Computational cosmology: the Lyman-α forest

Pat McDonald

(CITA)

U. Seljak, A. Makarov, R. Cen, S. Burles, D. J. Schlegel, R. Mandelbaum, H. Trac, D. H. Weinberg, P. Bode, D. Shih, E. Switzer, J. Schaye, D. P. Schneider, J. P. Ostriker, and everyone who worked on SDSS

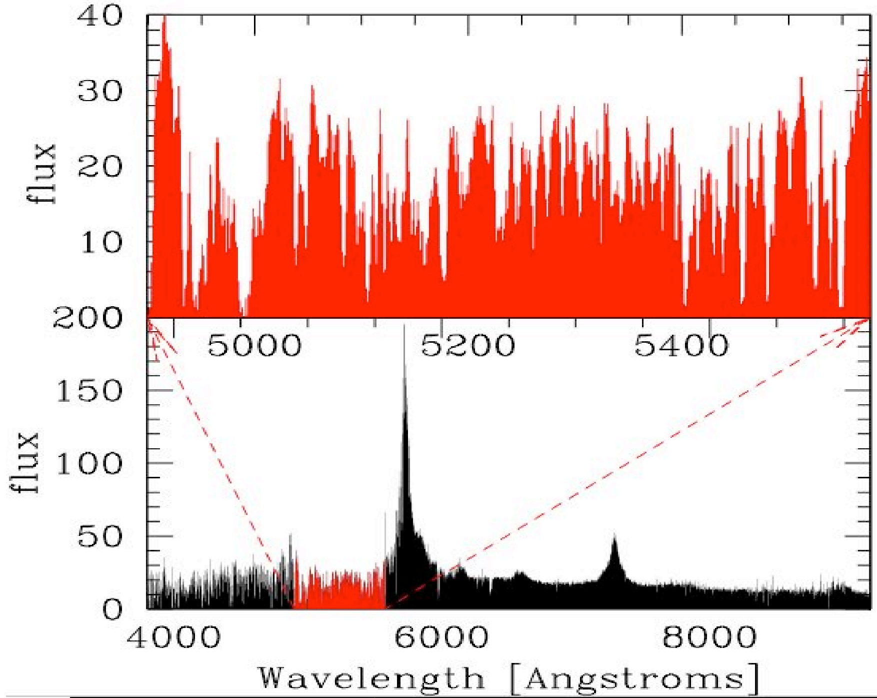
ICTP, June 3, 2005

The Lyman-α forest is 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

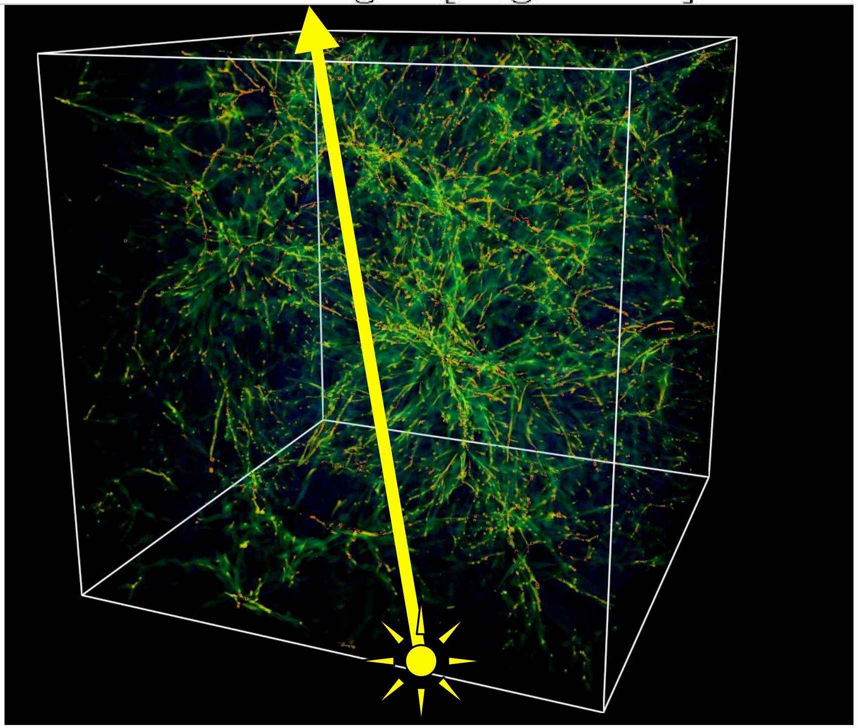
Ly-alpha forest

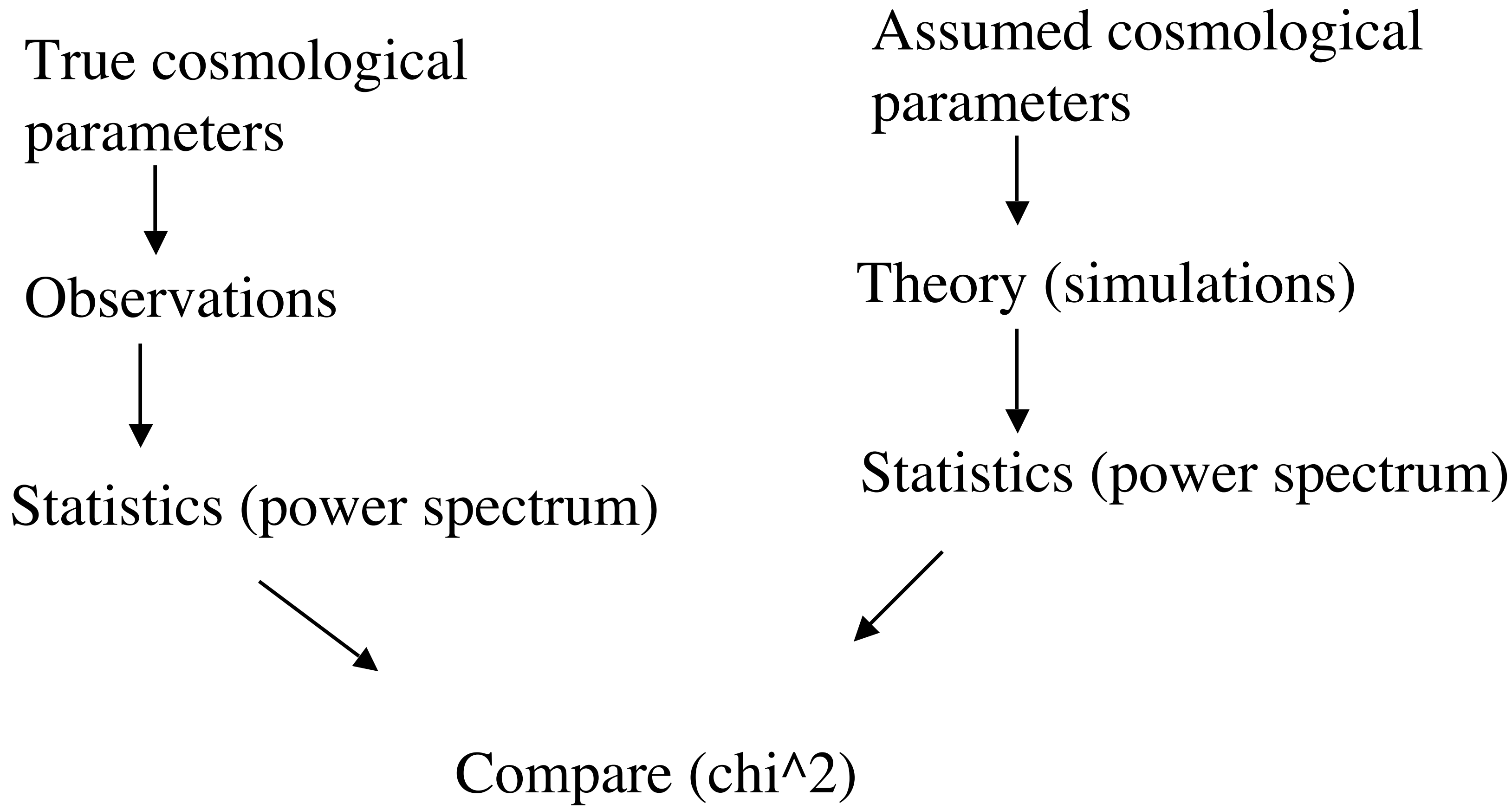
SDSS quasar spectrum



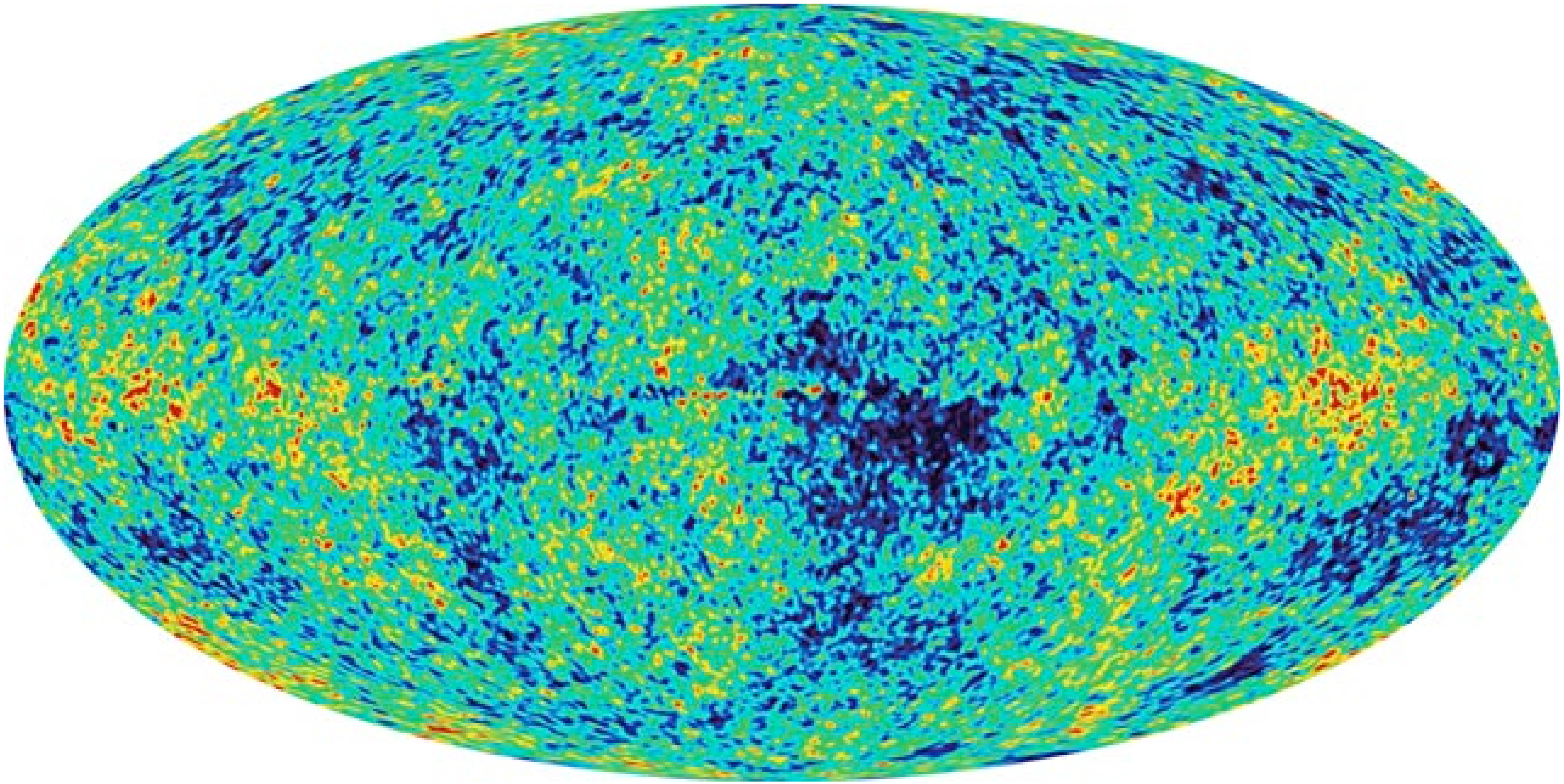
Cen simulation of the IGM (neutral hydrogen)

