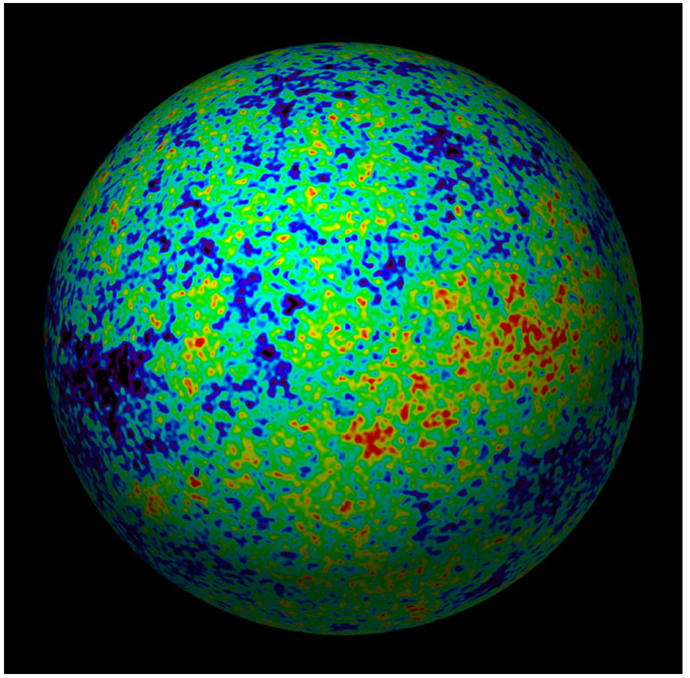


# Neutrino mass and number from cosmology

International Meeting for Large Neutrino Infrastructures,

APC Paris, 24.06.2014

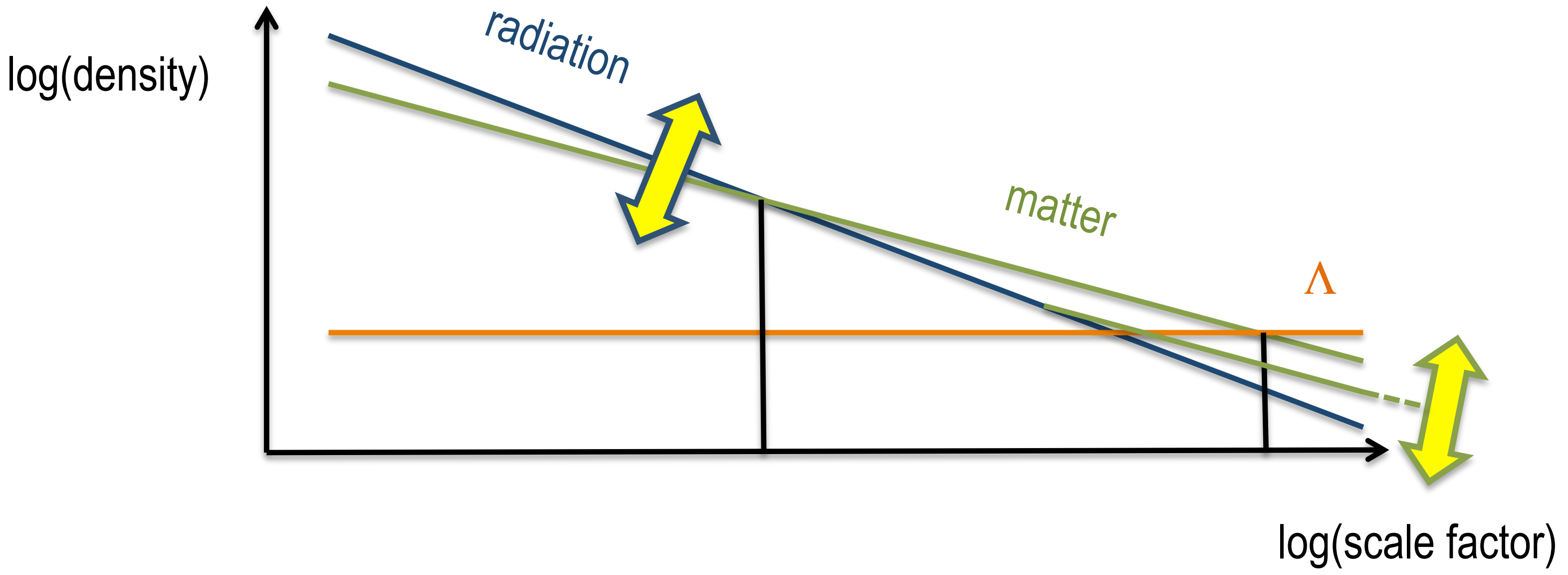
J. Lesgourgues (EPFL, Lausanne & CERN, Geneva & LAPTh, Annecy)

1. Neutrino signatures in cosmology
2. Current bounds
3. Future sensitivity
4. FAQs:
    - Model-dependence of cosmological bounds ?
    - Complementarity with laboratory bounds ?
    - Sensitivity to individual masses ?

