UNIVERSITÀ DI TORINO

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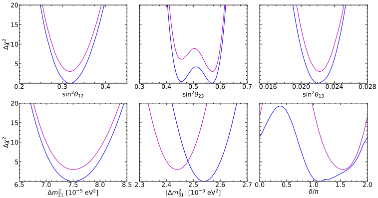
Unveiling neutrino physics with early universe probes

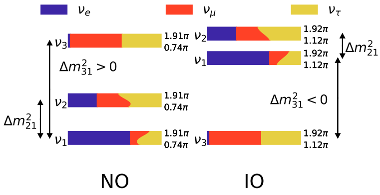
Webinar at IPM, Teheran, Iran, 10/06/2025

N Neutrinos

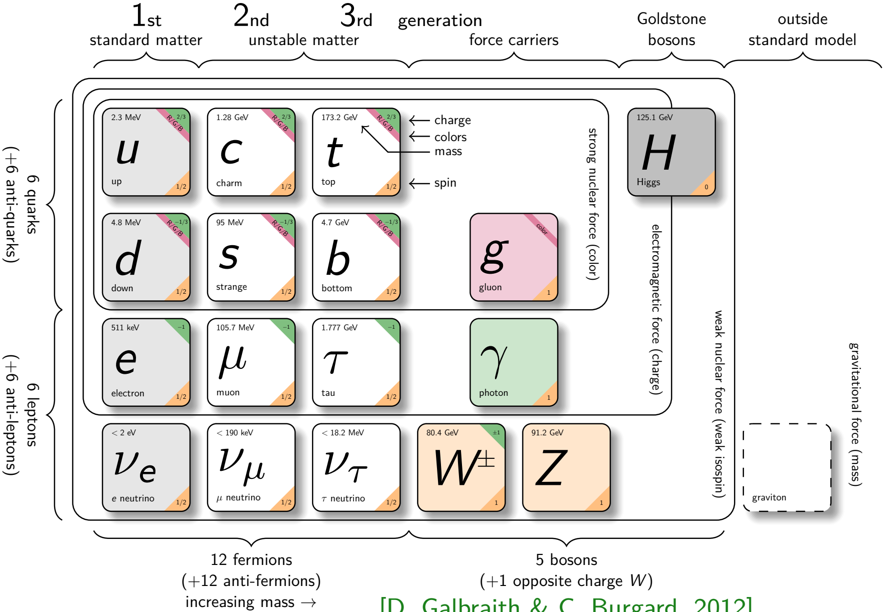
A general introduction, based on



JHEP 02 (2021) 071 and update



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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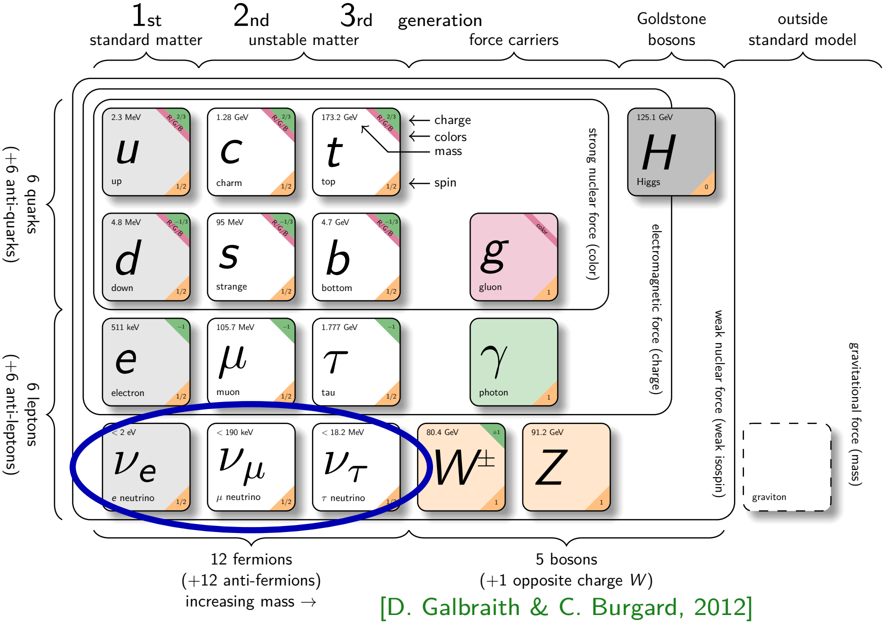
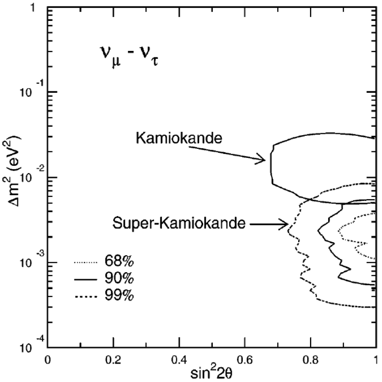


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

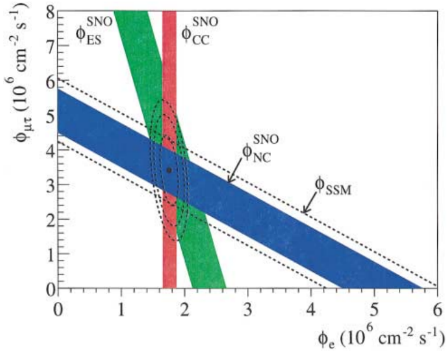
Major discoveries:

[SuperKamiokande, 1998]



first discovery of $\nu_\mu \to \nu_\tau$ oscillations from atmospheric ν

[SNO, 2001-2002]



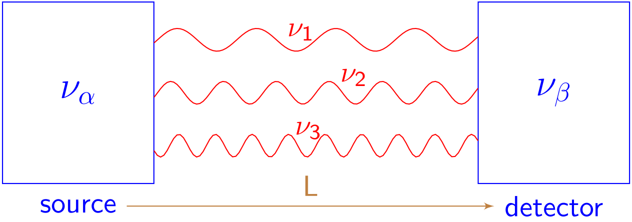
first discovery of $\nu_e \to \nu_\mu, \nu_\tau$ oscillations from solar ν

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

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

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

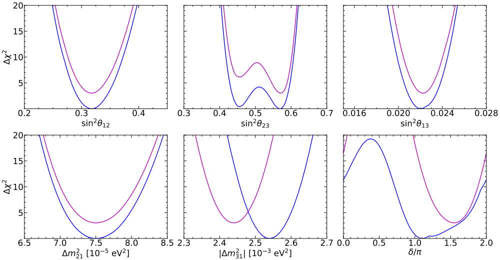
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

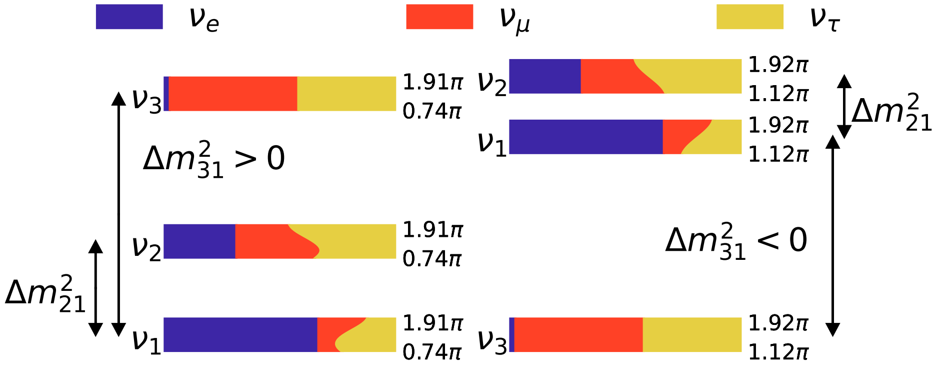
[de Salas+, Frontiers 5 (2018) 36]

Normal ordering (NO)

$$m_1 < m_2 < m_3$$
$$\sum m_k \gtrsim 0.06 \text{ eV}$$

Inverted ordering (IO)

$$m_3 < m_1 < m_2$$
$$\sum m_k \gtrsim 0.1 \text{ eV}$$

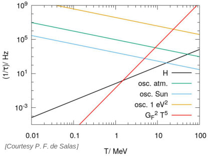


Absolute scale unknown!

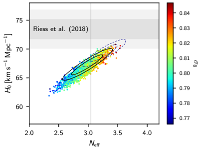
Can we constrain the mass ordering using bounds on $\sum m_\nu$?

