H2020 MSCA COFUND
G.A. 754496

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(Cosmological) Relic neutrinos, from A to Z

Seminar at the University of Birmingham, online, 03/03/2021

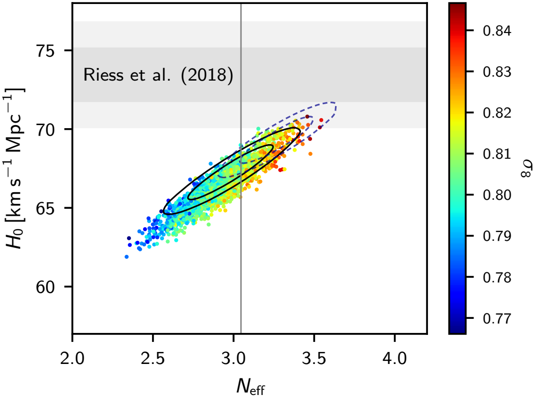
A

Active neutrinos

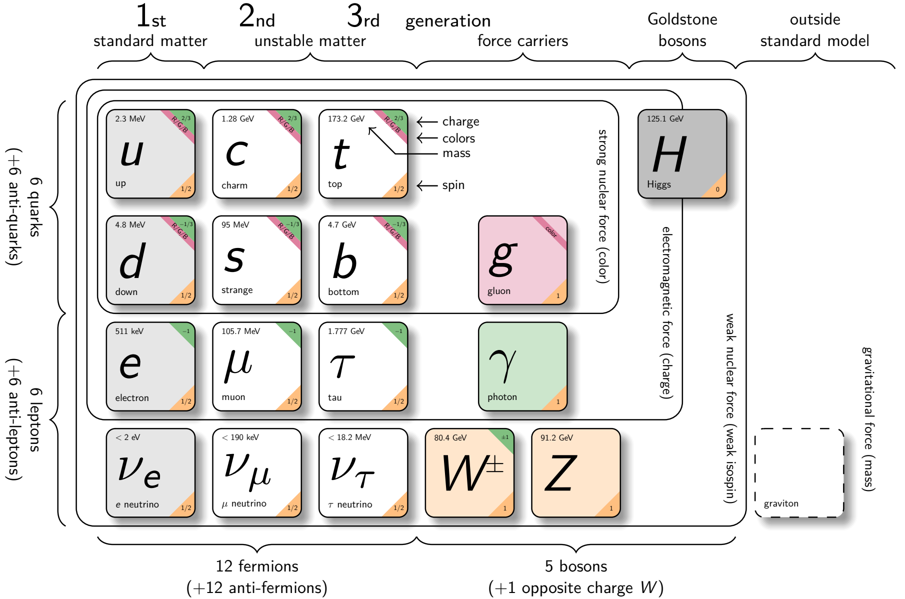
Spoiler: “Sterile” will come later

Based on:

- Planck 2018
- arxiv:2012.02726



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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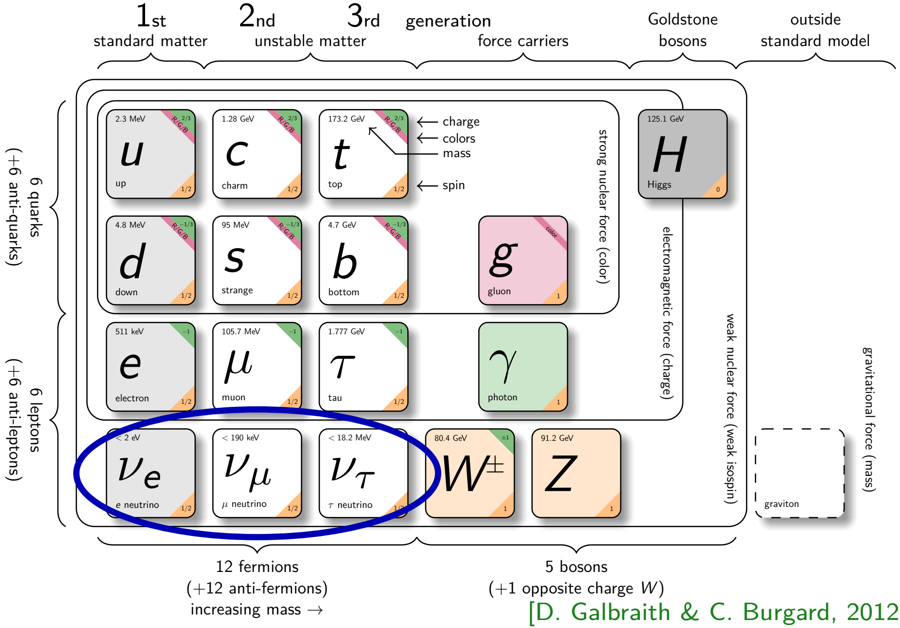
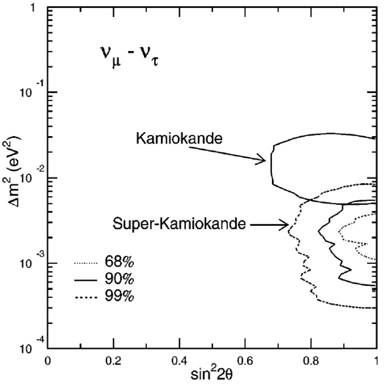


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

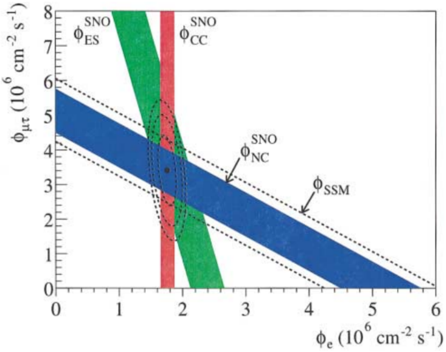
Major discoveries:

[SuperKamiokande, 1998]



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

[SNO, 2001-2002]



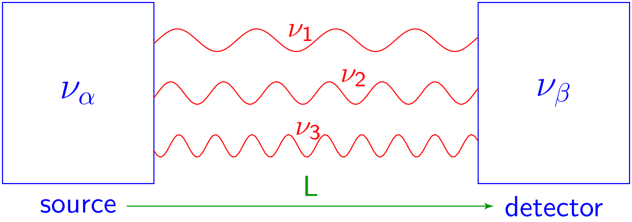
first discovery of $\nu_e \to \nu_\mu, \nu_\tau$ oscillations from solar ν

Nobel prize in 2015

Two neutrino bases

flavor neutrinos ν_α | $|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$ | massive neutrinos ν_k

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



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

$E_k^2 = p^2 + m_k^2$ ⟵ define ⟶ $t = L$

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

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

The mixing matrix

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

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

Majorana phases irrelevant for oscillation experiments ← M

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

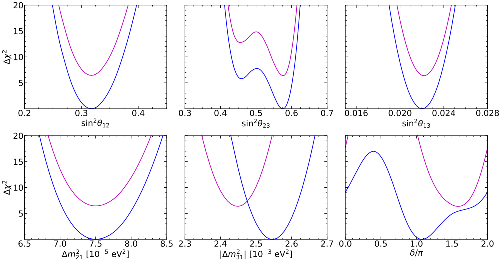
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021)]

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

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.55^{+0.02}_{-0.03}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.45^{+0.02}_{-0.03}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$10 \sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2 \sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\mathrm{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO})$$
$$10 \sin^2(\theta_{23}) = 5.74 \pm 0.14\ (\mathrm{NO})$$
$$= 5.78^{+0.10}_{-0.17}\ (\mathrm{IO})$$

$$\delta/\pi = 1.08^{+0.13}_{-0.12}\ (\mathrm{NO})$$
$$= 1.58^{+0.15}_{-0.16}\ (\mathrm{IO})$$

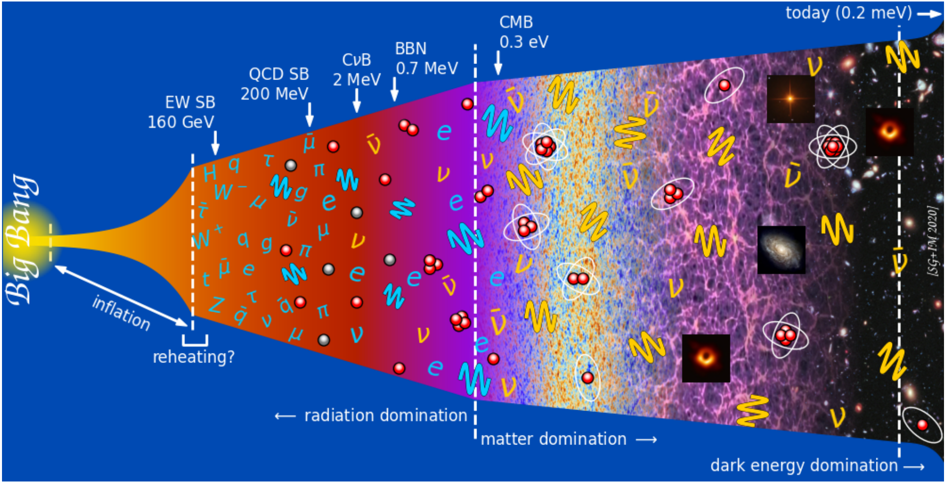


mass ordering still unknown

δ still unknown

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

History of the universe



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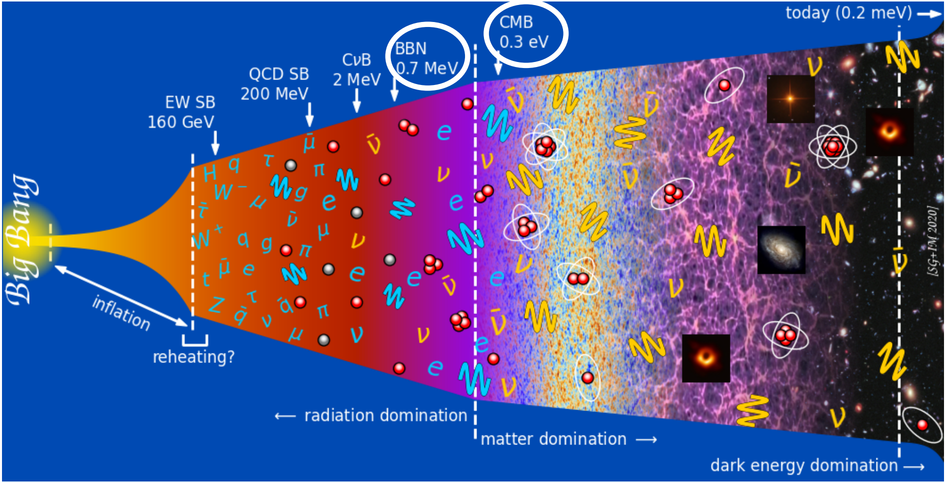
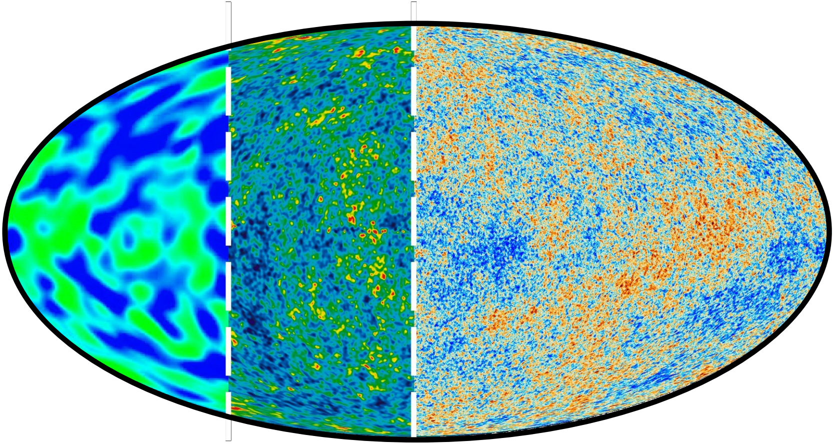


