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Neutrino Properties and the Cosmological Tensions in the ΛCDM Model

15th Marcel Grossmann Meeting, Roma (IT), 01–07/07/2018

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.

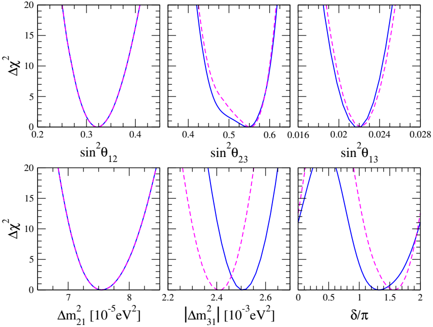
Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

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

$$\begin{aligned}\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\ |\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\ &= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})\end{aligned}$$

$$\begin{aligned}\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\ \sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\ &= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\ \sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\ &= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})\end{aligned}$$

First hints for $\delta_{\mathrm{CP}} \simeq 3/2\pi$



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$= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}$ [illegible]

$\sin^2(\theta_{12})$ [illegible]

$\sin^2$[illegible] $= 0.0210^{+0.008}_{-0.007}$ (NO)

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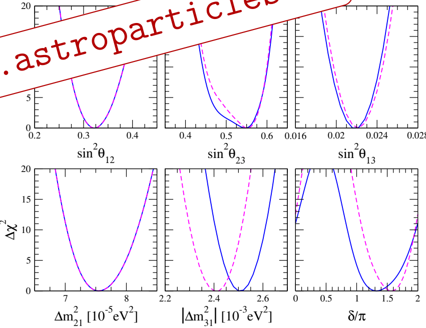
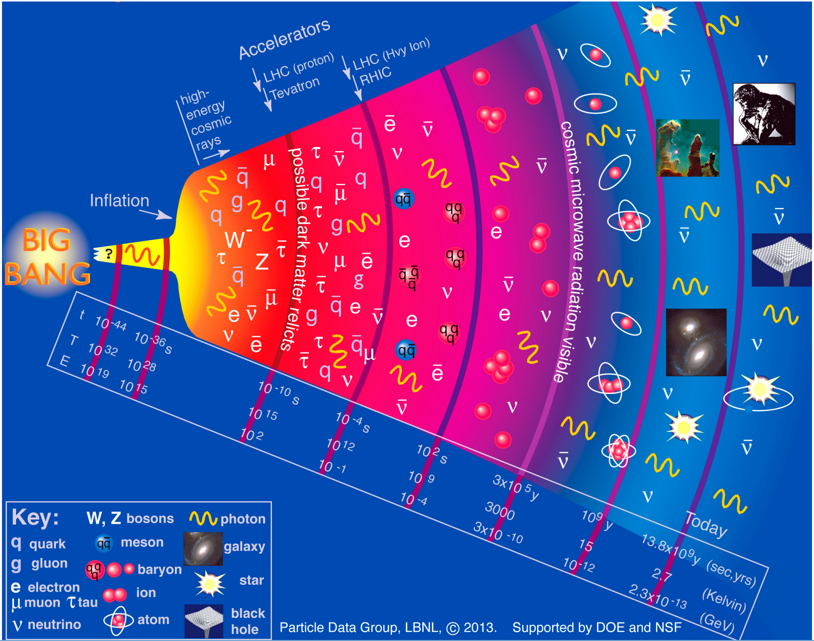


see also: http://globalfit.astroparticles.es

History of the universe



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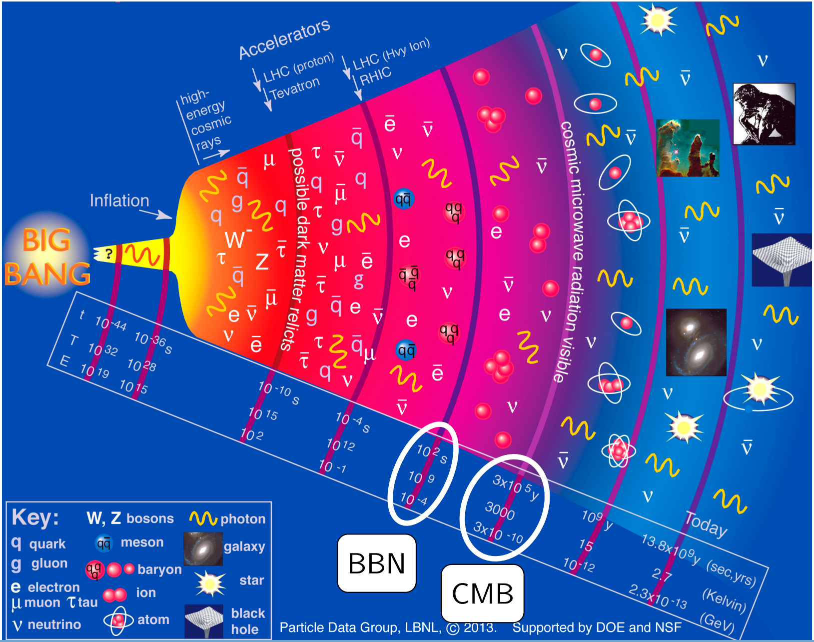

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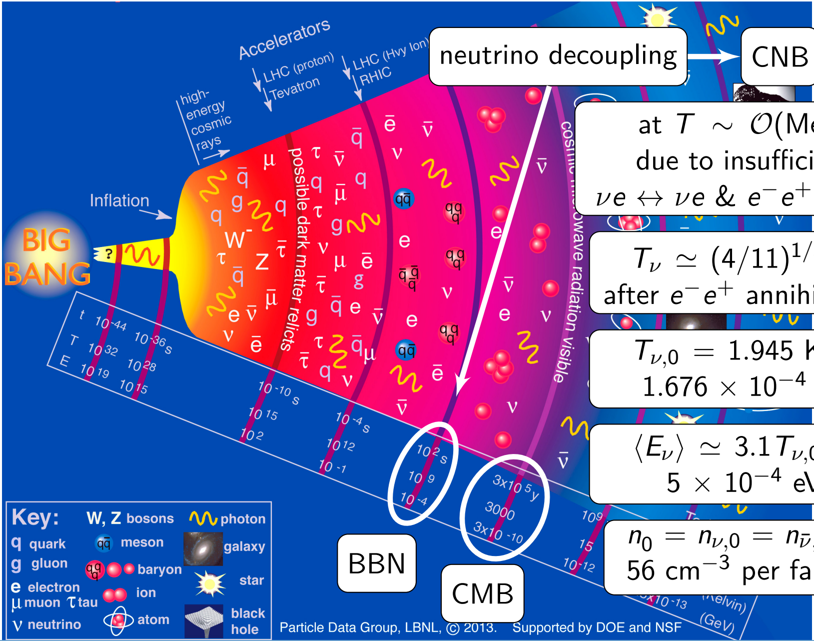

neutrino decoupling → CNB

at $T \sim \mathcal{O}(\mathrm{MeV})$
due to insufficient
$\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

