

# Lyman $\alpha$ forest の3次元分布 による大規模構造の測定

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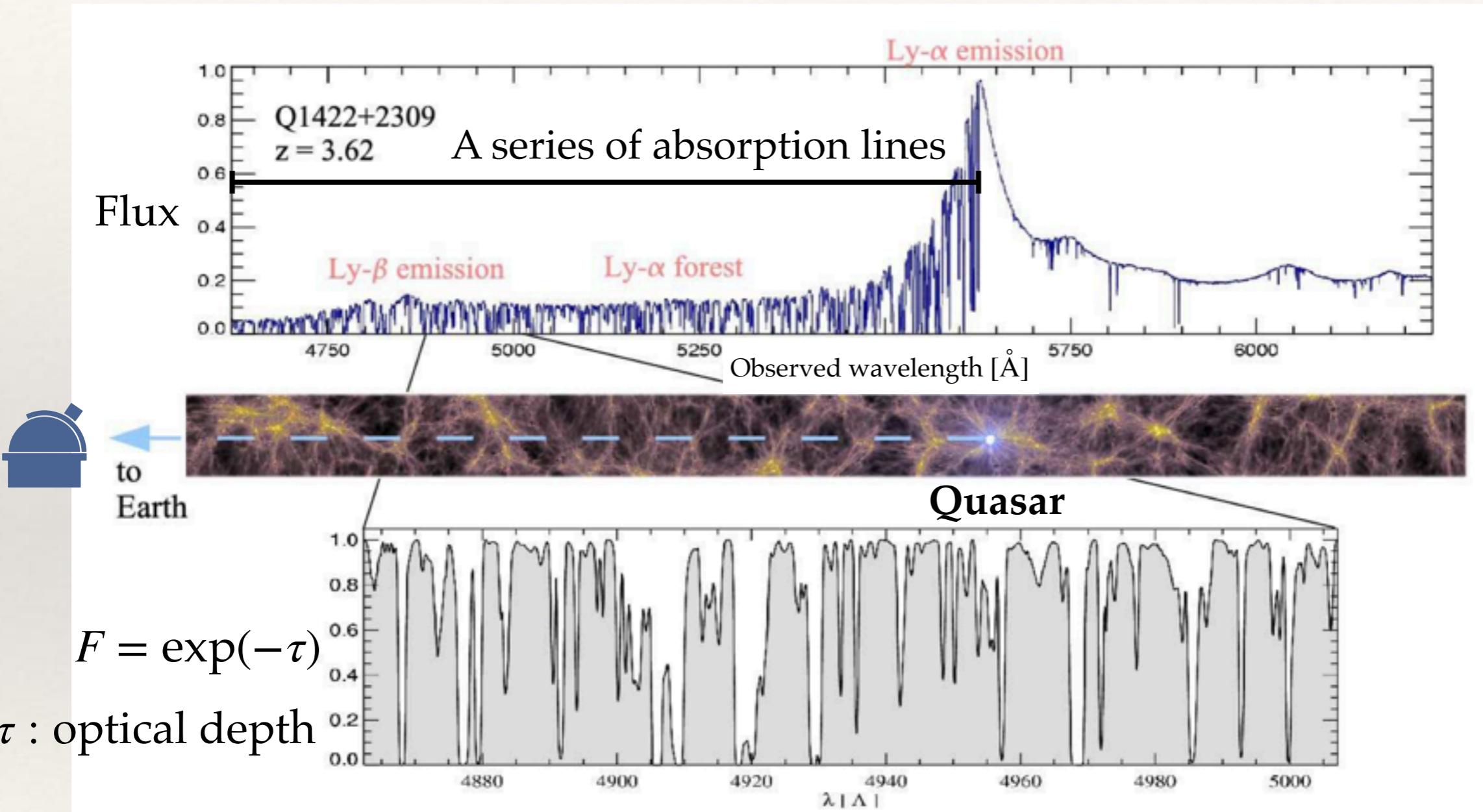
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# Outline

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- Ly $\alpha$  forest & IGM tomography
- Ly $\alpha$  forest  $\times$  Large Scale Structure
- How can we constrain  $f\sigma_8$  using Ly $\alpha$  forest?
- Simulation & 3D power spectrum
- Future works

# Quasar absorption line and LAF

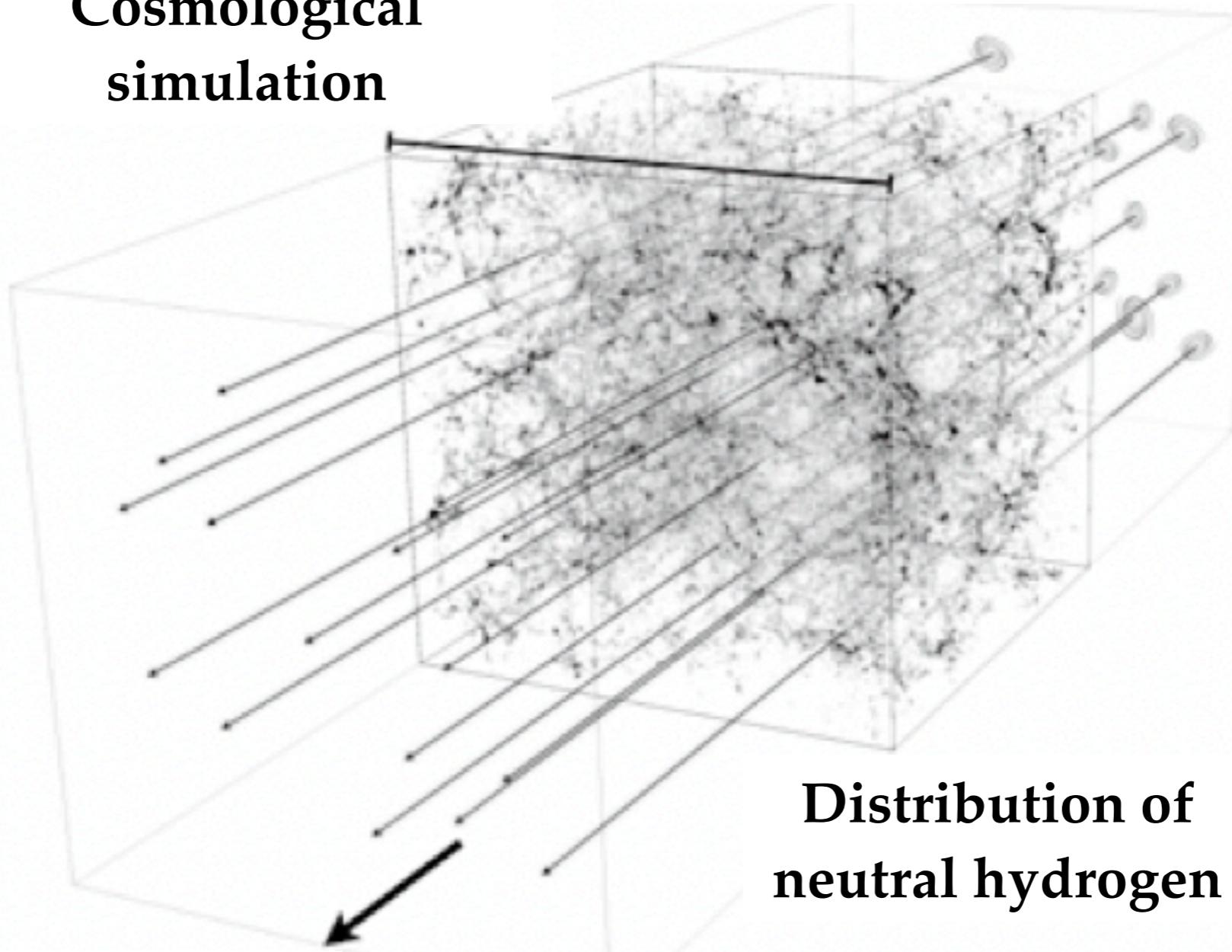


# IGM tomography

IGM = Intergalactic medium

Cosmological  
simulation

Background sources (e.g. QSOs)



Distribution of  
neutral hydrogen

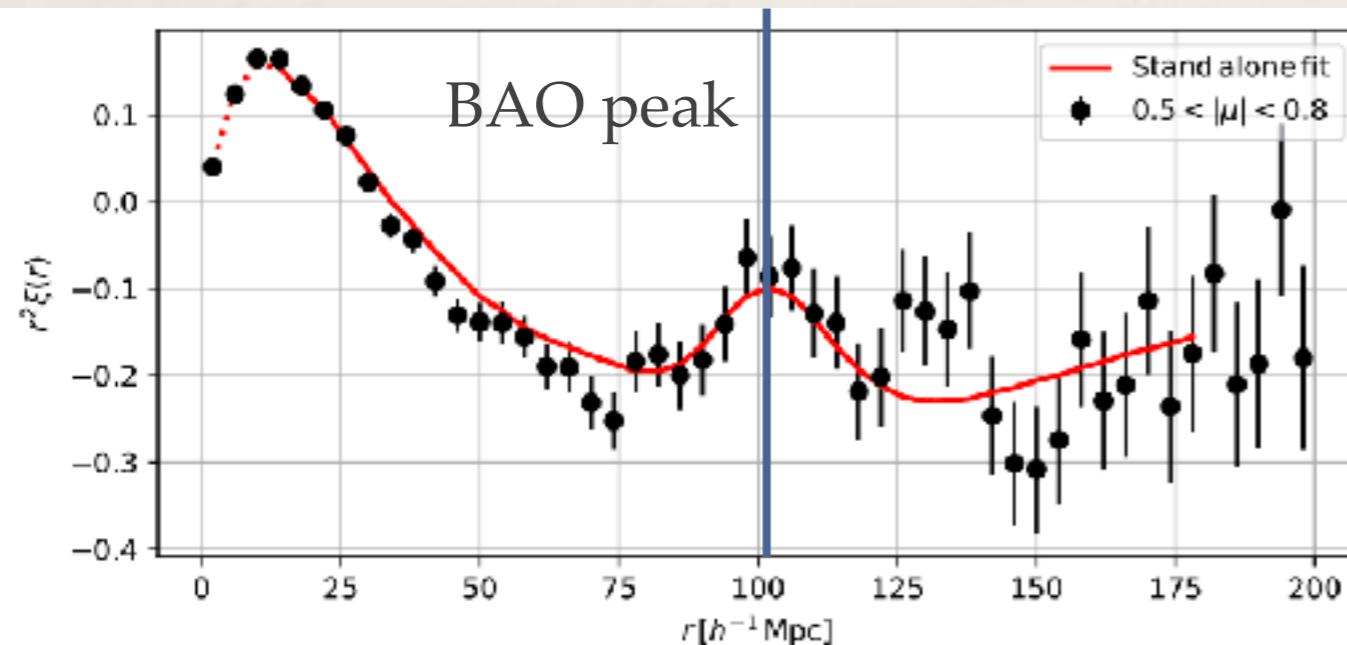
Observer

Shimizu & Nagamine ; TMT JP Science Book 2020

# Ly $\alpha$ forest $\times$ Large Scale Structure

Mas des Bourboux+2020 measured BAO using eBOSS data  
BAO = Baryon Acoustic Oscillation

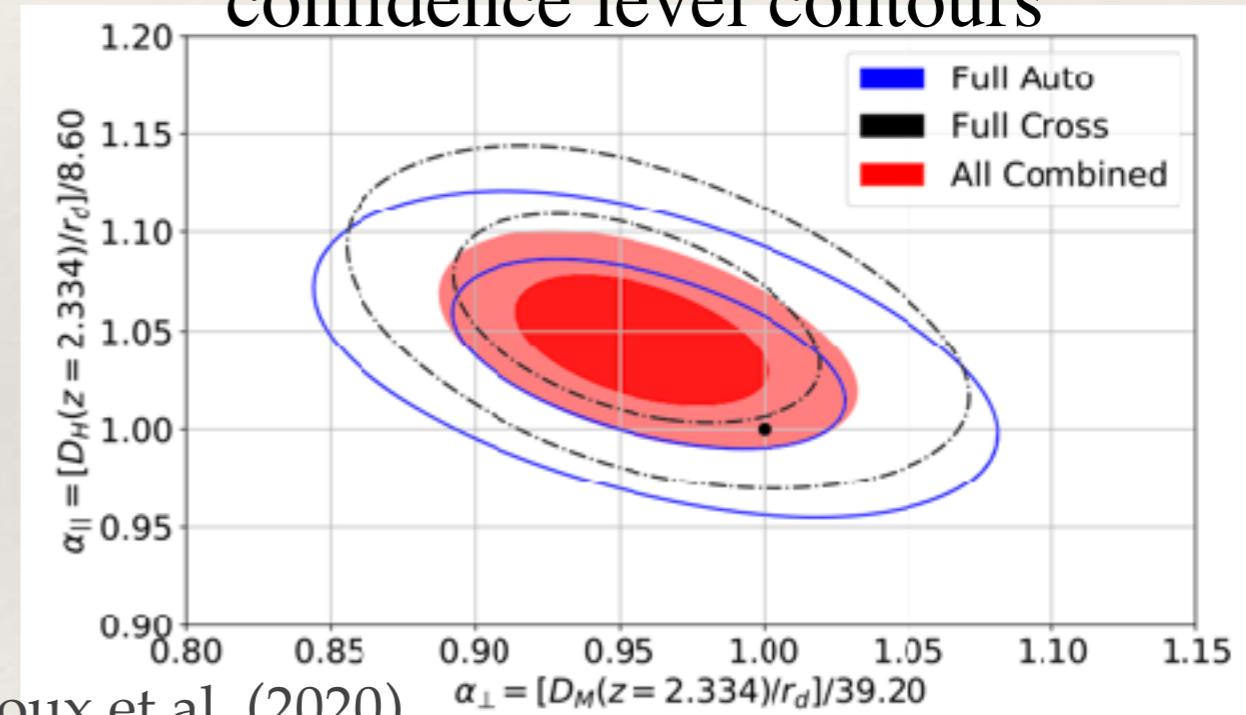
Ly $\alpha$  correlation function



Mas des Bourboux et al. (2020)

$$r_{\text{peak}} \sim 100 h^{-1} \text{Mpc}$$

The 68% and 95% confidence level contours



$$\alpha = r_{\text{peak}}^{\text{obs}} / r_{\text{peak}}^{\text{fid}}$$

# Beyond BAO – RSD

RSD = Redshift Space Distortion

Linear power spectrum (Kaiser 1987)

$$P_s(\mathbf{k}) = P_r(k) \frac{(1 + f\mu_{\mathbf{k}}^2)^2}{\text{Clustering amplified}}$$