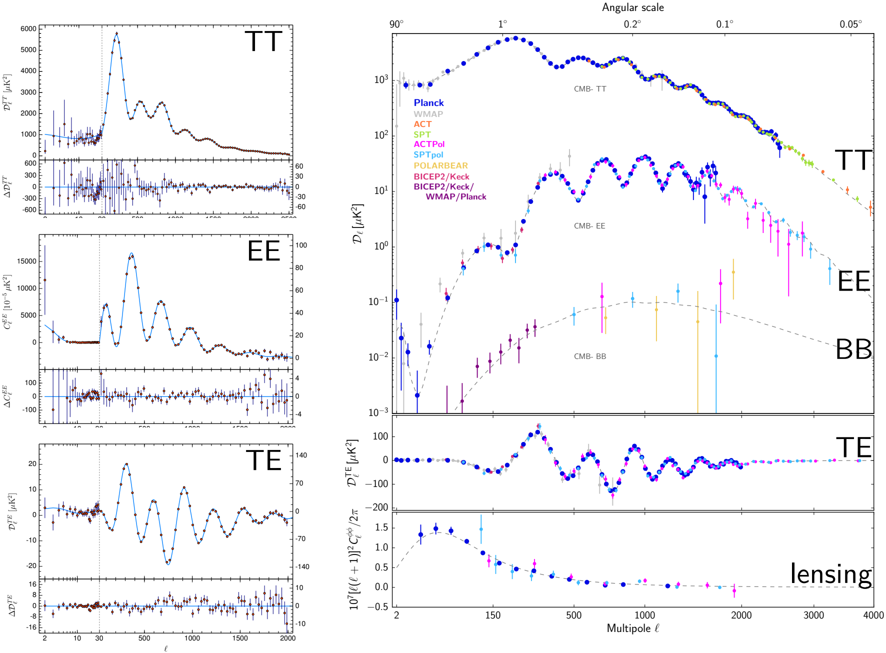
The oldest picture of the Universe

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



CMB spectra as of 2018

[Planck Collaboration, 2018]



Big Bang Nucleosynthesis (BBN)

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

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

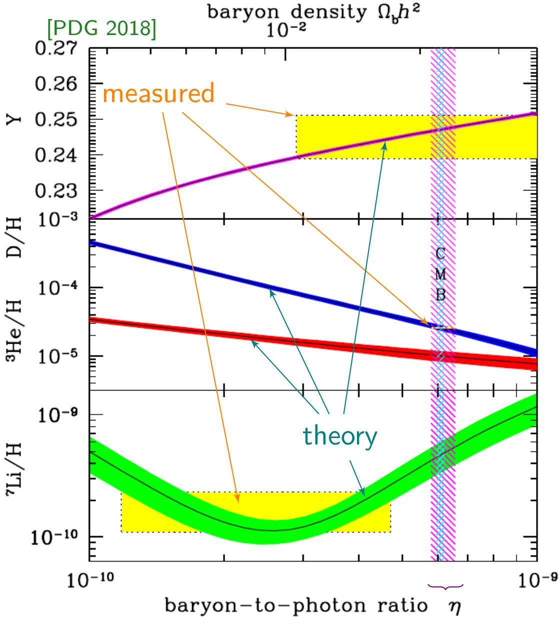
much earlier than CMB!

strong probe for physics
before the CMB

e.g. neutrinos!

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

[PDG 2018]



BBN concordance

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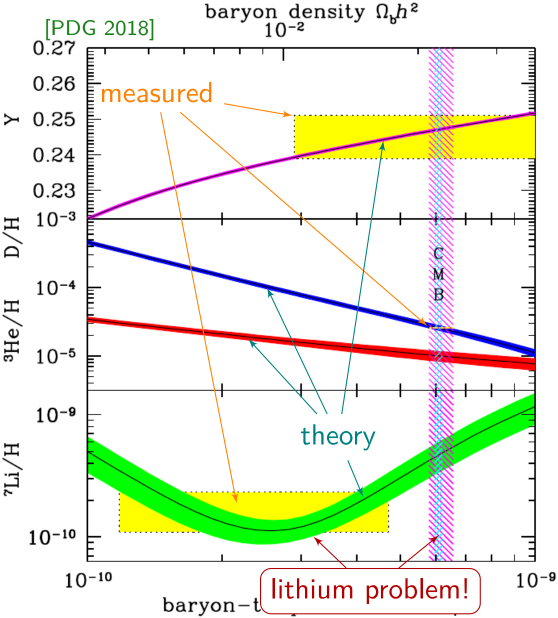
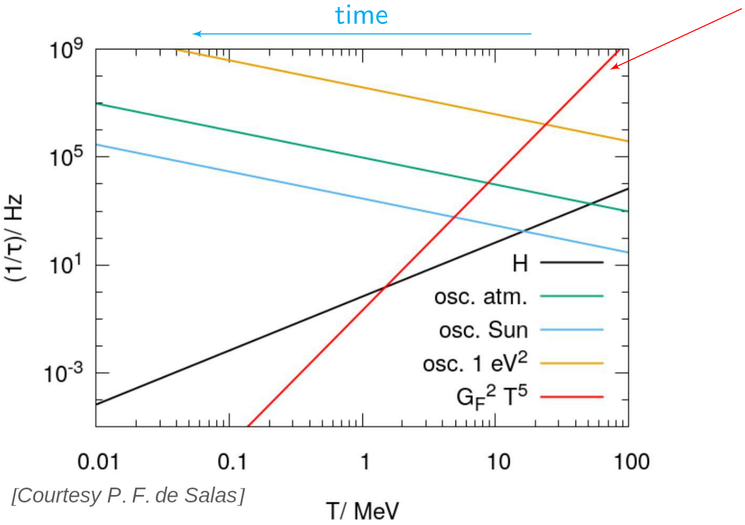


BBN concordance

Neutrinos in the early Universe

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



[Courtesy P. F. de Salas]

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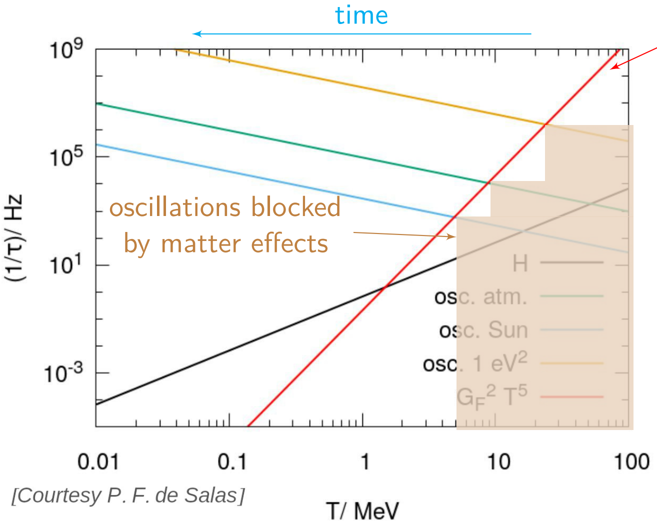

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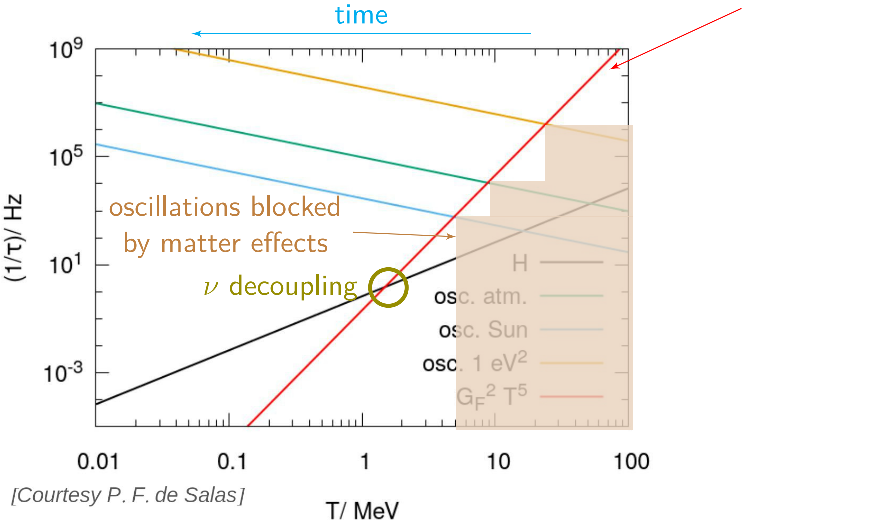

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ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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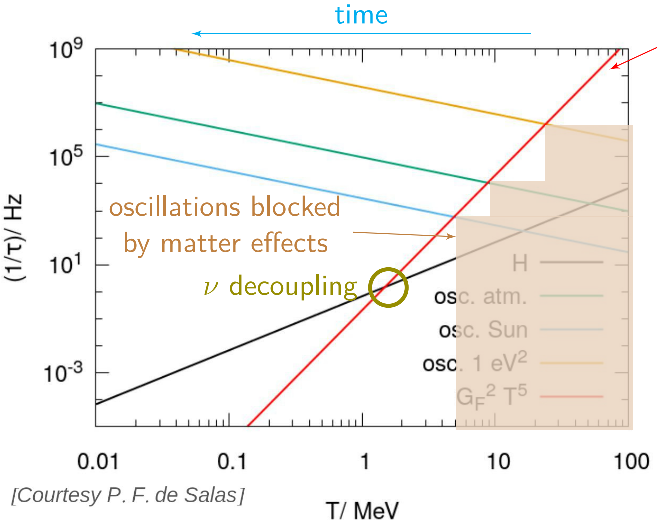

[Courtesy P. F. de Salas]

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

f_ν: frozen Fermi-Dirac distribution

Today:

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

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

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

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

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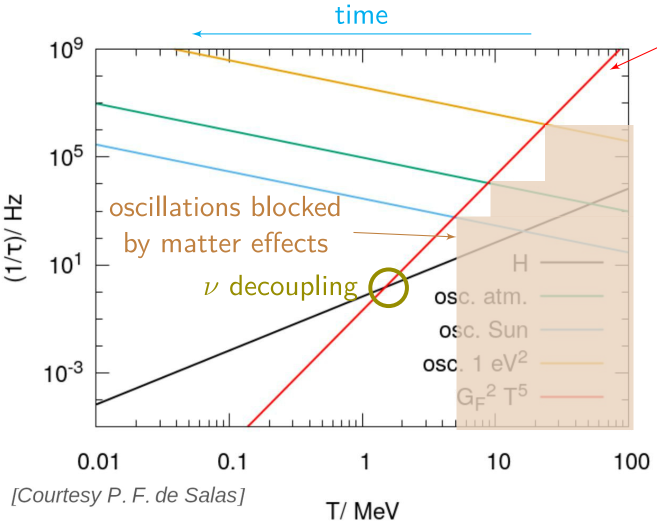

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actually, the decoupling T is momentum dependent!

distortions to equilibrium f_ν!

ν oscillations in the early universe

[Bennett, SG+, 2012.02726]

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

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

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

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

$$\mathbb{M} = \mathrm{diag}(m_1^2, \ldots, m_N^2)$$

$$U = R^{23} R^{13} R^{12}$$

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

ν oscillations in the early universe

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

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

take into account matter effects in oscillations

ν oscillations in the early universe

[Bennett, SG+, 2012.02726]

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

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

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

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

ν oscillations in the early universe

[Bennett, SG+, 2012.02726]

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

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

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

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

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

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

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

ν oscillations in the early universe

[Bennett, SG+, 2012.02726]

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

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

m_{P}... Planck mass ... total energy density ... mass of the W, Z bosons ... Fermi constant ... [,] commutator

FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)

https://bitbucket.org/ahep_cosmo/fortepiano_public

from continuity equation

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

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

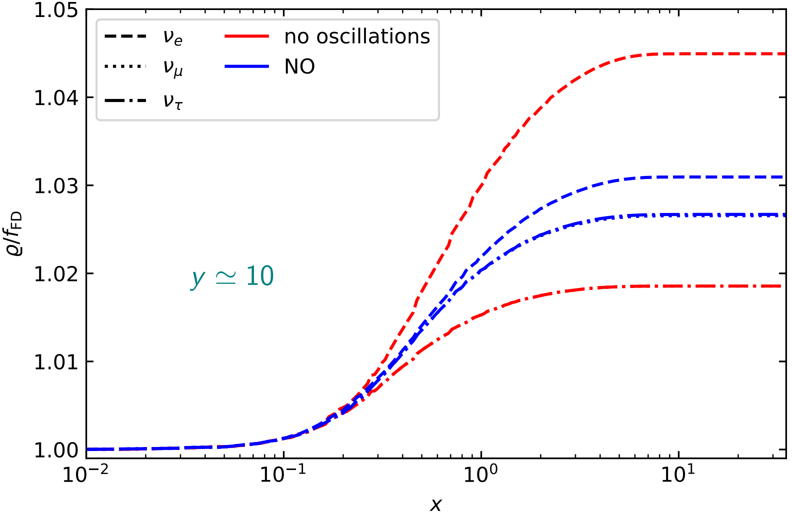
will be public soon

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

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

Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, 2012.02726]

