



New Developments in Cosmology



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1 Cosmology

- Cosmic Microwave Background (CMB)
- Tensions between local and CMB measurements

2 Light Sterile Neutrino

- Neutrino Oscillation Anomalies
- Parameterization in Cosmology
- Cosmological Effects of Additional Neutrinos
- Cosmological Constraints on the Light Sterile Neutrino

3 Inflationary Freedom

- The Inflationary Paradigm
- Beyond Power-Law Primordial Power Spectrum
- Constraints on Light Sterile Neutrino Properties
- Constraints on the Primordial Power Spectrum

4 Coupled Dark Energy Scenario

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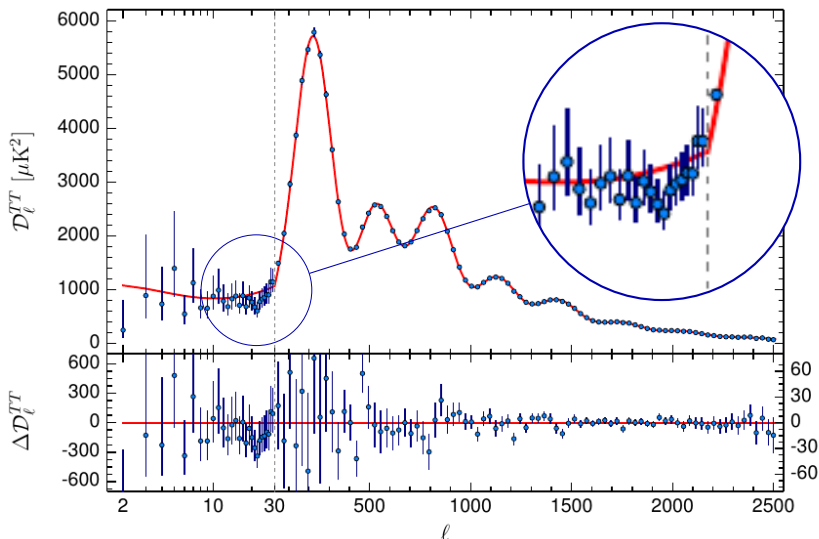
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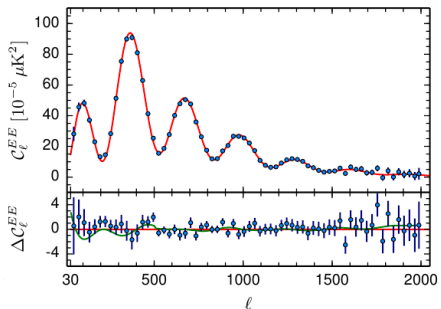
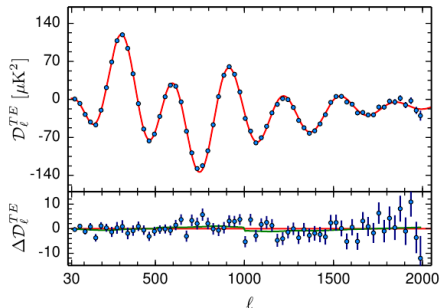
Planck DR2 results - Temperature

Planck DR2 temperature auto-correlation power spectrum:



Planck DR2 results - Polarization

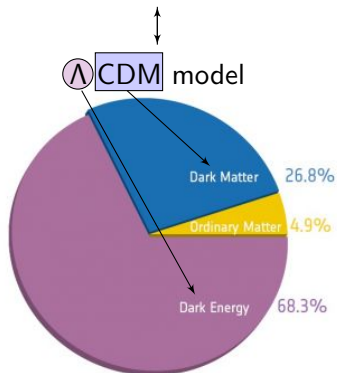
- TE cross-correlation and EE auto-correlation measured with high precision;
- Λ CDM explains very well the data;
- Note: in the plots, the red curve is the prediction based on the TT only best-fit for Λ CDM model \rightarrow very good consistency between temperature and polarization spectra.



Cosmological parameters

General Relativity + Homogeneity and isotropy

Cosmological evolution



[Planck collaboration, 2015]

Λ CDM model described by 6 base parameters:

$\omega_b = \Omega_b h^2$ baryon density today;

$\omega_c = \Omega_c h^2$ CDM density today;

τ optical depth to reionization;

θ angular scale of acoustic peaks;

n_s tilt and

A_s amplitude of the power spectrum of initial curvature perturbations.

Other quantities can be studied:

H_0 Hubble parameter today;

σ_8 mean matter fluctuations at small scales;

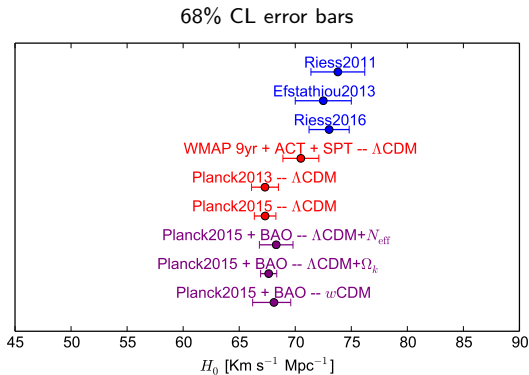
...

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,
but systematics?)

