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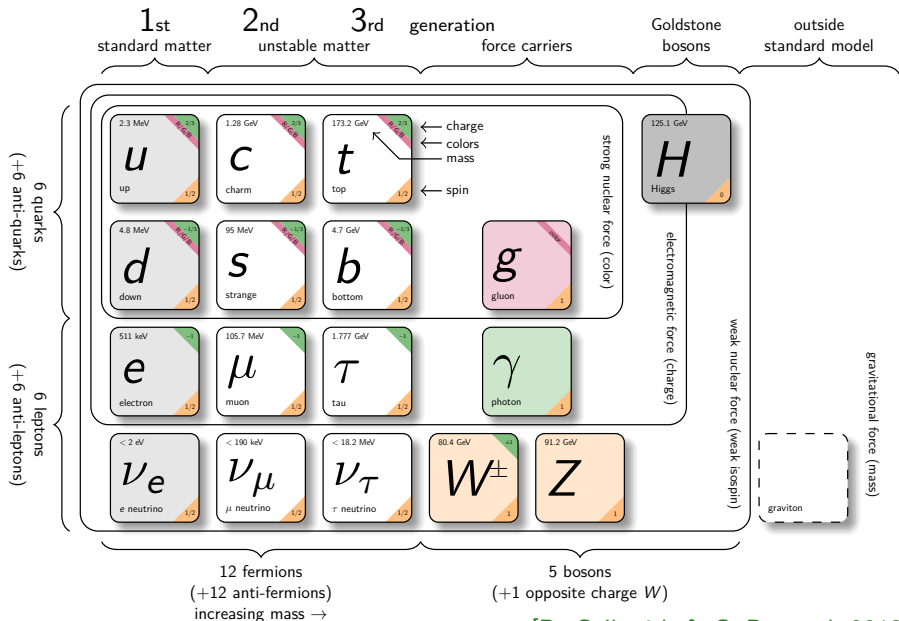
`http://personalpages.to.infn.it/~gariazzo/`

NEURAL

Neutrinos Re-fitted with Active Learning

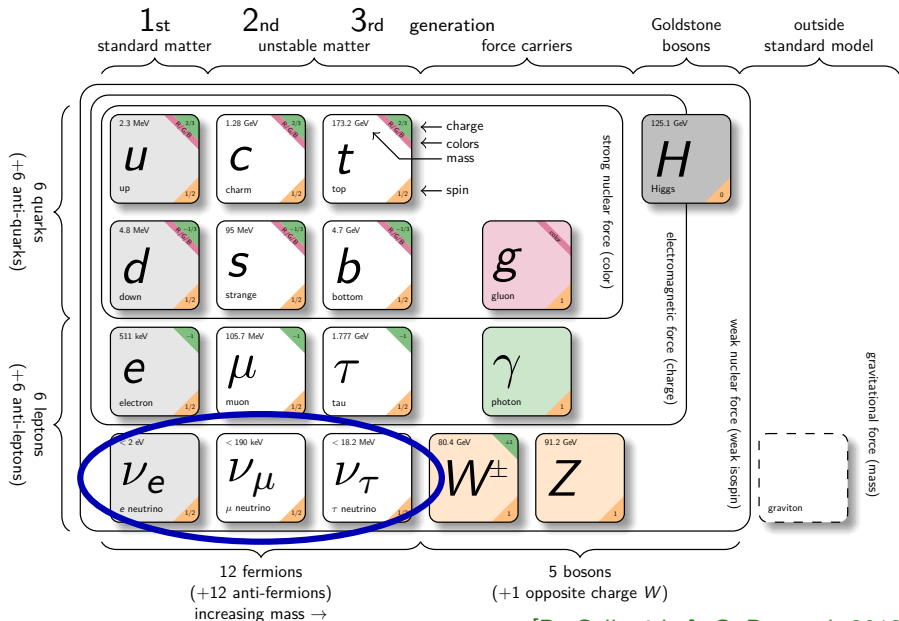
General Meeting of the Fellini programme, 14/02/2023