z = 3.7 quasar

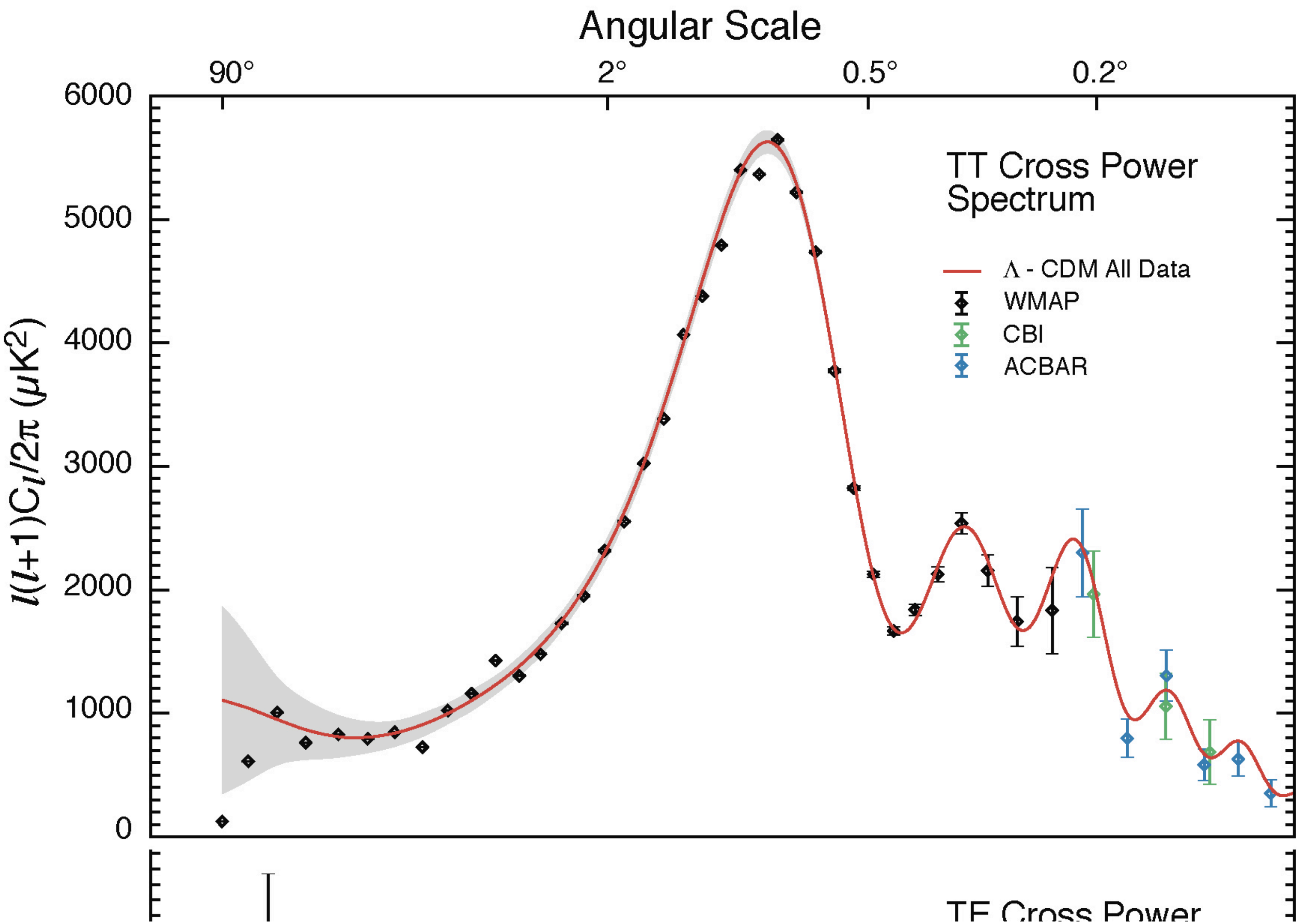



True cosmological parameters
Observations
Statistics (power spectrum)
Assumed cosmological parameters
Theory (simulations)
Statistics (power spectrum)
Compare (chi^2)

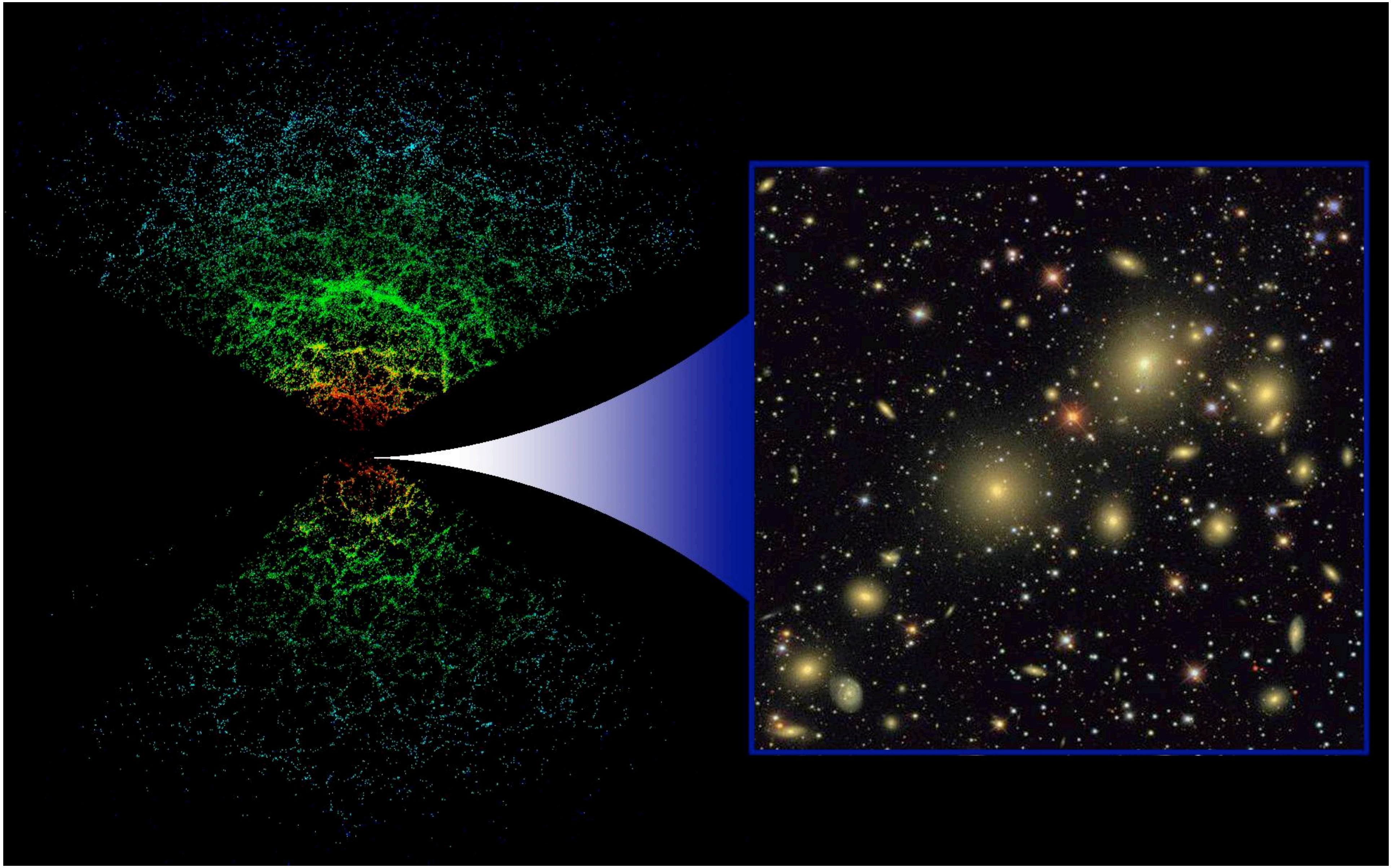
WMAP CMB map



WMAP CMB power spectrum

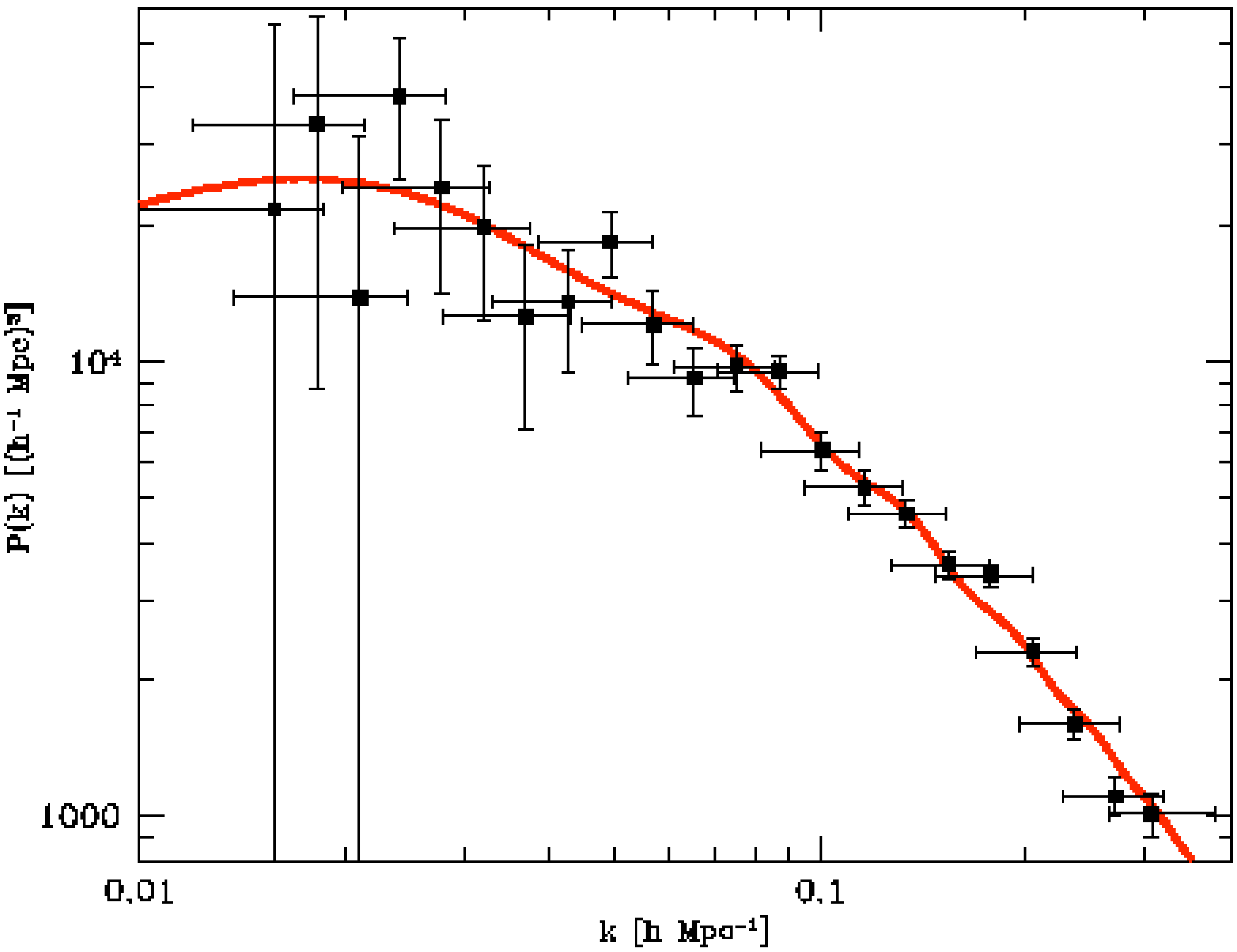


SDSS Galaxy map

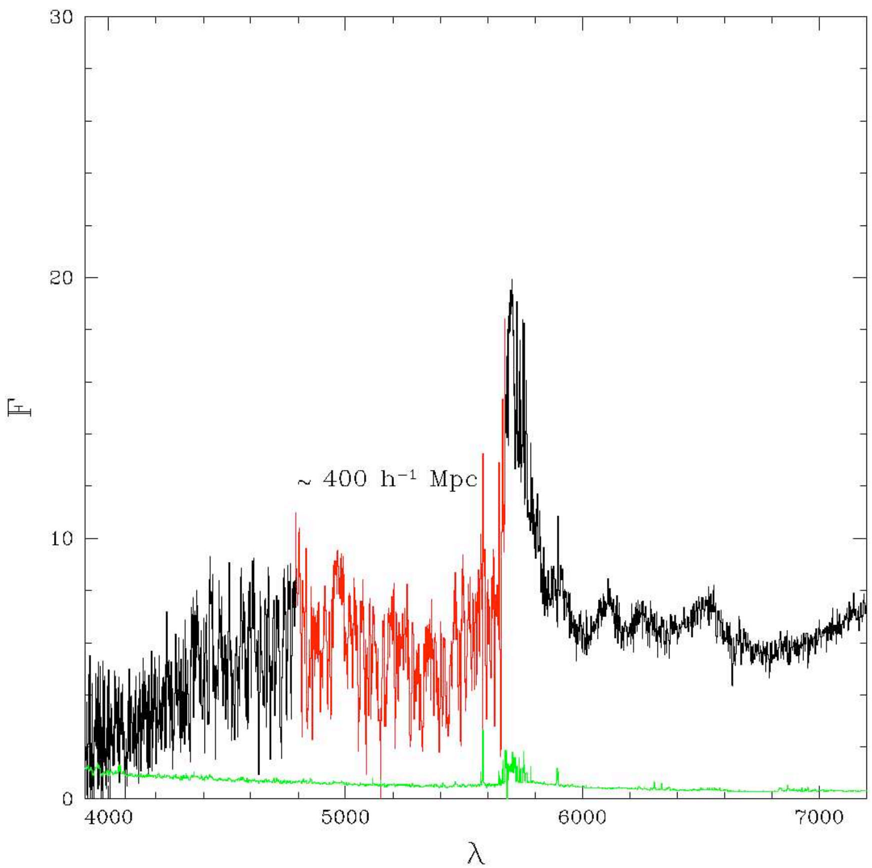


SDSS galaxy power spectrum

(Tegmark et al.)



