Massive Neutrinos in Cosmology

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TeV Particle Astrophysics

Columbus, August 8^{th}, 2017

The Cosmic Neutrino Background

The presence of a background of relic neutrinos (***CνB***) is a basic prediction of the standard cosmological model

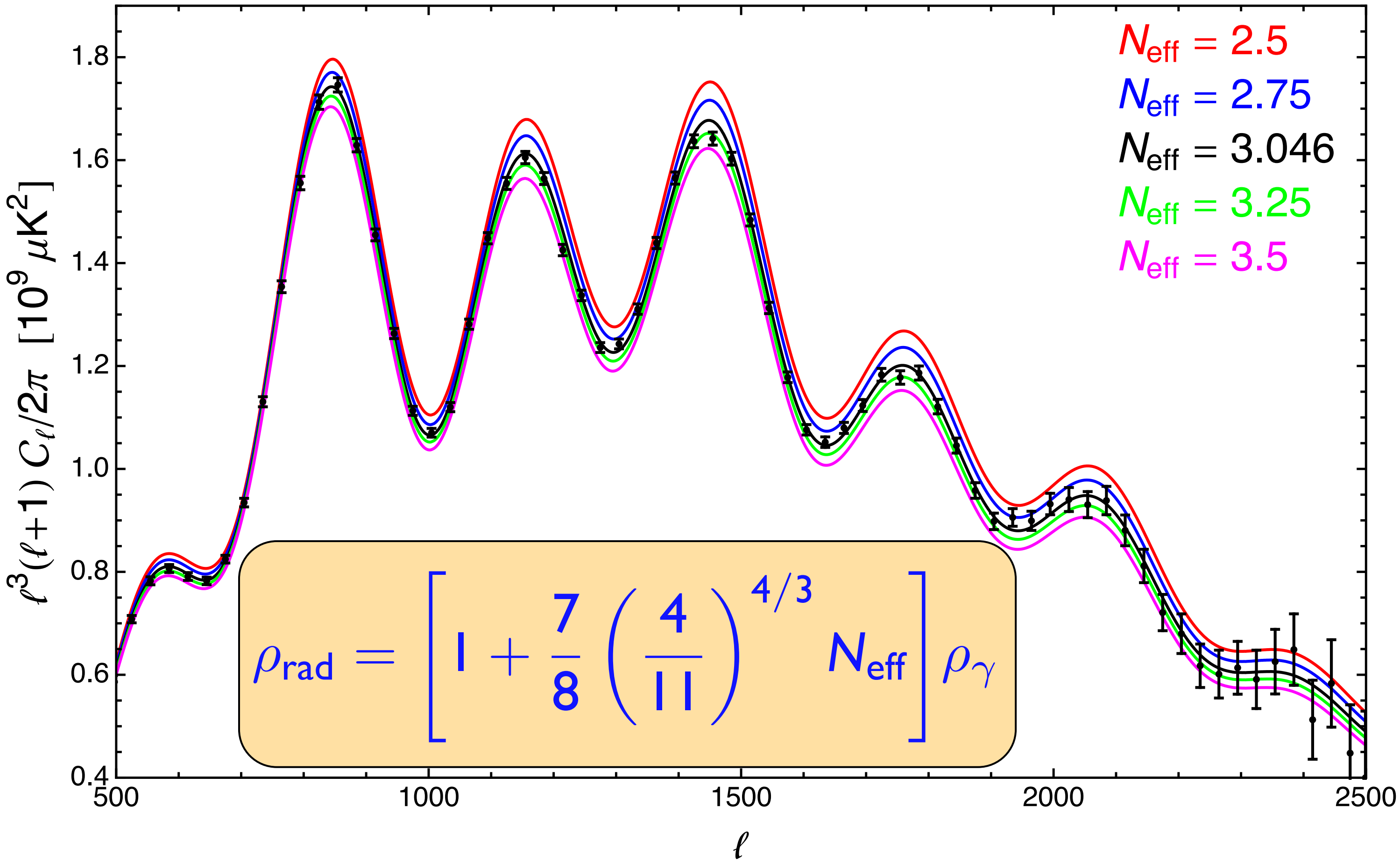
- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});
- Below T ~ 1 MeV, neutrino free stream keeping an equilibrium spectrum:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

THE COSMIC NEUTRINO BACKGROUND

This picture is consistent with current CMB observations:

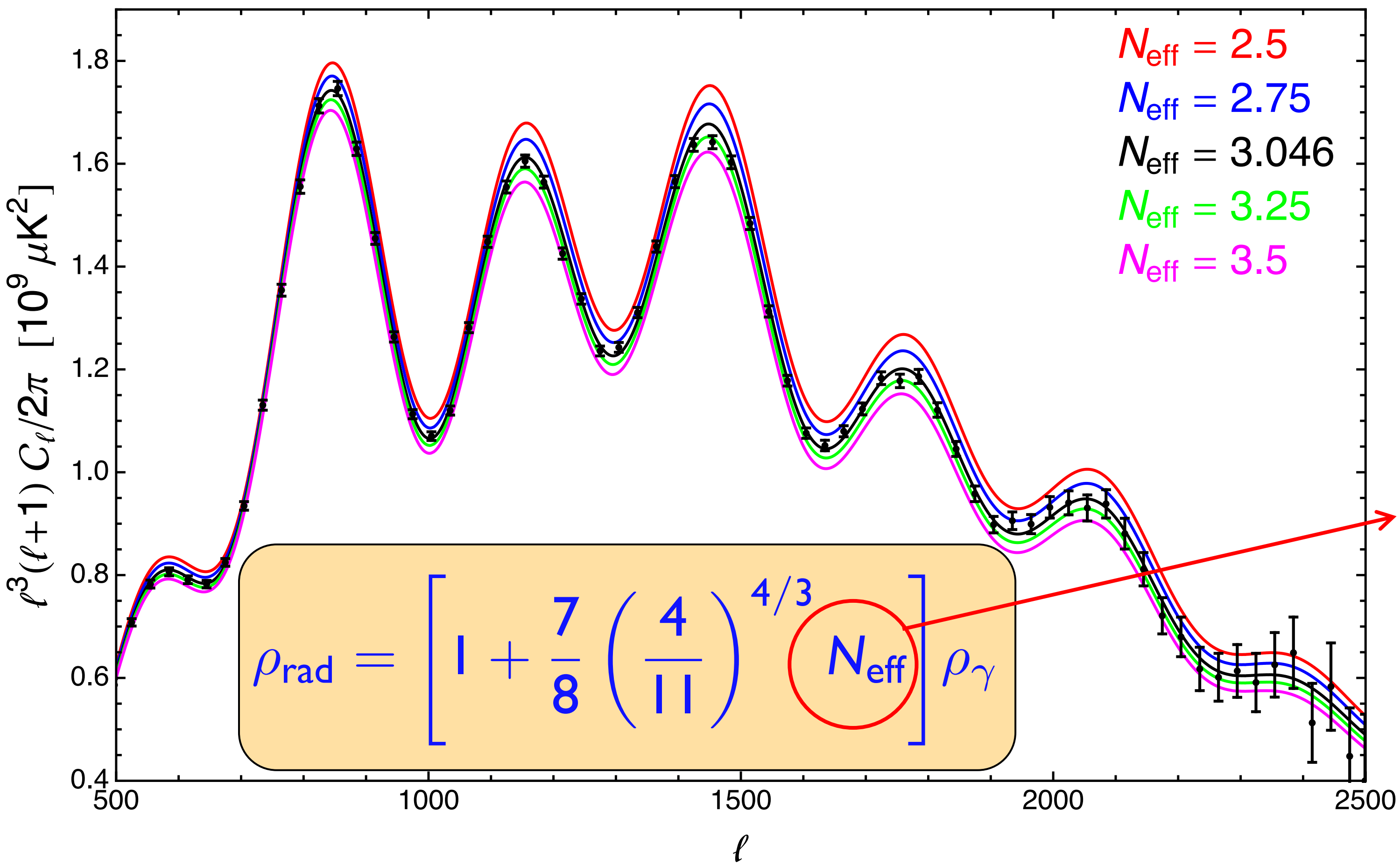


$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

(note I am showing ~ $l^4\,C_l$, not $l^2\,C_l$)

THE COSMIC NEUTRINO BACKGROUND

This picture is consistent with current CMB observations:

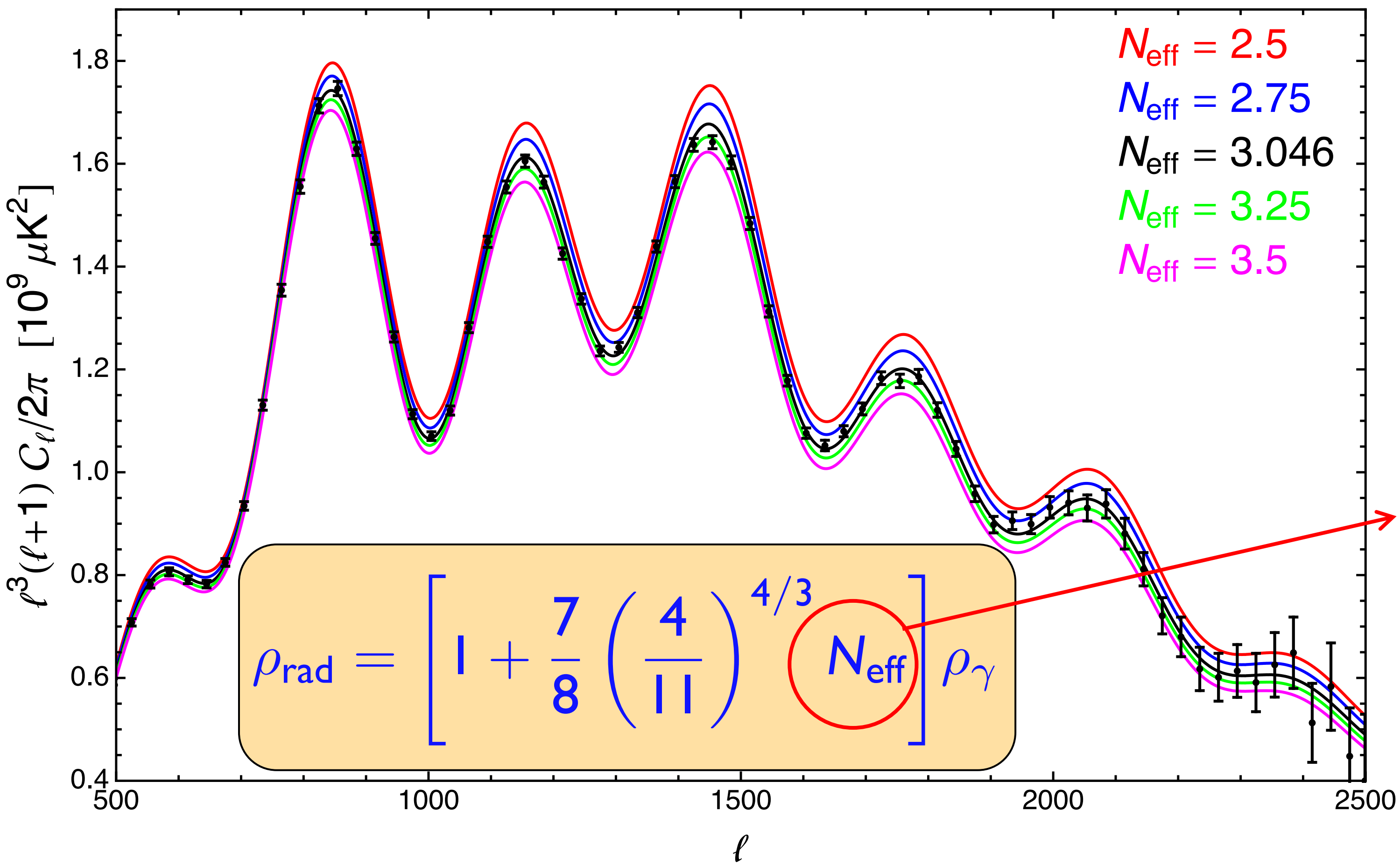


Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

(note I am showing ~ $l^4\,C_l$, not $l^2\,C_l$)

THE COSMIC NEUTRINO BACKGROUND

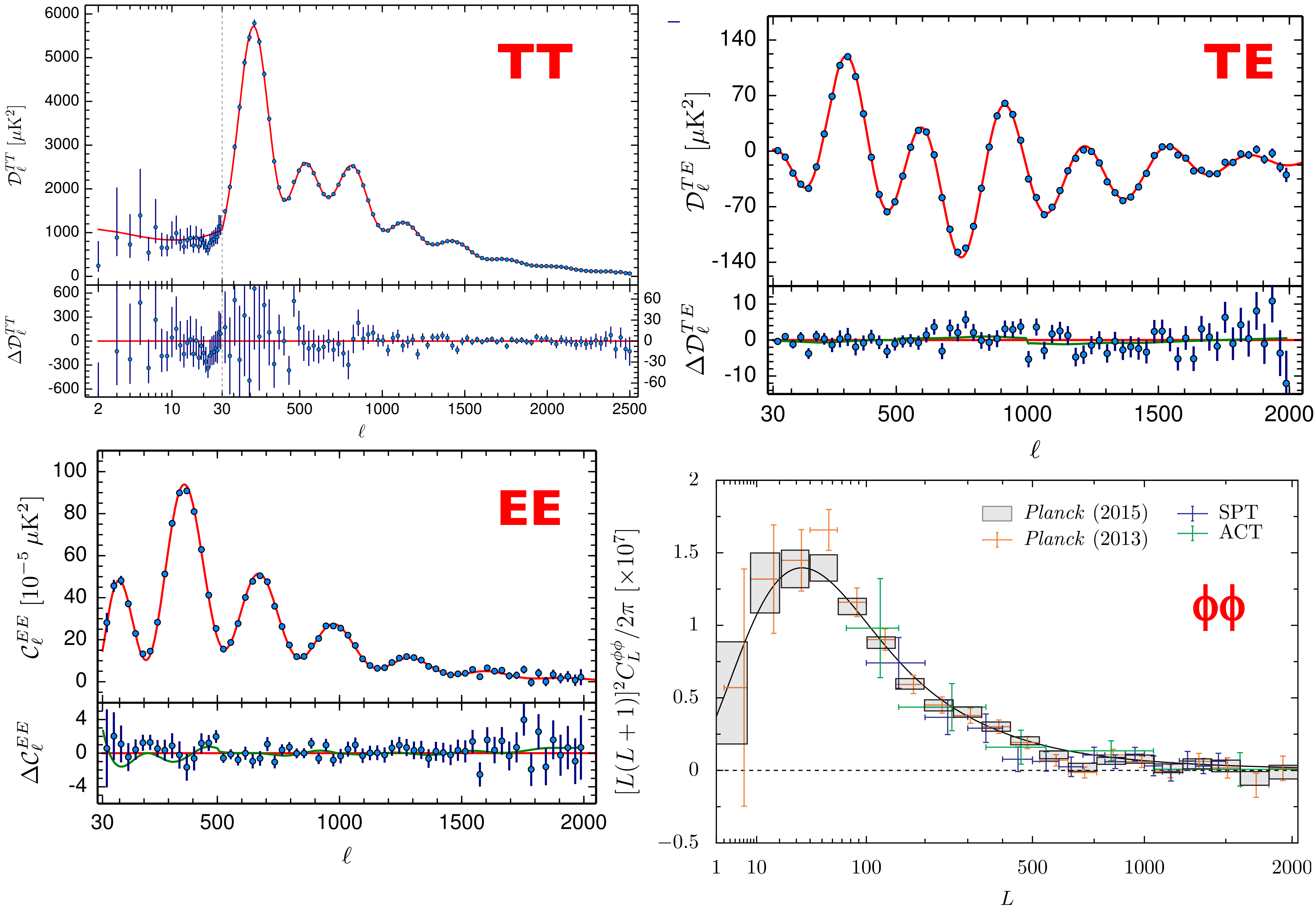
This picture is consistent with current CMB observations:



