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Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

(Cosmological) Relic neutrinos, from A to Z

Max-Planck-Institute for Nuclear Physics, Heidelberg, online, 17/01/2022

A Active neutrinos

Spoiler: "Sterile" will come later

Based on:

- JHEP 02 (2021) 071 and update
- Planck 2018
- 10.1088/1475-7516/2021/04/073

[D. Galbraith & C. Burgard, 2012]
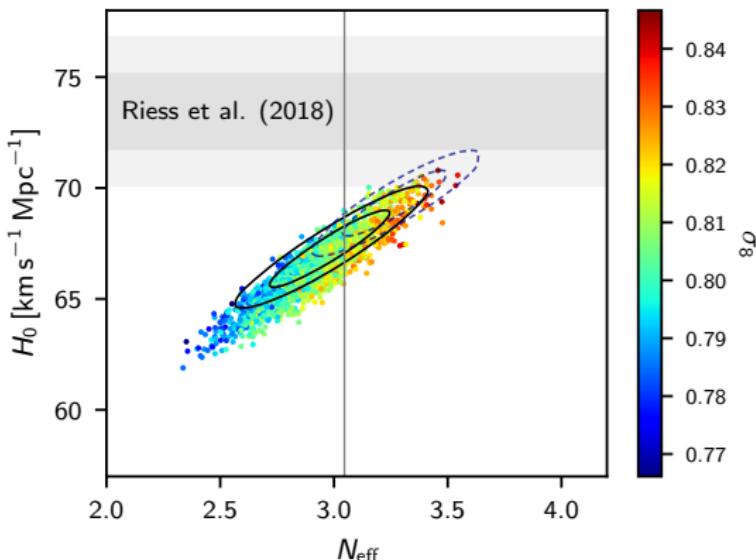
The Standard Model of Particle Physics
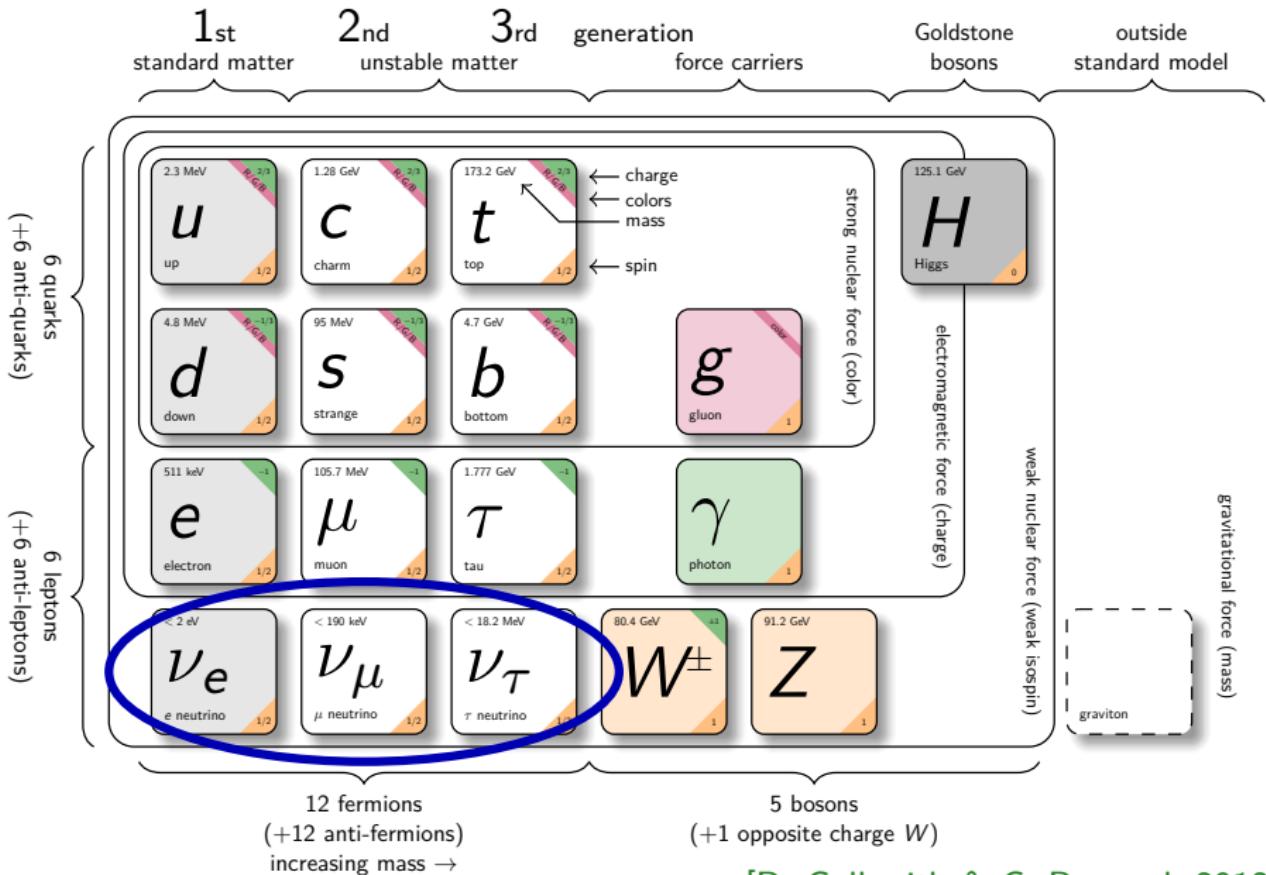

[D. Galbraith & C. Burgard, 2012]

Major discoveries:

[SuperKamiokande, 1998]
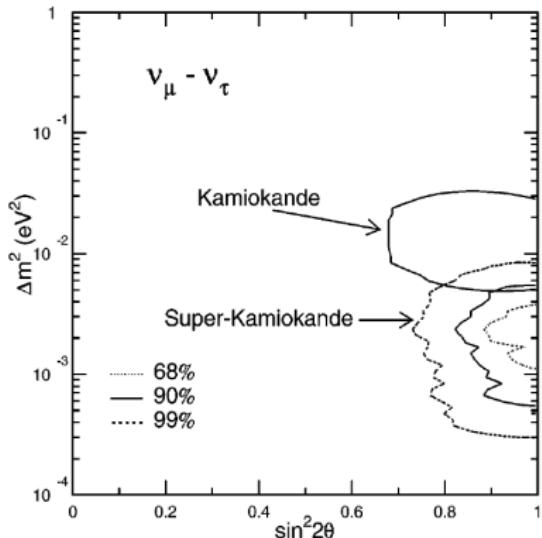
[SNO, 2001-2002]

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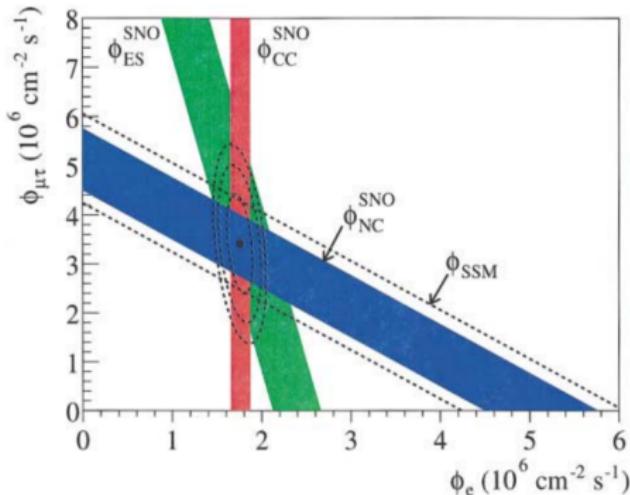
first discovery of $\nu_e \rightarrow \nu_\mu, \nu_\tau$
oscillations from solar ν

Nobel prize in 2015

Two neutrino bases

flavor neutrinos ν_α

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

massive neutrinos ν_k

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

ν_α ν_1 ν_β

ν_2

ν_3

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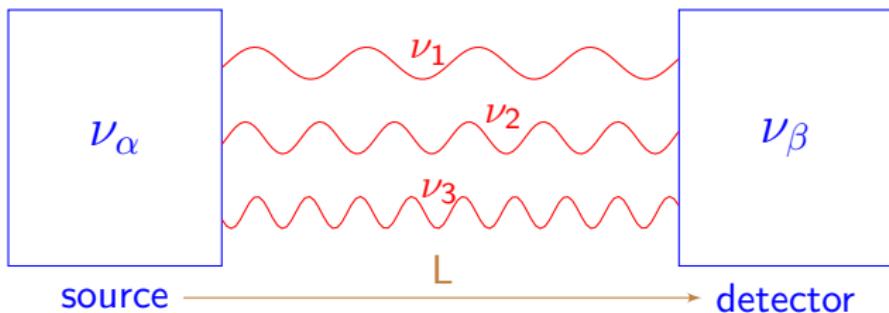
$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\,e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

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

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

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

The mixing matrix

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

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} M$$

mainly atmospheric and LBL accelerator disappearance

mainly SBL reactors and LBL accelerator appearance

mainly solar and LBL reactors

Majorana phases irrelevant for oscillation experiments $\leftarrow$

Relevant for example in neutrinoless double-beta decay

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

SBL = short baseline; LBL = long baseline

Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase δ

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

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

$\Delta m_{21}^2 = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5} \text{ eV}^2$

$|\Delta m_{31}^2| = (2.54 \pm 0.03) \cdot 10^{-3} \text{ eV}^2$ (NO)

$= (2.44 \pm 0.03) \cdot 10^{-3} \text{ eV}^2$ (IO)

$10\sin^2(\theta_{12}) = 3.18 \pm 0.16$

$10^2\sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}$ (NO)

$= 2.225^{+0.064}_{-0.070}$ (IO)

$10\sin^2(\theta_{23}) = 4.55 \pm 0.13 U 5.71 \pm 0.12$ (NO)

$= 5.71^{+0.14}_{-0.17}$ (IO)

$\delta/\pi = 1.10^{+0.27}_{-0.12}$ (NO)

$= 1.54 \pm 0.14$ (IO)
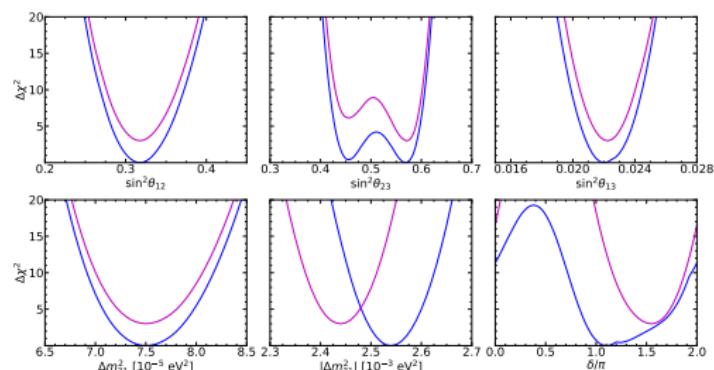
mass ordering still unknown

δ still unknown

see also: http://globalfit.astroparticles.es
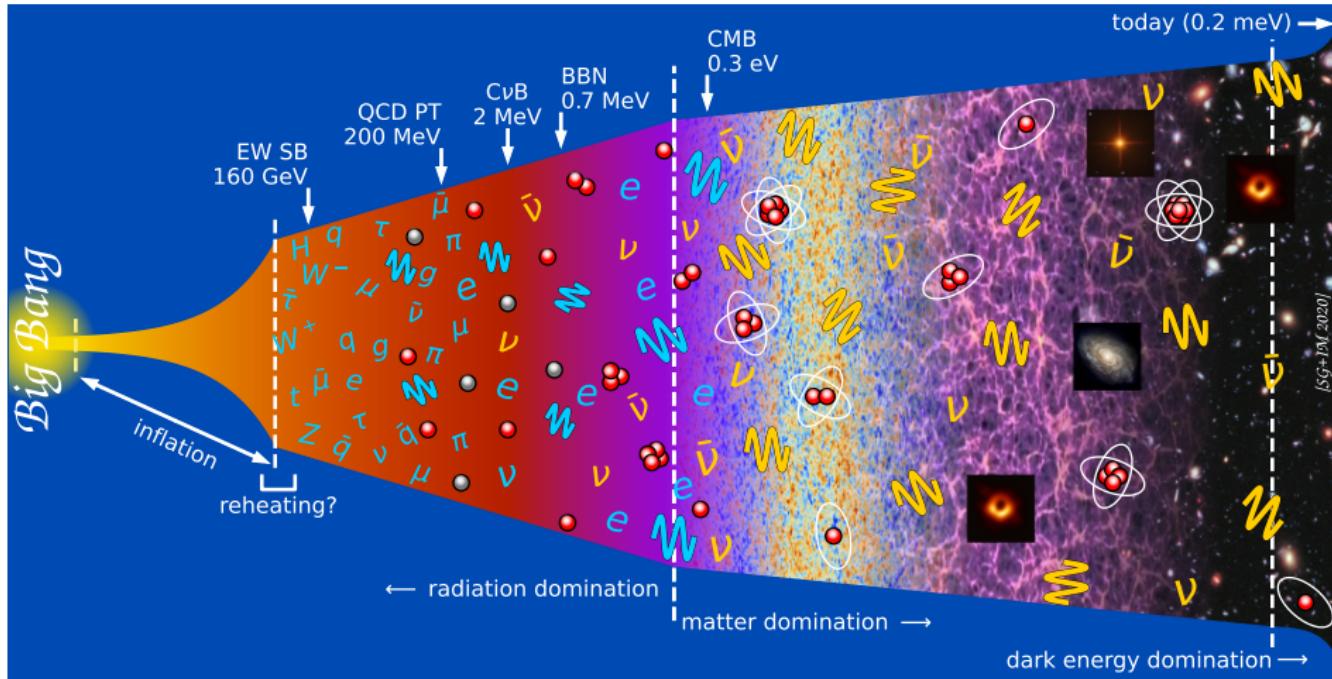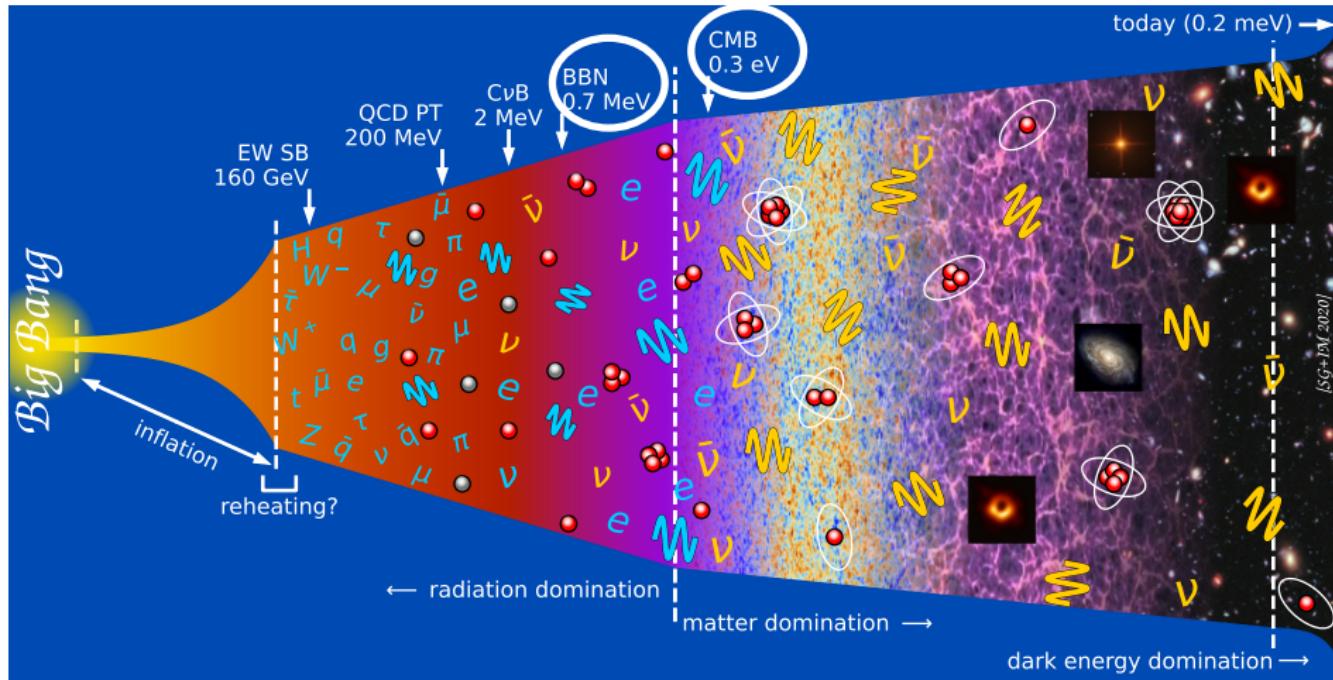
The oldest picture of the Universe

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

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

CMB spectra as of 2018

Big Bang Nucleosynthesis (BBN)

BBN: production of light nuclei at $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

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

much earlier than CMB!

strong probe for physics before the CMB

e.g. neutrinos!