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



Using HST Cepheids:

[Efstathiou 2013] $H_0 = 72.5 \pm 2.5 \text{ Km s}^{-1} \text{ Mpc}^{-1}$

[Riess et al., 2016] $H_0 = 73.02 \pm 1.79 \text{ Km s}^{-1} \text{ Mpc}^{-1}$

(most recent)

(Λ CDM model - 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: Matter perturbations at small scales

Assuming Λ CDM 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):

$$\sigma_8(\Omega_m/0.27)^{0.46 \pm 0.02} = 0.774 \pm 0.04$$

CMB results

[Planck 2013] (68% CL):

$$2\sigma \text{ discrepancy!} = 0.89 \pm 0.03$$

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):

$$3\sigma \text{ discrepancy!} = 0.87 \pm 0.02$$

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

Alert!

- is the nonlinear evolution well known?
see e.g. [Planck 2015 Results, papers XIII and XIV]
- are we taking into account all the astrophysical systematics?
[Joudaki et al., 2016] [Kitching et al., 2016]

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Neutrino Oscillations

Analogous to CKM mixing for quarks: [Pontecorvo, 1958]
[Maki, Nakagawa, Sakata, 1962]

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

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

Current knowledge of the 3 active ν mixing: [PDG - Olive et al. (2015)]

$\Delta m_{ij}^2 = m_j^2 - m_i^2$, θ_{ij} mixing angles

NO: Normal Ordering, $m_1 < m_2 < m_3$

IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned} \Delta m_{SOL}^2 &= (7.53 \pm 0.18) \cdot 10^{-5} \text{ eV}^2 &&= \Delta m_{21}^2 \\ \Delta m_{ATM}^2 &= (2.44 \pm 0.06) \cdot 10^{-3} \text{ eV}^2 \text{ (NO)} &&= |\Delta m_{32}^2| \simeq |\Delta m_{31}^2| \\ &= (2.49 \pm 0.06) \cdot 10^{-3} \text{ eV}^2 \text{ (IO)} \end{aligned}$$

$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$

$$\sin^2(2\theta_{23}) = 0.999_{-0.018}^{+0.001} \text{ (NO)} - 1.000_{-0.017}^{+0.000} \text{ (IO)}$$

$$\sin^2(2\theta_{13}) = 0.085 \pm 0.005$$

CP violating phase δ_{CP} still unknown. Hint: $\delta_{CP} = -\pi/2$? [T2K Collaboration, 2015]

Short Baseline (SBL) anomaly

Problem: **anomalies** in SBL experiments \Rightarrow $\left\{ \begin{array}{l} \text{errors in flux calculations?} \\ \text{deviations from 3-}\nu \text{ description?} \end{array} \right.$

A short review:

LSND search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

Reactor re-evaluation of the expected anti-neutrino flux \Rightarrow disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]

Gallium calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

MiniBooNE (**inconclusive**) search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 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]

Possible explanation:

Additional squared mass difference

$$\Delta m_{\text{SBL}}^2 \simeq 1 \text{ eV}^2$$

3+1 Neutrino Model

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



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



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

We must update our mixing paradigm:

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

ν_s is mainly ν_4 :

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

Active ν :

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

Sterile ν :

$$0.82 \leq m_s^2 / \text{eV}^2 \leq 2.19 \quad (3\sigma)$$

[Giunti et al, 2013]

Relativistic Sterile Neutrino: Effective Number N_{eff}

Radiation energy density ρ_r in the early Universe:

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

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

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

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

ρ_ν energy density for one active neutrino species, ρ_s^{rel} energy density of $LS\nu$ 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}

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

LS ν density parameter today:

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

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

Alternatively:

$$m_s^{\text{eff}} = 94.1 \text{ eV } \omega_s$$

[Planck 2013 Results, XVI]

The factor (94.1 eV) is the same for the active neutrinos:

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

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

The momentum distribution function $f_s(p)$

ΔN_{eff} , m_s^{eff} depend on the momentum distribution function $f_s(p)$.

LS ν relativistic at decoupling $\Rightarrow f_s(p)$ independent of m_s .

Active neutrinos decoupled at $T_\nu \simeq 1$ MeV. Is the same for LS ν ?

Oscillations + sterile \Rightarrow LS ν 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

$$\Delta N_{\text{eff}} = \alpha^4$$

$$\omega_s = \alpha^3 m_s / (94.1 \text{ eV})$$

\Downarrow

$$m_s^{\text{eff}} = \alpha^3 m_s = \Delta N_{\text{eff}}^{3/4} m_s$$

Non-thermal production:

[Dodelson, Widrow 1993] (DW) model

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

\Downarrow

$$\Delta N_{\text{eff}} = \beta$$

$$\omega_s = \beta m_s / (94.1 \text{ eV})$$

\Downarrow

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

Additional Radiation in the Early Universe

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

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

N_{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:

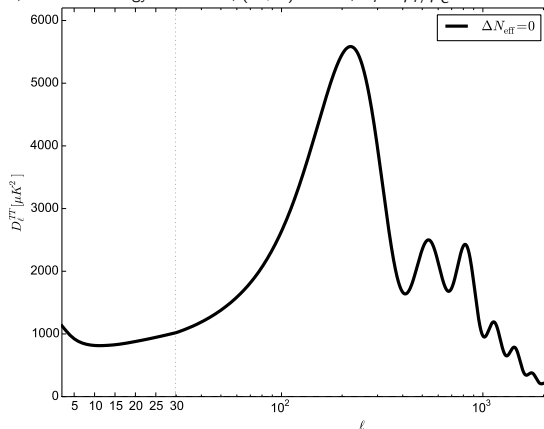
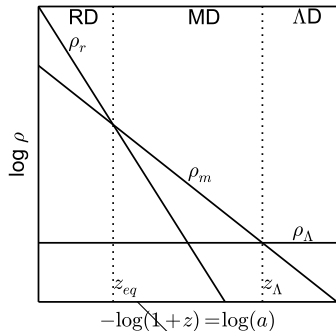
$\Delta N_{\text{eff}} \lesssim 0.2$ at 95% CL

[Cyburt et al., 2015]

Additional Radiation: Effects on the CMB

Starting configuration:

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

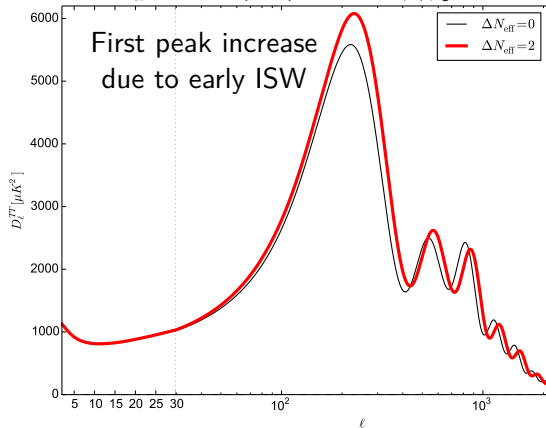
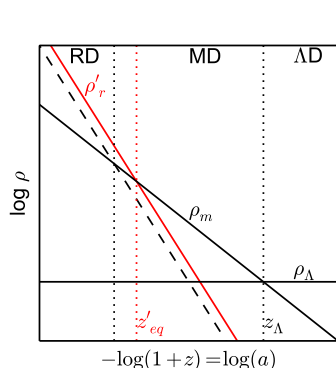


$$1 + z_{eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.2271 N_{\text{eff}}}$$

Additional Radiation: Effects on the CMB

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

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

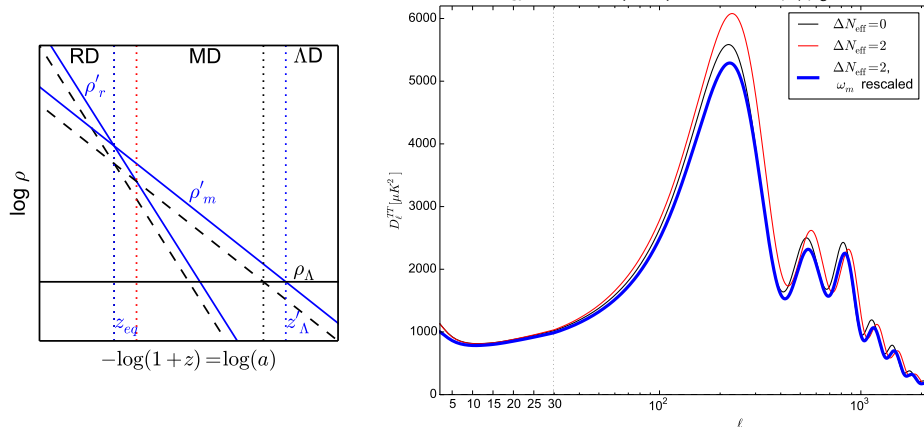


At z_{CMB} : higher $H \propto \rho_r \Rightarrow$ smaller comoving sound horizon $r_s \propto H^{-1}$
 \Rightarrow decrease of the angular scale of the acoustic peaks $\theta_s = r_s / D_A$
 \Rightarrow shift of the peaks at higher ℓ

Additional Radiation: Effects on the CMB

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

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

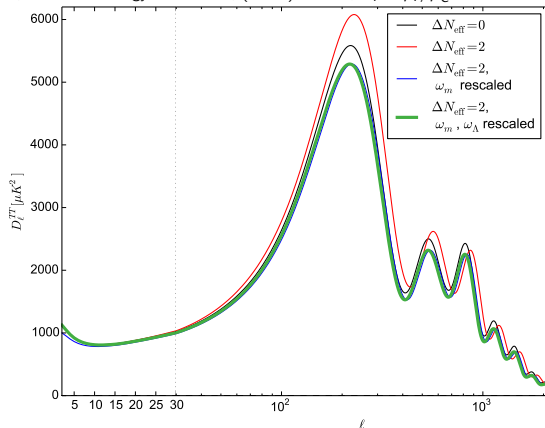
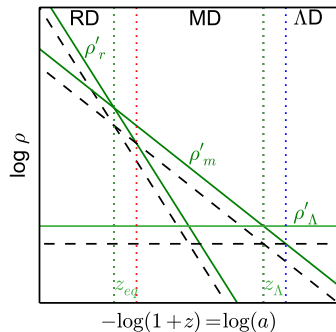


- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high- ℓ peaks \Rightarrow due to later z_Λ

