The Lyman-α Forest: SDSS to BOSS

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What are we trying to do?

- Learn about the early Universe (i.e., inflation) by determining the statistics of the initial perturbations.
- Learn about the basic contents of the Universe and physical laws by studying the background evolution of the Universe and growth of structure (e.g., dark energy, modified gravity, neutrino masses, etc.)

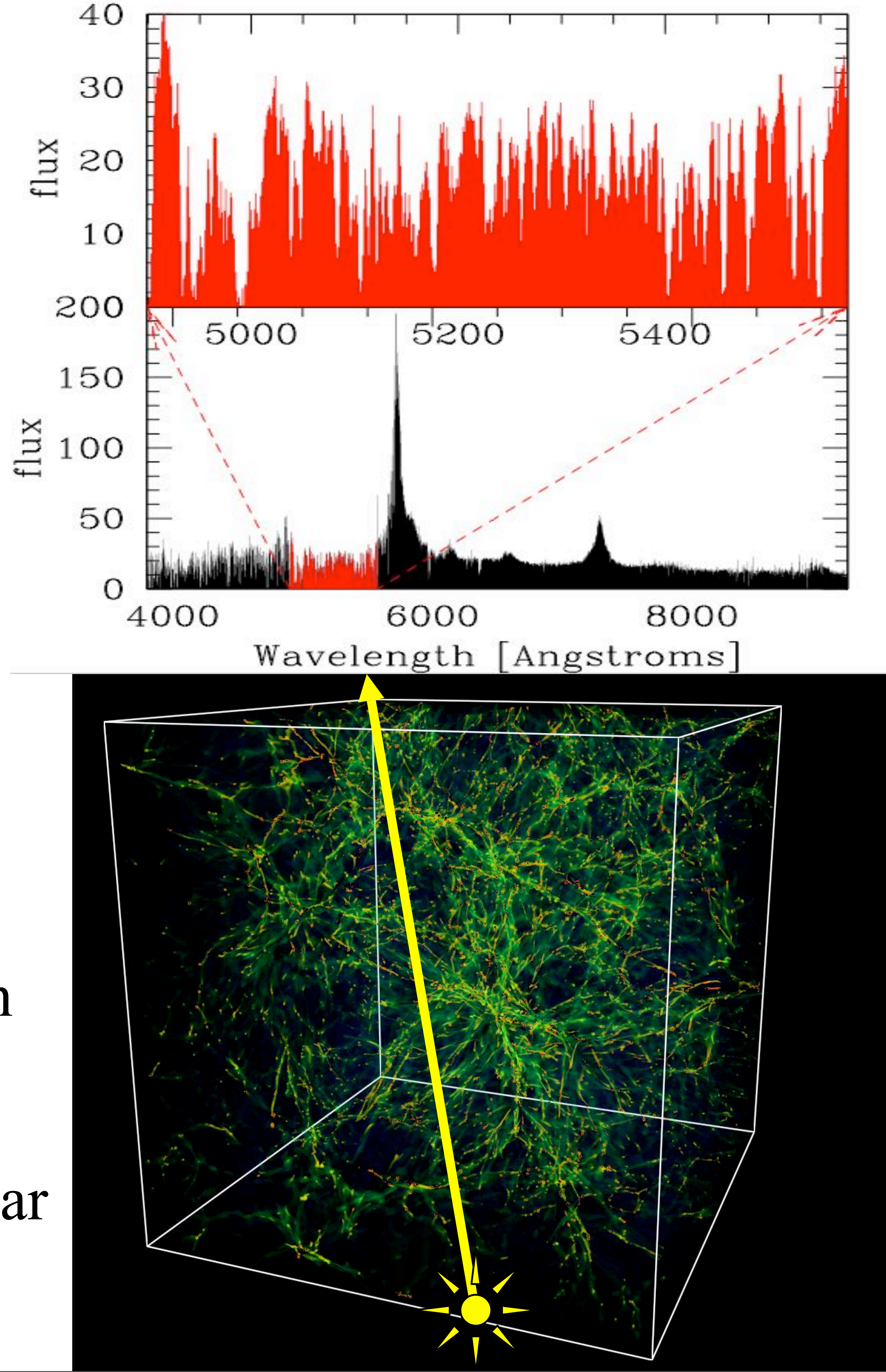
What is the Lyman-α forest?

The Lyα absorption by neutral hydrogen in the intergalactic medium (IGM) observed in the spectra of high redshift quasars.

A probe of large-scale structure.

Lyα forest

SDSS quasar spectrum



Neutral hydrogen

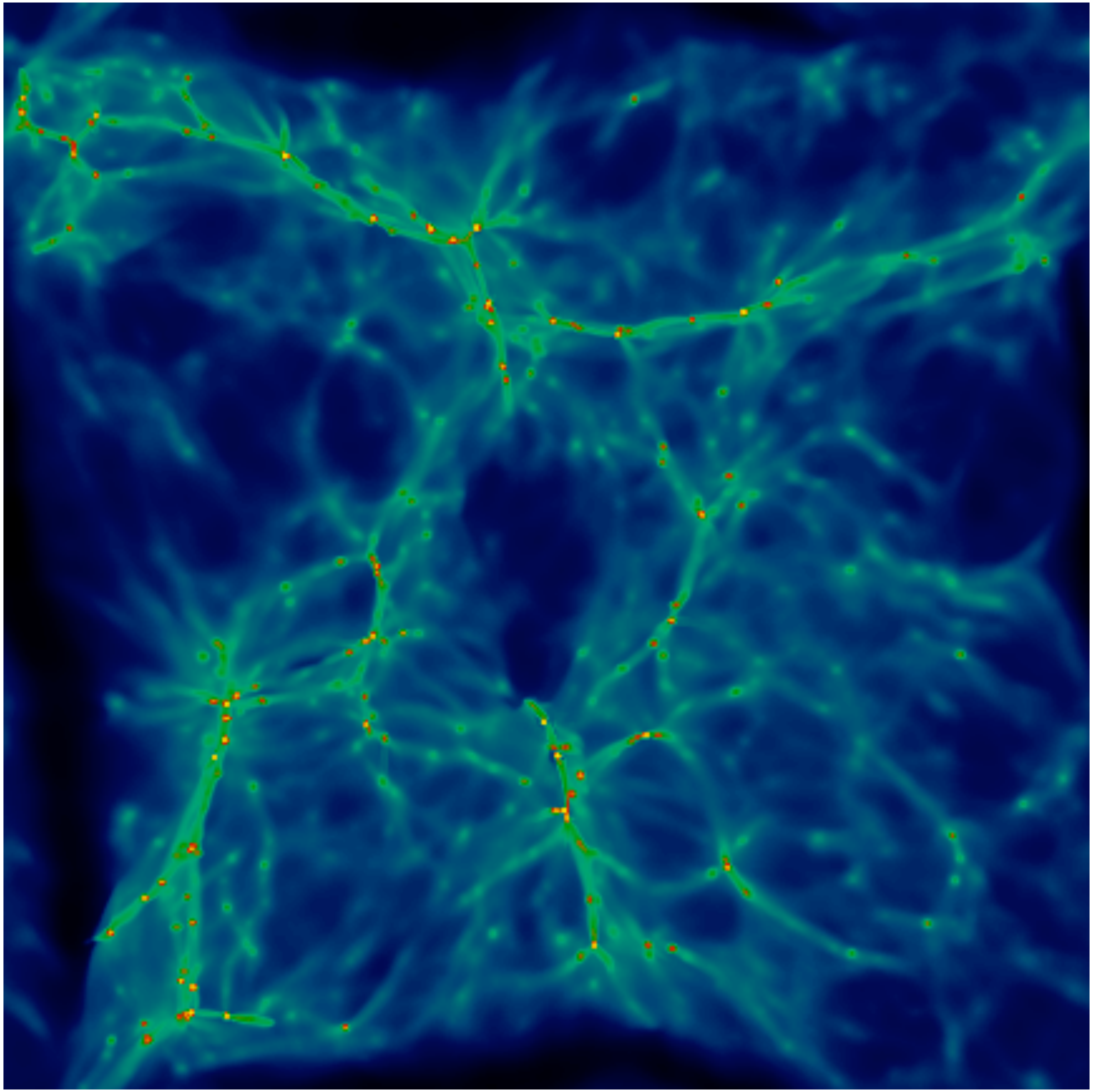
z = 3.7 quasar

25 Mpc/h cube simulation of the IGM by R. Cen

Numerical simulation of the IGM

(R. Cen)

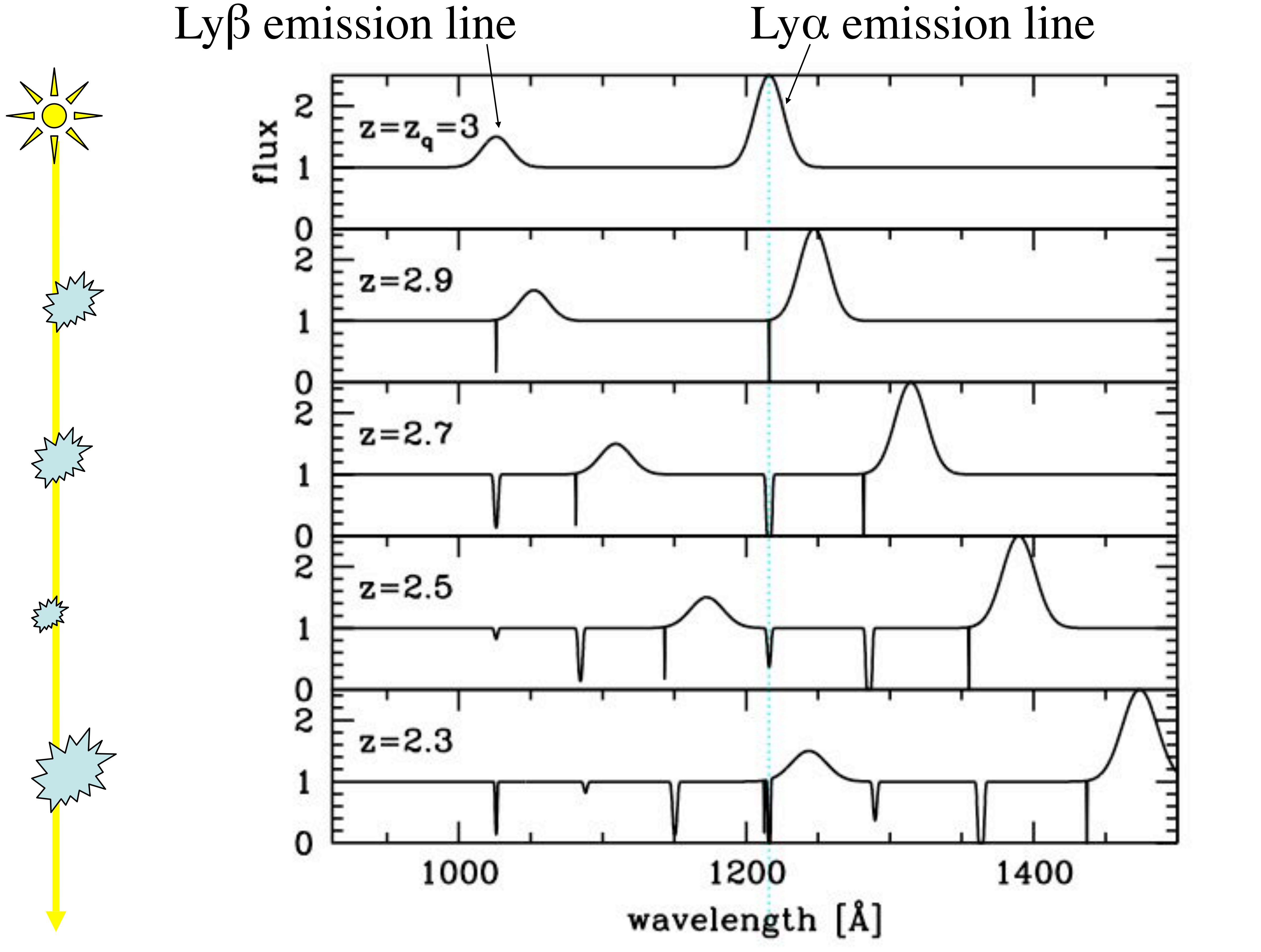
25 Mpc/h



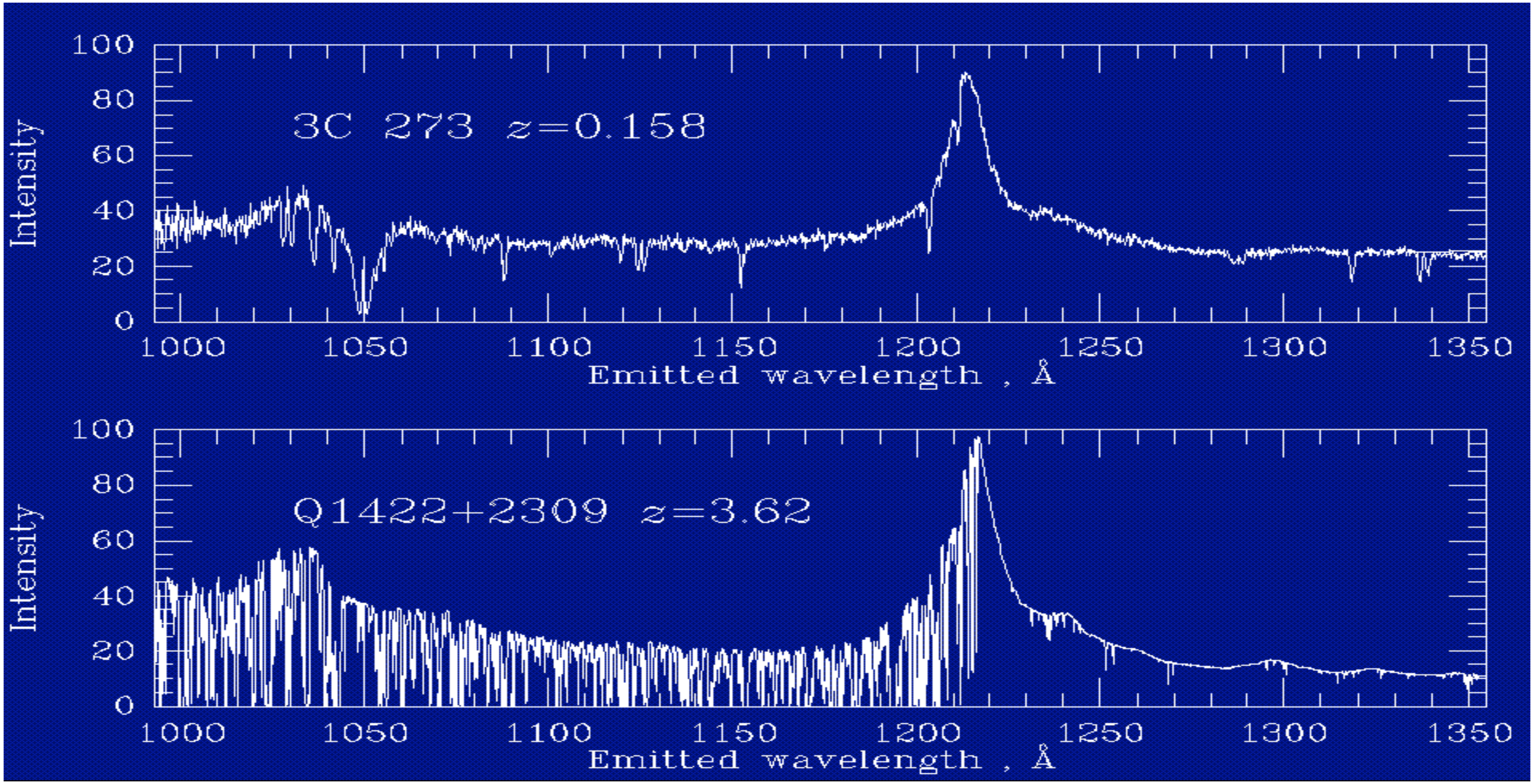
Absorption by gas at redshift z appears in an observed quasar spectrum at wavelength

