"la Caixa" Foundation
Junior Leader
Fellowship
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Neutrino decoupling in standard and non-standard scenarios

Based on JCAP 04 (2021) 073, JCAP 07 (2019) 014, JCAP 03 (2023) 046

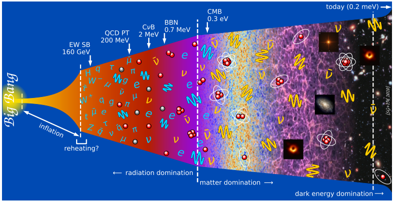
Neutrinos from Home, online, 23/04-01/05/2024

1 ***Cosmic Neutrino Background***

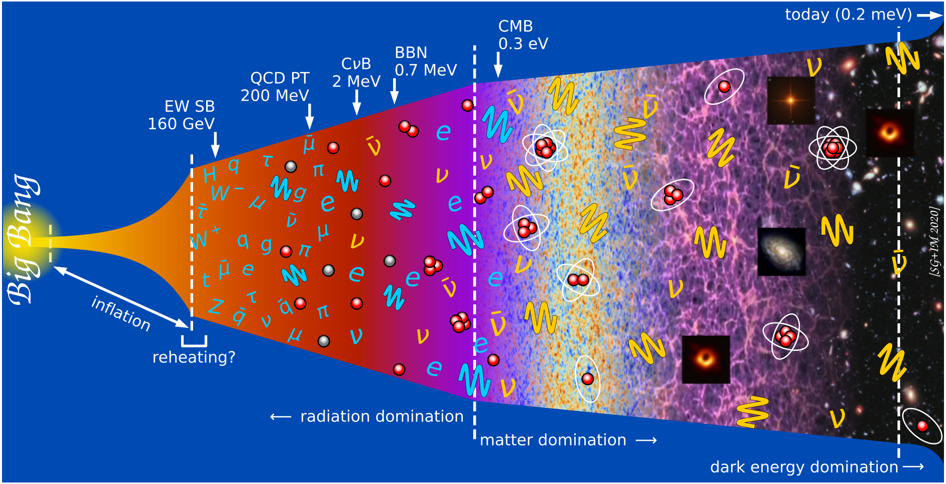
2 ***Standard three neutrino scenario***

3 ***Non-standard: light sterile neutrino***

4 ***Conclusions***



History of the universe



Big Bang

inflation

reheating?

EW SB
160 GeV

QCD PT
200 MeV

CνB
2 MeV

BBN
0.7 MeV

CMB
0.3 eV

today (0.2 meV) ⟶

⟵ radiation domination

matter domination ⟶

dark energy domination ⟶

[SG+IM 2020]

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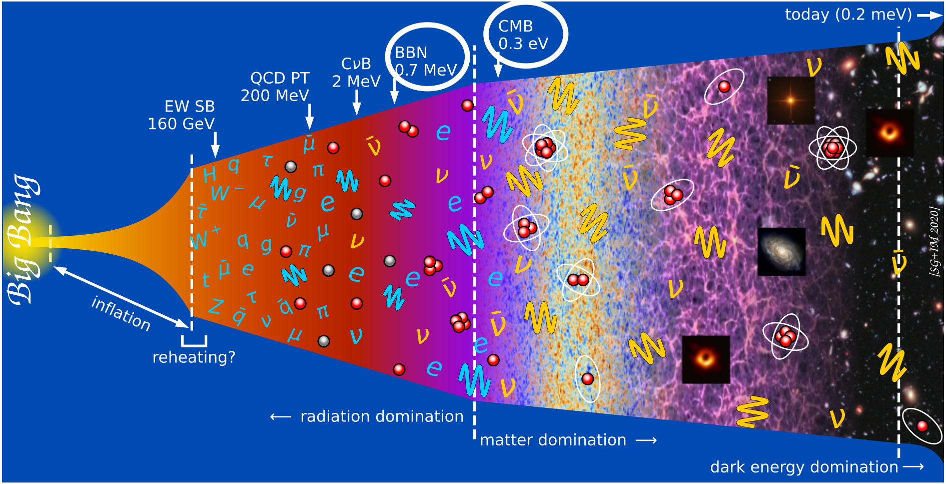

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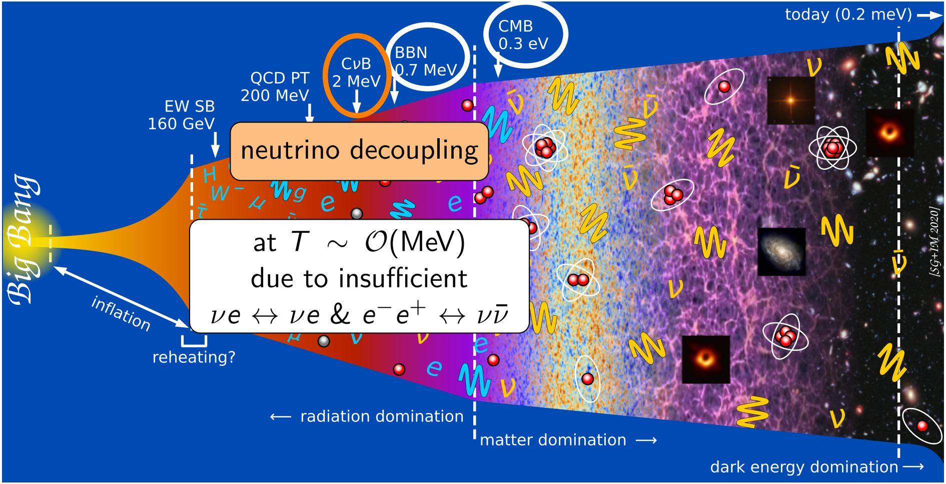


neutrino decoupling

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

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

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

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

prediction:

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

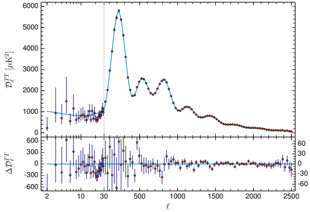
>3 because of entropy transfer
to photons when electrons
become non-relativistic

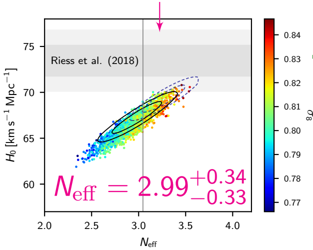
recommended value (3ν):

