RSD analysis with Lyman alpha forest on nonlinear scales

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Outline

Introduction

- Lyα forest & IGM tomography

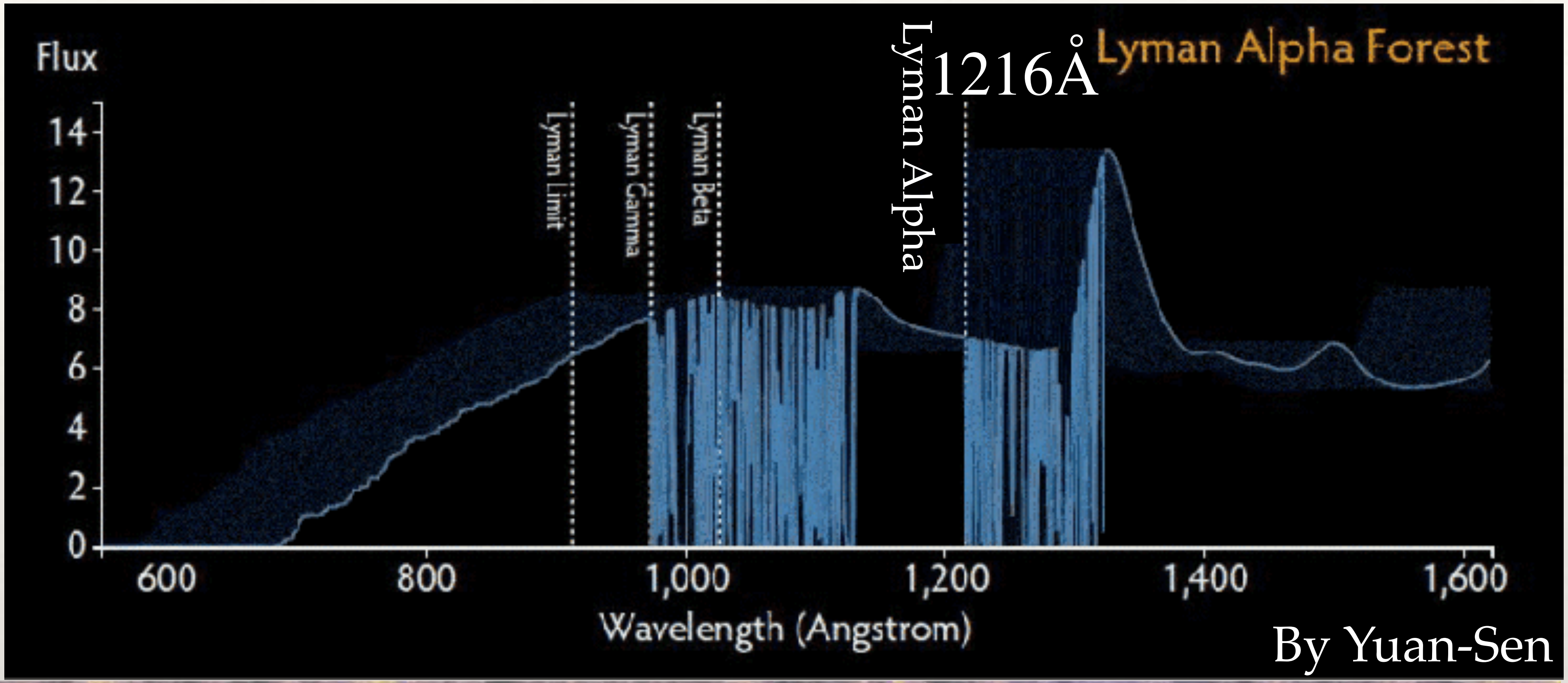
Lyα forest × Large Scale Structure

- Redshift Space Distortions (RSD) analysis
- Lyα forest on nonlinear scales

RSD analysis with 3D Lyα forest on nonlinear scales

- Mock generation : GADGET3-Osaka simulation
- PFS forecast & results

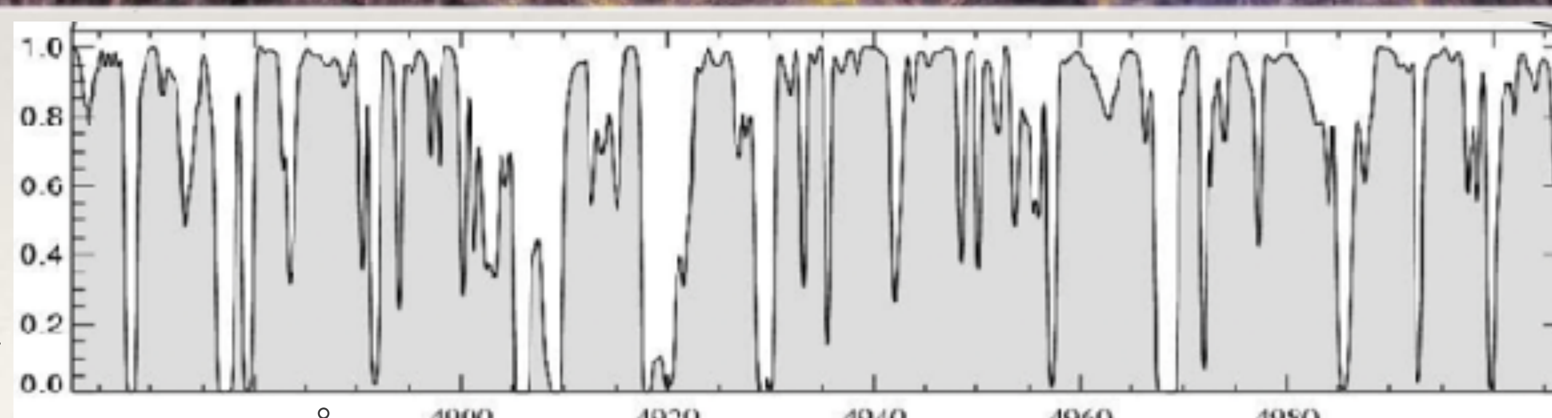
What is the LAF ?



to Earth

$F = \exp(-\tau)$

τ : optical depth



4880Å

$z_{\rm IGM} \sim 3.01$

Wavelength[Å]

