"la Caixa" Foundation
Junior Leader
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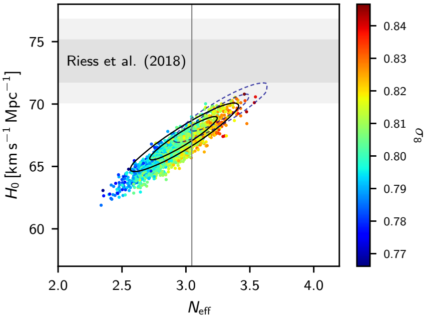
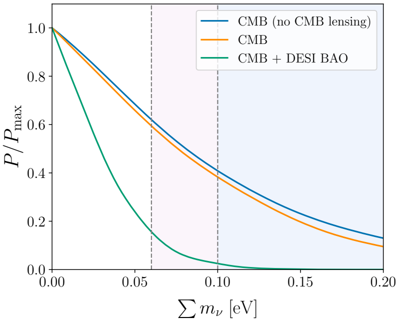
# $\nu$ non-standard scenarios and cosmology

*Don't be tricked!*
*cosmological $\nu$ bounds are not what they seem...*

XXXI International Conference on Neutrino Physics and Astrophysics,
Milan, Italy, 16-22/06/2024

# Selected neutrino constraints from cosmology




Expectation: $N_{\rm eff} = 3.044$

[Akita+, 2020] [Froustey+, 2020]

[Bennett, SG+, 2020] [Drewes+, 2024]

Measurement:

$N_{\rm eff} = 2.99 \pm 0.17$

(CMB+lens+BAO)

[Planck Collaboration, 2018]

Oscillations:

$\Sigma m_\nu \gtrsim 60$ meV (normal ord.)

$\Sigma m_\nu \gtrsim 100$ meV (inverted ord.)

[any global fit]

Measurement:

$\Sigma m_\nu < 72$ meV

(95%, CMB+DESI BAO)

[DESI 2024]

# C Clarifications

## about the cosmological presence of neutrinos

# What is $N_{\rm eff}$?

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

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

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

It is a measurement of the energy density of relativistic neutrinos!

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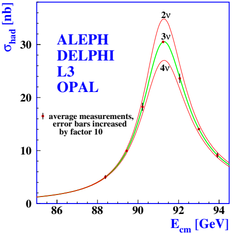
Nothing to do with [LEP (2006)]
$N_\nu^{(Z)} = 2.9840 \pm 0.0082$



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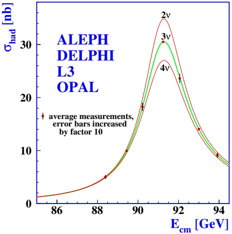



instantaneous decoupling:
$N_{\rm eff}^{\nu} = 1$ for each $\nu$ family

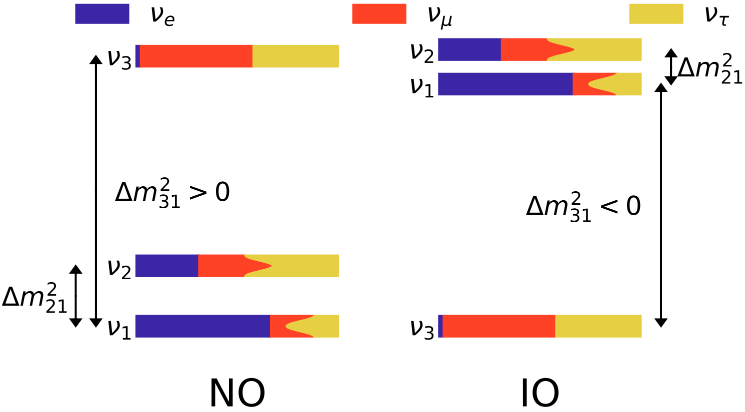
non-instantaneous decoupling:
$N_{\rm eff}^{\nu} > 3$ because of entropy transfer to photons and neutrinos when electrons become non-relativistic

Other relativistic species?

# What is $\Sigma m_\nu$?

normal ordering (NO):
$m_2 \gtrsim 9$ meV, $m_3 \gtrsim 50$ meV

inverted ordering (IO):
$m_{1,2} \gtrsim 50$ meV




[Valencia global fit]

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relic neutrinos have a Fermi-Dirac distribution with $T_\nu \approx \mathcal{O}(0.1)$ meV!

many relic neutrinos are non-relativistic today!

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

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

Background measurements are sensitive to $\omega_\nu$, not $\Sigma m_\nu$!

