Cosmological constraints on neutrino masses

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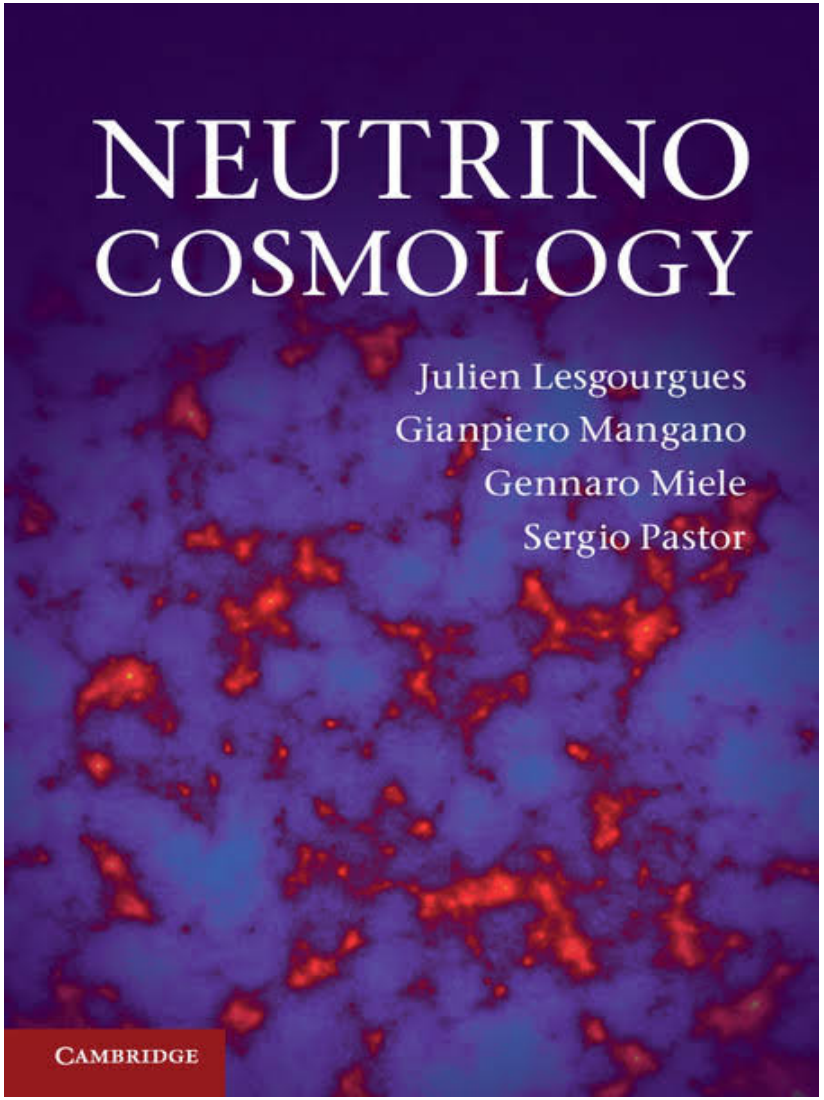
Plan of Talk

- Neutrinos in cosmology
- Planck 2015 results
- Tensions in the standard model
  - combining with large scale structure probes
- Future probes

Plan of Talk

- Neutrinos in cosmology
- Planck 2015 results
  - safe limit from CMB alone
- Tensions in the standard model
  - combining with large scale structure probes
  - complicated story
- Future probes
  - very bright future

Neutrino Cosmology : a good reference



Standard Cosmological Model

GEOMETRY & GRAVITY

$$ds^2 = dt^2 - a^2(dr^2 + r^2 d\Omega^2)$$

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

$$\dot{\rho} = -3H(\rho + P)$$

MATTER CONTENT

$$\rho = \rho_{\rm r} + \rho_{\rm b} + \rho_{\rm c} + \rho_d$$

$$P = \frac{1}{3}\rho_{\rm r} - \rho_{\rm d}$$

COLD DM

BARYONS

RAD

COSMOLOGICAL CONSTANT

INITIAL PERTURBATIONS

$$P_i(k) = A_{\rm S}\left(\frac{k}{k_{\rm p}}\right)^{n_{\rm S}}$$

ASSUMED SCALAR
CURVATURE PERTS

7 PARAMETERS

H_0	HUBBLE'S CONSTANT
$\rho_{\rm r}, \rho_{\rm b}, \rho_{\rm c}$	MATTER DENSITIES TODAY
$A_{\rm S}, n_{\rm S}$	INITIAL PERTURBATIONS
τ	OPTICAL DEPTH

Power spectrum norm : σ_8

- R.M.S. density contrast in R=8h^{-1}Mpc

$$\sigma_R^2 = 4\pi \int \frac{dk}{k} k^3 P(k) [W(kR)]^2$$

Filter function for a sphere of radius R

- Value ~1 – in fact approx 0.8

- Related to A_S

  - plus other cosmological parameters relating large and small scales

Active neutrinos : textbook stuff

- Decoupling

$$T_{\mathrm{dec}} \approx 1\,\mathrm{MeV}$$

- Fermi-Dirac Temperature

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB}} = 1.945\,\mathrm{K} = 1.676 \times 10^{-4}\,\mathrm{eV}/k_{\mathrm{B}}$$

- Number Density for each flavour

$$n_\nu = n_{\bar{\nu}} \approx 56\,\mathrm{cm}^{-3}$$

- Contribution to the energy density budget

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94.1\,\mathrm{eV}}$$

Impact on cosmological observables

- One parameter : $\sum m_\nu$

Sensitivity to individual masses is limited

- Contribution to the energy density

→ Changes the time of equal-matter radiation

- Evolution of perturbations

→ Neutrinos are "hot" and therefore free stream

→ They do not fall into potential wells until they become non-relativistic

Sterile Neutrinos

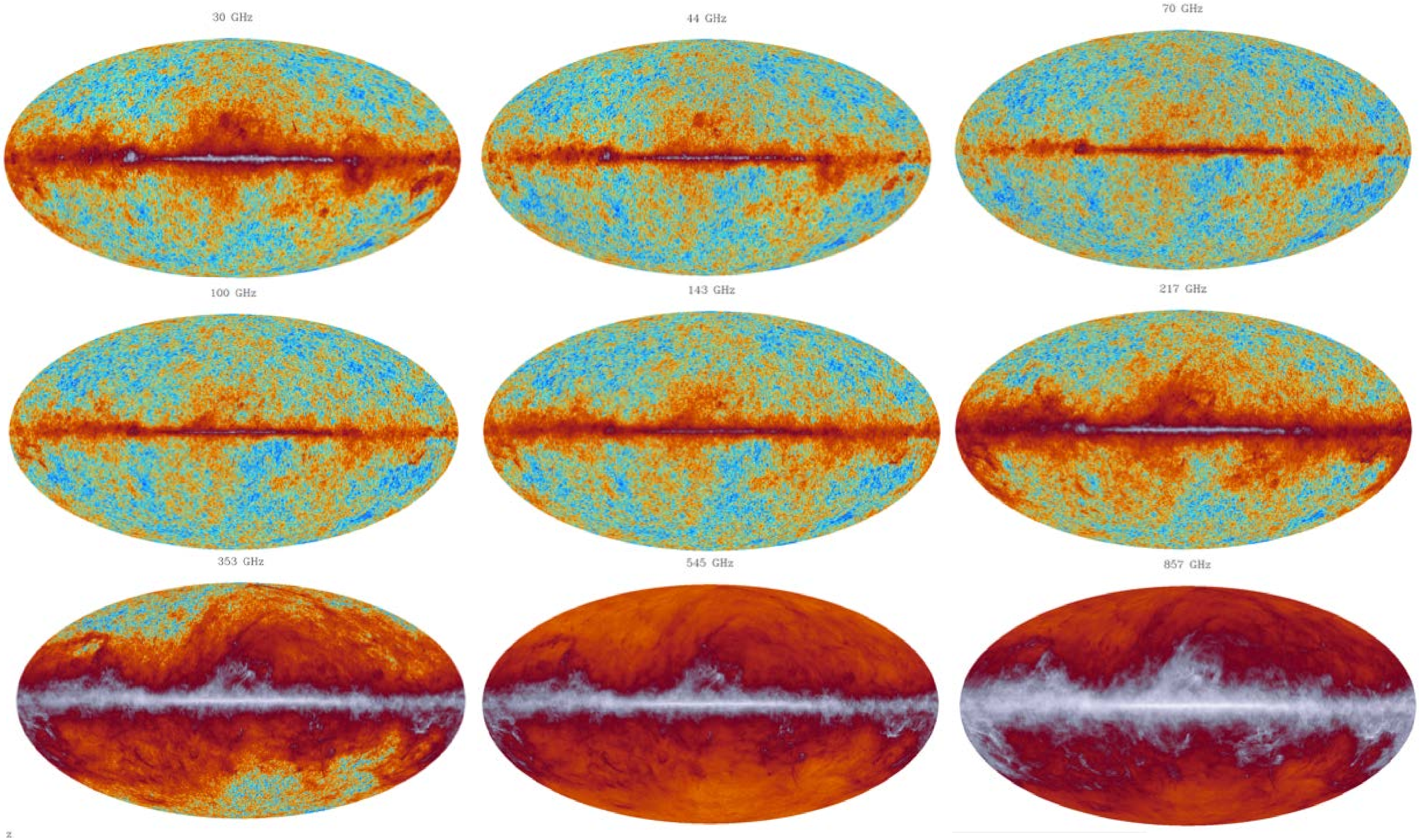
- Effects governed by two parameters
  - N_{eff} and m_{ν}

- N_{eff}>3 - effective number of neutrinos
  - not necessarily an integer: partial thermalization
  - governs contribution to energy density

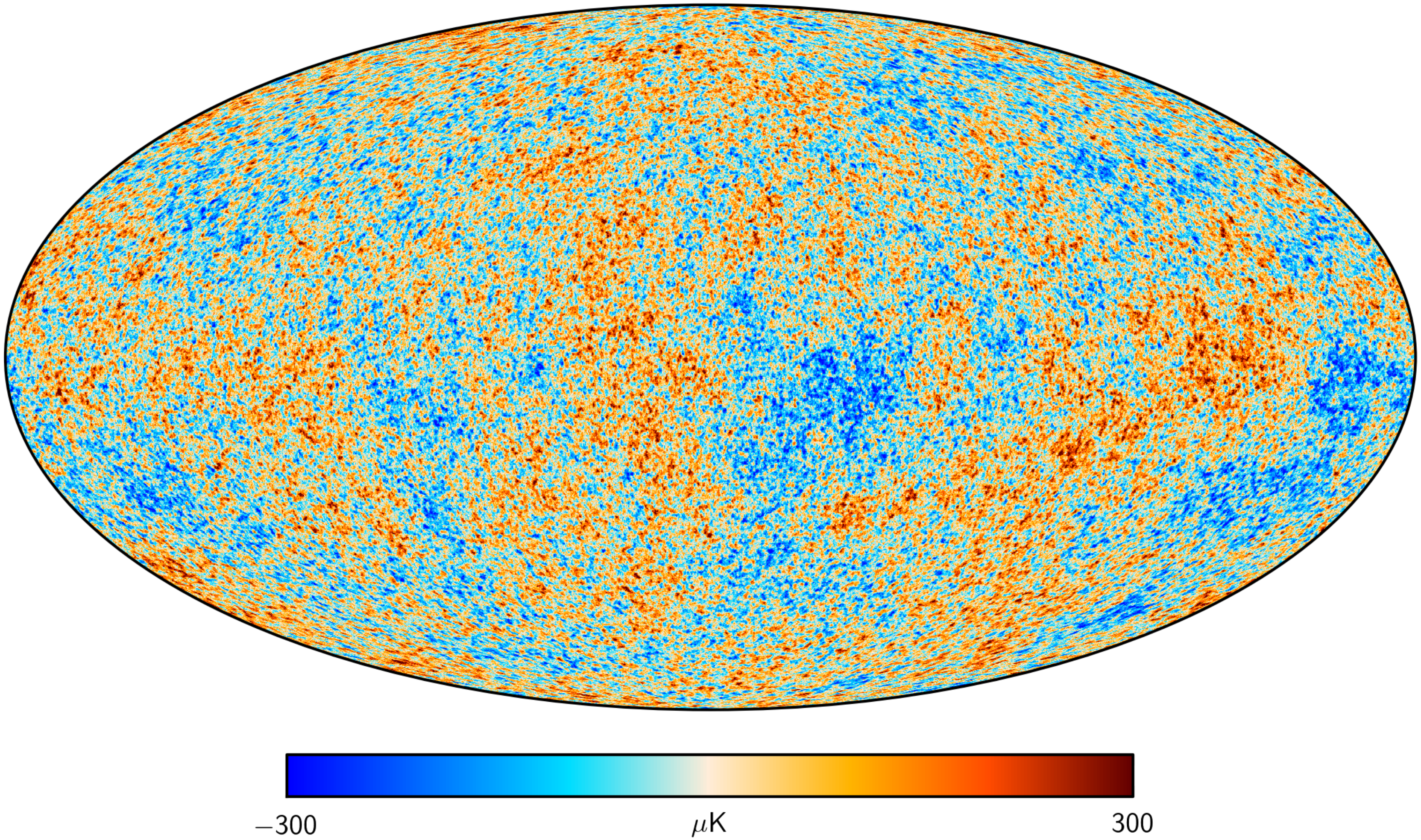
- M_{ν}
  - impacts perturbations via rel v non-rel

