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SEZIONE DI TORINO

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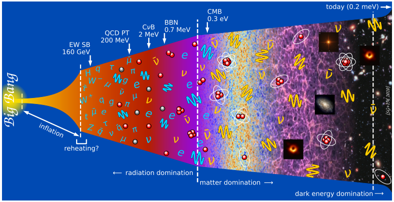
Neutrino decoupling in standard and non-standard scenarios

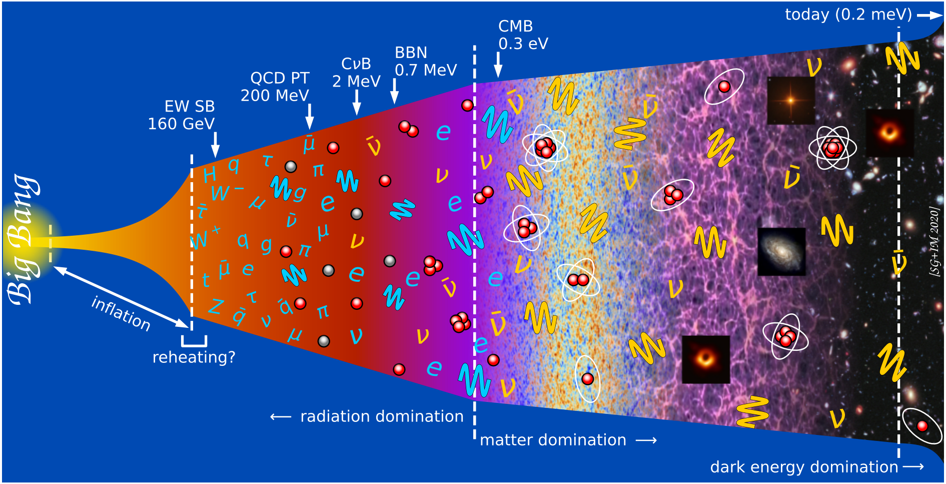
Based on JCAP 04 (2021) 073, JCAP 07 (2019) 014, arxiv:2211.10522, in preparation

8th Conference on HEP in the LHC Era, Valparaiso, 12/01/2023



today (0.2 meV)
CMB
0.3 eV
BBN
0.7 MeV
CνB
2 MeV
QCD PT
200 MeV
EW SB
160 GeV
Big Bang
inflation
reheating?
⟵ radiation domination
matter domination ⟶
dark energy domination ⟶

History of the universe



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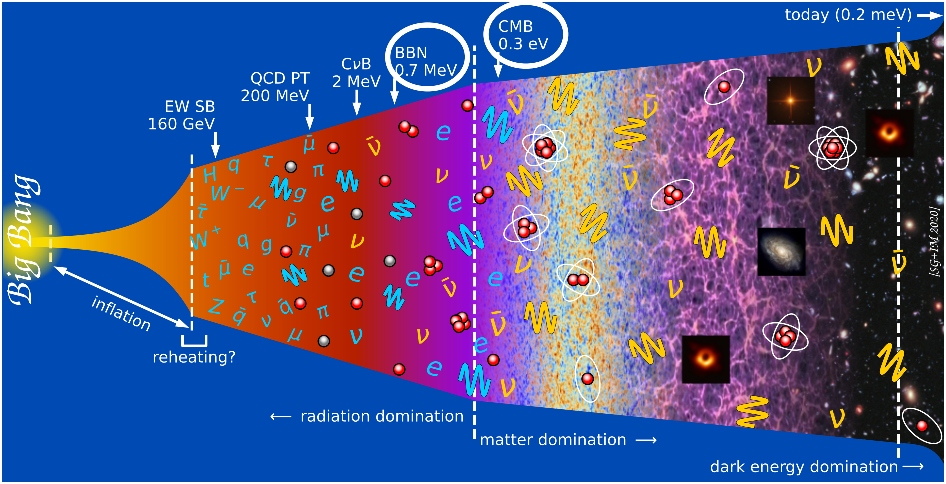

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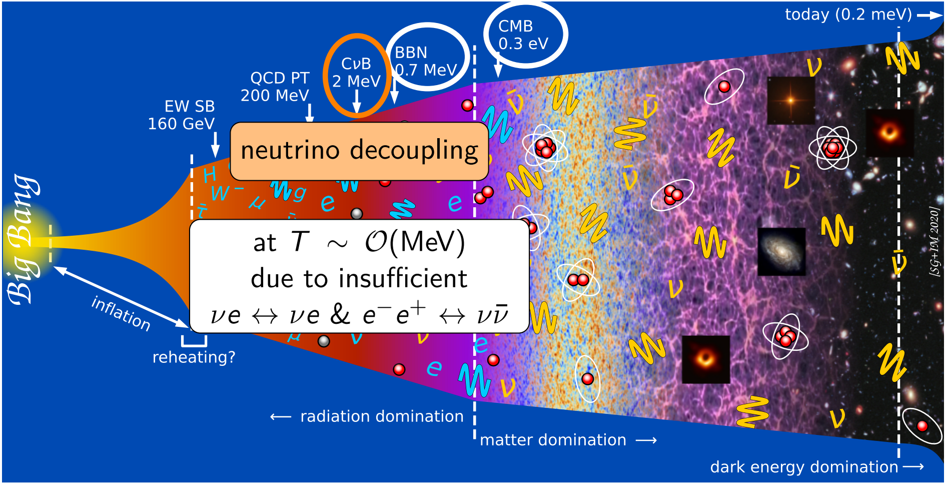


Relic neutrinos in cosmology: $N_{\rm eff}$

radiation density: $$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

ρ_γ photon energy density, 7/8 for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

prediction:

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

$>$ 3 because of entropy transfer to photons when electrons become non-relativistic

recommended value (3ν):

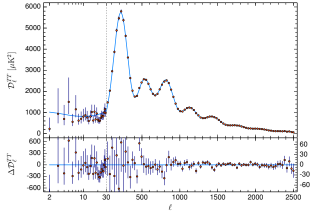
$N_{\rm eff} = 3.044$

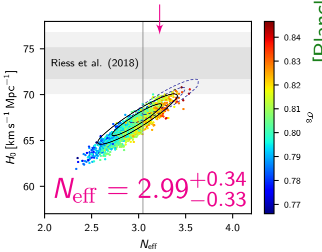
[Bennett+, 2020]