# What does cosmology actually probes?

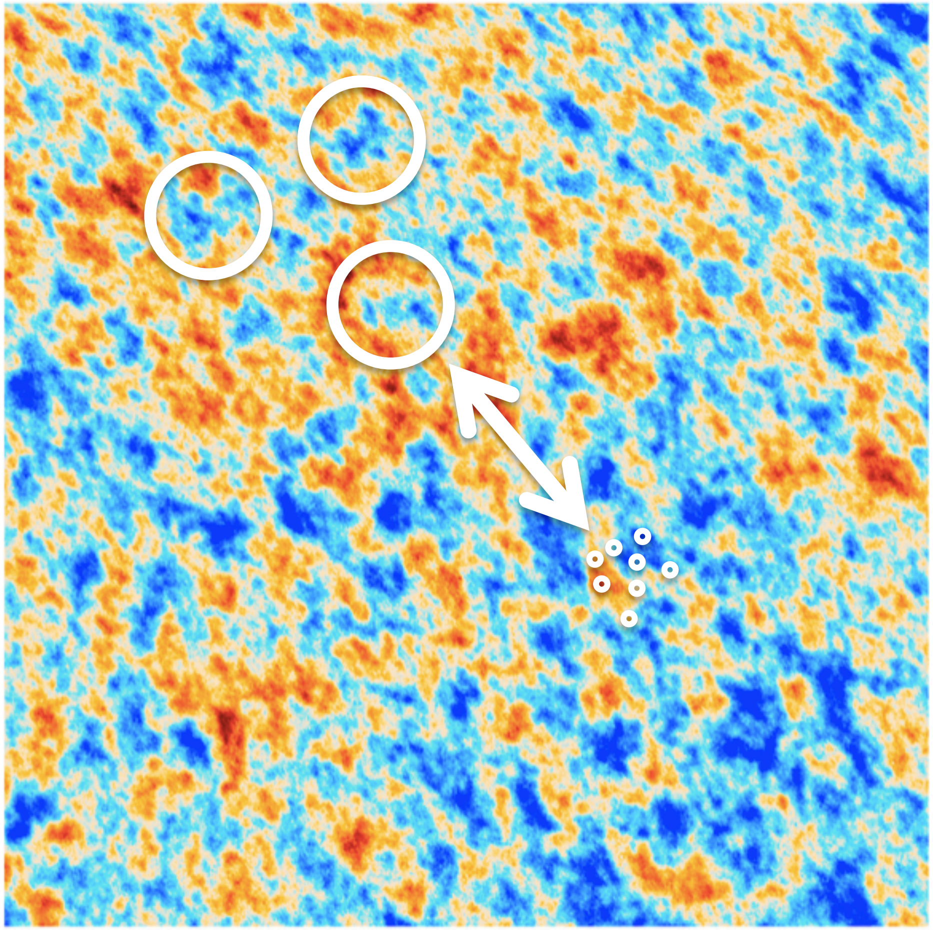
TWO independent questions:

- 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

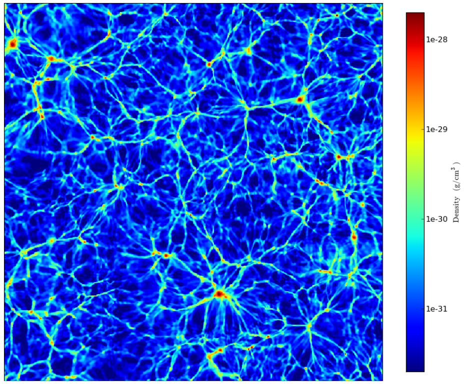
    less dark matter fluctuations on small scales

    *Probed by:*
    - galaxy correlation
    - galaxy cosmic shear
    - cluster abundance
    - CMB lensing
    - Ly$\alpha$ forests in quasar spectra

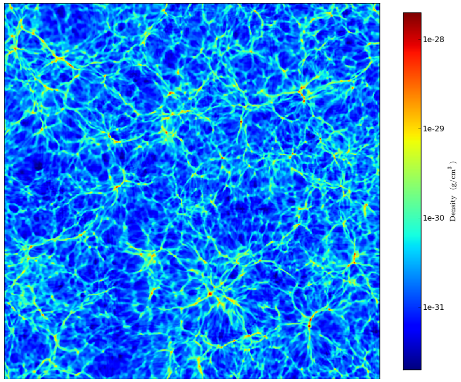
    *Depends on scale and time/redshift*
  - Primary CMB

    depletion from eISW

*reference*




*with hot component*




ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

# First effect…

… parametrised by $N_{eff}$ :

$N_{eff}$ = energy density of radiation, besides photons, in early universe,
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- 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; connection with possible anomalies in reactors, Galium, short baseline experiments)
- 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.

