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Stefano Gariazzo

IFIC, Valencia (ES)
CSIC – Universitat de Valencia

gariazzo@ific.uv.es
http://ific.uv.es/~gariazzo/

Neutrinos and Cosmology

Strenghts and weaknesses of cosmological bounds on effective number and masses of neutrinos

European Neutrino "Town" Meeting, CERN, 22–24/10/2018

1 ***Introduction***
- Neutrinos and early Universe
- Relativistic neutrinos in the early Universe
- Massive neutrinos in the late Universe

2 ***Current constraints***
- Cosmological observables
- Current status
- Extending the cosmological model
- Mass ordering

3 ***Direct detection of relic neutrinos***

4 ***Conclusions***

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Three Neutrino Oscillations

Analogous to CKM mixing for quarks: [Pontecorvo, 1968]
[Maki, Nakagawa, Sakata, 1962]

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

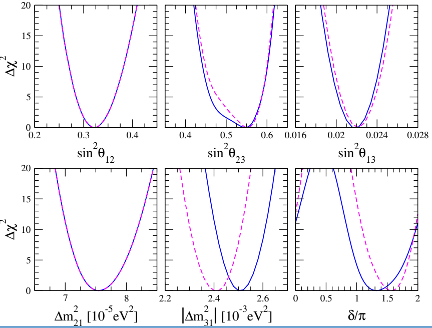
ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

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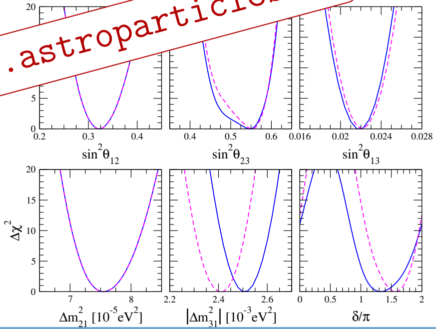
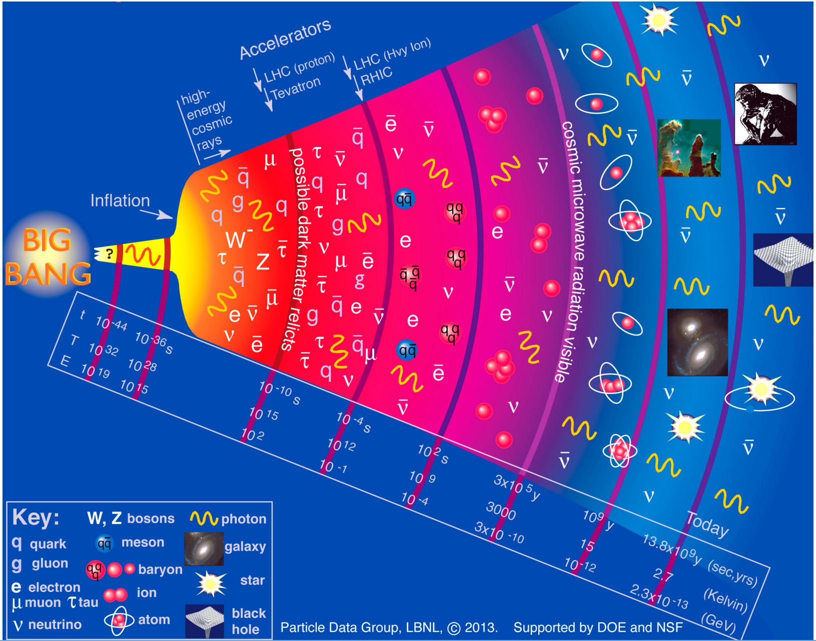
First hints for $\delta_{\mathrm{CP}} \simeq 3/2\pi$

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



History of the universe



Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

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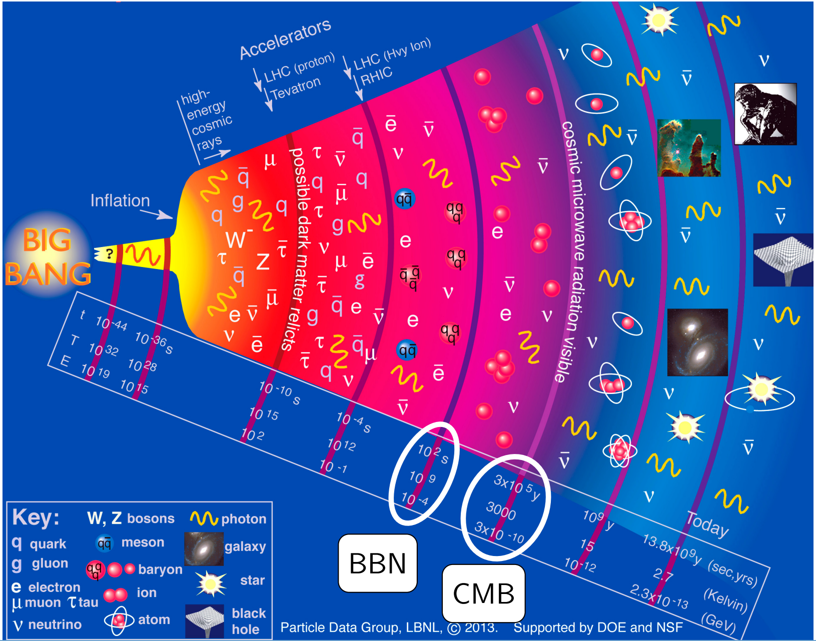

BBN

CMB

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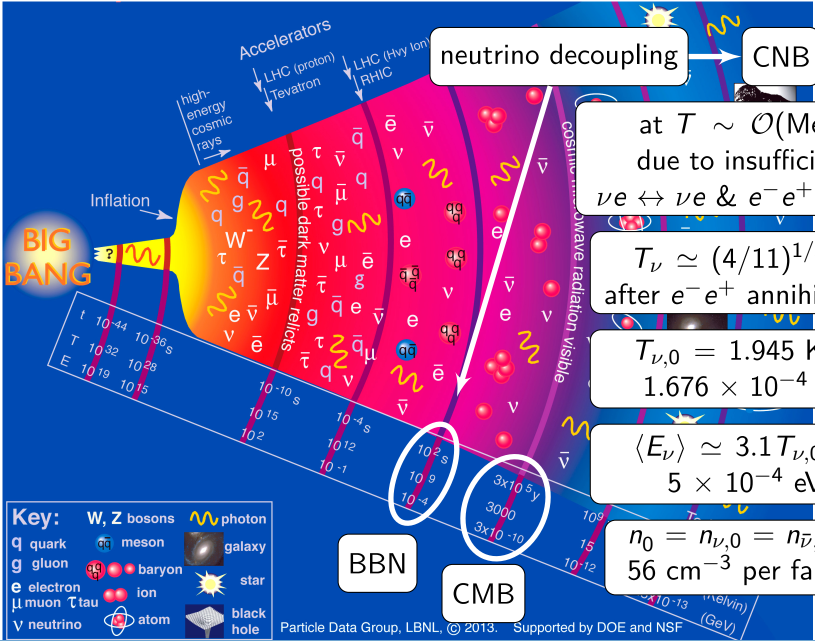

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neutrino decoupling → CNB

at $T \sim \mathcal{O}(\text{MeV})$ 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

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

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

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

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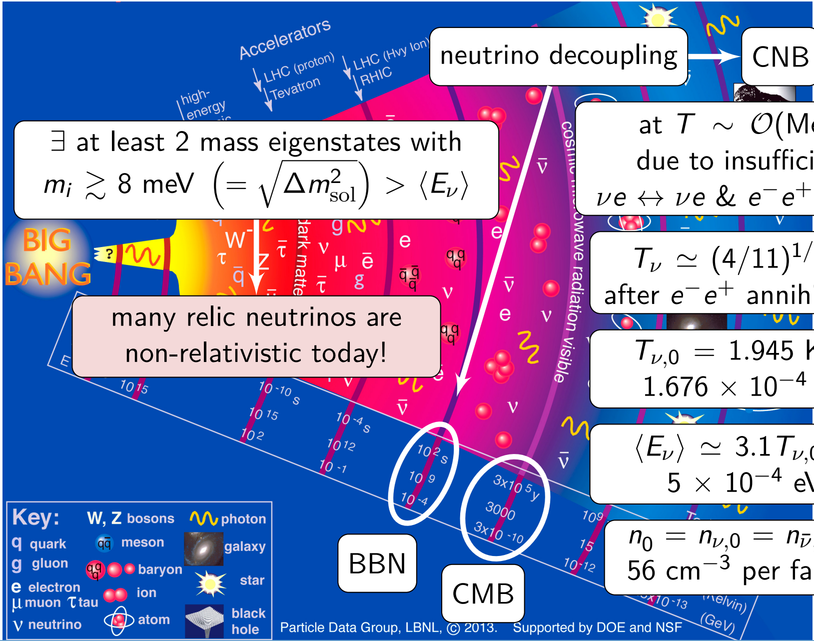

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neutrino decoupling → CNB

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

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

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many relic neutrinos are non-relativistic today!

BBN

CMB

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

Radiation energy density ρ_r in the early Universe:

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

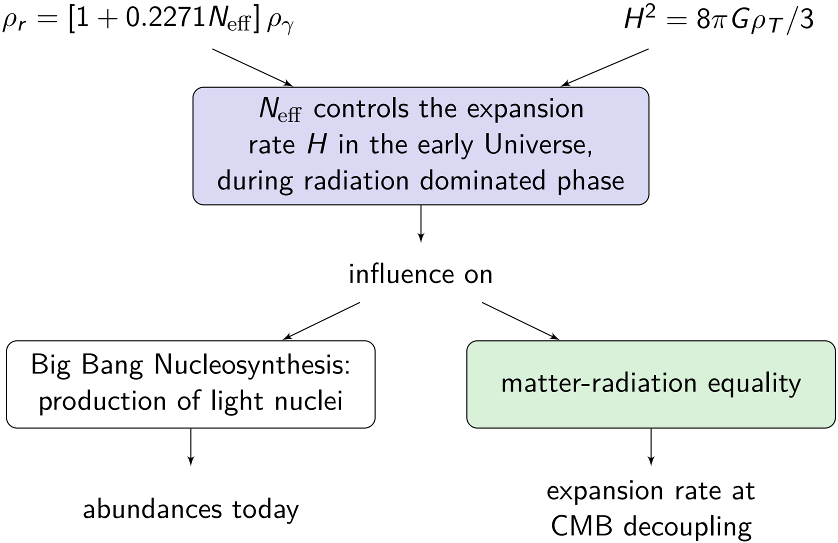
ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \rightarrow$ 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: $N_{\rm eff} \simeq 3.0 \pm 0.2$ [Planck 2018]
Indirect probe of cosmic neutrino background!

$\gg 10\sigma$!