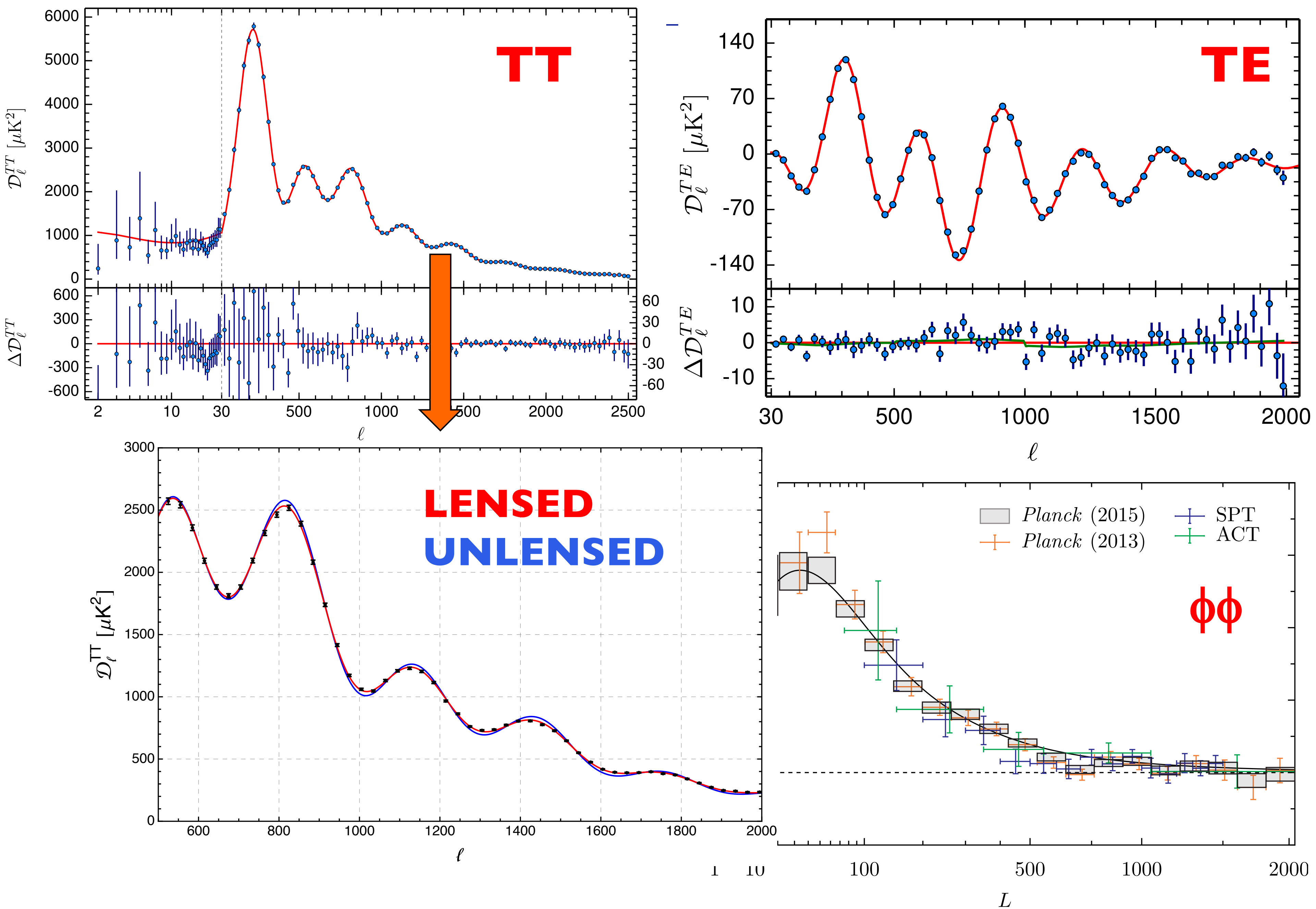
Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

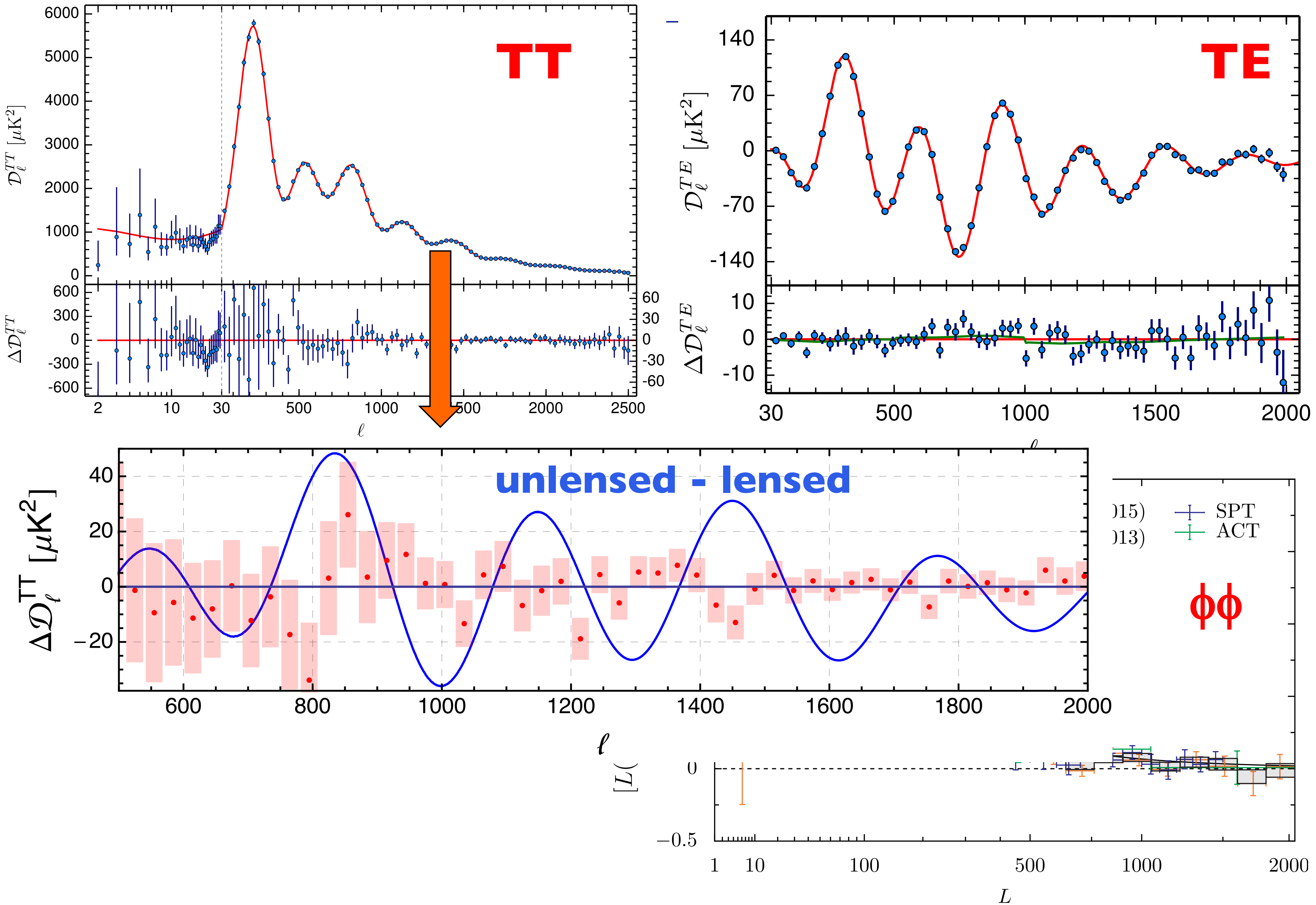
Due to non-instantaneous decoupling, the standard expectation is **$N_{\rm eff}$ = 3.046** (updated calculation gives $N_{\rm eff}$ = 3.045; see de Salas & Pastor 2016)

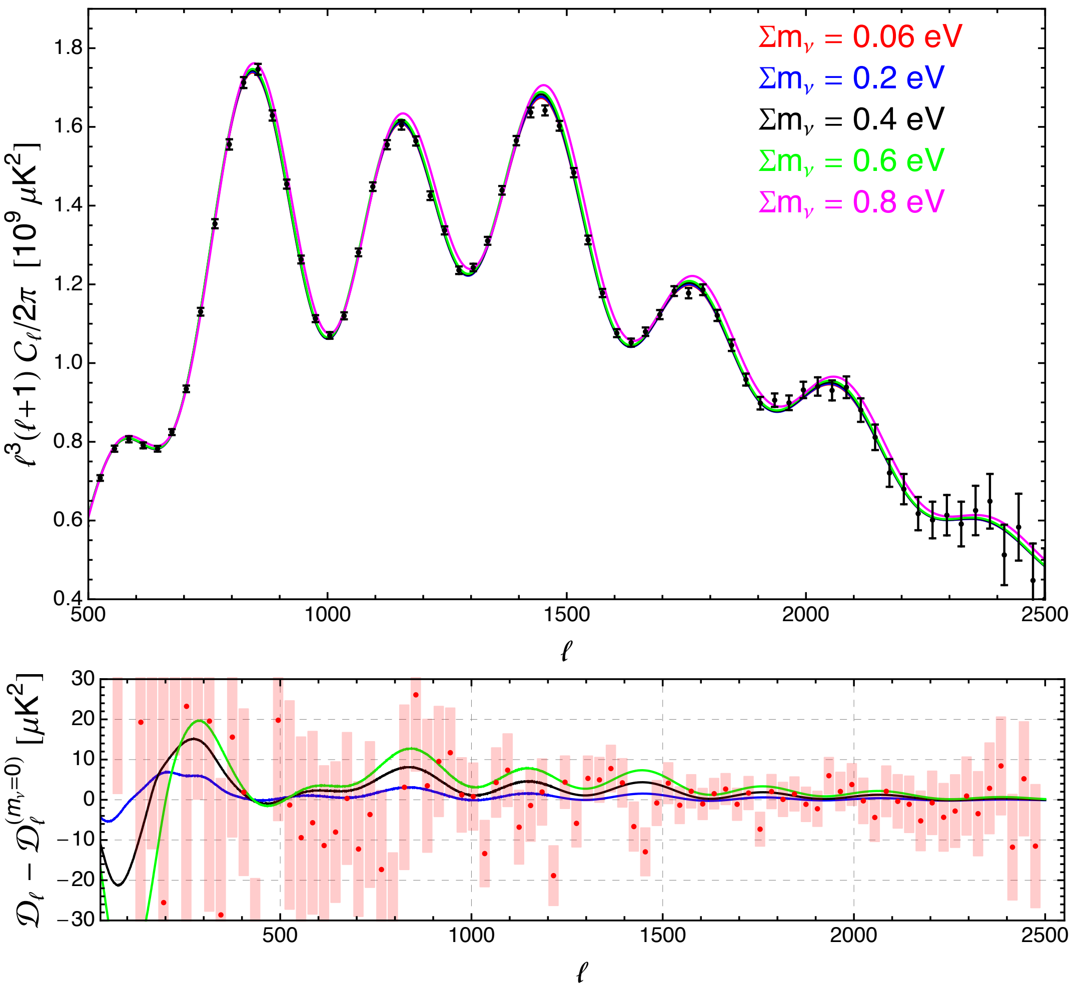
(note I am showing ~ $l^4 C_l$, not $l^2 C_l$)



TT
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ
TE
$\mathcal{D}_\ell^{TE}$ [μK^2]
140
70
0
-70
-140
$\Delta\mathcal{D}_\ell^{TE}$
10
0
-10
30
500
1000
1500
2000
ℓ
EE
$\mathcal{C}_\ell^{EE}$ [$10^{-5}\,\mu$K^2]
100
80
60
40
20
0
$\Delta\mathcal{C}_\ell^{EE}$
4
0
-4
30
500
1000
1500
2000
ℓ
ϕϕ
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi$ [$\times 10^7$]
Planck (2015)
Planck (2013)
SPT
ACT
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000
L


TT
TE
LENSED
UNLENSED
ϕϕ
Planck (2015)
Planck (2013)
SPT
ACT
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$
ℓ
L


TT
TE
unlensed - lensed
ϕϕ
SPT
ACT



CMB angular power spectrum and neutrino masses

Background effects can be mostly reabsorbed by varying other parameters

Perturbations: free streaming, damping of small-scale perturbations

Net effect is to ***decrease lensing***

- proportional to the neutrino energy density
- the effect is larger for larger masses

LARGE SCALE STRUCTURES

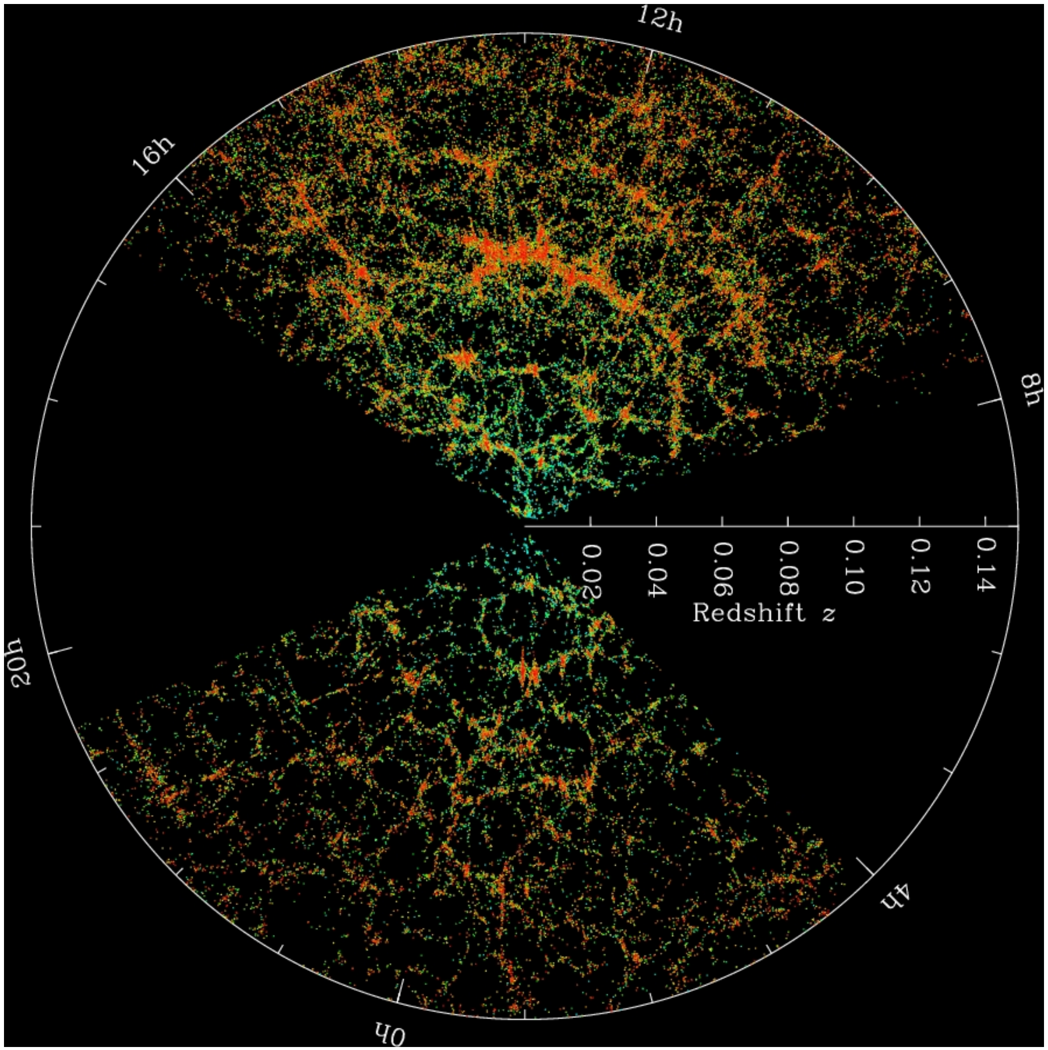
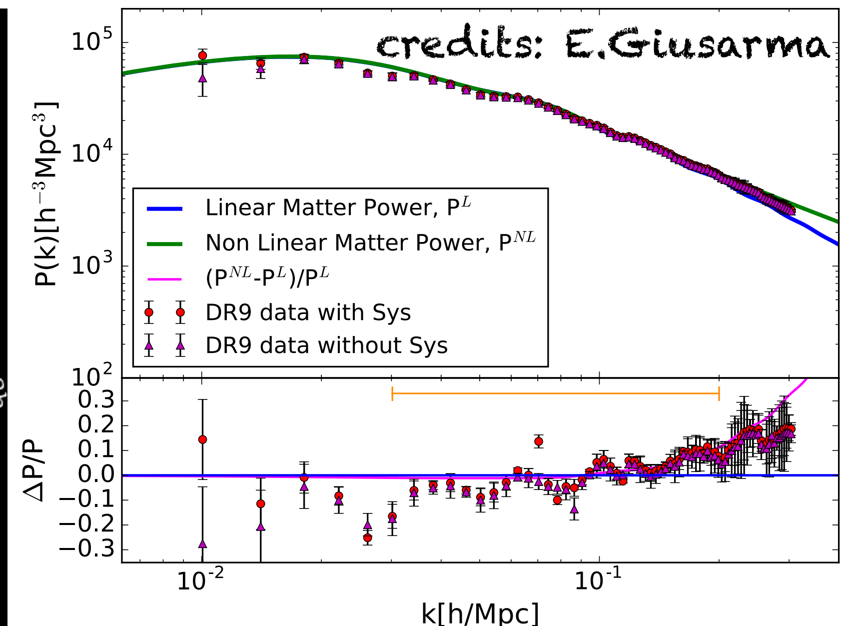
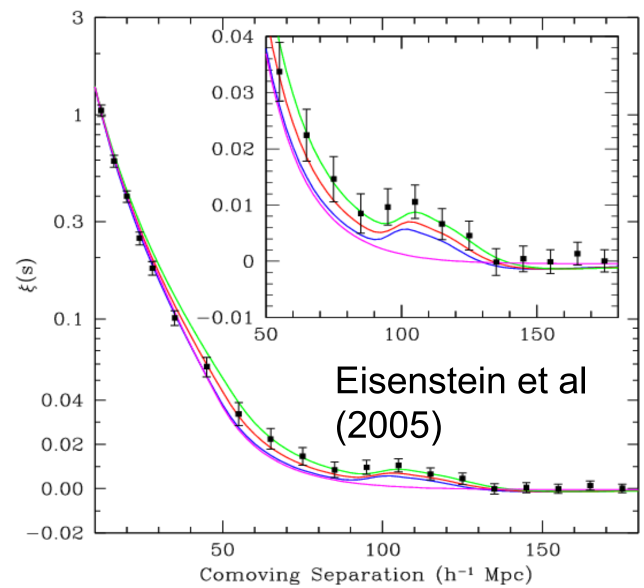


