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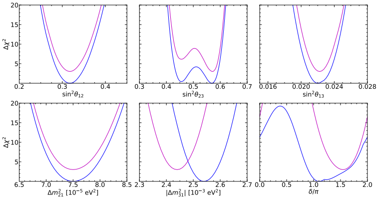
Standard and non-standard neutrino properties from cosmology

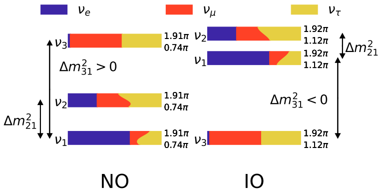
Seminar at IFIC, Valencia, Spain, 06/09/2024

N Neutrinos

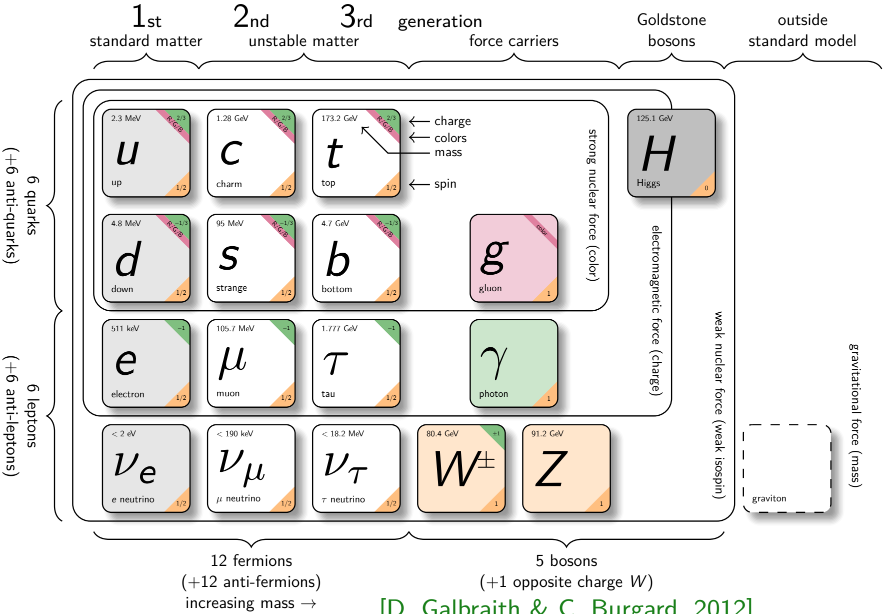
A general introduction, based on



JHEP 02 (2021) 071 and update



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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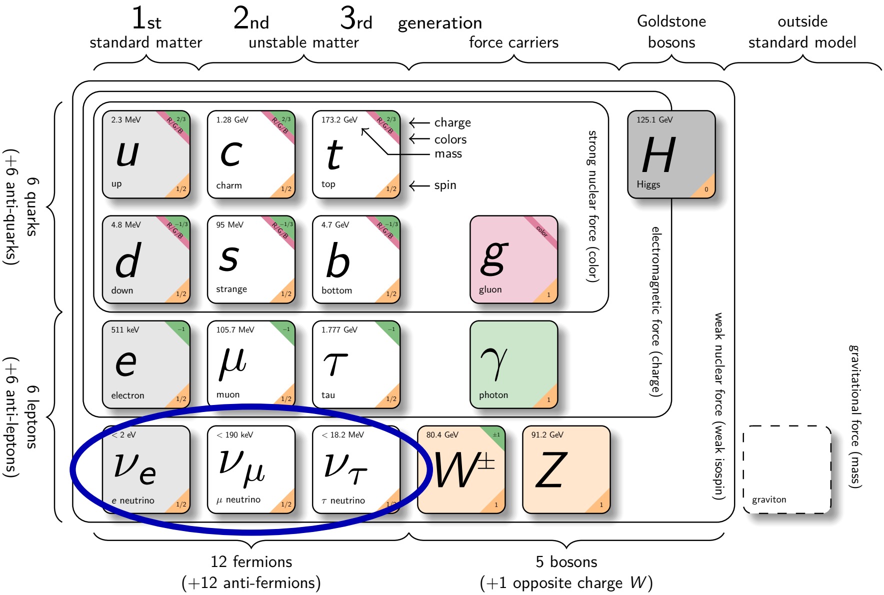
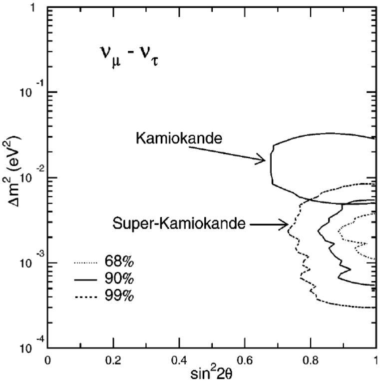


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

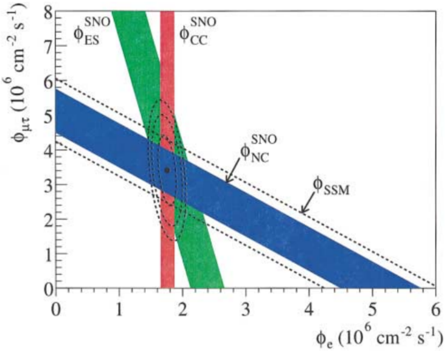
Major discoveries:

[SuperKamiokande, 1998]



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

[SNO, 2001-2002]



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

Nobel prize in 2015

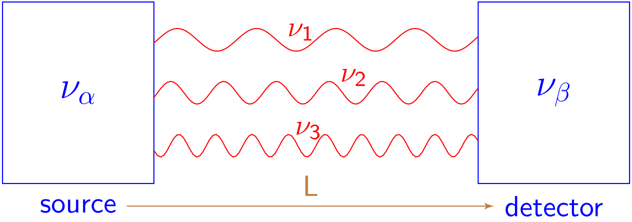
Two neutrino bases

flavor neutrinos ν_α

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

massive neutrinos ν_k

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



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

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

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

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

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

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

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

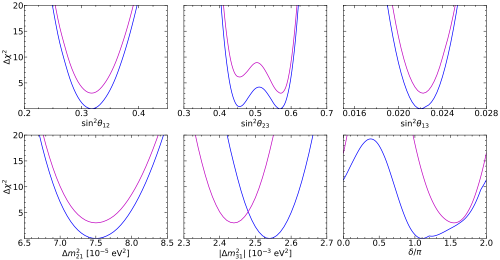
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$ IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

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

$$\begin{aligned}
10 \sin^2(\theta_{12}) &= 3.18 \pm 0.16 \\
10^2 \sin^2(\theta_{13}) &= 2.200^{+0.069}_{-0.062}\ (\mathrm{NO}) \\
&= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO}) \\
10 \sin^2(\theta_{23}) &= 4.55 \pm 0.13 U 5.71 \pm 0.12\ (\mathrm{NO}) \\
&= 5.71^{+0.14}_{-0.17}\ (\mathrm{IO})
\end{aligned}$$

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



mass ordering still unknown

δ still unknown

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

Neutrinos and their masses

[de Salas+, Frontiers 5 (2018) 36]

Normal ordering (NO)

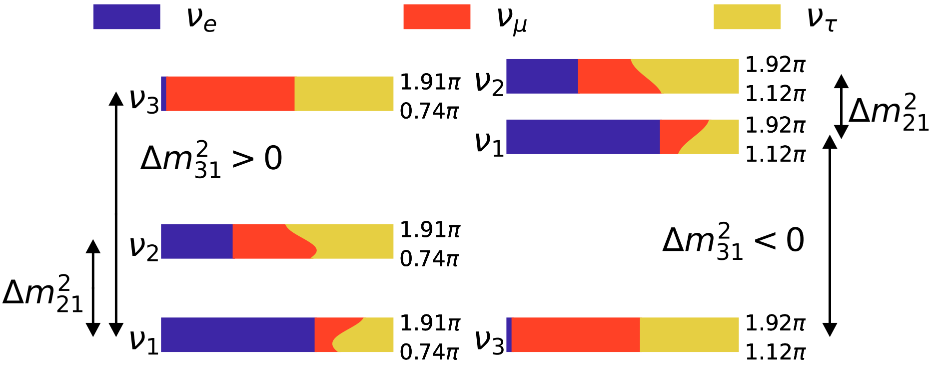
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV

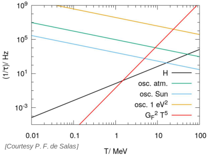


Absolute scale unknown!

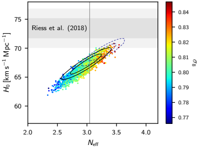
Can we constrain the mass ordering using bounds on $\sum m_\nu$?

