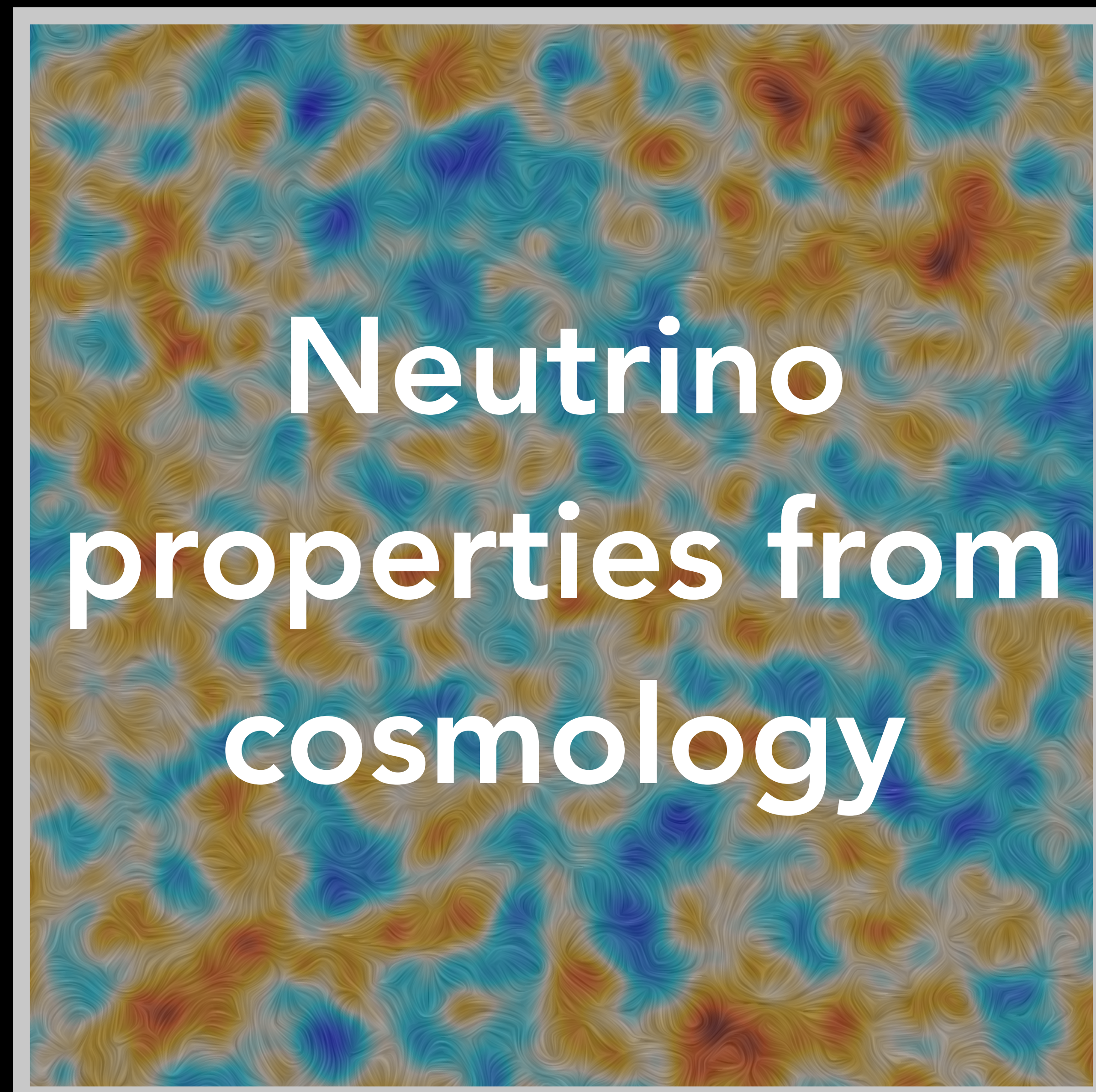
NEUTRINO 2018, Heidelberg, 8.06.2018



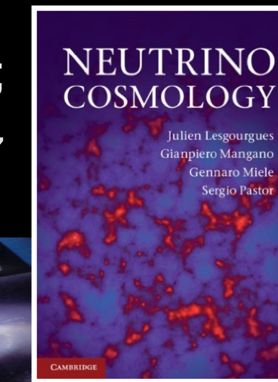
Neutrino properties from cosmology

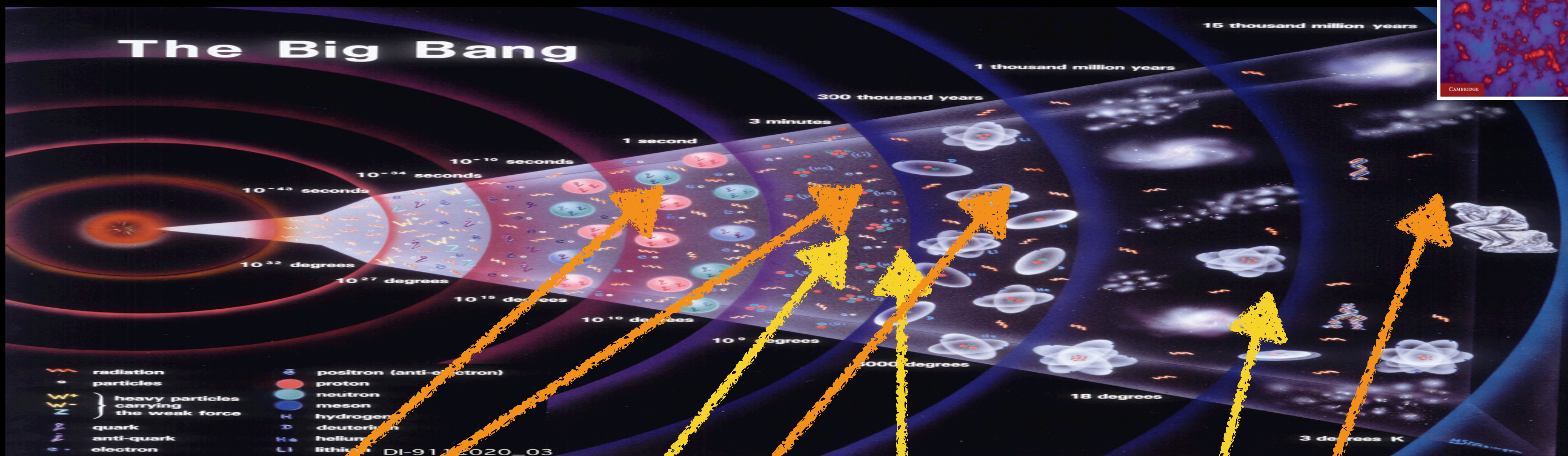
Julien Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

What neutrino effects are we testing?

JL & Pastor Pys. Rep. 2016; JL, Mangano, Miele, Pastor “Neutrino Cosmology” CUP;
Drewes et al. 1602.04816; PDG review: JL & Verde “Neutrinos in Cosmology”; Gerbino & Lattanzi 2017





relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

neutrino slow down early dark matter clustering

neutrino propagation and dispersion velocity

neutrino slow down late ordinary/dark matter clustering

Plan

1. Best current bounds on active neutrino mass, density, asymmetry, light sterile neutrinos, with minimalistic assumptions on underlying cosmological models

2. How much should we believe these bounds (given model-dependence and unexplained anomalies in cosmological data like H_0 tension)

