Neutrinos and the Universe: Cosmology

- Neutrino Abundance
- Constraints on Neutrino Masses

Neutrinos are produced in the early universe

Alpher, Herman, & Gamow 1953

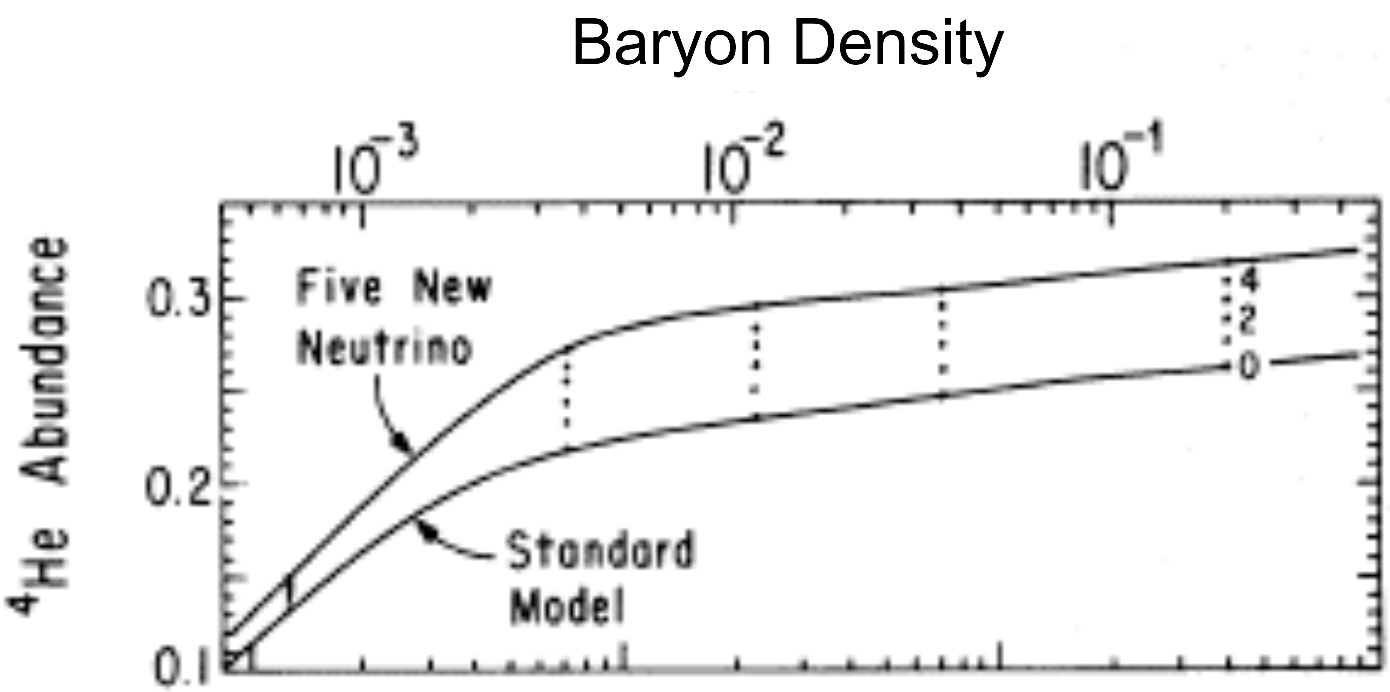
- Neutrinos interact very weakly: need high temperatures/energies
- Early on, the universe was much hotter, so the rate for, e.g.

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

was very large

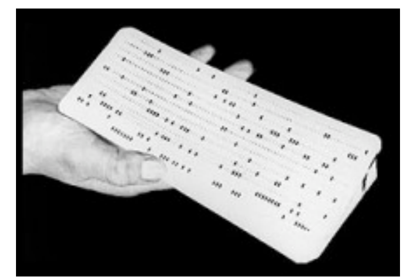
Expect about as many neutrinos in the universe today as photons (37 N_ν cm^{-3} , trillions passing through this screen every second)

Number of Neutrinos affects the abundances of light elements



*Yang, Schramm, Steigman, & Rood (**1979!)***

Multiple techniques:



Notation

Cosmologists measure densities in units of the *critical density*,

$$\rho_{cr} = 1.88\, h^2 \times 10^{-29}\ \mathrm{g\ cm^{-3}}$$

where *h* defines the Hubble constant

$$H_0 = 100h\ \mathrm{km\ sec^{-1}\ Mpc^{-1}}$$

Two popular ways of writing the baryon density are:

$$\Omega_b = \rho_b / \rho_{cr}$$

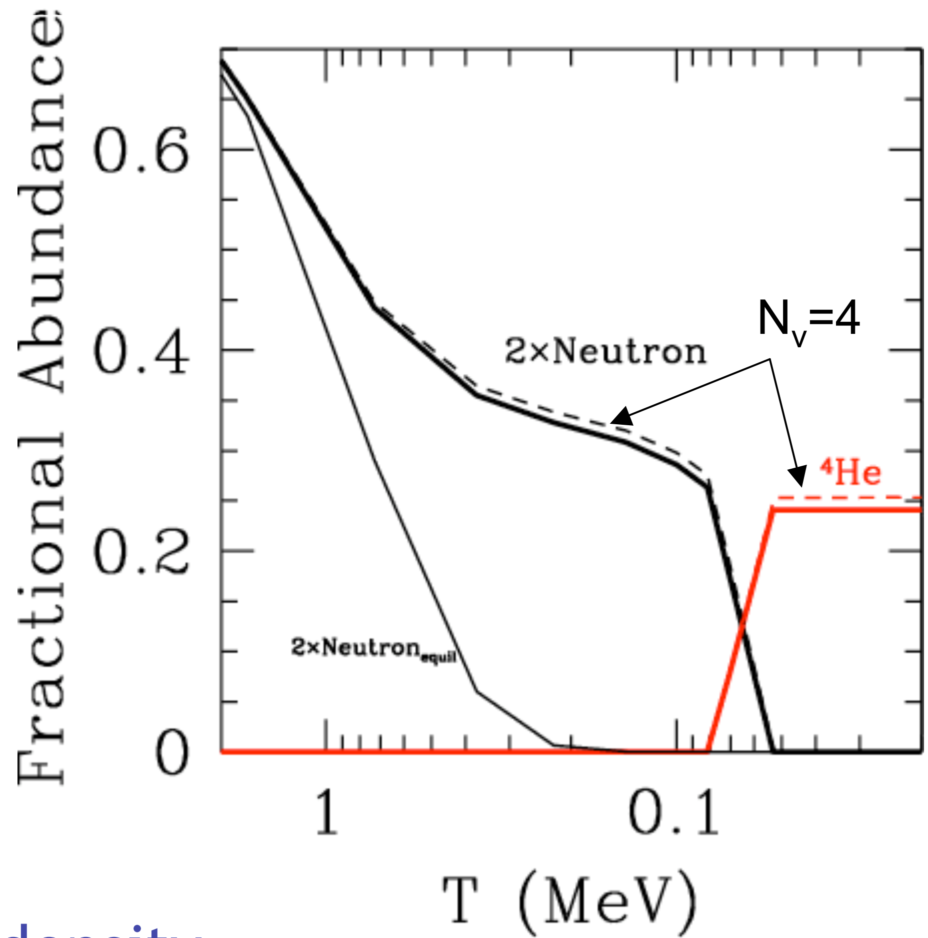
$$\omega_b = \Omega_b h^2$$

Primordial Neutrons → Helium

Neutrons do **not** stay in equilibrium because weak interactions become slower than expansion rate

What happens if the number of neutrino species differs from 3?

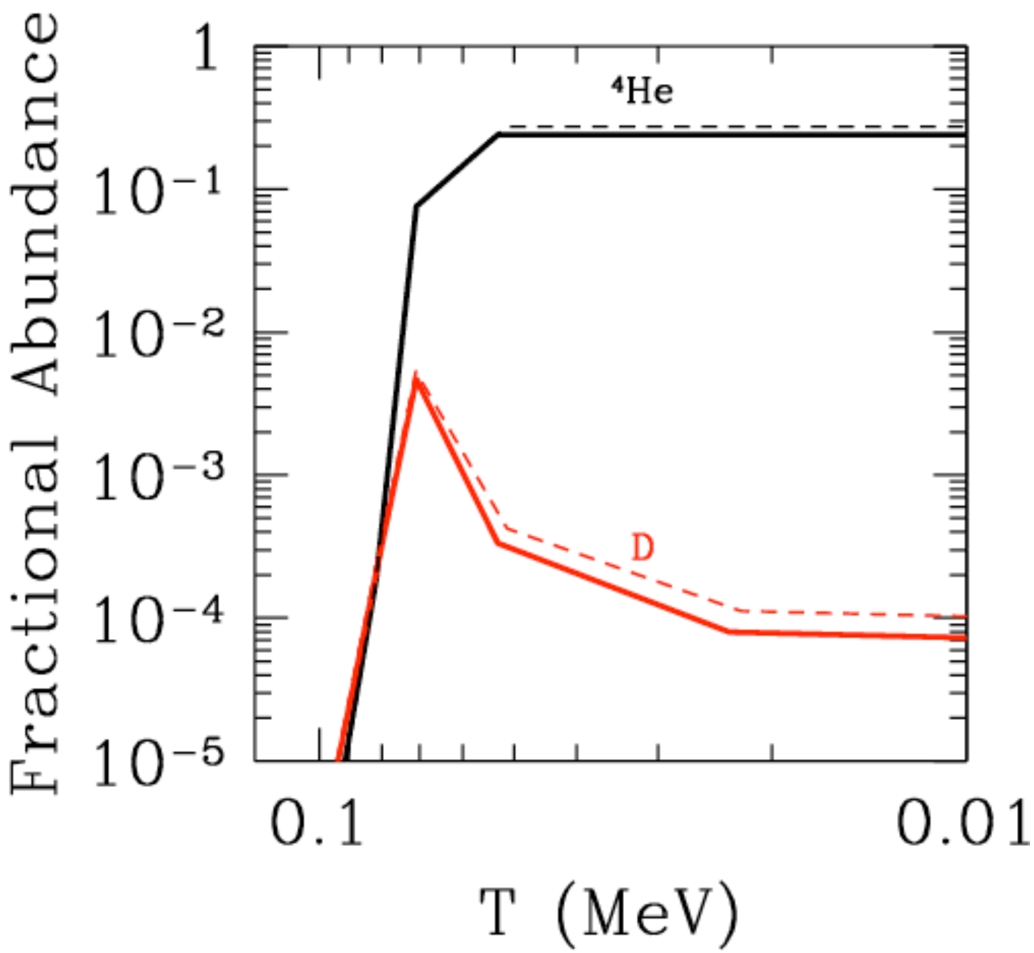
Hint: Expansion Rate is proportional to energy density



Residual Deuterium also affected

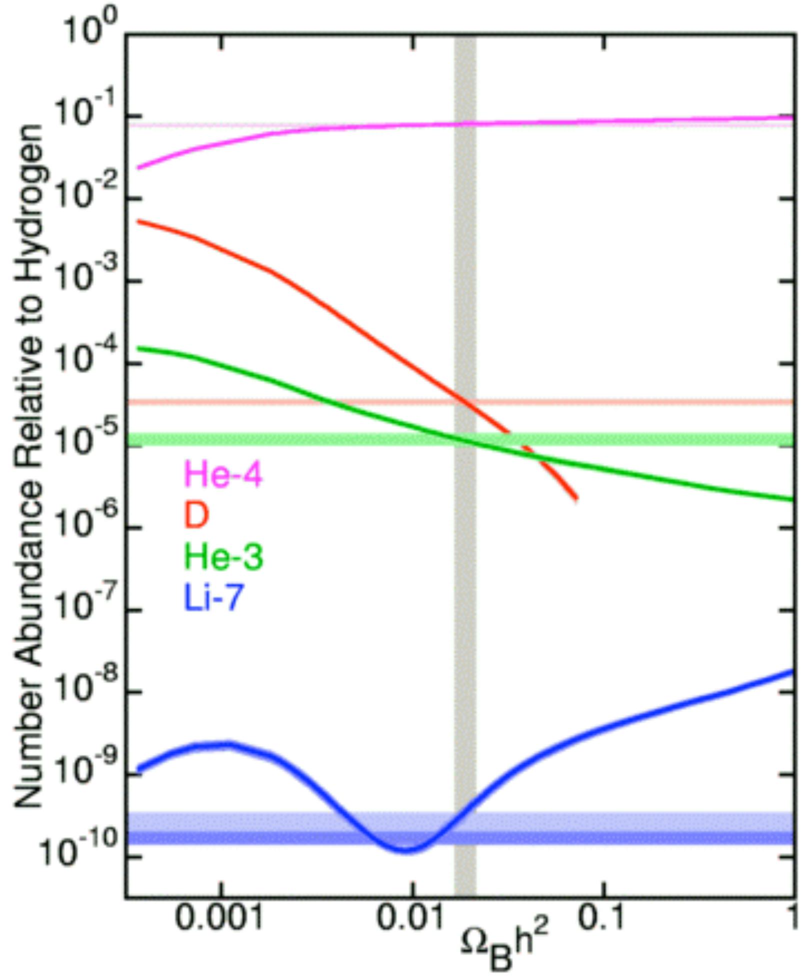
Small amount of deuterium does not get converted into helium.

