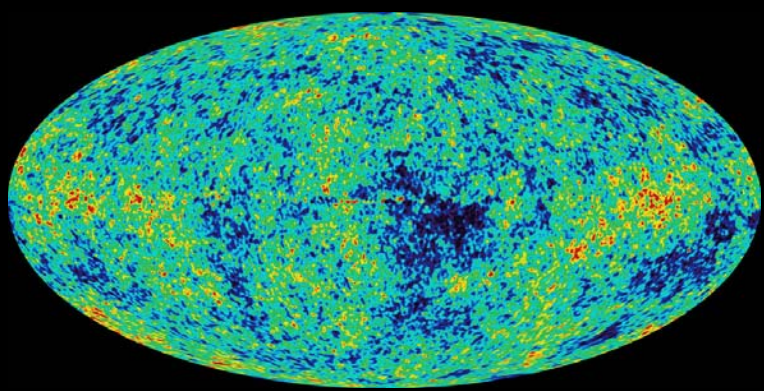
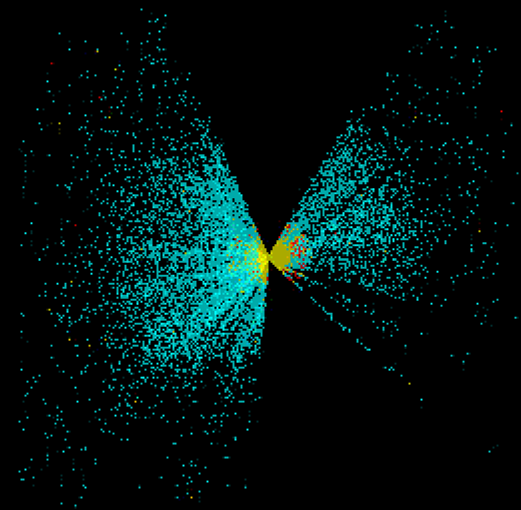
Cosmological Measurements of Neutrino Parameters



+



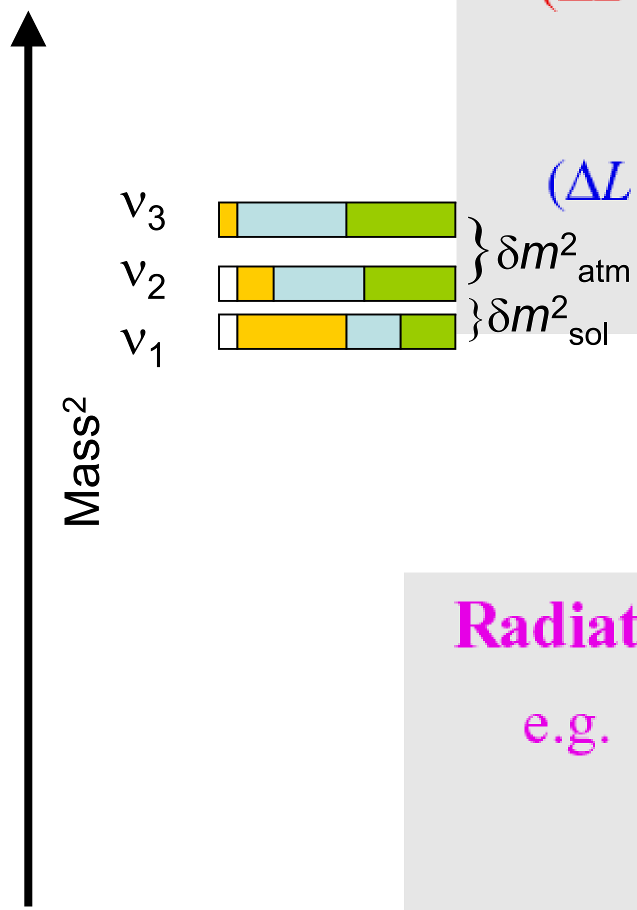
Kev Abazajian

Los Alamos National Lab

Weak Interactions and Neutrinos Workshop 2003

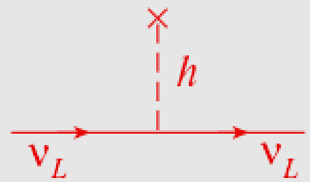
9 October 2003

What is the absolute neutrino mass scale?



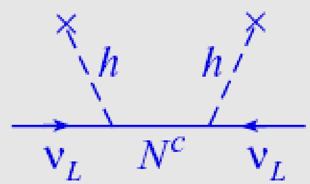
Tree-level mass generation

$(\Delta L = 0)$



Dirac mass m_D

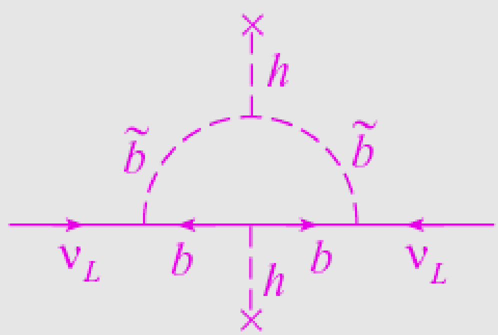
$(\Delta L = 2)$



Majorana mass m_M

Radiative mass generation via new interactions

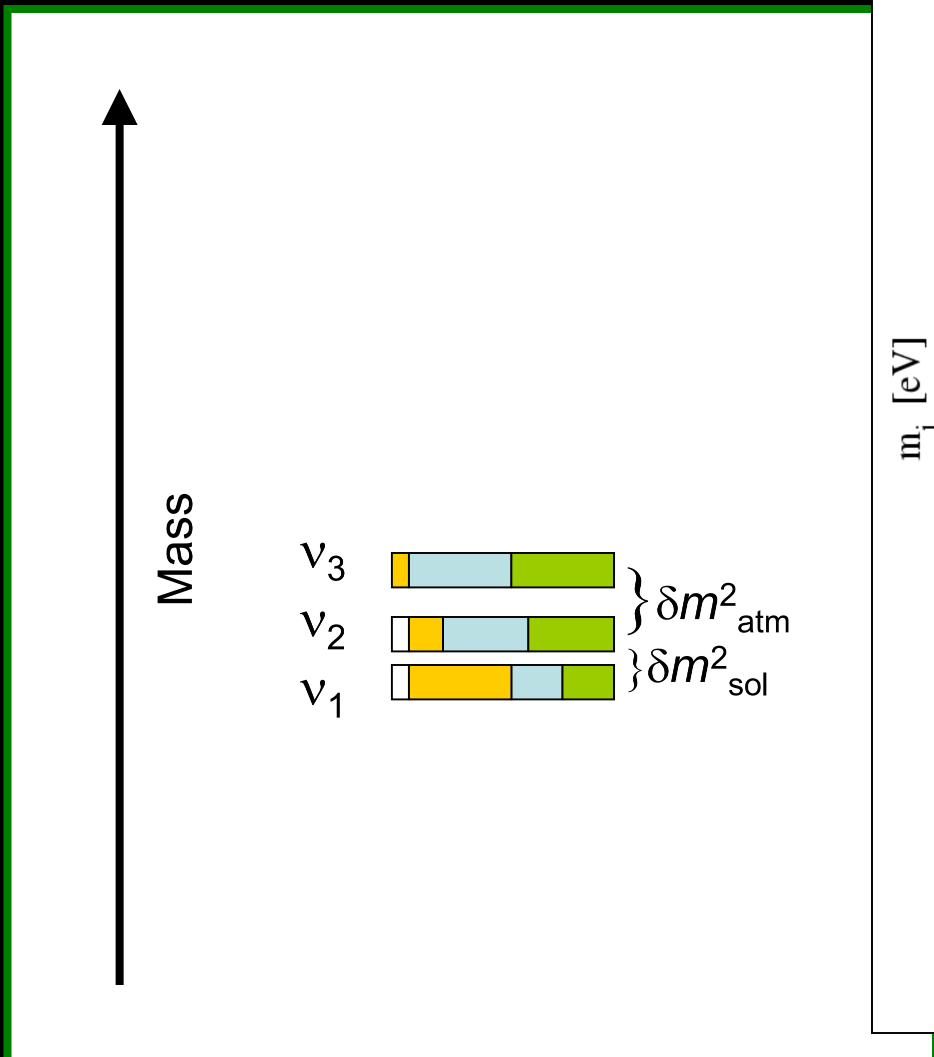
e.g.

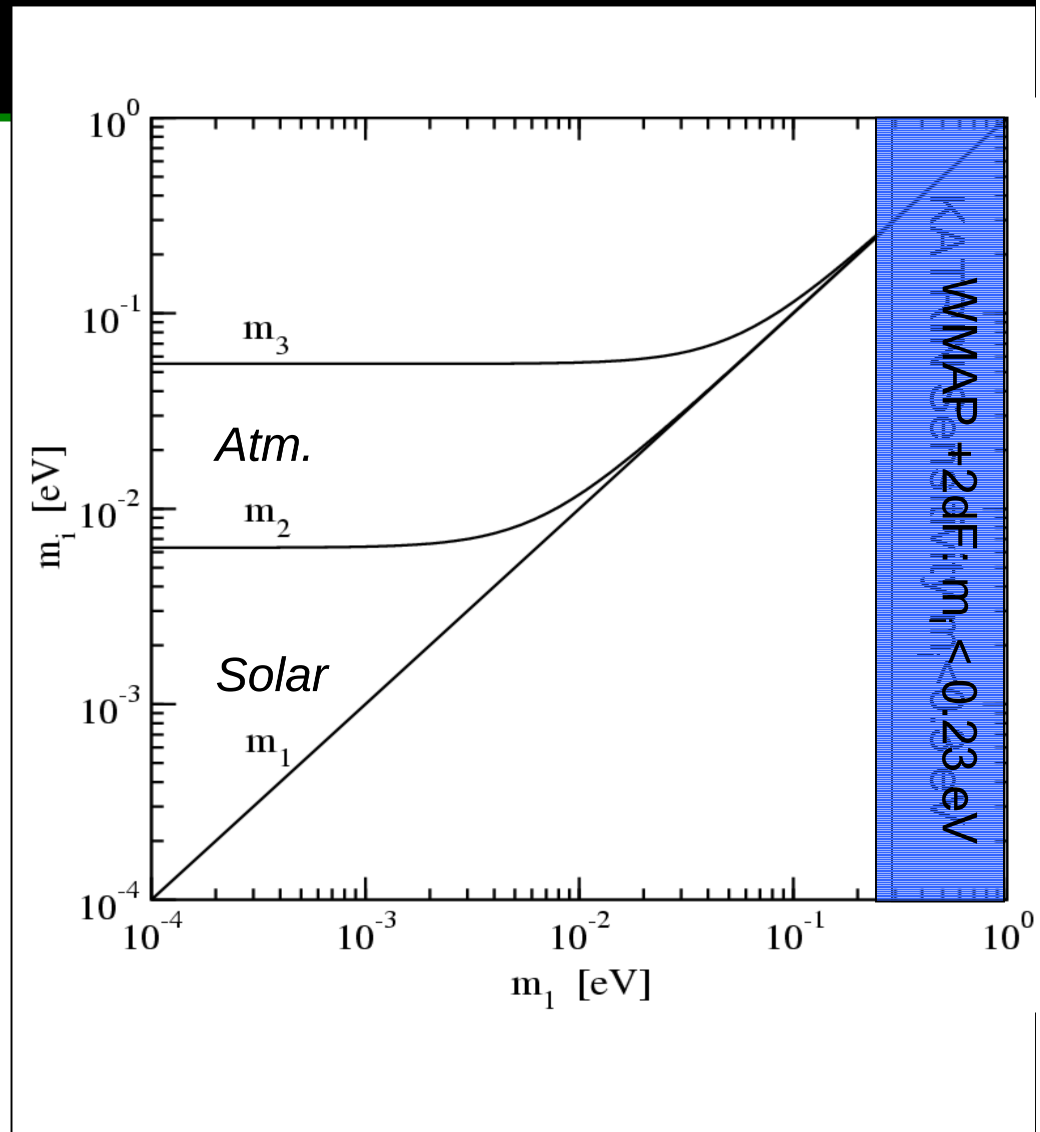


Ma and Sarkar (98)
Drees et al. (98)

Cheung & Kong (99)
Babu (98)
Mohapatra & Senjanovic (81)
Zee (80)

What is the absolute neutrino mass scale?

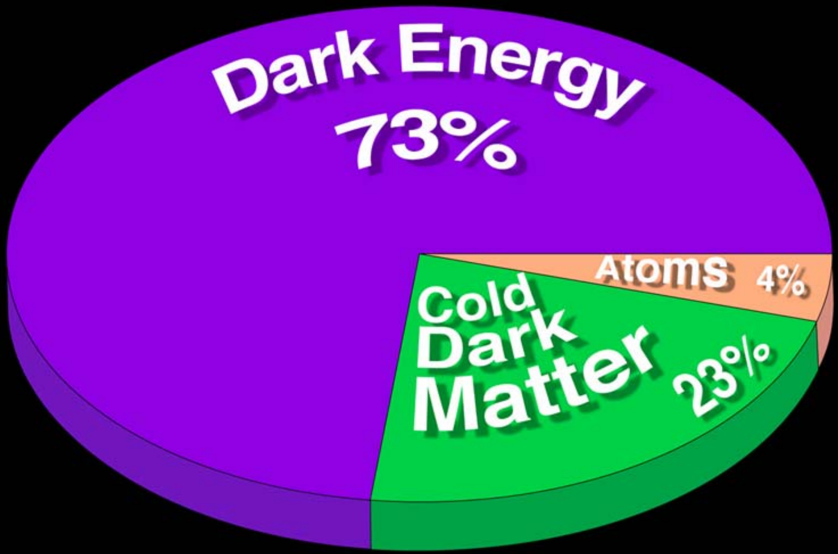




The Cosmological Concordance Model

The pillars of modern inflationary big-bang cosmology:

1. The presence of a thermal cosmic radiation background
2. The observed Hubble expansion
3. The abundance of the light elements from primordial nucleosynthesis
4. The consistency of the formation of structure from adiabatic, Gaussian perturbations as initial conditions



Data concordance: HST Key Hubble expansion, SNIa Luminosity distance, Cosmic Microwave Background, Large Scale Structure, Light element abundances

