Stefano Gariazzo

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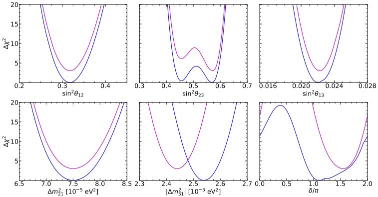
Neutrino non-standard scenarios in cosmology

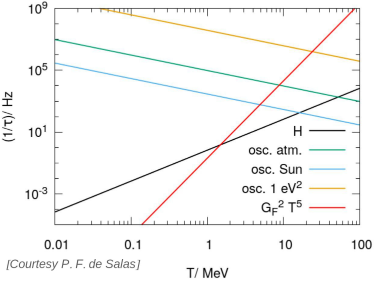
22nd Lomonosov Conference, Moscow (Russia) / hybrid, 25/08/2025

N Neutrinos

Neutrino decoupling



JHEP 02 (2021) 071 and update



[Courtesy P. F. de Salas]

JCAP 04 (2021) 073

Three Neutrino Oscillations

Analogous to CKM mixing for quarks:

[Pontecorvo, 1968]
[Maki, Nakagawa, Sakata, 1962]

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

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

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

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles

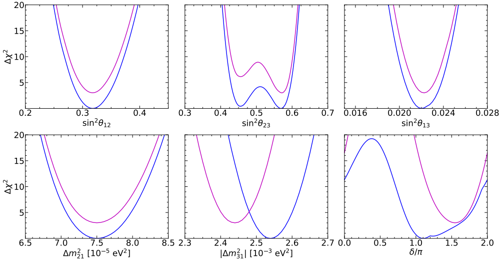
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

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

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$10\,\sin$ … 5.71 ± 0.12 (NO)

$= 5.71^{+0.14}_{-0.17}$ (IO)

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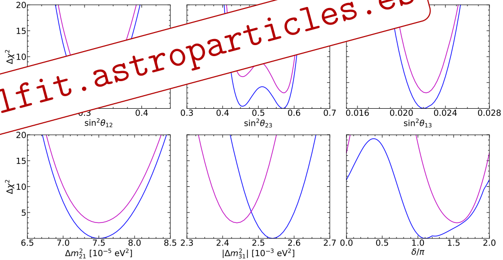

see also: http://globalfit.astroparticles.es

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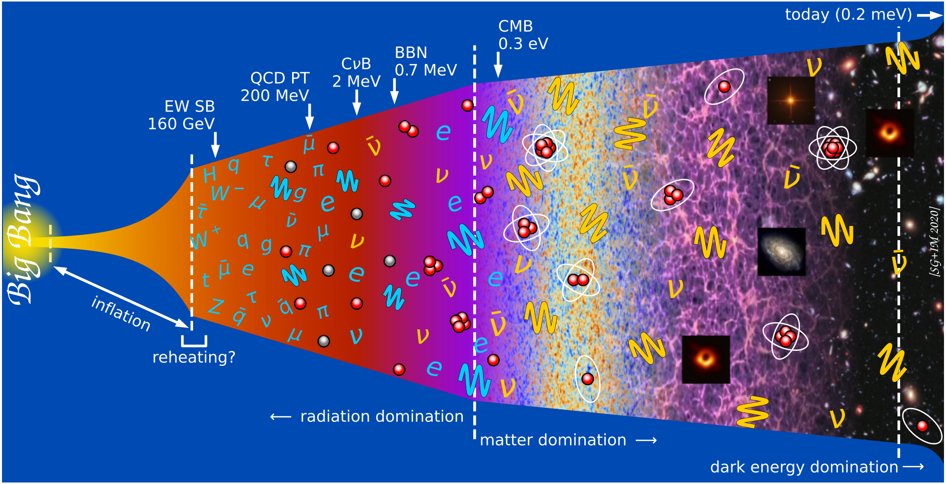
History of the universe



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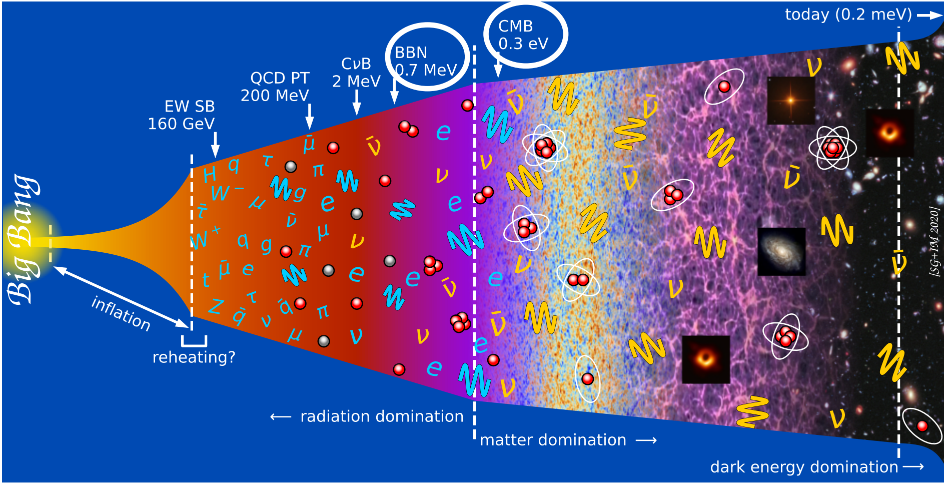
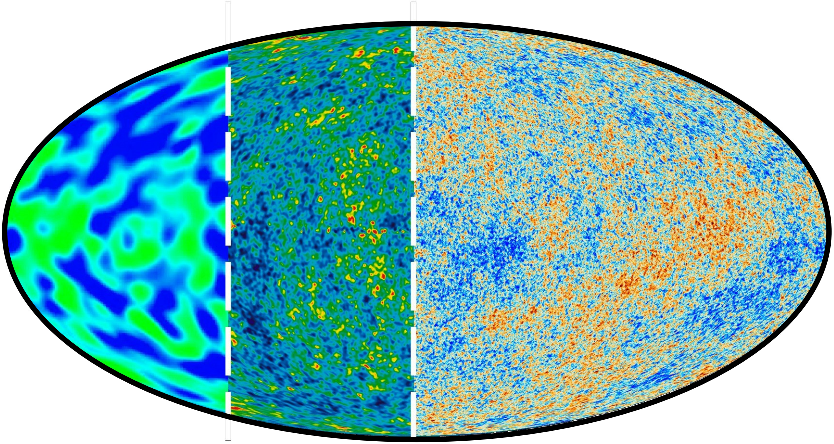