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

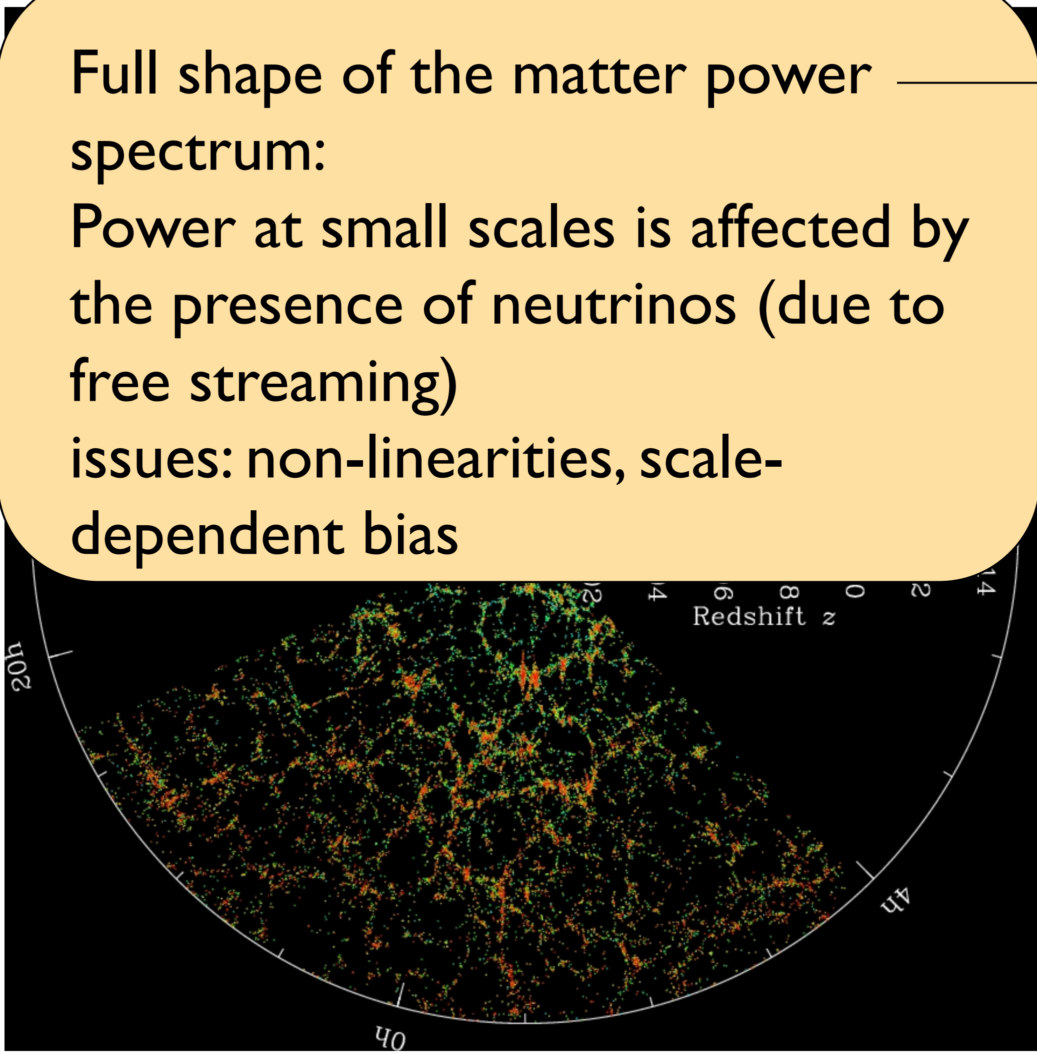




Eisenstein et al (2005)

LARGE SCALE STRUCTURES

Full shape of the matter power spectrum:
Power at small scales is affected by the presence of neutrinos (due to free streaming)
issues: non-linearities, scale-dependent bias



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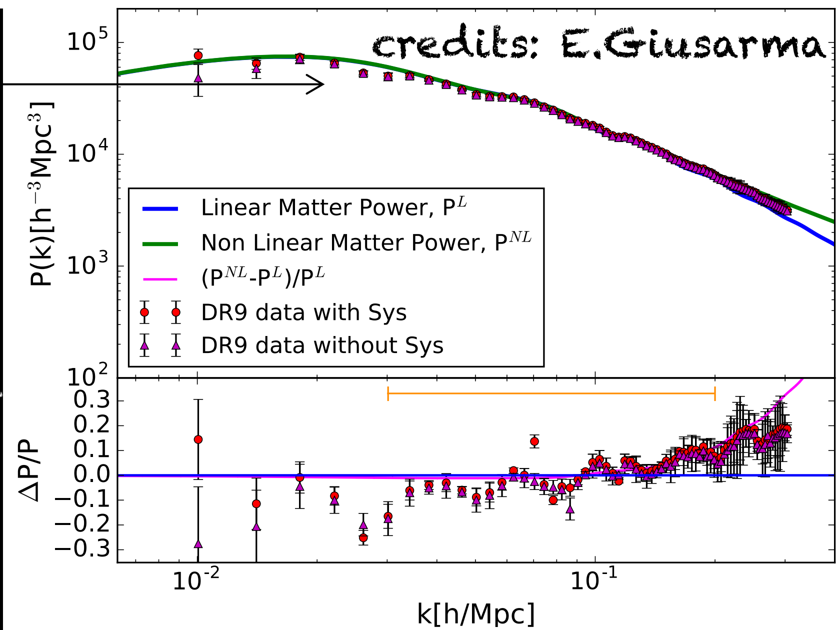

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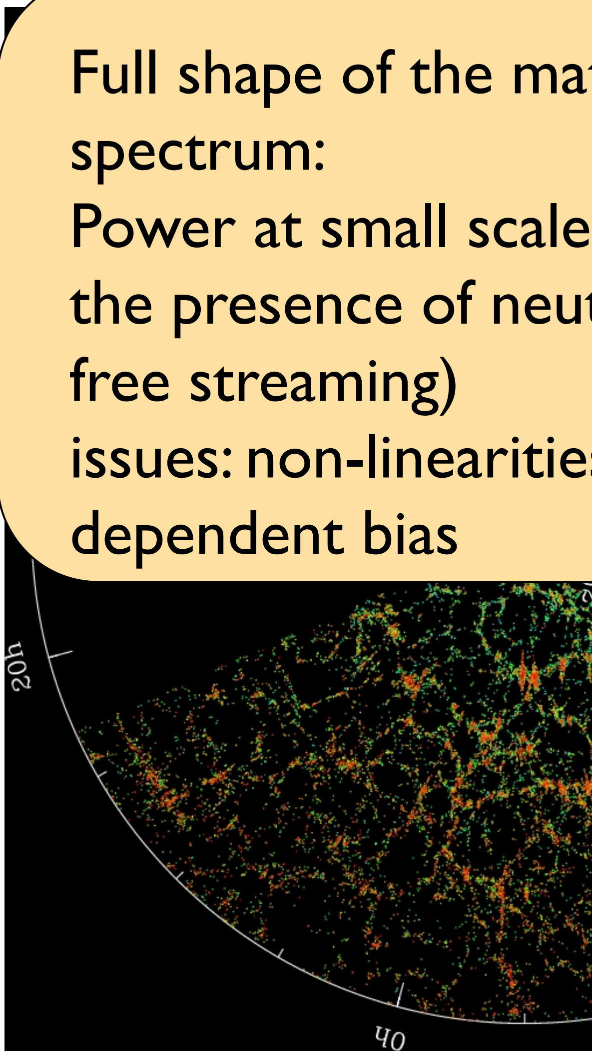

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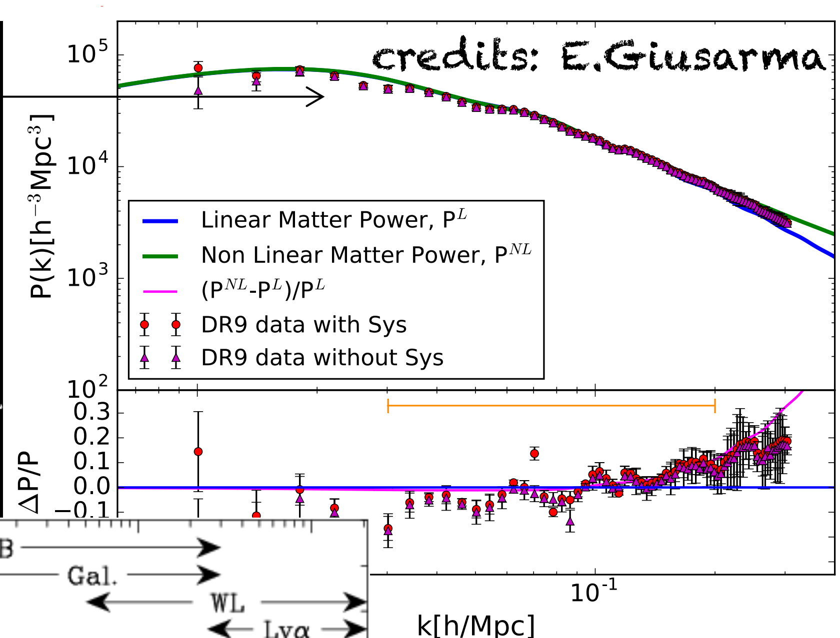
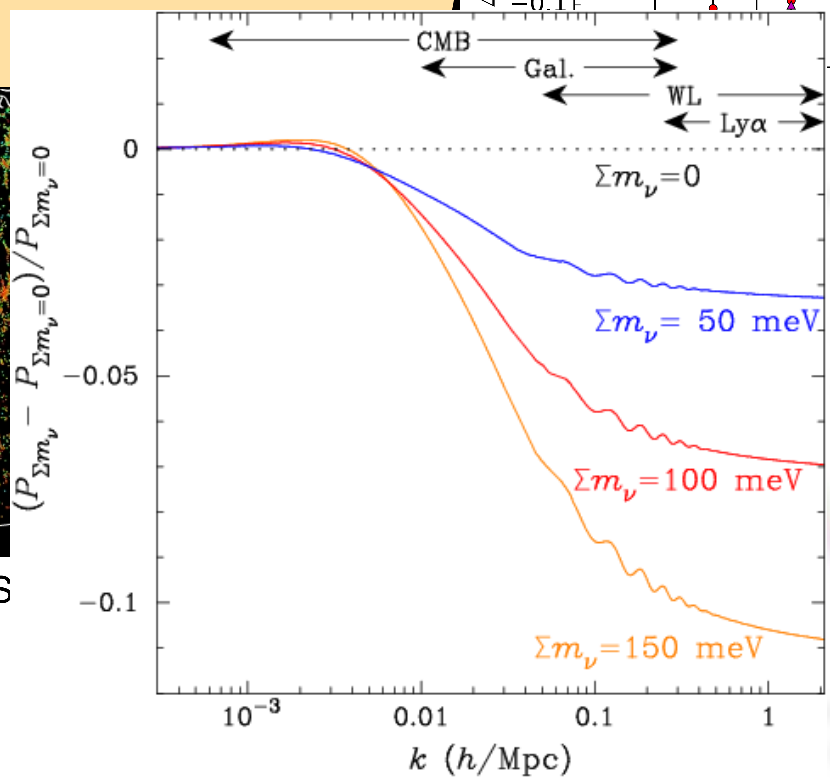
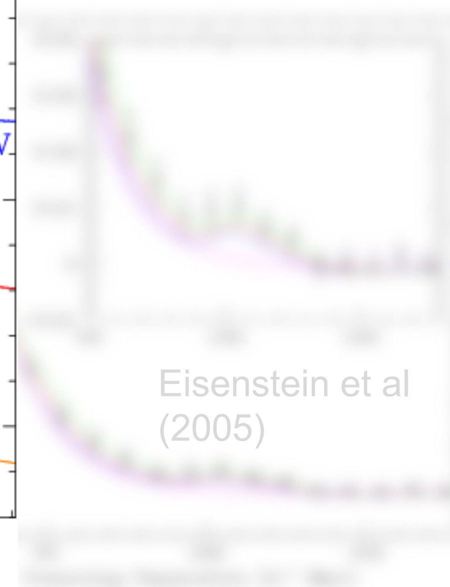






LARGE SCALE STRUCTURES

Baryon acoustic oscillations (BAO): Imprint of a characteristic scale (the sound horizon at the drag epoch) on the matter two-point CF

Standard ruler: BAO allow to constrain the expansion history and solve geometrical degeneracies

Less affected by systematics (e.g. nonlinear evolution)