3. Robust sensitivity forecasts from future experiments

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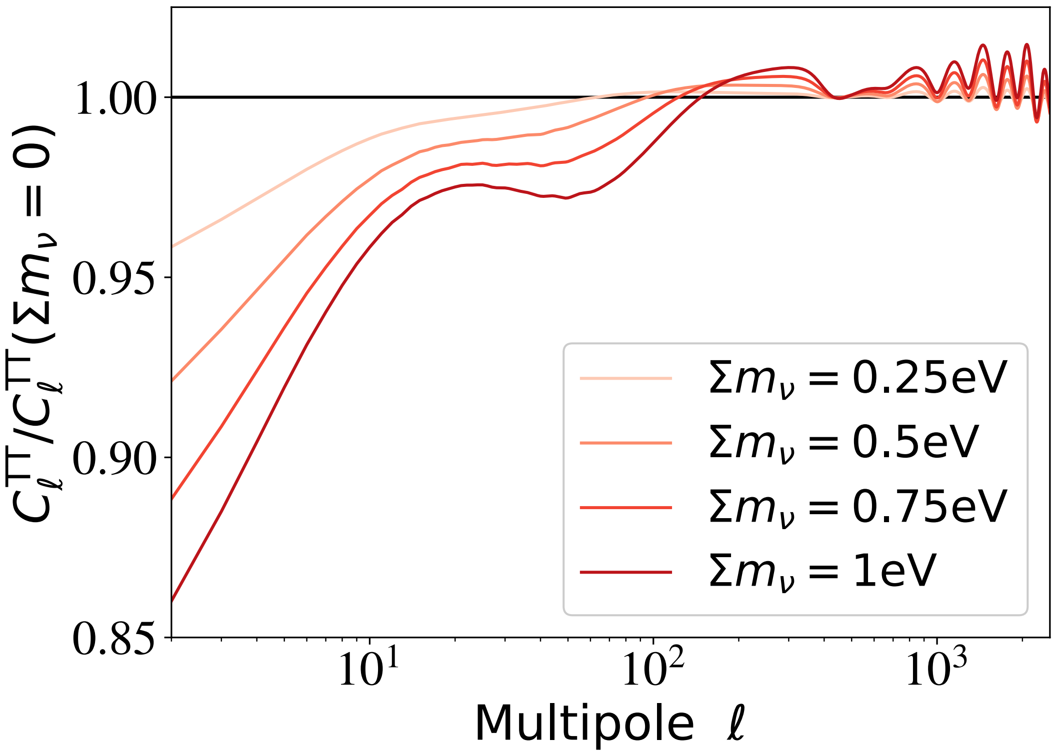
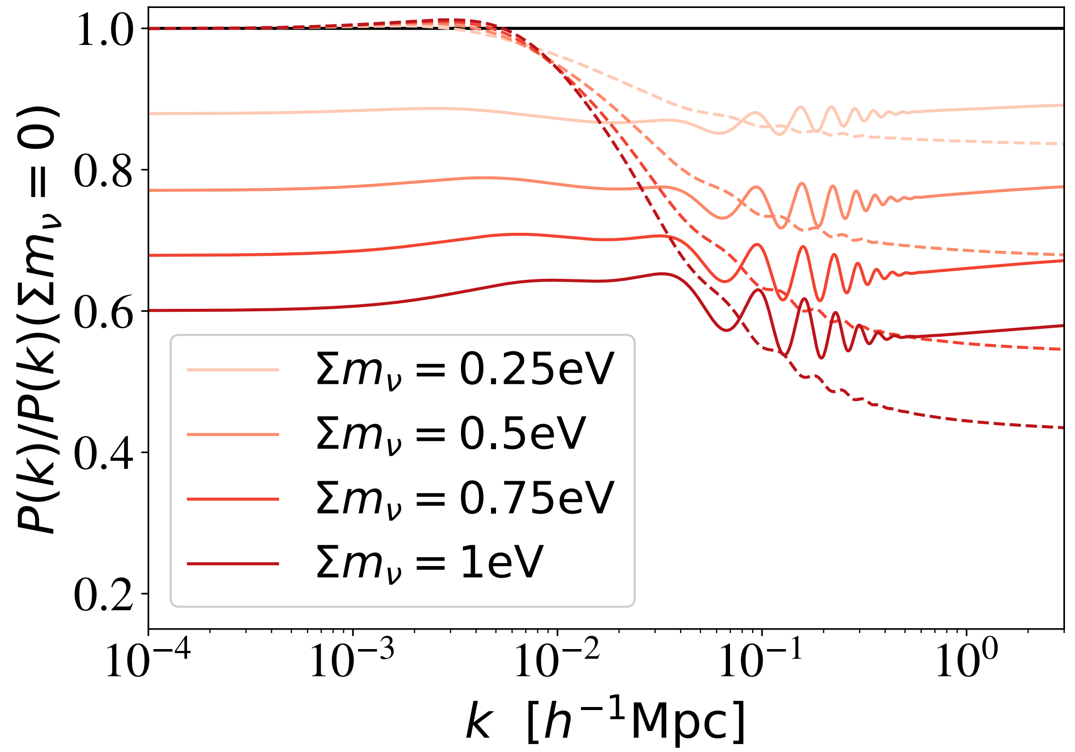
Summed mass of active neutrinos

Very specific effects on:

CMB spectrum LSS



LSS (Large Scale Structure) spectrum

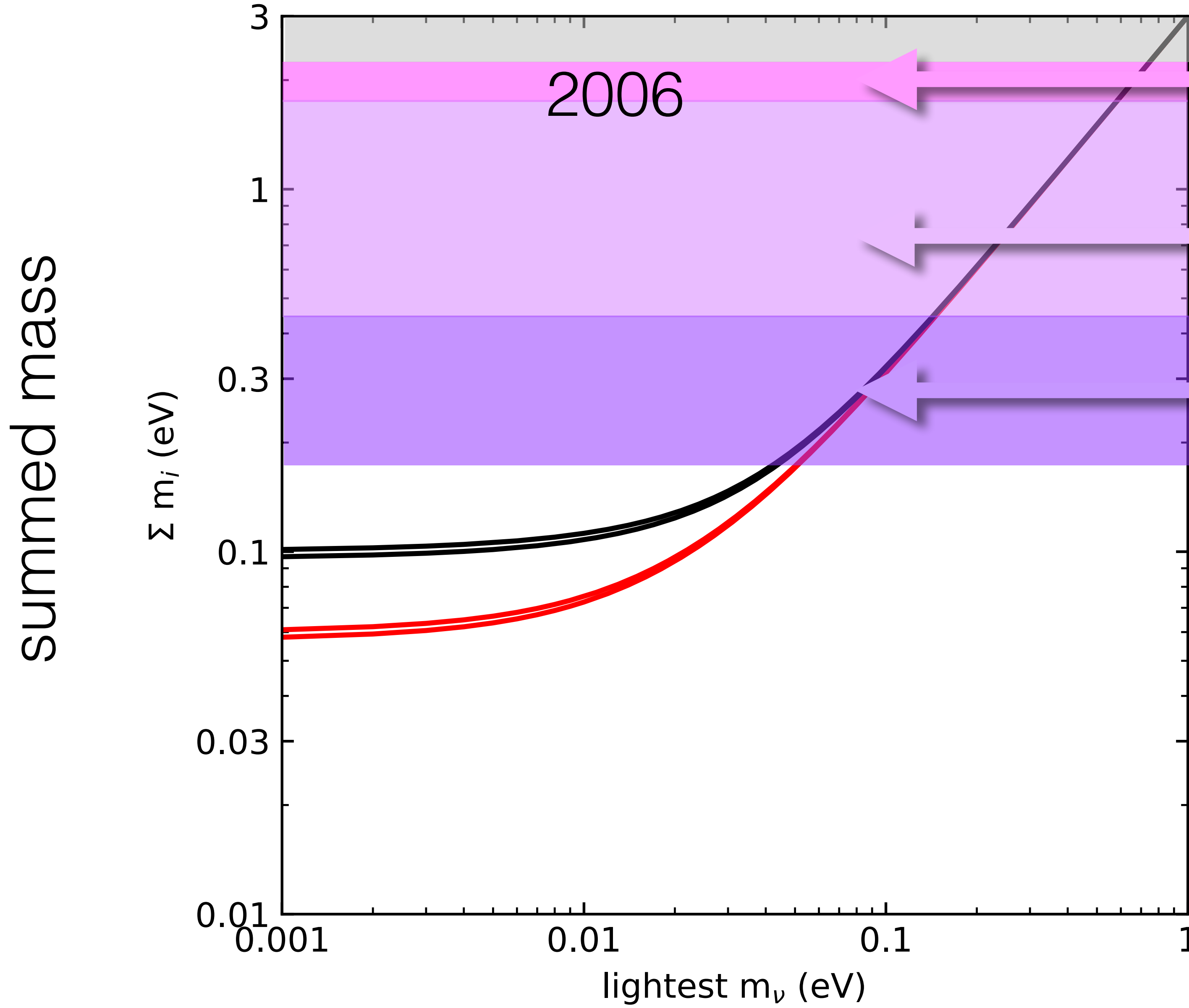


from PDG review on Neutrinos in Cosmology (JL & Verde)