$\boxed{N_{\rm eff} = 3.04}$

[Bennett+, 2020] [Akita+, 2020]
[Froustey+, 2020] [Cielo+, 2023]

measurement:



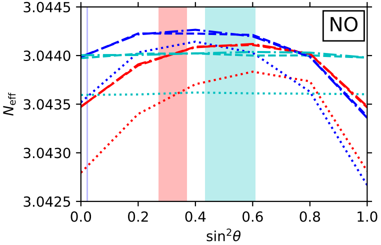


$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$

[Planck 2018]
(95%, TT,TE,EE+lowE+lensing+BAO)

1 *Cosmic Neutrino Background*

2 ***Standard three neutrino scenario***

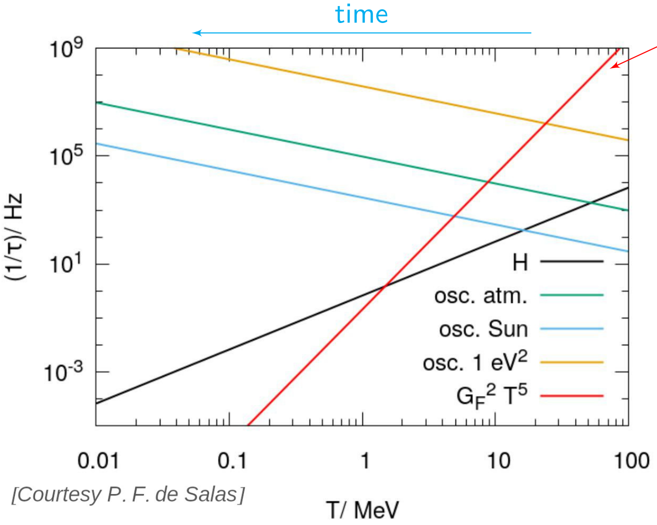


3 *Non-standard: light sterile neutrino*

4 *Conclusions*

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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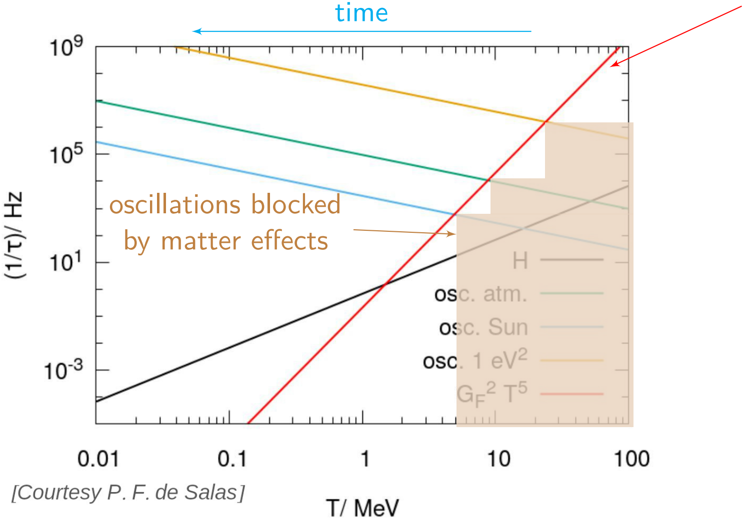

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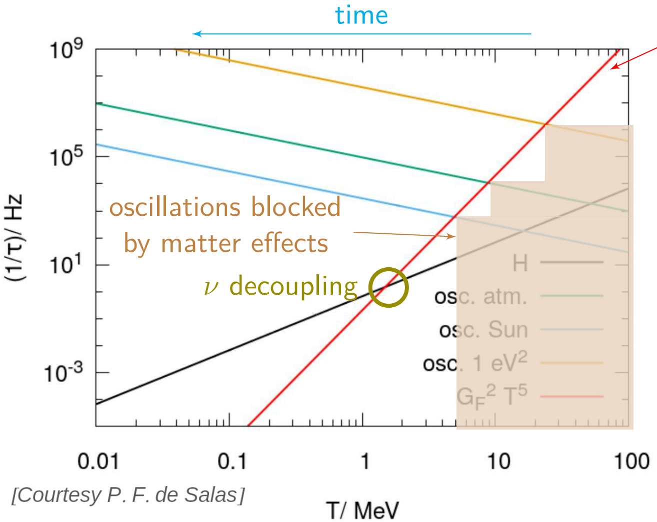

oscillations blocked by matter effects

ν decoupling

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

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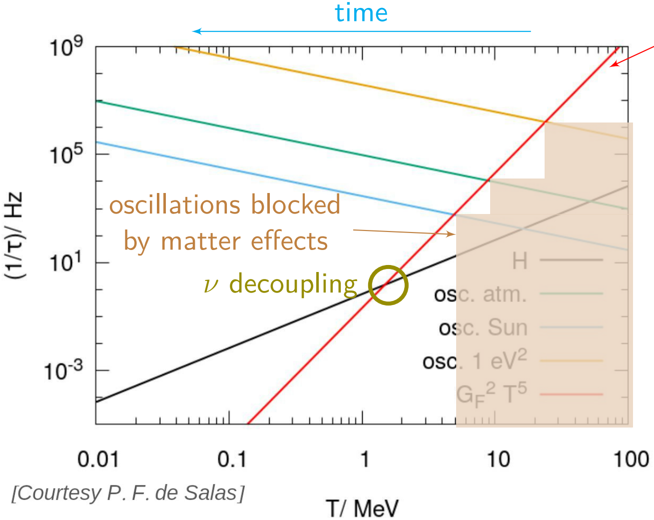

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ν decoupling

[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

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56\ \mathrm{cm}^{-3}$ per family

