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New neutrino physics with terrestrial and early universe probes

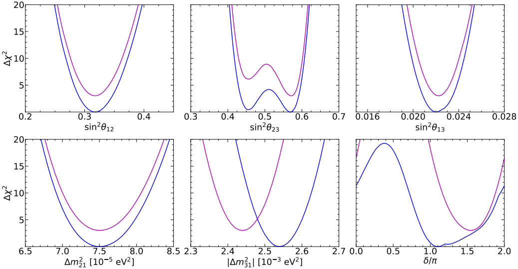
Instituto de Fisica Teorica (UAM/CSIC), 11/05/2023

A Active neutrinos

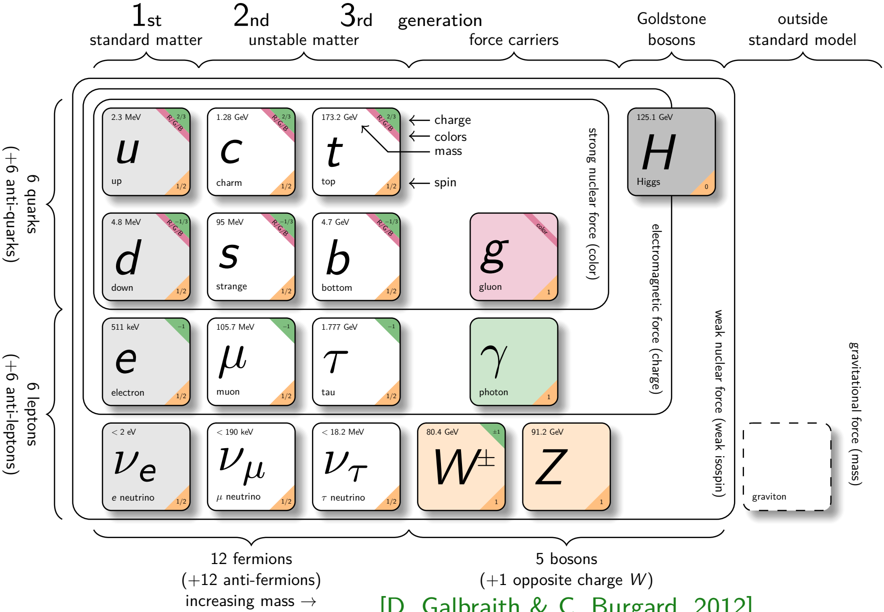
Spoiler: “Sterile” will come later

Based on:

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

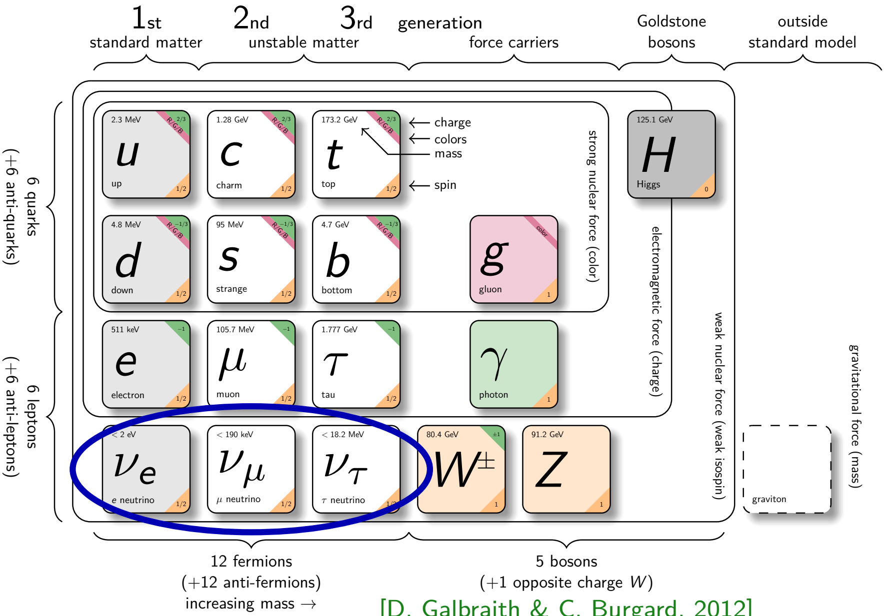


The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics



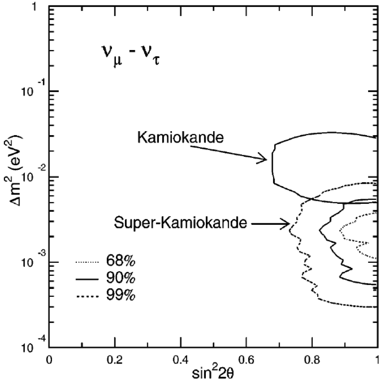
[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

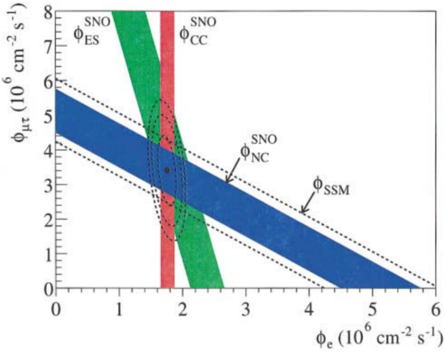
Major discoveries:

[SuperKamiokande, 1998]

[SNO, 2001-2002]



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



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

Nobel prize in 2015

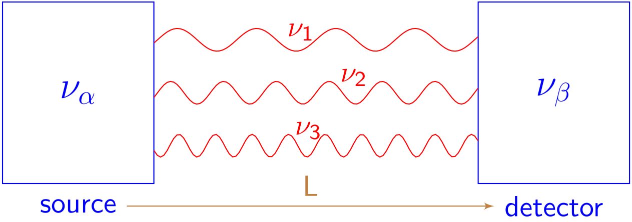
Two neutrino bases

flavor neutrinos ν_α

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

massive neutrinos ν_k

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



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

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

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

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

The mixing matrix

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

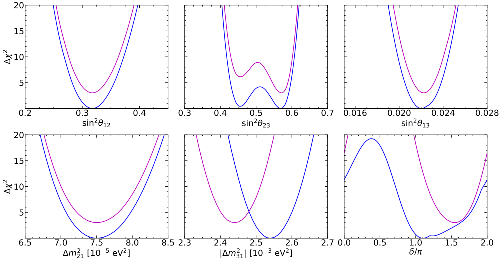
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

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

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

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

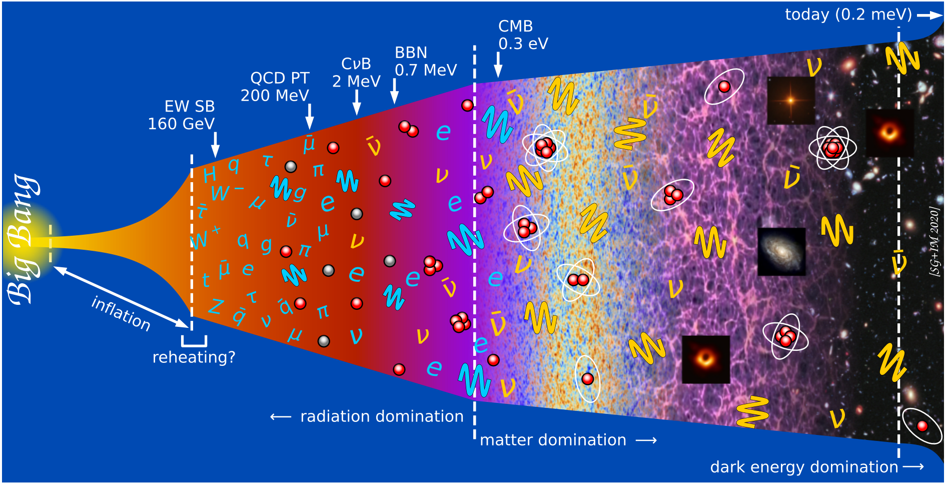


mass ordering
still unknown

δ still unknown

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

History of the universe



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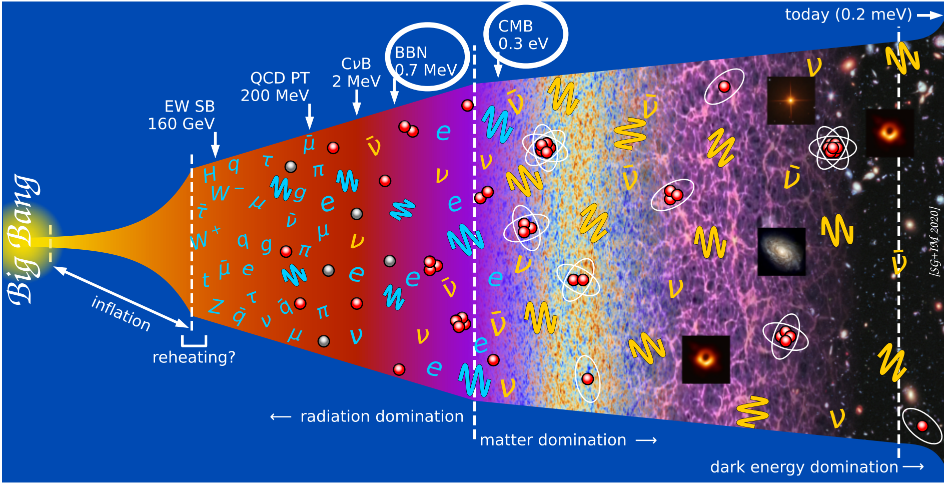

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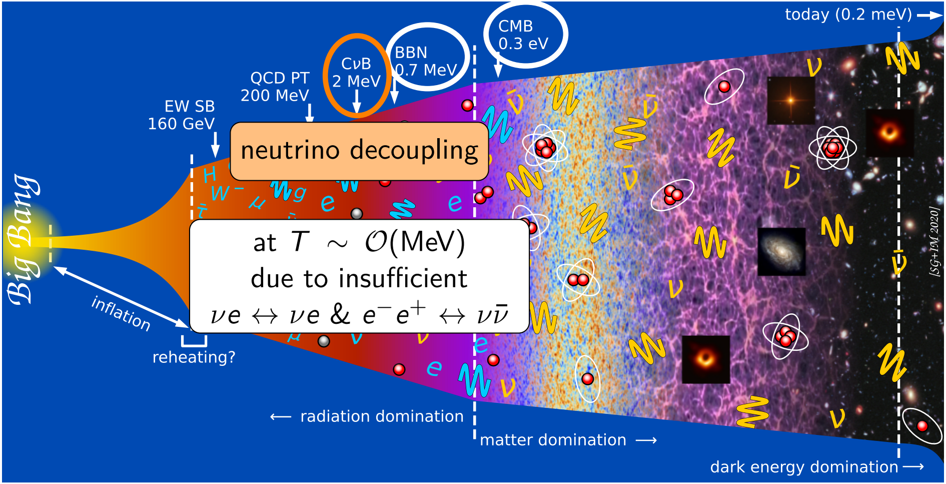


neutrino decoupling

at $T \sim \mathcal{O}(\mathrm{MeV})$

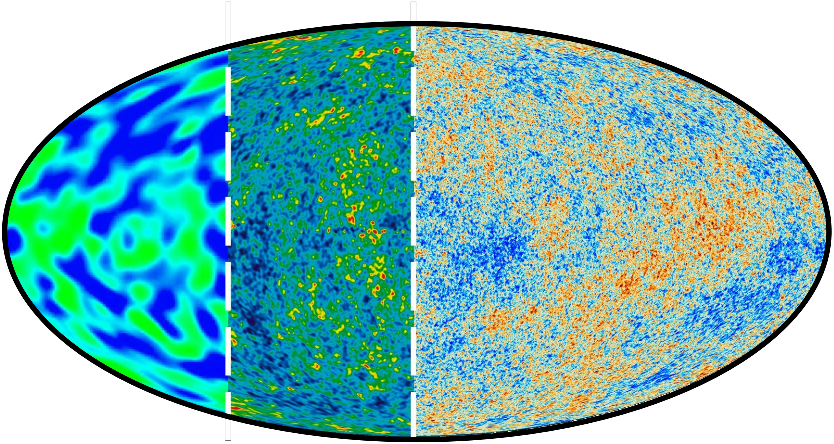
due to insufficient

$\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

The oldest picture of the Universe

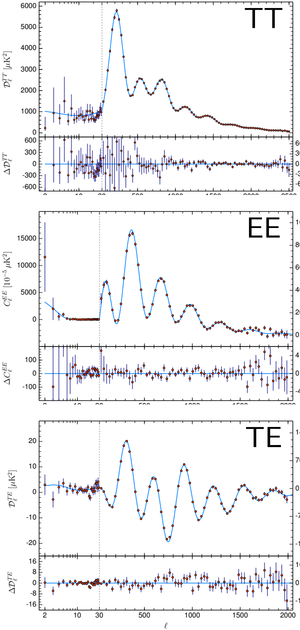
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