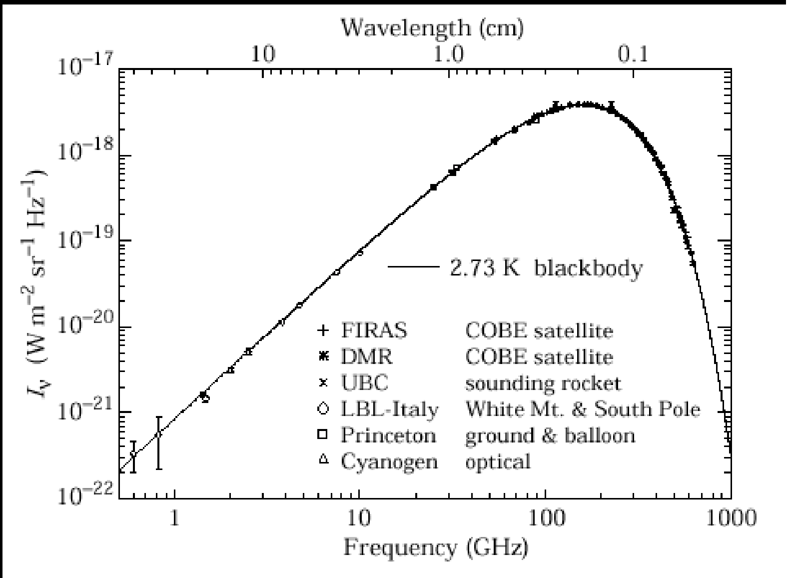
Cosmological Neutrinos

<u>From the CMB temperature:</u>

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3 \approx 410 \text{ cm}^{-3}$$

$$n_\nu \approx N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

(Assuming neutrinos' thermal equilibrium)



$$n_\nu \approx 10^{10} n_{baryon}$$

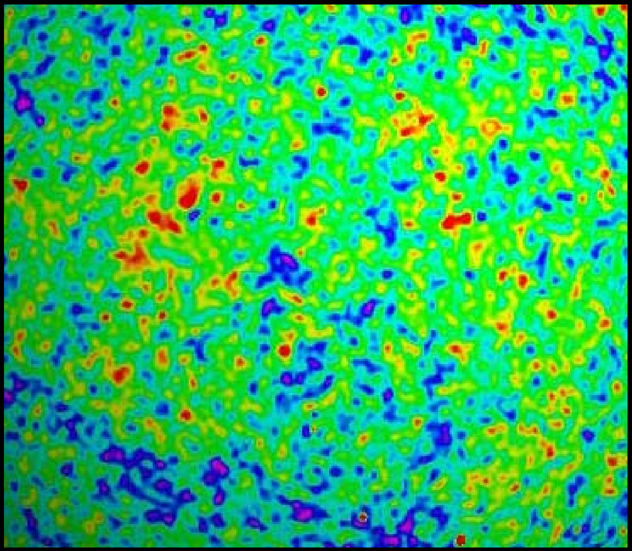
$$n_\nu \approx 10^{7-9} n_{dark\,matter}$$

Dolgov et al '02; Abazajian, Beacom & Bell '02; Wong '02 ➔ LMA requires that they must be close to thermal

Given neutrinos are massive:

$$\rho_\nu = \sum m_i n_{\nu i}$$

The cosmological density perturbation spectrum

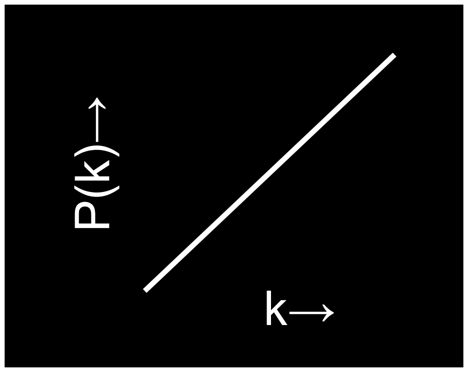


- Power spectrum of cosmological density fluctuations: P(*k*) ~ wave number *k*

- Primordial Harrison-Zeldovich: from scale invariance

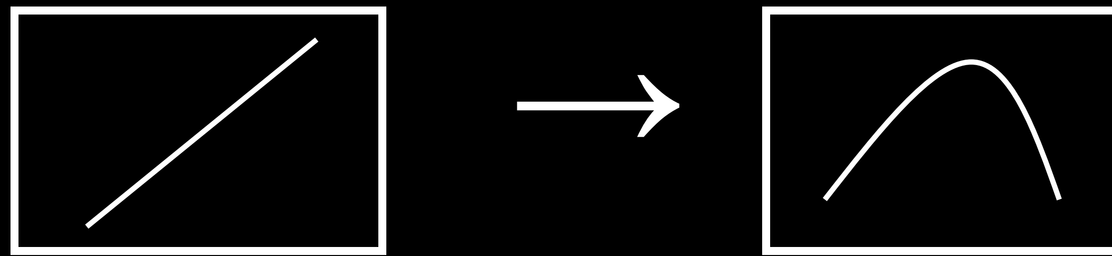
$$P(k) \propto k$$

  - Natural solution to perturbation spectrum: self-similar evolution



- Predicted by inflation $P(k) \propto k^n \quad n \approx 1$

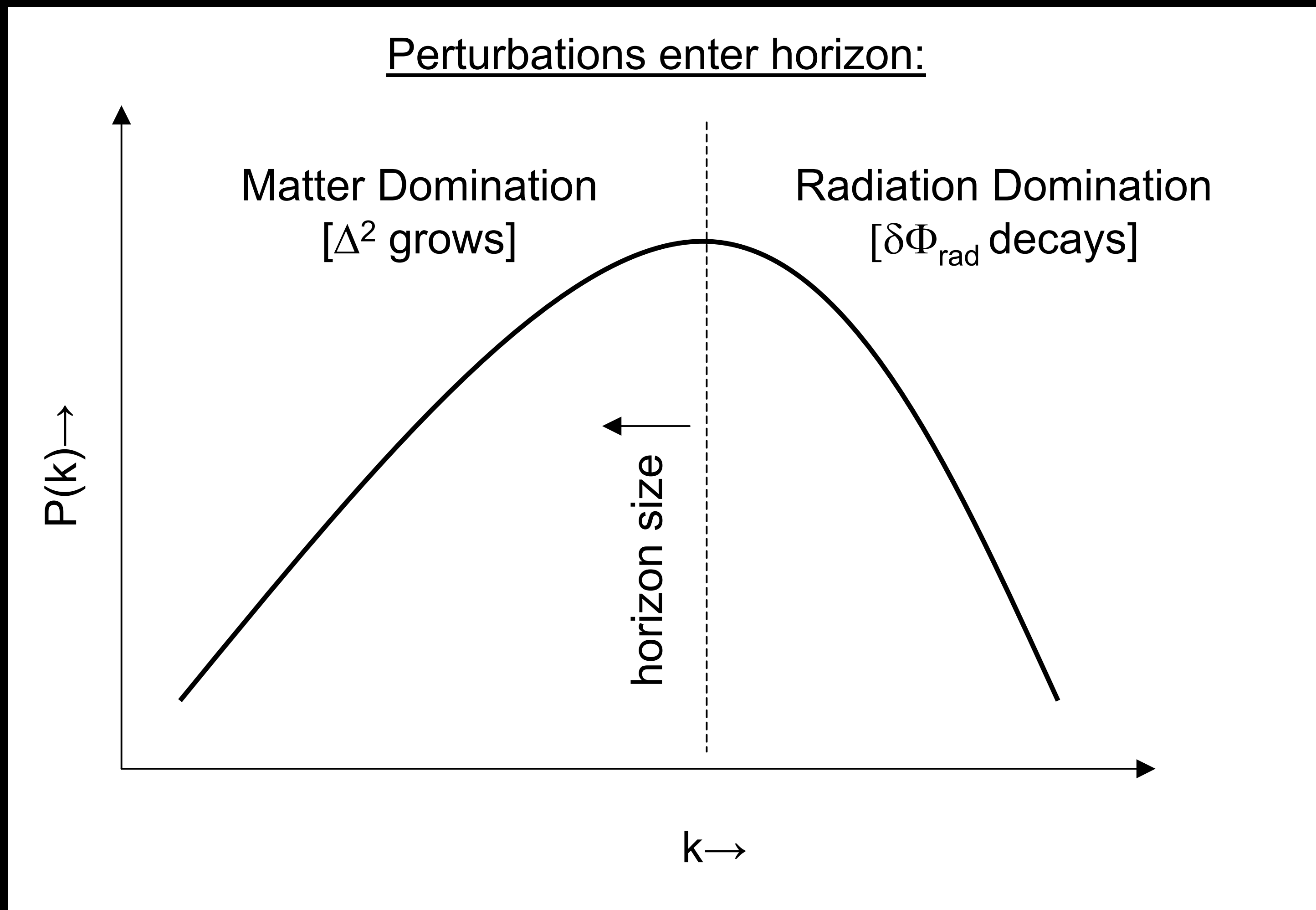
$$P(k) \propto k$$

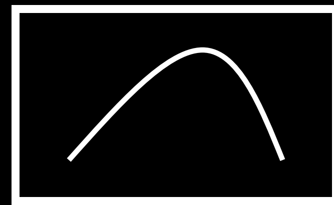


?

$$\rho_{mat} \propto a^{-3}$$

$$\rho_{rad} \propto a^{-4}$$



What does  have to do with neutrinos?

$$n_\nu \approx N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$ *(Assuming thermal equilibrium)*

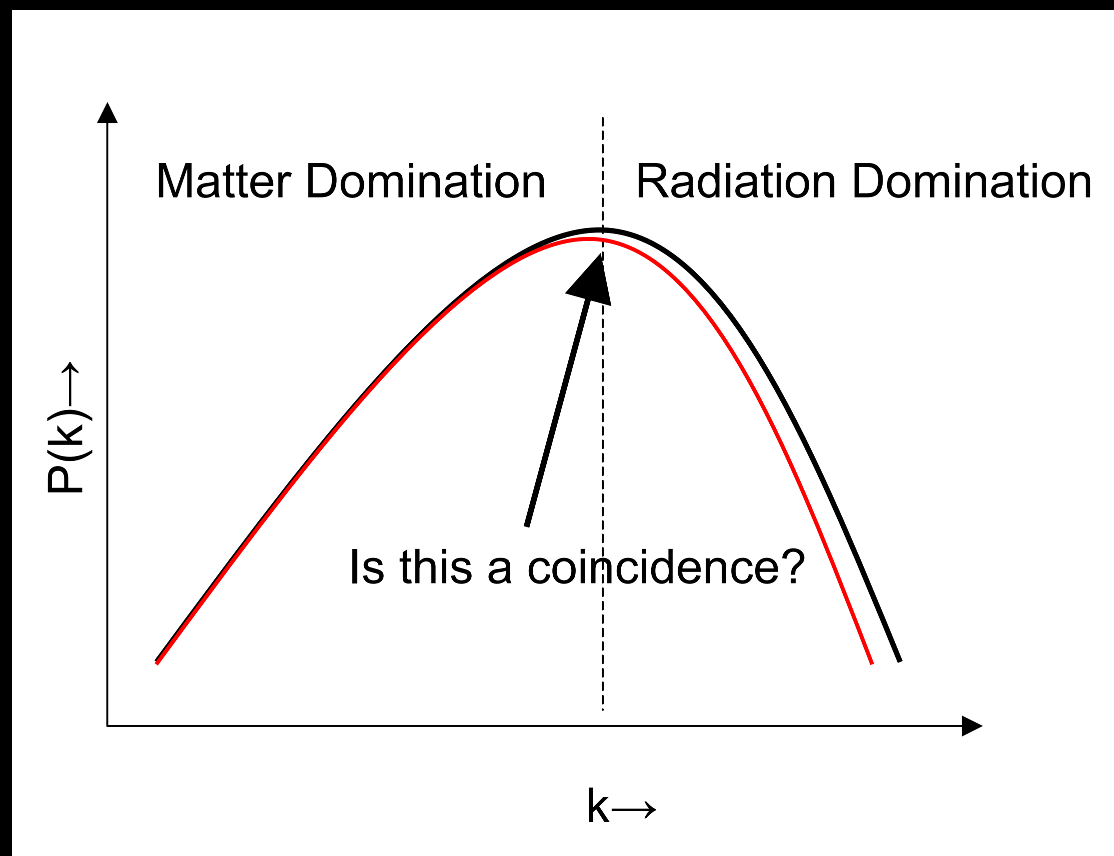
$$\rho_\nu = \sum m_i \, n_{\nu i}$$

$$\Omega_\nu = \frac{\sum m_i \, n_{\nu i}}{\rho_{crit}} = \frac{\sum m_i}{92.5 \text{ eV } h^2}$$

$$E_\nu = \sqrt{p^2 + m^2}$$

Detailed pedagogical treatment in:

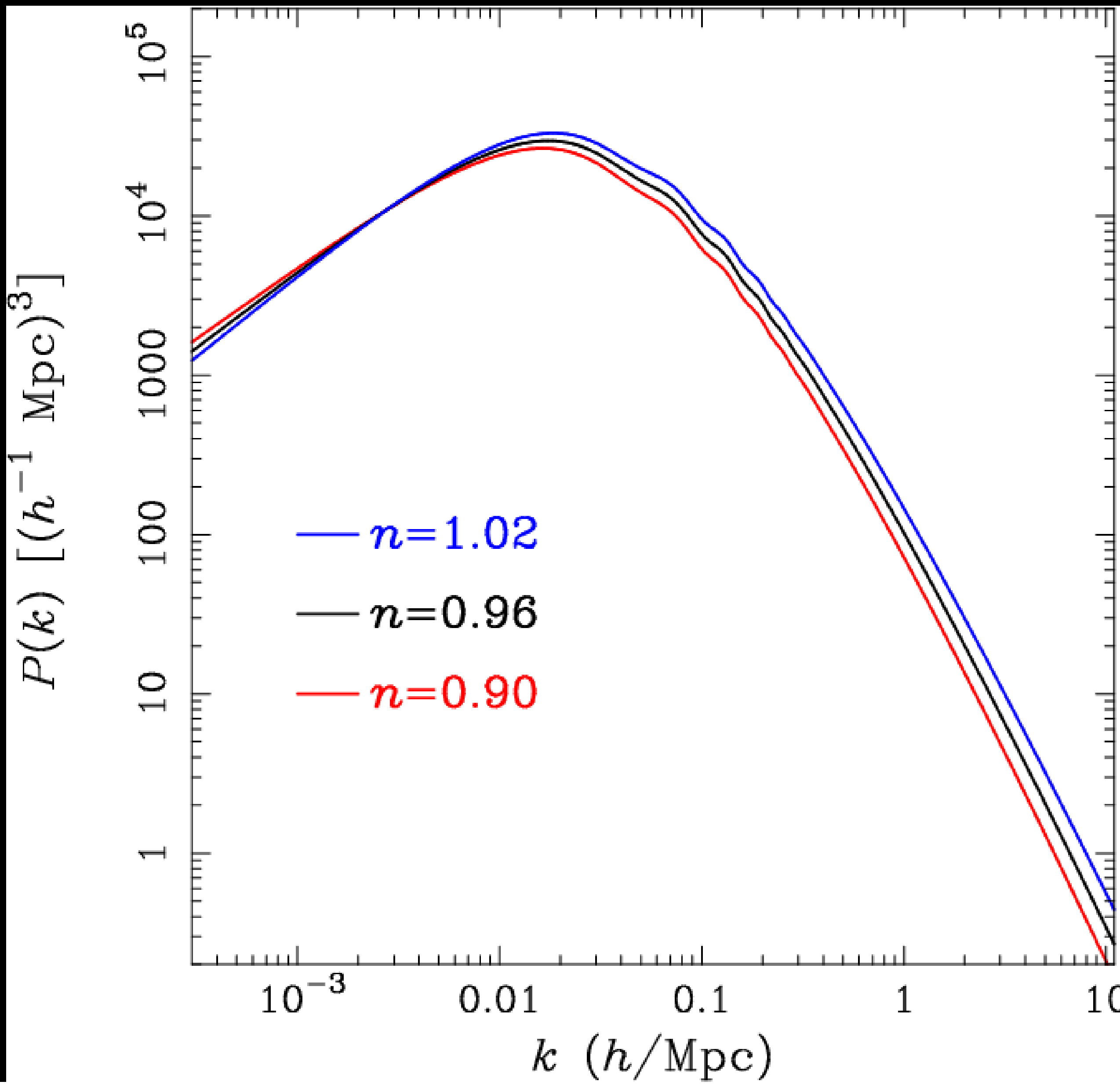
Scott Dodelson, *Modern Cosmology* (2003)



