



UNIVERSITÀ
DI TORINO



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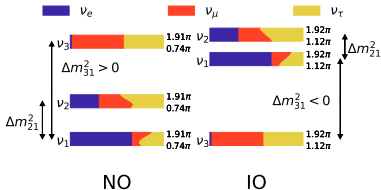
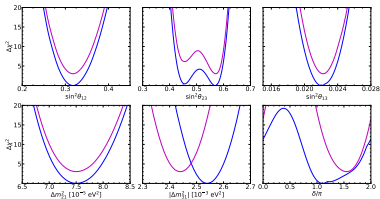
Standard and non-standard neutrino properties from cosmology

Seminar at TLDI, Shanghai, China, 19/11/2024

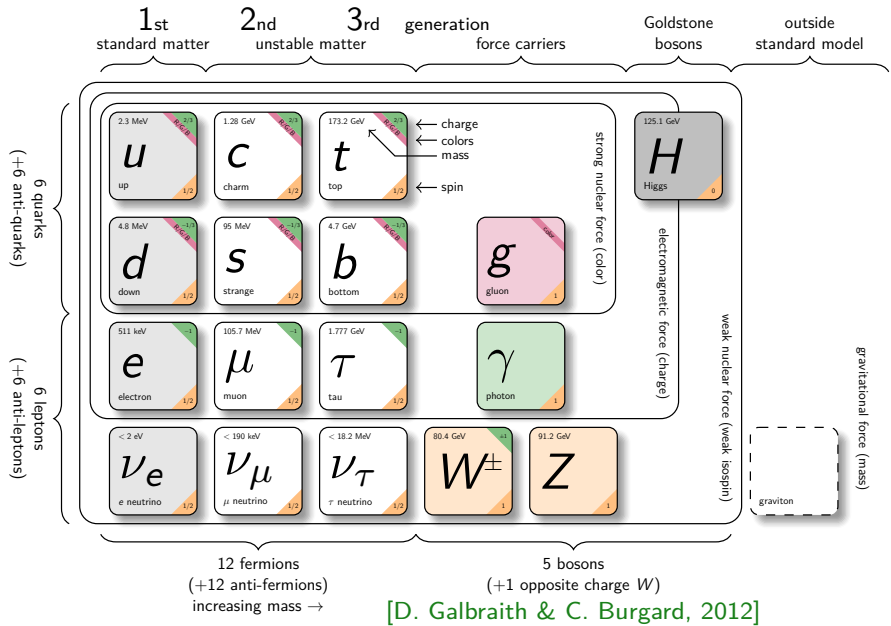
N Neutrinos

A general introduction, based on

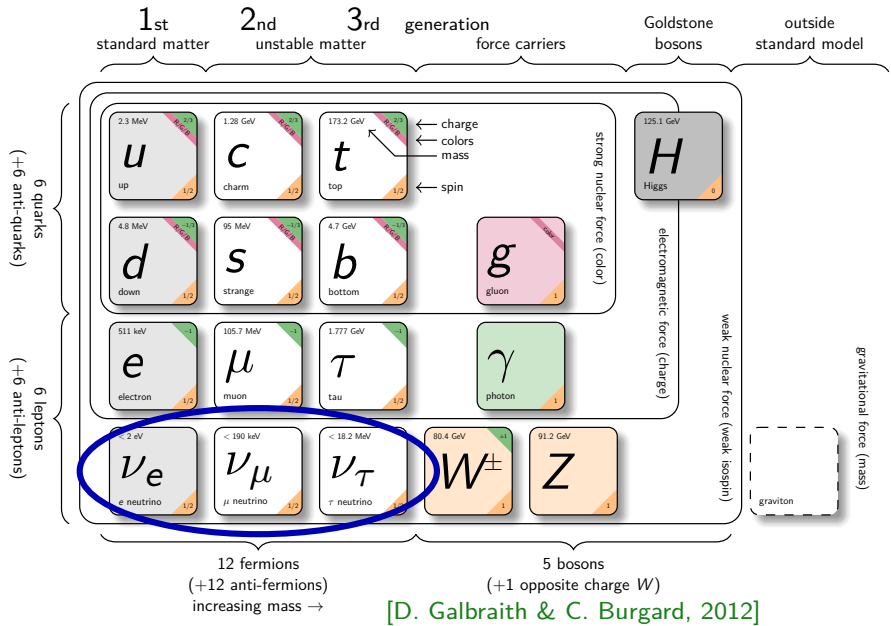
JHEP 02 (2021) 071 and update



The Standard Model of Particle Physics



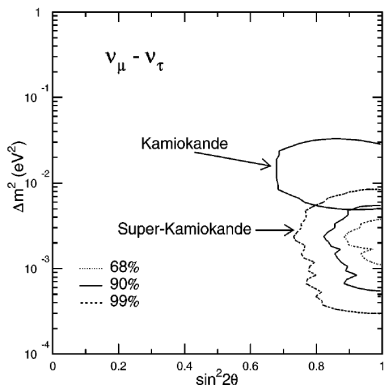
The Standard Model of Particle Physics



Neutrino oscillations

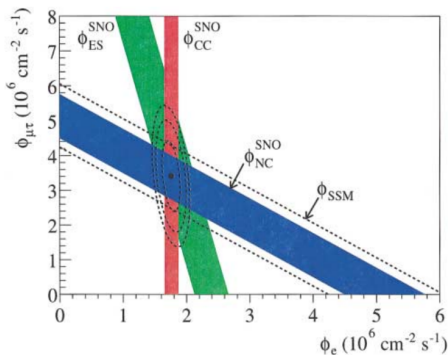
Major discoveries:

[SuperKamiokande, 1998]



first discovery of $\nu_\mu \rightarrow \nu_\tau$
oscillations from atmospheric ν

[SNO, 2001-2002]



first discovery of $\nu_e \rightarrow \nu_\mu, \nu_\tau$
oscillations from solar ν

Nobel prize in 2015

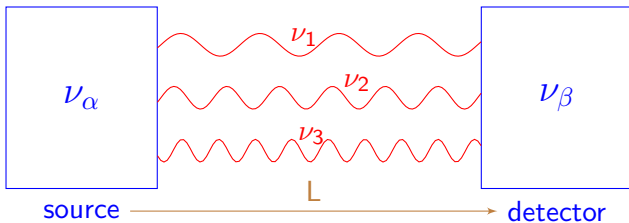
Two neutrino bases

flavor neutrinos ν_α

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1} |\nu_1\rangle + U_{\alpha 2} |\nu_2\rangle + U_{\alpha 3} |\nu_3\rangle$$



$$|\nu(t > 0)\rangle = |\nu_\beta\rangle = U_{\alpha 1} e^{-iE_1 t} |\nu_1\rangle + U_{\alpha 2} e^{-iE_2 t} |\nu_2\rangle + U_{\alpha 3} e^{-iE_3 t} |\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$E_k^2 = p^2 + m_k^2 \longleftarrow \text{define} \longrightarrow t = L$$

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L) = |\langle \nu_\beta | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

The mixing matrix

U can be parameterized using 3 angles (θ_{12} , θ_{13} , θ_{23}) and max 3 (1 Dirac δ , 2 Majorana [$\exists$ only for Majorana ν]) phases

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{mainly atmospheric} \\ \text{and LBL} \\ \text{accelerator} \\ \text{disappearance}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{mainly LBL reactors and} \\ \text{LBL accelerator} \\ \text{appearance}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{mainly solar and} \\ \text{VLBL reactors}}} M$$

Majorana phases irrelevant for oscillation experiments

Relevant for example in neutrinoless double-beta decay

$$s_{ij} \equiv \sin \theta_{ij}; c_{ij} \equiv \cos \theta_{ij}$$

LBL = long baseline; VLBL = very long baseline;

Three Neutrino Oscillations

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

$U_{\alpha k}$ described by 3 mixing angles θ_{12} , θ_{13} , θ_{23} and one CP phase δ

Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

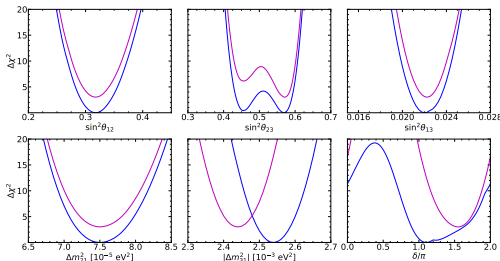
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\begin{aligned} \Delta m_{21}^2 &= (7.50^{+0.22}_{-0.20}) \cdot 10^{-5} \text{ eV}^2 \\ |\Delta m_{31}^2| &= (2.54 \pm 0.03) \cdot 10^{-3} \text{ eV}^2 \text{ (NO)} \\ &= (2.44 \pm 0.03) \cdot 10^{-3} \text{ eV}^2 \text{ (IO)} \end{aligned}$$

$$\begin{aligned} 10 \sin^2(\theta_{12}) &= 3.18 \pm 0.16 \\ 10^2 \sin^2(\theta_{13}) &= 2.200^{+0.069}_{-0.062} \text{ (NO)} \\ &= 2.225^{+0.064}_{-0.070} \text{ (IO)} \\ 10 \sin^2(\theta_{23}) &= 4.55 \pm 0.13 \text{ (NO)} \\ &= 5.71^{+0.14}_{-0.17} \text{ (IO)} \end{aligned}$$

$$\begin{aligned} \delta/\pi &= 1.10^{+0.27}_{-0.12} \text{ (NO)} \\ &= 1.54 \pm 0.14 \text{ (IO)} \end{aligned}$$



mass ordering
still unknown

δ still unknown

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

Neutrinos and their masses

Normal ordering (NO)

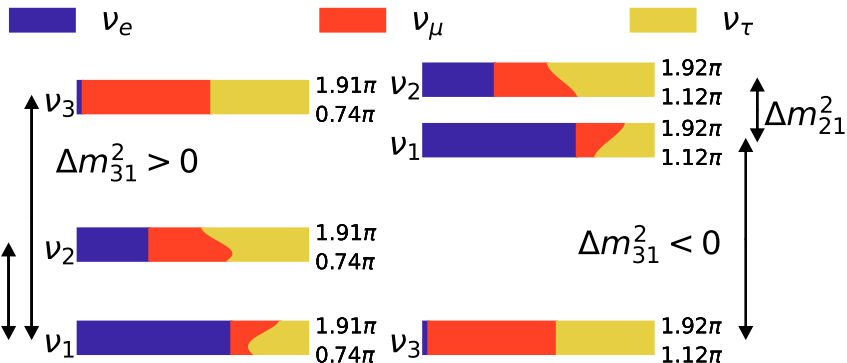
$$m_1 < m_2 < m_3$$

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

Inverted ordering (IO)

$$m_3 < m_1 < m_2$$

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



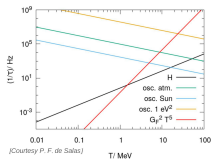
Absolute scale unknown!

