Massive Neutrinos and the Cosmos

- Neutrinos affect Mass Distribution
- Measures of the Mass Distrtribution
- A way out

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May 28, 2004

Neutrinos are produced in the early universe

Alpher, Herman, & Gamow 1953

- Neutrinos interact very weakly: need high temperatures/energies
- Early on, the universe was much hotter, so, e.g.

$$e^{-}e^{+} \rightarrow \nu\bar{\nu}$$

occurred frequently

Expect about as many neutrinos in the universe today as photons (~100 cm^{3})

50 eV mass ν would dominate the energy density in the Universe

- There is non-baryonic dark matter in the universe (i.e., something beyond the standard model)
- Simplest extension which gives dark matter is neutrino mass
- But …

Massive Neutrinos affect large scale structure

Bond, Efstathiou, & Silk 1980, Melott 1982; Bond & Szalay 1983; White, Frenk & Davis 1983; Shandarin, Dorshkevich, & Zel'dovich 1983

- We know the neutrino abundance in the universe:
- Neutrinos stream out of overdense regions when kT ~ 1 eV.
- Less clustering in universe with massive neutrinos

$$\Omega_\nu \equiv \frac{\rho_\nu}{\rho_{critical}} = \frac{m_\nu n_\nu}{\rho_{critical}} = 0.02\frac{m_\nu}{1\,eV}$$

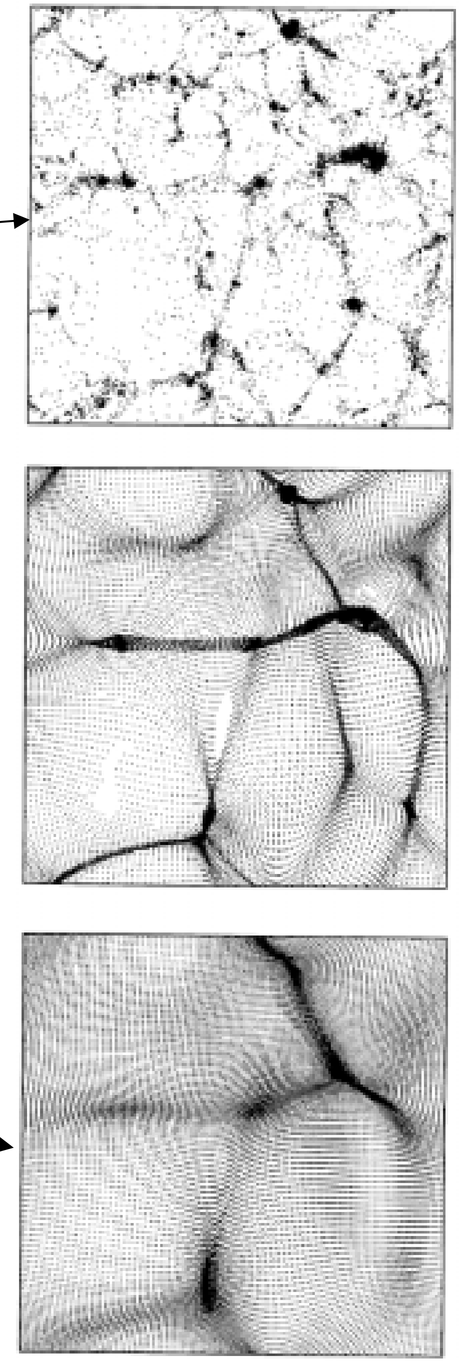
Suppression proportional to

$$\Omega_\nu / \Omega_{matter}$$

Cold Dark Matter
(no neutrino mass)

If neutrinos are important, they smooth out the distribution: no small scale structure

Hot + Cold Dark Matter
(non-zero neutrino mass)