(angular diameter distance, early ISW dip, CMB lensing, reduction of growth rate)

Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



CMB only : WMAP, VSA, ACBAR, CBI…

CMB + LSS : 2dF, SDSS-BAO, SDSS-power spectrum

CMB + LSS : Lyman-alpha

Seljak et al. 2006; Viel et al. 2006

… bounds could weaken considerably for > 7 parameters

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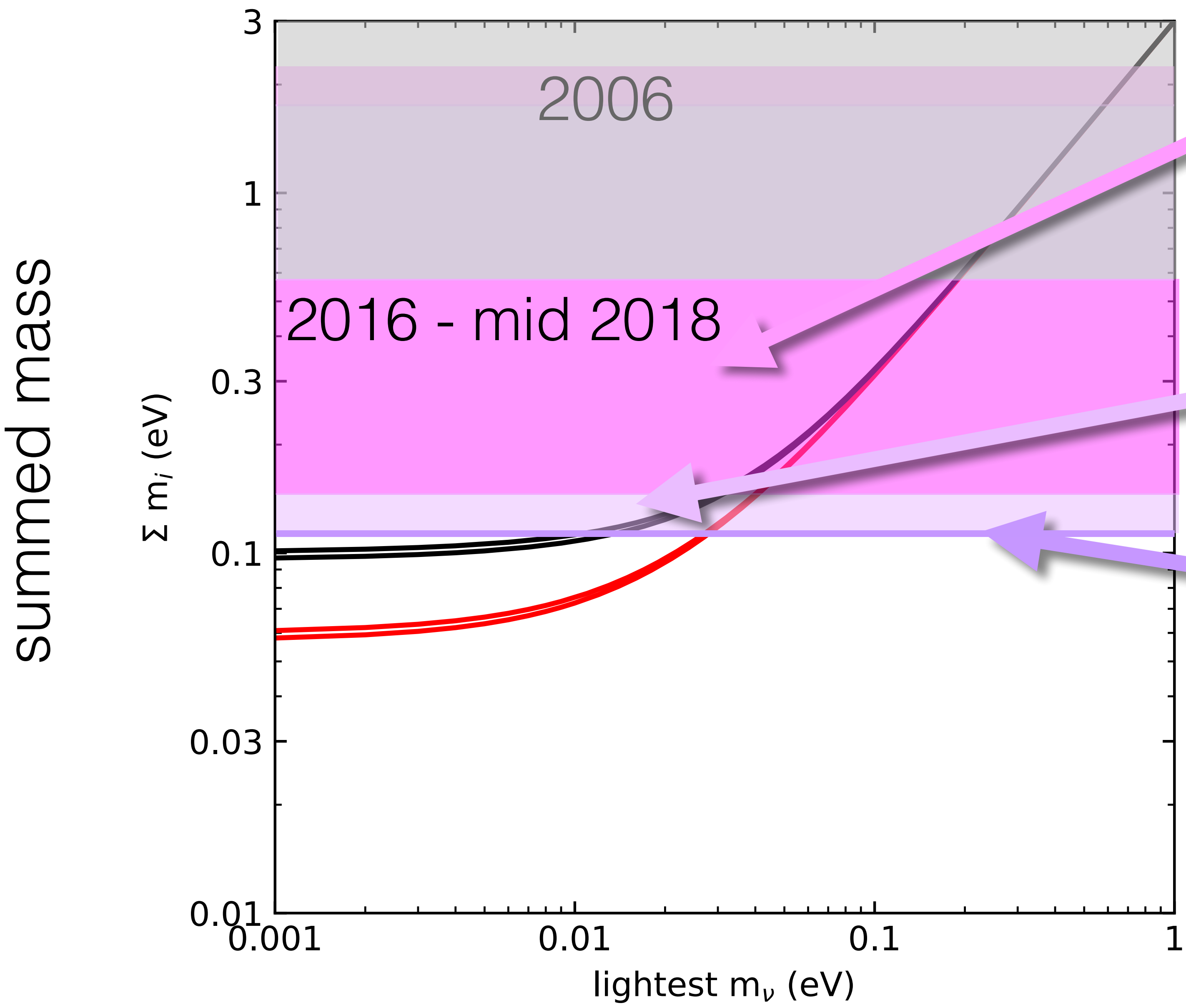

CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

CMB + conservative LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO: $\Sigma_i m_i$ < **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO: $\Sigma_i m_i$ < **120 meV** (95%CL)

- Planck 2015 + Lyman-α: $\Sigma_i m_i$ < **120 meV** (95%CL)

[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzi et al. 1701.08172;
PDG "Neutrino Cosmology" [JL & Verde]

… harder to avoid bounds with simple cosmological model extensions

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Neutrino density

N_{eff} = density of active neutrinos + any other light relics (<few eV) before any of them becomes non-relativistic (typically at $z\sim10^5$), in units of one active neutrino in the "instantaneous decoupling limit". Should be 3.045 in minimal model (de Salas et al. 2017)

Planck:

$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,;$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}\,.$$

(68%)

Unique "phase shift effect" seen in Planck and SDSS spectra (Baumann et al. 2018)

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Unique "phase shift effect" seen in Planck and SDSS spectra (Baumann et al. 2018)

Can be translated into constraint on asymmetry (Oldengott & Schwarz 2017)

$$\left| \sum_{\alpha=e,\mu,\tau} \frac{n_{\nu_\alpha}^{\rm dec} - \bar{n}_{\nu_\alpha}^{\rm dec}}{n_\gamma^{\rm dec}} \right| < 0.084 \qquad (95\%, \quad \mathrm{PlanckTT,TE,EE + lowP + lensing})$$

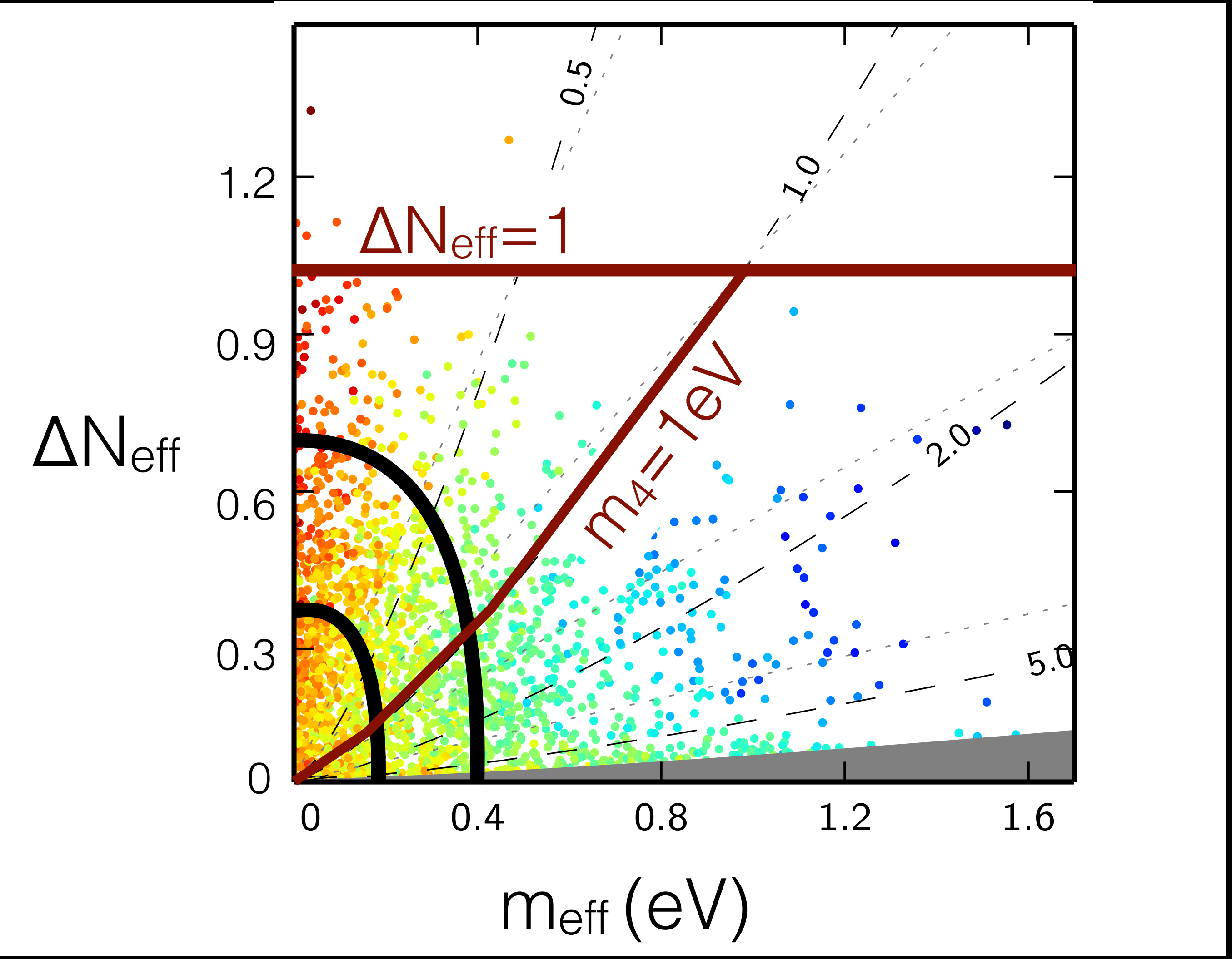
But in that case, still better constraints from BBN and primordial Helium measurements, with full simulation of neutrino oscillations in early universe and current knowledge of mixing angles (Castorina et al. 2012)