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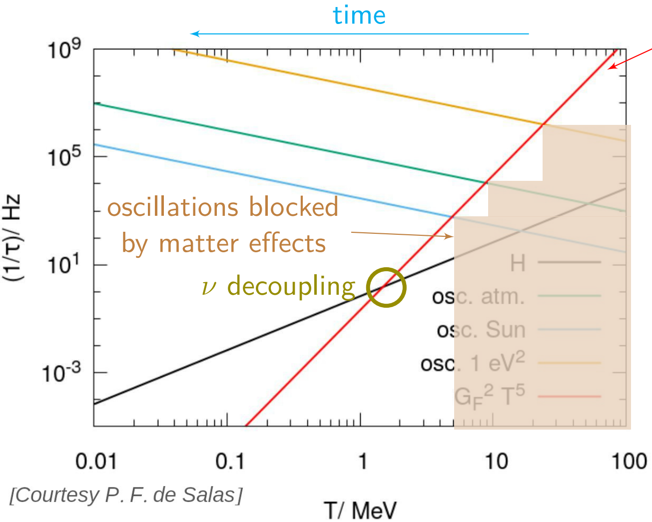
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actually, the decoupling T is momentum dependent! →

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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FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

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

vacuum oscillations

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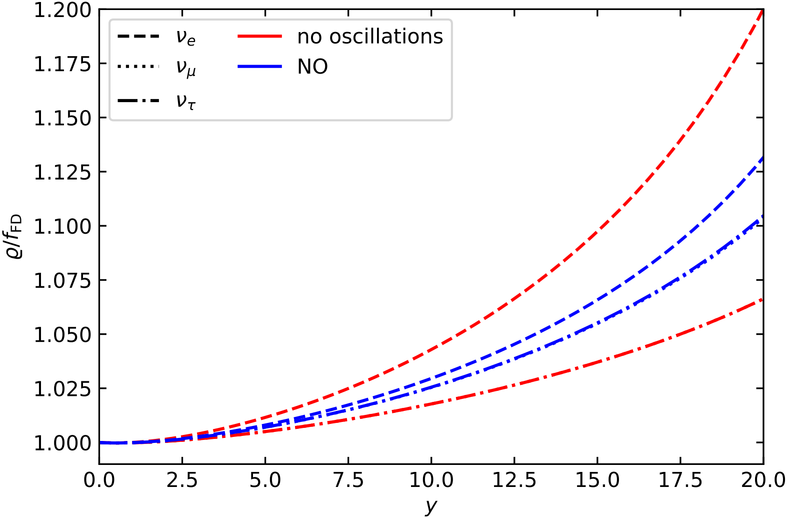
Neutrino momentum distribution and N_{eff} [Bennett, SG+, JCAP 2021]

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



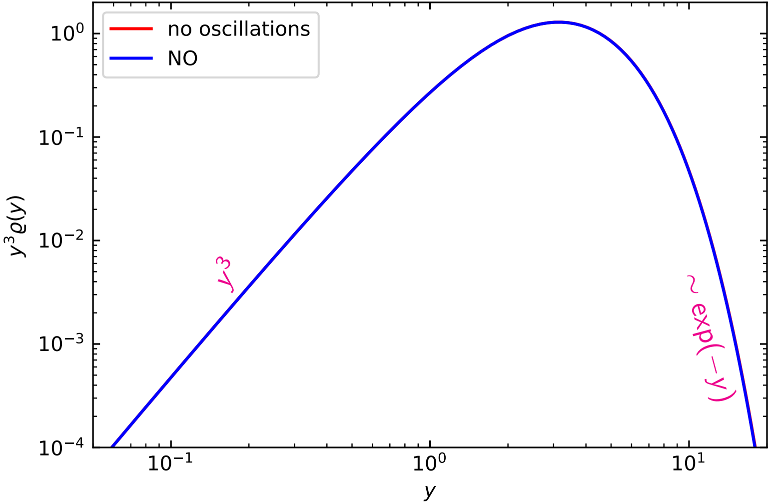
Neutrino momentum distribution and $N_{\rm eff}$

[Bennett, SG+, JCAP 2021]

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

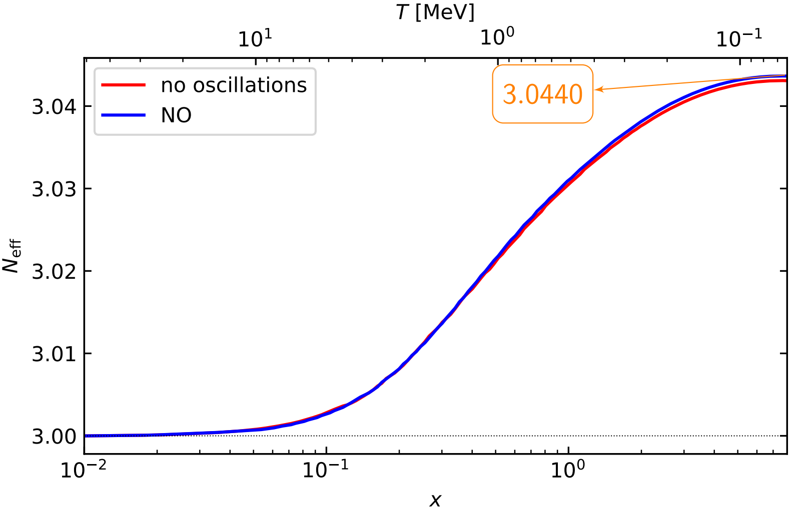
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