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Totally indistinguishable if all these components are very relativistic (typically $m_\nu$<0.01 eV)

# 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

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

*(e.g. on different ways to split total mass between species, which affect time of non-relativistic transitions…)*

# Measuring $N_{eff}$

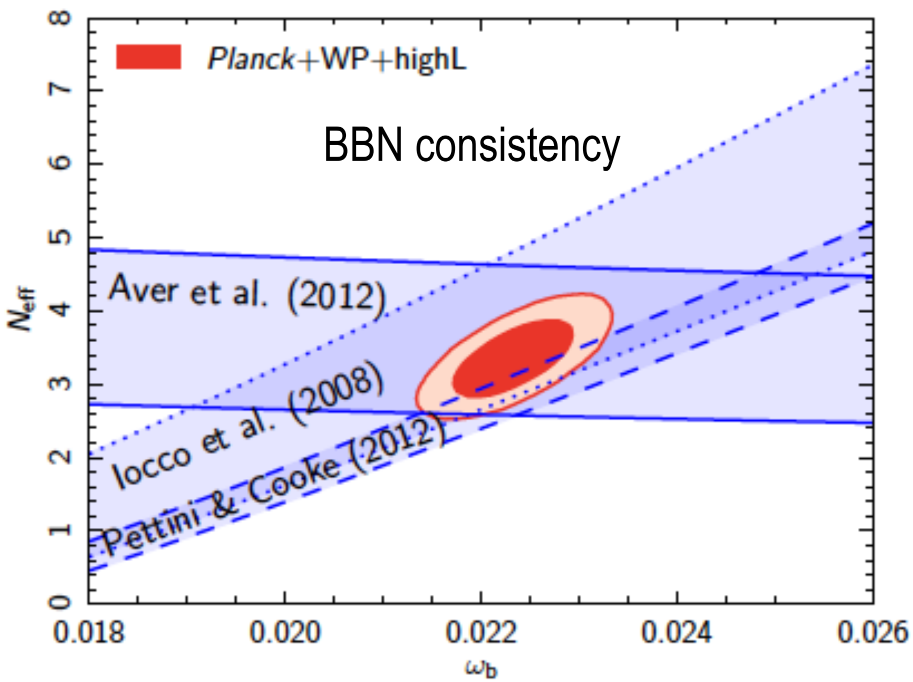
- Ultimately, constraints driven by CMB damping tail
  - WMAP+SPT see anomalously low tail: $N_{eff} > 3$ at 2 sigma
  - Planck and Planck+BAO well compatible with standard value at 1 sigma

CMB alone (Planck+WP+HighL)

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

With lensing and BAO:

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



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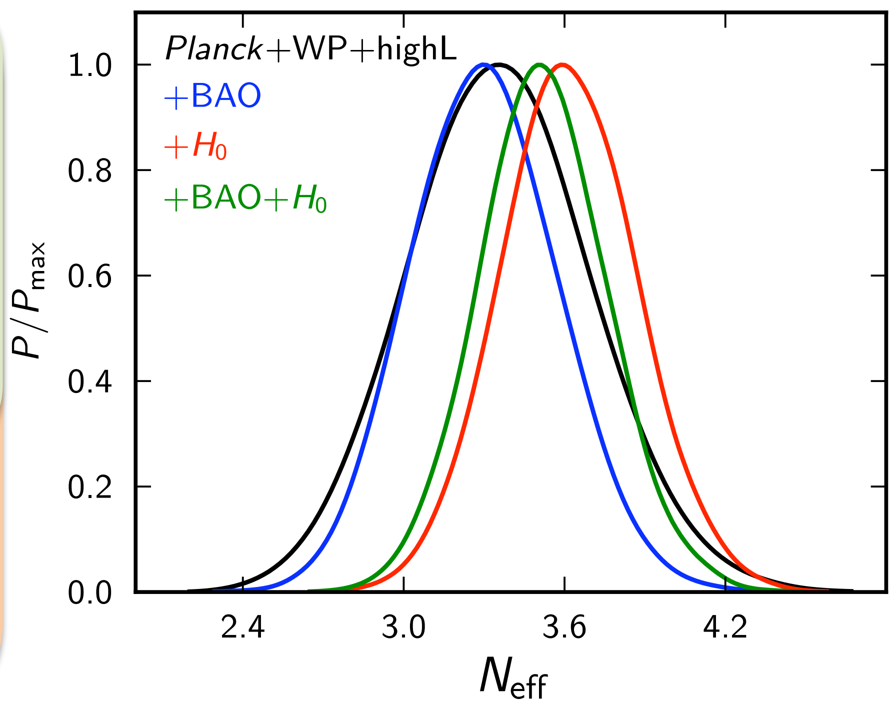

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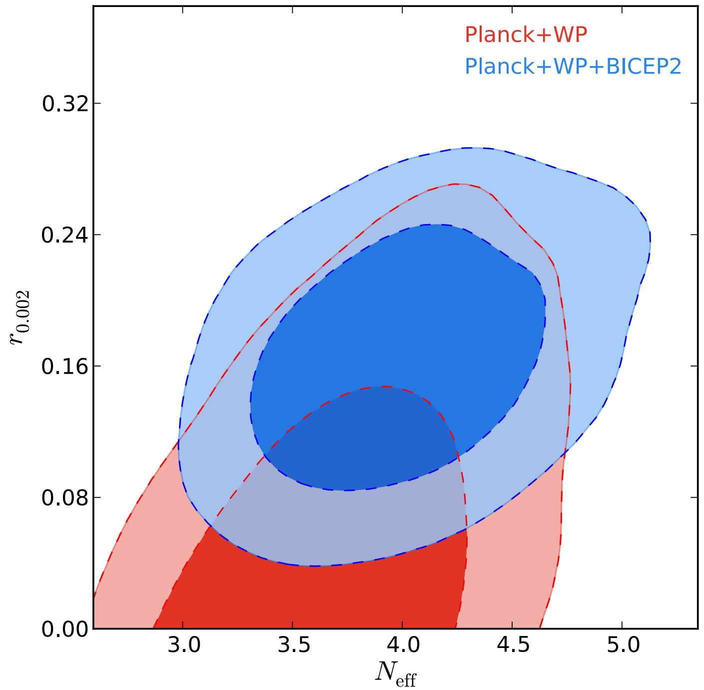
  - Planck + BICEP2 : to decrease r tension, also higher $N_{eff}$

