Light Sterile Neutrinos in Cosmology

Based on [SG et al., arxiv:1507.08204]

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Summary on Neutrino Oscillations

Neutrino oscillations: analogous to CKM mixing for quarks, with

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

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates

Current knowledge of the active ν mixing
($\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles):

$$\begin{aligned} \Delta m^2_{SOL} &= (7.53 \pm 0.18) \cdot 10^{-5}\ \mathrm{eV}^2 & &= \Delta m^2_{21} \\ \Delta m^2_{ATM} &= (2.44 \pm 0.06) \cdot 10^{-3}\ \mathrm{eV}^2 (\mathrm{NH}) & &= |\Delta m^2_{32}| \simeq |\Delta m^2_{31}| \\ &= (2.52 \pm 0.07) \cdot 10^{-3}\ \mathrm{eV}^2 (\mathrm{IH}) & & \end{aligned}$$

$$\begin{aligned} \sin^2(2\theta_{12}) &= 0.846 \pm 0.021 \\ \sin^2(2\theta_{23}) &= 0.999^{+0.001}_{-0.018} (\mathrm{NH}) - 1.000^{+0.000}_{-0.017} (\mathrm{IH}) \\ \sin^2(2\theta_{13}) &= (9.3 \pm 0.8) \cdot 10^{-2} \end{aligned}$$

[PDG - Olive et al. (2014)]

Further details:
[C. Giunti talk]

CP violation through phase δ (still unknown) possible only if $\sin\theta_{13} \neq 0$.

Neutrino Oscillation Anomalies

Observed oscillation anomalies in Short BaseLine (SBL) experiments.

A short review: [SG et al., 2015]

- *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, 2013]
- *Reactor anomaly*: re-evaluation of the expected anti-neutrino flux ⇒ excess of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]
- *Gallium anomaly*: calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

Possible explanation:

Additional squared mass difference $\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$

3+1 Neutrino Model

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

$\Downarrow$

Existence of an additional neutrino degree of freedom,
mass around 1 eV, no weak interaction $\Rightarrow$ *light, sterile neutrino (LSν)*

$\Downarrow$

3 active ($m_i \ll 1$ eV) + 1 sterile ($m_s \simeq 1$ eV) ν scenario

We must update our mixing paradigm:

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

Active ν:
$\sum m_{\nu,\text{active}} \simeq 0$

ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\text{SBL}}}$$

Sterile ν:
$0.82 \le m_s^2/\text{eV}^2 \le 2.19\ (3\sigma)$

[Giunti et al, 2013]

Relativistic Sterile Neutrino: Effective Number $N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = [1 + 0.2271 N_{\rm eff}]\,\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \to$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos: $N_{\rm eff} = 3.046$ [Mangano et al., 2005] due to not instantaneous decoupling for the neutrinos
- additional LSν contributes with $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$:

$$\Delta N_{\rm eff} = \frac{\rho_s^{\rm rel}}{\rho_\nu} = \left[\frac{7}{8}\frac{\pi^2}{15}{T_\nu}^4\right]^{-1} \frac{1}{\pi^2}\int dp\, p^3 f_s(p)$$ [Acero et al., 2009]

ρ_ν energy density for one active neutrino species, $\rho_s^{\rm rel}$ energy density of LSν when relativistic,
p neutrino momentum, $f_s(p)$ momentum distribution, $T_\nu = (4/11)^{1/3}\, T_\gamma$

Non-Relativistic Sterile Neutrino: Effective Mass m_s^{eff}

$m_s \simeq 1$ eV $\rightarrow \nu_s$ is non-relativistic today ($T_\nu \propto 10^{-4}$ eV)
LSν density parameter today:

$$\omega_s = \Omega_s h^2 = \frac{\rho_s}{\rho_c} h^2 = \frac{h^2}{\rho_c}\frac{m_s}{\pi^2}\int dp\, p^2 f_s(p)$$ [Acero et al., 2009]

ρ_s energy density of non-relativistic LSν, ρ_c critical density and h reduced Hubble parameter