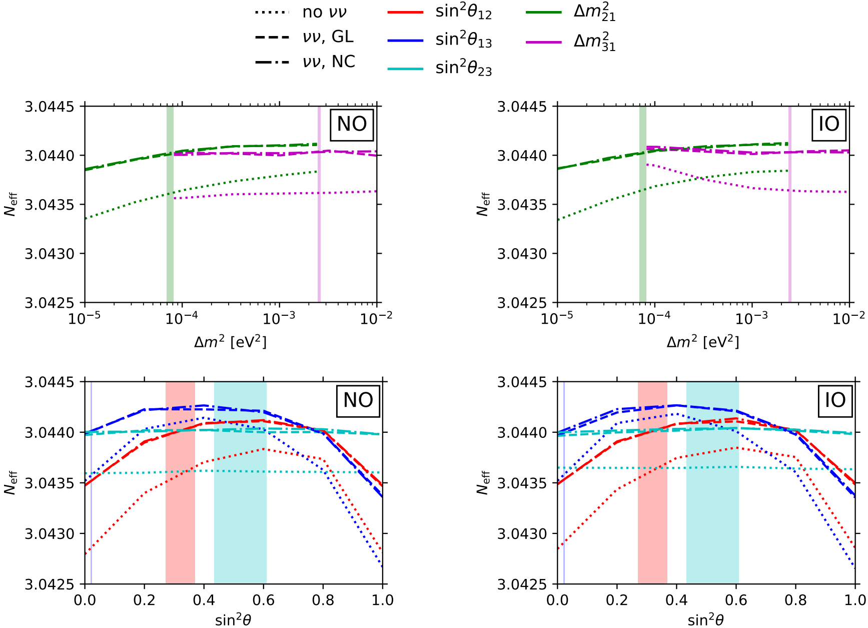
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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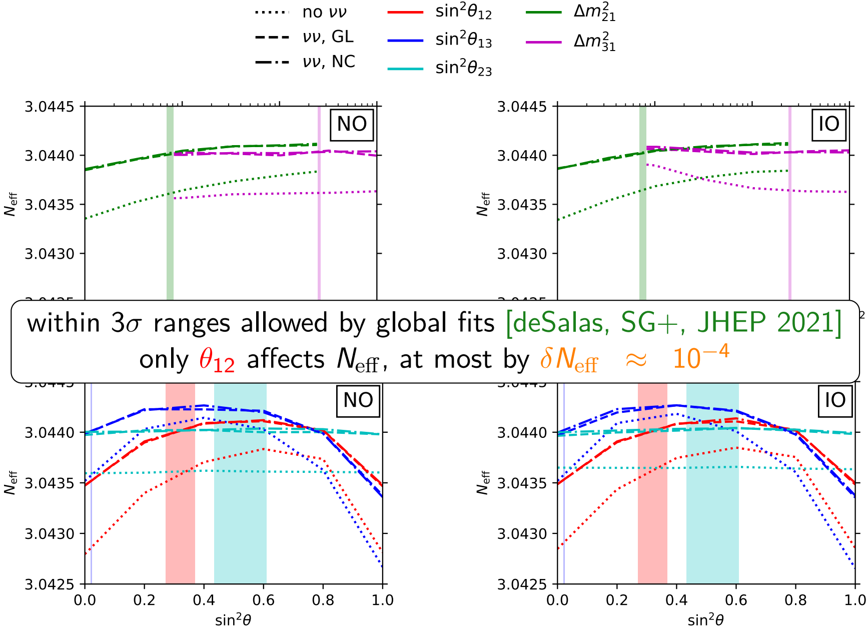
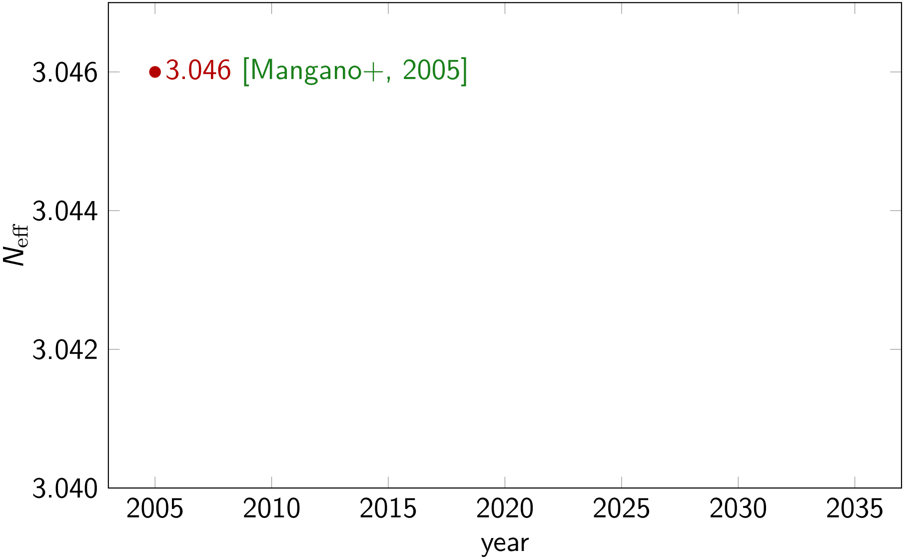


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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

How precise is $N_{\mathrm{eff}} = 3.04\ldots$?

Full 3ν mixing results:



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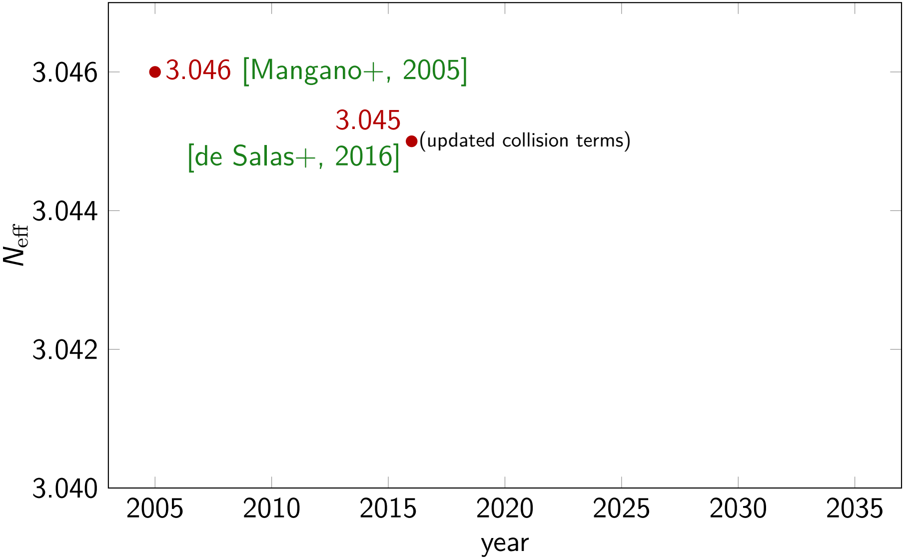

