Stefano Gariazzo

UniTO and INFN, Turin (IT)
IFIC (CSIC-UV), Valencia (ES)

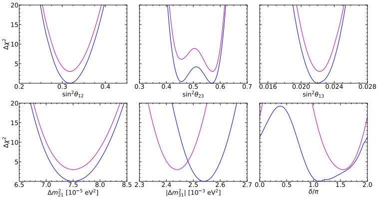
`stefano.gariazzo@unito.it`
`gariazzo@ific.uv.es`

Testing new physics scenarios with neutrino decoupling and BBN

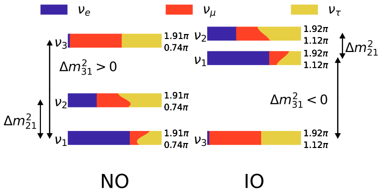
Copernicus Webinar at Jagiellonian University, Krakov, 05/05/2026

Neutrinos

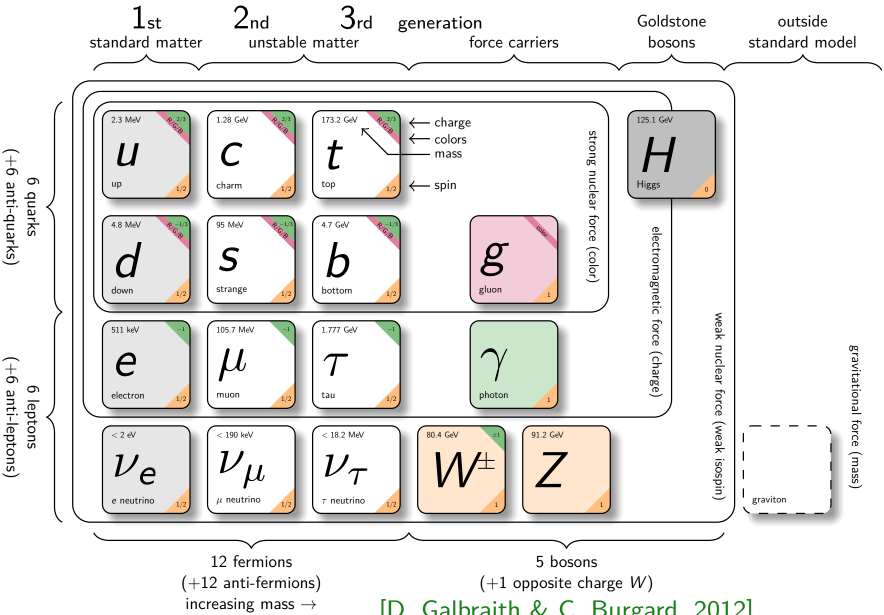
A general introduction, based on



JHEP 02 (2021) 071 and update

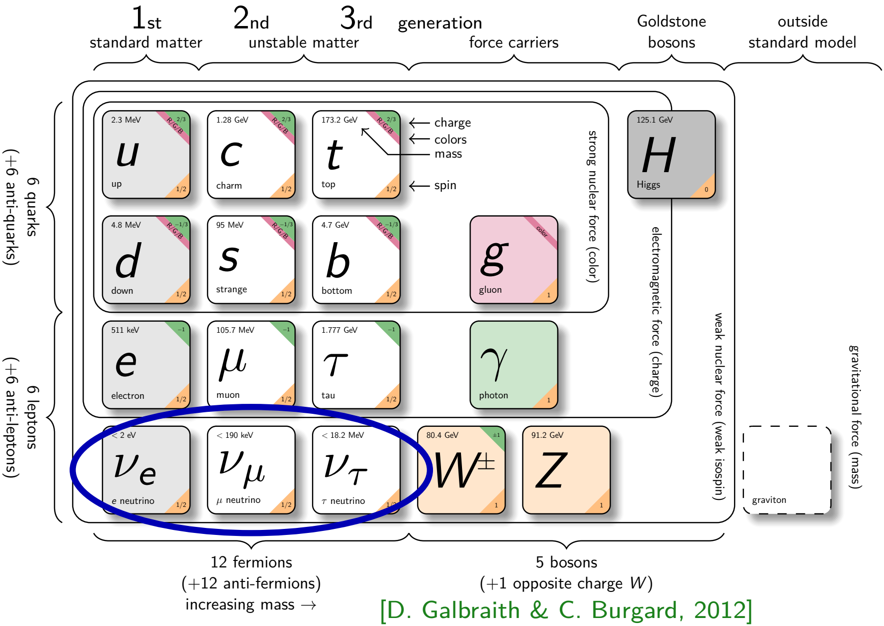


The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics

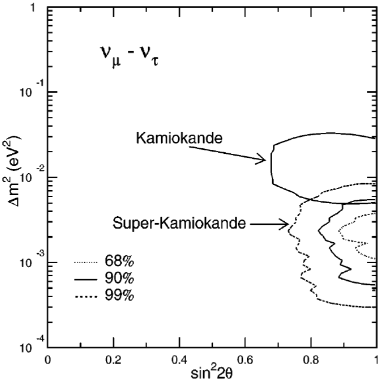


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

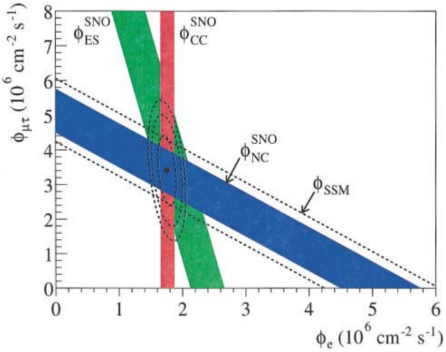
Major discoveries:

[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

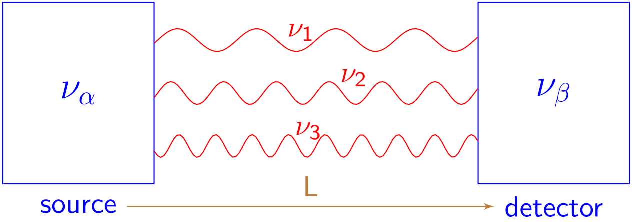
Two neutrino bases

flavor neutrinos ν_α

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

massive neutrinos ν_k

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



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

$E_k^2 = p^2 + m_k^2 \longleftarrow$ 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

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

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

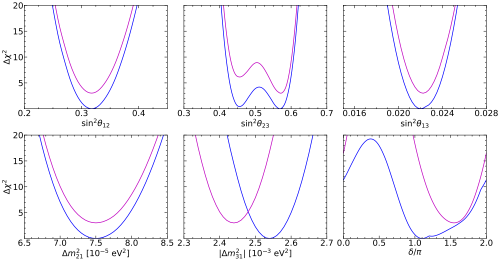
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

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

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

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



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)

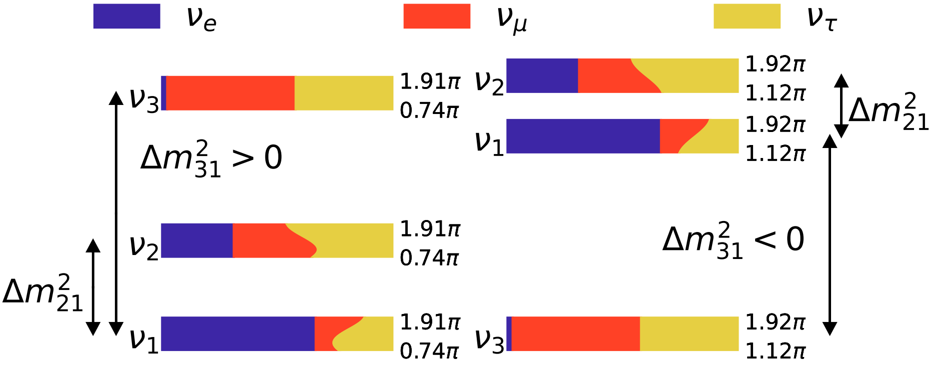
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV

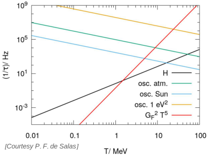


Absolute scale unknown!

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

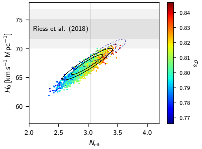
E Neutrinos in the Early Universe

Based on

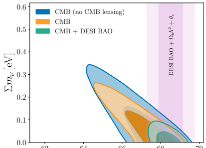


[Courtesy P. F. de Salas]