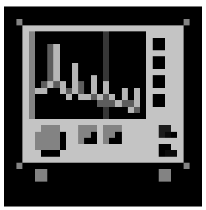


Colombi, Dodelson, & Widrow 1995

Musical Acoustics

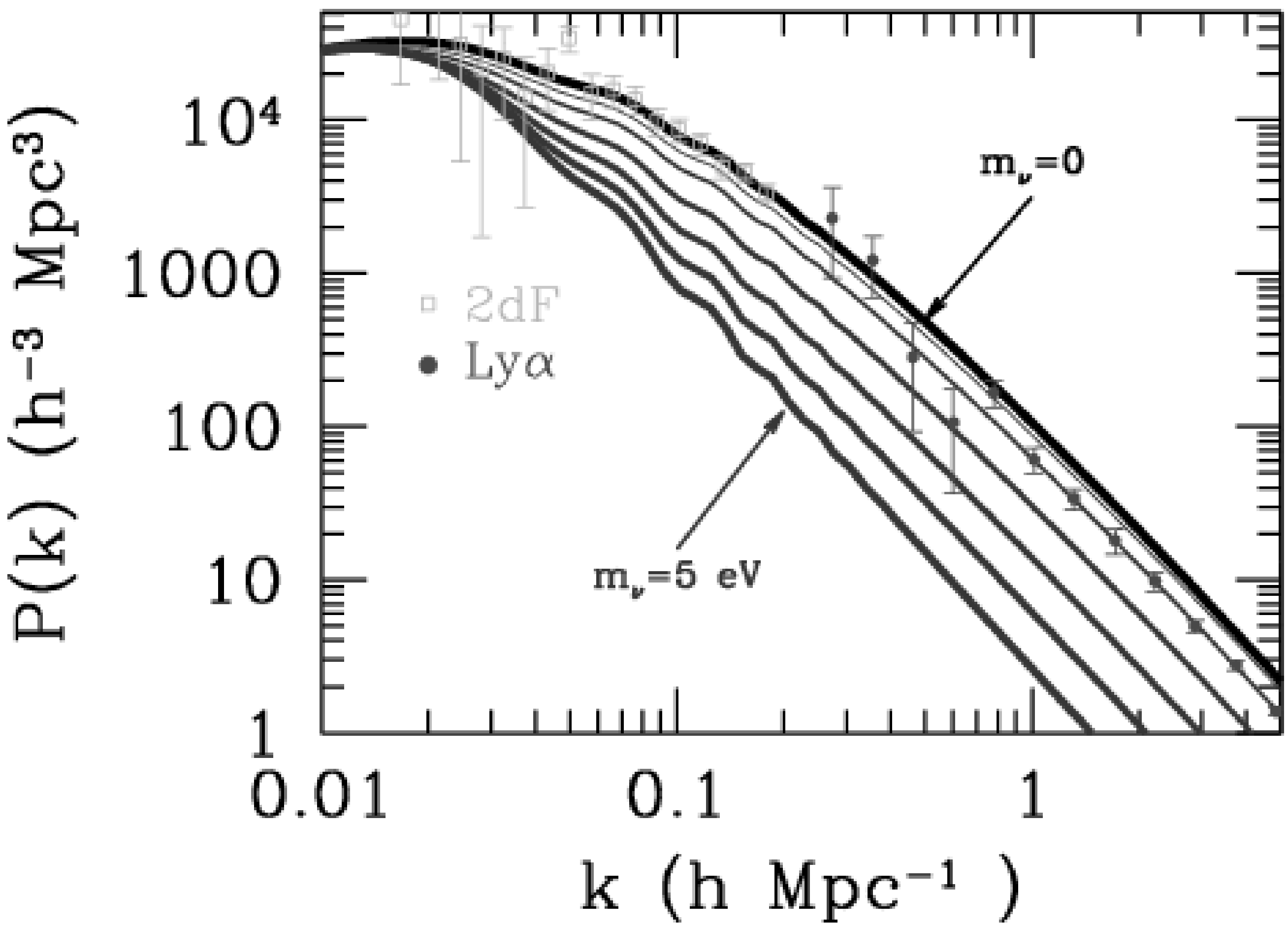
- Middle C 

- Middle C
  on a piano 



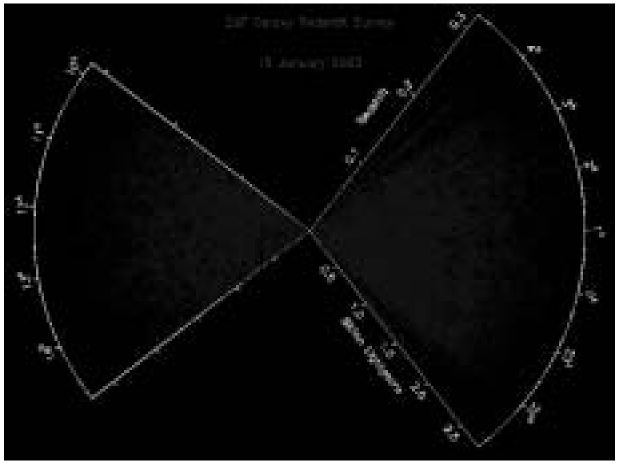
Analyser.exe

Quantitative Measure: Power Spectrum



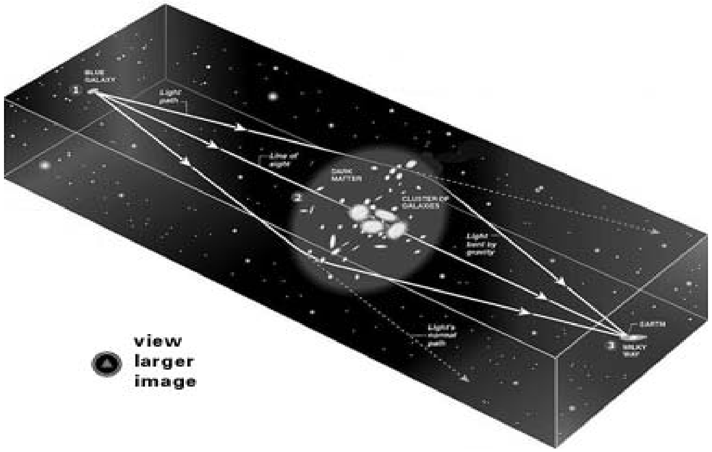
Probes of the Power Spectrum

- Galaxy distribution



- Lyman alpha forest

- Weak Lensing



Sloan Digital Sky Survey

- 2.5 meter telescope in Apache Point, New Mexico

- Collaboration of: Fermilab, Princeton, U. Chicago, U.Washington, Johns Hopkins, New Mexico State, Max Planck, Japan, Pittsburgh, …

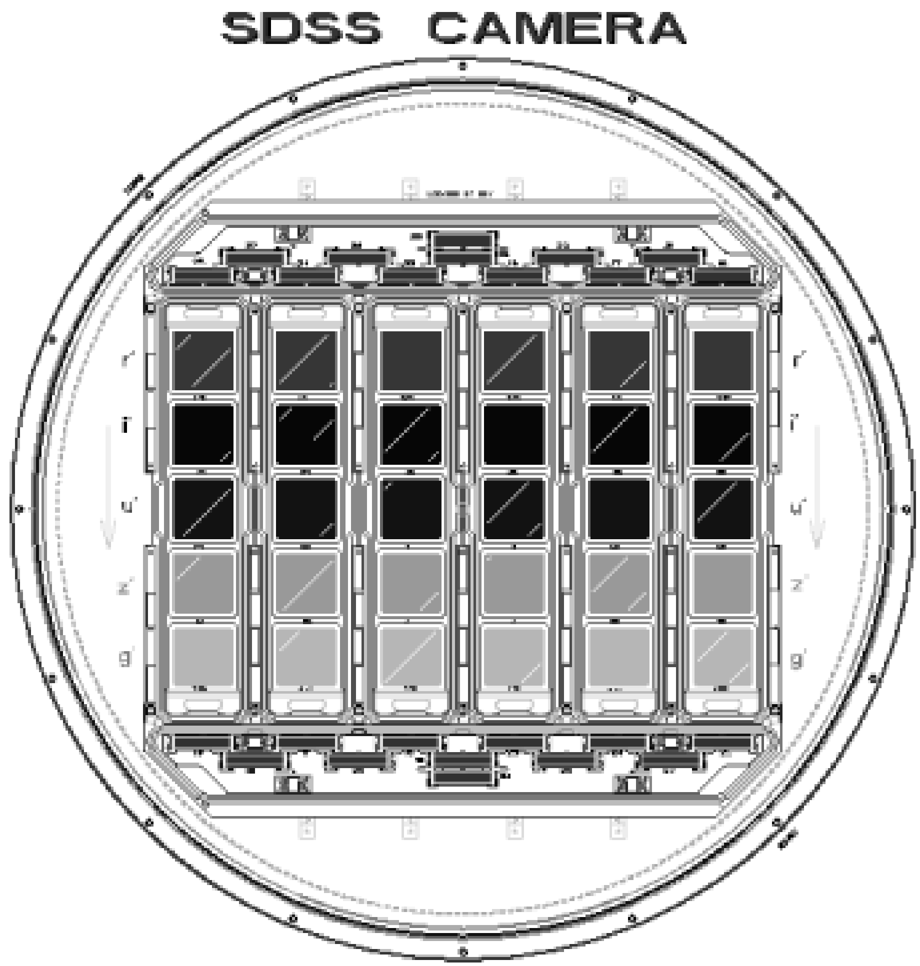
- Scheduled to end in 2005; may be extended until 2007; will cover ¼ of the sky

Two surveys in one

• Photometric survey: hundreds of millions of objects in 5 bands

• Spectroscopic survey: ~1 million objects with spectra

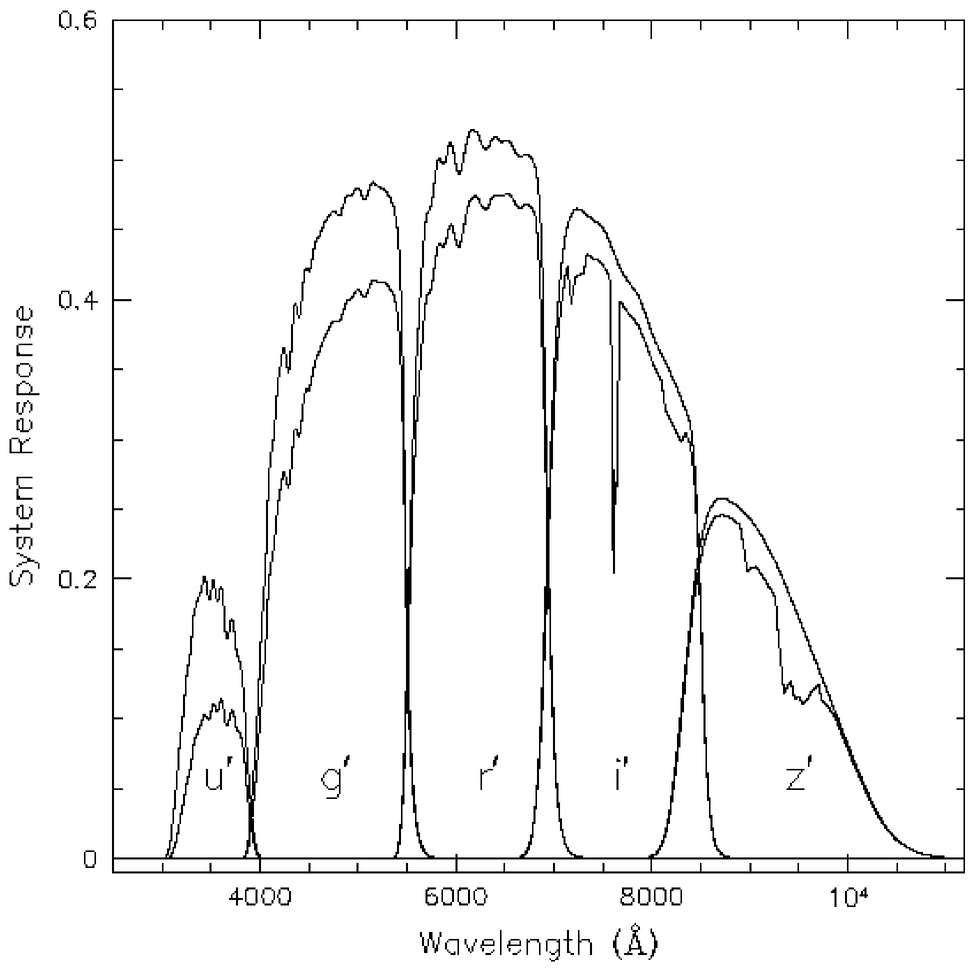
• Spectroscopic survey targets objects found in photometric survey. Reduces systematic effects (typically objects targeted for redshifts are found in different survey, leads to complicated selection function).