E Neutrinos in the Early Universe

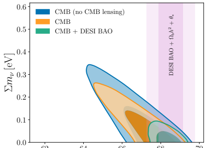
Based on



JCAP 04 (2021) 073

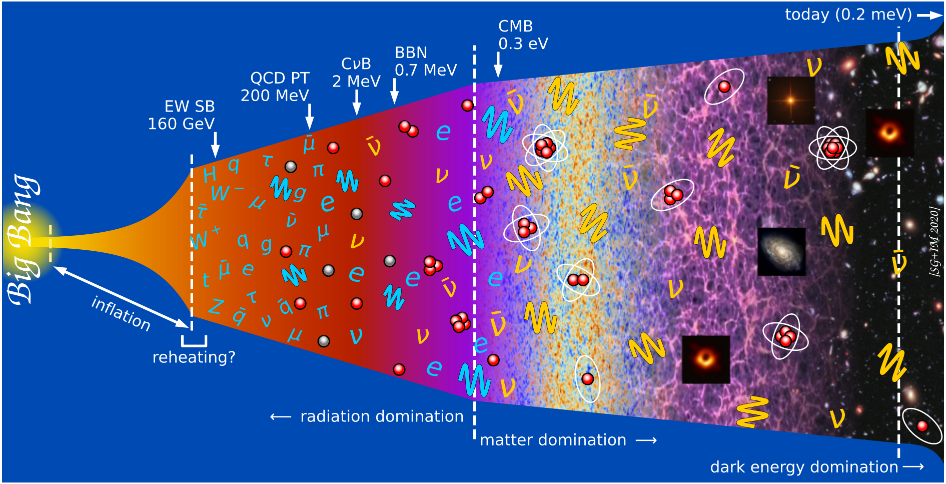


Planck 2018



JCAP 02 (2025) 021

History of the universe



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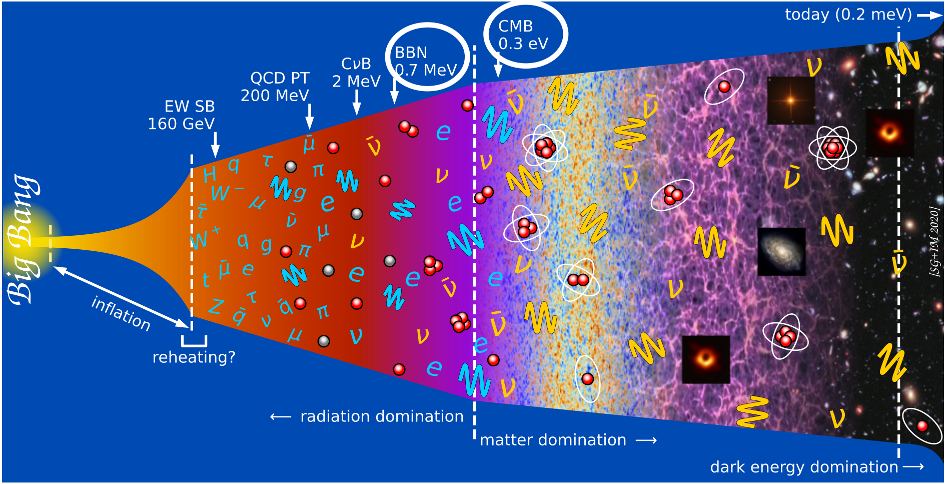
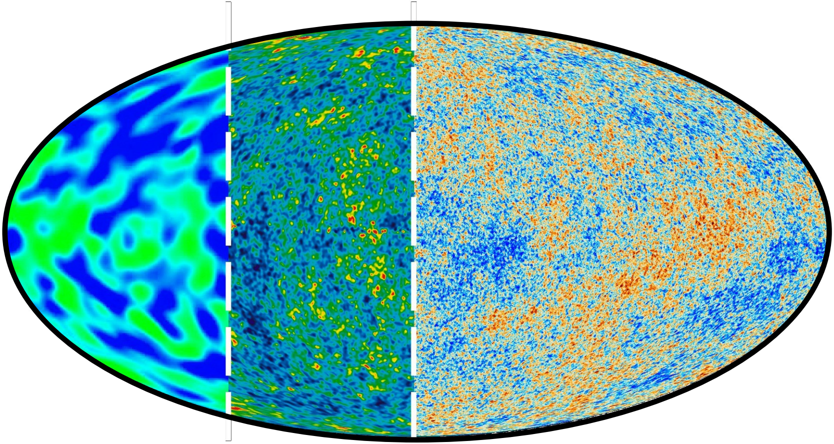


The oldest picture of the Universe

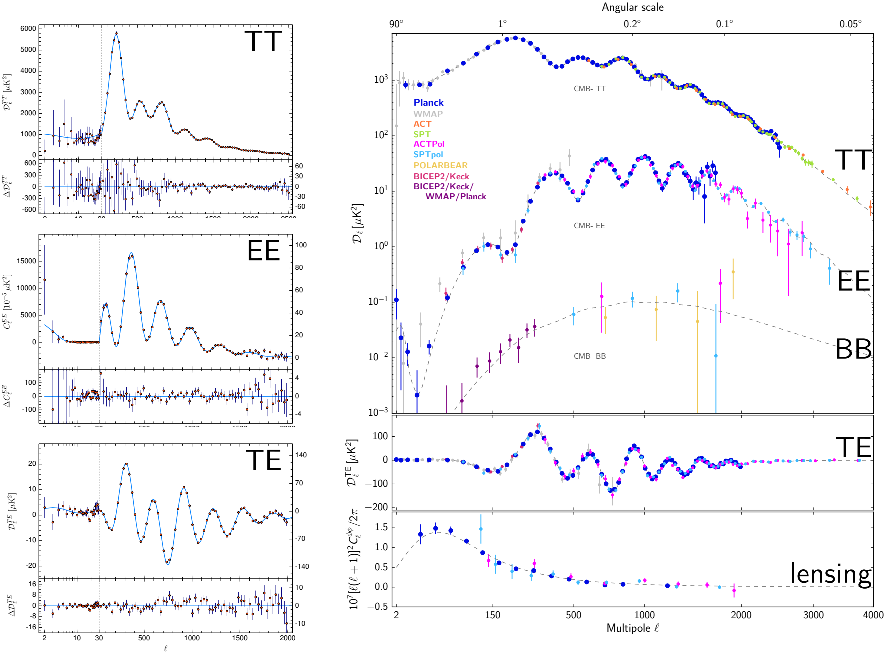
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

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



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

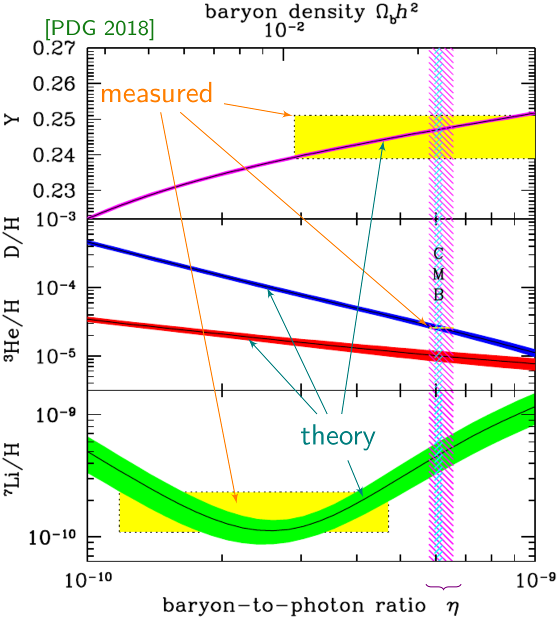
much earlier than CMB!

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

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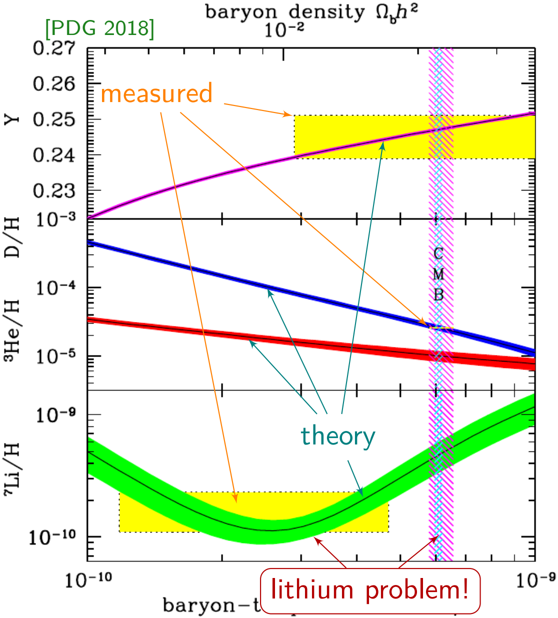
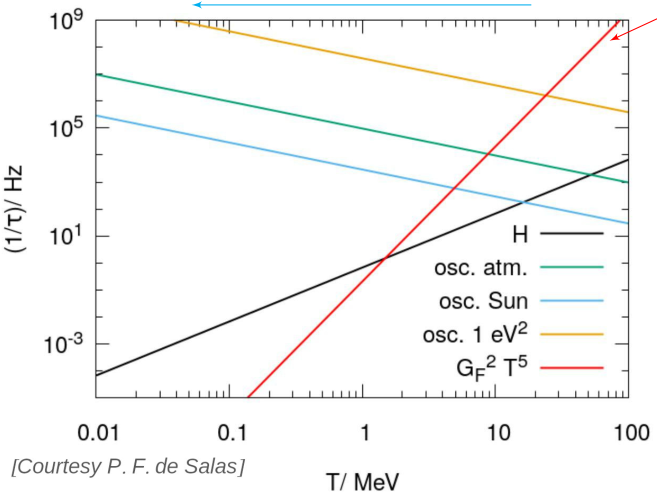


