New Developments in Cosmology

PhD Defense

Stefano Gariazzo

University of Torino, INFN of Torino

`gariazzo@to.infn.it`
`http://personalpages.to.infn.it/~gariazzo/`

Supervisors:
C. Giunti
N. Fornengo

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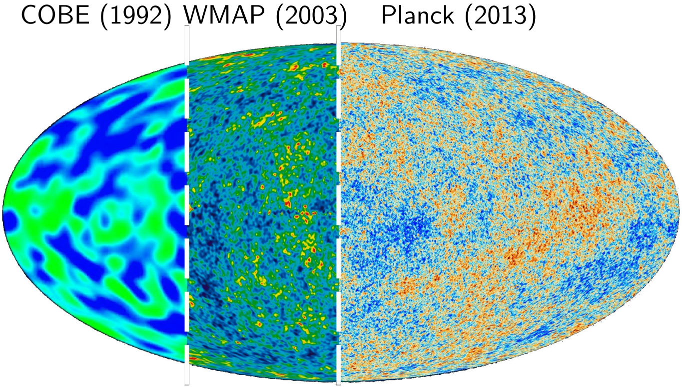
Cosmic Microwave Background (CMB)

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.

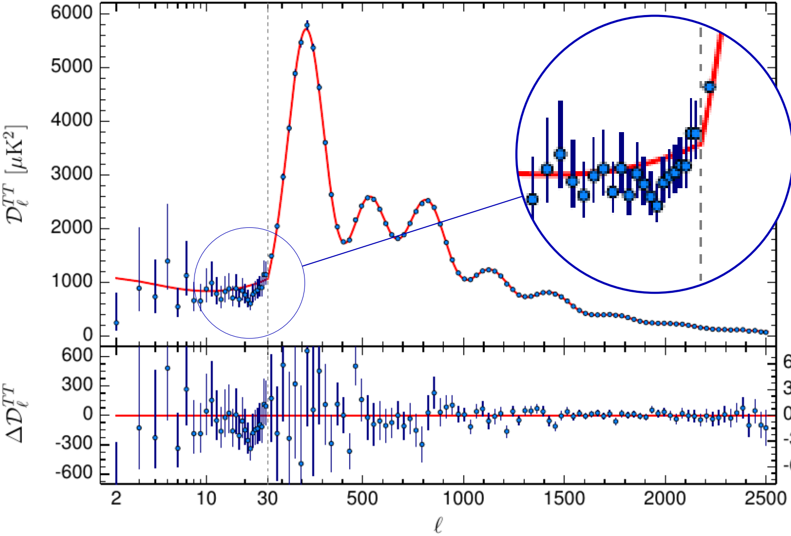
Anisotropies at the level of 10^{-5}: very high precision measurements are needed.
Improvement of the CMB experiments in 20 years:



[Planck Collaboration, 2015]

Planck DR2 results - Temperature

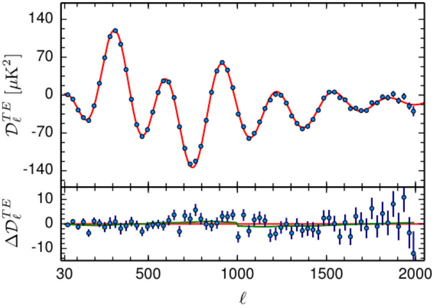
Planck DR2 temperature auto-correlation power spectrum:

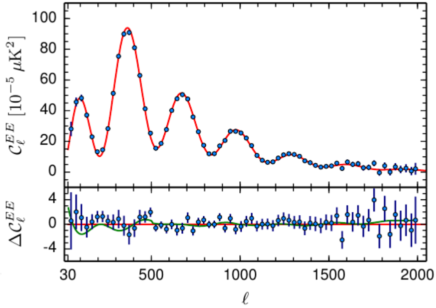


[Planck Collaboration, 2015]

Planck DR2 results - Polarization

- 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.

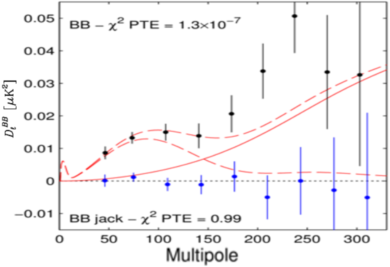




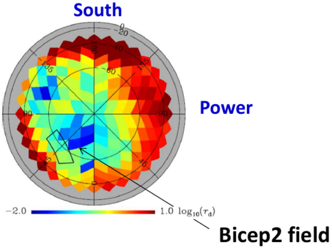
Tensor modes: current status

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

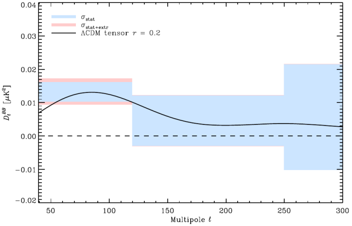
March 2014: $r = A_t(k_\star)/A_s(k_\star) = 0.2^{+0.07}_{-0.05}$



[Planck Intermediate Results XXX, 2014]



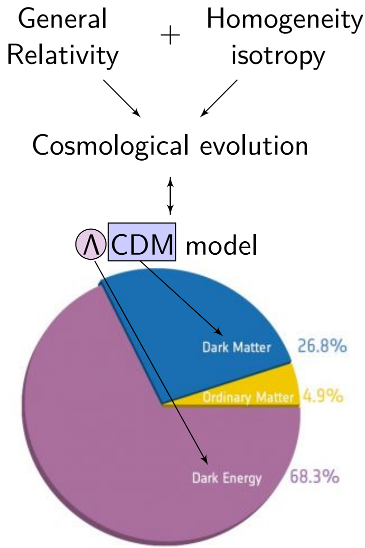
Estimated dust emission:



[BICEP2/Keck and Planck Collaborations, 2015]

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

Cosmological parameters


General Relativity + Homogeneity isotropy

Cosmological evolution

ΛCDM model

[Planck collaboration, 2015]

ΛCDM 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;
- ...

