What can cosmological observations tell us about early universe

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Arcetri/Florence, September 19, 2005

Observational cosmology as a probe of fundamental physics

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Garching, dec 17, 2004

Outline

1) Galaxy clustering: LRG photometric sample
2) Weak lensing: new results, some trouble ahead
3) Lya forest: improved constraints
3) What have we learned so far and what can we expect in the future?

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

Outline

1) What can cosmology tell about fundamental physics and what are the methods to achieve it?

2) 3 examples: galaxy clustering, weak lensing, Ly-alpha forest

3) What have we learned so far and what can we expect in the future?

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

Goals of observational cosmology from fundamental physics perspective

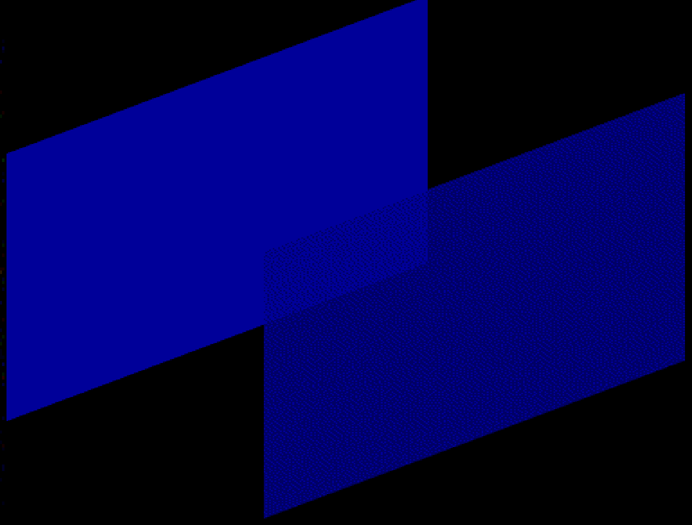
- Ingredients and their properties (e.g. neutrino mass, nature of dark energy)
- Nature of creation of structure in the universe (inflation or something else?)

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

plenty of astrophysics along the way!

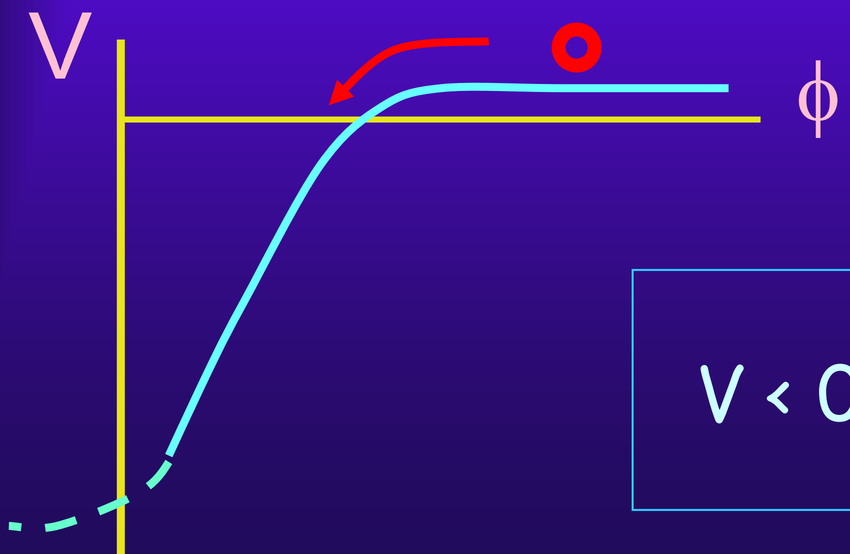
Cyclic Model

Steinhardt and Turok



4d Field Theory Picture

extra dimension → ϕ



interbrane potential → $V(\phi)$

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

How to test fundamental theories?

1) Classical tests: redshift-distance relation (SN1A etc): matter components

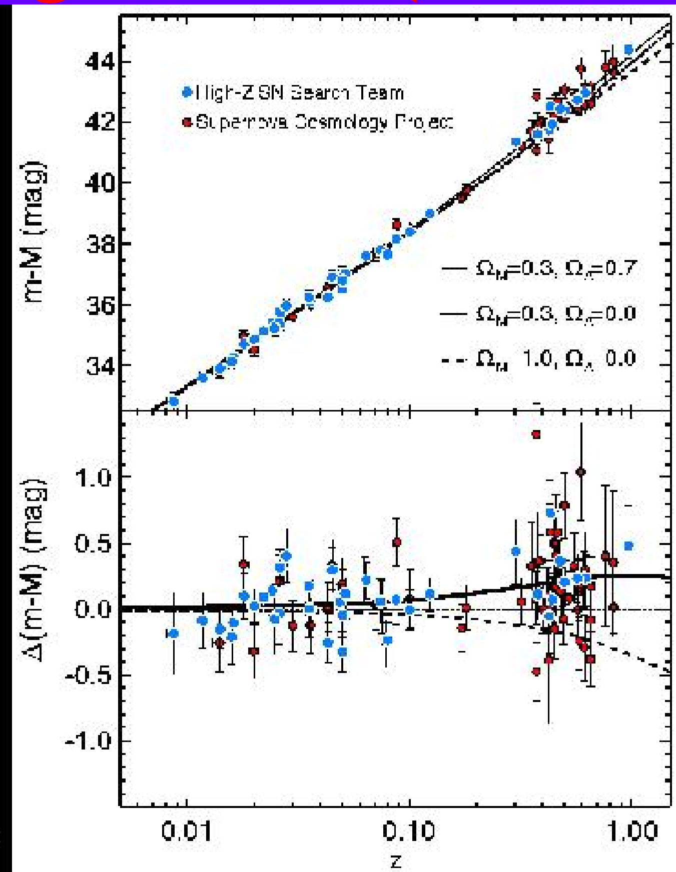
Classical cosmological tests (in a new form)

Type Ia supernovae are standardizable candles; observations of many at high redshift test the time evolution of the expansion rate.

Result: the universe is accelerating!

There must be some sort of dark energy which doesn't redshift away; maybe a cosmological constant Λ, maybe something dynamical.

[Riess et al.; Perlmutter et al.]



$$a = \frac{1}{1+z}$$

$$s = c\int \frac{dt}{a(t)}$$

$$w = \frac{p_{\rm de}}{\rho_{\rm de}}$$

$$\left(\frac{\dot a}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar\rho - Ka^{-2}$$

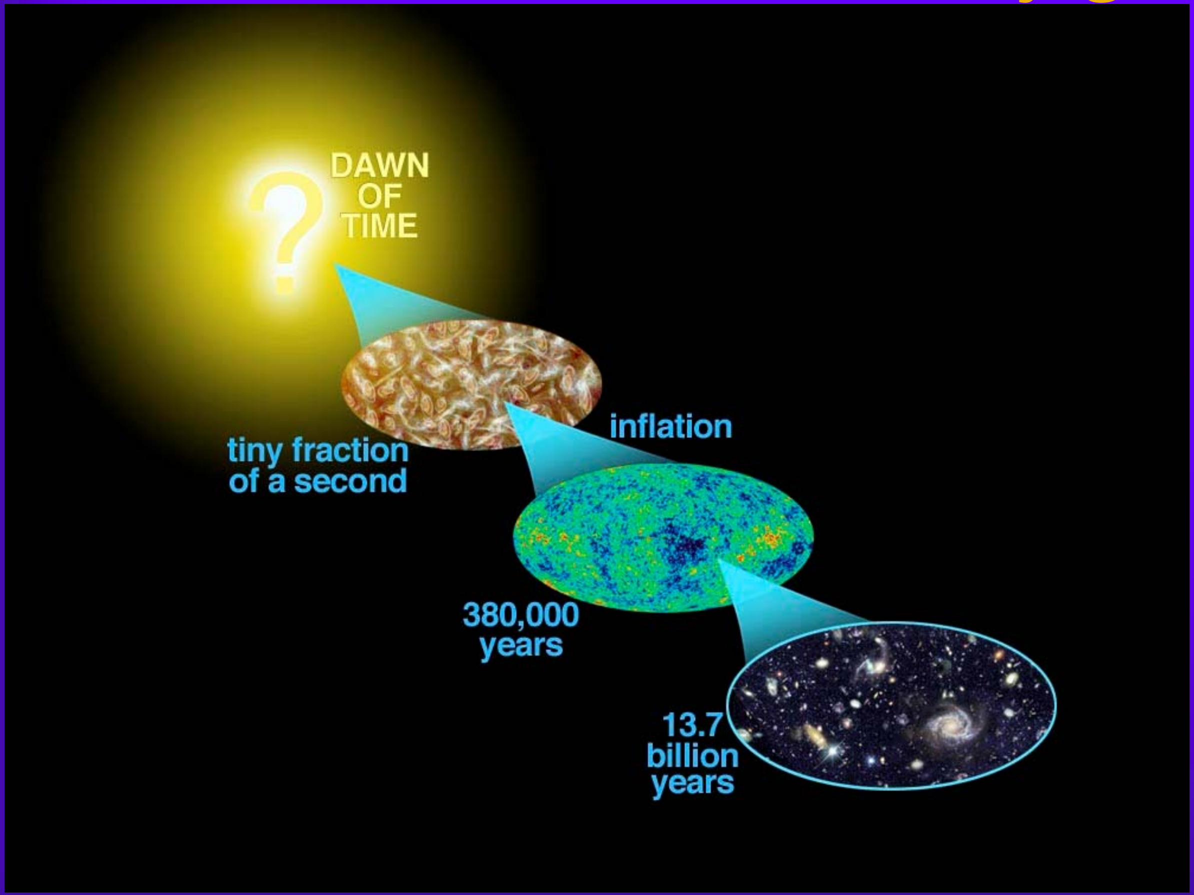
Friedmann's (Einstein's) equation

$$\bar\rho = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

How to test fundamental theories?

1) Classical tests: redshift-distance relation (SN1A etc): matter components
2) Growth of structure: dark energy, neutrino mass

Growth of structure by gravity



♦ Perturbations can be measured at different epochs:

1. CMB z=1000
2. 21cm z=10-20 (?)
3. Ly-alpha forest z=2-4
4. Weak lensing z=0.3-2
5. Galaxy clustering z=0-1 (3?)

Sensitive to dark energy, neutrinos…

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta \longrightarrow \delta(t)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar{\rho} - Ka^{-2}$$

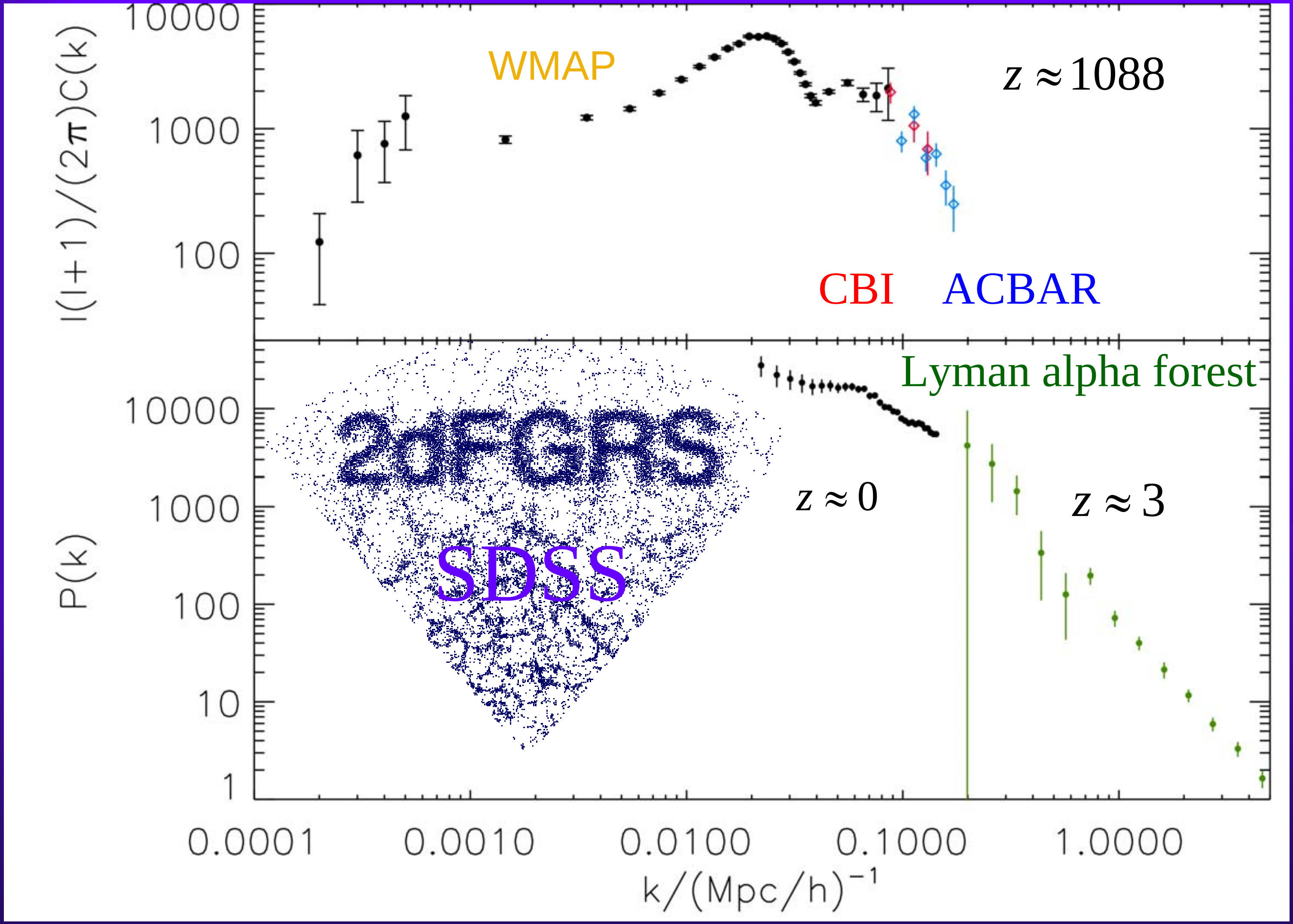
$$\bar{\rho} = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

How to test fundamental theories?

1) Classical tests: redshift-distance relation (SN1A etc): matter components
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

Scale dependence of cosmological probes

$$\langle \delta(k)\delta^*(k')\rangle = P(k)\delta_D(k-k')$$



Complementary in scales and redshift

How to test fundamental theories?

1) Classical tests: redshift-distance relation (SN1A etc): matter components
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) Gravity waves (r=T/S): cmb polarization
5) Other: gaussianity, adiabaticity

Initial conditions: Inflation

$$H^2 = V$$

Consider a scalar field with non-zero potential

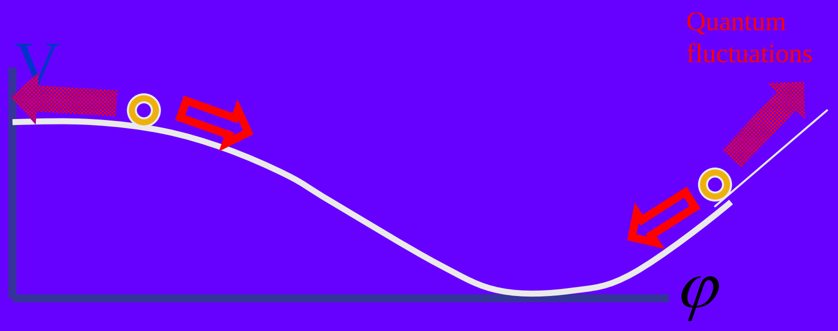
If $V(\varphi) >>$ all space and time derivative (squared) terms

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

$$a \sim e^{Ht}$$

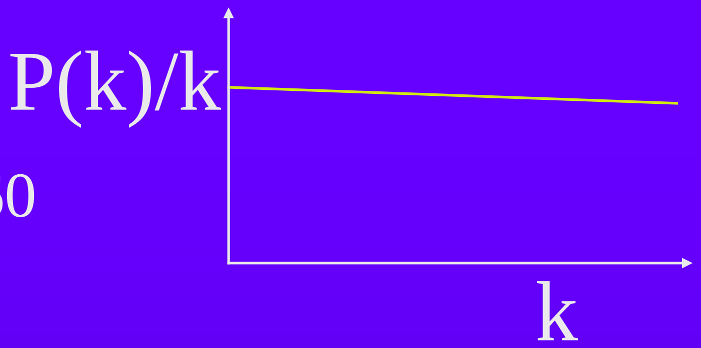
Inflation

$$P(k) \propto \frac{H^2}{\dot{\phi}}$$



Quantum fluctuations converted into classical space-time perturbations of scalars and tensors (gravity waves)

Initial conditions: inflation predictions



- Inflation must end, number of e-folds 50-60
- Predicts almost scale invariant spectrum

$$P(k) \propto k^{n_s}$$

$$|n_s - 1| \sim 10^{-2}, \alpha_s = \frac{dn_s}{d\ln k} \sim (n_s - 1)^2 \sim 10^{-3}$$

- Tensors/Scalars can be anything between 0 and 1
- Adiabatic, almost gaussian fluctuations
- Curvature=0
- Testable, ie easy to disprove
- Focus on slope n and running α ,in future also T/S
- Need large range of scales, best combination: CMB+Ly-alpha forest

How to weight neutrinos?

- Neutrino mass is of great importance in particle physics (are masses degenerate? Is mass hierarchy inverted?): large next generation experiments proposed (KATRIN…)

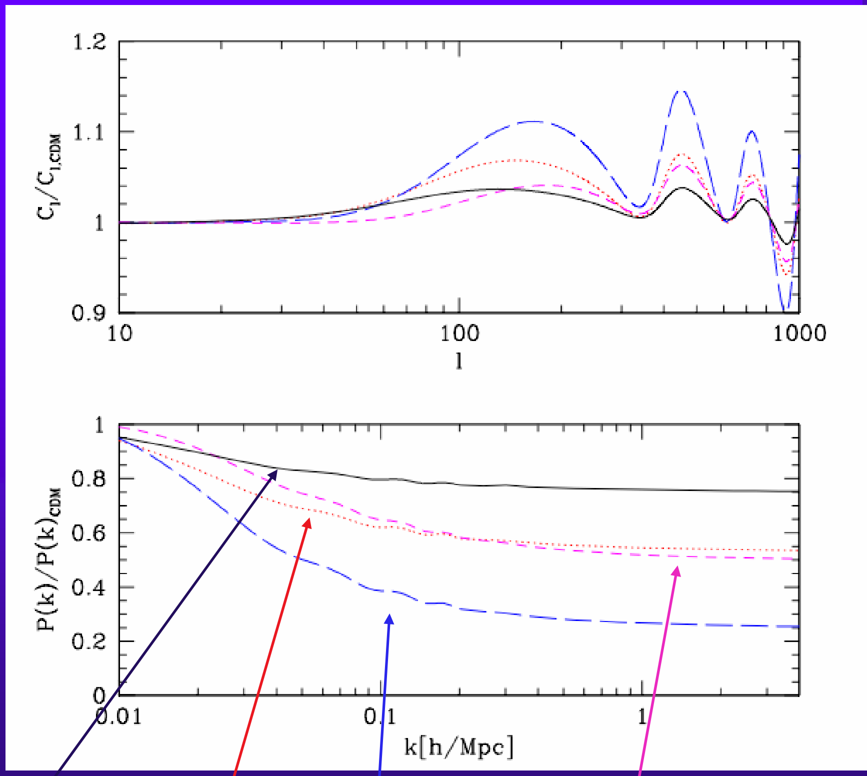
$$f_\nu = \frac{\sum m_\nu}{94eV\omega_m} \sim \frac{\sum m_\nu}{12eV}$$

- Neutrino free streaming inhibits growth of structure on scales smaller than free streaming distance

$$\frac{\delta(f_\nu)}{\delta(f_\nu=0)} = (a/a_{eq})^p \sim 4000^p$$

- If neutrinos have mass they are dynamically important and suppress dark matter as well, 50% suppression for 1eV mass $P(f_\nu)/P(f_\nu=0) \sim e^{-8f_\nu}$
- For m=0.1-1eV free-streaming scale is >10Mpc
- Neutrinos are quasi-relativistic at z=1000: CMB is also important, opposite sign

$$\delta \propto a^p, \quad p = \frac{1}{4}\left[5 - \sqrt{1+24f_\nu}\right]$$



m=0.15x3, 0.3x3, 0.6x3, 0.9x1 eV

Dark energy: theoretical possibilities

- Parametrized with equation of state $w(z)=p/\rho$
- If $w=-1$ always then cosmological constant
- Models in which dark energy is dynamical predict w changing in time and not equal to -1 (tracker models etc)
- Can cluster, could be observable on large scales
- Cannot be explained by perturbations alone (backreaction)

Can backreaction mimic dark energy?

- Usual approach: Friedmann equation is based on assumption of homogeneous universe
- better approach: averaging in a perturbed universe (best if done on observables, but this can be computationally difficult)
- What is backreaction: Einstein's equations are nonlinear in metric, so there are quadratic terms in metric that do not average to 0
- Two possible divergences have been proposed: IR and UV

Can IR divergence be observed?

- If spectrum of fluctuations is red ($n<1$) fluctuations divergent for wavelengths very large compared to horizon
- Causality: any observable can only depend on initial data set on a Cauchy hypersurface slice within past lightcone (finite size)
- Free to reparametrize coordinates on hypersurface or to change the hypersurface itself (gauge freedom)
- Spacetime metric perturbation can be made to locally vanish (equivalence principle), so any large long wavelength perturbation can be absorbed in redefinition of coordinates: Riemann normal coordinate construction is an explicit construction to achieve this (Hirata and Seljak 2005)

Can small scale fluctuations mimic dark energy?

$$ds^2 = a^2[-(1+2\phi)d\tau^2 + (1-2\phi)\delta_{ij}dx^i dx^j]$$

$$3(\dot{a}/a)^2 = 8\pi G < \rho > a^2 + < (\nabla\phi)^2 > + 8\pi G a^2 < \rho v^2 >$$

- Perturbative calculation valid as long as phi is small
- The fact that phi is small does not imply backreaction terms must be small compared to 0-th order because of gradients
- One can compute 2nd term on RHS using nonlinear power spectrum of ϕ
- Estimate: 10^-5 (Seljak and Hui 1995), negligible
- Such perturbative calculation impossible in synchronous gauge used in Kolb etal (metric perturbation diverge when orbits cross)

The role of simulations

Kravtsov etal

Simulations used in interpretation of most observations (primary CMB is an exception)

Dark matter

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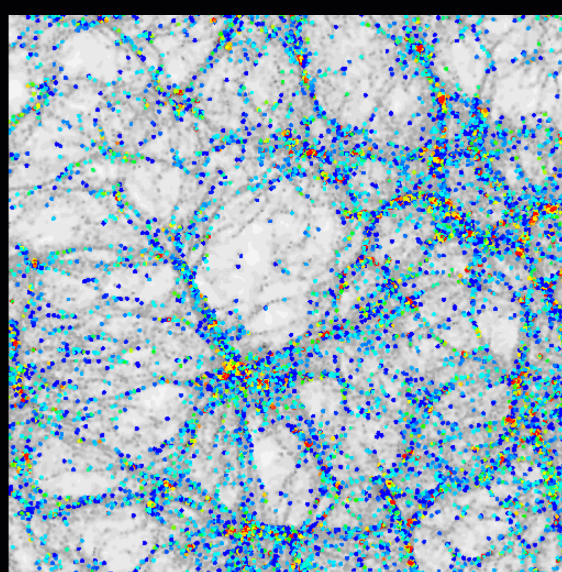
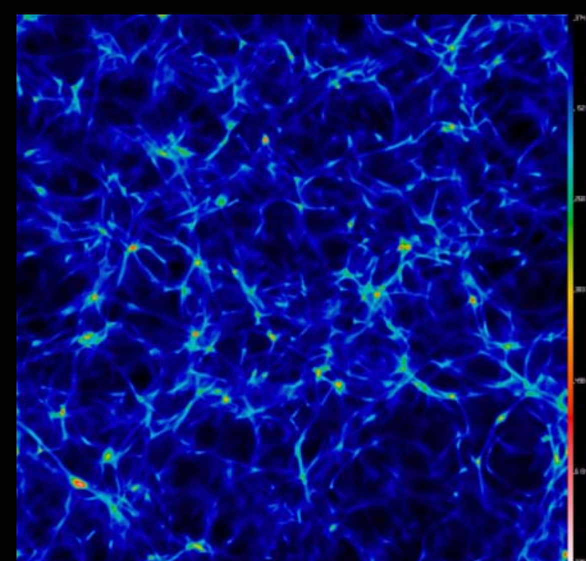
State of the art: billion particles, 100-1000Mpc comoving volume

Hydrodynamics: H+He gas

Galaxies



Mpa group



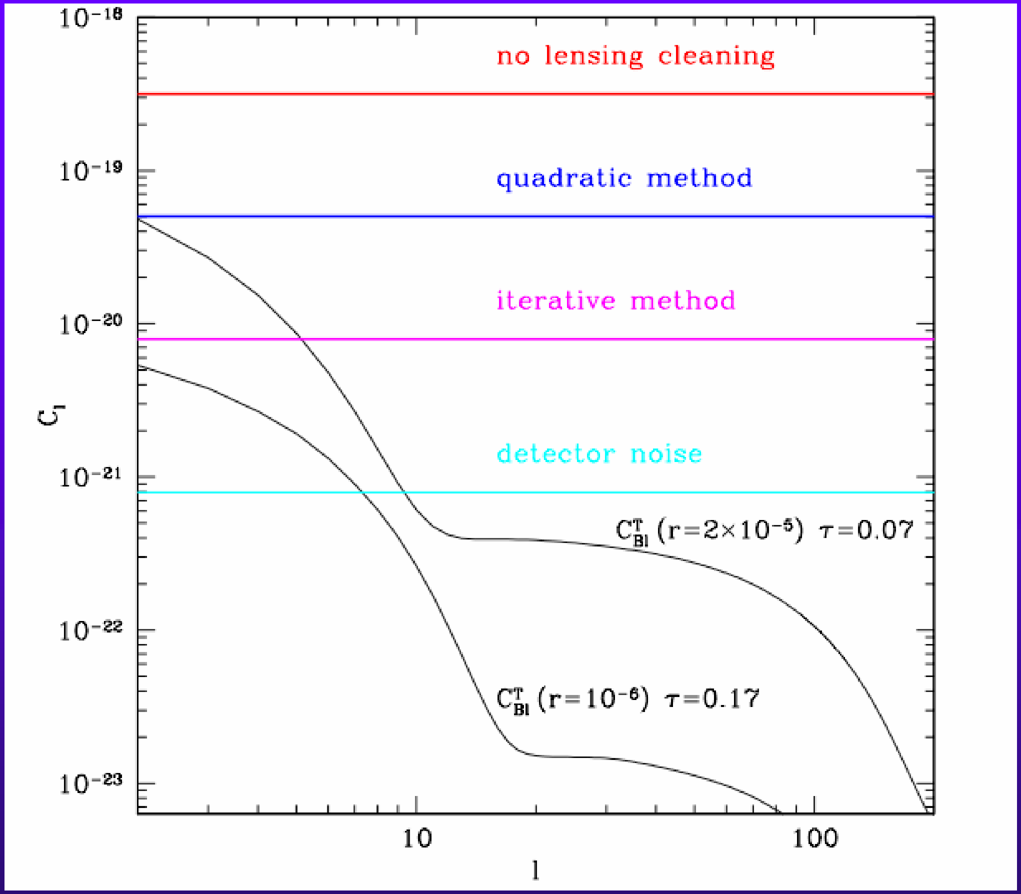
US etal 2000

Testing models against data

- Initial conditions: gaussian random field with a specified 2-pt function
- Linear evolution: GR+fluid equations (baryons, CDM)+Boltzmann equation (photons, neutrinos) $\longrightarrow$ CMB anisotropies
- Nonlinear evolution: N-body simulations+hydrodynamics $\longrightarrow$ dark matter, galaxies, gas
- Statistical data analysis:likelihood evaluation, Monte Carlo Markov Chains $\longrightarrow$ final probability distributions

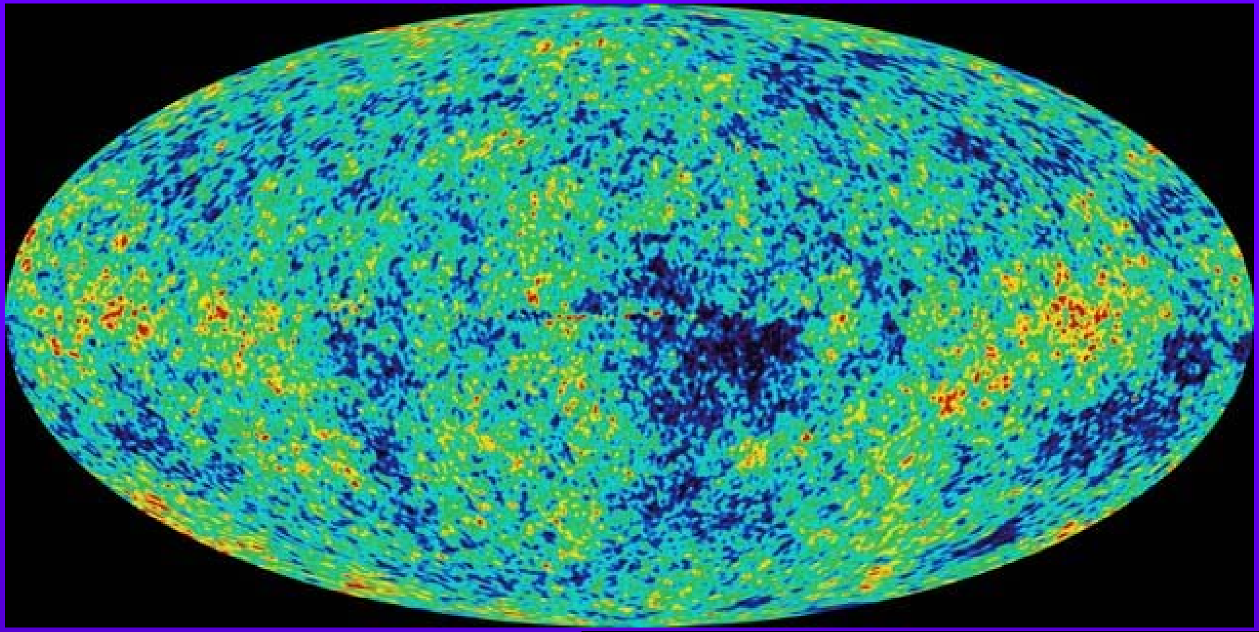
Gravity waves from CMB polarization

- inflationary models predict them, but some are not at an observable level. Polarization of CMB is the key experimental input, one of NASA Beyond Einstein missions
- Can reach T/S<0.0001 in principle, difficult in practice (foregrounds, lensing, noise…)

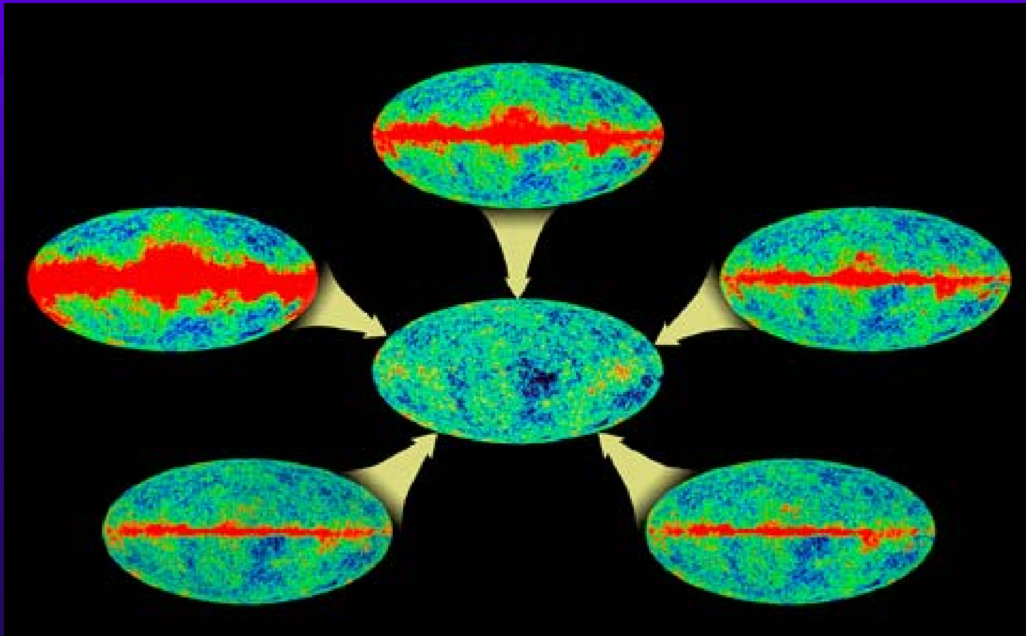


US & Hirata 2003

CMB: WMAP and other experiments



WMAP produced maps in 5 frequency bands



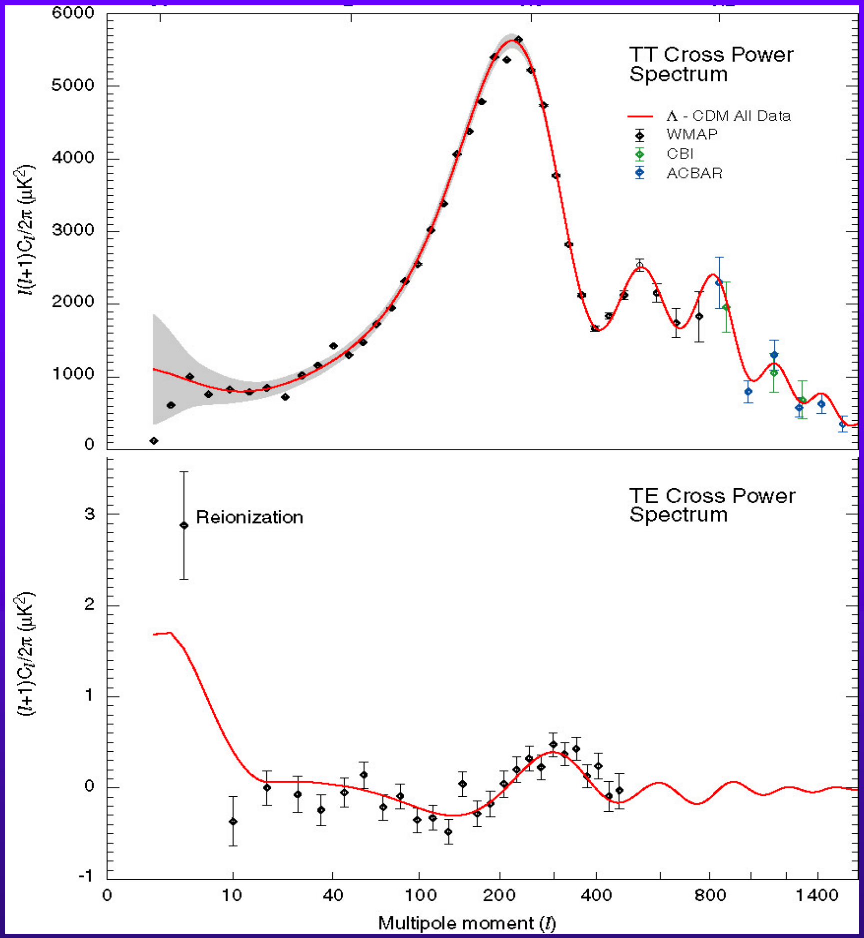
Current 1 year WMAP analysis/data situation

Current data favor the simplest scale invariant model

Evidence for high optical depth from TE, but 2nd yr verification is needed (coming up soon?)