5000Å

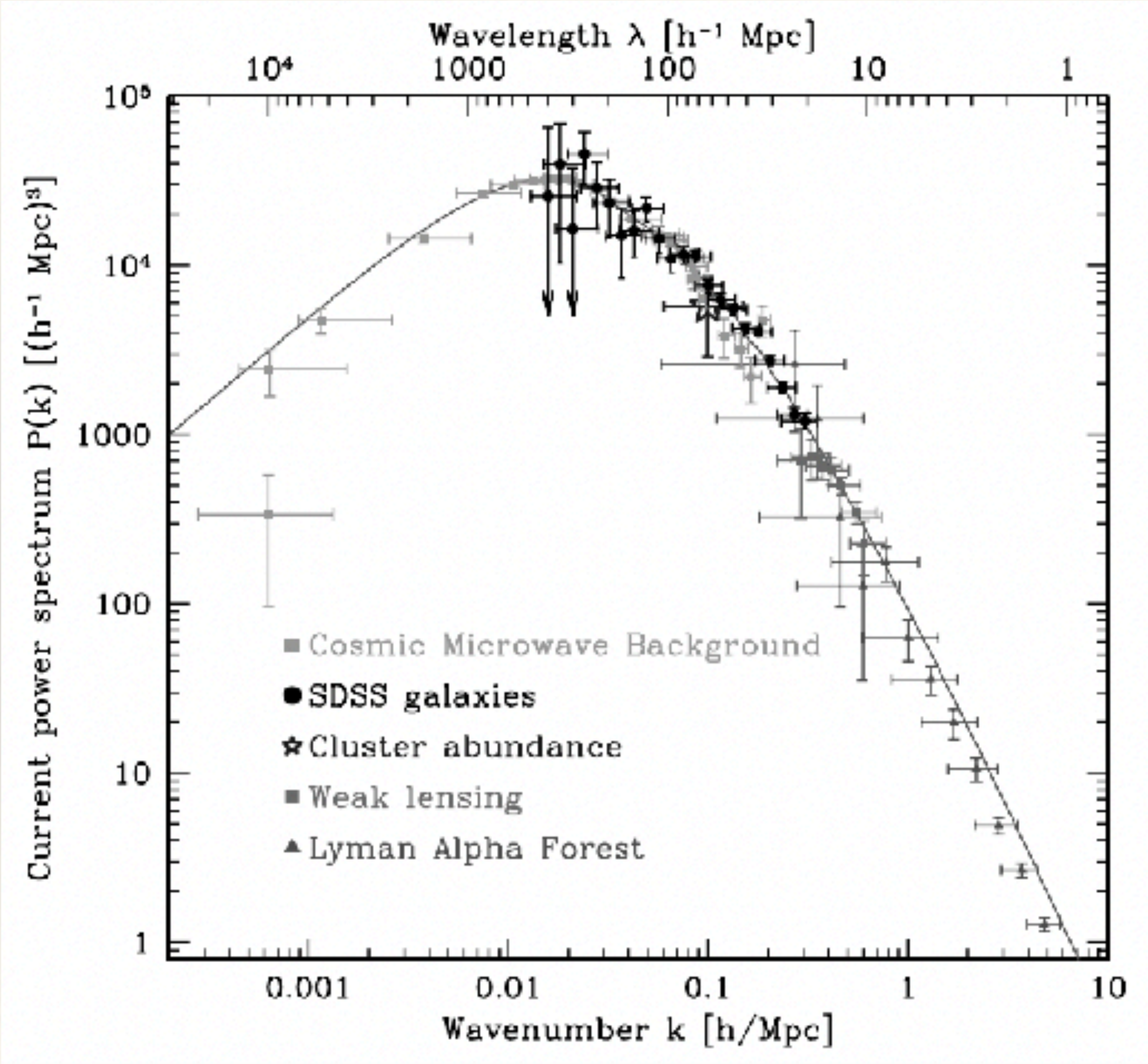
$z_{\rm IGM} \sim 3.11$

Quasar at $z \sim 3.62$

V. Springel+ '06

Cosmological constraint with LAF

⭐ Small scale structure $< 30\mathrm{Mpc}/h$



Tegmark+2004

- Dark Matter Model

  e.g. Viel+2013
  Irsic+2017

- Neutrino Mass

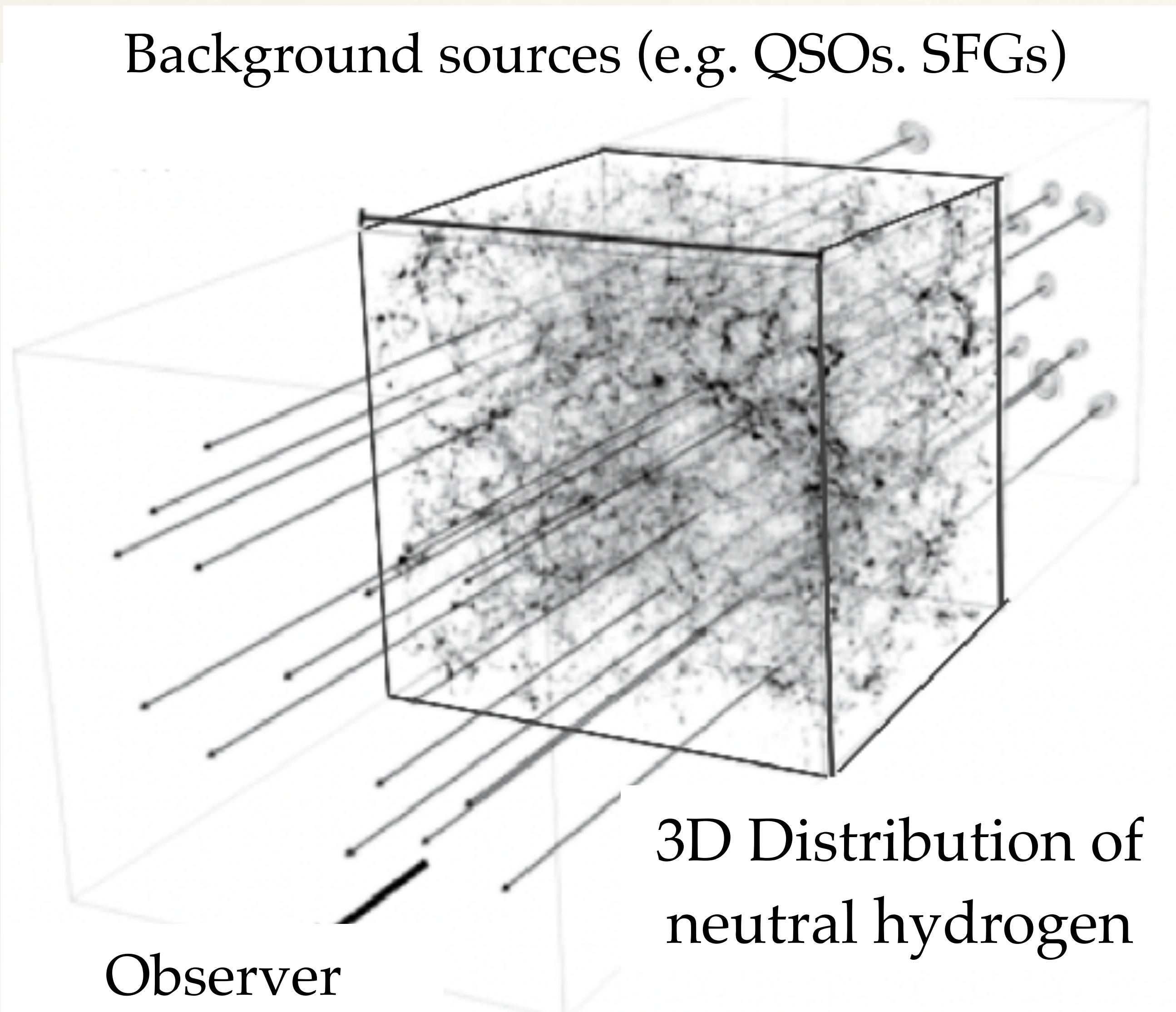
  e.g. Seljak+2006
  Delabrouille+2019

- Primordial Black Holes as Dark Matter

  e.g. Murgia+2019

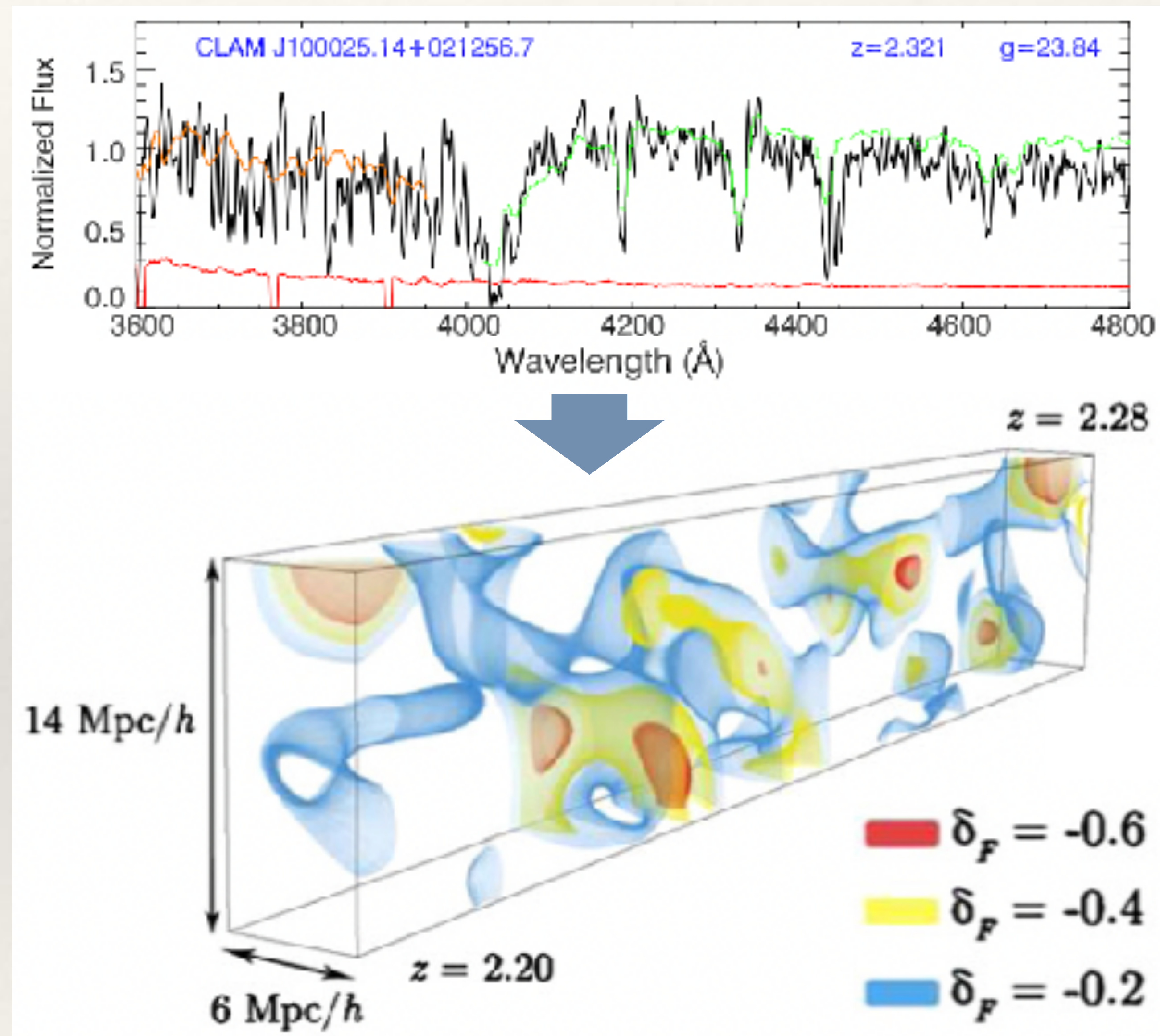
IGM tomography

3D Lyα forest absorption



Shimizu & Nagamine ; TMT JP Science Book 2020

Tomographic Reconstruction



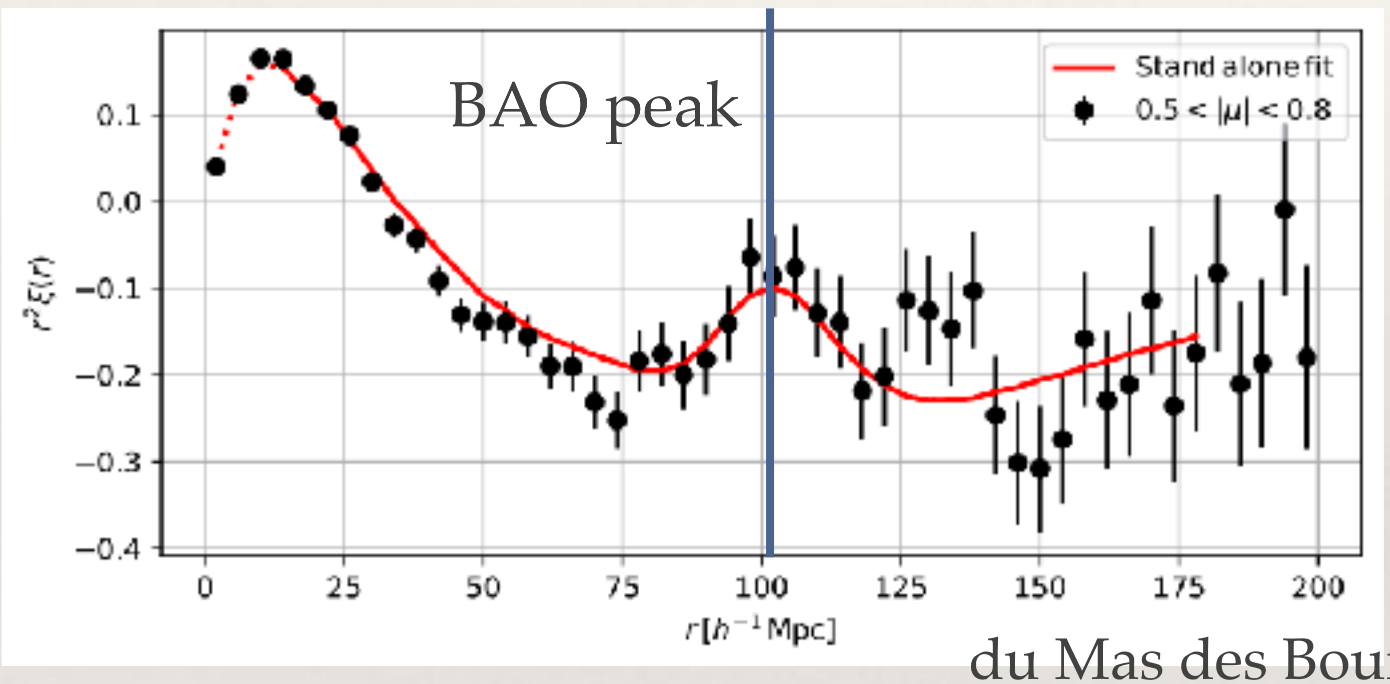
CLAMATO survey (Lee+ ’14)

Lyα 3D Power spectrum × LSS

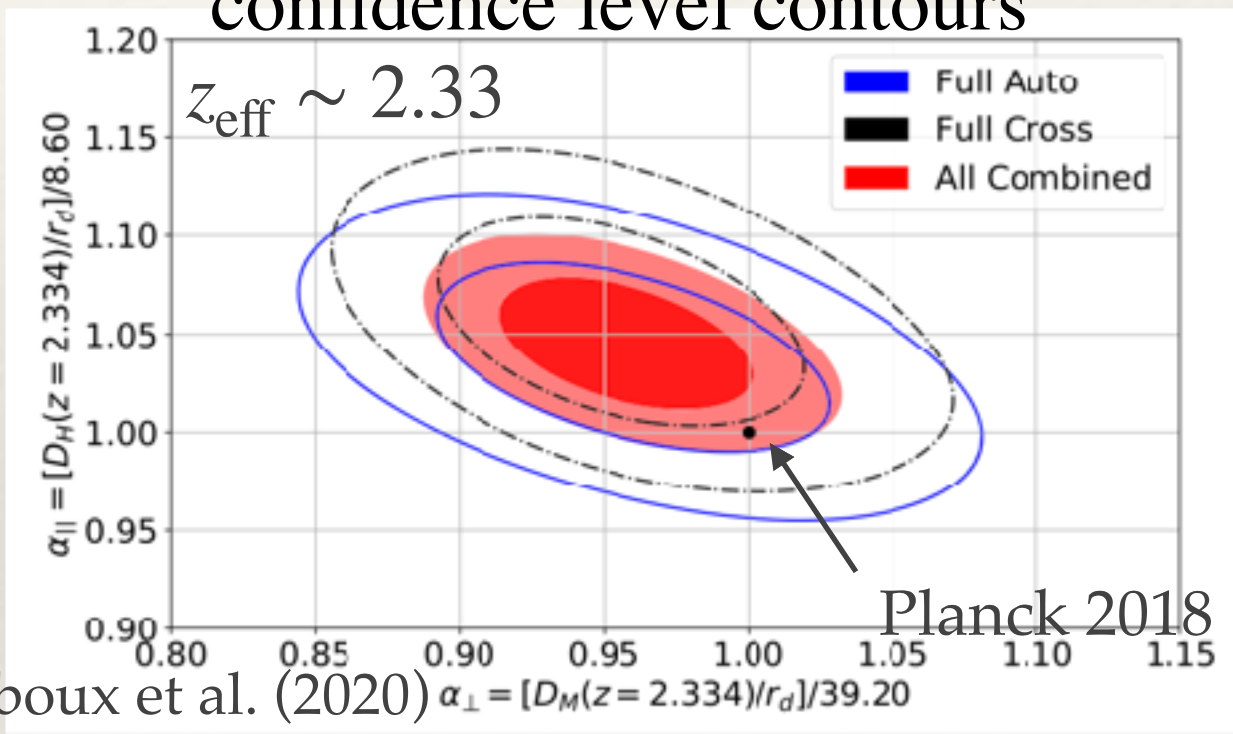
Baryon Acoustic Oscillation with the Lyα forest using BOSS, eBOSS data

e.g. Slosar+2011, Busca+2013, Delubac+2015, de Sainte Agathe+2019, …

Lyα correlation function



The 68% and 95% confidence level contours



du Mas des Bourboux et al. (2020)

$r_{\rm peak} \sim 100 h^{-1}{\rm Mpc}$ $\qquad$ $\alpha = r_{\rm peak}^{\rm obs} / r_{\rm peak}^{\rm fid}$

At $z \geq 2$, $n_{\rm galaxy}$ and $n_{\rm quasar}$ is insufficient for high-precision clustering measurements

⟶ BAO studies have been performed using Lyα forest instead

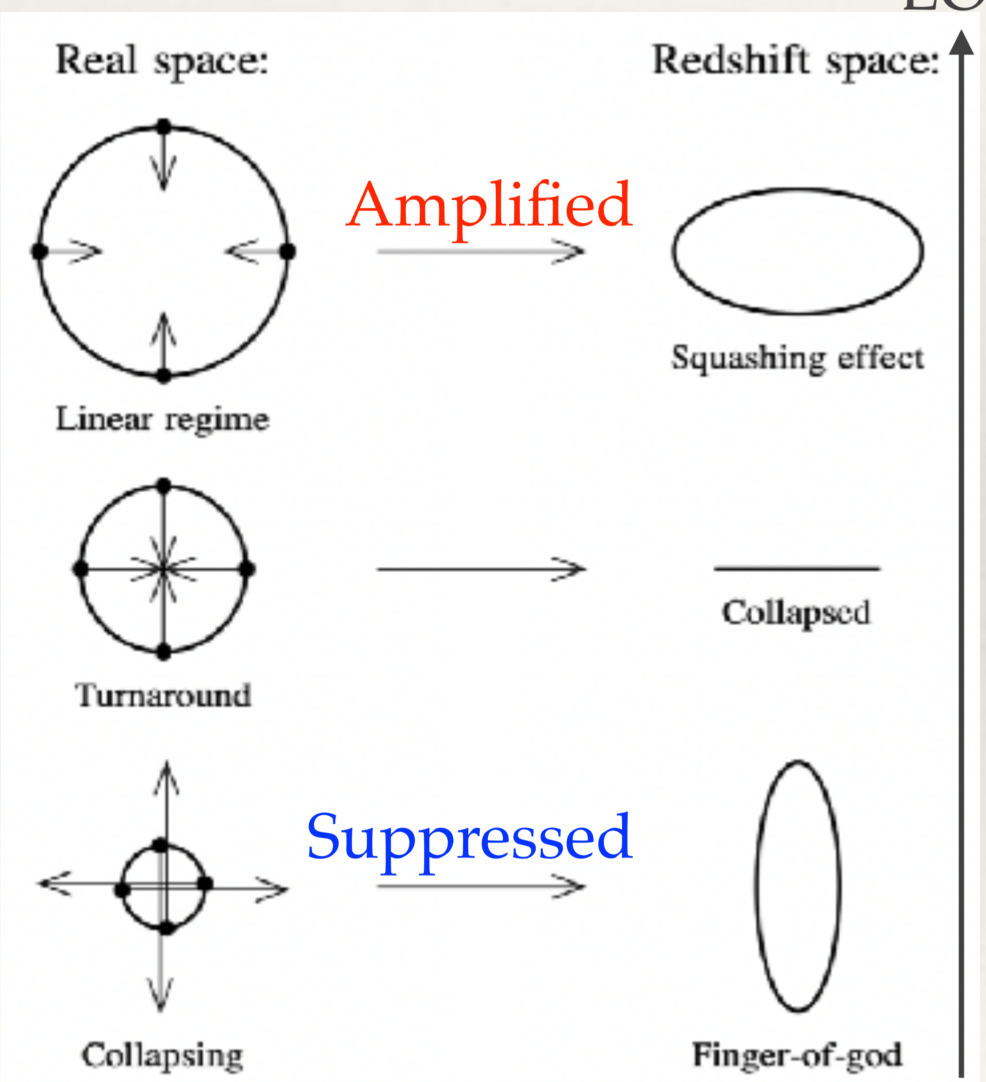
Redshift Space Distortions (RSD)

Linear model (Kaiser 1987)

