H2020 MSCA COFUND
G.A. 754496

Stefano Gariazzo

INFN, Turin section
Turin (IT)

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

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

New neutrino physics with terrestrial and early universe probes

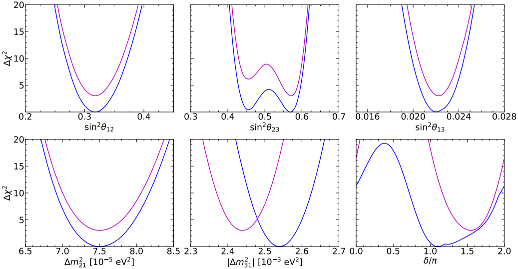
Dipartimento di Fisica e Astronomia, Università di Bologna, 07/03/2023

A Active neutrinos

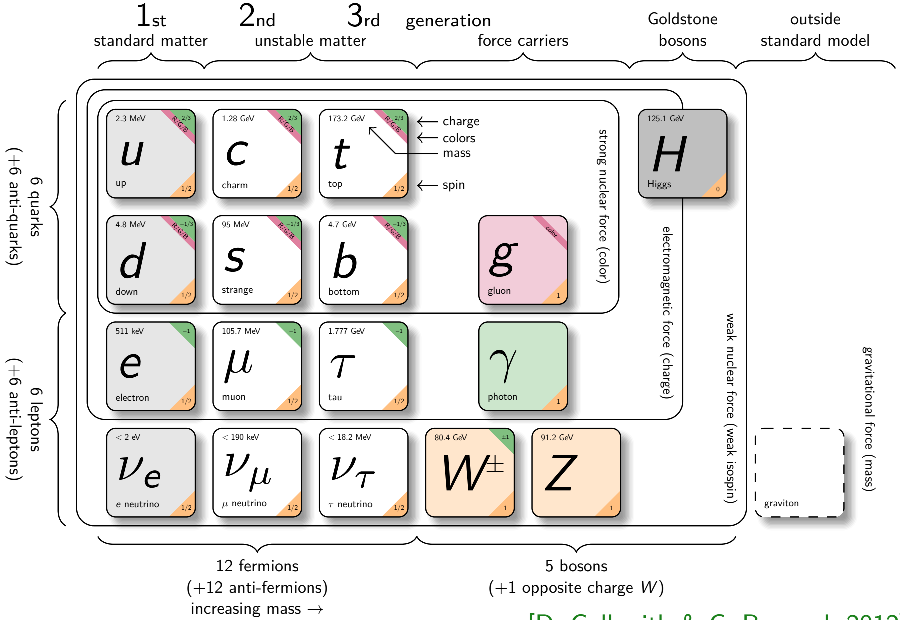
Spoiler: “Sterile” will come later

Based on:

- JHEP 02 (2021) 071 and update
- Planck 2018
- JCAP 04 (2021) 073



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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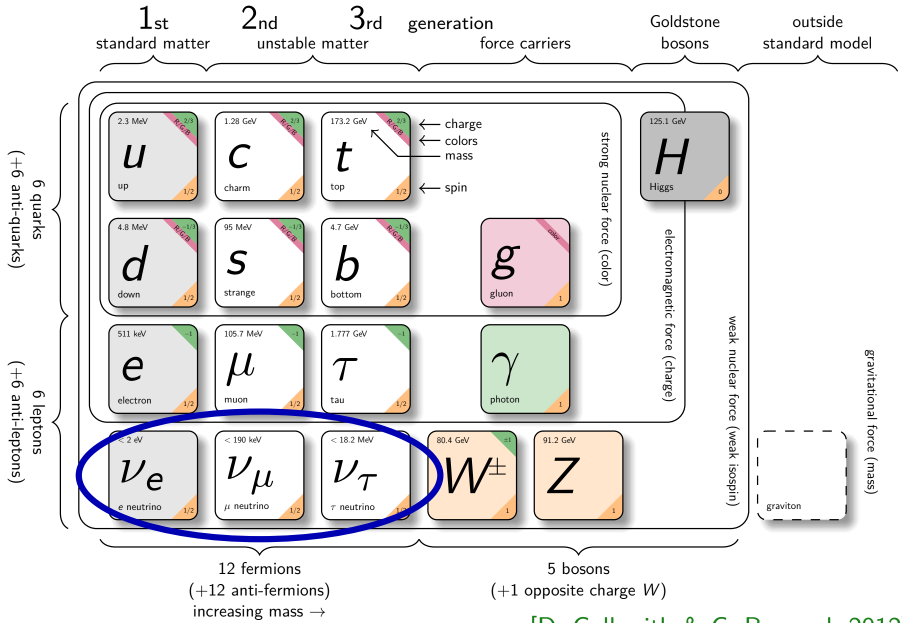


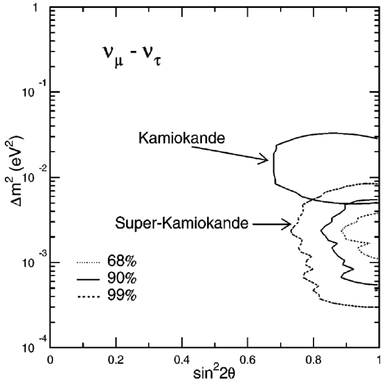
[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

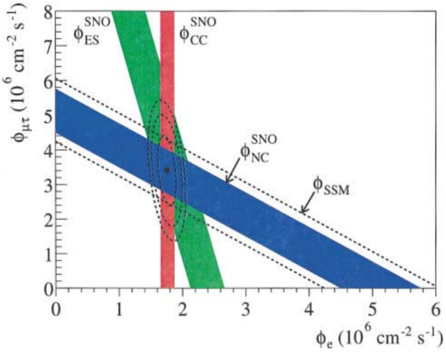
Major discoveries:

[SuperKamiokande, 1998]

[SNO, 2001-2002]



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



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

Nobel prize in 2015

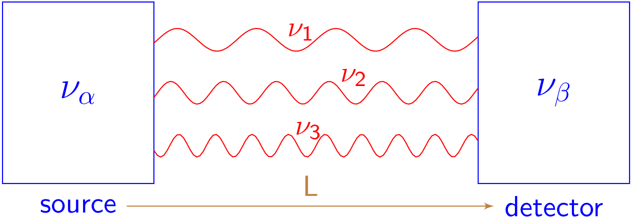
Two neutrino bases

flavor neutrinos ν_α

$|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$

massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$



$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\, e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\, e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$E_k^2 = p^2 + m_k^2 \longleftarrow \text{define} \longrightarrow t = L$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

The mixing matrix

U can be parameterized using 3 angles (θ_{12}, θ_{13}, θ_{23}) and max 3 (1 Dirac δ, 2 Majorana [∃ only for Majorana ν]) phases

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

Majorana phases irrelevant for oscillation experiments

Relevant for example in neutrinoless double-beta decay

$$s_{ij} \equiv \sin\theta_{ij};\ c_{ij} \equiv \cos\theta_{ij}$$

SBL = short baseline; LBL = 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

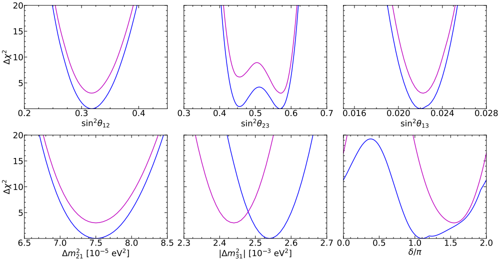
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$ IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

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

$$\begin{aligned}
10 \sin^2(\theta_{12}) &= 3.18 \pm 0.16 \\
10^2 \sin^2(\theta_{13}) &= 2.200^{+0.069}_{-0.062}\ (\mathrm{NO}) \\
&= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO}) \\
10 \sin^2(\theta_{23}) &= 4.55 \pm 0.13 U 5.71 \pm 0.12\ (\mathrm{NO}) \\
&= 5.71^{+0.14}_{-0.17}\ (\mathrm{IO})
\end{aligned}$$

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

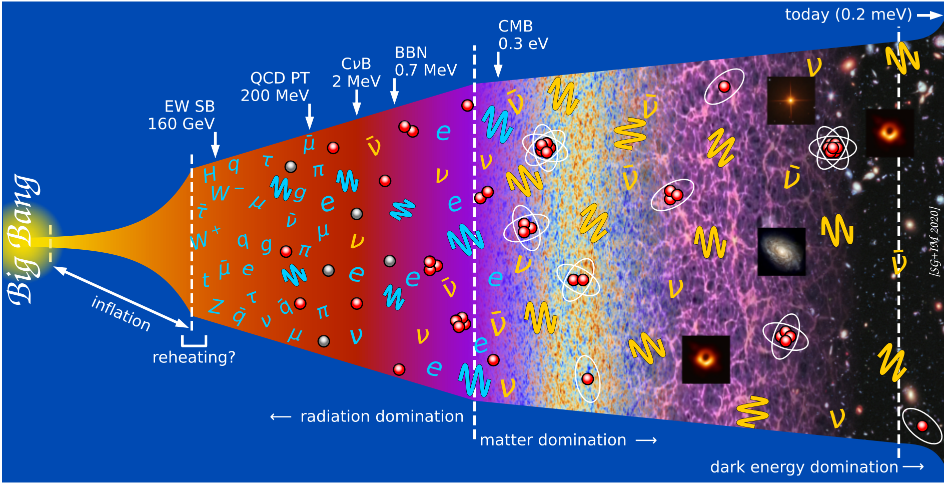


mass ordering
still unknown

δ still unknown

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

History of the universe



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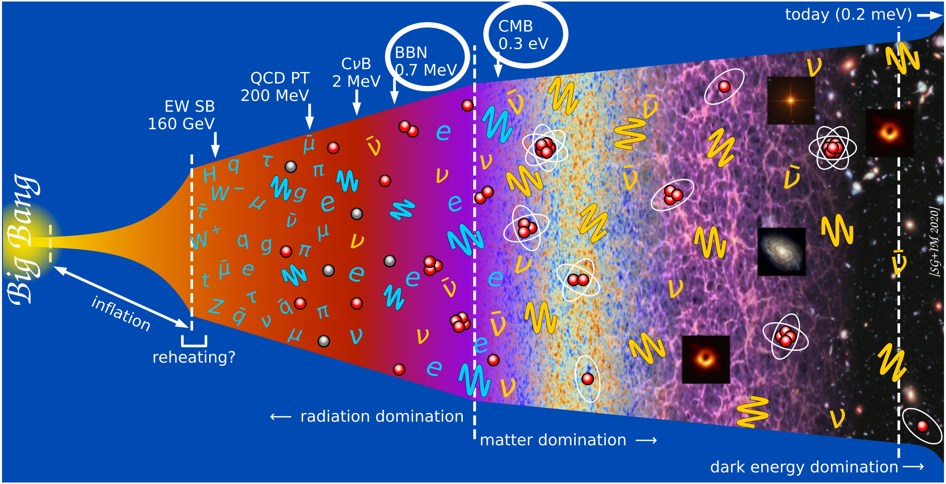

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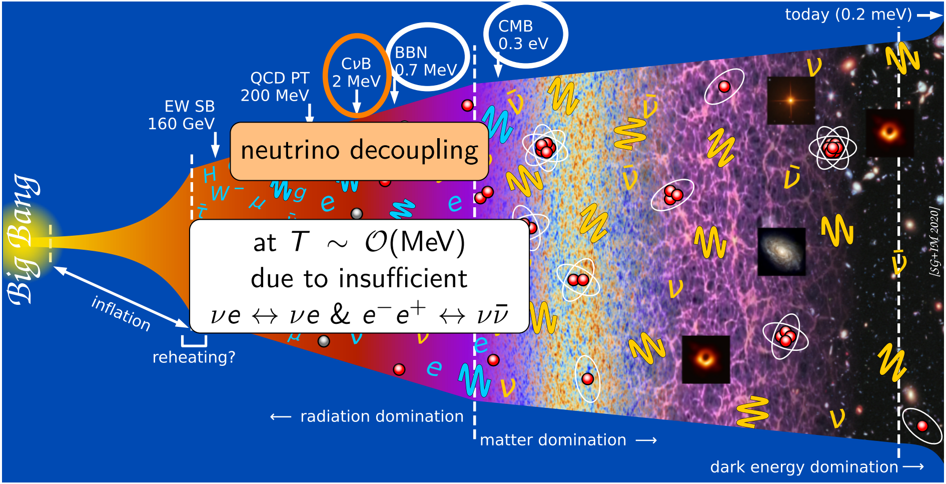