Exact likelihood analysis: no evidence of low octupole, quadrupole moderately low: 3-4% no evidence of primordial scale dependence on large scales (Slosar, US, Makarov)

SZ contamination below 2% from frequency information (Huffenberger, US, Makarov)



Current 1 year WMAP analysis/data situation

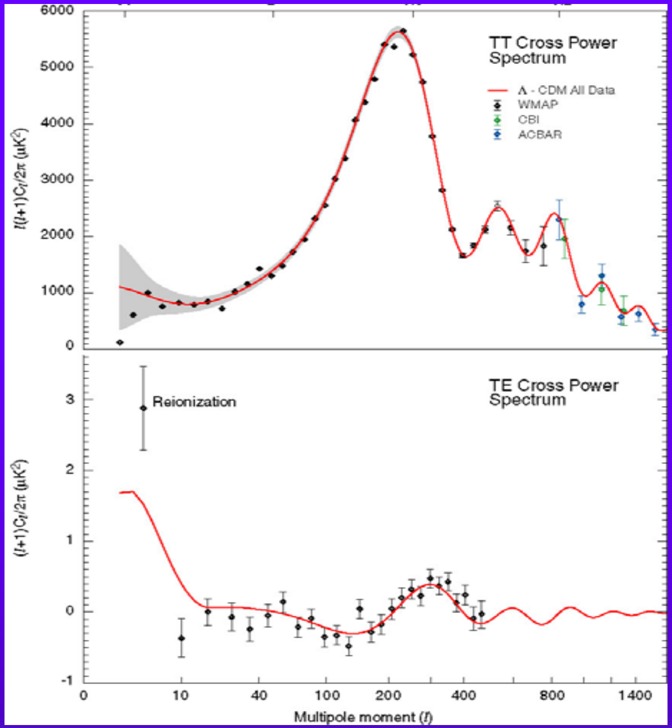
Current data favor the simplest scale invariant model

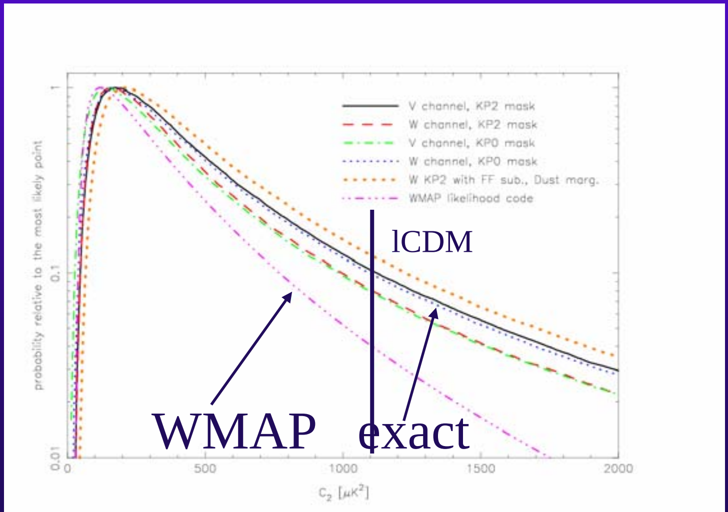
Evidence for high optical depth from TE, but needs 2nd yr confirmation (coming up soon?)

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

Exact likelihood analysis: no evidence of low octupole, quadrupole modestly low: 3-4% no evidence of primordial scale dependence on large scales (Efstathiou; Slosar, US, Makarov)

SZ contamination below 2% from frequency information (Huffenberger, US, Makarov)



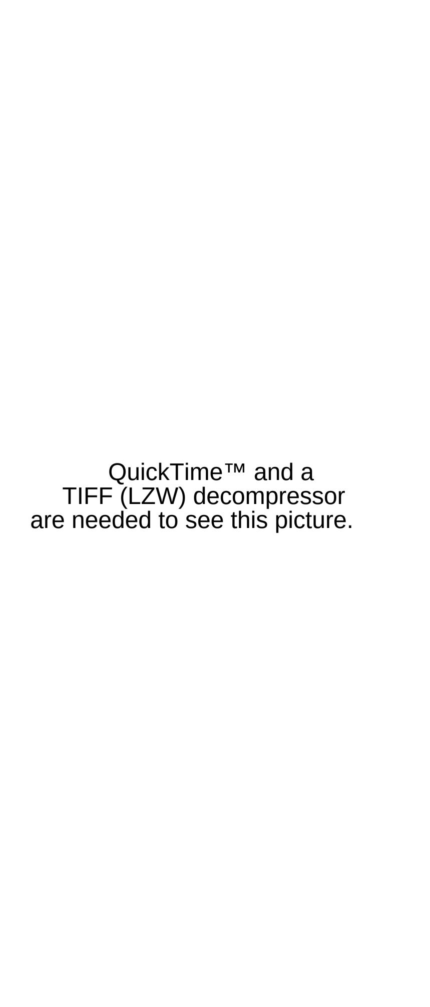


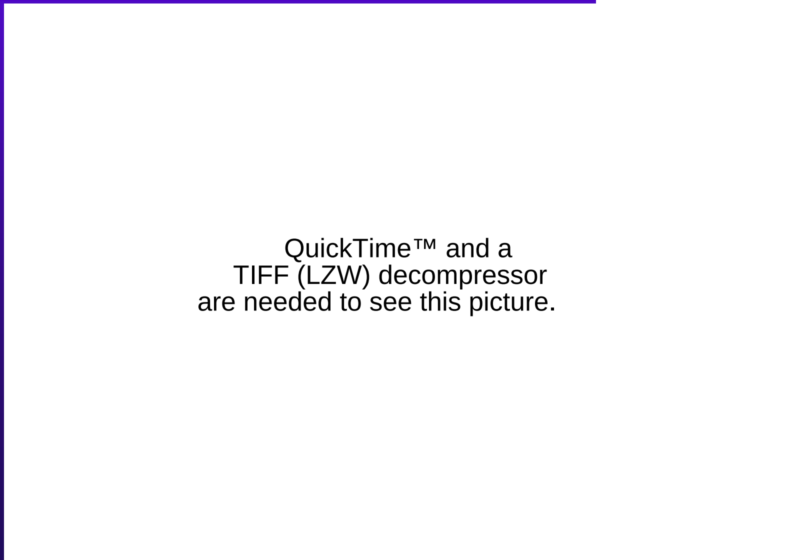
Limits on SZ from WMAP

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)

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





WMAP exact likelihood analysis of low multipoles

Slosar, US, Makarov

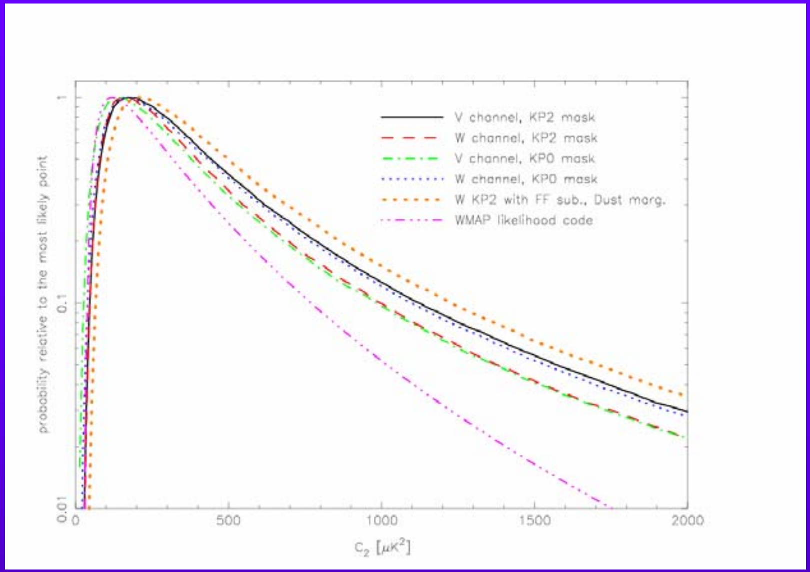
Low l multipoles are contaminated by foregrounds, best removed by marginalization

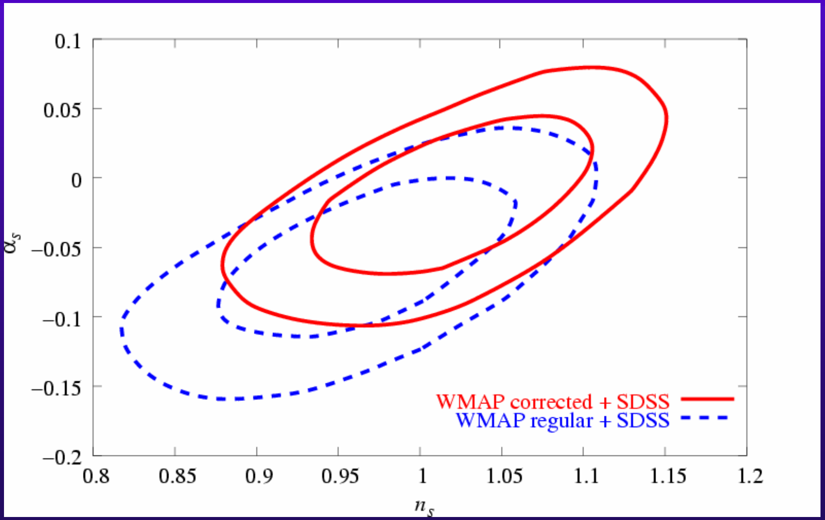
Approximations to exact likelihood do not work in this regime

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





Sloan Digital Sky Survey (SDSS)

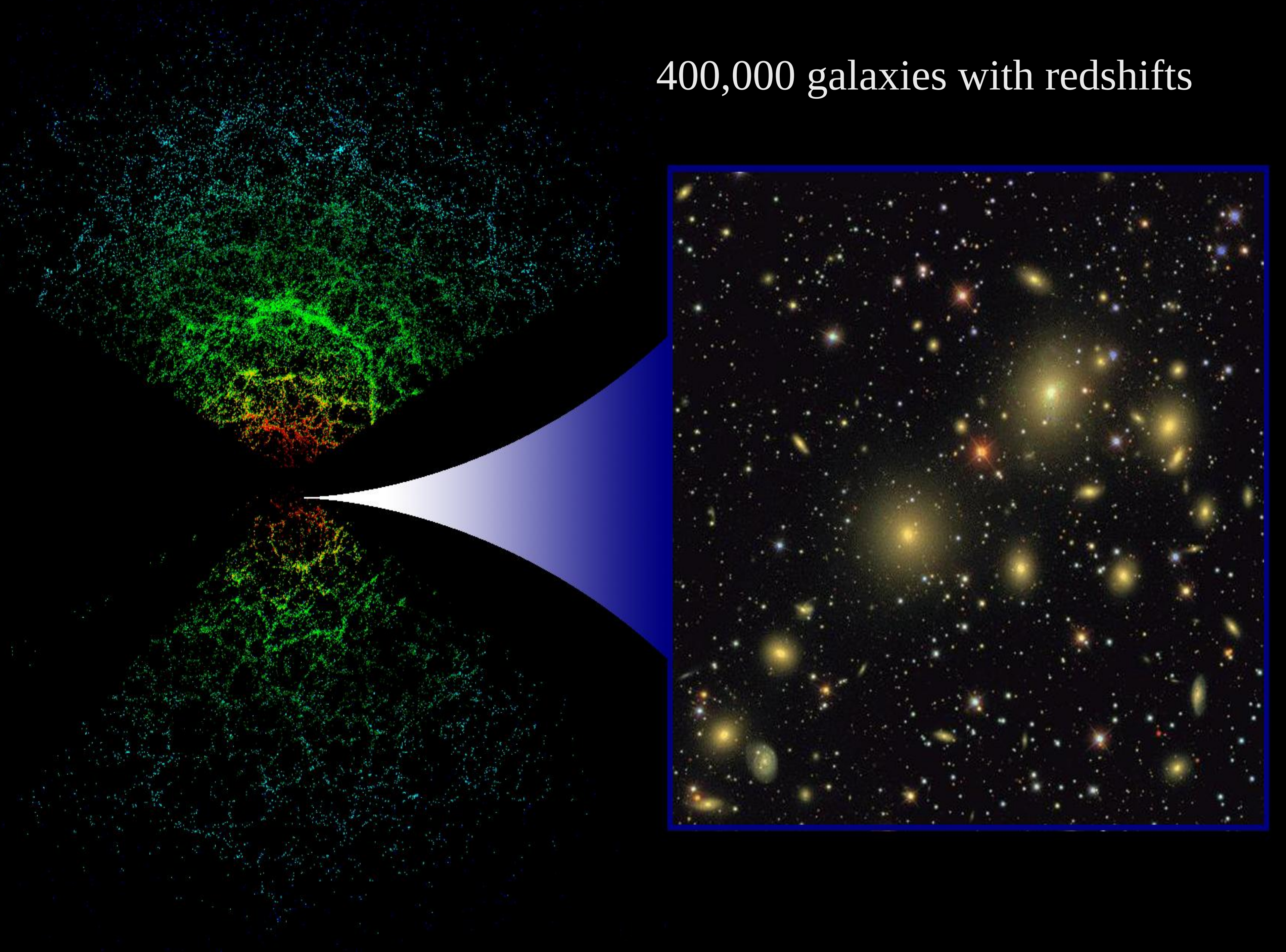
- 2.5 m aperture
- 5 colors *ugriz*
- 6 CCDs per color, 2048x2048, 0.396”/pixel
- Integration time ~ 50 sec per color
- Typical seeing ~ 1.5”
- Limiting mag *r*~23
- current 7000 deg^2 of imaging data, 40 million galaxies
- 400,000 spectra (r<17.77 main sample, 19.1 QSO,LRG)

Image Credit: Sloan Digital Sky Survey

What other surveys (SDSS…) brings to the mix?

- Galaxy clustering: main sample and LRGs, constraints on matter/dark energy density, Hubble parameter, primordial slope
- Weak lensing: galaxy power spectrum amplitude: dark energy, neutrinos
- Ly-alpha forest: z=3 small scale amplitude

400,000 galaxies with redshifts



1) Galaxy clustering analysis

- determine accurately the shape of the galaxy power spectrum
- By relating it to linear power spectrum on large scales it gives constraints on the shape of the power spectrum, important for primordial slope, Hubble parameter, matter density etc.
- Since we do not know the galaxy bias we cannot use the overall amplitude information, but other methods can add this information

Cosmology with Luminous Red Galaxies

Padmanabhan, Schlegel, US etal 2004

- Bright red galaxies, easy to identify (2 million galaxies)
- volume limited sample up to z=0.6: a 10-fold increase over regular sample (z=0.1)
- Photometric redshifts accurate to 0.02-0.03, we have full error distributions from 2dF-SDSS spectroscopic analysis
- On large scales (k<0.1h/Mpc) there is no advantage in having more accurate redshifts

Photometric LRG analysis

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

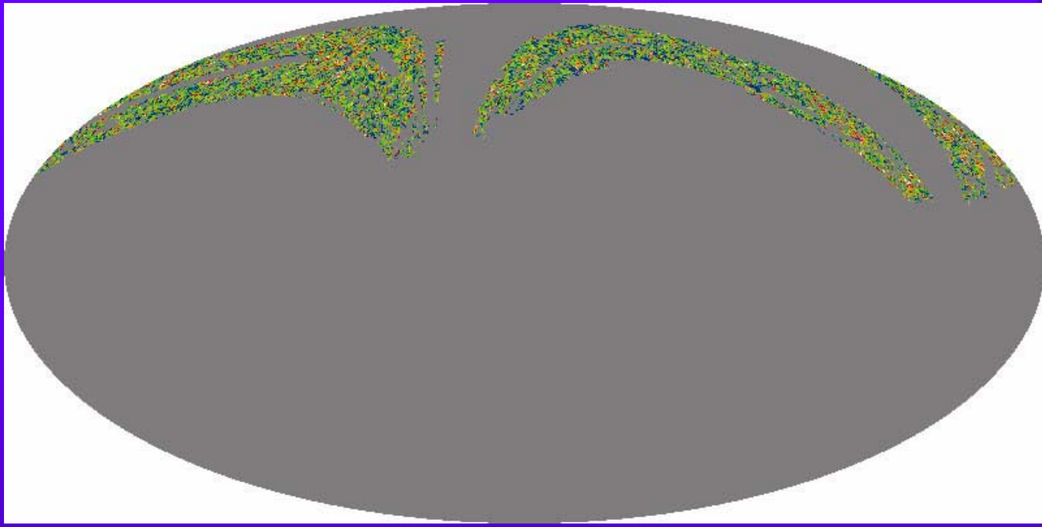
Padmanabhan etal 2004

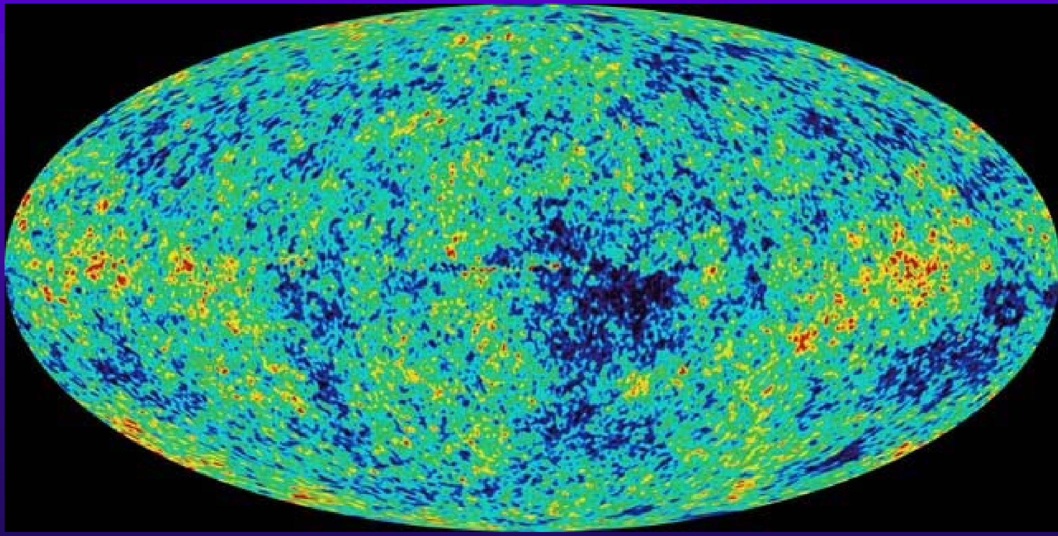
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

WMAP-LRG cross-correlation: ISW

N. Padmanabhan, C. Hirata, US etal 2005

•4000 degree overlap
•Unlike previous analyses (Boughn and Crittenden, Nolta etal, Afshordi etal, Scranton etal…) we combine with auto-correlation bias determination (well known redshifts)





- 2.5 sigma detection

$$b(\Omega_m = 0.3) = 3.8 \pm 1.5$$

$$b(\Omega_m = 0.2) = 1.56 \pm 0.67$$

$$b(LRG) = 1.69 \pm 0.02$$

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TIFF (LZW) decompressor
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TIFF (LZW) decompressor
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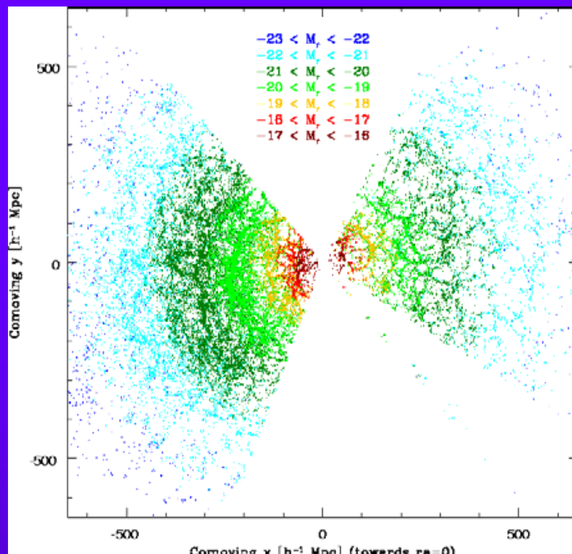
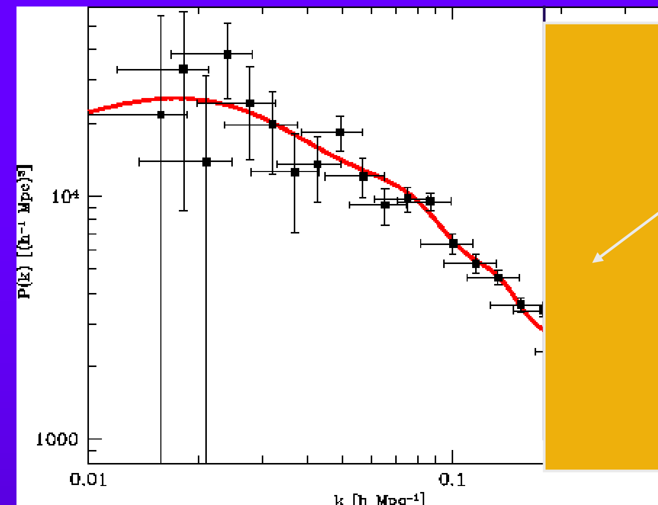
$$\Omega_m = 1 - \Omega_{\mathrm{de}} = 0.21^{+0.06}_{-0.04}{}^{+0.22}_{-0.06}$$

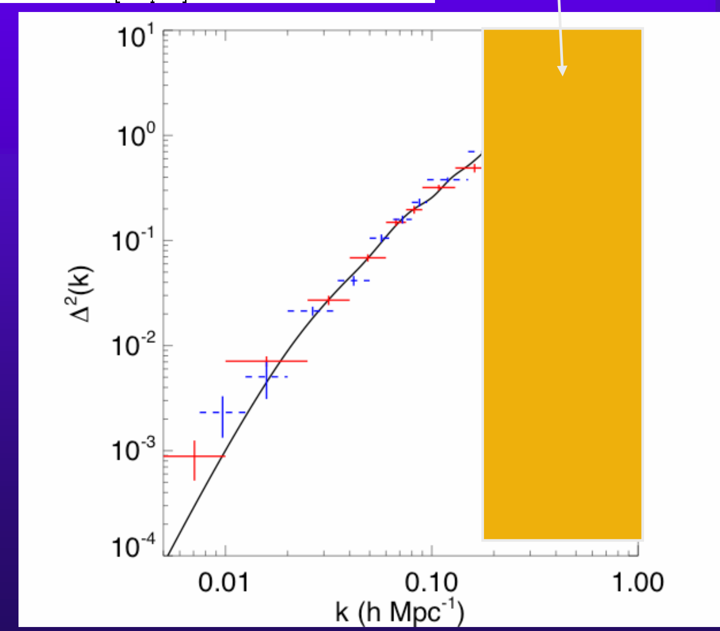
Consistent with other probes

SDSS galaxy power spectrum shape analysis





Nonlinear scales



Galaxy clustering traces dark matter on large scales

Current results: redshift space power spectrum analysis based on 200,000 galaxies (Tegmark etal, Pope etal), comparable to 2dF

In progress (Padmanabhan etal): LRG power spectrum analysis, 10 times larger volume, 2 million galaxies

Amplitude not useful (bias unknown)

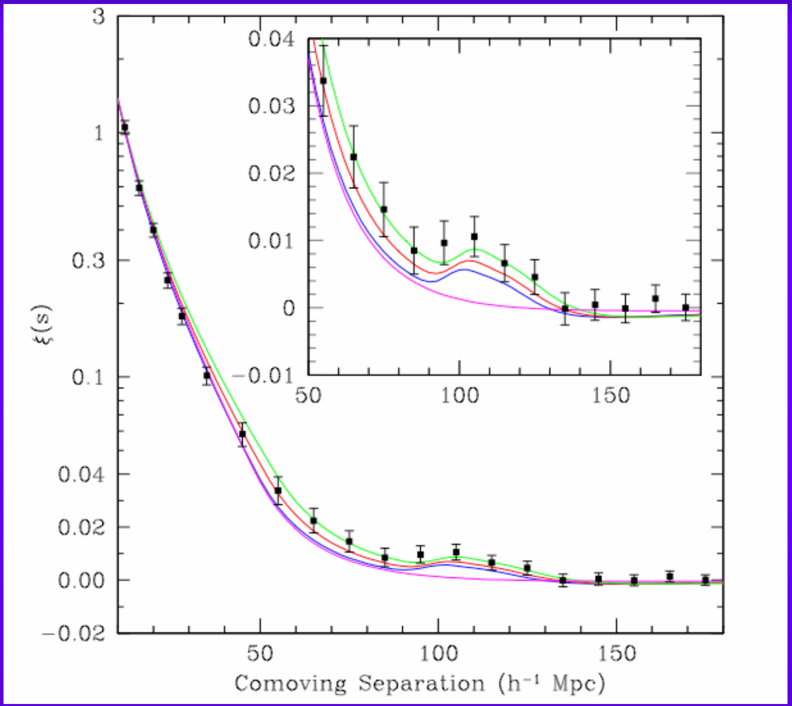
Baryonic wiggles?

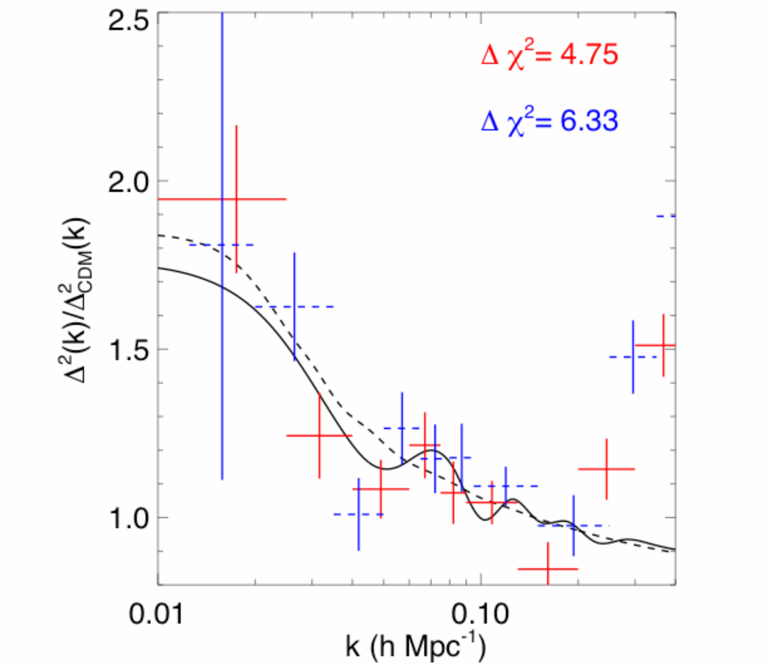
Best evidence: SDSS LRG spectroscopic sample (Eisenstein etal 2005), about 3 sigma evidence

SDSS LRG photometric sample (Padmanabhan, Schlegel, US etal 2005): 2 sigma evidence

Gives acoustic horizon scale at z=0.5, which can be compared to the same scale measured in CMB (z=1000): best constraint on curvature to date

$$\Omega_K = 0.02 \pm 0.02$$





Are galaxy surveys consistent with each other?

