Stefano Gariazzo

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

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

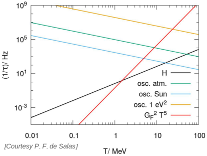
Cofinanciado por la Unión Europea

Neutrino non-standard scenarios in cosmology

Neutrinos from Home 2025, online conference

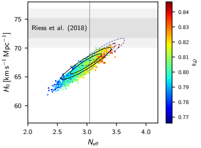
E Neutrinos in the Early Universe

Based on



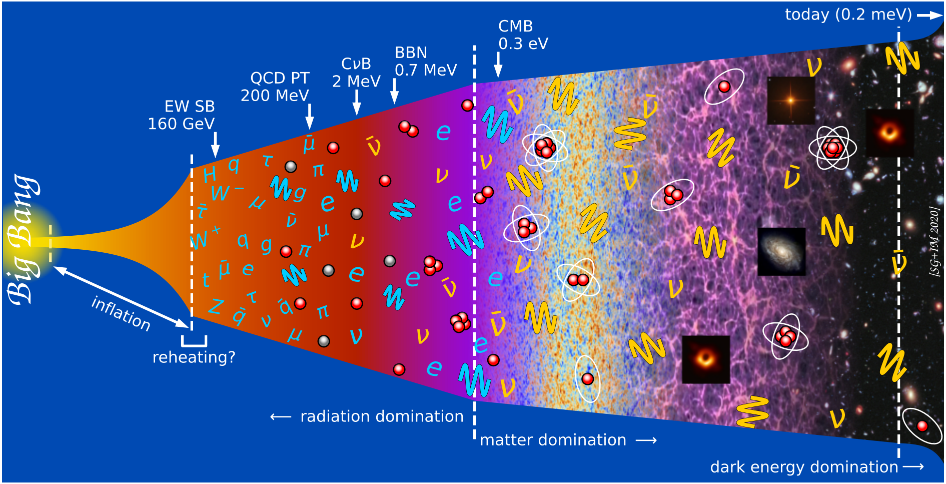
[Courtesy P. F. de Salas]

JCAP 04 (2021) 073



Planck 2018

History of the universe



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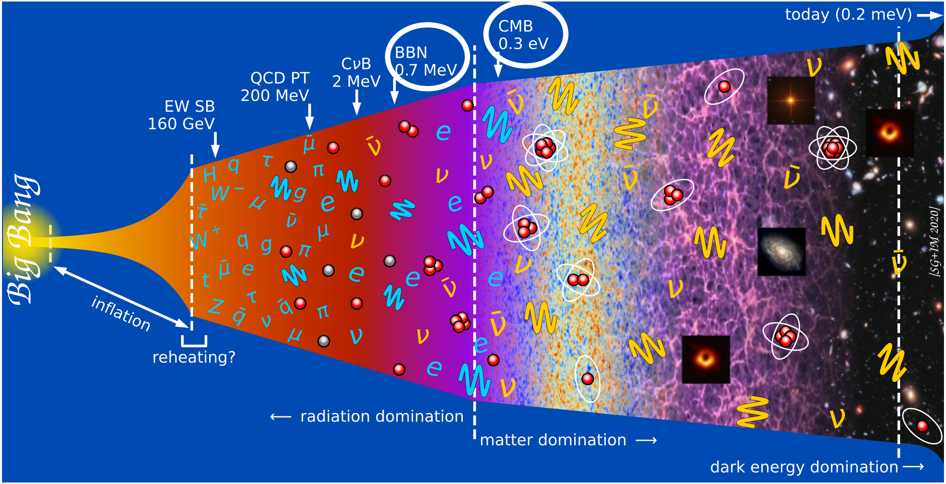
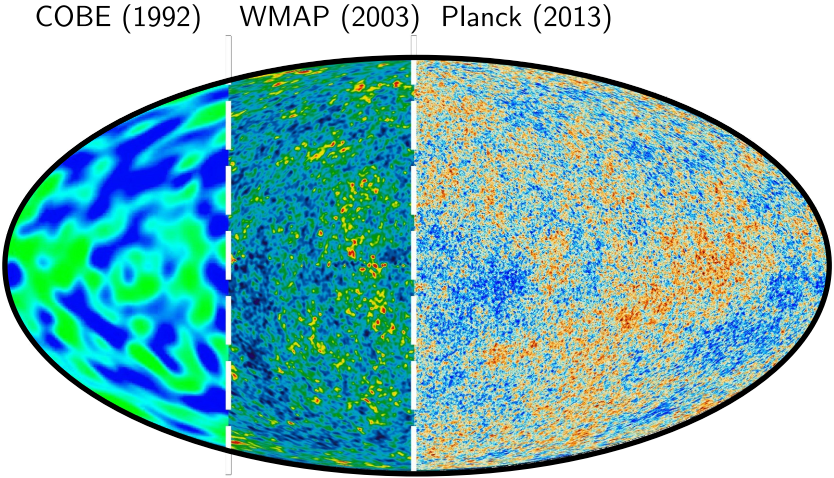