Alternatively:

$$m_s^{\mathrm{eff}} = 94.1\,\mathrm{eV}\,\omega_s$$

[Planck 2013 Results, XVI]

The factor $(94.1\,\mathrm{eV})$ is the same for the active neutrinos:

$$\omega_{\nu,\text{active}} = \sum_{\text{active}} m_\nu/(94.1\,\mathrm{eV})$$

If $f_s(p) = f_{\mathrm{active}}(p)$, $m_s^{\mathrm{eff}} \equiv m_s$

The momentum distribution function $f_s(p)$

$\Delta N_{\rm eff}$, $m_s^{\rm eff}$ depend on the momentum distribution function $f_s(p)$.

LSν relativistic at decoupling $\Rightarrow$ $f_s(p)$ independent of m_s.
Active neutrinos decoupled at $T_\nu \simeq 1$ MeV. Is the same for LSν?

Oscillations + sterile $\Rightarrow$ LSν decouples not later than active neutrinos.

Production mechanism?

Thermal production (TH):
temperature $T_s = \alpha T_\nu$

$$f_s(p) = \frac{1}{e^{p/T_s}+1}$$

$$\Downarrow$$

$$\Delta N_{\rm eff} = \alpha^4$$
$$\omega_s = \alpha^3\, m_s/(94.1\,{\rm eV})$$
$$\Downarrow$$
$$m_s^{\rm eff} = \alpha^3 m_s = \Delta N_{\rm eff}^{3/4} m_s$$

Non-thermal production:
[Dodelson, Widrow 1993] (DW) model

$$f_s(p) = \frac{\beta}{e^{p/T_\nu}+1}$$

$$\Downarrow$$

$$\Delta N_{\rm eff} = \beta$$
$$\omega_s = \beta\, m_s/(94.1\,{\rm eV})$$
$$\Downarrow$$
$$m_s^{\rm eff} = \beta m_s = \Delta N_{\rm eff}\, m_s$$

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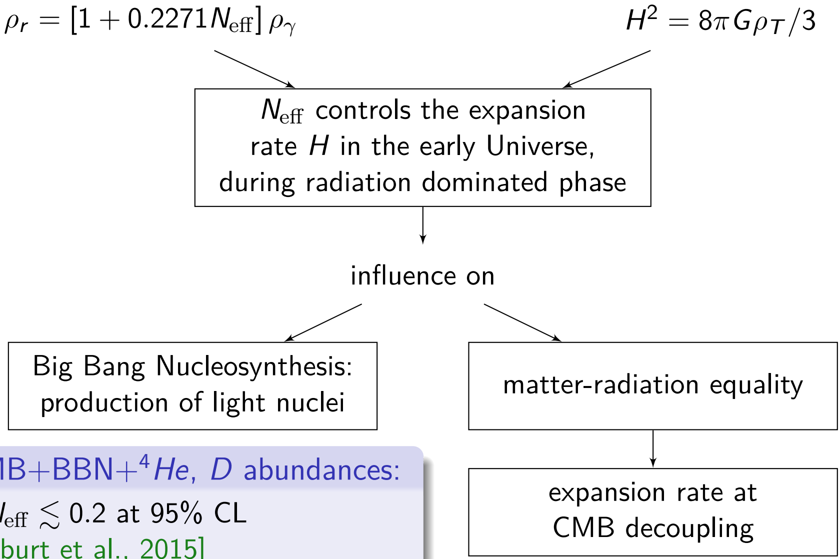
    - Tensions: CMB vs local measurements

