Neutrinos in the era of precision Cosmology

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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Rencontres du Vietnam

Quy Nhon - 21 July 2017

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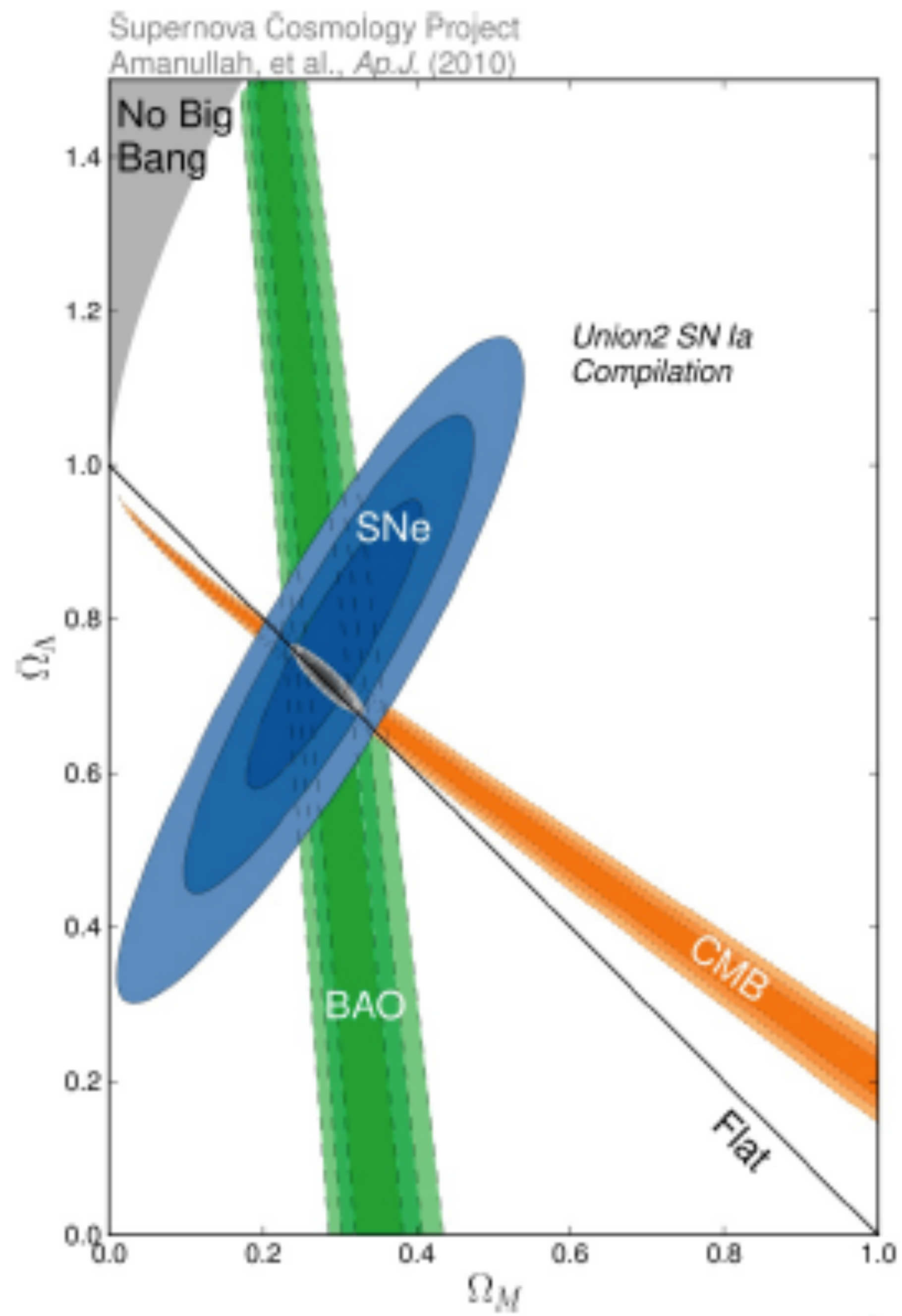
The vanilla model: Λ-CDM

- matter primordial perturbation (scalar, adiabatic) $P_s(k) = A_s(\frac{k}{k_0})^{n_s - 1}$
- expansion rate H_0 (or angular size of the sound horizon θ_s)
- optical depth to reionisation: τ
- energy density of baryons and cold dark matter $\Omega_b h^2$, $\Omega_c h^2$ (or dark energy $\Omega_\Lambda h^2$)
- flat universe: $\Omega_\Lambda = 1 - \Omega_\mathrm{m}$



Cosmic Microwave Background + Baryon Acoustic Oscillations + Supernovae

Concordance model: $\Omega_\Lambda \sim 0.7$, $\Omega_\mathrm{m} \sim 0.3$

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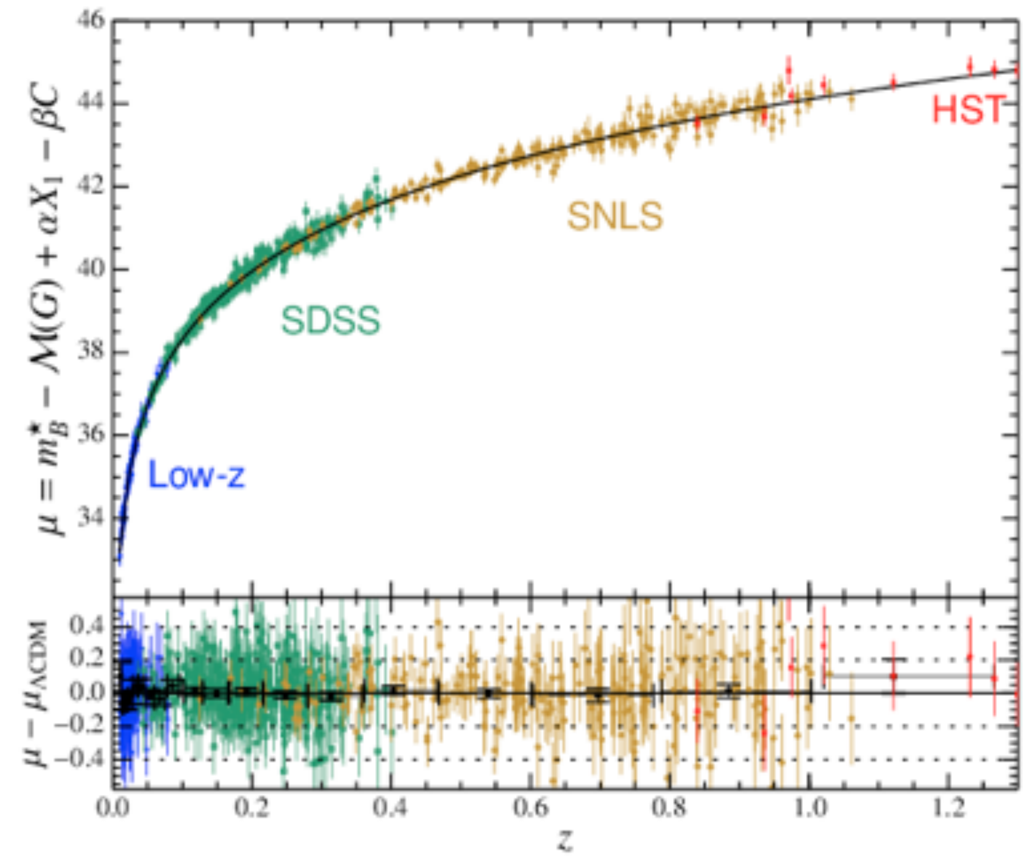
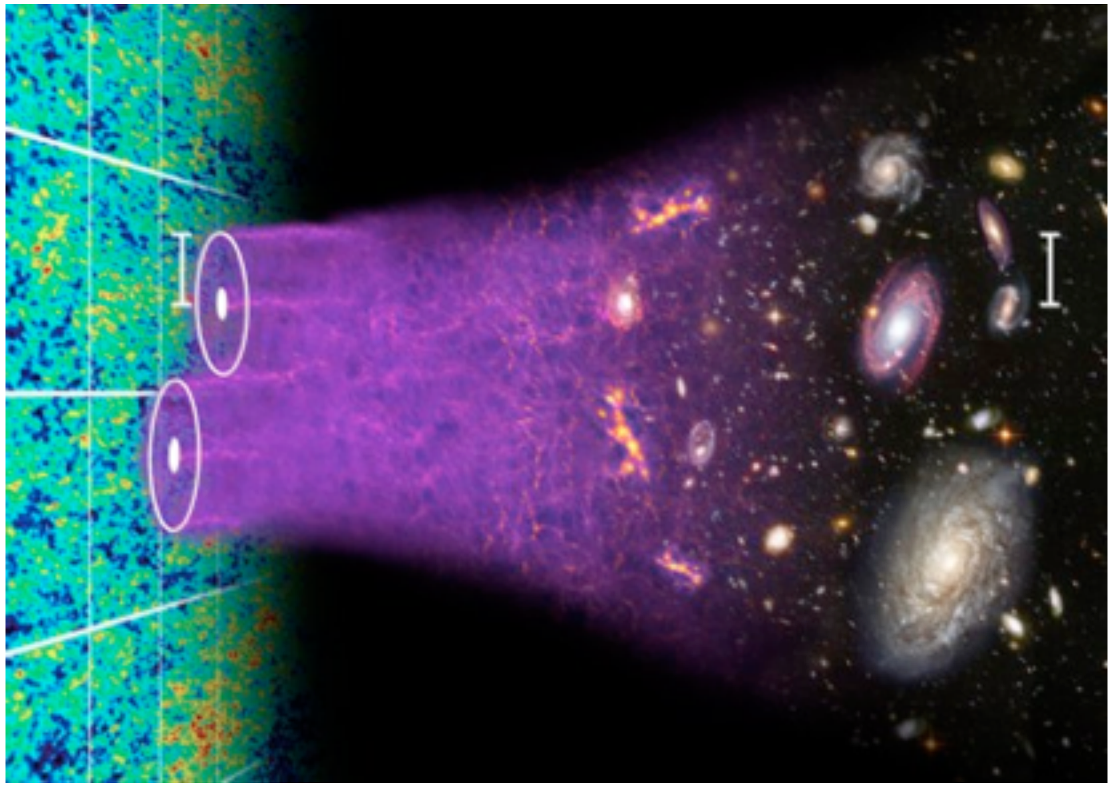
(Late times) cosmological probes



Supernovae Ia

- standard candles
- fundamental in discovering the acceleration of the Universe
- give constraints on Ω_m

JLA compilation -Betoule et al 2014



Baryon Acoustic Oscillations (BAO):

- imprint on present structures of acoustic waves in primordial fluid
- mesure angular diameter distance $D_A(z)$, H(z) and RSD