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

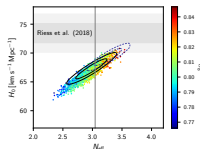
E

Neutrinos in the Early Universe

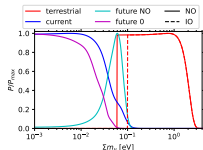
Based on



JCAP 04 (2021) 073

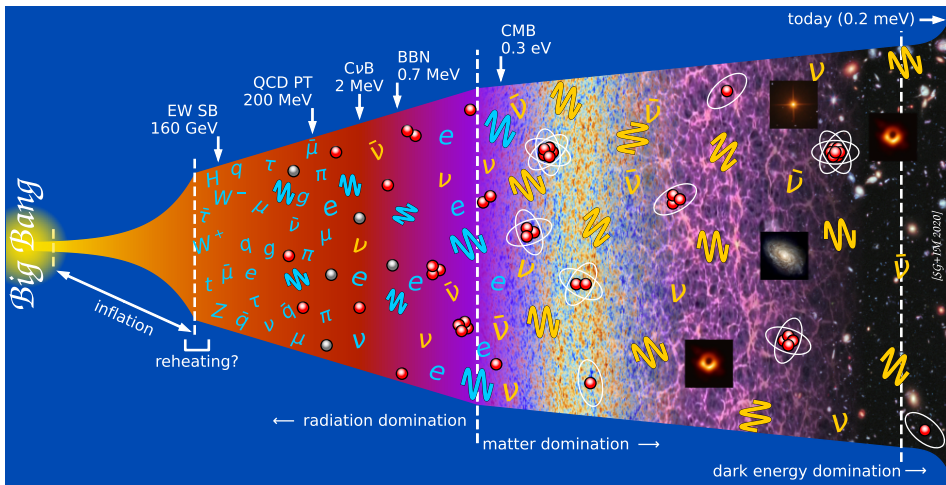


Planck 2018

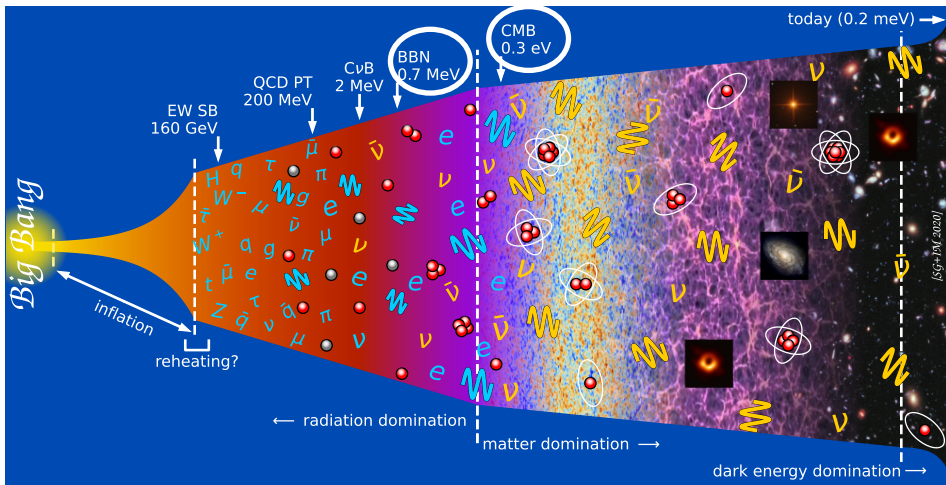


PDU 40 (2023) 101226

History of the universe



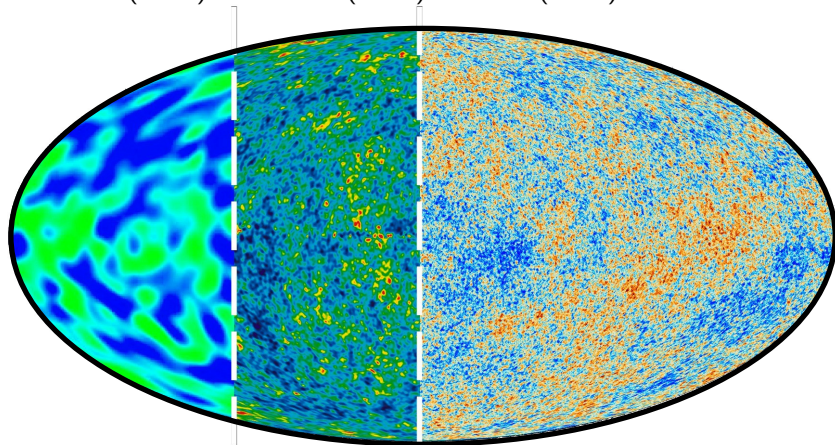
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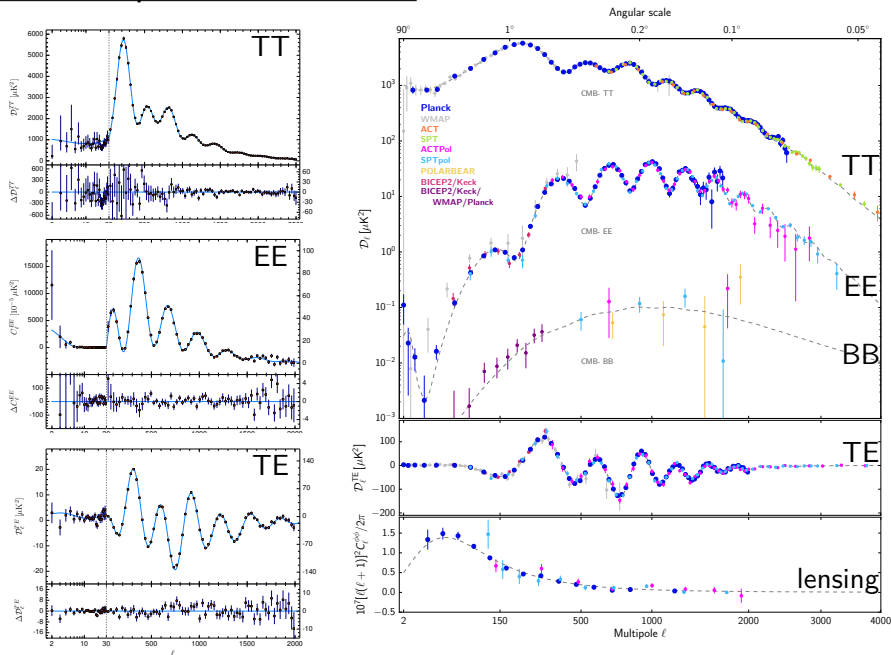


The oldest picture of the Universe

The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

COBE (1992) WMAP (2003) Planck (2013)





Big Bang Nucleosynthesis (BBN)

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

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

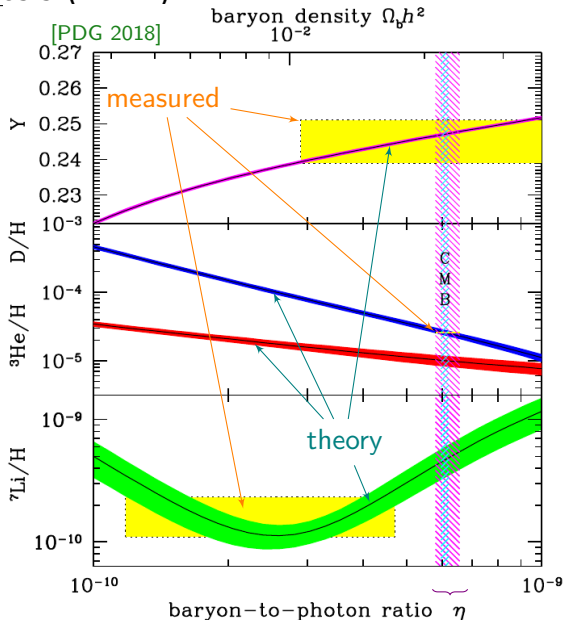
much earlier than CMB!

strong probe for physics
before the CMB

e.g. neutrinos!

ν affect
universe expansion
and

reaction rates ($\nu_e/\bar{\nu}_e$)
at BBN time...



BBN concordance

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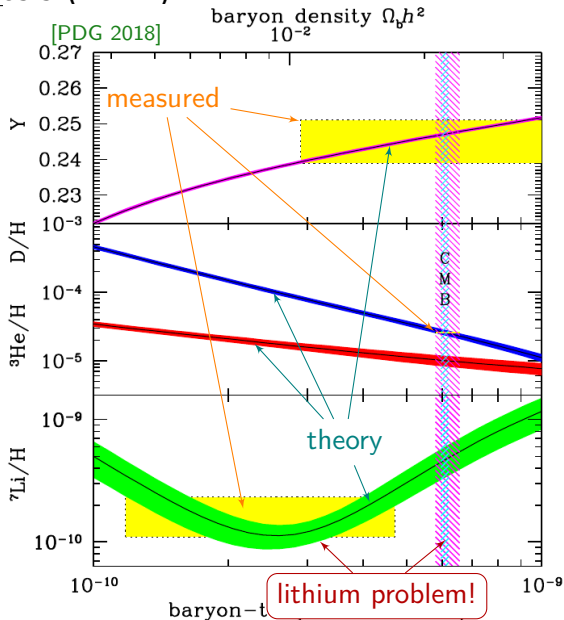
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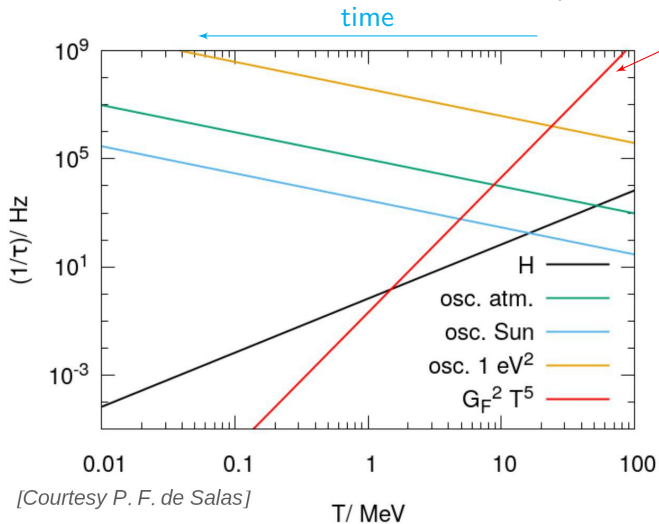
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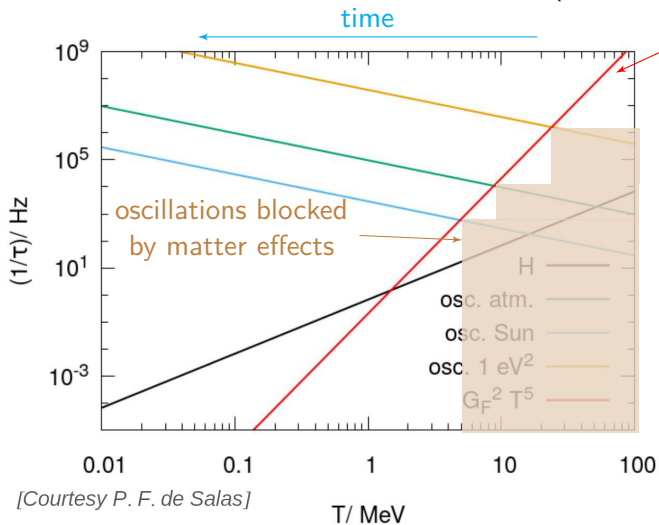
Neutrinos in the early Universe

before BBN: neutrinos coupled to plasma ($\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$, $\nu e \leftrightarrow \nu e$)



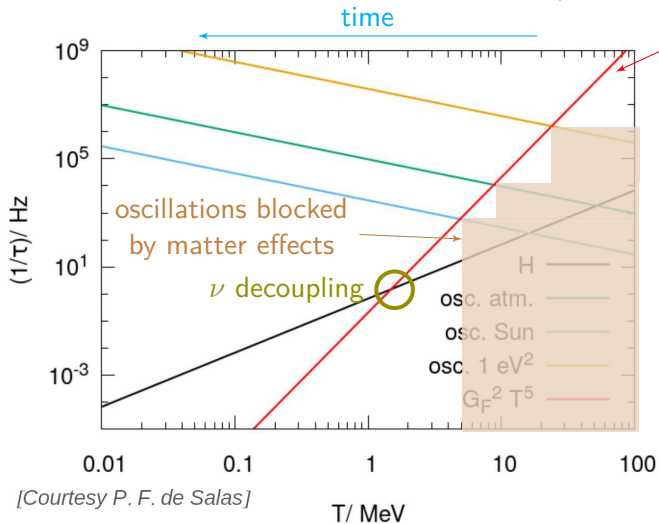
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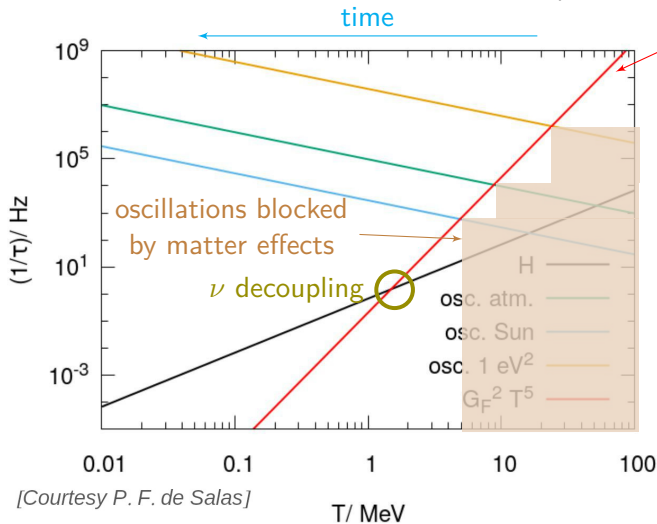
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ν decouple mostly before $e^+ e^- \rightarrow \gamma\gamma$ annihilation!