JCAP 04 (2021) 073

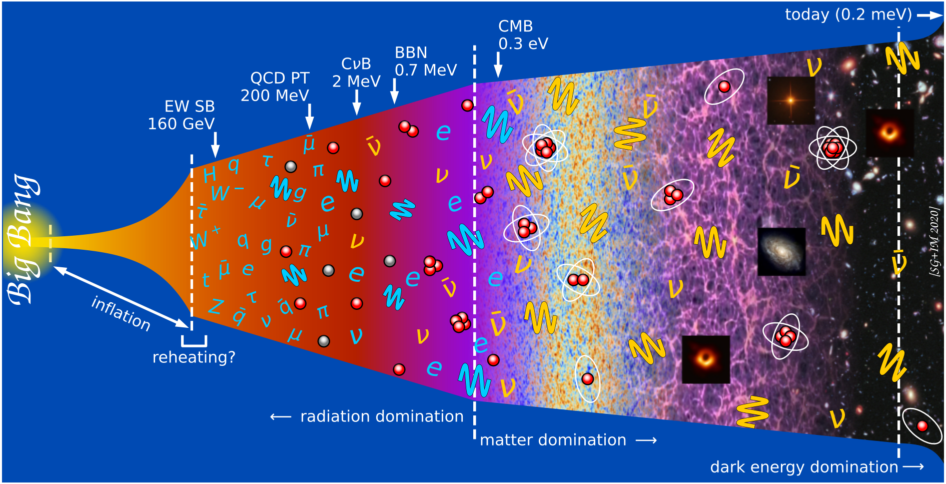


Planck 2018

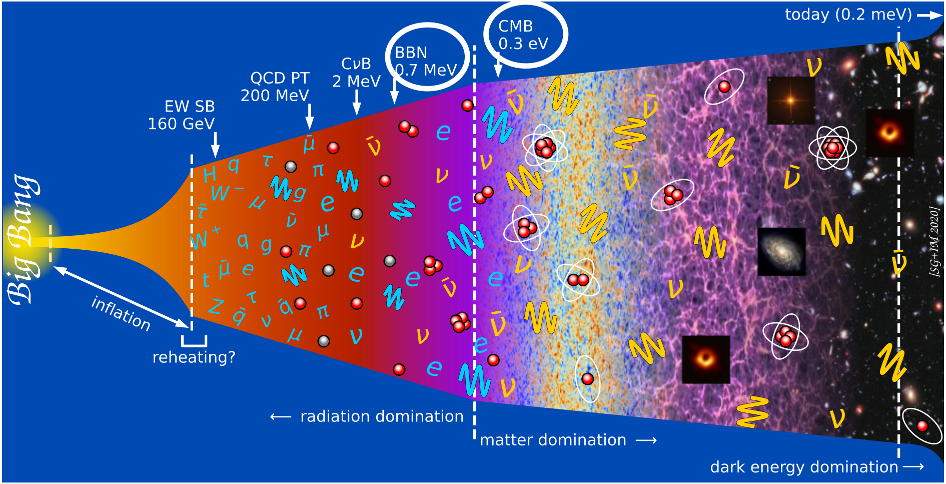


JCAP 02 (2025) 021

History of the universe



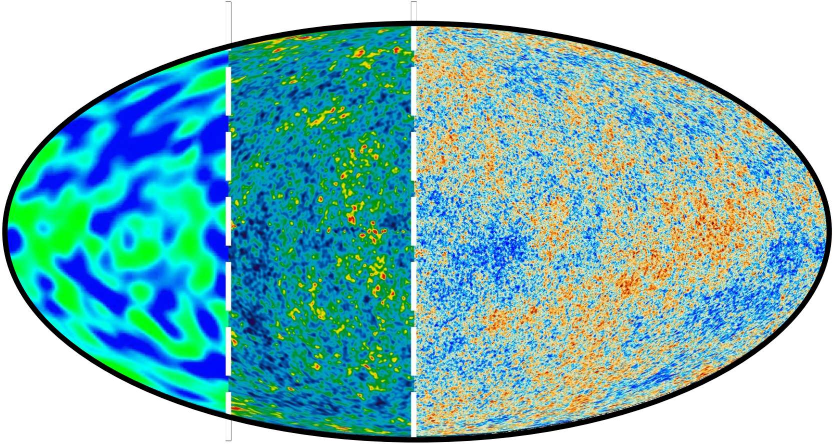
History of the universe



The oldest picture of the Universe

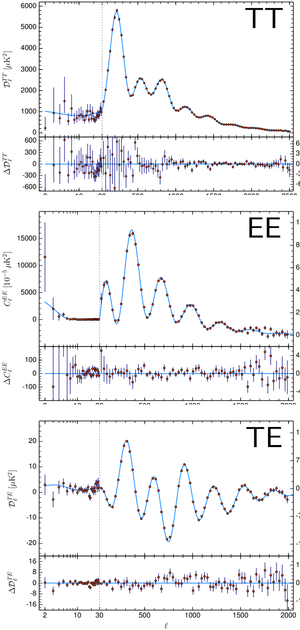
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

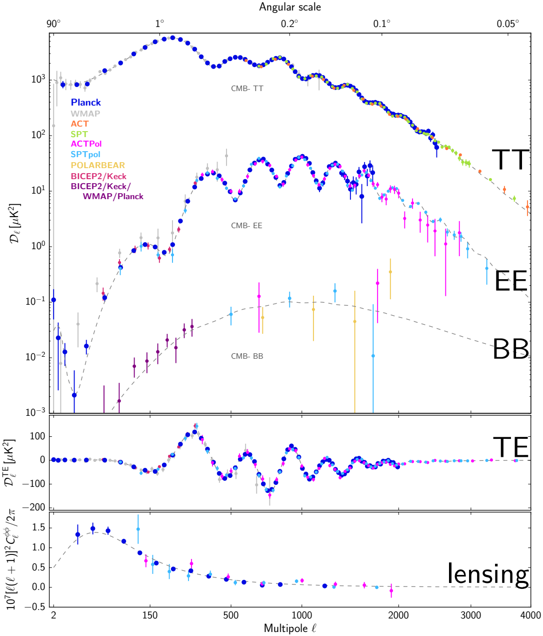
COBE (1992) WMAP (2003) Planck (2013)



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

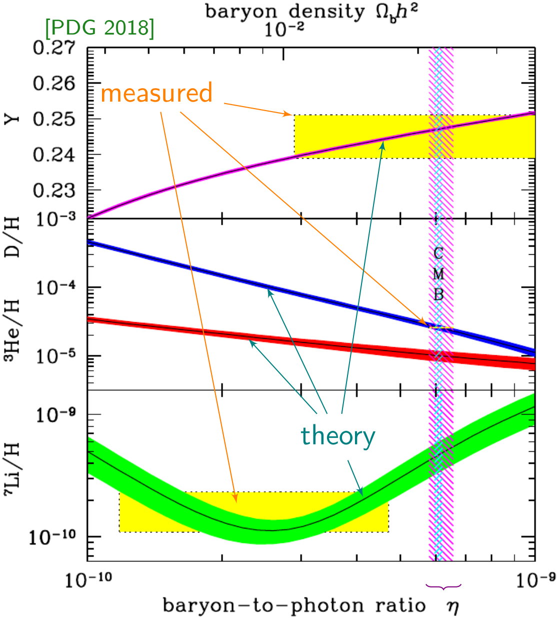
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

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

Big Bang Nucleosynthesis (BBN)

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

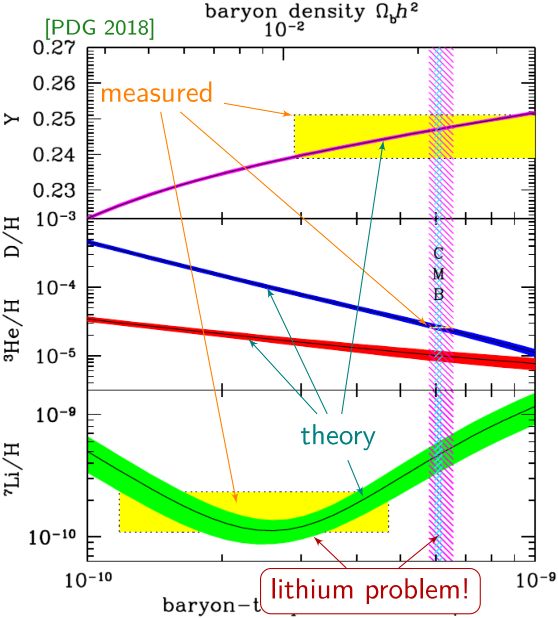
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

much earlier than CMB!

strong probe for physics
before the CMB

e.g. neutrinos!

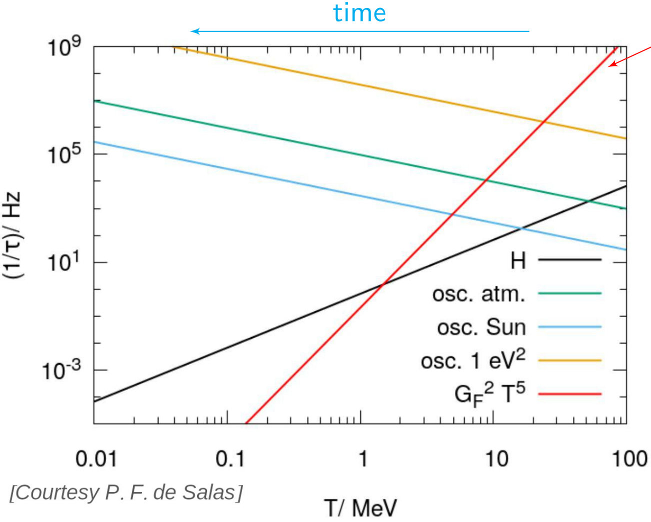
ν affect
universe expansion
and
reaction rates $(\nu_e/\bar{\nu}_e)$
at BBN time...



BBN concordance

Neutrinos in the early Universe

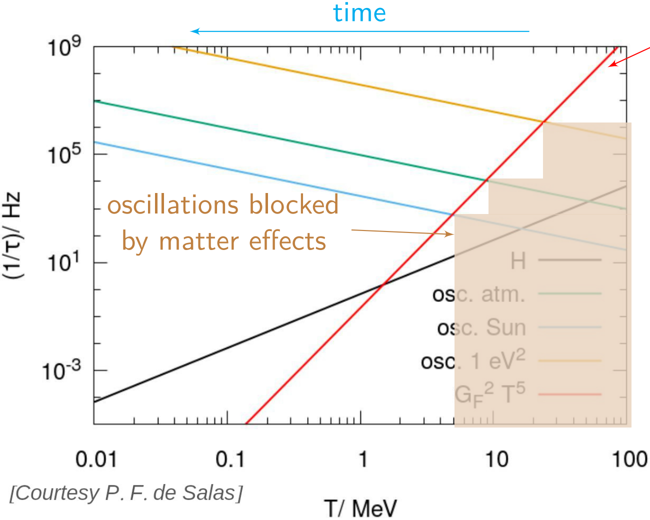
before BBN: neutrinos coupled to plasma ($\nu_\alpha\bar{\nu}_\alpha \leftrightarrow e^+e^-$, $\nu e \leftrightarrow \nu e$)



[Courtesy P. F. de Salas]

