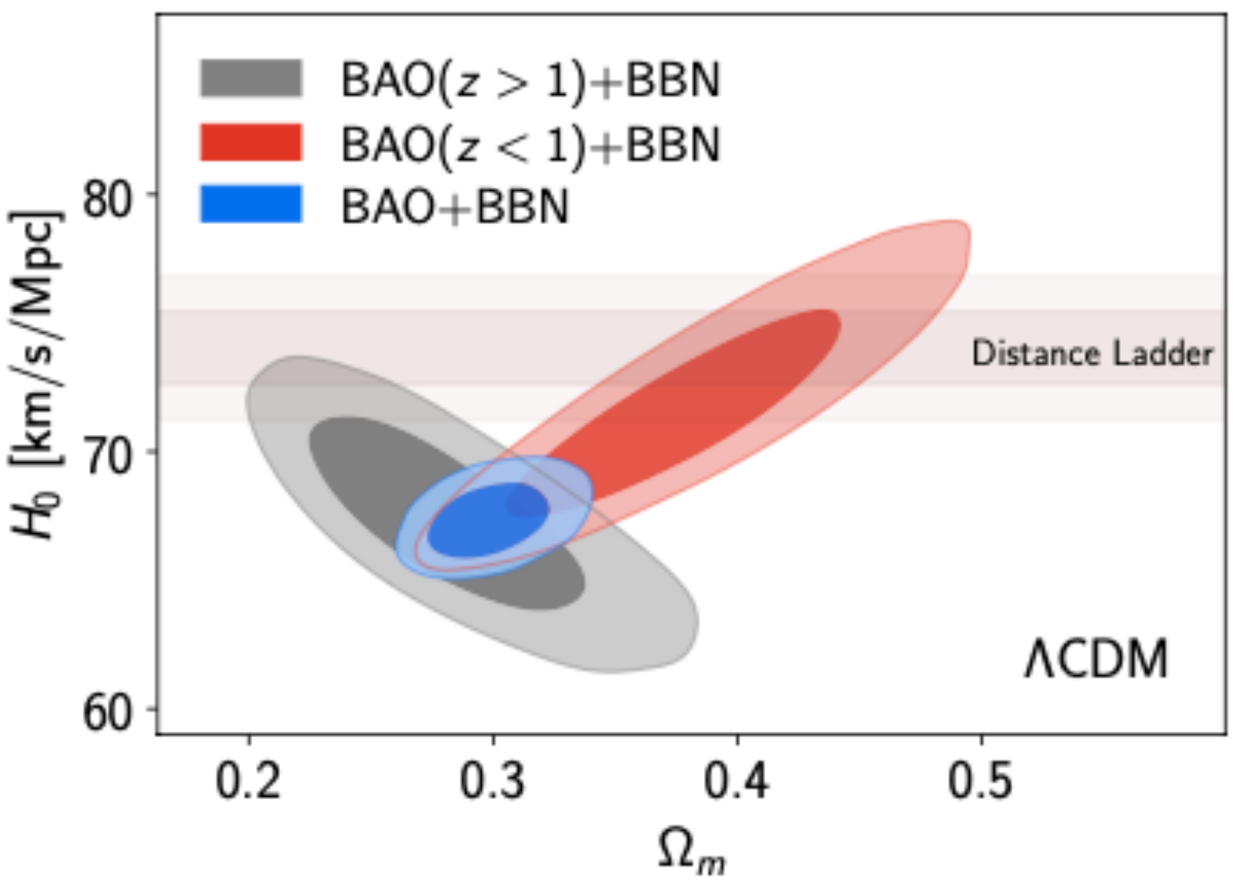
2 HALO TERM

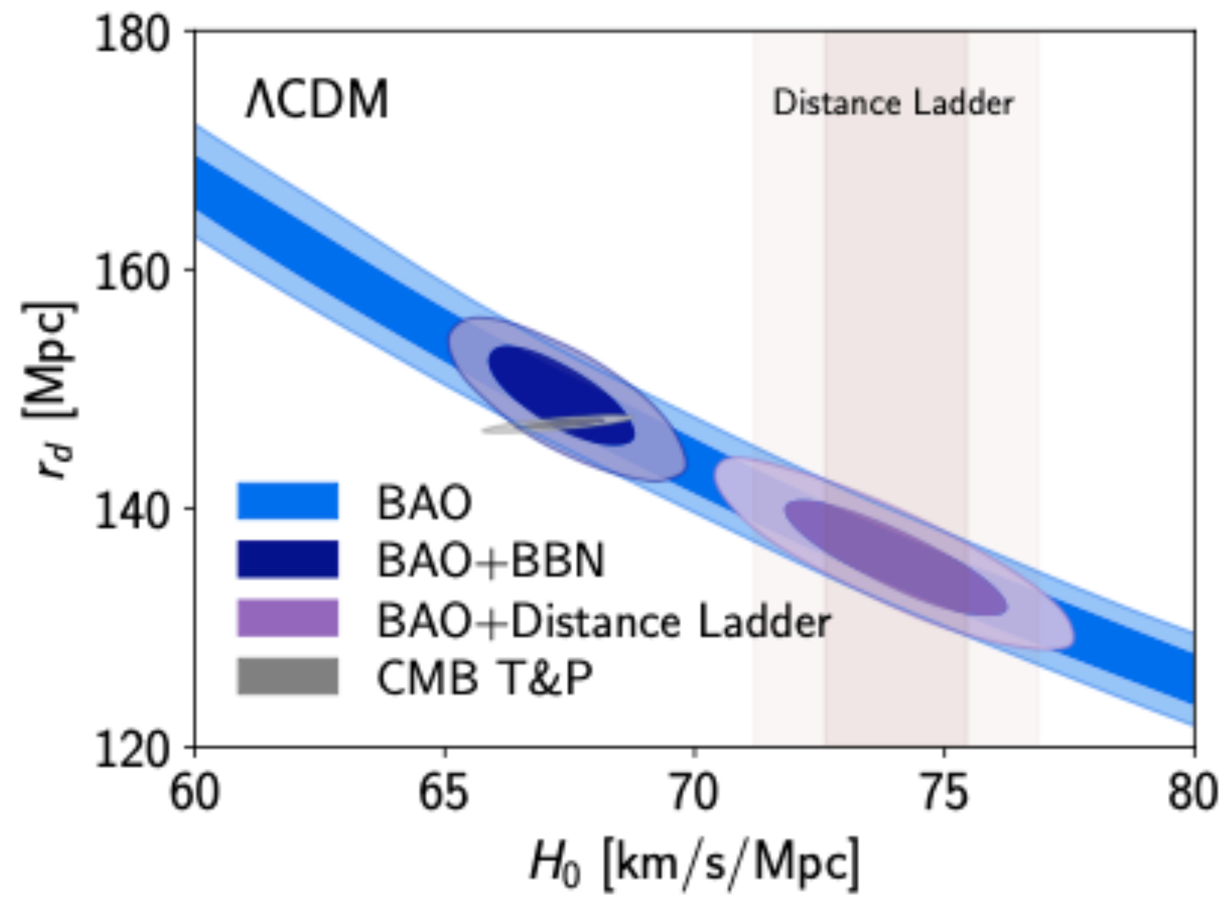
$$P_{NFW}(r|M) = \frac{\rho_{NFW}(r|M) \times 4\pi r^2 dr}{M}$$

Increase H_0 crisis



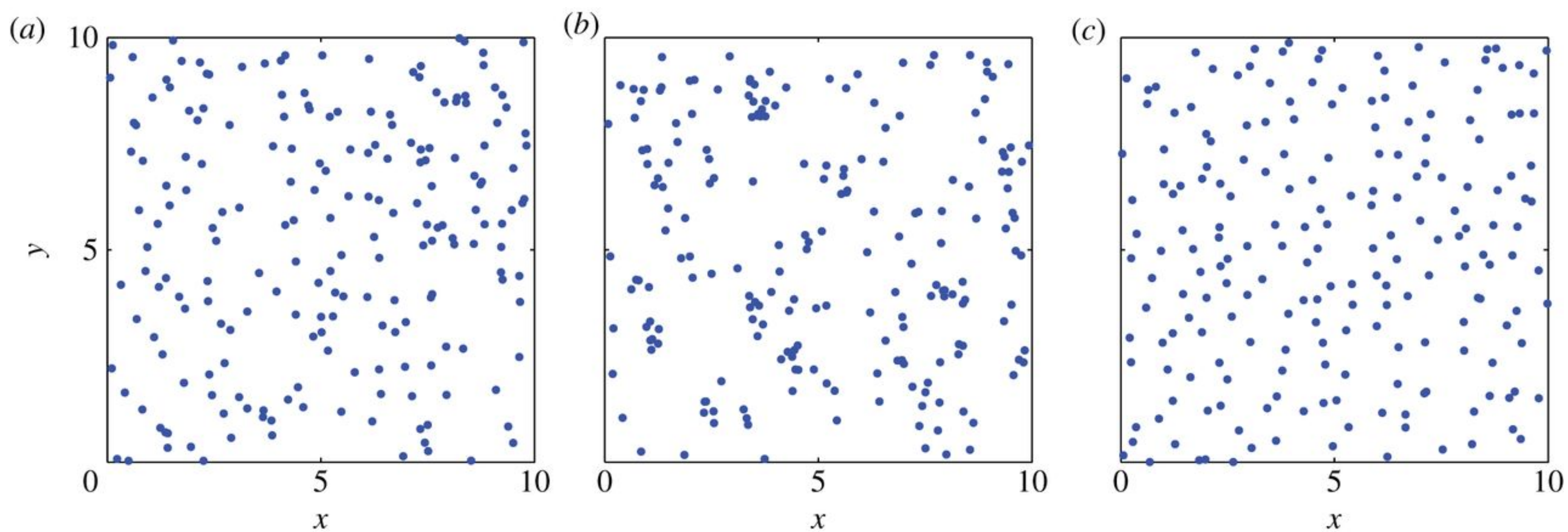
Increase H_0 crisis





eBOSS collaboration 2020 (in prep.)

2-point correlation function



We count the number of pairs of galaxies for each distance r

We compare with the number obtain for random distribution

Estimator

$$\xi(r) = \frac{Npairs(r) - Npairs_{rand}(r)}{Npairs_{rand}(r)}$$

Quantity

$$P(r) = 4\pi r^2 dr\,.\,\bar{n}\left[1 + \xi(r)\right]$$

2-point correlation function