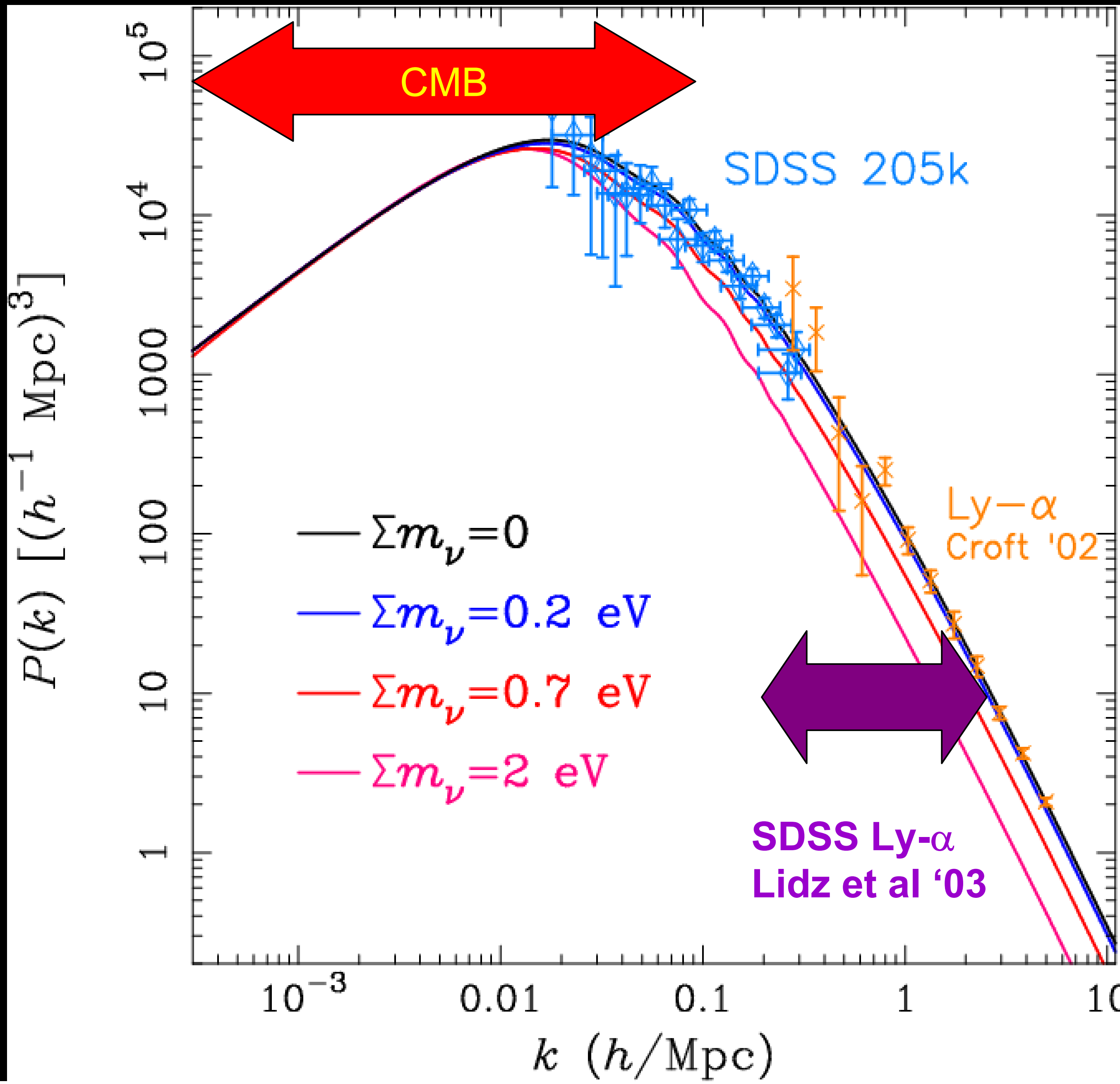
Neutrino distortion of the shape of P(k)

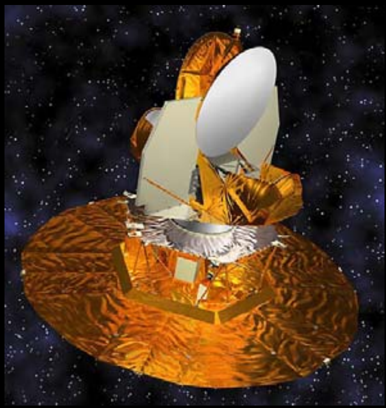
Degeneracies in theoretical predictions:

- Ω_m
- n
- n_{run}
- w

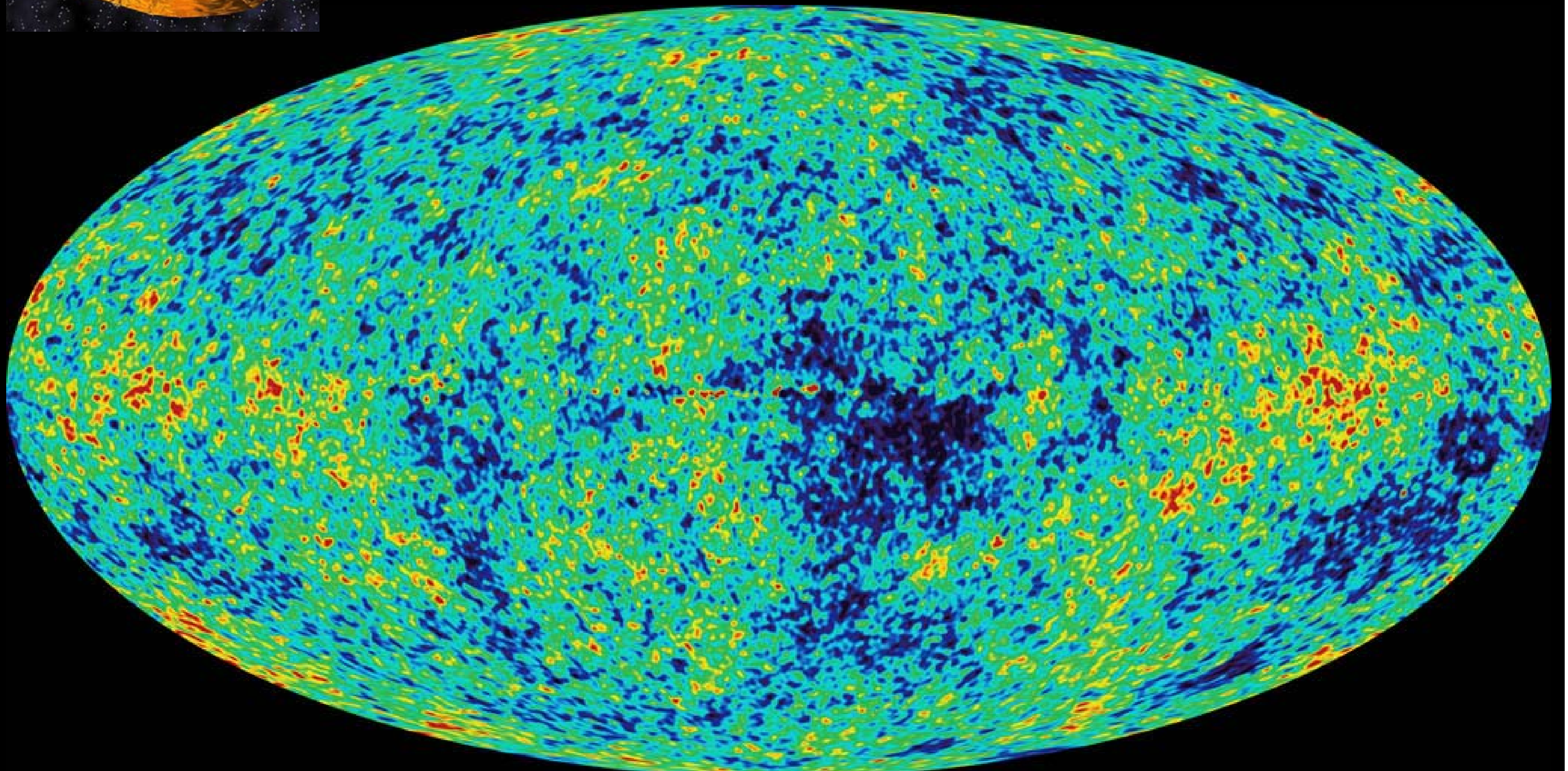


Measuring P(k)

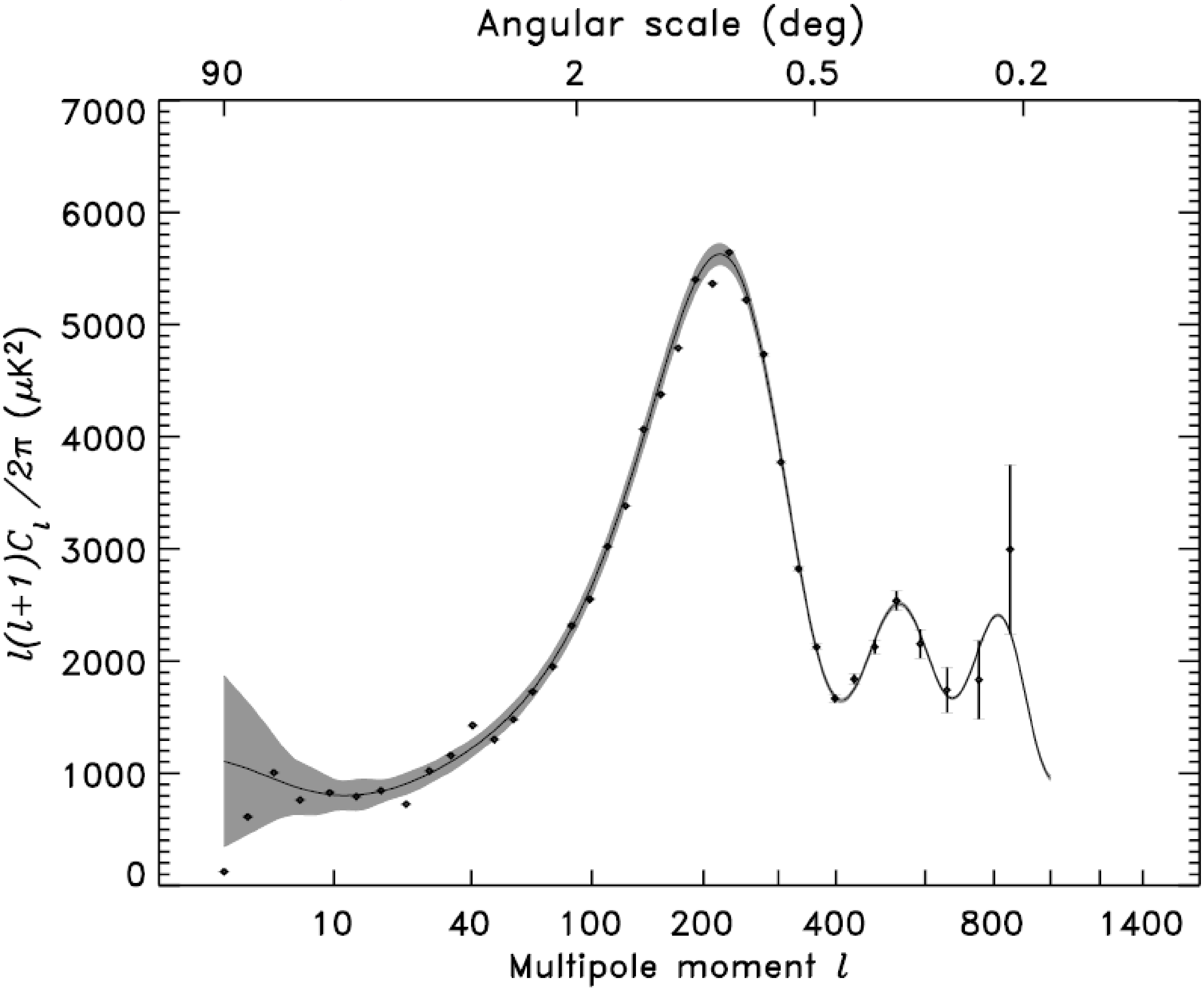




WMAP & The era of precision cosmology



Before→After WMAP



Hinshaw et al '03

about parameters…
WMAP+ACBAR+CBI + 2dF + Lyman-α forest

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_\nu h^2 < 0.0076$ (95%CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d \ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0.^\circ598^{+0.002}_{-0.002}$

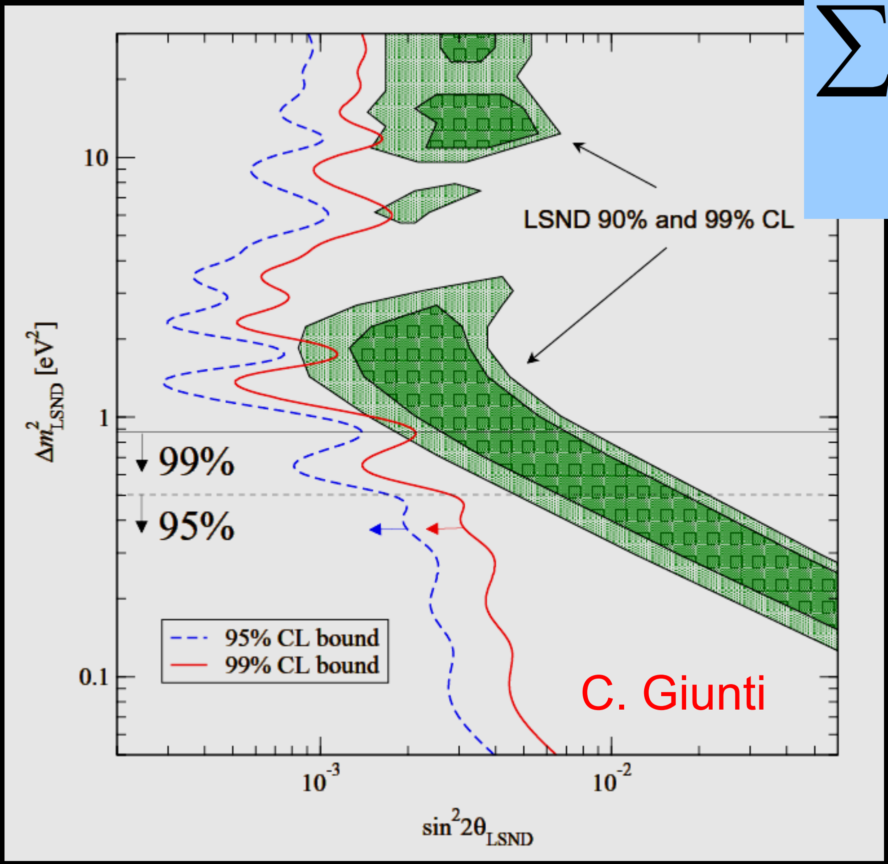
$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc

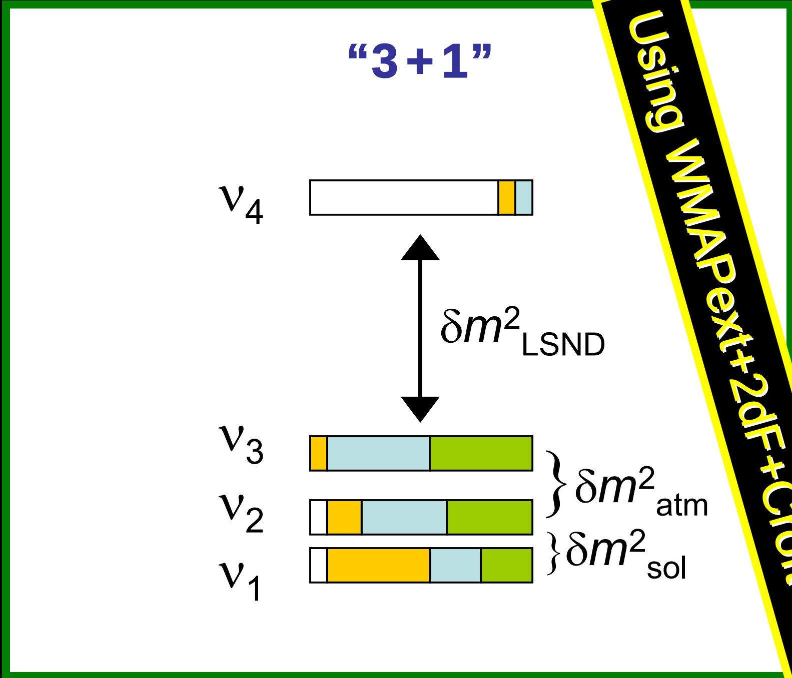
Spergel et al. (WMAP team), 2003

WMAP+2dFGRS+Ly-α, Neutrino Mass, and 4-Neutrino Models



$$\sum m_\nu < 0.69\,\mathrm{eV}\ (95\%\ \mathrm{CL})$$

[Spergel et al WMAP]



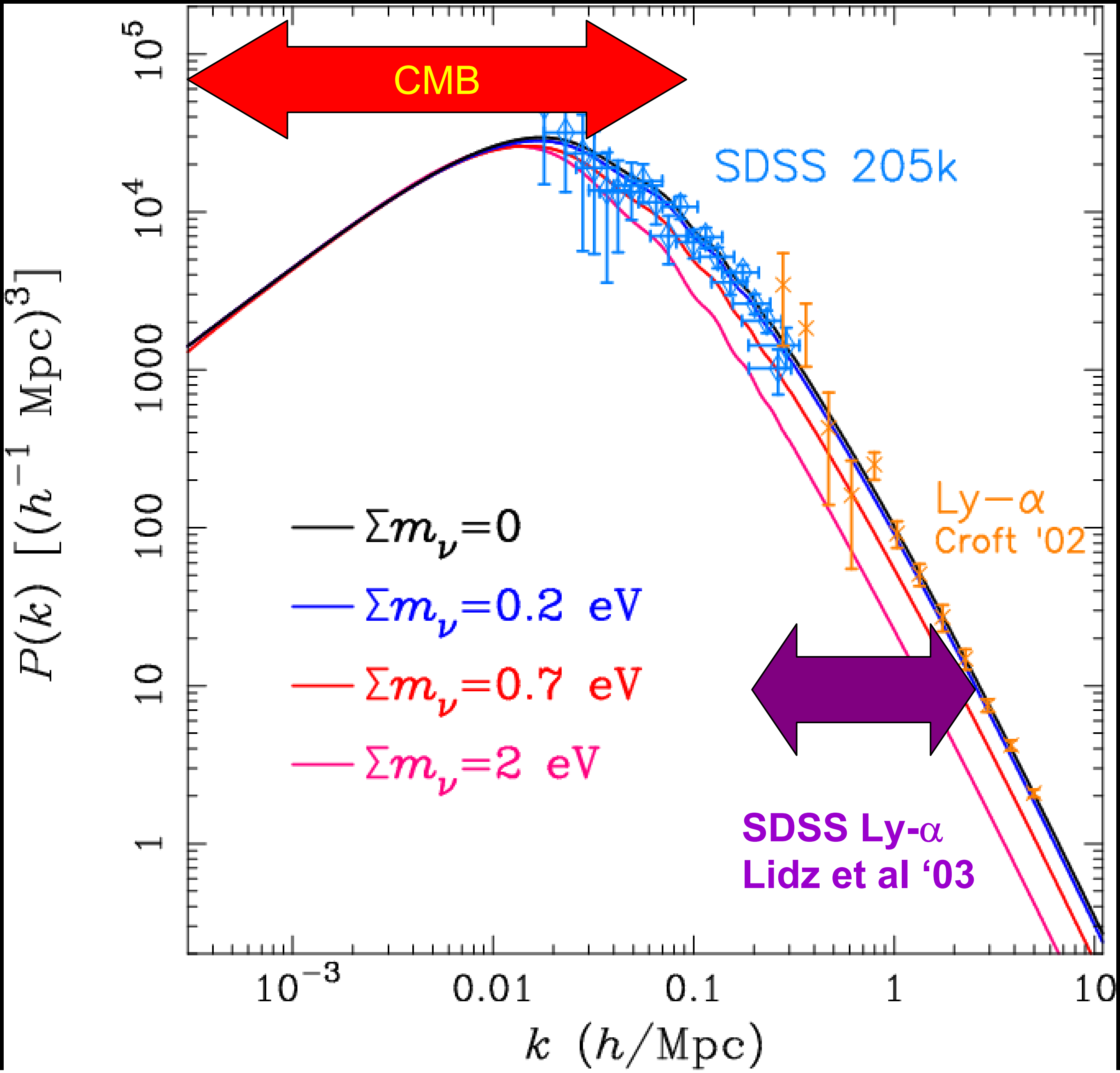
Using WMAPext+2dF+Croft et al Ly-a

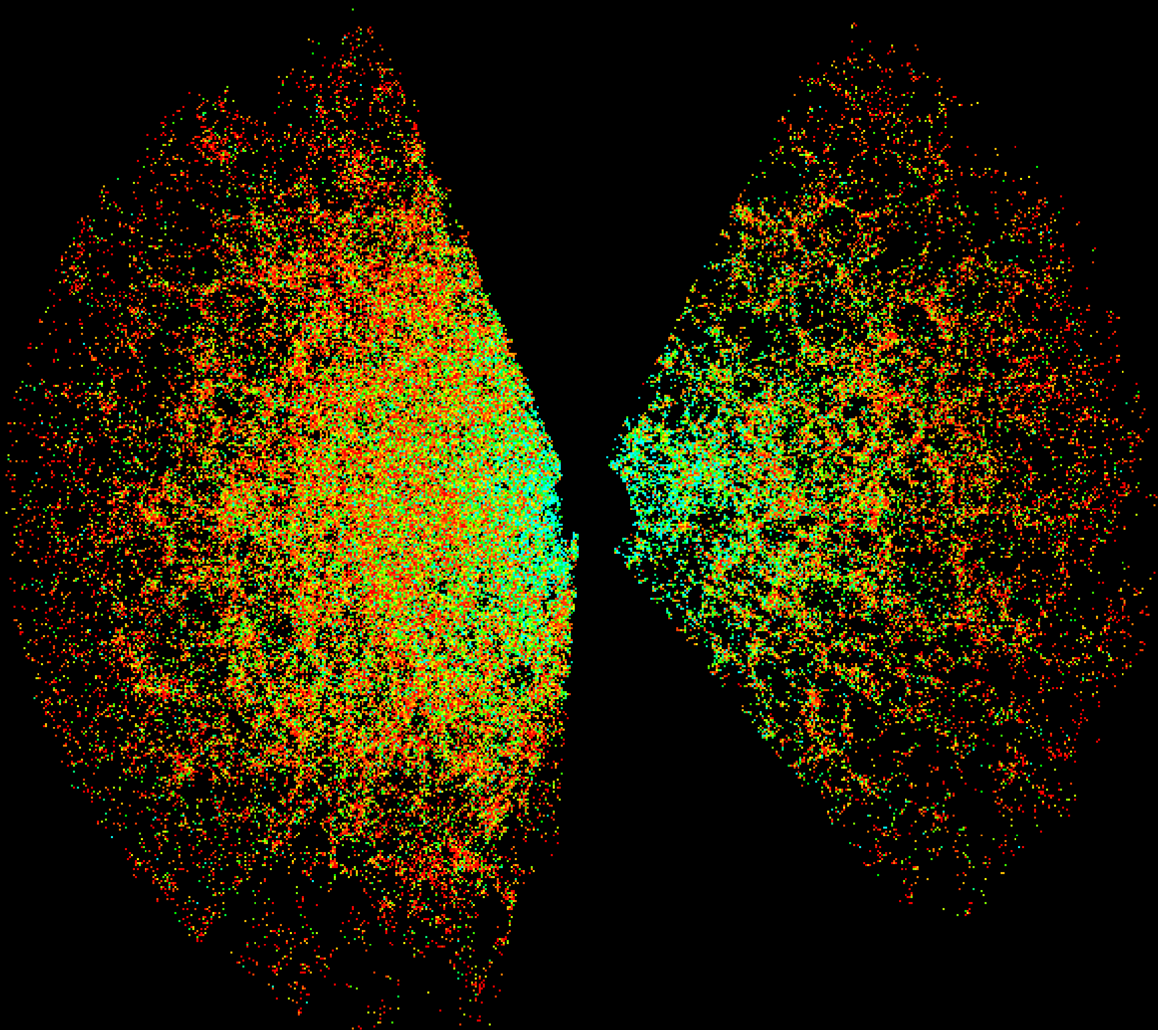
Pierce & Murayama [hep-ph/0302131]; C. Giunti [hep-ph/0302173];
But, see Seljak, McDonald & Makarov [astro-ph/0302571];
Hannestad [astro-ph/0303076]

Approximations & Constraints

- The WMAP team mass bound:
  - Relied on Large Scale Structure data (Galaxies and Ly-α)
  - WMAP (CMB) only tightened constraints on degenerate parameters
- The tight neutrino limit required at least one of two very optimistic LSS measurements
  - Bias: The WMAP team used Verde et al '03 measure of bias, whose technique was calibrated by qualitative agreement with specific galaxy formation simulations, and this uncertainty was not quantified
  - $P_m(k)$ from Ly-α forest: calibrated as one simulation that depends on cosmology, underestimating uncertainties particularly on the transmission optical dept [amplitude of $P_m(k)$]

Measuring P(k)





Sloan Digital Sky Survey

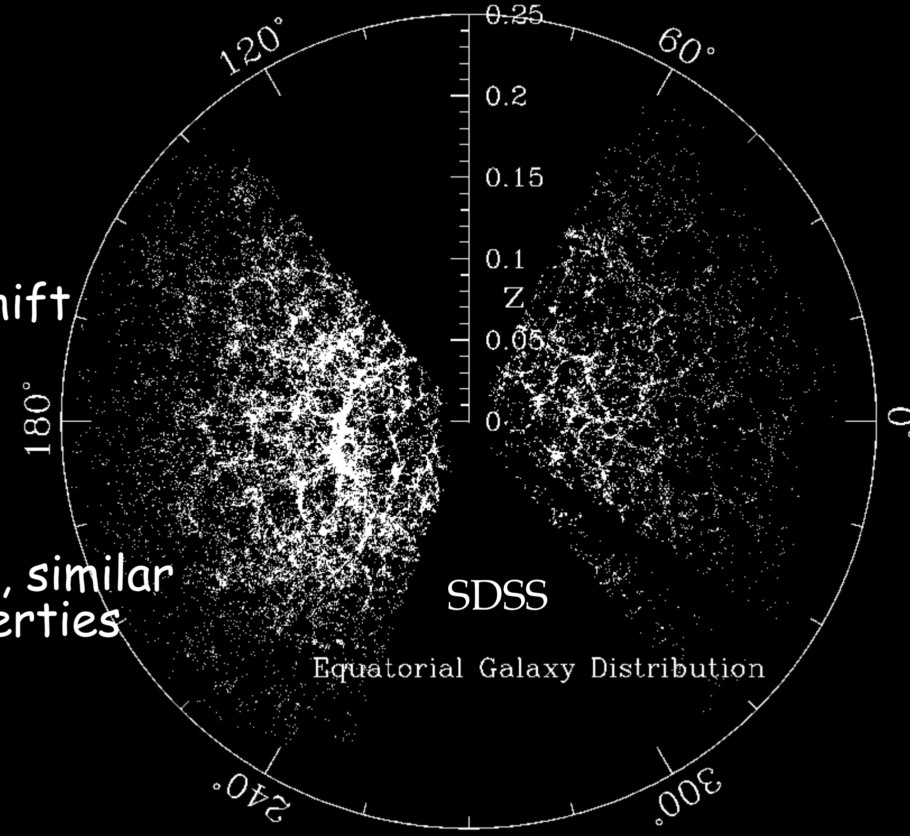
¼ of sky

Position of 10^6 galaxies, 10^5 quasars

Galaxy surveys

- "Average" L* galaxies
  - Sloan Digital Sky Survey Main Galaxy Sample [to be 10^6 galaxies with *z*]
  - Two-degree Field Galaxy Redshift Survey (2dFGRS) [200k]

- Luminous Red Galaxies
  - Of one color & brightness type, similar "histories" and clustering properties
  - Observable over large *k* scale



Galaxies vs. Dark Matter

- Galaxies are formed by nonlinear processes whose use as a precision cosmological tool will be a "footnote" in precision cosmology
- Galaxy formation occurs and affects regions of space only ~10 Mpc in scale, therefore does not effect the large scale galaxy/dark matter distribution (Berlind et al. '02; Blanton et al. '99)

Bias

- The galaxy field is, necessarily, some "biased" tracer of the matter density field:

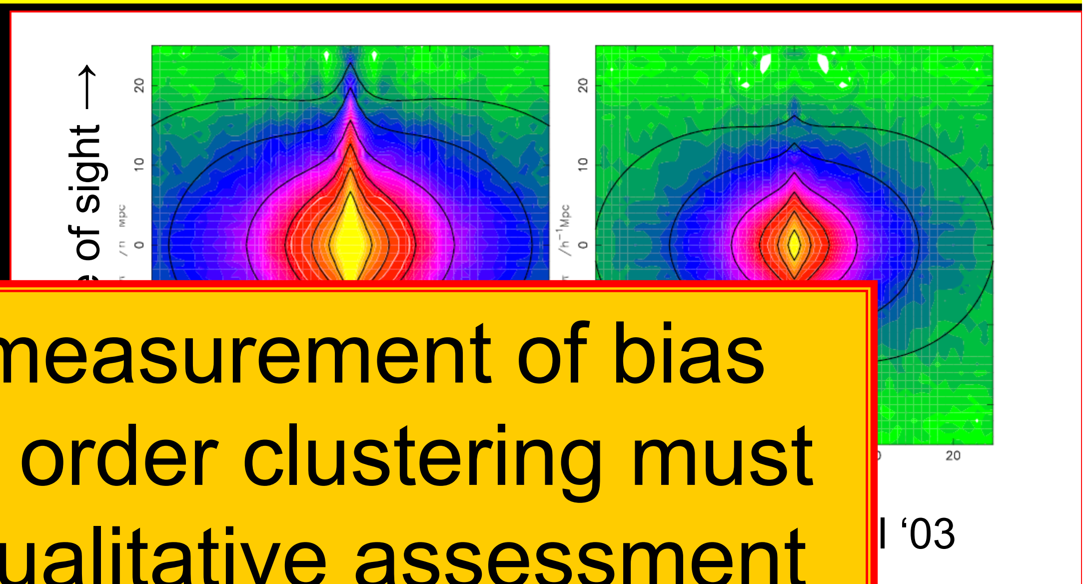
$$P_g(k) = b^2 P(k)$$

- What is *b*?
  - Semi-analytic calculations and numerical simulations of galaxy formation tend to agree with scale-invariant bias at large scales… conservatively, let *b* be a free value and only using the shape of $P_g(k)$… used by most m_ν analyses
  - If it varies with scale (definitely true at small scales), it is measurable via higher-order correlations [Frieman & Gaztañaga] – these results were used by WMAP team's parameter analysis (using overall amplitude information)