If the expansion rate is *larger*, conversion reactions become *less* efficient and *more* deuterium is left over



Standard Model (N_ν=3) Agrees well with Data

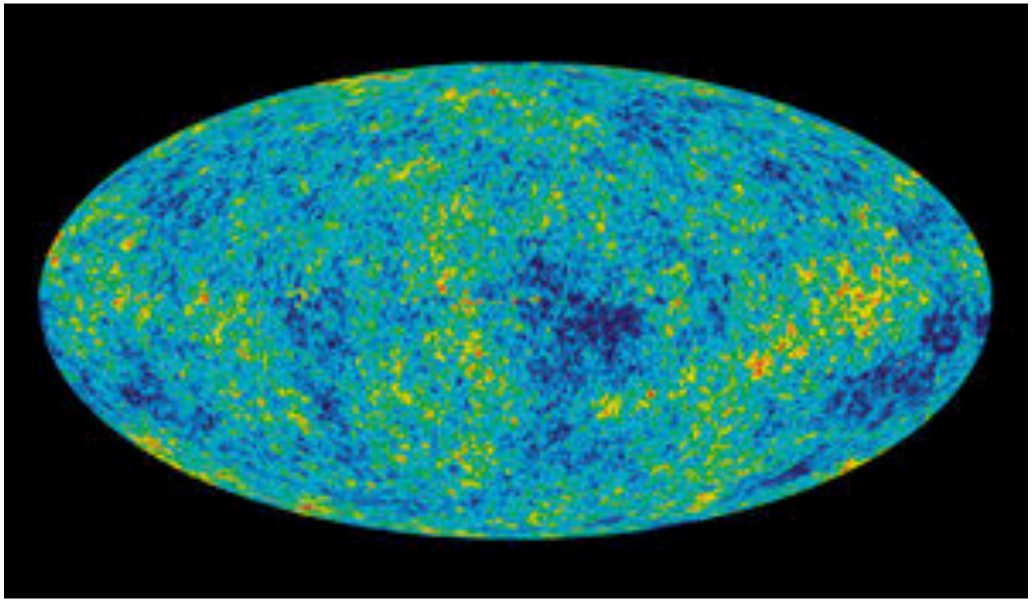
Might expect tight constraints, but …



Beware of Degeneracies

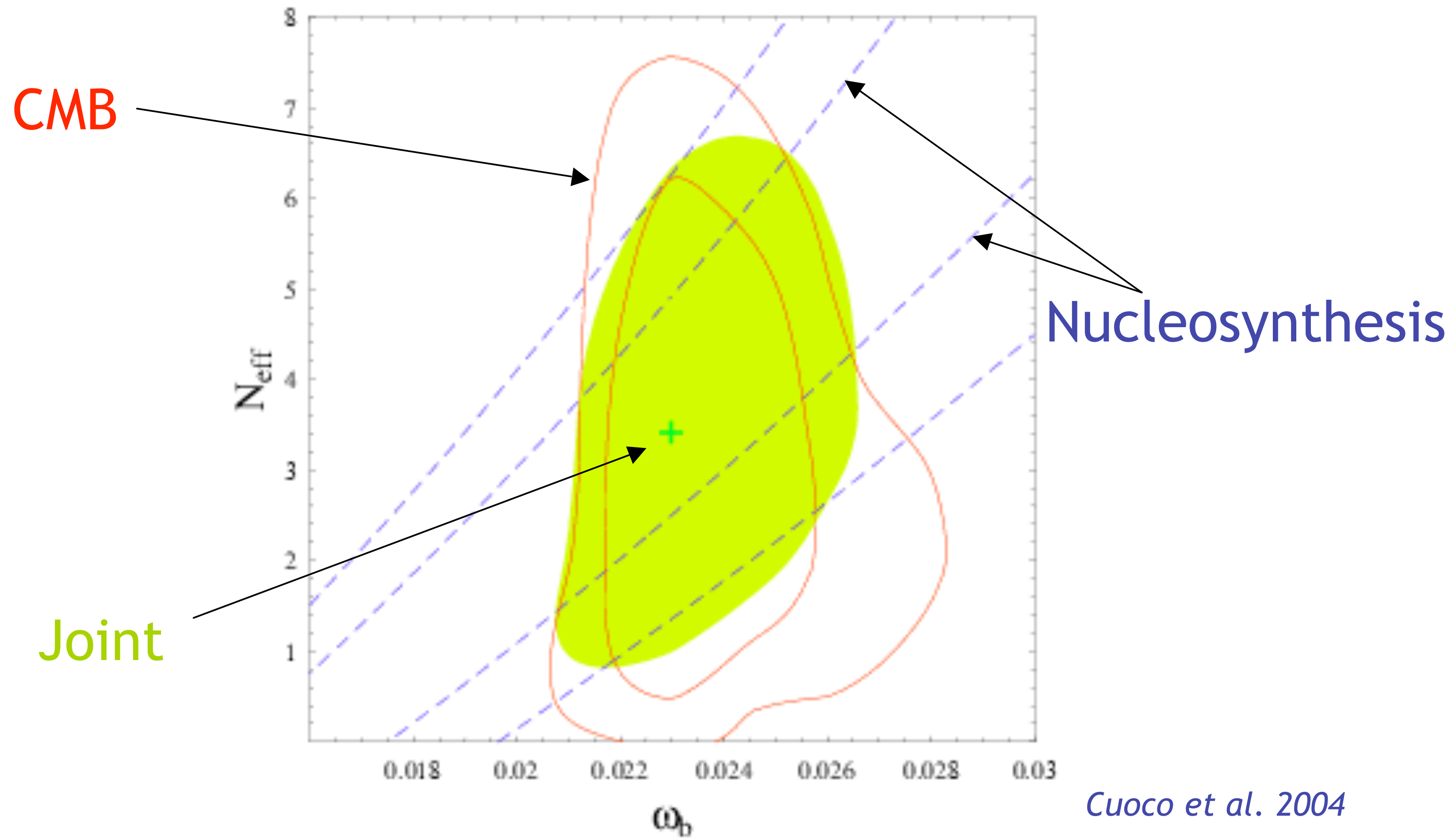
Can offset extra neutrinos by changing baryon density

The Cosmic Microwave Background (CMB) provides complementary information by measuring the baryon density very accurately



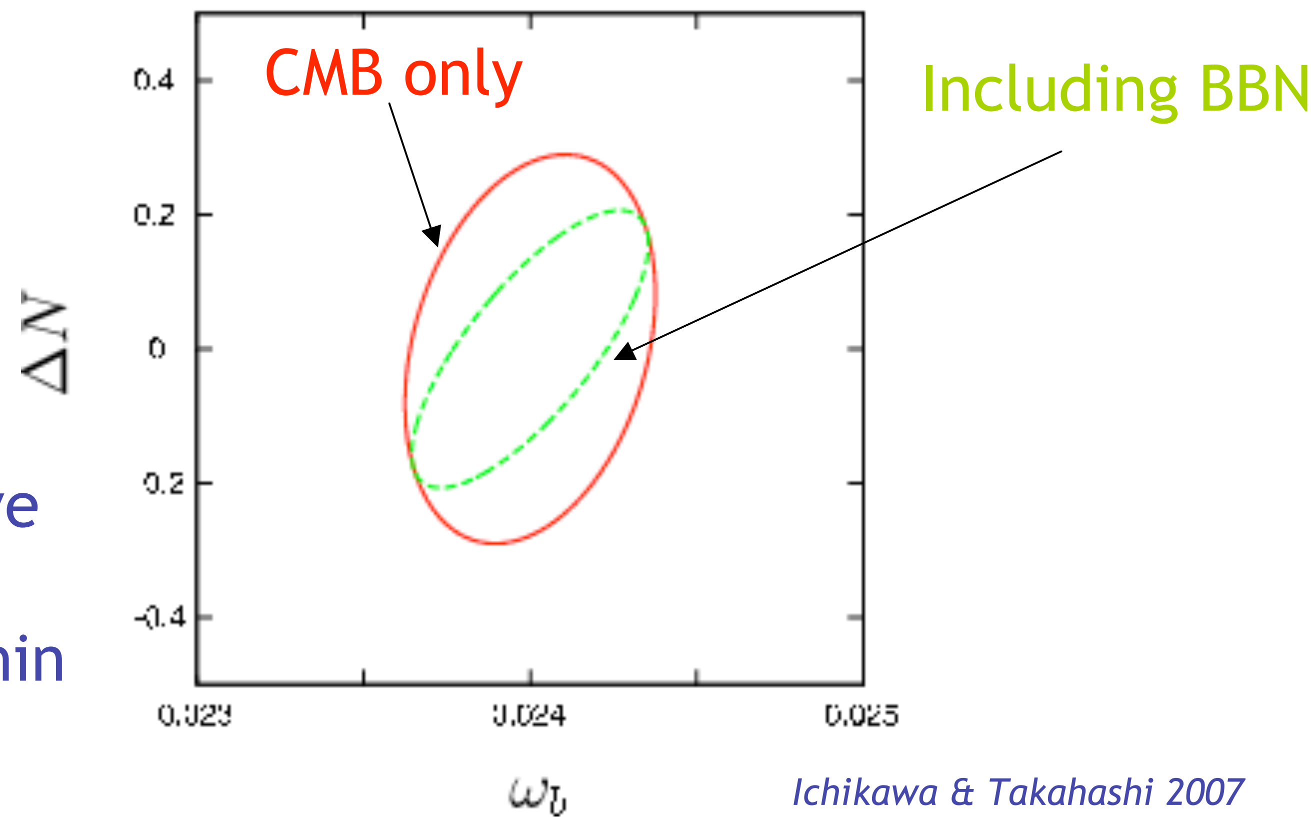
WMAP

CMB+BBN have 3-sigma evidence for neutrino background



Cuoco et al. 2004

The Planck satellite will tightly constrain neutrino abundance



Ichikawa & Takahashi 2007

We should have a 10-sigma detection within 5 years

Massive Neutrinos affect large scale structure

- We know the neutrino abundance in the universe:
- Neutrinos stream out of overdense regions *after* structure starts to grow.
- Less clustering in universe with massive neutrinos

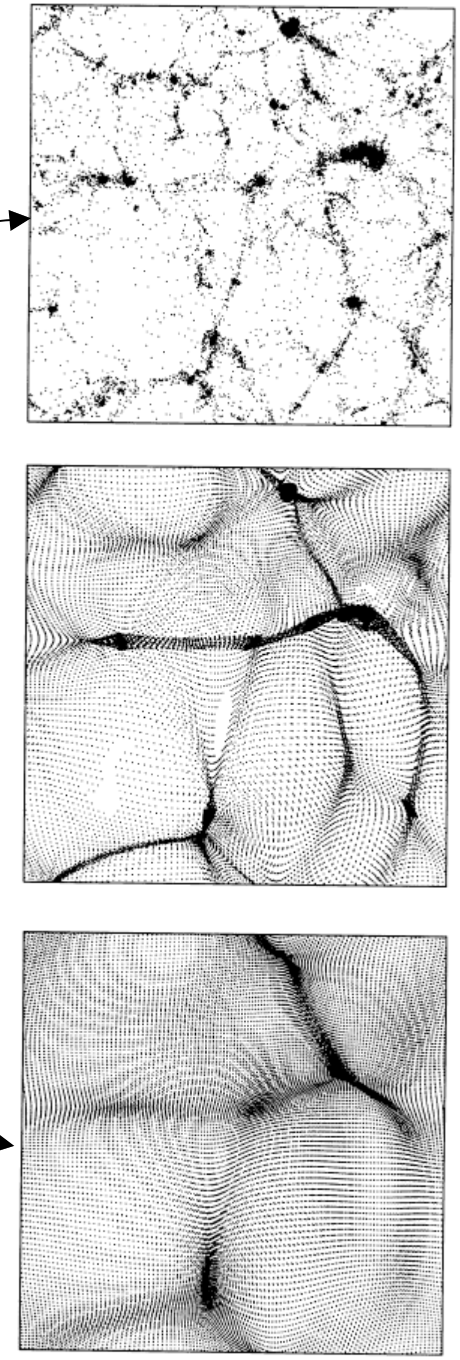
$$\frac{\rho_\nu}{\rho_{critical}} = \frac{m_\nu n_\nu}{\rho_{critical}} = 0.02\frac{m_\nu}{1\,eV}$$

Compare this to the total matter density $\Omega_m \approx 0.25$

Cold Dark Matter
(no neutrino mass)

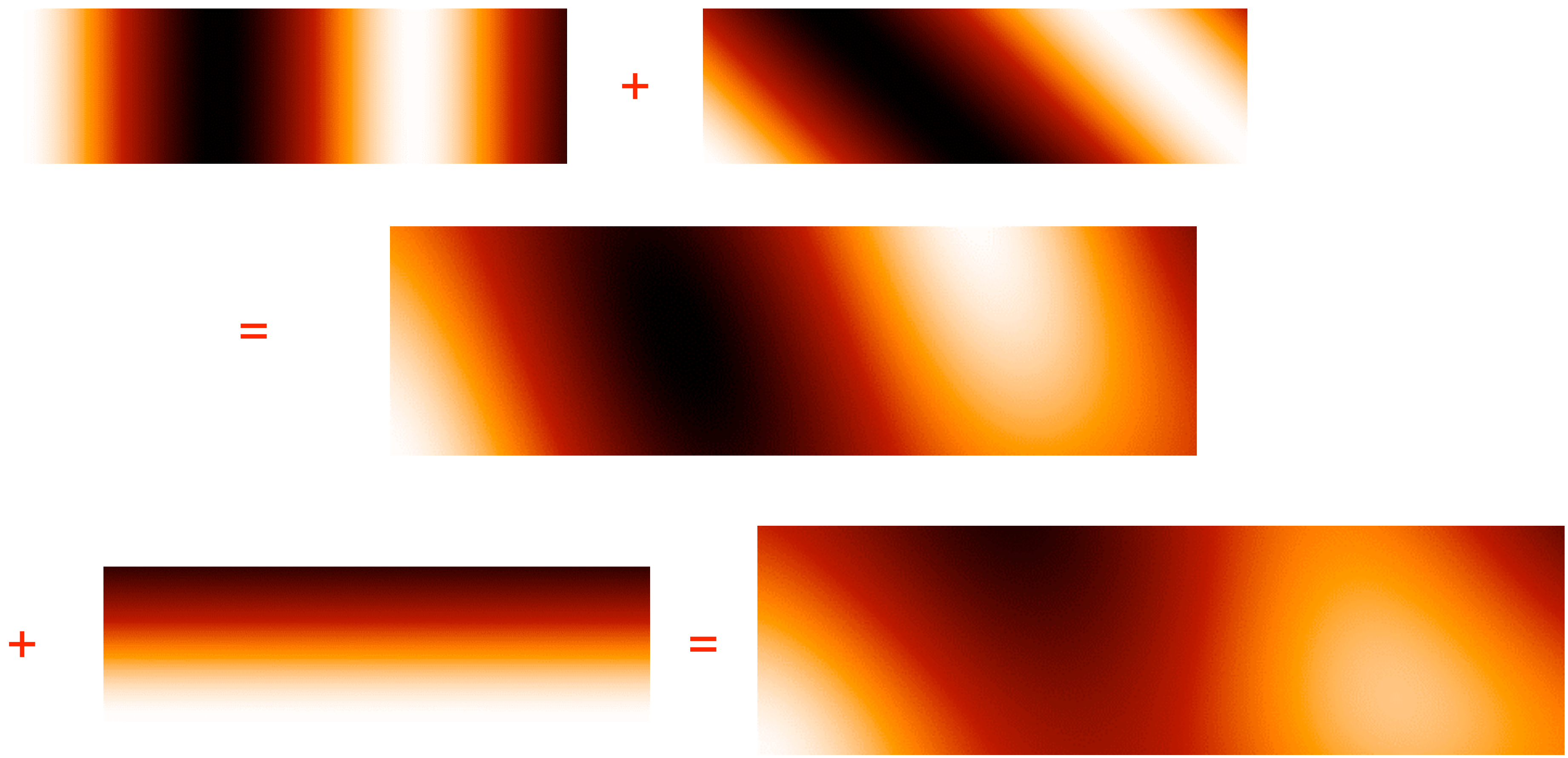
If neutrino density is a non-negligible fraction of the matter density, small scale structure is inhibited.