$$\lambda_{\rm observed} = \lambda_\alpha(1 + z_{\rm gas})$$

$$\lambda_\alpha = 1216\ \text{Å} = 121.6\ \text{nm}$$

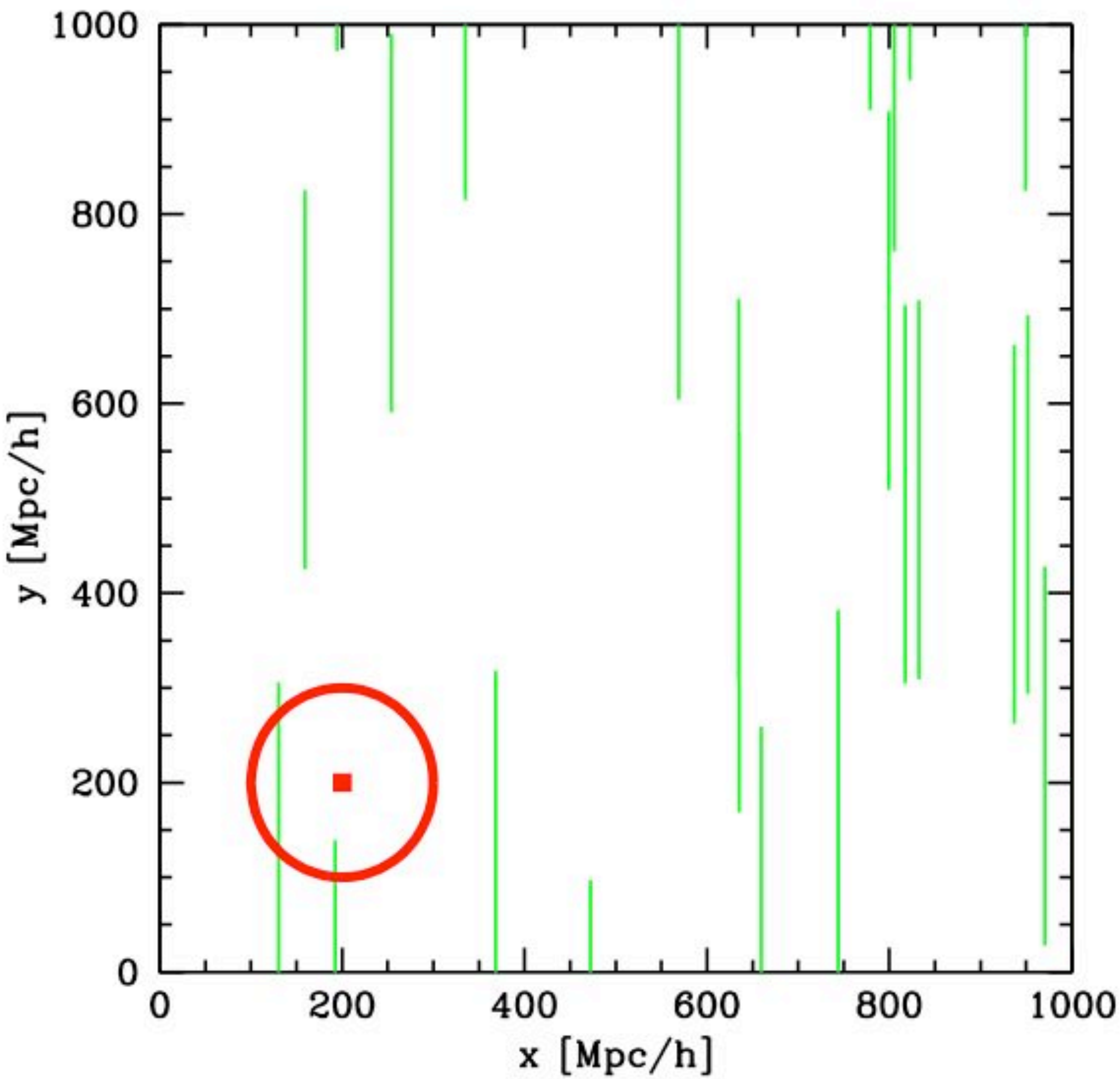

Lyβ emission line
Lyα emission line
flux
z=z_q=3
z=2.9
z=2.7
z=2.5
z=2.3
0
1
2
1000
1200
1400
wavelength [Å]

z~0 shows a relatively unabsorbed spectrum



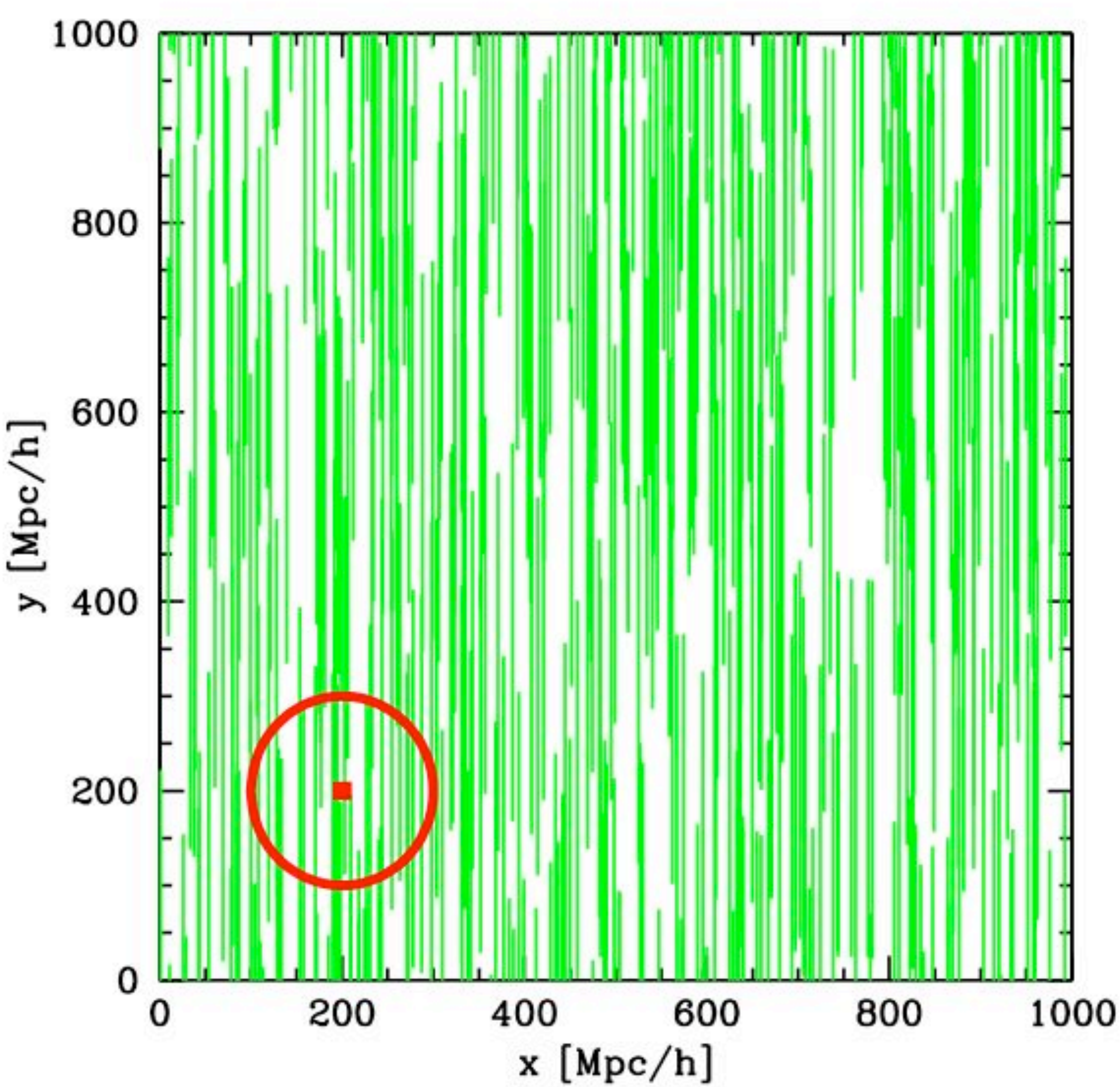
Much higher neutral densities at higher z

Current SDSS: very sparse



- SDSS-II quasar density (1 per sq. deg.)
- 100 Mpc/h deep
- 400 times this volume in SDSS

BOSS LyaF: 3D map of LSS



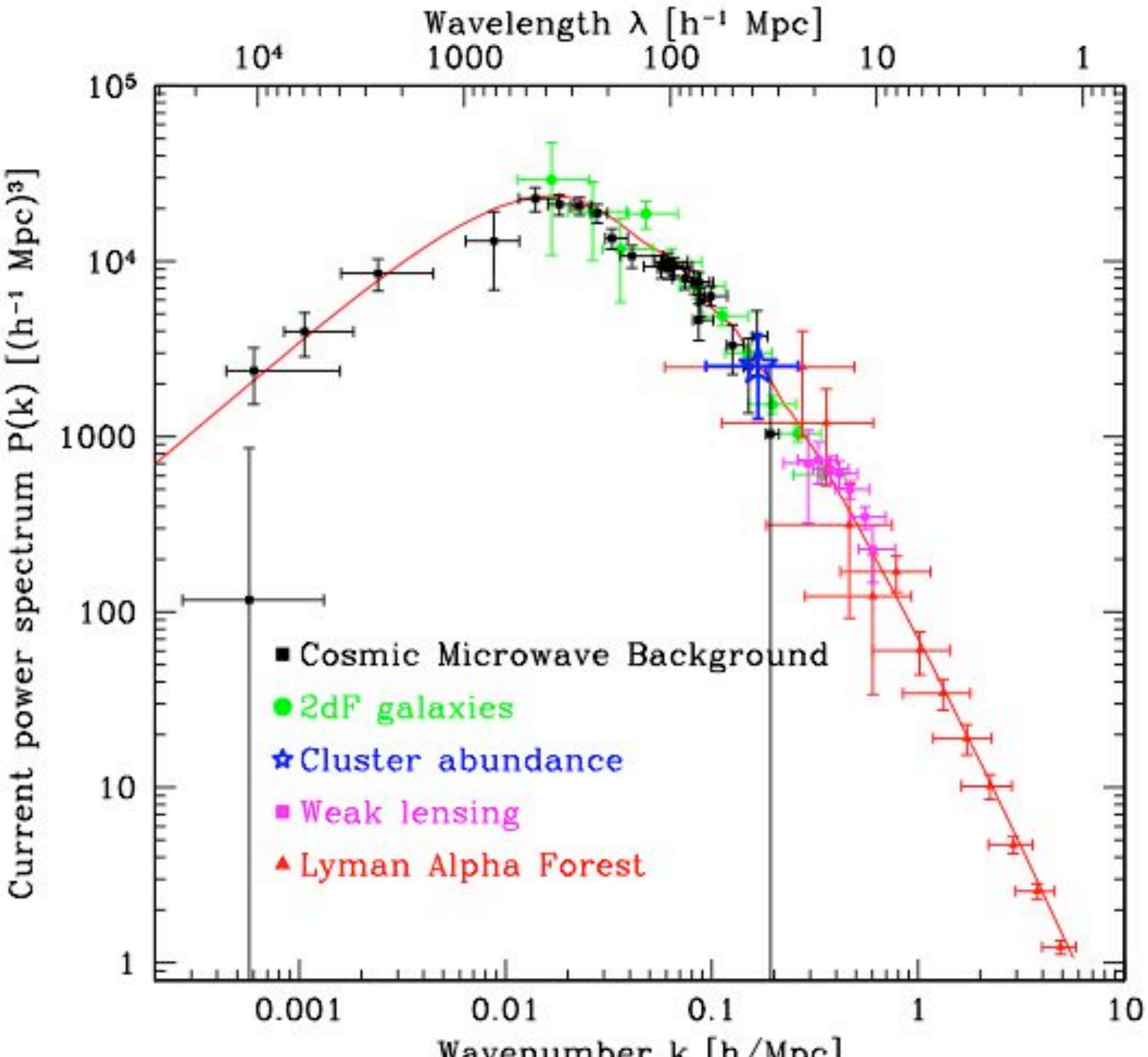
- BOSS quasar density (~20 per sq. deg.)
- this slice is 100 Mpc/h deep
- 400 times this volume in BOSS

What is the Lyα Forest good for?

Unique capabilities:

- Probe of large-scale structure at intermediate redshifts ($z \sim 3$).
- Probe of relatively small scales while they are still relatively linear.

The LyaF is sensitive to relatively small scales

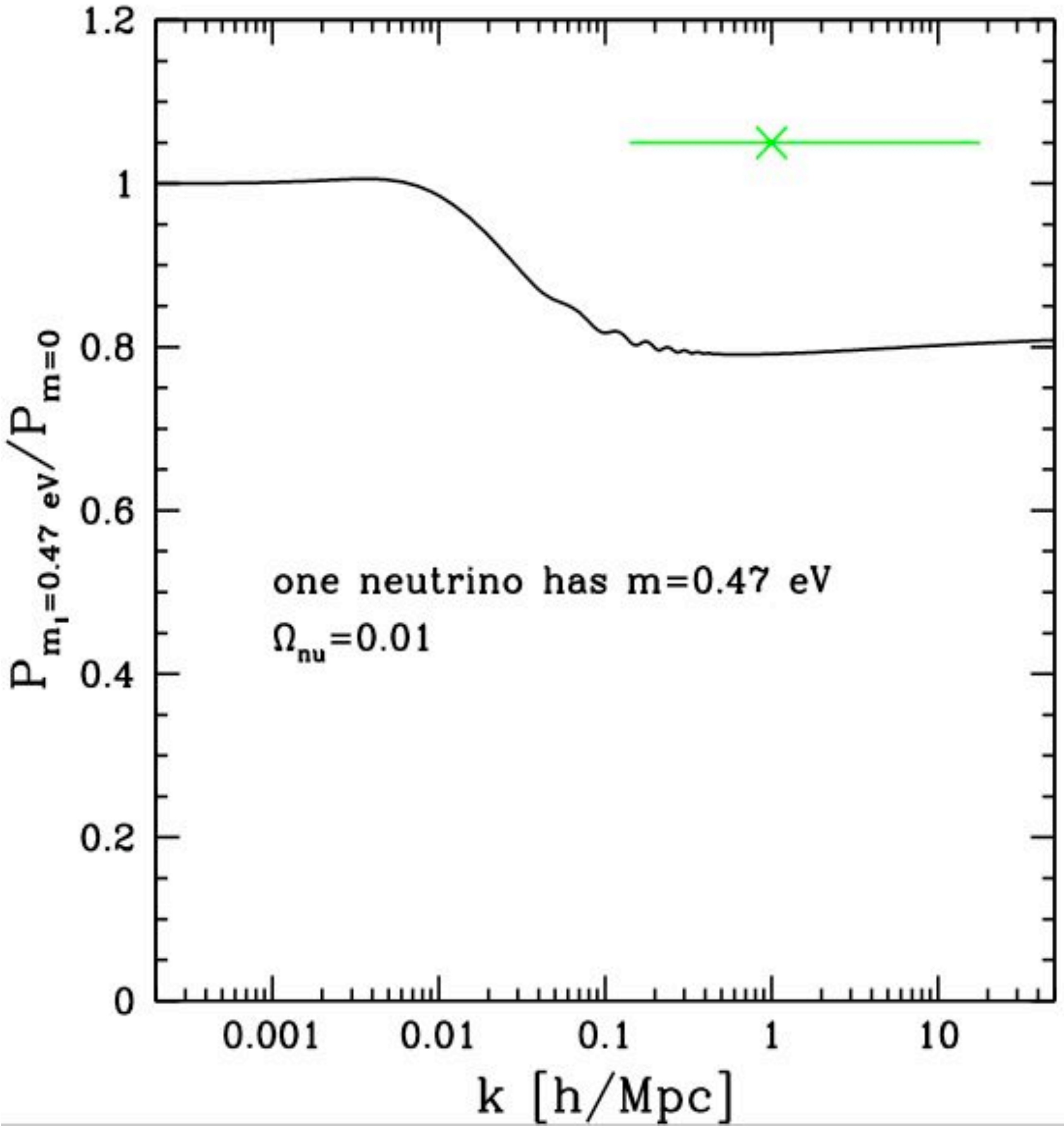


(out of date figure by Max Tegmark)

Measure physics that affects the power on LyaF scales.