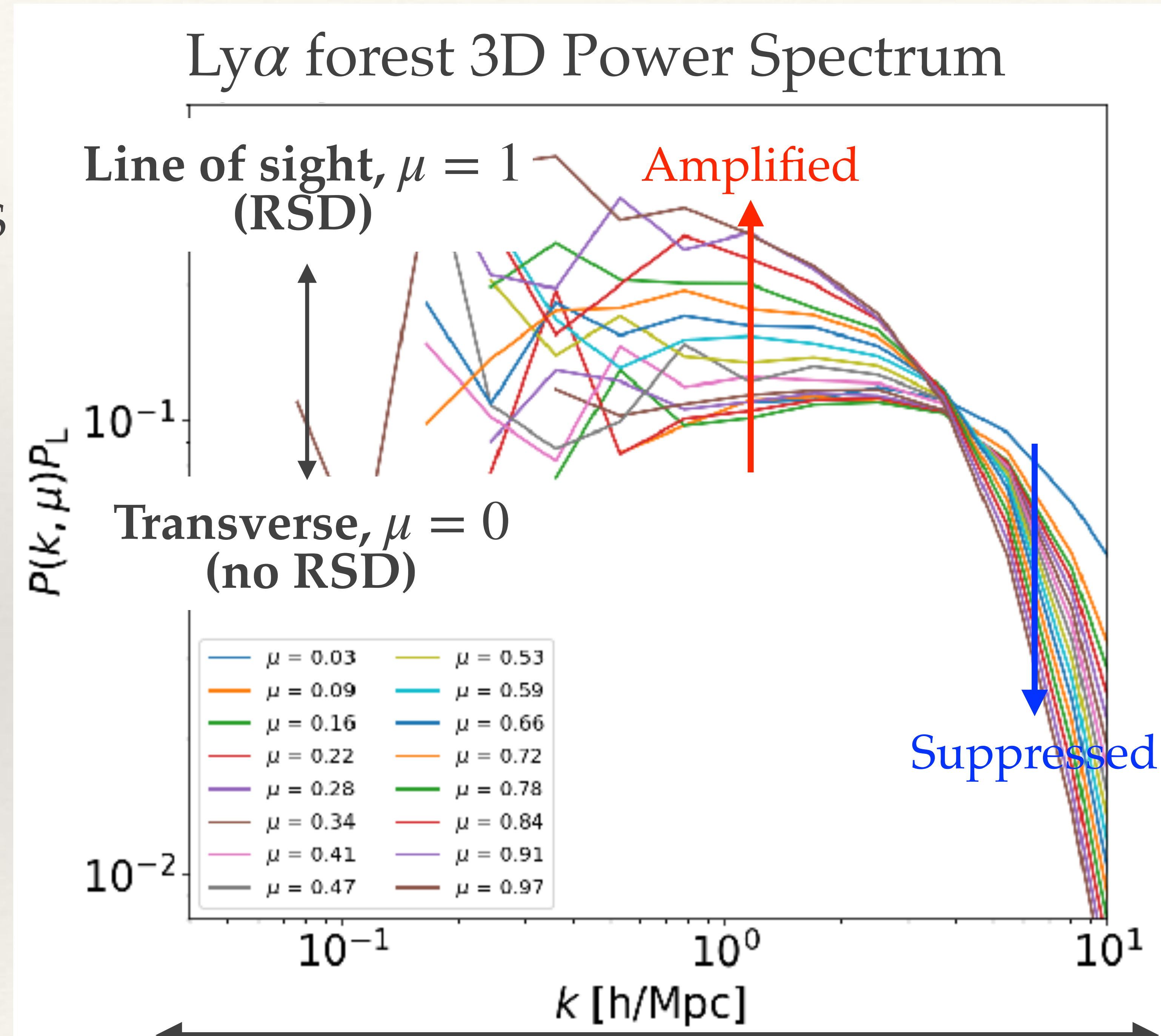
$$P_s(\mathbf{k}) = P_r(k)\underline{(1 + f\mu_{\mathbf{k}}^2)^2}$$

$$f = d\ln\delta / d\ln a$$

LOS



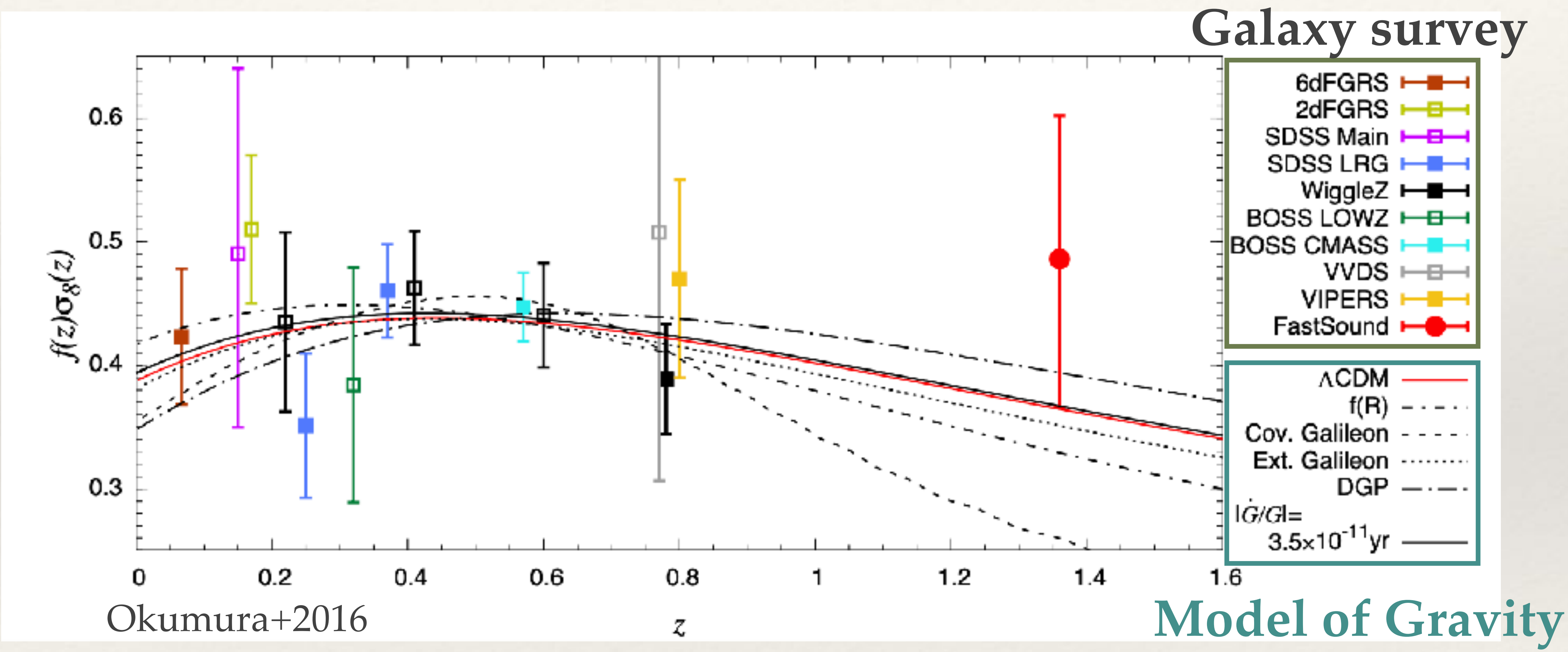
Hamilton (1997)



Large scale **Small scale**

$f\sigma_8$ constraints by galaxy surveys

- $f\sigma_8$ constraints can test Gravity Theories



In order to distinguish these models,
we should measure $f\sigma_8$ at $z > 2$

RSD analysis with Lyα forest

Lyα auto power spectrum

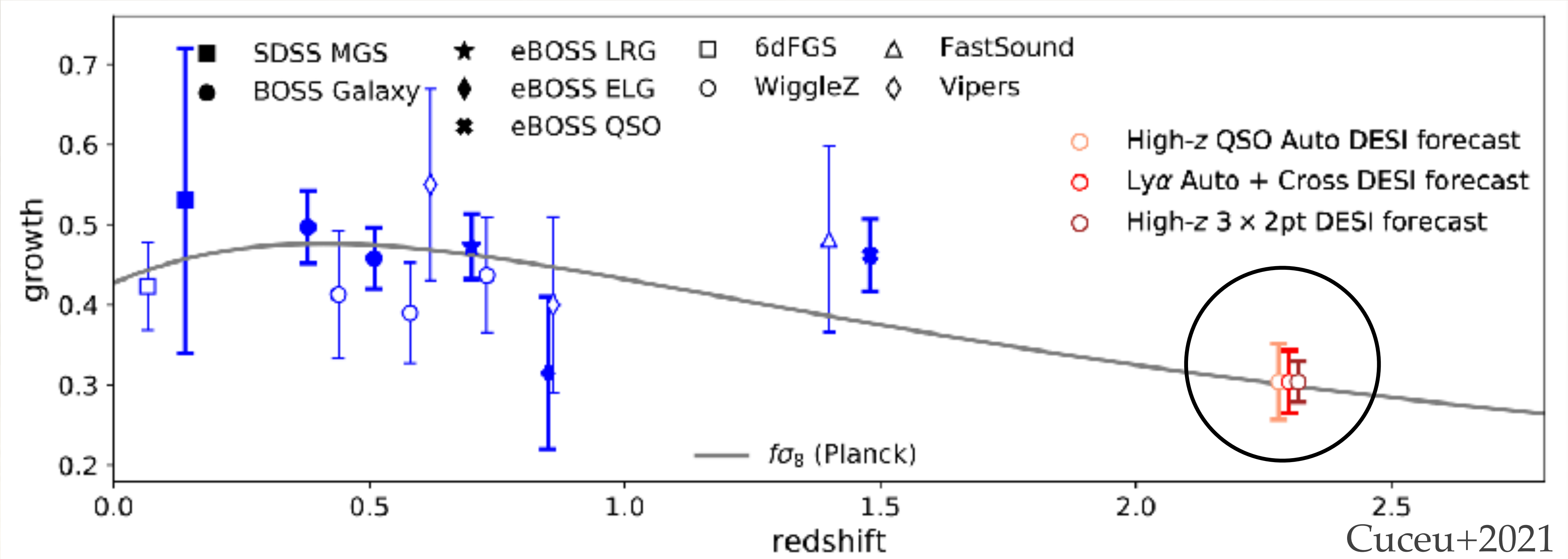
$$P_{\mathrm{F}}(k,\mu) = (b_{\mathrm{F}\delta} + b_{\mathrm{F}\eta} f \mu^2)^2 P_{\mathrm{Lin,fid}}(k) D_{\mathrm{NL}}$$

f degenerates with $b_{\mathrm{F}\eta}$! $\leftrightarrow F_{\mathrm{Ly}\alpha} = \exp[-\tau]$

Lyα-QSO cross power spectrum

$$P_{\times}(k,\mu) = (b_{\mathrm{F}\delta} + b_{\mathrm{F}\eta} f \mu^2) \times (b_{\mathrm{q}\delta} + f \mu^2)\ P_{\mathrm{Lin,fid}}(k) D_{\mathrm{NL}}$$