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



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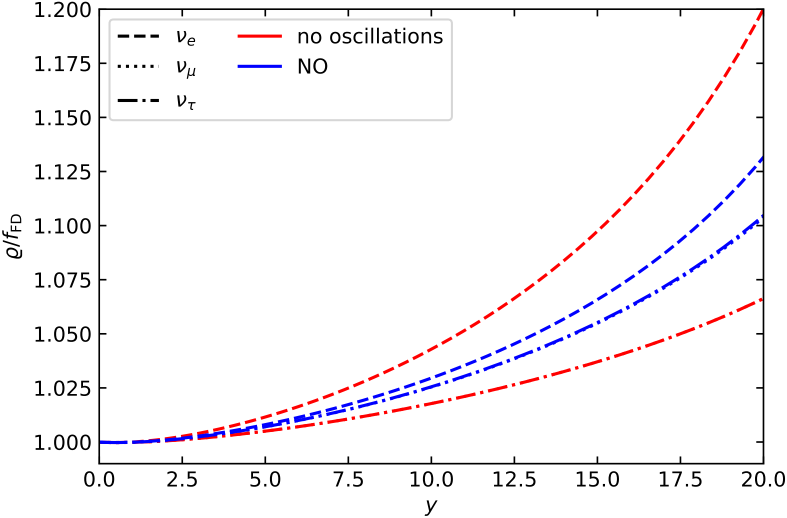
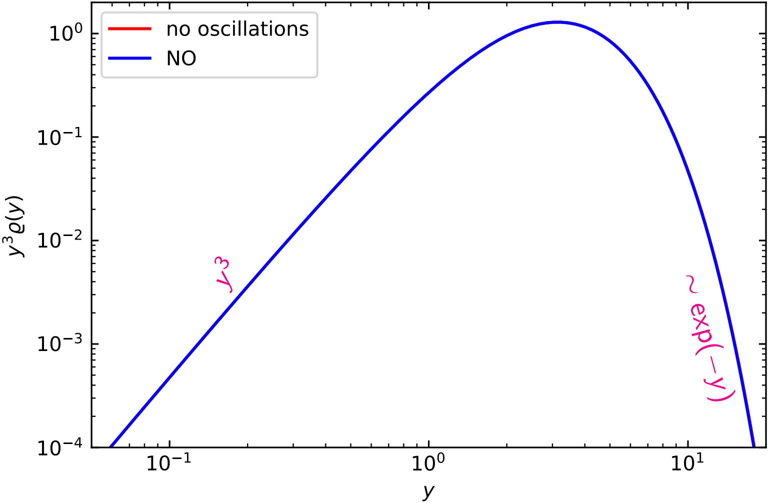


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, 2012.02726]

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

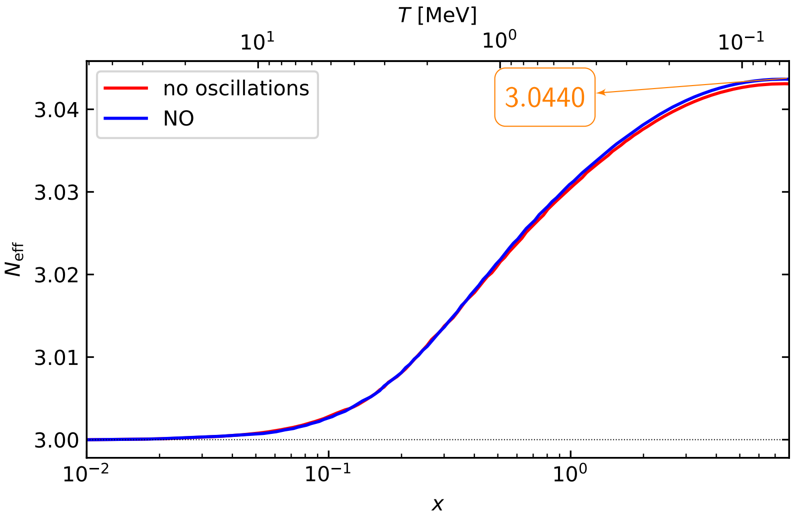
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



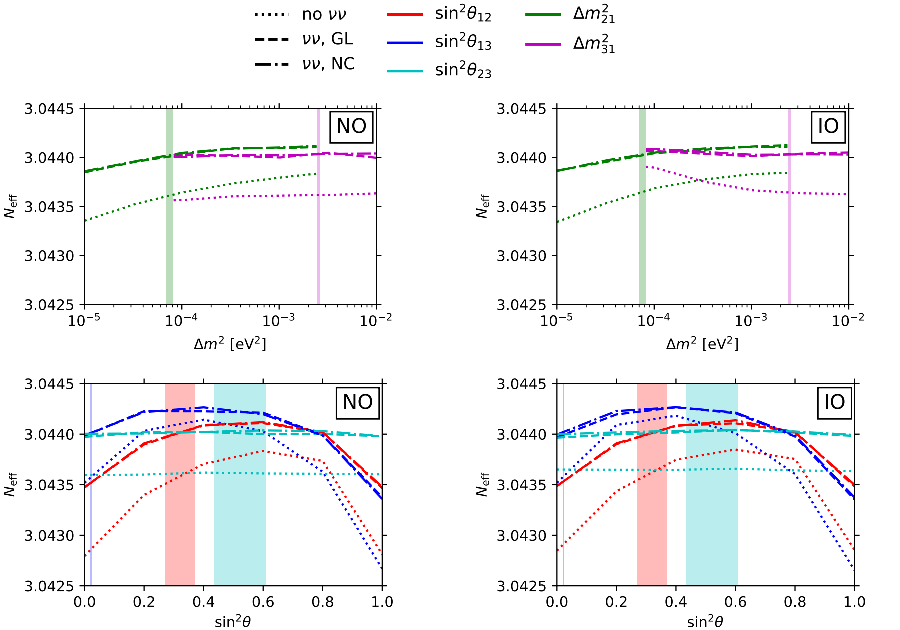
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, 2012.02726]

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



Effect of neutrino oscillations

[Bennett, SG+, 2012.02726]



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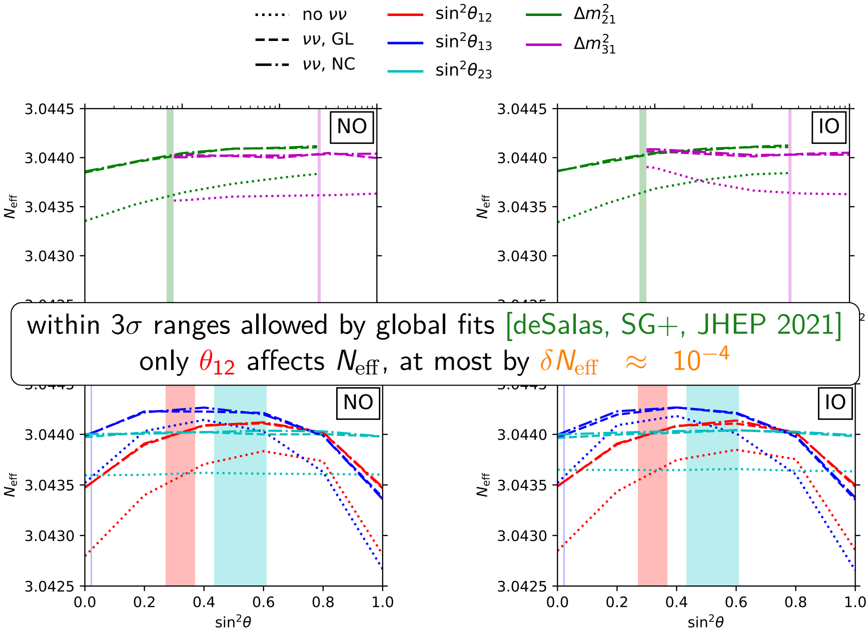


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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

Sampling the y momenta

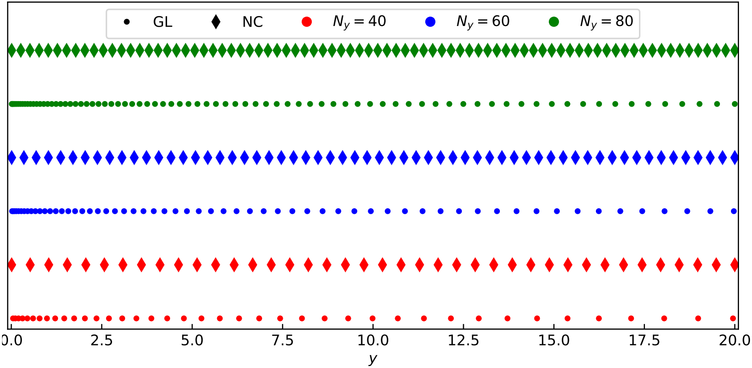
[Bennett, SG+, 2012.02726]

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 ($y_{\rm min} \leq y \leq y_{\rm max}$) and number of nodes N_y

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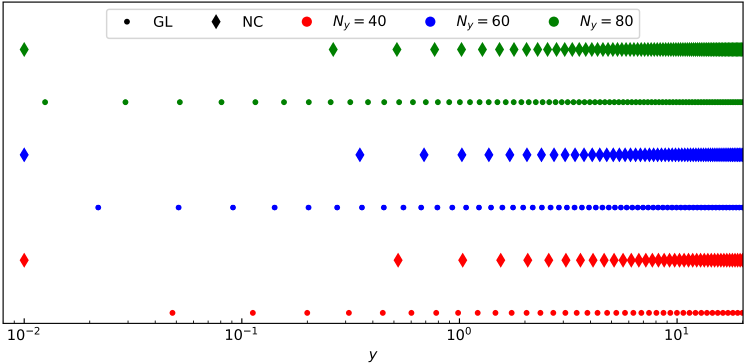

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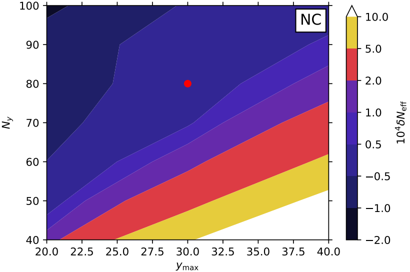
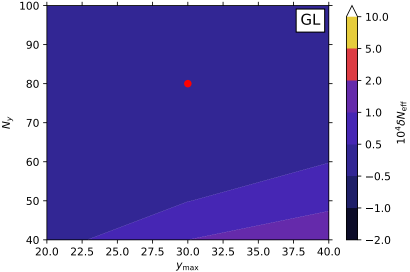
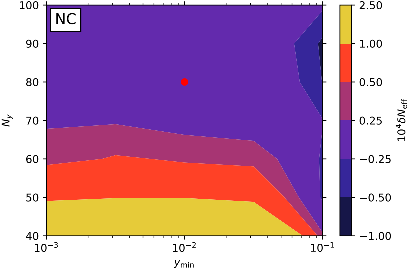
Discretize neutrino momenta to compute integrals and evolution

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







at same N_y,
GL results are more stable!