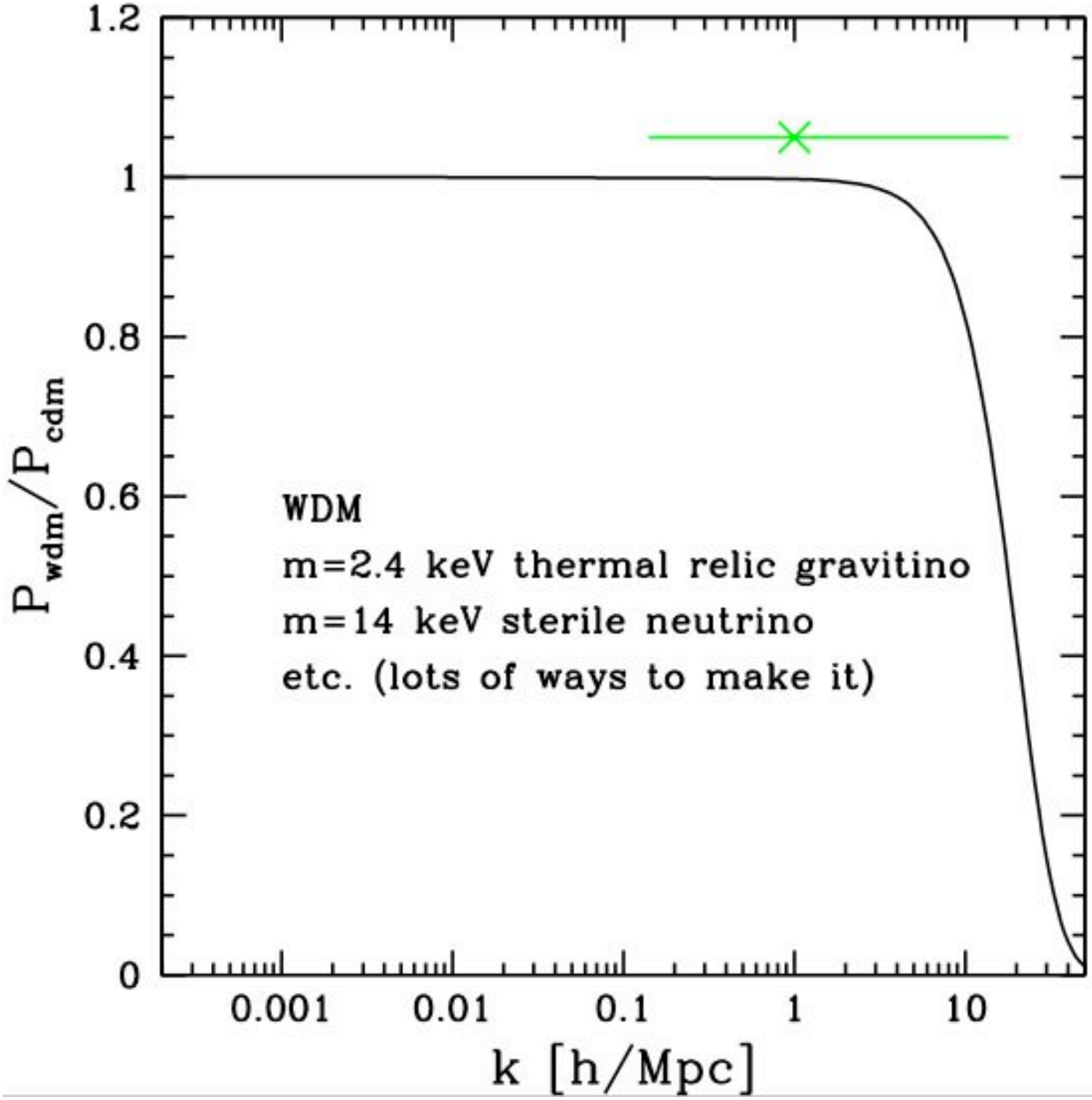
- ~100 kpc/h scales
  - Warm dark matter (erasure of small-scale structure)
    - Gravitinos
    - Sterile neutrinos
    - Dark matter from decays
  - Sources of extra small-scale structure (e.g., primordial black holes)
- ~1 Mpc/h scales
  - Inflation: running spectral index
  - Light neutrino masses
  - Anything else that affects power on this scale at z~3
- >10 Mpc/h scales
  - Dark energy & curvature: baryonic acoustic oscillations

Example of parameter dependence of P(k)



- Effect of massive neutrinos (linear power)
- Current constraint including the LyaF: $\sum m_\nu < 0.22$ eV (95%)

Effect of warm dark matter



- linear power
- masses model dependent

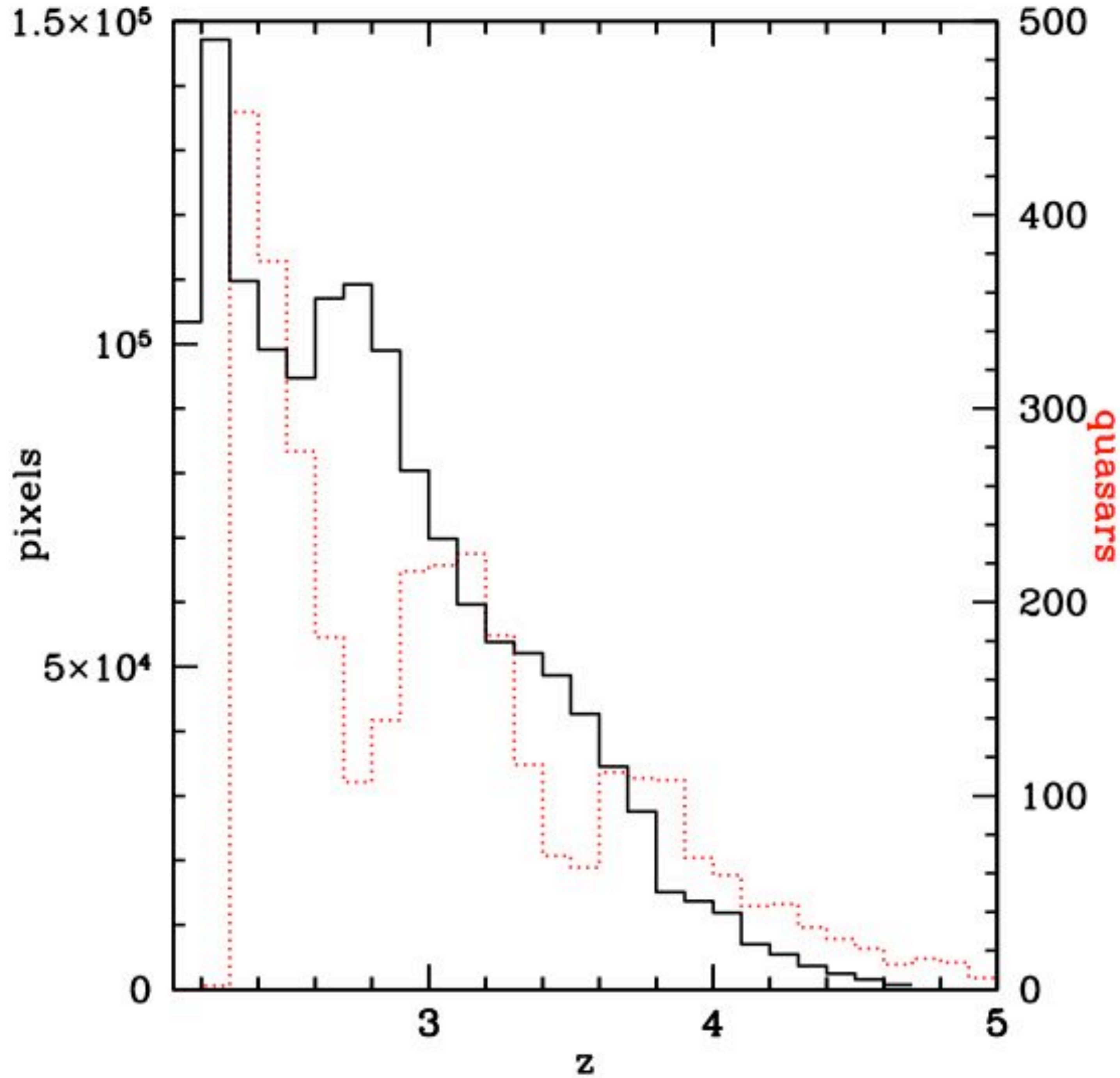
Outline

- ~~What the LyaF is and what it is good for~~
- Review the SDSS analysis (intro to BOSS analysis)
  - Measurement of the transmitted flux power spectrum from data
  - Theory/Simulation predictions as a function of model parameters
  - Cosmological parameter results
- BOSS projections
  - BAO (baryonic acoustic oscillations)
  - Smaller scales (~repeat above)
  - BigBOSS

Follow the usual LSS analysis procedure:

- Measure the power spectrum from the data.
- Compare to model predictions to constrain models.

SDSS data set (McDonald et al. 2006)



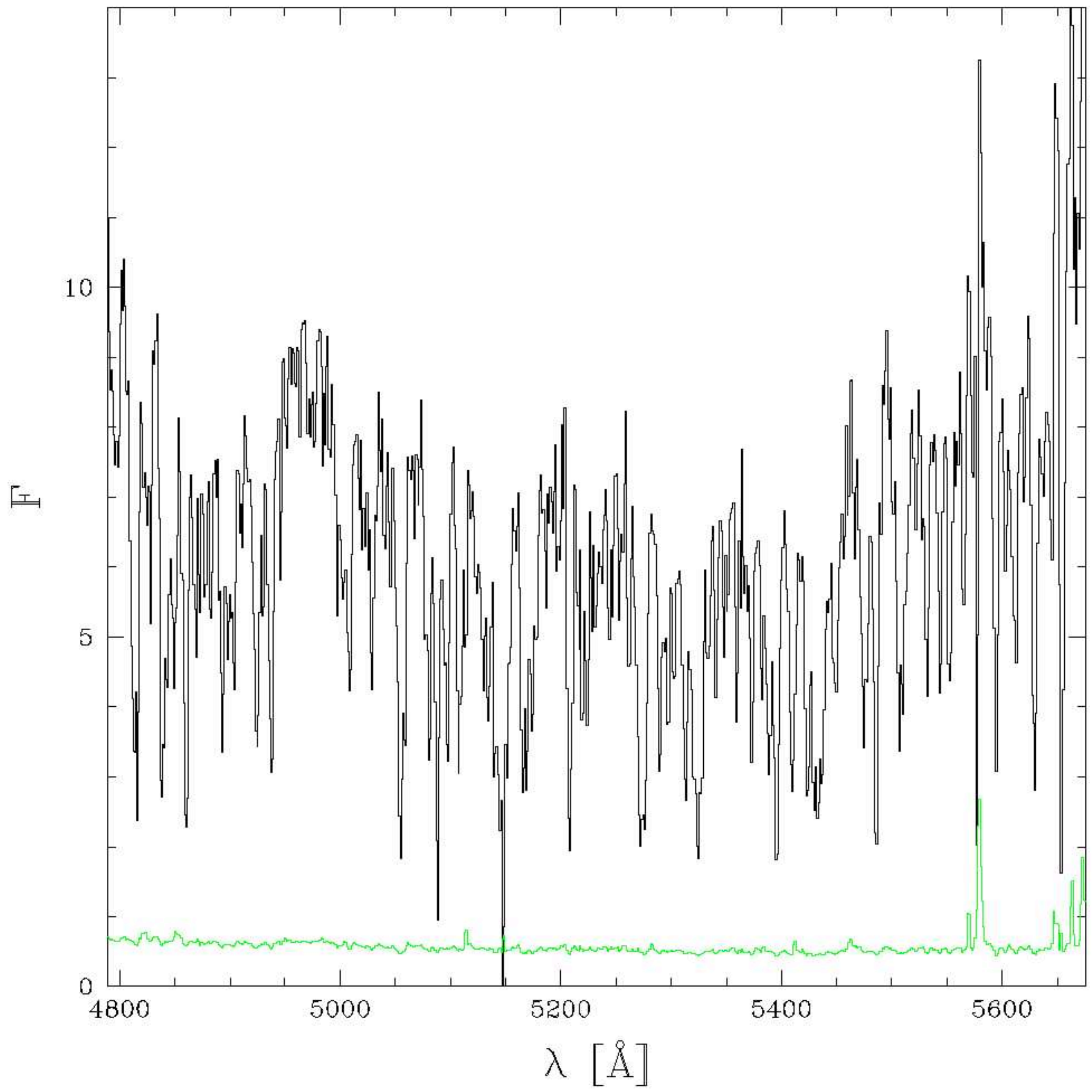
3300 spectra with z_{qso}>2.3

redshift distribution of quasars

1.4 million pixels in the forest

redshift distribution of Lyα forest pixels

Measure the power in thousands of vectors like this



- Each spectrum is a 1D probe of ~400 Mpc/h through the IGM

Usually show velocity as the radial coordinate
(model independent)

$$\Delta v \simeq \frac{c\ \Delta\lambda}{\lambda} \simeq \frac{c\ \Delta z}{1+z} \simeq \frac{H(z)}{1+z}\Delta x$$