4. Open issues

Additional Radiation in the Early Universe



$\rho_r = [1 + 0.2271 N_{\rm eff}]\, \rho_\gamma$

$H^2 = 8\pi G \rho_T / 3$

$N_{\rm eff}$ controls the expansion rate H in the early Universe, during radiation dominated phase

influence on

Big Bang Nucleosynthesis: production of light nuclei

matter-radiation equality

expansion rate at CMB decoupling

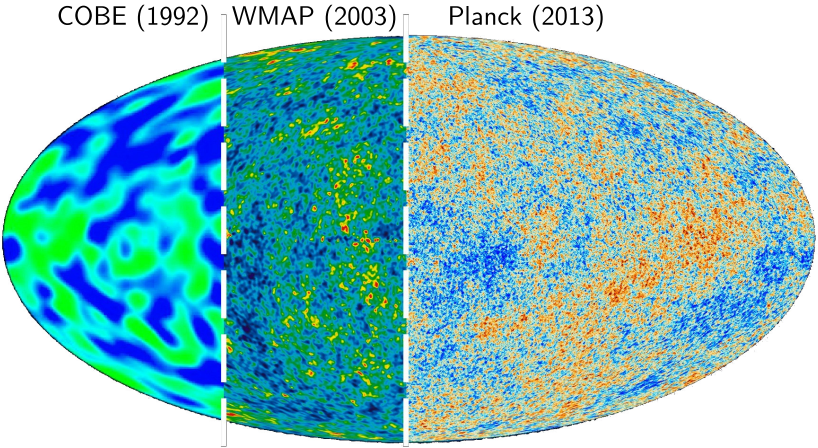
CMB+BBN+^4He, D abundances:

$\Delta N_{\rm eff} \lesssim 0.2$ at 95% CL

[Cyburt et al., 2015]

Cosmic Microwave Background (CMB)

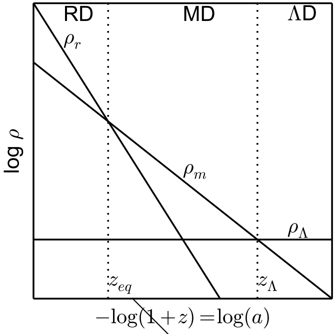
Anisotropies at the level of 10^{-5}: very high precision measurements are needed.
Improvement of the CMB experiments in 20 years:

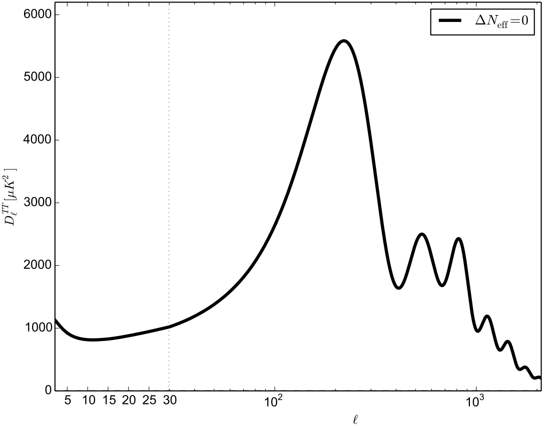


Additional Radiation: Effects on the CMB

Starting configuration:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$



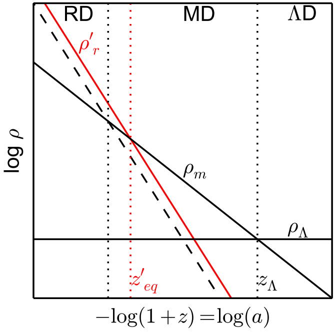


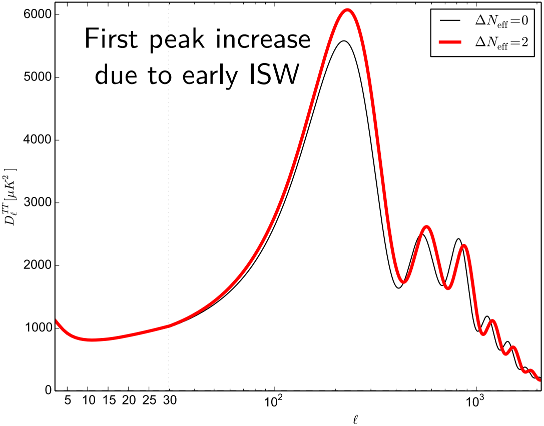
$$1 + z_{\rm eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{\omega_\gamma}\frac{1}{1 + 0.2271\,N_{\rm eff}}$$