GL is more efficient

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

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

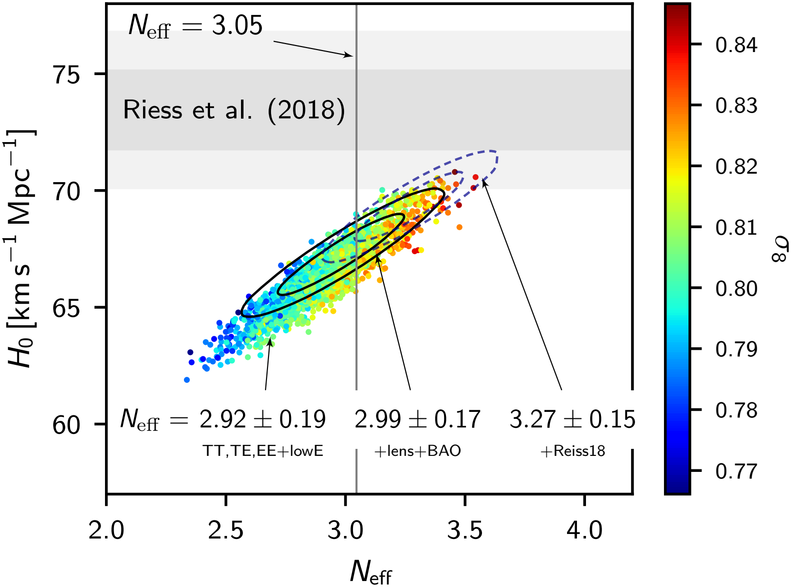
[Akita+, 2020]:
$N_{\rm eff} = 3.044 \pm 0.0005$ — equations in mass and flavor basis
approximated $\nu\nu$ collisions

[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

$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]



$N_{\rm eff}$ and BBN

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

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

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

$$\downarrow$$

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

enters

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

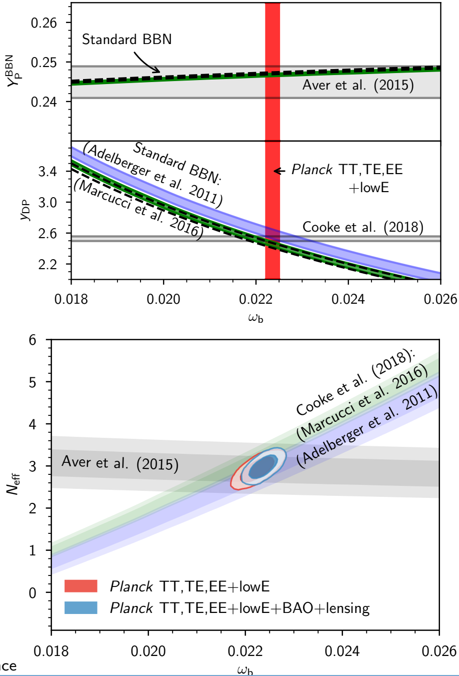
which controls element abundances

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

$$\downarrow$$

abundances depend on $N_{\rm eff}$

[Planck Collaboration, 2018]



G_F Fermi constant
G_N Newton constant

n, p: neutron, proton density number
$Q = 1.293$ MeV neutron–proton mass difference

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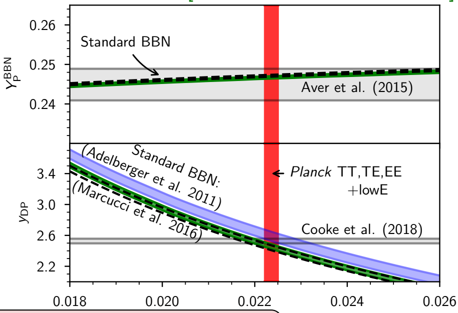
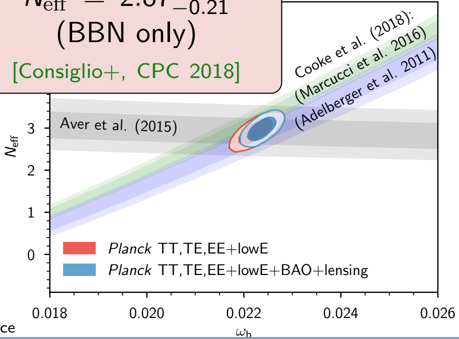


$N_{\rm eff} = 2.87^{+0.24}_{-0.21}$ (BBN only)

[Consiglio+, CPC 2018]



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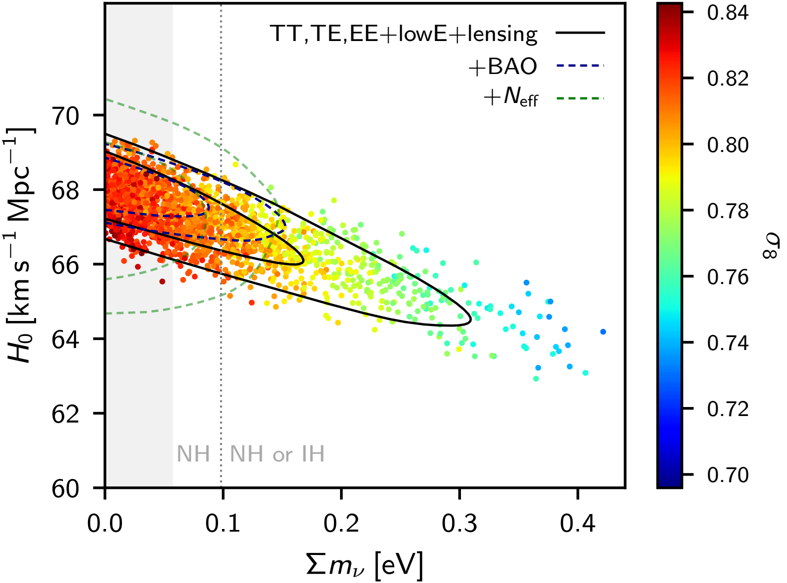
Σm_ν and CMB

[Planck Collaboration, 2018]

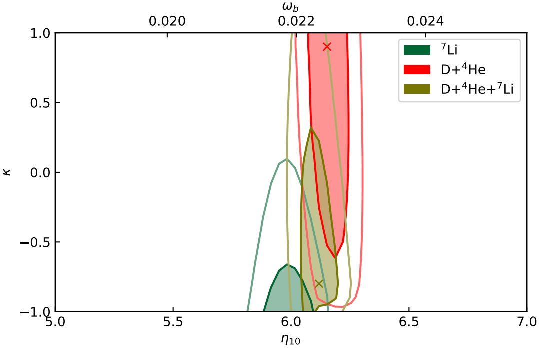


B Bosonic neutrinos

(?!? what?)

Based on:

- JCAP 03 (2018) 050



Motivation

Neutrinos are fermions ⟶ they obey Fermi-Dirac statistics

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Do they obey Fermi-Dirac statistics?

No experimental confirmation of spin-statistics theorem for neutrinos!

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Can we find violations of the Pauli exclusion principle?

electrons

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]

...

nucleons

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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$A \to A' + 2\bar{\nu} + 2e^-$ 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 $\leftarrow \kappa_\nu = -1$ ⟵ $\kappa_\nu = 0$ MB ⟶ $\kappa_\nu = +1 \rightarrow$ FD

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

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

Constraints on κ_ν from BBN

[de Salas, SG+, JCAP 03 (2018) 050]

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,

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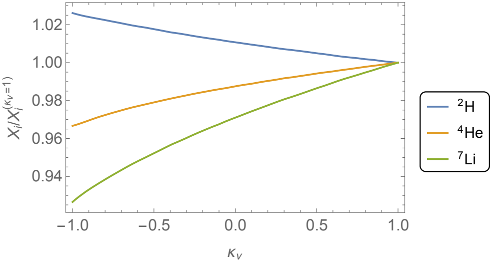
↓

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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$\downarrow$

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[Dolgov+, JCAP 2005]

less He, more D, less Li

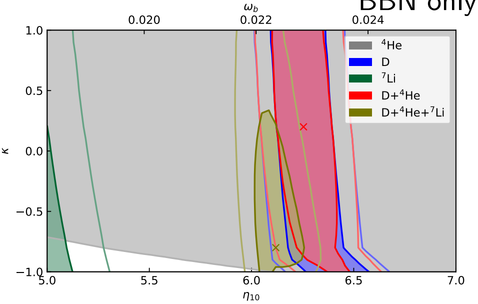
He or D alone cannot constrain κ_ν

Li problem drives ω_b down

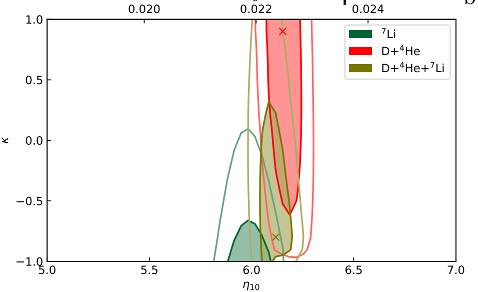
and κ_ν to -1

also when prior on ω_b is included

BBN only



CMB prior on ω_b



Neutrino densities and κ_ν

[de Salas, SG+, JCAP 03 (2018) 050]

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

κ_ν affects background evolution:

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

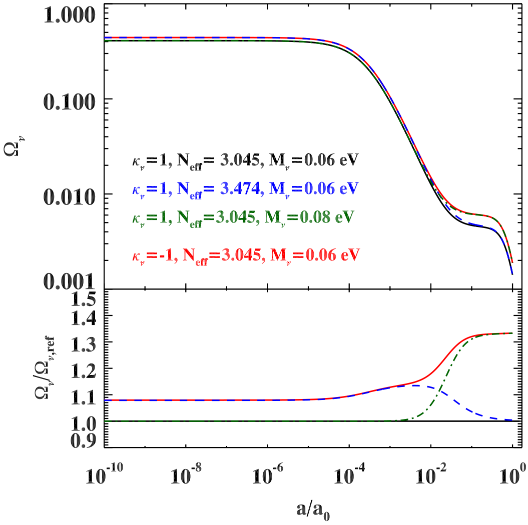
bosons: $\frac{\pi^2}{30} g_i\, T^4$

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

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

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

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



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

partial degeneracies with $N_{\rm eff}$ and Σm_ν

CMB/BAO constraints on κ_ν

[de Salas, SG+, JCAP 03 (2018) 050]

need to cover κ_ν–Σm_ν degeneracy:
vary both!

degeneracy affects
mostly CMB only bounds

with BAO, bound on Σm_ν is stronger

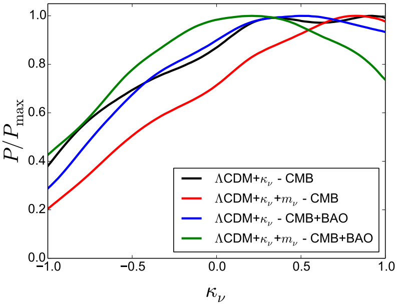
adding radiation (through κ_ν) and Ω_Λ alters H_0 and compensates a bit the larger mass

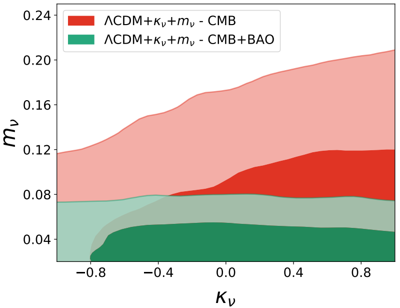
bounds: $\kappa_\nu \gtrsim -0.1$ at 68%

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

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

inside Planck 2σ region!
reasonably it's not excluded

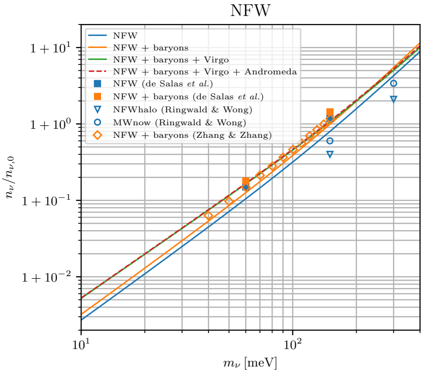




C Clustering in the local Universe

Based on:

- JCAP 09 (2017) 034
- JCAP 01 (2020) 015



ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

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 $(r,\ \theta,\ p_r,\ l)$

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

Assumptions:

- νs are independent
- only gravitational interactions
- νs do not influence matter evolution ($\rho_\nu \ll \rho_{\rm DM}$)

how many νs is "N"?

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

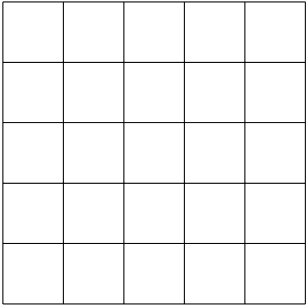
$\rightarrow$ must include all possible νs that reach the MW (fastest ones may come from several (up to $\mathcal{O}(100)$) Mpc!)

