Constraints on Light Sterile Neutrinos from CMB and Cosmological Measurements

Based on
[SG et al., JHEP 1311 (2013) 211]
[SG et al., arxiv:1412.7405]

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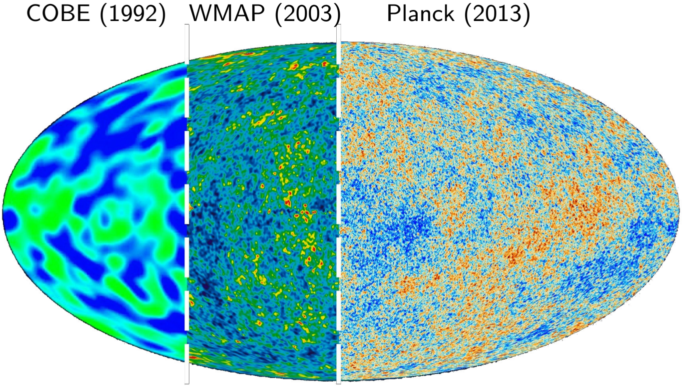
Cosmic Microwave Background (CMB)

First predicted in 1948 (Alpher, Herman): blackbody background radiation at $T \simeq 5$ K.
Discovery (accidental): Penzias, Wilson 1964 → Nobel prize 1978

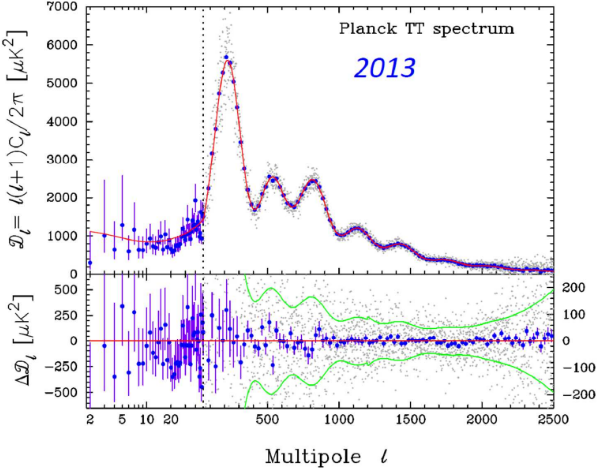
Observations: perfect black body spectrum at $T_{\rm CMB} = 2.72548 \pm 0.00057$ K [Fixsen, 2009]
→ CMB is a remnant of the Big Bang.

Anisotropies at the level of 10^{-5}: very high precision measurements are needed.
Improvement of the CMB experiments in 20 years:



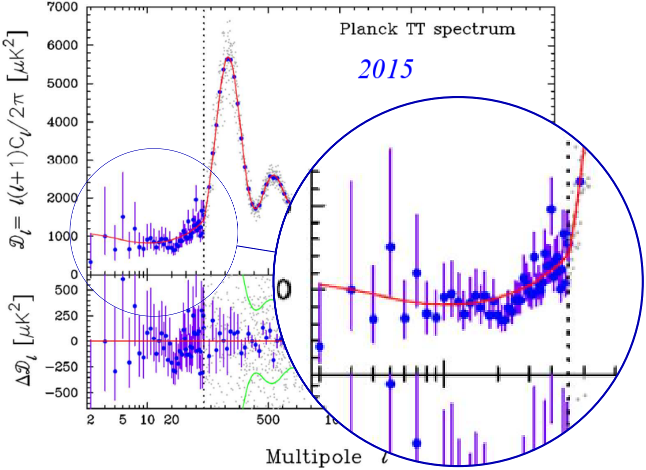
Planck DR1 results

Planck DR1 temperature auto-correlation power spectrum: [Planck Collaboration, 2013]



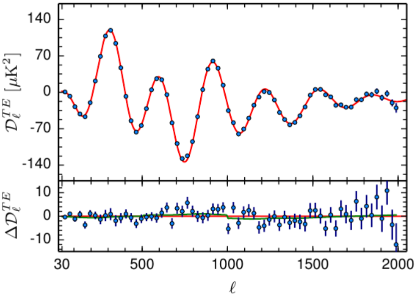
Planck DR2 results - I

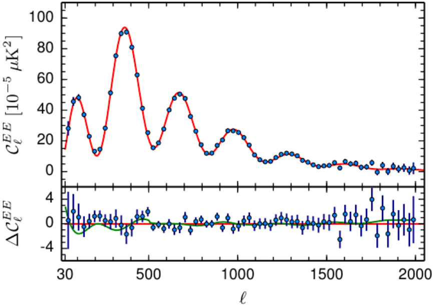
Planck DR2 temperature auto-correlation power spectrum: [Planck Collaboration, 2015]