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$$T_\nu \simeq (4/11)^{1/3} T_\gamma$$

after $e^+ e^- \rightarrow \gamma\gamma$

f_ν : frozen Fermi-Dirac distribution

Today:

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

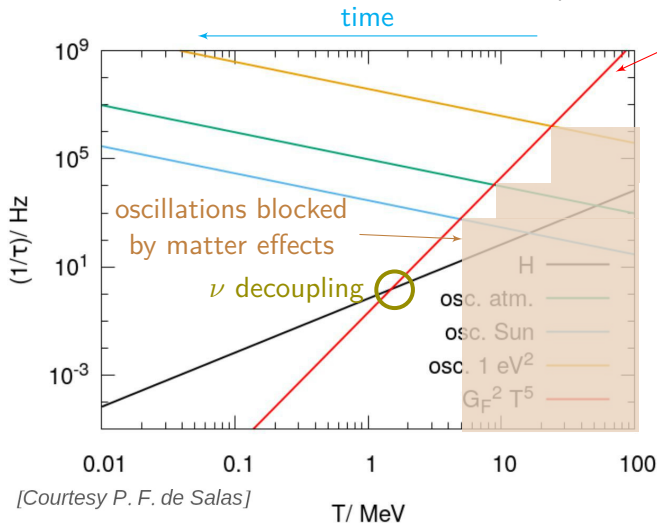
$$\langle E_\nu \rangle \simeq 3.1 T_{\nu,0} \simeq 5 \times 10^{-4} \text{ eV}$$

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

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ν decouple mostly before $e^+ e^- \rightarrow \gamma\gamma$ annihilation!
 actually, the decoupling T is momentum dependent!

distortions to equilibrium f_ν !

ν oscillations in the early universe

comoving coordinates: $a = 1/T$ $x \equiv m_e a$ $y \equiv p a$ $z \equiv T_\gamma a$ $w \equiv T_\nu a$

density matrix: $\varrho(x, y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} \end{pmatrix}$
 $\propto \langle a_j^\dagger(p, t) a_i(p, t) \rangle$
 off-diagonals to take into account coherency in the neutrino system

$$\varrho \text{ evolution from } x \text{ to } y: \frac{d\varrho(y, x)}{dx} = -ia[\mathcal{H}_{\text{eff}}, \varrho] + b\mathcal{I}$$

H Hubble factor $\rightarrow$ expansion (depends on universe content)

effective Hamiltonian $\mathcal{H}_{\text{eff}} = \frac{M_F}{2y} - \frac{2\sqrt{2}G_F y m_e^6}{x^6} \left(\frac{E_\ell + P_\ell}{m_W^2} + \frac{4}{3} \frac{E_\nu}{m_Z^2} \right)$

vacuum oscillations $\longleftarrow$ $\longrightarrow$ matter effects

$\mathcal{I}$ collision integrals

take into account ν -e scattering and pair annihilation, ν - ν interactions

2D integrals over momentum, take most of the computation time

$$\text{solve together with } z \text{ evolution, from } x \frac{d\rho(x)}{dx} = \rho - 3P$$

ρ, P total energy density and pressure, also take into account FTQED corrections

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FORTran-Evolved Primordial Neutrino Oscillations
(FortEPiano)

https://bitbucket.org/ahp_cosmo/fortepiano_public

vacuum oscillations

matter effects

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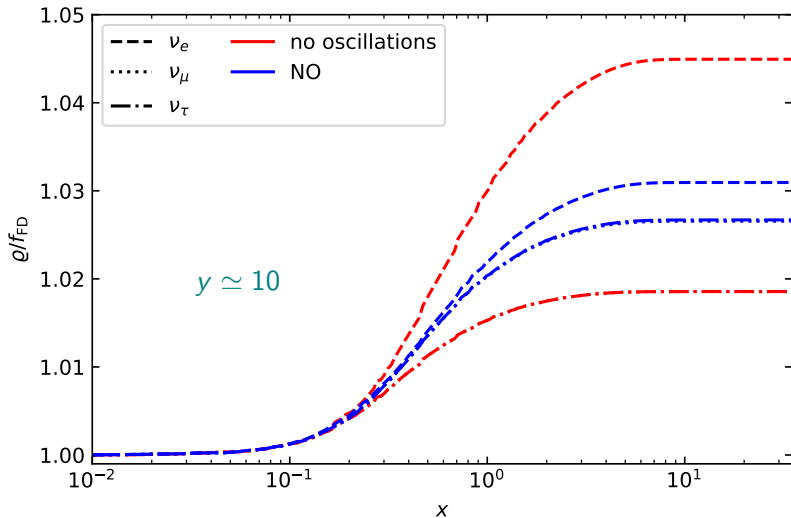
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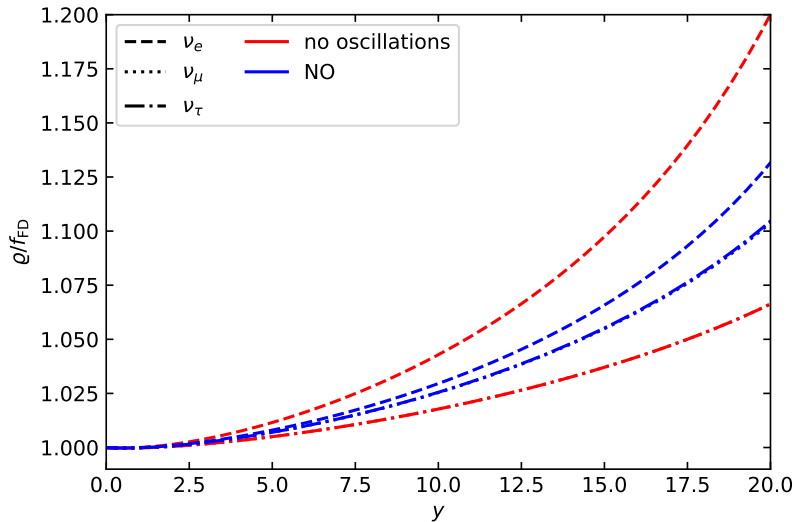
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Distortion of the momentum distribution (f_{FD} : Fermi-Dirac at equilibrium)



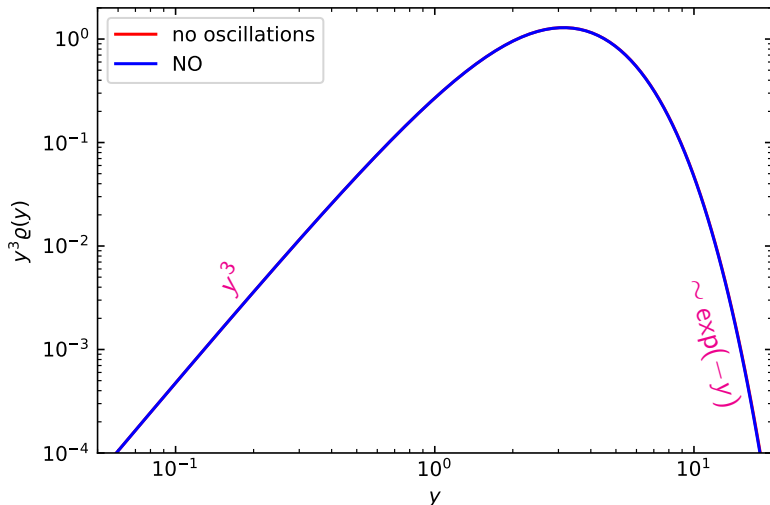
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Neutrino momentum distribution and N_{eff}

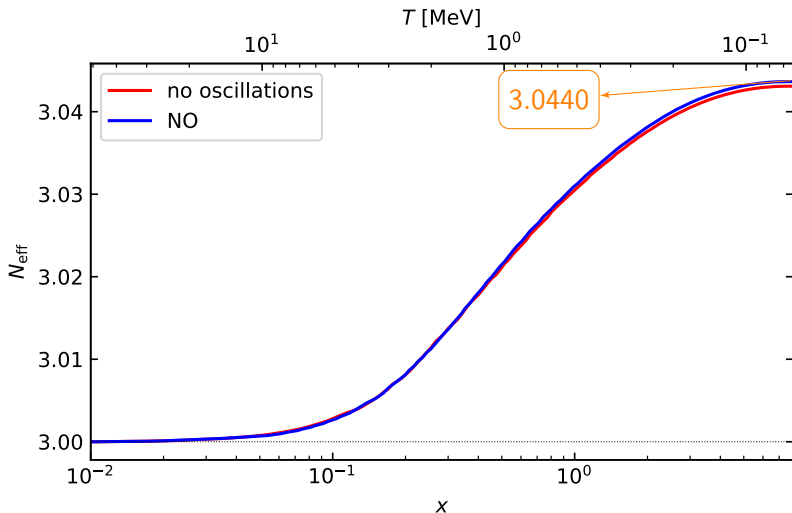
$$N_{\text{eff}}^{\text{final}} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{1}{\rho_\gamma} \sum_i g_i \int \frac{d^3 p}{(2\pi)^3} E(p) f_{\nu,i}(p)$$

$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\text{fin}}$
 $\hookrightarrow \propto y^3 \varrho_{ii}(y)$



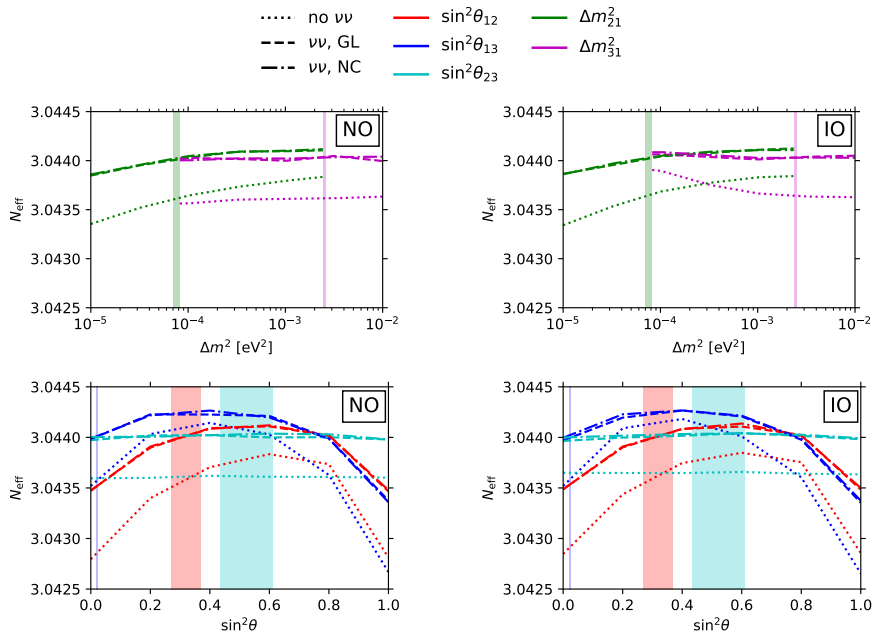
Neutrino momentum distribution and N_{eff}

$$N_{\text{eff}}^{\text{any time}} = \frac{8}{7} \left(\frac{T_\gamma}{T_\nu} \right)^4 \frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7} \left(\frac{T_\gamma}{T_\nu} \right)^4 \frac{1}{\rho_\gamma} \sum_i g_i \int \frac{d^3 p}{(2\pi)^3} E(p) f_{\nu,i}(p)$$