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

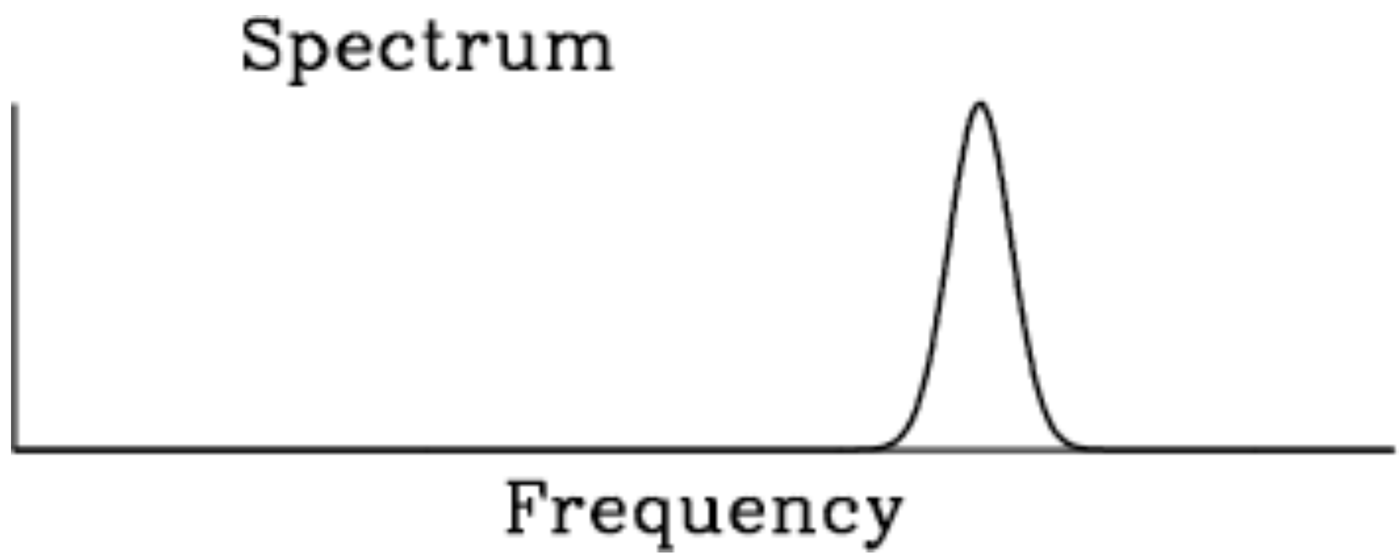


Colombi, Dodelson, & Widrow 1995

To analyze quantitatively, decompose into Fourier modes



In this simple example, all modes have have wavelength/frequency



More generally, at each wavelength/frequency, need to average over many modes to get spectrum

Why are massive neutrinos like a tuning fork?

C string on a ukulele

C note on a tuning fork

Clumping on Scale *k*

- Dimensionless quantity akin to $l^2 C_l$

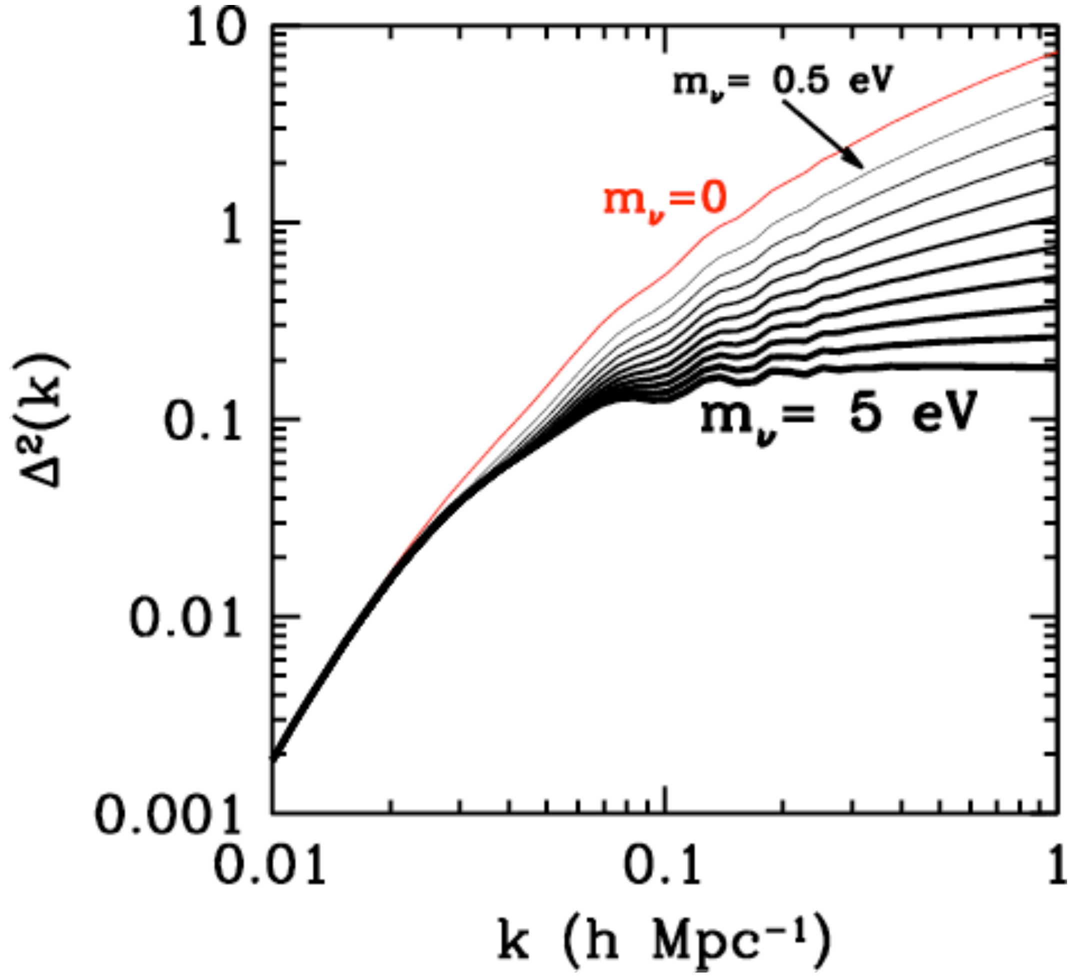
$$\Delta^2 \equiv \frac{k^3 P(k)}{2\pi^2}$$

- Variance of density:

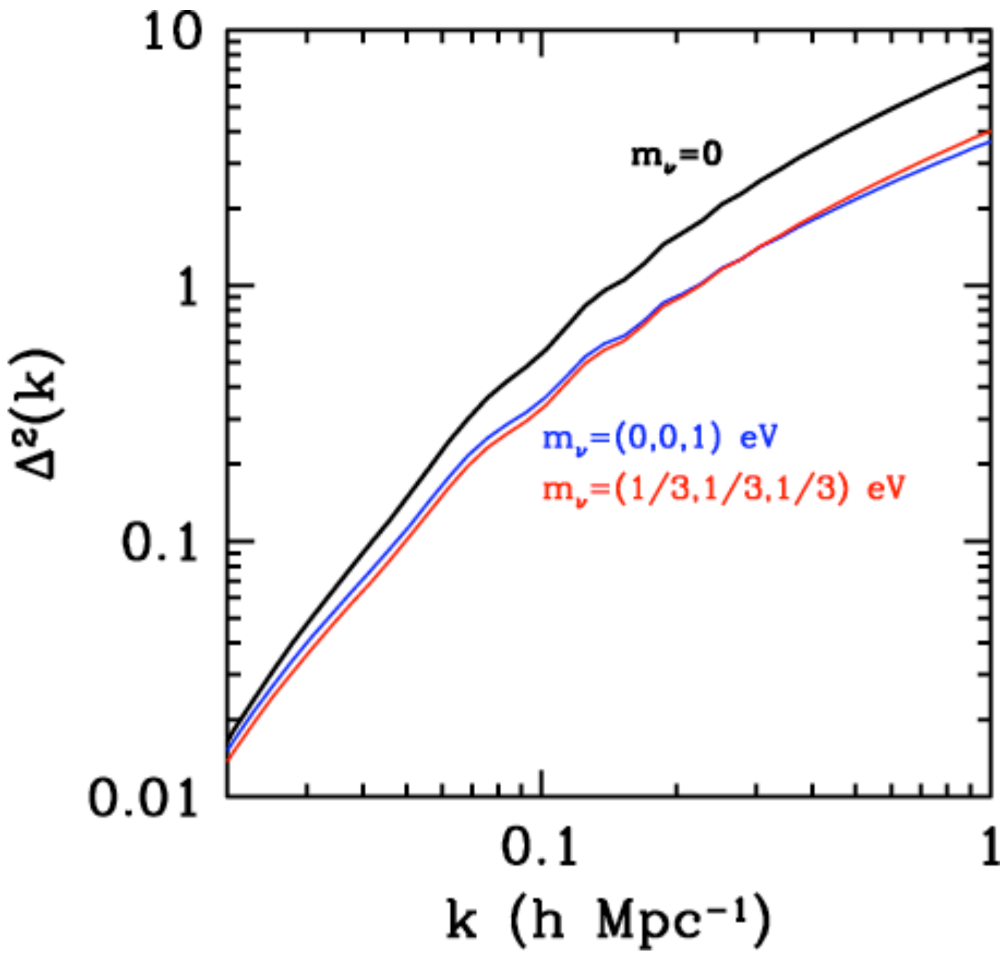
$$\left\langle \left(\frac{\delta\rho}{\rho} \right)^2 \right\rangle = \int \frac{dk}{k} \Delta^2(k)$$

- Onset on nonlinearity: $\Delta^2 > 1$

Massive Neutrinos Suppress Power on Small Scales



Power spectrum depends only on massive neutrino energy density



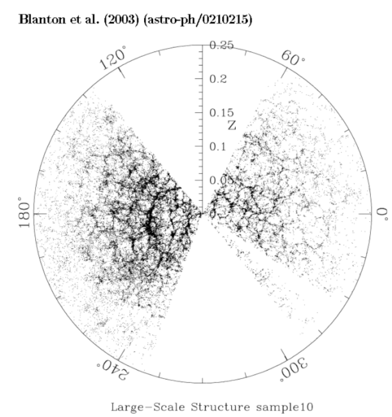
Large Scale Structure probes Σm_ν

How do we probe the matter distribution?

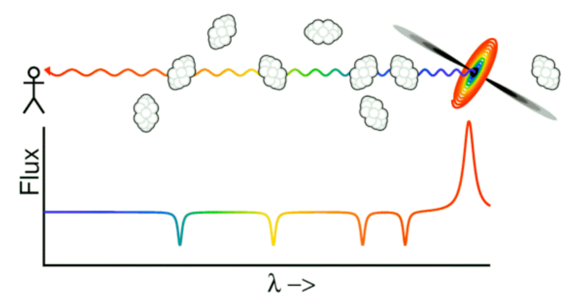
Most of the matter in the universe is dark, i.e. does not emit light. How can we probe its distribution?

There are several tracers of the *matter* power spectrum

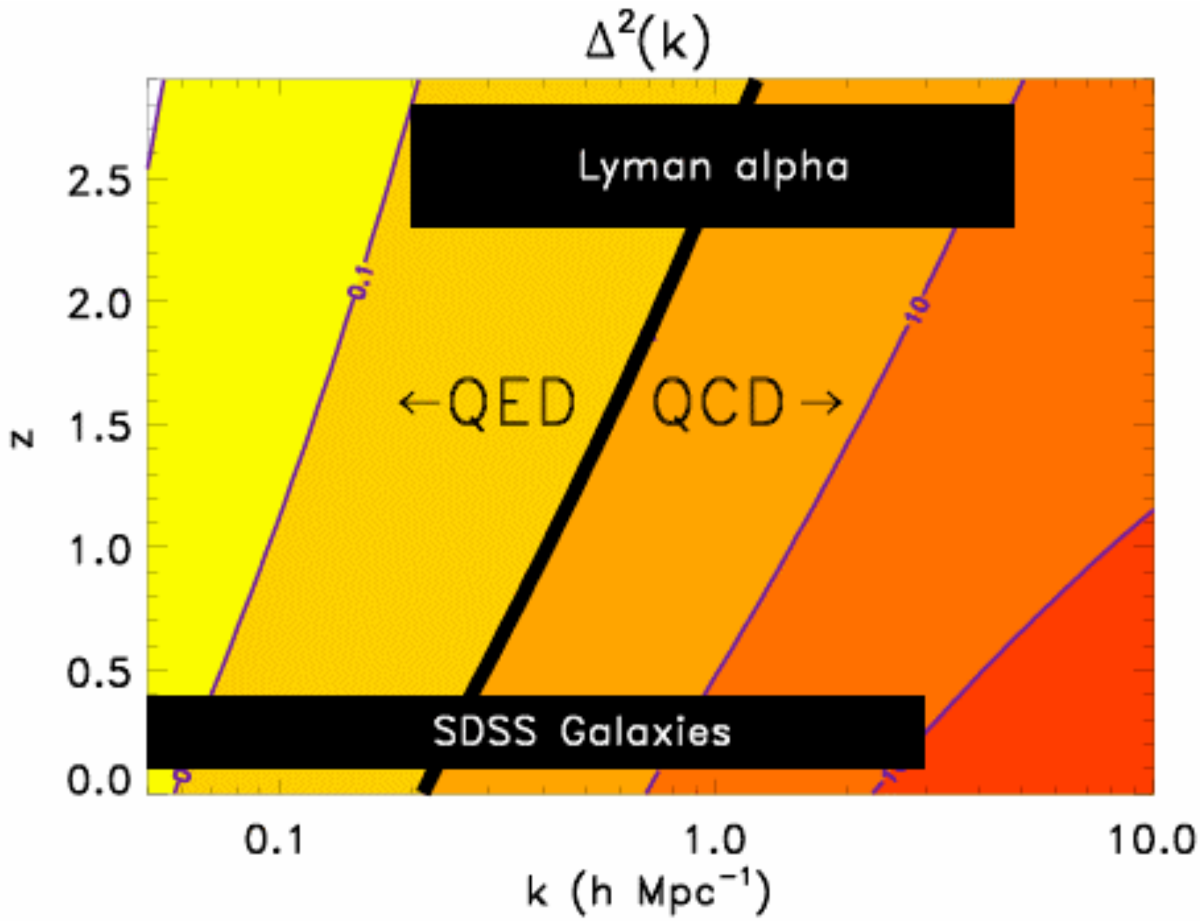
- Galaxy Distribution
  Should trace matter distribution on large scales. Difference is called *bias.*



- Lyman alpha (n=1→2 transition of H) Forest
  Regions w/ lots of absorption (neutral Hydrogen) correspond to overdense regions.