Some claims (eg 2dF analysis) that SDSS main sample gives more than 2 sigma larger value of Ω

Fixing h=0.7

SDSS LRG photo	$\Omega_m = 0.266 \pm 0.020$
2dF	$\Omega_m = 0.266 \pm 0.020$
SDSS main spectro	$\Omega_m = 0.291 \pm 0.028$

Bottom line: no evidence for discrepancy, new analyses improve upon SDSS main

ISW: theoretical predictions depend on Ω

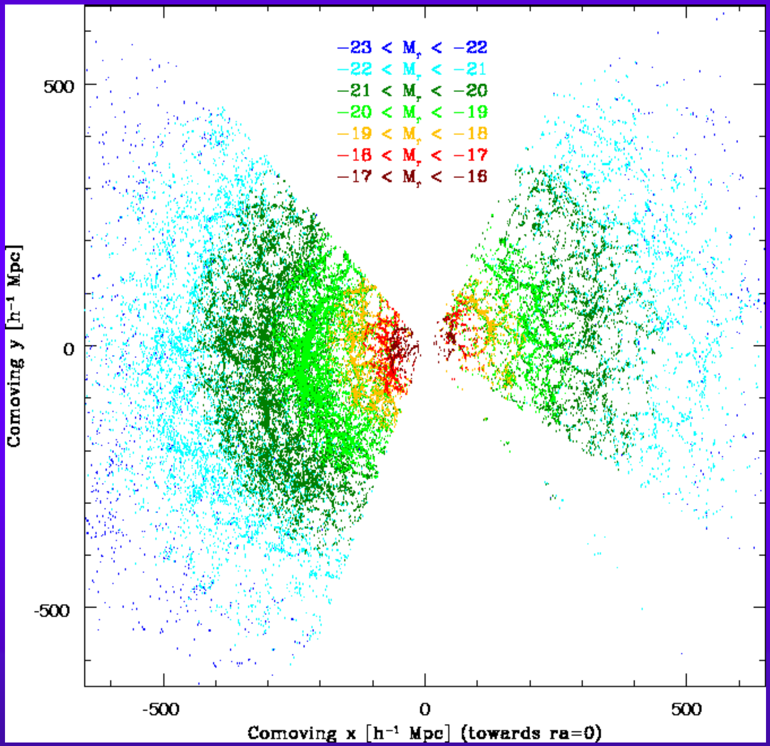
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

SDSS Galaxy bias determination

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

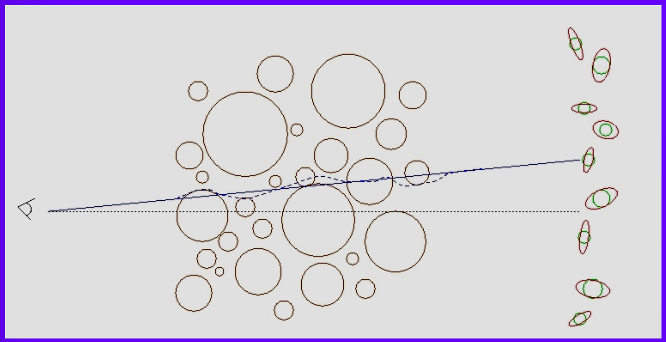
- Galaxies are biased tracers of dark matter; the bias is believed to be scale independent on large scales ($k<0.1$-0.2/Mpc)
- If we can determine the bias we can use galaxy power spectrum to determine amplitude of dark matter spectrum σ_8
- High accuracy determination of σ_8 is important for neutrino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

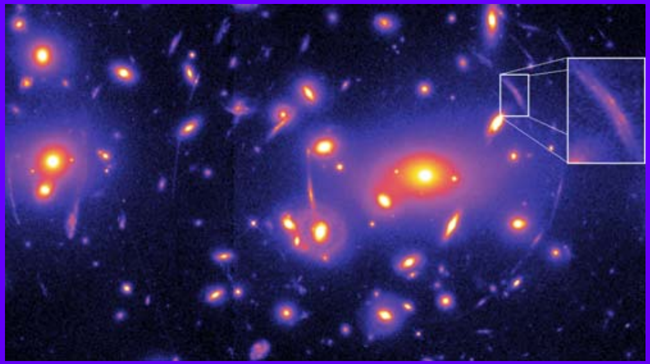
Galaxy bias: luminosity dependence of clustering



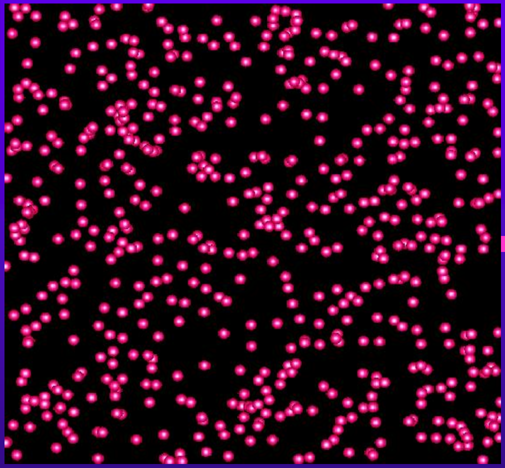
Bias relative to L* changes from 0.75 to 1.7 (Tegmark etal 2004), in agreement with previous attempts at smaller scales (Norberg etal, Zehavi etal)

How Gravitational Lensing Works

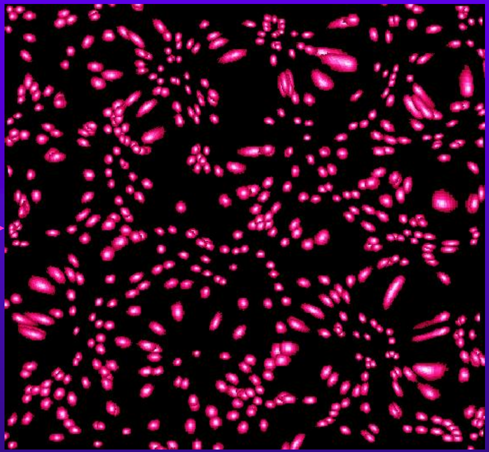




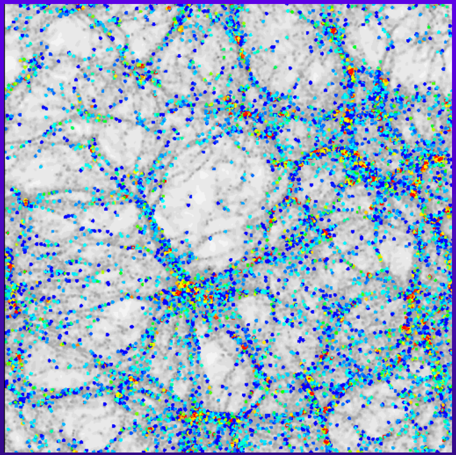
Distortion of background images by foreground matter



Unlensed

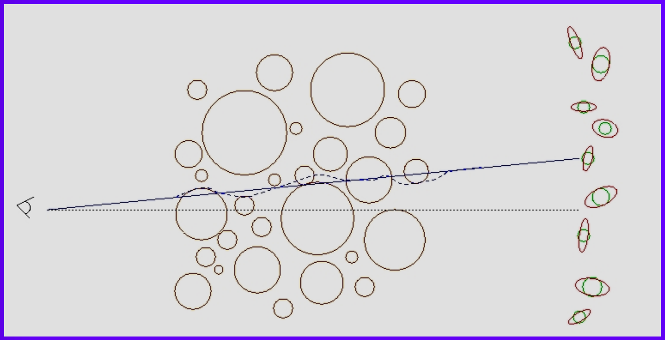


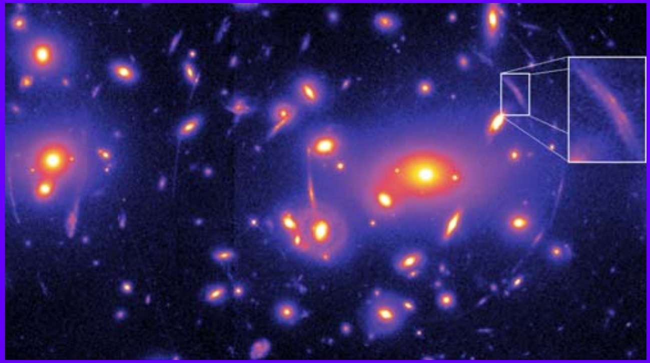
Lensed



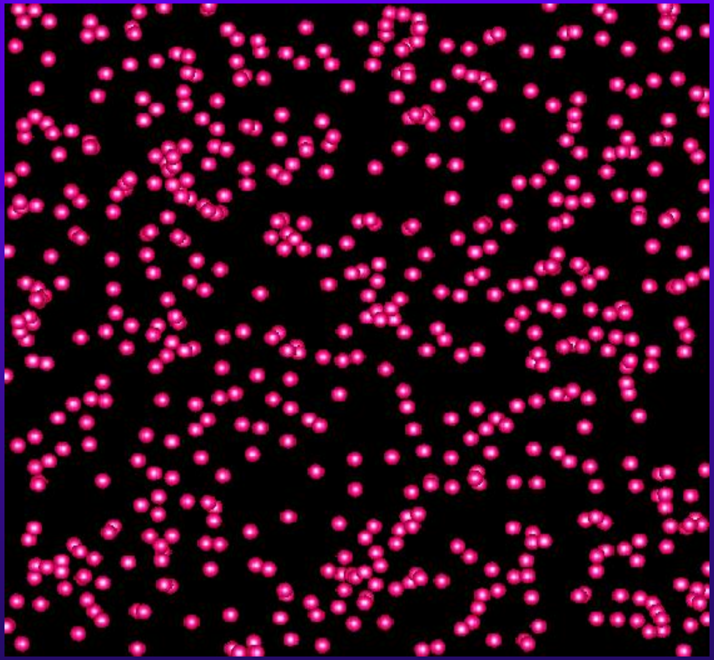
galaxies+DM

How Gravitational Lensing Works

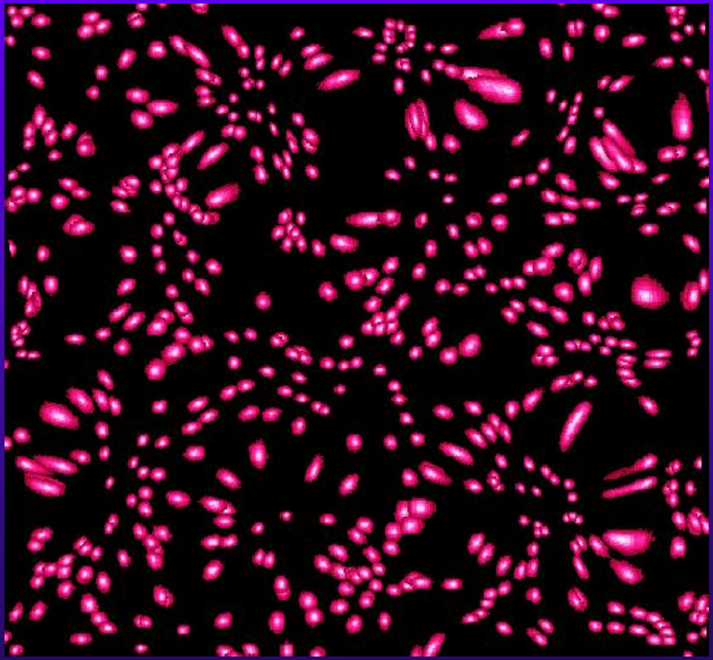




Distortion of background images by foreground matter



Unlensed



Lensed

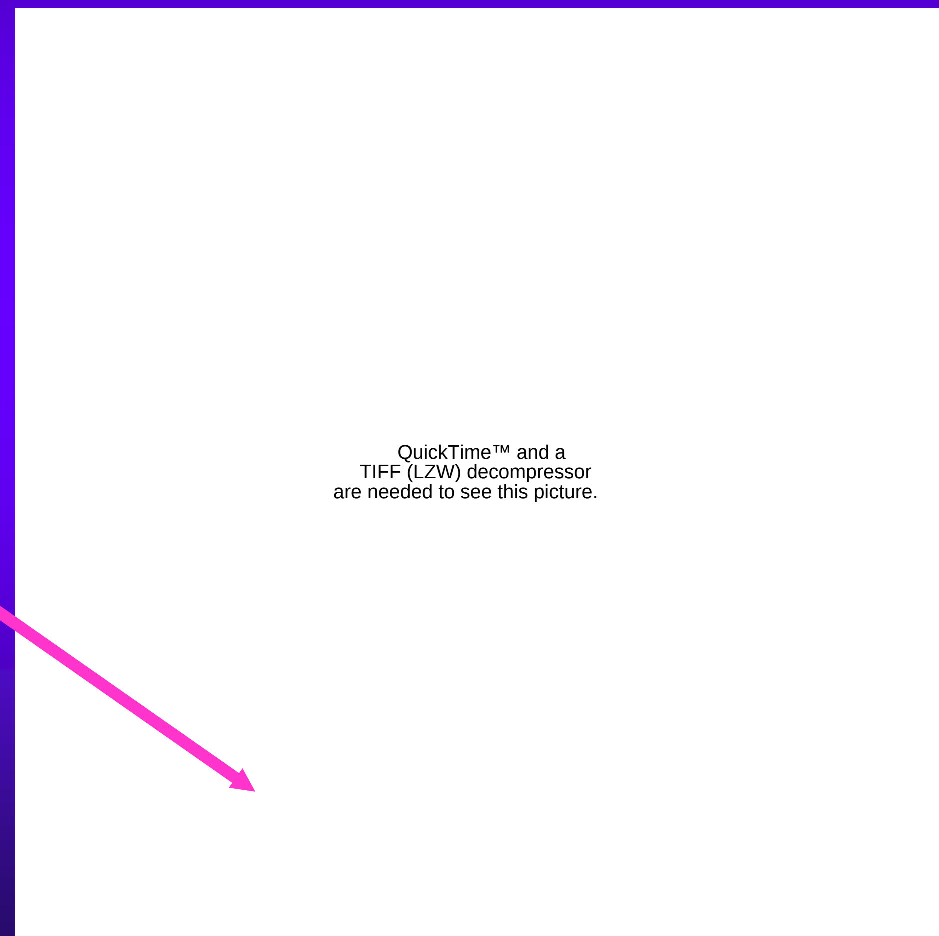
Bias mass relation is nearly universal if mass is in units of nonlinear mass (mass within the sphere with rms 1.68)

Nonlinear mass grows with amplitude of power spectrum and matter density

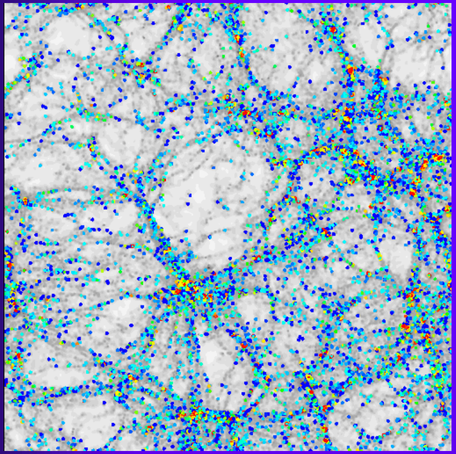
If we could establish halo clustering at low mass end we would have determined the amplitude of fluctuations (cf lensing)

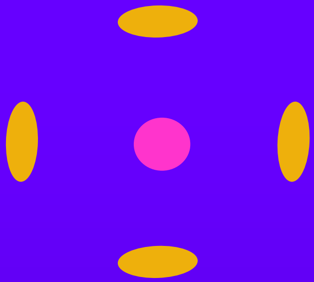
We do not observe halos, but galaxies

Seljak and Warren 2004



Weak lensing in SDSS: galaxy-galaxy lensing





$$R = r_L \Theta$$

$$\gamma_T = \frac{\Delta\Sigma(R)}{\Sigma_{\rm crit}}$$

$$\Delta\Sigma(R) = \bar{\Sigma}(R) - \Sigma(R)$$

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{r_S}{(1+z_L) r_L r_{LS}}$$

- dark matter around galaxies induces tangential distortion of background galaxies: extremely small, 0.1%
- ♦ Important to have redshifts of foreground galaxies: SDSS (McKay etal 02, Sheldon etal 03,04, Seljak etal 04)
- ♦ Express signal in terms of projected surface density and transverse r
- ♦ Signal as a function of galaxy luminosity

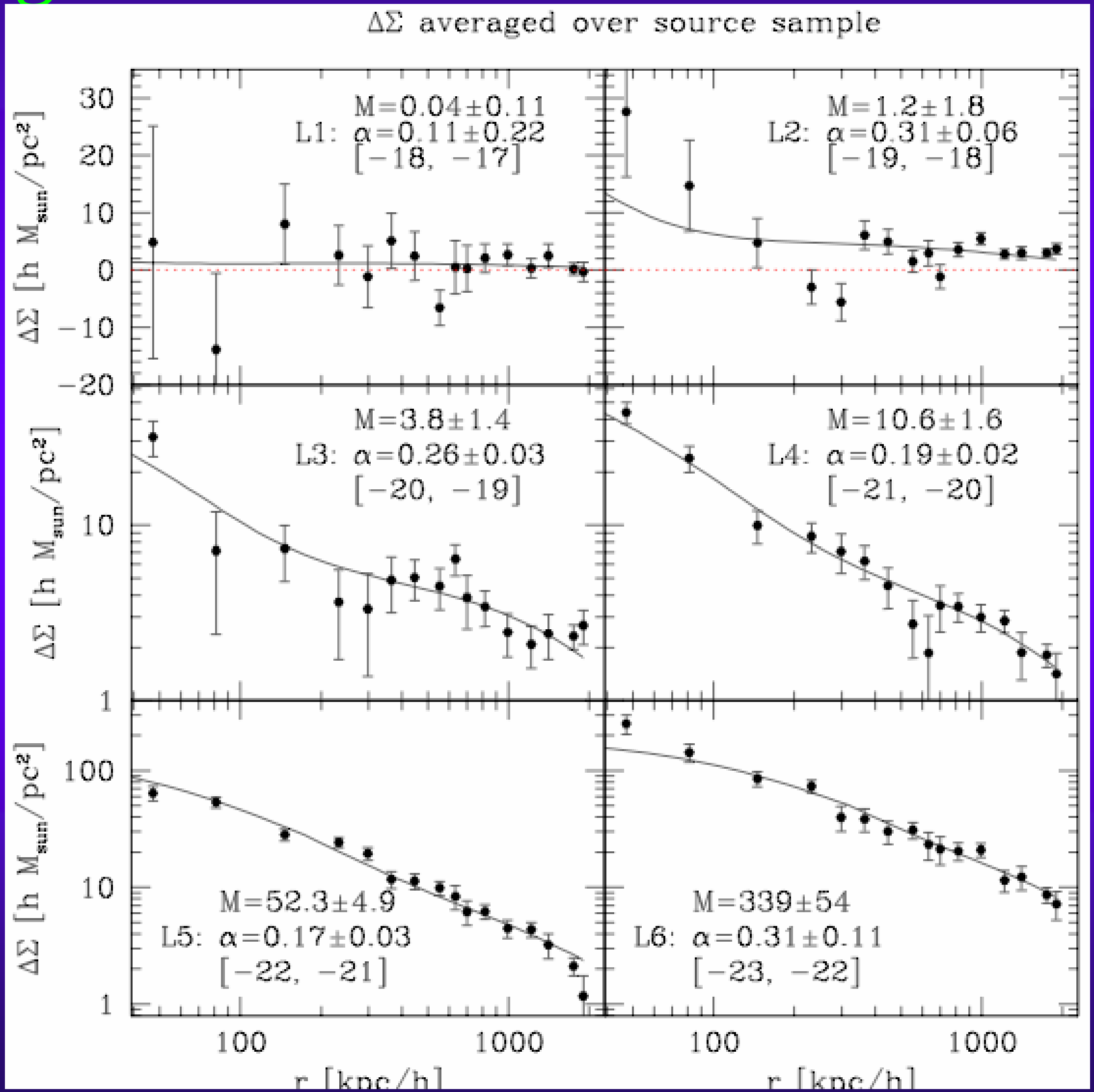
halo mass probability distribution p(M;L) from galaxy-galaxy lensing

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

Halo mass increases with galaxy luminosity

SDSS gg: 300,000 foreground galaxies, 20 million background, S/N=30, the strongest weak lensing signal to date

testing ground for future surveys such as LSST,SNAP



Seljak etal 2004

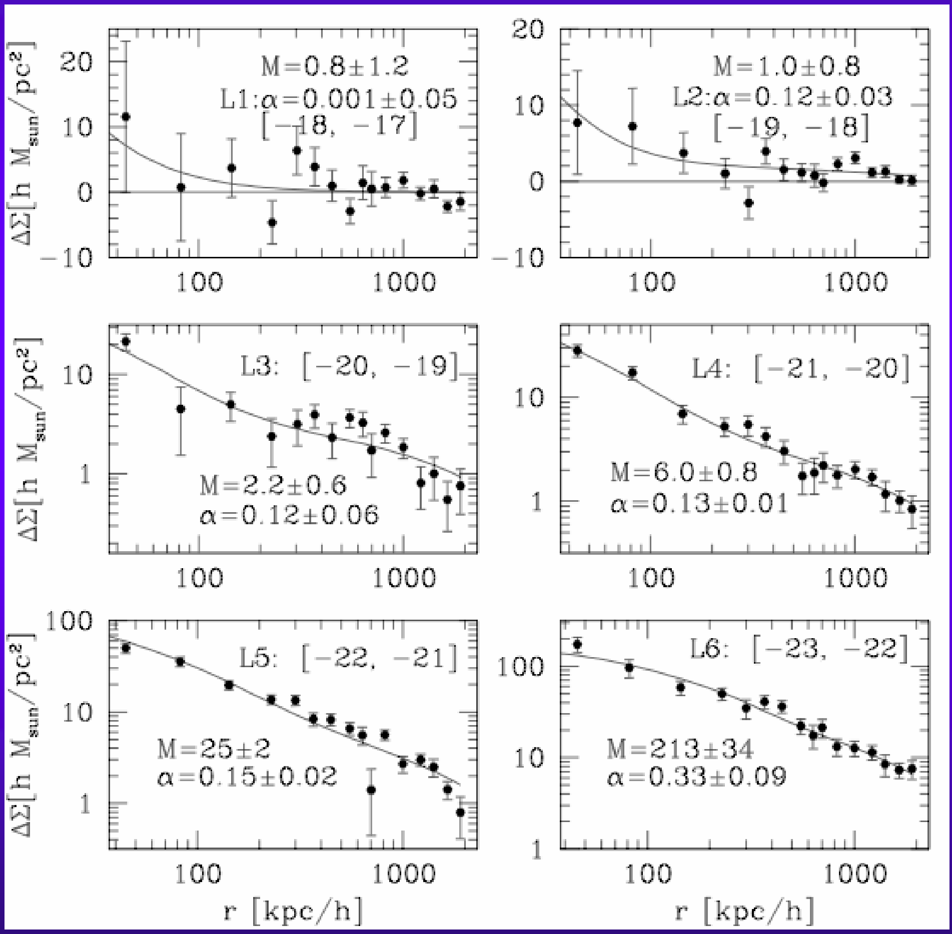
halo mass probability distribution p(M;L) from galaxy-galaxy lensing

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

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

SDSS gg: 300,000 foreground galaxies, 20 million background!

G-g lensing least model dependent, but used to have poor statistics, no longer the case, S/N=30!



Seljak etal 2004

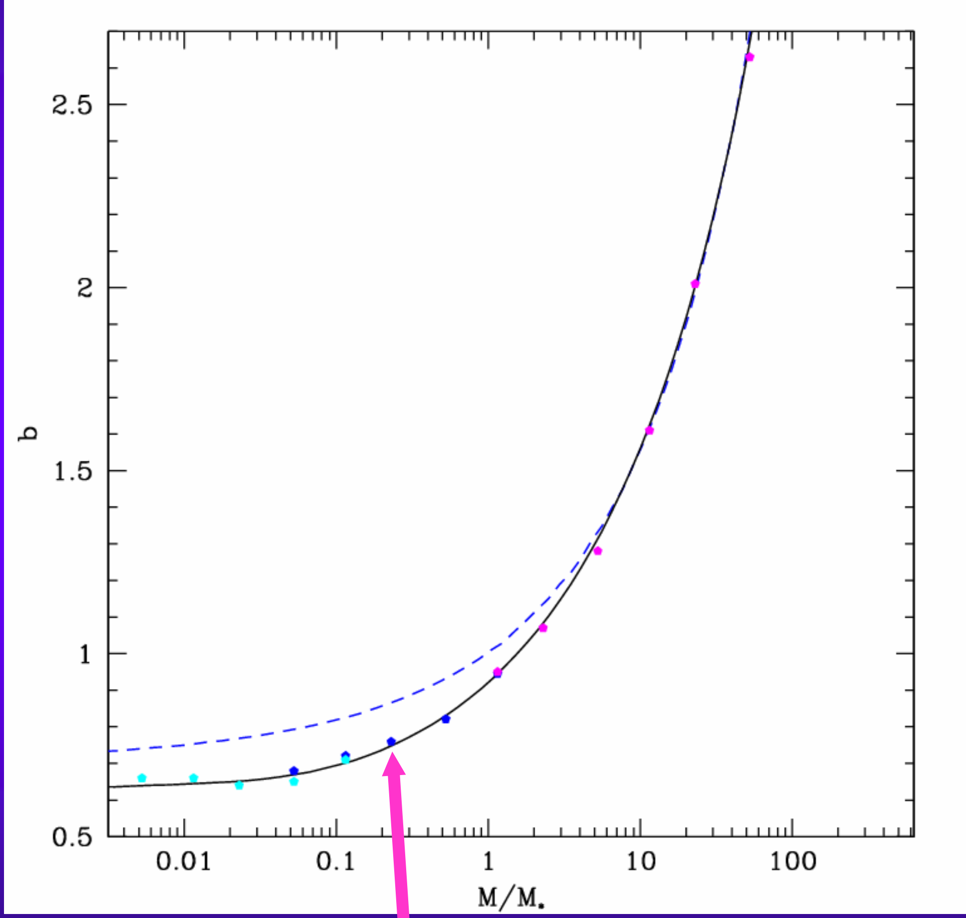
Halo bias as a function of halo mass

Galaxies live in halos

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, US and Warren 2004)

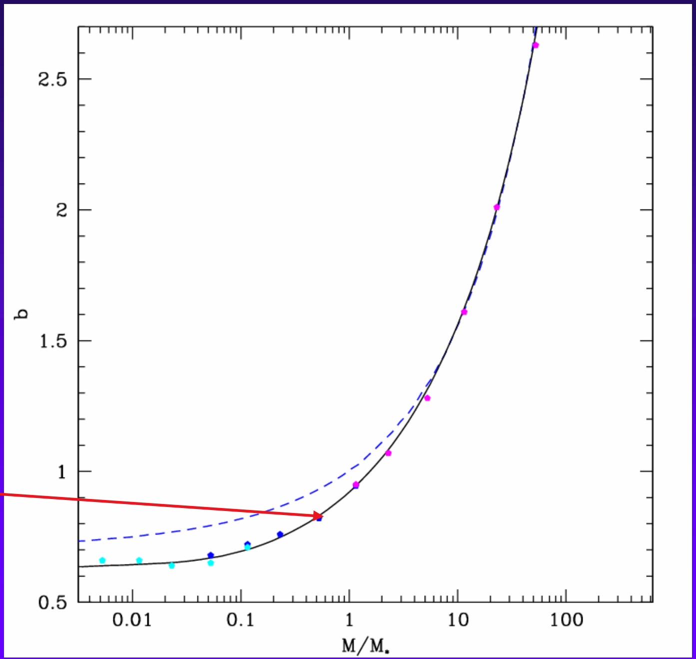


US and Warren 2004

Bias determination

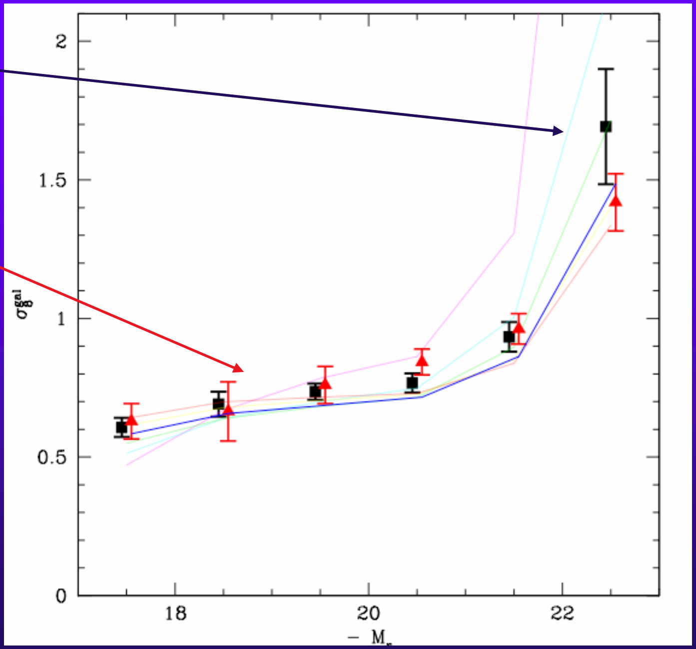
$$b(L) = \int b(M)\,p(M;L)\,dM$$

b(M) is theoretically predicted from N-body simulations (US & Warren 2004)



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

We also measure b(L) from galaxy clustering



Theoretical predictions agree with observations

Only cosmological models where the two constraints agree are acceptable

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

Bias determination

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

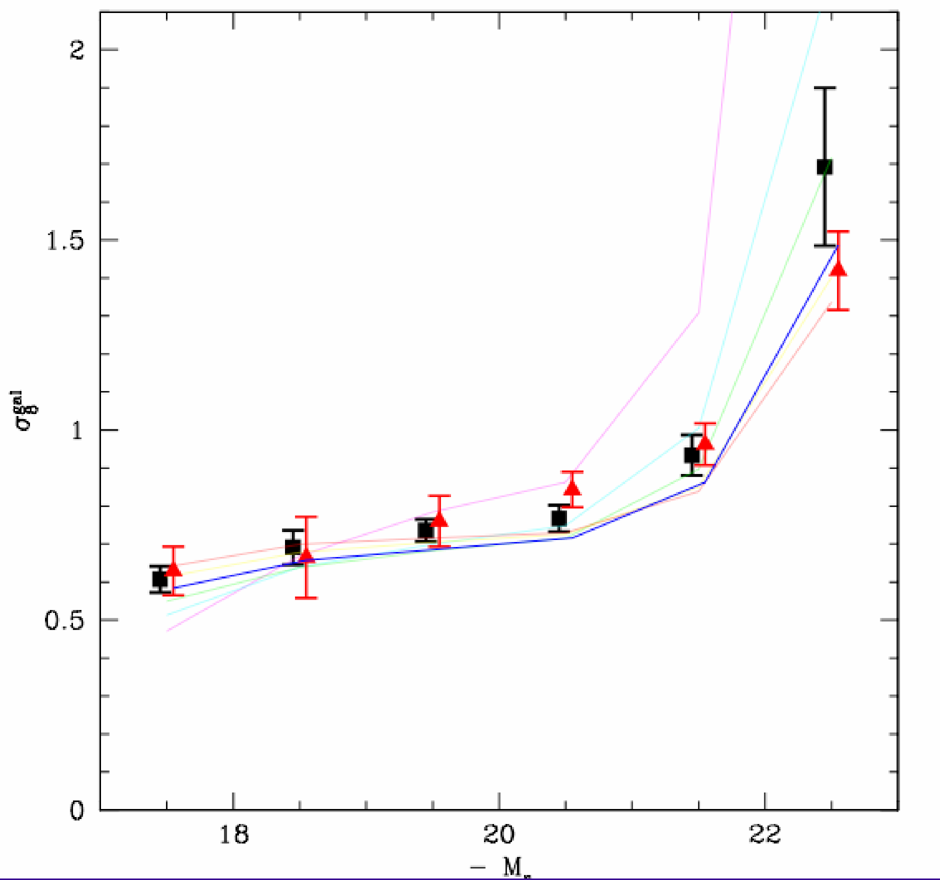
For any cosmological model we can determine b(L) from above

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.

