Neutrino properties from Cosmology:
status and outlook including sterile neutrinos

IPA 2016

Marta Spinelli

UNIVERSITY of the WESTERN CAPE

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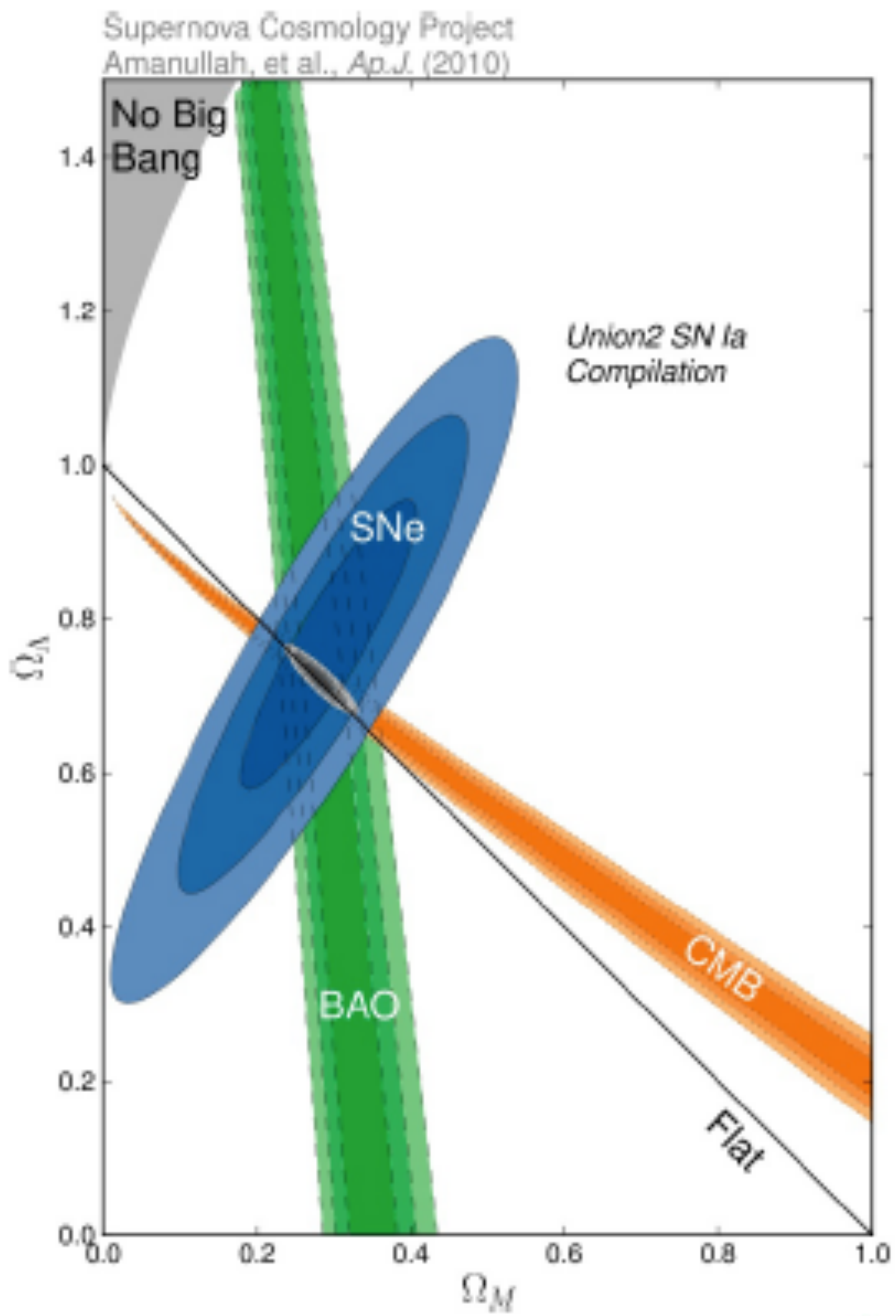
The vanilla model: Λ-CDM

- 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: $\Omega_\Lambda = 1 - \Omega_m$



Cosmic Microwave Background + Baryon Acoustic Oscillations + Supernovae

Concordance model: $\Omega_\Lambda \sim 0.7$, $\Omega_m \sim 0.3$

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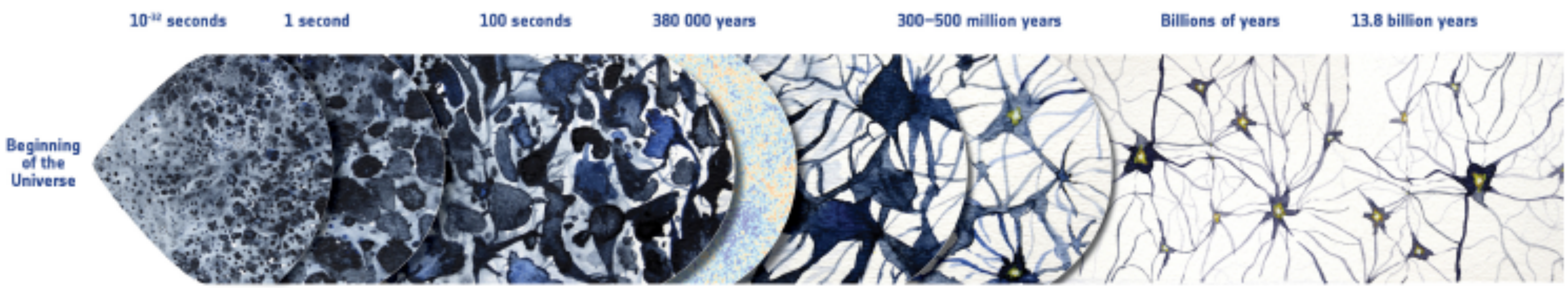
Neutrinos and cosmology



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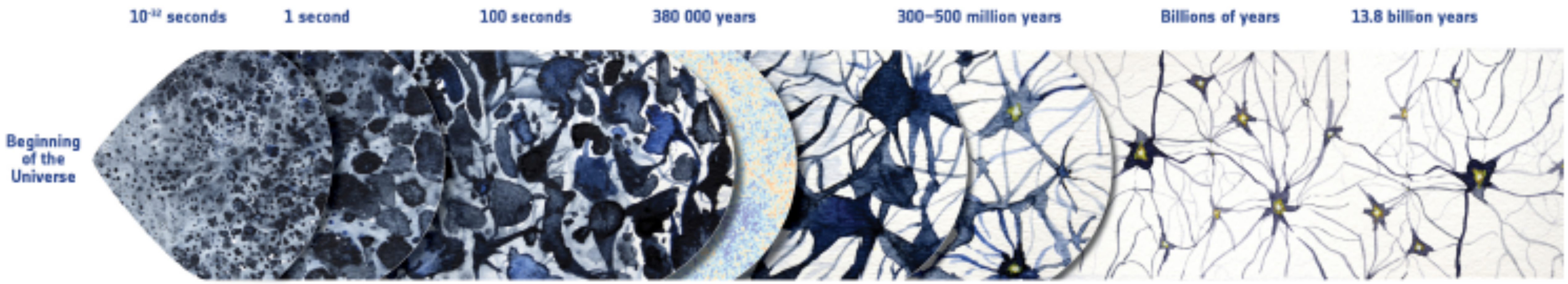
Neutrinos and cosmology



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

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

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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:

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

  - (photons are hotter thanks to electron-positron annihilation)
  - 3 generations and follow Fermi-Dirac statistics:

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

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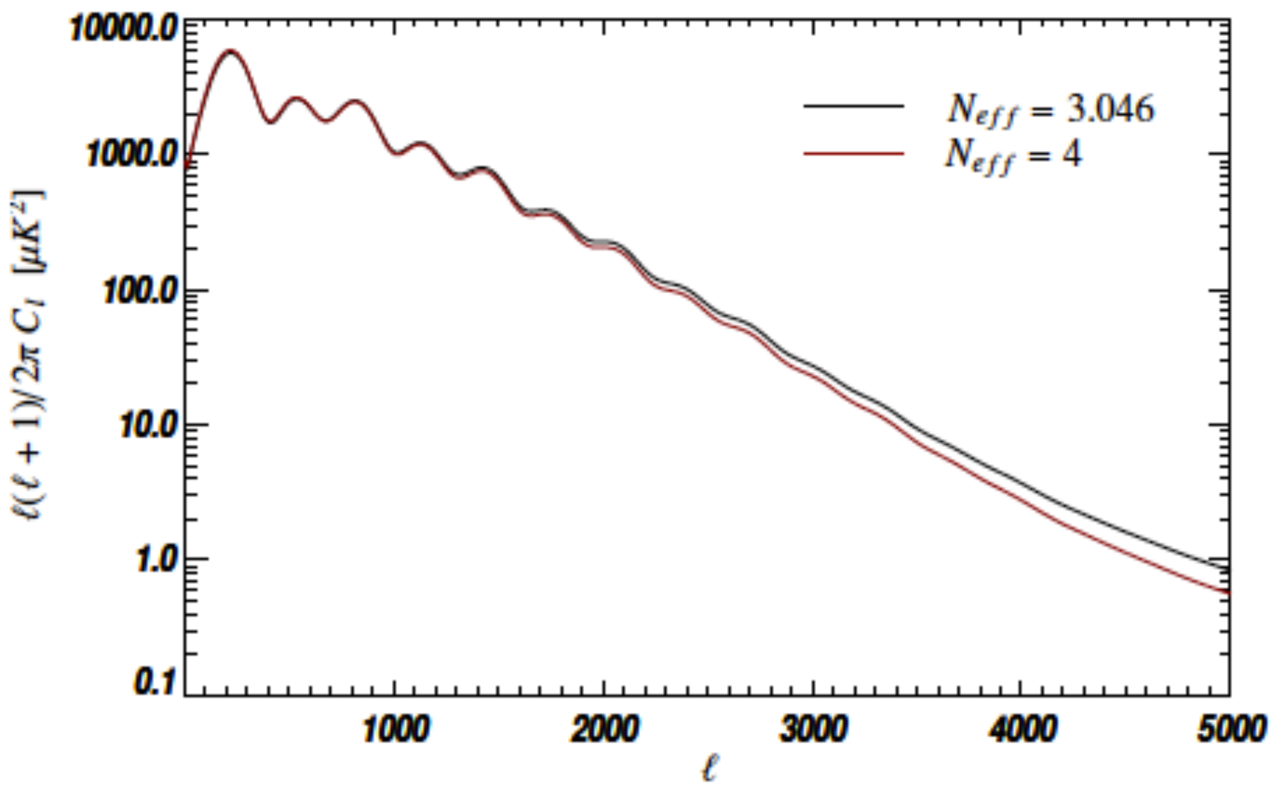
Neff

$N_{\rm eff}$ (~massless) degrees of freedom beyond photons relativistic during radiation domination (account for any light relics, axions, stochastic gravitational waves, etc.)

- $\rho_\nu = N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\rho_\gamma$
- standard neutrinos $N_{\rm eff} = 3.046$



if $N_{\rm eff}$ ⇑, the age of the Universe at recombination ⇓
⇒ **effect on the damping tail**

correlation $N_{\rm eff}$-H_0

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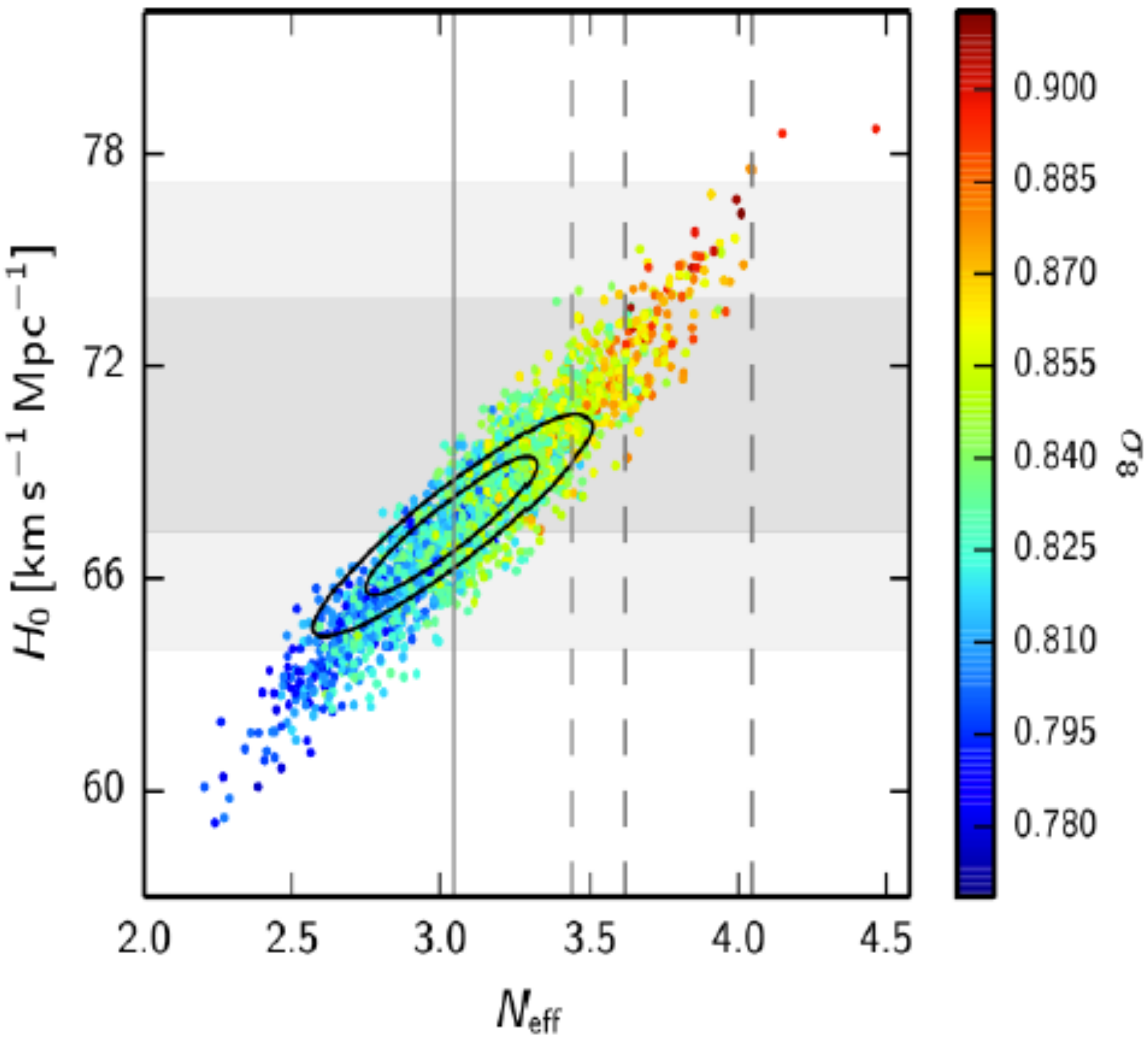
Neff

$N_{\rm eff} = 3.13 \pm 0.32$
(PlanckTT+lowP; 68%CL)
tighter constraint adding 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 $\sim 3 - 5\sigma$
- larger $N_{\rm eff}$ would allow larger H_0



arXiv:1502.01589

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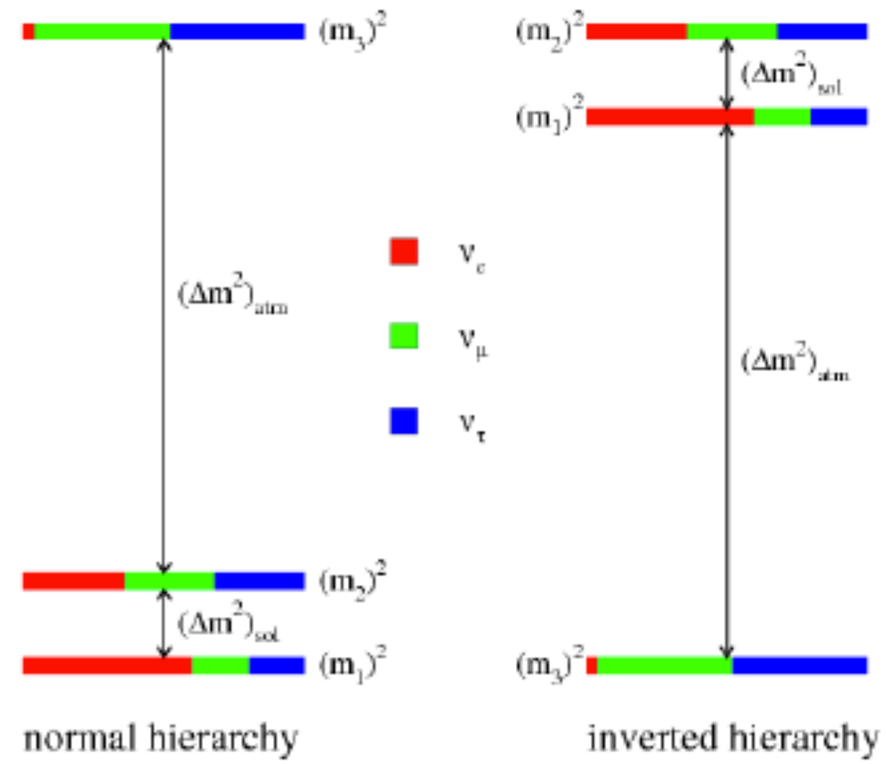
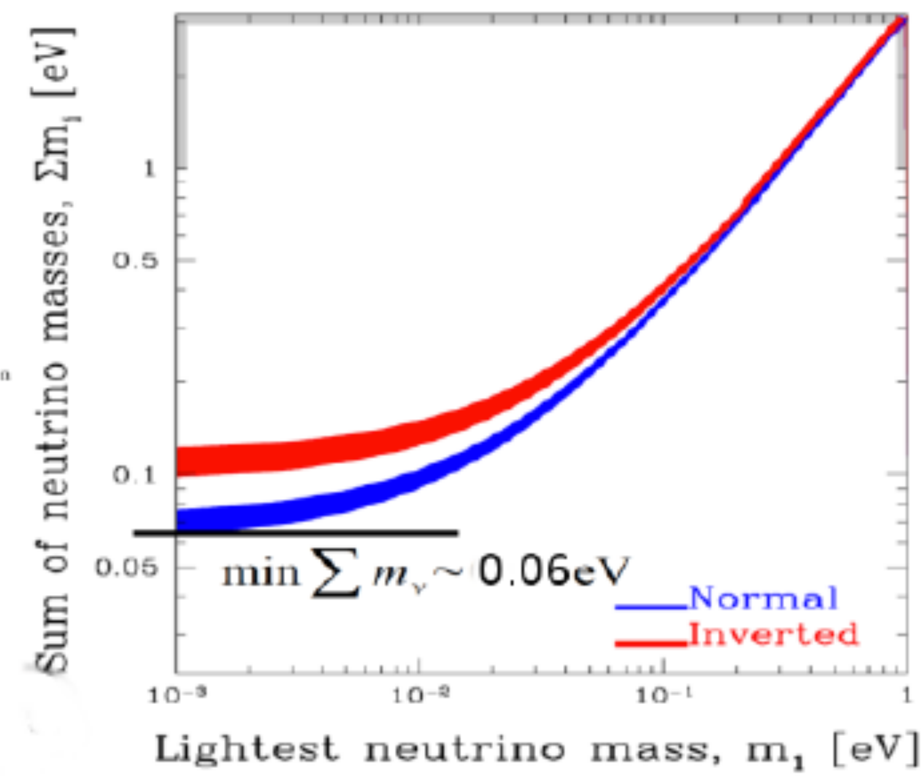
The absolute scale of neutrino masses