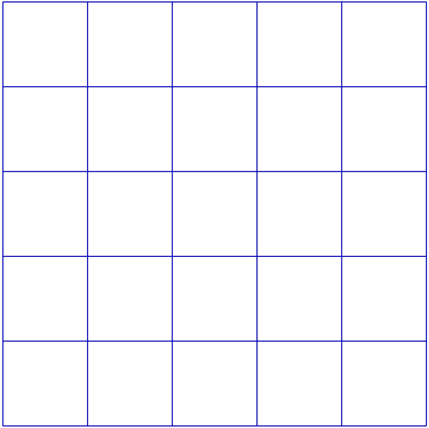
given N ν:

$\rightarrow$ weigh each neutrinos

Forward-tracking and back-tracking

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

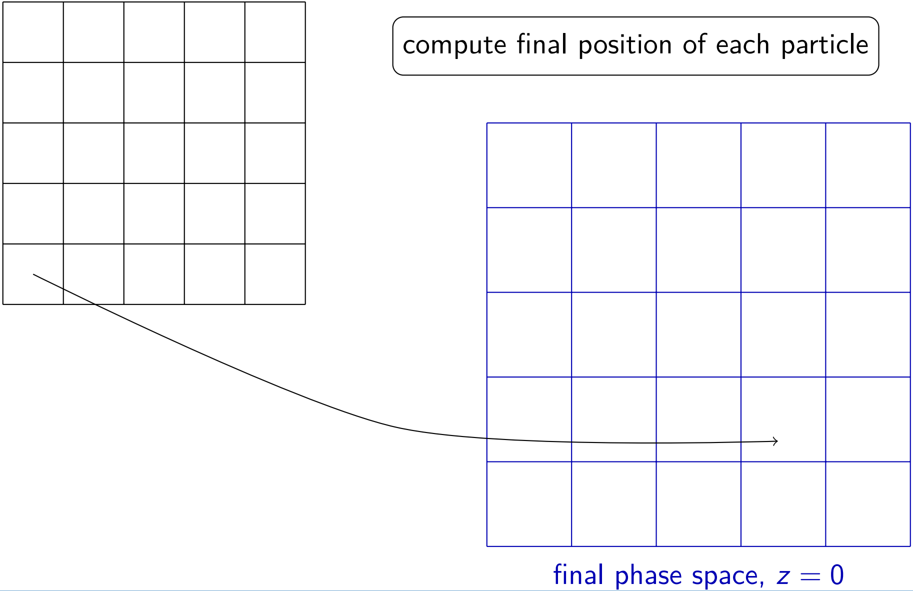




final phase space, $z = 0$

Forward-tracking and back-tracking

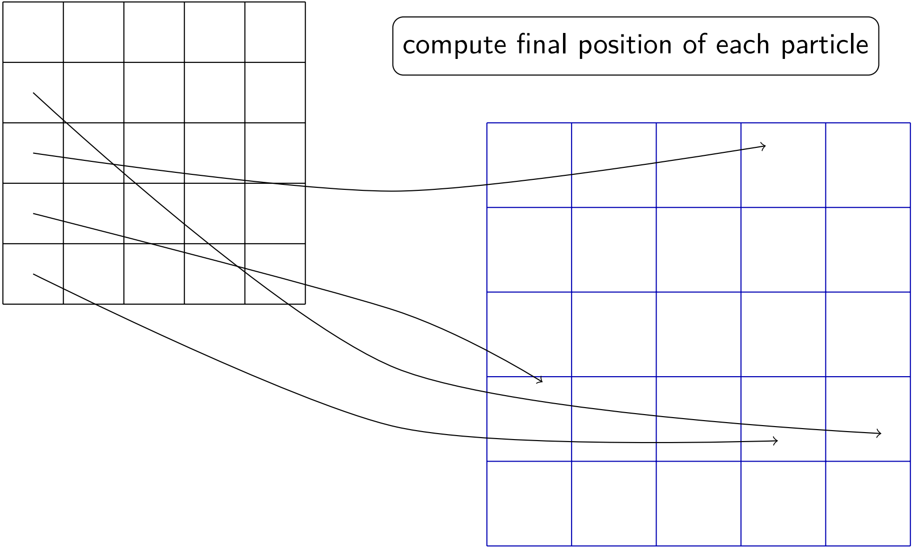
initial phase space, $z = 4$ $\longrightarrow$ homogeneous Fermi-Dirac distribution



Forward-tracking and back-tracking

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

compute final position of each particle



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Forward-tracking and back-tracking

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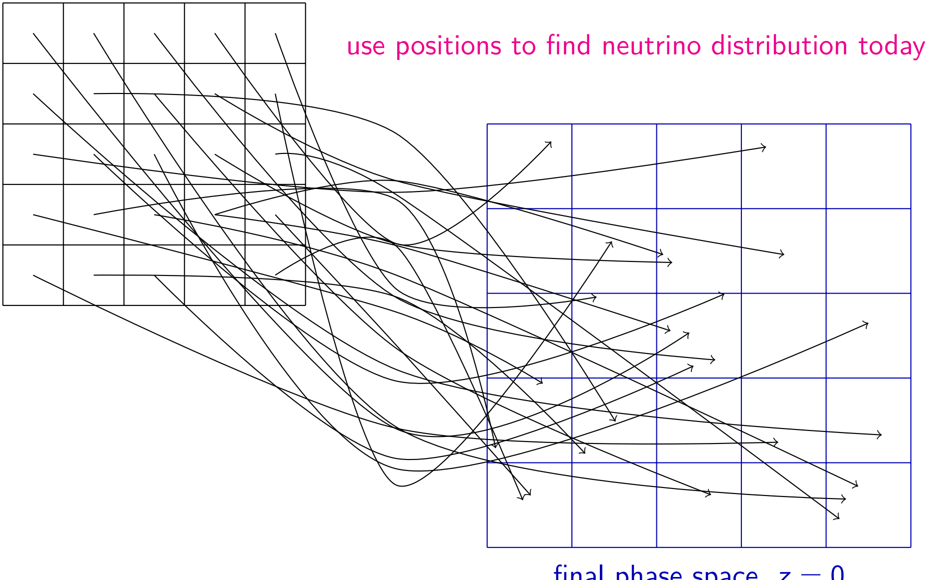

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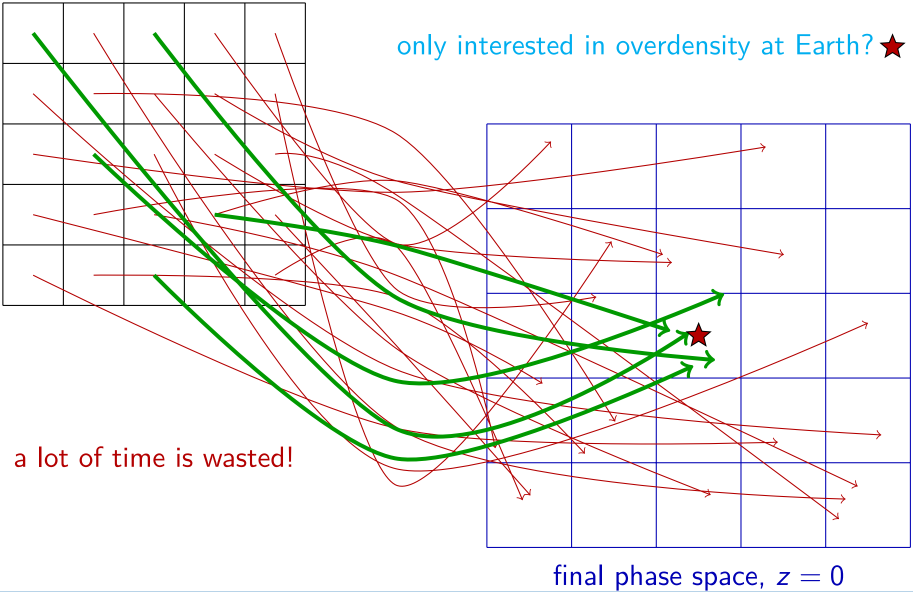
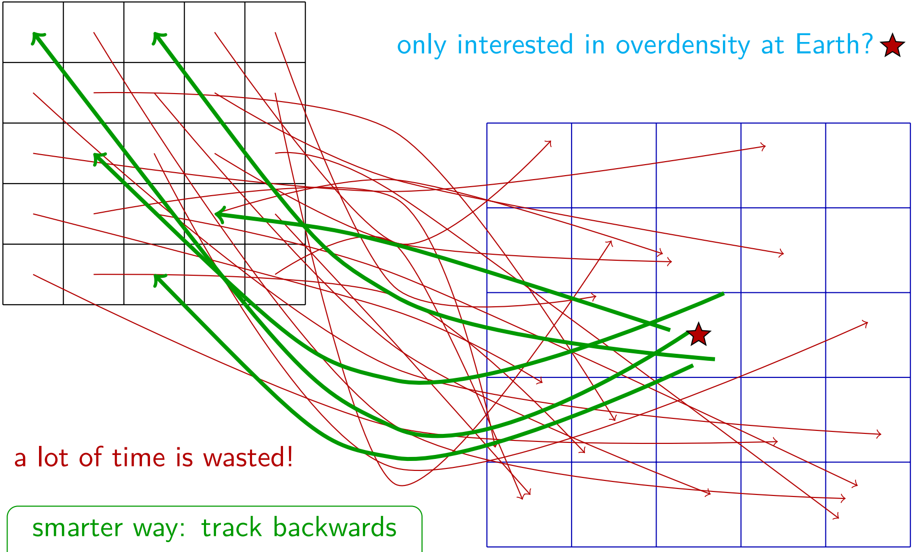


Forward-tracking and back-tracking

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

only interested in overdensity at Earth? ★



a lot of time is wasted!

smarter way: track backwards
only interesting particles!

final phase space, $z = 0$

Advantages of tracking back

[JCAP 01 (2020) 015]

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

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[JCAP 01 (2020) 015]

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

Second advantage: no need to use spherical symmetry!

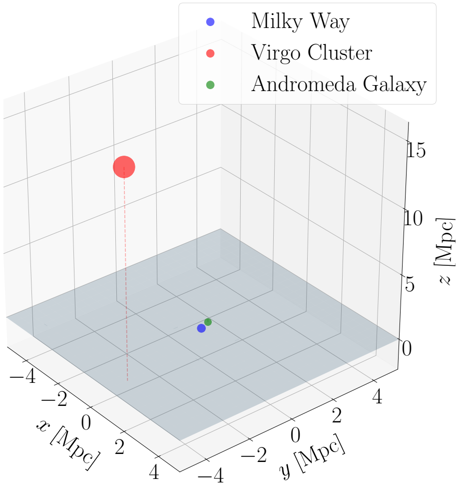
Forward-tracking	Back-tracking
initial conditions need to sample 1D for position + 2D for momentum when using spherical symmetry	"Initial" conditions only described by 3D in momentum
with full grid would require 3+3 dimensions!	(position is fixed, apart for checks)
Impossible to relax spherical symmetry!	can do the calculation with any astrophysical setup

Advantages of tracking back

[JCAP 01 (2020) 015]

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

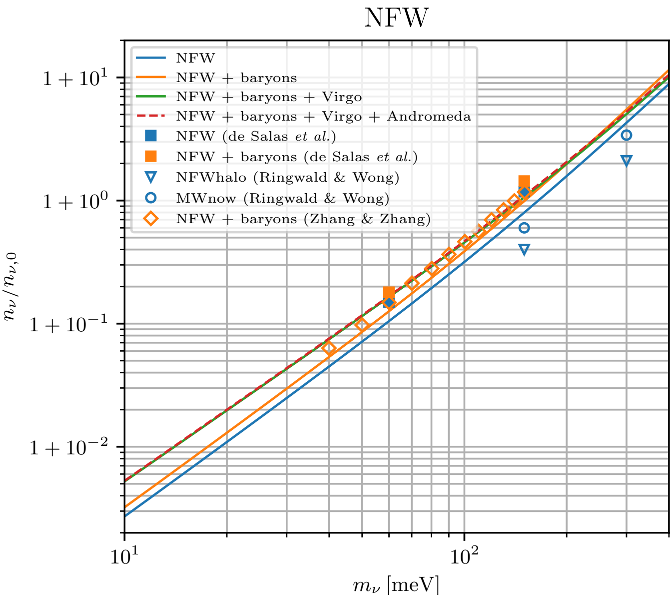
Second advantage: no need to use spherical symmetry!



Clustering results with back-tracking

[JCAP 01 (2020) 015]

In comparison with previous results:



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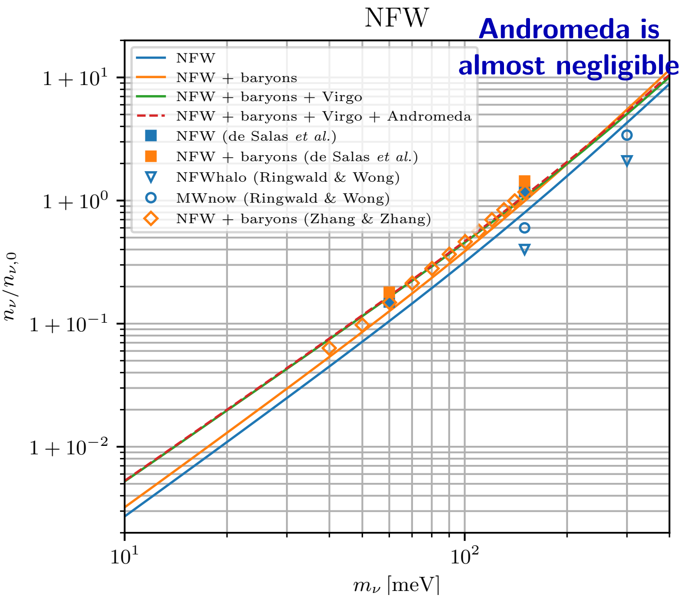

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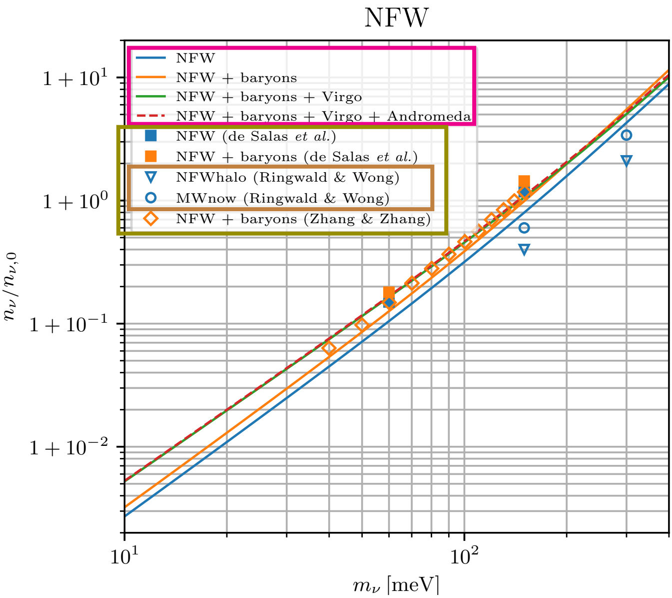

Warning: NFW is not the same for all the cases!