Cuceu+2021, Givans+2022, Gerardi+2022



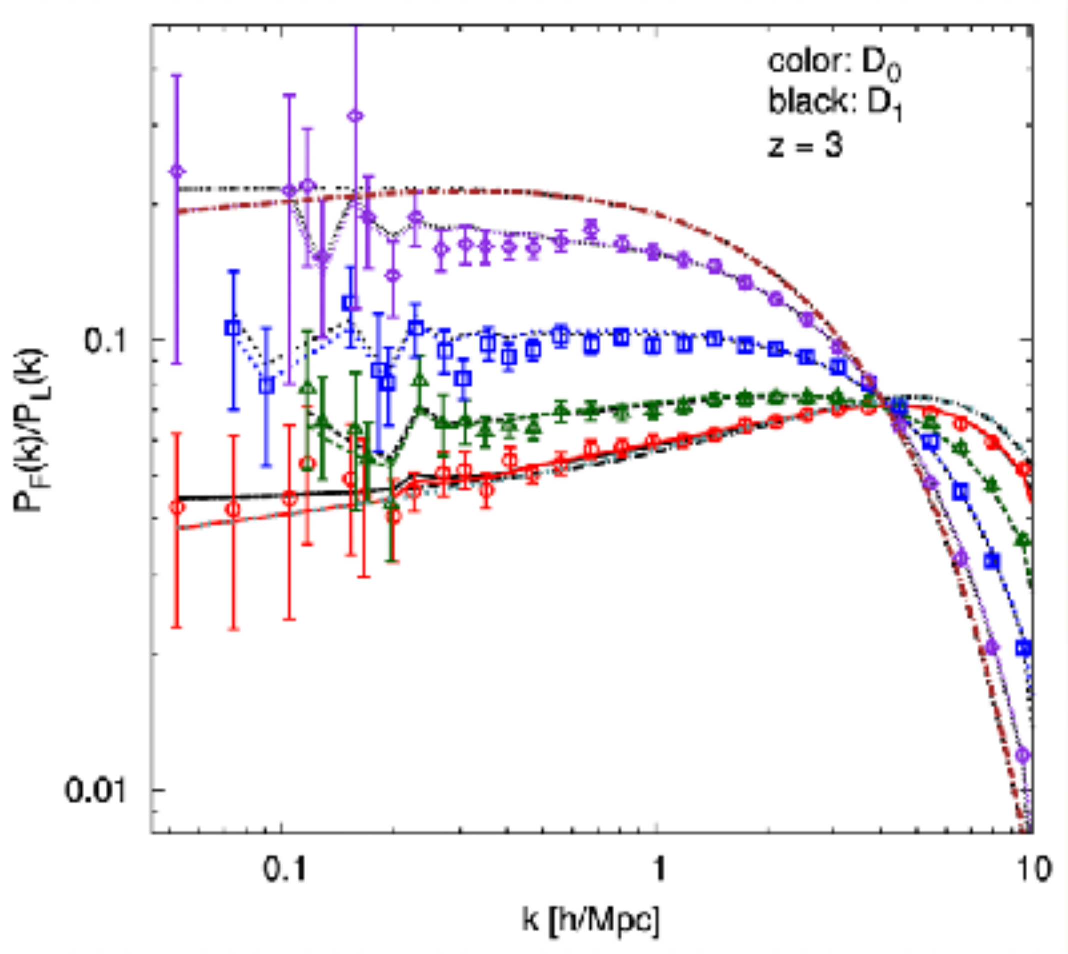
Cuceu+2021

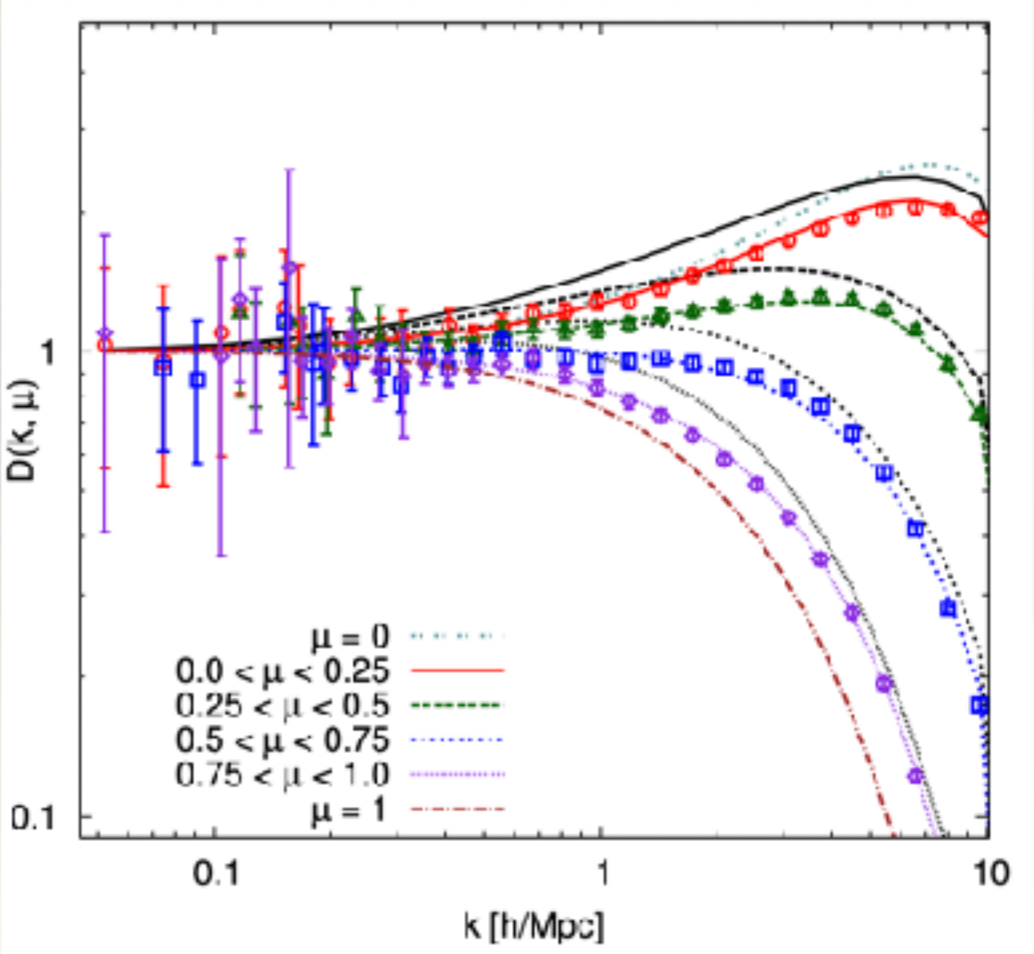
Non linearity on small scale

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

$$D_{NL}(k,\mu) = \exp\left\{ [q_1\Delta^2(k) + q2\Delta^4(k)] \left[1 - \left(\frac{k}{k_v}\right)^{a_v} \mu^{b_v}\right] - \left(\frac{k}{k_p}\right)^2 \right\}$$ Arinyo+ 2015

Non-linear enhancement **LOS broadening** **Jeans smoothing**





Simulation

Nagamine et al. (2021)

Probing Feedback via IGM tomography and the Lyα Forest with Subaru PFS, TMT/ELT, and JWST

Kentaro Nagamine[1,2,3], Ikkoh Shimizu[4], Katsumi Fujita[1], Nao Suzuki[2], Khee-Gan Lee[2], Rieko Momose[5], Shiro Mukae[5,6], Yongming Liang[5,7], Nobunari Kashikawa[5], Masami Ouchi[5,6,7], and John D. Silverman[2]

[1] 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

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

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

- 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)

Subaru PFS Forecast

We assumed Subaru Prime Focus Spectrograph (2024 -)

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^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

Nagamine+2021

Survey Area : $A \sim 15\ \mathrm{deg}^2$

Survey Volume : $V \sim 4 \times 10^7\ (\mathrm{cMpc/h})^3$

Background Sources : $\mathrm{Number}/1.25\ \mathrm{deg}^2 \sim 1800$

Spectral Resolution : $R \equiv \lambda/\Delta\lambda \sim 2000 - 4000 \rightarrow \Delta\lambda \sim 2.5\ \mathrm{\AA}$

Foreground Galaxy : $n_{\mathrm{halo}}(M > 10^{11} M_\odot) \sim 500\ /(100 h^{-1}\mathrm{Mpc})^3$

We used the halo catalog instead of galaxy

Results

Joint analysis of 3×2pt (Lyα auto, Lyα-Halo cross, Halo auto)

$$P_{\mathrm{F}}(k,\mu) = (b_{\mathrm{F}\delta} + b_{\mathrm{F}\eta} f\,\mu^2)^2 P_{\mathrm{Lin,fid}}(k) D_{\mathrm{NL}}$$

Arinyo+2015

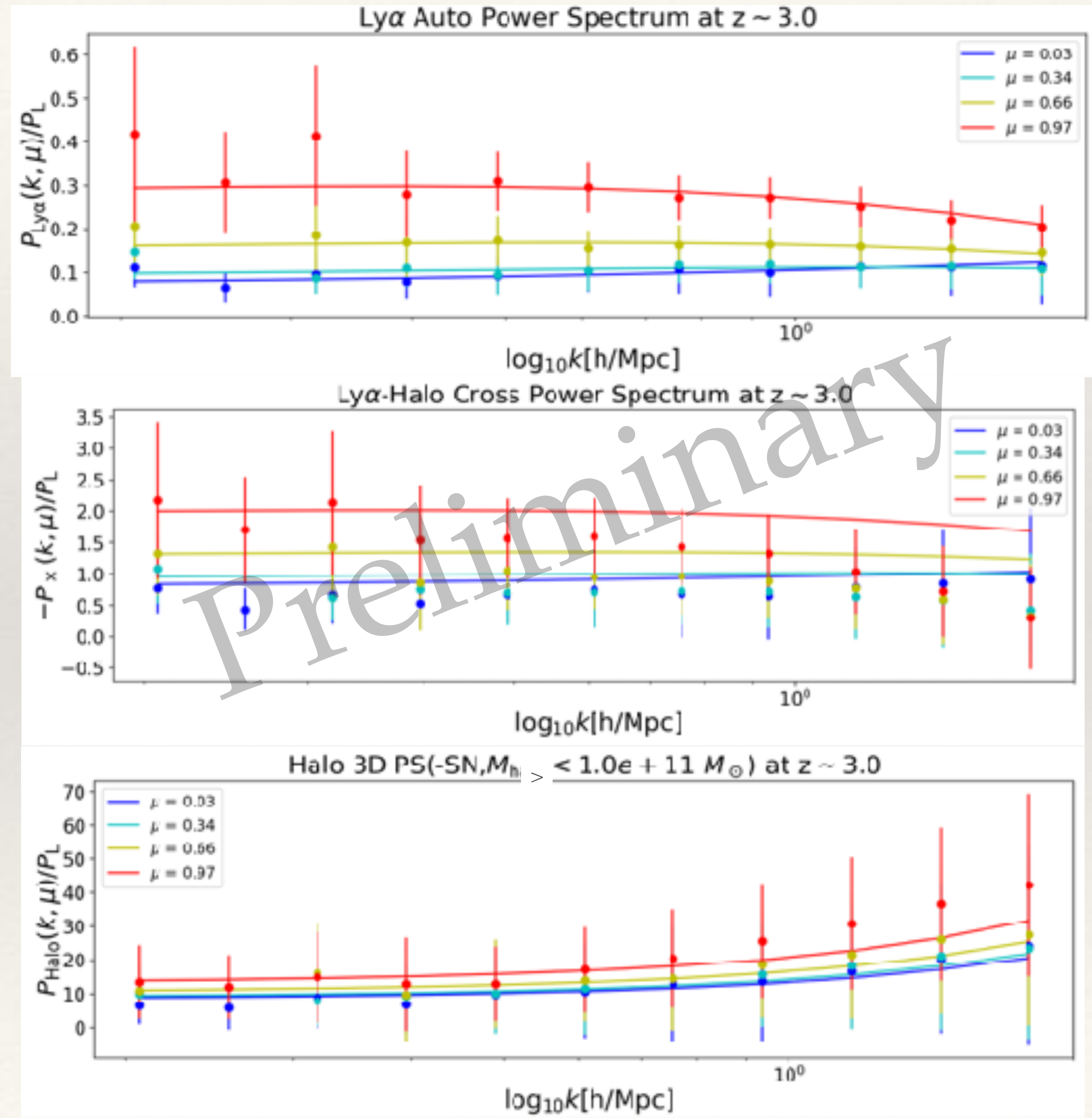
$$P_{\times}(k,\mu) = (b_{\mathrm{F}\delta} + b_{\mathrm{F}\eta} f\,\mu^2) \times (b_{\mathrm{q}\delta} + f\,\mu^2)\, P_{\mathrm{Lin,fid}}(k)\sqrt{D_{\mathrm{NL}} D_{\mathrm{FoG}}}$$

Givans+2022

$$D_{\mathrm{FoG}}(k\mu\sigma_v) = \left[1 + (k\mu\sigma_v)^2\right]^{-1}$$

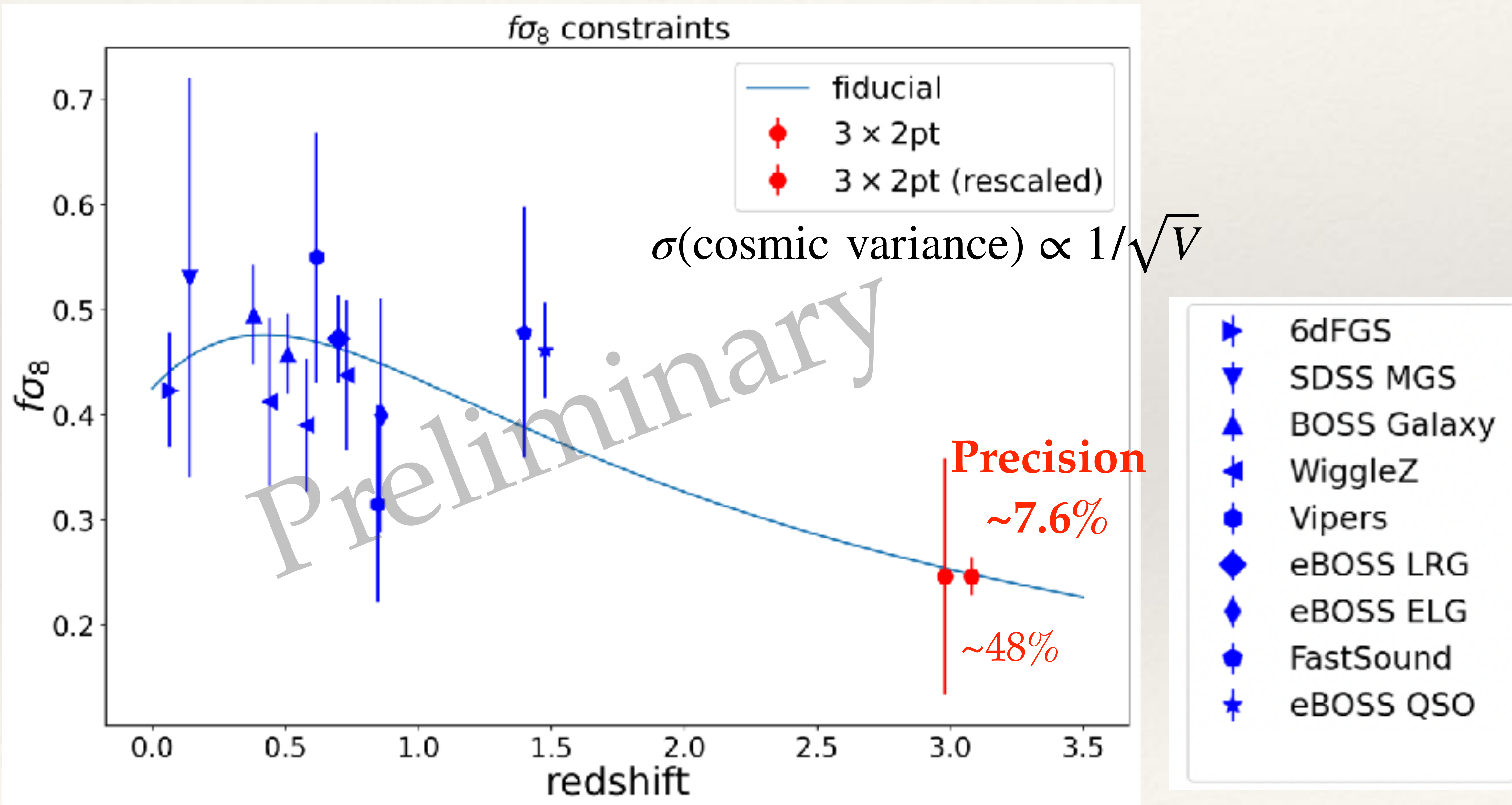
$$P_{\mathrm{halo}}(k,\mu) = (b_{\mathrm{h}\delta} + f\mu^2)^2 P_{\delta\delta}(k) D_{\mathrm{FoG}}(k\mu\sigma_v)$$