CMB alone (Planck+WP+HighL+BICEP2)

$N_{eff} = 4.00 \pm 0.82$ (95%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 $M_{\nu eff}$

CMB + LSS:

- Vulnerable to systematics and parameter degeneracies due to limited number of: scales, redshifts, independent tracers of dark matter

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

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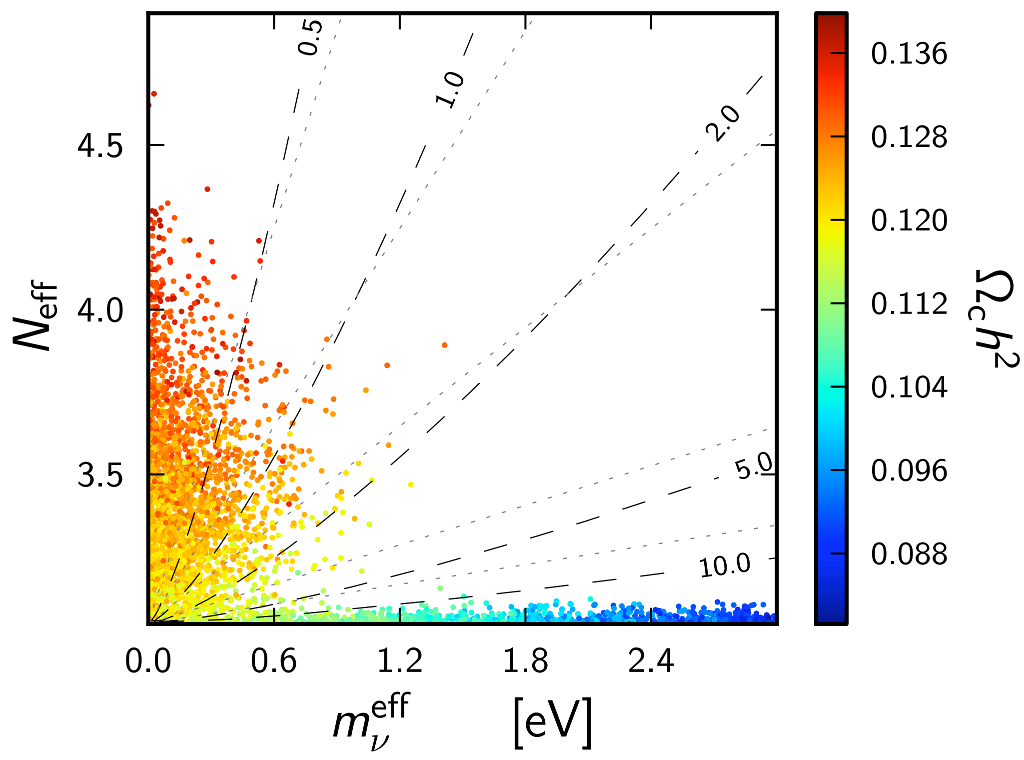
Any experiment seeing high amplitude disfavors high neutrino mass:

- SDSS Ly-$\alpha$ of 2006
  $M_\nu < 0.17$ eV (95%)

# Joint constraints

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



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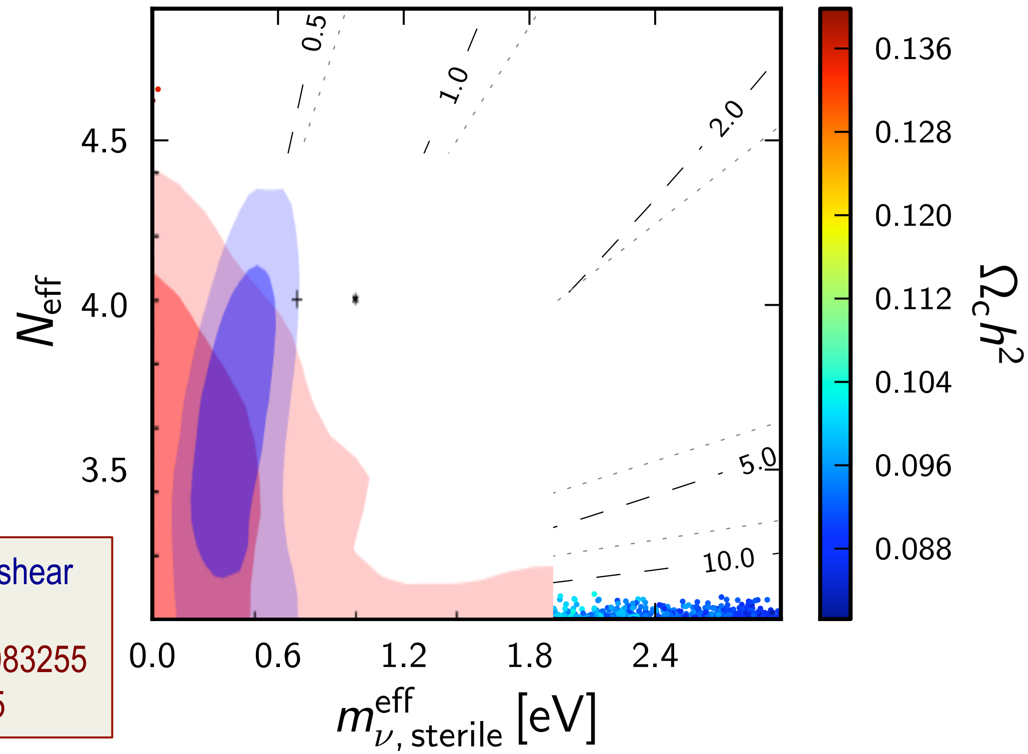