BOSS-SDSS collaboration results

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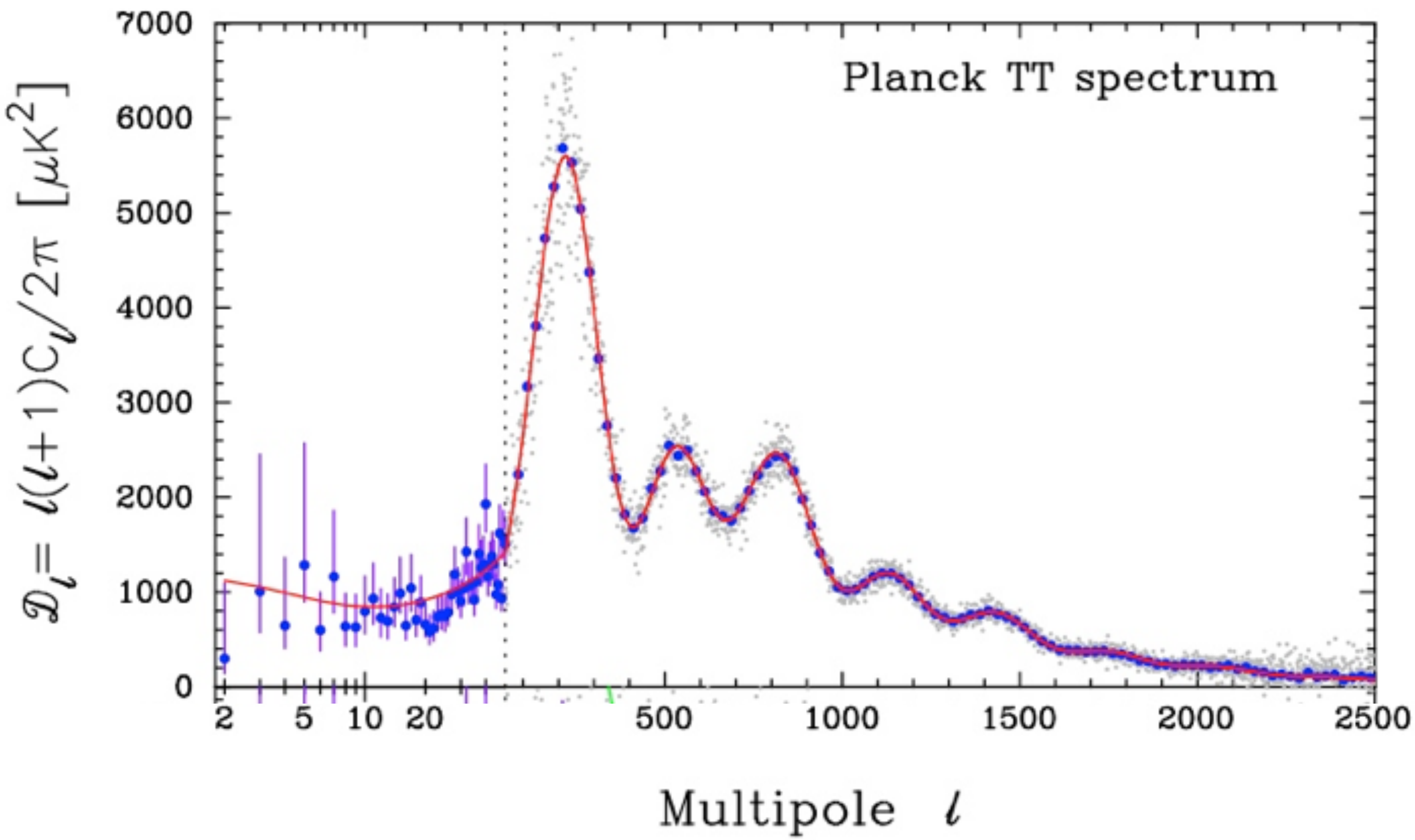
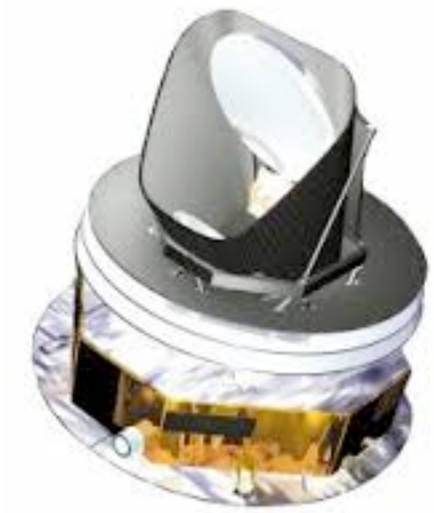
The (early times) cosmological probe

Cosmic Microwave Background: Planck CMB data in temperature and polarisation

Planck collaboration





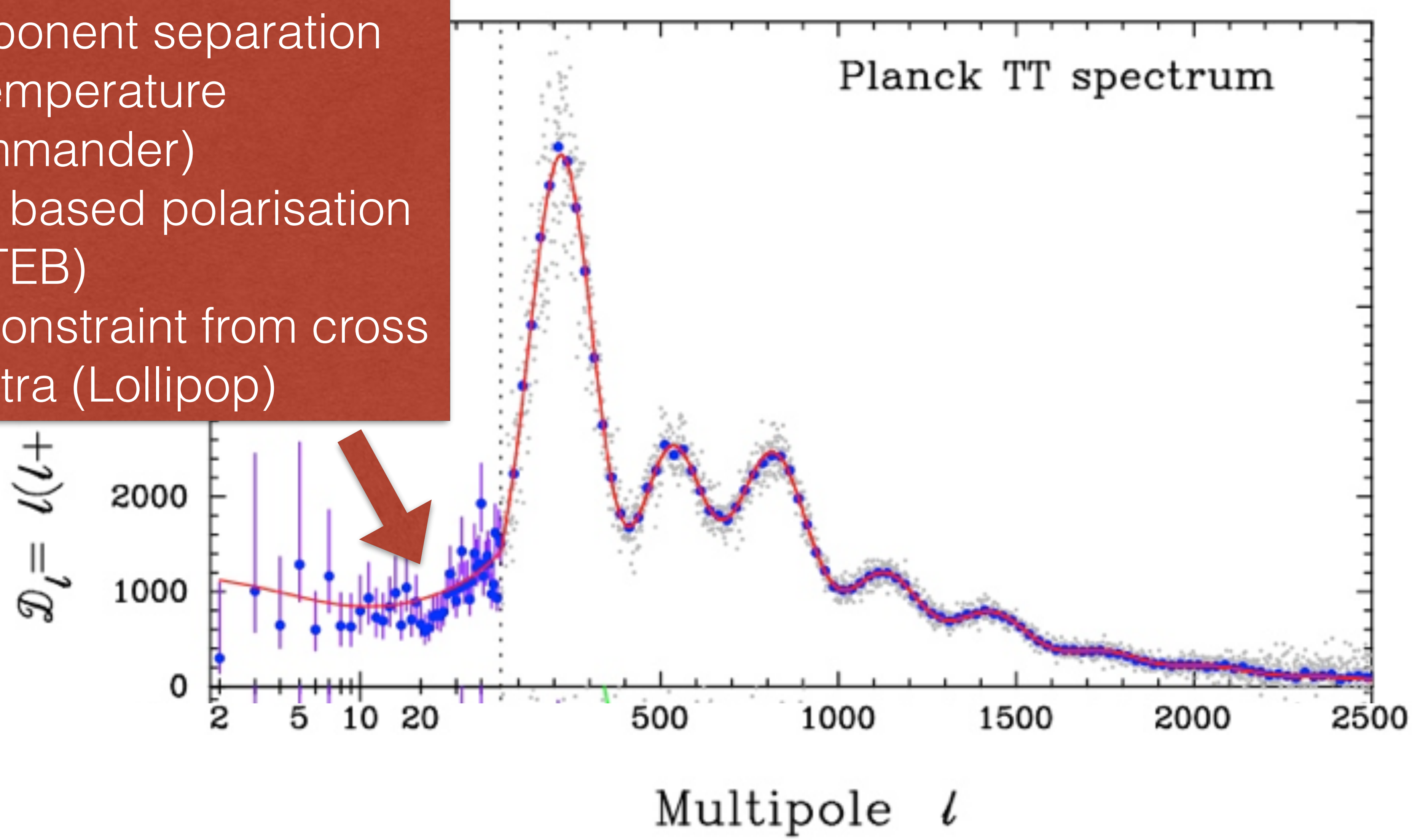
The (early times) cosmological probe

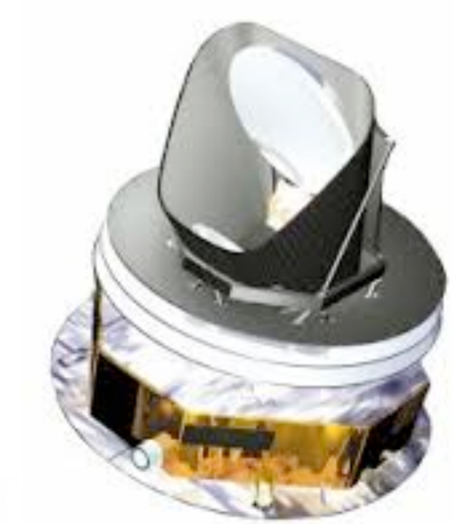
Cosmic Microwave Background: Planck CMB data in temperature and polarisation

Low-l likelihood:
constraint on A_s ad tau

- component separation for temperature (Commander)
- pixel based polarisation (lowTEB)
- tau constraint from cross spectra (Lollipop)

Planck collaboration





The (early times) cosmological probe

Cosmic Microwave Background: Planck CMB data in temperature and polarisation

Low-l likelihood:
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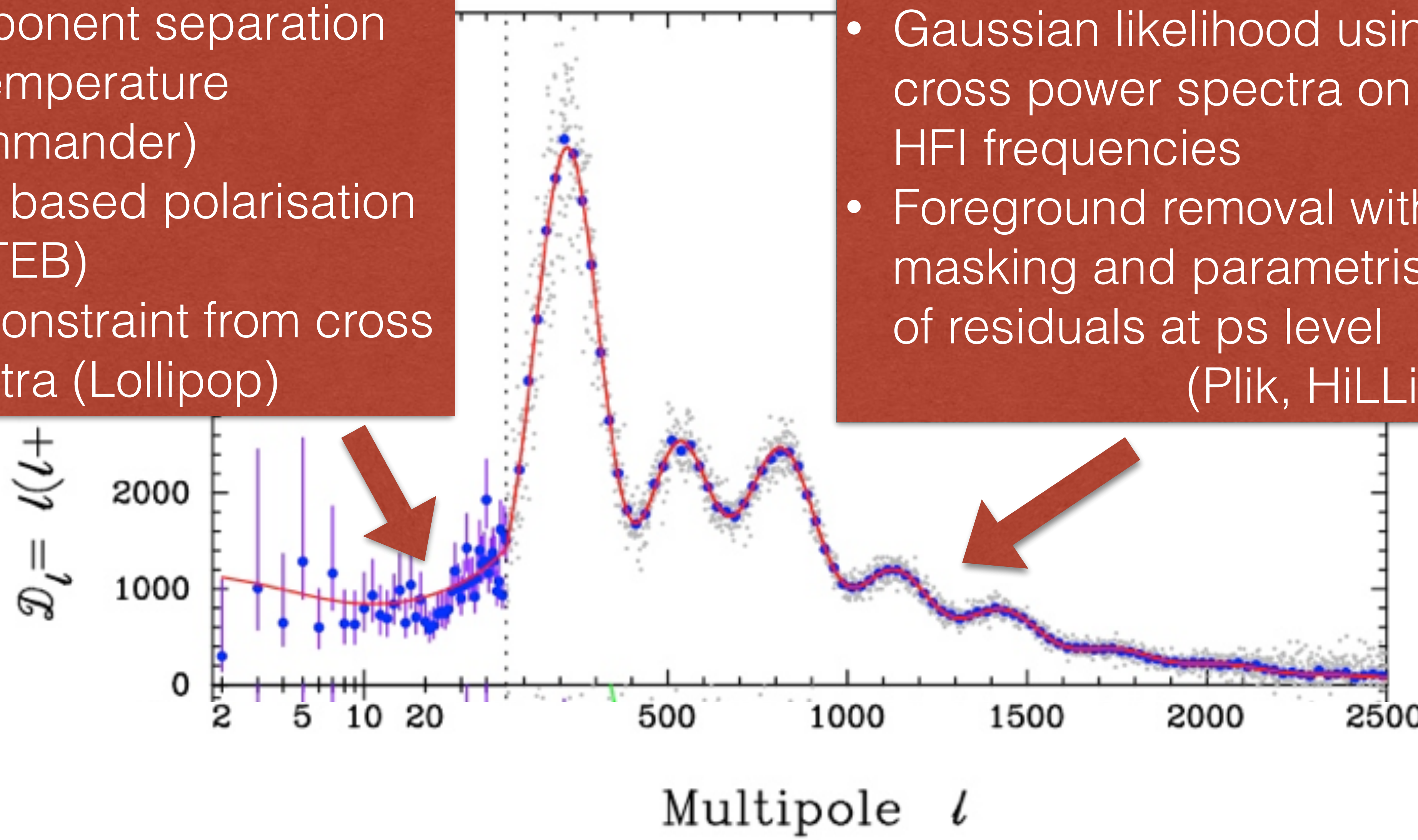
High-l likelihood:
constraints on all parameters

- Gaussian likelihood using cross power spectra on lower HFI frequencies
- Foreground removal with masking and parametrisation of residuals at ps level (Plik, HiLLiPOP)



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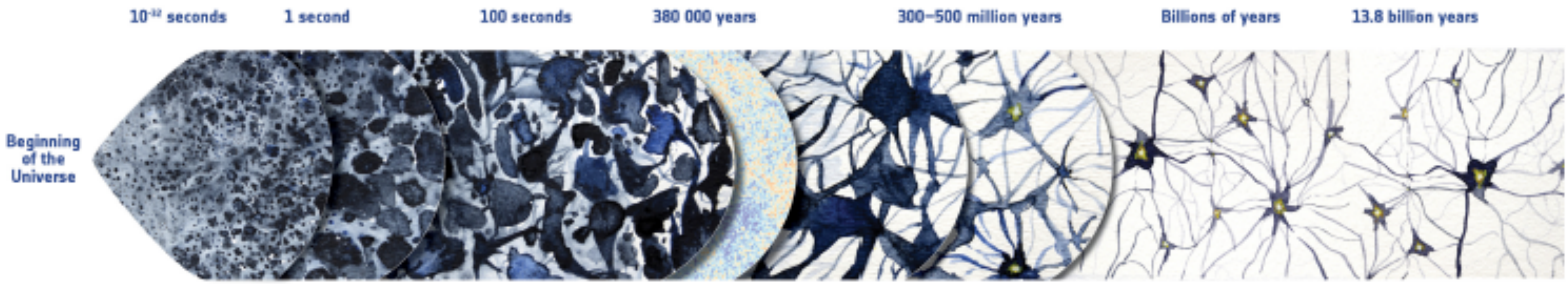
Neutrinos and cosmology



