Neutrino cosmology

Yvonne Y. Y. Wong
RWTH Aachen

International workshop on the interconnection between particle physics and cosmology, CERN, June 14--18, 2011

Hot relics

~~Neutrino~~ cosmology

Yvonne Y. Y. Wong
RWTH Aachen

International workshop on the interconnection between particle physics and cosmology, CERN, June 14--18, 2011

Hot relics: what are they?

- Any particle species whose production is associated with some thermal process and that decoupled while relativistic at relatively late times [T< O(100) MeV].
  - **Generic property**: significant relativistic energy density before and around matter-radiation equality
- If **non-relativistic today**:
  - Contribute to dark matter, but not all (otherwise inconsistent with hierarchical structure formation).

Hot relics: candidates...

“Guaranteed”

Standard model neutrinos
Questions:
→ What is their energy density? **Or**
→ What is the absolute neutrino mass scale?

``Non-standard"

Light (sub-eV to eV mass) sterile neutrinos; motivated by anomalies in neutrino experiments.

QCD axions (dependent on the Peccei-Quinn scale); axion telescope searches.

Many BSM theories predict hot relics.

Hot relics: why should we care?

- **Disclaimer**: We do not expect hot relics to make up all of the dark matter.

- We study them because of the possibility to constrain or detect physics of or beyond the standard model.
  - Consistency checks against lab experiments.

- Even if you don't care about this particular sort of physics:
  - The presence of hot relics may shift the values of those cosmological parameters you care about, e.g., w_{DE}.

Plan...

- **Standard model neutrinos**
  - Status of the absolute neutrino mass measurement.
- Searching for **non-standard hot relics**.
  - $N_{eff} > 3$??
- What the **future** holds.

1. “Guaranteed” hot relics: e, μ, τ neutrinos

Cosmic neutrino background...

- Prediction of the standard hot big bang.
- Process of decoupling fixed by weak interactions.
  - **Temperature** today: $T_{\nu,0}=\left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB},0}=1.95\,\mathrm{K}$
  - **Number density** per flavour: $n_{\nu,0}=\frac{6}{4}\frac{\zeta(3)}{\pi^2}T^3_{\nu,0}=112\ \mathrm{cm}^{-3}$
  - **Energy density** per flavour: $\Omega_\nu h^2=\frac{m_\nu}{93\,\mathrm{eV}}$

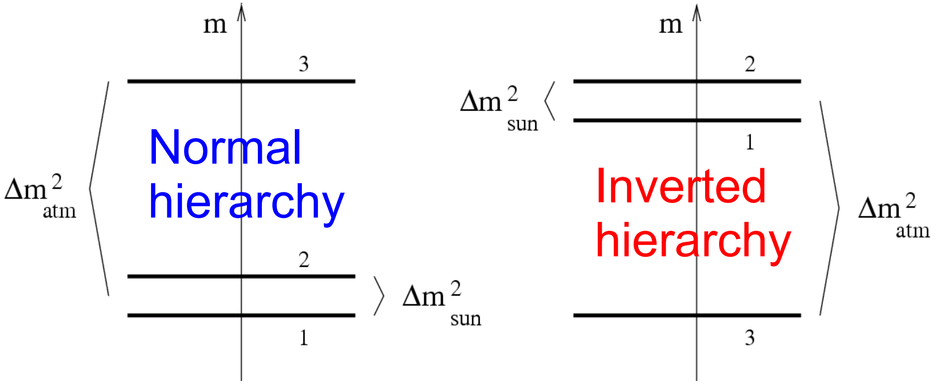
If $m_\nu > 1$ meV

Neutrinos can be a significant component of the total dark matter content.

Neutrino dark matter...

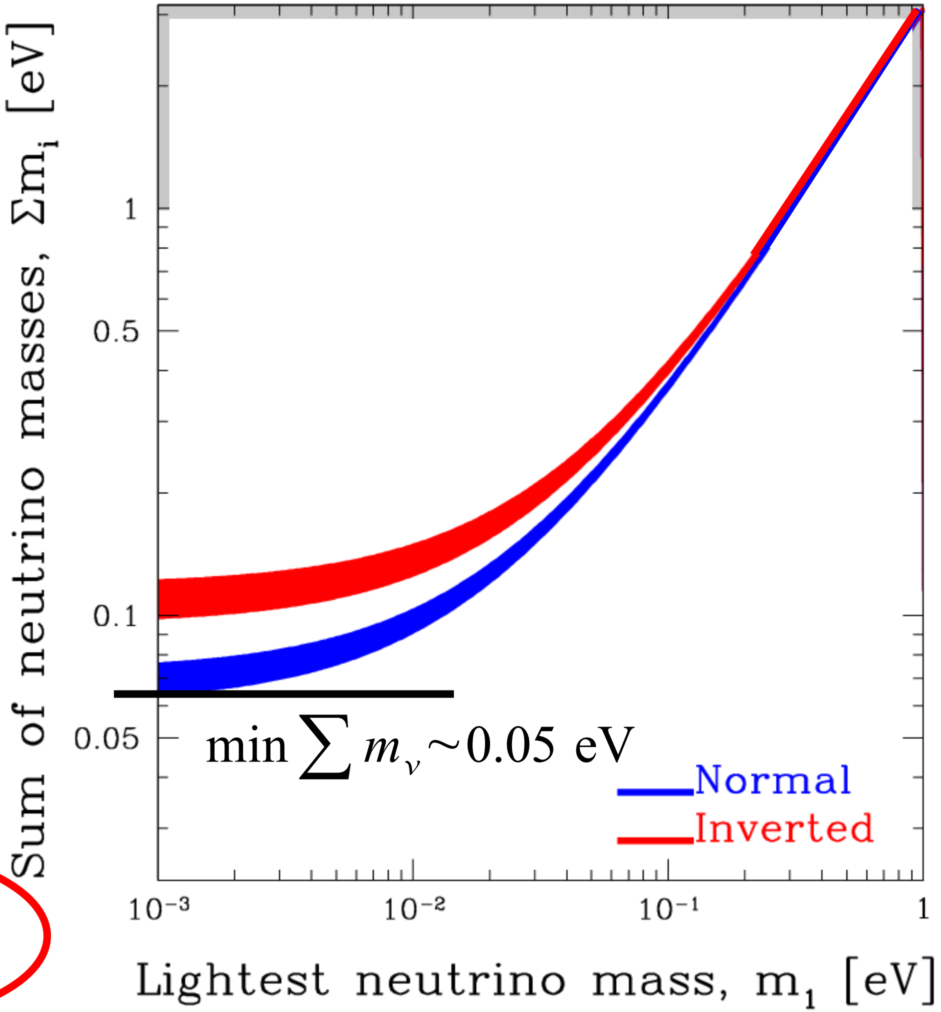
- Neutrino oscillations:

$$\Delta m^2_{\mathrm{atm}} \sim 10^{-3}\ \mathrm{eV}^2 \quad \Delta m^2_{\mathrm{sun}} \sim 10^{-5}\ \mathrm{eV}^2$$



Mininum amount of neutrino dark matter

$$\min \sum m_\nu \sim 0.05\ \mathrm{eV} \rightarrow \min \Omega_\nu \sim 0.1\,\%$$

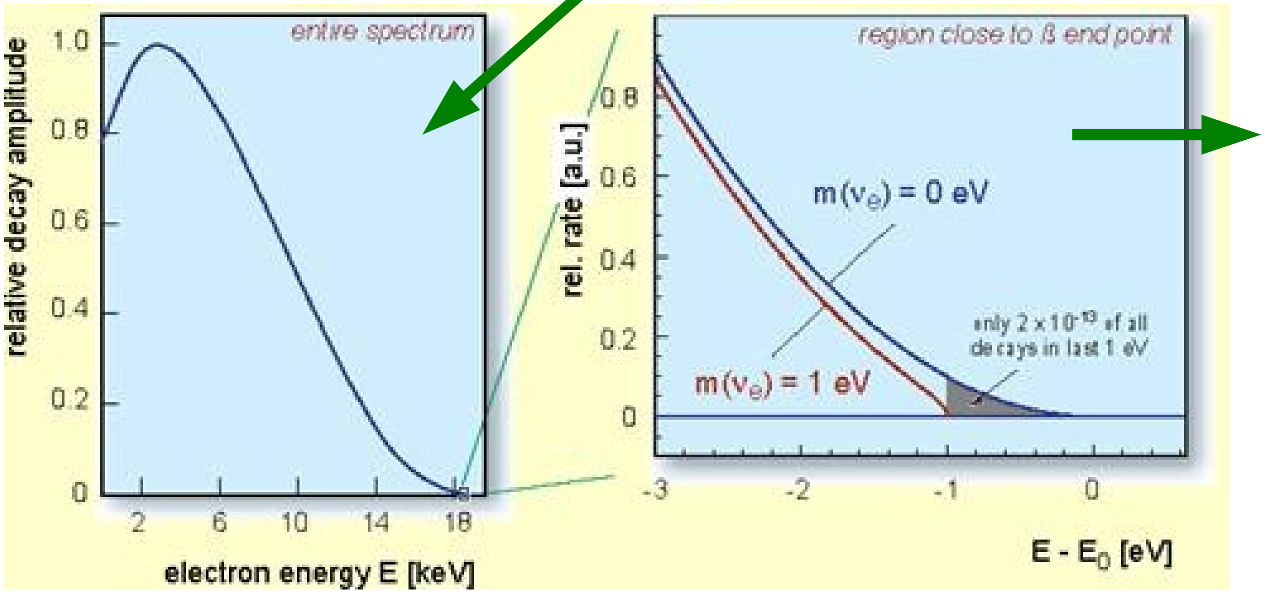


- Upper limit on neutrino masses from tritium β-decay:

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$$

Large mixing means

$$|U_{ei}|^{2} \sim O(0.1 \rightarrow 1)$$



$$\boxed{m_{e} \equiv \left(\sum_{i} |U_{ei}|^{2} m_{i}^{2} \right)^{1/2} < 2.2\ \mathrm{eV}}$$

Lobashev [Troitsk] 2003
Krauss et al. [Mainz] 2005

$$\max \sum m_{\nu} \sim 7\ \mathrm{eV} \rightarrow \max \Omega_{\nu} \sim 12\,\%$$

Free-streaming neutrinos...