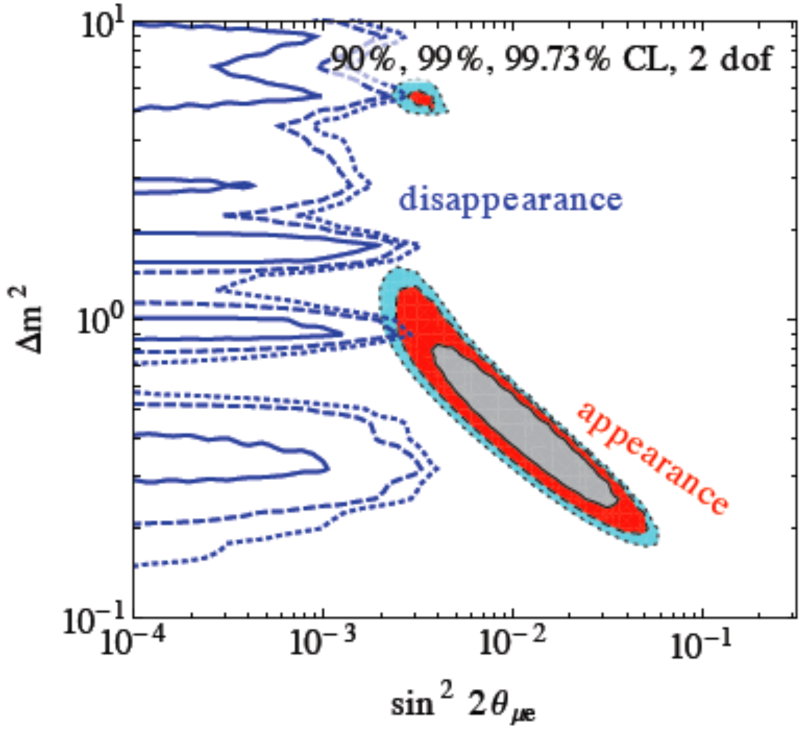

Using H0 + BAO + clusters + gal.shear

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

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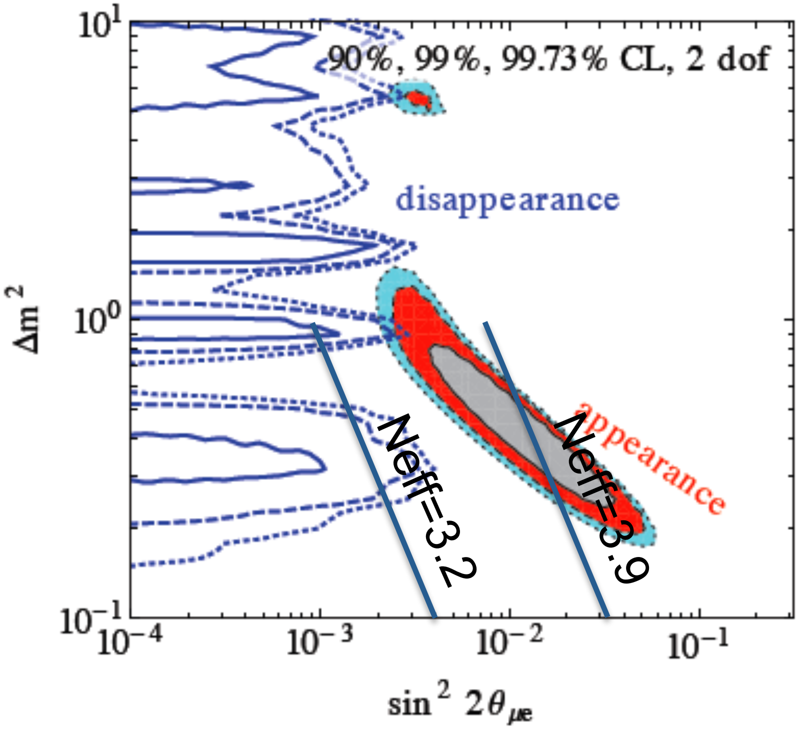