E Neutrinos in the Early Universe

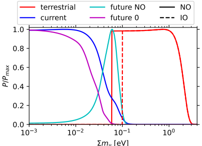
Based on



JCAP 04 (2021) 073

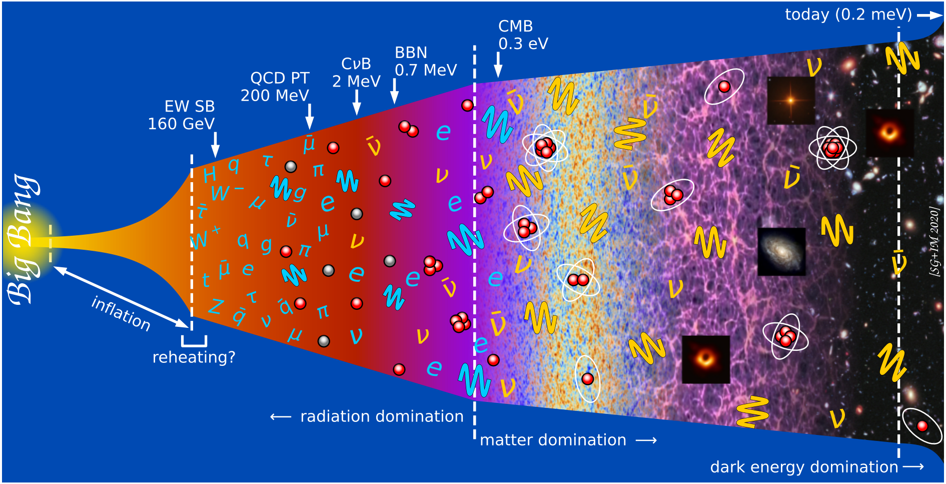


Planck 2018



PDU 40 (2023) 101226

History of the universe



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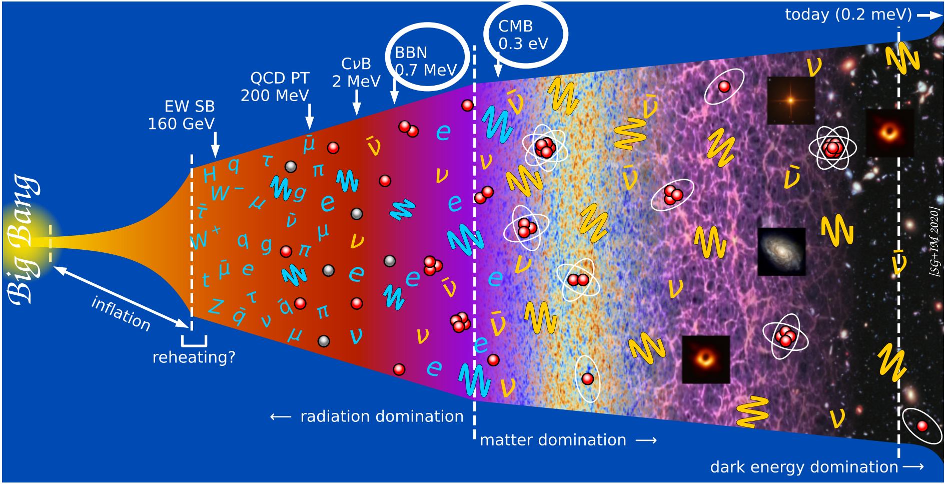
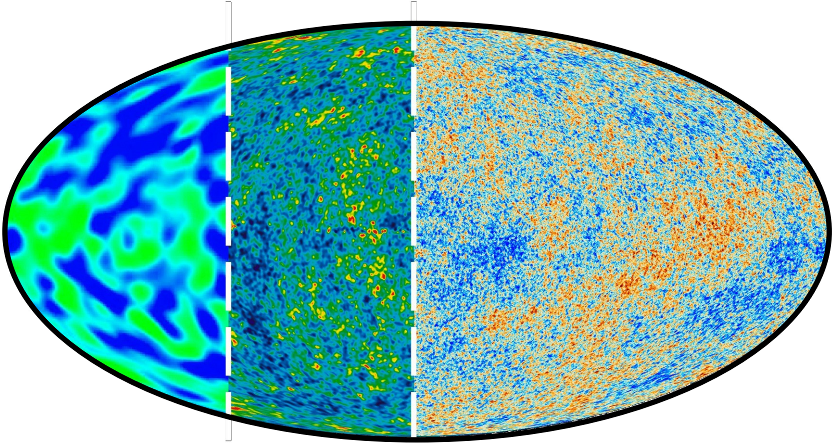


The oldest picture of the Universe

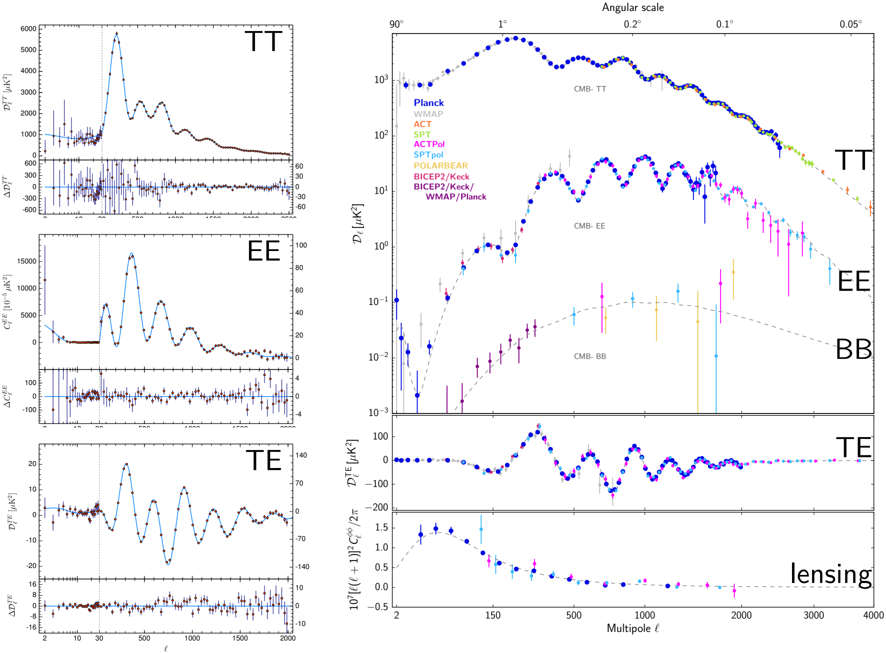
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

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



CMB spectra as of 2018

[Planck Collaboration, 2018]



Big Bang Nucleosynthesis (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

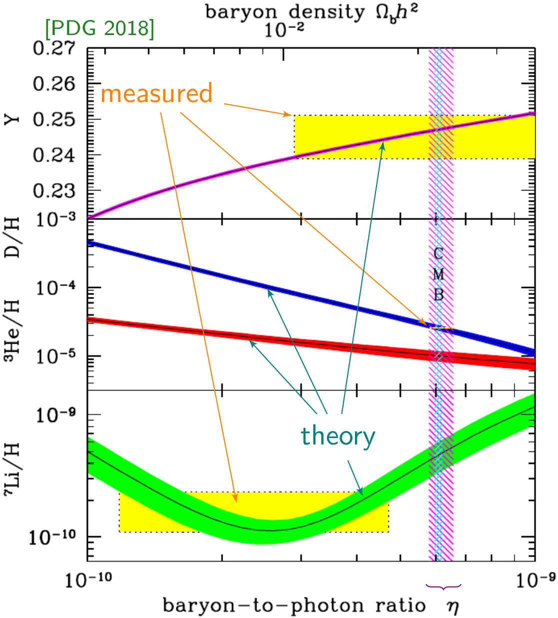
much earlier than CMB!

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...

[PDG 2018]



BBN concordance

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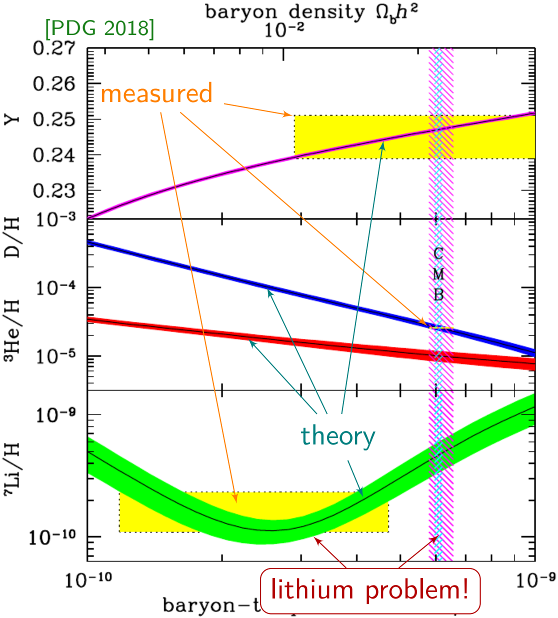
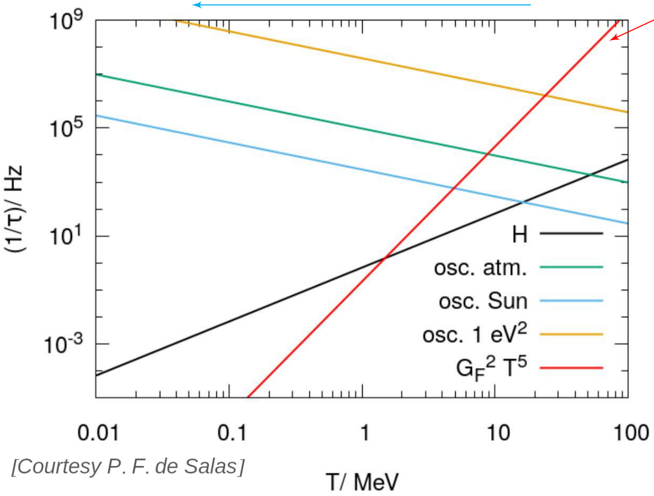