$N_{\rm eff}$ $\sum m_\nu$

Early Universe

- $T \gg 1$ MeV νs populated by weak interaction
- $T_{\rm dec} \sim$ sec (1 MeV)

Late time

- still relativistic at decoupling
- $T_\nu \lesssim m_\nu$ contribute to matter content and structure formation

Effect on CMB and Large Scale Structures (LSS)

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Cosmic neutrino properties

- After neutrinos decoupled → cosmic neutrino background (like CMB for photons)
- If we assume they are massless
  - from entropy conservation calculate their temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.95\text{K}$$

(photons are hotter thanks to electron-positron annihilation)

  - 3 generations and follow Fermi-Dirac statistics:

$$\rho_\nu c^2 = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

↗ 3.046 (e.g. Mangano et al. 2005)

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Neff

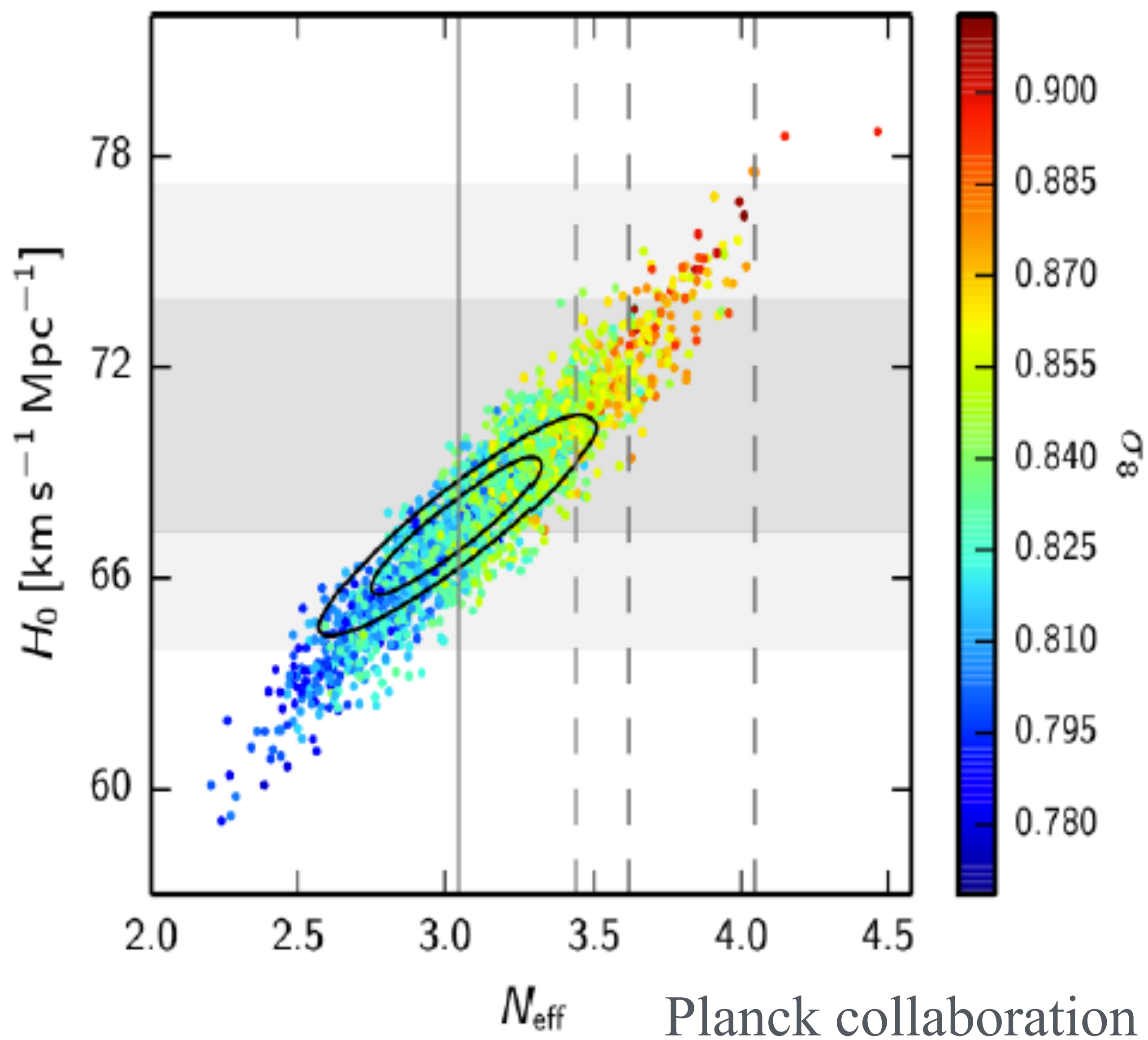
(~ massless) degree of freedom beyond photons, relativistic during radiation domination (any light relic, axions, …)

$$\rho_\nu c^2 = \textbf{Neff} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

Planck 2015 TT +BAO

$N_{\rm eff} = 3.15 \pm 0.23$

- $N_{\rm eff} \neq 0$ CνB existence ($\sim 15\sigma$)
- $N_{\rm eff} = 4$ excluded at $\sim 3-5$

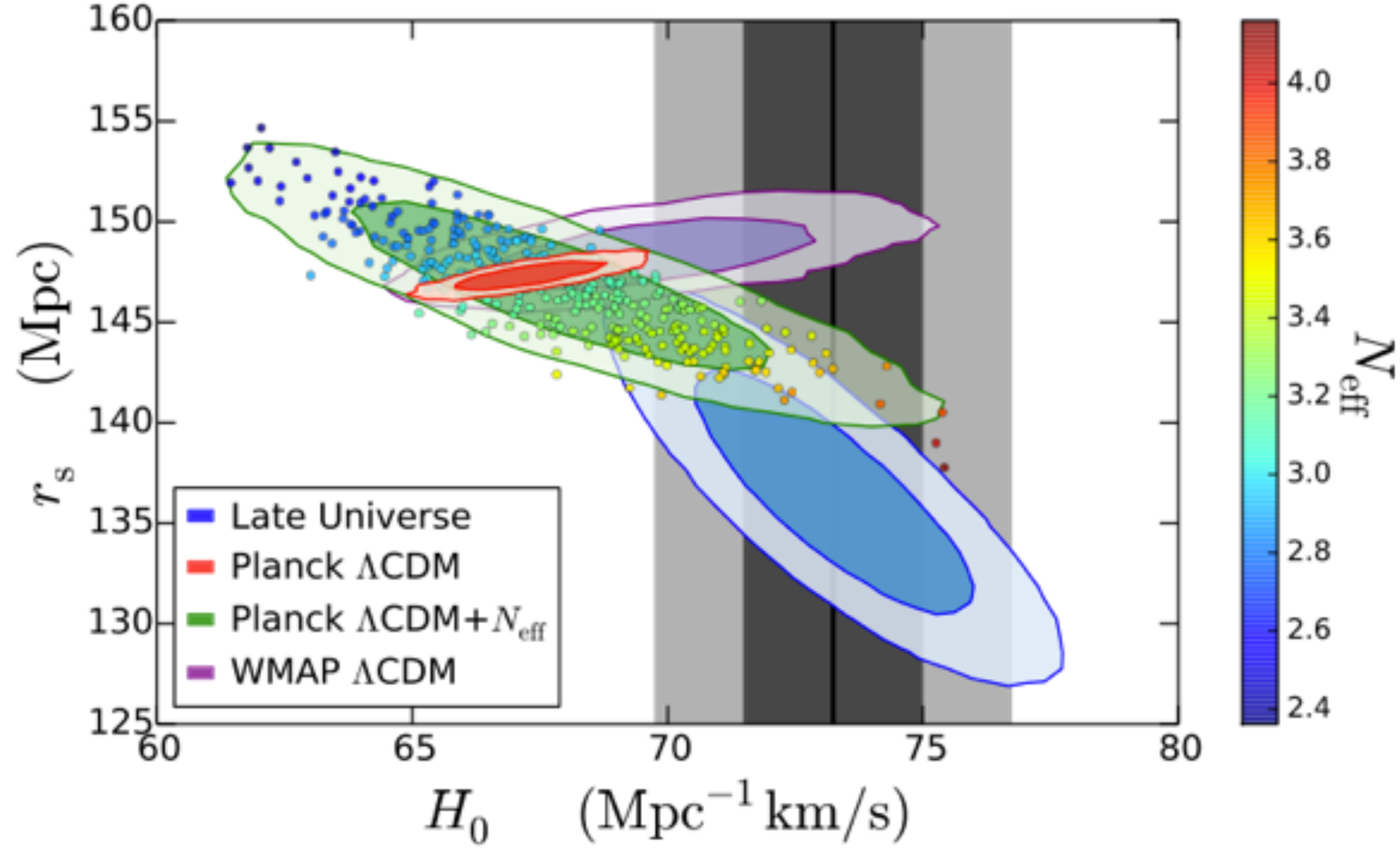


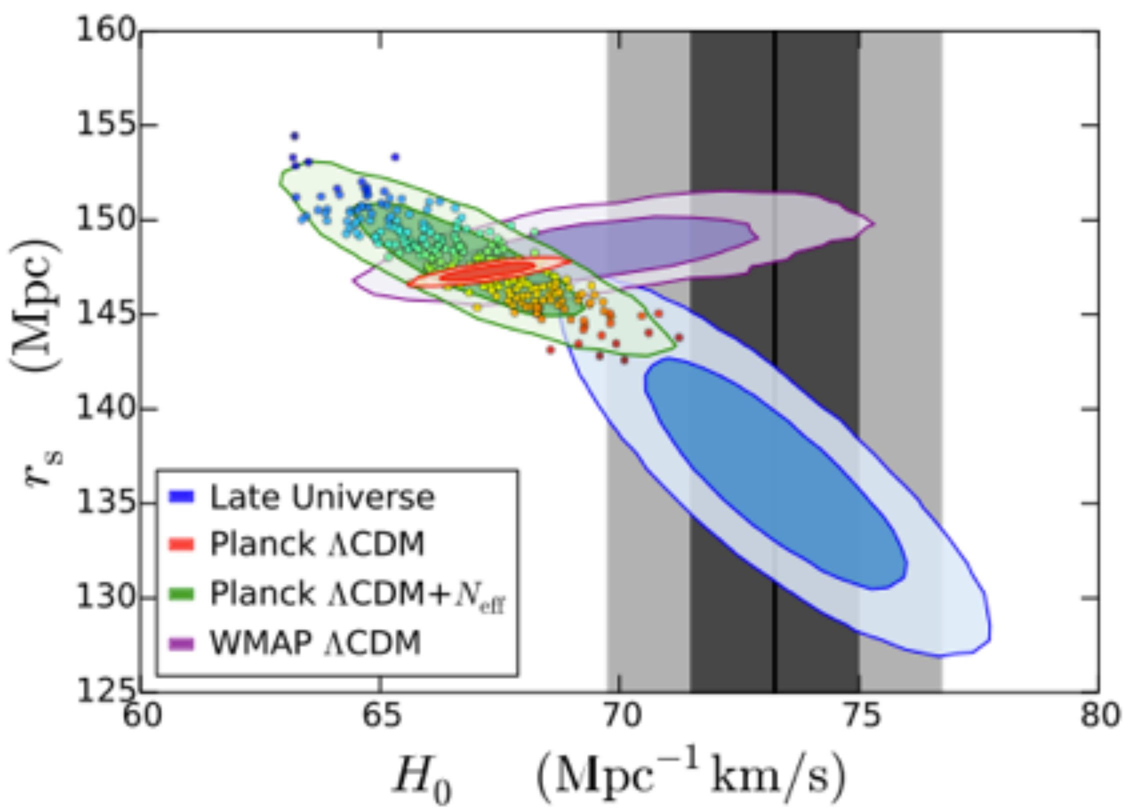
Planck collaboration

Neff and H0

- Planck H0 *vs.* local H0 (3 sigma)
- BAO and SNIa constrain rs-h
- Can Neff help in solving this tension?