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, all the other parameters fixed:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$



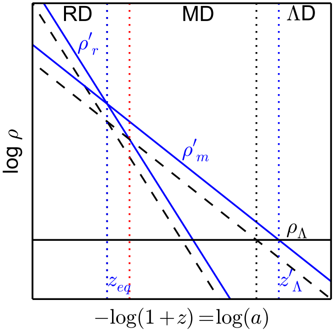


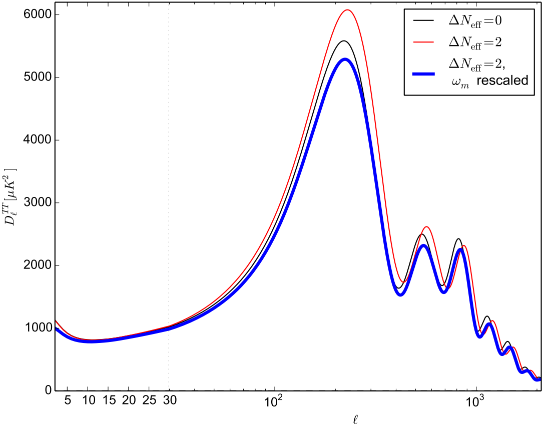
At z_{CMB}: higher $H \propto \rho_r \Rightarrow$ smaller comoving sound horizon $r_s \propto H^{-1}$
$\Rightarrow$ decrease of the angular scale of the acoustic peaks $\theta_s = r_s/D_A$
$\Rightarrow$ shift of the peaks at higher ℓ

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, plus ω_m to fix $z_{\rm eq}$:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$



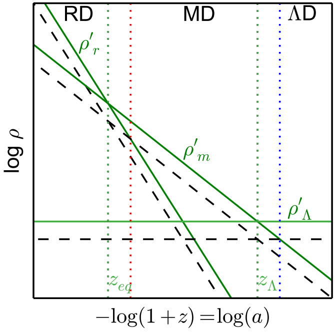


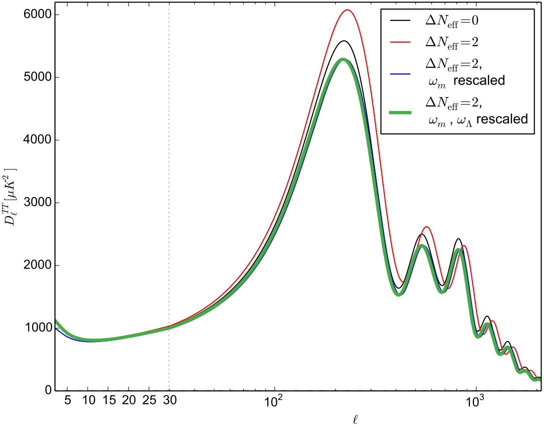
- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high-ℓ peaks ⇒ due to later z_Λ

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, plus ω_m, ω_Λ to fix $z_{\rm eq}$, z_Λ:

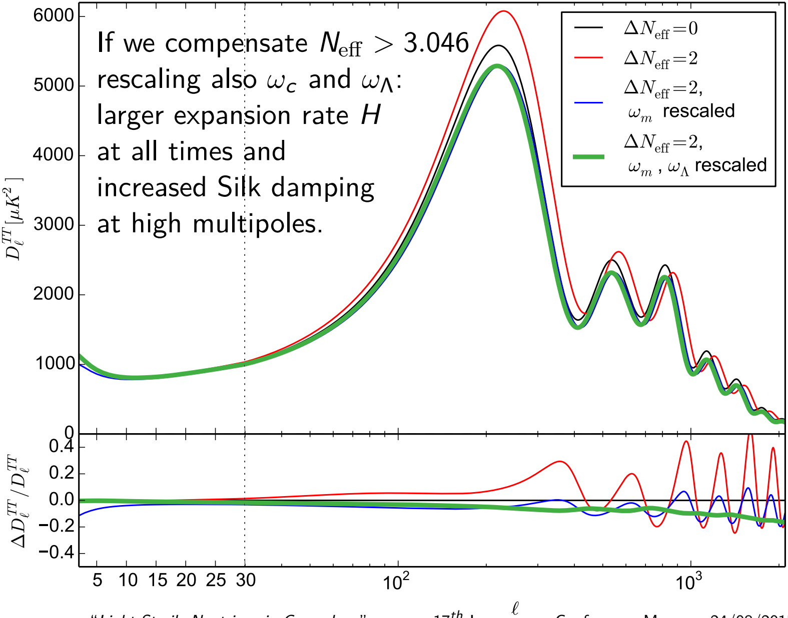
RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$