BBN concordance

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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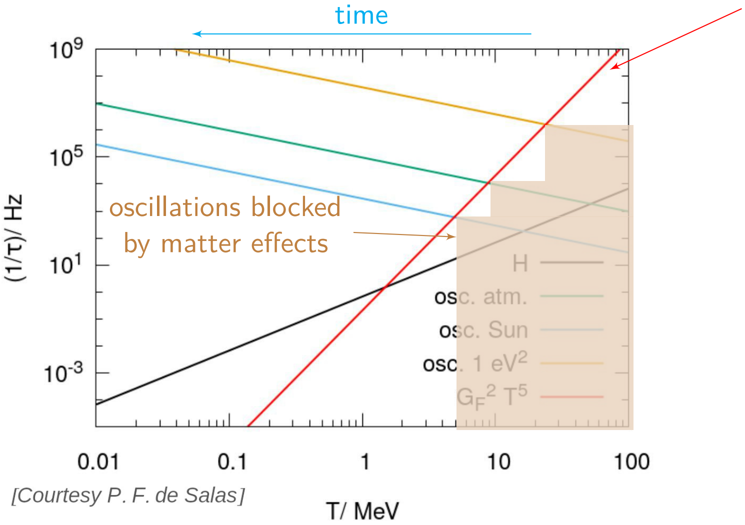

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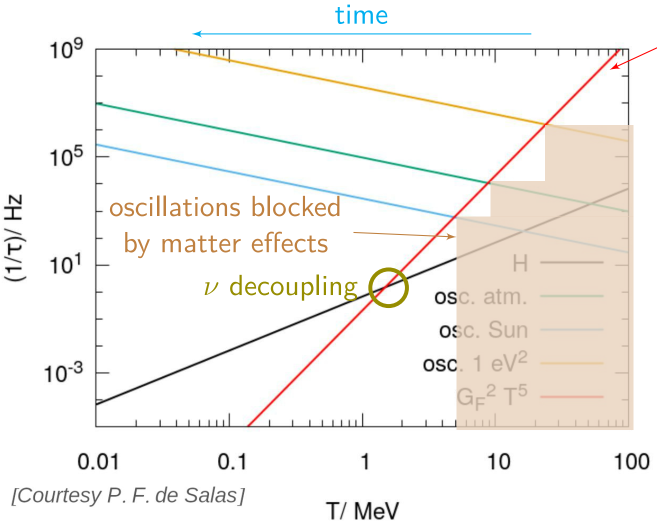

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ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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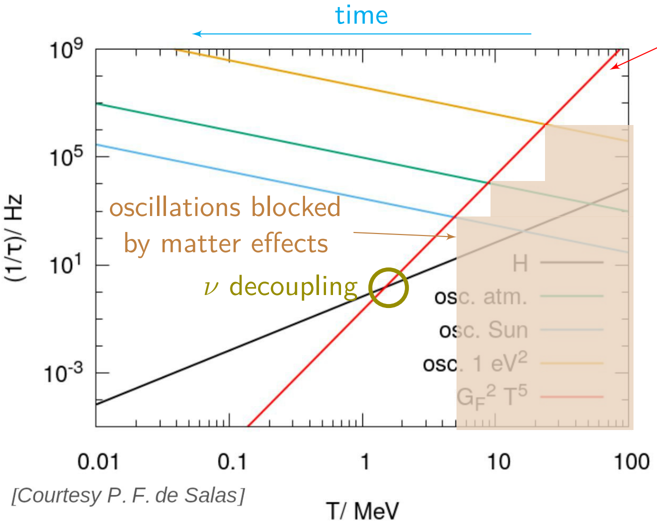

[Courtesy P. F. de Salas]

$T_\nu \simeq (4/11)^{1/3}\,T_\gamma$ 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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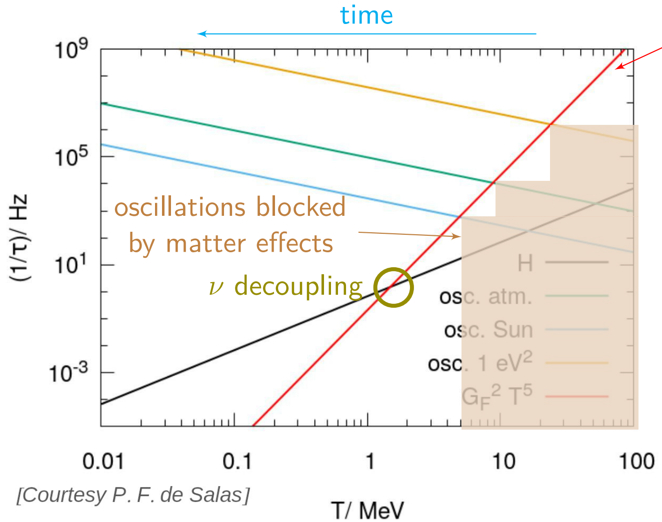

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actually, the decoupling T is momentum dependent!

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

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

H Hubble factor $\rightarrow$ expansion (depends on universe content)

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

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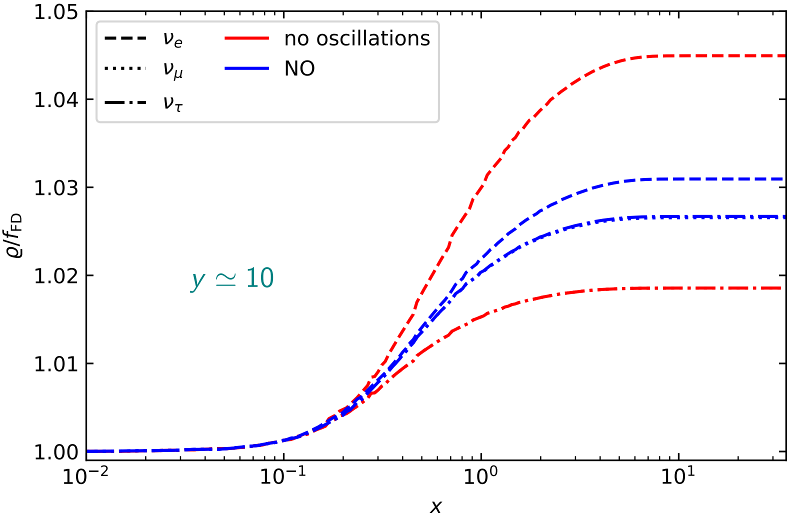
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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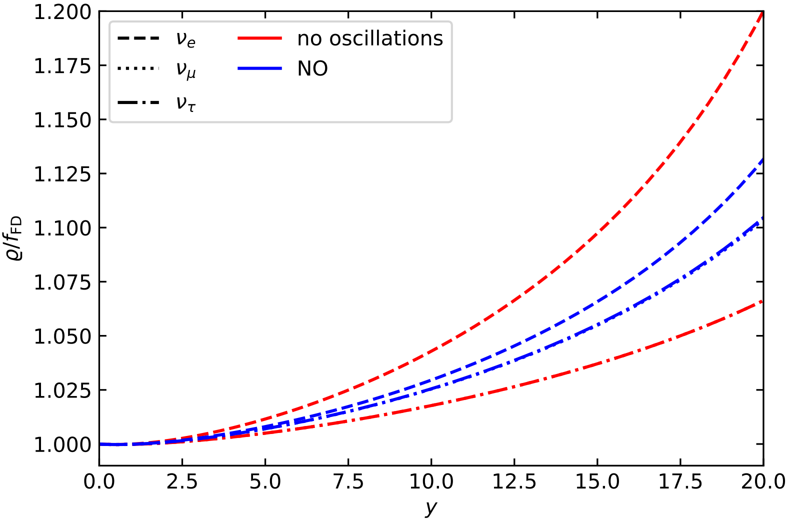
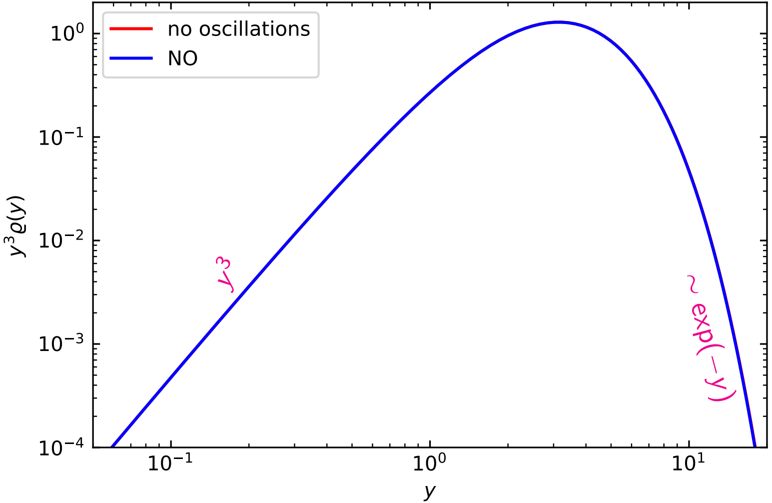


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

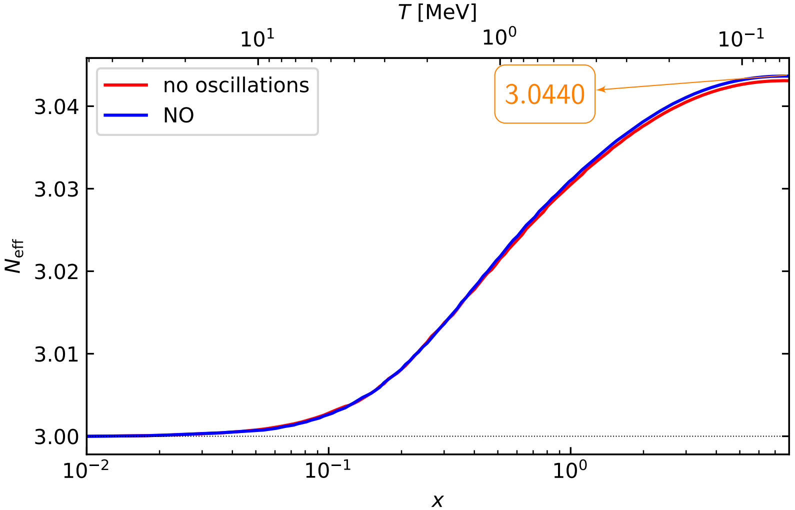
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