Additional Radiation in the Early Universe



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

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

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

influence on

Big Bang Nucleosynthesis: production of light nuclei

matter-radiation equality

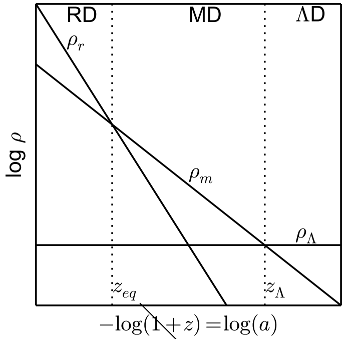
abundances today

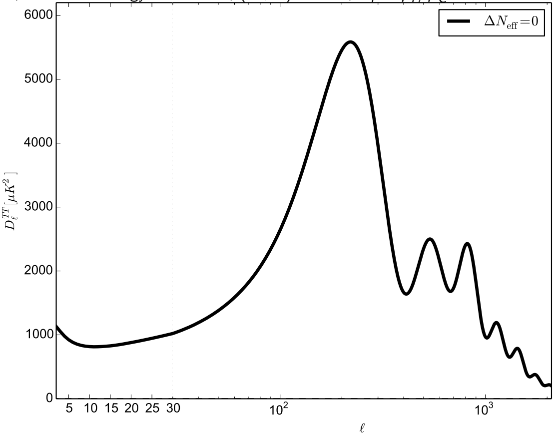
expansion rate at CMB decoupling

Additional Radiation: Effects on the CMB

Starting configuration:

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



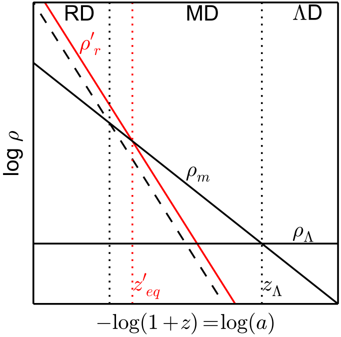


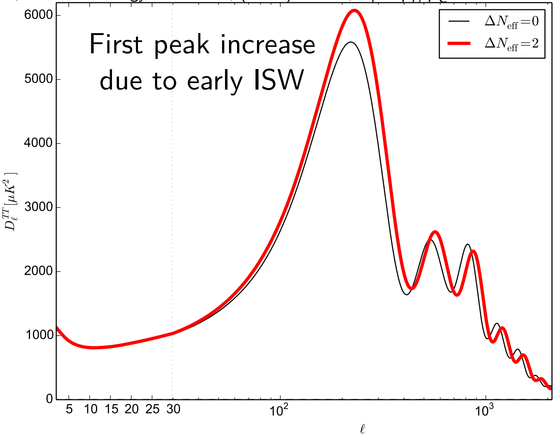
$$1+z_{\rm eq}=\frac{\omega_m}{\omega_r}=\frac{\omega_m}{\omega_\gamma}\frac{1}{1+0.2271\,N_{\rm eff}}$$

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; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$




First peak increase due to early ISW

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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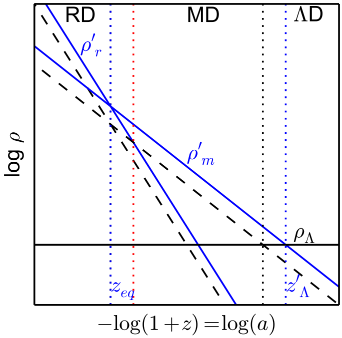

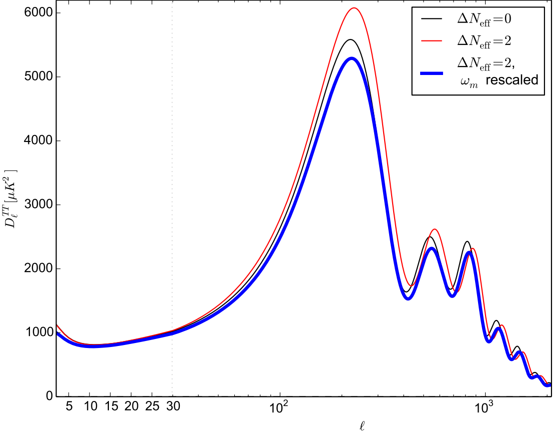

- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high-ℓ peaks ⇒ due to later z_Λ

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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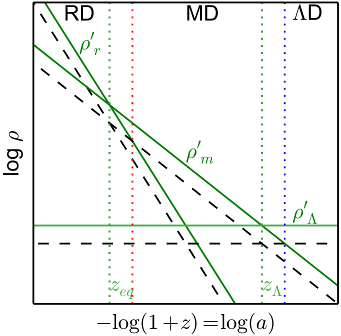
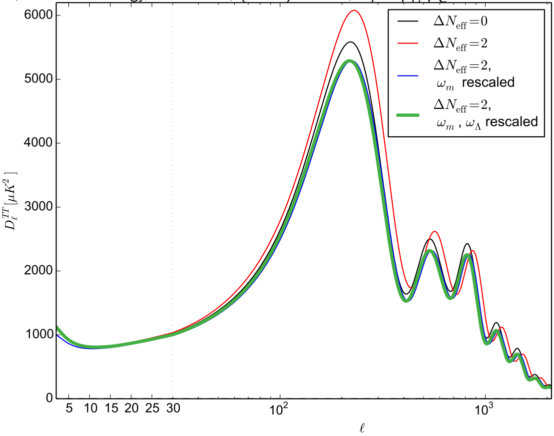
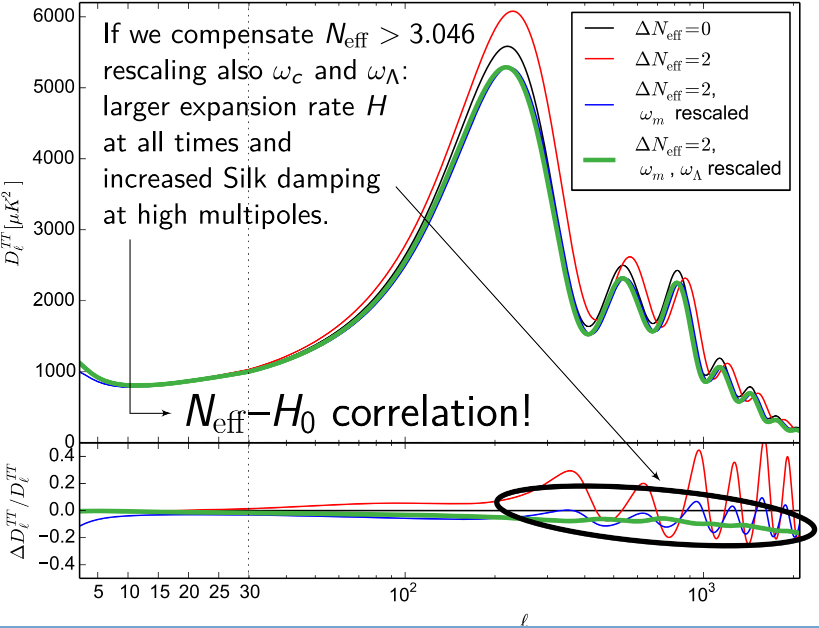




- peak positions recovered;
- slope of the Sachs-Wolfe plateau recovered;
- peak amplitude not recovered!

Additional Radiation: Effects on the CMB



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.

$N_{\rm eff}$–H_0 correlation!

$N_{\rm eff}$ and BBN

BBN: production of light nuclei at $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out:

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 \;=\; H \sim \sqrt{g_\star G_N}\, T^2$$

$$\downarrow$$

$$\boxed{T_{fr} \simeq (g_\star G_N / G_F^4)^{1/6}}$$

enters

$$n/p = \exp(-Q/T_{fr})$$

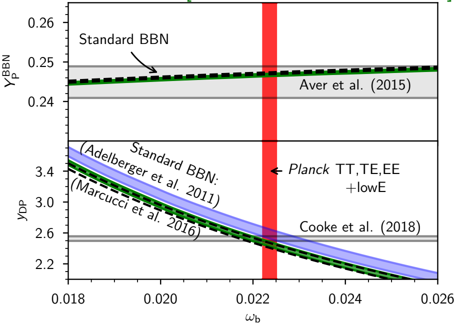
which controls element abundances

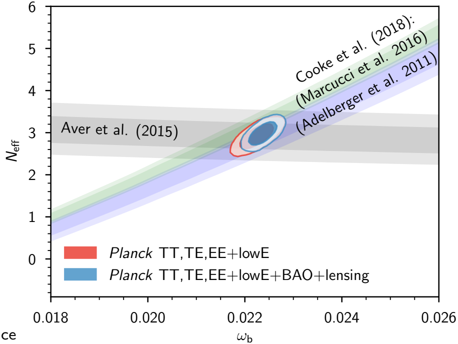
$$\boxed{g_\star \text{ depends on } N_{\rm eff}}$$

$$\downarrow$$

abundances depend on $N_{\rm eff}$

[Planck Collaboration, 2018]





G_F Fermi constant
G_N Newton constant

n, p: neutron, proton density number
$Q = 1.293$ MeV neutron–proton mass difference

$N_{\rm eff}$ and BBN

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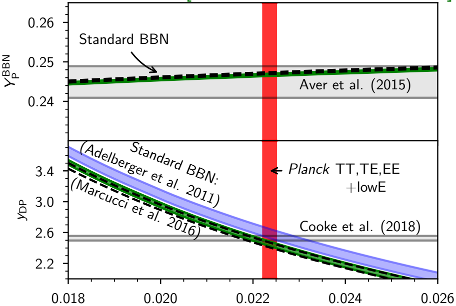

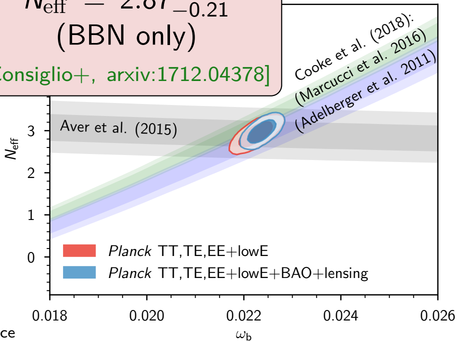

$N_{\rm eff} = 2.87^{+0.24}_{-0.21}$
(BBN only)

[Consiglio+, arxiv:1712.04378]

G_F Fermi constant

G_N Newton constant

n, p: neutron, proton density number

$Q = 1.293$ MeV neutron–proton mass difference

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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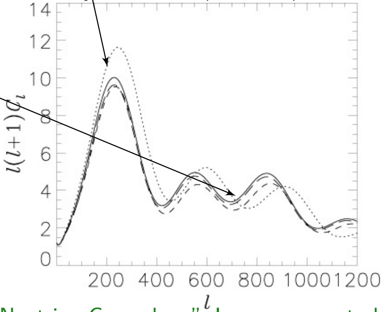


["Neutrino Cosmology", Lesgourgues et al.]

Free-streaming - I

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

Growth equation: $\ddot{\delta} + \underbrace{\boxed{2H\dot{\delta}}}_{\text{Hubble drag}} - \underbrace{\boxed{c_s^2 k^2 \frac{\delta}{a^2}}}_{\text{pressure}} = \underbrace{\boxed{4\pi G_N \rho\, \delta}}_{\text{gravity}}$

Jeans scale: pressure=gravity

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

$k \quad < \quad k_J$

growth of density perturbations

$k \quad > \quad k_J$

no growth can occur

neutrino free-streaming scale

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

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

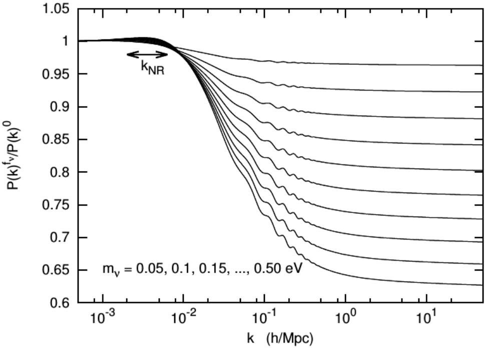
Damping occurs for all $k \gtrsim k_{\rm nr}$

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

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

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



Expected constraints from future surveys:

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

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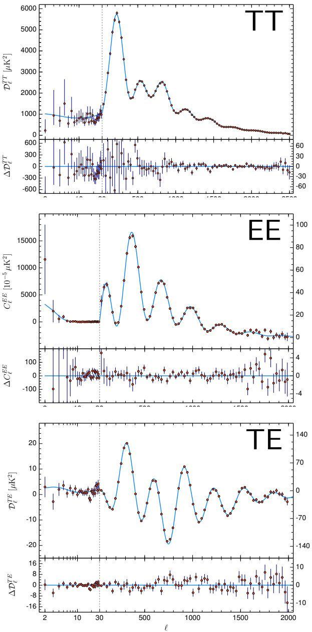
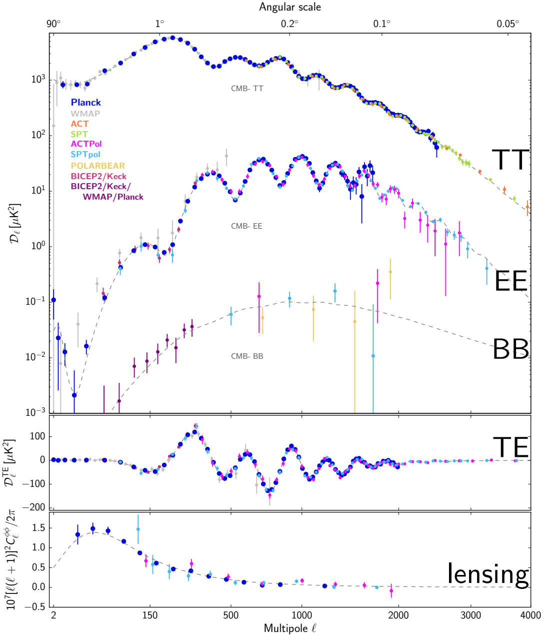
CMB spectra as of 2018