- Neutrinos have large thermal speed even after becoming nonrelativistic:

$$c_\nu \simeq 81(1+z)\left(\frac{\text{eV}}{m_\nu}\right)\ \text{km s}^{-1}$$

→ hinders ν clustering on small scales

- Free-streaming wavenumber at z:

$$k_{\text{FS}}(z)=\sqrt{\frac{3\Omega_m H^2}{8\pi c_\nu^2}}\simeq 2.4\sqrt{\frac{\Omega_{m,0}}{1+z}}\left(\frac{m_\nu}{\text{eV}}\right)\ h\ \text{Mpc}^{-1}$$

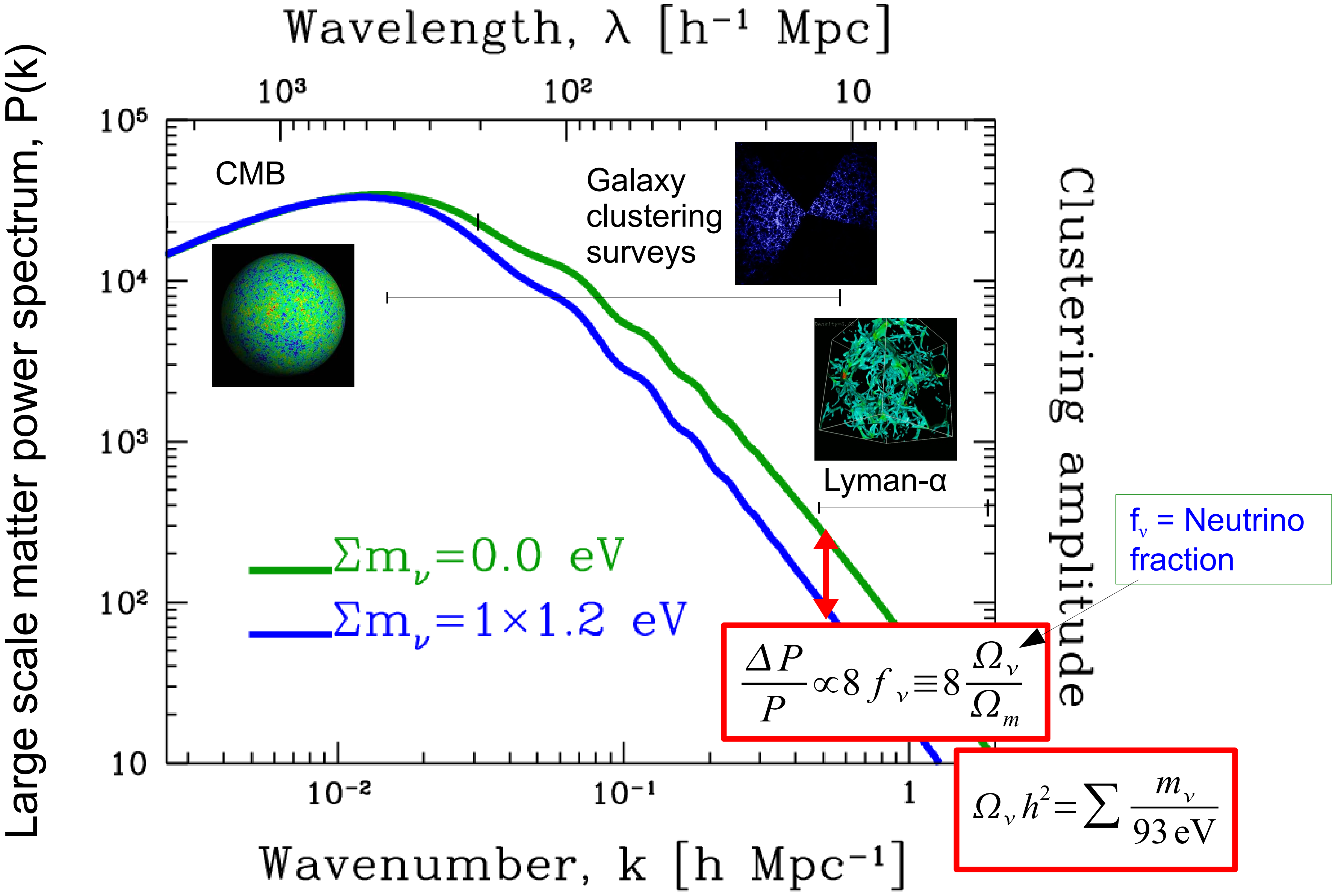
$k \ll k_{\text{FS}}$ Clustering

$k \gg k_{\text{FS}}$ Non-clustering

- Smallest value of k at which we expect to see an effect:

z_{nr} = redshift at which neutrinos become nonrel.

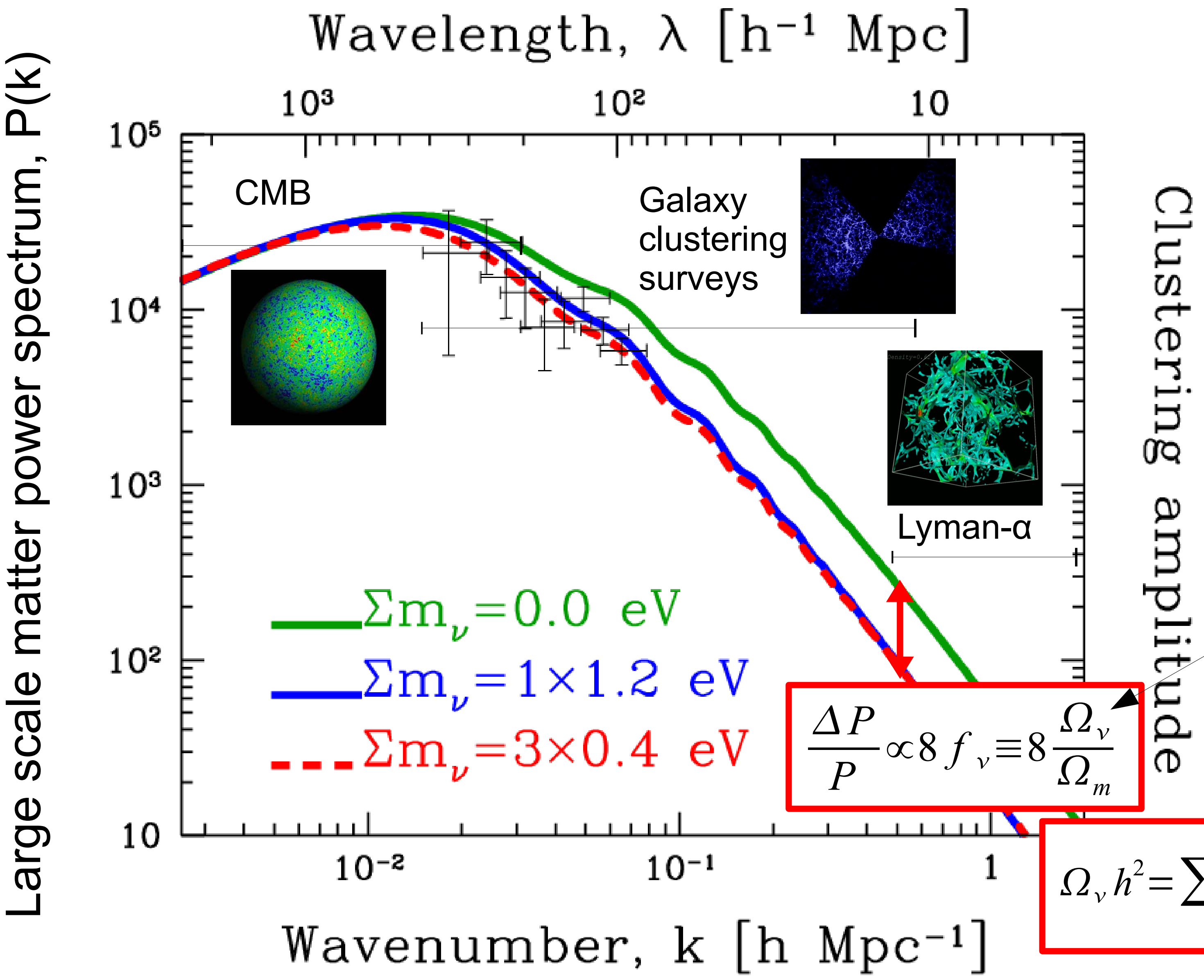
$$\boxed{k_{\text{FS,min}}=k_{\text{FS}}(z_{\text{nr}})\simeq 0.03\,\Omega_{m,0}^{1/2}\left(\frac{m_\nu}{\text{eV}}\right)^{1/2}\ h\ \text{Mpc}^{-1}}$$



f_ν = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$$



f_ν = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$$

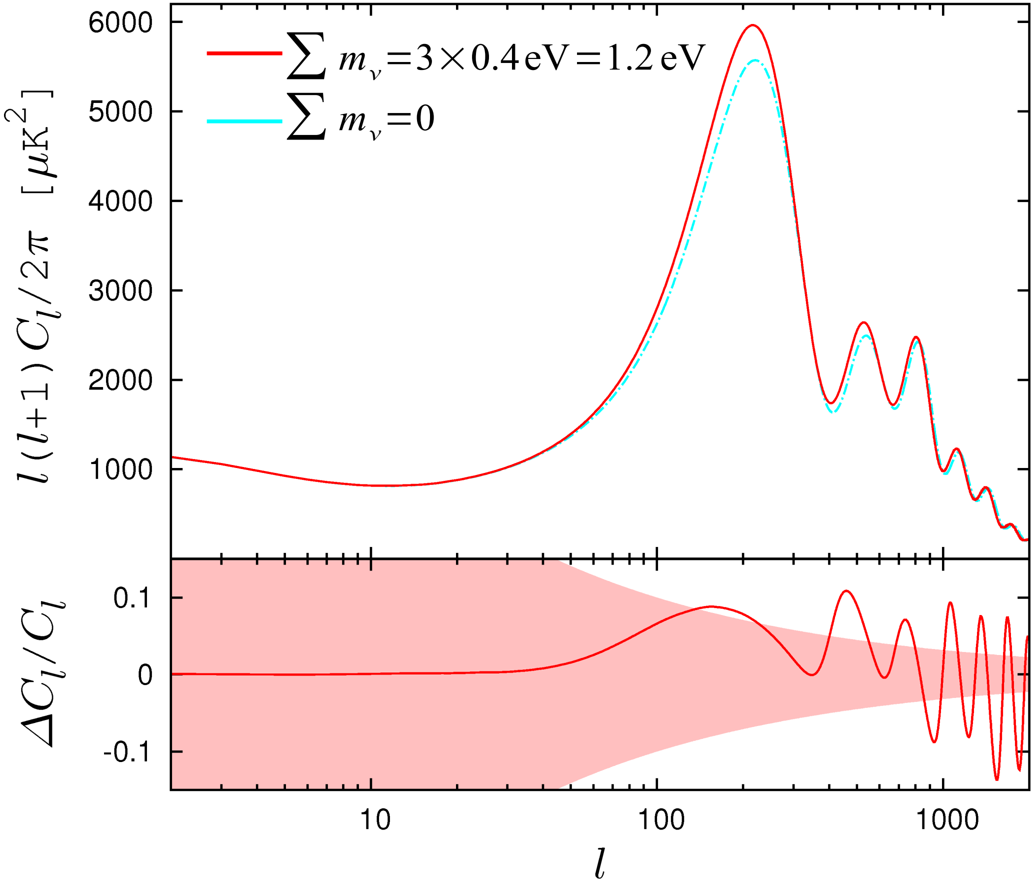
Neutrino effects on the CMB anisotropies...

- Present constraints come mainly via the early ISW effect:
  - γ decoupling: T ~ 0.26 eV.
  - Equality at T ~ 1 eV.

- A **O(0.1-1) eV** neutrino becomes nonrelativistic in the same time frame.