ν affect universe expansion and reaction rates $(\nu_e/\bar{\nu}_e)$ at BBN time...

[PDG 2018]

baryon density $\Omega_b h^2$

measured

theory

BBN concordance

baryon−to−photon ratio η

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[PDG 2018]

baryon density $\Omega_b h^2$

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

$(1/\tau)/$ Hz

- H
- osc. atm.
- osc. Sun
- osc. 1 eV^2
- $G_F^2 T^5$

T/ MeV

[Courtesy P. F. de Salas]
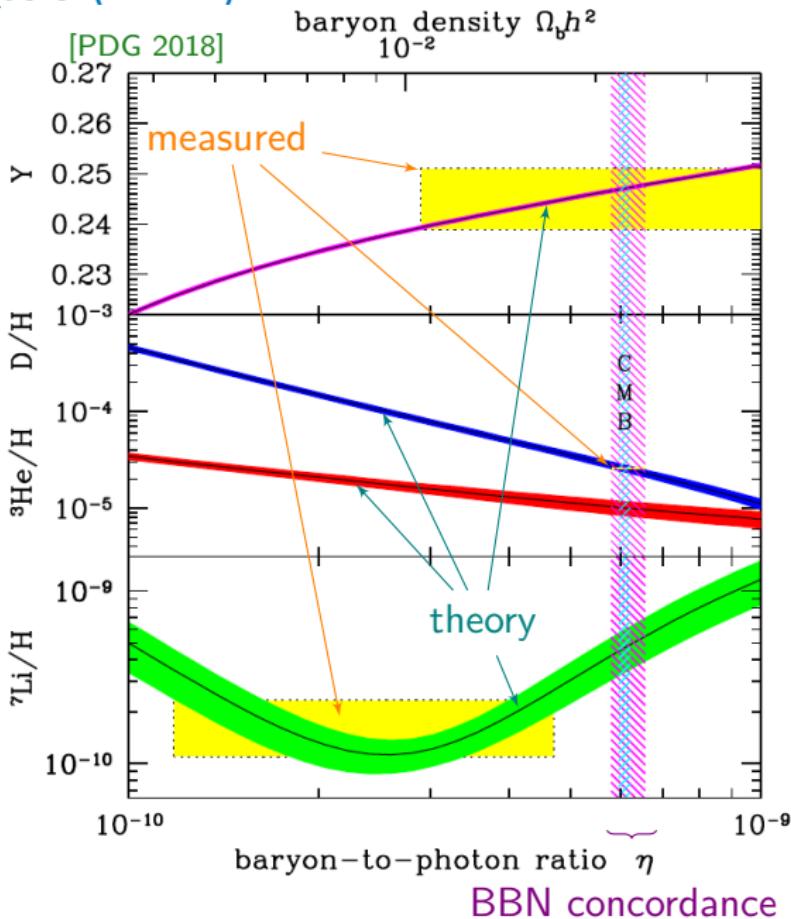
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[Courtesy P. F. de Salas]

Neutrinos in the early Universe

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

oscillations blocked by matter effects

ν decoupling

H
osc. atm.
osc. Sun
osc. 1 eV^2
G_F^2 T^5

time

$(1/\tau)$/ Hz

T/ MeV

[Courtesy P. F. de Salas]

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

Neutrinos in the early Universe

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time

$T_\nu \simeq (4/11)^{1/3} T_\gamma$
after $e^+ e^- \to \gamma\gamma$

f_ν: frozen Fermi-Dirac distribution

Today:

$T_{\nu,0} = 1.945$ K $\simeq$
1.676×10^{-4} eV

$\langle E_\nu \rangle \simeq 3.1 T_{\nu,0} \simeq$
5×10^{-4} eV

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

oscillations blocked
by matter effects

ν decoupling

H

osc. atm.

osc. Sun

osc. 1 eV^2

$G_F^2 T^5$

[Courtesy P. F. de Salas]

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

actually, the decoupling T is momentum dependent!

distortions to equilibrium f_ν!

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

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

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

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

ν oscillations in the early universe

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

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

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

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

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

$$\mathbb{M} = \mathrm{diag}(m_1^2, m_2^2, m_3^2)$$

$$U = R^{23} R^{13} R^{12} \qquad \text{e.g. } R^{13} = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

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

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

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

take into account matter effects in oscillations

ν oscillations in the early universe

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

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

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

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

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

◼ ν oscillations in the early universe

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

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

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

$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\qquad J(r), Y(r)$ from non-relativistic transition of $e^\pm$, $\mu^\pm$
$G_1(r)$ and $G_2(r)$ from electromagnetic corrections

ν oscillations in the early universe

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neutrino temperature w: same equation as z, but electrons always relativistic

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neutrino temperature w: same equation as z, but electrons always relativistic

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

ν oscillations in the early universe

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m: Planck mass, ρ: total energy density, m: mass of the W, Z bosons, G: Fermi constant, [,] commutator

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

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

neutrino temperature w: same equation as z, but electrons always relativistic

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

Distortion of the momentum distribution (f_{FD}: Fermi-Dirac at equilibrium)
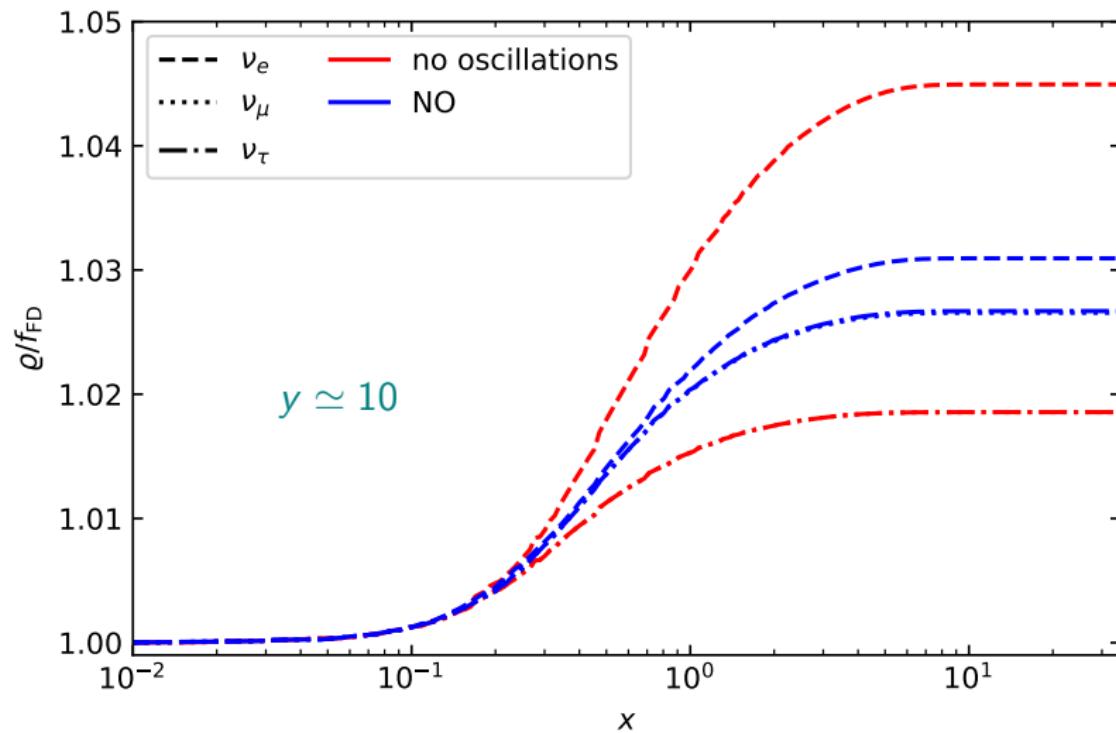
Distortion of the momentum distribution (f_{FD}: Fermi-Dirac at equilibrium)
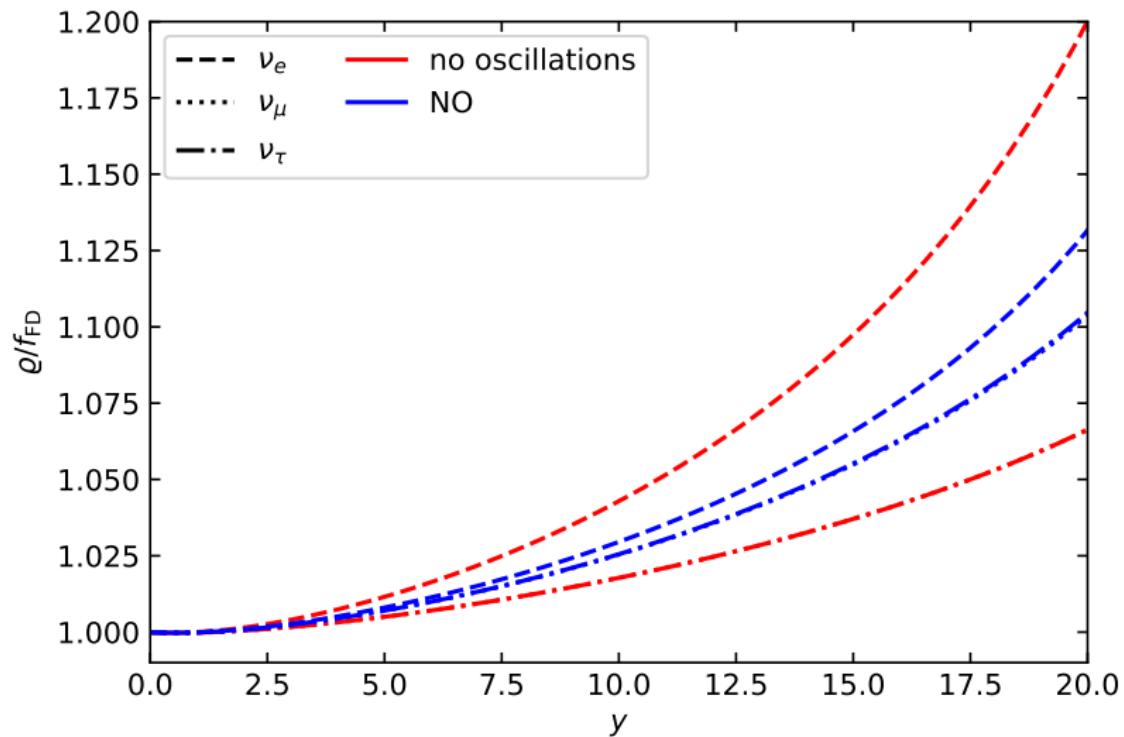
$$N_{\mathrm{eff}}^{\mathrm{final}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{1}{\rho_\gamma}\sum_i g_i \int \frac{d^3p}{(2\pi)^3} E(p)\, f_{\nu,i}(p)$$