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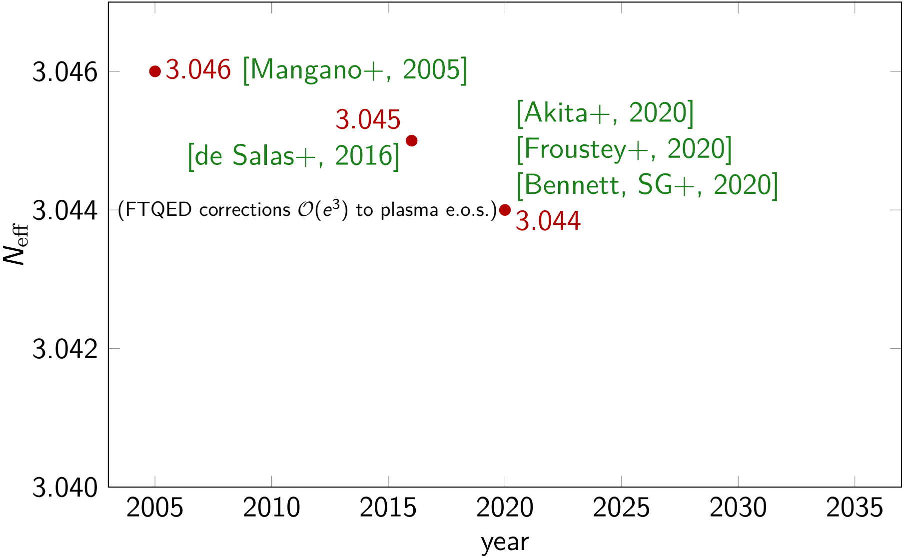

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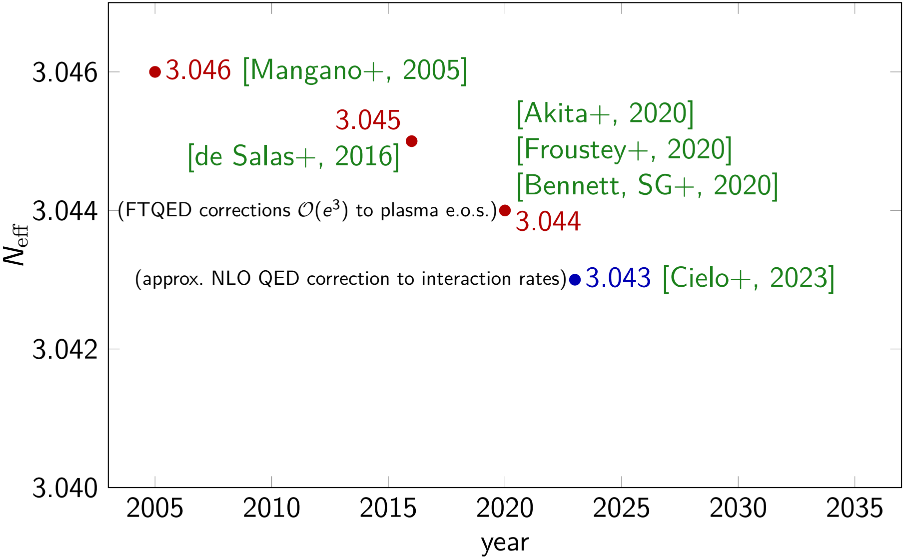

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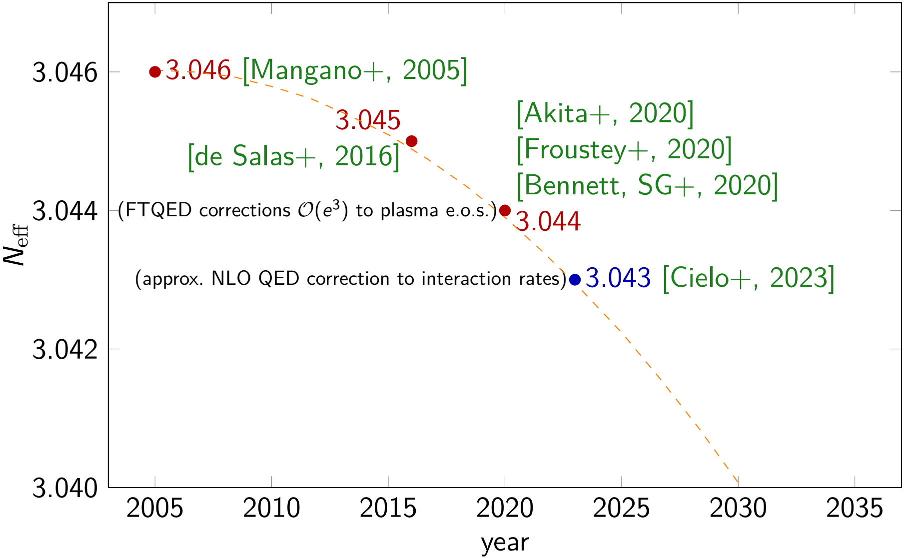

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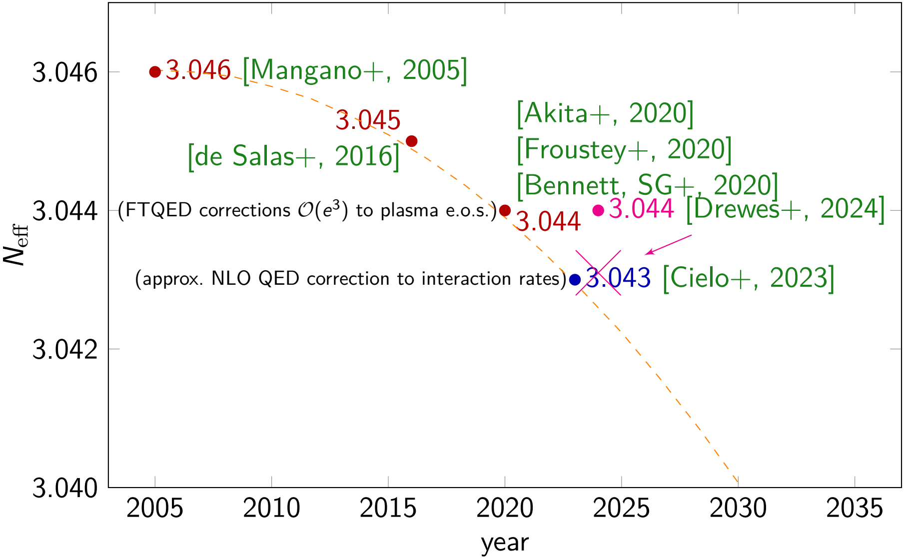