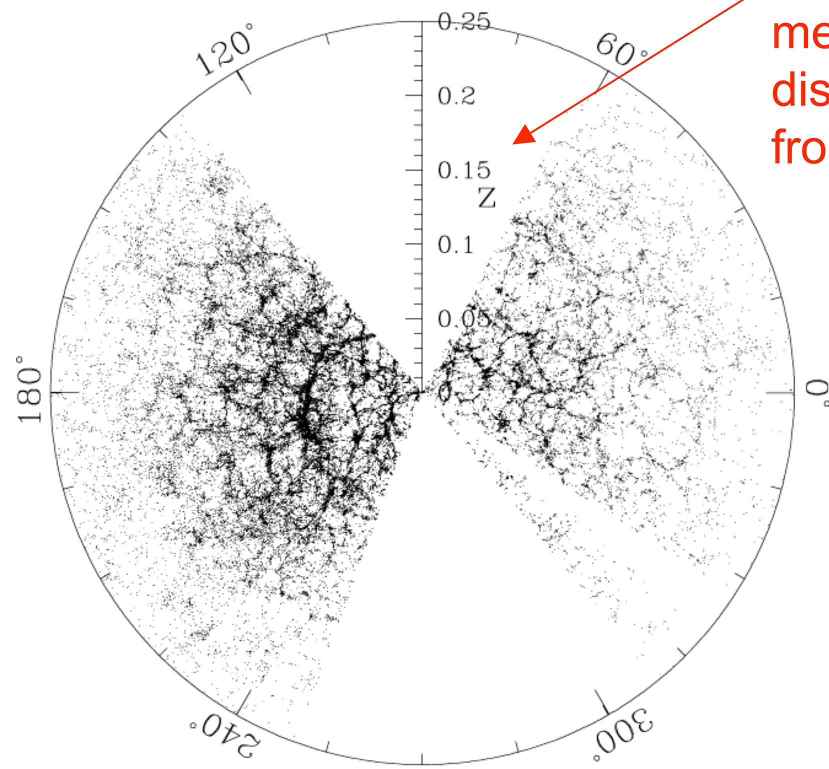
Comparing to predictions is easy only on large scales



Several Large Galaxy Surveys

The *Sloan Digital Sky Survey (SDSS)* and the *Two Degree Field (2dF)* both have measured positions and redshifts (which are related to distances) of hundreds of thousands of galaxies

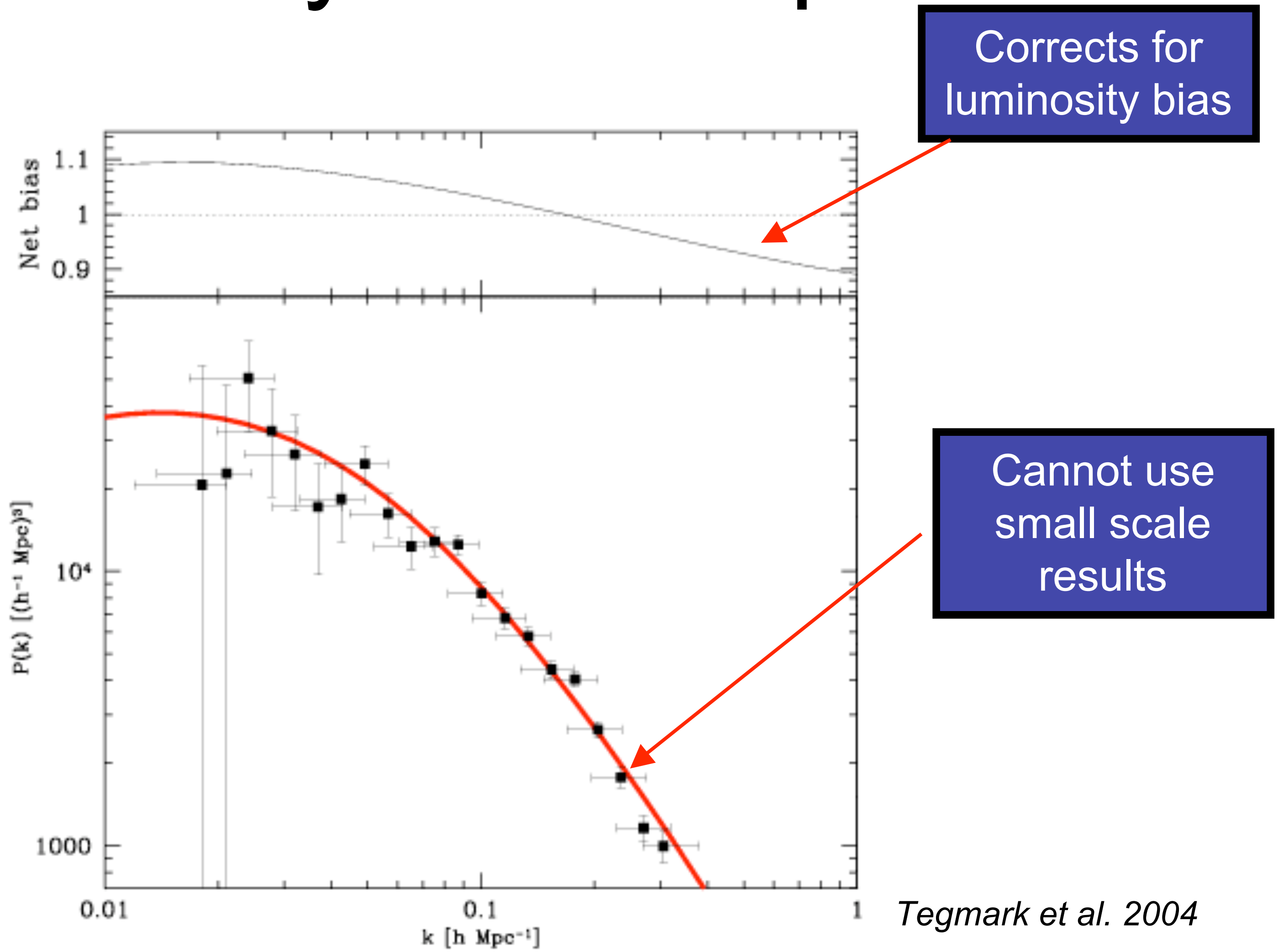
Blanton et al. (2003) (astro-ph/0210215)



Redshift z is measure of distance from us

SDSS Galaxy Power Spectrum

SDSS analysis of >200,000 galaxies

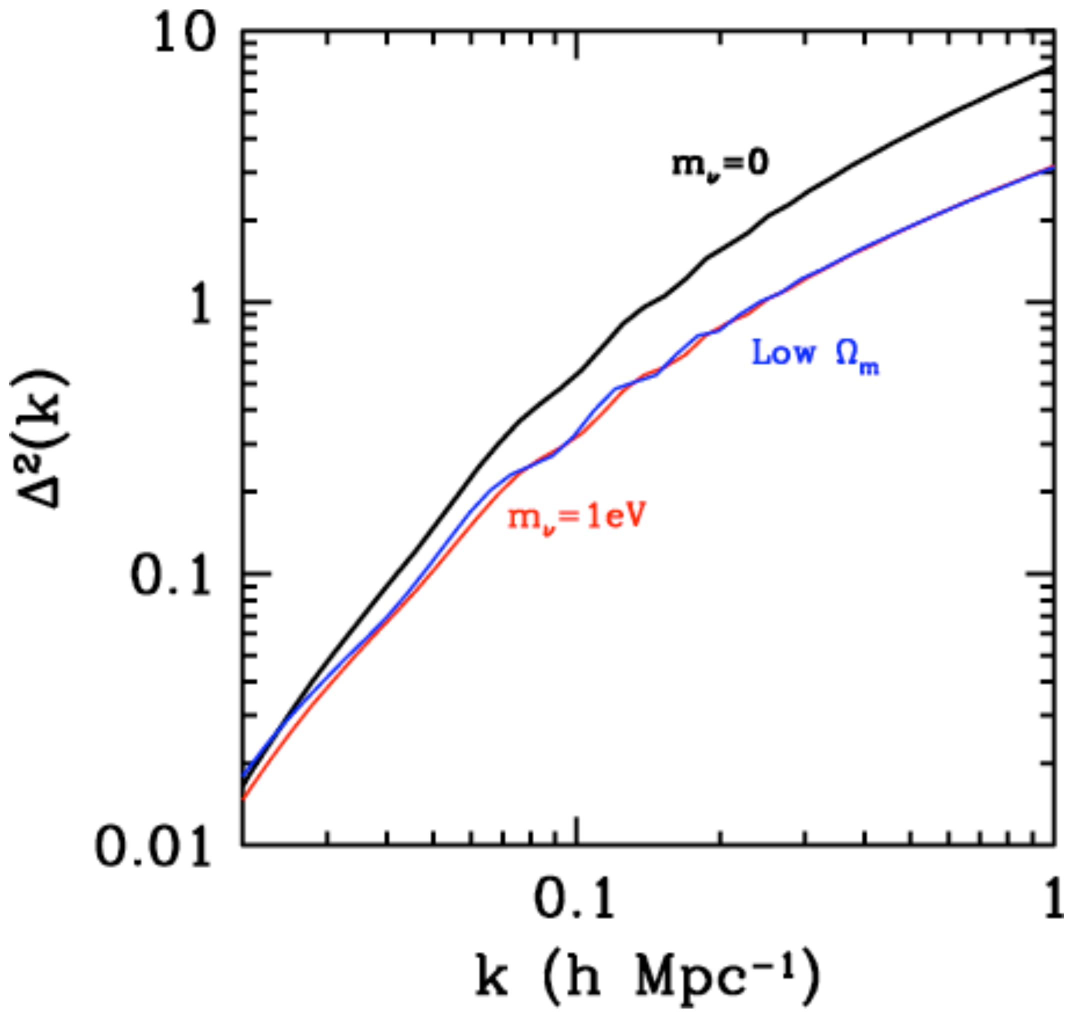


Tegmark et al. 2004

Degeneracies

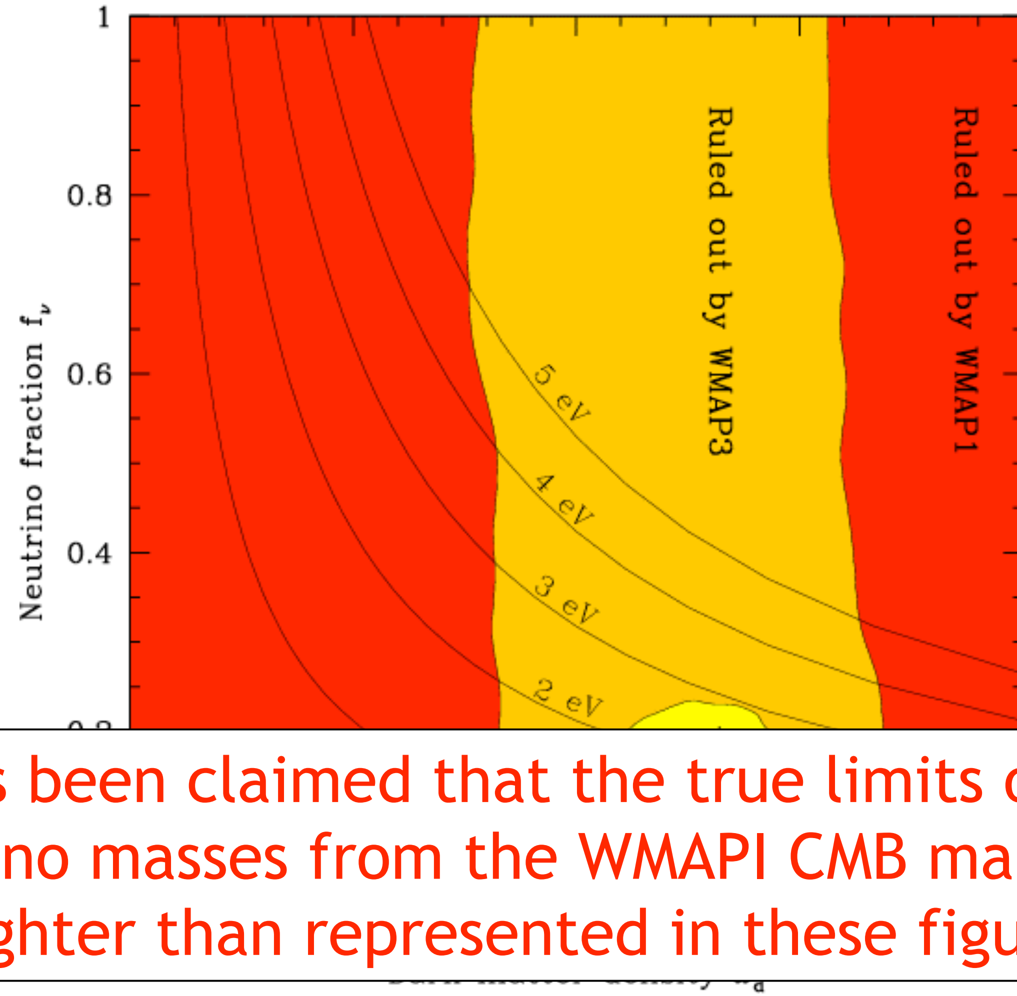
- Lowering the matter density suppresses the power spectrum

- Close to degenerate with non-zero neutrino mass



Complementarity

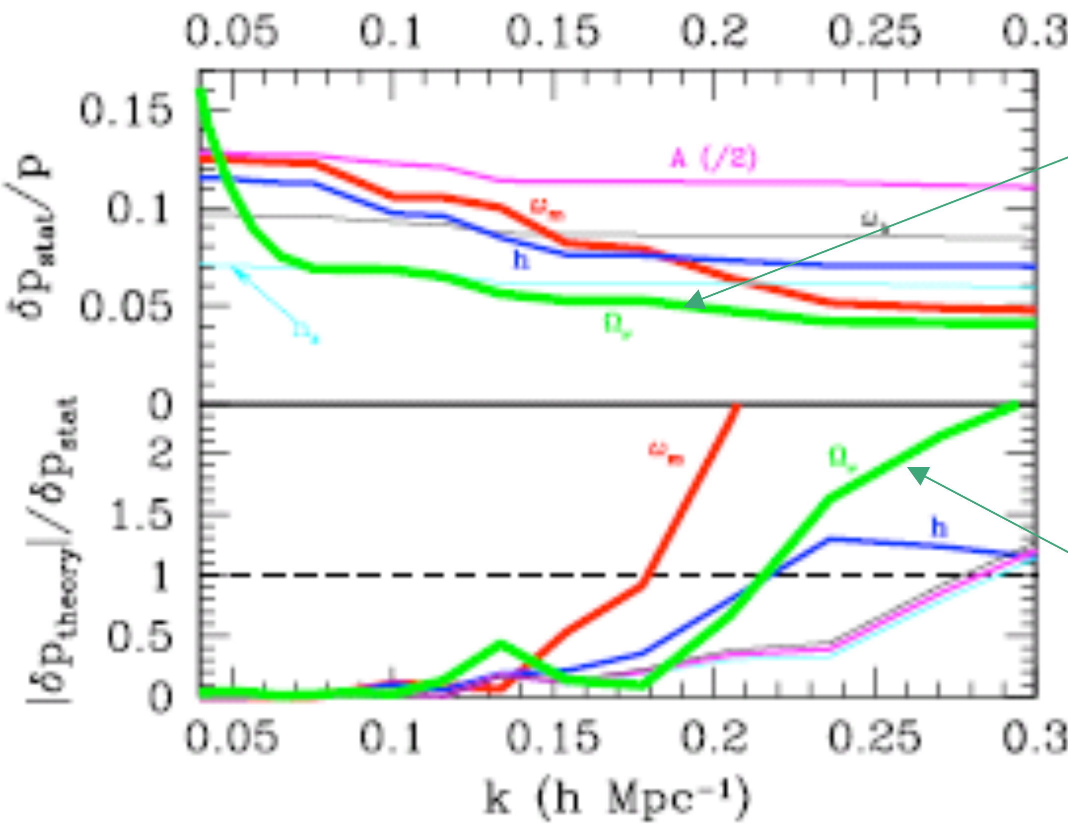
Peaks and troughs in CMB sensitive to matter density: need both CMB and large scale structure to tighten constraints on neutrino mas



*It has been claimed that the true limits on neutrino masses from the WMAPI CMB maps are tighter than represented in these figures.