$$-0.071 < \sum_{\alpha=e,\mu,\tau} \frac{n_{\nu_\alpha}^{\rm ini} - \bar{n}_{\nu_\alpha}^{\rm ini}}{n_\gamma^{\rm ini}} < 0.054 \qquad (95\%, \quad \mathrm{WMAP + Helium})$$

Extra relics (small mass case)

Current bounds on one early-decoupled or non-thermalized extra light species (e.g. ν_4 of 3+1 scenario, abusively called "sterile neutrino")

Effective density parameters	Planck 2015 (TT+lowP+lensing) + BAO
ΔN_{eff} (extra contribution to density *before* NR transition)	<0.7 (95%CL)
m_{eff} (extra contribution to density *after* NR transition)	< 400 meV (95%CL)



For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

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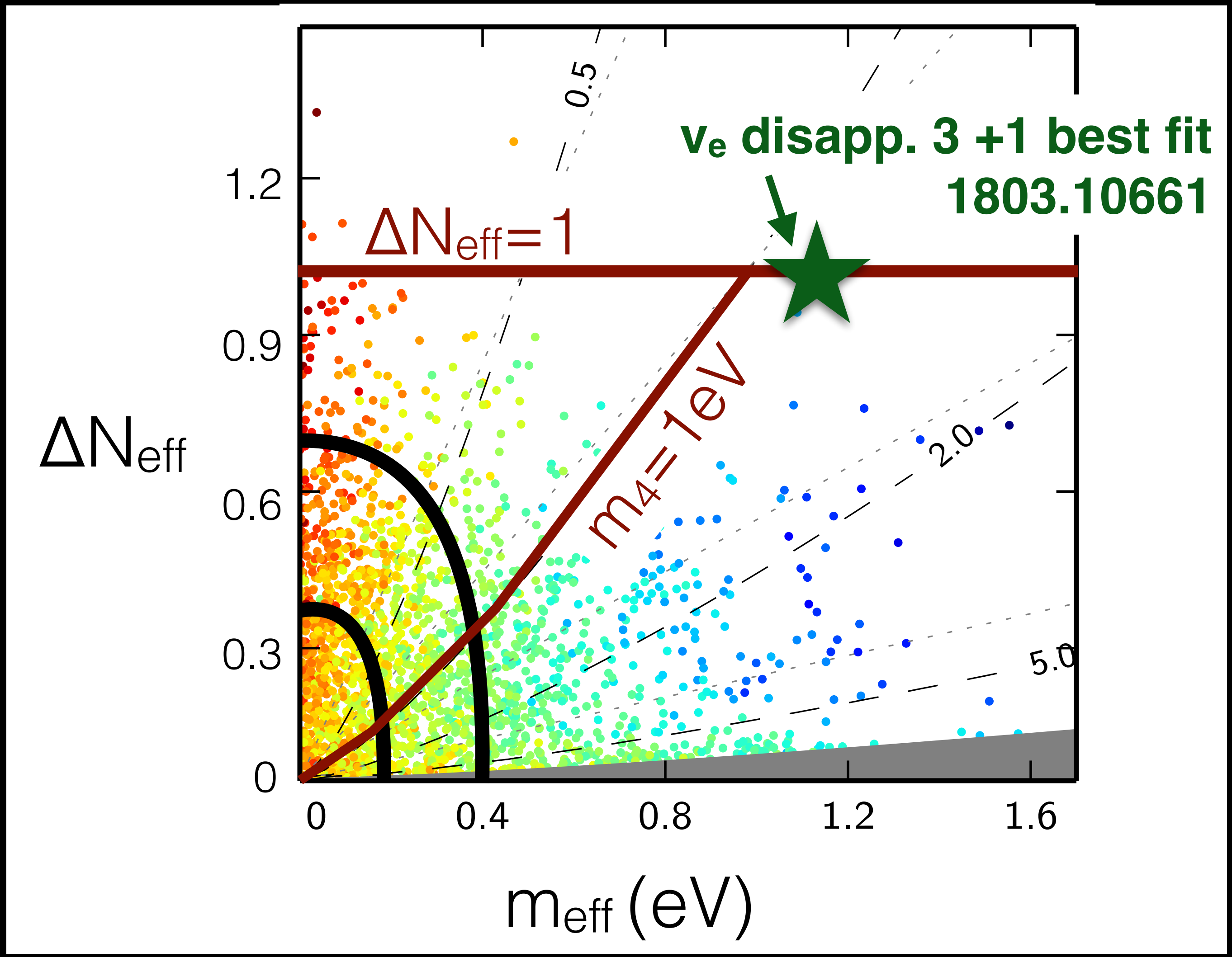

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Extra relics (small mass case)

How to suppress the ν_4 density in both relativistic and non-relativistic regimes?

- Low-temperature reheating — Gelmini et al. 2014, de Salas et al. 2015
- Leptonic asymmetry and resonant oscillations… *issues with BBN* (μ_e)

  Di Bari et al. 2001; …; Hannestad, Tambora & Tram 2012; Mirizzi et al. 2012; Saviano et al. 2013
- NSI (need to pass bounds on fifth force and SN energy loss…)
  - ν_4 interacts with (dark) gauge boson

    Dasgupta, Kopp 2015 ; Saviano et al. 2014; Mirizzi et al. 2014; Chu, Dasgupta, Kopp 2015
  - ν_4 interacts with (dark) pseudoscalar

    Hannestad et al. 2013; Saviano et al. 2014; Archidiacono et al. 2016
    - ν_4 production is suppressed, ϕ-ν_s recouple —> neutrinos as relativistic fluid *(maybe testable with future CMB data)*, ν_4 annihilate into ϕ at late times…

For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

Plan

1. Best current bounds on active neutrino mass, density, chemical potential, light sterile neutrinos, etc., with minimal assumptions on underlying cosmological models

2. How much should we believe these bounds (given model-dependence and unexplained anomalies in cosmological data like H_0 tension)
    1. Do neutrino bounds relax with simple extensions of LCDM?
    2. De we need a change of paradigm to explain cosmo. data anomalies?