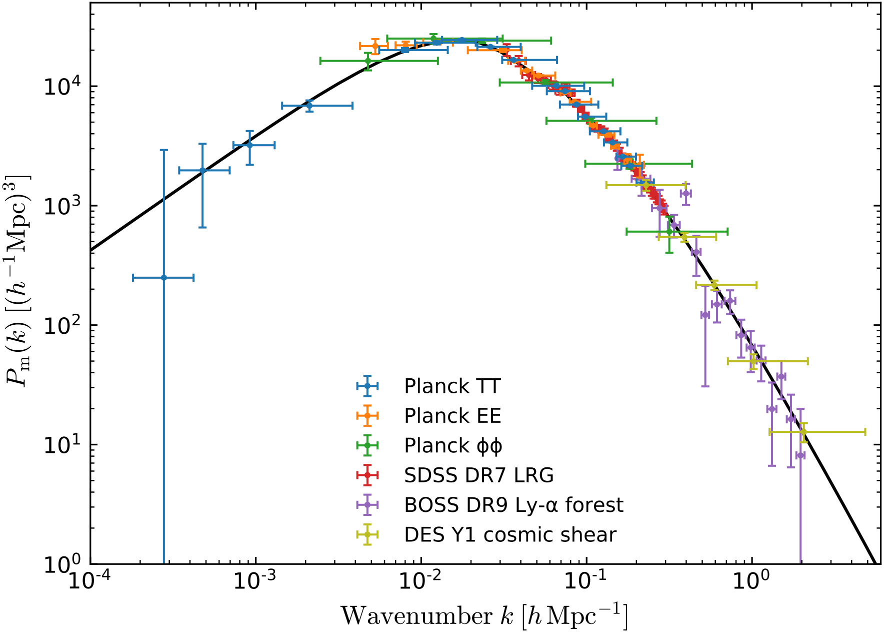
[Planck Collaboration, 2018]





(Linear) matter power spectrum

[Planck Collaboration, 2018]



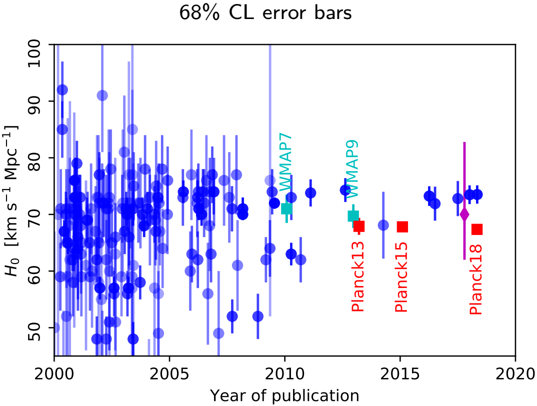
Tension I: the Hubble parameter H_0

[Planck Collaboration, 2018]

$$\boxed{\begin{array}{c} v = H_0 d, \\ \text{with } H_0 = H(z=0) \end{array}}$$

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)



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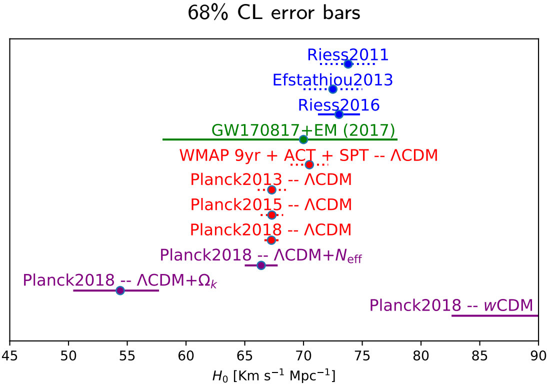

Using HST Cepheids:
[Efstathiou 2013] $H_0 = 72.5 \pm 2.5\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Riess et al., 2016] $H_0 = 73.24 \pm 1.74\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

GW: [Abbott et al., 2017] $H_0 = 70^{+12}_{-8}\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

(ΛCDM model - CMB data only)
[Planck 2013]: $H_0 = 67.3 \pm 1.2\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Planck 2018]: $H_0 = 67.27 \pm 0.60\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

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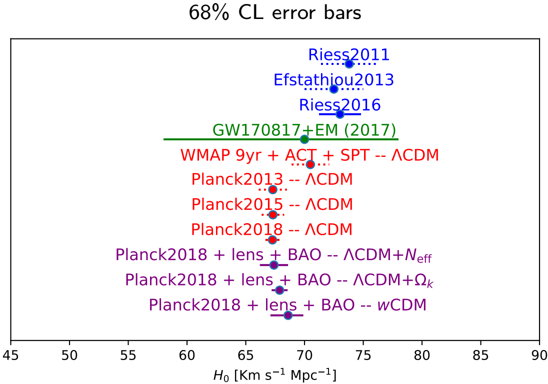


Using HST Cepheids:
[Efstathiou 2013] $H_0 = 72.5 \pm 2.5\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Riess et al., 2016] $H_0 = 73.24 \pm 1.74\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

GW: [Abbott et al., 2017] $H_0 = 70^{+12}_{-8}\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

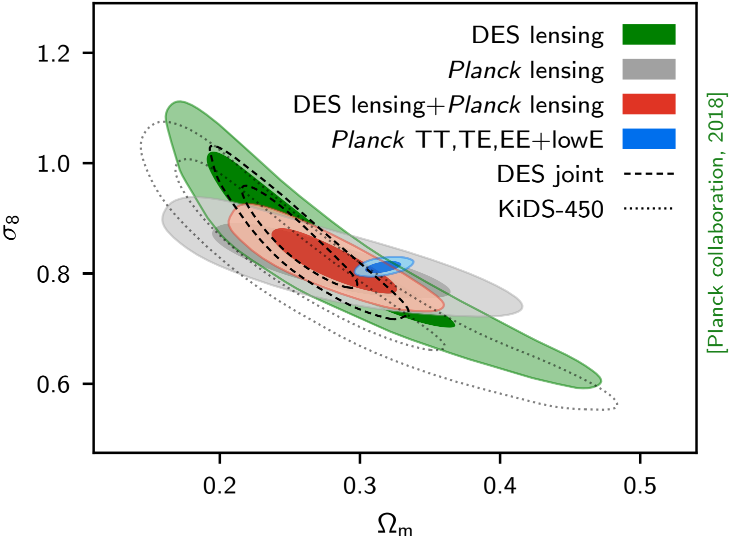
(ΛCDM model - CMB data only)
[Planck 2013]: $H_0 = 67.3 \pm 1.2\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Planck 2018]: $H_0 = 67.27 \pm 0.60\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

Tension II (?): the matter distribution at small scales

Assuming ΛCDM model:

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

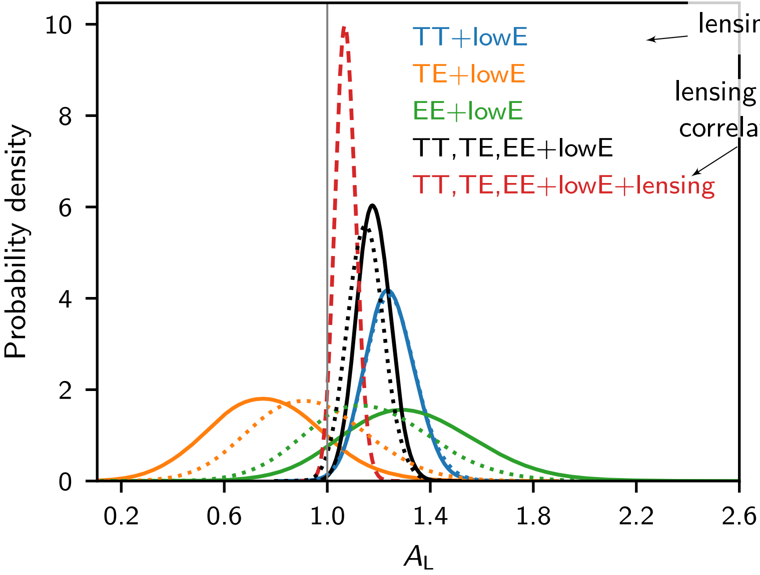
Ω_m: total matter density today divided by the critical density



[Planck collaboration, 2018]

Planck and CMB lensing

[Planck Collaboration, 2018]

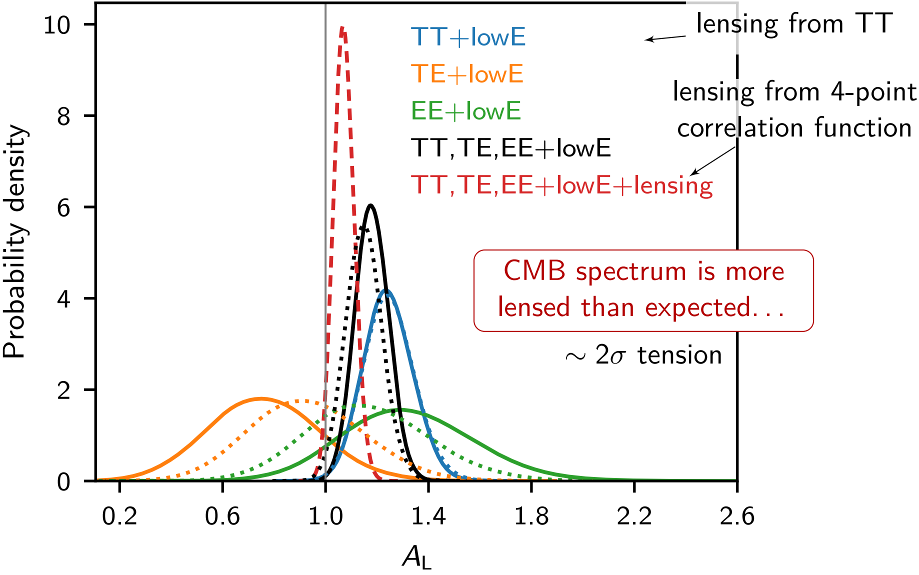


lensing from TT

lensing from 4-point correlation function

Planck and CMB lensing

[Planck Collaboration, 2018]



lensing from TT

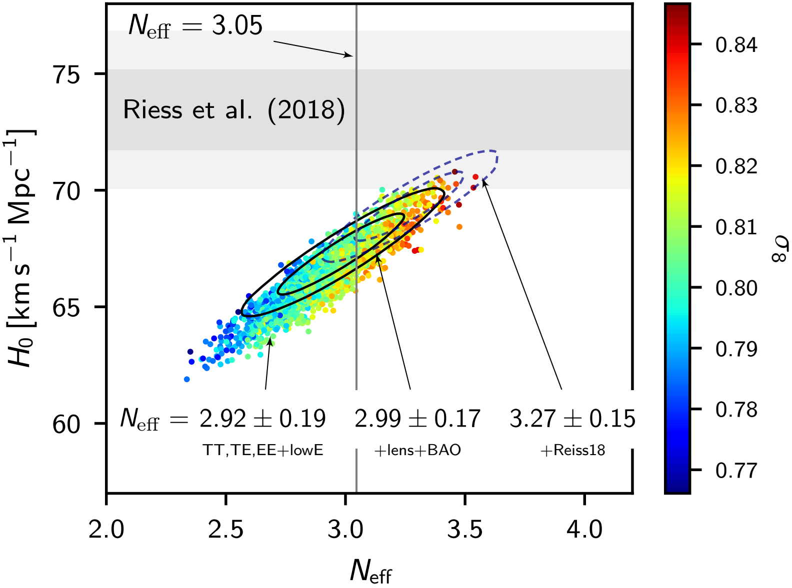
lensing from 4-point correlation function

CMB spectrum is more lensed than expected...