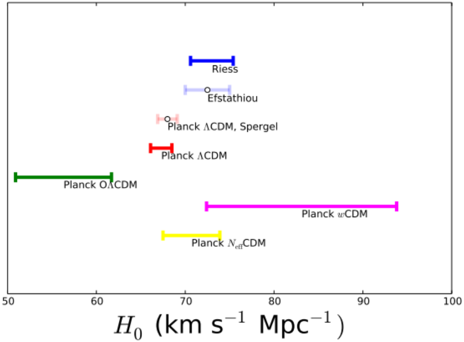
Tension I: Hubble parameter

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)

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



Using HST Cepheids, different calibrations:
[Riess et al., 2011] $H_0 = 73.8 \pm 2.4\,$Km s^{-1} Mpc^{-1}
(SNe Ia calibrated distance)
[Efstathiou 2013] $H_0 = 72.5 \pm 2.5\,$Km s^{-1} Mpc^{-1}
(distance calibrated with several methods, combined)

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

Tension II: Cosmic Shear measurements

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):

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

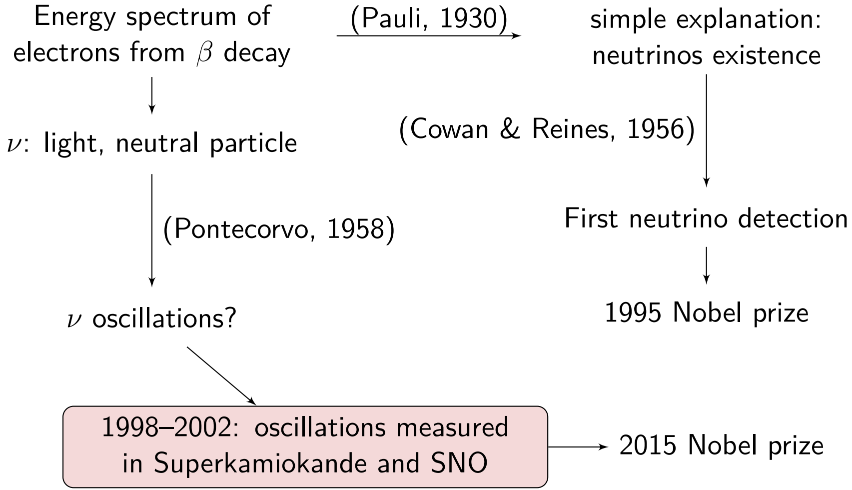
Planck + WMAP pol + ACT/SPT
[Planck 2013] (68% CL):

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

3σ discrepancy!

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

Brief Neutrino Hystory



Energy spectrum of electrons from β decay

(Pauli, 1930)

simple explanation: neutrinos existence

ν: light, neutral particle

(Cowan & Reines, 1956)

(Pontecorvo, 1958)

First neutrino detection

ν oscillations?

1995 Nobel prize

1998–2002: oscillations measured in Superkamiokande and SNO

2015 Nobel prize

Oscillations $\Longrightarrow$ massive neutrinos!

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)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

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

$$\begin{aligned}
\sin^2(2\theta_{12}) &= 0.846 \pm 0.021 \\
\sin^2(2\theta_{23}) &= 0.999^{+0.001}_{-0.018} (\mathrm{NO}) - 1.000^{+0.000}_{-0.017} (\mathrm{IO}) \\
\sin^2(2\theta_{13}) &= 0.085 \pm 0.005
\end{aligned}$$

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

[SG et al., JPG 43 (2016) 033001]

Short Baseline (SBL) anomaly

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

A short review:

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]
Reactor	re-evaluation of the expected anti-neutrino flux ⇒ 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 $\nu_\mu \to \nu_e$ 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]

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:

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

ν_s is mainly ν_4:

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

Active ν:

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

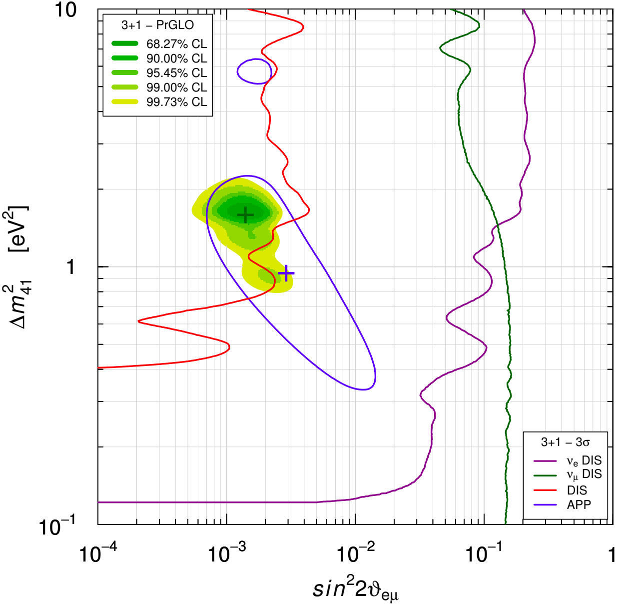
Sterile ν:

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

[Giunti et al, 2013]

[SG et al., JPG 43 (2016) 033001]

Appearence–Disappearance Tension



SBL anomalies from

APPearance

measurements

+

DISappearance

measurements

⇓

APP–DIS tension?

DIS bound
excludes part
of the APP
allowed region

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

Radiation energy density ρ_r in the early Universe:

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

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 $m_s^{\rm eff}$

$m_s \simeq 1$ 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:

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

[Planck 2013 Results, XVI]

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

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

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

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

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

$$\Downarrow$$

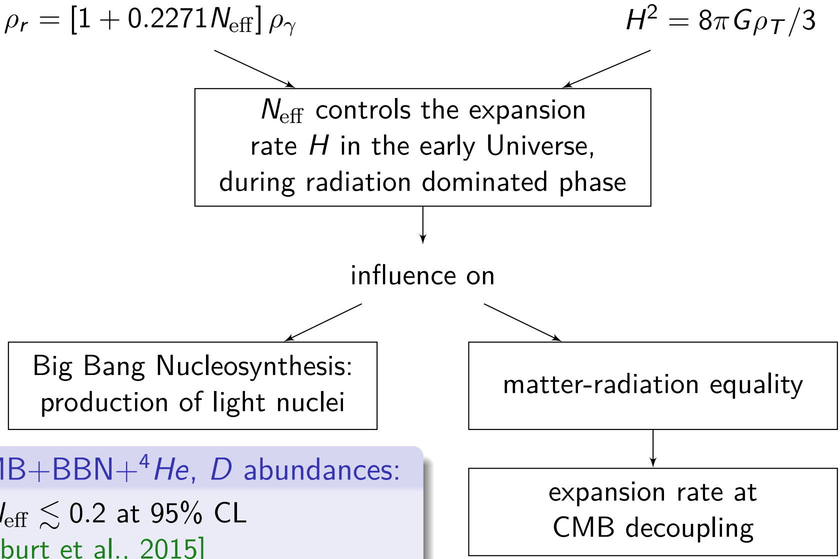
$$\Delta N_{\rm eff} = \beta$$

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

$$\Downarrow$$

$$m_s^{\rm eff} = \beta m_s = \Delta N_{\rm eff}\, m_s$$

Additional Radiation in the Early Universe



$$\rho_r = \left[1 + 0.2271 N_{\mathrm{eff}}\right] \rho_\gamma$$

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

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:

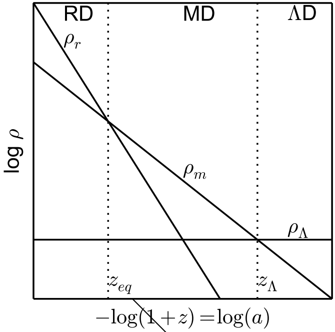
$\Delta N_{\mathrm{eff}} \lesssim 0.2$ at 95% CL