"Cosmological" $\Sigma m_\nu$ measures the energy density of non-relativistic $\nu$s

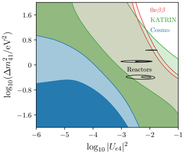
Note: free-streaming scale directly depends on $m_\nu$:

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

N

# $N_{\text{eff}}$

## $\Rightarrow$ energy density of relativistic neutrinos

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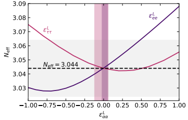
e.g. sterile neutrino [JCAP 07 (2019) 014]

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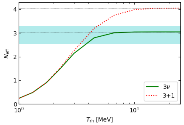


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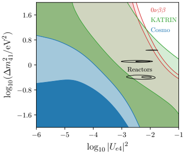


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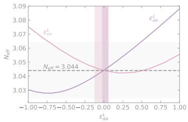


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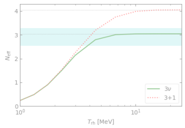


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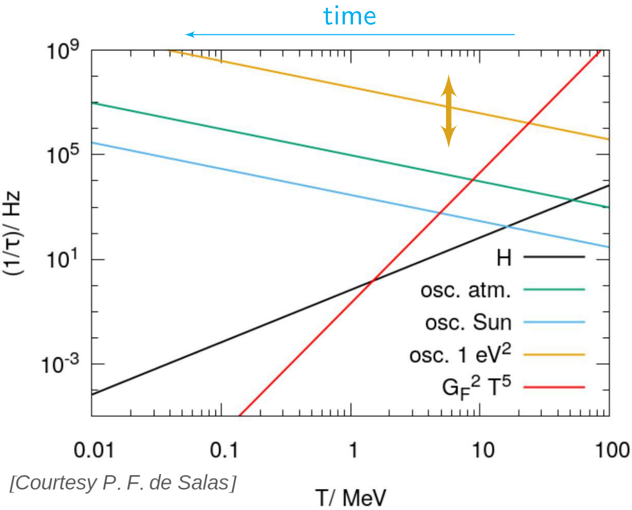


[Courtesy P. F. de Salas]

beginning of oscillations depends on $\Delta m^2_{41}$

later oscillations

$\Downarrow$

less time before $\nu$ decoupling!

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

no sterile production — active&sterile in equilibrium

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

[Dolgov&Villante, 2004]

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

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

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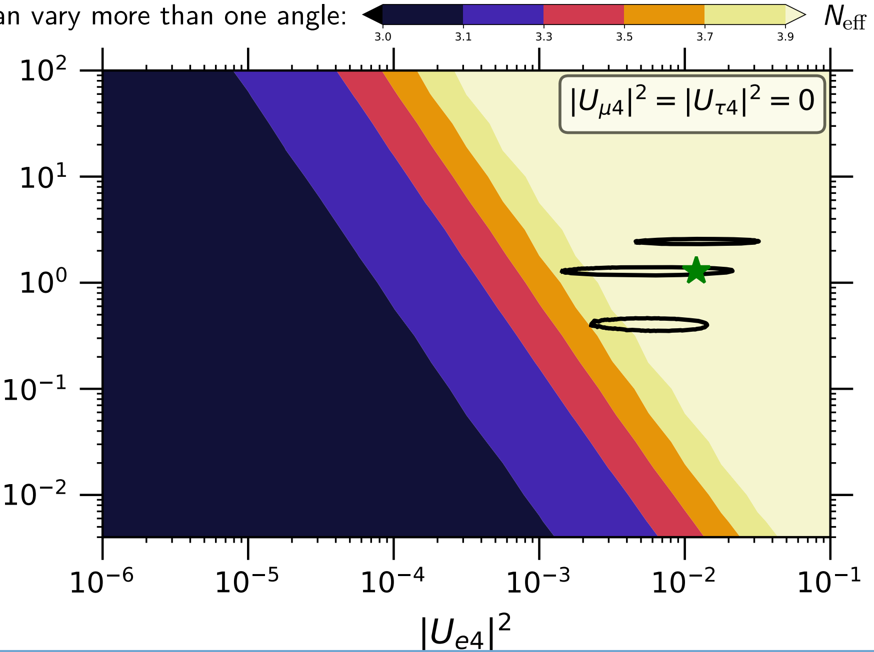
Full calculation: use numerical code!

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

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

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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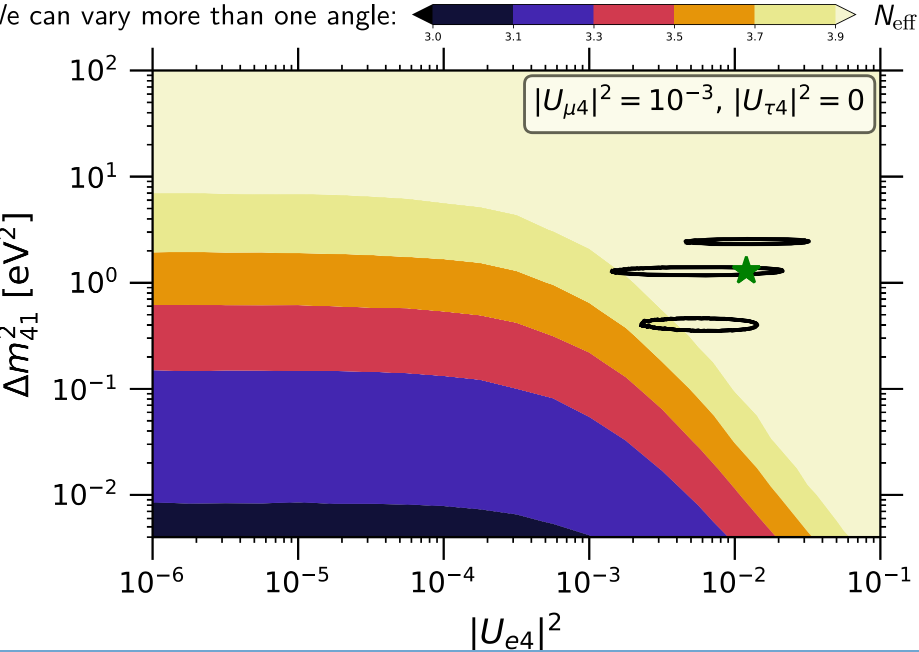