Okumura+2015



Discussion

Mocks from 1 simulation box → $f\sigma_8 \sim 0.248 \pm 0.120$ at $z \sim 3.0$



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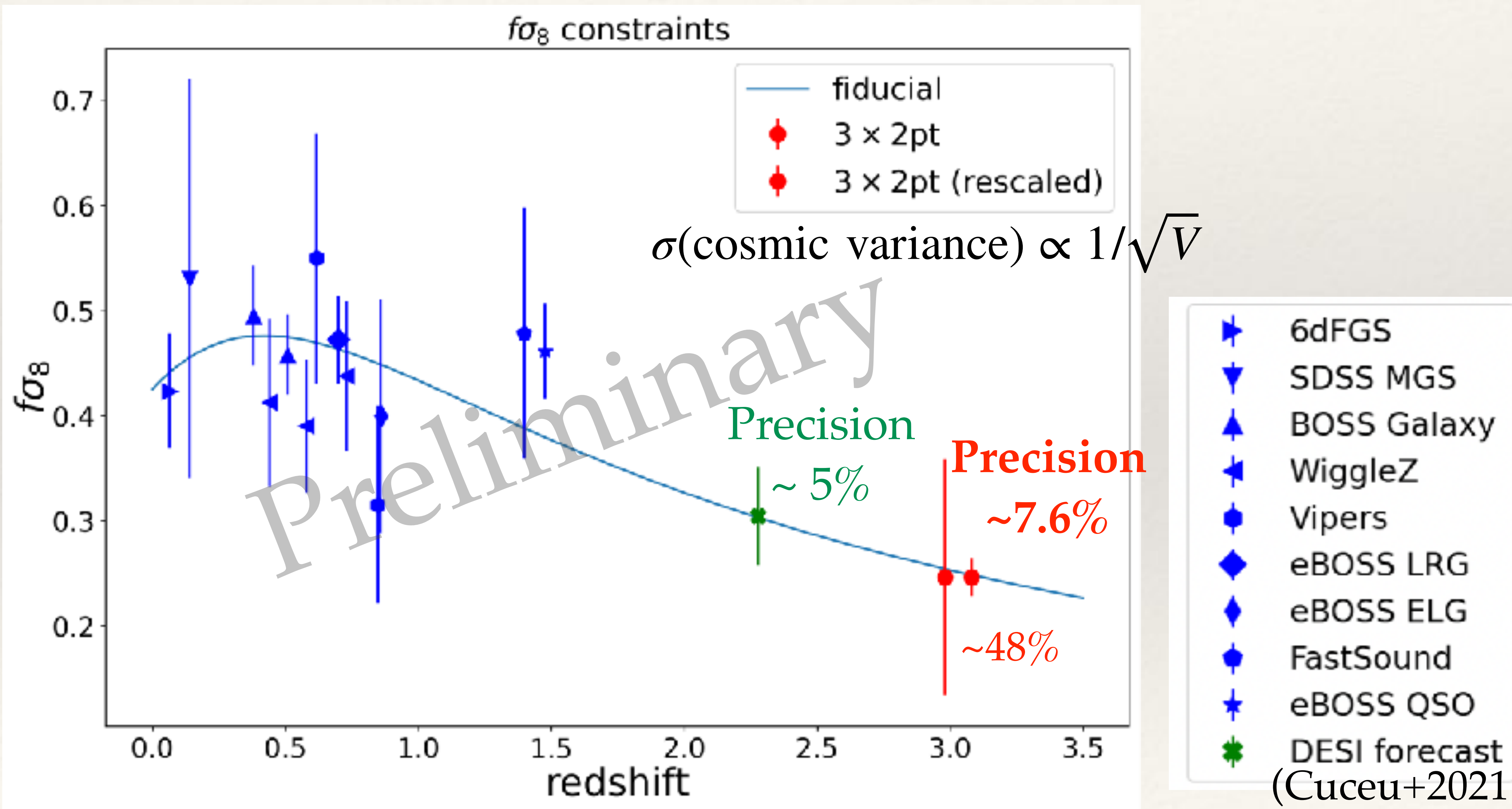


Summary

The advantages of Lyα forest for cosmological analysis

- ⭐ High-z universe over a wide range ($z > 2$)

RSD analysis with 3D Lyα forest on NL scales

- Simulation : GADGET3-Osaka (Nagamine+`21)

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

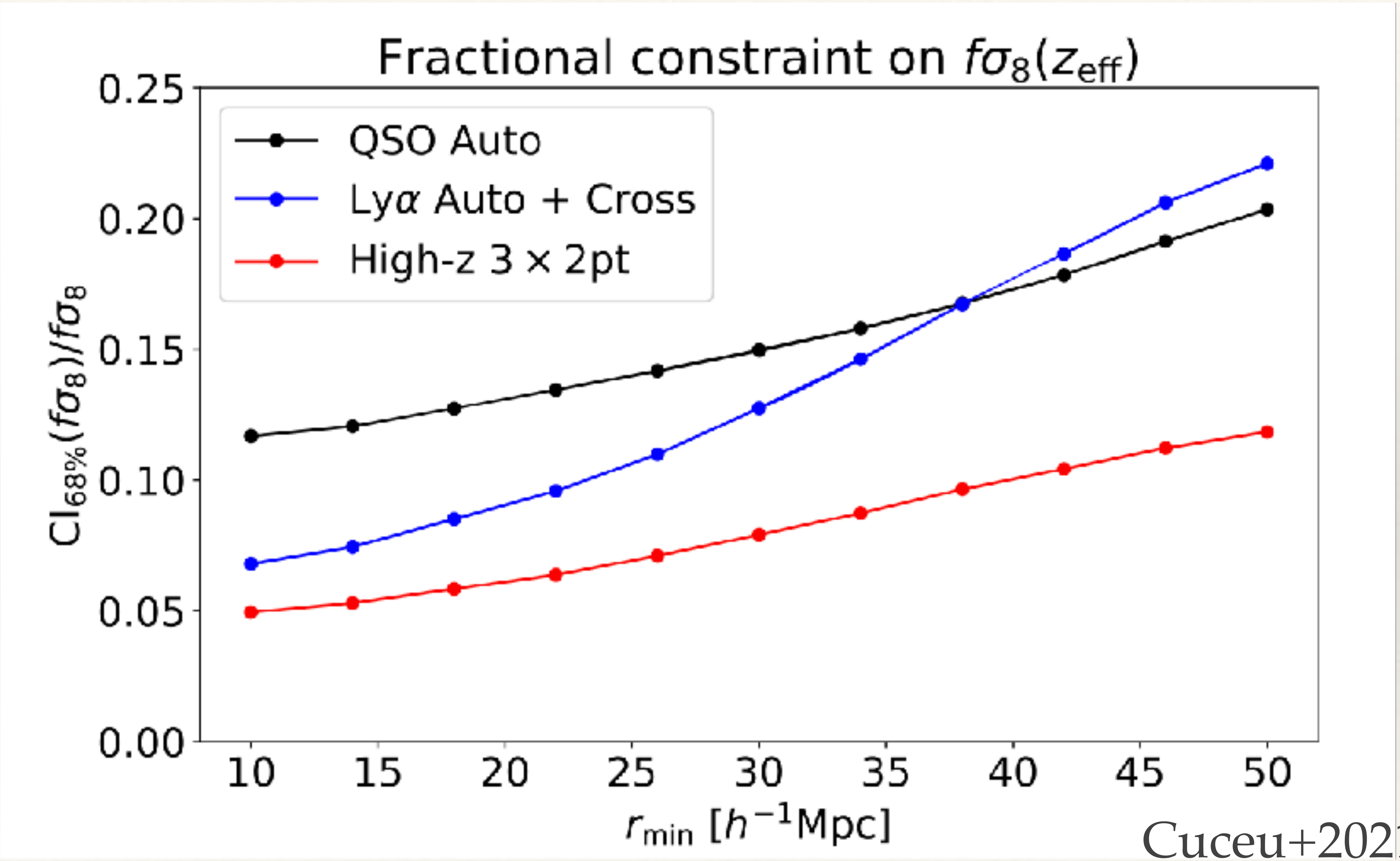
- Forecast : Subaru PFS (2024 -)

- Result : joint analysis of 3×2pt

$$f\sigma_8 \sim 0.248 \pm 0.120(0.023) \text{ at } z \sim 3.0$$

is consistent with assumed cosmological parameter

Tight constraint on small scale

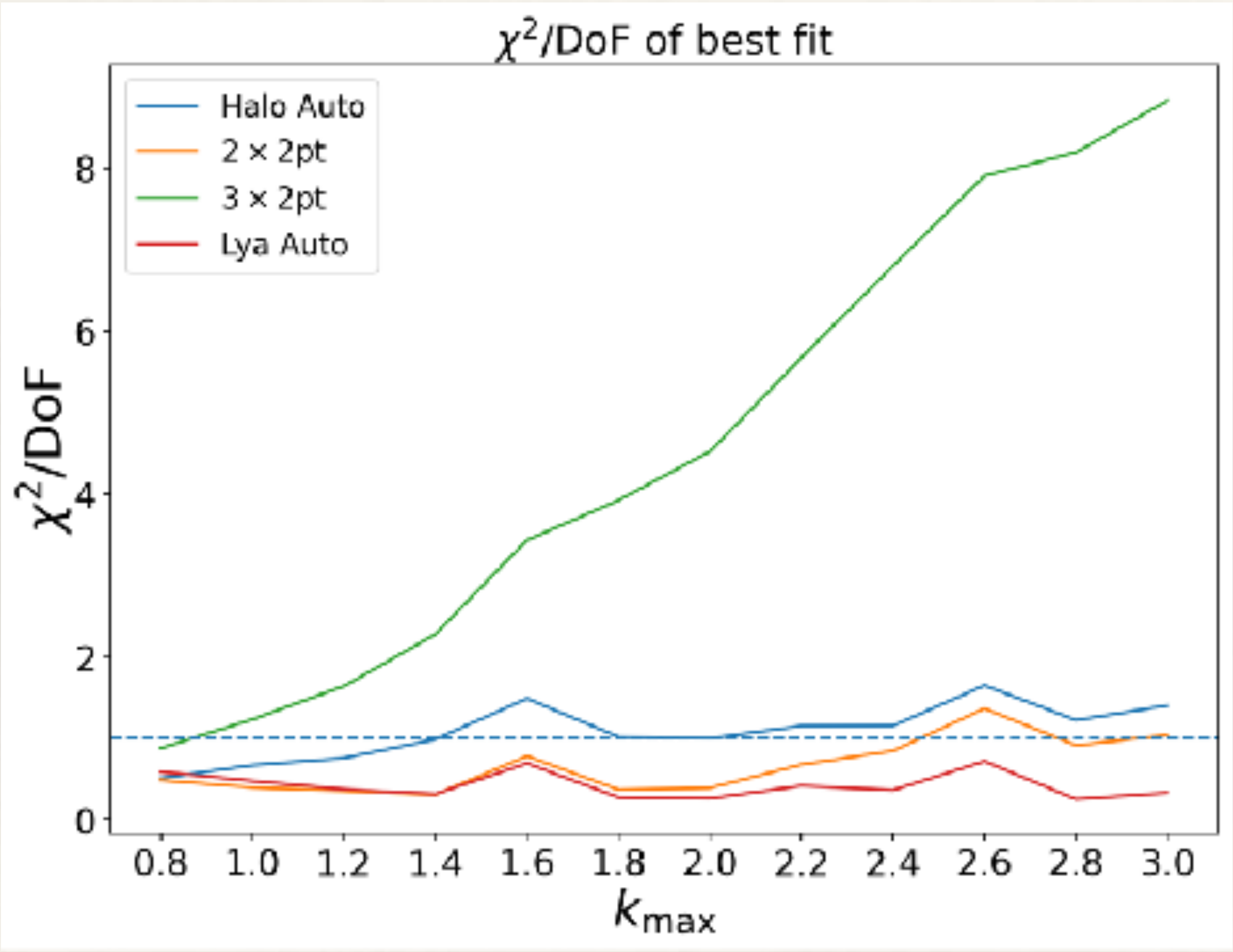


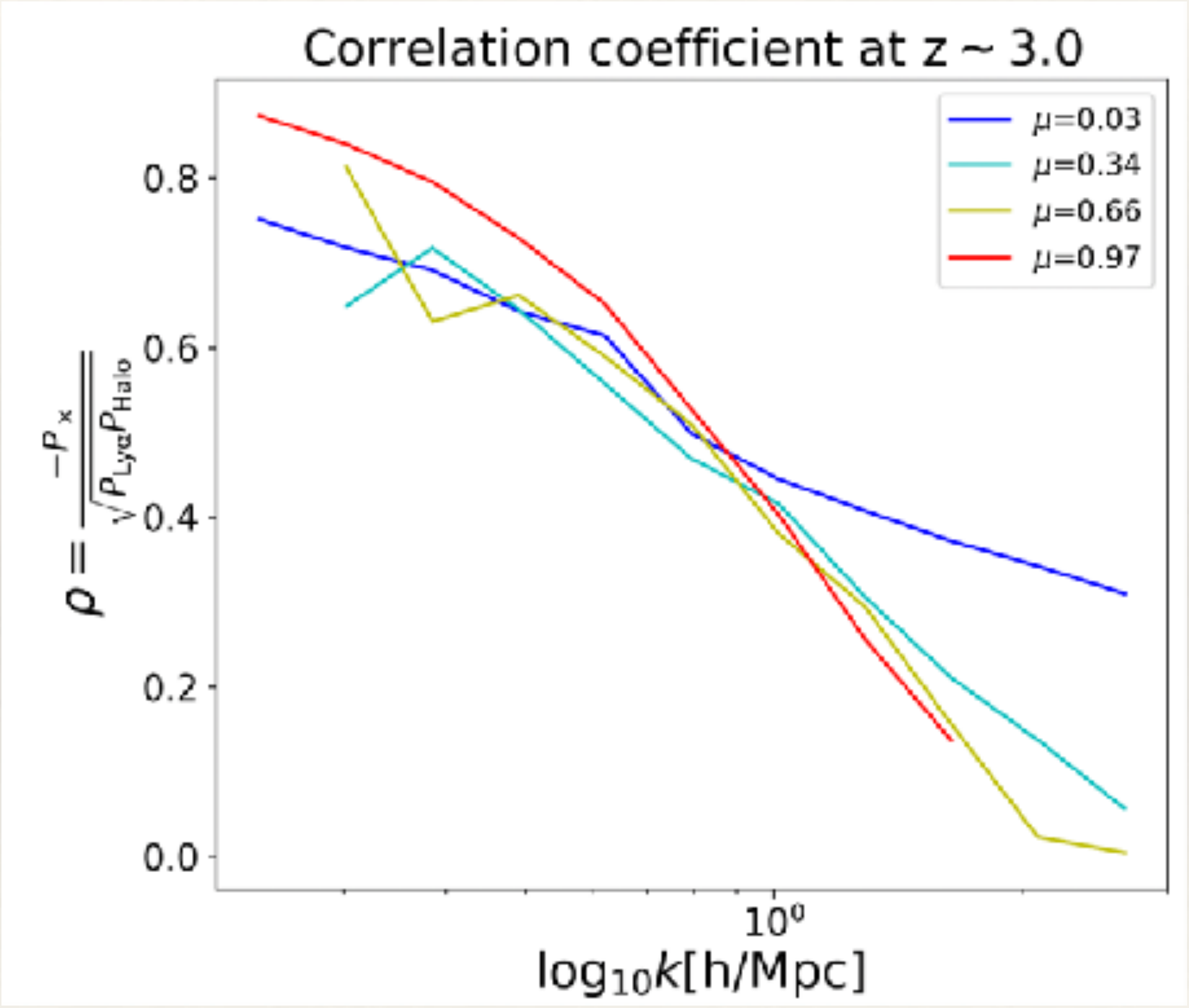
Cuceu+2021

Constraints on small scales

$$P_{\times}(k,\mu) = (b_{F\delta} + b_{F\eta} f\,\mu^2) \times (b_{q\delta} + f\,\mu^2)\ P_{\rm Lin,fid}(k)\sqrt{F_{\rm NL}F_{\rm FoG}}$$