$T_\nu \simeq (4/11)^{1/3} T_\gamma$
after $e^- e^+$ annihilation

$T_{\nu,0} = 1.945\ \mathrm{K} \simeq 1.676 \times 10^{-4}\ \mathrm{eV}$

$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}\ \mathrm{eV}$

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56\ \mathrm{cm}^{-3}$ per family

BBN

CMB

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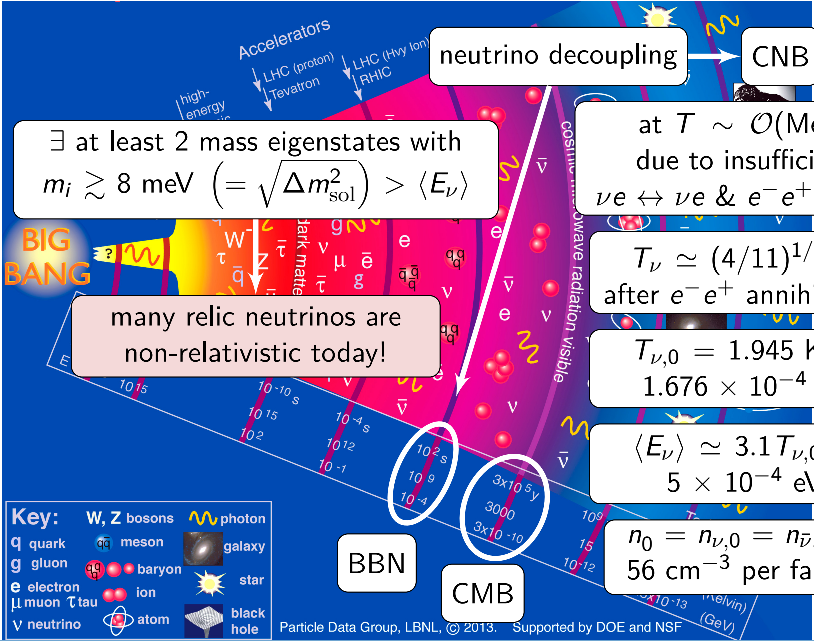

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∃ at least 2 mass eigenstates with
$m_i \gtrsim 8\text{ meV}\ \left(= \sqrt{\Delta m^2_{\rm sol}}\right) > \langle E_\nu \rangle$

many relic neutrinos are
non-relativistic today!

BBN

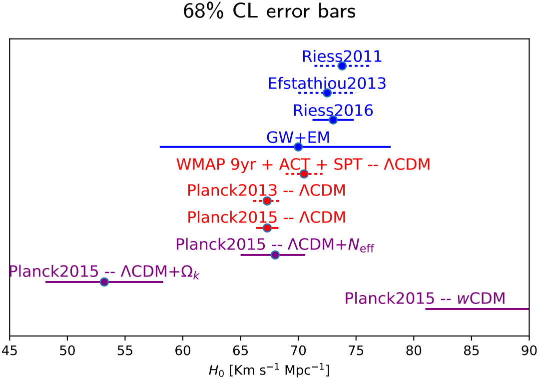
CMB

Tension I: the 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] $H_0 = 72.5 \pm 2.5\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$
[Riess et al., 2016] $H_0 = 73.24 \pm 1.74\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$
(most recent)

(ΛCDM model - CMB data only)
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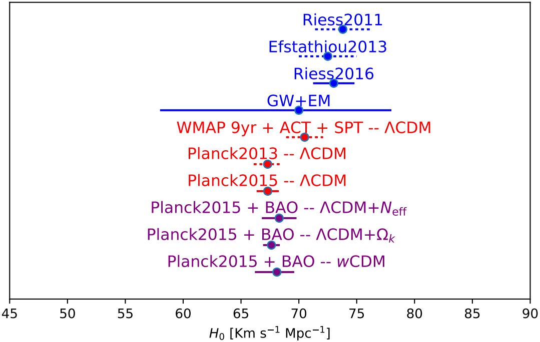
68% CL error bars



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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

KiDS-450 (68% CL):
[Hildebrandt et al., 2016]

$$\sigma_8(\Omega_m)^{0.5} = 0.408 \pm 0.021$$

CMB results (68% CL):
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Count of satellites galaxies of the Milky Way

Observed (classical + SDSS): $N_{\rm sat} = 63 \pm 13$

Predicted (CDM only): $N_{\rm sat} \simeq 160$

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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]
- did we count all the satellite galaxies? (very difficult detection)

Relic neutrinos in cosmology: $N_{\rm eff}$

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] (damping factors approximations) $\sim$
  $N_{\rm eff} = 3.045$ [de Salas et al., 2016] (full collision terms)
  due to not instantaneous decoupling for the neutrinos
- $+$ Non Standard Interactions: $3.040 < N_{\rm eff} < 3.059$ [de Salas et al., 2016]

Observations: $N_{\rm eff} \simeq 3.04 \pm 0.2$ [Planck 2015]
Indirect probe of cosmic neutrino background!

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

abundances today

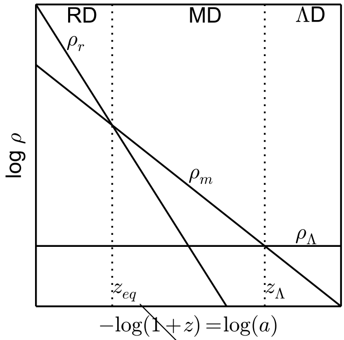
matter-radiation equality

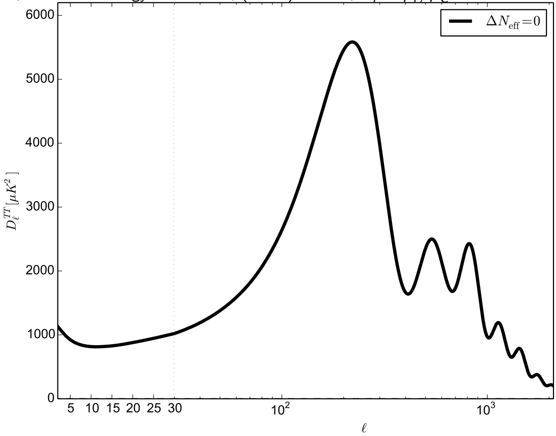
expansion rate at CMB decoupling

Additional Radiation: Effects on the CMB

Starting configuration:

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



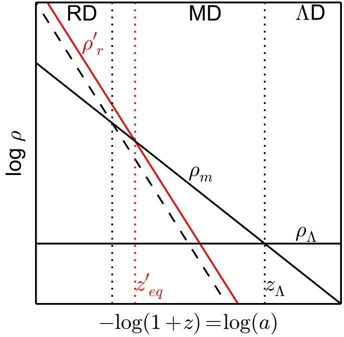


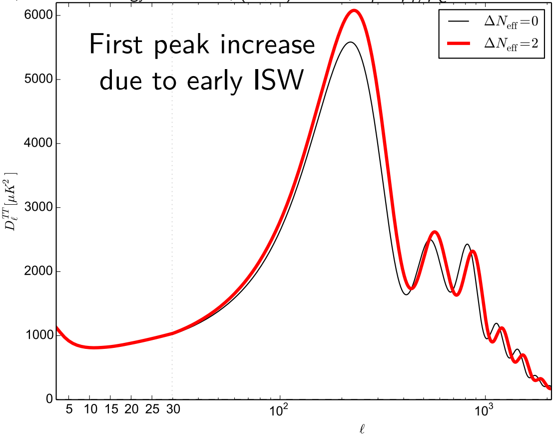
$$1 + z_{\rm eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.2271\, N_{\rm eff}}$$

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 $z_{\rm eq}$:

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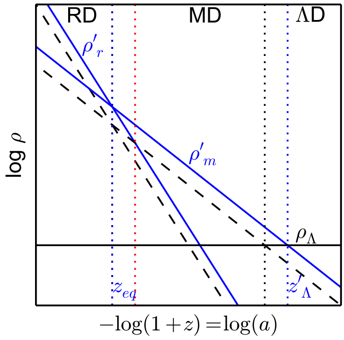

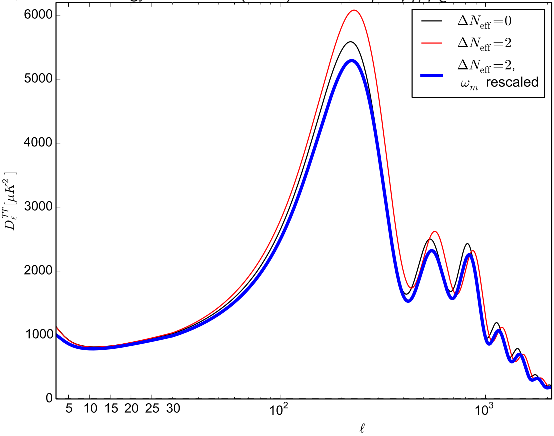

- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high-ℓ peaks ⇒ due to later z_Λ

Additional Radiation: Effects on the CMB

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

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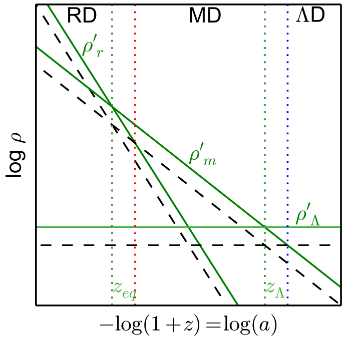
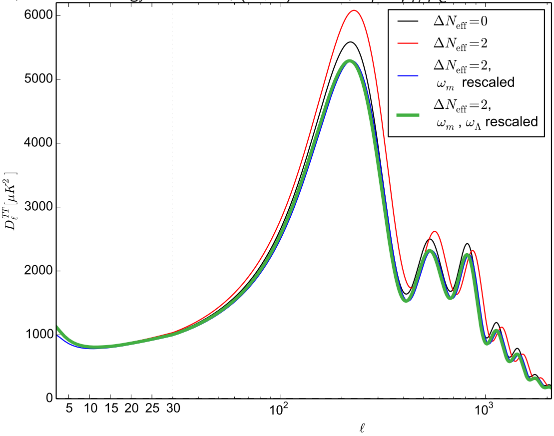
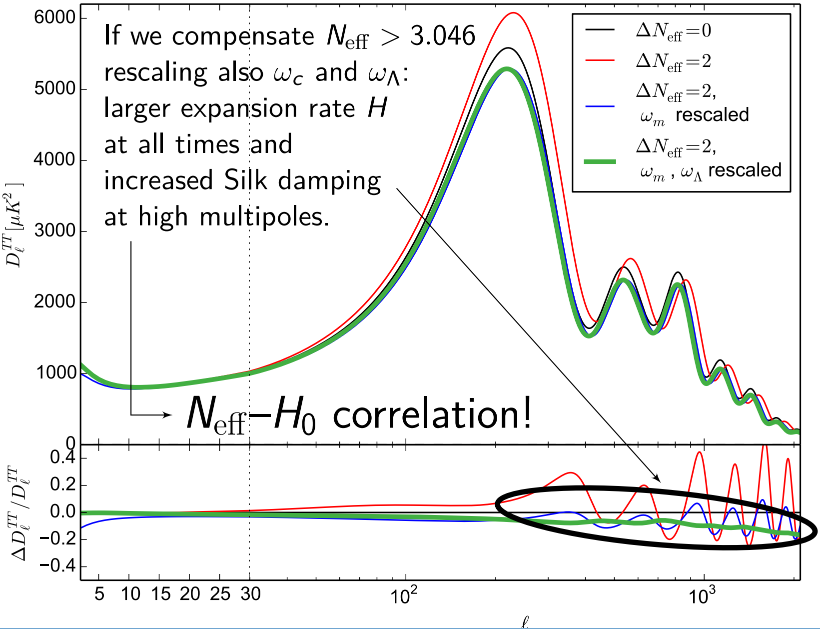




- peak positions recovered;
- slope of the Sachs-Wolfe plateau recovered;
- peak amplitude not recovered!

Additional Radiation: Effects on the CMB



Neutrino masses from CMB

ω_i energy density of species i,
$i \in$ (radiation, matter, baryons, cold dark matter, ν)
$z_{\rm eq}$ matter-radiation equality redshift

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

independent of m_ν

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

mass of species relativistic at recombination affects late time evolution only

small effects on the SW plateau (cosmic variance, degeneracies...)