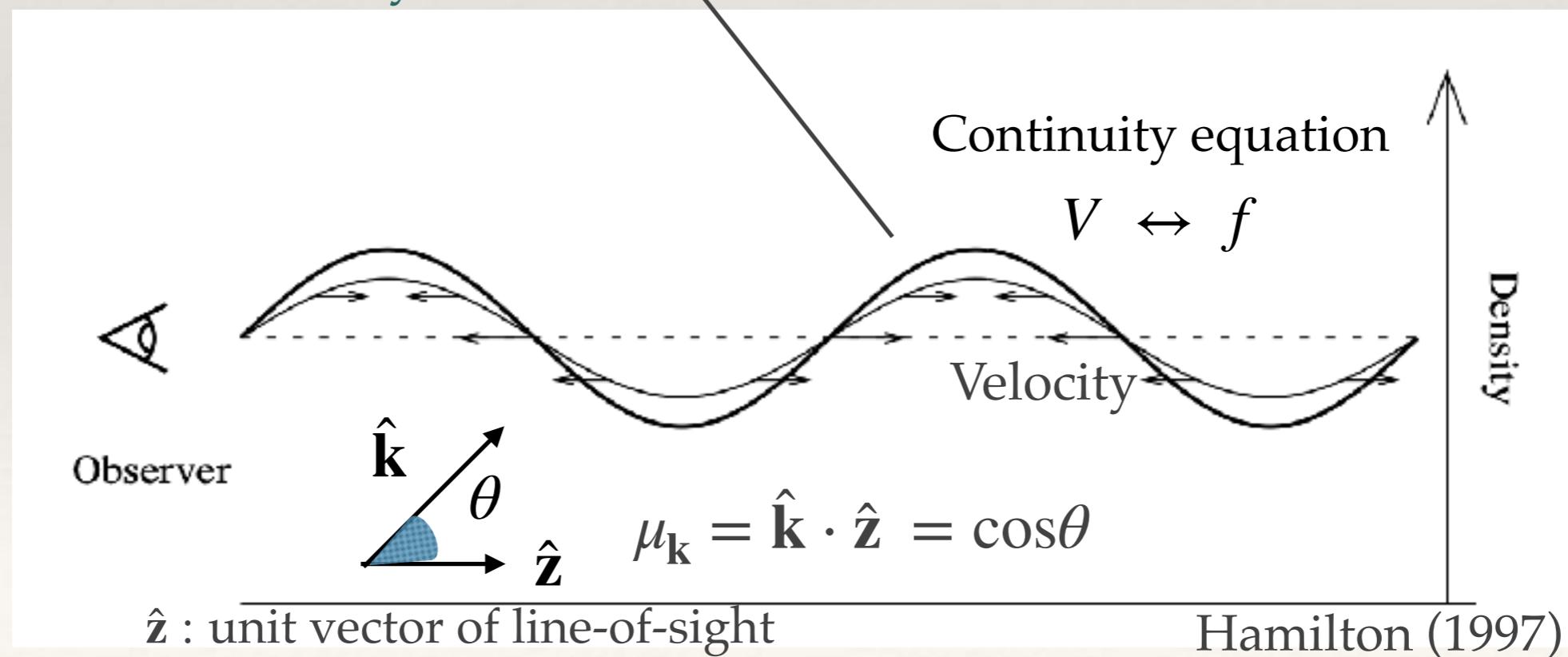
Redshift space      Real space  
                        ↑  
                        Theory

Linear growth rate

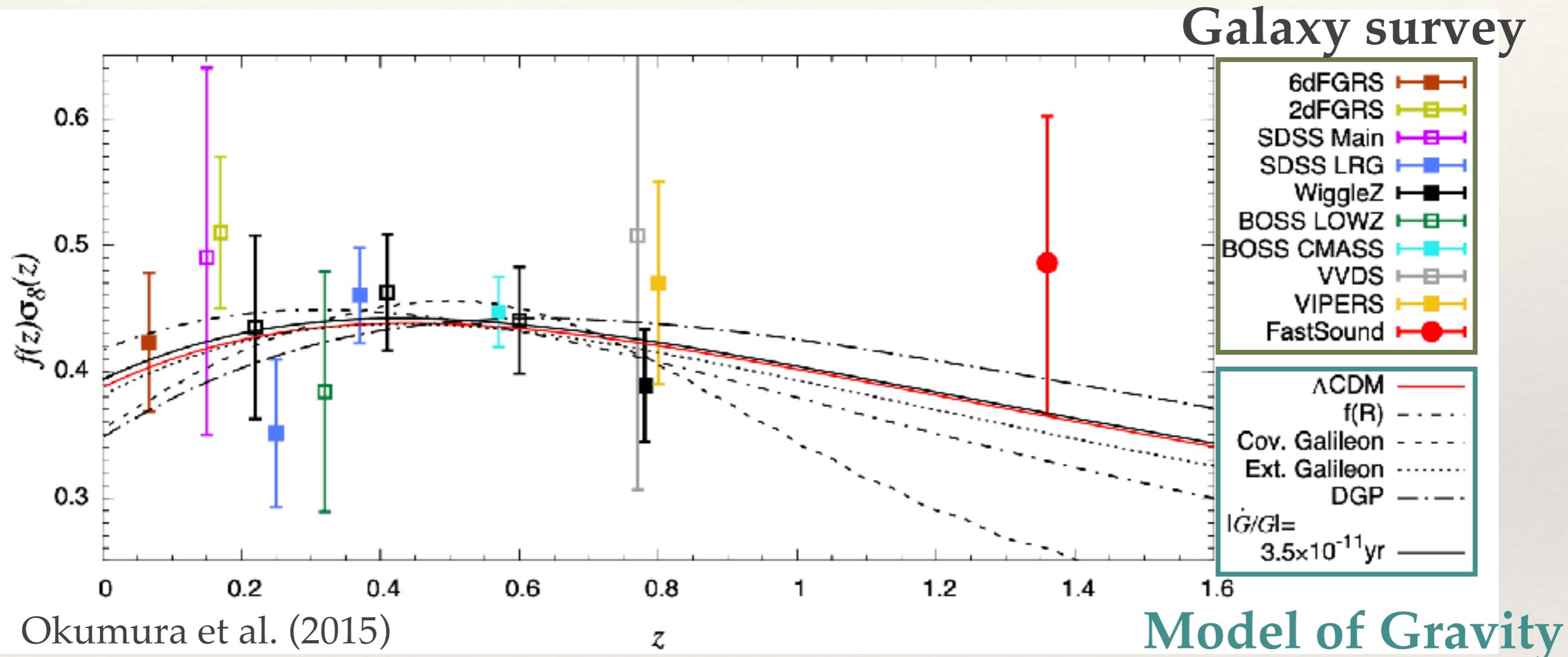
$$f = \frac{\dot{D}}{HD}$$

$D$  : linear growth factor  
of density fluctuation

Gravity theory



# Constraints by galaxy surveys



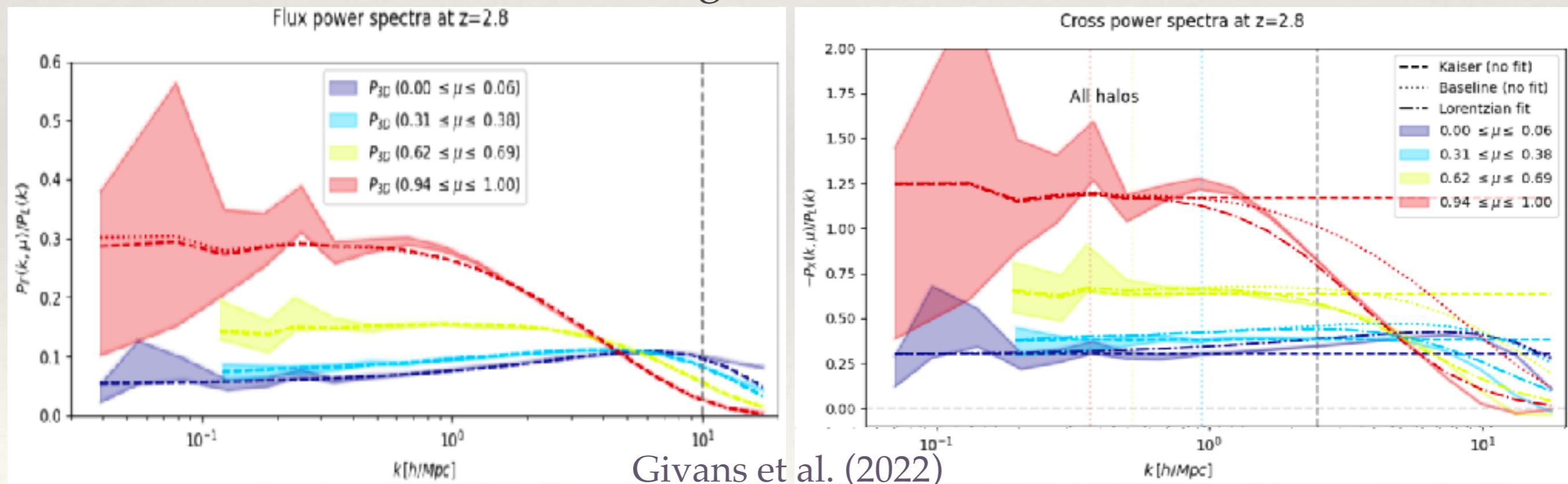
We want to constrain  $f\sigma_8$  at  $z > 2$  using Ly $\alpha$  forest

# Method : 3D PS of LAF

$$P_{\text{Ly}\alpha}(k, \mu_k, z) = (b_{\text{Ly}\alpha} + \underbrace{b_{\eta, \text{Ly}\alpha} f(z) \mu_k^2}_{\text{Degenerate}})^2 \underbrace{F_{\text{nl}, \text{Ly}\alpha}}_{\text{Non-linearity in small scale}} P_{\text{lin}}(k, z)$$

$$P_{\times}(k, \mu_k, z) = (b_{\text{Ly}\alpha} + \underbrace{b_{\eta, \text{Ly}\alpha} f(z) \mu_k^2}_{}) \times (b_{\text{QSO}} + \underbrace{f(z) \mu_k^2}_{}) \underbrace{F_{\text{nl}, \text{QSO-Ly}\alpha}}_{} P_{\text{lin}}(k, z)$$

3D PS in Givans+2022 (using *Sherwood* simulation(Bolton+2017))



# Simulation

Nagamine et al. (2021)

## Probing Feedback via IGM tomography and the Ly $\alpha$ Forest with Subaru PFS, TMT/ELT, and JWST

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<sup>1</sup> Theoretical Astrophysics, Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043,

### GADGET3-Osaka

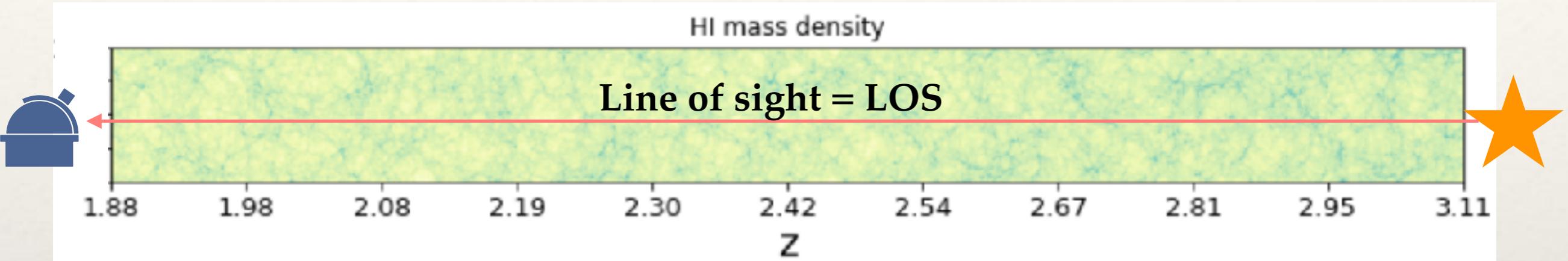
Cosmological Smoothed Particle Hydrodynamics (SPH) simulation

$$L_{\text{box}} = 100 \text{ cMpc}/h \quad N_{\text{particle}} = 2 \times 512^3$$

$$z \sim 2 - 3 \text{ ( 10 snapshots ) }$$

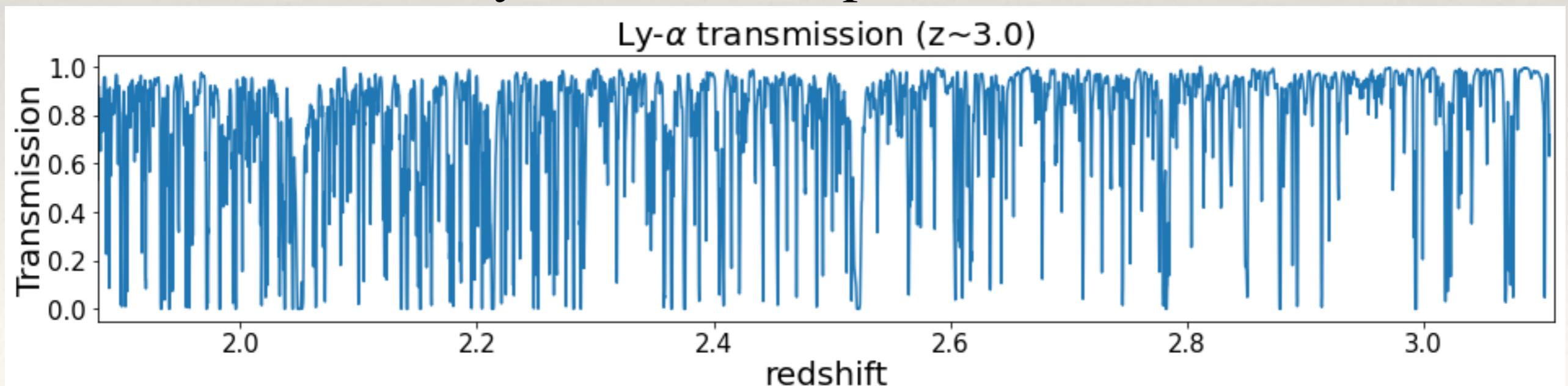
- Radiative cooling (primordial + metal line) using Grackle (Smith '17)
- Star formation & SN feedback (Shimizu+'19)
- Chemical enrichment by SN Ia, II, AGB (CELib package; Saitoh'17)

