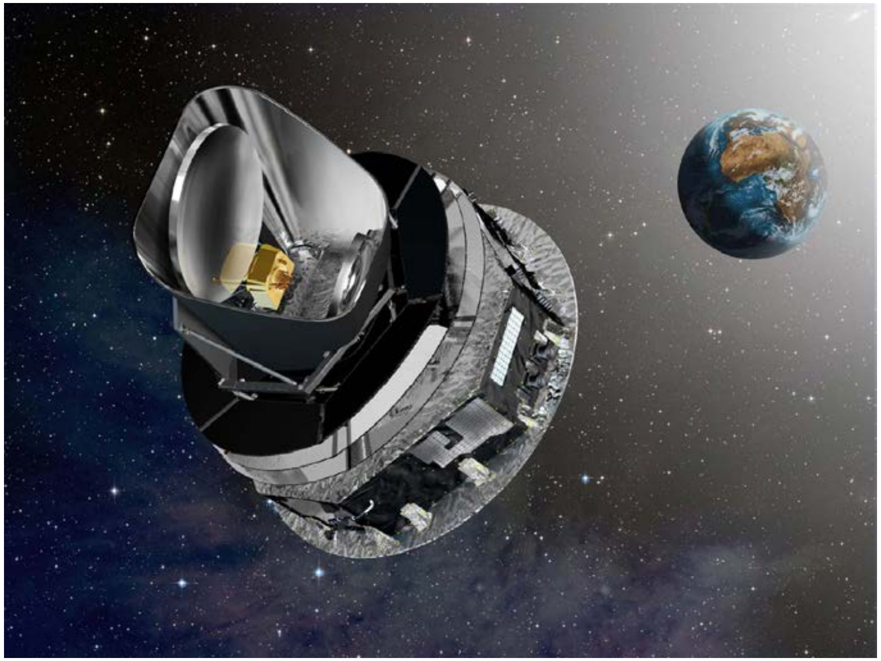


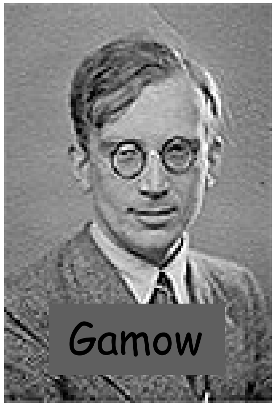
Planck results and neutrinos

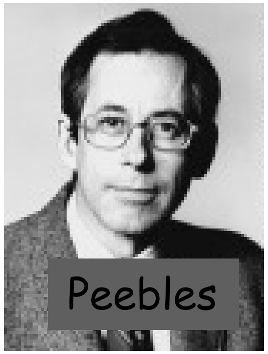
GDR Neutrino, Paris VI, 22.05.2013

J. Lesgourgues (EPFL, CERN, LAPTh)

The Cosmic Microwave Background

- … is the thermal radiation originating from the primordial plasma, predicted by Gamow, Zel'dovitch, Peebles, etc. (following theoretical arguments based on nucleosynthesis and the presence of hydrogen in the universe)





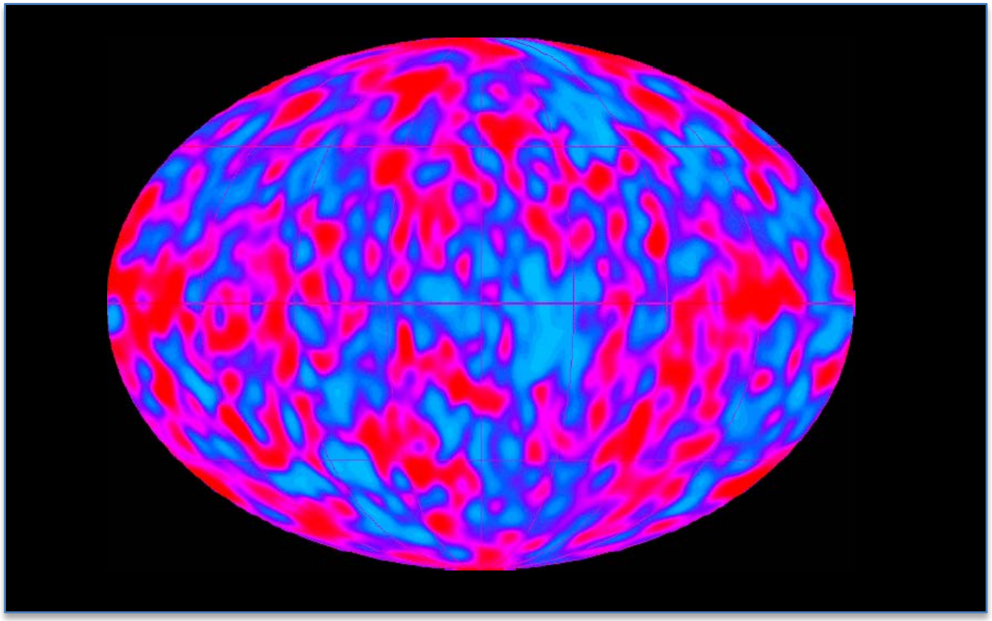
- … was emitted at photon decoupling, billions years ago, when T~eV

- … first observed by Penzias and Wilson in 1964

The Cosmic Microwave Background

- … should contain temperature/density inhomogeneities, that are the seeds of all large structures in the universe (formed by gravitational collapse), predicted by theorists in the 70's to be of the order of 10^{-5}

- … first observed on large angular scales by COBE in 1992 in the form of temperature anisotropies… and later by DASI as polarisation anisotropies …



The Cosmic Microwave Background

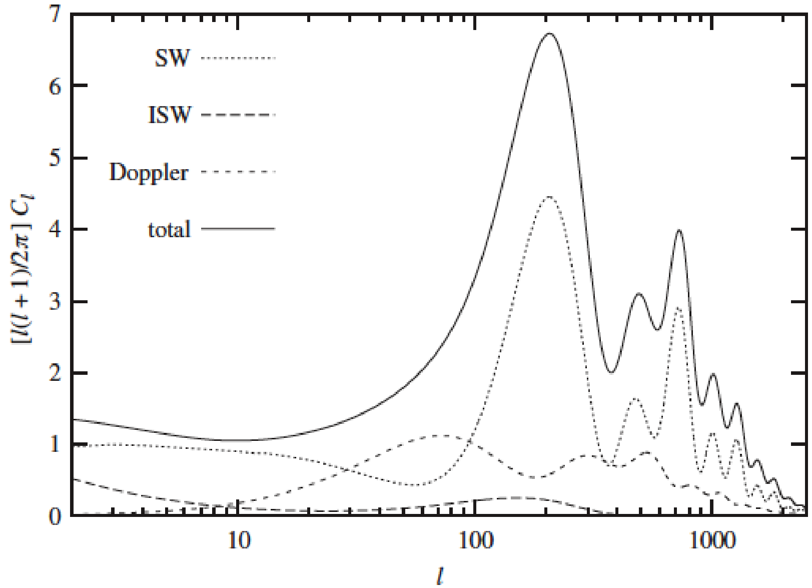
- … anisotropies should contain non-trivial spatial correlations
- Detailed characteristics of these correlations predicted in the 70's (Silk, Yu, Peebles, Zel'dovitch, …)
- Standard model for CMB anisotropies:

ingredients

- General relativity, simple QED, assumption of homogeneous and isotropic Friedmann-Lemaître universe with at least photons, electrons, baryons, neutrinos, CDM, Λ
- Primordial fluctuations from inflation induce temperature fluctuations in photon-baryon fluid
- Acoustic waves due to photon pressure, modulated by baryon inertia and gravitational interactions
- Photon-electron decoupling: diffusion processes inducing fluctuation damping and photon polarization

The Cosmic Microwave Background

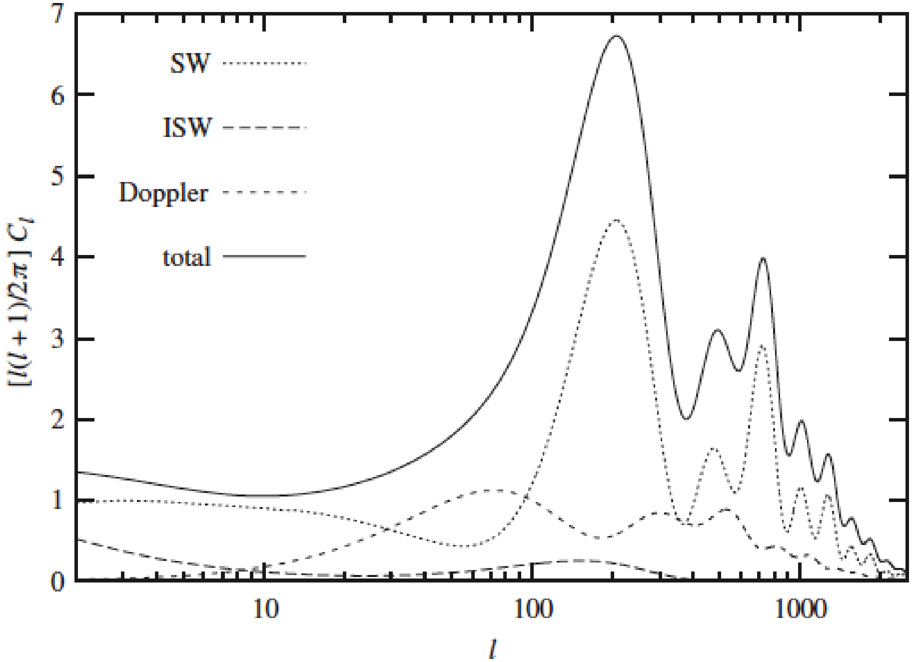
- Primary anisotropies: temperature 2-point function at decoupling features one correlation length = sound horizon at decoupling (real space), or peak series (multipole space)



- Secondary anisotropies:
  - Light deflection by gravitational lenses
  - Gravitational redshifting by structures along line of sight
  - Rescattering in reionized universe at low redshift

Primary CMB spectrum

- In simplest cosmological models, CMB spectrum affected by 8 physical effects



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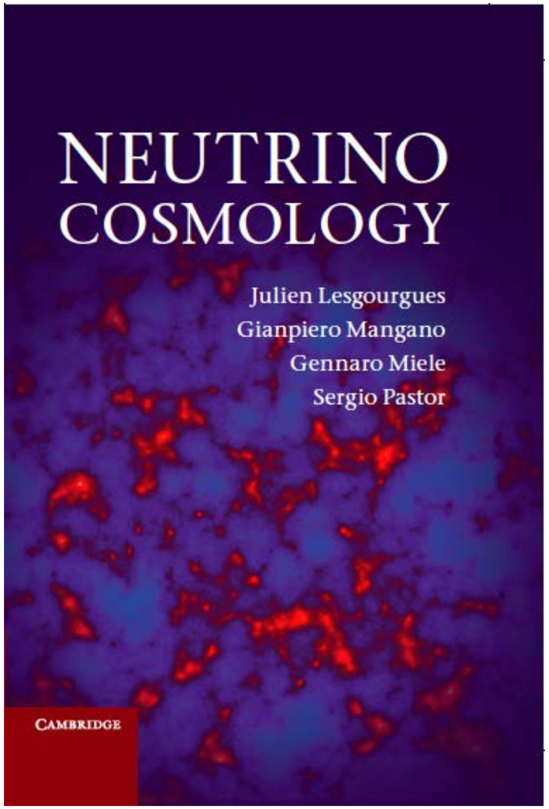

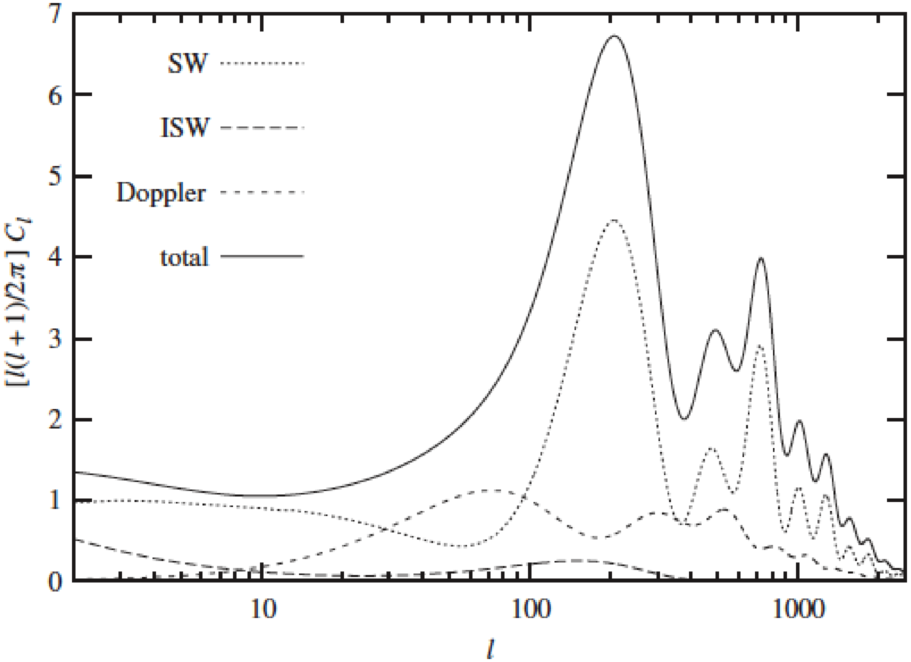

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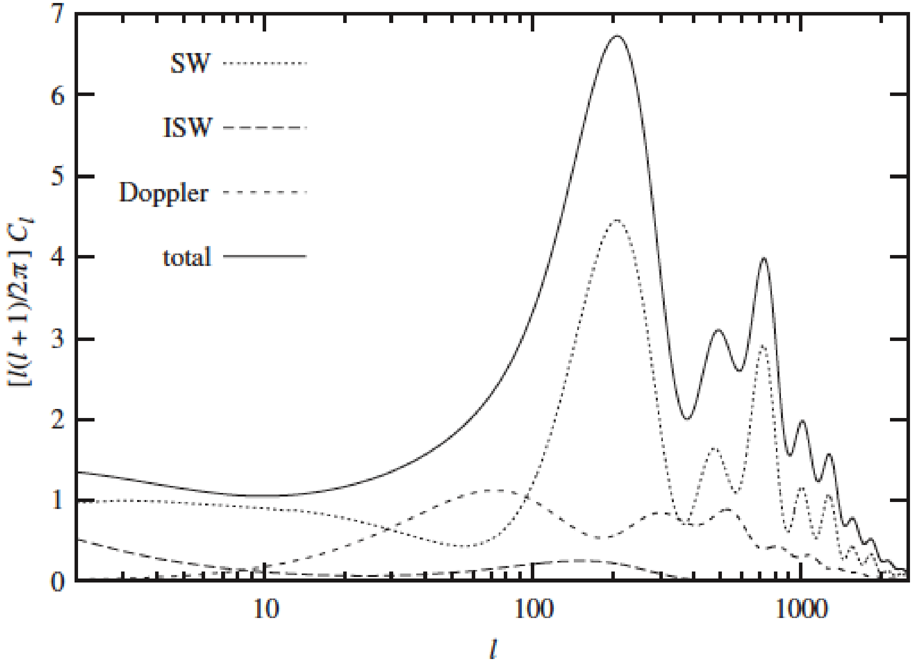