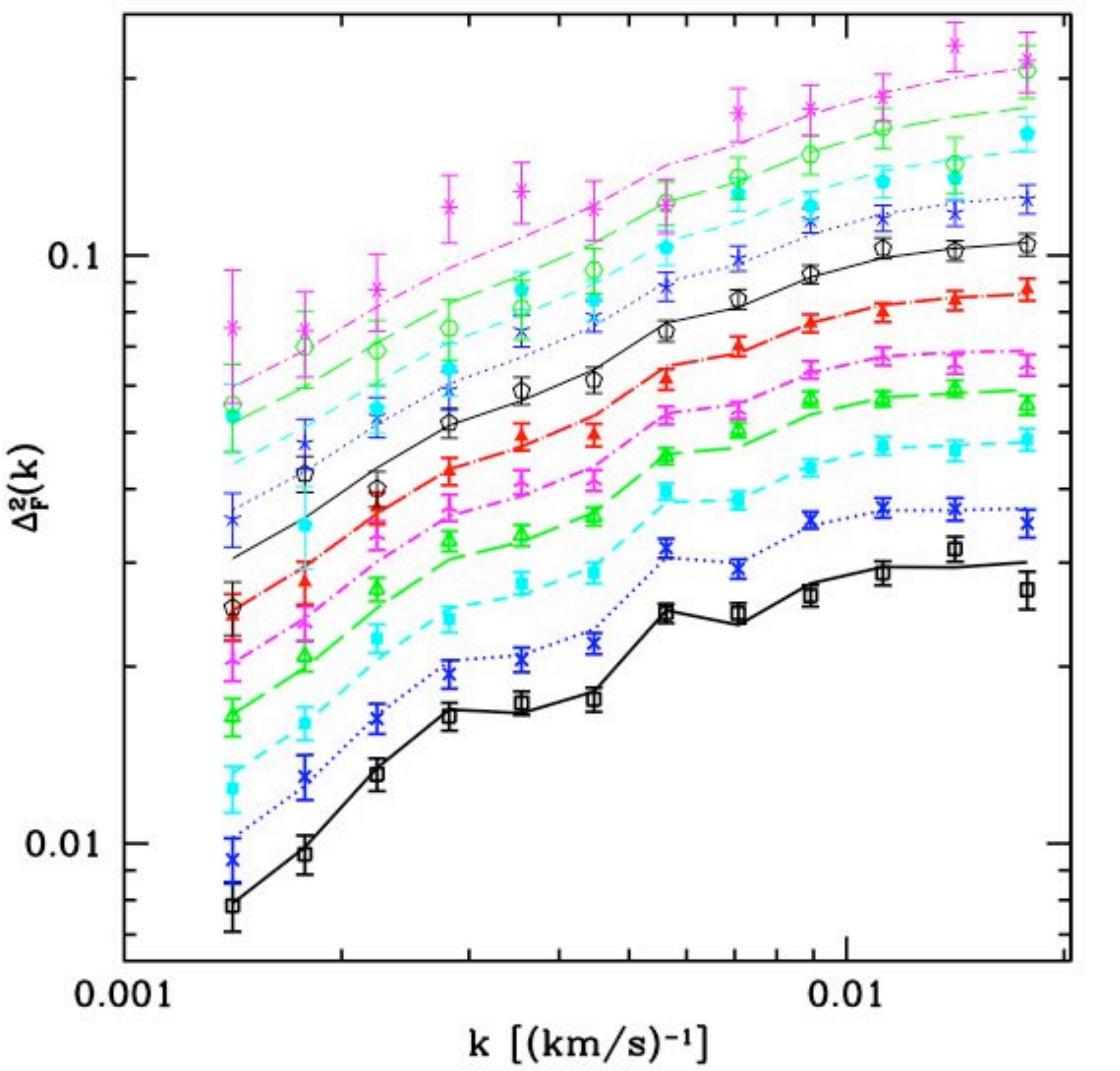
(relevant separations always small)

$$1\ h^{-1}\mathrm{Mpc} = 112\ \mathrm{km/s} = 1.8\ \mathrm{\AA}$$

$$\mathrm{For}\ \Omega_m = 0.3,\ \ \Omega_\Lambda = 0.7,\ \ z = 3$$

1 Mpc = 3 million light years

LyaF power from SDSS



- $\Delta_F^2(k) = \pi^{-1}\, k\, P_F(k)$

  (0.01 s/km ~ 1 h/Mpc)
- Colors correspond to redshift bins centered at z = 2.2, 2.4, …, 4.2 (from bottom to top)
- $1041 < \lambda_{rest} < 1185$ Å
- Computed using optimal weighting
- Noise subtraction
- Resolution correction
- Background subtraction using regions with $\lambda_{rest} > 1268$ Å
- Error bars from bootstrap resampling
- Code tested on semi-realistic mock spectra
- HIRES/VLT data probes smaller scales

After measuring the power spectrum from the data, we need model predictions to fit to it...

Why is the Lyα forest a good tracer of LSS (dark matter/initial perturbations)?

- First, baryons in the IGM trace dark matter except on small scales where pressure matters (~100 kpc).
- Photoionization equilibrium with a near-uniform ionizing background gives the neutral density (the gas is almost completely ionized).

$$\Gamma n_{HI} = \alpha(T) n_p n_e \qquad n_{HI} \propto \frac{\alpha(T)\rho_b^2}{\Gamma}$$

- Competition between photoionization heating and adiabatic expansion cooling produces a roughly power law relation between temperature and gas density.

$$T \simeq T_0 \left(\frac{\rho}{\rho_0}\right)^{\gamma-1} \qquad n_{HI} \propto \left(\frac{\rho}{\rho_0}\right)^{2-0.7(\gamma-1)}$$

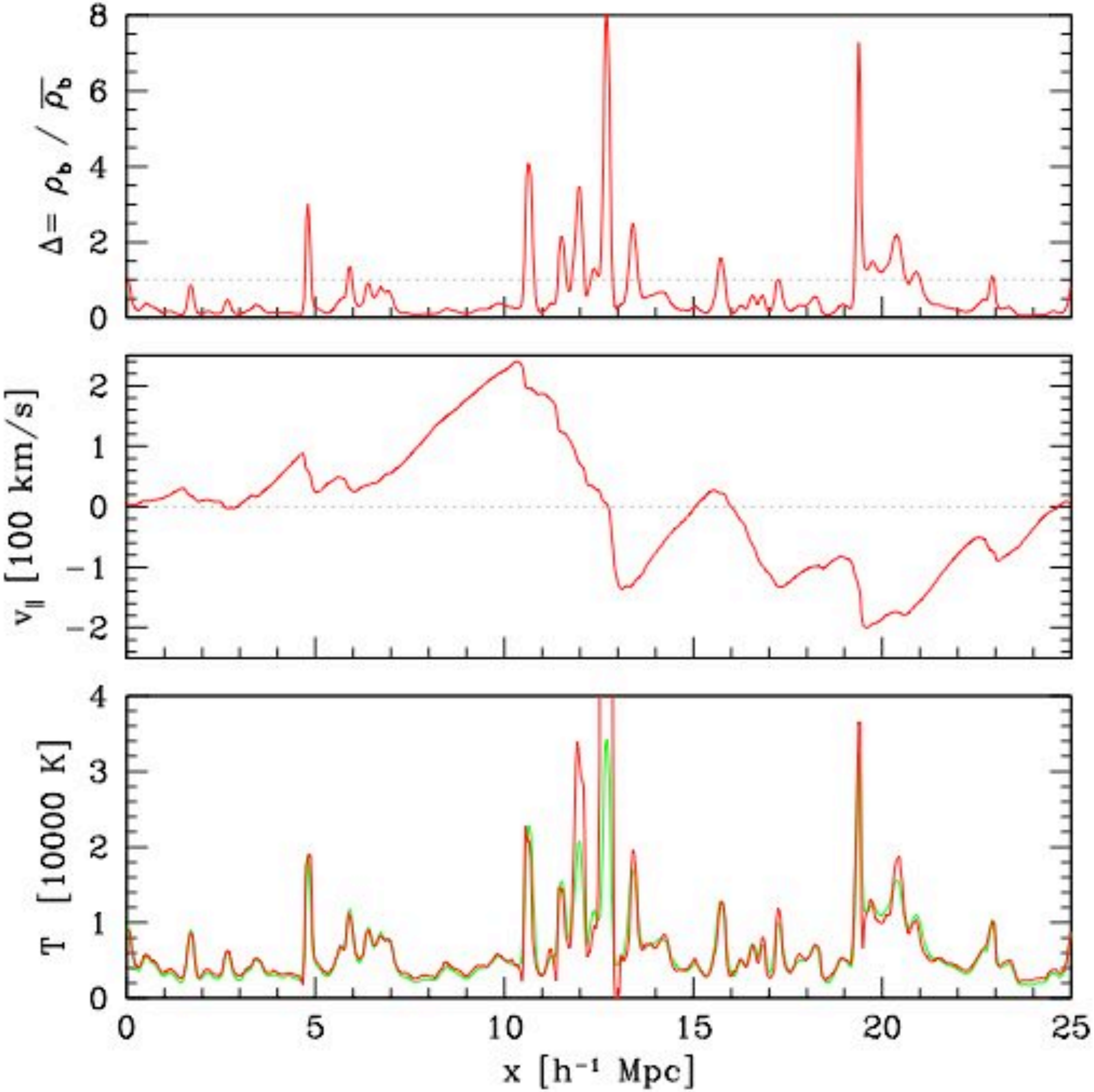
- Bottom line: the history of most of the gas just is not very complicated or very non-linear.

R. Cen simulation

gas density

velocity

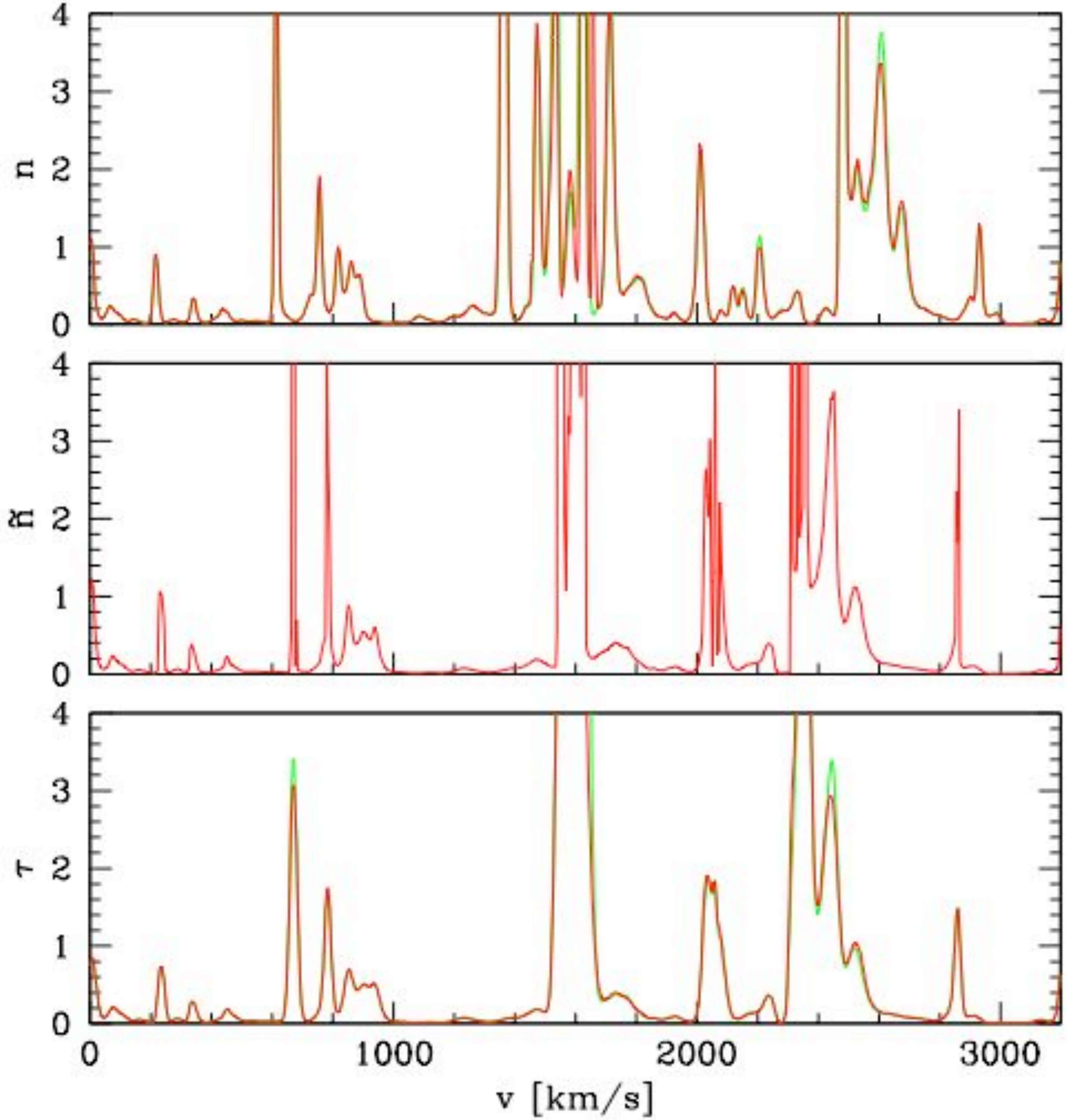
temperature



neutral density

applied peculiar velocities (redshift)

optical depth (applied thermal broadening)