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

$\hookrightarrow \propto y^3 \varrho_{ii}(y)$
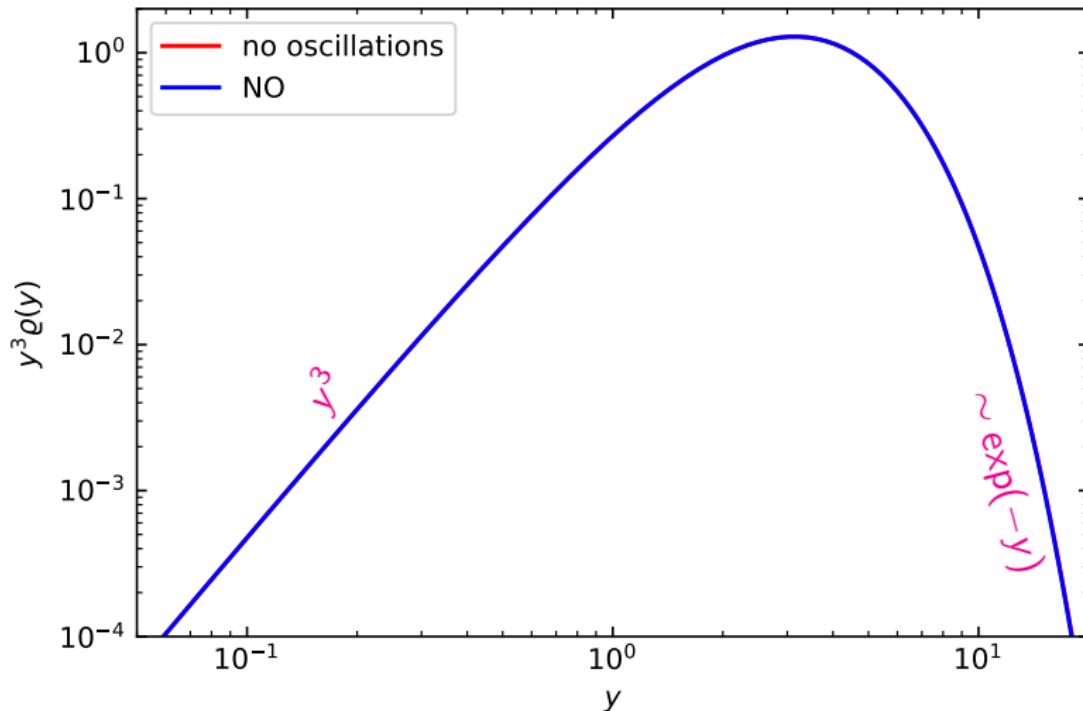
$$N_{\text{eff}}^{\text{any time}} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4 \frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4 \frac{1}{\rho_\gamma}\sum_i g_i \int \frac{d^3p}{(2\pi)^3} E(p)\, f_{\nu,i}(p)$$
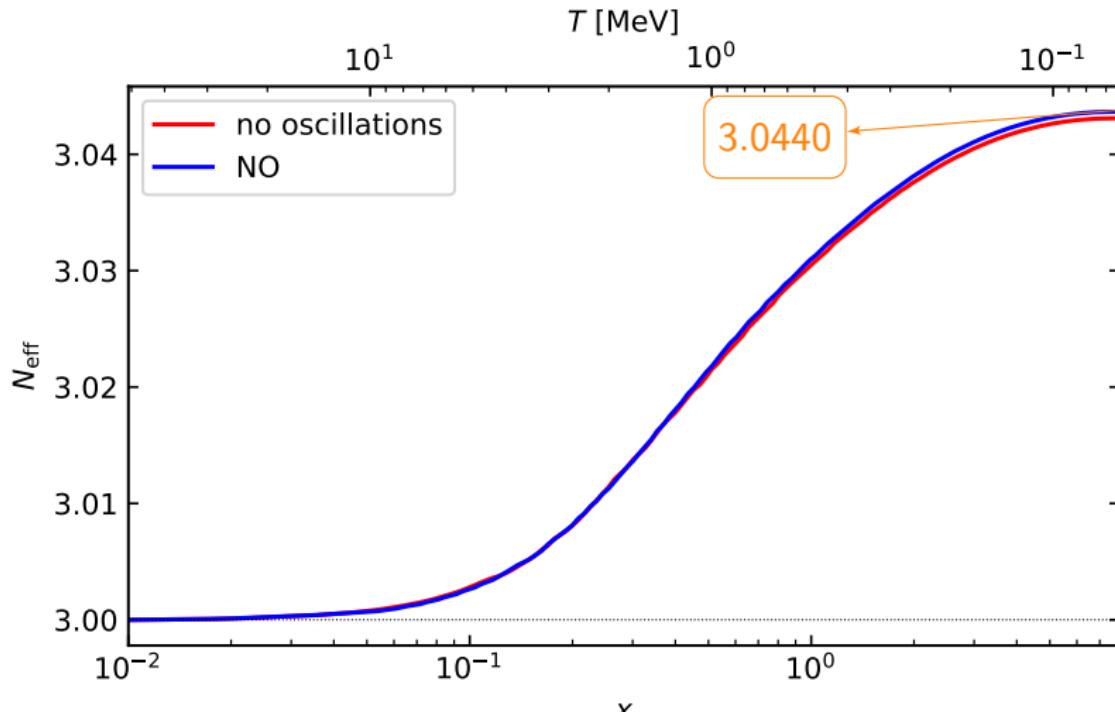
Effect of neutrino oscillations
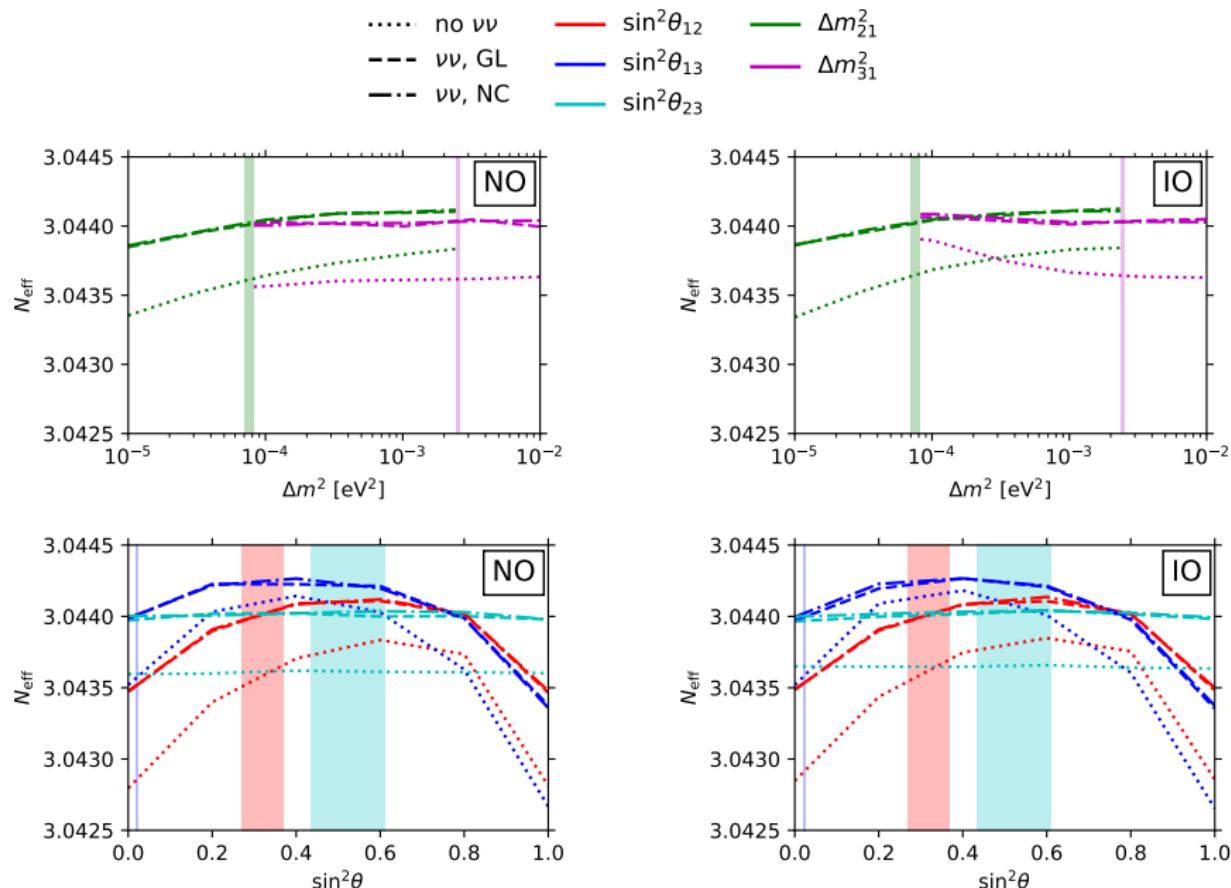
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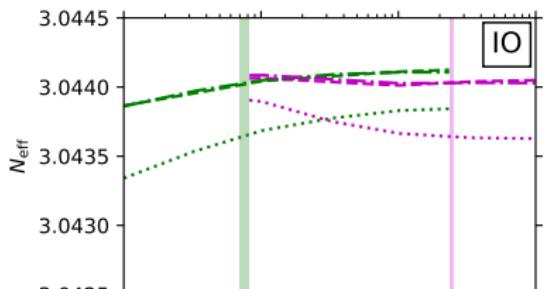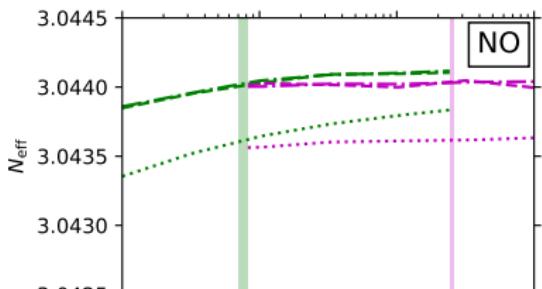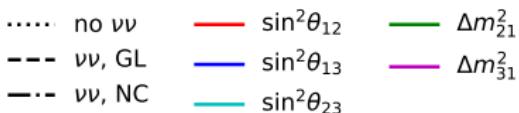
within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]
only θ_{12} affects N_{eff}, at most by $\delta N_{\text{eff}} \approx 10^{-4}$

Discretize neutrino momenta to compute integrals and evolution

two sampling methods for y_i, with $i = 1, \ldots, N_y$:

linear spacing,
Newton-Cotes (NC) integration

Gauss-Laguerre (GL)

optimized for computing $\int_0^\infty dy\, f(y)e^{-y}$

Need to define range ($y_{\min} \leq y \leq y_{\max}$) and number of nodes N_y

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Sampling the y momenta

Discretize neutrino momenta to compute integrals and evolution

Results may depend on $y_{\min}$, $y_{\max}$, N_y

at same N_y,
GL results are more stable!

↓

GL is more efficient

$\delta N_{\mathrm{eff}} \approx 10^{-4}$ from varying N_y, $y_{\max}$

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

Long list of previous works... always less than 3ν mixing

[Mangano+, 2005]: $N_{\rm eff} = 3.046$ 1st with 3ν mixing (still most cited value)

[de Salas+, 2016]: $N_{\rm eff} = 3.045$ updated collision terms

[SG+, 2019]: $N_{\rm eff} = 3.044$
FortEPiaNO code

more efficient and precise code,
$N > 3$ neutrinos allowed,
minor differences in numerical integrals

[Bennett+, 2019]: $N_{\rm eff} = 3.043$
(no full calculation)

finite-T QED corrections at $\mathcal{O}(e^3)$!
further terms should be almost negligible

[Akita+, 2020]:
$N_{\rm eff} = 3.044 \pm 0.0005$

equations in mass and flavor basis
approximated $\nu\nu$ collisions

[Froustey+, 2020]:
$N_{\rm eff} = 3.0440 \pm \mathcal{O}(10^{-4})$

full $\nu\nu$ interactions
1st estimate effect of CP-violating phase

[Bennett, SG+, 2020]:
$N_{\rm eff} = 3.0440 \pm 0.0002$
FortEPiaNO improved

1st full discussion on effect of oscillation
parameters, full estimation of current
numerical and physical uncertainty

N_{eff} and BBN

BBN: production of light nuclei
at $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

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

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

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

enters
$n/p = \exp(-Q/T_{fr})$
which controls element abundances

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

$\downarrow$

abundances depend on N_{eff}

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

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$\downarrow$

abundances depend on $N_{\rm eff}$

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

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

Σm_ν and CMB

B   Bosonic neutrinos

(?!? what?)

Based on:

- JCAP 03 (2018) 050
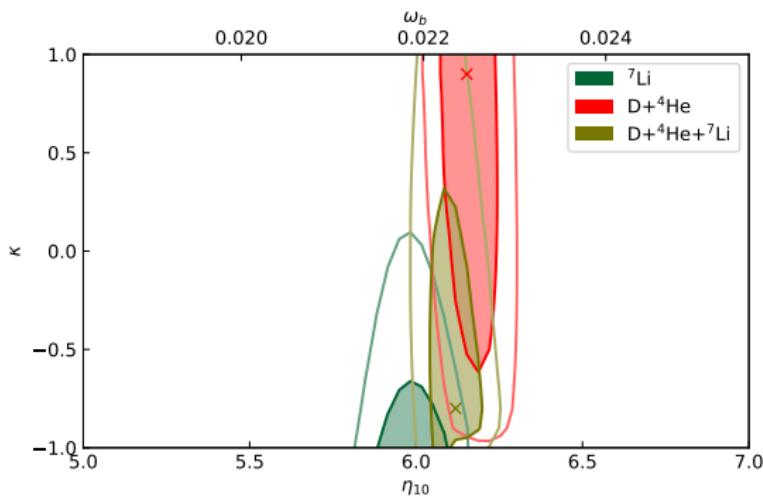
Neutrinos are fermions $\longrightarrow$ they obey Fermi-Dirac statistics

Motivation

Neutrinos are fermions $\longrightarrow$ they obey Fermi-Dirac statistics

Do they obey Fermi-Dirac statistics?

No experimental confirmation of spin-statistics theorem for neutrinos!

Can we find violations of the Pauli exclusion principle?

Motivation

Neutrinos are fermions ⟶ they obey Fermi-Dirac statistics

Do they obey Fermi-Dirac statistics?

No experimental confirmation of spin-statistics theorem for neutrinos!

Can we find violations of the Pauli exclusion principle?

| electrons | nucleons |

no violations for atomic electrons
e.g. look for anomalous X-rays from
atomic decays

[Goldhaber&Scharff-Goldhaber, 1948]

[Fischbach&Kirsten&Schaeffer, 1968]

[Reines&Sobel, 1974]

. . .

no violations for protons/neutrons
e.g. look for anomalous star (Sun)
dynamics or transitions in nuclei

[Plaga, 1989]

[Miljanić+, 1990]

[Borexino, 2004]

. . .

see detailed discussion in [Dolgov&Smirnov, PLB 2005]

The neutrino case

important: since spin-statistics relation confirmed for electrons,
              difficult to imagine large deviation for neutrinos

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violation of the Pauli principle for ν should show up in elementary processes where identical ν are involved

for example the two-neutrino double beta decay, $A \to A' + 2\bar{\nu} + 2e^-$ or $A \to A' + 2\nu + 2e^+$

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Fermi-Bose parameter κ_ν [Dolgov+, JCAP 2005]

$$f_\nu(E) = \frac{1}{\exp(E/T) + \kappa_\nu}$$

"mixed" distribution!

BE $\leftarrow \kappa_\nu = -1 \xleftarrow{\quad} \underset{\text{MB}}{\kappa_\nu = 0} \xrightarrow{\quad} \kappa_\nu = +1 \rightarrow$ FD

[Barabash+, NPB 2007]: $\kappa_\nu \gtrsim -0.2$

100% violation excluded [Barabash+, NPB 2007], but still 50% admixture of bosonic component allowed

what can cosmology say about κ_ν?

different $f_\nu(p)$ affects BBN!

statistics factor becomes $(1 - \kappa_\nu f_\nu)$
$(1 + f_\nu) \rightarrow$ Bose enhancement,
$(1 - f_\nu) \rightarrow$ Pauli blocking

Constraints on κ_ν from BBN

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$\downarrow$

change of n/p ratio at BBN

[Dolgov+, JCAP 2005]

less He, more D, less Li
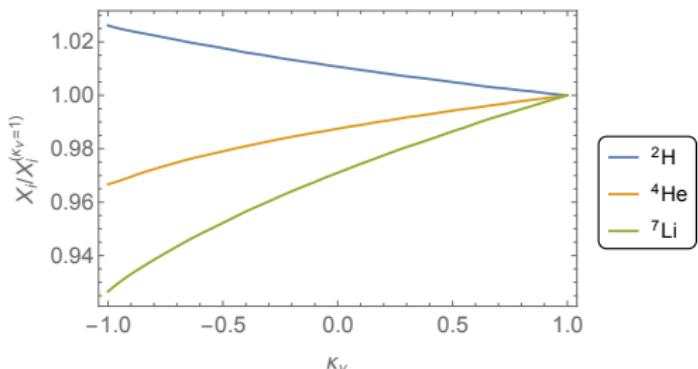
deviation from $\kappa_\nu = 1$
obtained with a modified version
of PArthENoPE

[Consiglio+, CPC 2018]

Constraints on κ_ν from BBN

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change of n/p ratio at BBN

[Dolgov+, JCAP 2005]

less He, more D, less Li

He or D alone cannot constrain κ_ν

Li problem drives $\omega_{\rm b}$ down

and κ_ν to -1

also when prior on $\omega_{\rm b}$ is included
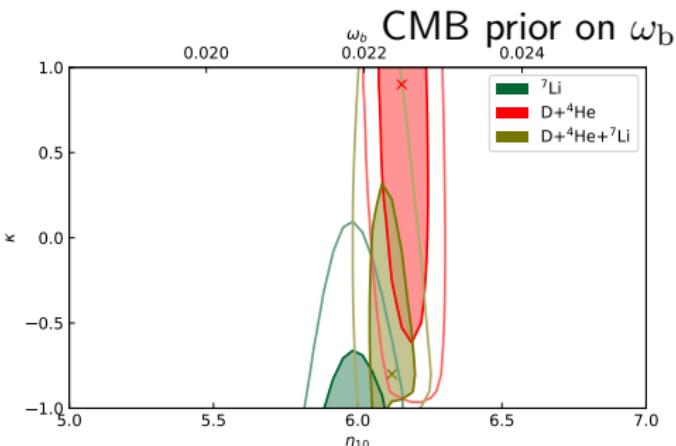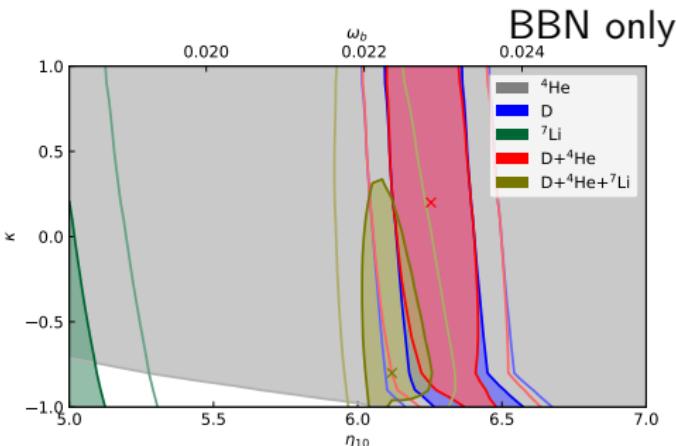
$$f_\nu(E) = \frac{1}{\exp(E/T) + \kappa_\nu}$$