WMAP7 only (ΛCDM+m_ν):

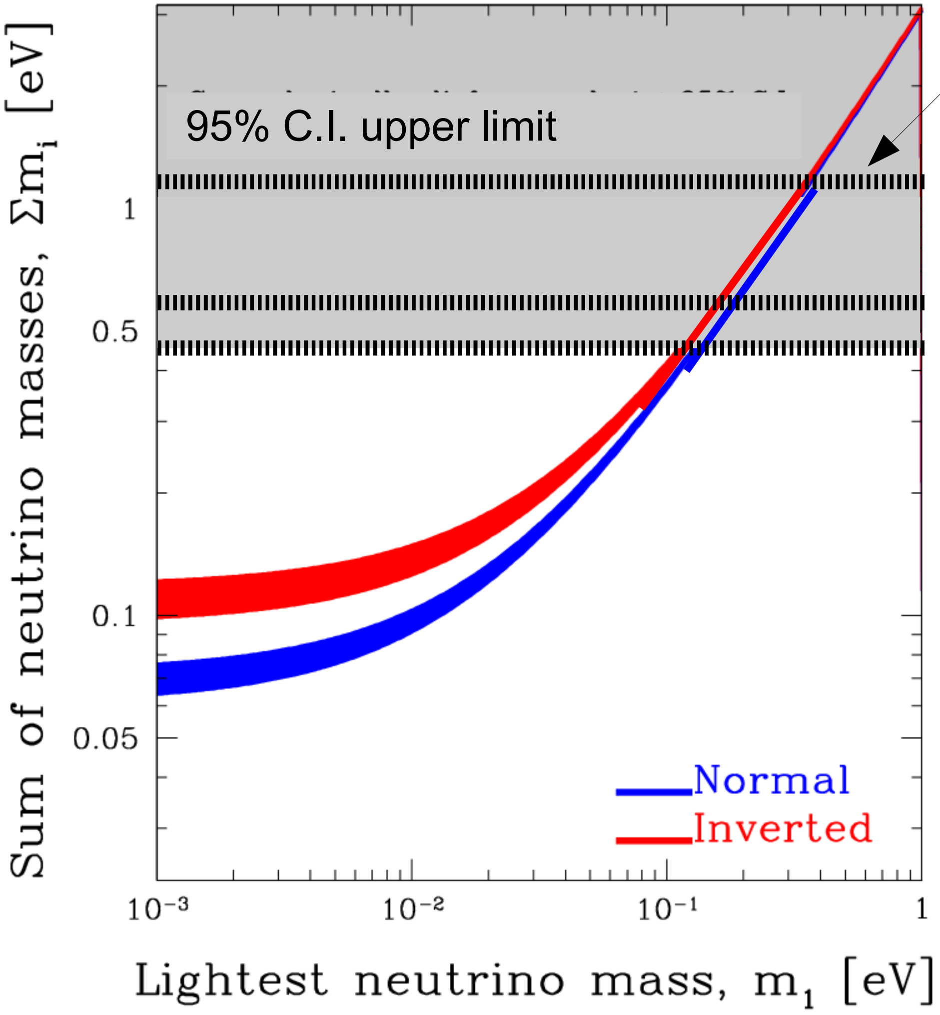
$$\sum m_\nu < 1.3\,\mathrm{eV}\,(95\,\%\,\mathrm{C.I.})$$

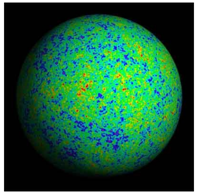


Komatsu et al. 2010, Hannestad et al. 2010

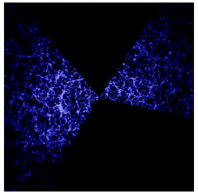
* (ΛCDM+m_ν)

Present status...



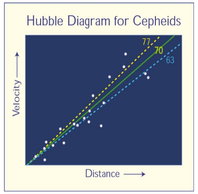


CMB only*
(WMAP7+ACBAR+
BICEP+QuAD)



CMB+SDSS-HPS *

$$\sum m_\nu < 0.61\,\mathrm{eV}\,(95\%\,\mathrm{CI})$$



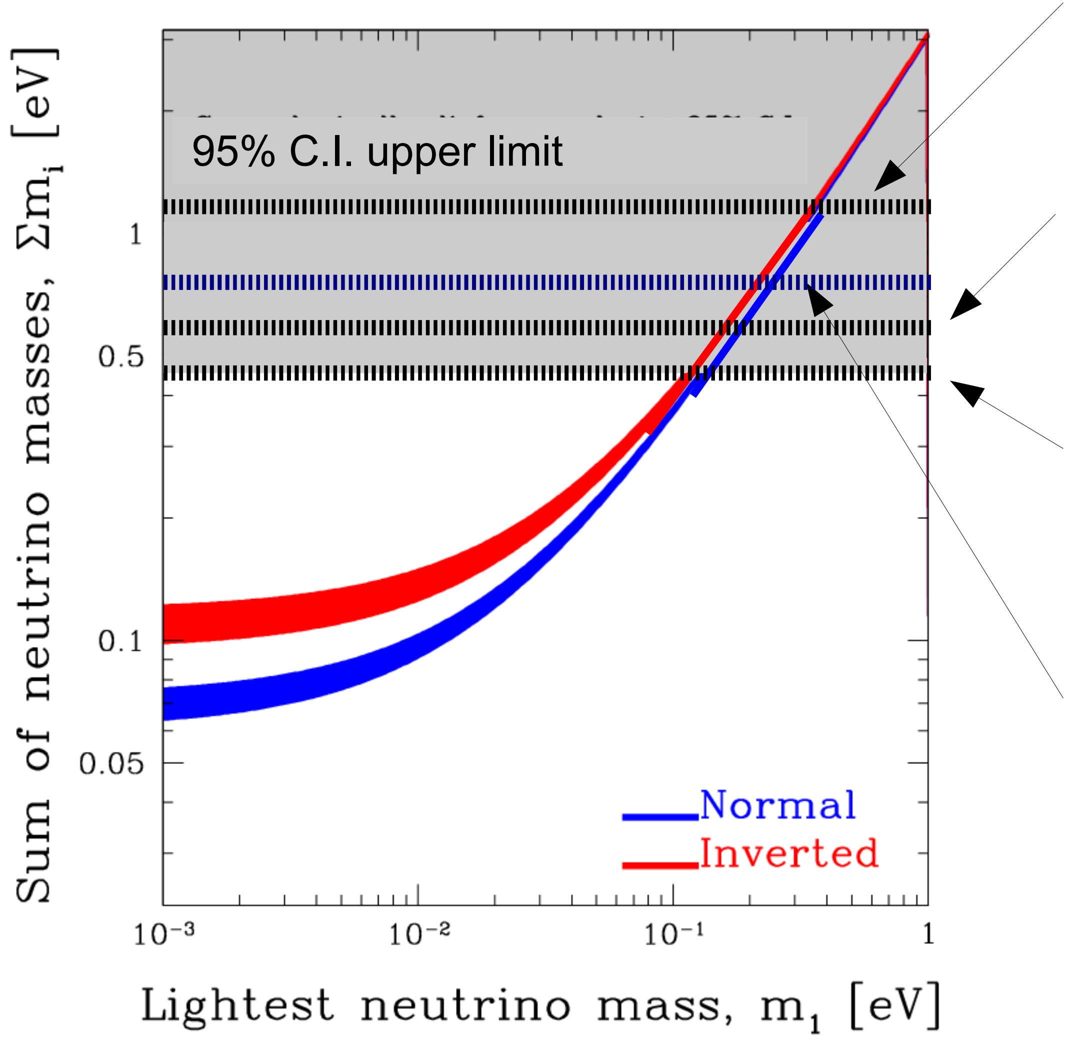
CMB+SDSS-HPS+HST *

$$\sum m_\nu < 0.44\,\mathrm{eV}\,(95\%\,\mathrm{CI})$$

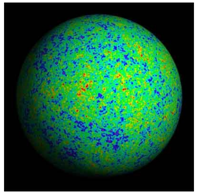
Hannestad, Mirizzi, Raffelt & Y^{3}W 2010

$*$ (ΛCDM+m_ν)

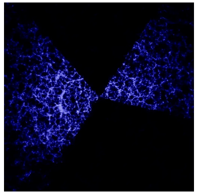
Present status...



Hannestad, Mirizzi, Raffelt & Y^{3}W 2010

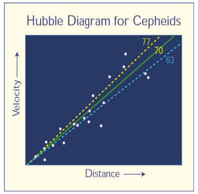


CMB only*
(WMAP7+ACBAR+
BICEP+QuAD)



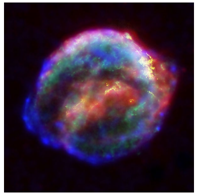
CMB+SDSS-HPS *

$$\sum m_\nu < 0.61\,\text{eV}\,(95\%\,\text{CI})$$



CMB+SDSS-HPS+HST *

$$\sum m_\nu < 0.44\,\text{eV}\,(95\%\,\text{CI})$$

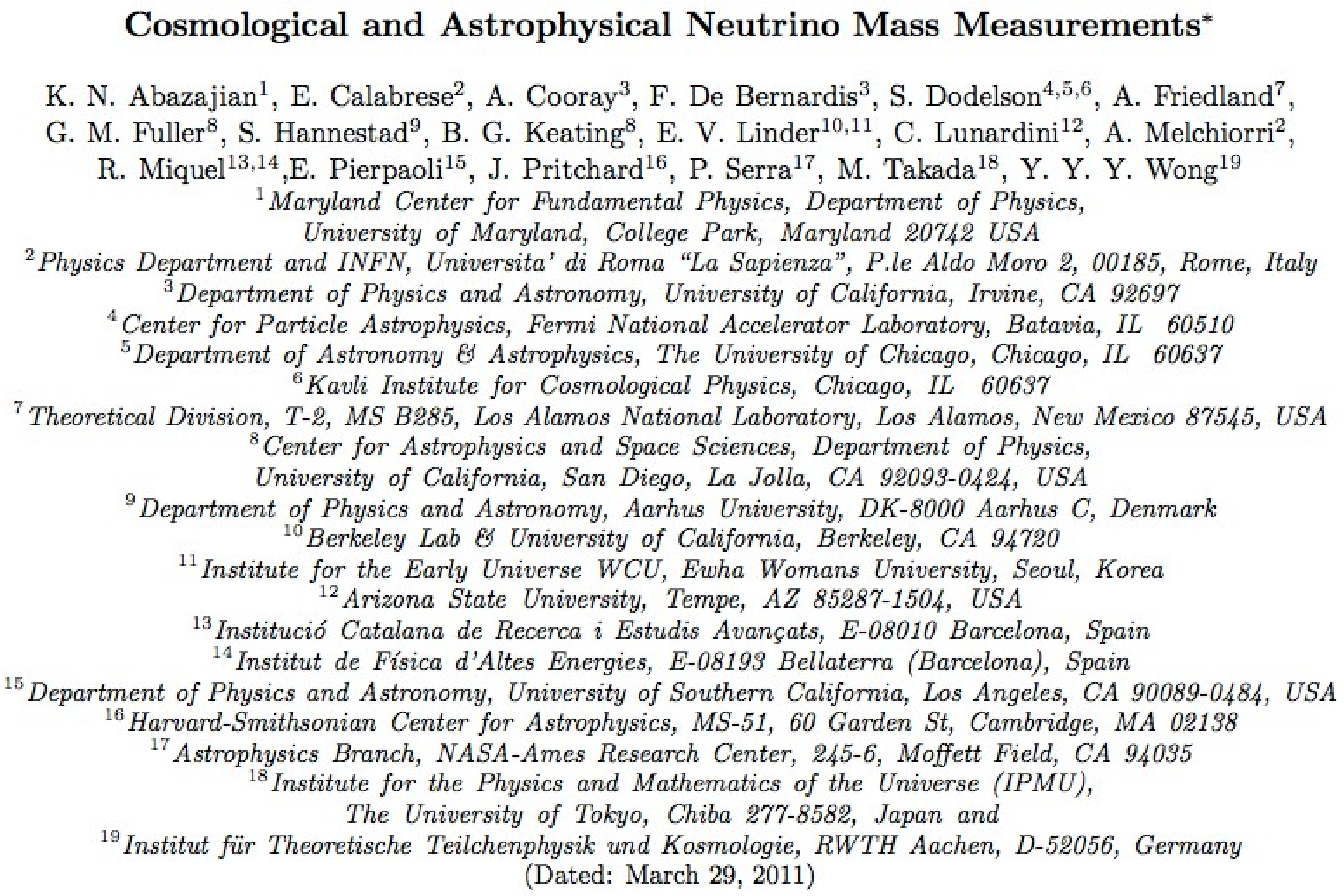


+Supernovae (+w+N_{eff})

$$\sum m_\nu < 0.76\,\text{eV}\,(95\%\,\text{CI})$$

Gonzalez-Garcia et al. 2010

(No degeneracy with r, α_s, CDI)