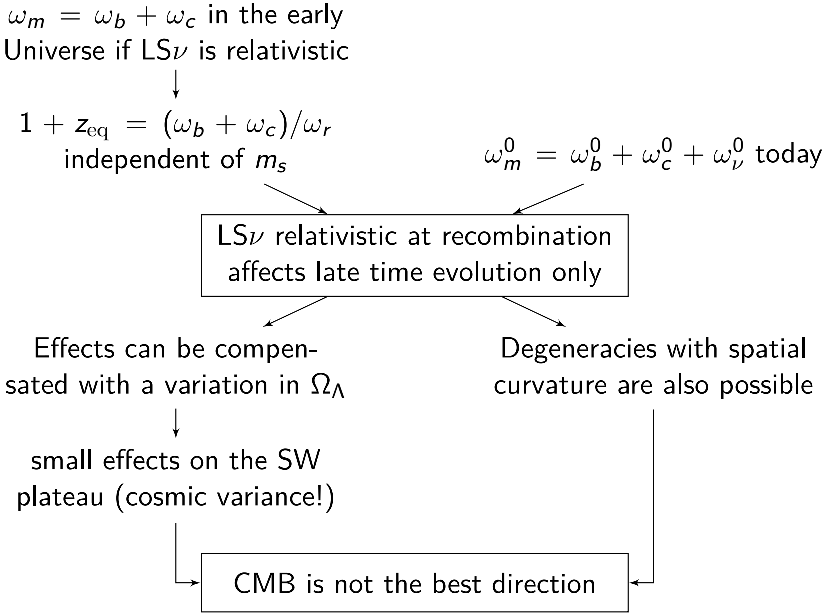
- peak positions recovered;
- slope of the Sachs-Wolfe plateau recovered;
- peak amplitude not recovered!

Additional Radiation: Effects on the CMB



If we compensate $N_{\rm eff} > 3.046$ rescaling also ω_c and ω_Λ: larger expansion rate H at all times and increased Silk damping at high multipoles.

Impact of additional non-relativistic neutrinos on the CMB



$\omega_m = \omega_b + \omega_c$ in the early Universe if LSν is relativistic

$1 + z_{\rm eq} = (\omega_b + \omega_c)/\omega_r$ independent of m_s

$\omega_m^0 = \omega_b^0 + \omega_c^0 + \omega_\nu^0$ today

LSν relativistic at recombination affects late time evolution only

Effects can be compensated with a variation in Ω_Λ

Degeneracies with spatial curvature are also possible

small effects on the SW plateau (cosmic variance!)

CMB is not the best direction

Free-streaming - I

Massive neutrino

$$\Downarrow$$

damping in the perturbations due to free-streaming length λ_{FS}

Relativistic neutrinos

$$\text{velocity } v_s \simeq c$$

$$\boxed{\lambda_{FS}/a \propto (aH)^{-1} \propto t^{1/3}\ (\mathrm{MD})}$$

Non-relativistic neutrinos

$$\langle v_s \rangle = \frac{\int p^2 dp\, f(p)\, p/m_s}{\int p^2 dp\, f(p)} \propto \frac{\Delta N_{\mathrm{eff}}}{\omega_s}$$

$$\boxed{\lambda_{FS}/a \propto (a^2 H)^{-1} \propto t^{-1/3}\ (\mathrm{MD})}$$

$\Rightarrow$ Maximum λ_{FS}/a at the time of non-relativistic transition.

