# The Large-Scale Galaxy Power Spectrum from the Sloan Digital Sky Survey

*Michael A. Strauss, Princeton University,*

*for the SDSS Collaboration*

- A brief introduction to the SDSS
- Measuring the large-scale real-space power spectrum
- Combining with WMAP and other surveys
- What SDSS has to say about reionization
- What lies ahead

# The Sloan Digital Sky Survey

A consortium of the University of Chicago, Fermilab, the Institute for Advanced Study, the Johns Hopkins University, Los Alamos National Laboratory, the Japan Participation Group, the Max-Planck Institutes for Astronomy in Garching and Heidelberg, New Mexico State University, University of Pittsburgh, Princeton University, the US Naval Observatory, and the University of Washington.

The goals:

An imaging survey in five photometric bands using modern CCD technology over 10,000 square degrees.

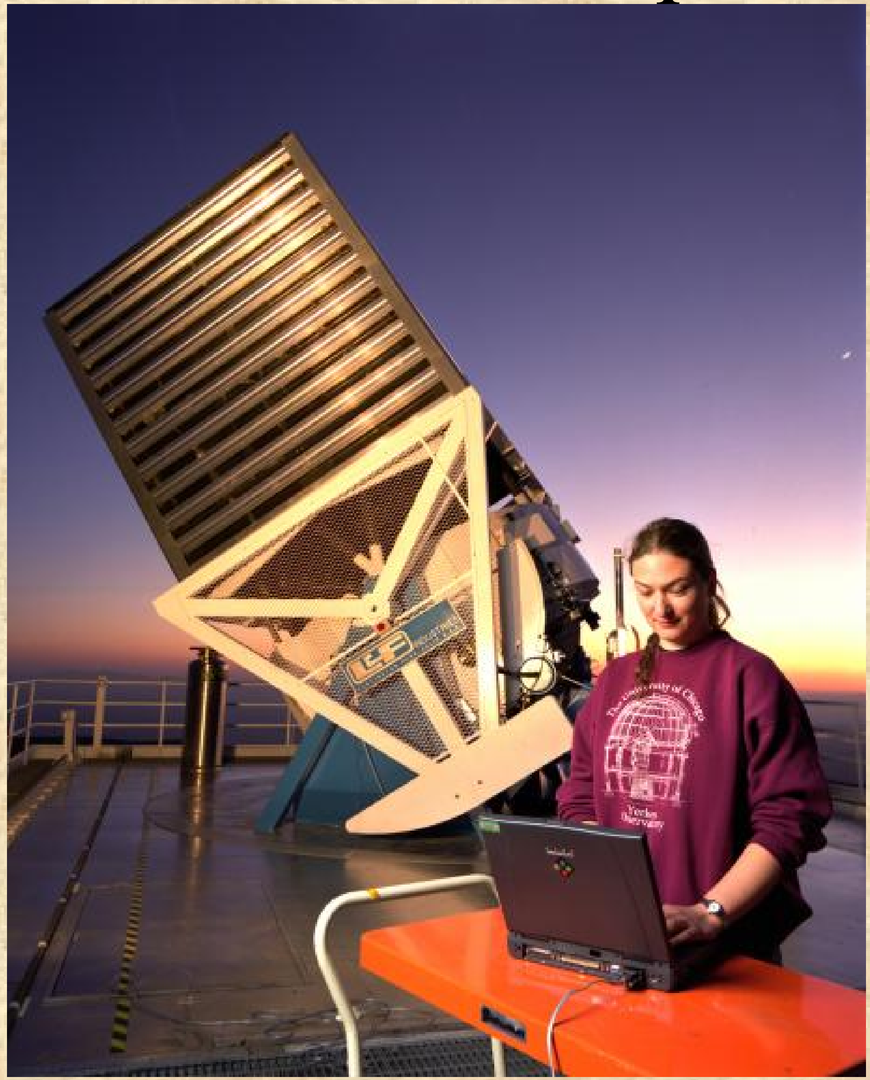
A spectroscopic redshift survey of a million galaxies and one hundred thousand quasars to study their distribution in space.

An emphasis on highest quality photometric and astrometric calibration.

# A dedicated 2.5m wide-field telescope

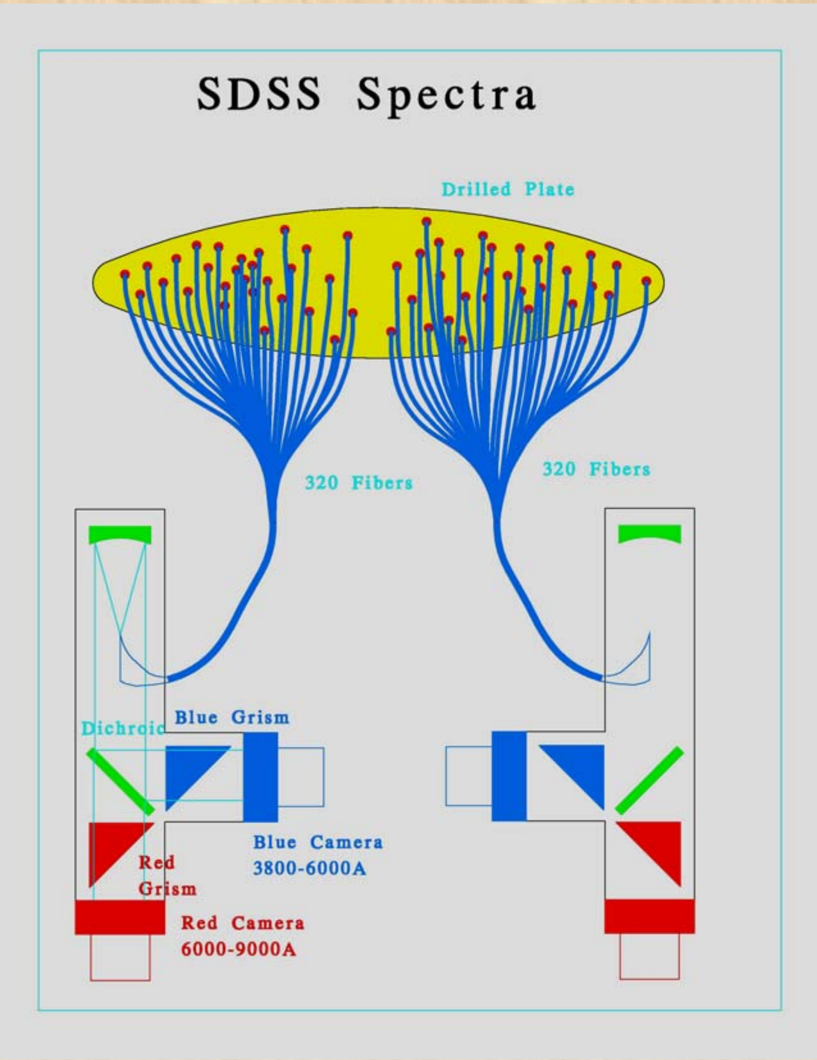
Telescope has a 3 degree field of view, focal ratio of five. Located at Apache Point Observatory in Southeast New Mexico.

A 145 Megapixel imaging camera images the sky in driftscan mode to r~22.5 at 20 $deg^2$/hr in five filters.

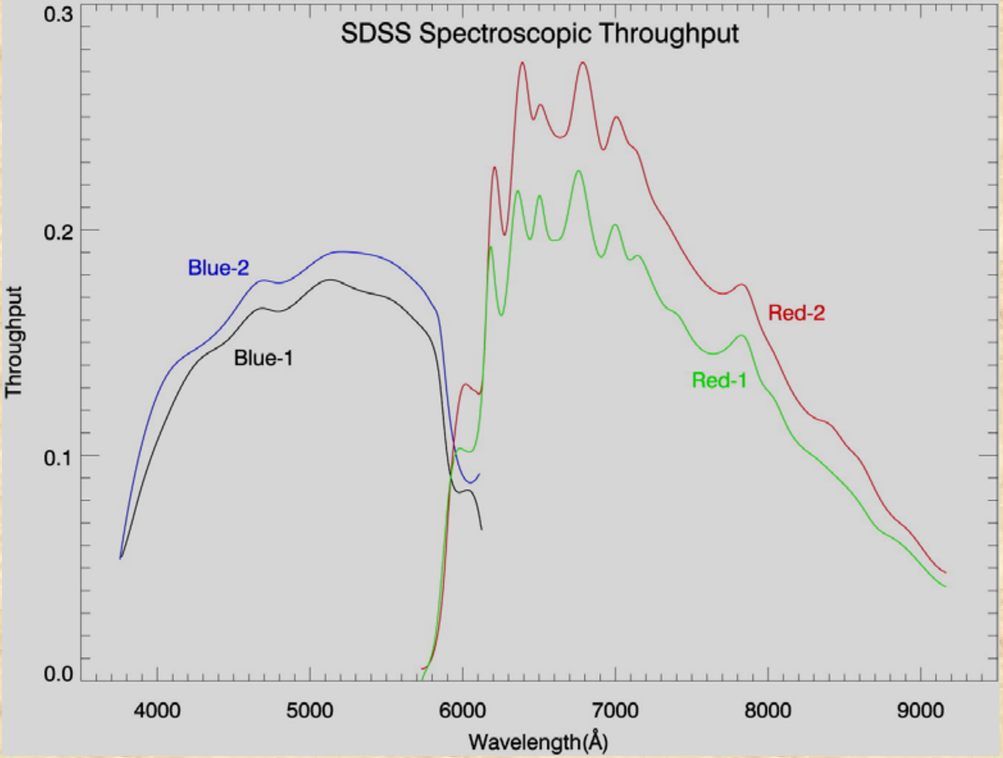


608 objects are observed simultaneously with fiber-fed spectrographs. Samples are selected from imaging data, and include galaxies (to r=17.77), luminous red ellipticals (to r=19.5, z~0.5) and quasars (0 < z < 5.5). Typical exposures of 45 minutes.

Fibers feed a pair of double spectrographs




SDSS spectrographs are **hot**!



# The Basic Parameters of the SDSS

- 2.5m telescope, 3 degree field of view.
- Photometric calibration in five bands is good to 2%; improvable to 1% (see
. Padmanabhan's talk).
- Typical seeing ~1.4".
- Spectra of ~100 galaxies, and 10 quasars, per square degree. Spectra through
. a 3" fiber.
- Spectra have resolution $\lambda/\Delta\lambda = 2000$, 3800-9200Å.
- Galaxy redshifts are good to ~20 km/s (for stars, accuracy is 5-10 km/s).
- Spectra are calibrated to ~5% photometrically.

- We have imaged of order 6500 square degrees, and have taken spectra of
. ~ 600,000 objects.
- (About 500 refereed papers to date mention SDSS in their abstract).

It takes a lot of people to carry out this survey!

## The First Data Release of the Sloan Digital Sky Survey

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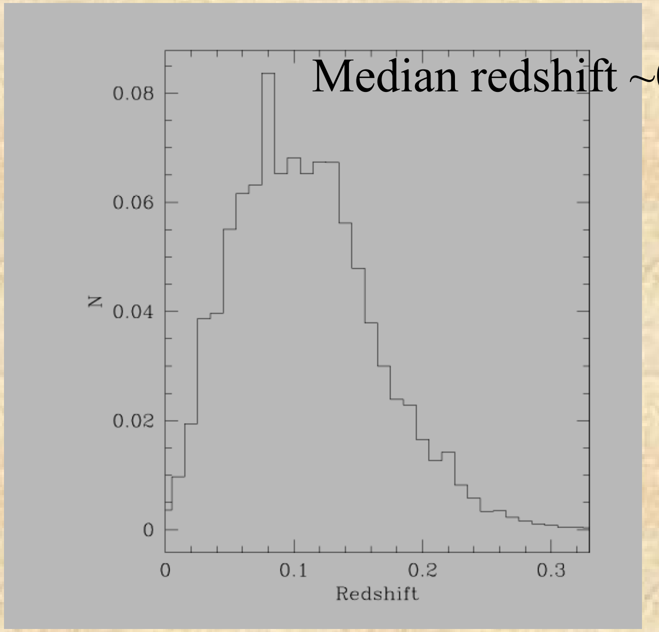
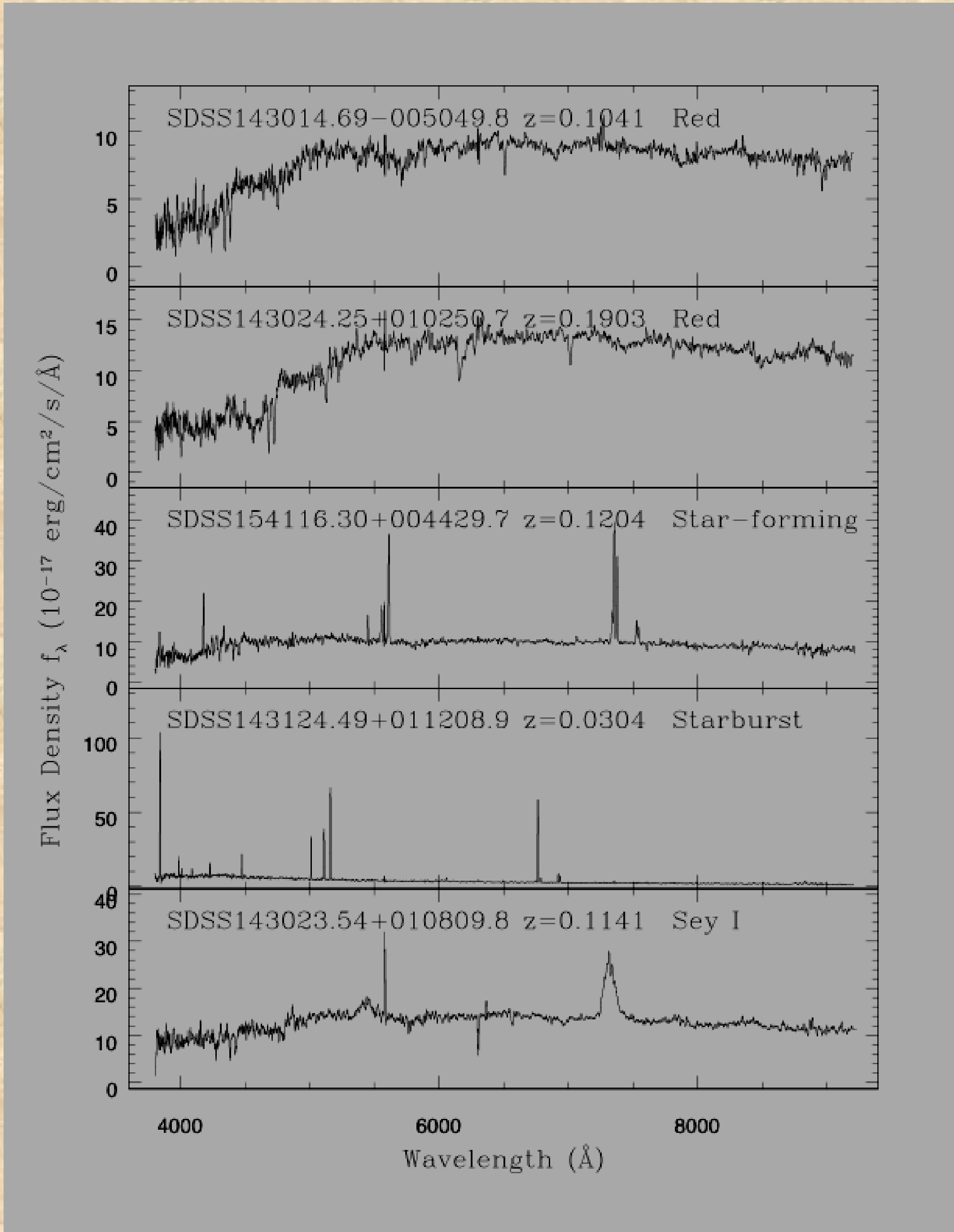
SDSS galaxy sample is magnitude-limited to r=17.77 (Petrosian, corrected for Galactic reddening).

The SDSS spectra are of very high S/N; we get a successful redshift for essentially every galaxy.