The Standard Model of Particle Physics

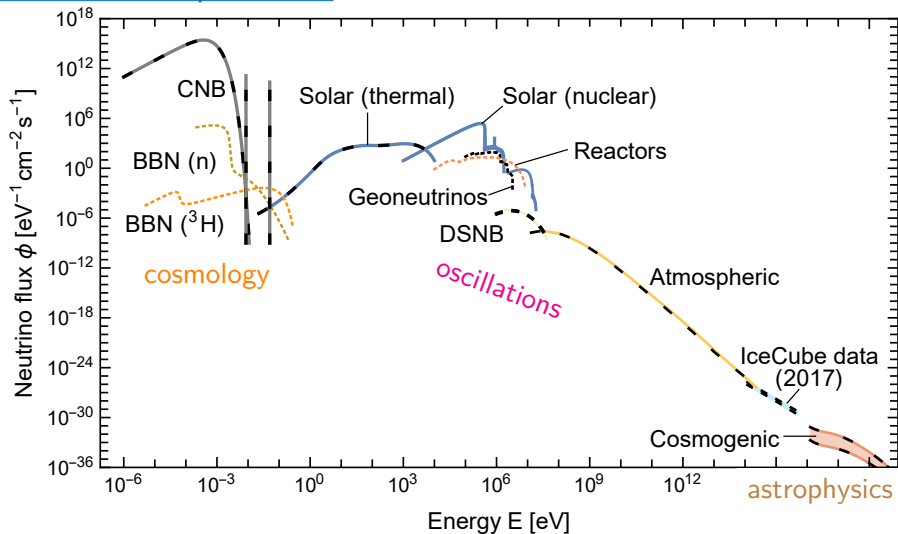


[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]



neutrinos at all energies provide valuable information!

NEURAL: Neutrinos Re-fitted with Active Learning

We obtain neutrino properties from different probes:

terrestrial

cosmological/early universe



Numerical techniques for global fits need improvements:

multi-parameter fits

systematic parameters

computation time

Many of these issues can be addressed with machine learning methods!

advanced interpolation
of pre-computed results

smart selection of points
for training neural networks

Other issues must be tackled with new numerical codes

Neutrino calculations at
terrestrial experiments

early universe (neu-
trino decoupling+BBN)

extended proposal submitted as **ERC StG 2023** (evaluation ongoing)

- de Salas+, JHEP 02 (2021) 071 [arxiv:2006.11237].
- Archidiacono+, JCAP 12 (2020) 029 [arxiv:2006.12885].
- Vagnozzi+, Phys.Dark Univ. 33 (2021) 100851 [arxiv:2010.02230].
- Bennett+, JCAP 04 (2021) 073 [arxiv:2012.02726].
- Gariazzo+ CPC 271 (2022) 108205 [arxiv:2103.05027].
- de Salas+, Phys.Lett.B 820 (2021) 136508 [arxiv:2105.08168].
- di Valentino+, Phys.Rev.D 104 (2021) 083504 [arxiv:2106.15267].
- di Valentino+, Phys.Rev.D 105 (2022) 103511 [arxiv:2110.03990].
- Gariazzo+, Phys.Rev.D 106 (2022) 023530 [arxiv:2111.03152].
- Corona+, JCAP 06 (2022) 010 [arxiv:2112.00037].
- Archidiacono+, Universe 8 (2022) 175 [arxiv:2201.10319].
- Gariazzo+, JCAP 10 (2022) 010 [arxiv:2205.02195].
- di Valentino+, Phys.Rev.D 106 (2022) 043540 [arxiv:2207.05167].
- Gariazzo+, under review [arxiv:2211.10522].
- di Valentino+, under review [arxiv:2212.11926].

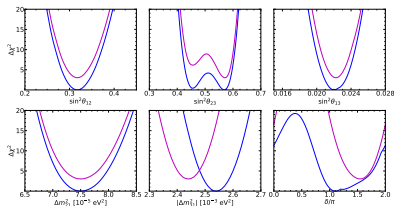
1 Constraints on neutrino properties

2 Neutrinos in the universe

3 Secondment in Chile (12/2021–05/2022)

4 Secondment in Valencia (03-09/2023)

5 Conclusions



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)]

$$\Delta m_{ji}^2 = m_j^2 - m_i^2, \theta_{ij} \text{ mixing angles}$$

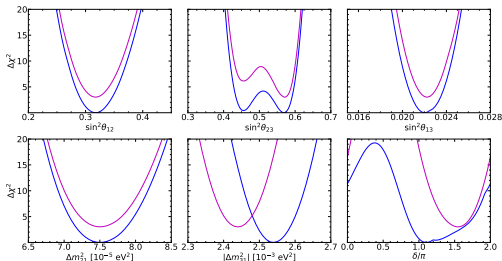
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