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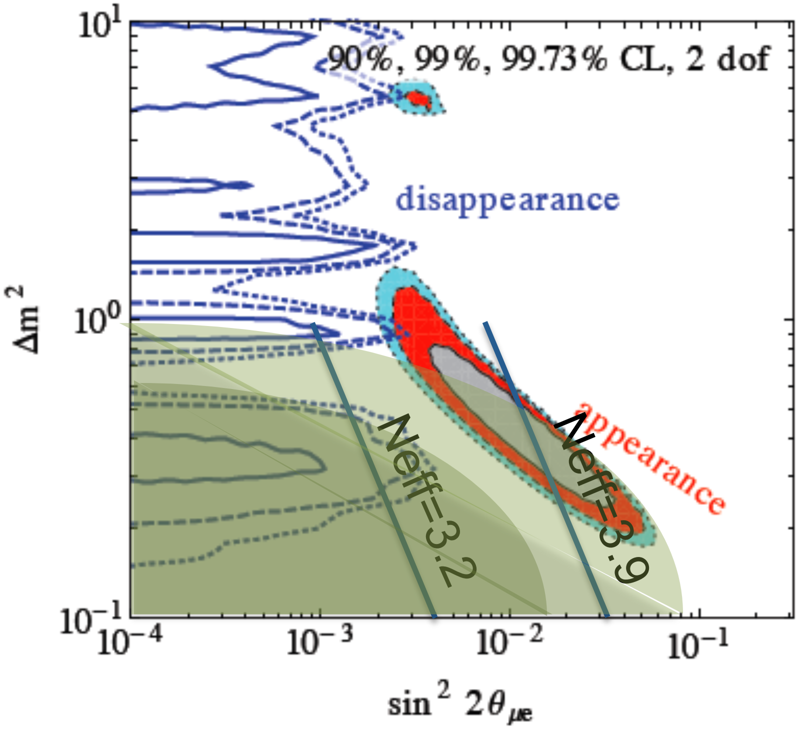


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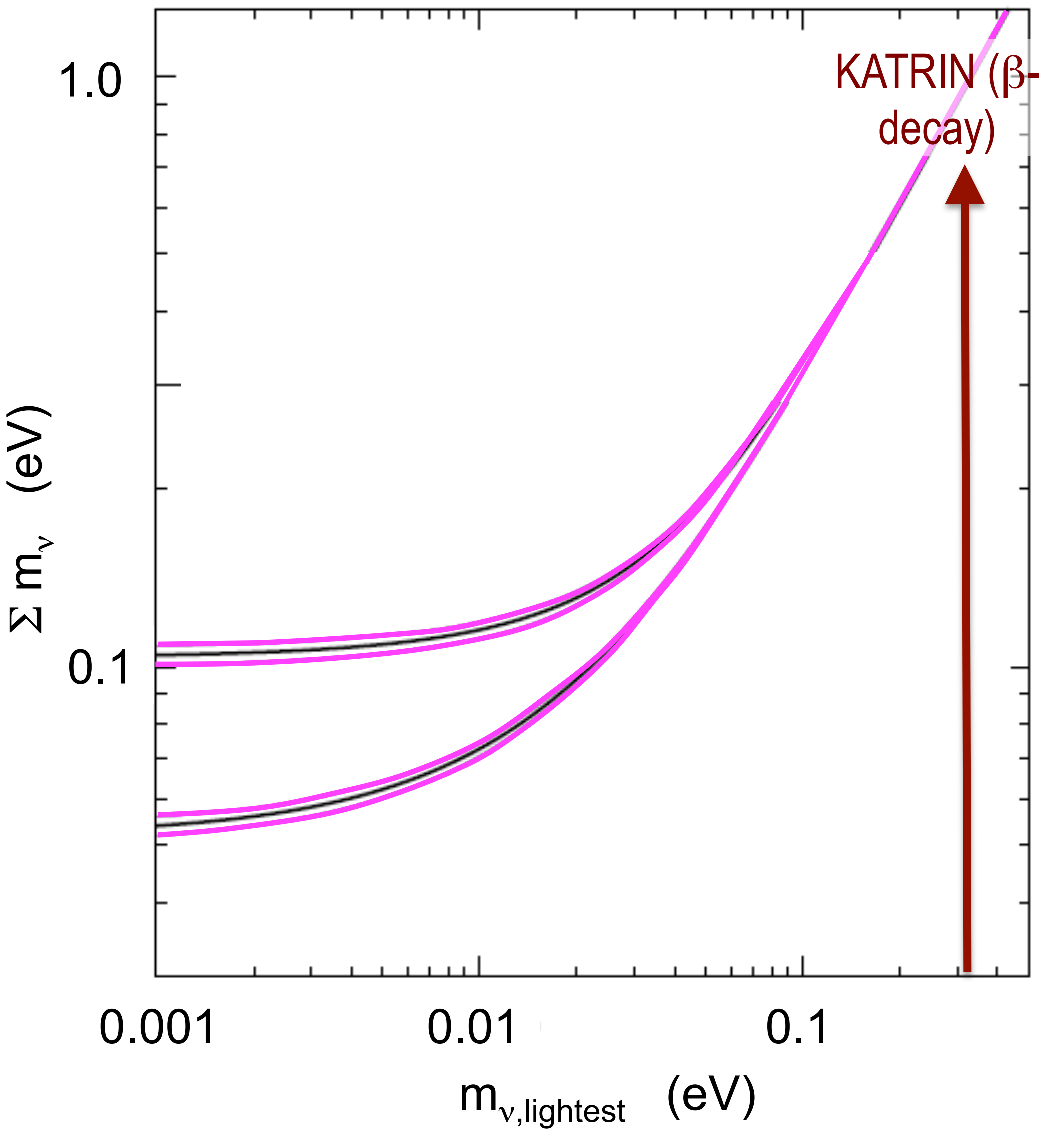
# Future mass sensitivity