5 Filters very efficient

Ultimately will get redshifts for ~750,000 galaxies; 100,000 QSOs

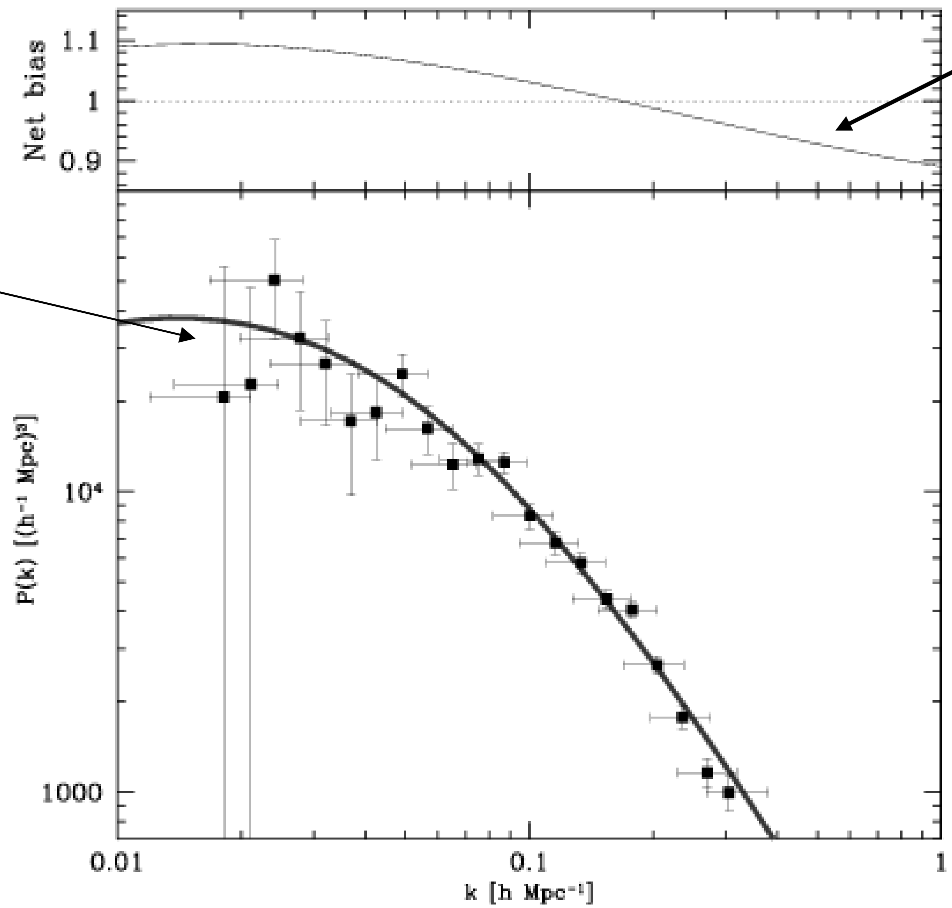
I' and z' bands especially important for high redshift QSOs. Lyman alpha line (1215 Å) redshifted to 1215*(1+z) Å. Can get z>6 QSOs.