Neutrinos in the early Universe

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

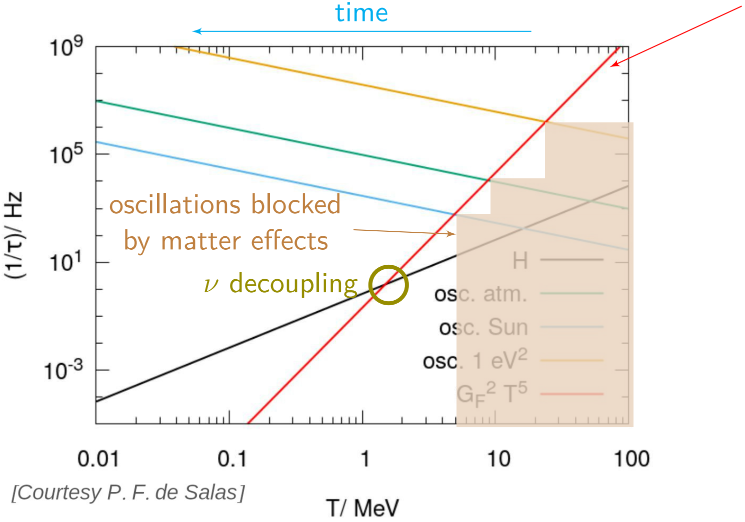

time

oscillations blocked by matter effects

[Courtesy P. F. de Salas]

Neutrinos in the early Universe

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



oscillations blocked by matter effects

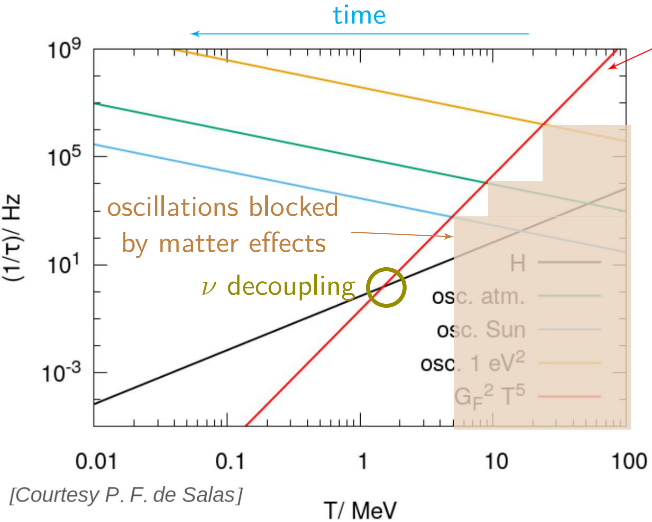
ν decoupling

[Courtesy P. F. de Salas]

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

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

oscillations blocked by matter effects

ν decoupling

[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

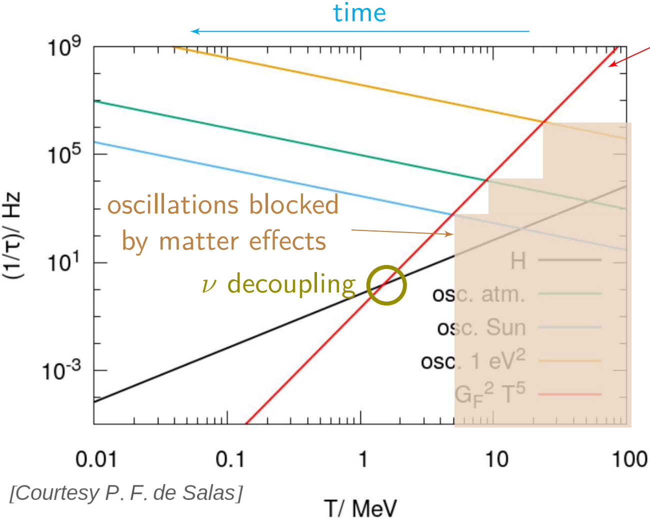
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}$ eV

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

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

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

oscillations blocked by matter effects

ν decoupling

[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

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

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

density matrix: $\propto \langle a_j^\dagger(p,t)\, a_i(p,t)\rangle$

$$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} \end{pmatrix}$$

off-diagonals to take into account coherency in the neutrino system

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

H Hubble factor → expansion (depends on universe content)

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

vacuum oscillations ←

→ 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

solve together with z 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

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

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

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

vacuum oscillations ← → matter effects

$\mathcal{I}$ collision integrals

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

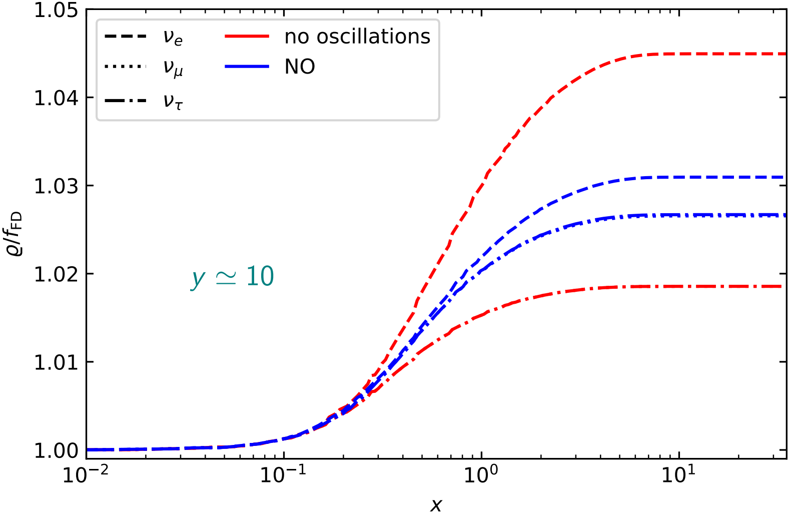
2D integrals over momentum, take most of the computation time

solve together with z 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

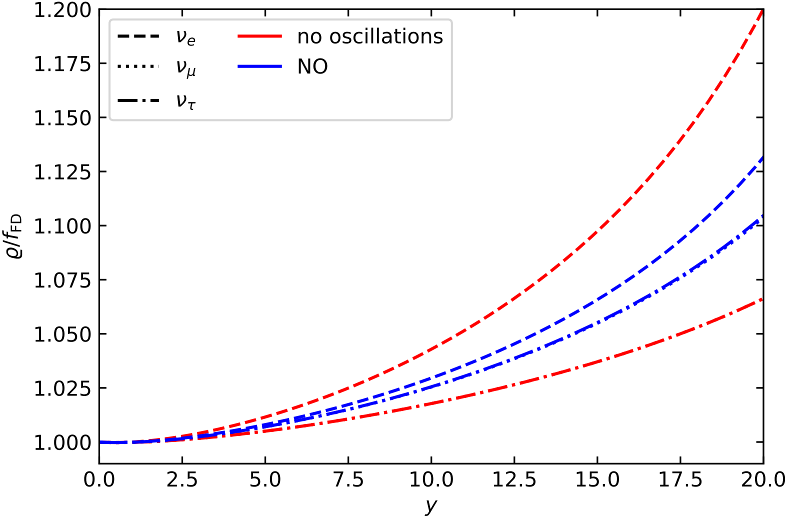
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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

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



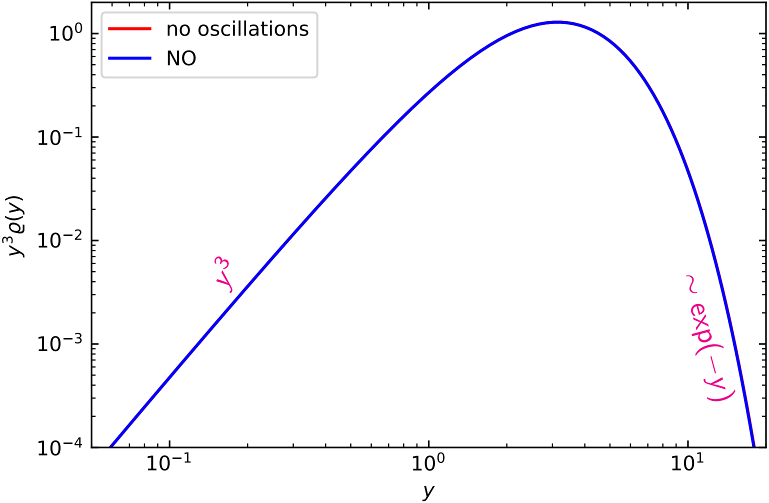
Neutrino momentum distribution and $N_{\rm eff}$

[Bennett, SG+, JCAP 2021]

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

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

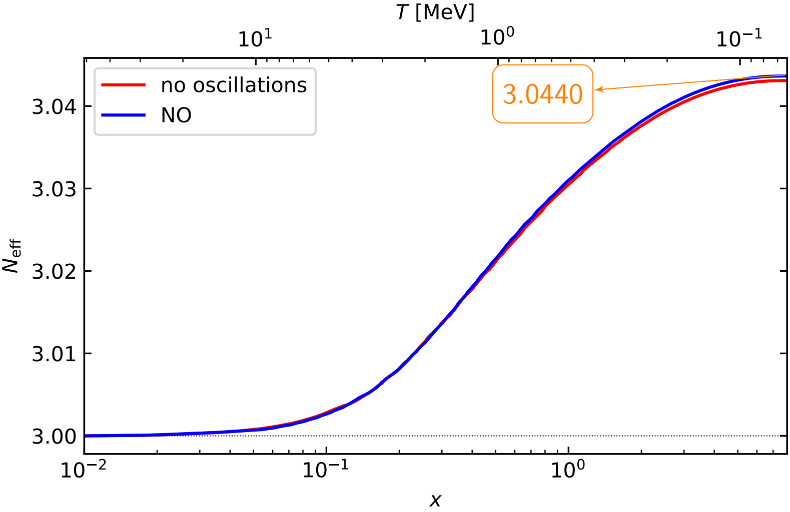
$\hookrightarrow \propto y^3 \varrho_{ii}(y)$