Planck DR2 results - II

[Planck Collaboration, 2015]



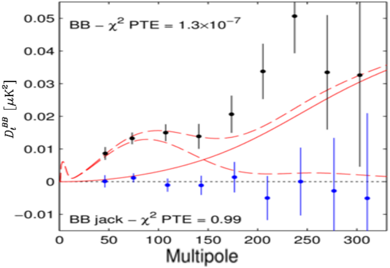


- TE cross-correlation and EE auto-correlation measured with high precision;
- ΛCDM explains very well the data;
- Note: in the plots, the red curve is the prediction based on the TT only best-fit for ΛCDM model → very good consistency between temperature and polarization spectra.

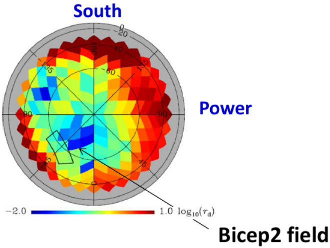
The BICEP2 experiment

[BICEP2, 2014]: claim for detection of primordial tensor modes.
Non-zero value for tensor-to-scalar ratio r.

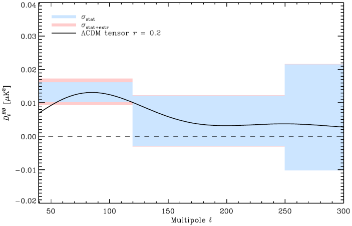
March 2014: $r = A_t(k_\star)/A_s(k_\star) = 0.2^{+0.07}_{-0.05}$



[Planck Intermediate Results XXX, 2014]



Estimated dust emission:



[BICEP2/Keck and Planck Collaborations, 2015]

Conclusion, from the joint analysis: $r_{0.05} < 0.12$ at 95% CL.

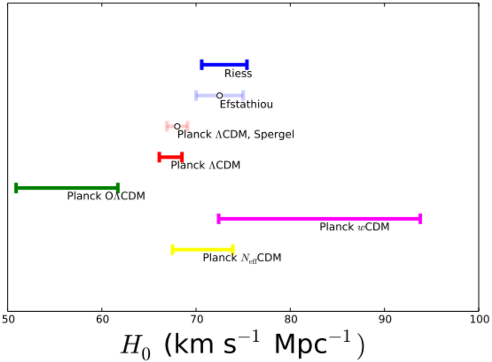
Tension I: Hubble parameter

Hubble parameter today: $v = H_0 d$, with $H_0 = H(z = 0)$

Local measurements: $H(z = 0)$, local and independent on evolution (model independent, systematics?)

CMB measurements (probe $z \simeq 1100$): H_0 from the cosmological evolution (model dependent, well controlled systematics)

[Cuesta et al., 2014] 68% CL error bars



(HST Cepheids)
[Riess et al., 2011] (SNe Ia calibrated distance):
$H_0 = 73.8 \pm 2.4\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Efstathiou 2013] (NGC 4258 calibrated distance):
$H_0 = 70.6 \pm 3.3\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

(ΛCDM - CMB data only)
[Planck 2013]: $H_0 = 67.3 \pm 1.2\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Planck 2015]: $H_0 = 67.27 \pm 0.66\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

Tension II: Cosmic Shear measurements

Cosmic shear: distortion of distant galaxy images by gravitational lensing of large scale structures ⇒ sensitive to non-linear matter density along the line of sight, amplitude of matter power spectrum.

Assuming ΛCDM model:

σ_8: rms fluctuation in total matter (baryons + CDM + neutrinos) in $8h^{-1}$ Mpc spheres, today;
Ω_m: total matter density today divided by the critical density

CFHTLenS weak lensing data alone [Heymans et al., 2013] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.46\pm0.02} = 0.774 \pm 0.04$$

Planck + WMAP polarization + ACT/SPT [Planck 2013 Results XVI] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.46} = 0.89 \pm 0.03$$

2σ discrepancy!

