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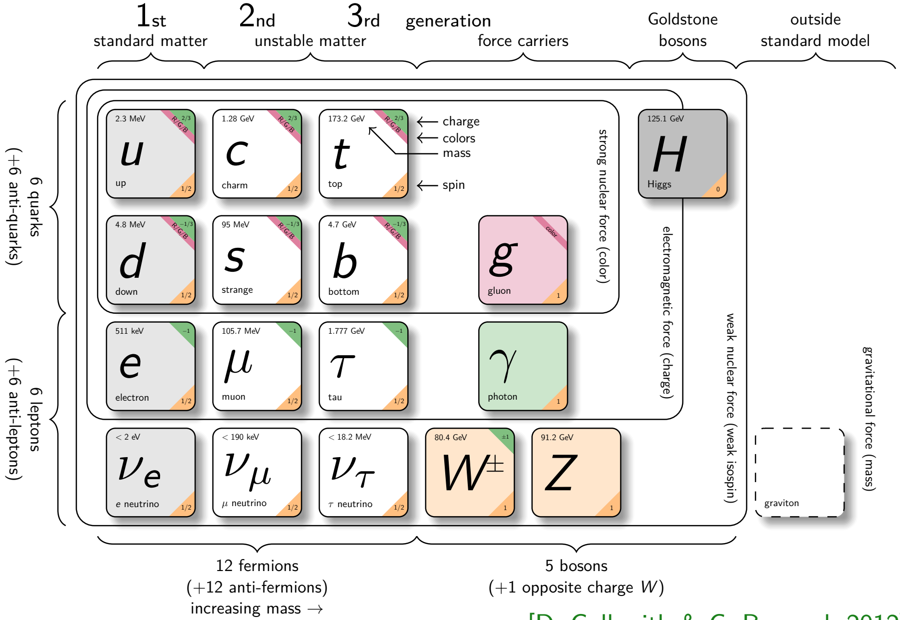
NEURAL

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]

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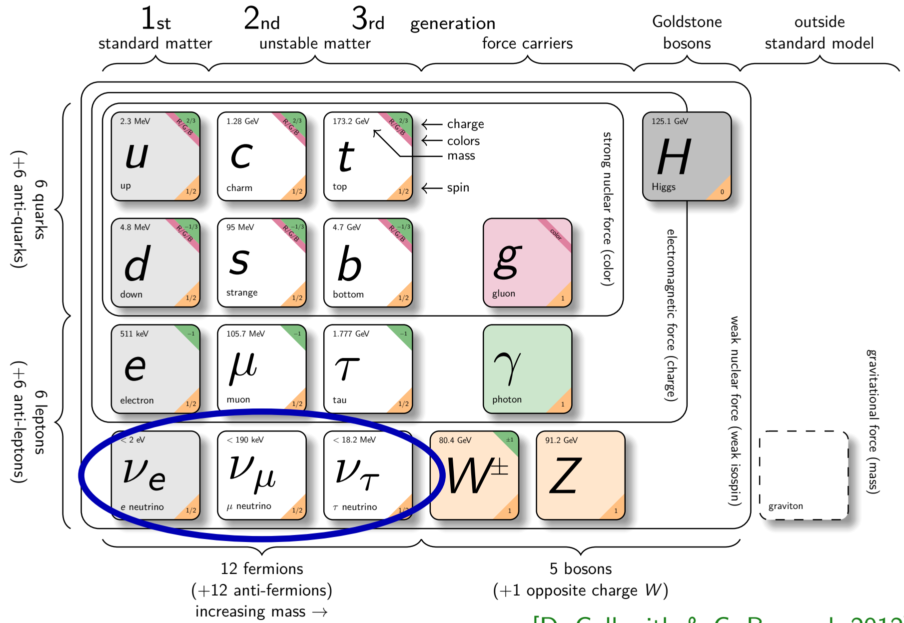
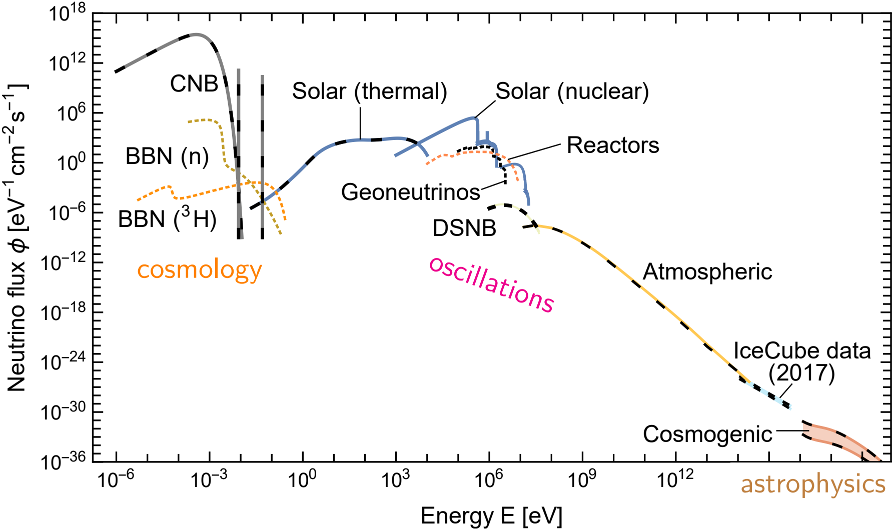