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

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

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

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



mass ordering
still unknown

δ still unknown

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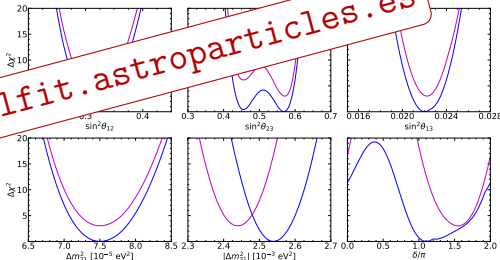
$$10^2 \sin^2(\theta_{13}) = 2.200^{+0.060}$$

$$10 \sin^2 \delta = 5.71 \pm 0.12 \text{ (NO)}$$

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

$$\delta/\pi = 1.10^{+0.27}_{-0.12} \text{ (NO)}$$

$$= 1.54 \pm 0.14 \text{ (IO)}$$



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

mass ordering
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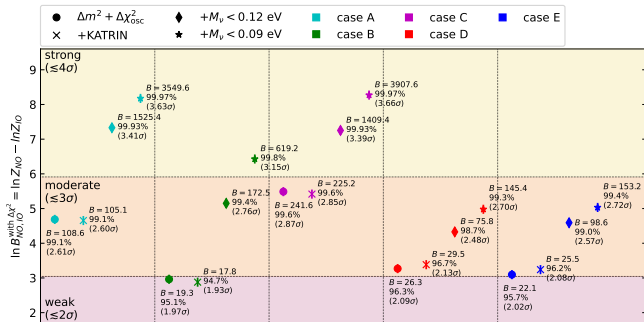
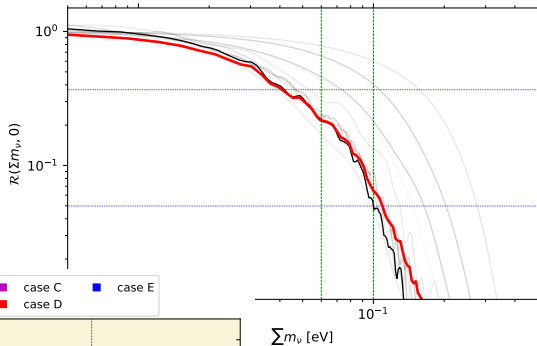
δ still unknown

Constraints on ν masses and mass ordering

Constraints on Σm_ν :

marginalize over extended cosmological models

$\Sigma m_\nu \lesssim 0.1$ eV at 95% CL,
Planck+BAO+SN
[PRD 106 (2022)]



Constraints on mass ordering: careful with the choice of parameterizations/priors for Bayesian model comparison [JCAP 10 (2022)]

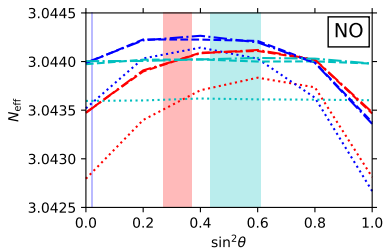
1 *Constraints on neutrino properties*

2 *Neutrinos in the universe*

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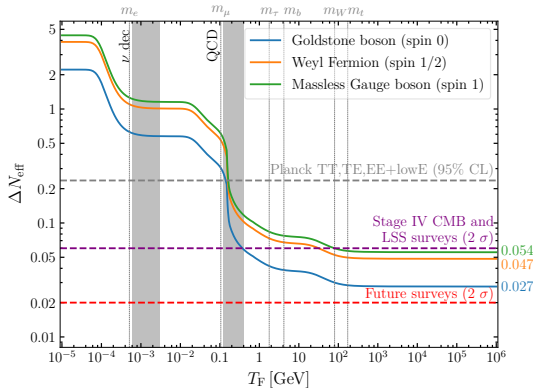
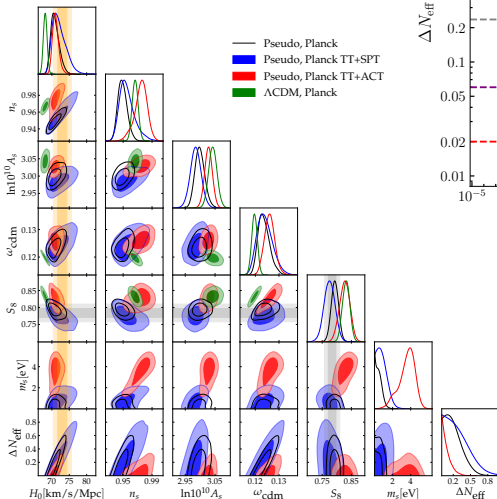
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Dark radiation studies

Review [Universe 8 (2022)]:
status of dark radiation
(including light sterile
neutrino) searches



Light sterile neutrino:
 $m_s \sim \mathcal{O}(\text{eV})$
as a solution of the Planck vs
ACT discrepancy?