$$\Delta N_{\rm eff} \sim 0.4$$





- NOT true anymore if Planck polarisation is included

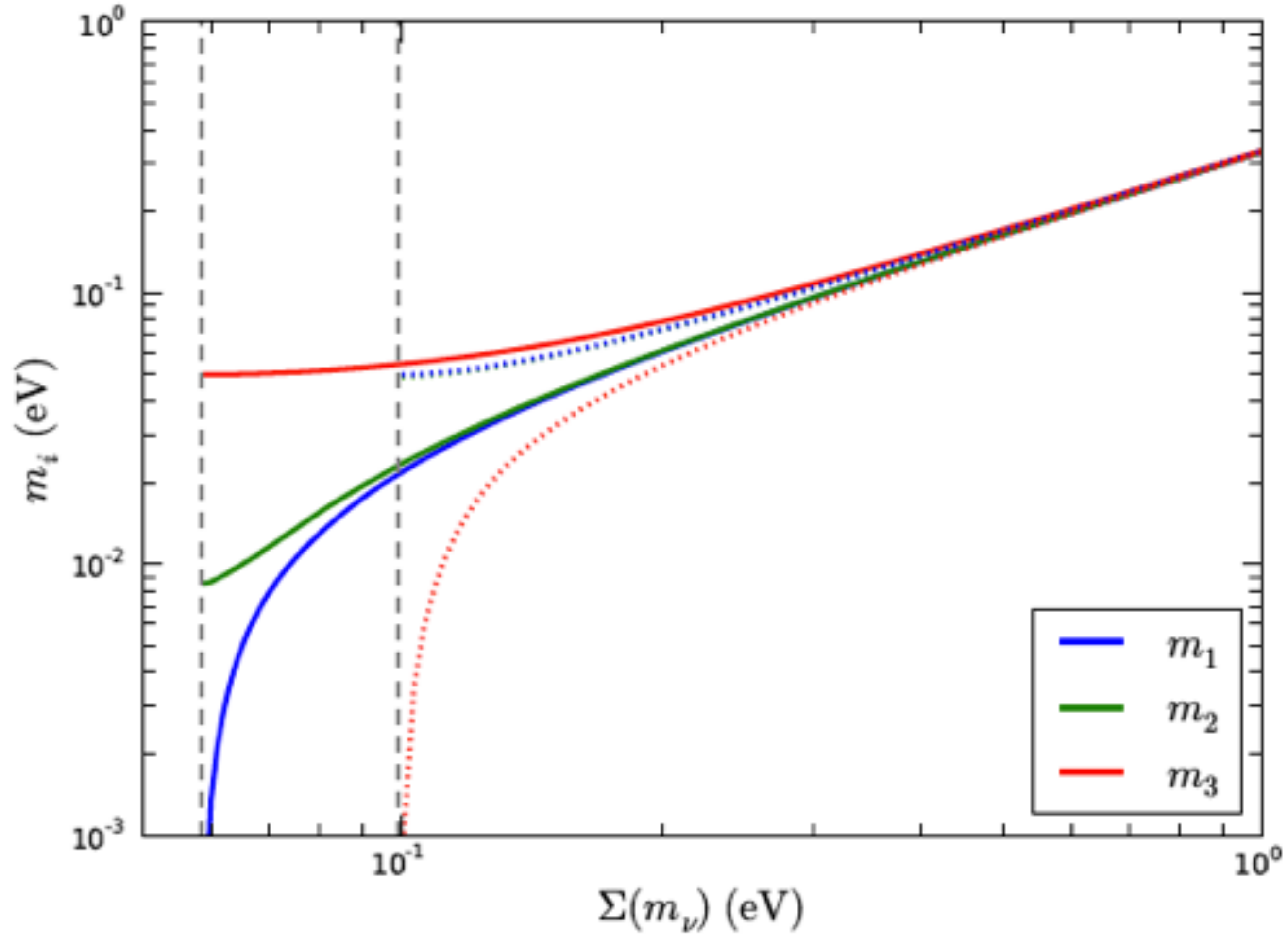
Bernal et al 2016 (arXiv:1607.05617)

The absolute scale of neutrino masses

- neutrino MO not known but lower limits from oscillations (0.06 eV NO, 0.10 eV IO)
- model dependent constraints
  Λ-CDM + neutrino sector
  - Neff=3.046
  - 1m 20, 3m (deg, NO, IO)
- mass limit (95% CL)
  (from various ref)

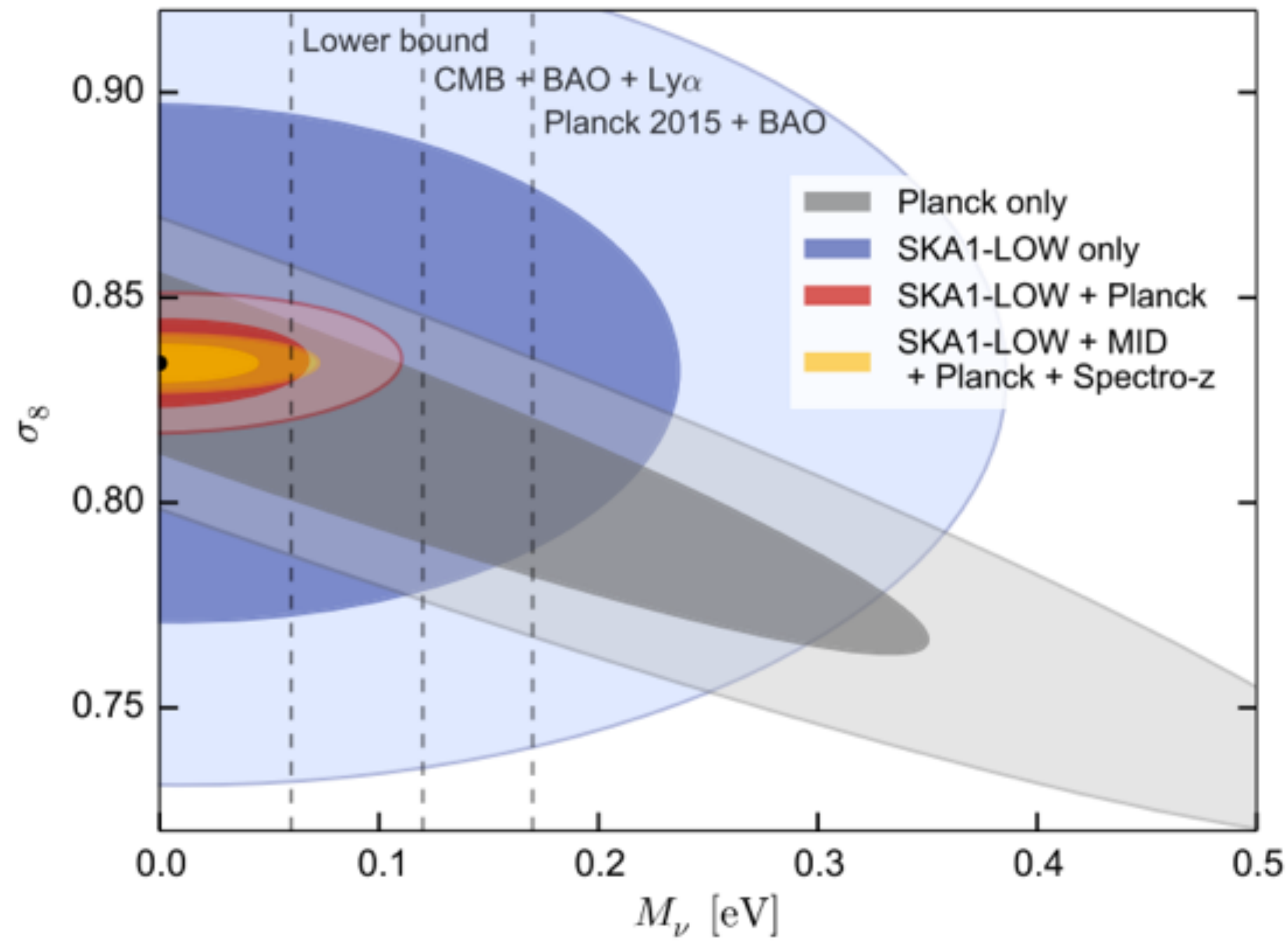
$$\Sigma m_\nu < 0.11 - 0.23 \text{ eV}$$

Planck + BAO/SN/Lensing…



Forecast from 21cm

Villaescusa-Navarro et al 2015



- HI more clustered for cosmology with massive neutrino
- hydrodynamic sims with massive neutrino for HI spatial distribution
- fisher matrix forecast for SKA
  - SKA-LOW $3 \lesssim z \lesssim 6$ (interferometric mode)
  - SKA-MID $z \lesssim 3$ (single dish)

$$\sigma(M_\nu) \lesssim 0.3 \text{ eV } (95\% \text{ CL})$$

- SKA+Planck+Spectro-z $\sigma(M_\nu) \simeq 0.06 \text{ eV } (95\% \text{ CL})$

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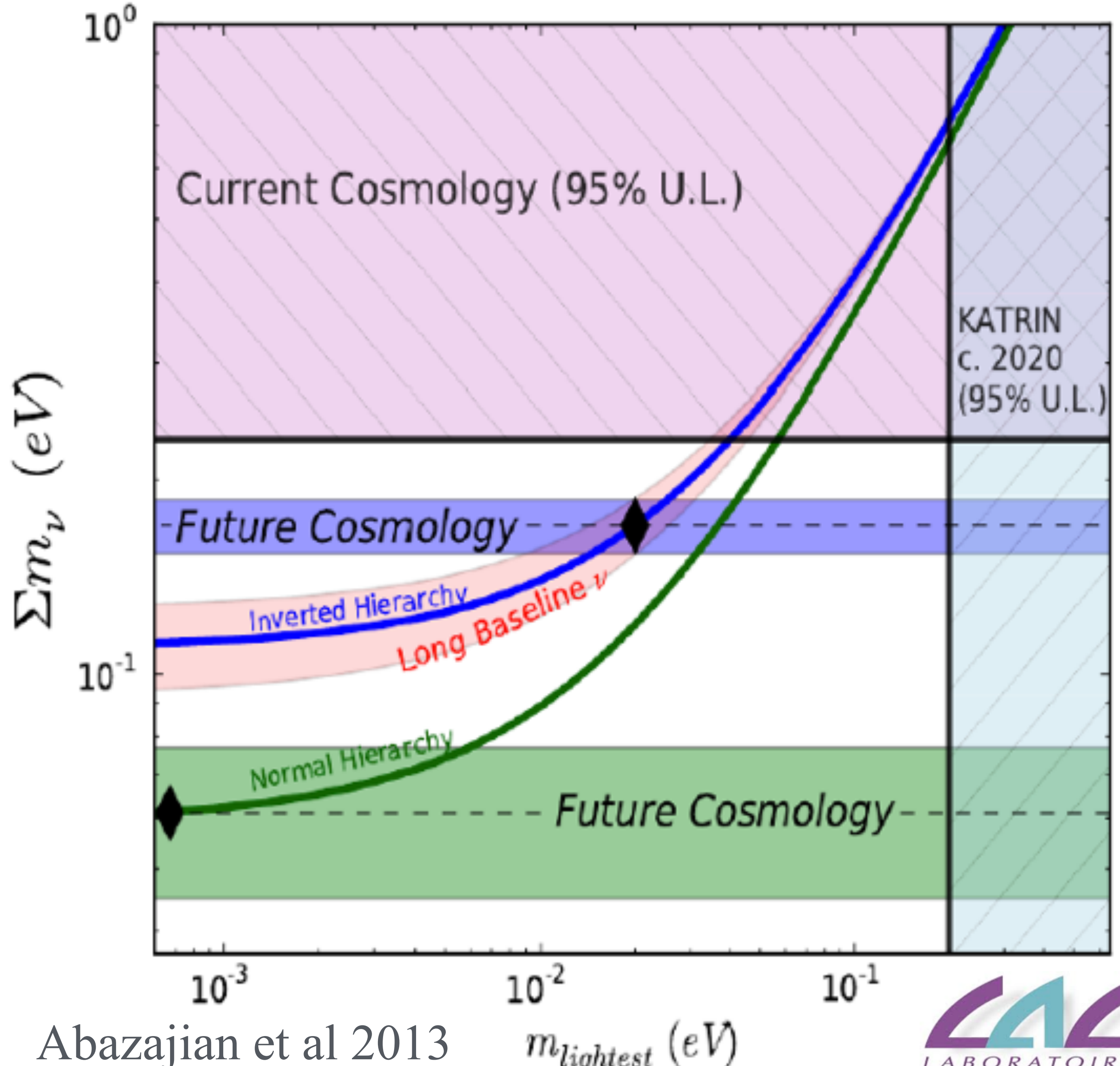
How close to a mass measurement?

