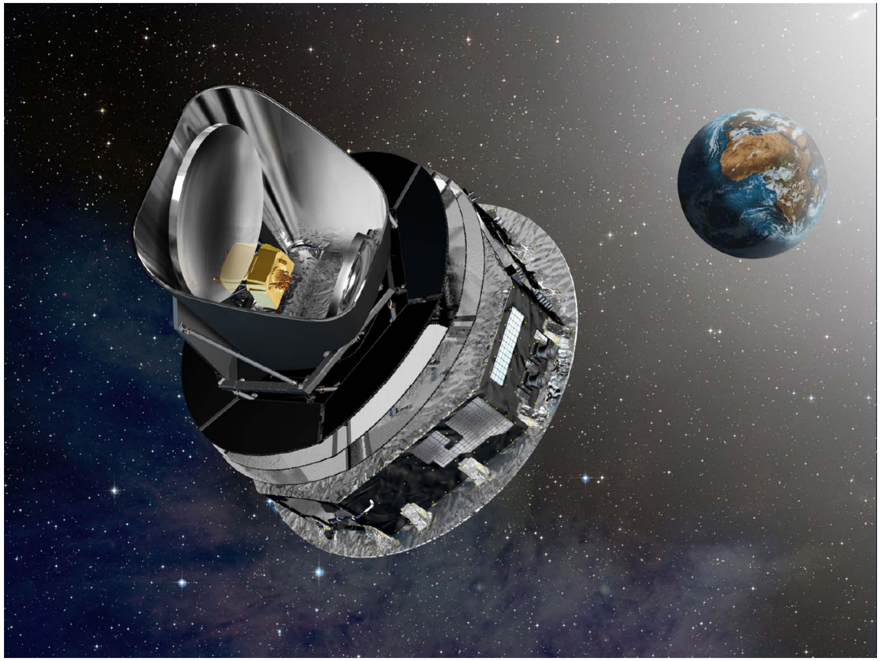


Sterile neutrinos and Planck results

SWAPS 2014, Cartigny, 13.06.2014

J. Lesgourgues (EPFL, Lausanne & CERN, Geneva & LAPTh, Annecy)

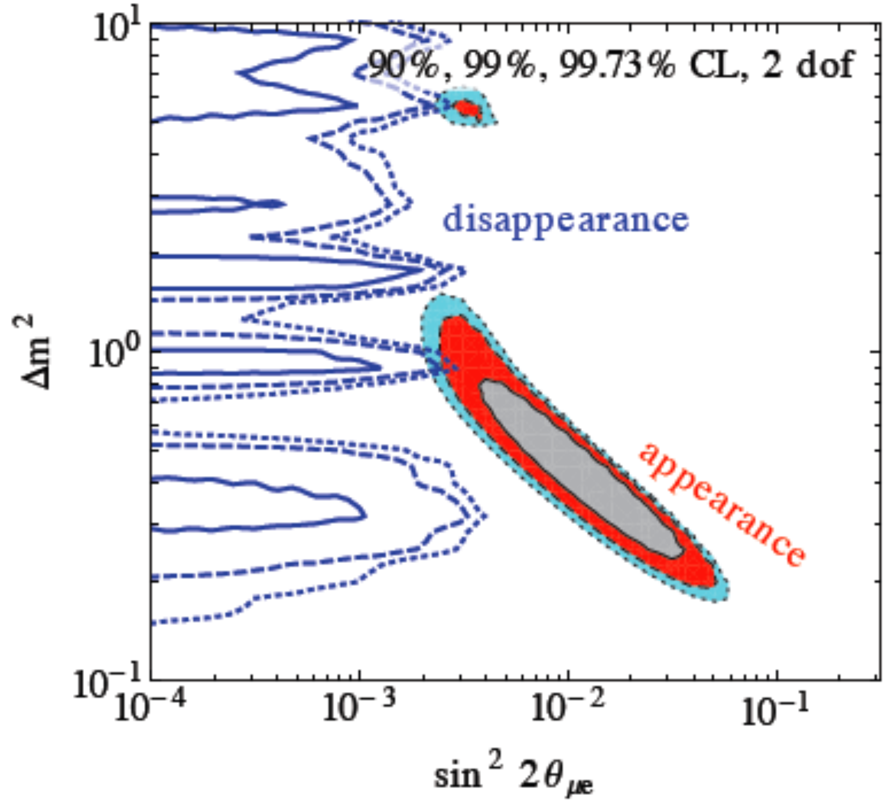
Neutrino anomalies

Experiment	What do they measure?	Estimate of significance
Nuclear reactors (ILL, Bugey, Gösgen...)	A small deficit in the $\bar{\nu}_e$ flux from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu fission.	2.5σ? 1101.2755 1309.4146
Galium detectors (SAGE and GALLEX)	A small deficit in the ν_e-flux from ^{51}Cr and ^{37}Ar decay.	3.0σ 1006.3244
Short baseline oscillation experiments (LSND and MiniBooNE)	$\bar{\nu}_\mu - \bar{\nu}_e$ and $\nu_\mu - \nu_e$ oscillations.	$3.8\sigma + 0\sigma + 3.0\sigma$ (1007.1150 + ...)