[D. Galbraith & C. Burgard, 2012]

Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]



neutrinos at all energies provide valuable information!

NEURAL: Neutrinos Re-fitted with Active Learning

We obtain neutrino properties from different probes:

terrestrial → Global fits ← cosmological/early universe

Numerical tecnhiques 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 (neutrino decoupling+BBN)

extended proposal submitted as ERC StG 2023 (evaluation ongoing)

Publications

- 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].

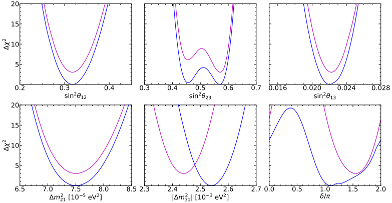
1 ***Constraints on neutrino properties***

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)]

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

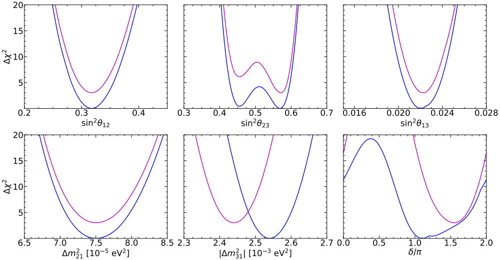
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

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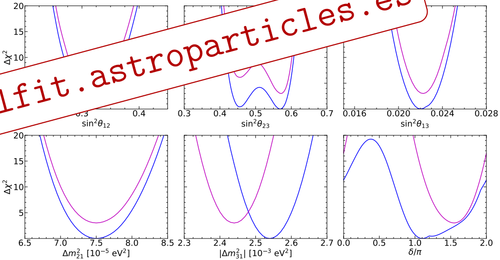
see also: http://globalfit.astroparticles.es



mass ordering still unknown

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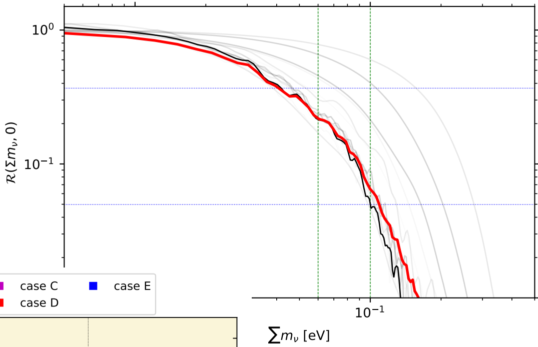
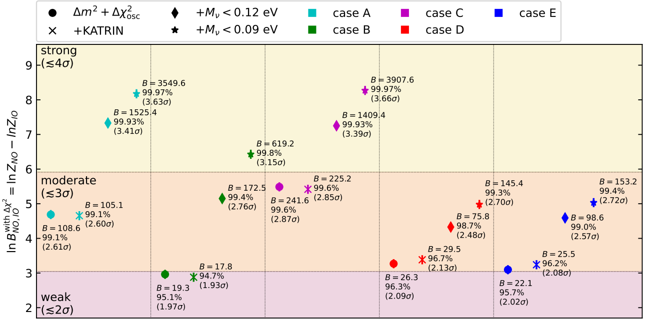
Constraints on ν masses and mass ordering

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)]