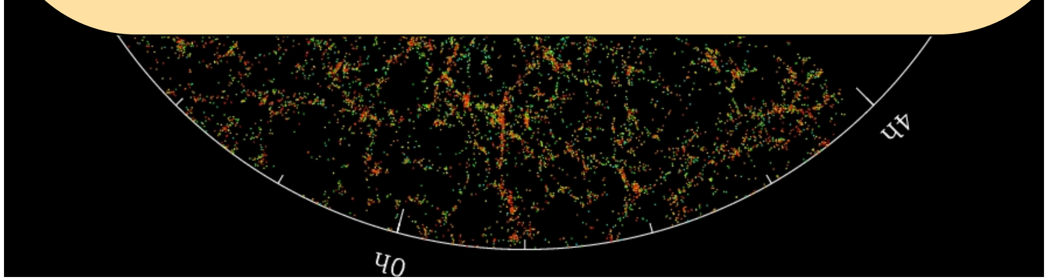
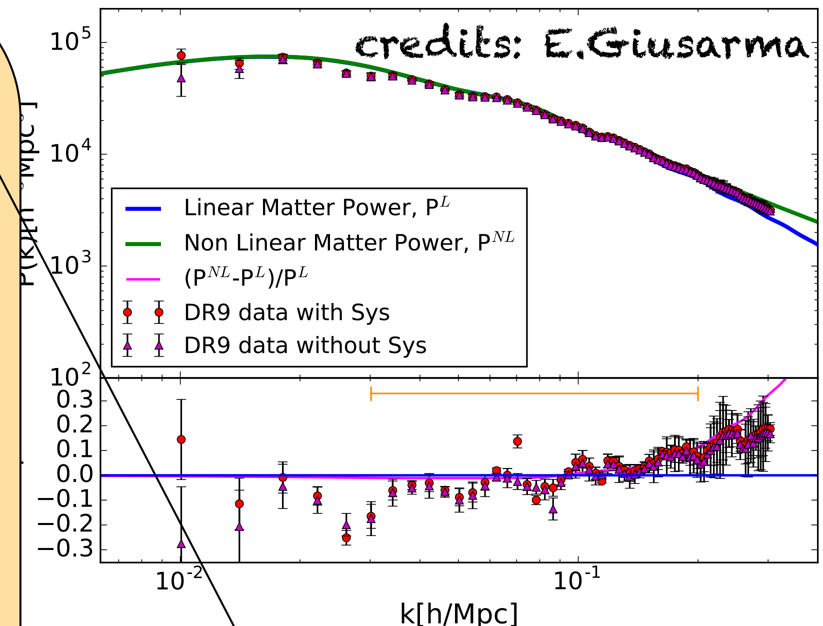
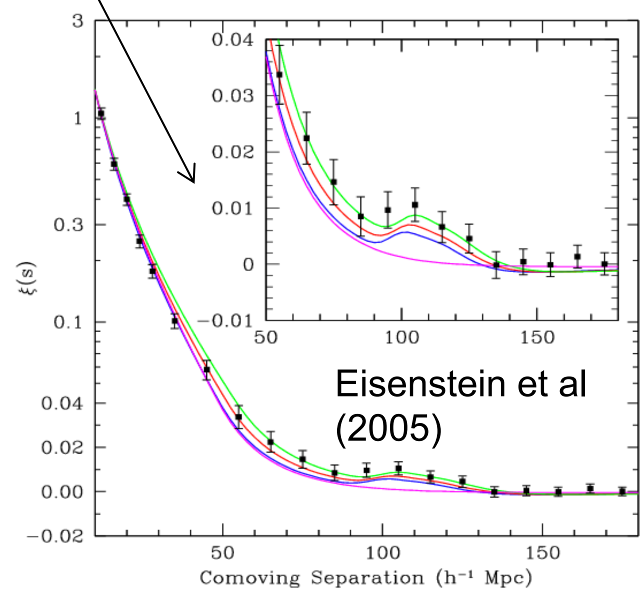
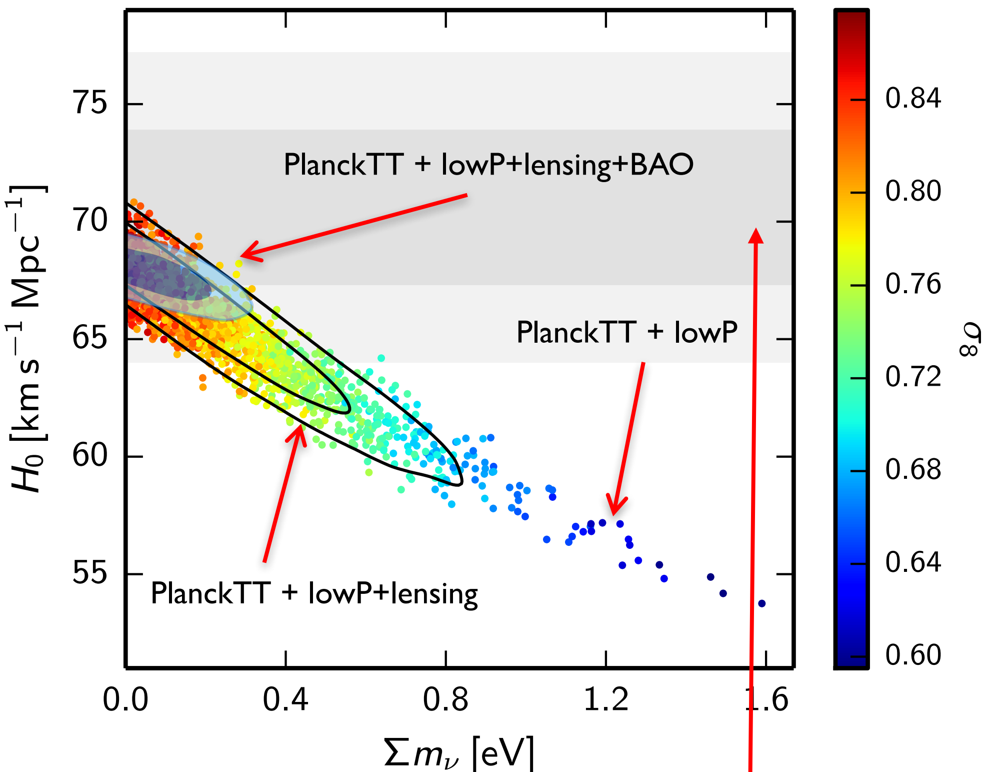


Image Credit: M. Blanton and the Sloan Digital Sky Survey.





Planck 2015 constraints on neutrino mass



PLANCK TT + lowP + lensing
$\Sigma m_\nu < 0.68$ eV

~ one order of magnitude better than present kinematic constraints already at the same level than near-future expectations for e.g. KATRIN

Inclusion of external data like BAO allows to better constrain the expansion history and reduce degeneracy with H0:

PLANCK TT+lowP+lensing+BAO
$\Sigma m_\nu < 0.23$ eV

Note that non-zero neutrino mass does not alleviate tension with direct measurements of H0

(Planck 2015 XIII)

How heavy?

95% constraints on total mass	*PlanckTT*	*PlanckTTTEEE*
+lowP	<0.72 eV	<0.49 eV
+lowP+lensing	<0.68 eV	<0.59 eV
+lowP+BAO	<0.21 eV	<0.17 eV
+lowP+ext	<0.20 eV	<0.15 eV
+lowP+lensing+ext	<0.23 eV	<0.19 eV

Planck 2015 + BOSS Lyman-α:

$\Sigma m_\nu < 0.12$ eV (@95%)

(Palanque-Delabrouille et al. 2015)

Planck 2015 + BOSS DR12 (BAO+shape):

$\Sigma m_\nu < 0.16$ eV (@95%)

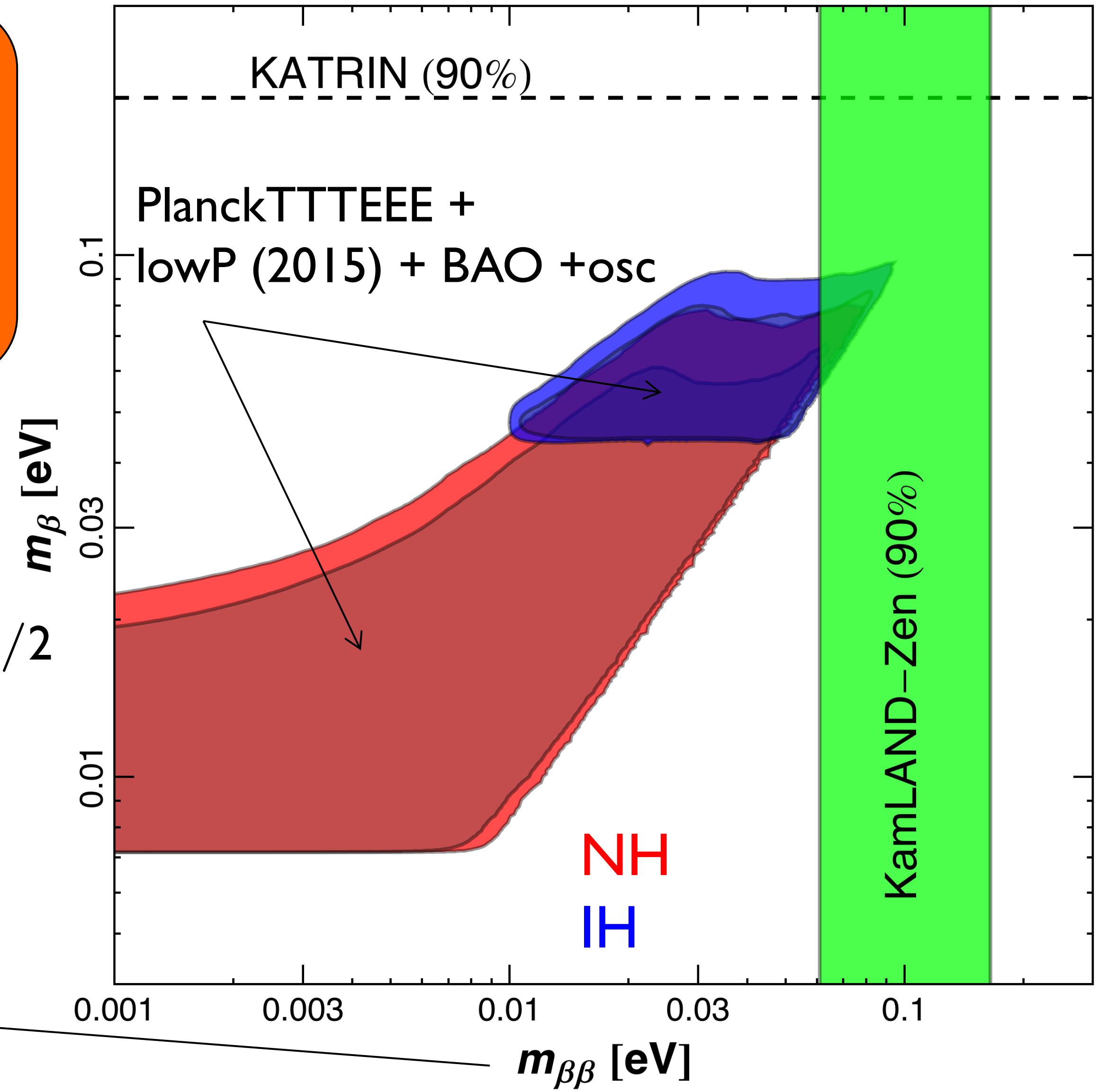
(BOSS collab., arXiv:1607.03155)

IMPLICATIONS FOR MASS PARAMETERS

Cosmology constraints can be combined with data from oscillation experiments

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$



Adapted from Gerbino, ML, Melchiorri, 2016

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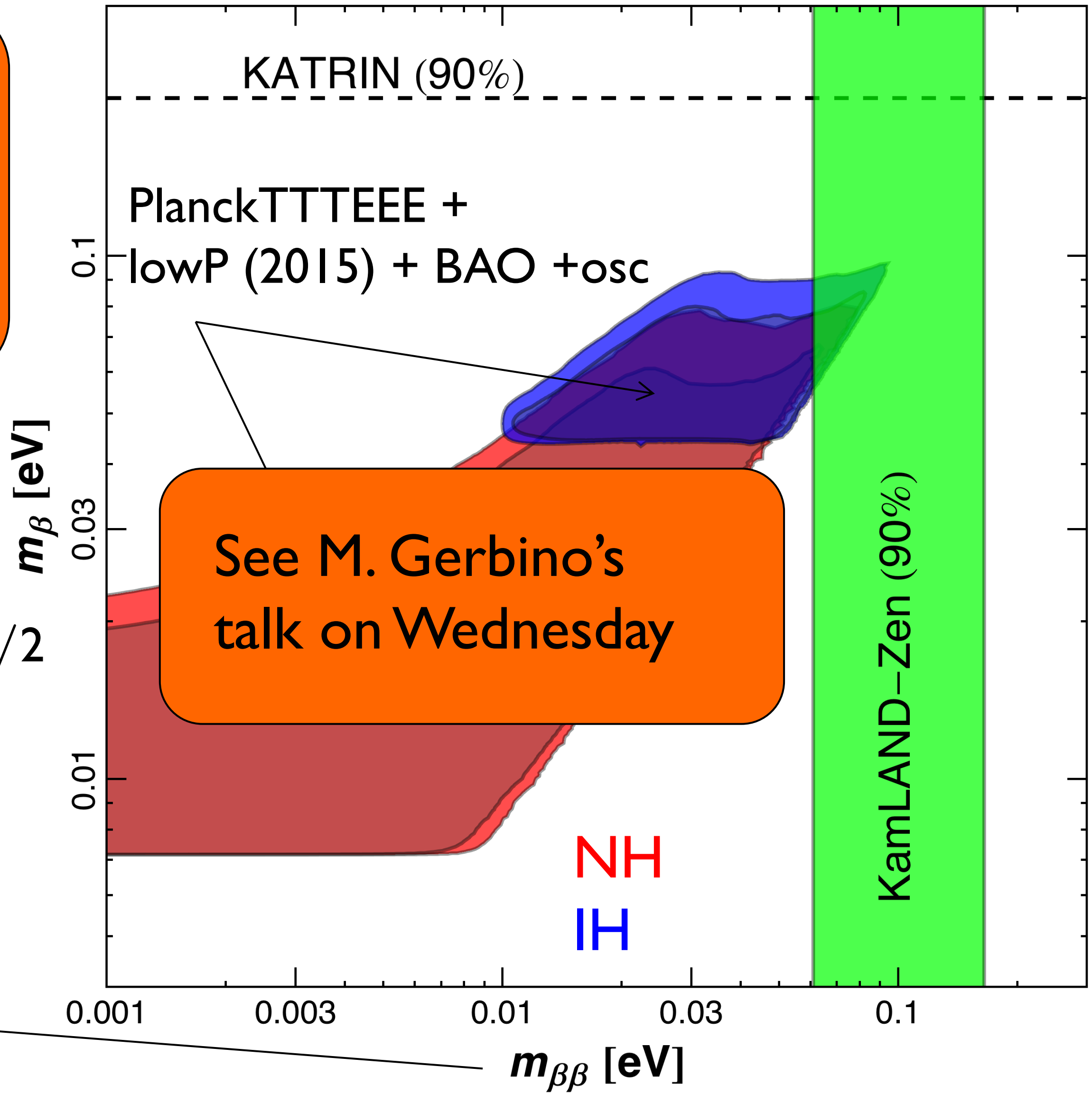

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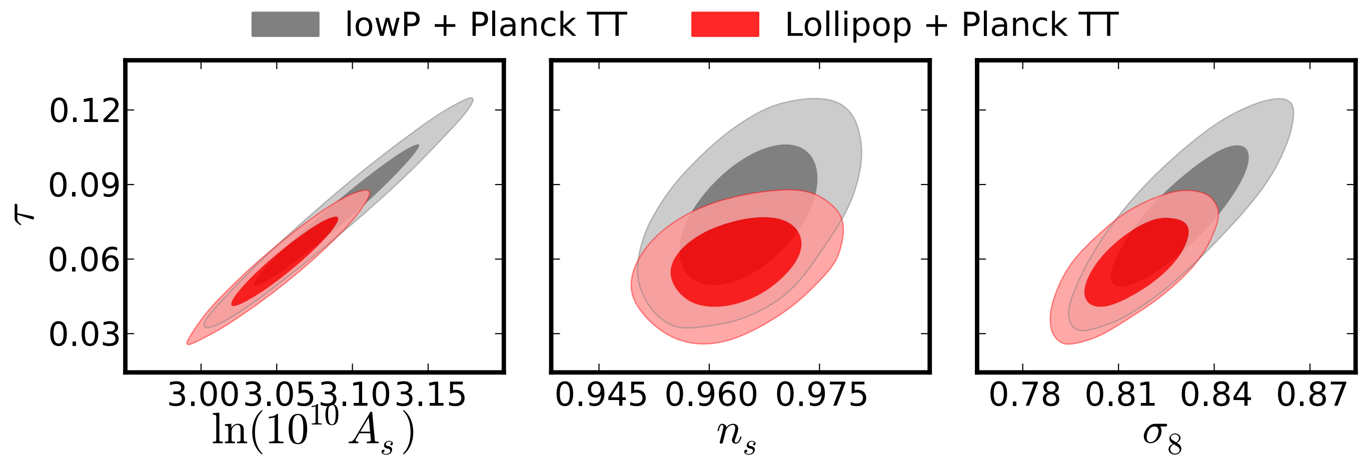
2016 POLARIZATION DATA

New large-scale polarization data has been released in May 2016 (Planck int. res. XLVI)