Similar results from cluster counts:

Planck SZ Cluster Counts [Planck 2013 Results XX] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.76 \pm 0.03$$

Planck + WMAP polarization + ACT/SPT [Planck 2013 Results XVI] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.87 \pm 0.02$$

3σ discrepancy!

Qualitatively similar results from *SPT* clusters, *Chandra Cluster Cosmology Project*.

Unexplained discrepancies! Solutions?

Solving the Tensions

Possible solution

Non-zero neutrino masses can help reconciling local Universe with CMB measurements.

Reasons:

- neutrino are relativistic in the primordial Universe
  $\Rightarrow$ free-streaming reduces the perturbations at small scales $\Rightarrow$ lower σ_8;
- additional content in the early Universe
  $\Rightarrow$ shift in the matter-radiation equality $\Leftrightarrow$ perturbation evolution is delayed.

Aim: to study if the neutrinos can help reconciling the different measurements.

Method:

- assume a cosmological model (ΛCDM + neutrinos);
- integrate Boltzmann equations to generate predictions;
- compare predictions with observations;
- put constraints on the theoretical model.

Framework: Bayesian analysis, Markov Chain Monte Carlo approach.

Datasets for the analysis

`CAMB` for Boltzmann equation integration
$+$
`CosmoMC` for Markov Chain Monte Carlo (MCMC),

with different cosmological data:

- *Planck*: Planck 2013 TT spectra.
- *WP*: WMAP 9-year polarization data.
- *high-ℓ* spectra from Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT).
- *Barionic Acoustic Oscillations (BAO)*: values obtained from the SDSS-DR7, the SDSS BOSS-DR9 and the 6dFGS.
- *LSS*: WiggleZ Dark Energy Survey matter power spectrum at 4 different redshifts.
- *H_0/HST*: $H_0 = 73.8 \pm 2.4\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$, using *Cepheids* and *SN Ia calibration*.
- *LGC*: Local Galaxy Cluster data from the Chandra Cluster Cosmology Project.
- *CFHTLens*: the CFHTLens 2D cosmic shear correlation function (from redshifts and shapes of 4.2 million galaxies with $0.2 < z < 1.3$).
- *PSZ*: 189 galaxy clusters identified through the Sunayev Zel'Dovich (SZ) effect from Planck SZ (2013) catalogue.

In the following: *CMB* = Planck 2013 TT + WMAP 9-year polarization + ACT + SPT.

Neutrino Oscillations

Analogous to CKM mixing for quarks:

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau)$$

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.
Oscillations sensitive only to mass differences, not to absolute mass scale!

Two neutrino mixing ($\Delta m^2_{21} = m^2_2 - m^2_1$, θ_{12} mixing angle):

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Current knowledge of the 3 active neutrino mixing: [PDG - Olive et al. (2014)]

$$\begin{aligned} \Delta m^2_{21} &= (7.53 \pm 0.18)\cdot 10^{-5}\ \mathrm{eV}^2 \\ |\Delta m^2_{32}| &= (2.44 \pm 0.06)\cdot 10^{-3}\ \mathrm{eV}^2 \ \to \text{ hierarchy unknown} \end{aligned}$$

$$\left.\begin{array}{l} \sin^2(2\theta_{12}) = 0.846 \pm 0.021 \\ \sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018} \\ \sin^2(2\theta_{13}) = 0.093 \pm 0.008 \\ \text{CP violating phase } \delta_{\mathrm{CP}} \text{ still unknown} \\ \text{2 Majorana phases? only if } \nu \text{ is Majorana particle} \end{array}\right\} U_{\alpha k}$$

Short Baseline (SBL) anomaly

Neutrino oscillations $\Rightarrow \theta_{ij}$, Δm^2_{ij} (and $\delta_{\rm CP}$).

Problem: anomalies in SBL experiments $\Rightarrow \begin{cases} \text{error in flux calculations?} \\ \text{deviations from 3-}\nu\text{ description?} \end{cases}$

A short review: [Abazajian et al., 2012]

- *LSND*: search for $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]
- *MiniBooNE*: search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No ν_e excess detected, but $\bar{\nu}_e$ excess observed at 2.8σ [MiniBooNE Collaboration, 2013]
- *Reactor anomaly*: re-evaluation of the expected anti-neutrino flux $\Rightarrow$ excess of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]
- *Gallium anomaly*: GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

Possible explanation: oscillations between active ν and a sterile ν at eV scale, driven by

$$\Delta m^2_{\rm SBL} \simeq 1 \text{ eV}^2$$

Possible commonly used models: [Giunti et al., 2013]

- 3 active ($m_i \ll 1$ eV) + 1 sterile ($m_s \simeq 1$ eV) $\to$ minimal extension
- 3 active ($m_i \ll 1$ eV) + 2 sterile ($m_s \simeq 1$ eV) $\to$ CP violation in SBL experiments

Cosmological Model: Neutrino Sector

Additional neutrinos ⇒ effects on Universe evolution!

