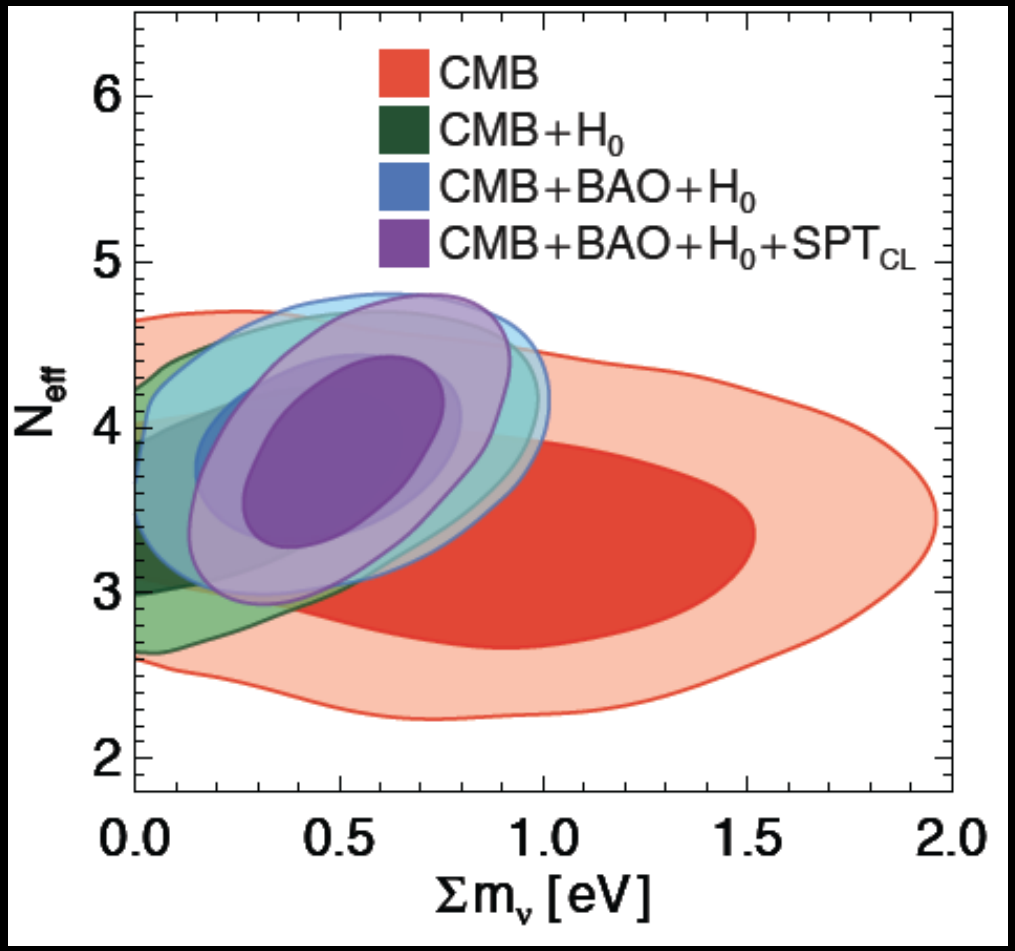
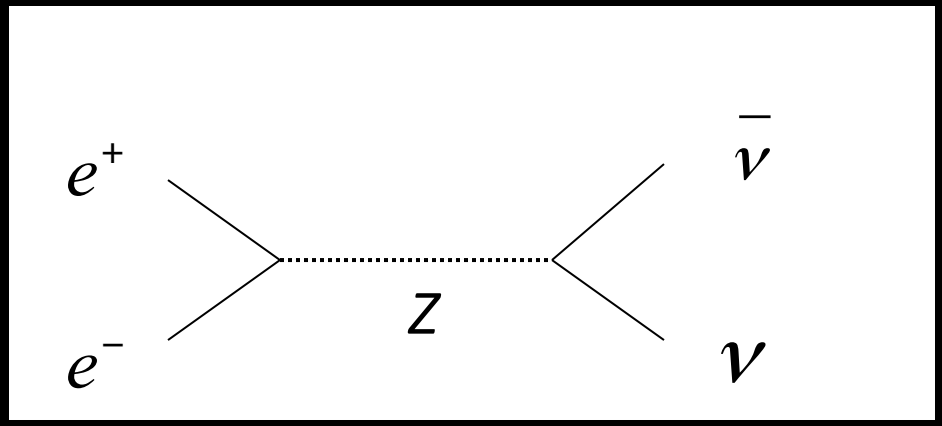
Current and Future Cosmological Constraints on Neutrinos



Standard Model neutrinos are produced in the early universe

Alpher, Herman, & Gamow 1953

Even if no neutrinos initially when the temperature is much larger than m_e, rate for producing them via, e.g.,



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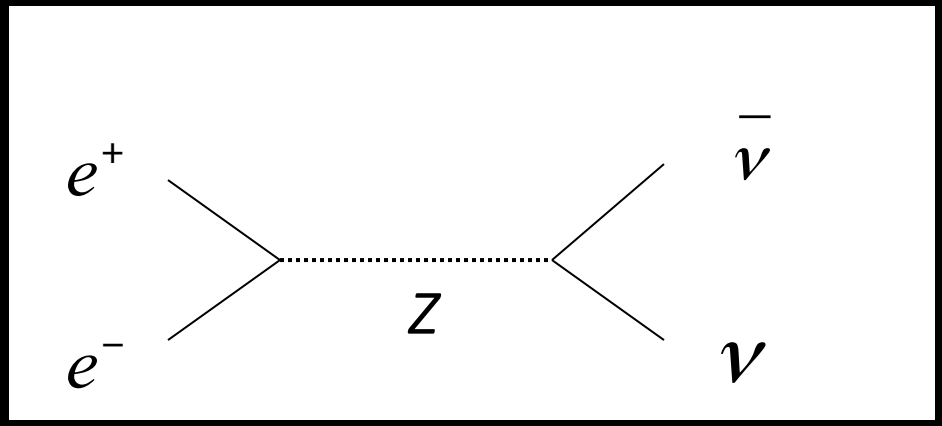


is

$$n\sigma \sim T^3 \frac{\alpha^2 T^2}{m_Z^4}$$

Compare this to the expansion rate

$$H = \sqrt{\frac{8\pi G\rho}{3}} \sim \frac{T^2}{m_{Planck}}$$

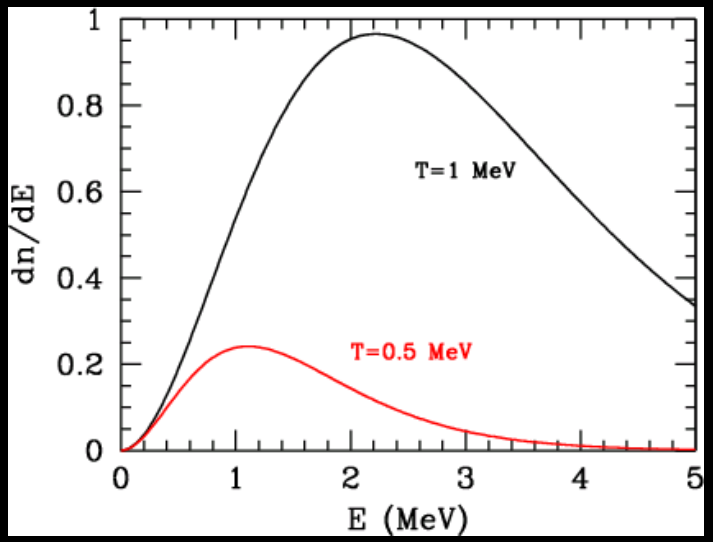
the universe is radiation dominated at early times

ratio of neutrino production rate to expansion rate

$$\frac{\Gamma_\nu}{H} \sim \left(\frac{T}{5MeV}\right)^3$$

Above 5 MeV, neutrinos are in equilibrium with the rest of the cosmic plasma

Fermi-Dirac distribution with temperature *T* equal to the electron/photon temperature.