Neutrino momentum distribution and $N_{\rm eff}$

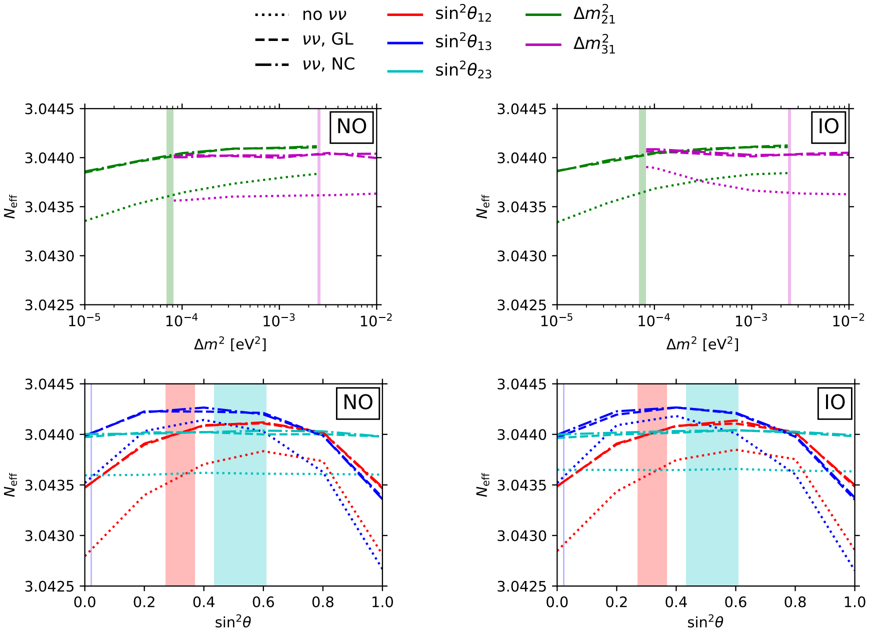
[Bennett, SG+, JCAP 2021]

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



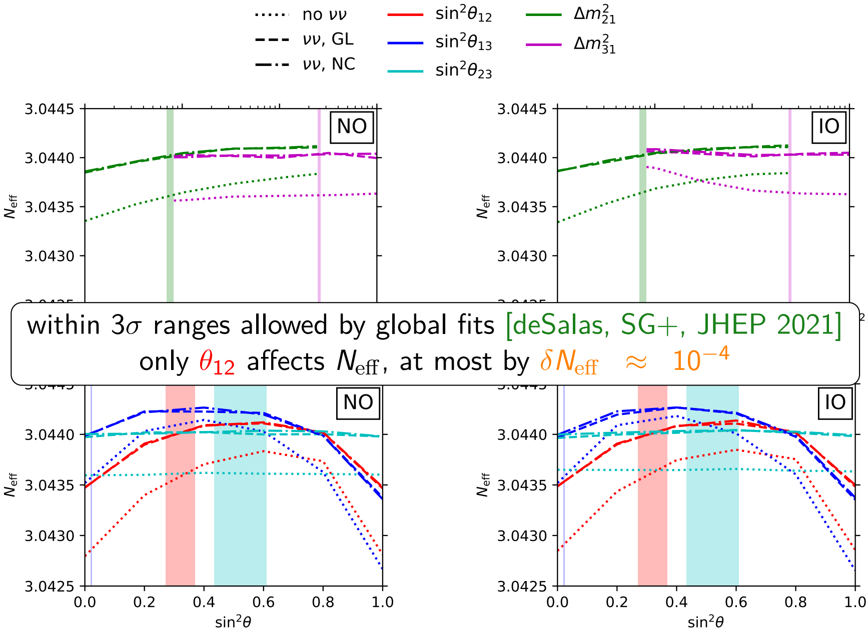
Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]

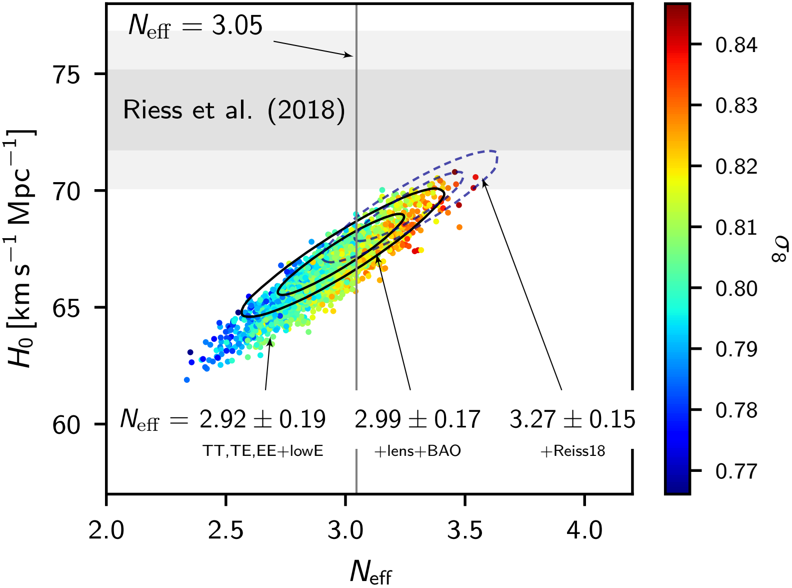


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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!

What is $N_{\rm eff}$?

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

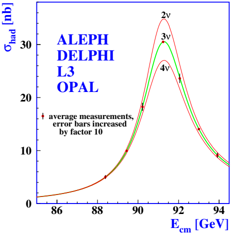
ρ_γ photon energy density, 7/8 for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

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

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

Nothing to do with [LEP (2006)]

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



What is $N_{\rm eff}$?

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

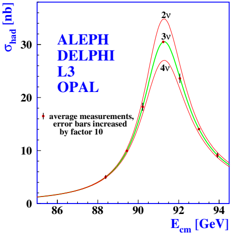
ρ_γ photon energy density, 7/8 for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

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

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

Nothing to do with [LEP (2006)]

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



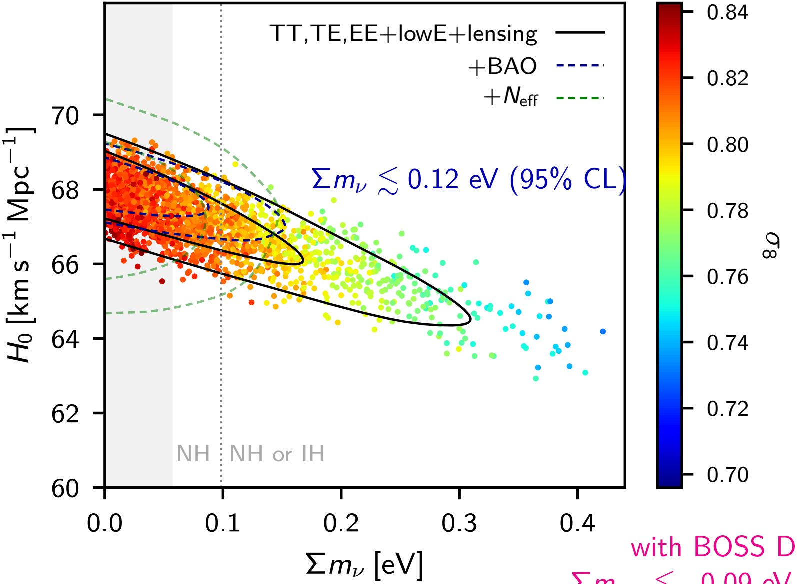
instantaneous decoupling:
$N_{\rm eff}^{\nu} = 1$ for each ν family

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

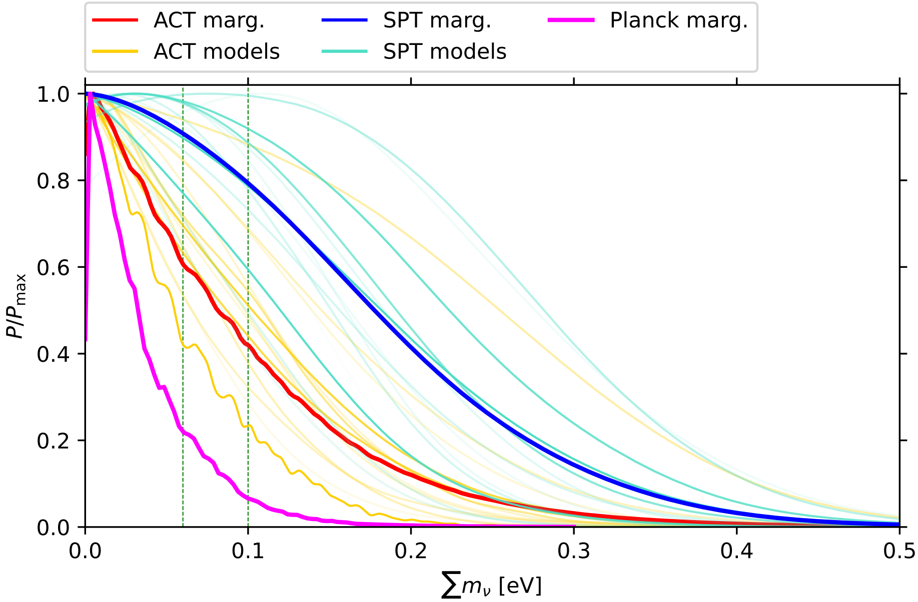
[Planck Collaboration, 2018]