SDSS Spectra

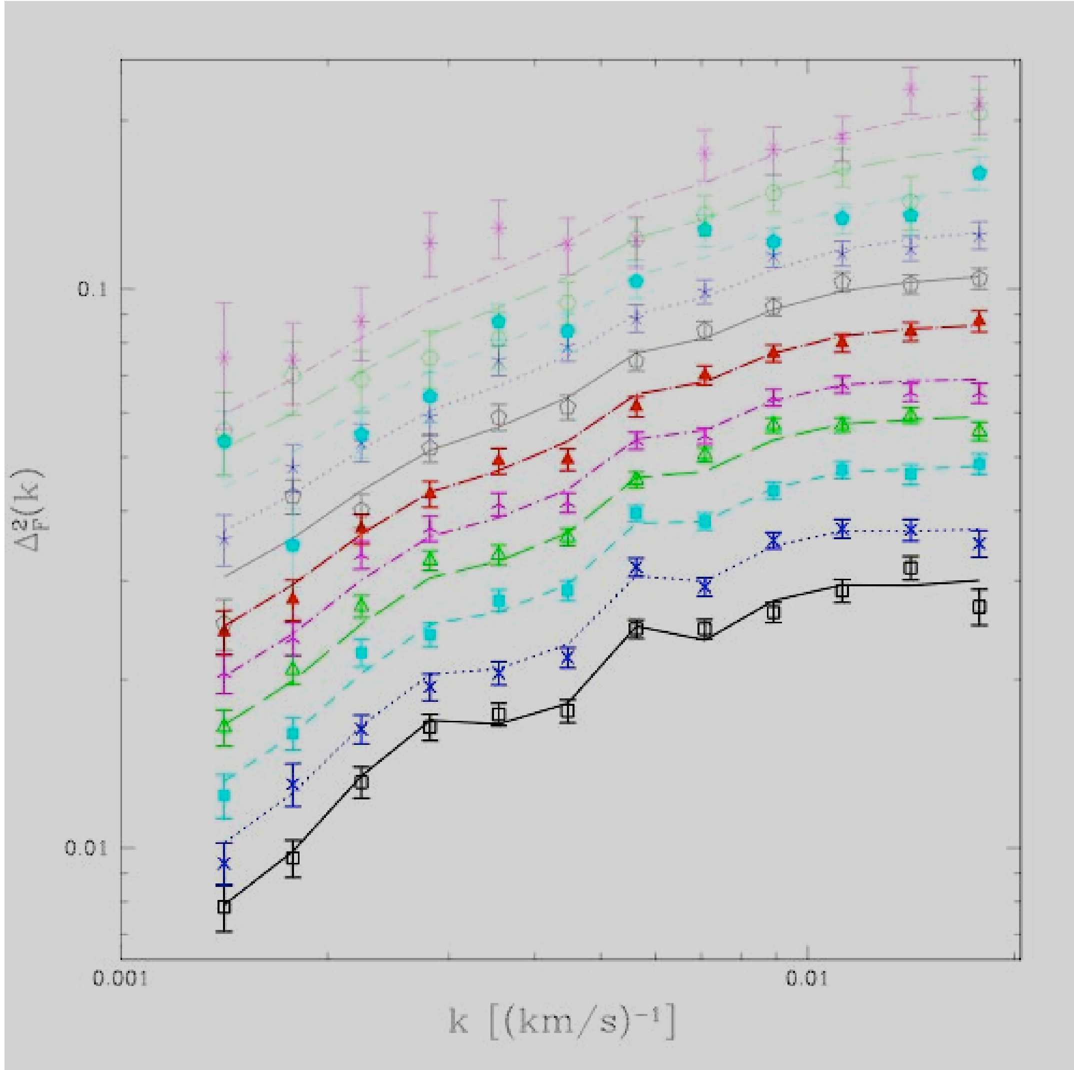


- Resolution typically 160 km/s (FWHM)
- Pixel size 70 km/s
- We use spectra with S/N>1, with a typical S/N≈4 (per pixel)
- This is an unusually good one

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

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

Ly-alpha Power

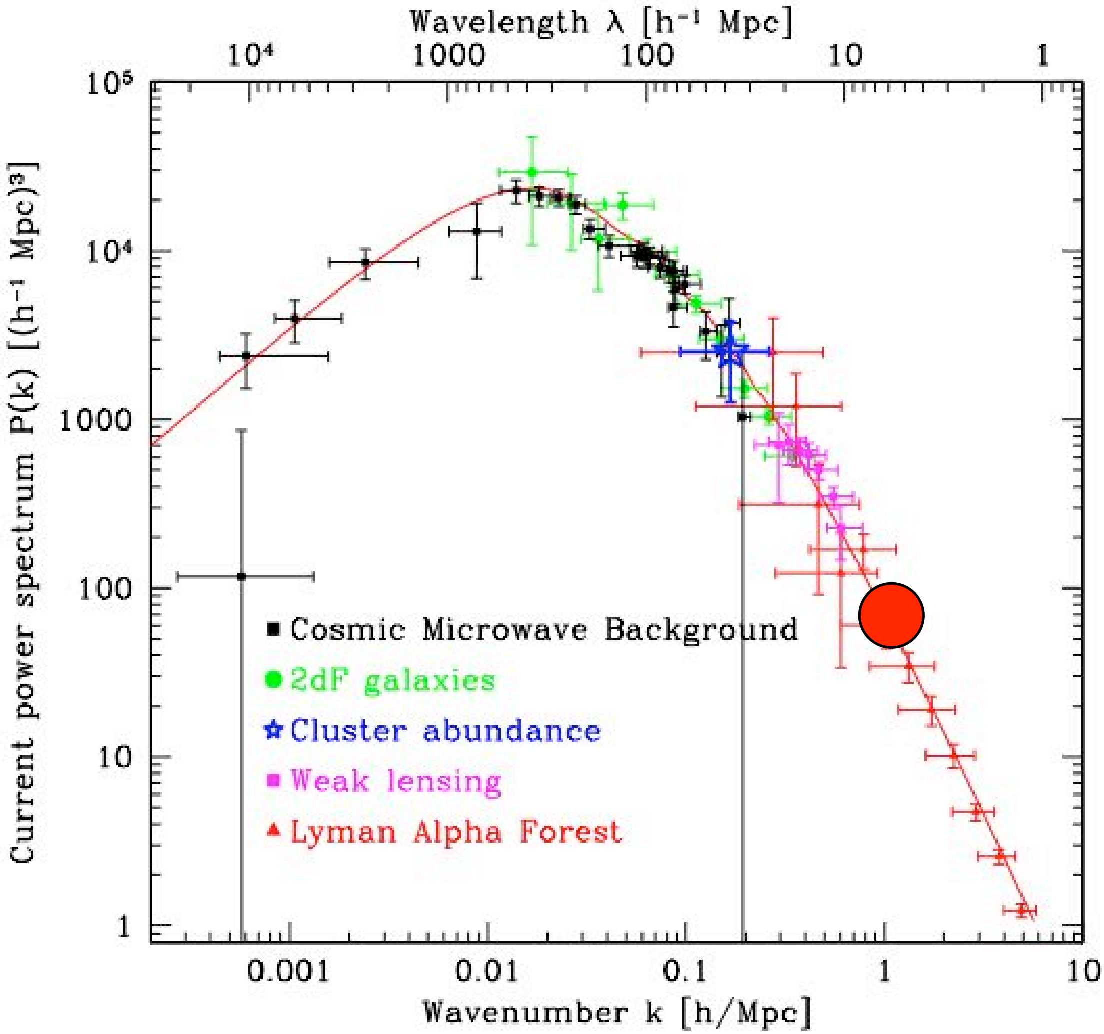


- $\Delta^2(k) = \pi^{-1}\, k\, P(k)$
  (0.01 s/km ~ 1 h/Mpc)
- Colors correspond to redshift bins centered at z = 2.2, 2.4, …, 4.2 (from bottom to top)
- $1041<\lambda_{rest}<1185$ Å
- Computed using optimal weighting
- Noise subtraction
- Resolution correction
- Background subtraction using regions with $\lambda_{rest}>1268$ Å
- Error bars from bootstrap resampling
- Code tested on semi-realistic mock spectra
- HIRES/VLT data probes smaller scales

What can we learn from Ly-alpha?

- Dark matter fluctuations on relatively small (few Mpc) scales: amplitude, slope, curvature of the linear power spectrum
- Growth of fluctuations over $2<z<4$
- More leverage when combined with the CMB
- Improve neutrino mass limits, and cosmological parameters in general

Scales of various LSS probes



The Lyα forest is great for determining the running of the spectral index, $\boxed{\alpha \equiv \frac{dn}{d\ln k}}$, because it extends our knowledge to small scales

We only report an amplitude and slope
no band powers

(out of date figure by Max Tegmark)

Basic linear power spectrum constraint from the LyaF:

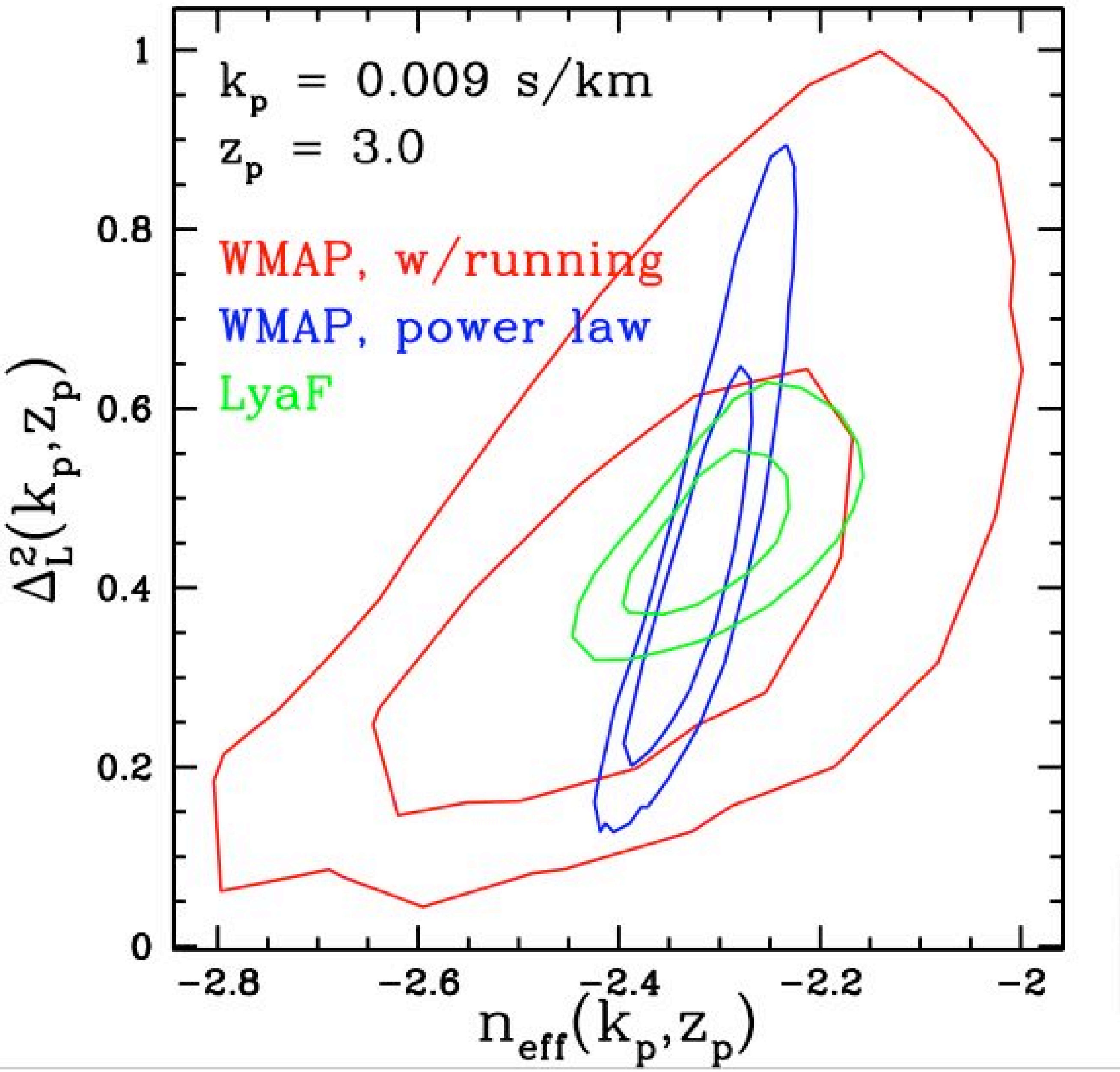
$$\boxed{\Delta_L^2(k_p, z_p) = 0.452^{+0.069\ +0.141}_{-0.057\ -0.116}}$$