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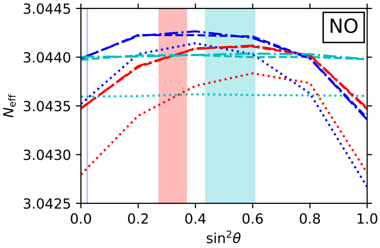
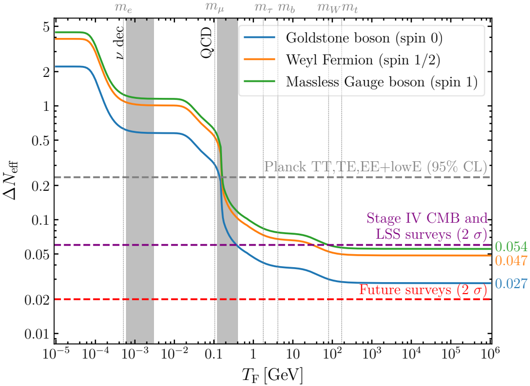
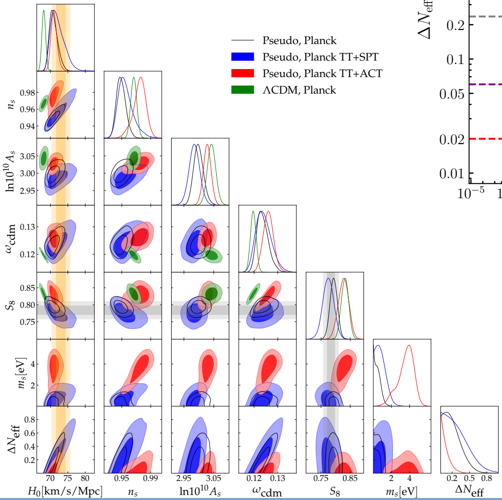


Dark radiation studies

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





Light sterile neutrino:

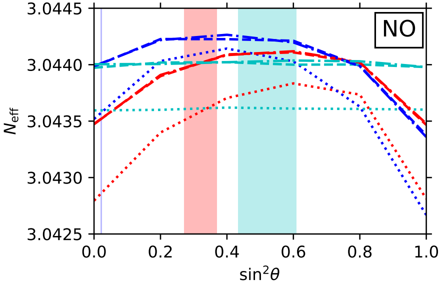
$m_s \sim \mathcal{O}(\text{eV})$

as a solution of the Planck vs ACT discrepancy?

[JCAP 06 (2022) 010]

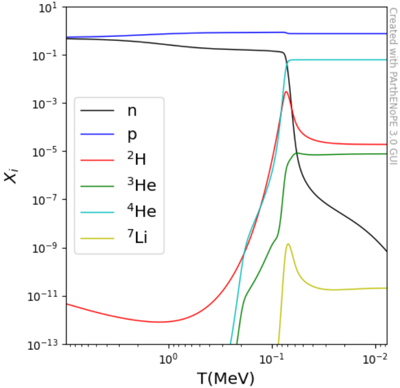
Early universe calculations (public codes)

Neutrino decoupling:
state-of-the-art $N_{\rm eff} = 3.044$
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/

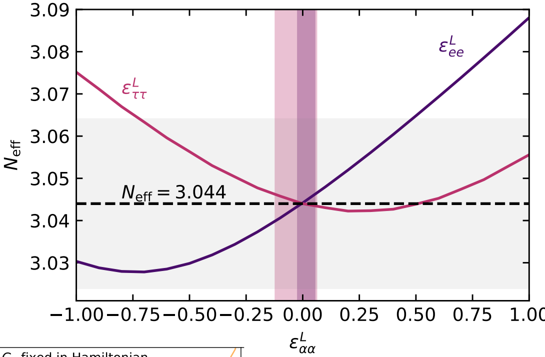


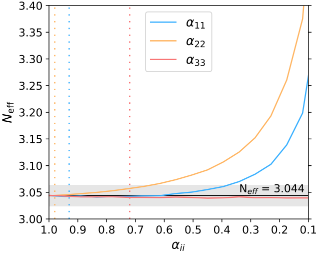
updated nuclear rates after LUNA results, new GUI

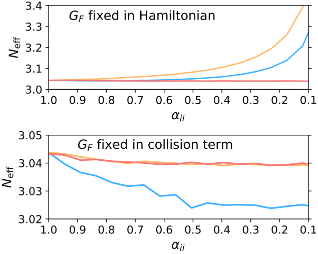
Neutrino properties from early universe physics

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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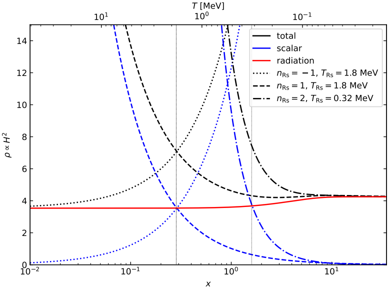

Additional particles in the early universe?