3. Robust sensitivity forecasts from future experiments

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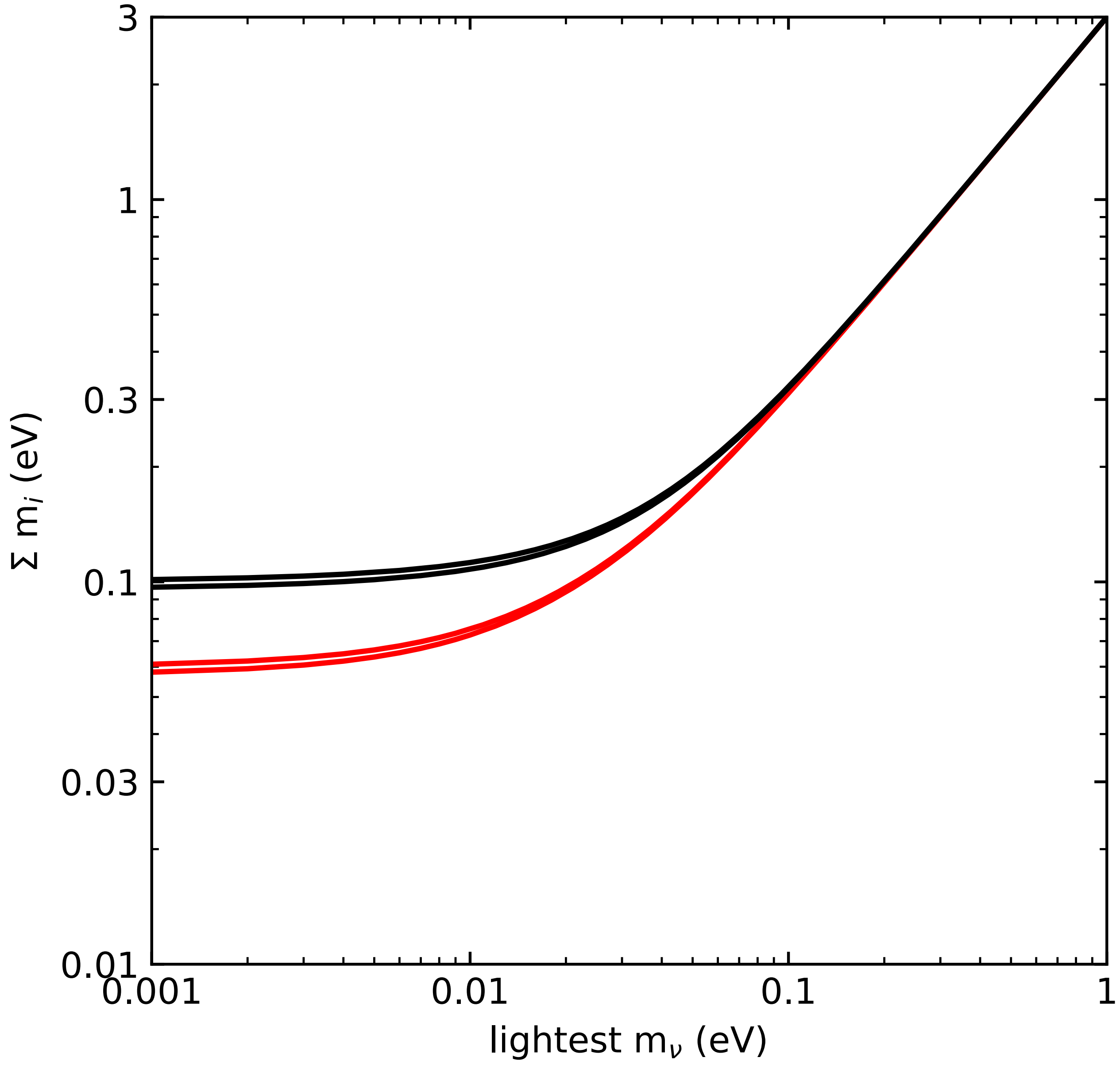
Robustness of mass bounds against cosmological model extensions

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters

summed mass



Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- primordial perturbations

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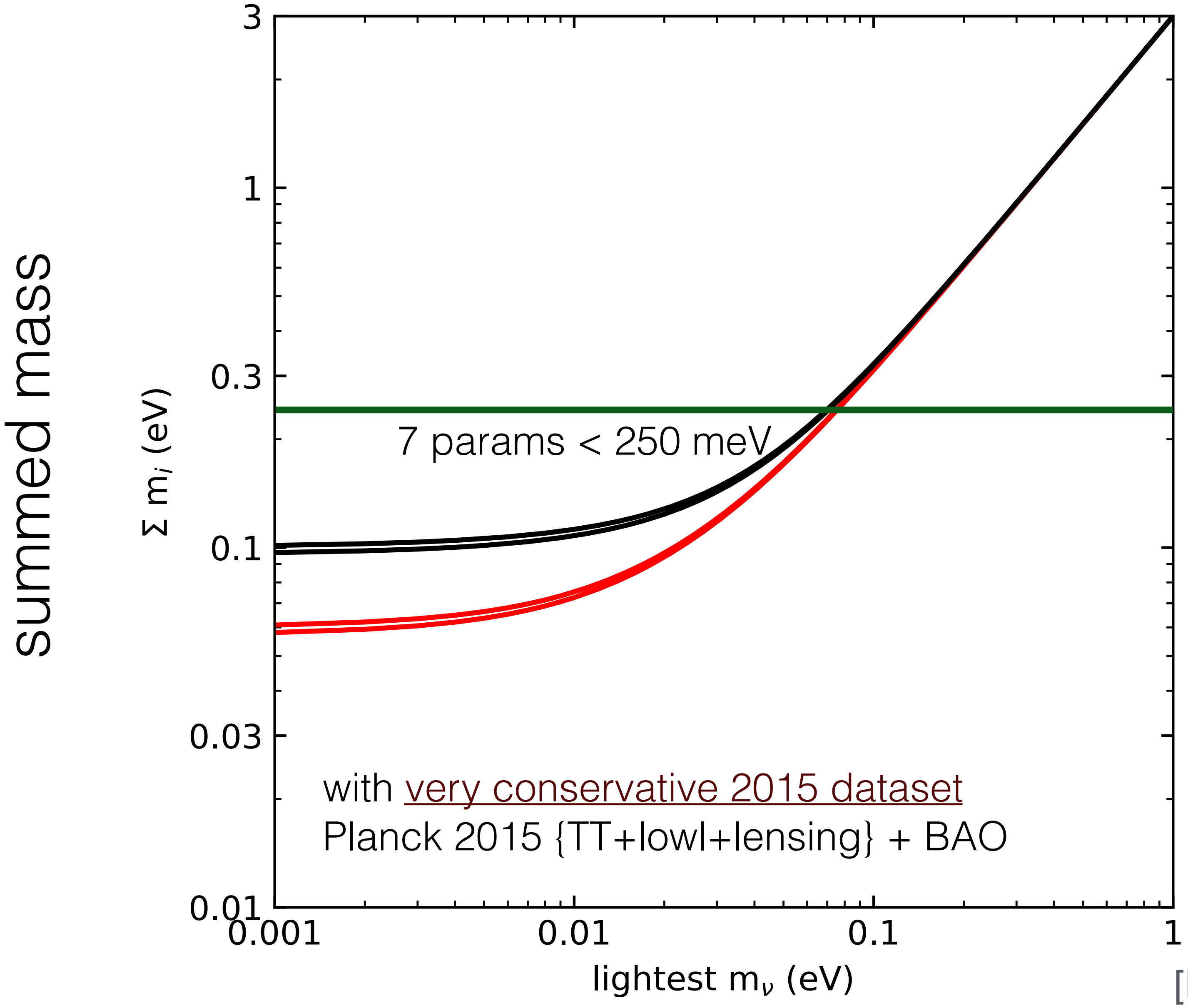

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[Planck col.] 1502.01589;