Givans+2022

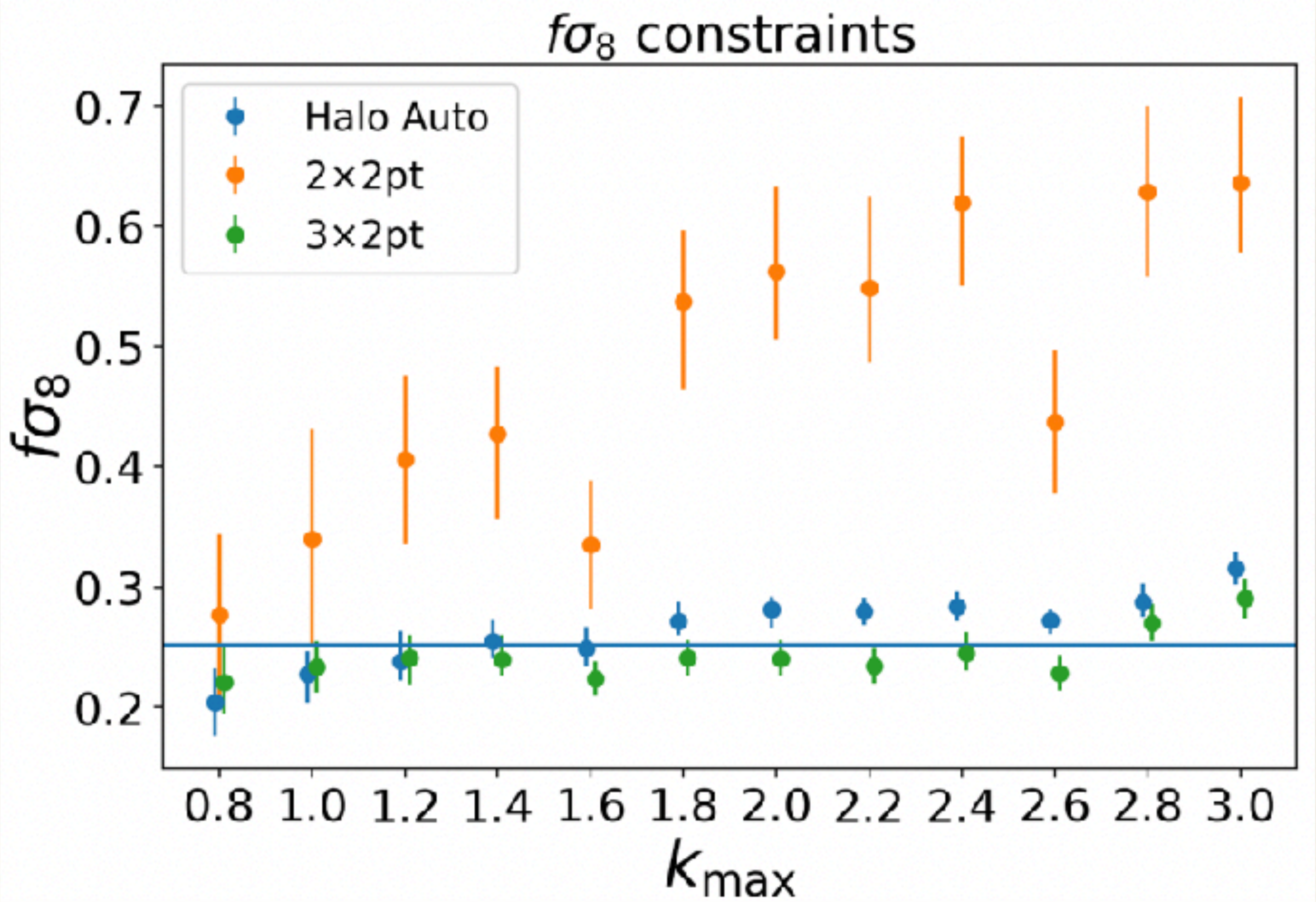




Constraints on small scales

$$P_{\times}(k,\mu) = (b_{\mathrm{F}\delta} + b_{\mathrm{F}\eta} f\,\mu^2) \times (b_{\mathrm{q}\delta} + f\,\mu^2)\ P_{\mathrm{Lin,fid}}(k)\sqrt{F_{\mathrm{NL}} F_{\mathrm{FoG}}}$$

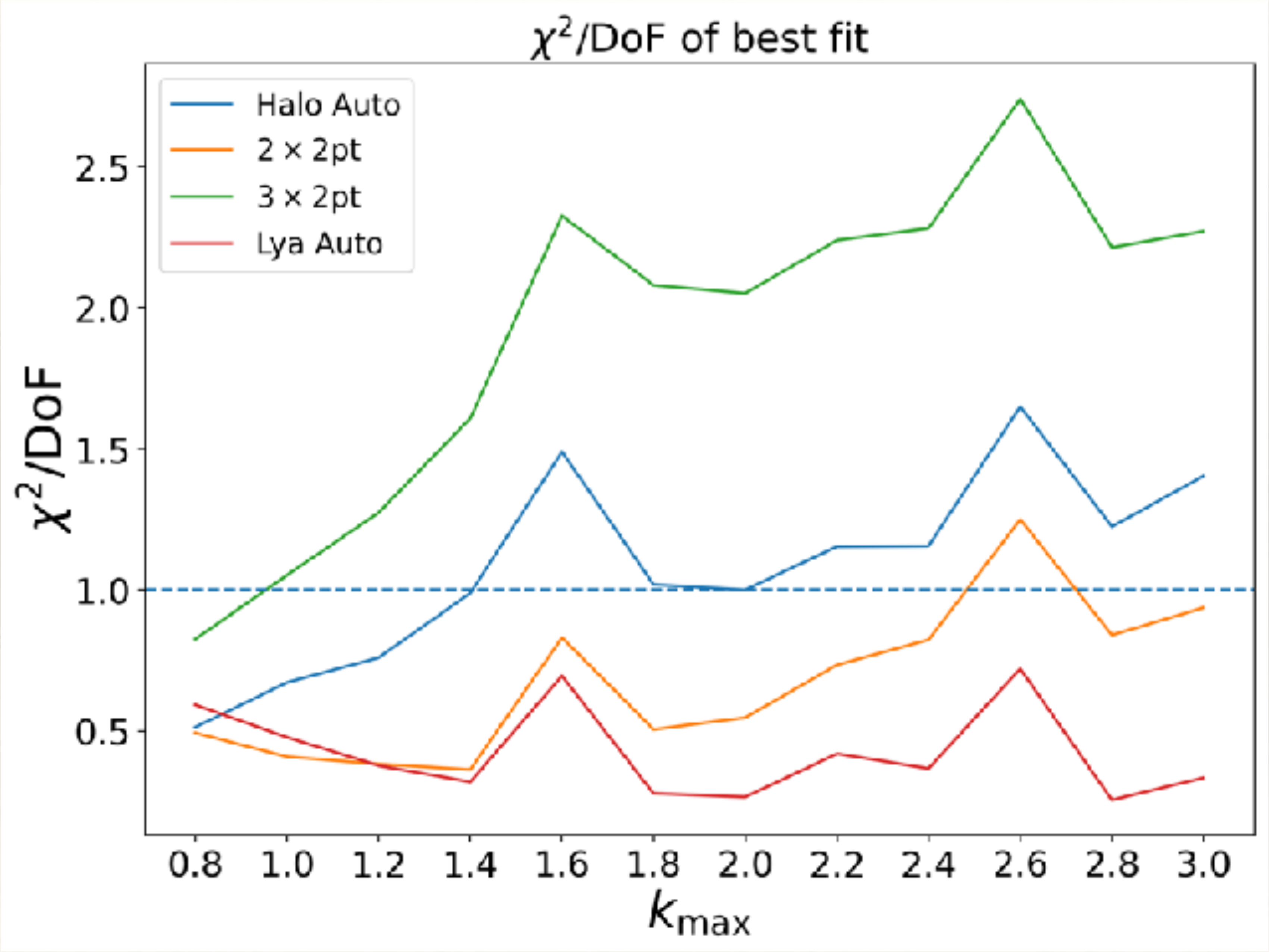
Givans+2022



Extended model of cross PS

$$P_\times(k,\mu) = (b_{\mathrm{F}\delta} + b_{\mathrm{F}\eta} f\,\mu^2) \times (b_{\mathrm{q}\delta} + f\,\mu^2)\;\; P_{\mathrm{Lin,fid}}(k)\sqrt{F_{\mathrm{NL}}}\,D_{\mathrm{M}}$$

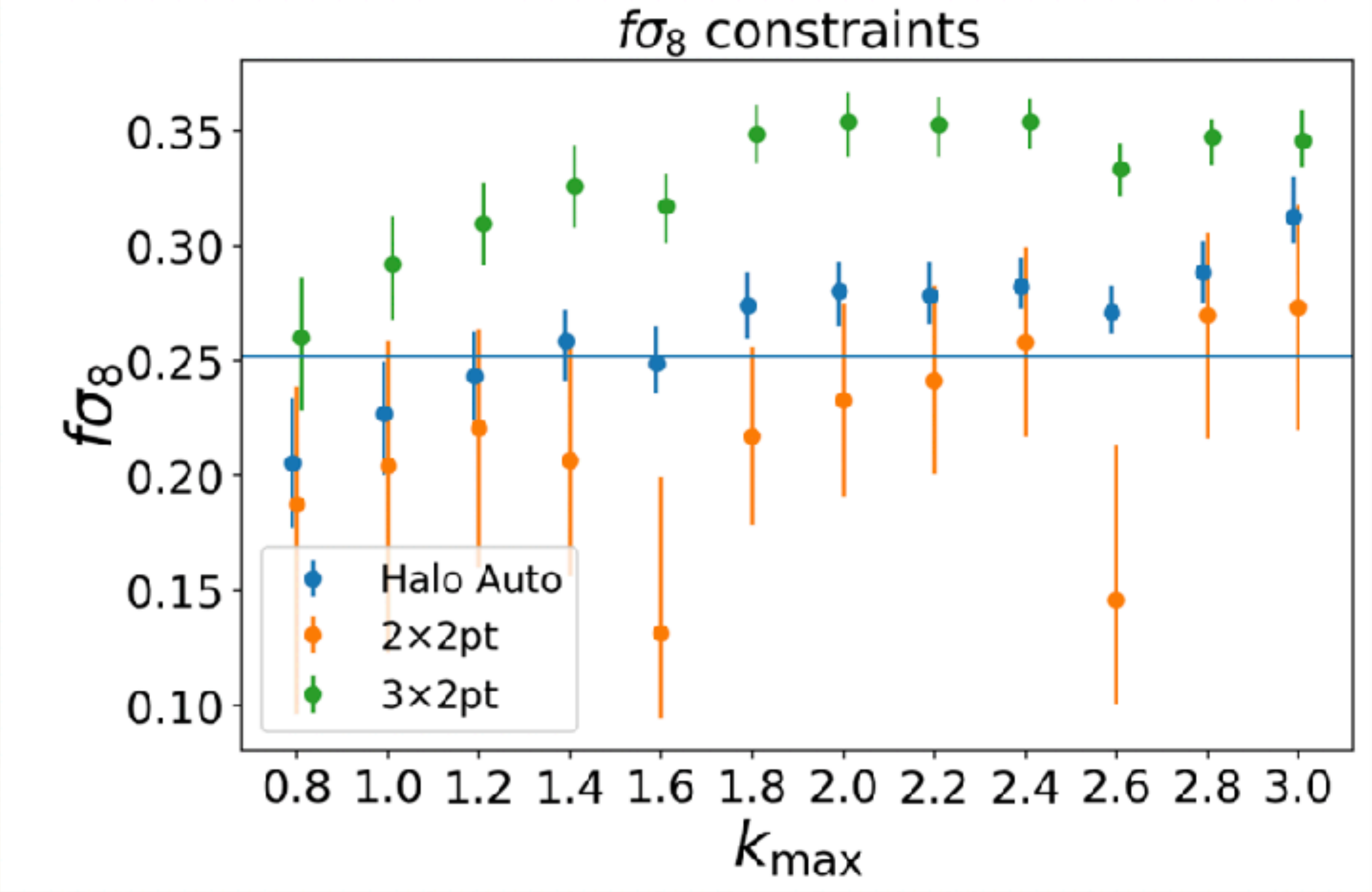
$$D_{\mathrm{M}} = \exp\left[(\alpha + \gamma\mu^2)\Delta^2(k) - (k\mu\nu)^4\right]$$ Givans+2022