- oscillation experiment results require massive neutrinos
- need for non trivial extension to Particle Physics SM (Dirac/Majorana?)
- neutrino hierarchy not known but lower limits from oscillations (0.06 eV NH, 0.10 eV IH)





Effect on CMB and LSS

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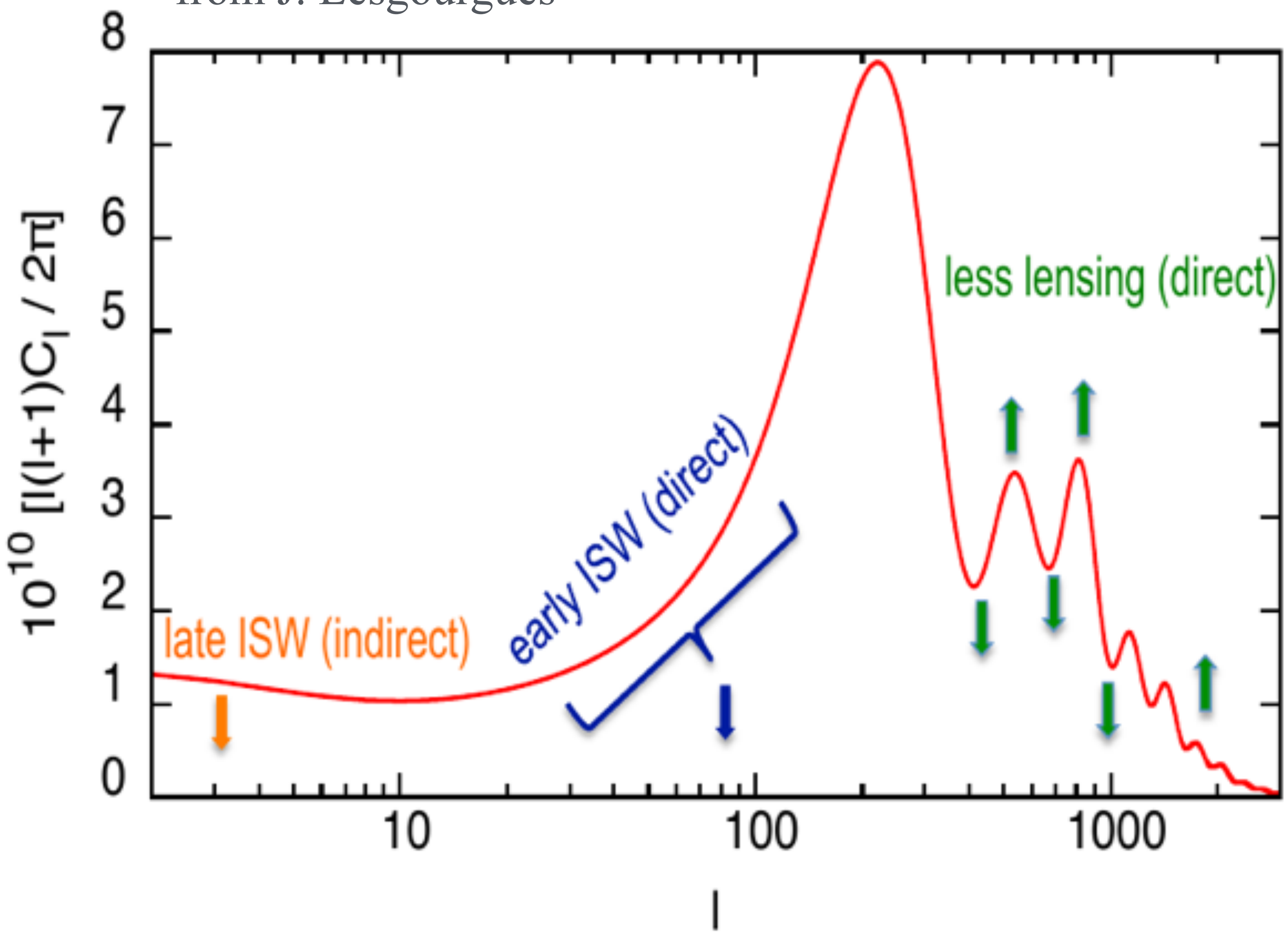
Effect on CMB

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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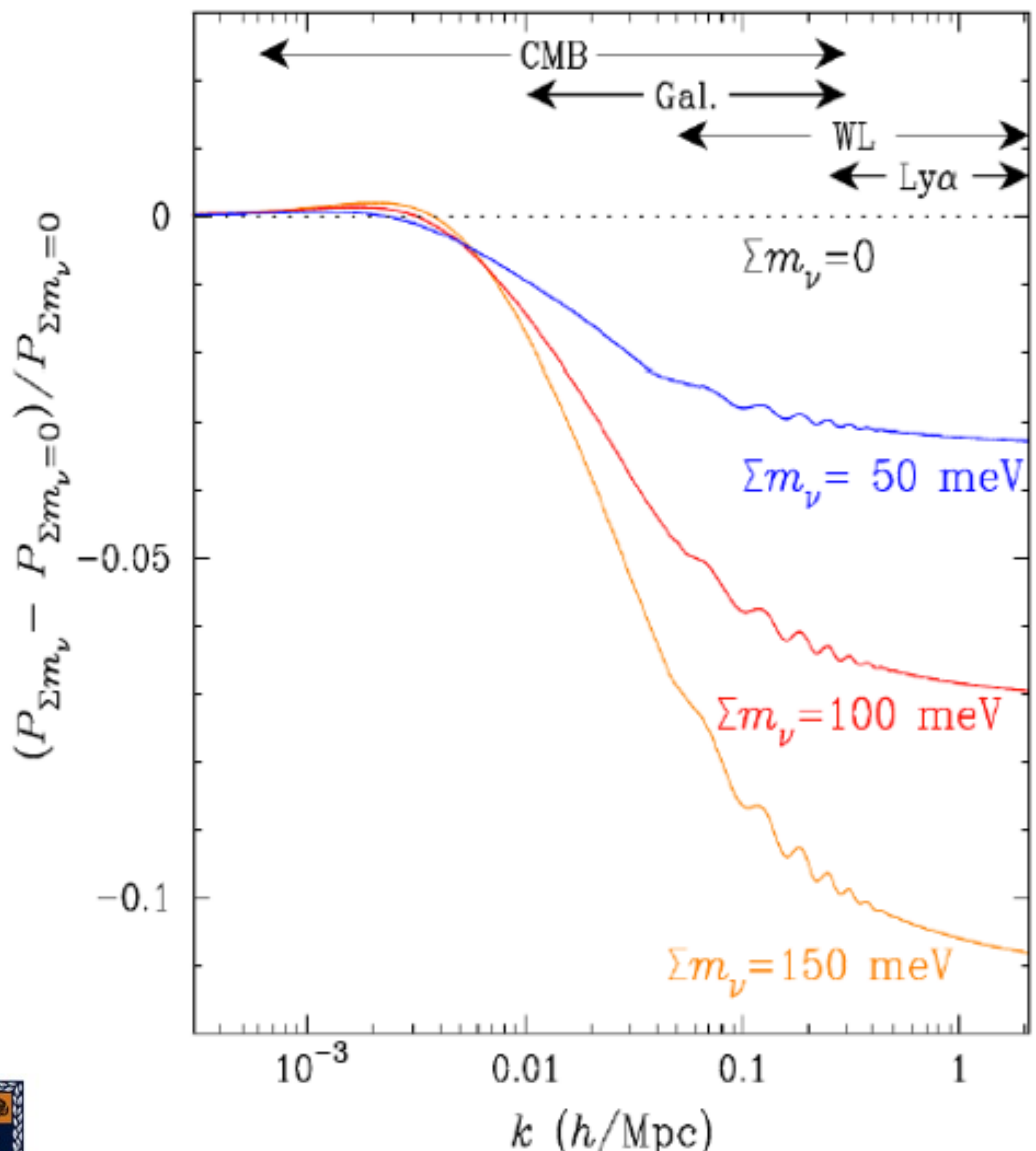
Effect on structure formation