Median redshift ~0.1

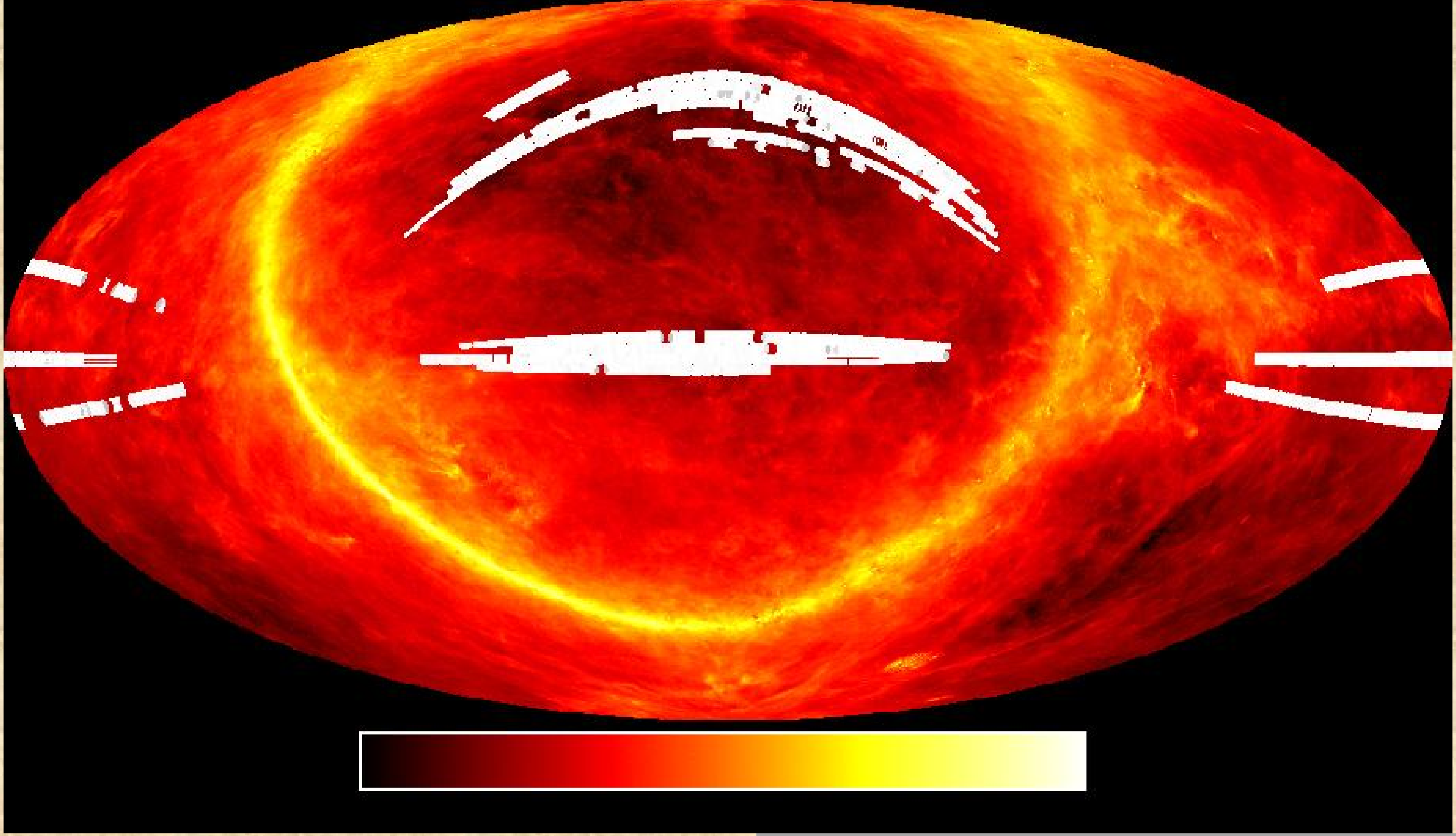


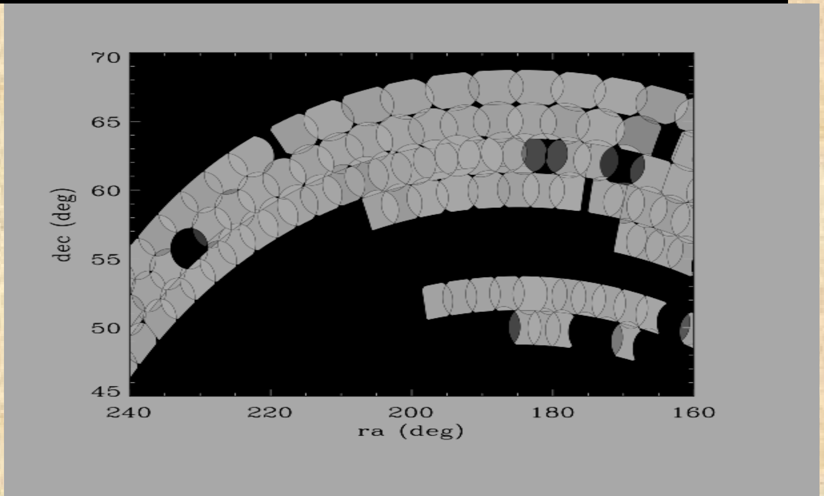
# Measuring the SDSS Galaxy Power Spectrum

## Tegmark et al. 2004, ApJ, 606, 703

Challenges:

- Complicated survey geometry
- Redshift space distortions
- Non-linear effects
- Bias relative to the dark matter
- Possible systematics in the sample selection

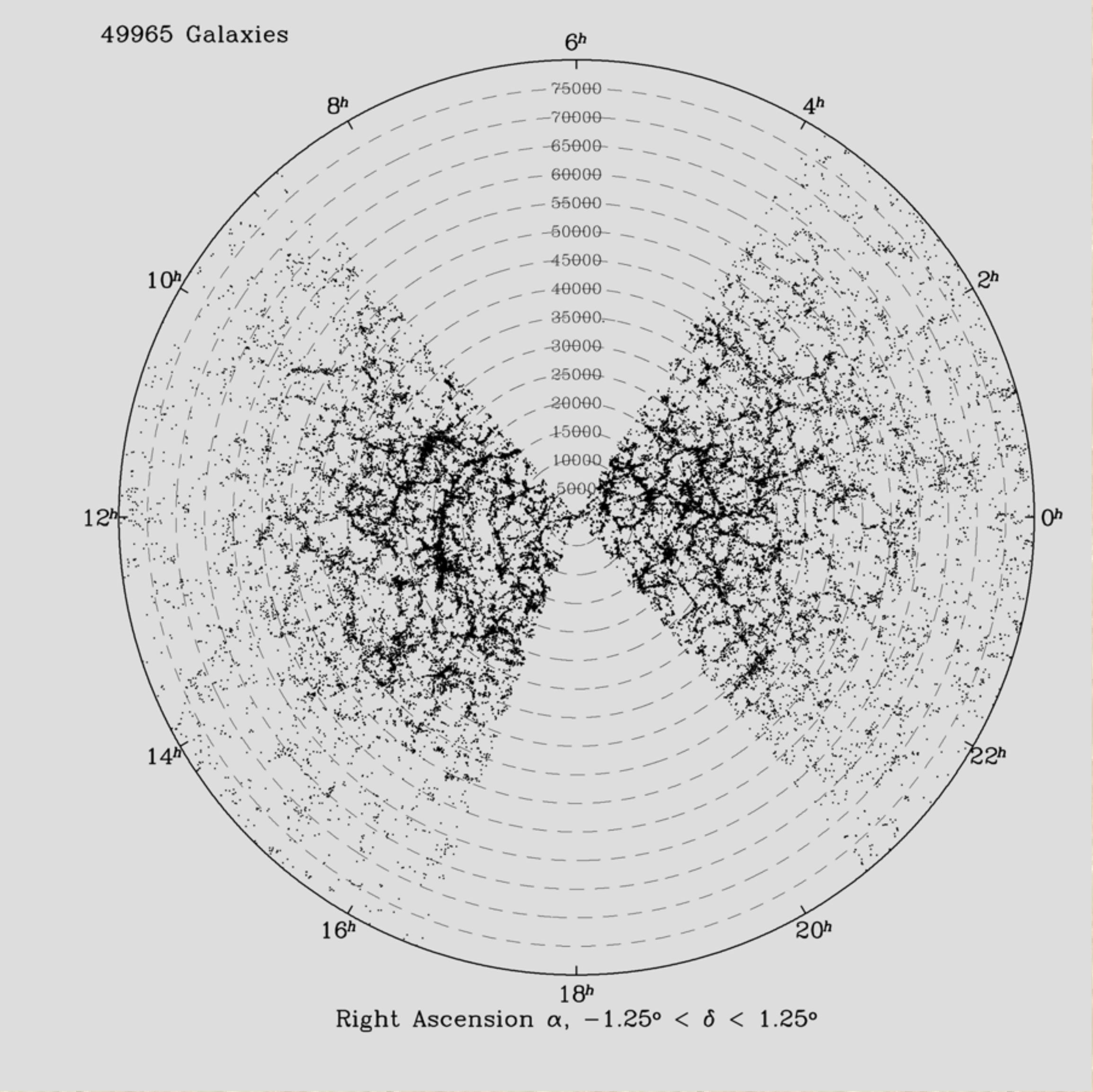




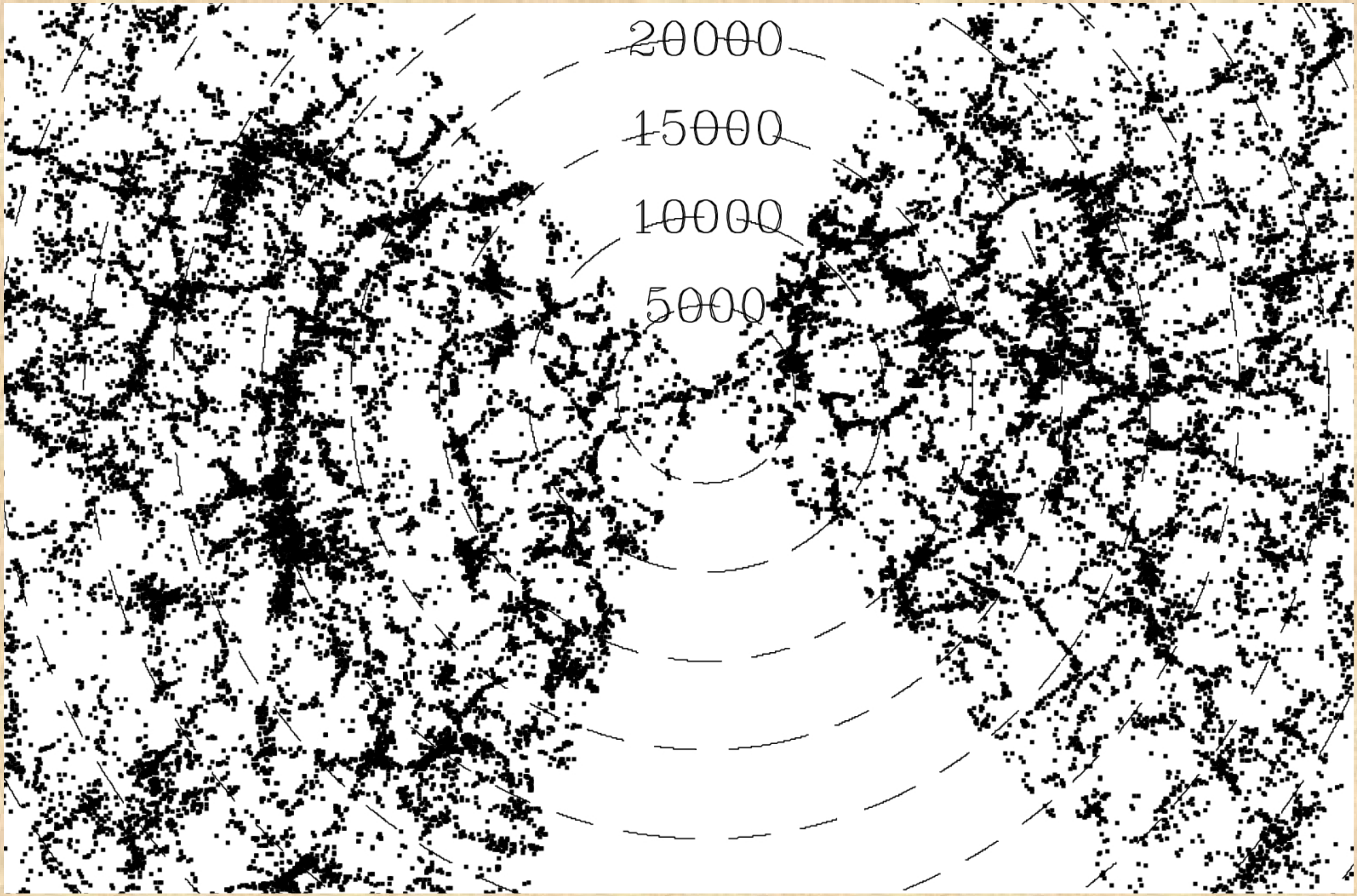

The sky coverage of the analyzed SDSS sample, superposed on the Galactic reddening map. Greyscale indicates the completeness of the sample.

Effective sky coverage: 2417 square degrees. Roughly 200,000 galaxies.

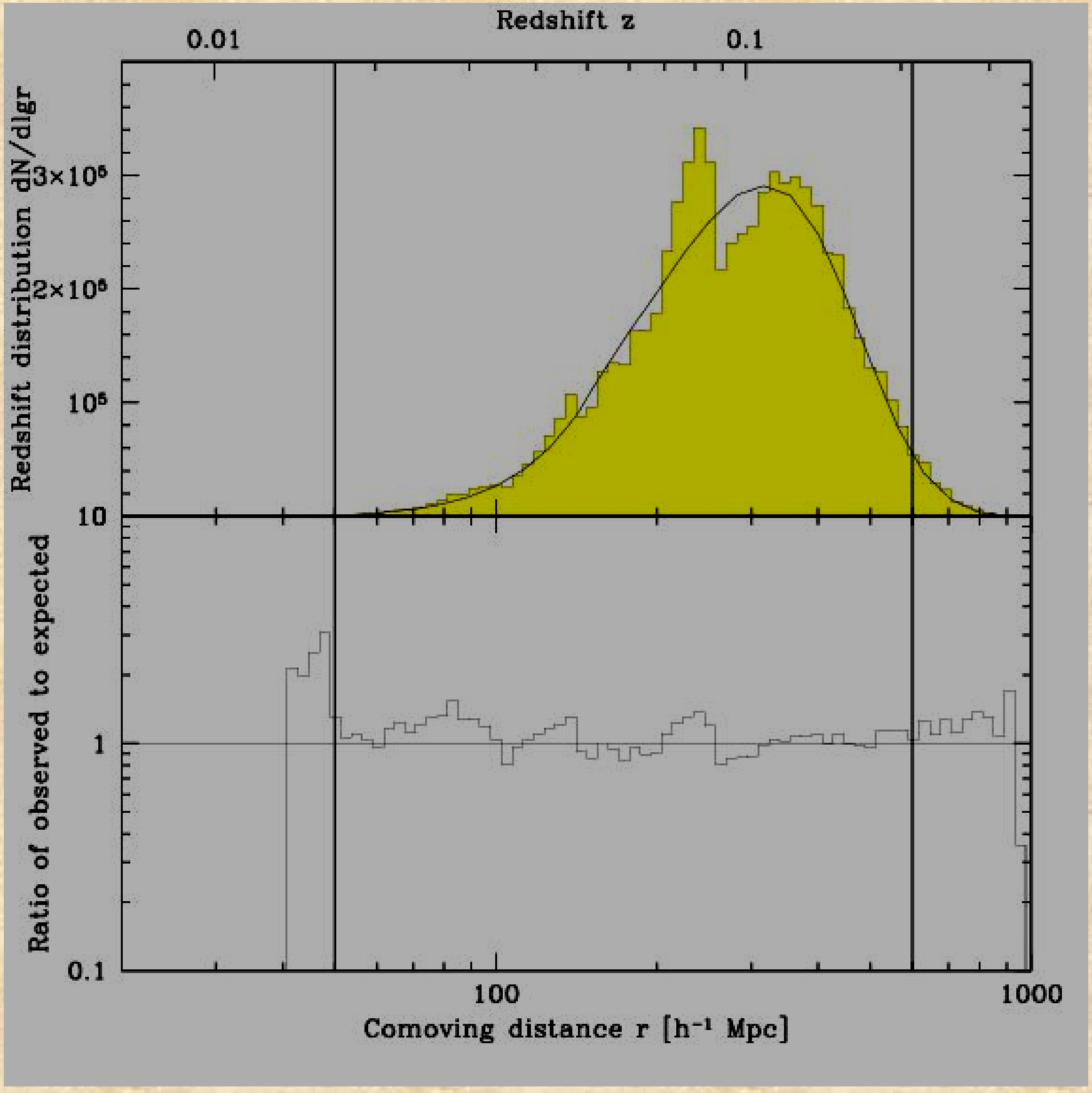
5% of the SDSS galaxy redshift survey.  Median redshift of 0.1 (30,000 km/s = 400 Mpc)