$\sim 2\sigma$ tension

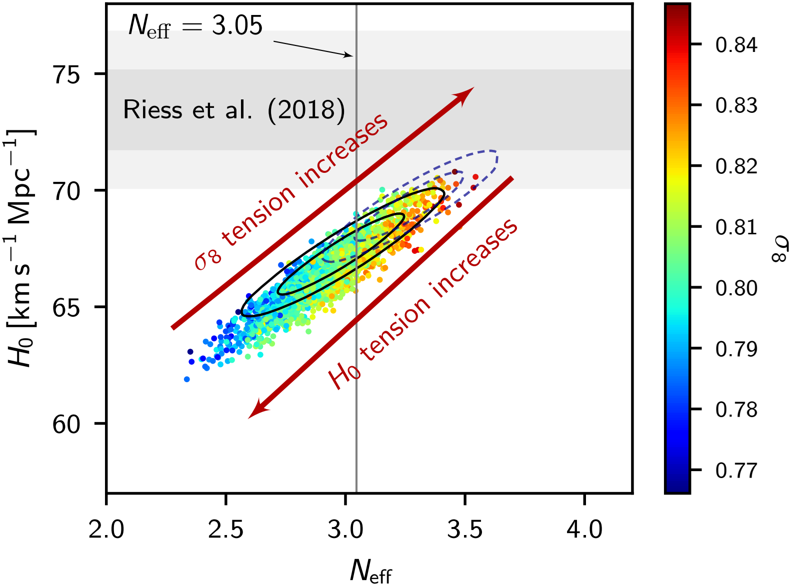
$N_{\rm eff}$ and the local tensions

[Planck Collaboration, 2018]



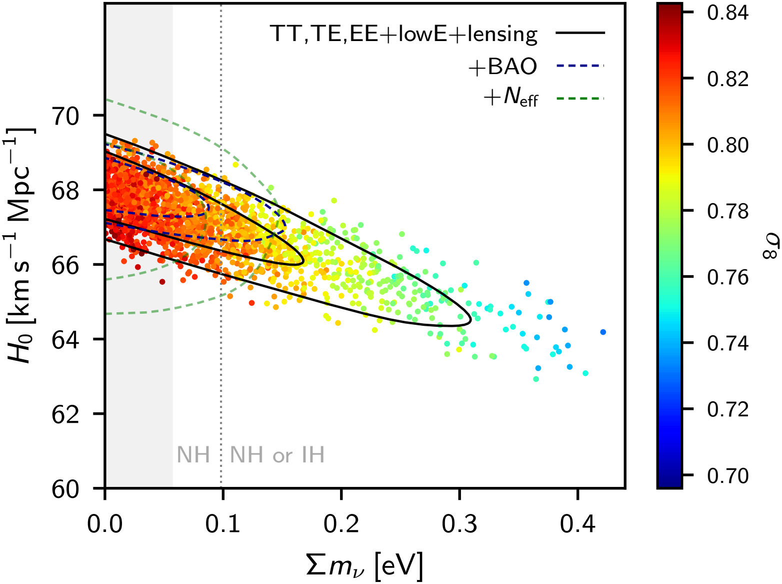
$N_{\rm eff}$ and the local tensions

[Planck Collaboration, 2018]



Σm_ν and the local tensions - I

[Planck Collaboration, 2018]



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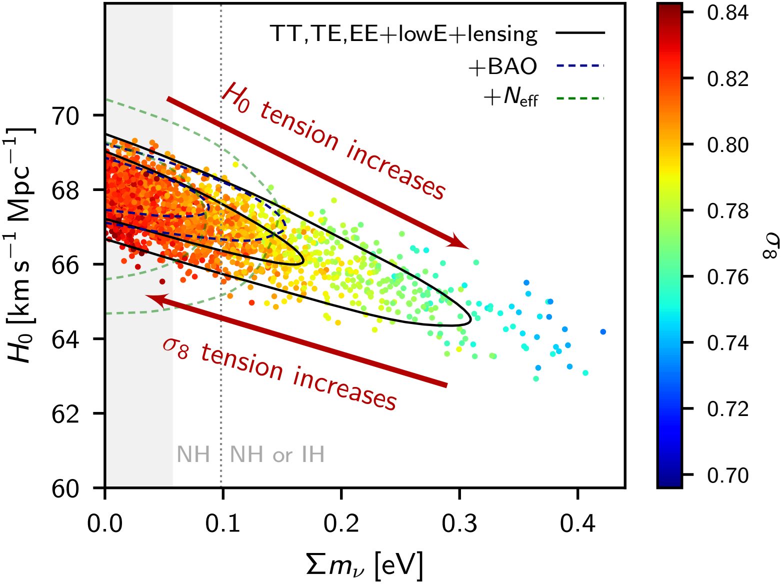
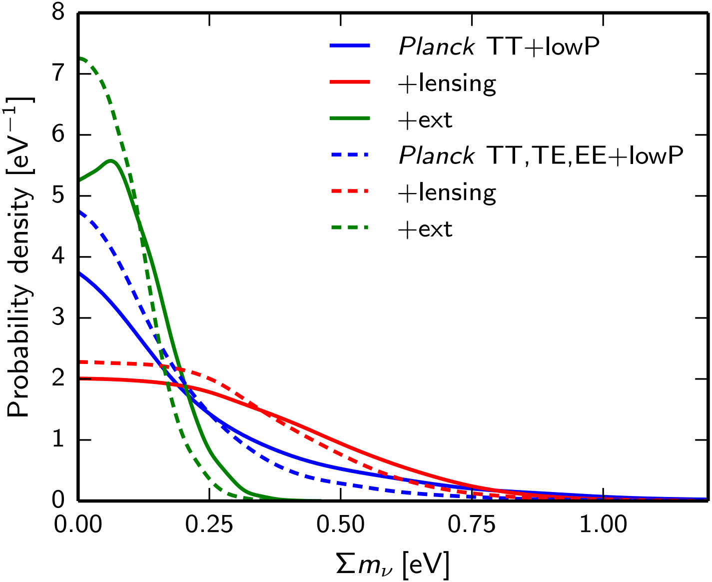


Neutrino masses and CMB lensing

[Planck Collaboration, 2015]



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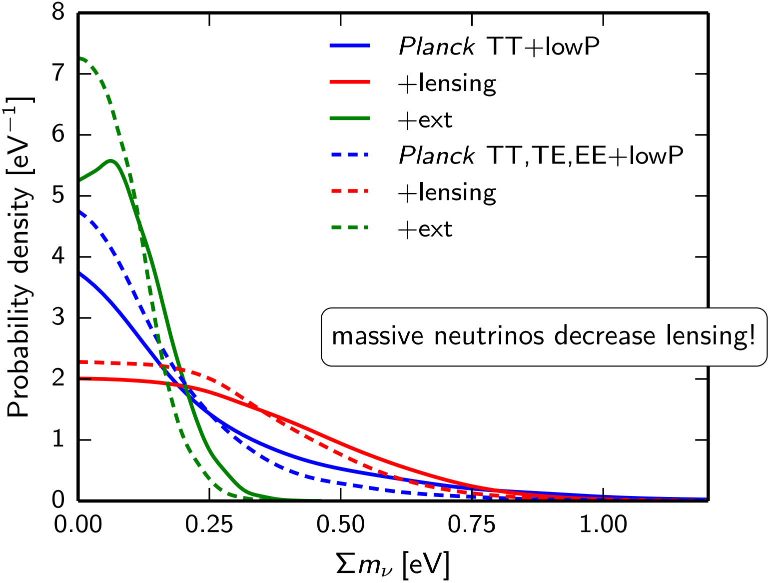


massive neutrinos decrease lensing!

Neutrinos and their masses

[de Salas et al., arxiv:1806.11051]

Normal ordering (NO)

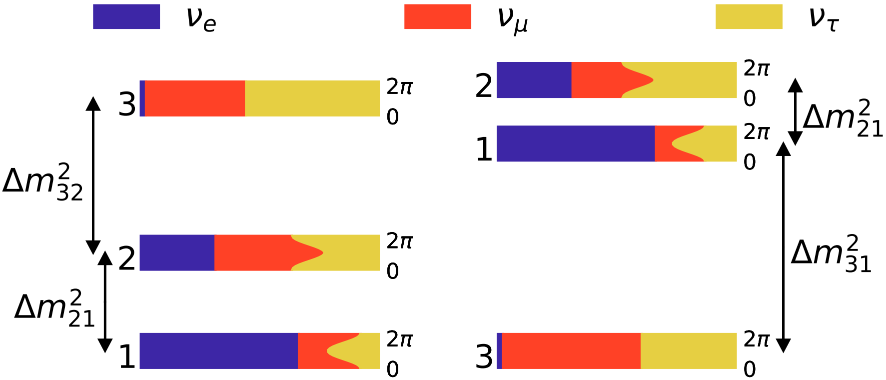
$$m_1 < m_2 < m_3$$

$$\sum m_k \gtrsim 0.06 \text{ eV}$$

Inverted ordering (IO)

$$m_3 < m_1 < m_2$$

$$\sum m_k \gtrsim 0.1 \text{ eV}$$



Absolute scale unknown!

Can we constrain the mass ordering using bounds on $\sum m_\nu$?

Playing with priors

Bayes theorem:

$$\boxed{p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}}$$

posterior depends on prior!

parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_{\mathcal{M}}$ Bayesian evidence

Playing with priors

Bayes theorem:

$$p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}$$

posterior depends on prior!

[Planck 2018]: prior
$0 < \Sigma m_\nu < \mathcal{O}(1)$ eV

strongest upper limit (95%):
$\Sigma m_\nu < 113$ meV
(CMB+lens+BAO+SN)

corresponding to
$\Sigma m_\nu < 53.6$ meV (68%)

below minimum for NO!
does it make sense?

parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_{\mathcal{M}}$ Bayesian evidence

Playing with priors

Bayes theorem:

$$\boxed{p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_\mathcal{M}}}$$

posterior depends on prior!

[Wang+, 2017]

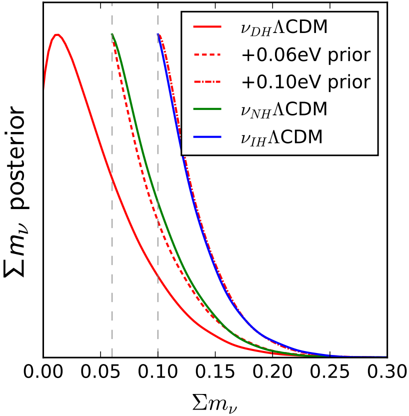
degenerate (DH)

vs normal (NH)

vs inverted (IH) hierarchy

(i.e. change the prior lower bound)

Different limits if you consider simply $\Sigma m_\nu > 0$ or you take into account oscillation results. . .



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Playing with priors

Bayes theorem:

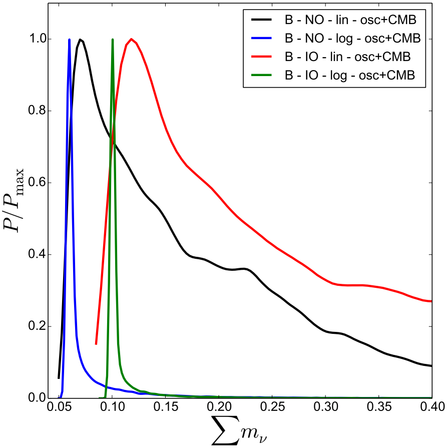
$$p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}$$

posterior depends on prior!

You can artificially tighten
the bounds on Σm_ν
with different priors. . .

[SG+, 2018]

logarithmic
vs **lin**ear prior
on $m_{\rm lightest}$



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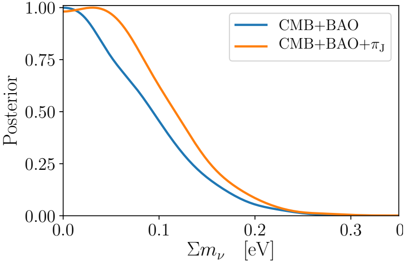
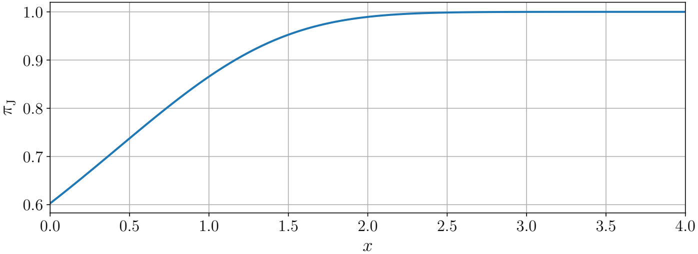


[Hannestad+, 2017]

Jeffreys prior (π_J) for Σm_ν

π_J makes the posterior maximally sensitive to data
for constrained parameter, compensate border effect



parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_{\mathcal{M}}$ Bayesian evidence

Playing with the baseline model

what if we release the assumption of the ΛCDM model?