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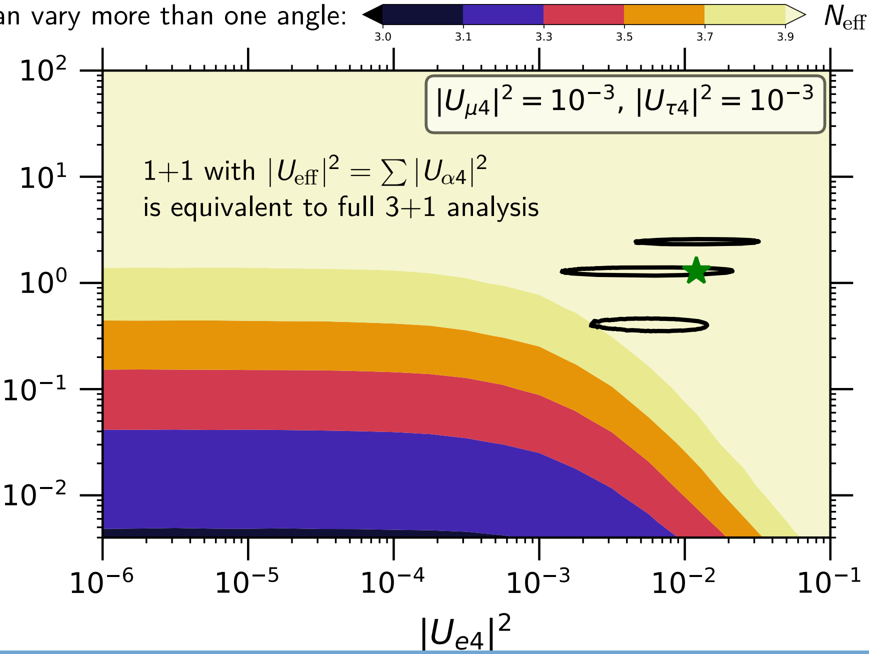
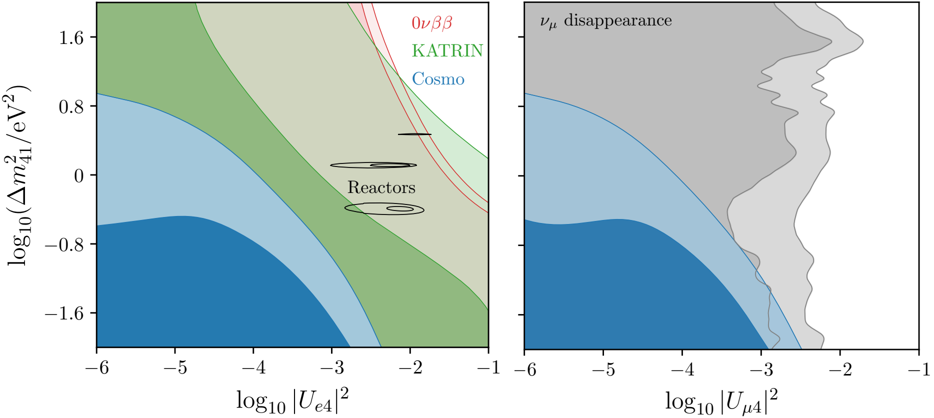


# Comparing constraints

[PRD 104 (2021) 123524]

Cosmological constraints are stronger than most other probes

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



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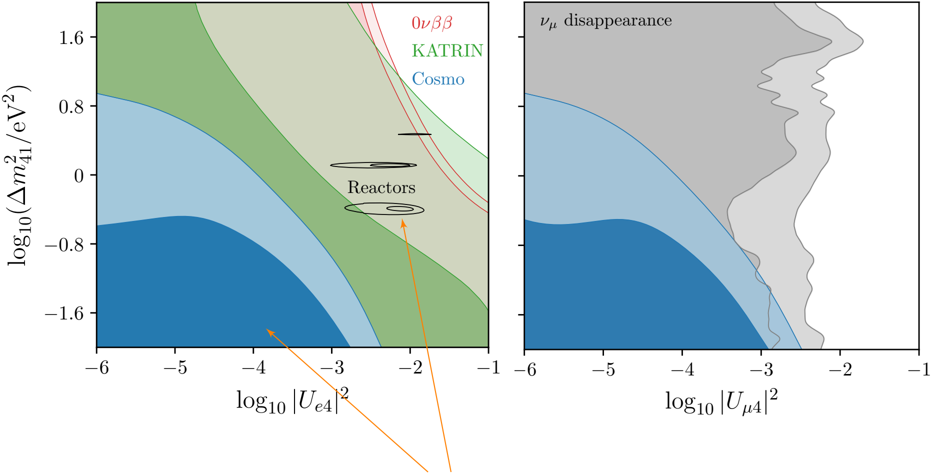