Further considerations…

Redshift Distortions

> To get the real-space $P_g(k)$, one must map the observed redshift-space c
this is c
velociti

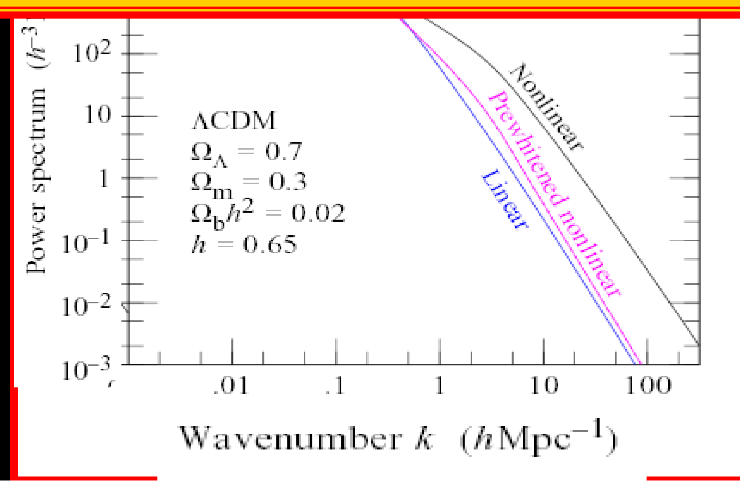


An accurate measurement of bias through higher order clustering must go beyond a qualitative assessment of agreement with numerical simulations of galactic clustering

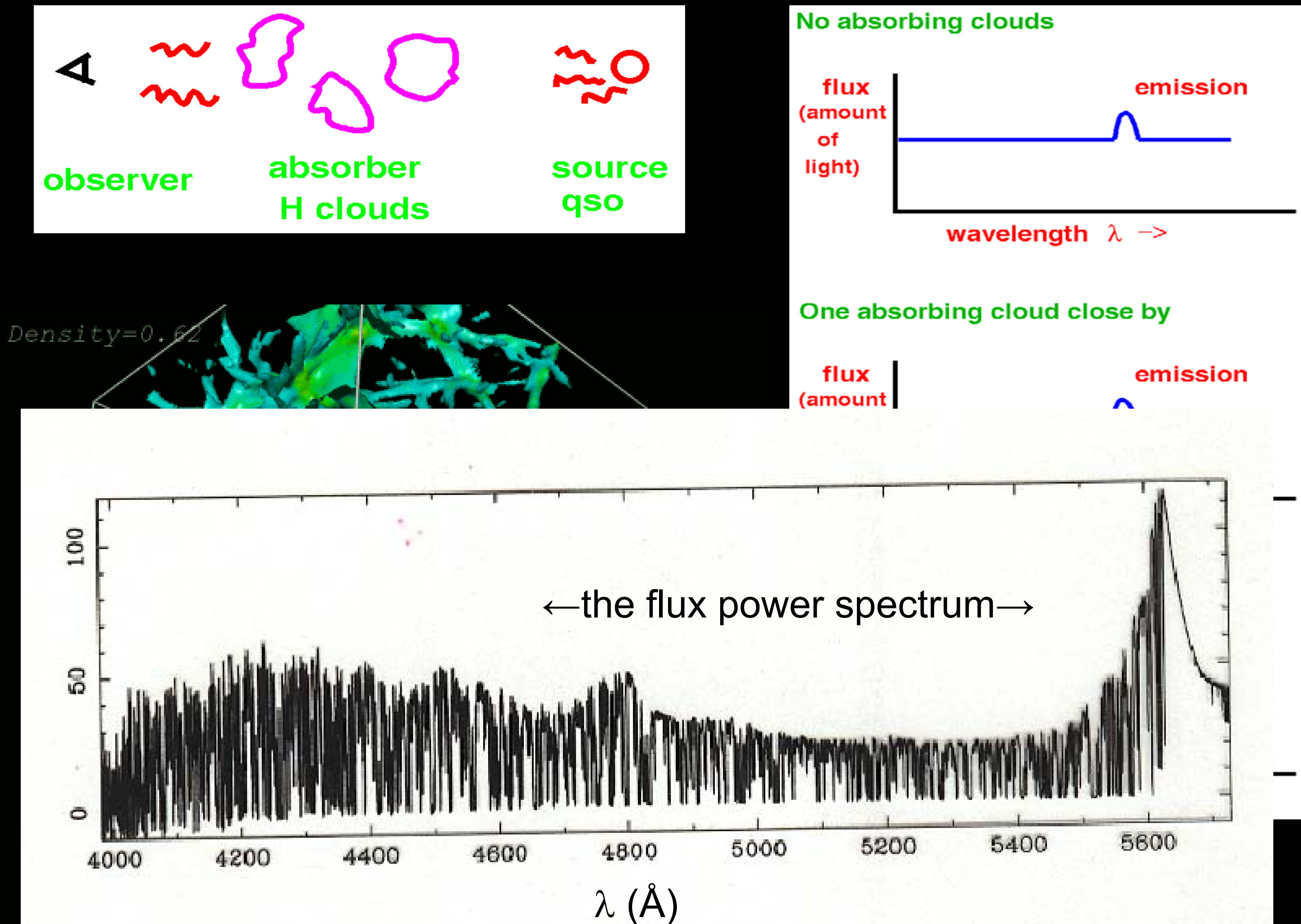
Nonlin

> To com
one must
collapse and clustering is occuring – generally above scale where bias should become scale-free

> ***k*** cut often taken to be where linear power is taken to be comparable to nonlinear power… precision measurements require nonlinearity to be *subdominant* (<1%) the signal you are trying to measure…
***k* > 0.1 *h* Mpc^{-1}**



Lyman-α forest



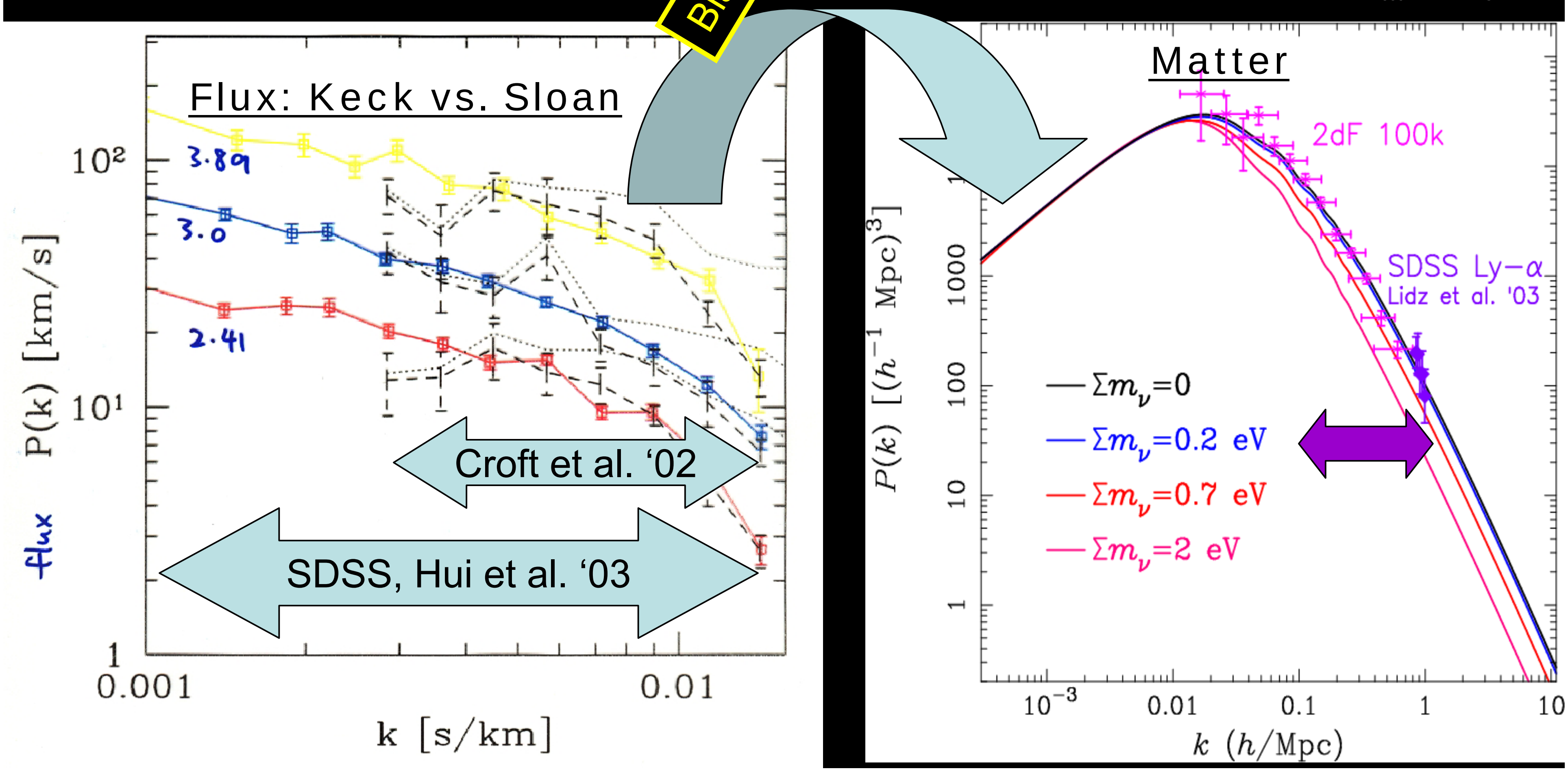
Measuring $P_m(k)$ with Lyman-α forest $P_F(k)$

Using > 3000 quasar spectra from the SDSS quasar survey…
Much broader range in *k* and much higher statistical precision

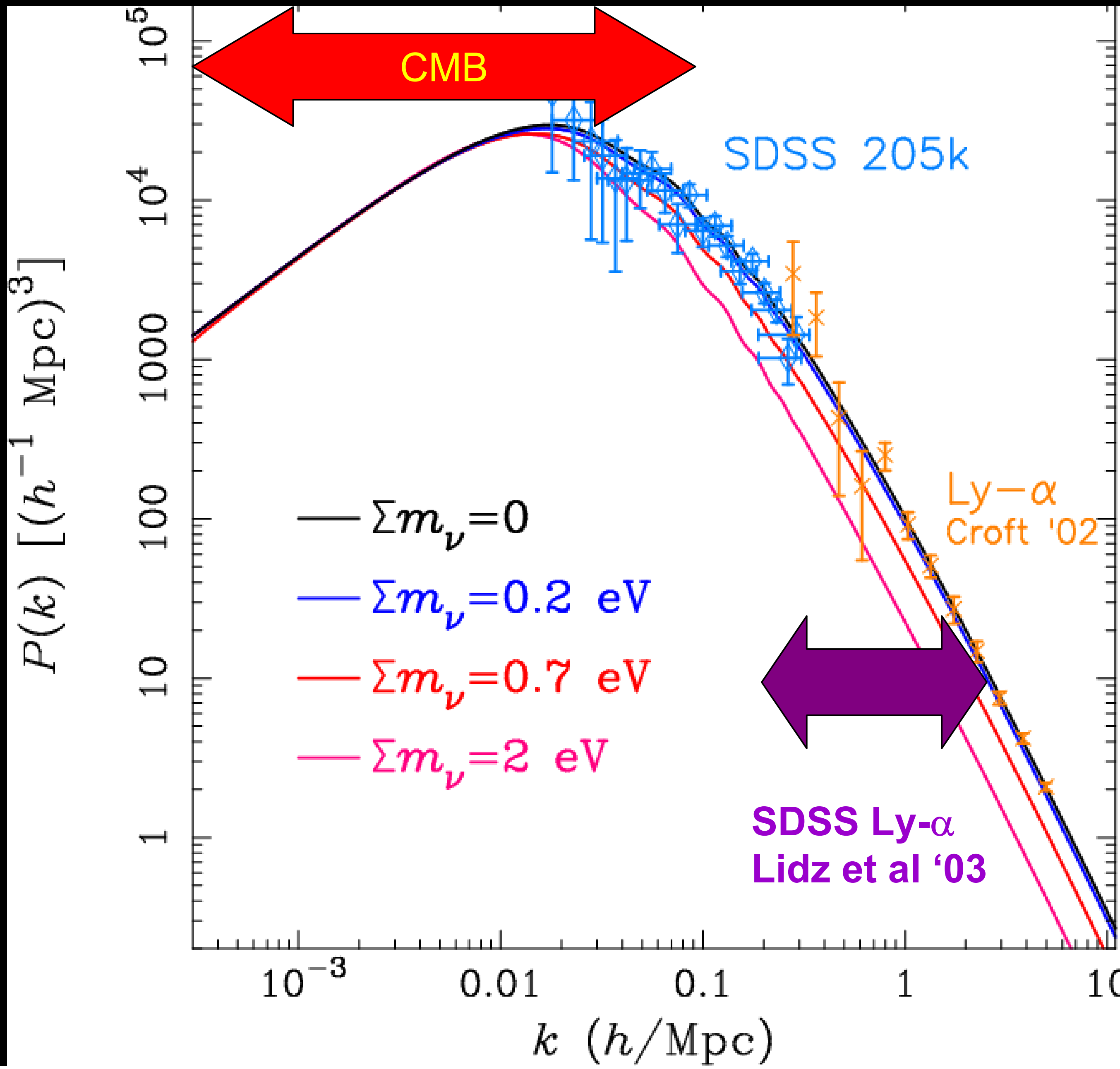
$$P_{flux}(k) = b^2(k, \text{cosmology}) P_m(k)$$

Bias (again!)