CMB TT + lens

CMB TT,TE,EE

$\Sigma m_\nu < 0.68$ eV

$\Sigma m_\nu < 0.49$ eV

[Planck 2015]

ΛCDM

CMB TT + lens + BAO

CMB TT,TE,EE + BAO

$\Sigma m_\nu < 0.25$ eV

$\Sigma m_\nu < 0.17$ eV

Playing with the baseline model

what if we release the assumption of the ΛCDM model?

CMB TT + lens **CMB TT,TE,EE**		CMB TT + lens + BAO **CMB TT,TE,EE + BAO**
$\Sigma m_\nu < 0.68$ eV $\Sigma m_\nu < 0.49$ eV	[Planck 2015] ΛCDM	$\Sigma m_\nu < 0.25$ eV $\Sigma m_\nu < 0.17$ eV
-	wCDM free dark energy equation of state $w \neq -1$	$\Sigma m_\nu < 0.37$ eV [Planck 2015] $\Sigma m_\nu < 0.27$ eV [Wang+, 2016]

Playing with the baseline model

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-	[Planck 2015] ΛCDM+A_{lens} free phenomenological lensing amplitude $A_{\mathrm{lens}} \neq -1$	$\Sigma m_\nu < 0.41$ eV

Playing with the baseline model

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CMB TT + lens **CMB TT,TE,EE**		CMB TT + lens + BAO **CMB TT,TE,EE + BAO**
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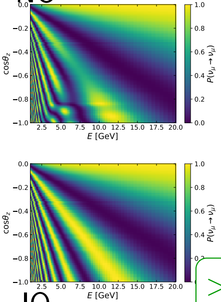
$\Sigma m_\nu < 0.96$ eV	[Di Valentino+, 2015] eCDM 12-parameters cosmological model, ΛCDM based	$\Sigma m_\nu < 0.53$ eV

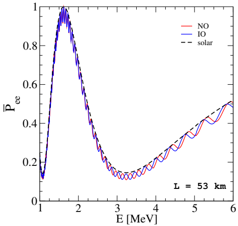
Constraining the mass ordering

[de Salas et al., arxiv:1806.11051]

NO

oscillations





IO

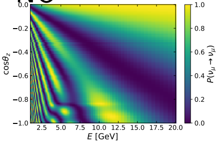
$> 3\sigma$ preference for NO

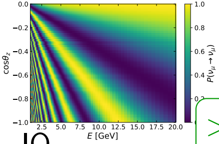
Constraining the mass ordering

[de Salas et al., arxiv:1806.11051]

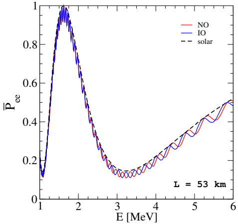
oscillations

NO



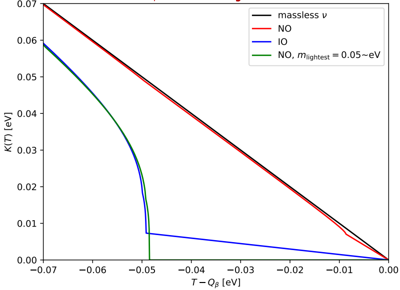


IO

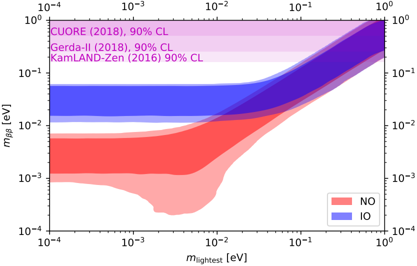


$> 3\sigma$ preference for NO

β decay



$0\nu\beta\beta$ decay



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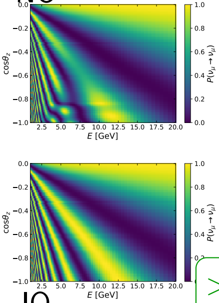
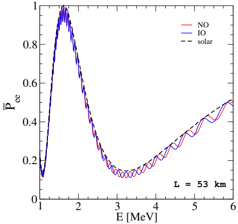
NO

oscillations



IO



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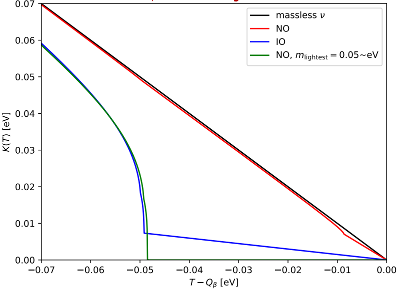

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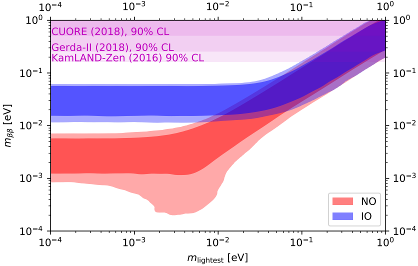
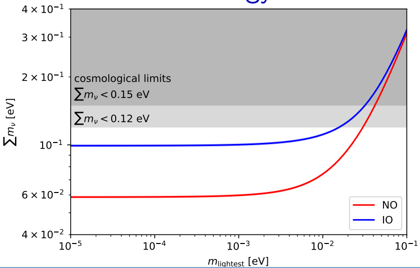


cosmology



(Bayesian) results

[de Salas et al., arxiv:1806.11051]

Bayes theorem for models:

$$\boxed{p(\mathcal{M}|d) \propto Z_{\mathcal{M}}\pi(\mathcal{M})}$$

Bayesian evidence:

$$\boxed{Z_{\mathcal{M}} = \int_{\Omega_{\mathcal{M}}} \mathcal{L}(\theta)\,\pi(\theta)\,d\theta}$$

Bayes factor NO vs IO:

$$\boxed{B_{\mathrm{NO,IO}} = Z_{\mathrm{NO}}/Z_{\mathrm{IO}}}$$

Posterior probability:

$$\boxed{\begin{aligned} P_{\mathrm{NO}} &= B_{\mathrm{NO,IO}}/(B_{\mathrm{NO,IO}}+1) \\ P_{\mathrm{IO}} &= 1/(B_{\mathrm{NO,IO}}+1) \end{aligned}}$$

$\pi(\mathcal{M})$ model prior

$p(\mathcal{M}|d)$ model posterior

$\mathcal{L}(\theta)$ likelihood

$\Omega_{\mathcal{M}}$ parameter space, for parameters θ

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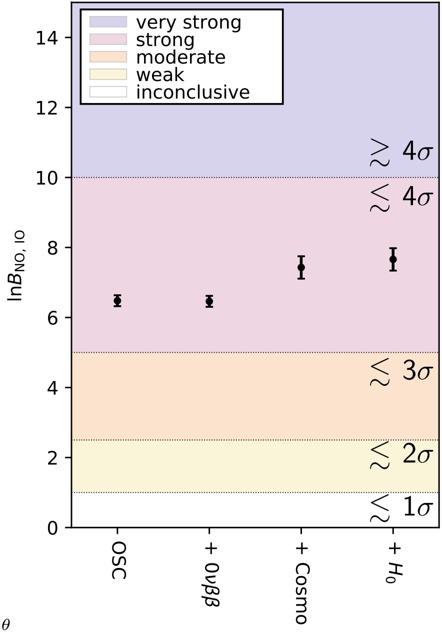

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- Massive neutrinos in the late Universe

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- Mass ordering

3 ***Direct detection of relic neutrinos***

4 *Conclusions*

A viable detection method

[Long et al., JCAP 08 (2014) 038]

How to directly detect non-relativistic neutrinos?

Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today → a process without energy threshold is necessary

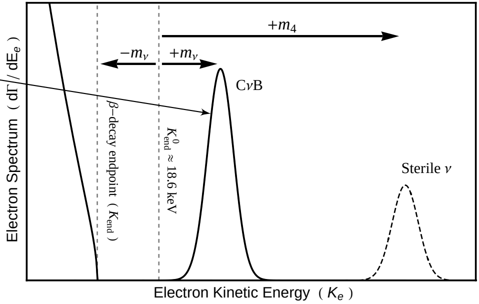
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

Main background: β decay $n \to p + e^- + \bar{\nu}$!

signal is a peak at $2m_\nu$
above β–decay endpoint

only with a lot of material

need a very good energy resolution



PTOLEMY

[Long et al., JCAP 08 (2014) 038]
[Betts et al., arxiv:1307.4738]
[PTOLEMY LoI, arxiv:1808.01892]

PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq$ ~~0.1 eV~~? 0.05 eV?

built mainly for CNB

can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

$M_T = 100$ g of atomic ^{3}H

$$\boxed{\Gamma_{\rm CNB} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})]\, N_T\, \bar\sigma} \quad \sim \mathcal{O}(10)\ \text{yr}^{-1}$$

N_T number of ^{3}H nuclei in a sample of mass M_T $\bar\sigma \simeq 3.834 \times 10^{-45}$ cm^2 n_i number density of neutrino i

(without clustering)

PTOLEMY

[Long et al., JCAP 08 (2014) 038]
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ehnancement from ν clustering in the galaxy?

$$\Gamma_{\text{CNB}} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})]\, N_T\, \bar{\sigma} \quad \sim \mathcal{O}(10)\ \text{yr}^{-1}$$

N_T number of ^{3}H nuclei in a sample of mass M_T $\bar{\sigma} \simeq 3.834 \times 10^{-45}$ cm^2 n_i number density of neutrino i

(without clustering)

Detection of the relic neutrinos

[PTOLEMY LoI, arxiv:1808.01892]

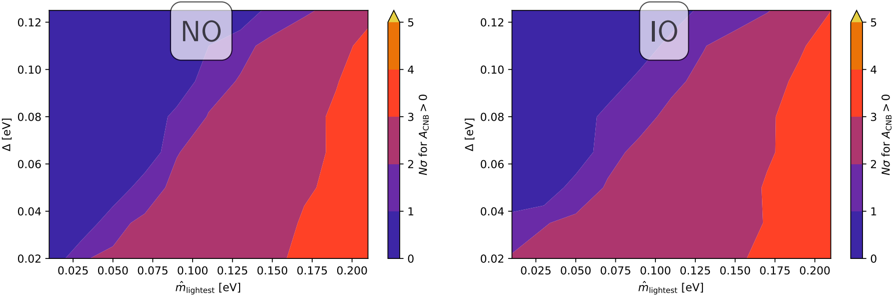
using the definition:

$$\boxed{N^i_{\rm th}(\boldsymbol{\theta}) = A_\beta N^i_\beta(\hat{E}_{end} + \Delta E_{end}, m_i, U) + \boldsymbol{A}_{\mathbf{CNB}} N^i_{\rm CNB}(\hat{E}_{end} + \Delta E_{end}, m_i, U) + N_b}$$

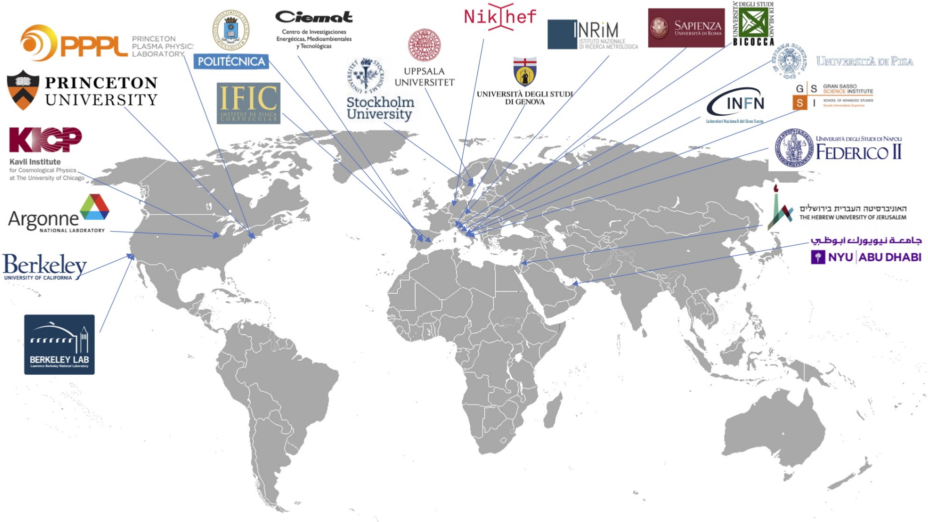
if $\boldsymbol{A}_{\mathbf{CNB}} > 0$ at $N\sigma$, direct detection of CNB accomplished at $N\sigma$

statistical only!

significance on $A_{\rm CNB} > 0$
as a function of $\hat{m}_{\rm lightest}$, Δ



PTOLEMY collaboration



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Conclusions

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Cosmology is an excellent tool
for studying neutrino properties!