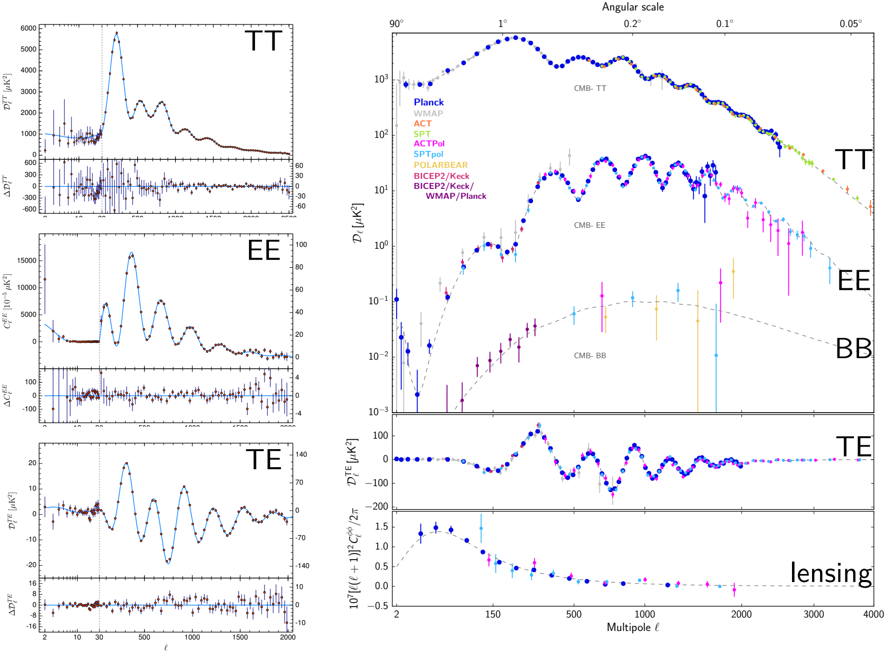
The oldest picture of the Universe

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



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

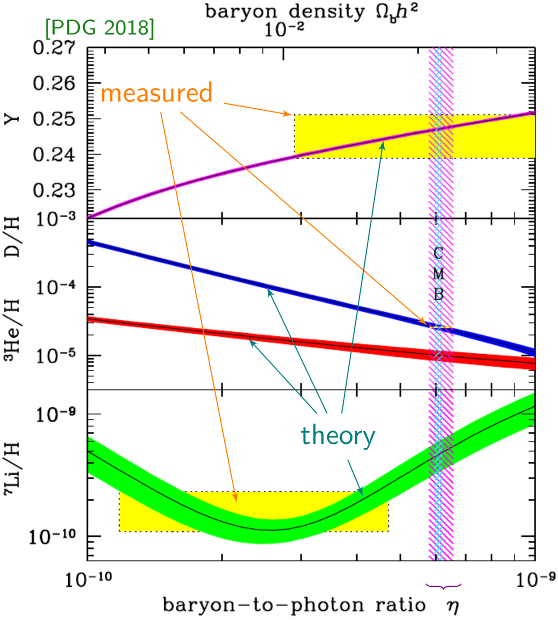
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

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]

measured

theory

BBN concordance

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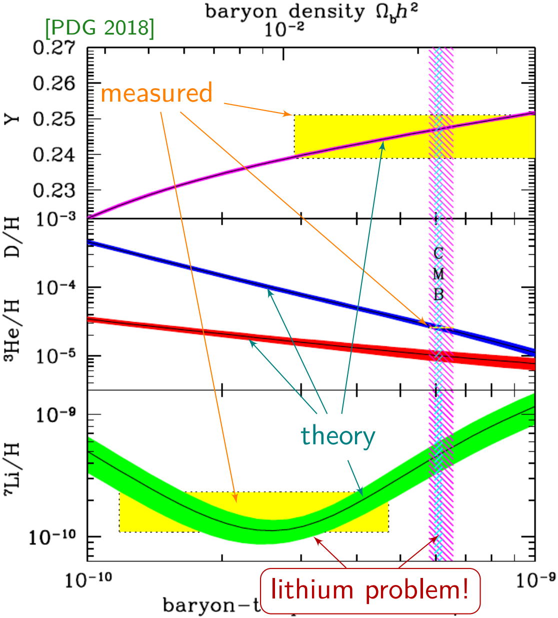
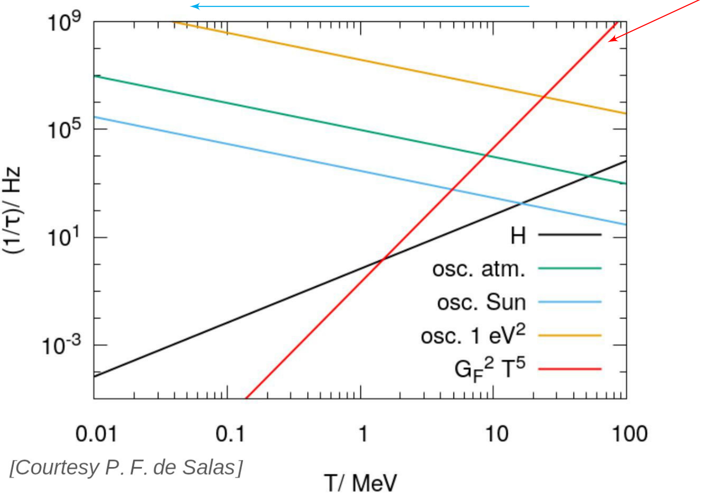


[PDG 2018]