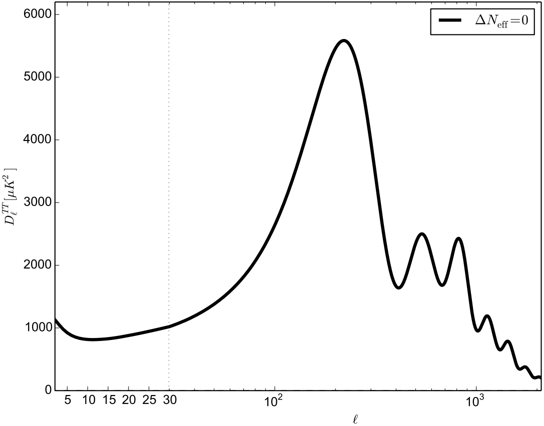
[Cyburt et al., 2015]

Additional Radiation: Effects on the CMB

Starting configuration:

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



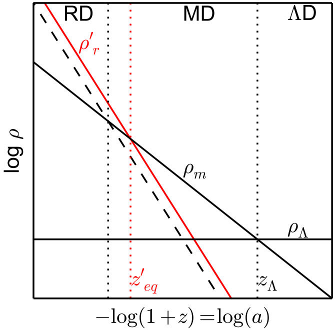


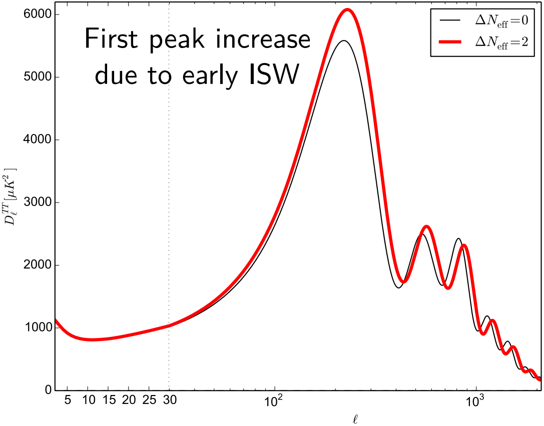
$$1 + z_{\rm eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{\omega_\gamma}\frac{1}{1 + 0.2271\,N_{\rm eff}}$$

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 $r_s \propto H^{-1}$

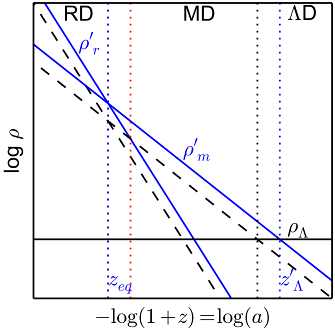
$\Rightarrow$ decrease of the angular scale of the acoustic peaks $\theta_s = r_s/D_A$

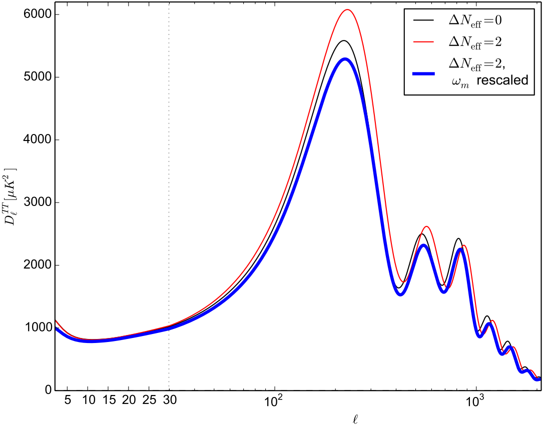
$\Rightarrow$ shift of the peaks at higher ℓ

Additional Radiation: Effects on the CMB

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

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



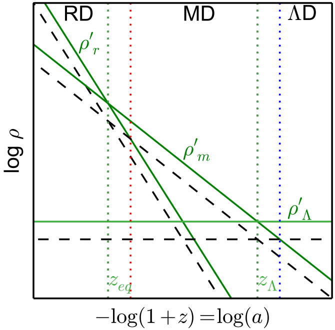


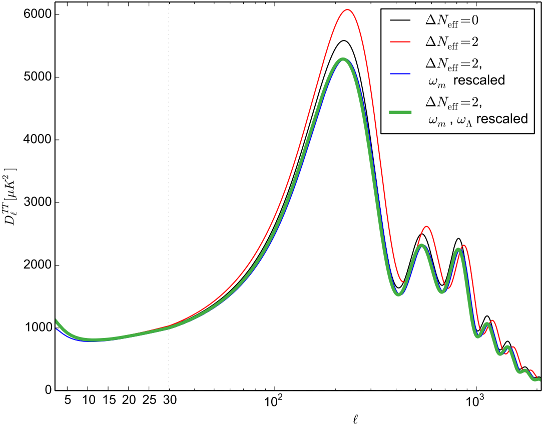
- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high-ℓ peaks ⇒ due to later z_Λ

Additional Radiation: Effects on the CMB

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

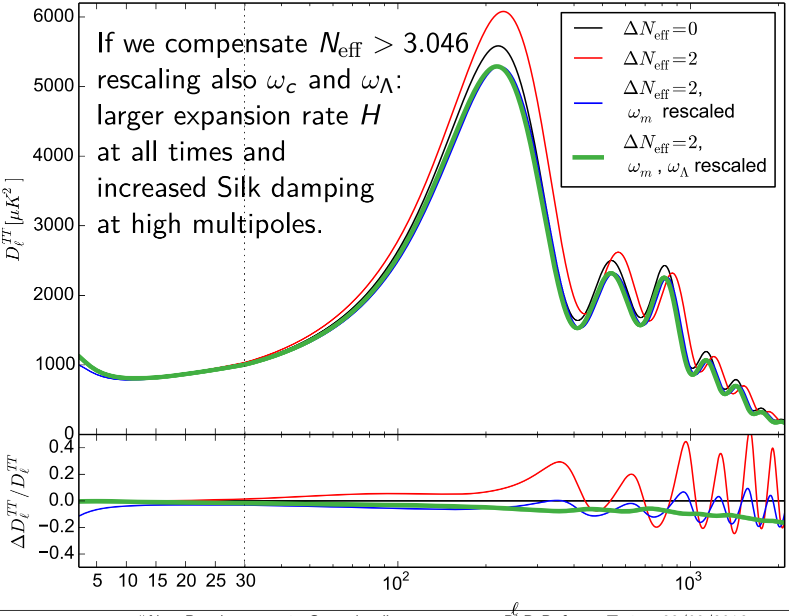
RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z)=a^{-1}$; $\omega_i=\rho_i/\rho_C$