# The Richness of the Cosmic Web

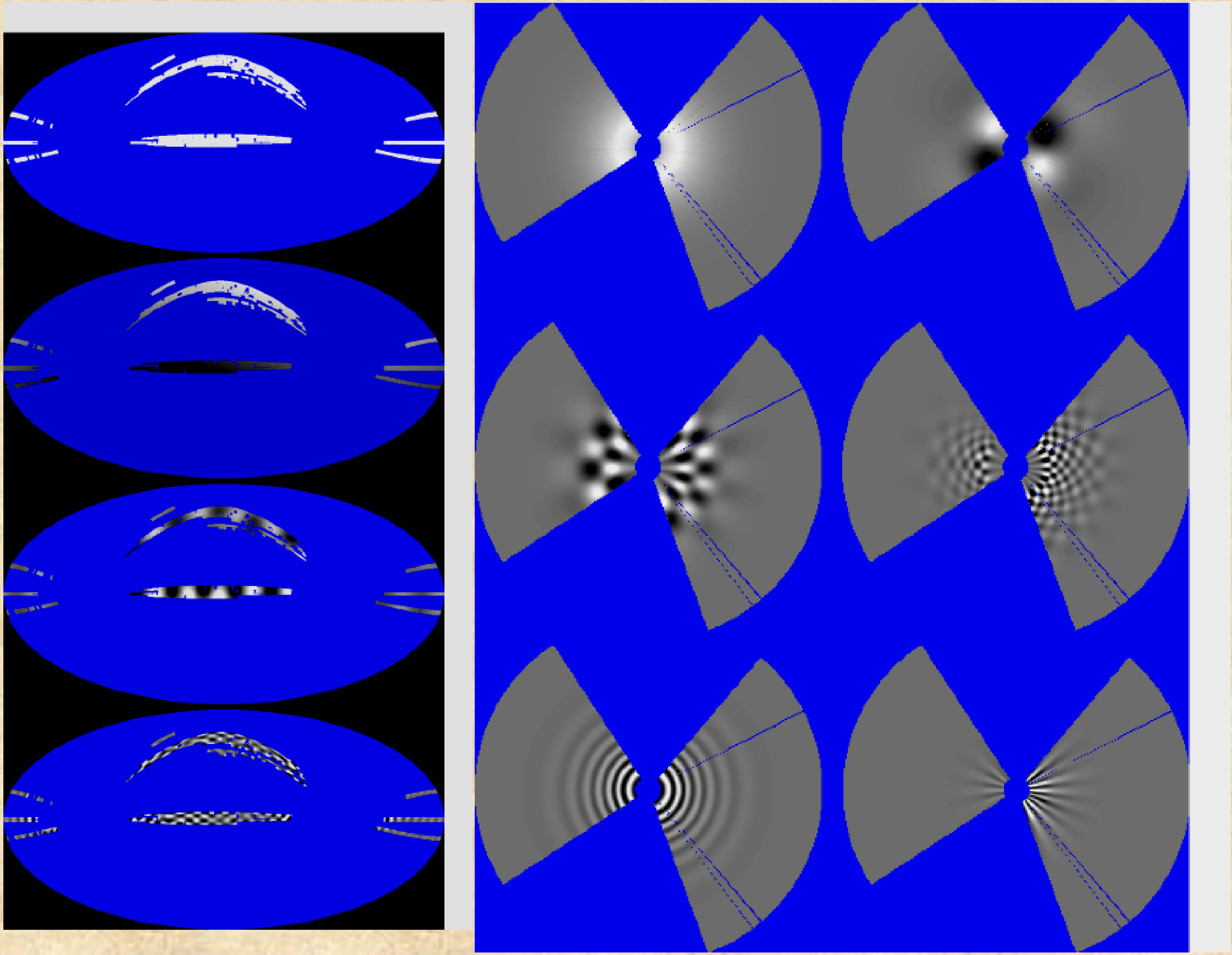


# The observed and expected redshift distribution of galaxies

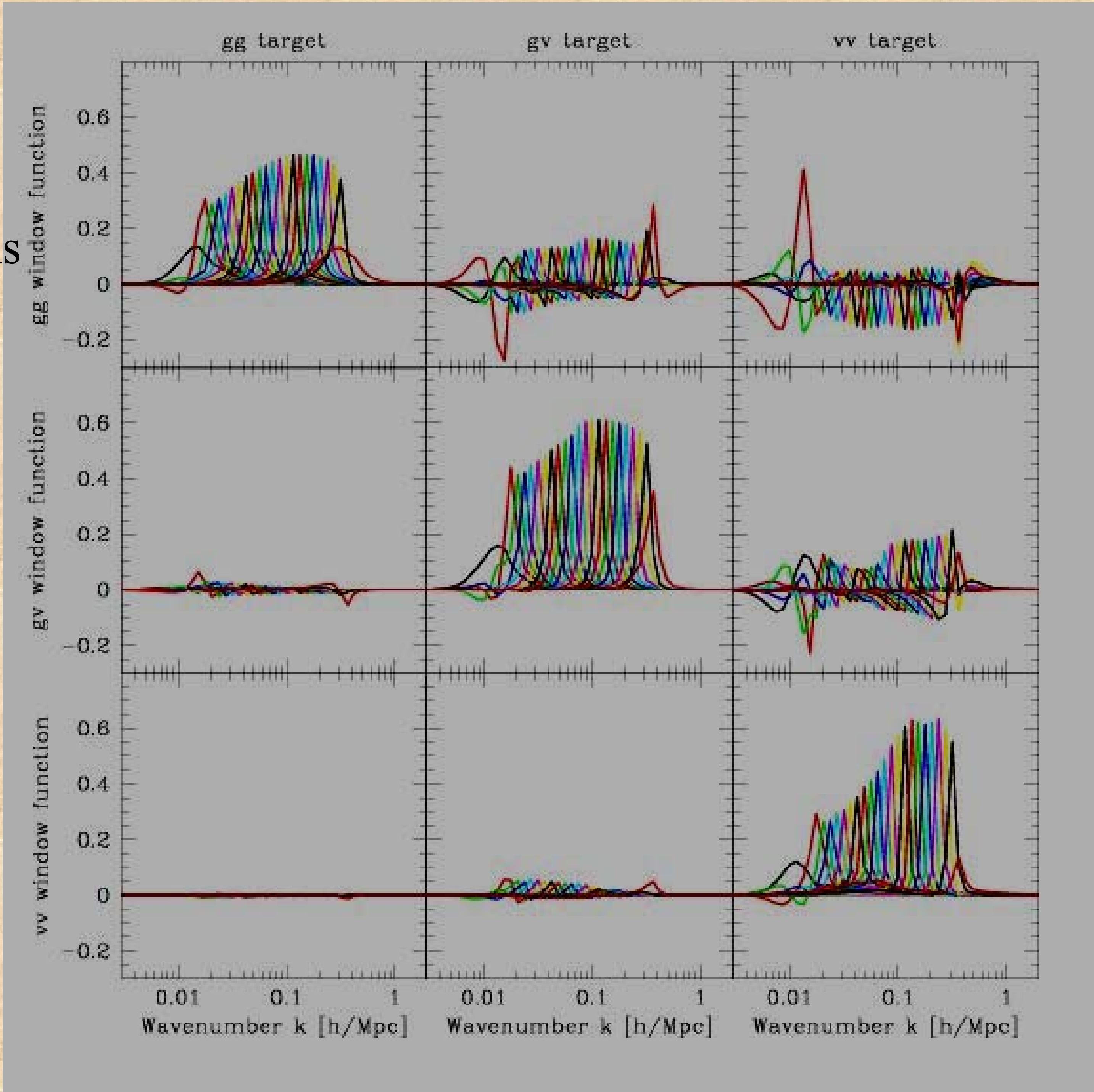


## Challenge: Dealing with the awkward survey geometry

Solution: Expand in Karhunen-Loève eigenmodes (orthogonal modes which respect the survey geometry).



(After lots of clever manipulations), window functions are narrow, and show very little cross-talk.



(Red lines are fiducial curves)

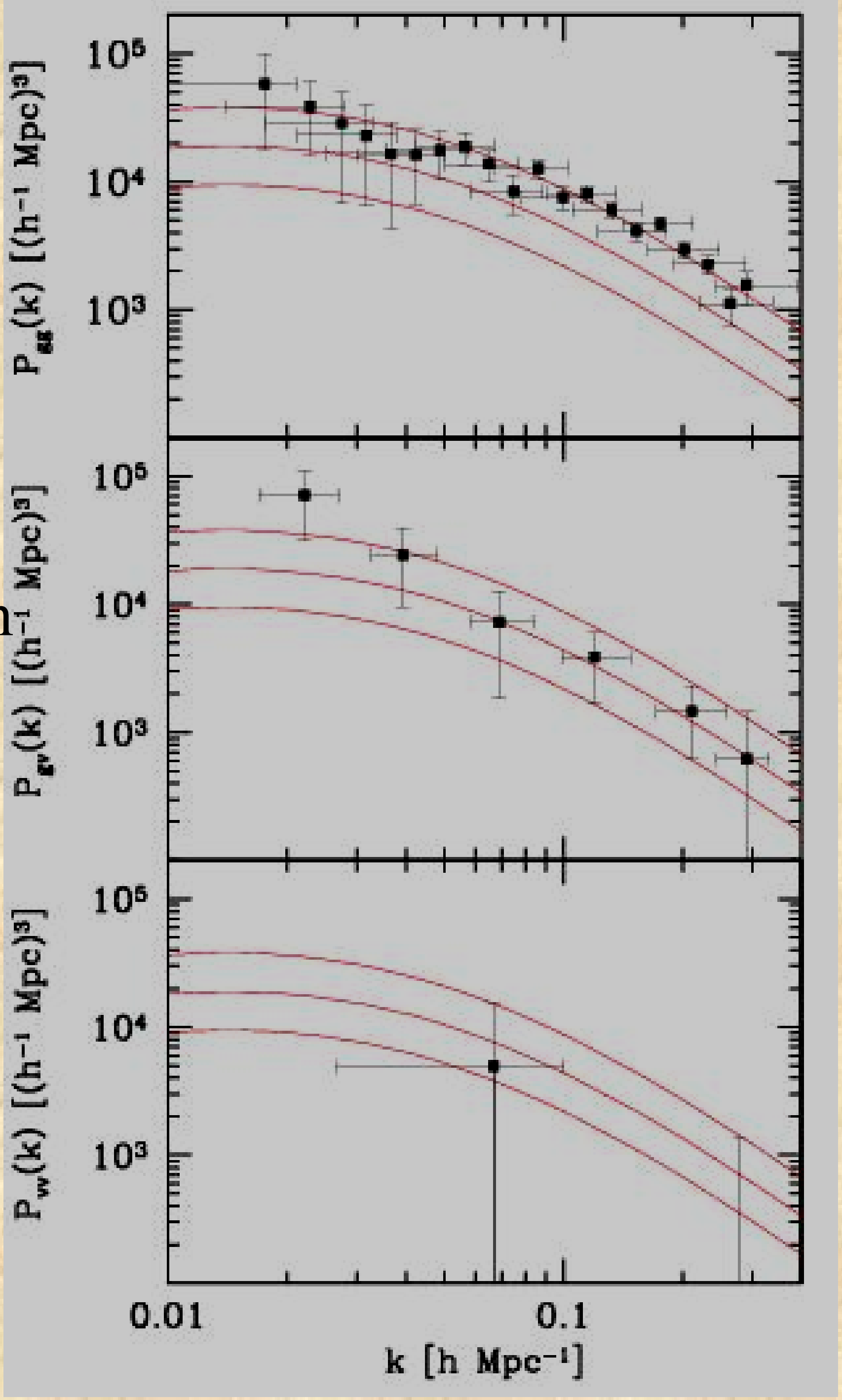
Real space

(most of the information is here)

Formalism takes redshift distortions into account explicitly.

Real-velocity cross-term

Pure velocity space

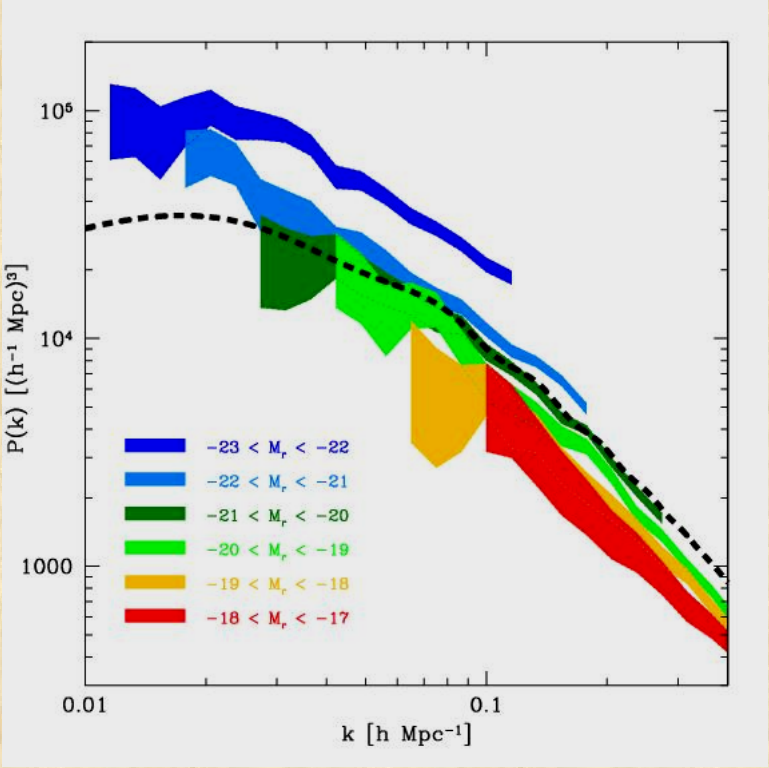


# Challenge: Galaxies are biased relative to dark matter

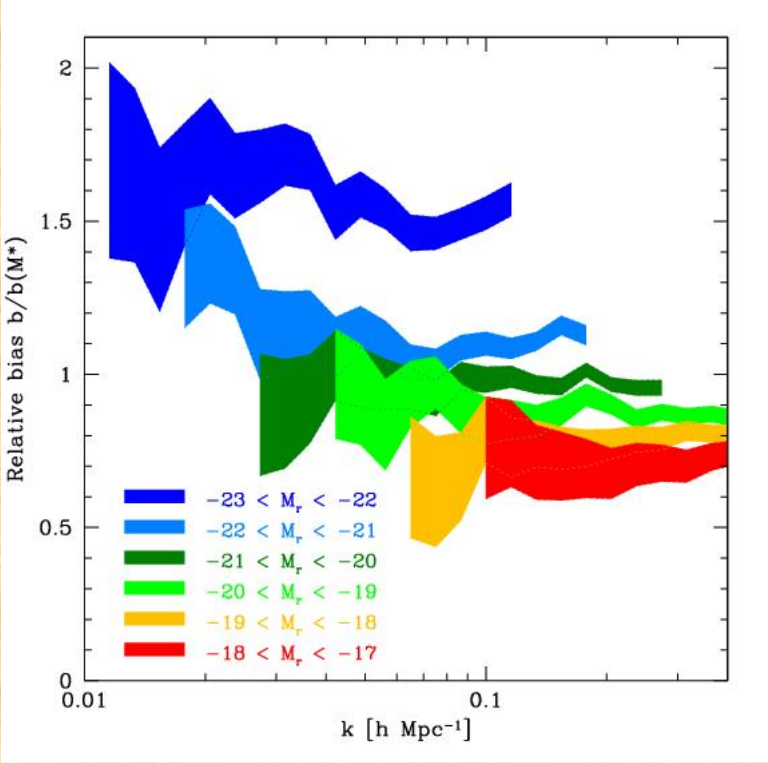
We can't observe the dark matter directly.  The problem is even worse than that: galaxies of different luminosities are known to have different clustering strengths.  More luminous galaxies dominate the sample at high redshift, therefore dominate P(k) on largest scales.