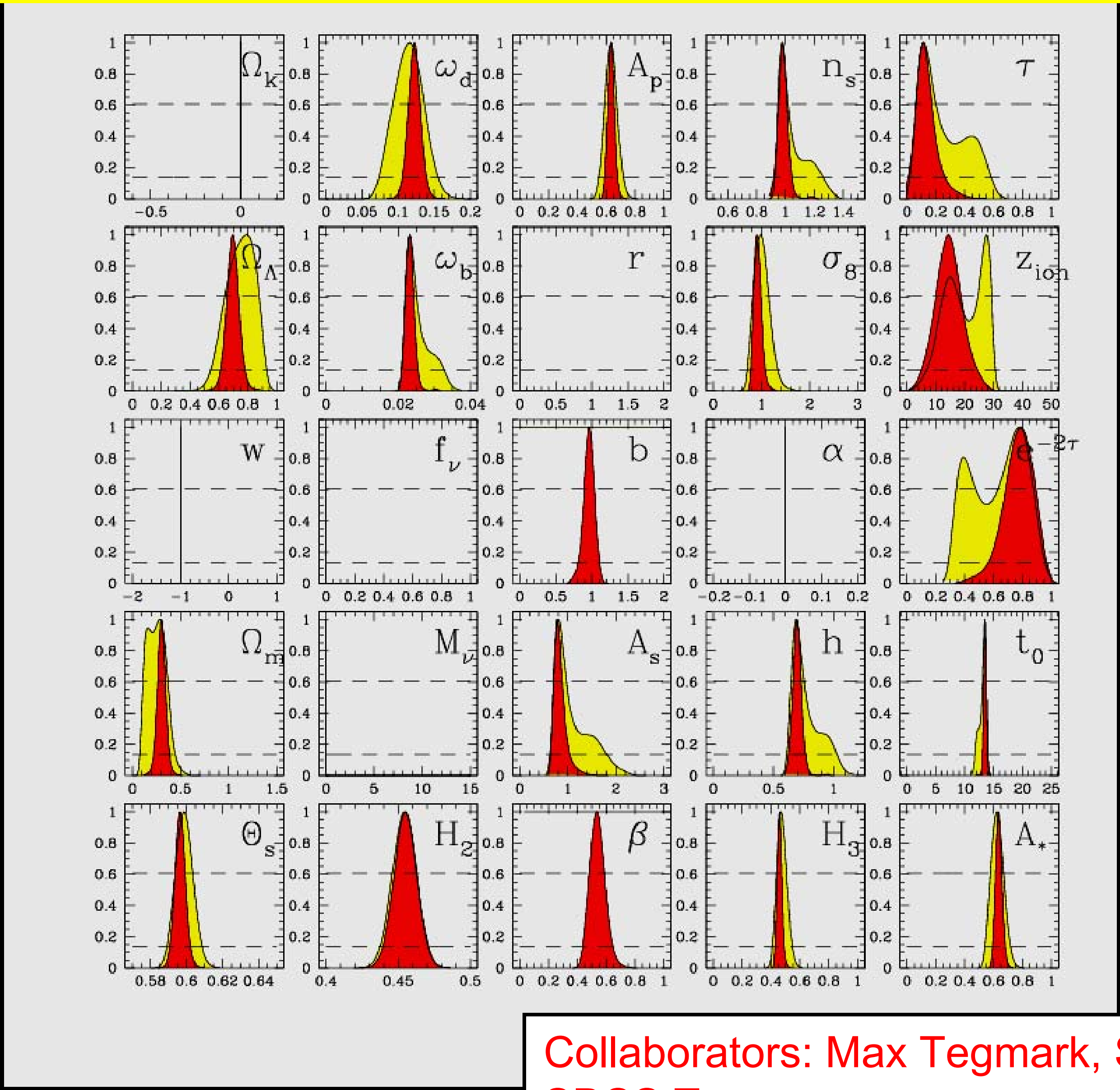
- Normalized through *N*-body simulations
- Monte-Carlo of likelihood for $(P_m(k)|P_F(k))$



Combining WMAPext+SDSS $P_g(k)$+SDSS Ly-α $P_m(k)$

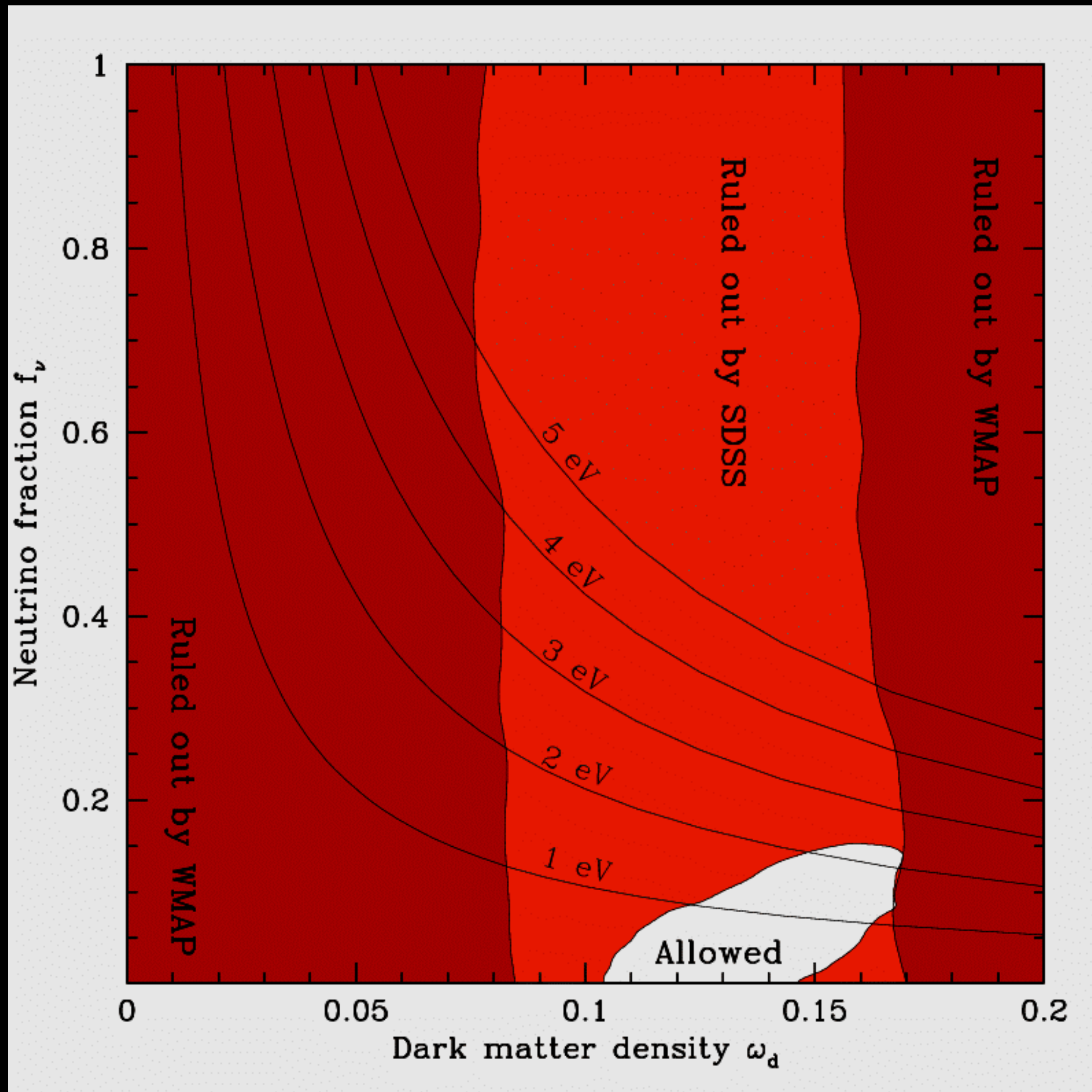


Gives much of information: $\Omega_b h^2$, $\Omega_c h^2$, H_0, τ, A_s, n, dn/dlnk, f_ν

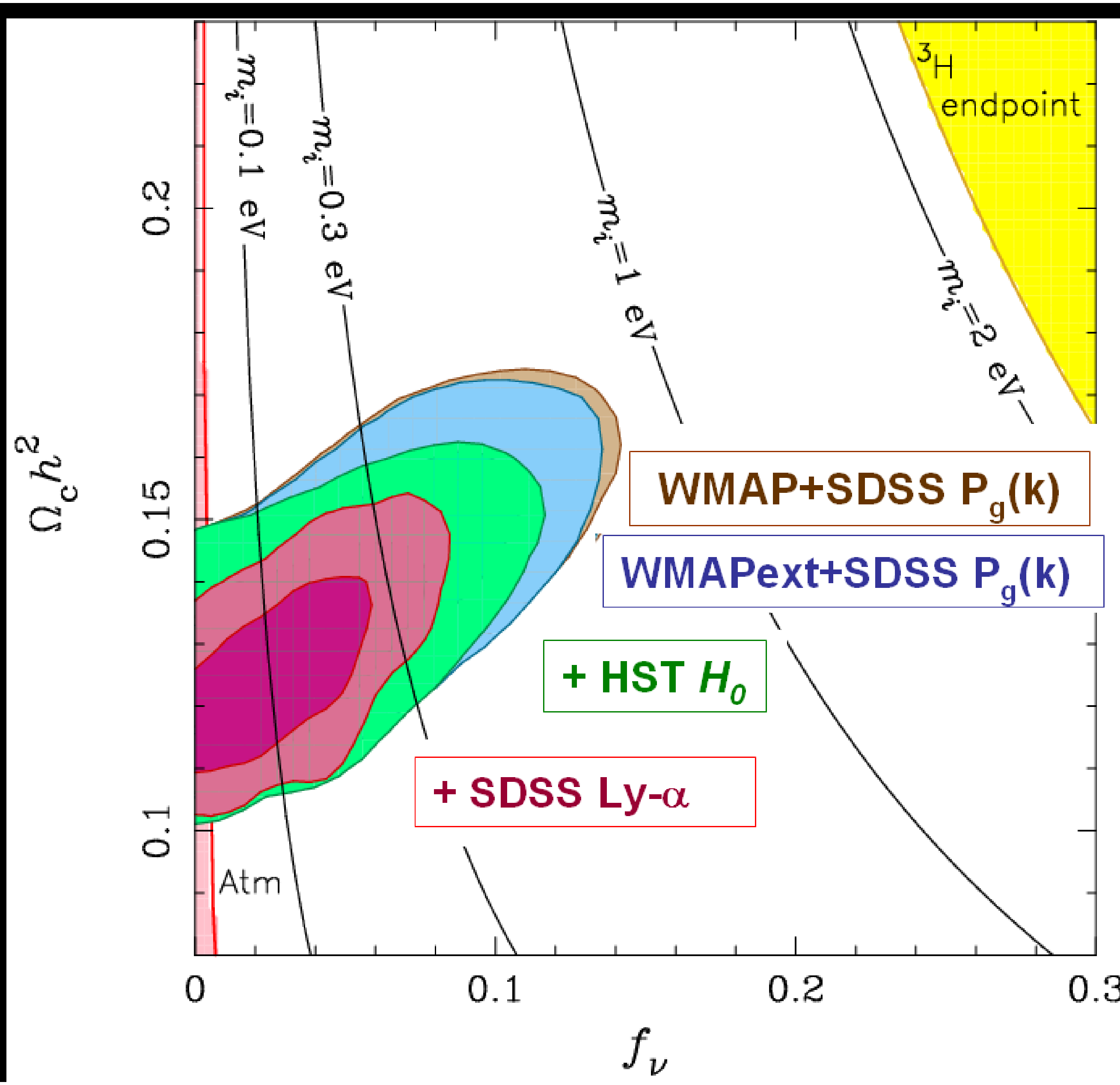


Collaborators: Max Tegmark, Scott Dodelson, SDSS Team

Neutrino Dark Matter Fraction: f_ν



WMAP$_{+ACBAR+CBI}$ + SDSS + HST: Dark Matter



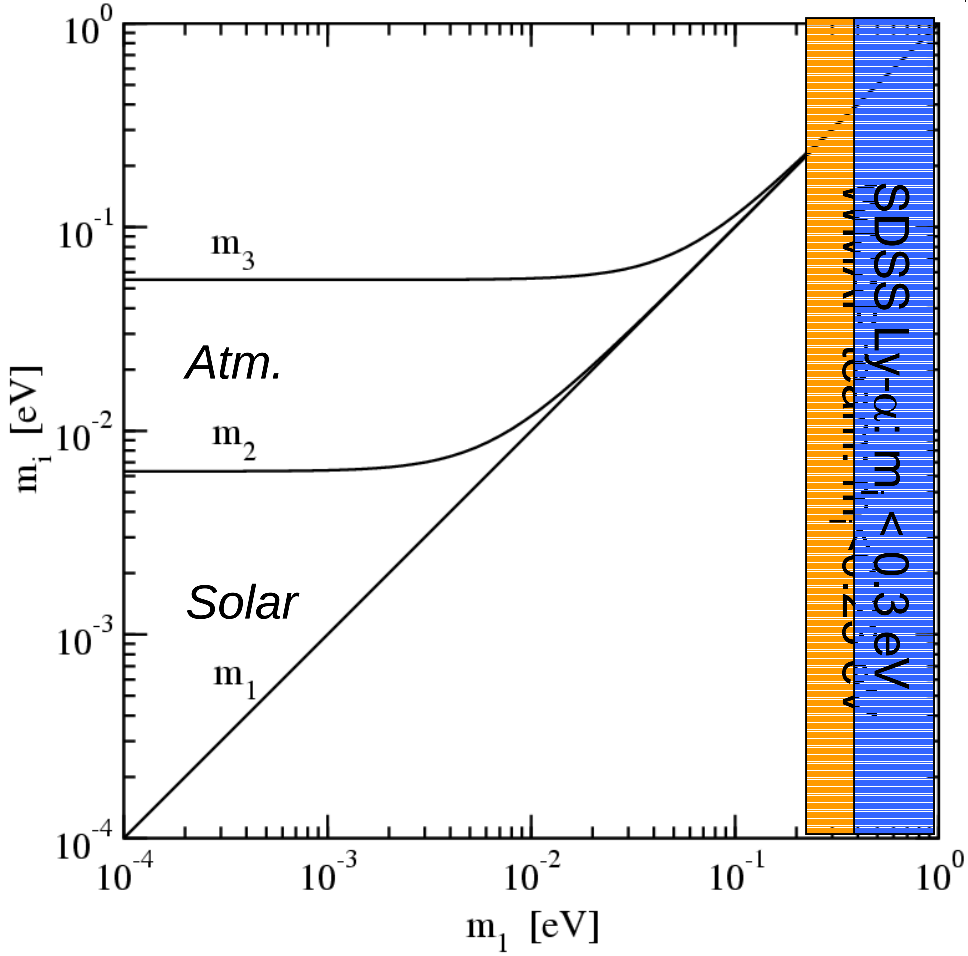
Preliminary estimate of Σm_ν from WMAPext + SDSS $P_g(k)$ (sans bias) + SDSS Ly-α

Using WMAP + ACBAR + CBI (CMB) and SDSS $P_g(k)$ – no assumption of bias except for scale-invariance, and letting the power spectrum run ($dn/d\ln k \neq 0$):

$$\Sigma m_\nu \leq 1.7\,\text{eV} \quad (95\%\ \text{CL})$$

Adding SDSS Ly-α data (Lidz et al '03):

$$\Sigma m_\nu \leq 0.90\ \text{eV}$$
$$(95\%\ \text{CL},\ \textit{preliminary})$$



Plot: Beacom & Bell '02

Is m_ν detected?