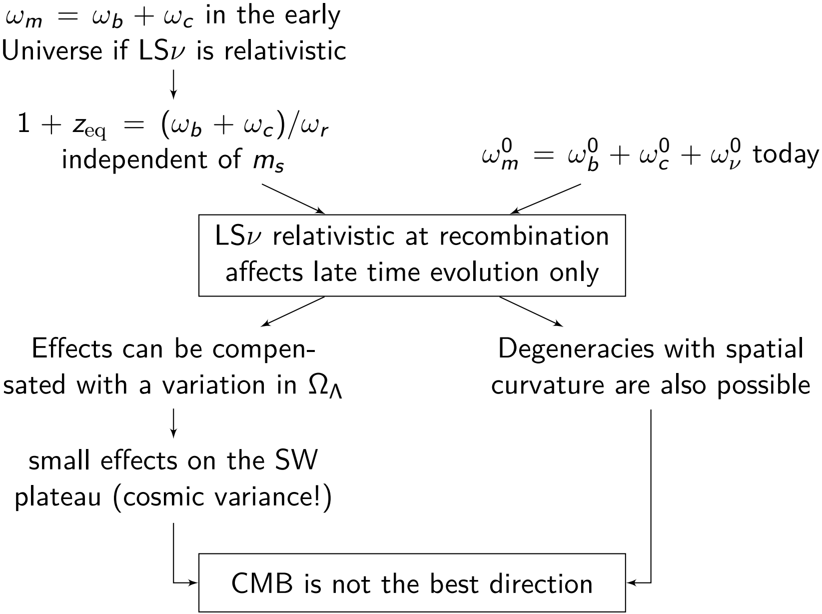
- peak positions recovered;
- slope of the Sachs-Wolfe plateau recovered;
- peak amplitude not recovered!

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

small effects on the SW plateau (cosmic variance!)

Degeneracies with spatial curvature are also possible

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

velocity $v_s \simeq c$

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

Non-relativistic neutrinos

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

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

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

$$\Downarrow$$

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

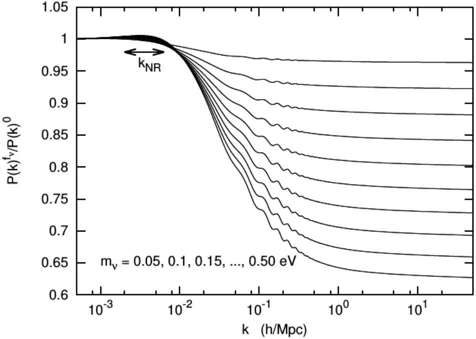
Free-streaming - II

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
- $\Delta P/P \simeq -7(8)\,(m_\nu/1\ \mathrm{eV})$

["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]

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

CMB and SBL joint constraints

CMB:

(no SBL)

+SBL (DW)

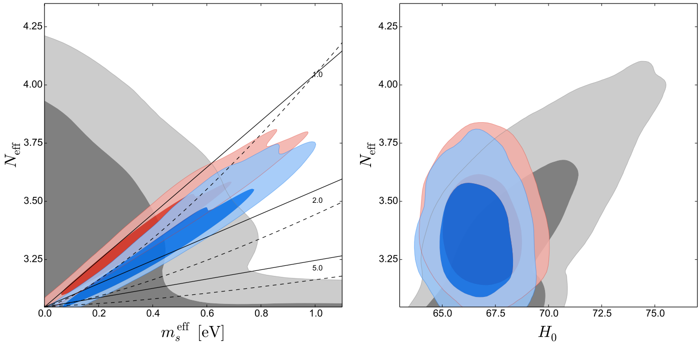
+SBL (TH)

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

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

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

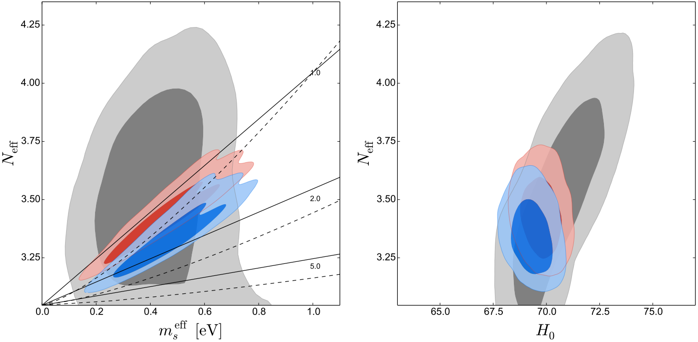
Solving σ_8 Tension with the sterile neutrino

CMB+H_0+BAO+LSS:

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

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

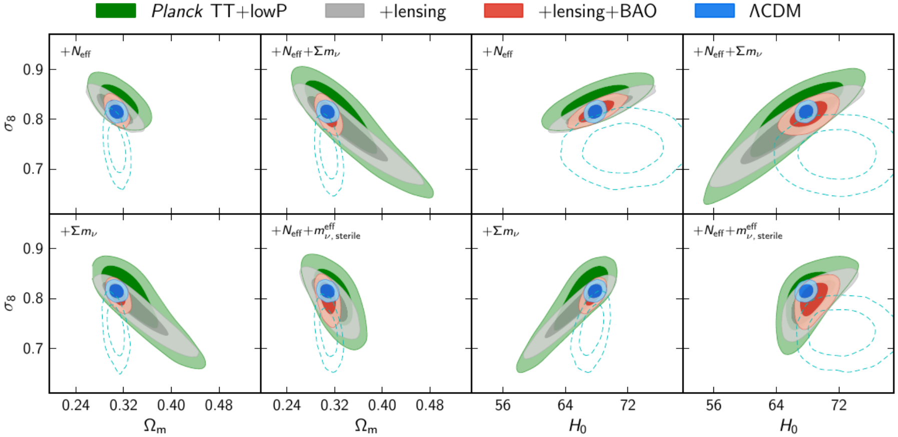
dashed lines: (TH)
$m_s^{\rm eff} = m_s (\Delta N_{\rm eff})^{3/4}$



- LSS results give preference for non-zero $m_s^{\rm eff} \rightarrow$ non-zero m_s: smaller σ_8 from LSS as a consequence of ν_s free streaming;
- no SBL prior: $N_{\rm eff}$ constraints almost unchanged;
- with SBL prior: preference for $N_{\rm eff} > 3.046$ at more than 2σ;
- with SBL prior: $N_{\rm eff} \simeq 4$ still hardly disfavoured

[Planck Collaboration, 2015]

Solving both σ_8 and H_0 Tension?



dashed: local measurements – ΛCDM model, ΛCDM + $\nu_{a,s}$ models: full cosmological dataset

H_0 increases $\Rightarrow$ σ_8 increases (and viceversa)!
The correlations do not help.