[in preparation]

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: $\bar{\rho}_{\rm Rs} \propto a^{n_{\rm Rs}+4}$

$n_{\rm Rs} = 0 \rightarrow$ radiation; $n_{\rm Rs} = -1 \rightarrow$ matter; $n_{\rm Rs} = -2 \rightarrow$ curvature, ...

effect on early universe phenomena is purely gravitational

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

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

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

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

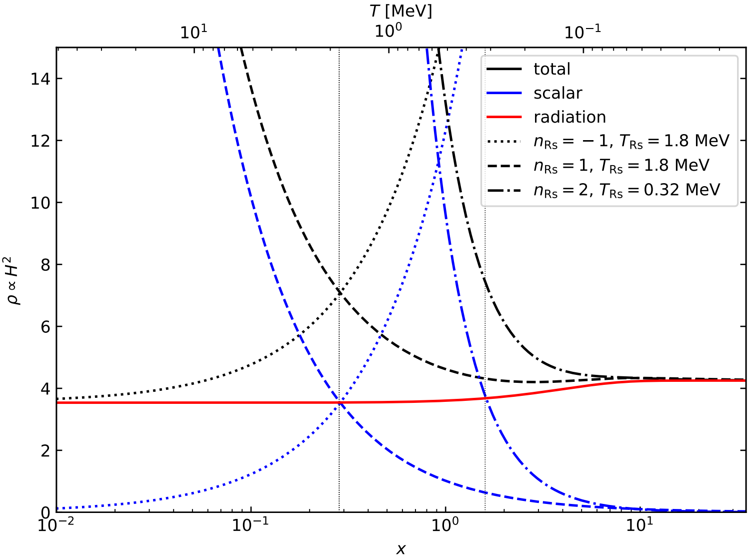
$X_i = n_i/N_B$ abundance relative to total baryons, Γ_i effective reaction rate for nuclide i

Results from $N_{\rm eff}$

[in preparation]

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

Evolution of the energy density:



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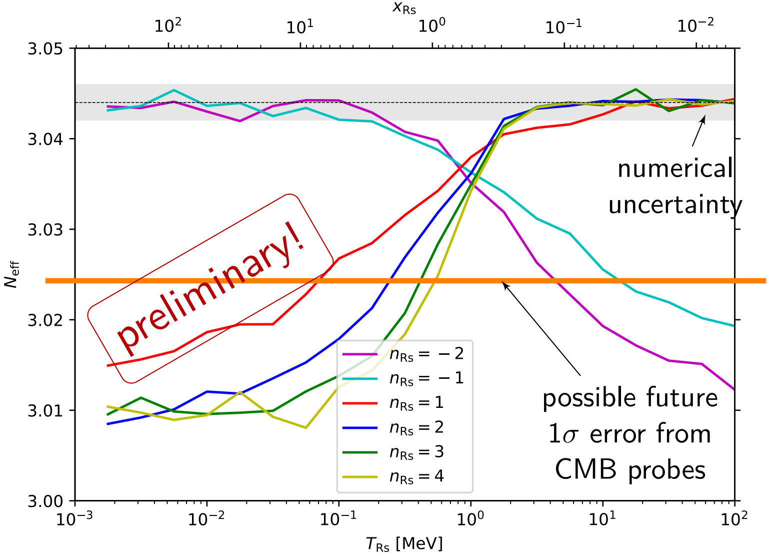
From neutrino decoupling we obtain:

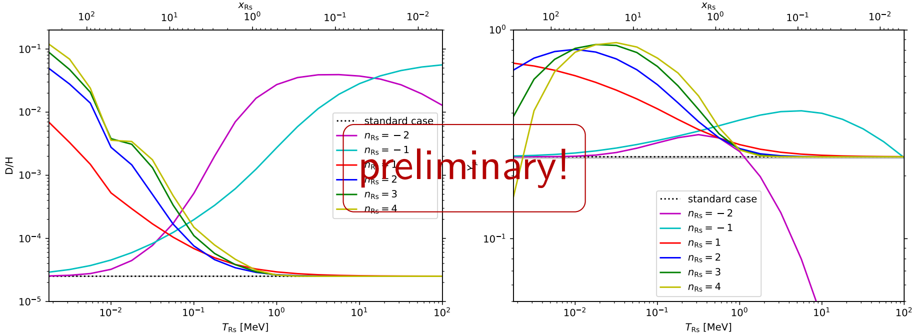


Results from BBN

[in preparation]

consider $\rho_{\rm Rs} = \rho_{\rm rad}$ at $x_{\rm Rs} = m_e/T_{\rm Rs}$ 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 $T_{\rm Rs}$