# Producing light-cone

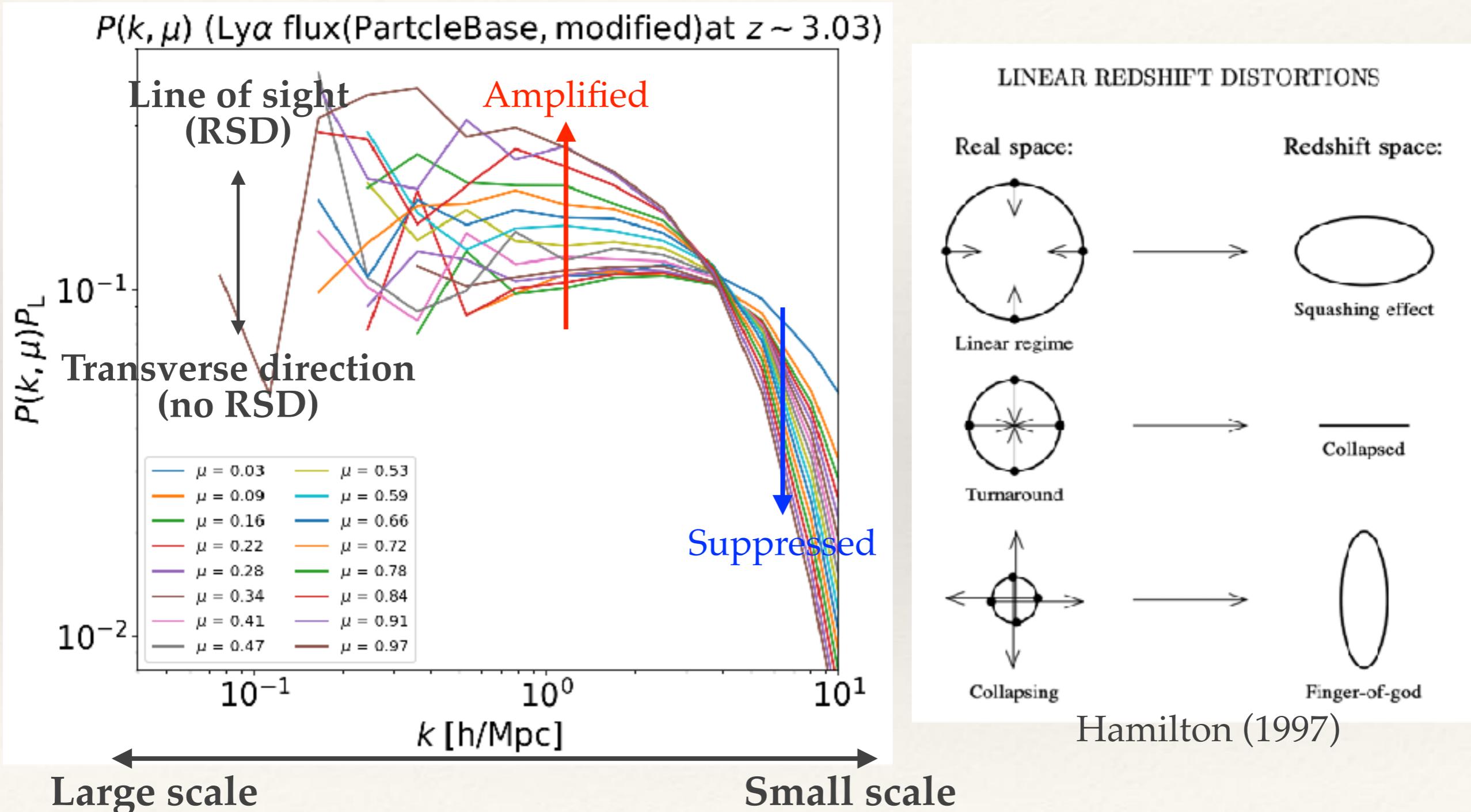


Ly $\alpha$  forest transmitted flux

$$F_{\text{Ly}\alpha}(\rho_{\text{HI}}, T, V_{\text{pec}}) = e^{-\tau}$$



# Result - 3D Power spectrum

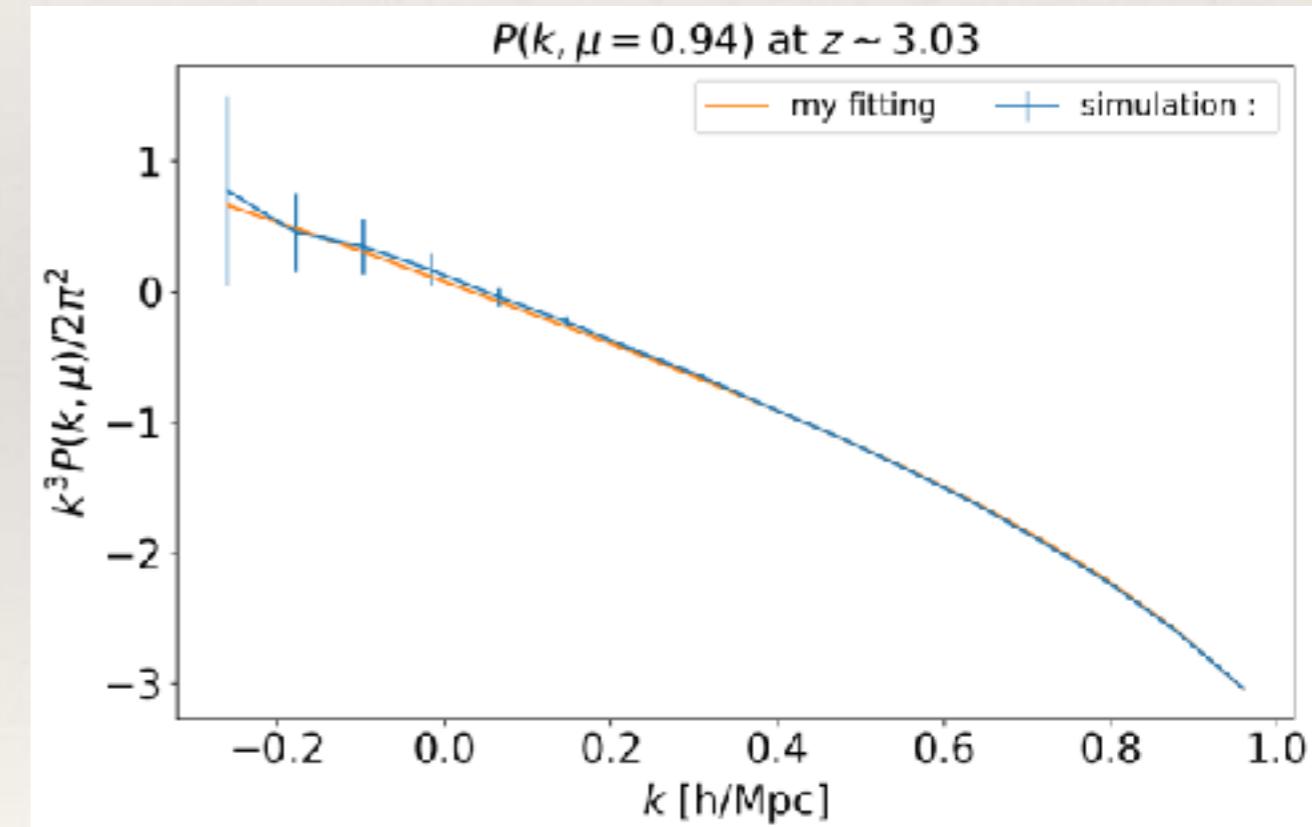
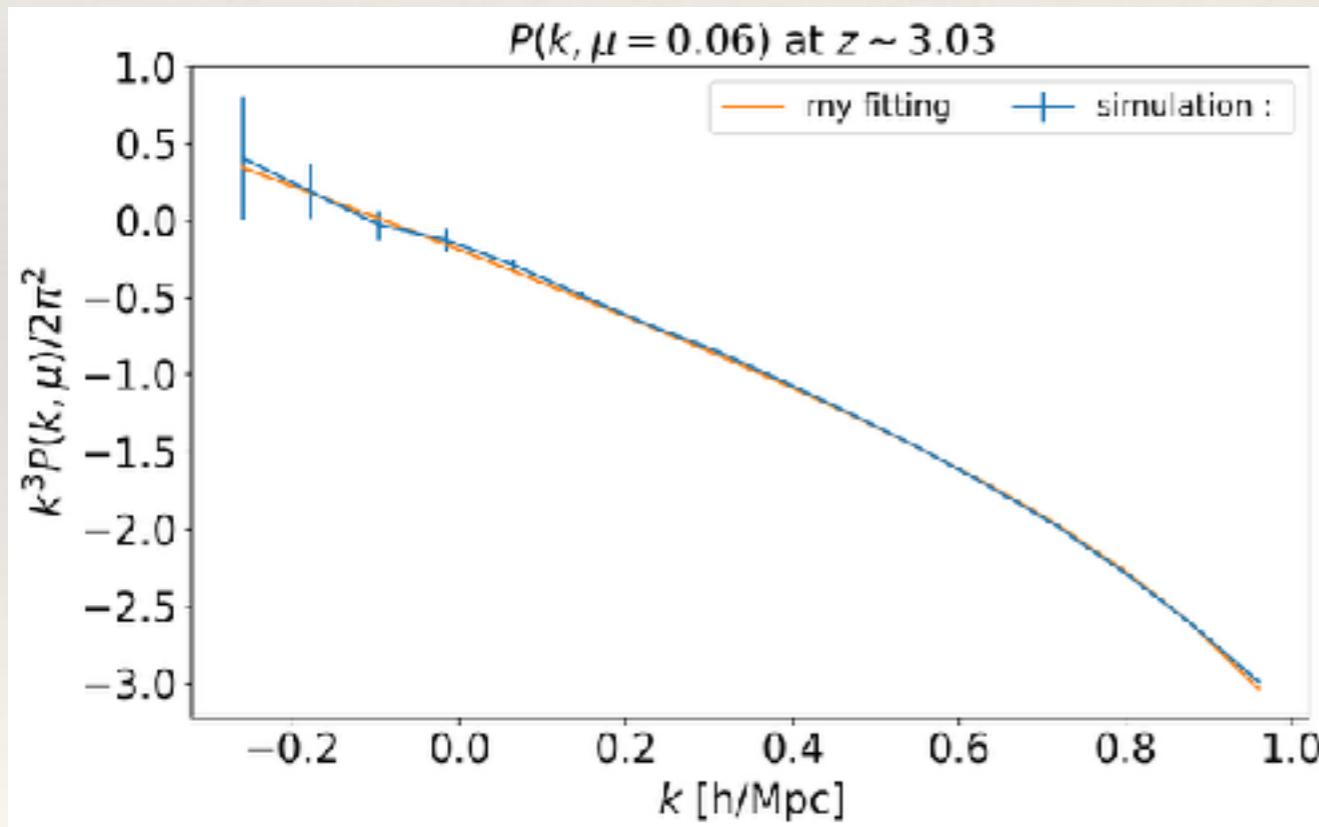


# Fitting result - Ly $\alpha$ auto PS

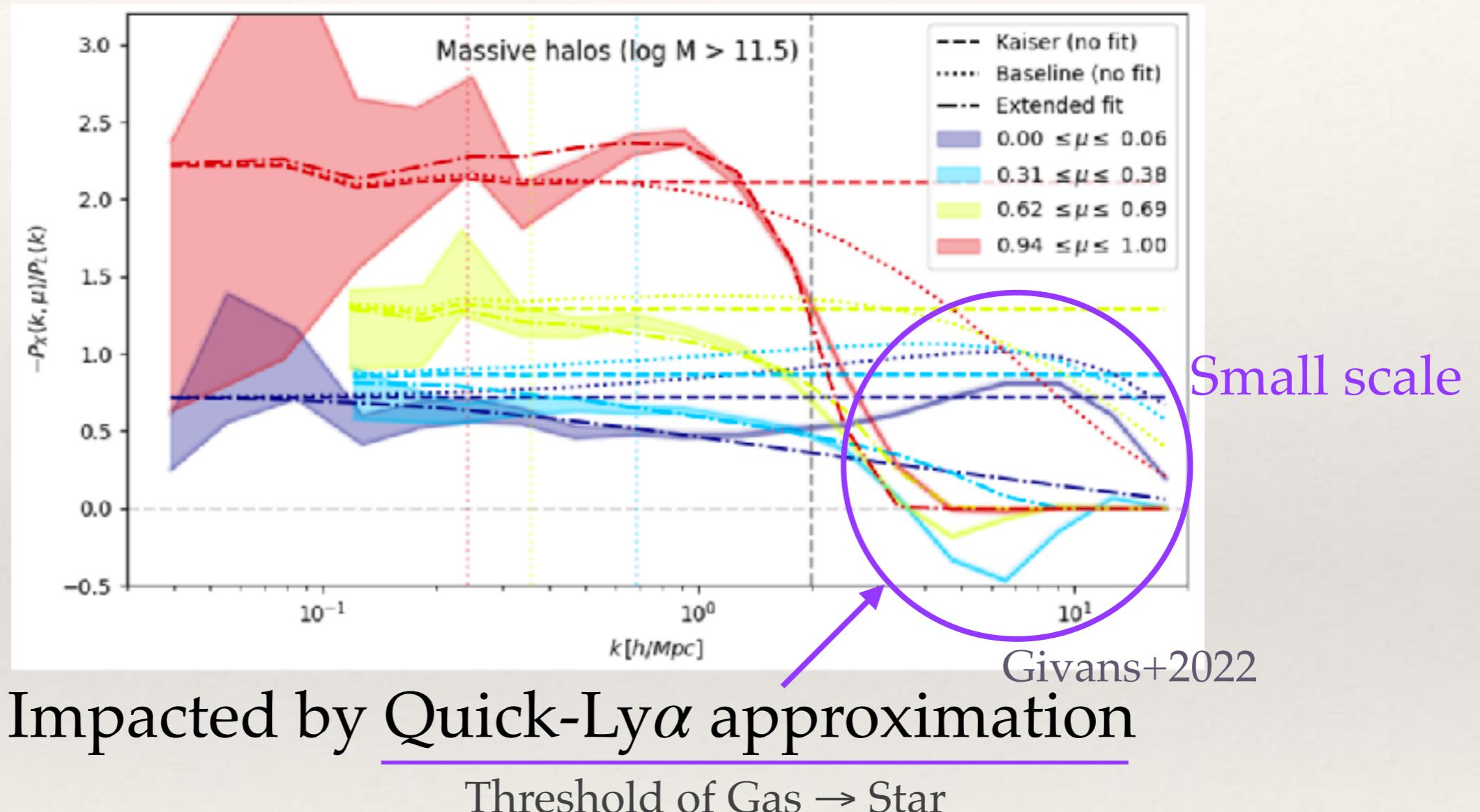
$$P_F(k, \mu) = b_{F\delta}^2(1 + \beta\mu^2)^2 P_L(k) \underline{D(k, \mu)}$$