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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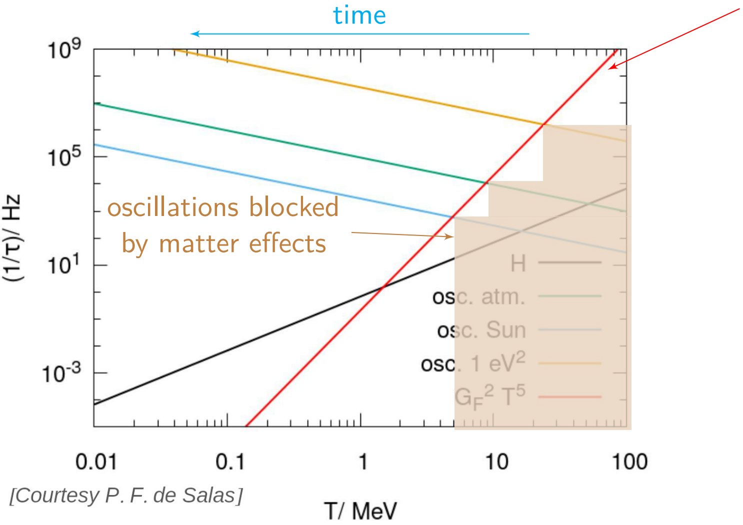

oscillations blocked
by matter effects

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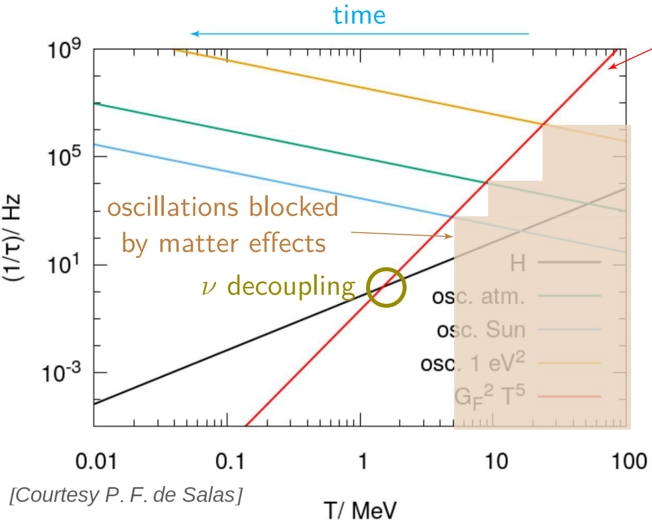

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ν decoupling

[Courtesy P. F. de Salas]

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

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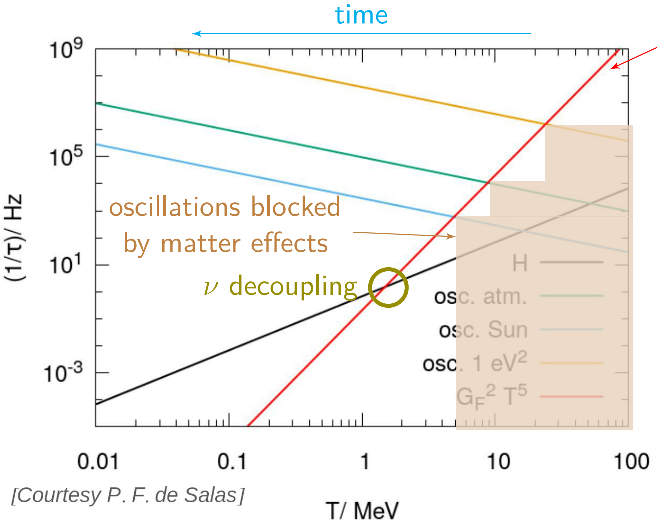

oscillations blocked by matter effects

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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 $\simeq 1.676 \times 10^{-4}$ 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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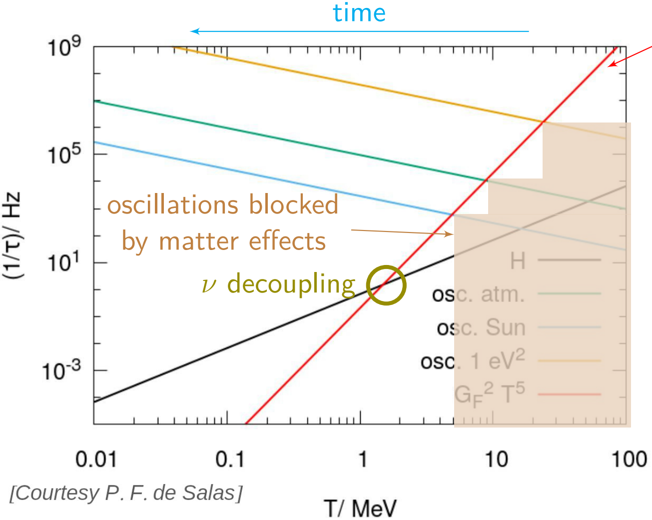

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actually, the decoupling T is momentum dependent!