Effects on the early ISW effect

$$\frac{\Delta C_\ell}{C_\ell} \simeq -\left(\frac{\sum m_\nu}{0.1\text{ eV}}\right)\%$$

effects on the position of peaks

$$\theta_s = r_s(\eta_{LS})/D_A(\eta_{LS})$$

$$D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

(this effect can be compensated reducing H_0)

correlation m_ν–H_0

["Neutrino Cosmology", Lesgourgues et al.]

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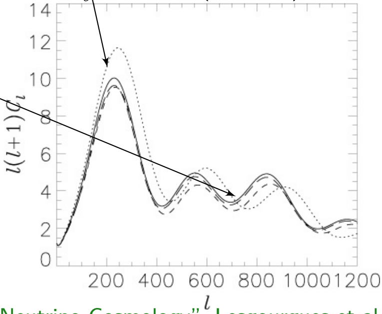


[“Neutrino Cosmology”, Lesgourgues et al.]

Free-streaming - I

Non-cold relics $\Longrightarrow$ damping in the perturbations due to free-streaming

Growth equation: $\ddot{\delta} + 2H\dot{\delta} - c_s^2 k^2 \frac{\delta}{a^2} = 4\pi G_N \rho\, \delta$

($2H\dot{\delta}$: Hubble drag; $c_s^2 k^2 \frac{\delta}{a^2}$: pressure; $4\pi G_N \rho\, \delta$: gravity)

Jeans scale: pressure=gravity

$$k_J \equiv \sqrt{\frac{4\pi G_N \rho}{c_s^2 (1+z)^2}}$$

$k < k_J$
growth of density perturbations

$k > k_J$
no growth can occur

neutrino free-streaming scale

$$k_{fs}(z) \equiv \sqrt{\frac{3}{2}\frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}} \simeq 0.7 \left(\frac{m_\nu}{1\ \text{eV}}\right) \sqrt{\frac{\Omega_M}{1+z}}\, h/\text{Mpc}$$

ρ energy density of a given fluid
$\delta = \delta\rho/\rho$ perturbation (single fluid)
c_s sound speed of the fluid

$\sigma_{v,\nu}(z)$ ν velocity dispersion
$H = H(z)$ Hubble factor at redshift z
h reduced Hubble factor today

Free-streaming - II

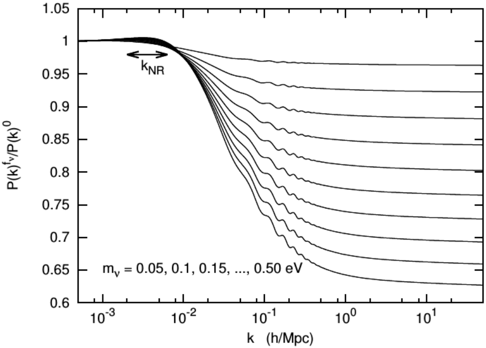
Damping occurs for all $k \gtrsim k_{\rm nr}$

k_{nr}: corresponding
to ν non-relativistic transition

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

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
- $\dfrac{\Delta P}{P} \simeq -\dfrac{8\Omega_\nu}{\Omega_M} \simeq -\dfrac{\sum m_\nu}{0.01\ \mathrm{eV}}\%$



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]

Summary: H_0, σ_8 and neutrino properties

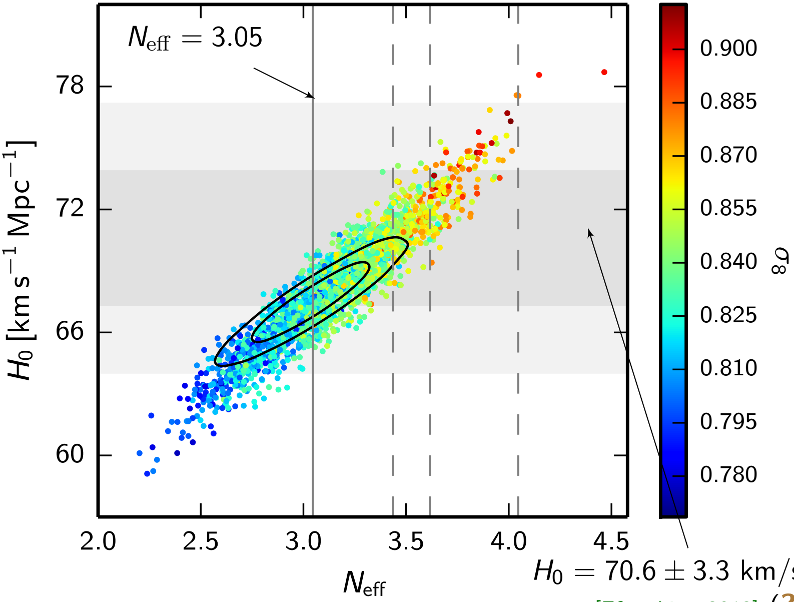
Many useful degeneracies:

1. Increase $N_{\rm eff} \longrightarrow$ increase H_0
2. Increase $\sum m_\nu \longrightarrow$ decrease σ_8
3. Increase $\sum m_\nu \longrightarrow$ decrease H_0

use more data to break more degeneracies!

$N_{\rm eff}$ and the local tensions

[Planck Collaboration, 2015]



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[Efstathiou 2013] (?)

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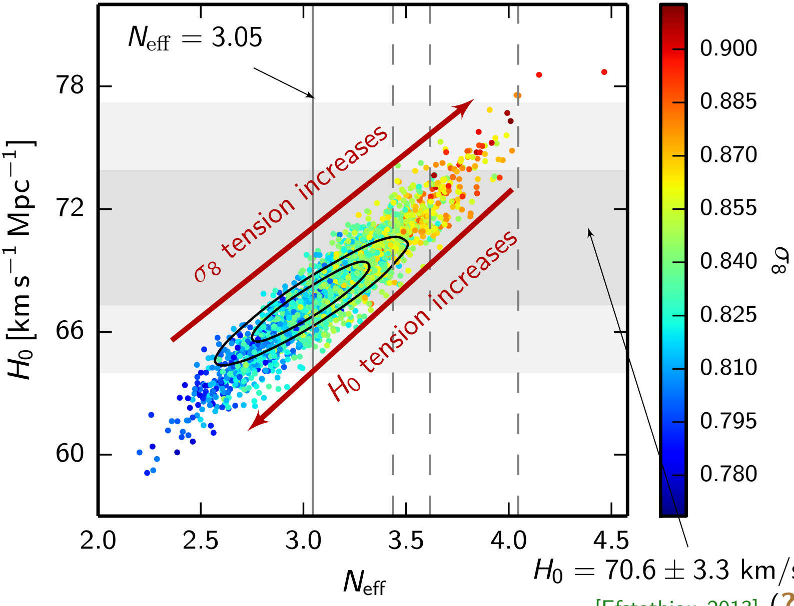