Additional Radiation: Effects on the CMB

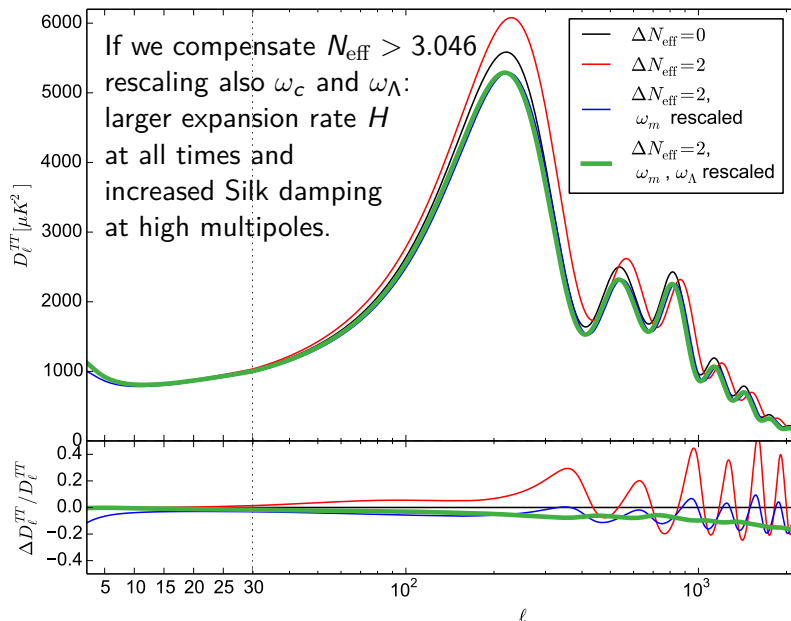
If we increase N_{eff} , plus ω_m, ω_Λ to fix z_{eq}, z_Λ :

RD: Radiation Dominated, MD: Matter Dominated, Λ D: 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



Free-streaming - I

Massive neutrino



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

Relativistic neutrinos

velocity $v_s \simeq c$

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

Non-relativistic neutrinos

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

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

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



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

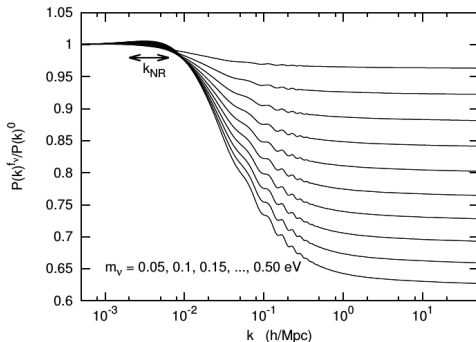
Free-streaming - II

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

["Neutrino Cosmology", Lesgourgues et al.]
(fixed $h, \omega_m, \omega_b, \omega_\Lambda$)

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

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



Expected constraints from future surveys:

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

CMB and SBL joint constraints

CMB:

(no SBL)

+SBL (DW)

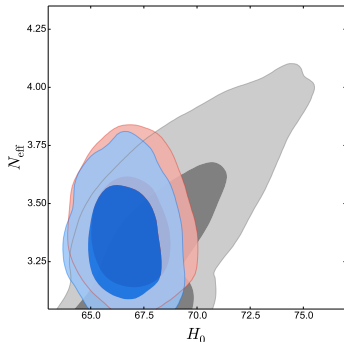
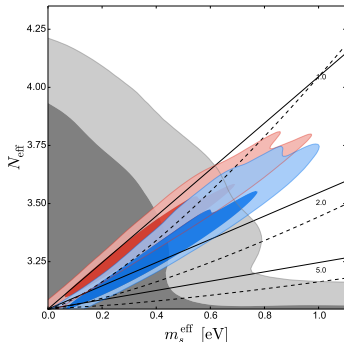
+SBL (TH)

solid lines: (DW)

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

dashed lines: (TH)

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



- ν_s as Warm Dark Matter (WDM): $N_{\text{eff}} \simeq 3.046$, large m_s^{eff} (large m_s);
- SBL prior: $m_s \simeq 1.2$ eV, but

$N_{\text{eff}} \simeq 4$ ($\Rightarrow \nu_s$ thermalized) disfavoured;
- (DW), (TH) models give similar results (N_{eff} slightly higher in (DW)).

Solving σ_8 Tension with the sterile neutrinoCMB+ H_0 +BAO+LSS:

(no SBL)

+SBL (DW)

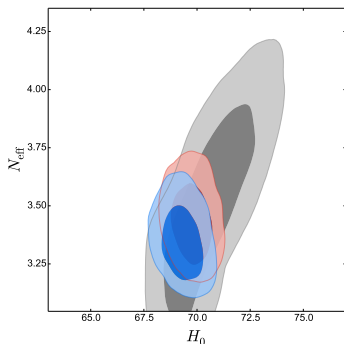
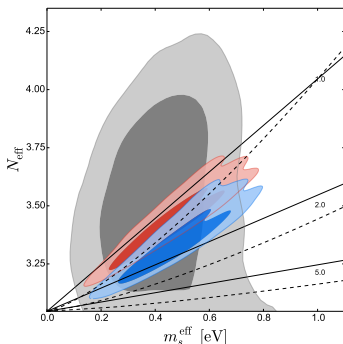
+SBL (TH)

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 for non-zero $m_s^{\text{eff}} \rightarrow$ non-zero m_s : smaller σ_8 from LSS as a consequence of ν_s 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

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

mixing parameters from SBL data $\implies \Delta N_{\text{eff}} \simeq 1$

[Hannestad et al., 2012] [Mirizzi et al., 2012]

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:

- 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]
- *new interaction between the sterile neutrino and a new massless pseudoscalar* [SG et al., in preparation, 2016]

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Primordial Power Spectrum from 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 varying 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.