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

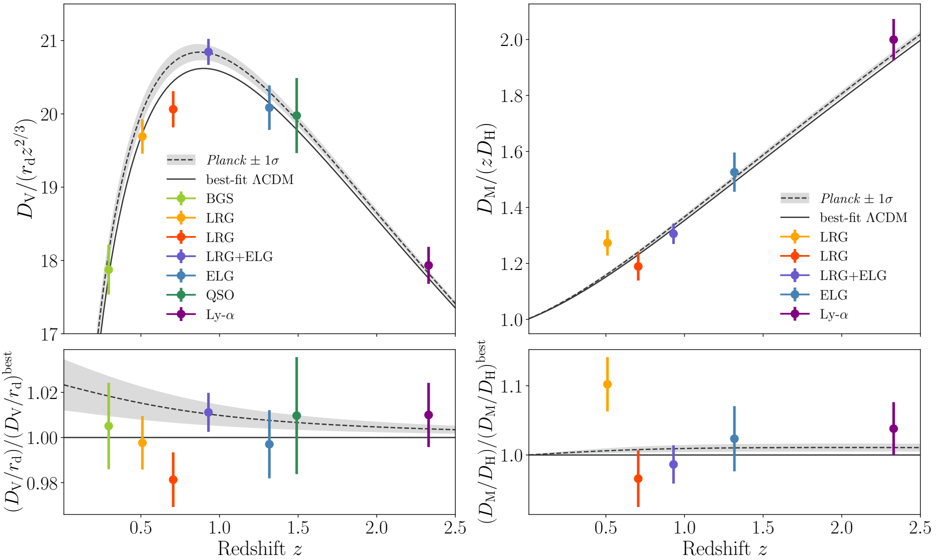
Constraints on the sum of neutrino masses

[PRD 108 (2023)]



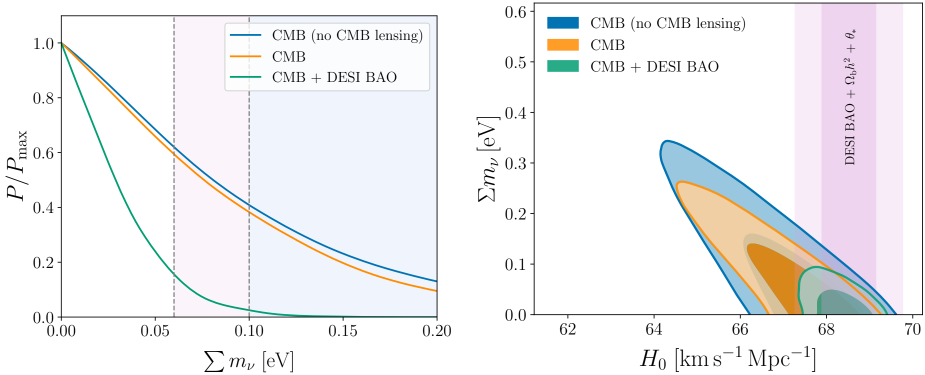
DESI BAO data from DR1

[JCAP 2025]



DESI BAO data from DR1

[JCAP 2025]



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

close to disfavoring normal ordering minimum value

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

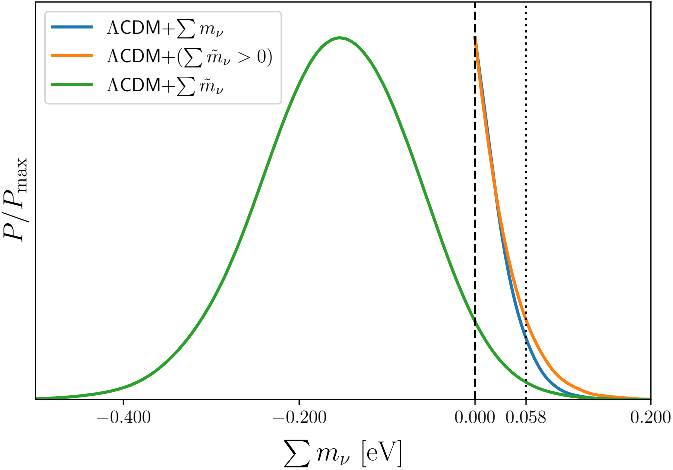
at 95%!

Negative neutrino masses?

[Craig+, JHEP 09 (2024)]
[Green+, PRD 111 (2025)]

"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

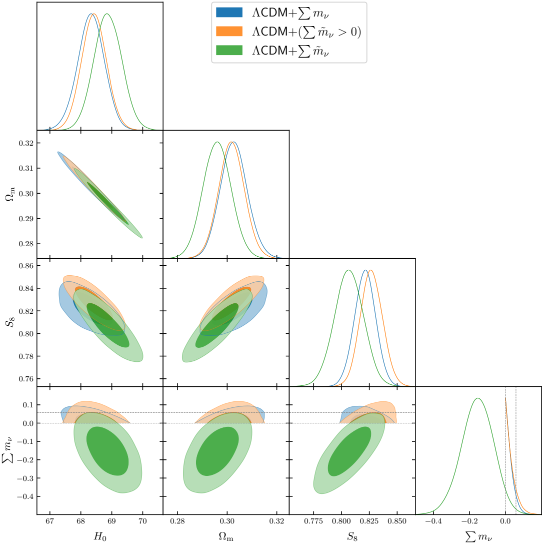


Planck 2018 CMB, ACT+Planck lensing, DESI BAO

Negative neutrino masses?

[Craig+, JHEP 09 (2024)]
[Green+, PRD 111 (2025)]

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



Planck 2018 CMB, ACT+Planck lensing, DESI BAO

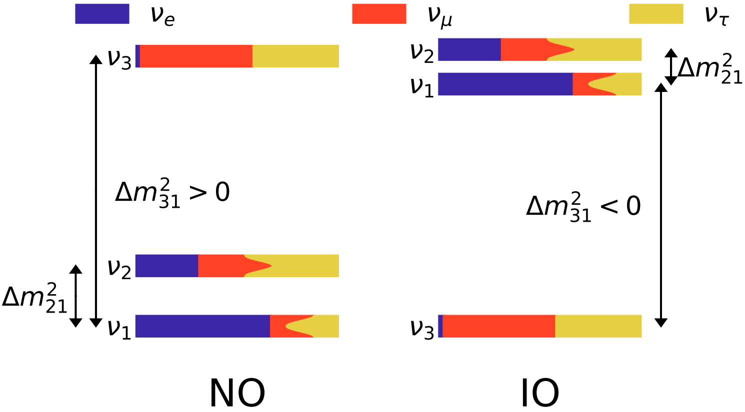
What is $\sum m_\nu$?

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]

What is Σm_ν?

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

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

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

many relic neutrinos are non-relativistic today!

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

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

Background measurements are sensitive to ω_ν, not Σm_ν!

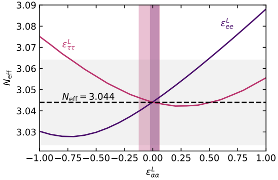
"Cosmological" Σm_ν measures the energy density of non-relativistic νs

Note: free-streaming scale directly depends on m_ν:

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

N $N_{\mathrm{eff}} \simeq 3$?

Neutrino physics can have small impacts on N_{eff}!



e.g.:
Non-Standard Interactions (NSI) [PLB 820 (2021)]

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

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

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

$\downarrow$

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

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)]

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

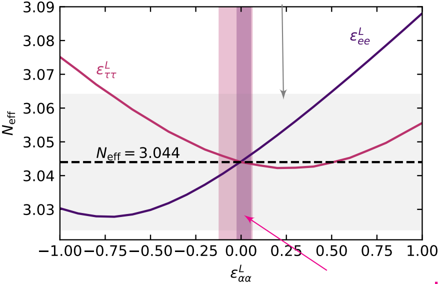
e.g.:

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

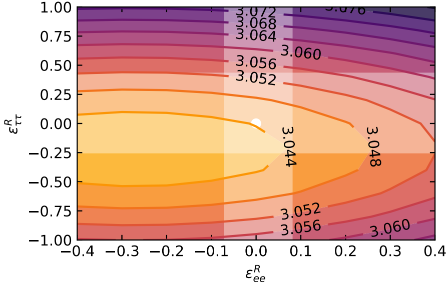
$G^L_{\tau\tau} \to -0.273 + \epsilon^L_{\tau\tau}$

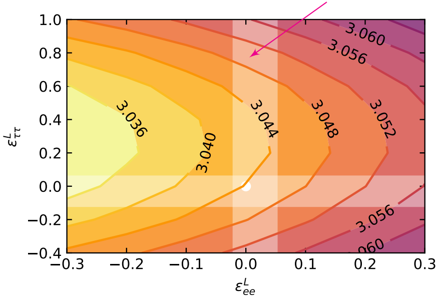
$G^R_{\alpha\alpha} \to 0.233 + \epsilon^R_{\alpha\alpha}$

future CMB



current terrestrial

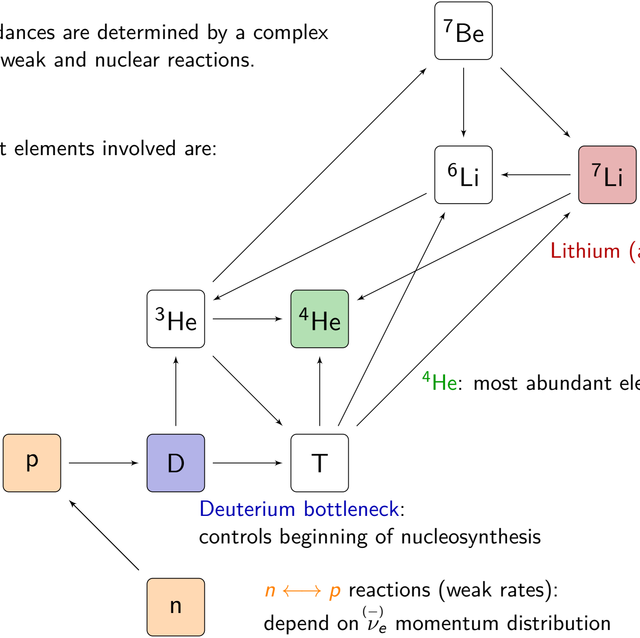




Reactions governing BBN

BBN abundances are determined by a complex network of weak and nuclear reactions.