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

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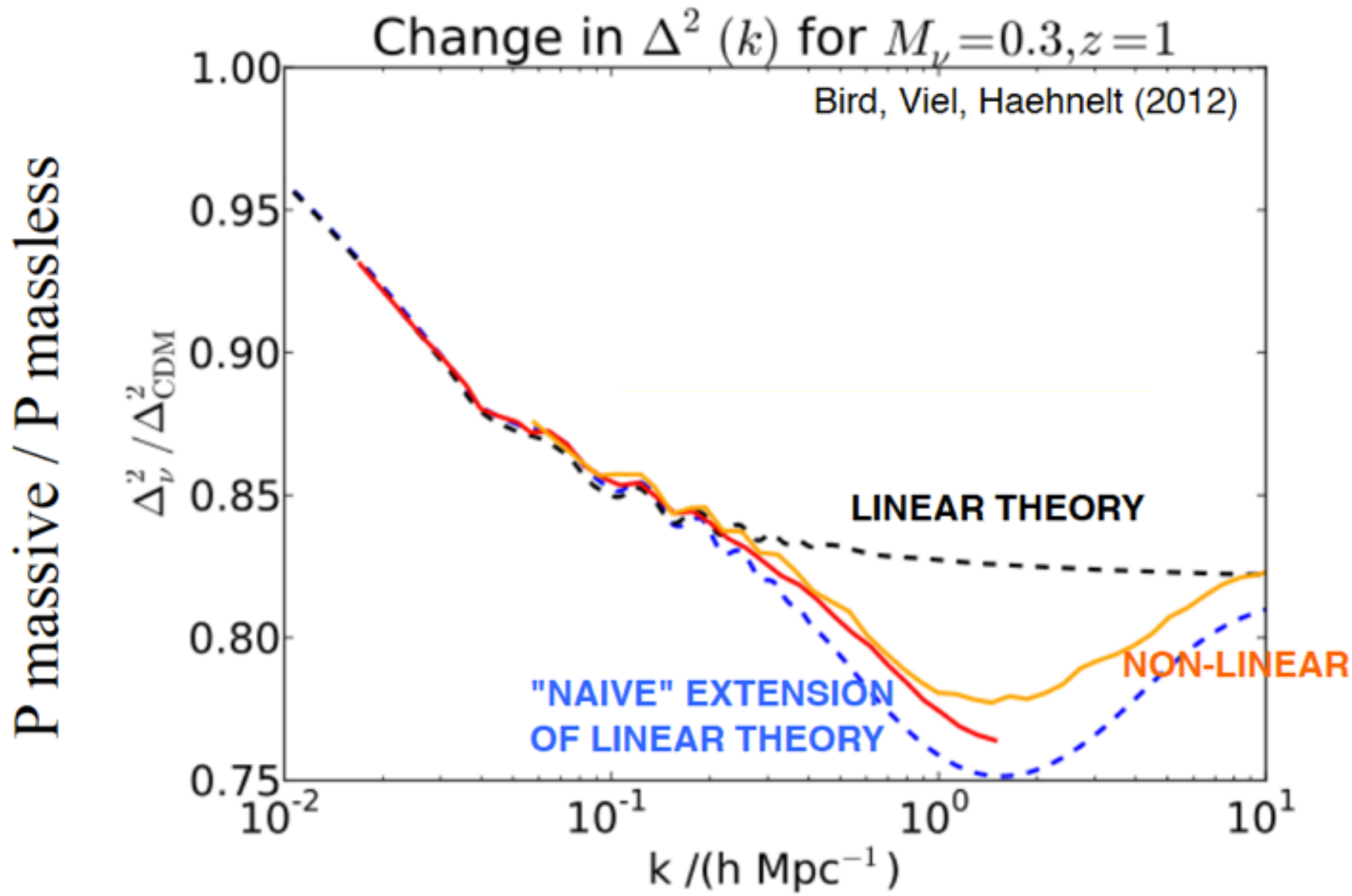
Non-linear corrections

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



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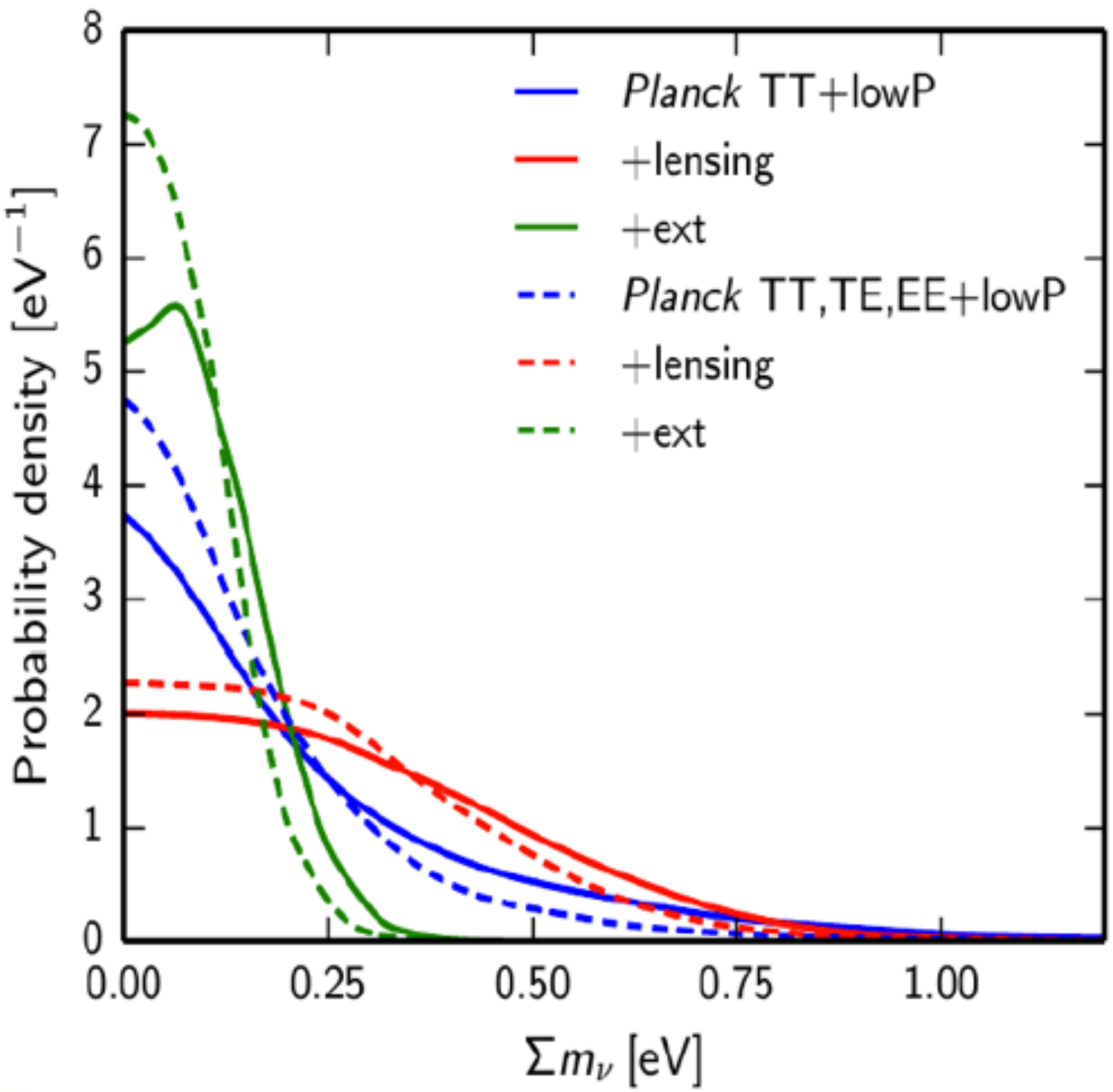
Constraint on Σm_ν



Full Mission TT data (still residual systematic in polarisation)

- (95%CL; PlanckTT+lowP) $\sum m_\nu < 0.72$ eV
- $+lensing$ $\sum m_\nu < 0.68$ eV
- $+ext\ (BAO, SN, H_0)$