Our approach: let's measure this effect directly from the data: determine the power spectrum separately from subsamples of different luminosity.

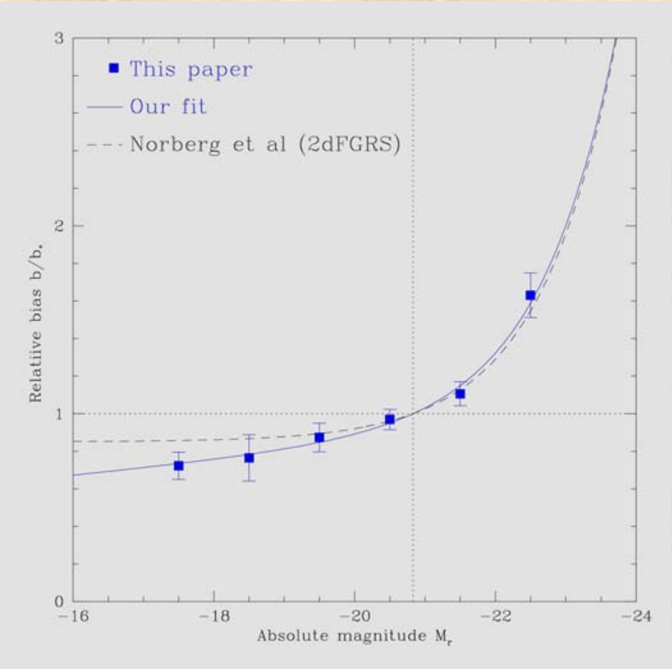
Higher-luminosity galaxies show stronger clustering!



Within the errors, the relative bias is independent of scale.



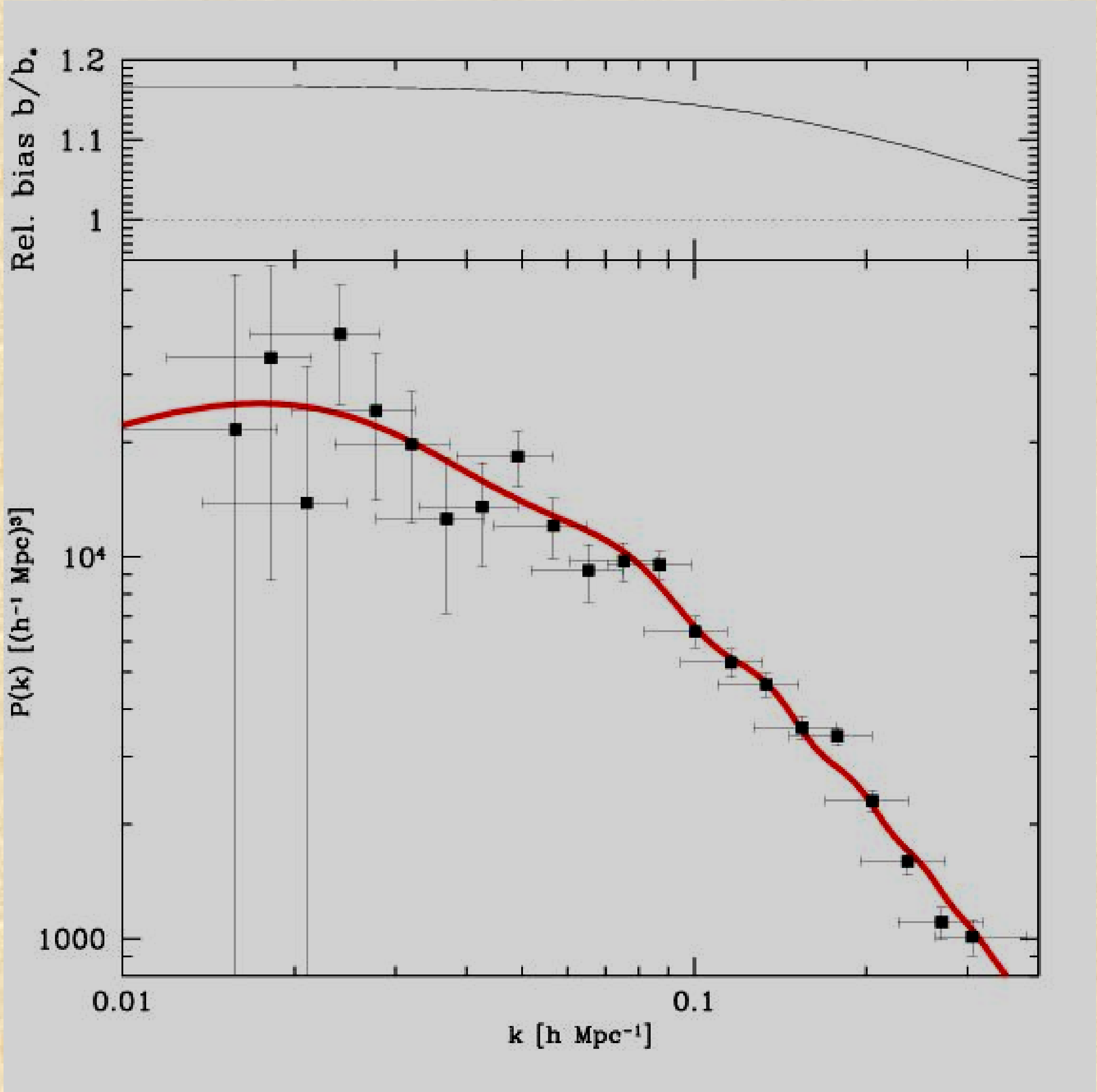

The effective relative bias as a function of luminosity. We can use this to correct our determination of the power spectrum.



# So, what's the answer?

Red line: A LCDM model with $\Omega$=0.30±0.02 (assuming h=0.72, n=1, $\Omega_b/\Omega_m$ = 0.17 from WMAP)

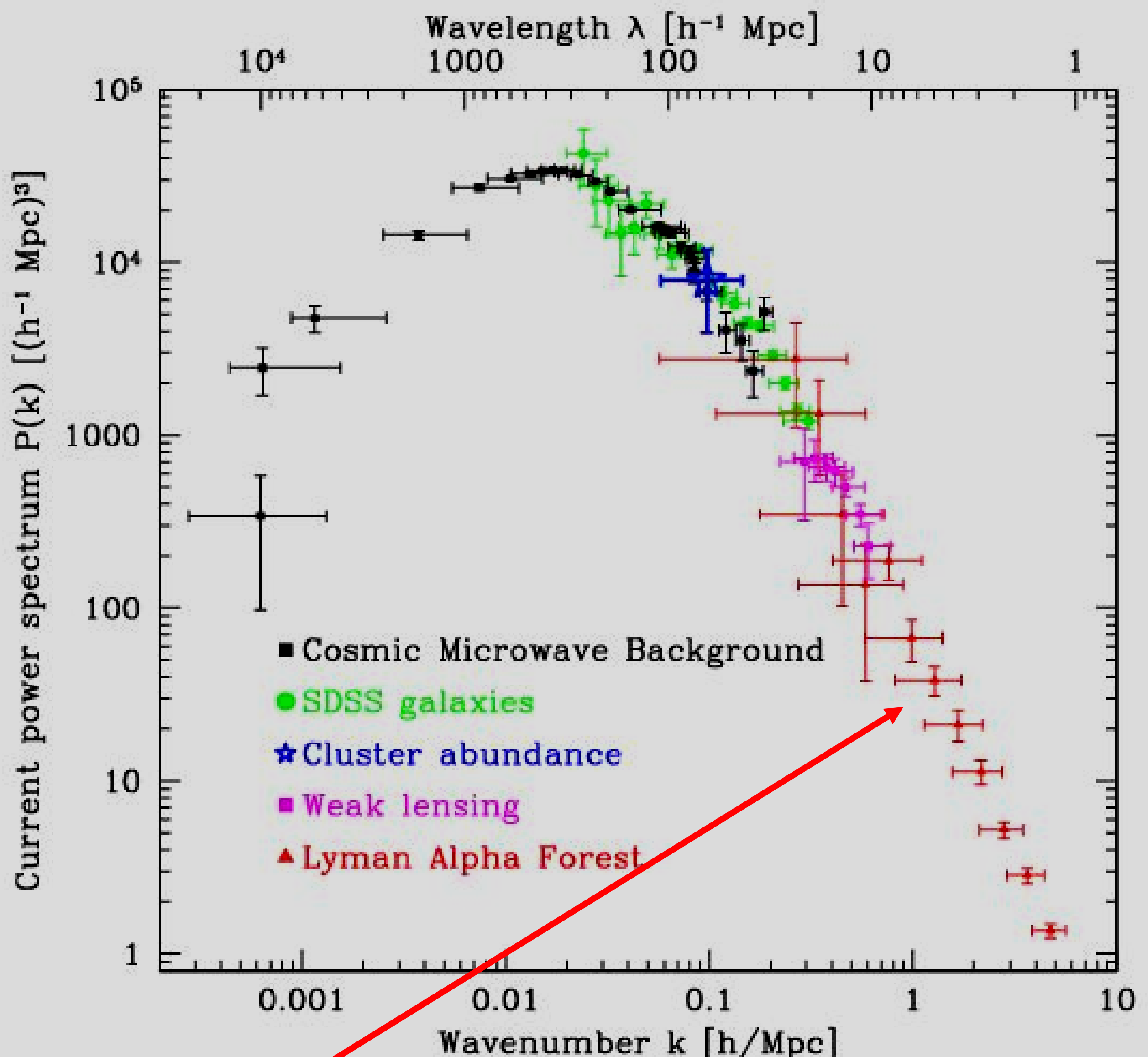
Baryonic wiggles are ***not*** statistically significant.



How various probes of the power spectrum fit together. This assumes a WMAP cosmology and no bias for SDSS $L_*$ galaxies.

Let's make this quantitative, and do parameter estimation from SDSS P(k), WMAP, and other data.

Tegmark et al. 2004, PRD, 69, 103501




*To be updated in Seljak's talk!*

The WMAP team (Spergel et al; Verde et al) carried out a joint analysis of WMAP and large-scale structure data from 2dF. They found a minimal set of parameters consistent with all extant data. Using SDSS and WMAP, we do further explorations of constraints in parameter space.

We start with a "standard" model with adiabatic Gaussian fluctuations. The free parameters are:

Dark matter density $\Omega_d h^2$
Baryon density $\Omega_b h^2$
Dark Energy density $\Omega_\Lambda h^2$
Reionization optical depth $\tau$
Amplitude of fluctuations $A$
Galaxy Bias $b$

"***Vanilla Parameters***"

Massive neutrinos
Quintessence parameter $w \neq -1$
Spatial curvature
Primordial index $n \neq 1$
Running of spectral index
Tensor to scalar ratio
Running of tensor spectral index

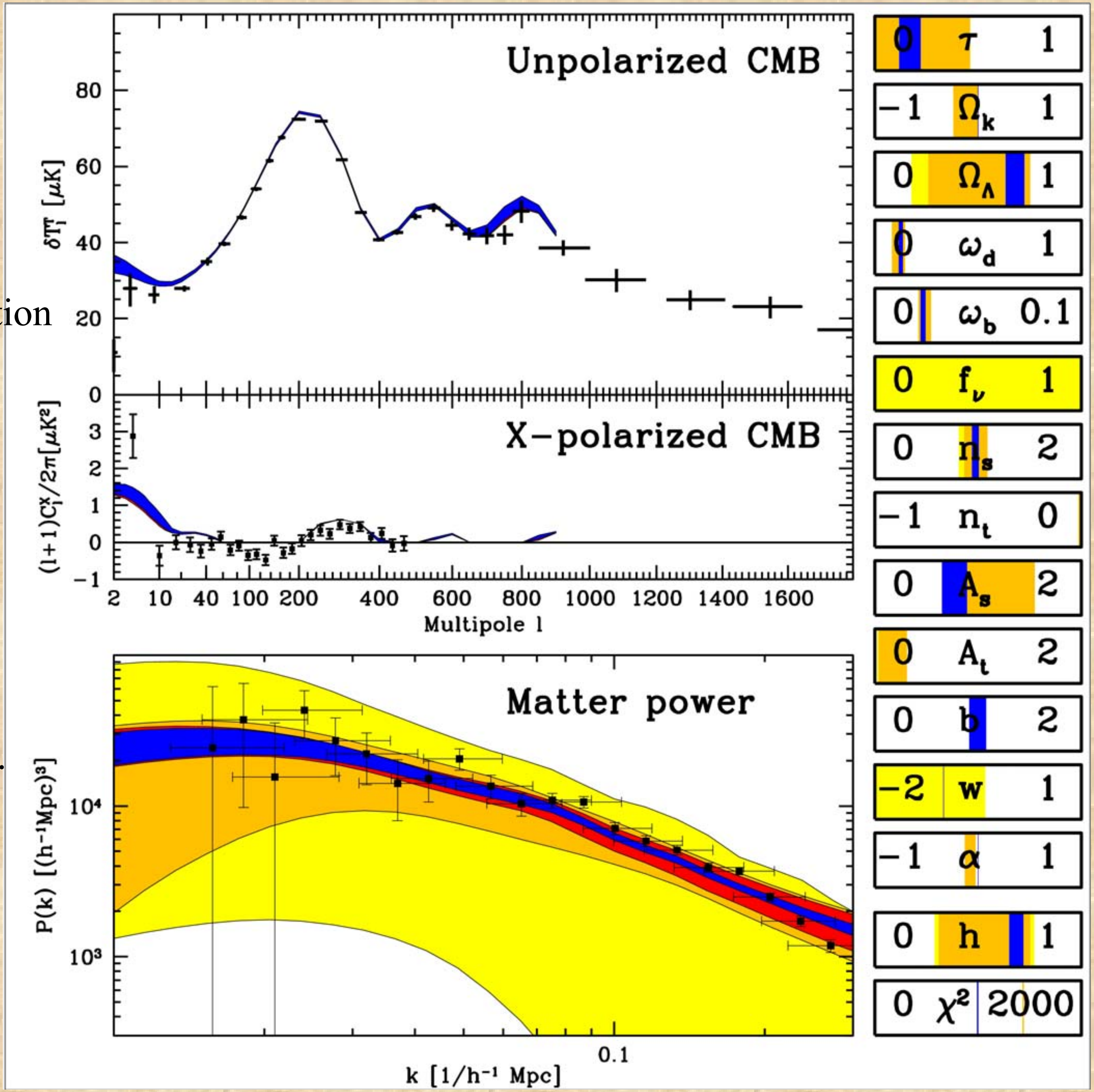
***Additional degrees of freedom***

Data:
WMAP, Boomerang, ACBAR, DASI, etc., *plus*
WMAP cross-polarization
*plus*
SDSS galaxy P(k).

Yellow: WMAP fit, no priors.
Orange: w=-1, no ν
Red: no curvature, tensors, or running.
Blue: including SDSS.