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

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

[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]

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 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 Primordial Power Spectrum (PPS) of scalar perturbations:

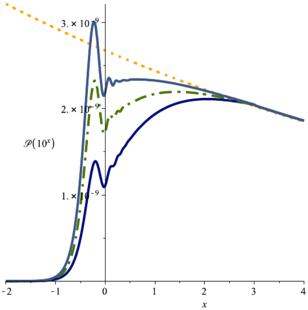
$$(n_s - 1) \equiv \frac{d \ln P_s(k)}{d \ln k} = 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2 ,$$

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

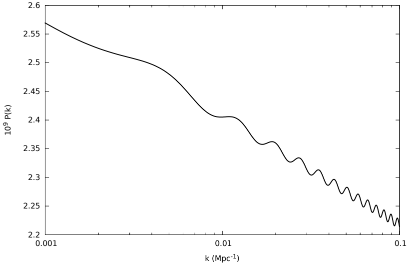
Is n_s constant?
Can the PPS deviate from a Power-Law (PL)?

Beyond Power-Law PPS: Theory

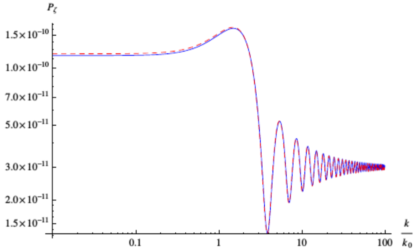
[Sagnotti et al, 2014]



[Mukhanov, 2013]



[Romano et al., 2014]

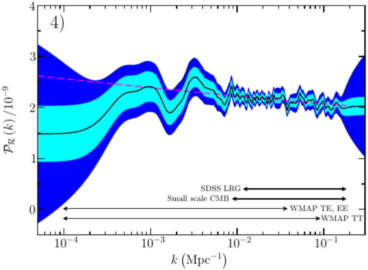


Given an inflationary model one gets one Primordial Power Spectrum (PPS), more or less complicated

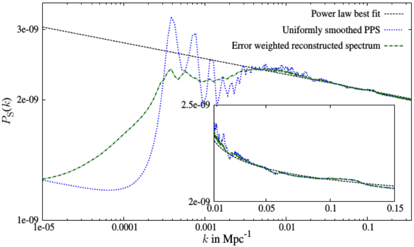
Much more models were developed: see e.g. ["Encyclopædia Inflationaris", Martin et al., 2014]

Beyond Power-Law PPS: Reconstructions

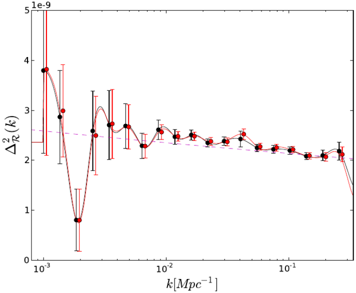
[Hunt et al., 2014] (WMAP data)



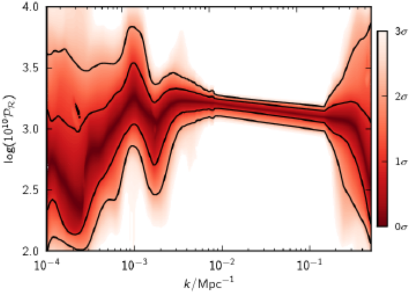
[Hazra et al, 2014] (Planck 2013 data)



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



[Planck Collaboration, 2015]



[SG et al., JCAP 1504 (2015) 023]

PCHIP Parametrization

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

$\Rightarrow$ analysis with free, non-parametric form for the PPS.

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

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

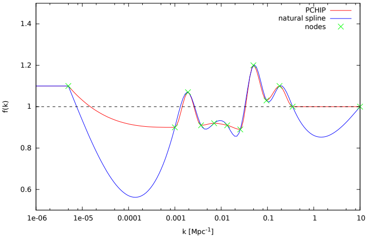
In our case we use:

PCHIP [Fritsch et al., 1980]

"piecewise cubic Hermite interpolating polynomial"

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

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.

[SG et al., JCAP 1504 (2015) 023]

Light Sterile Neutrino Results - I

PPS

Standard: Power-Law (PL)

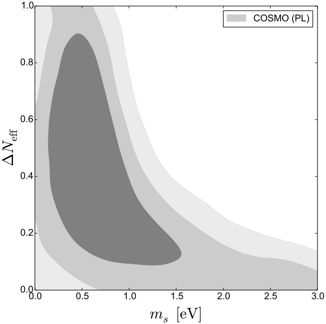
free form: nodes $P_{s,1}, \ldots, P_{s,12}$,
interpolate with PCHIP function

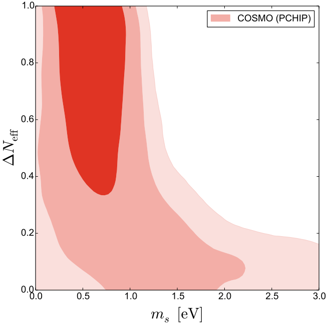
$\boxed{\Lambda\mathrm{CDM}(\mathtt{PL}\,\mathrm{PPS}) + \nu_s \text{ model}}$ versus $\boxed{\Lambda\mathrm{CDM}(\mathtt{PCHIP}\,\mathrm{PPS}) + \nu_s \text{ model}}$

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

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

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

[SG et al., JCAP 1504 (2015) 023]

Light Sterile Neutrino Results - II

PPS

Standard: Power-Law (PL)

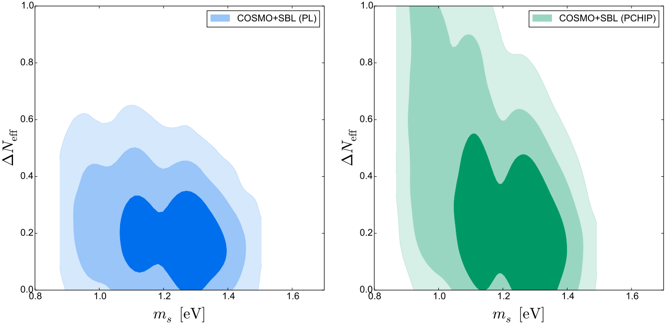
free form: nodes $P_{s,1}, \dots, P_{s,12}$, interpolate with PCHIP function

$\boxed{\Lambda\text{CDM}(\texttt{PL}\,\text{PPS}) + \nu_s \text{ model}}$ versus $\boxed{\Lambda\text{CDM}(\texttt{PCHIP}\,\text{PPS}) + \nu_s \text{ model}}$

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

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

Results for the Thermal sterile neutrino, mass m_s, <u>with SBL prior on m_s</u>:

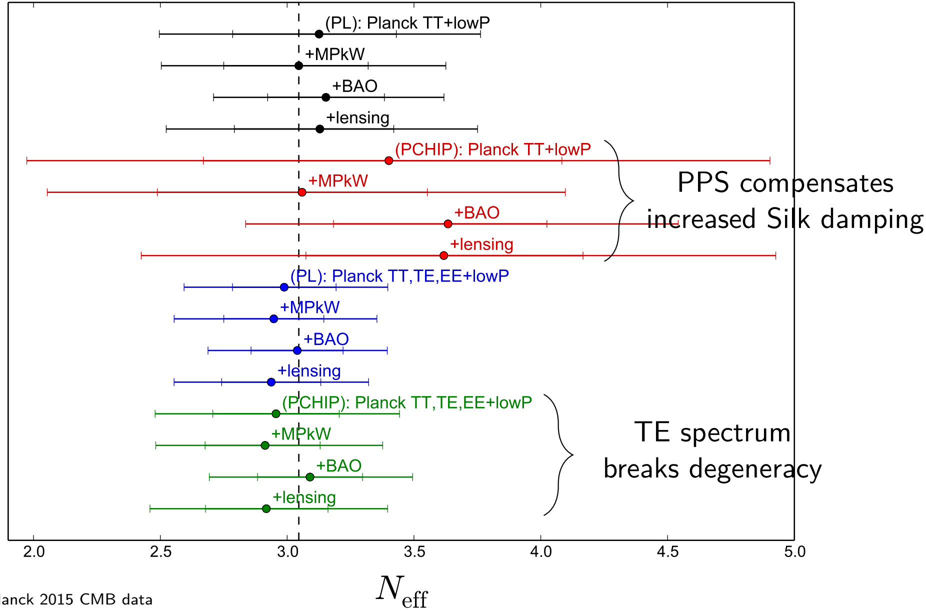


- higher $\Delta N_{\rm eff}$ admitted;
- no change on m_s constraints;
- fully thermalized sterile neutrino admitted (inside 2σ region).

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

[Di Valentino et al., 1601.07557]

Degeneracy between PPS and Radiation Content



PPS compensates increased Silk damping

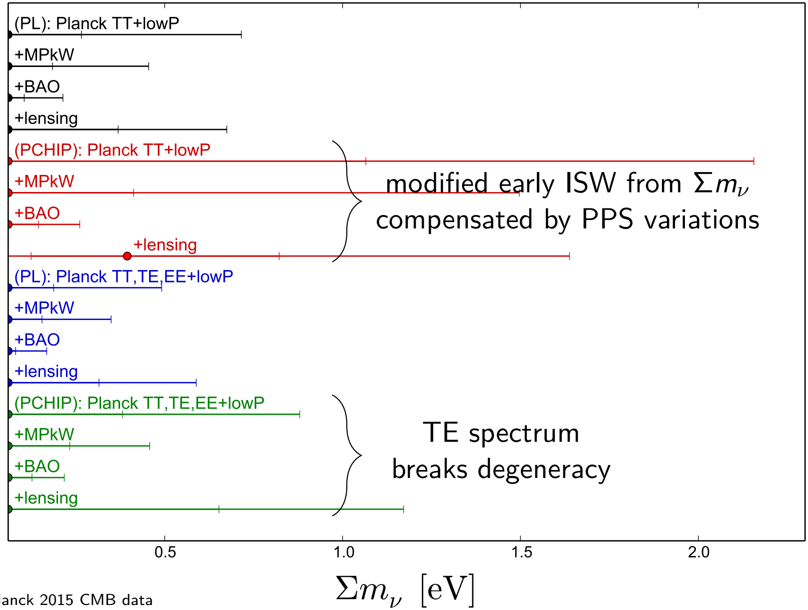
TE spectrum breaks degeneracy

Planck 2015 CMB data

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

[Di Valentino et al., 1601.07557]

Degeneracy between PPS and Neutrino Masses



modified early ISW from Σm_ν
compensated by PPS variations

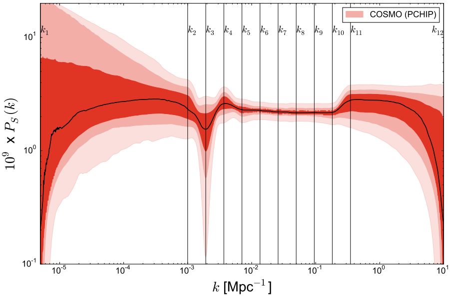
TE spectrum
breaks degeneracy

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

PPS Results

$\Lambda\mathrm{CDM}(\texttt{PCHIP}\ \mathrm{PPS}) + \nu_s$

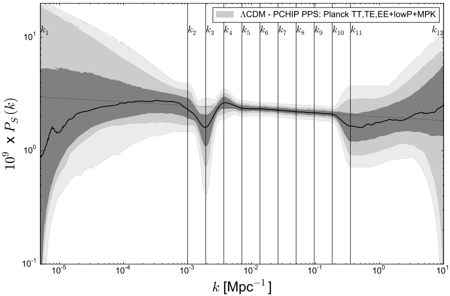
CMB(Planck13+WMAP Polarization+ACT/SPT)+
LSS(WiggleZ)+HST(Riess2011)+CFHTLenS+PlanckSZ



[SG et al., JCAP 1504 (2015) 023]

$\Lambda\mathrm{CDM}(\texttt{PCHIP}\ \mathrm{PPS})$

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



[Di Valentino et al., 1601.07557]

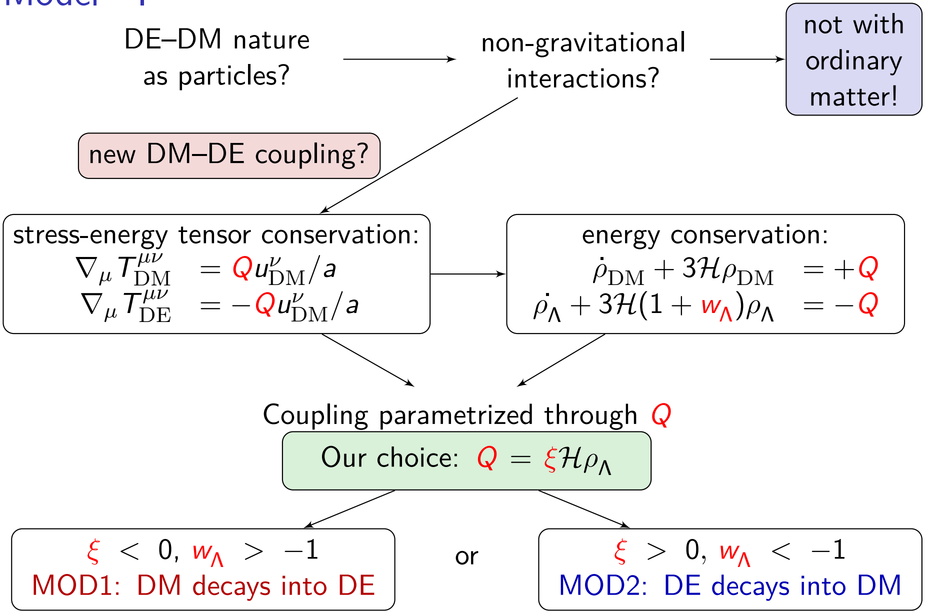
Different cosmological models, similar results:

- CMB constraints for $1 \times 10^{-4}\,\mathrm{Mpc}^{-1} (\ell = 2) \leq k \leq 0.3\,\mathrm{Mpc}^{-1} (\ell \simeq 2500)$;
- 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 $\ell \simeq 40$.