Borrowed from Thomas Tram

Neutrino anomalies

3+1 analysis in
Kopp et al. 2013



Appearance: LSND, MiniBoone, NOMAD, KARMEN, ICARUS, E776
Disappearance: reactor, Gallium, MiniBoone, CDHS, Minos, KARMEN

Light sterile Neutrino production

… through *active-sterile neutrino oscillations*

Large mixing angle leads to same number density as one active neutrino species (thermalisation)

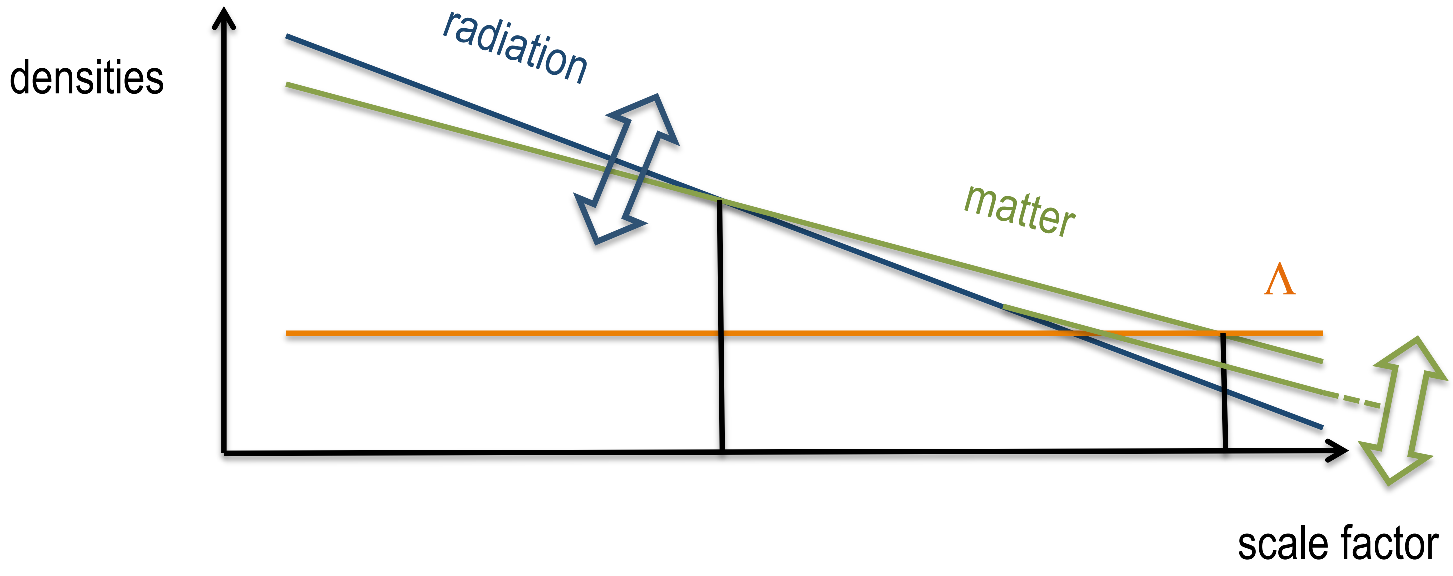
Density can be suppressed by:

- Small mixing angle *(then, no explanation of short baseline oscillations)*
- Resonant oscillations related to lepton asymmetry — Hannestad et al. 1204.5861, Mirizzi et al. 1303.5368
- Non-standard interactions with dark particles — Hannestad et al. 1310.5926
- Low-temperature reheating (if ~~BICEP~~)

Point of view of cosmological observations

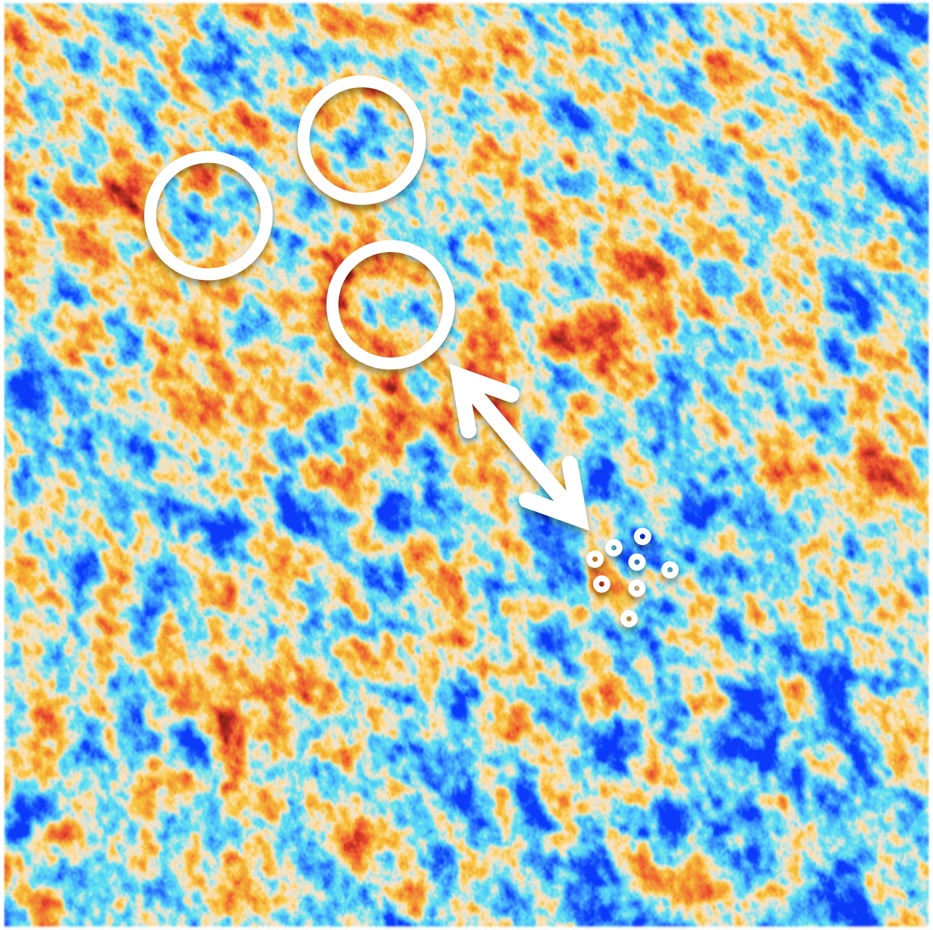
TWO independent questions:

- Is there extra radiation on top of photons and standard neutrinos?
- Is part of the radiation content becoming non-relativistic at late times (HDM) ?



Different observables

- Is there extra radiation on top of photons and standard neutrinos?
  - CMB:
    peak scale relative to diffusion scale,
    peak amplitude patterns
  - LSS:
    BAO peak patterns



Different observables

- Is part of the radiation content becoming non-relativistic at late times (HDM) ?

  - LSS

    less dark matter fluctuations on small scales

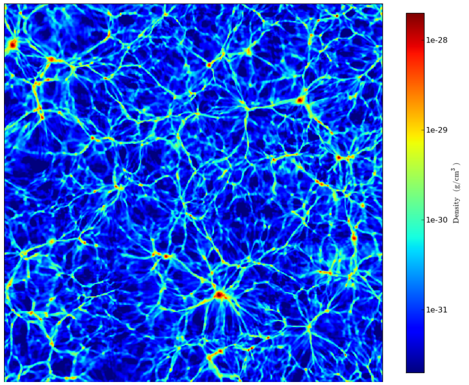
    Probed by:

    - galaxy correlation
    - galaxy cosmic shear
    - cluster abundance
    - CMB lensing
    - Lyα forests in quasar spectra

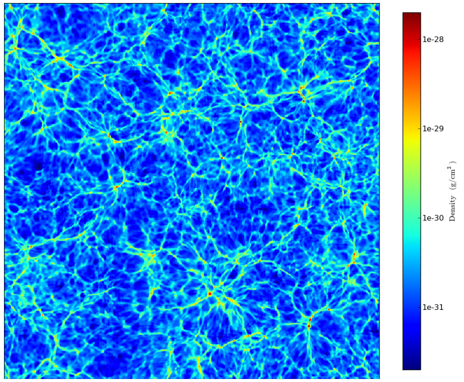
  - Primary CMB

    depletion from eISW

reference



with hot component



First effect…

… parametrised by N_{eff} :

energy density of radiation, besides photons, in early universe,

in units of the density of one standard neutrino family (omitting technical details)

$N_{eff} > 3$ could be due to:

- Neutrino-antineutrino asymmetry
- Extra production of neutrinos after decoupling (e.g. from decay of exotic particle)
- Light sterile neutrinos (not seen by LEP since not weakly coupled)
- Any other massless or light relic (thermal axion, gravitinos, dark hidden sector …)
- Unusually large background of gravity waves
- Effective dark radiation from modified gravity
- Etc.

Second effect…

… parametrised by $M_{\nu eff}$ (eV):

Energy density of matter behaving as "hot" instead of "cold", in late universe, divided by appropriate factor so that $M_{\nu eff}$ = physical mass if all hot particles have the number density as standard neutrinos

$M_{\nu eff} > 0$ could be due to:

- Neutrino masses, contributing to at least $M_{\nu eff} > 0.06$ eV (NH) or 0.11 eV (IH)
- Light sterile neutrinos with masses of $\mathcal{O}(10^{-1})$ eV at least (otherwise, undetectable)
- Any other light relic (thermal axion, gravitinos, dark hidden sector …)