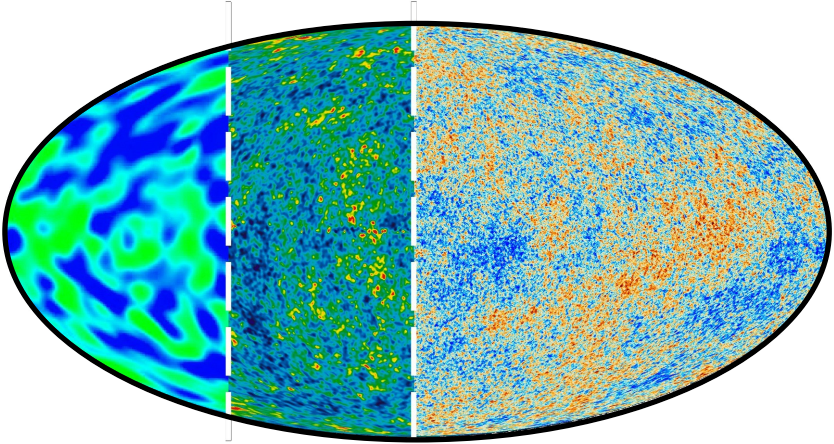
neutrino decoupling

at $T \sim \mathcal{O}(\text{MeV})$
due to insufficient
$\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

The oldest picture of the Universe

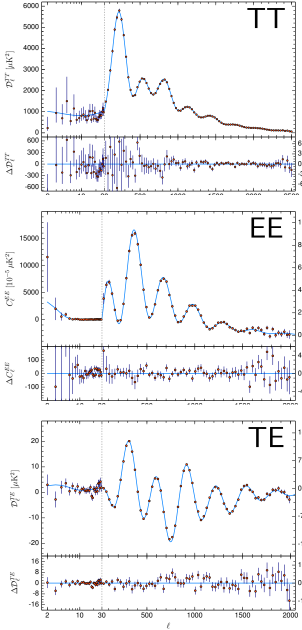
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

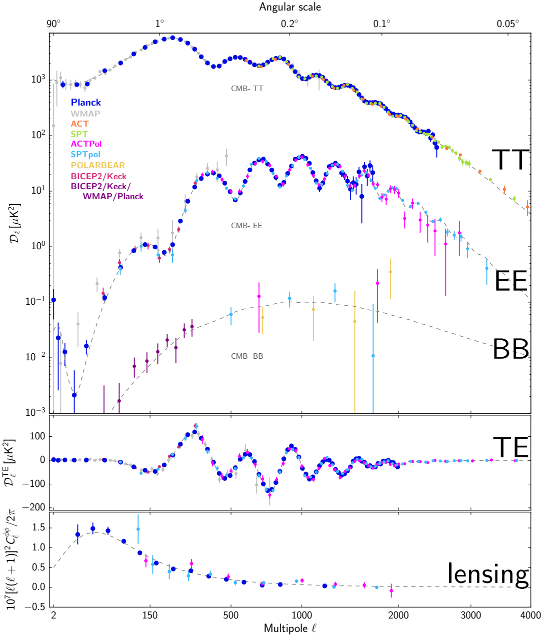
COBE (1992) WMAP (2003) Planck (2013)



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

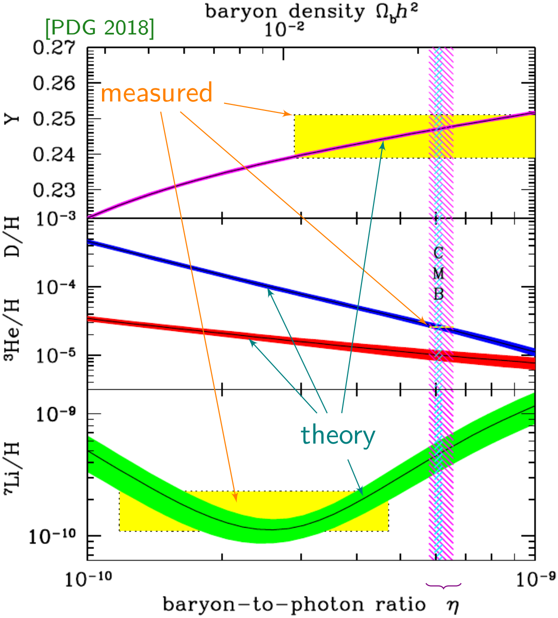
much earlier than CMB!

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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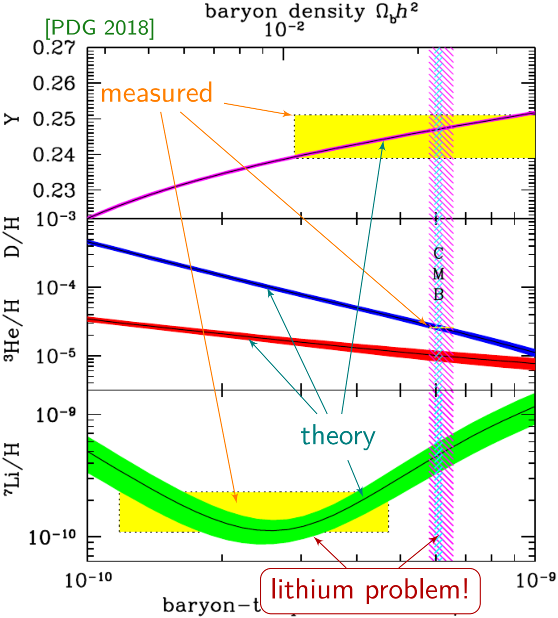


[PDG 2018]

measured

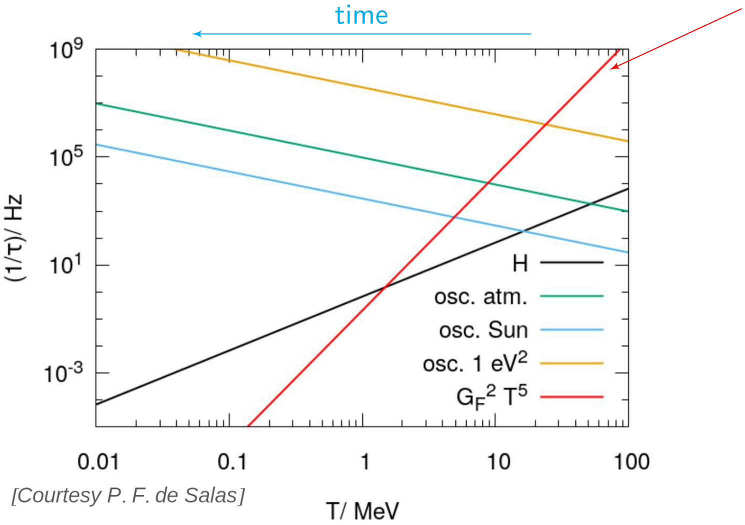
theory

lithium problem!

BBN concordance

Neutrinos in the early Universe

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



[Courtesy P. F. de Salas]

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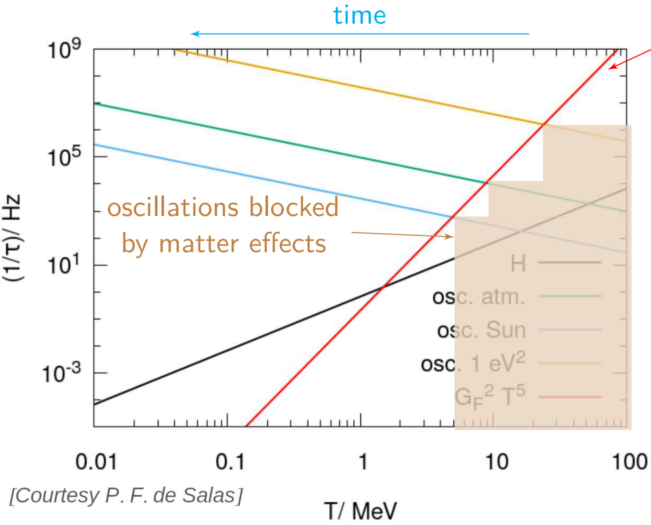

oscillations blocked
by matter effects

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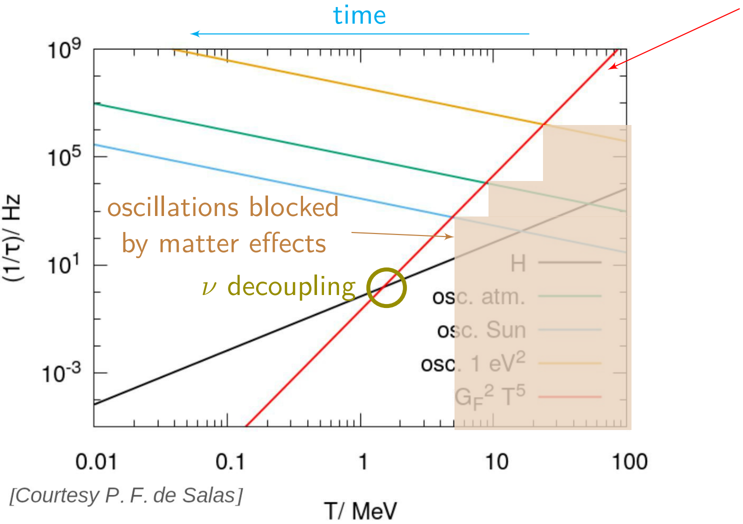

time

oscillations blocked by matter effects

ν decoupling

[Courtesy P. F. de Salas]

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

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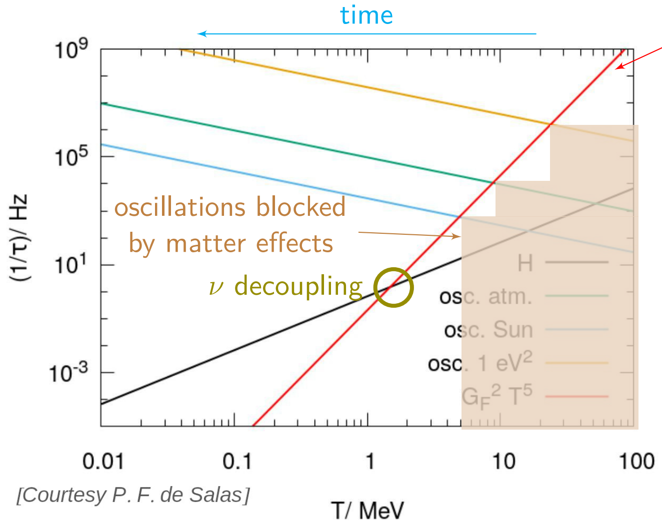

[Courtesy P. F. de Salas]

$T_\nu \simeq (4/11)^{1/3}\, T_\gamma$ 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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Neutrinos in the early Universe

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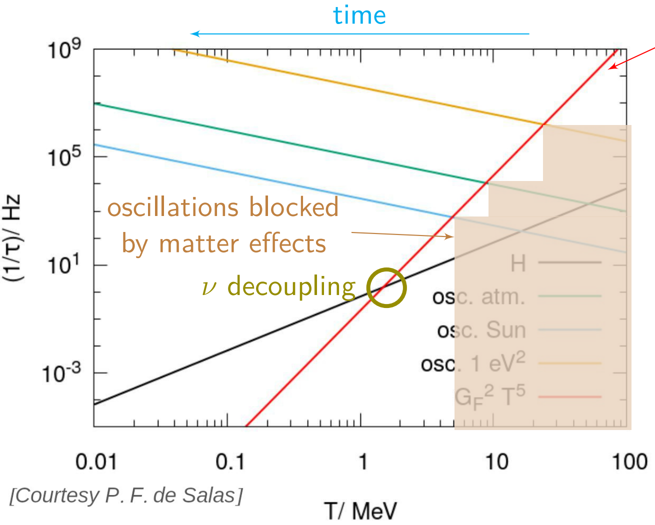

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actually, the decoupling T is momentum dependent!