- Minimal ΛCDM: 8 effects controlled by 6 parameters
- Some easy to detect, some are more difficult (cosmic variance): degeneracies

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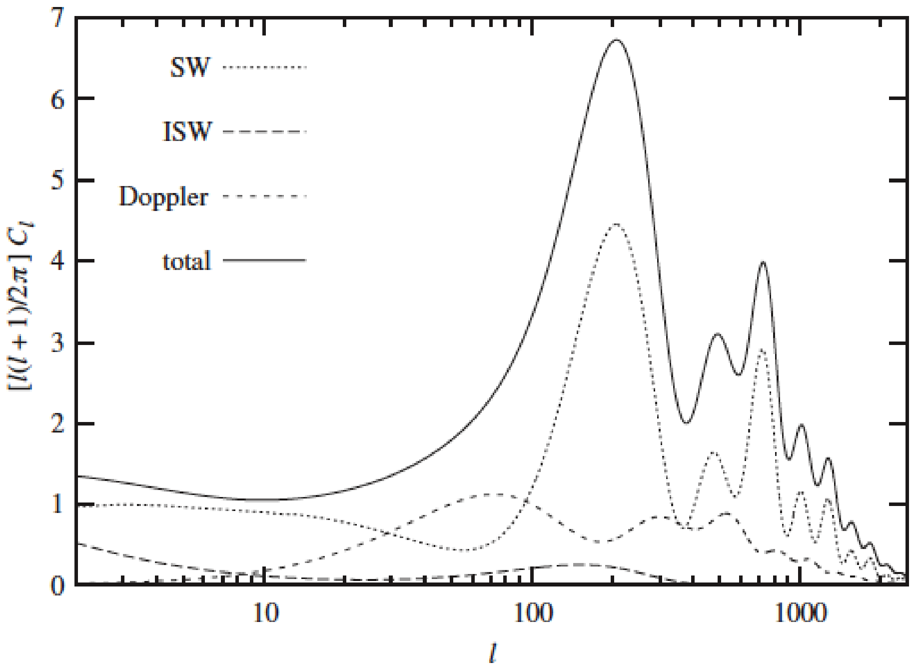

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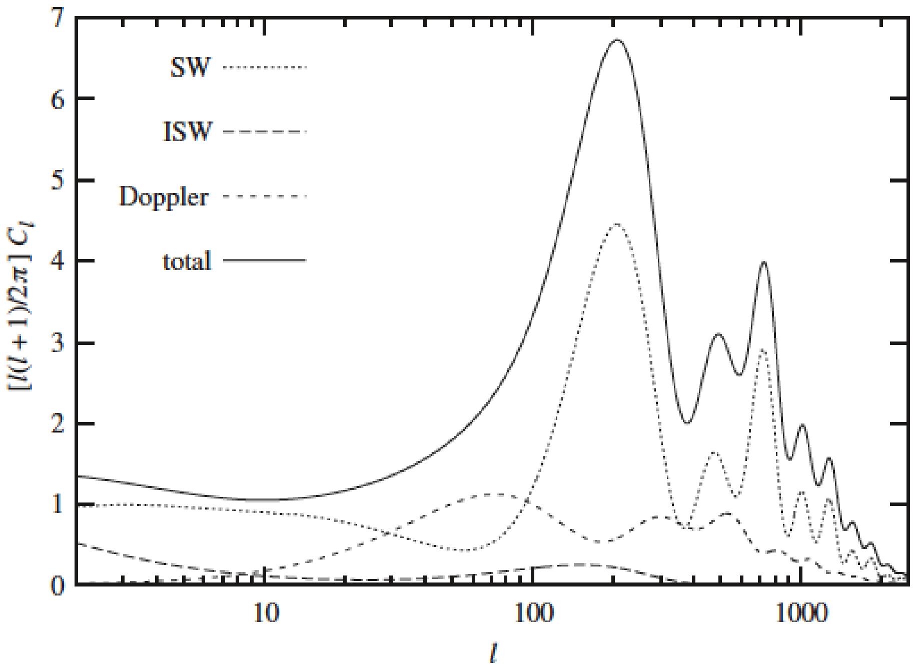

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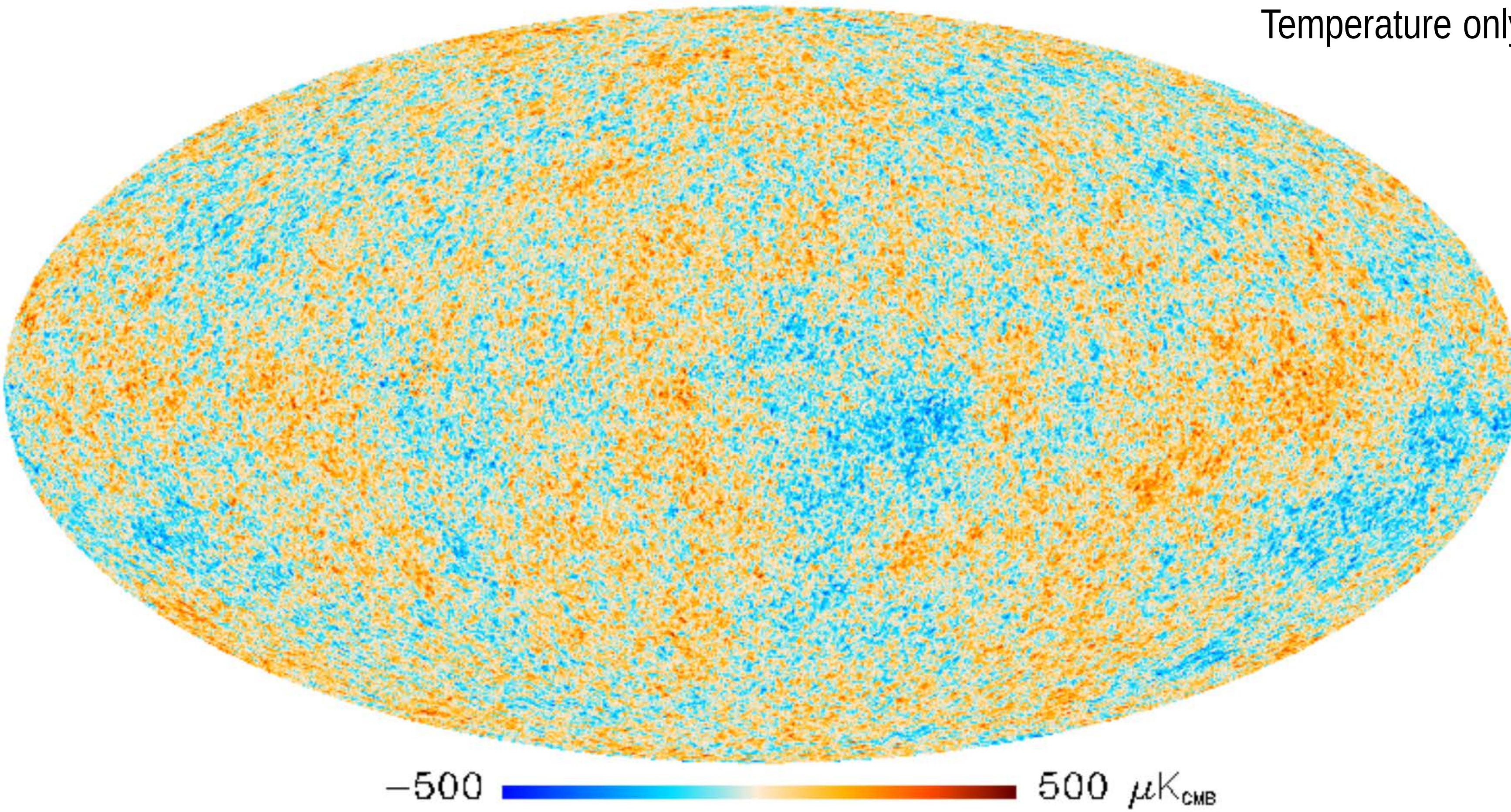
- Some easy to detect, some are more difficult (cosmic variance): degeneracies
- Extended models: some extensions bring more independent effects [neutrino masses, variations of N_{eff}], some do not [curvature]
- Theoretical predictions for C_l precise at 0.01% level (0.1% in Planck analysis) with CAMB (www.cosmologist.info) or CLASS (class-code.net)

Planck results

15 months of data
Temperature only



Combined CMB map

Planck results

15 months of data
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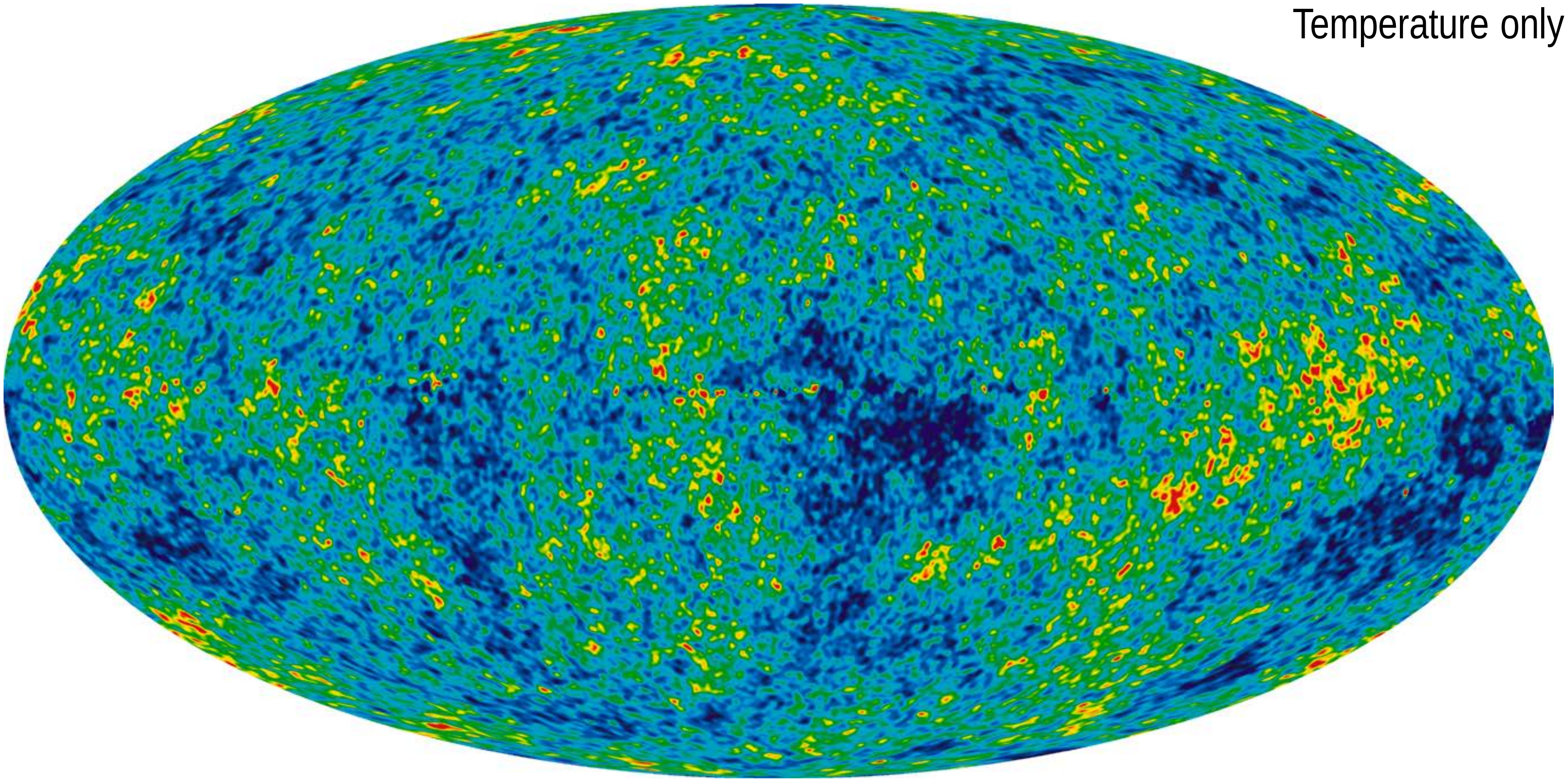

CMB map from WMAP (different color scale)