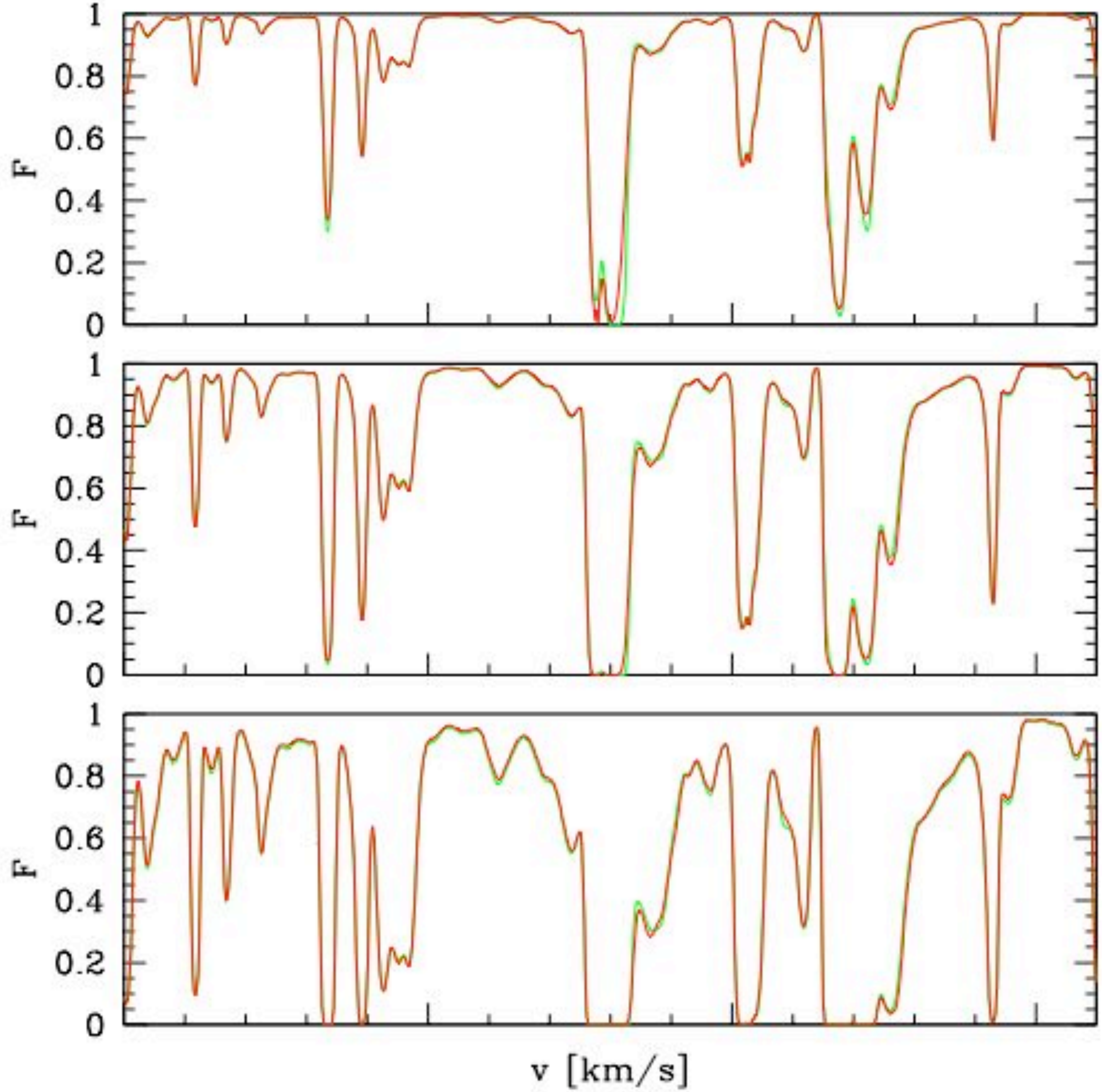
transmitted flux

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

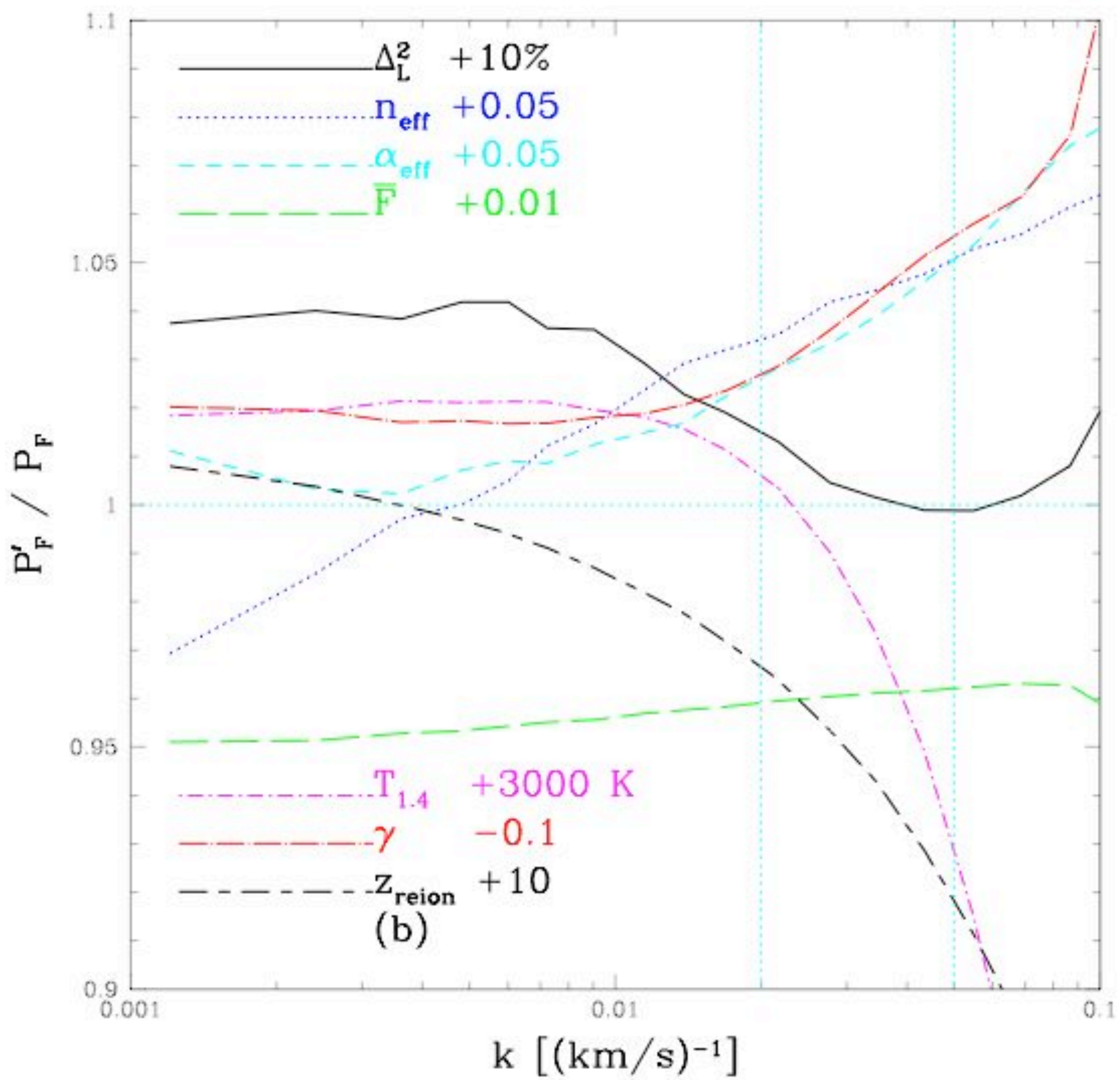
z=2

z=3

z=4

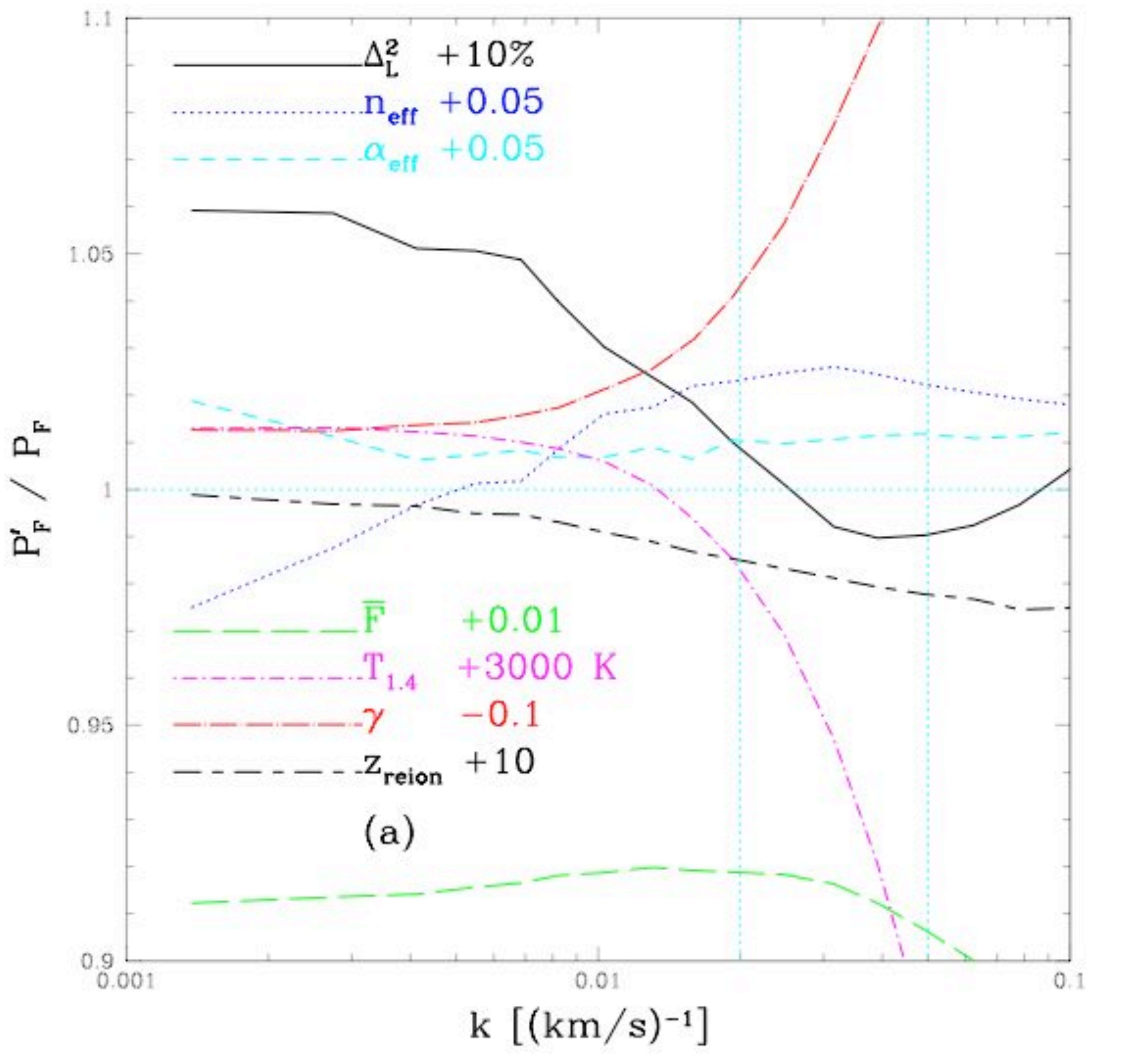


Basic parameter dependences at z~3

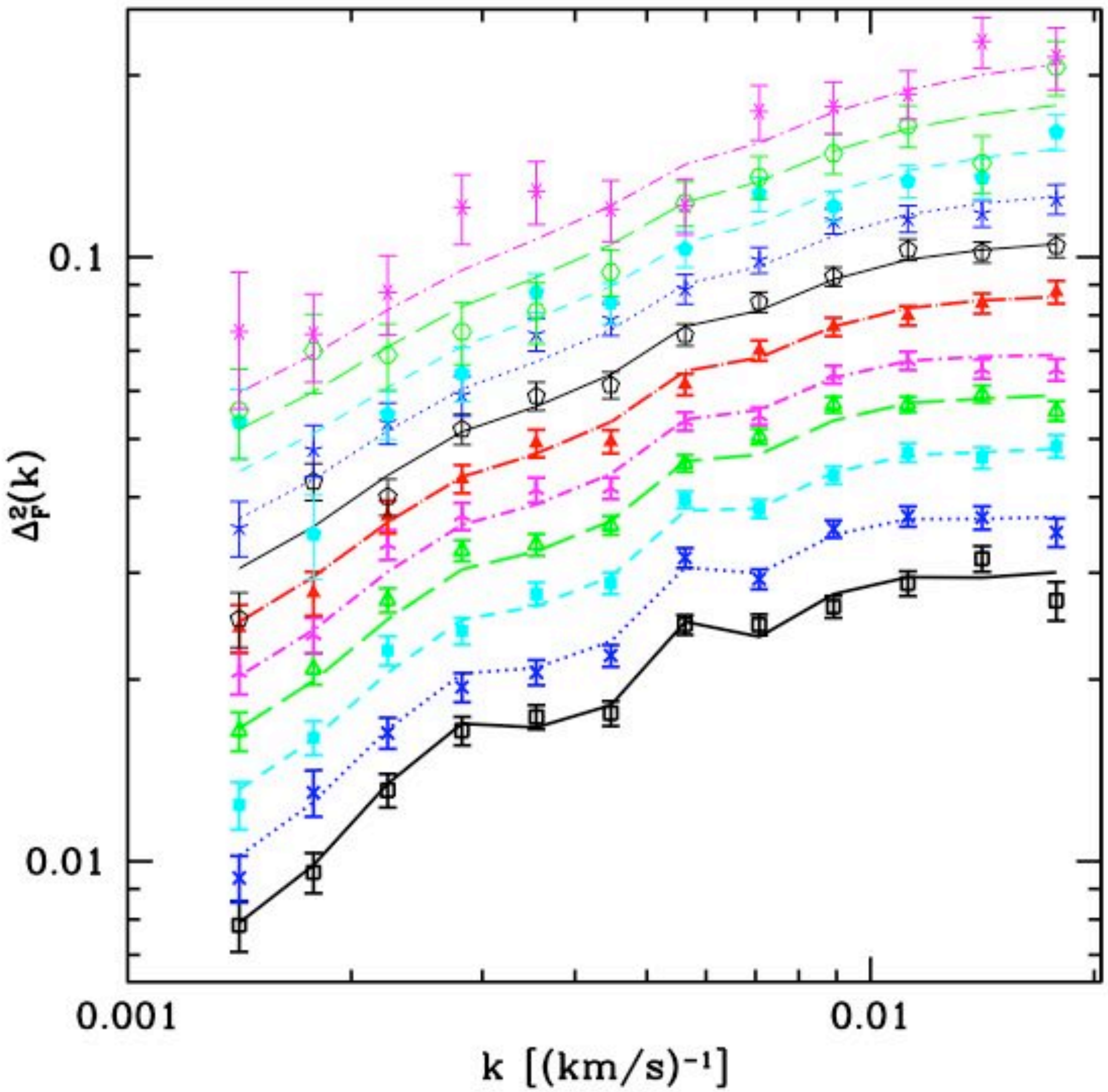


The structure is mildly non-linear so a large grid of numerical simulations is required to fit for the interesting parameters and marginalize over the rest.

Parameter dependence of the power spectrum at z~2



A good fit



- **$\chi^2 \approx 185.6$ for 161 d.o.f. (w/ HIRES)**
- The model fits the data over a wide range of redshift and scale
- Wiggles from SiIII-Lyα cross-correlation

Basic linear power spectrum constraint from the LyaF:

$$\Delta_L^2(k_p, z_p) = 0.452^{+0.069\ +0.141}_{-0.057\ -0.116}$$

$$n_{\rm eff}(k_p, z_p) = -2.321^{+0.055\ +0.131}_{-0.047\ -0.102}$$

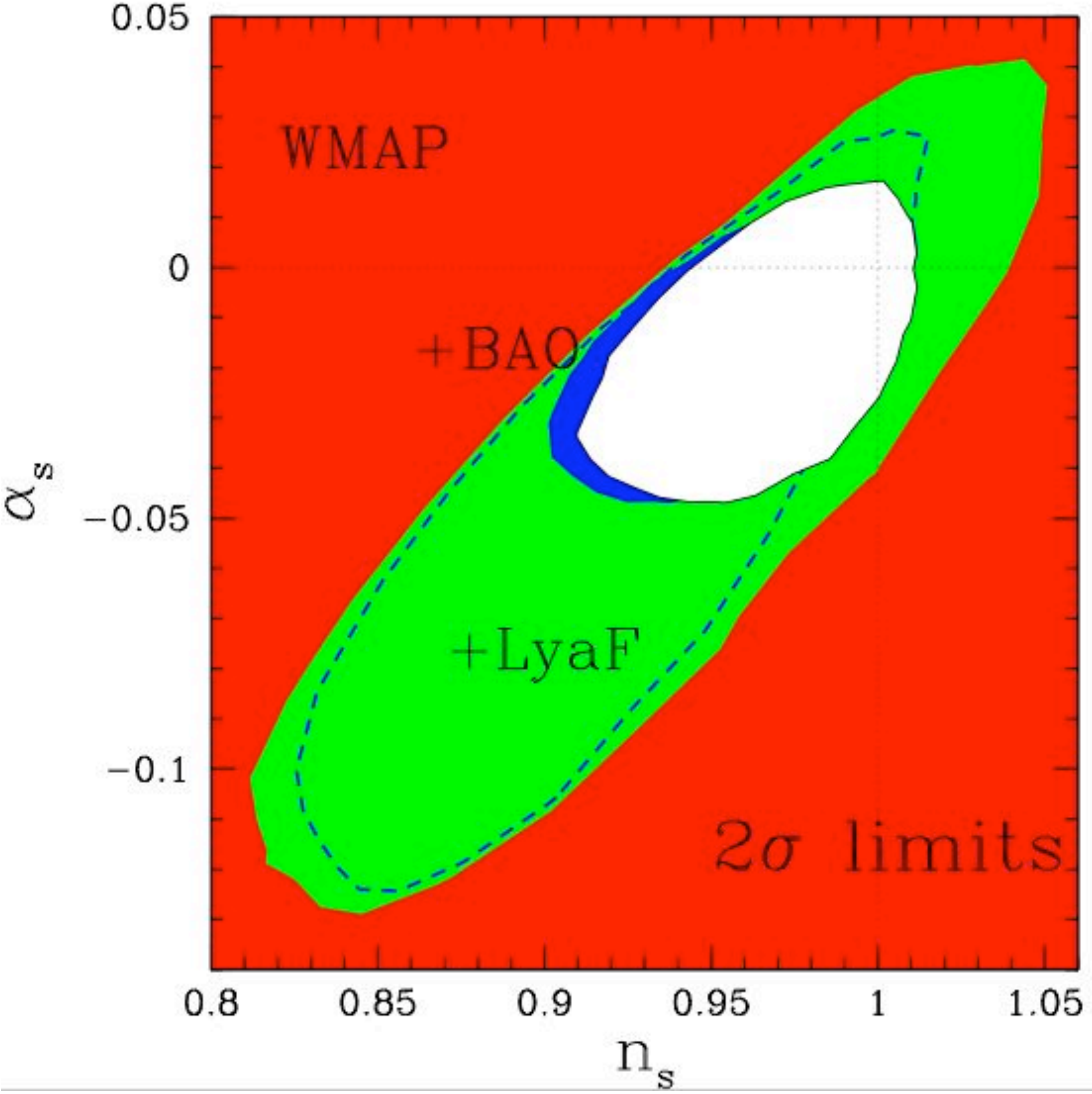
$$k_p = 0.009\ {\rm s/km} \simeq 1\ h\ {\rm Mpc}^{-1}$$

$$z_p = 3.0$$

$$\Delta^2(k) = \frac{k^3}{2\pi^2} P(k) \qquad n_{\rm eff}(k) = \frac{d \ln P(k)}{d \ln k}$$