- Specific models link the two parameters

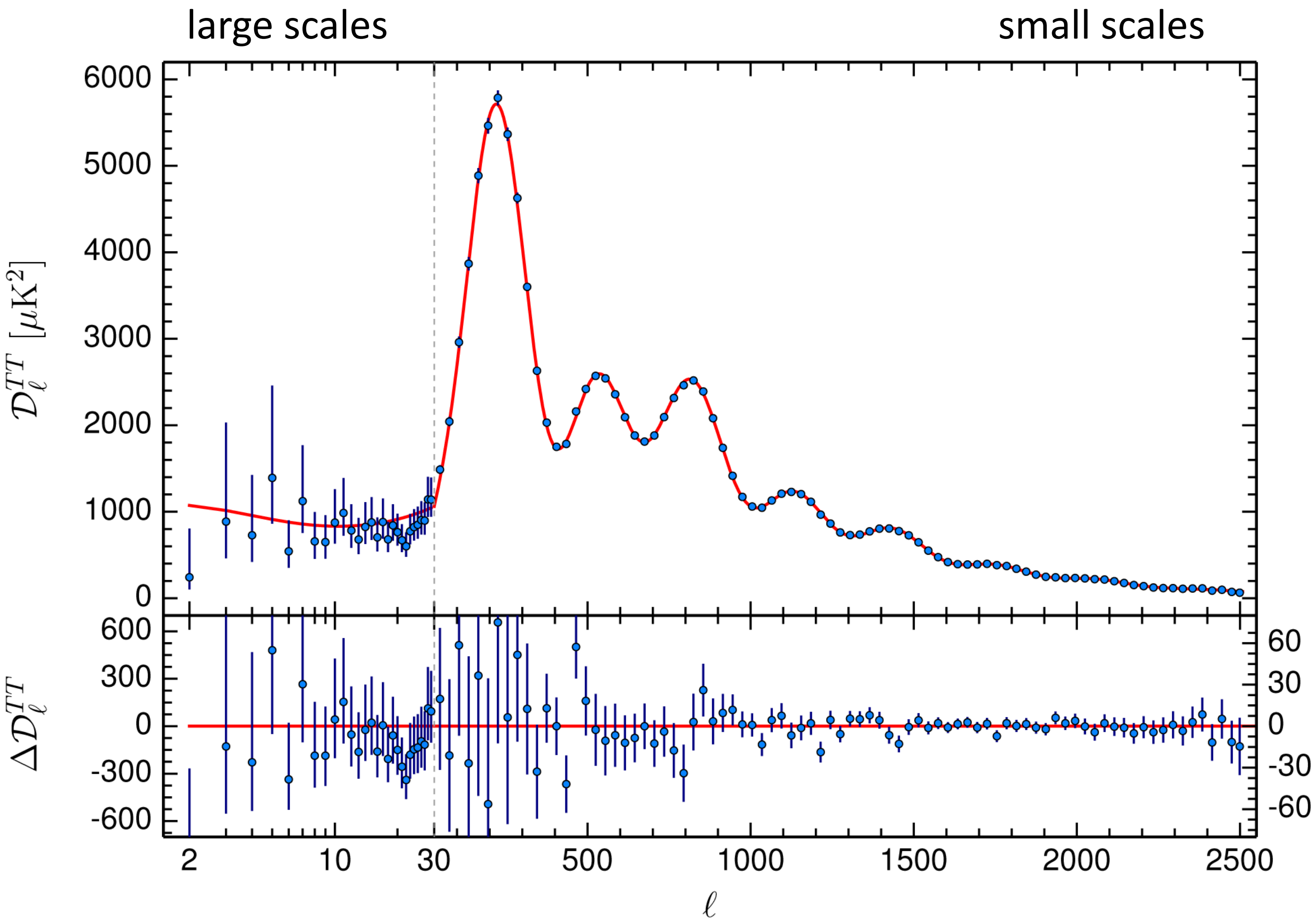
Observables : CMB



Observables : CMB



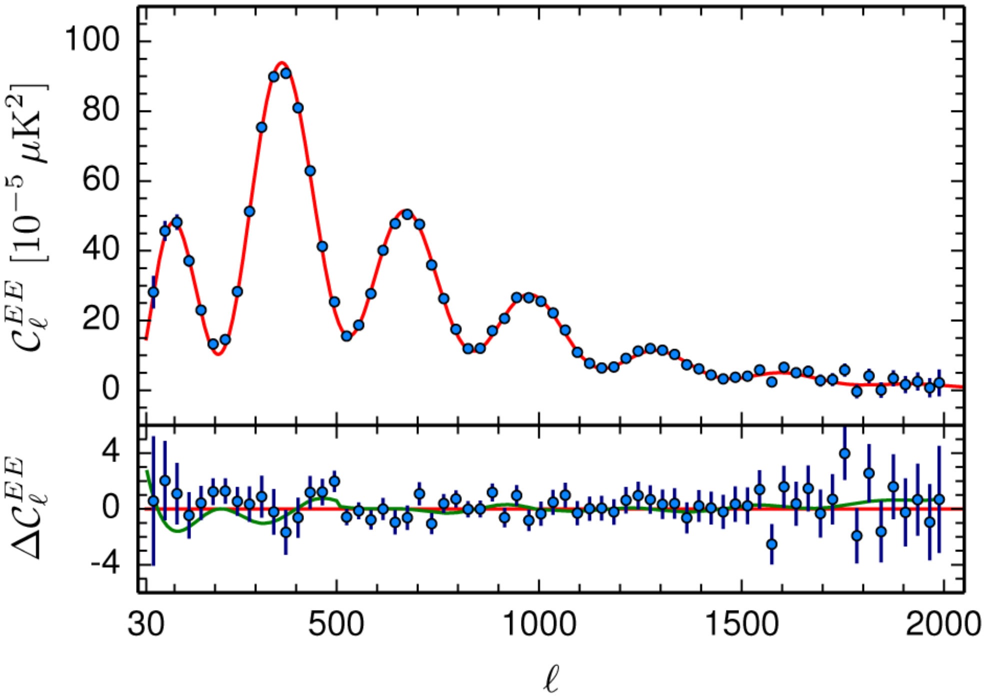
Observables : CMB



Temperature power spectrum

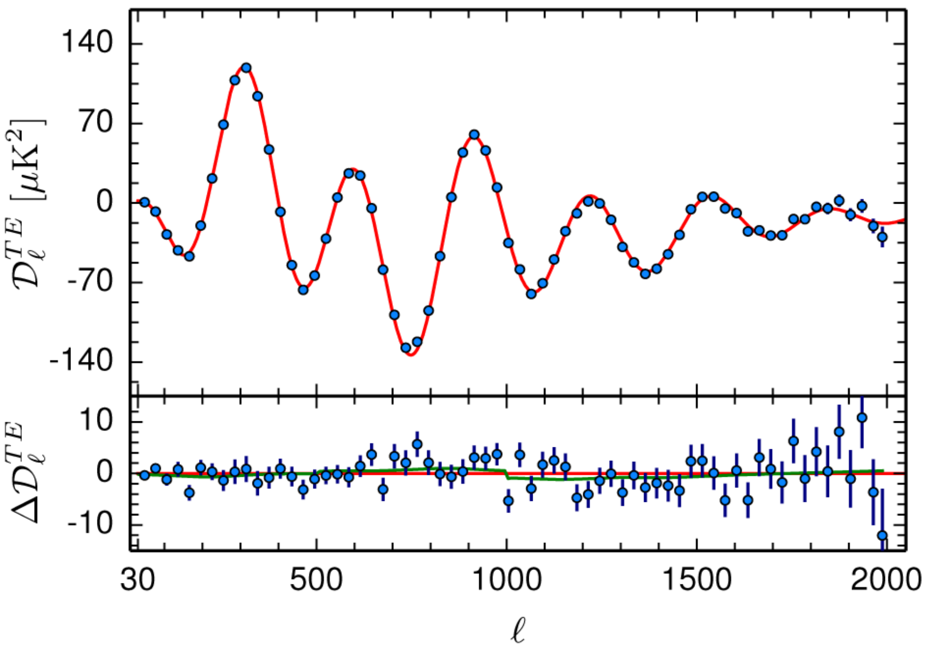
– where the most reliable constraints come from

Observables : CMB

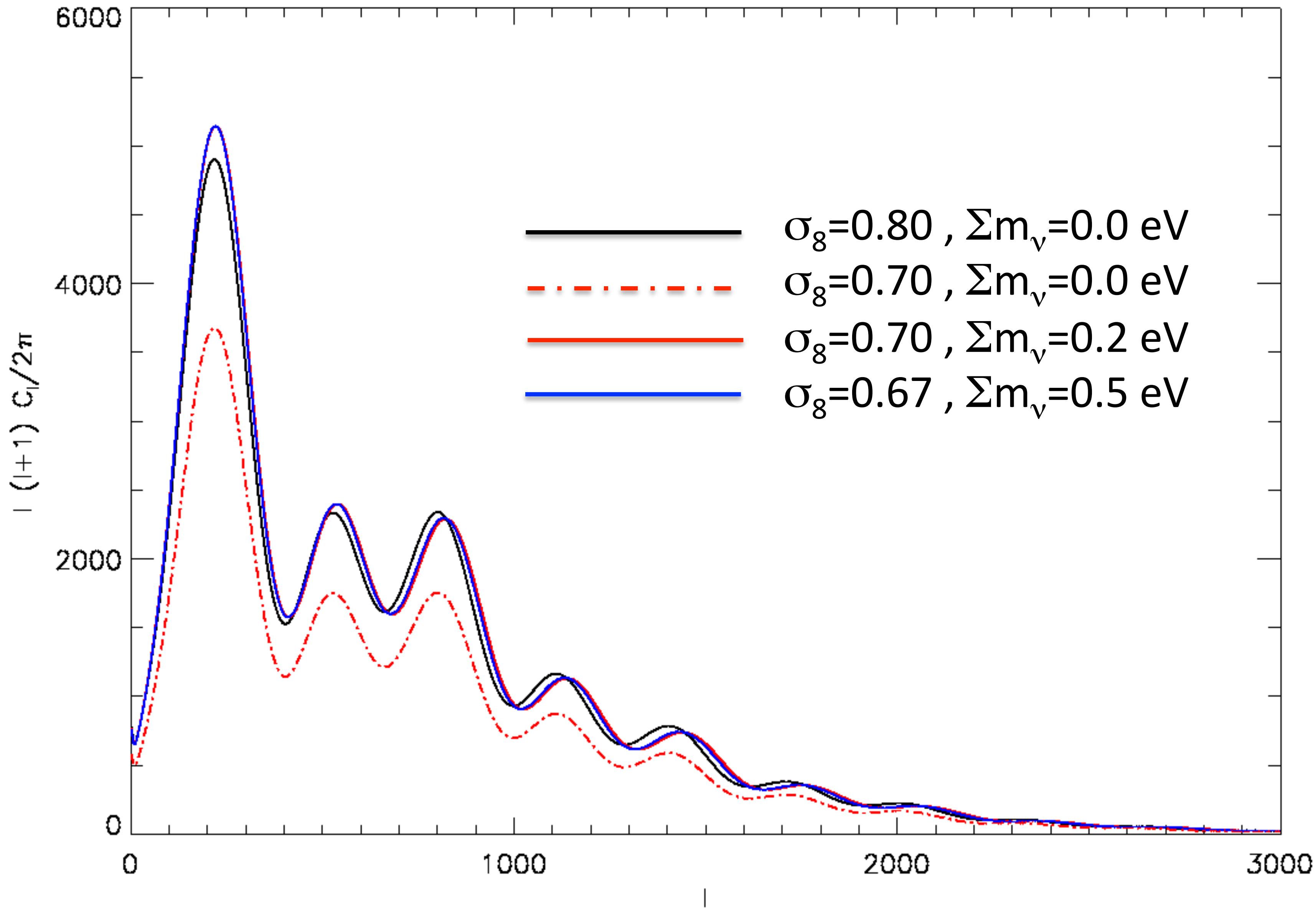


E-mode polarization power spectrum

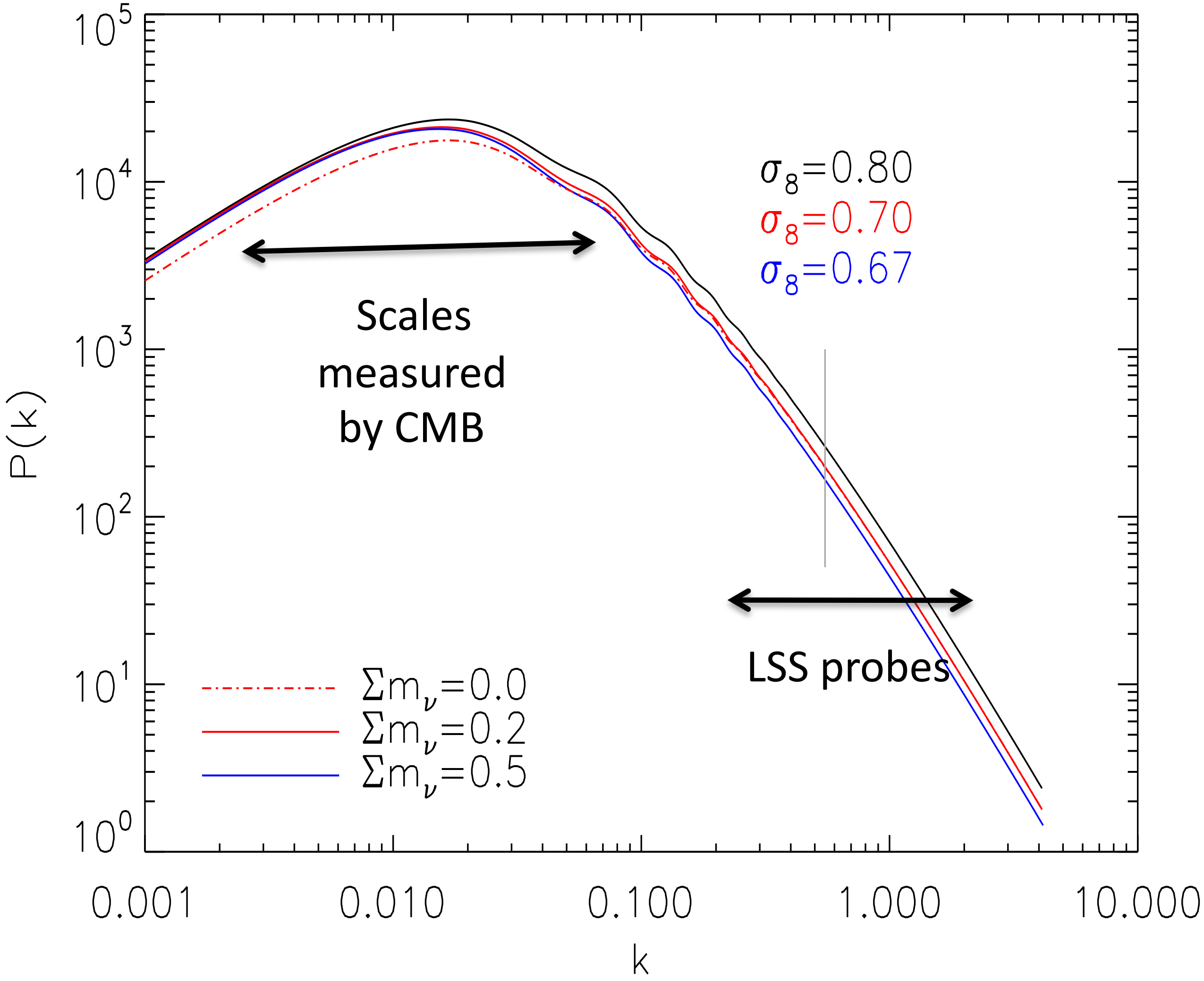
Temperature-polarization cross power spectrum



Sensitivity of CMB to neutrinos



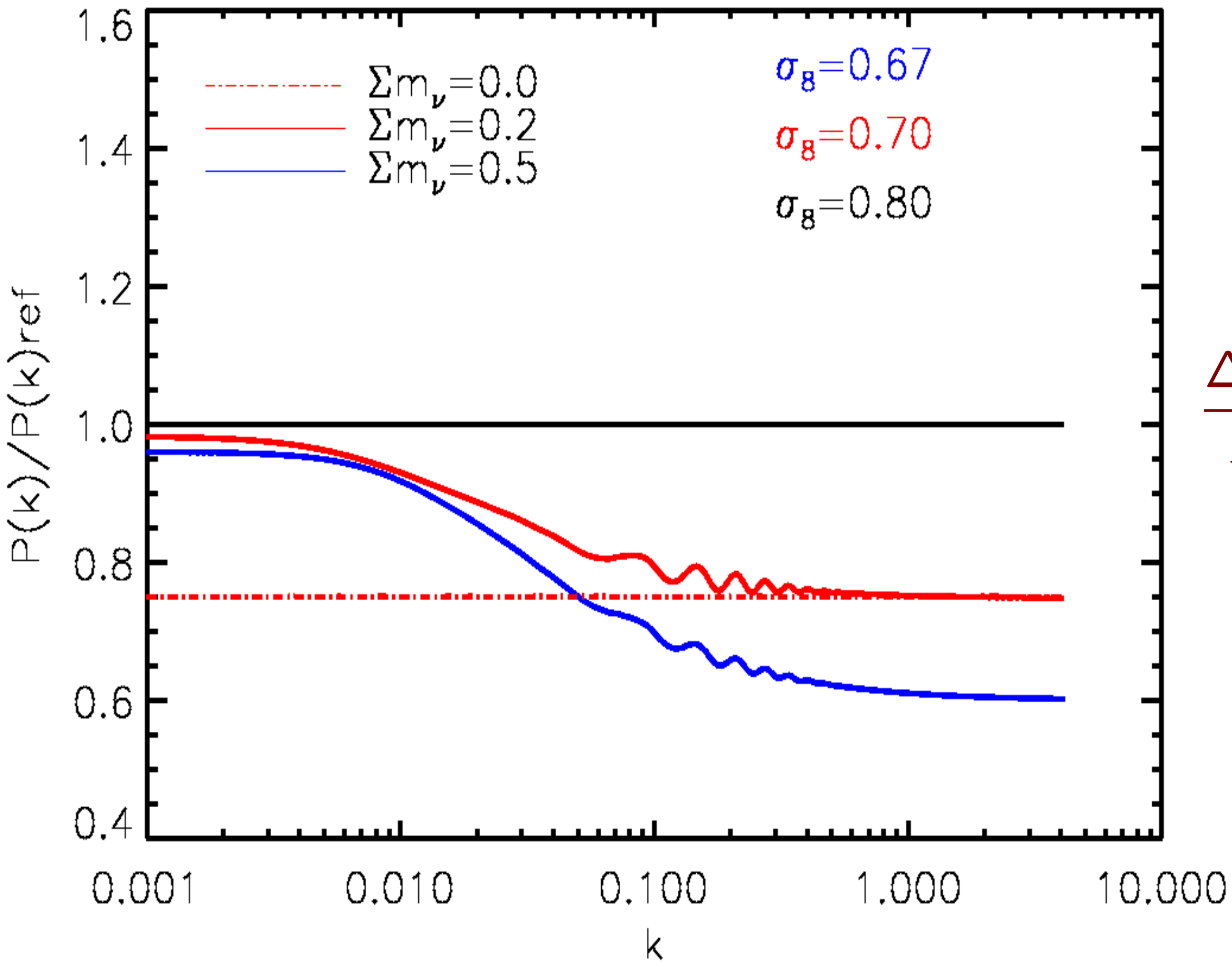
Observables : matter power spectrum



large scales

small scales

Impact of massive neutrinos



$$\frac{\Delta P}{P} \approx -8\frac{\Omega_\nu}{\Omega_{\rm m}} \text{ for } k > k_{\rm FS}$$

Probing the matter power spectrum

- Galaxy redshift surveys
- Lensing effects
  - CMB temperature anisotropies lensing
  - Cosmic shear (weak lensing of galaxy shapes)
  - CMB polarization lensing
- Cluster counts
  - Using the SZ effect, X-ray or optical
- Redshift space distortions
- …

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Large scale structure probes

