Cosmology with SDSS+WMAP

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Outline

1) Quick overview of recent results on WMAP

2) SDSS luminosity bias analysis

3) SDSS Ly-alpha forest analysis

4) implications for inflation, neutrino mass and dark energy (factors of several reductions in error on parameters)

Princeton Physics group: P. McDonald, A. Makarov, R. Mandelbaum, C. Hirata, K. Huffenberger, N. Padmanabhan, etal for SDSS collaboration

NEW: Ly=alpha forest analysis official (after 3 years of “preliminary”)

Goals of observational cosmology

- Matter components (neutrino mass?), nature of dark matter
- Nature of dark energy
- Nature of creation of structure in the universe (inflation or something else?)

These are fundamental physics goals, in addition to this we also want to know how the universe got into what it looks like today

The Inflaton:

Consider a scalar field with:

$$\mathcal{L}(\varphi(x)) = \frac{1}{2}\partial_\mu\varphi(x)\partial^\mu\varphi(x) - V(\varphi(x))$$

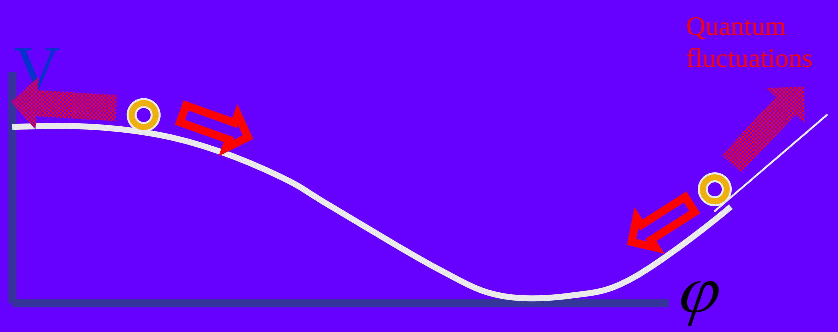
⇨ If $V(\varphi) >>$ all space and time derivative (squared) terms

⇨ $\frac{\partial\rho}{\partial a} = 0$

⇨ $a \sim e^{Ht}$

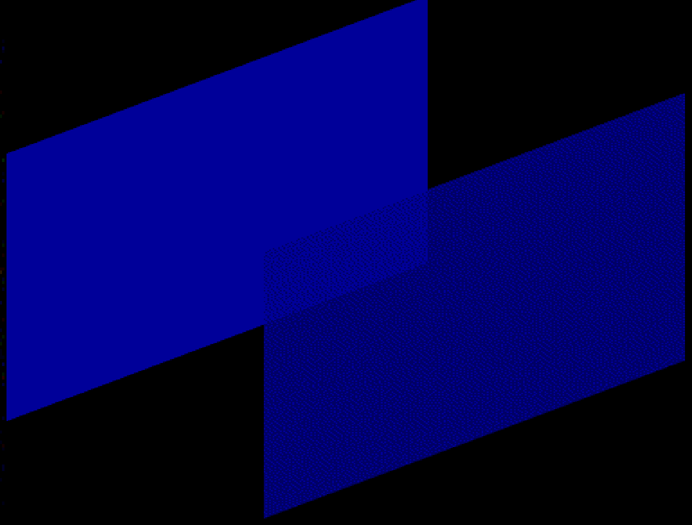
Inflation

$\approx \Lambda$



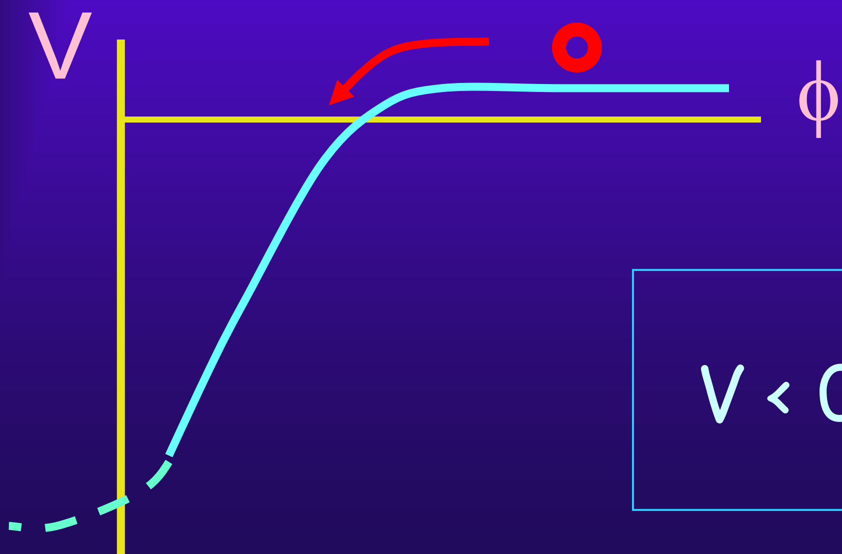
Quantum fluctuations converted into classical space-time perturbations

Cyclic Model



Steinhardt and Turok

4d Field Theory Picture



extra dimension → ϕ

interbrane potential → $V(\phi)$

$V < 0$ ⟺ $$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} > 1$$

How to test fundamental theories?

1) Gravity waves (r): some inflationary models predict them, others do not. Polarization of CMB is the key experimental input, one of NASA Beyond Einstein missions
2) Growth of structure: dark energy, neutrino mass
3) Spectrum of primordial fluctuations (amplitude, slope, running of the slope): most models predict something non scale-invariant
4) Other: gaussianity, adiabaticity, curvature tests

Current 1 year WMAP analysis/data situation

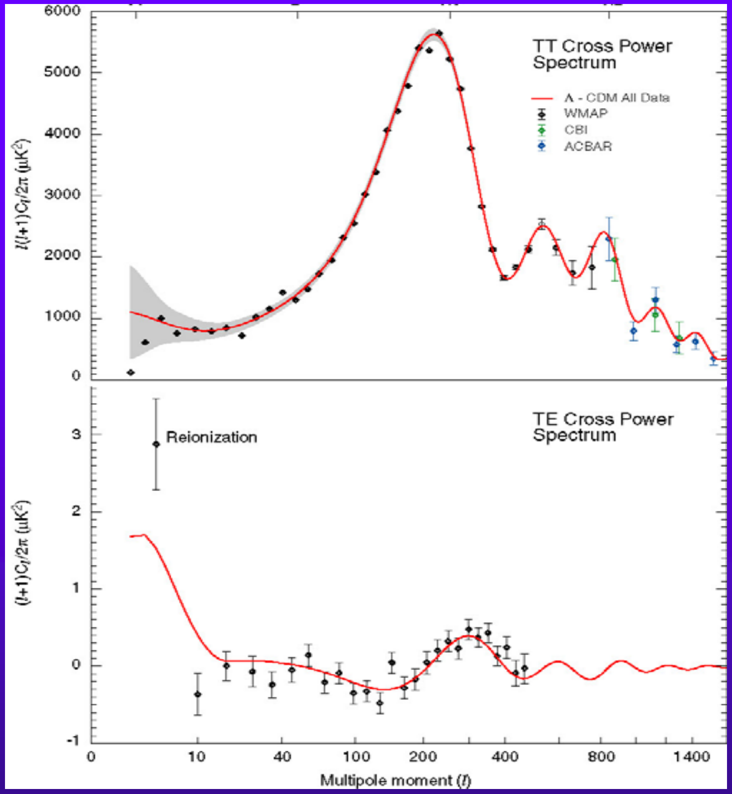
Current data favor the simplest scale invariant model

Evidence for optical depth from TE, but needs 2nd yr confirmation

Standard model works remarkably well: “funny” correlations on large scales likely due to residual foreground contamination (see talk by Slosar)

No SZ contamination (Huffenberger, US, Makarov)

No evidence of running (Slosar, US, Makarov)



Limits on SZ from WMAP

Huffenberger, US, Makarov

- SZ power spectrum amplitude increases by 50% from WW to QQ
- Optimal linear combinations
- SZ less than 2% in WW at l=200 (refuting Myers etal claim)

$$\sigma_8 < 1.05 (95\% c.l.)$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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WMAP exact likelihood analysis of low multipoles

Slosar, US, Makarov

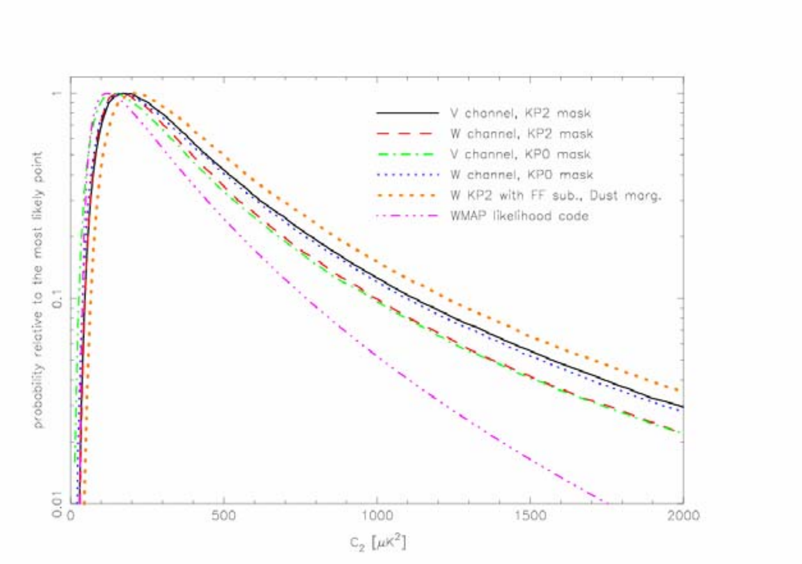
Low l multipoles are contaminated by foregrounds, best removed by marginalization

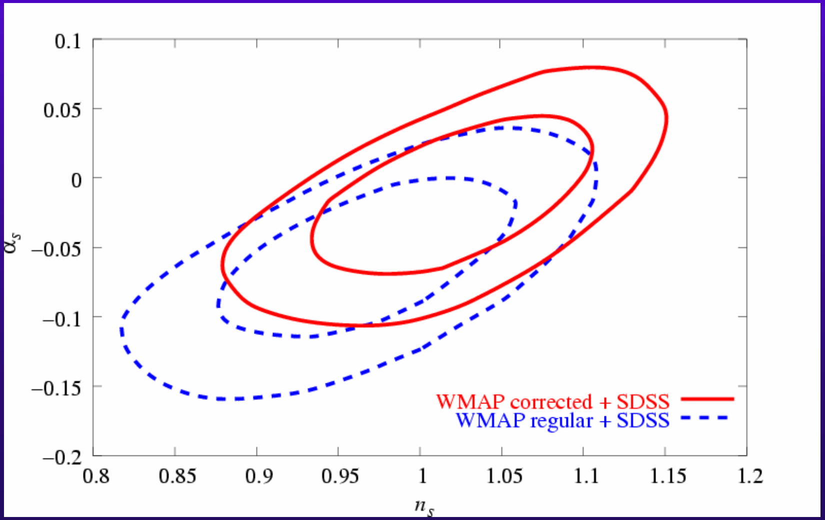
Approximations to exact likelihood do not work in this regime

n=1, dn/dlnk=0 solution is acceptable!

Relevance for joint WMAP+Ly-alpha analysis: reduces running by 1 sigma

Quadrupole is not particularly low (4%), rest are just fine





SDSS Galaxy bias determination

$$b^2(k) = \frac{P_{gg}(k)}{P_{dm}(k)}$$

- Galaxies are biased tracers of dark matter; the bias is believed to be scale independent on large scales (k<0.1-0.2/Mpc)
- If we can determine the bias we can use galaxy power spectrum to determine amplitude of dark matter spectrum σ_8
- High accuracy determination of σ_8 is important for neutrino mass and dark energy constraints
- Existing methods have poor statistics (>10% error)

Galaxy clustering: luminosity dependence of linear amplitude

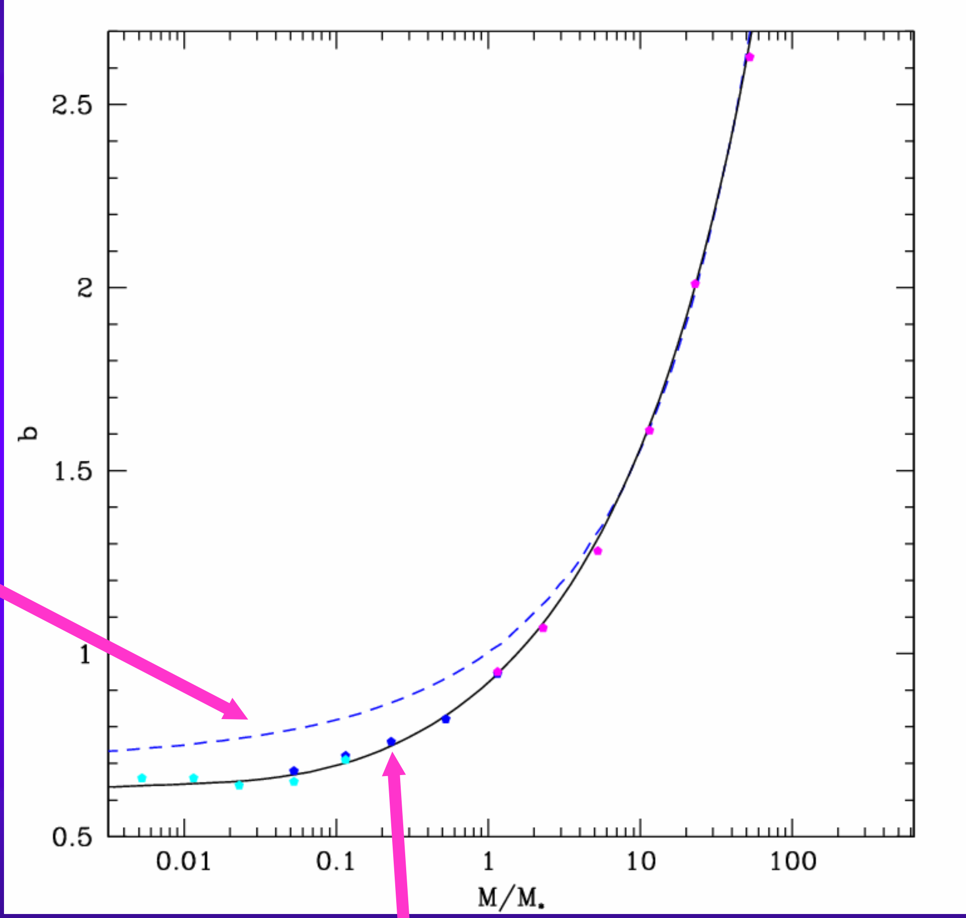
Bias relative to L* changes from 0.75 to 1.7 (Tegmark etal 2004), in agreement with previous attempts at smaller scales (Norberg etal, Zehavi etal)