After the neutrinos decouple from the rest of the plasma (*T*<MeV), they still maintain Fermi-Dirac distribution with *T~1/a.*

Calibrate off the well-known photon temperature to get the prediction

$$n_{\bar{\nu}\nu} = 115 N_\nu \, cm^{-3}$$

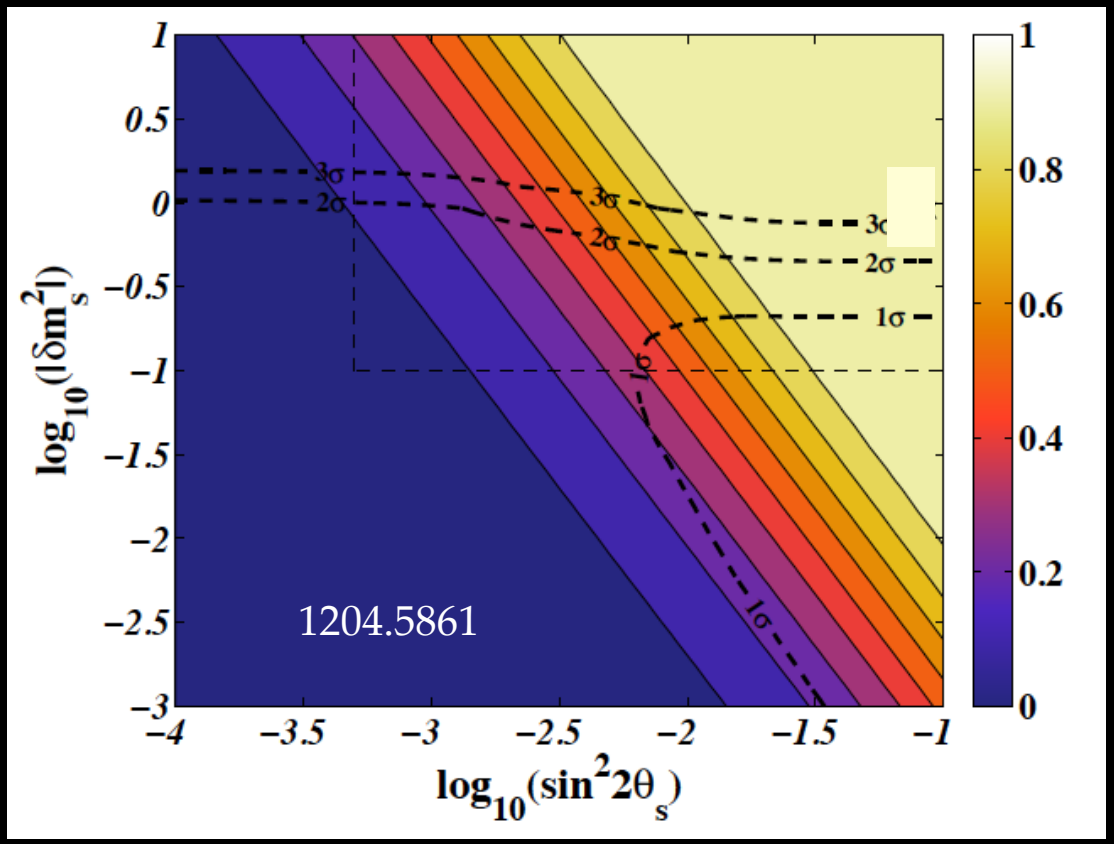
Number of species of weakly interacting neutrinos (3)

a hundred quadrillion cosmic neutrinos passing through this screen every second

Sterile Neutrinos produced via oscillations

$$Rate = \frac{1}{2}\sin^2(2\theta_m)\Gamma_{weak}$$

where the mixing angle needs to be computed in matter and the usual $sin^2(\Delta E\ t)$ term averages to ½ since the interaction time is very fast



For direct detection, see next talk

- “Every experimentalist passes through a phase in which s/he goes after the cosmic neutrino background” (Formaggio in the name of Fisher)

- Last scattering was much earlier than that of photons (1 sec vs. 480,00 years) but the neutrino last scattering surface is actually much **closer** to us than is the photon last scattering surface

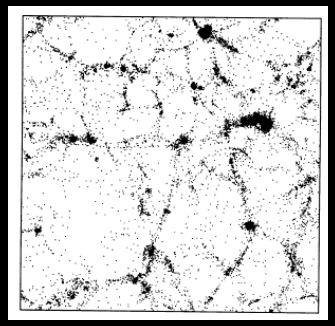
Indirect Detection

Extra neutrinos affect the energy density, and therefore the expansion rate

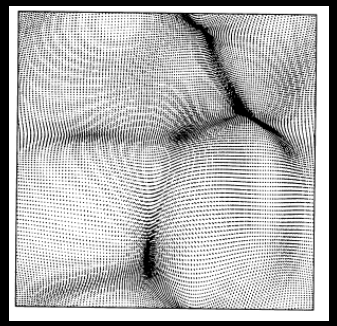
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

Massive neutrinos contribute to the energy density **today** so affect the formation of structure

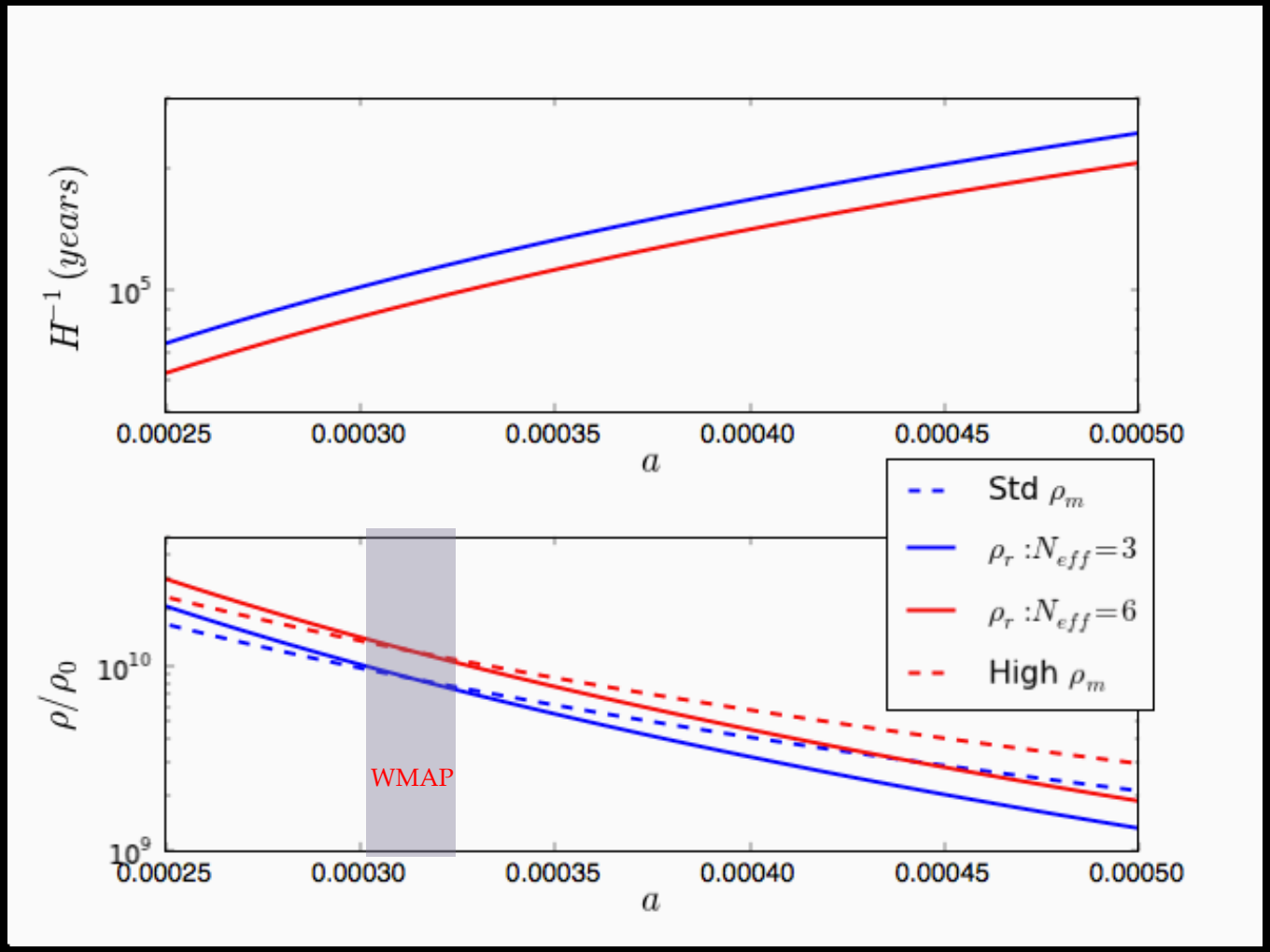
Cold Dark Matter



Cold+ Hot Dark Matter



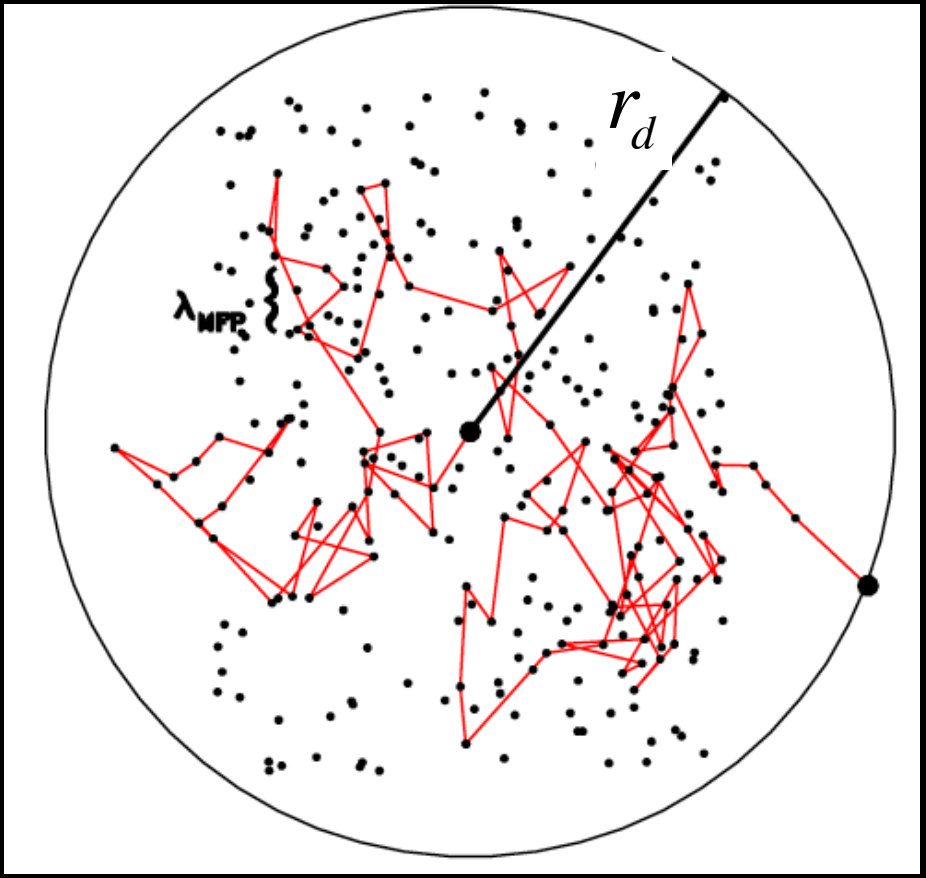
Neutrinos contribute to energy density of the early Universe