Seljak etal 2004

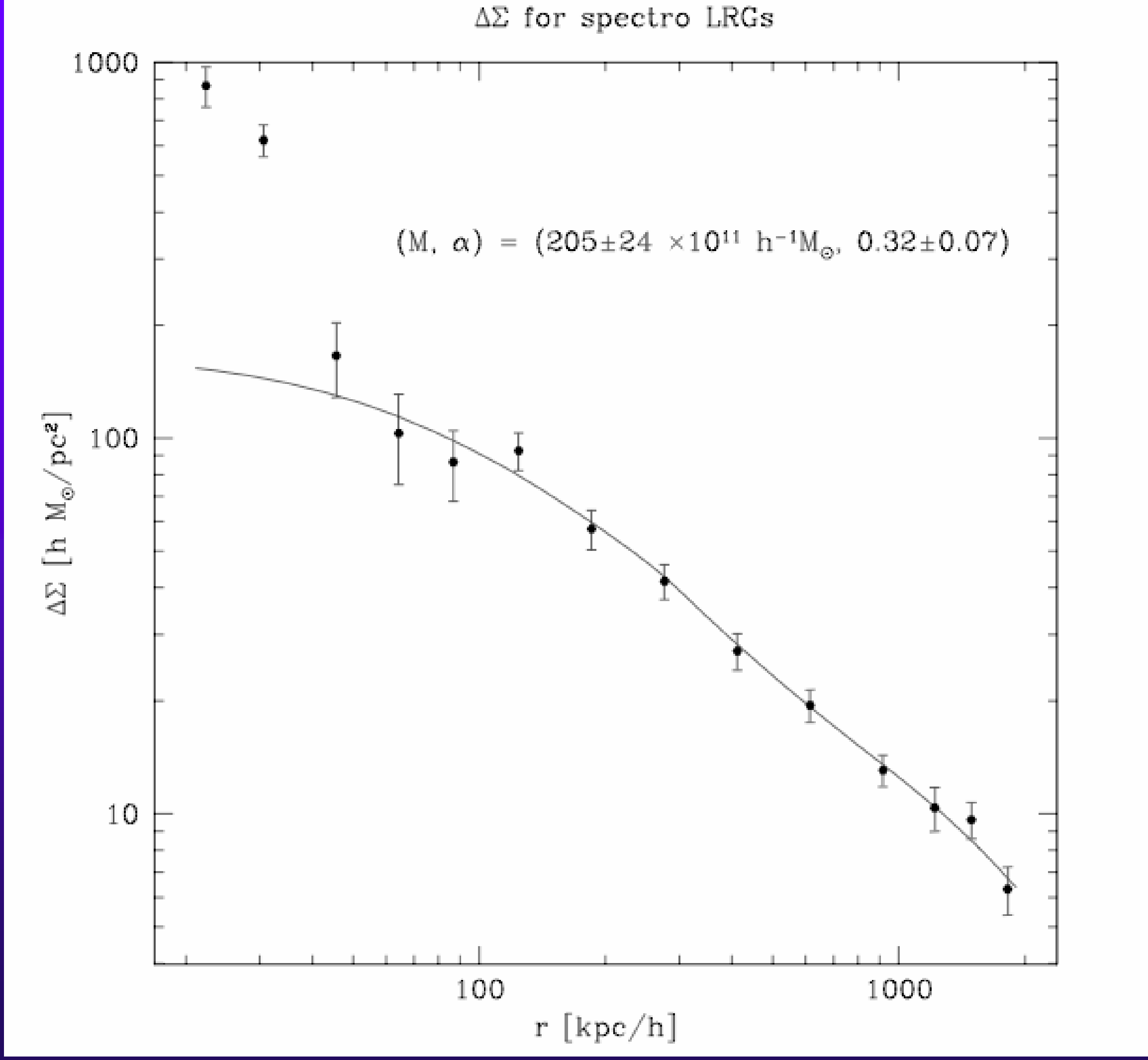
$$\sigma_8 = 0.88 \pm 0.06$$

Expect significant improvements in future

gg lensing of LRGs: dark matter profile of clusters and bias

S/N=30
Small scale: evidence of departure from NFW (baryonic effects?)

large scale: bias determination in combination with LRG autocorrelation analysis



Intrinsic correlations in shear-shear analysis

- Galaxy ellipticities can be intrinsically correlated
- linear model: ellipticity is proportional to tidal field (Es?) (Catalan etal, Croft and Metzler, Heavens etal)
- Quadratic model: angular momentum spin-up (Ss)

(Lee and Pen, Crittenden etal, Hui and Zheng)

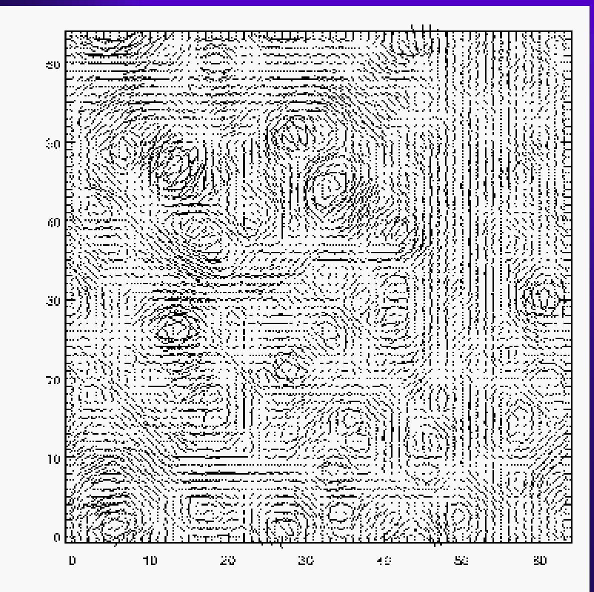
- May dominate at low z (Super-COSMOS detection?)
- For deep surveys with broad redshift distribution intrinsic-intrinsic (I-I) correlations are small (1%)
- I-I can be eliminated by cross-correlating background galaxies with different (photo)z's (Heymans and Heavens 02, King and Schneider 02, White 03)

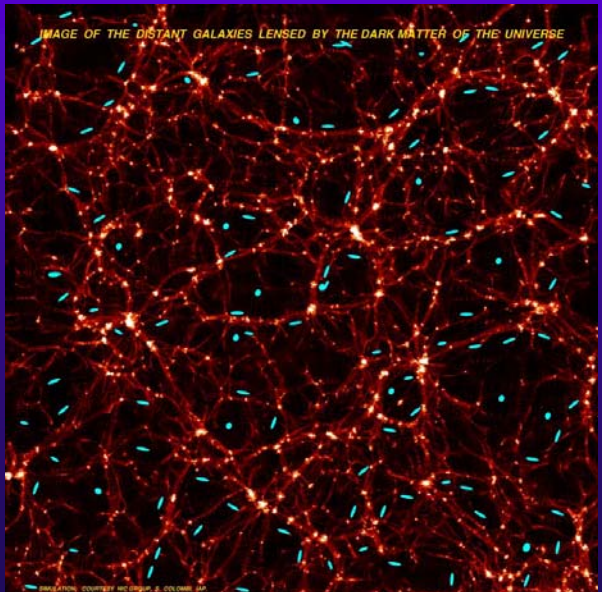
Shear-intrinsic (GI) correlation

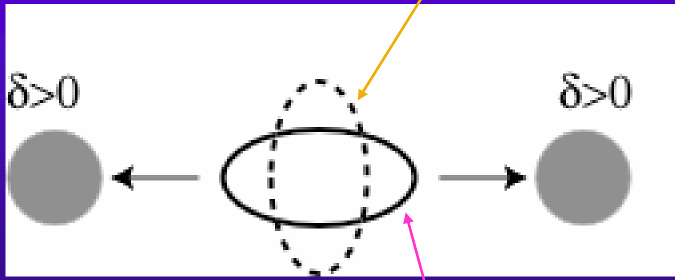
Hirata and Seljak 2004

- Same field shearing is also tidally distorting, opposite sign
- What was ϵ^2 is now ϵ, possibly an order of magnitude increase
- Cross-correlations between redshift bins does not eliminate it
- B-mode test useless (parity conservation)
- Vanishes in quadratic models

Lensing shear







Tidal stretch

Intrinsic correlations in SDSS

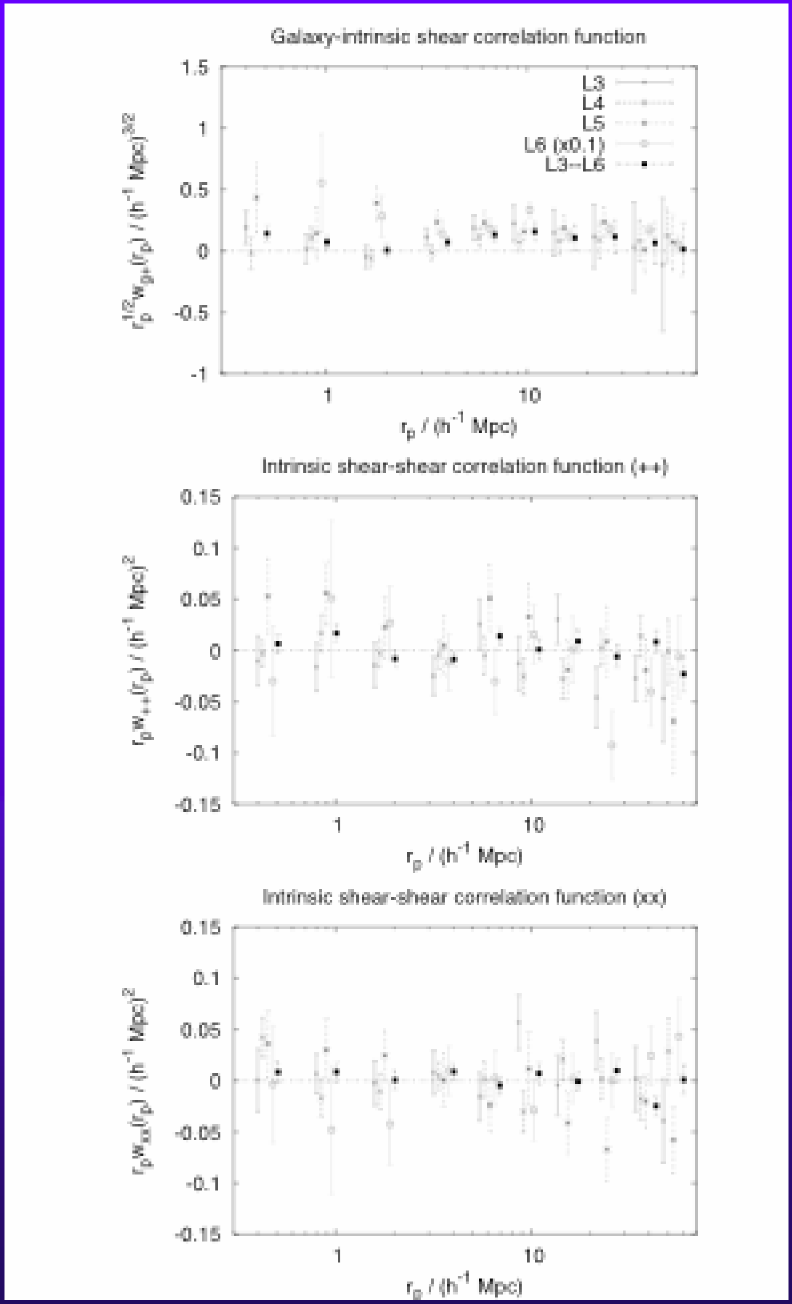
Mandelbaum, Hirata, Ishak, US etal 2005

300,000 spectroscopic galaxies

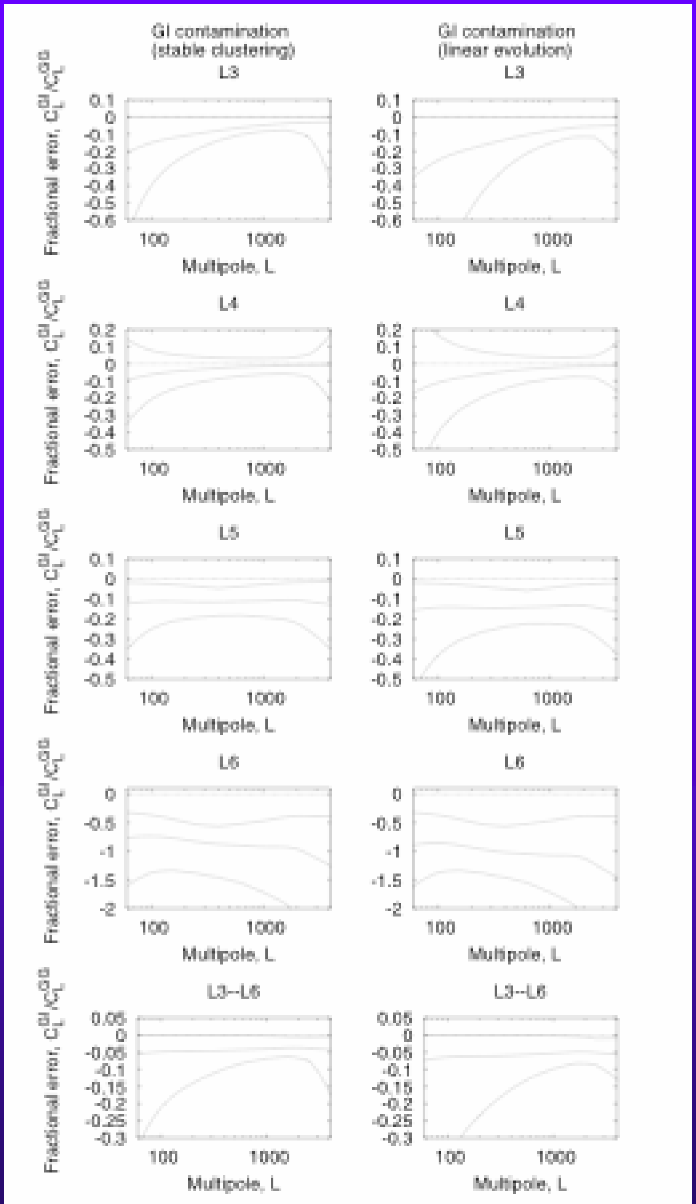
No evidence for II correlations

Clear evidence for GI correlations on all scales up to 60Mpc/h

Gg lensing not sensitive to GI



Implications for shear surveys



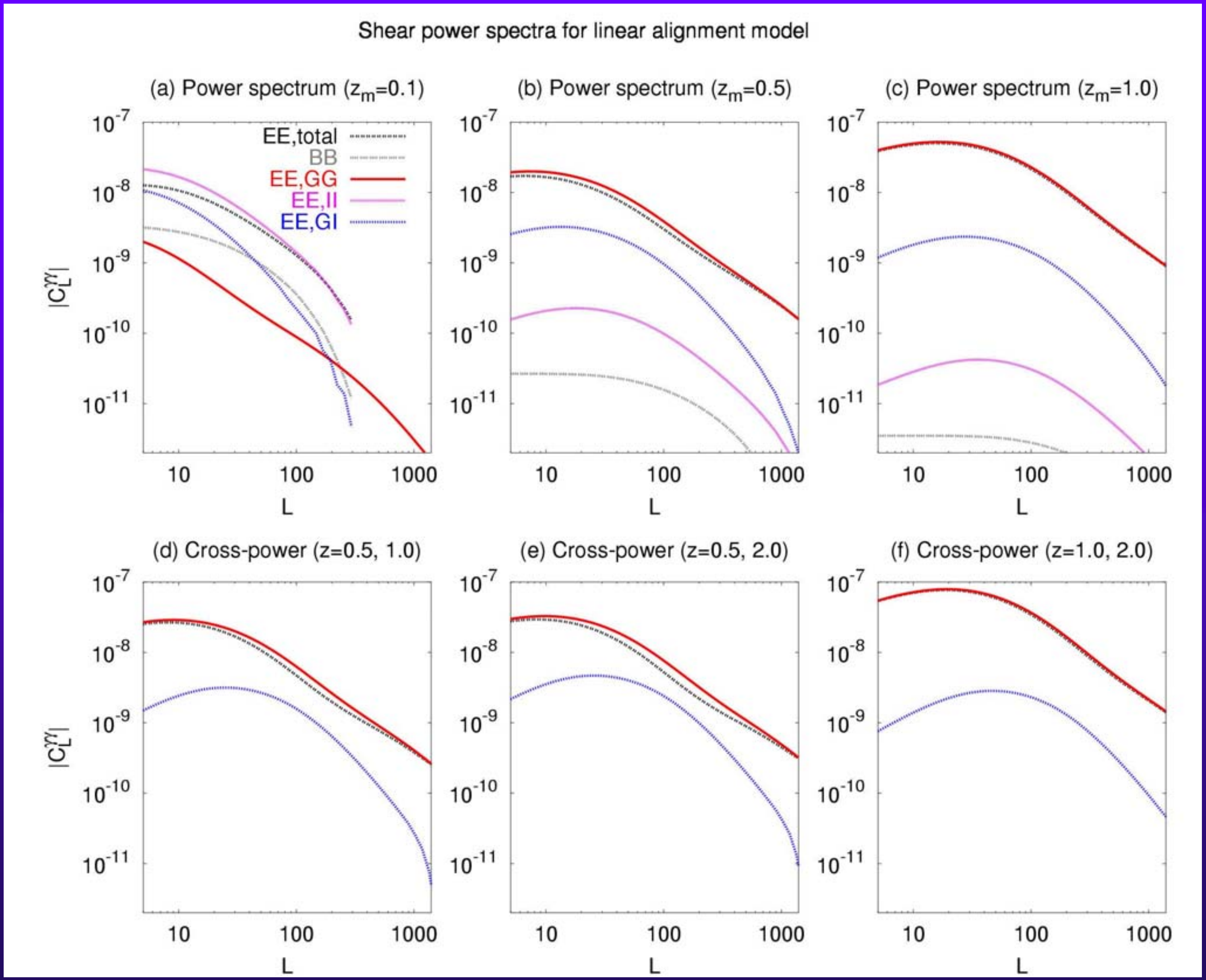
Implications for future surveys

Mandelbaum etal 2005, Hirata and US 2004

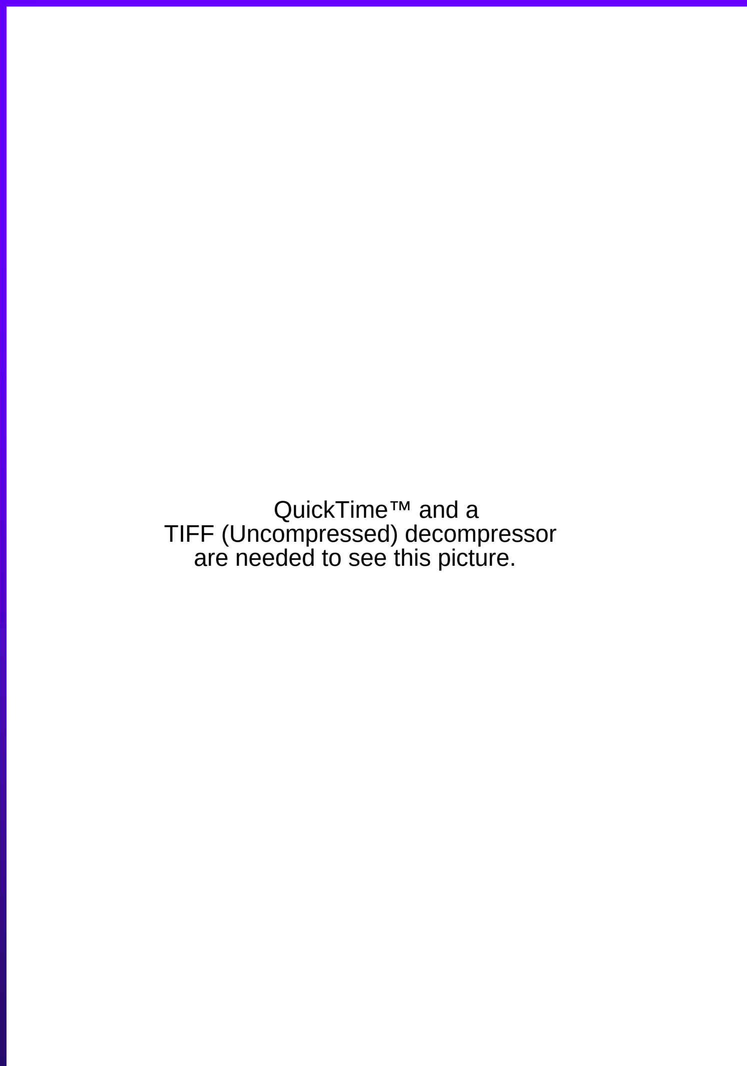
Up to 30% for shallow survey at z=0.5

10% for deep survey at z=1: current surveys underestimate σ_8

More important for cross-redshift bins

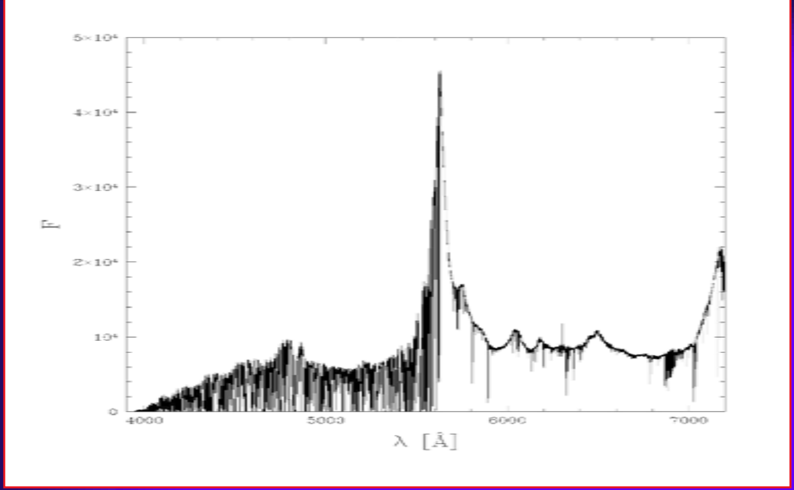


Ly-alpha forest



SDSS Quasar Spectrum

- Neutral hydrogen leads to Lyman-α absorption at $\lambda < 1216\,(1+z_q)$ Å; it traces baryons, which in turn trace dark matter
- Very difficult probe, but one of critical importance for cosmological constraints
- Complex analysis (McDonald etal 2004abc, Seljak etal 2004), results are based on current understanding of Ly-alpha forest



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

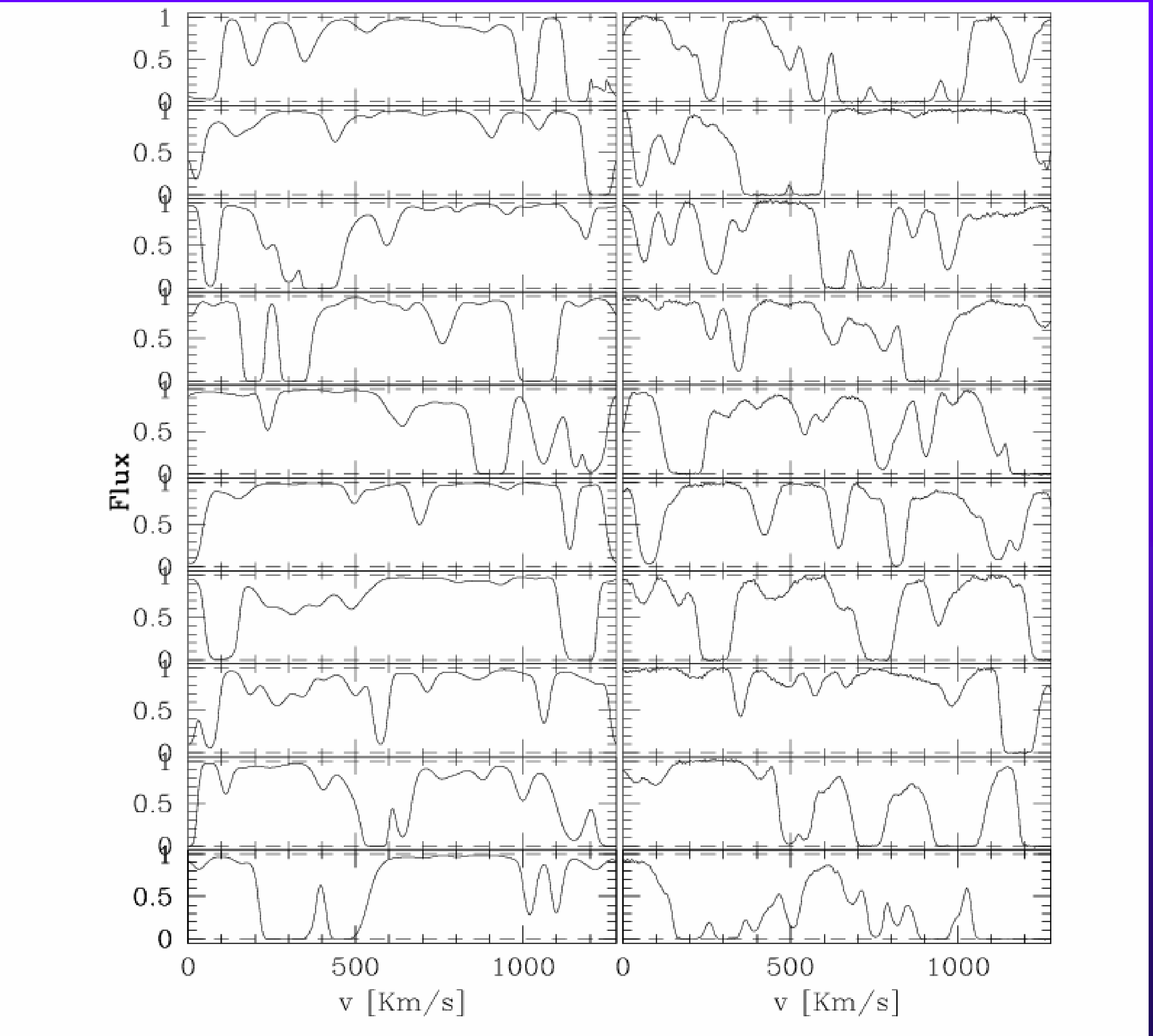
$$\rho_{HI} \propto \rho_{gas}^{2}$$

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)

Fully specified within the model, no bias issues

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



Katz etal 1999

Advantages of Ly-α

Fully specified within the model, no bias issues

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)

SDSS Lya-forest results

McDonald etal 04abc, Seljak etal 04

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

- 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

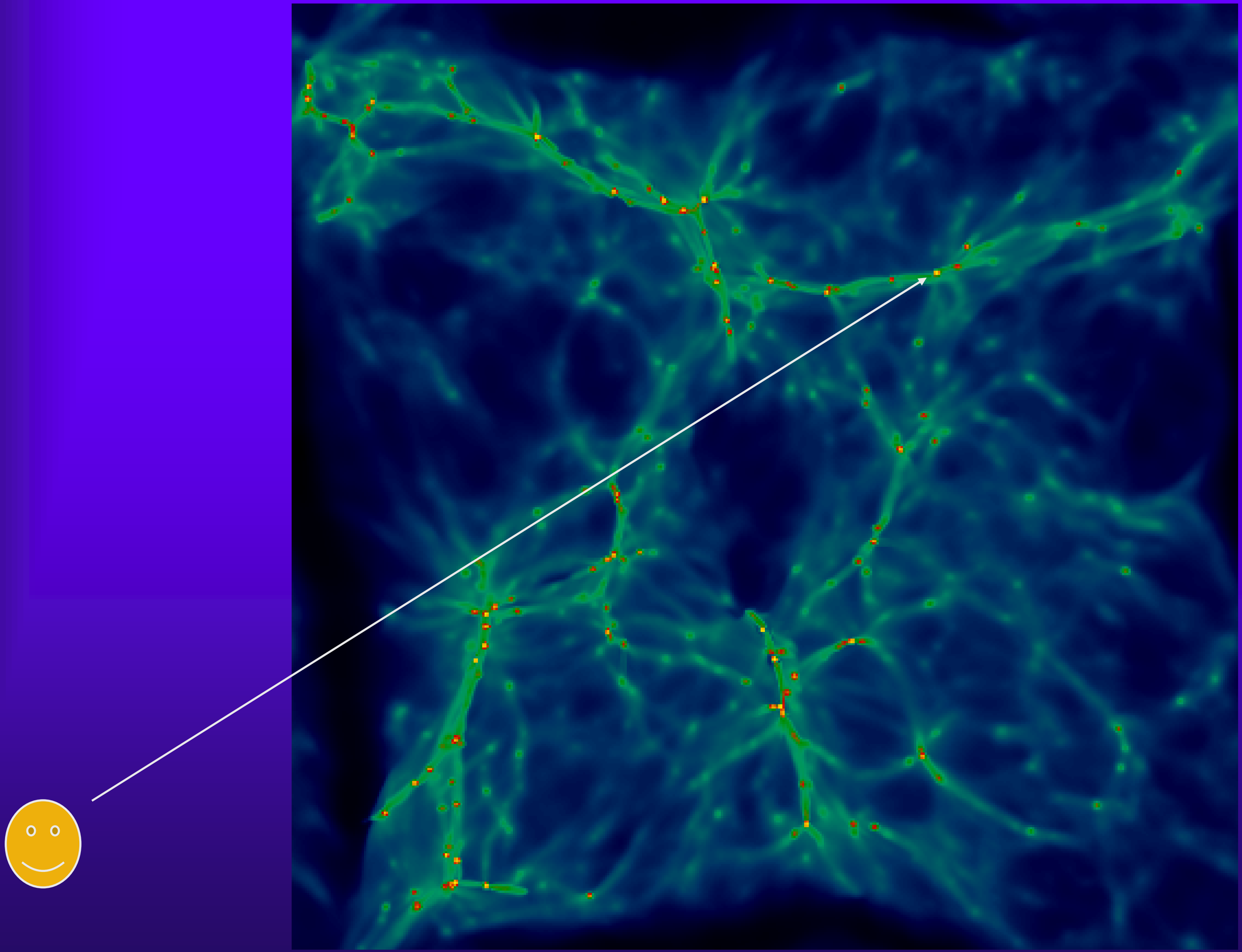
SDSS Ly-alpha forest analysis

Pat McDonald, Alexey Makarov+SDSS

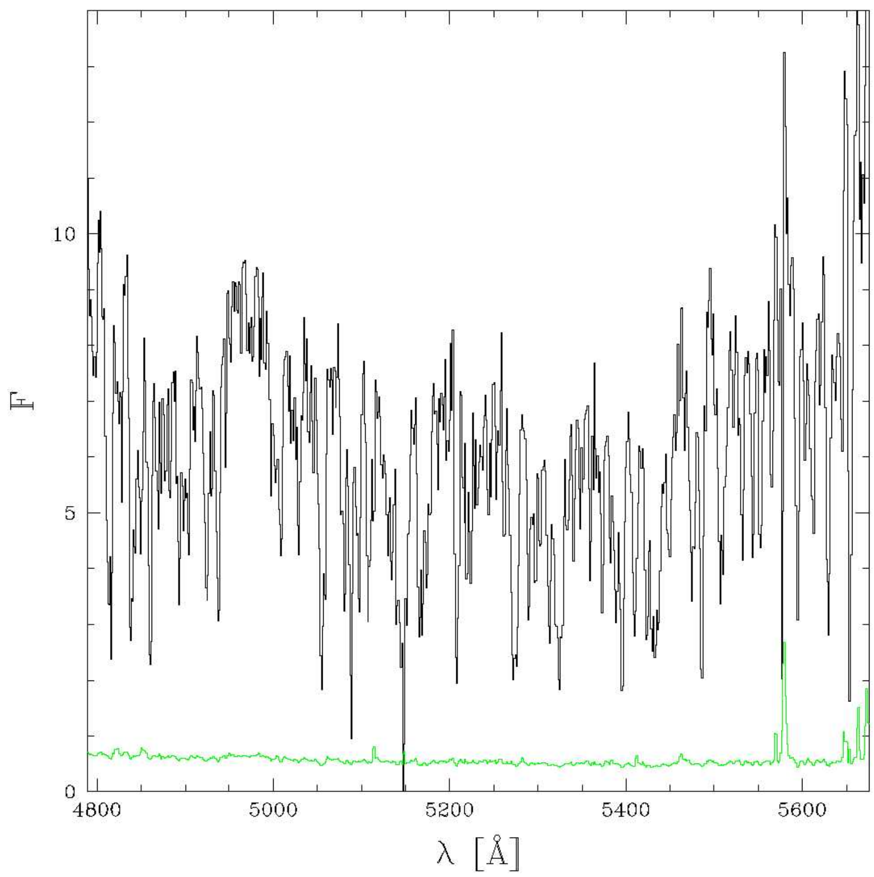
The promise:

- 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

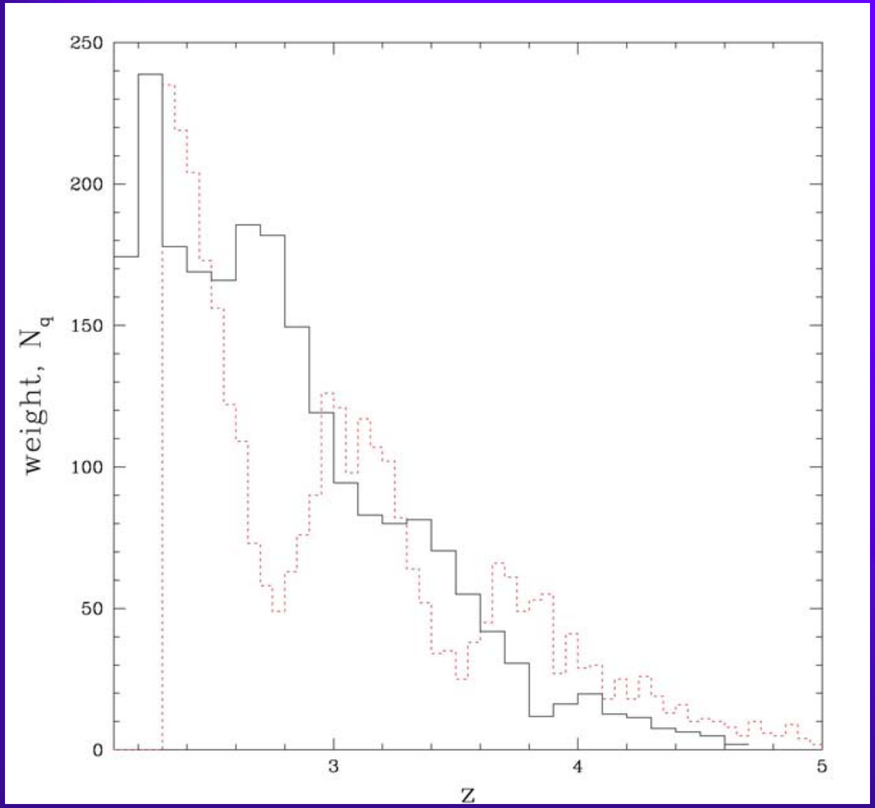


Lyα Forest as a tool for cosmology



- 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 (two orders of magnitude more than previous samples)

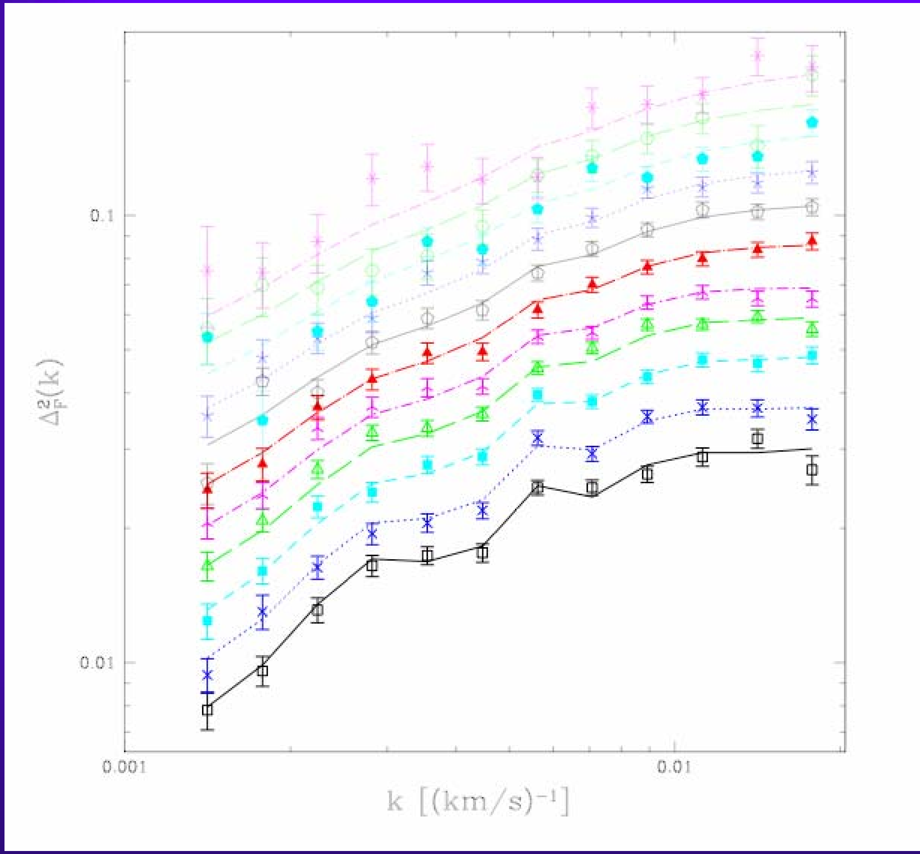
redshift distribution of quasars

1.1 million pixels in the forest

redshift distribution of Lyα forest pixels (noise weighted)