The oldest picture of the Universe

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 $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

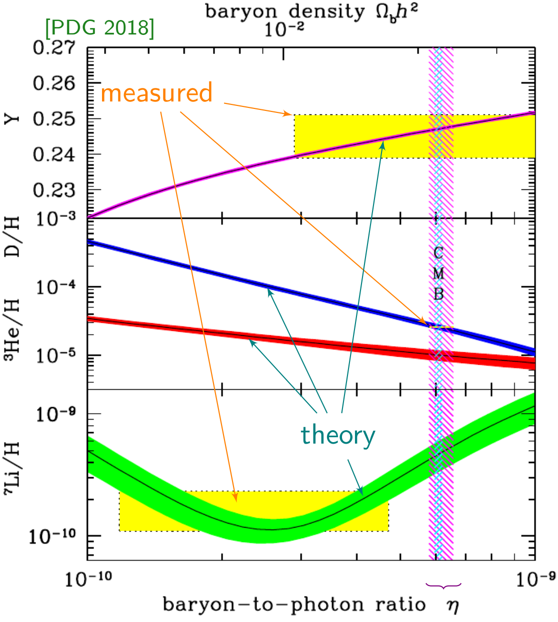
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

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

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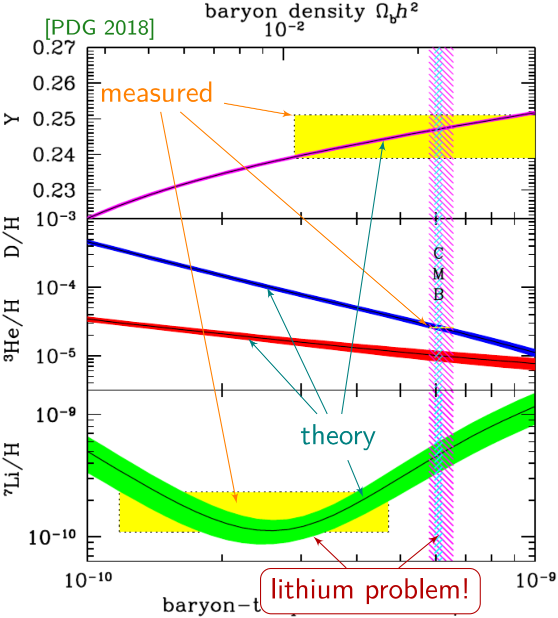


[PDG 2018]

measured

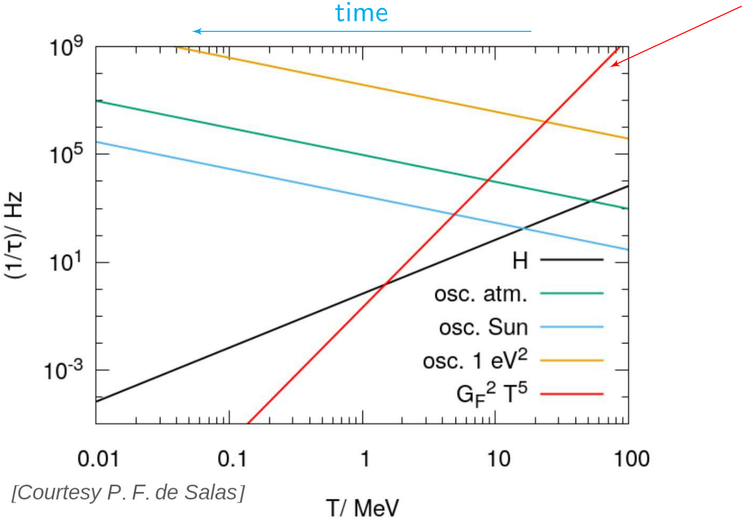
theory

lithium problem!