Smaller τ means less overall power (thus smaller fluctuations) and less lensing

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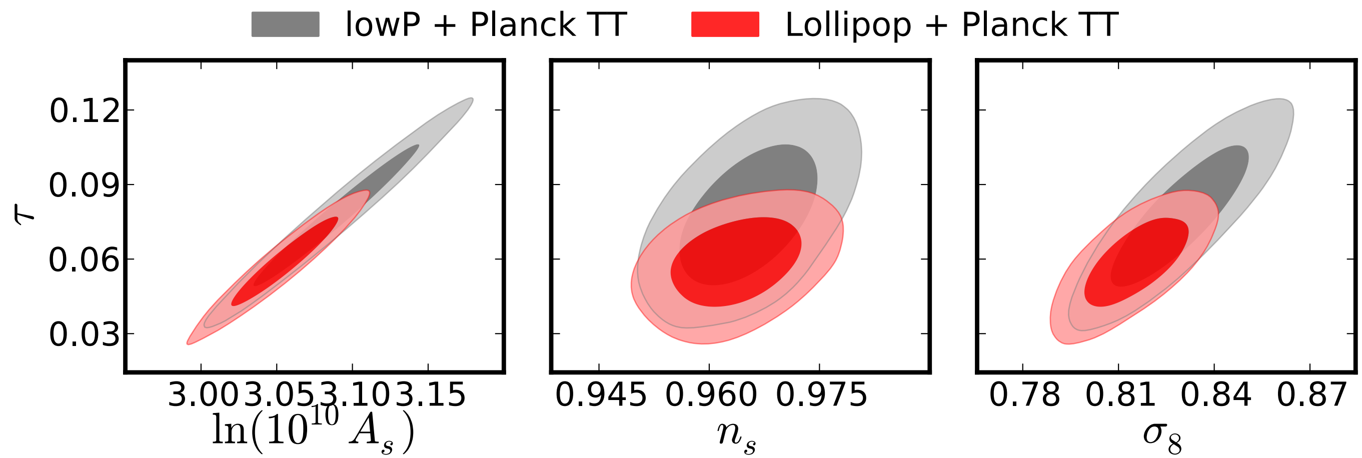
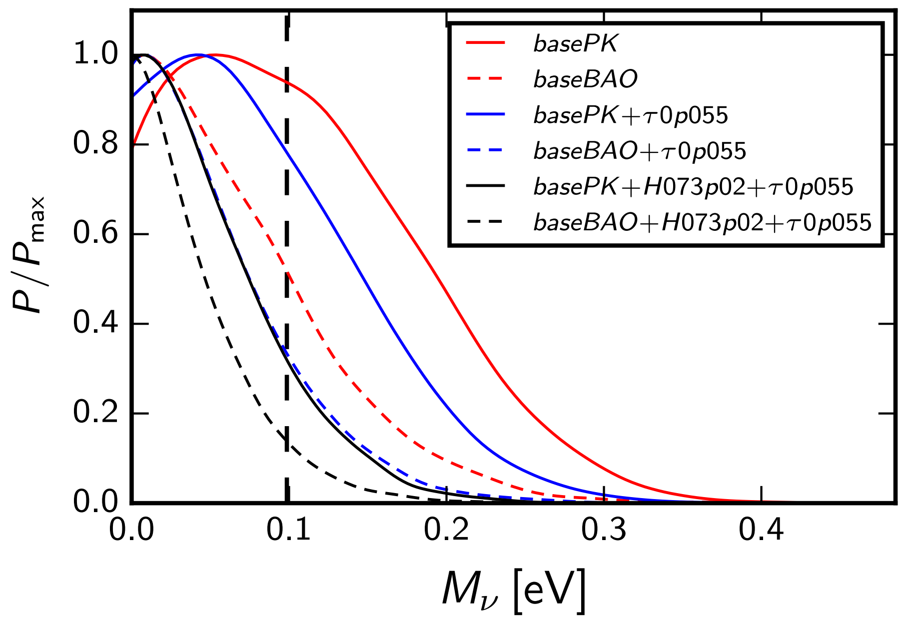


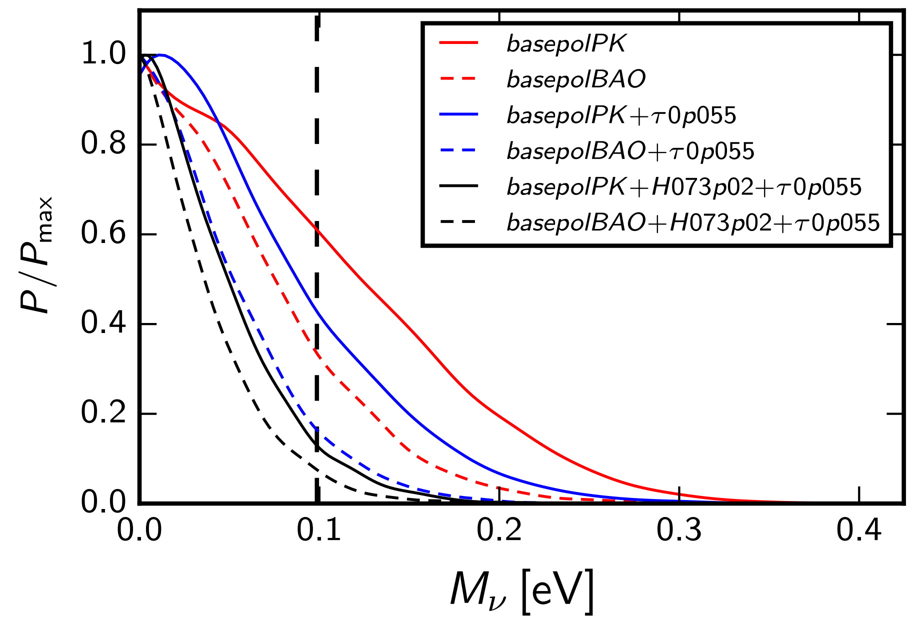
Smaller τ means less overall power (thus smaller fluctuations) and less lensing

Tighter constraints on neutrino mass:

$\Sigma m_\nu < 0.59$ eV (PlanckTT+2016lowP)

$\Sigma m_\nu < 0.34$ eV (PlanckTTTEEE +2016lowP)





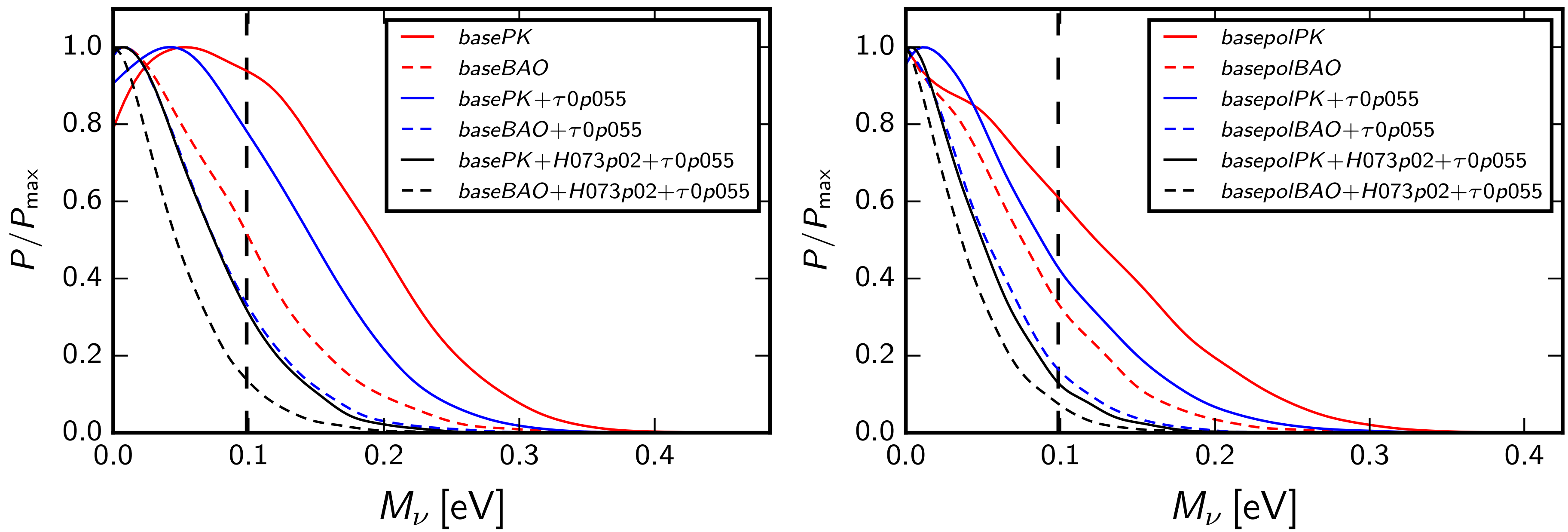
Update using latest data (limits are 95% CL)

M_ν < 0.19 eV (PlanckTT+lowP+BAO)

M_ν < 0.15 eV (PlanckTT+lowP2016+BAO)

M_ν < 0.09 eV
(PlanckTTTEEE+lowP2016+BAO+H0)

Vagnozzi et al., arXiv:1701.09172



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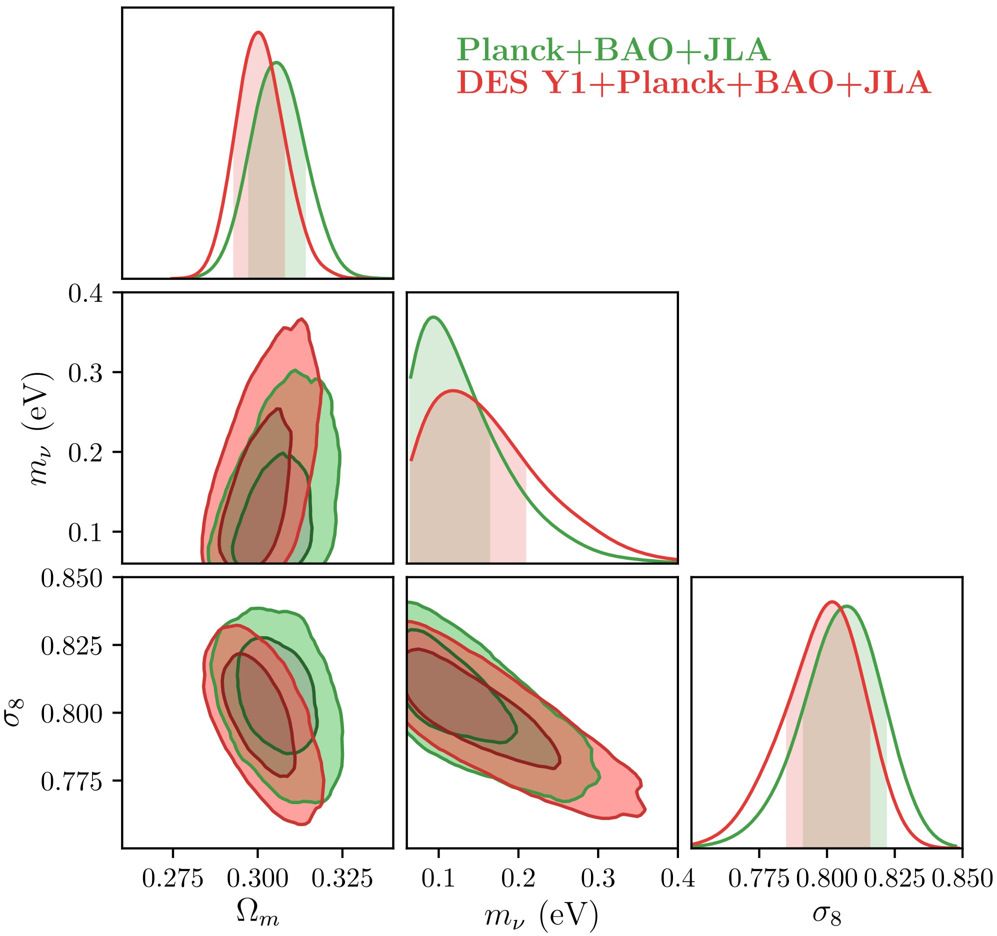
M_ν < 0.09 eV (PlanckTTTEEE+lowP2016+BAO+H0)

Normal hierarchy is favoured with odds ~3:1 for the most constraining dataset combinations

Vagnozzi et al., arXiv:1701.09172

DES Year-1 results (arXiv:1708.01530)



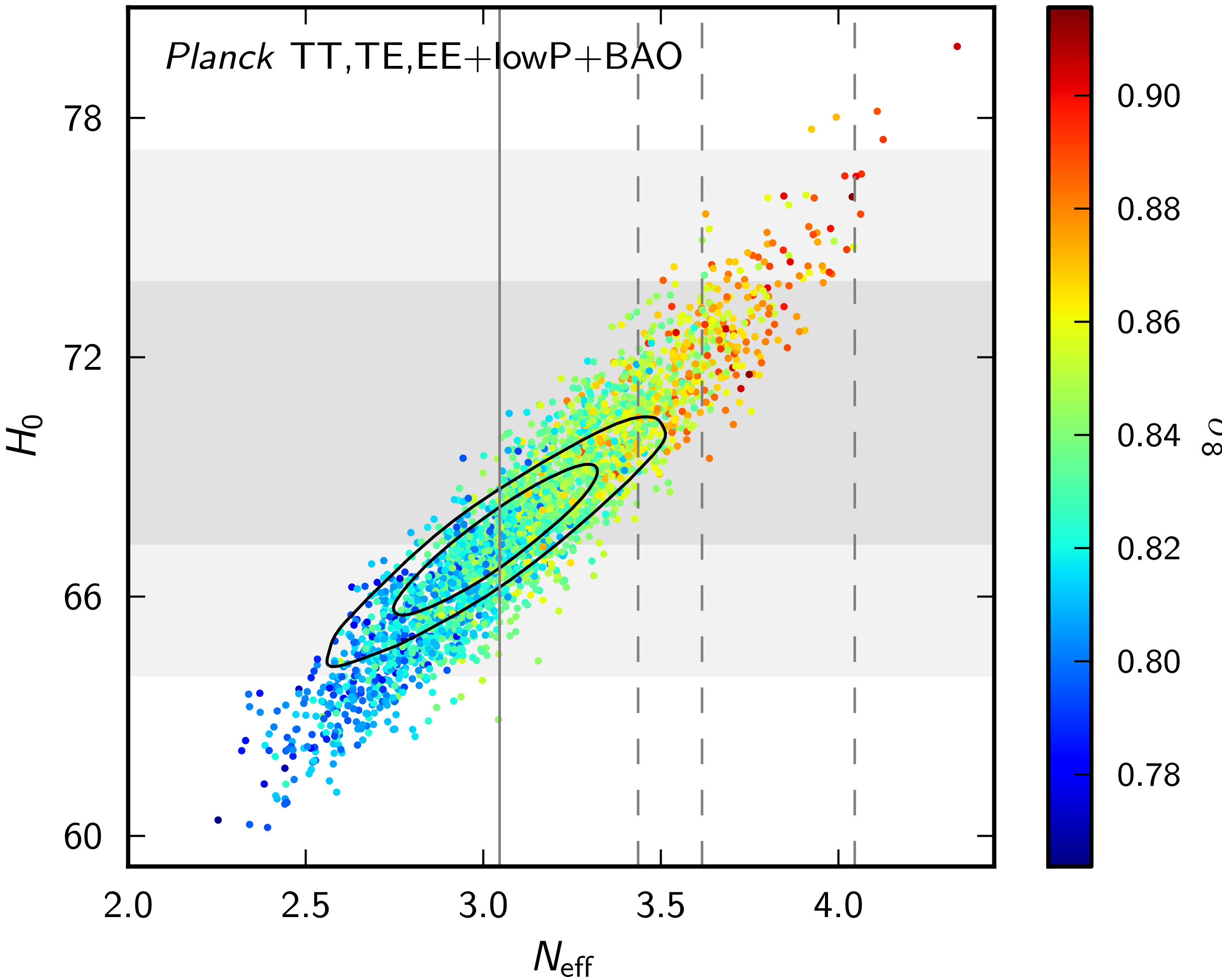
$M_\nu < 0.29$ eV
DES-Y1+Planck+JLA+BAO

Constraints are looser by ~20% when DES is added

This is related to the reduced clustering amplitude that is preferred by DES (wrt Planck)

See E. Krause's plenary talk on Wednesday

EFFECTIVE NUMBER OF NEUTRINO FAMILIES



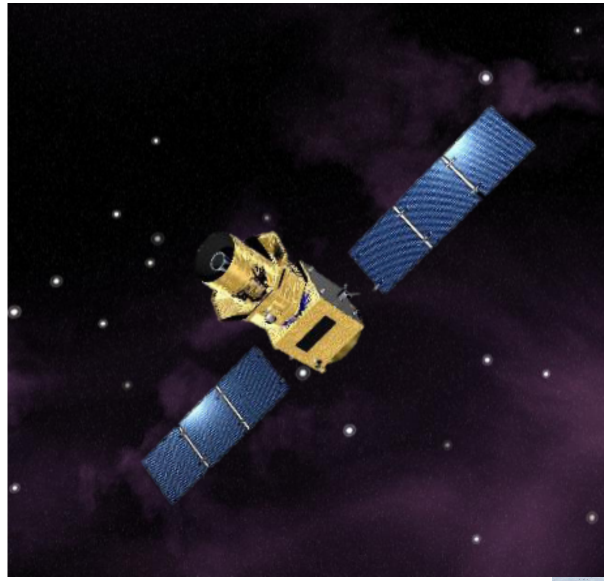
Higher values of N_{eff} can help relieve the tension with astrophysical measurements of H_0

However, they imply a larger σ_8 and thus worsen the tension with LSS probes.