  $\sum m_\nu < 0.23$ eV

Planck+BOSS DR12 down to 0.16 eV

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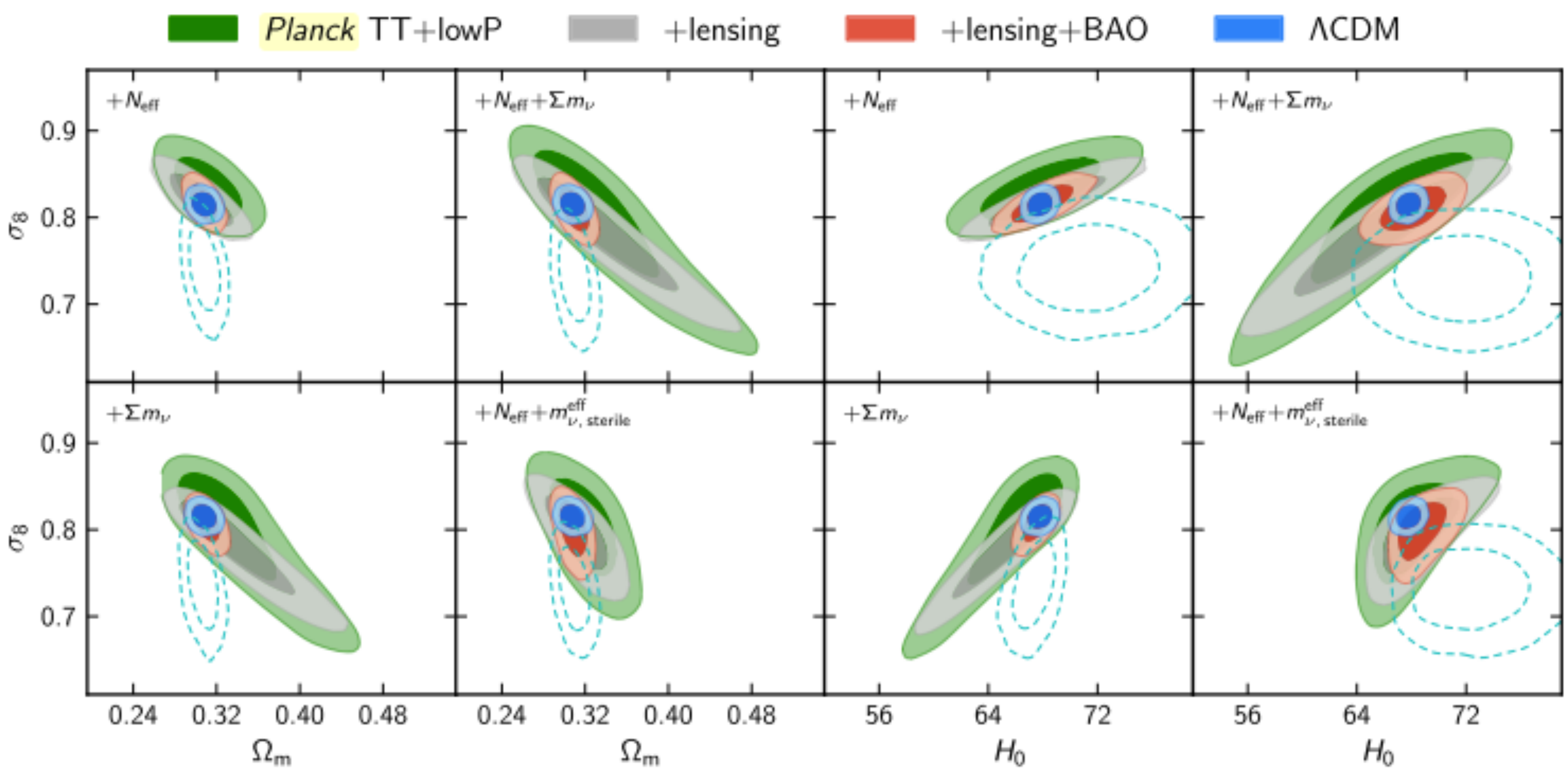
Beyond the standard picture

- standard cosmological model is preferred but still some tensions with clusters, direct H0, CFHTLenS
- can we use neutrino sector to alleviate them?
- do data really need non standard neutrino sector?



arXiv:1502.01589

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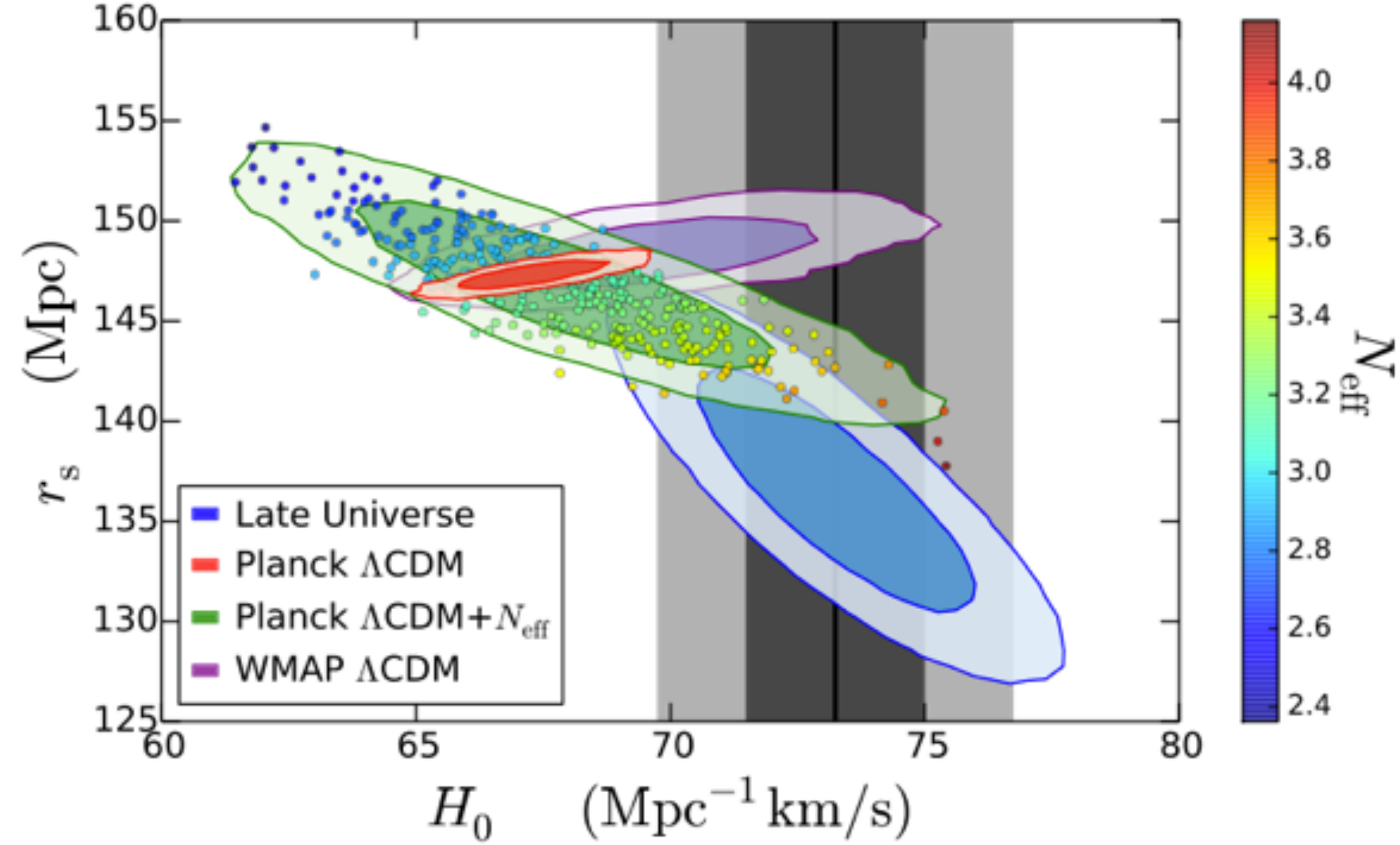
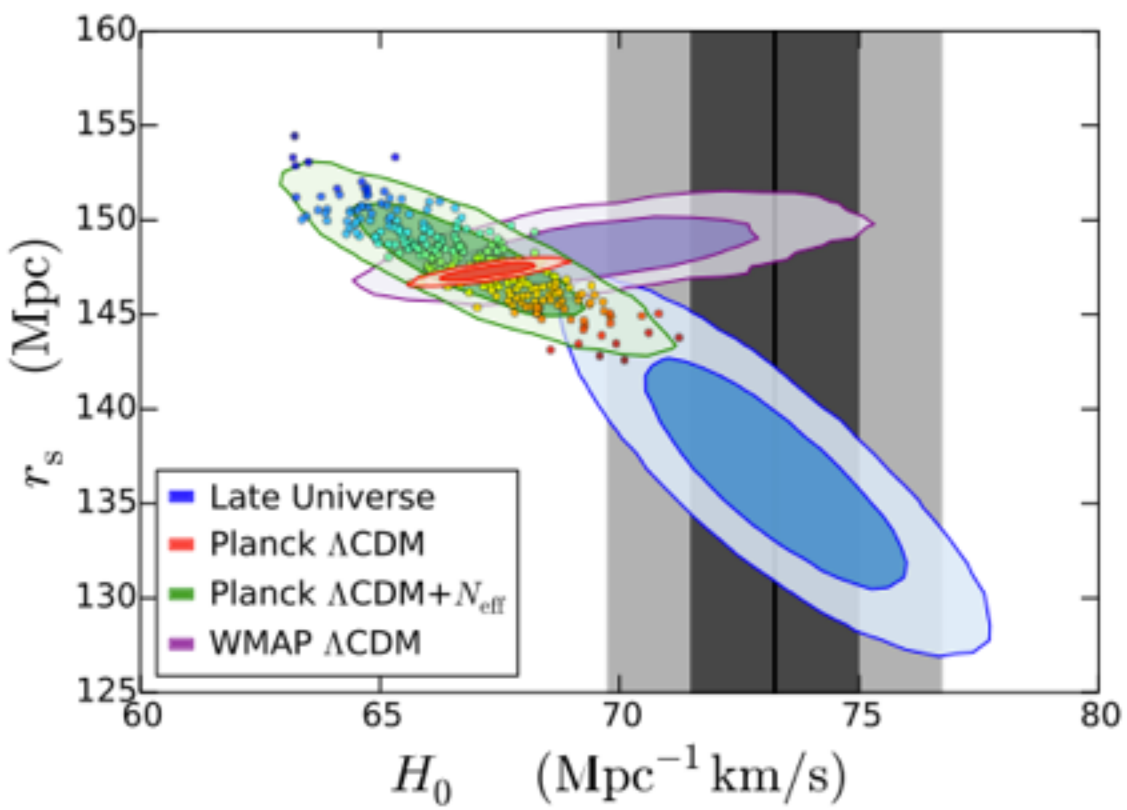
Neff and H0