In particular, **masses** and **effective number**

2

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

In particular: **priors**, **model extensions**

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We need more data in order to
break degeneracies
between different parameters!

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Bonus

For a not-so-near future:
direct detection of relic neutrinos**???**
A long way to go. . .

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Bonus

For a not-so-near future:
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A long way to go. . .

Thank you for the attention!

5 Neutrinos

6 PTOLEMY

7 Light sterile neutrinos

Cosmological neutrino mass bounds

Cosmology can constrain $M_\nu = \sum m_\nu$

standard

based on ΛCDM model

[Planck Collaboration 2015, AA594 (2016) A13]

95%

$M_\nu < 0.72$ eV (PlanckTT+lowP)

$M_\nu < 0.21$ eV (+BAO)

$M_\nu < 0.49$ eV (PlanckTTTEEE+lowP)

$M_\nu < 0.17$ eV (+BAO)

see also:

[Vagnozzi et al., PRD96 (2017) 123503]

[Planck Collaboration 2016, AA596 (2016) A107]

95%

$M_\nu < 0.59$ eV (PlanckTT+`SimLow`)

$M_\nu < 0.17$ eV (+BAO)

$M_\nu < 0.34$ eV (PlanckTTTEEE+`SimLow`)

$M_\nu < 0.14$ eV (+BAO)

(`SimLow` not public yet)

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[Planck Collaboration 2016, AA596 (2016) A107]

95%

$M_\nu < 0.59$ eV (PlanckTT+`SimLow`)

$M_\nu < 0.17$ eV (+BAO)

$M_\nu < 0.34$ eV (PlanckTTTEEE+`SimLow`)

$M_\nu < 0.14$ eV (+BAO)

(`SimLow` not public yet)

Modified gravity?

[Barreira et al., 2014]:

νGalileon

68%

$M_\nu = 0.98 \pm 0.24$ eV (CMB)

$M_\nu = 0.65 \pm 0.11$ eV (CMB+BAO)

[Bellomo et al., 2016]:

95%

Horndeski scalar-tensor

$M_\nu < 0.76$ eV

[Dirian, 2017]:

68%

nonlocal gravity

$M_\nu = 0.21 \pm 0.08$ eV

[Peirone et al, 2017]:

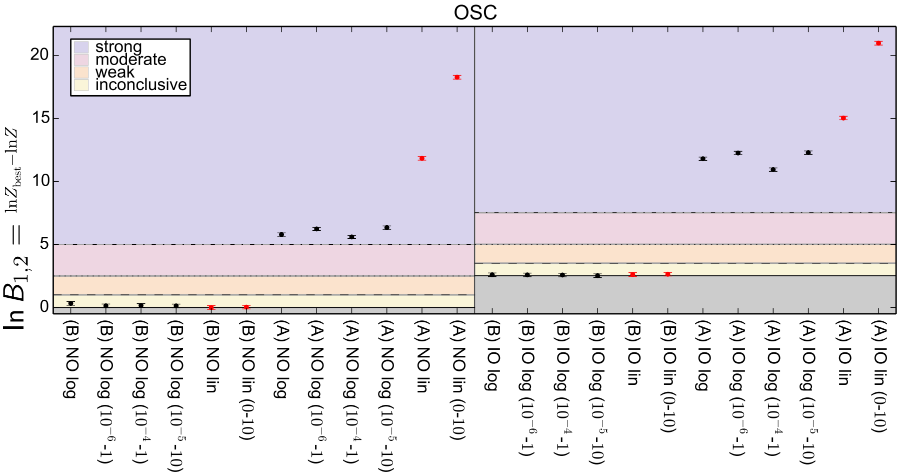
68%

Covariant Galileon

$M_\nu = 0.8 \pm 0.1$ eV

Comparing parameterizations/priors

[SG et al., JCAP 03 (2018) 11]

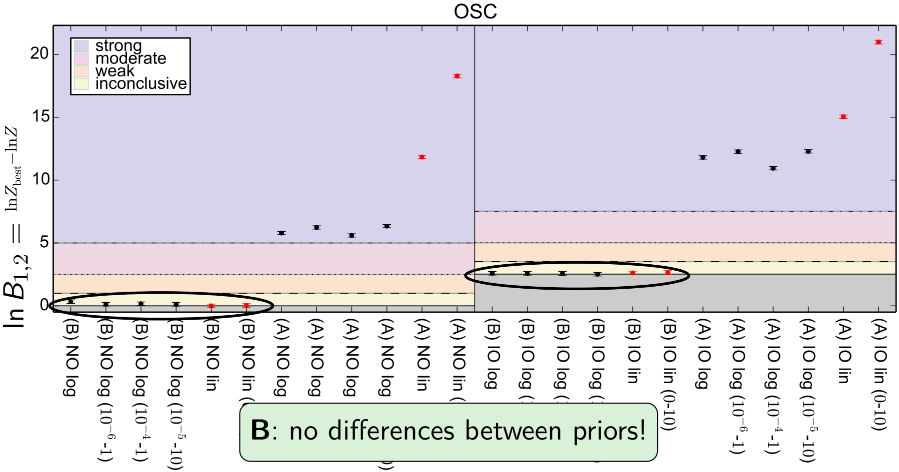


A: $(m_1,\ m_2,\ m_3)$

B: $(m_{\rm lightest},\ \Delta m^2_{21},\ \Delta m^2_{31})$

Comparing parameterizations/priors

[SG et al., JCAP 03 (2018) 11]

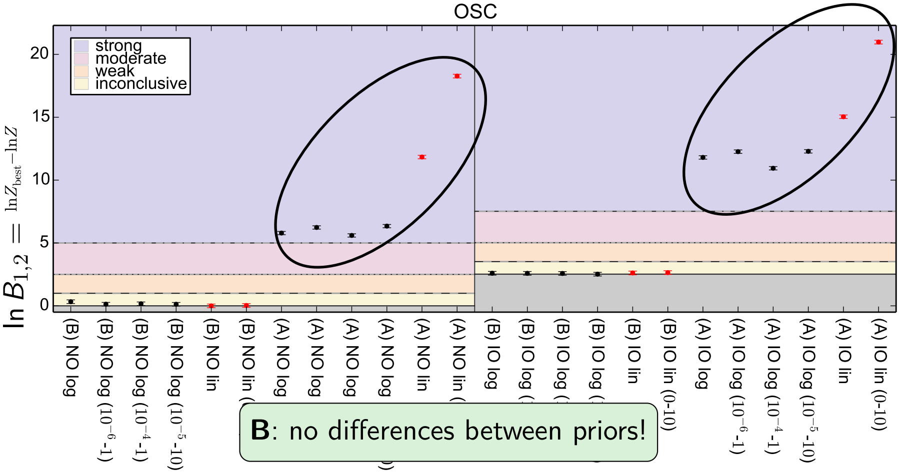


B: no differences between priors!

(no penalty for unconstrained parameter $m_{\rm lightest}$!)

Comparing parameterizations/priors

[SG et al., JCAP 03 (2018) 11]



B: no differences between priors!

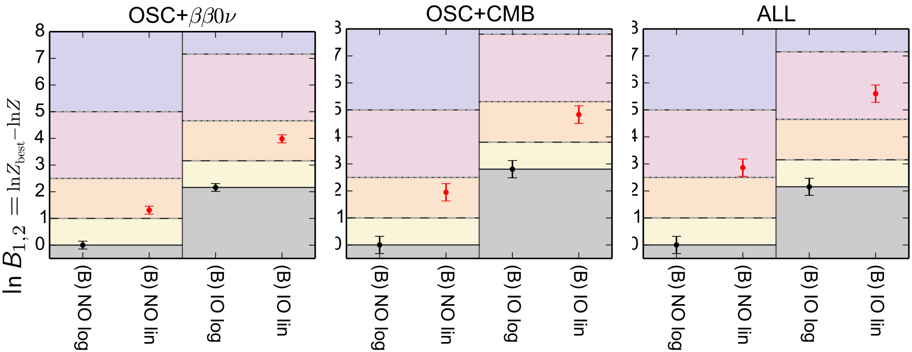
(no penalty for unconstrained parameter $m_{\rm lightest}$!)

A: always strongly disfavored!

(waste of parameter space, no unconstrained parameters due to Δm^2_{i1}!)

Comparing parameterizations/priors

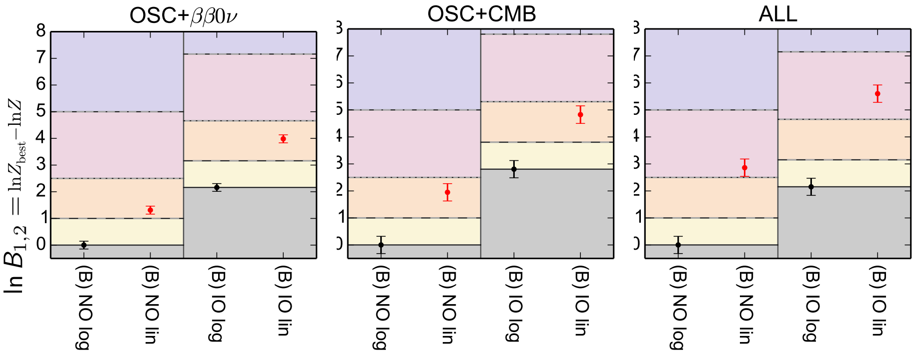
[SG et al., JCAP 03 (2018) 11]



compare linear versus **logarithmic**

Comparing parameterizations/priors

[SG et al., JCAP 03 (2018) 11]



compare linear versus **logarithmic**

log priors are
weakly-to-moderately more efficient

summary: $(m_\text{lightest}, \Delta m^2_{21}, \Delta m^2_{31})$, log prior is better!

5 *Neutrinos*

6 ***PTOLEMY***

7 *Light sterile neutrinos*

β and Neutrino Capture spectra

[PTOLEMY LoI, arxiv:1808.01892]

$$\boxed{\frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{i=1}^{N_\nu}\bar{\sigma}\,N_T\,|U_{ei}|^2\,f_{c,i}\,n_0 \times e^{-\frac{[E_e-(E_{\rm end}+m_i+m_{\rm lightest})]^2}{2\sigma^2}}}$$

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2}N_T\sum_{i=1}^{N_\nu}|U_{ei}|^2H(E_e,m_i)$$

$$\boxed{\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty}dx\,\frac{d\Gamma_\beta}{dE_e}(x)\,\exp\left[-\frac{(E_e-x)^2}{2\sigma^2}\right]}$$

$\bar{\sigma}$ cross section, N_T number of tritium atoms in $M_T = 100$ g, $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

β and Neutrino Capture spectra

[PTOLEMY LoI, arxiv:1808.01892]

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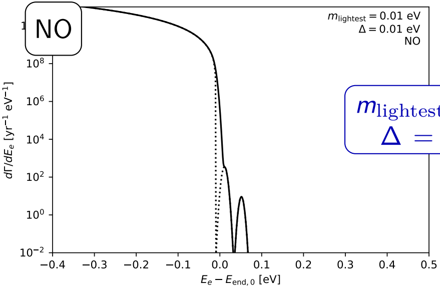

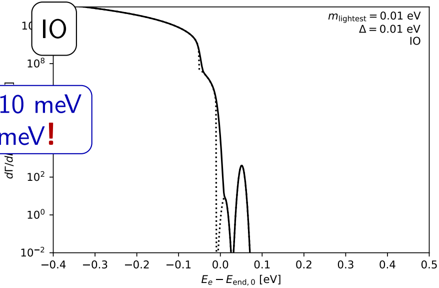

$m_{\rm lightest} = 10$ meV
$\Delta = 10$ meV!