[Akita+, 2020]

[Froustey+, 2020]

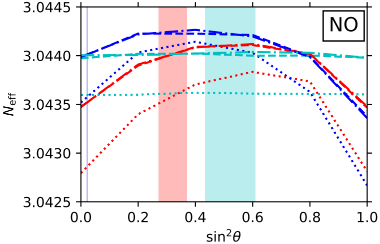
measurement:





[Planck 2018]

(95%, TT,TE,EE+lowE+lensing+BAO)

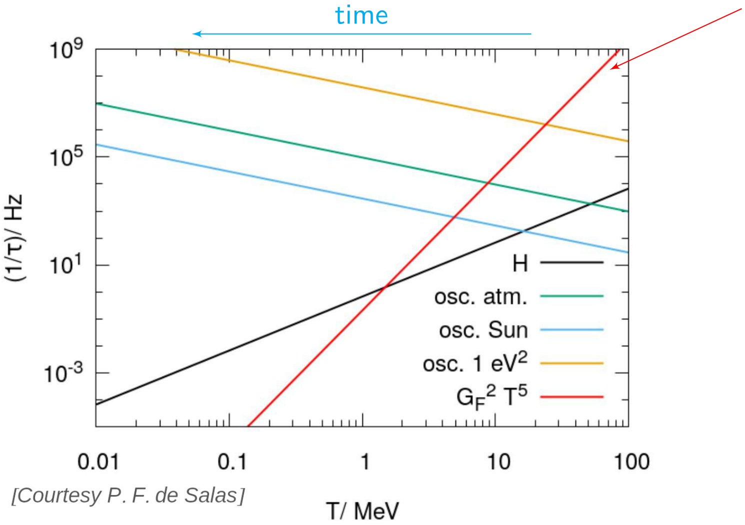


NO
3.0445
3.0440
3.0435
3.0430
3.0425
$N_{\rm eff}$
0.0
0.2
0.4
0.6
0.8
1.0
$\sin^2\theta$

$N_{\rm eff} = 3.044$

Neutrinos in the early Universe

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



[Courtesy P. F. de Salas]

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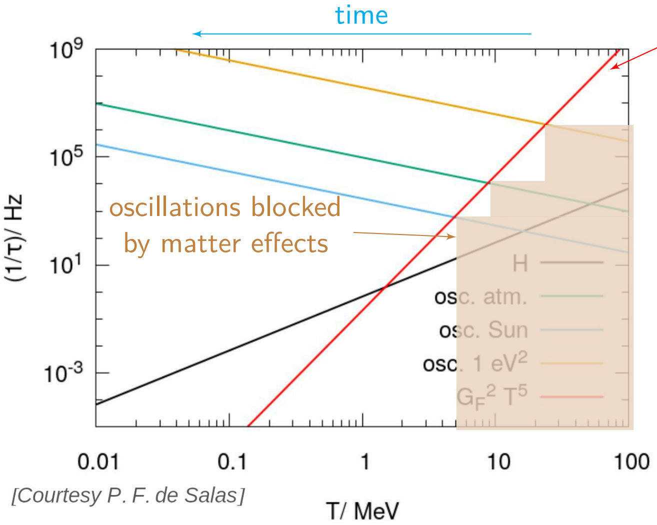

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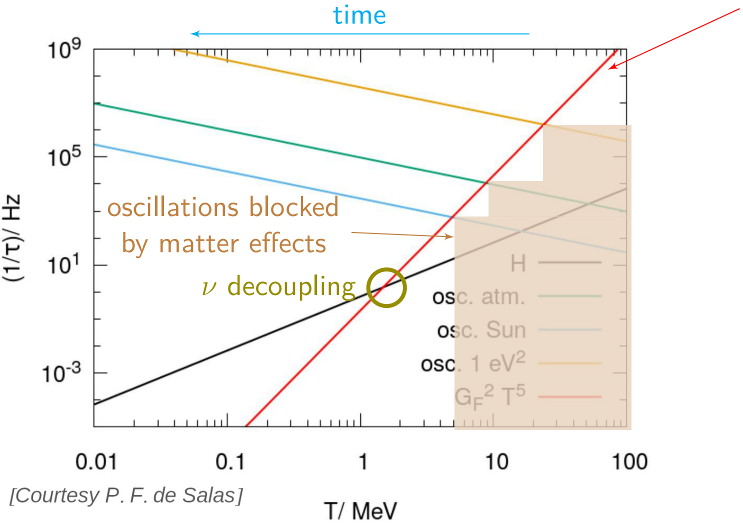

[Courtesy P. F. de Salas]

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

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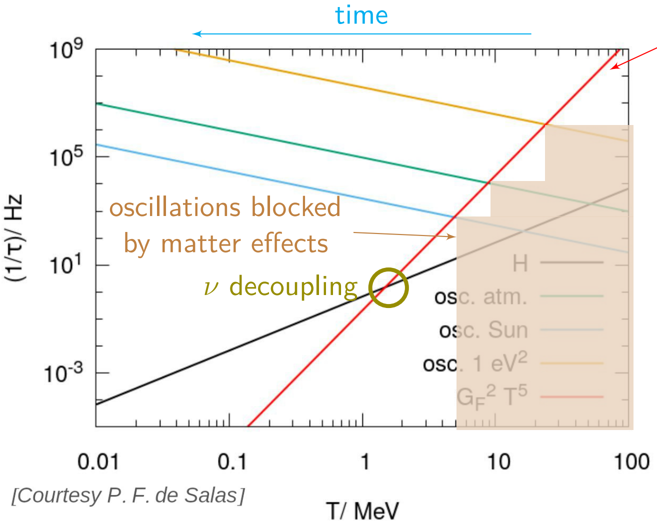

[Courtesy P. F. de Salas]