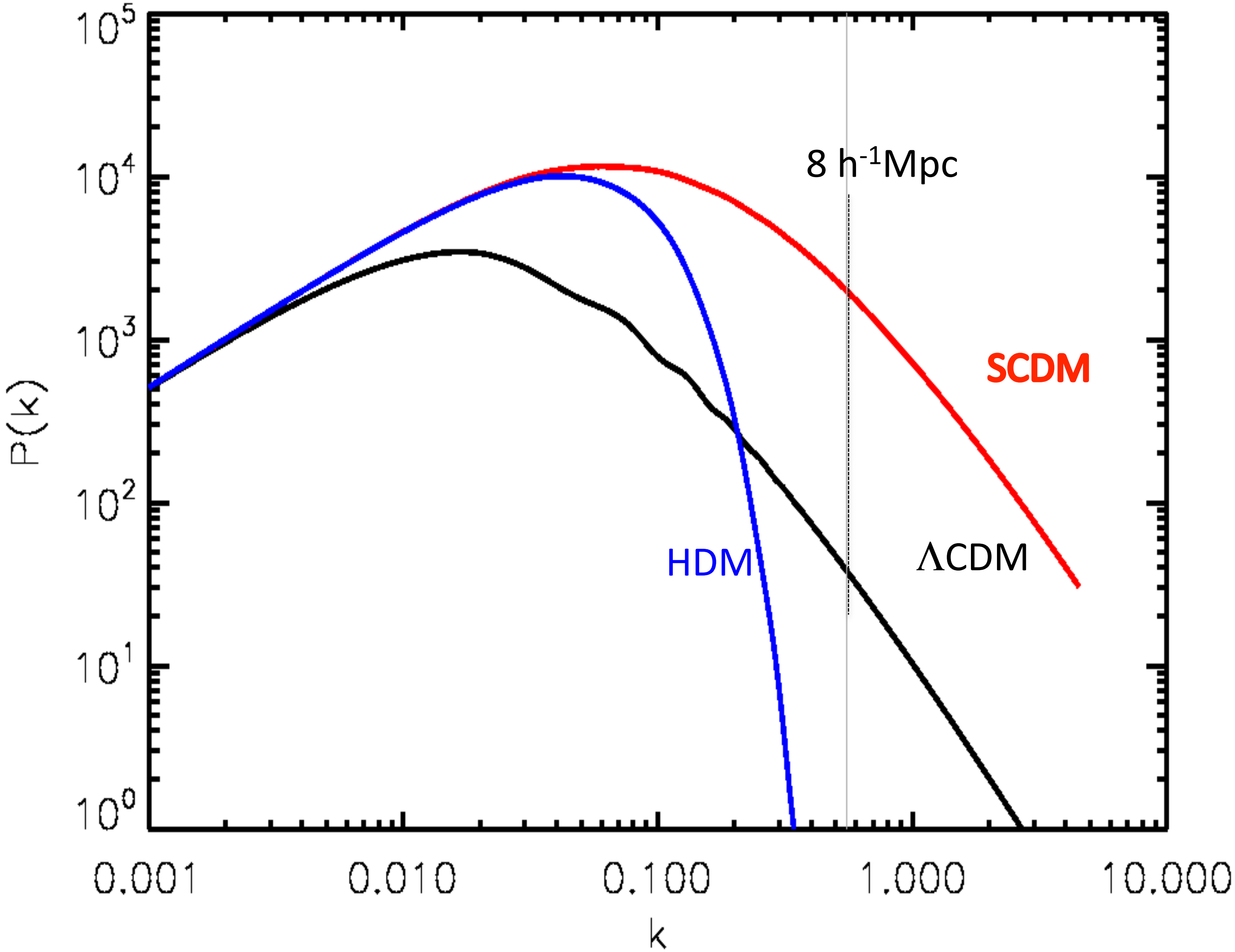
Typically constrain :

$$s_8 = \sigma_8 \left(\frac{\Omega_m}{0.30} \right)^{0.5}$$

Amplitude of perturbations

Amount of matter in the Universe

Ruling out of pure HDM & pure CDM

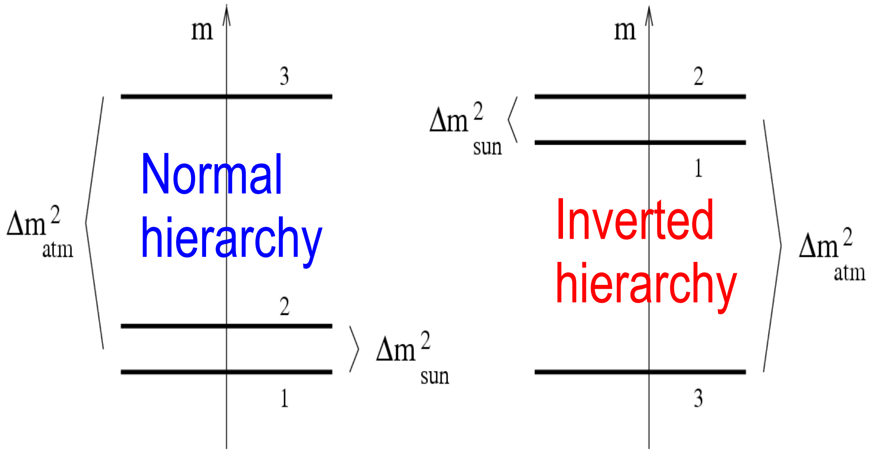


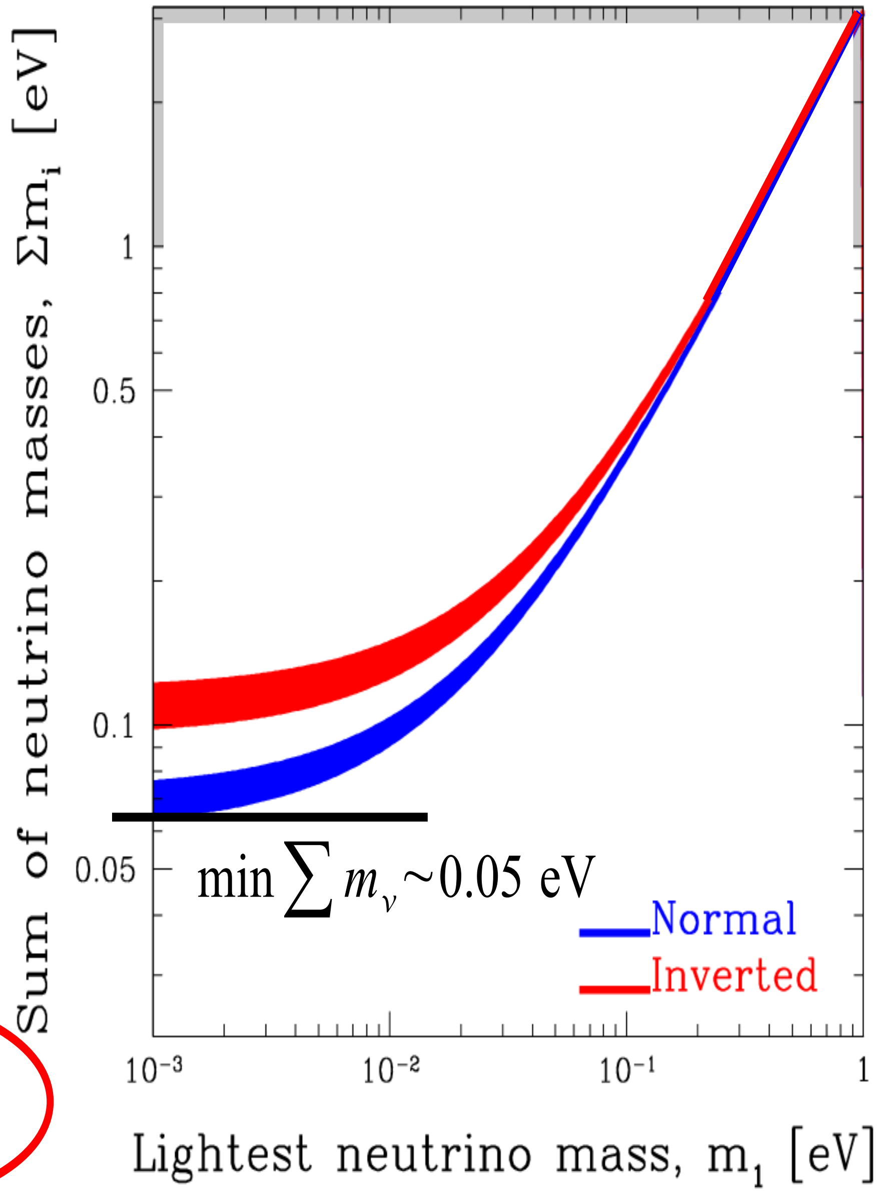
Credit : Y. Wong

Limit on the sum of neutrino masses

- Neutrino oscillations:

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





Mininum amount of neutrino dark matter

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

!!! Health Warning !!!

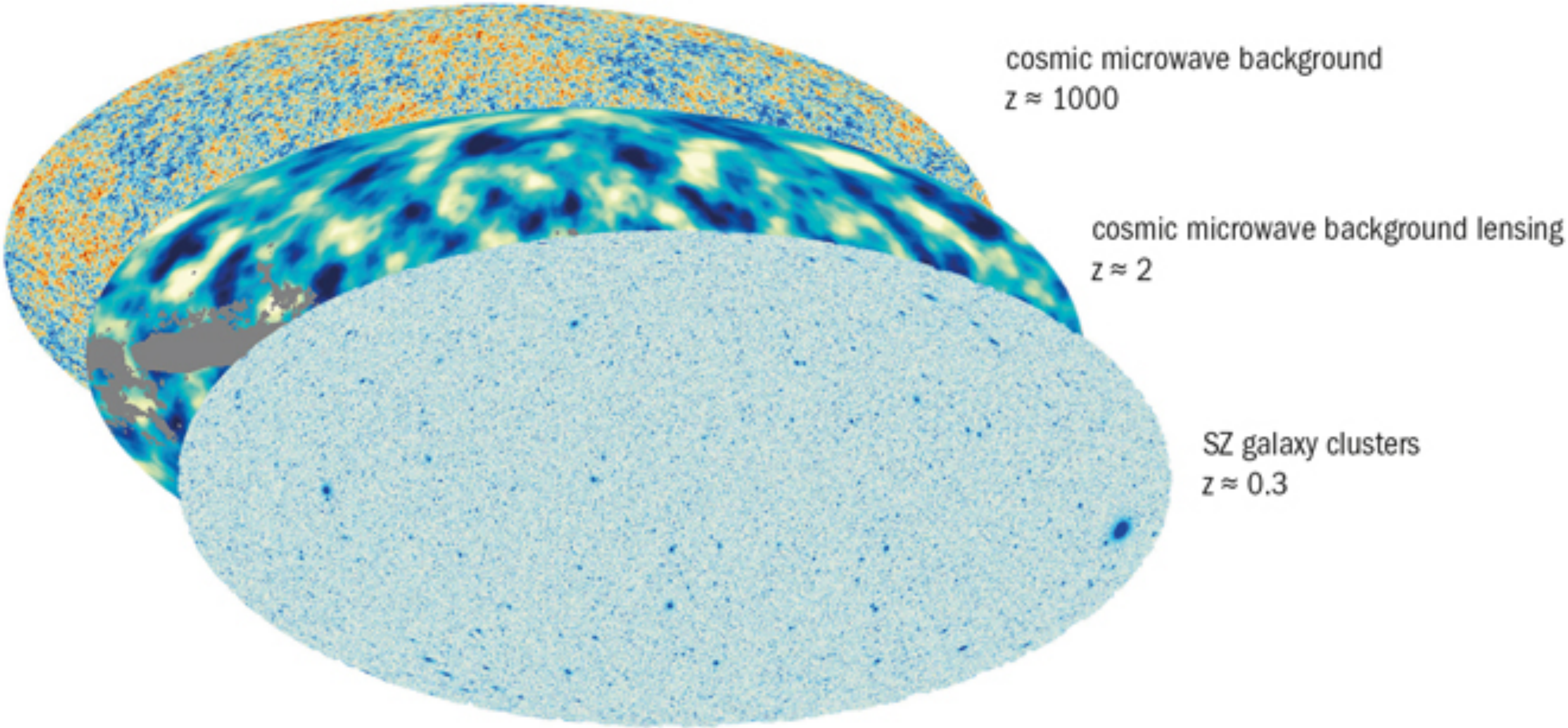
- All cosmological limits on neutrino masses are <u>model dependent</u>

- Standard cosmological limits on all other parameters are sensitive to neutrino history

- At the moment $\sum m_\nu = 0.06\,\mathrm{eV}$ is used with 2 equal masses and 1 zero mass

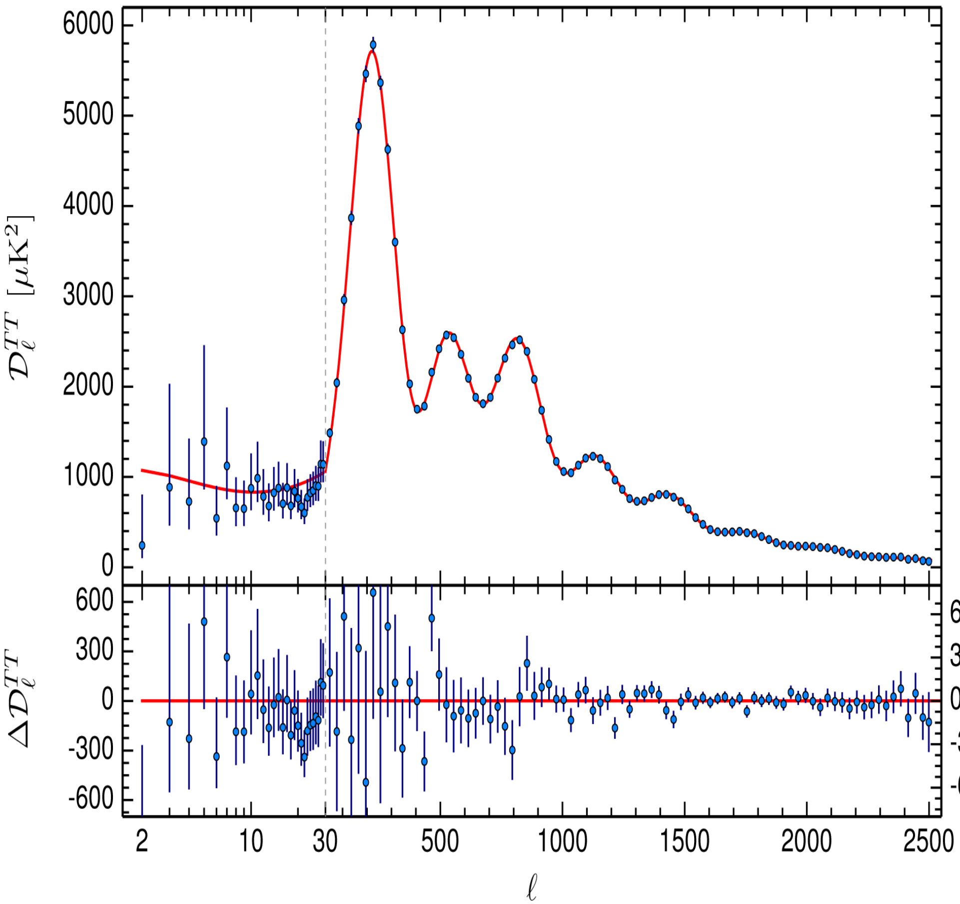
- Probes of LSS are less mature at the moment

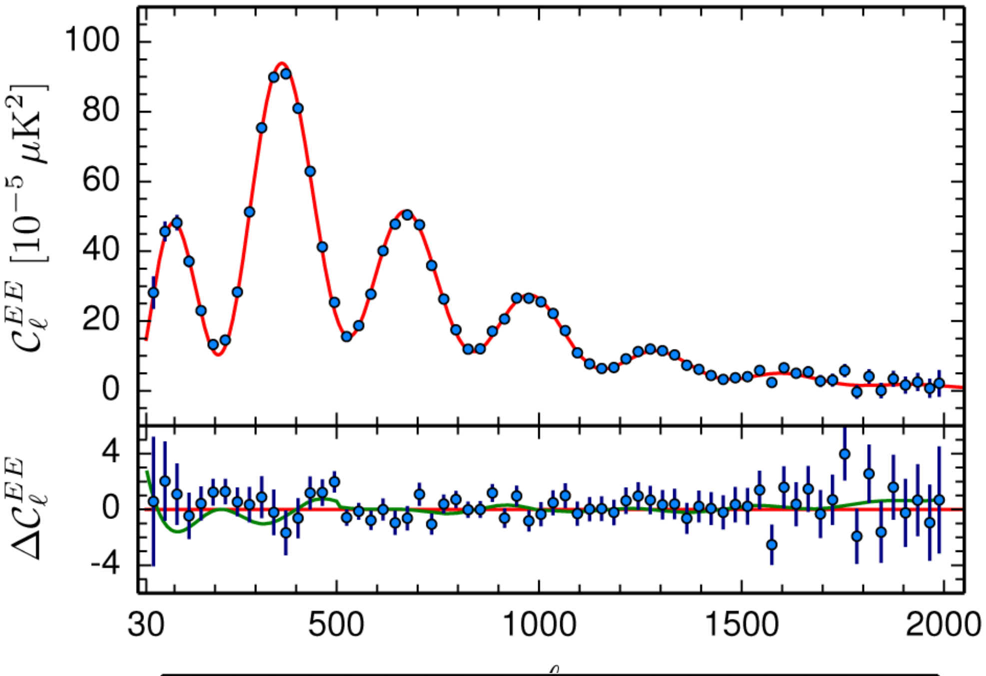
Planck 2015 results

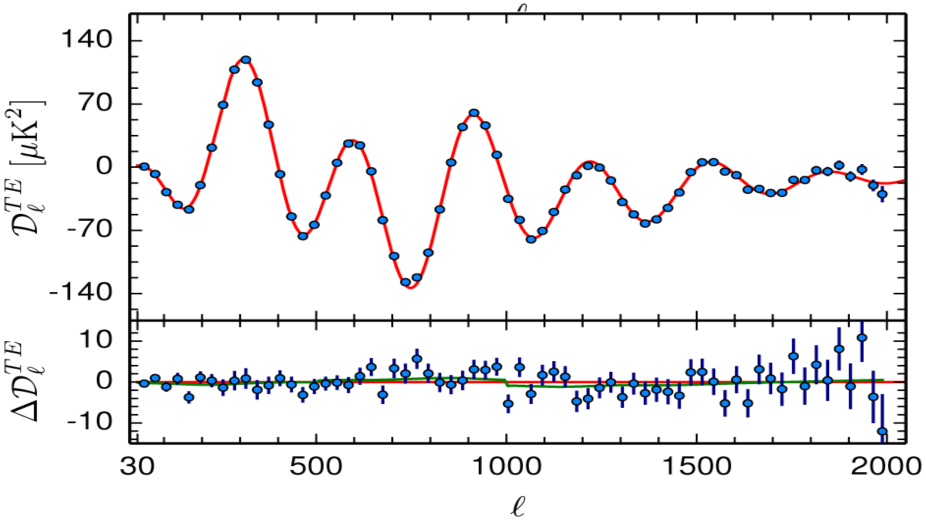


Three separate probes of cosmology !