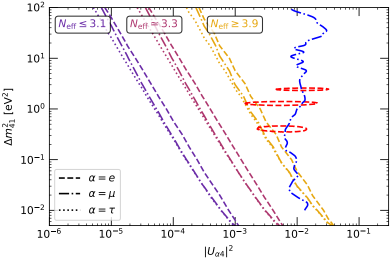
$N_{\rm eff} \leq 3.1$
$N_{\rm eff} \simeq 3.3$
$N_{\rm eff} \geq 3.9$
$\alpha = e$
$\alpha = \mu$
$\alpha = \tau$
Δm^2_{41} [eV^2]
$|U_{\alpha 4}|^2$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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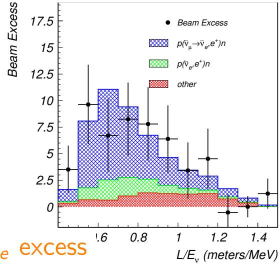
LSND



[Aguilar+, 2001]

3.8σ

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

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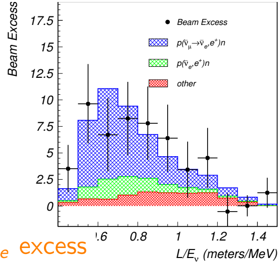

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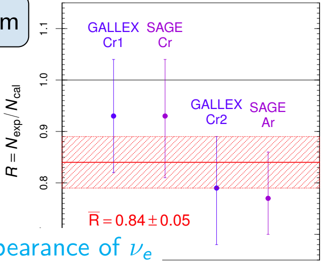
[Aguilar+, 2001]

Gallium

2.7σ

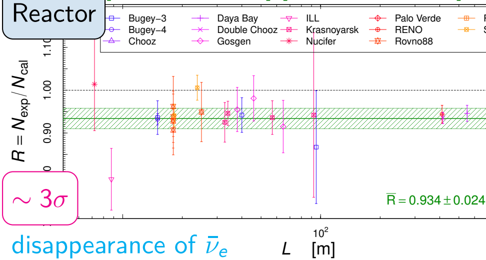


disappearance of ν_e

[Giunti, Laveder, 2011]

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

Reactor



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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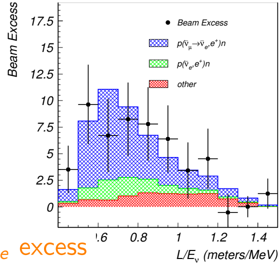

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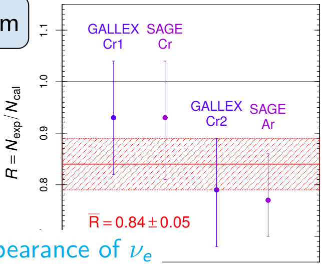
Gallium



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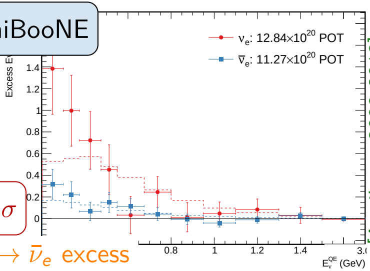
disappearance of ν_e

MiniBooNE



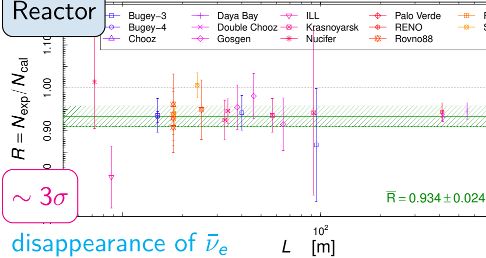
[Aguilar+, 2008-2018]

$\sim 5\sigma$

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

Reactor

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



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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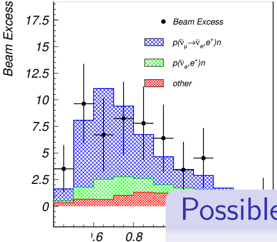

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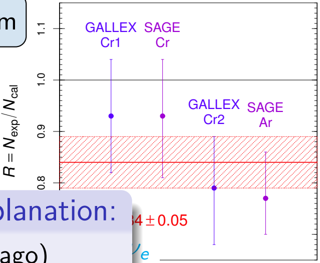
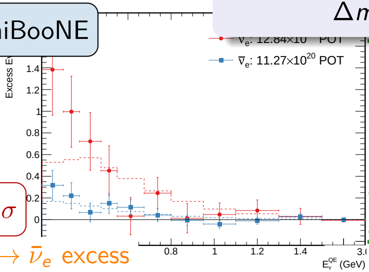


ν_e

[Giunti, Laveder, 2011]

MiniBooNE



~ 5σ

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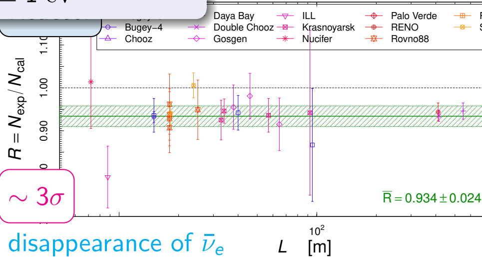

~ 3σ

disappearance of $\bar\nu_e$

Possible common explanation:

(until a few years ago)

Additional squared mass difference

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

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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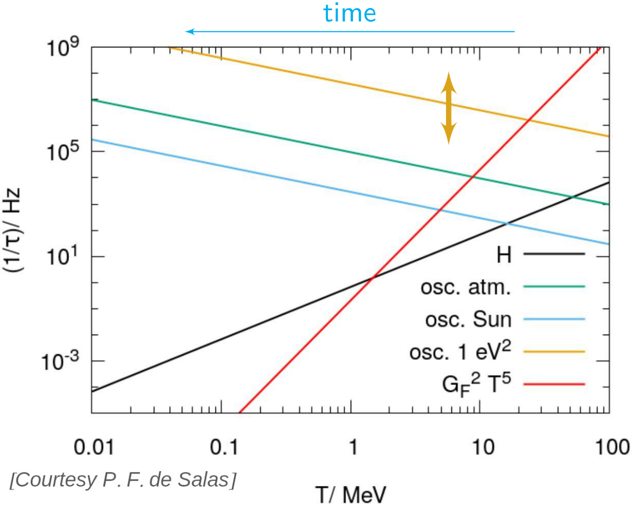

[Courtesy P. F. de Salas]

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

later oscillations

$\Downarrow$

less time before ν decoupling!