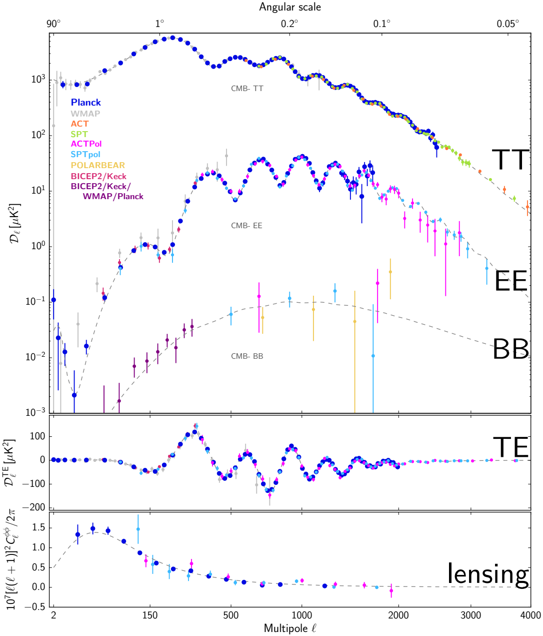
COBE (1992) WMAP (2003) Planck (2013)



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

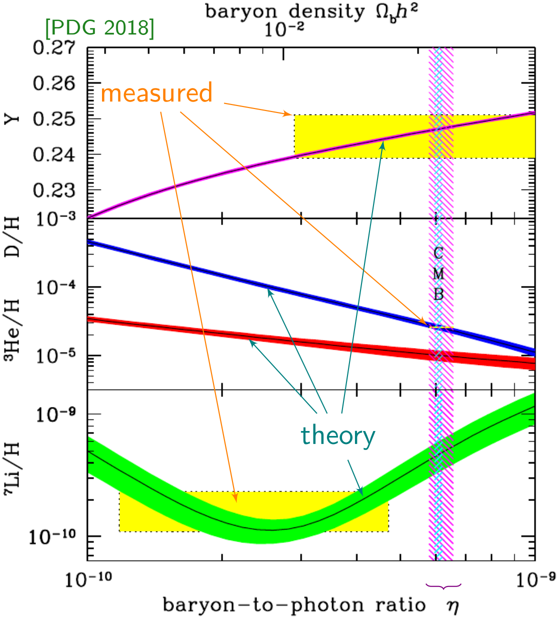
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

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. . .



BBN concordance

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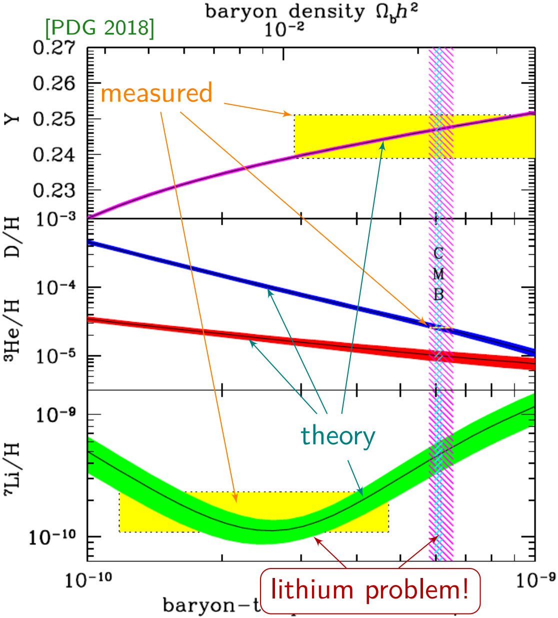


[PDG 2018]

measured

theory

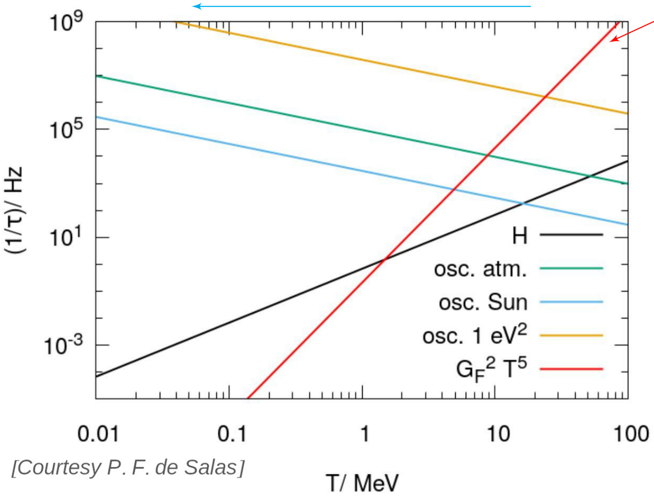
lithium problem!

BBN concordance

Neutrinos in the early Universe

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

time



[Courtesy P. F. de Salas]

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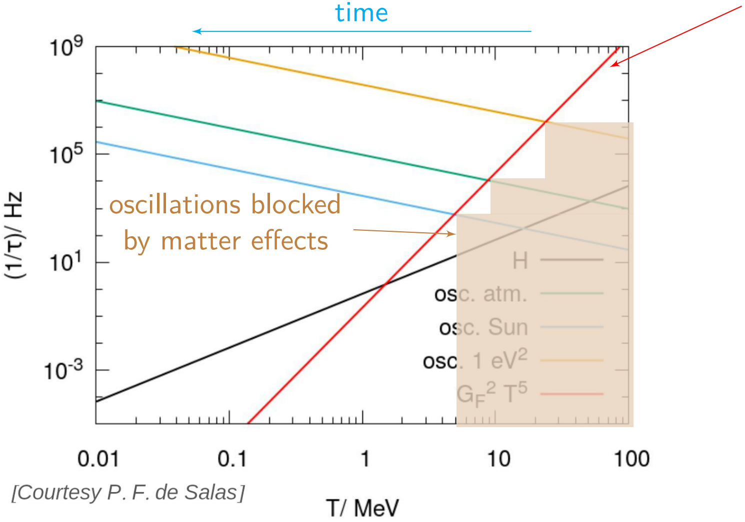

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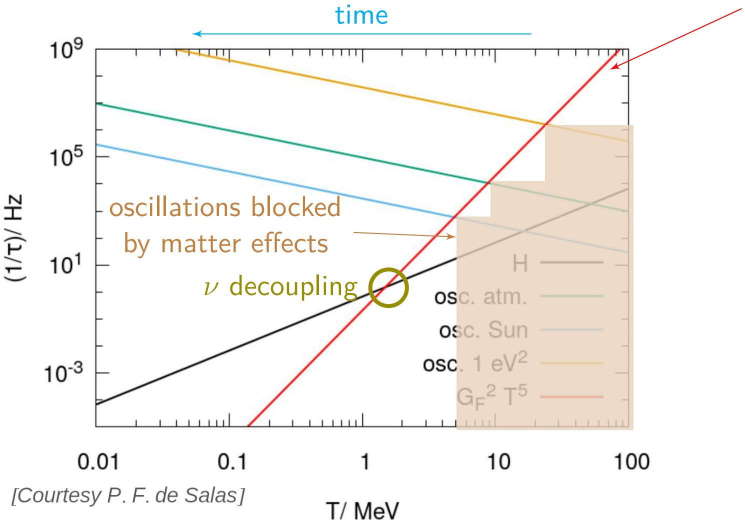
time

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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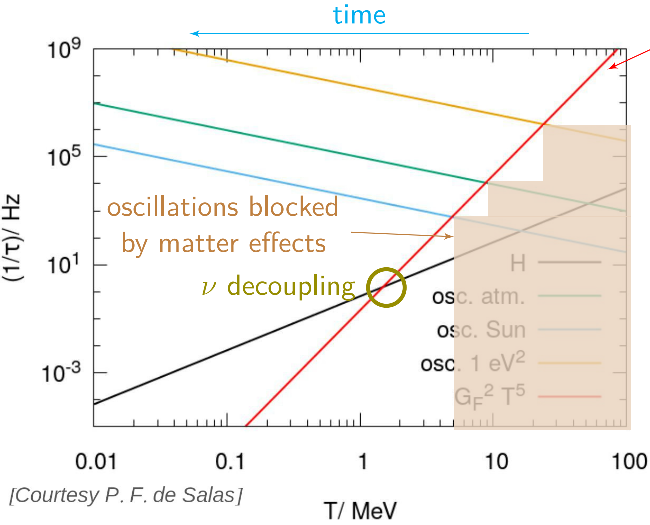

oscillations blocked by matter effects

ν decoupling

[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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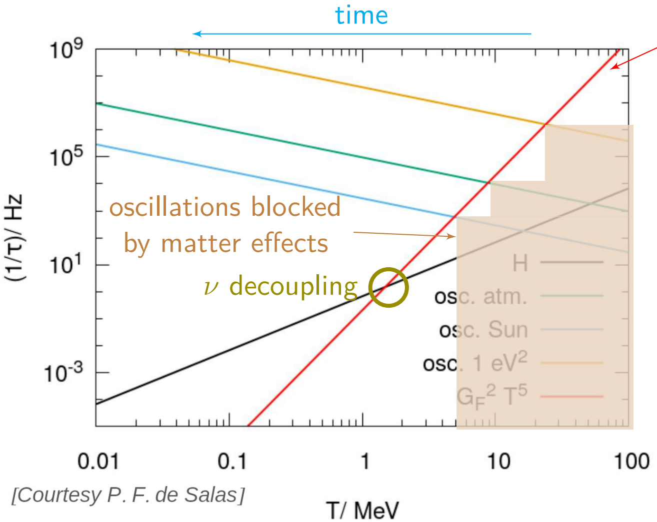

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actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

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

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

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

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

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

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$\propto \langle a_j^\dagger(p,t)\, a_i(p,t) \rangle$

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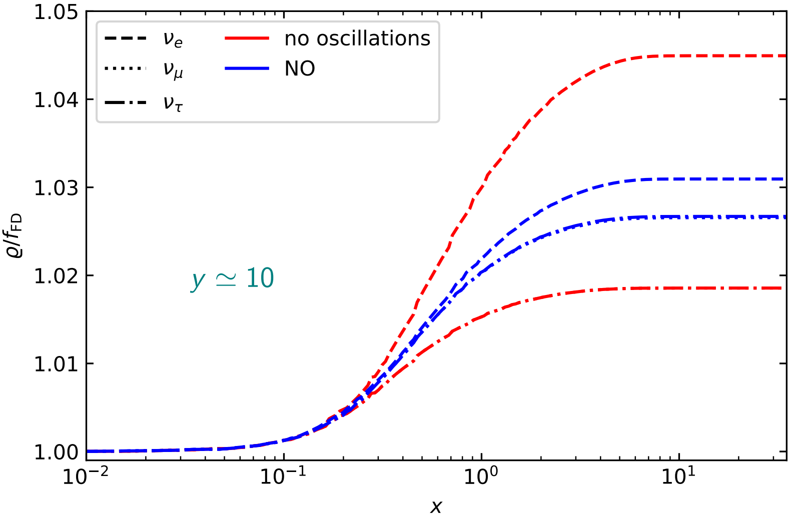
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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