Primary CMB measurements

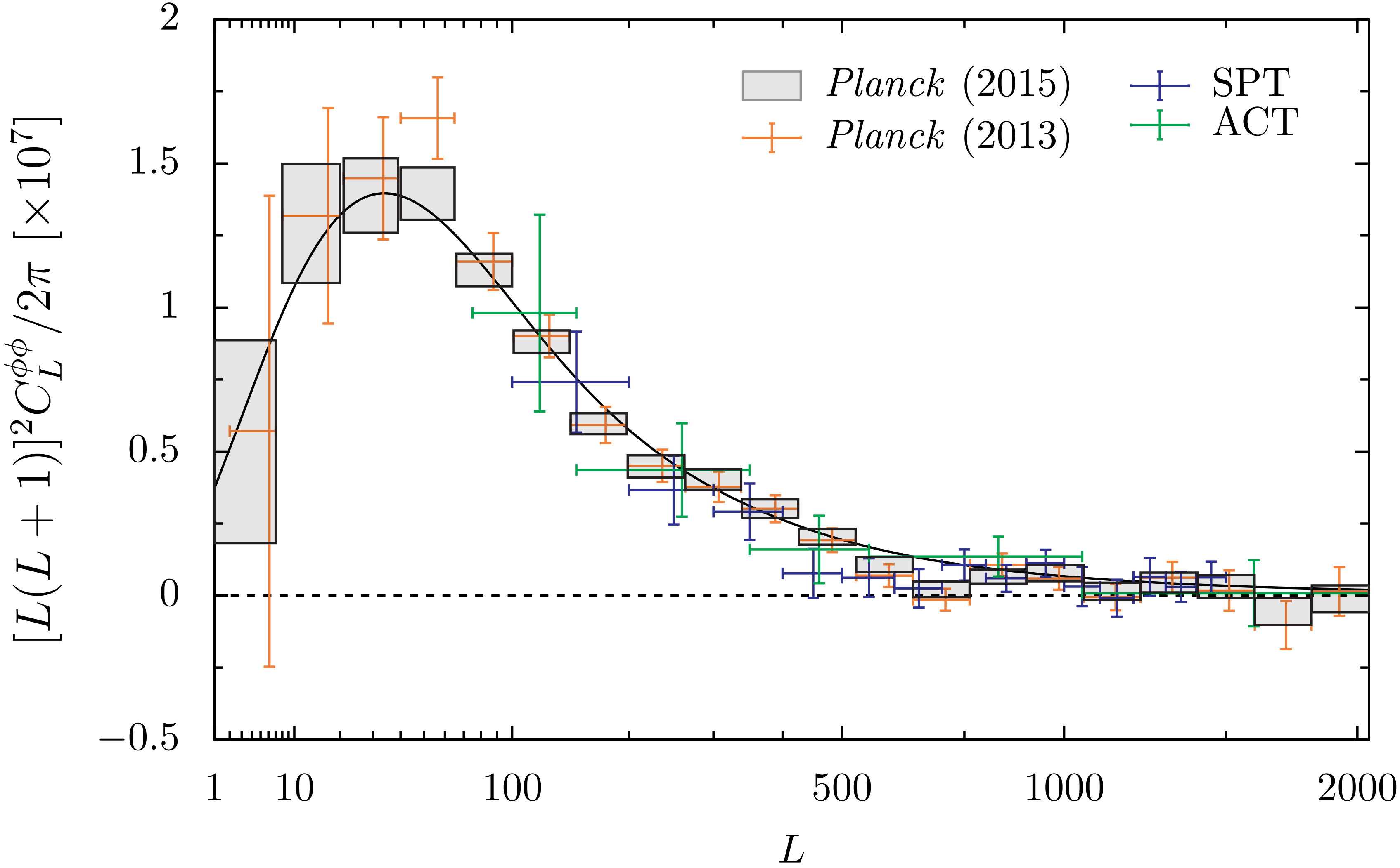






+ low P : large scale polarization

CMB lensing power spectrum



From Planck Collaboration (2016) : arXiv: 1502.01589v3 published in A&A

Constraints on base ΛCDM

Fitted parameters

$$100\Omega_{\rm b}h^2 = 2.225 \pm 0.016$$

$$\Omega_{\rm c}h^2 = 0.1198 \pm 0.015$$

$$100\theta_{\rm MC} = 1.04077 \pm 0.00052$$

$$\tau = 0.079 \pm 0.017$$

$$\log(10^{10}A_{\rm s}) = 3.094 \pm 0.034$$

$$n_{\rm s} = 0.9645 \pm 0.0049$$

NB paper now
Cited > 4000 times

Derived parameters

$$\Omega_{\rm m} = 0.3156 \pm 0.0091$$

$$\sigma_8 = 0.831 \pm 0.013$$

$$10^9 A_{\rm s} e^{-2\tau} = 1.882 \pm 0.012$$

Planck TT, TE, EE + low P (ie just CMB) : 68% confidence

From Planck Collaboration (2016) : arXiv: 1502.01589v3 published in A&A

Extensions to ΛCDM

$$\Omega_{\mathrm{k}} = -0.04 \pm 0.04$$

$$\sum m_\nu/\mathrm{eV} < 0.492$$

$$N_{\mathrm{eff}} = 2.99 \pm 0.40$$

$$Y_{\mathrm{p}} = 0.25 \pm 0.03$$

$$dn_{\mathrm{S}}/d(\log k) = -0.006 \pm 0.014$$

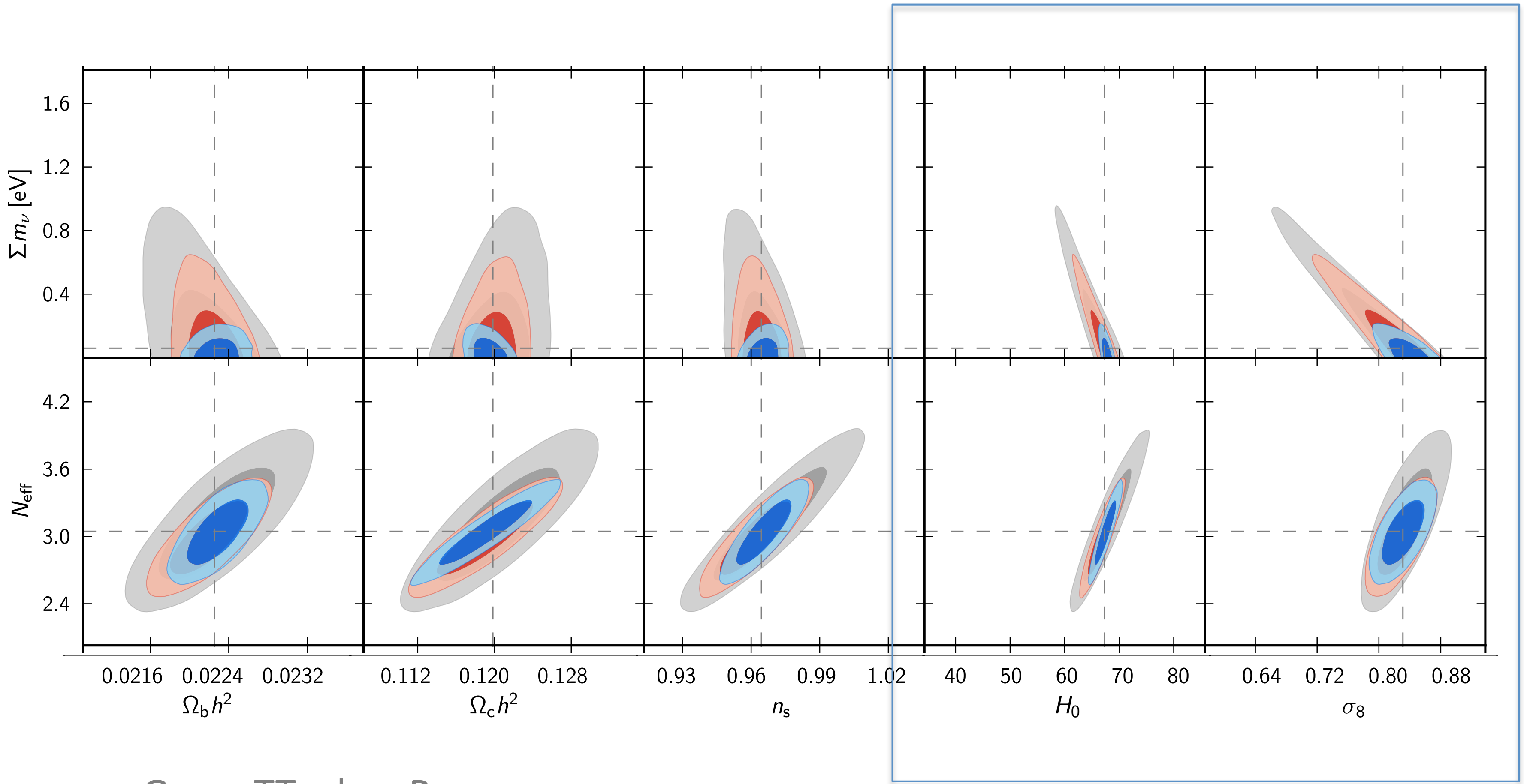
$$r_{0.002} < 0.0987$$

$$w = -1.5 \pm 0.5$$

Our interest here !

From Planck Collaboration (2016) : arXiv: 1502.01589v3 published in A&A

Degeneracies with standard parameters



Grey : TT + low P

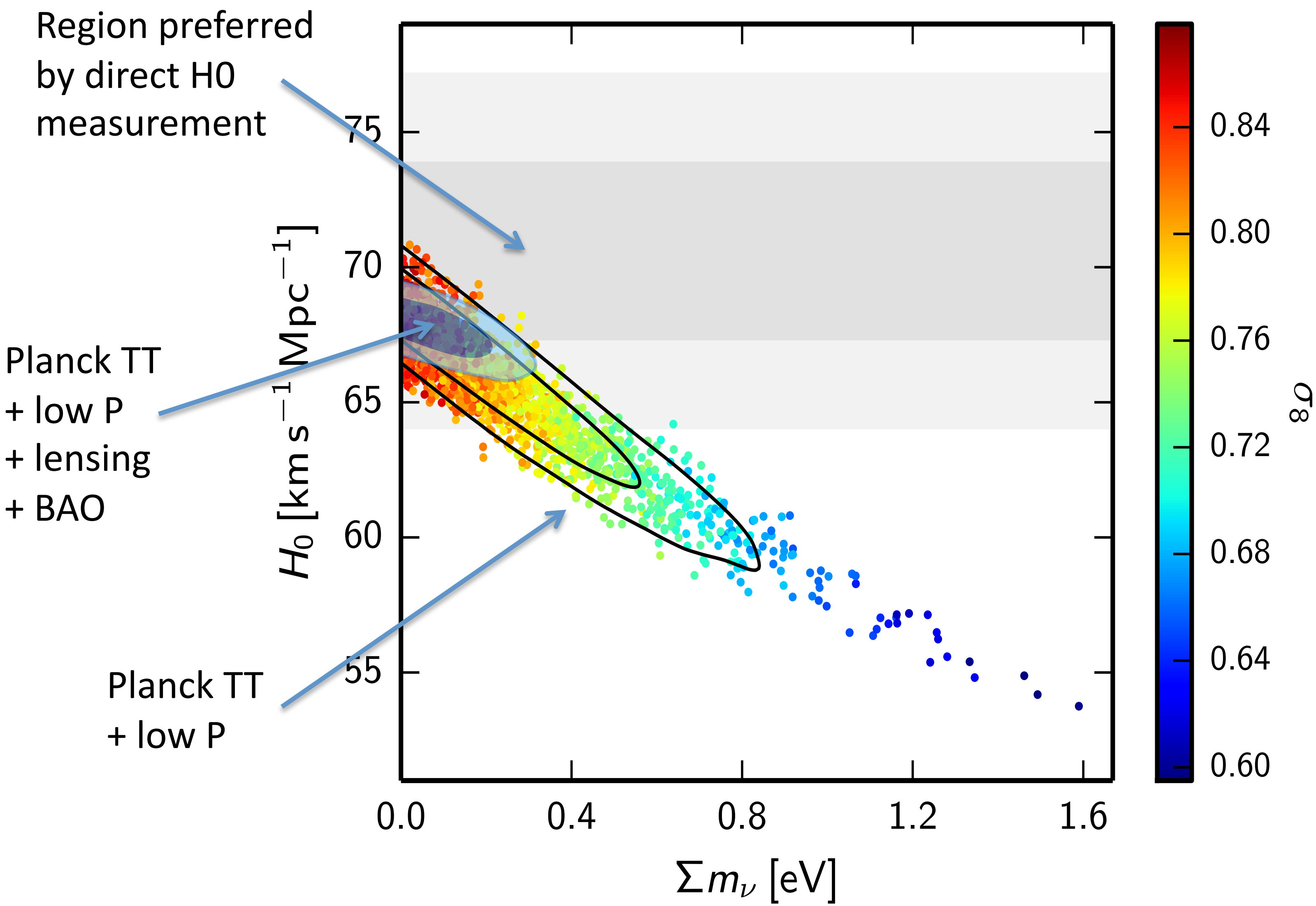
Red : TT, EE, TE + low P

Blue : TT, EE, TE, low P + BAO

Key degeneracies

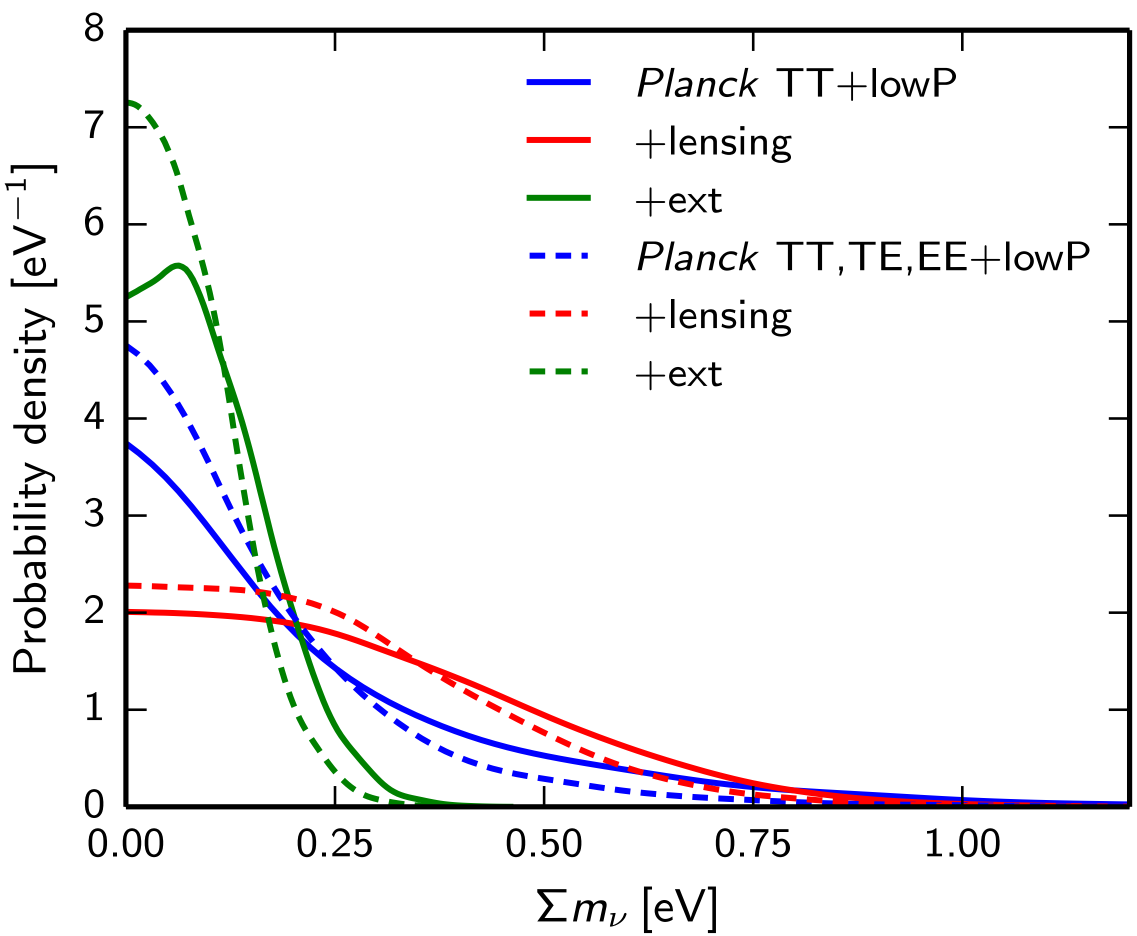
From Planck Collaboration (2016) : arXiv: 1502.01589v3 published in A&A