BBN concordance

Neutrinos in the early Universe

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



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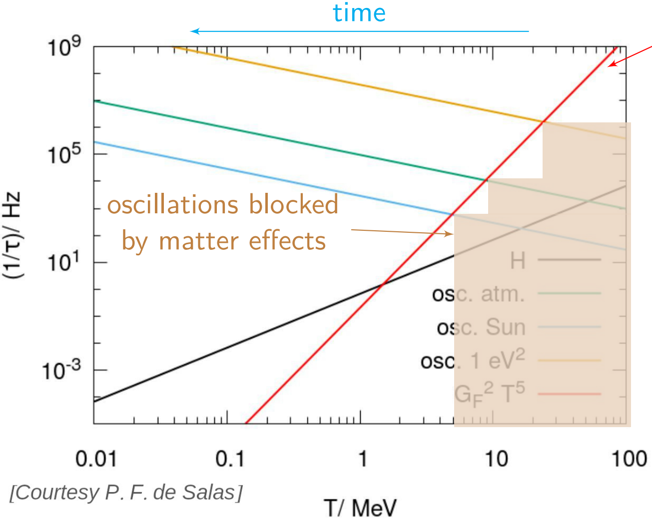

oscillations blocked by matter effects

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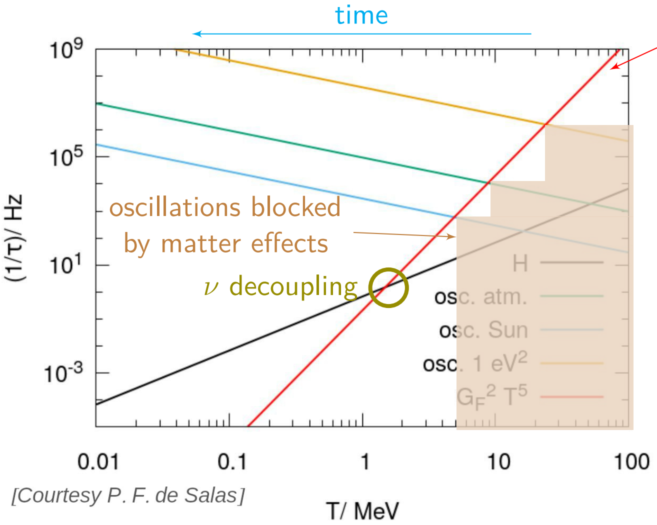

time

oscillations blocked by matter effects

ν decoupling

[Courtesy P. F. de Salas]

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

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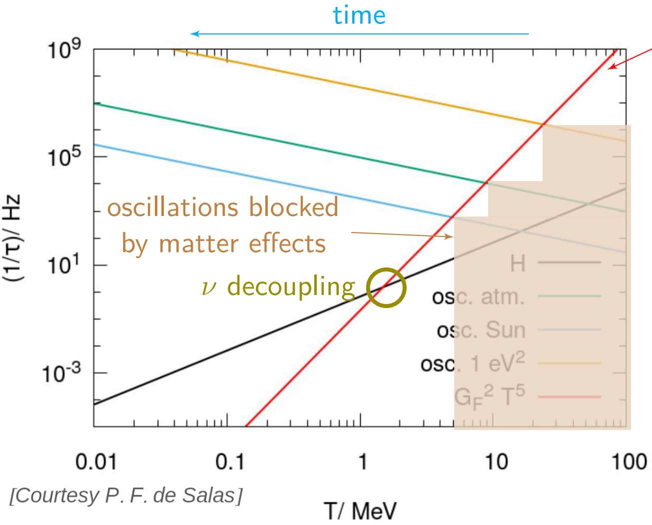

oscillations blocked by matter effects

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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 $\simeq$ 1.676×10^{-4} eV

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

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

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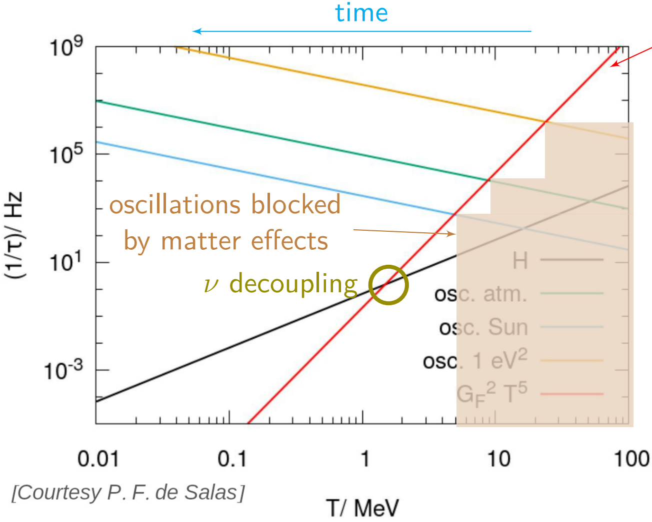

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actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

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

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

H Hubble factor → expansion (depends on universe content)

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

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 $x \dfrac{\mathrm{d}\rho(x)}{\mathrm{d}x} = \rho - 3P$