Bounds on $M_{\nu eff}$ are model-dependent

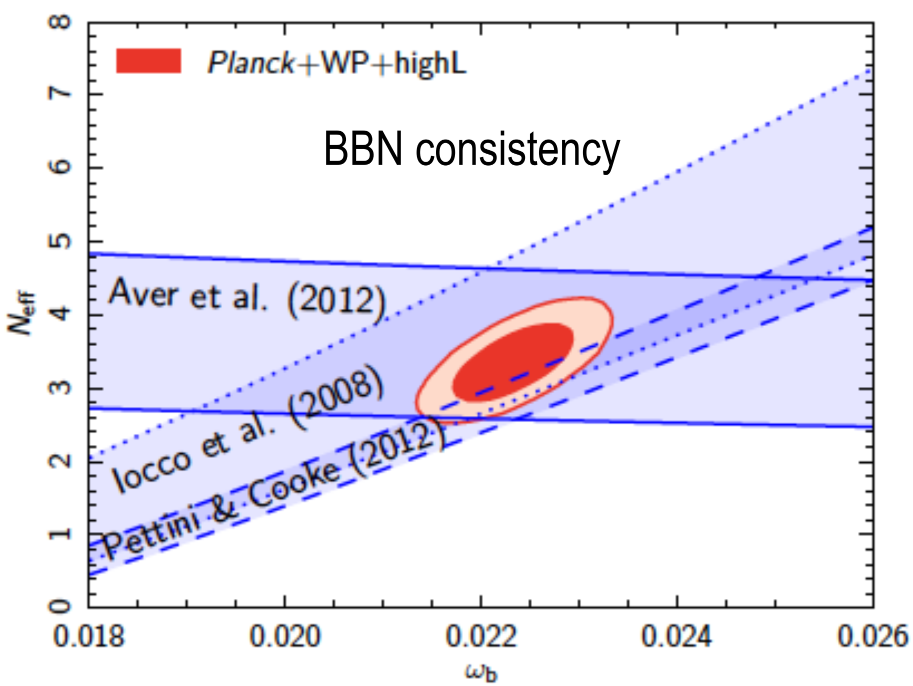
(e.g. depends on N_{eff}; on different ways to split total mass between species with same number density; either more freedom if species have different number densities…)

Measuring N_{eff}

- Ultimately, constraints driven by CMB damping tail
  - WMAP+SPT see anomalously low tail: $N_{eff} > 3$ at 2 sigma
  - Planck and Planck+BAO well compatible with standard value at 1 sigma

CMB alone (Planck+WP+HighL)

$N_{eff} = 3.36 \pm 0.66$ (95%CL)



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  - Planck (+BAO) + HST : enforce higher H_0, hence also higher N_{eff}

CMB alone (Planck+WP+HighL)

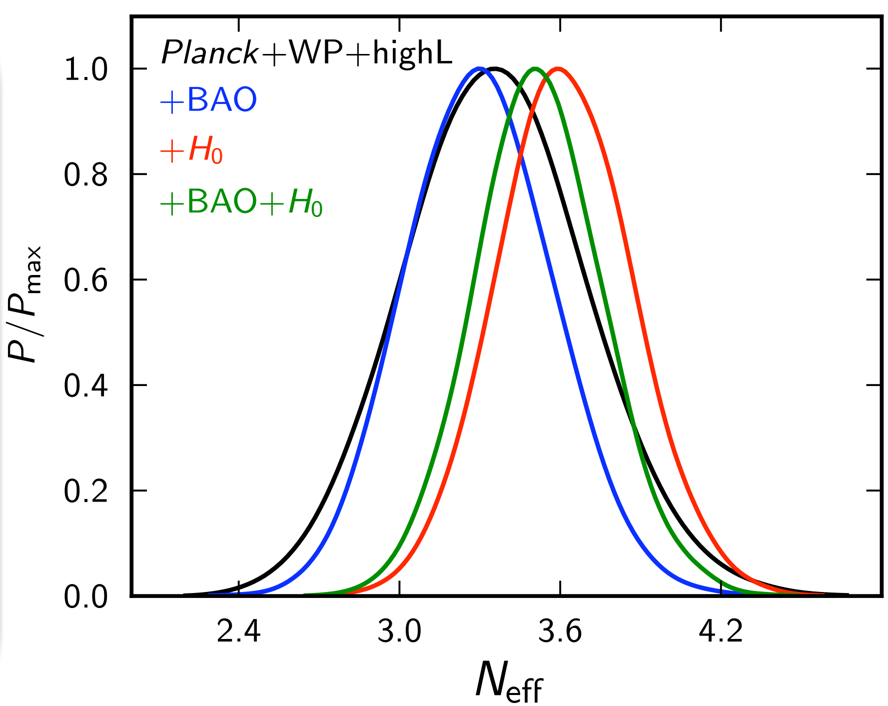
$N_{eff} = 3.36 \pm 0.66$ (95%CL)

With lensing and BAO:

$N_{eff} = 3.30 \pm 0.52$ (95%CL)

With H_0:

$N_{eff} = 3.63 \pm 0.49$ (95%CL)



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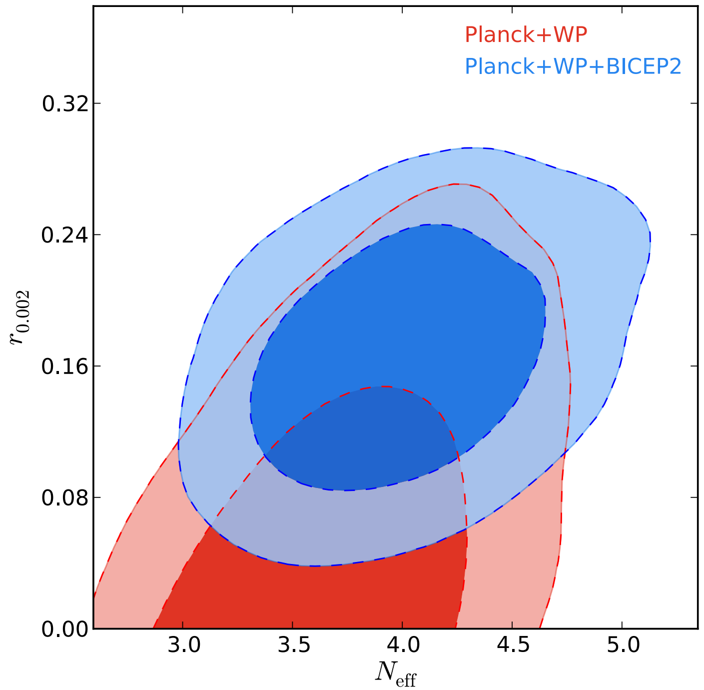
  - Planck and Planck+BAO well compatible with standard value at 1 sigma
  - Planck (+BAO) + HST : enforce higher H_0, hence also higher N_{eff}
  - Planck + BICEP2 : to decrease r tension, also higher N_{eff}