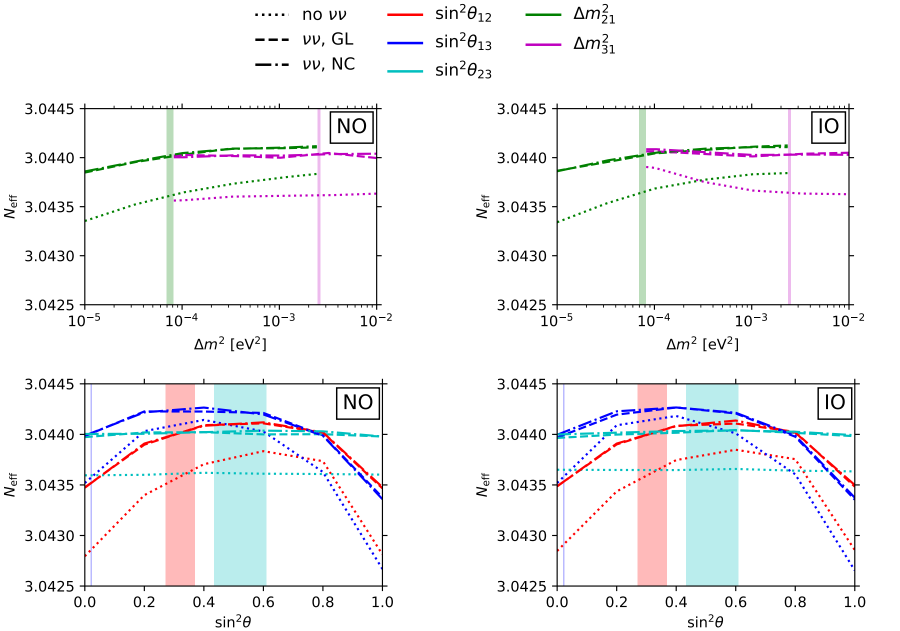
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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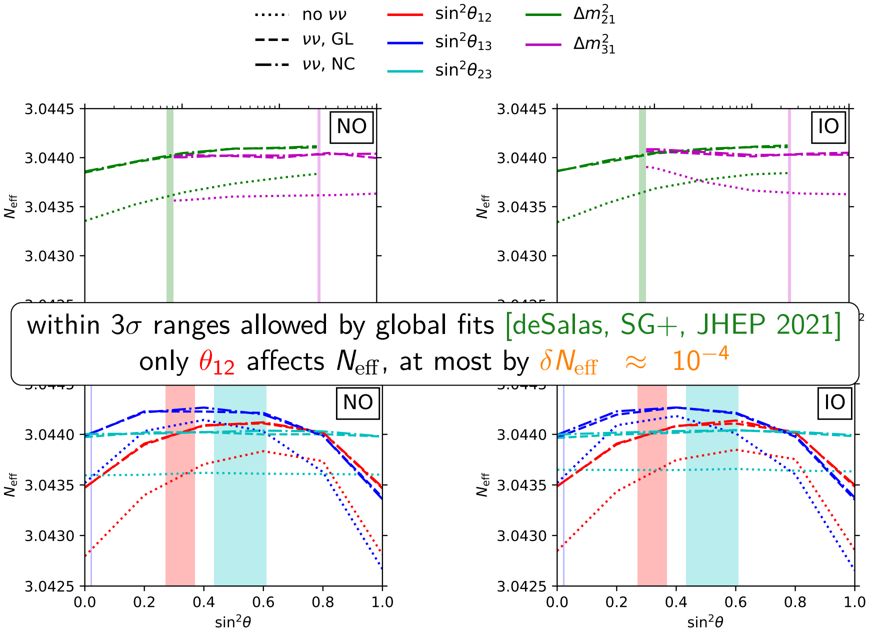
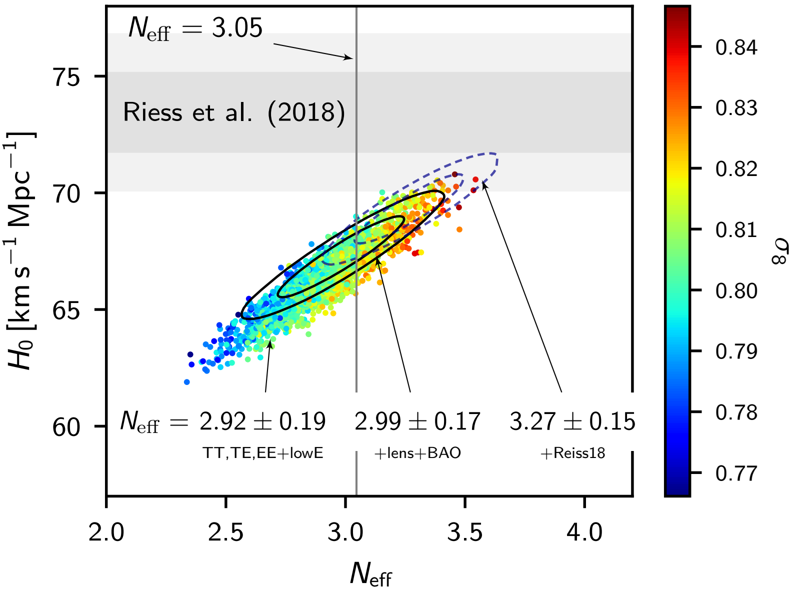


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]
only θ_{12} affects $N_{\rm eff}$, at most by $\delta N_{\rm eff} \approx 10^{-4}$

N_{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!

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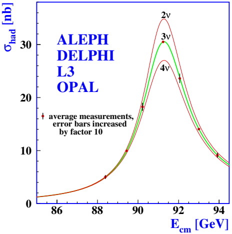
Nothing to do with [LEP (2006)]

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



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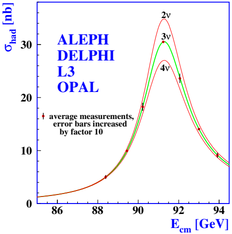


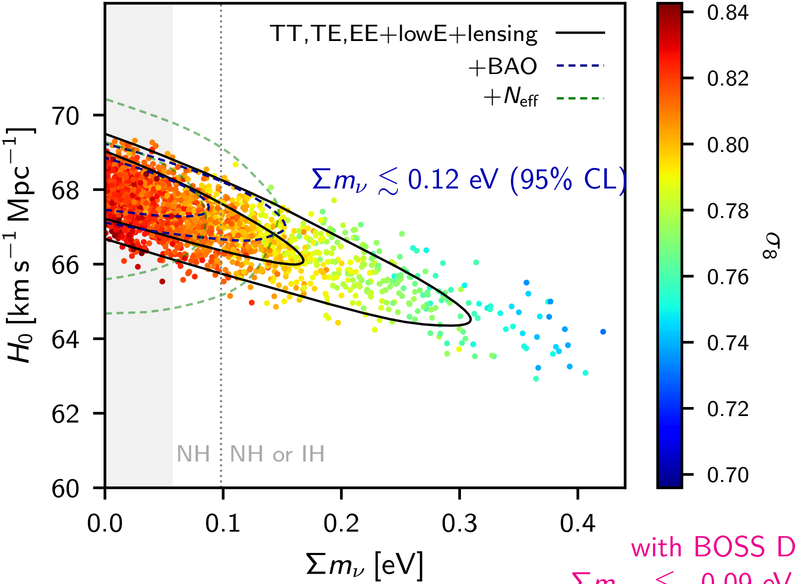
instantaneous decoupling:
$N_{\rm eff}^{\nu} = 1$ for each ν family

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

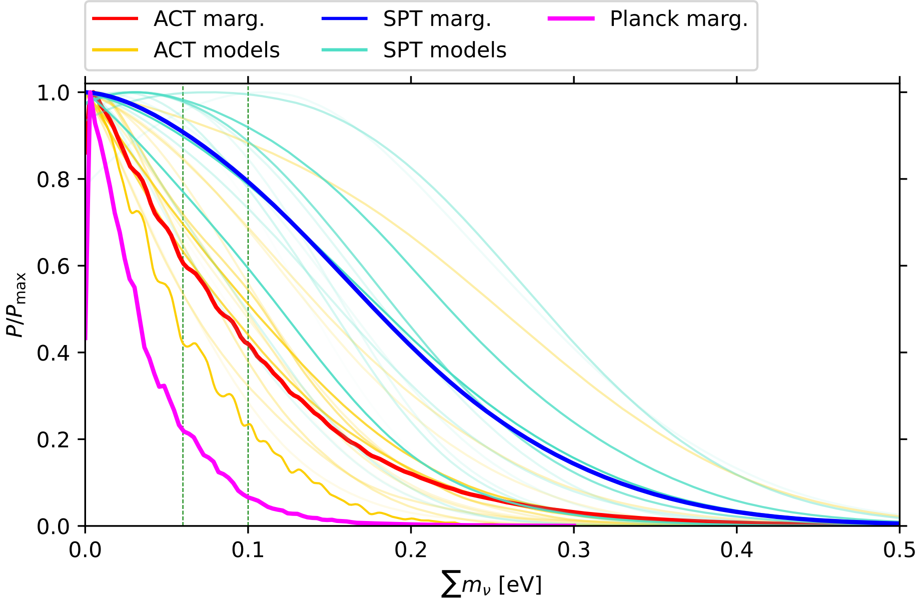
[Planck Collaboration, 2018]