κ_ν affects
background evolution:

$$\rho_\nu^{\text{rel}} \simeq \frac{g_\nu}{2\pi^2} \int_0^\infty dp\, p^3\, f_\nu(p)$$

bosons:
$\frac{\pi^2}{30} g_i\, T^4$

fermions:
$\frac{7}{8} \frac{\pi^2}{30} g_i\, T^4$

$$\rho_\nu^{\text{nr}} \simeq m_\nu \frac{g_\nu}{2\pi^2} \int_0^\infty dp\, p^2\, f_\nu(p)$$

bosons:
$\frac{\zeta(3)}{\pi^2} m_\nu g_i\, T^3$

fermions:
$\frac{3}{4} \frac{\zeta(3)}{\pi^2} m_\nu g_i\, T^3$

$\kappa_\nu = 1$, $N_{\text{eff}} = 3.045$, $M_\nu = 0.06$ eV
$\kappa_\nu = 1$, $N_{\text{eff}} = 3.474$, $M_\nu = 0.06$ eV
$\kappa_\nu = 1$, $N_{\text{eff}} = 3.045$, $M_\nu = 0.08$ eV
$\kappa_\nu = -1$, $N_{\text{eff}} = 3.045$, $M_\nu = 0.06$ eV

changing κ_ν "mimics" altering N_{eff} or Σm_ν (at late or early times)

partial degeneracies with N_{eff} and Σm_ν
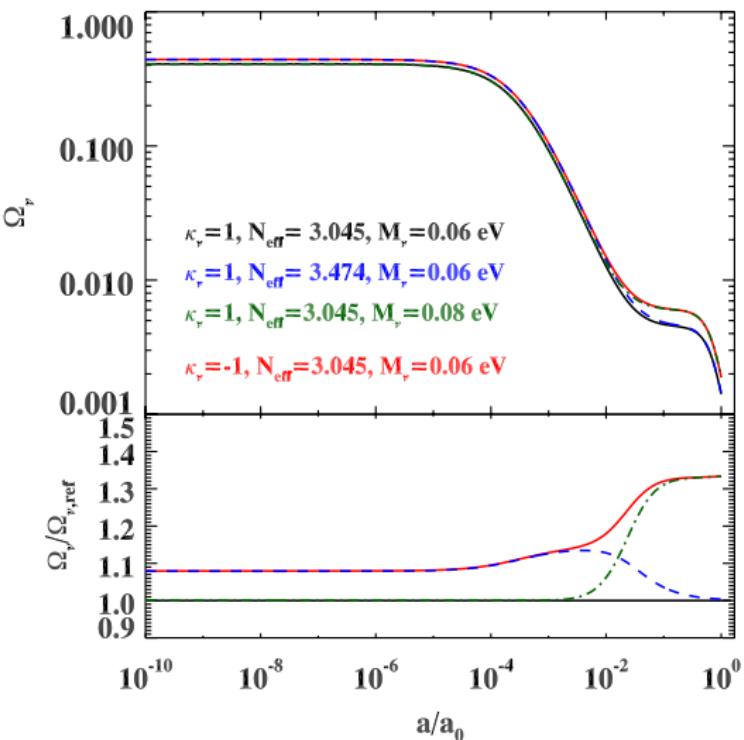
need to cover κ_ν–Σm_ν degeneracy:
vary both!

degeneracy affects
mostly CMB only bounds

with BAO, bound on Σm_ν is stronger

adding radiation (through κ_ν) and Ω_Λ alters
H_0 and compensates a bit the larger mass

bounds: $\kappa_\nu \gtrsim -0.1$ at 68%

$-1 \leq \kappa_\nu \leq 1$ at 95%

$\kappa_\nu = -1$ corresponds to
$N_{\text{eff}} \simeq 3.47$ at early times

inside Planck 2σ region!
reasonably it's not excluded
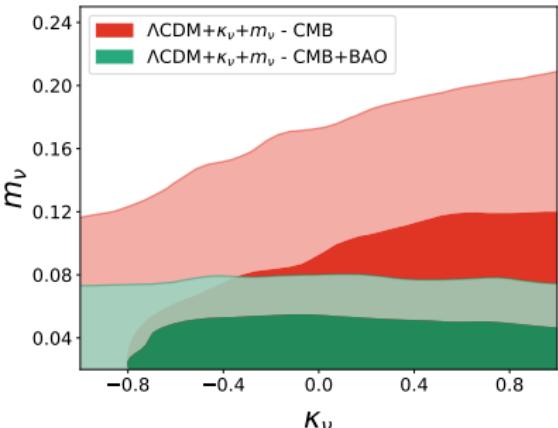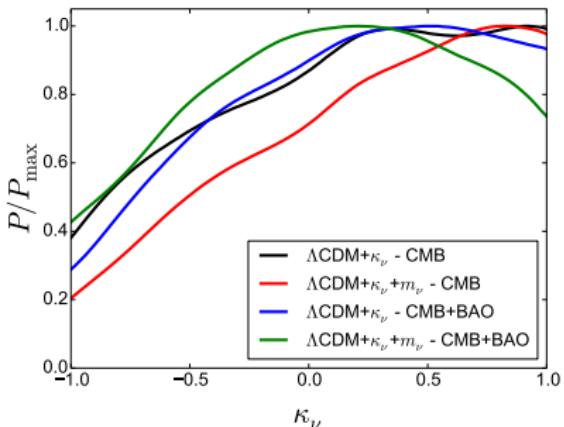
C Clustering in the local Universe

Based on:

- JCAP 09 (2017) 034

- JCAP 01 (2020) 015
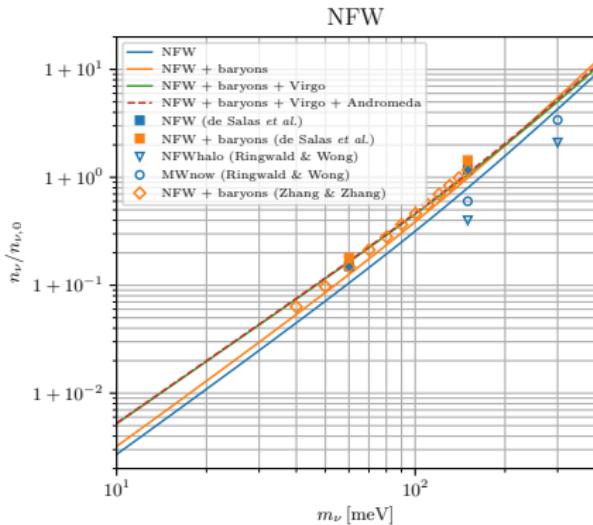
ν clustering with N-one-body simulations

Relic neutrinos are slow! $[c_\nu \sim 160(1 + z)(1 \text{ eV}/m_\nu) \text{ km s}^{-1}]$

Can be trapped in the gravitational potential of the Milky Way and neighbours

$f_c(m_i) = n_i/n_{i,0}$ clustering factor $\longrightarrow$ How to compute it?

Idea from [Ringwald & Wong, 2004] $\longrightarrow$ N-one-body= N $\times$ single ν simulations

$\rightarrow$ each ν evolved from initial conditions at $z = 3$

$\rightarrow$ spherical symmetry, coordinates (r, θ, p_r, l)

$\rightarrow$ need $\rho_{\mathrm{matter}}(z) = \rho_{\mathrm{DM}}(z) + \rho_{\mathrm{baryon}}(z)$

Assumptions:

νs are independent

only gravitational interactions

νs do not influence matter evolution

$(\rho_\nu \ll \rho_{\mathrm{DM}})$

how many νs is "N"?

$\rightarrow$ must sample all possible r, p_r, l

$\rightarrow$ must include all possible νs that reach the MW

(fastest ones may come from

several (up to $\mathcal{O}(100)$) Mpc!)

given N ν:

$\rightarrow$ weigh each neutrinos

$\rightarrow$ reconstruct final density profile with kernel method from [Merritt&Tremblay, 1994]

Forward-tracking and back-tracking

initial phase space, $z = 4$ $\longrightarrow$ homogeneous Fermi-Dirac distribution

final phase space, $z = 0$

Forward-tracking and back-tracking

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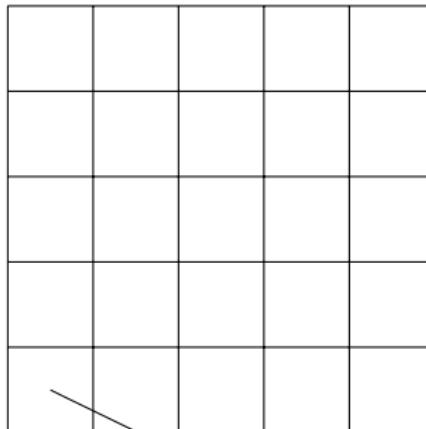
compute final position of each particle
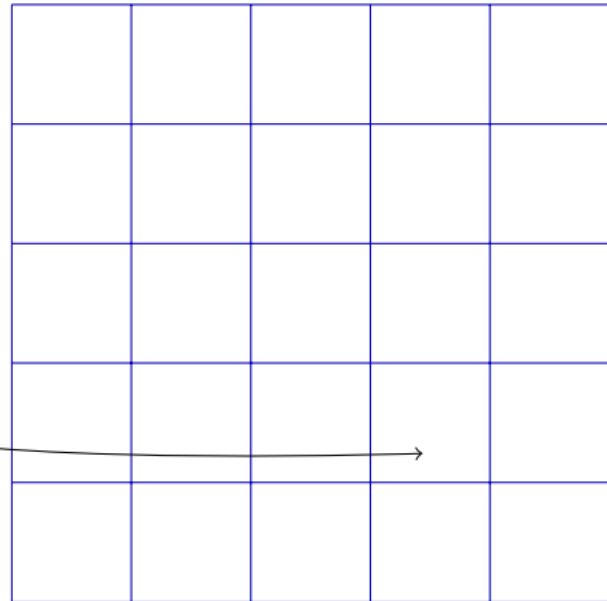
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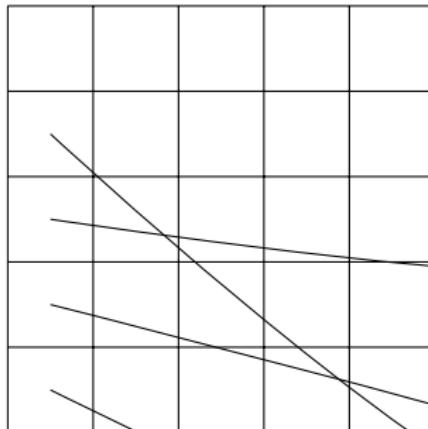
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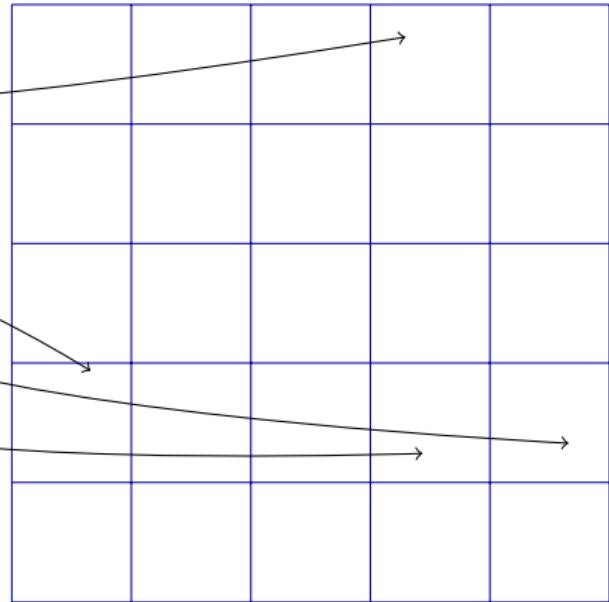
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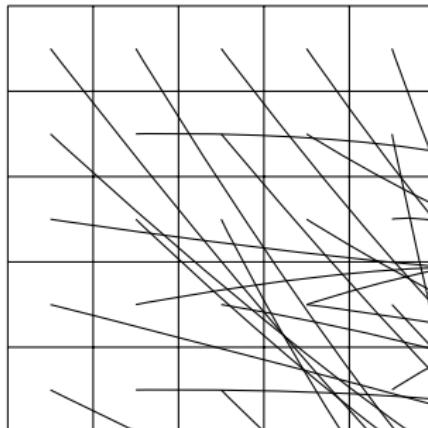
use positions to find neutrino distribution today
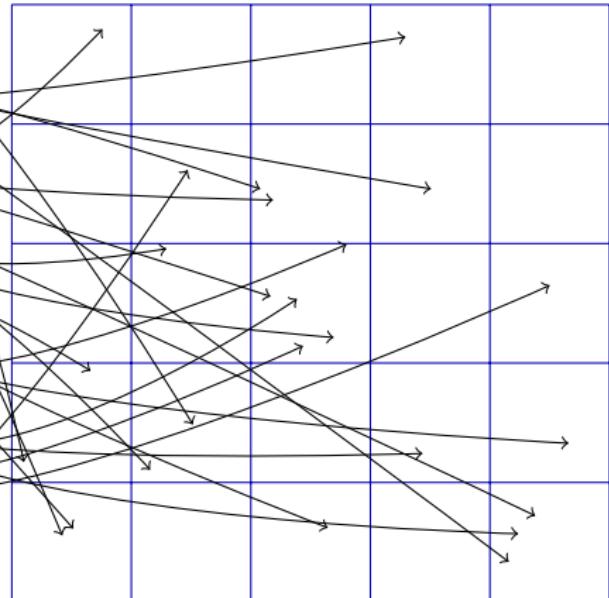
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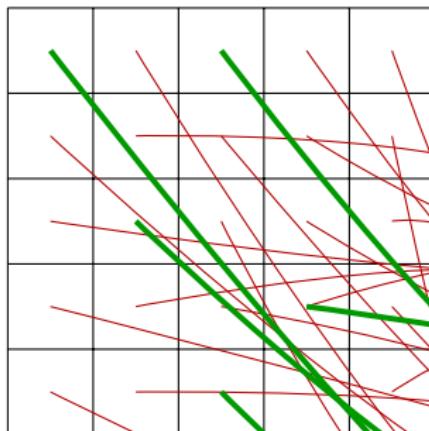
only interested in overdensity at Earth? ★
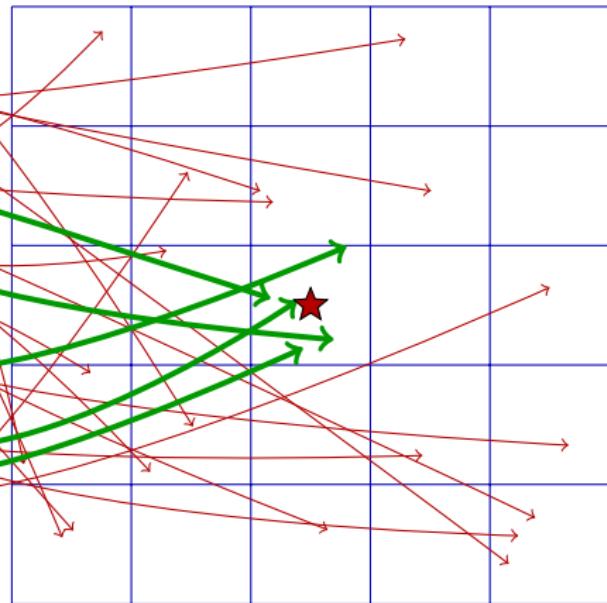
a lot of time is wasted!

final phase space, $z = 0$

Forward-tracking and back-tracking

initial phase space, $z = 4$ ⟶ homogeneous Fermi-Dirac distribution
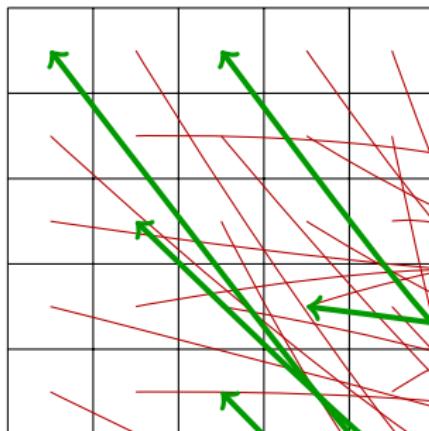
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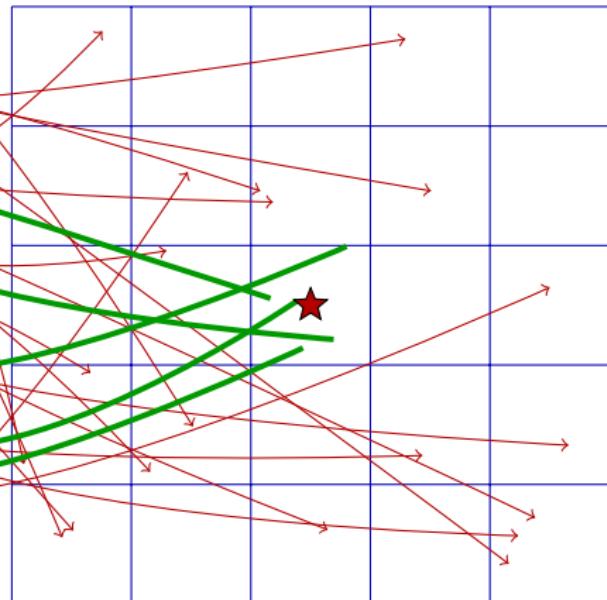
a lot of time is wasted!

smarter way: track backwards
only interesting particles!

final phase space, $z = 0$

Advantages of tracking back

First advantage is in computational terms: much less points to compute

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Second advantage: no need to use spherical symmetry!