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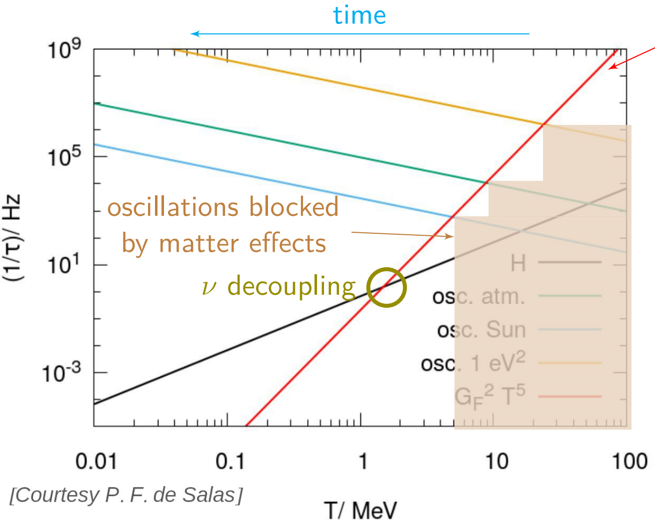

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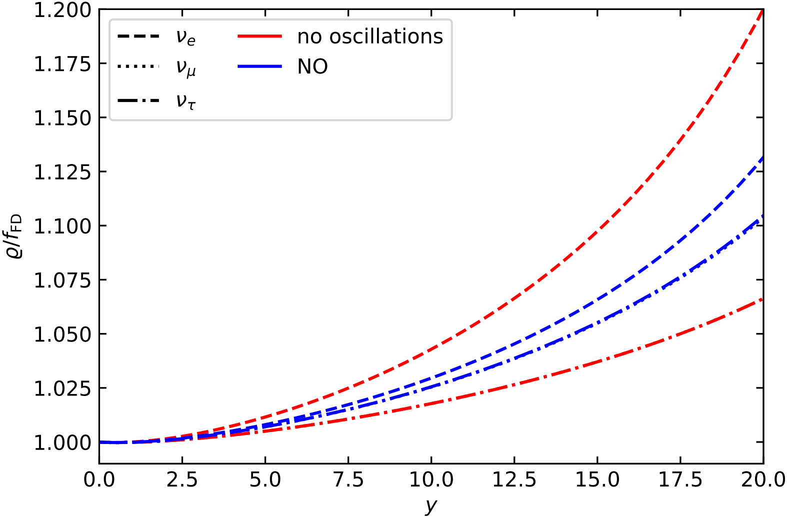
ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

actually, the decoupling T is momentum dependent!

distortions to equilibrium f_ν!

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

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

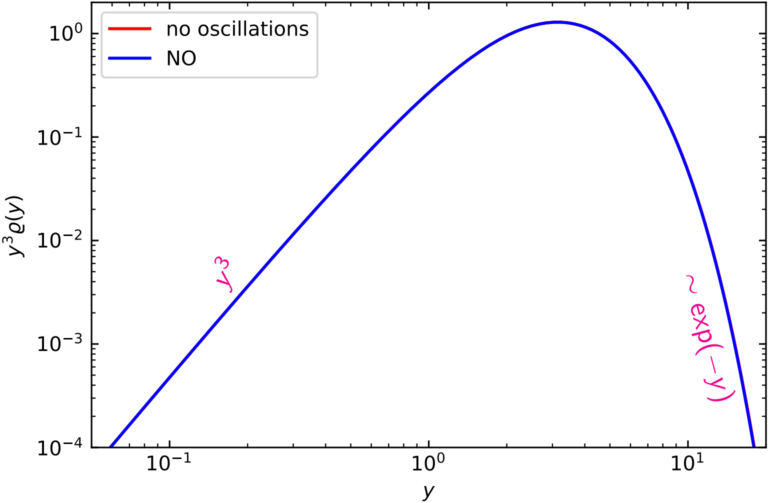


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

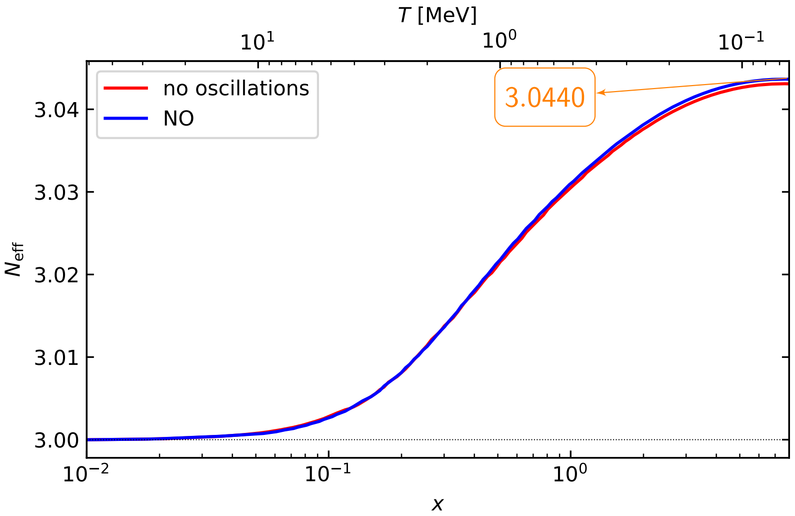
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