Fitting model  $D(k, \mu) = \exp \left\{ [q_1 \Delta^2(k) + q_2 \Delta^4(k)] \left[ 1 - (k/k_v)^{a_v} \mu^{b_v} \right] - \left( k/k_p \right)^2 \right\}$

Arinyo+2015

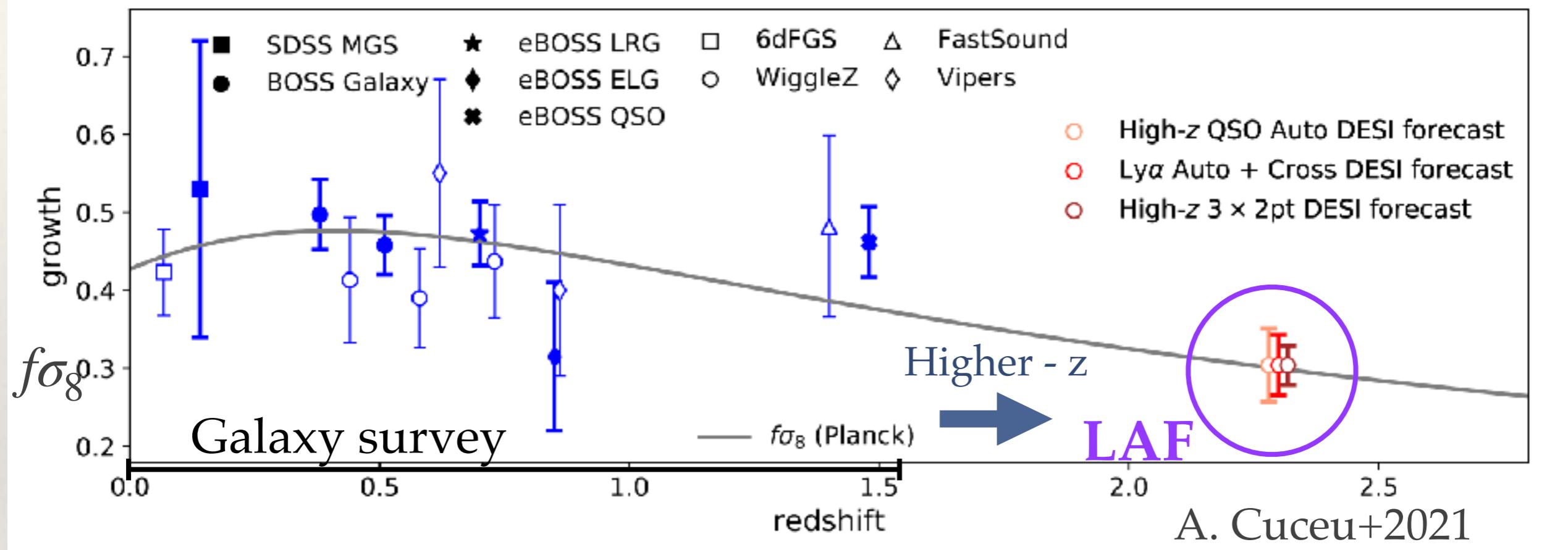


# Next step 1 - Model dependence



Effect of different simulation model  
(compare this  $P$  with that of Osaka simulation)

# Next step 2 - Cosmology



Mocks were created by *LyCoLoRe* package

Initial random Gaussian field → Optical depth (using a number of fast approximation)

Can we constrain  $f\sigma_8$  using Hydrodynamical simulation?

# Summary

- Ly $\alpha$  forest  $\times$  Large Scale Structure
  - Cosmological test
    - BAO  $\rightarrow$  
    - RSD  $\rightarrow$  next topic
  - How can we constrain  $f\sigma_8$  using Ly $\alpha$  forest?
    - Anisotropic 3D power spectrum  $P(k, \mu(\theta))$
  - Simulation & 3D power spectrum
    - We can see RSD in 3D PS
    - (Prediction) some differences from previous work on small scale

Back up slides

# Motivation

The present accelerated expansion of our universe

Einstein's equations

$$\underline{G_{\mu\nu}} = \frac{8\pi G}{c^4} \underline{T_{\mu\nu}}$$

Modified gravity ?

Dark energy ?



Growth rate of density perturbation

Expansion rate of universe

Probes of large-scale structure

- Redshift Space Distortions (RSD)
- Baryon Acoustic Oscillation (BAO)
- ⋮

# Ly $\alpha$ optical depth

Definition

$$\begin{aligned}\tau(\nu) &\equiv \int dl \ n_{\text{HI}} \ \sigma_{\text{Ly}\alpha}(\nu) \\ &= \int_0^l d\tilde{l} \ du_p \sigma_L[\nu(1 - u_p/c)] \sqrt{\frac{m_p}{2\pi k_B T}} n_{\text{HI}} \exp\left(-\frac{m_p u_p^2}{2k_B T}\right)\end{aligned}$$

Calculate of optical depth from physical values at each pixel

$$\tau(x) = \frac{\pi e^2}{m_e c} \sum_j f \phi(x - x_j) n_{\text{HI}}(x_j) dl$$

# RSD analysis

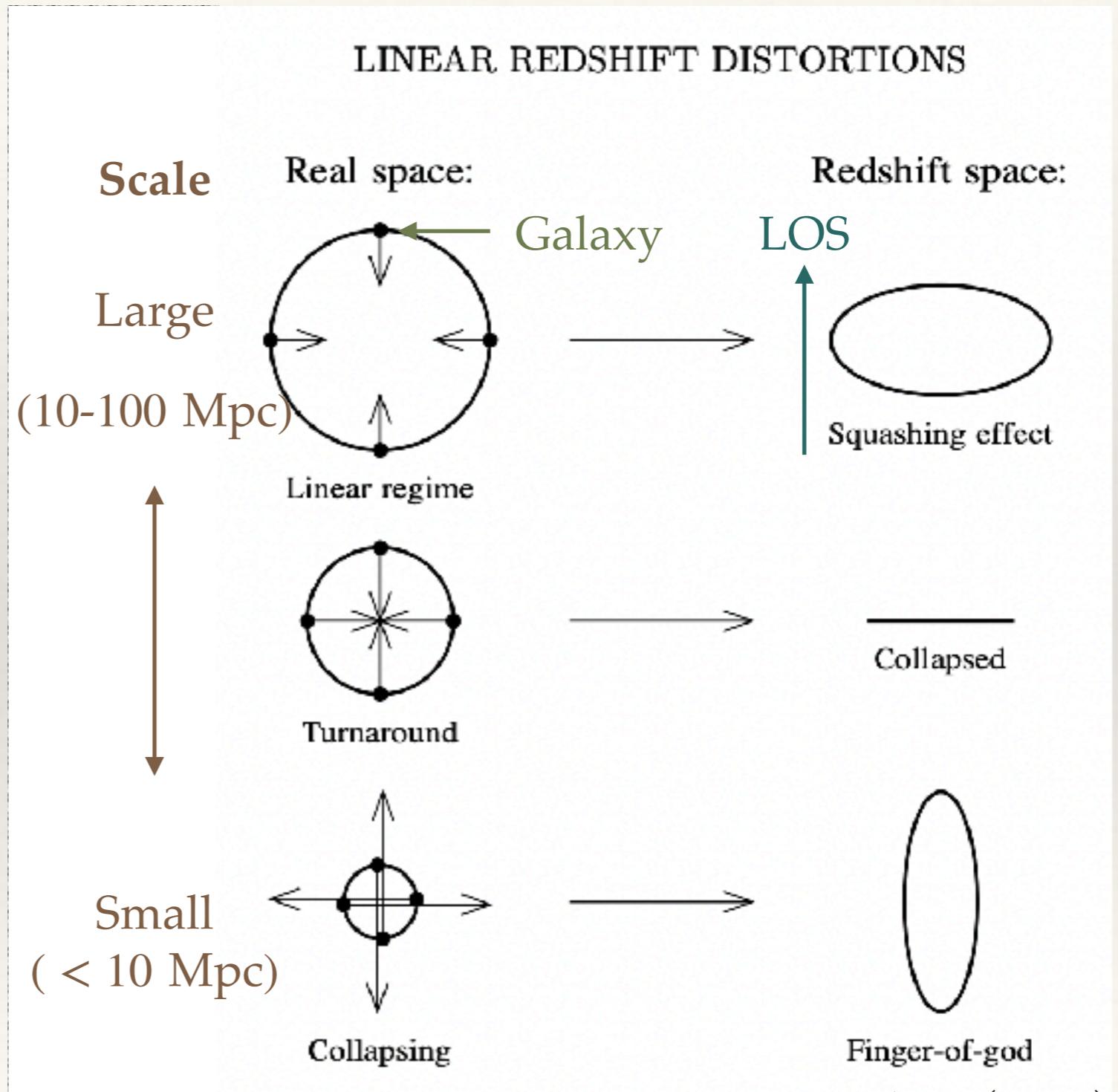
Distance between objects and us

$$z_{\text{obs}} \sim z_{\text{real}} + \frac{V_{\text{pec}}}{c a}$$

Hubble flow

$$\chi_s \sim \chi_r + \frac{V_{\text{pec}}}{a H}$$

Redshift space      Real space      Peculiar velocity



# Problem - velocity bias

Gradient of peculiar velocity

$$\eta = -\frac{1}{aH} \frac{\partial v_p}{\partial x_p}$$

Fluctuation of optical depth

$$\delta_\tau = b_{\tau\delta} \delta_{\text{gas}} + \eta$$



$$F = \exp(-\tau)$$

Fluctuation in transmission

$$\delta_F = b_{F\delta} \delta_{\text{gas}} + b_{F\eta} \eta$$

$$P_F(k, \mu_k, z) = (b_{F\delta} + b_{F\eta} f(z) \mu_k^2)^2 P_L(k, z)$$

Problem → Bias is degenerate with  $f\sigma_8$

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# Solution - cross correlation with QSO

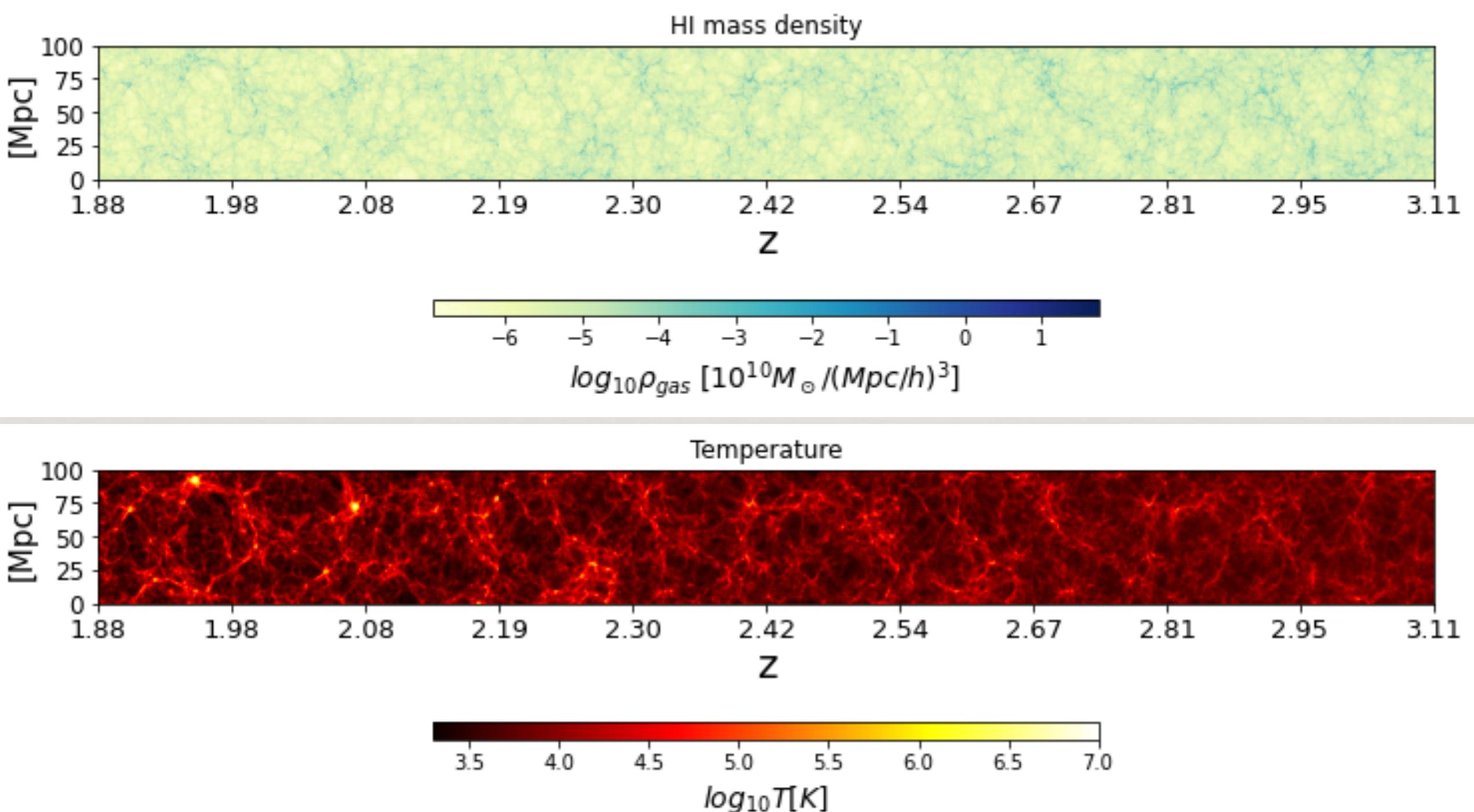
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Cuceu et al. (2021) suggests a joint full-shape analysis  
of the Ly $\alpha$  auto and cross-correlation with quasars