→ 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 → 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 ←

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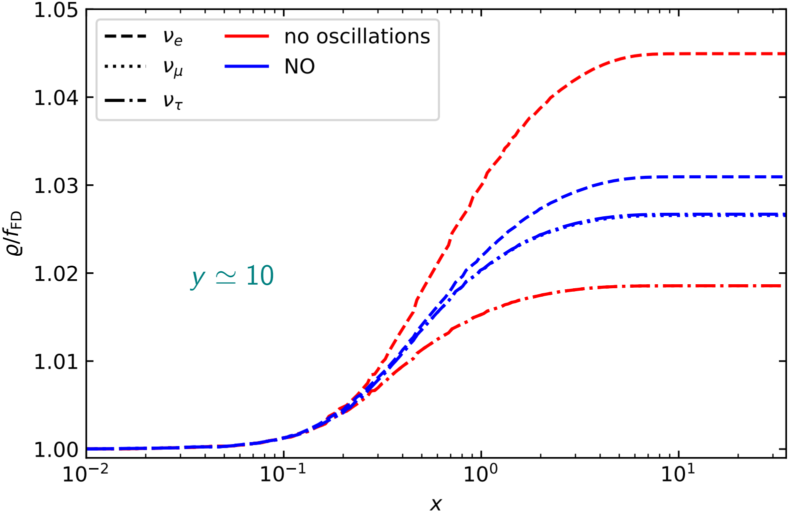
Neutrino momentum distribution and $N_{\rm eff}$

[Bennett, SG+, JCAP 2021]

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



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

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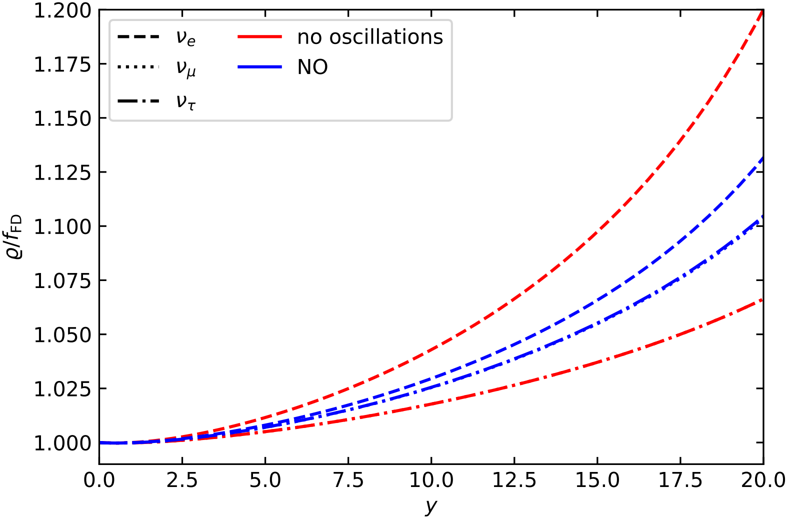


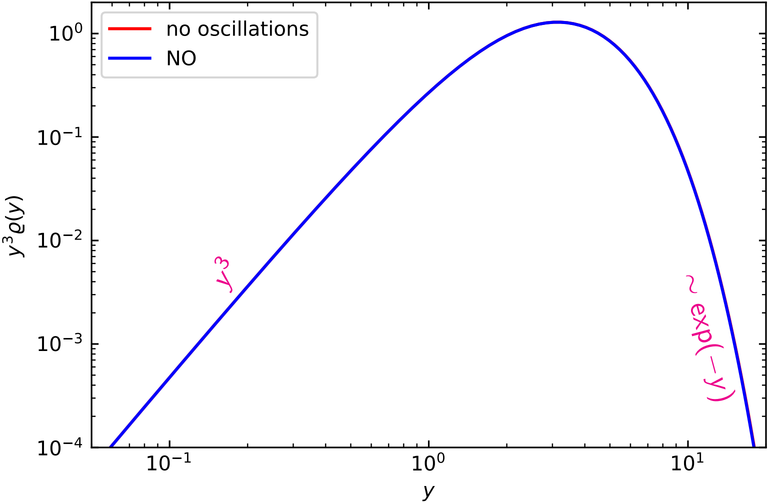
Neutrino momentum distribution and $N_{\rm eff}$

[Bennett, SG+, JCAP 2021]

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

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

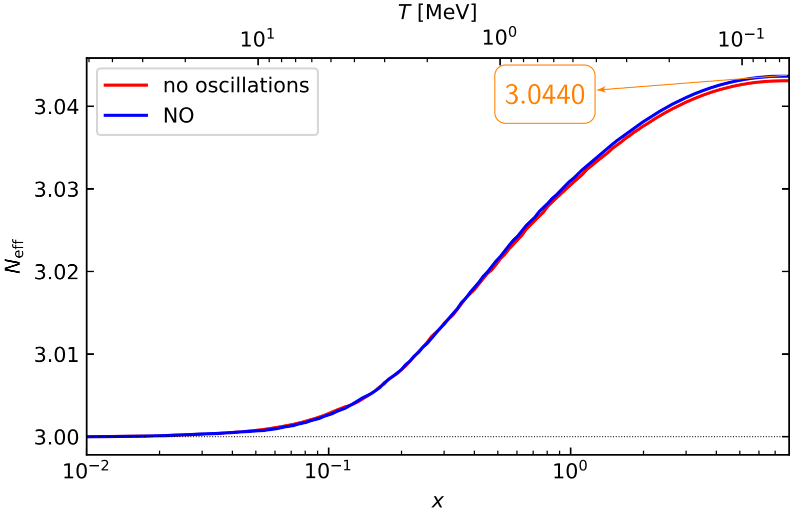
$\hookrightarrow \propto y^3 \varrho_{ii}(y)$