Neutrinos v H_0 and σ_8



From Planck Collaboration (2016) : arXiv: 1502.01589v3 published in A&A

Limits on active neutrinos



ext = {BAO, JLA, H_0}

From Planck Collaboration (2016) : arXiv: 1502.01589v3 published in A&A

Limits on active neutrinos

TT, TE, EE $\sum m_\nu < 0.492\,\mathrm{eV}$

TT, TE, EE + Planck lensing $< 0.589\,\mathrm{eV}$

Safe bound

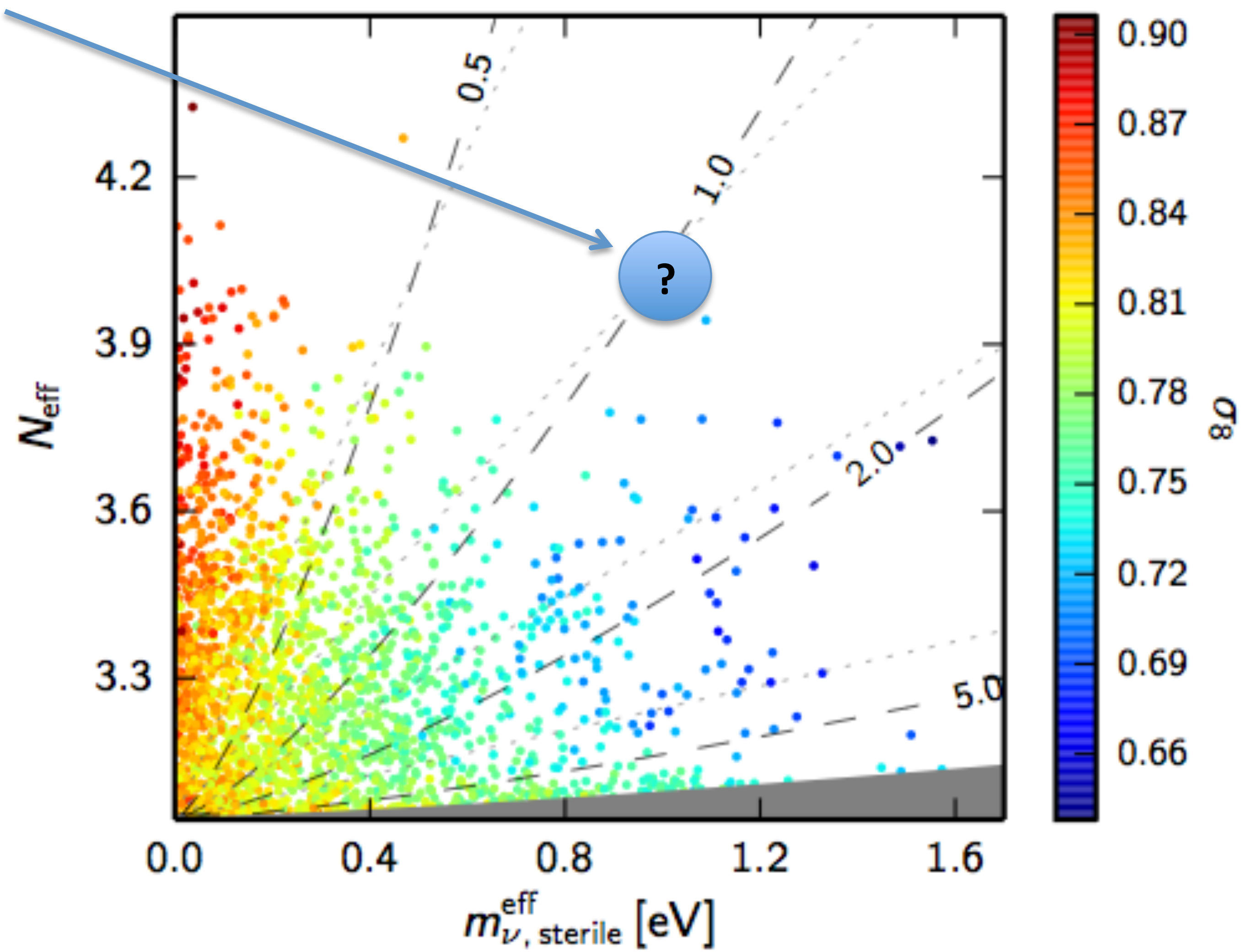
TT, TE, EE + lensing + ext $< 0.194\,\mathrm{eV}$

ext = {BAO, JLA, H_0}

(95 % upper limits)

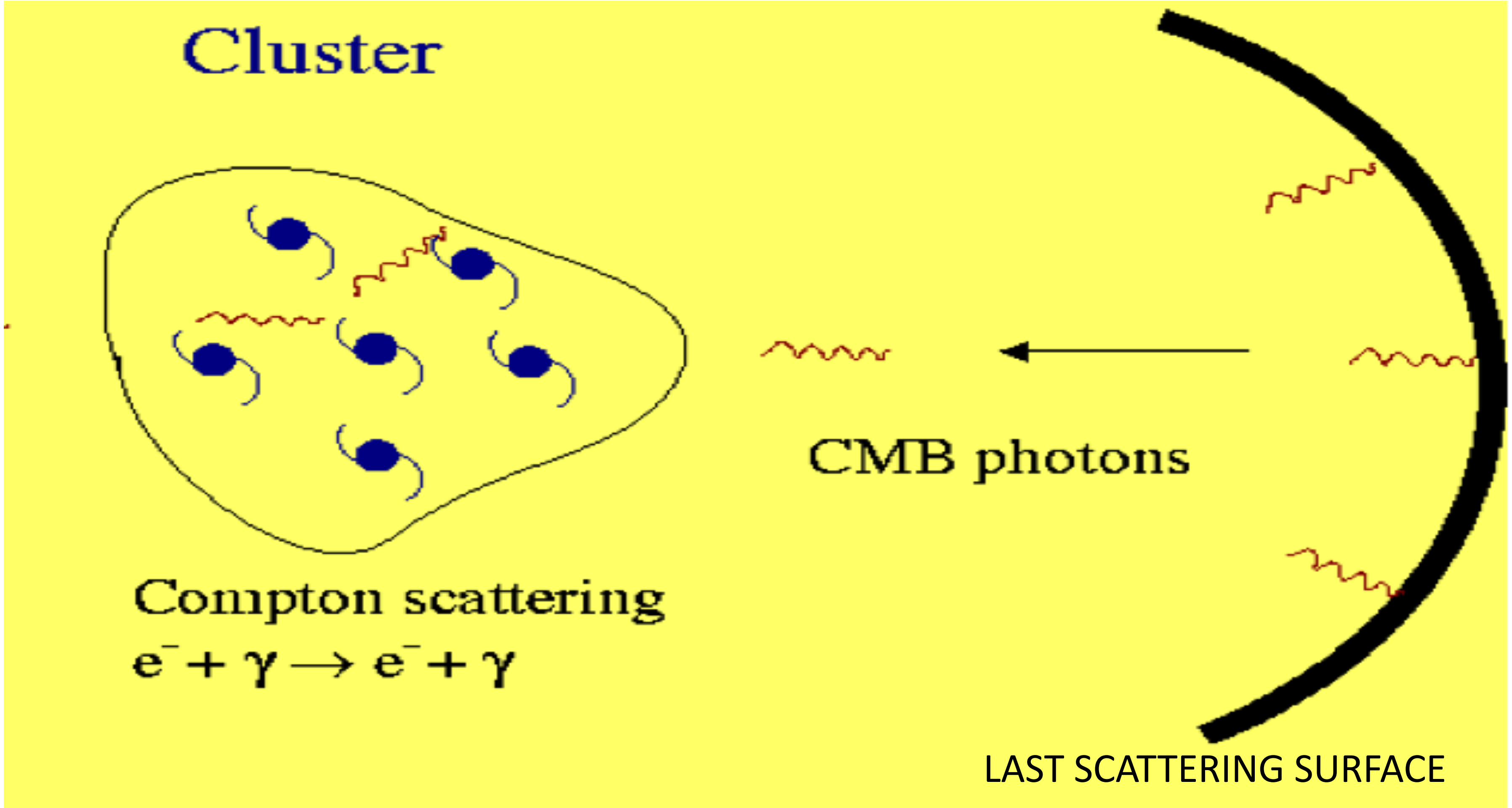
Sterile Neutrinos

Possible solution to reactor anomalies



$N_{\text{eff}} < 3.7 \quad m^{\text{eff}}_{\nu,\text{sterile}} < 0.52\,\text{eV}$

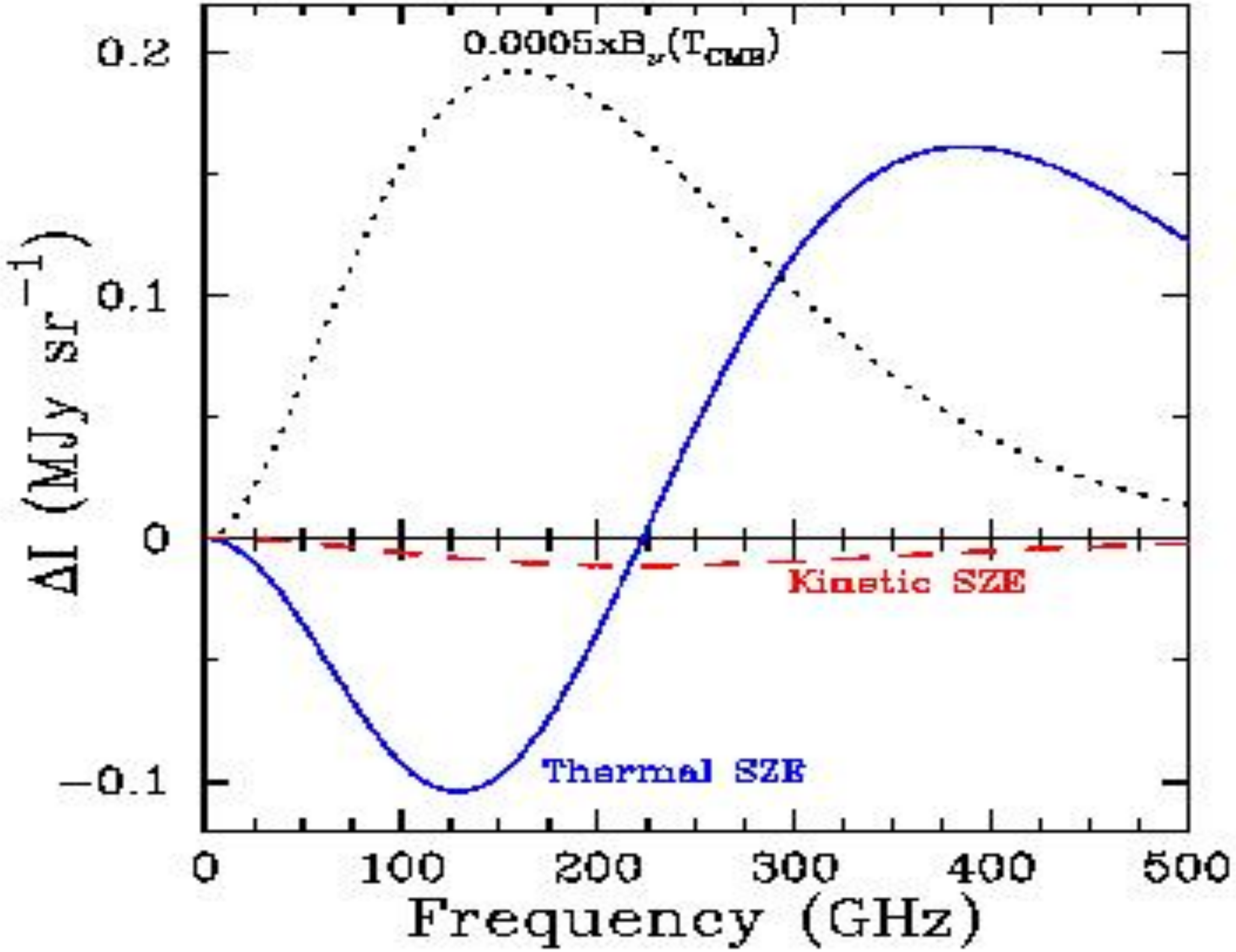
Sunyaev-Zeldovich Effect



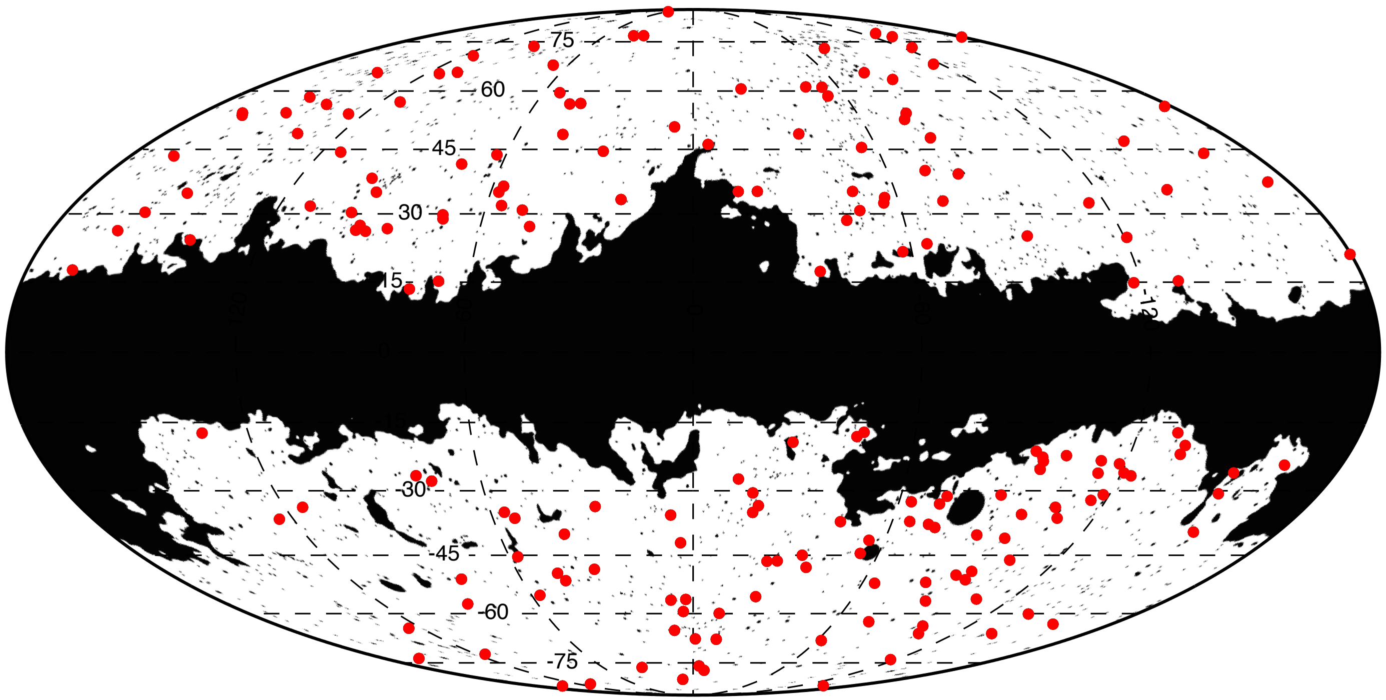
$$\frac{\Delta T}{T} \propto \sigma_T \int n_e T_e dl$$