→ distortions to equilibrium f_ν!

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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

off-diagonals to take into account coherency in the neutrino system

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

H Hubble factor → expansion (depends on universe content)

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

vacuum oscillations ← → matter effects

$\mathcal{I}$ collision integrals

take into account ν–e scattering and pair annihilation, ν–ν interactions

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

solve together with z evolution, from $x\frac{\mathrm{d}\rho(x)}{\mathrm{d}x} = \rho - 3P$

ρ, P total energy density and pressure, also take into account FTQED corrections

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]

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FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

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

vacuum oscillations

matter effects

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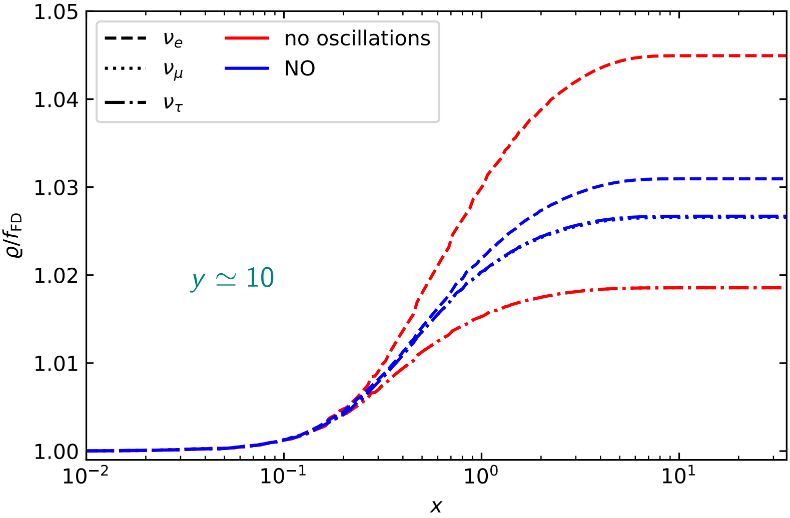
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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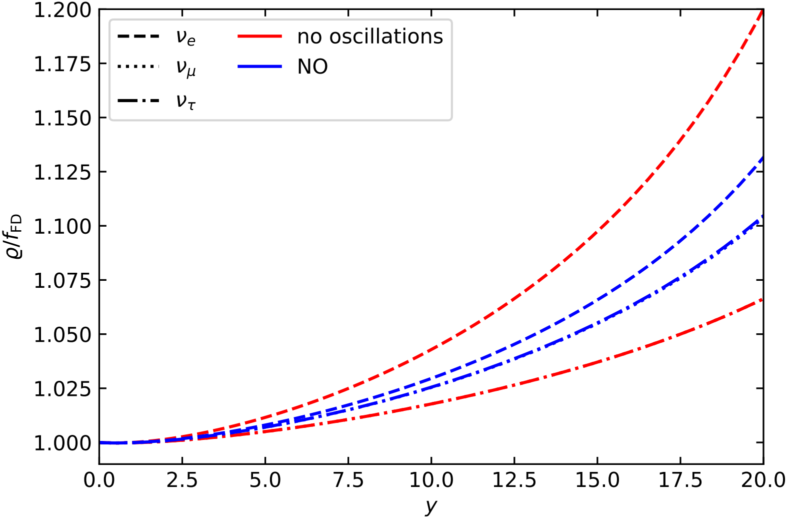
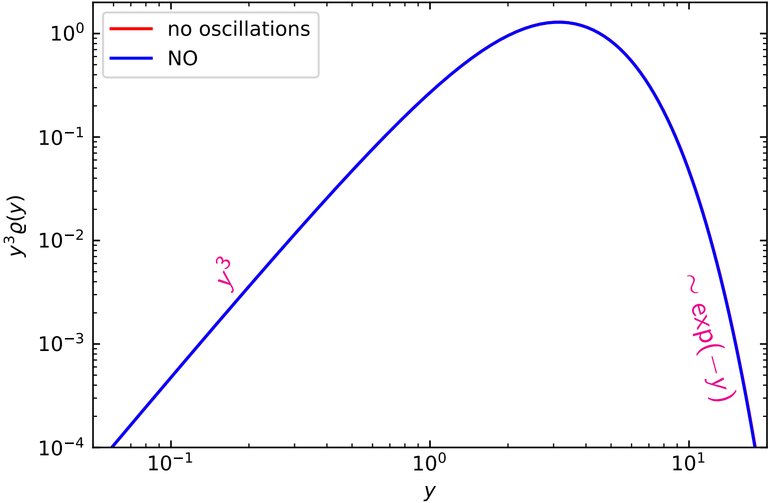


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

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

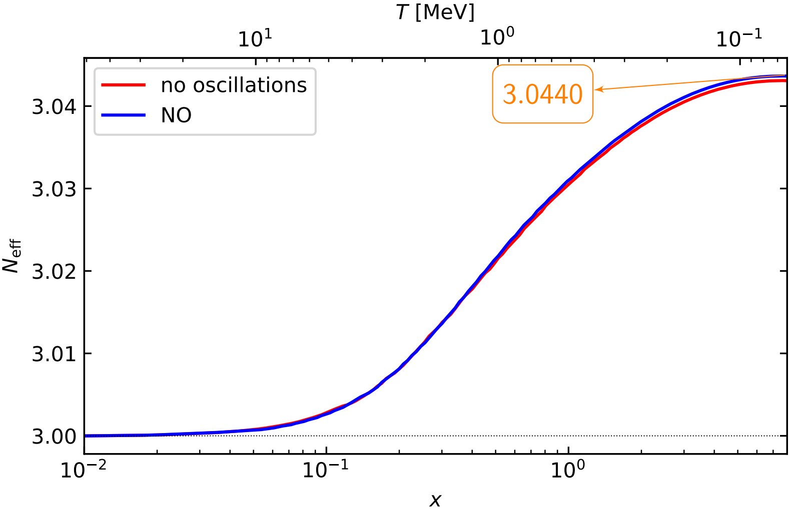
$\hookrightarrow \propto y^3 \varrho_{ii}(y)$



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

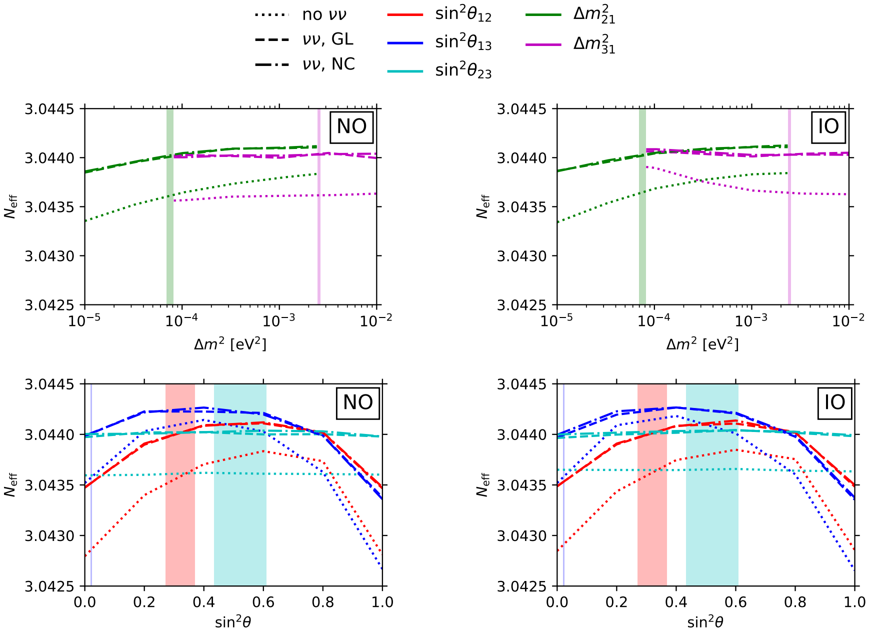
[Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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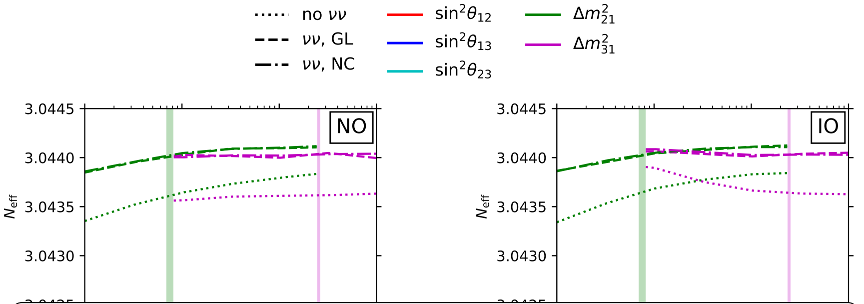
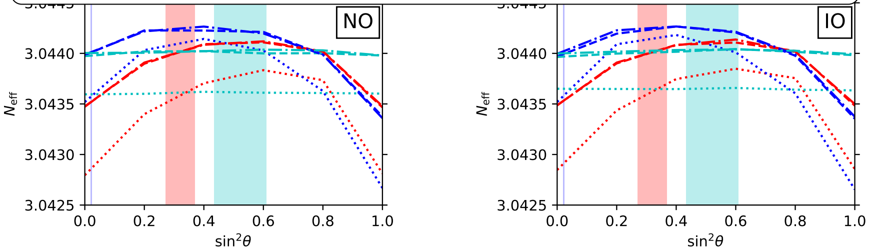
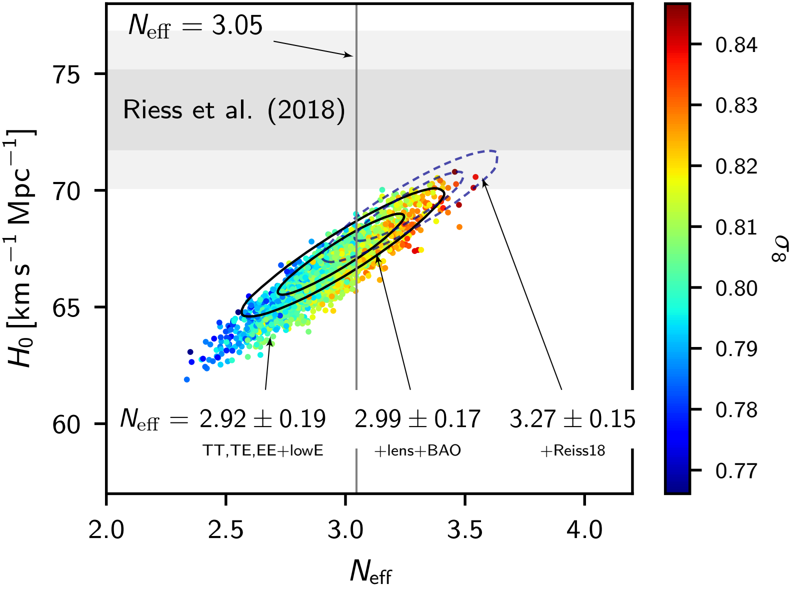


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]
only θ_{12} affects $N_{\rm eff}$, at most by $\delta N_{\rm eff} \approx 10^{-4}$



$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]



$N_{\rm eff}$ and 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:

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 \;=\; H \sim \sqrt{g_\star G_N}\, T^2$$

$$\downarrow$$

$$\boxed{T_{fr} \simeq (g_\star G_N/G_F^4)^{1/6}}$$

enters

$n/p = \exp(-Q/T_{fr})$

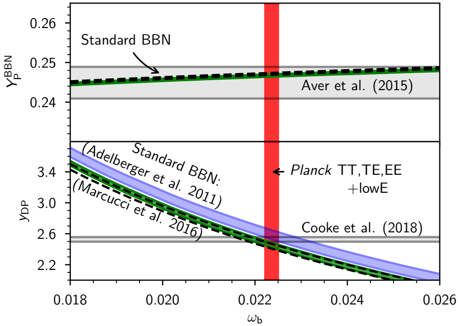
which controls element abundances

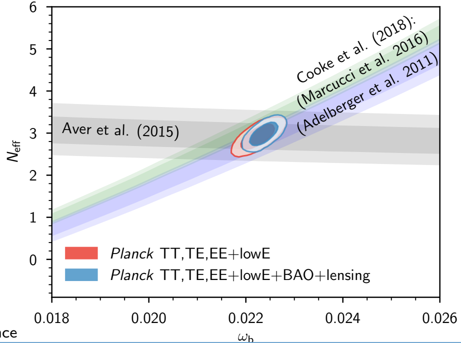
$\boxed{g_\star \text{ depends on } N_{\rm eff}}$

$$\downarrow$$

abundances depend on $N_{\rm eff}$

[Planck Collaboration, 2018]