CMB alone (Planck+WP+HighL+BICEP2)

$N_{eff} = 4.00 \pm 0.41$ (68%CL)



Giusarma et al. 1403.4852

Measuring $M_{\nu eff}$

CMB:

- Not observed by Planck (within error bars)!
- Planck + WP alone: $M_\nu < 0.66$ eV (95% CL)
- adding BAO: $M_\nu < 0.23$ eV

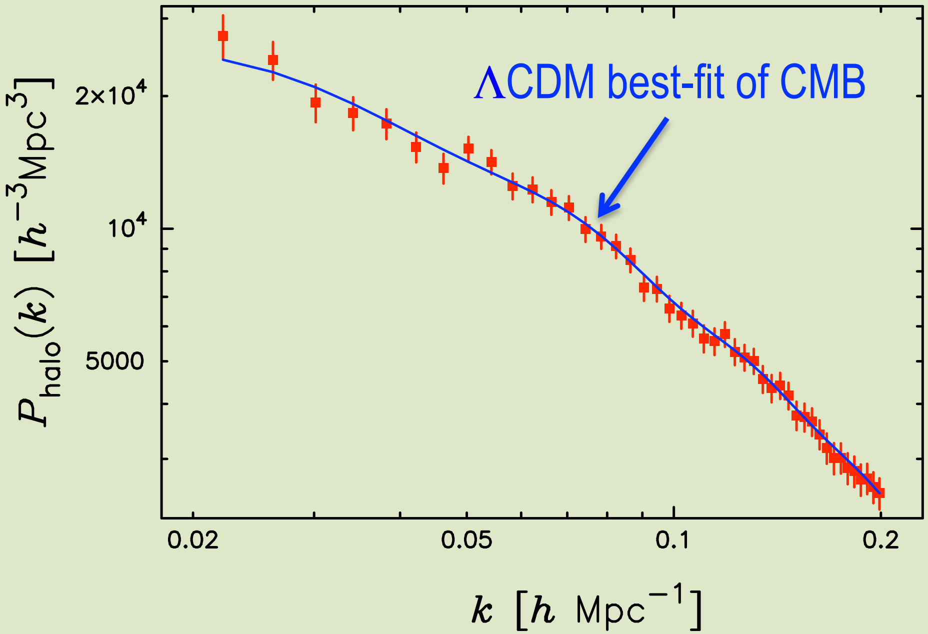
Planck XVI paper, 2013

CMB + LSS:

- Contradictions: compatible with $M_\nu < 0.23$ eV or pointing at ~0.3-0.4 eV

Measuring $M_{\nu eff}$

Most probably issue with systematics…



Measuring $M_{\nu eff}$

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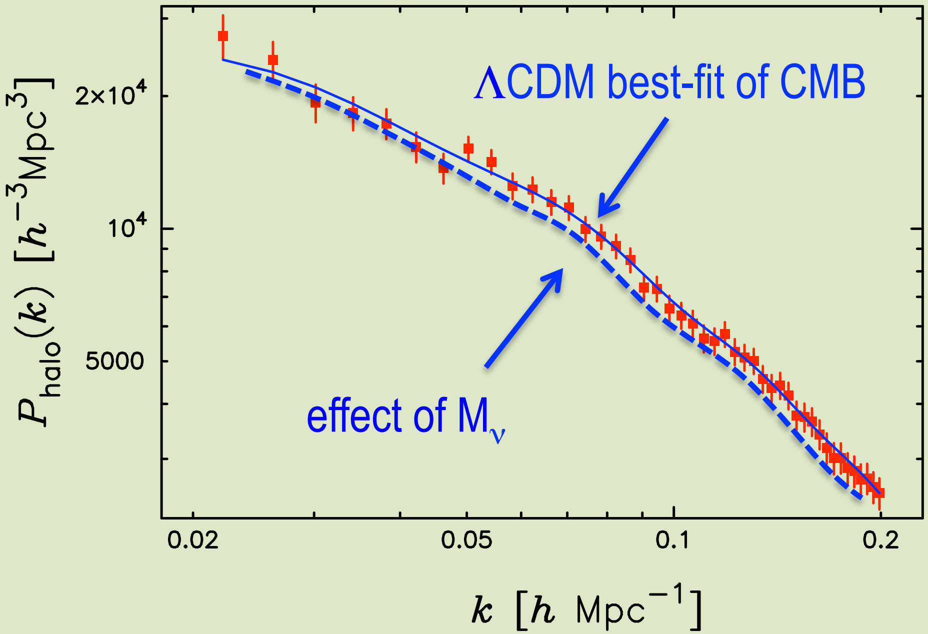