Halo bias as a function of halo mass

High mass halos strongly biased

Low mass halos antibiased, b=0.7

Theory is in reasonable agreement with simulations (Sheth and Tormen 1999; Jing 1999, Seljak and Warren 2004)



Seljak and Warren 2004

Bias mass relation is nearly universal if mass is in units of nonlinear mass (mass within the sphere with rms 1.68)

Nonlinear mass grows with amplitude of power spectrum and matter density

If we could establish halo clustering at low mass end we would have determined the amplitude of fluctuations (cf lensing)

We do not observe halos, but galaxies

Seljak and Warren 2004

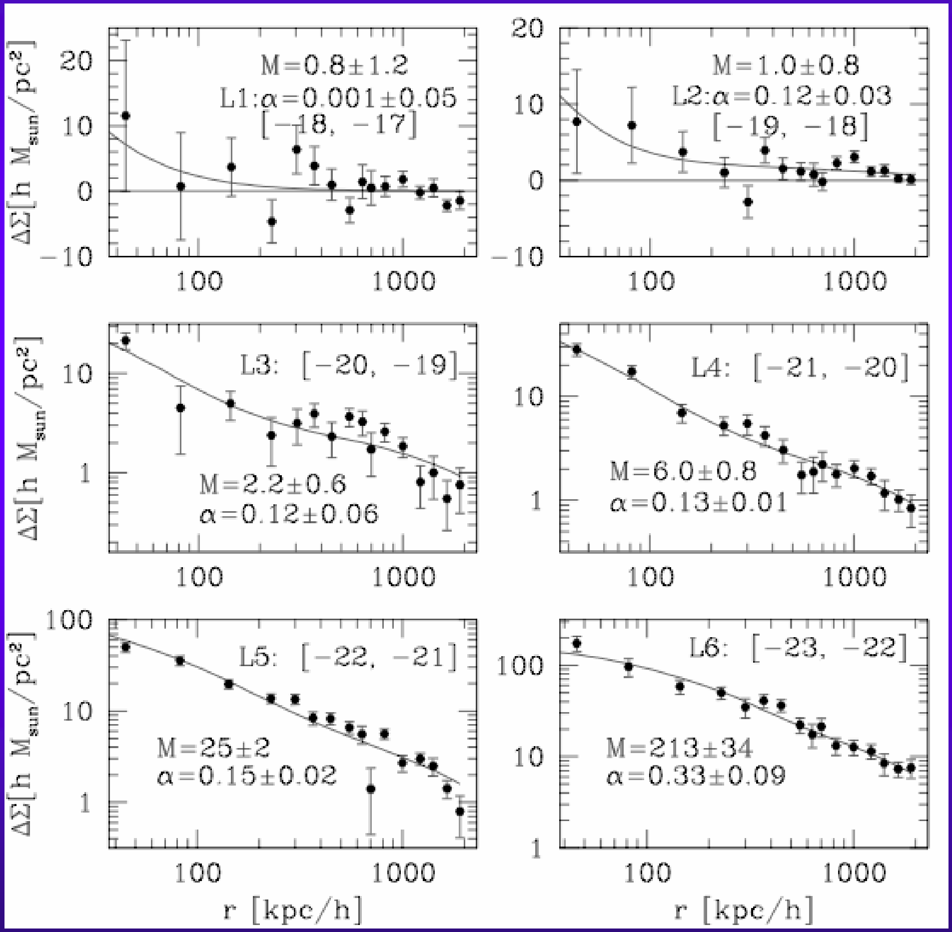
halo mass probability distribution p(M;L) from galaxy-galaxy lensing

Goal: lensing determines halo masses (in fact, full mass distribution, since galaxy of a given L can be in halos of different mass)

If halo mass is low compared to nonlinear mass bias is less than one, otherwise more than one…

Halo model: galaxies can be halo hosts or satellites (Guzik and Seljak 2002), parametrized as the halo mass of central component and fraction of galaxies that are non-central

G-g lensing least model dependent, but used to have poor statistics, no longer the case



Seljak etal 2004

Bias determination

$$b(L) = \int b(M)\, p(M;L)\, dM$$

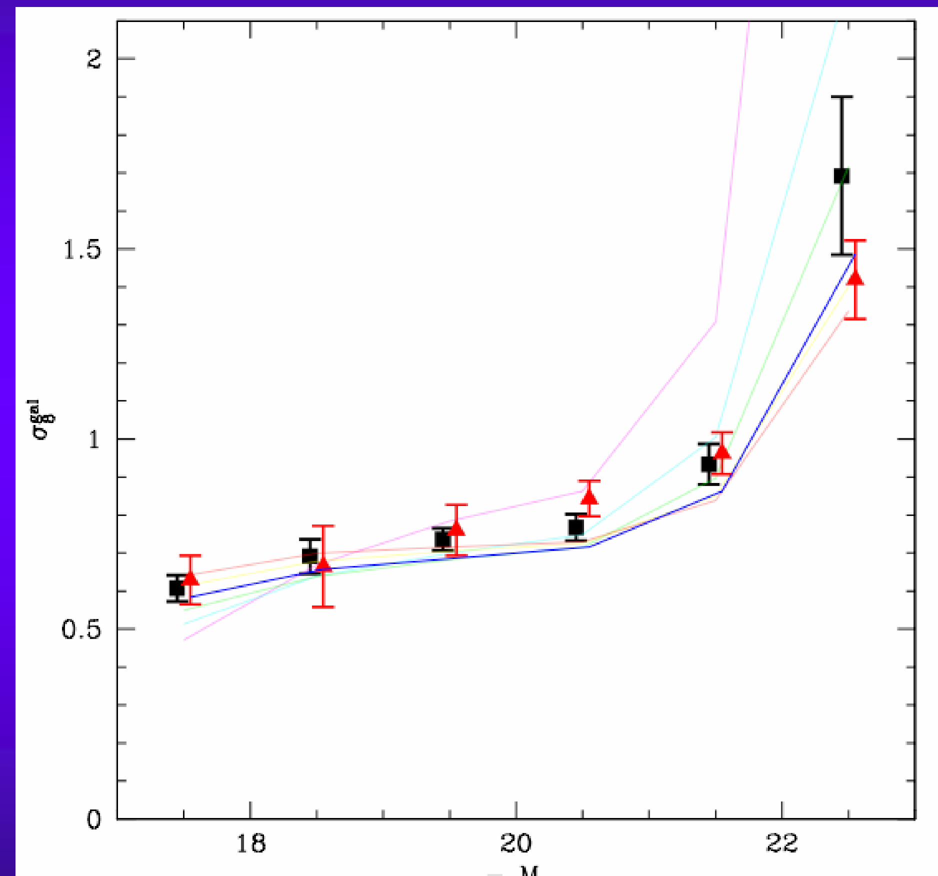
For any cosmological model we can determine b(L) from above

Theoretical halo bias is confirmed!

We also measure b(L) from galaxy clustering

Only cosmological models where the two constraints agree are acceptable

Robust: 20% error in lensing gives only 0.03 error in bias



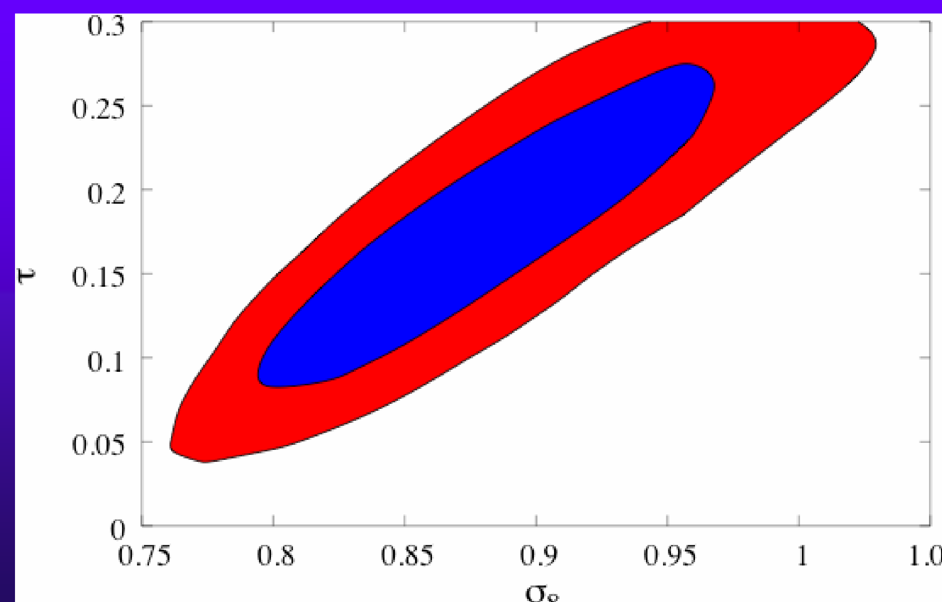
Bias error is still large

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

$$\sigma_8 = 0.88 \pm 0.06$$

Data prefer low nonlinear mass, low matter density

$$\Omega_m = 0.25 \pm 0.05$$



SDSS Ly-alpha forest analysis

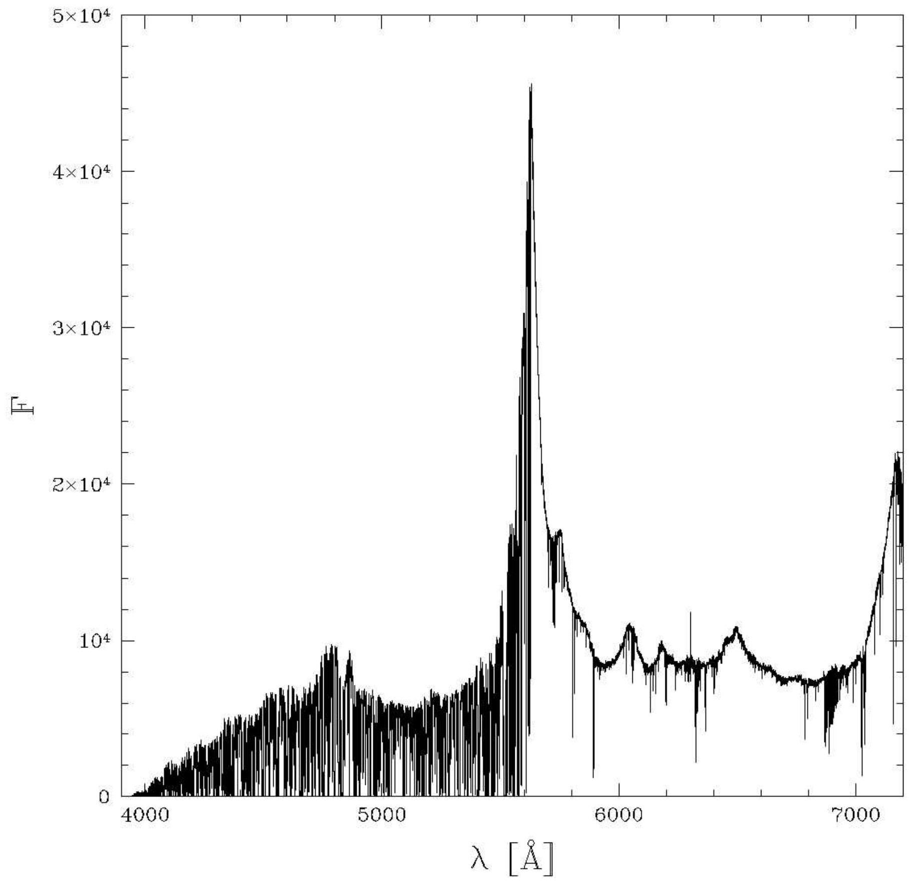
Pat McDonald, Alexey Makarov+SDSS

The promise:

- Dark matter fluctuations on 0.1-10Mpc scale: amplitude, slope, running of the slope
- Growth of fluctuations between 2<z<4
- very powerful when combined with CMB or galaxy clustering (slope, running of the slope)

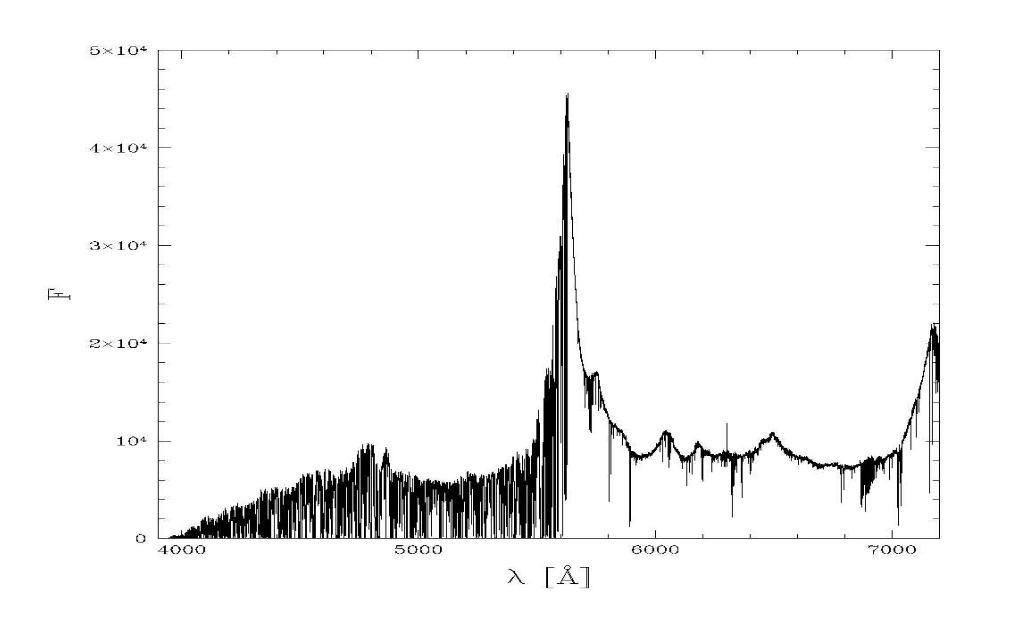
Very difficult analysis (described in 4 long papers), results are based on current understanding of ly-alpha forest

What is Ly-alpha forest



- Neutral hydrogen
- Lyman-α absorption at $\lambda < 1216\ (1+z_q)$ Å
- Metal absorption small but everywhere
- Continuum fluctuations significant on large scales
- From Rauch & Sargent or Cowie

HIRES Quasar Spectrum



Ly-alpha forest as a tracer of dark matter

Basic model: neutral hydrogen (HI) is determined by ionization balance between recombination of e and p and HI ionization from UV photons (in denser regions collisional ionization also plays a role), this gives

$$\rho_{HI} \propto \rho_{gas}^2$$

Recombination coefficient depends on gas temperature

Neutral hydrogen traces overall gas distribution, which traces dark matter on large scales, with additional pressure effects on small scales (parametrized with filtering scale k_F)

Advantages of Ly-α

Fully specified within the model

Once the model is specified many independent tests to verify it (higher order correlations, cross-correlations…)