If m=0.06 eV we need 20 meV sensitivity for 3 sigma.
If m=0.12 eV then 40 meV in enough

- Simons Array: 58 meV from lensed B modes
- SA+BAO: 16 meV

  http://bolo.berkeley.edu/polarbear

- Euclid (2020): 3meV
  enough for MO
- Forecasts for DESI+
  (arXiv:1308.4164)
  by 2020 something either from Planck+DESI/LSST/S4&BAO



Abazajian et al 2013

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Precision cosmology

- How robust is the Planck+LSS limit on Σm_ν?
  - does it depend on foreground parametrisation?
  - how it relates to lensing? (the A_L issue)
  - …

→ some work done @ LAL
(F. Couchot, S. Henrot-Versillé, O. Perdereau, S. Plaszczynski, B. Rouillé d’Orfeuil, M. Spinelli and M. Tristram)

http://camel.in2p3.fr

- HiLLiPOP *(Planck 2015 Likelihood paper)*
- A_L and tau *(Couchot et al 2016)*
- CAMEL framework *(Henrot-Versillé et al 2016)*
- all that and Σm_ν (Couchot et al 2017)

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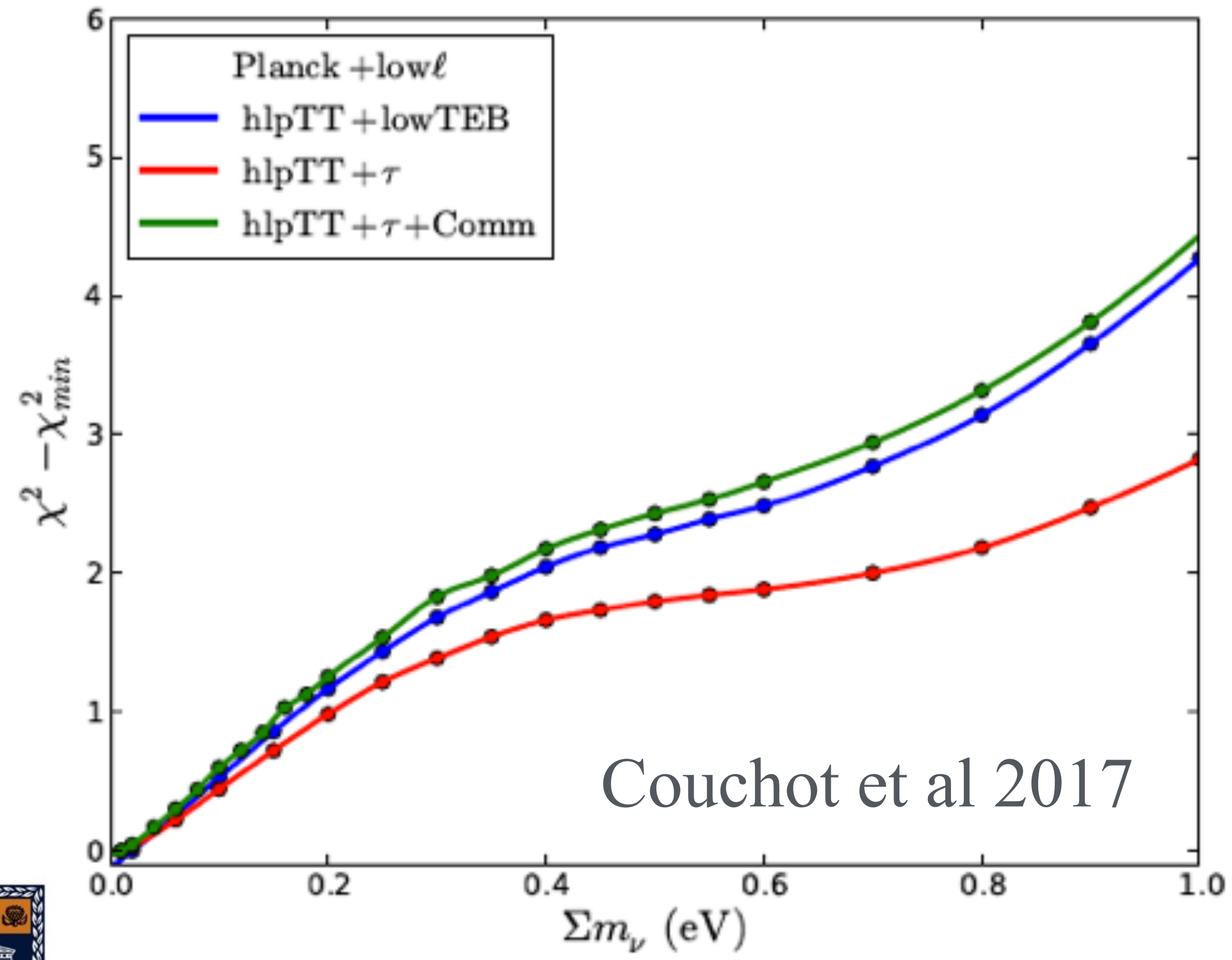
Large scale (low-l) information

Low-l likelihoods:

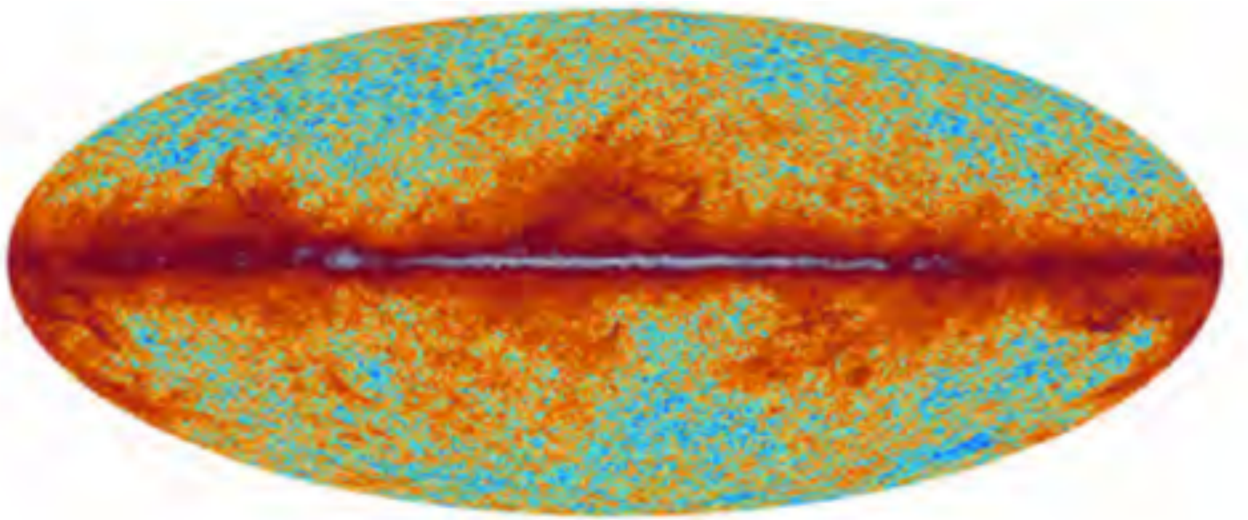
- Commander - temperature component separation
- tau constraint from large scale cross power spectra polarisation data
- lowTEB - Commander-like temperature and pixel based polarisation

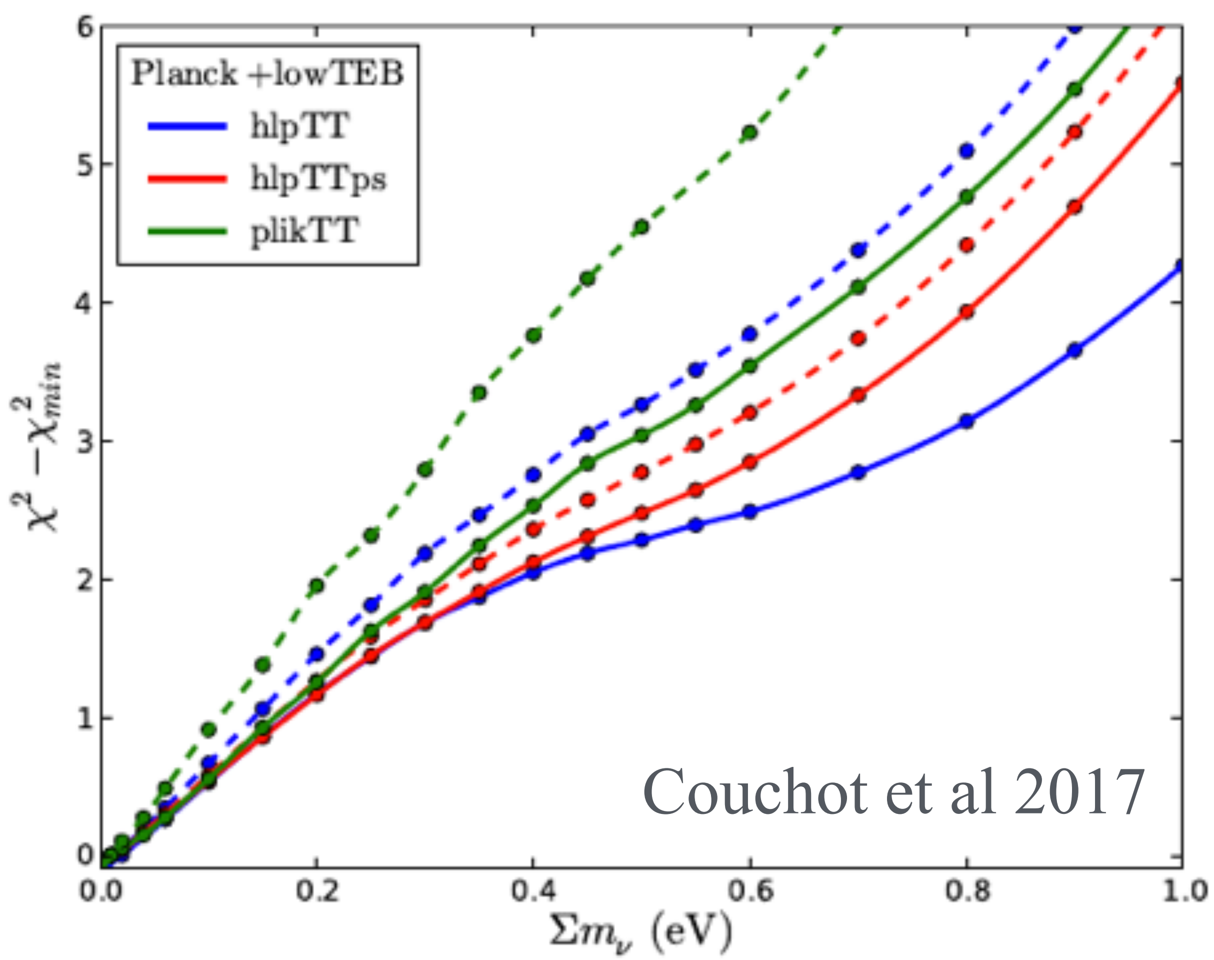


- Large scale CMB information is crucial for breaking As-tau degeneracy (in particular polarisation)
- Different likelihood choices give slightly different results

Impact of foreground modelling

Planck @ 217 GHz



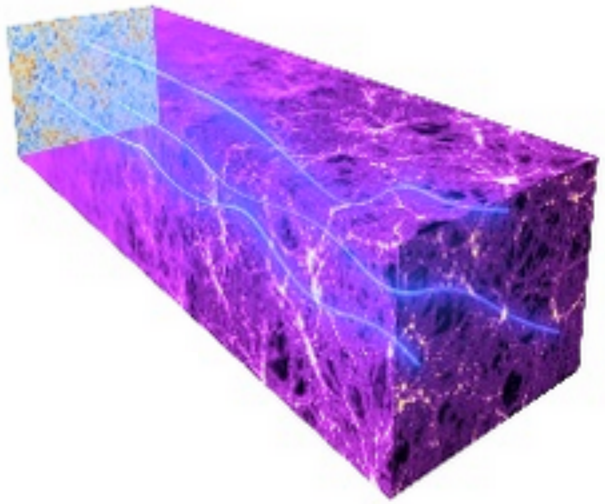


Couchot et al 2017

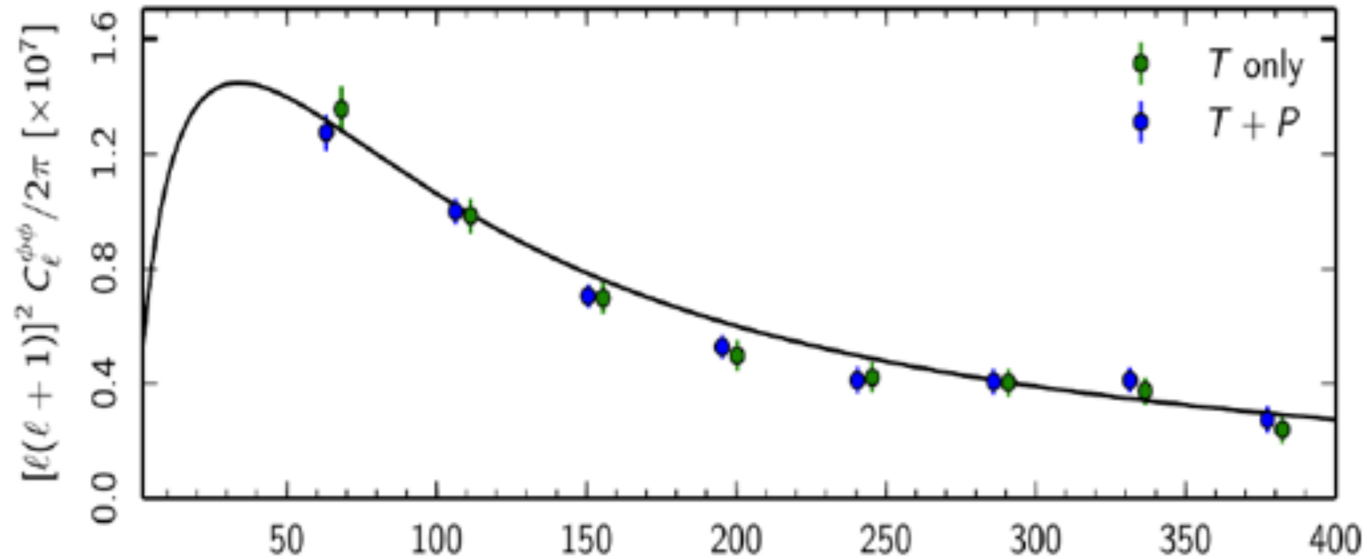
- CMB data comes with astrophysical foregrounds: galactic dust, unresolved point sources, background from galaxies and clusters
- Masking strategy and (data driven) parametric residual modelling
- Different high-l likelihoods HiLLiPOP, HiLLiPS, Plik have slightly different models

we can estimate a systematic error

CMB lensing and AL



$C_\ell^{\phi\phi}$ from 4-point correlation function:
good consistency with ΛCDM