⇒ small scale dependence of the Primordial Power Spectrum (PPS) of scalar perturbations:

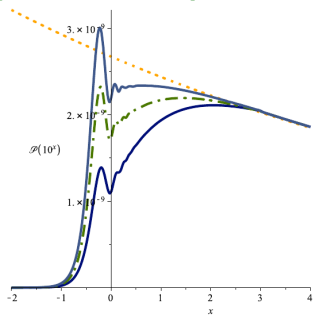
$$(n_s - 1) \equiv \frac{d \ln P_s(k)}{d \ln k} = 2 \frac{V''}{V} - 3 \left(\frac{V'}{V} \right)^2,$$

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

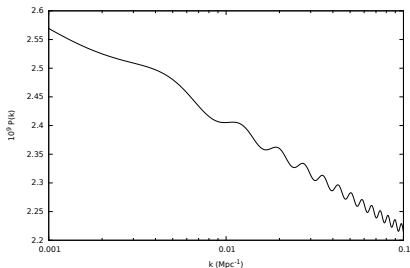
Is n_s constant?
Can the PPS deviate from a Power-Law (PL)?

Beyond Power-Law PPS: Theory

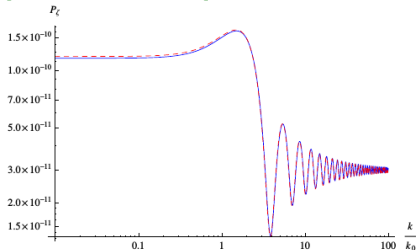
[Sagnotti et al, 2014]



[Mukhanov, 2013]



[Romano et al., 2014]

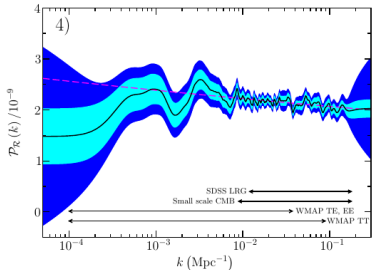


Given an inflationary model one gets one Primordial Power Spectrum (PPS), more or less complicated

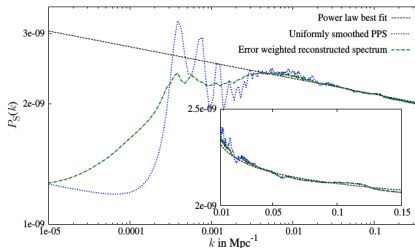
Much more models were developed: see e.g. [[“Encyclopædia Inflationaris”, Martin et al., 2014](#)]

Beyond Power-Law PPS: Reconstructions

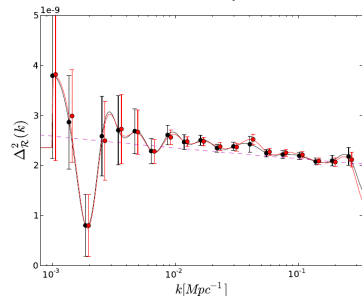
[Hunt et al., 2014] (WMAP data)



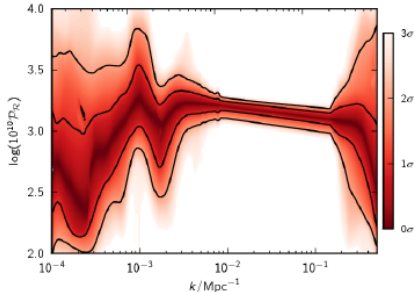
[Hazra et al, 2014] (Planck 2013 data)



[de Putter et al, 2014] (Planck 2013)



[Planck Collaboration, 2015]



PCHIP Parametrization

Fix the Primordial Power Spectrum (PPS) form leads to possible bias:

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

Proposal: fix a series of nodes k_1, \dots, k_{12} and use an interpolating function among them,

$$P_s(k) = P_0 \times f(k; P_{s,1}, \dots, P_{s,12}) \quad \text{with } P_0 = 2.2 \times 10^{-9}, P_{s,j} = P_s(k_j)$$

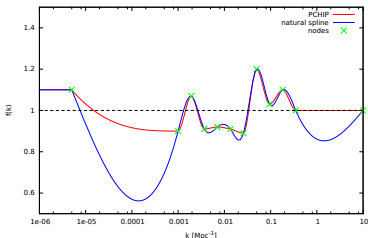
In our case we use:

PCHIP [Fritsch et al., 1980]

“piecewise cubic Hermite interpolating polynomial”

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

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



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:
 - ▶ 1st derivative in the node fixed using the secants between consequent nodes;
 - ▶ if the monotonicity changes, the node is a local extremum;
- 2nd derivative not continue in the nodes.