BBN concordance

Neutrinos in the early Universe

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

time



[Courtesy P. F. de Salas]

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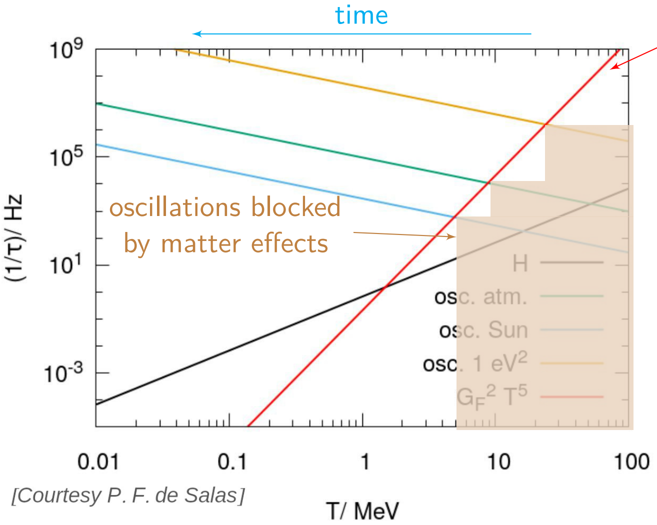

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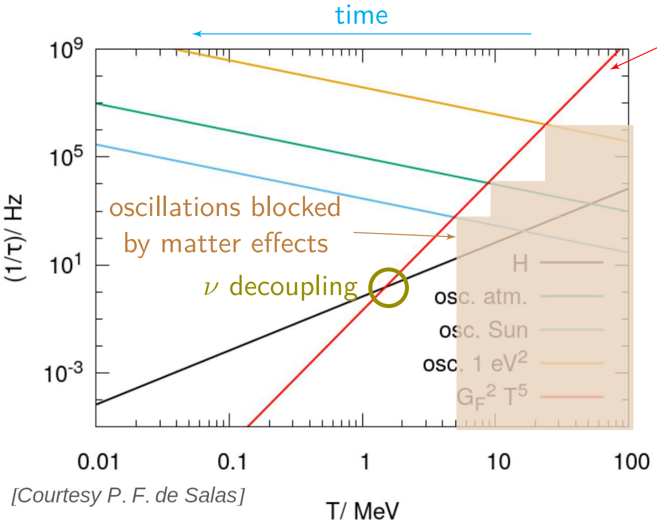

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ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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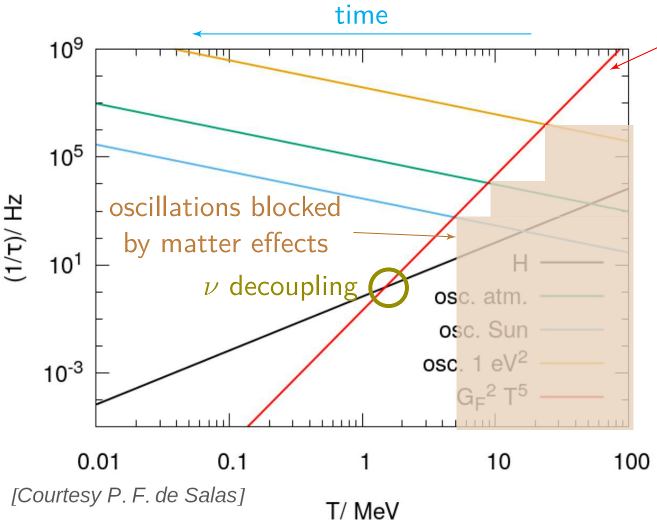

[Courtesy P. F. de Salas]

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

f_ν: frozen Fermi-Dirac distribution

Today:

$T_{\nu,0} = 1.945$ 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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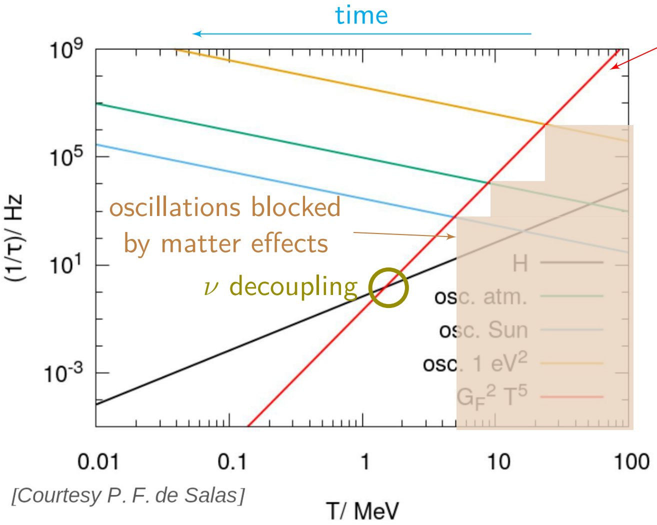

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actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]
[Sigl, Raffelt, 1993]

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

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

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

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

effective Hamiltonian $\mathcal{H}_{\mathrm{eff}} = \frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{2\sqrt{2}G_{\mathrm{F}}\, y\, m_e^6}{x^6}\left(\frac{\mathbb{E}_\ell + \mathbb{P}_\ell}{m_W^2} + \frac{4}{3}\frac{\mathbb{E}_\nu}{m_Z^2}\right)$

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

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

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/ahep_cosmo/fortepiano_public

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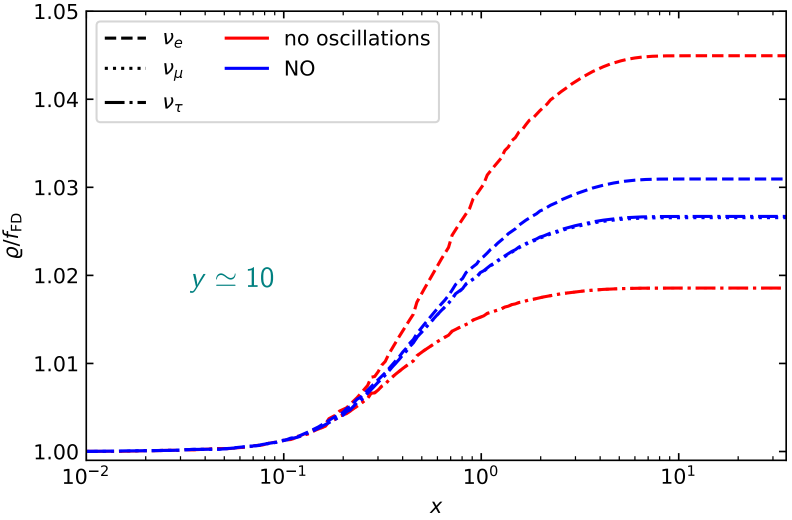
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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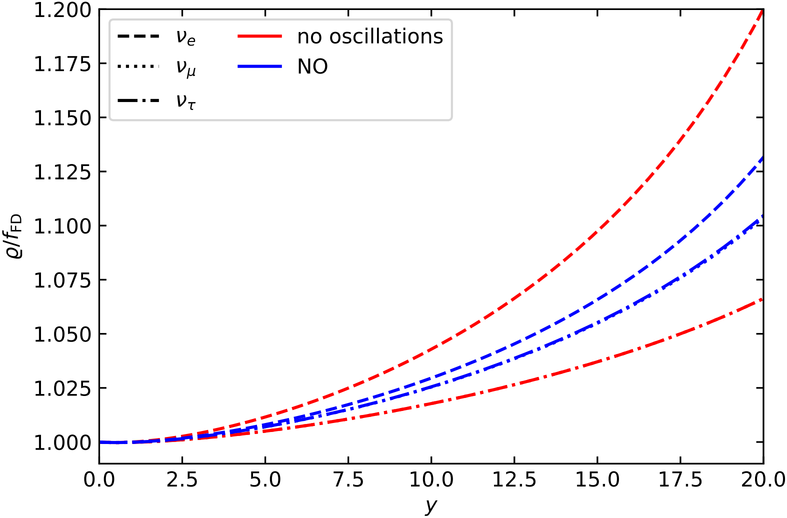
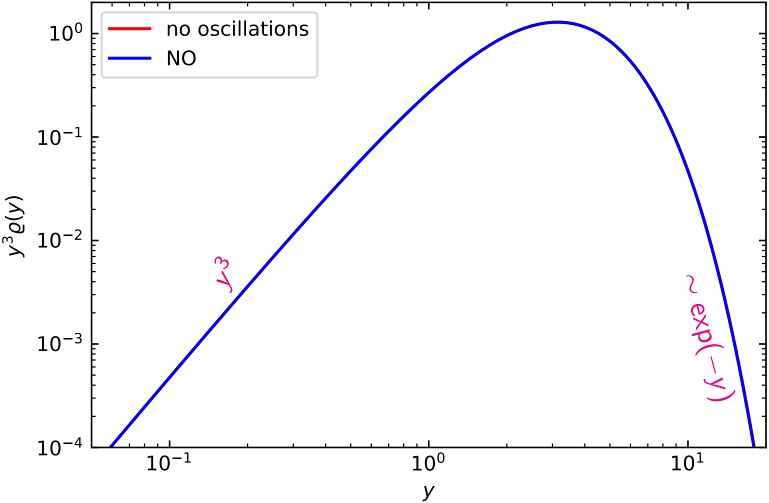