Primordial power spectrum parameters

$$P(k) \propto (k/k_p)^{n+\frac{1}{2}\alpha \ln(k/k_p)}$$

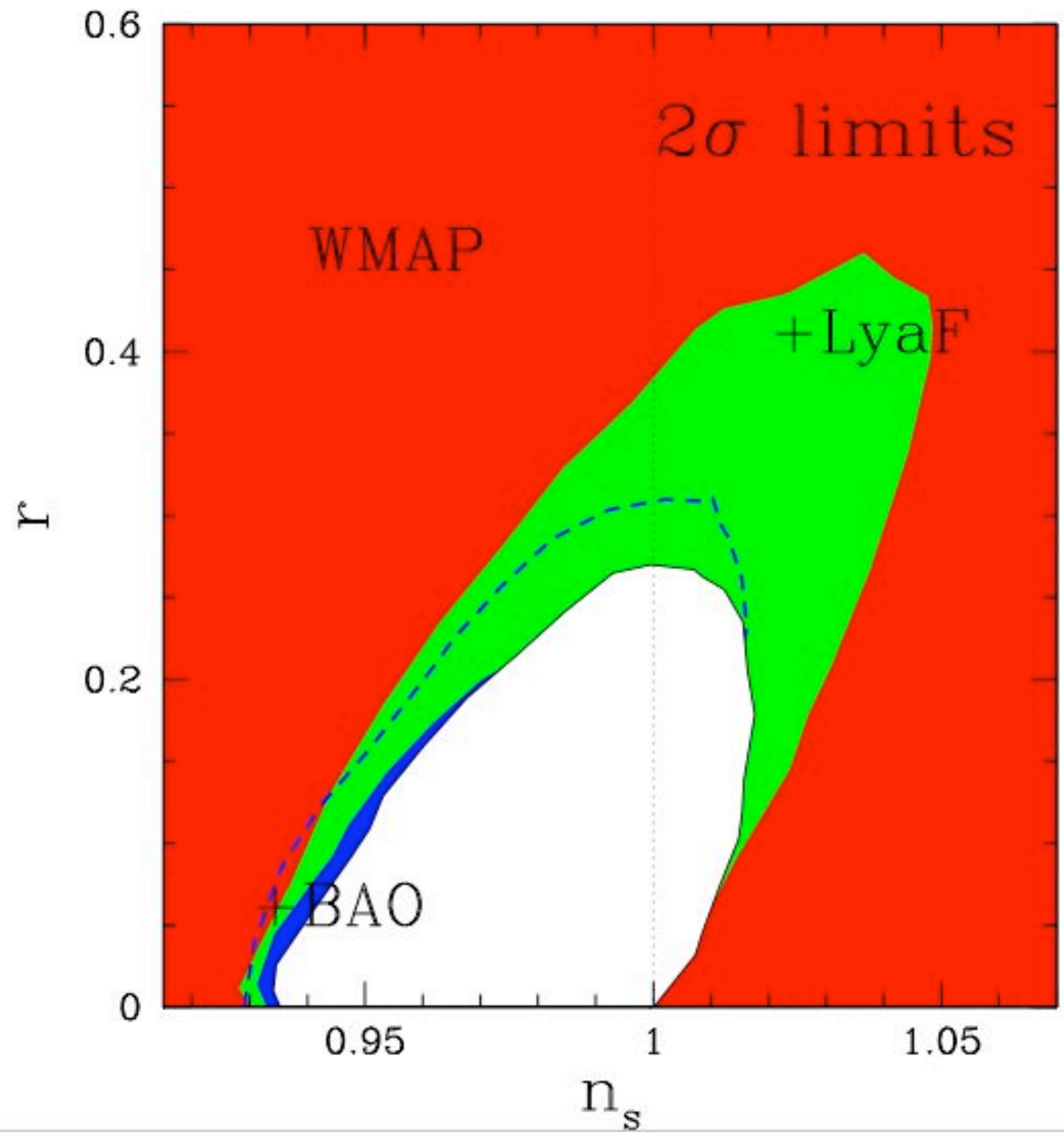


WMAP 5-year

Eisenstein et al. BAO

Includes tensors

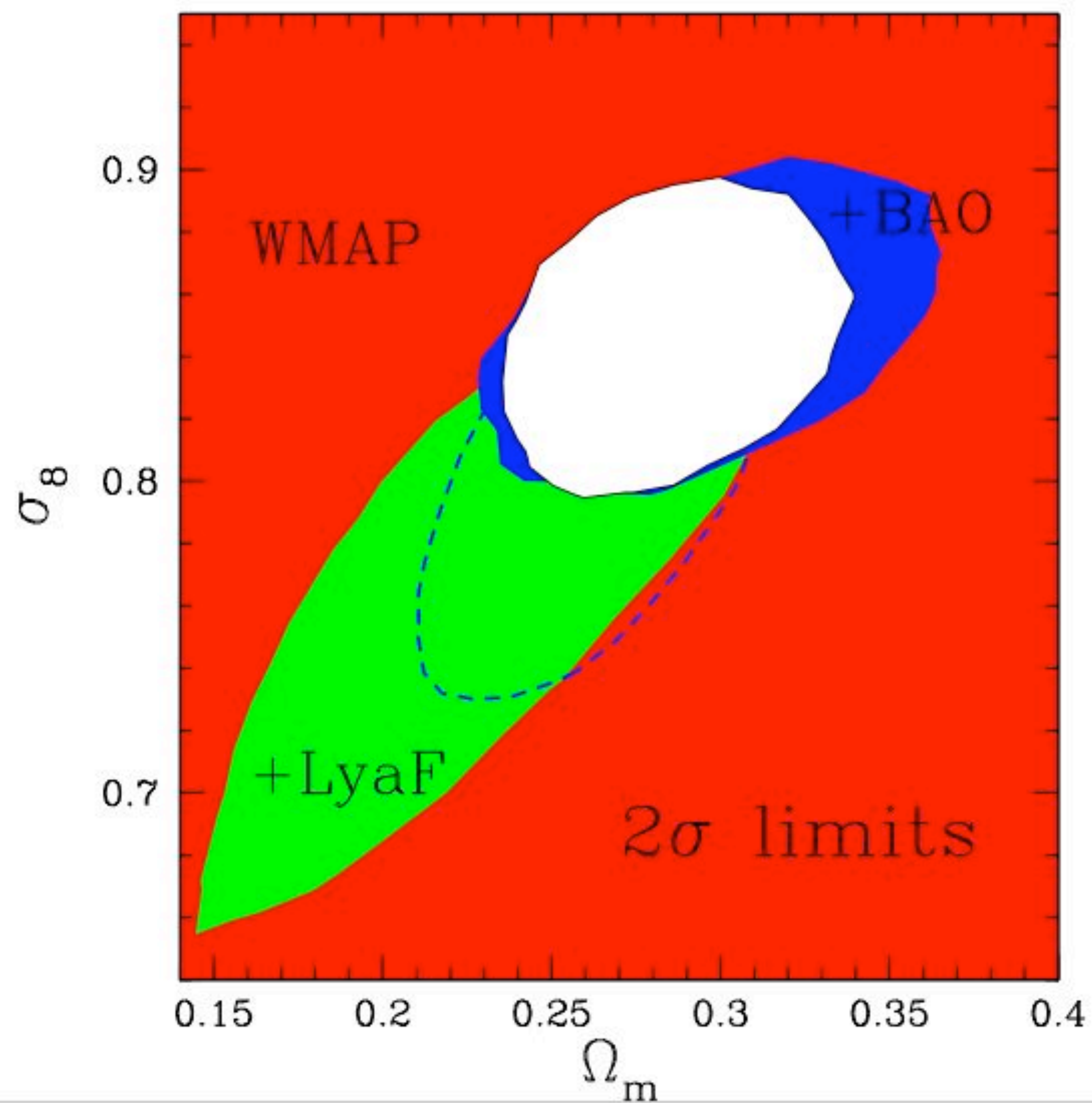
Primordial power spectrum parameters



WMAP 5-year

Eisenstein et al. BAO

Matter density-power amplitude constraint



WMAP 5-year

Eisenstein et al. BAO

Includes tensors

Current parameter highlights

All include tensors, $k_p = 0.05\ \mathrm{Mpc}^{-1}$, WMAP5+Eisenstein BAO+LyaF.

$\sigma_8 = 0.844^{+0.020\ +0.042\ +0.063}_{-0.019\ -0.037\ -0.054}$

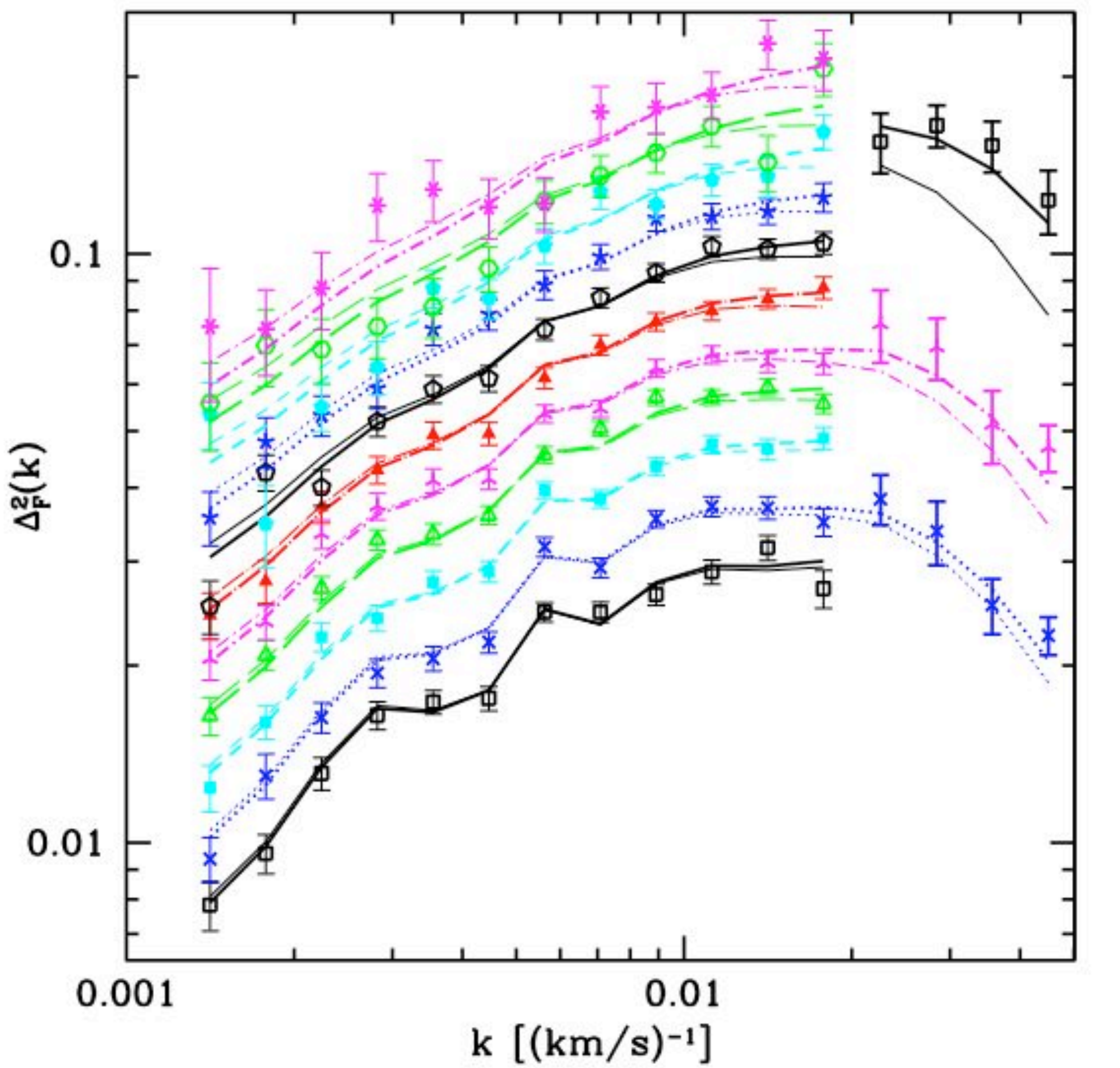
$\Omega_m = 0.284^{+0.021\ +0.042\ +0.067}_{-0.019\ -0.038\ -0.057}$

$\alpha_s = -0.018^{+0.014\ +0.028\ +0.041}_{-0.013\ -0.023\ -0.035}$

$T/S < 0.21$ (95%) $\quad < 0.31$ (99.7%)
(LyaF and BAO independently find similar T/S bound)

$\sum m_\nu < 0.22$ eV (95%) $\quad < 0.32$ eV (99.7%)

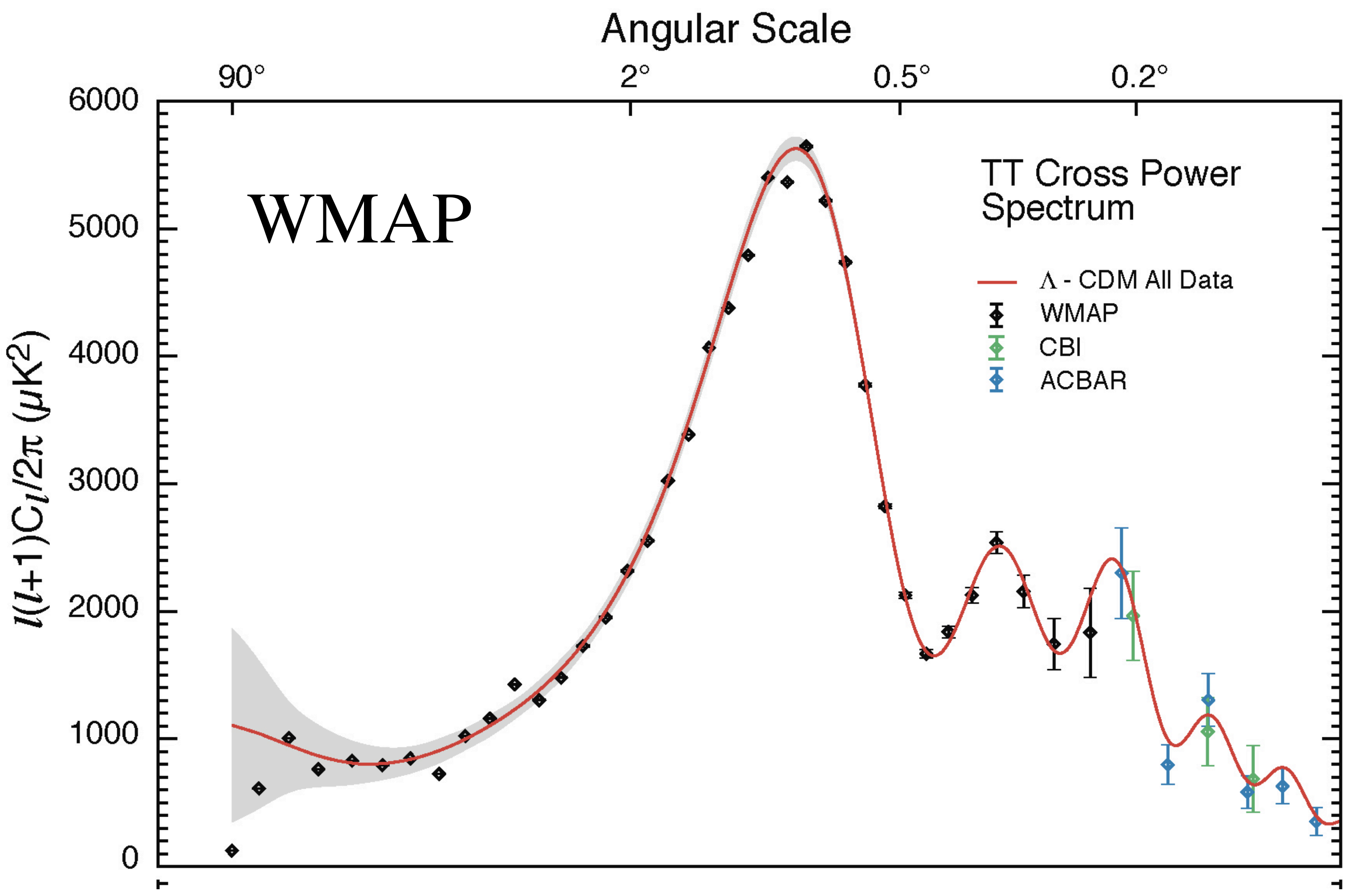
Warm Dark Matter constraints



- Free-streaming of WDM particles suppresses power on small scales.
- Model independent: 50% power suppression scale restricted to k>18 h/Mpc (Gaussian rms smoothing ~<45 kpc/h)
- Translation to particle masses is model dependent
  - Thermal relic (gravitino): mass>2.5 keV
  - Sterile neutrino: mass>14 keV
- Seljak et al. (2006)