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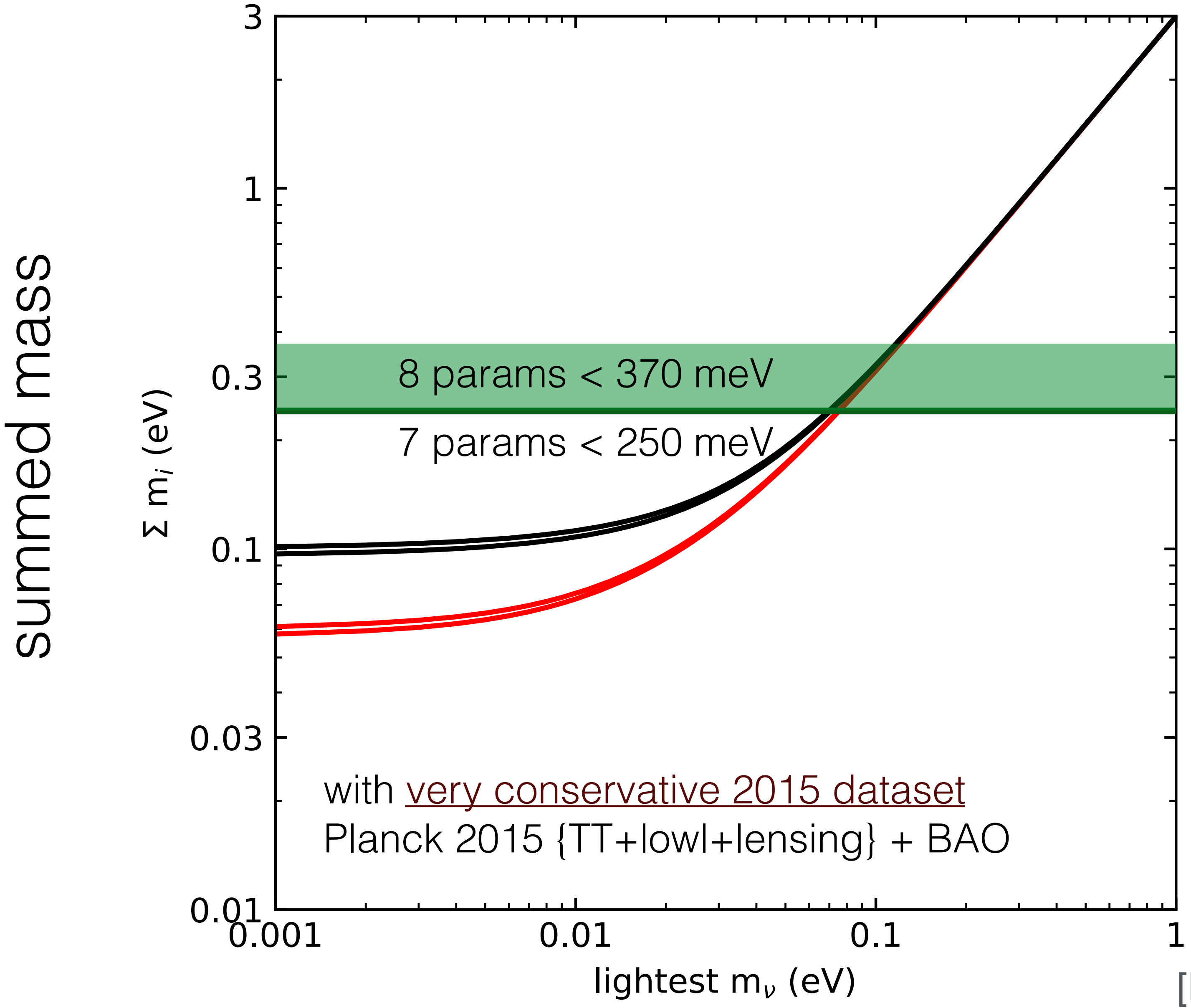

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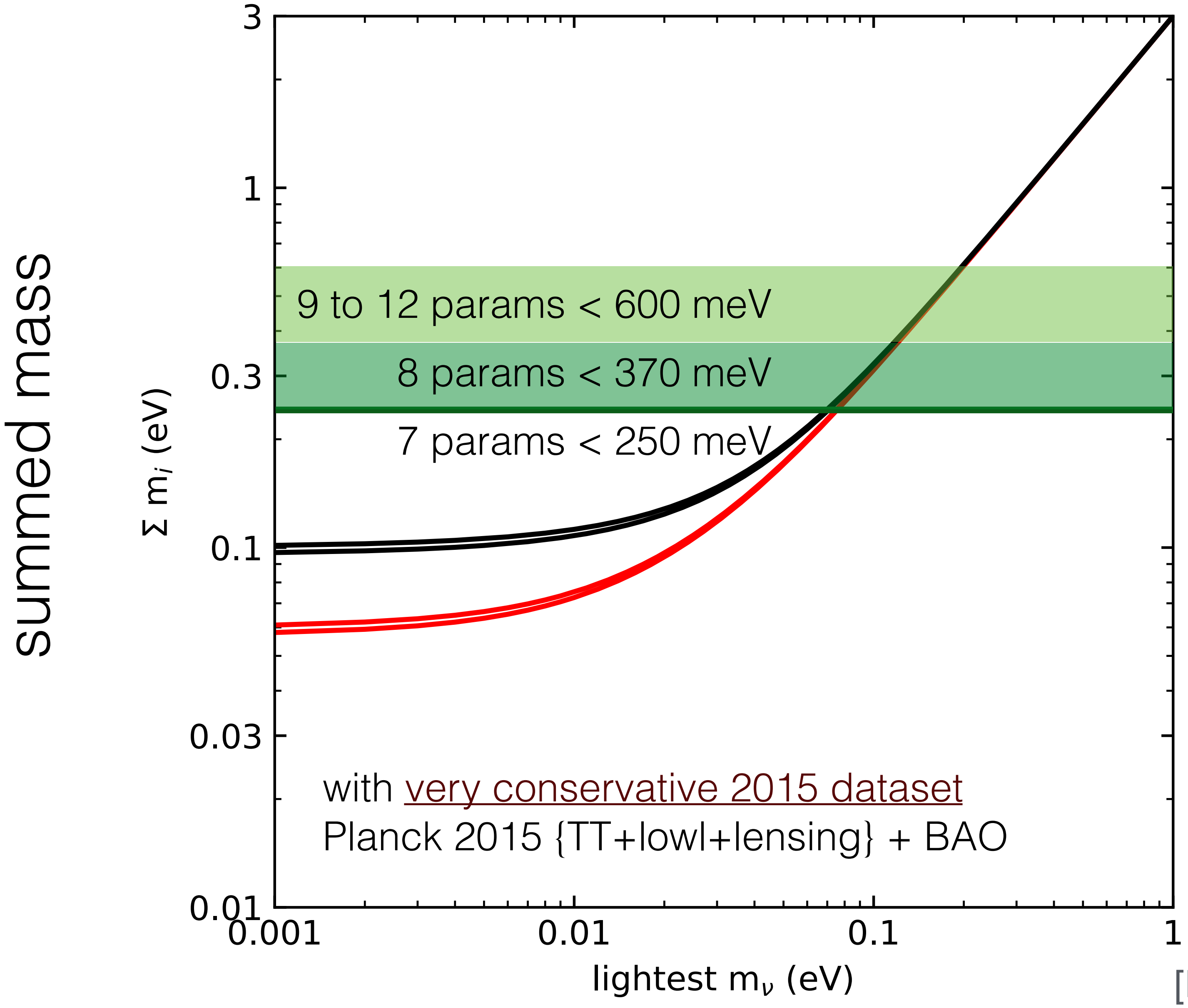

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[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