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

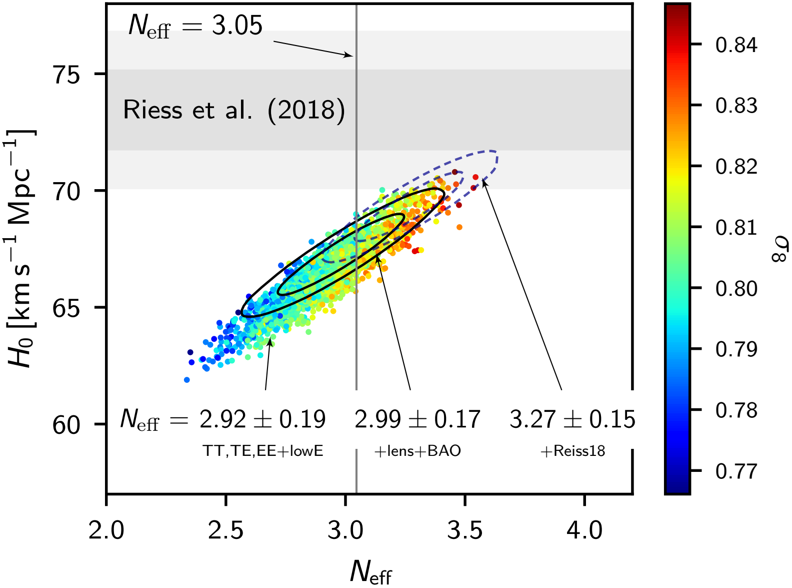
[Bennett, SG+, JCAP 2021]

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

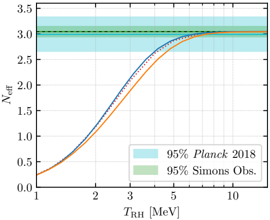


$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]



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



e.g. low-temperature reheating scenarios

[PRD 92 (2015) 123534], [PRL 135 (2025) 181003]

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

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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!

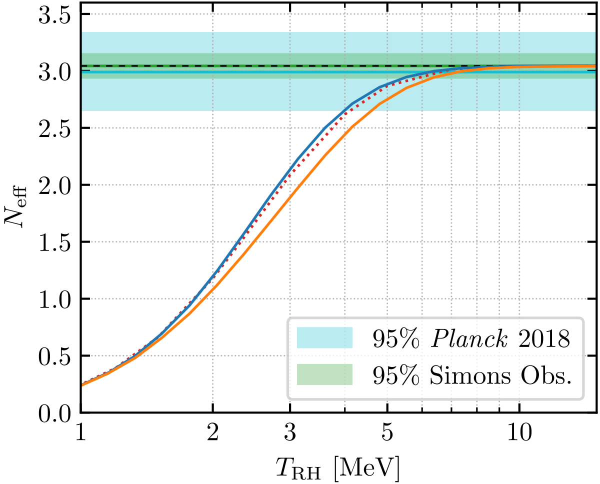
3 neutrino oscillations start to be affected when $T_{\rm rh} \lesssim 8$ MeV

what about sterile neutrinos?

$N_{\rm eff}$ with low reheating

[PRL 135 (2025)]

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

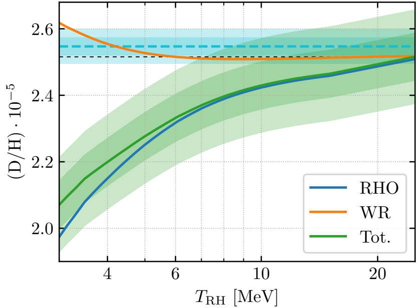


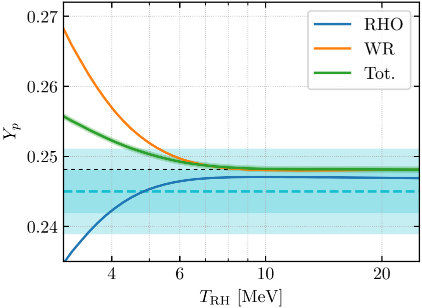
Planck constraint: $N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

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)

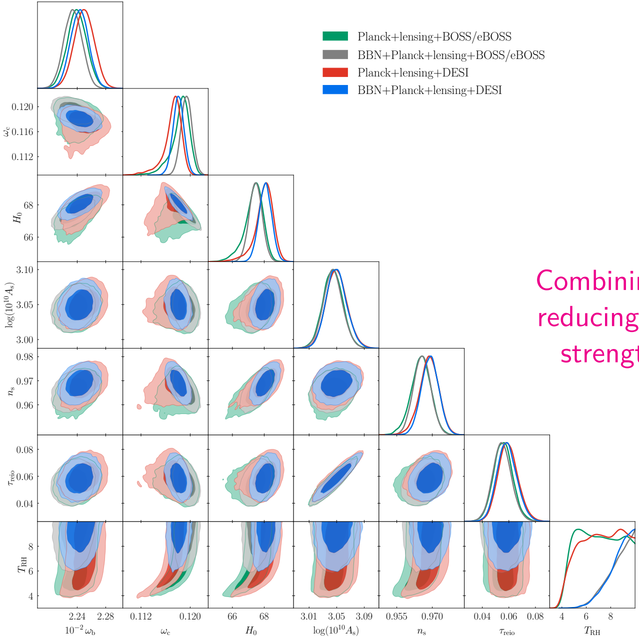
↓

$\overset{(-)}{\nu_e}$ momentum distribution

Both effects are important to get Helium right!