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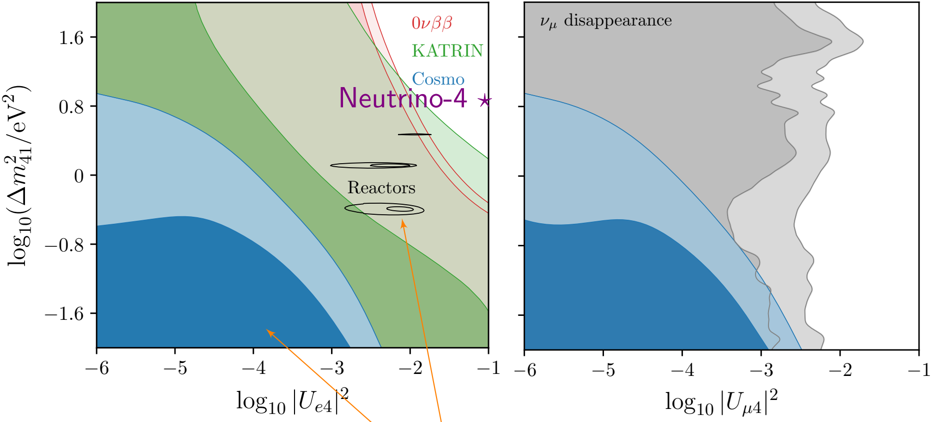


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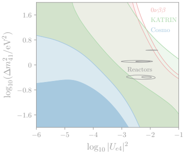
## ⇒ energy density of relativistic neutrinos

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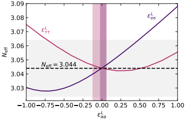


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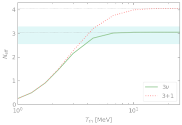


$N_{\rm eff} < 3$?

e.g. low-reheating [PRD 92 (2015) 123534], [update in prep.]

# Non-standard neutrino-electron interactions

[PLB 820 (2021)]

Can neutrinos have interactions beyond the SM ones?

e.g.: $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NSIe}$, with $\mathcal{L}_{\rm NSIe} \propto G_F \sum_{\alpha,\beta} \epsilon^{L,R}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{e}\gamma_\mu P_{L,R} e)$
see e.g. [Farzan+, 2018]

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

new interactions affect all phenomena involving neutrinos and electrons

including neutrino decoupling:

collision terms

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

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

↓

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

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)]

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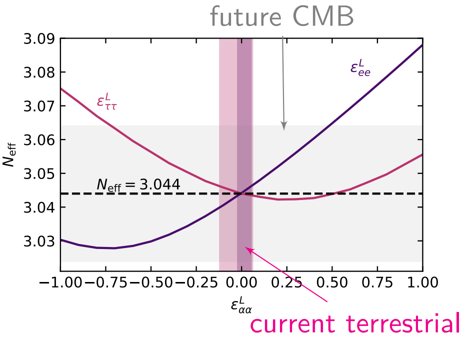
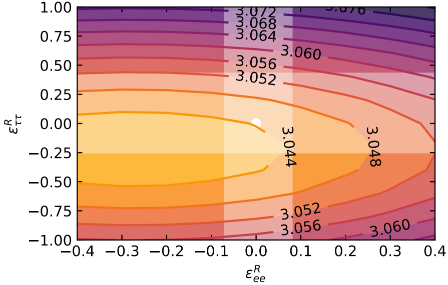
e.g.:

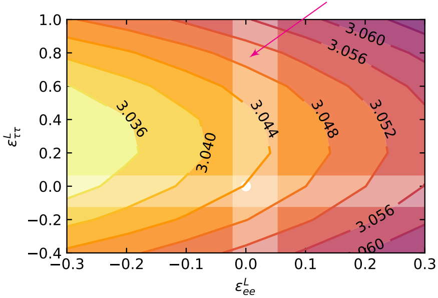
$G^{L}_{ee} \to 0.727 + \epsilon^{L}_{ee}$

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

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



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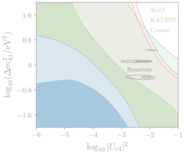


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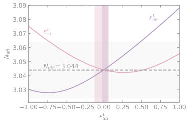


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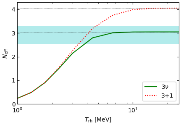