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

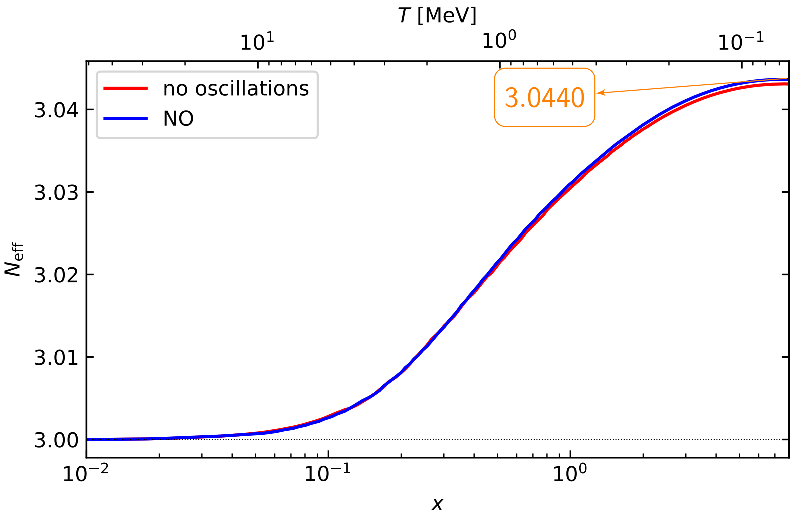
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

$\hookrightarrow \propto y^3 \varrho_{ii}(y)$



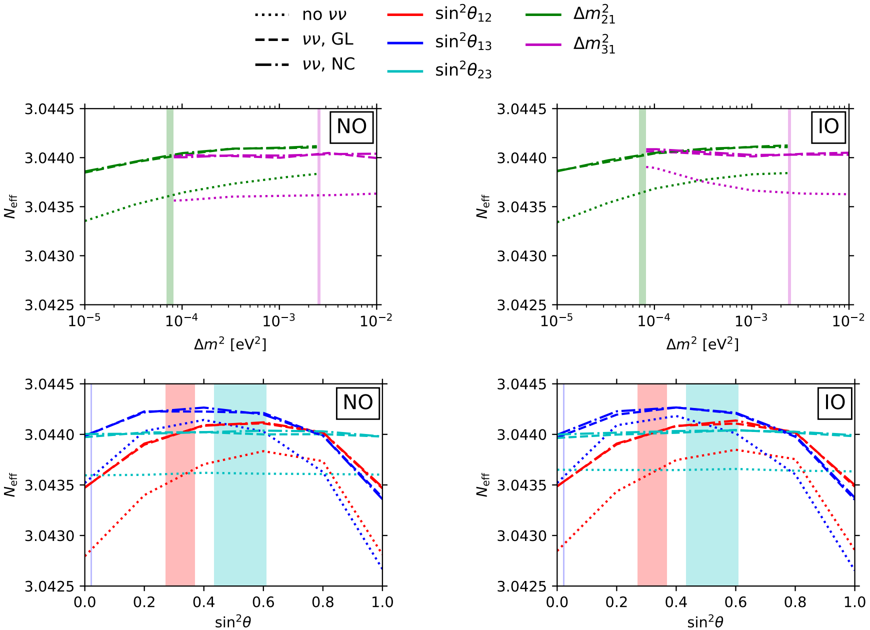
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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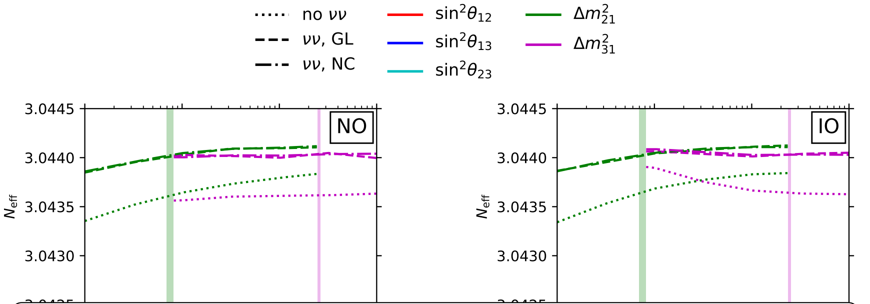
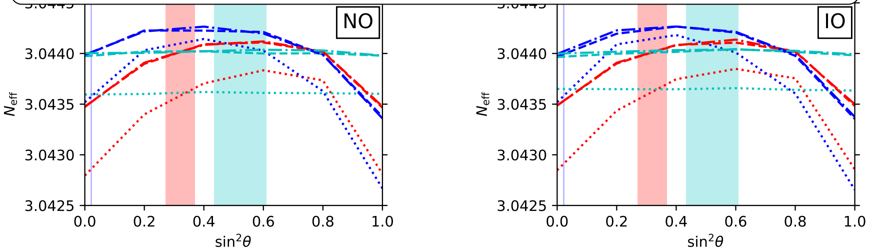


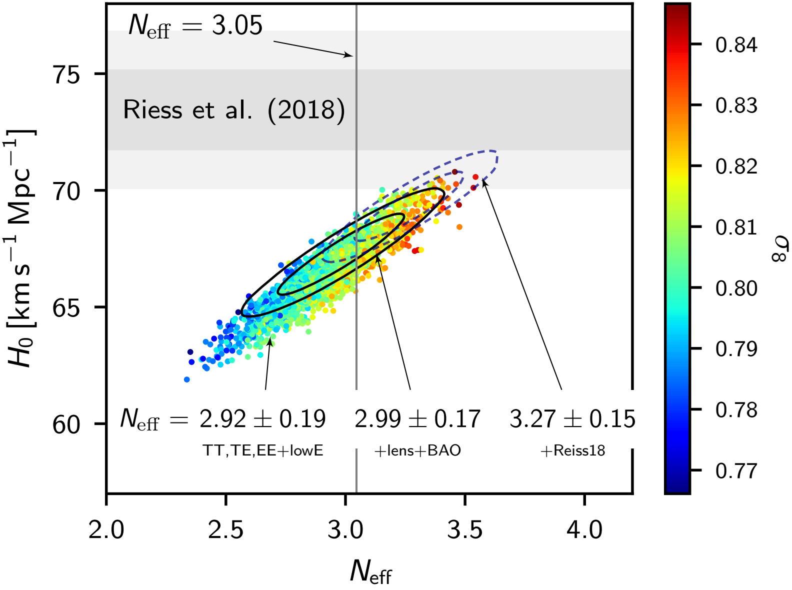
within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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



$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]



What is $N_{\rm eff}$?

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

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

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

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

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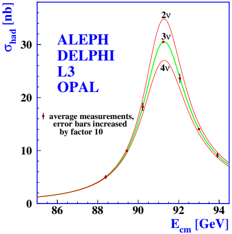
$$N_\nu^{(Z)} = 2.9840 \pm 0.0082$$



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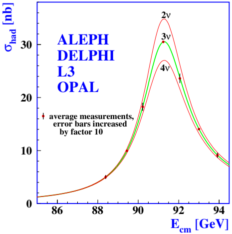


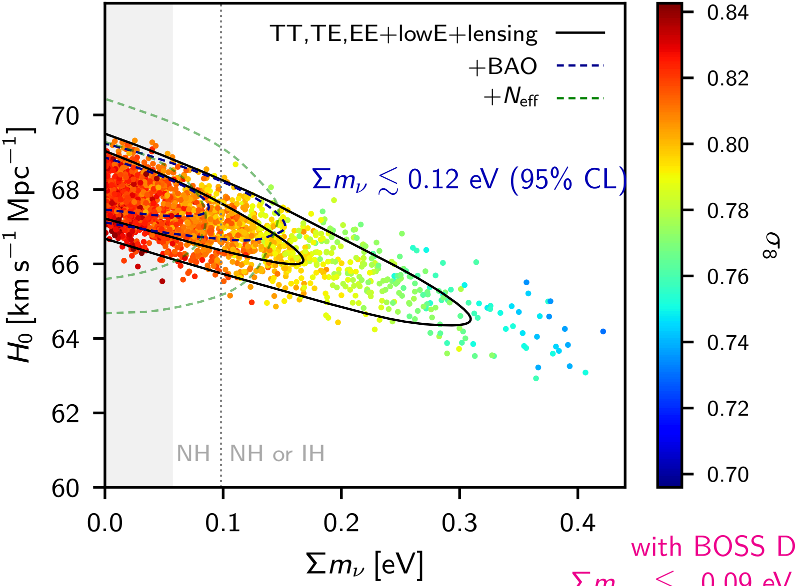
instantaneous decoupling:
$N_{\rm eff}^{\nu} = 1$ for each ν family

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

Non-standard physics? see later!