Light Sterile Neutrino Results - I

Standard: Power-Law (PL)

Λ CDM(PL PPS) + ν_s model

$$P_s(k) = A_s(k/k_{\text{pivot}})^{n_s-1}$$

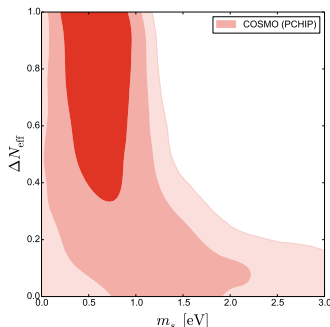
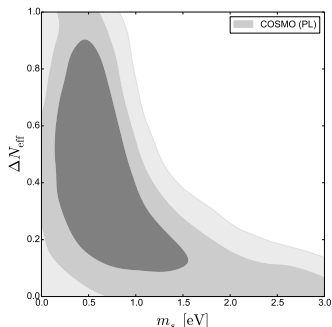
PPS

free form: nodes $P_{s,1}, \dots, P_{s,12}$,
interpolate with PCHIP function

Λ CDM(PCHIP PPS) + ν_s model

$$P_s(k) = P_0 \times f(k; P_{s,1}, \dots, P_{s,12})$$

Results for the **Thermal sterile neutrino**, mass m_s , no SBL prior on m_s :



- higher ΔN_{eff} admitted;
- change on m_s constraints due to ΔN_{eff} change;
- fully thermalized sterile neutrino preferred.

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

Light Sterile Neutrino Results - II

Standard: Power-Law (PL)

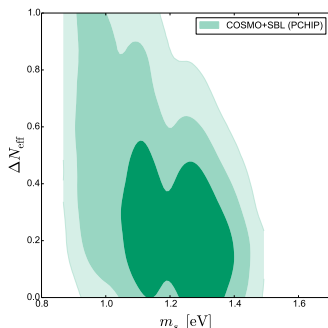
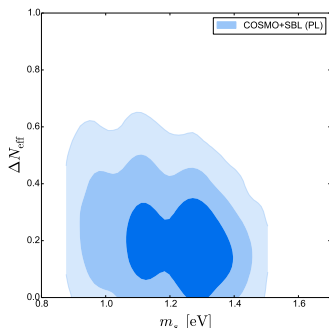
 Λ CDM(PL PPS) + ν_s model

$$P_s(k) = A_s(k/k_{\text{pivot}})^{n_s-1}$$

PPS

free form: nodes $P_{s,1}, \dots, P_{s,12}$,
interpolate with PCHIP function Λ CDM(PCHIP PPS) + ν_s model

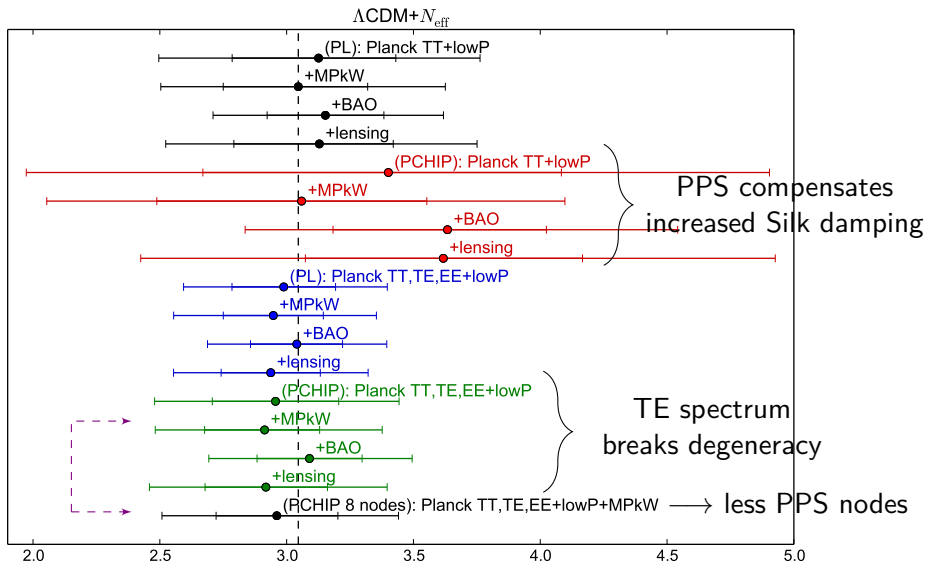
$$P_s(k) = P_0 \times f(k; P_{s,1}, \dots, P_{s,12})$$

Results for the Thermal sterile neutrino, mass m_s , with SBL prior on m_s :

- higher ΔN_{eff} admitted;
- no change on m_s constraints;
- fully thermalized sterile neutrino admitted (inside 2σ region).

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

Degeneracy between PPS and Radiation Content



Planck 2015 CMB data

MPkW: matter power spectrum (WiggleZ) – BAO: BOSS DR11 + SDSS MGS + 6dF – lensing: Planck 2015 trispectrum

S. Gariazzo

"New Developments in Cosmology"