Forward-tracking

Back-tracking

initial conditions need to sample
1D for position + 2D for momentum
when using spherical symmetry

"Initial" conditions only described
by 3D in momentum

(position is fixed, apart for checks)

with full grid would re-
quire 3+3 dimensions!

Impossible to relax
spherical symmetry!

can do the calculation with
any astrophysical setup

Advantages of tracking back

First advantage is in computational terms: much less points to compute

Second advantage: no need to use spherical symmetry!

In comparison with previous results:

NFW

Clustering results with back-tracking

In comparison with previous results:

NFW

Andromeda is almost negligible

Clustering results with back-tracking

In comparison with previous results:

NFW

Warning: NFW is not the same for all the cases!

[de Salas+, 2017] and [Zhang[2], 2018] use $\gamma \neq 1$, now we have $\gamma = 1$

[Ringwald&Wong, 2004] uses old parameters

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D Direct Detection

i.e. currently science-fiction, but in few years…

Based on:

- arxiv:1808.01892
- JCAP 07 (2019) 047
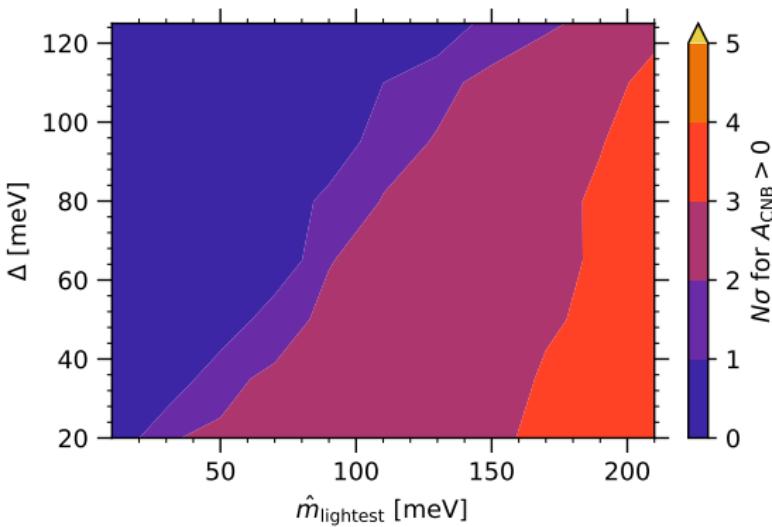
The oldest picture of the Universe

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

COBE (1992)   WMAP (2003) Planck (2013)
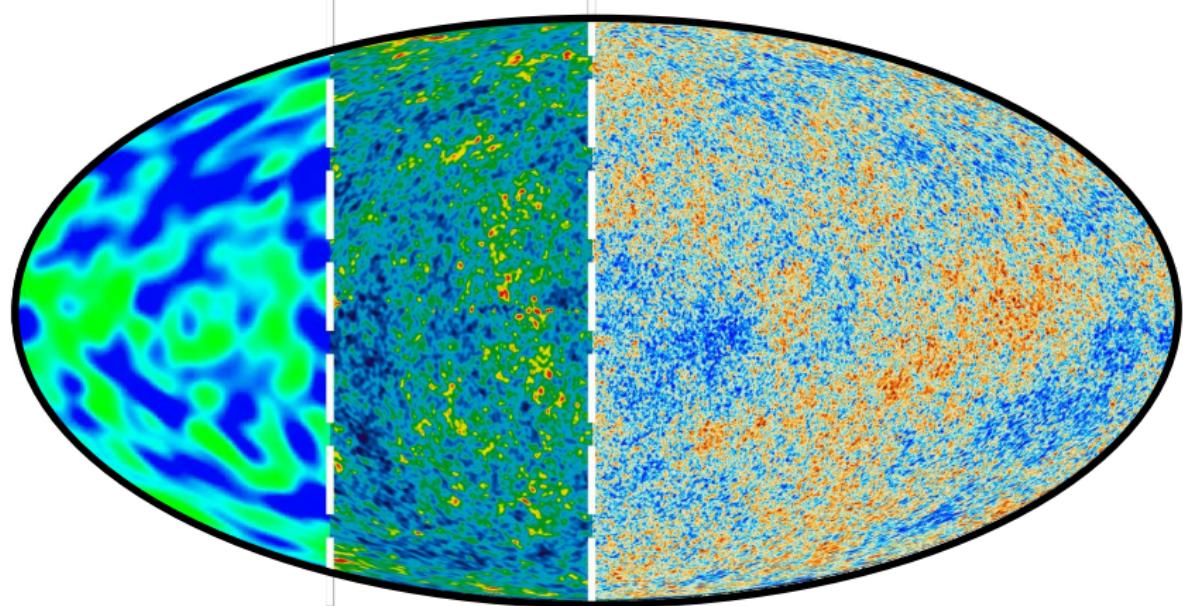
The Cosmic Neutrino Background, generated at $t \simeq 1$ s

$$\ldots \to 2022 \to \ldots$$

How to capture relic neutrinos?
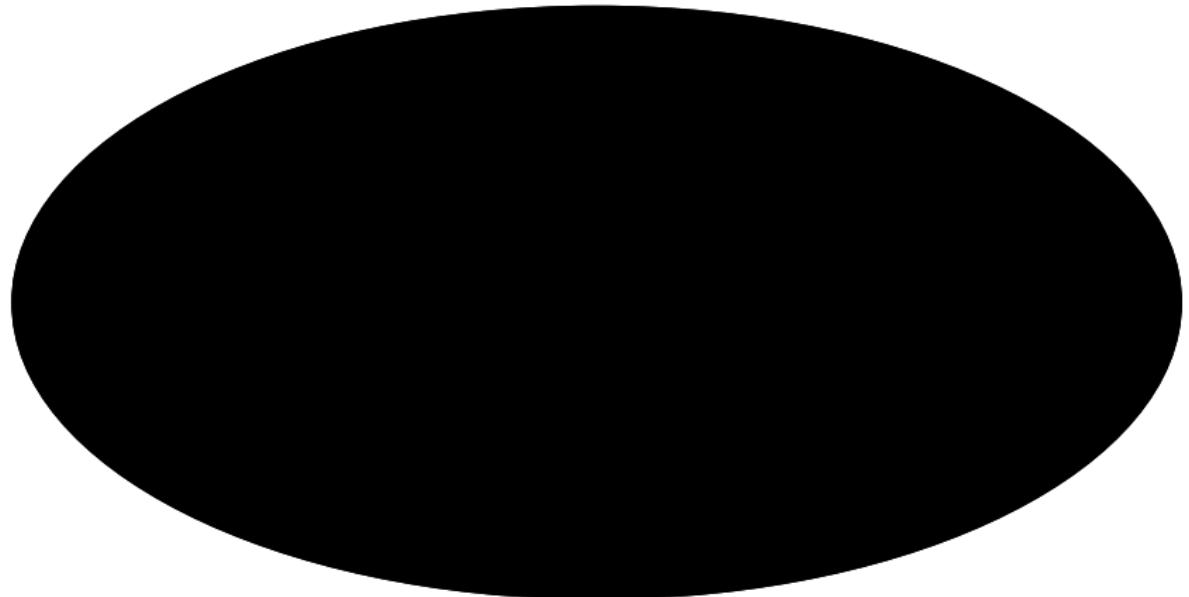
How to directly detect non-relativistic neutrinos?

Remember that
$\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today $\longrightarrow$ a process without energy
threshold is necessary

[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

Main background: β decay $n \to p + e^- + \bar{\nu}$!

signal is a peak at $2m_\nu$
above β–decay endpoint

only with a lot of material

need a very good energy resolution

$$\frac{d\widetilde{\Gamma}_{\mathrm{CNB}}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma} \sum_{i=1}^{N_\nu} \bar{\sigma}\, N_T\, |U_{ei}|^2\, n_0\, f_c(m_i) \times e^{-\frac{[E_e - (E_{\mathrm{end}} + m_i + m_{\mathrm{lightest}})]^2}{2\sigma^2}}$$

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2} N_T \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i)$$

$$\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{+\infty} dx\, \frac{d\Gamma_\beta}{dE_e}(x) \exp\left[-\frac{(E_e - x)^2}{2\sigma^2}\right]$$

$$\frac{d\widetilde{\Gamma}_{\mathrm{CNB}}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma} \sum_{i=1}^{N_\nu} \bar{\sigma}\, N_T\, |U_{ei}|^2\, n_0\, f_c(m_i) \times e^{-\frac{[E_e - (E_{\mathrm{end}} + m_i + m_{\mathrm{lightest}})]^2}{2\sigma^2}}$$

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PTOLEMY

Pontecorvo Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq 0.1$ eV**?**
0.05 eV**?**

→ built mainly for CNB

can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

$M_T = 100$ g of atomic ^{3}H

$$\Gamma_{\text{CNB}} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] \, N_T \, \bar{\sigma} \qquad \sim \mathcal{O}(10) \text{ yr}^{-1}$$

N_T number of ^{3}H nuclei in a sample of mass M_T $\bar{\sigma} \simeq 3.834 \times 10^{-45}$ cm^2 n_i number density of neutrino i

(without clustering)

PTOLEMY

Pontecorvo Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq 0.1$ eV**?**
0.05 eV**?**

built mainly for CNB

can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

$M_T = 100$ g of atomic ^{3}H

ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

$$\Gamma_{\text{CNB}} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] \, N_T \, \bar{\sigma}$$

$\sim \mathcal{O}(10)$ yr^{-1}

N_T number of ^{3}H nuclei in a sample of mass M_T $\bar{\sigma} \simeq 3.834 \times 10^{-45}$ cm^2 n_i number density of neutrino i

(without clustering)

using the definition:

$$N_{\text{th}}^i(\boldsymbol{\theta}) = A_\beta N_\beta^i(\hat{E}_{end} + \Delta E_{end}, m_i, U) + \boldsymbol{A}_{\text{CNB}} N_{\text{CNB}}^i(\hat{E}_{end} + \Delta E_{end}, m_i, U) + N_b$$

if $\boldsymbol{A}_{\text{CNB}} > 0$ at $N\sigma$, direct detection of CNB accomplished at $N\sigma$

statistical only!   significance on $A_{\text{CNB}} > 0$
as a function of $\hat{m}_{\text{lightest}}$, Δ
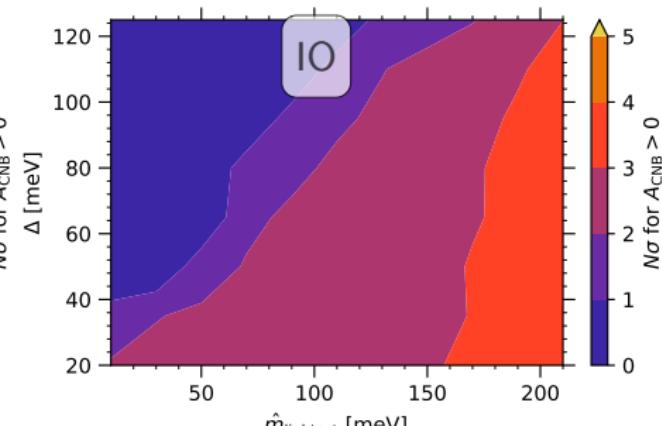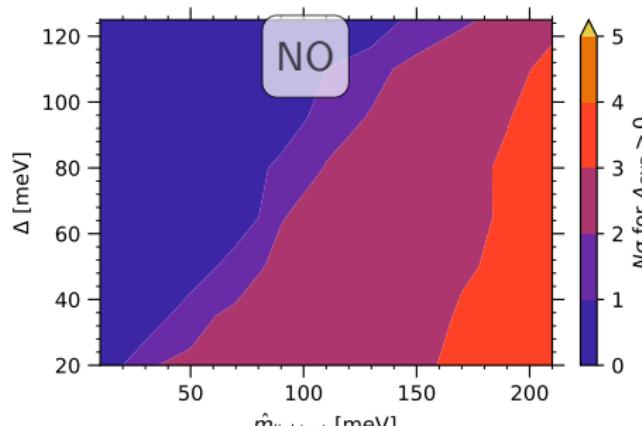
E-R (skipping. . .)

seriously, I cannot go
through the entire alphabet in 50 minutes!