3 active + 1 sterile ν scenario, we assume: $m_1 \simeq 0 \to \Delta m^2_{\mathrm{SBL}} = \Delta m^2_{41} \simeq m^2_4$.

Furthermore, sterile ν_s is weakly mixed with active ν: $m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{\mathrm{SBL}}}$

Sterile ν contribution in cosmology parametrized with: [Acero, Lesgourgues, 2009]

- energy density in the early universe, described by $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046$:
  ν_s contribution to $\rho_R = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\mathrm{eff}}\right]\rho_\gamma$;
- energy density today, described by $m_s^{\mathrm{eff}} = (94.1\,\mathrm{eV})\,\omega_{\mathrm{s}} = \rho_{\mathrm{s}}/\rho^0_{\mathrm{c}}$.
  [Non relativistic: $\rho_s = m_s\, n_s$]
  Constant is given by $\sum m_i = (94.1\,\mathrm{eV})\,\omega_\nu$ for SM neutrinos.

Problem: not independent observables (ΔN_{eff}, m_s^{eff} in cosmology, m_s from oscillations)!

Two different possibilities:

[Dodelson, Widrow, 1994] (DW) model:

$$m^{\mathrm{eff}}_{DW} = m_s\,\Delta N^{DW}_{\mathrm{eff}}$$

Thermal (TH) distribution for ν_s:

$$m^{\mathrm{eff}}_{TH} = m_s\,(\Delta N^{TH}_{\mathrm{eff}})^{3/4}$$

SBL data included as a prior on m_s.

[SG et al., JHEP 1311 (2013) 211]

Cosmological Model: ΛCDM sector

In the following we will study the Universe evolution considering a

$\Lambda\mathrm{CDM} + \nu_s$ model

with 8 free parameters:

$$\{\omega_{\mathrm{CDM}}, \omega_b, \theta_s, \tau, \ln(10^{10} A_s), n_s\} + \{N_{\mathrm{eff}}, m^{\mathrm{eff}}_{DW,TH}\}$$

ω_{CDM} - CDM density today
ω_b - baryon density today
θ_s - angular sound horizon
τ - optical depth to reionization
$\ln(10^{10} A_s)$ - amplitude and
n_s tilt of the primordial power spectrum

N_{eff} effective number of ν_s
$m^{\mathrm{eff}}_{DW,TH}$ physical mass of ν_s (DW or TH scenarios)

Primordial Power Spectrum (PPS) of scalar perturbations:

$$P_s(k) = A_s (k/k_0)^{n_s - 1}$$

with k_0 pivot scale, n_s and A_s as above.

Assume:

- $\sum m_{\nu,\mathrm{active}} = 0.06$ eV (minimal value for Normal Hierarchy)
- $0 \leq m^{\mathrm{eff}}_{DW,TH} \leq 5$
- $3.046 \leq N_{\mathrm{eff}} \leq 6$

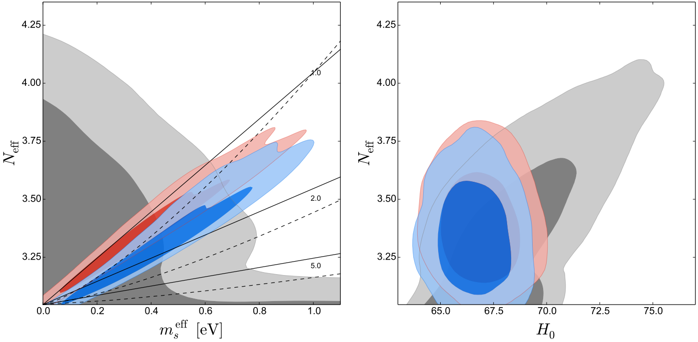
Neutrino Constraints with Planck DR1

[SG et al., JHEP 1311 (2013) 211]

CMB:

(no SBL)
+SBL (DW)
+SBL (TH)

solid lines: (DW)
$m_s^{\rm eff} = m_s\,\Delta N_{\rm eff}$
dashed lines: (TH)
$m_s^{\rm eff} = m_s\,(\Delta N_{\rm eff})^{3/4}$



- ν_s as Warm Dark Matter (WDM): $N_{\rm eff} \simeq 3.046$, large $m_s^{\rm eff}$ (large m_s);
- SBL prior: $m_s \simeq 1.2$ eV, but $N_{\rm eff} = 4$ (ν_s thermalized as $\nu_{\rm SM}$) disfavoured;
- (DW), (TH) models give similar results ($N_{\rm eff}$ slightly higher in (DW));
- only without SBL prior: positive correlation among $N_{\rm eff}$ and H_0 → tension with local measurements partially solved at large $N_{\rm eff}$.

Adding BAO and HST

[SG et al., JHEP 1311 (2013) 211]

CMB+H_0+BAO:

(no SBL)

+SBL (DW)

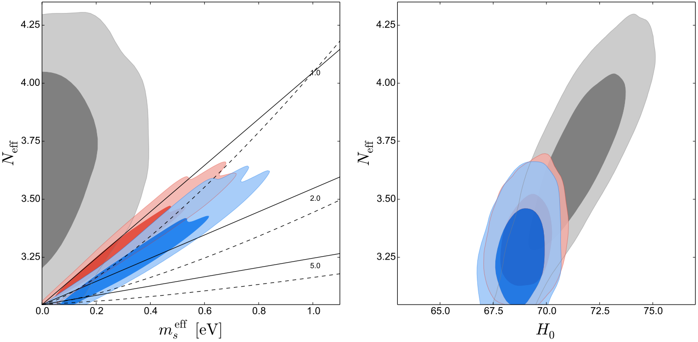
+SBL (TH)

solid lines: (DW)

$m_s^{\text{eff}} = m_s \, \Delta N_{\text{eff}}$

dashed lines: (TH)

$m_s^{\text{eff}} = m_s \, (\Delta N_{\text{eff}})^{3/4}$



- stronger limits on m_s^{eff}, no ν_s WDM tail at small N_{eff};
- no SBL prior: higher N_{eff} admitted → higher H_0 (correlation with N_{eff} holds);
- with SBL prior: slightly smaller N_{eff};
- with SBL prior: improvement in solving H_0 tension (driven by H_0 prior), but still low values. Due to direction in m_s^{eff}, N_{eff} plane forced by SBL prior on m_s.

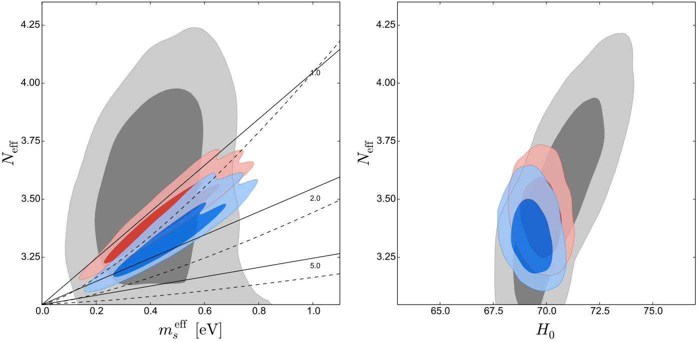
MPK constraints and mass evidence

[SG et al., JHEP 1311 (2013) 211]

CMB+H_0+BAO+LGC:

(no SBL)
+SBL (DW)
+SBL (TH)

solid lines: (DW)
$m_s^{\mathrm{eff}} = m_s\,\Delta N_{\mathrm{eff}}$
dashed lines: (TH)
$m_s^{\mathrm{eff}} = m_s\,(\Delta N_{\mathrm{eff}})^{3/4}$



- LGC results give preference towards non-zero $m_s^{\mathrm{eff}} \to$ non-zero m_s: smaller σ_8 from LGC can be addressed with massive ν_s (due to free streaming);
- no SBL prior: N_{eff} constraints almost unchanged;
- with SBL prior: preference for $N_{\mathrm{eff}} > 3.046$ at more than 2σ;
- with SBL prior: $N_{\mathrm{eff}} = 4$ still hardly disfavoured.

Why Inflation?

Inflation developed in the 1980s to solve several shortcomings in the Big Bang model:

- *Horizon problem*: why is the Universe homogeneous and isotropic? widely separated regions cannot equilibrate during gravitational expansion, since there is no causal contact during the Universe evolution.