[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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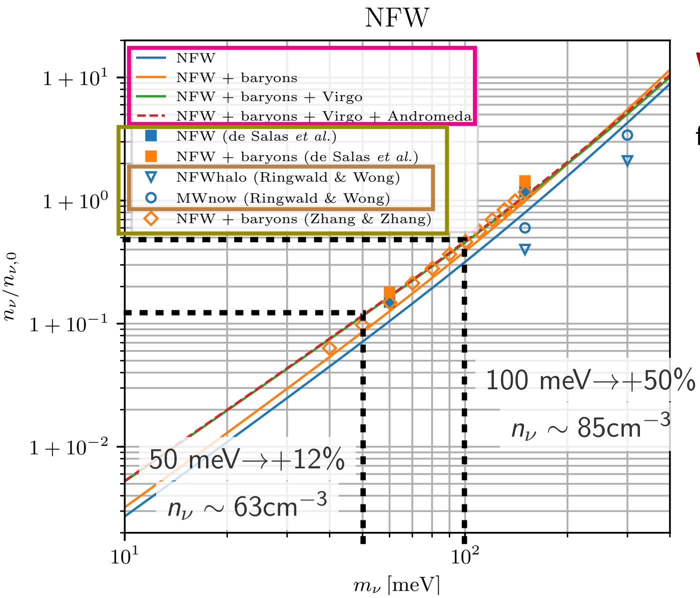

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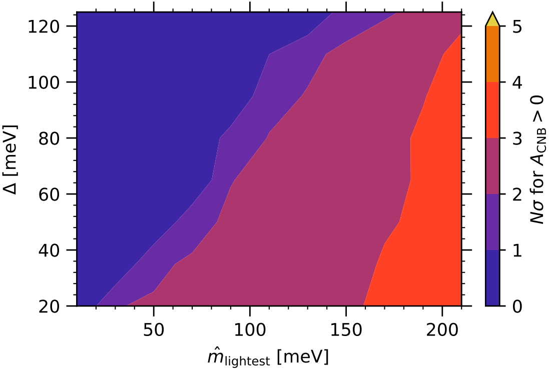
D Direct Detection

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

Based on:

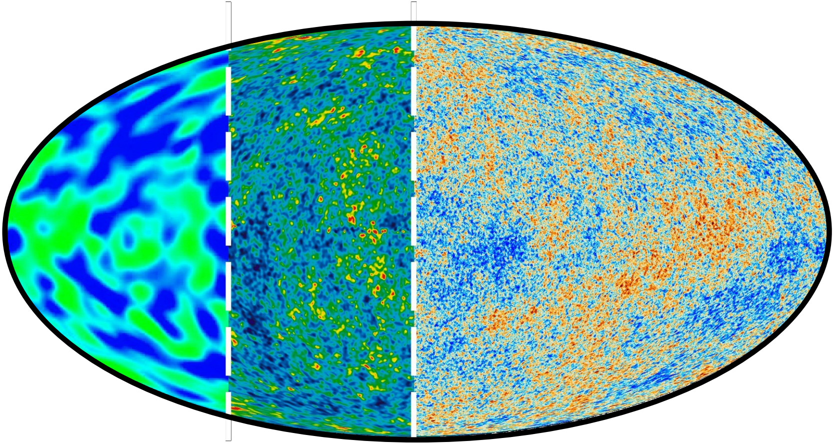
- arxiv:1808.01892
- JCAP 07 (2019) 047



The oldest picture of the Universe

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

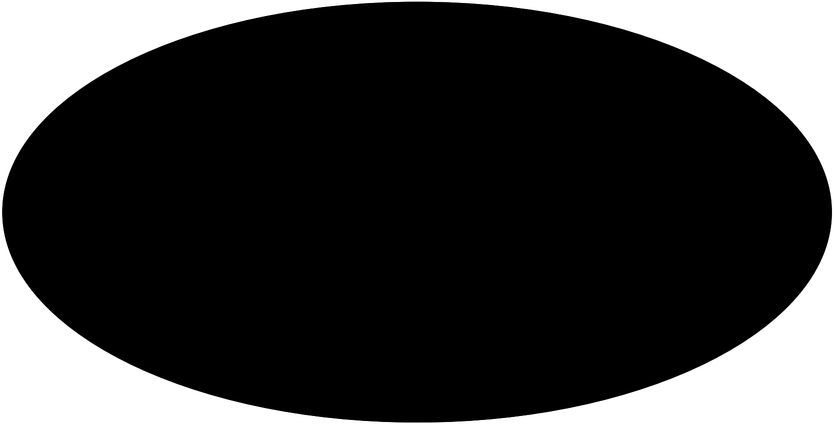
COBE (1992) WMAP (2003) Planck (2013)



The oldest picture of the Universe

The Cosmic Neutrino Background, generated at $t \simeq 1$ s

$\ldots \rightarrow 2021 \rightarrow \ldots$



How to capture relic neutrinos?

[Long et al., JCAP 08 (2014) 038]

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

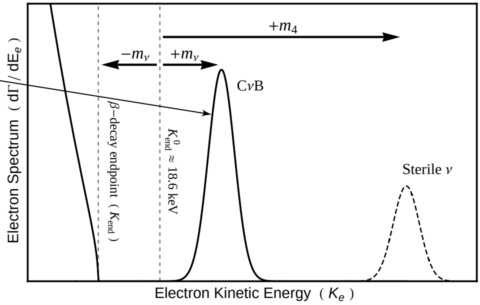
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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



β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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

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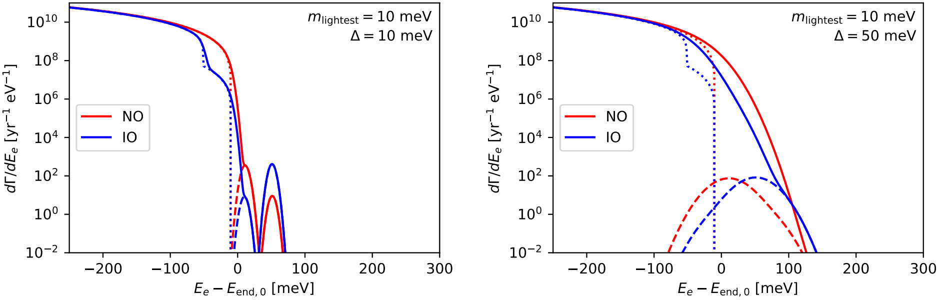

[PTOLEMY LoI, arxiv:1808.01892]

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

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

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

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

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)

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ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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

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Detection of the relic neutrinos

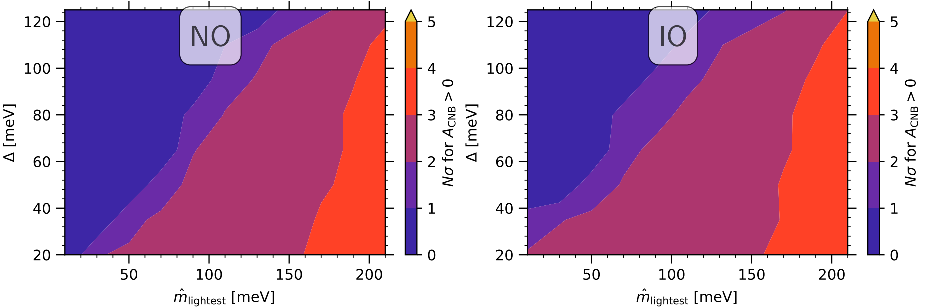
using the definition:

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

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

statistical only!

significance on $A_{\rm CNB} > 0$
as a function of $\hat{m}_{\rm lightest}$, Δ



E-R (skipping. . .)

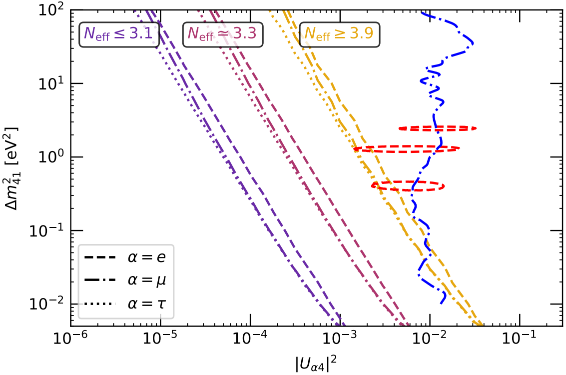
seriously, I cannot go
through the entire alphabet in 50 minutes!

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
- arxiv:2003.02289
- JCAP 07 (2019) 047



Short Baseline (SBL) anomaly

[SG+, JPG 43 (2016) 033001]

Problem: anomalies in SBL experiments → { errors in flux calculations? / deviations from 3-ν description? }

A short review:

LSND search for $\bar{\nu}_\mu \to \bar{\nu}_e$, 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 ⇒ 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]

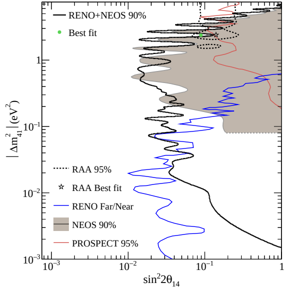
MiniBooNE See next

Possible explanation:

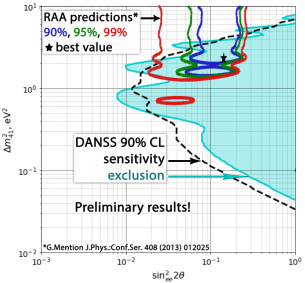
Additional squared mass difference $\Delta m^2_{\text{SBL}} \simeq 1\ \mathrm{eV}^2$

ν_s at reactors in 2020

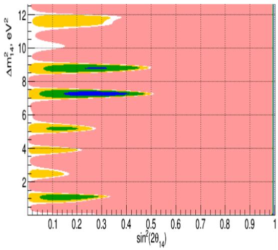
[RENO+NEOS, 2020]



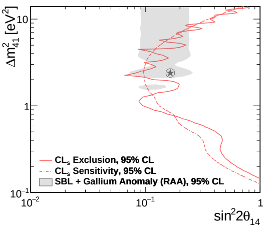
[DANSS, 2020]



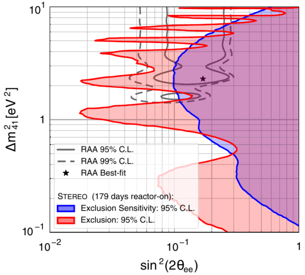
[Neutrino-4, PZETF 2020]



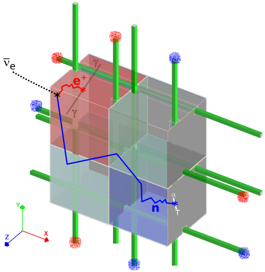
[PROSPECT, PRD 2020]



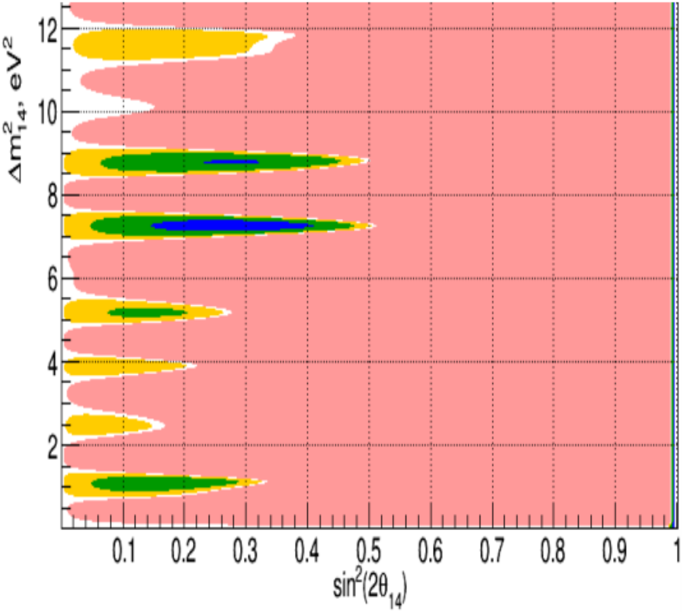
[STEREO, PRD 2020]