Lots of data

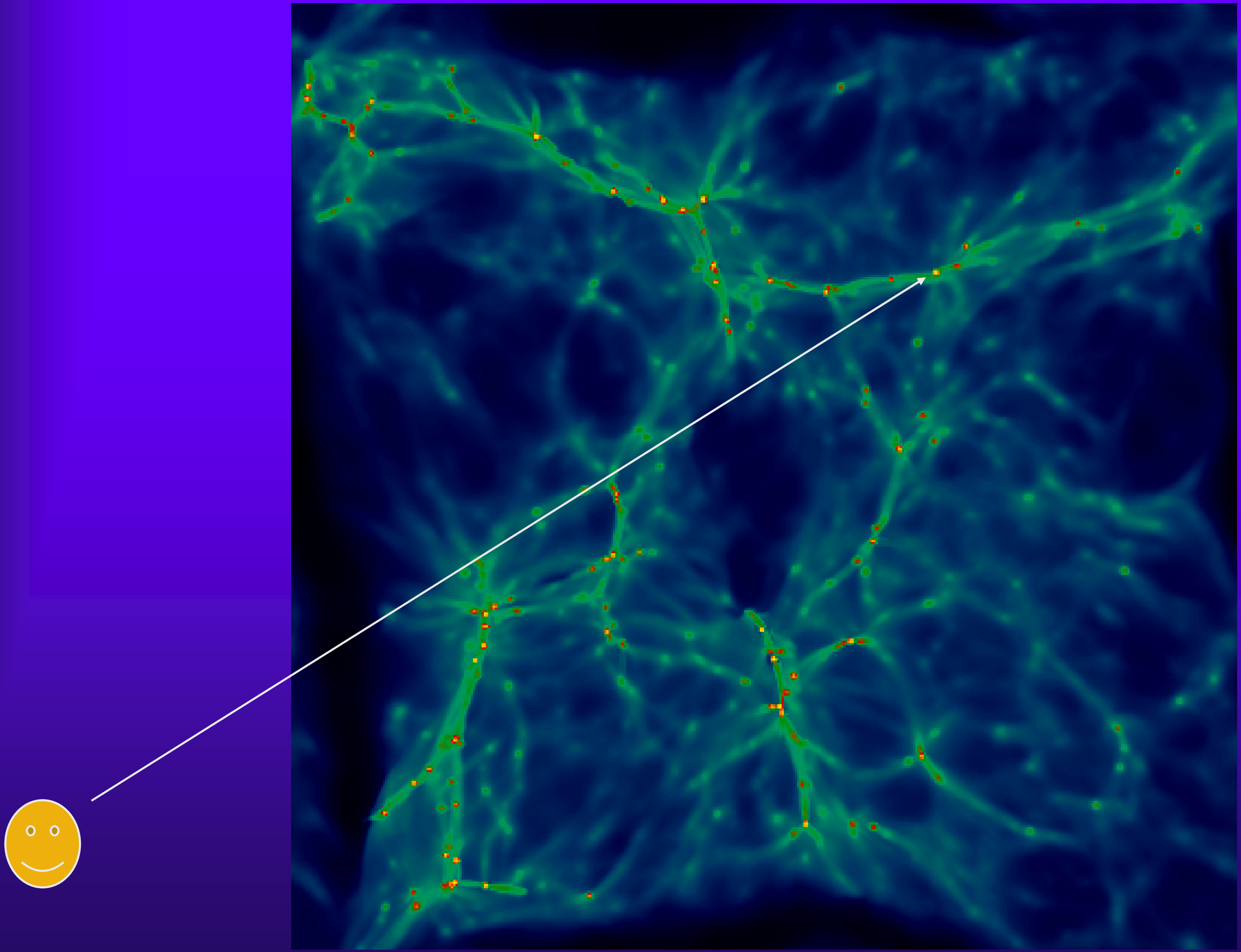
High z ($2<z<4$), small scales (1Mpc) provide a large leverage arm when combined with CMB and good statistics (SDSS)

Wide redshift range allows to test growth of structure

disadvantages

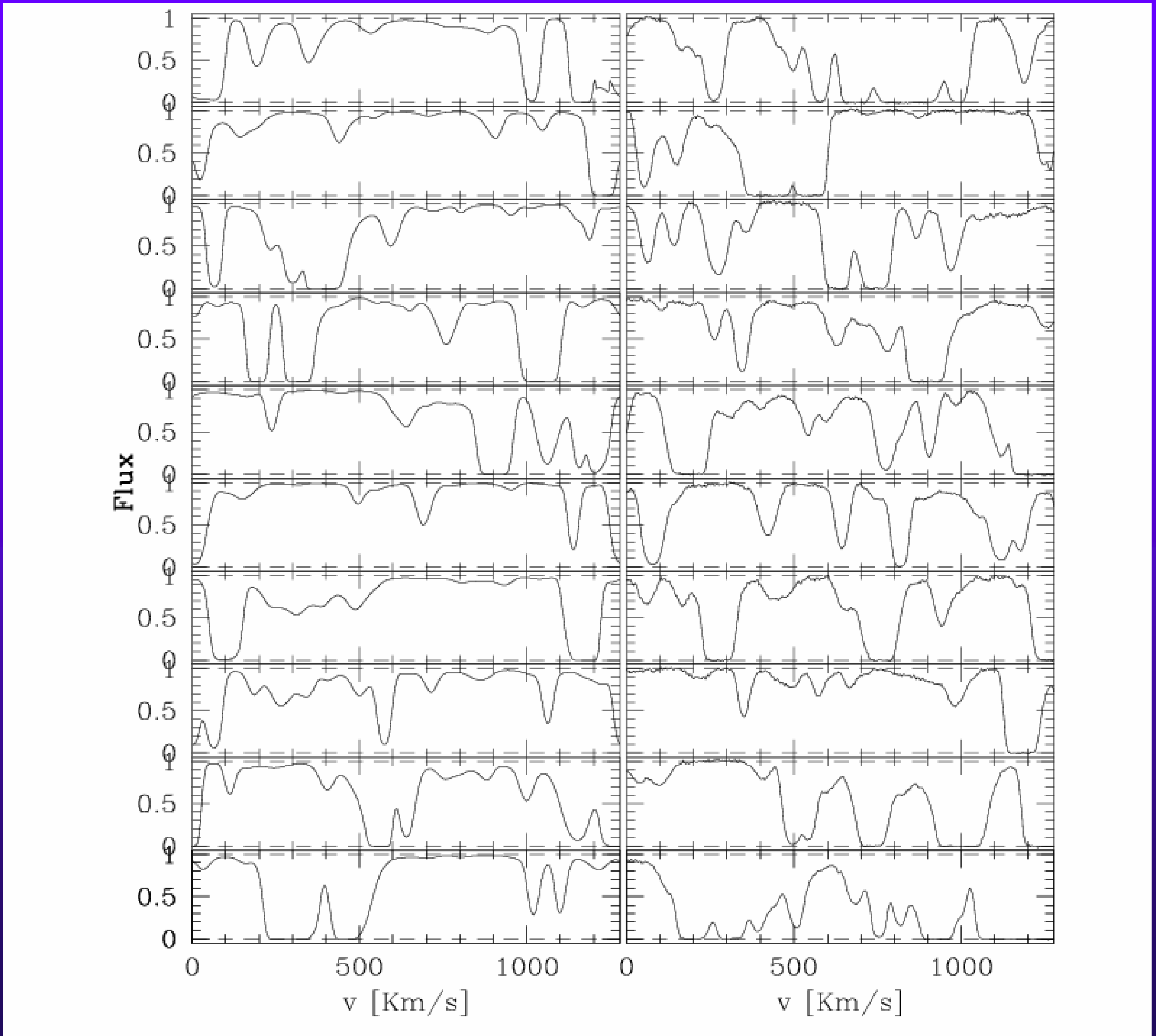
Nonlinear (need large simulations)

Messy astrophysics (winds, fluctuations in UV/T, QSO continuum)

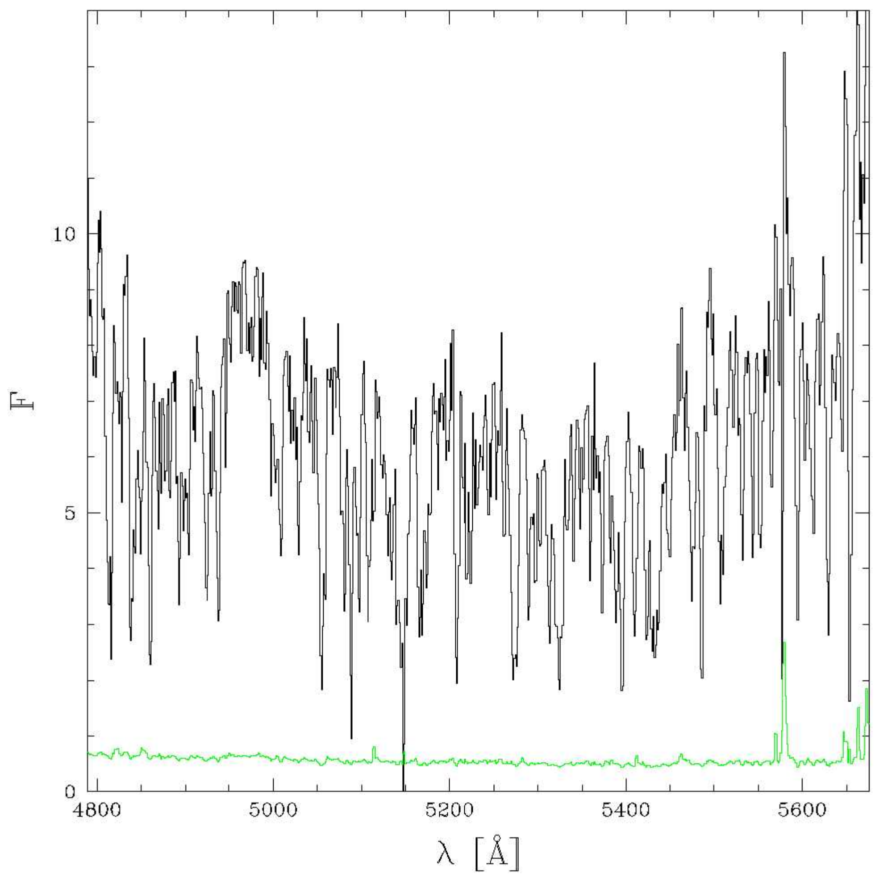


Cosmological simulations of Ly-α forest: a success story of cosmological hydrodynamics

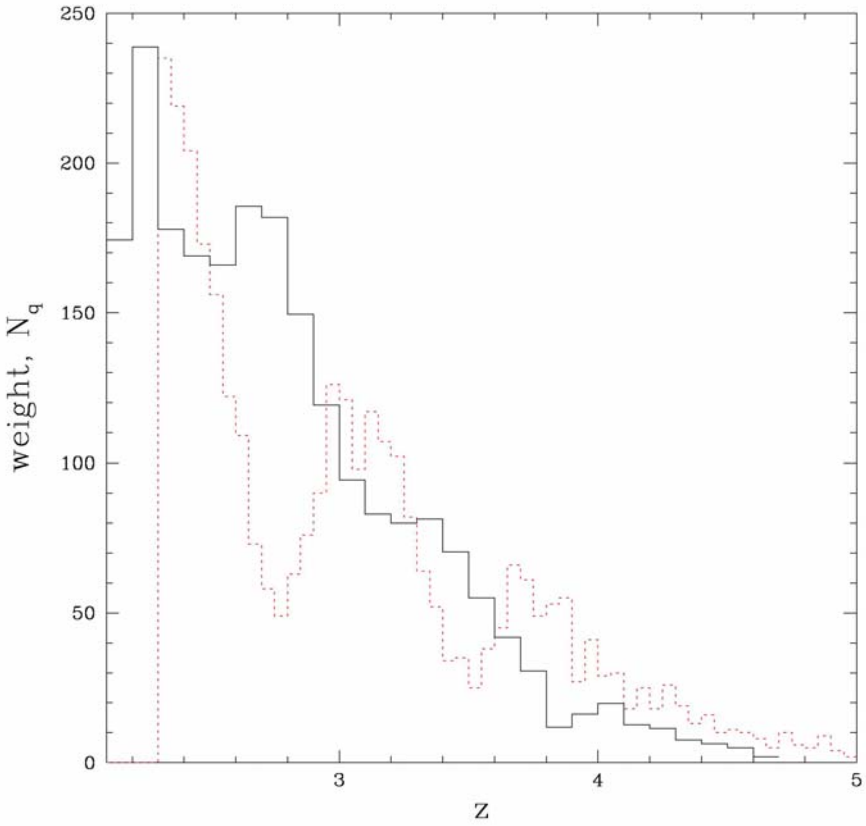
Katz etal 1999



Lyα Forest as a tool for cosmology



- Each spectrum is a 1D probe of ~400 Mpc/h through the IGM (with full wavelength coverage)
- Fluctuations in absorption trace the underlying mass distribution