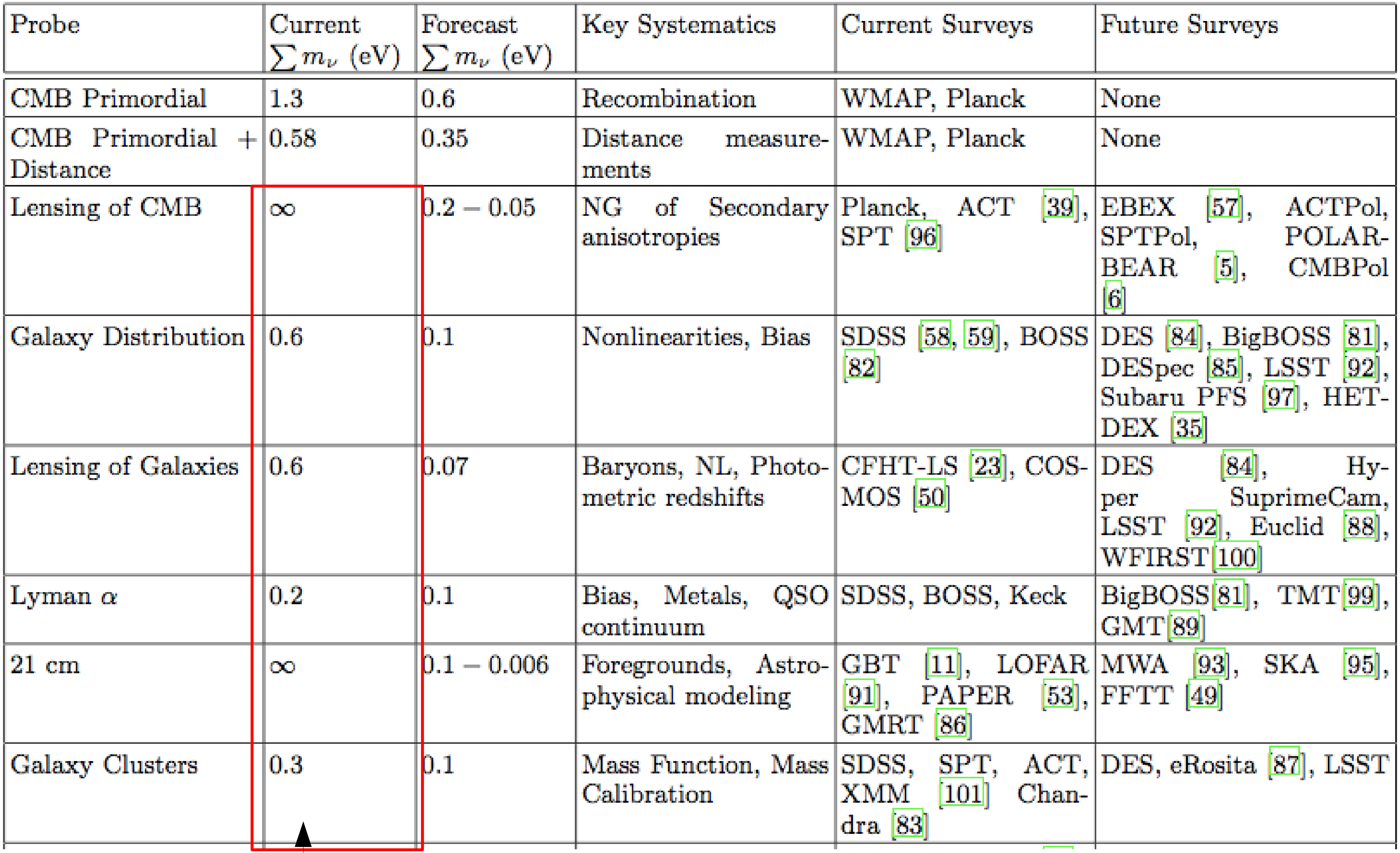


Cosmological and Astrophysical Neutrino Mass Measurements*

K. N. Abazajian[1], E. Calabrese[2], A. Cooray[3], F. De Bernardis[3], S. Dodelson[4,5,6], A. Friedland[7],
G. M. Fuller[8], S. Hannestad[9], B. G. Keating[8], E. V. Linder[10,11], C. Lunardini[12], A. Melchiorri[2],
R. Miquel[13,14],E. Pierpaoli[15], J. Pritchard[16], P. Serra[17], M. Takada[18], Y. Y. Y. Wong[19]
[1]*Maryland Center for Fundamental Physics, Department of Physics,*
University of Maryland, College Park, Maryland 20742 USA
[2]*Physics Department and INFN, Universita' di Roma "La Sapienza", P.le Aldo Moro 2, 00185, Rome, Italy*
[3]*Department of Physics and Astronomy, University of California, Irvine, CA 92697*
[4]*Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[5]*Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637*
[6]*Kavli Institute for Cosmological Physics, Chicago, IL 60637*
[7]*Theoretical Division, T-2, MS B285, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[8]*Center for Astrophysics and Space Sciences, Department of Physics,*
University of California, San Diego, La Jolla, CA 92093-0424, USA
[9]*Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*
[10]*Berkeley Lab & University of California, Berkeley, CA 94720*
[11]*Institute for the Early Universe WCU, Ewha Womans University, Seoul, Korea*
[12]*Arizona State University, Tempe, AZ 85287-1504, USA*
[13]*Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain*
[14]*Institut de Física d'Altes Energies, E-08193 Bellaterra (Barcelona), Spain*
[15]*Department of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089-0484, USA*
[16]*Harvard-Smithsonian Center for Astrophysics, MS-51, 60 Garden St, Cambridge, MA 02138*
[17]*Astrophysics Branch, NASA-Ames Research Center, 245-6, Moffett Field, CA 94035*
[18]*Institute for the Physics and Mathematics of the Universe (IPMU),*
The University of Tokyo, Chiba 277-8582, Japan and
[19]*Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen, D-52056, Germany*

(Dated: March 29, 2011)

arXiv:1103.5083 [astro-ph.CO]



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

in combination with WMAP; 95% upper limits

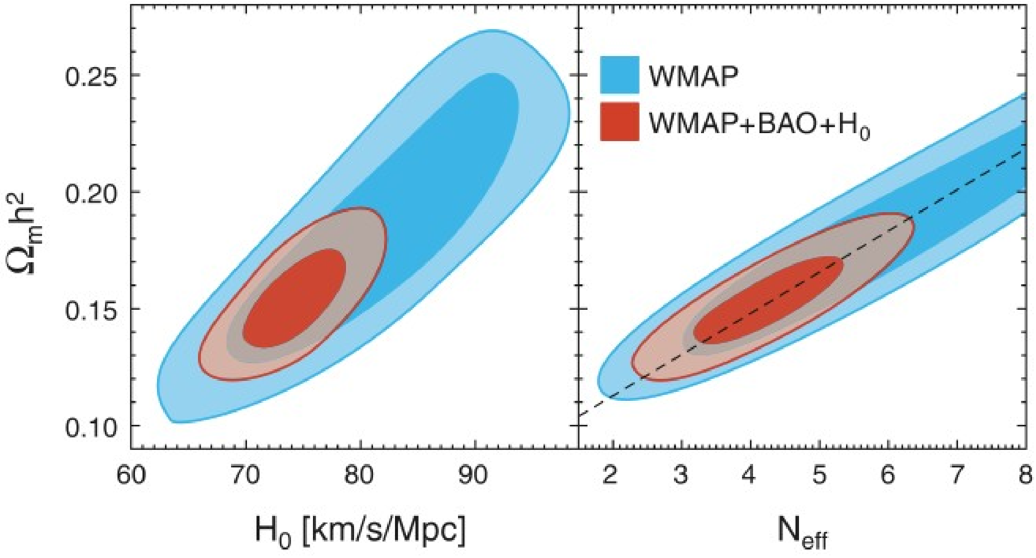
Abazajian et al. 1103.5083

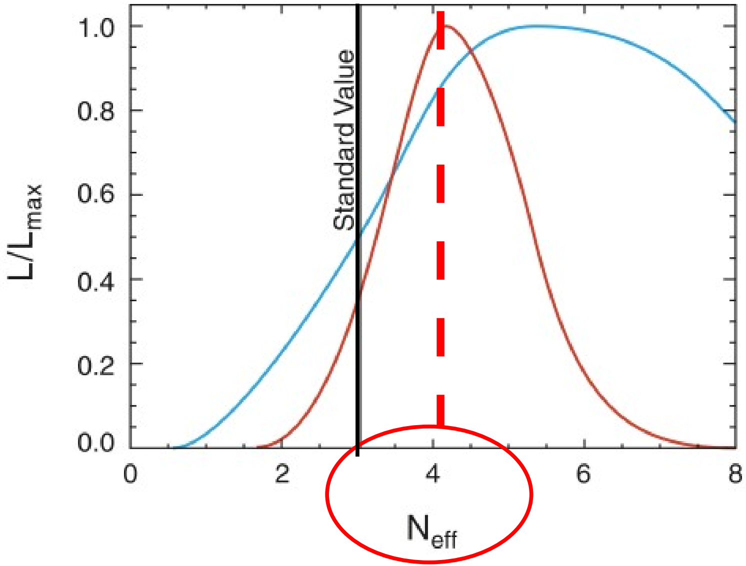
2. Non-standard hot relics...

Searching for extra hot relics in precision cosmology...

- The simplest phenomenological model is to represent any excess relativistic energy density in terms of extra species of massless neutrinos.

$$\rho_\nu + \rho_X = \underline{N_{\mathrm{eff}}}\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right) = (3.04 + \underline{\Delta N_{\mathrm{eff}}})\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right)$$





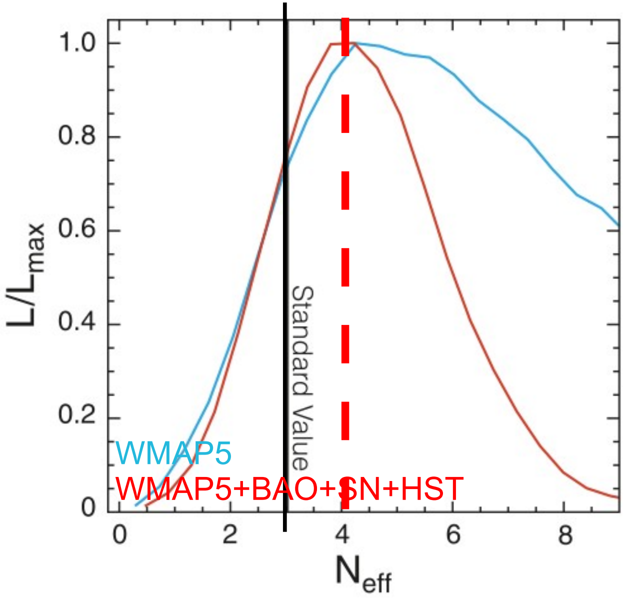
Komatsu [WMAP7] et al. 2010

- The trend has been there since WMAP3...