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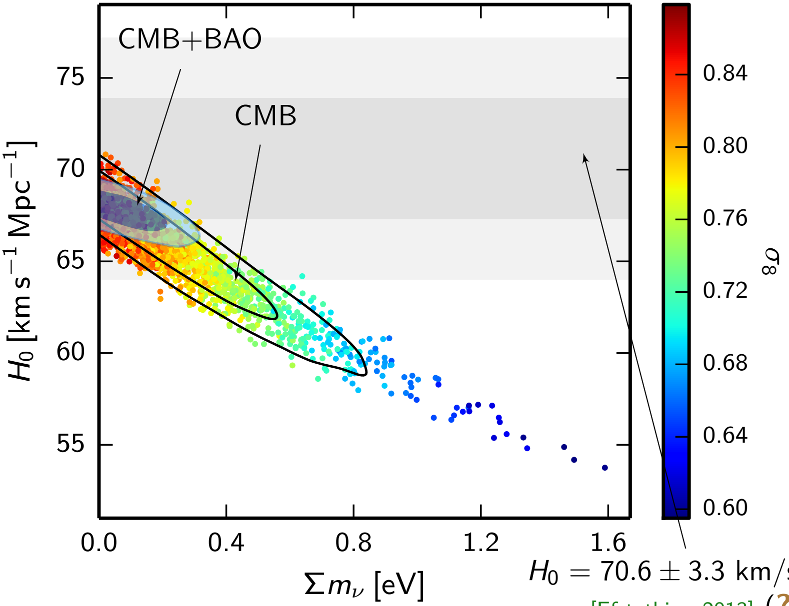

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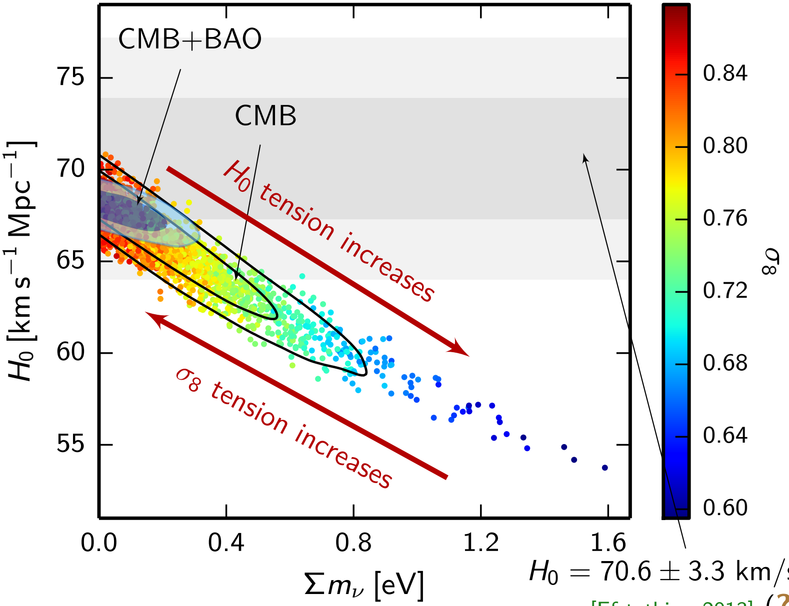
Σm_ν and the local tensions - I



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Neutrino masses and CMB lensing

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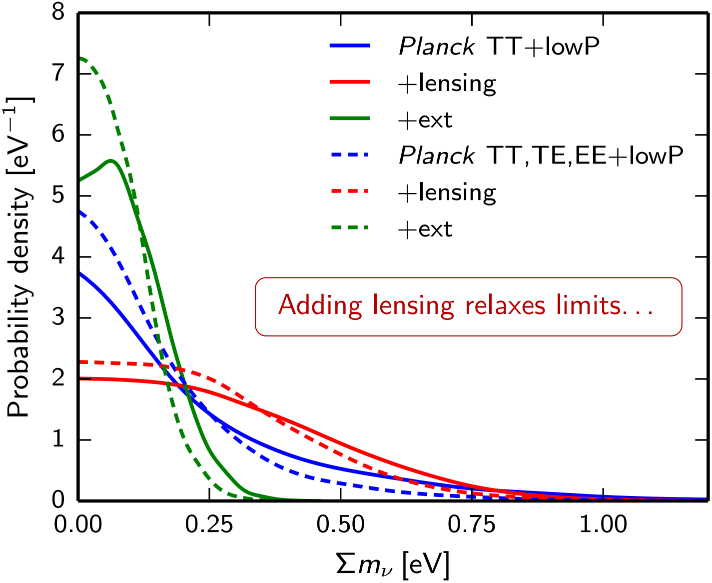

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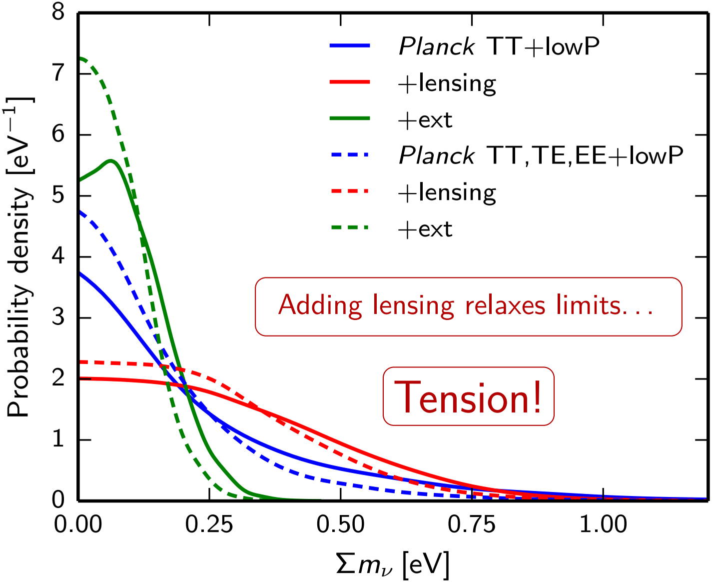