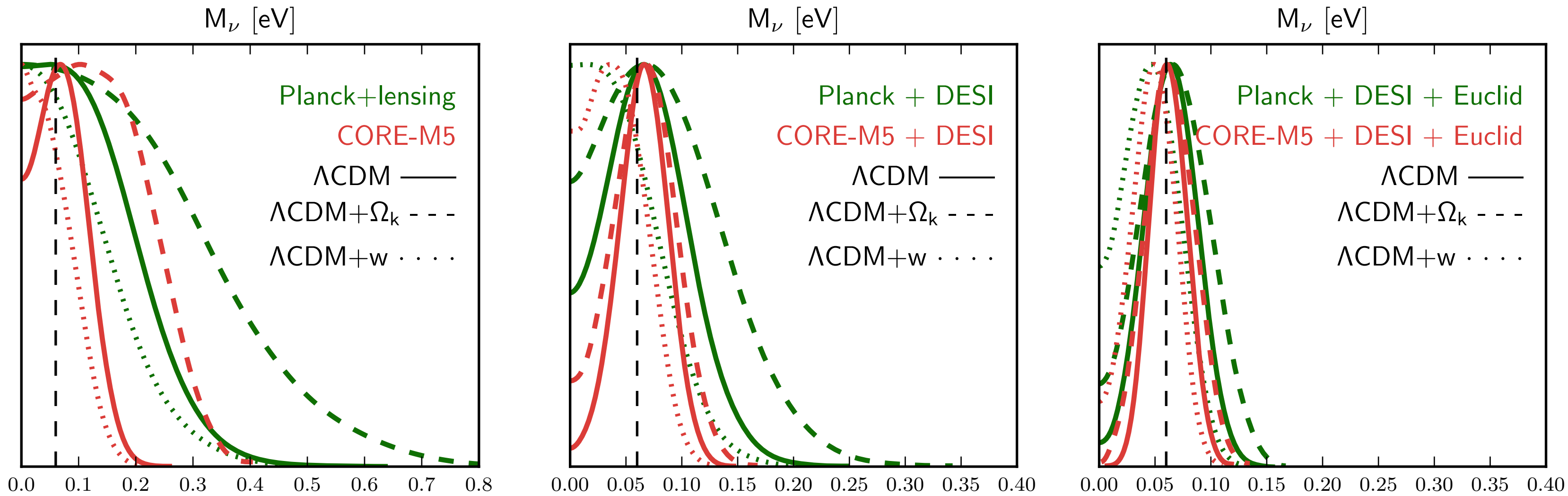
N_{eff} = 3.15 ± 0.23
(PlanckTT+lowP+BAO)

(Planck 2015 XIII)

FUTURE EXPERIMENTS



NEUTRINO MASSES FROM CORE-M5



Di Valentino et al (CORE collaboration), arXiv:1612.00021

Expected uncertainty on Σm_ν from CORE (+LSS) in ΛCDM+M_ν

$\sigma(m_\nu)$ = 0.044 (0.016) eV

Uncertainty from CORE+LSS degrades to 0.02 eV in some extended models

In combination with LSS, guarantees at least a 4σ detection

However, beware that all forecast shown here and in the following assume perfect control of systematics

THE FUTURE: GROUND-BASED EXPERIMENTS

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+\tau_e$ prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

CMB-S4 Science Book (arXiv: 1610:02743)

Future prospects

	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(N_{eff})$
CMB Stage IV	45	0.021
CMB Stage IV + DESI BAO	16	0.020
Planck + Euclid	25 - 30	-
CORE	44	0.04
CORE + LSS	15 - 20	0.04

Comparison with lab

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

(2.05 – 2.3 eV @ 95%CL)
(Troisk-Mainz)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

(0.06 – 0.16 eV @ 90%CL)
(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$

(0.2 – 0.7 eV @ 95%CL)
(Planck)

U is the neutrino mixing matrix: $|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$

COMPARISON WITH LAB

The absolute mass scale can be measured through:
(numbers on the right are forecast for future sensitivities)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

(200 meV @ 68%CL)
(Katrin)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

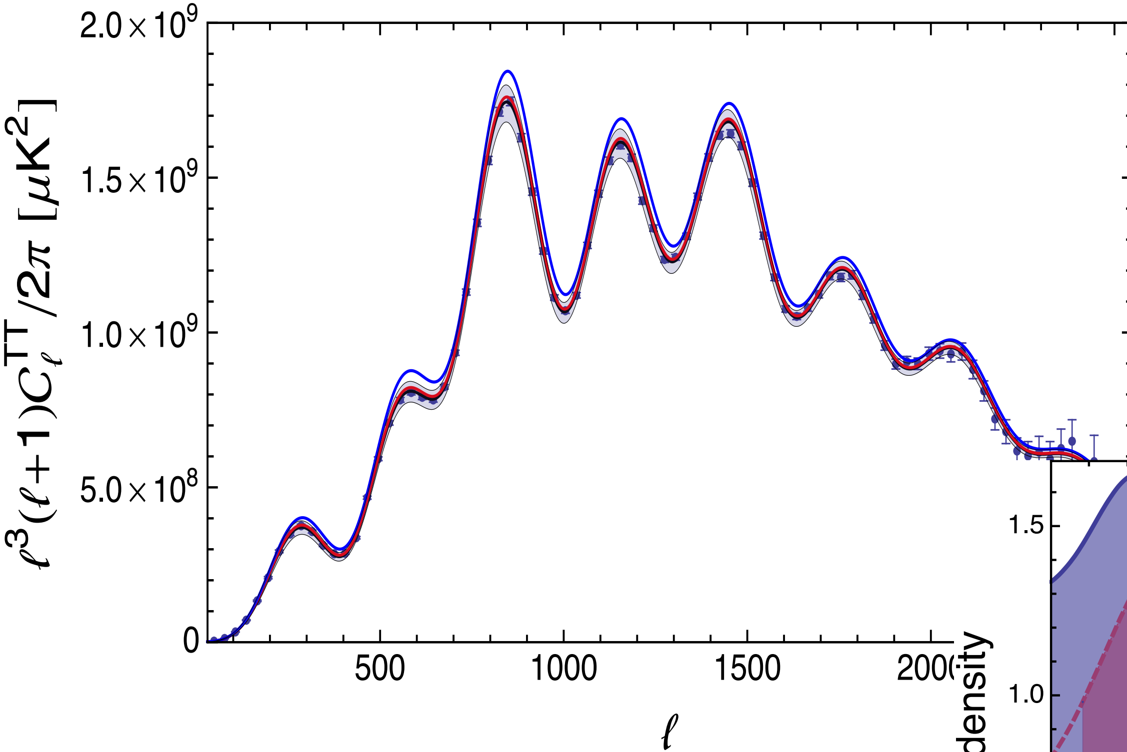
(8 – 20 meV @ 90%CL)
(nEXO, 5-year exposure)

- cosmological observations

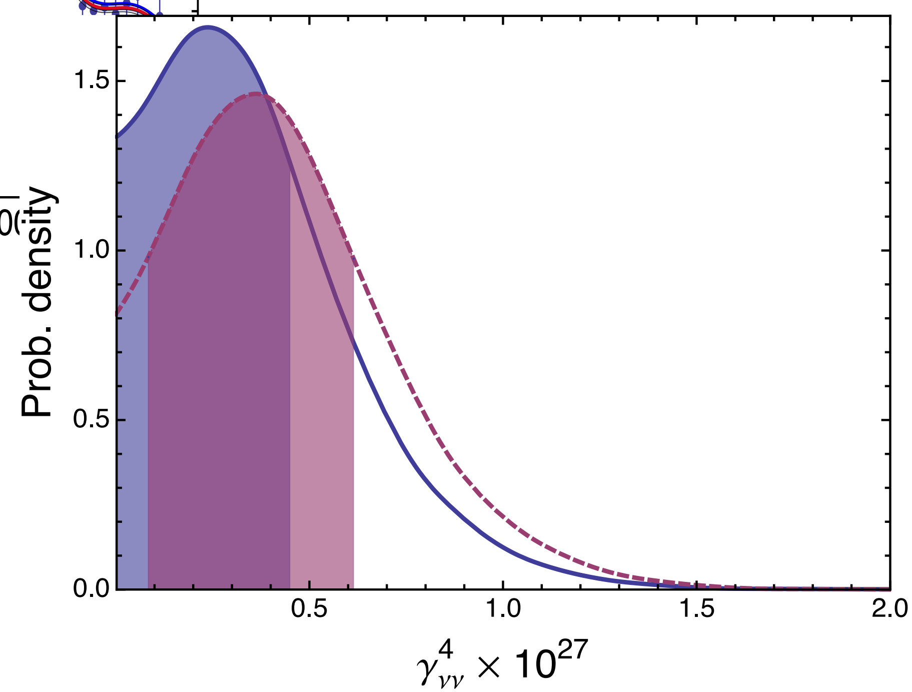
$$\sum m_\nu \equiv \sum_i m_i$$

(16 – 45 meV @ 68%CL)
(CORE, CORE+LSS)

A window on new physics: neutrino self-interactions in the CMB



See I. Oldengott's and F. Forastieri's talks!



(coupling constant)^4

SUMMARY

- Cosmological data can be used to constrain neutrino properties
- Until now, no deviation from standard expectations (i.e LCDM) has been observed
- Planck can constrain neutrino masses mainly thanks to the lensing of the power spectrum. From PlanckTT+lowP: $\Sigma m_\nu < 0.72$ eV
- Geometrical probes (e.g. BAO) can greatly improve the constraints: PlanckTT+lowP+BAO gives $\Sigma m_\nu < 0.21$ eV
- Cosmological observations, combined with information from oscillation experiments, also give tight constraints on m_β and $m_{\beta\beta}$
- Present data show a weak (odds 3:2) preference for normal hierarchy – this is mainly driven by the preference for small neutrino mass
- Planck is compatible with 3 neutrino families; $N_{eff} = 4$ is excluded at between 3 and 5 sigma, depending on the dataset

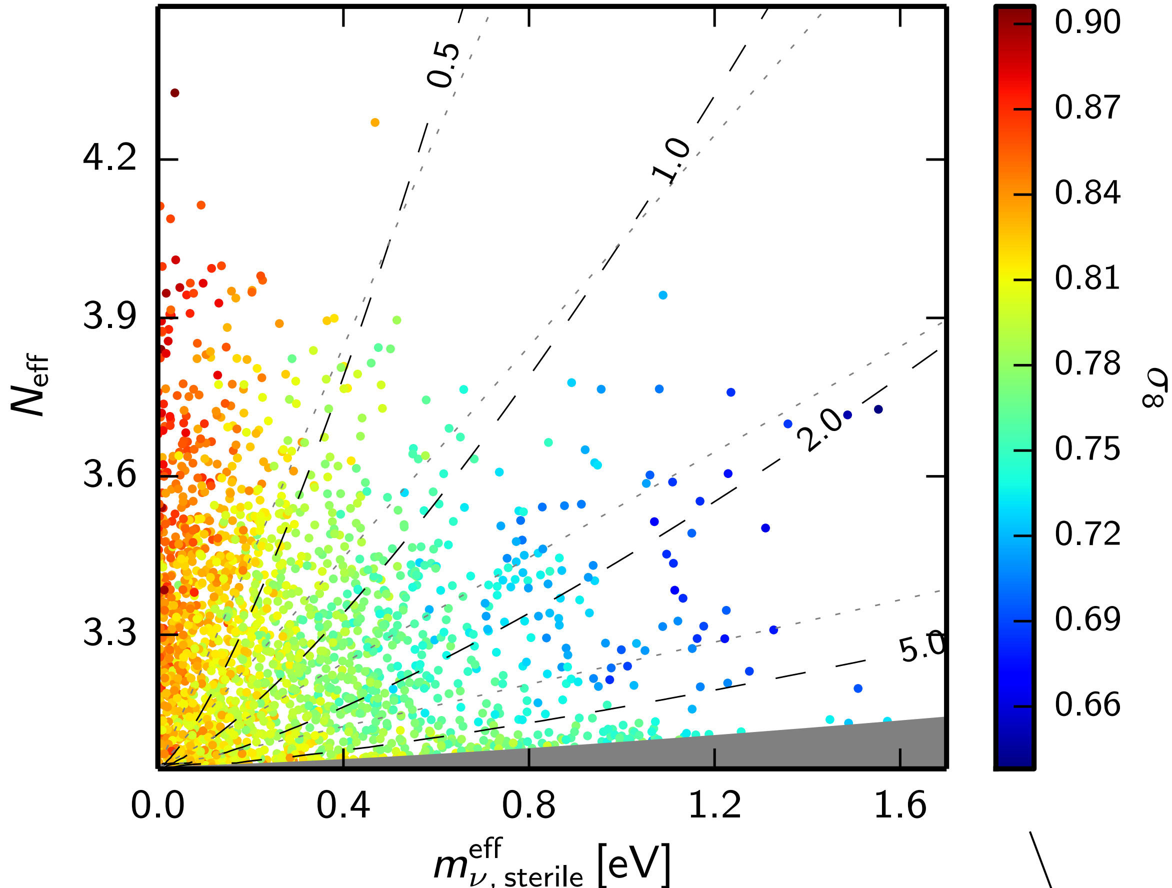
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

BACKUP SLIDES

PLANCK CONSTRAINTS ON MASSIVE STERILE NEUTRINOS

Early energy density



Present-day energy density

Planck TT+lowP+lensing+BAO

$N_{eff} < 3.7$

$m^{eff}{}_{sterile} < 0.52$ eV

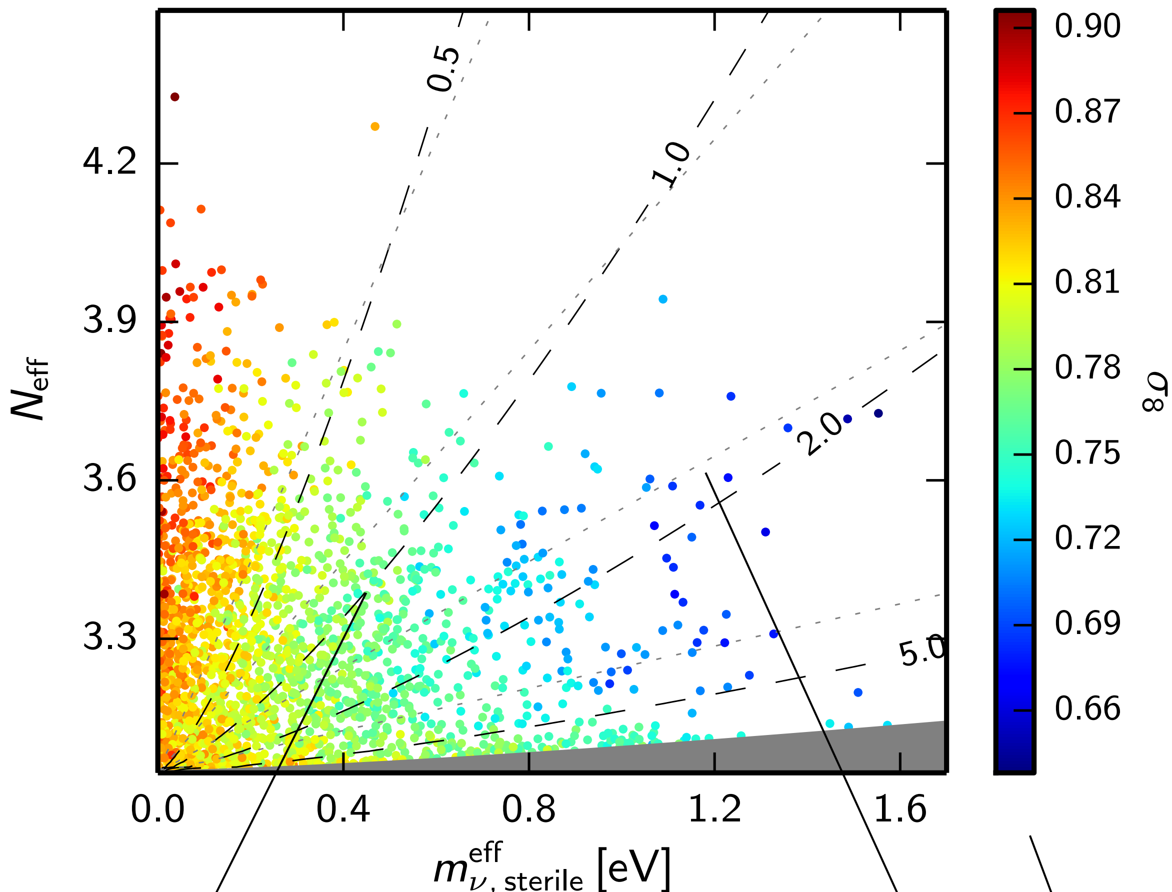
One sterile eigenstate; total active mass fixed to 0.06 eV