Σm_ν and CMB

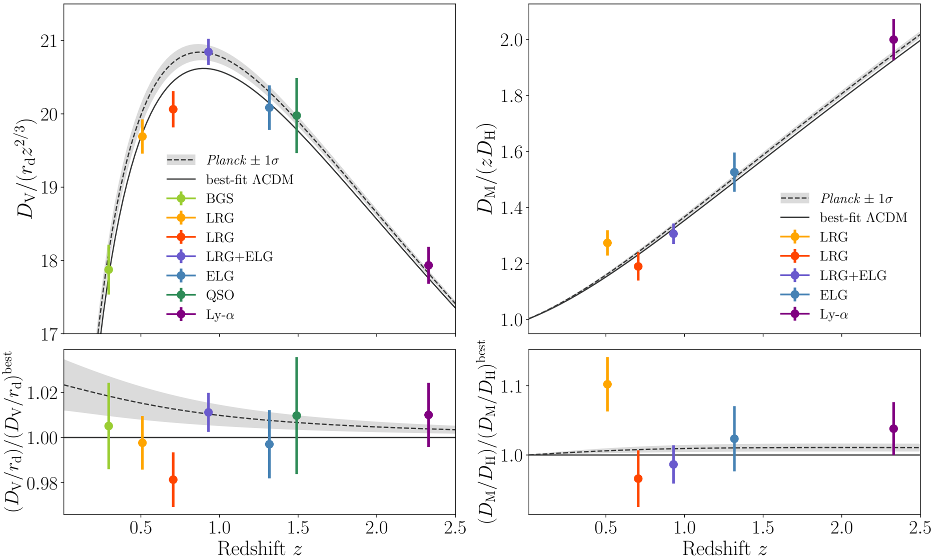
[Planck Collaboration, 2018]



with BOSS DR16 BAO:
$\Sigma m_\nu \lesssim 0.09$ eV (95% CL)

DESI BAO data from DR1

[arxiv:2404.03002]



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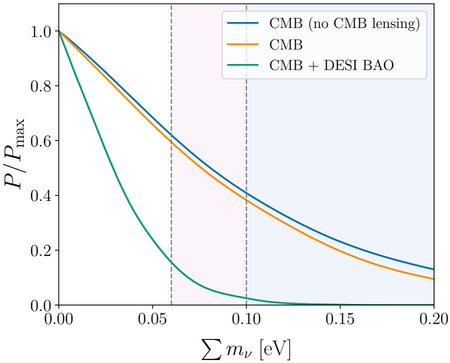
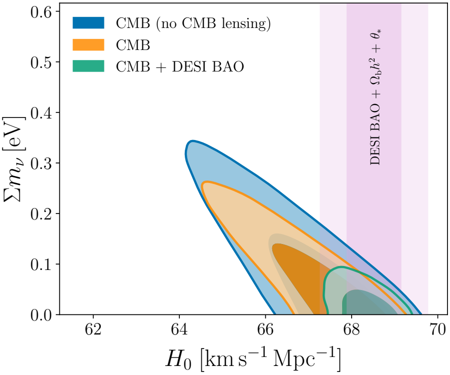




$\sum m_\nu < 0.072$ eV (95%, DESI BAO+CMB)

close to disfavoring normal ordering minimum value

$\sum m_\nu \quad \sim \quad 0.06$ eV

at 95%!

Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

standard factor

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

NO: $\Sigma m_\nu \gtrsim 0.06$ eV Current: $\Sigma m_\nu \lesssim 0.1$ eV (95%) IO: $\Sigma m_\nu \gtrsim 0.1$ eV

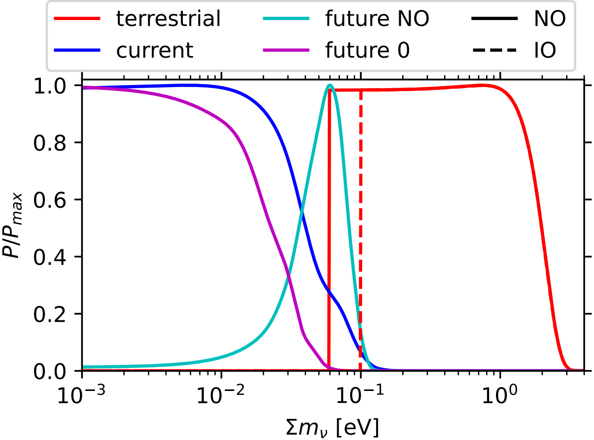
Future sensitivity: $\sigma(\Sigma m_\nu) \simeq 0.02$ eV

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

tension even with NO!

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

confirm NO, disfavor IO



Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

standard factor

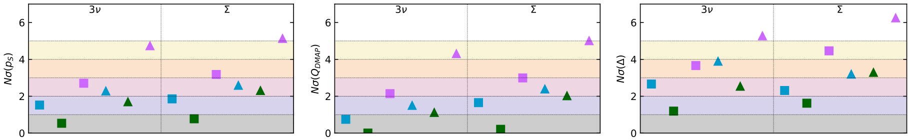
Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\text{ eV})$

Is there a tension between cosmology and oscillations?

or will there be a tension?

several possible tests can be considered, similar results

$\Sigma m_\nu \lesssim 0.1$ eV (95%)	●	current	■	NO
$\Sigma m_\nu = 0.06 \pm 0.02$ eV (1σ)	●	future NO	▲	IO
$\Sigma m_\nu = 0.00 \pm 0.02$ eV (1σ)	●	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

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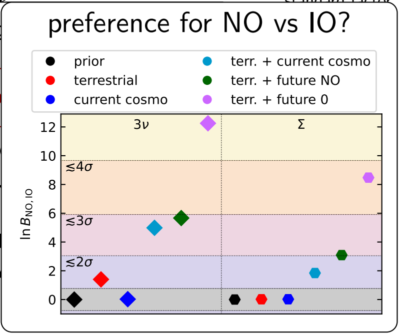

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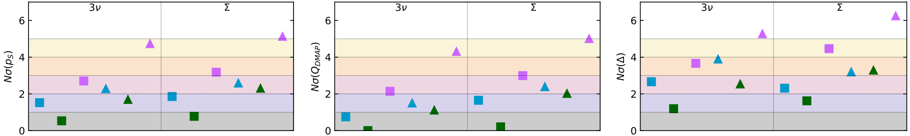

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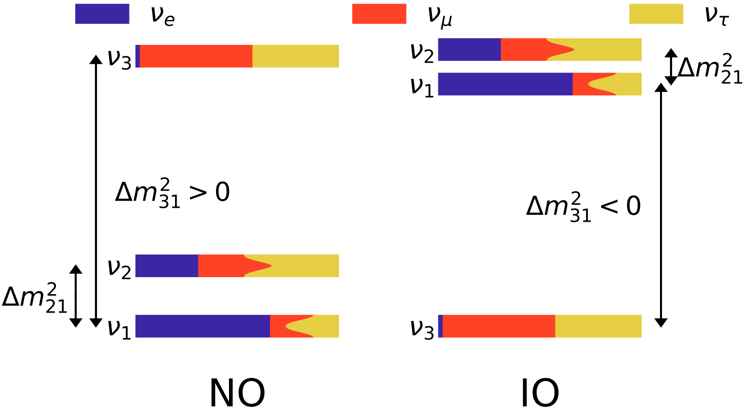
What is $\sum m_\nu$?

normal ordering (NO):
$m_2 \gtrsim 9$ meV, $m_3 \gtrsim 50$ meV

inverted ordering (IO):
$m_{1,2} \gtrsim 50$ meV



[Valencia global fit]

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

many relic neutrinos are non-relativistic today!

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

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

Background measurements are sensitive to ω_ν, not Σm_ν!

"Cosmological" Σm_ν measures the energy density of non-relativistic νs

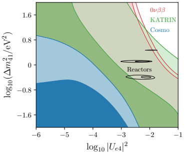
Note: free-streaming scale directly depends on m_ν:

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

R

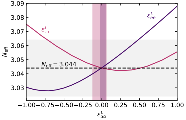
N_{eff}

⇒ energy density of relativistic neutrinos



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

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



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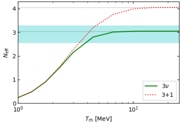

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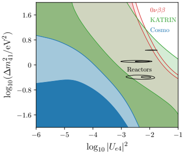

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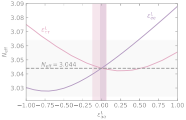

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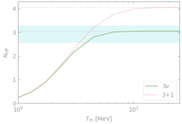

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Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

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

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

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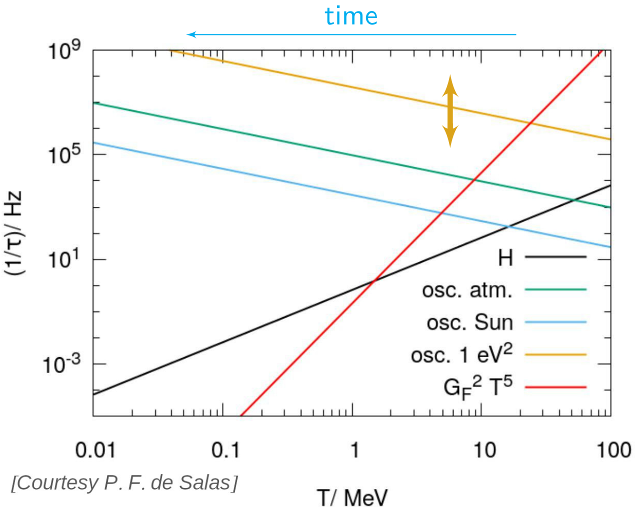

[Courtesy P. F. de Salas]

beginning of oscillations depends on Δm^2_{41}

later oscillations

$\Downarrow$

less time before ν decoupling!