[JCAP 06 (2022) 010]

Early universe calculations (public codes)

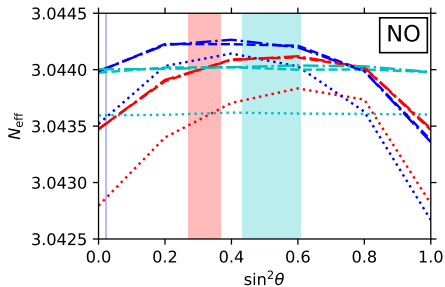
Neutrino decoupling:

state-of-the-art $N_{\text{eff}} = 3.044$

plus study of dependence on

oscillation and numerical parameters

[JCAP 04 (2021)]



see [FortEPiano](#) code

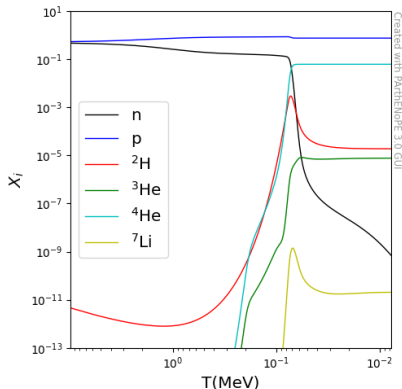
https://bitbucket.org/ahep_cosmo/fortepiano_public/src

Big Bang Nucleosynthesis:

PARthENoPE v3.0

[CPC 271 (2022)]

<http://parthenope.na.infn.it/>



updated nuclear rates after LUNA results, [new GUI](#)

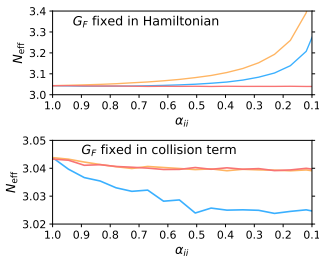
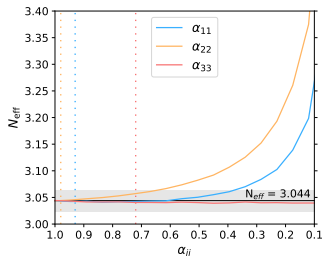
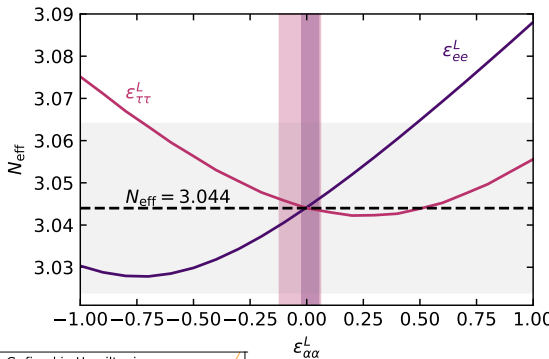
Neutrino properties from early universe physics

Impact of non-standard neutrino properties on neutrino decoupling:

Non-Standard Interactions

between ν_e and electrons:
constraints on the *diagonal and off-diagonal*
new couplings $\epsilon_{\alpha\beta}^{L,R}$

[PLB 820 (2021)]



Non-Unitarity (NU) of
the mixing matrix:
constraints on *diagonal*
and *off-diagonal*
NU parameters α_{ij}

[arxiv:2211.10522]

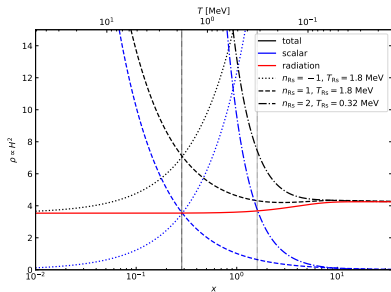
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Additional particles in the early universe?