Planck results

15 months of data
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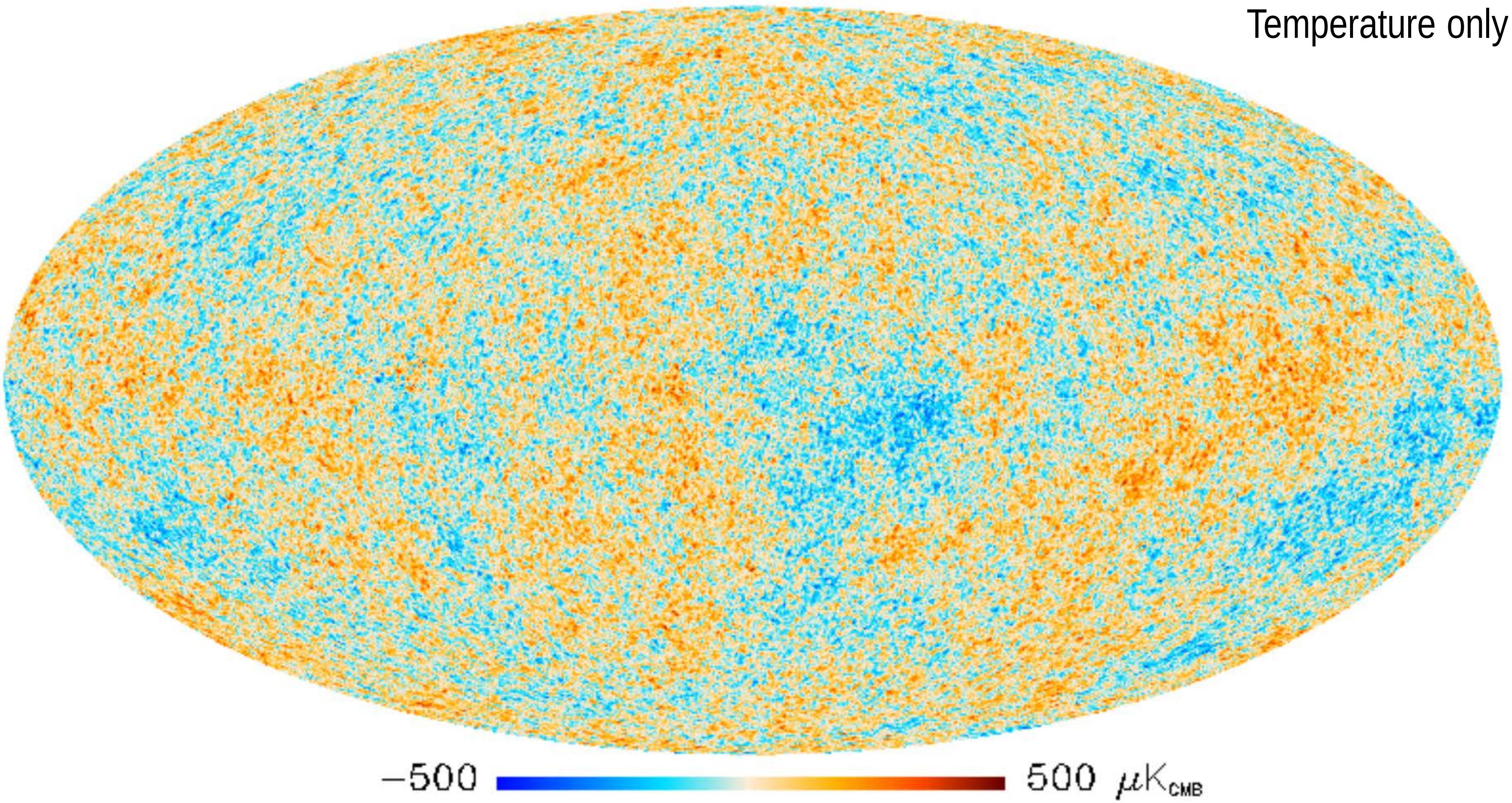
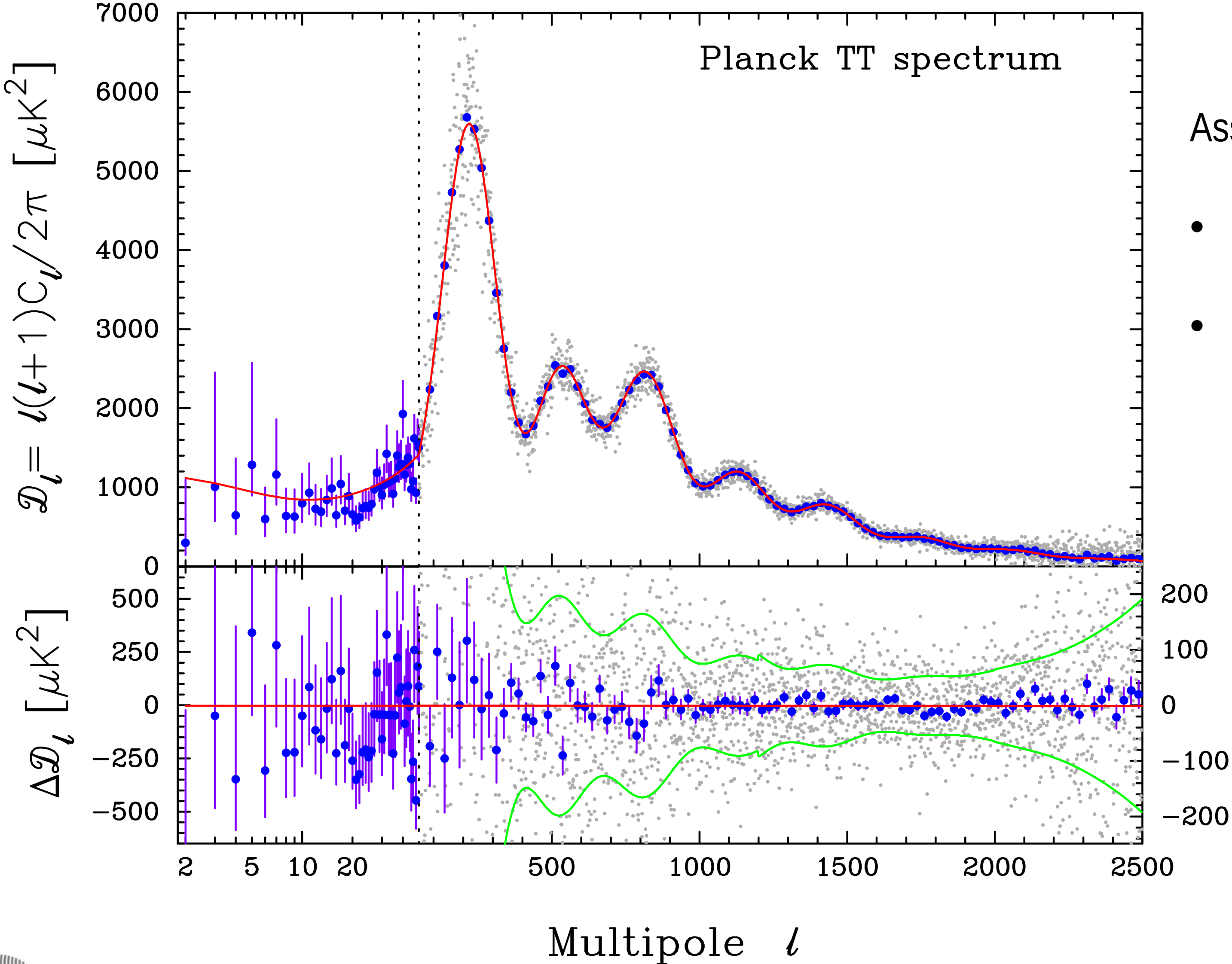


Combined CMB map

ΛCDM is a very good fit



Assuming:

- N_{eff}=3.046
- Minimal neutrino masses (0.06, 0, 0) eV

ΛCDM is a very good fit

Using Planck + WP (= EE +TE from WMAP for $l \leq 23$), at 1-sigma:

- Peak scale 0.060%
- Baryon density 1.3%
- CDM density 2.3%
- Primordial amplitude 2.5%
- Primordial spectral index 0.76%
- Reionization optical depth 0.13%

Derived (model-dependent) parameters:

- Hubble parameter
- Λ fractional density

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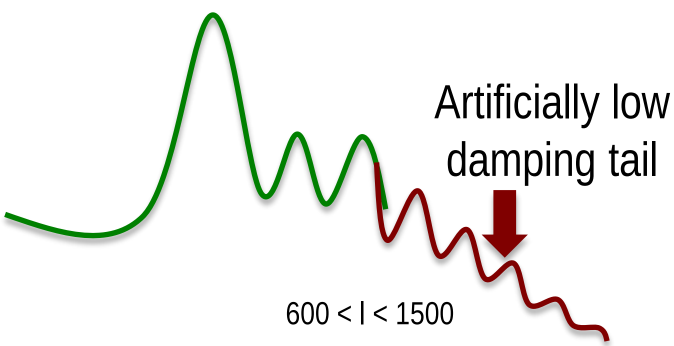
Excellent agreement with WMAP alone but tension with WMAP+SPT, explained as WMAP/SPT relative calibration error



led to high H_0 in agreement with direct measurements but in tension with BAO

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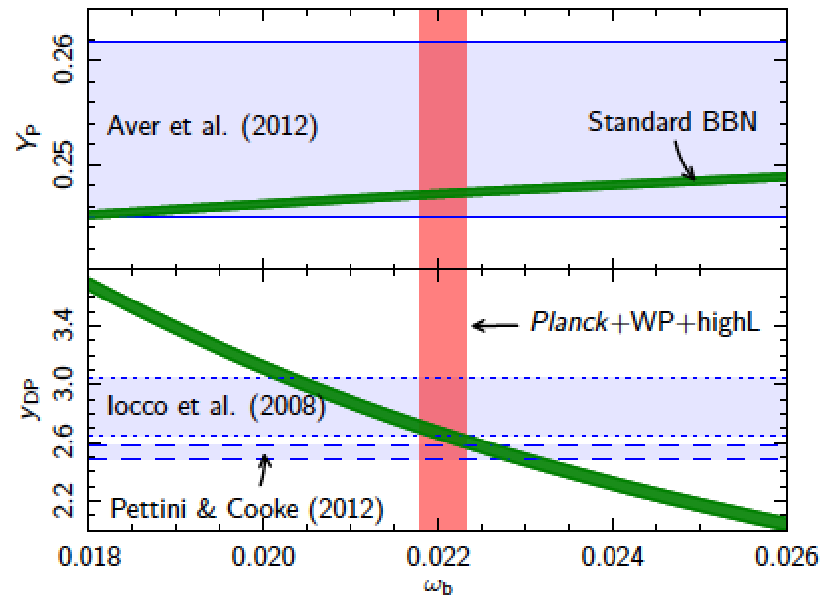
BBN consistency:



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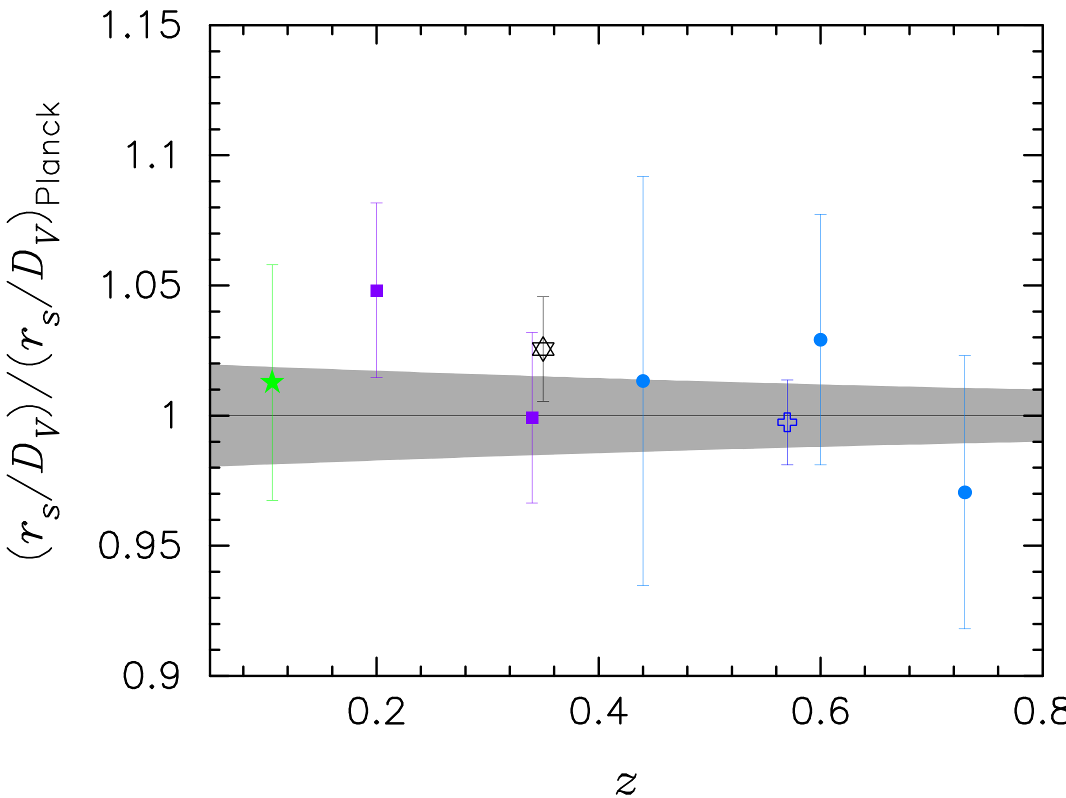
BAO consistency:



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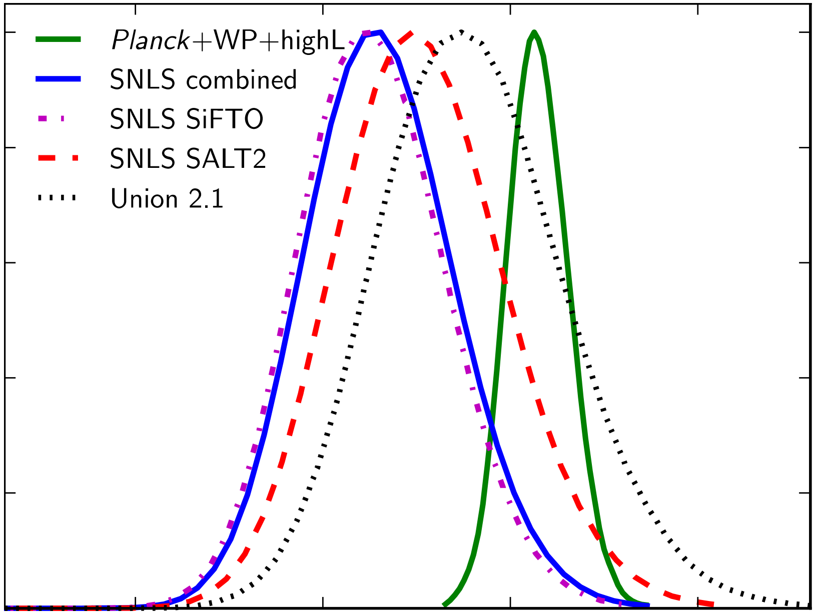
SNIa luminosity tension:



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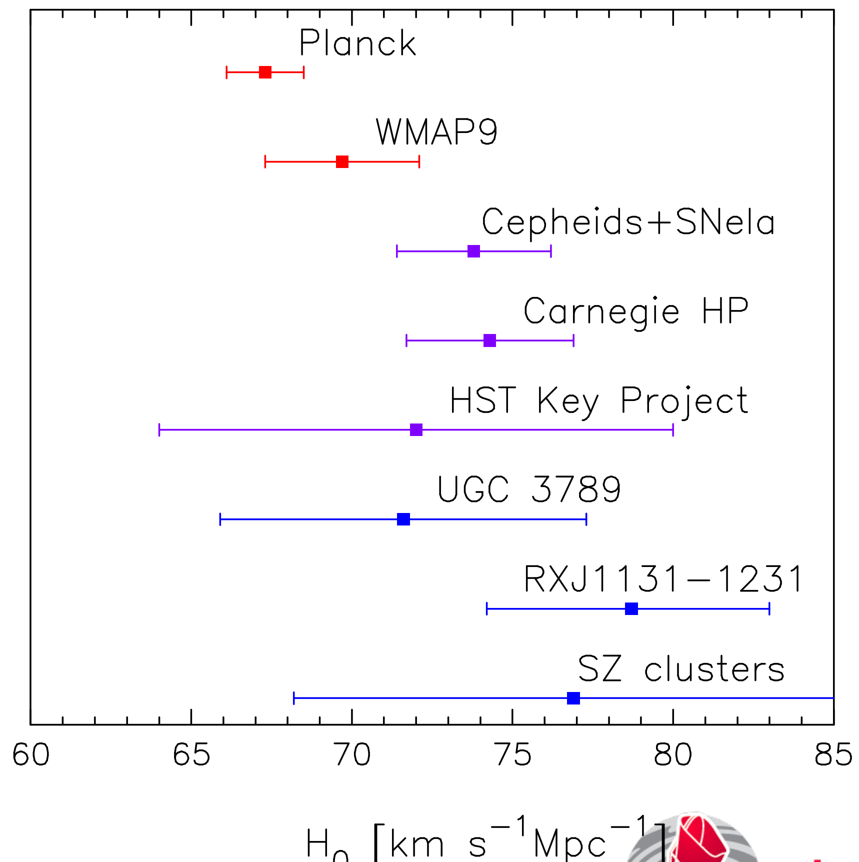
Derived (model-dependent) parameters:

- Hubble parameter
- Λ fractional density

direct H_0 measurement tension:



ΛCDM is a very good fit

Using Planck + WP, at 1-sigma:

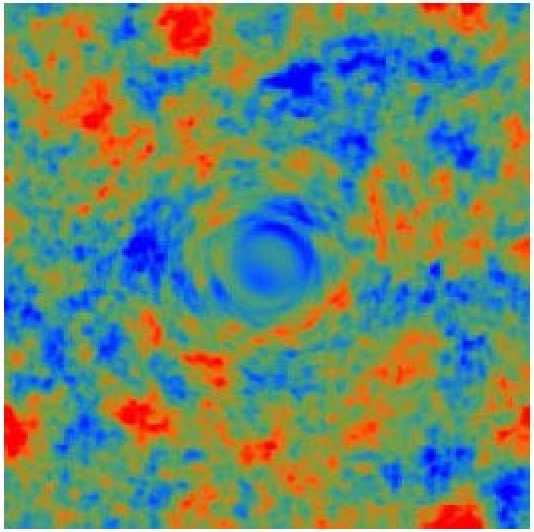
• Peak scale	0.060%	galaxy correlation consistency:
• Baryon density	1.3%	
• CDM density	2.3%	
• Primordial amplitude	2.5%	
• Primordial spectral index	0.76%	
• Reionization optical depth	0.13%	

Derived (model-dependent) parameters:

- Hubble parameter
- Λ fractional density

Lensing extraction

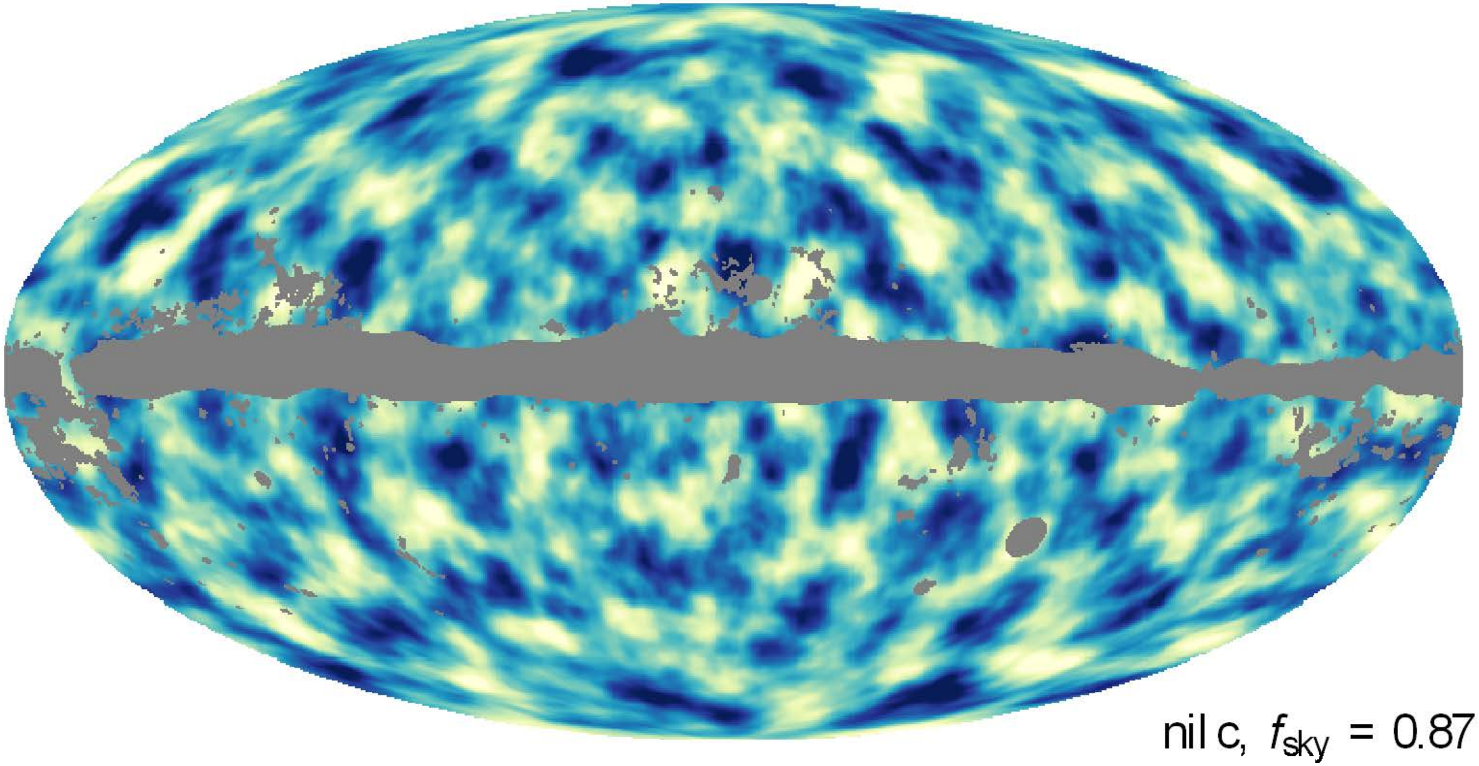
- exaggerated effect of a huge cluster:



- In fact, only 2'-3' deflections, coherent over large scales: invisible by eye
- Lensing potential = projected gravitational field (with some kernel: sensitive to structures at z~1-3)
- Induces non-gaussianity with very specific correlations. Can be extracted with specific "quadratic estimator" (= 4-point correlations)
- Proposed by Hu & Okamoto (2001) First success in 2012 (SPT-ACT)

Lensing extraction

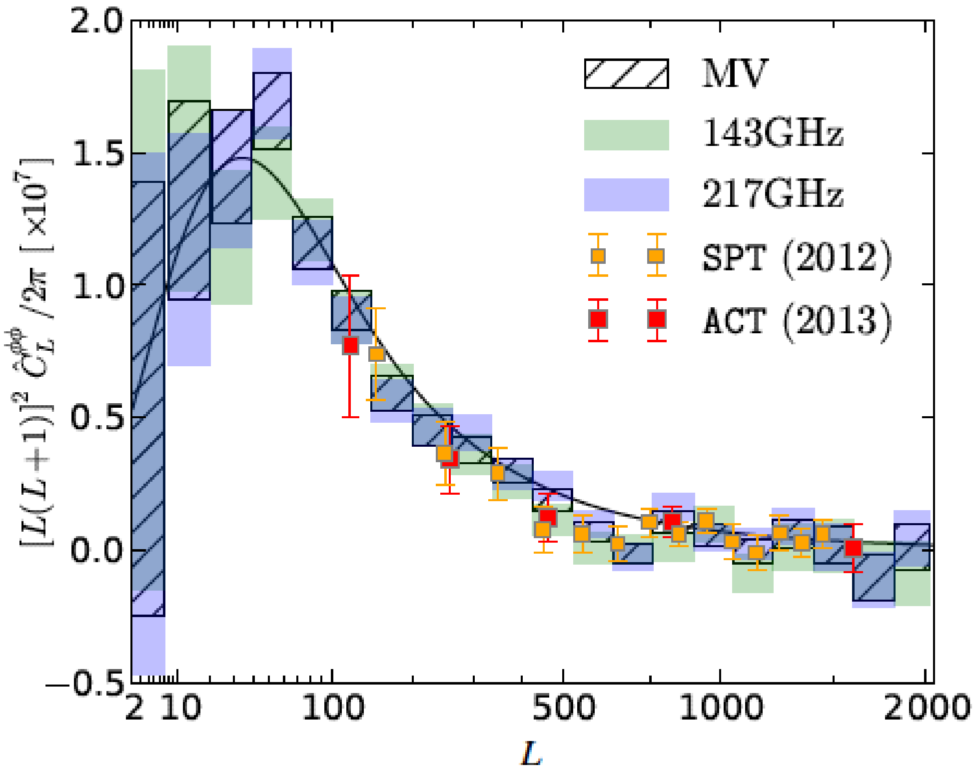
Lensing potential map:



Low signal-to-noise, but correlates at high level with different tracers of LSS (20 sigma with NVSS quasars, 10 sigma with SDSS LRG, 42 sigma with Planck's CIB)

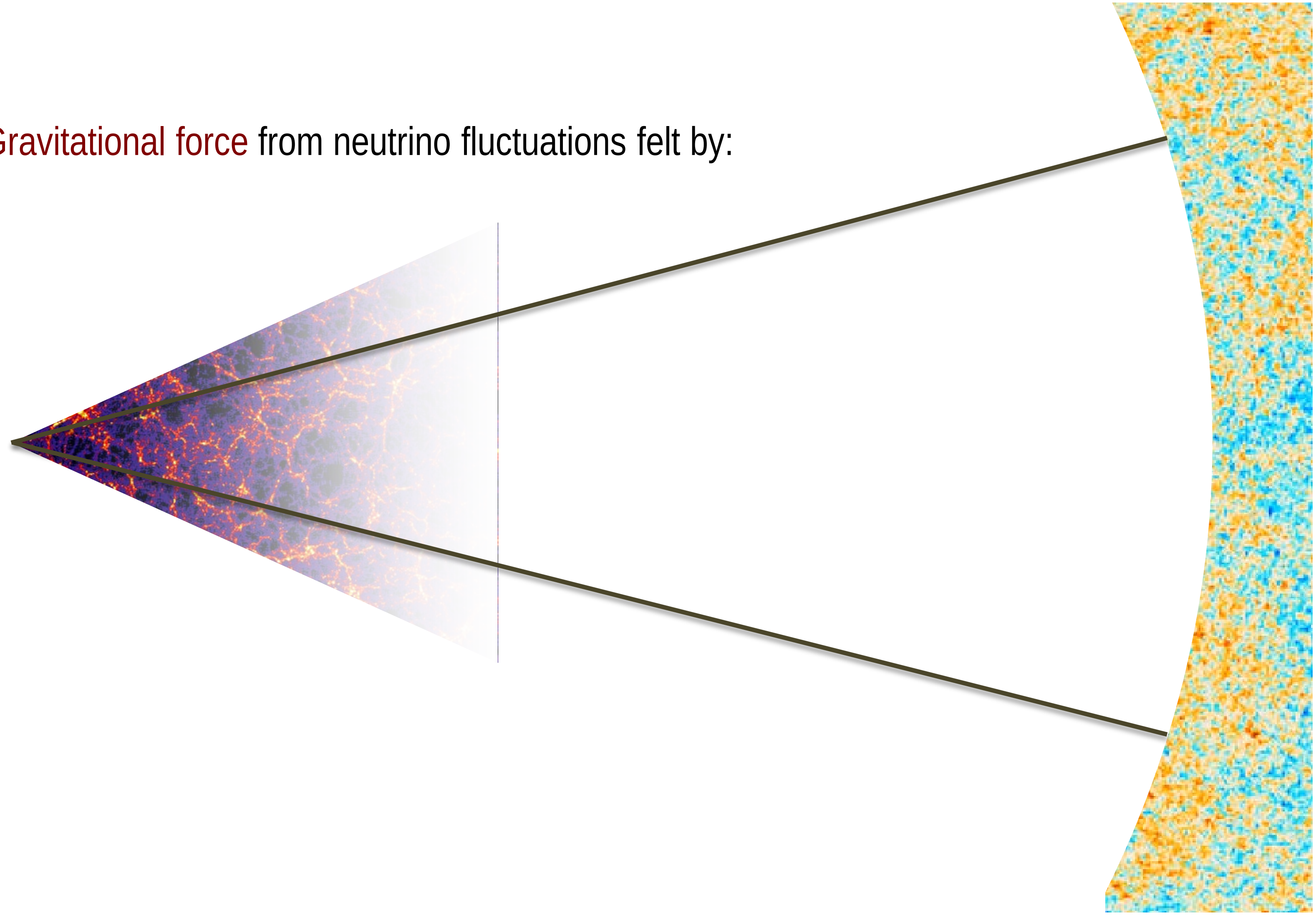
Lensing extraction

- Lensing power spectrum consistent with ΛCDM
- Helps removing degeneracies and measuring extended model parameters with Planck alone



Neutrinos and cosmological perturbations

Gravitational force from neutrino fluctuations felt by:



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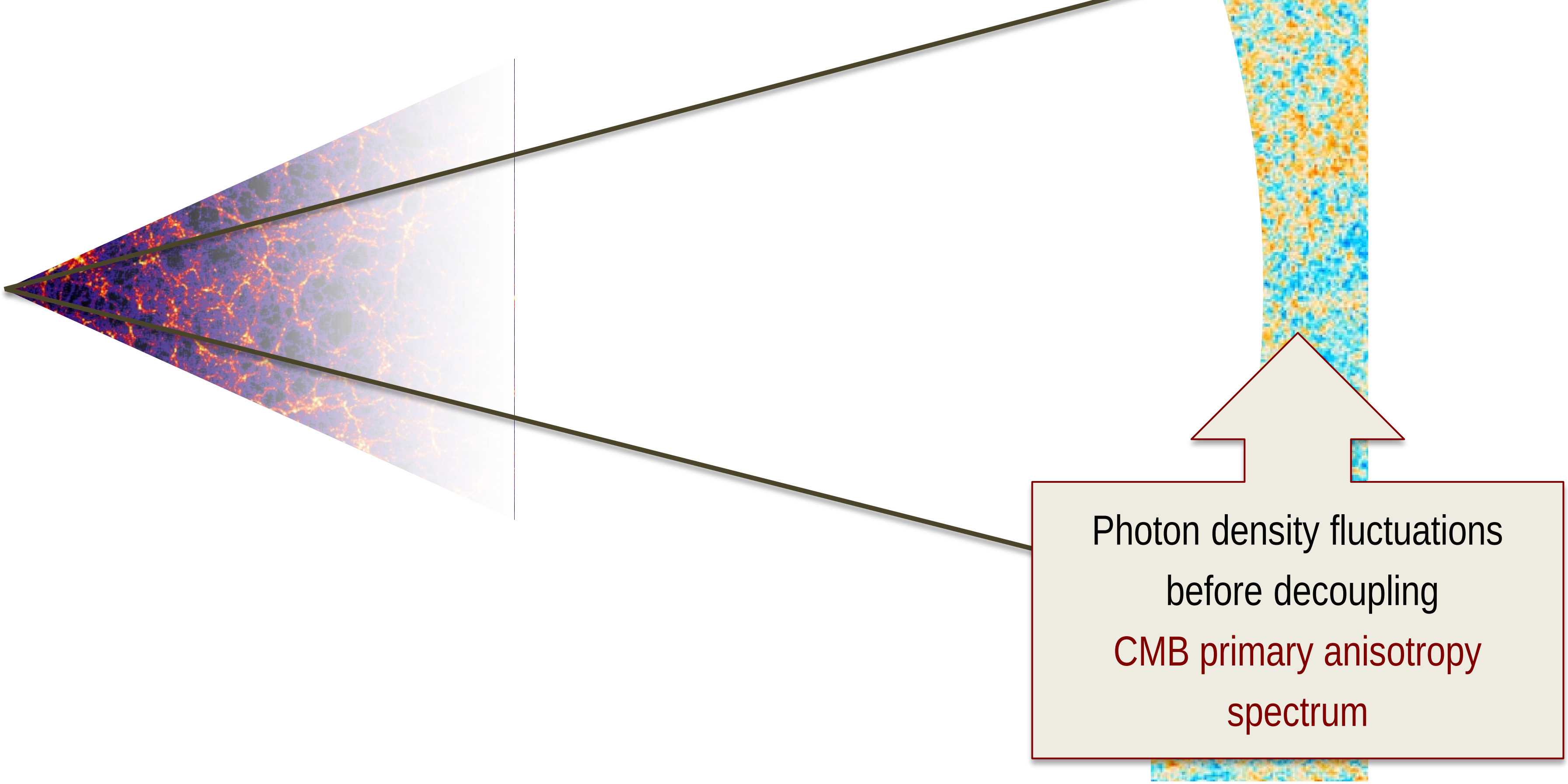

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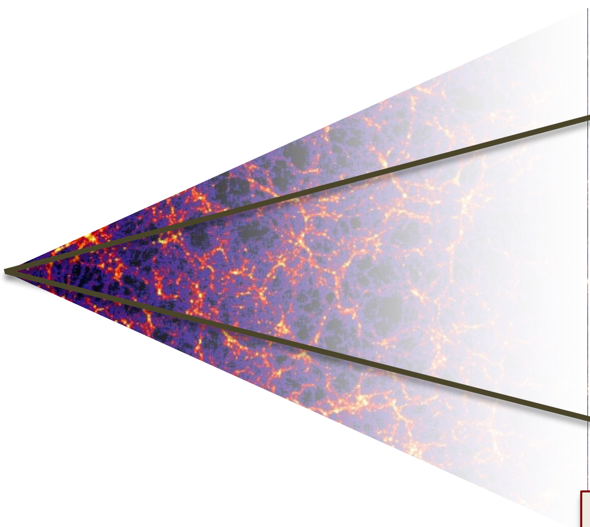

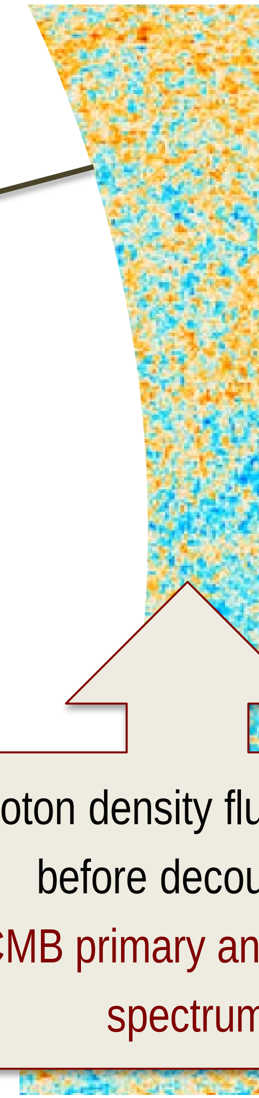

Photon momentum
after decoupling
CMB secondary anisotropy
spectrum

Photon density fluctuations
before decoupling
CMB primary anisotropy
spectrum

Neutrinos and cosmological perturbations

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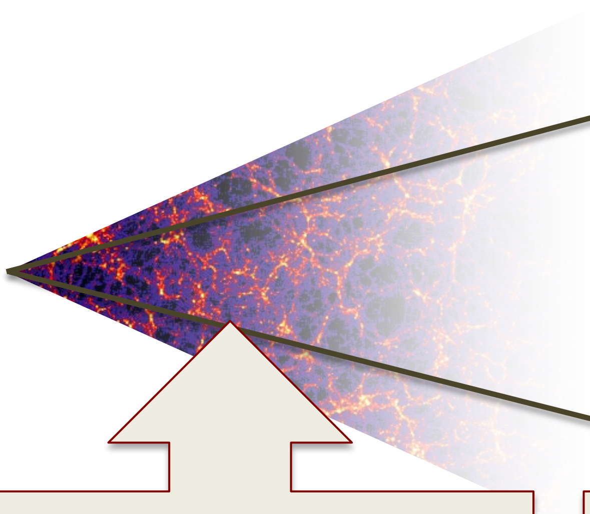
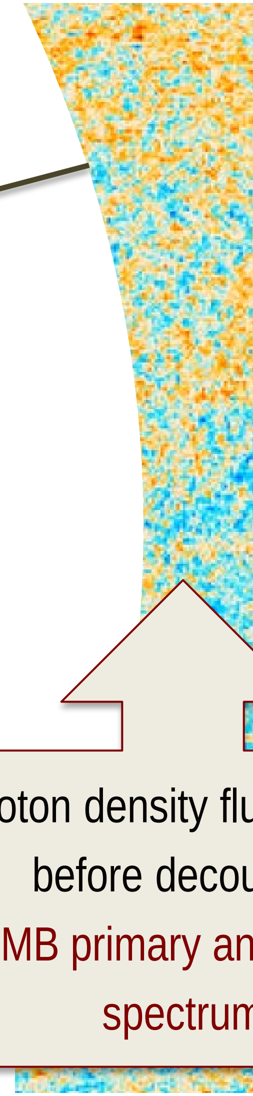




matter density fluctuations

LSS [galaxy / cosmic shear / Lyα] spectrum

Photon momentum after decoupling

CMB secondary anisotropy spectrum

Photon density fluctuations before decoupling

CMB primary anisotropy spectrum

Measuring N_{eff}

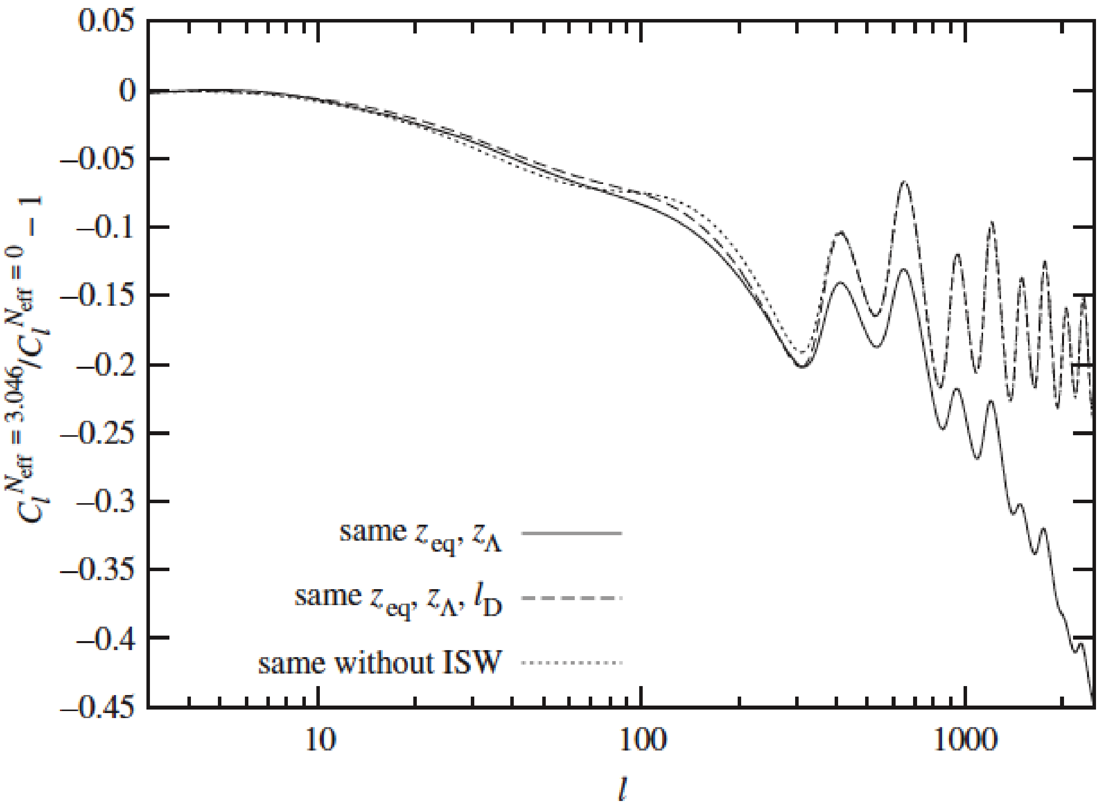
- N_{eff} is a parameter for the relativistic density in general: $\omega_r = [1+0.227N_{eff}]\ \omega_\gamma$
- "background effects" (change in expansion history) versus "perturbation effects" (gravitational interactions between photons and relativistic species)
- "effect of N_{eff}" depends on what is kept fixed.
- Fixing quantities best probed by CMB (angular peak scale, redshift of equality, …):
  - possible with simultaneous enhancement of radiation, matter, Λ densities, with fixed photon and baryon densities
  - then increase in N_{eff} goes with increase in H_0: positive correlation between the two

Measuring N_{eff}

- Fixing quantities best probed by CMB (angular peak scale, redshift of equality, …):

simultaneous enhancement of radiation, matter, Λ densities, with fixed photon and baryon densities

unlensed C_l^{TT} for N_{eff}=3 vs N_{eff}=0 :



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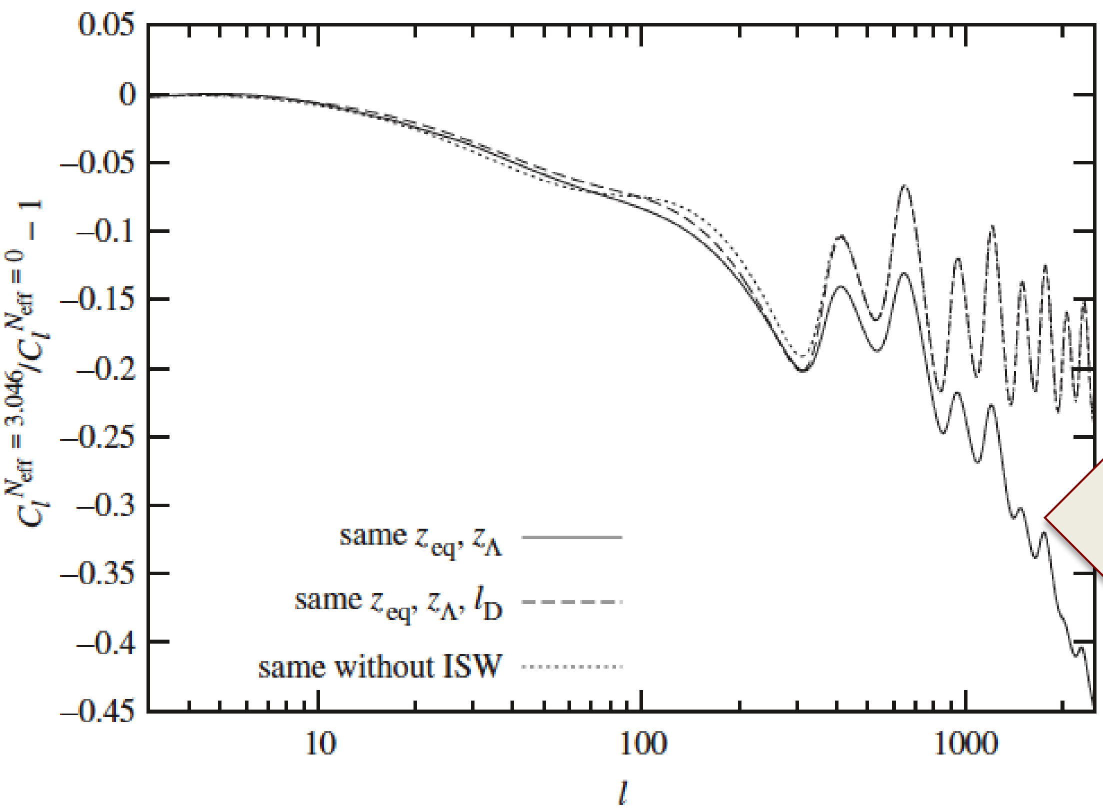

Background
Change in diffusion damping scale: extra Silk damping

Measuring N_{eff}

- Fixing quantities best probed by CMB (angular peak scale, redshift of equality, …):