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# Scenarios with low reheating temperature

[in preparation]

Reheating: phase ending inflation

during inflation, the inflaton (non-rel. scalar) dominates the energy density

during reheating: inflaton decays into standard model particles

$\Longrightarrow$ photons, electrons, ... are populated directly

radiation domination begins after reheating

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

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

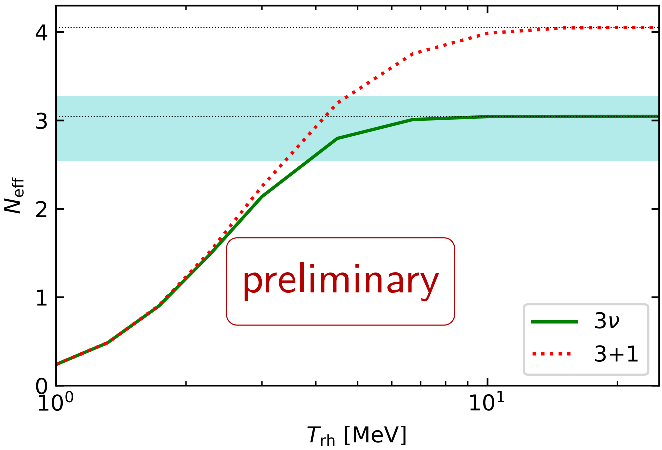
3 neutrino oscillations start to be affected when $T_{\rm rh} \lesssim 8$ MeV

what about sterile neutrinos?

# $N_{\rm eff}$ with low reheating

[in preparation]

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

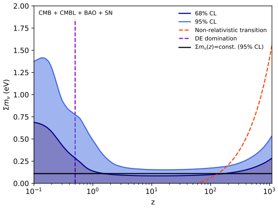



Planck constraint: $N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

M

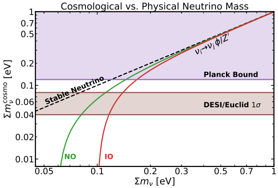
# $\Sigma m_\nu^{\mathrm{cosmo}}$

$\Rightarrow$ energy density of non-relativistic neutrinos




$\Sigma m_\nu^{\mathrm{cosmo}} < \Sigma m_\nu$ by time-varying masses?

e.g. [Lorenz+, PRD 104 (2021) 123518]

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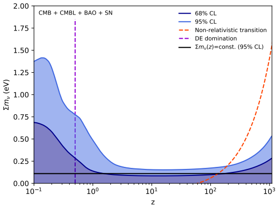


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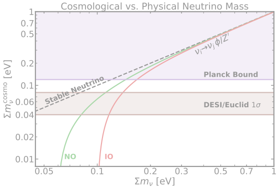


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# Time-varying neutrino masses

How to make neutrino masses non-constant in time?

new coupling!

$a$ scale factor

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How to make neutrino masses non-constant in time?

new coupling!

To new scalar field
(early) dark energy?
e.g. [Ayaita+, PRD 2016]

$m_\nu = 0$ at early times, then

phase transition generates
$m_\nu$ at late times ($a \gtrsim 0.2$)

Masses can grow up to
$m_\nu = 0.6$ eV at $a = 1$

$\nu$ may decay to radiation later

if supercooled transition, data
prefer it at $a \sim 1$ [Lorenz+, PRD 2019]

↓

Massless $\nu$ at all times!

$a$ scale factor

# Time-varying neutrino masses

How to make neutrino masses non-constant in time?

new coupling!

To new scalar field
(early) dark energy?
e.g. [Ayaita+, PRD 2016]

$m_\nu = 0$ at early times, then

phase transition generates
$m_\nu$ at late times ($a \gtrsim 0.2$)

Masses can grow up to
$m_\nu = 0.6$ eV at $a = 1$

$\nu$ may decay to radiation later

if supercooled transition, data
prefer it at $a \sim 1$ [Lorenz+, PRD 2019]

↓

Massless $\nu$ at all times!

To dark radiation
e.g. [Dvali+, PRD 2016]

assume anomalous symmetry
("axial" neutrino lepton number)
broken at scale $\Lambda_G$

s.b. generates effective $m_\nu$

$m_\nu = 0$ at early times, then
generation of masses at $T_\Lambda \lesssim m_\nu$
($T_\Lambda < T_{\rm CMB}$ in order to preserve recombination)

Massive $\nu$ may decay into lightest $\nu$
and annihilate into Goldstone bosons

↓

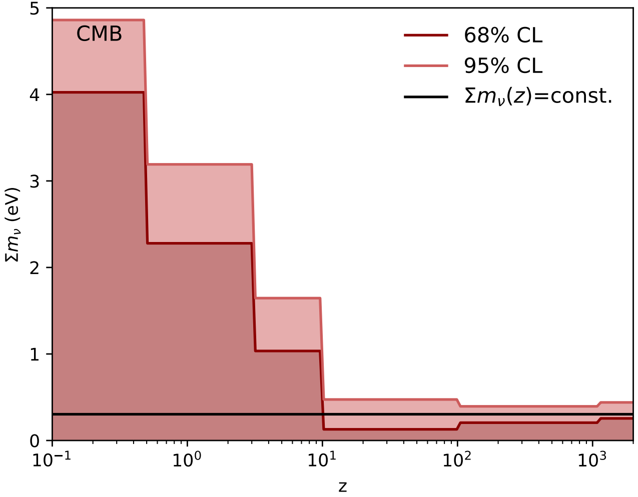
cosmological mass bound is avoided!