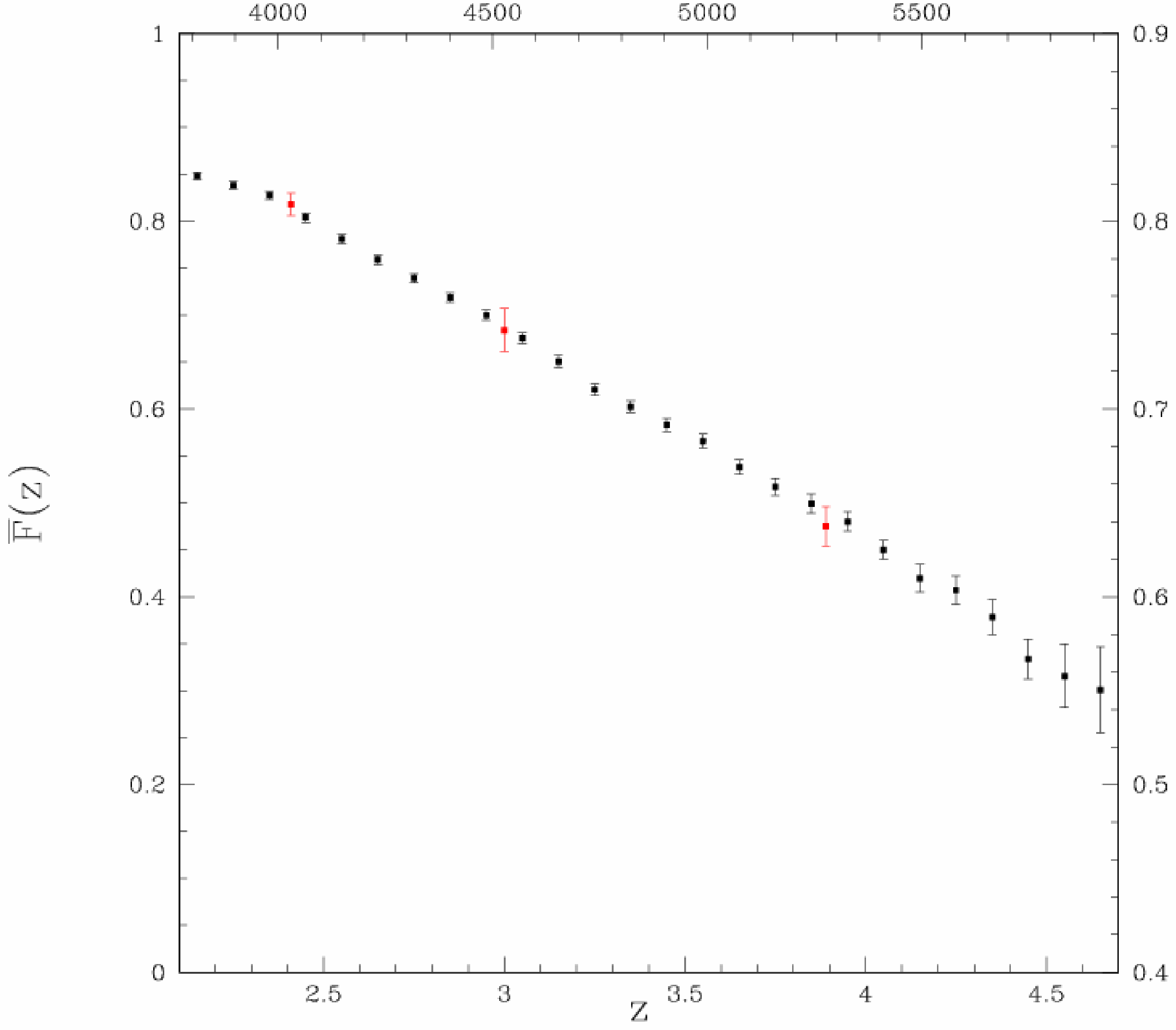
SDSS Data

3300 spectra with $z_{qso}>2.3$

.... redshift distribution of quasars

1.1 million pixels in the forest

——— redshift distribution of Lyα forest pixels (noise weighted)



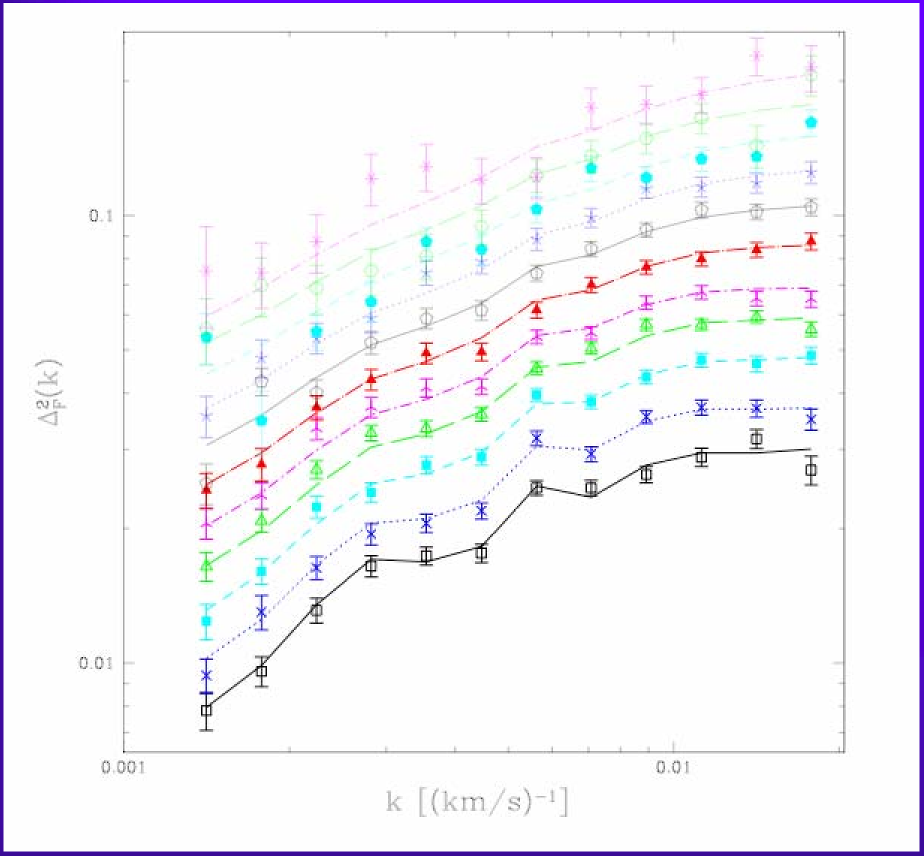
PCA analysis of QSO spectra

Evolution of mean flux consistent with external constraints

No feature at z=3.2

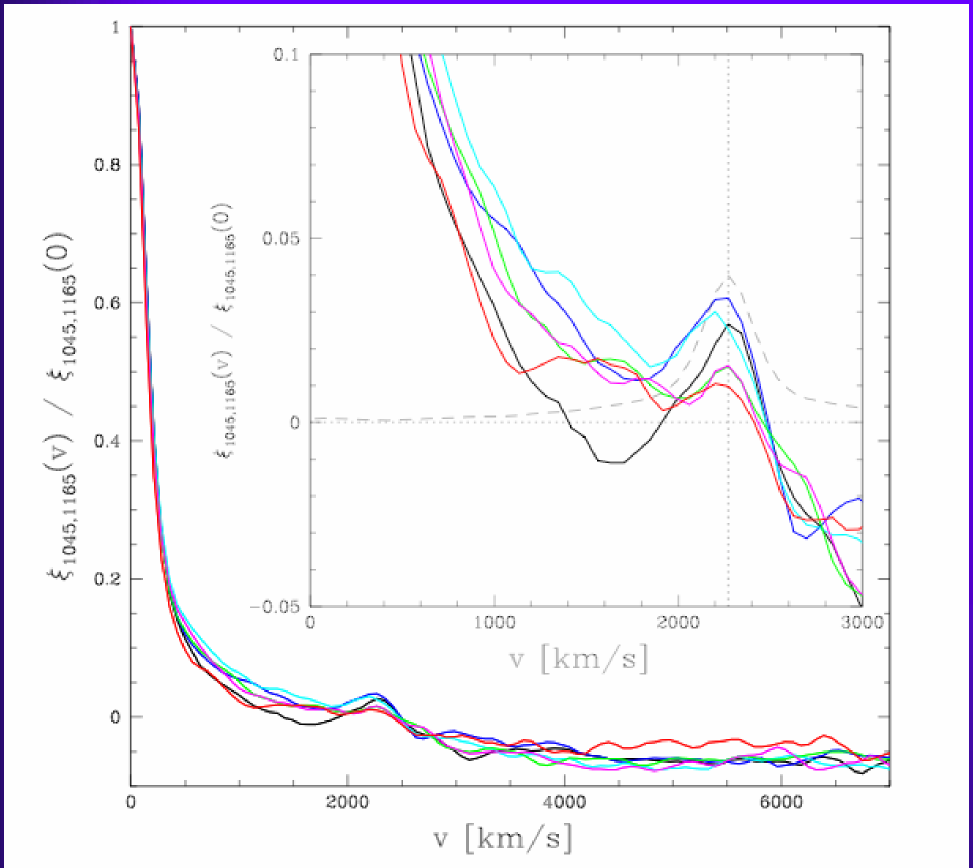
Best fitted model

McDonald etal 2004



- 2<z<4
- **$\chi^2 \approx$ 129 for 104 d.o.f.**
- **A single model fits the data over a wide range of redshift and scale**

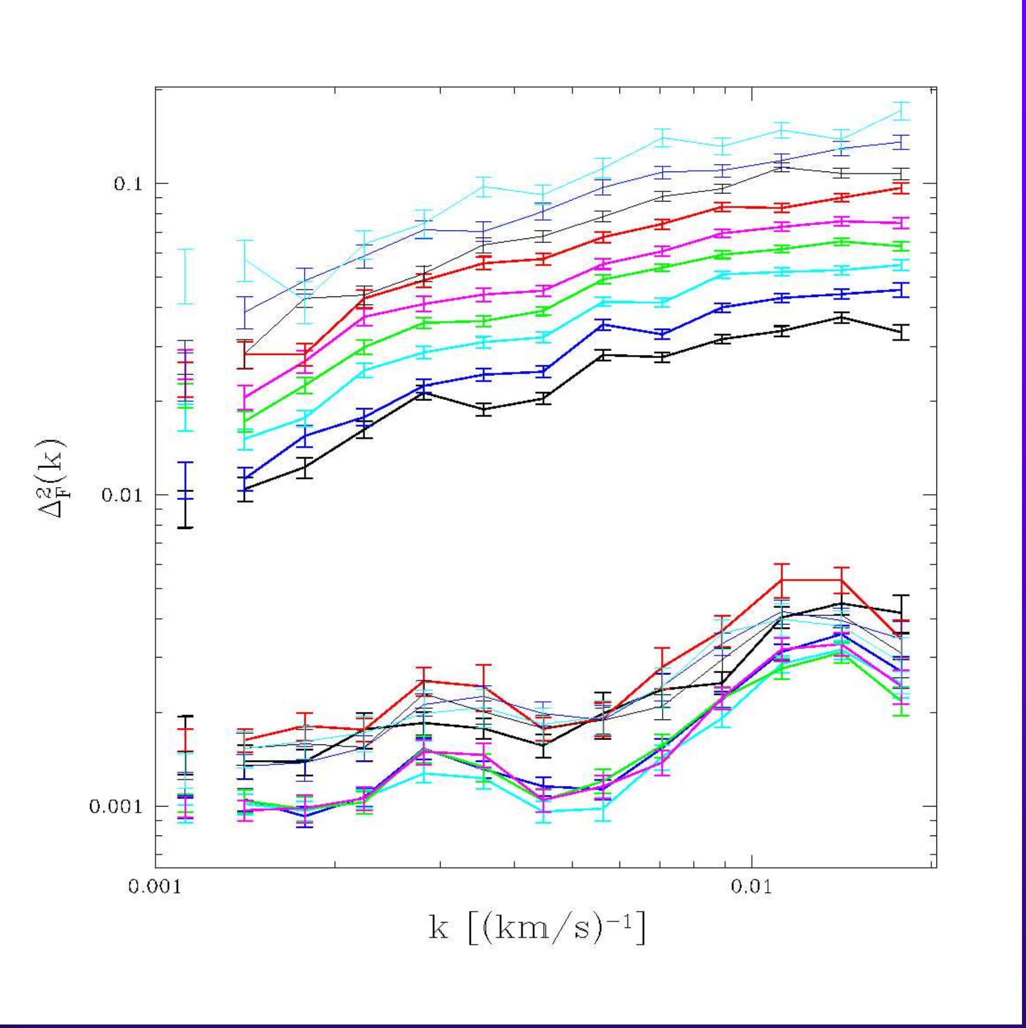
SiIII-Lyα cross-correlation bump



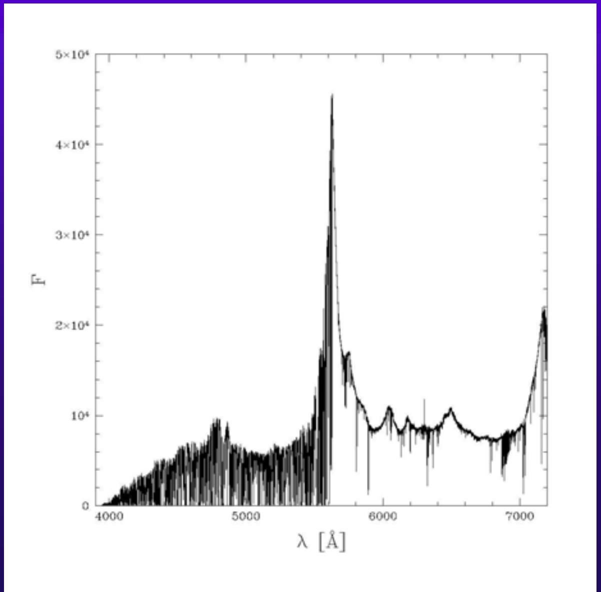
- SiIII absorbs at 1207 Å, corresponding to a velocity offset 2271 km/s
- Vertical line at 2271 km/s
- No other obvious bumps out to about 7000 km/s
- Dashed line shows

  $0.04\ \xi_F(v-2271\ \text{km/s})/\ \xi_F(0)$

Background Contamination



- The top set of lines shows the Lyα forest power
- The bottom set of lines shows the power in the region $1270<\lambda_{rest}<1380$Å

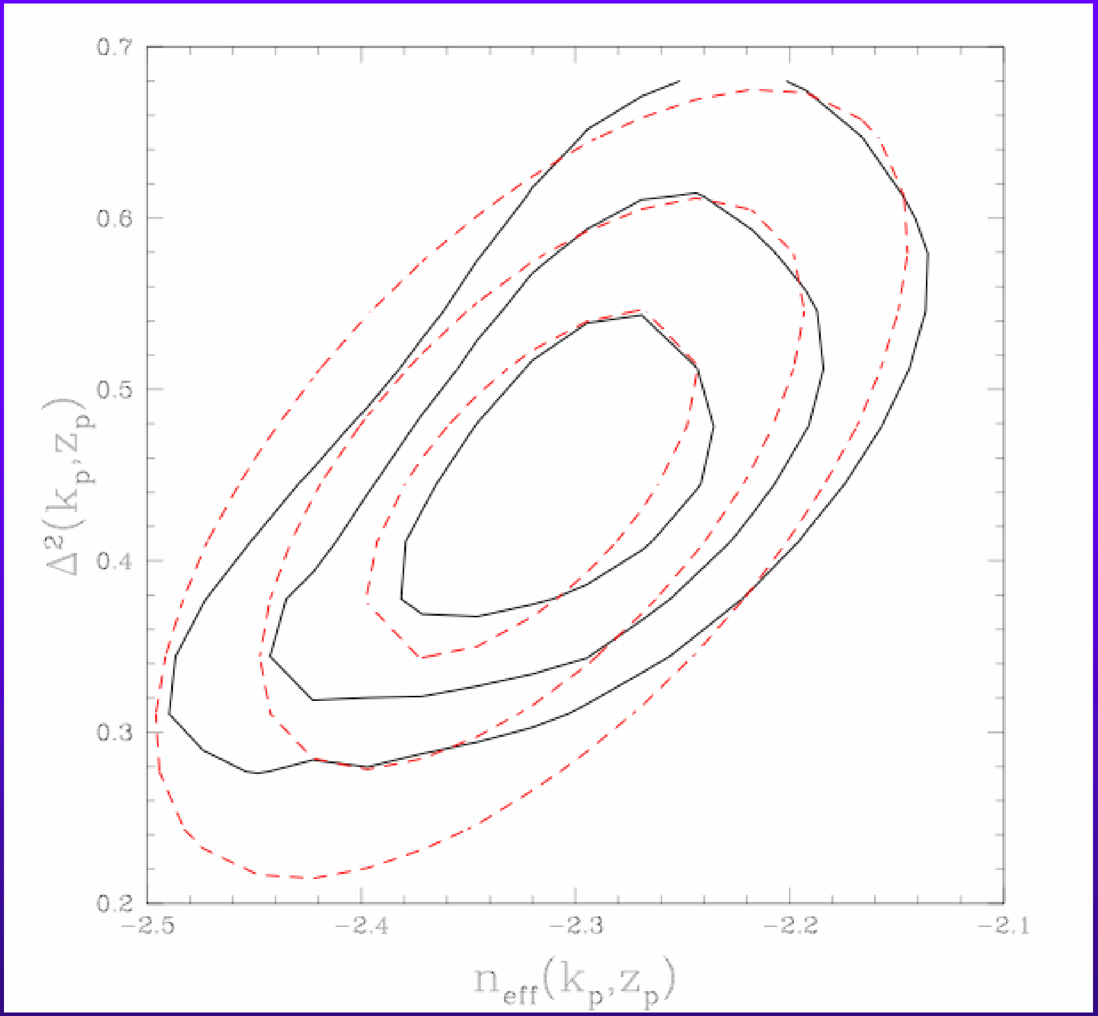


Cosmological implications: need to revisit WMAP with exact likelihood analysis of low multipoles