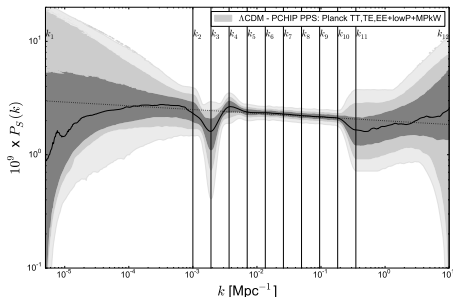
IFIC - Valencia, 27/04/2016

30

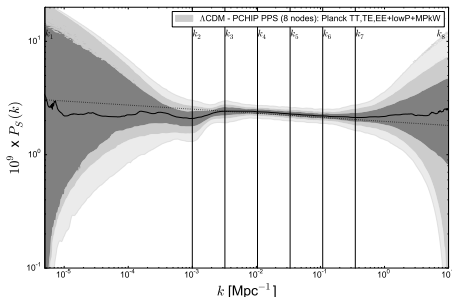
PPS Results

 Λ CDM(PCHIP PPS) – 12 nodes

CMB(Planck15 TT,TE,EE+lowP) + MPkW

 Λ CDM(PCHIP PPS) – 8 nodes

CMB(Planck15 TT,TE,EE+lowP) + MPkW



Different cosmological models, similar results:

- CMB constraints for $1 \times 10^{-4} \text{ Mpc}^{-1} (\ell = 2) \leq k \leq 0.3 \text{ Mpc}^{-1} (\ell \simeq 2500)$;
- power-law is a good approximation in the range $7 \times 10^{-3} \text{ Mpc}^{-1} \leq k \leq 0.2 \text{ Mpc}^{-1}$;
- features at $k = 2 \times 10^{-3} \text{ Mpc}^{-1} (\rightarrow \ell \simeq 25)$ and $k = 3.5 \times 10^{-3} \text{ Mpc}^{-1} (\rightarrow \ell \simeq 40)$ visible only with adequately positioned nodes.

1 Cosmology

- Cosmic Microwave Background (CMB)
- Tensions between local and CMB measurements

2 Light Sterile Neutrino

- Neutrino Oscillation Anomalies
- Parameterization in Cosmology
- Cosmological Effects of Additional Neutrinos
- Cosmological Constraints on the Light Sterile Neutrino

3 Inflationary Freedom

- The Inflationary Paradigm
- Beyond Power-Law Primordial Power Spectrum
- Constraints on Light Sterile Neutrino Properties
- Constraints on the Primordial Power Spectrum

4 Coupled Dark Energy Scenario

Model

DE–DM nature
as particles?non-gravitational
interactions?not with
ordinary
matter!

new DM–DE coupling?

stress-energy tensor conservation:

$$\begin{aligned}\nabla_{\mu} T_{\text{DM}}^{\mu\nu} &= Q u_{\text{DM}}^{\nu}/a \\ \nabla_{\mu} T_{\text{DE}}^{\mu\nu} &= -Q u_{\text{DM}}^{\nu}/a\end{aligned}$$

energy conservation:

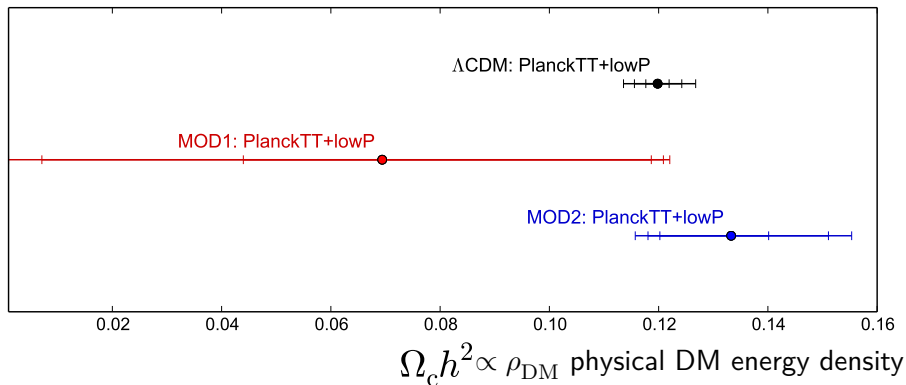
$$\begin{aligned}\dot{\rho}_{\text{DM}} + 3\mathcal{H}\rho_{\text{DM}} &= +Q \\ \dot{\rho}_{\Lambda} + 3\mathcal{H}(1 + w_{\Lambda})\rho_{\Lambda} &= -Q\end{aligned}$$

Coupling parametrized through Q Our choice: $Q = \xi\mathcal{H}\rho_{\Lambda}$
 $\xi < 0, w_{\Lambda} > -1$
MOD1: DM decays into DE

or

 $\xi > 0, w_{\Lambda} < -1$
MOD2: DE decays into DM

Results - I



● MOD1

DM \rightarrow DE

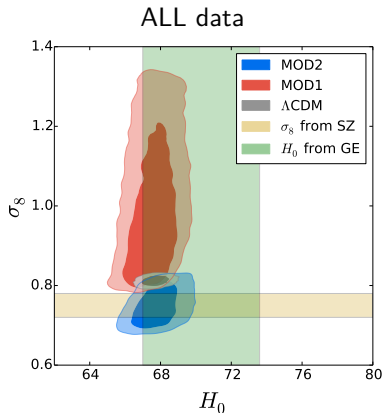
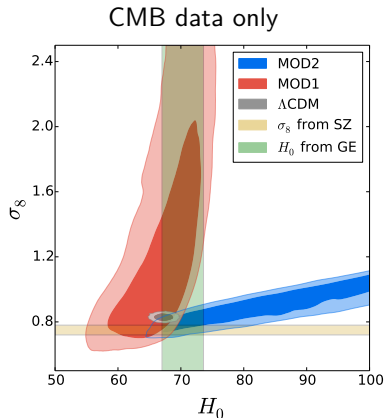
more DM in the early Universe
less DM today

● MOD2

DE \rightarrow DM

less DM in the early Universe
more DM today

As expected...