$$\Downarrow$$

Corresponds to $k_{\mathrm{nr}} \simeq 0.0178\, \Omega_m^{1/2} \left(\frac{T_\nu}{T_s}\right)^{1/2} \left(\frac{m_s}{1\,\mathrm{eV}}\right)^{1/2} h\,\mathrm{Mpc}^{-1}$

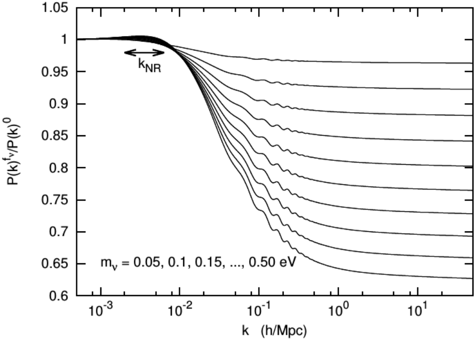
Free-streaming - II

Damping occurs for all $k \gtrsim k_{\rm nr}$

Plot: $\dfrac{P_{m_\nu>0}(k)}{P_{m_\nu=0}(k)}$

- top to bottom: $m_\nu = 0.05$ eV to $m_\nu = 0.5$ eV
- $\Delta P/P \simeq -7(8)(m_\nu/1\ {\rm eV})$

[Neutrino Cosmology, Lesgourgues et al.]
(fixed h, ω_m, ω_b, ω_Λ)



Expected constraints from future surveys:

- Planck CMB + DES: $\sigma(m_\nu) \simeq 0.04$–$0.06$ eV [Font-Ribera et al., 2014]
- Planck CMB + Euclid: $\sigma(m_\nu) \simeq 0.03$ eV [Audren et al., 2013]

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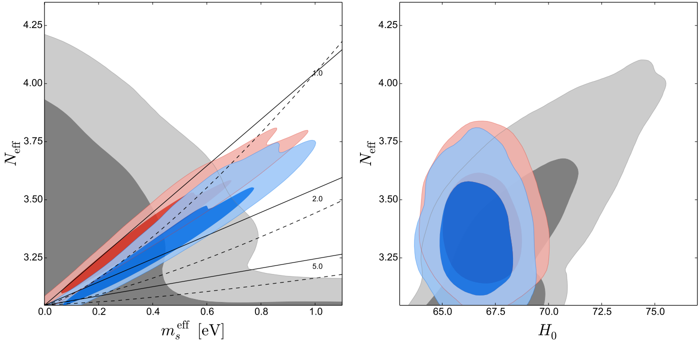
[SG et al., JHEP 1311 (2013) 211]

CMB and SBL joint constraints

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

$N_{\rm eff} \simeq 4$ (ν_s thermalized as $\nu_{\rm SM}$) disfavoured;

- (DW), (TH) models give similar results ($N_{\rm eff}$ slightly higher in (DW)).

σ_8 Tension: cluster counts, weak lensing

Cosmic shear: distortion of distant galaxy images by gravitational lensing of LSS $\Rightarrow$ 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):

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

CMB results [Planck 2013] (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):

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.764 \pm 0.025$$

Planck + WMAP pol + ACT/SPT [Planck 2013] (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*.

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

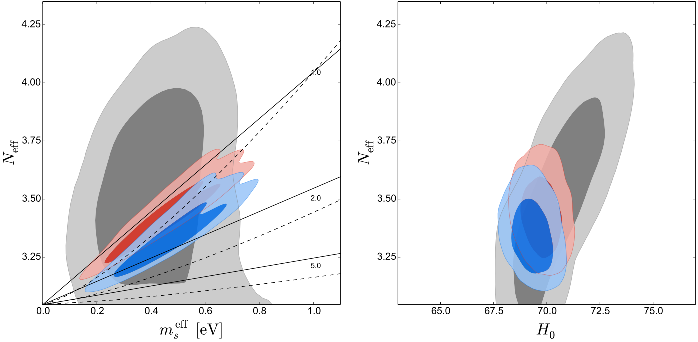
Solving σ_8 Tension with the sterile neutrino