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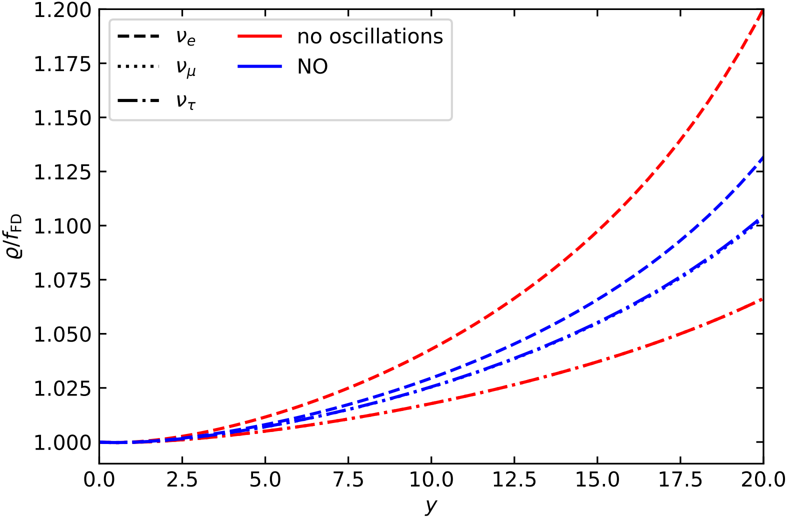
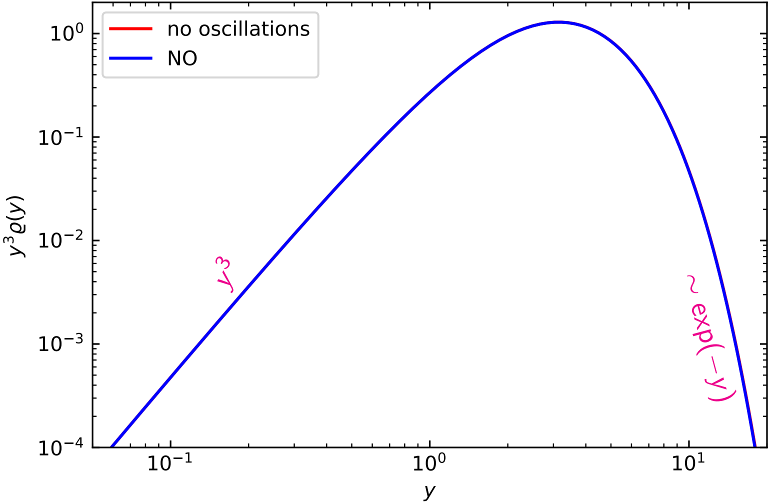


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

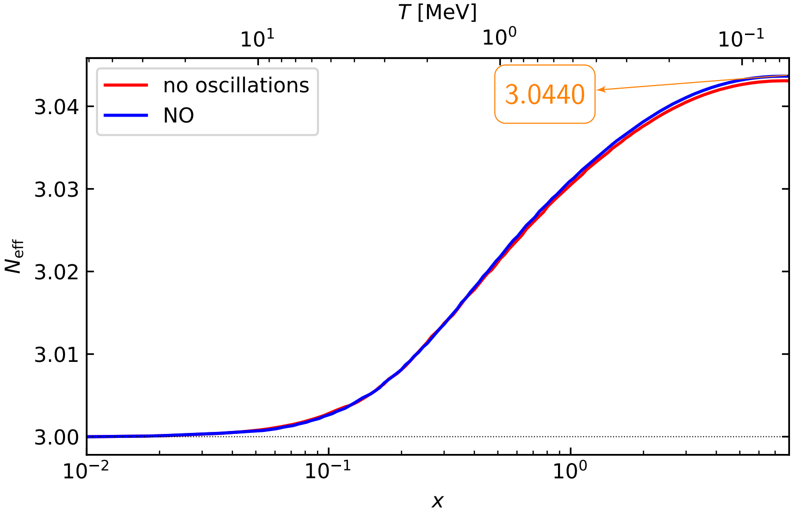
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



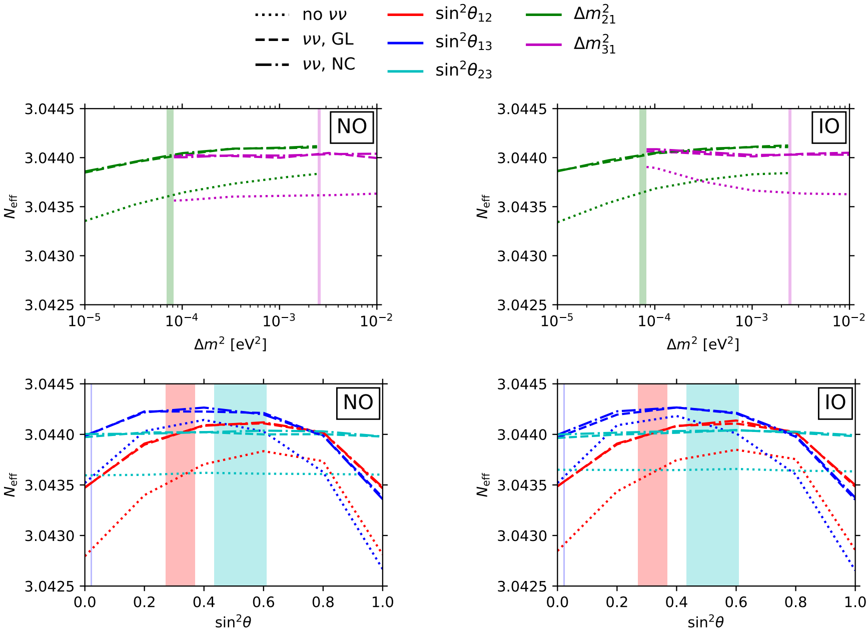
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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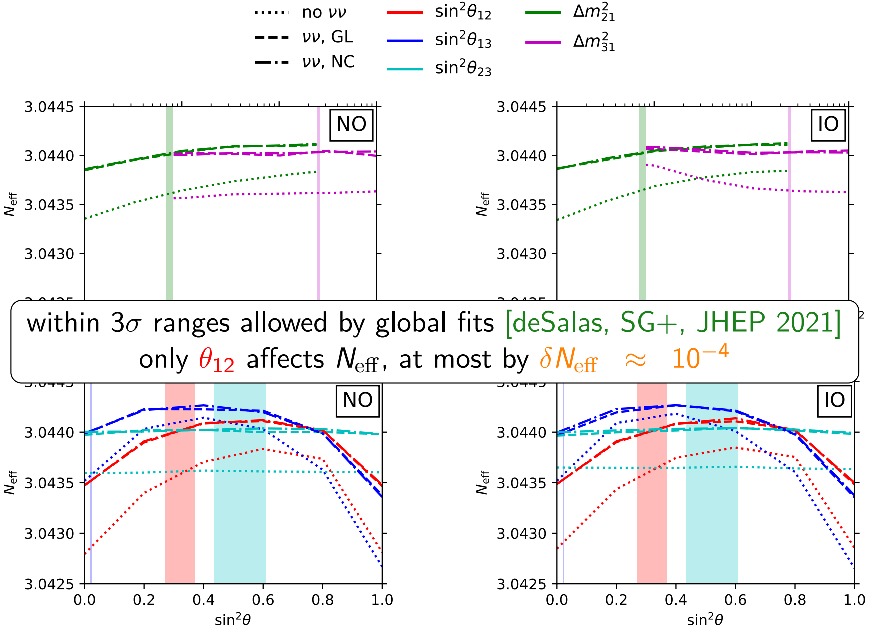
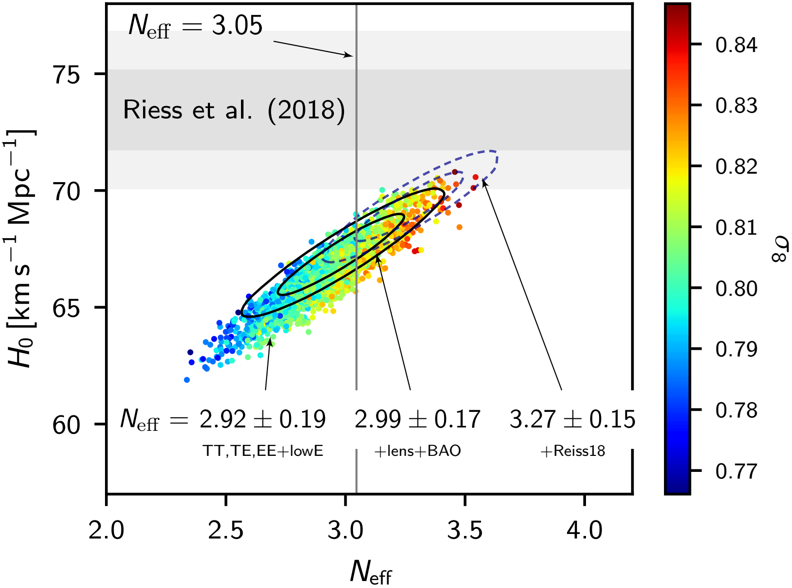


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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

$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]



$N_{\rm eff}$ and BBN

$$\boxed{\begin{array}{c}\text{BBN: production of light nuclei} \\ \text{at } t \sim 1\text{s to } t \sim \mathcal{O}(10^2)\text{s}\end{array}}$$

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

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

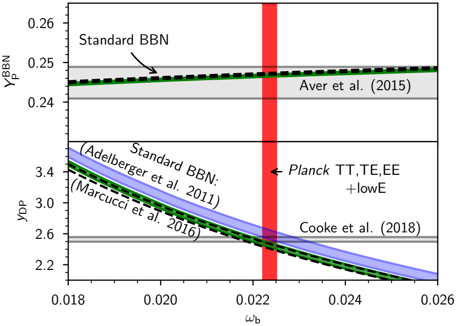
which controls element abundances

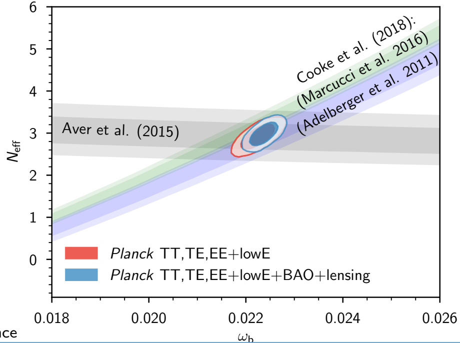
$$\boxed{g_\star \text{ depends on } N_{\rm eff}}$$

$$\downarrow$$

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_{eff} and BBN

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$g_\star$ depends on N_{eff}

$$\downarrow$$

abundances depend on N_{eff}

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n, p: neutron, proton density number
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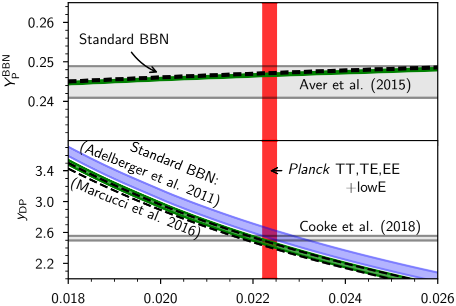
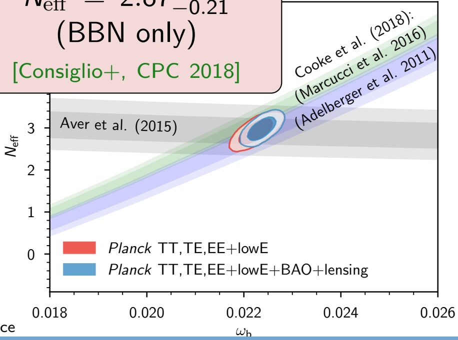
[Planck Collaboration, 2018]