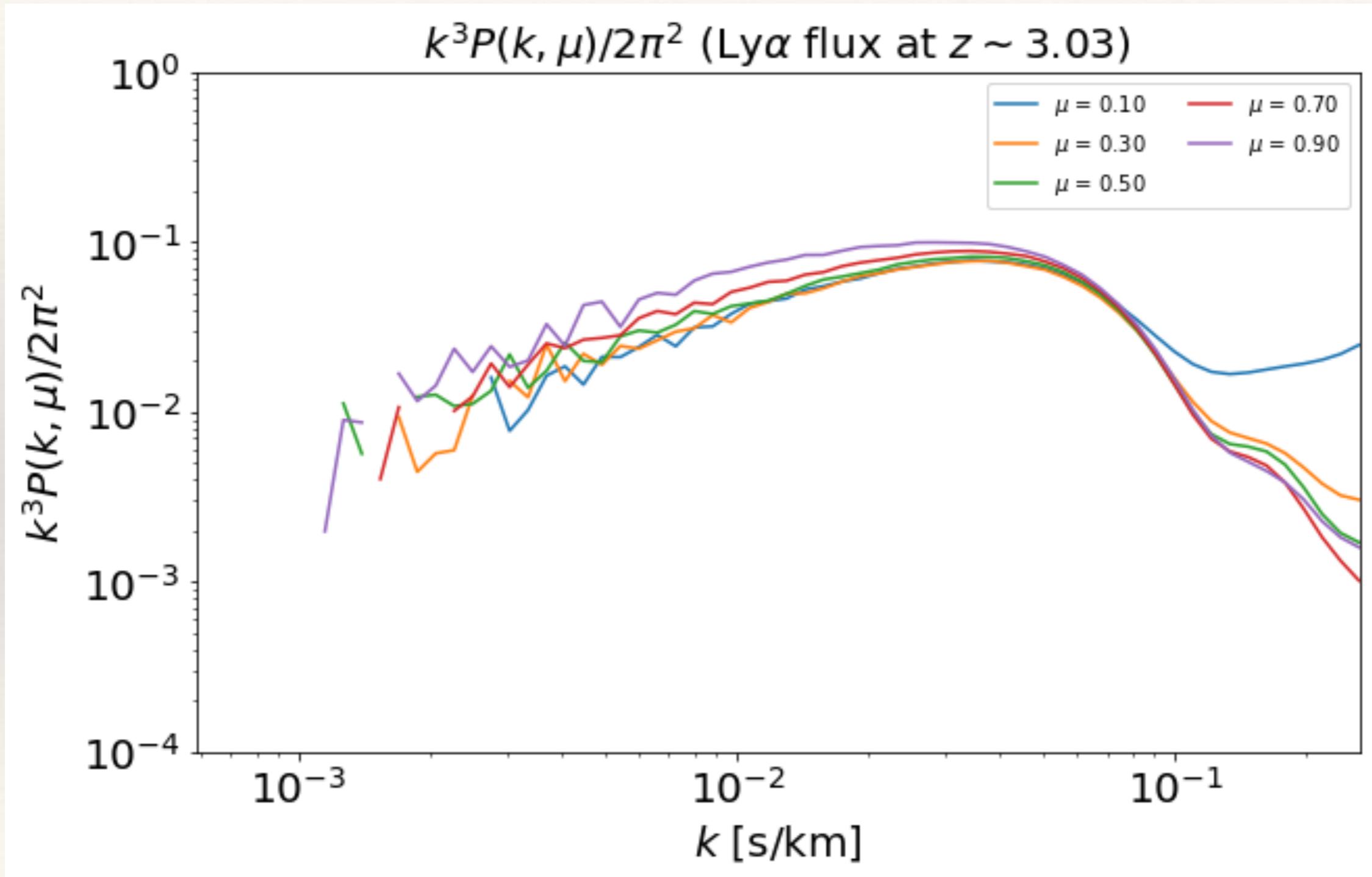
$$P_{\text{Ly}\alpha}(k, \mu_k, z) = (b_{\text{Ly}\alpha} + b_{\eta, \text{Ly}\alpha} f(z) \mu_k^2)^2 F_{\text{nl}, \text{Ly}\alpha}^2 P_{\text{lin}}(k, z)$$

$$\begin{aligned} P_x(k, \mu_k, z) &= (b_{\text{Ly}\alpha} + b_{\eta, \text{Ly}\alpha} f(z) \mu_k^2) \\ &\quad \times (b_{\text{QSO}} + f(z) \mu_k^2) F_{\text{nl}, \text{QSO-Ly}\alpha} P_{\text{lin}}(k, z) \end{aligned}$$

# Light-cone data



# Ly $\alpha$ Auto 3D Power spectrum

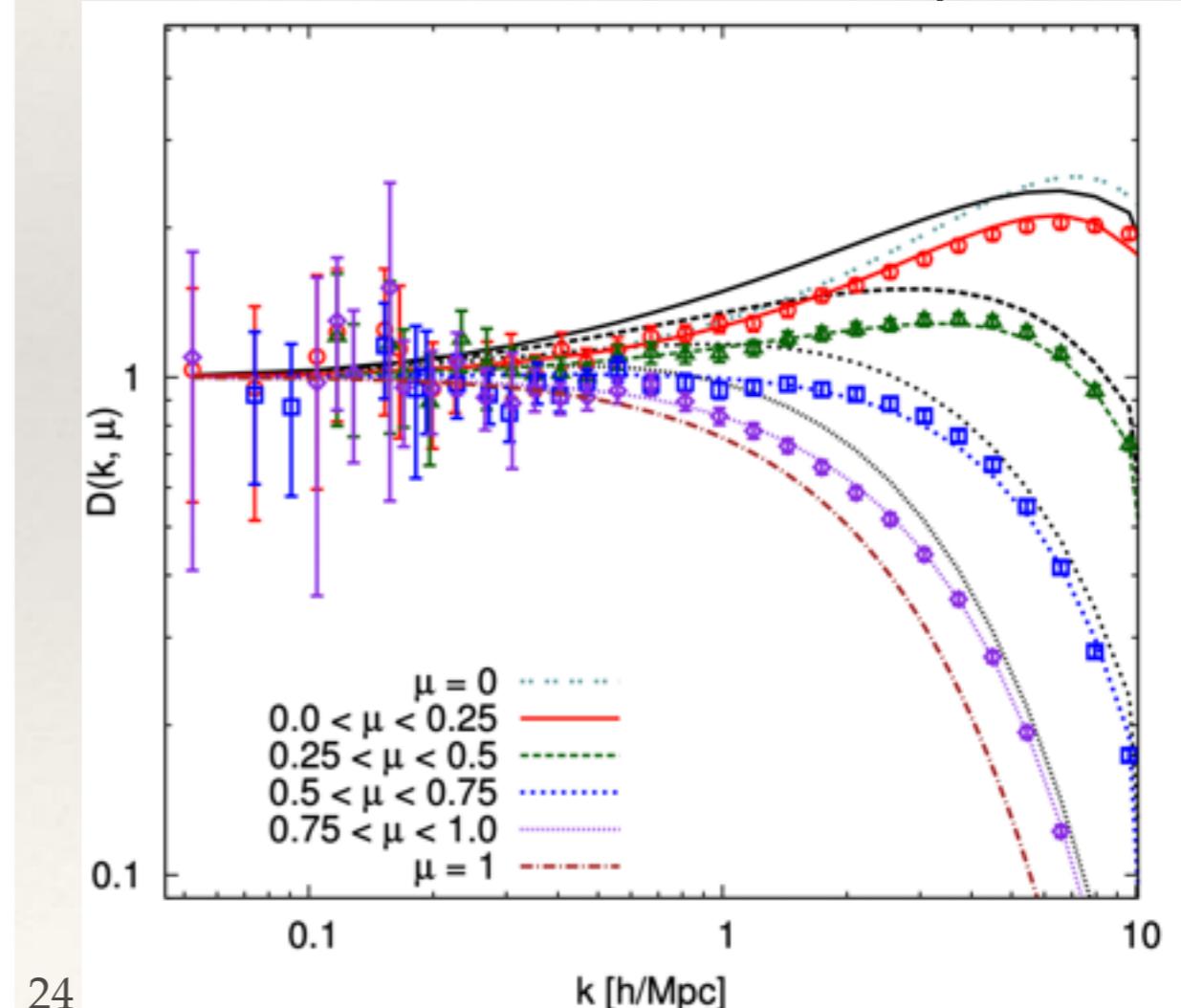
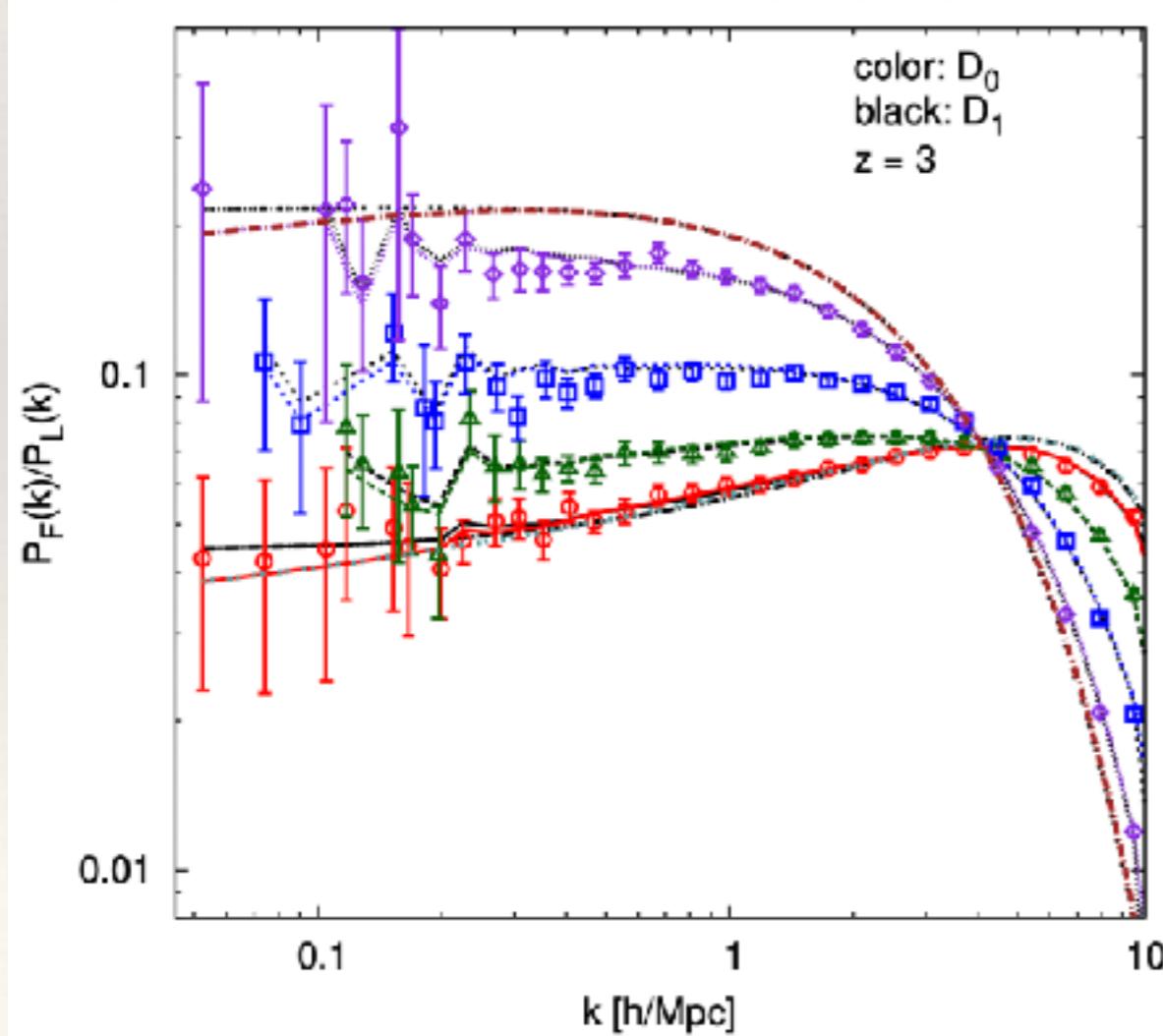