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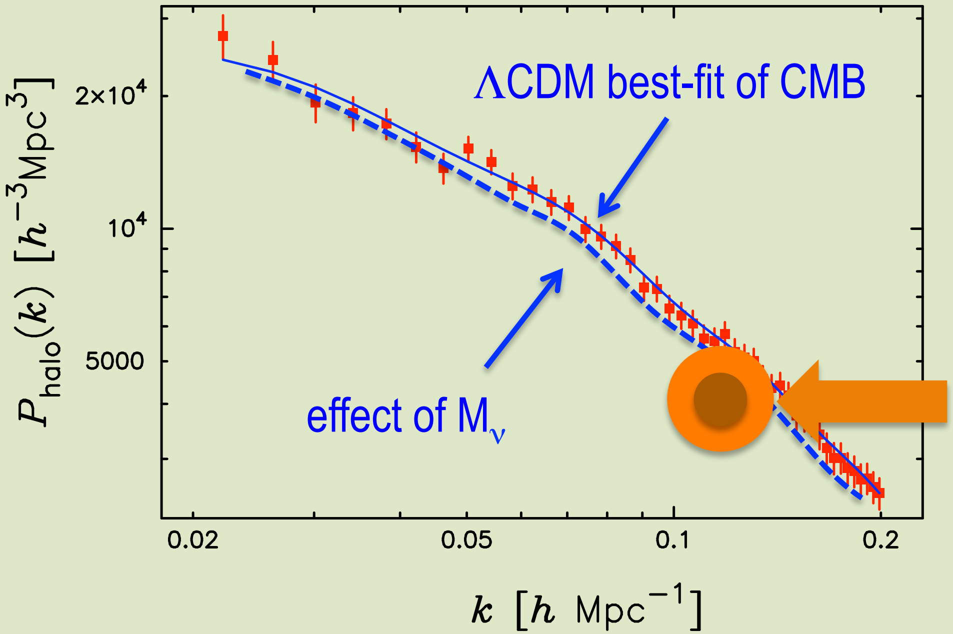


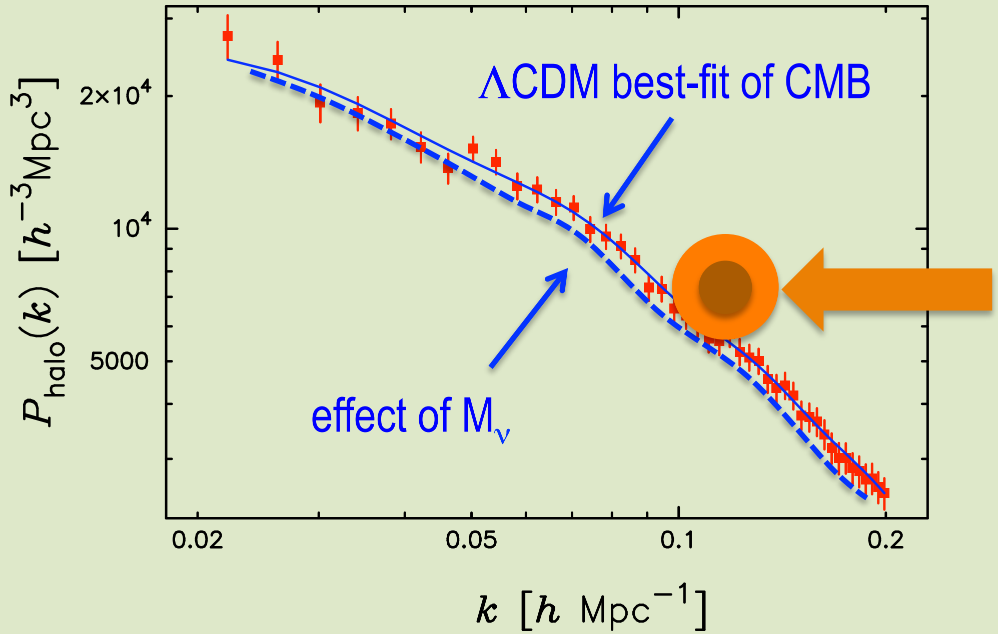
Any experiment seeing low amplitude favors high neutrino mass but conflicts CMB TT

- CMB lensing,
- (SZ) clusters,
- CFHTLens weak lensing,
- BOSS red.-space dist.

Claims for M_ν~0.3eV – 0.8eV

Measuring $M_{\nu eff}$

Most probably issue with systematics…



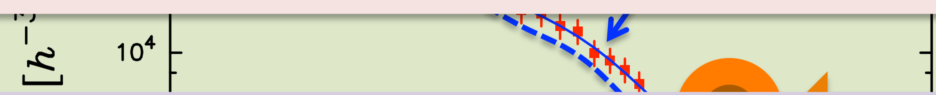
Any experiment seeing high amplitude disfavors high neutrino mass:

- SDSS Ly-α of 2006

Measuring $M_{\nu eff}$

Need better data!