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$$0 \longleftarrow \Delta N_{\rm eff} = N_{\rm eff}^{4\nu} - N_{\rm eff}^{3\nu} \longrightarrow \simeq 1$$

no sterile production — active&sterile in equilibrium

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

[Dolgov&Villante, 2004]

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

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

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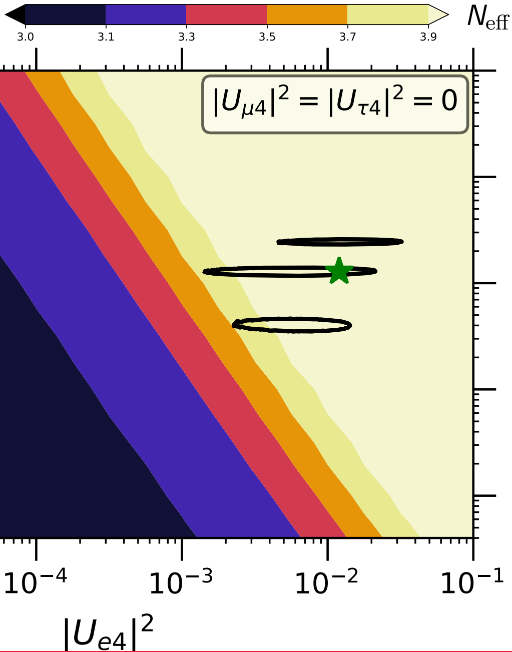
Full calculation: use numerical code!

`FORTran-Evolved PrimordIAl Neutrino Oscillations`
`(FortEPiaNO)`
`https://bitbucket.org/ahep_cosmo/fortepiano_public`

$N_{\rm eff}$ and the new mixing parameters

We can vary more than one angle:



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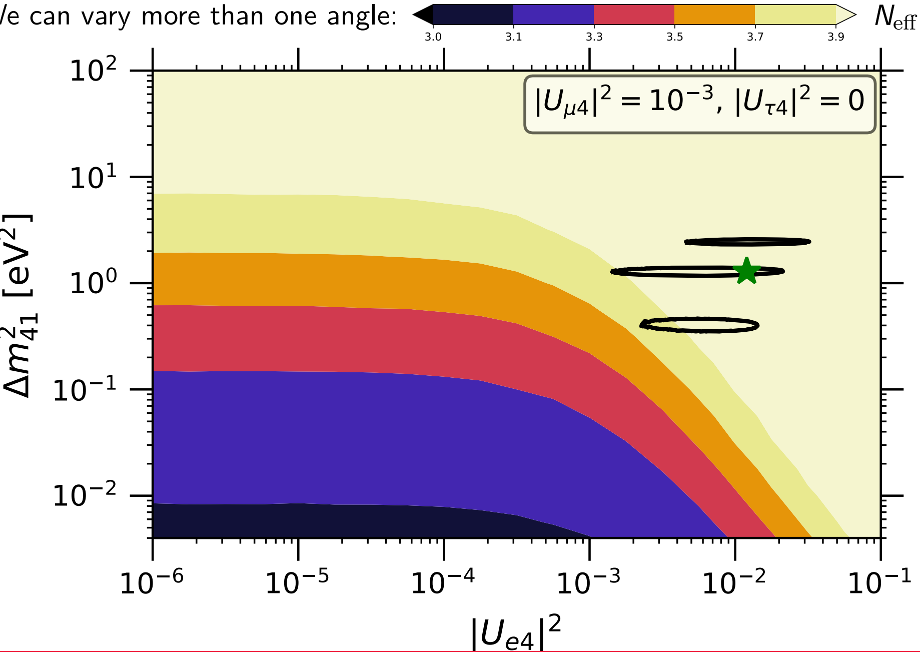

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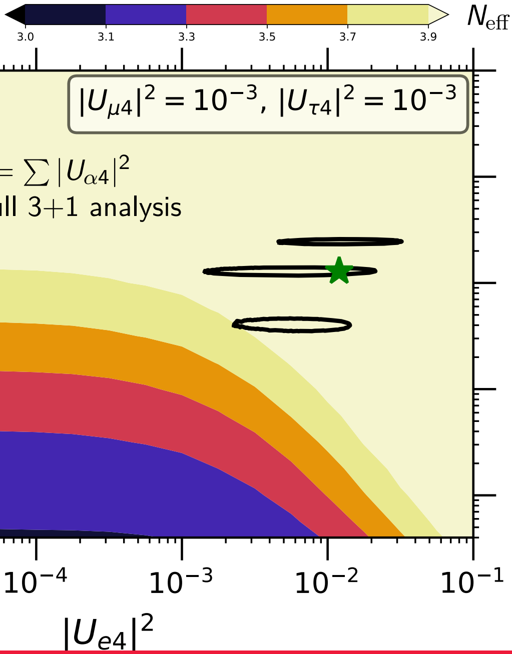
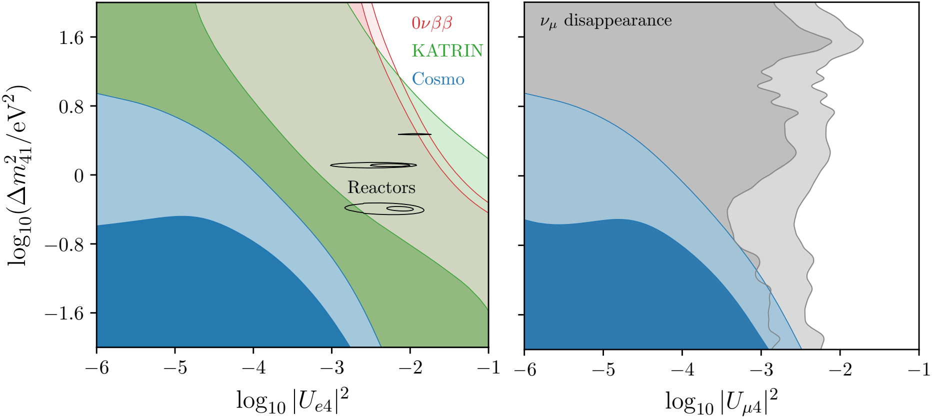


Comparing constraints

[PRD 104 (2021) 123524]

Cosmological constraints are stronger than most other probes

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



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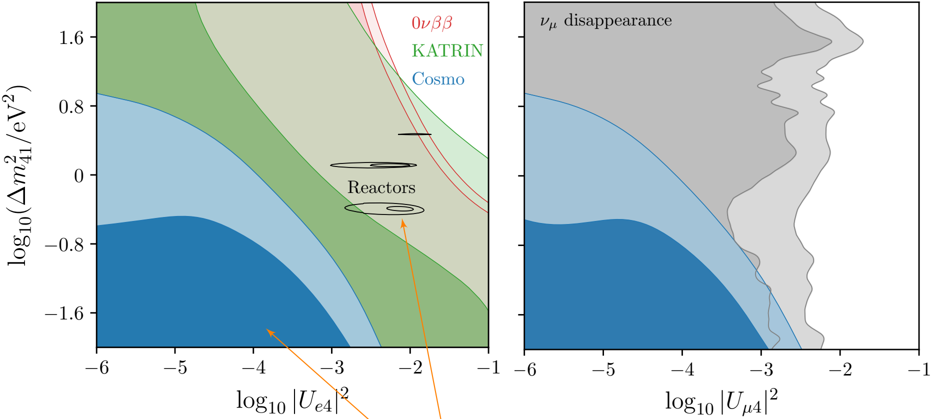

Warning: tension between (old) reactor experiments and CMB bounds!

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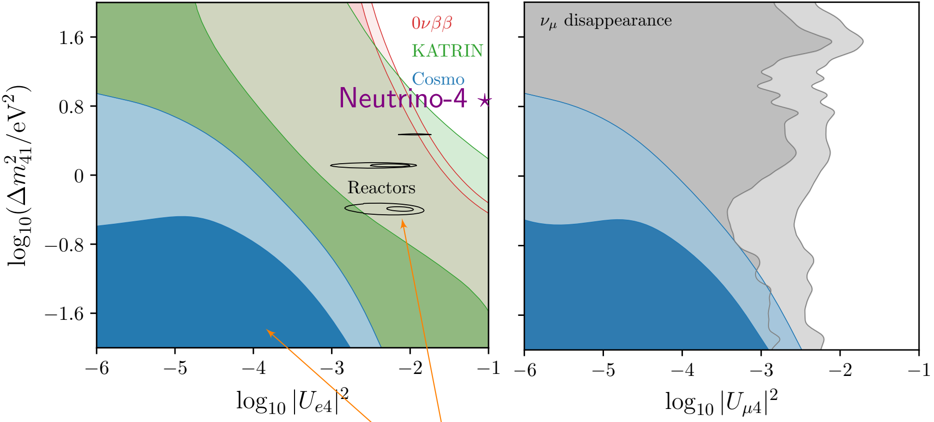

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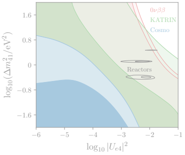
R

N_{eff}

$\Rightarrow$ energy density of relativistic neutrinos



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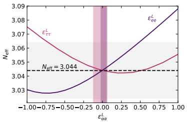

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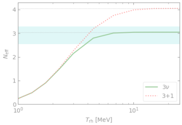


$N_{\text{eff}} < 3$?

e.g. low-reheating [PRD 92 (2015) 123534], [update in prep.]

Non-standard neutrino-electron interactions

[PLB 820 (2021)]

Can neutrinos have interactions beyond the SM ones?