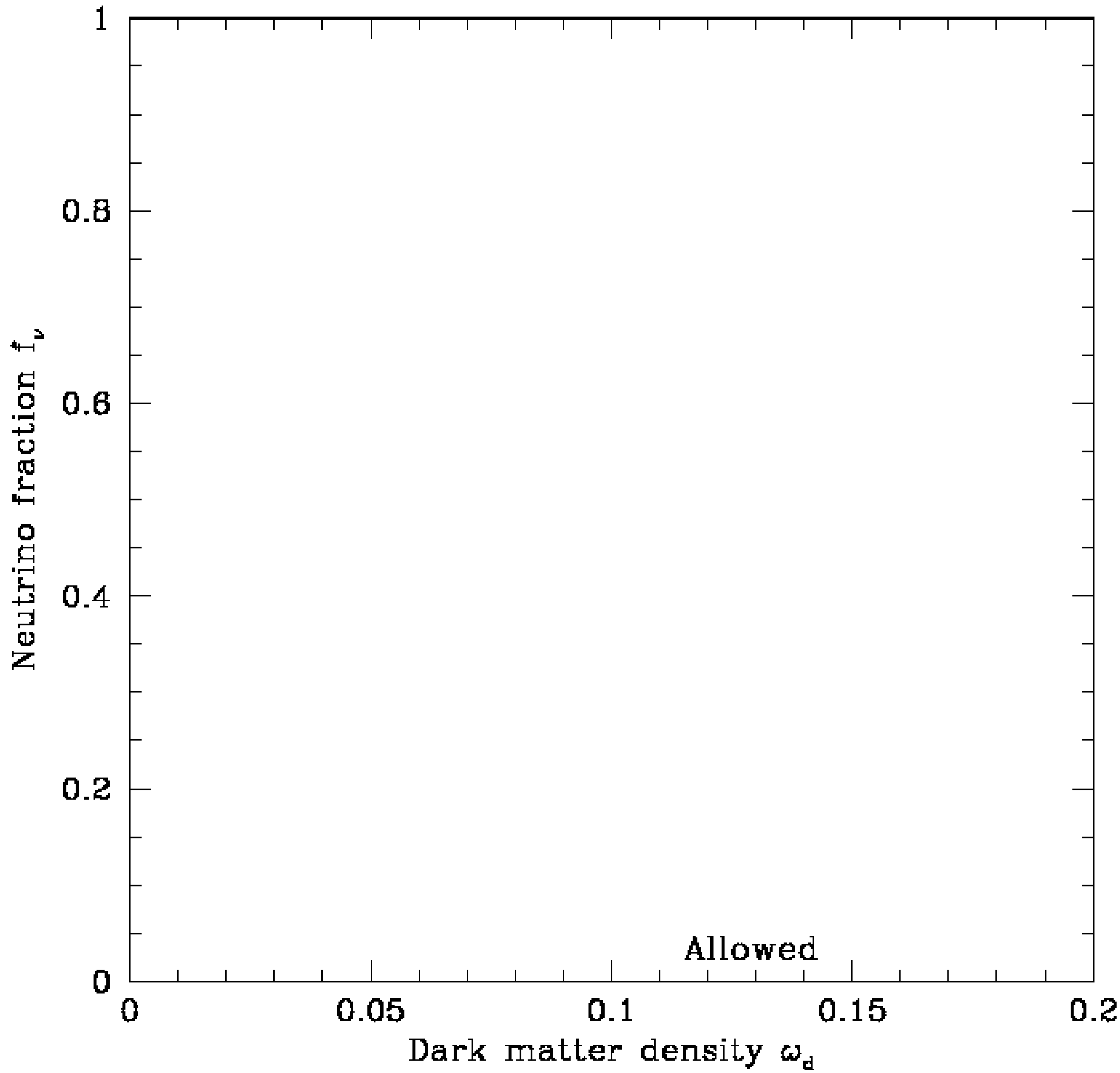
SDSS Galaxy Power Spectrum

Corrects for luminosity bias

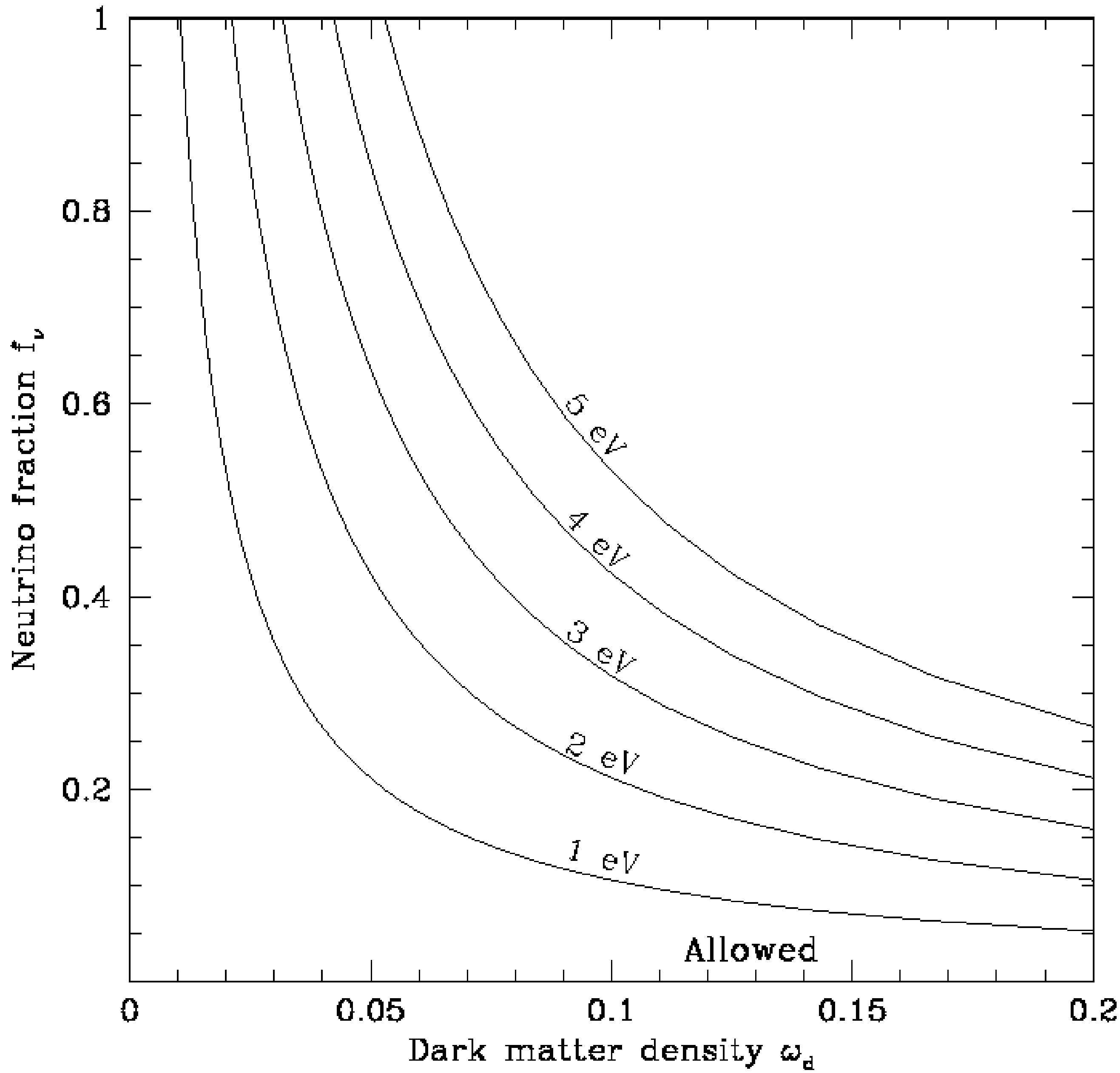
Pixelize and then apply FKP, etc.



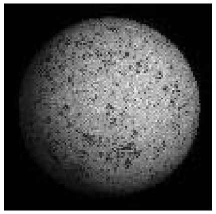
Tegmark et al. 2003



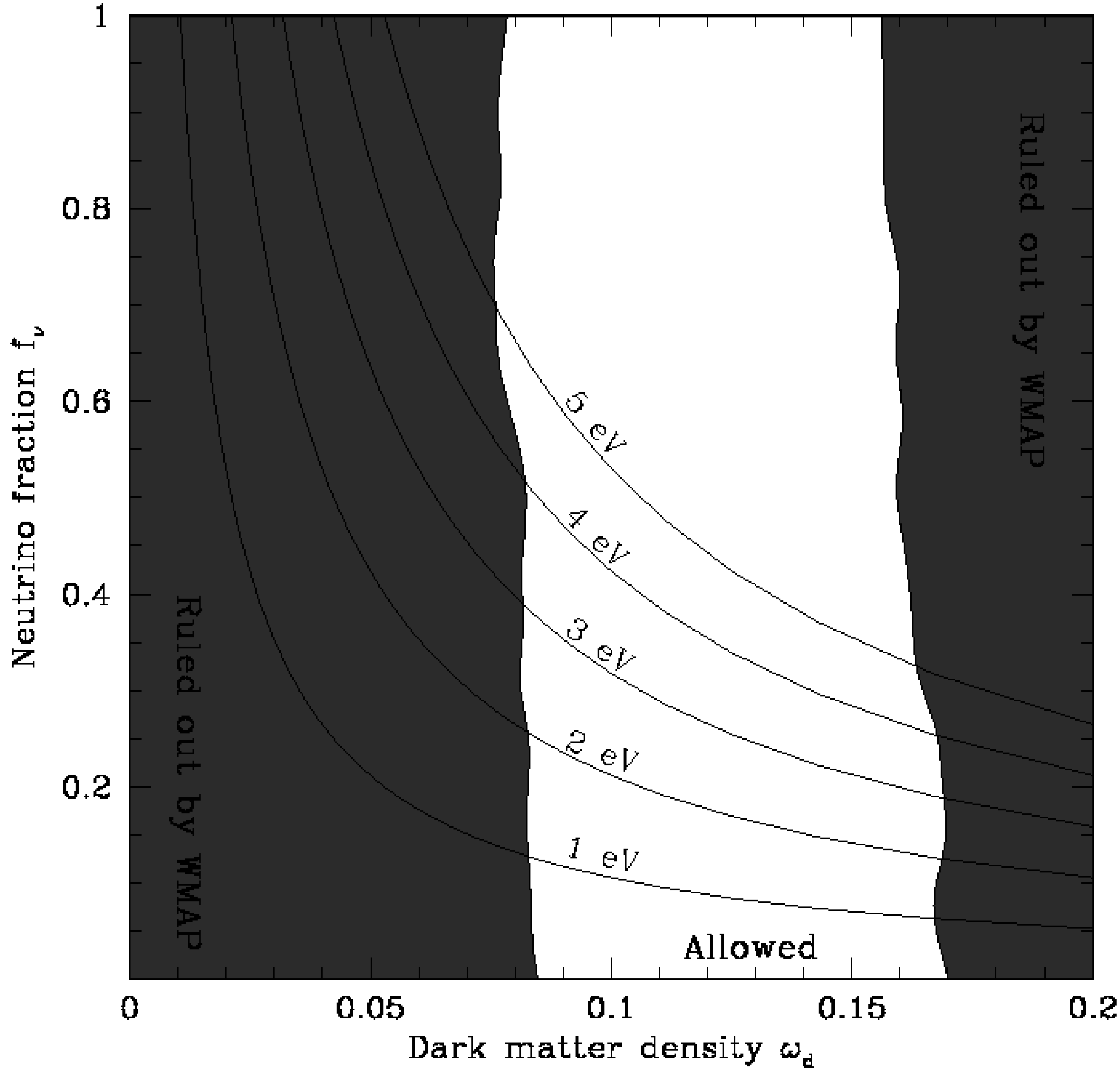
Neutrino fraction f_ν
Dark matter density ω_d
Allowed
0
0.2
0.4
0.6
0.8
1
0.05
0.1
0.15

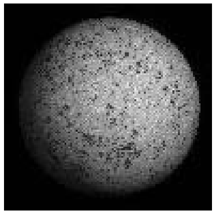


1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2
Neutrino fraction f_ν
Dark matter density ω_d
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed