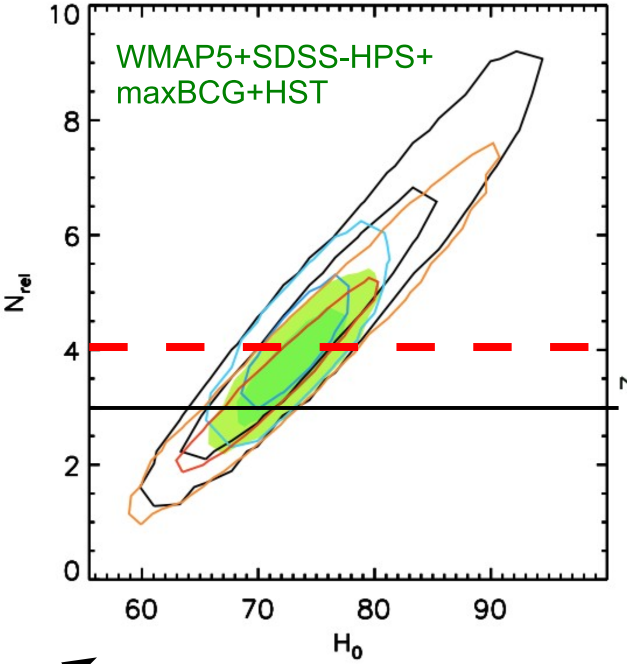
$$N_{\rm eff} = 4.2^{+3.7,+6.8}_{-2.0,-3.0}(68\,\%\,,\,95\,\%\,\mathrm{C.I.})$$

WMAP3 +
h prior 0.4→1.0

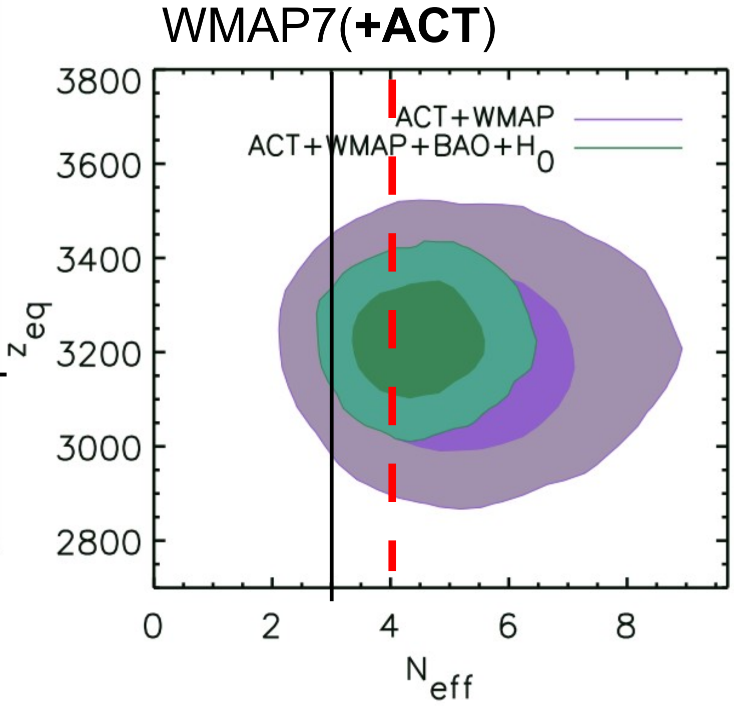
Hamann, Hannestad,
Raffelt & Y^3W 2007



Komatsu et al. [WMAP5] 2008



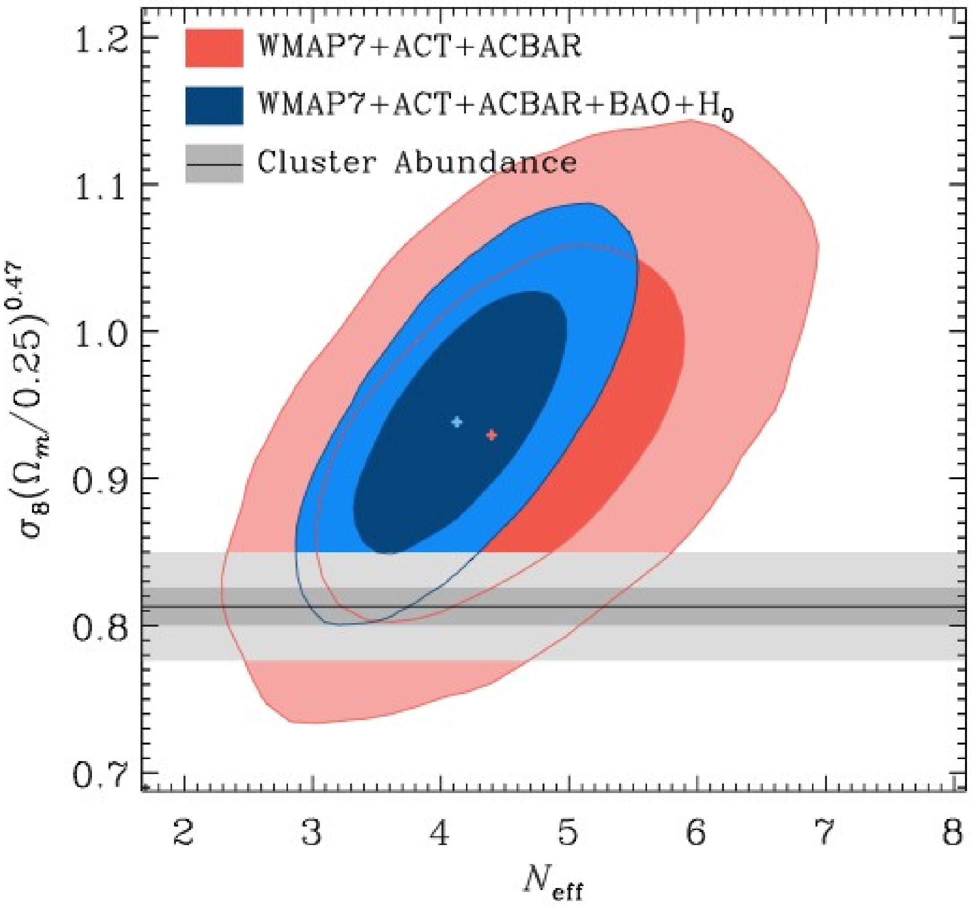
Reid, Verde,
Jimenez & Mena 2009



Dunkley et al. [ACT] 2010

WMAP5

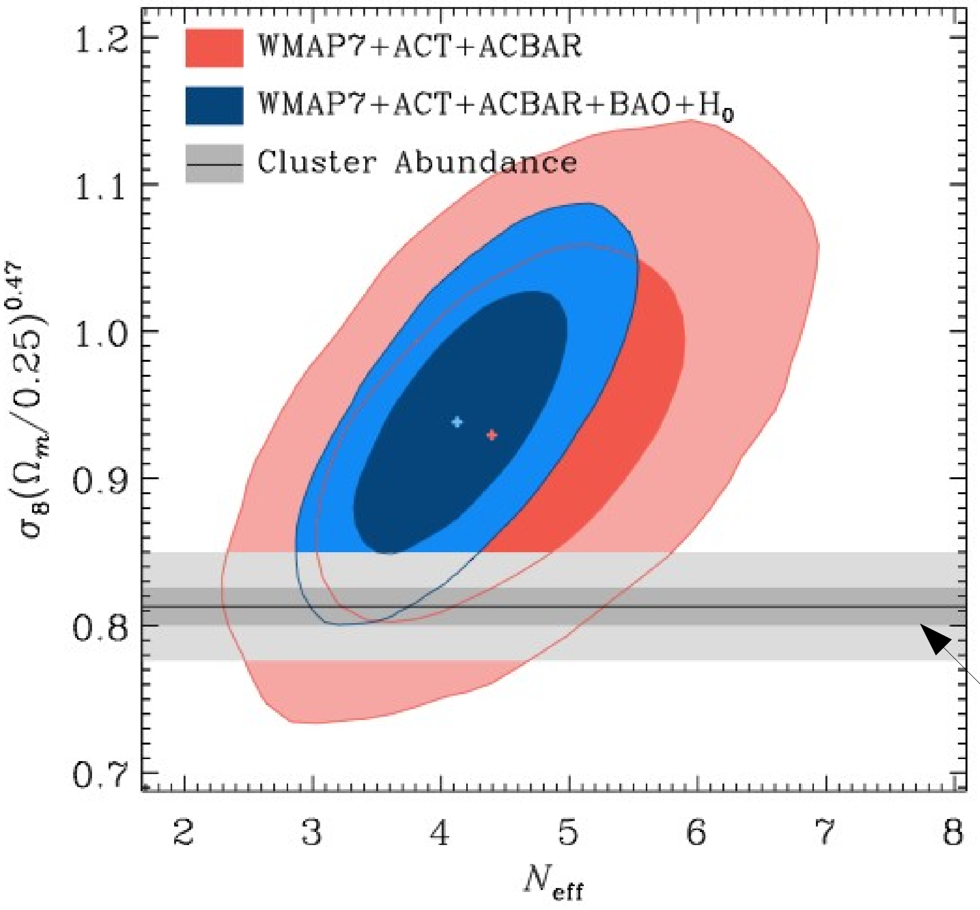
- The strongest claim so far...



- The most recent analysis using WMAP7+ACT+ ACBAR+BAO+H_0 finds $N_{\rm eff}$ = 3.04 is disfavoured at 98.4% confidence. (ΛCDM+$N_{\rm eff}$)

Hou, Keisler, Knox et al. 1104.2333

- The strongest claim so far...



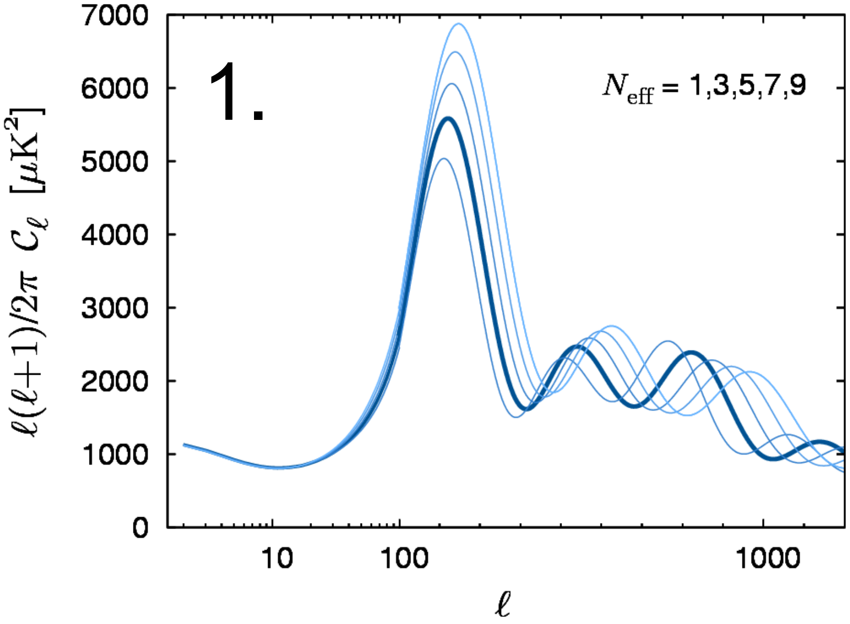
- The most recent analysis using WMAP7+ACT+ ACBAR+BAO+H_0 finds N_{eff} = 3.04 is disfavoured at 98.4% confidence. (ΛCDM+N_{eff})