1. Cosmology
   - Cosmic Microwave Background (CMB)
   - The ΛCDM model
   - Tensions between local and CMB measurements
2. Light Sterile Neutrino
   - Neutrino Oscillation Anomalies
   - Parameterization in Cosmology
   - Cosmological Effects of Relativistic Neutrinos
   - Cosmological Effects of non-Relativistic 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**

[Murgia et al., 1602.01765]

Model - I



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

new DM–DE coupling?

stress-energy tensor conservation:

$$\begin{aligned}\nabla_\mu T^{\mu\nu}_{\rm DM} &= Q u^\nu_{\rm DM}/a\\ \nabla_\mu T^{\mu\nu}_{\rm DE} &= -Q u^\nu_{\rm DM}/a\end{aligned}$$

energy conservation:

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

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

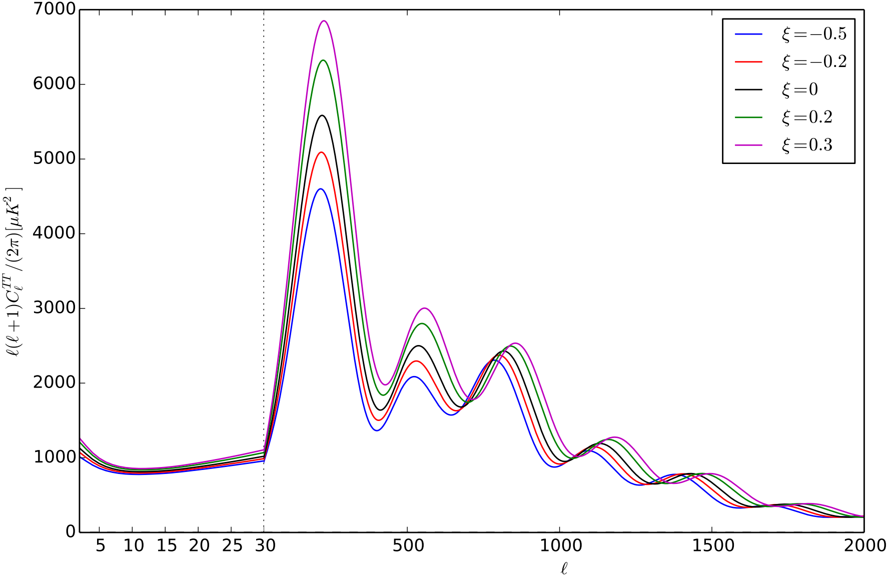
ξ dimensionless coupling parameter – a scale factor – $\mathcal{H}$ Hubble parameter

$\rho_{\rm DM}$ (ρ_Λ) DM (DE) energy density – $u^\nu_{\rm DM}$ DM four-velocity – w_Λ DE equation of state parameter ($p_\Lambda = w_\Lambda\rho_\Lambda$)

[Murgia et al., 1602.01765]

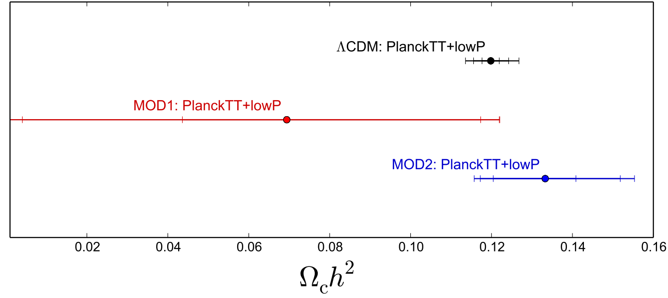
Model - II

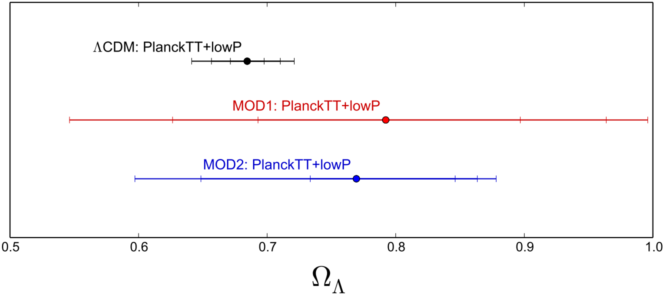
Coupled Dark Energy (CDE) influences the CMB spectrum:



[Murgia et al., 1602.01765]

Results - I





- $\Omega_c h^2 \propto \rho_{\rm DM}$ is physical
- MOD1
  DM→DE
  $\Downarrow$
  less DM today
- MOD2
  DE→DM
  $\Downarrow$
  more DM today
  also higher h!

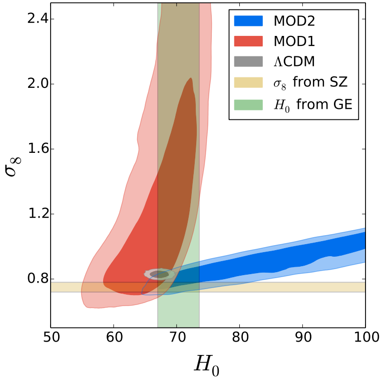
$\Omega_\Lambda \propto \rho_\Lambda / h^2$ is non-physical, depends on h!

$h = H_0/(100\,\mathrm{Km\ s^{-1}\ Mpc^{-1}})$ dimensionless Hubble parameter

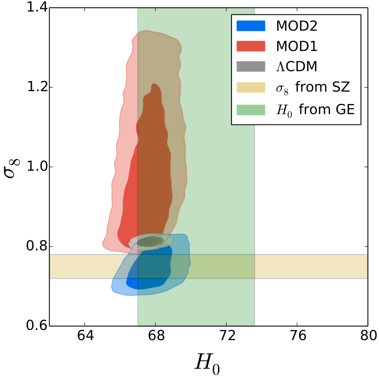
[Murgia et al., 1602.01765]

Results - II - H_0 and σ_8 tensions

CMB data only



ALL data



more DM in the early Universe $\Longrightarrow$ stronger nonlinear evolution in MOD1