S (Light) 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
- JCAP 07 (2019) 047

Short Baseline (SBL) anomaly
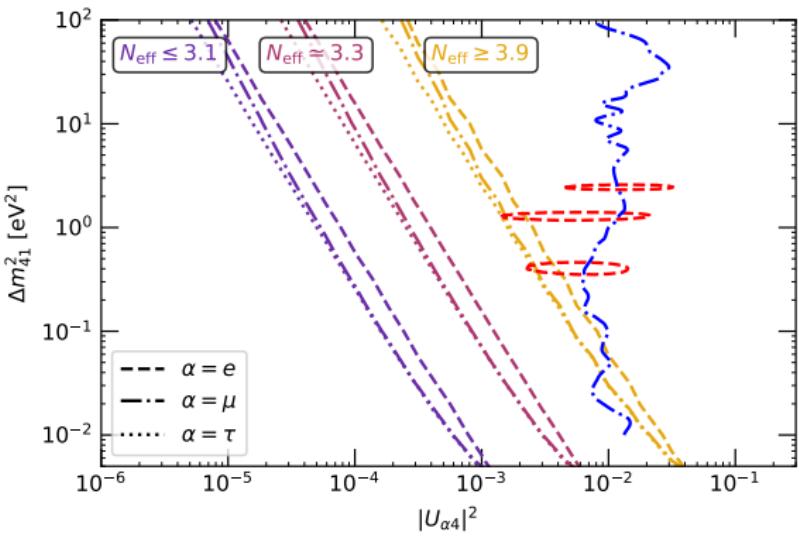
Problem: anomalies
in SBL experiments $\longrightarrow$ $\begin{cases} \text{errors in flux calculations?} \\ \text{deviations from 3-}\nu\text{ description?} \end{cases}$

A short review:

LSND search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

Reactor re-evaluation of the expected anti-neutrino flux $\Rightarrow$ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m
[Mention et al, 2011], [Azabajan et al, 2012]

Gallium calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e)
[Giunti, Laveder, 2011]

MiniBooNE | See next |

Possible explanation:

Additional squared mass difference $\Delta m_{\text{SBL}}^2 \simeq 1$ eV^2

ν_s at reactors in 2020
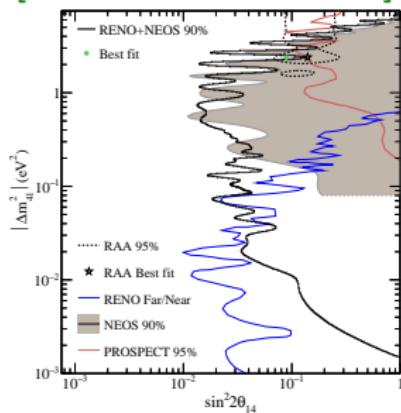
[RENO+NEOS, 2020]   [DANSS, 2020]   [Neutrino-4, PZETF 2020]
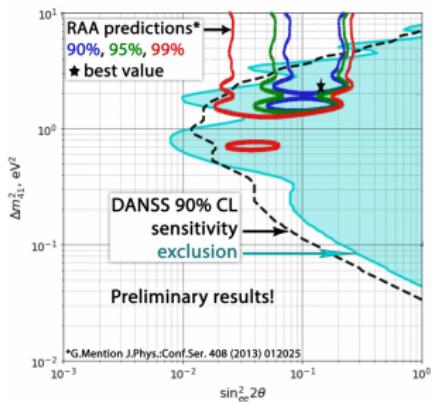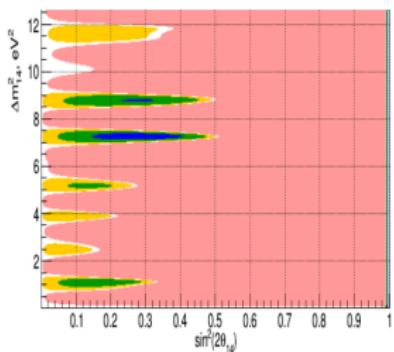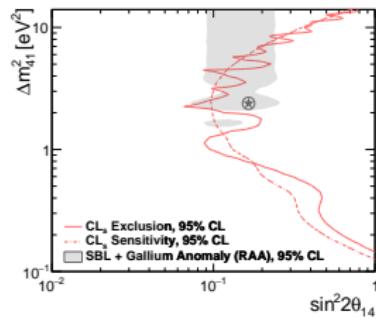
[PROSPECT, PRD 2020]   [STEREO, PRD 2020]   [SoLiD, JINST 2021]
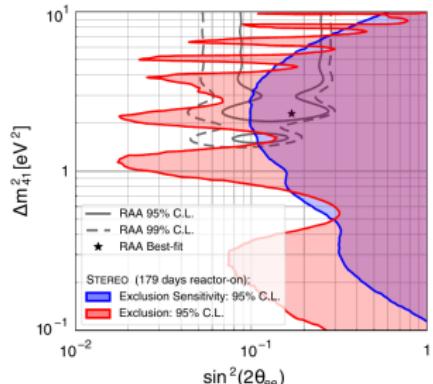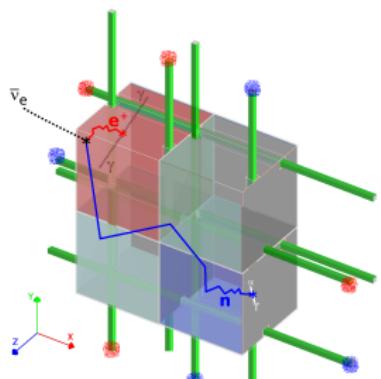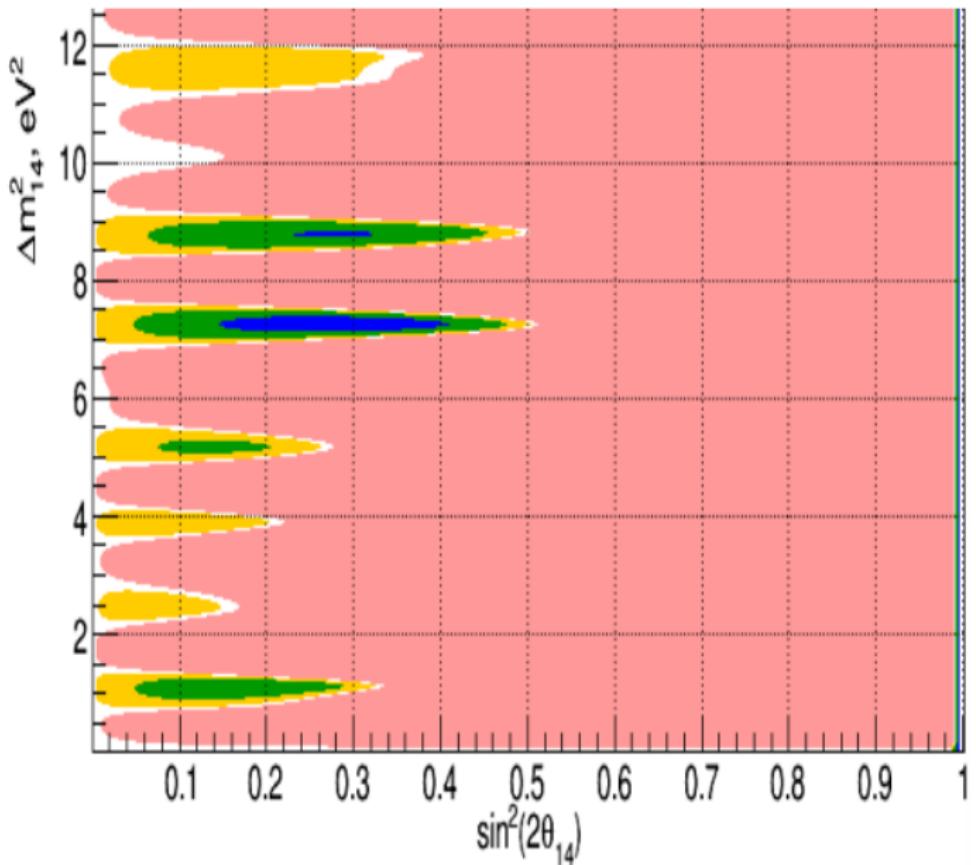
claimed $> 3\sigma$
preference for
$3+1$ over 3ν case

best fit
incompatible
with other
reactor
experiments
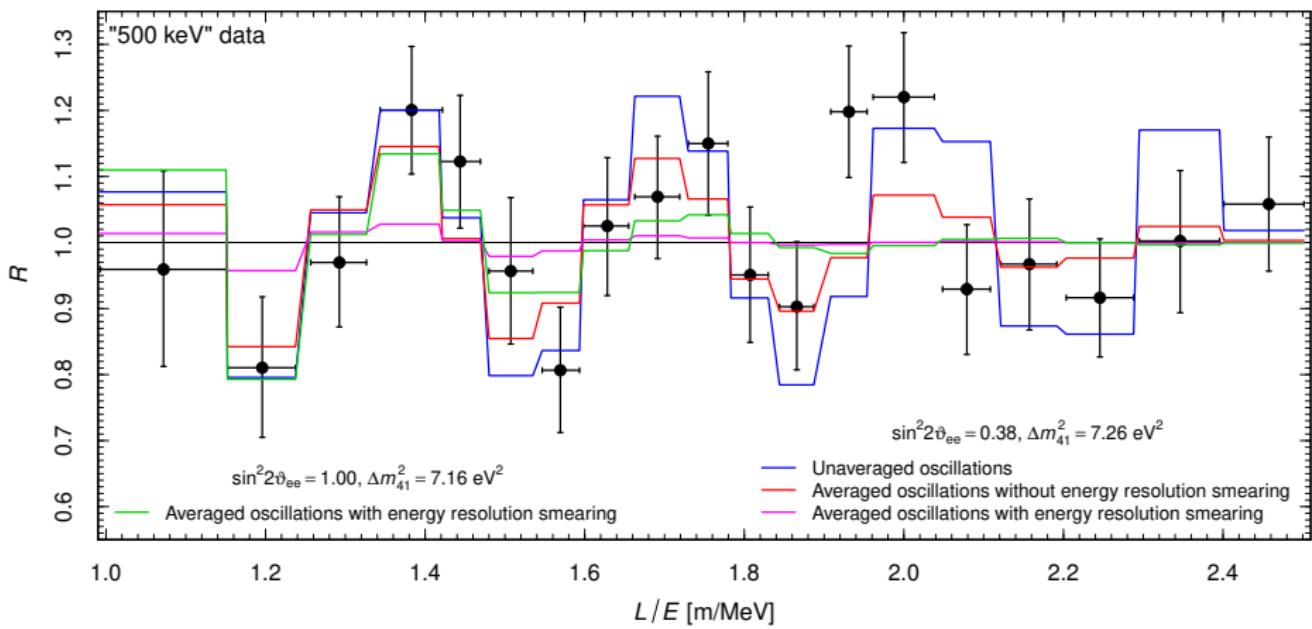
energy resolution smearing not properly taken into account?

Neutrino-4
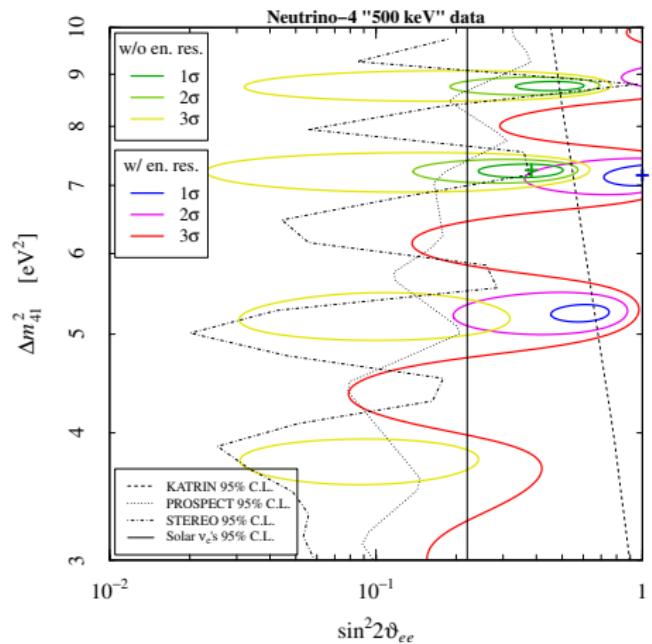
proper energy resolution treatment
moves best-fit $\rightarrow$ $\sin^2 2\vartheta \simeq 1$
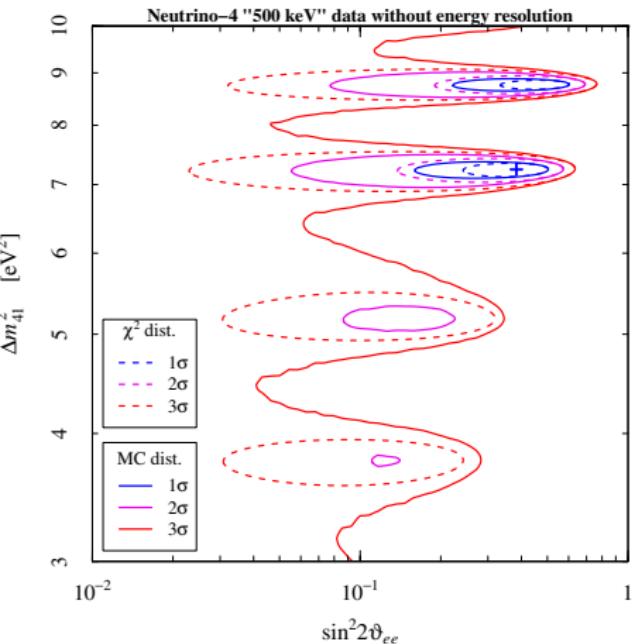
need to take into account
violation of Wilk's theorem
$\downarrow$
relaxed constraints

MiniBooNE

purpose: check LSND signal

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

no money, no near detector

ν sample

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

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MicroBooNE disfavors oscillations to explain the excess