Hou, Keisler, Knox et al. 1104.2333

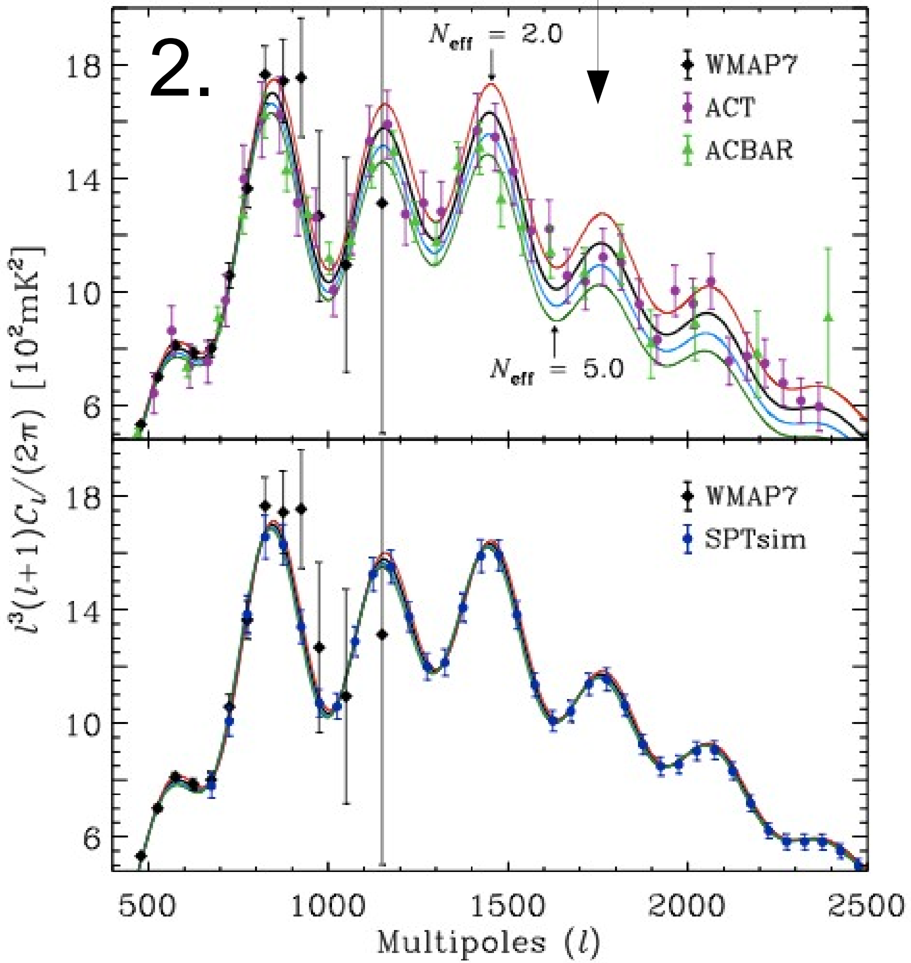
Tension (claimed by authors) with cluster abundance?? See however Mantz, Allen & Rapetti 2009

How it works...

- **Primary effect** of N_{eff}: shifts epoch of equality.
- **Secondary effect**: enhances expansion rate at equality and hence Silk damping.



Fixed z_{eq}, ρ_b, θ_s



Hou, Keisler, Knox et al. 1104.2333

Light (eV) sterile neutrinos as a candidate...

- Oscillation signals in LSND and MiniBooNE (anti-neutrino channel) in **conflict** with the standard 3-neutrino interpretation of global neutrino oscillation data.

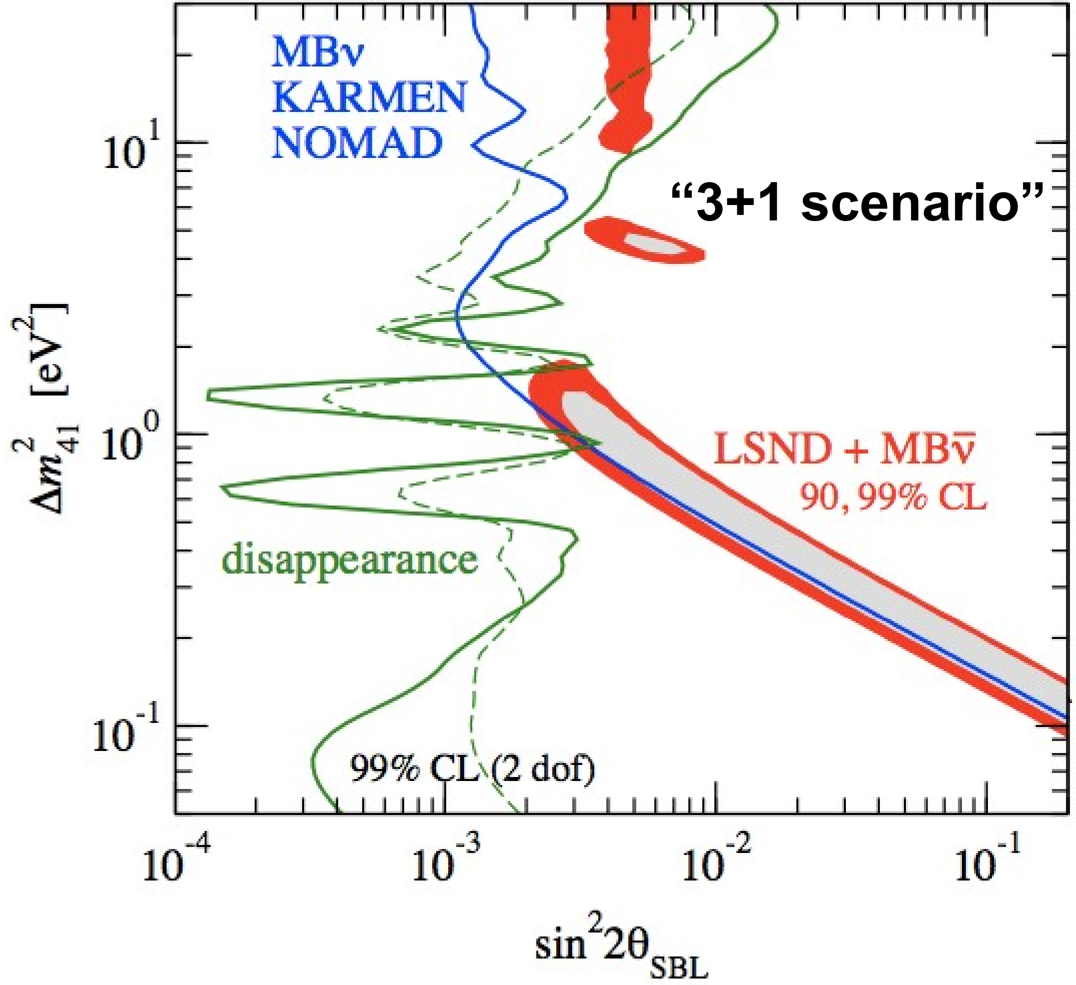
- The simplest solution: introduce a fourth neutrino flavour.
  - Must not couple to W, Z, or LEP would have seen it.

$$N_\nu = 2.9840 \pm 0.0082$$

Z invisible decay width
Particle Data Group 2010

→ Fourth flavour = “Sterile neutrino”.

(e, μ, τ neutrinos = “Active neutrinos”.)



Kopp, Maltoni &
Schwetz 1103.4570

New reactor fluxes

Old reactor fluxes

- Tension between LSND/ MiniBooNE and reactor disappearance experiments.

- New analysis of reactor fluxes finds 3% higher mean flux.
  → disappearance @98.6% confidence (old: 68% CL).
  Mention et al. 1101.2755
  Huber 1106.0687

- "3+1" best-fit: $\Delta m^2_{41} \sim 1 \ \ \mathrm{eV}^2$

$$\rightarrow \boxed{m_s \sim 1 \ \ \mathrm{eV}}$$

If lightest neutrino mass ~ 0 eV

- 3 active + 2 sterile scenarios fit even better.

3+2

$$\Delta m^2_{41} \sim 0.47 \quad \text{eV}^2$$

$$\Delta m^2_{51} \sim 0.87 \quad \text{eV}^2$$

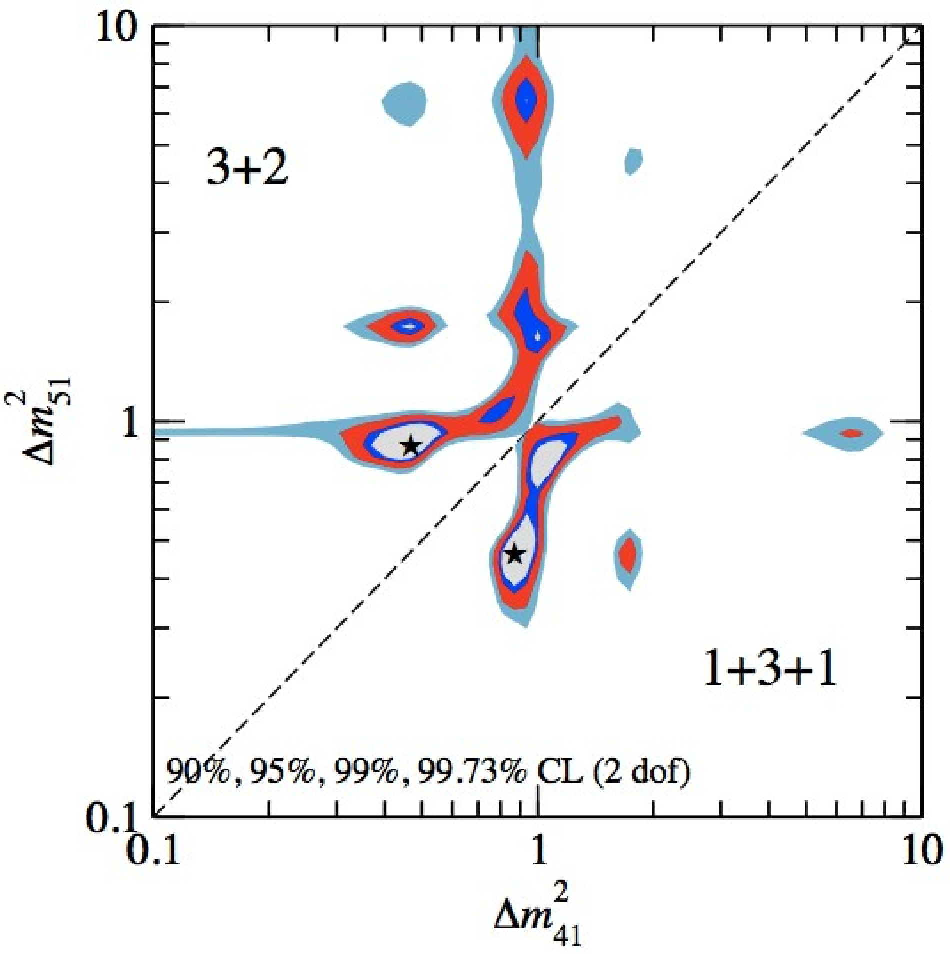
$$\chi^2/\,\text{dof} = 110.1/130$$

↓

$$m_1 \sim m_2 \sim m_3 \quad 0 \quad \text{eV}$$

$$m_{s1} \sim 0.7 \quad \text{eV}$$

$$m_{s2} \sim 0.9 \quad \text{eV}$$



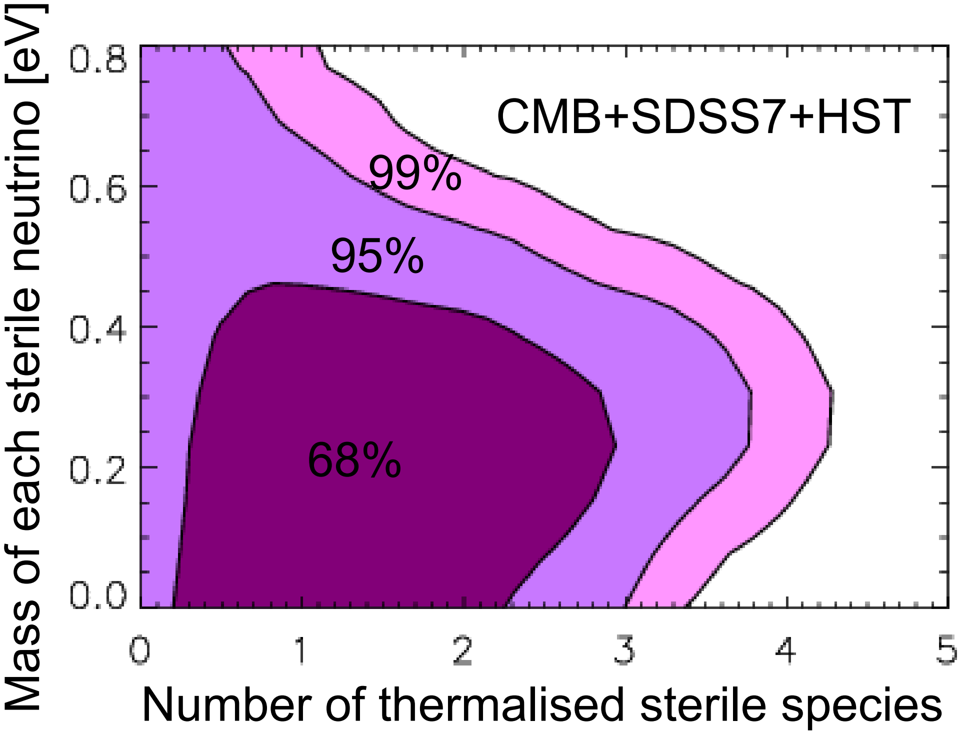
Kopp, Maltoni & Schwetz 1103.4570

Sterile neutrino thermalisation in the early universe...