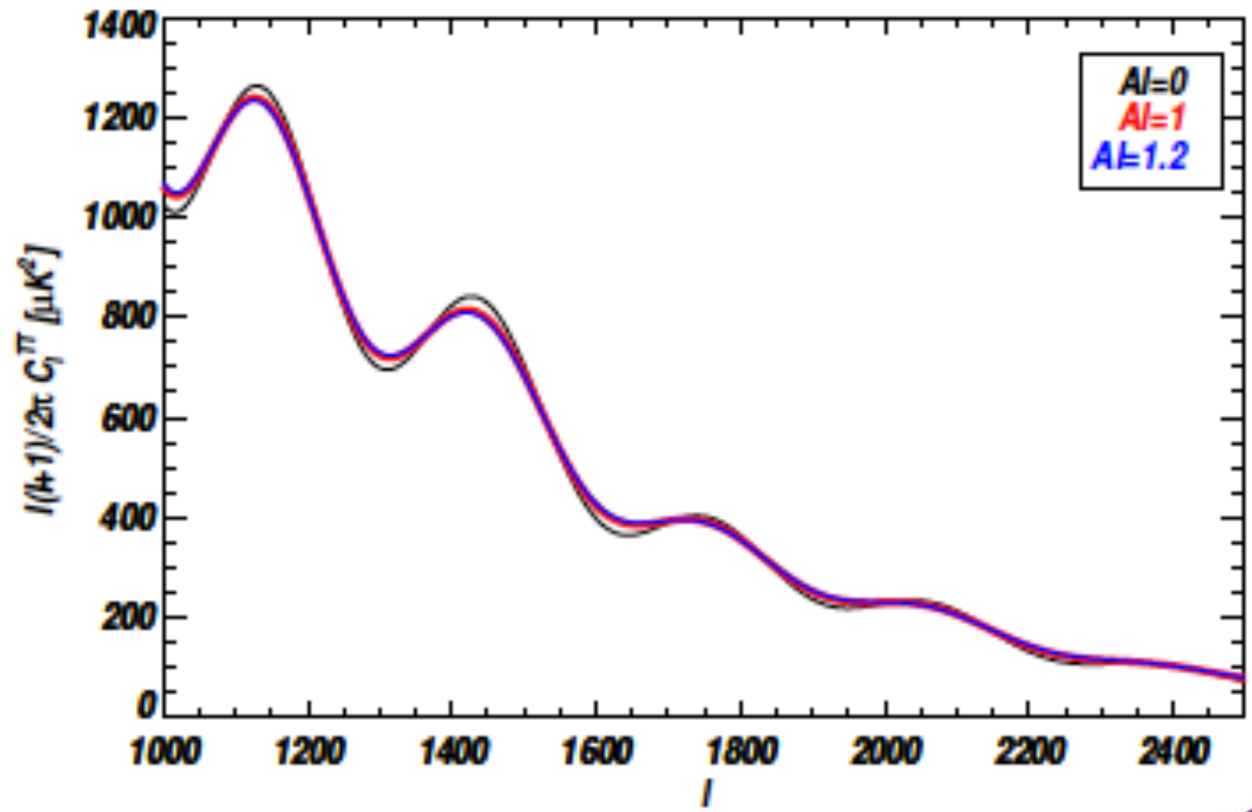
- too much lensing at power spectrum level

$A_L > 1 (\sim 2\sigma)$

↳ Σm_ν artificially low

☐ include AL in the fit to propagate the error

☑ find a consistent framework



Planck+Lensing has AL ~1

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Neutrino mass repartition

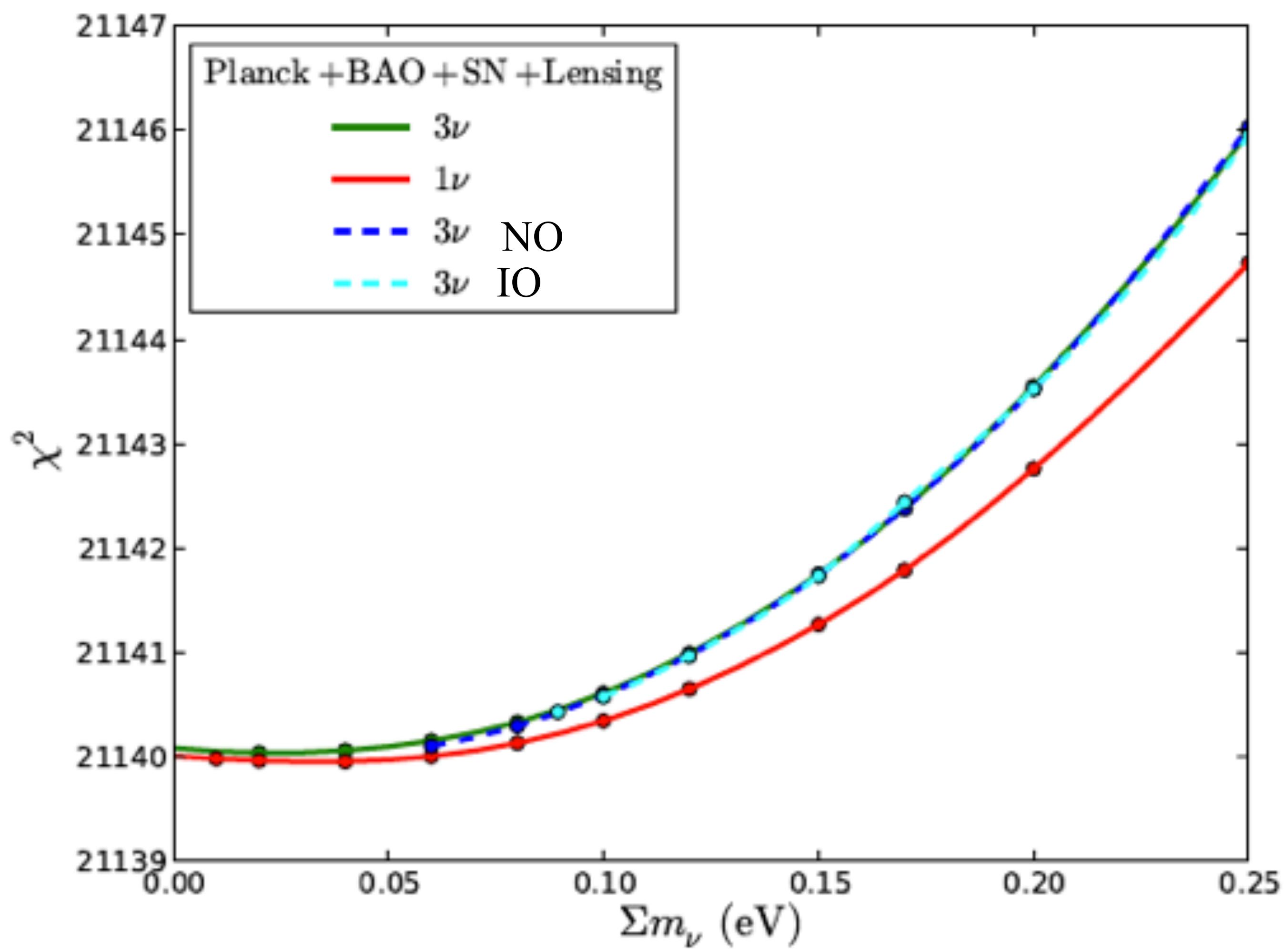
Possible models:

- 3 degenerate masses
- 1 massive 2 massless
- 3 massive with NO
- 3 massive with IO

if only one massive neutrino computationally more efficient but too raw approximation

nowadays no hint for a preference for NO or IO

Couchot et al 2017



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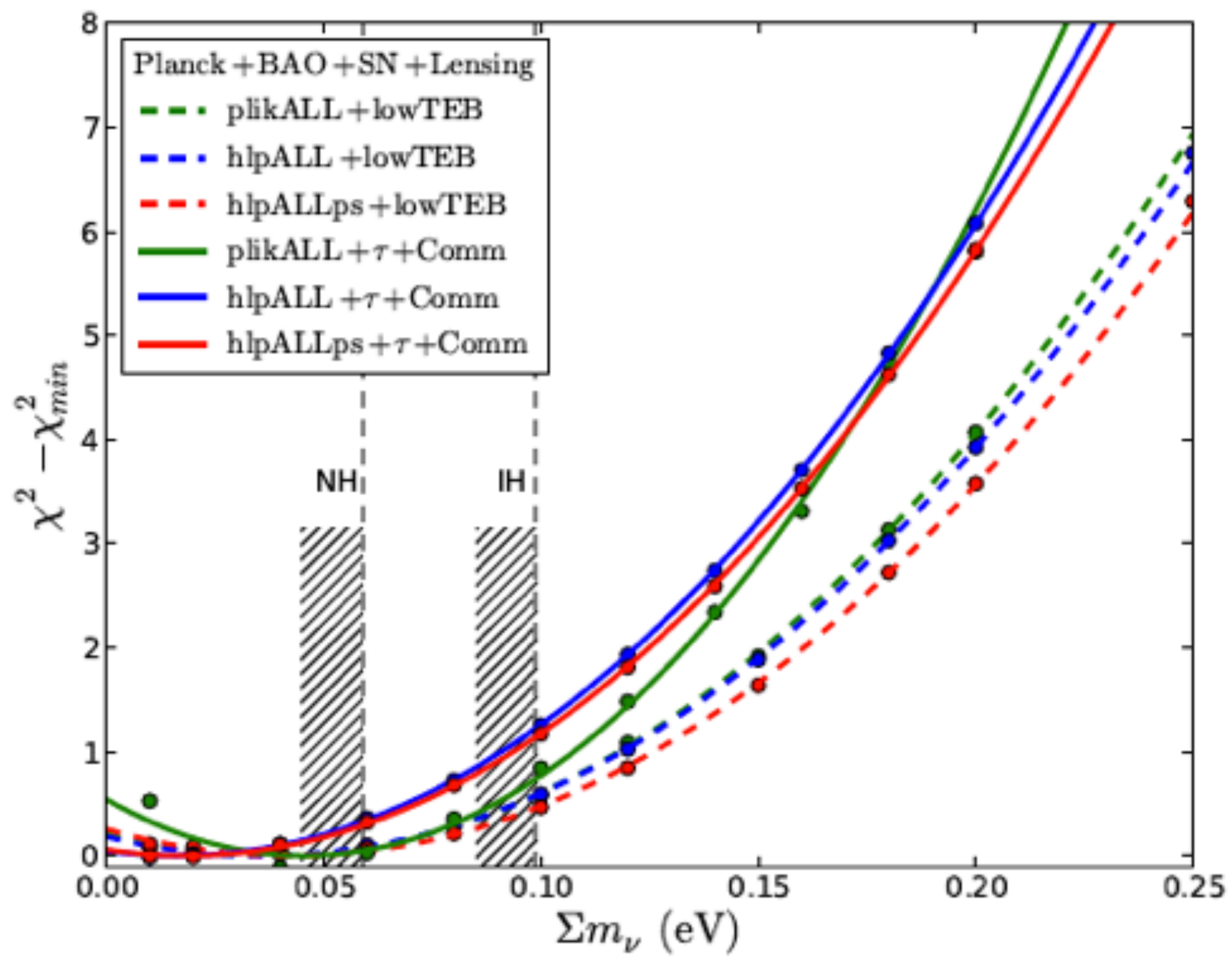
A robust constraint