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

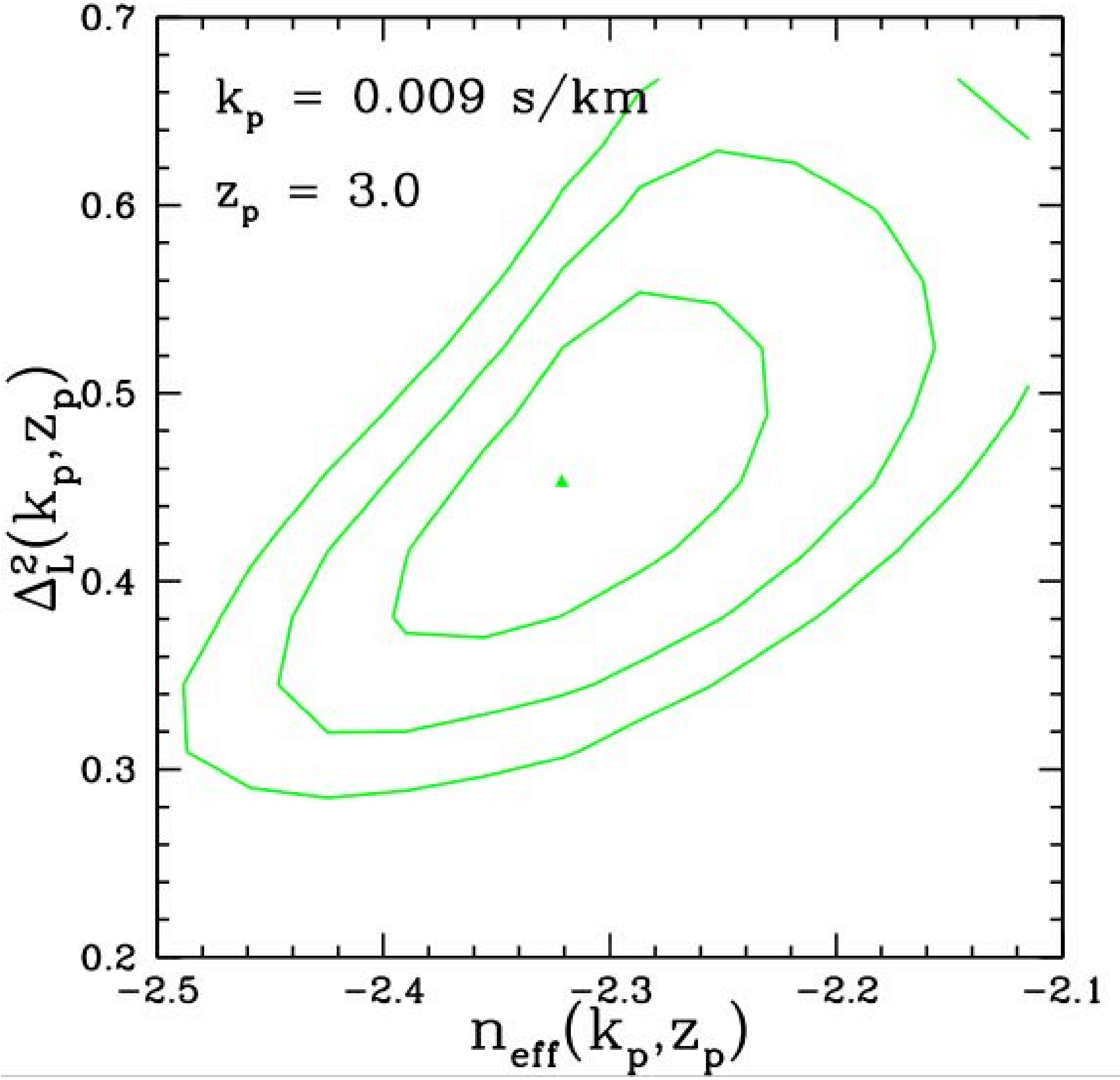
$$k_p = 0.009 \text{ s/km} \simeq 1\ h \text{ Mpc}^{-1}$$
$$z_p = 3.0$$

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

Constraints in the natural LyaF plane from WMAP, minimal model, with and without running

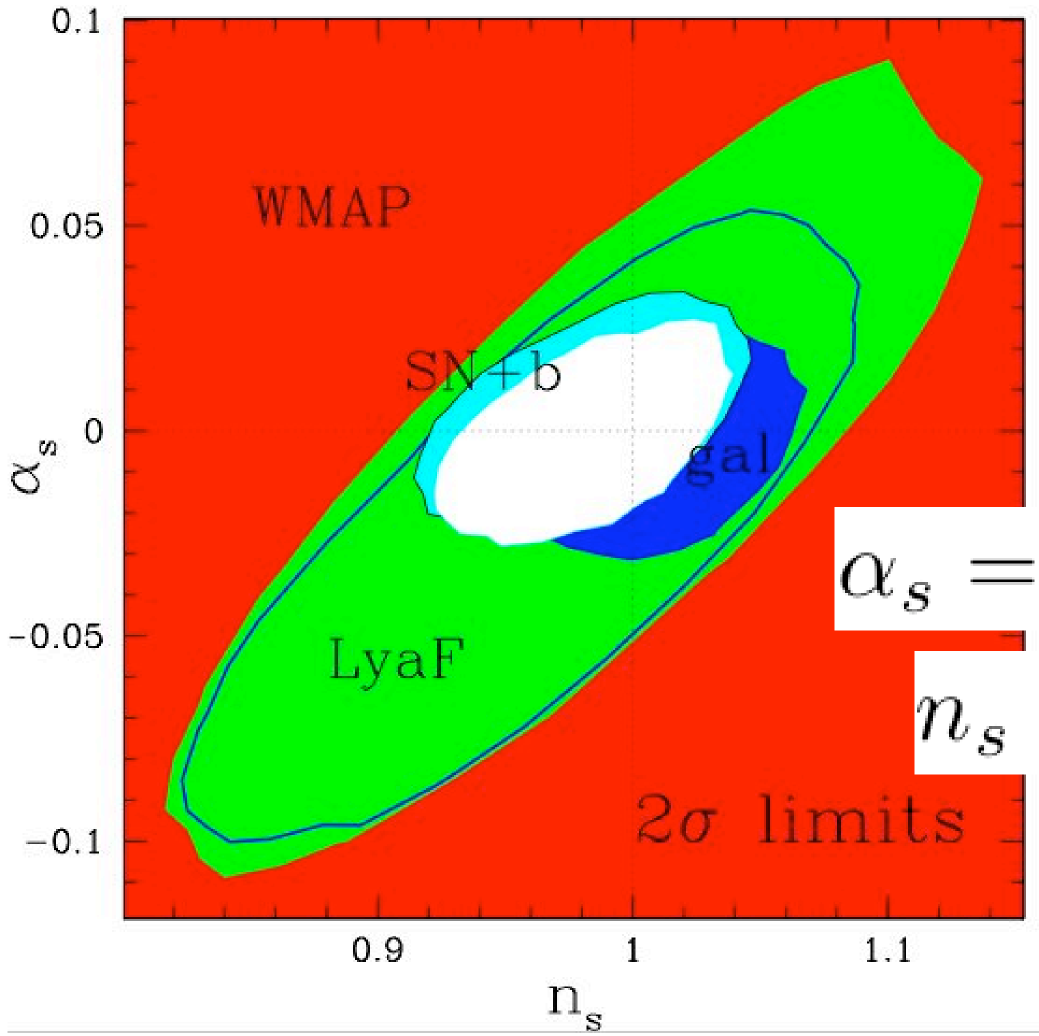


Linear Power Spectrum Constraint



1, 2, and 3-sigma error contours for the amplitude and slope of the linear power spectrum at z=3.0 and k=0.009 s/km

No evidence for departure from scale-invariance n=1, dn/dlnk=0



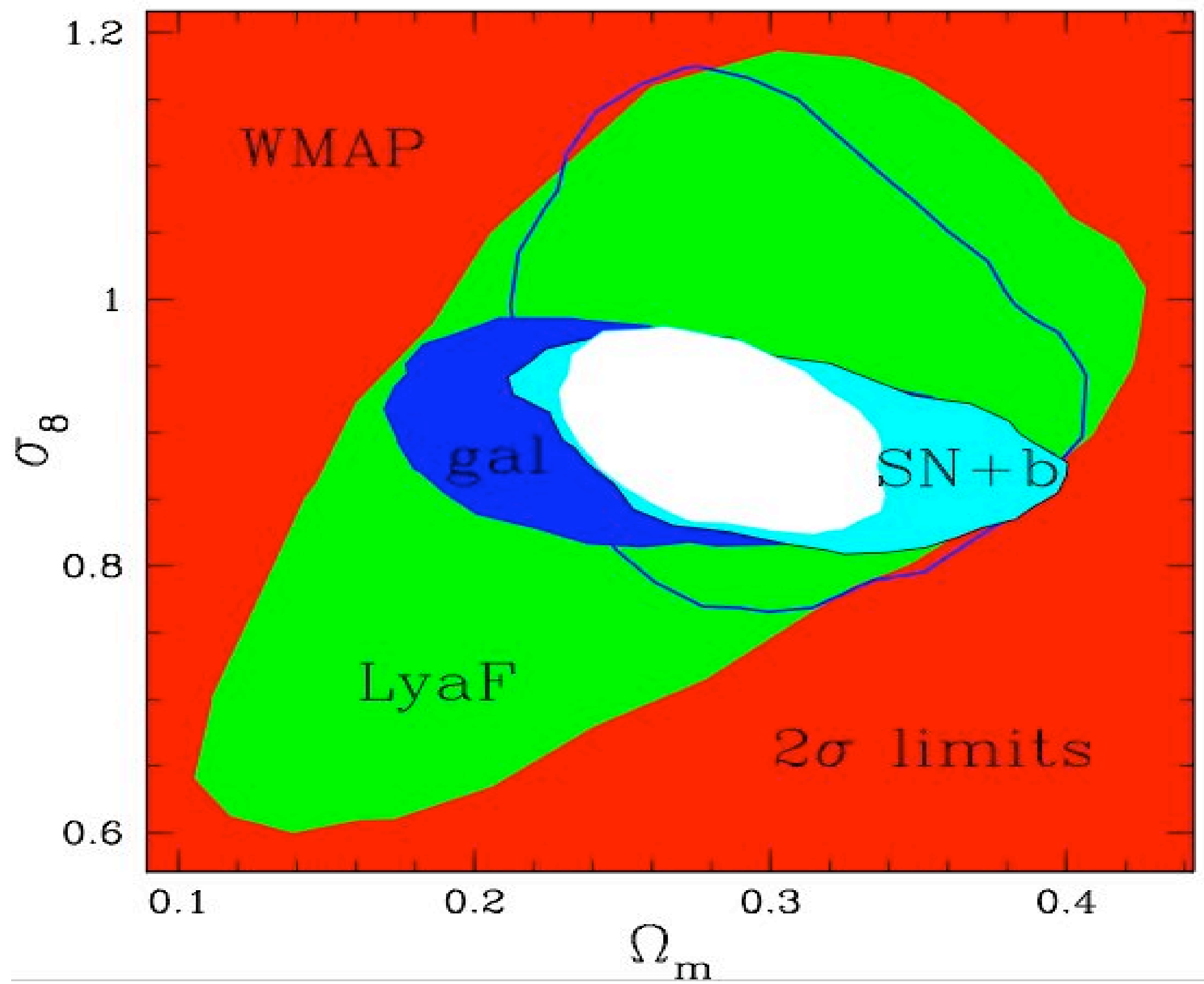
3-fold reduction in errors on alpha_s

Very large running ruled out

$$\alpha_s = -0.003^{+0.011\ \ +0.024}_{-0.010\ \ -0.018}$$

$$n_s = 0.977^{+0.025\ \ +0.052}_{-0.021\ \ -0.040}$$

$$\Omega_m = 0.281 \pm 0.022$$
$$\sigma_8 = 0.897 \pm 0.032$$



Internal consistency checks

- Evolution of power spectrum amplitude: fit for ν in $\Delta^2 \propto (1+z)^\nu$;
- Evolution of the power spectrum slope at fixed comoving scale: fit for m in $n_{eff} = m\, z + n_0$.