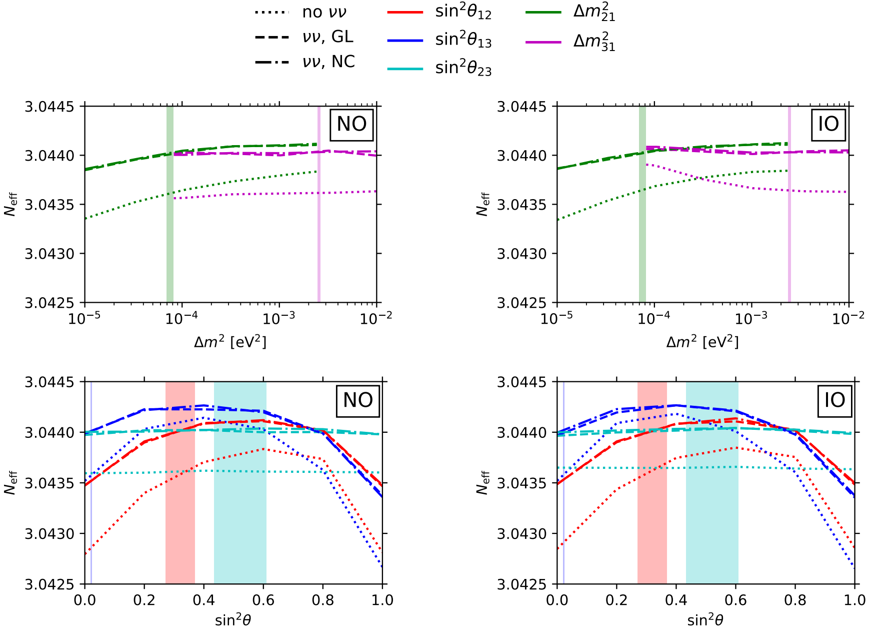
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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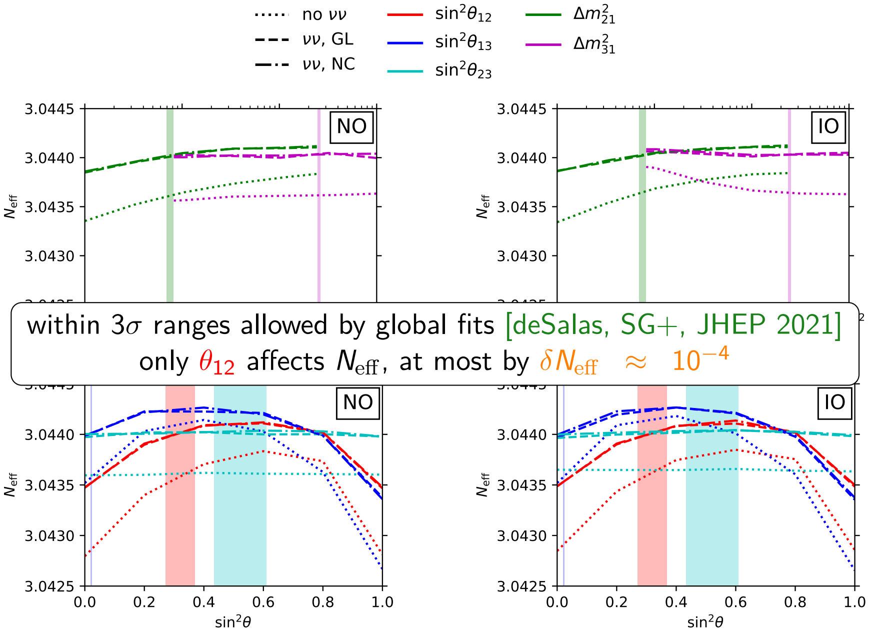
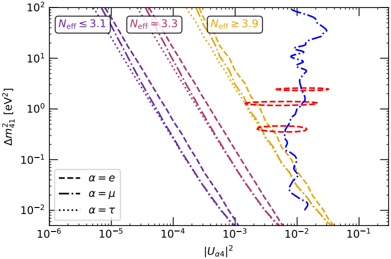


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

only θ_{12} affects $N_{\rm eff}$, at most by $\delta N_{\rm eff} \approx 10^{-4}$


$N_{\mathrm{eff}} \leq 3.1$
$N_{\mathrm{eff}} \simeq 3.3$
$N_{\mathrm{eff}} \geq 3.9$
$\alpha = e$
$\alpha = \mu$
$\alpha = \tau$
Δm^2_{41} [eV^2]
$|U_{\alpha 4}|^2$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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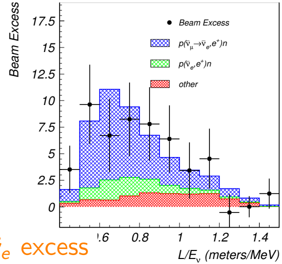
Do three-neutrino oscillations explain all experimental results?

LSND



[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Short Baseline (SBL) anomalies

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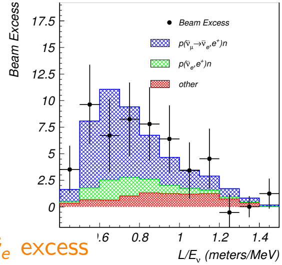
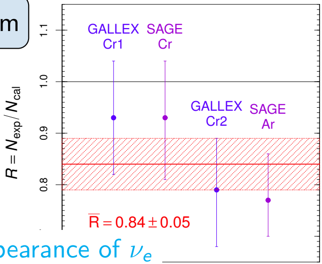


[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Gallium



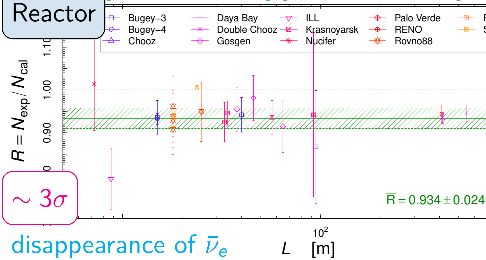
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

Reactor

[Mention+, 2011] [Azabajian+, 2012]



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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[SG+, JPG 43 (2016) 033001]

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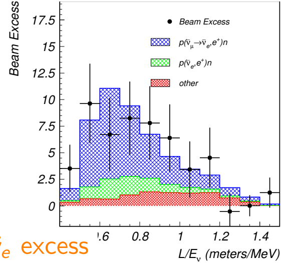

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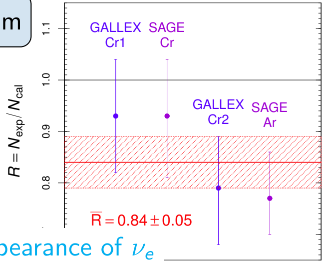
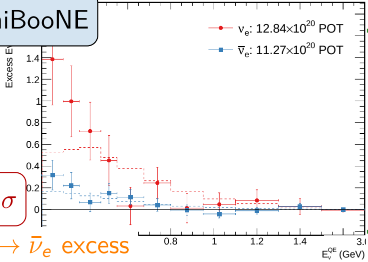


[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

MiniBooNE



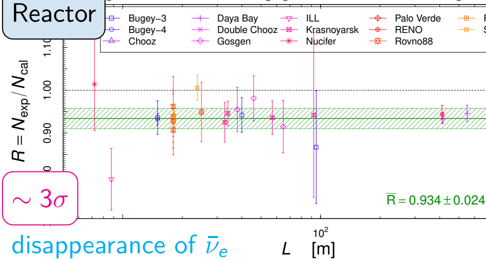
[Aguilar+, 2008-2018]