[SoLiD, JINST 2018]



Neutrino-4

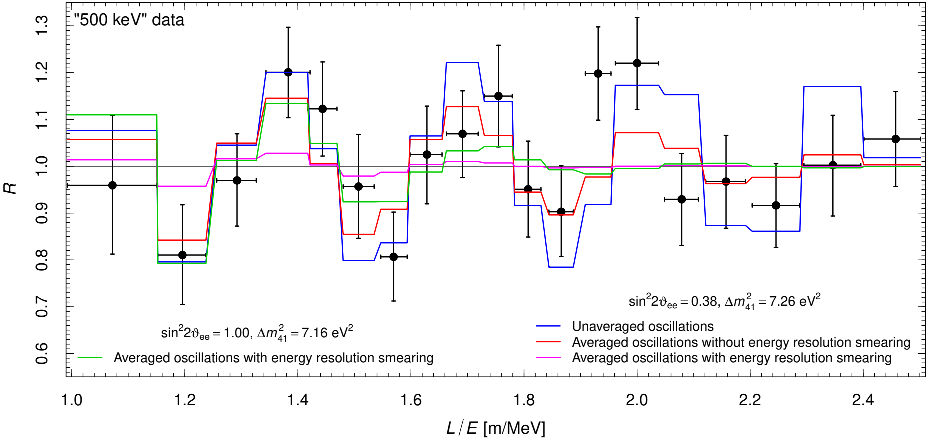


claimed $> 3\sigma$ preference for 3+1 over 3ν case

best fit incompatible with other reactor experiments

Neutrino-4

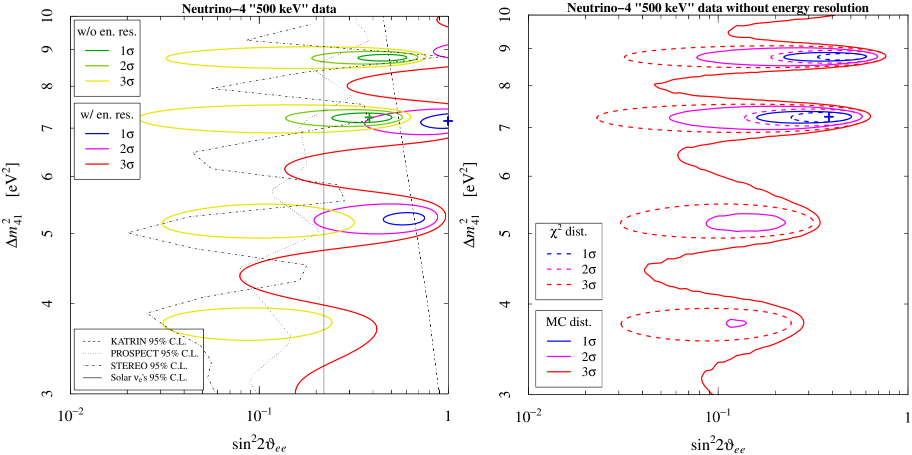
[Giunti+, arxiv:2101.06785]



energy resolution smearing not properly taken into account?

Neutrino-4

[Giunti+, arxiv:2101.06785]



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

need to take into account

violation of Wilk's theorem

↓

relaxed constraints

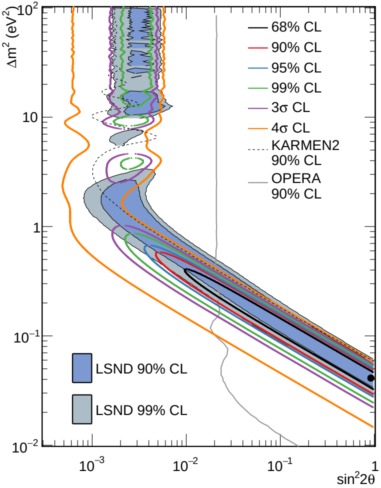
MiniBooNE

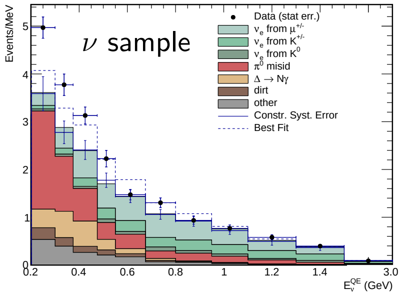
[PRL 121 (2018) 221801]

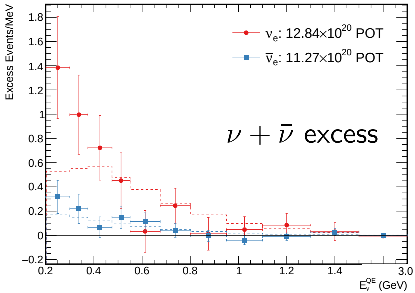
purpose: check LSND signal

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

no money, no near detector







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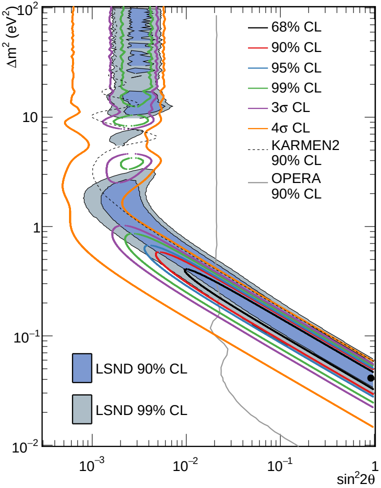
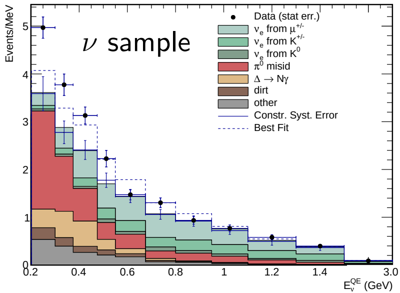
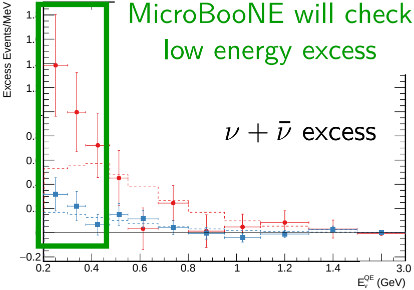


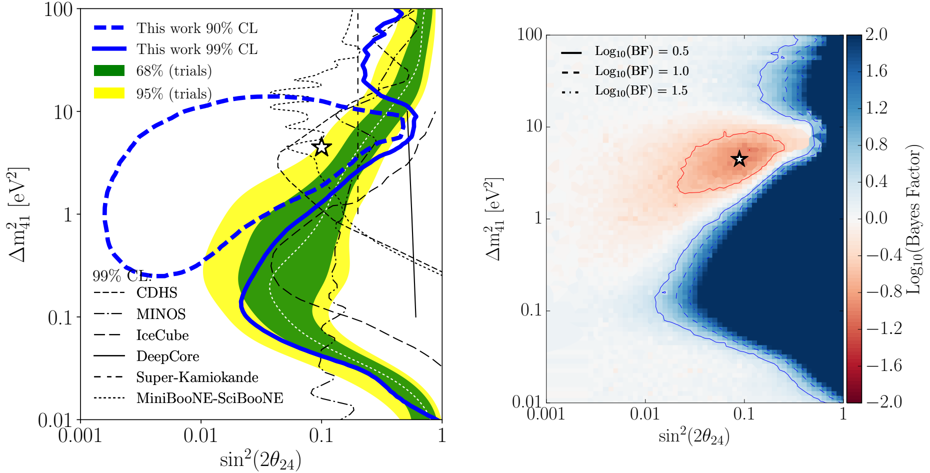


MicroBooNE will check low energy excess



IceCube 8 yr update

[IceCube, PRL 2020]



first indication in favor of sterile from ν_μ DIS!

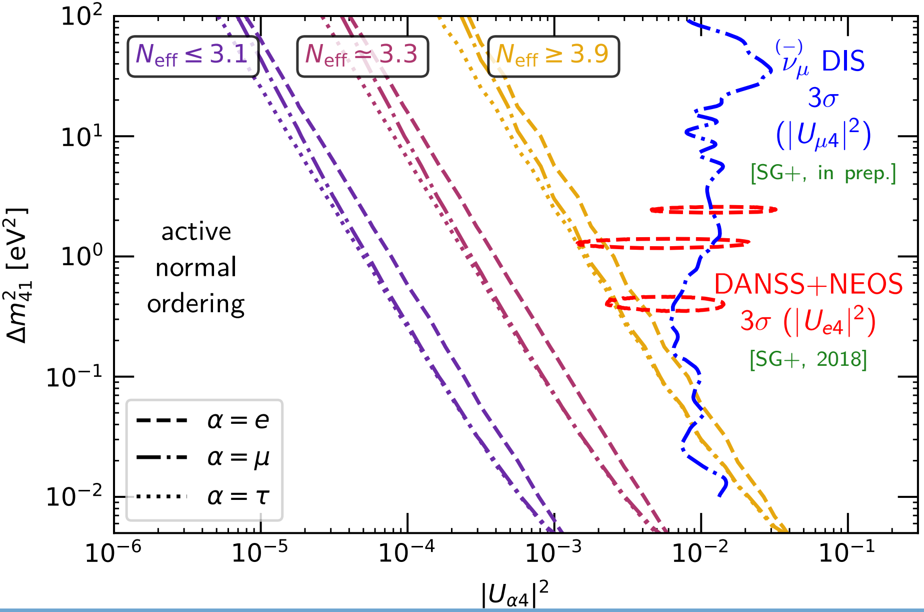
although rather weak: $\log_{10} BF \simeq 1$ (weak preference)

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

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

[SG+, JCAP 07 (2019) 014]

Only vary one angle and fix two to zero: do they have the same effect?



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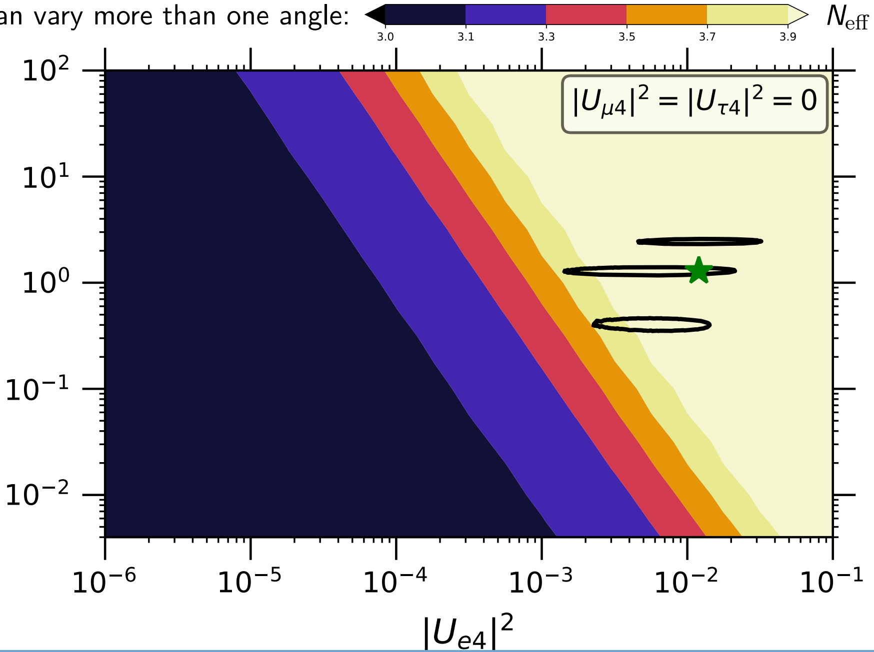
[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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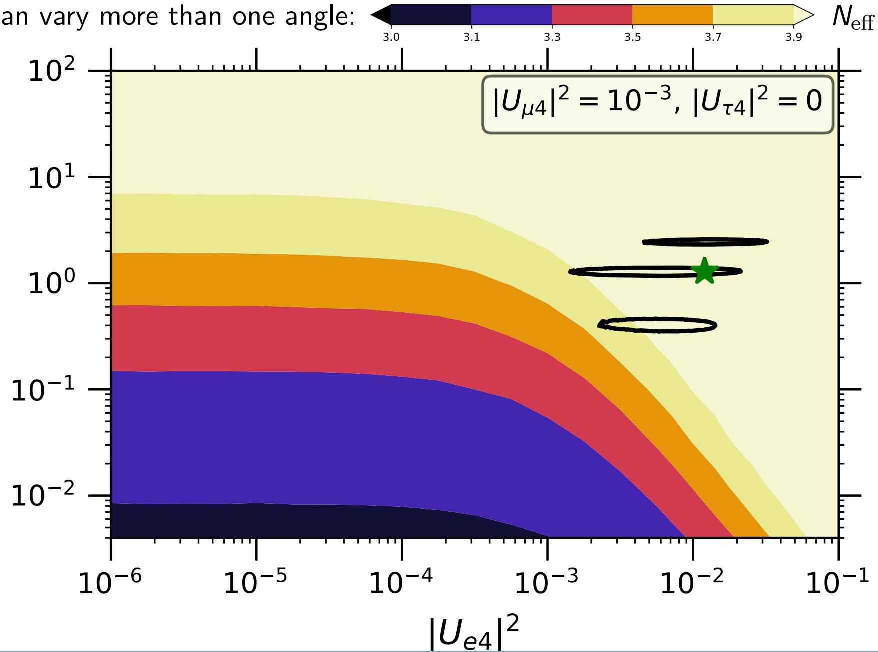