2σ error bars

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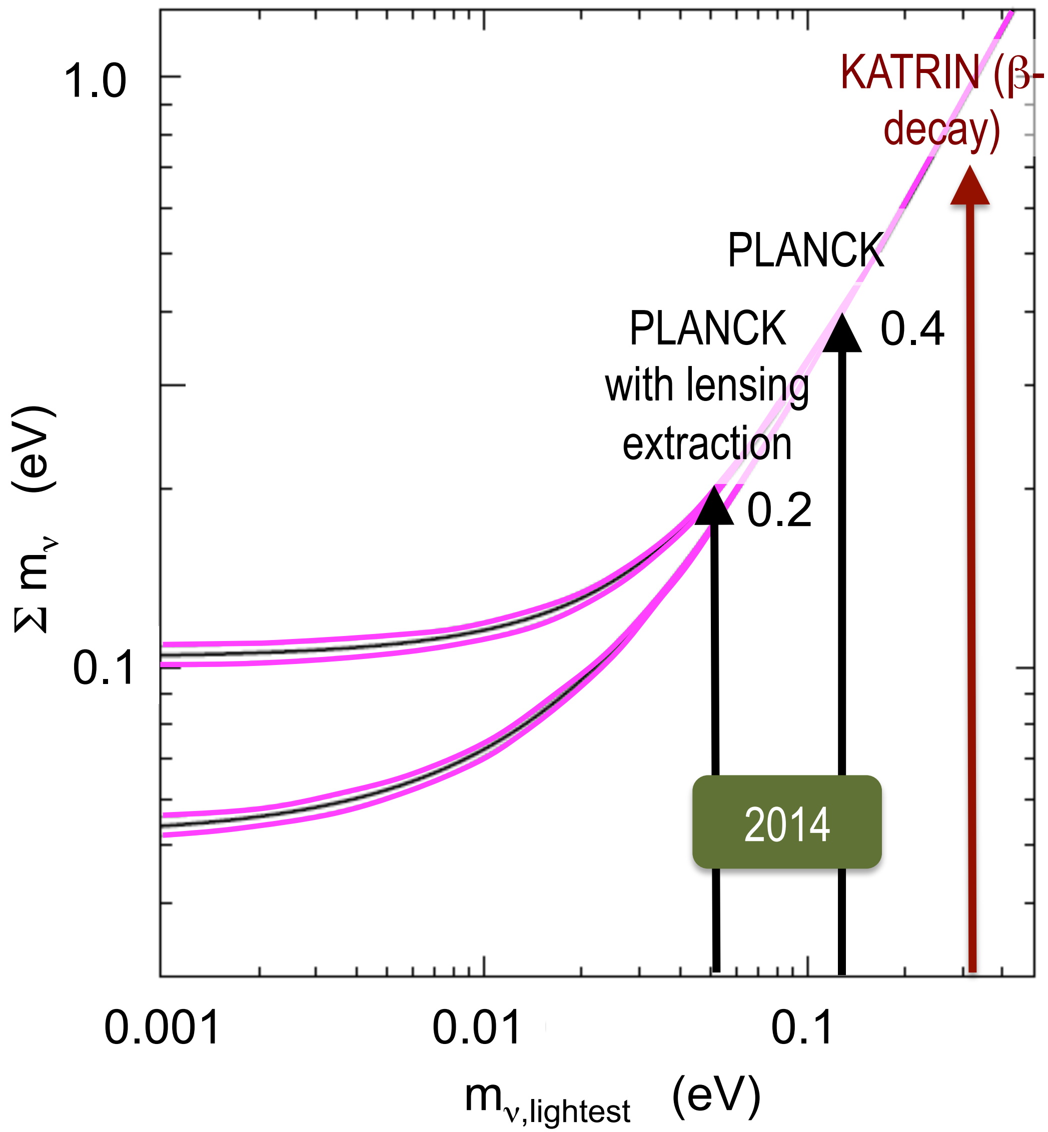