$\sim 5\sigma$

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

[Mention+, 2011] [Azabajian+, 2012]

Reactor



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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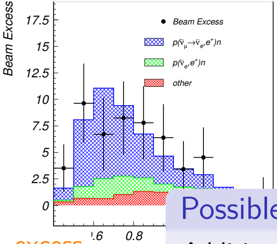
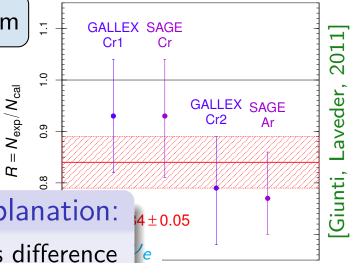


3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Gallium

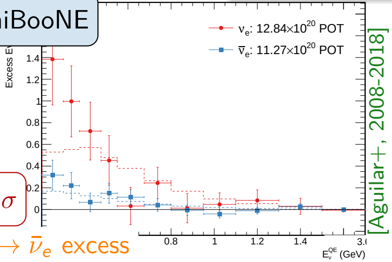


Possible common explanation:

Additional squared mass difference

$$\Delta m^2_{SBL} \simeq 1 \text{ eV}^2$$

MiniBooNE



$\sim 5\sigma$

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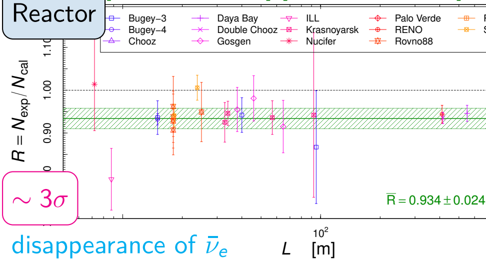
Reactor



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{2\sqrt{2}G_{\mathrm{F}}\,y}{x^6/m_e^6}\left(\frac{\mathbb{E}_\ell + \mathbb{P}_\ell}{m_W^2} + \frac{4\mathbb{E}_\nu}{3m_Z^2}\right), \varrho\right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho) \right\}$$

m_{Pl} Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – G_{F} Fermi constant – $[.,.]$ commutator

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$$\mathbb{M}_{\mathrm{F}} = U\mathbb{M}_{\mathrm{M}}U^\dagger$$

$$\mathbb{M}_{\mathrm{M}} = \mathrm{diag}(m_1^2,\ldots,m_4^2)$$

$$U = R^{34}R^{24}R^{14}R^{23}R^{13}R^{12}$$

e.g. $$R^{13} = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$|U|^2 = \begin{pmatrix} \ldots & \ldots & \ldots & \sin^2\theta_{14} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\sin^2\theta_{24} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34} \end{pmatrix}$$

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$$\mathbb{M}_{\mathrm{F}} = U \mathbb{M}_{\mathrm{M}} U^\dagger$$

$\mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0)$ $\quad$ $\mathbb{E}_\nu = S_a \left(\int dy y^3 \varrho\right) S_a$ $\quad$ with $S_a = \mathrm{diag}(1,1,1,0)$

lepton densities $\quad$ neutrino densities $\quad$ (only for active neutrinos)

take into account matter effects in oscillations

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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$\mathcal{I}(\varrho)$ collision integrals

take into account neutrino-electron scattering and pair annihilation, plus neutrino–neutrino interactions

2D integrals over momentum, take most of the computation time

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{2\sqrt{2}G_{\mathrm{F}}\,y}{x^6/m_e^6}\left(\frac{\mathbb{E}_\ell + \mathbb{P}_\ell}{m_W^2} + \frac{4\mathbb{E}_\nu}{3m_Z^2} \right), \varrho \right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho) \right\}$$

m_{Pl} Planck mass – ρ_T total energy density – $m_{W,Z}$ mass of the W, Z bosons – G_{F} Fermi constant – $[.,.]$ commutator

$$\mathbb{M}_{\mathrm{F}} = U \mathbb{M}_{\mathrm{M}} U^\dagger \qquad \mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0) \qquad \mathbb{E}_\nu = S_a \left(\int dy y^3 \varrho \right) S_a$$

$\mathcal{I}(\varrho)$ collision integrals

from continuity equation

$$\dot\rho = -3H(\rho + P)$$

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J(r_\ell)\right] + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s} \frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\quad J(r)$, $Y(r)$ from non-relativistic transition of $e^\pm$, $\mu^\pm$

$G_1(r)$ and $G_2(r)$ from electromagnetic corrections

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

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initial conditions: $\varrho_{\alpha\alpha}$ = Fermi-Dirac at $x_{\rm in} \simeq 0.001$, with $z \simeq 1$

ν oscillations in the early universe

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FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