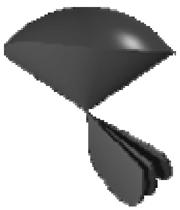


CMB

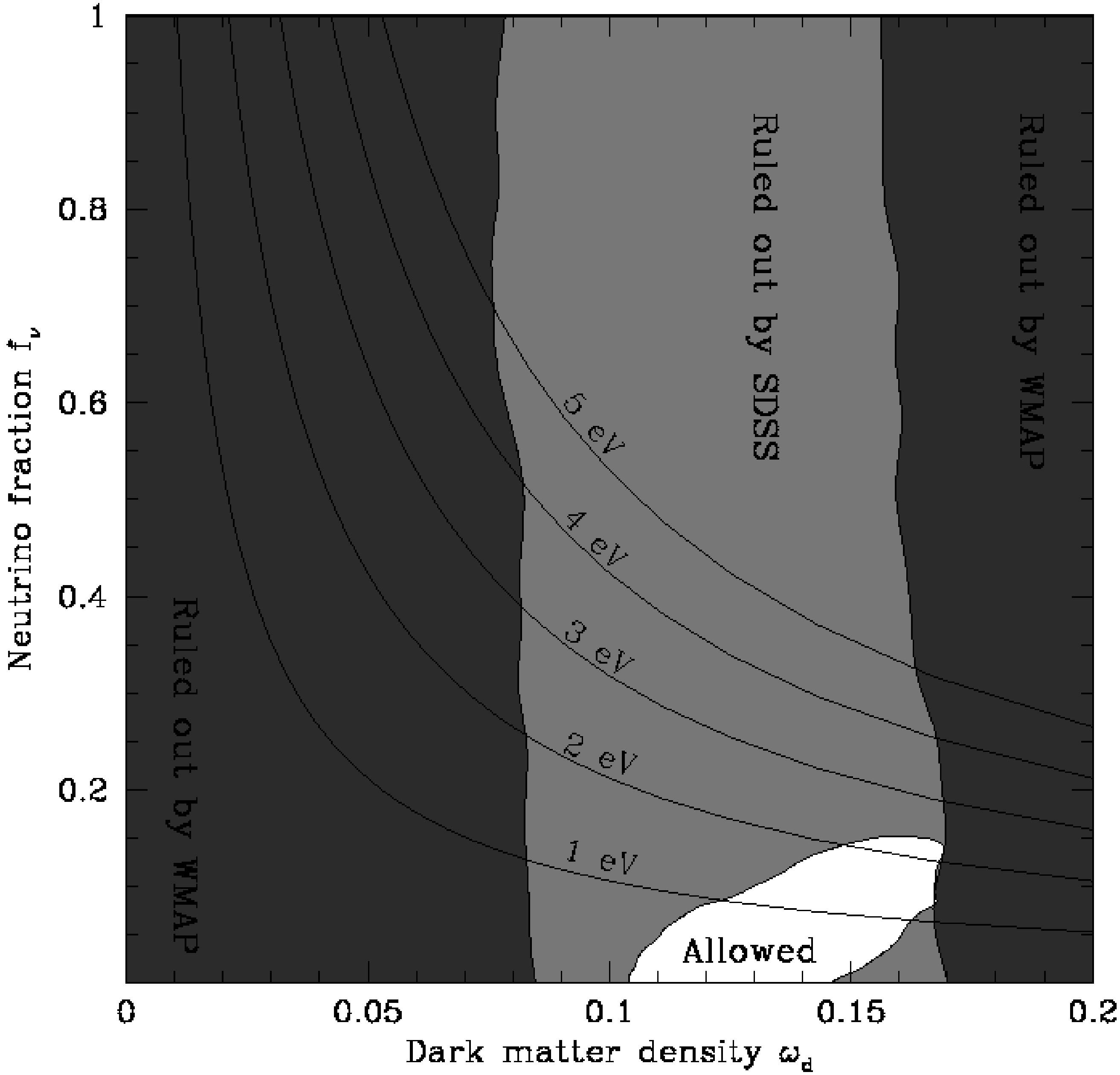

1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2
Neutrino fraction f_ν
Dark matter density ω_d
Ruled out by WMAP
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed



CMB
+



LSS

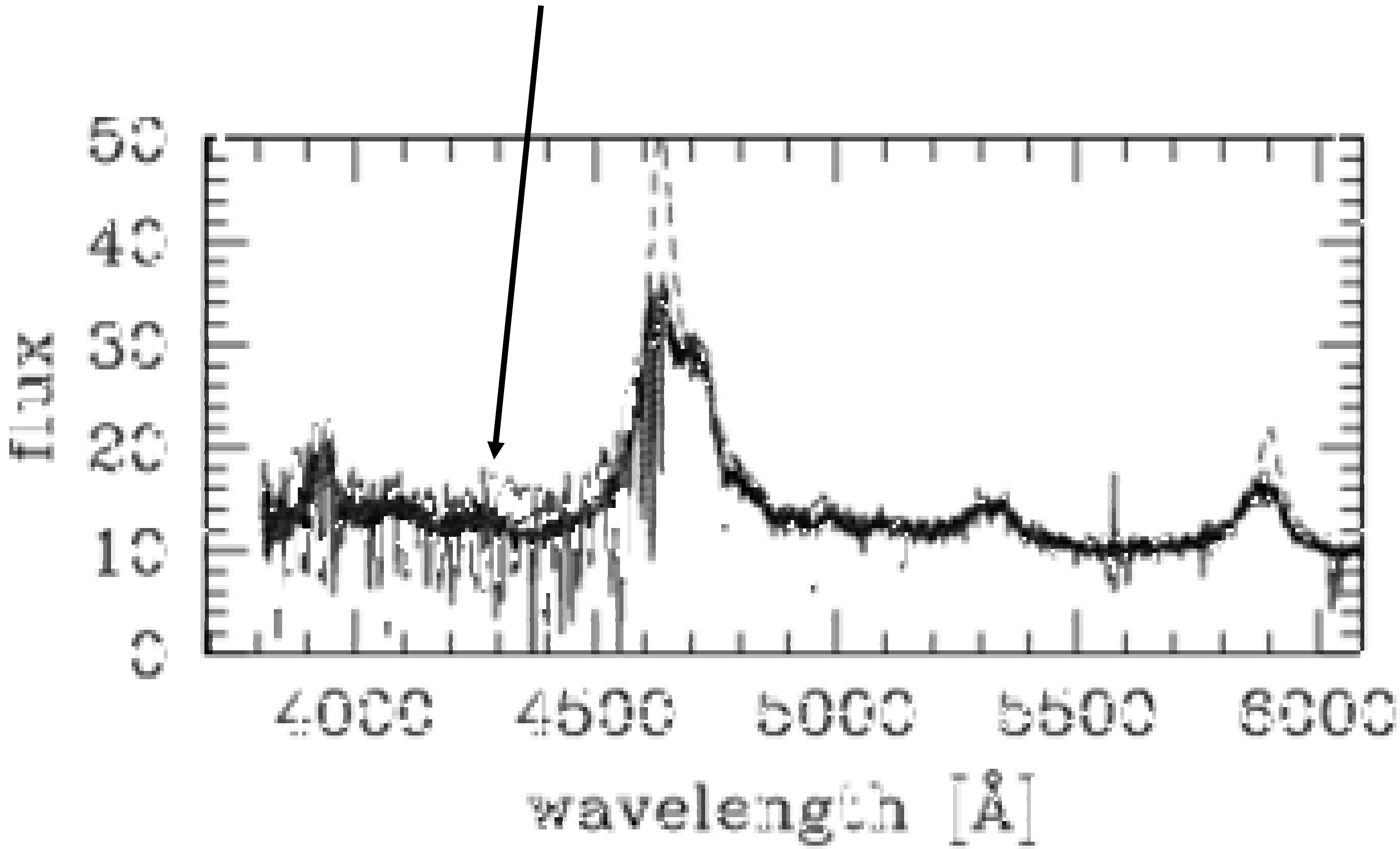


Ruled out by SDSS
Ruled out by WMAP
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed
Neutrino fraction f_ν
Dark matter density ω_d
0
0.05
0.1
0.15
0.2
0.2
0.4
0.6
0.8
1