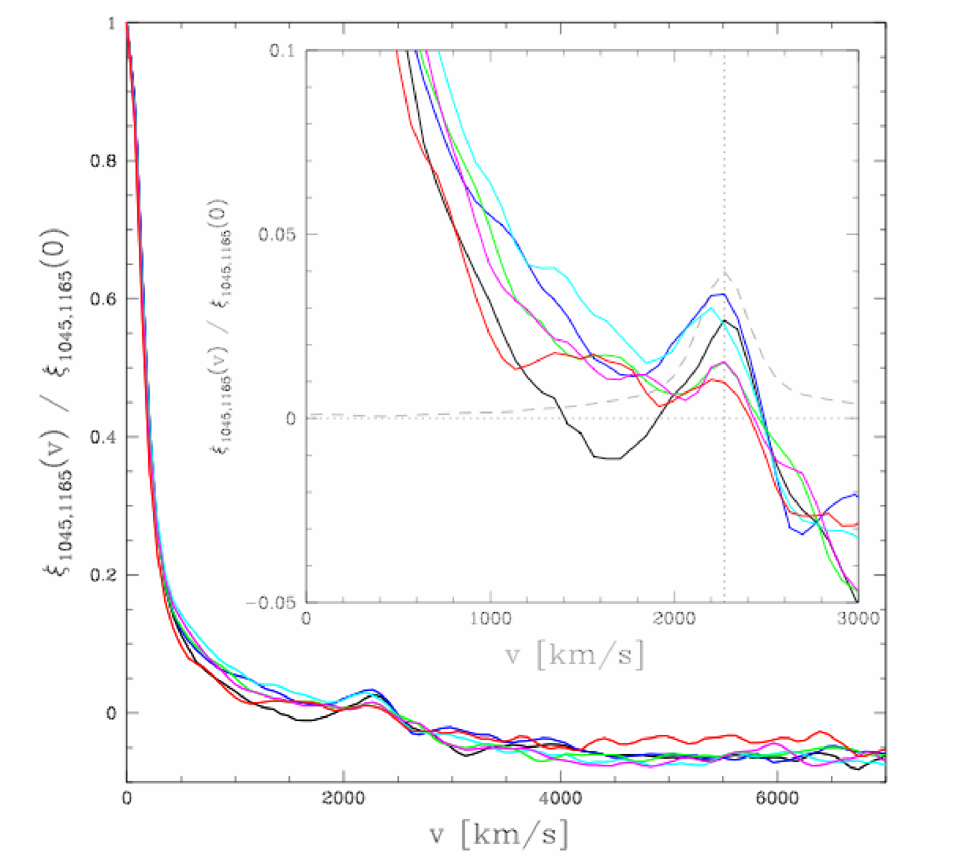
Power spectrum analysis

McDonald, US etal 2004



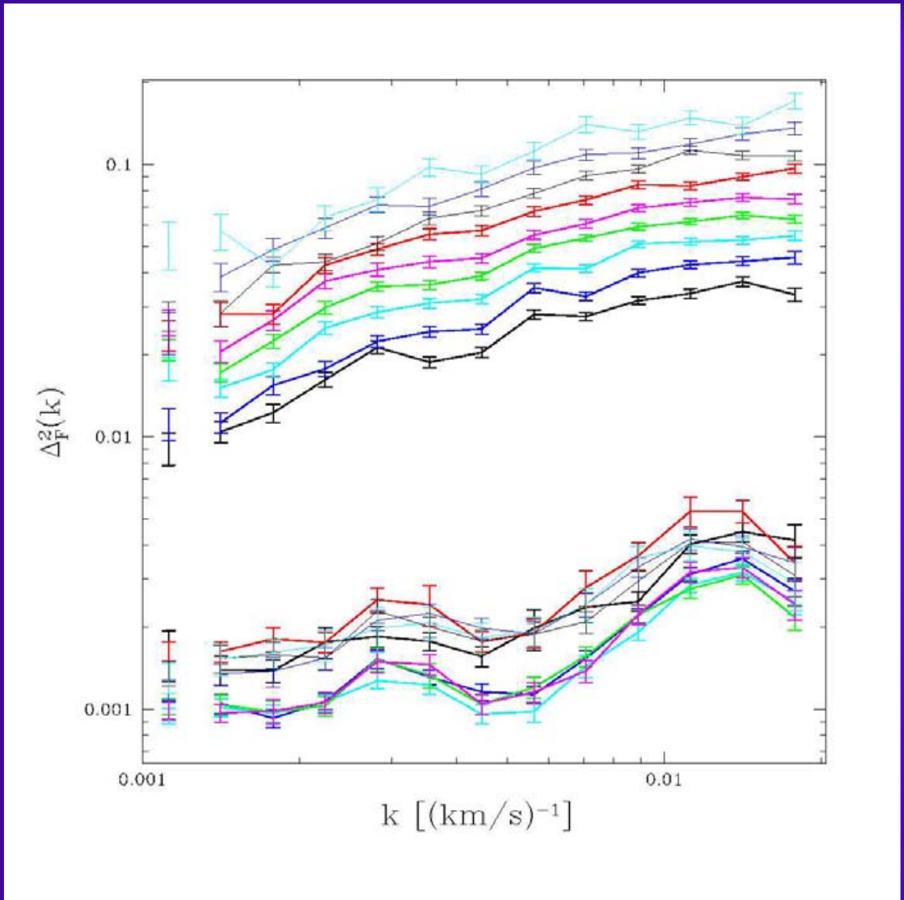
- Combined statistical power is better than 1% in amplitude, comparable to WMAP
- 2<z<4 in 11 bins
- **$\chi^2 \approx 129$ for 104 d.o.f.**
- **A single model fits the data over a wide range of redshift and scale**

SiIII-Lyα cross-correlation bump



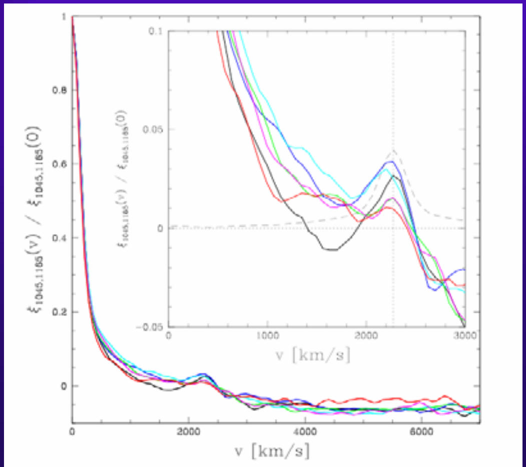
- SiIII absorbs at 1207 Å, corresponding to a velocity offset 2271 km/s
- Vertical line at 2271 km/s
- No other obvious bumps out to about 7000 km/s
- Dashed line shows

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

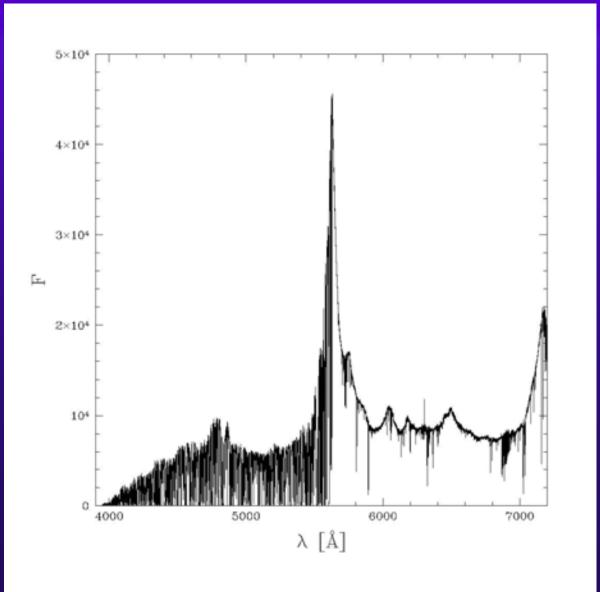


Background Contamination

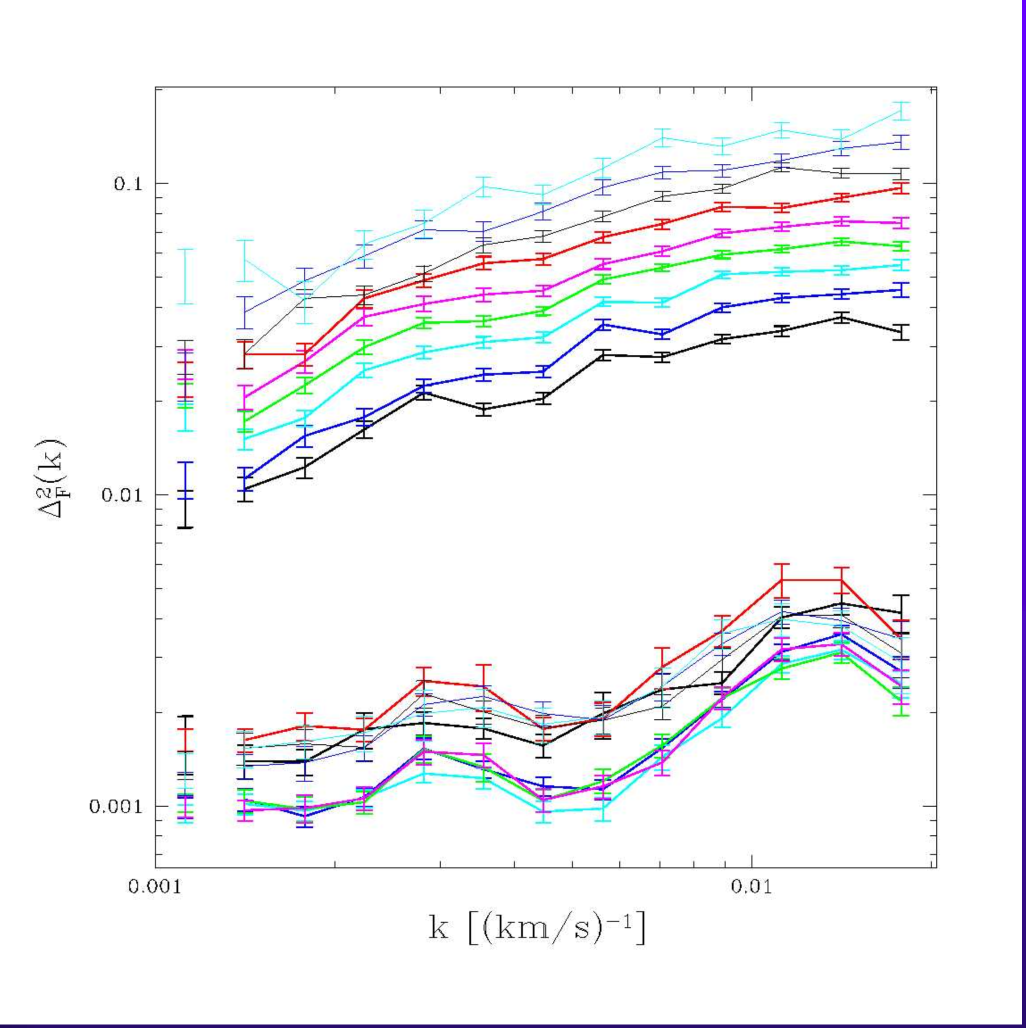
- The top set of lines shows the Lyα forest power
- The bottom set of lines shows the power in the region $1270<\lambda_{rest}<1380$Å



Si III correlated with H



Background Contamination



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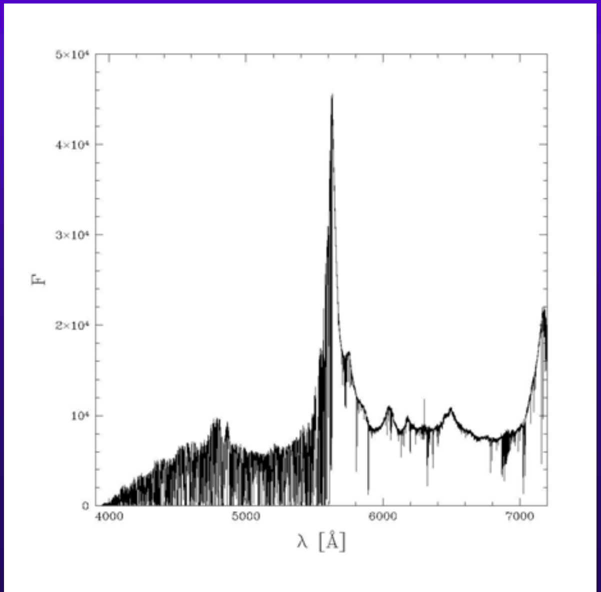
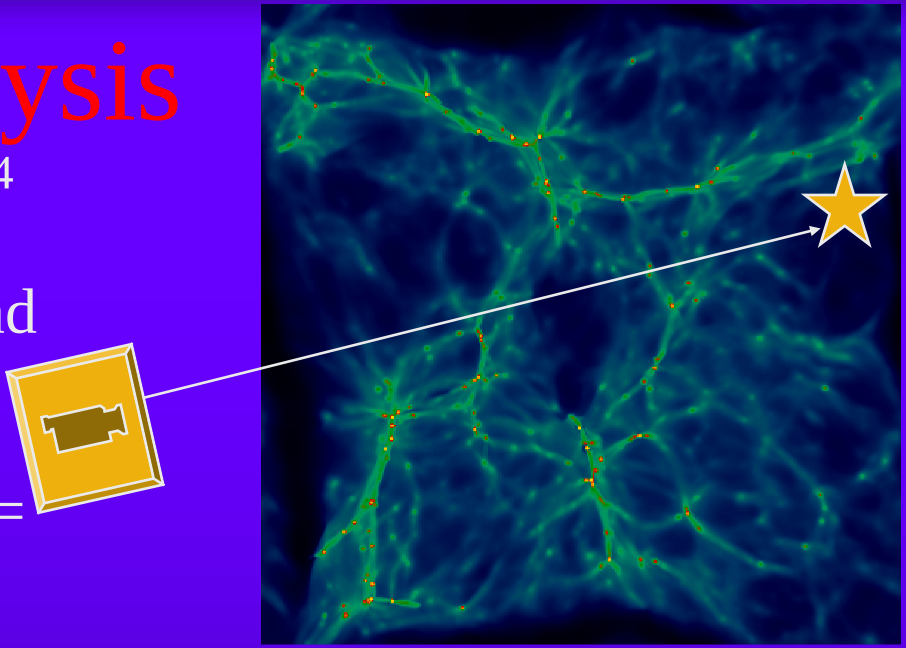
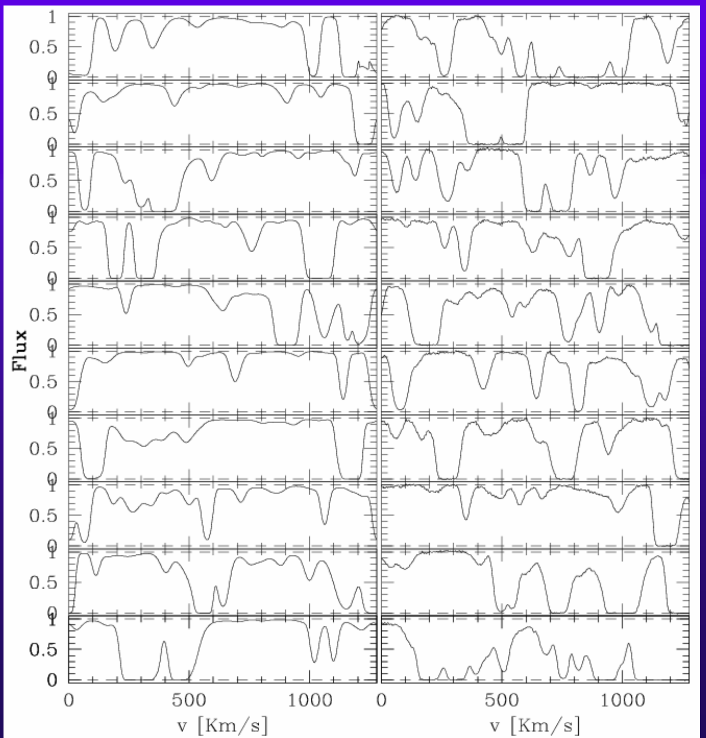


Theoretical analysis

McDonald, US, Cen etal 2004

- 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.
- Overall hundreds of different simulations were run (challenge: numerical convergence on all scales)
- Need to marginalize over several astrophysical parameters (T, UV flux…)





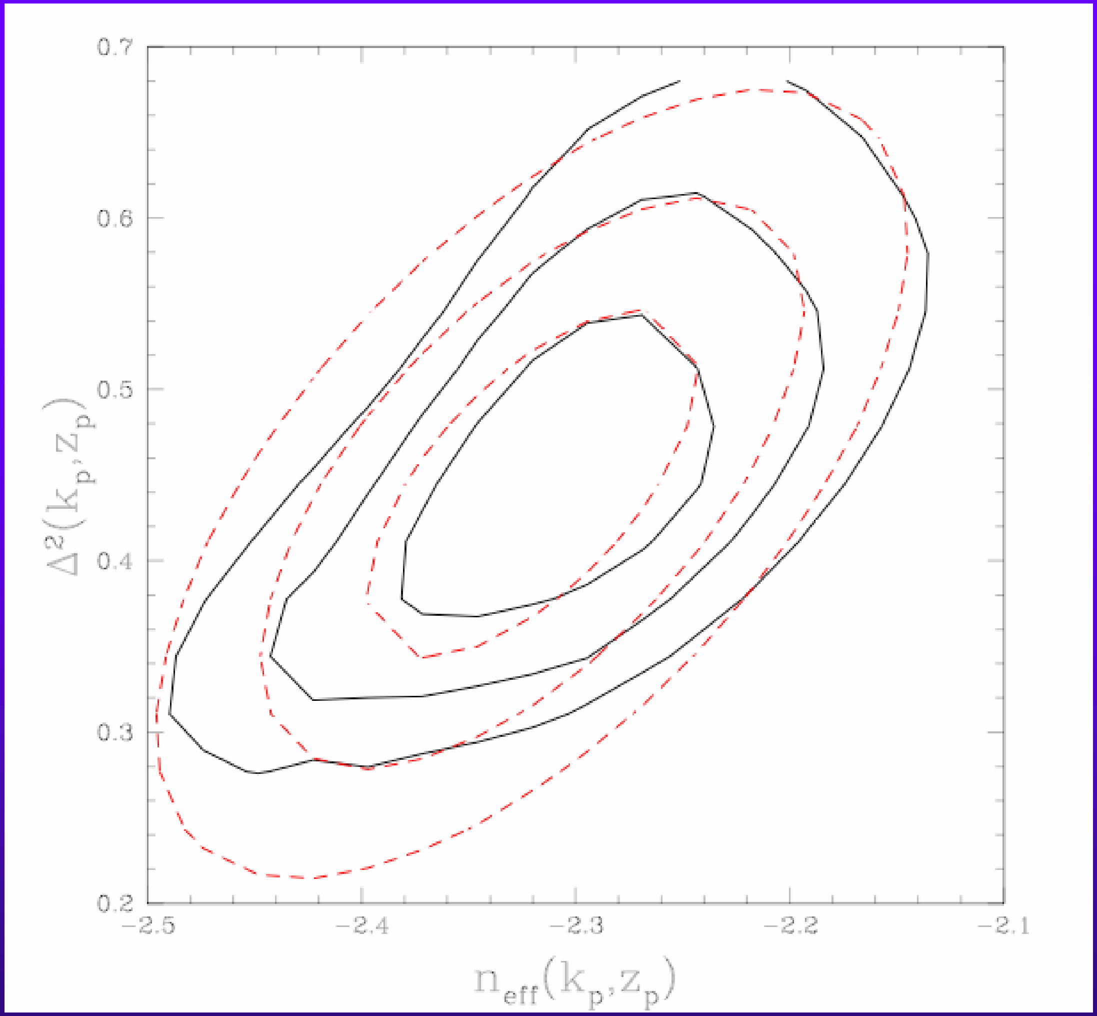
Katz etal 1999

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



Astrophysical parameters we marginalize over

Density and temperature are correlated, modeled as a power law with slope $\gamma-1$ 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…)

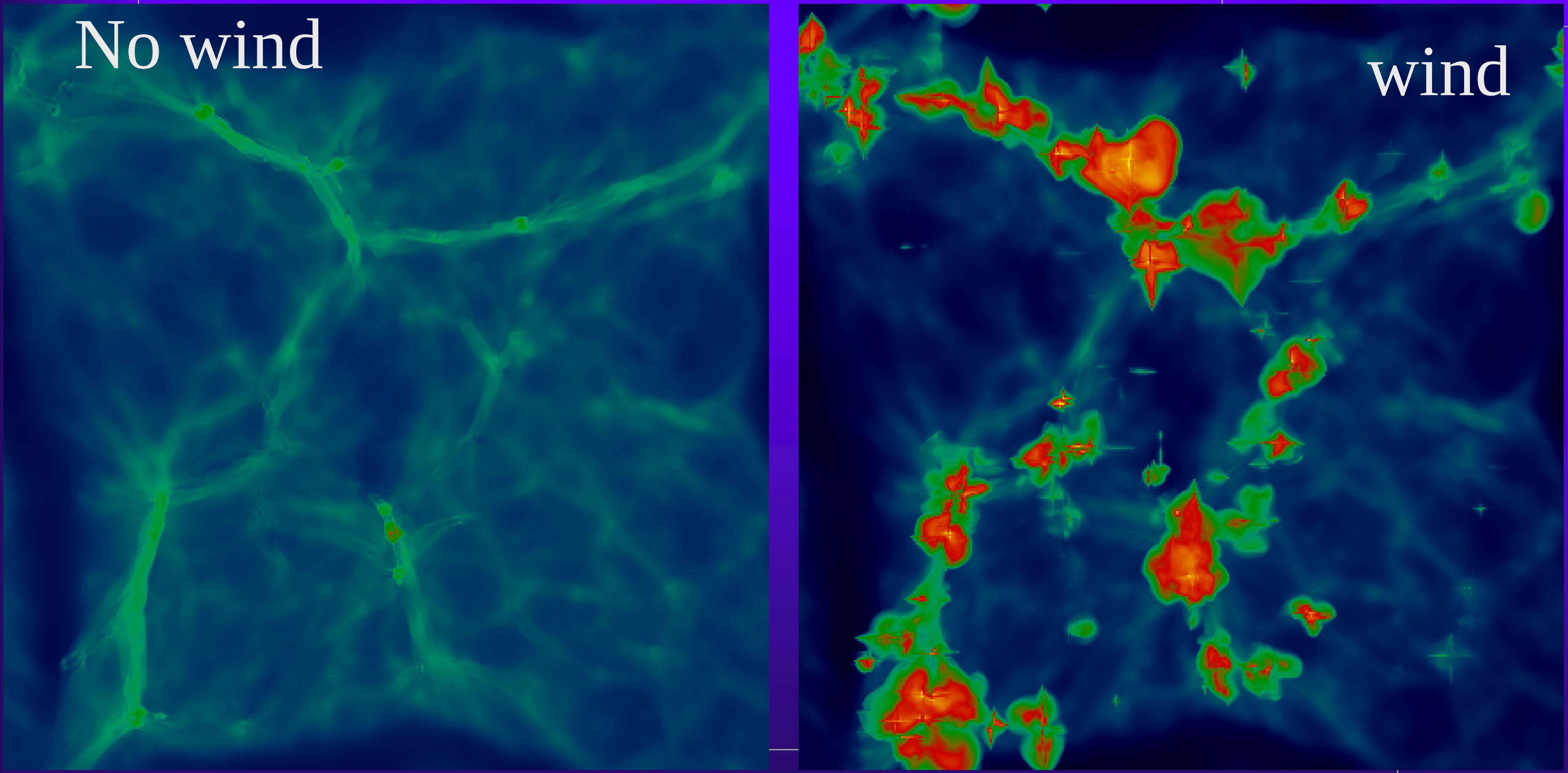
Additional physical effects

Things we accounted for:

- Galactic superwinds (known to exist in starburst galaxies and LBGs): not much effect(?)
- Ionizing background fluctuations from quasars: no evidence for it(?)
- Damped and Lyman limit systems, which are self-shielded: important effect, reduces the slope if ignored, once included eliminates any evidence of running

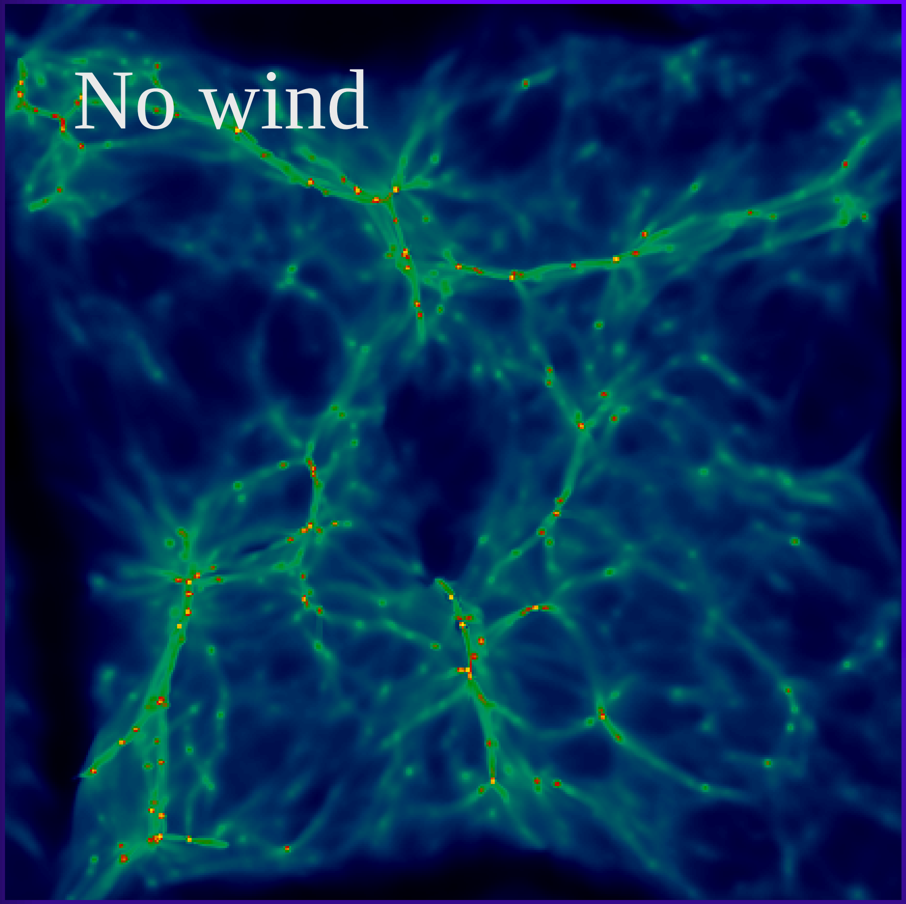
Galactic winds heat IGM to 100,000K and pollute IGM with metals