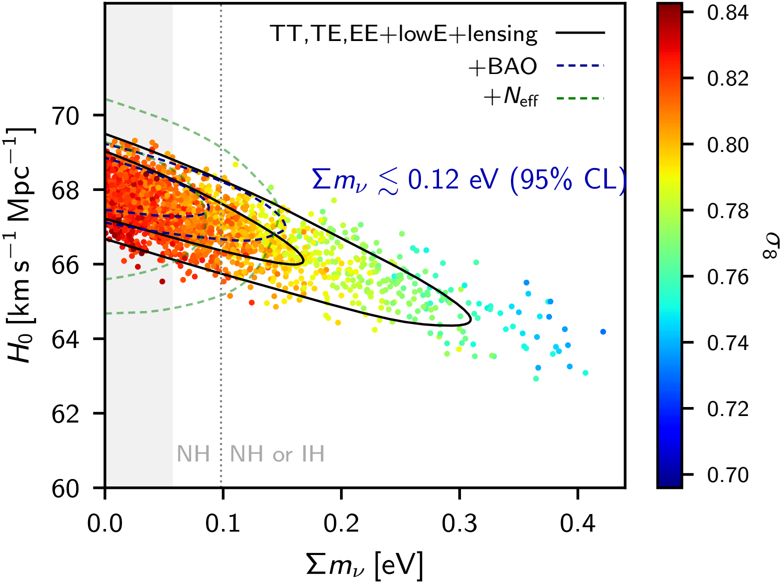


$N_{\mathrm{eff}} = 2.87^{+0.24}_{-0.21}$
(BBN only)
[Consiglio+, CPC 2018]

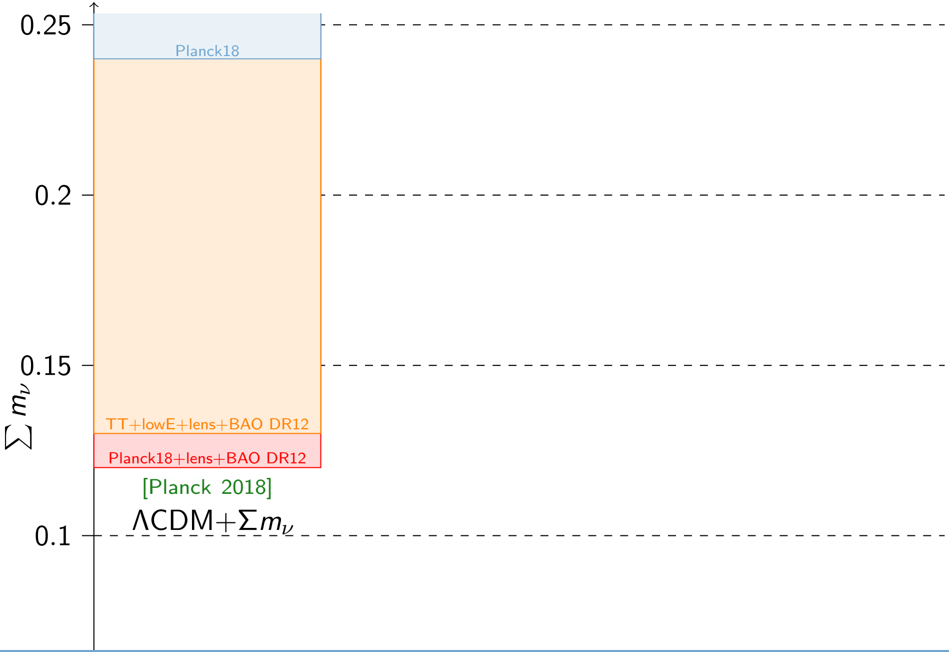


Σm_ν and CMB

[Planck Collaboration, 2018]



Cosmological neutrino mass bounds (95% CL)



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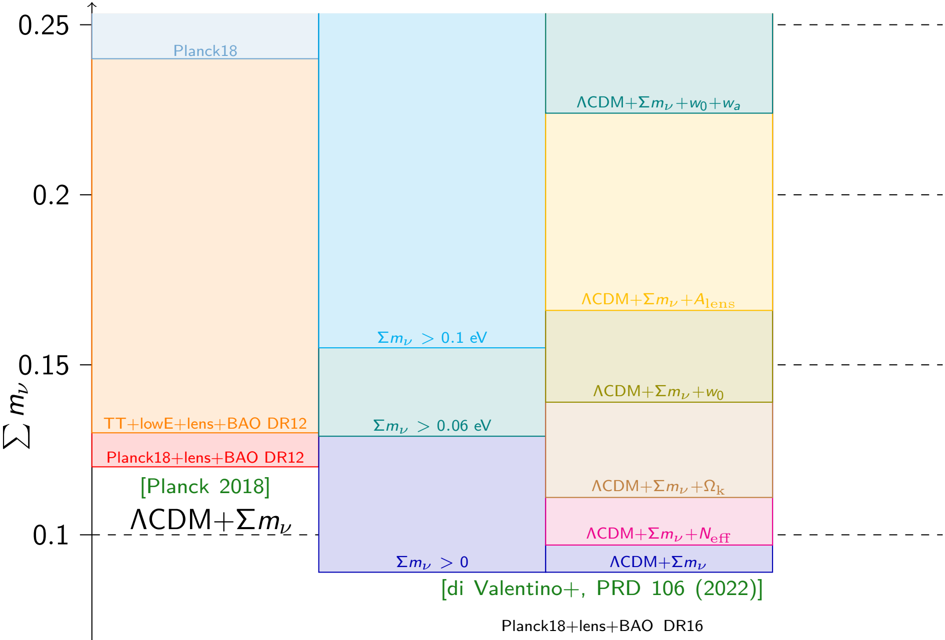

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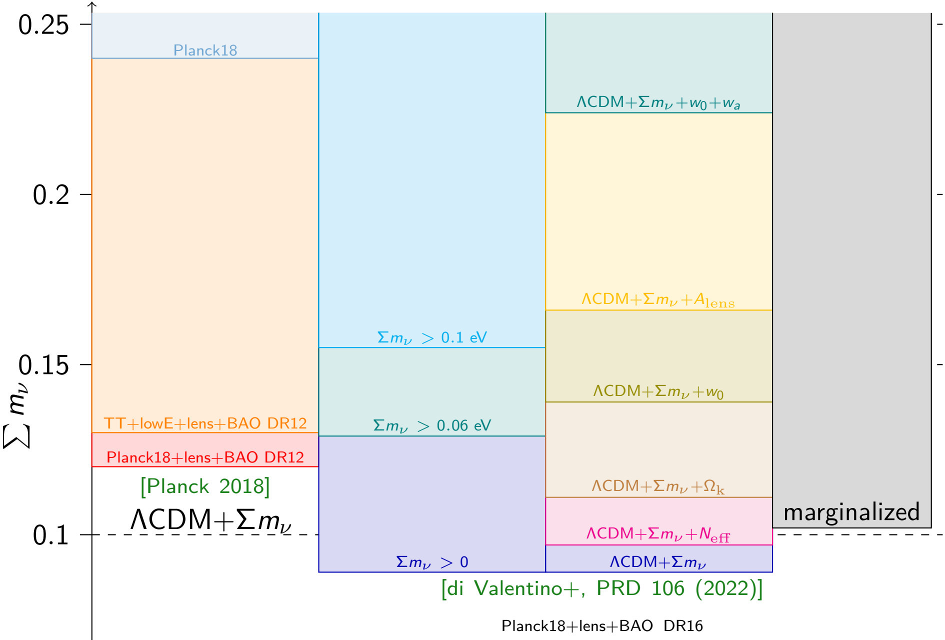


Can a cosmological limit on Σm_ν disfavor IO?

[PDU (2023)]

standard factor

Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\text{ eV})$

NO: $\Sigma m_\nu \gtrsim 0.06$ eV

Current: $\Sigma m_\nu \lesssim 0.1$ eV (95%)

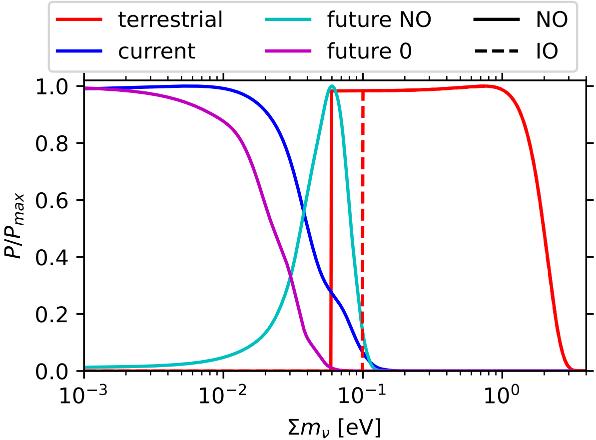
IO: $\Sigma m_\nu \gtrsim 0.1$ eV

Future sensitivity: $\sigma(\Sigma m_\nu) \simeq 0.02$ eV

Still preferring $\Sigma m_\nu = 0$?

Will measure e.g. $\Sigma m_\nu = 0.06$ eV?

tension ever
with NO!



confirm NO,
disfavor IO

Can a cosmological limit on Σm_ν disfavor IO?

[PDU (2023)]

standard factor

Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12 \text{ eV})$

Is there a tension between cosmology and oscillations?

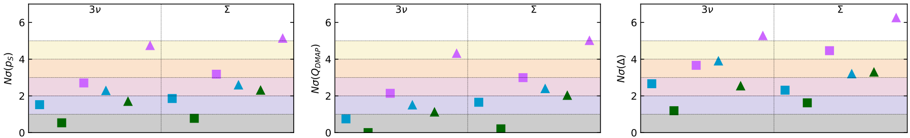
or will there be a tension?

several possible tests can be considered, similar results

$\Sigma m_\nu \lesssim 0.1$ eV (95%) ● current ■ NO

$\Sigma m_\nu = 0.06 \pm 0.02$ eV (1σ) ● future NO ▲ IO

$\Sigma m_\nu = 0.00 \pm 0.02$ eV (1σ) ● future 0



currently only mild tension between cosmology and oscillations

future NO can be at $\sim 2\sigma$ tension with IO

future 0 can be at $\sim 2-3\sigma$ tension with NO, $\gtrsim 4\sigma$ with IO

Can a cosmological limit on Σm_ν disfavor IO?

[PDU (2023)]

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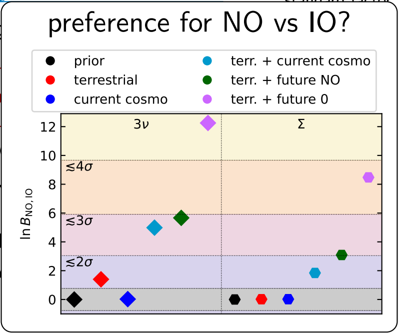
Is there a tension between cosmo

or will there be a t

several possible tests can be co



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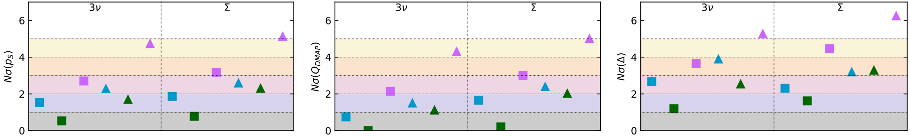


currently only mild tension between cosmology and oscillations

future NO can be at $\sim 2\sigma$ tension with IO

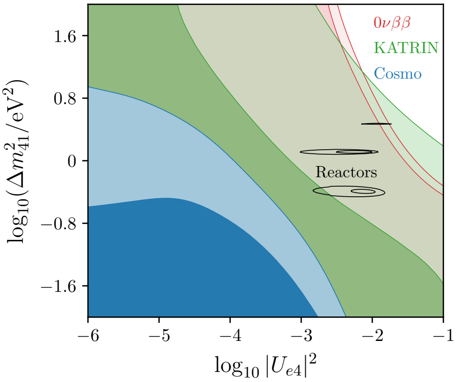
future 0 can be at $\sim 2-3\sigma$ tension with NO, $\gtrsim 4\sigma$ with IO

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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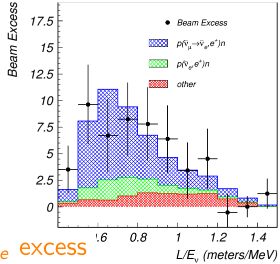
LSND



[Aguilar+, 2001]

3.8σ

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

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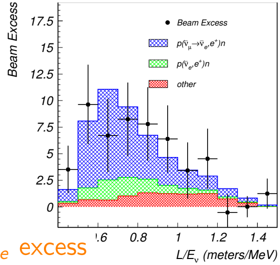

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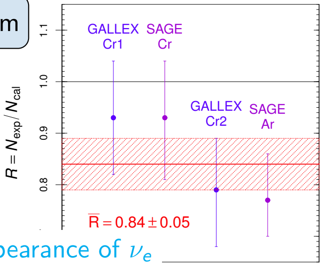
Gallium