G_F Fermi constant
G_N Newton constant
n, p: neutron, proton density number
$Q = 1.293$ MeV neutron–proton mass difference

$N_{\rm eff}$ and BBN

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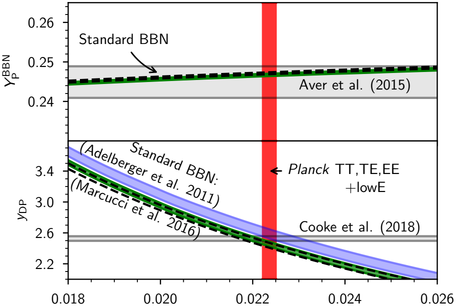
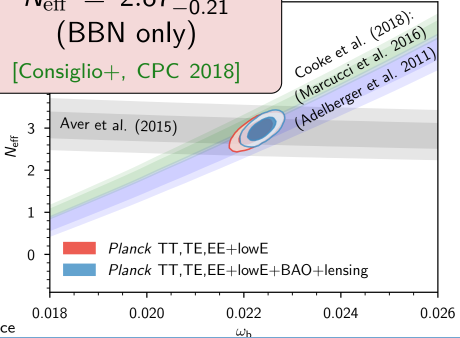


$$N_{\rm eff} \;=\; 2.87^{+0.24}_{-0.21}$$

(BBN only)

[Consiglio+, CPC 2018]



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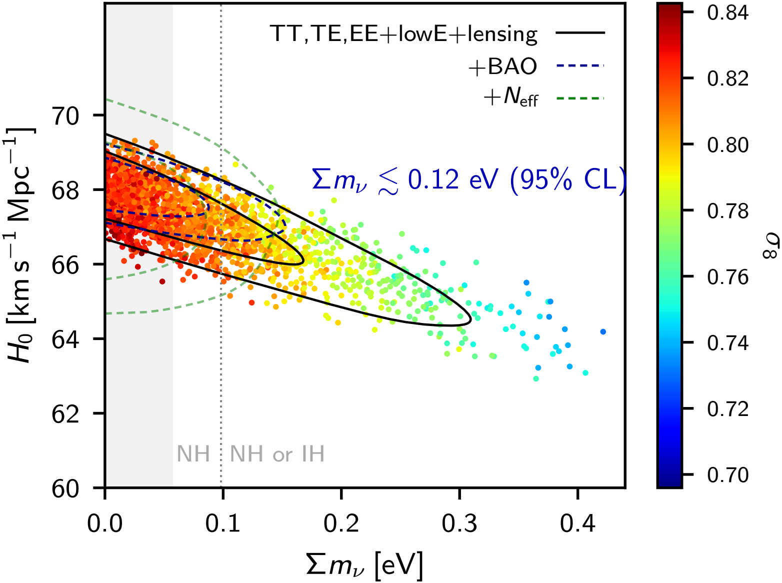
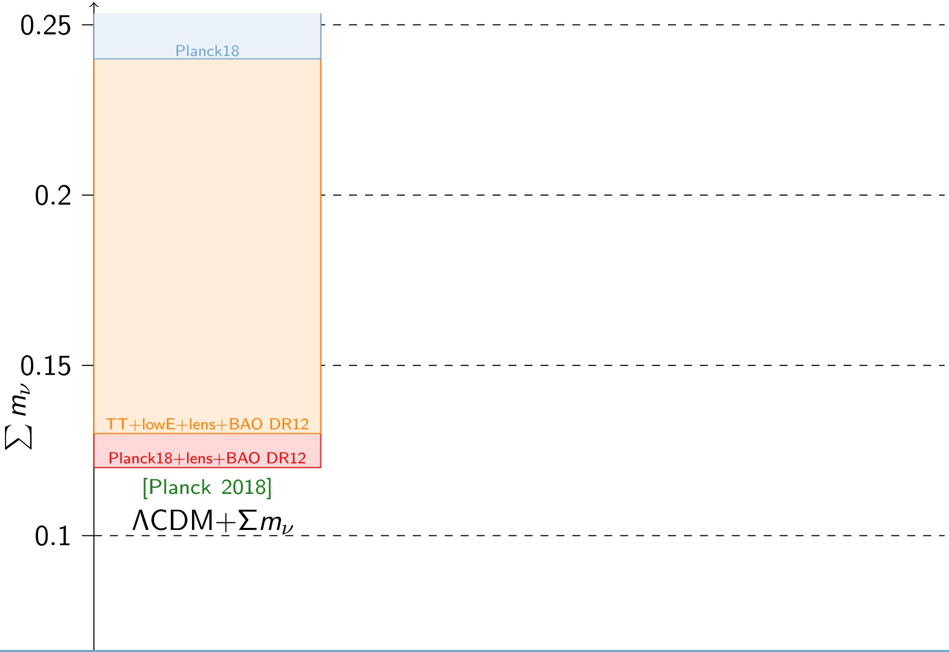
Σm_ν and CMB

[Planck Collaboration, 2018]



Cosmological neutrino mass bounds (95% CL)



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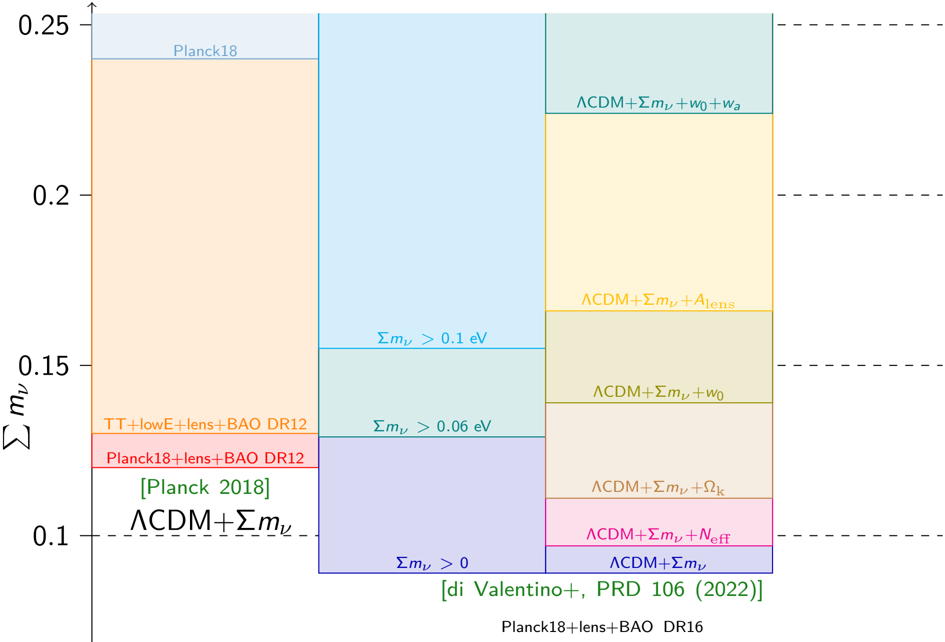
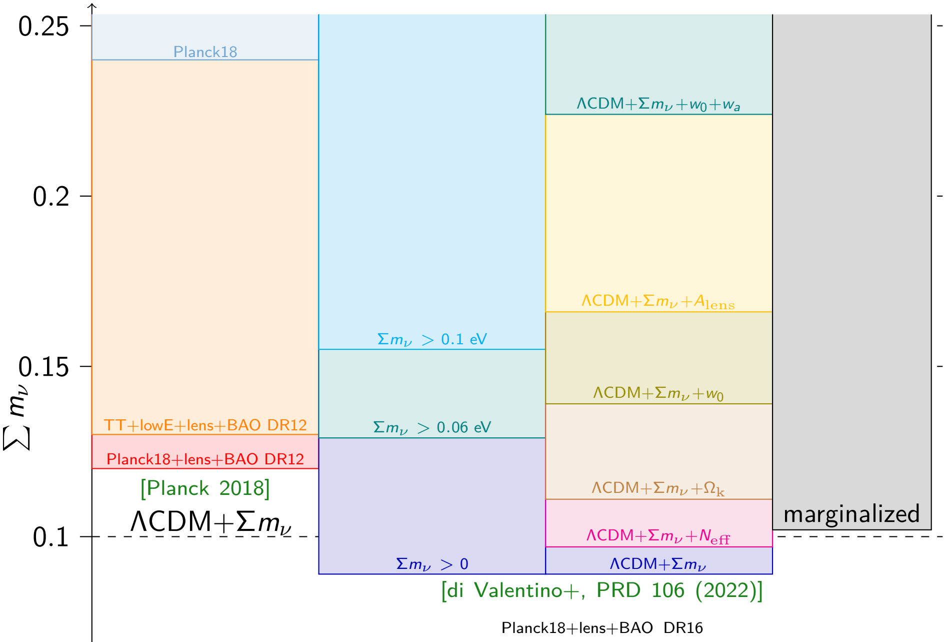


[Planck 2018]

[di Valentino+, PRD 106 (2022)]

Cosmological neutrino mass bounds (95% CL)



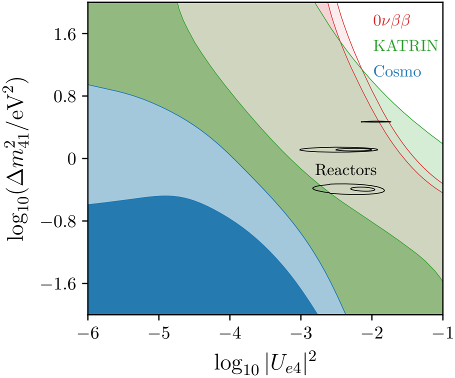
B

Sterile neutrinos

let’s pretend they exist

Based on:

- JPG 43 (2016) 033001
- JHEP 06 (2017) 135
- PLB 782 (2018) 13-21
- in preparation
- JCAP 07 (2019) 014
- PRD 104 (2021) 123524
- arxiv:2211.10522



Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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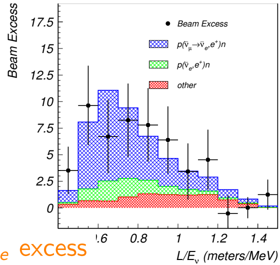
Do three-neutrino oscillations explain all experimental results?

LSND



[Aguilar+, 2001]

3.8σ

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

Short Baseline (SBL) anomalies

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Do three-neutrino oscillations explain all experimental results?

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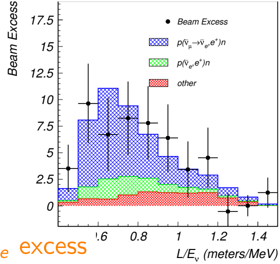

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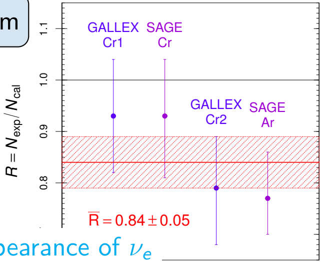
Gallium



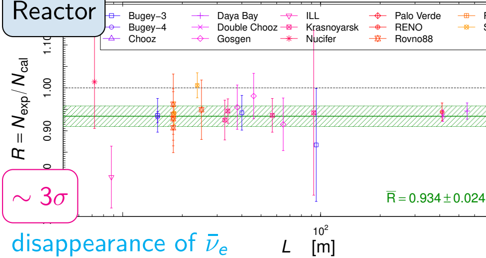
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

Reactor

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



∼ 3σ

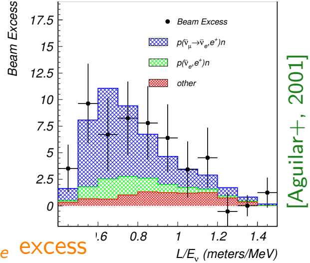
disappearance of $\bar\nu_e$

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

LSND



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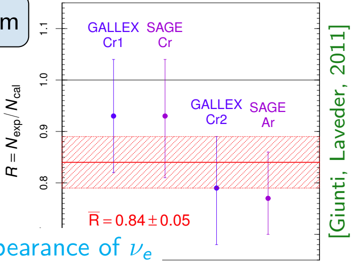
$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

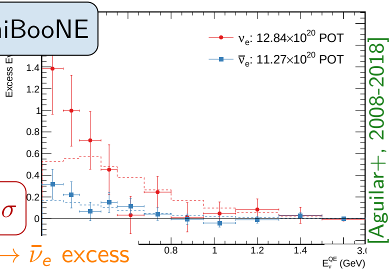
Gallium



2.7σ

disappearance of ν_e

MiniBooNE

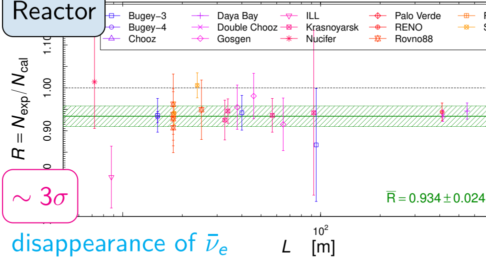


$\sim 5\sigma$

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

Reactor

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



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Do three-neutrino oscillations explain all experimental results?