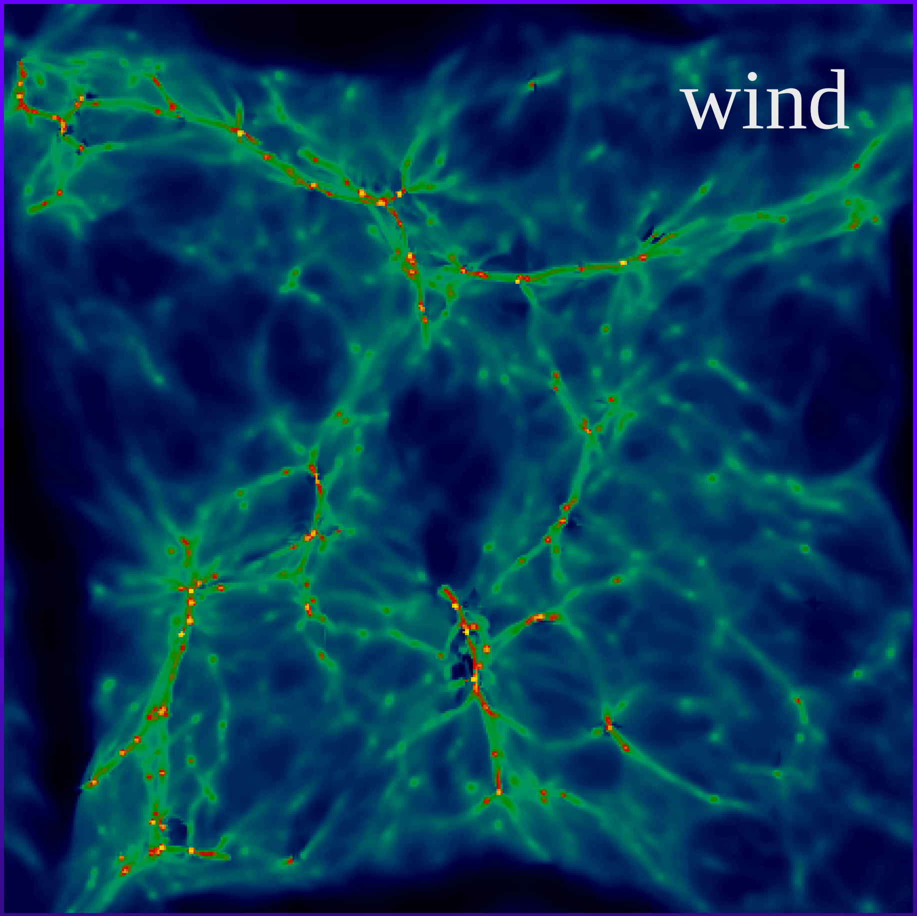
Temperature maps



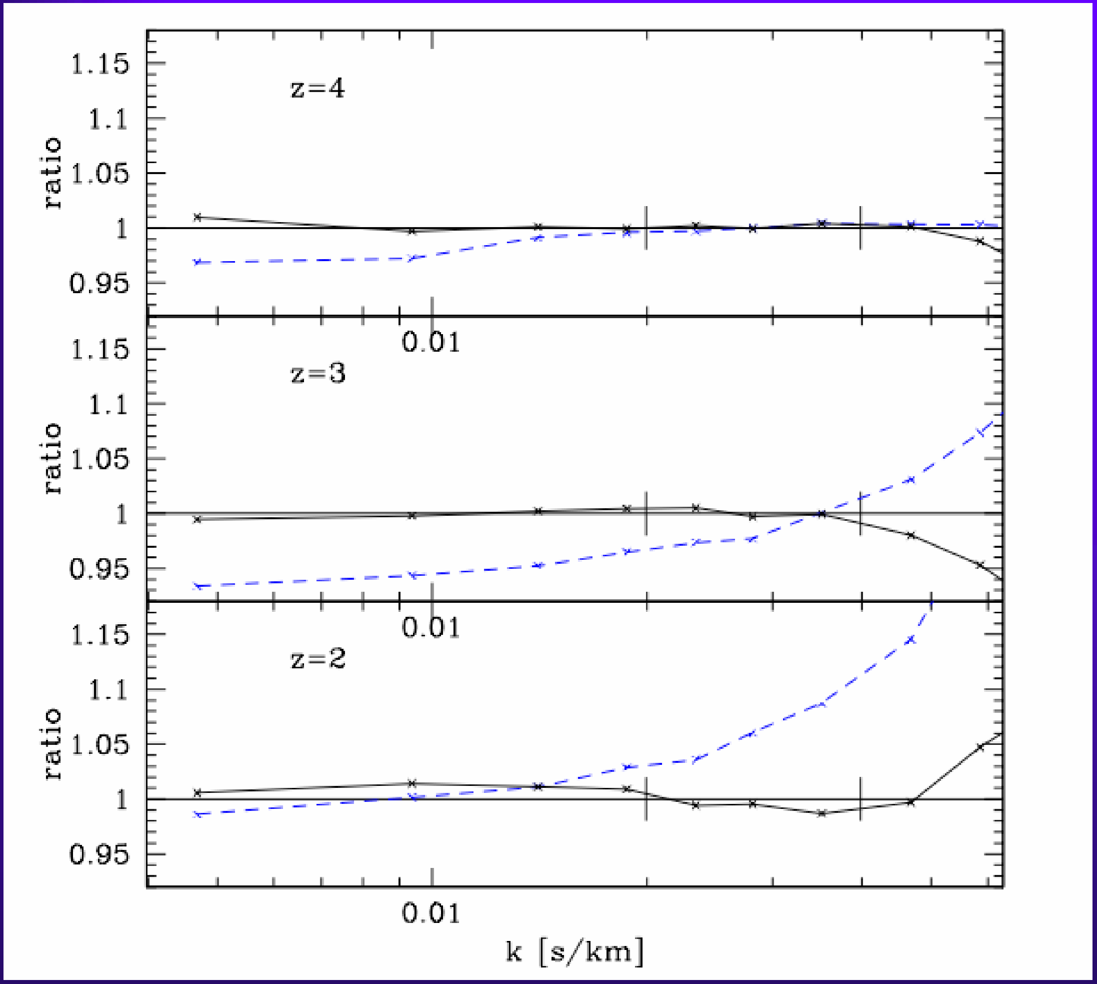
Cen, Nagamine, Ostriker 2004

Neutral hydrogen maps show much less effect





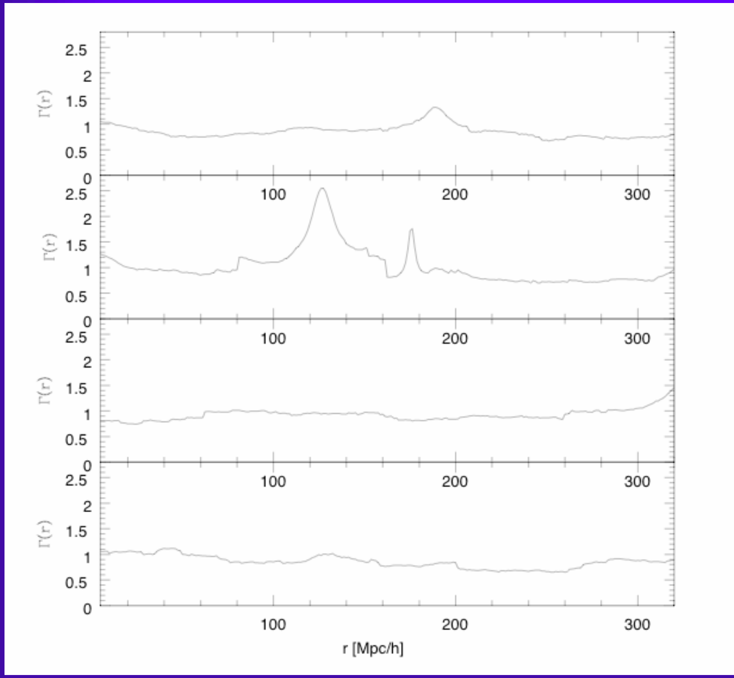
Strong wind versus no wind simulations



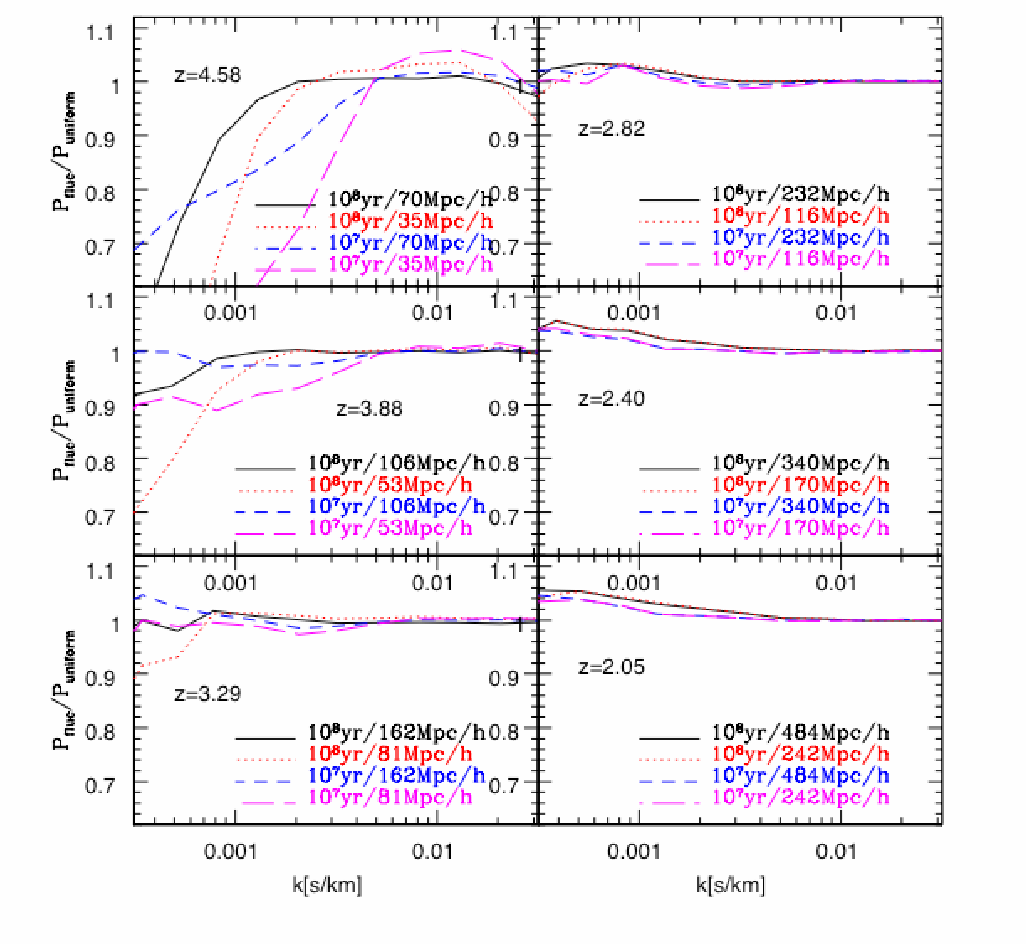
Winds have no effect after simulations have been adjusted for temperature change

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

Fluctuations in ionizing background



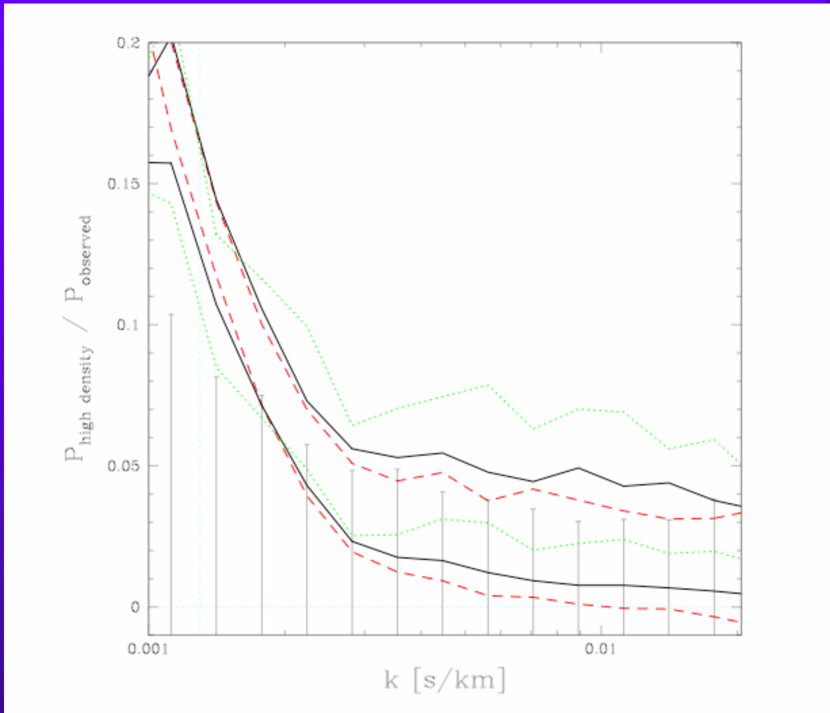
Attenuation length is rapidly decreasing with redshift, so effect can be large at z>4, negligible at lower redshifts



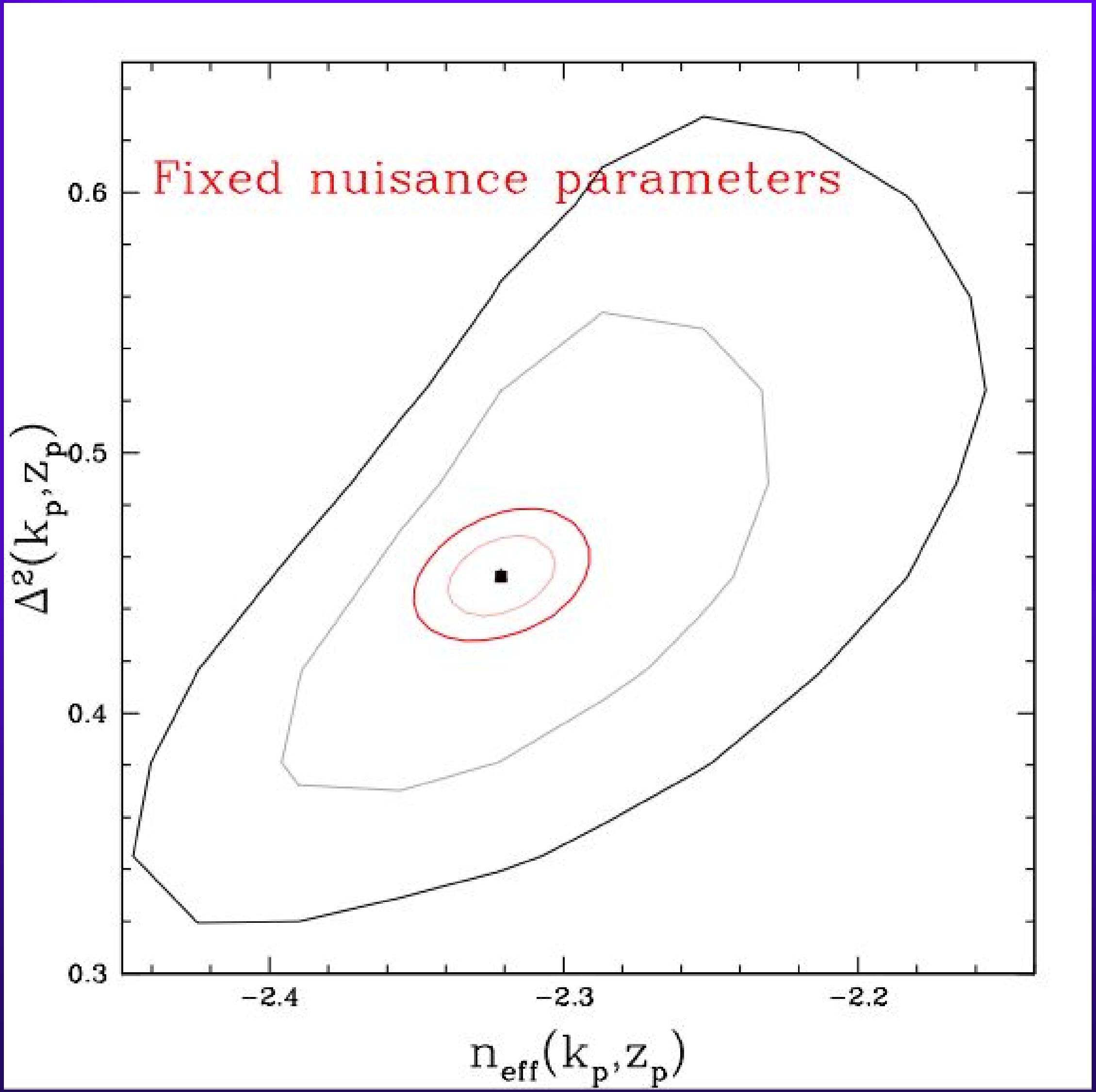
No evidence in the data

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, makes running less negative

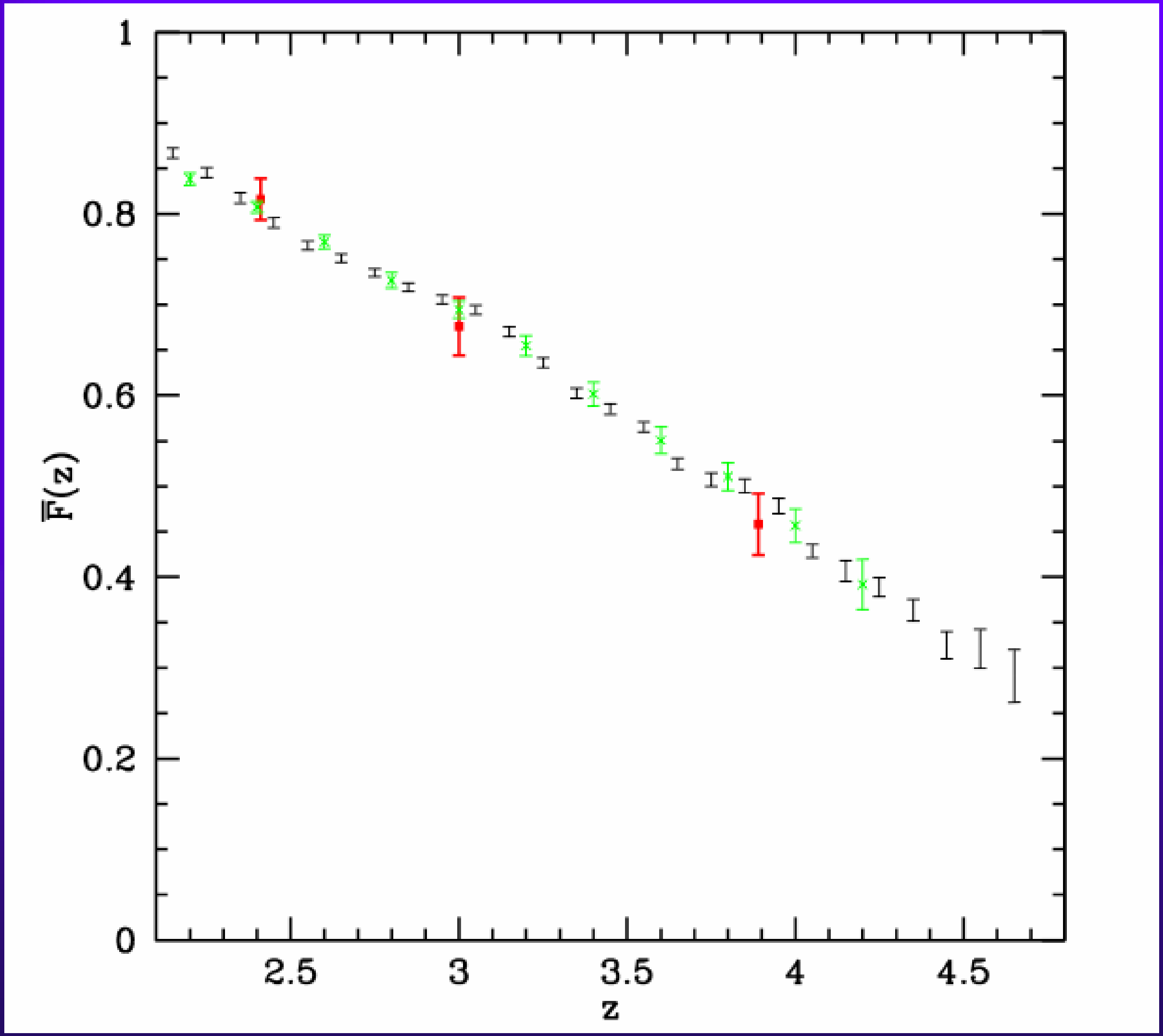


Amplitude and slope at k=1Mpc/h and z=3



- If potential systematic errors were ignored, errors would be a factor of 5 smaller!
- Main effects:
  - radiation density of photons with >13eV
  - temperature
  - gas hydrodynamics: feedback, winds…
- A lot of room for future improvement

New: evolution of mean flux



PCA analysis of QSO spectra

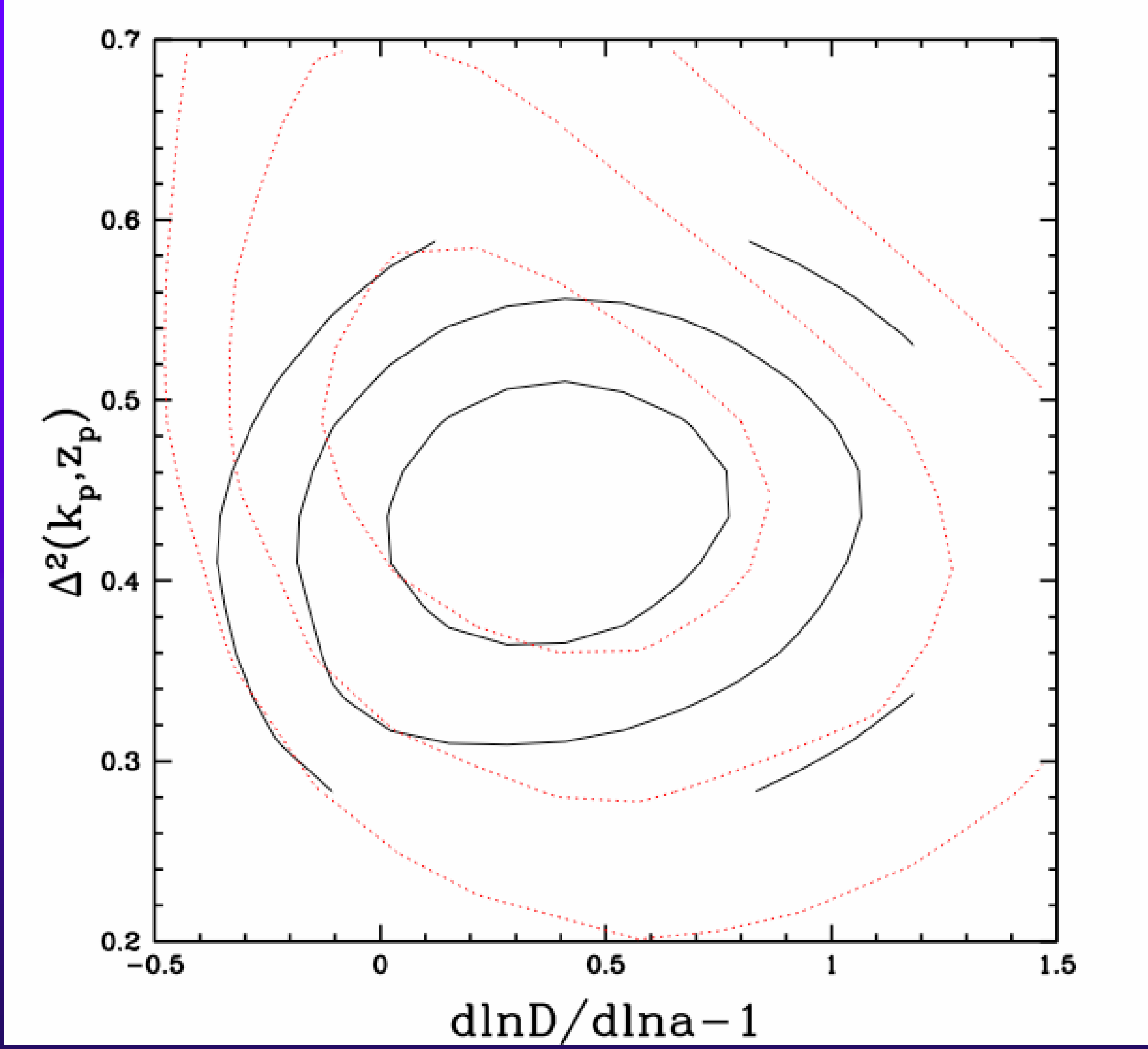
PCA evolution of mean flux is consistent with power spectrum

No feature at z=3.2

Tracking dark energy at z=2-4

No evidence for deviation from EdS

Errors on amplitude reduced



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

Cosmological constraints

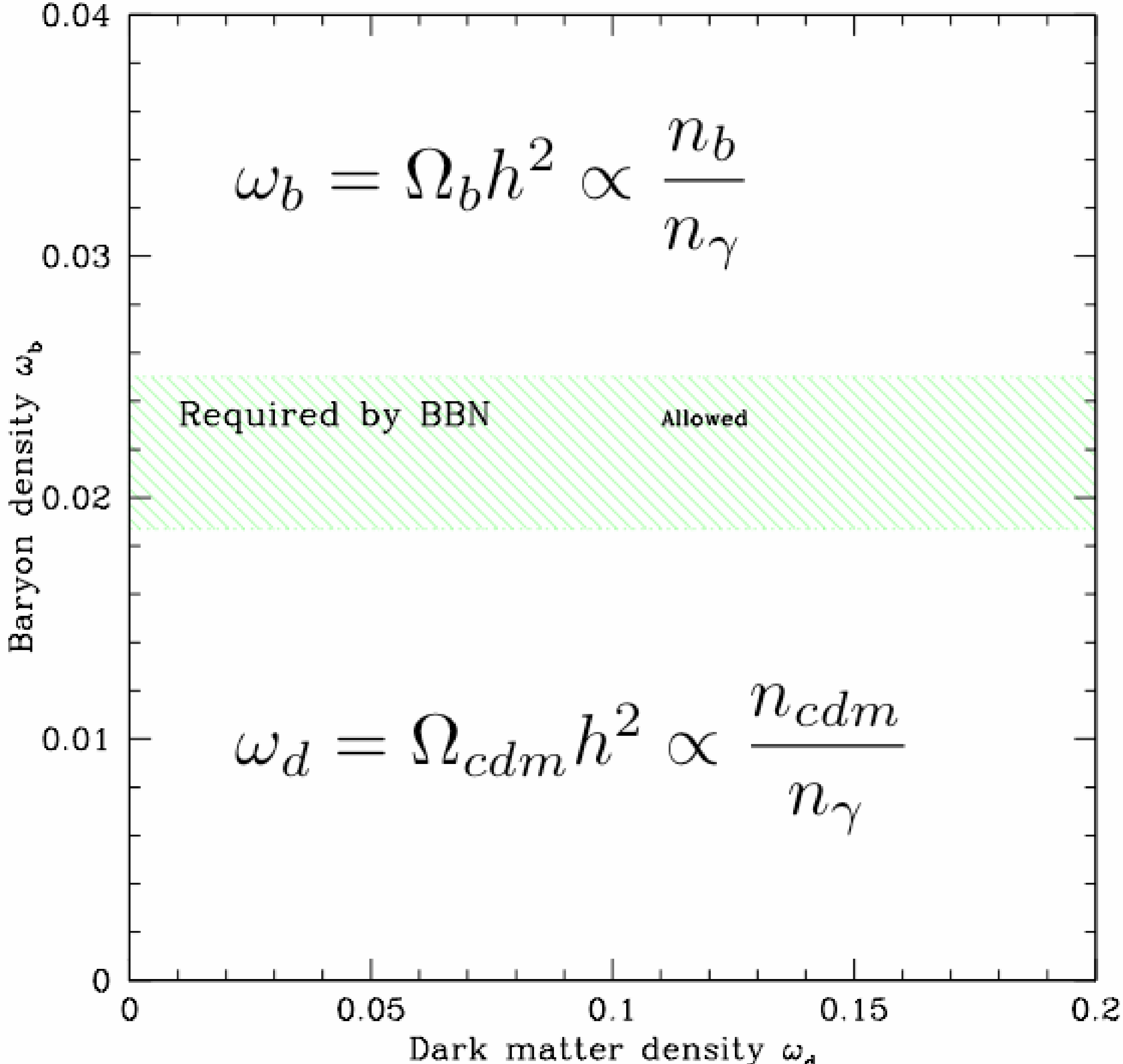
Seljak etal 2004

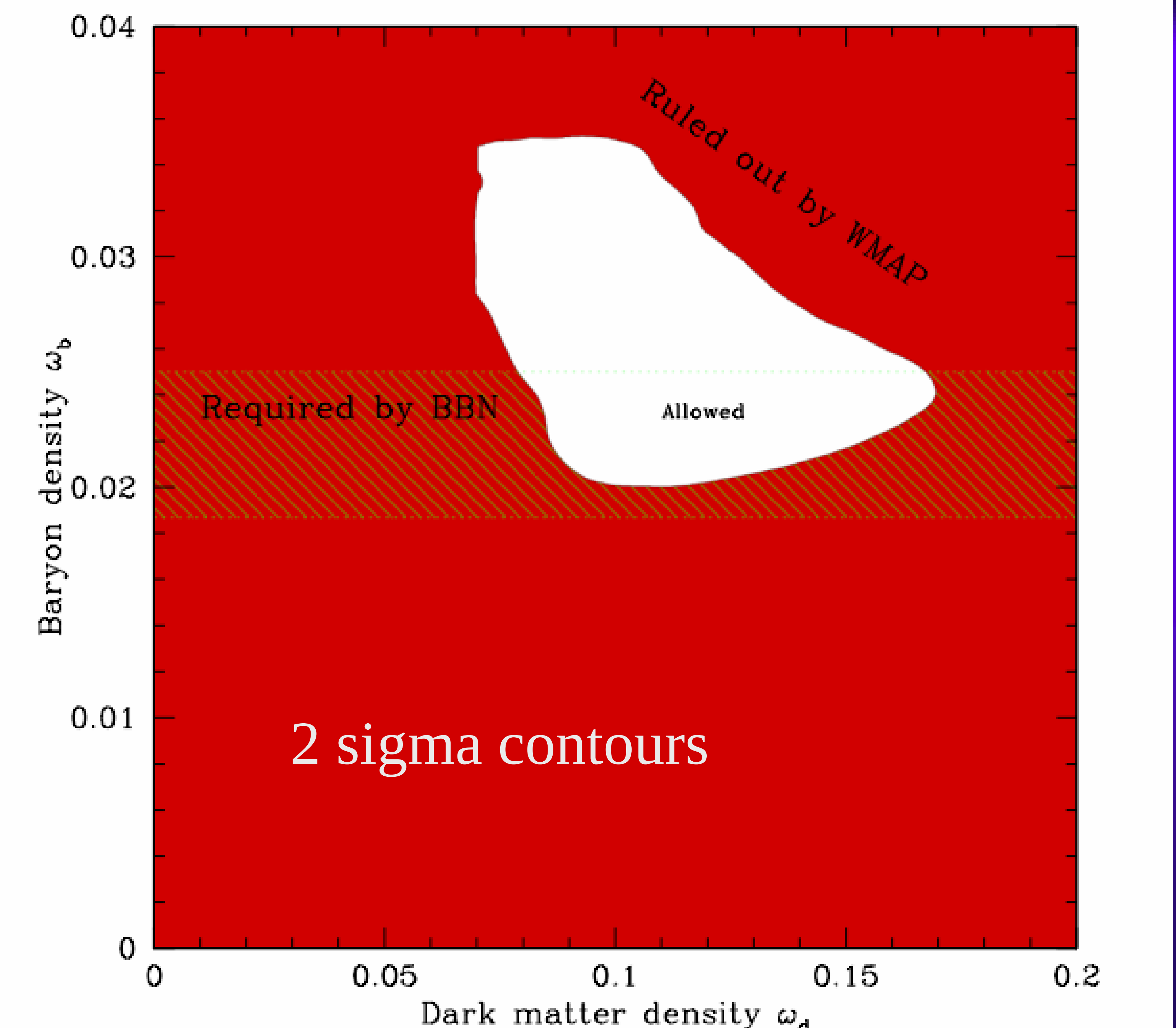
- Ly-alpha combined with WMAP, with SDSS galaxy power spectrum, SDSS bias constraints or SN1A.
- MCMC analysis: choose a model, compute its likelihood given data, compare to previous model, accept/reject, repeat. This leads to correct probability distributions of cosmological parameters
- constraints can and do change if the parameter space changes and are rarely model independent; (theoretical) prejudice must be applied
- 1-sigma contours are not very meaningful (so multiply by 2-3)

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

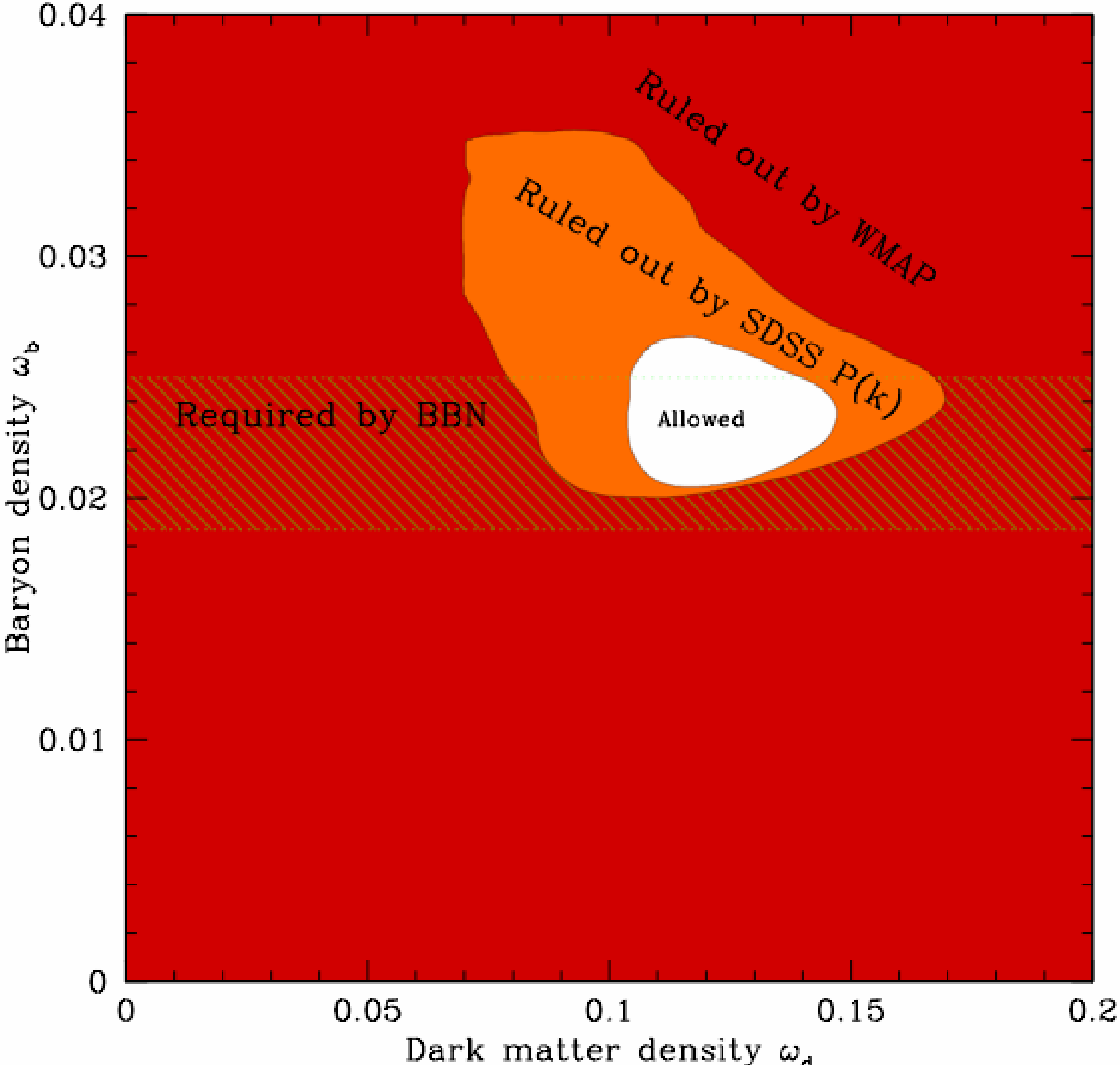
$$\Omega_b, \Omega_m, H_0, \sigma_8, n_s, \tau, \alpha_s, m_\nu, T/S, w, \Omega_K$$

- Redundancy very important because of possible systematics: agreement between different data sets gives confidence in the results