https://bitbucket.org/ahep_cosmo/fortepiano_public

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$\dot\rho = -3H(\rho + P)$

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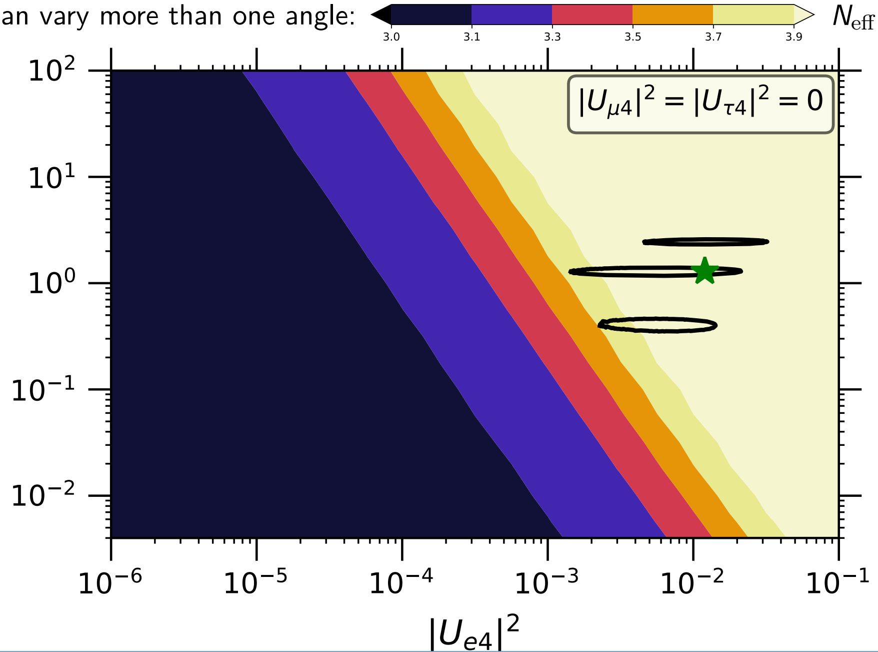
$N_{\rm eff}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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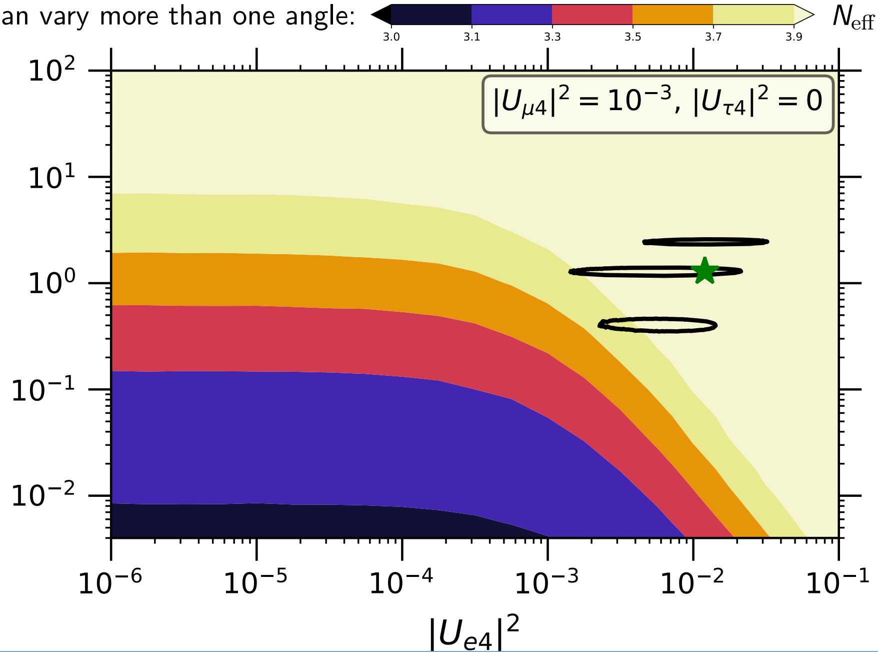

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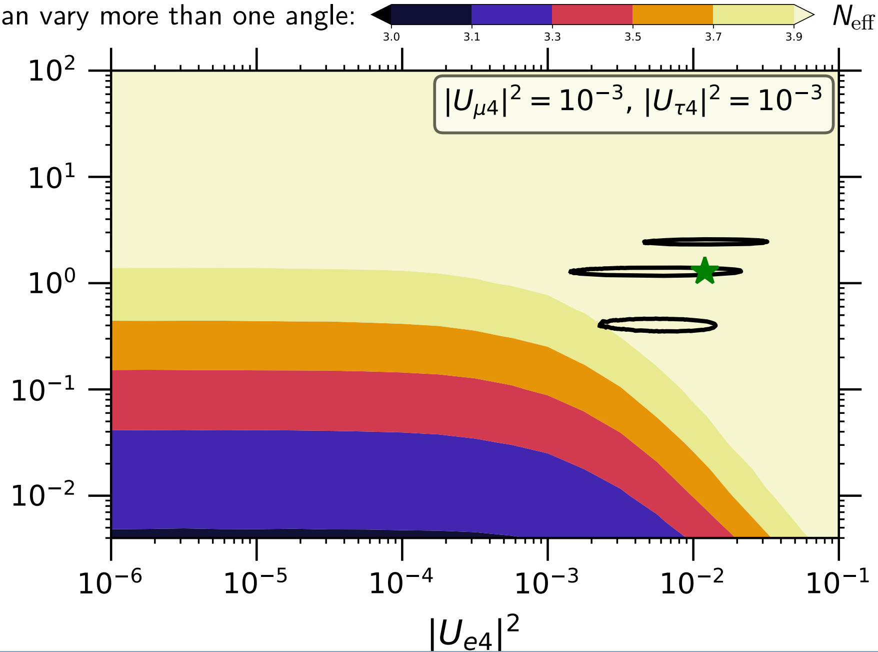
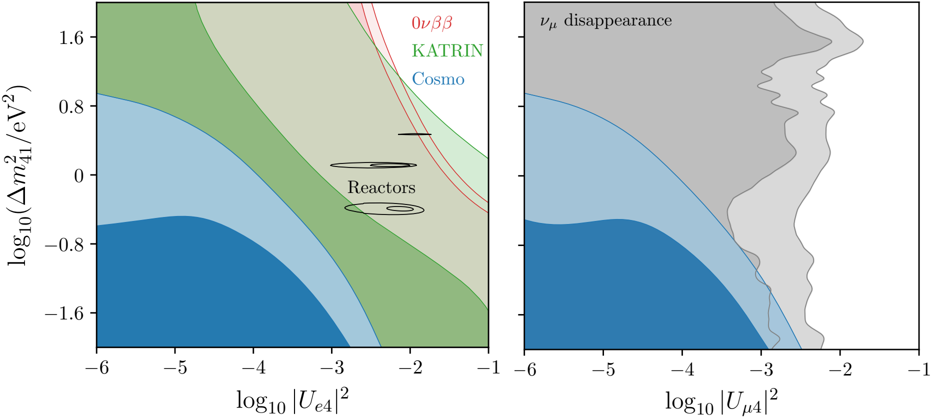


Comparing constraints

[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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[PRD 104 (2021) 123524]