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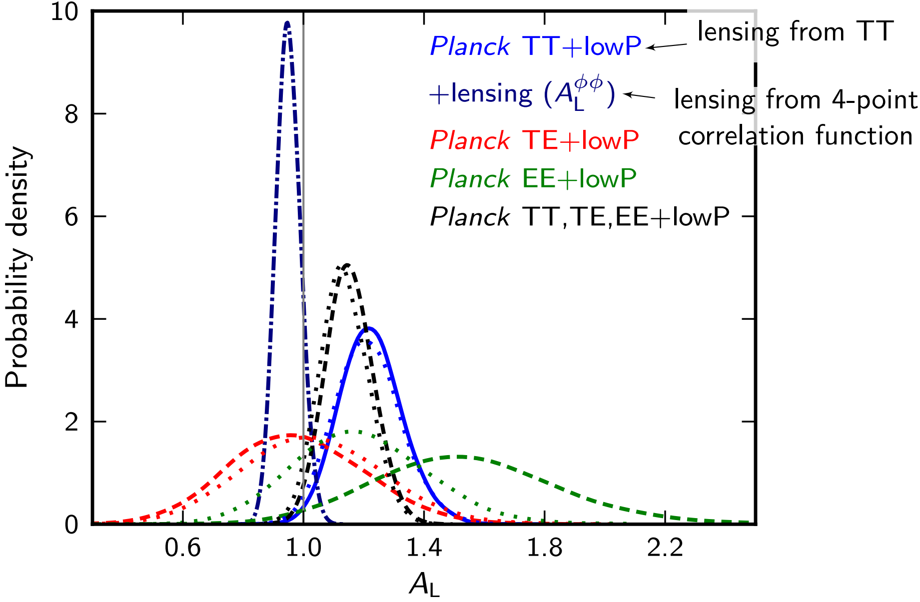

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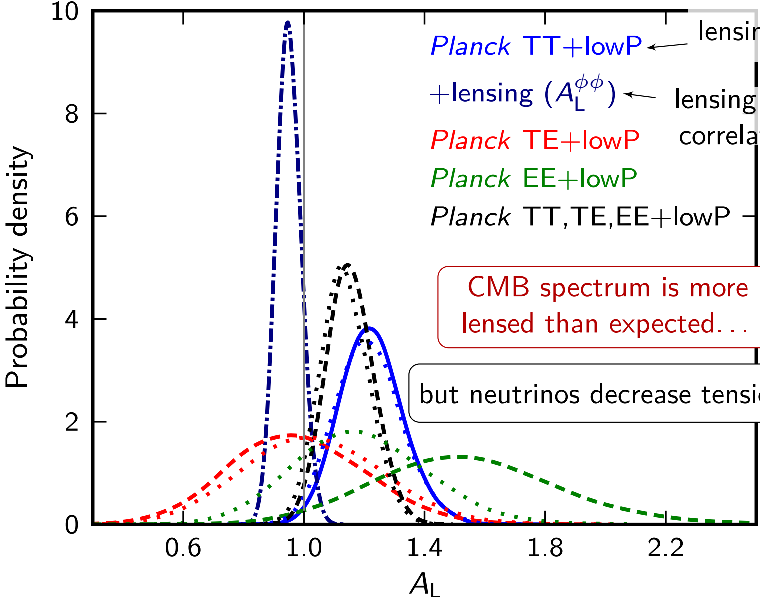


lensing from TT

lensing from 4-point correlation function

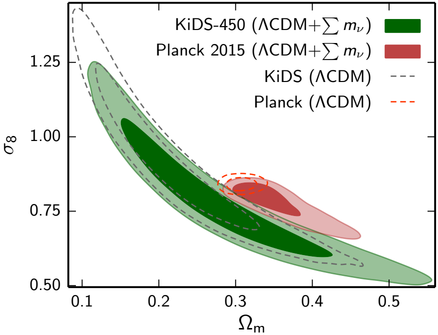
CMB spectrum is more lensed than expected. . .

2σ tension

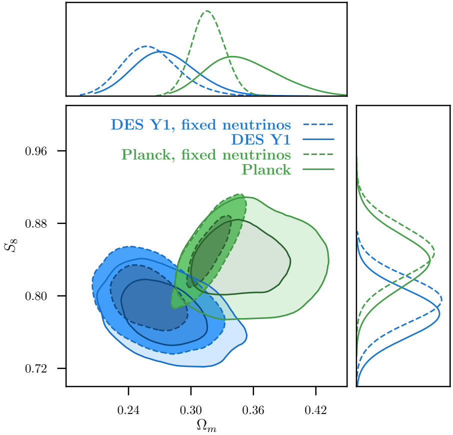
but neutrinos decrease tension!

Σm_ν and the local tensions - II

[KiDS collaboration, MNRAS 471 (2017) 1259]



[DES collaboration, arxiv:1708.01530]



Overlapping of regions does not improve so much with massive neutrinos

Short Baseline (SBL) anomaly

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

Problem: anomalies in SBL experiments → { errors in flux calculations? deviations from 3-ν description? }

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 $\Rightarrow$ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Mention et al, 2011], [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]

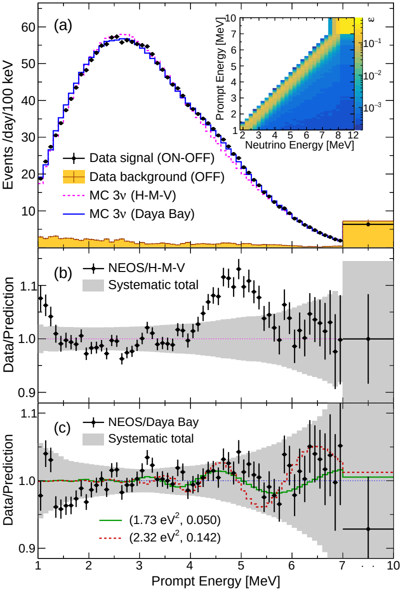
MiniBooNE See next

Possible explanation:

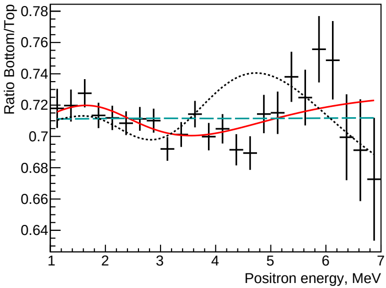
Additional squared mass difference $\Delta m^2_{\mathrm{SBL}} \simeq 1\ \mathrm{eV}^2$

Recent results. . .