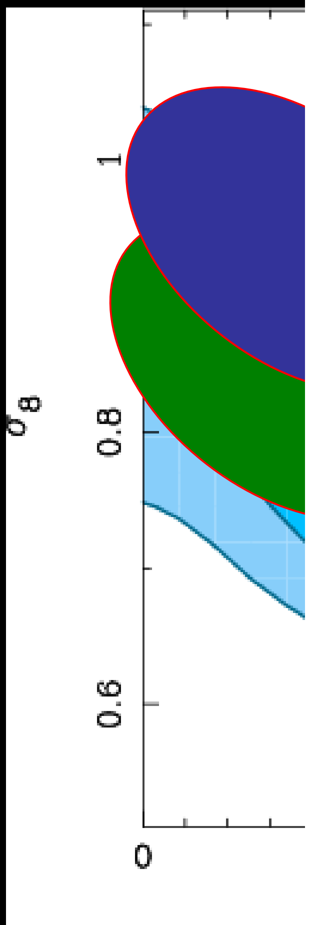


Table 5: Recent constraints in the (Ω_m, σ_8)-plane.

Analysis		Measurement
Clusters:		
Bahcall & Bode '03, $z < 0.2$	[39]	$\sigma_8(\Omega_m/0.3)^{0.60} = 0.68 \pm 0.06$
Bahcall & Bode '03, $z > 0.5$	[39]	$\sigma_8(\Omega_m/0.3)^{0.14} = 0.92 \pm 0.09$
Pierpaoli *et al.* '02	[40]	$\sigma_8 = 0.77^{+0.05}_{-0.04}$
Allen *et al.* '03	[41]	$\sigma_8(\Omega_m/0.3)^{0.25} = 0.69 \pm 0.02$
Schuecker*et al.* '02	[42]	$\sigma_8 = 0.711^{+0.039}_{-0.031}$
Viana *et al.* '02	[43]	$\sigma_8 = 0.61 \pm 0.05$
Seljak '02)	[44]	$\sigma_8(\Omega_m/0.3)^{0.44} = 0.75 \pm 0.06$
Reiprich & Böhringer '02	[45]	$\sigma_8(\Omega_m/0.3)^{0.38} \approx 0.68$
Borgani *et al.* '01	[46]	$\sigma_8 = 0.76^{+0.08}_{-0.05}$
Pierpaoli *et al.* '01	[47]	$\sigma_8\Omega_m^{0.60} = 0.495^{+0.034}_{-0.037}$
Weak lensing:		
Jarvis *et al.* '02	[48]	$\sigma_8(\Omega_m/0.3)^{0.57} = 0.71^{+0.06}_{-0.08}$
Brown *et al.* '02	[49]	$\sigma_8(\Omega_m/0.3)^{0.50} = 0.74 \pm 0.09$
Hoekstra *et al.* '02	[50]	$\sigma_8(\Omega_m/0.3)^{0.52} = 0.86^{+0.05}_{-0.07}$
Refregier*et al.* '02	[52]	$\sigma_8 = 0.94 \pm 0.14$
Bacon *et al.* '02	[51]	$\sigma_8(\Omega_m/0.3)^{0.68} = 0.97 \pm 0.13$
Van Waerbeke *et al.* (2002)	[53]	$\sigma_8 = 0.97 \pm 0.06$

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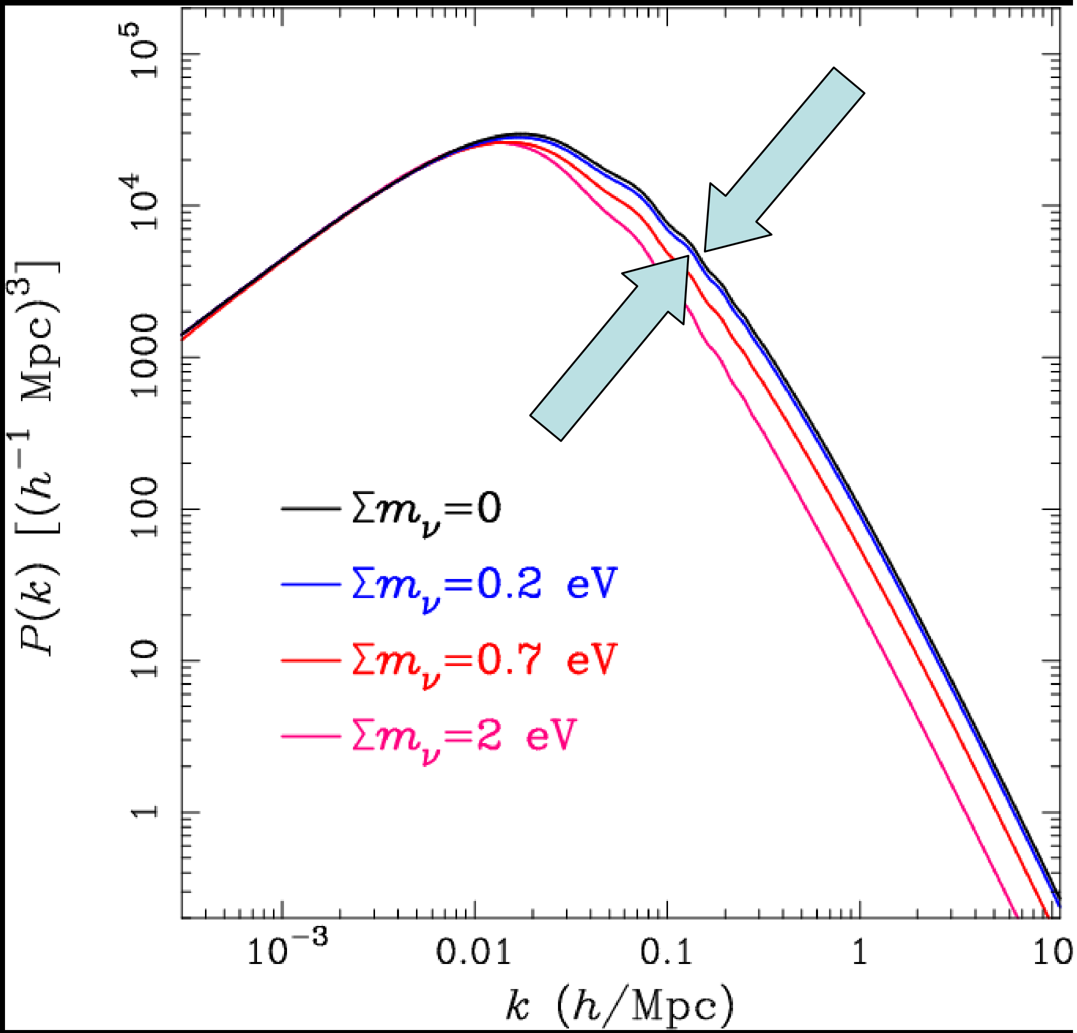
Can cosmology detect heirarchical neutrino masses?

► Galaxy redshift surveys with 10x the volume of SDSS (Hannestad, astro-ph/0211106)

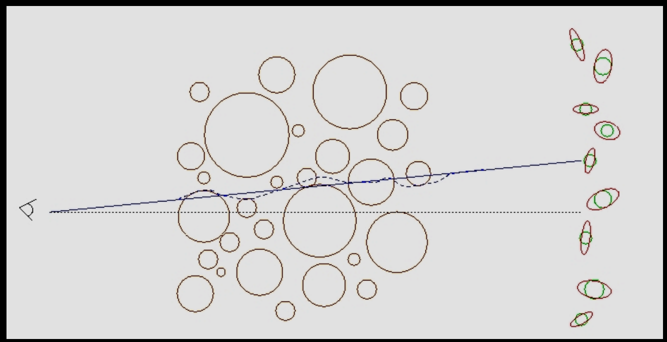
► Weak lensing of galaxies by intervening large scale structure (z~0.5)

(Abazajian & Dodelson, astro-ph/0212216)

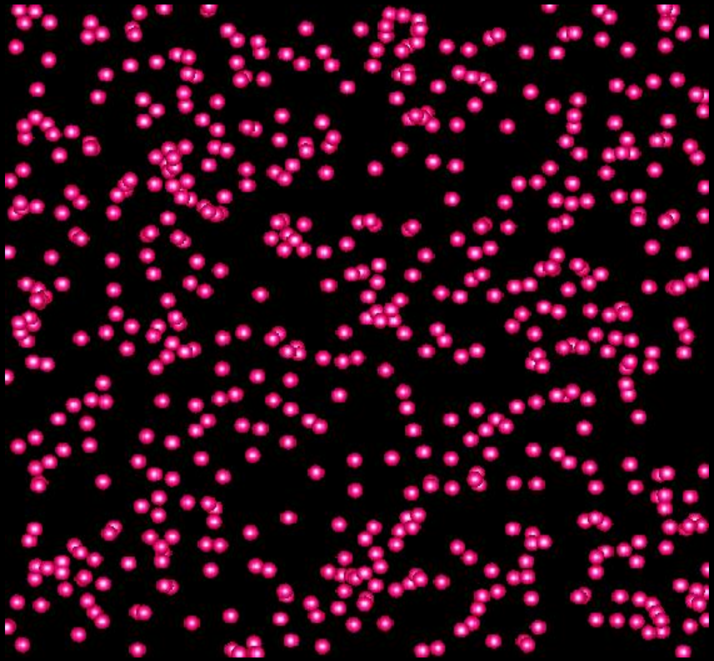
►Weak lensing of the CMB by intervening large scale structure (z~200) with a satellite 20x more sensitive than Planck (Kaplinghat, Knox & Song, astro-ph/0303344)