Tegmark, et al. 2006

Small scales are hard to predict

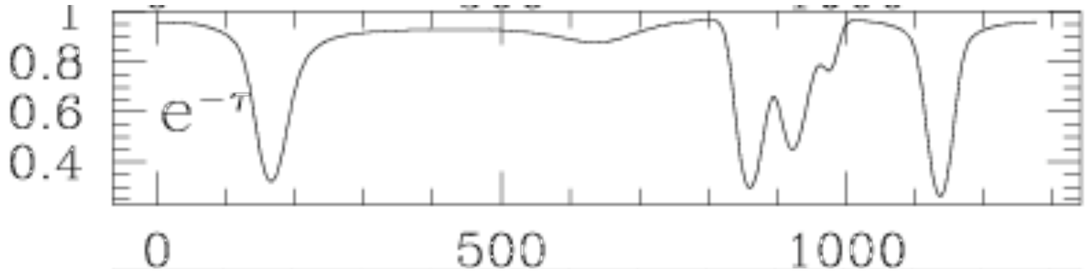


Statistical Error goes down as more small scale data are included …

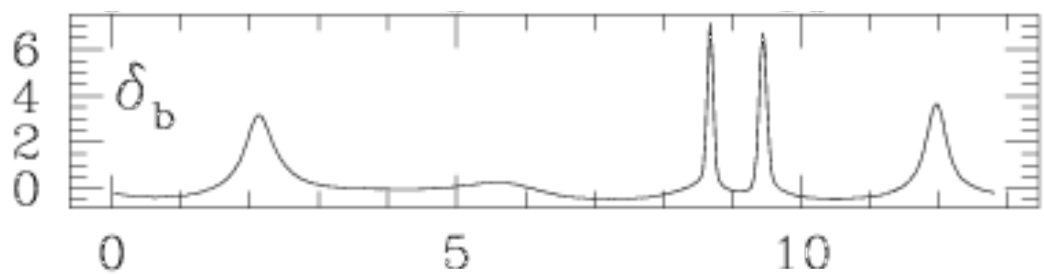
… But systematic error, due to uncertainty in theoretical prediction, goes up

Fluctuations in forest trace fluctuations in density

Flux



Baryon Density

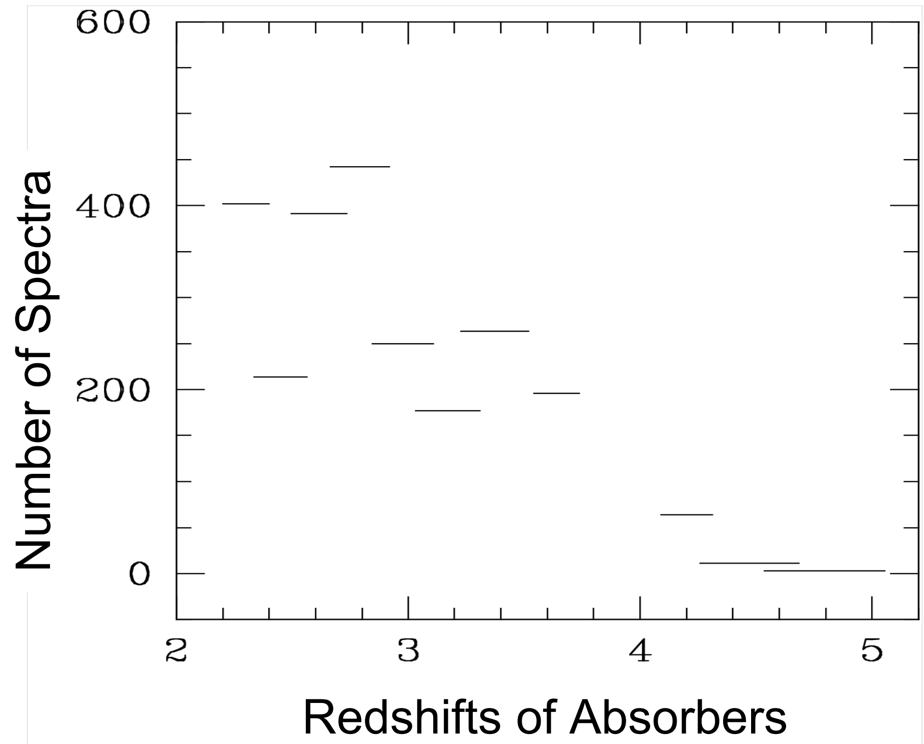


Position along line of Sight

Gnedin & Hui, 1997

Lyman alpha observes universe at early times

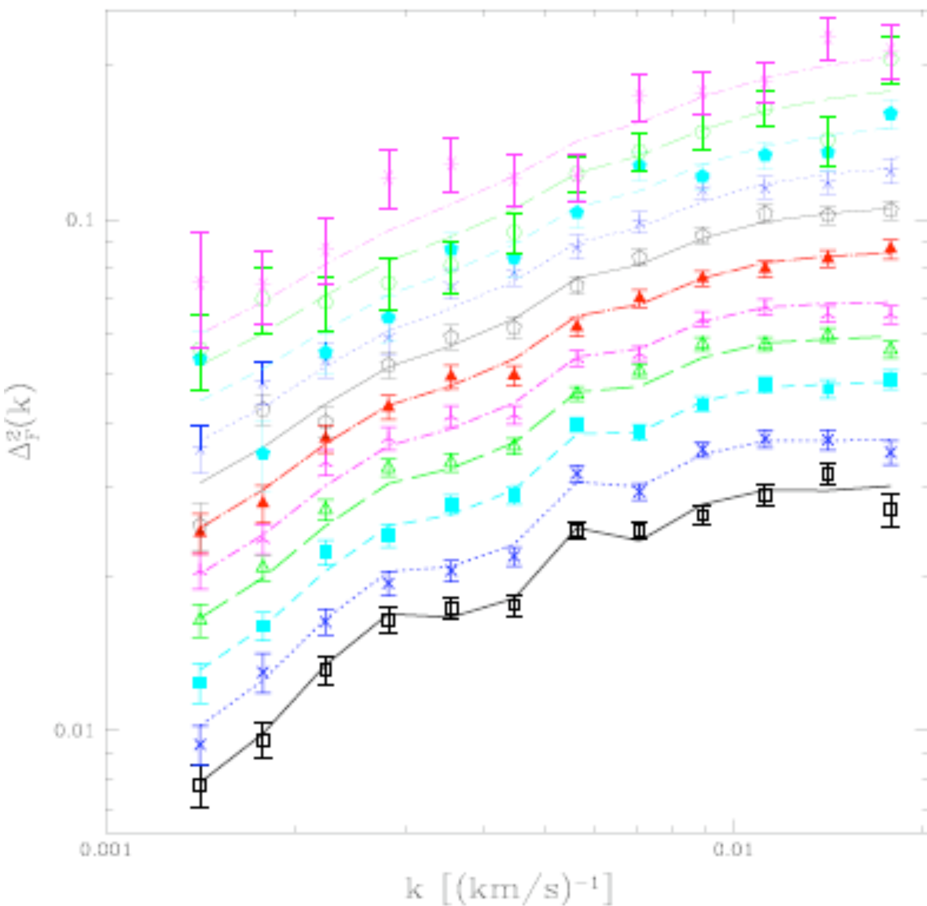
Sloan Digital Sky Survey (SDSS)



At high redshift, even small scales were linear!

SDSS Spectra of 3300 Quasars

1D Power Spectrum of the Flux

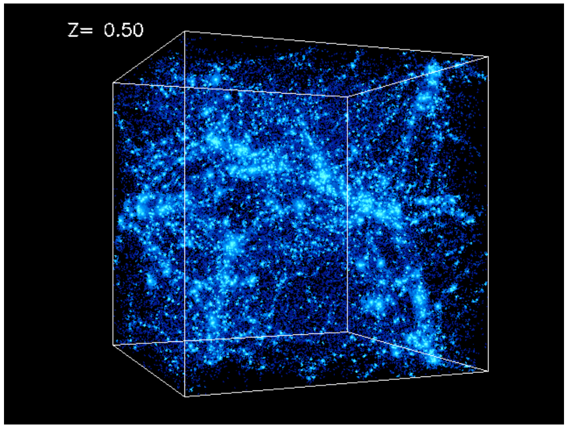


11 redshift bins

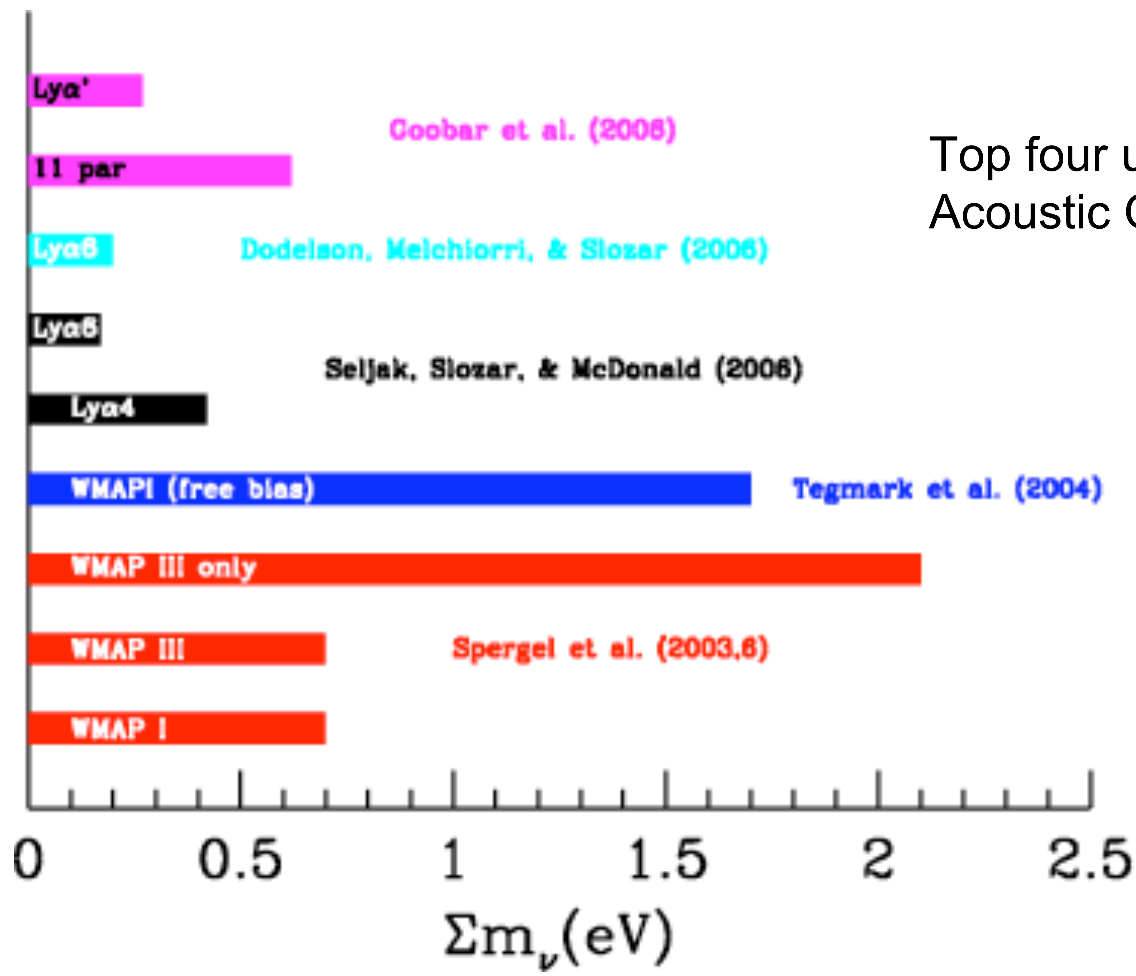
McDonald et al. (2004)

This is only half the battle!

- Want to test cosmology
- Need to run simulations which generate 1D flux spectra for every parameter set
- Do likelihood analysis to see which simulations are closest to observations

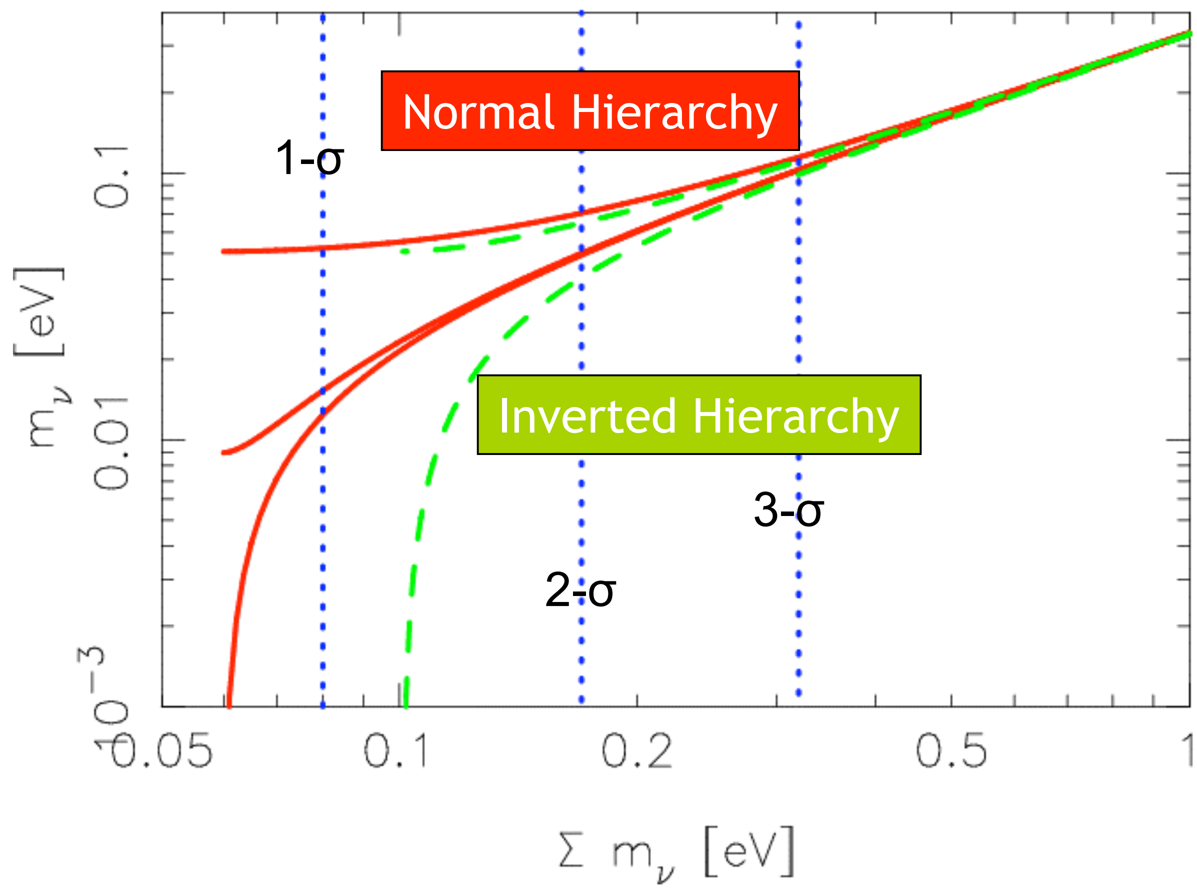


Constraints are typically sub-eV



Top four use Baryon Acoustic Oscillations

Most aggressive limit disfavors 3 degenerate neutrinos

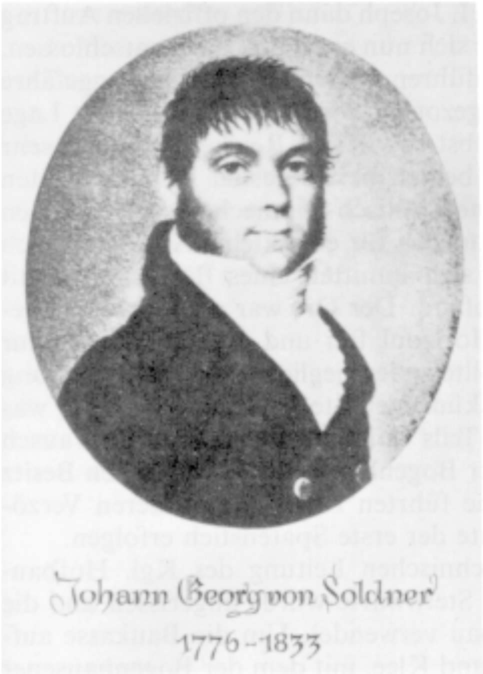


Seljak, Slosar, & McDonald 2006

Can we do better?