CMB+H_0+BAO+LSS:

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

solid lines: (DW)
$m_s^{\text{eff}} = m_s \, \Delta N_{\text{eff}}$

dashed lines: (TH)
$m_s^{\text{eff}} = m_s (\Delta N_{\text{eff}})^{3/4}$



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

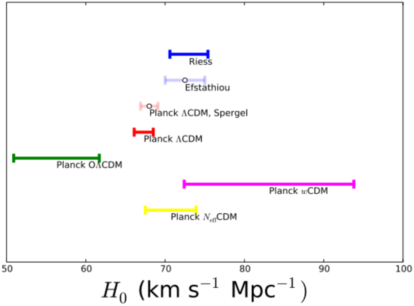
The Hubble Parameter H_0 Tension

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)

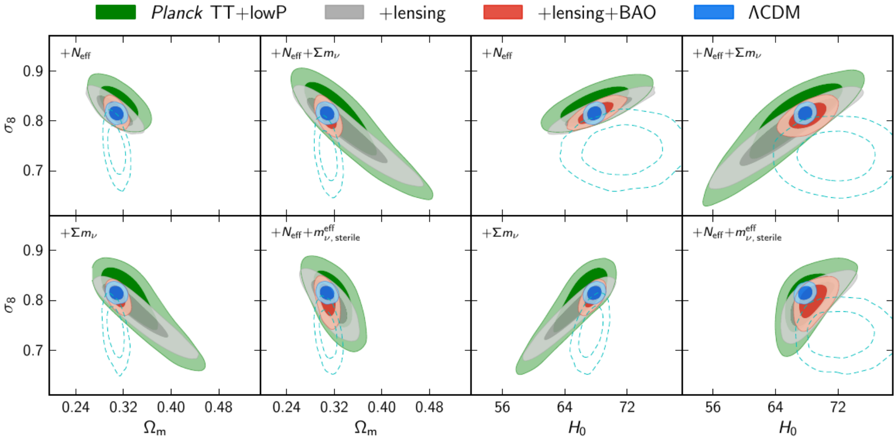
[Cuesta et al., 2014] 68% CL error bars



(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]: $H_0 = 67.27 \pm 0.66\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

Solving both σ_8 and H_0 Tension?



H_0 increases ⇒ σ_8 increases (and viceversa)!
The correlations do not help.

Incomplete Thermalization

Many probes constrain $\Delta N_{\text{eff}} < 1$. Do we need

- a mechanism to suppress oscillations and full thermalization of ν_s?
- to compensate $\Delta N_{\text{eff}} = 1$ with additional mechanisms in Cosmology?

Some ideas: (see references in [SG et al., arxiv:1507.08204])

- large lepton asymmetry [Foot et al., 1995; Mirizzi et al., 2012; many more]
- new neutrino interactions [Bento et al., 2001; Dasgupta et al., 2014; Hannestad et al., 2014; Saviano et al., 2014; many more]
- entropy production after neutrino decoupling [Ho et al., 2013]
- very low reheating temperature [Gelmini et al., 2004; Smirnov et al., 2006]
- time varying dark energy components [Giusarma et al., 2012]
- larger expansion rate at the time of ν_s production [Rehagen et al., 2014]
- freedom in the Primordial Power Spectrum (PPS) of scalar perturbations from inflation compensate damping due to $N_{\text{eff}} \neq 3.046$ [SG et al., 2015]

Conclusions

- Short BaseLine (SBL) oscillations suggest the presence of an additional neutrino, sterile, with $m_s \simeq m_4 \simeq 1$ eV;
- ν_s can have measurable effects on cosmological observables;
- CMB measurements give strong constraints on ν_s properties;
- tension between CMB observations and local observations;
  - unaccounted systematics?
  - new physics?
- sterile neutrinos suggested by SBL oscillation anomalies can help solving the tensions,
  - but problems in producing them with small ΔN_{eff} (preferred by cosmology);
- further investigation and/or new ideas needed!

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Thank you for the attention