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

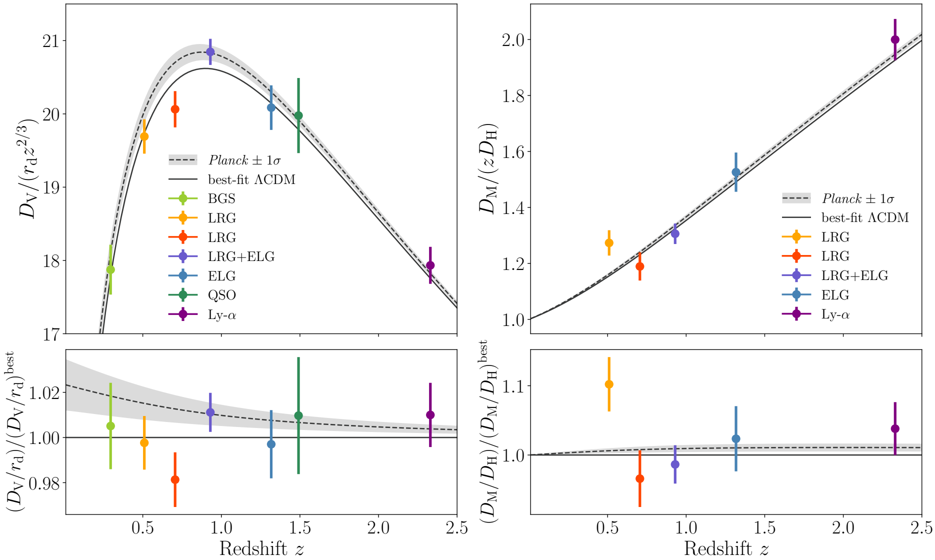
Constraints on the sum of neutrino masses

[PRD 108 (2023)]



DESI BAO data from DR1

[JCAP 2025]



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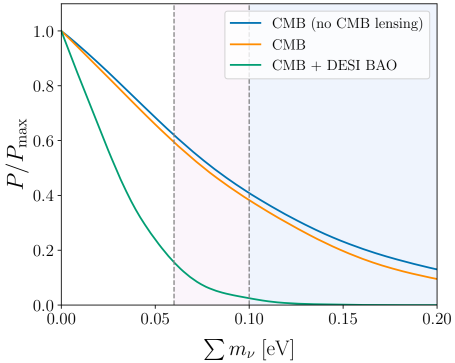
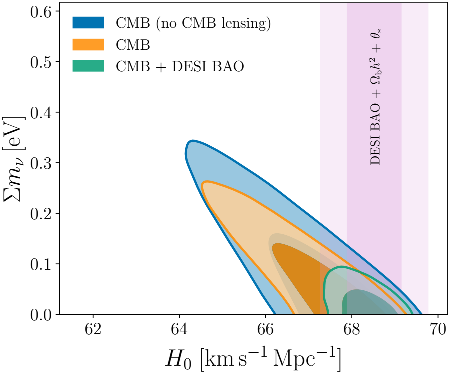




$\sum m_\nu < 0.072$ eV (95%, DESI BAO+CMB)

close to disfavoring normal ordering minimum value

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

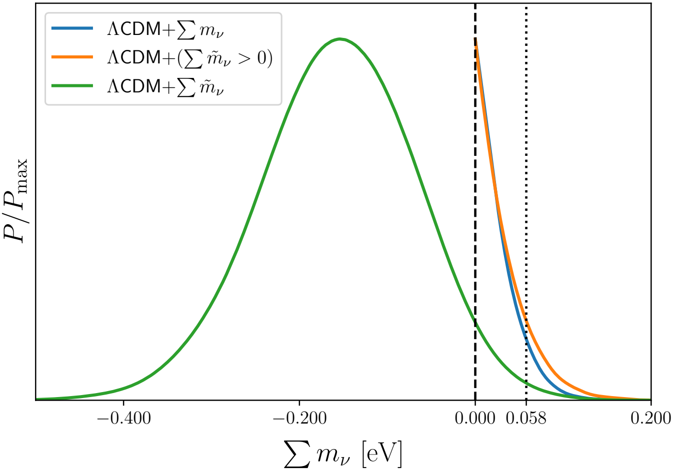
at 95%!

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

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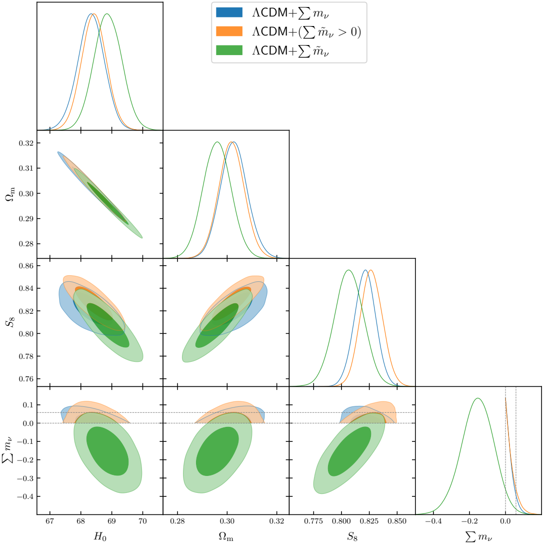
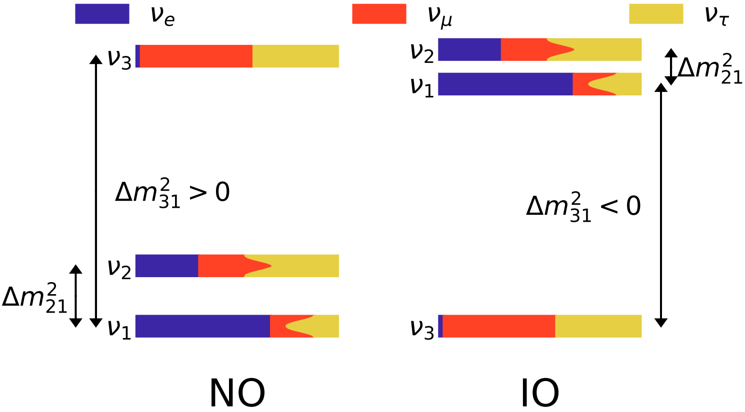


Planck 2018 CMB, ACT+Planck lensing, DESI BAO

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!

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

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

Background measurements are sensitive to ω_ν, not Σm_ν!

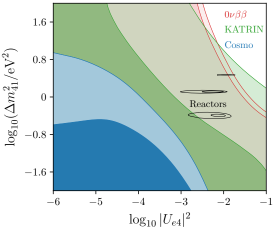
"Cosmological" Σm_ν measures the energy density of non-relativistic νs

Note: free-streaming scale directly depends on m_ν:

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

S

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



e.g. sterile neutrinos [JCAP 07 (2019) 014]

Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos $\longrightarrow$ new oscillations in the early Universe

sterile $\Longrightarrow$ no weak/em interactions in the thermal plasma

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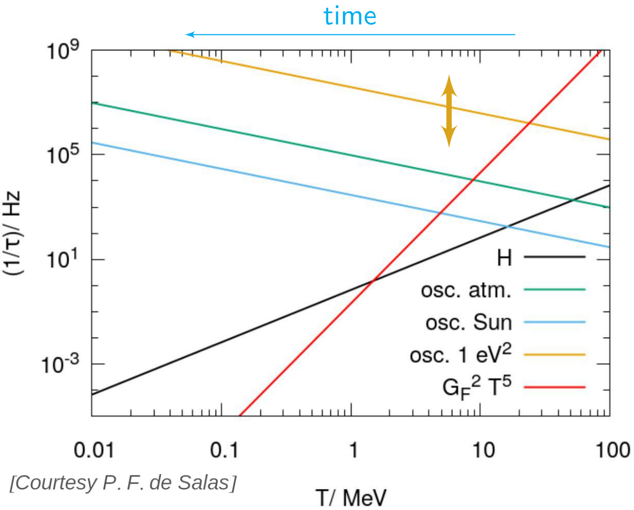

[Courtesy P. F. de Salas]

beginning of oscillations depends on Δm^2_{41}

later oscillations
$\Downarrow$
less time before ν decoupling!