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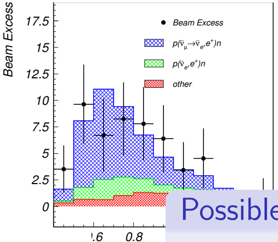

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guilar+, 2001]

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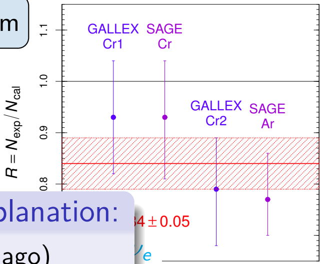


ν_e

[Giunti, Laveder, 2011]

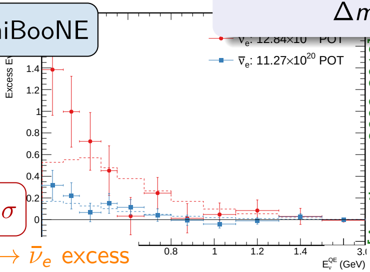
Possible common explanation:

(until a few years ago)

Additional squared mass difference

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

MiniBooNE

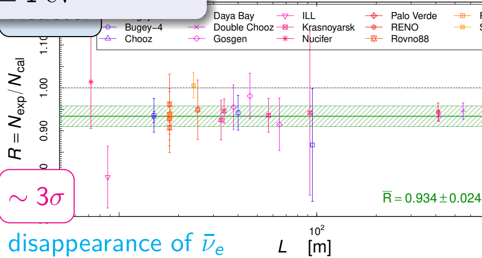


$\sim 5\sigma$

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

[Aguilar+, 2008-2018]

2011] [Azabajian+, 2012]

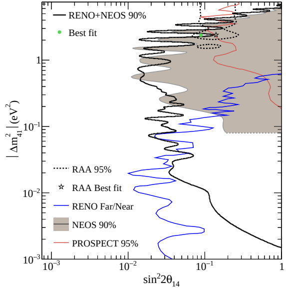


$\sim 3\sigma$

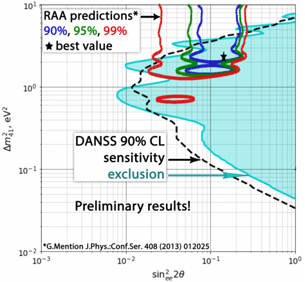
disappearance of $\bar{\nu}_e$

ν_s at reactors in 2020

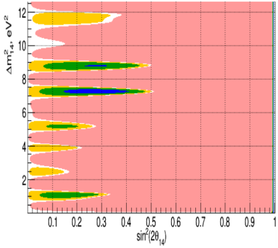
[RENO+NEOS, 2020]



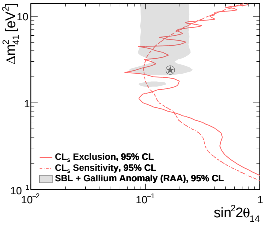
[DANSS, 2020]



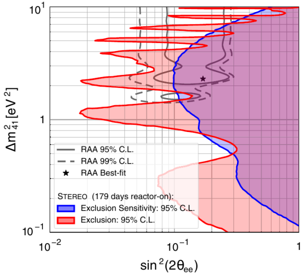
[Neutrino-4, PZETF 2020]



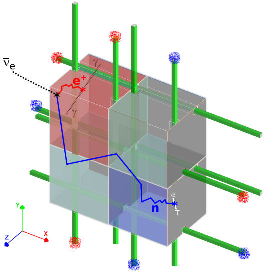
[PROSPECT, PRD 2020]



[STEREO, PRD 2020]

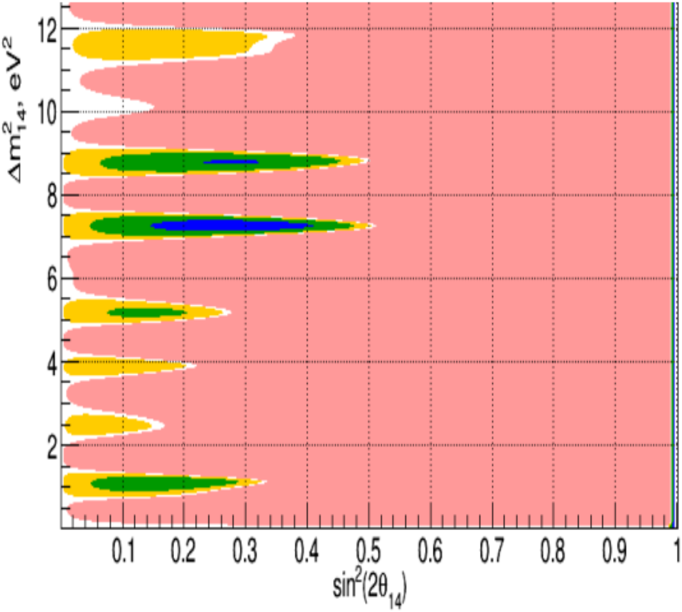


[SoLiD, JINST 2021]



Neutrino-4

[Neutrino-4 2020]

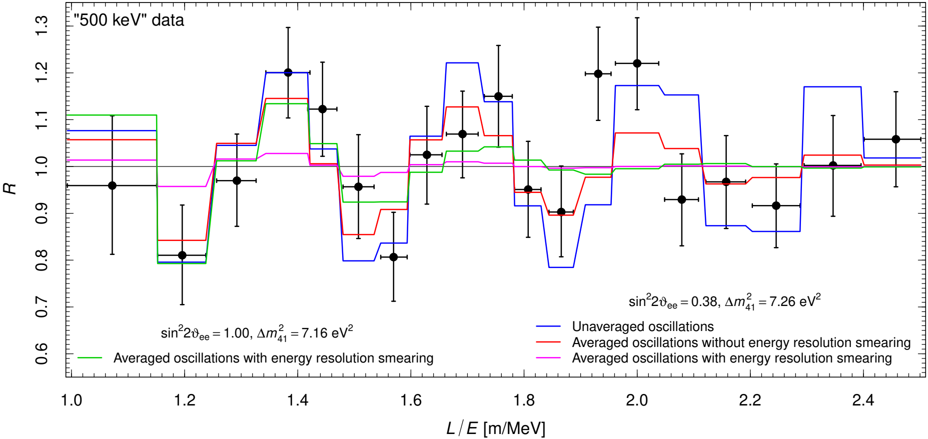


claimed $> 3\sigma$ preference for 3+1 over 3ν case

best fit incompatible with other reactor experiments

Neutrino-4

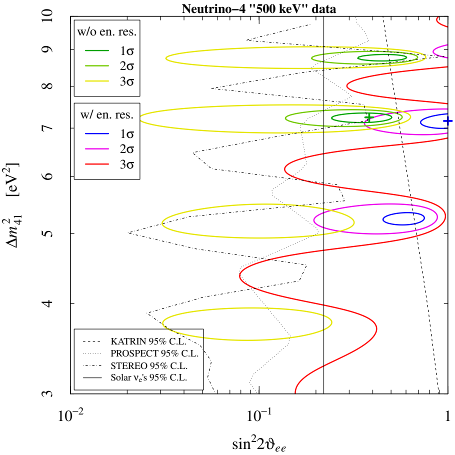
[Giunti+, PLB 2021]

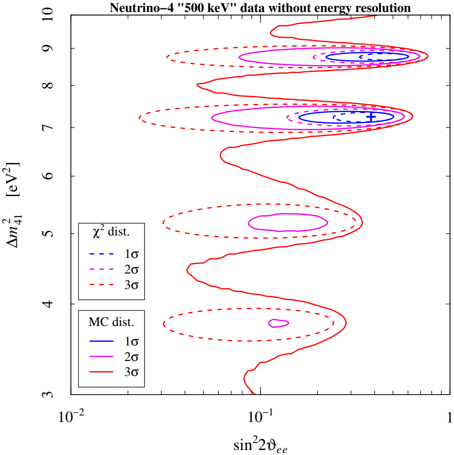


energy resolution smearing not properly taken into account?

Neutrino-4

[Giunti+, PLB 2021]





proper energy resolution treatment
moves best-fit → $\sin^2 2\vartheta \simeq 1$

need to take into account
violation of Wilk's theorem
↓
relaxed constraints

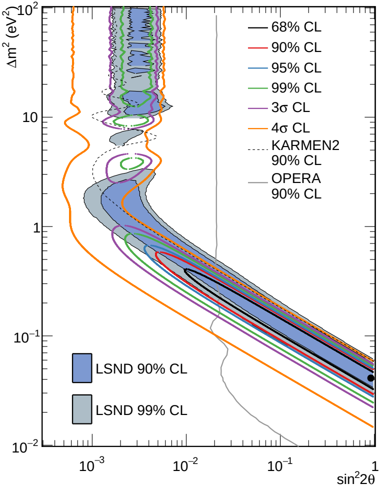
MiniBooNE

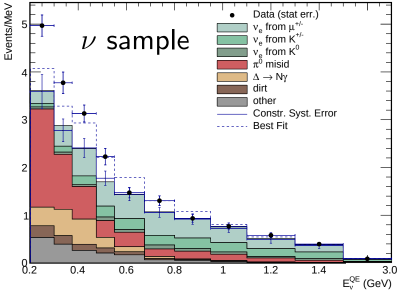
[PRL 121 (2018) 221801]

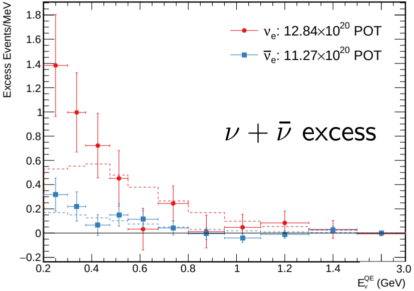
purpose: check LSND signal

$L \simeq 541$ m, 200 MeV $\leq E \lesssim 3$ GeV

no money, no near detector







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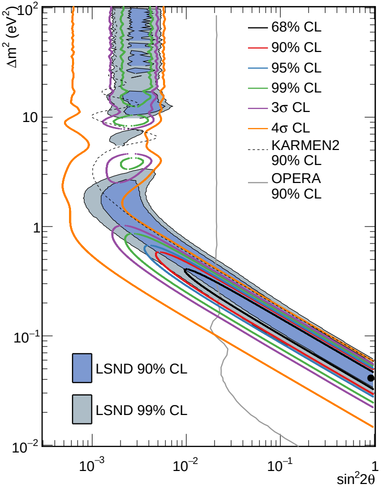
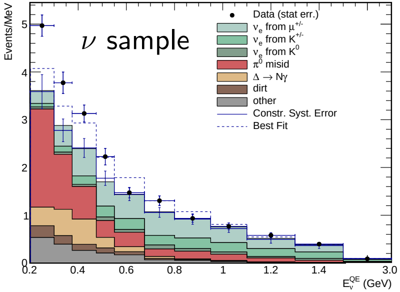
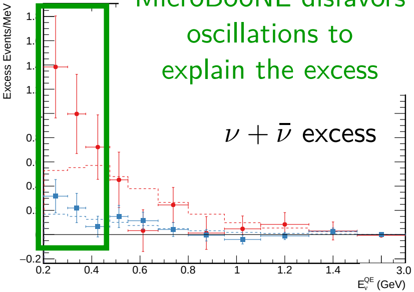