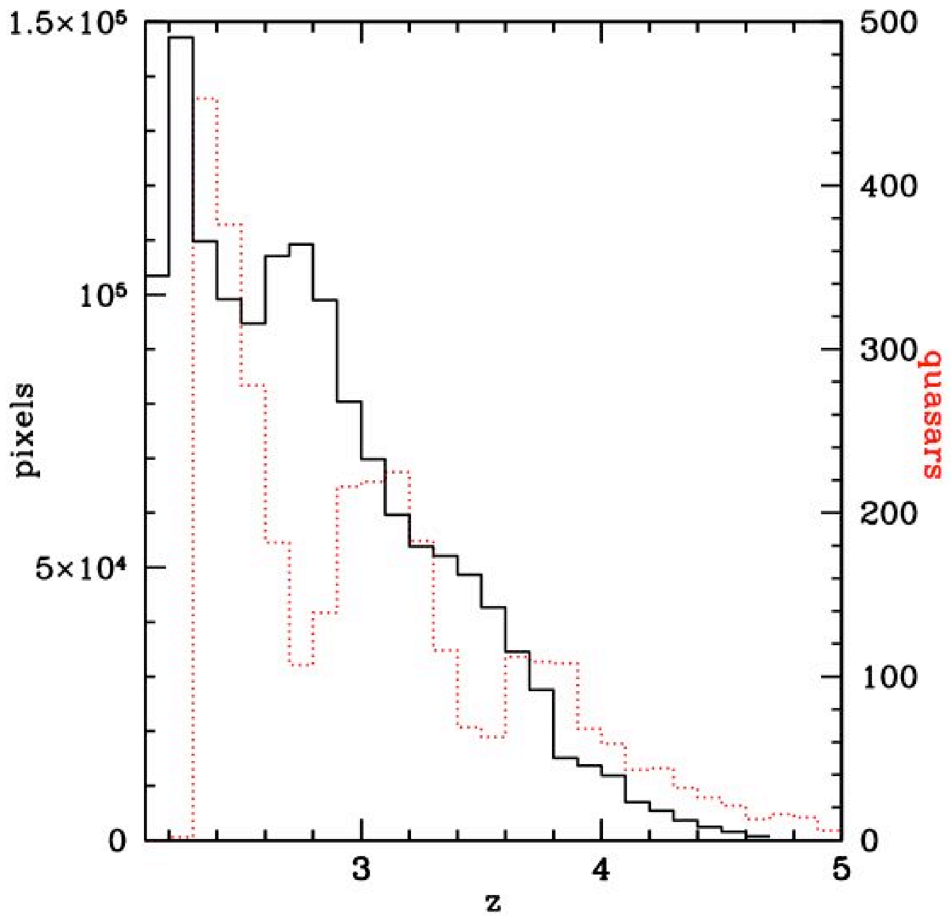
$\nu = -2.92 +/- 0.58$: no evidence of dark energy at $z>2$

$m = 0.051 +/- 0.041$

Pre-SDSS LyaF power spectrum measurements:

- Croft et al. (1999)
  19 low resolution spectra
- McDonald et al. (2000)
  8 Keck/HIRES spectra
- Croft et al. (2002)
  30 Keck/HIRES, 23 Keck/LRIS spectra
- Kim et al. (2004)
  27 VLT/UVES spectra

SDSS Data



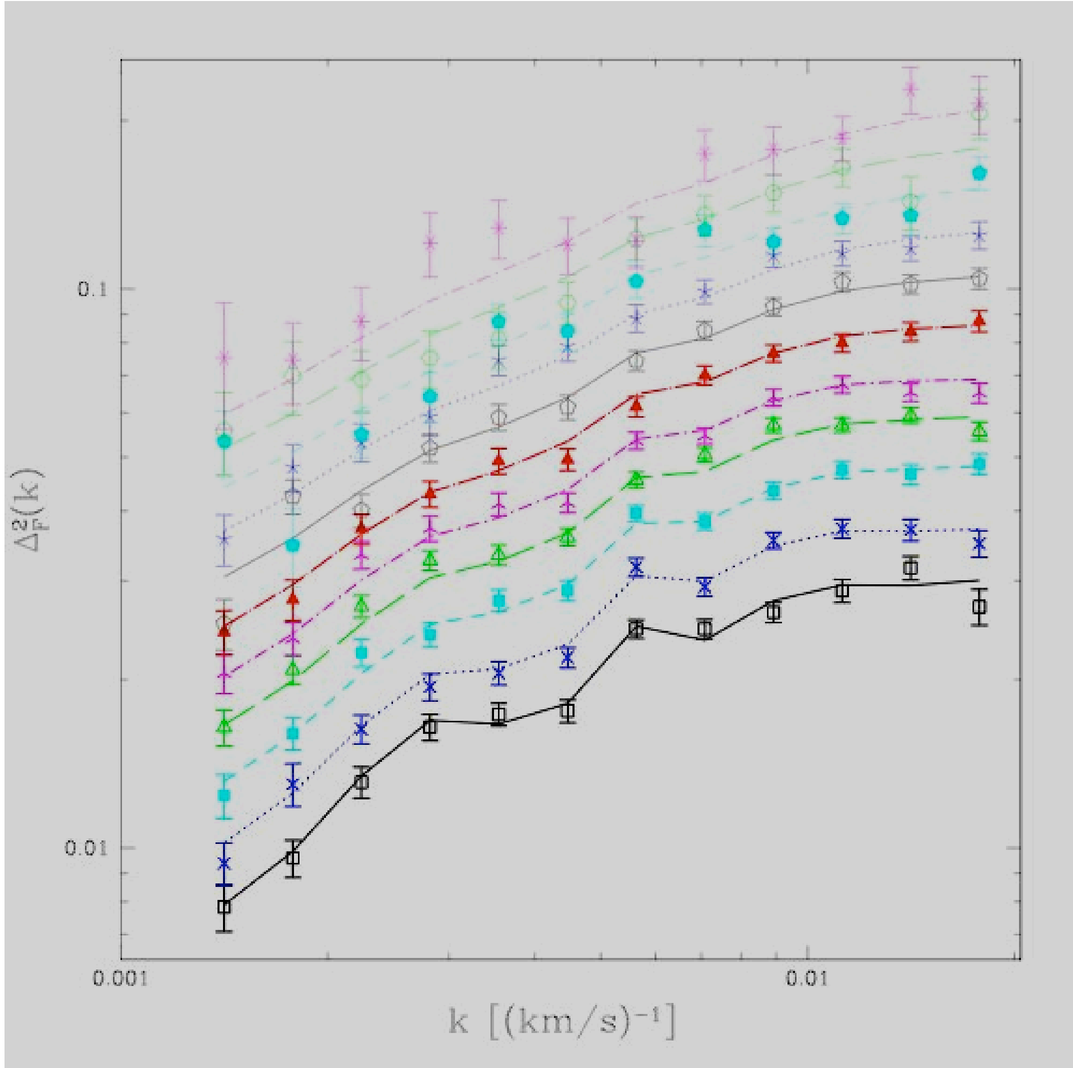
3300 spectra with $z_{qso}>2.3$
(DR3 has 5767)

.... redshift distribution of quasars

1.4 million pixels in the forest

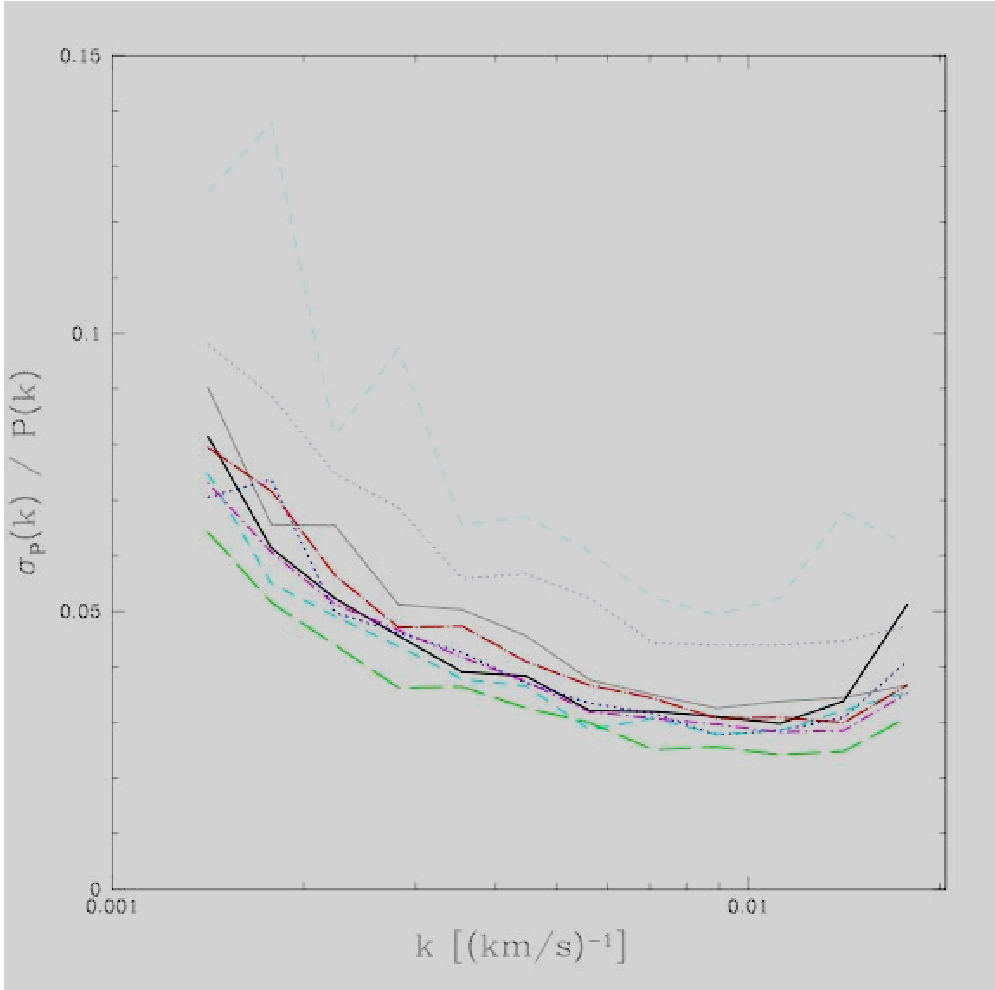
——— redshift distribution of Lyα forest pixels

Measured Power



- $\Delta^2(k) = \pi^{-1}\, k\, P(k)$
  (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
- Computationally only modestly challenging

Fractional Errors



- Lines connect the fractional errors on $P_F(k)$ points
- Equivalent to an overall amplitude measurement to +-0.6%
- Logarithmic slope measurement to +-0.006

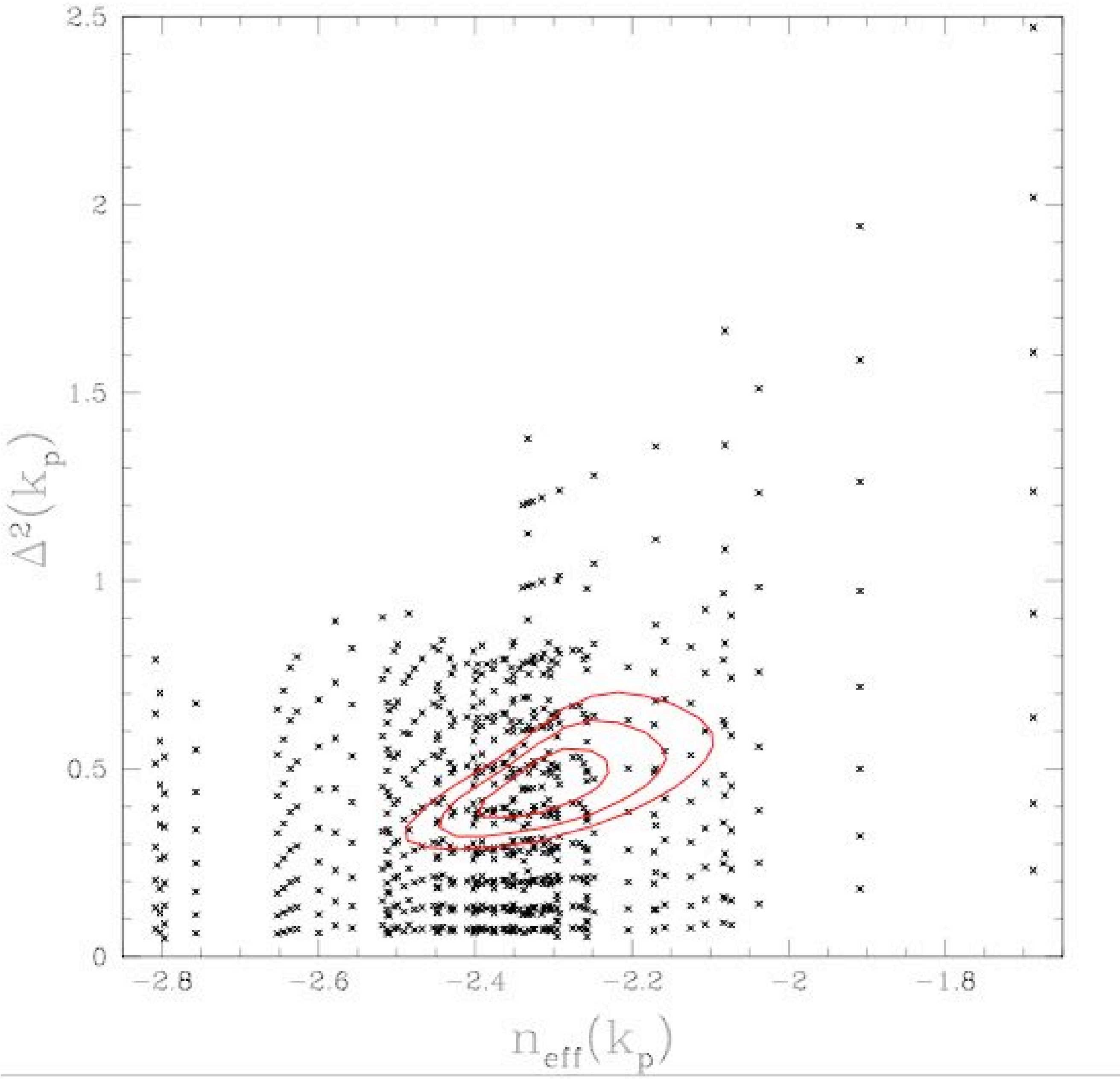
Theory prediction rely on numerical simulations - we use several types:

- Lognormal for code testing and damped systems
- Pure N-body (Bode/Ostriker TPM) for large-scale radiation background fluctuations
- Hydro-PM (Gnedin) for parameter space coverage
- Hydrodynamic for galactic winds and calibrating HPM (Cen, lately Trac, ENZO, GADGET)

Our Simulations

- Predict $P_F(k)$ using simulations of a large grid in parameter space and compare directly to the observed $P_F(k)$.
- Allow general relation $P_F(k) = f[P_L(k)]$ (but only amplitude, slope, and curvature of $P_L(k)$], no band powers).
- IGM gas in ionization equilibrium with a not necessarily homogeneous UV background (still assuming homogeneous reionization).
- Assume IGM not arbitrarily badly disturbed by feedback from galaxies (but allow for some winds).
- Fully hydrodynamic simulations near the best-fit cosmological model are used to calibrate approximate hydro-PM simulations which are used to explore parameter space.
- Marginalize over temperature density relation parameters, $T=T_0(1+\delta)^{\gamma-1}$, mean absorption level, reionization history, etc.