- latest BAO data *(Alam et al 2016)* and SN from JLA compilation
- low tau constraint from Planck-pol
- AL consistent with standard cosmology *(CMB Lensing)*
- data driven mass splitting scenario *(3m deg)*
- including systematic error related to foreground modelling

Couchot et al 2017



$$\Sigma m_\nu < 0.17 \text{ [incl. } 0.01 \text{ (foreground syst.)] eV at } 95\%$$

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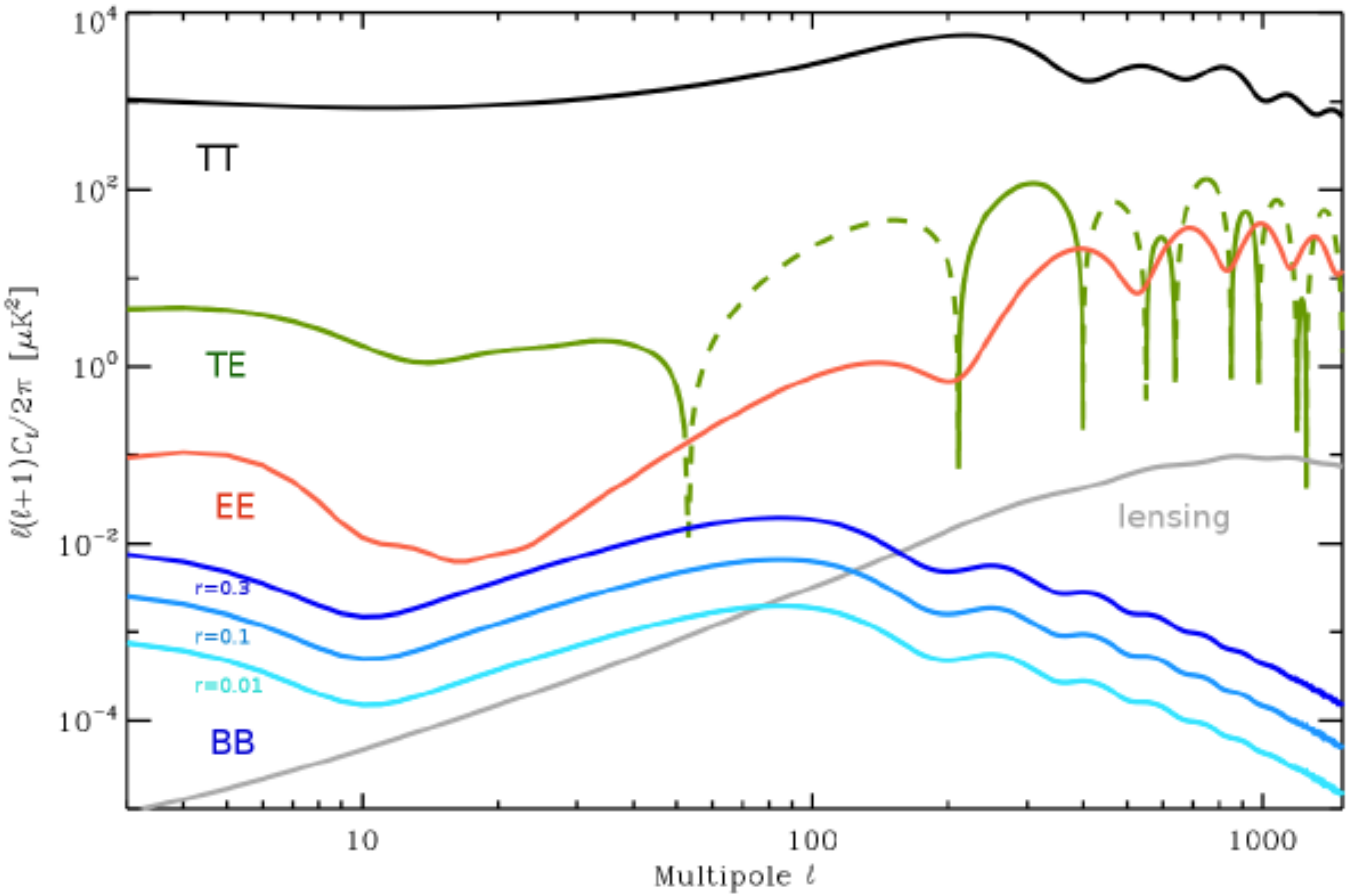
Conclusions

- Cosmology is a rich laboratory to test neutrino properties
- CMB and LSS can constrain the sum of the masses and will reach impressive precision in the future
  forecasts say that we will know more by the end of 2020
- Planck full-sky CMB measurements will remain crucial
- Finer constraints need finer control of all the systematics in the data

At present: addition of lensing + foreground systematic error result in a consistent cosmological limit

Backup

CMB spectra



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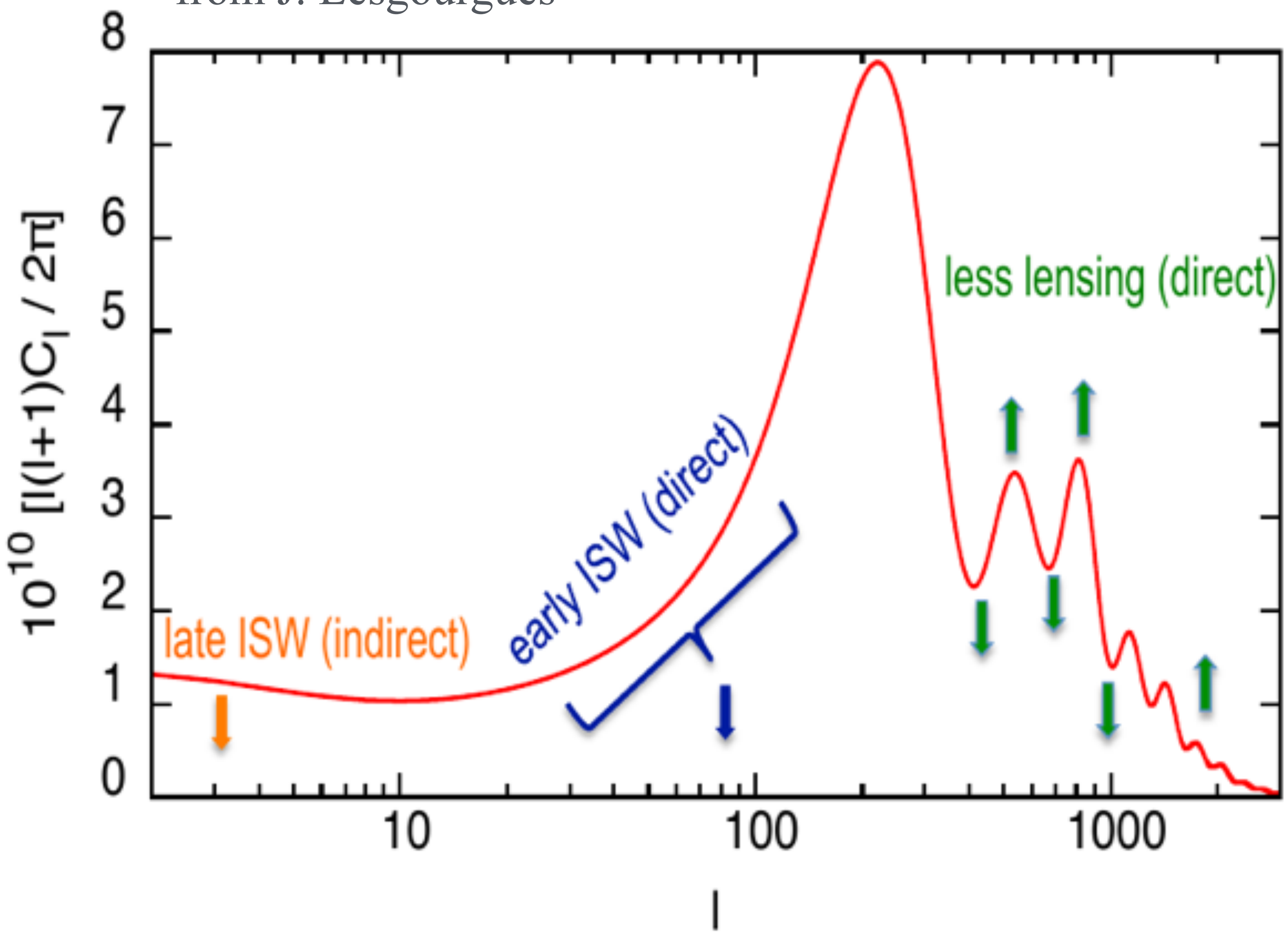
Effect on CMB

from J. Lesgourgues



- indirect role in the duration of DE domination: late ISW at low multipole
- around the fist peak: early-ISW (WMAP limit)

- neutrino damps scales smaller then their free-streaming length: less lensing at small angular scales (that's why Planck is important)

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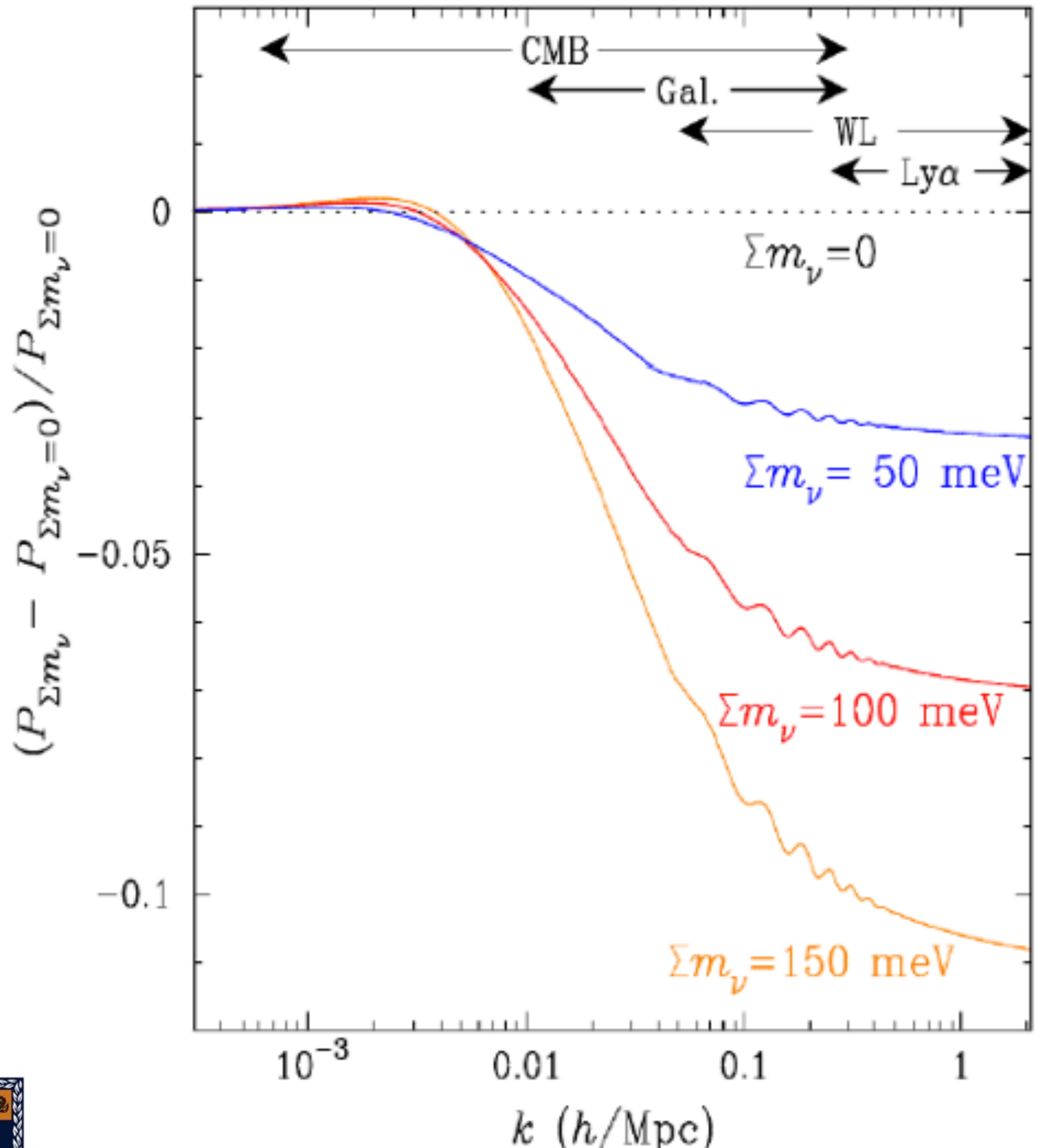
Effect on structure formation