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

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



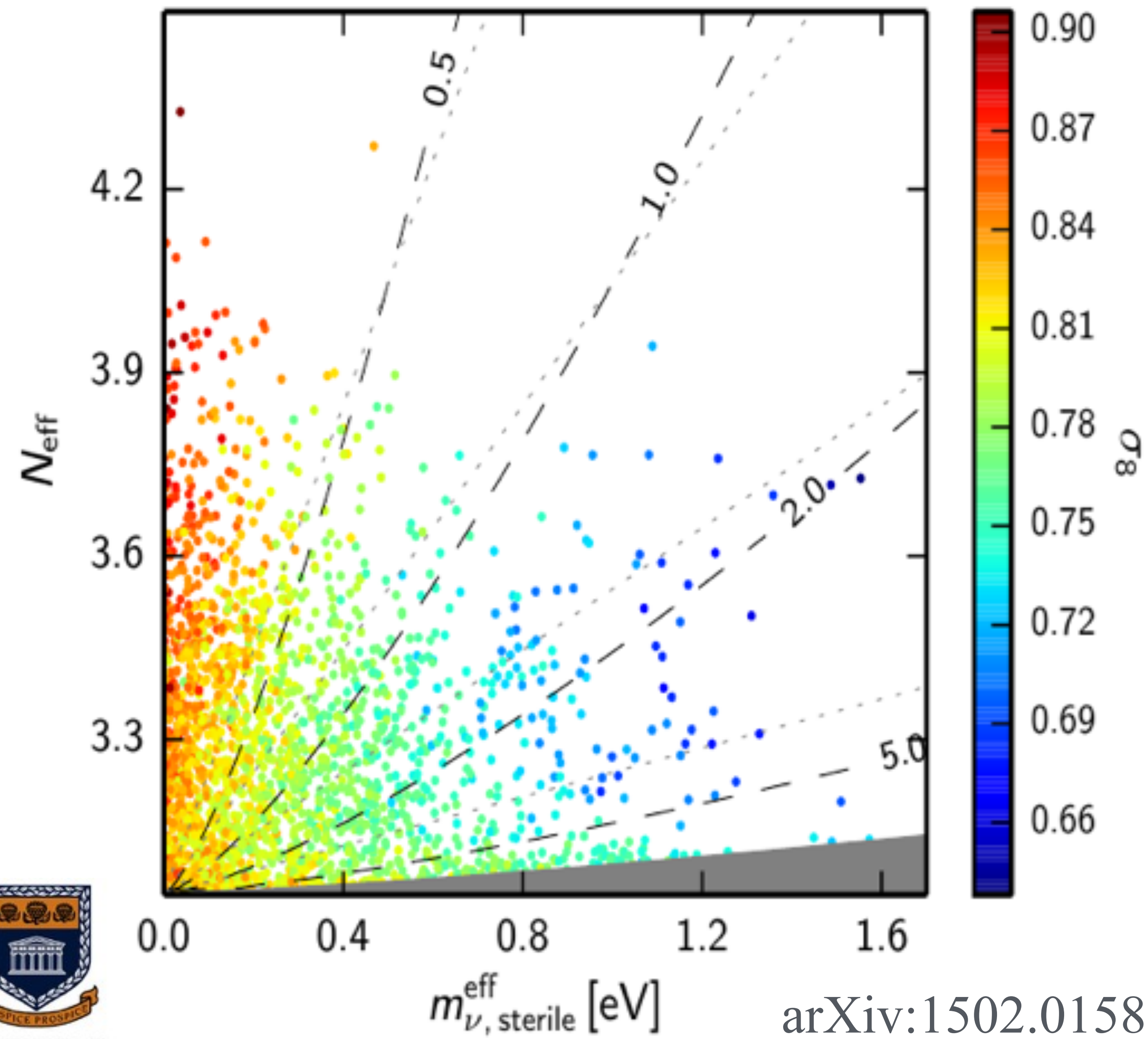


- NOT true anymore
  if Planck polarisation is included

Bernal et al 2016 (arXiv:1607.05617)

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

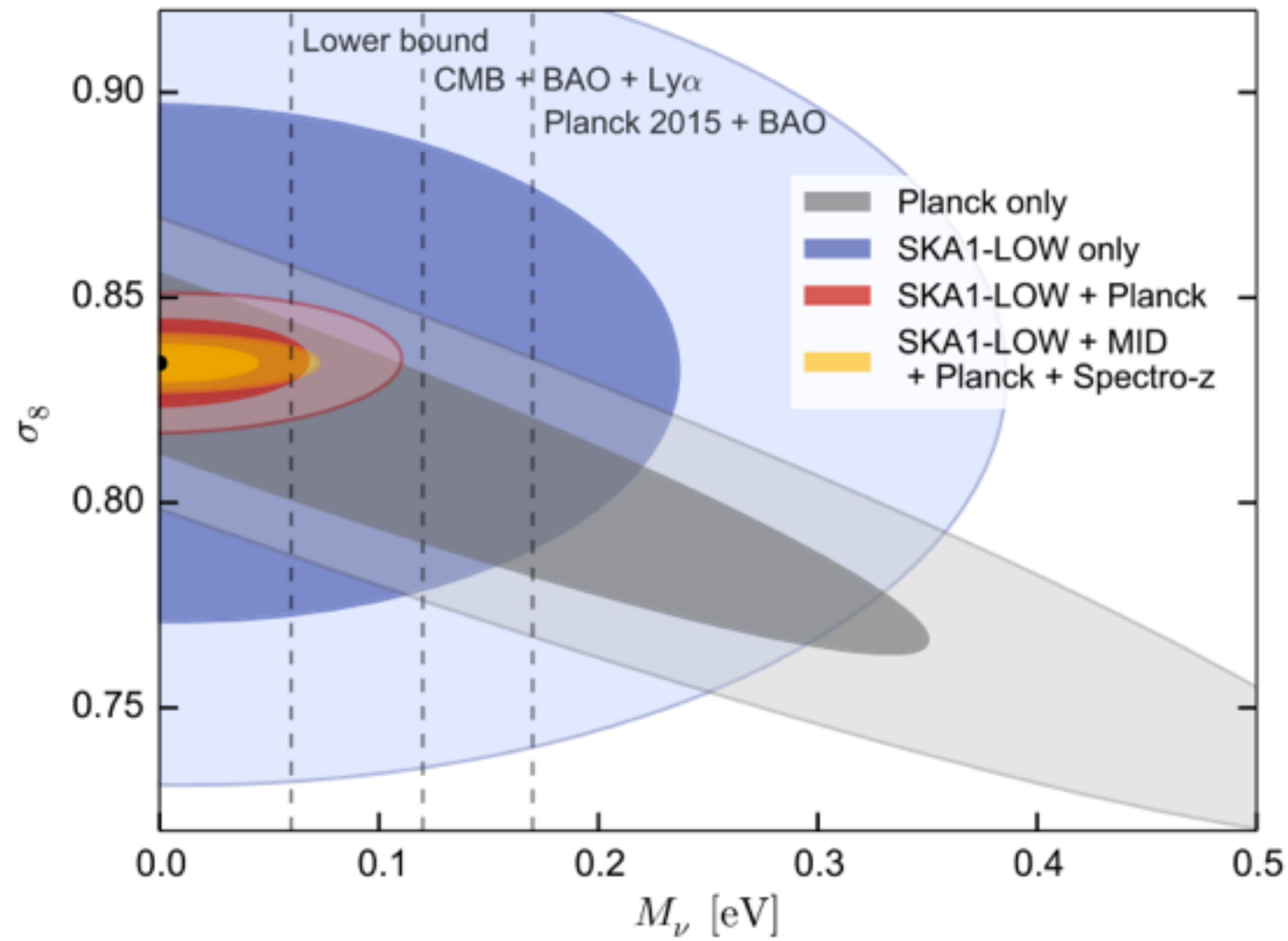
Forecast from 21cm

- hydrodynamic sims with massive neutrino for HI spatial distribution
- HI more clustered for cosmology with massive neutrino
- 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 $\sigma(M_\nu) \simeq 0.06 \text{ eV } (95\% \text{ CL})$

Villaescusa-Navarro et al 2015



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How close to a mass measurement?