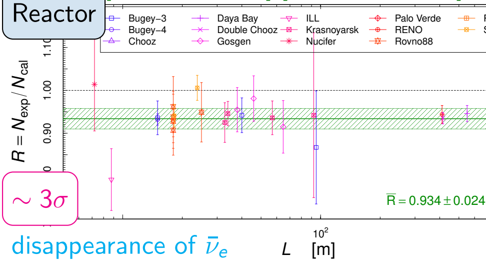
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

Reactor

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



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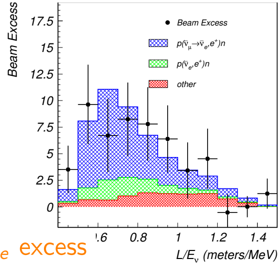

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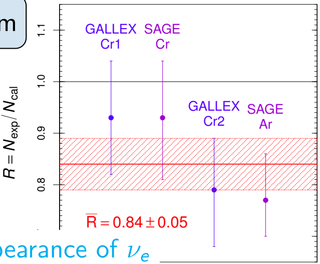

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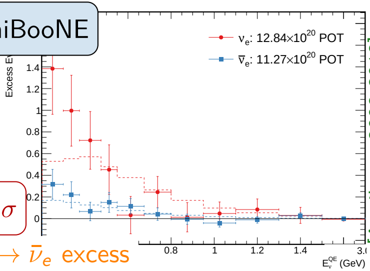
MiniBooNE



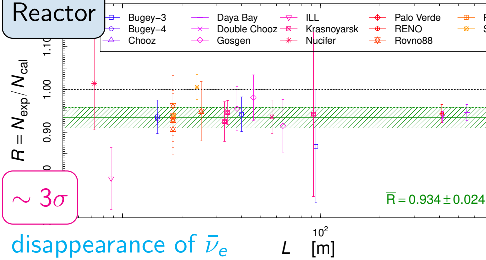
[Aguilar+, 2008-2018]

$\sim 5\sigma$

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

Reactor

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



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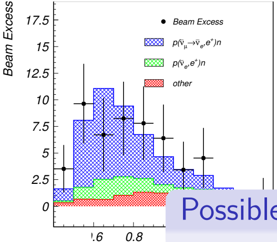

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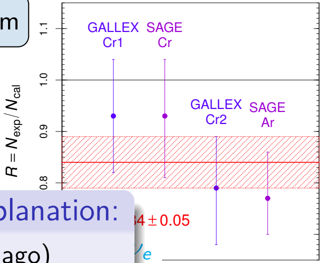
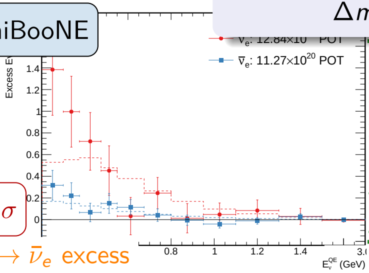


ν_e

[Giunti, Laveder, 2011]

MiniBooNE



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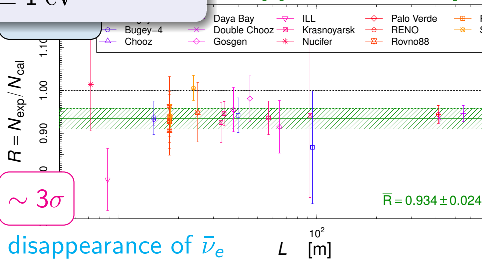

$\sim 3\sigma$

disappearance of $\bar{\nu}_e$ L [m]

Possible common explanation:

(until a few years ago)

Additional squared mass difference

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

Short BaseLine (SBL)

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

If $m_4 \gg m_\ell$, faster oscillations

ν_4 oscillations are averaged in most neutrino oscillation experiments

Effect of 4th neutrino only visible as global normalization

Short BaseLine (SBL) oscillations: $\frac{\Delta m^2_{41} L}{E} \simeq 1$

At SBL, oscillations due to Δm^2_{21} and $|\Delta m^2_{31}|$ do not develop

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source of $\overset{(-)}{\nu}_\alpha$

detect different flavor $\overset{(-)}{\nu}_\beta$

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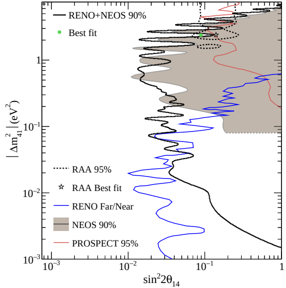
$\overset{(-)}{\nu}_s$ goes undetected

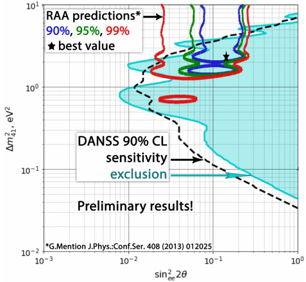
CP violation cannot be observed in SBL experiments!

ν_s at reactors in 2020

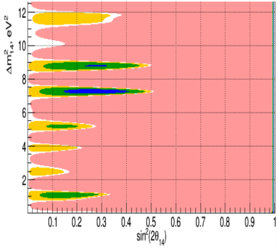
[RENO+NEOS, 2020]



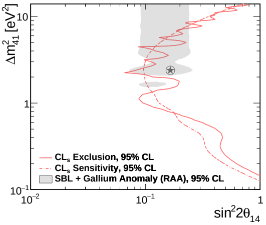
[DANSS, 2020]



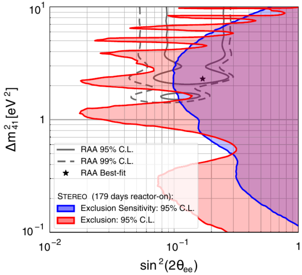
[Neutrino-4, PZETF 2020]



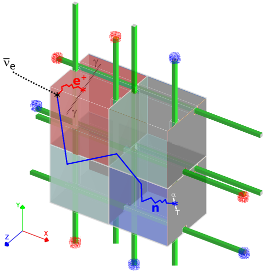
[PROSPECT, PRD 2020]



[STEREO, PRD 2020]

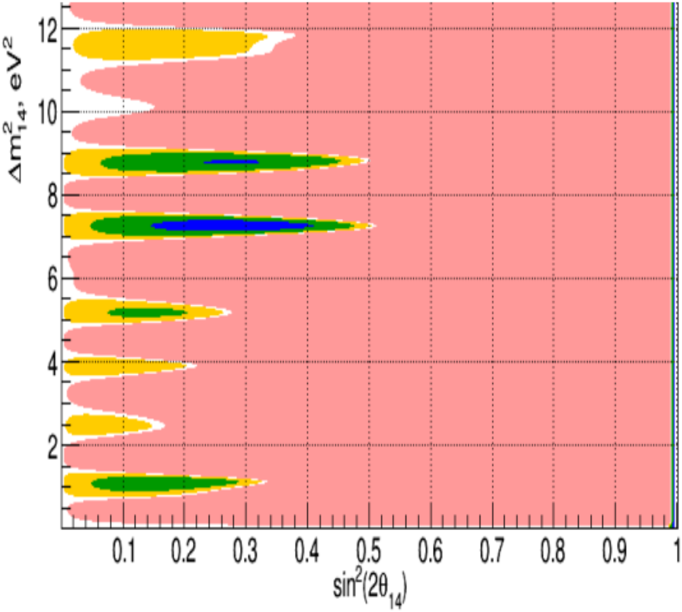


[SoLiD, JINST 2021]



Neutrino-4

[Neutrino-4 2020]

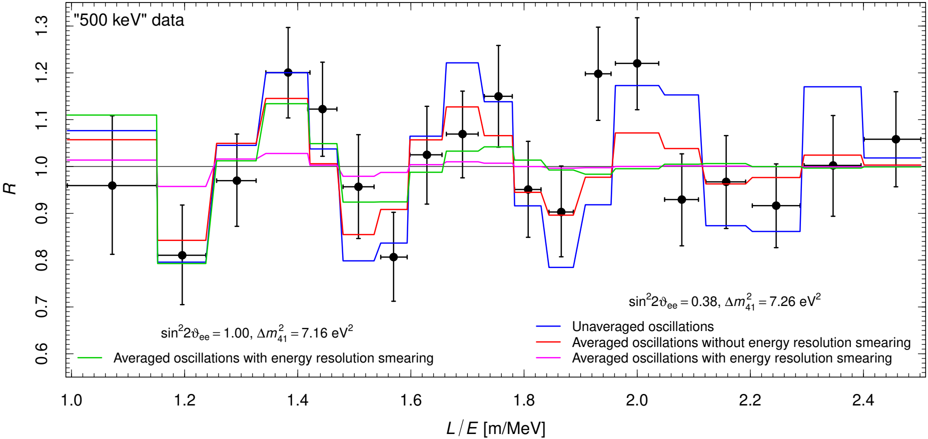


claimed $> 3\sigma$ preference for 3+1 over 3ν case

best fit incompatible with other reactor experiments

Neutrino-4

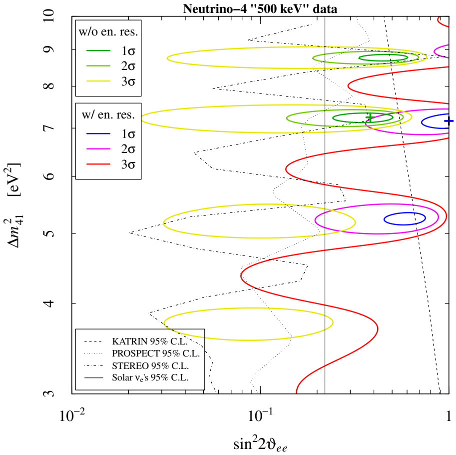
[Giunti+, PLB 2021]



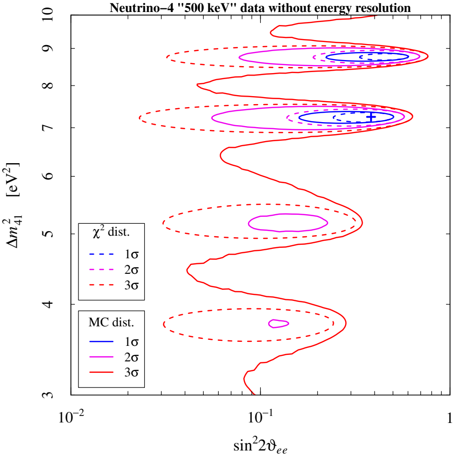
energy resolution smearing not properly taken into account?

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

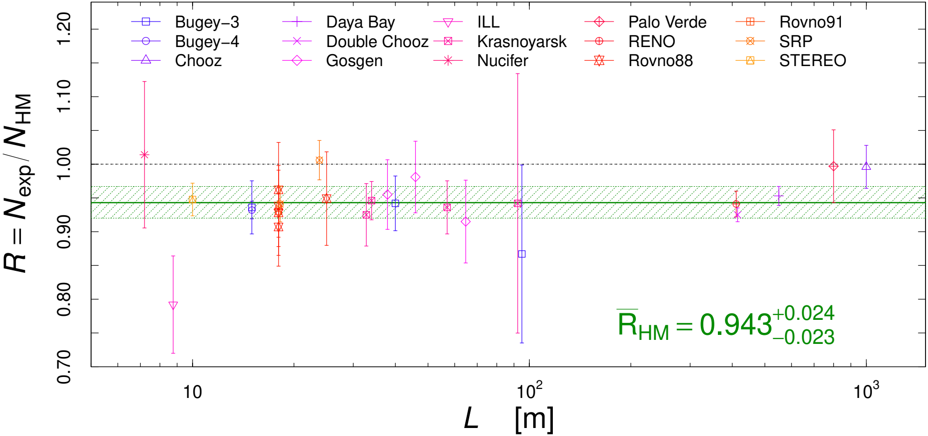
Reactor antineutrino spectrum and RAA

[Giunti+, PLB 2022]

When the RAA was discovered:

conversion method (ILL data) and *ab initio* calculations in agreement

[Huber, 2011], [Mueller+, 2011] spectra



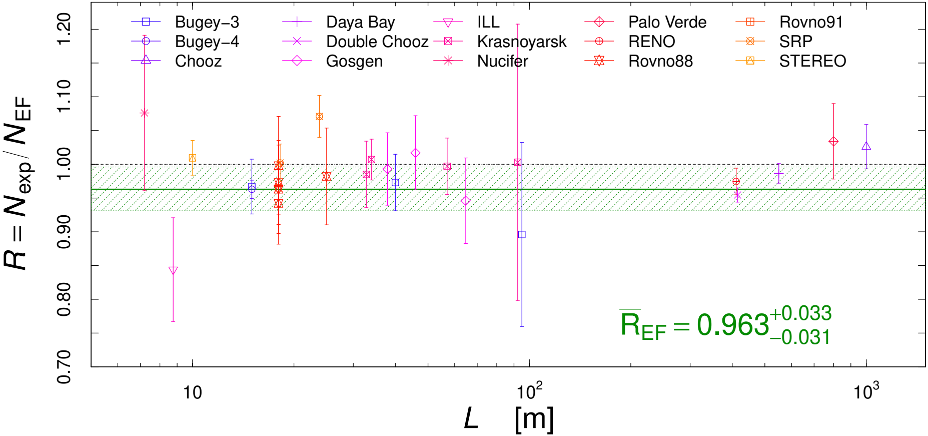
$\sim 2.4\sigma$ deficit $\Longrightarrow$ anomaly!