- Production process is a combination of active-sterile neutrino oscillations and weak scattering of the active neutrinos.
  - Extent of sterile neutrino thermalisation depends sensitively on the square-mass splitting and the mixing matrix.
  - $\Delta m^2 > 1$ eV^2 → complete thermalisation expected: same temperature and abundance as active neutrinos.*

*Based on 2-flavour analyses;
3+1 and 3+2 analyses have
have **never** been attempted.

Compatibility of 3+1 and 3+2 with cosmology?



- 3+1 thermalised sterile:

$$m_s < 0.48 \ \text{eV} \ (95\%\text{C.I.})$$

Lab best-fit: $m_s \sim 1 \ \text{eV}$

- 3+2 thermalised sterile:

$$m_{s1} + m_{s2} < 0.9 \ \text{eV} \ (95\%\text{C.I.})$$

Lab best-fit: $m_{s1} \sim 0.7 \ \text{eV}$
$m_{s2} \sim 0.9 \ \text{eV}$

Hamann, Hannestad, Raffelt,
Tamborra & Y^{3}W 2010
also Giusarma et al. 2011

→ Tension between experiment results and cosmology!

Compatibility with BBN?

- Depending on the data set used, it may be difficult to accommodate two thermalised sterile states.

Number of thermalised sterile neutrinos

Data	Posterior max	95% C.I.
$Y_{\rm p}^{\rm IT}+({\rm D/H})_{\rm p}$	0.68	0.01–1.39
$Y_{\rm p}^{\rm A}+({\rm D/H})_{\rm p}$	0.69	< 2.42
$({\rm D/H})_{\rm p}+\omega_{\rm b}^{\rm CMB}$	0.49	< 2.12

Helium 4

Deuterium

Baryon density from CMB

"Best-fits"

Hamann et al. 2010
also Mangano & Serpico 2011

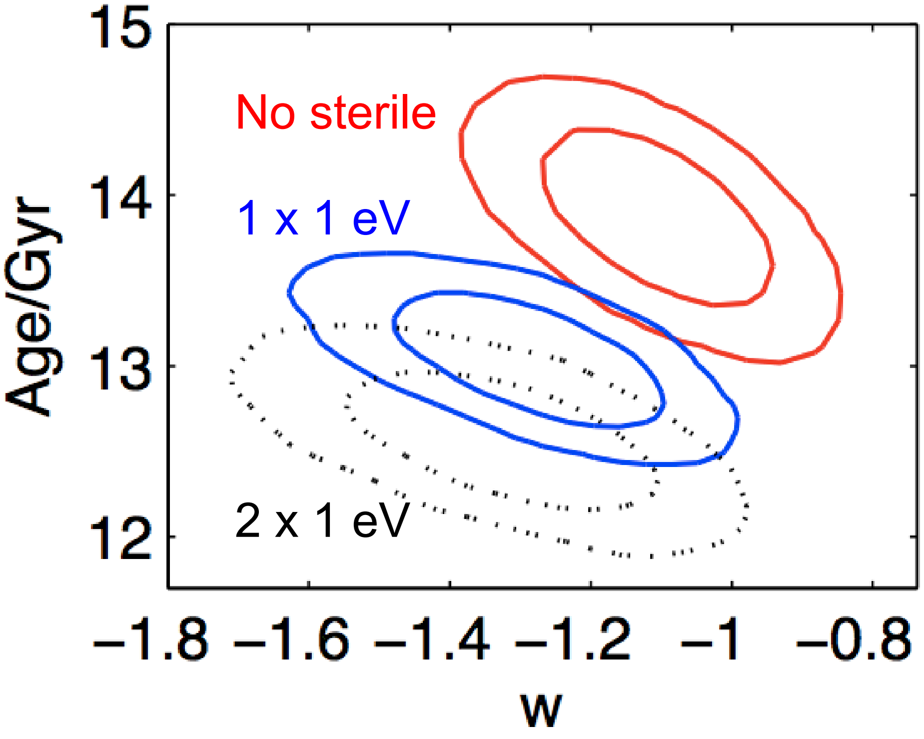
$Y_p^{\rm IT}=0.2565\pm0.001({\rm stat})\pm0.005({\rm syst})$ Izotov & Thuan 2010

$Y_p^{\rm A}=0.2561\pm0.011$ Aver et al. 2010

$\log({\rm D/H})_p=4.56\pm0.04$ Pettini et al. 2008

Suppose 1eV sterile neutrinos are for real...

- How would other cosmological parameters have to change in order to accommodate two massive sterile neutrinos?



→ Cosmolgical constant disfavoured at > 95% confidence!?!?

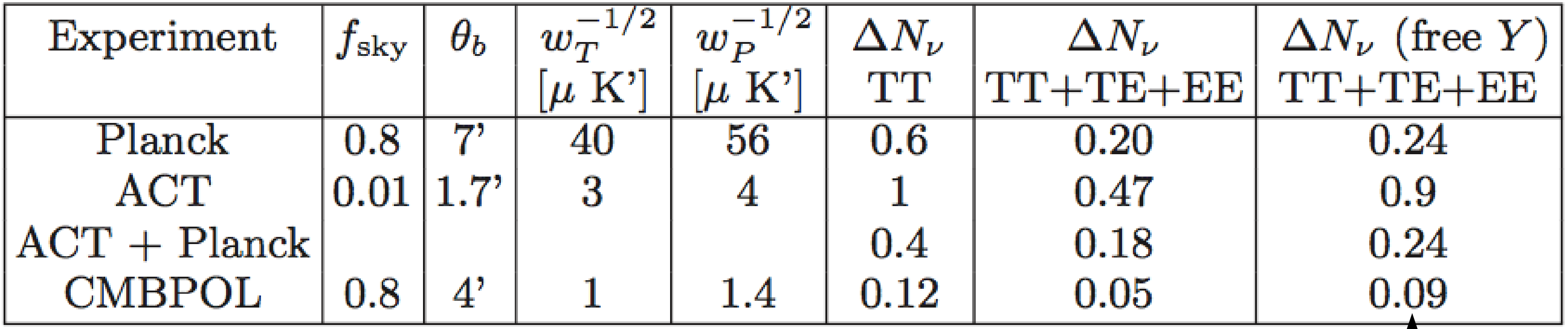
(wCDM+Ω_k+sterile)
(CMB+LSS+SN)

Kristiansen & Elgaroy 1104.0704

3. What the future holds…

Planck and N_{eff}...

- The question of whether or not $N_{eff} \sim 4$ will be settled almost immediately with Planck!



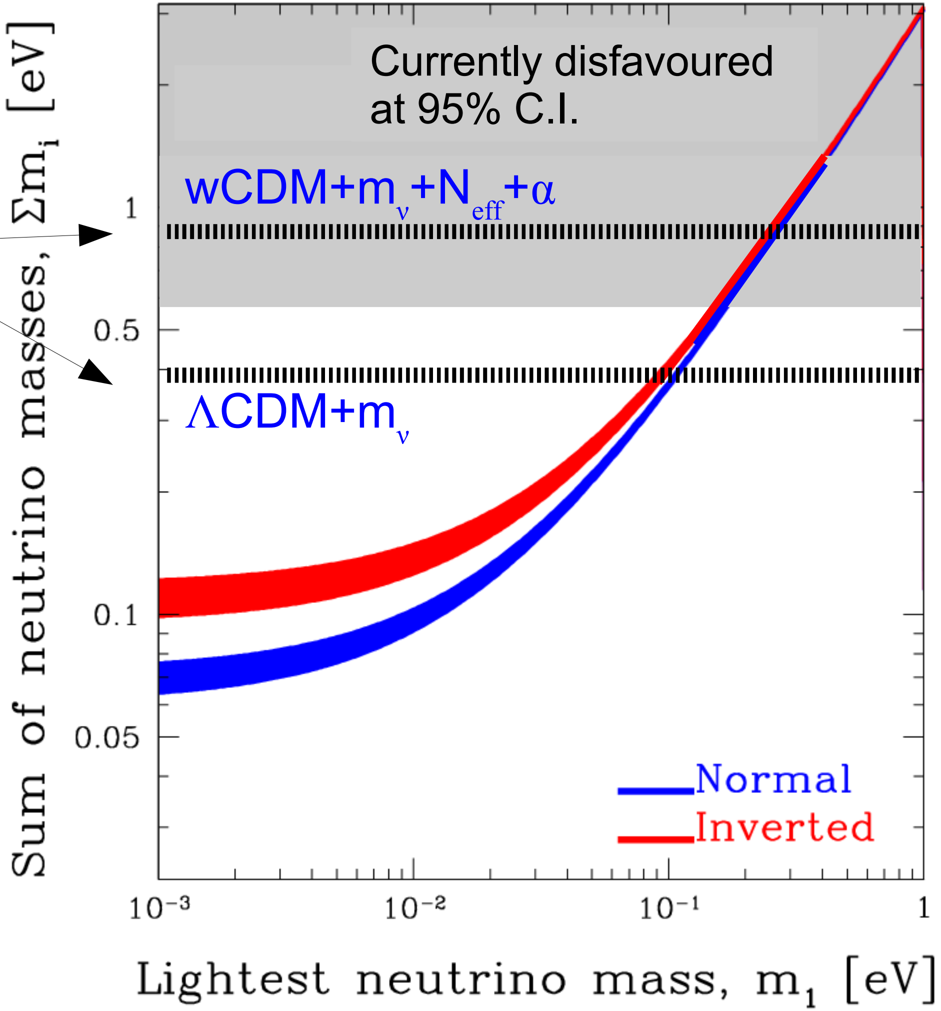
Experiment	f_{sky}	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Bashinsky & Seljak 2004

Free Helium fraction

Planck and neutrino masses...