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when are they enough to allow full equilibrium of active-sterile states?

$$0 \longleftarrow \Delta N_{\rm eff} = N_{\rm eff}^{4\nu} - N_{\rm eff}^{3\nu} \longrightarrow \simeq 1$$

no sterile production — active&sterile in equilibrium

$$\frac{\Delta m^2_{as}}{\mathrm{eV}^2} \sin^4(2\vartheta_{as}) \simeq 10^{-5} \ln^2(1 - \Delta N_{\rm eff}) \qquad \text{(1+1 approx.)}$$

[Dolgov&Villante, 2004]

e.g.: $\Delta m^2_{as} = 1\ \mathrm{eV}^2$, $\sin^2(2\vartheta_{as}) \simeq 10^{-3} \Longrightarrow \Delta N_{\rm eff} \simeq 1$

$N_{\rm eff}^{3\nu} = 3.044$ [JCAP 2021]

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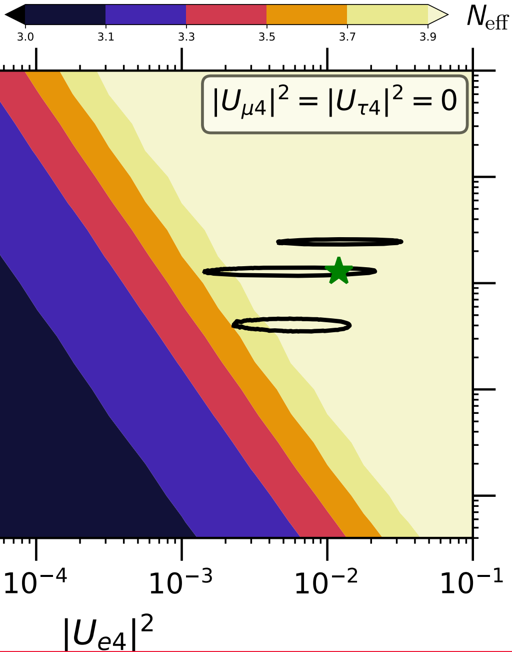
Full calculation: use numerical code!

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

$N_{\rm eff}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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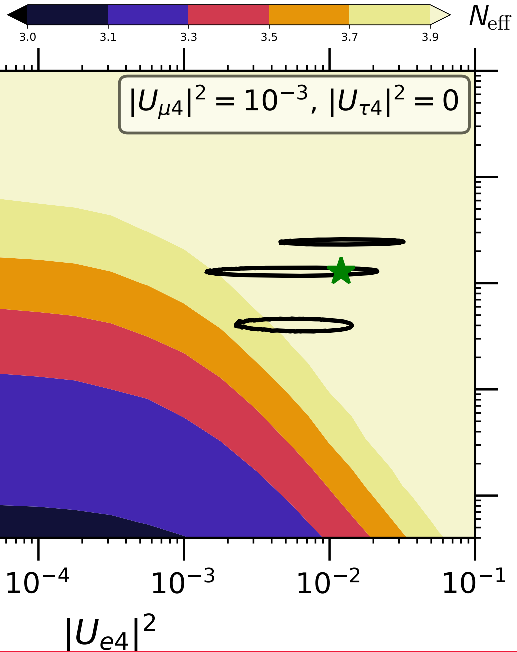

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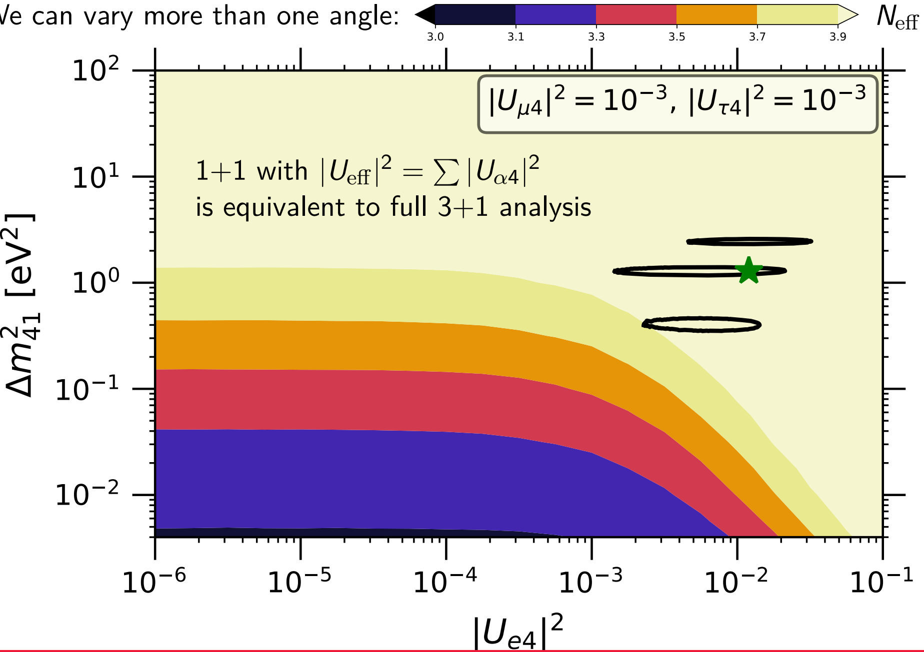
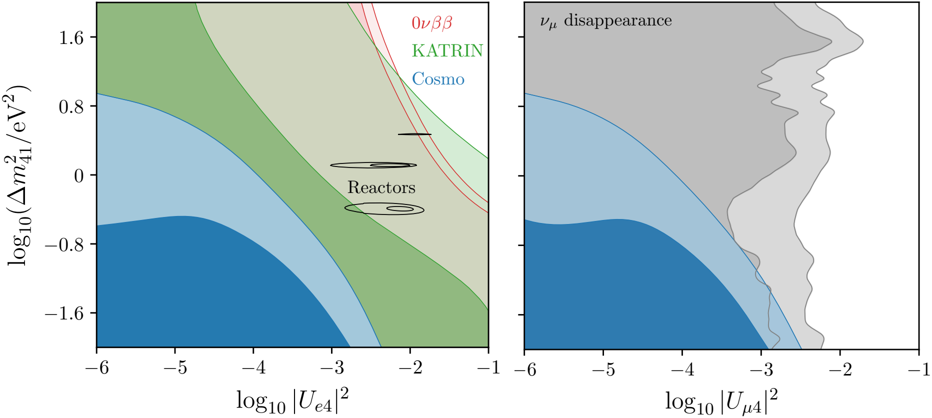


Comparing constraints

[PRD 104 (2021) 123524]

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!



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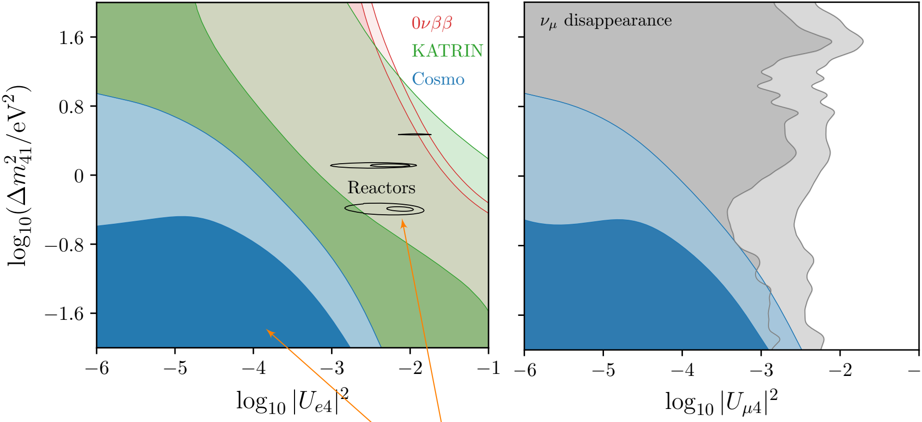

Warning: tension between (old) reactor experiments and CMB bounds!

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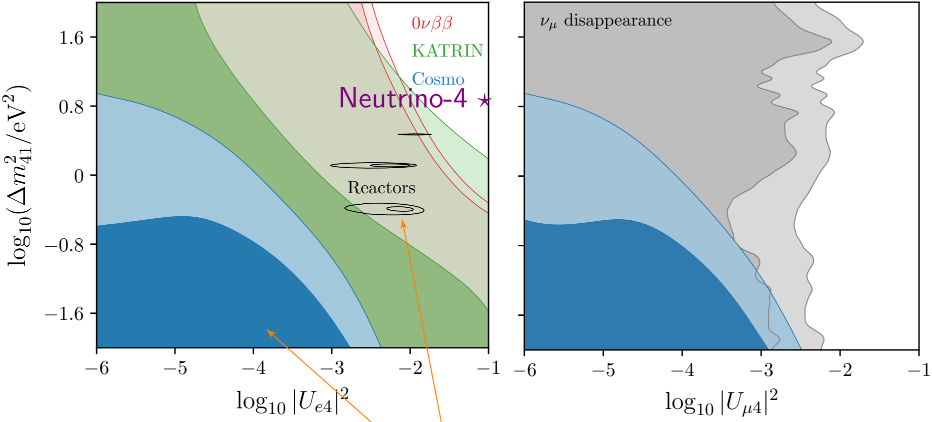

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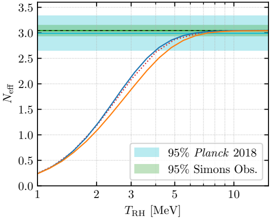
R

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



e.g. low-temperature reheating scenarios

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

Scenarios with low reheating temperature

[in preparation]

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 $T_{\mathrm{rh}} \lesssim 20$ MeV

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

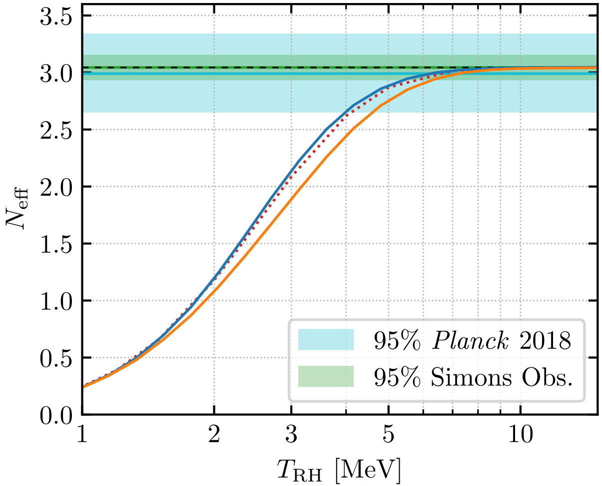
3 neutrino oscillations start to be affected when $T_{\mathrm{rh}} \lesssim 8$ MeV

what about sterile neutrinos?