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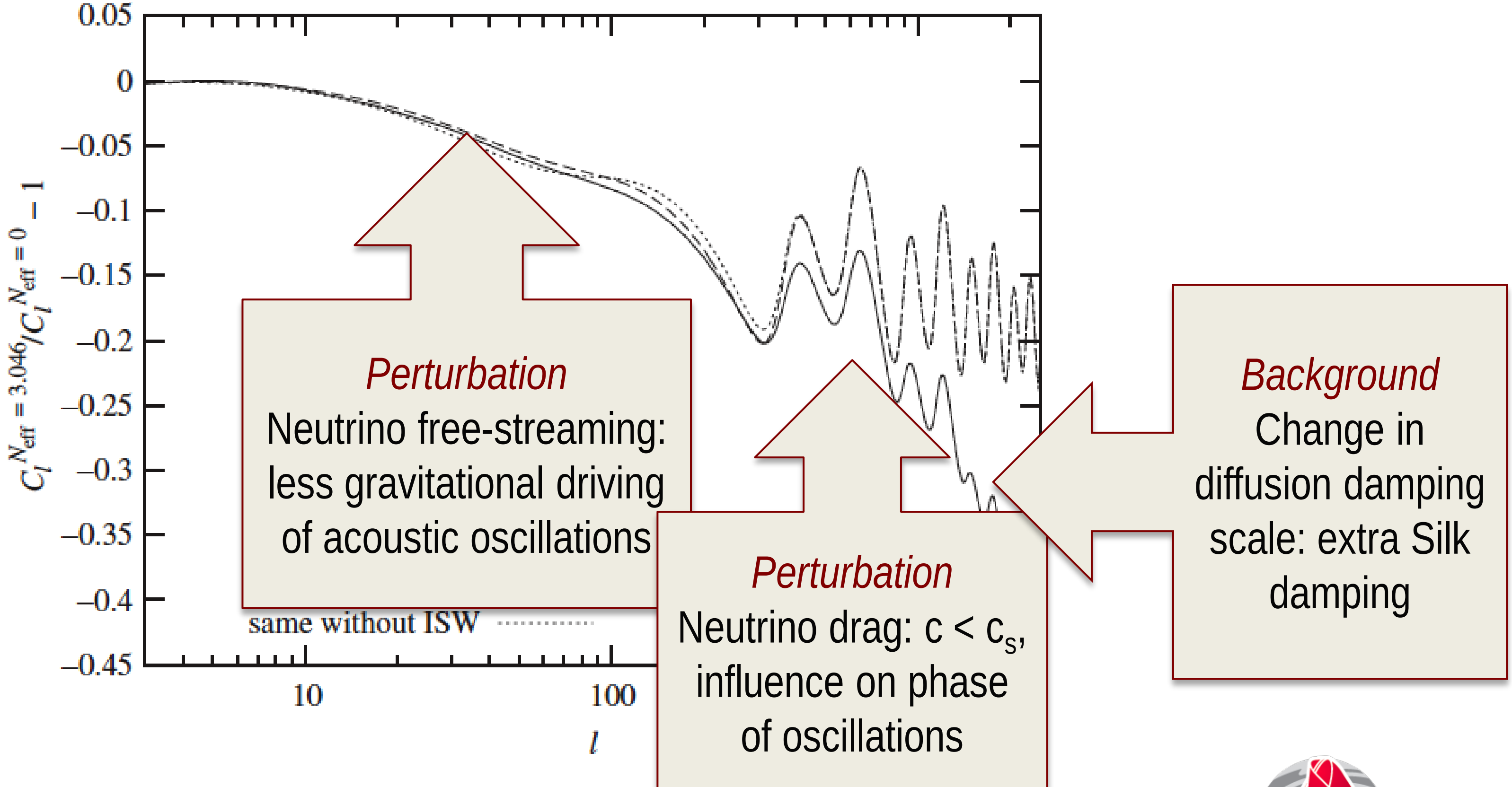

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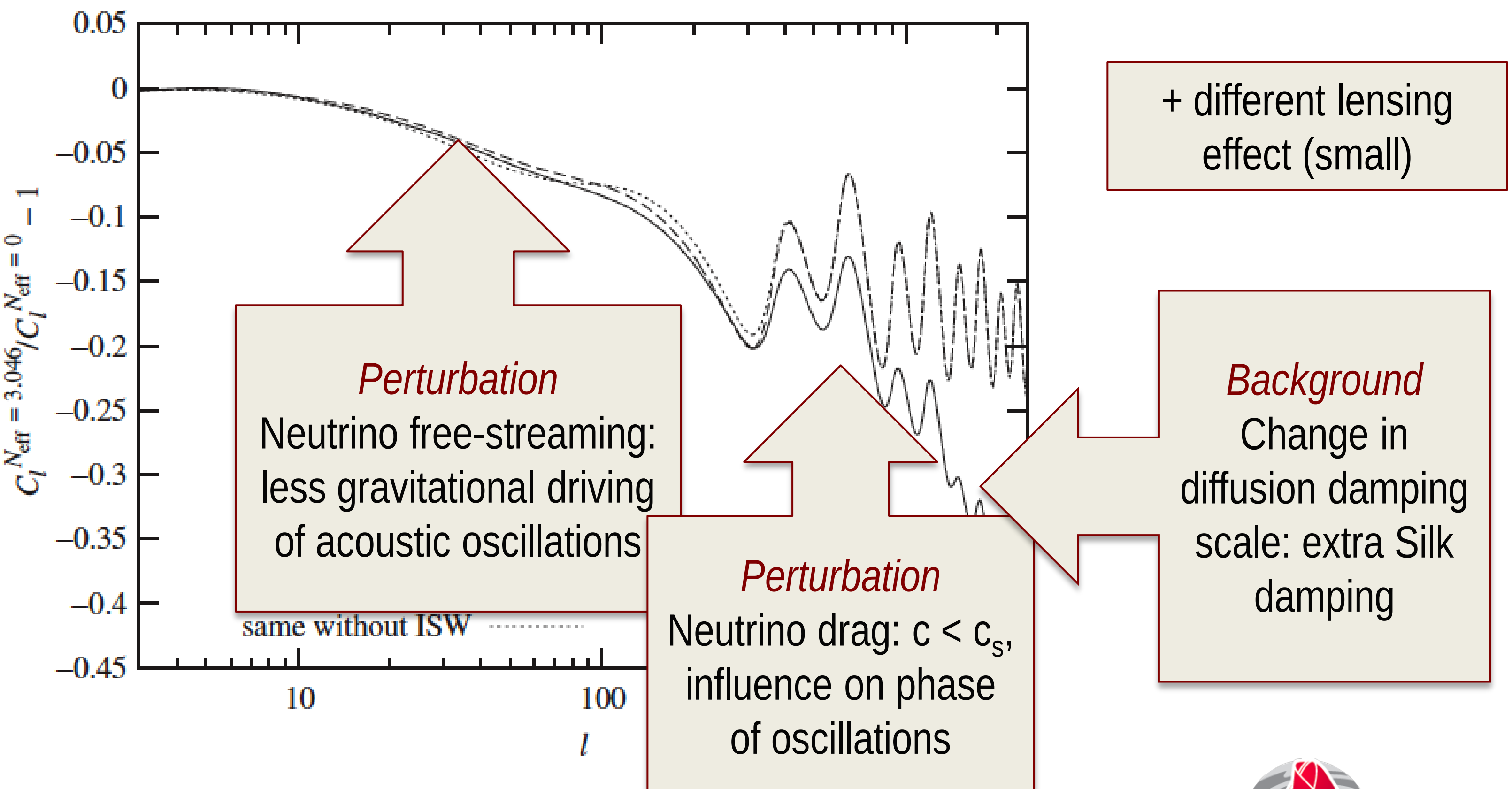


Measuring N_{eff}

- 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 3.046 at 1 sigma
  - 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)

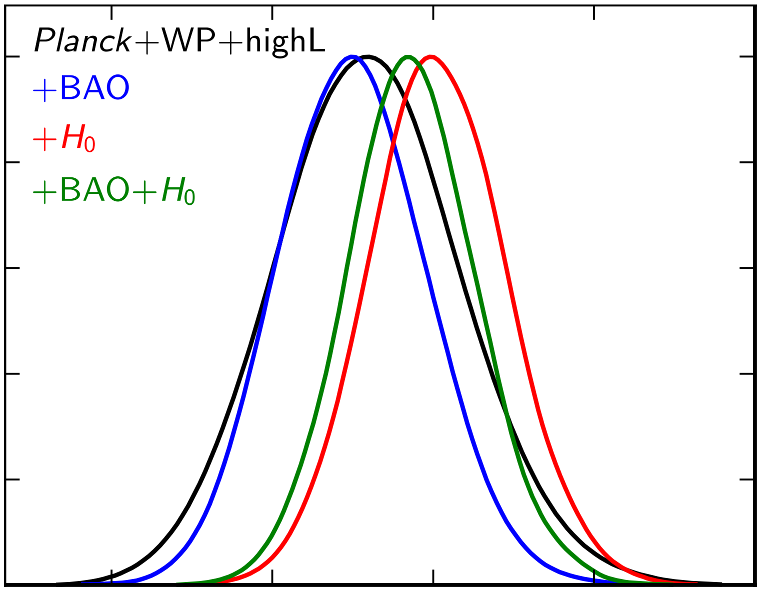
- With lensing and BAO:

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

- With H_0 and BAO:

  $N_{eff} = 3.53 \pm 0.46$ (95%CL)

  $\Delta\chi^2 = -3.6 = -3.3 + 2.0 - 2.8 + 0.4$



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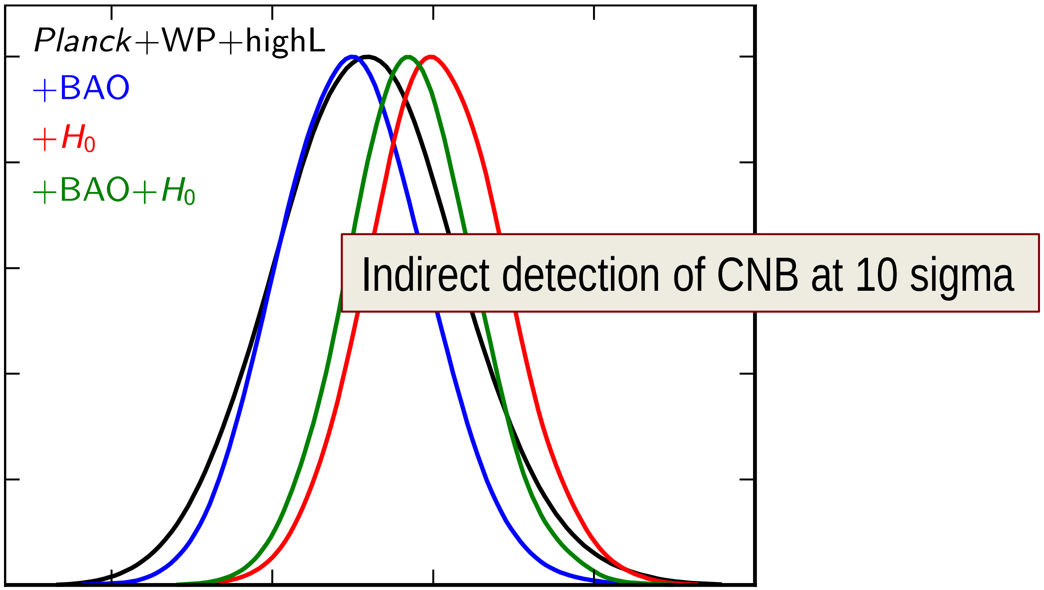

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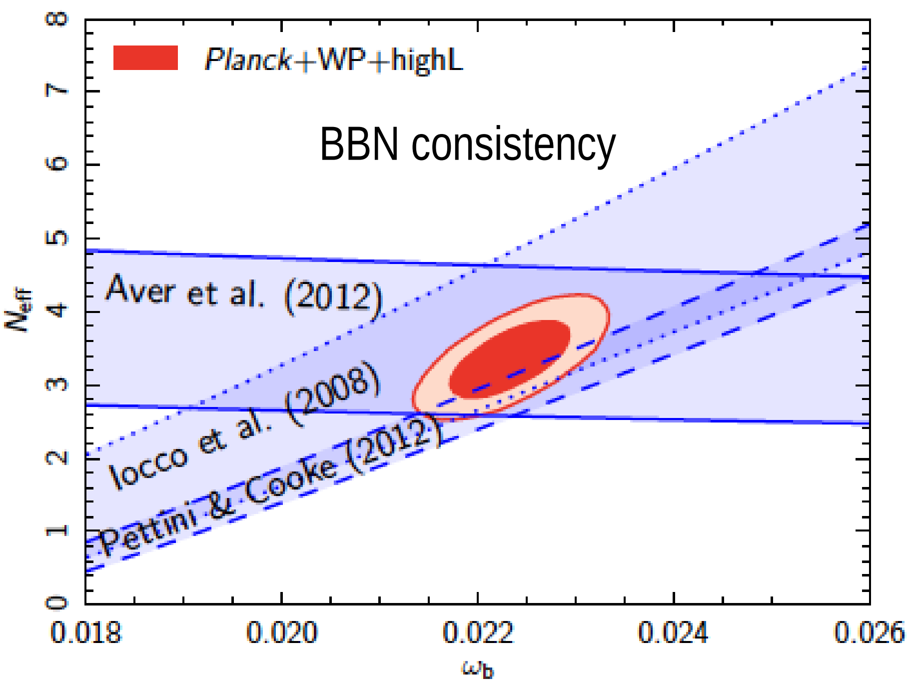


Measuring neutrino masses

- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.
- "effect of m_ν" depends on what is kept fixed.

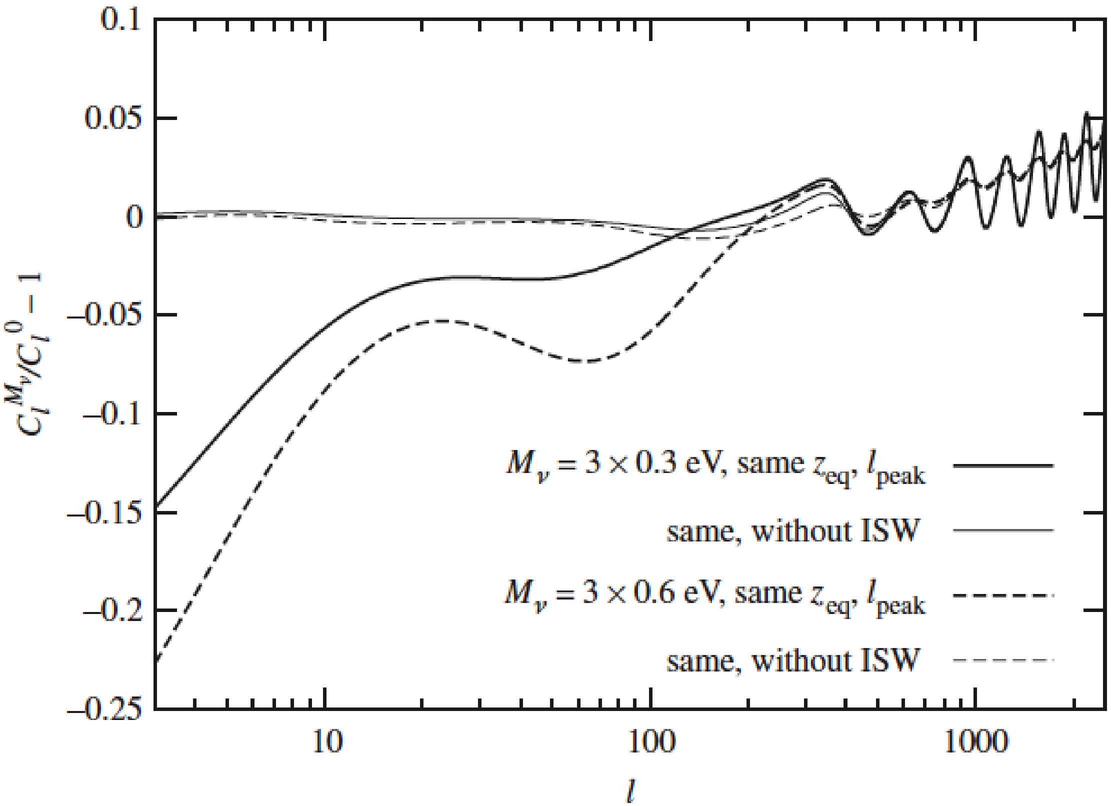
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:
  - Possible by fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ
  - then increase in m_ν goes with decrease in H_0: negative correlation between the two
  - "base model" in Planck has (0.06, 0, 0) eV masses: shifts best-fitting H_0 by -0.6 h/km/Mpc with respect to massless case