Anisotropies damp on small scales because photons random walk

$$r_d \approx \lambda_{MFP}\sqrt{n_e \sigma_T H^{-1}}$$
$$= \frac{1}{\sqrt{n_e \sigma_T H}}$$

Other distances scale as H^{-1}



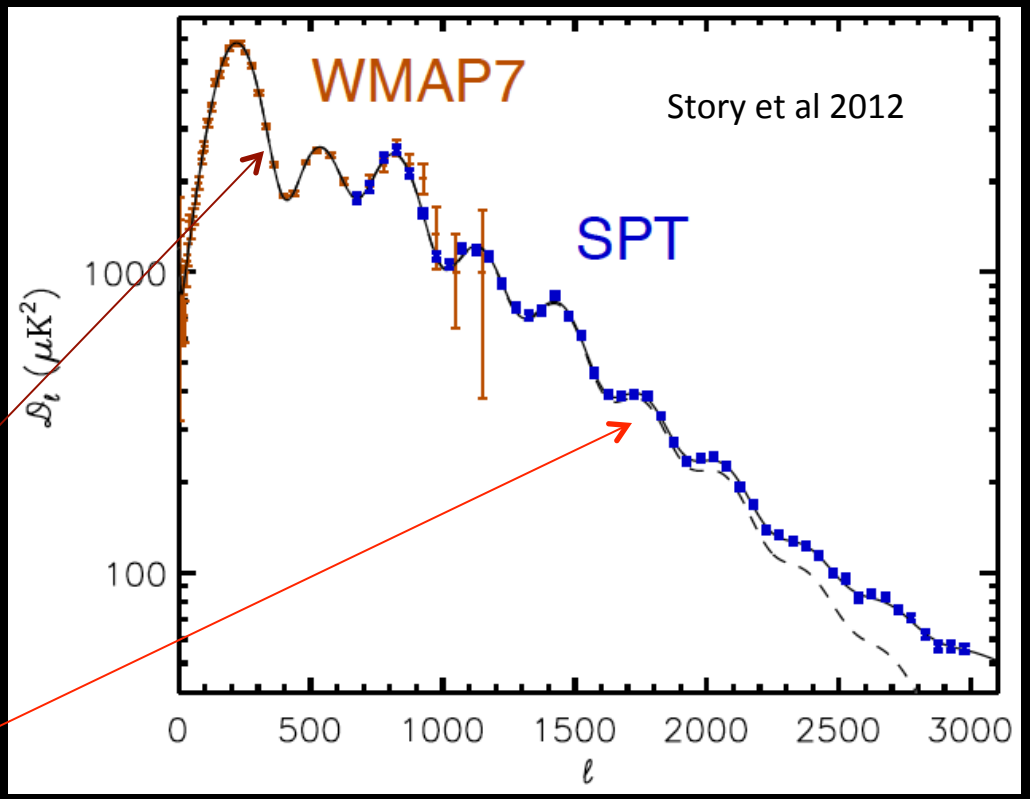
CMB Spectrum

$$\frac{r_d}{D} \propto H^{1/2}$$

Larger N_{eff} leads to more damping

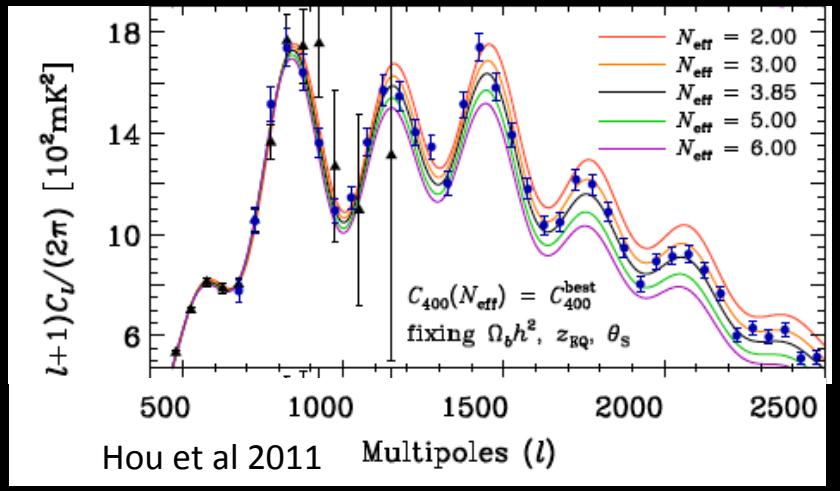
Angular scale of acoustic peaks (r_s/D) is known precisely

Angular scale of damping (r_d/D) measured recently



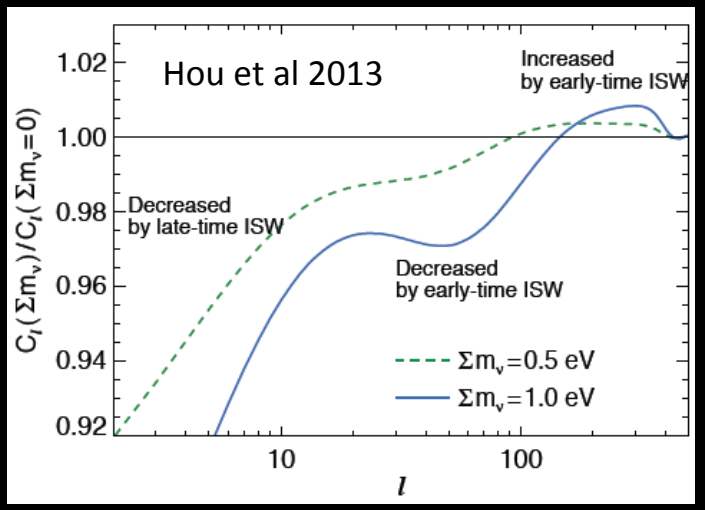
Effect on CMB Spectrum

N_{eff}

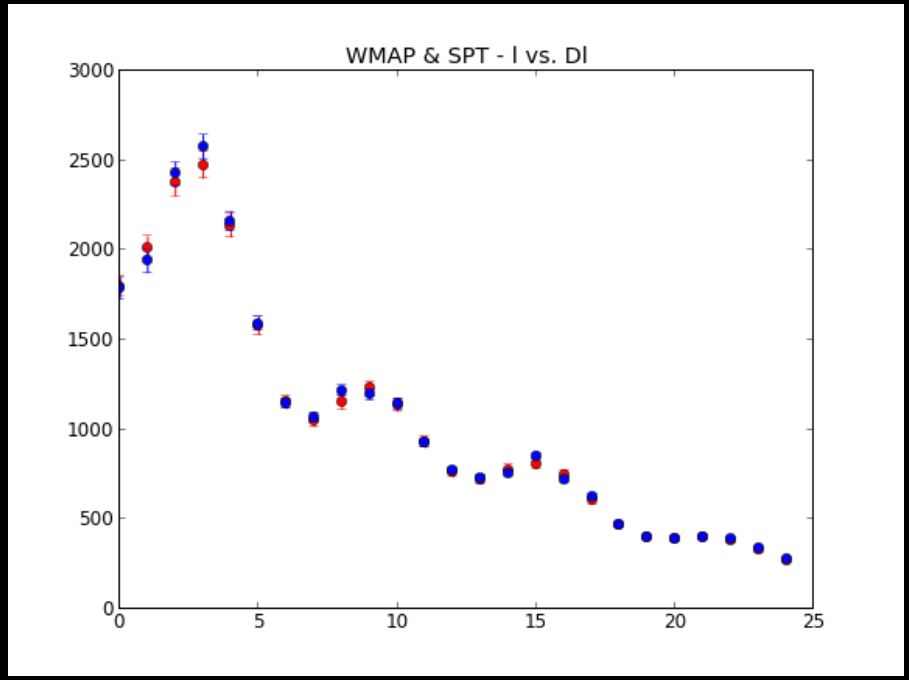


Hou et al 2011

Mass



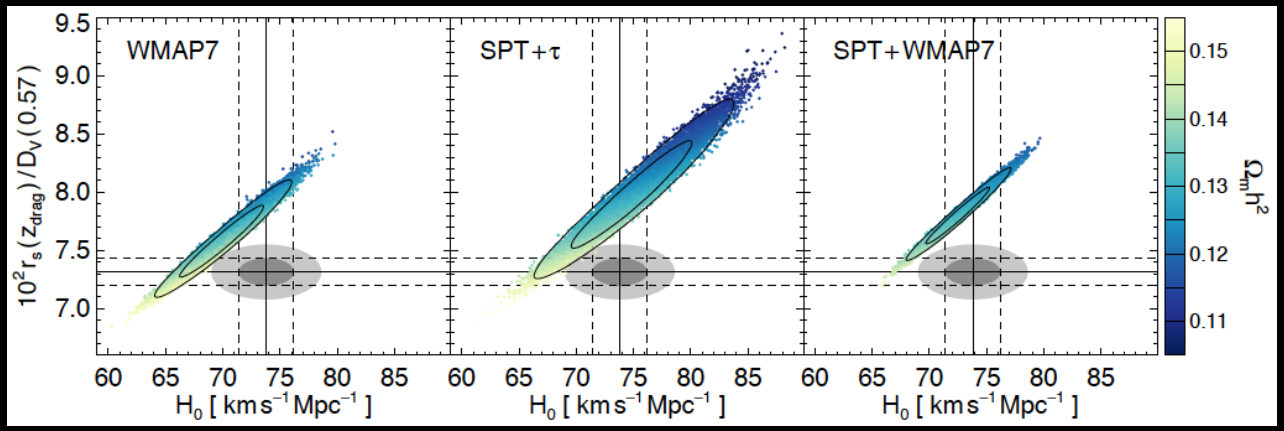
Consistency



SPT+WMAP lead to N_{eff} =3.62±0.48, a 7.5 sigma detection of the neutrino background