Constraints on low reheating scenarios

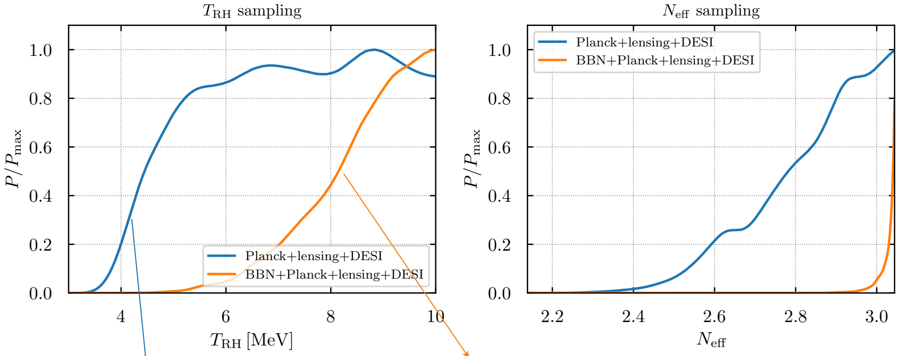
[PRL 135 (2025)]



Combining probes helps in reducing degeneracies and strengthening bounds!

Constraints on low reheating scenarios

[PRL 135 (2025)]



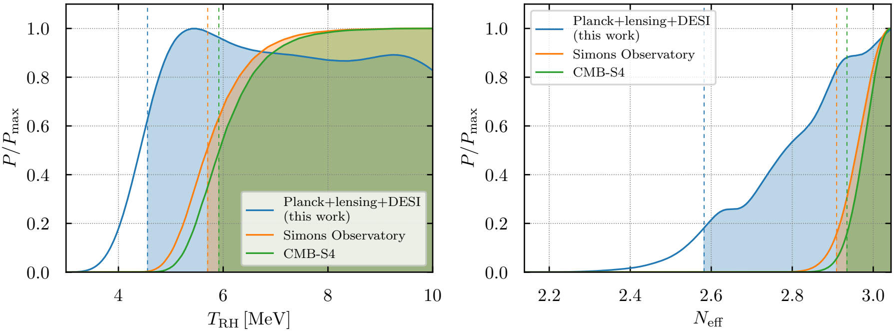
$T_{\rm rh} > 5.96$ MeV (95%)

$T_{\rm rh} > 3.79$ 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

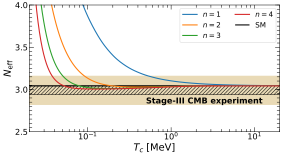
[PRL 135 (2025)]



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



e.g.: additional particles

[JCAP 12 (2023) 20]

Additional particles in the early universe?

[JCAP 12 (2023)]

Sterile neutrinos are coupled via oscillations to the thermal plasma
(photons, electrons, neutrinos, (muons), . . .)

What if we add a decoupled particle?

let us assume a non-standard evolution of the energy density: $\bar{\rho}_{\rm US} \propto a^{n+4}$
$n = 0 \rightarrow$ radiation; $n = -1 \rightarrow$ matter; $n = -2 \rightarrow$ curvature, . . .

effect on early universe phenomena is purely gravitational

total energy density: $\rho = \rho_\gamma + \rho_e + \rho_\nu + \delta\rho_{\rm FTQED} + \rho_{\rm US}$

Hubble factor: $H^2 = 8\pi\rho/(3M_{\rm Pl}^2)$

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neutrino decoupling: $$\frac{{\rm d}\varrho(y)}{{\rm d}x} = \frac{1}{xH}\left\{-i\frac{x^3}{m_e^3}\left[\mathcal{H}_{\rm eff},\varrho\right] + \frac{m_e^3}{x^3}\mathcal{I}(\varrho)\right\}$$

BBN abundances: $$\frac{dX_i}{dx} = \frac{\Gamma_i}{xH}$$

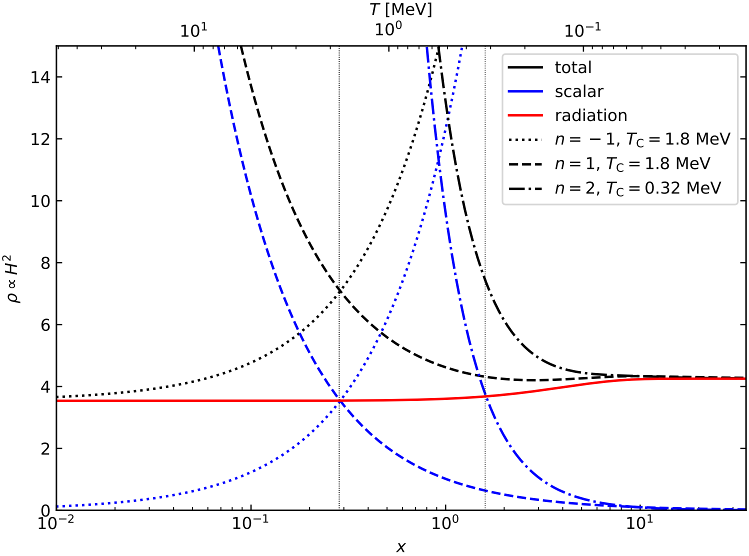
$X_i = n_i/N_B$ abundance relative to total baryons, Γ_i effective reaction rate for nuclide i