Anze Slosar, Alexey Makarov

- Quadrupole is not very low (4% as opposed to 0.8%)
- The significance of low l multipoles has been exaggerated
- No evidence for running in the data (despite recent reports from CBI/VSA), less than 1-sigma signal

Ly-alpha forest analysis is constraining the linear amplitude and slope of matter fluctuation spectrum at k=1h/Mpc at z=3



Theoretical analysis

- Predict $P_F(k)$ using hydrodynamic simulations and compare it directly to the observed $P_F(k)$.
- Allow general relation $P_F(k) = f[P_L(k)]$.
- Assume: IGM gas in ionization equilibrium with a homogeneous UV background.
- Assume: IGM not too badly disturbed by feedback from galaxies.
- Fully hydrodynamic simulations near the best-fit cosmological model are used to correct approximate hydro-PM simulations which are used to explore parameter space.
- Overall hundreds of different simulations were run

Astrophysical parameters we marginalize over

Density and temperature are correlated, modeled as a power law with slope γ–1 and amplitude T0

$$T = T_0(1+\delta)^{\gamma-1}$$

Filtering length: on large scales baryons are just like CDM, on small scales pressure suppresses fluctuations, modeled as a filter scale 1/kF

The astrophysics uncertainties in the model can be parametrized with γ, kF, T0 and mean flux F (ionizing background) as a function of z

They all have some external constraints (T from line widths…)

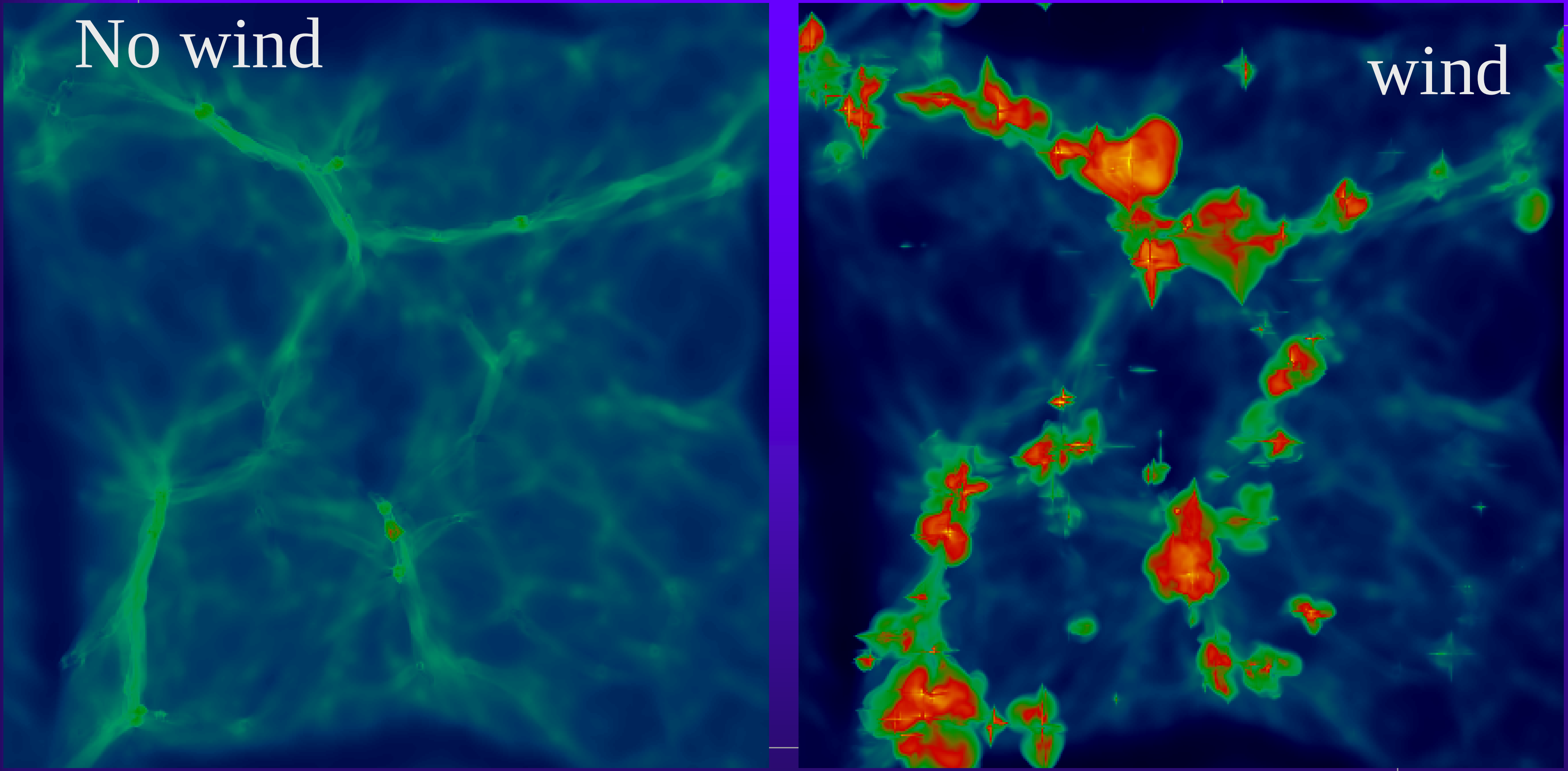
Additional physical effects

Simulations we use do not include:

- Galactic superwinds (known to exist in starburst galaxies and LBGs)
- Ionizing background fluctuations from quasars
- Damped and lyman limit systems, which are self-shielded

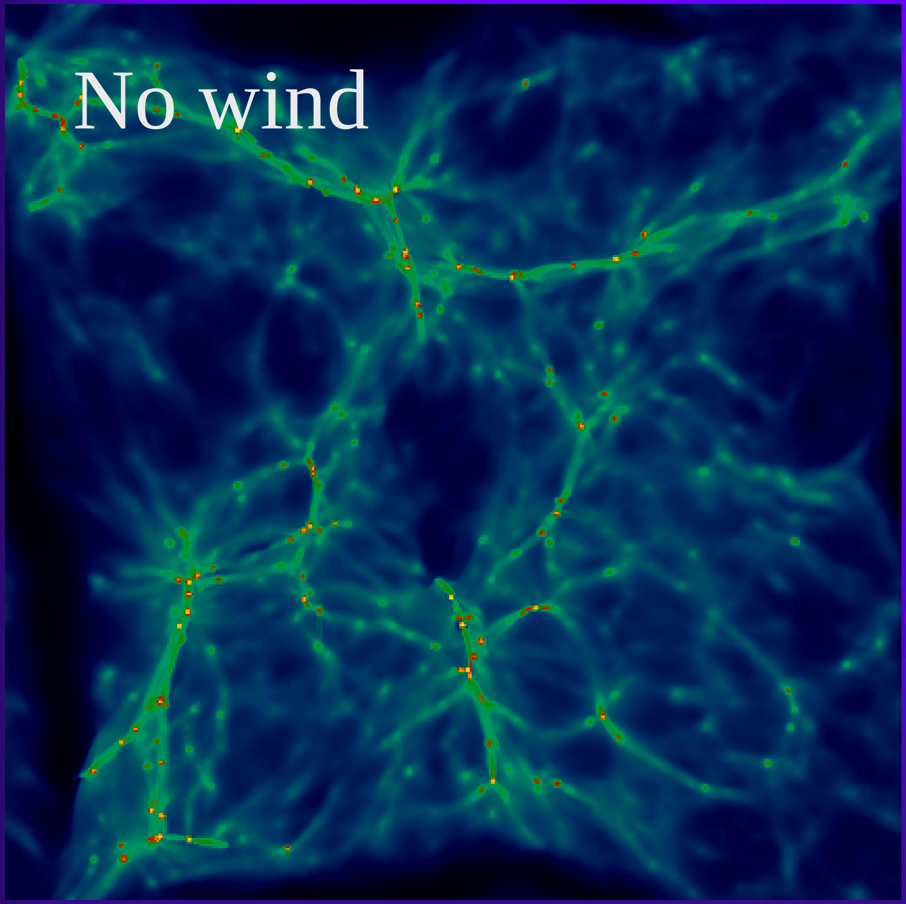
Galactic winds heat IGM to 100,000K and pollute IGM with metals