Reactor antineutrino spectrum and RAA

[Giunti+, PLB 2022]

Revised *ab initio* calculation:

[Estienne, Fallot+, PRL 123 (2019)]



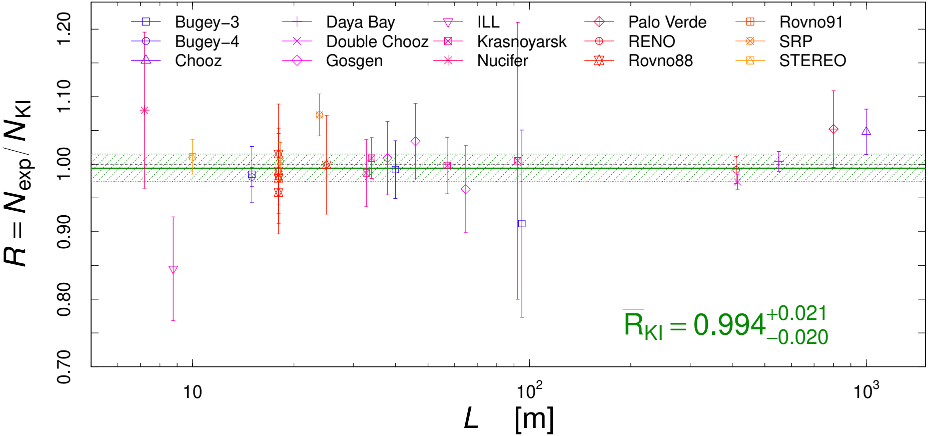
$\sim 1.2\sigma$ deficit $\Longrightarrow$ no anomaly!

Reactor antineutrino spectrum and RAA

[Giunti+, PLB 2022]

Conversion method on new measurements of electron spectrum at Kurchatov Institute (KI) (updates ILL measurements from the 80's):

[Kopeikin+, PRD 2021]



approximate agreement with EF fluxes, no anomaly!

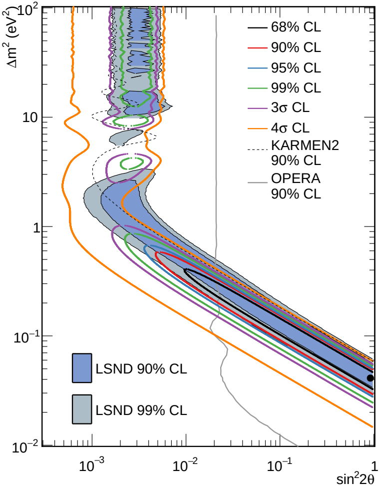
MiniBooNE

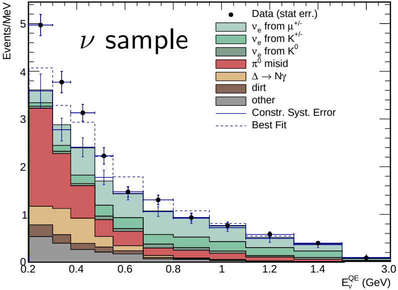
[PRL 121 (2018) 221801]

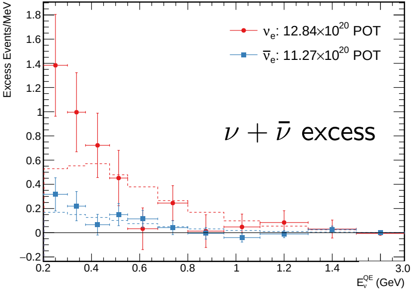
purpose: check LSND signal

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

no money, no near detector







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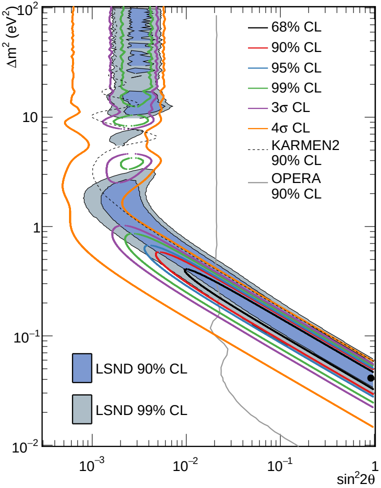
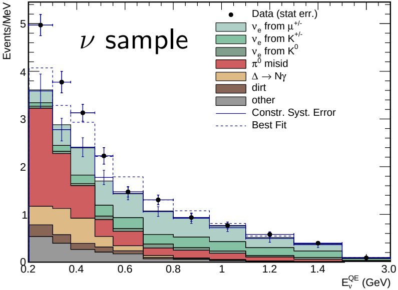
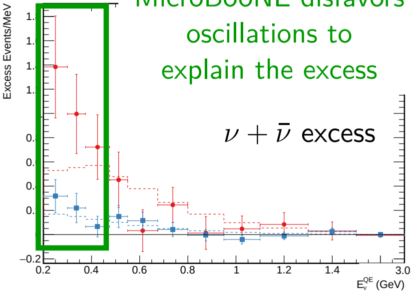


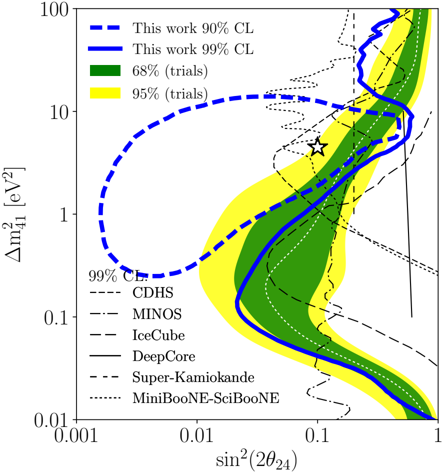


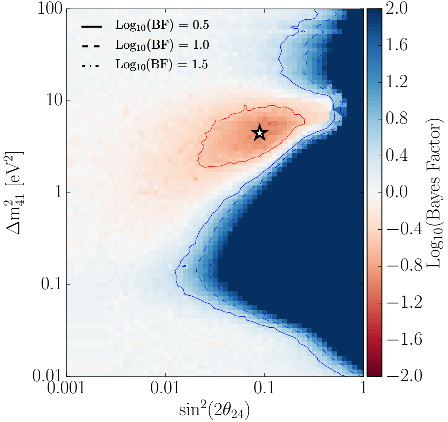


MicroBooNE disfavors oscillations to explain the excess

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%

Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos ⟶ new oscillations in the early Universe

sterile ⟹ no weak/em interactions in the thermal plasma

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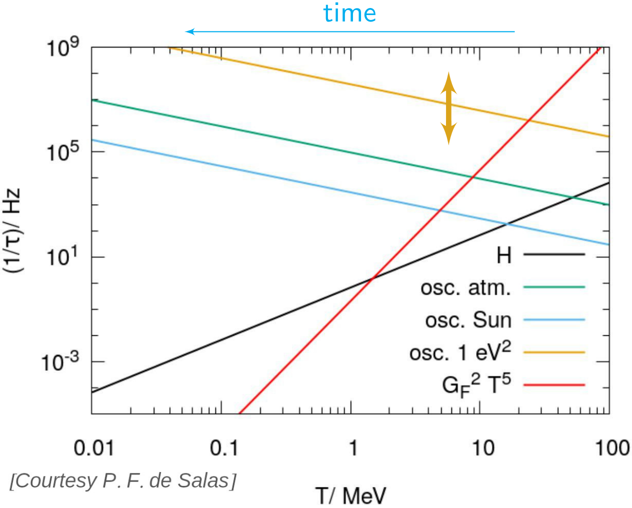
need to produce it through oscillations, but matter effects may block them



[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

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

[Dolgov&Villante, 2004]

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

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

Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

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[Dolgov&Villante, 2004]

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

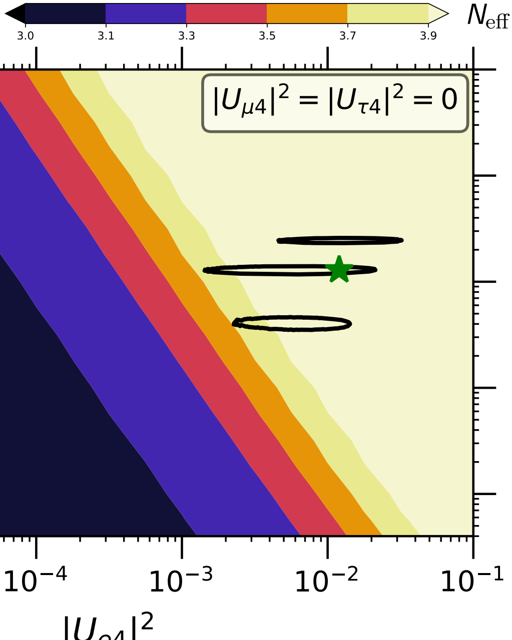
Full calculation: use numerical code!

`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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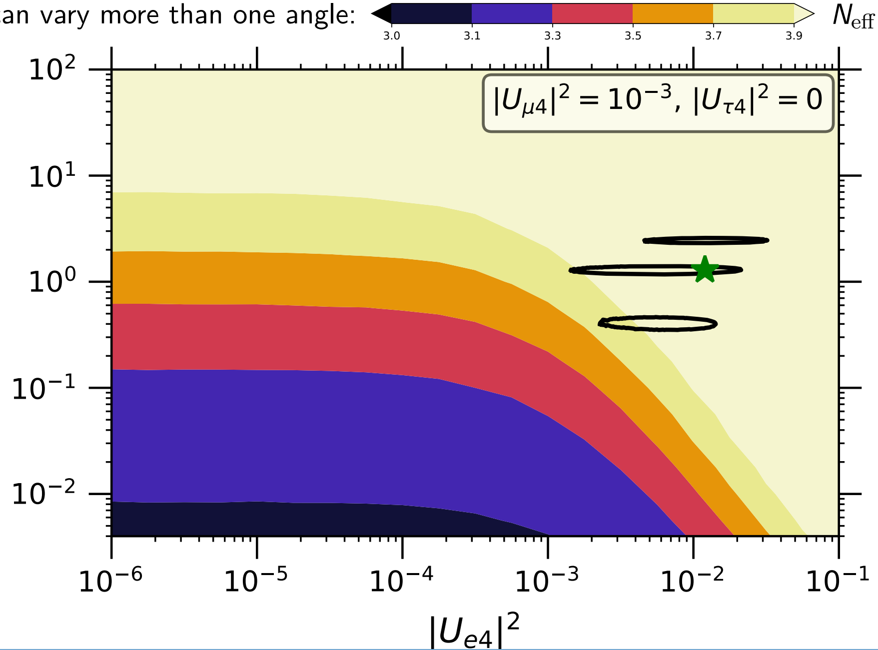