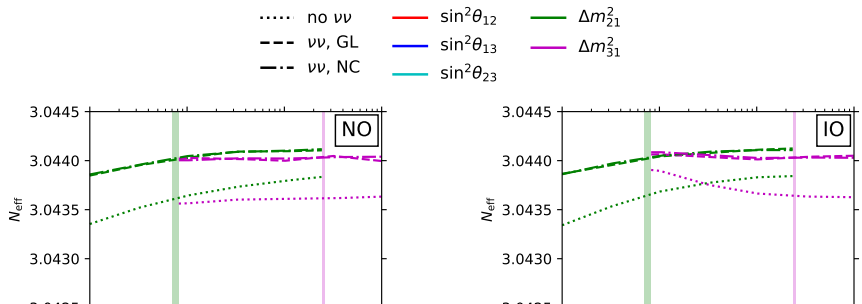
Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



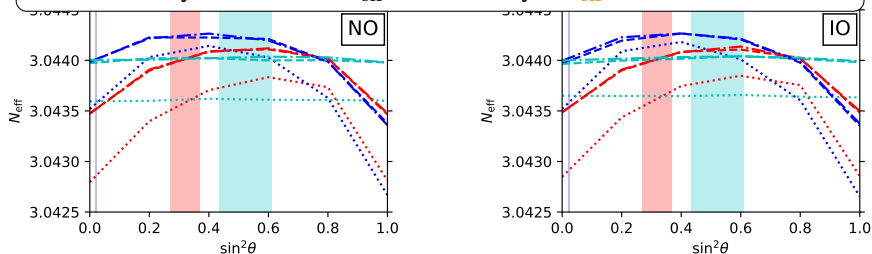
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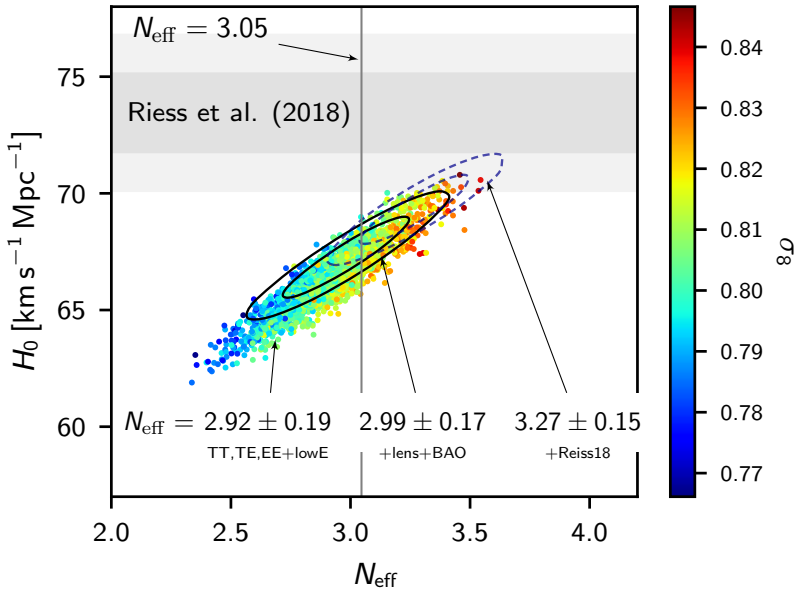
[Bennett, SG+, JCAP 2021]



within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

only θ_{12} affects N_{eff} , at most by $\delta N_{\text{eff}} \approx 10^{-4}$





What is N_{eff} ?

radiation density:

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

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

$$N_{\text{eff}}^\nu = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{1}{\rho_\gamma} \sum_i g_i \int \frac{d^3 p}{(2\pi)^3} E(p) f_{\nu,i}(p)$$

It is a measurement of the energy density of **relativistic neutrinos**!

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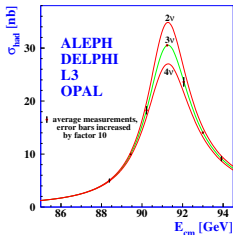
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Nothing to do with [LEP (2006)]

$$N_\nu^{(Z)} = 2.9840 \pm 0.0082$$



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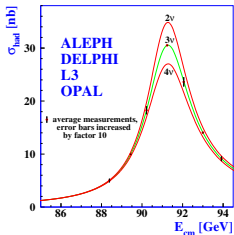
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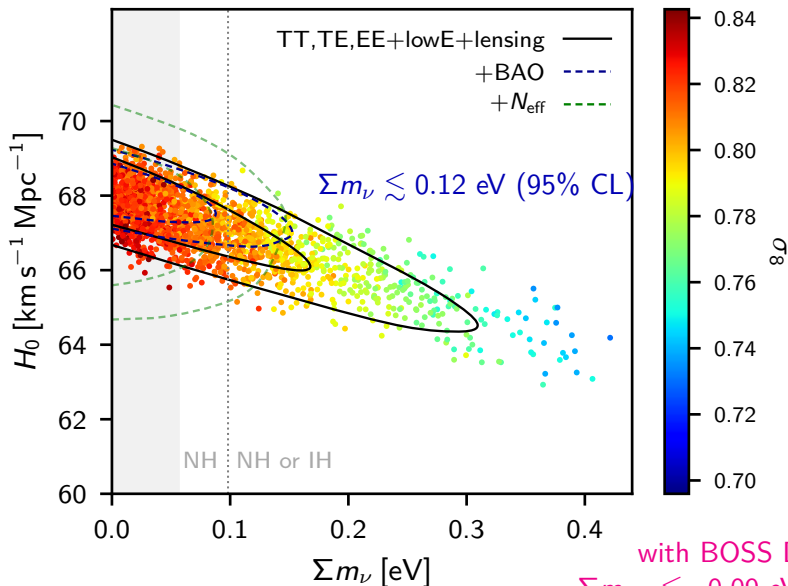
instantaneous decoupling:

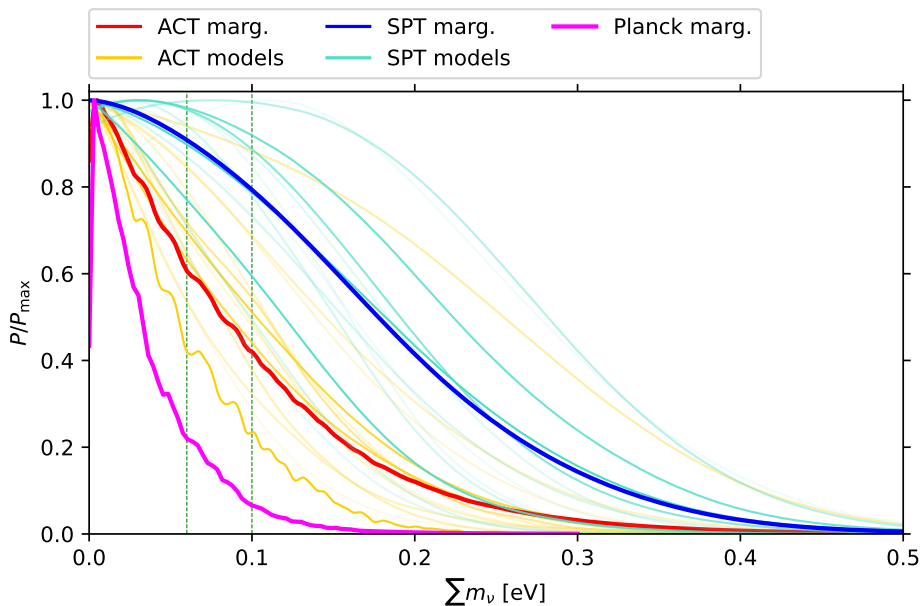
$$N_{\text{eff}}^\nu = 1 \text{ for each } \nu \text{ family}$$

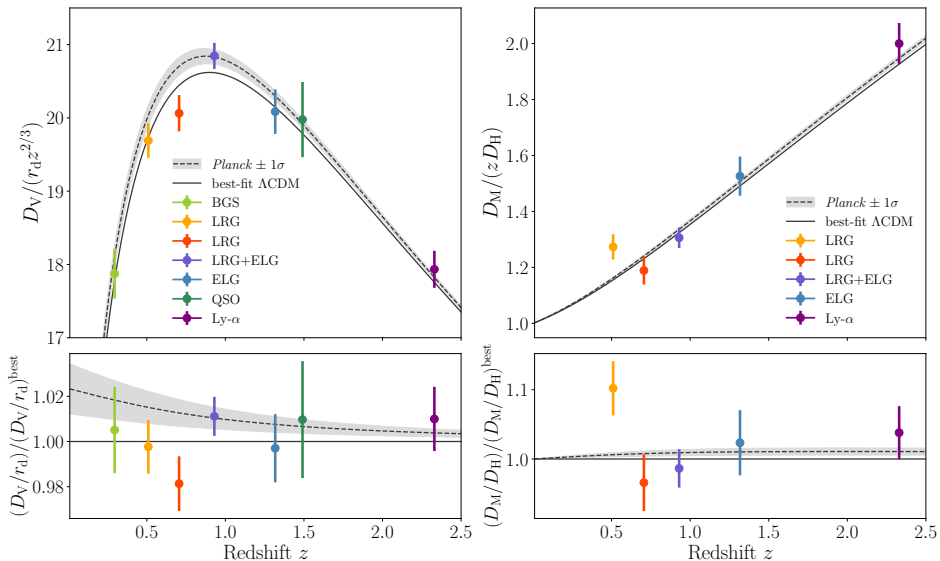
non-instantaneous decoupling:

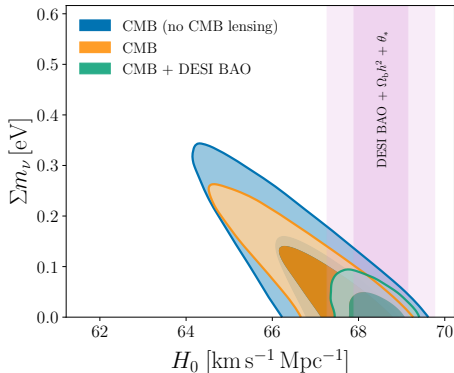
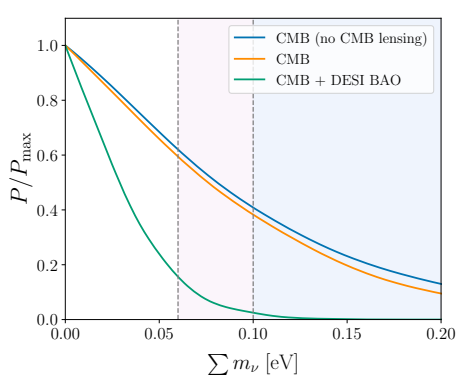
$N_{\text{eff}}^\nu > 3$ because of entropy transfer to photons and neutrinos when electrons become non-relativistic

Non-standard physics? see later!