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**: $\bar{\rho}_{\text{Rs}} \propto a^{n_{\text{Rs}}+4}$
 $n_{\text{Rs}} = 0 \rightarrow$ radiation; $n_{\text{Rs}} = -1 \rightarrow$ matter; $n_{\text{Rs}} = -2 \rightarrow$ curvature, ...

effect on early universe phenomena is purely gravitational

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

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

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

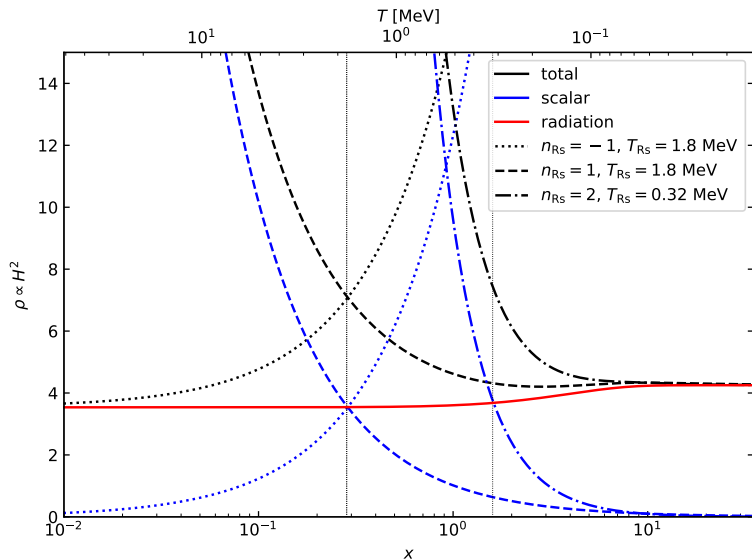
BBN abundances:
$$\frac{dX_i}{dx} = \frac{\Gamma_i}{xH}$$

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

Results from N_{eff}

consider $\rho_{\text{RS}} = \rho_{\text{rad}}$ at $x_{\text{RS}} = m_e/T_{\text{RS}}$ for the new particle

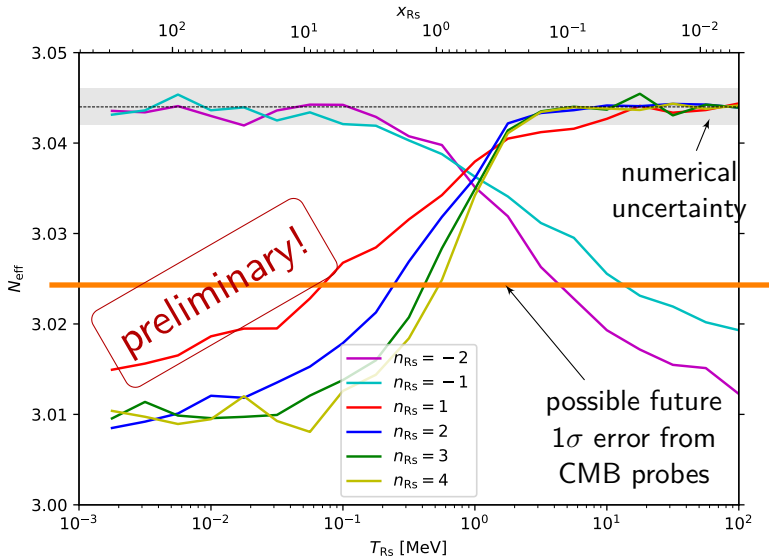
Evolution of the energy density:



Results from N_{eff}

consider $\rho_{\text{RS}} = \rho_{\text{rad}}$ at $x_{\text{RS}} = m_e/T_{\text{RS}}$ for the new particle

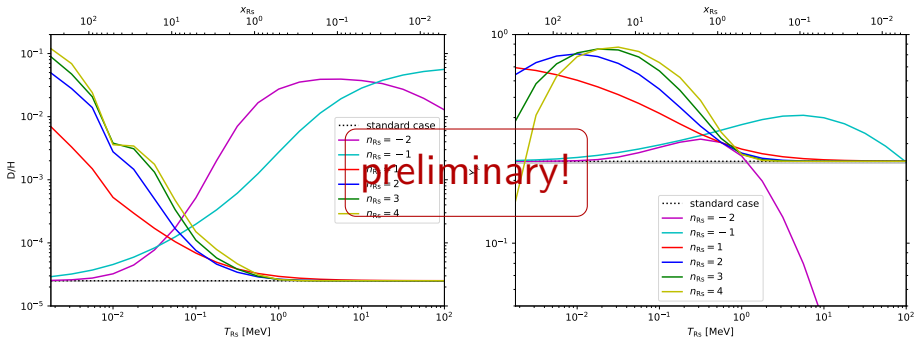
From neutrino decoupling we obtain:



Results from BBN

consider $\rho_{R_s} = \rho_{\text{rad}}$ at $x_{R_s} = m_e/T_{R_s}$ for the new particle