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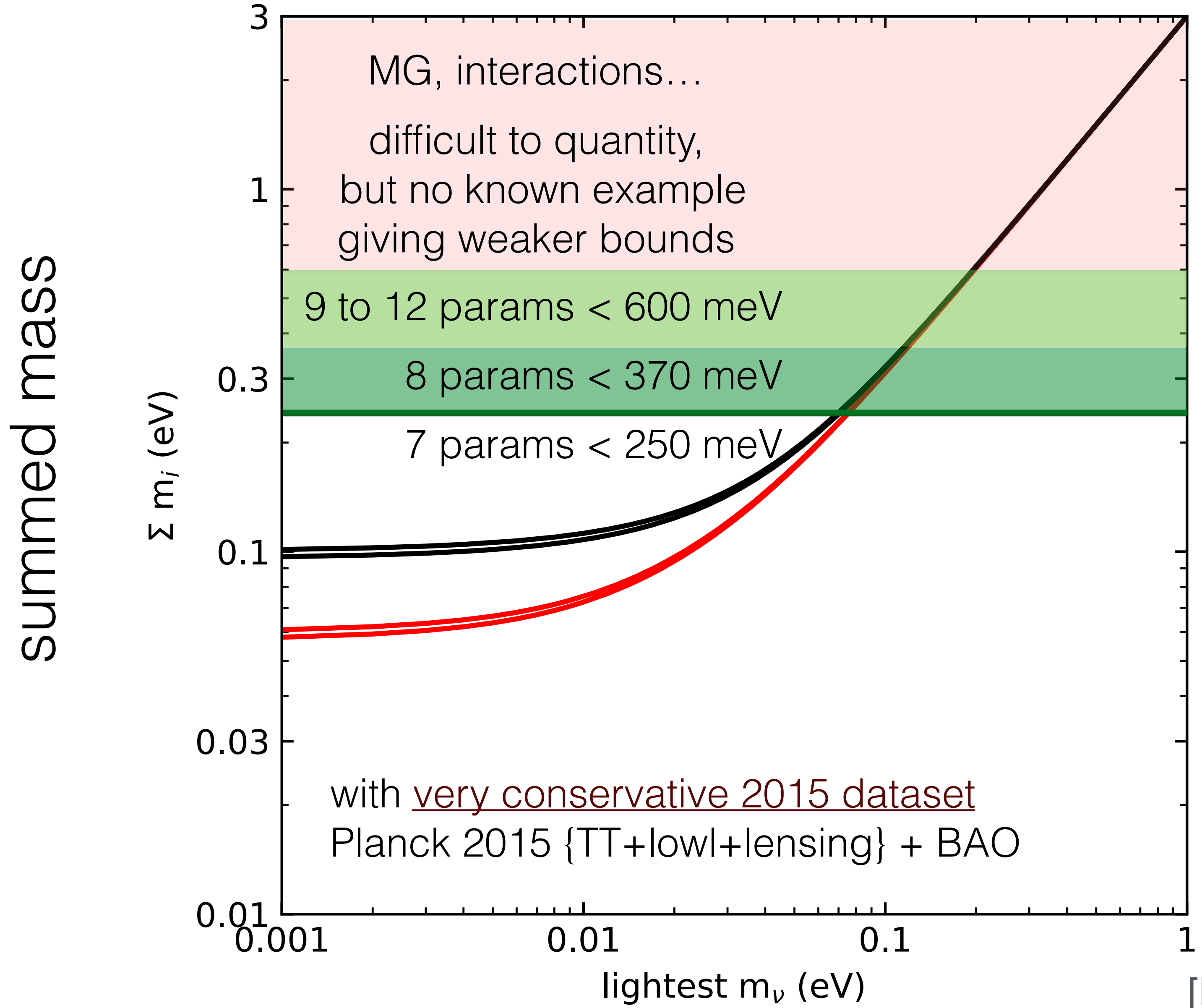

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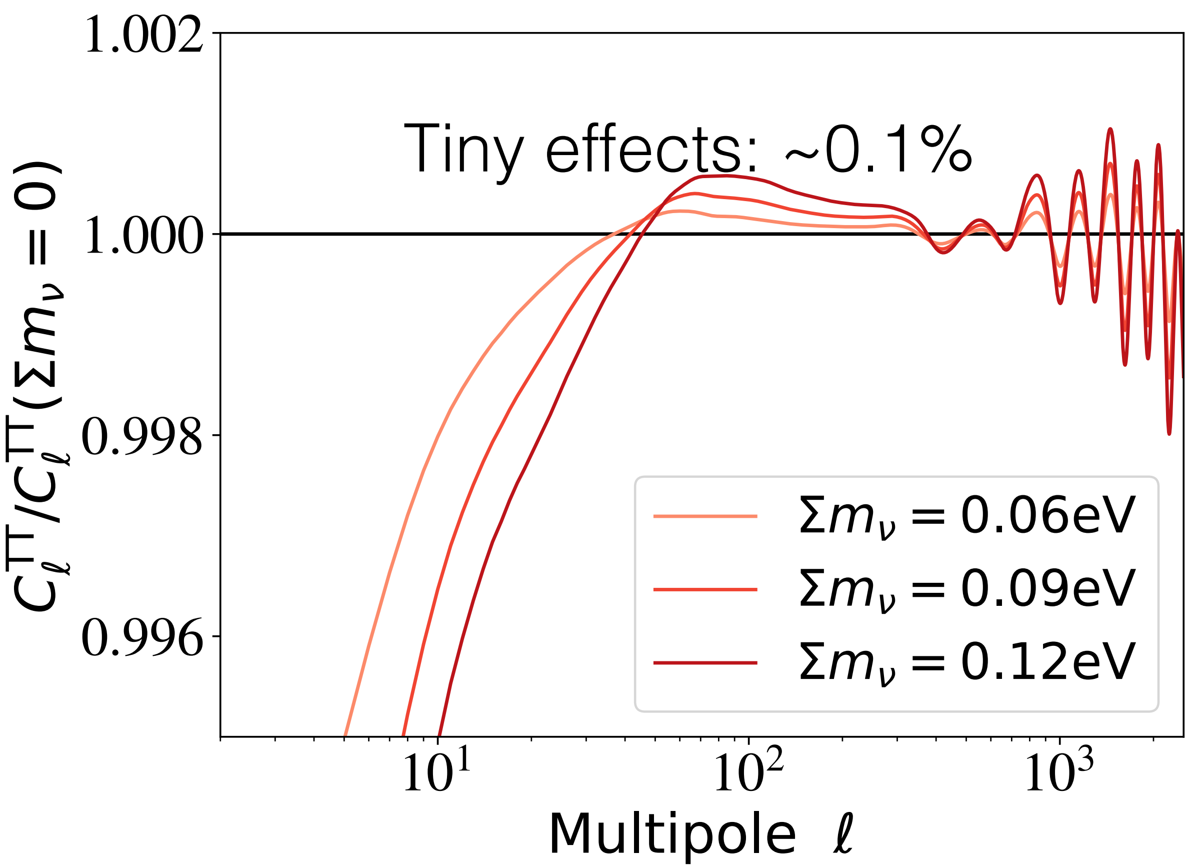
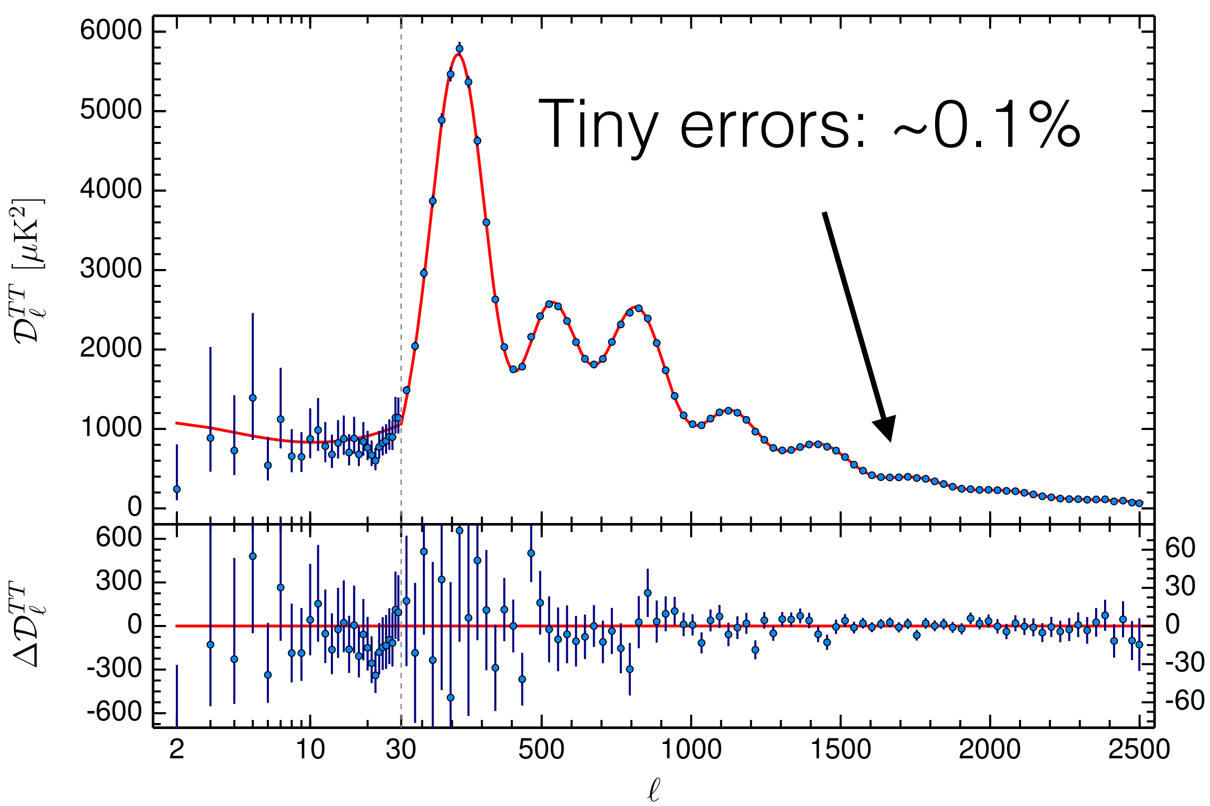
Robustness of mass bounds against measured CMB spectrum