[NEOS, PRL 118 (2017) 121802]



[DANSS, arxiv:1804.04046]

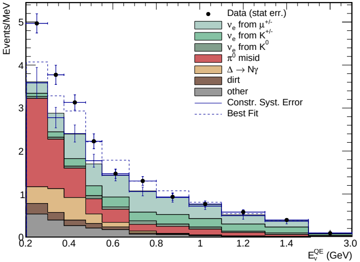


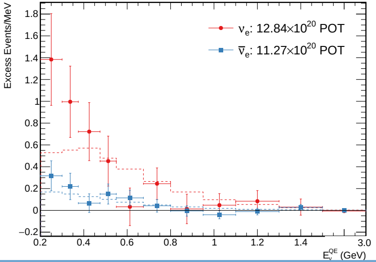
first *model independent* indications in favor of SBL oscillations

DANSS alone gives a $\Delta\chi^2 \simeq 13$ in favor of a light sterile neutrino!

Recent results. . .

[MiniBooNE, arxiv:1805.12028]





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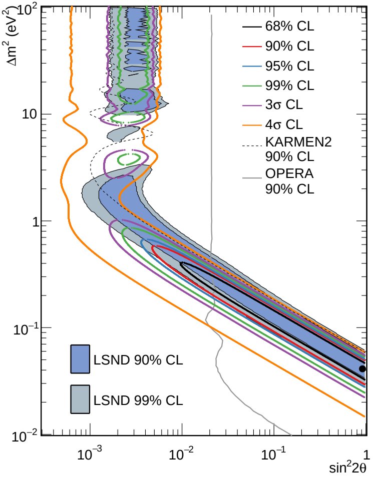
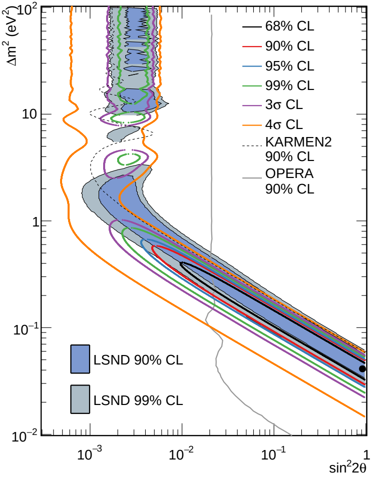
[MiniBooNE, arxiv:1805.12028]

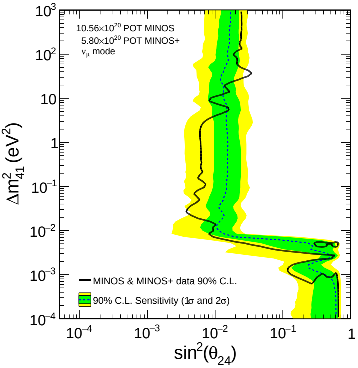


Recent results. . .

[MiniBooNE, arxiv:1805.12028]

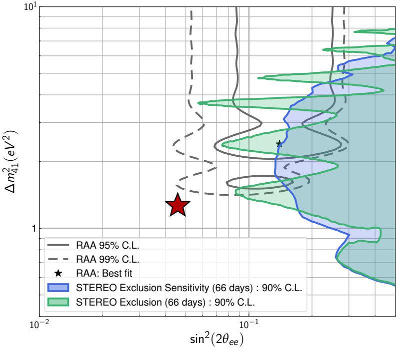


[MINOS+, arxiv:1710.06488]

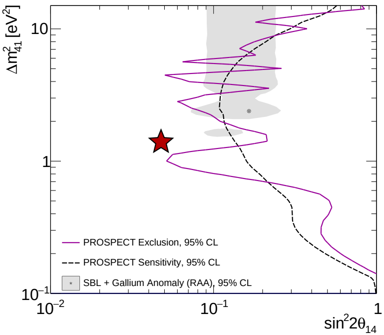


First results from...

[STEREO, arxiv:1806.02096]



[PROSPECT, arxiv:1806.02784]



★ = current DANSS+NEOS best fit

[SG et al., PLB782 (2018) 13–21]

We will have soon new constraints (or evidences?)

3+1 Neutrino Model

new $\Delta m^2_{SBL} \Rightarrow$ 4 neutrinos!

$\downarrow$

ν_4 with $m_4 \simeq 1$ eV,

no weak interactions

$\downarrow$

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

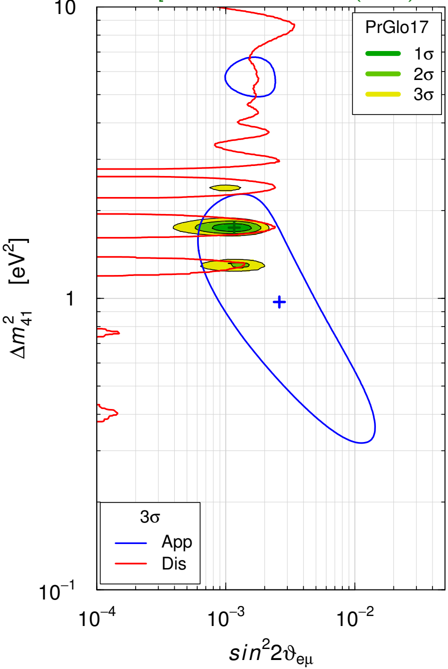
$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau, s)$$

ν_s is mainly ν_4:

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

assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$

[SG et al., JHEP 06 (2017) 135]



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[SG et al., in preparation (2018)]

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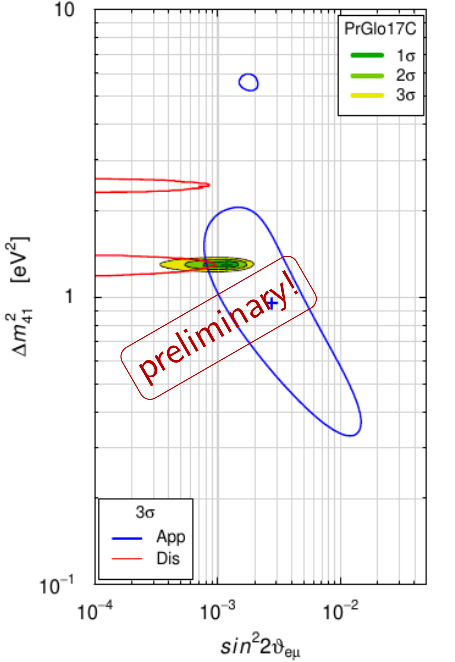