HPM simulation grid



Nuisance parameters

Errors +-0.01 on both parameters if modeling uncertainty is ignored:

Noise/resolution

Mean absorption

Temperature-density

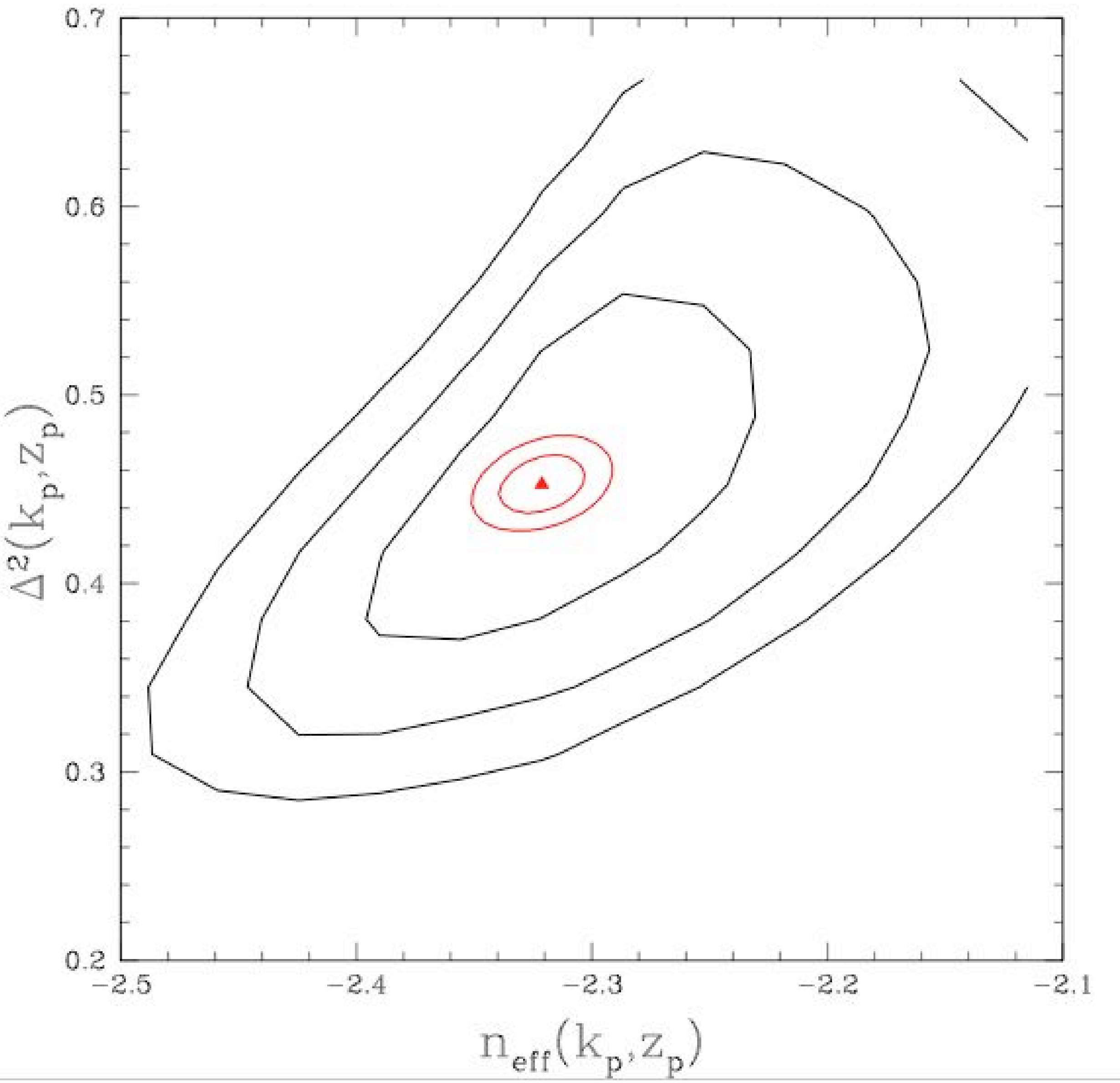
Damping wings

SiIII

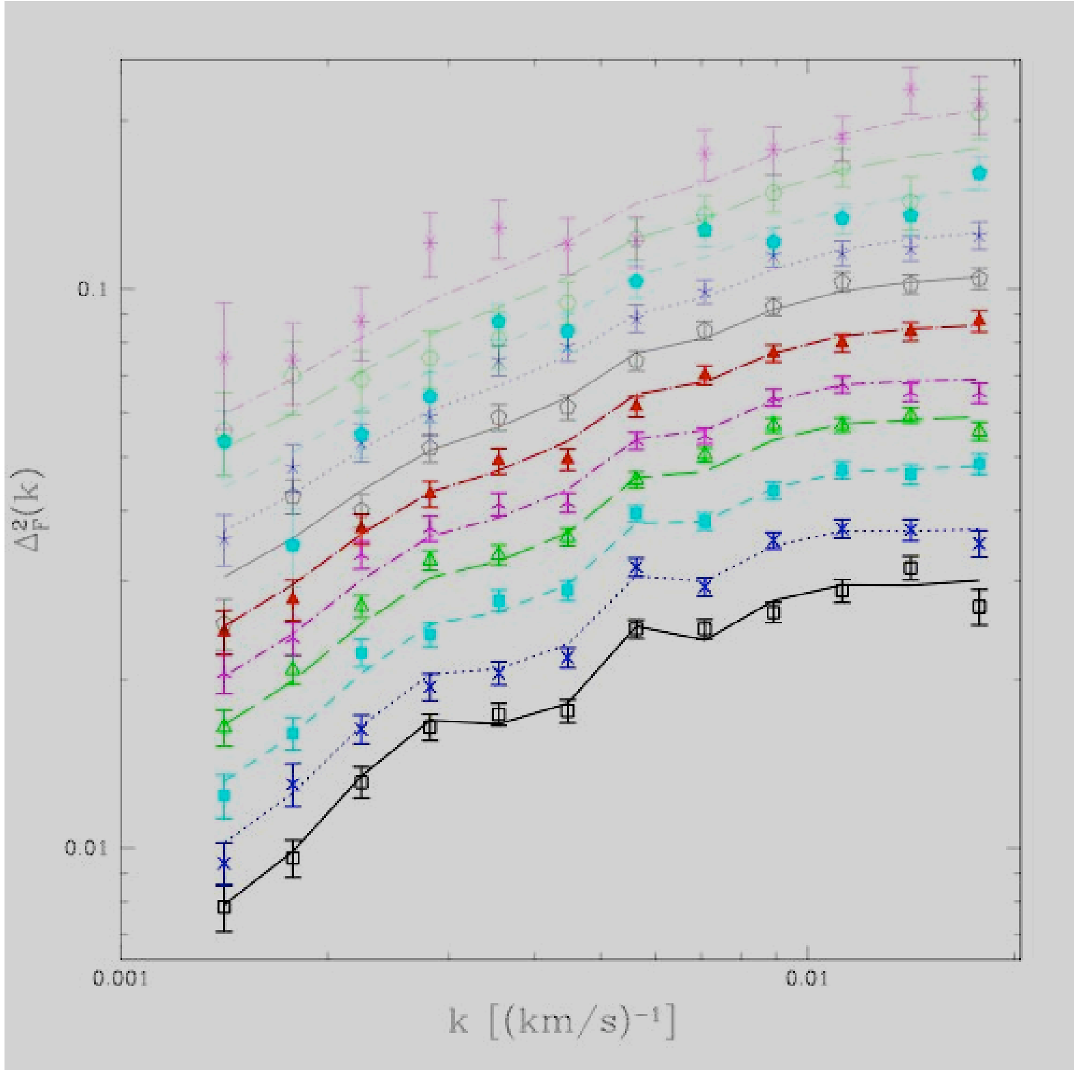
UV background fluctuations

Galactic winds

reionization



Best fitted model

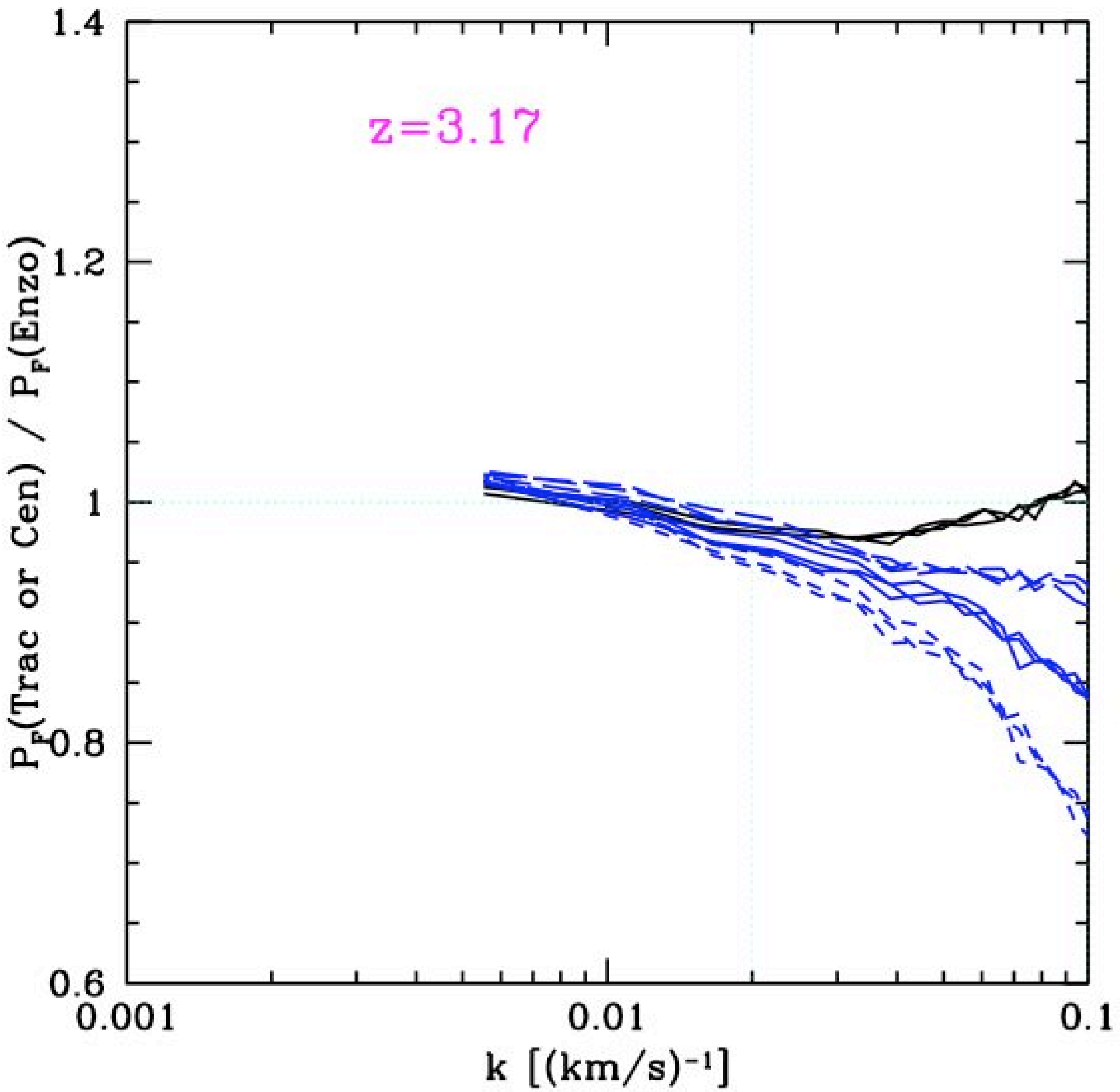


- **$\chi^2 \approx$ 185.6 for 161 d.o.f.**
- A single model fits the data over a wide range of redshift and scale
- Wiggles from SiIII-Lyα cross-correlation
- Helped some by HIRES data