The lightest elements involved are:



Lithium (anomaly)

^{4}He: most abundant element

Deuterium bottleneck:
controls beginning of nucleosynthesis

$n \longleftrightarrow p$ reactions (weak rates):
depend on $\overset{(-)}{\nu}_e$ momentum distribution

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- \\ n + e^+ &\leftrightarrow p + \bar{\nu}_e \end{aligned}$$

NSI effects on BBN

[JCAP 08 (2025)]

NSI with electrons, such as $\mathcal{L}^{\rm NC}_{\rm NSIe} \propto \sum \epsilon^{L,R}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{e}\gamma_\mu P_{L,R} e)$,

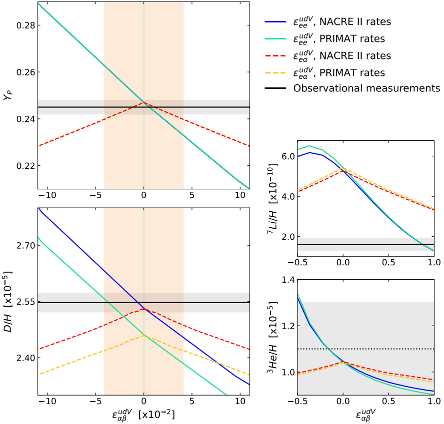
have secondary effect on BBN rates because there are no $\overset{(-)}{\nu} e$ interactions!

WR depend on $n \leftrightarrow p$ processes, for which it is more relevant

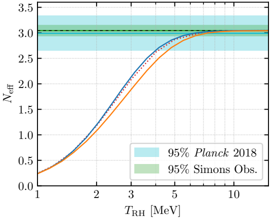
$$\mathcal{L}^{\rm CC}_{\rm NSIq} \propto G_F V_{ud} \sum_\alpha \epsilon^{udV}_{e\alpha} (\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_{L,R}\nu_\alpha)!$$

Effect of $\epsilon^{udV}_{e\alpha}$
on BBN abundances
can be exploited
to derive constraints:

Bounds are comparable and
complementary to the ones
from terrestrial experiments!



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



e.g. low-temperature reheating scenarios

[PRD 92 (2015) 123534], [arxiv:2501.01369]

Scenarios with low reheating temperature

[PRL 135 (2025)]

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

Scenarios with low reheating temperature

[PRL 135 (2025)]

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

neutrinos are populated by weak interactions with electrons!

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

Scenarios with low reheating temperature

[PRL 135 (2025)]

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

neutrinos are populated by weak interactions with electrons!

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

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

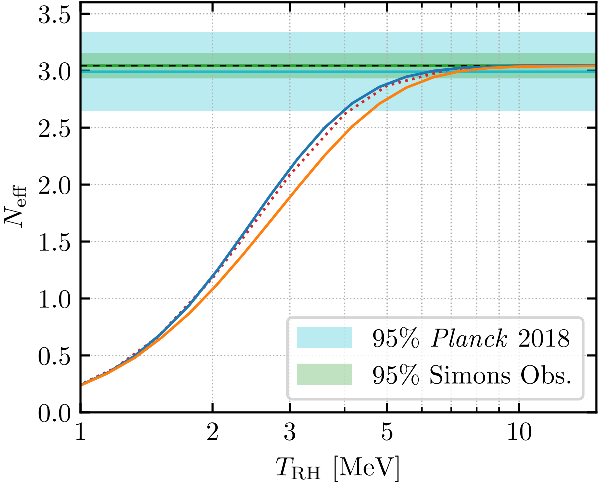
notice: if $T_{\rm rh} \lesssim 3$ MeV, BBN is broken!

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

$N_{\rm eff}$ with low reheating

[PRL 135 (2025)]

$N_{\rm eff}$ as a function of $T_{\rm rh}$:

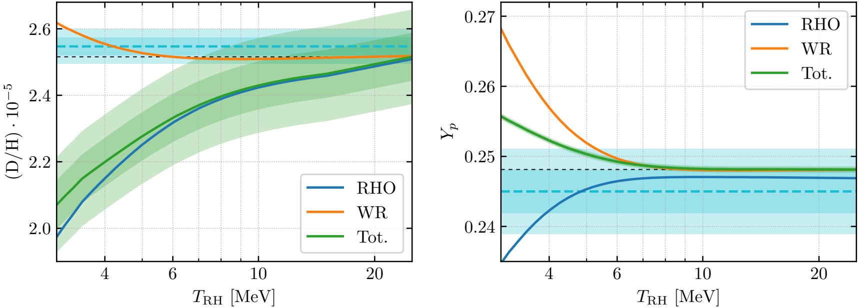


Planck constraint: $N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

BBN and low reheating

[PRL 135 (2025)]

Light element abundances depend on $T_{\rm rh}$:



- RHO: total energy density, expansion rate

↓

neutrino energy density, $N_{\rm eff}$

- WR: weak rates ($n \leftrightarrow p, \overset{(-)}{\nu}_e$ interactions)

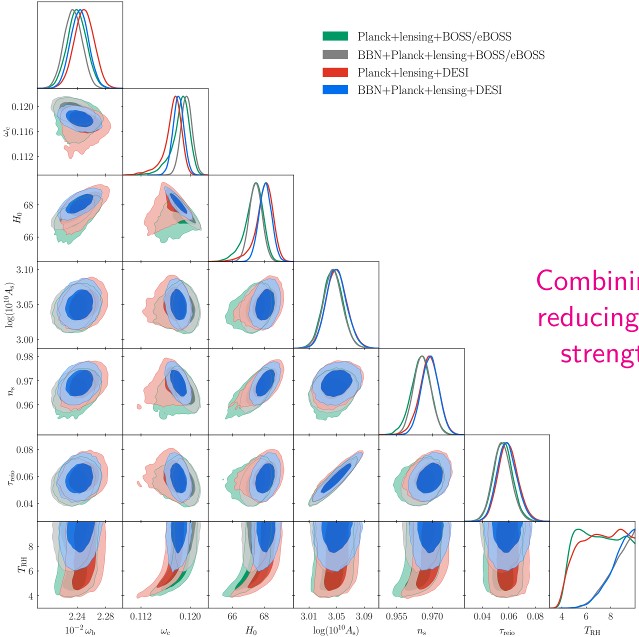
↓

$\overset{(-)}{\nu}_e$ momentum distribution

Both effects are important to get Helium right!

Constraints on low reheating scenarios

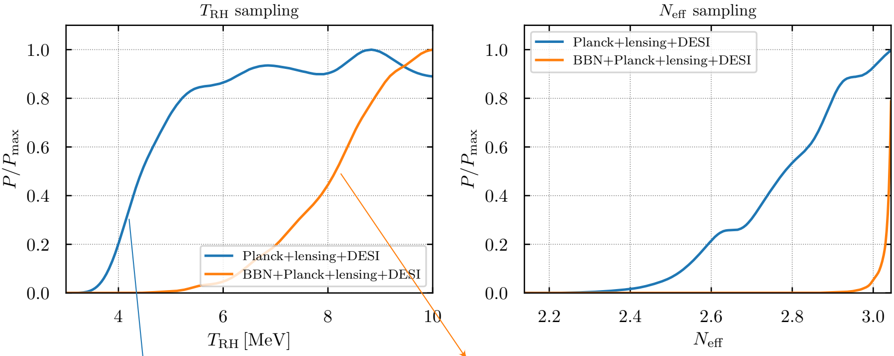
[PRL 135 (2025)]



Combining probes helps in reducing degeneracies and strengthening bounds!

Constraints on low reheating scenarios

[PRL 135 (2025)]



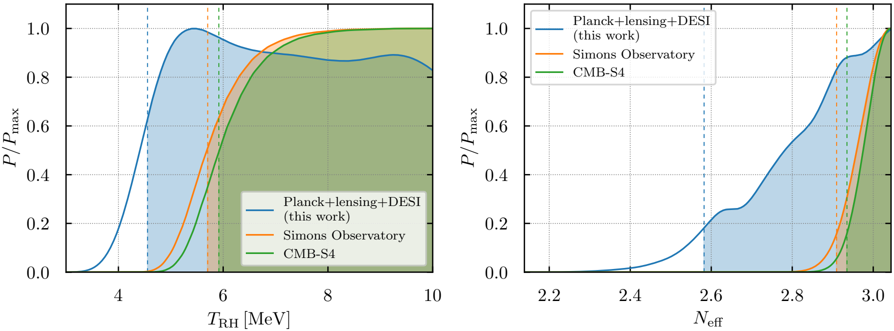
$T_{\rm rh} > 5.96$ MeV (95%)

$T_{\rm rh} > 3.79$ MeV (95%)

BBN occurs at earlier time than CMB and is more sensitive to $N_{\rm eff}$ (RHO) and $\overset{(-)}{\nu}_e$ momentum distribution functions (WR) as a function of $T_{\rm rh}$!