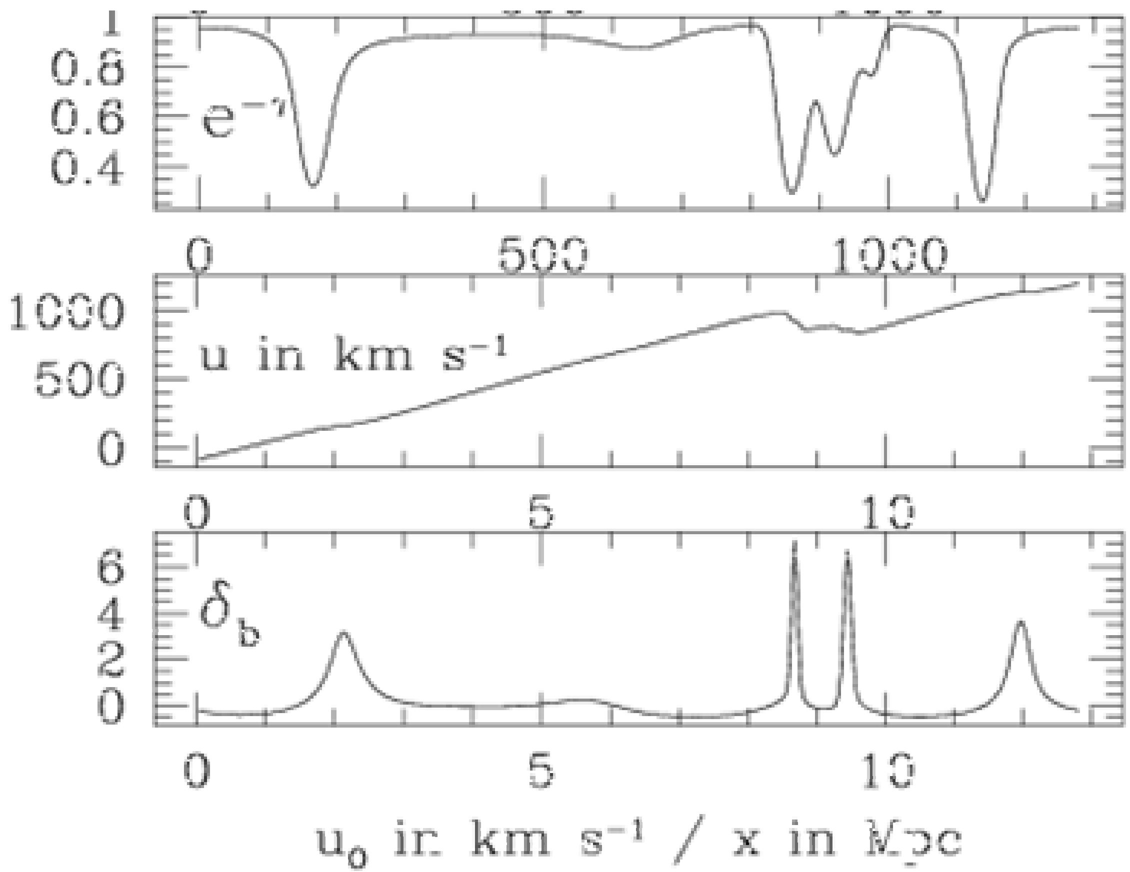
Lyman alpha forest

Photons with energy > (n=1 to n=2 transition energy) get absorbed along the line of sight as they lose energy due to cosmic redshift.

Every absorption line corresponds to *cloud* of neutral hydrogen.



Fluctuations in density mimicked by fluctuations in forest

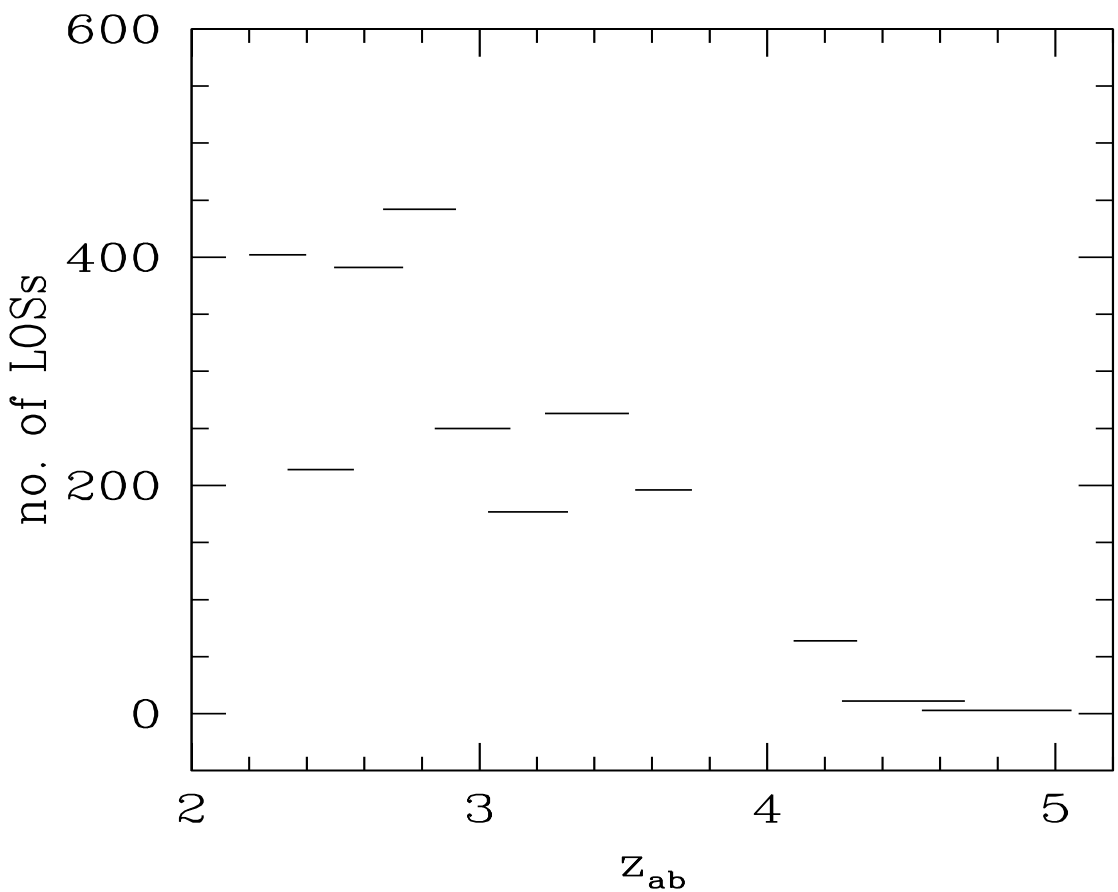


This is also a form of bias

Gnedin & Hui, 1997

SDSS: Lyman Alpha Forest

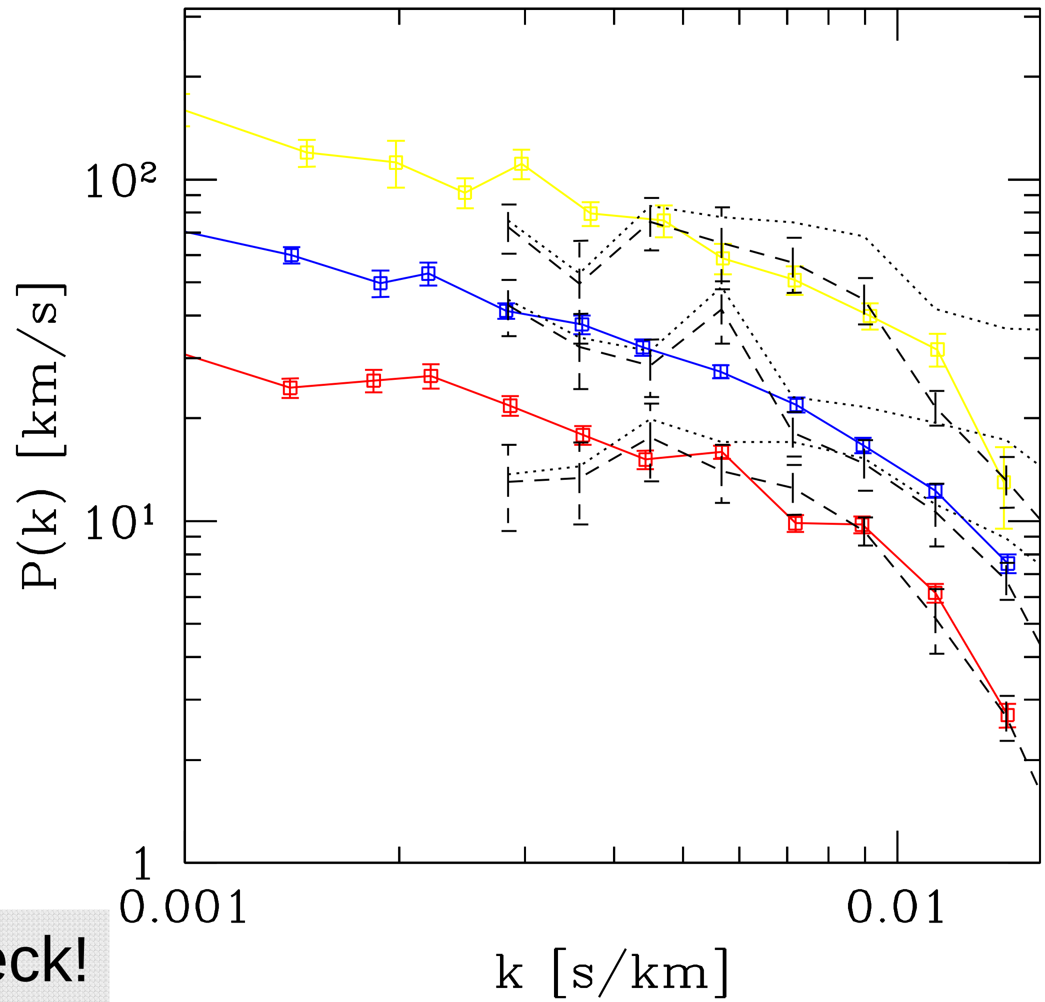
3000 QSOs with absorption lines from redshifts 2 to 4.2