Results from N_{eff}

[JCAP 12 (2023)]

consider $\rho_{\mathrm{US}} = \rho_{\mathrm{rad}}$ at $x_{\mathrm{C}} = m_e / T_{\mathrm{C}}$ for the new particle

Evolution of the energy density:



Results from N_{eff}

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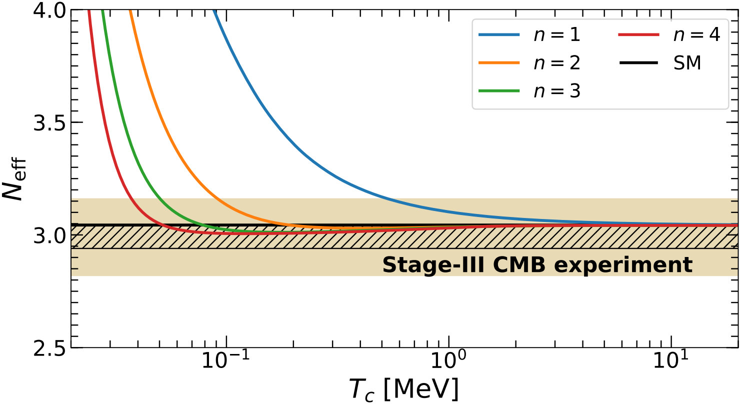
From neutrino decoupling we obtain:

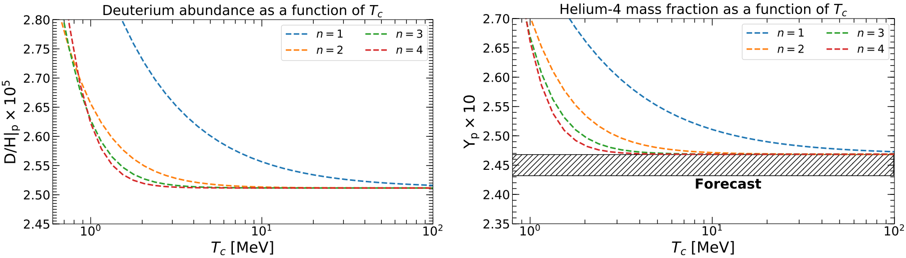


Results from BBN

[JCAP 12 (2023)]

consider $\rho_{\rm US} = \rho_{\rm rad}$ at $x_{\rm C} = m_e/T_{\rm C}$ for the new particle

Compare to current measurements (Deuterium, Helium):



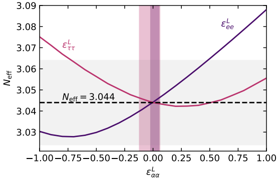
error bands (gray) are current constraints on the abundances

even current precision can strongly constrain $T_{\rm C}$

N

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

It can still relate to new physics!



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

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

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

↓

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

matter effects in oscillations

(subdominant!)

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

↓

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

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

NSI effects on $N_{\rm eff}$

[PLB 820 (2021)]

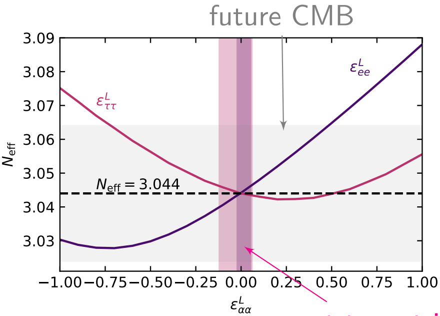
$$G^{L,R} = G^{L,R}_{SM} + \begin{pmatrix} \epsilon^{L,R}_{ee} & \epsilon^{L,R}_{e\mu} & \epsilon^{L,R}_{e\tau} & \cdots \\ \epsilon^{L,R}_{e\mu} & \epsilon^{L,R}_{\mu\mu} & \epsilon^{L,R}_{\mu\tau} & \cdots \\ \epsilon^{L,R}_{e\tau} & \epsilon^{L,R}_{\mu\tau} & \epsilon^{L,R}_{\tau\tau} & \cdots \\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

e.g.:

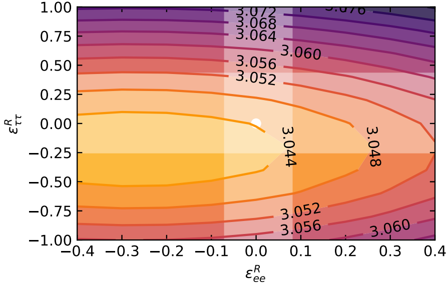
$G^L_{ee} \to 0.727 + \epsilon^L_{ee}$

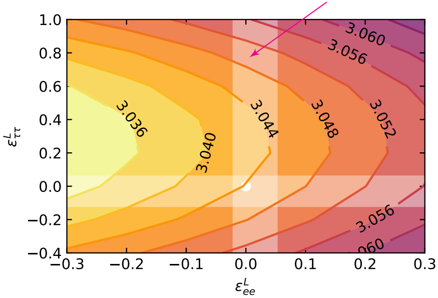
$G^L_{\tau\tau} \to -0.273 + \epsilon^L_{\tau\tau}$