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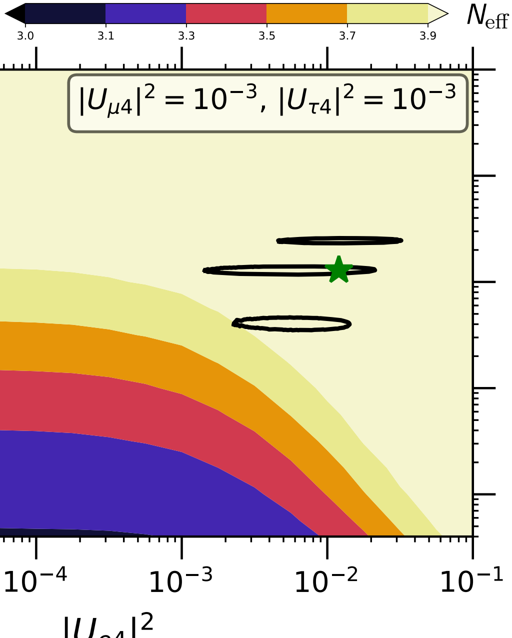
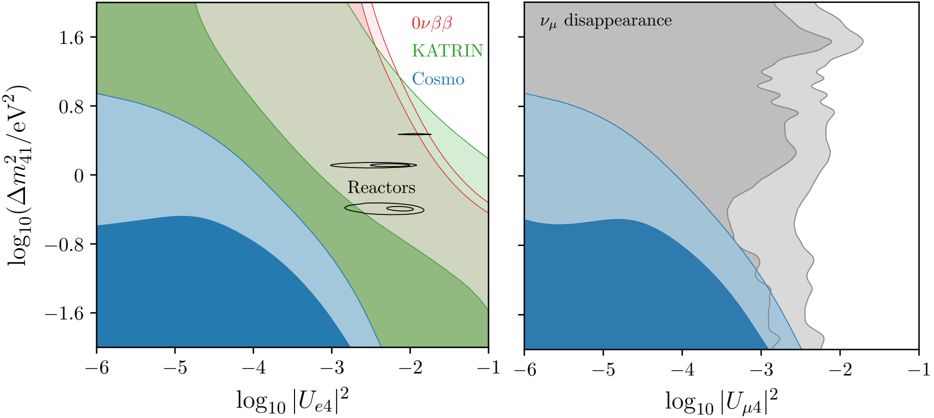


Comparing constraints

[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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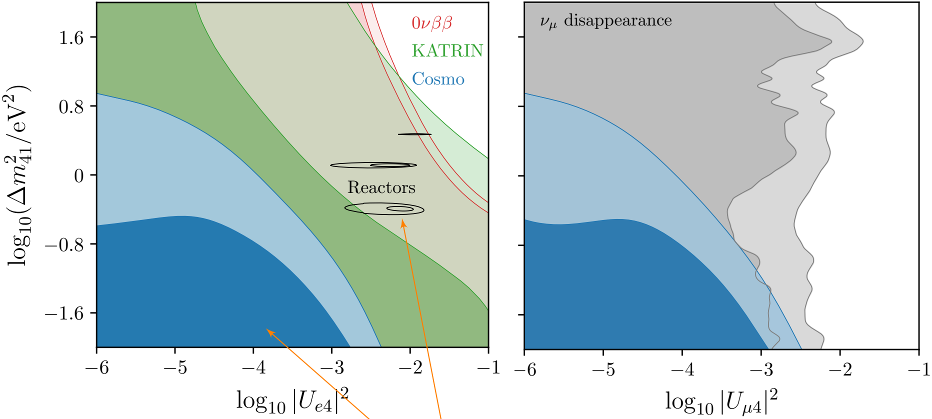

Warning: tension between reactor experiments and CMB bounds!

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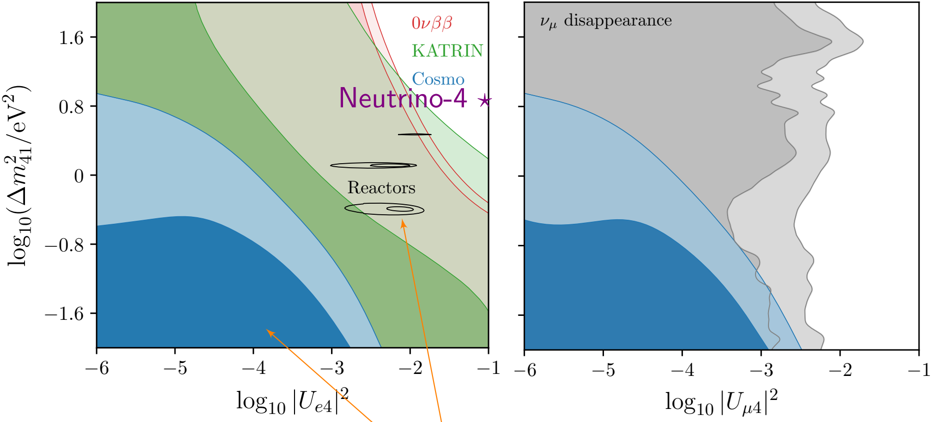

Warning: tension between reactor experiments and CMB bounds!

Non-unitarity of the 3×3 mixing matrix

[arxiv:2211.10522]

Consider we have N_ν neutrino states

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

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

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the 3×3 sector (N)

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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:

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

Fermi constant:

$$G_F^\mu = G_F$$

Non-unitary case

interactions:

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matter effects:

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

Fermi constant:

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

$$G_F^\mu = 1.1663787(6)\times10^{-5}\ \mathrm{GeV}^{-2}$$ [CODATA]

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

Non-unitarity parameters and N_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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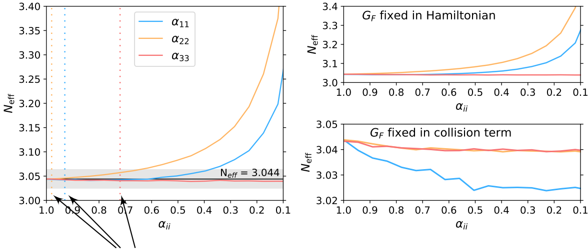

terrestrial bounds

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

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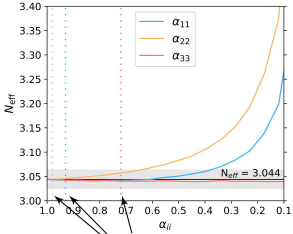
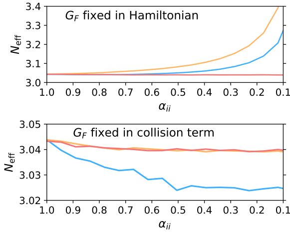
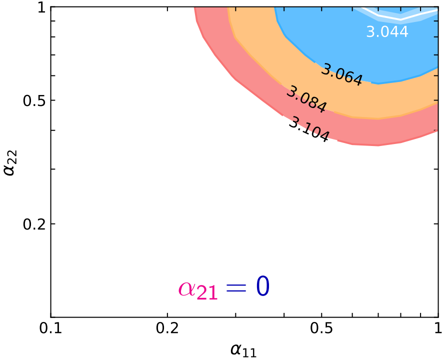
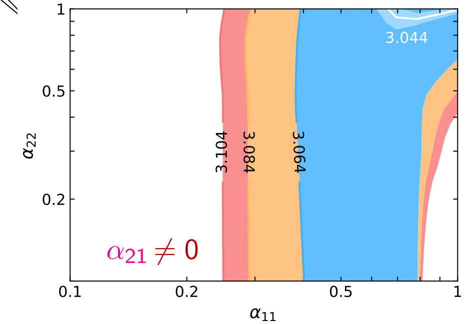








(α_{21} marginalized over)

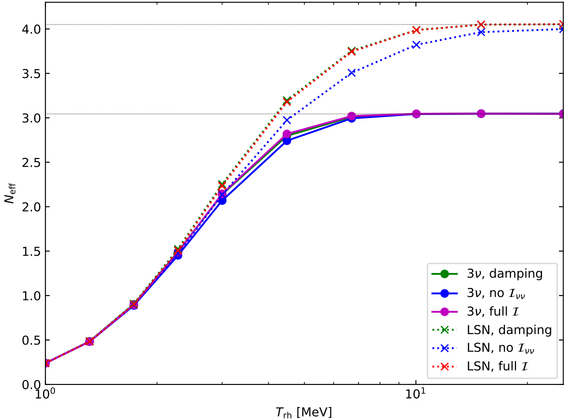
Confidence regions from future CMB measurements with $\delta N_{\rm eff} = 0.02$

C Non-standard cosmology

if sterile neutrinos are not enough

Based on:

- in preparation



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

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radiation domination begins after reheating

neutrinos are populated by weak interactions with electrons!

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

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:

$$\frac{\mathrm{d}\varrho(y)}{\mathrm{d}x} = \text{unchanged}$$

$$\frac{\mathrm{d}\rho_\phi}{\mathrm{d}x} = -\frac{x\rho_\phi\Gamma_\phi}{m_e^2}\sqrt{\frac{3m_{\rm Pl}^2}{8\pi\rho_{\rm tot}}}$$

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J_2(r_\ell)\right] + G_1(r) - \frac{1}{2z^3}\sum_{\alpha=e}^{s}\frac{\mathrm{d}\rho_{\nu_\alpha}}{\mathrm{d}x} - \frac{x}{2z^3}\frac{\mathrm{d}\rho_\phi}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J_2(r_\ell) + J_4(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

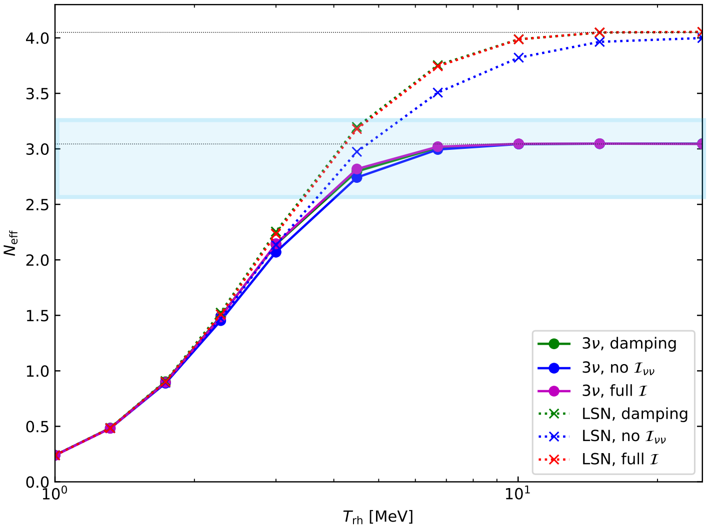
$$\rho_{\rm tot} = \sum_{i=\gamma,\nu_j,e,\mu}\rho_i + \delta\rho(x,z) + x\rho_\phi$$

$$\Gamma_\phi \simeq \left(\frac{T_{\rm rh}}{0.7\text{MeV}}\right)^2 \text{sec}^{-1}$$

$N_{\rm eff}$ with low reheating

[in preparation]

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

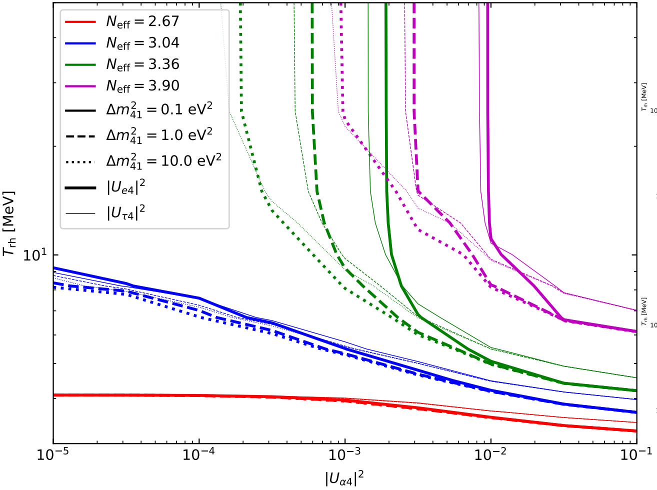


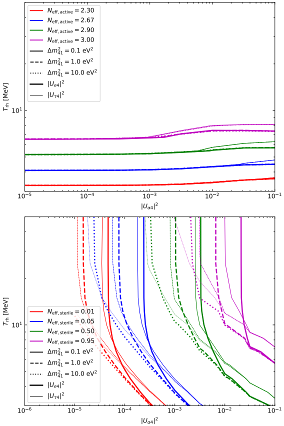
Planck constraint: $N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