Current Constraints

More damping than expected in CMB tail; only way to fit in Standard Model is to decrease D, in tension with BAO



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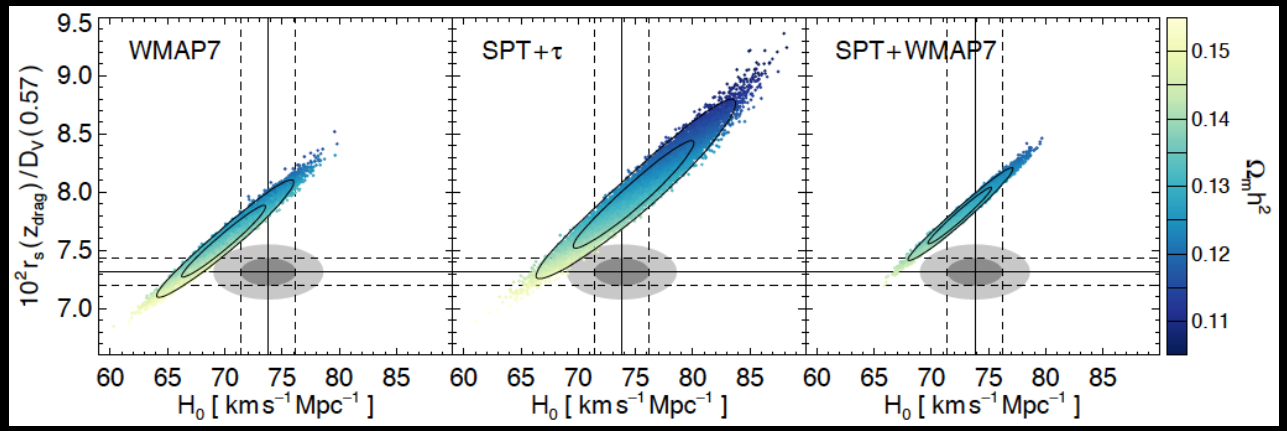
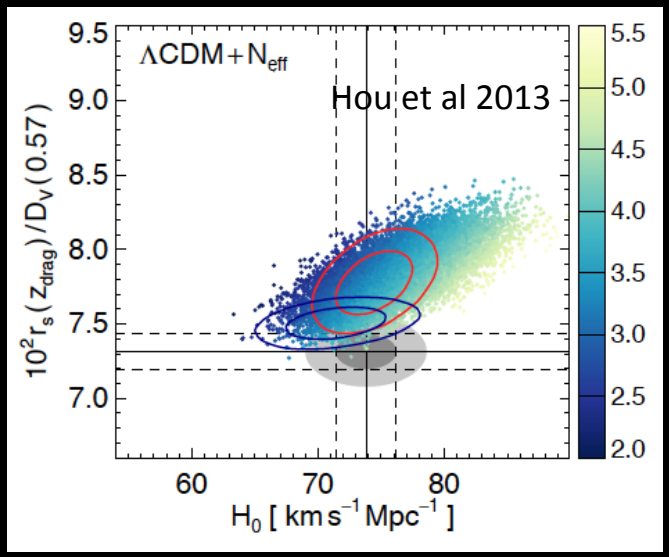


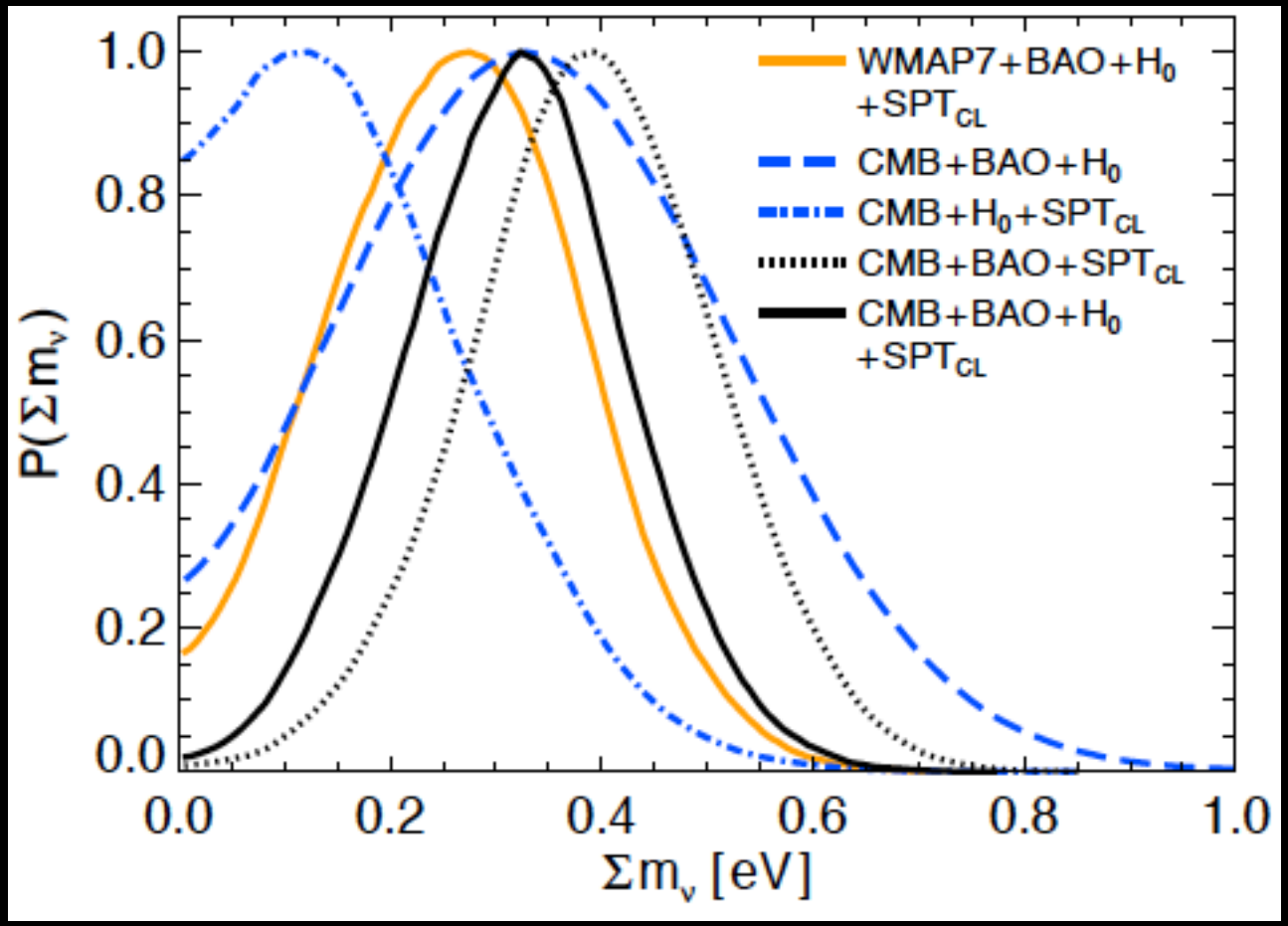
Adding N_{eff} leads to better fit : 3.71±0.35