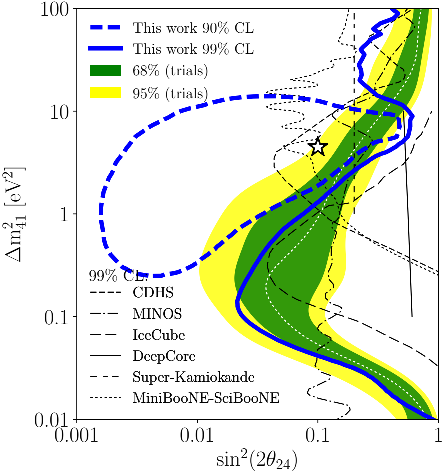

ν sample

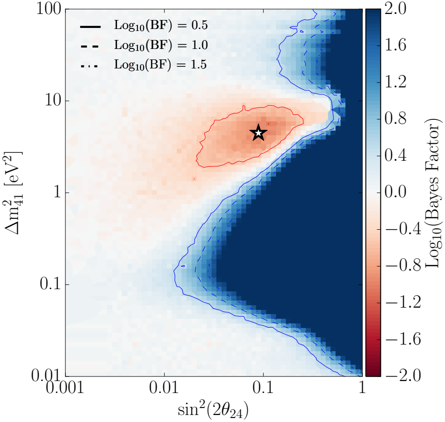

MicroBooNE disfavors oscillations to explain the excess

$\nu + \bar{\nu}$ excess

IceCube 8 yr update

[IceCube, PRL 2020]





first indication in favor of sterile from ν_μ DIS!

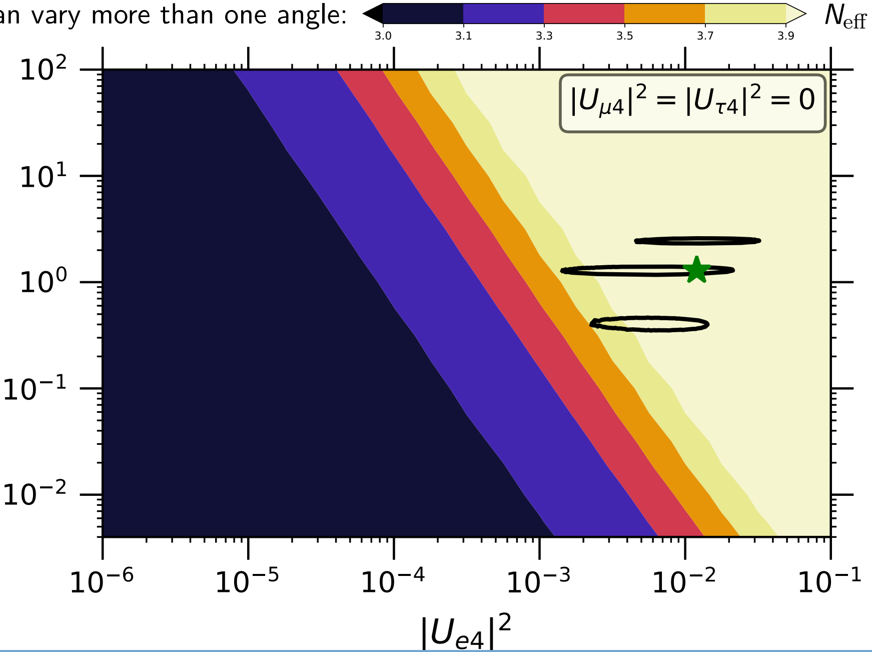
although rather weak: $\log_{10} BF \simeq 1$ (weak preference)

or compatible with no oscillations at p-value of 8%

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

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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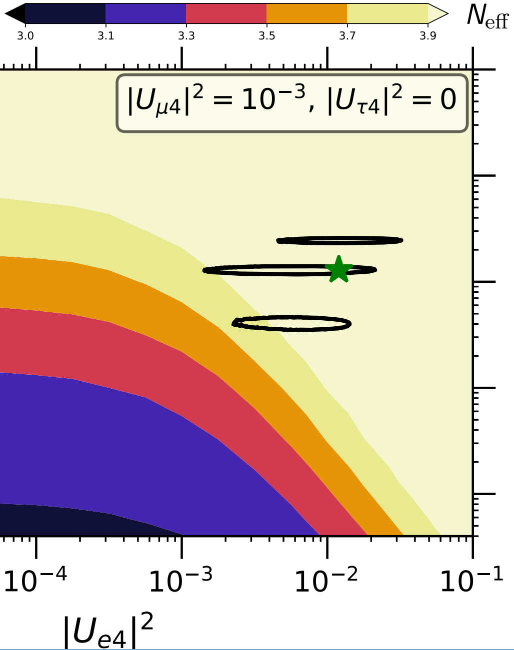

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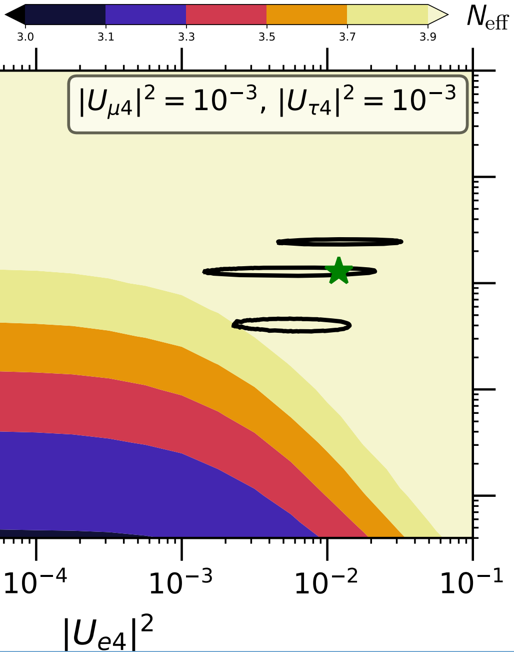
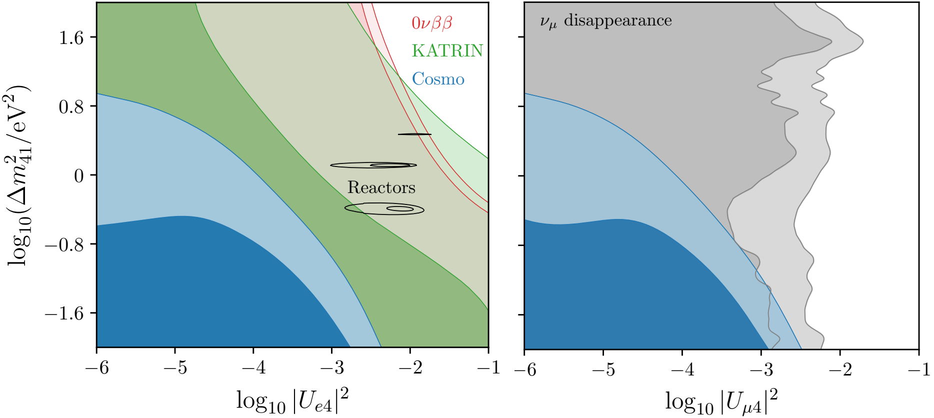


Comparing constraints

[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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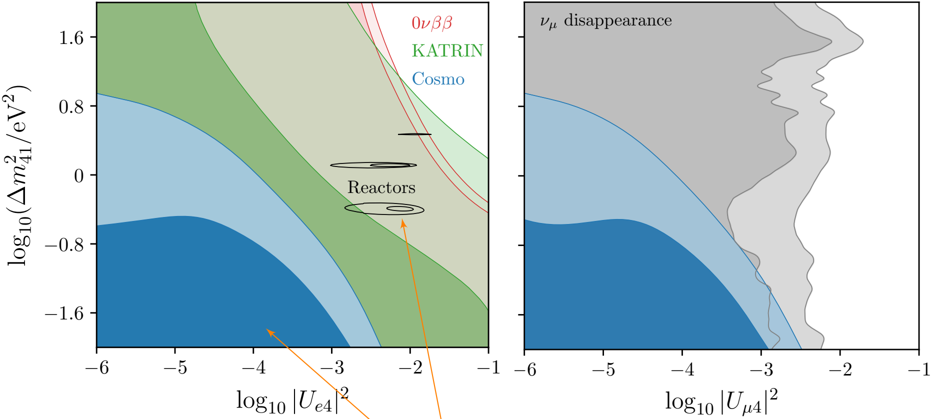

Warning: tension between reactor experiments and CMB bounds!

Comparing constraints

[PRD 104 (2021) 123524]

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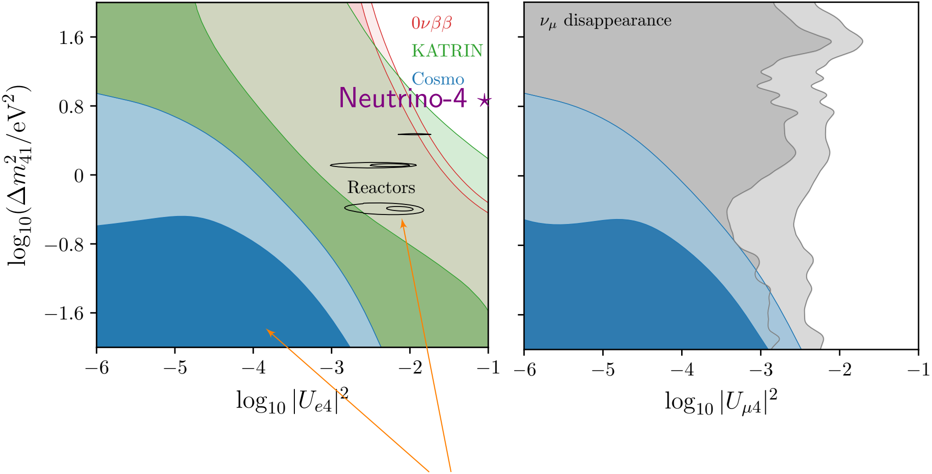

Warning: tension between reactor experiments and CMB bounds!