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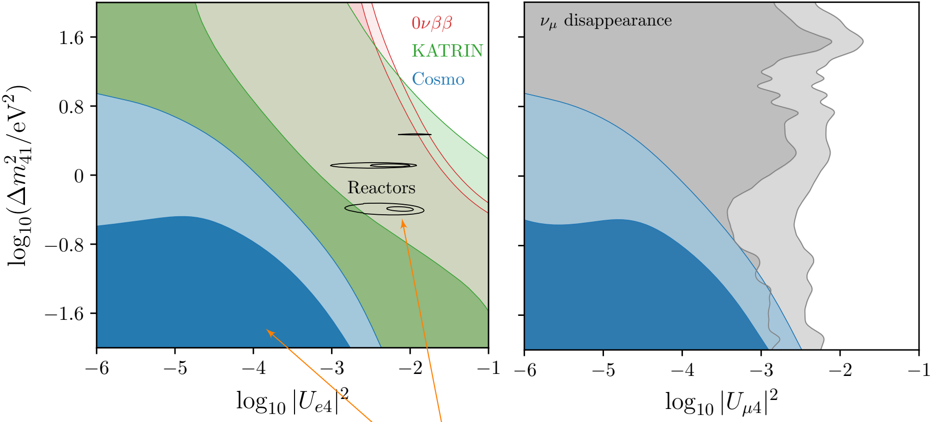
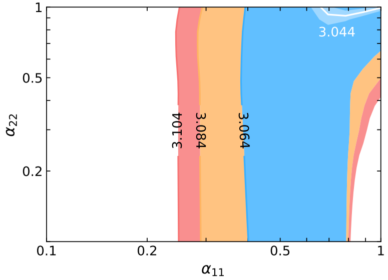


Warning: tension between reactor experiments and CMB bounds!


3.044
3.104
3.084
3.064
α_{22}
α_{11}
1
0.5
0.2
0.1
0.2
0.5
1

Non-unitarity of the 3×3 mixing matrix

[arxiv:2211.10522]

Consider we have N_ν neutrino states

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

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

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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

[arxiv:2211.10522]

Neutrino density matrix evolution in mass basis:

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

Unitary case

interactions:

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

matter effects:

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

Fermi constant:

$$G_F^\mu = G_F$$

Non-unitary case

interactions:

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

matter effects:

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

Fermi constant:

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

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

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

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

[arxiv:2211.10522]

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

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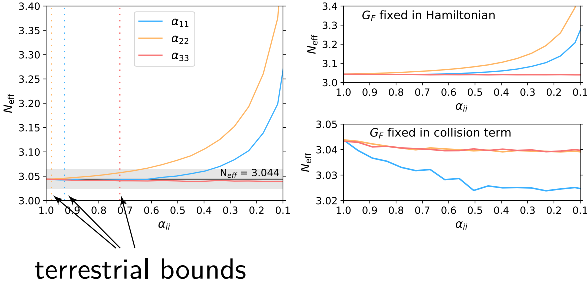
[CODATA]



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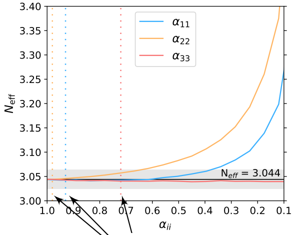
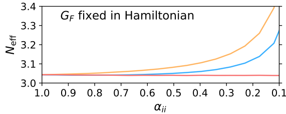
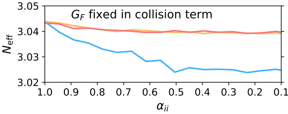
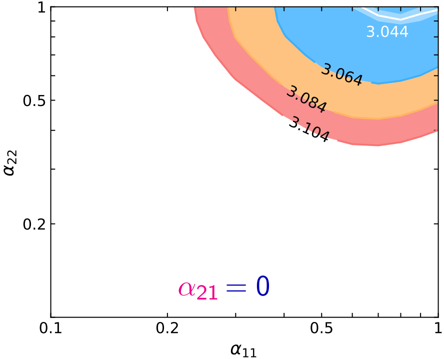
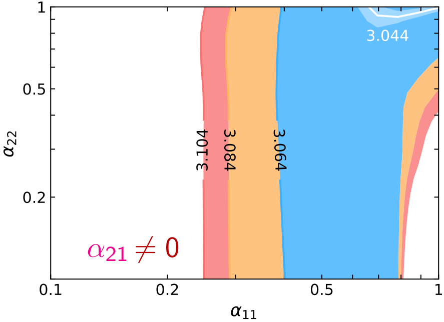




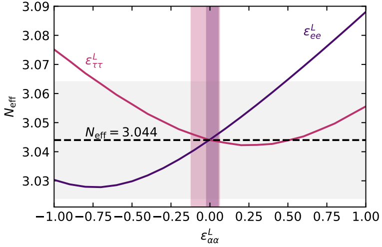






(α_{21} marginalized over)

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


3.09
3.08
3.07
3.06
3.05
3.04
3.03
$N_{\rm eff}$
ε^L_{ee}
$\varepsilon^L_{\tau\tau}$
$N_{\rm eff} = 3.044$
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
$\varepsilon^L_{\alpha\alpha}$

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

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

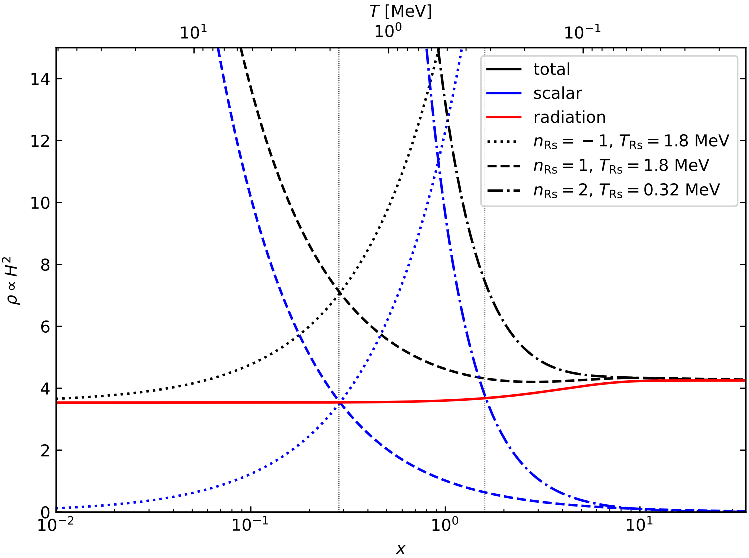
BBN abundances: $$\frac{dX_i}{dx} = \frac{\Gamma_i}{xH}$$

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

Results from $N_{\rm eff}$

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:

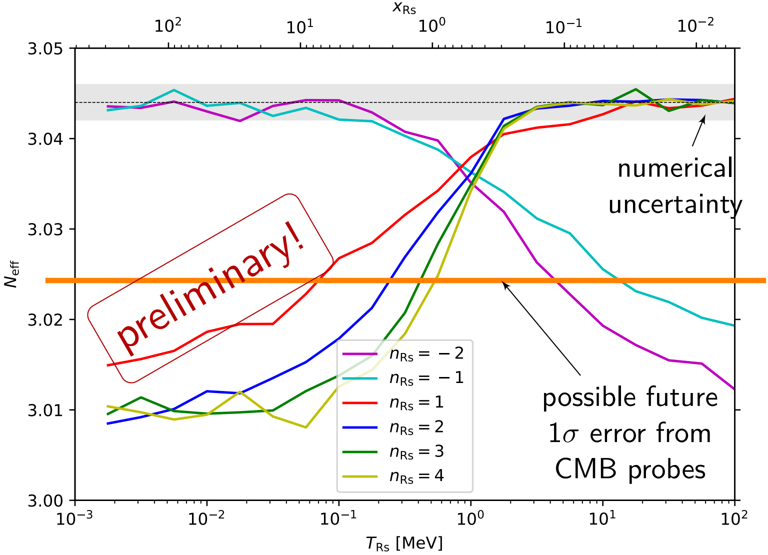


Results from $N_{\rm eff}$

[in preparation]

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

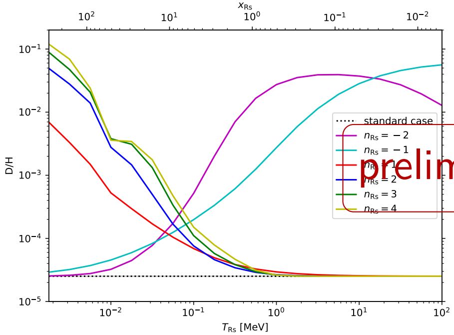
From neutrino decoupling we obtain:

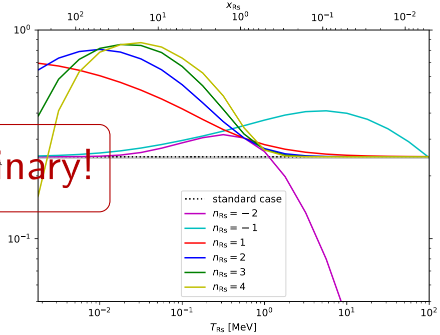


Results from BBN

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):

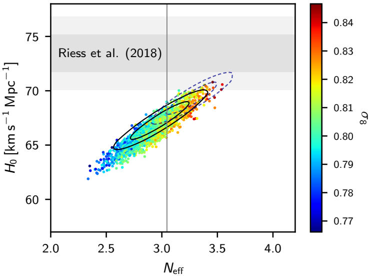




error bands (gray) are current constraints on the abundances

barely visible!! even current precision can strongly constrain $T_{\rm Rs}$

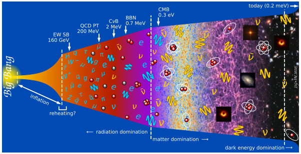
calculations ongoing with prof. D. Aristizabal and A. Villanueva (UTFSM)

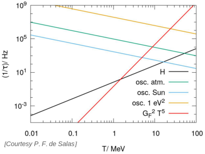

Riess et al. (2018)
75
70
65
60
2.0
2.5
3.0
3.5
4.0
$N_{\rm eff}$
$H_0\,[{\rm km\,s^{-1}\,Mpc^{-1}}]$
0.84
0.83
0.82
0.81
0.80
0.79
0.78
0.77
σ_8

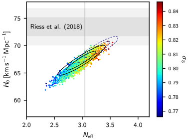
Conclusions

1

Neutrinos in the early universe – probe lowest energies

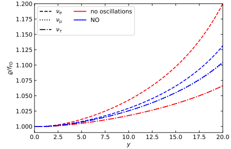


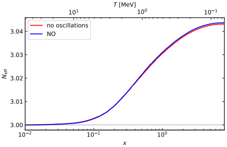


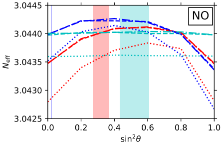


2

Active neutrinos: precision calculations

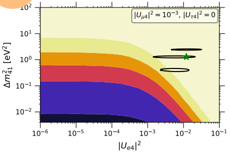


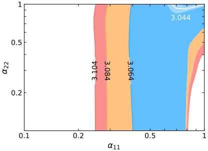


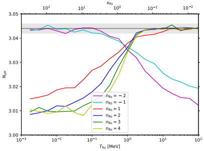


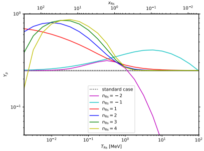
3

Non-standard scenarios: complementary bounds



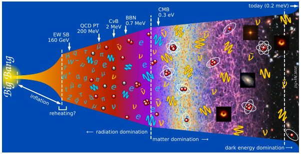


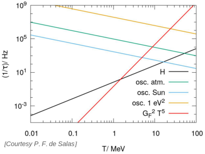




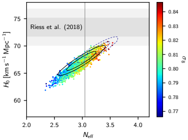
Conclusions

1 Neutrinos in the early universe – probe lowest energies

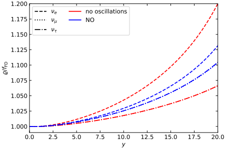


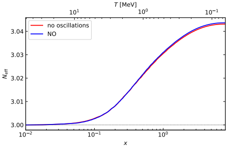


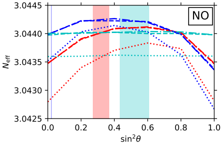
[Courtesy P. F. de Salas]



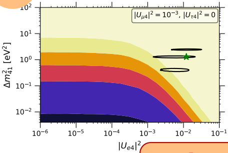
2 Active neutrinos: precision calculations

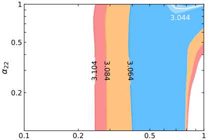


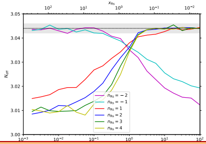


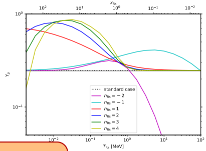


3 Non-standard scenarios: complementary bounds









Thanks for your attention!