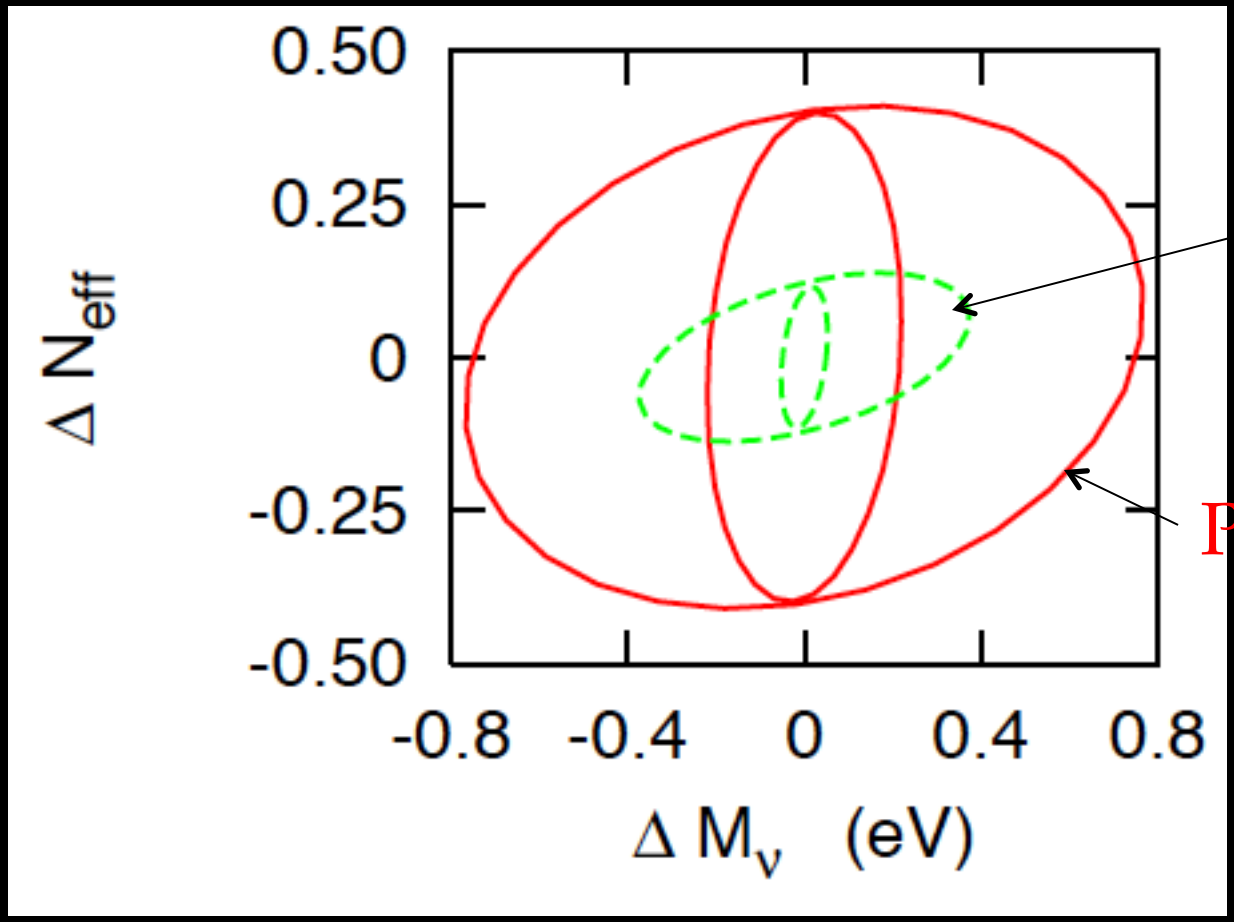
Current Constraints

Several 1-sigma hints combine to give a 3-sigma "detection":

$$\sum m_\nu = 0.32 \pm 0.11 eV$$



Future Constraints



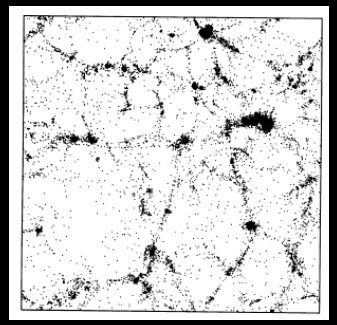
Structure

current energy density of massive neutrinos

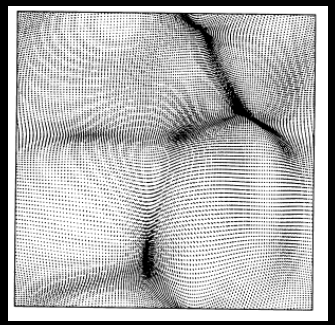
$$\Omega_\nu = \frac{\rho_\nu}{\rho_{cr}} = \frac{n_\nu \sum m_\nu}{\rho_{cr}} = \frac{0.01}{h^2}\left(\frac{\sum m_\nu}{1eV}\right)$$

Neutrinos have relatively large thermal velocities so do not cluster on small scales. This non-clustering component could be as large as 10% of the total matter, so inhibits the formation of large scale structure.

Cold Dark Matter



Cold+ Hot Dark Matter



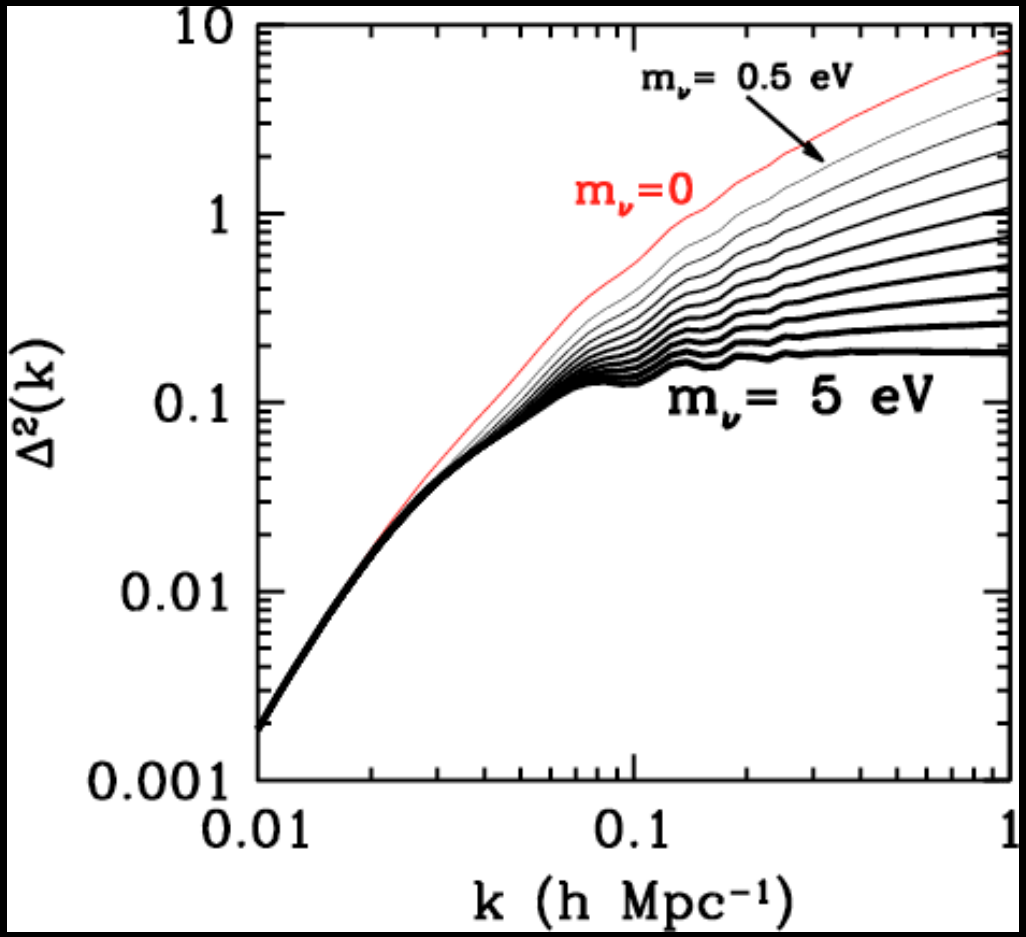
Structure

- Growth of structure delicate balance between gravitational instability and expansion
- Potentials remain constant if all matter participates
- Potentials decay if some of the matter does not cluster
- So clumpiness in the universe is very sensitive to the total mass density of all neutrinos:

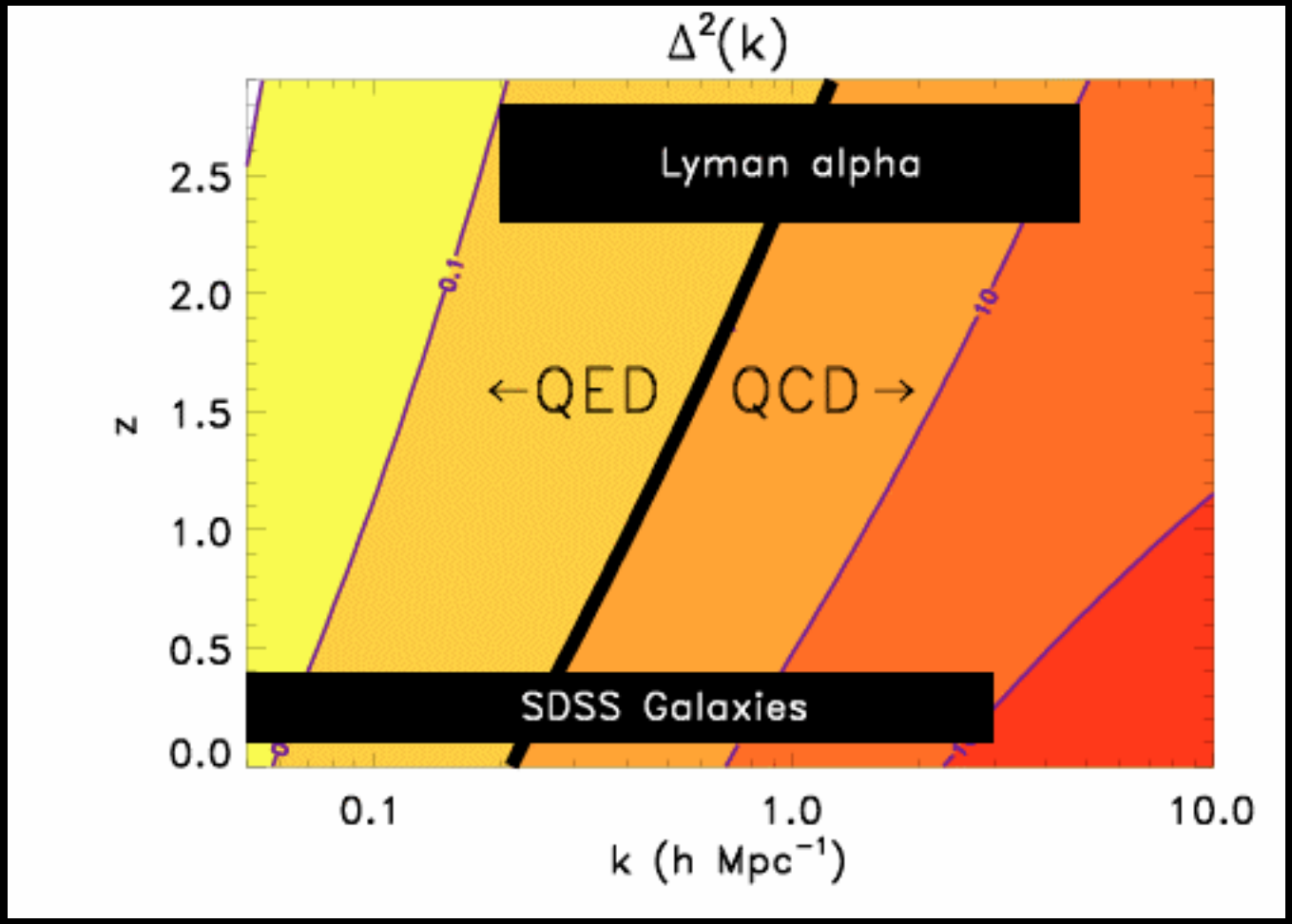
$$\sum_i m_i \frac{N_i}{N^{std}}$$

Structure

quantify this with the power spectrum, or the dimensionless $k^3P(k)$. When this dimensionless number is less than one, inhomogeneities are linear



Structure


$\Delta^2(k)$
Lyman alpha
SDSS Galaxies
←QED
QCD→
0.1
1
10
z
2.5
2.0
1.5
1.0
0.5
0.0
0.1
1.0
10.0
k (h Mpc^{-1})

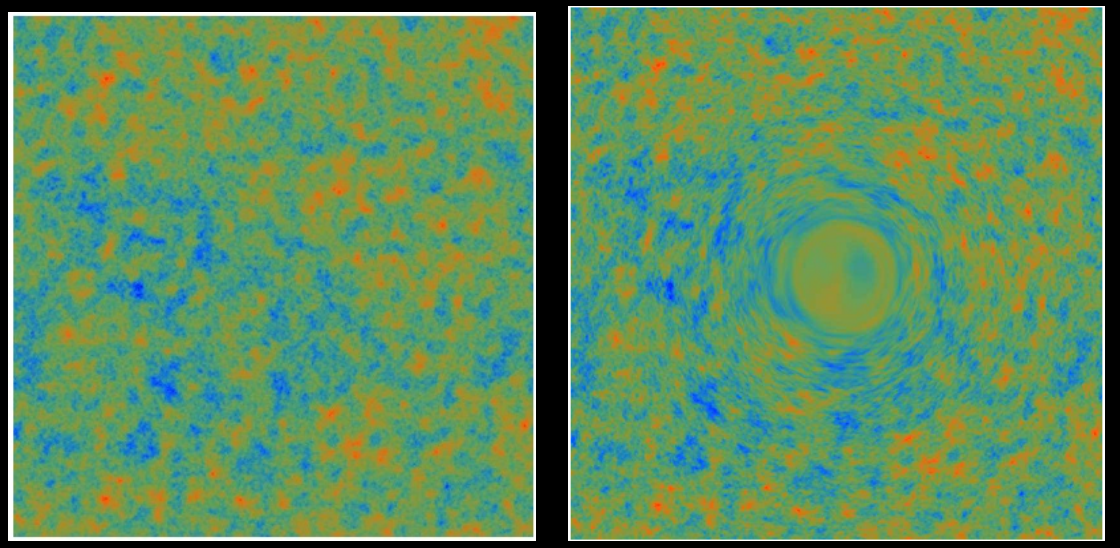
Probes of Structure

1103.5083

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

CMB Lensing

CMB photons from the last scattering surface are deflected (~few arcminutes) by coherent large scale structure (~few degrees)