  > Solution: parts of the Universe in casual contact before inflation were widely separated during inflation, while today they are re-entering the expanding causal horizon.

- *Flatness problem*: is the Universe flat? Planck DR2: $\Omega_K = 0.000 \pm 0.005$ today, but this corresponds to exponentially small values in the early Universe ($|\Omega_{\rm tot} - 1| < 10^{-18}$ at nucleosynthesis, even smaller at earlier times). Fine-tuning?

  > Solution: $|\Omega_{\rm tot}(t) - 1| \propto \exp\left(-\sqrt{\frac{4\Lambda}{3}}t\right)$. If inflation lasts enough (at least 60 e-folds, namely $a_{\rm end}/a_{\rm begin} \simeq e^{60}$), $\Omega_{\rm tot}$ is very small still today.

Inflation: $H^2 \simeq \frac{\Lambda}{3} \implies \dot{a} = \sqrt{\frac{\Lambda}{3}}a \implies a(t) \propto \exp\left(\sqrt{\frac{\Lambda}{3}}t\right) = \exp(Ht)$

H Hubble parameter and Λ cosmological constant during inflation, a scale factor

Primordial Power Spectrum from Slow Roll Inflation

Slow roll inflation [Linde, 1982]:

inflation occurred by a scalar field (Inflaton) rolling down a potential energy hill.

End of inflation depends on

- the shape of the inflaton potential $V(\phi)$;
- the spatially variating perturbation of the inflaton field $\delta\phi(t,\vec{x})$.

Fluctuations in the inflaton modulate the end of inflation:
in different regions, inflation ends at different times.
$\delta\phi(t,\vec{x})$ converted into energy density fluctuations $\delta\rho$ after inflation.

$\Rightarrow$ small scale dependence of the PPS:

we define $$(n_s-1)\equiv\frac{d\ln P_s(k)}{d\ln k}=2\frac{V''}{V}-3\left(\frac{V'}{V}\right)^2,$$

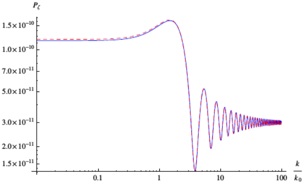
more general than $P_s(k)=A_s(k/k_\star)^{n_s-1}$.

Is n_s constant? Can the PPS deviate from a power-law?

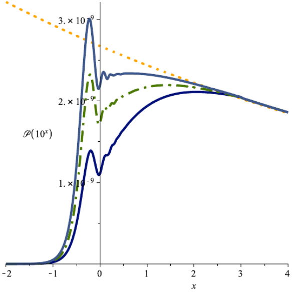
Beyond Power-Law PPS

Theory

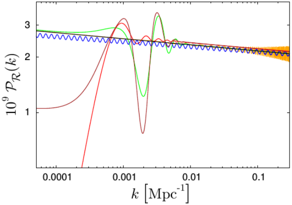
[Romano et al., 2014]



[Sagnotti et al, 2014]

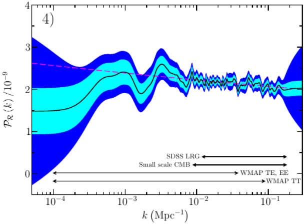


[Planck Collaboration, 2015]

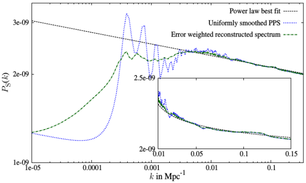


Reconstructions

[Hunt et al., 2014]



[Hazra et al, 2014]



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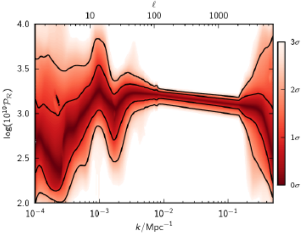


PCHIP Parametrization

Fix the PPS form leads to possible bias:

⇒ analysis with free, non-parametric form for the PPS.