= integrated gas pressure along the line of sight

Spectral Signature



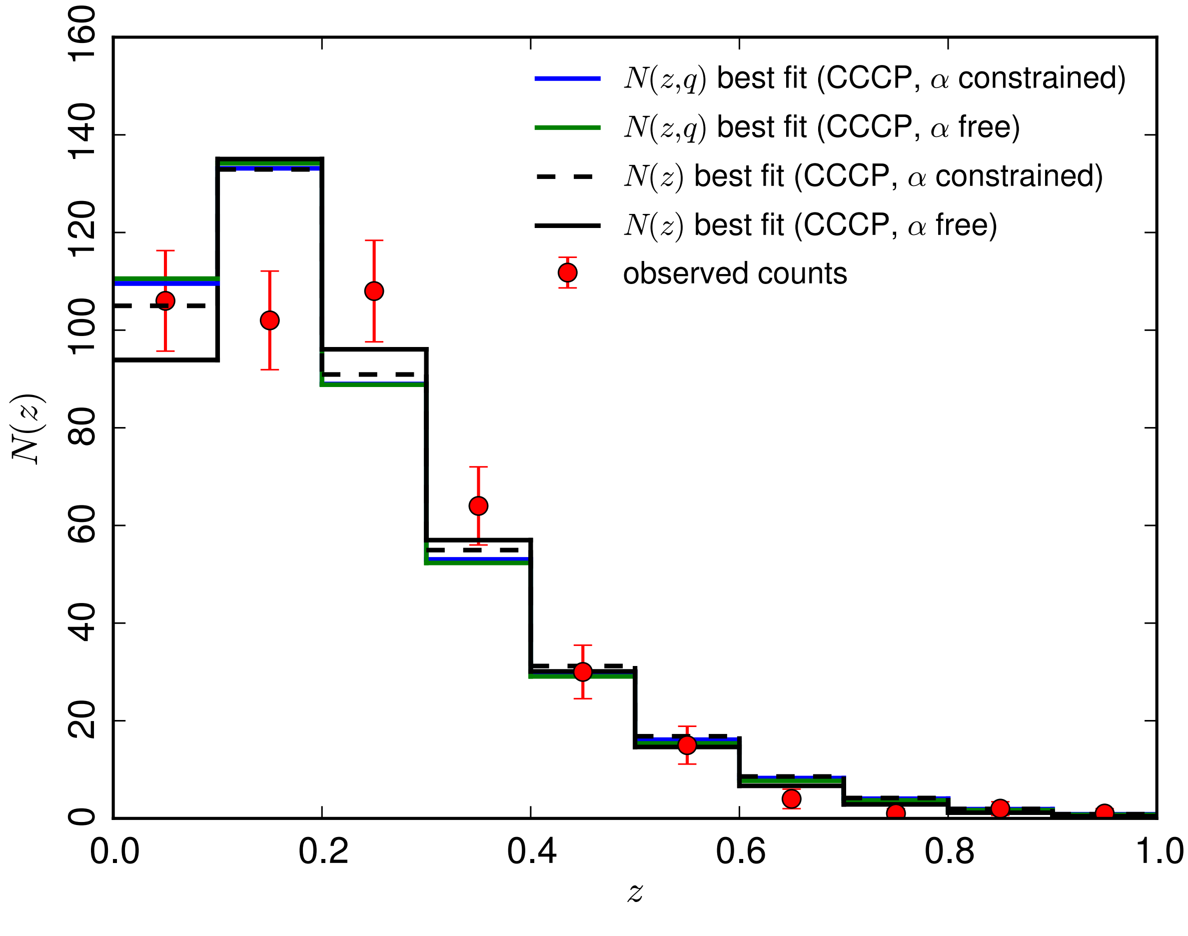
SZ cluster survey



Planck 2013 : 189 clusters with S/N > 7

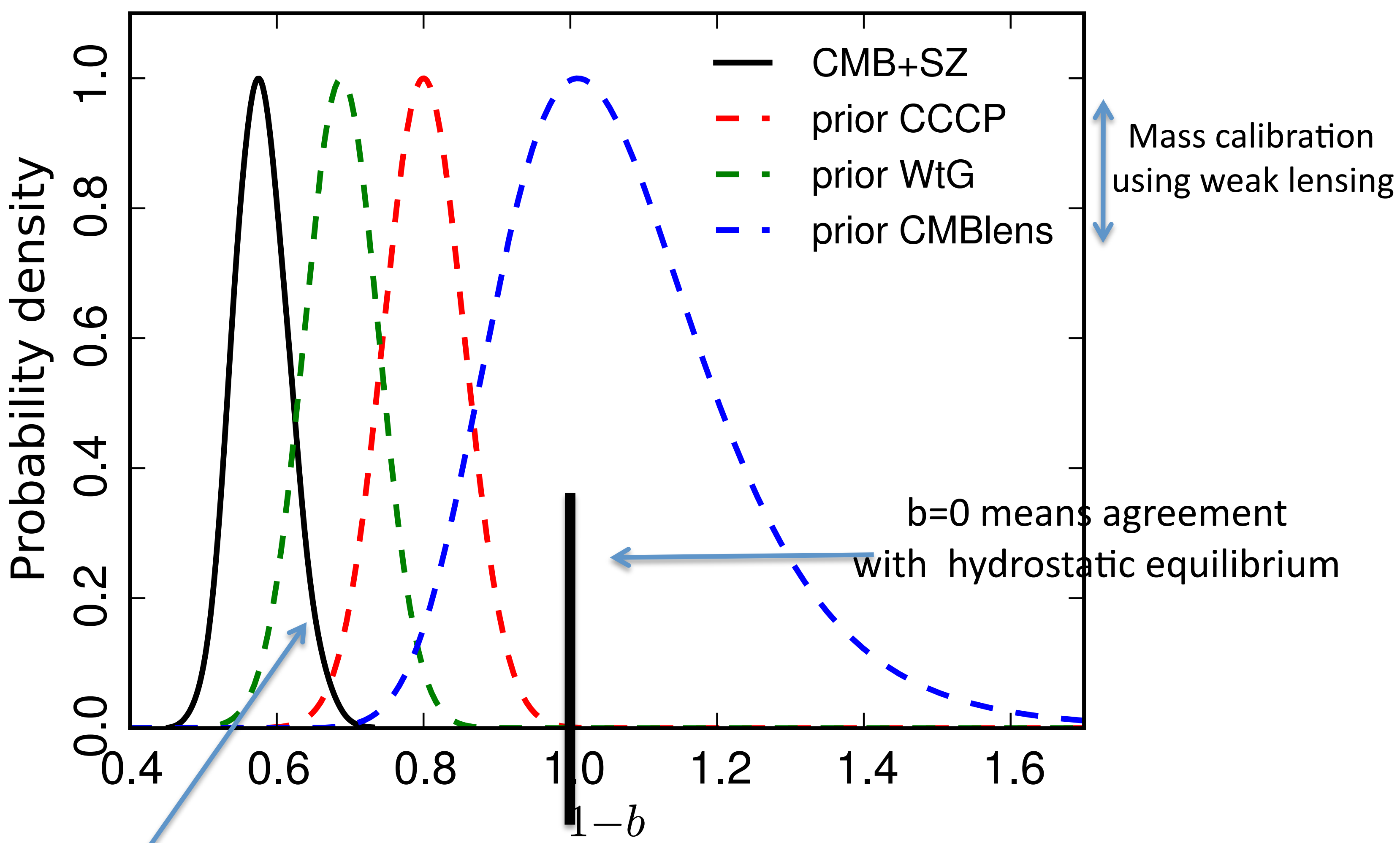
Planck 2015 : 439 clusters with S/N > 6

Cluster Number Counts from Planck



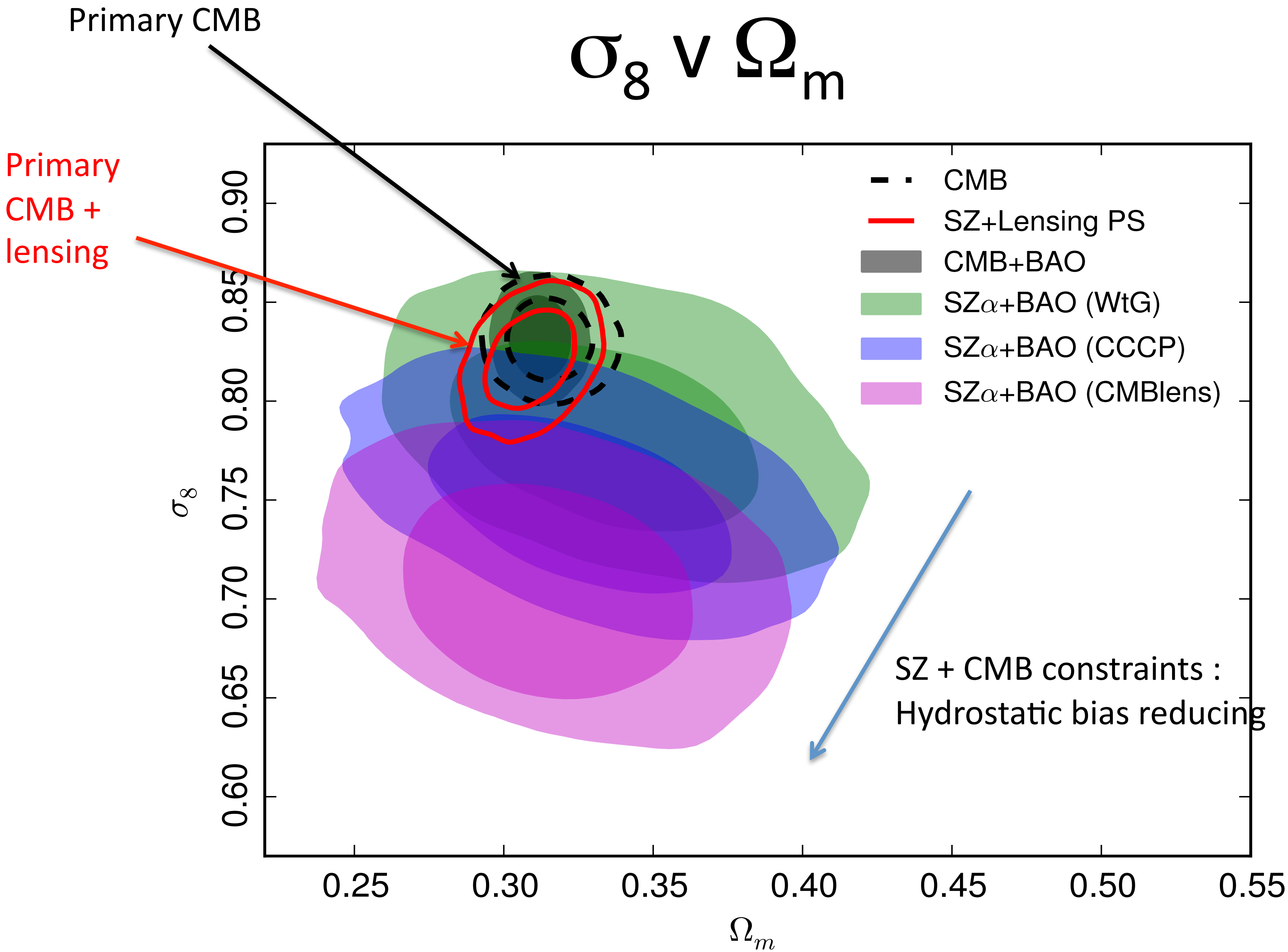
Number of clusters as a function of redshift