# Non-linear Power spectrum

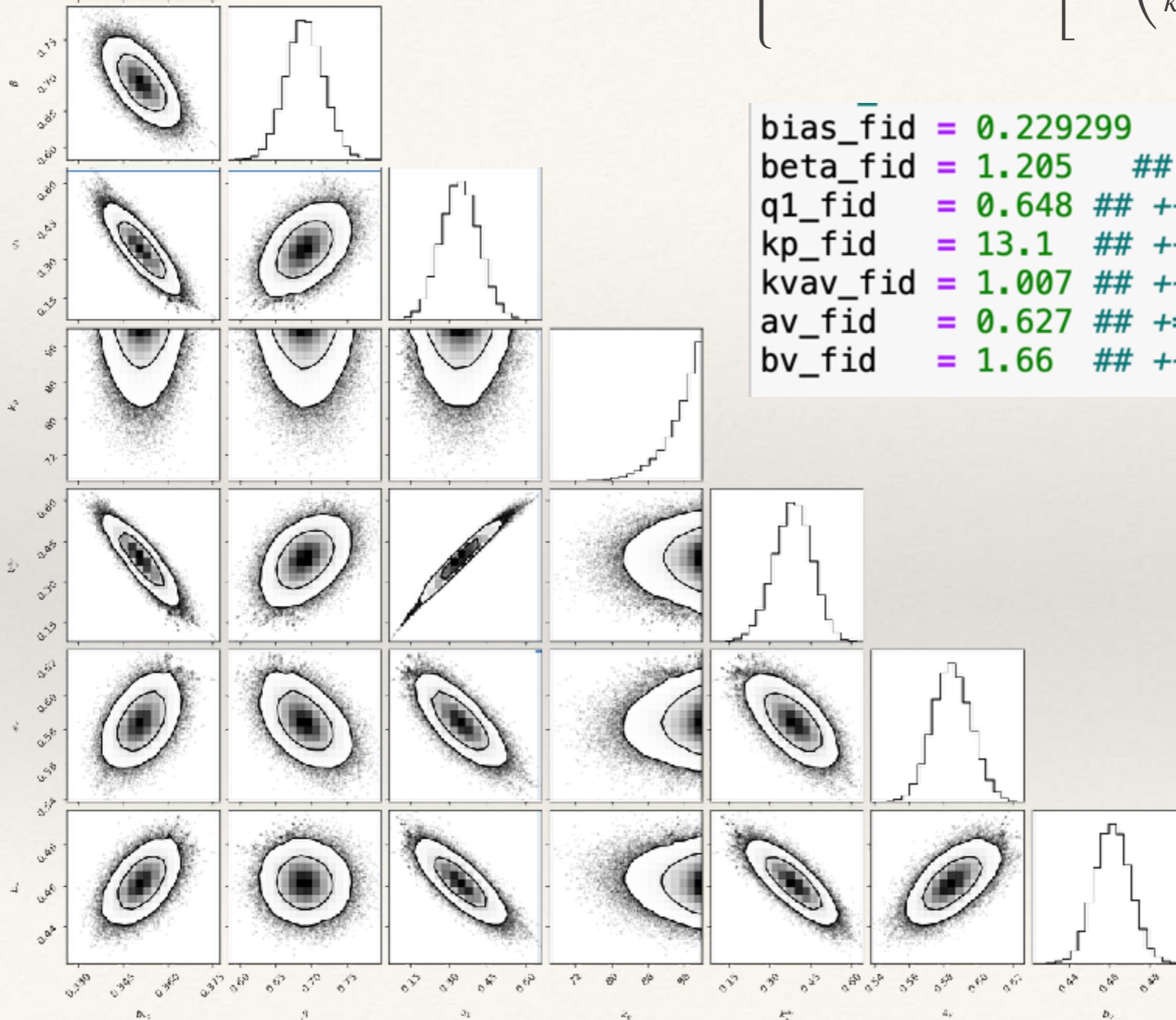
$$P_F(k, \mu) = b_{F\delta}^2(1 + \beta\mu^2)^2 P_L(k) \underline{D(k, \mu)}$$

Arinyo et al. 2015

$$D_1(k, \mu) = \exp \left\{ [q_1 \Delta^2(k) + q_2 \Delta^4(k)] \left[ 1 - \left( \frac{k}{k_v} \right)^{a_v} \mu^{b_v} \right] - \left( \frac{k}{k_p} \right)^2 \right\}$$



$$P_s(k, \mu) = b_{F\delta}^2(1 + \beta\mu^2)^2 P_L(k) \exp \left\{ [q_1 \Delta^2(k) + q_2 \Delta^4(k)] \left[ 1 - \left( \frac{k}{k_v} \right)^{a_v} \mu^{b_v} \right] - \left( \frac{k}{k_p} \right)^2 \right\}$$



```

bias_fid = 0.229299
beta_fid = 1.205 ## +- 0.061
q1_fid = 0.648 ## +- 0.042
kp_fid = 13.1 ## +- 0.5 [h/Mpc]
kvav_fid = 1.007 ## +- 0.114 [h/Mpc]^av
av_fid = 0.627 ## += 0.072
bv_fid = 1.66 ## +-0.02

```

$$b_{F\delta} = 0.3511_{-0.0105}^{0.0106}$$

$$\beta = 0.6900_{-0.0500}^{0.0528}$$

$$q_1 = 0.3416_{-0.1439}^{0.1492}$$

$$k_p = 96.3161_{-12.4347}^{3.5493}$$

$$k_v^{a_v} = 0.3858_{-0.1453}^{0.1315}$$

$$a_v = 0.5846_{-0.0215}^{0.0228}$$

$$b_v = 0.4615_{-0.0167}^{0.0172}$$

Density distribution of the IGM  
→ Lognormal approximation

$$\delta_{\text{lognormal}} = \exp \left[ \delta_{\text{Gauss}} - \frac{\sigma_{\text{Gauss}}^2}{2} \right] - 1$$

Bi & Davidsen (1997)

FGPA

$$\tau \propto \rho^2 T^{-0.7} \propto (1 + \delta)^\alpha$$

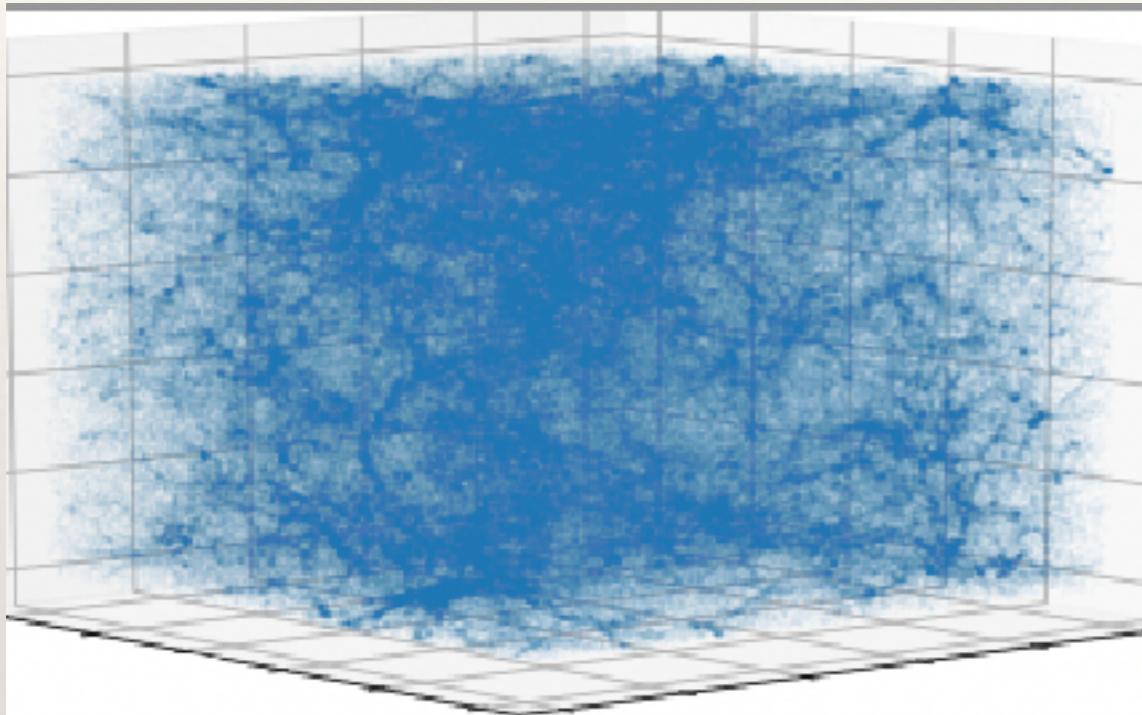
$$T = T_0(1 + \delta)^{\gamma-1} \quad \alpha = 2 - 0.7(\gamma - 1)$$

$$F = e^{-\tau} = e^{-A(1+\delta)^\alpha}$$

Brax & Valageas 2019

# Simulation

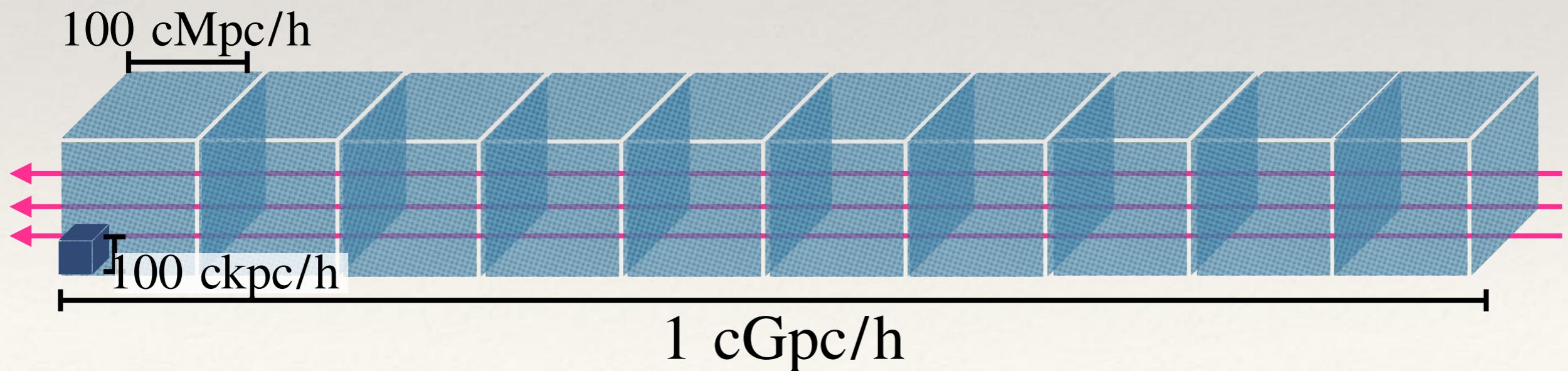
GADGET3-Osaka cosmological simulation in Nagamine et al. (2021)