- Neutrino bounds dominated by CMB spectrum (mainly through lensing effect) thanks to tiny error bars:





- Could result on neutrino mass be biased by residual systematics or statistical fluctuations?
- Possibly yes: possible hint from so-called "A_L tension"

Robustness of mass bounds against measured CMB spectrum

- A$_L$ tension: A$_L$ not a physical parameter; just way to say that a cosmological model predicting more contrasted oscillations in some l range (1100-2000) could be a slightly better fit, and that CMB χ^2 could decrease by ~6 with such hypothetical model; looks like additional CMB lensing, but cannot be CMB lensing (probed directly by lensing extraction).

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- Interesting however, since neutrino mass mainly probed by CMB lensing!! High neutrino mass => less CMB lensing, while data => “effectively” more lensing effect!
  - ➡ If comes from missing theoretical ingredient or residual systematic: after solving this, new observed spectrum would be compatible with higher masses (estimate: 60% weaker bound)
  - ➡ If statistical fluke: unluckily, our single observation of the CMB map could give posterior peaking below the true value of the parameter, which could then easily be 0.12 or a bit more

- Should be resolved with future precision LSS data!

Robustness of mass bounds against (small) change of paradigm

- Amazing consistency of minimal LCDM Planck best-fit with BAO, redshift-space distortions, BBN and primordial elements, supernovae, etc.

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- EDGES anomaly: hint of energy being injected into photons or pumped from baryons, maybe due to new particle physics; potential connection with evolution of perturbations

Robustness of mass bounds against (small) change of paradigm

- H_0 tension
- σ_8 tension
- EDGES anomaly…
  - ➡ do not suggest consistent picture … connected to background, perturbations, thermodynamical evolution
  - ➡ very difficult to explain by modifying something without conflicting CMB!
  - ➡ H_0 tension could be solved with increase of all densities including radiation (ΔN_{eff}~3.5) but then other problems pop-up: need subtle cancellations of other effects in CMB
  - ➡ could point at modifications of late cosmology only (background density and growth rate) normally excluded by CMB (angular diameter to z_{dec}, late ISW, CMB lensing potential…)

Robustness of mass bounds against (small) change of paradigm

- H_0 tension
- σ_8 tension
- EDGES anomaly…
  - ➡ some non-trivial models may work, e.g. non-standard interactions between light sterile neutrinos and a pseudoscalar (Archidiacono et al. 2016) also solving SBL anomaly and compatible with 5th force and supernovae; non-standard Dark Matter - Dark Relic Radiation (JL, Marques-Tavares, Schmaltz 2016)
  - ➡ All these are small deviations from ΛCDM inducing at most 10% effects
  - ➡ Normally not expected to relax neutrino mass bounds: large H_0 goes against large M_ν at level of angular diameter distance; extra ingredient leading to small σ_8 gives less room for neutrino free-streaming effects

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3. **Robust sensitivity forecasts from future experiments**

Sensitivity forecast to neutrino mass

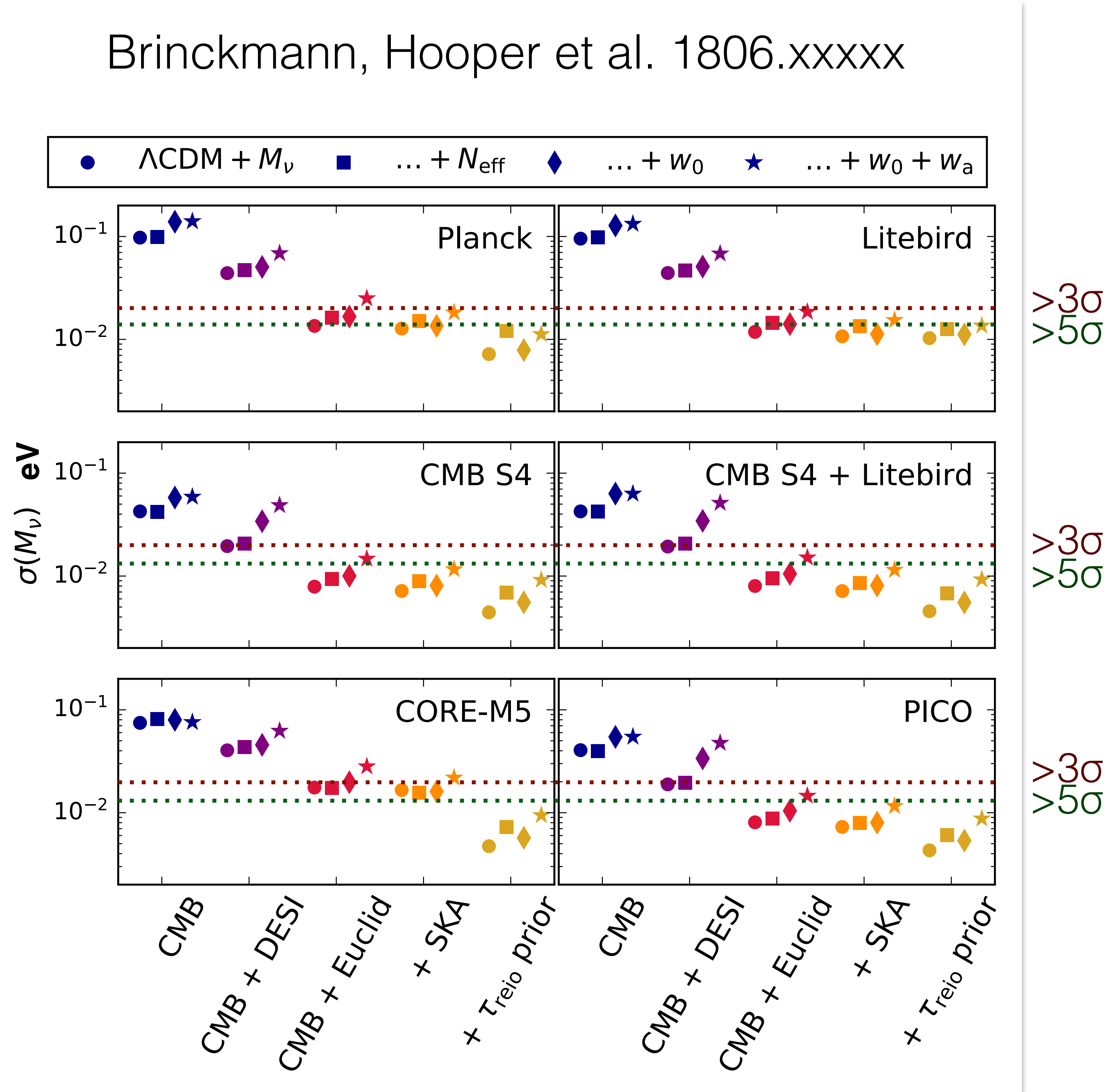
- Audren et al. 2015; Sprenger et al. 2018; Brinckmann, Hooper et al. 2018 in prep: production of robust forecasts (MCMC analysis of mock spectra, marginalisation over systematic and theoretical errors accounting for non-linear modelling uncertainties)

- Still ideal in the sense that ΛCDM + M_ν =0.06eV assumed to be correct fiducial model and that data has no anomalies or tensions

Sensitivity forecast to neutrino mass

- Y-axis: M_ν sensitivity
- Panels: different CMB
- X-axis/colors: different LSS
- Point styles: different cosmology

Critical progress: CMB S4 + Euclid



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