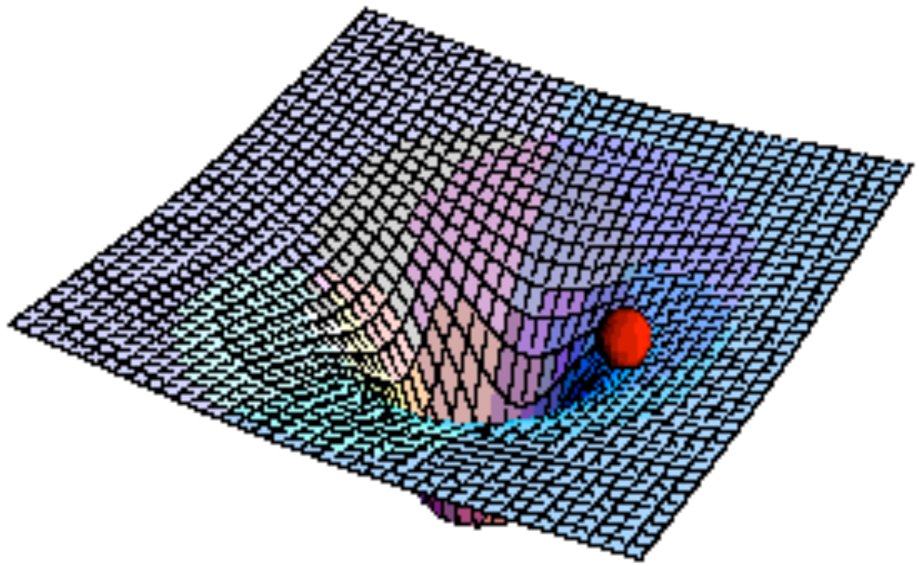
Currently running up against systematics, induced largely because we are depending on mass *tracers*.

1804: Astronomer Johann Soldner computes deflection of light due to Sun



Straightforward exercise in Newtonian gravity to show that particle passing within distance d of point mass *M* gets deflected by angle $2GM/d$

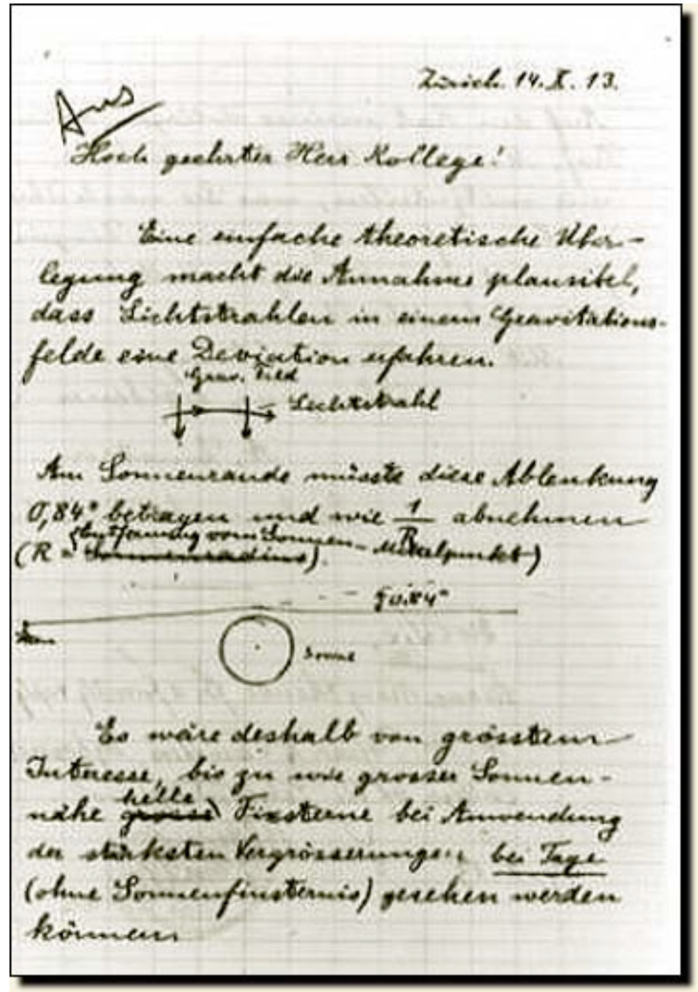
Over a hundred years later Einstein posits that mass distorts space: even light paths would be affected



Could this effect be detected?

Einstein writes to George Hale (Director of Mount Wilson Observatory) in 1913. He mentions the 0.84'' ($2GM_{\odot}/R_{\odot}c^2$) deflection expected from the Sun.

Wambsganss 1998



Zürich. 14. X. 13.

Aus

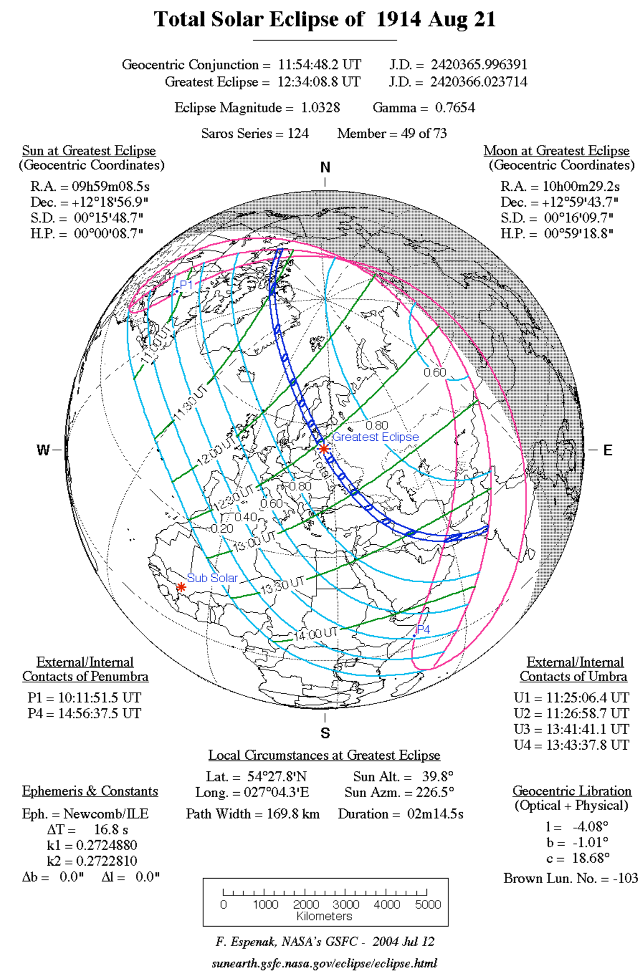
Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = ~~Sonnenradius~~ Entfernung vom Sonnen-Mittelpunkt).

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

The next total solar eclipse was August 21, 1914. An expedition was sent to observe in the region of greatest eclipse …



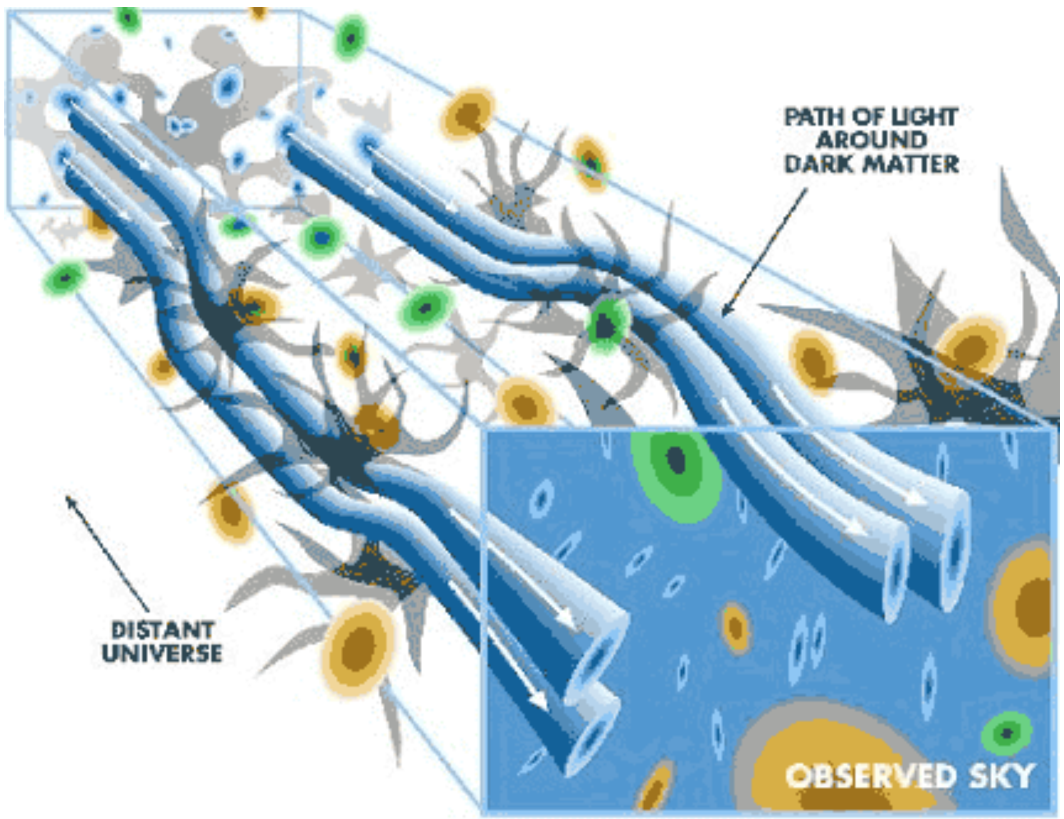
Russian Crimean Peninsula

1914 was not a good time to start a scientific expedition in Europe

The astronomers were captured by Russian soldiers and released a month later … with no data

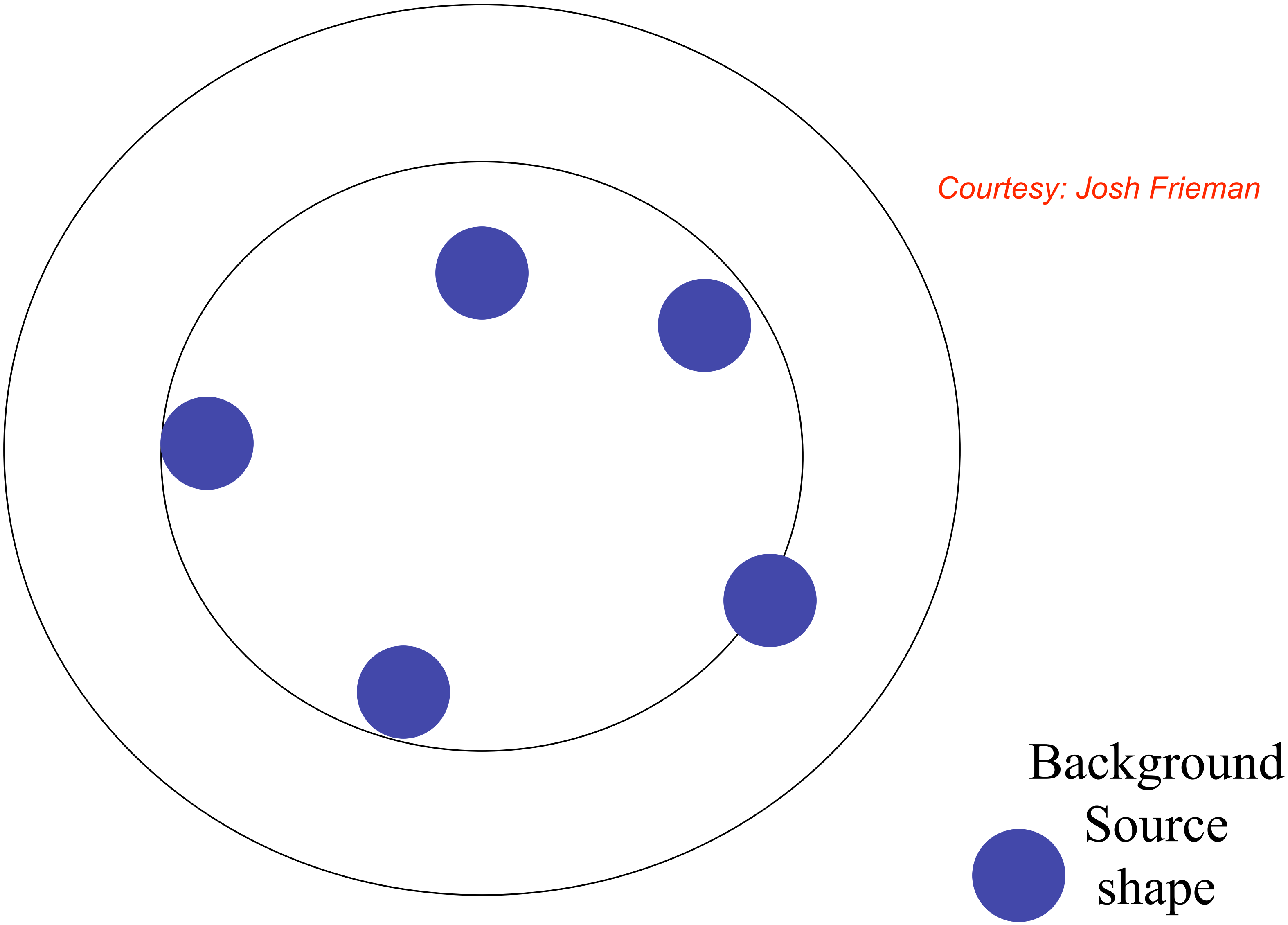
… which in retrospect is a good thing. Einstein improved his theory over the next several years. He eventually concluded that the deflection should be twice as large as the Newtonian result … And this was confirmed by the famous expeditions in 1919.