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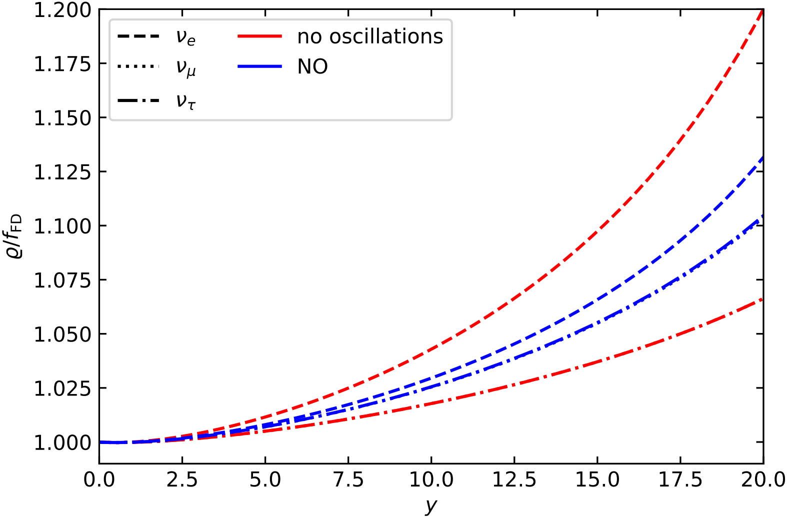
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



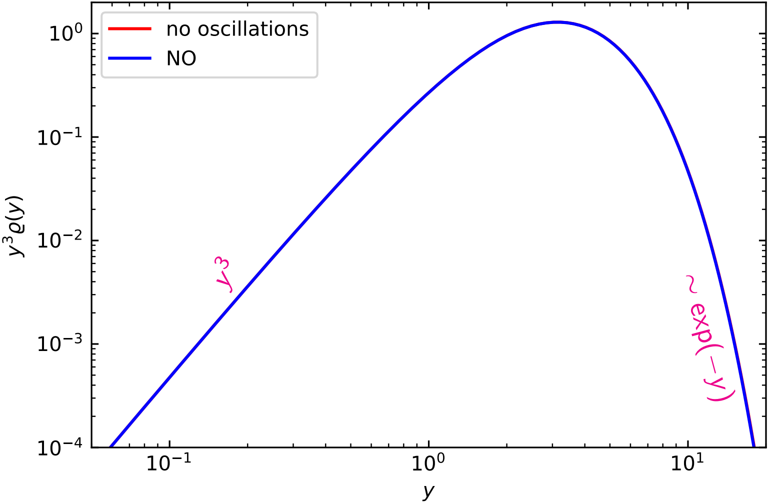
Neutrino momentum distribution and $N_{\rm eff}$

[Bennett, SG+, JCAP 2021]

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

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

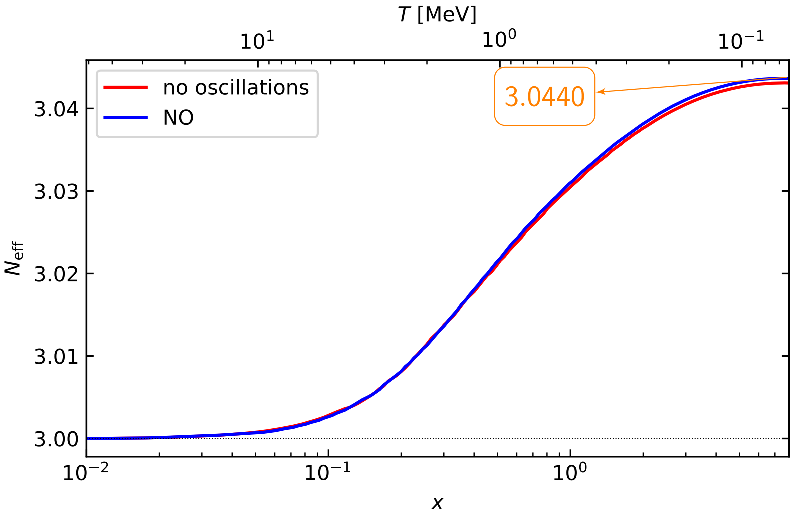
$\hookrightarrow \propto y^3 \varrho_{ii}(y)$



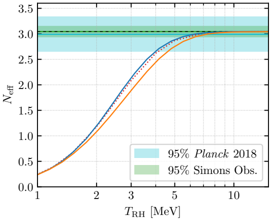
Neutrino momentum distribution and $N_{\rm eff}$

[Bennett, SG+, JCAP 2021]

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



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



e.g. low-temperature reheating scenarios

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

Scenarios with low reheating temperature

[arxiv:2501.01369]

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

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

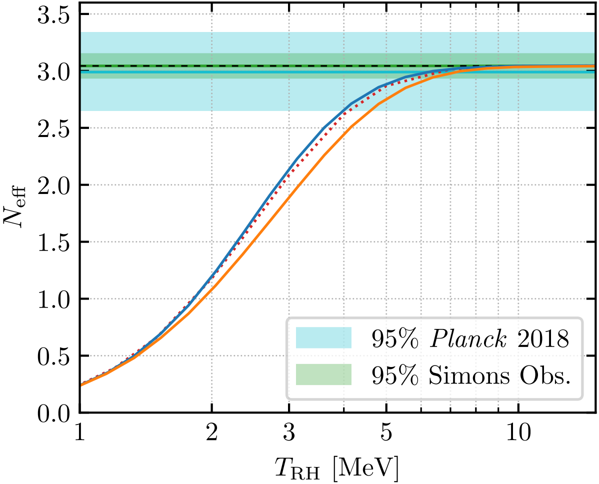
3 neutrino oscillations start to be affected when $T_{\rm rh} \lesssim 8$ MeV

what about sterile neutrinos?