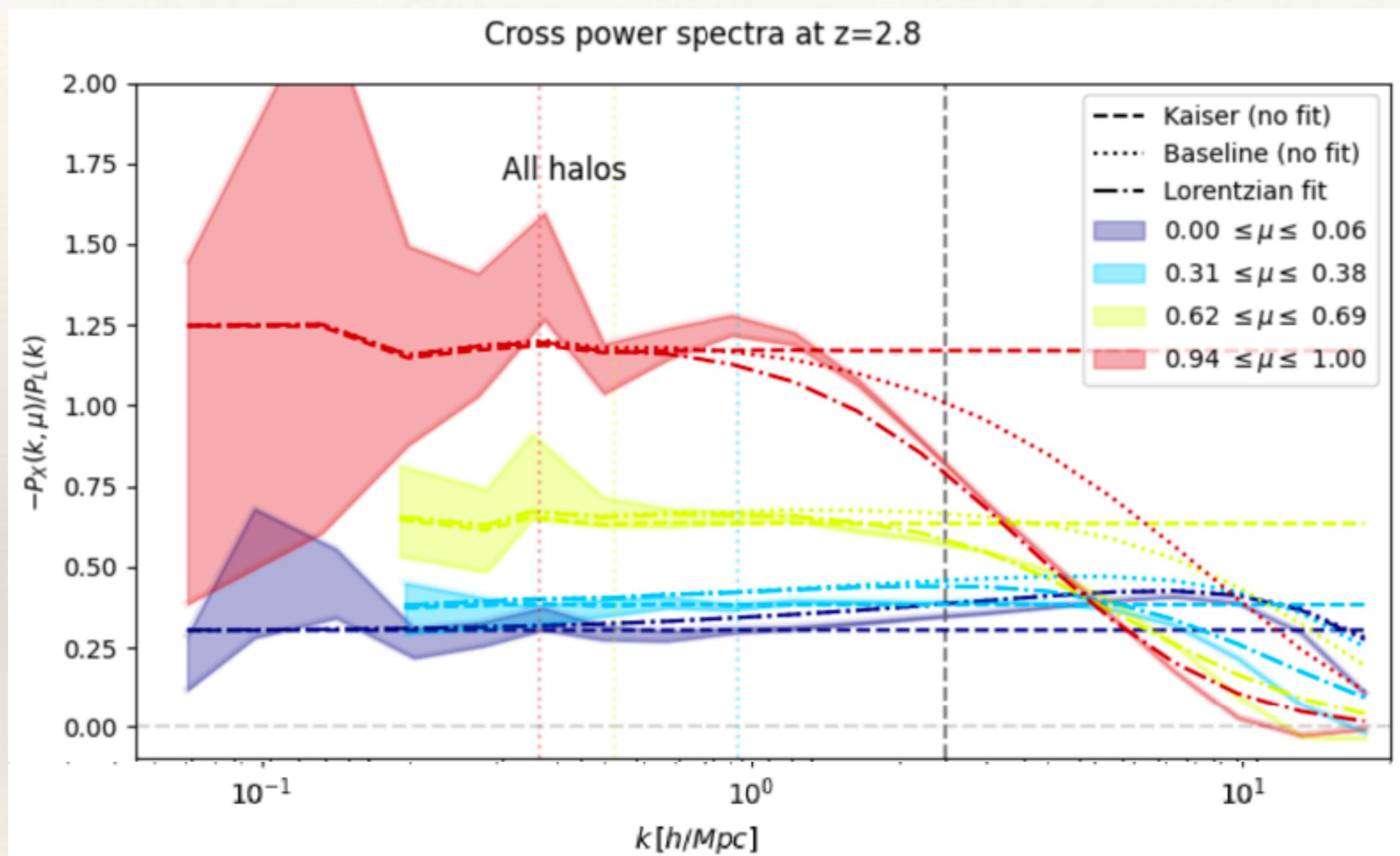


$$L_{\text{box}} = 100 \text{ cMpc}/h$$

$$N = 2 \times 512^3$$

$$z \sim 2 - 3$$



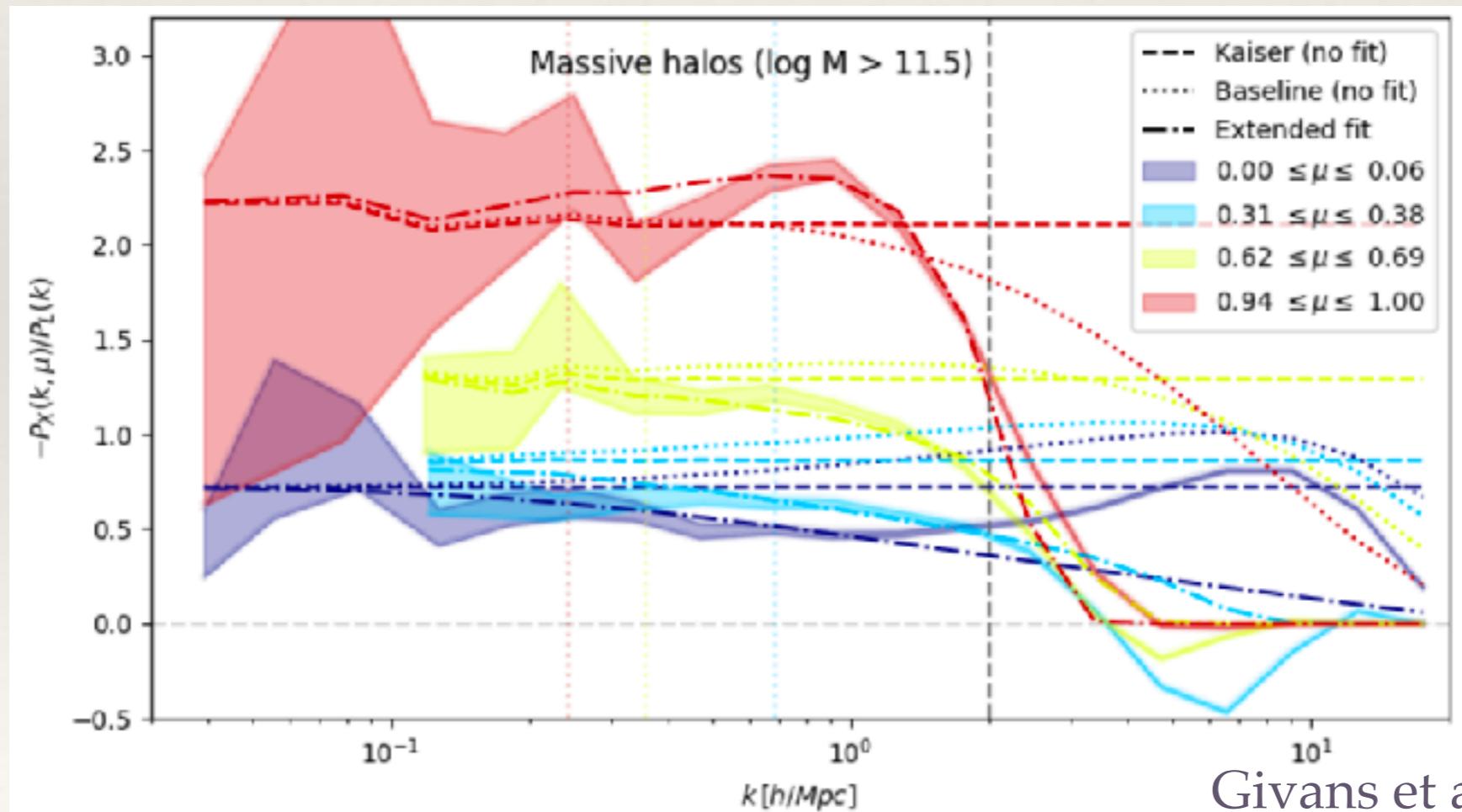


# Fitting function for cross-PS

$$P_{\times}(k, \mu_k, z) = (b_{\text{Ly}\alpha} + b_{\eta, \text{Ly}\alpha} f(z) \mu_k^2) \times (b_{\text{QSO}} + f(z) \mu_k^2) F_{\text{nl, QSO-Ly}\alpha} P_{\text{lin}}(k, z)$$

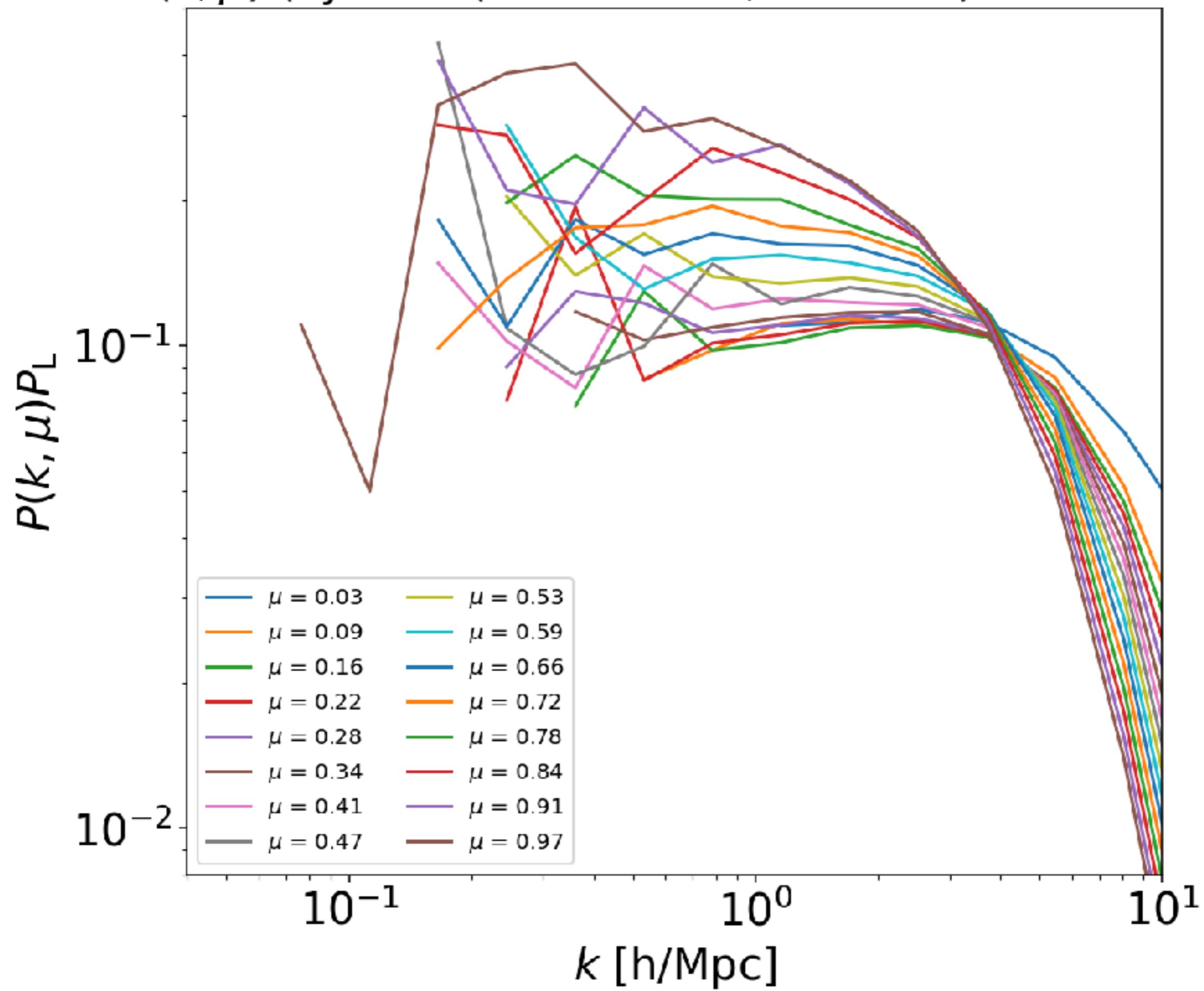
Fitting function for the cross-PS with Massive halos (Givans et al. 2022)

$$F_{\text{nl, halo-Ly}\alpha} = D_{\text{Arinyo}} \times \exp[(\alpha + \gamma \mu^2) \Delta^2(k) - (k \mu \nu)^4]$$



Givans et al. (2022)

$P(k, \mu)$  (Ly $\alpha$  flux(PartcleBase, modified) at  $z \sim 3.03$ )



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# MCMC Fitting

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Error of power spectrum

$$\sigma_P(k, \mu) = P_F(k, \mu) \left[ 1/\sqrt{n_F(k, \mu)} + \epsilon \right]$$

$n_F$  : Number of Fourier modes

$\epsilon$  : *Nose floor* (constant)

Minimize the  $\chi^2$  function

$$\chi^2 = \sum \frac{(P_s - P_m)^2}{(\sigma_P P_m / P_s)^2}$$

Arinyo et al. 2015

# Nagamine et al. (2021)

**Table 2**  
Subaru PFS IGM Tomography Targets

Target Class	Redshift Range	Selection	Exposure Time (hr)	Targeted Objects (Useful Spectra)	Number/PFS FOV (1.25 deg <sup>2</sup> )
IGM background (bright)	2.5–3.5	$y < 24.3, g < 24.2$	6	8300 (5810)	690
IGM background (faint)	2.5–3.5	$y < 24.3, 24.2 < g < 24.7$	12	14,000 (9800)	1170
IGM foreground	2.1–2.6	$y < 24.3$	6	22,000 (15,400)	1830

**Table 3**  
Simulation Parameters

Simulations	Box Size ( $h^{-1}$ cMpc)	$N_{\text{ptcl}}$	$m_{\text{DM}}$ ( $h^{-1} M_{\odot}$ )	$m_{\text{gas}}$ ( $h^{-1} M_{\odot}$ )	$\epsilon_g$ ( $h^{-1}$ ckpc)	$h_{\min}$ ( $h^{-1}$ pc)
L100N512 (Osaka20)	100	$2 \times 512^3$	$5.38 \times 10^8$	$1.00 \times 10^8$	7.8	260
L50N256	50	$2 \times 256^3$	$5.38 \times 10^8$	$1.00 \times 10^8$	7.8	260
L40N512	40	$2 \times 512^3$	$3.44 \times 10^7$	$6.43 \times 10^4$	2.6	87

**Note.** Parameters of the simulations used for resolution and box-size effect. The L100N512 simulation corresponds to the Osaka20 runs listed in Table 1. The listed parameters are as follows:  $N_{\text{ptcl}}$  is the total number of particles (dark matter and gas),  $m_{\text{DM}}$  is the dark matter particle mass,  $m_{\text{gas}}$  is the initial mass of gas particles (which may change over time due to star formation and feedback),  $\epsilon_g$  is the comoving gravitational softening length, and  $h_{\min}$  is the minimum physical gas smoothing length at  $z = 2$  (see Section 2.1).

**Table 4**  
Galaxy Counts

Simulations	$N_{\text{gal}}$			
	$10^8$ – $10^9$	$10^9$ – $10^{10}$	$10^{10}$ – $10^{11}$	$> 10^{11} M_{\odot}$
L100N512 (Osaka20)	8344	13893	3200	148
L50N256	1039	1705	425	14
L40N512	9476	3036	706	14

**Note.**  $N_{\text{gal}}$  is the number of galaxies in each galaxy stellar mass range.

**Table 1**  
List of Numerical Simulations

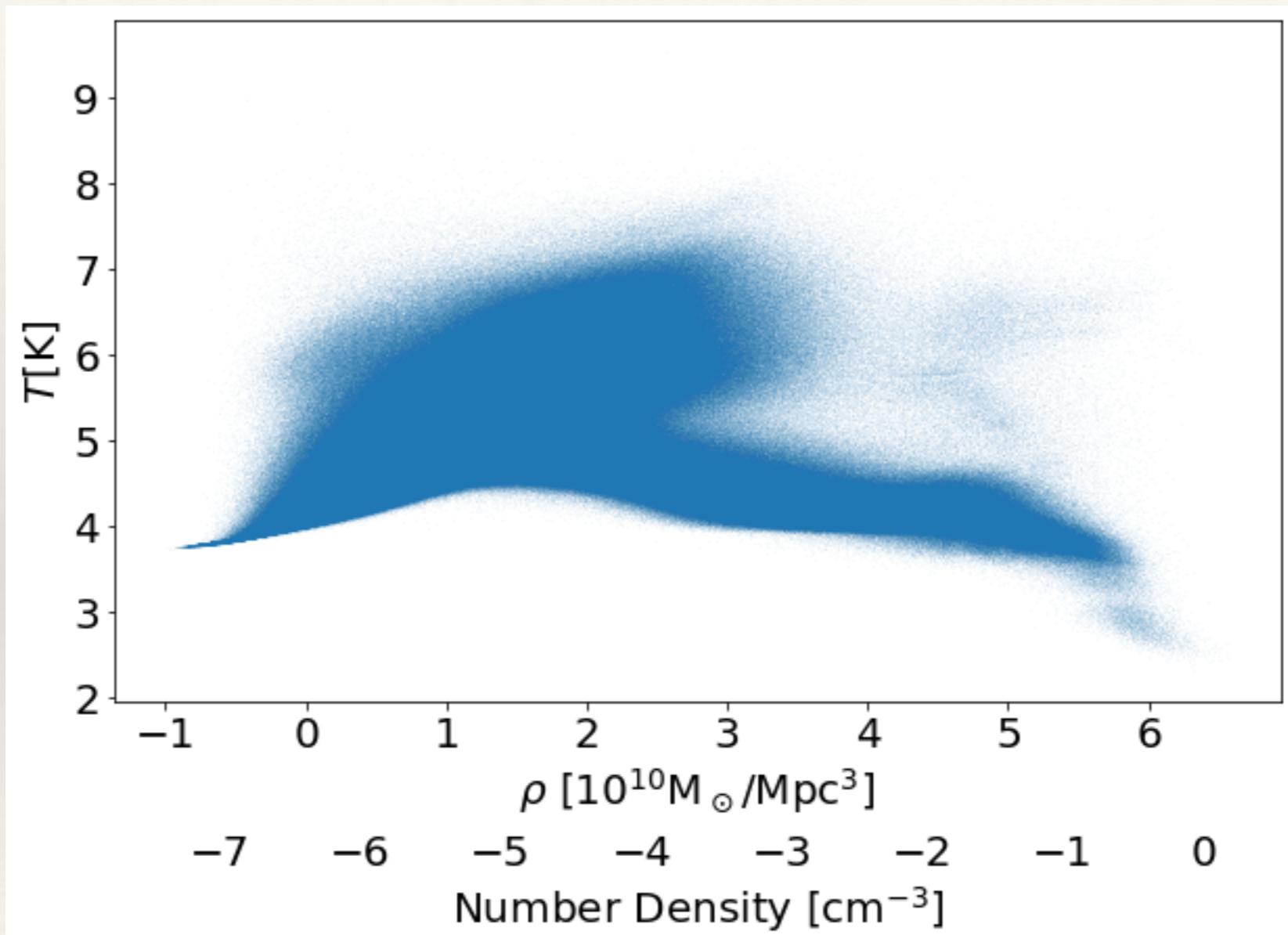
Model	Notes
Osaka20-Fiducial	No self-shielding
Osaka20-Shield	With self-shielding
Osaka20-NoFB	No SN feedback
Osaka20-CW	Constant-velocity galactic wind model <sup>a</sup>
Osaka20-FG09	UVB model of FG09 <sup>b</sup>

# Bolton+17, Sherwood simulation

**Table 1.** Summary of the Sherwood simulation suite. The models analysed in this work are listed in the upper part of the table. The naming convention in the first column,  $L\text{-}N\text{-}param$ , encodes the box size,  $L$ , in  $\text{h}^{-1}$  cMpc, the cube root,  $N$ , of the gas particle number and any parameters which have been varied from the reference run (40-2048). These are: *wdm* – warm dark matter consisting of a 3.5 keV thermal relic (Viel et al. 2013a); *zr9* – rapid reionization beginning at  $z_r = 9$  (cf.  $z_r = 15$  for the reference model); *ps13* – models including a sub-resolution treatment for star formation and galactic outflows (Puchwein & Springel 2013); *ps13+agn* – as for *ps13* but with the addition of AGN feedback. Subsequent columns list the dark matter and gas particle masses in  $\text{h}^{-1} \text{M}_\odot$ , the gravitational softening length in comoving  $\text{h}^{-1}$  kpc, the final redshift,  $z_{\text{end}}$ , of the simulation, the choice of random seed for the initial conditions and comments on each model.