Σm_ν and CMB







$$\sum m_\nu < 0.072 \text{ eV (95\%, DESI BAO+CMB)}$$

close to disfavoring normal ordering minimum value

$$\sum m_\nu \sim 0.06 \text{ eV}$$

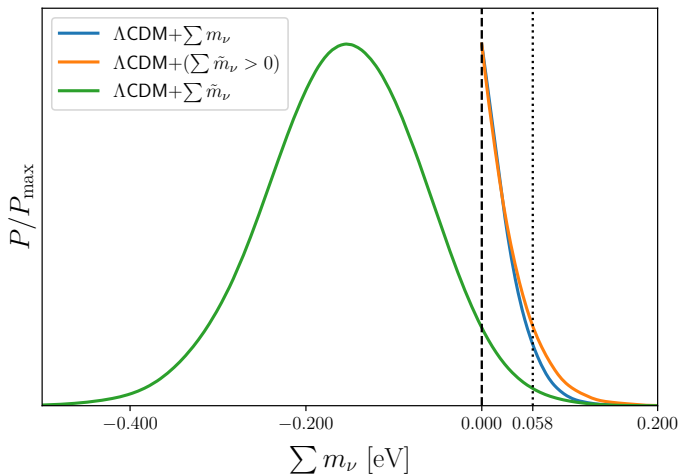
at 95%!

Negative neutrino masses?

[Craig+, JHEP 09 (2024)]
[Green+, arxiv:2407.07878]

“Effective ν mass $\Sigma \tilde{m}_\nu$ ” by extrapolating the effect of Σm_ν on lensing

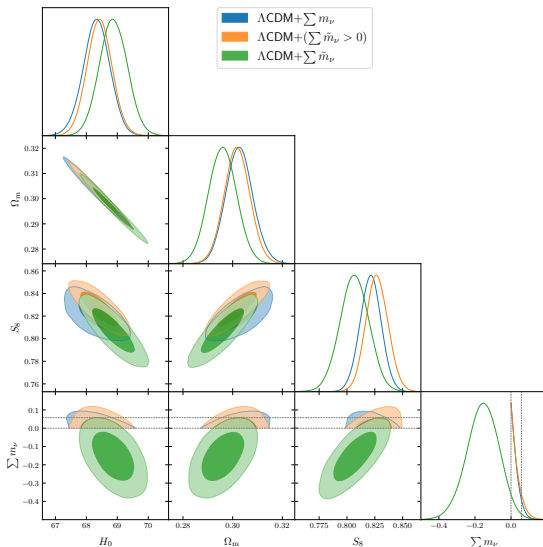
“Negative neutrino mass”: increased matter clustering compared to a model with only massless neutrinos



Planck 2018 CMB, ACT+Planck lensing, DESI BAO

Negative neutrino masses?

“Effective ν mass $\Sigma \tilde{m}_\nu$ ” by extrapolating the effect of Σm_ν on lensing



Planck 2018 CMB, ACT+Planck lensing, DESI BAO

Can a cosmological limit on Σm_ν disfavor IO?

standard factor

Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu / (94.12 \text{ eV})$

NO: $\Sigma m_\nu \gtrsim 0.06 \text{ eV}$

Current: $\Sigma m_\nu \lesssim 0.1 \text{ eV}$ (95%)

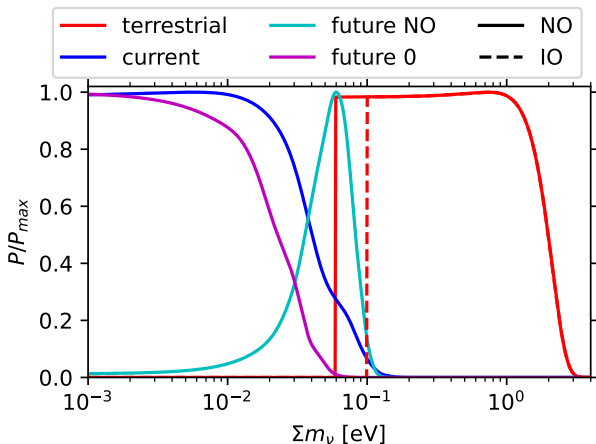
IO: $\Sigma m_\nu \gtrsim 0.1 \text{ eV}$

Future sensitivity: $\sigma(\Sigma m_\nu) \simeq 0.02 \text{ eV}$

Still preferring $\Sigma m_\nu = 0$?

Will measure e.g. $\Sigma m_\nu = 0.06 \text{ eV}$?

tension even
with NO!



confirm NO,
disfavor IO

Can a cosmological limit on Σm_ν disfavor IO?

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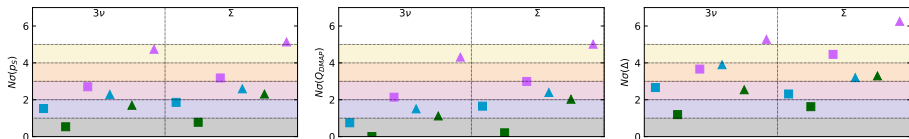
Is there a tension between cosmology and oscillations?

or will there be a tension?

several possible tests can be considered, similar results

$\Sigma m_\nu \lesssim 0.1 \text{ eV}$ (95%)
 $\Sigma m_\nu = 0.06 \pm 0.02 \text{ eV}$ (1σ)
 $\Sigma m_\nu = 0.00 \pm 0.02 \text{ eV}$ (1σ)

● current ■ NO
 ● future NO ▲ IO
 ● future 0



currently only mild tension between cosmology and oscillations

future NO can be at $\sim 2\sigma$ tension with IO

future 0 can be at $\sim 2 - 3\sigma$ tension with NO, $\gtrsim 4\sigma$ with IO

Can a cosmological limit on Σm_ν disfavor IO?

Cosmology measures $\omega_\nu = \Omega_\nu h^2$

Is there a tension between cosmo

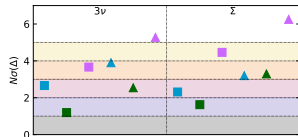
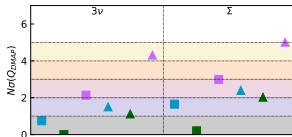
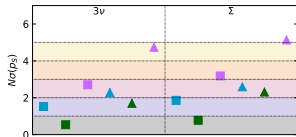
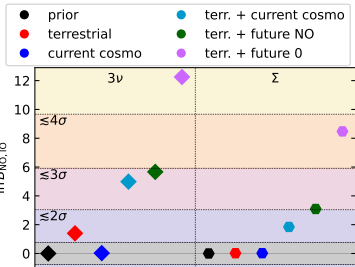
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● current
 ● future NO
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preference for NO vs IO?



currently only mild tension between cosmology and oscillations

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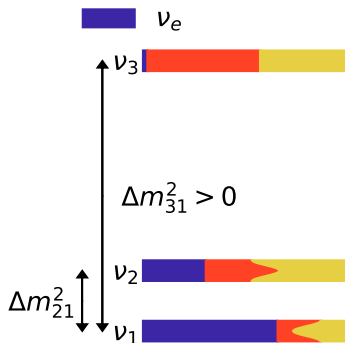
What is Σm_ν ?

normal ordering (NO):

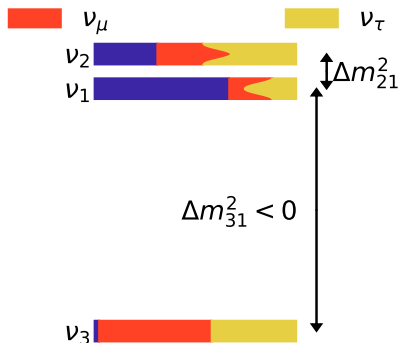
$$m_2 \gtrsim 9 \text{ meV}, m_3 \gtrsim 50 \text{ meV}$$

inverted ordering (IO):

$$m_{1,2} \gtrsim 50 \text{ meV}$$



NO



IO

[Valencia global fit]

What is Σm_ν ?

normal ordering (NO):

$$m_2 \gtrsim 9 \text{ meV}, m_3 \gtrsim 50 \text{ meV}$$

inverted ordering (IO):

$$m_{1,2} \gtrsim 50 \text{ meV}$$

relic neutrinos have a Fermi-Dirac distribution with $T_\nu \approx \mathcal{O}(0.1) \text{ meV}$!

many relic neutrinos are non-relativistic today!

$$\text{energy density } \rho_{\nu, \text{non-rel}} = \sum_i m_i n_i$$

$$\text{fractional energy density } \omega_\nu = \Omega_\nu h^2 = \frac{\sum_i m_i n_i}{\rho_{cr}} = \frac{\Sigma m_\nu}{94.1 \text{ eV}}$$

Background measurements are sensitive to ω_ν , not Σm_ν !

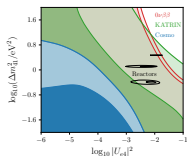
“Cosmological” Σm_ν measures the energy density of non-relativistic ν s

Note: free-streaming scale directly depends on m_ν :

$$\lambda_{\text{FS}} \propto v_{th}/H \propto \langle p \rangle / (m_\nu H) \propto \sim 3 T_\nu / (m_\nu H)$$

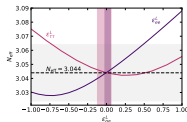
 N_{eff}

$\Rightarrow$ energy density of relativistic neutrinos



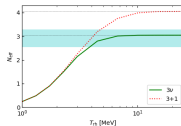
$N_{\text{eff}} > 3?$

e.g. sterile neutrino [JCAP 07 (2019) 014]



$N_{\text{eff}} \simeq 3?$

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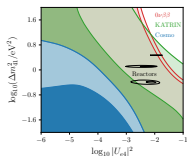
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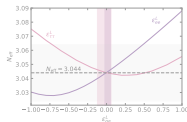
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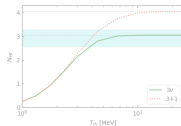
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Sterile neutrino in the early universe

Four neutrinos $\longrightarrow$ new oscillations in the early Universe

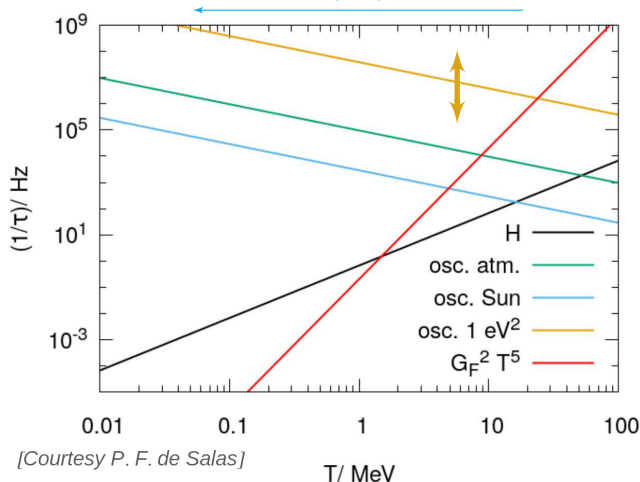
sterile $\implies$ no weak/em interactions in the thermal plasma

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need to produce it through oscillations, but matter effects may block them
time



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when are they enough to allow full equilibrium of active-sterile states?

$$0 \xleftarrow{\text{no sterile production}} \Delta N_{\text{eff}} = N_{\text{eff}}^{4\nu} - N_{\text{eff}}^{3\nu} \xrightarrow{\text{active\&sterile in equilibrium}} \simeq 1$$

$$\frac{\Delta m_{as}^2}{\text{eV}^2} \sin^4(2\vartheta_{as}) \simeq 10^{-5} \ln^2(1 - \Delta N_{\text{eff}}) \quad (1+1 \text{ approx.})$$