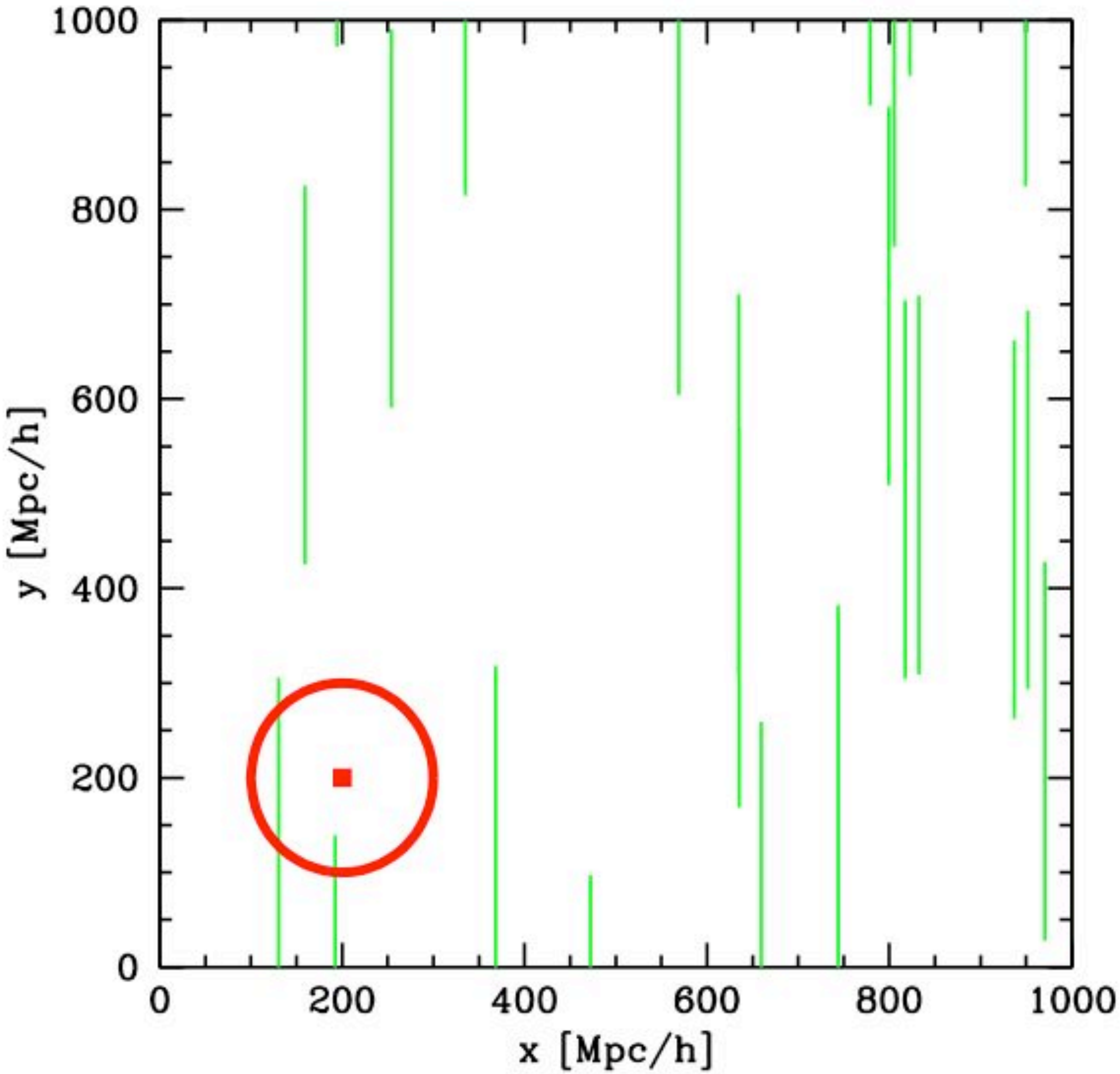
The Future: BOSS and BAO

Baryonic acoustic oscillations



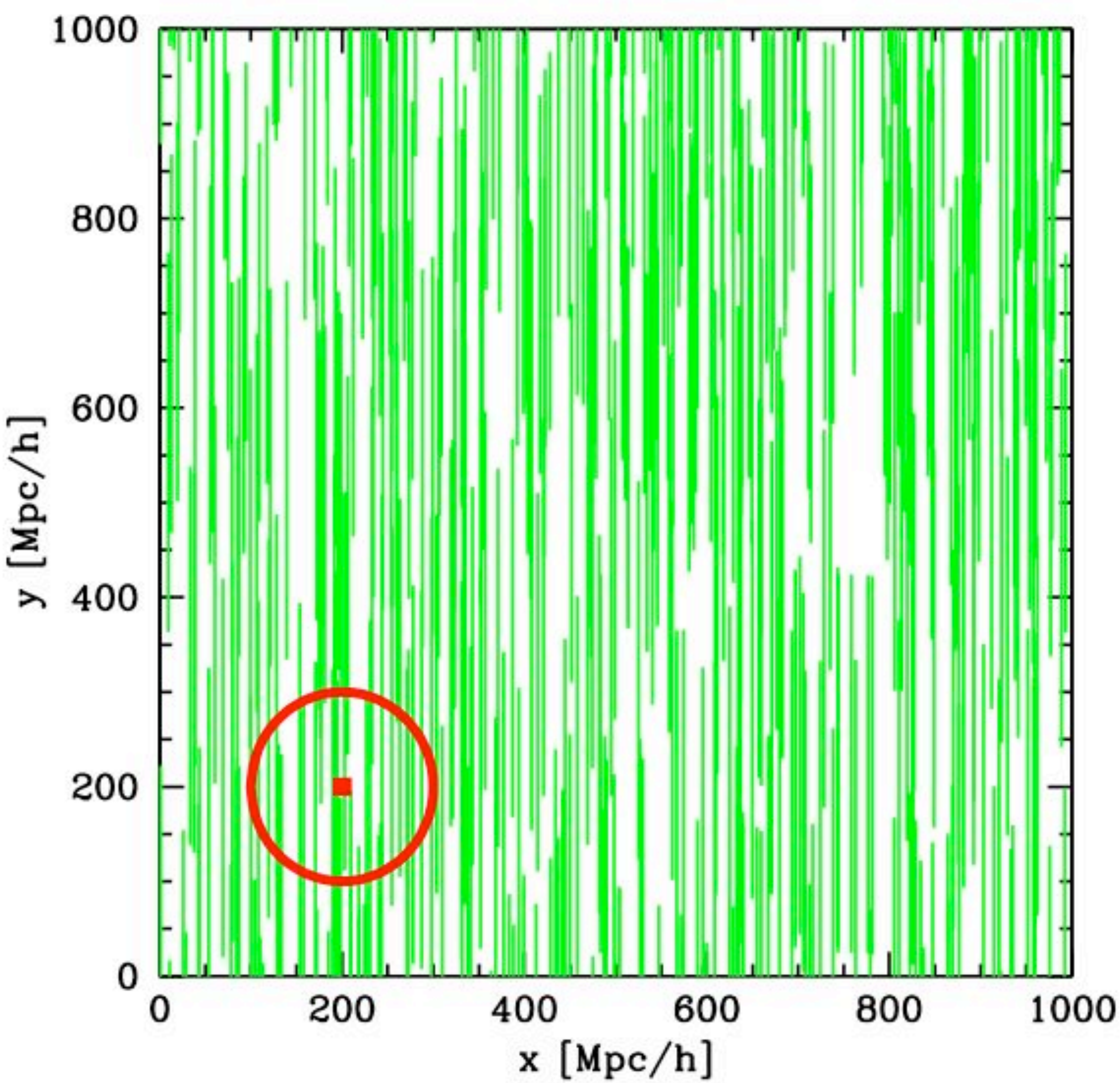
- Observable in principle in any tracer of LSS
- Standard ruler used to study dark energy and curvature
- See Daniel Eisenstein or Martin White's webpages for basic explanation and movies.

Current SDSS: very sparse



- SDSS-II quasar density (1 per sq. deg.)
- 100 Mpc/h deep
- 400 times this volume in SDSS

BOSS LyaF: 3D map of LSS



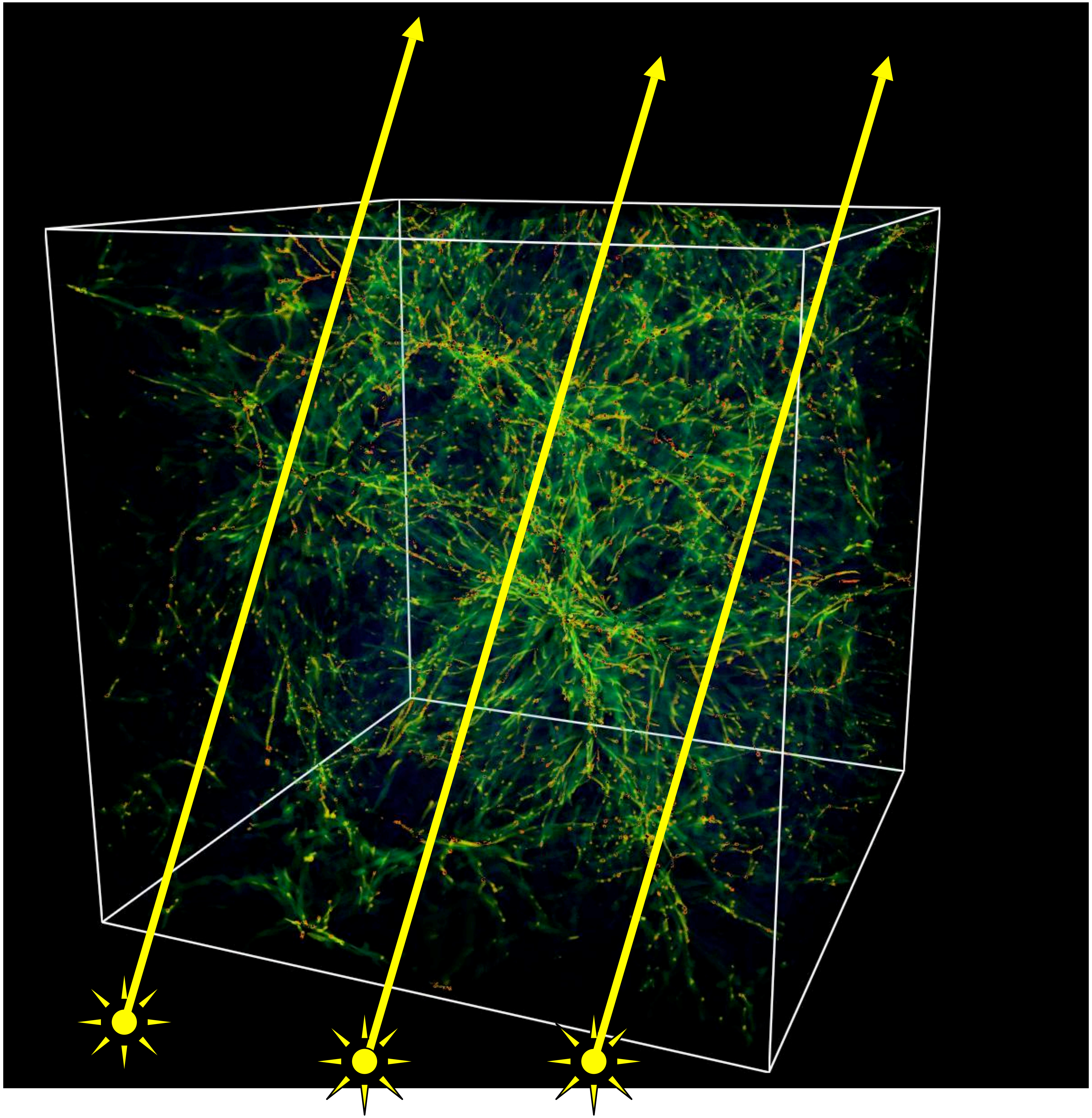
- BOSS quasar density (~20 per sq. deg.)
- this slice is 100 Mpc/h deep
- 400 times this volume in BOSS

BAO scale at $z \sim 3$
$\sim 100\ h^{-1}\mathrm{Mpc} \sim 1.3$ deg.

25 Mpc/h cube

A galaxy BAO survey would probe this volume with ~6 galaxies.
How will we do as a function of the number of quasars probing the volume?

(simulation: R. Cen)



- Standard Fisher matrix error projection requires us to know the 3D power spectrum of the absorption field (up until now, I have always discussed the 1D power spectrum)

Simulated 3D flux power, relative to real-space linear theory (McDonald 2003)

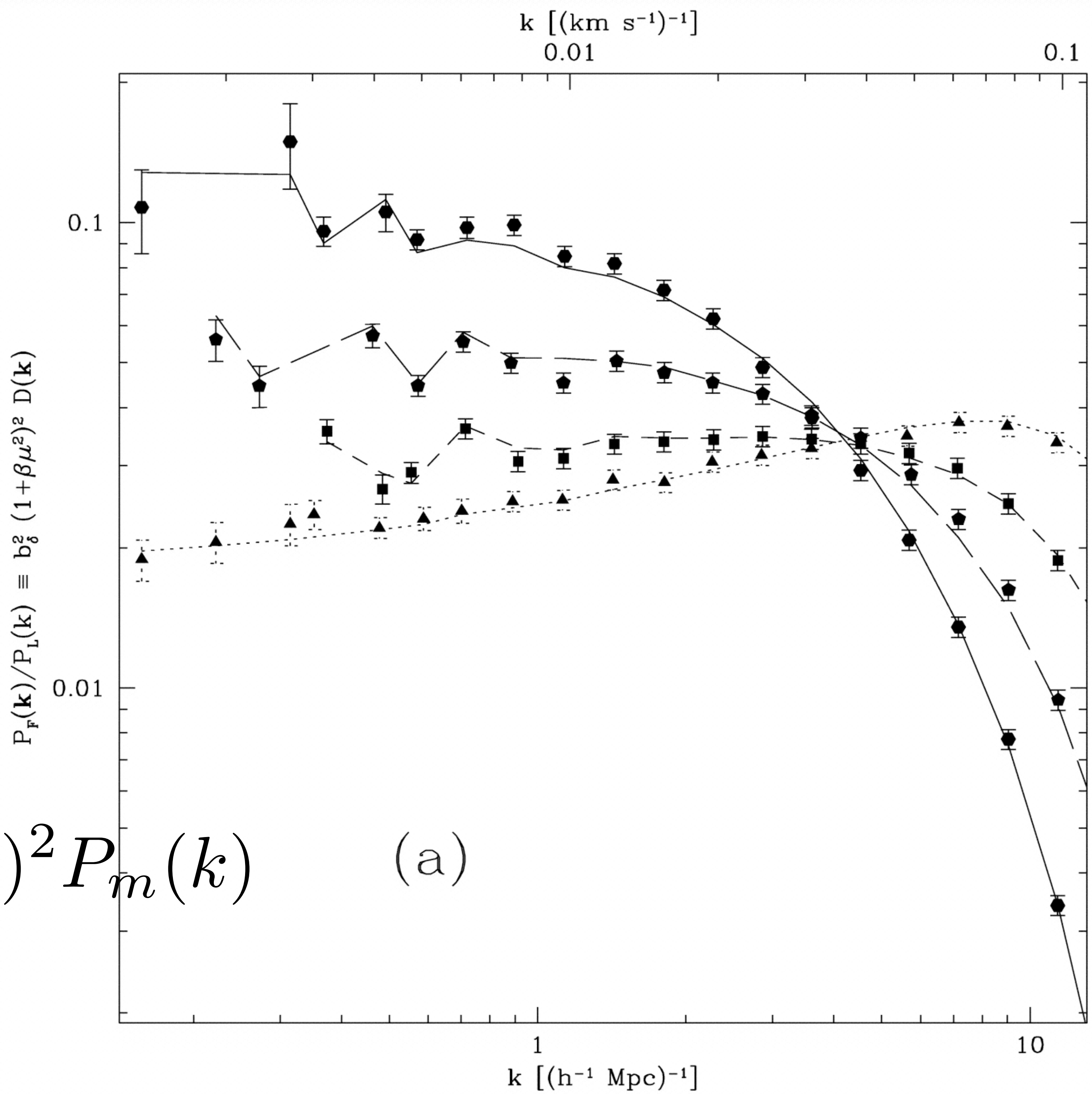
$$\mu = \frac{k_{\parallel}}{k}$$

$\mu = 0.75 - 1$

$\mu = 0.5 - 0.75$

$\mu = 0.25 - 0.5$

$\mu = 0 - 0.25$



$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_m(k)$$

3D flux power, relative to redshift-space linear theory with fitted beta (McDonald 2003)