Constraints on low reheating scenarios

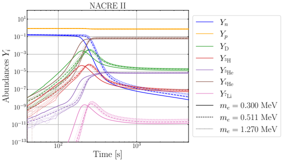
[PRL 135 (2025)]



Greater sensitivity will come with future CMB probes
(more precise in determining $N_{\rm eff}$)

Future CMB alone will reach the precision of
current BBN+CMB (Planck)+BAO (DESI) observations

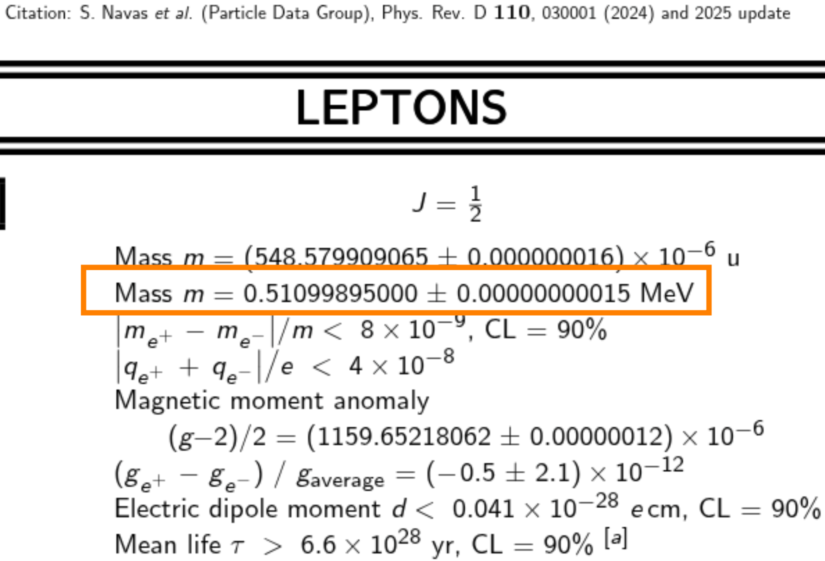
E $N_{\text{eff}} > 3$?



e.g. non-standard electron mass [arxiv:2602.05720]

The electron mass m_e

From [PDG 2024]:



Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024) and 2025 update

LEPTONS

e

$J = \frac{1}{2}$

Mass $m = (548.579909065 \pm 0.000000016) \times 10^{-6}$ u

Mass $m = 0.51099895000 \pm 0.00000000015$ MeV

$\left|m_{e^+} - m_{e^-}\right|/m < 8 \times 10^{-9}$, CL = 90%

$\left|q_{e^+} + q_{e^-}\right|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$(g{-}2)/2 = (1159.65218062 \pm 0.00000012) \times 10^{-6}$

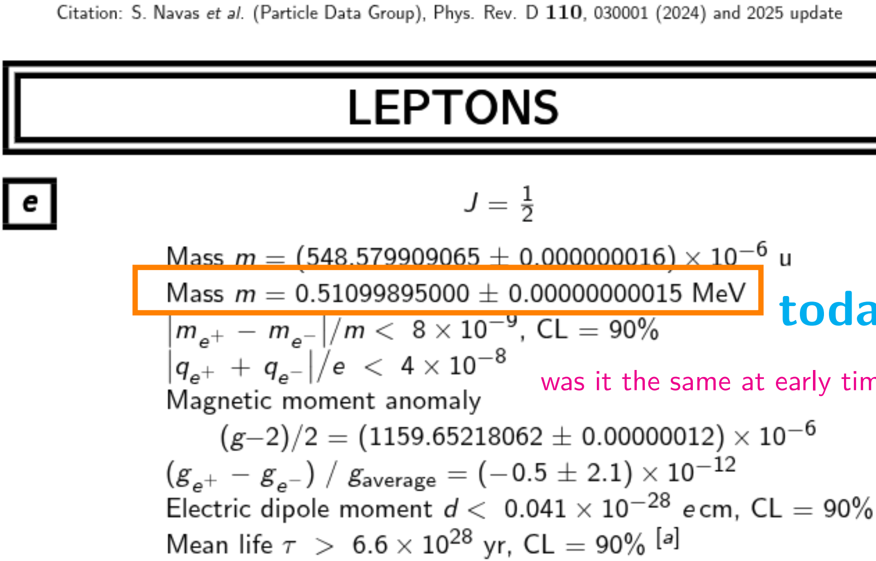
$(g_{e^+} - g_{e^-})\ /\ g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment $d < 0.041 \times 10^{-28}$ $e\,$cm, CL = 90%

Mean life $\tau > 6.6 \times 10^{28}$ yr, CL = 90% [a]

The electron mass m_e

From [PDG 2024]:



Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024) and 2025 update

LEPTONS

e

$J = \frac{1}{2}$

Mass $m = (548.579909065 \pm 0.000000016) \times 10^{-6}$ u

Mass $m = 0.51099895000 \pm 0.00000000015$ MeV

$\left|m_{e^+} - m_{e^-}\right|/m < 8 \times 10^{-9}$, CL = 90%

$\left|q_{e^+} + q_{e^-}\right|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$(g-2)/2 = (1159.65218062 \pm 0.00000012) \times 10^{-6}$

$(g_{e^+} - g_{e^-}) / g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment $d < 0.041 \times 10^{-28}$ $e\,$cm, CL = 90%

Mean life $\tau > 6.6 \times 10^{28}$ yr, CL = 90% [a]

today!

was it the same at early times?

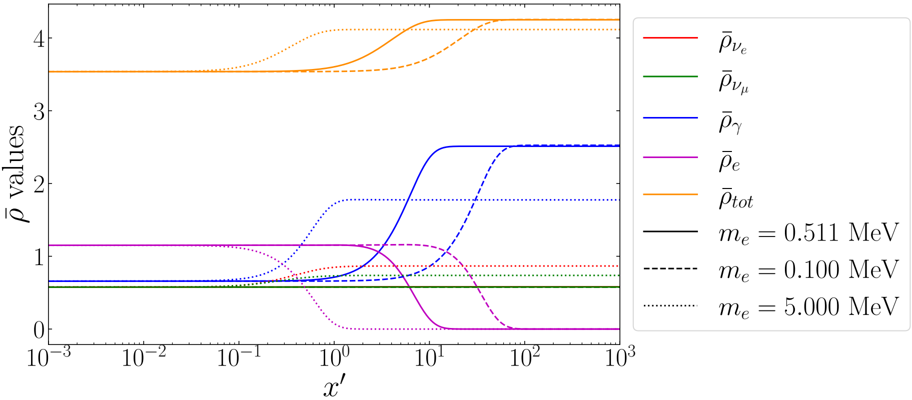
m_e and $N_{\rm eff}$

[arxiv:2602.05720]

In the early Universe, neutrino decoupling occurs at $T \simeq 1 - 2$ MeV

Electron-positron annihilation occurs slightly later if $m_e = 0.511$ MeV

Decoupled neutrinos do not receive energy from e^+e^- annihilation, which only goes to photons



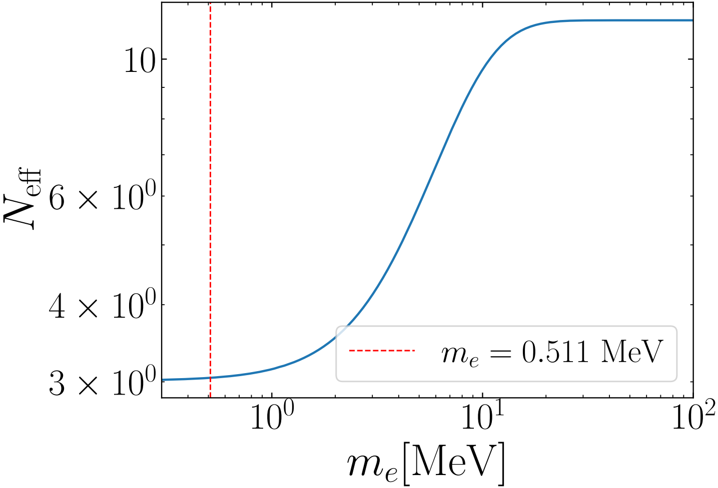
Energy density of neutrinos relative to photons depends on m_e!

m_e and $N_{\rm eff}$

[arxiv:2602.05720]

In the early Universe, neutrino decoupling occurs at $T \simeq 1-2$ MeV

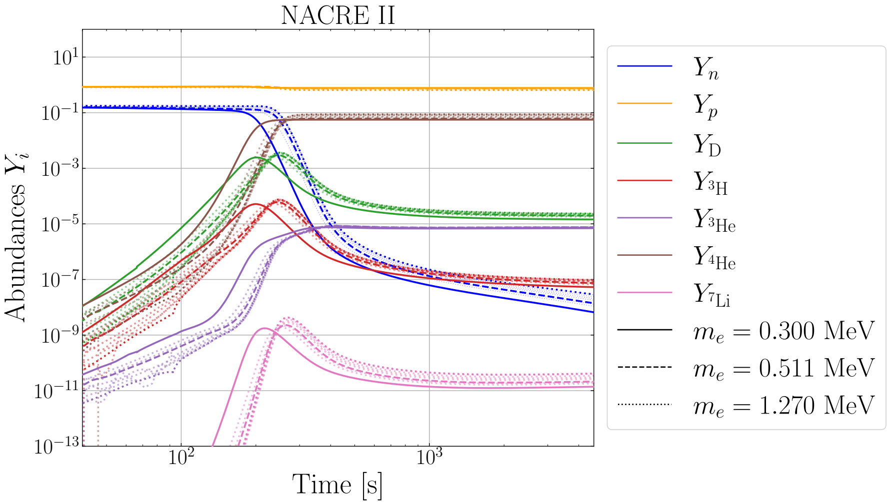
Energy density of neutrinos relative to photons depends on m_e!
but $N_{\rm eff}$ is the ratio!



m_e and BBN

[arxiv:2602.05720]
[BBN code: PRyMordial]

Different m_e shifts kinematics of neutron β-decay and expansion rate!