Hui et al., 2004
McDonald et al., 2004

Results

- Dashed lines are from Keck; solid from SDSS
- 3 sets of curves from low (bottom) to high (top) redshift
- SDSS goes to larger scales, but doesn't have small scales resolution



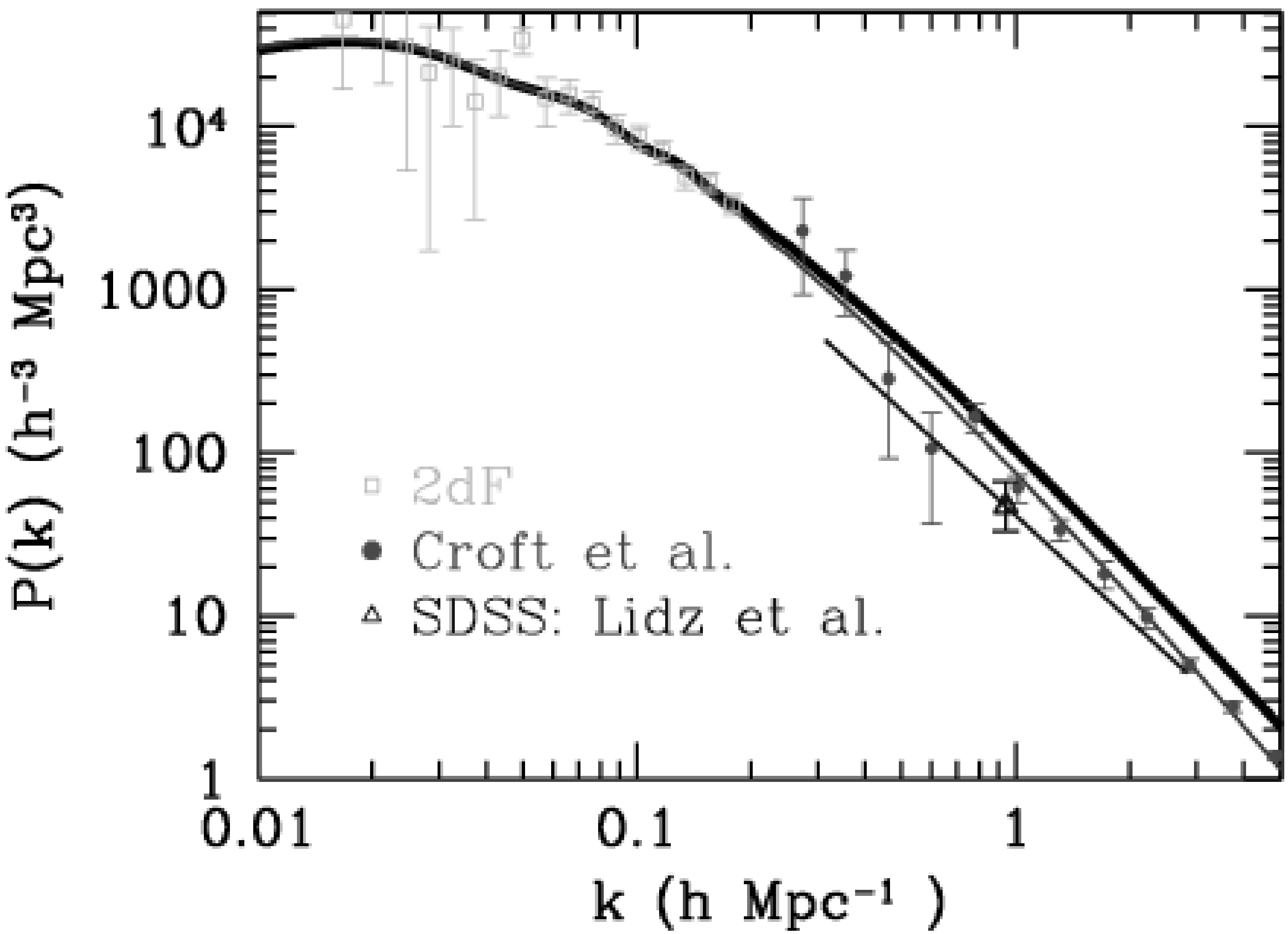
Good agreement with Keck!

Convert 1D Flux Spectrum to 3D Linear Matter Power Spectrum

- Run many simulations with CDM-like spectra
- Extract Flux power spectra from each simulation
- Fit amplitude and slope of power at 1 Mpc

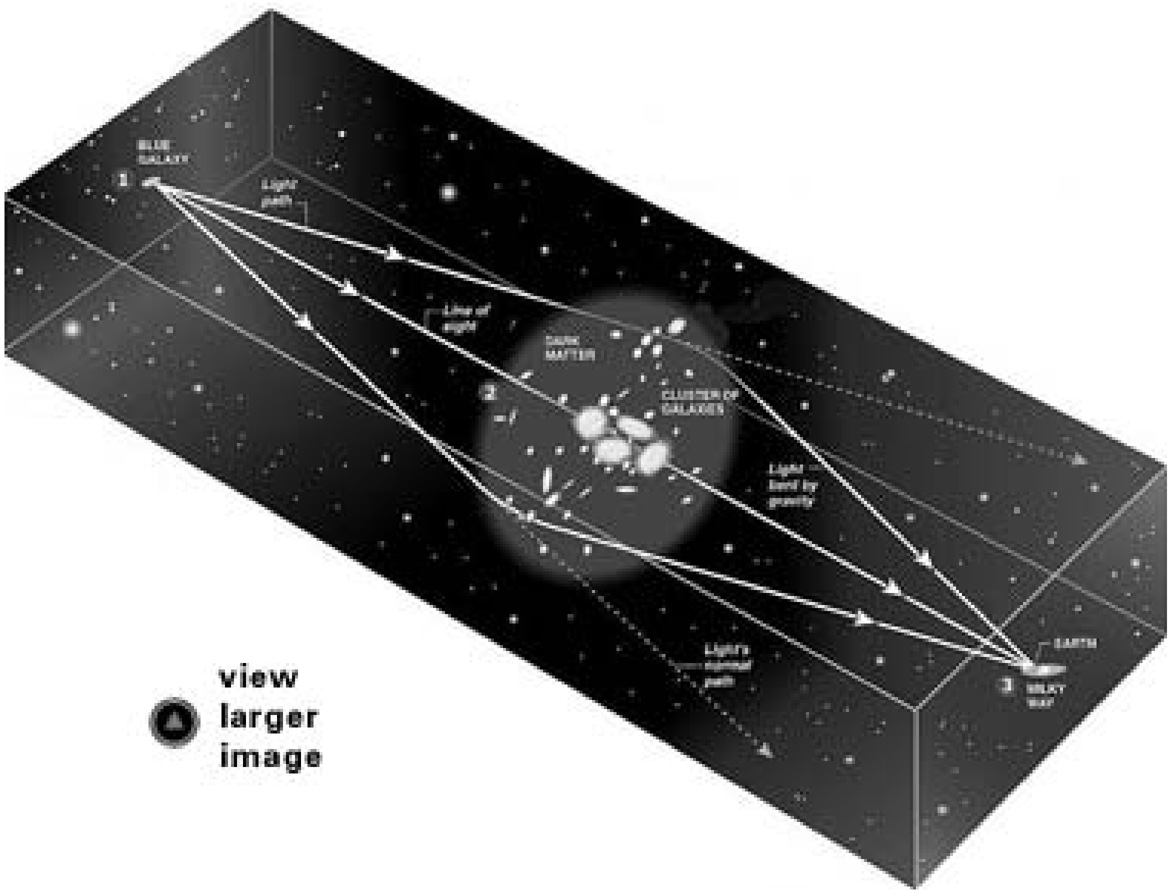
Lidz et al.