Amplitude of density fluctuations

Planck 2015 XVI

PLANCK CONSTRAINTS ON MASSIVE STERILE NEUTRINOS

Early energy density



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Amplitude of density fluctuations

Lines of constant m_s (thermal)

Lines of constant m_s (DW)

Planck 2015 XVI

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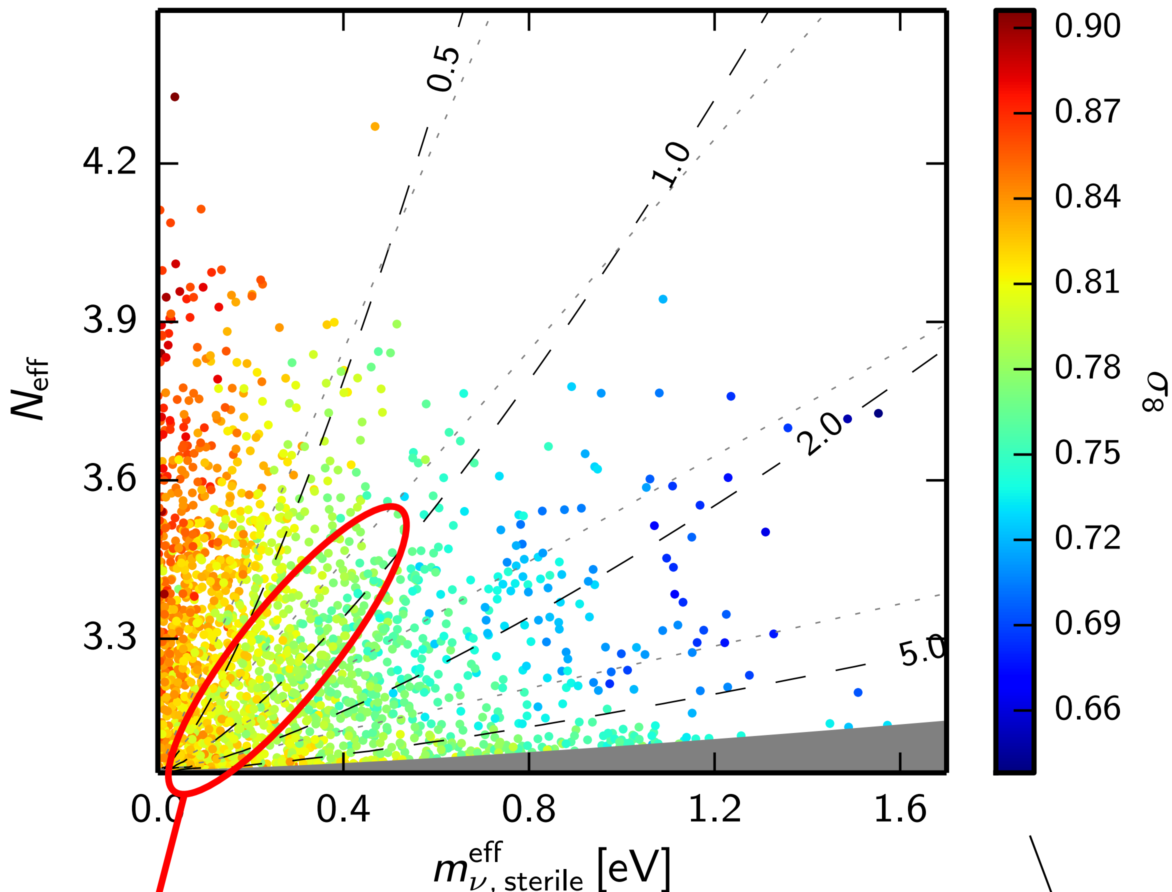
Early energy density



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$N_{eff} < 3.7$

$m^{eff}{}_{sterile} < 0.52$ eV

One sterile eigenstate; total active mass fixed to 0.06 eV

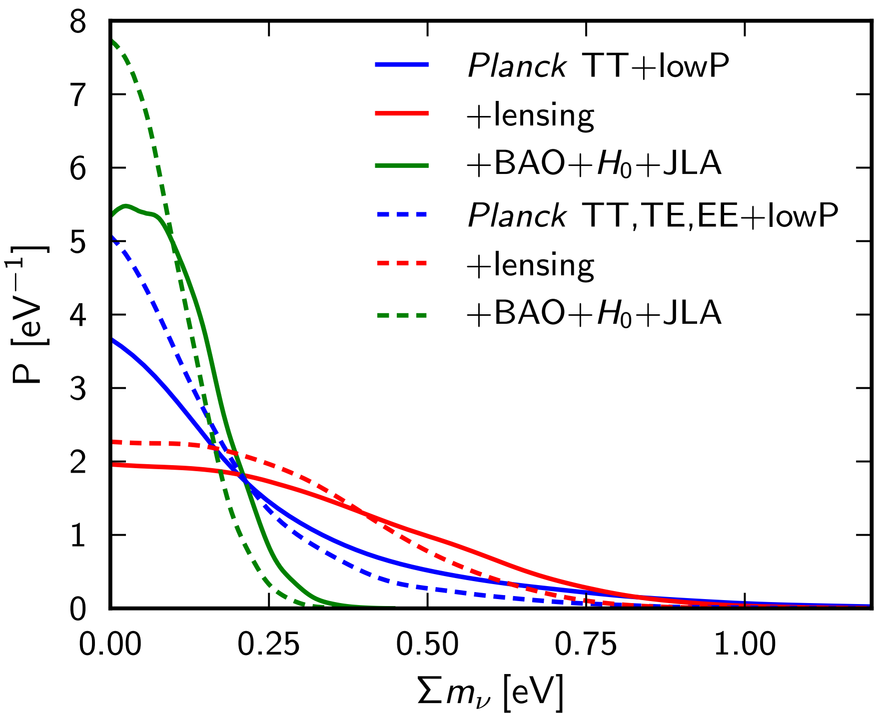
Amplitude of density fluctuations

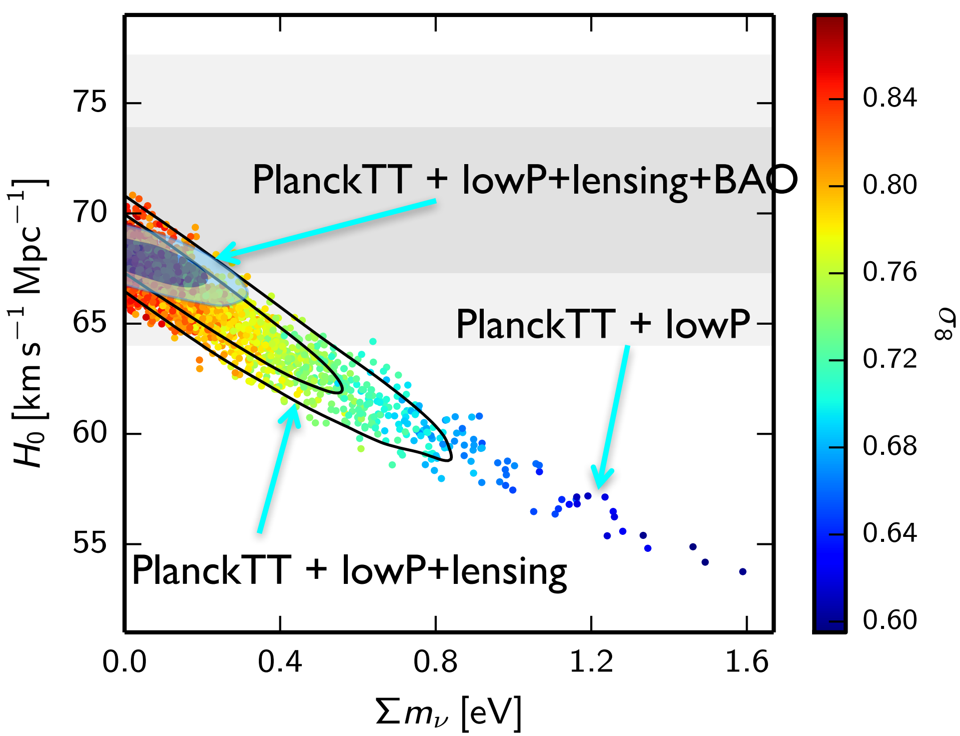
$m_s \sim 1$ eV is allowed if either $T_s < T_\nu$ or if distribution is a gray body

Planck 2015 XVI

HOW HEAVY?

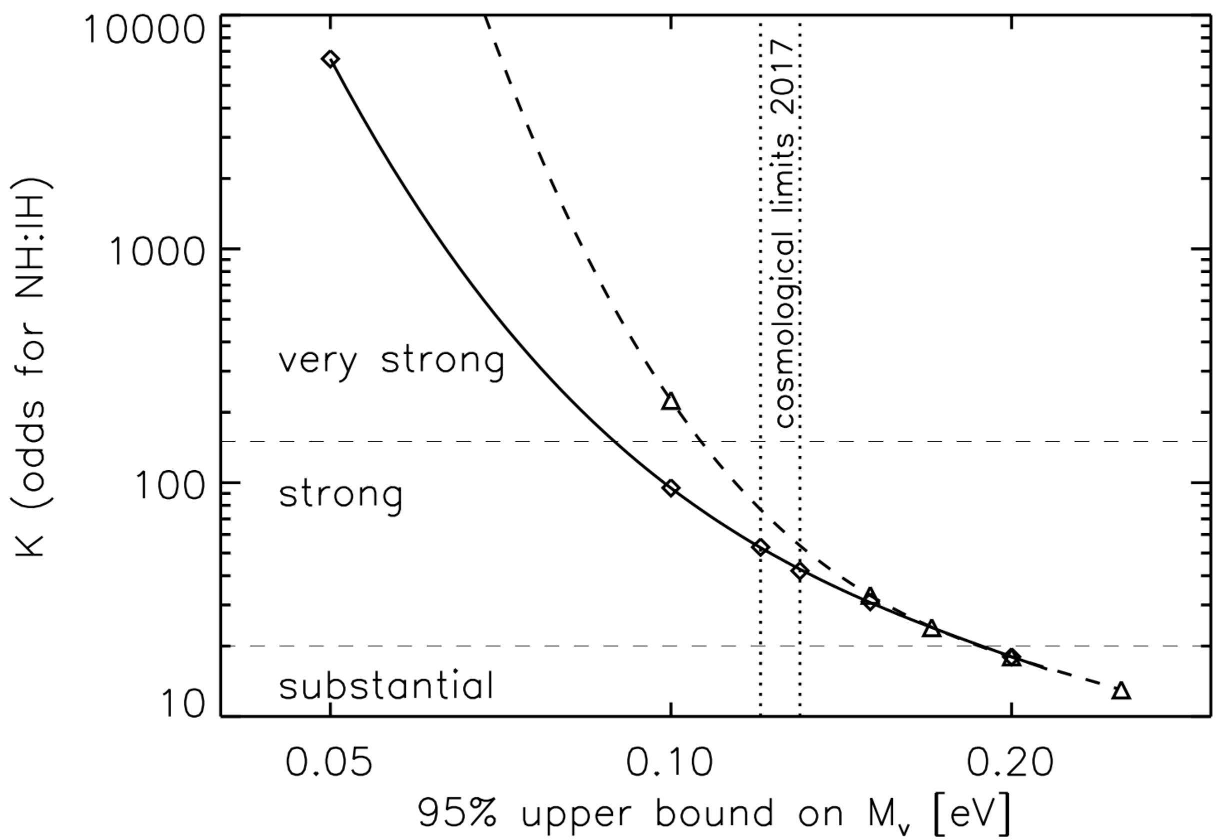
95% constraints on total mass	*PlanckTT*	*PlanckTTTEEE*
+lowP	<0.72 eV	<0.49 eV
+lowP+lensing	<0.68 eV	<0.59 eV
+lowP+BAO	<0.21 eV	<0.17 eV
+lowP+ext	<0.20 eV	<0.15 eV
+lowP+lensing+ext	<0.23 eV	<0.19 eV





(Planck 2015 XIII)

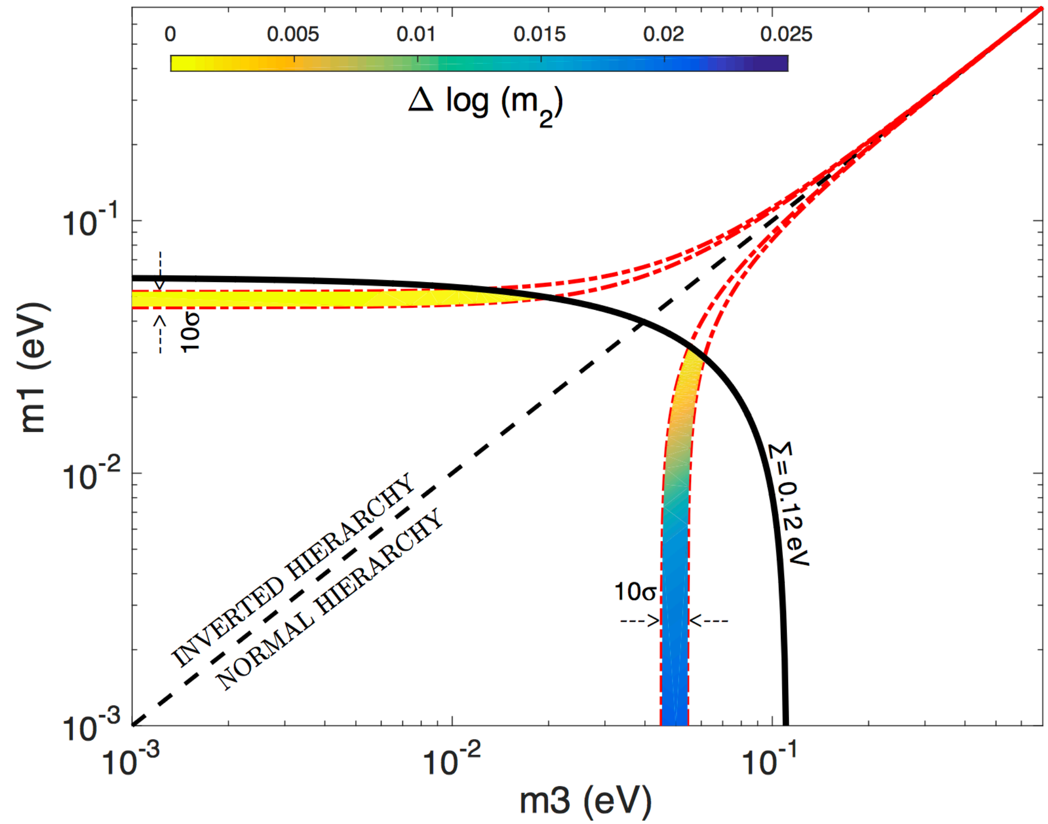
Recently a paper from Simpson et al. claimed ”strong” evidence in favour of NH (odds of 42:1) from cosmological data.
(Simpson et al., arXiv:1703.03425)



The results in the paper are based on the choice of a gaussian prior over $\log(m_i)$, that is further marginalized over. This is motivated as "less informative”, as it assigns equal probabilities to different orders of magnitude in the masses.