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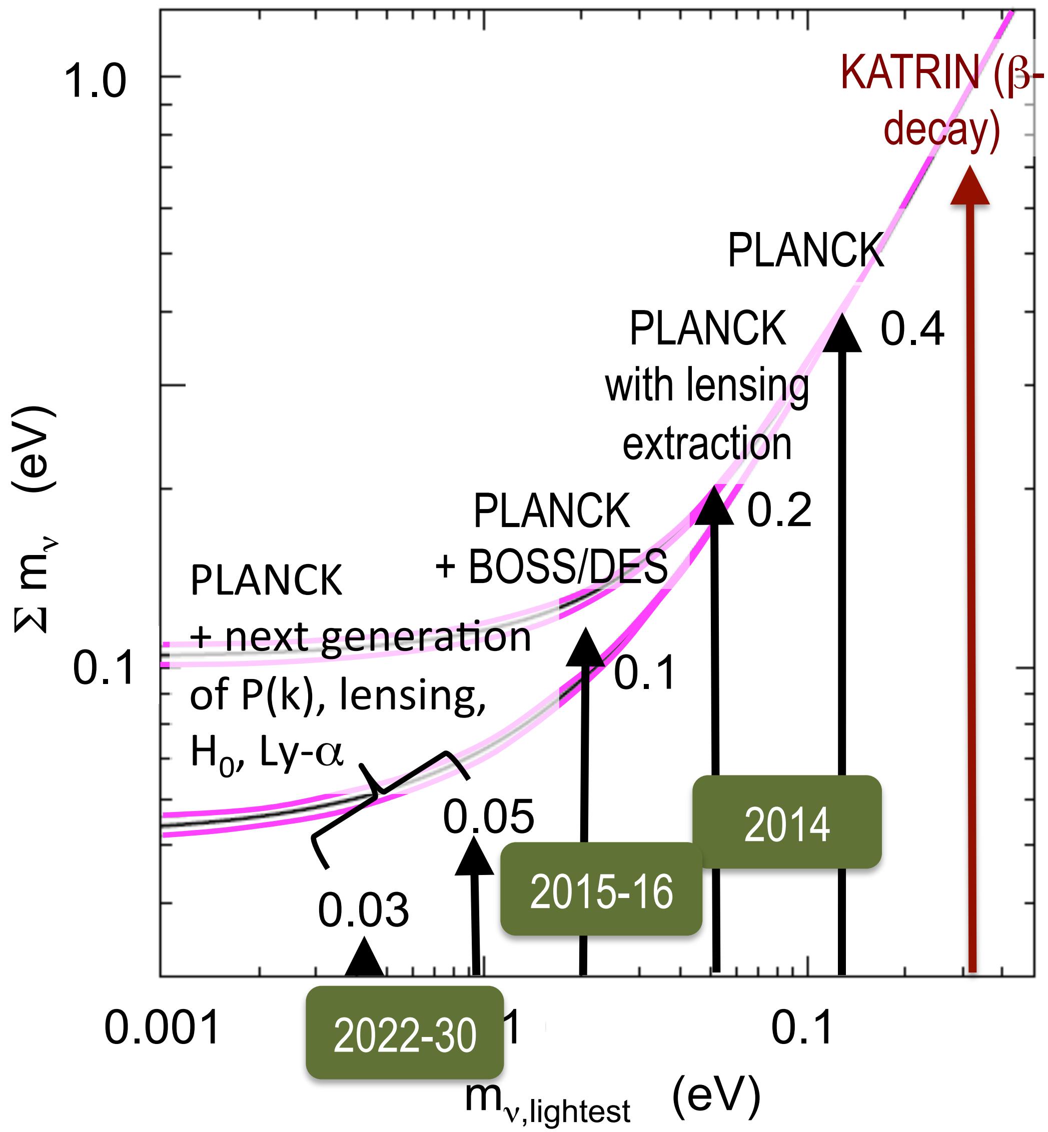


2σ error bars

# Future $N_{eff}$ sensitivity

| | | | |
|---|---|---|---|
| Full Planck data (including lensing) | : | $\sigma(N_{eff}) \sim 0.2$ | 2014 |
| Planck + LSST, Euclid (cosmic shear, galaxy correlation) | : | $\sigma(N_{eff}) \sim 0.1$ | ~ 2022 |
| Post-Planck + Euclid | : | $\sigma(N_{eff}) \sim 0.05$ | ~ 2030 |

# Model-dependence of bounds ?

- Bounds obtained by fitting given model (minimal 6-parameter $\Lambda$CDM, extensions with curvature, dark energy, more freedom in primordial spectrum, etc.)

- Effect of $N_{eff}$, $M_\nu$ could be confused with that of other parameters

- true with past experiments (e.g. degeneracies N -M , N -H , w-M , etc.)

- Less and less true: thousands of independent data points, at many different scales AND redshift; only ~10-20 model parameters

- Unique effect of M : scale-dependent growth factor, signature of free-streaming particles (different from changing primordial spectrum)

- Unique effects of N : e.g. baryon drag shifting peaks because c > c , signature of ultra-relativistic particles

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# Complementarity with laboratory experiments ?

- assuming $N_{eff} = 3$, $M_{\nu eff} = m_1+m_2+m_3$, independently of mixing angles, CP phases, Dirac/Majorana mass : different from $\beta$- and double $\beta$-decay

- What if there is a tension between cosmology and laboratory bounds? E.g. KATRIN find $m_\nu \sim 0.3$ eV and cosmology $M_\nu < 0.1$ eV?

- After checking for systematics and degeneracies, would bring evidence for non-standard $\nu$ interactions (decay into lighter species, effective mass from coupling with other fields, etc...) or strong deviation from standard cosmological model (low-scale reheating / entropy production after BBN and conspiracy with other light relics ...) : NEW PHYSICS

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# Sensitivity to individual masses ?

- $M_{\nu\mathrm{eff}}$ controls total density of free-streaming (hot) dark matter species today
- But individual masses control time of no-relativistic transitions
- Sensitivity to mass splitting with same M for extreme cases:
  - E.g. (minimal NH + 1eV thermal sterile) versus 4 x 0.26 eV
- No sensitivity for NH versus IH with same M
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Many more details in

Neutrino Cosmology

Lesgourgues, Mangano, Miele Pastor

CUP 2013