[Dolgov&Villante, 2004]

$$\text{e.g.: } \Delta m_{as}^2 = 1 \text{ eV}^2, \sin^2(2\vartheta_{as}) \simeq 10^{-3} \Rightarrow \Delta N_{\text{eff}} \simeq 1$$

$$N_{\text{eff}}^{3\nu} = 3.044 \text{ [JCAP 2021]}$$

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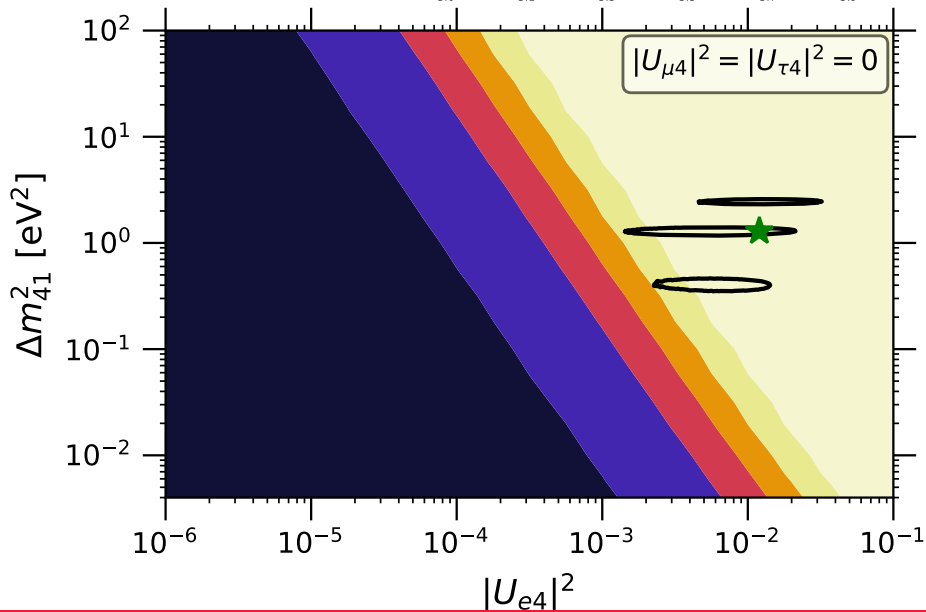
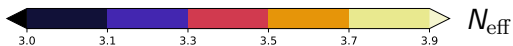
Full calculation: use numerical code!

FORTran-Evolved Primordial Neutrino Oscillations
(FortEPiaNO)

https://bitbucket.org/ahep_cosmo/fortepiano_public

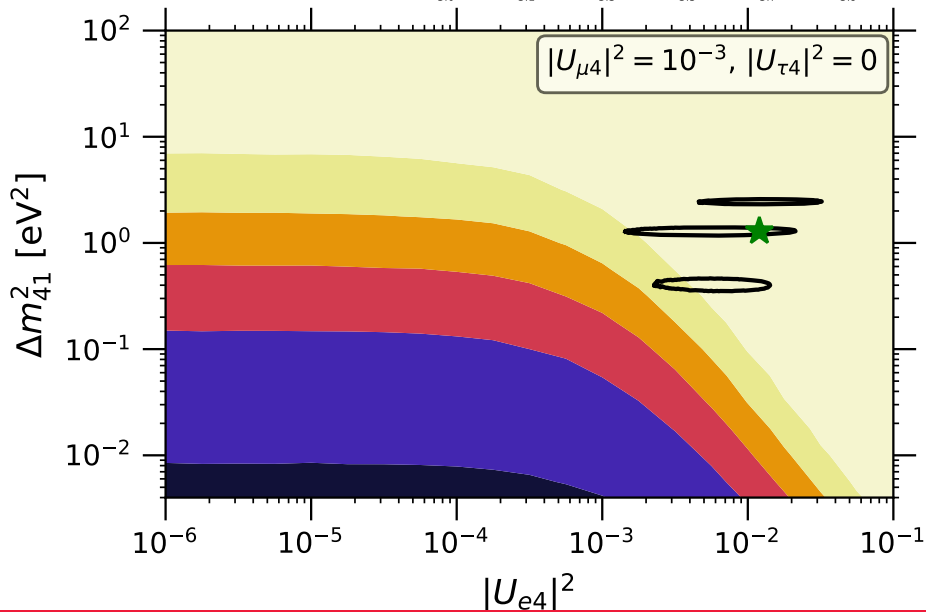
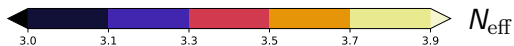
N_{eff} and the new mixing parameters

We can vary more than one angle:



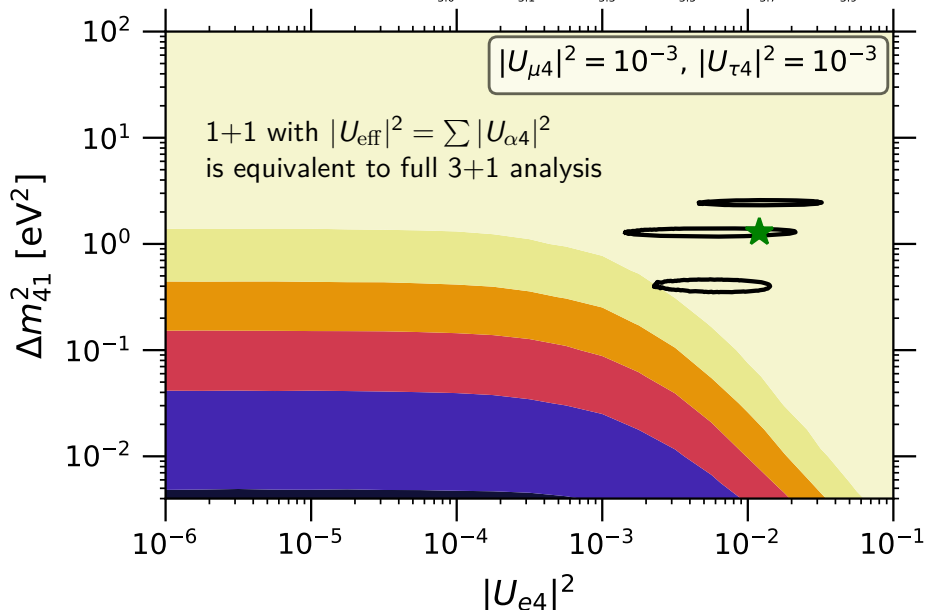
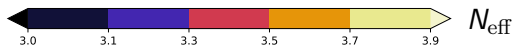
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N_{eff} and the new mixing parameters

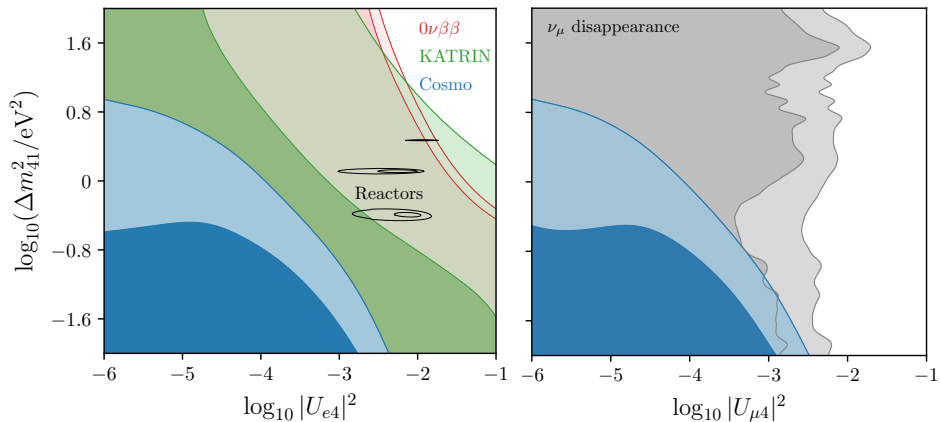
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Comparing constraints

Cosmological constraints are stronger than most other probes

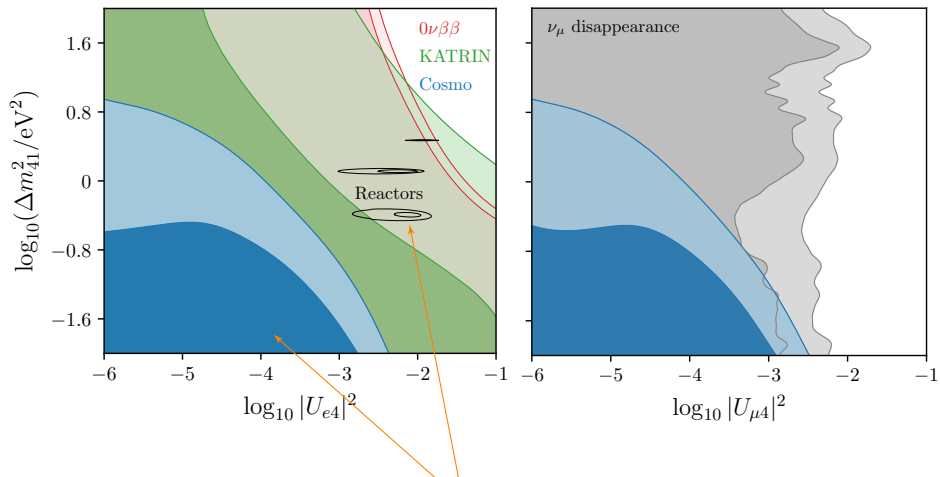
But much more model dependent (as all the cosmological constraints)!



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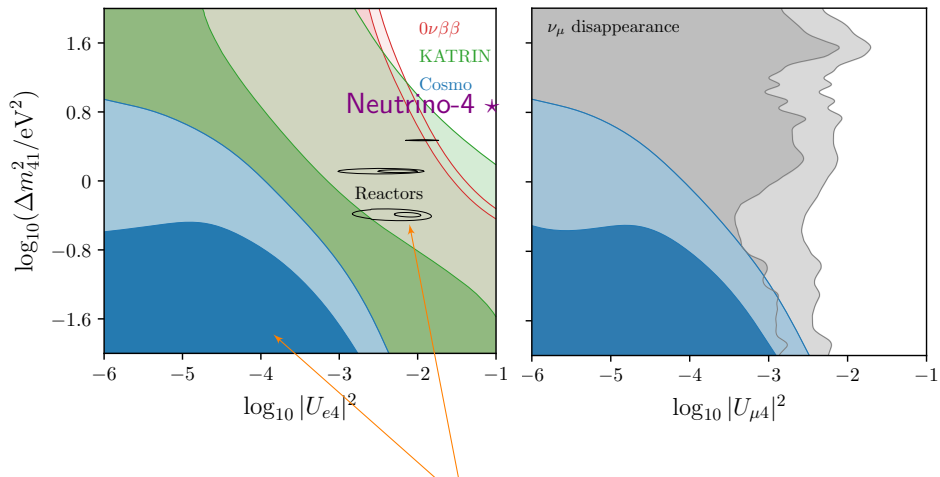


Warning: tension between (old) reactor experiments and CMB bounds!