$a$ scale factor

# Constraining $\Sigma m_\nu(z)$

[Lorenz+, PRD 104 (2021) 123518]

Phenomenological approach: $\Sigma m_\nu(z) = $ const in 6 redshift bins

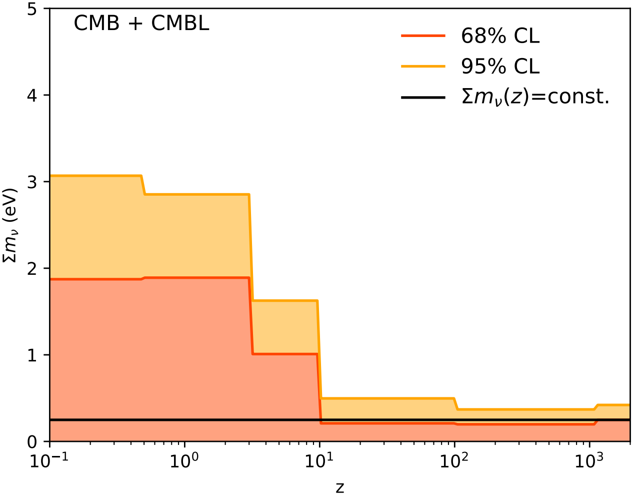



CMB: very high redshift, poor constraints on late universe

# Constraining $\Sigma m_\nu(z)$

[Lorenz+, PRD 104 (2021) 123518]

Phenomenological approach: $\Sigma m_\nu(z) = $ const in 6 redshift bins

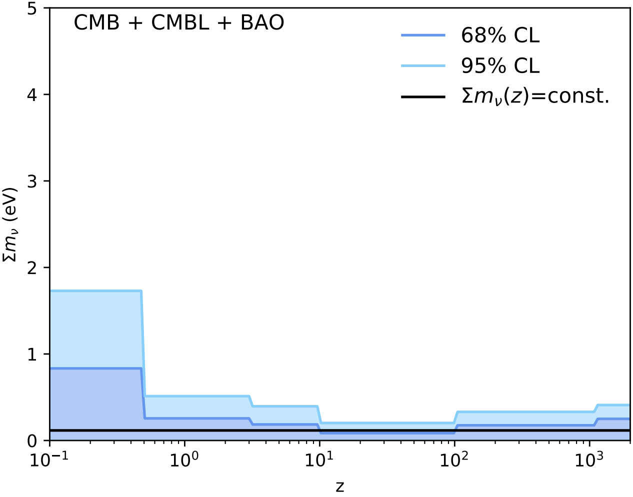



CMBL: lensing affects CMB evolution until today

# Constraining $\Sigma m_\nu(z)$

[Lorenz+, PRD 104 (2021) 123518]