Full Planck, full BOSS, eBOSS, DES, LSST, Euclid, Core, 21cm…

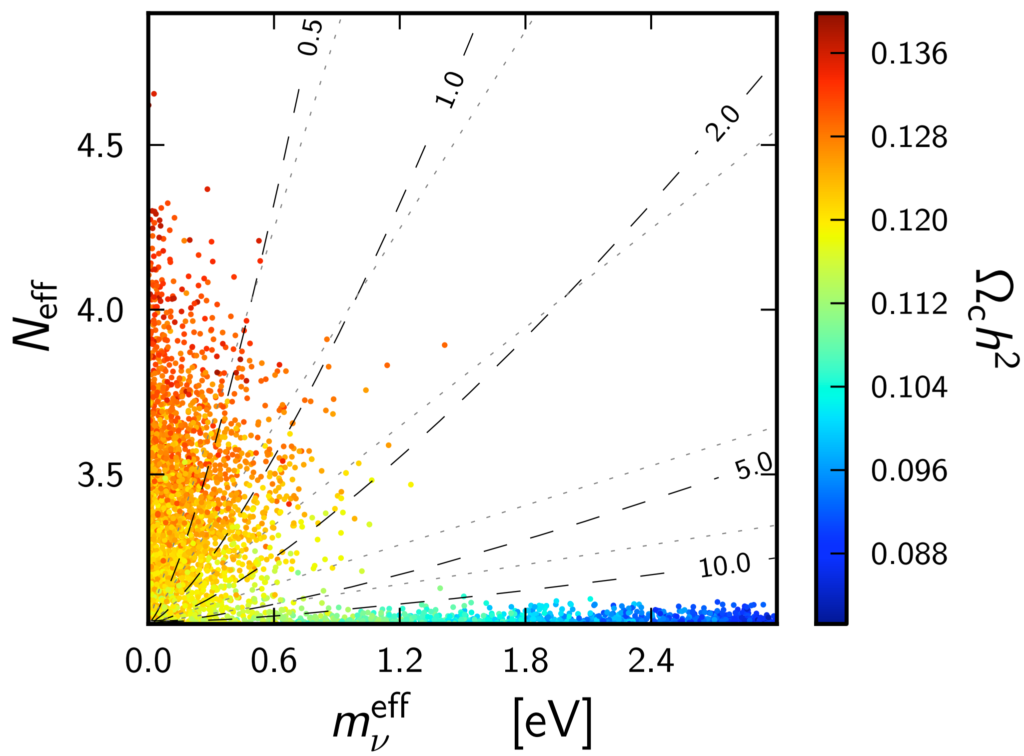


Any experiment seeing
high amplitude disfavors
mass
2006)

In worst case: minimal $M_{\nu eff}$ = 0.06 eV is within sensitivity of Planck+Euclid

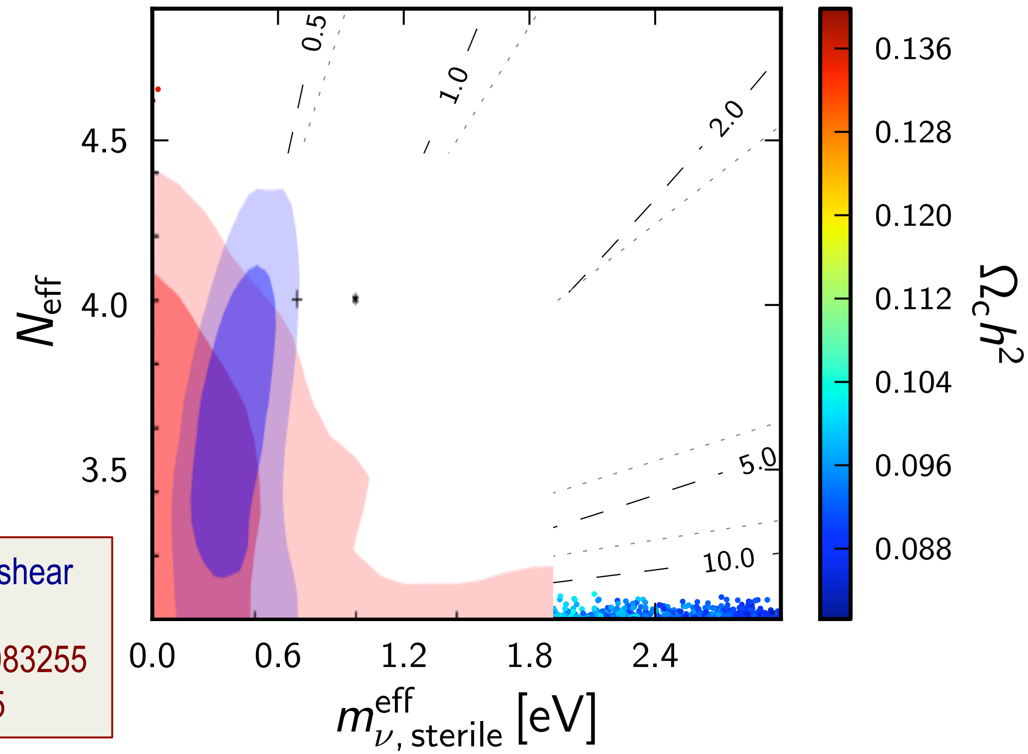
Joint constraints

CMB only (Planck + WP + highL) analysis for 3+1 case:



Light sterile neutrinos

CMB only (Planck + WP + highL) analysis for 3+1 case:



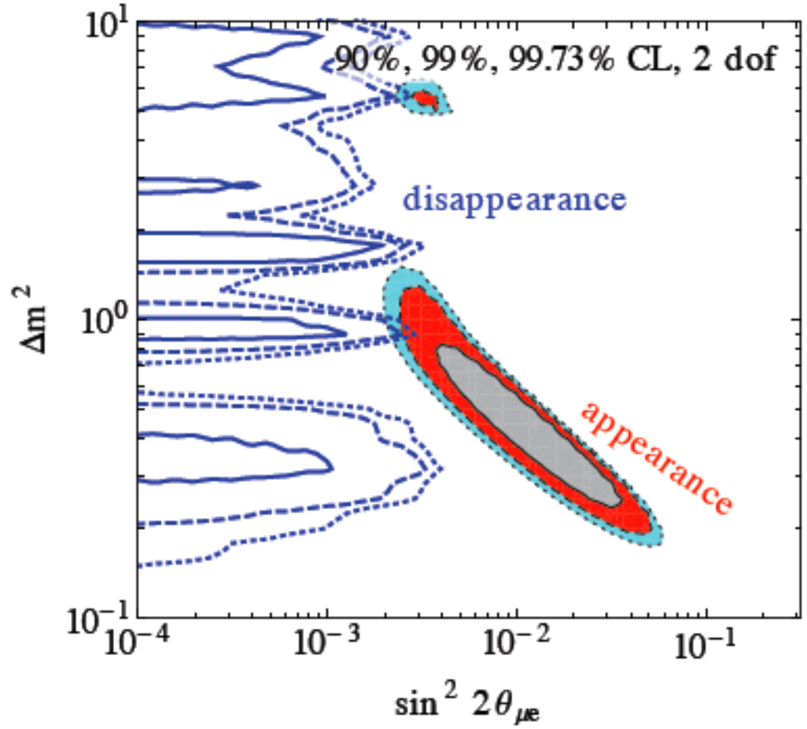
Using H0 + BAO + clusters + gal.shear

From Hamann & Hasenkamp 13083255
See also Wyman et al. 1307.7715

Light sterile neutrinos

Motivations: anomalies in short-baseline neutrino oscillation experiments

3+1 analysis in
Kopp et al. 2013



Appearance: LSND, MiniBoone, NOMAD, KARMEN, ICARUS, E776

Disappearance: atmospheric, solar, reactor, Gallium, MiniBoone, CDHS, Minos, KARMEN

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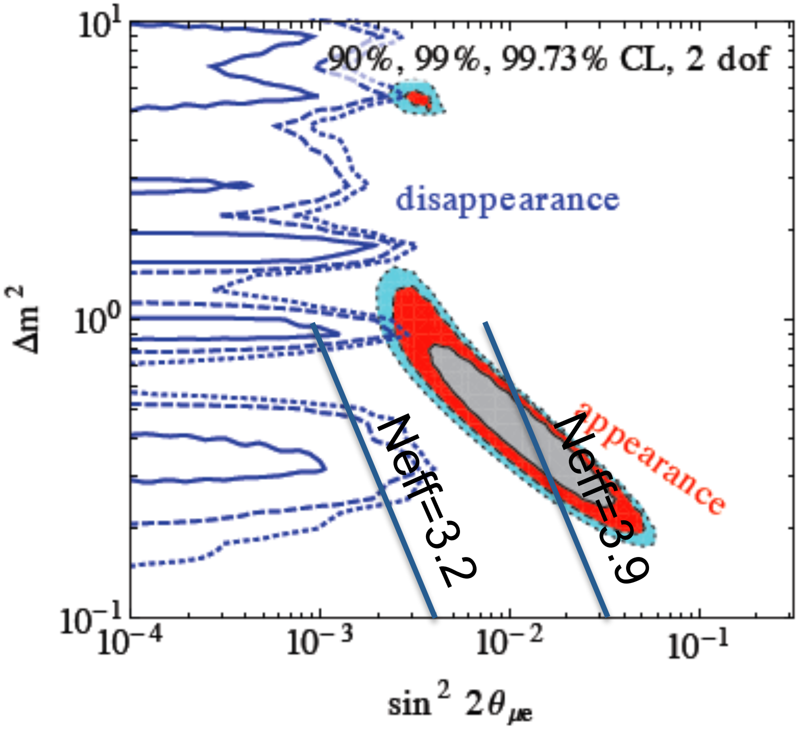

Appearance: LSND, MiniBoone, NOMAD, KARMEN, ICARUS, E776

Disappearance: reactor, Gallium, MiniBoone, CDHS, Minos, KARMEN

Conclusions

- No conclusive evidence yet for hot dark matter component or enhanced radiation density, although a few tensions need to be understood: H_0 measurements, lensing spectrum, SZ cluster count

- Full Planck: statement on BICEP2, $\sigma(N_{eff})$~ 0.3, full BOSS BAO measurements

- precise answer expected from cosmic shear surveys: DES, LSST, Euclid…
  - Safest output of these experiments
  - Importance of tomography

- … not talking of next CMB satellite, 21cm surveys, …