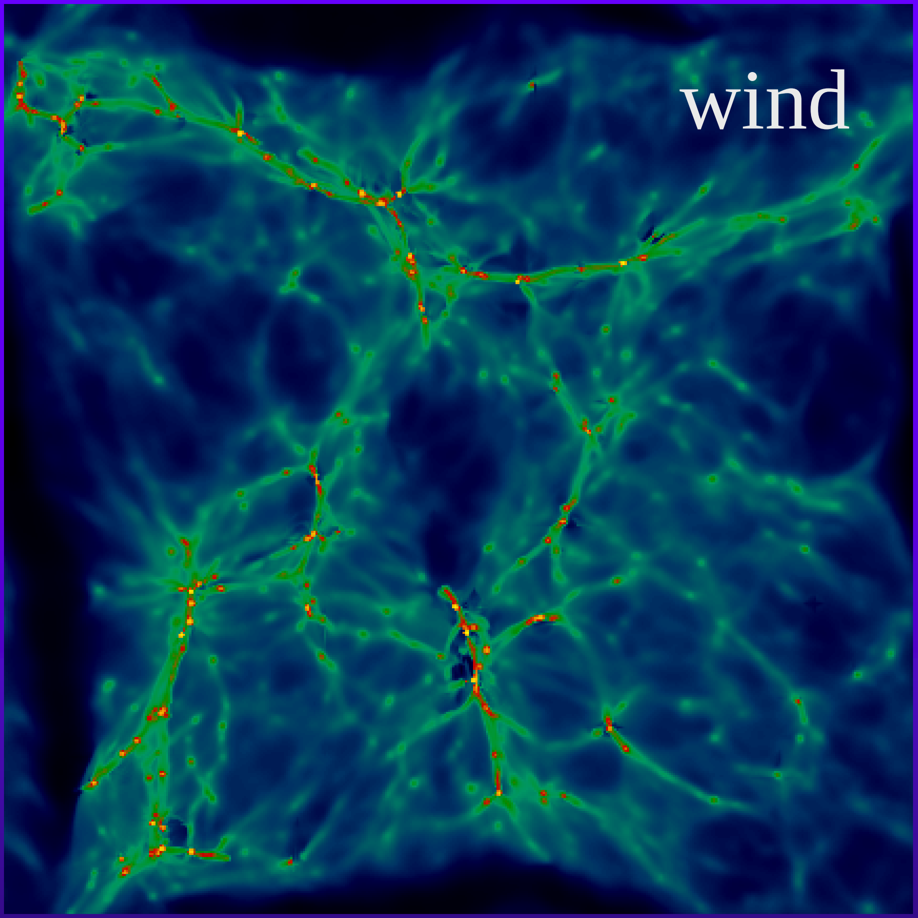
Temperature maps



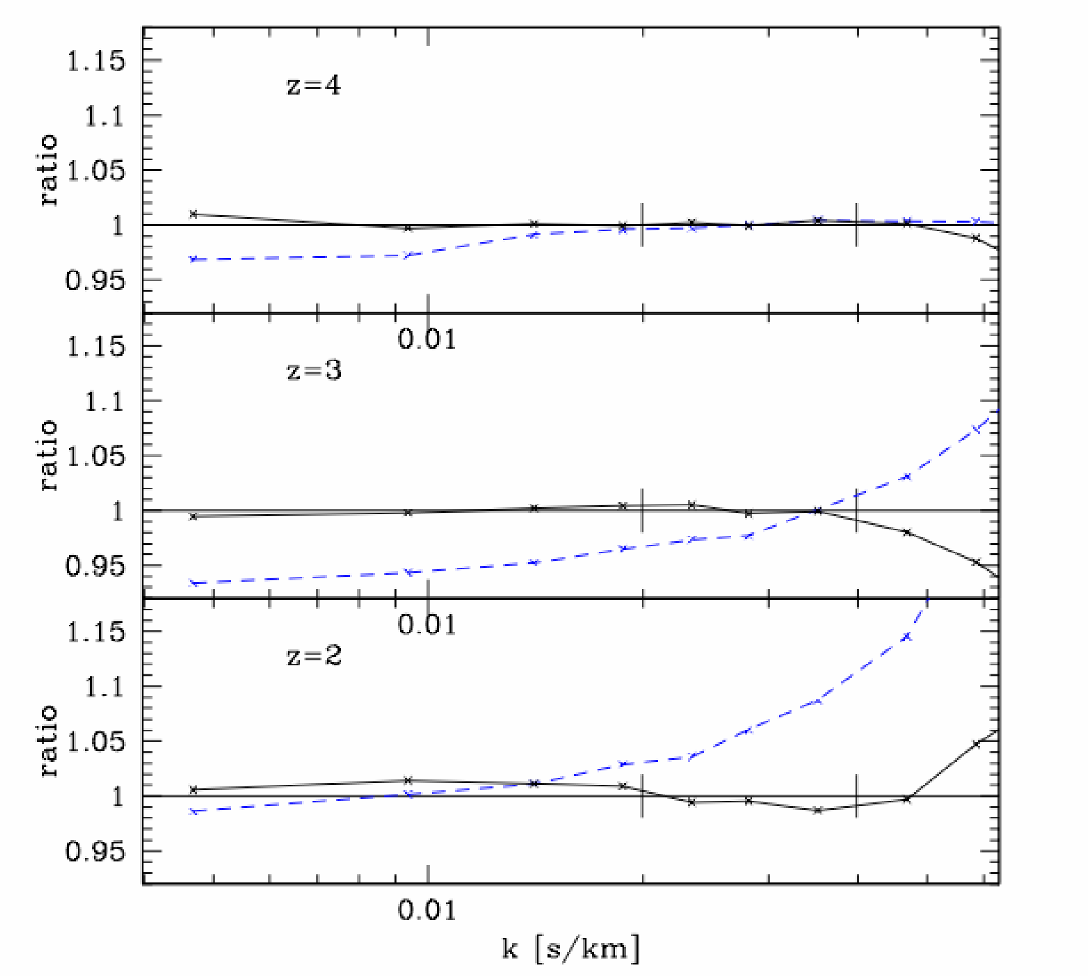
Cen, Nagamine, Ostriker 2004

Neutral hydrogen maps show much less effect





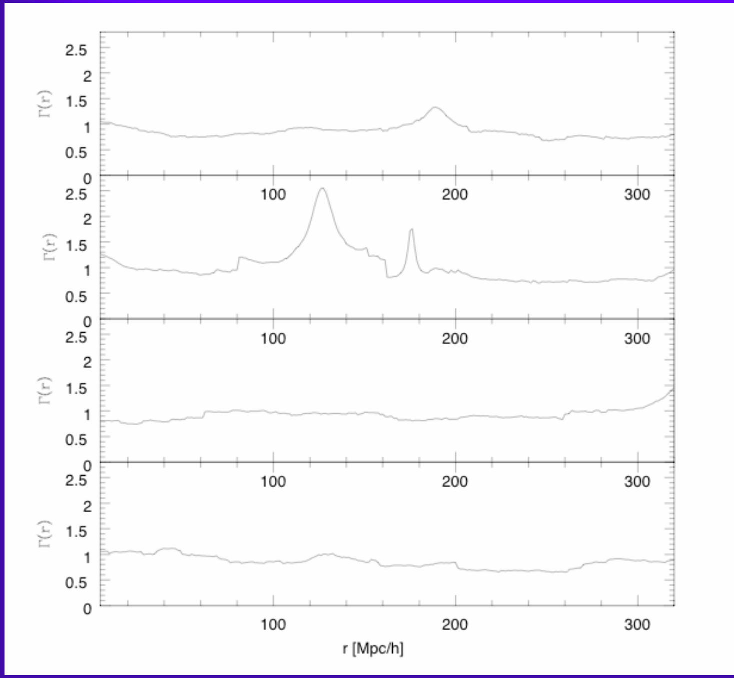
Strong wind versus no wind simulations

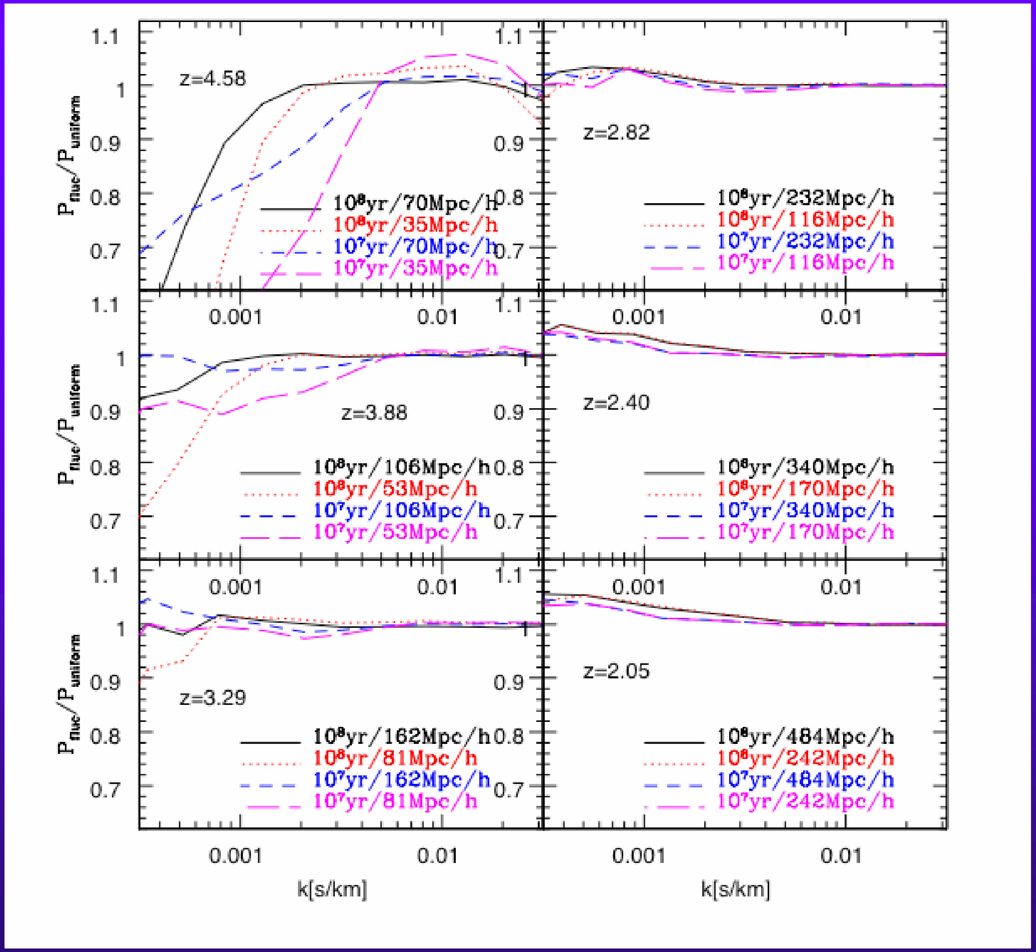


Winds have no effect after simulations have been adjusted for temperature change

This is not conclusive and more work is needed to investigate other possible wind models

Fluctuations in ionizing background



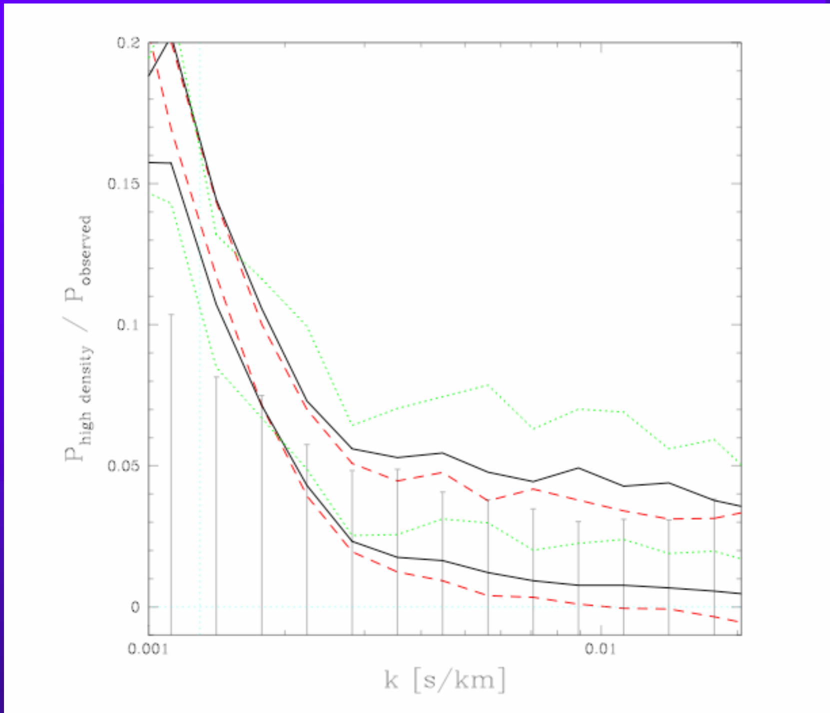


Attenuation length is rapidly decreasing with redshift, so effect can be large at z>4, negligible at lower redshifts

No evidence in the data

Damped and lyman limit systems

- When density of hydrogen is high photons get absorbed and do not ionize hydrogen (self-shielding)
- Simulations without proper radiative transfer cannot simulate this
- We have good measurements of number density of these systems as a function of column density and redshift
- We place these systems into densest regions of simulations
- Damping wings (Lorenzians) wipe out a large section of the spectrum
- This adds long wavelength power, removing it makes spectrum bluer
- Important effect which was not previously estimated



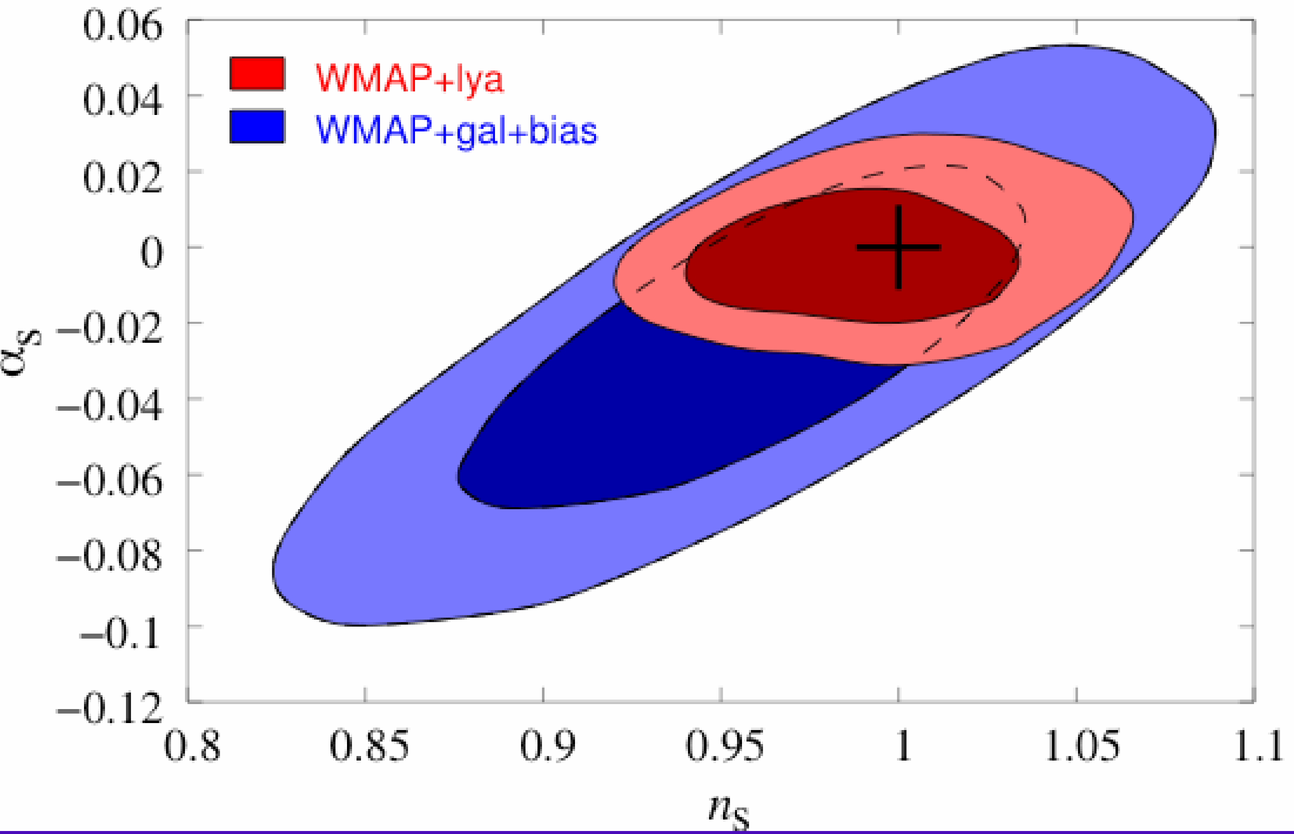
Internal checks

- Good fit to the data: consistent with the linear growth, no evidence for systematics as a function of z, evolution of slope better constrained than slope itself
- Curvature in the power spectrum consistent with predicted
- These checks cannot identify all possible sources of trouble, but allow elimination of some, such as in ionizing background fluctuation example

Cosmological constraints

- Combined with WMAP (always), sometimes with SDSS galaxy power spectrum, SDSS bias constraints or SN1A. No need to use 2dF or VSA,CBI,ACBAR
- On running two things have changed recently: WMAP low l have larger errors, weakening the constraints at large scales and
- Damped systems have increased Ly-alpha slope at small scales by 0.06

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



3-fold reduction in errors on running

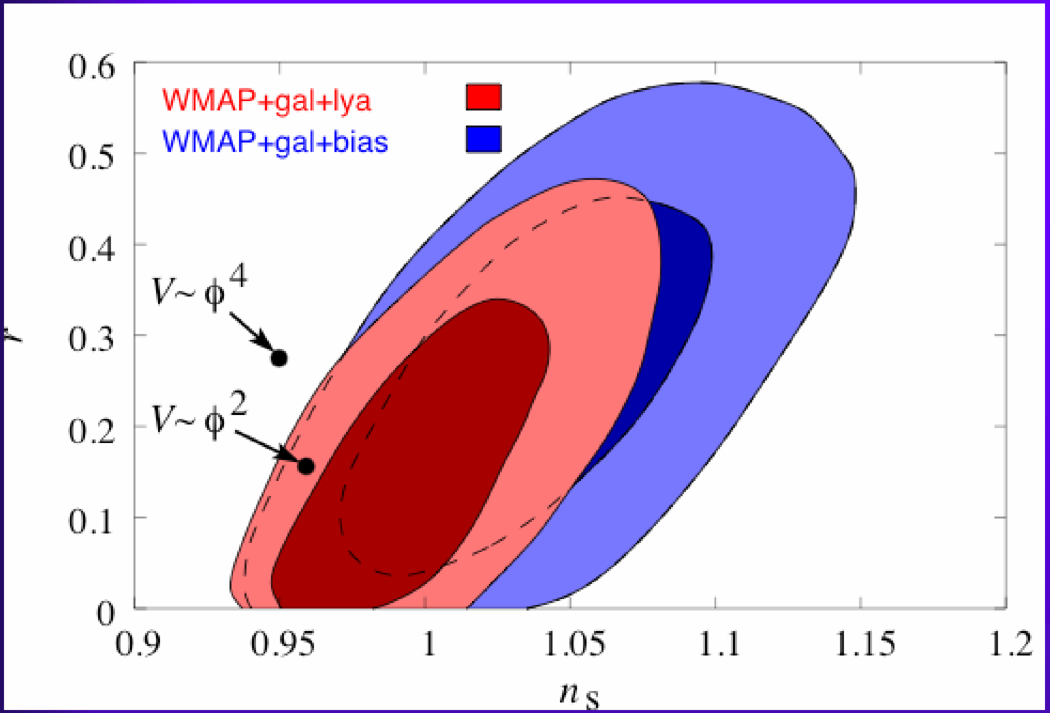
No large running!