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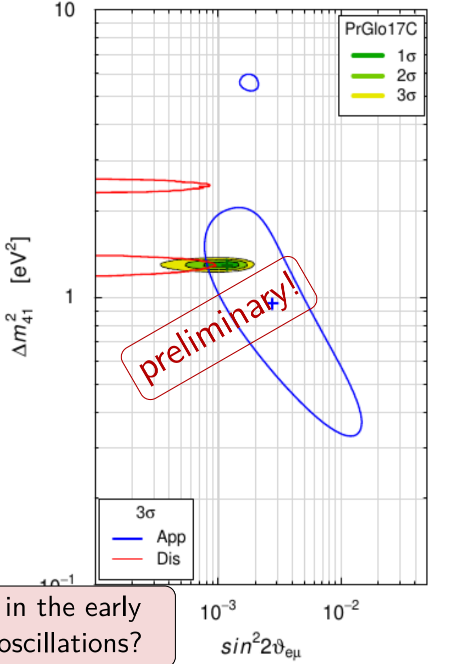
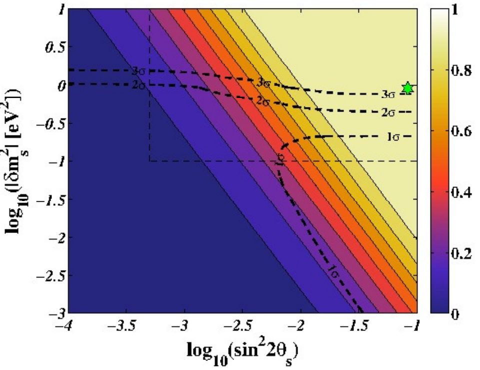


can ν_4 thermalize in the early Universe through oscillations?

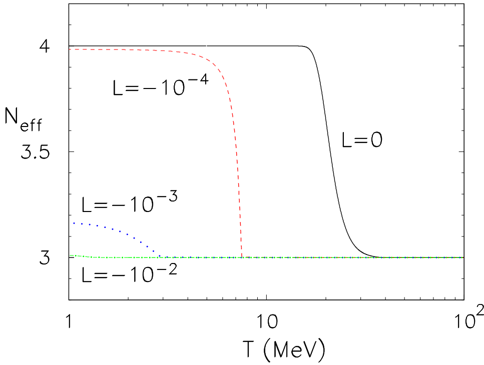
LSν thermalization

Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[Hannestad et al., JCAP 07 (2012) 025] [Mirizzi et al., PRD 86 (2012) 053009]



(colors coding $\Delta N_{\rm eff}$)



(L: lepton asymmetry)

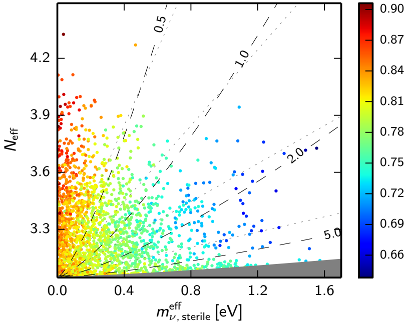
Unless $L \gtrsim \mathcal{O}(10^{-3})$, $\Delta N_{\rm eff} \simeq 1$

See also: [Saviano et al., PRD 87 (2013) 073006], [Hannestad et al., JCAP 08 (2015) 019]

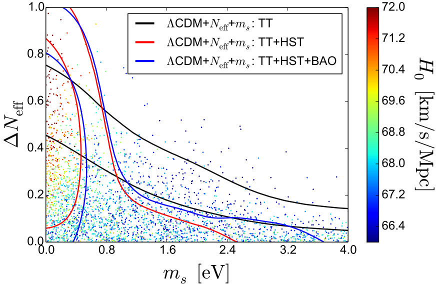
[to be precise: $\Delta N_{\rm eff}$ is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2015]



[Archidiacono et al., JCAP 08 (2016) 067]



$$\begin{cases} N_{\rm eff} < 3.7 \\ m_s^{\rm eff} < 0.52 \text{ eV} \end{cases}$$

(TT+lensing+BAO)
[$m_s < 5$ eV]

dataset	free $\Delta N_{\rm eff}$ [$m_s < 10$ eV]	$\Delta N_{\rm eff} = 1$
(TT)	$N_{\rm eff} < 3.5$	$m_s < 0.66$ eV
(+H_0)	$N_{\rm eff} < 3.9$	$m_s < 0.55$ eV
(+BAO)	$N_{\rm eff} < 3.8$	$m_s < 0.53$ eV

BBN constraints: $N_{\rm eff} = 2.90 \pm 0.22$ (BBN+Y_p) [Peimbert et al., 2016]

Summary: $\Delta N_{\rm eff} = 1$ from LSν incompatible with $m_s \simeq 1$ eV!

TT=Planck 2015 TT + lowTEB

All the constraints are at 2σ CL

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

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

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

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

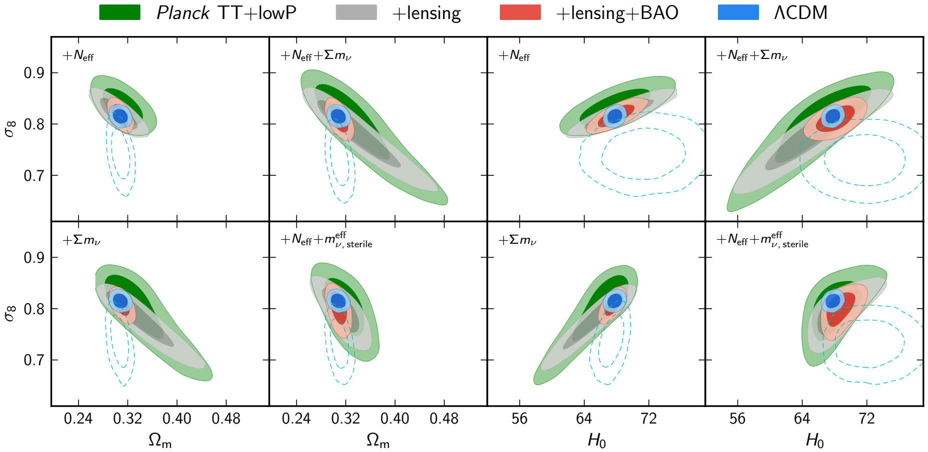
- a mechanism to suppress oscillations and full thermalization of ν_s?
- to compensate $\Delta N_{\rm eff} = 1$ with additional mechanisms in Cosmology?

Some ideas (an incomplete list!):

- 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; Archidiacono et al. 2016; 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]

Solving both σ_8 and H_0 Tension?

[Planck Collaboration, 2015]



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.

Conclusions

1

Cosmology is an excellent tool
for studying neutrino properties!

But beware of systematics/model dependency!
Situation less clear than what usually stated?

2

Is there a light sterile neutrino?

Not completely clear.
If yes, problems in early universe!
More new physics to be discovered?

3

Neutrinos cannot really solve
the H_0 and σ_8 tensions...

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Thank you for the attention!