N_eff with low reheating

[arxiv:2501.01369]

N_eff as a function of T_rh:

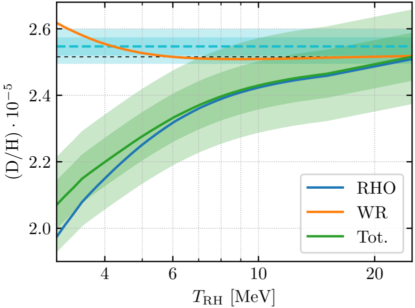


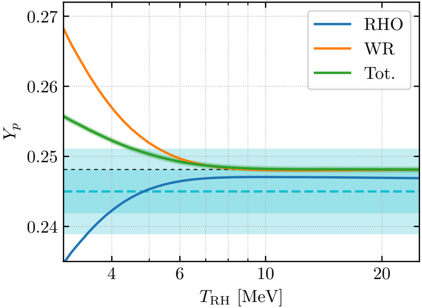
Planck constraint: $N_\mathrm{eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

BBN and low reheating

[arxiv:2501.01369]

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)

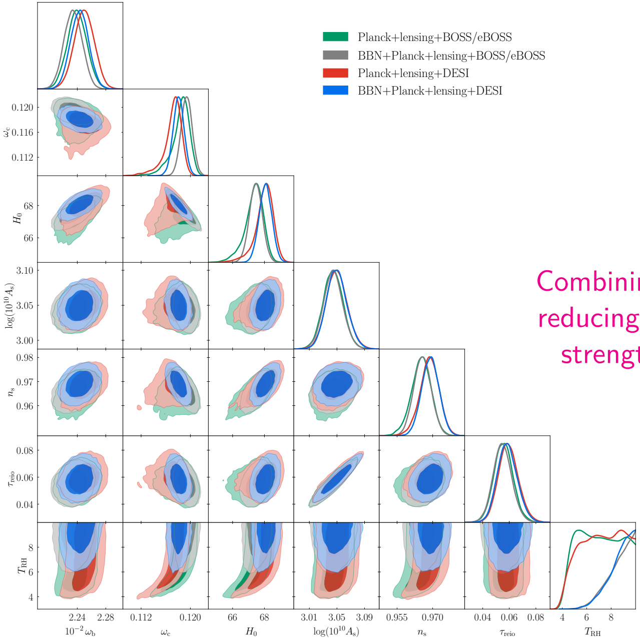
↓

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

Both effects are important to get Helium right!

Constraints on low reheating scenarios

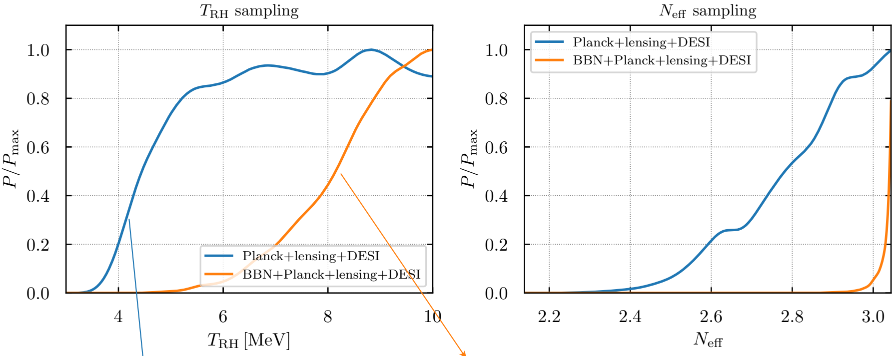
[arxiv:2501.01369]



Combining probes helps in reducing degeneracies and strengthening bounds!

Constraints on low reheating scenarios

[arxiv:2501.01369]



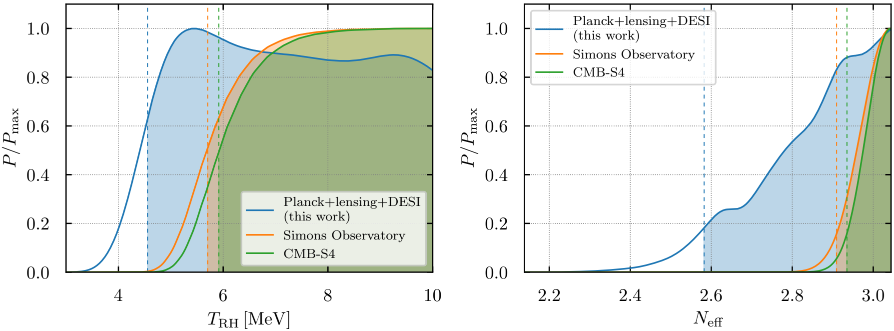
$T_{\rm rh} > 5.96$ MeV (95%)

$T_{\rm rh} > 3.79$ 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

[arxiv:2501.01369]



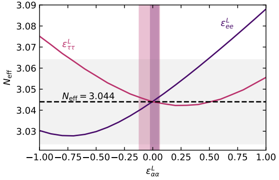
Greater sensitivity will come with future CMB probes
(more precise in determining $N_{\rm eff}$)

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

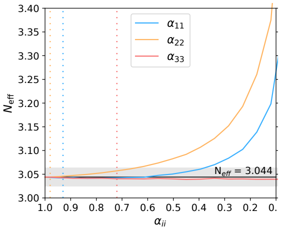
N

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

It can still relate to new physics!



e.g.:
Non-Standard Interactions (NSI),
Non-Unitary (NU) mixing
[PLB 820 (2021)], [arxiv:2503.21998]



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

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

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

↓

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

matter effects in oscillations (subdominant!)