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

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

[arxiv:2211.10522]

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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:

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

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:

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

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]

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

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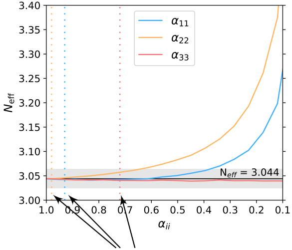
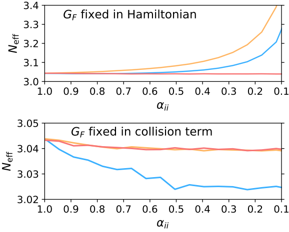


terrestrial bounds



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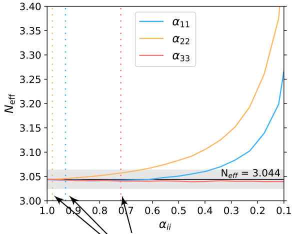
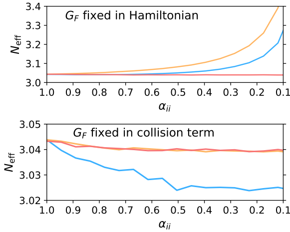
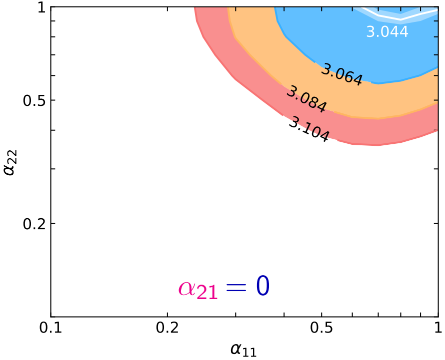
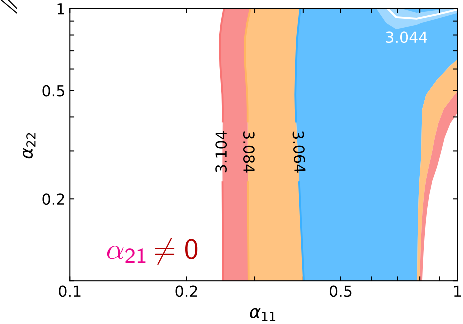






$\alpha_{21} = 0$



$\alpha_{21} \neq 0$

(α_{21} marginalized over)

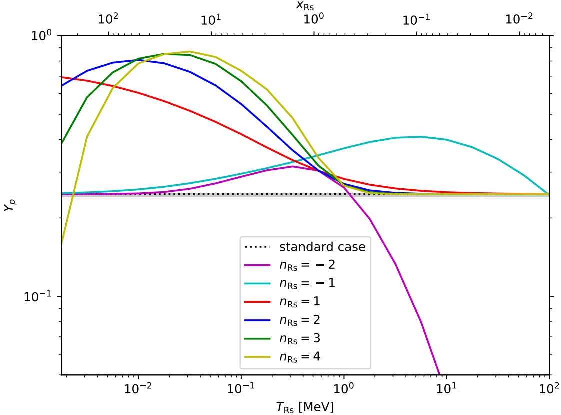
Confidence regions from future CMB measurements with $\delta N_{\rm eff} = 0.02$

C Additional particles

if sterile neutrinos are not enough

Based on:

- in preparation (1)
- in preparation (2)



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

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

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

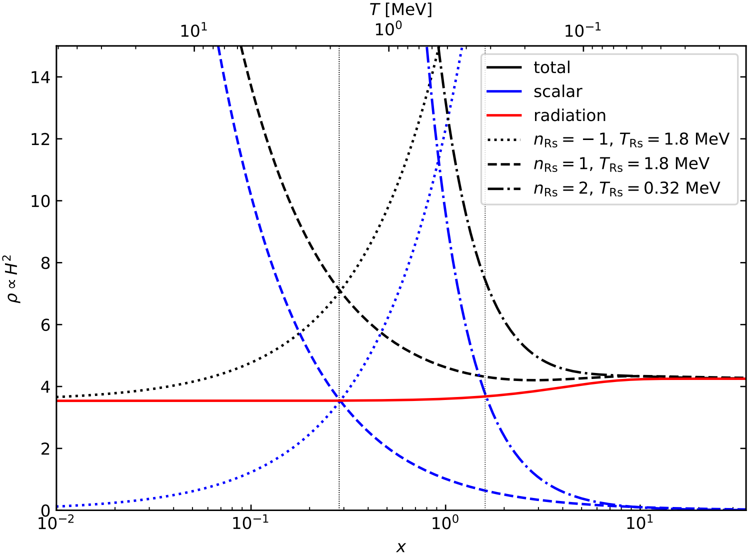
$X_i = n_i/N_B$ abundance relative to total baryons, Γ_i effective reaction rate for nuclide i

Results from $N_{\rm eff}$

[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:



Results from $N_{\rm eff}$

[in preparation]

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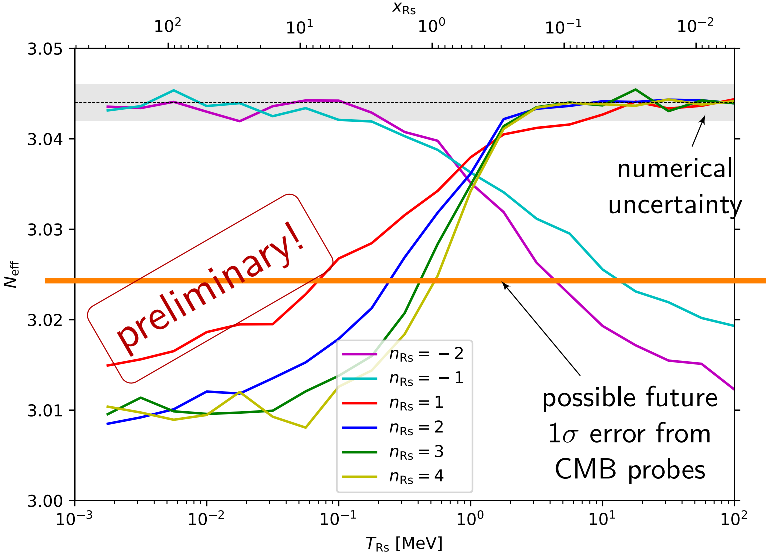
From neutrino decoupling we obtain:



numerical uncertainty

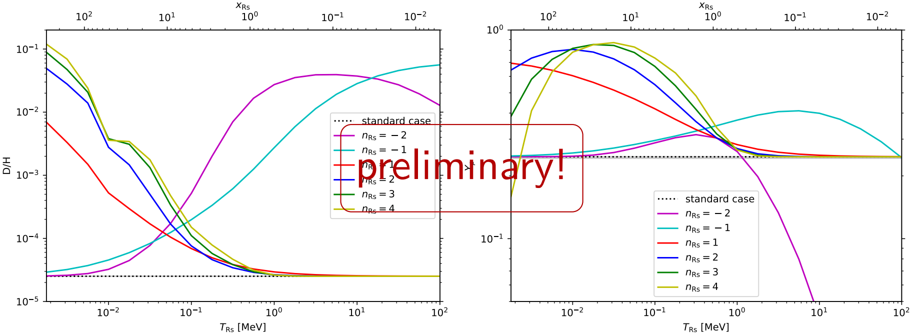
possible future 1σ error from CMB probes

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):



preliminary!

error bands (gray) are current constraints on the abundances

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

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

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

Scenarios with low reheating temperature

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neutrinos are populated by weak interactions with electrons!

if reheating occurs too late, neutrinos are not generated and $N_{\rm eff} < 3$

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Low reheating temperature: when reheating occurs at $T_{\rm rh} \lesssim 20$ MeV

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

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

what about sterile neutrinos?

$N_{\rm eff}$ with low reheating

[in preparation]

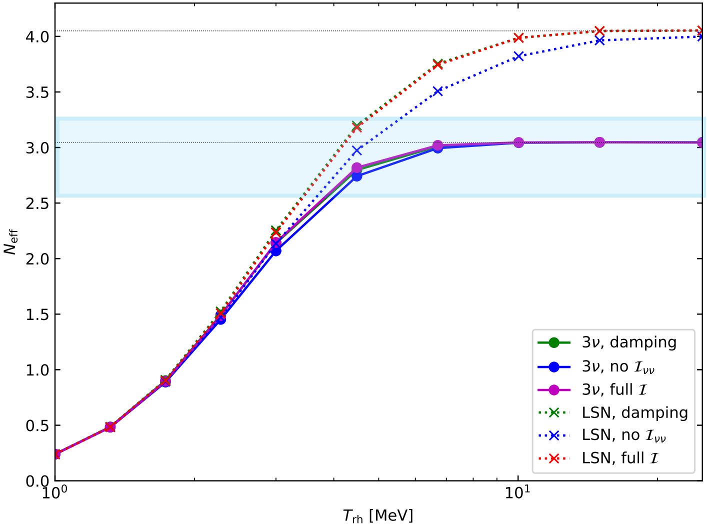
Need to edit equations for inflaton energy density and its contribution:

$$
\begin{aligned}
\frac{\mathrm{d}\varrho(y)}{\mathrm{d}x} &= \text{unchanged}\\
\frac{\mathrm{d}\rho_\phi}{\mathrm{d}x} &= -\frac{x\rho_\phi\Gamma_\phi}{m_e^2}\sqrt{\frac{3m_{\rm Pl}^2}{8\pi\rho_{\rm tot}}}\\
\frac{\mathrm{d}z}{\mathrm{d}x} &= \frac{\displaystyle\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J_2(r_\ell)\right]+G_1(r)-\frac{1}{2z^3}\sum_{\alpha=e}^{s}\frac{\mathrm{d}\rho_{\nu_\alpha}}{\mathrm{d}x}-\frac{x}{2z^3}\frac{\mathrm{d}\rho_\phi}{\mathrm{d}x}}{\displaystyle\sum_{\ell=e,\mu}\left[r_\ell^2J_2(r_\ell)+J_4(r_\ell)\right]+G_2(r)+\frac{2\pi^2}{15}}\\
\rho_{\rm tot} &= \sum_{i=\gamma,\nu_j,e,\mu}\rho_i+\delta\rho(x,z)+x\rho_\phi\\
\Gamma_\phi &\simeq \left(\frac{T_{\rm rh}}{0.7\mathrm{MeV}}\right)^2\mathrm{sec}^{-1}
\end{aligned}
$$

$N_{\rm eff}$ with low reheating

[in preparation]

$N_{\rm eff}$ as a function of $T_{\rm rh}$ (3 or 3+1 neutrinos):

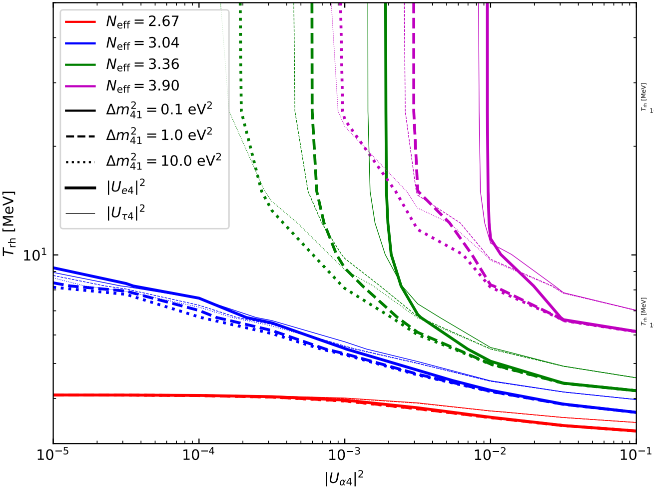


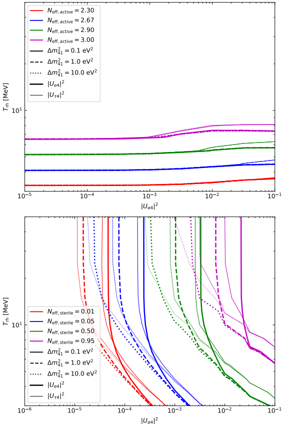
Planck constraint: $N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

$N_{\rm eff}$ with low reheating

[in preparation]

sterile case with varying mixing angle/mass splitting:





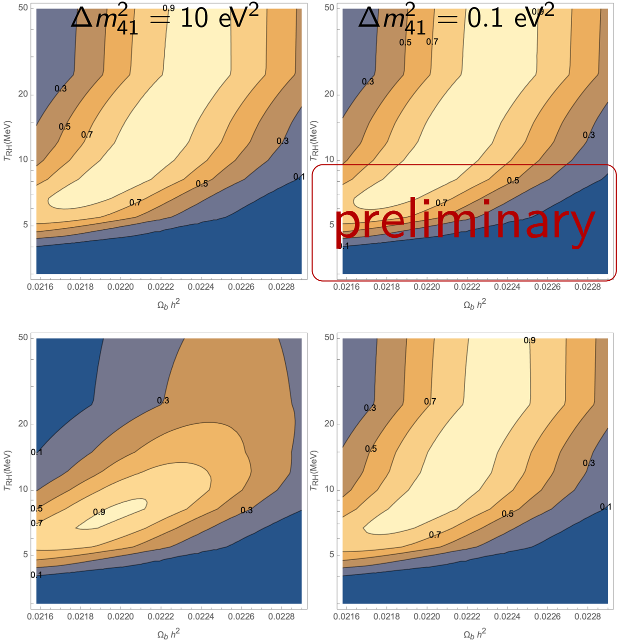
active,
sterile
contribution
to $N_{\rm eff}$

for low $T_{\rm rh}$, mixing parameters are irrelevant

for higher Δm^2_{41}, $T_{\rm rh}$ has more impact

BBN and low reheating

[in preparation]