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

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

new interactions affect all phenomena involving neutrinos and electrons

including neutrino decoupling:

collision terms

$$G^L_{\rm SM} = {\rm diag}(g_L, \tilde g_L, \tilde g_L)$$
$$G^R_{\rm SM} = {\rm diag}(g_R, g_R, g_R)$$

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

$\downarrow$

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

matter effects in oscillations (subdominant!)

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

$\downarrow$

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

with $\epsilon_{\alpha\beta} = \epsilon^L_{\alpha\beta} + \epsilon^R_{\alpha\beta}$

NSI effects on $N_{\rm eff}$

[PLB 820 (2021)]

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

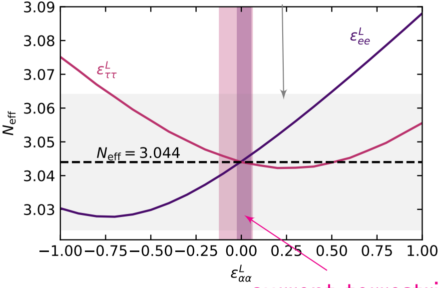
e.g.:

$G^L_{ee} \to 0.727 + \epsilon^L_{ee}$

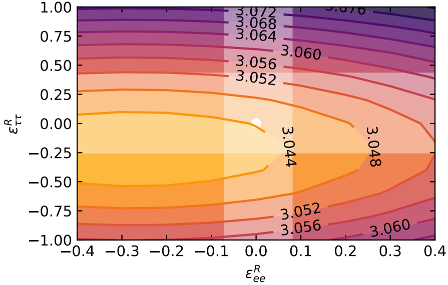
$G^L_{\tau\tau} \to -0.273 + \epsilon^L_{\tau\tau}$

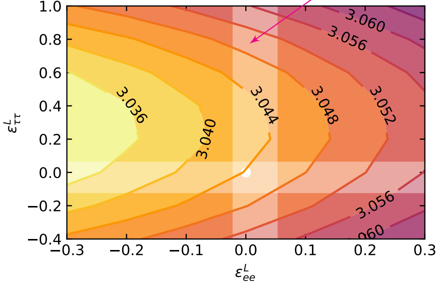
$G^R_{\alpha\alpha} \to 0.233 + \epsilon^R_{\alpha\alpha}$

future CMB



current terrestrial

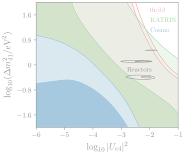




R

N_{eff}

$\Rightarrow$ energy density of relativistic neutrinos



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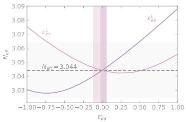
e.g. sterile neutrino [JCAP 07 (2019) 014]



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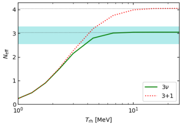

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e.g. low-reheating [PRD 92 (2015) 123534], [update in prep.]

Scenarios with low reheating temperature

[in preparation]

Reheating: phase ending inflation

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

during reheating: inflaton decays into standard model particles

$\Longrightarrow$ photons, electrons, ... are populated directly

radiation domination begins after reheating

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if reheating occurs too late, neutrinos are not generated and $N_{\rm eff} < 3$

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

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

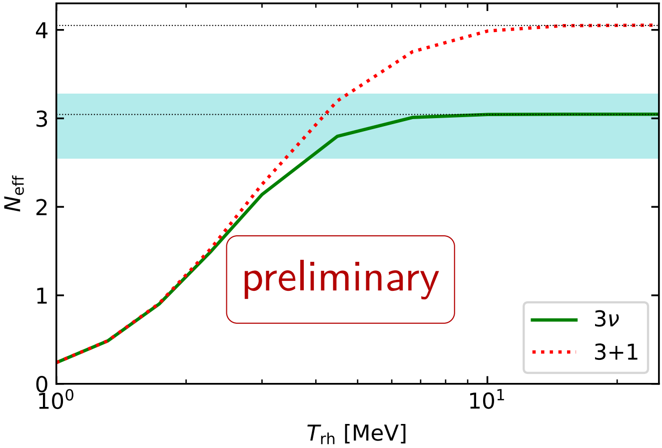
3 neutrino oscillations start to be affected when $T_{\rm rh} \lesssim 8$ MeV

what about sterile neutrinos?

N_{eff} with low reheating

[in preparation]

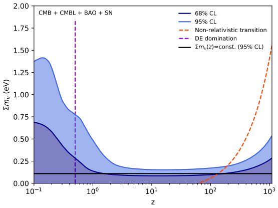
N_{eff} as a function of T_{rh} (3 or 3+1 neutrinos):



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

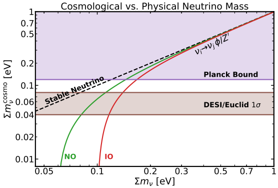
M $\Sigma m_\nu^{\rm cosmo}$

$\Rightarrow$ energy density of non-relativistic neutrinos



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

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



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

M

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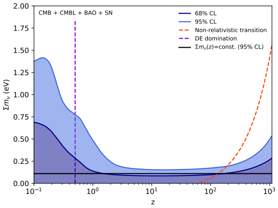

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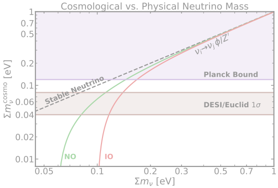

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e.g. [Escudero+, JHEP 12 (2020) 119]

Time-varying neutrino masses

How to make neutrino masses non-constant in time?

$\boxed{\text{new coupling!}}$

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!

a scale factor

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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 $T_\Lambda \lesssim m_\nu$

($T_\Lambda < T_{\rm CMB}$ in order to preserve recombination)

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

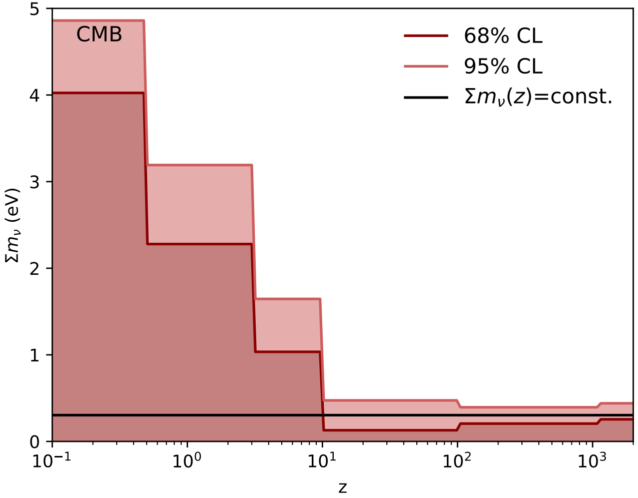
↓

cosmological mass bound is avoided!

a scale factor

Constraining $\Sigma m_\nu(z)$

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

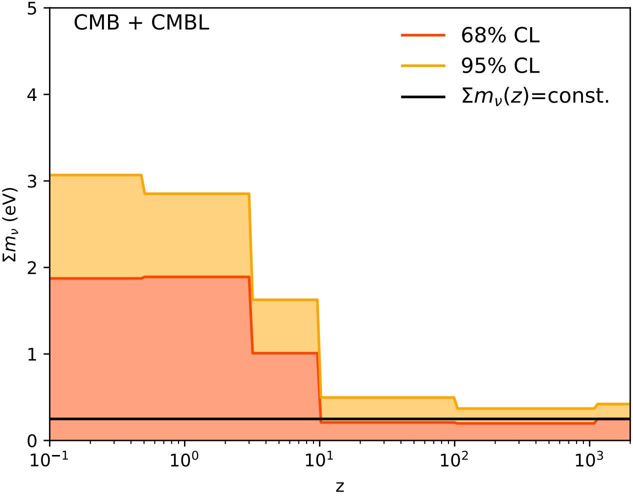


CMB: very high redshift, poor constraints on late universe

Constraining $\Sigma m_\nu(z)$

[Lorenz+, PRD 104 (2021) 123518]

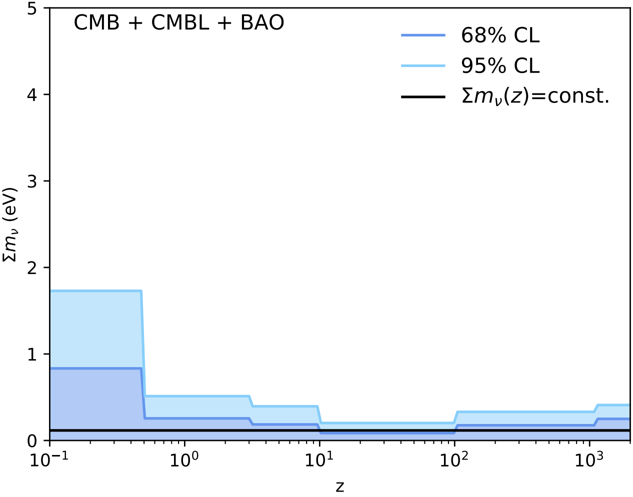
Phenomenological approach: $\Sigma m_\nu(z) = $ const in 6 redshift bins



CMBL: lensing affects CMB evolution until today

Constraining $\Sigma m_\nu(z)$

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



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

Constraining $\Sigma m_\nu(z)$

[Lorenz+, PRD 104 (2021) 123518]