$\bar{\sigma}$ cross section, N_T number of tritium atoms in $M_T = 100$ g, $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

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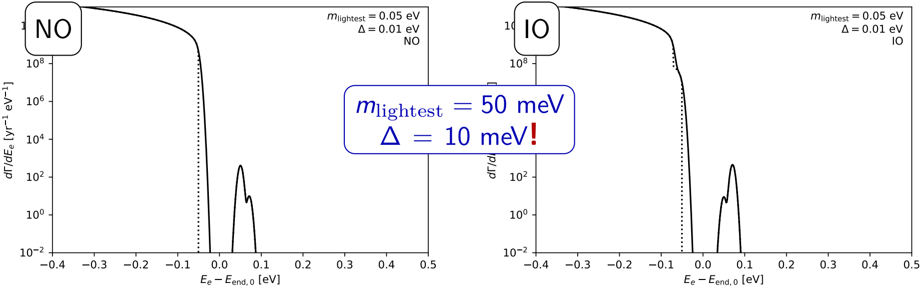

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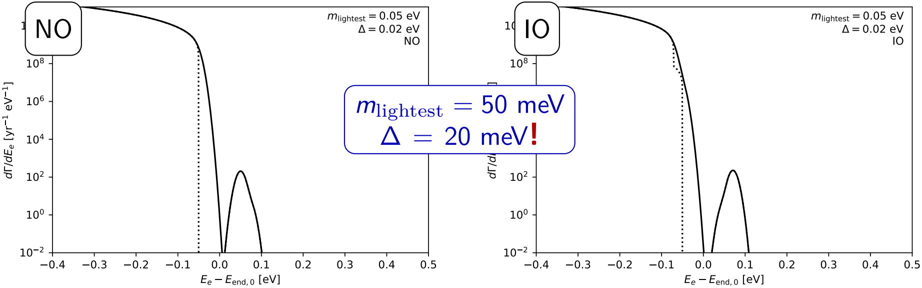

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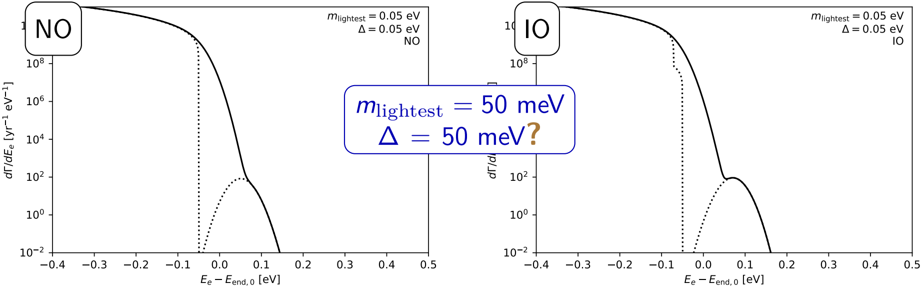


$m_{\rm lightest} = 50$ meV
$\Delta = 50$ meV?

$\bar{\sigma}$ cross section, N_T number of tritium atoms in $M_T = 100$ g, $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

Detection of the relic neutrinos

[PTOLEMY LoI, arxiv:1808.01892]

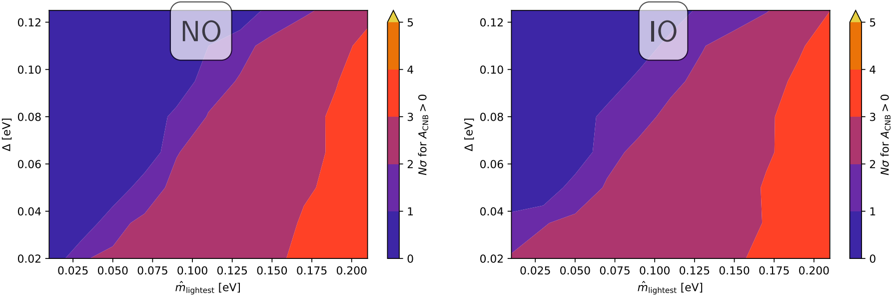
using the definition:

$$\boxed{N^i_{\mathrm{th}}(\boldsymbol{\theta}) = A_\beta N^i_\beta(\hat{E}_{end} + \Delta E_{end}, m_i, U) + \boldsymbol{A_{\mathrm{CNB}}} N^i_{\mathrm{CNB}}(\hat{E}_{end} + \Delta E_{end}, m_i, U) + N_b}$$

if $\boldsymbol{A_{\mathrm{CNB}}} > 0$ at $N\sigma$, direct detection of CNB accomplished at $N\sigma$

statistical only!

significance on $A_{\mathrm{CNB}} > 0$
as a function of $\hat{m}_{\mathrm{lightest}}$, Δ



Simulations - I

[PTOLEMY LoI, arxiv:1808.01892]

Events in **bin** i, centered at E_i:

$$N^i_\beta = T\int_{E_i-\Delta/2}^{E_i+\Delta/2}\frac{d\widetilde{\Gamma}_\beta}{dE_e}dE_e \qquad N^i_{\rm CNB} = T\int_{E_i-\Delta/2}^{E_i+\Delta/2}\frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e}dE_e$$

fiducial number of events: $\hat{N}^i = N^i_\beta(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) + N^i_{\rm CNB}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$

add **background** $\hat{N}_b = \hat{\Gamma}_b T$
with $\hat{\Gamma}_b \simeq 10^{-5}$ Hz

$$\longrightarrow \boxed{N^i_t = \hat{N}^i + \hat{N}_b}$$

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

Simulations - I

[PTOLEMY LoI, arxiv:1808.01892]

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$$\longrightarrow \boxed{N^i_t = \hat{N}^i + \hat{N}_b}$$

simulated experimental spectrum:

$$\boxed{N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) = N^i_t \pm \sqrt{N^i_t}}$$

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

Simulations - I

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simulated experimental spectrum: $\boxed{N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) = N^i_t \pm \sqrt{N^i_t}}$

repeat for theory spectrum, free **amplitudes** and **endpoint position**:

$$\boxed{N^i_{\rm th}(\boldsymbol{\theta}) = \boldsymbol{A_\beta} N^i_\beta(\hat{E}_{end} + \boldsymbol{\Delta E_{end}}, m_i, U) + \boldsymbol{A_{\rm CNB}} N^i_{\rm CNB}(\hat{E}_{end} + \boldsymbol{\Delta E_{end}}, m_i, U) + N_b}$$

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Simulations - I

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fit ⟶ $\boxed{\chi^2(\boldsymbol{\theta}) = \sum_i \left(\frac{N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) - N^i_{\rm th}(\boldsymbol{\theta})}{\sqrt{N^i_t}}\right)^2}$ or $\log\mathcal{L} = -\frac{\chi^2}{2}$

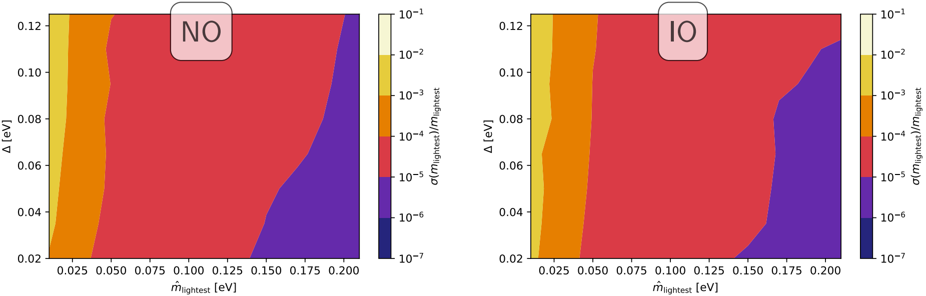
T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

Perspectives for the mass determination

[PTOLEMY LoI, arxiv:1808.01892]

statistical only!

relative error on $m_{\rm lightest}$
as a function of $\hat{m}_{\rm lightest}$, Δ



wonderful precision in determining the neutrino mass

(well, yes, with 100 g of tritium...)

Δ has almost no impact

Neutrino mass ordering

[PTOLEMY LoI, arxiv:1808.01892]

Bayesian method:

Fit fiducial ordering ($\widehat{\mathrm{NO}}$ or $\widehat{\mathrm{IO}}$) using both correct and wrong ordering

$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$

$\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

Neutrino mass ordering

[PTOLEMY LoI, arxiv:1808.01892]

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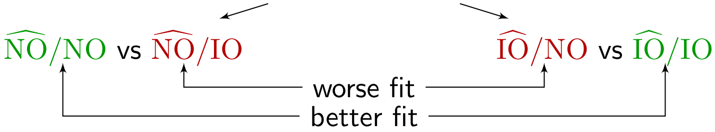

$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$

$\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit

better fit

Neutrino mass ordering

[PTOLEMY LoI, arxiv:1808.01892]

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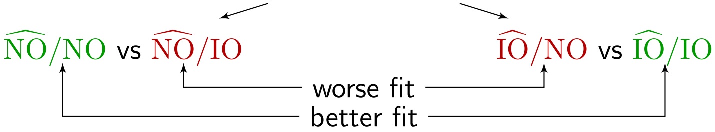


$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$

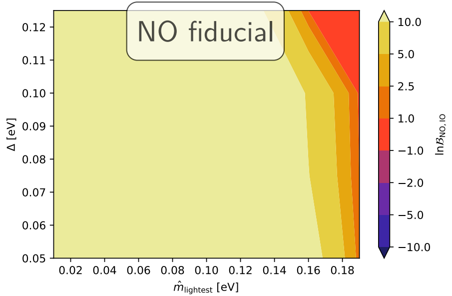
$\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit

better fit

statistical only!

(Bayesian) preference on $m_{\rm lightest}$
as a function of $\hat{m}_{\rm lightest}$, Δ



IO fiducial

work in progress

Neutrino mass ordering

[PTOLEMY LoI, arxiv:1808.01892]

Bayesian method:

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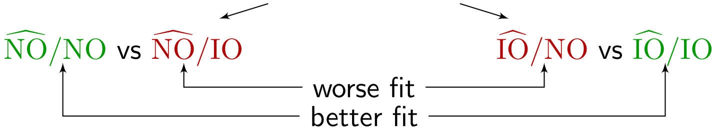


$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$

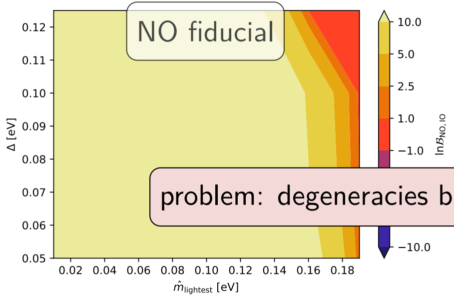
$\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit

better fit

statistical only!

(Bayesian) preference on m_{lightest}
as a function of $\hat{m}_{\mathrm{lightest}}$, Δ



NO fiducial

IO fiducial

work in progress

problem: degeneracies between m_{lightest} and Δm^2_{31}

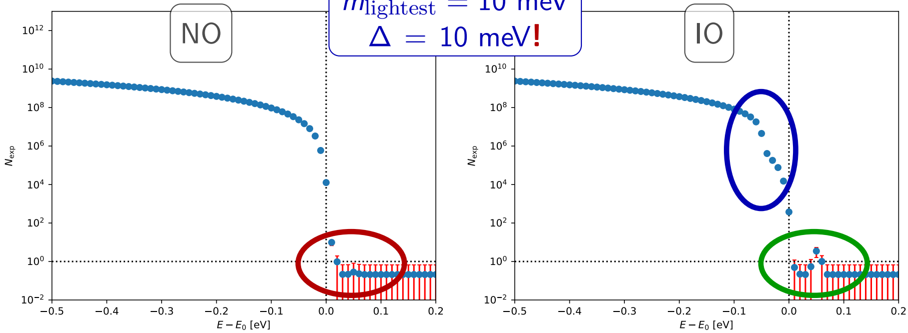
Simulations - II

[PTOLEMY LoI, arxiv:1808.01892]

no random noise?

$m_{\rm lightest} = 10$ meV

$\Delta = 10$ meV!

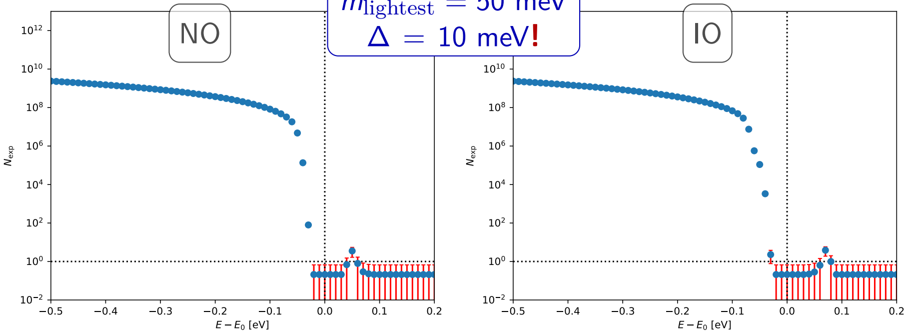


Simulations - II

[PTOLEMY LoI, arxiv:1808.01892]

no random noise?