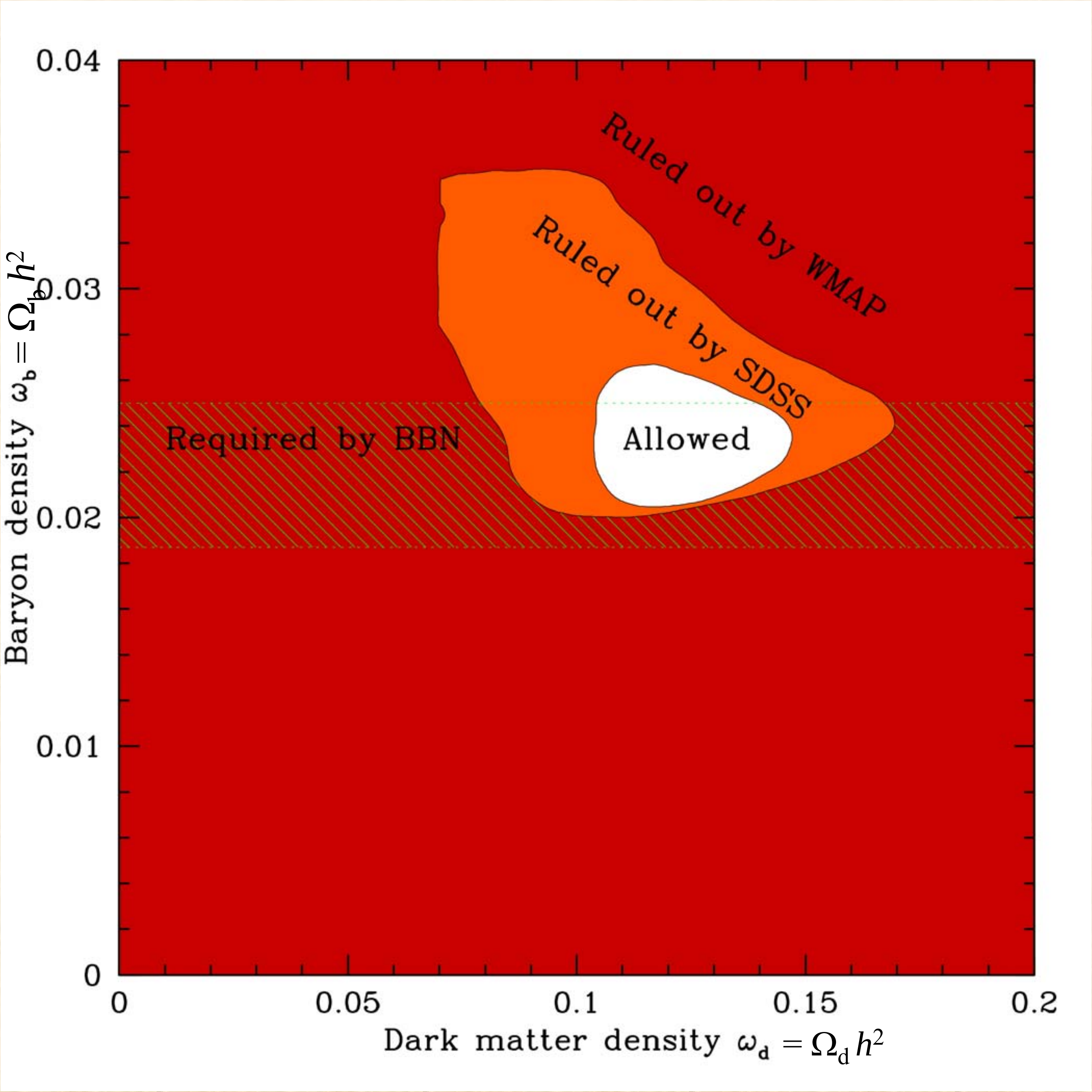
Confidence levels on parameters are shown on right.

***The vanilla model fits the data very well!***



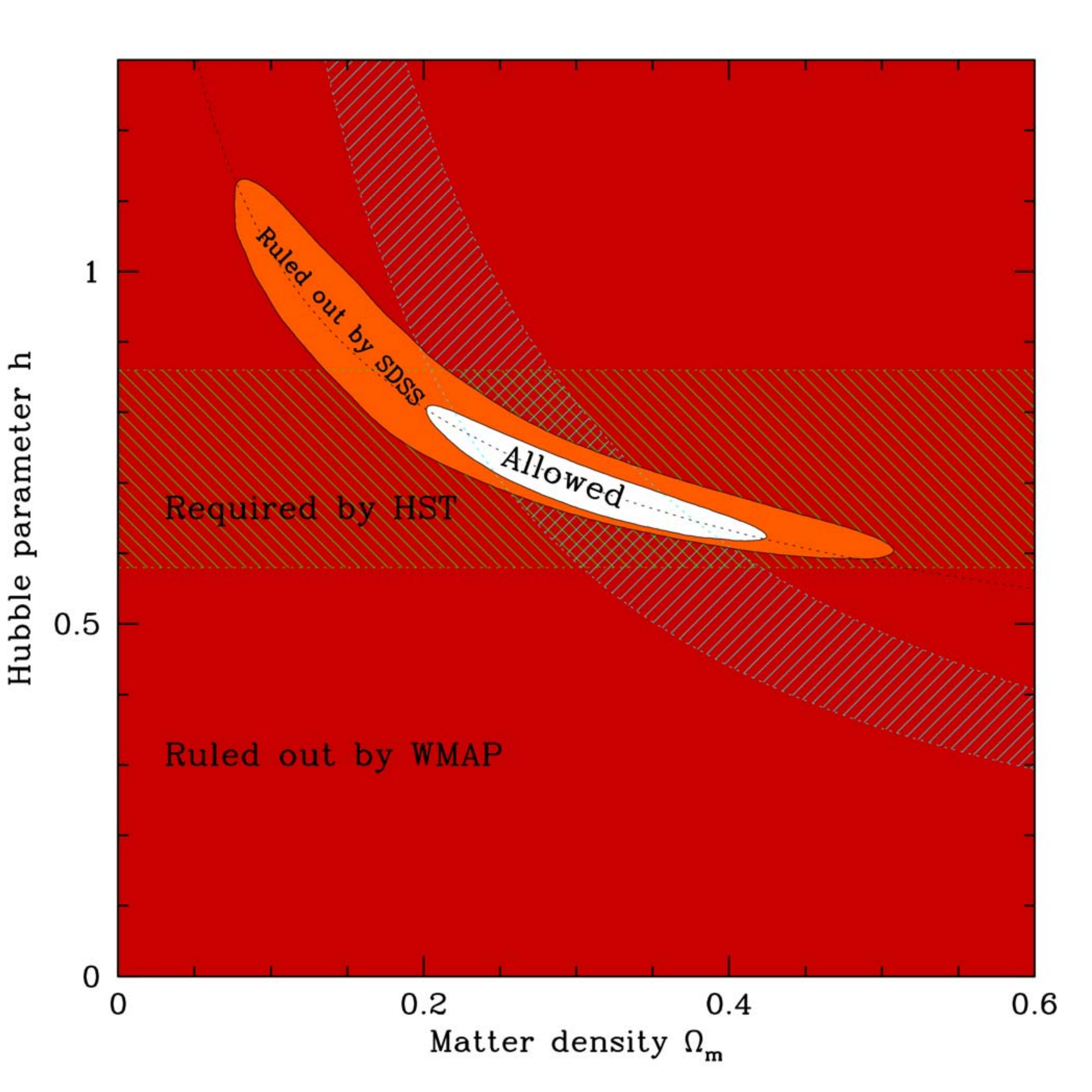
95% constraints on baryon and dark matter densities in the vanilla model. Markov-Chain Monte Carlo used throughout.

Unlike Spergel et al, *no* prior is put on reionization optical depth.

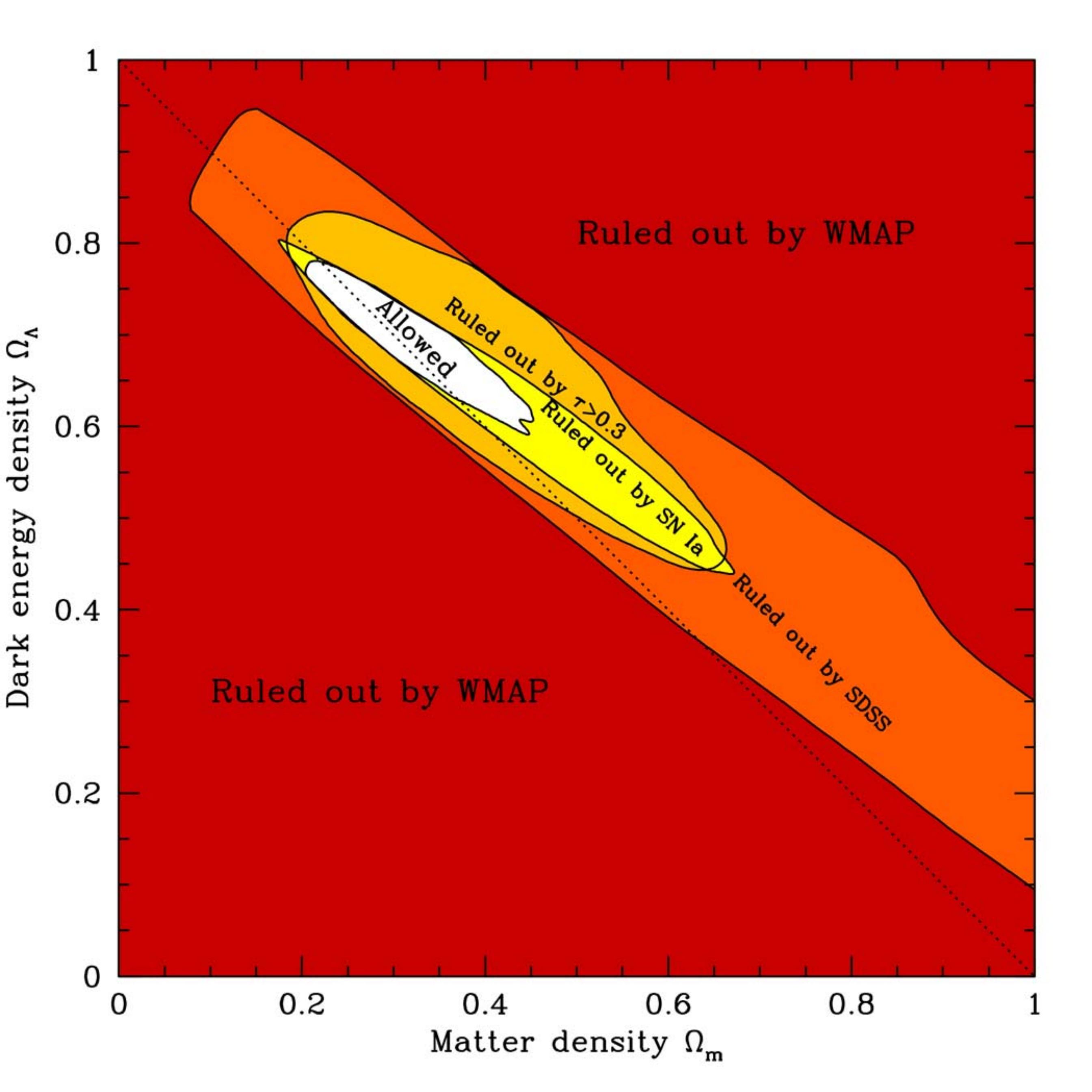


WMAP by itself does not constrain matter density well. When LSS data are added, the constraint becomes tight. Note that Hubble Constant comes out right.

Vanilla model assumed.

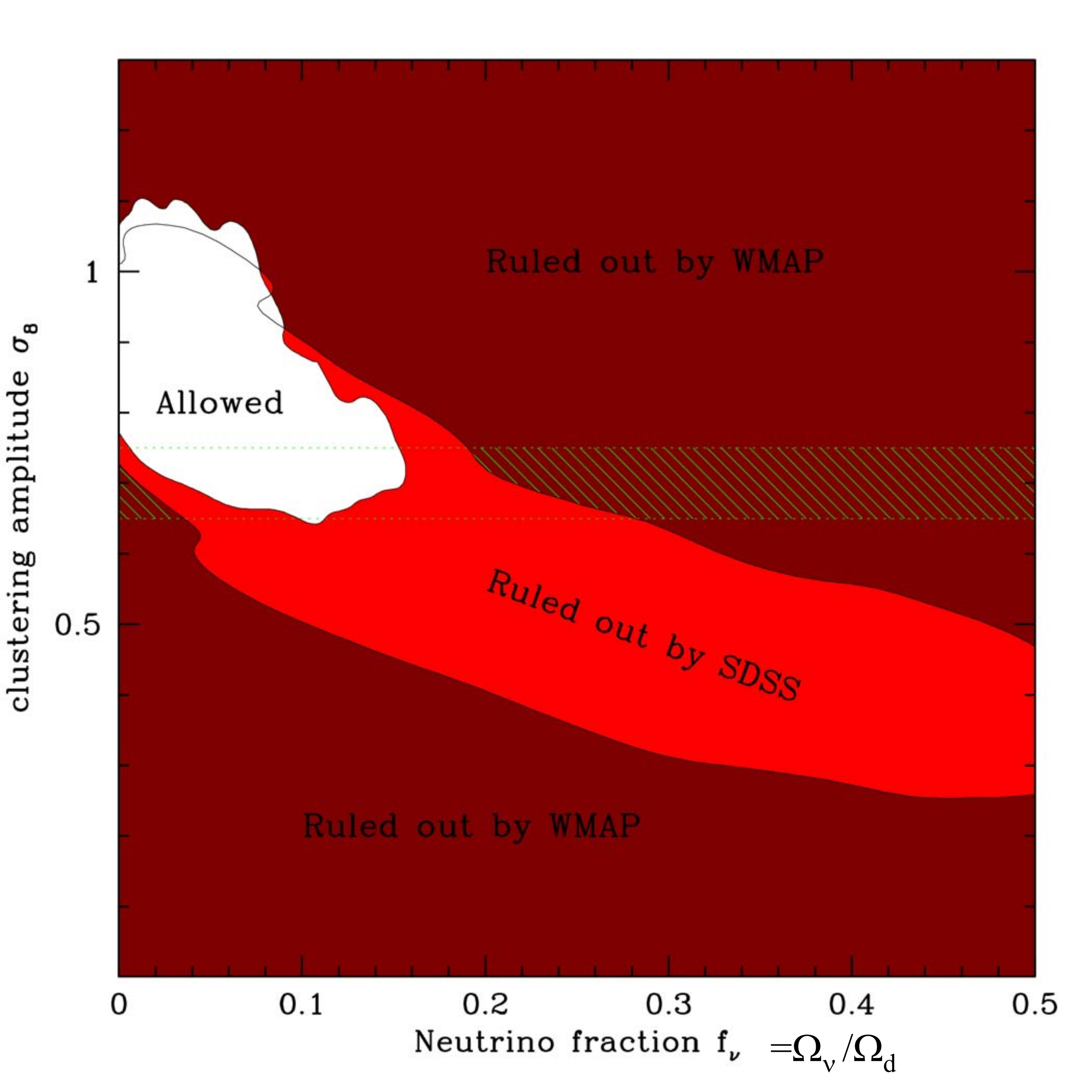


Allowing for non-zero curvature. Requires inclusion of optical depth prior, and data from high-z supernovae, to become interestingly tight.

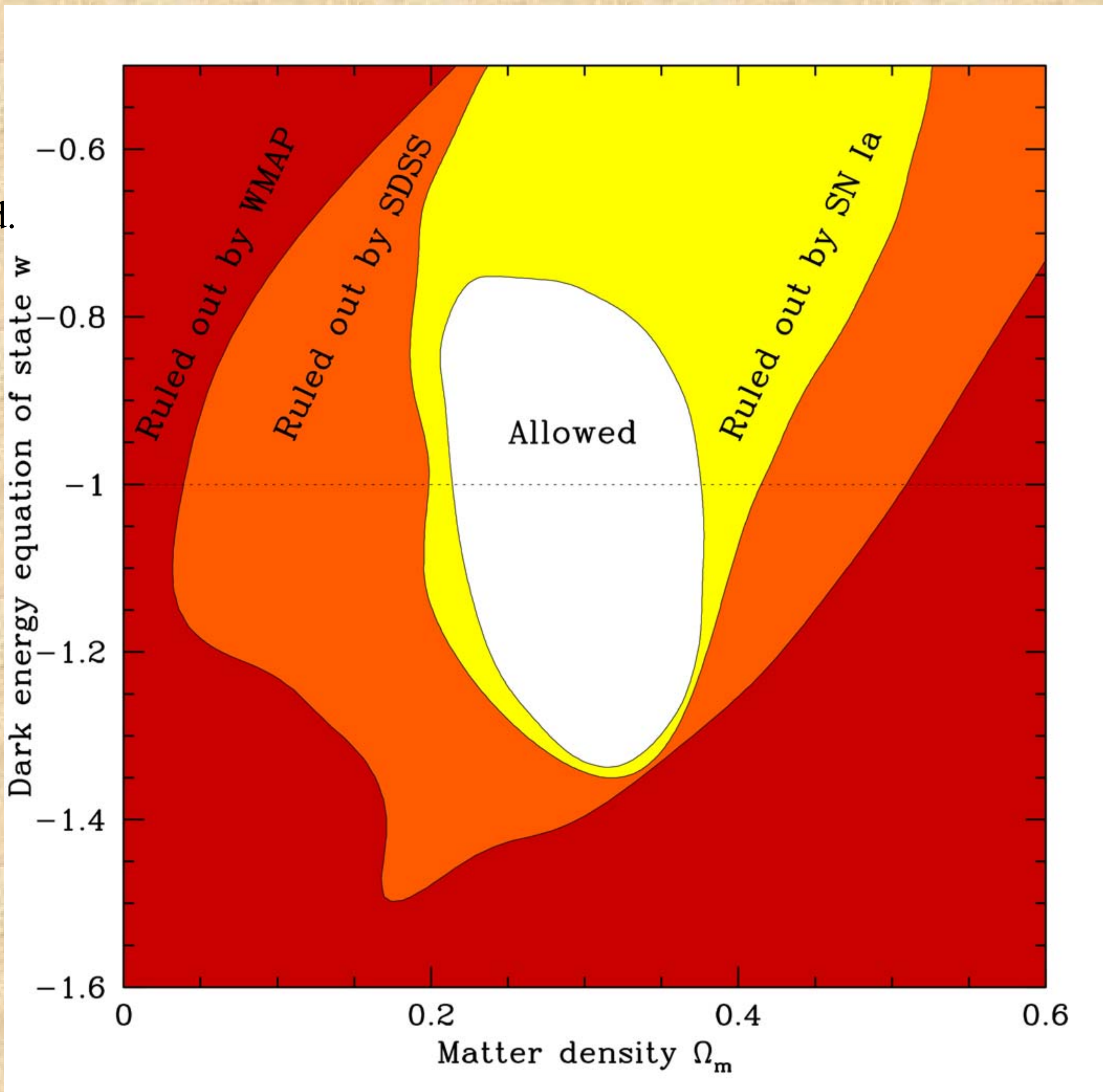


WMAP and SDSS are consistent with no neutrinos. For 3 species, this gives mass < 0.6 eV.