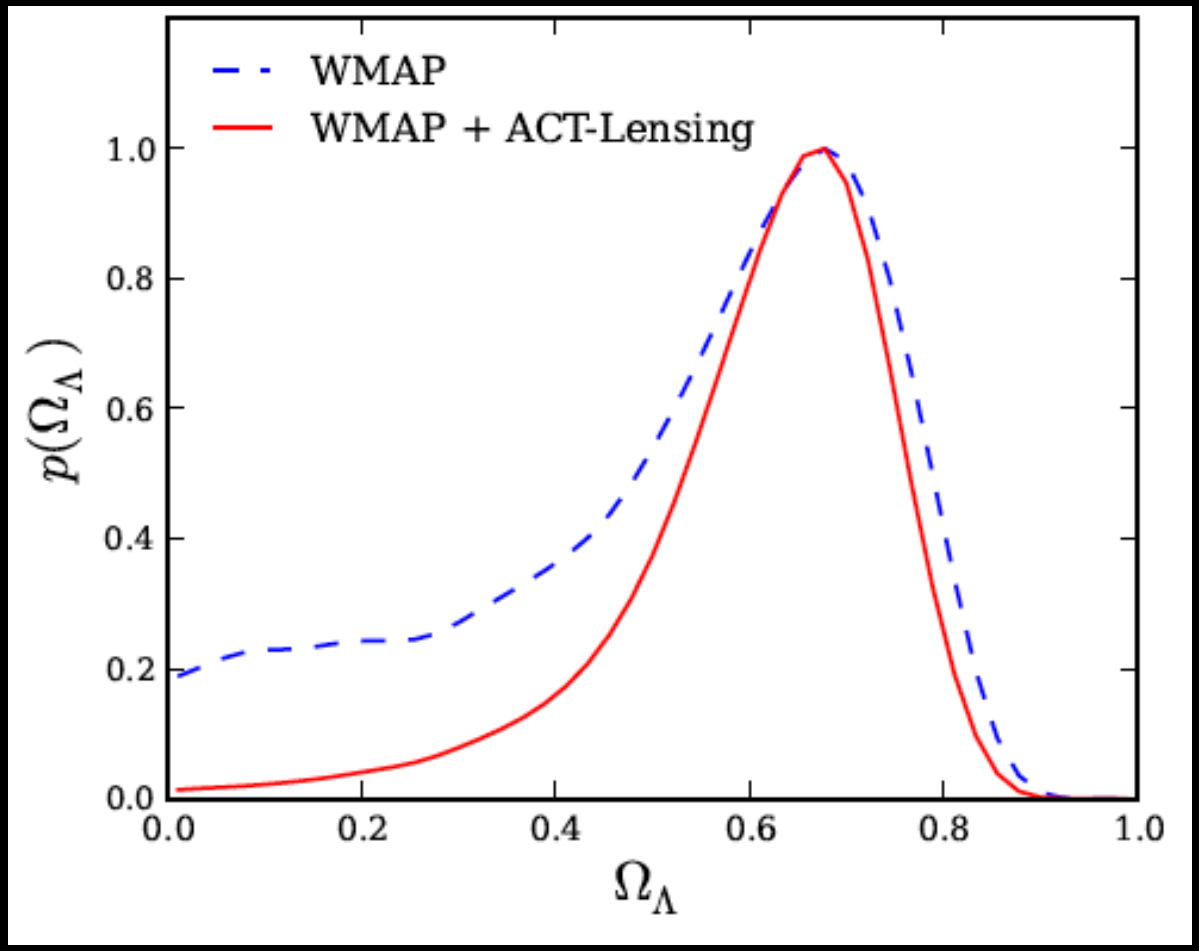


Hu 2002

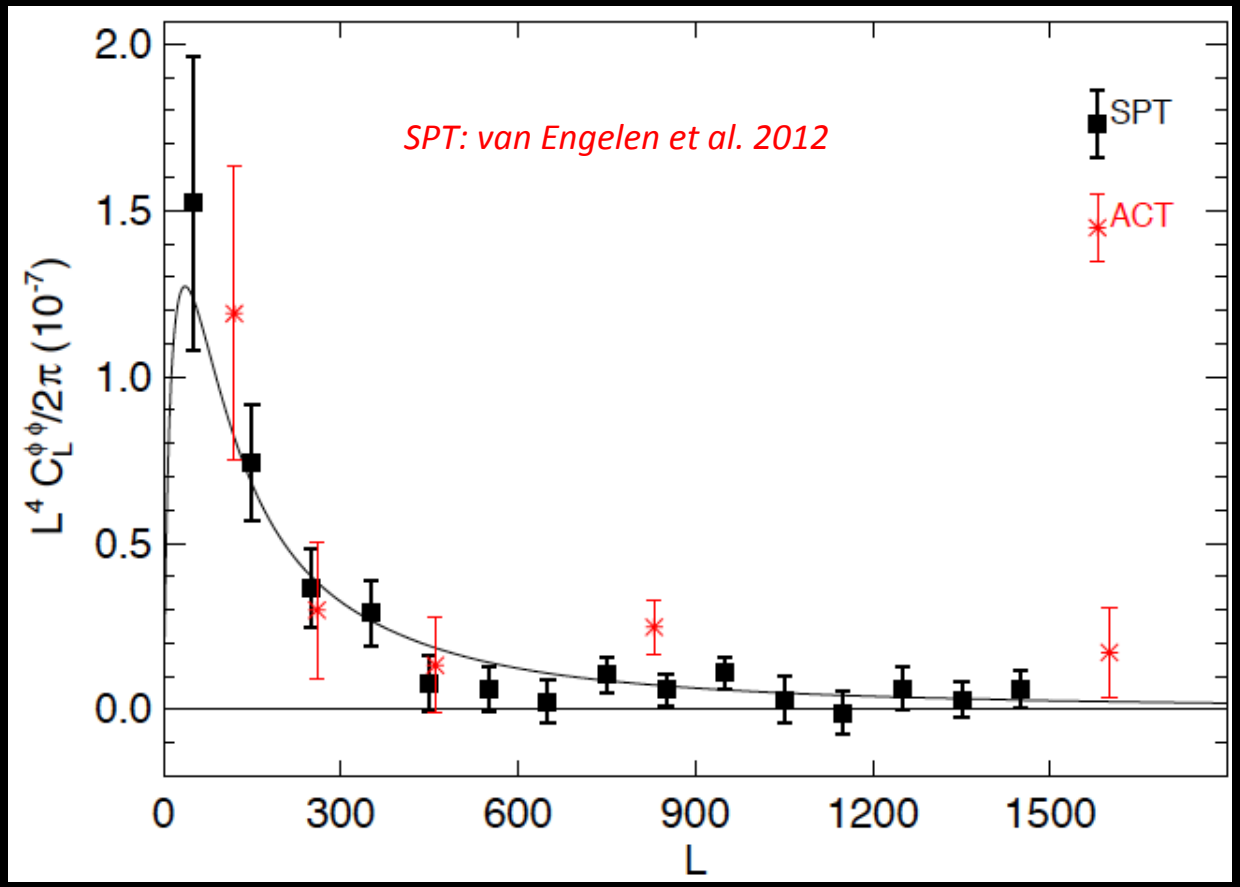
Effect is not as dramatic in real maps, but estimators of non-Gaussianity extract projected gravitational potential

Dark Energy and the CMB

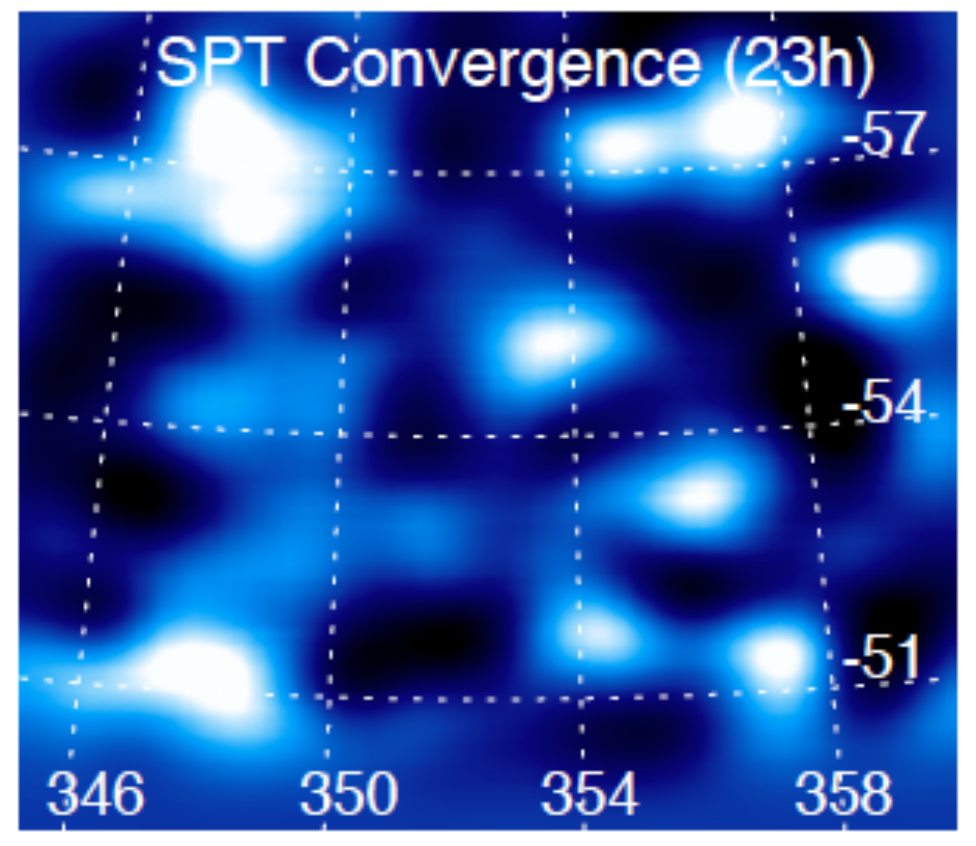
ACT: Sherwin et al. 2011



SPT has 6 sigma detection



with maps!