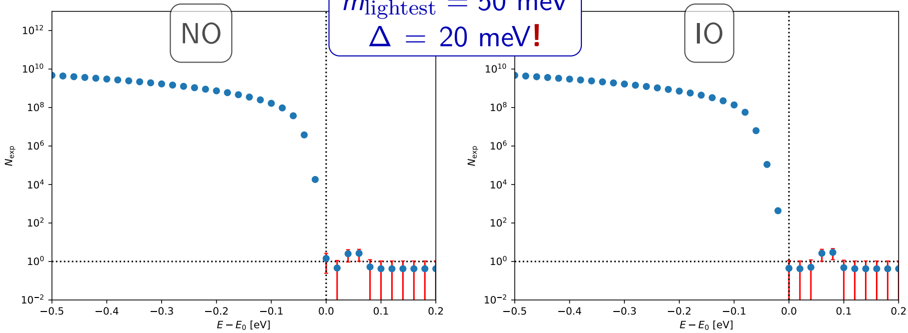
$m_{\text{lightest}} = 50$ meV
$\Delta = 10$ meV!



Simulations - II

[PTOLEMY LoI, arxiv:1808.01892]

no random noise?



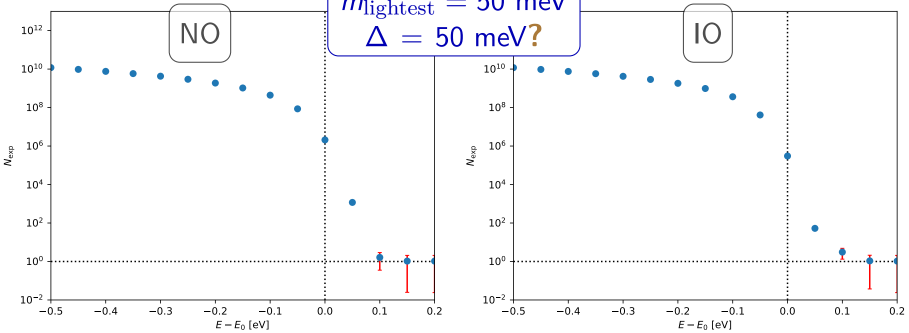
$m_{\rm lightest} = 50$ meV
$\Delta = 20$ meV!

Simulations - II

[PTOLEMY LoI, arxiv:1808.01892]

no random noise?

$m_{\text{lightest}} = 50$ meV
$\Delta = 50$ meV?

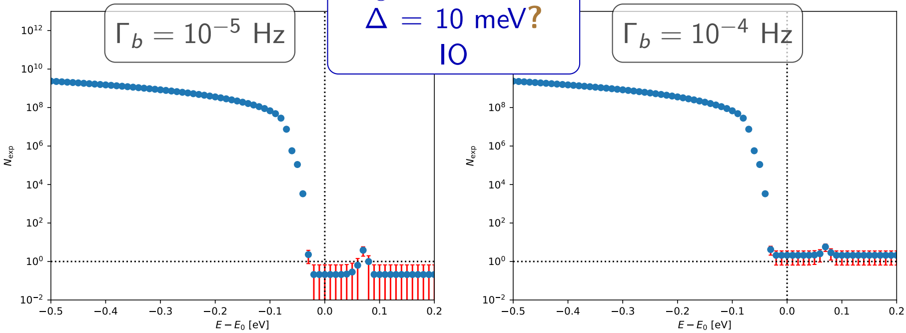


Simulations - II

[PTOLEMY LoI, arxiv:1808.01892]

no random noise?

$m_{\text{lightest}} = 50$ meV
$\Delta = 10$ meV?
IO


$\Gamma_b = 10^{-5}$ Hz

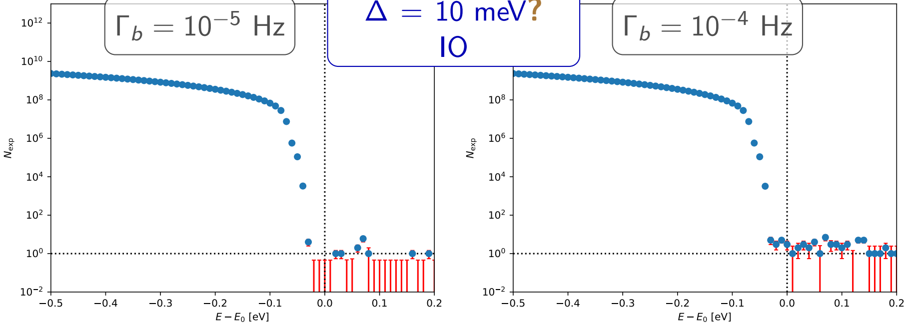
$\Gamma_b = 10^{-4}$ Hz

Simulations - II

[PTOLEMY LoI, arxiv:1808.01892]

with random noise!

$m_{\text{lightest}} = 50$ meV
$\Delta = 10$ meV?
IO



$\Gamma_b = 10^{-5}$ Hz

$\Gamma_b = 10^{-4}$ Hz

things are more complicated in this way...low background needed!

PTOLEMY and the ν_4

[PTOLEMY LoI, arxiv:1808.01892]

$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \mathcal{O}(10)/\mathrm{yr}$

$$\boxed{\Gamma_4 \simeq \Delta N_{\rm eff}\, |U_{e4}|^2\, f_c(m_4)\, \Gamma_{\rm CNB}}$$

[SG et al., 1801.06467]

$m_4 \simeq 1.15$ eV

$|U_{e4}|^2 \simeq 0.01$

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

[SG et al., 2017]

$f_c(m_4) = \mathcal{O}(10^2)$

Γ_4 probably too small to be measured!

PTOLEMY and the ν_4

[PTOLEMY LoI, arxiv:1808.01892]

$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \mathcal{O}(10)/\mathrm{yr}$

$$\boxed{\Gamma_4 \simeq \Delta N_{\mathrm{eff}}\,|U_{e4}|^2\, f_c(m_4)\,\Gamma_{\mathrm{CNB}}}$$

[SG et al., 1801.06467]

$m_4 \simeq 1.15$ eV

$|U_{e4}|^2 \simeq 0.01$

$\Delta N_{\mathrm{eff}} =$**??**

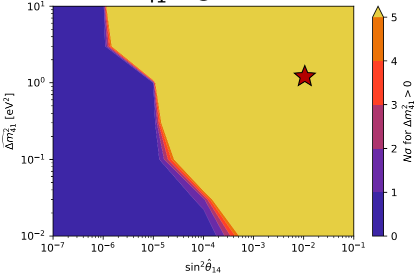
[SG et al., 2017]

$f_c(m_4) = \mathcal{O}(10^2)$

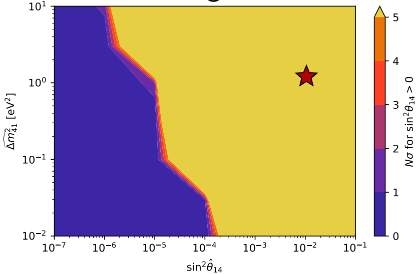
Γ_4 probably too small to be measured!

Still possible to measure mass/mixing through β spectrum

Δm^2_{41} significance



$\sin^2\theta_{14}$ significance



5 Neutrinos

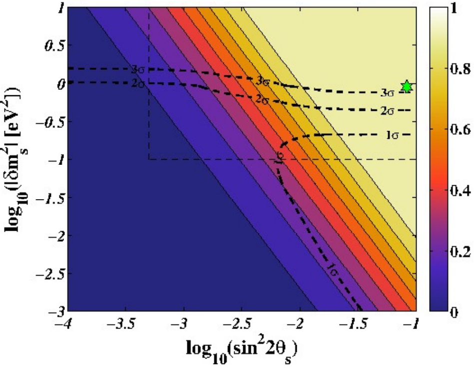
6 PTOLEMY

7 Light sterile neutrinos

LSν thermalization

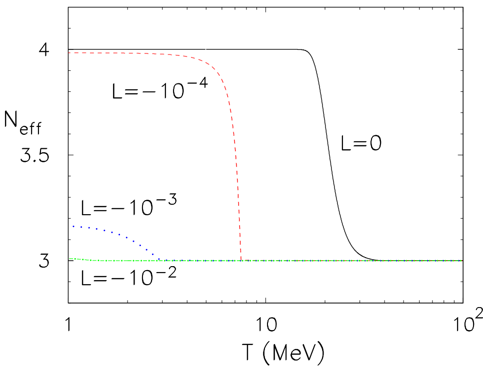
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[Hannestad et al., JCAP 07 (2012) 025]



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

[Mirizzi et al., PRD 86 (2012) 053009]



(L: lepton asymmetry)

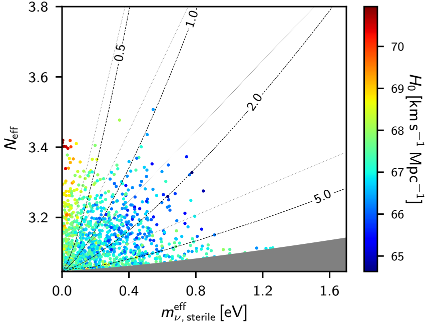
$$\boxed{\text{Unless } L \gtrsim \mathcal{O}(10^{-3}),\ \Delta N_{\rm eff} \simeq 1}$$

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

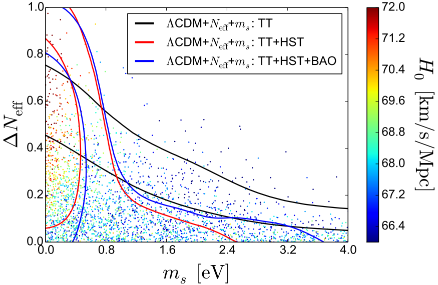
[to be precise: $\Delta N_{\rm eff}$ is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2018]



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



$$\begin{cases} N_{\rm eff} < 3.29 \\ m_s^{\rm eff} < 0.65\ \text{eV} \end{cases}$$

(Planck18+BAO)
[$m_s < 10$ 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!

Planck18=Planck 2018 TT,TE,EE + lowE + lensing

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

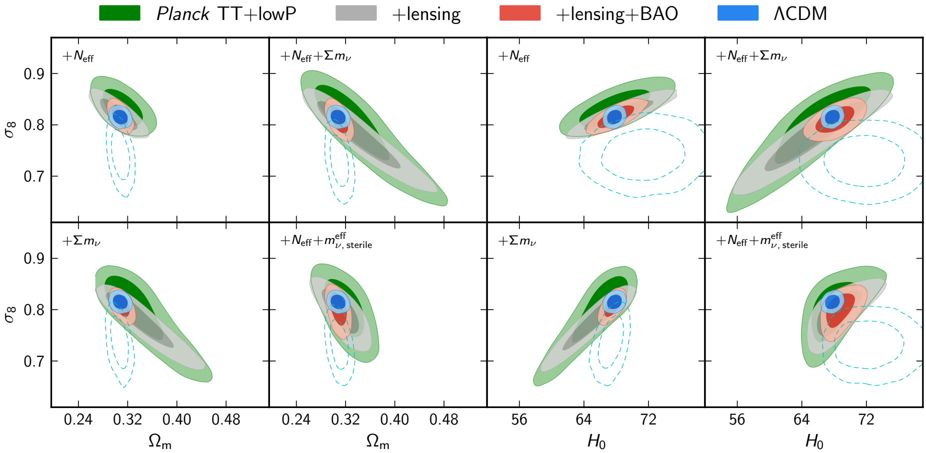
- a mechanism to suppress oscillations and full thermalization of ν_s?
- to compensate $\Delta N_{\rm eff} = 1$ with additional mechanisms in Cosmology?

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]
- freedom in the Primordial Power Spectrum (PPS) of scalar perturbations from inflation compensate damping due to $N_{\rm eff} \neq 3.046$ [SG et al., 2015]

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