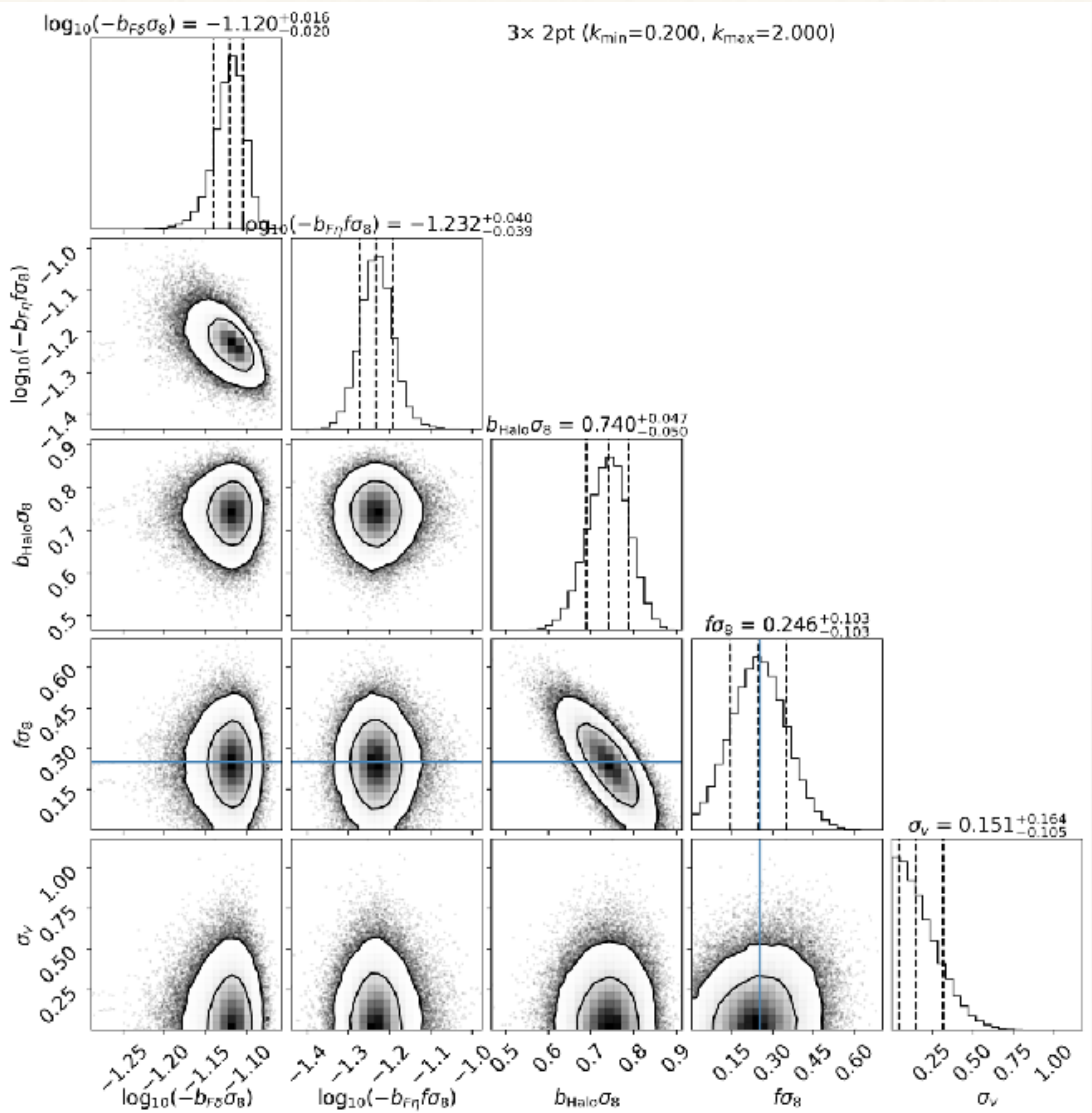


Extended model of cross PS

$$P_\times(k,\mu) = (b_{F\delta} + b_{F\eta} f\,\mu^2) \times (b_{q\delta} + f\,\mu^2) \quad P_{\rm Lin,fid}(k)\sqrt{F_{\rm NL}}\,D_{\rm M}$$

$$D_{\rm M} = \exp\left[(\alpha + \gamma\mu^2)\Delta^2(k) - (k\mu\nu)^4\right]$$ Givans+2022





3× 2pt ($k_{\rm min}$=0.200, $k_{\rm max}$=2.000)
$\log_{10}(-b_{F\delta}\sigma_8) = -1.120^{+0.016}_{-0.020}$
$\log_{10}(-b_{F\eta}f\sigma_8) = -1.232^{+0.040}_{-0.039}$
$b_{\rm Halo}\sigma_8 = 0.740^{+0.047}_{-0.050}$
$f\sigma_8 = 0.246^{+0.103}_{-0.103}$
$\sigma_v = 0.151^{+0.164}_{-0.105}$
$\log_{10}(-b_{F\delta}\sigma_8)$
$\log_{10}(-b_{F\eta}f\sigma_8)$
$b_{\rm Halo}\sigma_8$
$f\sigma_8$
σ_v

Lyα optical depth

Definition

$$\tau(\nu) \equiv \int dl \; n_{\rm HI} \; \sigma_{{\rm Ly}\alpha}(\nu)$$

$$= \int_0^l d\tilde{l} \; du_p \sigma_{\rm L}[\nu(1 - u_p/c)] \sqrt{\frac{m_p}{2\pi k_{\rm B} T}} n_{\rm HI} \exp\left(-\frac{m_p u_p^2}{2 k_{\rm B} T}\right)$$

Calculate of optical depth from physical values at each pixel

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

Fitting Model

$$P_{\rm F}(k,\mu) = (b_{{\rm F}\delta} + b_{{\rm F}\eta} f\,\mu^2)^2 P_{\rm L}(k) D_{{\rm Ly}\alpha}(k,\mu)$$

$$P_{\times}(k,\mu) = (b_{{\rm F}\delta} + b_{{\rm F}\eta} f\,\mu^2) \times (b_{{\rm h}\delta} + f\mu^2) P_{\rm L}(k)\sqrt{D_{{\rm Ly}\alpha}(k,\mu) D_{\rm FoG}(k\mu\sigma_v)}$$

Cuceu+2021 Givans+2022

$$P_{\rm halo}(k,\mu) = (b_{{\rm h}\delta} + f\mu^2)^2 P_{\rm NL}(k) D_{\rm FoG}(k\mu\sigma_v)$$

Okumura+2015

$$D_{{\rm Ly}\alpha}(k,\mu) = \exp\left\{ q_1 \Delta^2(k) \left[1 - \left(k/k_v\right)^{a_v} \mu^{b_v}\right] - \left(k/k_p\right)^2 \right\}$$

Arinyo+2015

$$D_{\rm FoG}(k\mu\sigma_v) = \left[1 + (k\mu\sigma_v)^2\right]^{-1}$$

Nagamine et al. (2021)

Table 2
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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_{ptcl}	m_{DM} ($h^{-1} M_\odot$)	m_{gas} ($h^{-1} M_\odot$)	ϵ_g (h^{-1} ckpc)	h_{min} (h^{-1} pc)
L100N512 (Osaka20)	100	2×512^3	5.38×10^8	1.00×10^8	7.8	260
L50N256	50	2×256^3	5.38×10^8	1.00×10^8	7.8	260
L40N512	40	2×512^3	3.44×10^7	6.43×10^4	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_{ptcl} is the total number of particles (dark matter and gas), m_{DM} is the dark matter particle mass, m_{gas} is the initial mass of gas particles (which may change over time due to star formation and feedback), ϵ_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

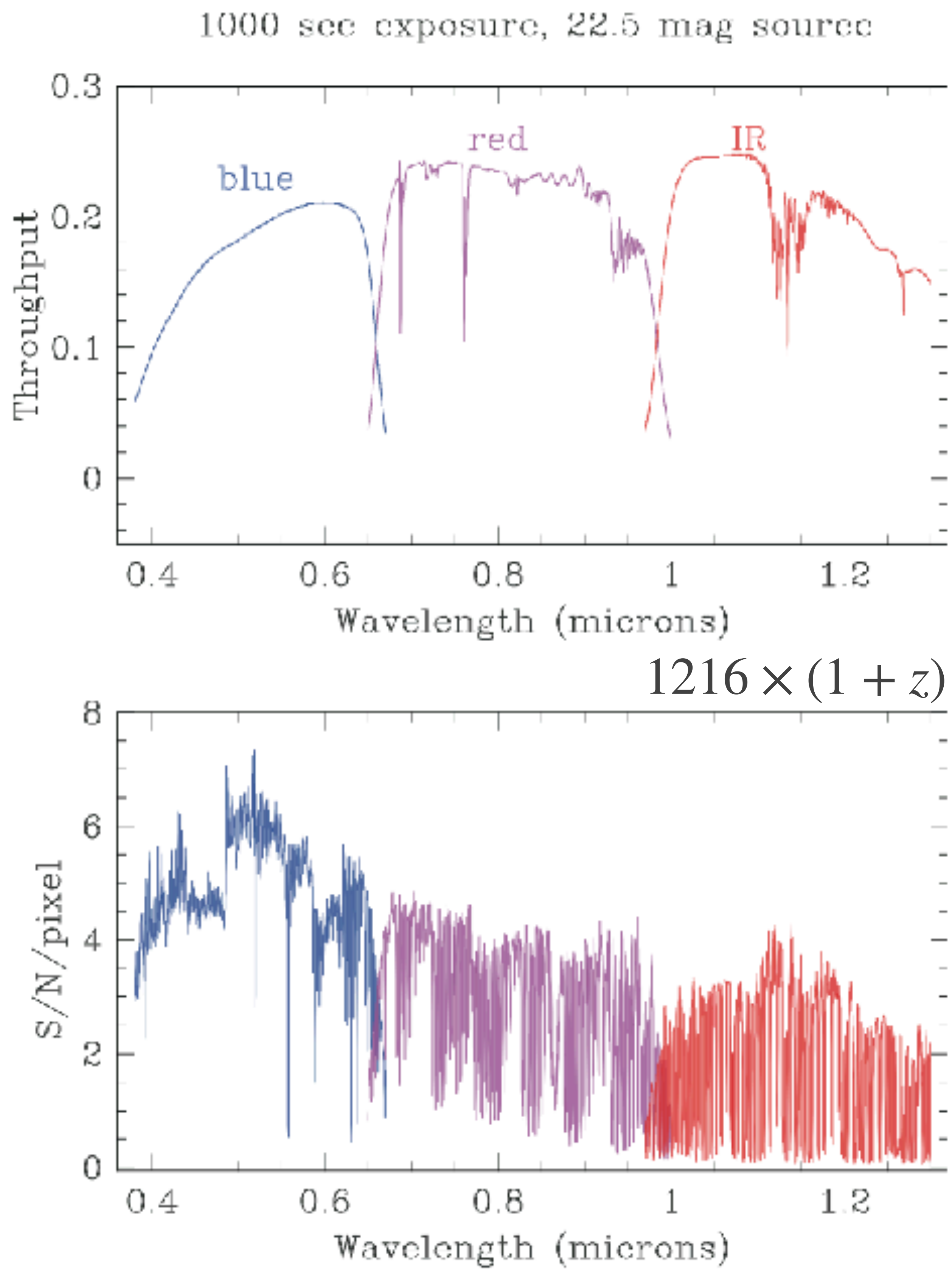
Simulations	N_{gal}			
	10^8–10^9	10^9–10^{10}	10^{10}–10^{11}	$> 10^{11} M_\odot$
L100N512 (Osaka20)	8344	13893	3200	148
L50N256	1039	1705	425	14
L40N512	9476	3036	706	14

Note. N_{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[a]
Osaka20-FG09	UVB model of FG09[b]

PFS white paper



$$1216 \times (1 + z)\ [\text{Å}] = 4886 \times \frac{1 + z}{1 + 3}\ [\text{Å}]$$

Figure 2.5: Top panel: The computed throughput of the spectrograph for a point source, including losses in the atmosphere, telescope, fibers, instrument optics, gratings, and detectors. Lower panel: The signal-to-noise ratio *per pixel* for a 1000-second exposure on a star with AB magnitude $m = 22.5$ at each wavelength. An airmass of 1.3 is assumed. The discontinuity at 4900Å is an artifact of the sky model assumed.

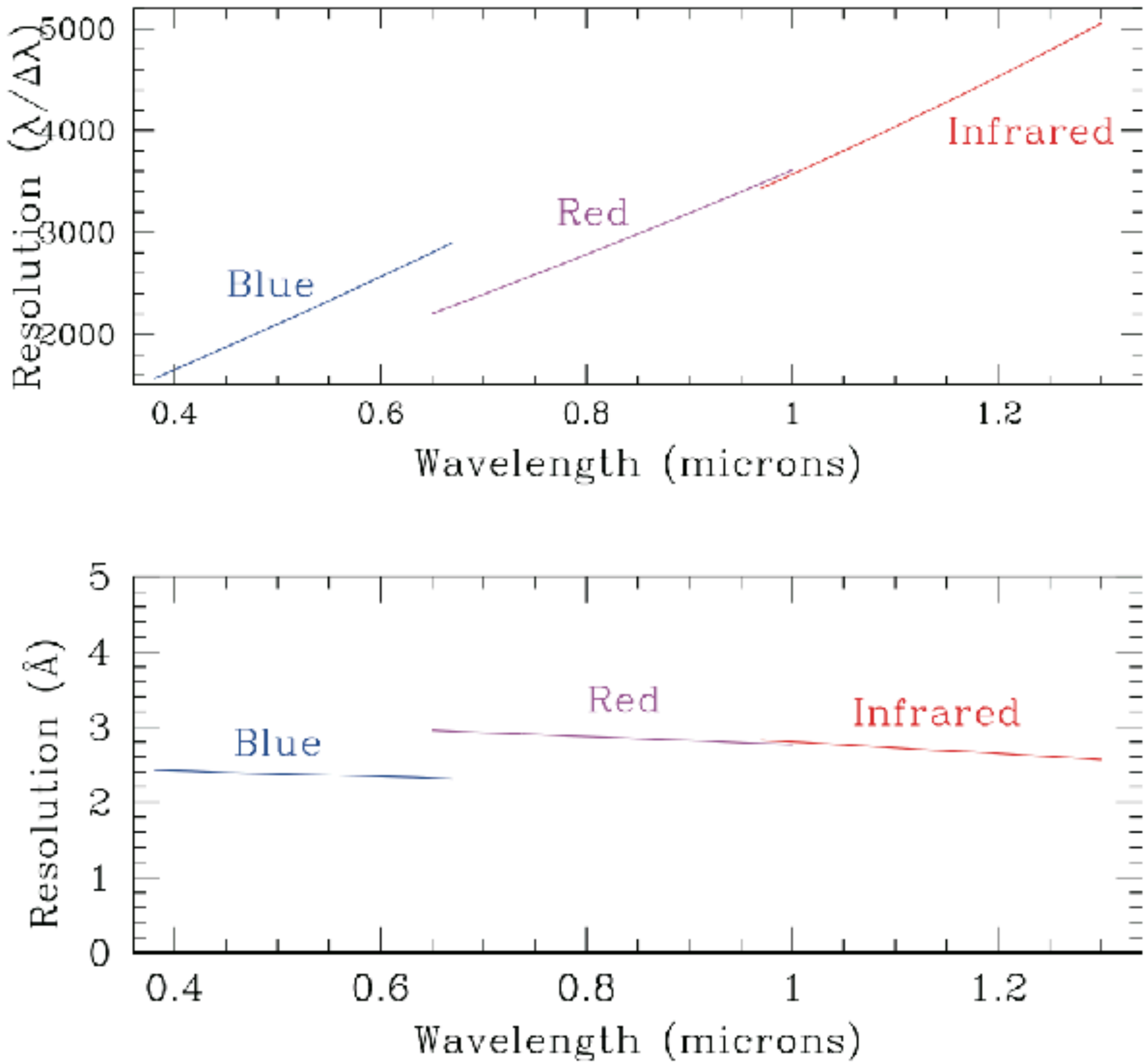


Figure 2.4: Design resolution (expressed as a fraction in the upper panel, and in Ångstroms in the lower panel) for each of the three arms of the spectrograph.