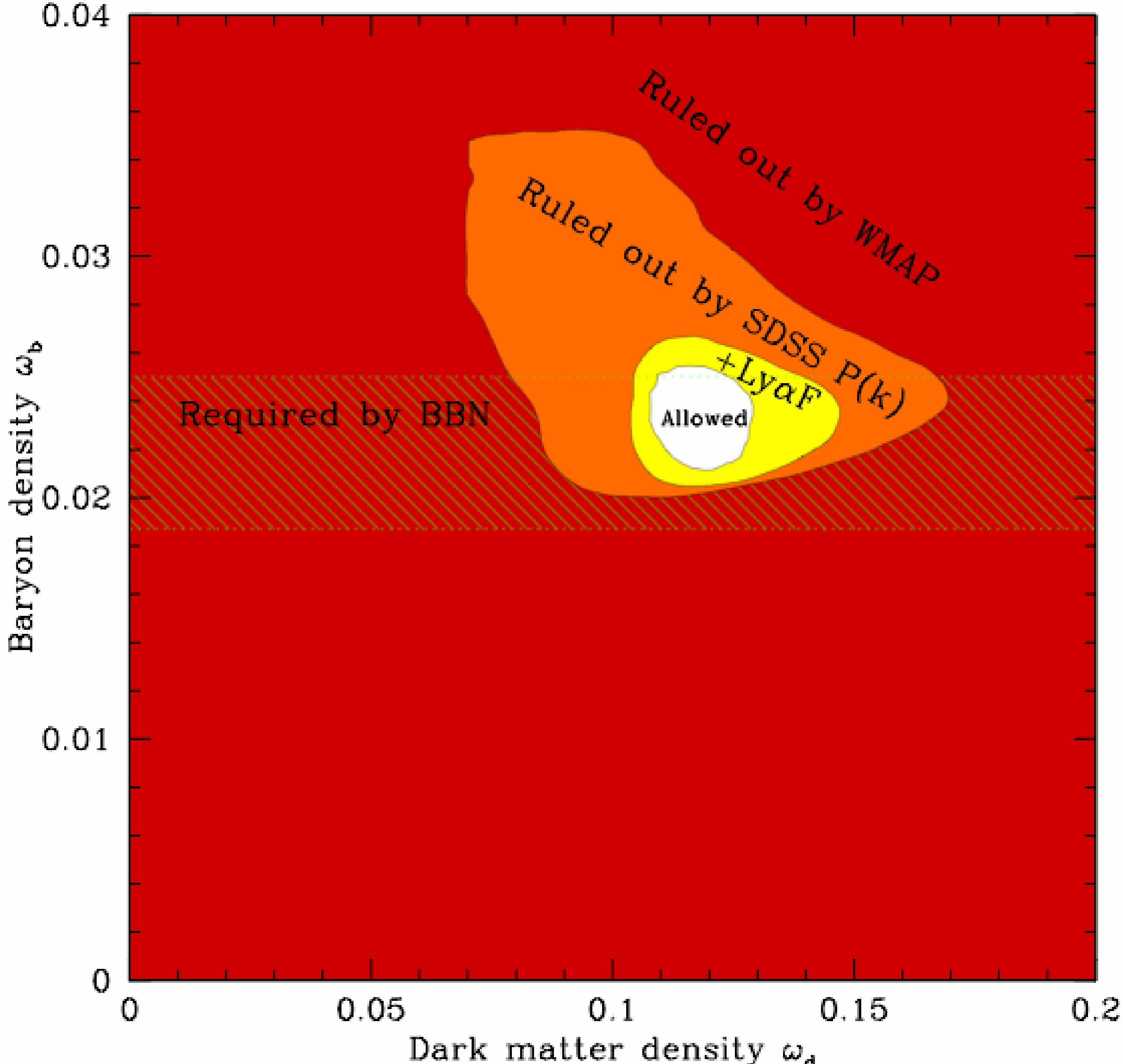

$\omega_b = \Omega_b h^2 \propto \frac{n_b}{n_\gamma}$
Required by BBN
Allowed
$\omega_d = \Omega_{cdm} h^2 \propto \frac{n_{cdm}}{n_\gamma}$
Baryon density ω_b
Dark matter density ω_d
0.04
0.03
0.02
0.01
0
0.05
0.1
0.15
0.2



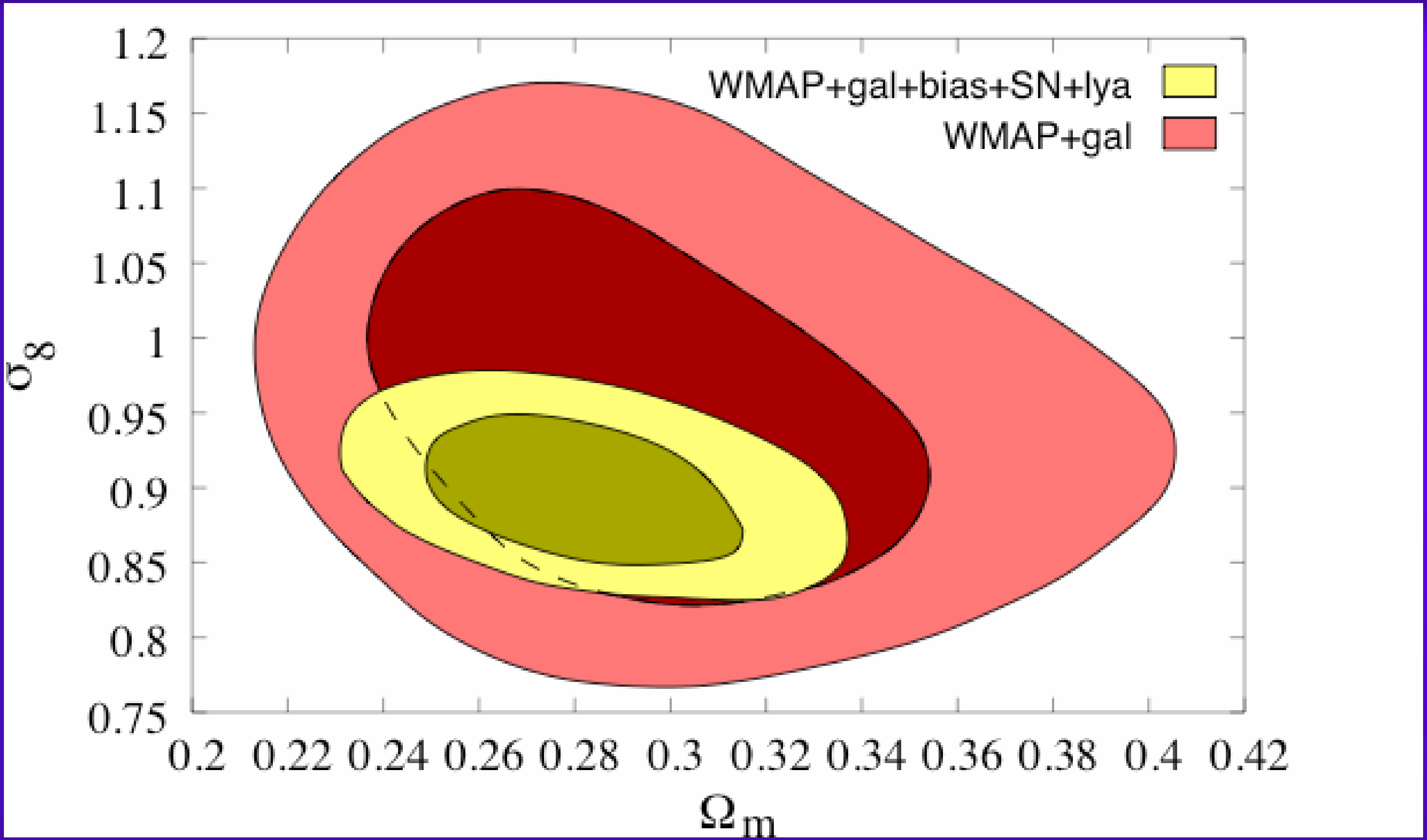
0.04
0.03
0.02
0.01
0
0
0.05
0.1
0.15
0.2
Baryon density ω_b
Dark matter density ω_d
Ruled out by WMAP
Required by BBN
Allowed
2 sigma contours



Ruled out by WMAP
Ruled out by SDSS P(k)
Allowed
Required by BBN
Baryon density ω_b
Dark matter density ω_d
0.04
0.03
0.02
0.01
0
0
0.05
0.1
0.15
0.2



Ruled out by WMAP
Ruled out by SDSS P(k)
+LyαF
Allowed
Required by BBN
Baryon density ω_b
Dark matter density ω_d
0.04
0.03
0.02
0.01
0
0.05
0.1
0.15
0.2

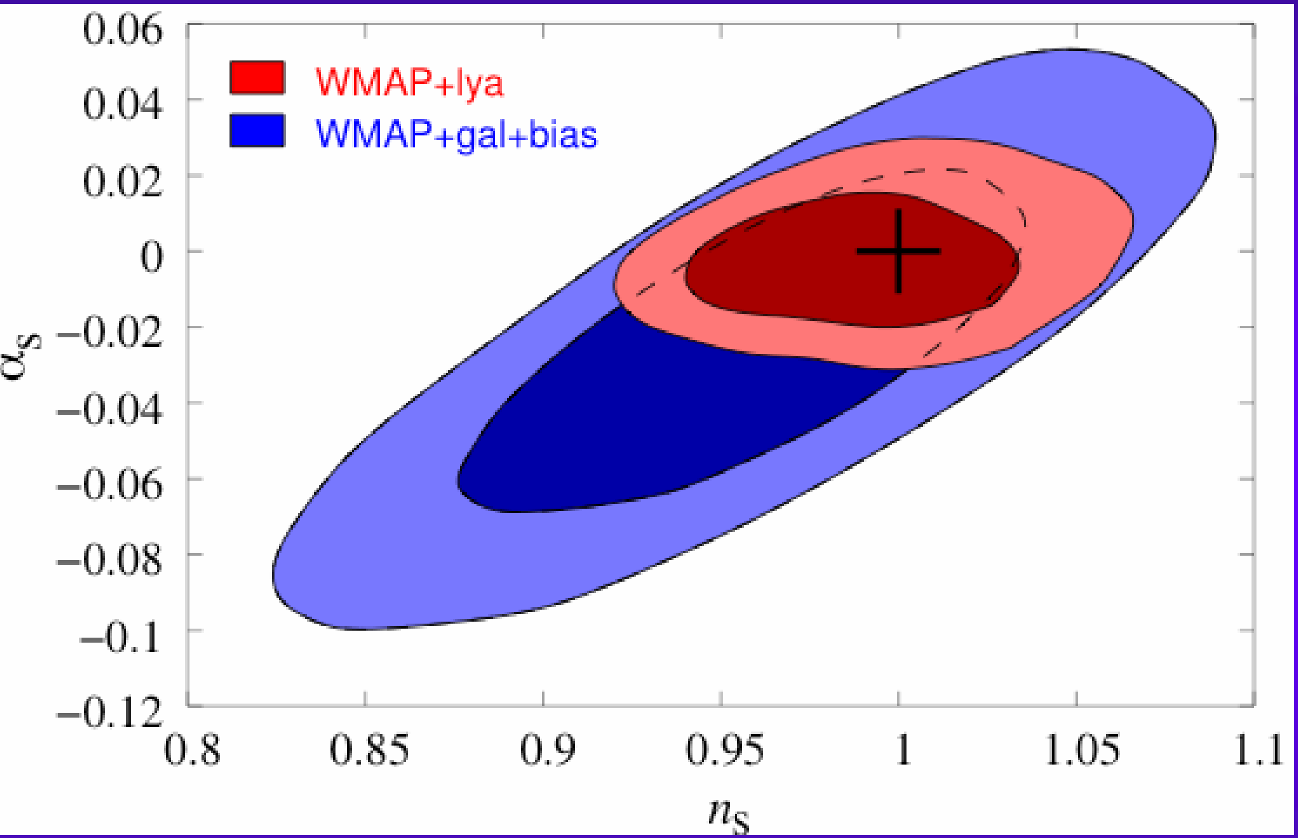


$$\sigma_8 = 0.90 \pm 0.03$$

$$\Omega_m = 0.28 \pm 0.02$$

$$h = 0.71 \pm 0.02$$

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



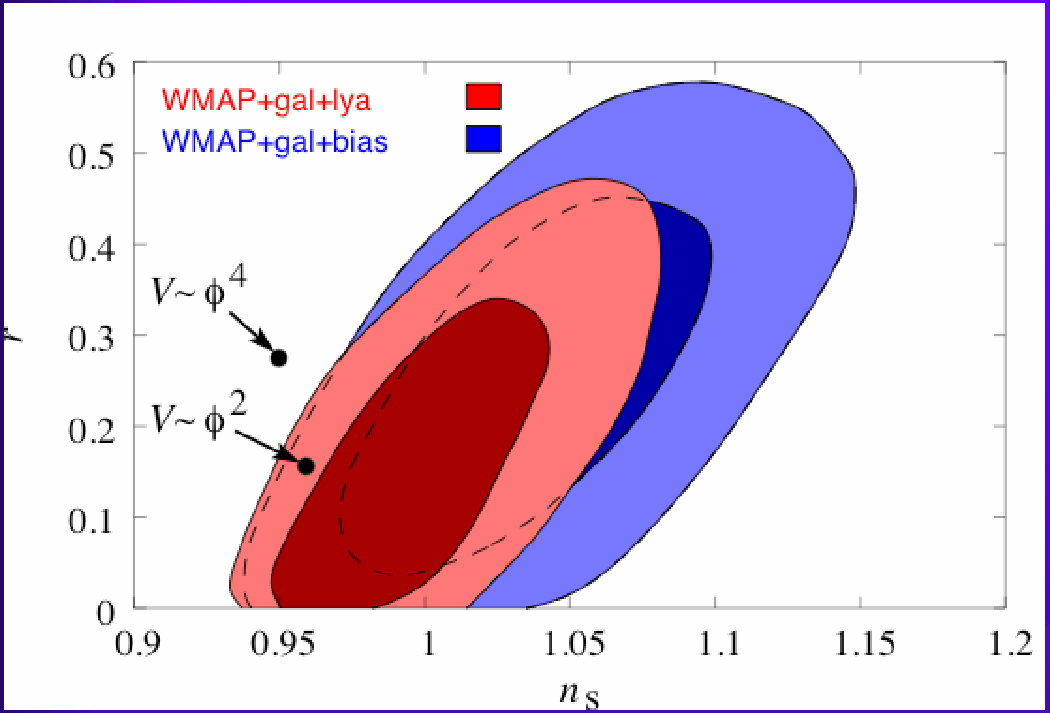
3-fold reduction in errors on running

No large running, good news for inflation

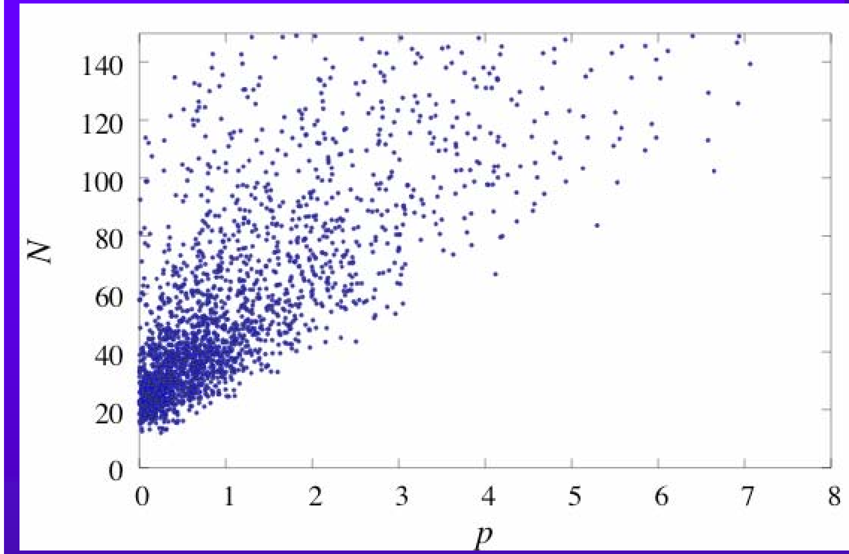
$$\alpha_s = dn_s/d\ln k = -0.002 \pm 0.010$$

$$n_s = 0.98 \pm 0.02$$

Constraints on inflation

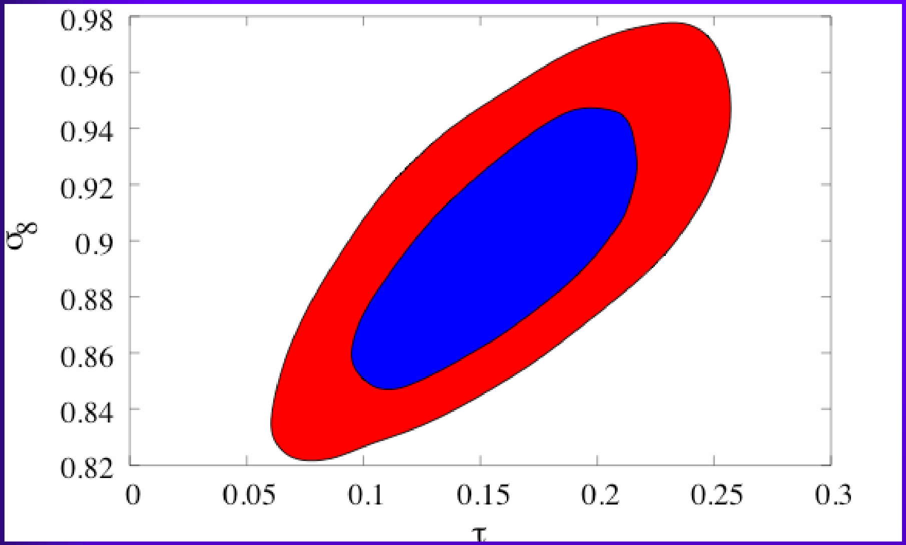


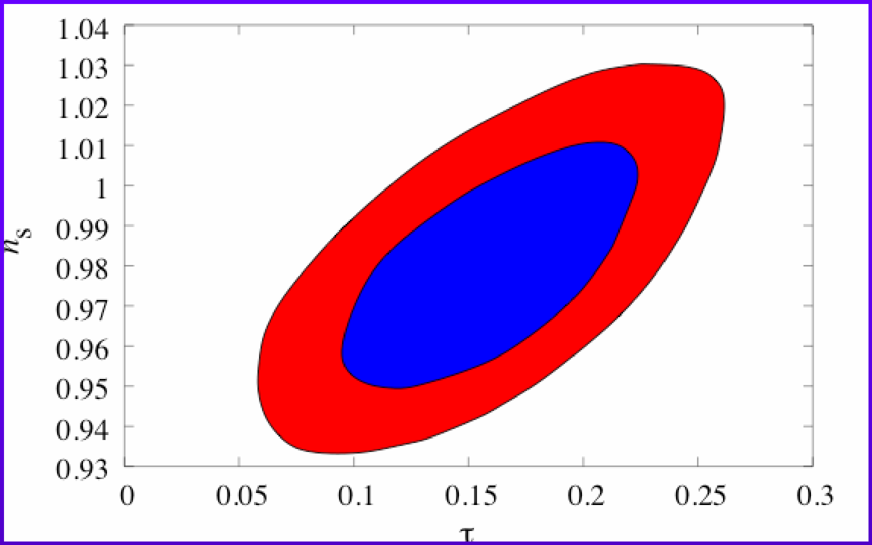
$$V = \phi^p$$

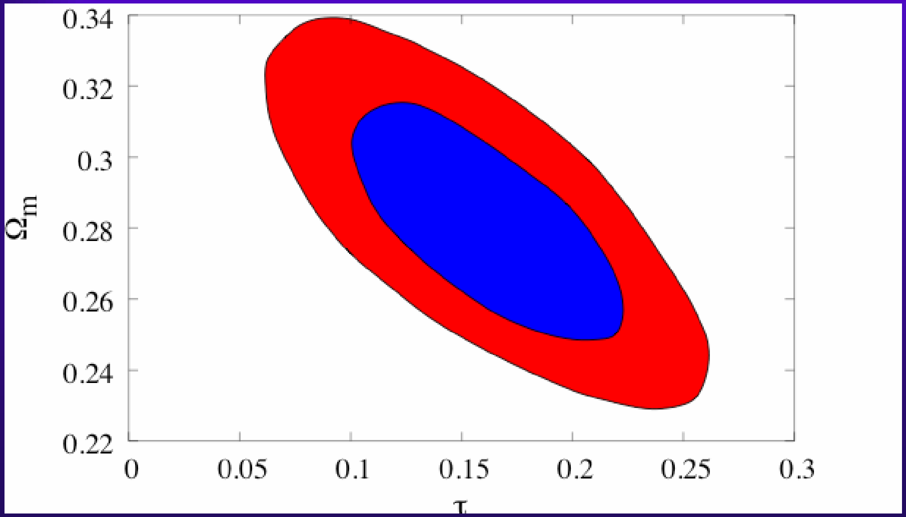


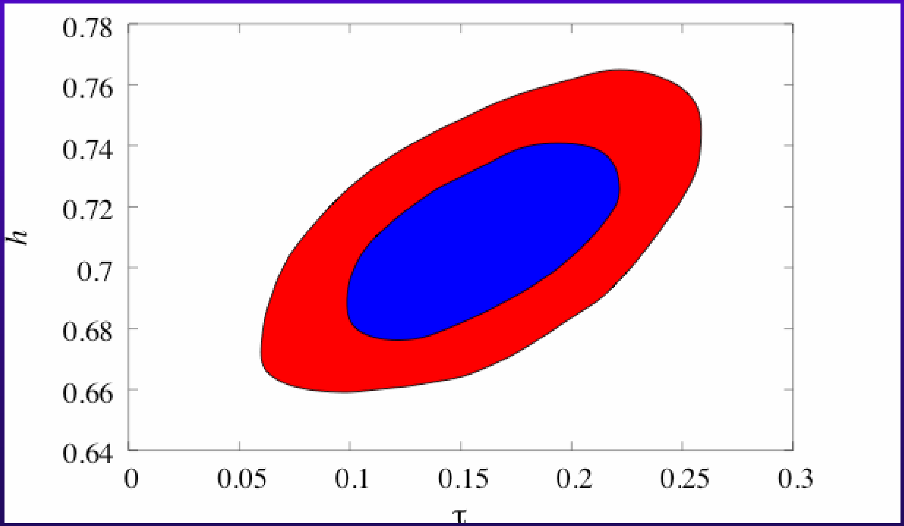
- No evidence of tensors, r<0.36 (95% cl)
- Chaotic potentials need shallow slope
- Hybrid models (n>1, r=0) disfavored

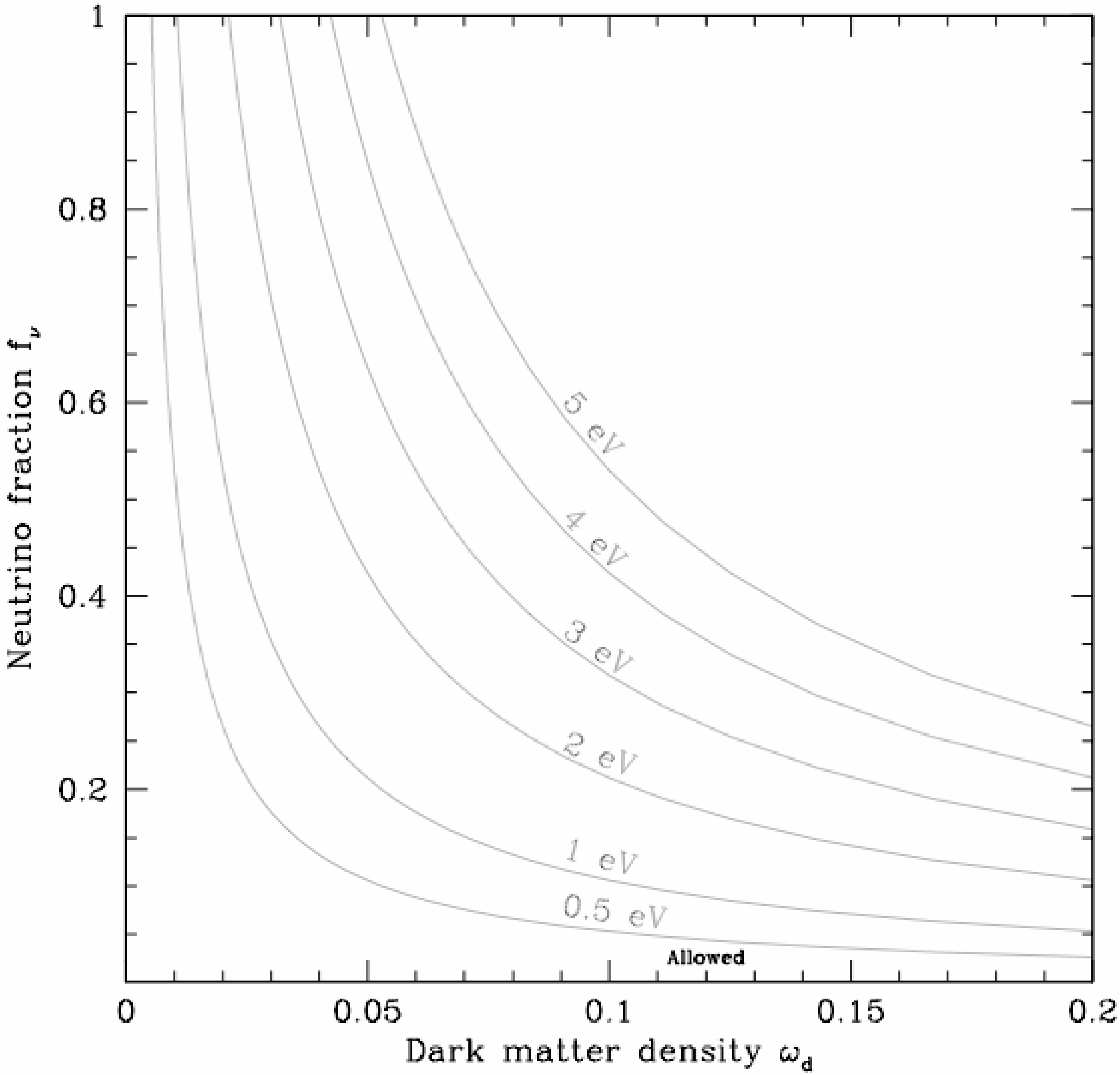
Correlations with optical depth



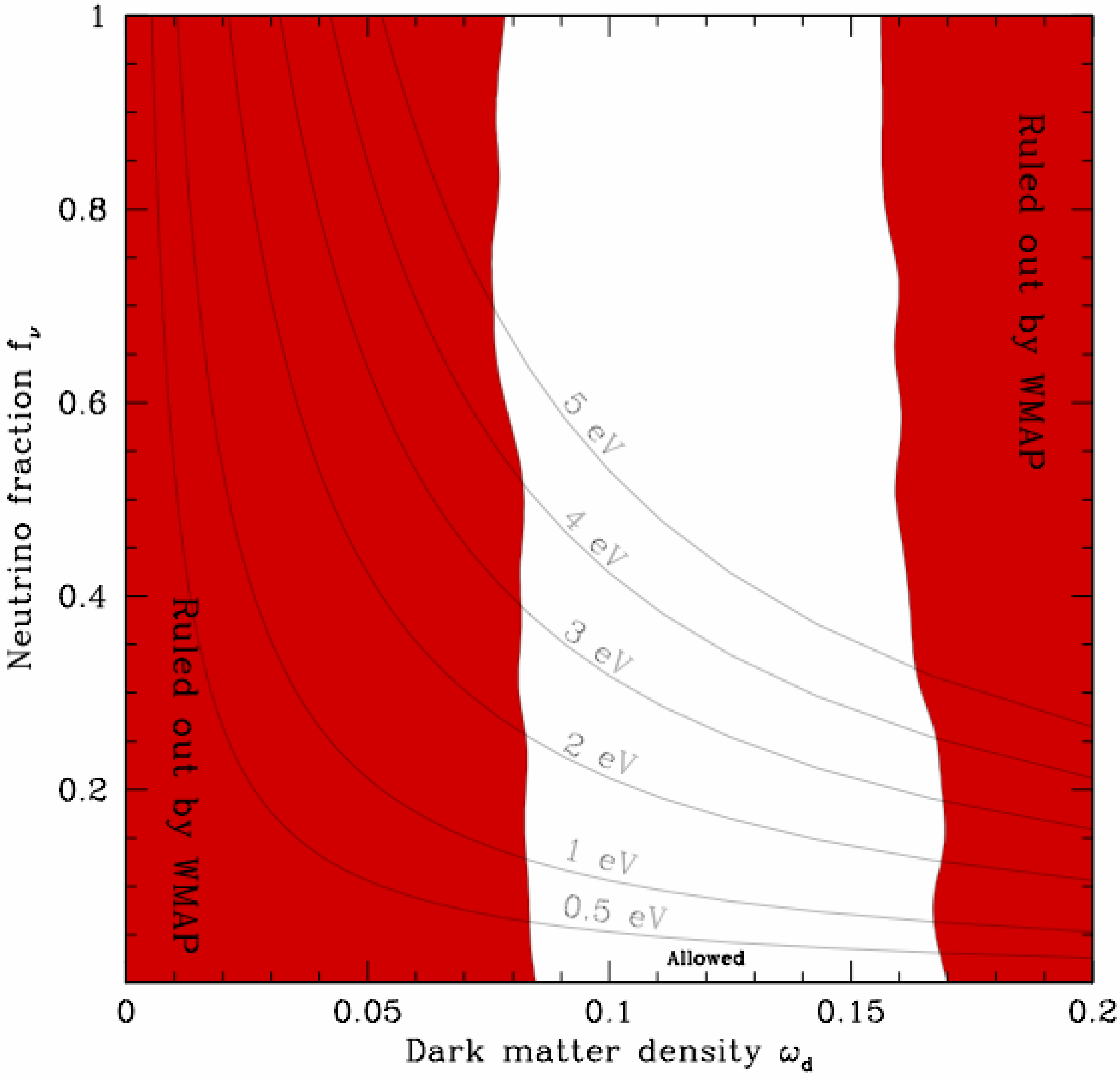




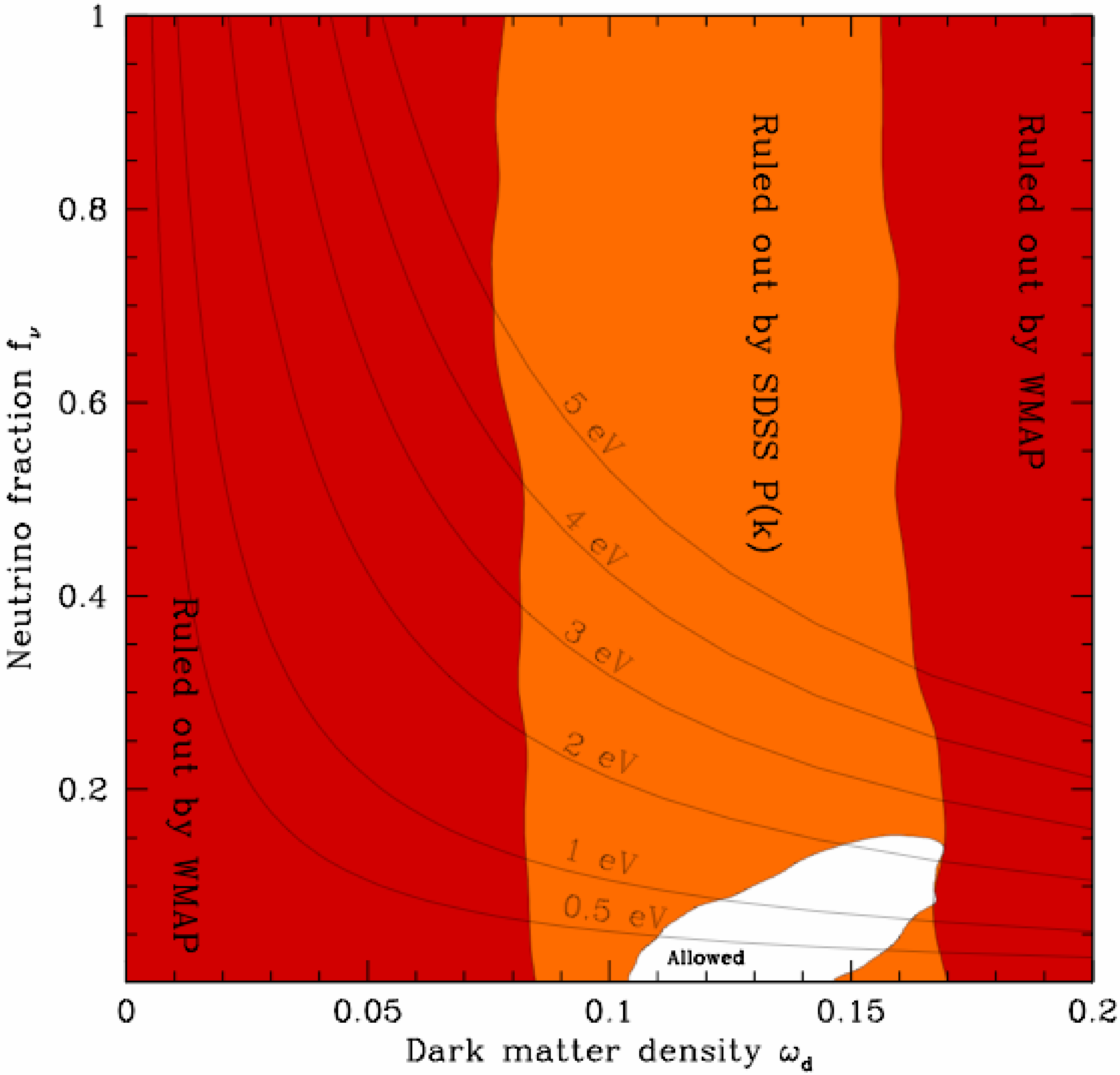




Neutrino fraction f_ν
Dark matter density ω_d
0
0.05
0.1
0.15
0.2
0.2
0.4
0.6
0.8
1
5 eV
4 eV
3 eV
2 eV
1 eV
0.5 eV
Allowed