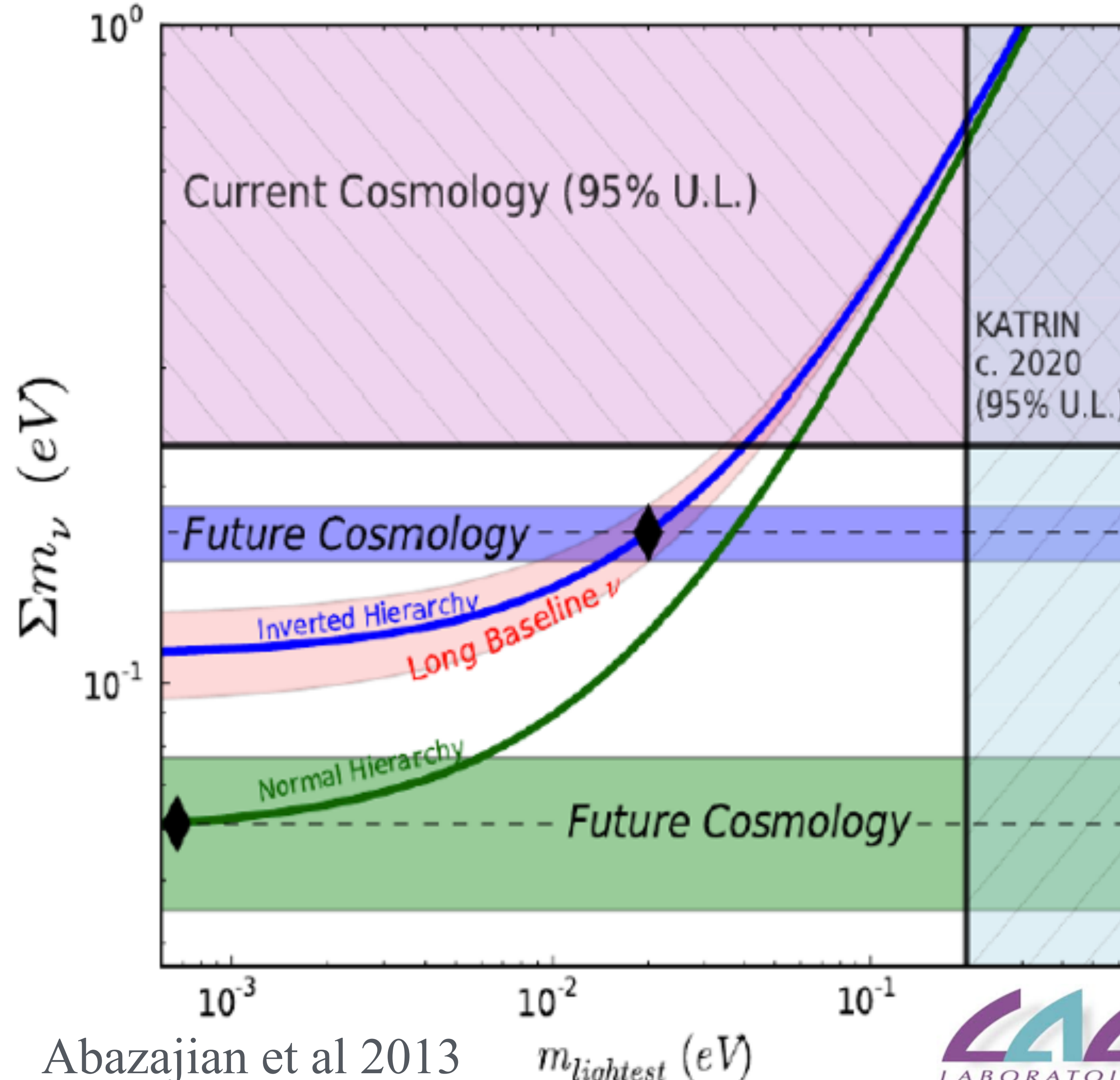
If m=0.06 eV we need 20 meV sensitivity for 3 sigma.
If m=0.12 eV then 40 meV in enough

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

  http://bolo.berkeley.edu/polarbear

- Euclid (2020): 3meV
  enough for hierarchy

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



Abazajian et al 2013

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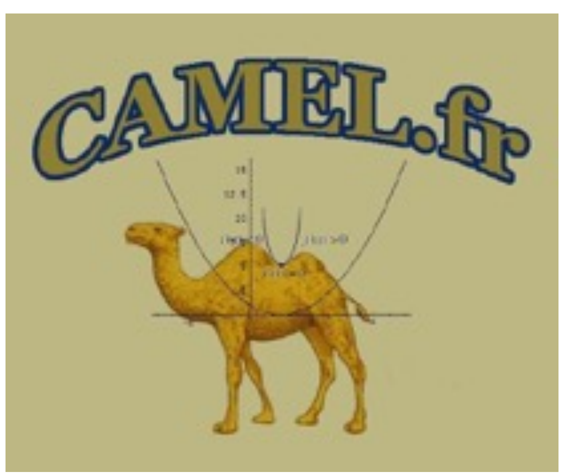
Caveat on precision cosmology

- How robust is the CMB limit on Σm_ν ?
  - how it relates to lensing? (the A_L issue)
  - does it depend on the way the non-linear effects are calculated?
  - does it depends on foreground parametrisation?

→ 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 (in preparation)

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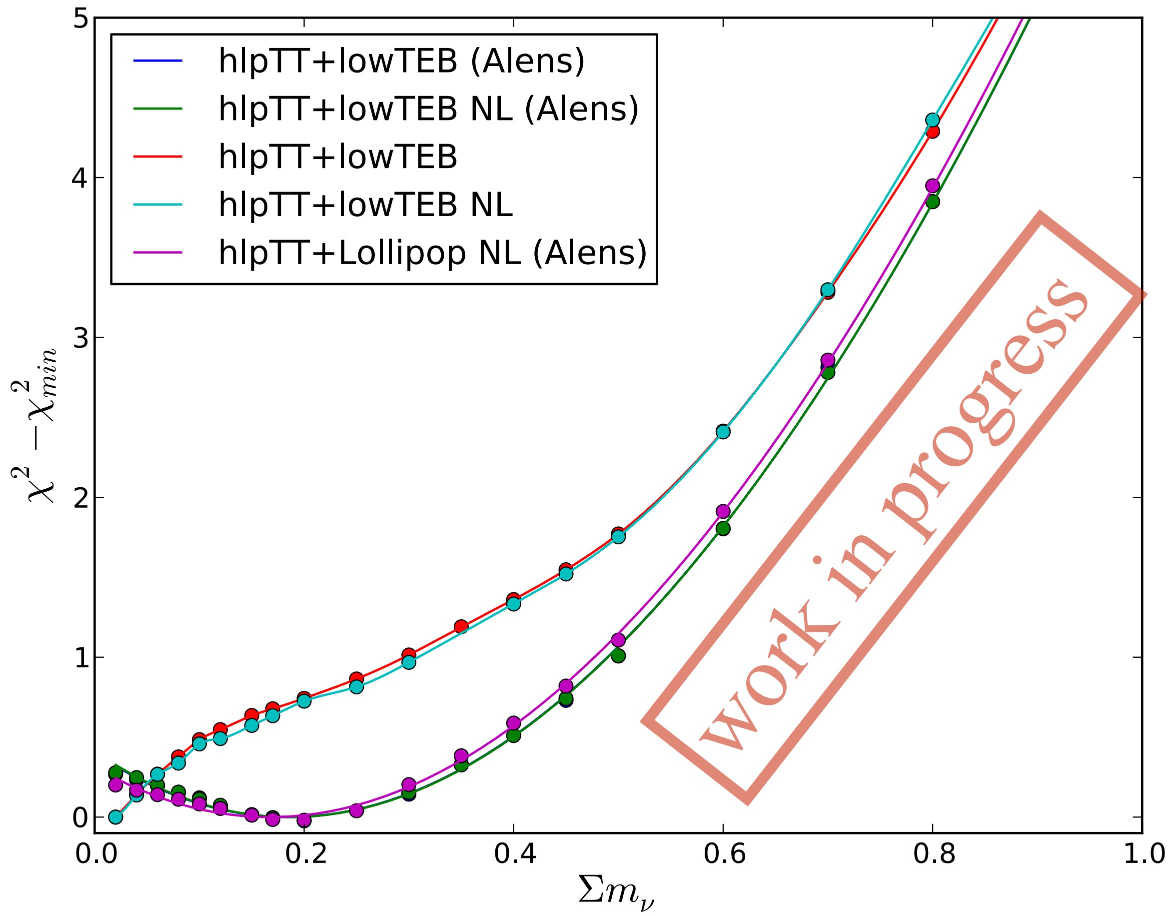
CMB lensing, A_L and neutrinos