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

IceCube 8 yr update
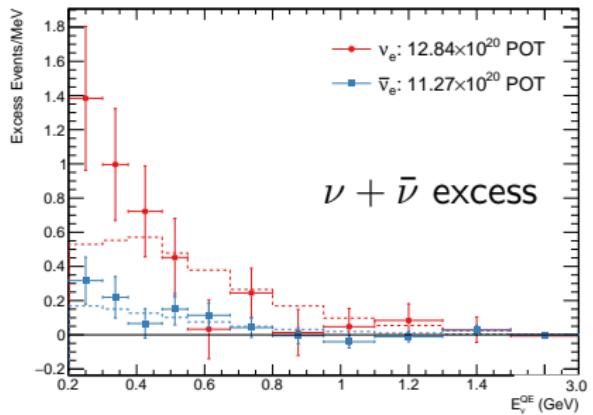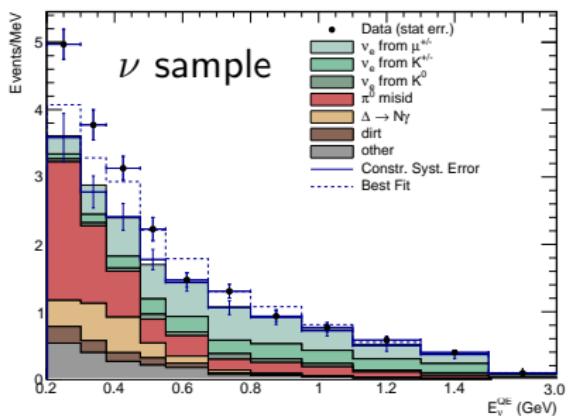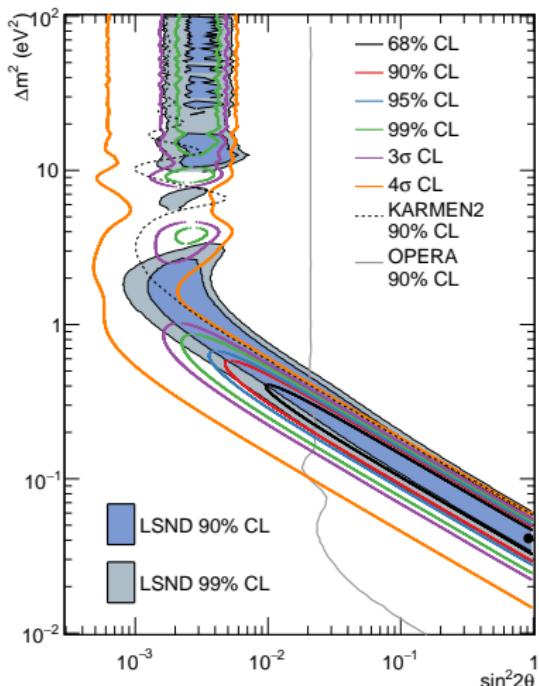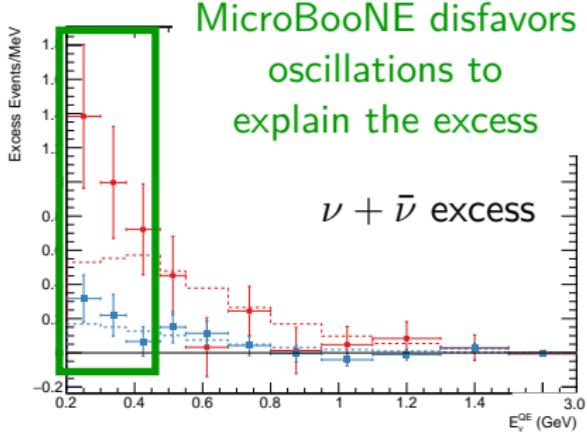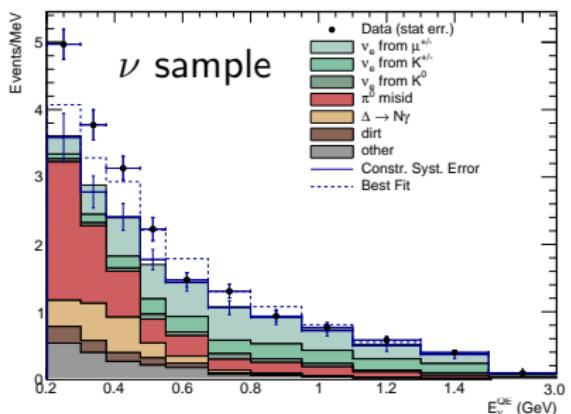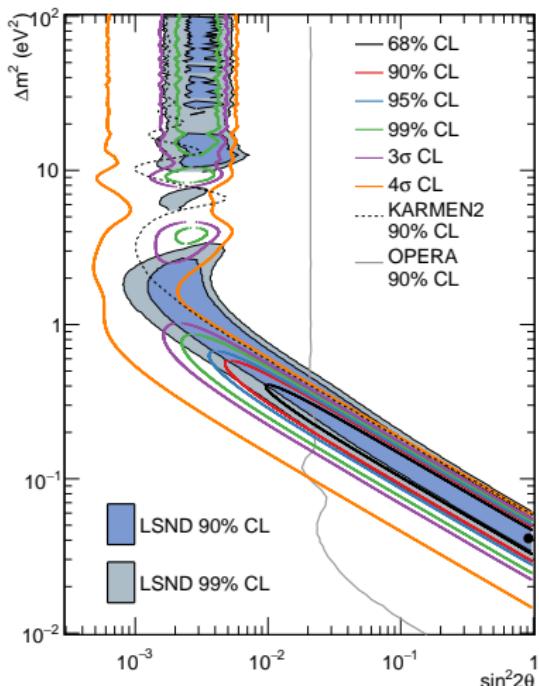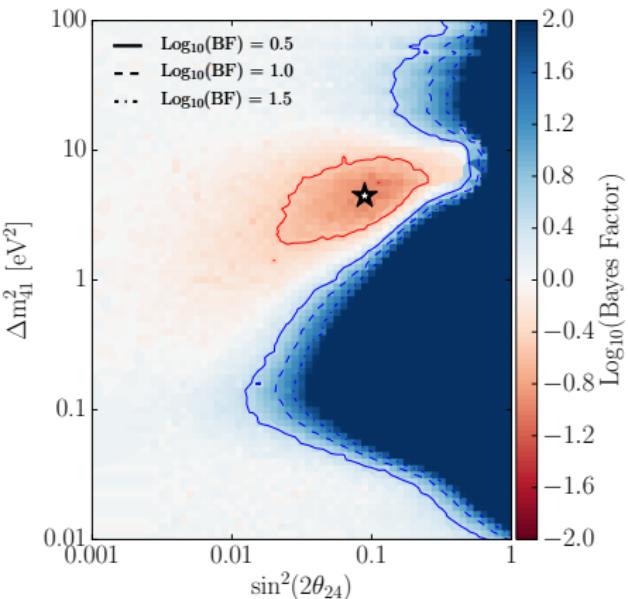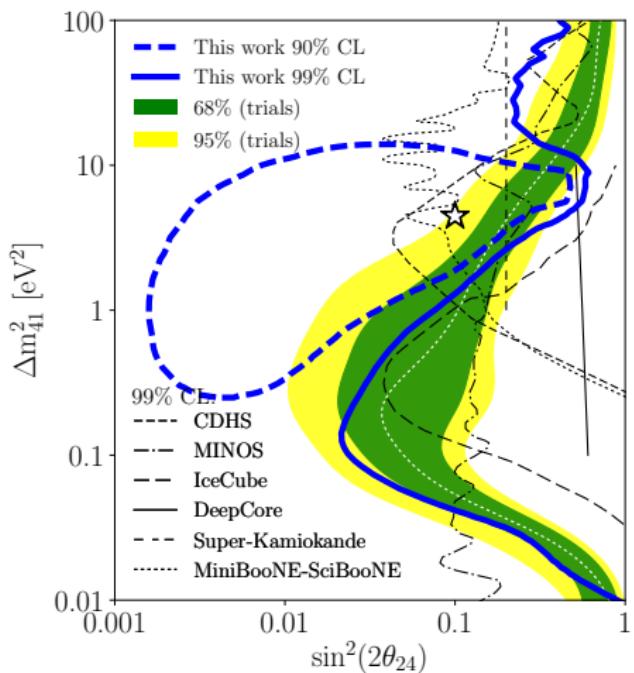
first indication in favor of sterile from ν_μ DIS!

although rather weak: $\log_{10} BF \simeq 1$ (weak preference)
or compatible with no oscillations at p-value of 8%

We can vary more than one angle:

We can vary more than one angle: N_{eff}

$|U_{\mu 4}|^2 = 10^{-3}, \ |U_{\tau 4}|^2 = 0$
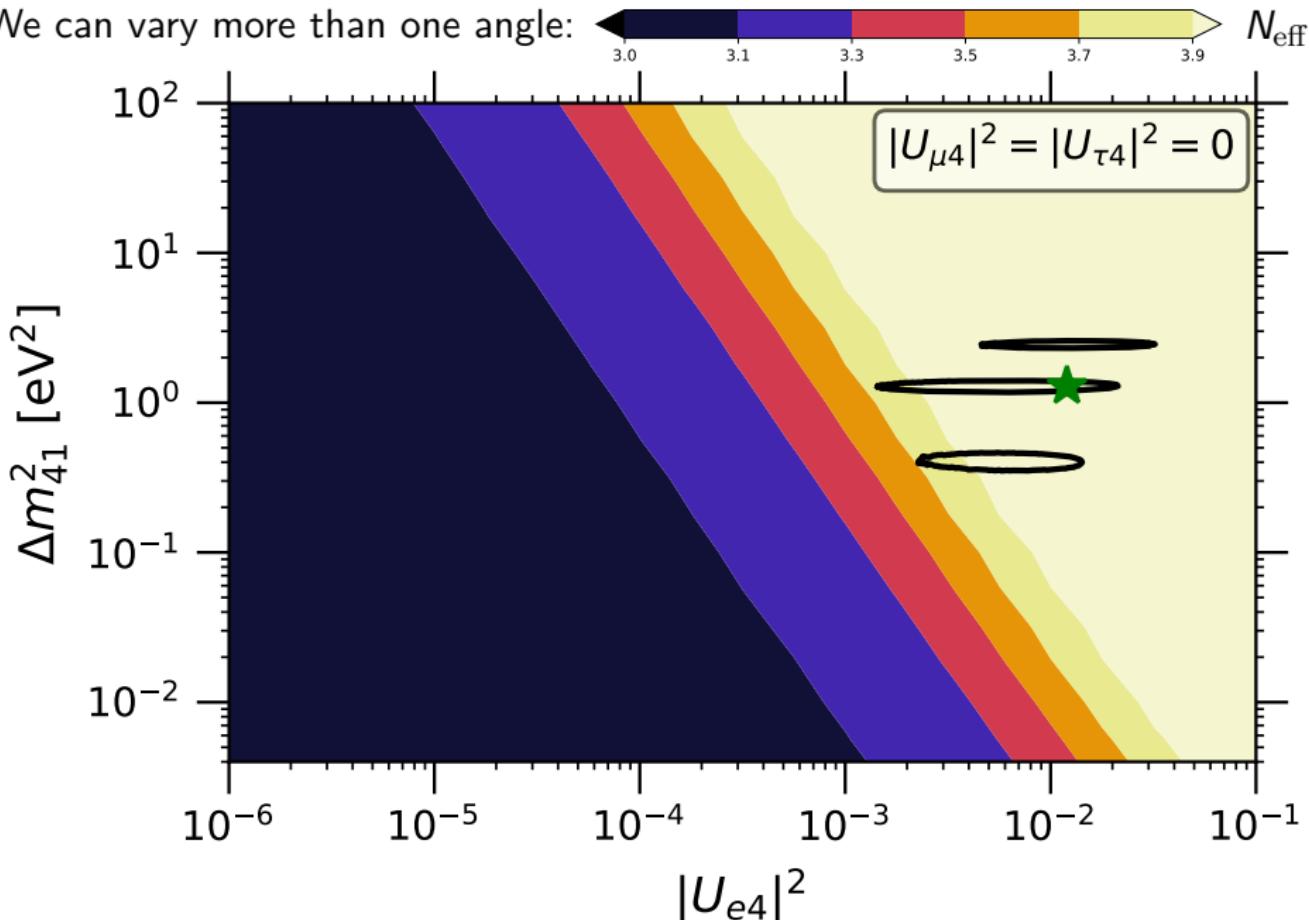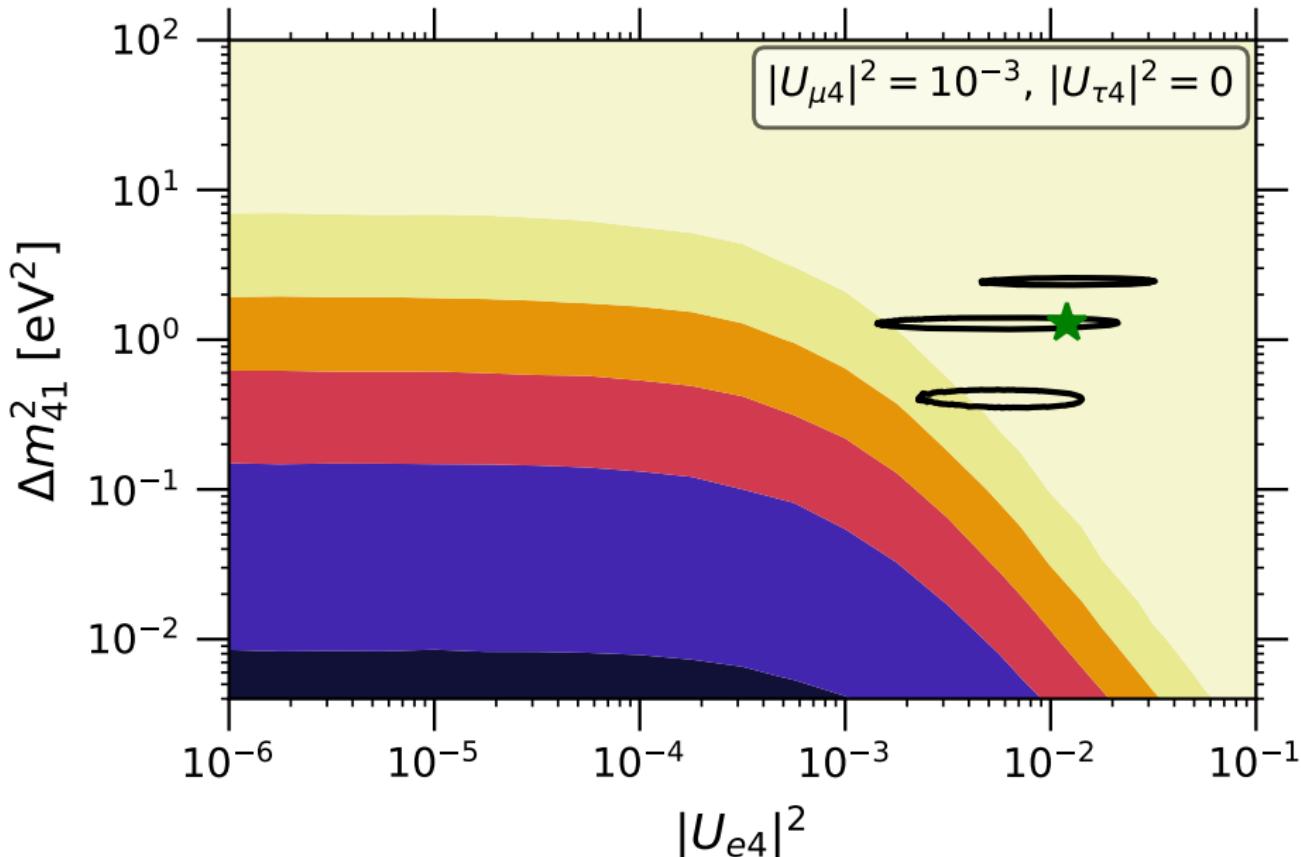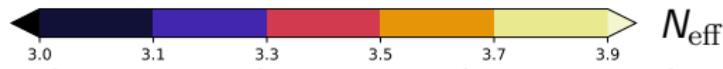
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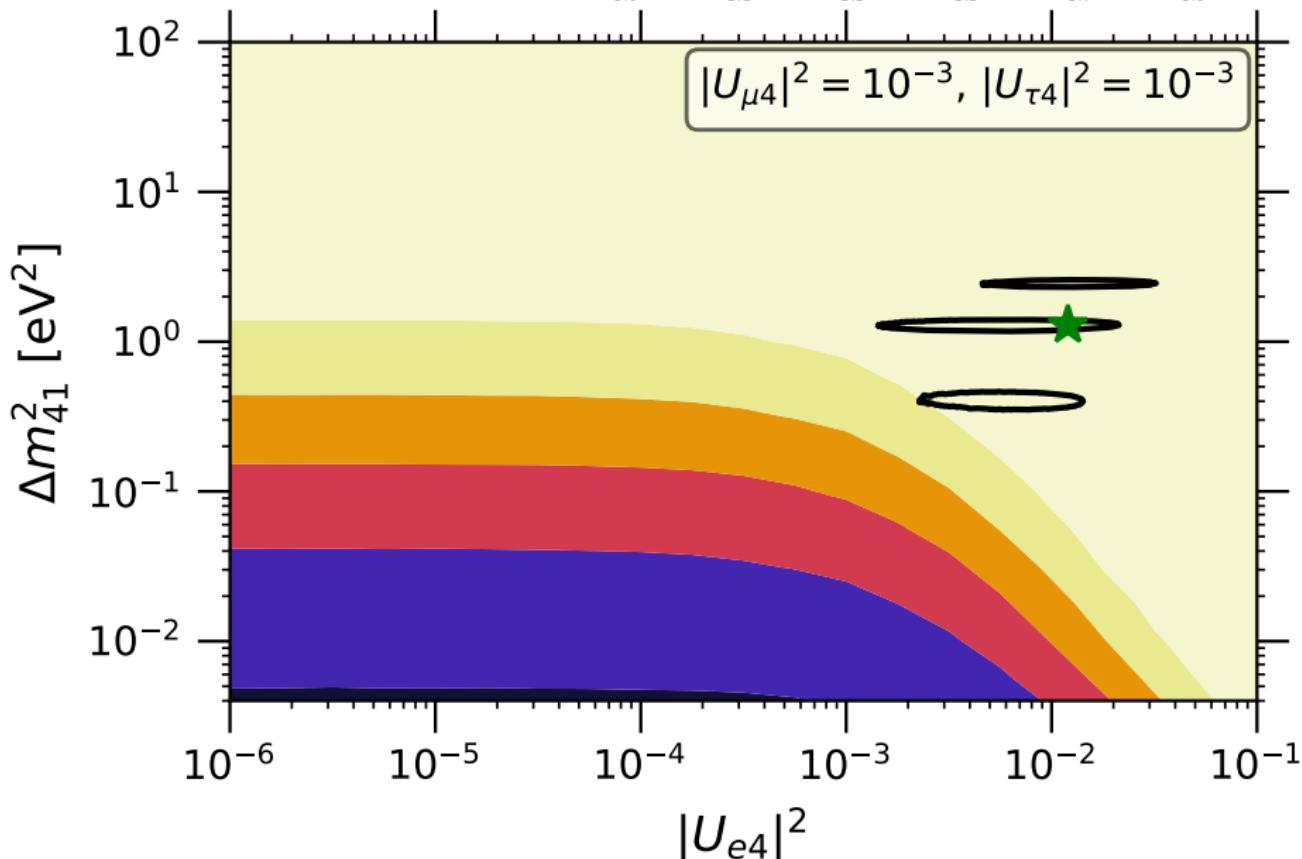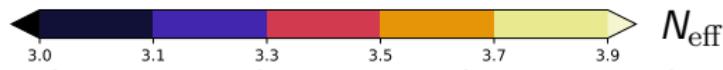
Comparing constraints