Exploit this: Gravitational Lensing



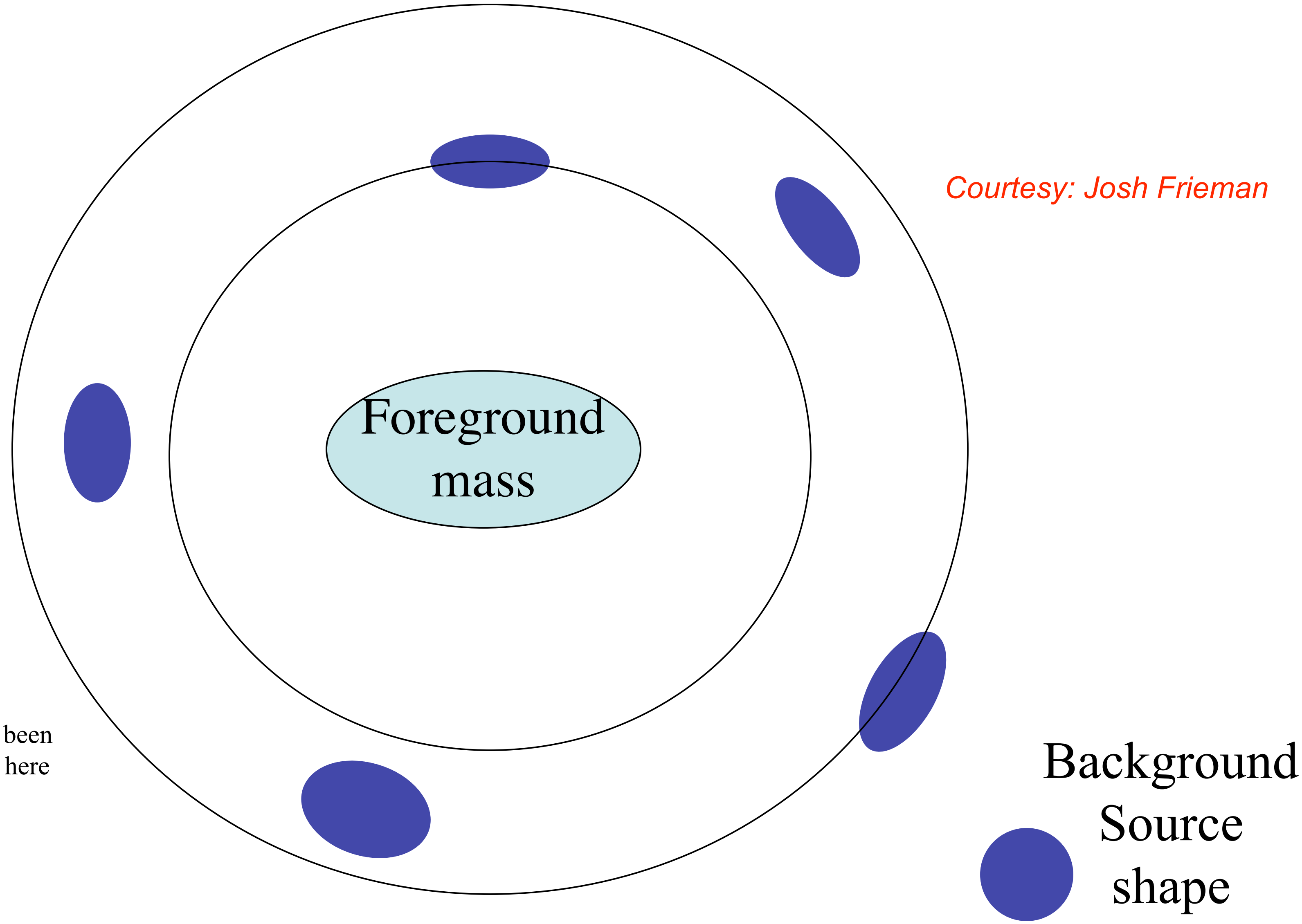
Constraints on neutrino mass via growth of structure

Faint Galaxies



Courtesy: Josh Frieman

Weak Lensing of Faint Galaxies: distortion of shapes

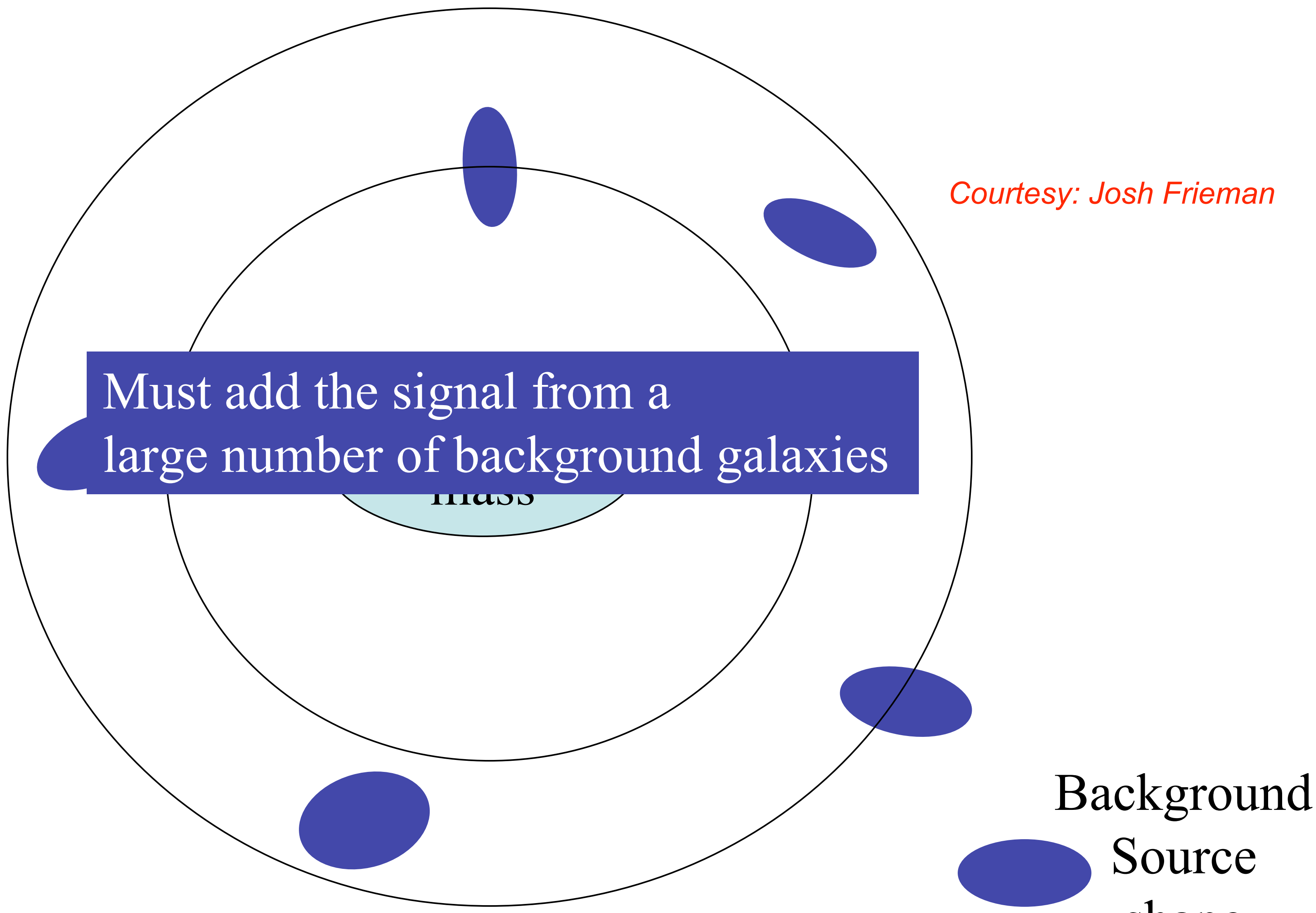


Courtesy: Josh Frieman

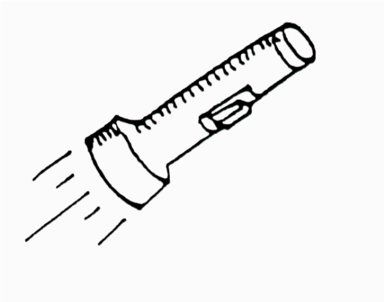
Note: the effect has been greatly exaggerated here

Lensing of real (elliptically shaped) galaxies

Courtesy: Josh Frieman

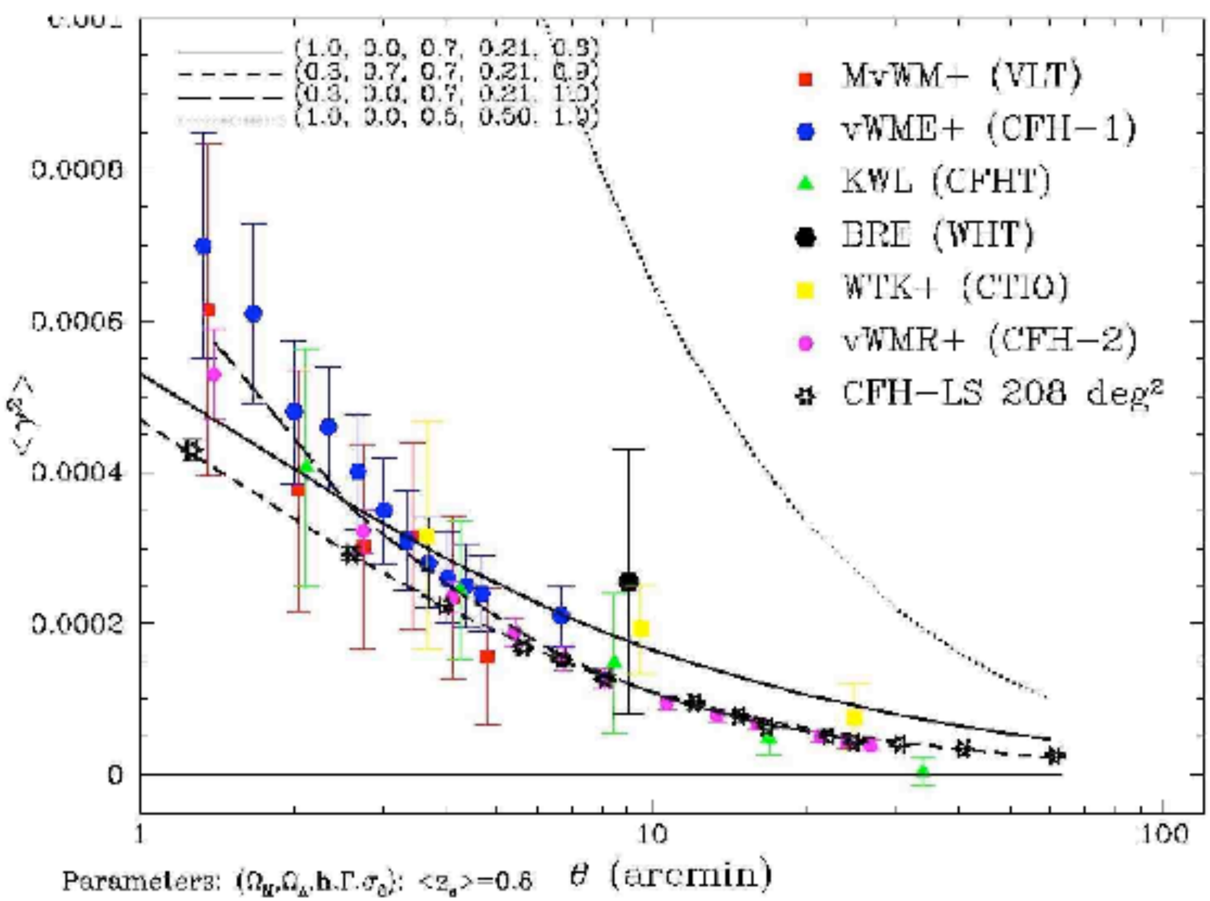


Big Advantage of Lensing: Sensitive to potential wells due to **all** matter



No longer need to use tracers

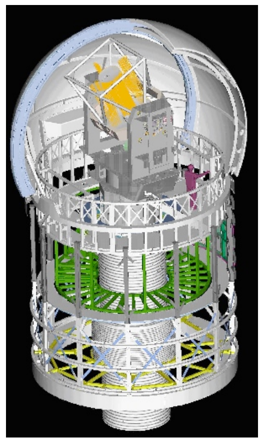
Four seminal measurements in 2000; ~dozen since then