- modification of Cl most significant on small scales
- consistency test: $A_L = 1$?
  - Planck data prefer $A_L > 1$ (2sigma)
  - this implies artificial low Σm_ν limit
  - better add ACT and SPT (VHL) before opening up parameter space to neutrinos



→ we need to understand how to propagate properly:

A. the error on the foreground templates
B. the dataset inter calibration error
C. the theoretical uncertainties on non-linear (NL) effect

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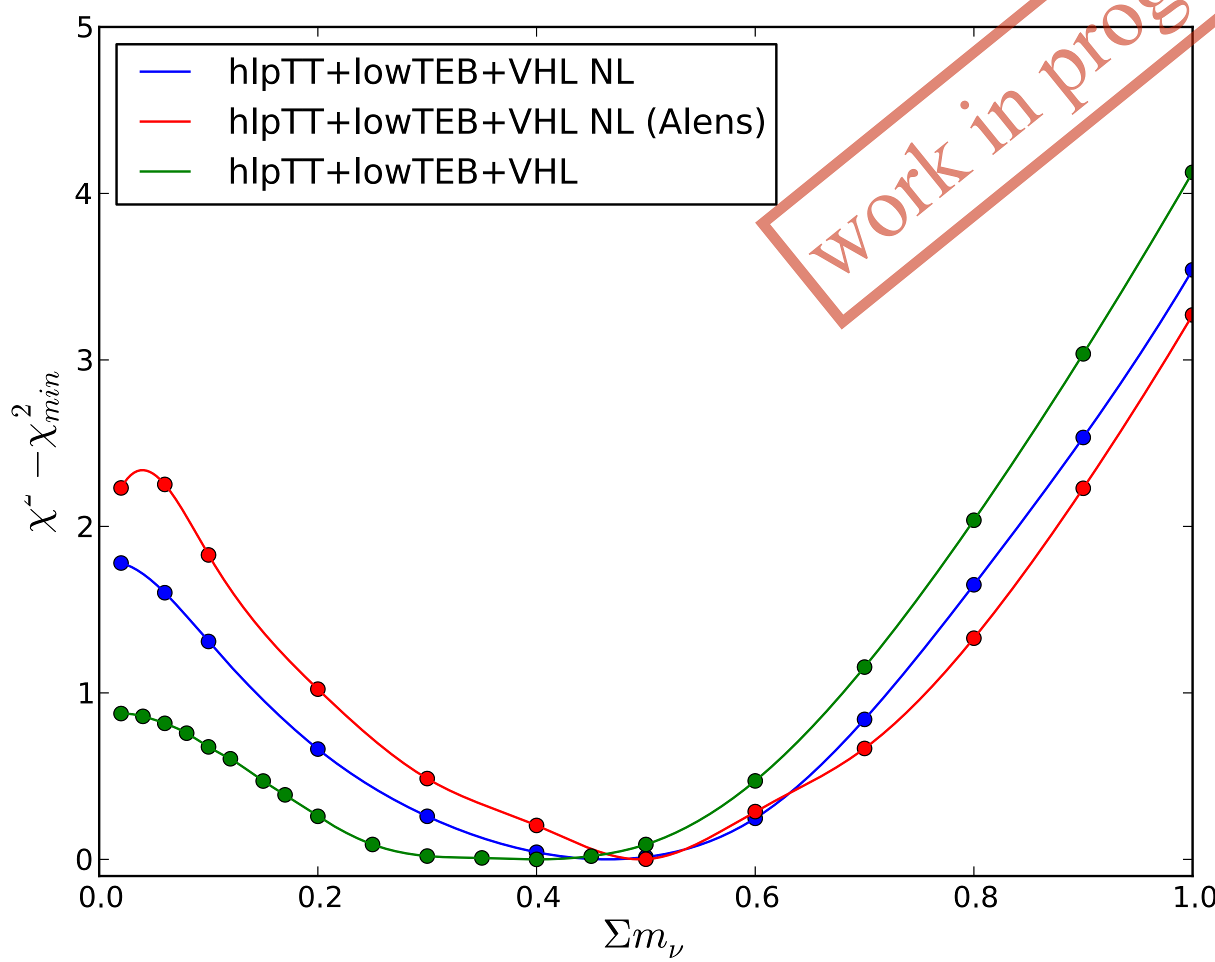
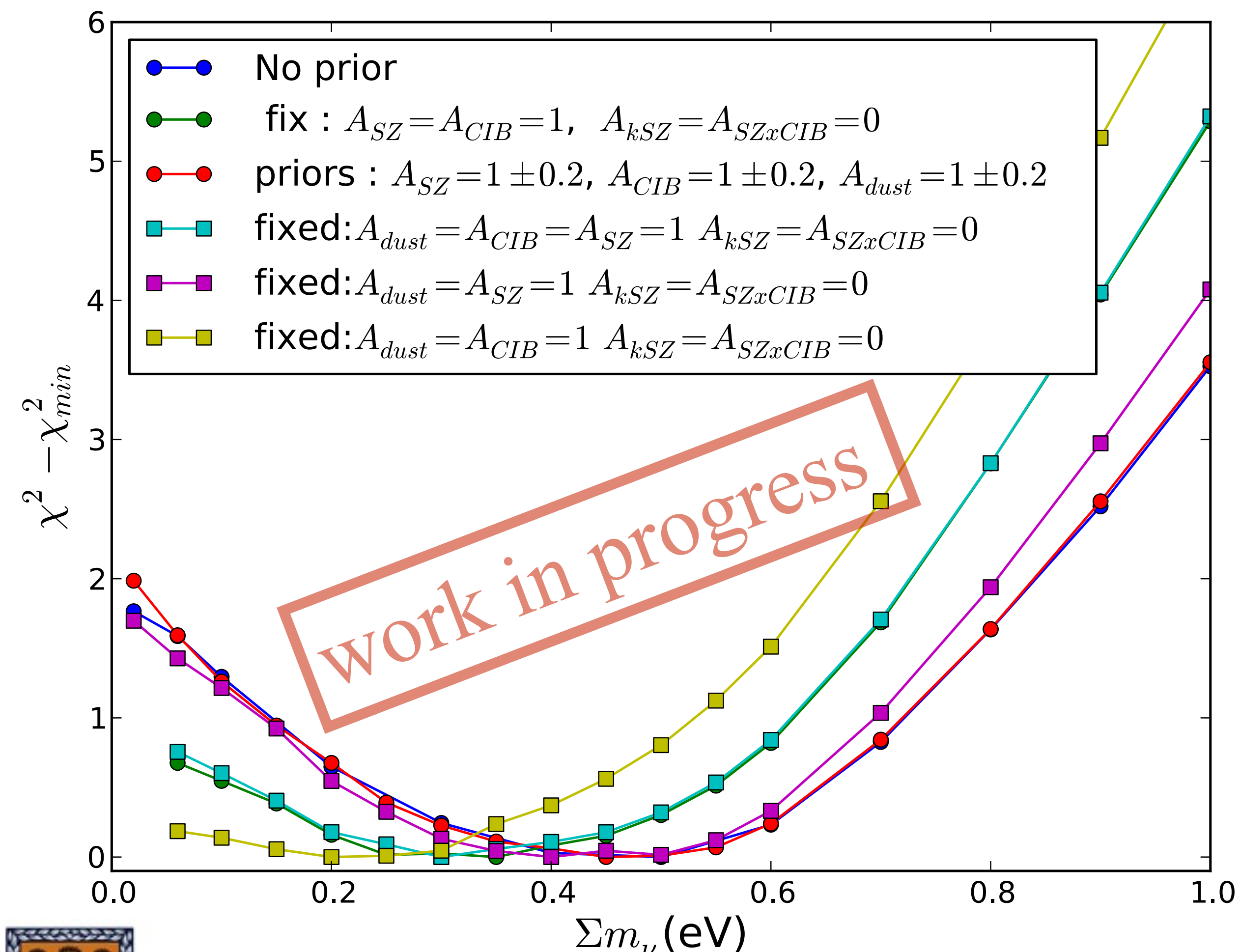
Where the preference for ~0.4 eV comes from?

- Effect of non-linearities
  - affect small scales
  - with NL increase of the profile for $\sum(m_\nu) \lesssim 0.4$ eV





- Impact of foreground parameters
  - also dominant at small scales (except for dust)
  - try to understand effects if their are not at their Planck preferred value

NB: the addition of BAO destroys this mild preference

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Conclusions

- Cosmology is a rich laboratory to test neutrino properties
- CMB and LSS can constraint the sum of the masses and the presence of extra relativistic degree of freedom
- N_{eff} compatible with the standard model
- Forecast for Σm_ν say that we will know more by the end of 2020
- The more we will get to stringent constraints, the more we need to be sure of what is in the data
- Still… exciting times to come!

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