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!
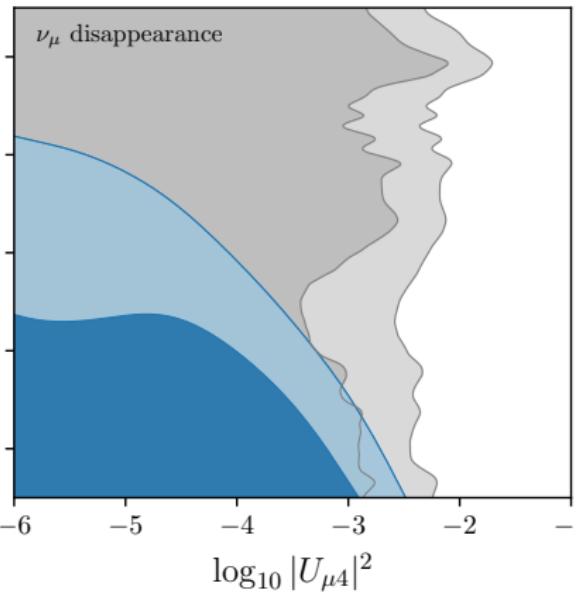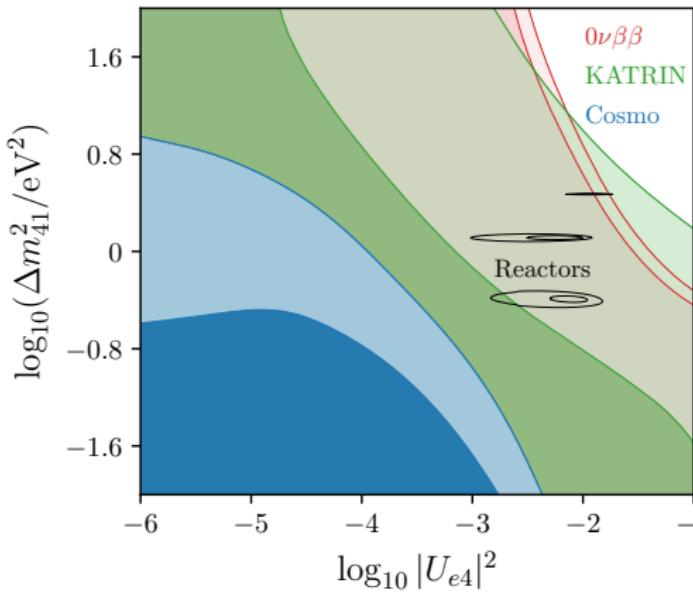
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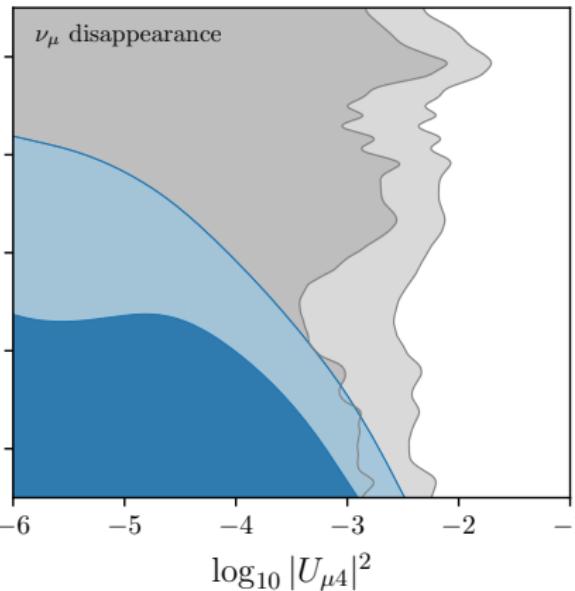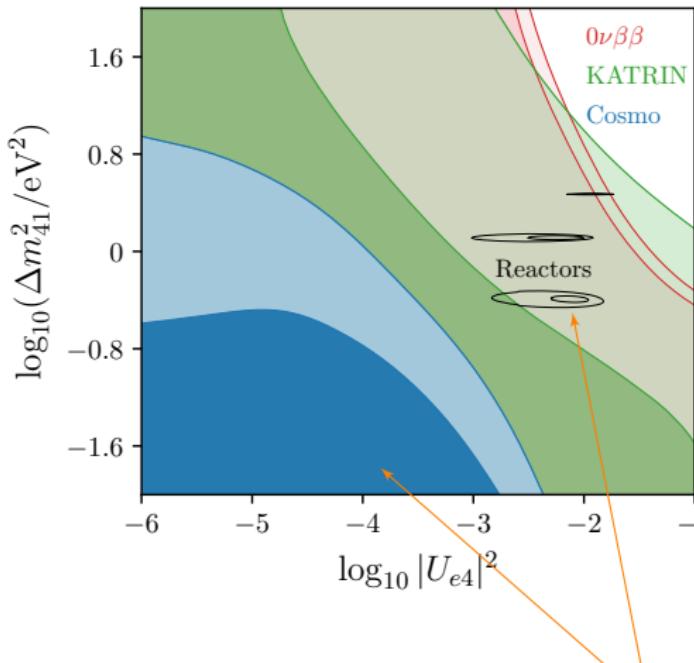
Warning: tension between reactor experiments and CMB bounds!

Collision terms with sterile neutrinos

Full collision integrals can be computed also with sterile neutrinos

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

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

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
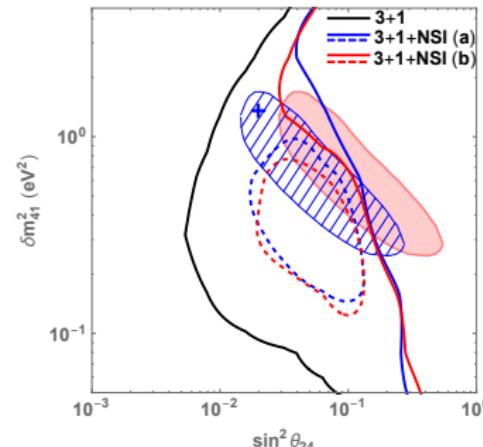
Reheating: phase ending inflation

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

during reheating: inflaton decays into standard model particles

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

radiation domination begins after reheating

Scenarios with low reheating temperature

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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_{eff} with low reheating

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

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

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

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

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

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

N_{eff} with low reheating

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

Legend:
- 3ν, no νν
- 3ν, νν off-diag
- 3ν, full νν
- LSN, no νν
- LSN, νν diag
- LSN, νν off-diag
- LSN, full νν
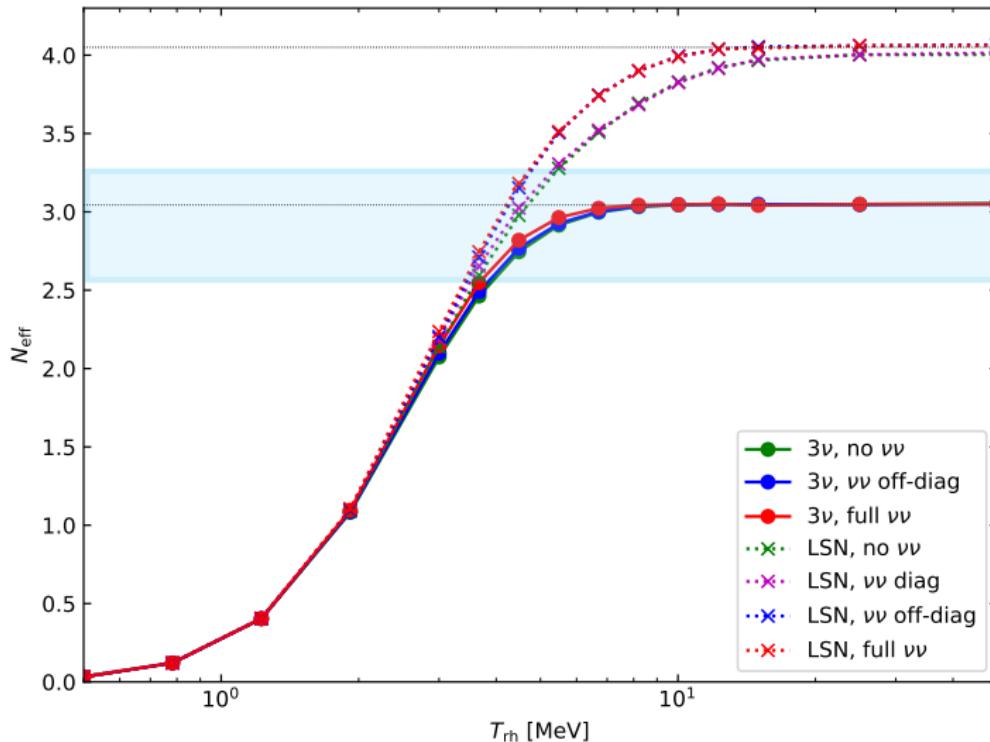
Planck constraint: $N_{\text{eff}} = 2.92^{+0.36}_{-0.37}$ (95%, TT,TE,EE+lowE)

sterile case with varying mixing angle/mass splitting:

for low T_{rh}, mixing parameters are irrelevant

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

N_{eff} with low reheating

sterile case with varying mixing angle/mass splitting:

| $N_{\text{eff}} = 2.30$ |
| $N_{\text{eff}} = 2.67$ |
| $N_{\text{eff}} = 3.04$ |
| $N_{\text{eff}} = 3.36$ |
| $N_{\text{eff}} = 3.90$ |
| $\Delta m^2_{41} = 0.1$ eV^2 |
| $\Delta m^2_{41} = 1.0$ eV^2 |
| $\Delta m^2_{41} = 10.0$ eV^2 |
| with $\nu\nu$ |
| no $\nu\nu$ |
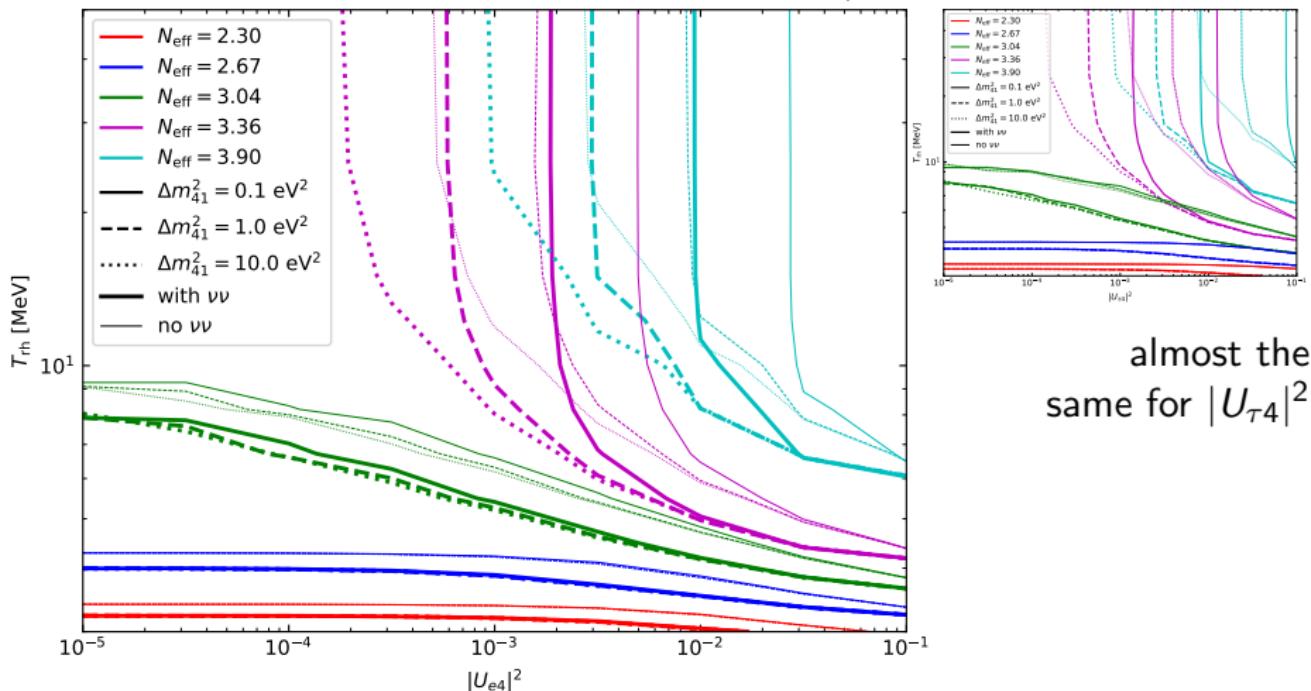
almost the same for $|U_{\tau 4}|^2$

for low T_{rh}, mixing parameters are irrelevant

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

Z Conclusions

almost there!

# What do we learn from relic neutrinos?

D   Direct detection - wonderful opportunities for the future
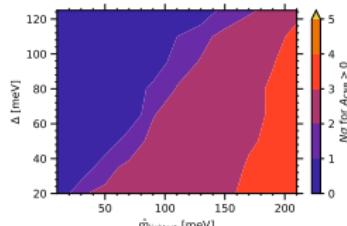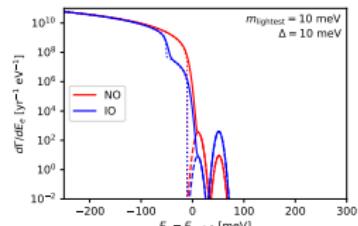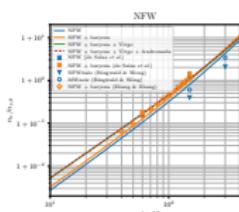
**I**   Indirect probes - what we have now, it's a lot and it will improve

N   New physics - beyond the corner? neutrinos will help us find it!

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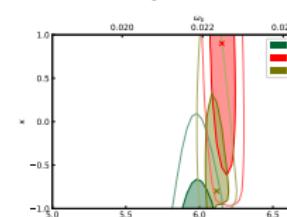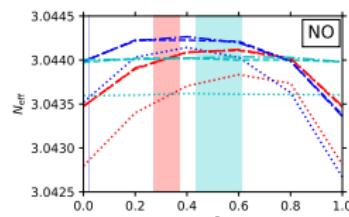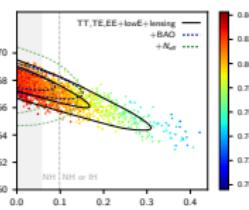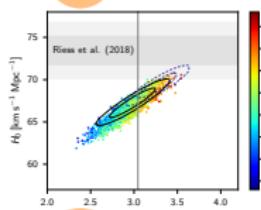
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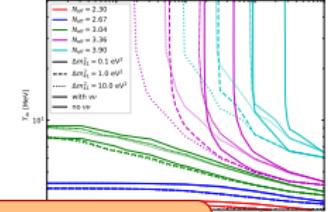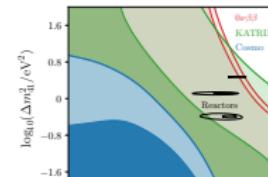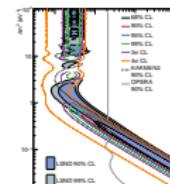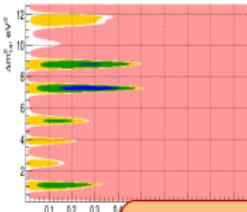
Thanks for your attention!