Name	$M_{\text{dm}}$ ( $\text{h}^{-1} \text{M}_\odot$ )	$M_{\text{gas}}$ ( $\text{h}^{-1} \text{M}_\odot$ )	$l_{\text{soft}}$ ( $\text{h}^{-1}$ ckpc)	$z_{\text{end}}$	Seed	Comments
40-2048	$5.37 \times 10^5$	$9.97 \times 10^4$	0.78	2	A	Reference model
40-2048-wdm	$5.37 \times 10^5$	$9.97 \times 10^4$	0.78	2	A	Warm dark matter, 3.5 keV thermal relic
40-2048-zr9	$5.37 \times 10^5$	$9.97 \times 10^4$	0.78	2	A	Ionizing background at $z \leq 9$ only
80-2048	$4.30 \times 10^6$	$7.97 \times 10^5$	1.56	2	B	
40-1024	$4.30 \times 10^6$	$7.97 \times 10^5$	1.56	2	A	
40-1024-ps13	$4.30 \times 10^6$	$7.97 \times 10^5$	1.56	2	A	Puchwein & Springel (2013) winds
20-512	$4.30 \times 10^6$	$7.97 \times 10^5$	1.56	2	C	
40-512	$3.44 \times 10^7$	$6.38 \times 10^6$	3.13	0	A	
40-2048-ps13	$5.37 \times 10^5$	$9.97 \times 10^4$	0.78	5.2	A	Puchwein & Springel (2013) winds
20-1024	$5.37 \times 10^5$	$9.97 \times 10^4$	0.78	2	C	
10-512	$5.37 \times 10^5$	$9.97 \times 10^4$	0.78	2	A	
160-2048	$3.44 \times 10^7$	$6.38 \times 10^6$	3.13	2	C	
80-1024	$3.44 \times 10^7$	$6.38 \times 10^6$	3.13	0	B	
20-256	$3.44 \times 10^7$	$6.38 \times 10^6$	3.13	0	C	
160-1024	$2.75 \times 10^8$	$5.10 \times 10^7$	6.25	2	C	
80-512	$2.75 \times 10^8$	$5.10 \times 10^7$	6.25	0	B	
80-512-ps13	$2.75 \times 10^8$	$5.10 \times 10^7$	6.25	0	B	Puchwein & Springel (2013) winds
80-512-ps13+agn	$2.75 \times 10^8$	$5.10 \times 10^7$	6.25	0	B	Puchwein & Springel (2013) winds and AGN
160-512	$2.20 \times 10^9$	$4.08 \times 10^8$	12.50	2	C	
80-256	$2.20 \times 10^9$	$4.08 \times 10^8$	12.50	0	B	

# $\rho$ – $T$ relation



zero. The quantity that reflects the relative amount by which the Ly $\alpha$  absorption fluctuates when the mass or the peculiar velocity gradient fluctuate is obtained from the fluctuation of an effective optical depth,  $\tau_e = -\log \bar{F}$  (where  $\bar{F}$  has been averaged over a large, linear scale before taking the logarithm), which has a relative fluctuation  $\delta_\tau = \delta_F / \log \bar{F} = -\delta_F / \tau_e$ . The bias factors for this effective optical depth fluctuation are:

$$b_{\tau\delta} = \frac{\partial \delta_\tau}{\partial \delta} = \frac{b_{F\delta}}{\log \bar{F}}, \quad b_{\tau\eta} = \frac{\partial \delta_\tau}{\partial \eta} = \frac{b_{F\eta}}{\log \bar{F}}. \quad (2.4)$$

adjust the mean transmission  $\bar{F}(z)$  to a certain value. The mean transmission fraction is fixed to the value given by the expression

$$\bar{F}(z) = \exp [-0.0023(1+z)^{3.65}], \quad (3.1)$$

which was found to adequately fit the observational data of high-resolution spectra by [31],  
Kim et al. 2007

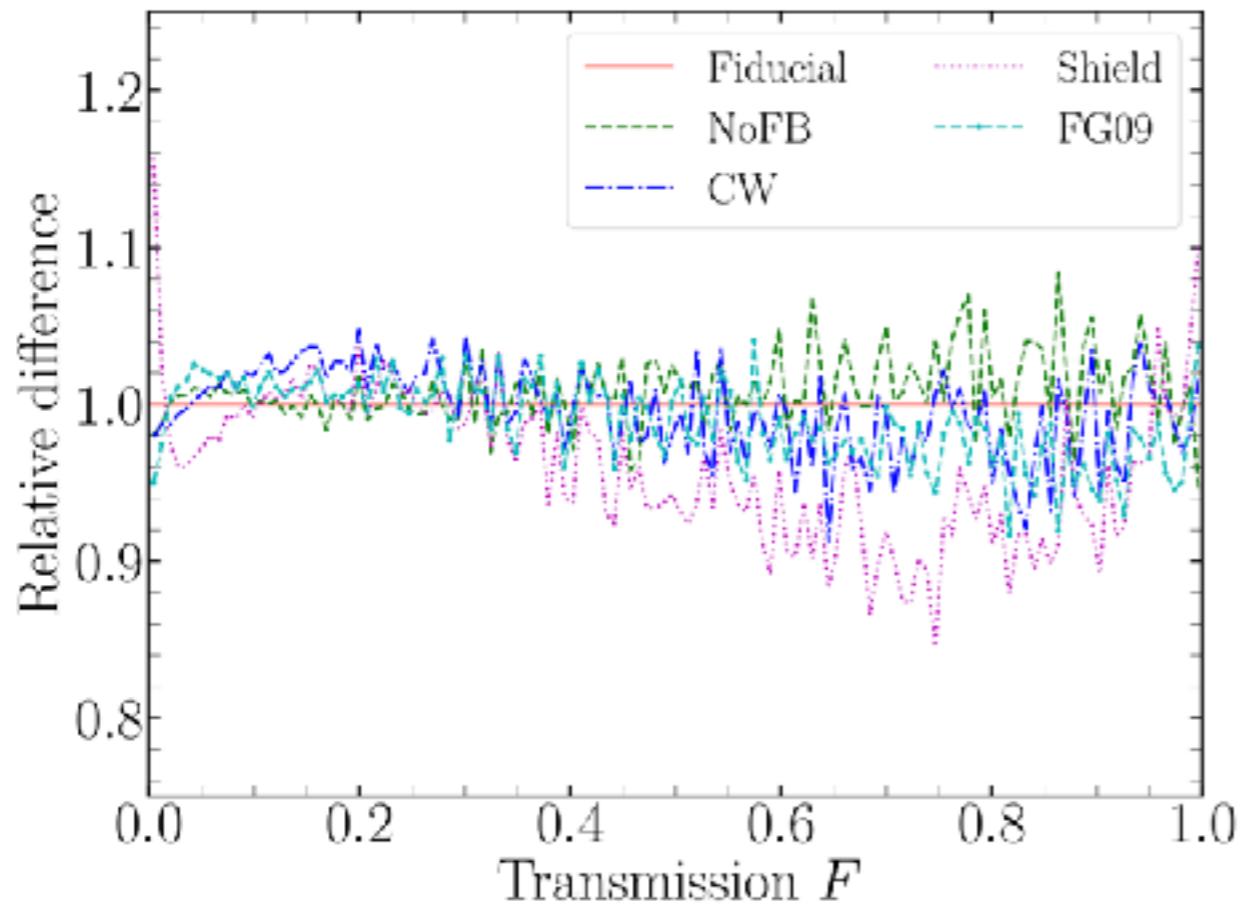
The Ly $\alpha$  transmission power spectrum obtained from the simulations will be fitted to the following analytic model:

$$P_F(k, \mu) = b_{F\delta}^2 (1 + \beta \mu^2)^2 P_L(k) D(k, \mu). \quad (3.3)$$

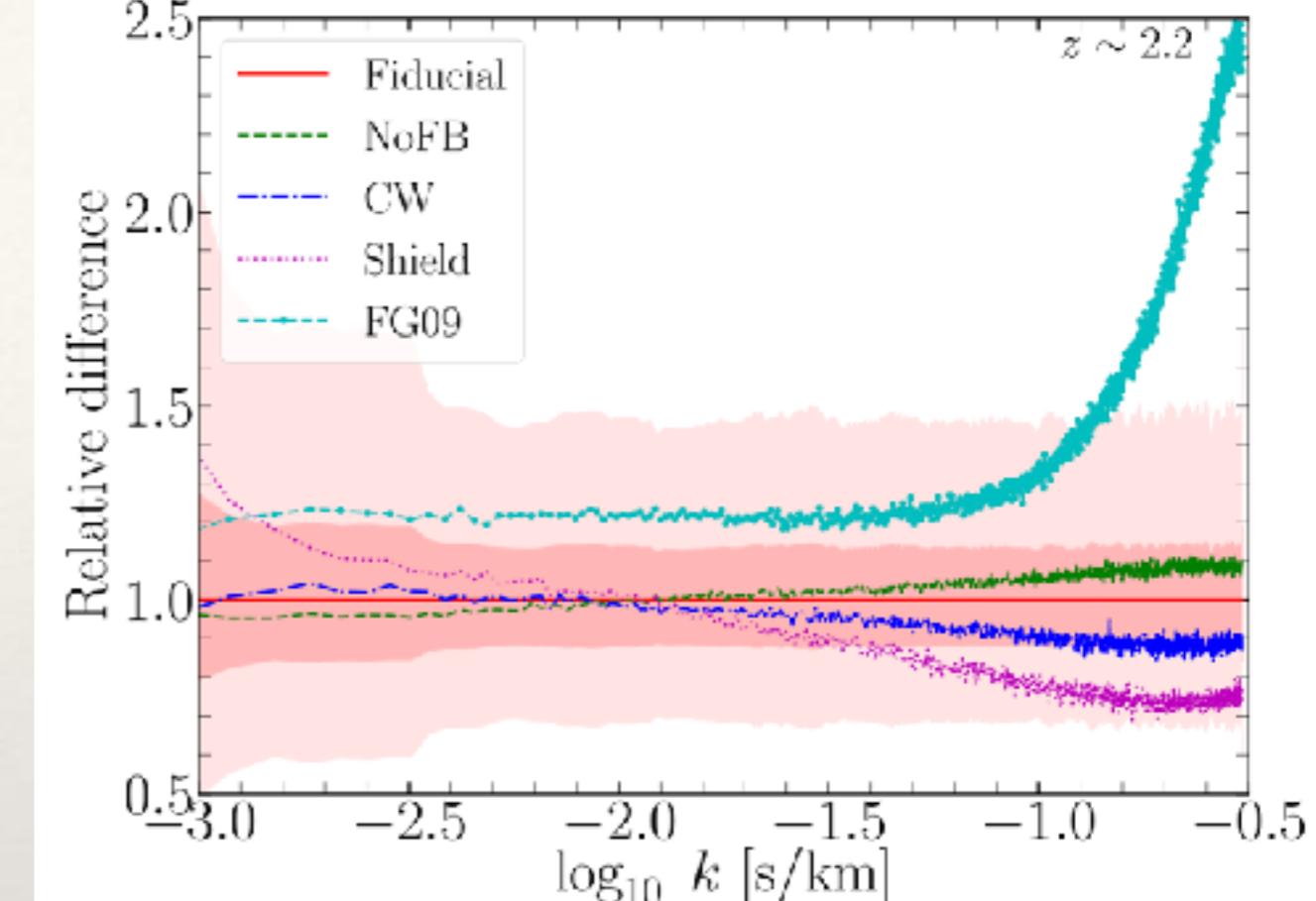
$z$	$\beta$	$b_{\tau\delta}$	$b_{\tau\eta}$
<b>Fiducial</b>			
3.0	$1.205 \pm 0.049$	$0.5546 \pm 0.0086$	$0.681 \pm 0.028$

KN+21

PDF



Power



**Table 2**  
Subaru PFS IGM Tomography Targets

Target Class	Redshift Range	Selection	Exposure Time (hr)	Targeted Objects (Useful Spectra)	Number/PFS FOV ( $1.25 \text{ deg}^2$ )
IGM background (bright)	2.5–3.5	$y < 24.3, g < 24.2$	6	8300 (5810)	690
IGM background (faint)	2.5–3.5	$y < 24.3, 24.2 < g < 24.7$	12	14,000 (9800)	1170
IGM foreground	2.1–2.6	$y < 24.3$	6	22,000 (15,400)	1830

# Feedback effect

SN feedback

## GALACTIC WINDS IN THE INTERGALACTIC MEDIUM<sup>1</sup>

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### ABSTRACT

We have performed hydrodynamical simulations to investigate the effects of galactic winds on the high-redshift ( $z = 3$ ) universe. Strong winds suppress the formation of low-mass galaxies significantly, and the metals carried by them produce C IV absorption lines with properties in reasonable agreement with observations. The winds have little effect on the statistics of the H I absorption lines, because the hot gas bubbles blown by the winds fill only a small fraction of the volume and because they tend to escape into the voids, thereby leaving the filaments that produce these lines intact.