Results - II - H_0 and σ_8 tensions

more DM in the early Universe \implies stronger nonlinear evolution in **MOD1**

$H^2 \propto \rho_\Lambda \propto a^{-3(w_\Lambda+1)-\xi} \implies$ higher H_0 in **MOD2**

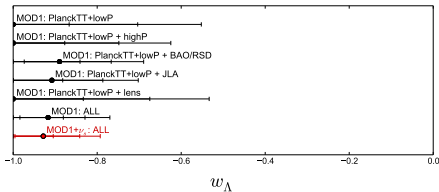
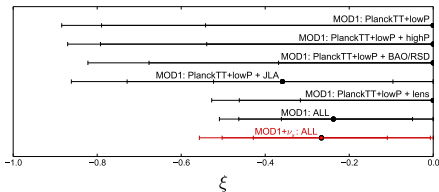
MOD2 is better for reconciling CMB and local determinations

CMB=Planck TT+low- ℓ polarization

ALL=CMB + high- ℓ polarization + BAO/RSD (BOSS DR11, SDSS MGS, 6dF) + Supernovae (JLA) + Planck lensing trispectrum

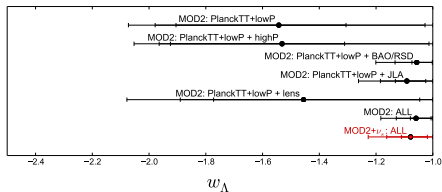
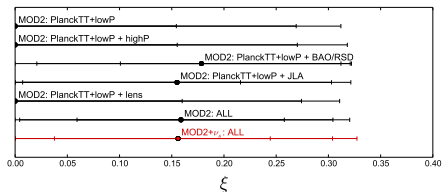
Results - III - ξ and w_Λ

MOD1



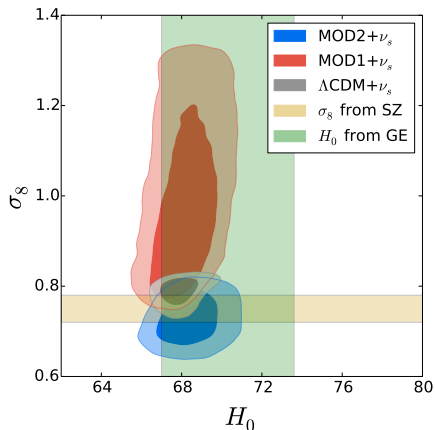
- JLA $\rightarrow \xi \neq 0?$
- BAO/RSD $\rightarrow w_\Lambda \neq -1?$

MOD2

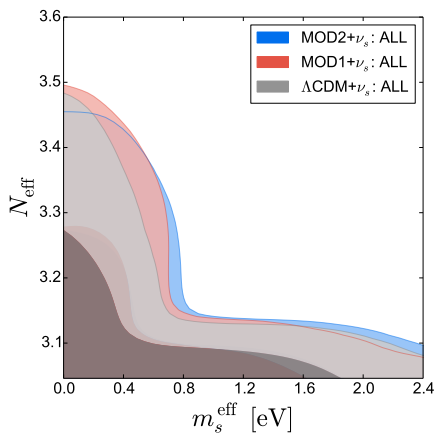


- CMB \rightarrow poor constraints on w_Λ
- BAO/RSD, JLA \rightarrow preference for less DM today, $w_\Lambda \simeq -1$

red points: CDE + LS ν models

Results - IV - What about $LS\nu$?

No significant variations for the 2D contours in the $\sigma_8 - H_0$ plane



CDE models does not affect the $LS\nu$ bounds!

Upper limits for m_s^{eff} , $N_{\text{eff}} \lesssim 3.5 \Rightarrow$ thermalized $LS\nu$ is still disfavoured

Conclusions

- Universe evolution explained well by Λ CDM model
 - ▶ cosmological constraints on standard particles (neutrinos) ✓
 - ▶ additional particles ?
 - ▶ tensions between cosmological and local measurements (H_0 , σ_8) ✗
 - ★ unaccounted systematics or new physics ?
- ν oscillations anomalies at Short-Baseline distances
 - ▶ light ($m_s \simeq 1$ eV) sterile neutrino (LS ν) ?
 - ▶ LS ν can reduce H_0 and σ_8 tensions ✓
 - ▶ cosmological bounds disfavor a thermalized, $m_s \simeq 1$ eV neutrino ✗
 - ★ new mechanisms suppress active-sterile oscillations in the early Universe ?
 - ★ new mechanisms compensate LS ν effects in cosmology ?
 - ▶ if $\Delta N_{\text{eff}} < 1$, the LS ν is allowed ✓
- CMB temperature spectrum at low- ℓ : inflationary freedom ?
 - ▶ primordial power spectrum can compensate LS ν effects in cosmology ✓
 - ▶ not if CMB polarization is included! ✗
- Coupling between Dark Matter (DM) and Dark Energy (DE) ?
 - ▶ can reduce H_0 and σ_8 tensions (DE \rightarrow DM) ✓
 - ▶ LS ν bounds unchanged ✗

Thank you for the attention