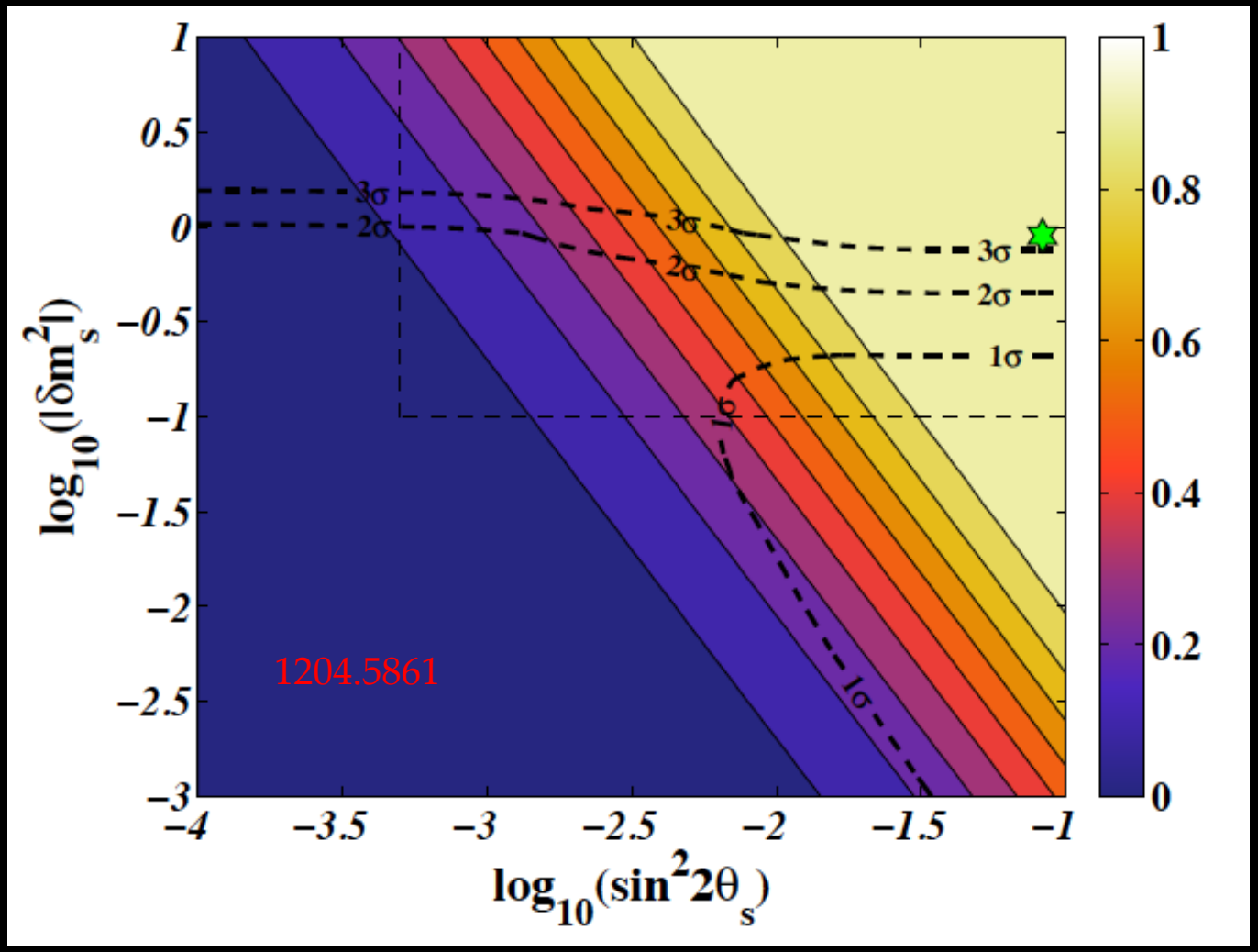
SPT: Bleem et al. 2012

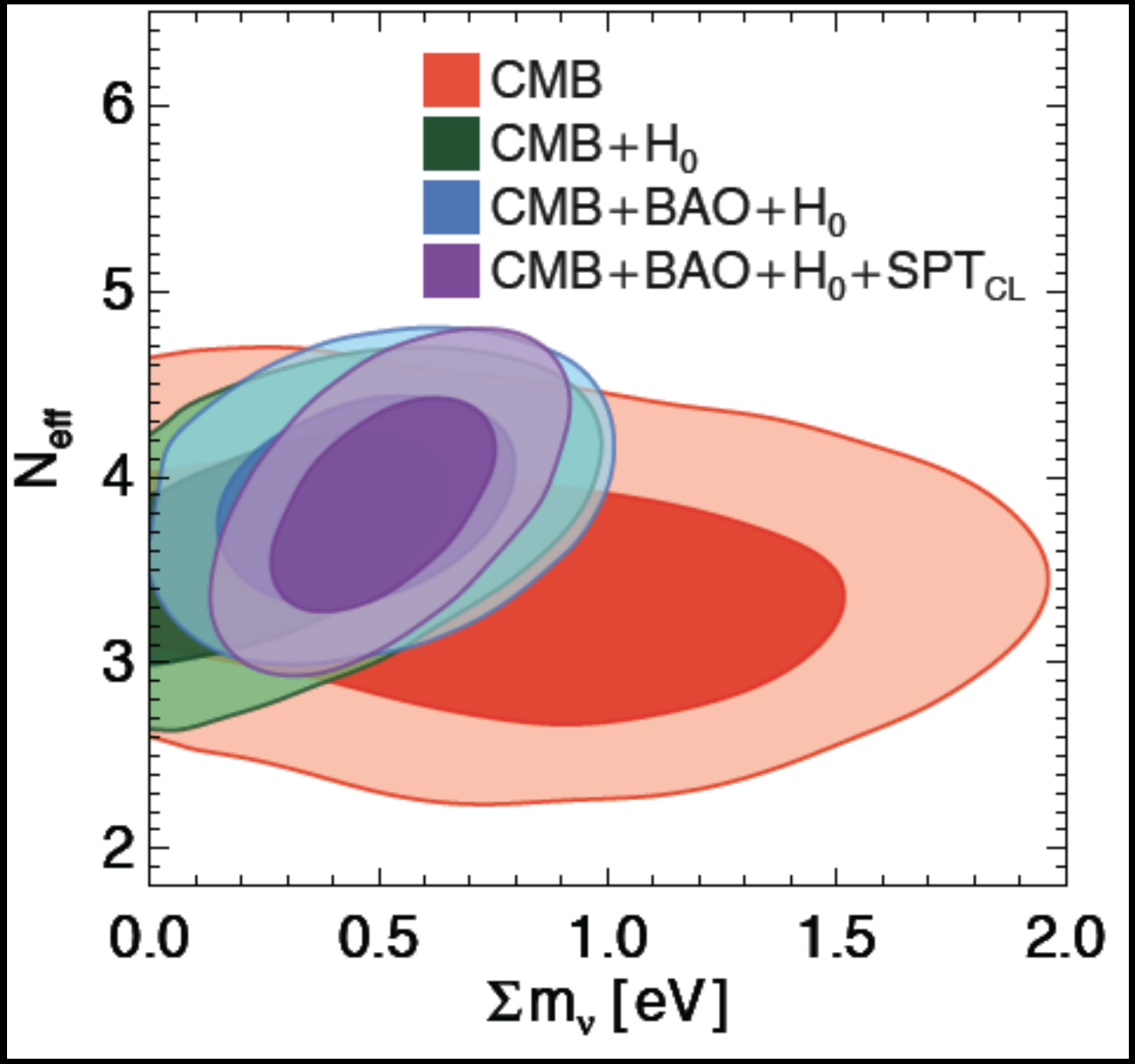
Conclusions

intriguing small scale CMB results; Planck to report in 6 weeks

CMB Lensing is blossoming with real hope of eventually detecting neutrino mass in the cosmos

Current Constraints




CMB
CMB+H0
CMB+BAO+H0
CMB+BAO+H0+SPTCL
Neff
6
5
4
3
2
0.0
0.5
1.0
1.5
2.0
Σmν [eV]

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arxiv.org/find/astro-ph/1/au:+Komatsu_E/0/1/0/all/0/1

Shin'ichiro Ando, Eiichiro Komatsu
Comments: 13 pages, 18 figures, comments welcome
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**; High Energy Astrophysical Phenomena (astro-ph.HE)

2. arXiv:1301.3607 [pdf, ps, other]

The Kinetic Sunyaev-Zel'dovich effect as a probe of the physics of cosmic reionization: the effect of self-regulated reionization

Hyunbae Park, Paul R. Shapiro, Eiichiro Komatsu, Ilian T. Iliev, Kyungjin Ahn, Garrelt Mellema
Comments: Submitted to ApJ; 16 pages, 8 figures
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**

3. arXiv:1212.5226 [pdf, other]

Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results

G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolta, M. Halpern, R. S. Hill, N. Odegard, L. Page, K. M. Smith, J. L. Weiland, B. Gold, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. Wollack, E. L. Wright
Comments: 31 pages, 12 figures, submitted to Astrophysical Journal Supplement Series. v2: slight correction to Neff for case with BAO; references added; typos corrected; clarification of description of Gibbs sampler. See the Legacy Archive for Microwave Background Data Analysis (LAMBDA): this http URL for further detail
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**

4. arXiv:1212.5225 [pdf, ps, other]

Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results

C. L. Bennett, D. Larson, J. L. Weiland, N. Jarosik, G. Hinshaw, N. Odegard, K. M. Smith, R. S. Hill, B. Gold, M. Halpern, E. Komatsu, M. R. Nolta, L. Page, D. N. Spergel, E. Wollack, J. Dunkley, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. L. Wright
Comments: 177 pages, 44 figures, submitted to Astrophysical Journal Supplement Series. v2: slight correction to Neff for case with BAO; references added; typos corrected; clarification of description of Gibbs sampler. See the Legacy Archive for Microwave Background Data Analysis (LAMBDA): this http URL for further detail
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**

5. arXiv:1212.0977 [pdf, other]

Cosmology from clustering of Lyman-alpha galaxies: breaking non-gravitational Lyman-alpha radiative transfer degeneracies using the bispectrum

Bradley Greig, Eiichiro Komatsu, J. Stuart B. Wyithe
Comments: 19 pages, 7 figures and 6 tables
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**

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arxiv.org/pdf/1212.5226.pdf

Draft version January 31, 2013
Preprint typeset using LaTeX style emulateapj v. 5/2/11

6v2 [astro-ph.CO] 30 Jan 2013

NINE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (*WMAP*) OBSERVATIONS: COSMOLOGICAL PARAMETER RESULTS

G. Hinshaw[1], D. Larson[2], E. Komatsu[3,4,5], D. N. Spergel[6,4], C. L. Bennett[2], J. Dunkley[7], M. R. Nolta[8], M. Halpern[1], R. S. Hill[9], N. Odegard[9], L. Page[10], K. M. Smith[6,11], J. L. Weiland[2], B. Gold[12], N. Jarosik[10], A. Kogut[13], M. Limon[14], S. S. Meyer[15], G. S. Tucker[16], E. Wollack[13], E. L. Wright[17]

Draft version January 31, 2013

ABSTRACT

We present cosmological parameter constraints based on the final nine-year *WMAP* data, in conjunction with a number of additional cosmological data sets. The *WMAP* data alone, and in combination, continue to be remarkably well fit by a six-parameter ΛCDM model. When *WMAP* data are combined with measurements of the high-l cosmic microwave background (CMB) anisotropy, the baryon acoustic oscillation (BAO) scale, and the Hubble constant, the matter and energy densities, $\Omega_b h^2$, $\Omega_c h^2$, and Ω_Λ, are each determined to a precision of ~1.5%. The amplitude of the primordial spectrum is measured to within 3%, and there is now evidence for a tilt in the primordial spectrum at the 5σ level, confirming the first detection of tilt based on the five-year *WMAP* data. At the end of the *WMAP* mission, the nine-year data decrease the allowable volume of the six-dimensional ΛCDM parameter space by a factor of 68,000 relative to pre-*WMAP* measurements. We investigate a number of data combinations and show that their ΛCDM parameter fits are consistent. New limits on deviations from the six-parameter model are presented, for example: the fractional contribution of tensor modes is limited to $r < 0.13$ (95% CL); the spatial curvature parameter is limited to $\Omega_k = -0.0027^{+0.0039}_{-0.0038}$; the summed mass of neutrinos is limited to $\sum m_\nu < 0.44$ eV (95% CL); and the number of relativistic species is found to lie within $N_{\rm eff} = 3.84 \pm 0.40$, when the full data are analyzed. The joint constraint on $N_{\rm eff}$ and the primordial helium abundance, $Y_{\rm He}$, agrees with the prediction of standard Big Bang nucleosynthesis. We compare recent *Planck* measurements of the Sunyaev–Zel'dovich effect with our seven-year measurements, and show their mutual agreement. Our analysis of the polarization pattern around temperature extrema is updated. This confirms a fundamental prediction of the standard cosmological model and provides a striking illustration of acoustic oscillations and adiabatic initial conditions in the early universe.

Subject headings: cosmic microwave background, cosmology: observations, early universe, dark matter, space vehicles, space vehicles: instruments, instrumentation: detectors, telescopes

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