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



current terrestrial

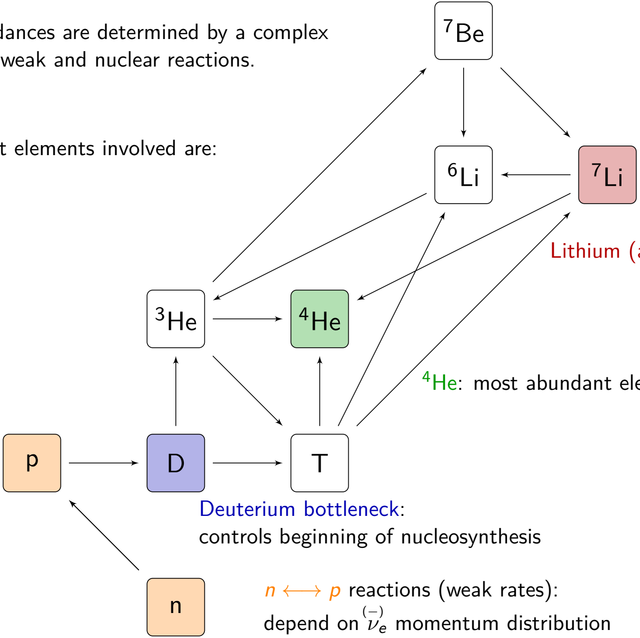




Reactions governing BBN

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)]

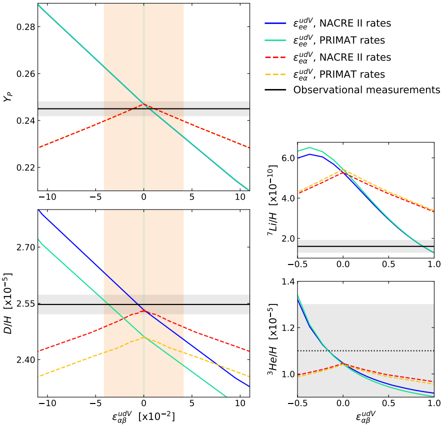
NSI with electrons, such as $\mathcal{L}^{\mathrm{NC}}_{\mathrm{NSIe}} \propto \sum \epsilon^{L,R}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{e}\gamma_\mu P_{L,R}e)$,
have secondary effect on BBN rates because there are no $\overset{(-)}{\nu}e$ interactions!

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

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

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!

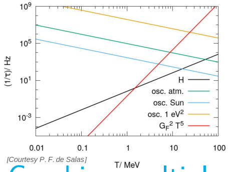


Z Conclusions

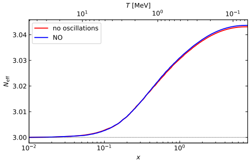
What do we learn about non-standard ν scenarios?

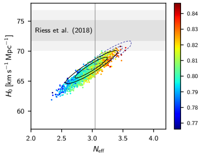
P

Neutrino decoupling: precision calculations



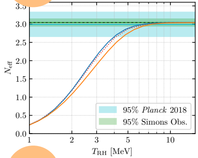
[Courtesy P. F. de Salas]

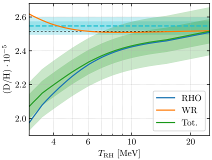


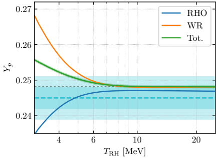


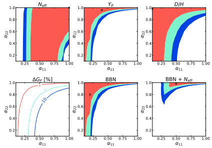
D

Combine multiple probes in order to reduce degeneracies!



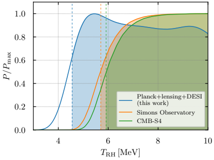


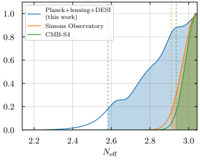


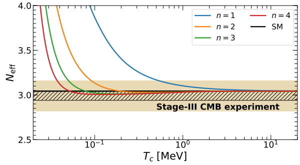


F

Future probes will have better sensitivity!



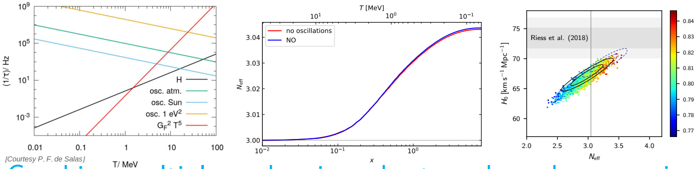




What do we learn about non-standard ν scenarios?

P

Neutrino decoupling: precision calculations



D

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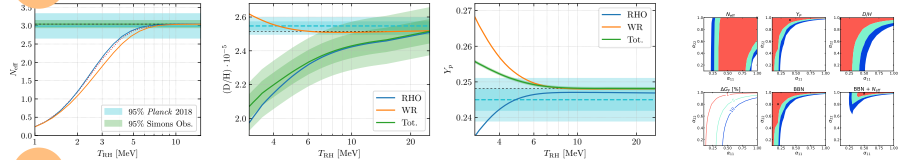

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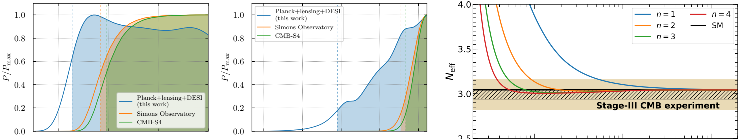

Thanks for your attention!