3D Power Spectrum



Future

Weak Gravitational Lensing



Unlike galaxy surveys and Lyman alpha, lensing directly probes mass distribution!

Lensing is sensitive to neutrino mass

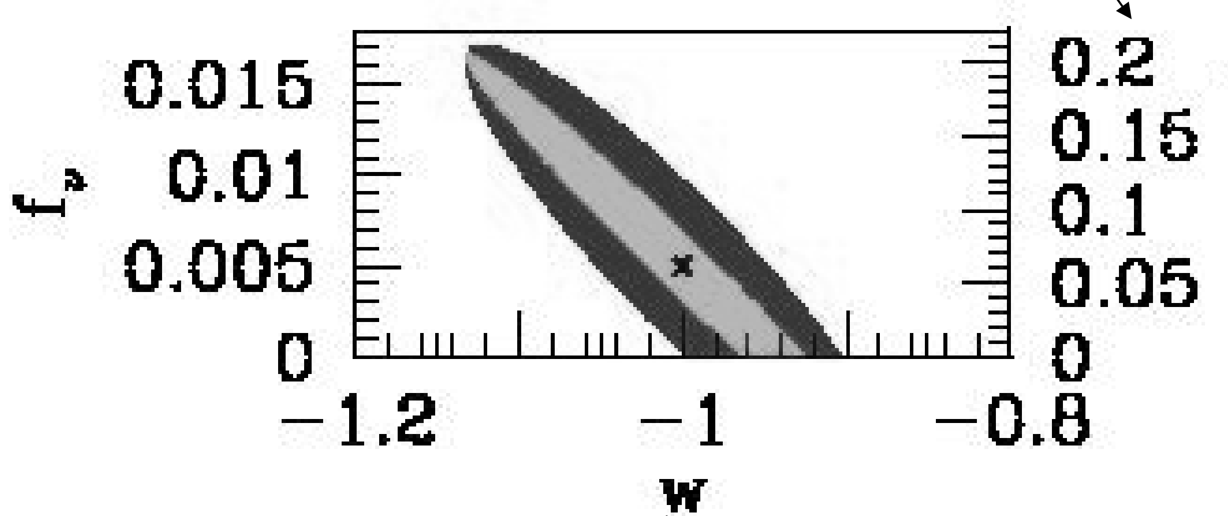
- Break up background galaxies into distinct redshift bins
- Probe time evolution of gravitational potential (sensitive to neutrino mass)

Future

Weak Lensing

- •Measure power spectrum AND/OR measure growth of spectrum at late time
- • Sensitive to ν mass AND dark energy
- • Accelerator ν experiments will teach us about dark energy!

Neutrino mass (eV)



Abazajian & Dodelson (2003)

Dark energy equation of state

Is there a way out?

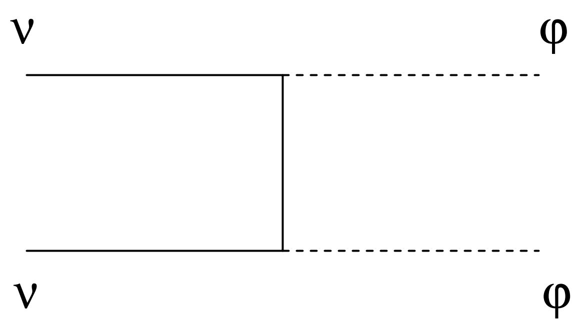
- We assumed neutrinos stop interacting at 1 MeV
- If they continued interacting, staying in equilibrium, their abundance would drop as exp(-m/T)
- No neutrinos around to inhibit structure formation!

Beacom, Bell, & Dodelson 2004

This can be done ...

- … if neutrinos interact with a massless scalar field

$$L \sim g\phi\nu\nu$$

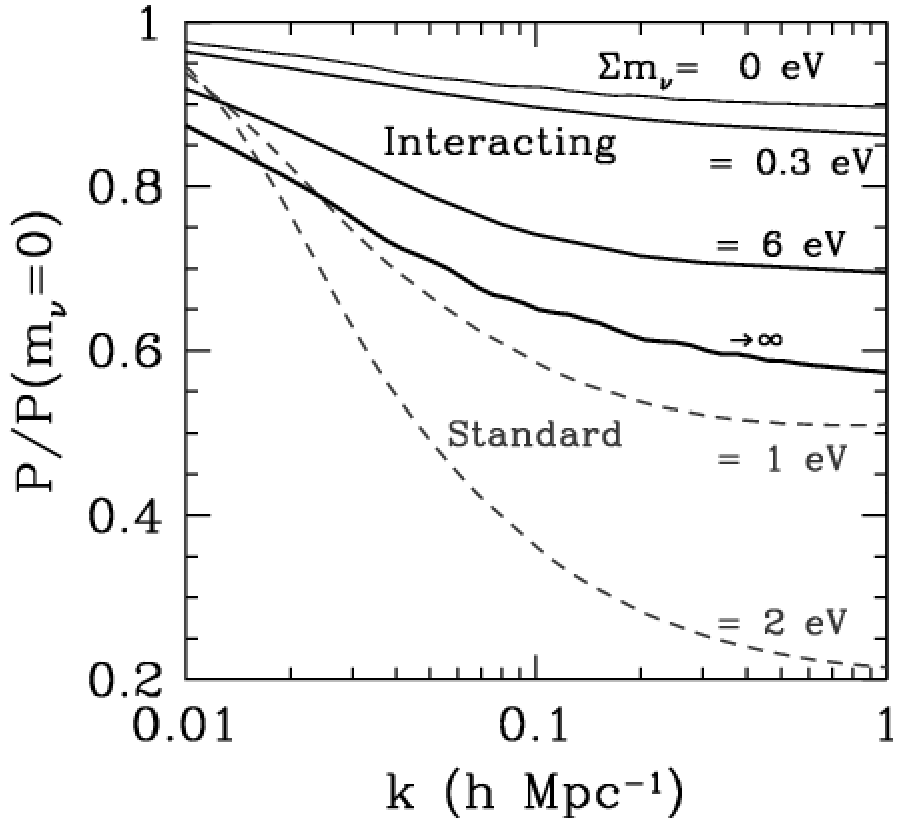


- To enforce equilibrium, require

$$g^4 T > H(T) \rightarrow g > 10^{-5.5}$$

Extra degrees of freedom leave minor impact on power spectrum

… but even large neutrino massses are currently allowed



Conclusion

- Cosmological constraints on neutrino mass (<1.8 eV total) arise from *power spectrum*

- Wide variety of techniques/experiments needed to eliminate systematics

- We must all become familiar with: Big Bang cosmology, large scale structure, dark energy, inflation, cosmic microwave background, …

Modern Cosmology

Scott Dodelson

Modern Cosmology begins with an introduction to the smooth, homogeneous universe described by a Friedman-Robertson-Walker metric, including careful treatments of dark energy, big bang nucleosynthesis, recombination, and dark matter. From this starting point, the reader is introduced to perturbations about an FRW universe: their evolution with the Einstein-Boltzmann equations, their generation by primordial inflation, and their observational consequences. These consequences include the anisotropy spectrum of the cosmic microwave background (CMB) featuring acoustic peaks and polarization, the matter power spectrum with baryonic wiggles, and their detection via photometric galaxy surveys, redshift distortions, cluster abundances, and weak lensing. The book concludes with a long chapter on data analysis. Modern Cosmology is the first book to explain in detail the structure of the acoustic peaks in the CMB, the E/B decomposition in polarization which may allow for detection of primordial gravity waves, and the modern analysis techniques used on increasingly large cosmological data sets. Readers will gain the tools needed to work in cosmology and will learn how modern observations are rapidly revolutionizing our picture of the universe.

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