Planck 95% sensitivities to neutrino masses

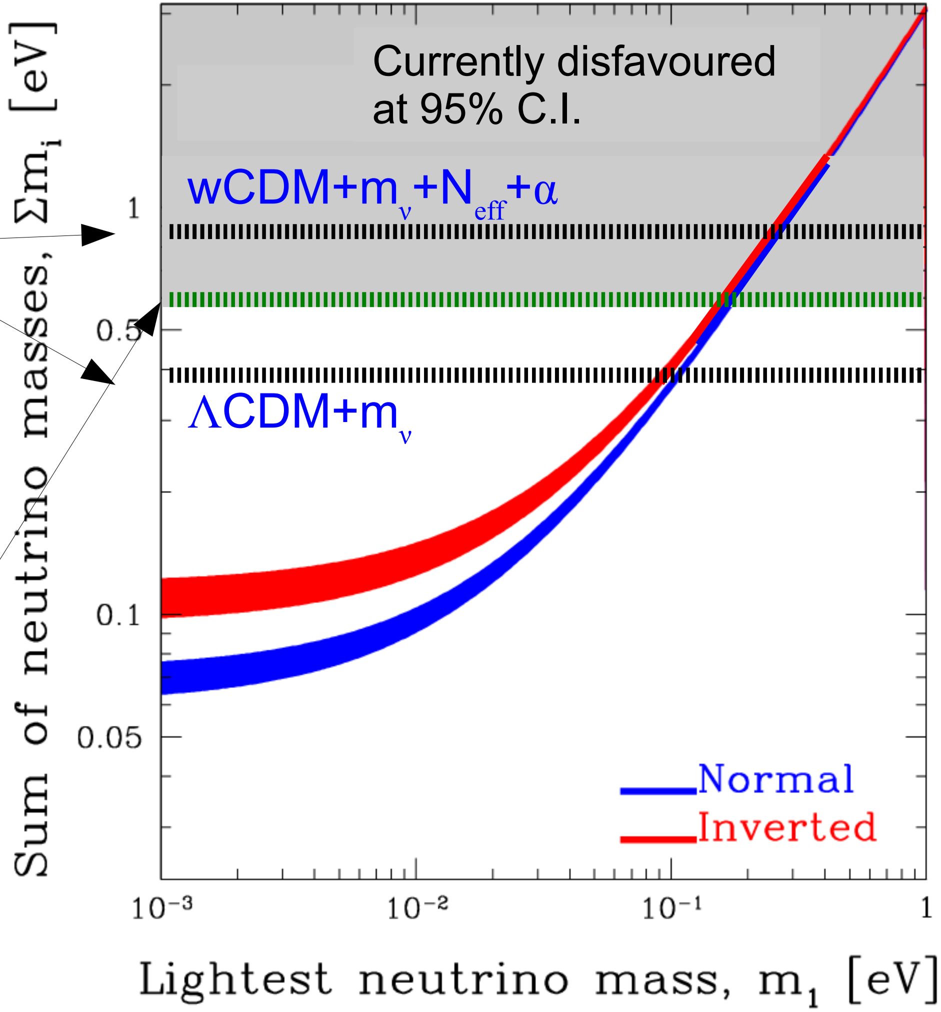


Perotto et al. 2006

Planck and neutrino masses...

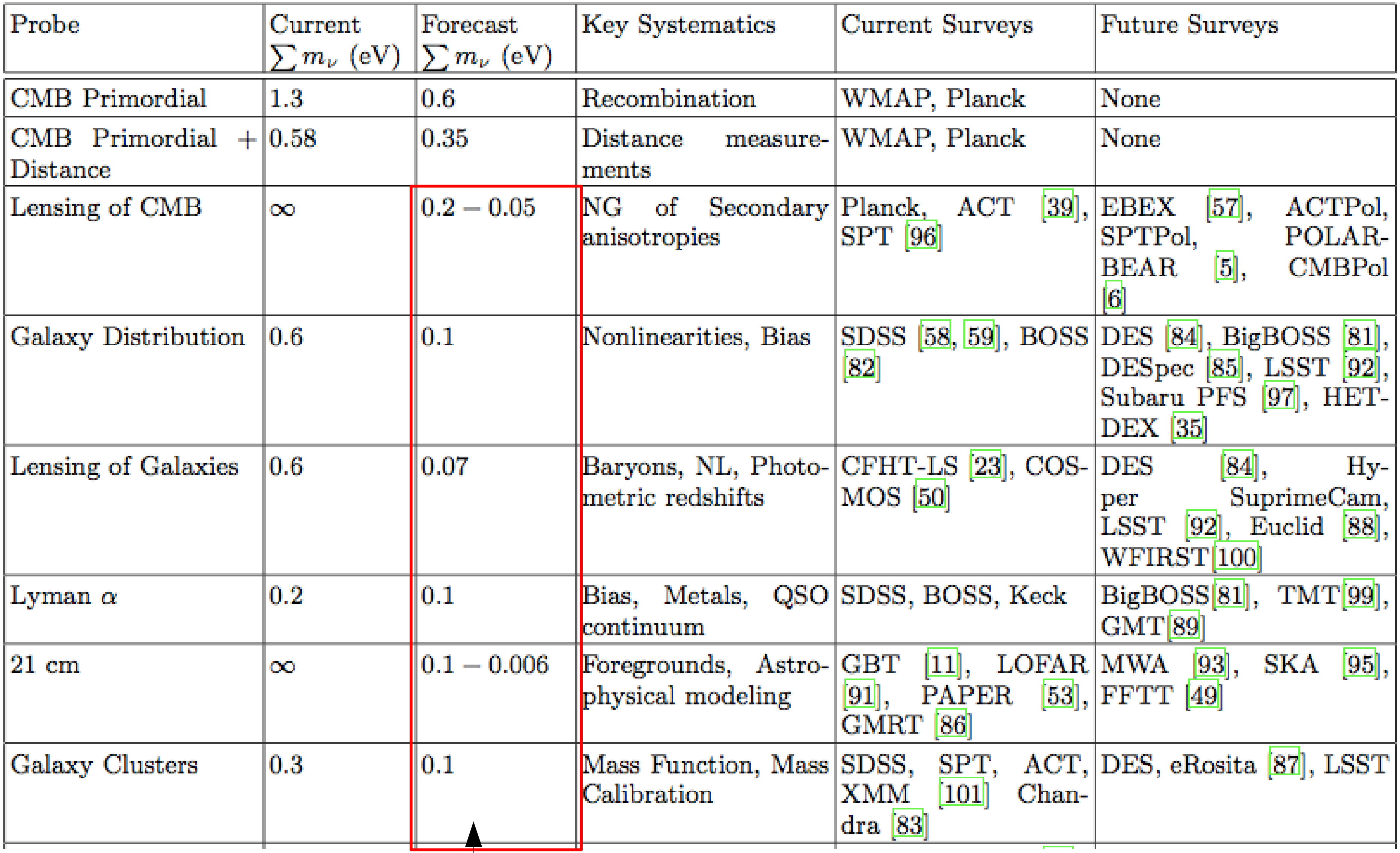
Planck 95% sensitivities to neutrino masses

Reach of KATRIN



Perotto et al. 2006

KATRIN main spectrometer



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

+Planck; 95% sensitivities

Abazajian et al. 1103.5083

Summary...

- Hot relics are still fun.
  - With present data: $\sum m_\nu < O(1)\ \mathrm{eV}$
  - We can do **even better** in the future with forthcoming probes/new techniques.

- Question of the moment: are there extra hot relics beyond 3 standard model neutrinos?
  - If so, it appears to be difficult to explain using the LSND/MiniBooNE preferred sterile neutrinos.
  - **Planck** will answer this soon!

Caution...

- Significance of evidence for $N_{\mathrm{eff}} > 3$ depends on your model parameter space.
  - An example: fitting WMAP7+BAO+HST

ΛCDM+N_{eff}

$$N_{\mathrm{eff}} = 4.34^{+0.86}_{-0.88}\,(68\,\%\,\mathrm{C.I.})$$

Komatsu et al. [WMAP7] 2010

+neutrino mass

$$N_{\mathrm{eff}} = 4.47^{+1.82}_{-1.74}\,(68\,\%\,\mathrm{C.I.})$$

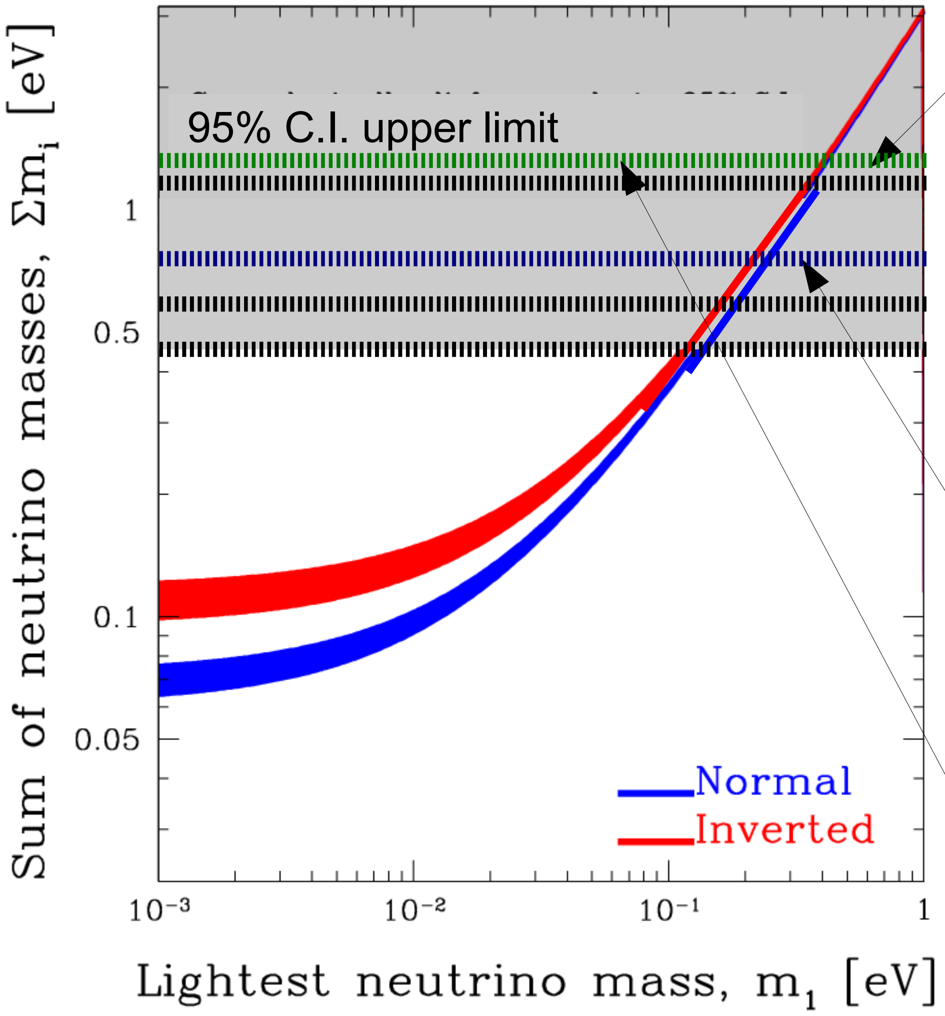
+neutrino mass
+$w_{\mathrm{DE}} \neq -1$

$$N_{\mathrm{eff}} = 3.68^{+1.90}_{-1.84}\,(68\,\%\,\mathrm{C.I.})$$

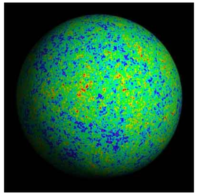
Hamann, Hannestad,
Lesgourgues,
Rampf & Y^{3}W 2010

$*$ (ΛCDM+m_ν)

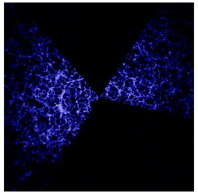
Present status...



Hannestad, Mirizzi, Raffelt & Y^3W 2010

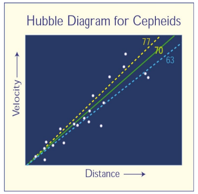


CMB only*
(WMAP7+ACBAR+
BICEP+QuAD)



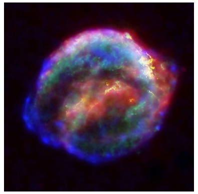
CMB+SDSS-HPS *

$$\sum m_\nu < 0.61\,\mathrm{eV}\,(95\%\,\mathrm{CI})$$



CMB+SDSS-HPS+HST *

$$\sum m_\nu < 0.44\,\mathrm{eV}\,(95\%\,\mathrm{CI})$$



+Supernovae (+w+N_{eff})

$$\sum m_\nu < 0.76\,\mathrm{eV}\,(95\%\,\mathrm{CI})$$

Gonzalez-Garcia et al. 2010

(No degeneracy with r, α_s, CDI)

Even if you don't believe SN. (+w+N_{eff})

Hamann et al. 2010