Spergel et al use a prior on galaxy bias, giving them a 2.5 times tighter constraint.



WMAP + SDSS does little to constrain *w*; for this, supernova data need to be included.



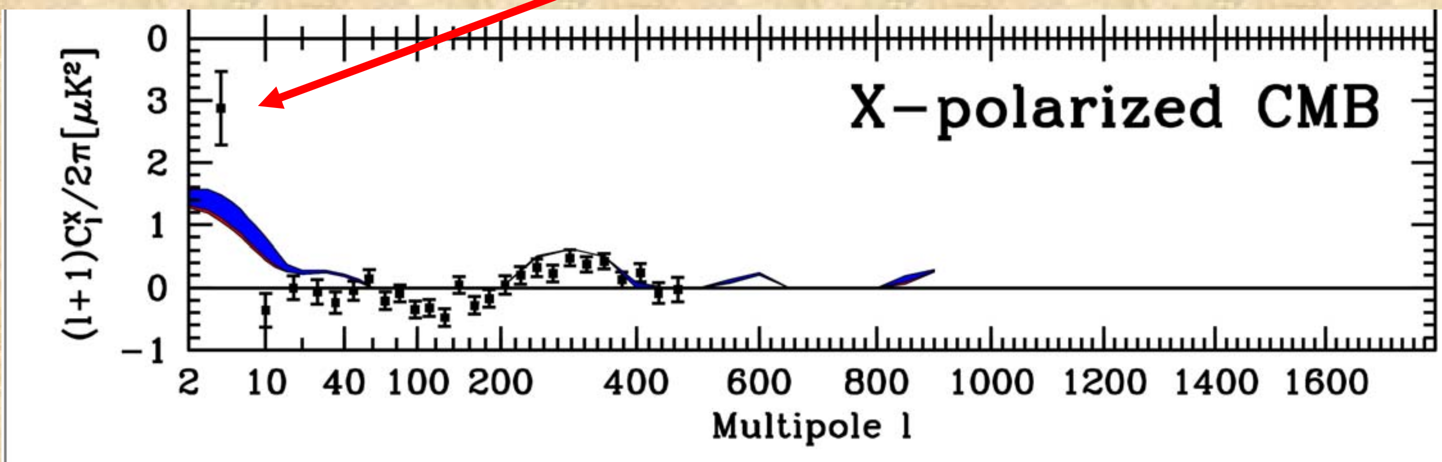
## The simplest model consistent with the data:

- $n_s \equiv 1$, no running
- $\Omega_k \equiv 0$
- No tensors, no neutrinos
- Reionization $\tau = 0.165 \pm 0.036$
- $\Omega_d h^2 = 0.123 \pm 0.008$
- $\Omega_b h^2 = 0.0238 \pm 0.0006$
- $\Omega_\Lambda = 0.707 \pm 0.035$
- Bias $b = 0.92 \pm 0.03$
- Hubble constant $h = 0.71 \pm 0.02$
- $\sigma_8 = 0.97 \pm 0.05$
- Age of the Universe: $13.4 \pm 0.13$ Gyr

***In excellent agreement with the results of the WMAP team!***

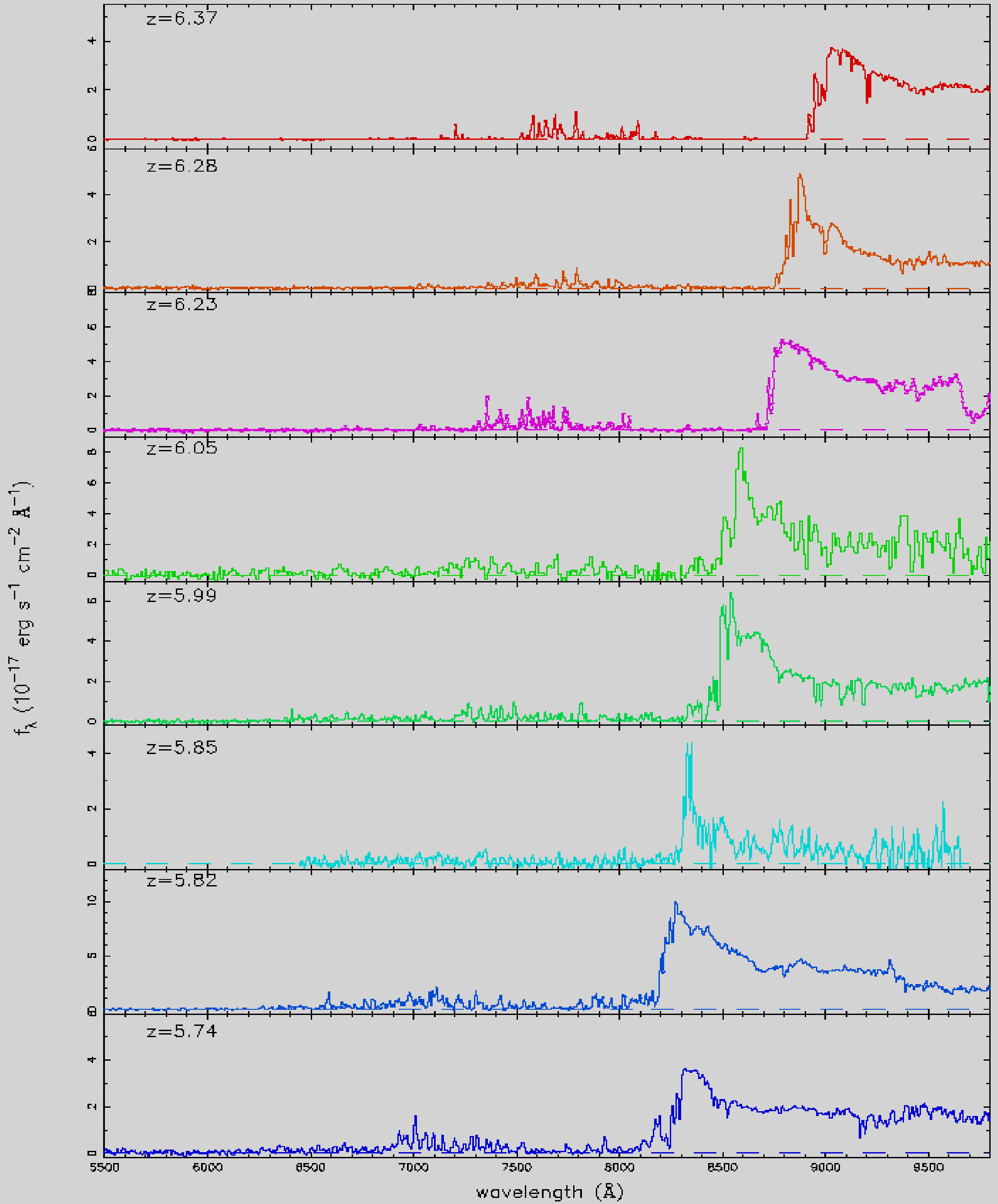
So what about that reionization anyway?

WMAP sees polarization at large scales:



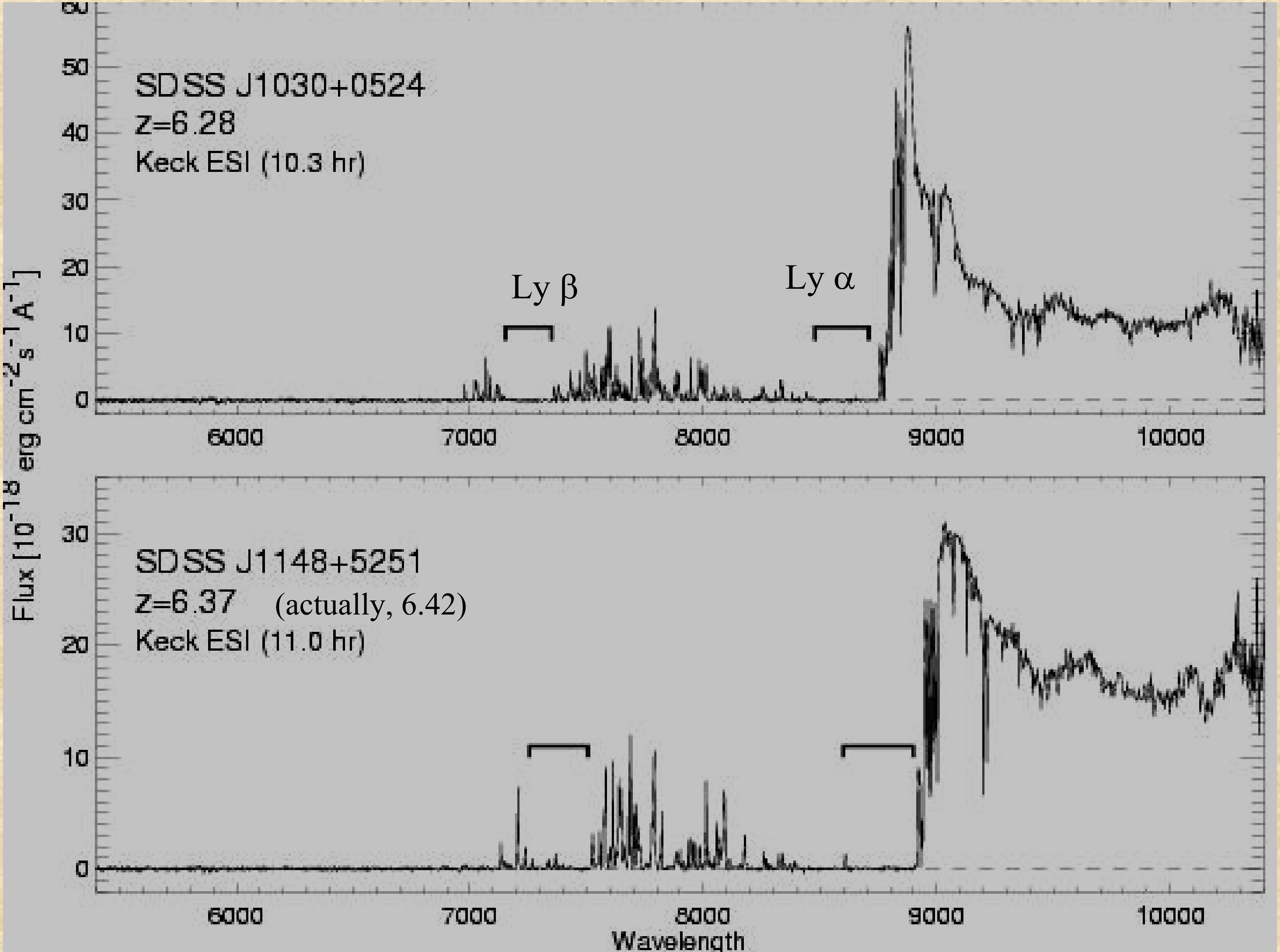

This is due to scattering off electrons at z=15-25. 50% of the hydrogen in the universe was ionized at this epoch. What does SDSS have to say about this?

Eight of the 16 quasars with z>5.7 we've discovered to date. Note the increasing optical depth of neutral hydrogen absorption at high redshift. The Gunn-Peterson effect, probing before reionization?