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

↓

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

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

NSI effects on $N_{\rm eff}$

[PLB 820 (2021)]

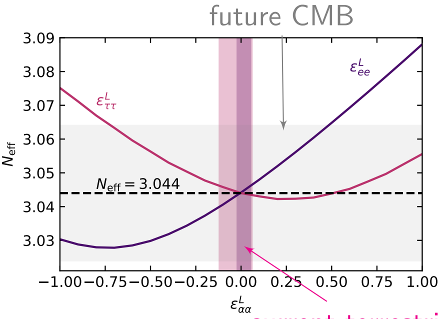
$$G^{L,R} = G^{L,R}_{SM} + \begin{pmatrix} \epsilon^{L,R}_{ee} & \epsilon^{L,R}_{e\mu} & \epsilon^{L,R}_{e\tau} & \cdots \\ \epsilon^{L,R}_{e\mu} & \epsilon^{L,R}_{\mu\mu} & \epsilon^{L,R}_{\mu\tau} & \cdots \\ \epsilon^{L,R}_{e\tau} & \epsilon^{L,R}_{\mu\tau} & \epsilon^{L,R}_{\tau\tau} & \cdots \\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

e.g.:

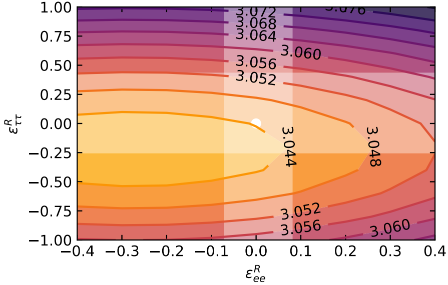
$G^L_{ee} \rightarrow 0.727 + \epsilon^L_{ee}$

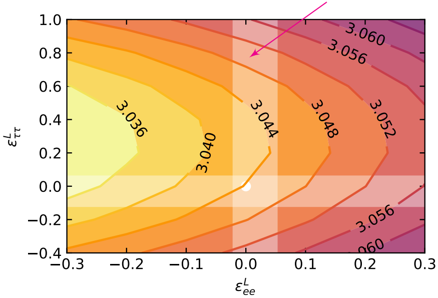
$G^L_{\tau\tau} \rightarrow -0.273 + \epsilon^L_{\tau\tau}$

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



current terrestrial

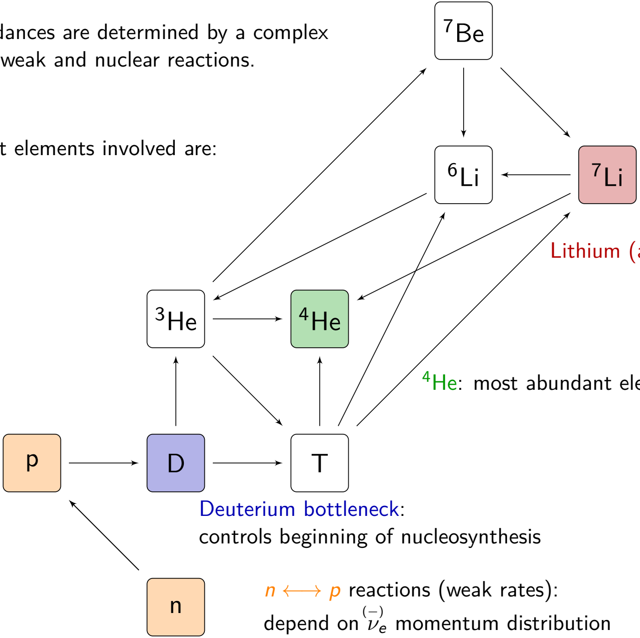




Reactions governing BBN

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

[arxiv:2503.21998]

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

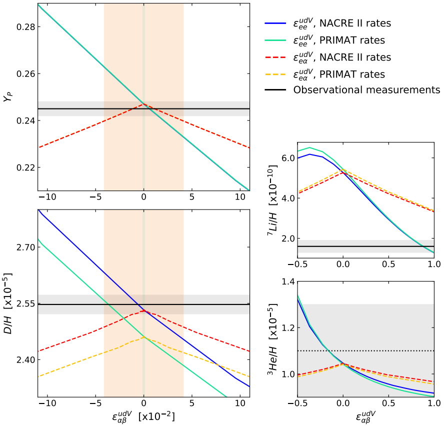
have secondary effect on BBN rates because there are no $\overset{(-)}{\nu} e$ interactions!

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!