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

MOD2 is better for reconciling CMB and local determinations

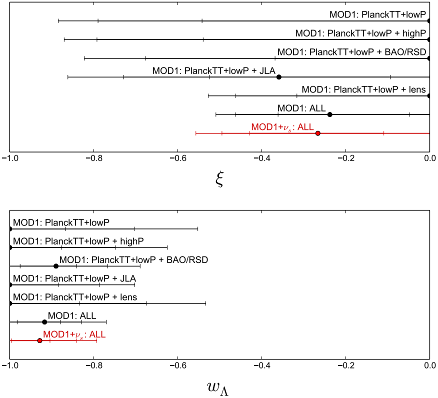
CMB=Planck TT+low-ℓ polarization

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

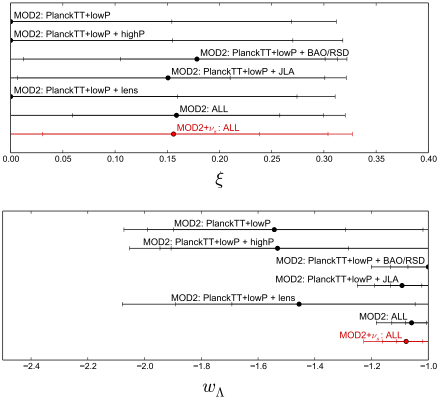
[Murgia et al., 1602.01765]

Results - III - ξ and w_Λ

MOD1



MOD2



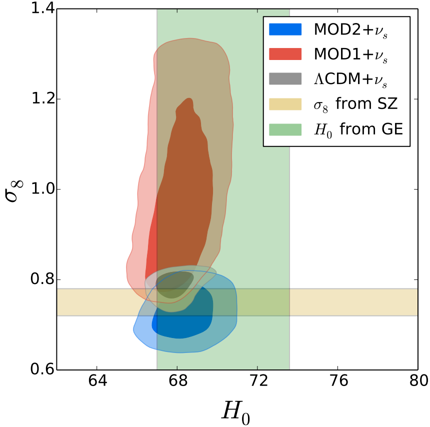
- JLA→ $\xi \neq 0$?
- BAO/RSD→ $w_\Lambda \neq -1$?

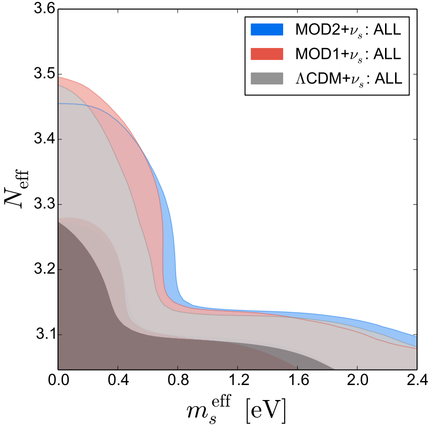
- CMB→ poor constraints on w_Λ
- BAO/RSD, JLA→ preference for less DM today, $w_\Lambda \simeq -1$

red points: CDE + LSν models

[Murgia et al., 1602.01765]

Results - IV - What about LSν?





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

CDE models does not affect the LSν bounds!

Upper limits for $m_s^{\rm eff}$, $N_{\rm eff} \lesssim 3.5$ $\Longrightarrow$ thermalized LSν is still disfavoured

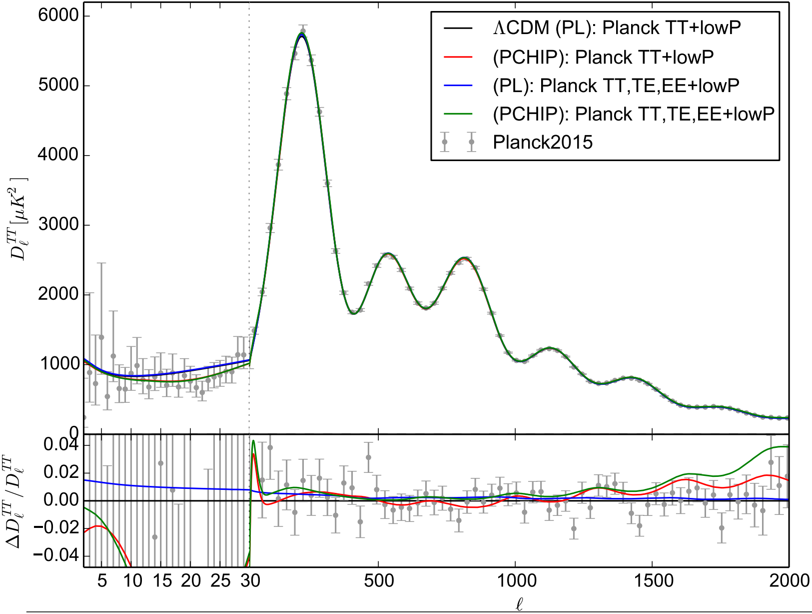
Conclusions

- Universe evolution explained well by ΛCDM 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 (LSν) ?
  - LSν 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 LSν effects in cosmology ?
  - if $\Delta N_{\rm eff} < 1$, the LSν is allowed ✓
- CMB temperature spectrum at low-ℓ: inflationary freedom ?
  - primordial power spectrum can compensate LSν 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→DM) ✓
  - LSν bounds unchanged ✗

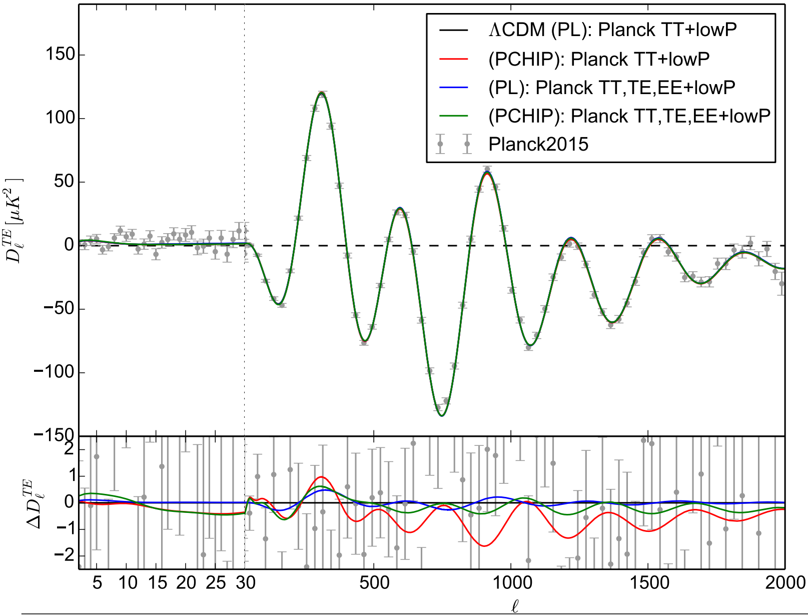
Thank you for the attention

5. Backup slides

Free PPS and CMB polarization - TT



Free PPS and CMB polarization - TE



Free PPS and CMB polarization - EE