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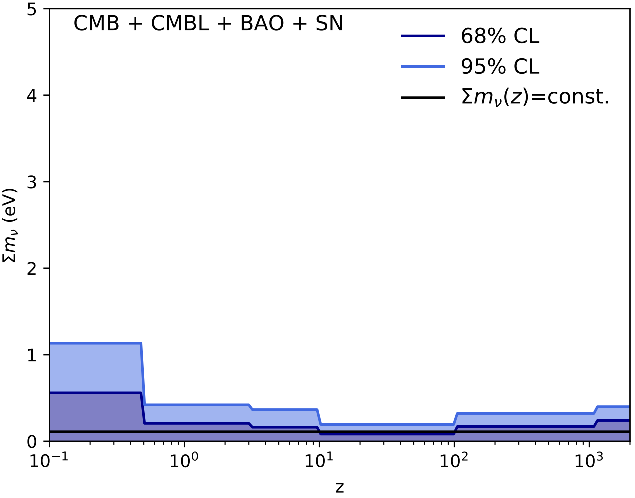
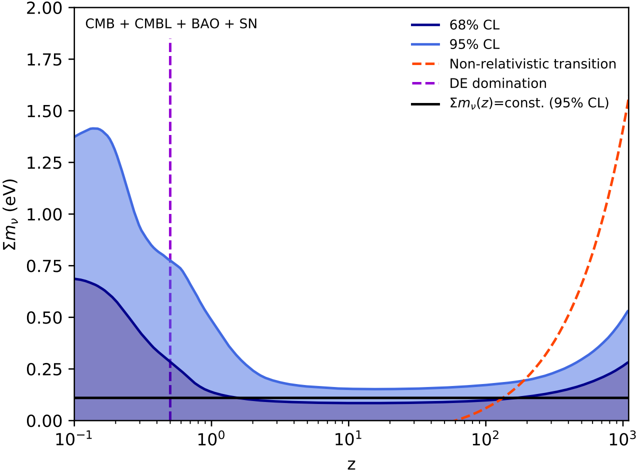


SN: Pantheon SN samples at $z < 2.3$ from SDSS, SNLS, HST

Constraining $\Sigma m_\nu(z)$

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

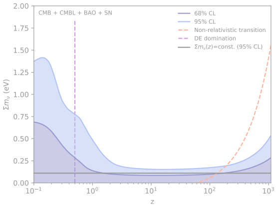


ν energy density is strongly constrained in the range $1 \lesssim z \lesssim \mathcal{O}(100)$, corresponding to matter domination while ν are non-relativistic

M

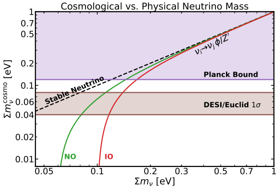
$\Sigma m_\nu^{\mathrm{cosmo}}$

$\Rightarrow$ energy density of non-relativistic neutrinos



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

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



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

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

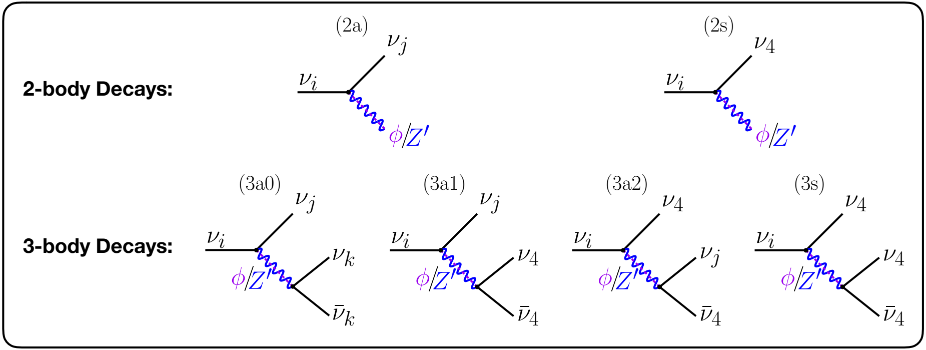
Decaying neutrinos in cosmology

[Escudero+, JHEP 12 (2020) 119]

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:



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

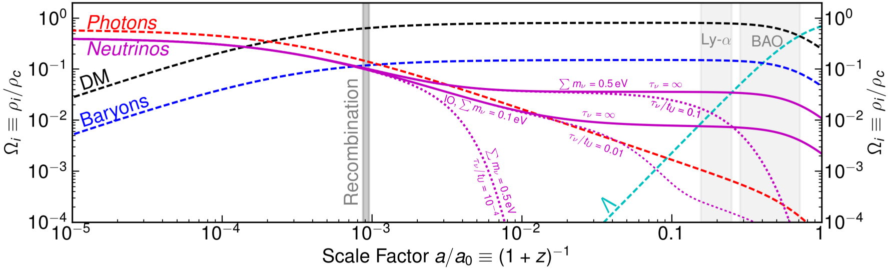
t_U age of the Universe – ν_i active neutrinos – ν_4 sterile neutrino – ϕ scalar – Z' vector

Decaying neutrinos in cosmology

[Escudero+, JHEP 12 (2020) 119]

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)

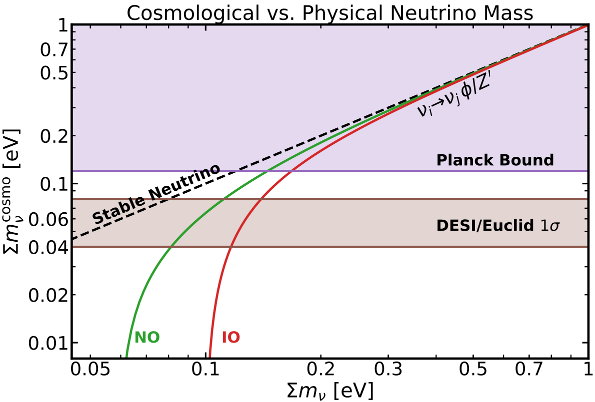
for large τ_ν, suppression may be partial

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

Bounds on the neutrino lifetime

[Escudero+, JHEP 12 (2020) 119]

Consider 2-body decay channels:



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

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

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

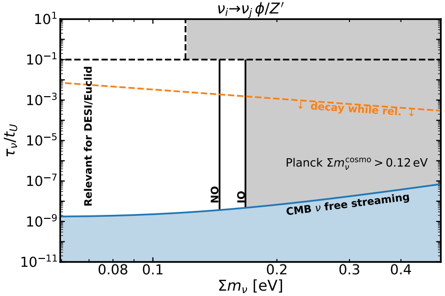
Bounds on the neutrino lifetime

[Escudero+, JHEP 12 (2020) 119]

Consider 2-body decay channels:

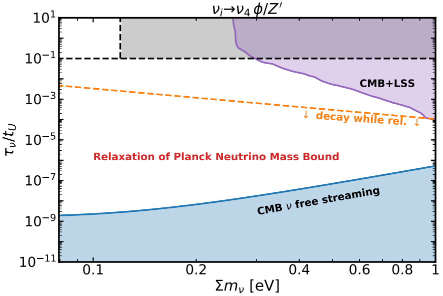
Constraints from Planck legacy or late time clustering+CMB lensing

Active neutrino + boson:



late time constraints not yet considered, may provide additional constraints

Sterile neutrino + boson:



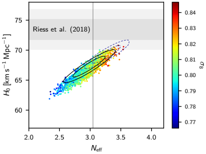
for appropriate τ_ν and Σm_ν, the mass bounds do not apply because all goes into radiation and $\Sigma m_\nu^{\rm cosmo} = 0$

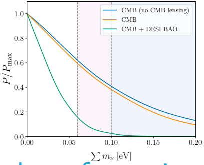
Z Conclusions

What do we learn about non-standard ν scenarios?

C

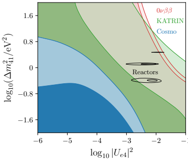
Cosmology measures (mostly) neutrino energy densities!

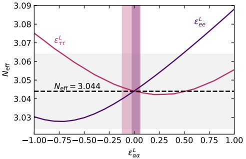


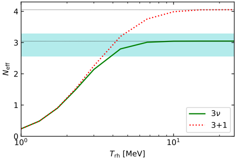


N

$N_{\rm eff}$ is NOT the number of neutrinos!

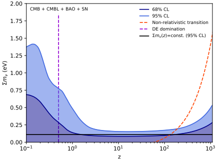


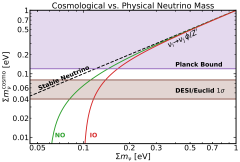




M

The "cosmological" Σm_ν is NOT the sum of neutrino masses!





What do we learn about non-standard ν scenarios?

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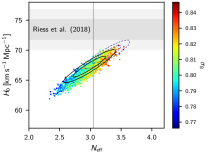

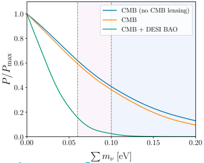

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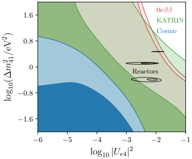

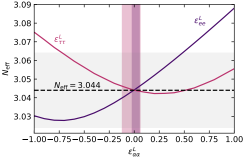

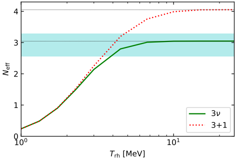

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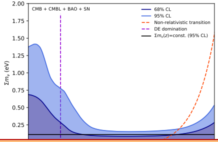

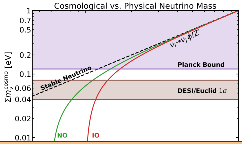

Thanks for your attention!