Phenomenological approach: $\Sigma m_\nu(z) = $ const in 6 redshift bins

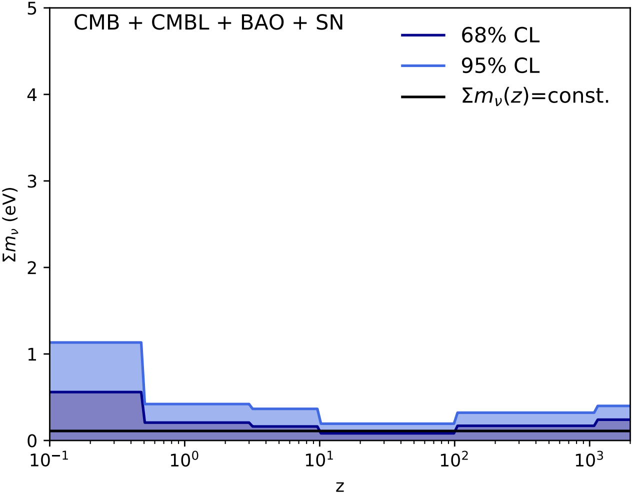



BAO: SDSS BAO+Lyman-$\alpha$+quasars measurements at $z < 2.3$

# Constraining $\Sigma m_\nu(z)$



Phenomenological approach: $\Sigma m_\nu(z) =$ const in 6 redshift bins

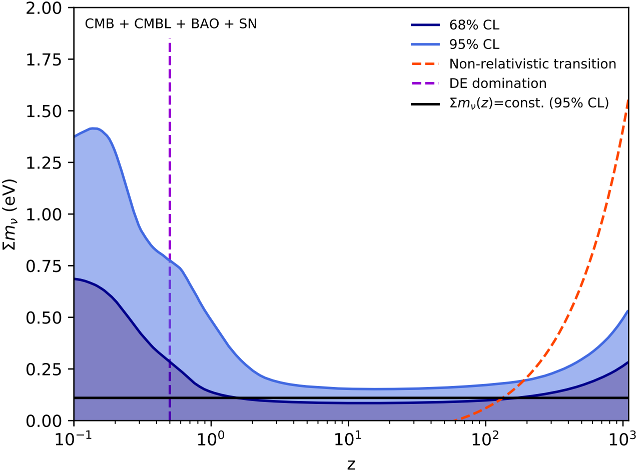



SN: Pantheon SN samples at $z < 2.3$ from SDSS, SNLS, HST

# Constraining $\Sigma m_\nu(z)$

[Lorenz+, PRD 104 (2021) 123518]

Phenomenological approach: $\Sigma m_\nu(z) = \text{const in 6 redshift bins}$

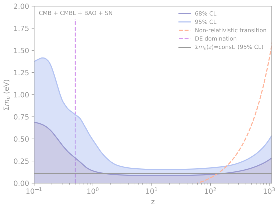



$\nu$ energy density is strongly constrained in the range $1 \lesssim z \lesssim \mathcal{O}(100)$, corresponding to matter domination while $\nu$ are non-relativistic

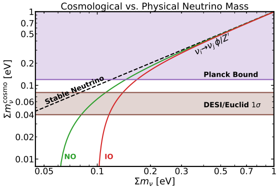
M

# $\Sigma m_\nu^{\text{cosmo}}$

$\Rightarrow$ energy density of non-relativistic neutrinos




$\Sigma m_\nu^{\text{cosmo}} < \Sigma m_\nu$ by time-varying masses?
e.g. [Lorenz+, PRD 104 (2021) 123518]




$\Sigma m_\nu^{\text{cosmo}} < \Sigma m_\nu$ by invisible decay?
e.g. [Escudero+, JHEP 12 (2020) 119]

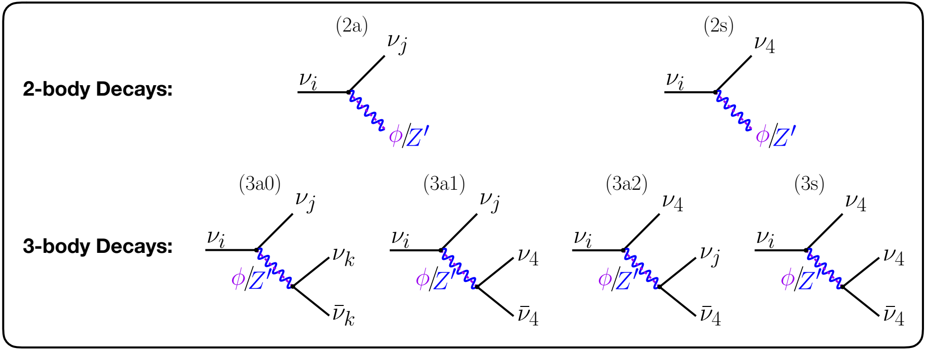
# Decaying neutrinos in cosmology

[Escudero+, JHEP 12 (2020) 119]

Can a neutrino decay? Is the decay lifetime $\tau_\nu$ constrained?

Decay into visible (e.m.) particles is constrained to $\tau_\nu > 10^2 t_U$

Invisible decay is much less constrained! A few examples:



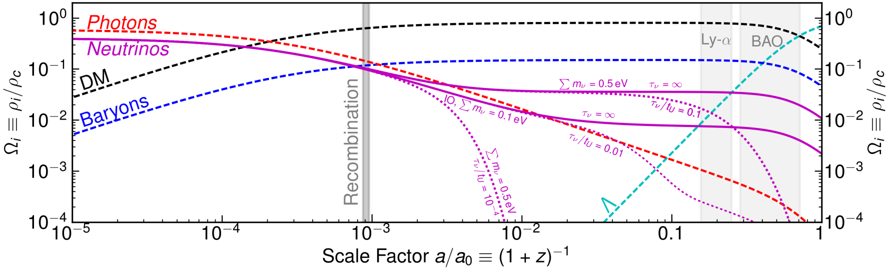

if $m_4 = m_\phi = m_{Z'} = 0$, neutrinos decay to radiation
and the mass bounds are avoided if $\tau_\nu \lesssim t_U$ is short enough

$t_U$ age of the Universe – $\nu_i$ active neutrinos – $\nu_4$ sterile neutrino – $\phi$ scalar – $Z'$ vector

# Decaying neutrinos in cosmology

Can a neutrino decay? Is the decay lifetime $\tau_\nu$ constrained?