Measuring neutrino masses

- Leaving both "early cosmology" and angular diameter dist. to decoupling invariant

fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ

unlensed C_l^{TT} for two degenerate masses vs massless:



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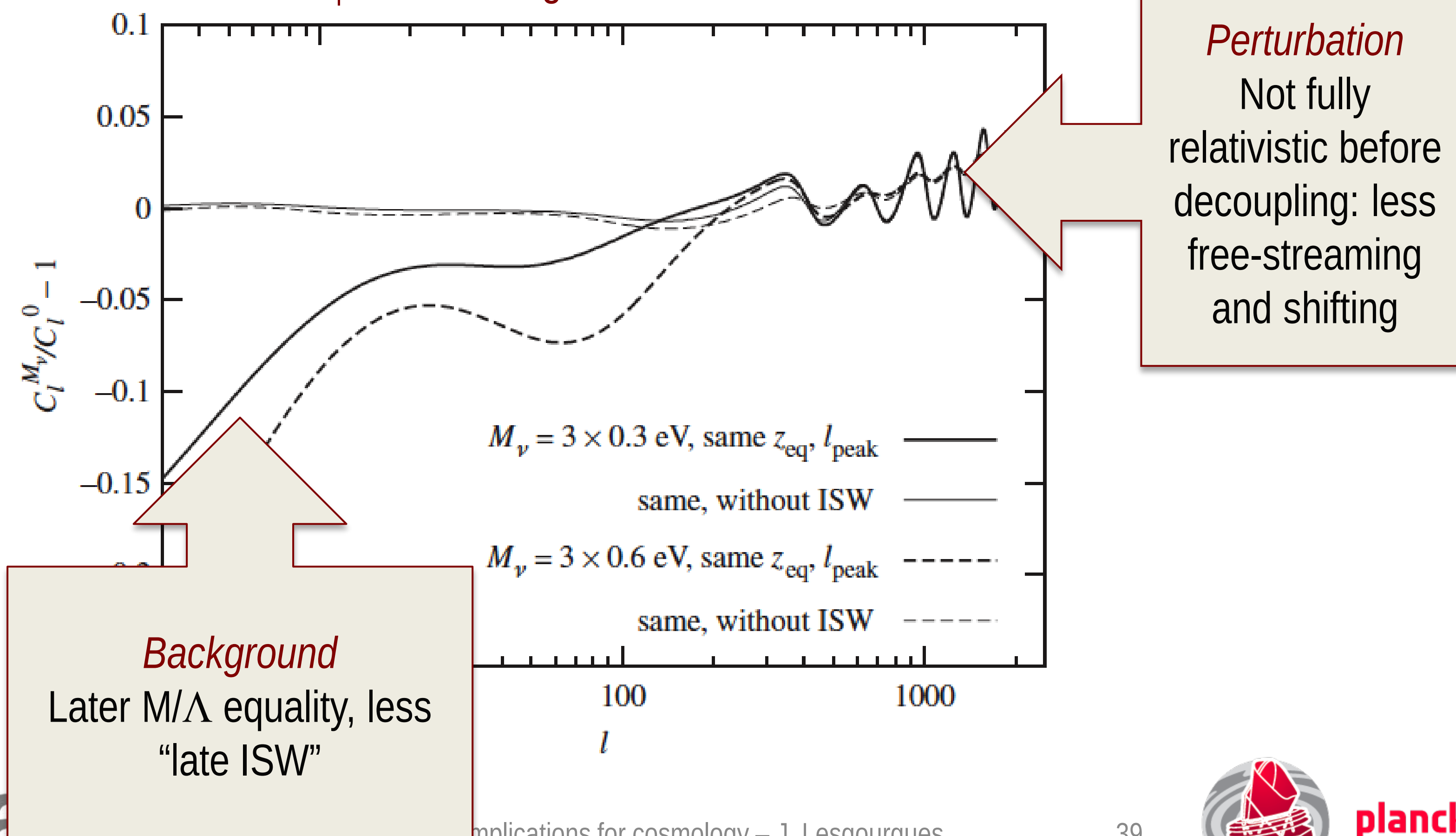

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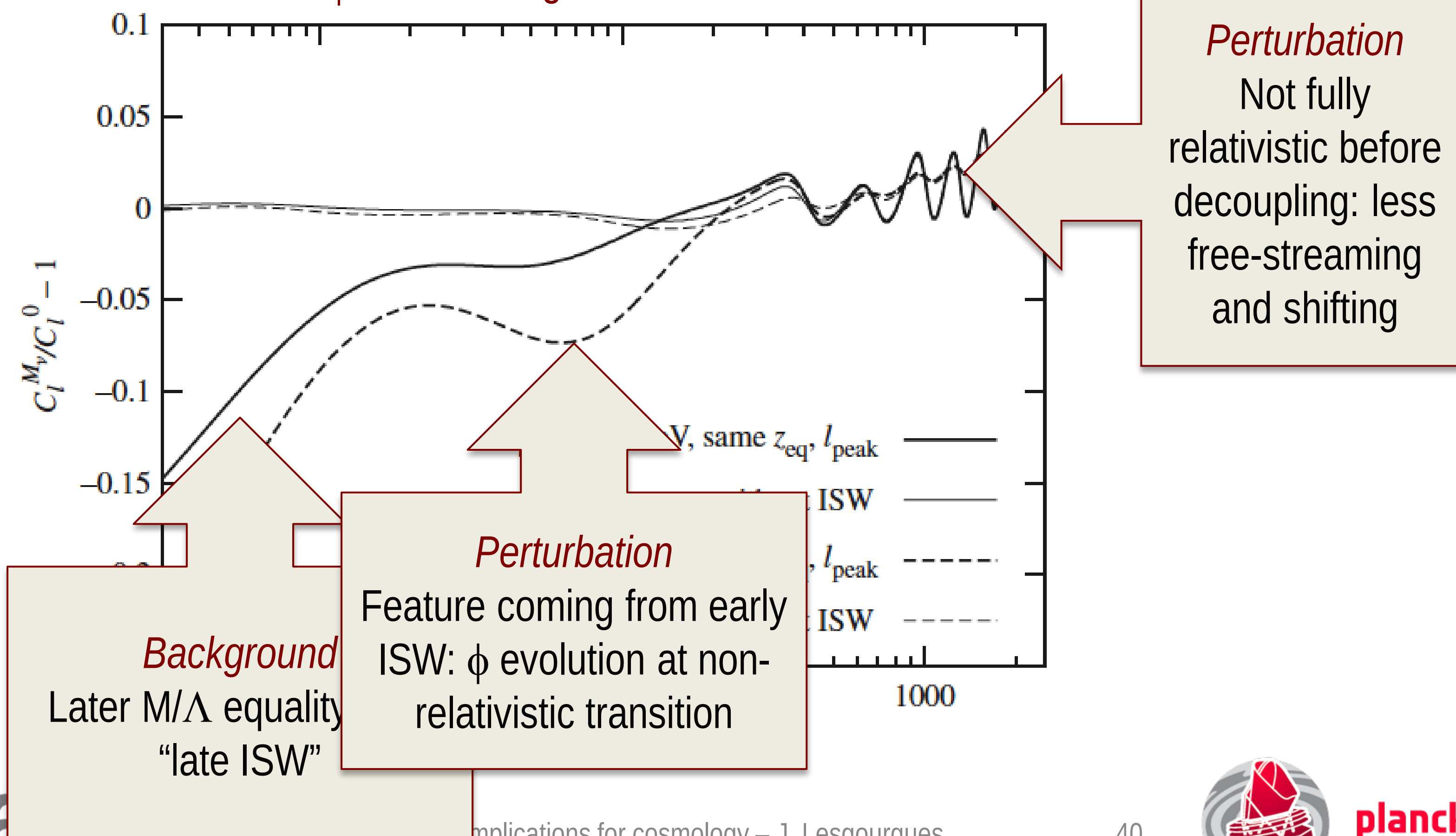

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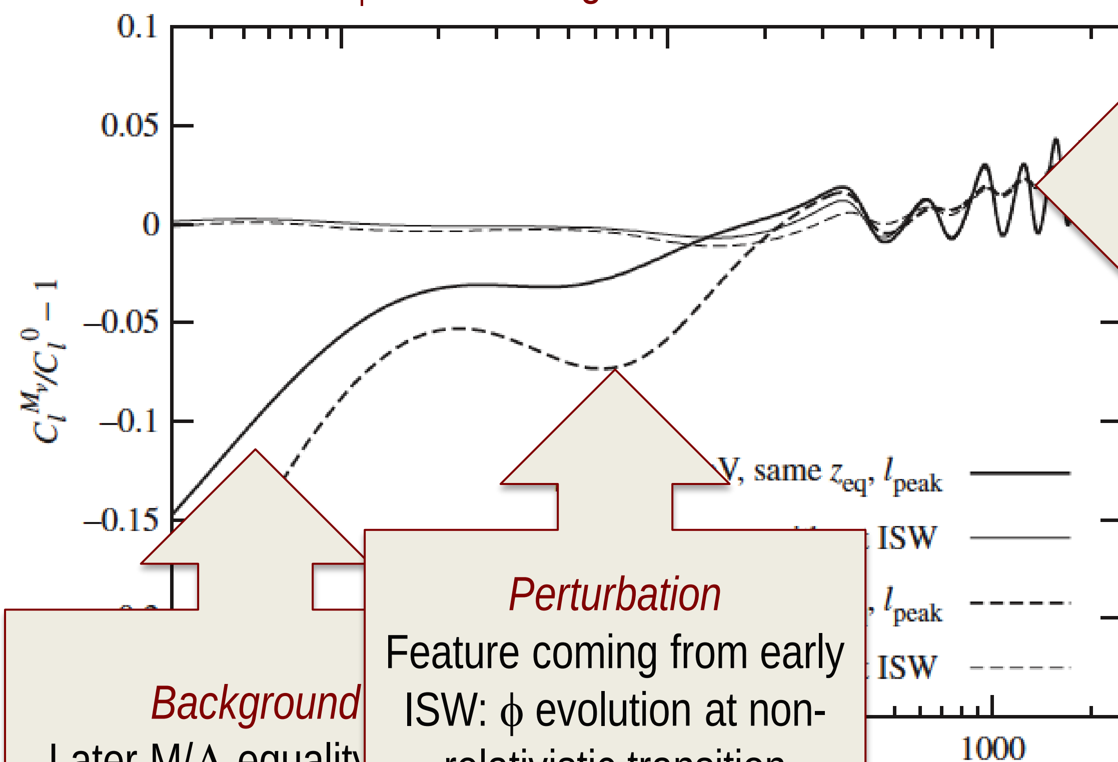


Perturbation
Not fully relativistic before decoupling: less free-streaming and shifting

+ different lensing effect

Perturbation
Feature coming from early ISW: ϕ evolution at non-relativistic transition

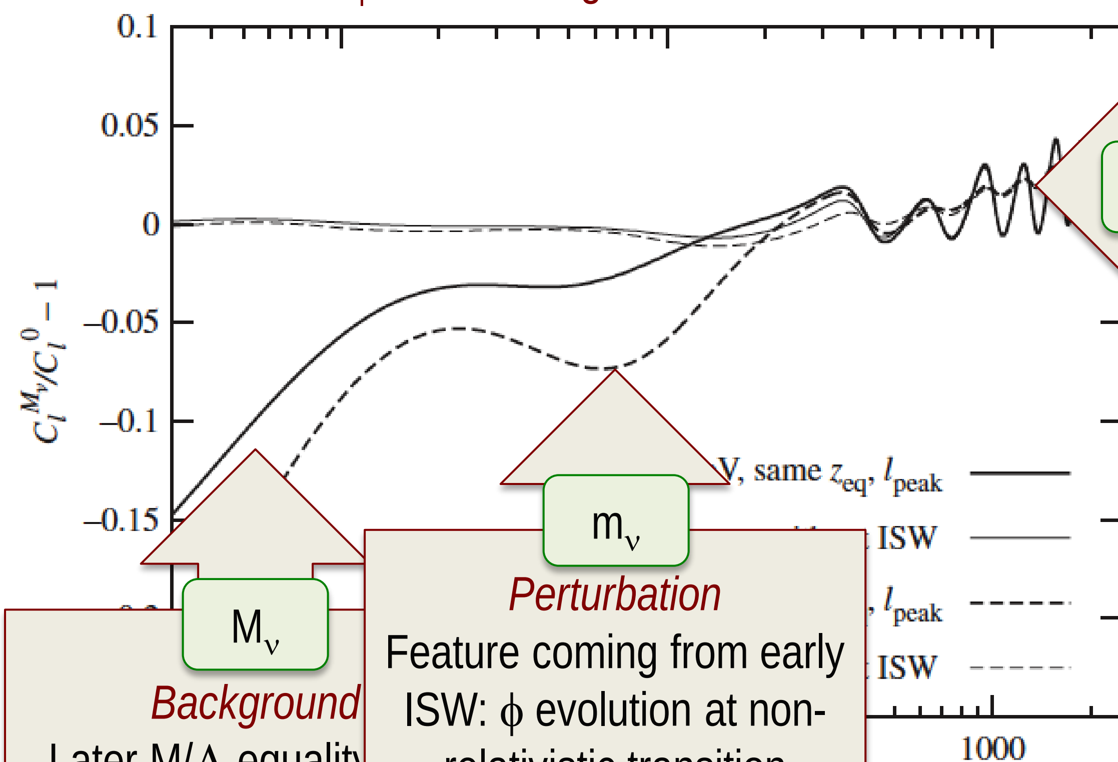
Background
Later M/Λ equality
“late ISW”

Measuring neutrino masses

- Leaving both "early cosmology" and angular diameter dist. to decoupling invariant

fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ

unlensed C_l^{TT} for two degenerate masses vs massless:



Perturbation
Not fully relativistic before decoupling: less free-streaming and shifting

m_ν

+ different lensing effect

M_ν

m_ν

Perturbation
Feature coming from early ISW: ϕ evolution at non-relativistic transition

M_ν

Background
Later M/Λ equality
"late ISW"

Measuring neutrino masses

CMB alone (Planck+WP+HighL):