Code comparison

ENZO
Hy Trac's code
Renyue Cen's code
GADGET

VERY SOON: ENZO/Trac-only analysis



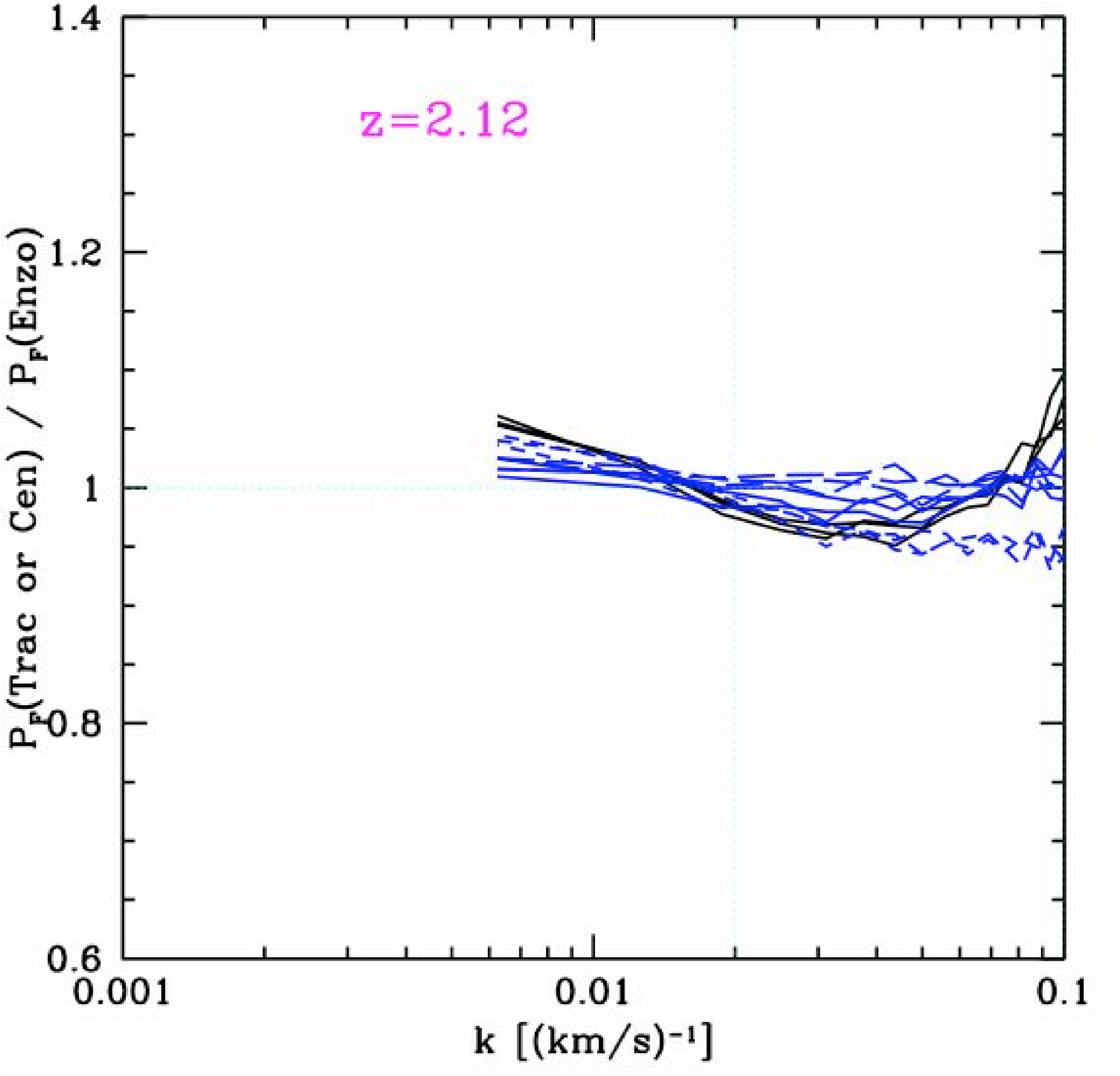
Code comparison

Blue: Cen

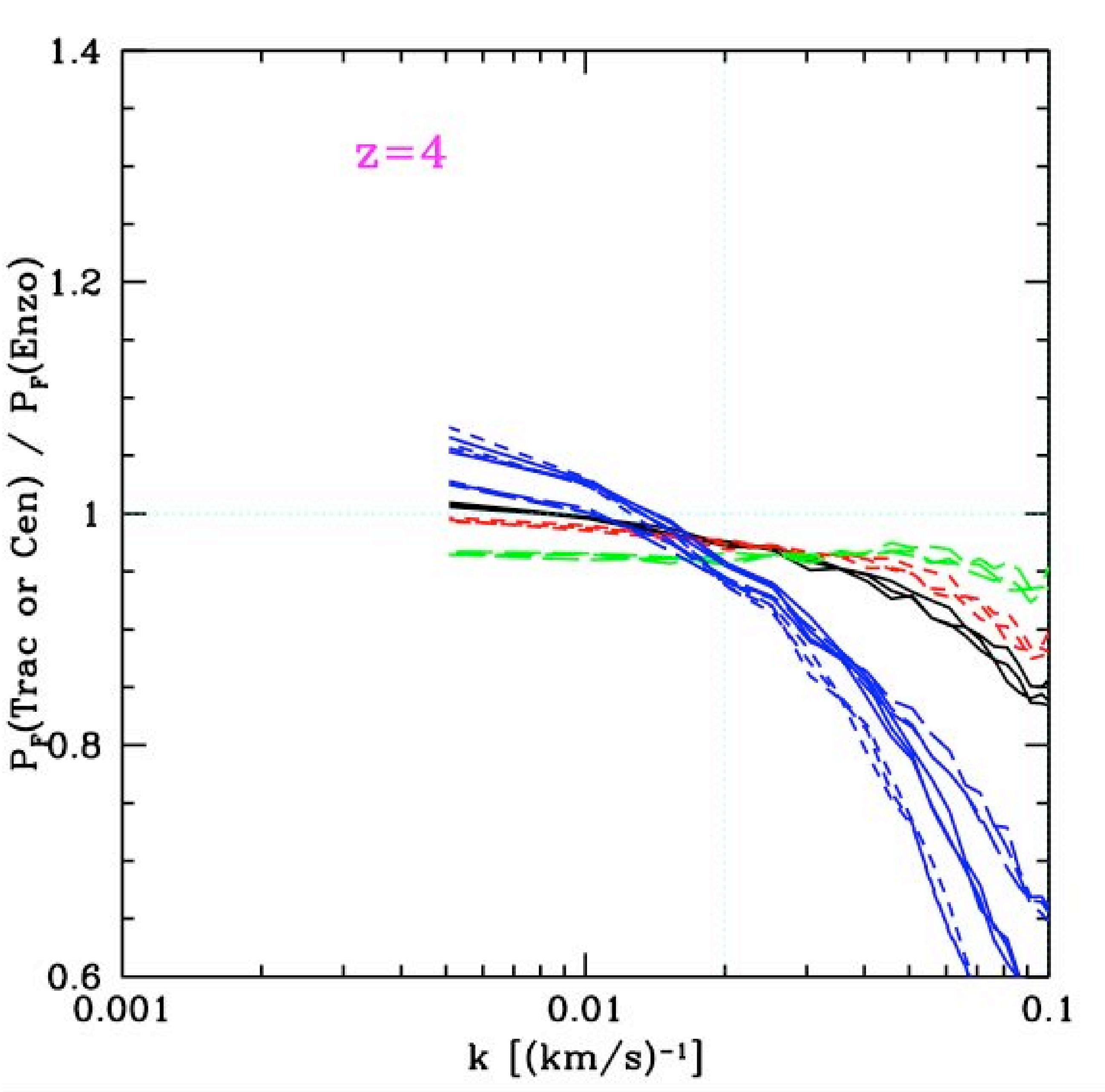
Black: Trac

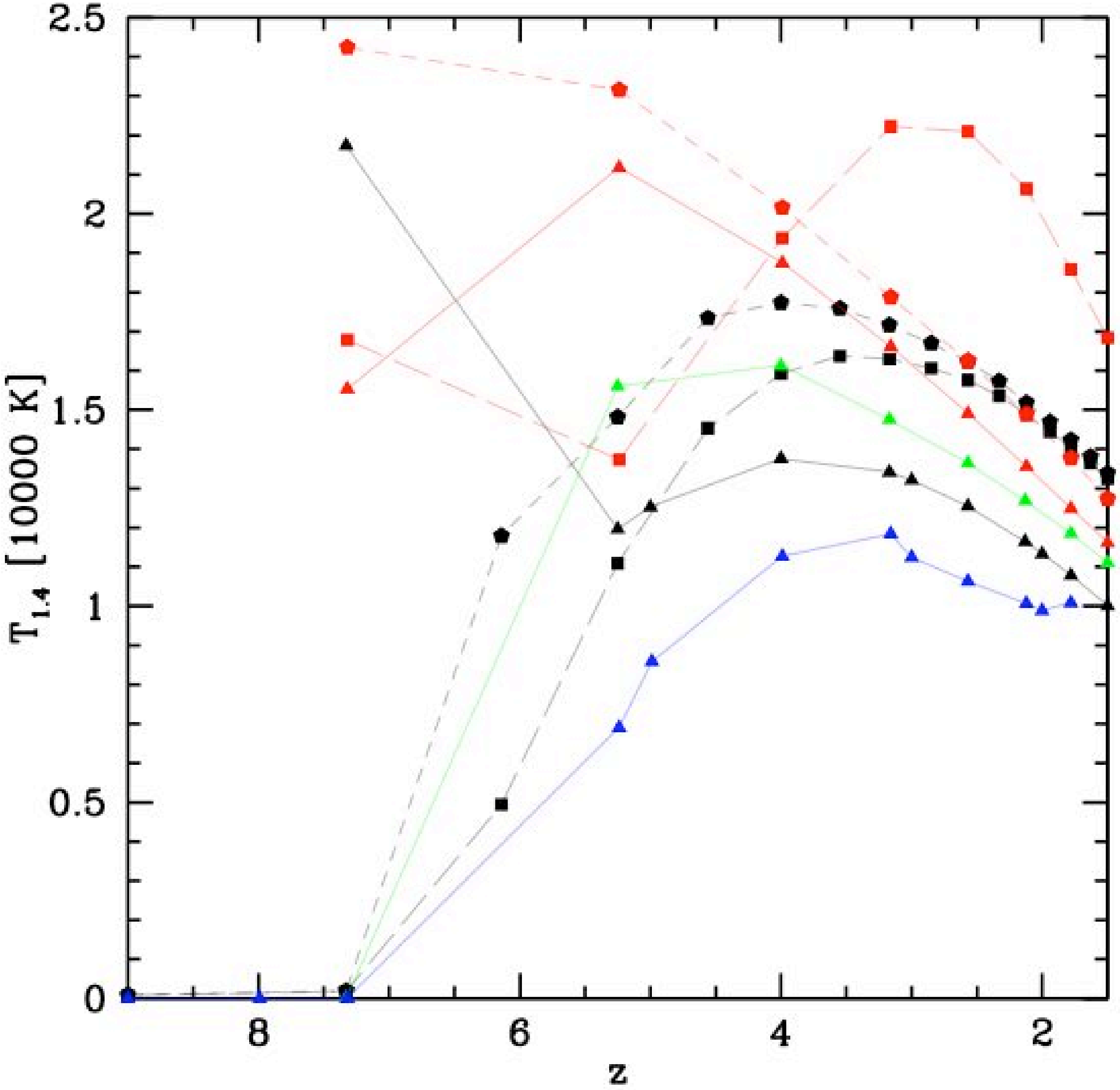
Denominator: ENZO

Code comparison



Code comparison





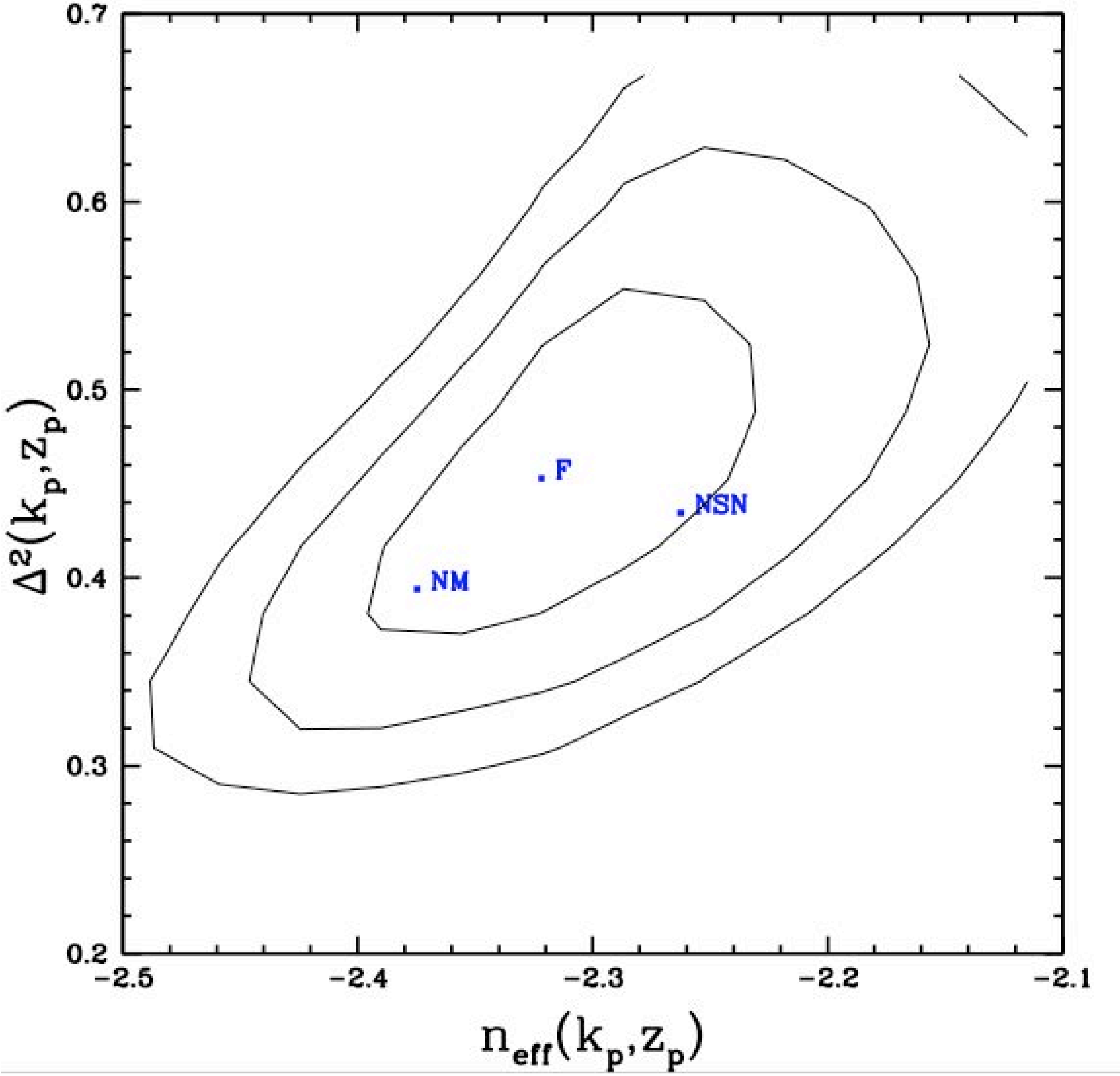
Thermal histories

Red: Cen

Black: Trac

Green: ENZO

Blue: GADGET



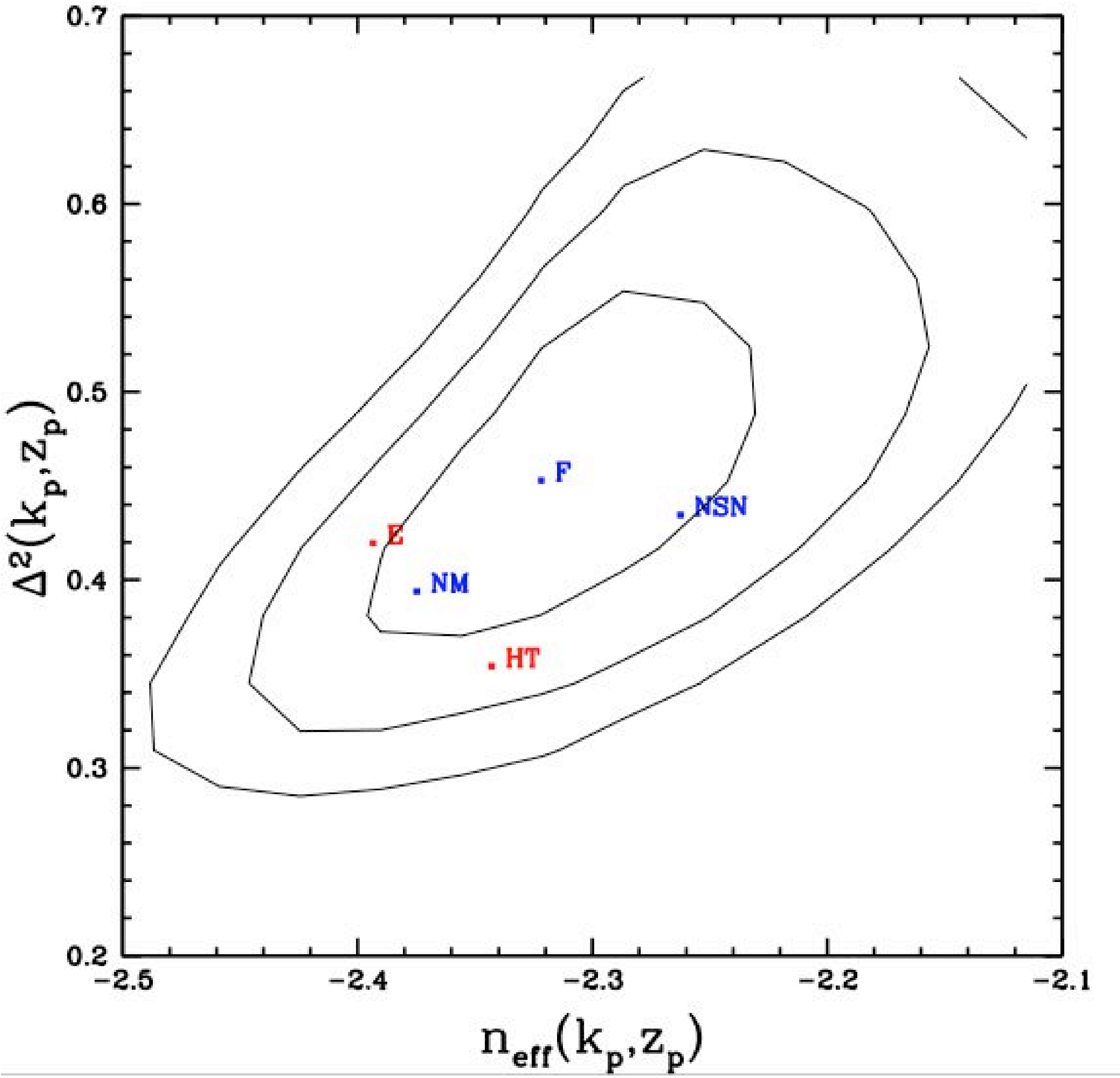
Dependence of

Cosmology result

On simulation type

(in analysis, we marginalized over the differences between 3 Cen simulations)

Code comparison



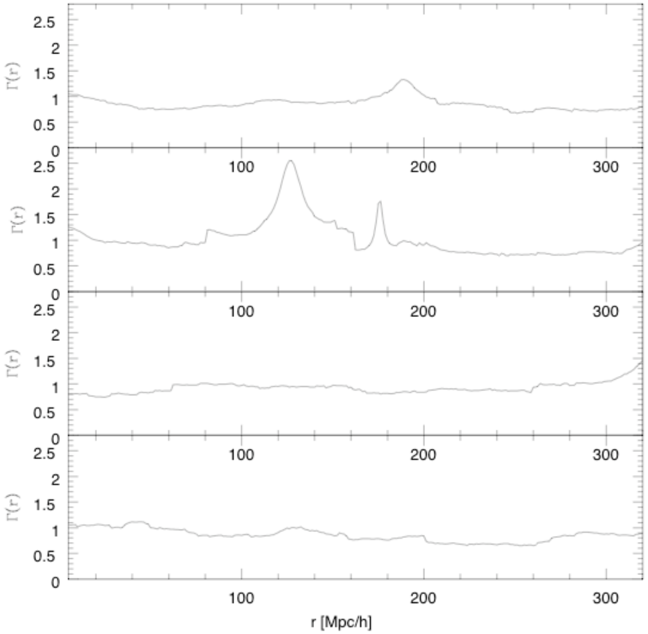
Theory now includes:

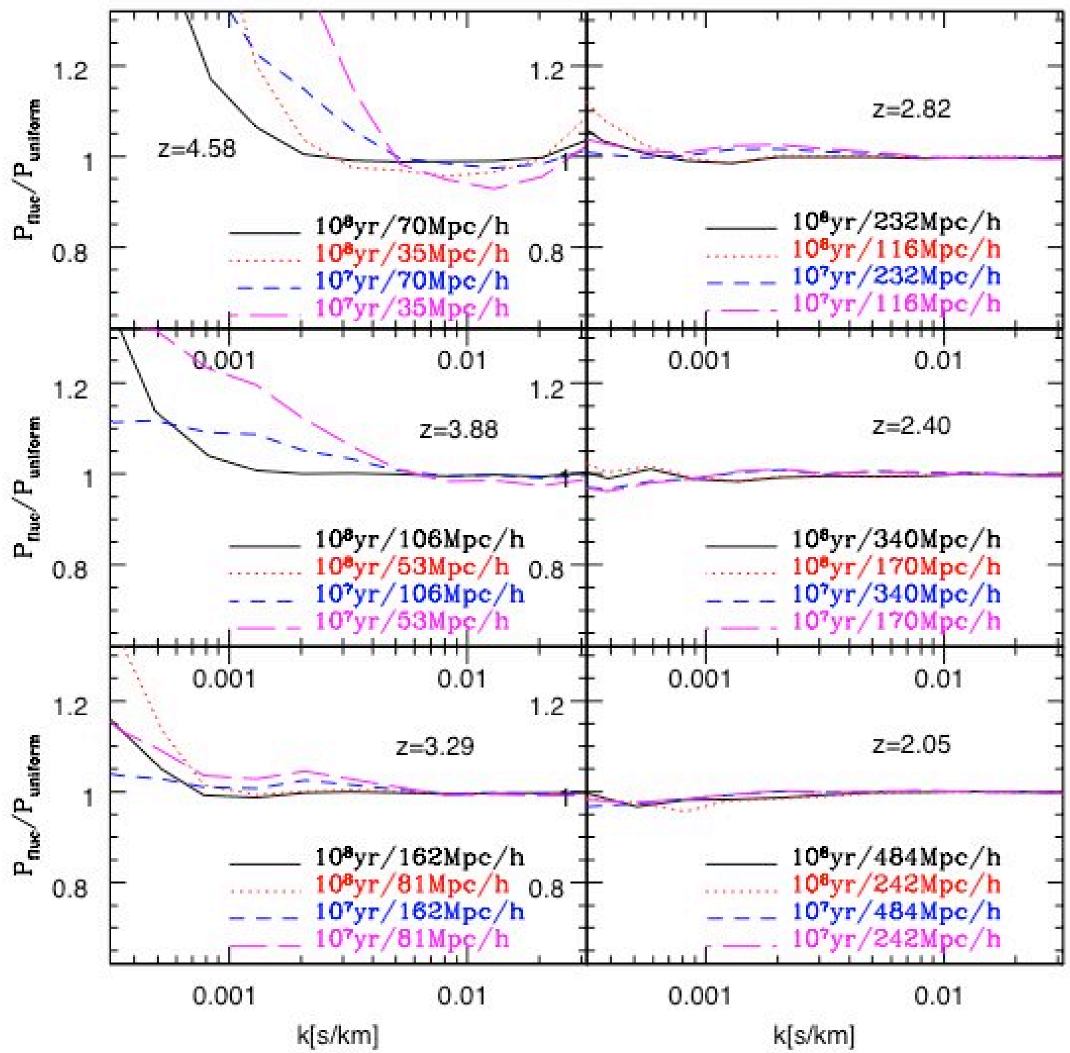
- Rudimentary galactic superwinds (known to exist in starburst galaxies and LBGs)
- Ionizing background fluctuations from quasars
- Damped and lyman limit systems, which are not well modeled in simulations

Fluctuations in the ionizing background

- Place quasars with a given luminosity function and lifetime in dark matter halos in a large (320 Mpc/h - Bode & Ostriker) N-body simulation (also try galaxies).
- Compute the radiation field produced by the sources, including attenuation by the IGM. (Uros Seljak)
- Fluctuations can be large at high redshift where the attenuation length is short.

Fluctuations in ionizing background





Attenuation length is rapidly decreasing with redshift, so effect can be large at z>4, negligible at lower redshifts

Fluctuations in ionizing background

Correlation of galaxies with density leads to coherent fluctions - suppression of power