Cluster Hydrostatic Bias

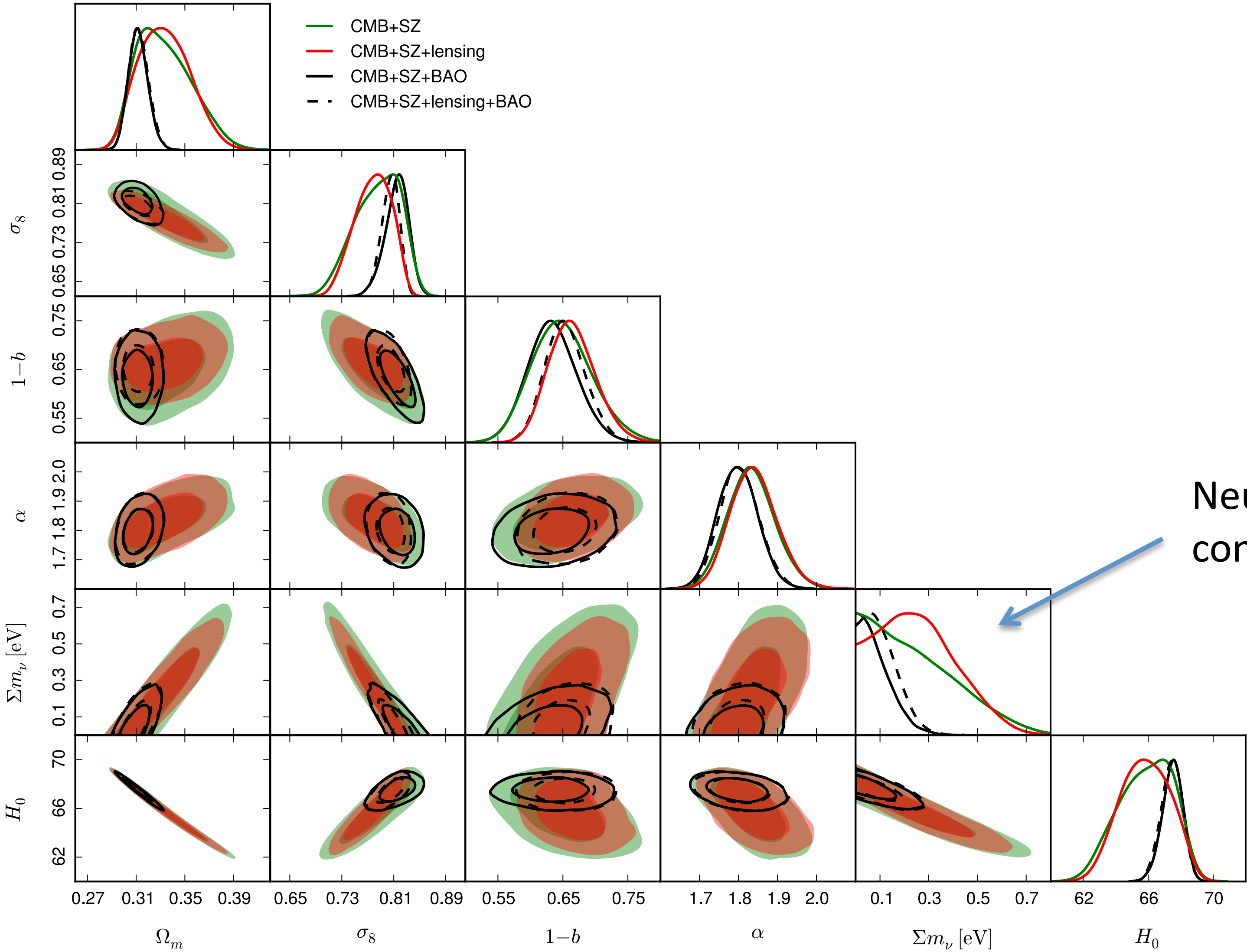


Suggests SZ counts may not be in agreement with other determinations

σ_8 v Ω_m

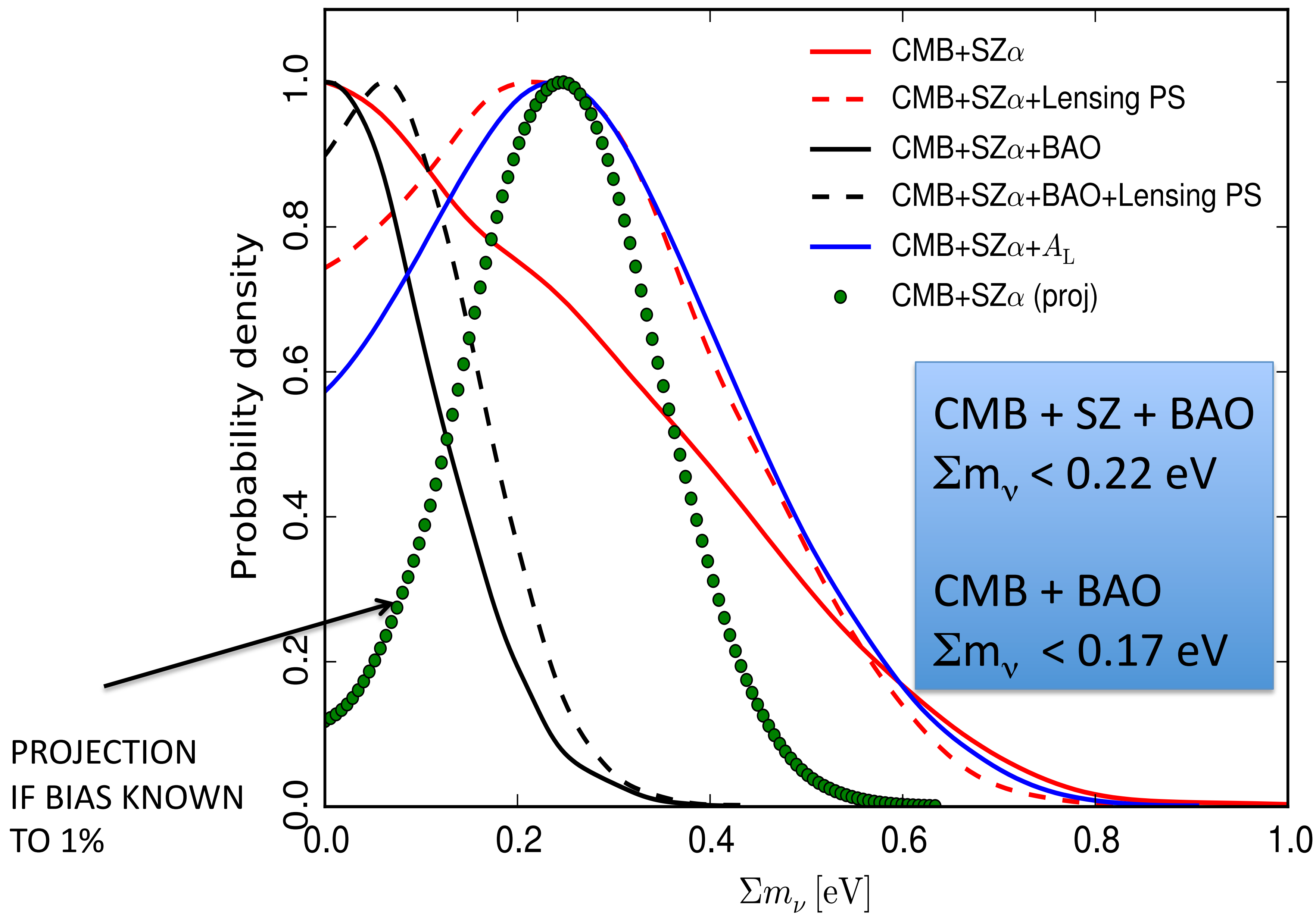


CMB + SZ + CCCP

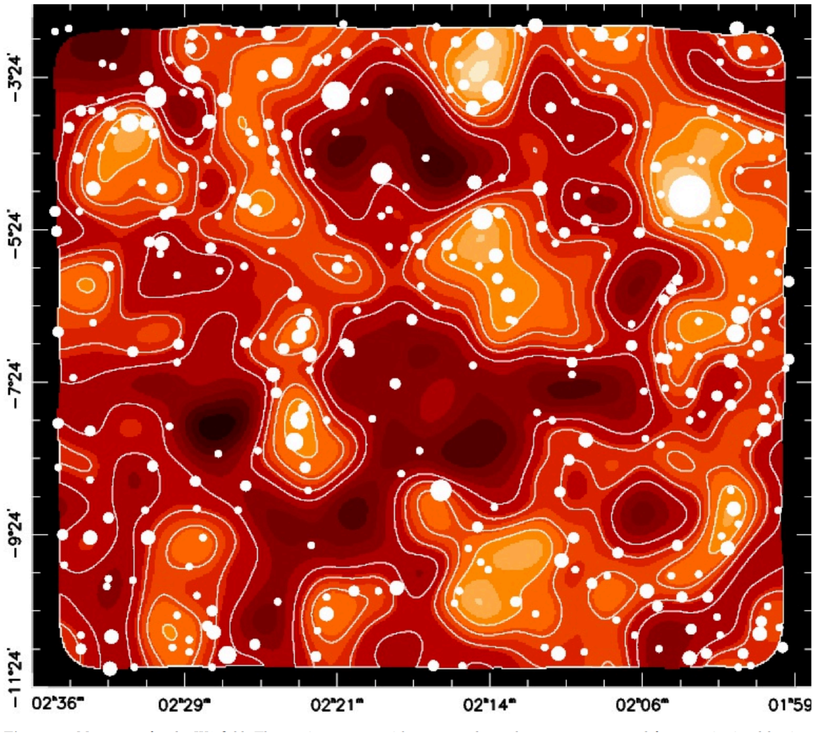


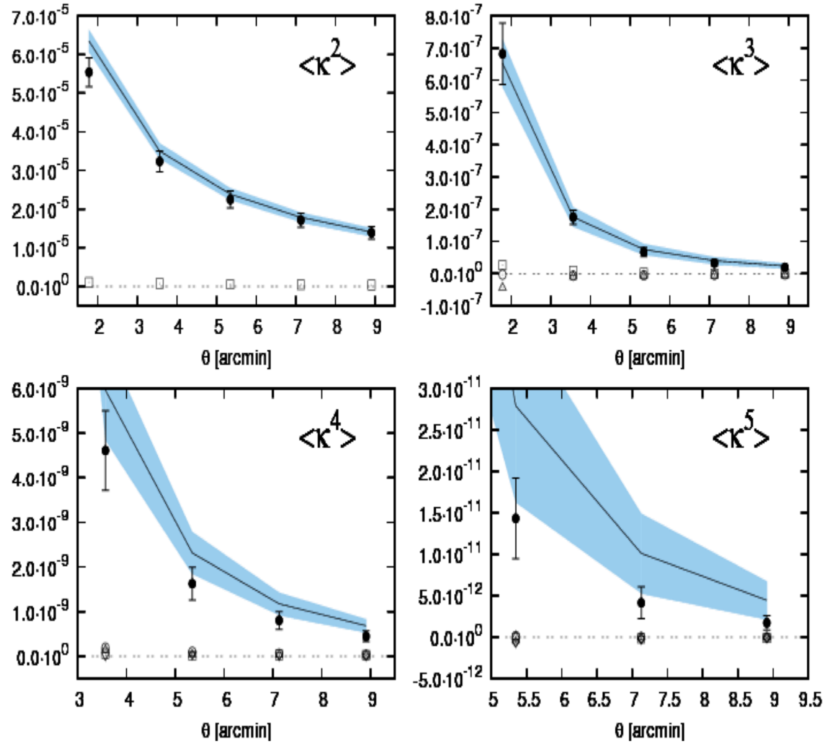
Neutrino mass constraint

Constraints on neutrino mass



CFHTLenS

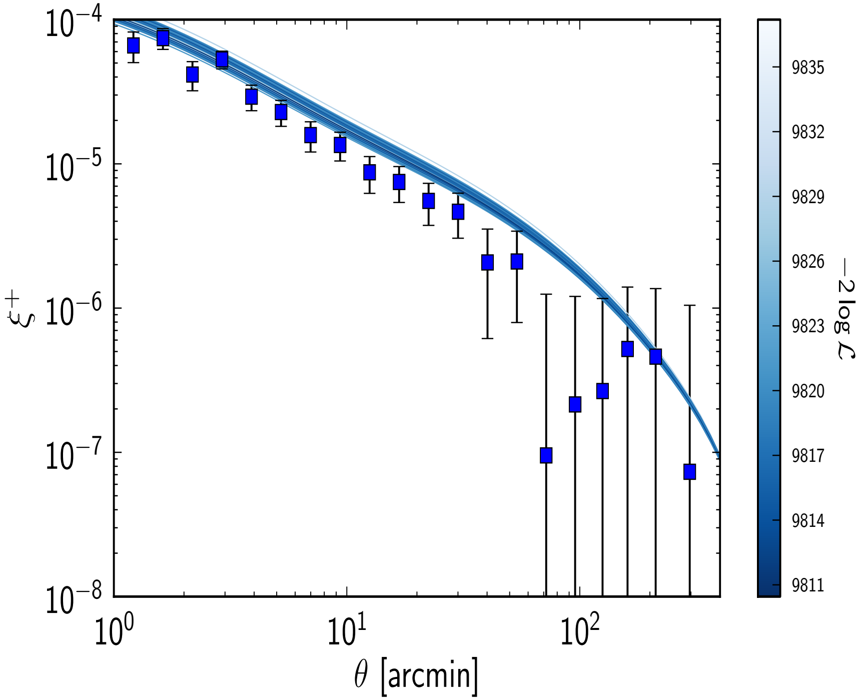




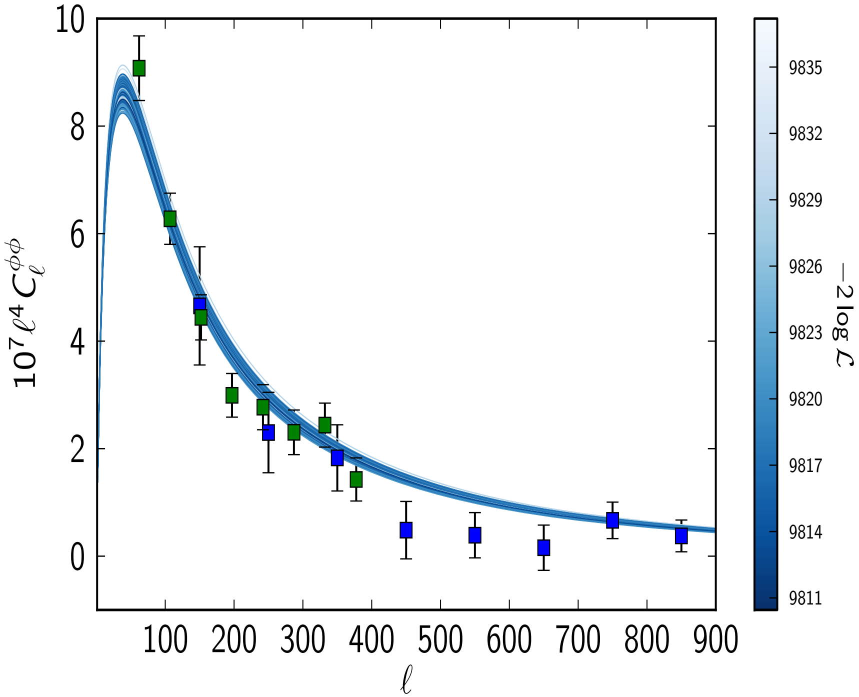
Around ~ 150 deg^2 survey using CFHT with high source density for weak lensing

(From Battye & Moss, PRL 2014)

Lensing spectra v Planck best fit



CFHTLenS

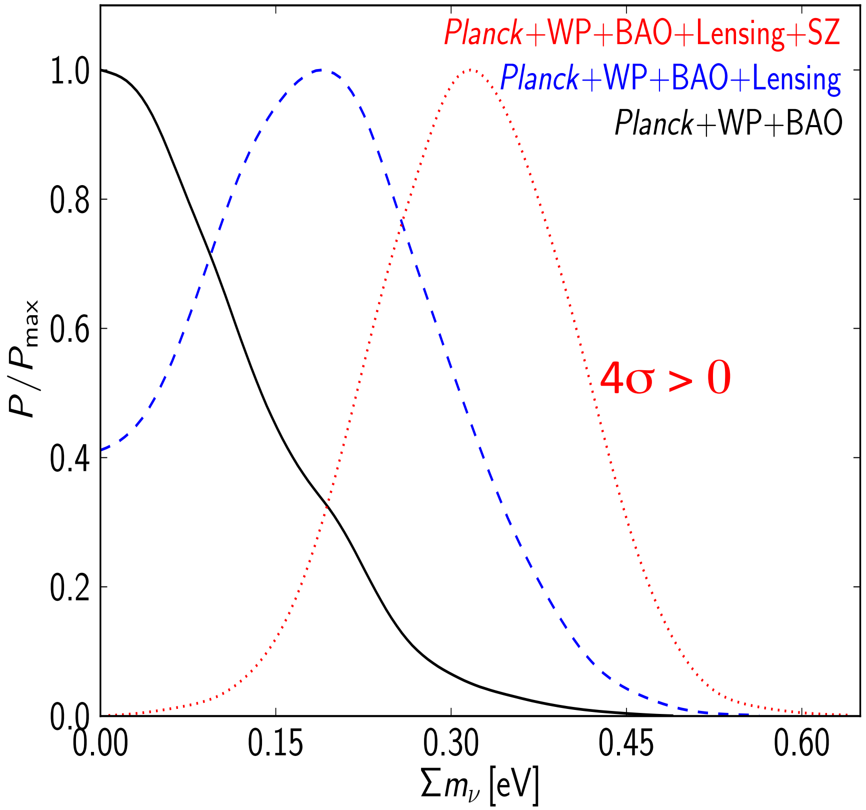


Planck & SPT CMB lensing

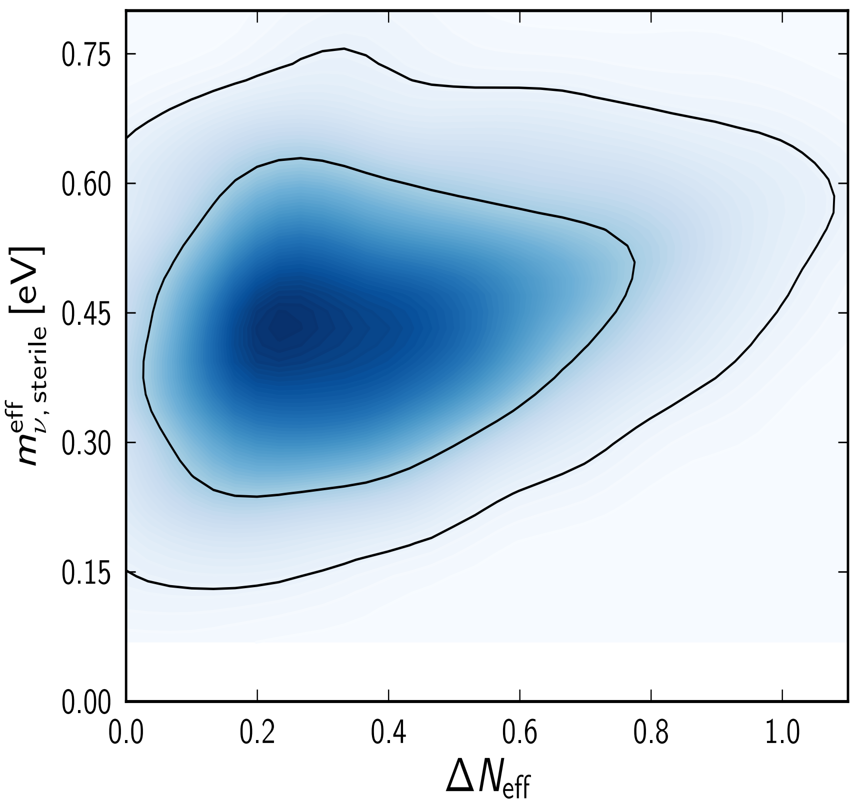
There is a discrepancy !