Proposal: fix a series of nodes and use an interpolating function among them,

$$P_s(k) = P_0 \times f(k; P_{s,1}, \ldots, P_{s,12})$$
$$P_0 = 2.36 \times 10^{-9}$$

In our case:

PCHIP

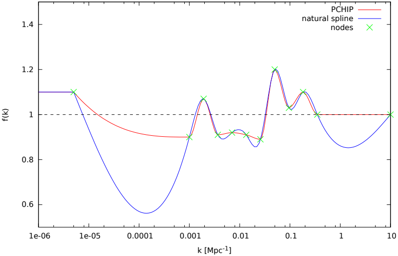
"piecewise cubic Hermite interpolating polynomial"

$$f(k; P_{s,1}, \ldots, P_{s,12}) = \mathtt{PCHIP}(k; P_{s,1}, \ldots, P_{s,12})$$

Interpolate piecewise a series of nodes $P_{s,j} = P_s(k_j)$ with $j \in [1, 12]$:

- continue and derivable;
- preserve monotonicity of the nodes:
  - 1^{st} derivative in the node fixed using the secants between consequent nodes;
  - if the monotonicity changes, the node is a local extremum;
- 2^{nd} derivative not continue in the nodes.

Advantage over *natural cubic splines*: no spurious oscillations.



Light Sterile Neutrino Results - I

Change in the parametrization: $\Lambda\mathrm{CDM}(\mathrm{PL\,PPS}) + \nu_s$ model with

$$\{\omega_{\mathrm{CDM}}, \omega_b, \theta_s, \tau, \ln(10^{10}A_s), n_s\} + \{N_{\mathrm{eff}}, m_s^{\mathrm{eff}}\}.$$

Light Sterile Neutrino Results - I

[SG et al., arxiv:1412.7405]

Change in the parametrization: ΛCDM(PCHIP PPS) + ν_s model with

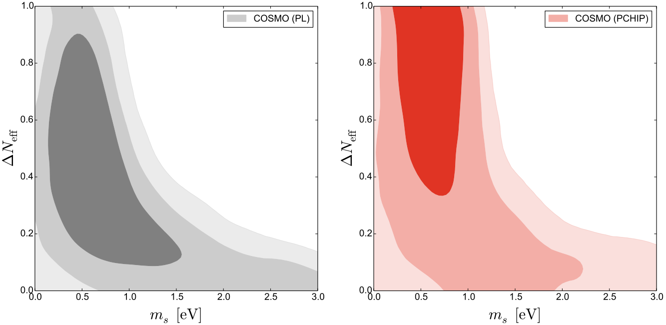
$$\{\omega_{\rm CDM}, \omega_b, \theta_s, \tau, P_{s,1}, \ldots, P_{s,12}\} + \{\Delta N_{\rm eff}, m_s\}.$$

We consider only thermal sterile neutrinos, physical mass m_s.

Results in ΛCDM sector almost unchanged (variations well inside 1σ range).

Changes in the Sterile neutrino sector:

COSMO = CMB(Planck13+WMAP Polarization+ACT/SPT)+LSS(WiggleZ)+HST(Riess2011)+CFHTLenS+PlanckSZ



no SBL prior:

- higher $\Delta N_{\rm eff}$ admitted;
- change on m_s constraints due to $\Delta N_{\rm eff}$ change;
- fully thermalized sterile neutrino preferred.

Light Sterile Neutrino Results - II

Change in the parametrization: ΛCDM(PCHIP PPS) + ν_s model with

$$\{\omega_{\rm CDM}, \omega_b, \theta_s, \tau, P_{s,1}, \ldots, P_{s,12}\} + \{\Delta N_{\rm eff}, m_s\}.$$

We consider only thermal sterile neutrinos, physical mass m_s.

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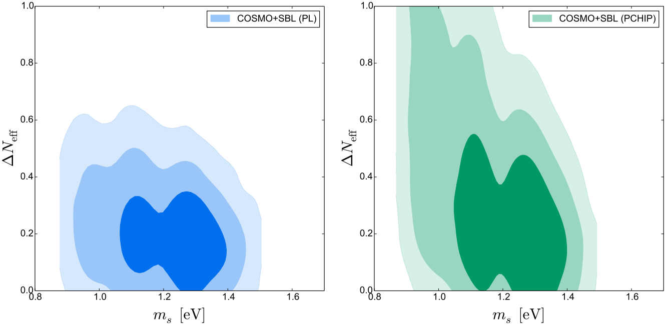
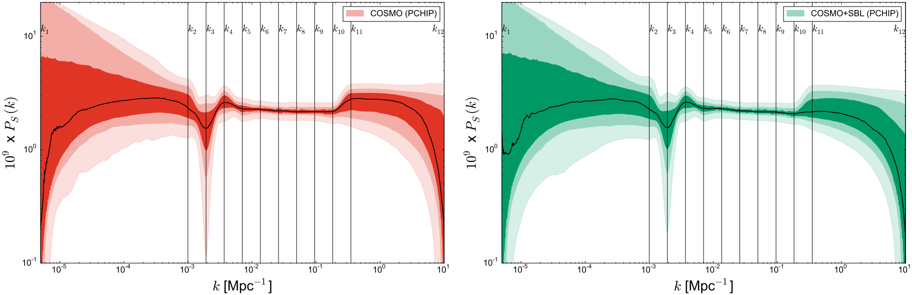