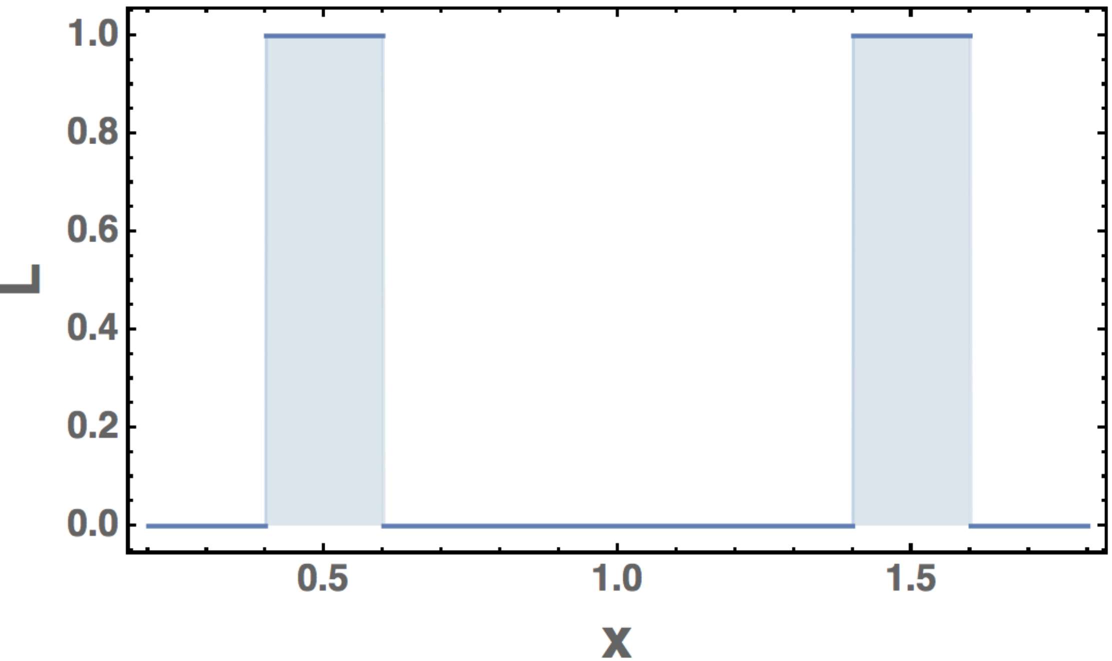
The fact that NH is favored by a log prior is perfectly natural in the framework of Bayesian statistics

Oscillation experiments single out regions in the (m_1, m_2, m_3) plane

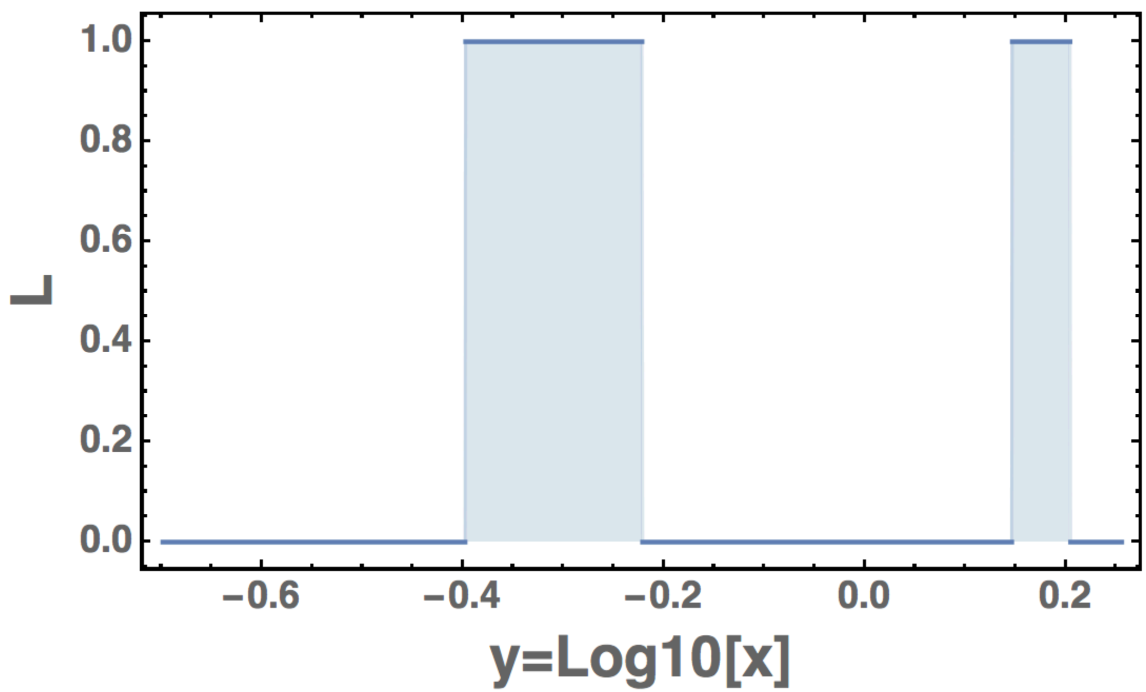


The regions singled out in NH or IH are different BUT they occupy the same volume in (m_1, m_2, m_3)

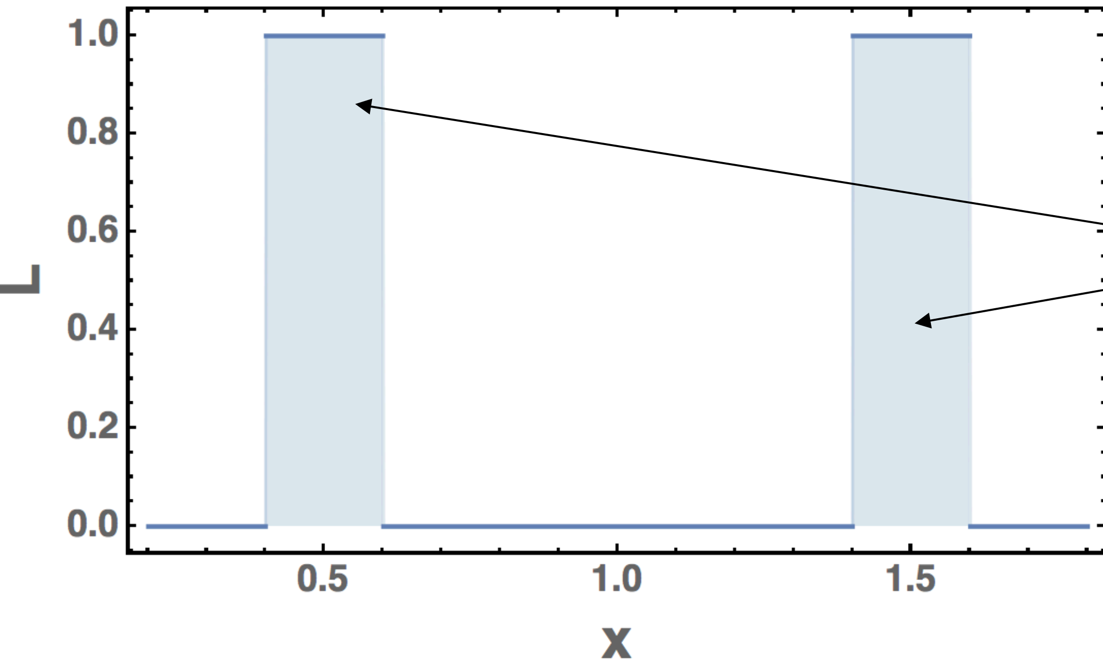
They do not occupy the same volume in $\mathrm{Log}[(m_1, m_2, m_3)]$


1.0
0.8
0.6
0.4
0.2
0.0
L
0.5
1.0
1.5
x

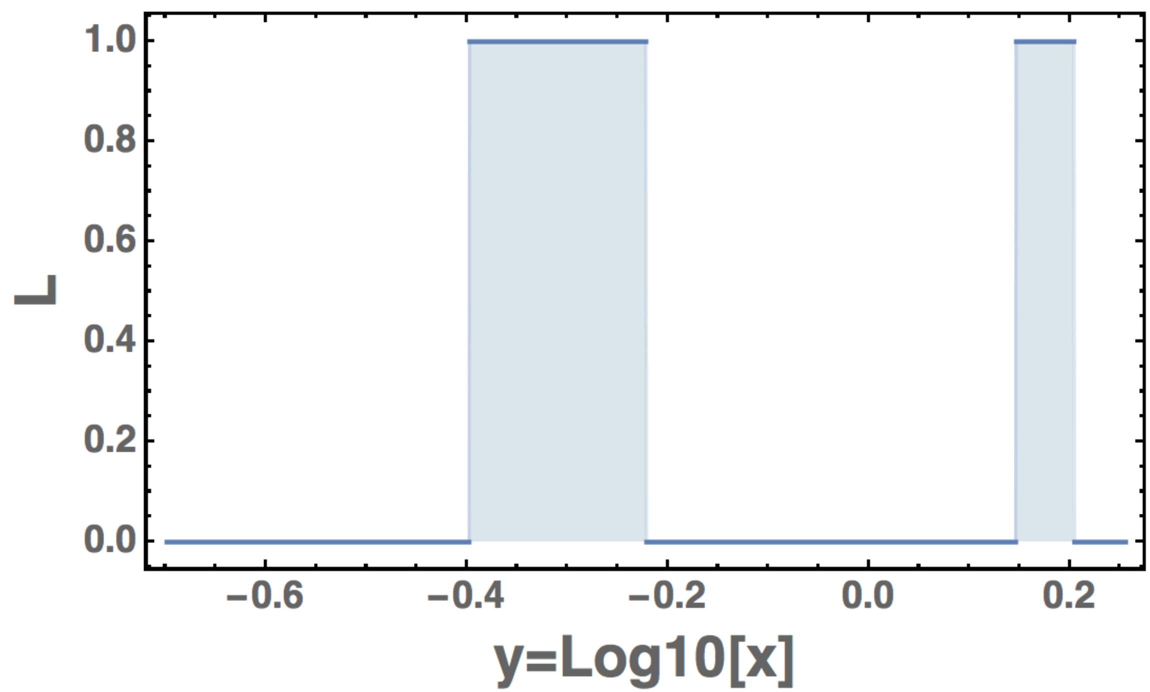
|x - 1| = 0.5 +/- 0.1


1.0
0.8
0.6
0.4
0.2
0.0
L
−0.6
−0.4
−0.2
0.0
0.2
y=Log10[x]

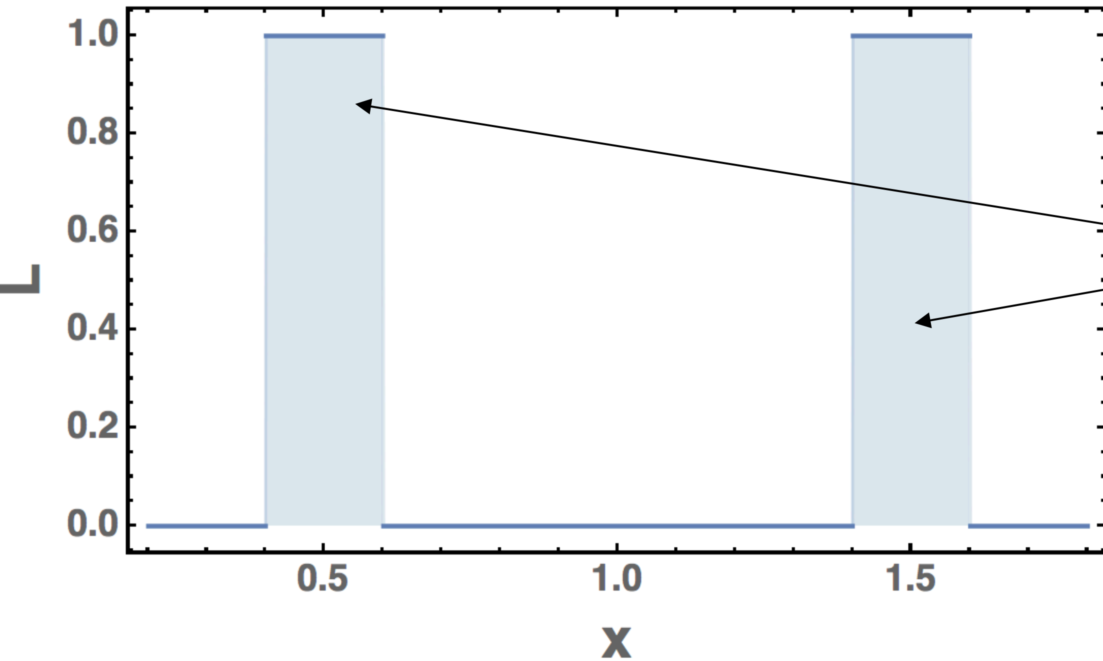
|x - 1| = 0.5 +/- 0.1



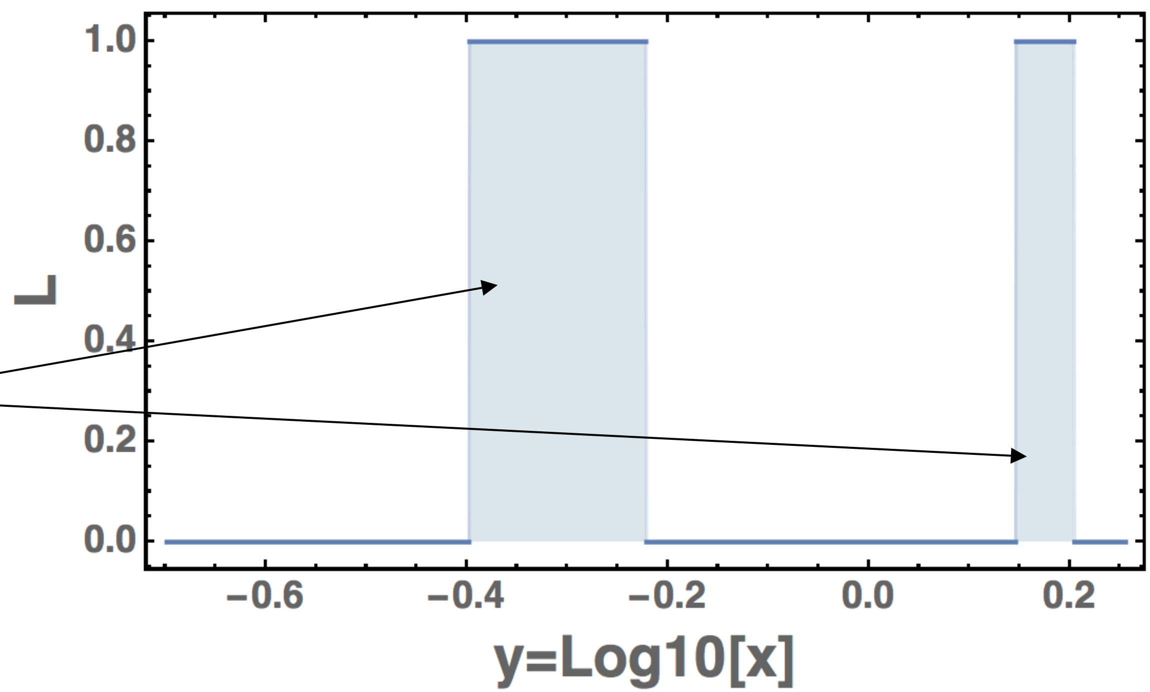
The two models (x-1 > 0 vs x-1<0) occupy the same volume in parameter space



|x - 1| = 0.5 +/- 0.1



The two models (x-1 > 0 vs x-1<0) occupy the same volume in parameter space



Here, two models (x-1 > 0 vs x-1<0) occupy different volumes in parameter space (we would prefer the x-1<0 hypothesis)