Non-unitarity of the 3 × 3 mixing matrix

[JCAP 03 (2023)]

Consider we have N_ν neutrino states

$$\text{Unitary } N_\nu \times N_\nu \text{ mixing matrix: } V = \begin{pmatrix} \boxed{\begin{matrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{matrix}} & \cdots \\ \vdots & \ddots \end{pmatrix}$$

the 3×3 sector (N)
describing mixing among lightest neutrinos
is non-unitary

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

α_{ii} real, α_{ij} $(i \neq j)$ complex $\Rightarrow$ CP violation

$U = R^{23} R^{13} R^{12}$ is the standard unitary mixing matrix

Non-unitarity of the 3×3 mixing matrix

[JCAP 03 (2023)]

Consider we have N_ν neutrino states

$$\text{Unitary } N_\nu \times N_\nu \text{ mixing matrix: } V = \left(\begin{array}{cc} \boxed{\begin{matrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{matrix}} & \cdots \\ \vdots & \ddots \end{array}\right)$$

the 3×3 sector (N)
describing mixing among lightest neutrinos
is non-unitary

Neutrino interactions depend only on kinematically accessible states

Oscillations depend on all states

Oscillations with states $n > 3$ much heavier than $n \leq 3$
are averaged out at experiments

Non-unitarity and neutrino decoupling

[JCAP 03 (2023)]

Neutrino density matrix evolution in mass basis:

$$\left.\frac{\mathrm{d}\varrho(y)}{\mathrm{d}x}\right|_{\mathrm{M}} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho}}\left\{-i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{M}}}{2y} - \frac{2\sqrt{2}G_F y m_e^6}{x^6}\mathcal{E}_{\mathrm{M}}, \varrho\right] + \frac{m_e^3}{x^4}\mathcal{I}(\varrho)\right\}$$

Unitary case

interactions:

$$(Y_L)_{ab} \equiv \tilde{g}_L\mathbb{I} + (U^\dagger)_{ea}U_{eb}$$
$$(Y_R)_{ab} \equiv g_R\mathbb{I}$$

matter effects:

$$\mathcal{E}_{\mathrm{M}} = \frac{\rho_e+P_e}{m_W^2}U^\dagger\mathrm{diag}(1,0,0)U$$

Fermi constant:

$$G_F^\mu = G_F$$

Non-unitary case

interactions:

$$(Y_L)_{ab} \equiv \tilde{g}_L(V^\dagger V)_{ab} + (V^\dagger)_{ea}V_{eb}$$
$$(Y_R)_{ab} \equiv g_R(V^\dagger V)_{ab}$$

matter effects:

$$\mathcal{E}_{\mathrm{NU}} \equiv \frac{\rho_e+P_e}{m_W^2}(Y_L - Y_R)$$

Fermi constant:

$$G_F^\mu = G_F\sqrt{\alpha_{11}^2\left(\alpha_{22}^2+|\alpha_{21}|^2\right)}$$

$$G_F^\mu = 1.1663787(6)\times 10^{-5}\ \mathrm{GeV}^{-2}$$ [CODATA]

$$\mathcal{I}(\varrho) \propto G_F^2$$

Non-unitarity parameters and $N_{\rm eff}$

[JCAP 03 (2023)]

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

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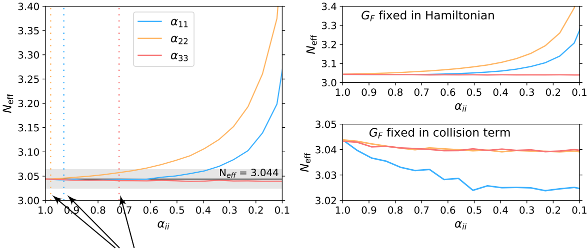

terrestrial bounds

Non-unitarity parameters and $N_{\rm eff}$

[JCAP 03 (2023)]

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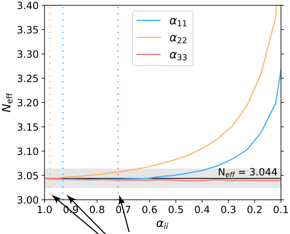
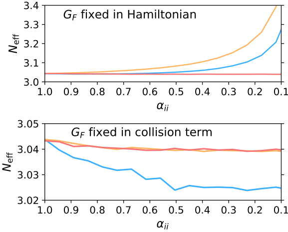
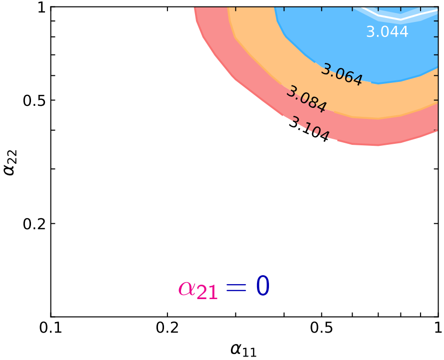
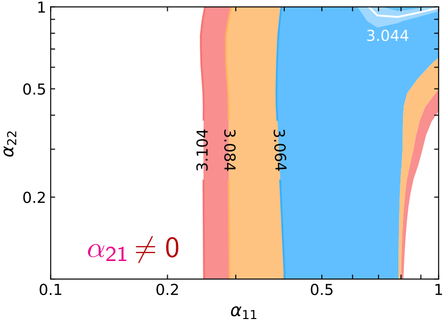