Top to bottom on right:

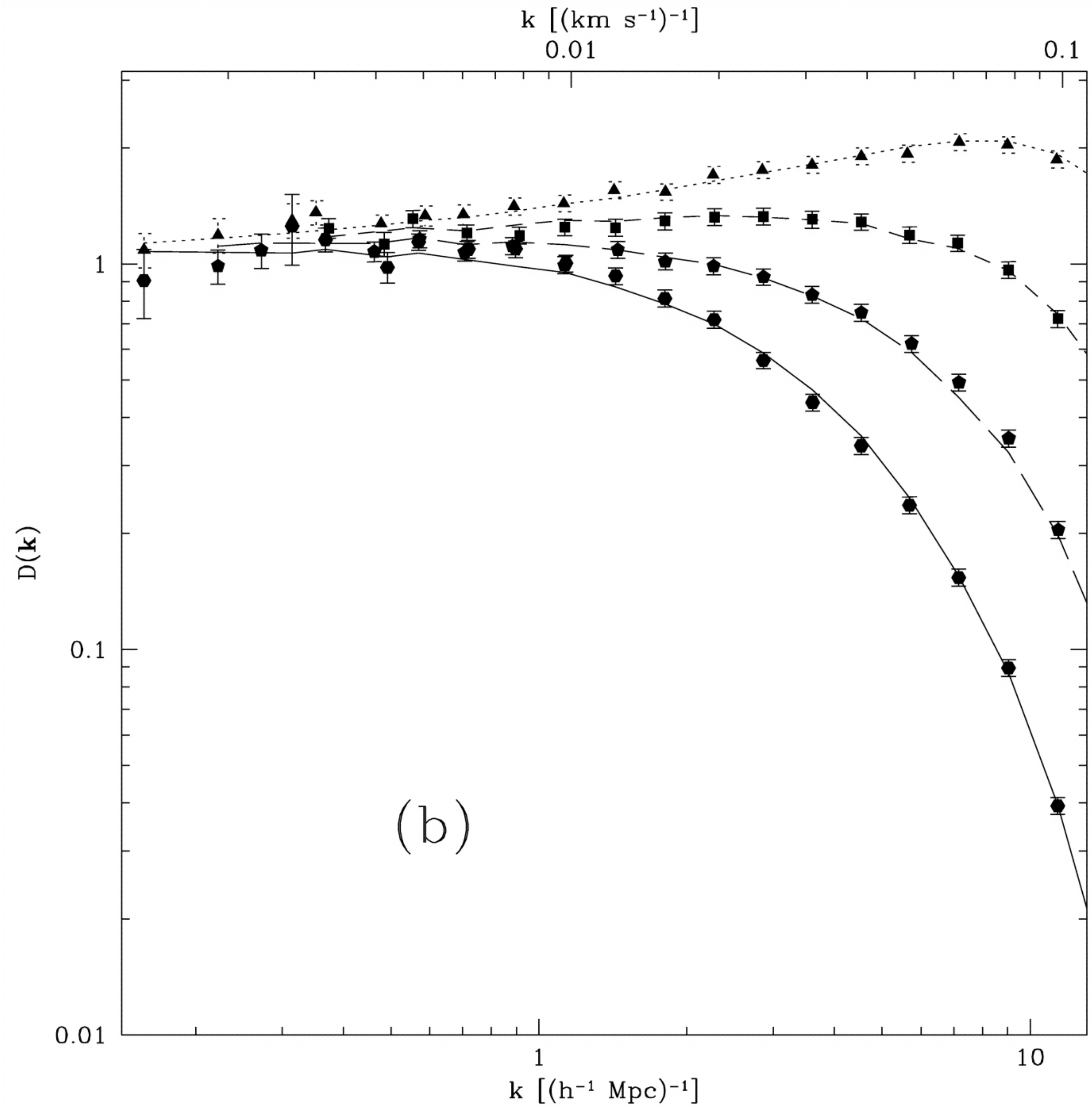
mu=

0-0.25,

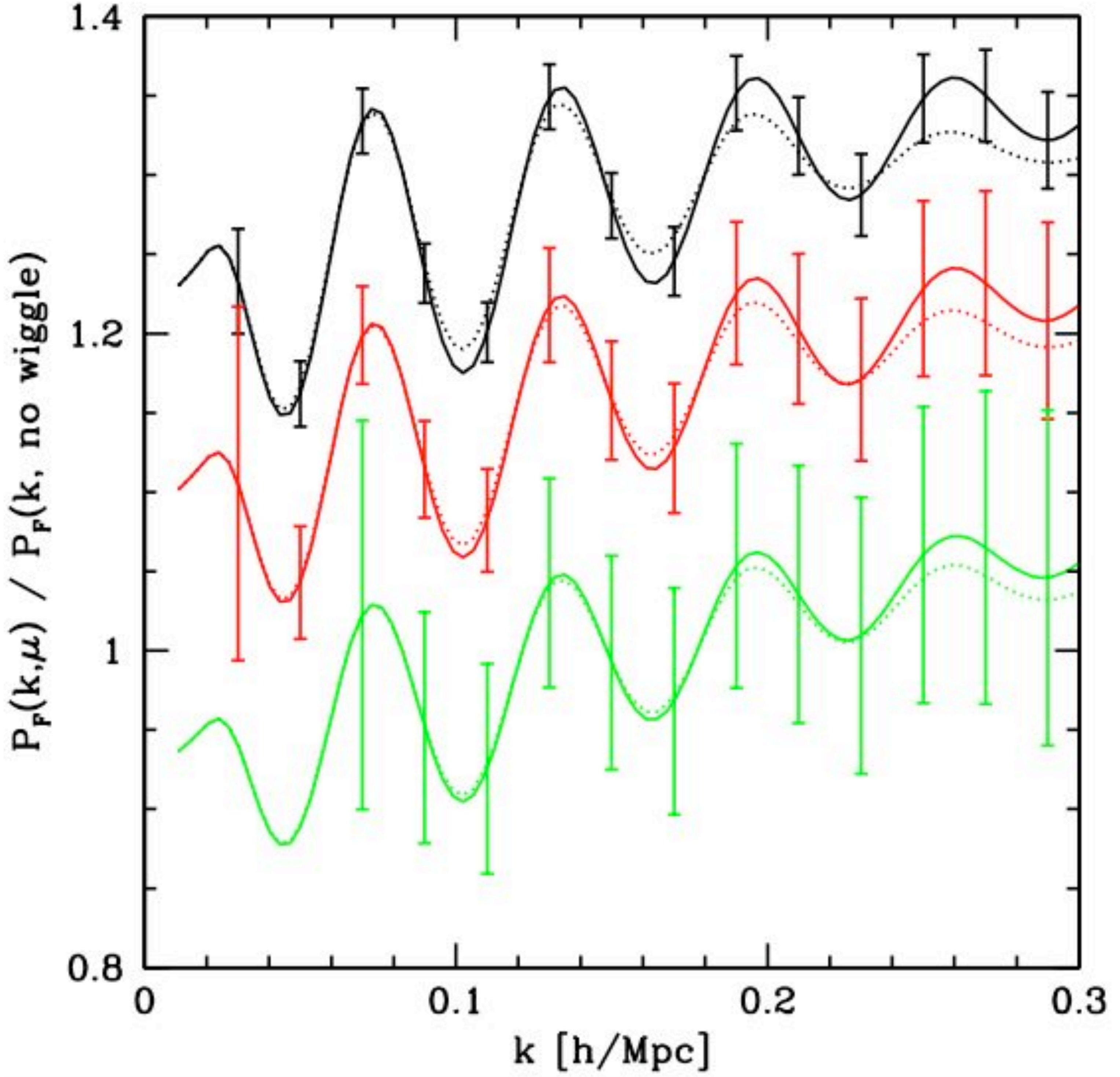
0.25-0.5,

0.5-0.75,

0.75-1.0

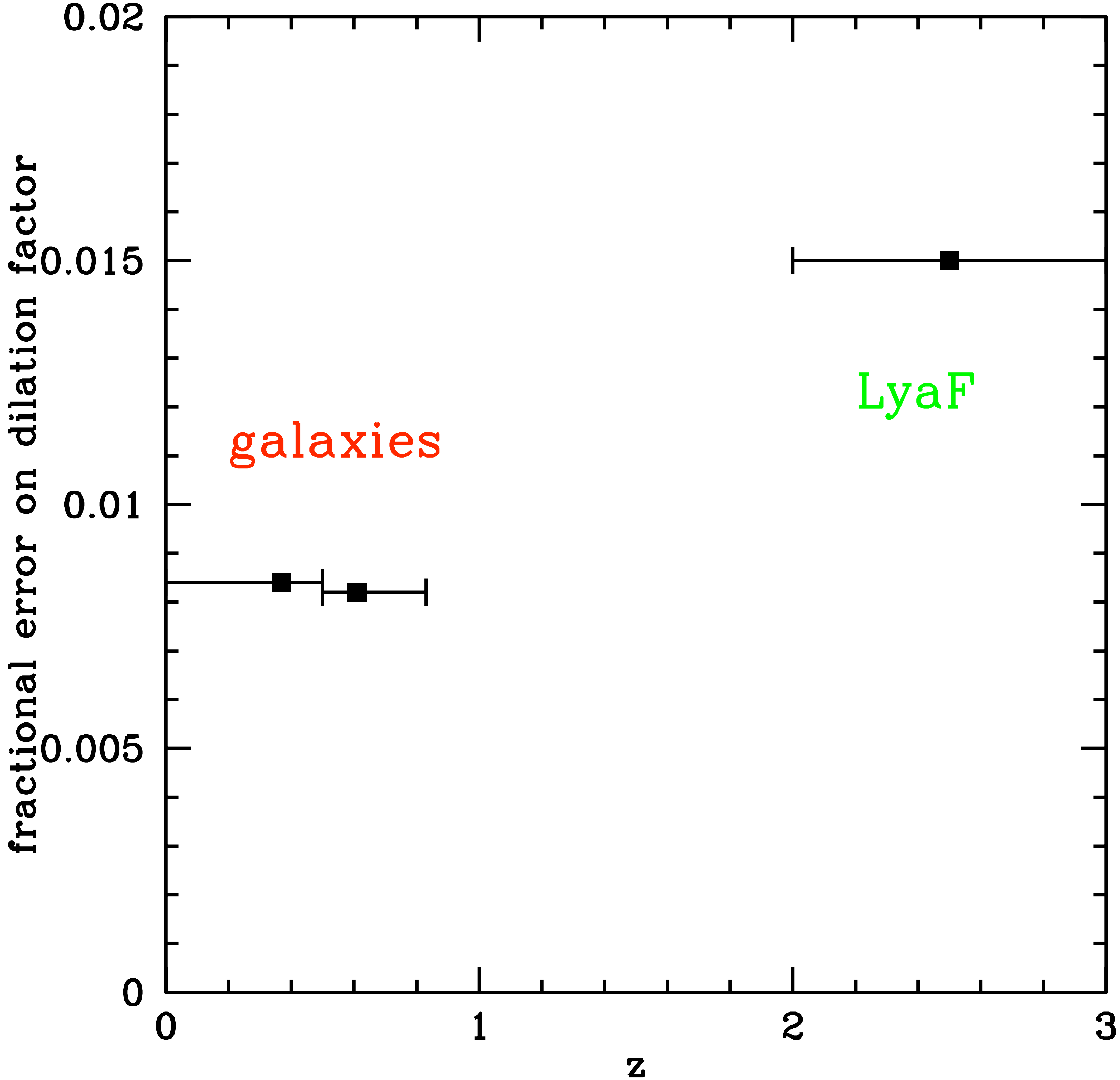


BOSS 3D band power projection



- Black: radial
- Green: transverse
- Red: diagonal
- Dotted: Seo & Eisenstein non-linear smearing
- Normalizations compressed.

Expected BAO distance scale constraints from BOSS



(Original) DETF FoM

- All include Planck, DETF Stage II (~ongoing) experiments, BOSS BAO only

Expt.	σ_{Ω_K}	σ_{w_p}	σ_{w_0}	$\sigma_{w'}$	FoM
Stage II	0.0031	0.036	0.12	0.52	53
+BOSS gal	0.0027	0.031	0.090	0.37	87
+BOSS gal & LyaF	0.0022	0.030	0.081	0.31	107

$$w(a) = \frac{p_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a(1-a)$$

General constraints (not just BAO)

- Running of the spectral index

	ω_m	ω_b	$\log_{10}(A)$	n_s	α_s	τ	h	Ω_m
value	0.128	0.0223	−8.64	0.950	0.00	0.0890	0.731	0.240
P+gB	0.00068	0.00015	0.0087	0.0029	0.0063	0.0098	0.0037	0.0035
P+gB+hr+ssI+boss	0.00058	0.00012	0.0082	0.0027	0.0026	0.0094	0.0030	0.0029

- Neutrino mass

	ω_m	ω_b	Σm_ν	$\log_{10}(A)$	n_s	τ	h	Ω_m
value	0.128	0.0223	0.0850	−8.64	0.950	0.0890	0.730	0.240
P+gB	0.00069	0.00017	0.094	0.0084	0.0046	0.0097	0.0046	0.0039
P+gB+hr+ssI+boss	0.00057	0.00013	0.056	0.0080	0.0035	0.0095	0.0041	0.0035

Why these results are conservative:

- Use only the power spectrum, while we know that the bispectrum can help break degeneracies between cosmological and gas model parameters.
- Similarly, other statistics, e.g., measurements in the Ly-beta forest, can help break degeneracies.
- Plenty of consistency checks: other statistics, redshift evolution, data splitting (especially if Planck-limited).

BigBOSS

- Qualitatively similar to BOSS, just more spectra, better S/N.
- For 24000 sq. deg., BAO distance error ~0.4%

Conclusions

- BOSS LyaF will measure the BAO distance scale at z~2.5 to ~1.5%, and future surveys like BigBOSS can do substantially better.
  - BOSS will ~double the Dark Energy FoM (over stage II)
  - Omega_K to +-0.0022
- Planck+BOSS can measure the running of the spectra index to +-0.0026.
- Planck+BOSS can measure the sum of neutrino masses to +-0.056 eV.
- Numerous other tests of the evolution of structure across the 2<z<4 redshift range should be possible, especially when including statistics other than the power spectrum (e.g., the bispectrum).