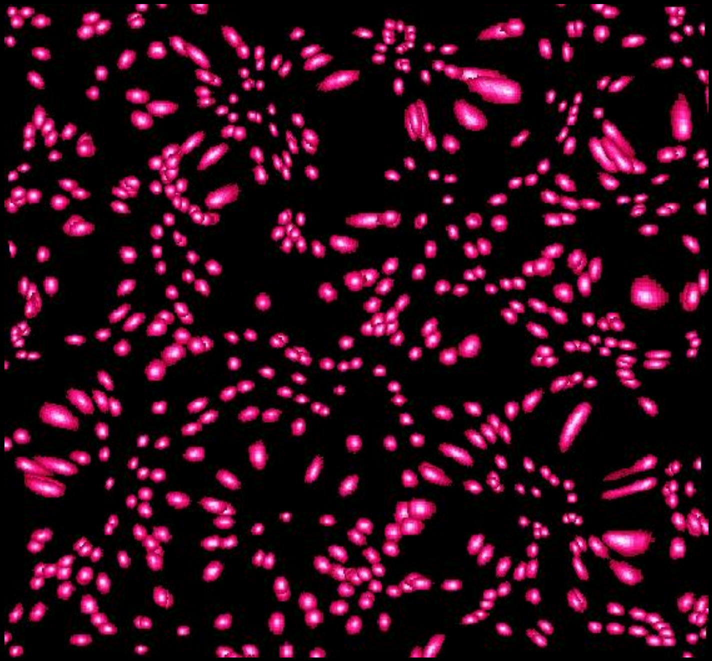
How Gravitational Lensing Works



Distortion of background images by foreground matter



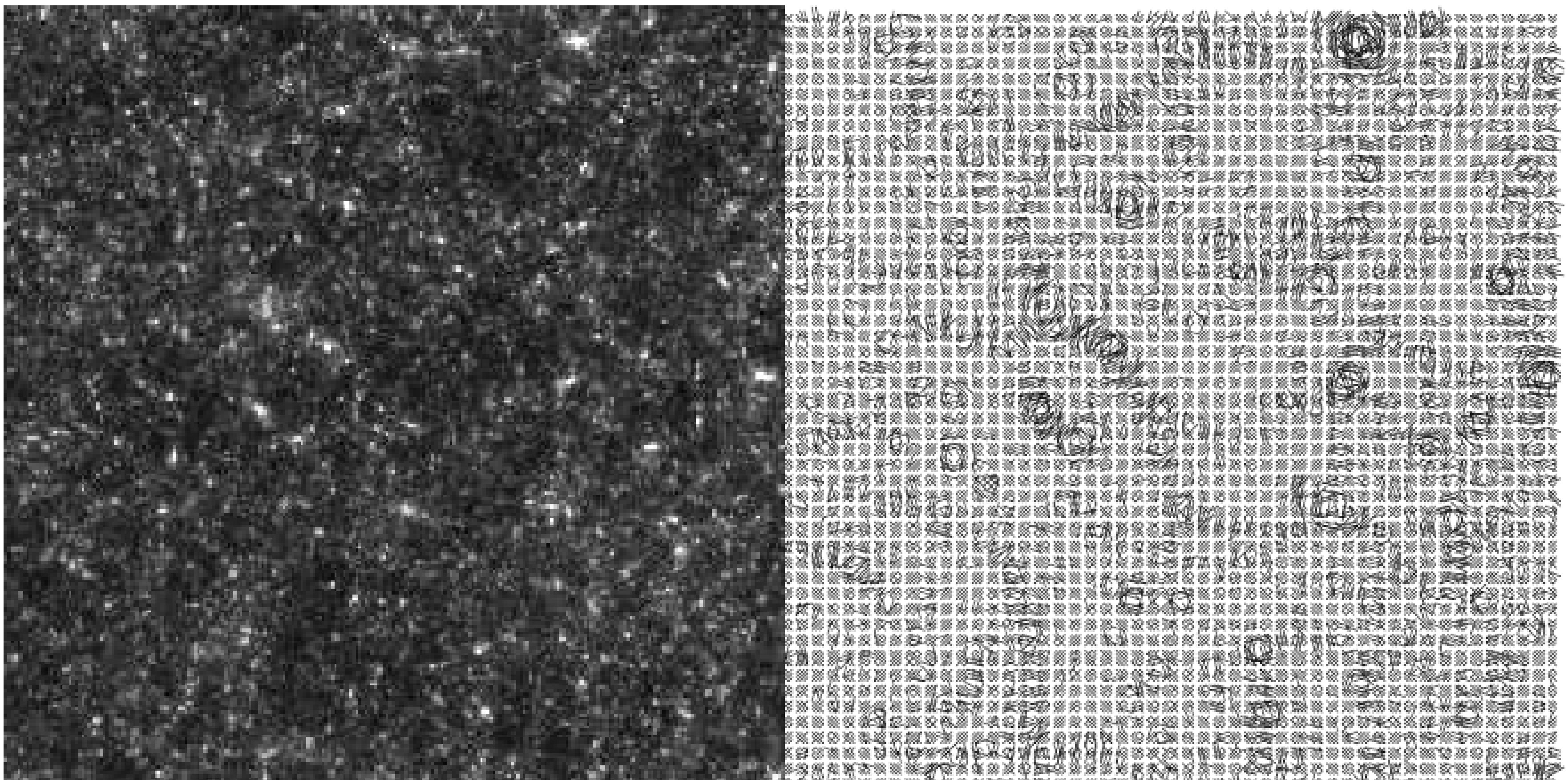
Unlensed



Lensed

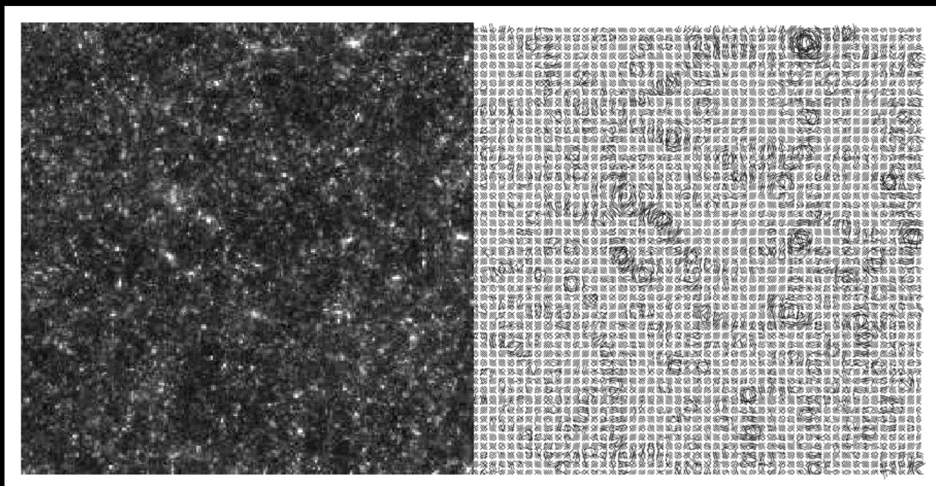
From Ellis '02

The weak lensing of galaxies by foreground large scale structure



White & Hu '00

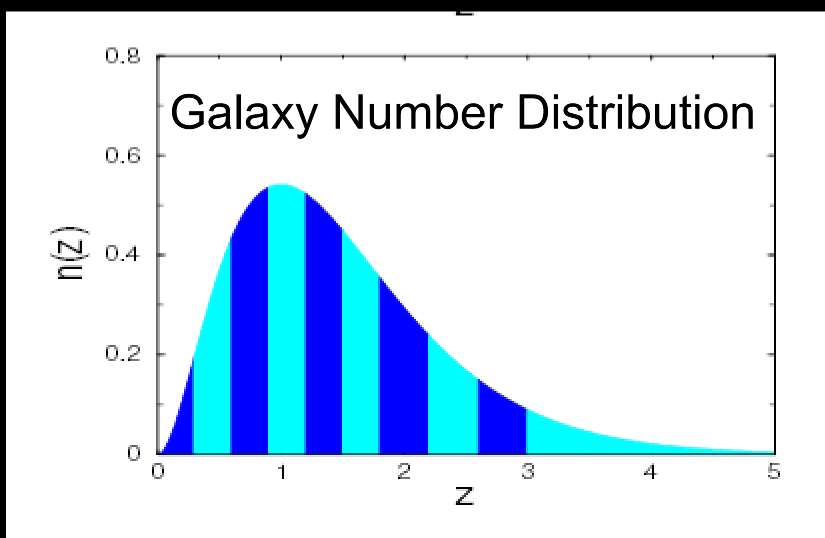
Cosmic Shear, Weak Lensing, and Dark Matter "Tomography"



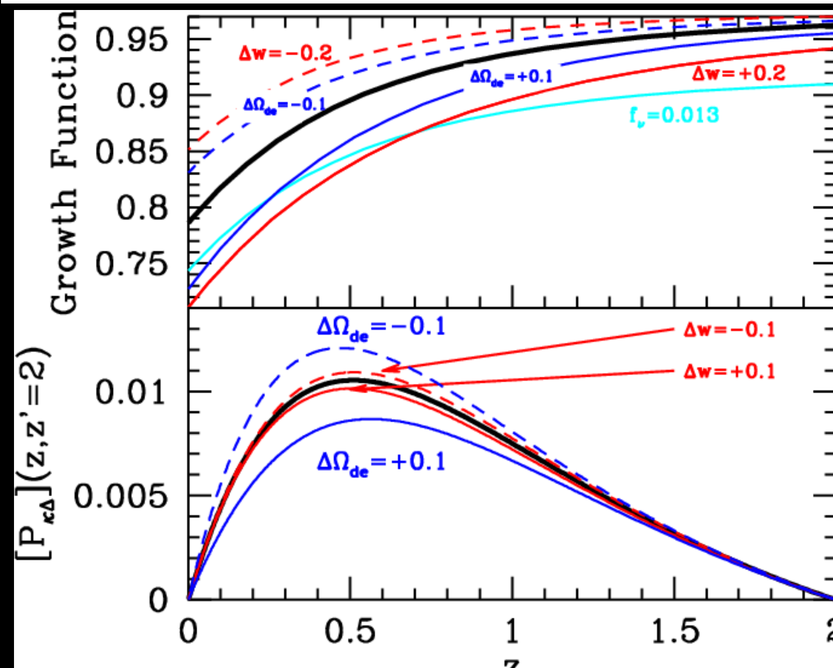
White & Hu '00

$$\kappa(z_s, \vec{\theta}) = \int_0^{z_s} dz P(z, z_s) \delta(z, \vec{\theta}) \, ,$$

$$[P_{\kappa\Delta}]_{ij} = \begin{cases} \frac{3}{2}\Omega_m H_0^2 \delta\chi_j \frac{(\chi_{i+1}-\chi_j)\chi_j}{\chi_{i+1}} & \chi_{i+1} > \chi_j \\ 0 & \chi_{i+1} \leq \chi_j \end{cases}$$

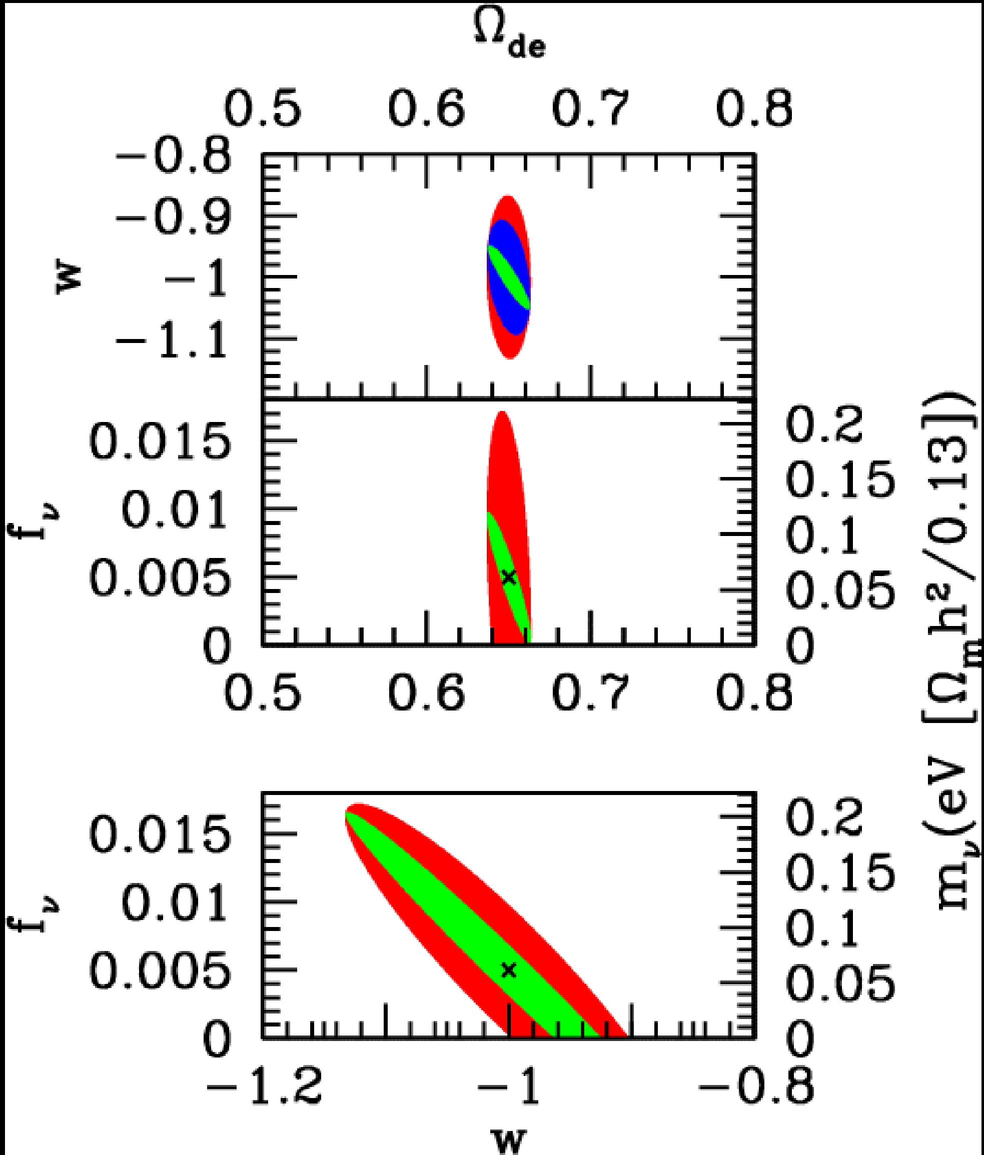


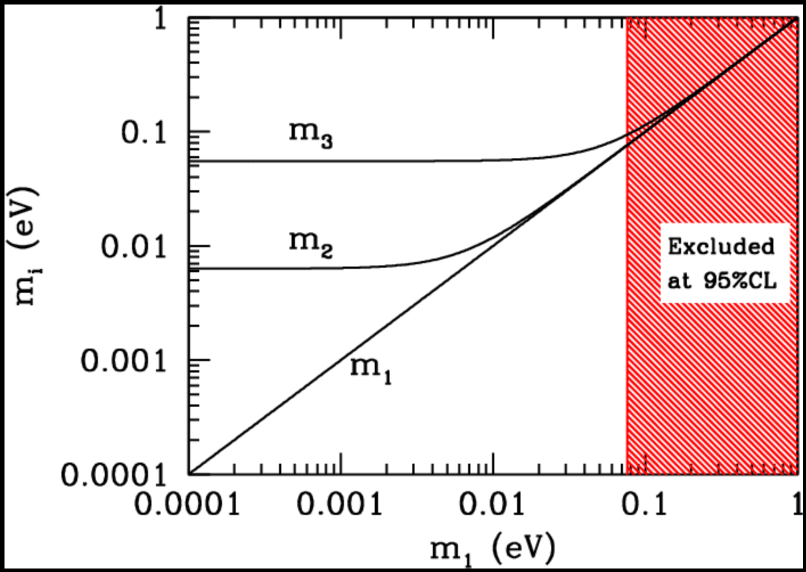
Huterer '01; Hu '02



Abazajian & Dodelson '03

How well can cosmic weak lensing do?





Using only the linear information from tomographic slicing:

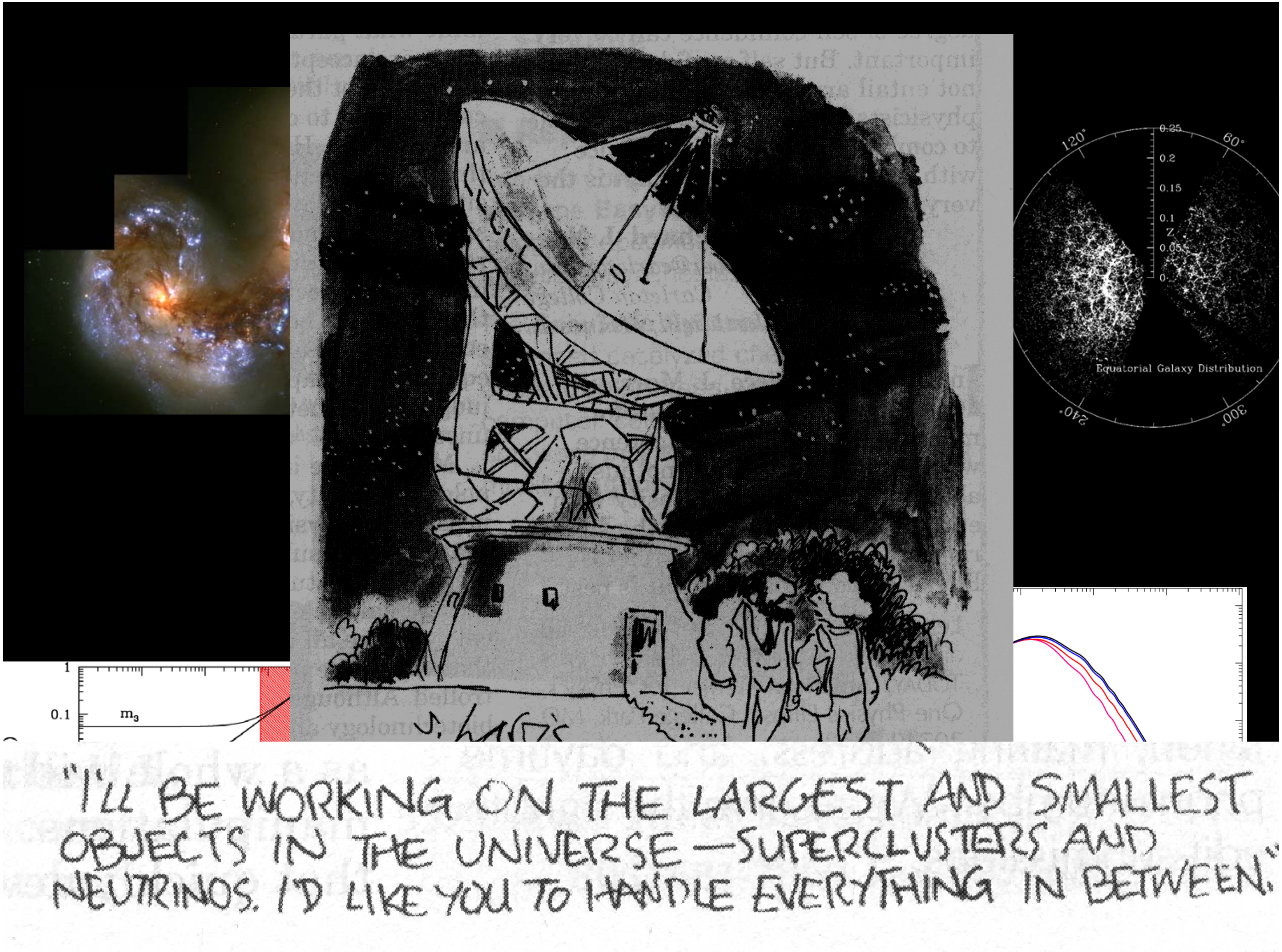
$m_\nu < 0.12$ eV

Conversely, if we know
$m_\nu < 0.1$ eV,
from, 0ν-$\beta\beta$, get a
10% measurement of w

Abazajian & Dodelson '03

Summary…

- The absolute neutrino mass is related to the mechanism of mass generation and new physics
- Absolute neutrino mass limits may be best probed by large scale structure
  - Handling of systematics in measurement of large scale structure are crucial in placing precision limits
    - bias in galaxy redshift surveys
    - the transmission amplitude of Ly-α power)
  - The Sloan Digital Sky Survey provides a wealth of information on galaxy and neutral gas (Ly-α) clustering and thus on large scale structure
  - using techniques of particle physics to handle uncertainties greatly improves accuracy
- Cosmology currently provides the best constraint on the absolute neutrino mass
- Future weak lensing and CMB measurements may detect down to near Atmospheric mass-level deviations in the matter power spectrum



1
0.1
m_3
120°
60°
0.25
0.2
0.15
0.1
Z
0.05
0
Equatorial Galaxy Distribution
240°
300°
"I'LL BE WORKING ON THE LARGEST AND SMALLEST OBJECTS IN THE UNIVERSE—SUPERCLUSTERS AND NEUTRINOS. I'D LIKE YOU TO HANDLE EVERYTHING IN BETWEEN."