$N_{\rm eff}$ with low reheating

[arxiv:2501.01369]

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

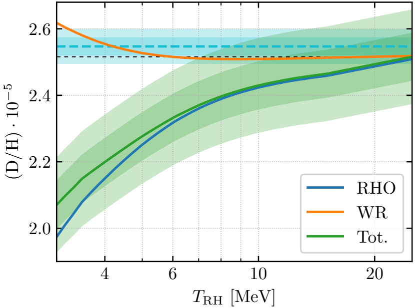


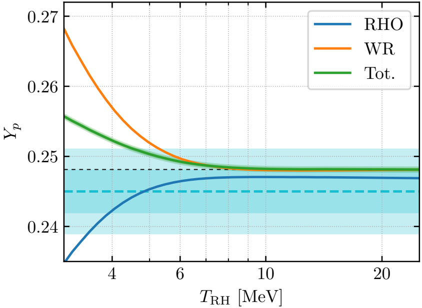
Planck constraint: $N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

BBN and low reheating

[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)

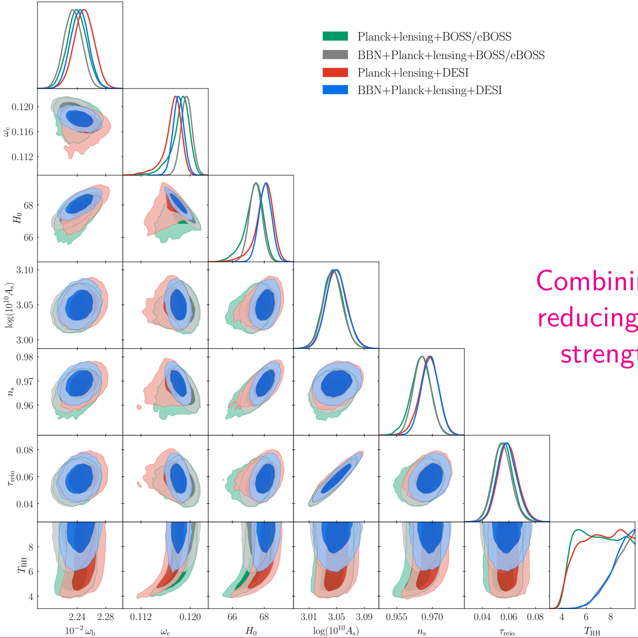
  ↓

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

$\boxed{\text{Both effects are important to get Helium right!}}$

Constraints on low reheating scenarios

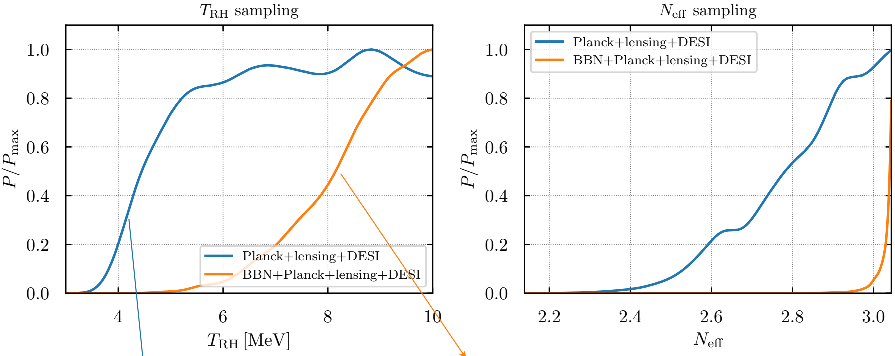
[arxiv:2501.01369]



Combining probes helps in reducing degeneracies and strengthening bounds!

Constraints on low reheating scenarios

[arxiv:2501.01369]



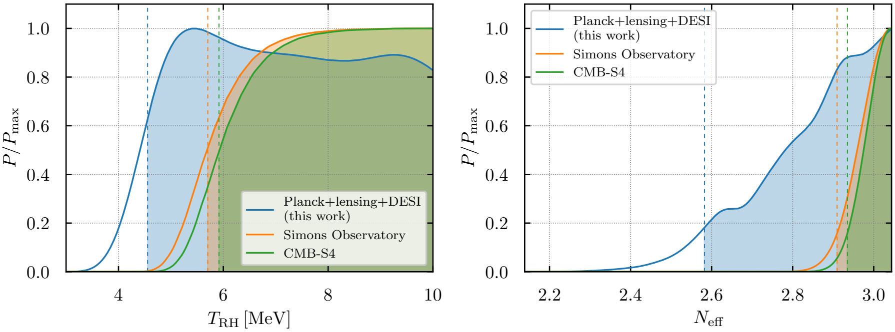
$T_{\rm rh} > 5.96$ MeV (95%)

$T_{\rm rh} > 3.79$ 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]

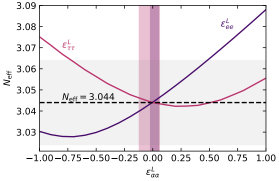


Greater sensitivity will come with future CMB probes (more precise in determining $N_{\rm eff}$)

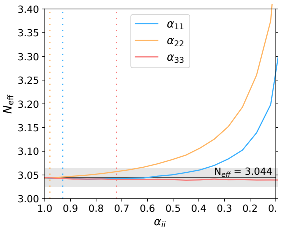
Future CMB alone will reach the precision of current BBN+CMB (Planck)+BAO (DESI) observations

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

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

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

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

$$\downarrow$$

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

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)]

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

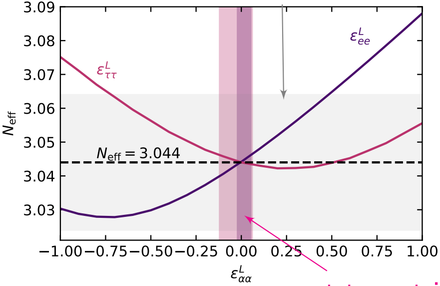
e.g.:

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

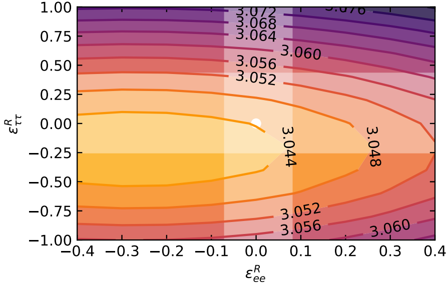
$G^L_{\tau\tau} \to -0.273 + \epsilon^L_{\tau\tau}$

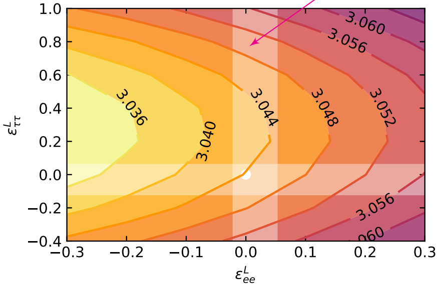
$G^R_{\alpha\alpha} \to 0.233 + \epsilon^R_{\alpha\alpha}$

future CMB



current terrestrial

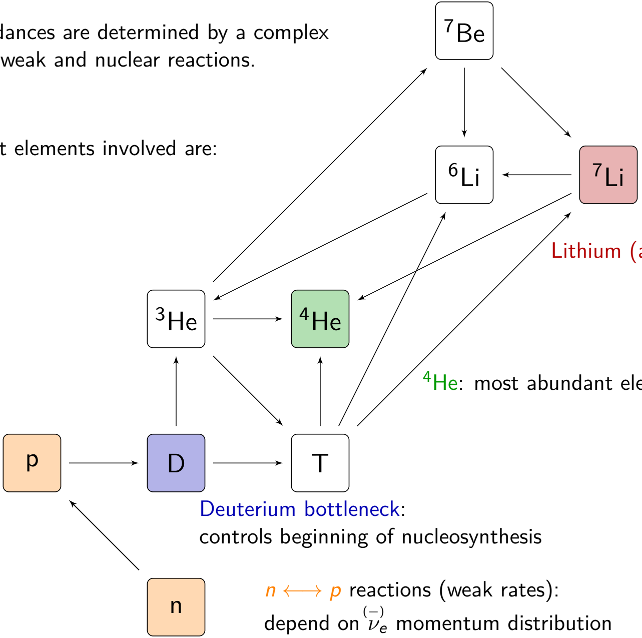




Reactions governing BBN

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

[arxiv:2503.21998]

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

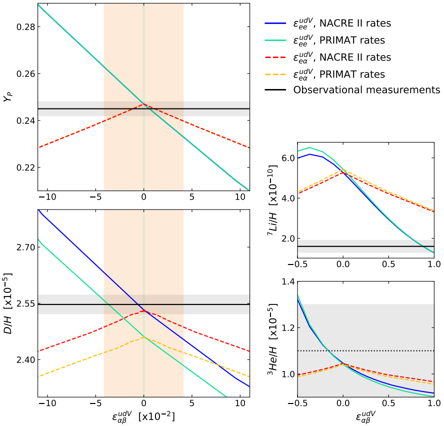
have secondary effect on BBN rates because there are no $\overset{(-)}{\nu}e$ interactions!