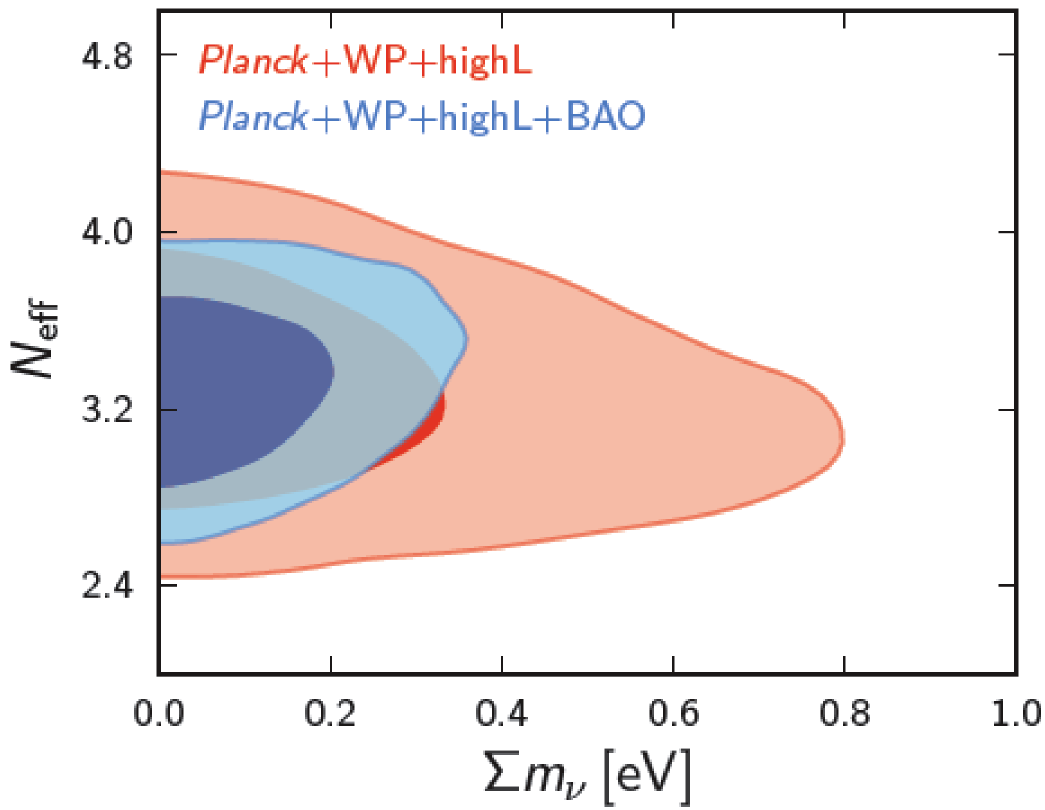
$\Sigma m_\nu < 0.66$eV (95%CL)

With BAO:

$\Sigma m_\nu < 0.23$eV (95%CL)

With lensing:

$\Sigma m_\nu < 0.85$eV (95%CL)



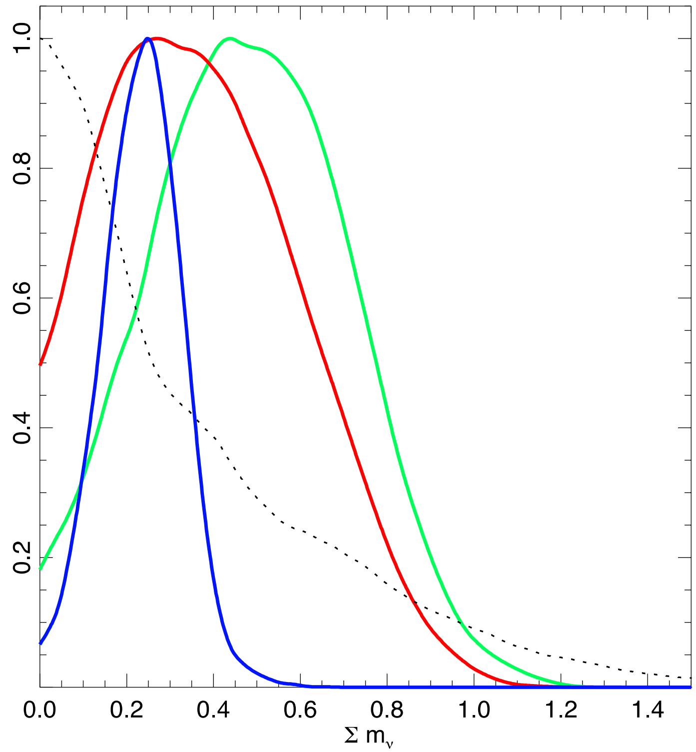
Issue with low l region…

Robust w.r.t cosmological extensions (excepted for curvature: 50% weakening)

Measuring neutrino masses

- Using SZ cluster count from Planck, issue with bias parameter
  (bias between hydrostatic and true mass)

… seems to be an issue with systematics rather than evidence for neutrino mass



Leptonic asymmetry

- BBN puts strong bounds on ν_e chemical potential (neutron to proton conversion) and weak bounds on ν_μ, ν_τ
- But flavor oscillations tend to equalize the potential

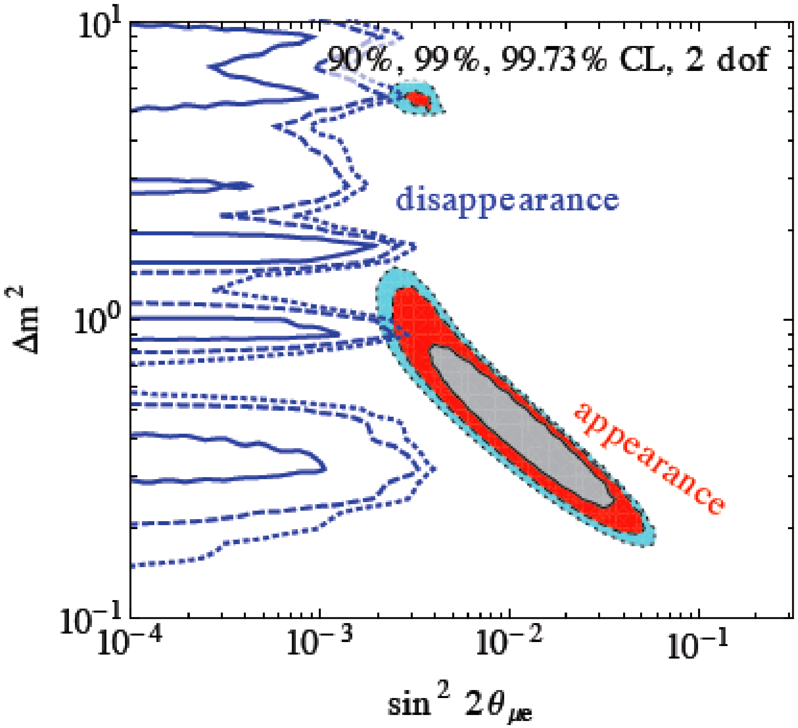
- Large mixing angle solution with measured θ_{13}:
  strong BBN bounds on all chemical potentials,
  $$| n_\nu - n_{\nu bar} | / n_\gamma < 0.07 \text{ (95\%CL)}$$
  leading to
  $$0 < N_{eff} < 3.5$$
  Castorina et al. 2012

- Planck not sensitive enough to improve these bounds

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

Light sterile neutrinos

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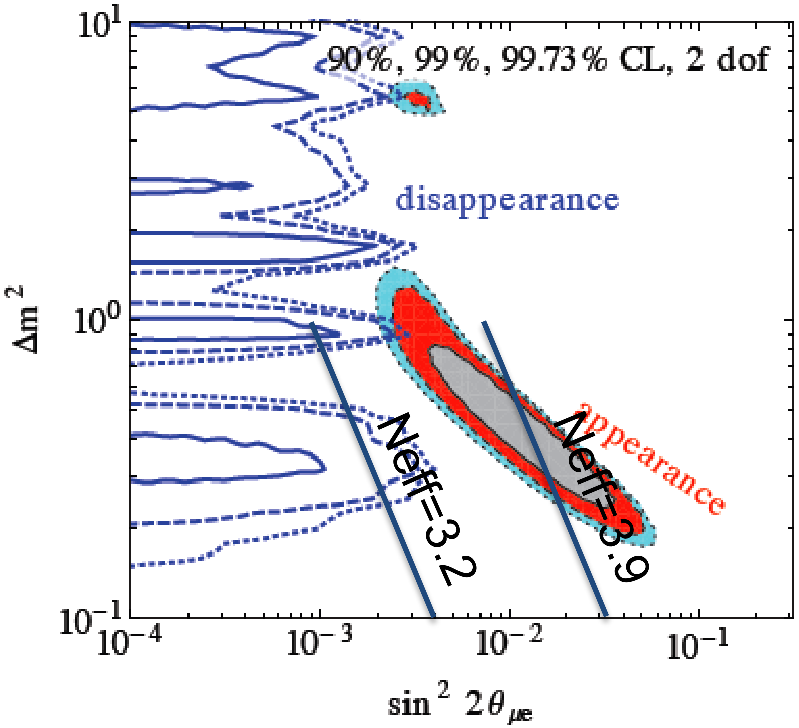

Appearance: LSND, MiniBoone, NOMAD, KARMEN, ICARUS, E776

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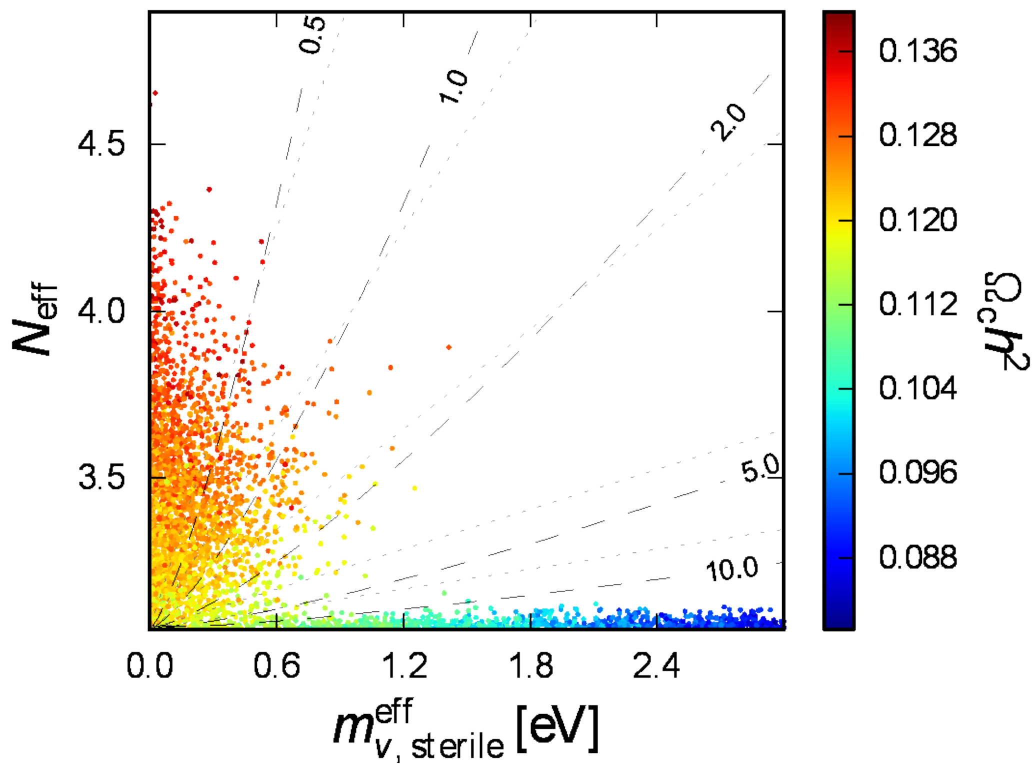
Light sterile neutrinos

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

Total neutrino density in early universe



Sterile neutrino density today $\omega_{\nu s}$

Light sterile neutrinos

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

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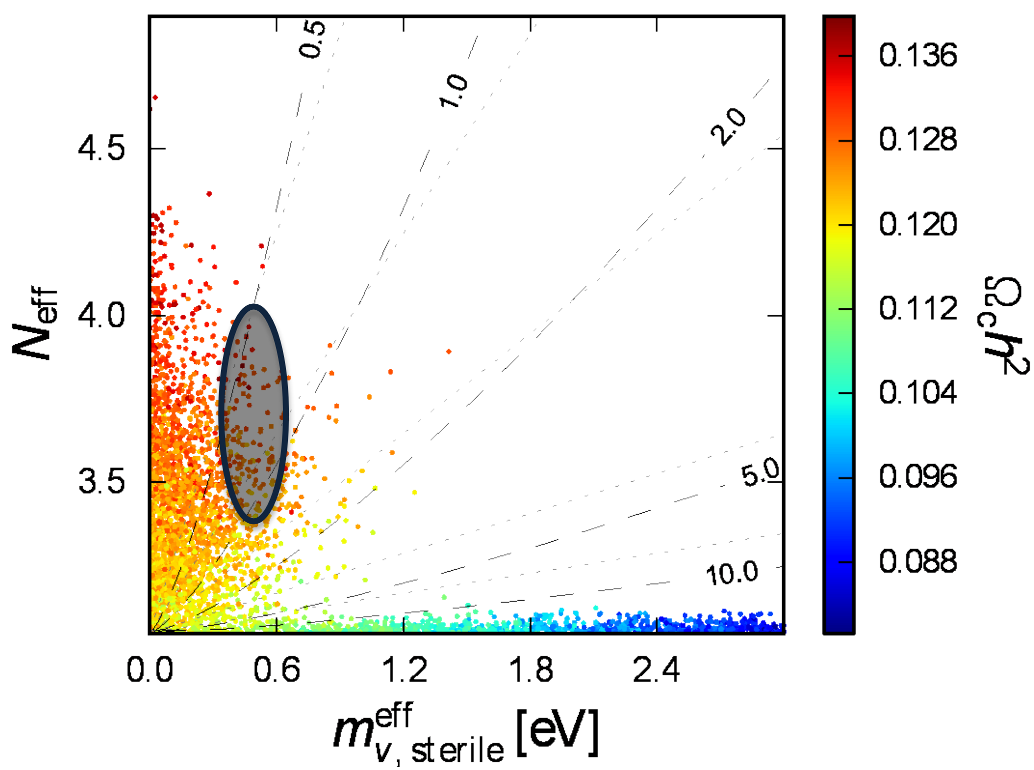

Sterile neutrino density today $\omega_{\nu s}$

Conclusions

- No evidence yet for neutrino mass or enhanced neutrino density, although a few marginal inconsistency need to be understood: H_0 measurements, low l's, lensing spectrum, SZ cluster count

- Neutrino mass remains to be seen by cosmic shear surveys: DES, LSST, Euclid…
  - Safest output of these experiments
  - Scale-dependent suppression of growth factor of matter pertutbations. Importance of tomography
  - Sensitivity increased if we can make accurate theoretical predictions on mildy non-linear scales for power spectrum, bias and redshift space distorsions