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Four neutrinos ⟶ new oscillations in the early Universe

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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

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

(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]

Four neutrinos ⟶ new oscillations in the early Universe

sterile ⟹ no weak/em interactions in the thermal plasma

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

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

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

[Dolgov&Villante, 2004]

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

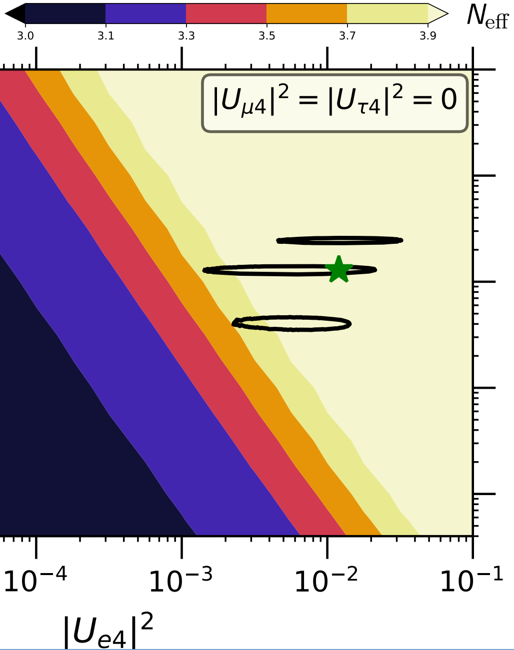
Full calculation: use numerical code!

`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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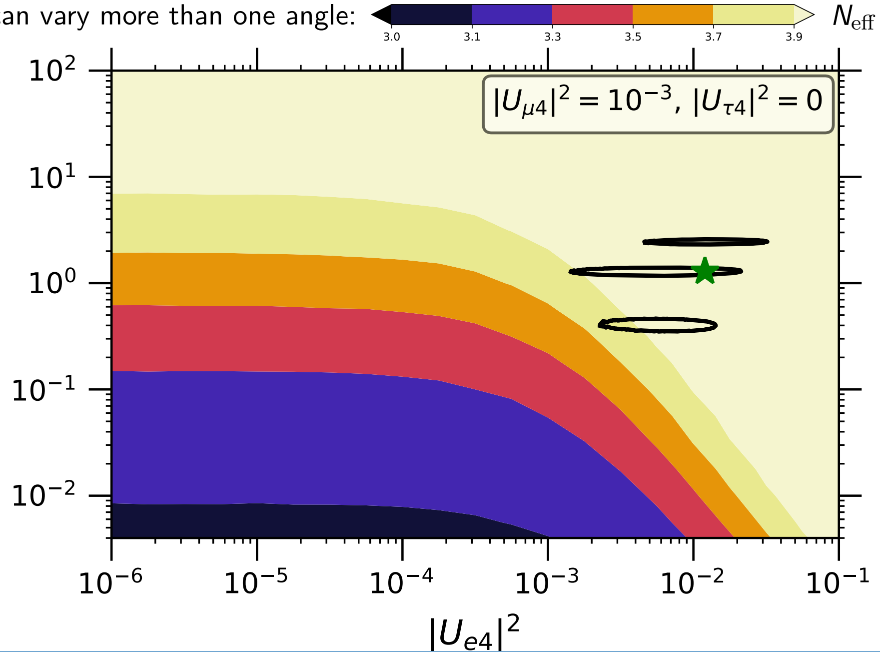

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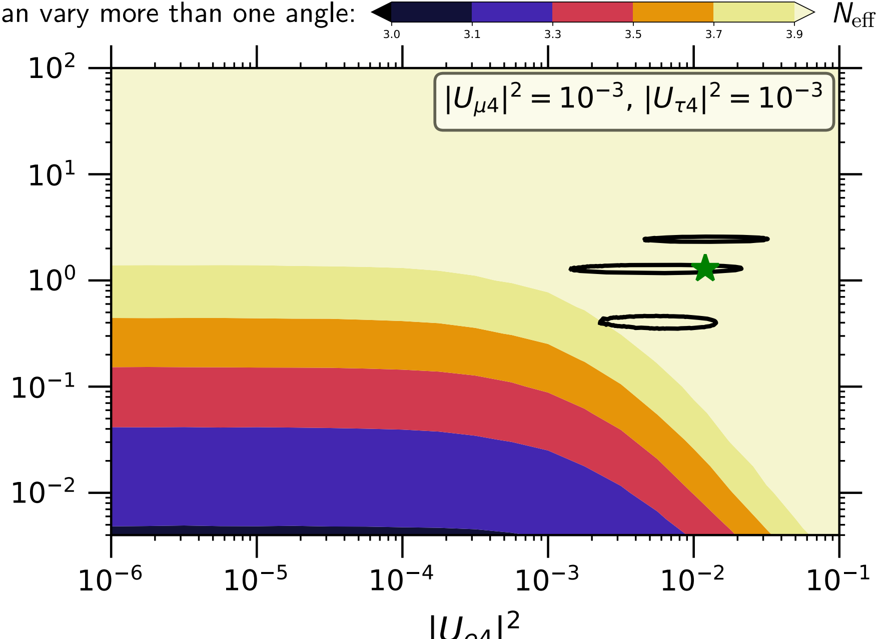
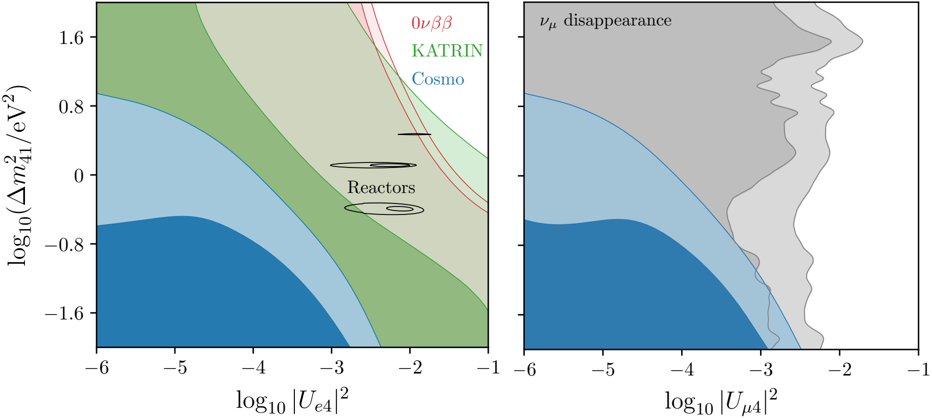