N_{eff} with low reheating

[in preparation]

sterile case with varying mixing angle/mass splitting:





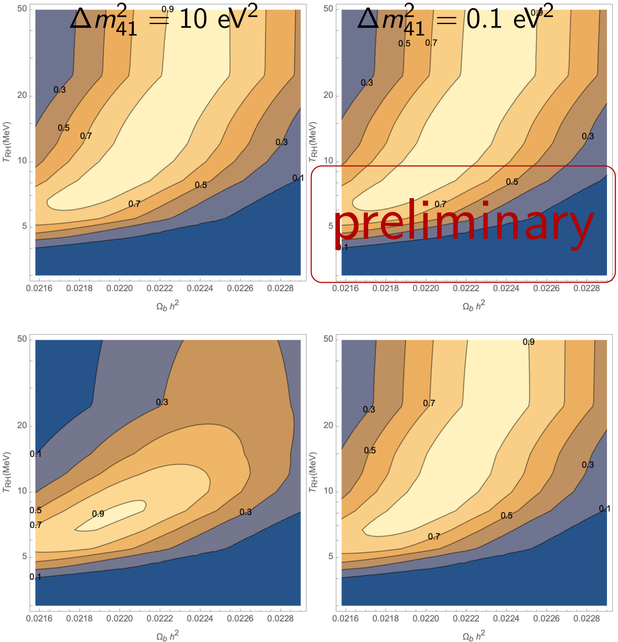
active,
sterile
contribution
to N_{eff}

for low T_{rh}, mixing parameters are irrelevant

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

BBN and low reheating

[in preparation]



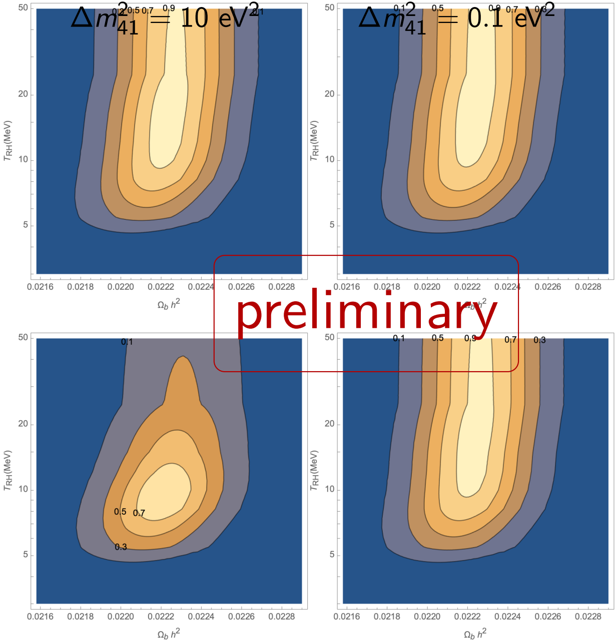
$|U_{e4}|^2 = 10^{-5}$

BBN (D+He) only

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

BBN and low reheating

[in preparation]



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

BBN + Planck18

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

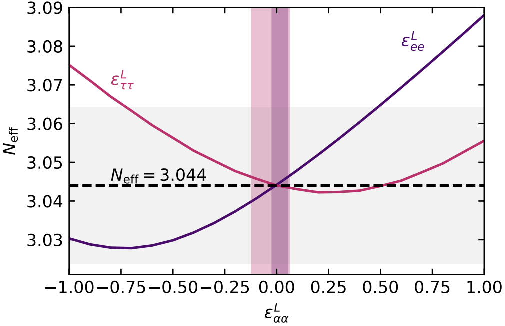
D

Non-standard neutrino interactions

Neutrino-electron interactions, other non-standard interactions

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

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

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

↓

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

matter effects in oscillations
(subdominant!)

$$\mathcal{H}_{\rm eff,SM} \supset k \cdot {\rm diag}(\rho_e + P_e, 0, 0)$$

↓

$$\mathcal{H}_{\rm eff} \supset k(\rho_e + P_e) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

with $\epsilon_{\alpha\beta} = \epsilon^L_{\alpha\beta} + \epsilon^R_{\alpha\beta}$

NSI effects on $N_{\rm eff}$

[PLB 820 (2021)]

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

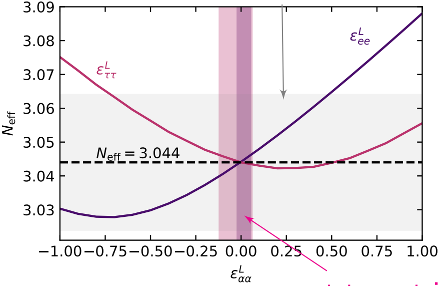
e.g.:

$G^{L}_{ee} \to 0.727 + \epsilon^{L}_{ee}$

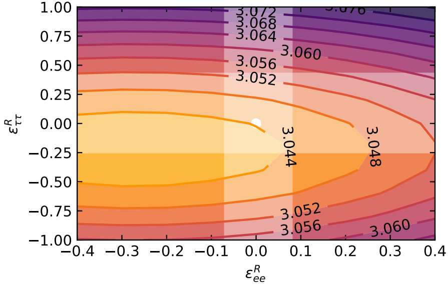
$G^{L}_{\tau\tau} \to -0.273 + \epsilon^{L}_{\tau\tau}$

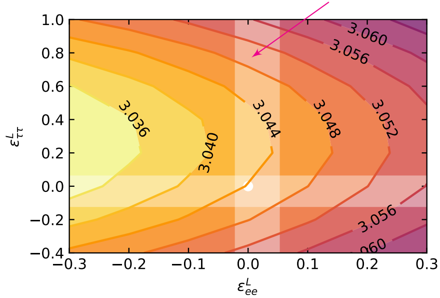
$G^{R}_{\alpha\alpha} \to 0.233 + \epsilon^{R}_{\alpha\alpha}$

future CMB



current terrestrial





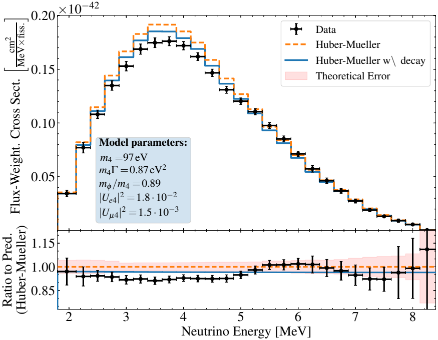
Can new physics solve the anomalies and tensions?

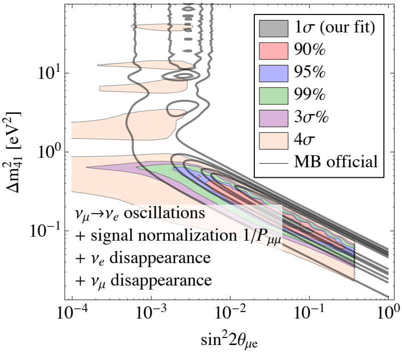
Many attempts to explain LSND/MiniBooNE anomalies,
APP vs DIS, oscillations vs cosmo tensions with new physics

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 $m_\phi \lesssim m_4$

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





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

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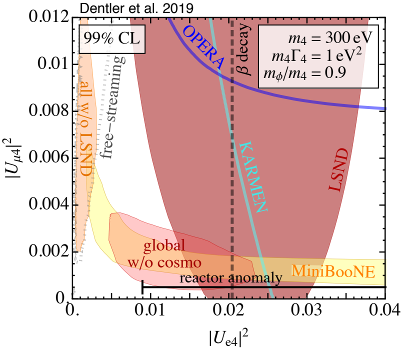

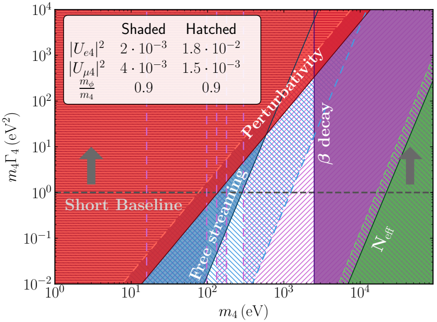

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$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon^{fC}_{\alpha\beta}[\overline{\nu_\alpha}\gamma^\rho P_L\nu_\beta]\left[\bar{f}\gamma_\rho P_C f\right]$$

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

Non-standard interactions (NSI) involving ν_s

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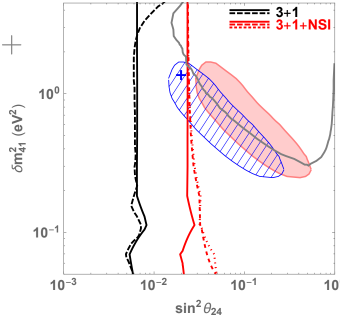
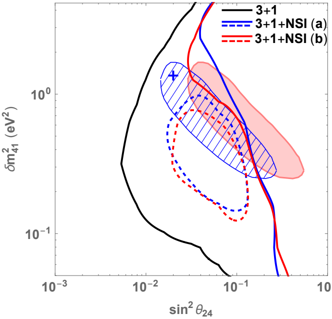
Non-standard interactions (NSI) involving ν_s

MINOS+
vs APP





IceCube/
DeepCore
vs APP

Z

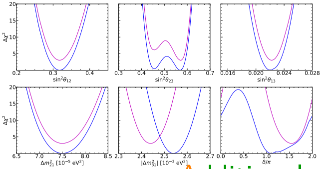
Conclusions

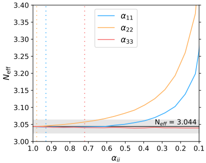
almost there!

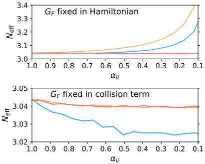
What do we know about neutrinos?

U

U: mixing matrix

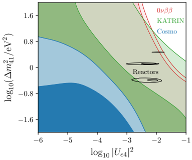


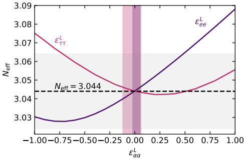


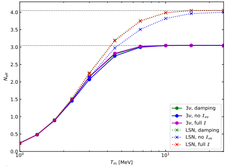


A

Additional particles/interactions

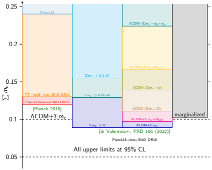


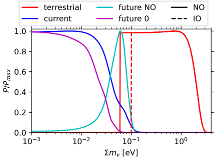


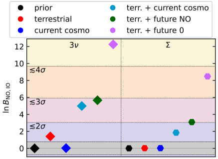


M

Masses and mass ordering



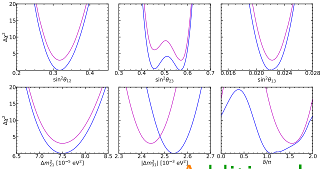


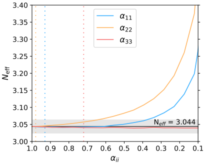


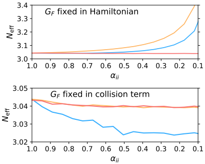
What do we know about neutrinos?

U

U: mixing matrix

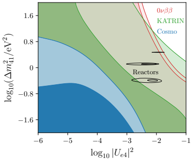


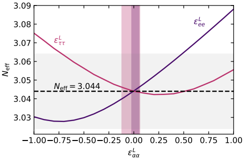


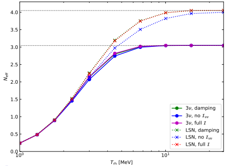


A

Additional particles/interactions

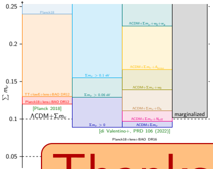


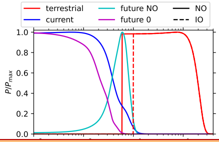


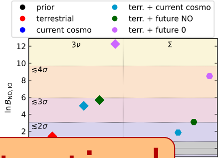


M

Masses and mass ordering







Thanks for your attention!