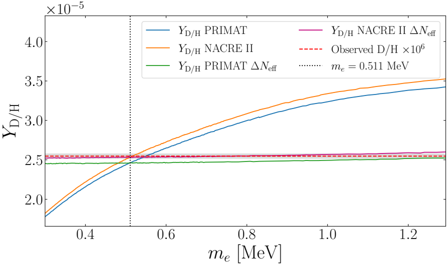


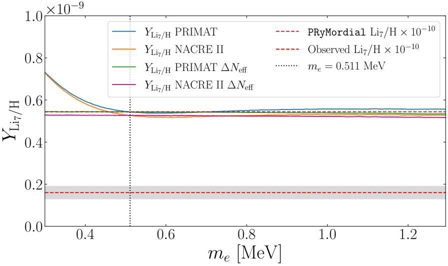
NACRE II (shown) and PRIMAT: alternative nuclear reaction networks

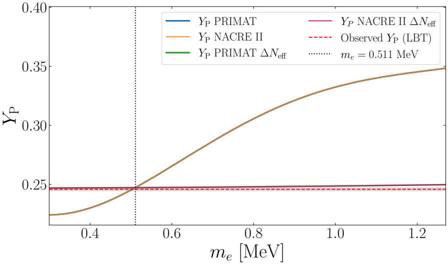
m_e and BBN

[arxiv:2602.05720]
[BBN code: PRyMordial]

Main abundances as a function of m_e:



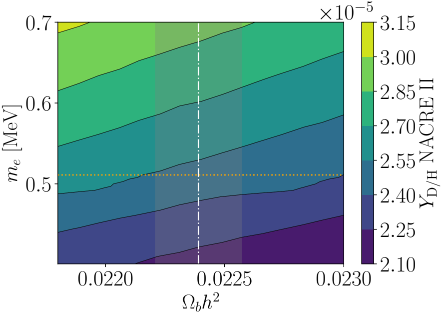




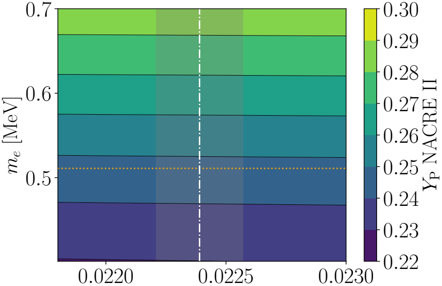
- Litium problem! unsolved
- Expansion effect ($\Delta N_{\rm eff}$) is marginal wrt weak rates
- PRIMAT vs NACRE II nuclear reaction network give differences in Deuterium!

m_e and BBN

[arxiv:2602.05720]
[BBN code: PRyMordial]



Deuterium abundance also depends on baryon density!



Helium abundance does not!

Which constraints do we get on m_e?

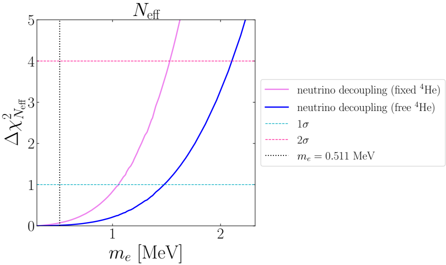
[arxiv:2602.05720]

CMB:

$N_{\rm eff} = 2.99 \pm 0.17$ (fixed Y_p)

$N_{\rm eff} = 2.97 \pm 0.29$ (free Y_p)

[Planck Collaboration, 2018]



Which constraints do we get on m_e?

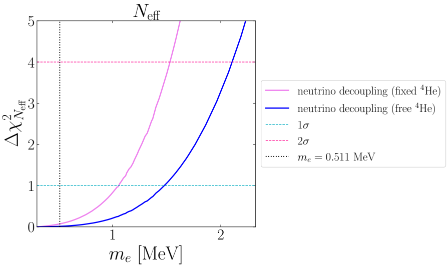
[arxiv:2602.05720]

CMB:

$N_{\rm eff} = 2.99 \pm 0.17$ (fixed Y_p)

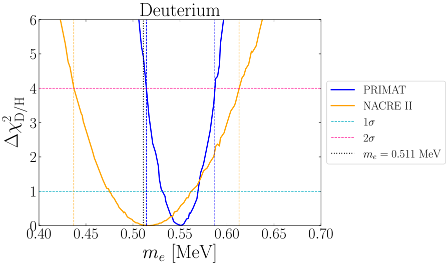
$N_{\rm eff} = 2.97 \pm 0.29$ (free Y_p)

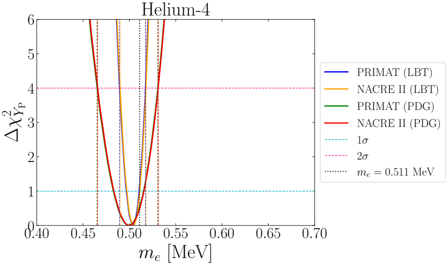
[Planck Collaboration, 2018]



$N_{\rm eff}$ irrelevant wrt BBN

Deuterium and Helium:

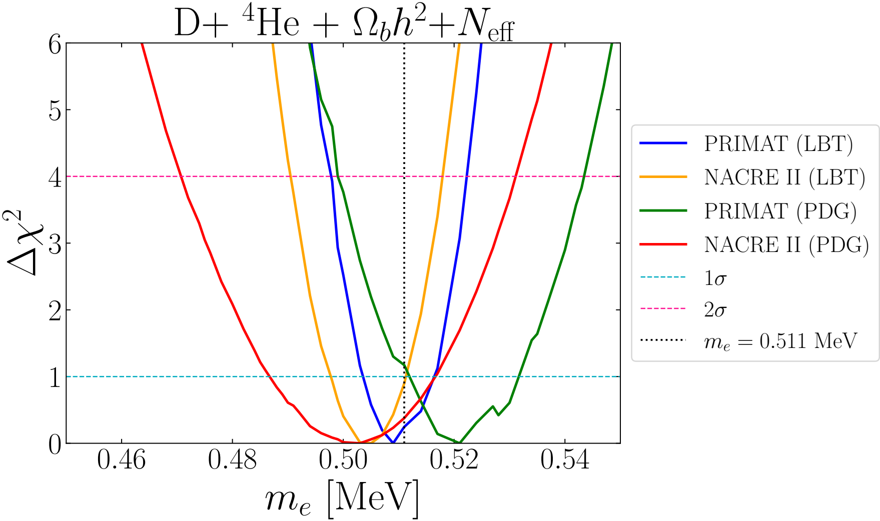




Which constraints do we get on m_e?

[arxiv:2602.05720]

Combination:

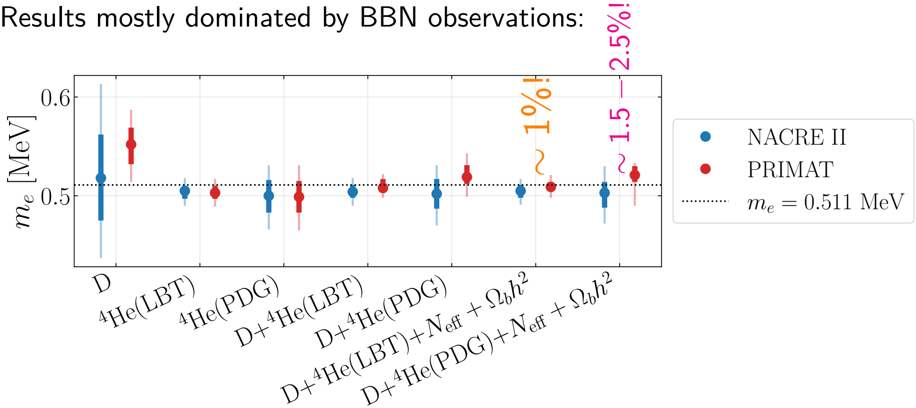


$\Omega_b h^2$: marginalization over baryon density from **CMB**

Constraints on m_e - summary

[arxiv:2602.05720]

Results mostly dominated by BBN observations:



- LBT: $Y_{\rm P} = 0.2458 \pm 0.0013$ (most precise) [LBT, arxiv:2601.22238];
- PDG: $Y_{\rm P} = 0.245 \pm 0.003$ (conservative) [PDG 2024];

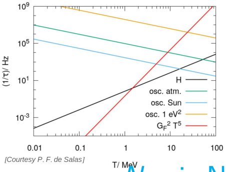
$1 - 2.5\%$ precision on m_e at earliest epoch ever!

Z Conclusions

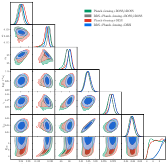
What did we learn from ν decoupling and BBN?

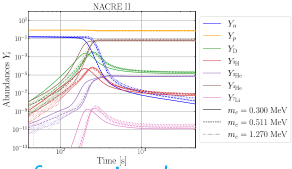
C

All cosmological and particle physics models matter!



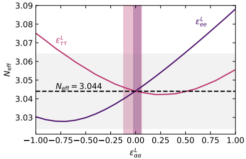
[Courtesy P. F. de Salas]

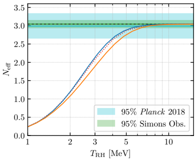


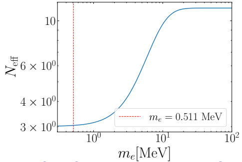


N

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

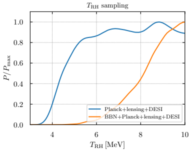


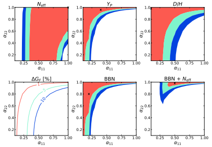


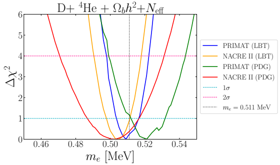


M

Combining different probes helps to break degeneracies!



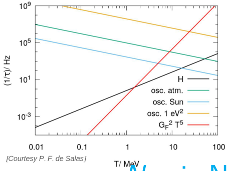




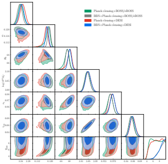
What did we learn from ν decoupling and BBN?

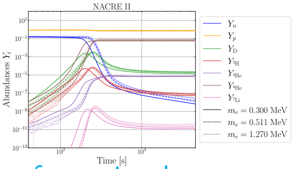
C

All cosmological and particle physics models matter!



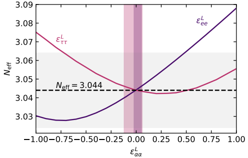
[Courtesy P. F. de Salas]

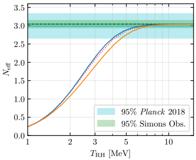


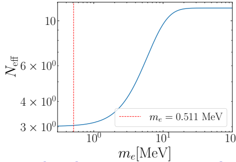


N

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

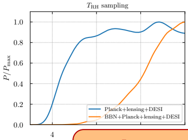


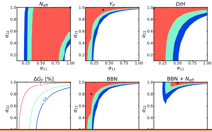


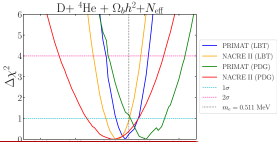


M

Combining different probes helps to break degeneracies!







Thanks for your attention!