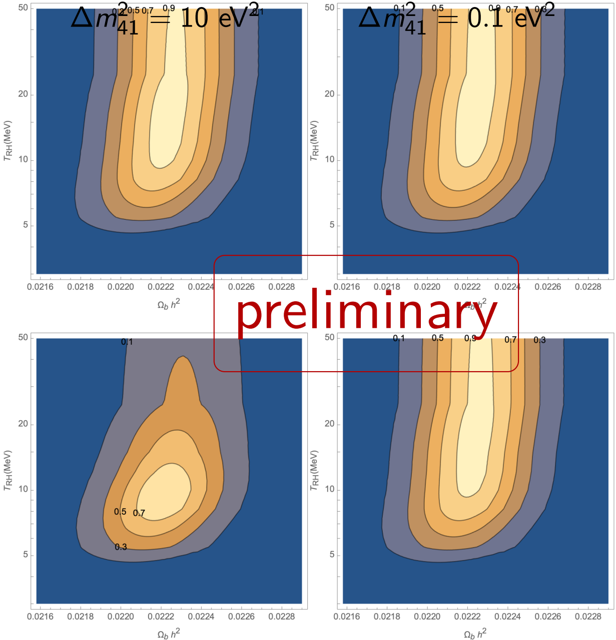
$|U_{e4}|^2 = 10^{-5}$

BBN (D+He) only

$|U_{e4}|^2 = 10^{-4}$

BBN and low reheating

[in preparation]



$\Delta m^2_{41} = 10$ eV^2

$\Delta m^2_{41} = 0.1$ eV^2

preliminary

$|U_{e4}|^2 = 10^{-5}$

BBN + Planck18

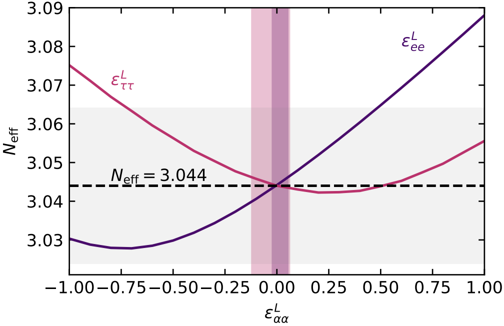
$|U_{e4}|^2 = 10^{-4}$

D Non-standard neutrino interactions

Neutrino-electron interactions, bosonic neutrinos (?!? what?)

Based on:

- JCAP 03 (2018) 050
- PLB 820 (2021) 136508



Non-standard neutrino-electron interactions

[PLB 820 (2021)]

Can neutrinos have interactions beyond the SM ones?

e.g.: $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NSIe}$, with $\mathcal{L}_{\rm NSIe} \propto G_F \sum_{\alpha,\beta} \epsilon^{L,R}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{e} \gamma_\mu P_{L,R} e)$

see e.g. [Farzan+, 2018]

coupling strength governed by the $\epsilon^{L,R}_{\alpha\beta}$ coefficients $(\alpha = e, \mu, \tau)$

new interactions affect all phenomena involving neutrinos and electrons

including neutrino decoupling:

collision terms

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

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

$\downarrow$

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

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)]

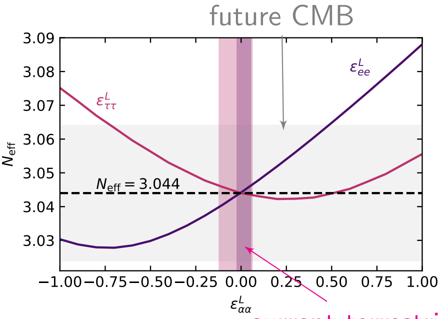
$$G^{L,R} = G^{L,R}_{SM} + \begin{pmatrix} \epsilon^{L,R}_{ee} & \epsilon^{L,R}_{e\mu} & \epsilon^{L,R}_{e\tau} & \cdots \\ \epsilon^{L,R}_{e\mu} & \epsilon^{L,R}_{\mu\mu} & \epsilon^{L,R}_{\mu\tau} & \cdots \\ \epsilon^{L,R}_{e\tau} & \epsilon^{L,R}_{\mu\tau} & \epsilon^{L,R}_{\tau\tau} & \cdots \\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

e.g.:

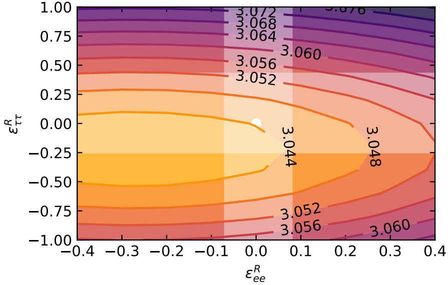
$G^L_{ee} \rightarrow 0.727 + \epsilon^L_{ee}$

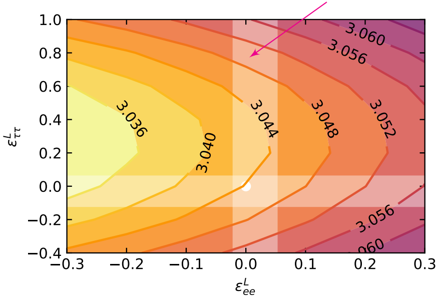
$G^L_{\tau\tau} \rightarrow -0.273 + \epsilon^L_{\tau\tau}$

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



current terrestrial





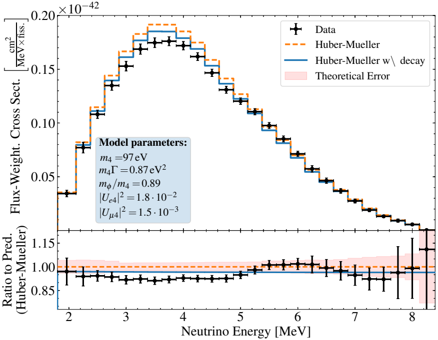
Can new physics solve the anomalies and tensions?

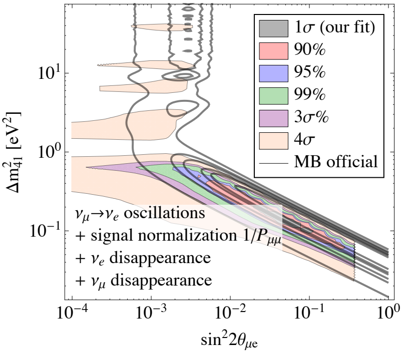
Many attempts to explain LSND/MiniBooNE anomalies,
APP vs DIS, oscillations vs cosmo tensions with new physics

one recent example: [Dentler+, 2019]

$\mathcal{L} \supset -g\bar{\nu}_s\nu_s\phi$ with $\mathcal{O}(\text{eV}) \lesssim m_4 \lesssim \mathcal{O}(100\ \text{keV})$ and $m_\phi \lesssim m_4$

$\hookrightarrow$ new interactions with scalar ϕ and ν_s decay





see also: [de Gouvea+, 2019], [Moulai+, 2019], [Fischer+, 2019], [Diaz+, 2019], ...

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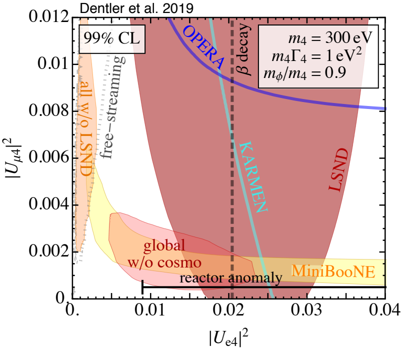

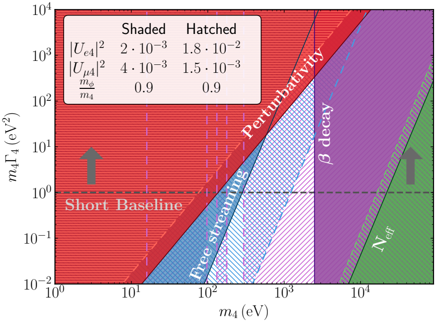

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another example: [Liao+, 2019]

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon^{fC}_{\alpha\beta}[\overline{\nu_\alpha}\gamma^\rho P_L\nu_\beta]\left[\bar{f}\gamma_\rho P_C f\right]$$

$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F\epsilon^{ff'C}_{\alpha\beta}[\overline{\nu_\beta}\gamma^\rho P_L\ell_\alpha]\left[\bar{f}'\gamma_\rho P_C f\right]$$

Non-standard interactions (NSI) involving ν_s

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Many attempts to explain LSND/MiniBooNE anomalies, APP vs DIS, oscillations vs cosmo tensions with new physics

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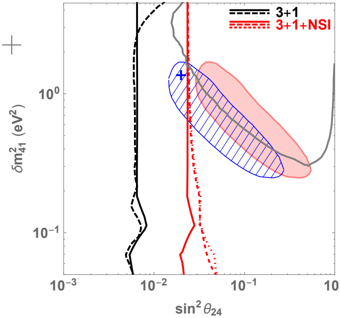
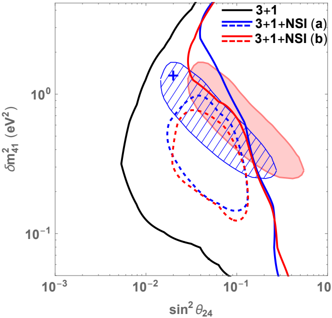
Non-standard interactions (NSI) involving ν_s

MINOS+ vs APP





IceCube/ DeepCore vs APP

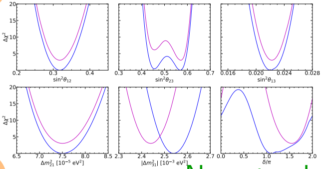
Z Conclusions

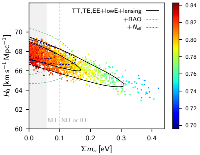
almost there!

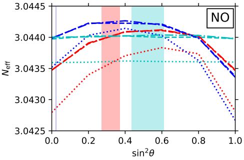
What do we know about neutrinos?

P

Standard scenario: precision

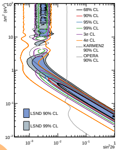


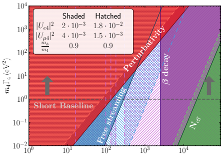


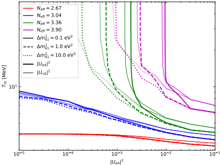


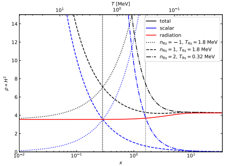
E

Non-standard scenarios: exploration



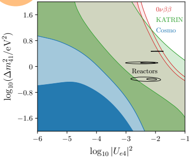


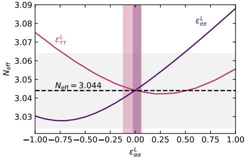


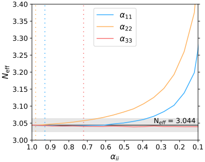


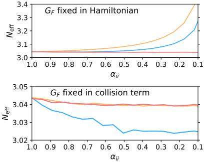
S

Terrestrial and different cosmological measurements - synergy









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P

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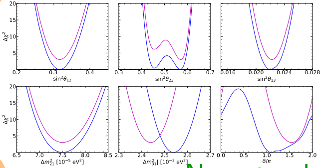
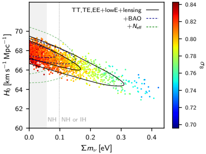
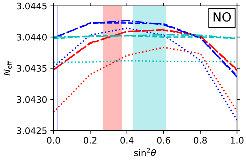
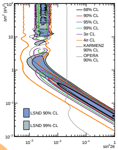


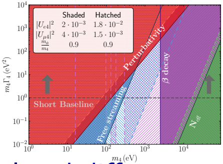


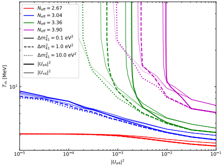


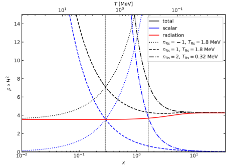
E

Non-standard scenarios: exploration









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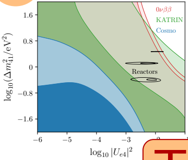

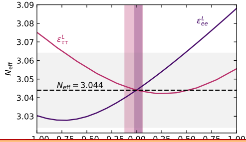

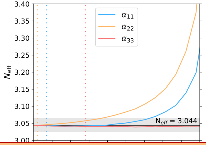

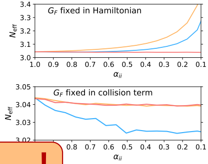

Thanks for your attention!