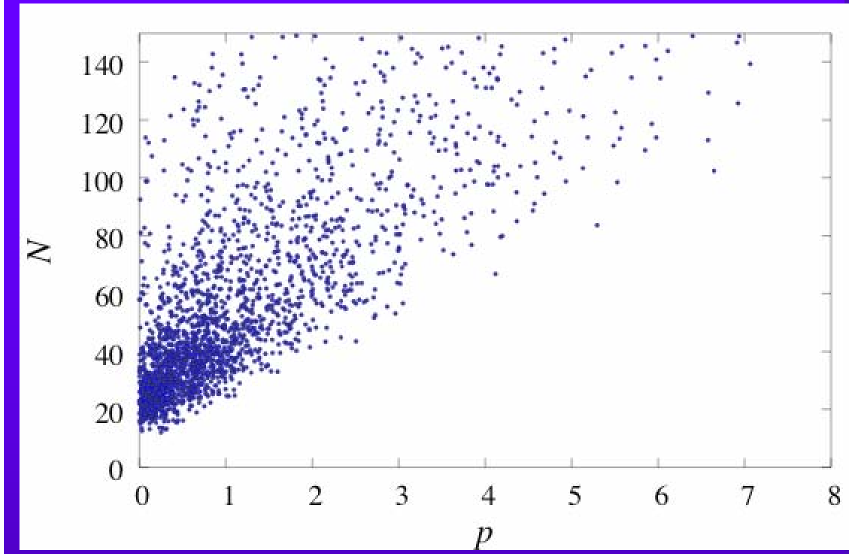
Different from before because of damped system effect at small scales and increased WMAP errors at large scales

$$\alpha_s = dn_s/d\ln k = -0.002 \pm 0.010$$

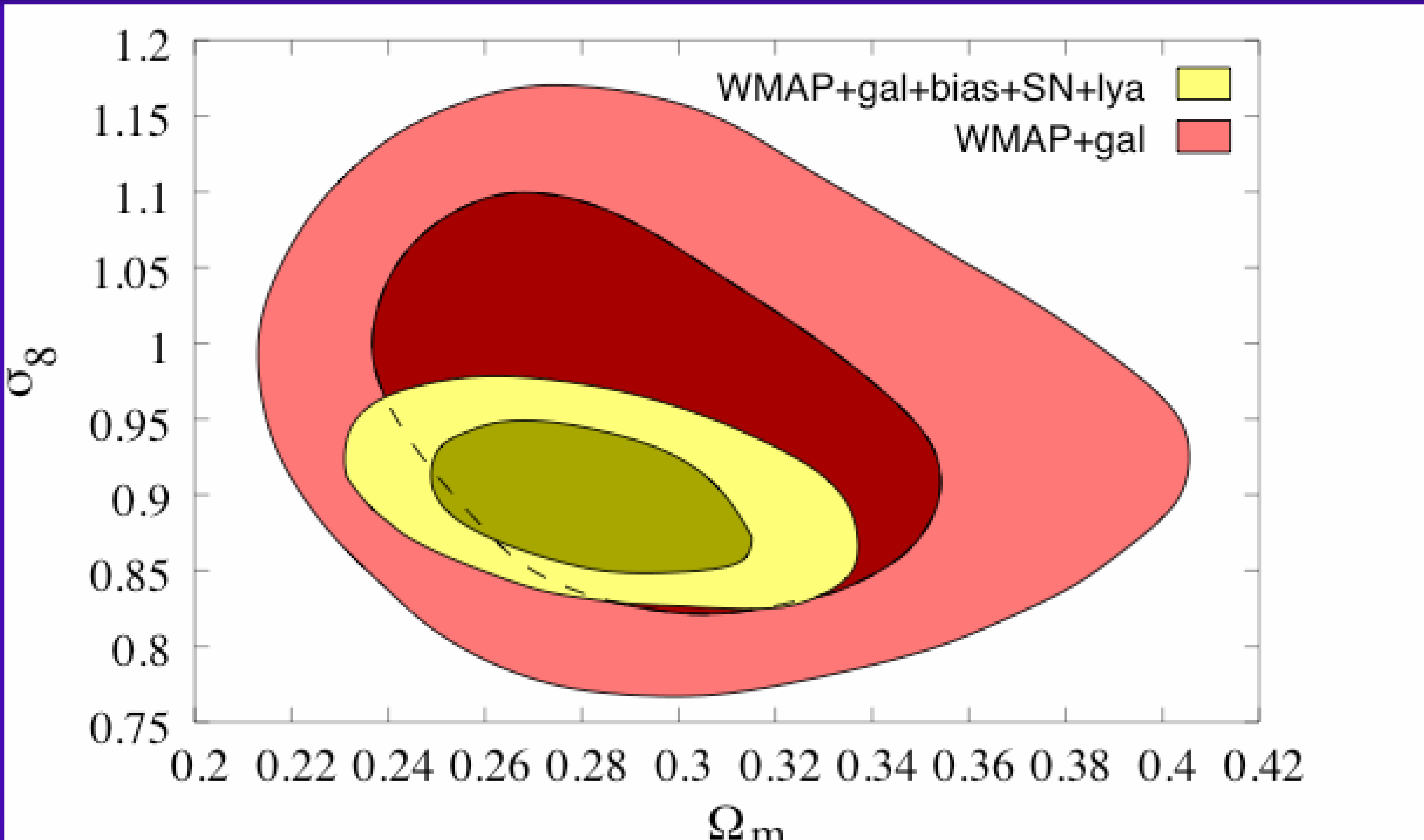
$$n_s = 0.98 \pm 0.02$$

Constraints on inflation





- No evidence of tensors, $r<0.36$ (95% cl)
- Chaotic potentials need shallow slope
- Hybrid models ($n>1$, $r=0$) disfavored

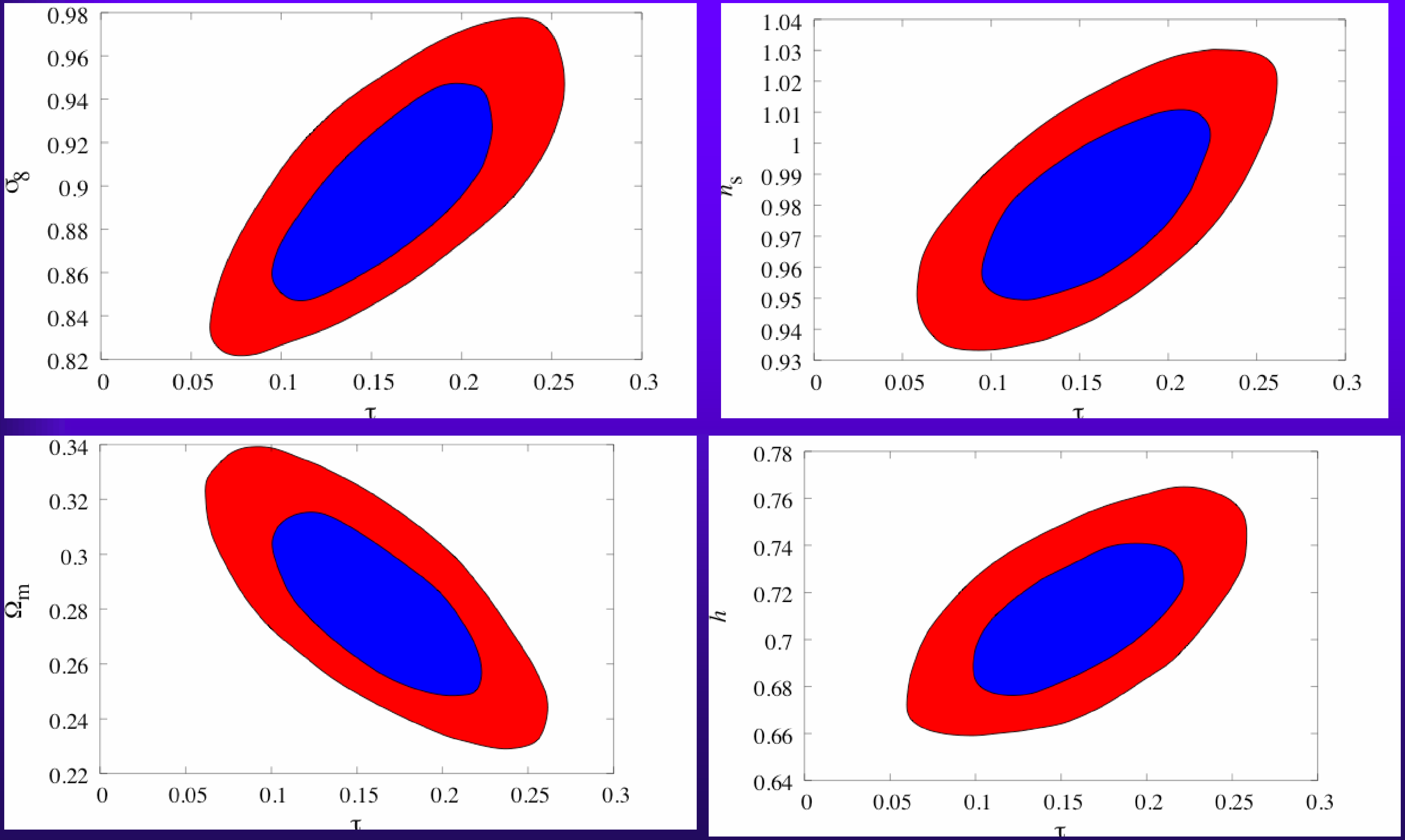


$$\sigma_8 = 0.90 \pm 0.03$$

$$\Omega_m = 0.28 \pm 0.02$$

$$h = 0.71 \pm 0.02$$

Correlations with optical depth



New limits on neutrino mass

- Factor of 3 better than with WMAP+SDSS

$$\sum m_\nu < 0.42eV\,(95\%)$$

- Together with SK and solar limits:

$$\Delta m_{12}^2 = 8 \times 10^{-5} eV^2,\ \Delta m_{23}^2 = 2.5 \times 10^{-3} eV^2$$

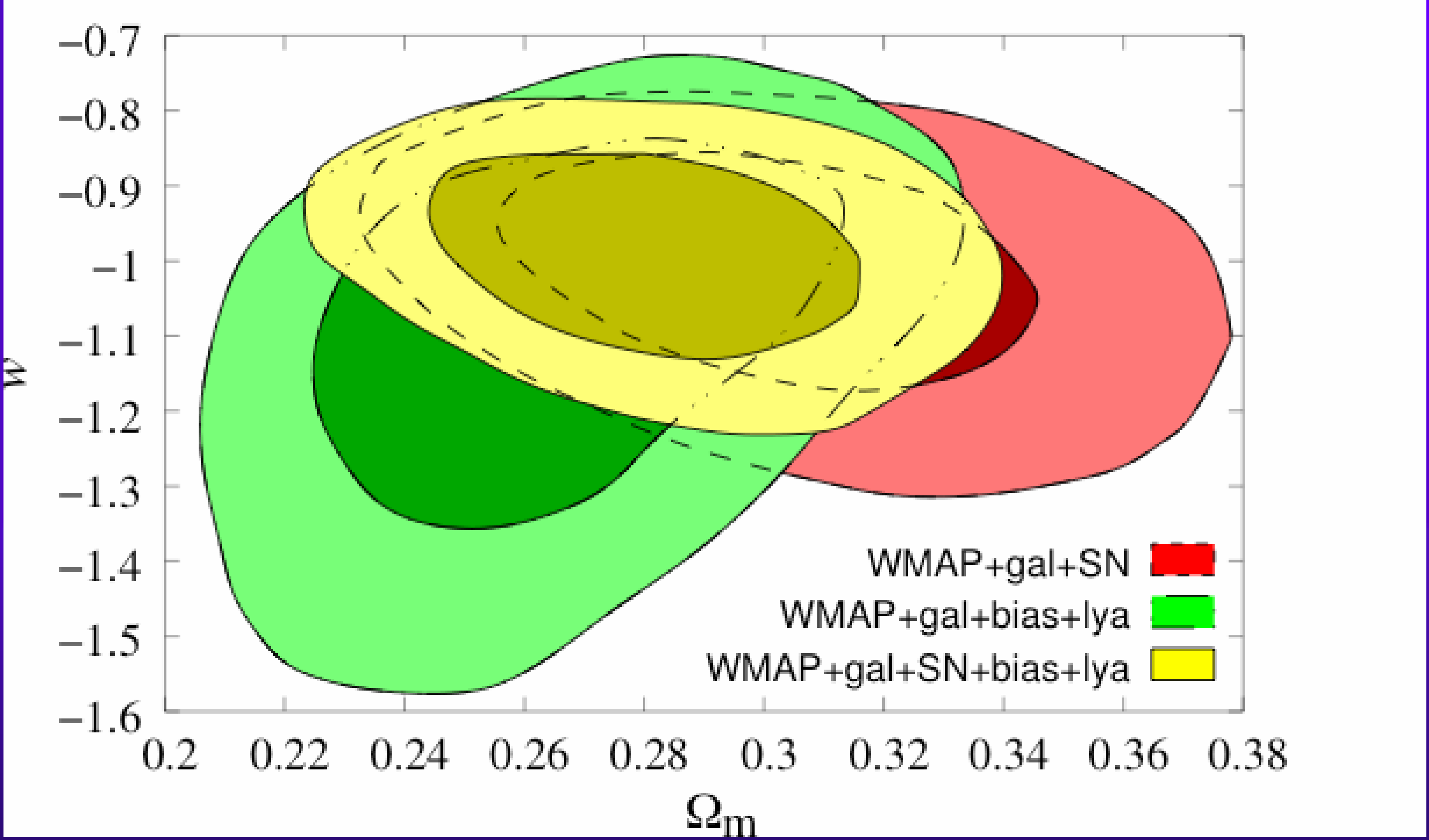
$$m_1 < 0.13eV,\ m_2 < 0.13eV,\ m_3 < 0.15eV$$