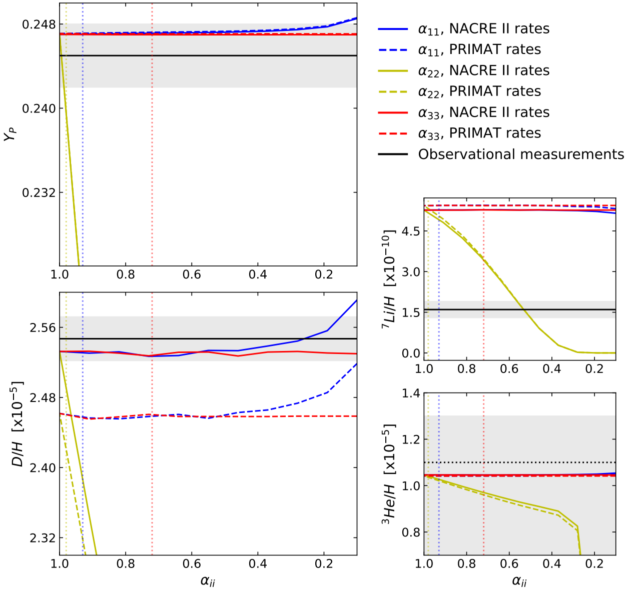
(α_{21} marginalized over)

Confidence regions from future CMB measurements with $\delta N_{\rm eff} = 0.02$

Non-unitarity parameters and BBN

[arxiv:2503.21998]

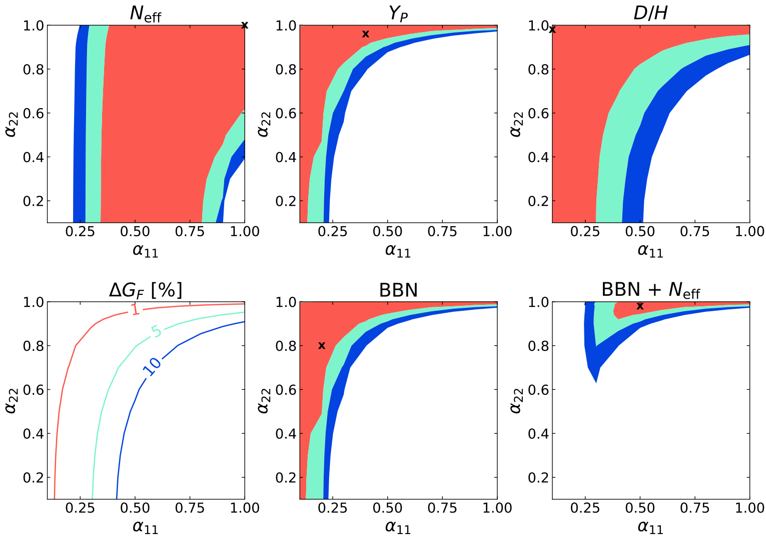
Non-unitarity parameters affect BBN abundances:



Non-unitarity parameters and BBN

[arxiv:2503.21998]

Usual reasoning: better constraints by combining different probes!

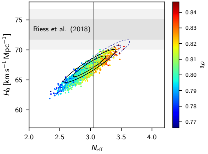


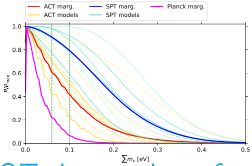
Z Conclusions

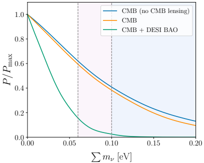
What do we learn about non-standard ν scenarios?

C

Cosmology measures (mostly) neutrino energy densities!

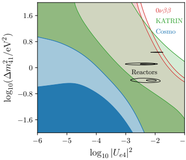


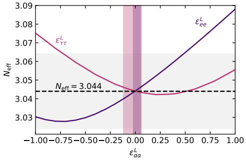


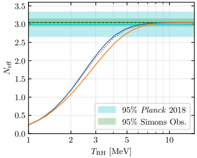


N

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

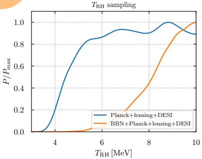


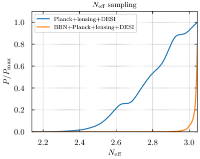


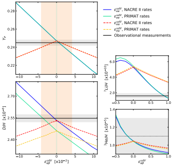


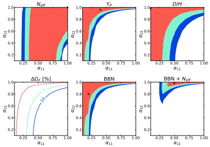
M

Combining different probes helps to break degeneracies!









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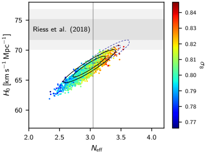

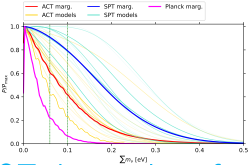

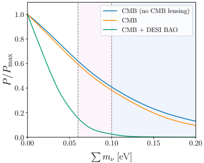

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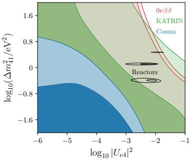

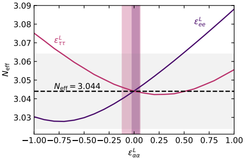

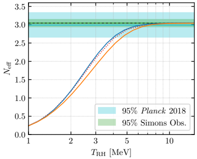

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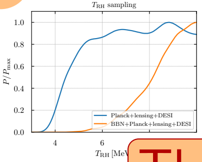

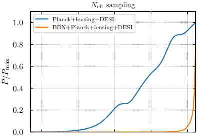

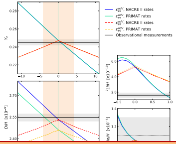

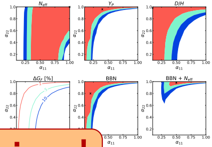

Thanks for your attention!