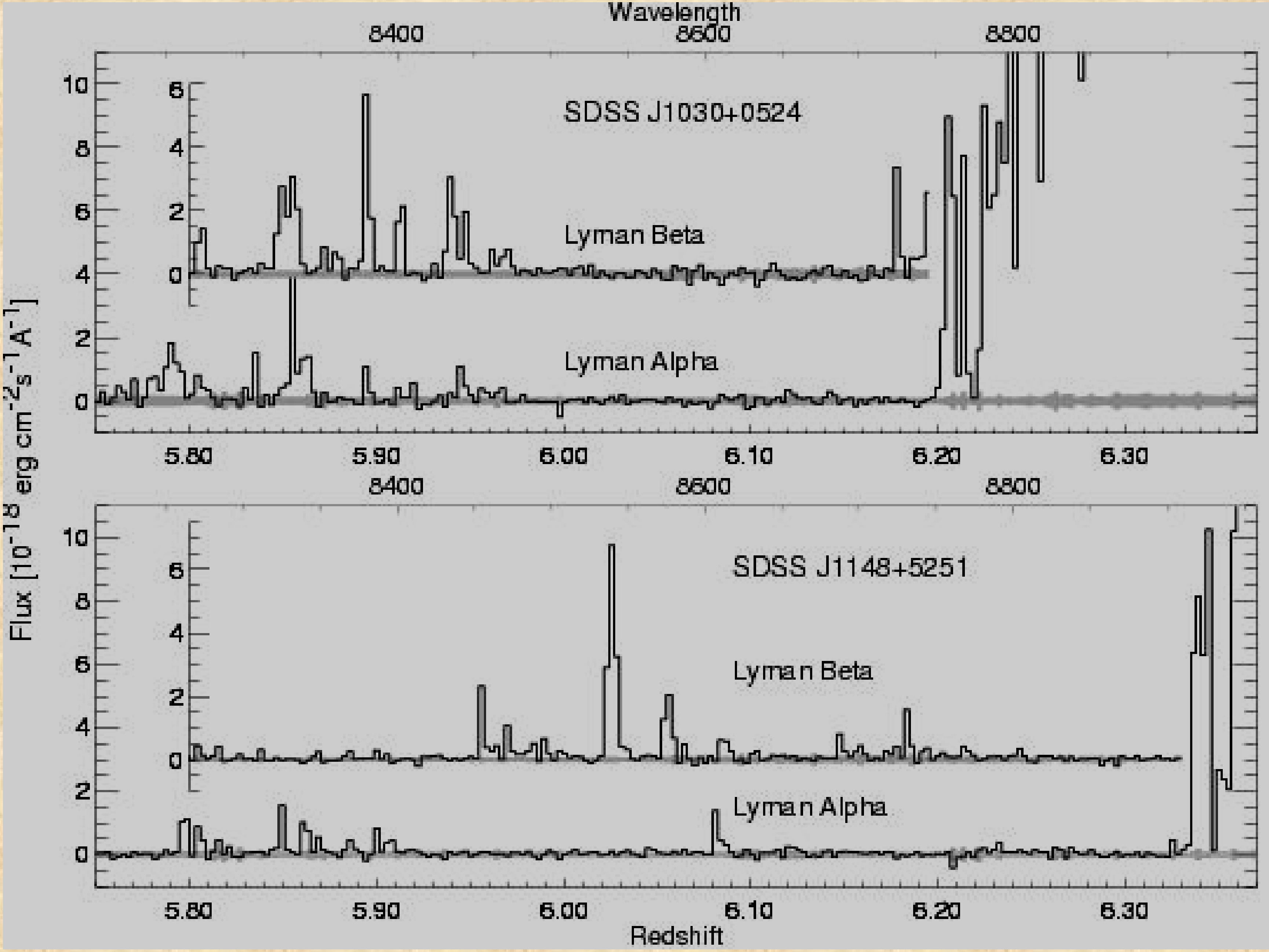


*White et al. 2003*

# Many hour exposures on the Keck telescope

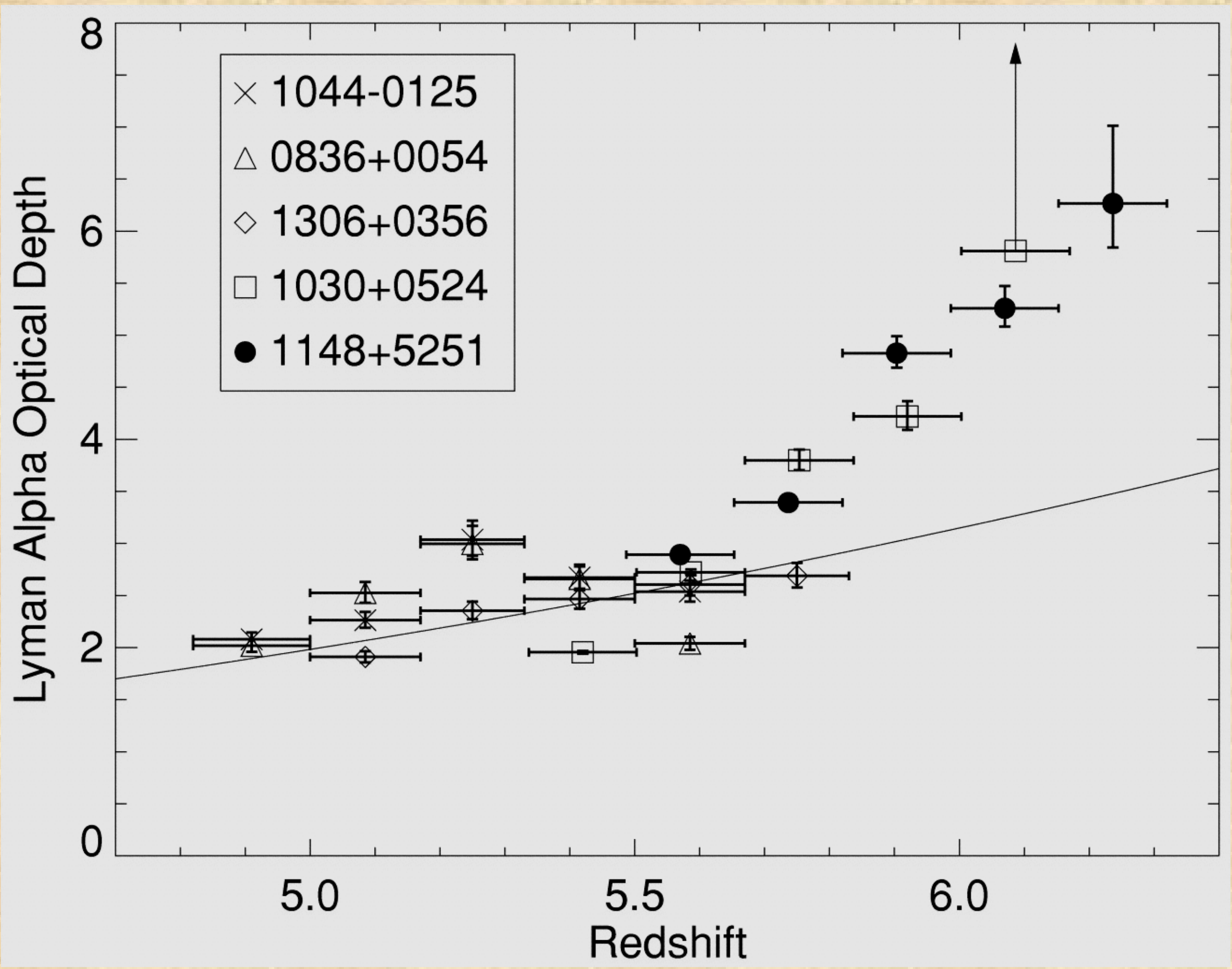


Measuring *nothing* with exquisite precision.



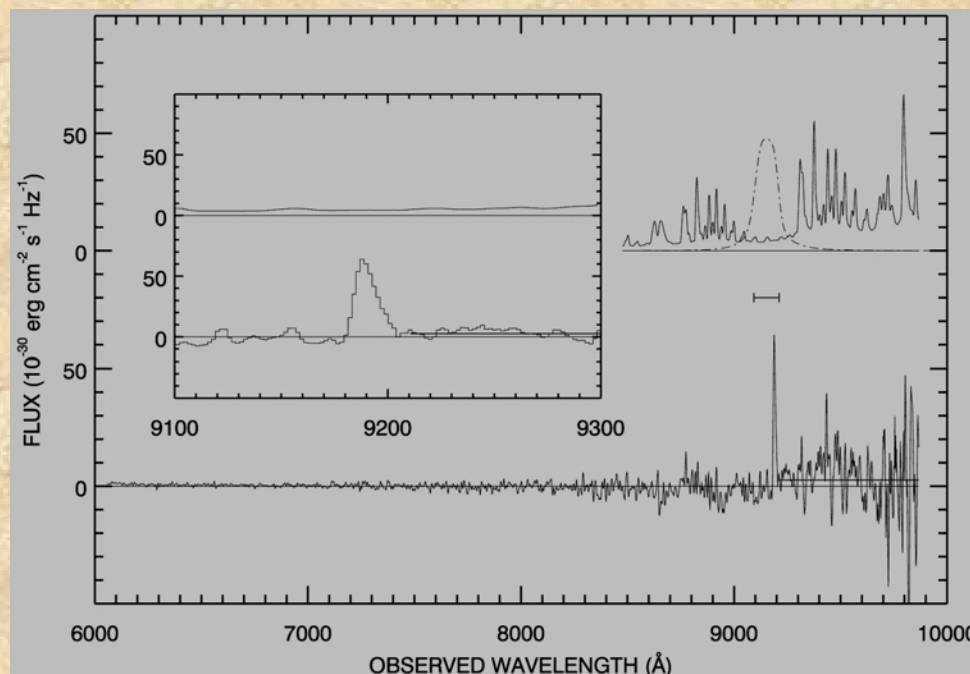
Ly β gives τ<22!

There is evidence for a phase transition at z~6, mostly from the Ly β trough. The inferred volume-weighted neutral fraction is still small, $< 10^{-2}$. Distinguishing between $e^{-20}$ and $e^{-100,000}$ isn't easy…



- The WMAP and SDSS quasar results are not in contradiction. SDSS says that the universe was < 99% ionized at z=6, while WMAP says that it was >50% ionized at z~20. Reionization now appears to be more complicated than we had originally thought.
- Ionization state of the universe at z=6-10 now very controversial, should Lyα emission in galaxies be seen?
- Pushing to higher redshift with quasars will be difficult; they are increasingly rare and difficult to find. Another approach is to look for high-redshift *galaxies.* They are too faint to look for the Gunn-Peterson trough, but their Ly α emission will be absorbed by the damping wing of the high optical depth trough.

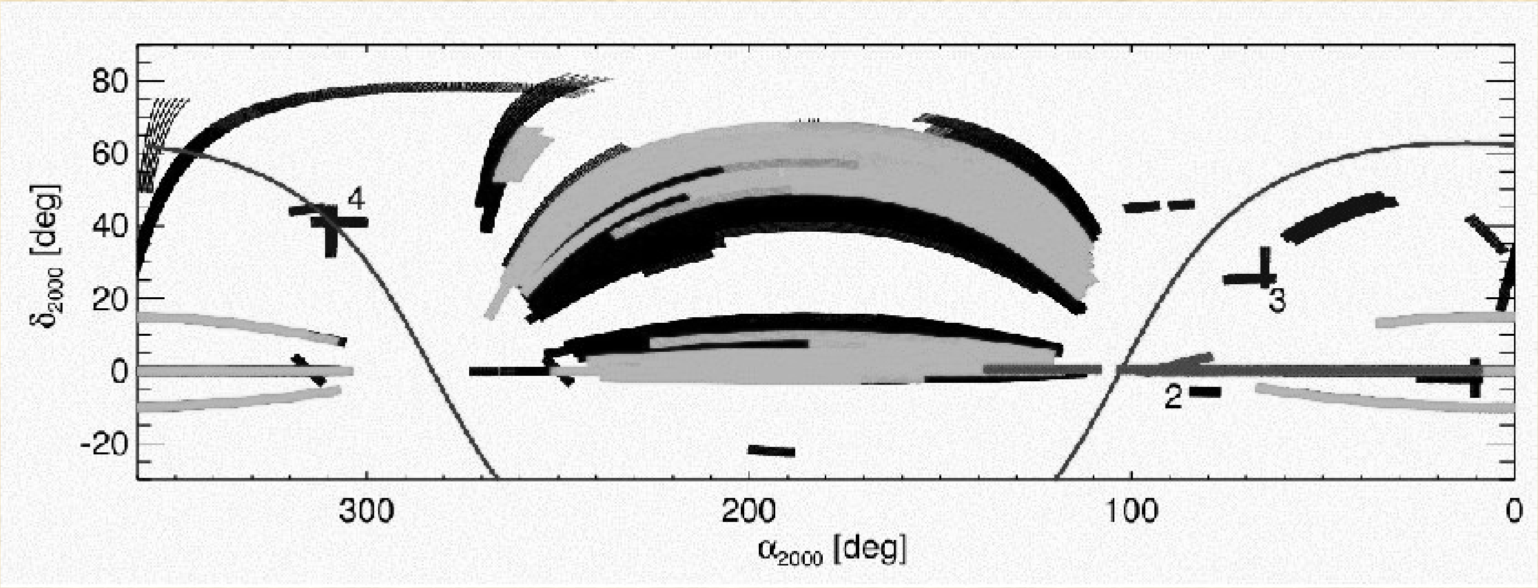
Galaxy at z=6.56 discovered by Cowie and Hu (4 hours on Keck).



# SDSS, CMB, and Cosmology: What lies ahead

- Roughly twice as much sky as was analyzed by Tegmark et al. is available now; by the end of the survey, it will be another factor of two.
- Measurements of the ISW effect; see talks by Fosalba, Crittenden, etc.
- Measurements of Lyman alpha forest clustering; see talk by Seljak.
- Measurements of weak lensing; see talk by Padmanabhan.
- Clustering of quasars to $z>5$, and luminous red ellipticals to $z=0.7$, from both photometric and spectroscopic redshifts.
- Number evolution and clustering of galaxy clusters.
- Strong lensing statistics.
- Higher-order clustering statistics, plus topology and void statistics.
- More high-z quasars to probe reionization.
- Etc., etc.

# Where we stand




Imaging to date

Spectroscopy

We will *not* fill the gap before running out of funds; we are currently applying for an extension.

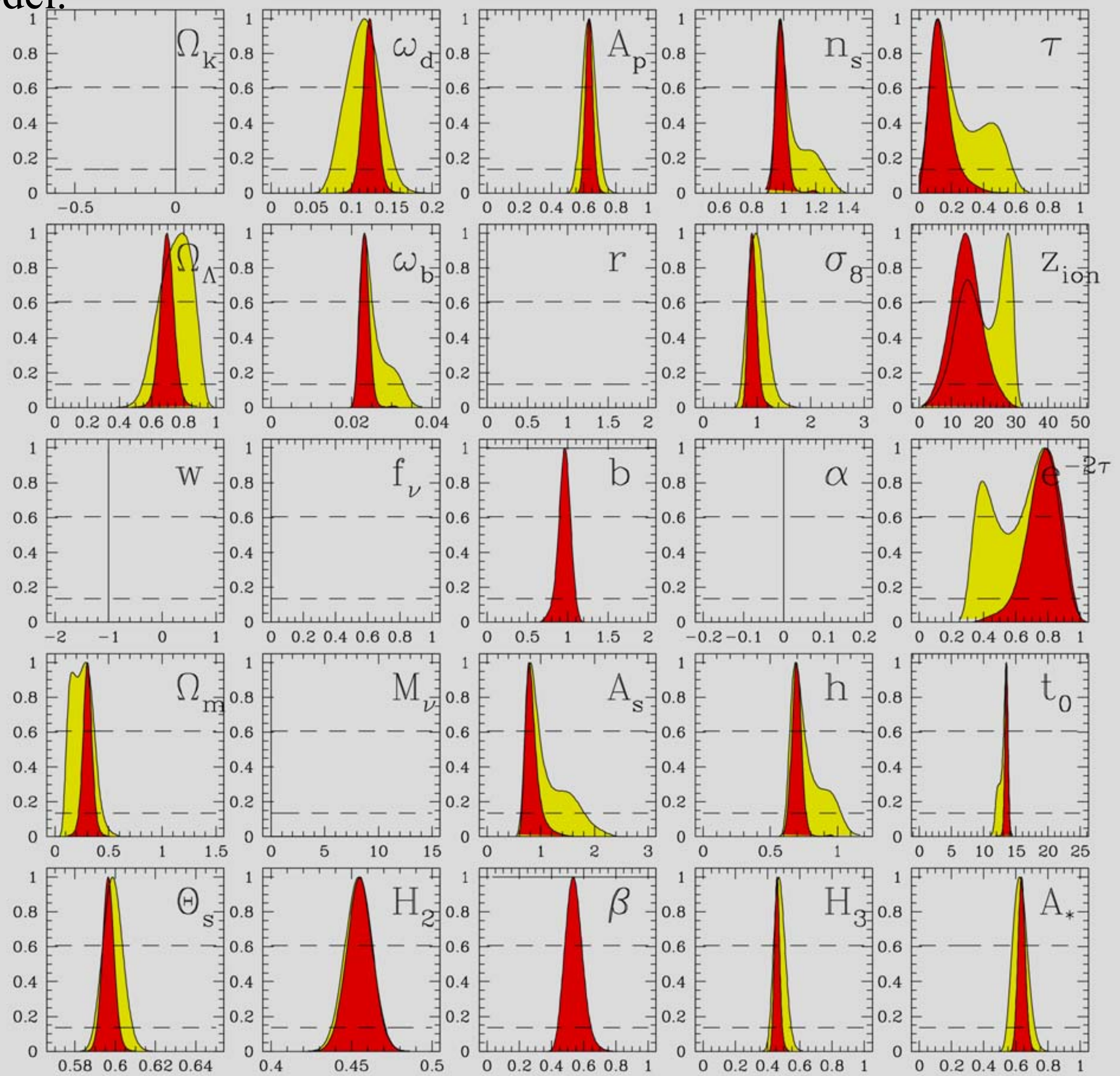
# The SDSS still has been mined for only a fraction of its cosmological worth.