$$\frac{m_3}{m_1} > 1.1$$

- Sterile neutrino case excludes LSND

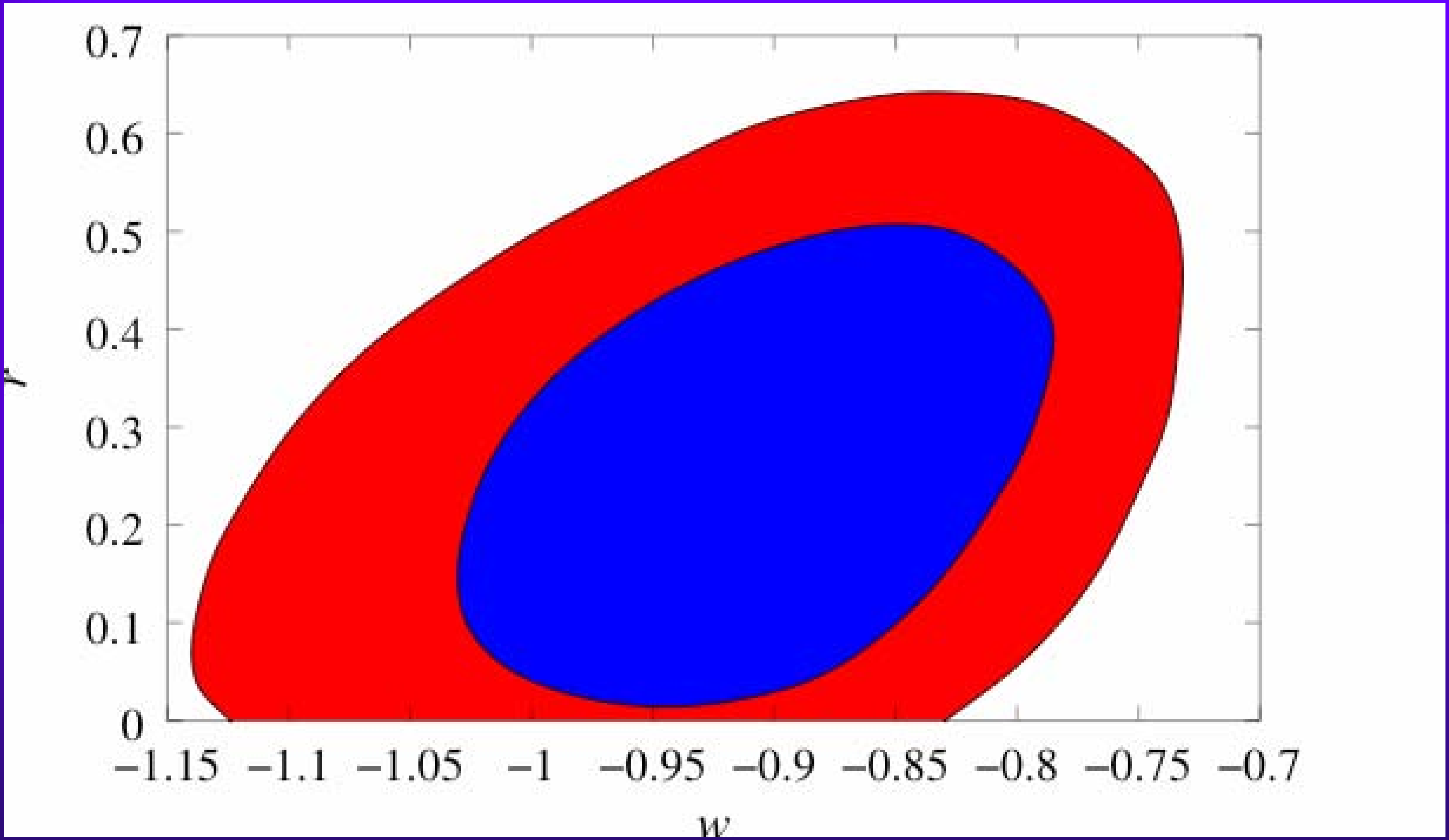
$$m_\nu < 0.79eV\,(95\%)$$

Dark energy constraints



$$w = -0.99 \pm 0.09$$

w is correlated with r

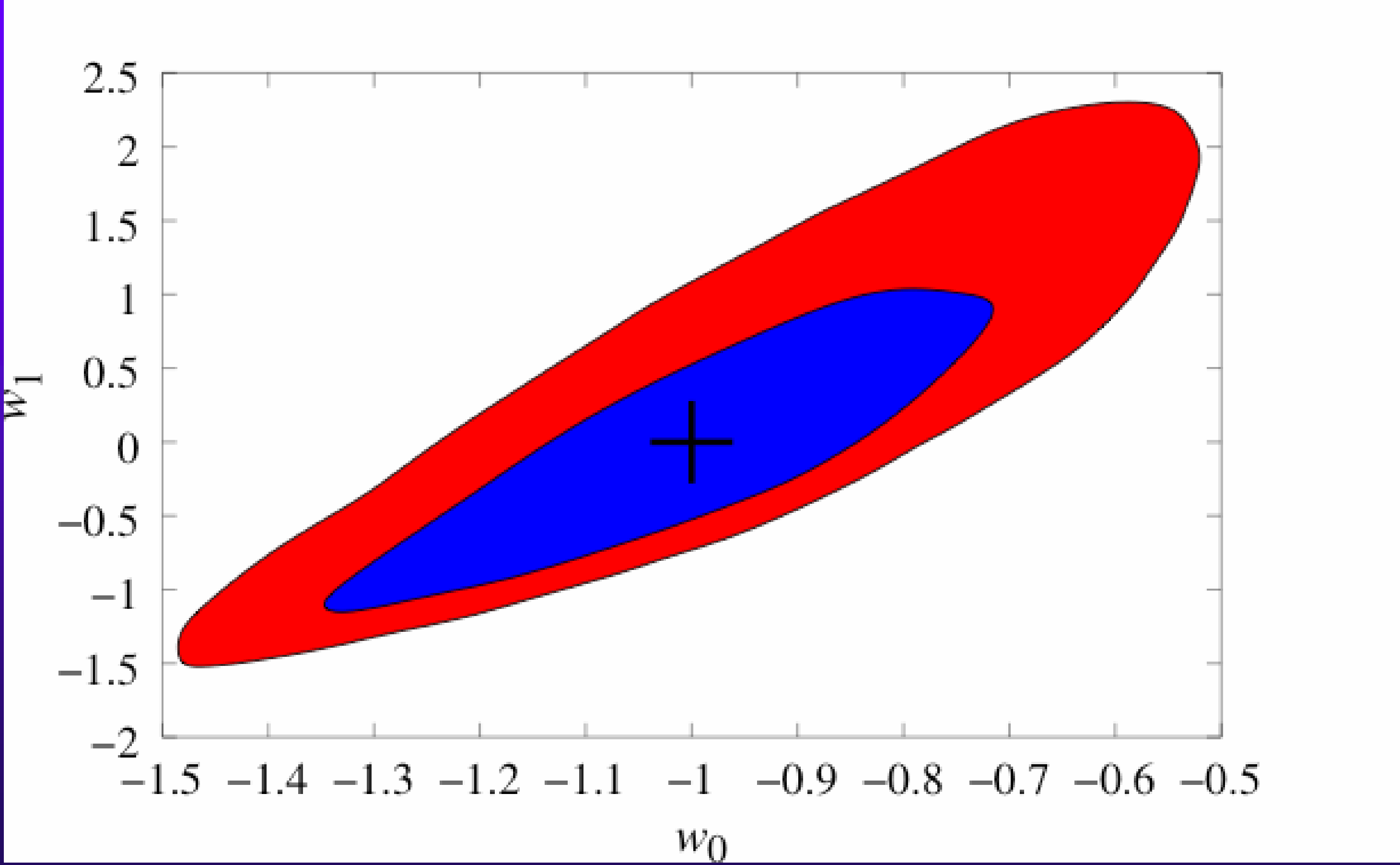


$$w = -0.91 \pm 0.09$$

Time evolution of equation of state

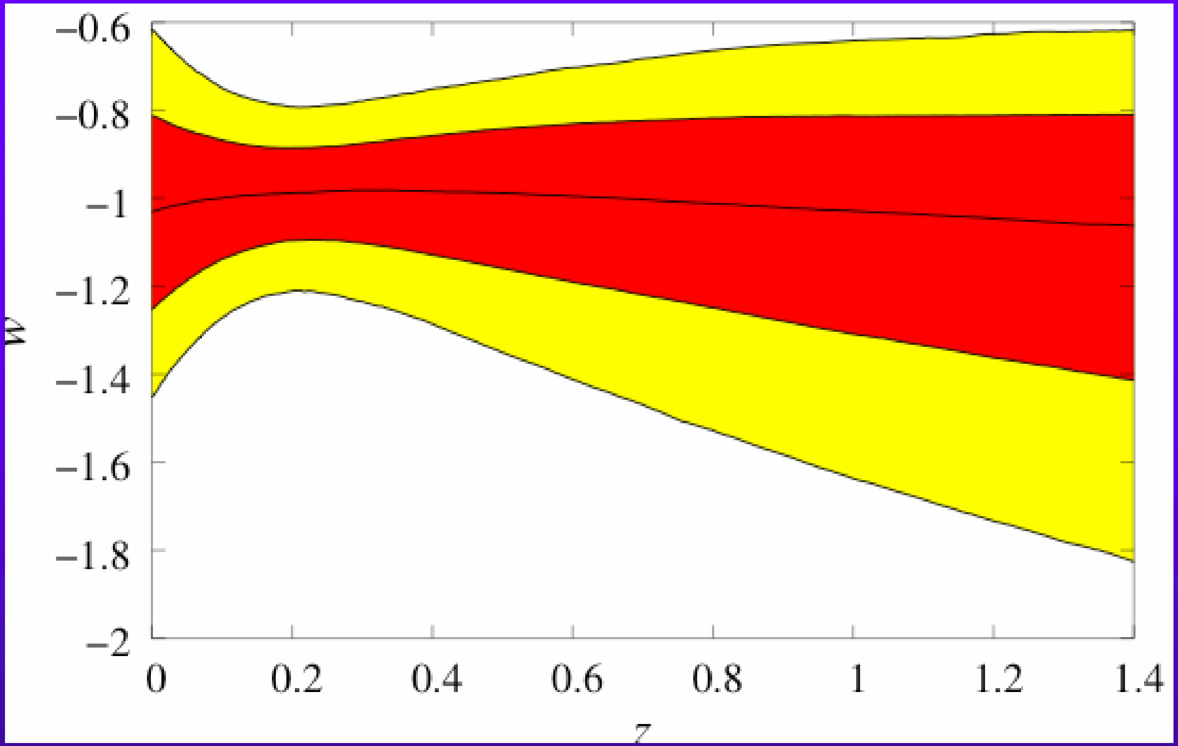
$$w = w_0 + (a-1)w_1 + (a-1)^2 w_2$$

Individual parameters very degenerate

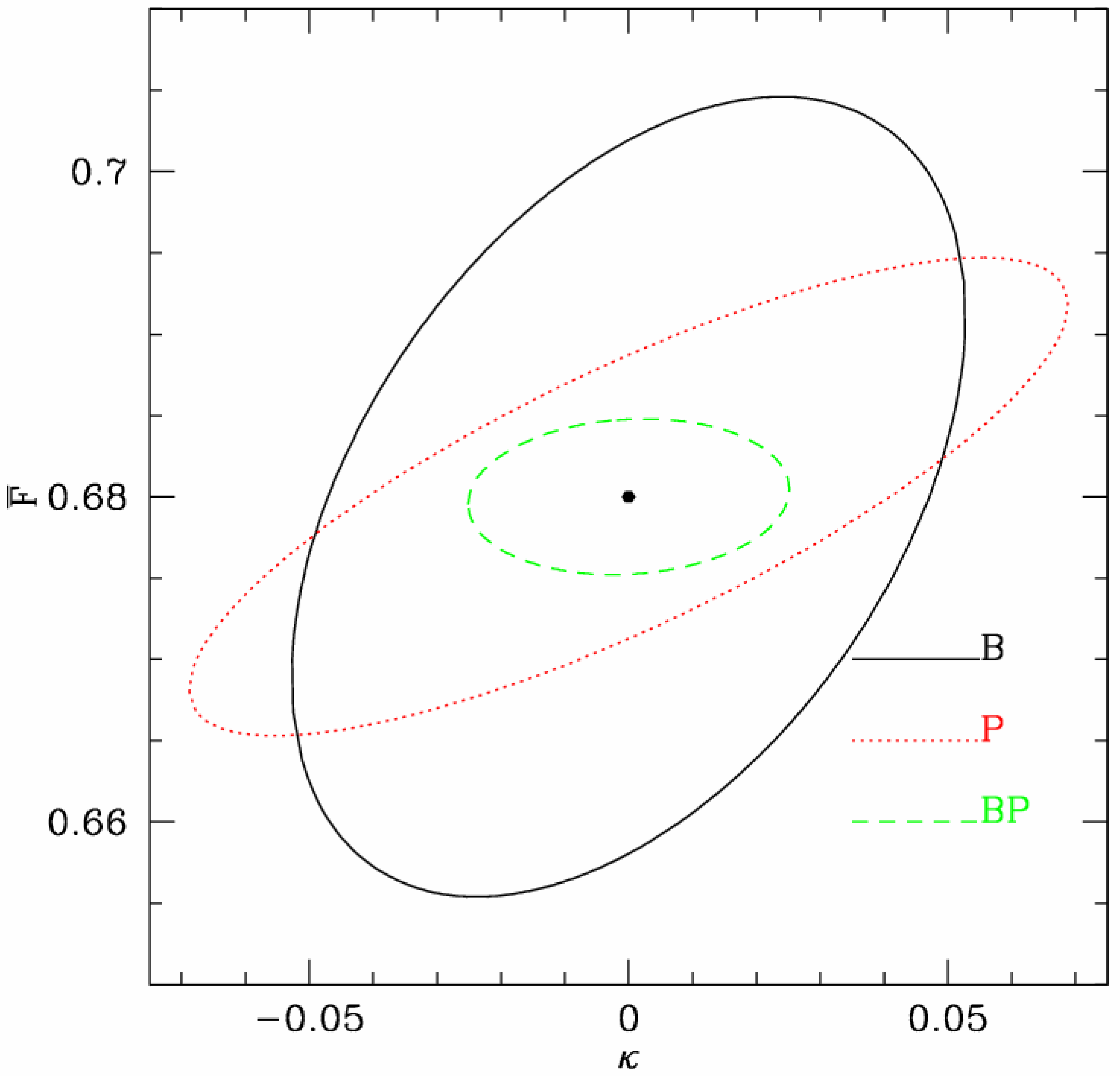


Time evolution of equation of state

- w remarkably close to -1
- Robust against adding more terms
- Best constraints at z=0.3
- Lya helps because there is no evidence for dark energy at z>2
- Best constraints to date



$$w(z=1) = -0.93^{+0.21}_{-0.25}$$



Can determine power law slope of the growth factor to 0.1

Mandelbaum etal 2003

Implications for structure formation models

- Overall the fact that $n<1$ and $dn/dlnk<0$ is in qualitative agreement with inflation
- The amplitude of the effect, if confirmed, is slightly larger than expected, but within 2-sigma of "standard predictions"

Future prospects and conclusions

- Ly-alpha power spectrum analysis reduces significantly errors on all parameters, specially on primordial power spectrum
- Results will be tested/improved with bispectrum analysis
- More work exploring additional physical processes is needed to confirm these conclusions
- No surprises have emerged, but constraints are getting tighter for alternative models, such as running, quintessence/phantom energy models and degenerate massive neutrinos
- SDSS is an enormous source of cosmological information that will keep us busy for years, this is just the beginning!