Depending on $\tau_\nu$, the standard energy density of neutrinos is suppressed:




if $\tau_\nu \simeq 10^{-4} t_U$, decay occurs at recombination
(if $\Sigma m_\nu < 0.6$ eV, neutrinos are still relativistic)

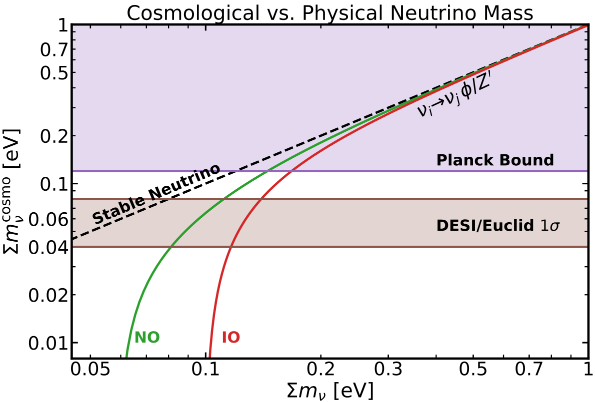
for large $\tau_\nu$, suppression may be partial

$t_U$ age of the Universe – $\nu_i$ active neutrinos – $\nu_4$ sterile neutrino – $\phi$ scalar – $Z'$ vector

# Bounds on the neutrino lifetime



Consider 2-body decay channels:




$\Sigma m_\nu^{\rm cosmo} = 3 m_{\rm lightest}$ if all except lightest neutrino decay to $\nu_{\rm lightest}\phi/Z'$

**Bounds** obtained with $\tau_\nu \lesssim t_U/10$

DESI/Euclid bound is forecast with $\Sigma m_\nu = 60$ meV

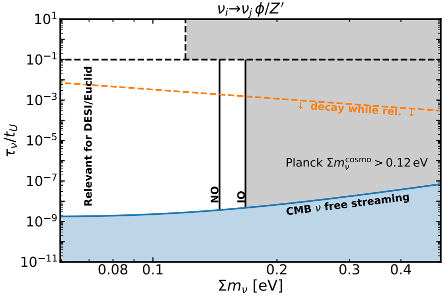
# Bounds on the neutrino lifetime

[Escudero+, JHEP 12 (2020) 119]

Consider 2-body decay channels:

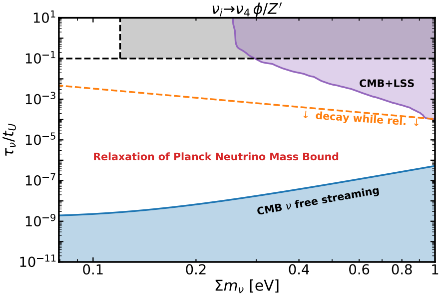
Constraints from Planck legacy or late time clustering+CMB lensing

Active neutrino + boson:




late time constraints not yet considered, may provide additional constraints

Sterile neutrino + boson:



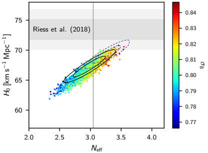

for appropriate $\tau_\nu$ and $\Sigma m_\nu$, the mass bounds do not apply because all goes into radiation and $\Sigma m_\nu^{\rm cosmo} = 0$

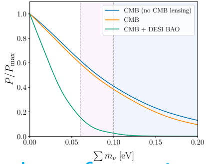
## E Conclusions

# What do we learn about non-standard $\nu$ scenarios?

C

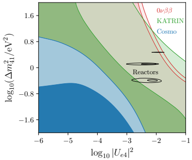
Cosmology measures (mostly) neutrino energy densities!

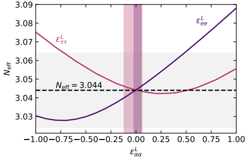


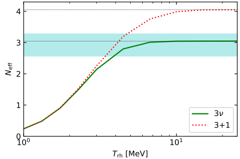




N

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

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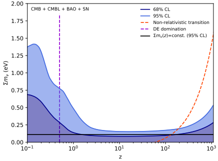
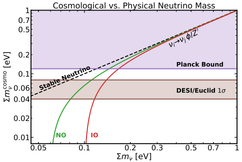
The "cosmological" $\Sigma m_\nu$ is NOT the sum of neutrino masses!



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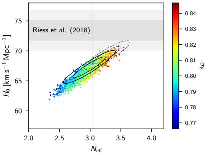


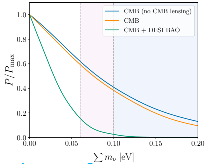


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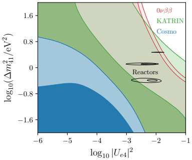


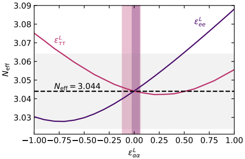


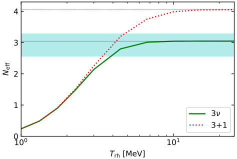


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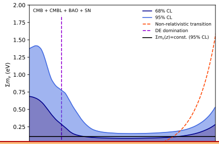


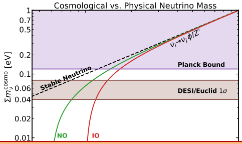


# Thanks for your attention!