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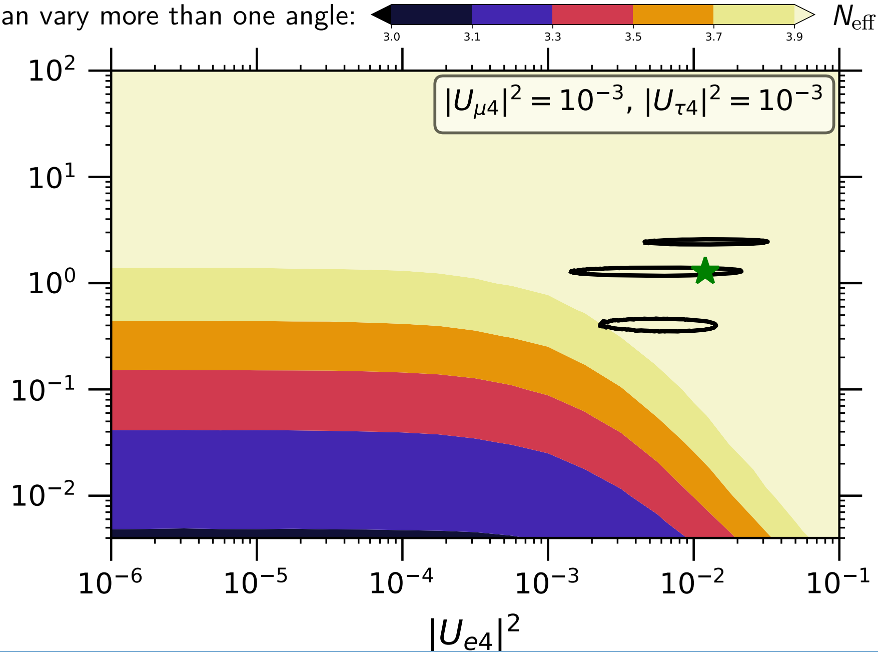
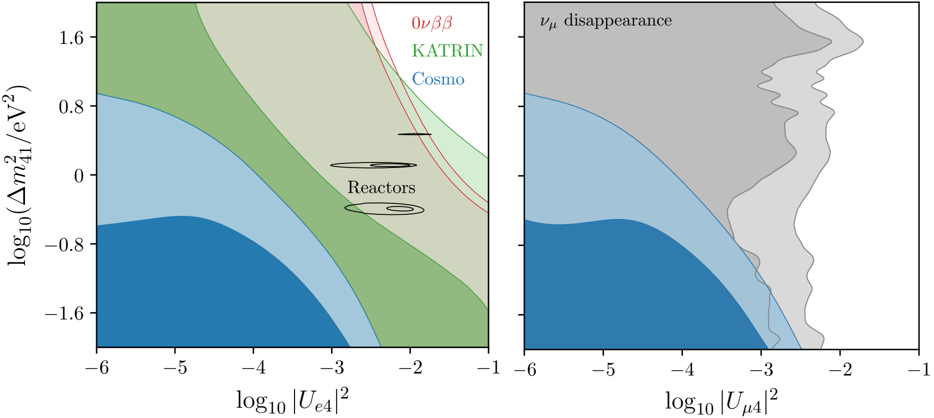


Comparing constraints

Cosmological constraints are stronger than most other probes

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



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[arxiv:2003.02289]

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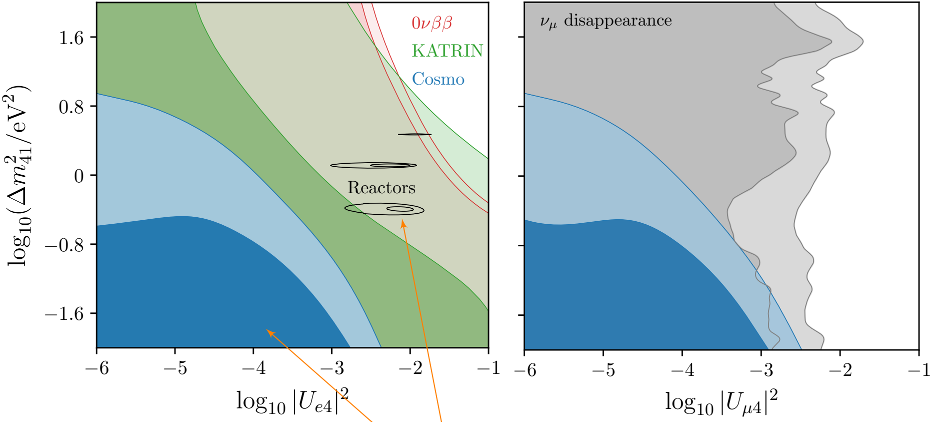


Warning: tension between reactor experiments and CMB bounds!

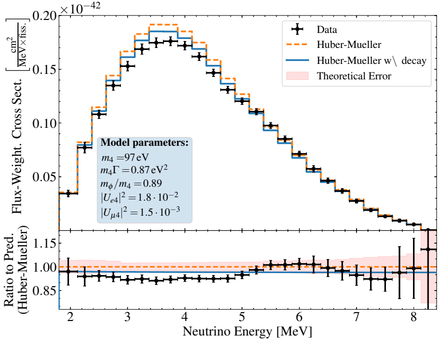
Can new physics solve the anomalies and tensions?

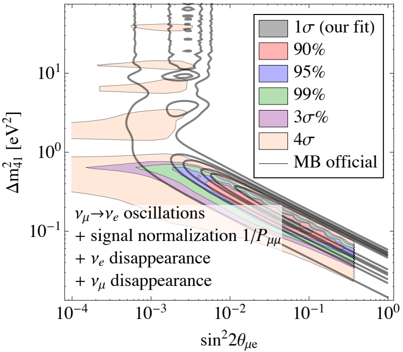
Many attempts to explain LSND/MiniBooNE anomalies, APP vs DIS, oscillations vs cosmo tensions with new physics

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 $m_\phi \lesssim m_4$

↳ new interactions with scalar ϕ and ν_s decay





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

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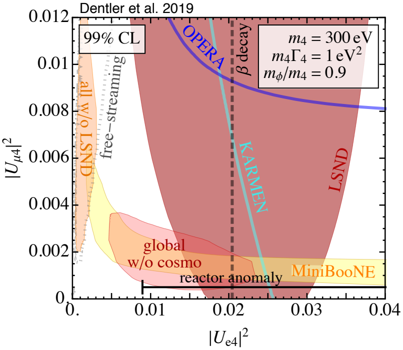

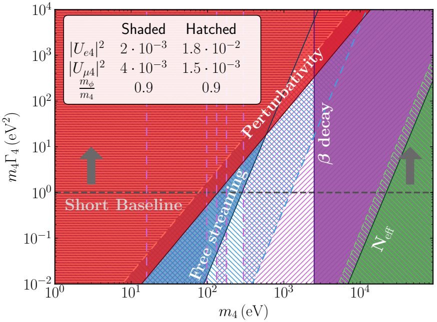

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$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2} G_F \epsilon^{fC}_{\alpha\beta} [\overline{\nu_\alpha} \gamma^\rho P_L \nu_\beta] \left[\bar{f} \gamma_\rho P_C f\right]$$

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

Non-standard interactions (NSI) involving ν_s

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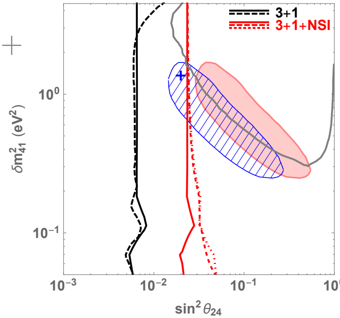
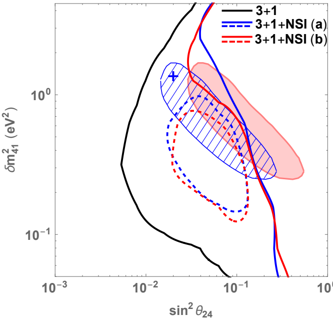
Non-standard interactions (NSI) involving ν_s

MINOS+ vs APP





IceCube/DeepCore vs APP

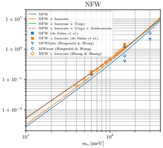
Z

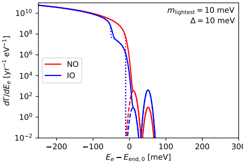
Conclusions

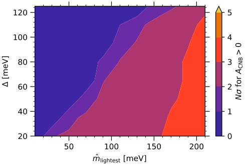
almost there!

What do we learn from relic neutrinos?

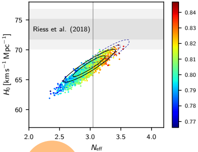
D Direct detection - wonderful opportunities for the future

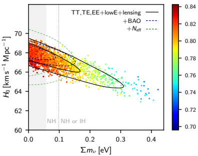


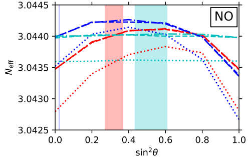


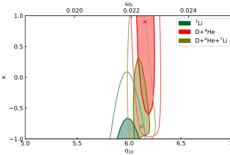


I Indirect probes - what we have now, it's a lot and it will improve

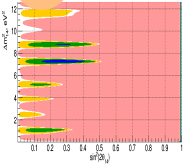


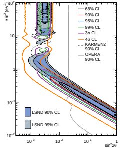


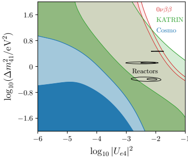


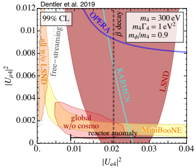


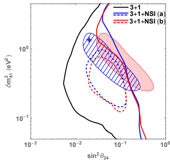
N New physics - beyond the corner? neutrinos will help us find it!











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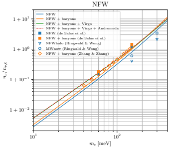

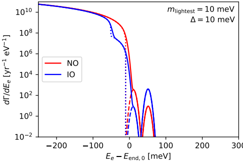

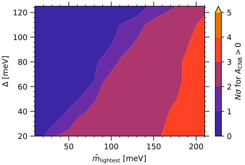

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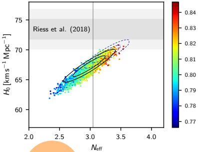

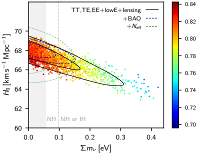

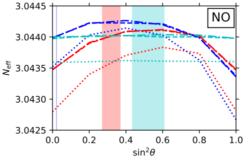

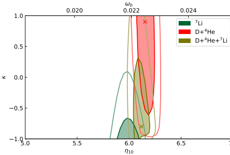

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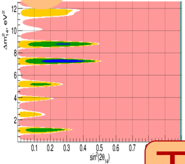

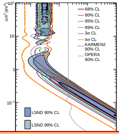

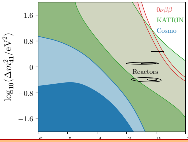

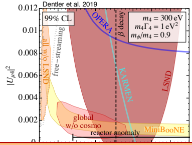

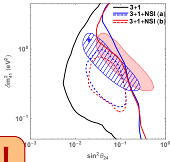

Thank you for the attention!