Neutrino fraction f_ν
Dark matter density ω_d
Ruled out by WMAP
Ruled out by WMAP
Allowed
5 eV
4 eV
3 eV
2 eV
1 eV
0.5 eV
1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2



Ruled out by WMAP
Ruled out by SDSS P(k)
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
0.5 eV
Allowed
Neutrino fraction f_ν
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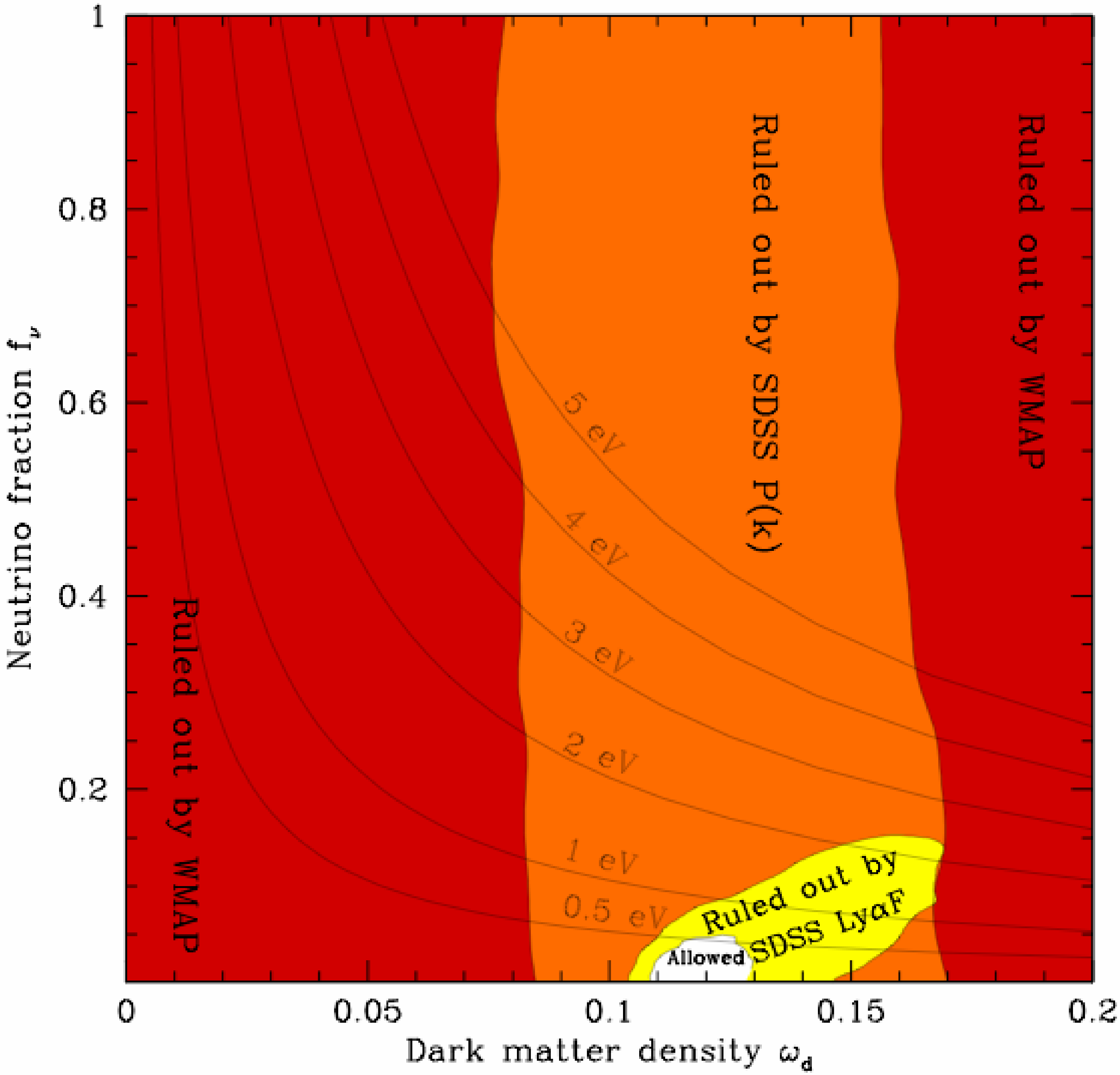
1



Neutrino fraction f_ν
Dark matter density ω_d
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0.1
0.15
0.2
0.2
0.4
0.6
0.8
1
Ruled out by WMAP
Ruled out by SDSS P(k)
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
0.5 eV
Ruled out by SDSS LyαF
Allowed

Cosmological limits on neutrino mass

- WMAP+SDSS 6p:

$$\sum m_\nu < 0.42eV\,(95\%) \quad < 0.66eV\,(99.9\%)$$

- +running and tensors

$$\sum m_\nu < 0.66eV\,(95\%) \quad < 0.93eV\,(99.9\%)$$

- Together with SK and solar limits:

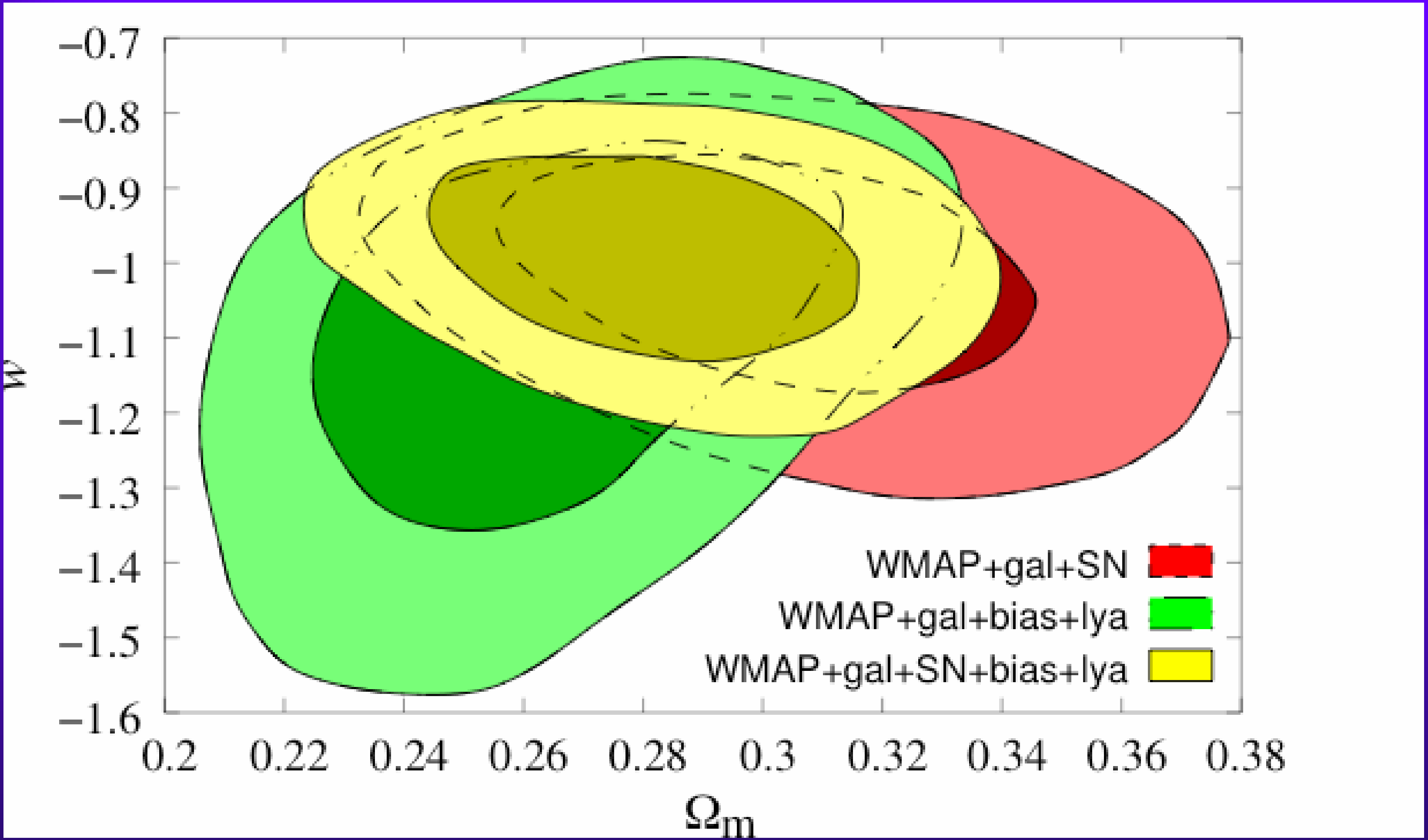
$$\Delta m_{12}^2 = 8 \times 10^{-5} eV^2,\ \Delta m_{23}^2 = 2.5 \times 10^{-3} eV^2$$

$$m_1 < 0.13eV,\ m_2 < 0.13eV,\ m_3 < 0.15eV \quad \frac{m_3}{m_1} > 1.1$$

- Sterile neutrino case almost excludes LSND result (m>1eV, will be verified by Miniboone)

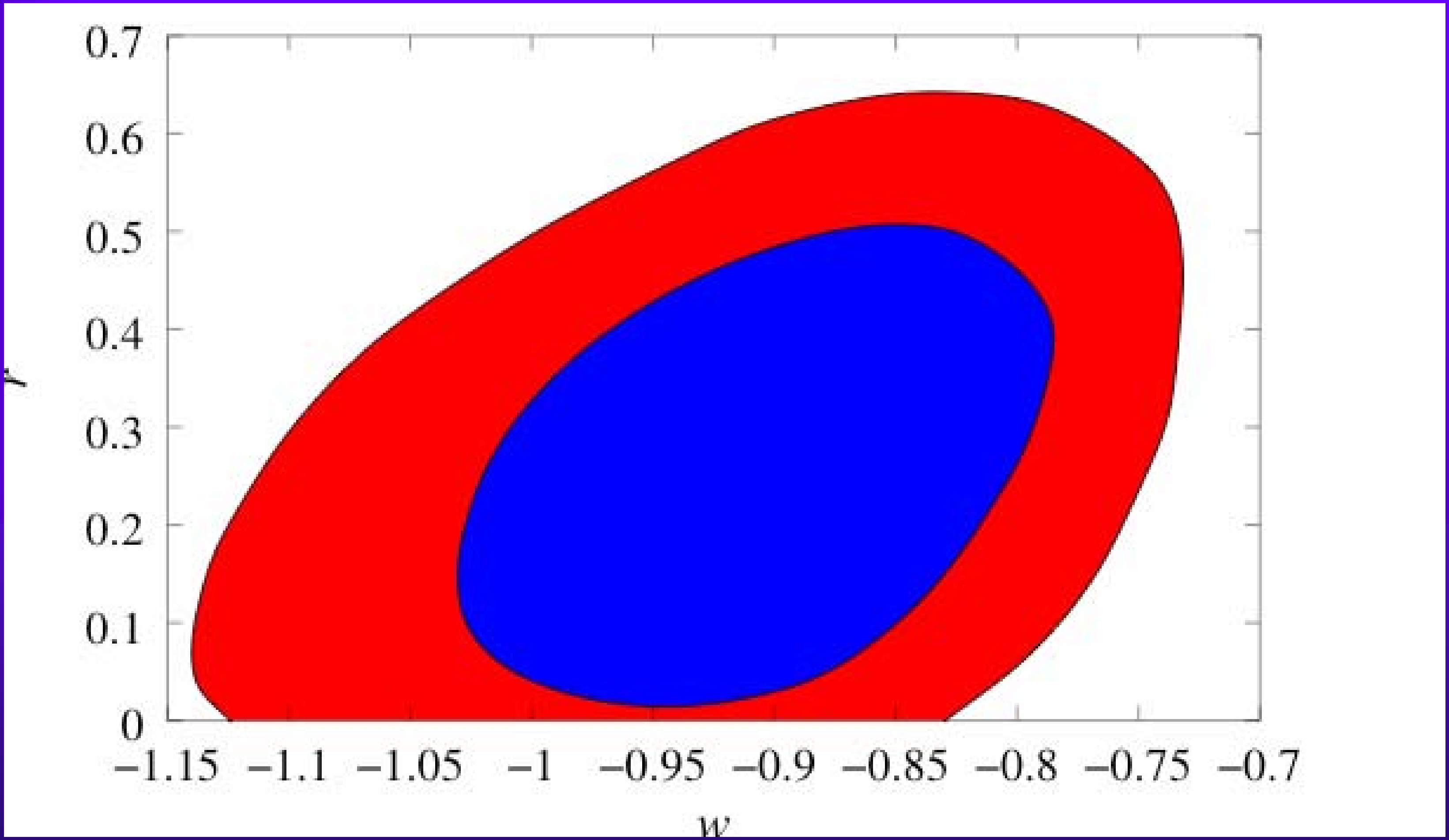
$$m_\nu < 0.84eV\,(95\%) \quad < 1.61eV\,(99.9\%)$$

Dark energy constraints



$$w = -0.99 \pm 0.09$$

w is correlated with r

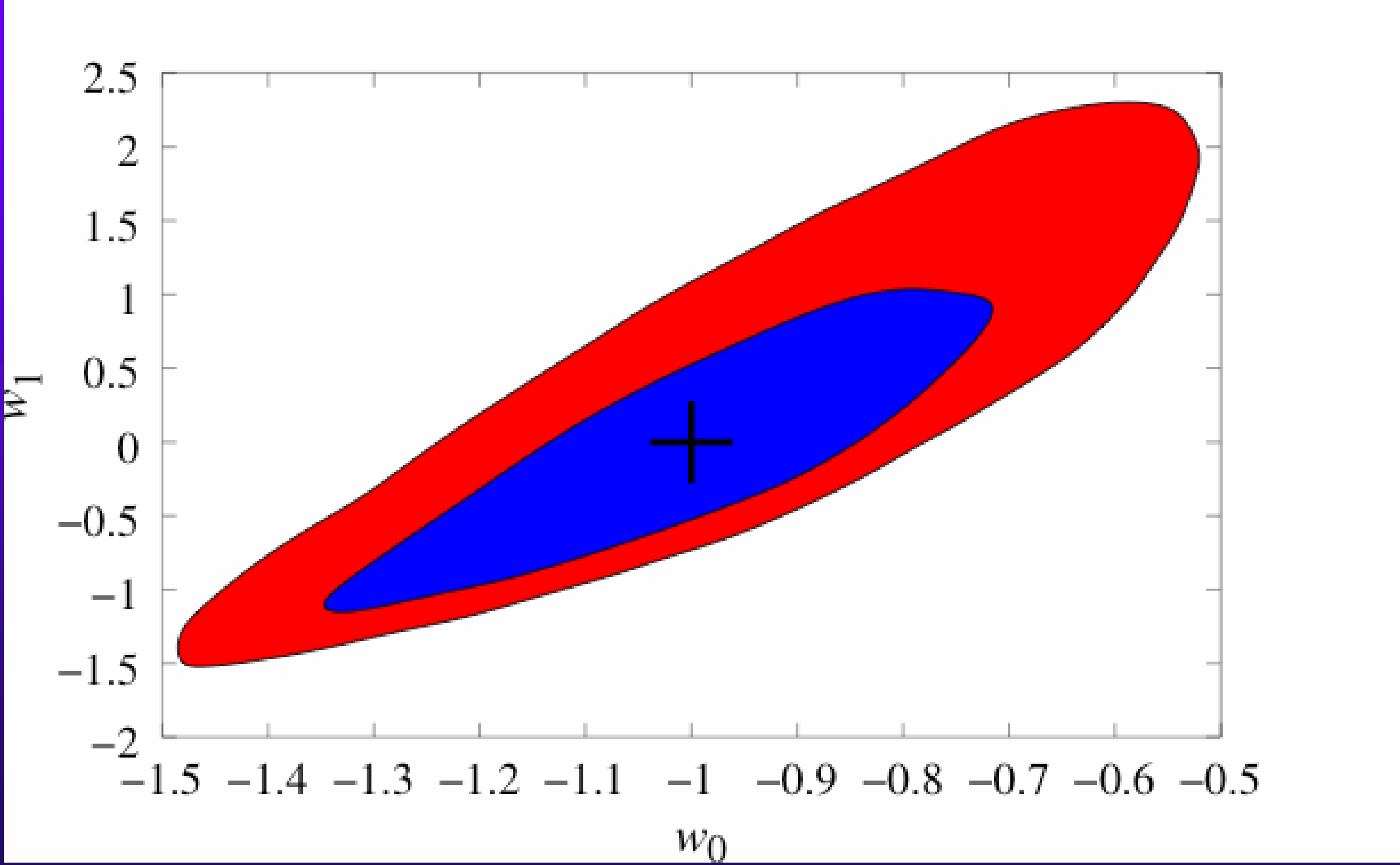


$$w = -0.91 \pm 0.09$$

Time evolution of equation of state w

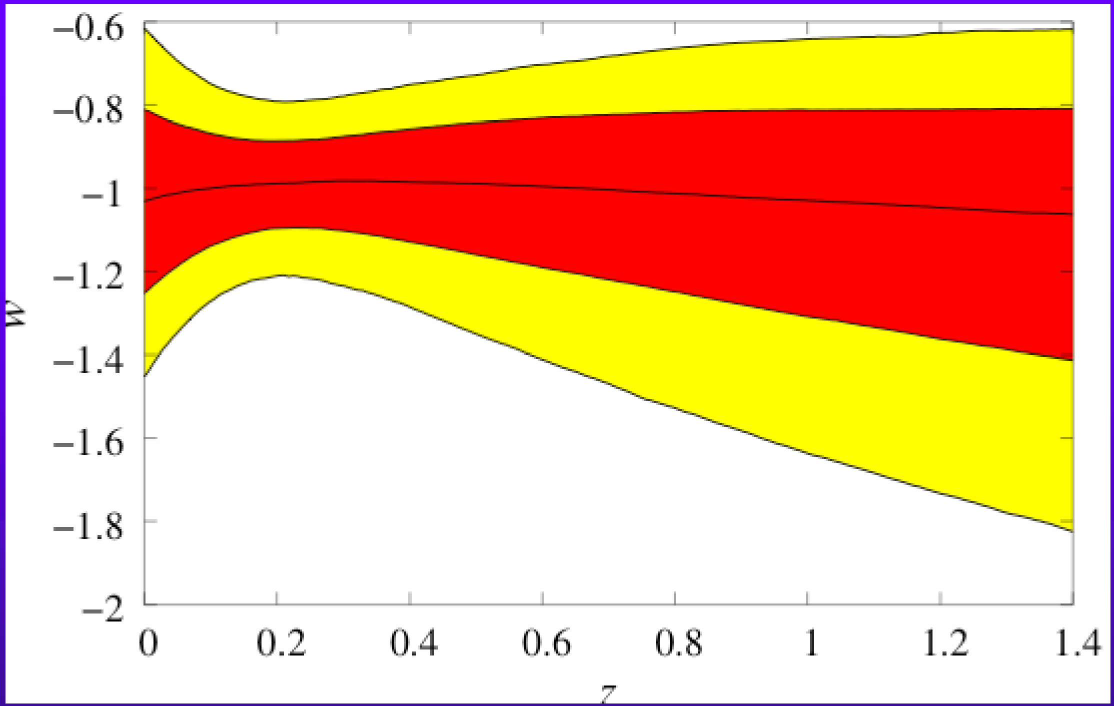
$$w = w_0 + (a-1)w_1 + (a-1)^2 w_2$$

Individual parameters very degenerate



Time evolution of equation of state

- w remarkably close to -1
- Best constraints at z=0.3, robust against adding more terms
- Lya helps because there is no evidence for dark energy at z>2
- Significant improvements over previous constraints



$$w(z=0.3) = -0.98^{+0.10}_{-0.12}$$

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

Time evolution of equation of state

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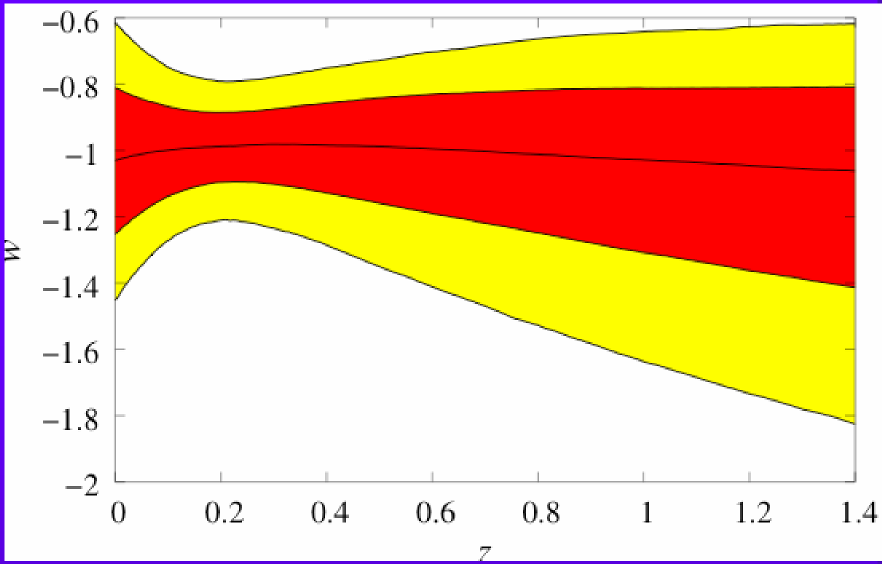
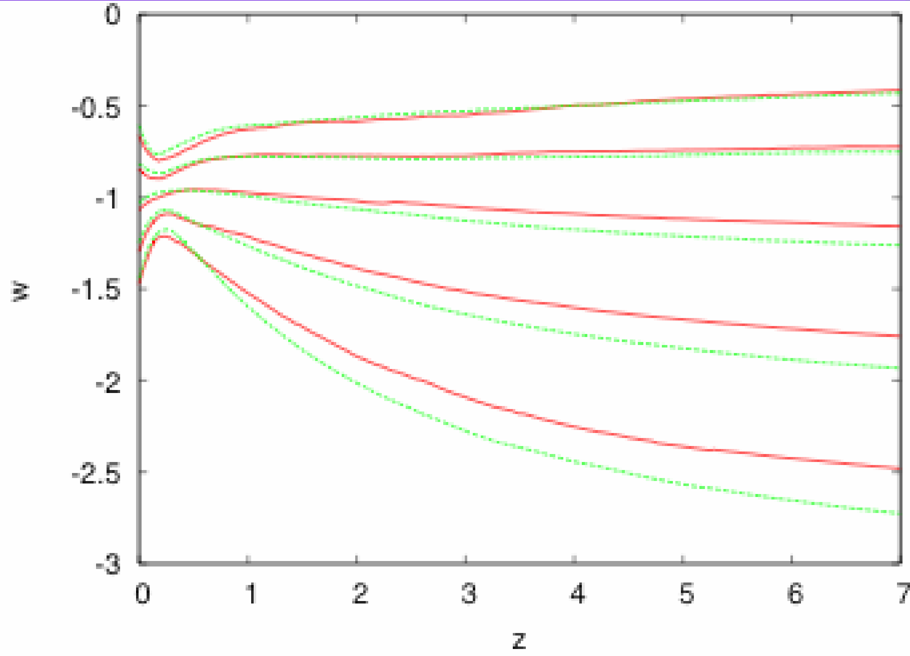


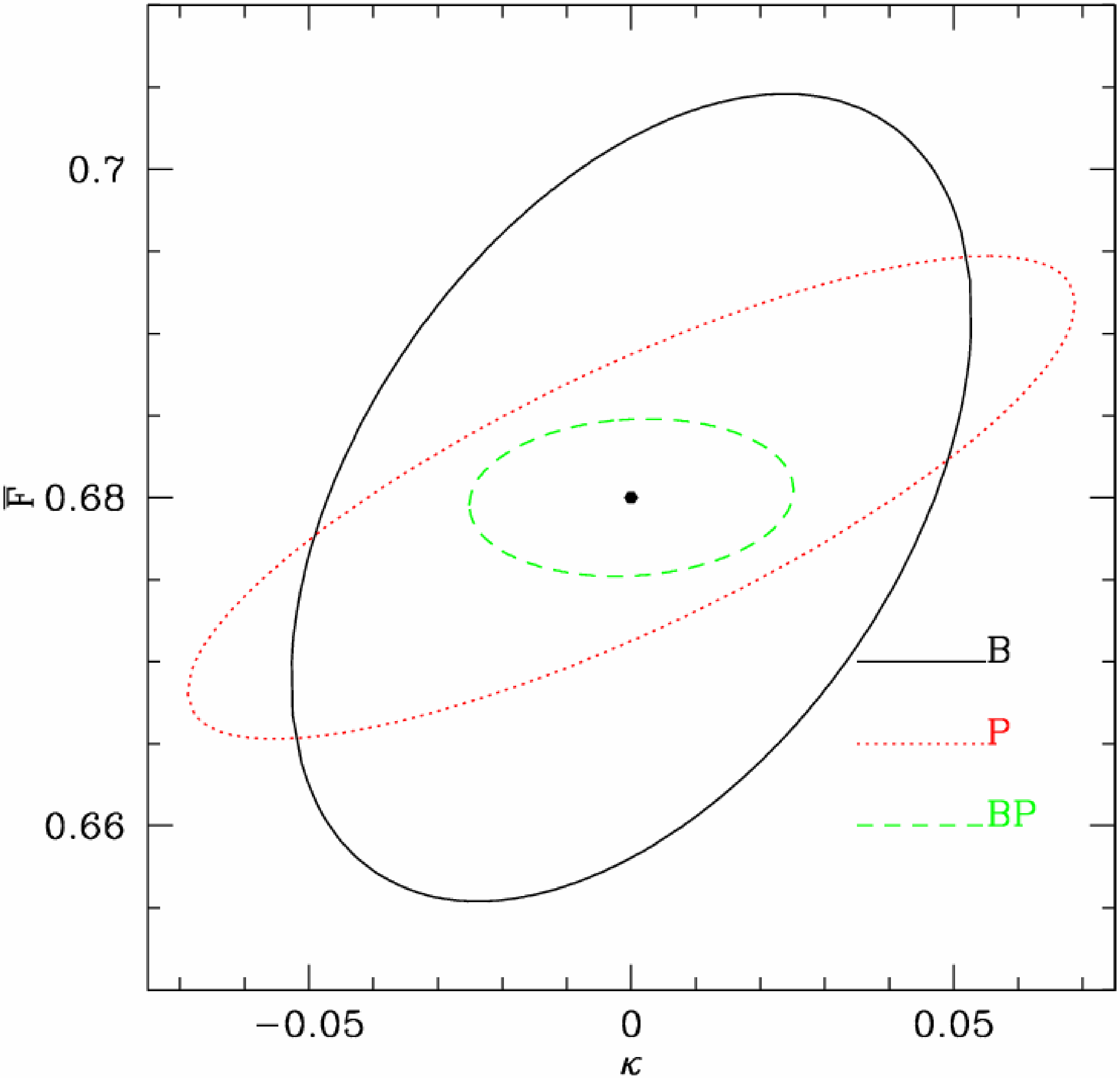


$$w(z=0.3) = -0.98^{+0.10}_{-0.12}$$

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

What is dark energy?

- Some of tracker models that predict w=-0.5 at z=1 are ruled out (SUGRA etc)
- Backreaction: Einstein equations are nonlinear, averaging does not lead to homogeneous FRW
- everyone agrees that superhorizon modes cannot mimick dark energy, since equivalence principle assures space is locally flat
- Subhorizon modes: perturbative calculation breaks down in synchronous gauge (Kolb etal 2005), but is well controlled in Newtonian gauge, negligible effect (Hui and Seljak 1995)
- There are small scale effects of lensing and peculiar velocities that give small 2nd order bias
- Best fit remains cosmological constant



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 $dn/d\ln k<0$ 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"

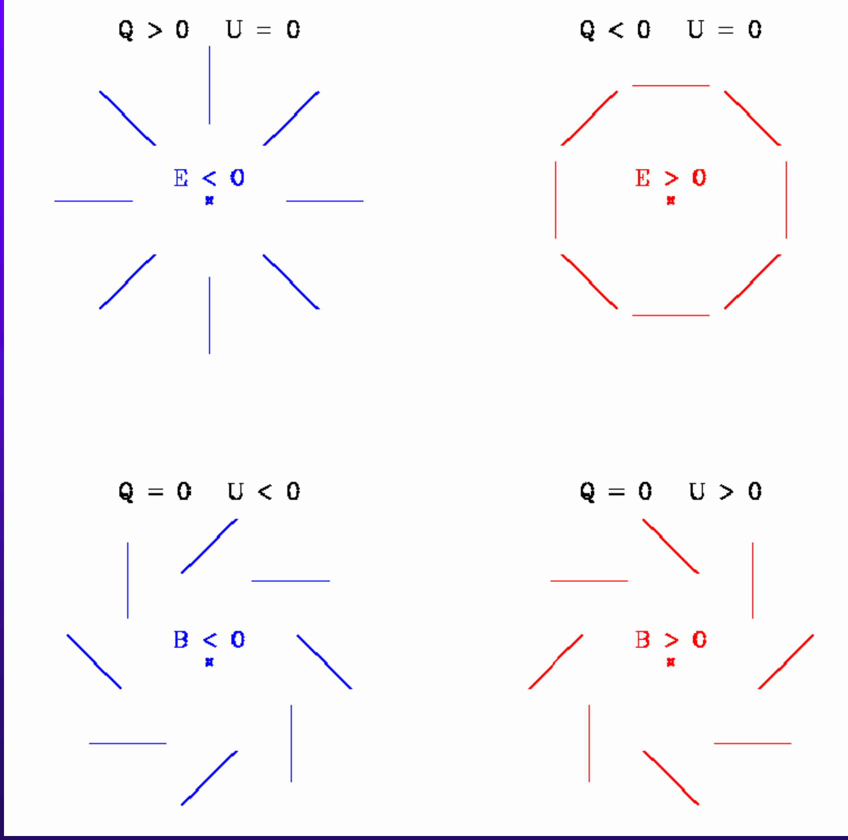
Future prospects

- Ly-alpha analysis: a lot of room for improvement in reducing systematics, more work exploring additional physical processes needed, additional analyses such as bispectrum
- Galaxy clustering: better statistics (larger volume in LRG sample), better understanding of nonlinear bias, better bias determination (weak lensing, bispectrum…)
- Weak lensing: huge datasets on the way (from CFHT legacy to Pan-Starrs, SNAP, LSST…)
- CMB: small scales, SZ… (ACT, SPT, Planck, CMBPOL)
- New frontiers: 21cm emission(?)

Future prospects: can we detect gravity waves?

US 1997, US & Zaldarriaga 1997
Kamionkowski etal 1997

Linear polarization is TT tensor with 2dof: scalar (E) and pseudoscalar (B)
Only gravity waves contribute to B
A dedicated polarization experiment can measure T/S>10^-4
Many inflationary models predict T/S in measurable range
Most “expected” surprise



Future prospects and conclusions

- Dark energy: evidence from several independent probes (SN, CMB/LSS), best fit with cosmological constant (w=-1)
- No evidence for neutrino mass yet (m<0.15-0.3eV)
- Universe is flat (to 1-2%)
- theories for origin of structure: data support models like inflation
- Data (Ly-alpha, galaxy clustering, weak lensing, SN1A, CMB…) will keep improving (big experiments on the way: Planck, Pan-Starrs, SNAP, LSST, ACT/SPT, CMBPOL…)
- New frontiers: 21cm emission(?)
- Best hope for a new result to be detected soon: deviation from scale invariance (n<>1)
- Possible, but less likely to happen soon: neutrino mass detection, w<>-1, running of spectral index, primordial nongaussianity
- Best hope for a major surprise: gravity wave detection with polarization of CMB

Conclusions

Fundamental physics can be tested with cosmological observations:

Dark energy: clear evidence for it from different sets of observations, best fit with cosmological constant, no evidence for equation of state changing with redshift, cannot be explained from inhomogeneities

Neutrino mass: no evidence for it, competitive with terrestrial experiments, approaching masses where it should be detected with LSS

Inflation or something else: inflation in good shape, hints of deviations from scale invariance as predicted, no evidence for running of spectral index (as predicted), no evidence for gravity waves (as predicted), but could be seen in future

Enormous progress on the data front over the past couple of years, more to come in the future

Thank you, Packard foundation!