Compare to current measurements (Deuterium, Helium):



error bands (gray) are current constraints on the abundances

barely visible!! even current precision can strongly constrain T_{R_s}

calculations ongoing with prof. D. Aristizabal and A. Villanueva (UTFSM)

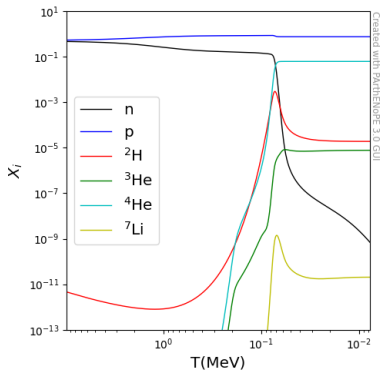
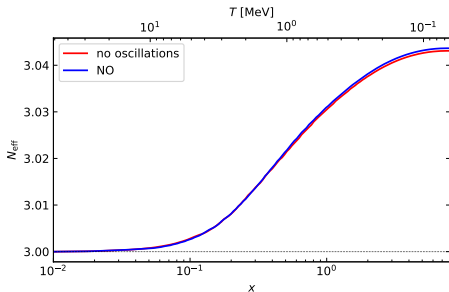
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Neutrino decoupling and BBN

NSI/NU constraints in previous slides only through N_{eff} , what about BBN?

BBN has not been studied much with non-standard neutrino physics

Neutrino decoupling and BBN occur almost at the same time!



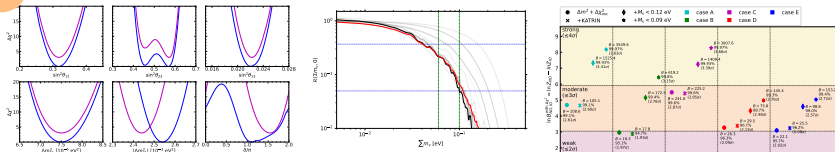
in preparation: neutrino decoupling+BBN code

secondment in collaboration with dr. S. Pastor, student P. Muñoz

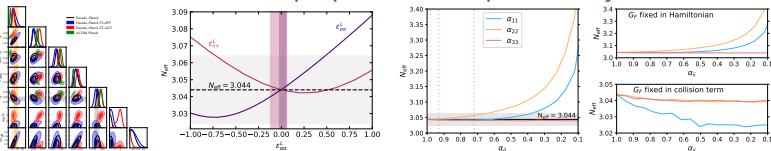
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Conclusions

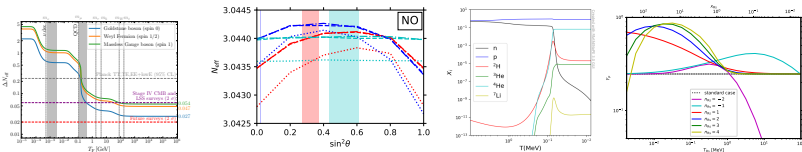
1 Standard neutrino properties: precision



2 Non-standard neutrino properties: complementary constraints

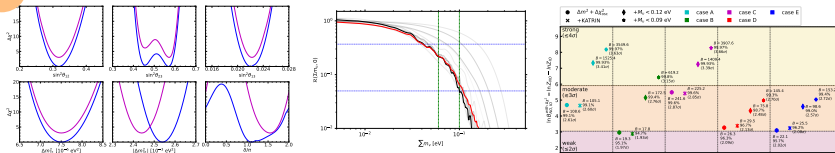


3 Early universe probes must be studied better!

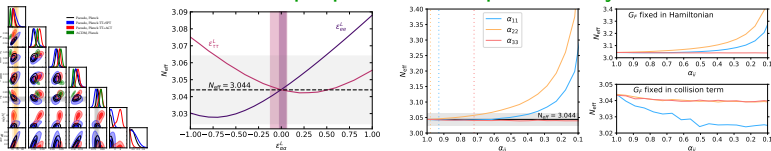


Conclusions

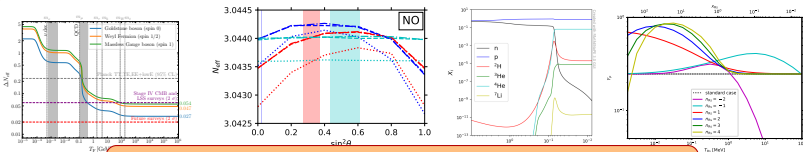
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Thanks for your attention!