Van Waerbeke & Mellier 2003

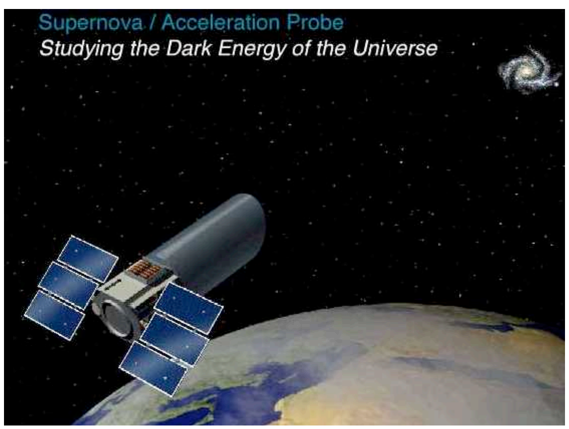
Several Upcoming Surveys

Panstarrs

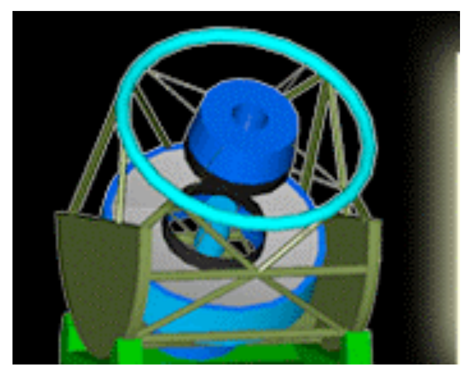


DARK ENERGY
Survey

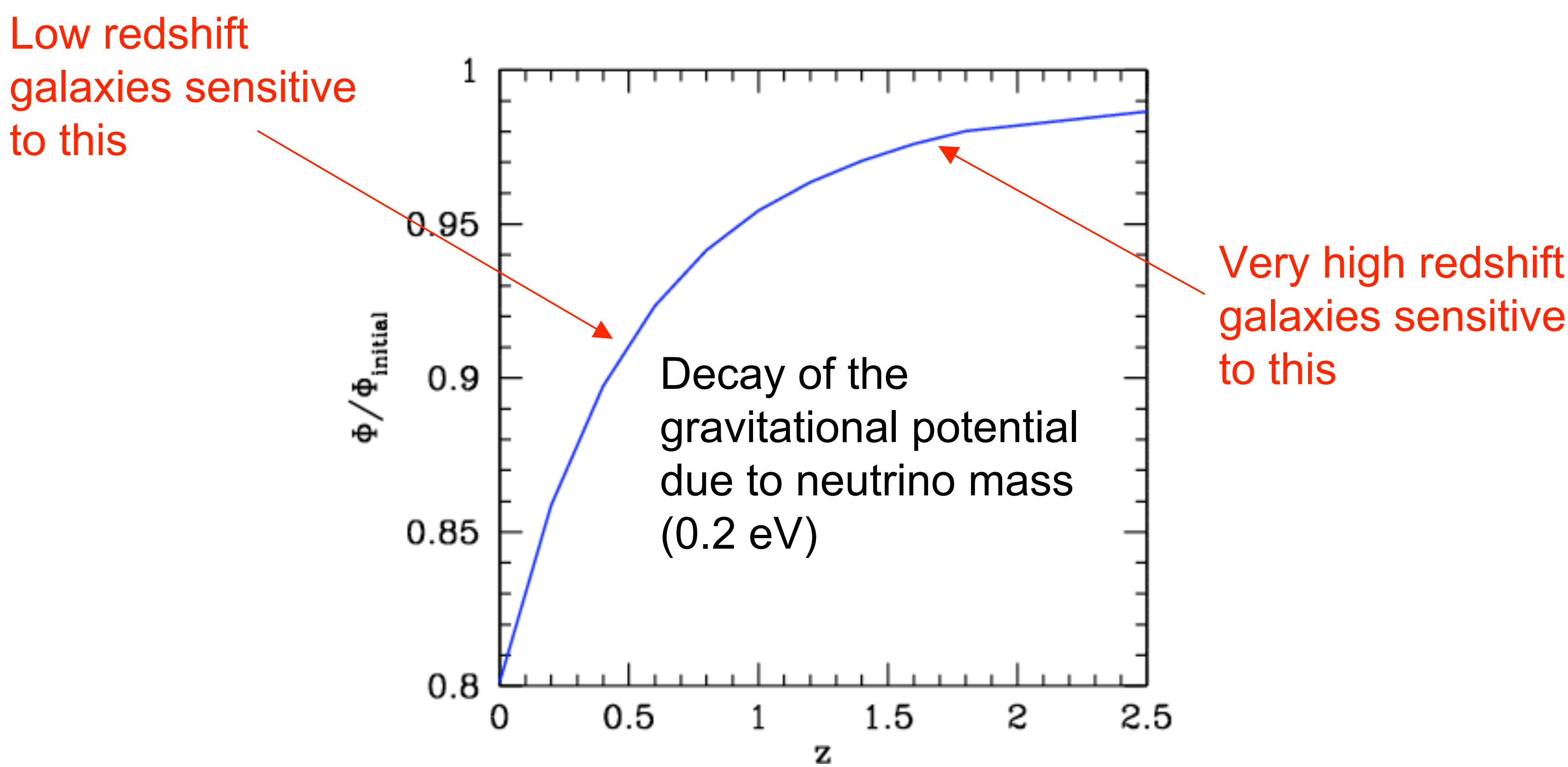
SNAP



LSST



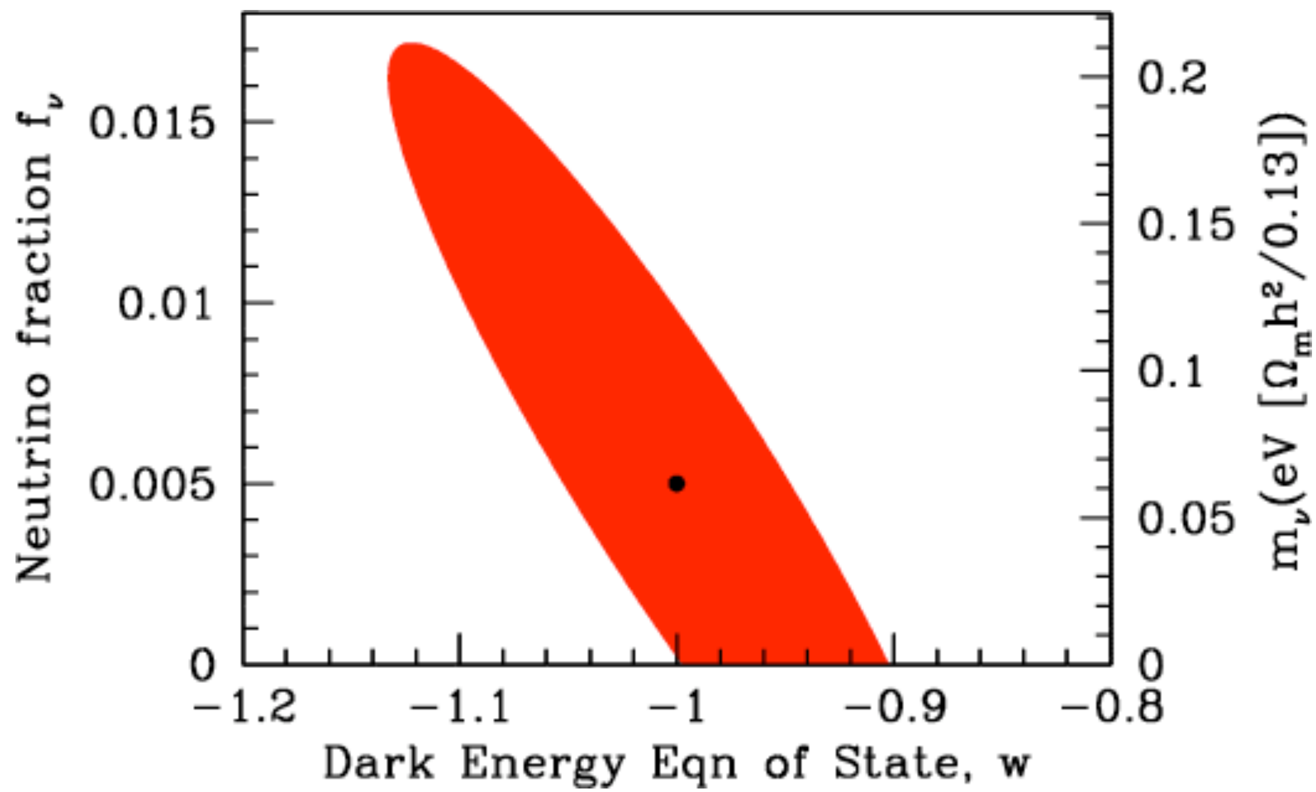
Tomography: Divide Background (Tracer) Galaxies into High and Low Redshift Bins



This effect can also be caused by…

Even if you're here only to learn about neutrinos, you need to understand dark energy

Projection for deep survey over 1/10 of the sky

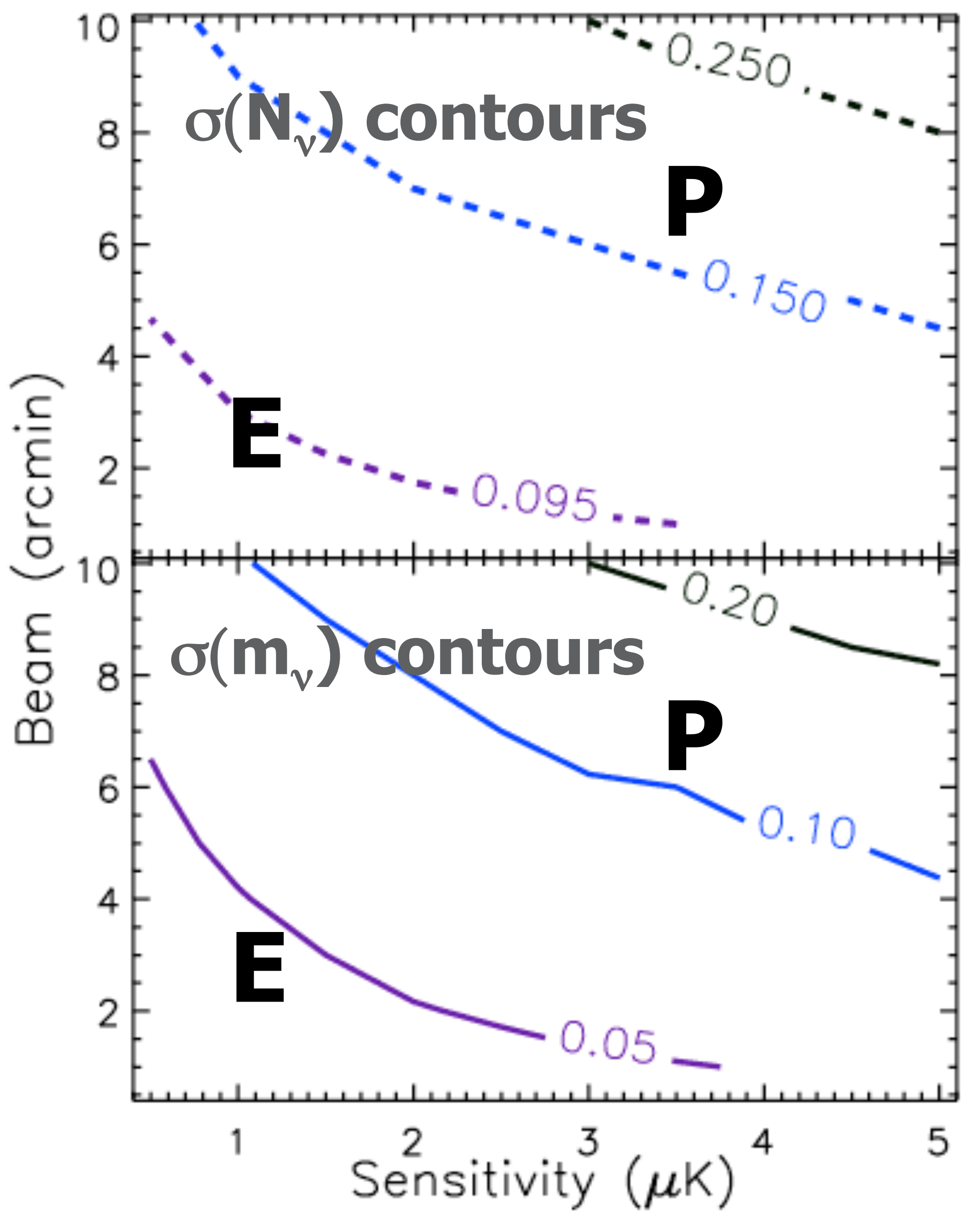


Abazjian & Dodelson 2003

Neutrinos and CMB

P = Planck
$\sigma(m_\nu)$=0.15 eV
$\sigma(N_\nu)$ = 0.22
E = EPIC: (0.052 eV,0.12)
With just one frequency channel.

Information about mass from lensing of the CMB while that about N_ν from primary CMB.

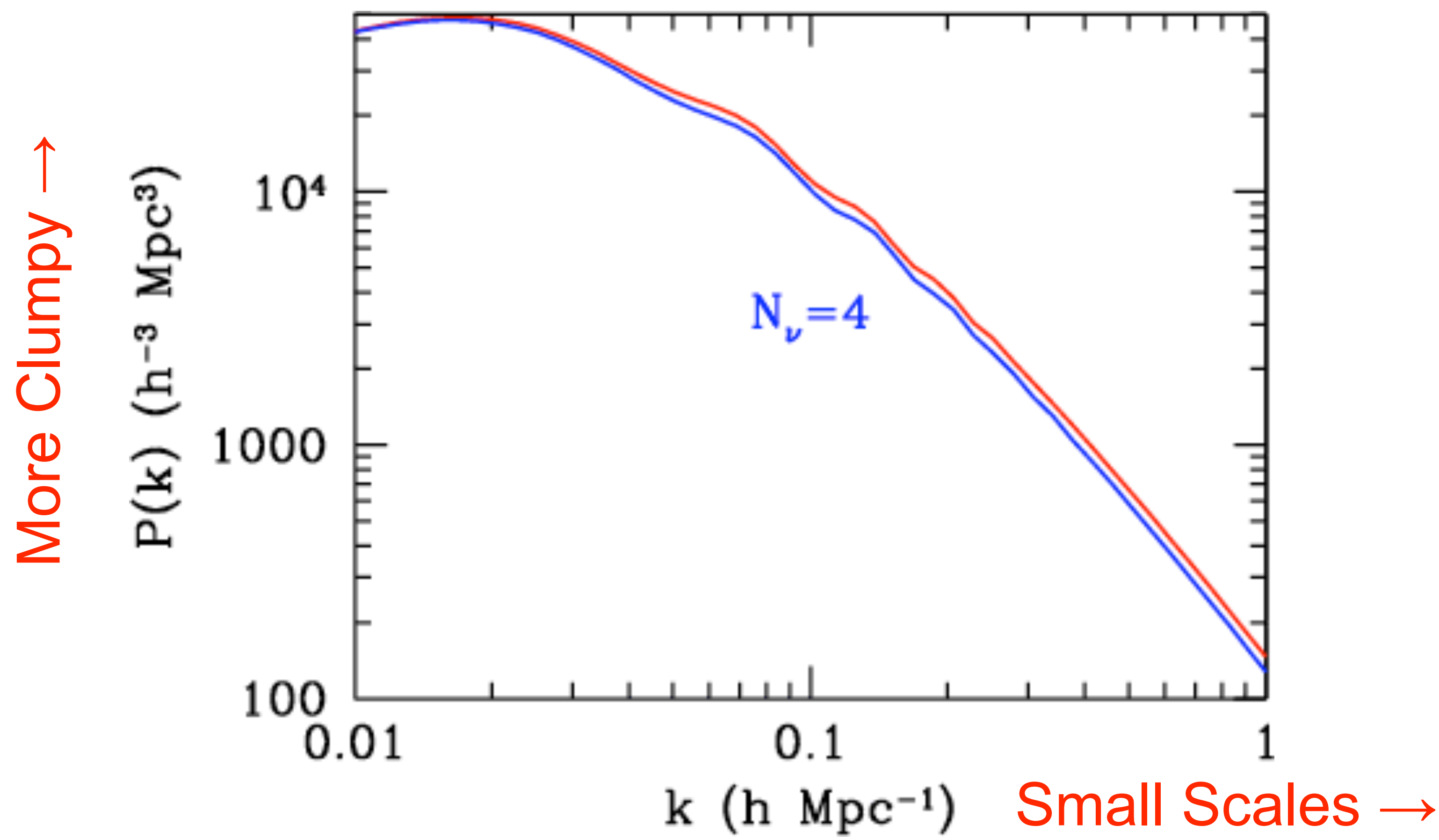


Kaplinghat

Conclusions

- **Cosmic neutrino abundance** inferred two ways: observations of light elements + large scale structure
- Cosmological **upper limit on sum of neutrino masses**: 0.2-0.7 eV
- Gravitational lensing may ultimately detect 0.05 eV neutrinos

Changing Number of Neutrinos leads to a reduction in the power on small scales



Cosmic Neutrino Abundance