- 3000 square degrees of imaging data (88 million detected objects) and 400,000 spectra are publically available at http://www.sdss.org/dr2.
- The SDSS Third Data Release (DR3) will occur in October, with 50% more data yet.
- Donations for funding the SDSS extension will be taken after the talk…

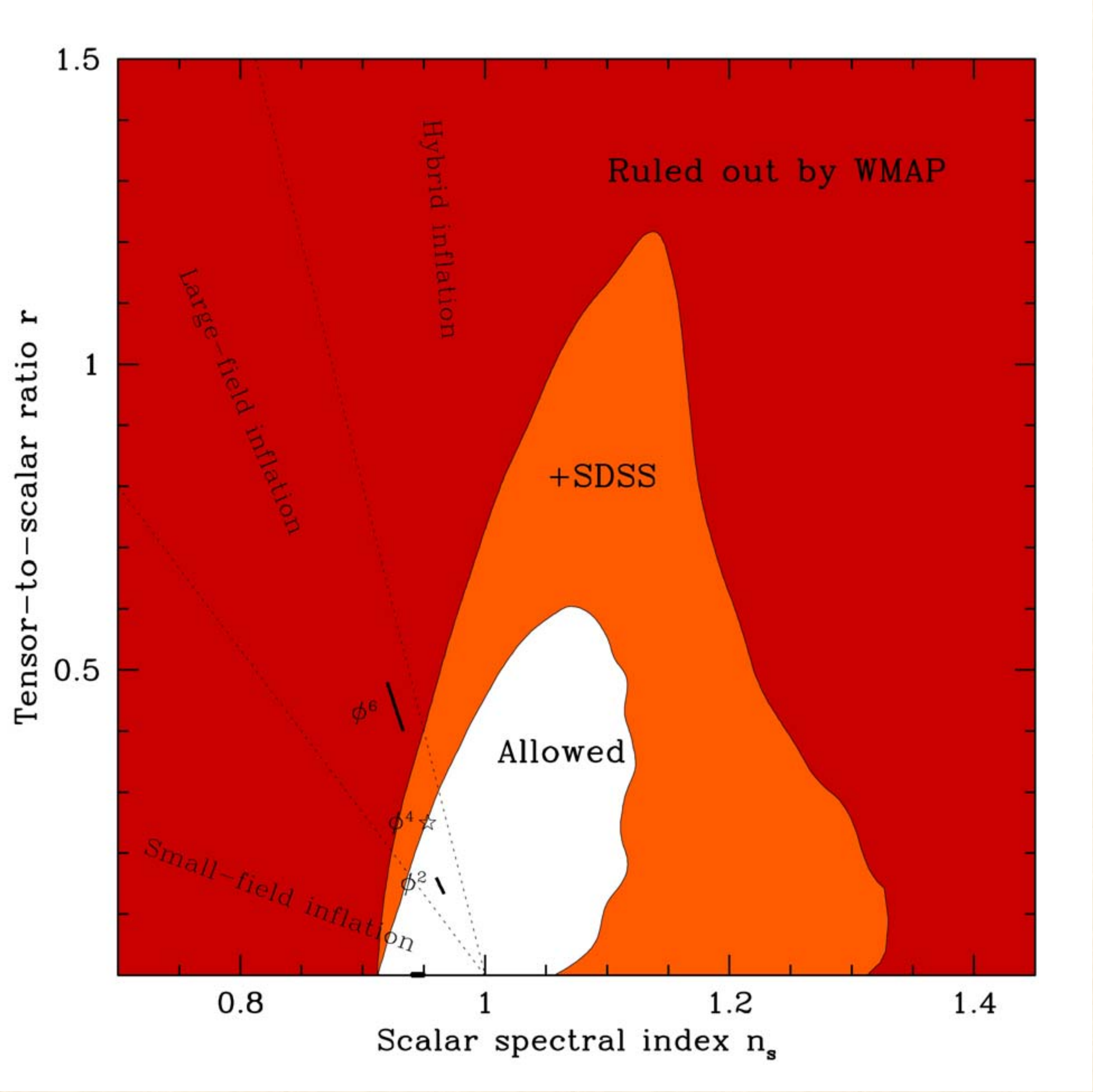
# Confidence levels on parameters from Markov Chain Monte-Carlo

*Yellow:* WMAP alone, vanilla model.

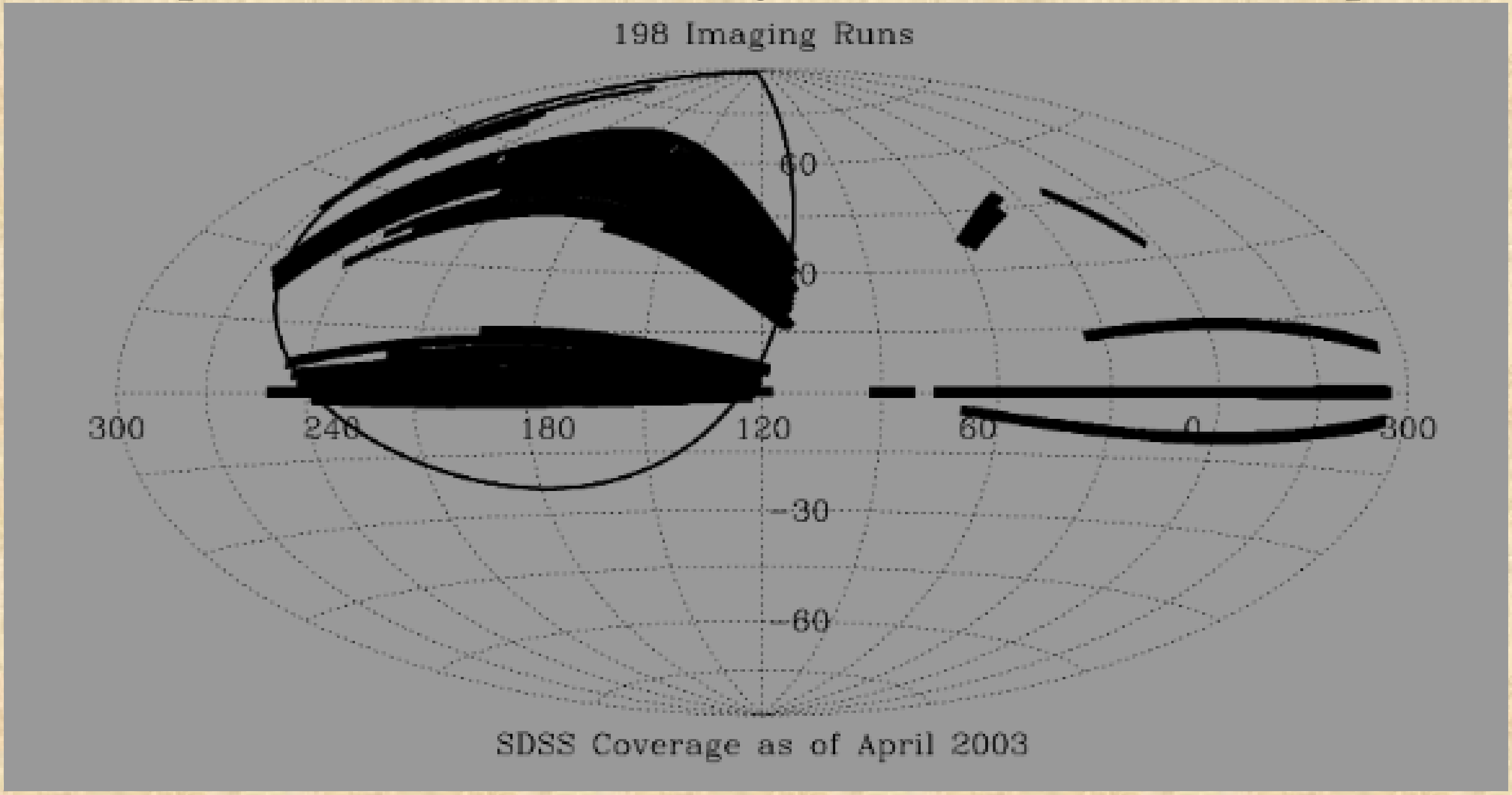
Red: SDSS included.



Inflation is constrained by the tensor-to-scalar ratio and the spectral index.



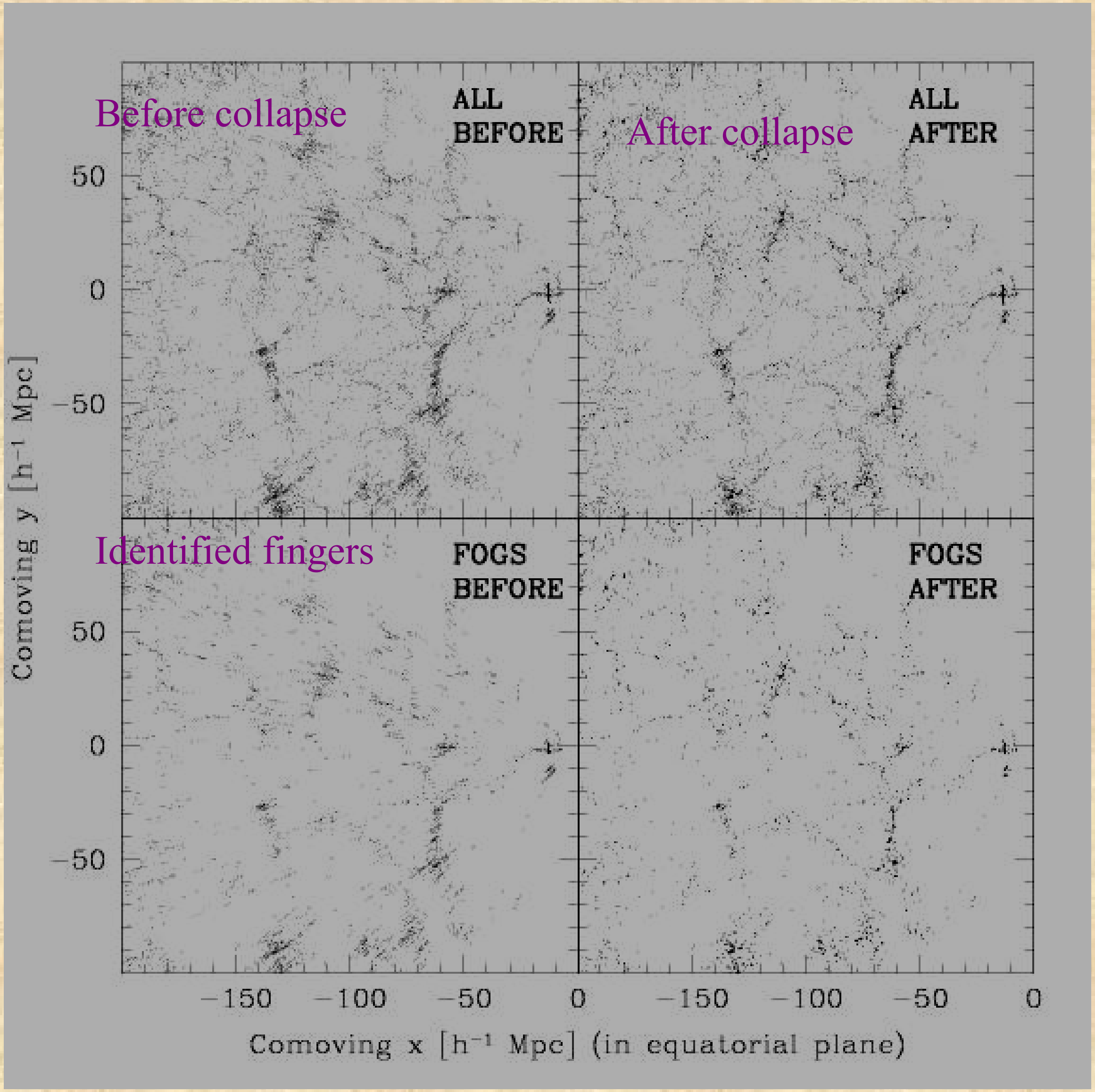
The SDSS has already covered close to 5000 square degrees of sky; 500,000 spectra (albeit not all of galaxies in the main sample).




Thus there are much more SDSS data already in the can for extending this analysis.

## Challenge: Dealing with peculiar velocities

Solution: on small scales, identify and collapse fingers of God.



# Redshift space distortions (continued)

On large scales, use linear theory to relate real-space density modes to velocity modes:

$$\nabla \cdot \mathbf{v} = -\Omega^{0.6}\delta(\mathbf{r})$$

This allows you to write down eigenmodes for the velocity field distortions directly.

The data "pixels" can be expressed as:

$$x_i \equiv \int \frac{n(\mathbf{r})}{\bar{n}(\mathbf{r})}\psi_i(\mathbf{r})d^3r$$

where $\psi_i$ is the K-L mode.

We can write down the covariance matrix for the $x_i$ in terms of A signal and noise piece; the signal piece looks like:

$$\mathbf{S} = \int_0^\infty \left[\mathbf{S}_{\mathrm{gg}}(k)P_{\mathrm{gg}}(k) + \mathbf{S}_{\mathrm{gv}}(k)P_{\mathrm{gv}}(k) + \mathbf{S}_{\mathrm{vv}}(k)P_{\mathrm{vv}}(k)\right]\frac{k^2dk}{(2\pi)^3},$$

which explicitly separates out the redshift-space pieces of all this.

Challenge: Determine the power spectrum directly from the $x_i$

In general, we write: $$\hat{p}_i \equiv \mathbf{x}^t \mathbf{Q}_i \mathbf{x} - \mathrm{tr}\,[\mathbf{N}\mathbf{Q}_i],$$

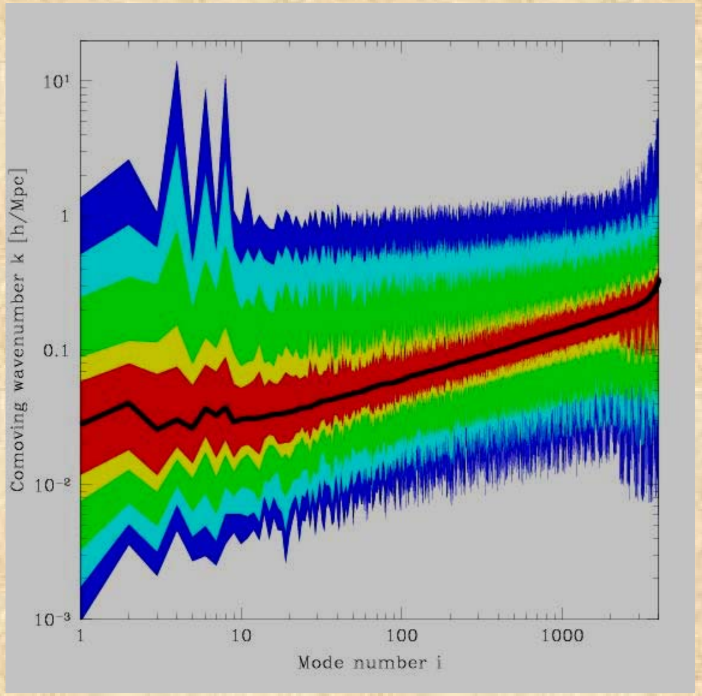
For some appropriate matrix $\mathbf{Q}_i$. If we're clever enough, then:

- The $p_i$ will each sample a narrow window of k space;
- The $p_i$ will be orthogonal to each other, with uncorrelated error bars;
- The $p_i$ will minimize leakage between the real space and velocity space pieces of the power spectrum.

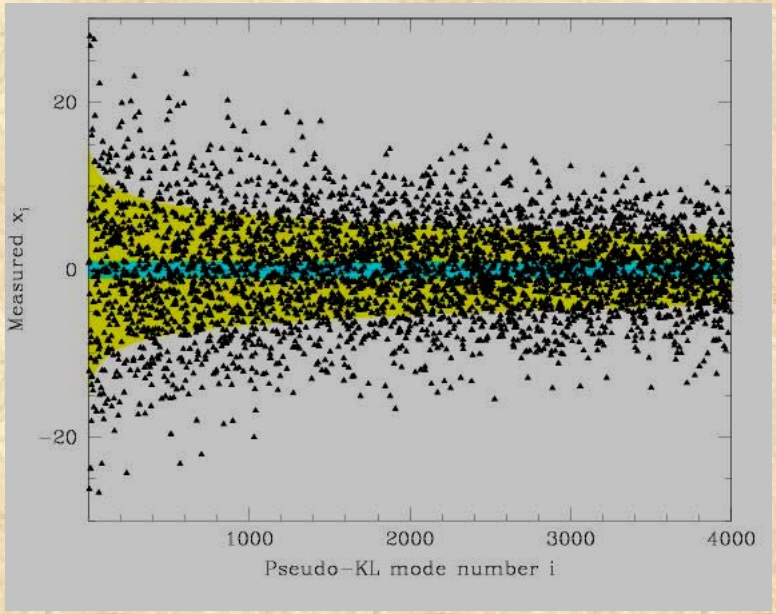
This is actually achievable:

K-L modes are in order of decreasing S/N and decreasing scale. By cutting off the K-L expansion after a finite number of modes, we keep most of the high S/N data, and we solve

Challenge: Dealing with non-linear effects.




These are the actual $x_i$ data, normalized to expected shot noise. Blue is distribution if no clustering; yellow is assuming prior model.



# Challenge: Test for systematic effects

Systematic errors in the photometric calibration, or in the selection function, could mask as large-scale structure.  Here we remove those modes that are purely angular or purely radial (as modes are orthogonal, any such problems will be isolated to those modes alone).

Black: original power spectrum

Red: Removing "special" modes

The two are essentially identical!