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

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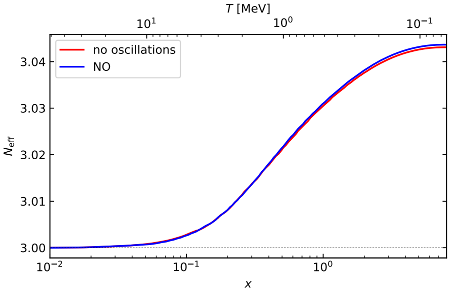
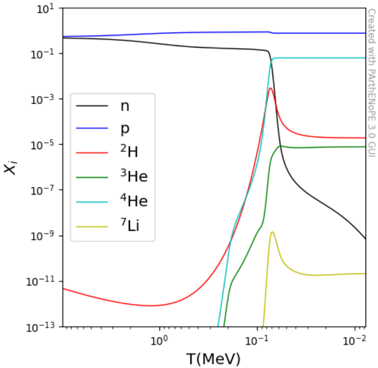
Neutrino decoupling and BBN

NSI/NU constraints in previous slides only through $N_{\rm eff}$, 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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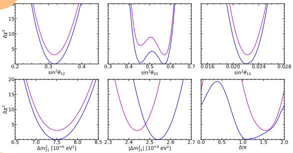
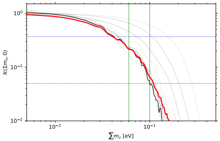
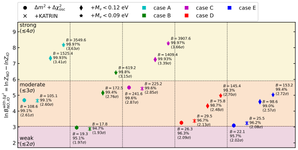
Conclusions

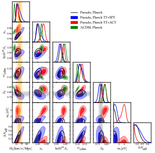
1 Standard neutrino properties: precision

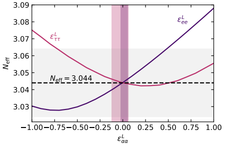


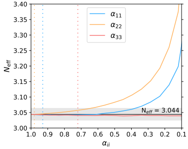


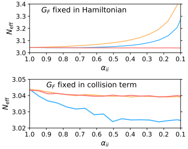


2 Non-standard neutrino properties: complementary constraints

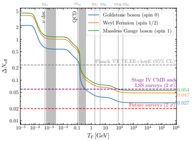


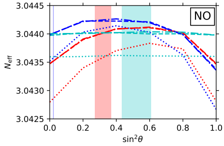


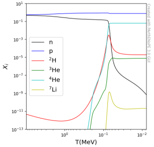


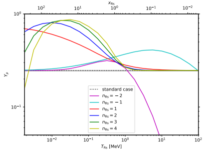


3 Early universe probes must be studied better!









Conclusions

1

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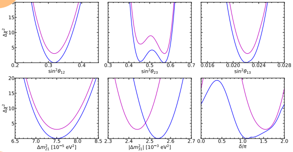

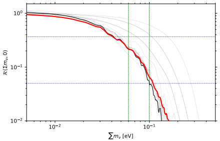

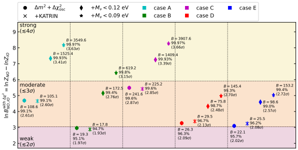

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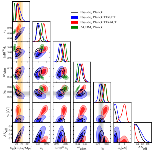

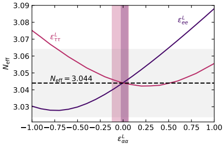

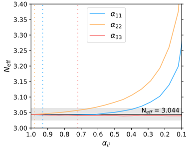

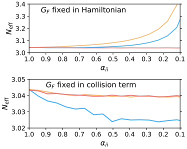

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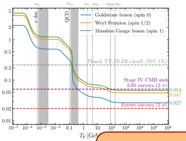

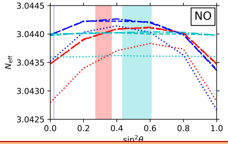

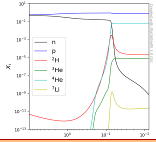

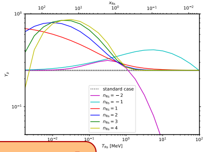

Thanks for your attention!