(From Battye & Moss, PRL 2014)

Joint Constraints on Massive Neutrinos



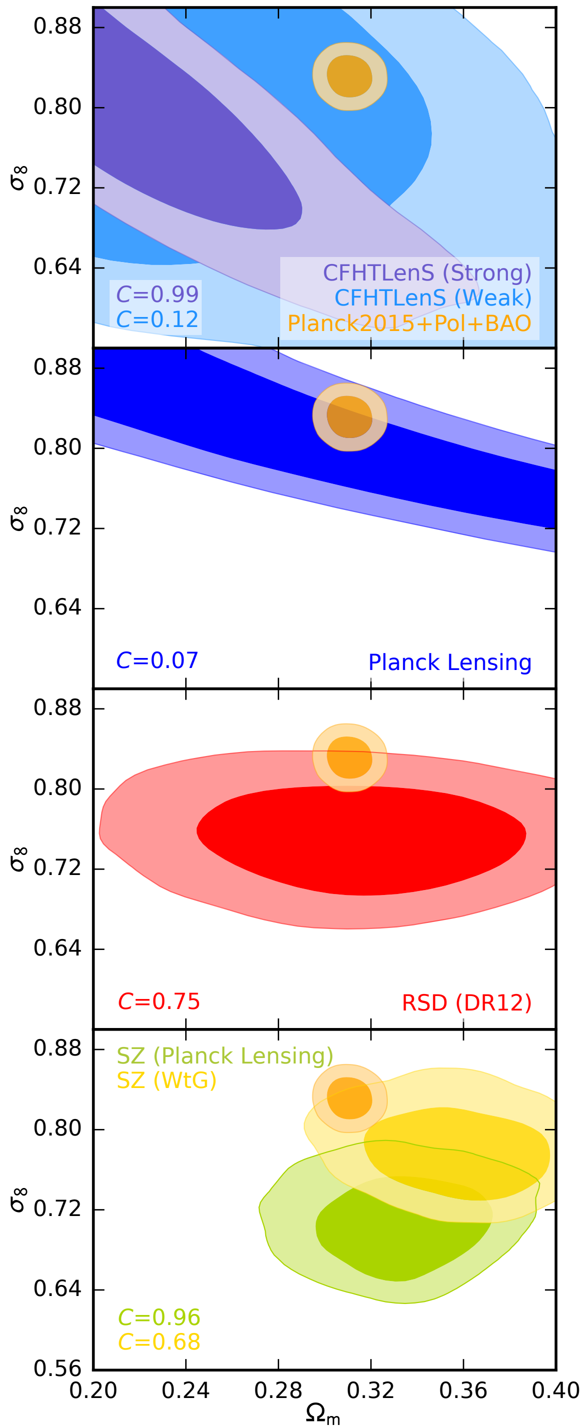
Active Neutrinos



Sterile Neutrinos

Based on Planck 2013 results !!!

Additional extra feature :
H_0 agrees with HST



Weak lensing measured from galaxy shapes

Weak lensing measured from CMB

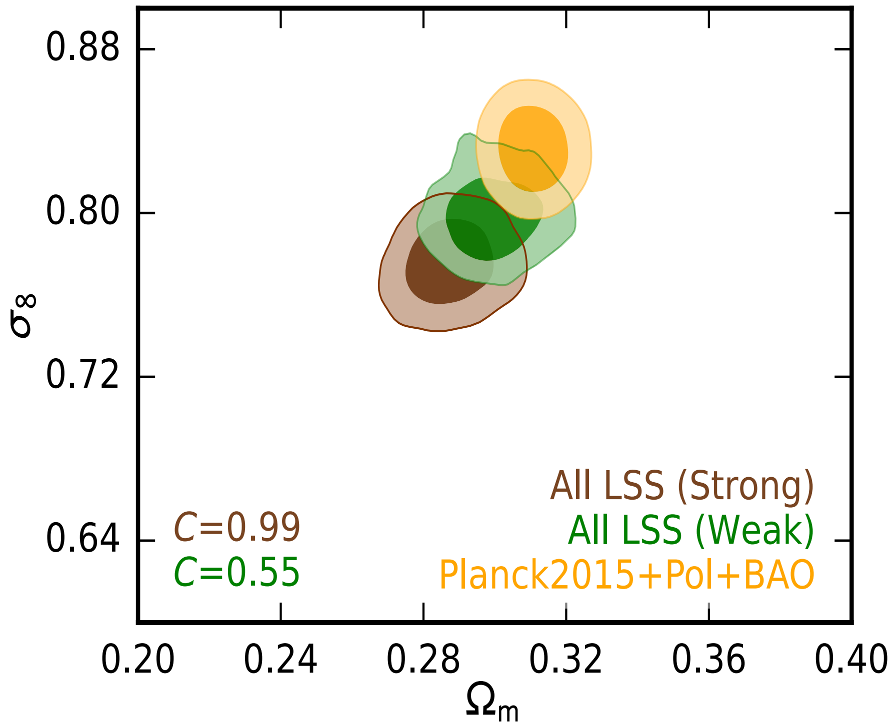
Redshift space distortions

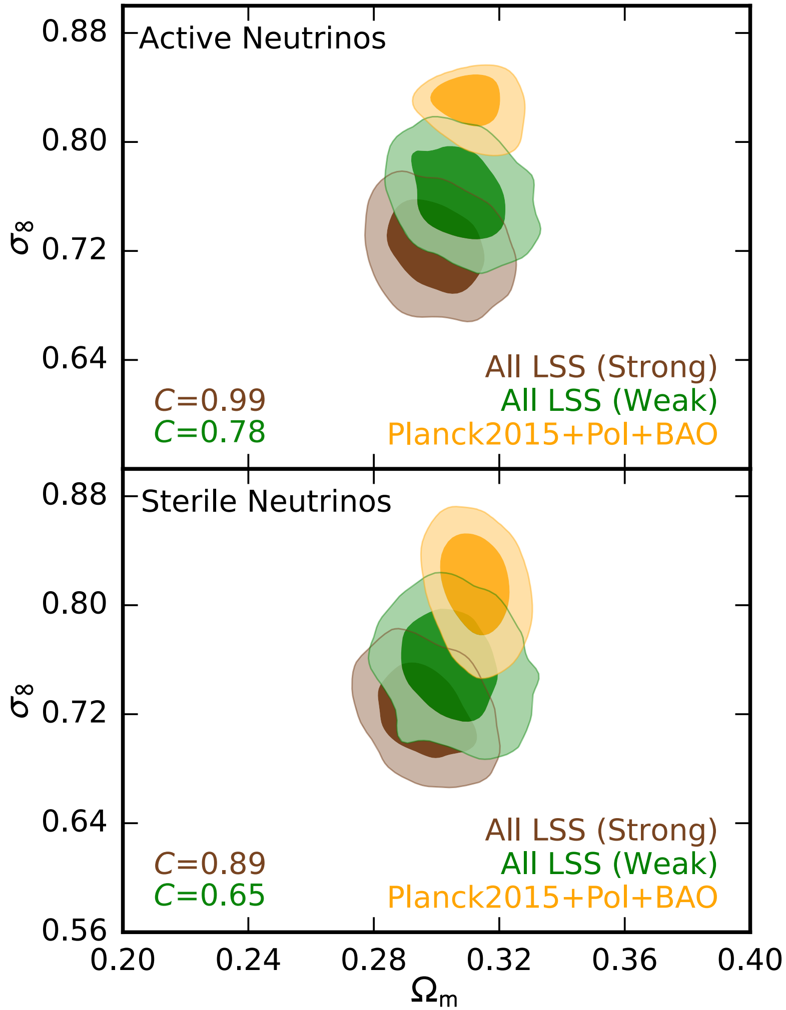
SZ cluster counts

ORANGE IS PRIMARY CMB + BAO

(From Charnock, Battye & Moss, PRD 2017)

Present status of CMB/LSS tension



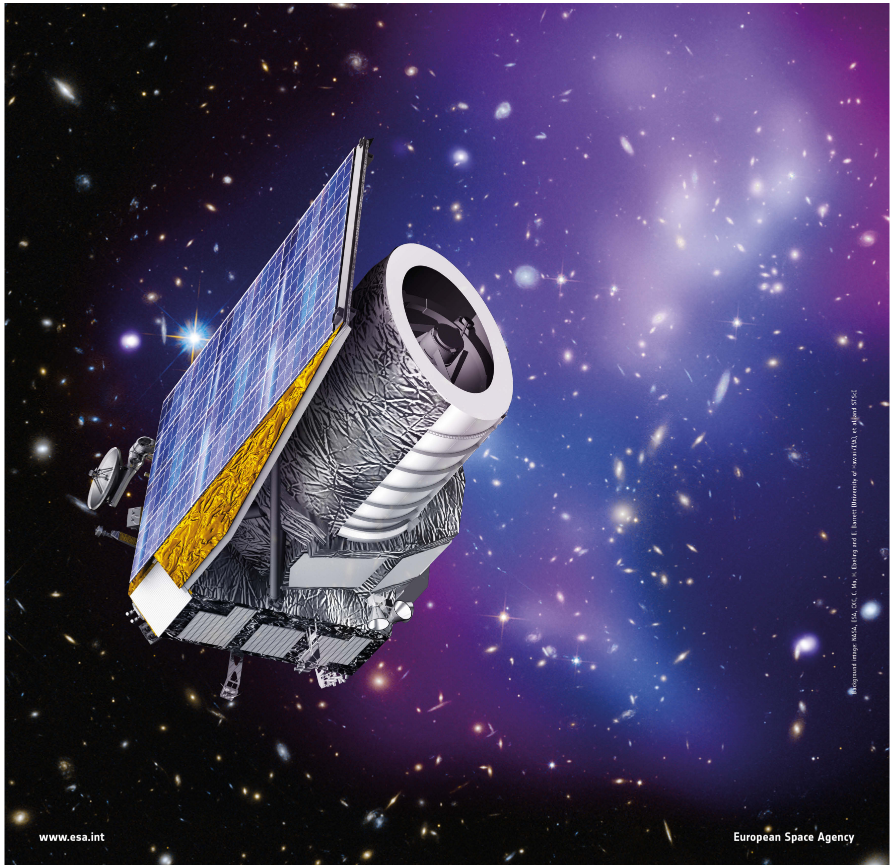


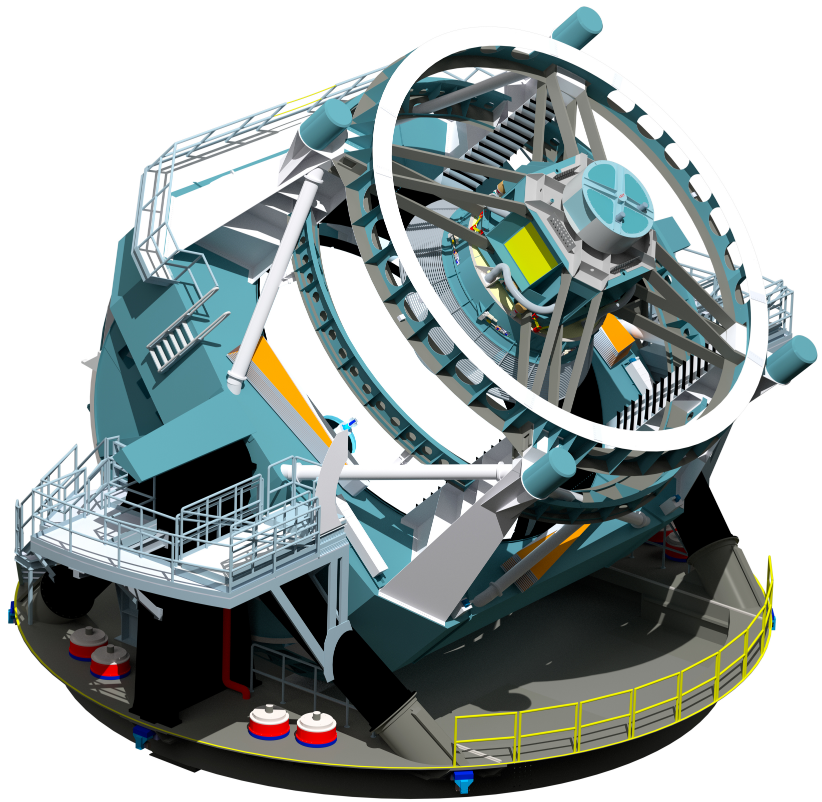
Strong LSS constraints are in tension with Planck at 2.5σ

Stage 4 Cosmology Probes

Euclid consortium

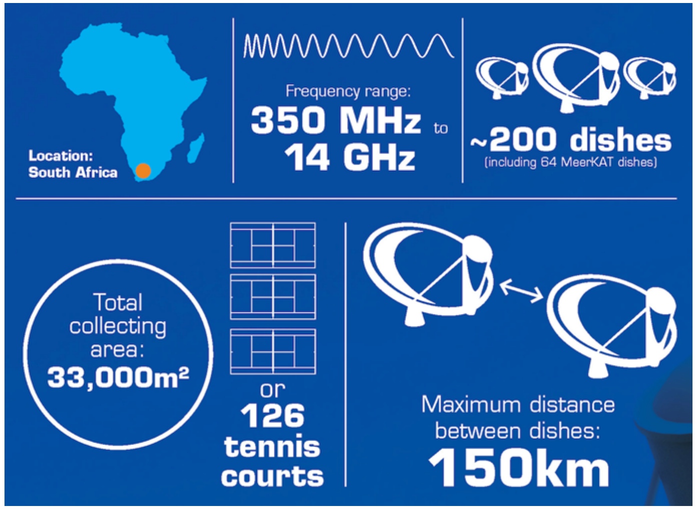
LSST
Large Synoptic Survey Telescope



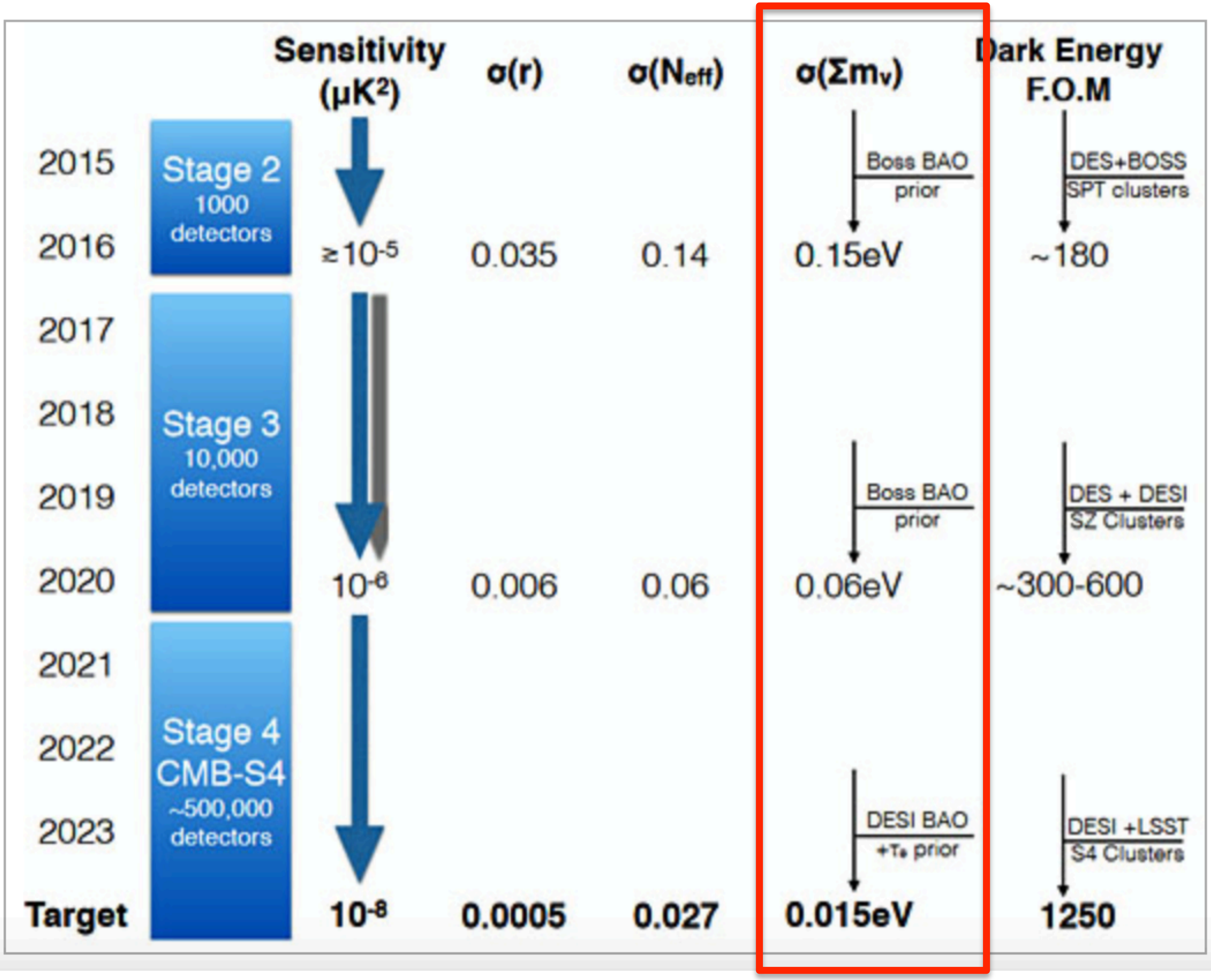


Stage 4 Cosmology Probes

SKA SQUARE KILOMETRE ARRAY



Future Probes



		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 +Ts prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

Conclusions

- Present safe limit : $\Sigma m_\nu < 0.6$ eV from CMB

- Most stringent limit : $\Sigma m_\nu < 0.2$ eV
  - needs input from other measurements eg BAO

- Issues with connecting with LSS – complex !

- Future : $\Sigma m_\nu < 60$ meV (2020ish)
  $\Sigma m_\nu < 15$ meV (2025ish)

At this level of precision we can start to think about separating the masses