Comparing constraints

[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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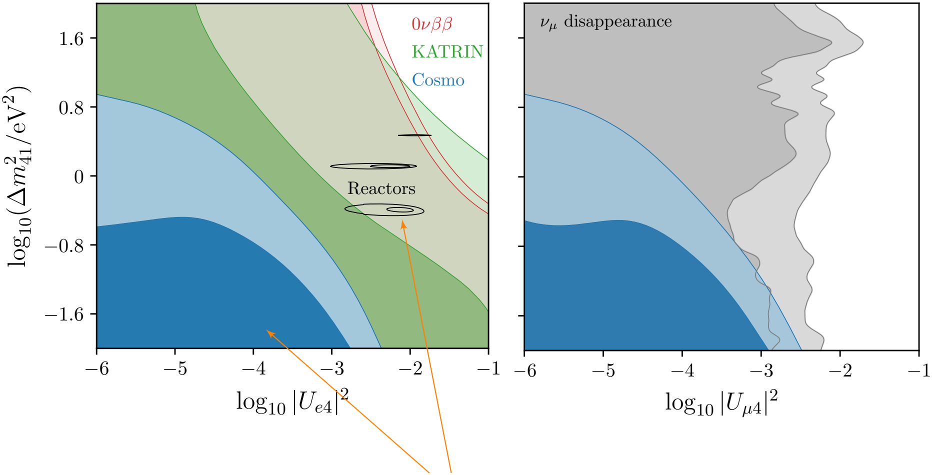

Warning: tension between reactor experiments and CMB bounds!

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[PRD 104 (2021) 123524]

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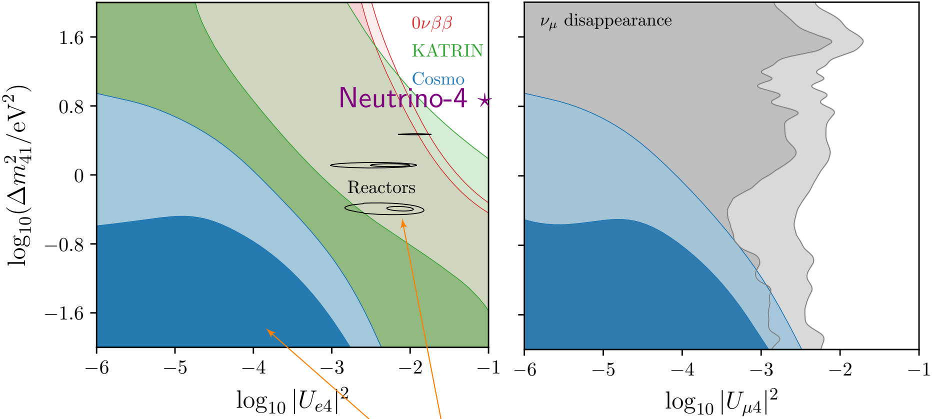


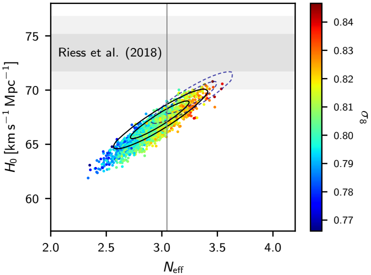
Warning: tension between reactor experiments and CMB bounds!

1 *Cosmic Neutrino Background*

2 *Standard three neutrino scenario*

3 *Non-standard: light sterile neutrino*

4 ***Conclusions***



Conclusions

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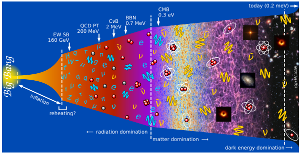
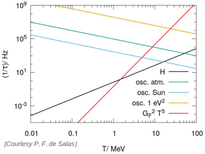
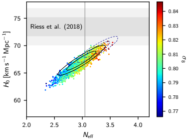
Neutrinos in the early universe – probe lowest energies



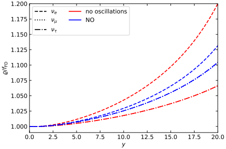


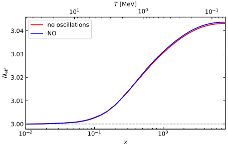
[Courtesy P. F. de Salas]

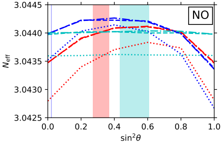


2

Active neutrinos: precision calculations







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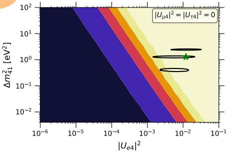
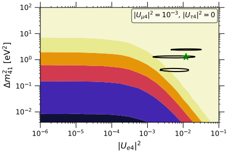
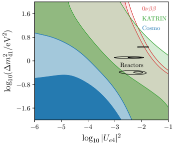
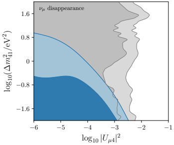
Non-standard scenarios: complementary bounds









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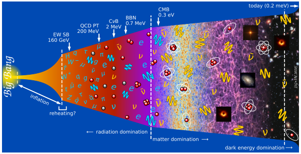

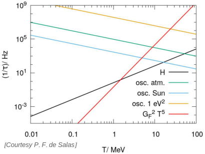

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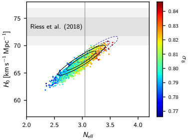

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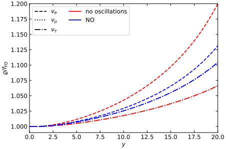

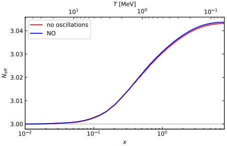

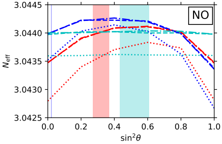

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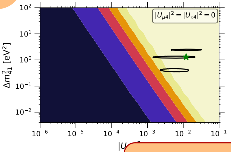

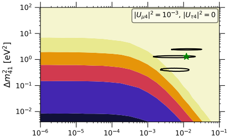

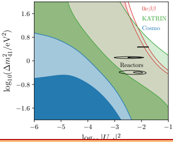

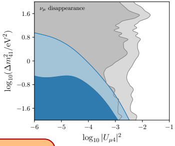

Thanks for your attention!