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

Consider we have N_ν neutrino states

Unitary $N_\nu \times N_\nu$ 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)]

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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	Non-unitary case
interactions:	interactions:
$(Y_L)_{ab} \equiv \tilde{g}_L\mathbb{I} + (U^\dagger)_{ea}U_{eb}$	$(Y_L)_{ab} \equiv \tilde{g}_L(V^\dagger V)_{ab} + (V^\dagger)_{ea}V_{eb}$
$(Y_R)_{ab} \equiv g_R\mathbb{I}$	$(Y_R)_{ab} \equiv g_R(V^\dagger V)_{ab}$
matter effects:	matter effects:
$\mathcal{E}_{\mathrm{M}} = \frac{\rho_e+P_e}{m_W^2} U^\dagger \mathrm{diag}(1,0,0) U$	$\mathcal{E}_{\mathrm{NU}} \equiv \frac{\rho_e+P_e}{m_W^2}(Y_L - Y_R)$
Fermi constant:	Fermi constant:
$G_F^\mu = G_F$	$G_F^\mu = G_F\sqrt{\alpha_{11}^2\left(\alpha_{22}^2 + \lvert\alpha_{21}\rvert^2\right)}$

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

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

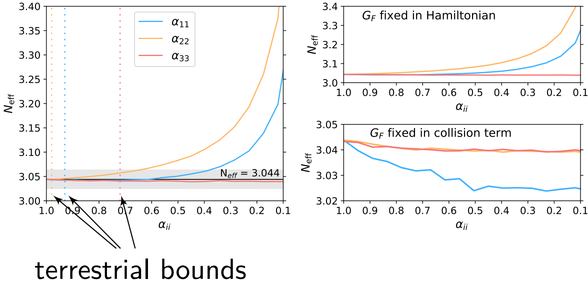
Non-unitarity parameters and $N_{\rm eff}$

[JCAP 03 (2023)]

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

$$G_F^\mu = G_F \sqrt{\alpha_{11}{}^2 \left(\alpha_{22}{}^2 + |\alpha_{21}|^2\right)}$$
$$= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

[CODATA]



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

[JCAP 03 (2023)]

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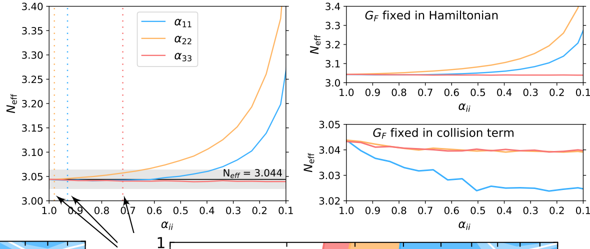
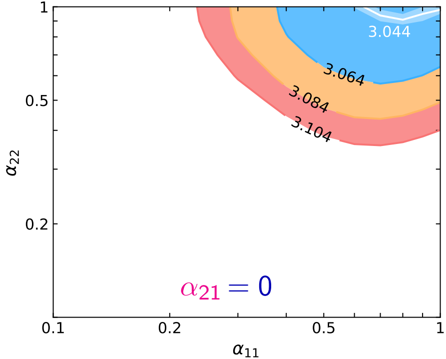
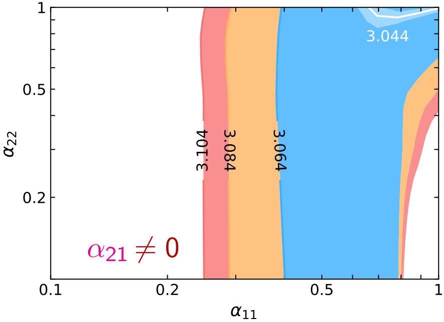






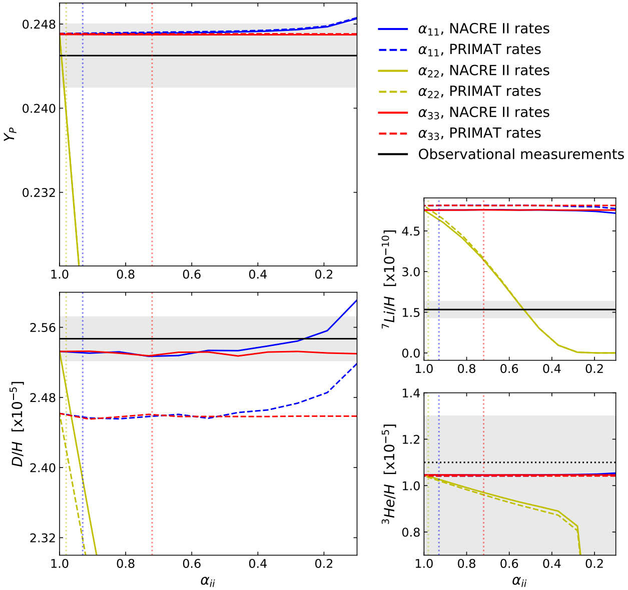
(α_{21} marginalized over)

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

Non-unitarity parameters and BBN

[arxiv:2503.21998]

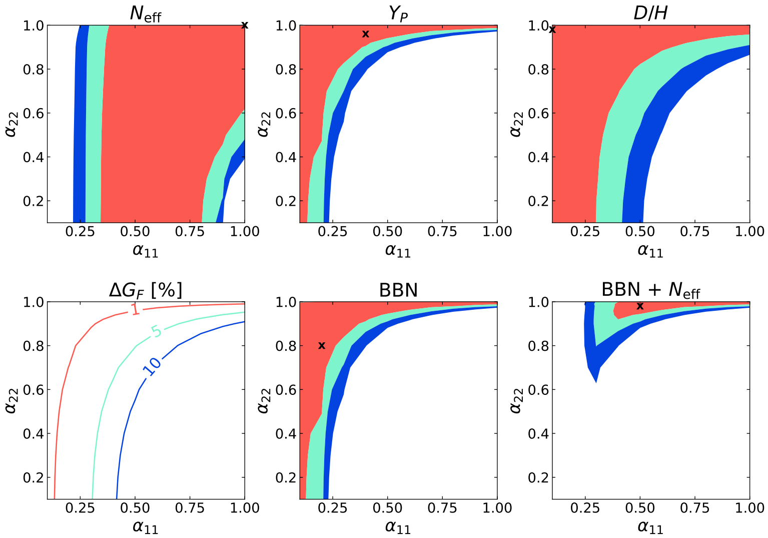
Non-unitarity parameters affect BBN abundances:



Non-unitarity parameters and BBN

[arxiv:2503.21998]

Usual reasoning: better constraints by combining different probes!

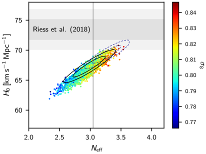


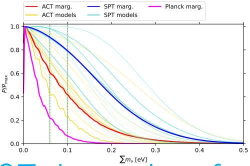
Z Conclusions

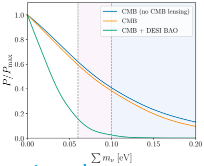
What do we learn about non-standard ν scenarios?

C

Cosmology measures (mostly) neutrino energy densities!







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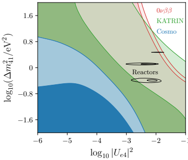
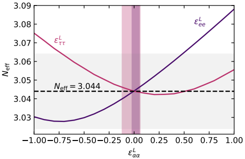
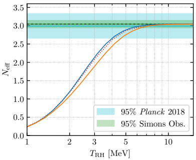
$N_{\rm eff}$ is NOT the number of neutrinos!







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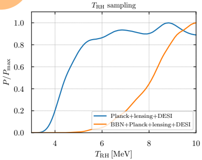
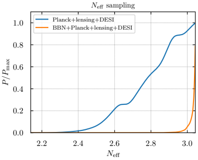
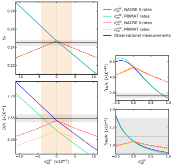
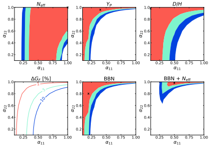
Combining different probes helps to break degeneracies!









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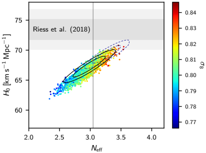

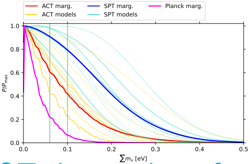

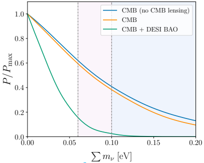

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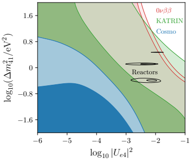

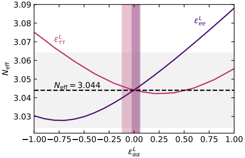

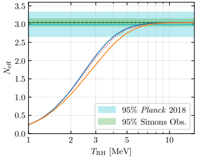

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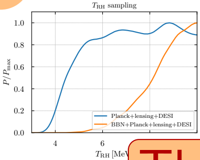

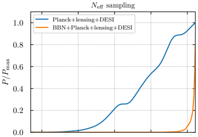

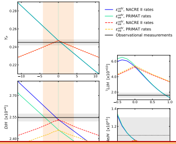

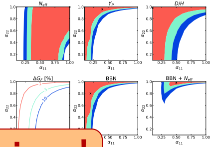

Thanks for your attention!