with SBL prior:

- higher $\Delta N_{\rm eff}$ admitted;
- no change on m_s constraints;
- fully thermalized sterile neutrino admitted (inside 2σ region).

PPS Results

[SG et al., arxiv:1412.7405]



- CMB constraints for $1 \times 10^{-4}\,\mathrm{Mpc}^{-1}(\ell = 2) \leq k \leq 0.3\,\mathrm{Mpc}^{-1}(\ell \simeq 2500)$;
- outer k are not constrained by data;
- power-law is a good approximation in the range $7 \times 10^{-3}\,\mathrm{Mpc}^{-1} \leq k \leq 0.2\,\mathrm{Mpc}^{-1}$;
- feature at $k = 2 \times 10^{-3}\,\mathrm{Mpc}^{-1}$ correspond to dip $\ell \simeq 22$ in CMB spectrum;
- feature at $k = 3.5 \times 10^{-3}\,\mathrm{Mpc}^{-1}$ correspond to small bump $\ell \simeq 40$ in CMB spectrum.

Conclusions

- ΛCDM explains very well CMB measurements;
- tension between CMB observations and local observations;
  - unaccounted systematics?
  - wrong models for the Universe evolution?
- sterile neutrinos suggested by SBL oscillation anomalies can help solving the tensions,
  - but problems in producing them with small N_{eff} (preferred by cosmology);
- non-standard inflation can help reconciling tensions through sterile neutrino presence in the early Universe.

Thank you for the attention!

Talks, Posters and Conferences

Talks

- **ISAPP 2013**, *International Doctoral School*, Canfranc (ES), July 20, 2013.
  "Testing 3+1 Neutrino Mass Models with Cosmology and Short-Baseline Experiments".
- **New Frontiers in Theoretical Physics**, Cortona (IT), May 29, 2014.
  "Reconciling cosmology and short-baseline experiments with invisible decay of light sterile neutrinos".

Posters

- **ISAPP 2013**, *International Doctoral School*, Canfranc (ES), July 14–23, 2013.
  "Testing 3+1 Neutrino Mass Models with Cosmology and Short-Baseline Experiments".
- **Planck 2014**, Ferrara (IT), December 1–5.
  "Light Sterile Neutrinos and Inflationary Freedom".
- **The Primordial Universe after Planck**, Paris (FR), December 15–19.
  "Light Sterile Neutrinos and Inflationary Freedom".

Other Conferences and Schools

- **ISAPP 2014**, *International Doctoral School*, Belgirate (IT), July 21–30.
  "Multi-Wavelength and Multi-Messenger Investigation of the Visible and Dark Universe".
- **Neutrino Oscillation Workshop (NOW) 2014**, Conca Specchiulla, Otranto (IT), September 8–14.

Papers

S. Gariazzo, C. Giunti, M. Laveder.
"Light Sterile Neutrinos in Cosmology and Short-Baseline Oscillation Experiments".
JHEP 1311 (2013), p. 211.
arXiv: 1309.3192 [hep-ph].

M. Archidiacono, N. Fornengo, **S. Gariazzo**, C. Giunti, S. Hannestad et al.
"Light sterile neutrinos after BICEP-2".
JCAP 1406 (2014), p. 031.
arXiv: 1404.1794 [astro-ph.CO].

S. Gariazzo, C. Giunti, M. Laveder.
"Cosmological Invisible Decay of Light Sterile Neutrinos".
Submitted for publication (2014).
arXiv: 1404.6160 [astro-ph.CO].

S. Gariazzo, C. Giunti, M. Laveder.
"Light Sterile Neutrinos and Inflationary Freedom".
Submitted for publication (2014).
arXiv: 1412.7405 [astro-ph.CO].