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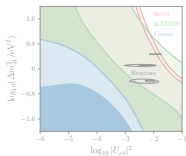
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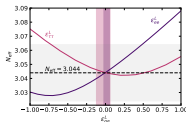
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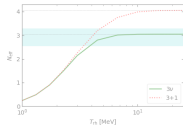
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Non-standard neutrino-electron interactions

Can neutrinos have interactions beyond the SM ones?

e.g.: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{NSIe}}$, with $\mathcal{L}_{\text{NSIe}} \propto G_F \sum_{\alpha,\beta} \epsilon_{\alpha\beta}^{L,R} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{e} \gamma_\mu P_{L,R} e)$
 see e.g. [Farzan+, 2018]

coupling strength governed by the $\epsilon_{\alpha\beta}^{L,R}$ coefficients ($\alpha = e, \mu, \tau$)

new interactions **affect all phenomena** involving neutrinos and electrons
 including neutrino decoupling:

collision terms

$$G_{\text{SM}}^L = \text{diag}(g_L, \tilde{g}_L, \tilde{g}_L)$$

$$G_{\text{SM}}^R = \text{diag}(g_R, g_R, g_R)$$

$$g_R = \sin^2 \theta_W, \quad g_L = g_R + 1/2, \quad \tilde{g}_L = g_R - 1/2$$

$$G^{L,R} = G_{\text{SM}}^{L,R} + \begin{pmatrix} \epsilon_{ee}^{L,R} & \epsilon_{e\mu}^{L,R} & \epsilon_{e\tau}^{L,R} & \cdots \\ \epsilon_{e\mu}^{L,R} & \epsilon_{\mu\mu}^{L,R} & \epsilon_{\mu\tau}^{L,R} & \cdots \\ \epsilon_{e\tau}^{L,R} & \epsilon_{\mu\tau}^{L,R} & \epsilon_{\tau\tau}^{L,R} & \cdots \\ \vdots & & & \ddots \end{pmatrix}$$

matter effects in oscillations
 (subdominant!)

$$\mathcal{H}_{\text{eff,SM}} \supset k \cdot \text{diag}(\rho_e + P_e, 0, 0)$$

$$\mathcal{H}_{\text{eff}} \supset k(\rho_e + P_e) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

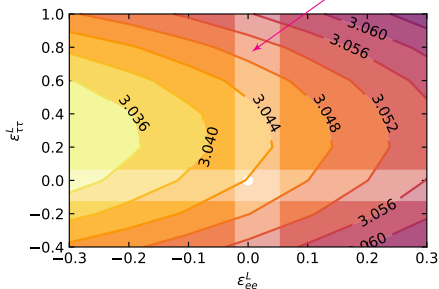
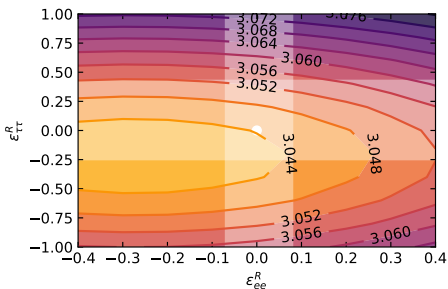
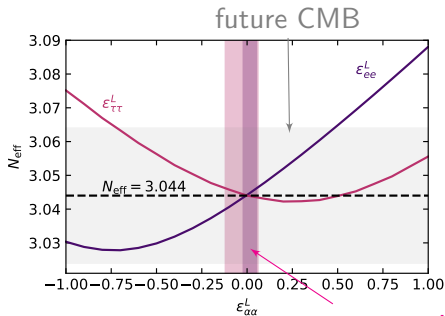
$$\text{with } \epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^L + \epsilon_{\alpha\beta}^R$$

NSI effects on N_{eff}

$$G^{L,R} = G_{SM}^{L,R} + \begin{pmatrix} \epsilon_{ee}^{L,R} & \epsilon_{e\mu}^{L,R} & \epsilon_{e\tau}^{L,R} & \dots \\ \epsilon_{e\mu}^{L,R} & \epsilon_{\mu\mu}^{L,R} & \epsilon_{\mu\tau}^{L,R} & \dots \\ \epsilon_{e\tau}^{L,R} & \epsilon_{\mu\tau}^{L,R} & \epsilon_{\tau\tau}^{L,R} & \dots \\ \vdots & & & \ddots \end{pmatrix}$$

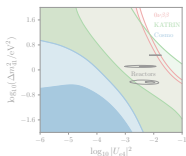
e.g.:

$$\begin{aligned} G_{ee}^L &\rightarrow 0.727 + \epsilon_{ee}^L \\ G_{\tau\tau}^L &\rightarrow -0.273 + \epsilon_{\tau\tau}^L \\ G_{\alpha\alpha}^R &\rightarrow 0.233 + \epsilon_{\alpha\alpha}^R \end{aligned}$$



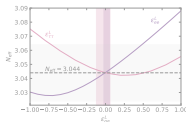
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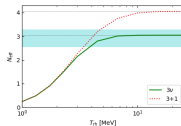
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■ Scenarios with low reheating temperature

Reheating: phase ending inflation

during inflation, the inflaton (non-rel. scalar) dominates the energy density

during reheating: inflaton decays into standard model particles

⇒ photons, electrons, ... are populated directly

radiation domination begins after reheating

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Low reheating temperature: when reheating occurs at $T_{\text{rh}} \lesssim 20 \text{ MeV}$

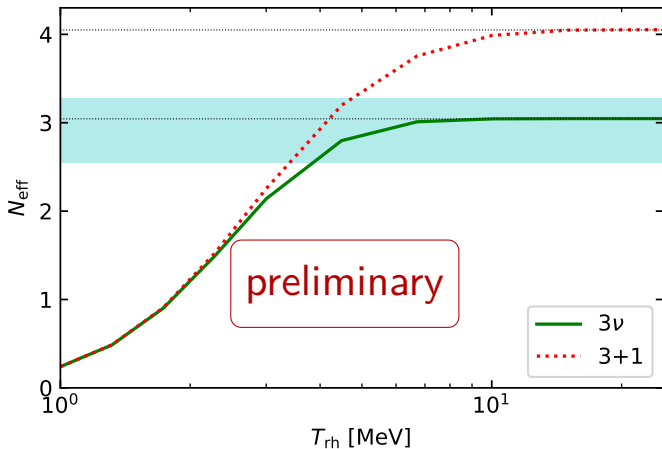
notice: if $T_{\text{rh}} \lesssim 3 \text{ MeV}$, BBN is broken!

3 neutrino oscillations start to be affected when $T_{\text{rh}} \lesssim 8 \text{ MeV}$

what about sterile neutrinos?

N_{eff} with low reheating

N_{eff} as a function of T_{rh} (3 or 3+1 neutrinos):

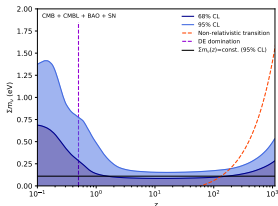


Planck constraint: $N_{\text{eff}} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)



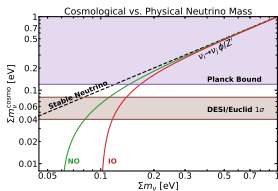
$$\Sigma m_{\nu}^{\text{cosmo}}$$

$\Rightarrow$ energy density of non-relativistic neutrinos



$\Sigma m_{\nu}^{\text{cosmo}} < \Sigma m_{\nu}$ by time-varying masses?

e.g. [Lorenz+, PRD 104 (2021) 123518]



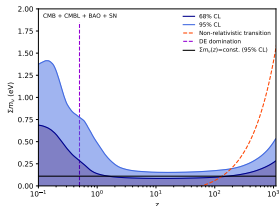
$\Sigma m_{\nu}^{\text{cosmo}} < \Sigma m_{\nu}$ by invisible decay?

e.g. [Escudero+, JHEP 12 (2020) 119]



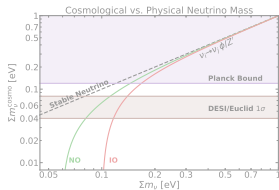
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■ Time-varying neutrino masses

How to make neutrino masses non-constant in time?

new coupling!

a scale factor

Time-varying neutrino masses

How to make neutrino masses non-constant in time?

new coupling!

To new scalar field
(early) dark energy?

e.g. [Ayaita+, PRD 2016]

$m_\nu = 0$ at early times, then

phase transition generates
 m_ν at late times ($a \gtrsim 0.2$)

Masses can grow up to

$m_\nu = 0.6$ eV at $a = 1$

ν may decay to radiation later

if supercooled transition, data
prefer it at $a \sim 1$ [Lorenz+, PRD 2019]

Massless ν at all times!

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Massless ν at all times!

To dark radiation

e.g. [Dvali+, PRD 2016]

assume anomalous symmetry
("axial" neutrino lepton number)

broken at scale Λ_G

s.b. generates effective m_ν

$m_\nu = 0$ at early times, then
generation of masses at $T_\Lambda \lesssim m_\nu$
($T_\Lambda < T_{\text{CMB}}$ in order to preserve recombination)

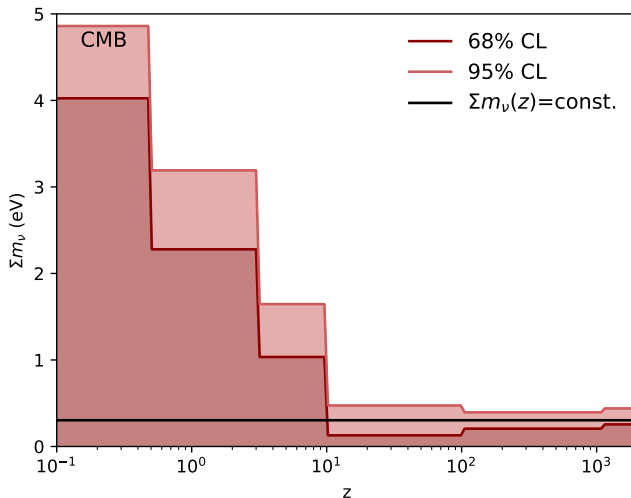
Massive ν may decay into lightest ν
and annihilate into Goldstone bosons

cosmological mass bound is avoided!

a scale factor

Constraining $\Sigma m_\nu(z)$

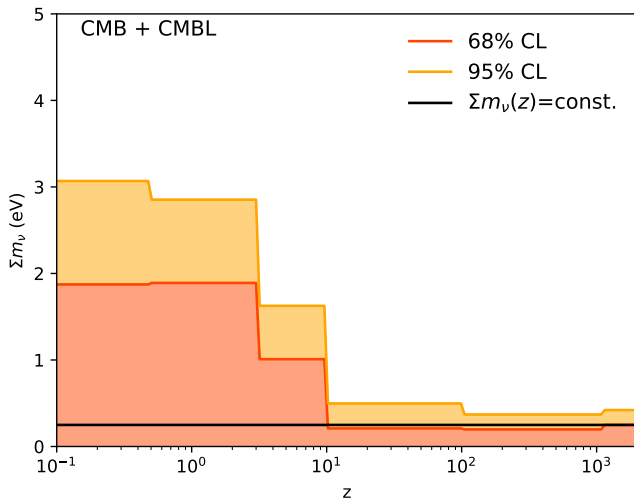
Phenomenological approach: $\Sigma m_\nu(z) = \text{const}$ in 6 redshift bins



CMB: very high redshift, poor constraints on late universe

Constraining $\Sigma m_\nu(z)$

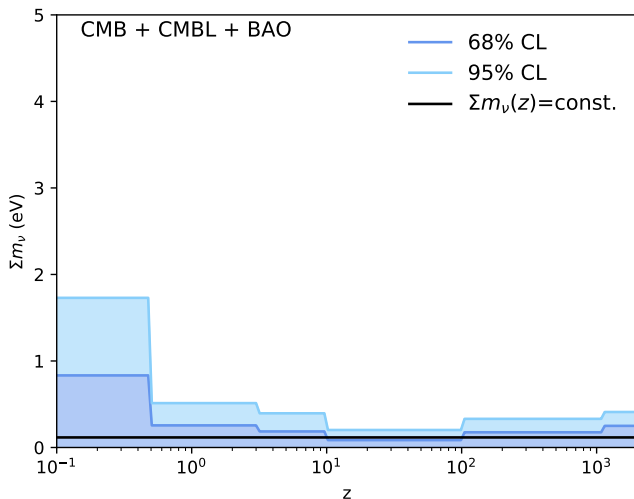
Phenomenological approach: $\Sigma m_\nu(z) = \text{const}$ in 6 redshift bins