$$1216 \times (1+z)\ [\text{Å}] = 4886 \times \frac{1+z}{1+3}\ [\text{Å}]$$

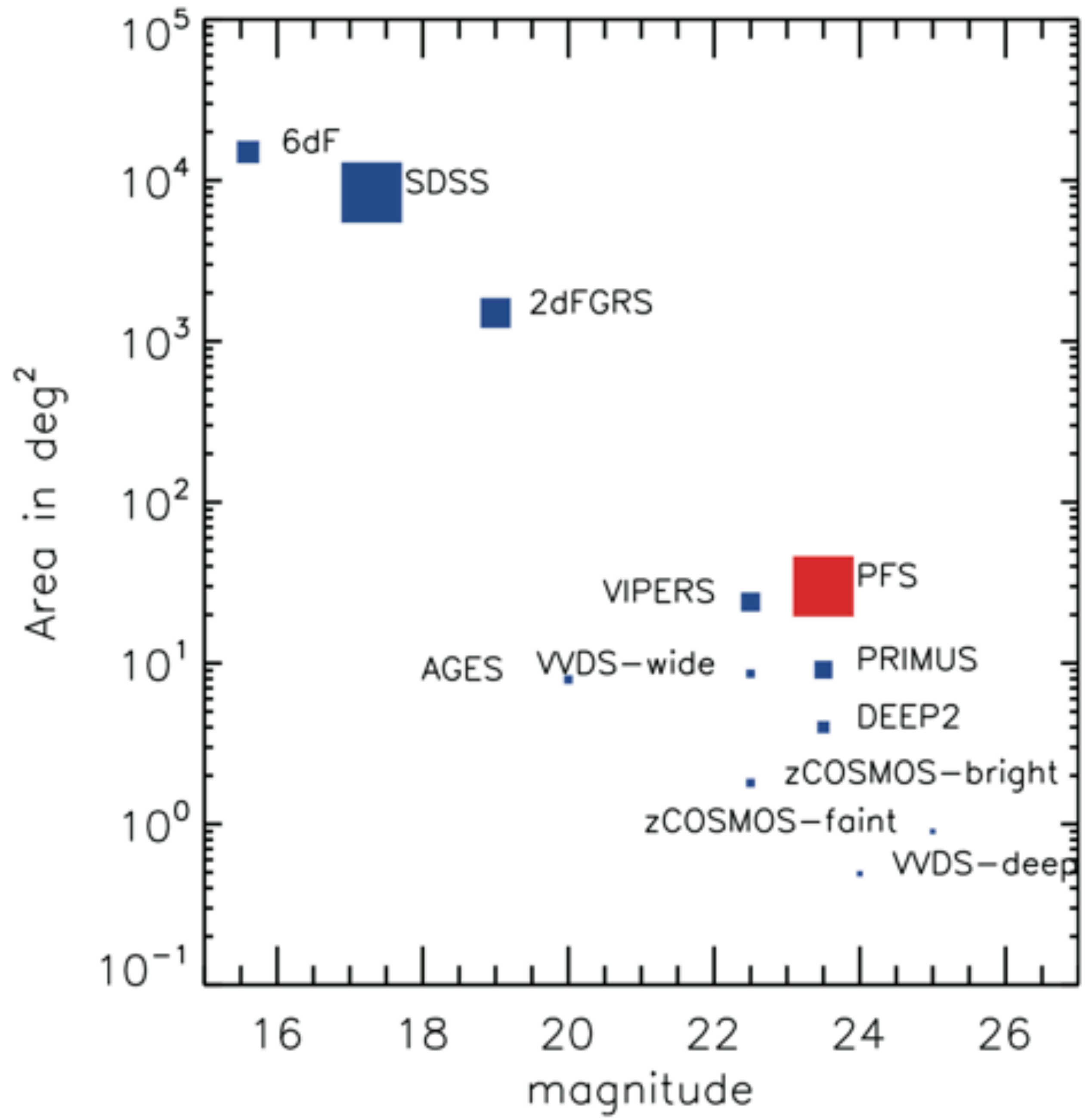


Figure 6.4: Area coverage versus limiting magnitude for various large extragalactic surveys. The point size represent the number of spectra; the SDSS symbol size corresponds to one million spectra. Clearly, a PFS survey occupies a unique position in this parameter space. The BigBoss survey is arbitrarily placed at 23rd magnitude since the continuum will not be detected in most galaxies.

PFS SSP

Table 1
Instrumentation parameters

Prime Focus Instrument				
Field of view	~ 1.38 deg (hexagonal - diameter of circumscribed circle)			
Field of view area	~ 1.25 deg^2			
Input f number to fiber	2.8			
Fiber core diameter[a]	127 μm (1.12 arcsec at the FoV center, 1.02 arcsec at the edge)			
Positioner pitch	8 mm (90.4 arcsec at the FoV center, 82.4 arcsec at the edge)			
Positioner patrol range	9.5 mm (107.4 arcsec at the FoV center, 97.9 arcsec at the edge)			
Minimum fiber separation[b]	~ 30 arcsec			
Fiber configuration time	~ 60–120 sec			
Number of fibers	Science fibers		Fixed fiducial fibers	
	2394		96	
Fiber density	~ 2000 deg^{-2} or ~ 0.6 $arcmin^{-2}$			
Spectrograph				
Spectral arms	Blue	Red		NIR
		Low Res.	Mid Res.	
Spectral coverage	380 – 650 nm	630 – 970 nm	710 – 885 nm	940 – 1260 nm
Dispersion	~ 0.7Å/pix	~ 0.9Å/pix	~ 0.4Å/pix	~ 0.8Å/pix
Spectral resolution	~ 2300	~ 3000	~ 5000	~ 4300
Detector type/read-out mode	CCD	CCD		HgCdTe/SUTR
Spectrograph throughput[c]	~ 53% (@500nm)	~ 52% (@800nm)	~ 47% (@800nm)	~ 34% (@1100nm)

[a] This is a diameter of the sky projected onto the fiber core through the microlens with a magnification of 1.28.
[b] The minimum separation includes a physical limitation and a margin for collision avoidance.
[c] These values include detector QEs. The typical total throughput including primary mirror reflectivity, WFC, fiber systems, spectrograph optics, detector QE, etc. in blue, red, NIR, and medium resolution arms are ~22% (@500nm), ~26% (@800nm), ~19% (@1100nm), and ~23% (@800nm), respectively

PFS SSP

Table 2
Sample and Depths

Layer	Field	Selection	exp. time[a]	# of FoVs[b]	nights[c]	# of spectra	Requirement(s)[d]	Main science[e]
Cosmology	HSC-W	*grizy*	15min	~ 1100	~70	~ 4M	redshift ([O II])	BAO, RSD, LSS
ancillary targets	HSC-W	*gri*(*zY*)+ext. data (*Gaia*, etc.)	15-30min	~ 1100	–	~ 100K	–	GA (stars, WDs), GE (e.g., QSOs)
gals $z \lesssim 1$	HSC-D	$i < 23$	2 hrs	11	~ 3.5	~ 28K	spectral features	GE (control sample, deep)
gals $0.7 < z < 1$	HSC-D	$y < 22.5 + z_{ph}$	2 hrs	11	~ 8.5	~ 68K	spectral features	GE ($0.7 < z < 1$)
gals $1 < z < 2$	HSC-D	$y < 22.5 + z_{ph}$	2 hrs	11	~ 8.7	~ 69K	spectral features	GE ($1 < z < 2$)
	HSC-D	$y > 22.5$, $J < 22.8 + z_{ph}$	2 hrs	11	~ 12	~ 96K	spectral features	GE ($1 < z < 2$, main)
gals $0.7 < z < 2$	HSC-D	$J < 22.8 + z_{ph}$	12 hrs	11	~ 16	~ 14K	spectral features	GE ($0.7 < z < 2$, deep)
gals $2.1 < z < 2.5$	HSC-D	$y < 24.3 + z_{ph}$	6 hrs	11	~ 8.3	~ 22K	spectral features	GE (IGM/foreground)
gals $2.5 < z < 3.5$	HSC-D	$y < 24.3$, $g < 24.2 + z_{ph}$	6 hrs	11	~ 3.1	~ 8.3K	spectral features	GE (IGM/background)
	HSC-D	$y < 24.3$, $24.2 < g < 24.7 + z_{ph}$	12 hrs	11	~ 10.5	~ 14K	spectral features	GE (IGM/background)
gals $3.5 < z < 7$	HSC-D	$y < 24.5 + z_{ph}$	6 hrs	11	~ 8.3	~ 22K	spectral features	GE (high-z)
$z \sim 2.2$ LAEs[f]	HSC-D	NB387, $L_{Ly\alpha} > 3 \times 10^{42}$	3 hrs	11	~ 1.4	~ 7.4K	spectral features	GE, cosmic reionization
$z \sim 5.7, 6.6$ LAEs	HSC-D	NB816,921, $L_{Ly\alpha} > 5 \times 10^{42}$	6 hrs	11	~ 1.7	~ 4.5K	redshift (Lyα)	cosmic reionization
	HSC-D	NB816,921, $L_{Ly\alpha} = 3 - 5 \times 10^{42}$	12 hrs	11	~ 2.1	~ 2.8K	redshift (Lyα)	cosmic reionization
AGN $0.5 \lesssim z \lesssim 6$	HSC-D	$i < 24$(*grizy*)	1-4hrs	11	~ 1.8	~ 9.7K	spectral features	GE, CGM, IGM
MW-dSphs/dIrr[g]	HSC[h]	$g < 23$	3hrs	40[i]	30.5	~ 60K	$S/N\|_{cont.} > 10$	DM profiles, [Fe/H] and [α/Fe] dist.
M31[g]	HSC[h]	$g < 23$	5hrs	47	29.4	~ 13K	$S/N\|_{cont.} > 10$	accretion history, DM subhalos, M33
MW[g]	HSC	$g < 22$	3hrs	83	31.1	~ 26K	$S/N\|_{cont.} > 10$	MW grav., macro DM (incl. PBH)

Notes – [a] The total exposure time for each sample on source. [b] The number of pointings (roughly corresponding to survey area). [c] The primary requirement on spectroscopic observation for each sample. [d] The primary science drivers. [e] The main science. [f] The units of $L_{Ly\alpha}$ are [erg s^{-1}]. [g] Medium-resolution mode spectroscopic observation is included. [h] Including NB515 narrow-band imaging to discriminate member giants from foreground dwarf stars. [i] Two visit observation of each pointing to identify binary stars.

PSF White Paper 2000 deg^2

Table 10.1: PFS Survey Forecast for the BAO measurement from the Lyα Forest at z=2.64

mag g(AB)	exptime (min)	nights	n_{quasar} (deg^{-2})	n_{fiber}	$\delta H/H$	$\delta D_a/D_a$	FoM_1	FoM_2	N_{total}
21.0	10	21	8.8	32	0.049	0.091	TBD	TBD	17600
22.0	20	41	22.5	81	0.021	0.035	TBD	TBD	45000
23.0	48	99	45.0	162	0.015	0.021	TBD	TBD	90000
24.0	120	246	76.6	276	0.013	0.017	TBD	TBD	153200

Nagamine+2021 多分 15 deg^2

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^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

$$n_{\rm DESI} = \frac{1.1\mathrm{e}+6\ \mathrm{QSOs}}{14000\ \mathrm{deg}^2} \sim 78.57[\mathrm{deg}^{-2}] \qquad n_{\rm PFS} \equiv 690 + 1170\ [1.25\mathrm{deg}^{-2}] = 1488\ [\mathrm{deg}^{-2}]$$

$$f_{\rm cov} = \left(\frac{n_{\rm DESI}}{n_{\rm PFS}}\right)^2 \frac{A_{\rm DESI}}{A_{\rm PFS}} = \left(\frac{78.57}{1488}\right)^2 \frac{14000}{15} \sim 2.60$$

Calculation of the optical depth

☆ The optical depth of 21 cm line

$$\tau_{\nu_{\rm obs}} \sim \int_0^{z_0} \underbrace{\sigma_0 \;\; \phi(\nu_{\rm obs}(1+z)) \;\times n_0(z)\frac{0.068}{T_{\rm S}}}_{=\alpha_{\nu_{\rm obs}}(z)} \times \underbrace{\frac{c}{H(z)(1+z)} \;\; dz}_{=ds}$$

ドップラー・プロファイル

$$\phi(\nu) = \frac{1}{\Delta\nu_D\sqrt{\pi}}\exp\left(-\frac{\nu-\nu_0^2}{\Delta{\nu_D}^2}\right)$$

ドップラー幅 [Hz]

$$\Delta\nu_D(z) = \frac{\nu_0}{c}\sqrt{\frac{2k_BT(z)}{m}}$$

$$n_0\left[1 \; - \; \exp\left(-\frac{0.068}{T_{\rm S}}\right)\right] \sim n_0\frac{0.068}{T_{\rm S}}$$

$(T_{\rm S} \gg 0.068 \ {\rm K})$

Absorption Stimulated emission