Abazajian et al 2013

- transition from relativistic to nr

$$z \sim 2000 \frac{m_\nu}{1\mathrm{eV}}$$

- wash out structures with k bigger than

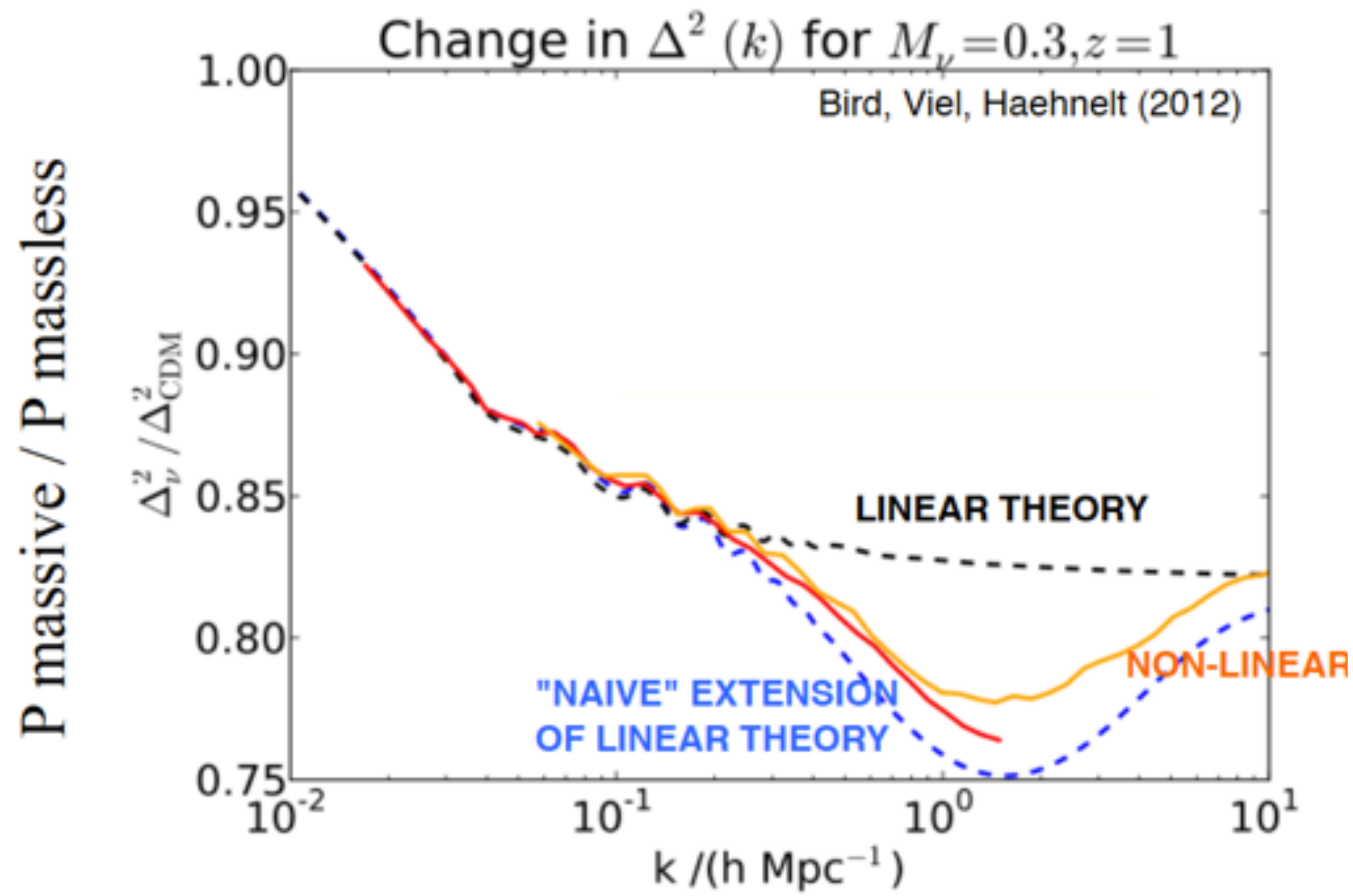
$$k_{\mathrm{nr}} \simeq 0.018 \sqrt{\Omega_m \frac{m_\nu}{1eV}}\, h/\mathrm{Mpc}$$

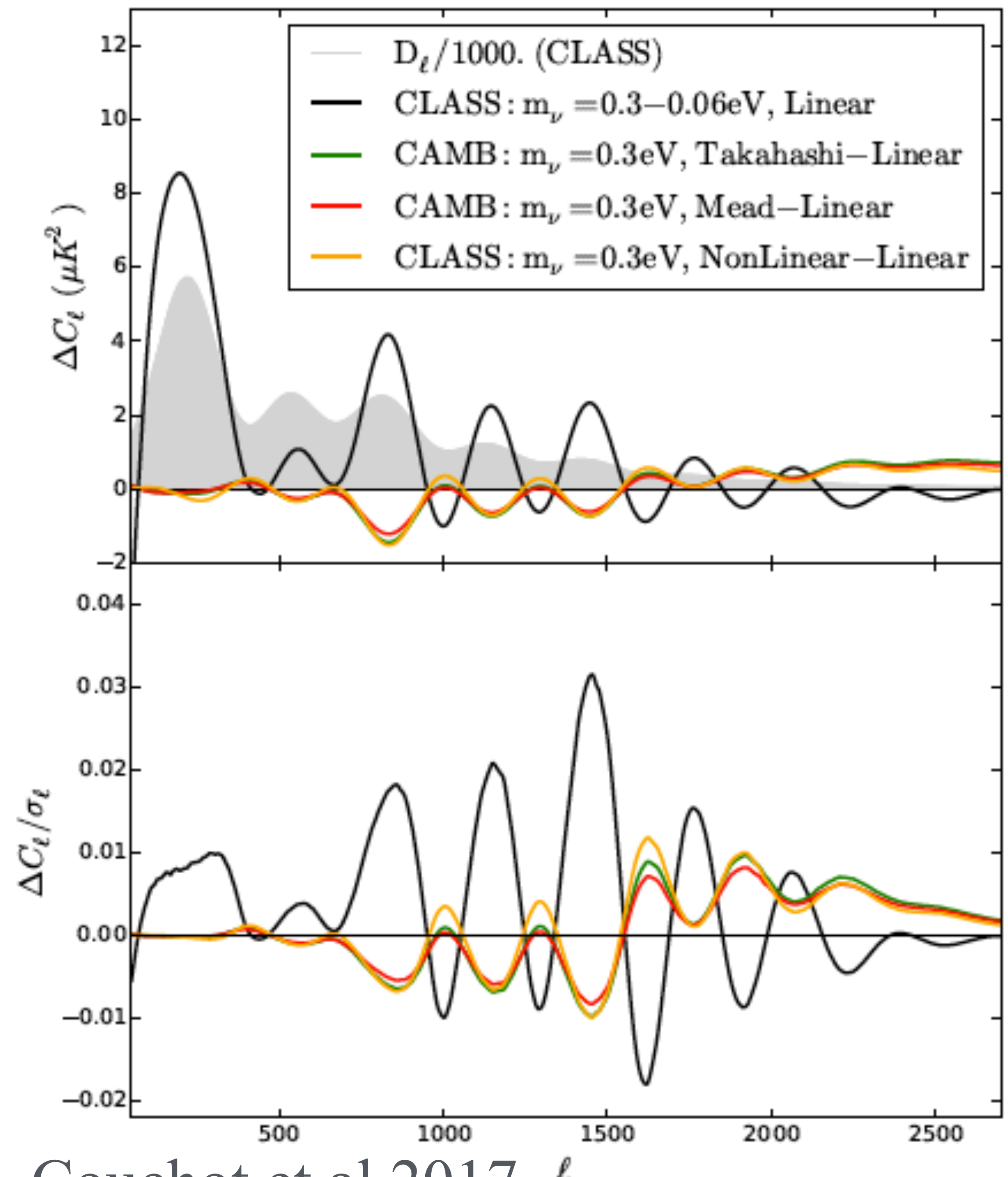
(Lesgourgues&Pastor 2006)

- different probes sensitive on different scales

Non-linear corrections

- precise constraints need/will need non-linear effect on the matter matter power spectrum





Couchot et al 2017

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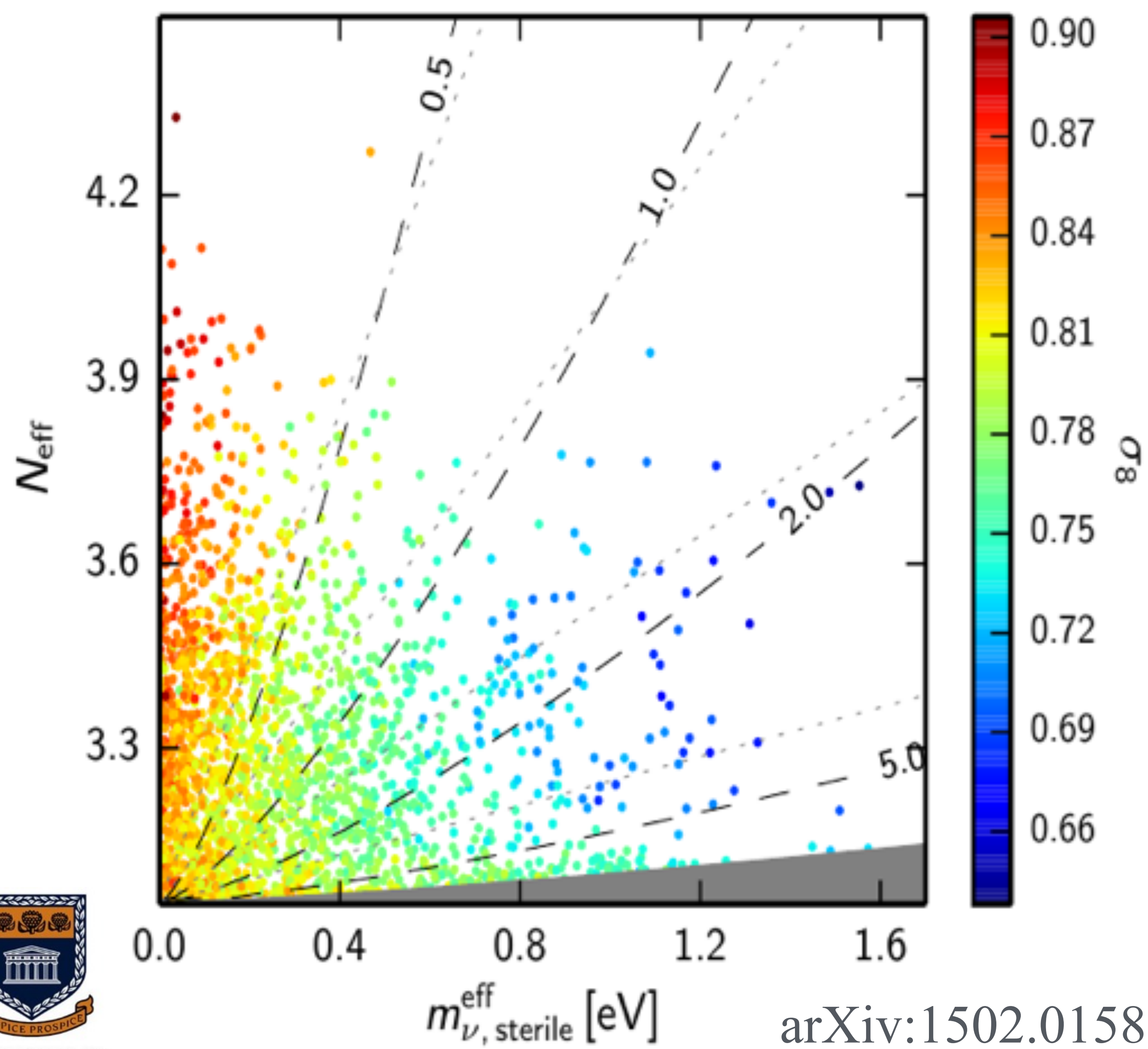
Any evidence for eV sterile neutrinos?

Model: extra massive neutrino thermally distributed with arbitrary temperature T_s $(\Delta N_{\rm eff} = (T_s/T_\nu)^4)$



arXiv:1502.01589

$$m^{\rm eff}_{\nu,\rm sterile} = (\Delta N_{\rm eff})^{3/4} m^{\rm thermal}_{\rm sterile}$$

- for low $N_{\rm eff}$ unconstrained within $\Omega_c h^2$
- for $m^{\rm thermal}_{\rm sterile} < 10$ eV
  $N_{\rm eff} < 3.7$
  $m^{\rm eff}_{\nu,\rm sterile} < 0.52$ eV
  not compatible with oscillation anomalies

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