CMBL: lensing affects CMB evolution until today

Constraining $\Sigma m_\nu(z)$

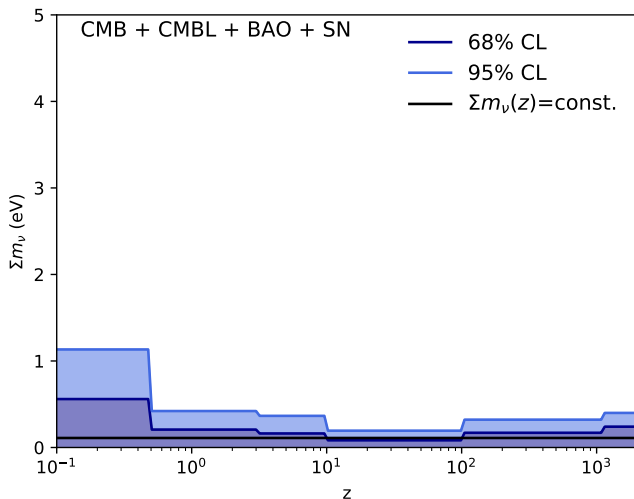
Phenomenological approach: $\Sigma m_\nu(z) = \text{const}$ in 6 redshift bins



BAO: SDSS BAO+Lyman- α +quasars measurements at $z < 2.3$

Constraining $\Sigma m_\nu(z)$

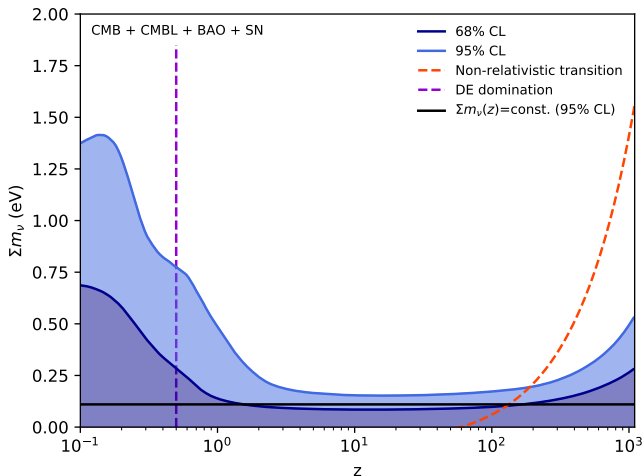
Phenomenological approach: $\Sigma m_\nu(z) = \text{const}$ in 6 redshift bins



SN: Pantheon SN samples at $z < 2.3$ from SDSS, SNLS, HST

Constraining $\Sigma m_\nu(z)$

Phenomenological approach: $\Sigma m_\nu(z) = \text{const}$ in 6 redshift bins

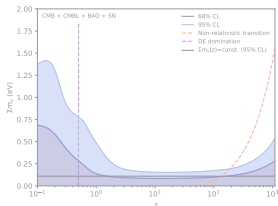


ν energy density is strongly constrained in the range $1 \lesssim z \lesssim \mathcal{O}(100)$, corresponding to matter domination while ν are non-relativistic



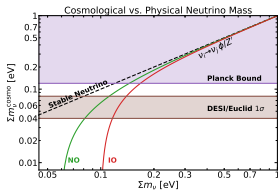
$$\Sigma m_{\nu}^{\text{cosmo}}$$

$\Rightarrow$ energy density of non-relativistic neutrinos



$\Sigma m_{\nu}^{\text{cosmo}} < \Sigma m_{\nu}$ by time-varying masses?

e.g. [Lorenz+, PRD 104 (2021) 123518]



$\Sigma m_{\nu}^{\text{cosmo}} < \Sigma m_{\nu}$ by invisible decay?

e.g. [Escudero+, JHEP 12 (2020) 119]

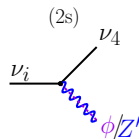
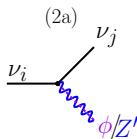
Decaying neutrinos in cosmology

Can a neutrino decay? Is the decay lifetime τ_ν constrained?

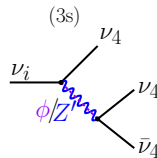
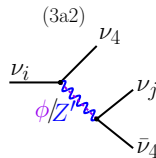
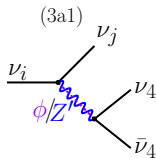
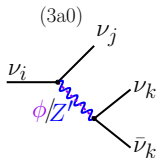
Decay into **visible (e.m.)** particles is constrained to $\tau_\nu > 10^2 t_U$

Invisible decay is much less constrained! A few examples:

2-body Decays:



3-body Decays:



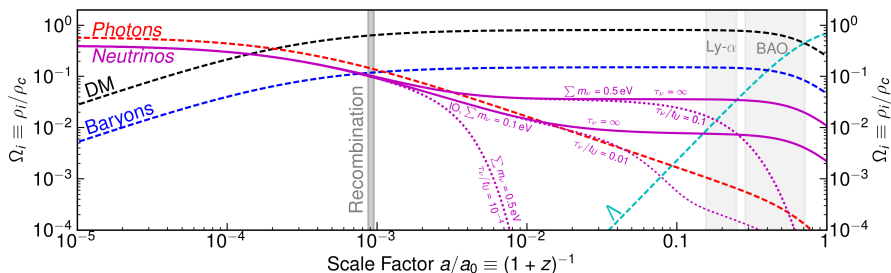
if $m_4 = m_\phi = m_{Z'} = 0$, neutrinos decay to radiation and the mass bounds are avoided if $\tau_\nu \lesssim t_U$ is short enough

t_U age of the Universe – ν_i active neutrinos – ν_4 sterile neutrino – ϕ scalar – Z' vector

Decaying neutrinos in cosmology

Can a neutrino decay? Is the decay lifetime τ_ν constrained?

Depending on τ_ν , the standard energy density of neutrinos is suppressed:



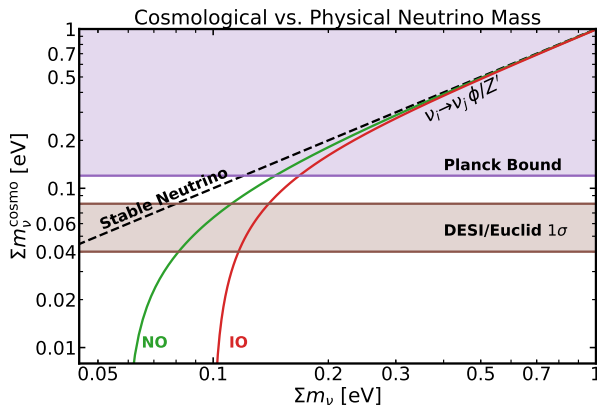
if $\tau_\nu \simeq 10^{-4} t_U$, decay occurs at recombination
(if $\Sigma m_\nu < 0.6$ eV, neutrinos are still relativistic)

for large τ_ν , suppression may be partial

t_U age of the Universe – ν_i active neutrinos – ν_4 sterile neutrino – ϕ scalar – Z' vector

Bounds on the neutrino lifetime

Consider 2-body decay channels:



$\Sigma m_\nu^{\text{cosmo}} = 3m_{\text{lightest}}$ if all except lightest neutrino decay to $\nu_{\text{lightest}}\phi/Z'$

Bounds obtained with $\tau_\nu \lesssim t_U/10$

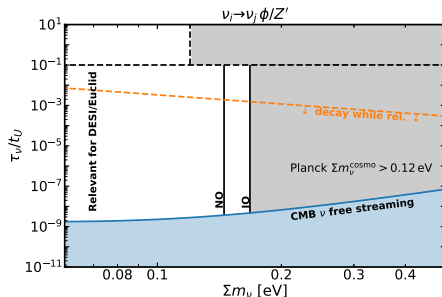
DESI/Euclid bound is forecast with $\Sigma m_\nu = 60 \text{ meV}$

Bounds on the neutrino lifetime

Consider 2-body decay channels:

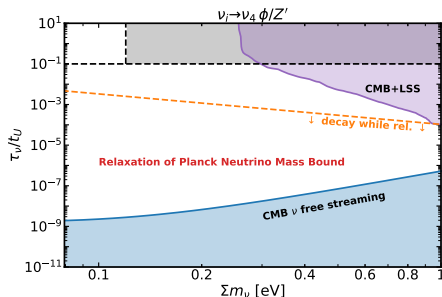
Constraints from **Planck legacy** or **late time clustering+CMB lensing**

Active neutrino + boson:



late time constraints not yet considered, may provide additional constraints

Sterile neutrino + boson:



for appropriate τ_ν and Σm_ν , the mass bounds do not apply because all goes into radiation and $\Sigma m_\nu^{\text{cosmo}} = 0$

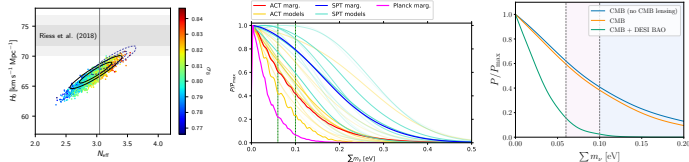


Conclusions

What do we learn about non-standard ν scenarios?

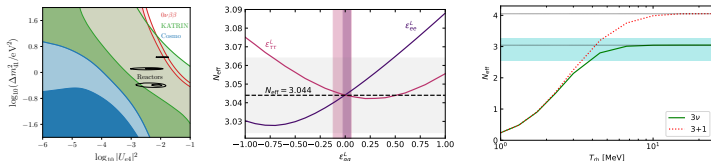
C

Cosmology measures (mostly) neutrino energy densities!



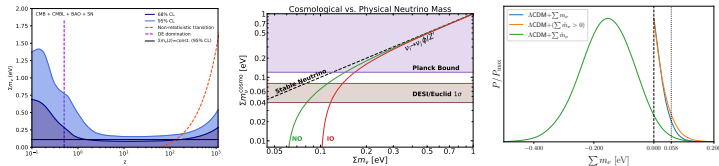
N

N_{eff} is NOT the number of neutrinos!



M

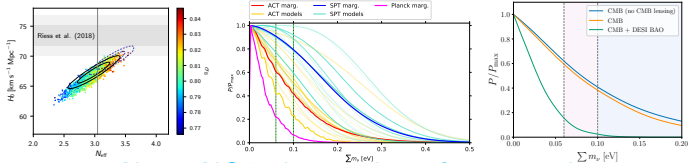
The “cosmological” $\sum m_\nu$ is NOT the sum of neutrino masses!



What do we learn about non-standard ν scenarios?

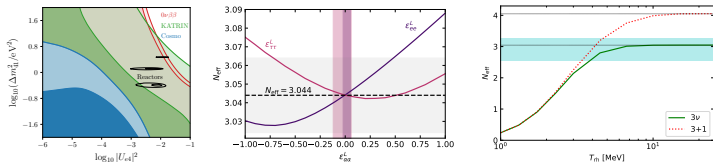
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Cosmology measures (mostly) neutrino energy densities!



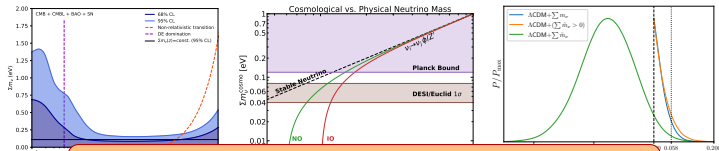
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The “cosmological” Σm_ν is NOT the sum of neutrino masses!



Thanks for your attention!