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(Cosmological) Relic neutrinos, from A to Z

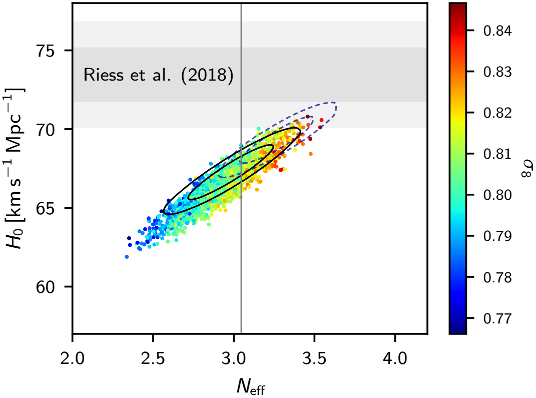
Seminar at SISSA, Trieste (IT), 25/11/2019

A Active neutrinos

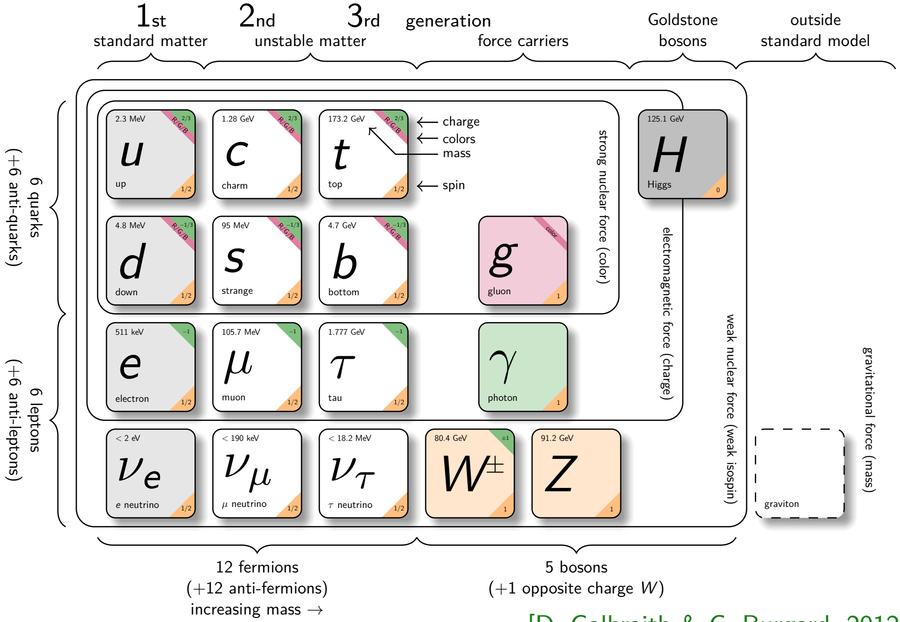
Spoiler: “Sterile” will come later

Based on:

- Planck 2018
- Mangano+ 2005
- de Salas+ 2016
- in preparation (1)



The Standard Model of Particle Physics



1st generation standard matter	2nd generation unstable matter	3rd generation unstable matter	force carriers	Goldstone bosons	outside standard model
2.3 MeV 2/3 R/G/B u up 1/2	1.28 GeV 2/3 R/G/B c charm 1/2	173.2 GeV 2/3 R/G/B t top 1/2	← charge ← colors mass ← spin	125.1 GeV H Higgs 0	
4.8 MeV −1/3 R/G/B d down 1/2	95 MeV −1/3 R/G/B s strange 1/2	4.7 GeV −1/3 R/G/B b bottom 1/2	color g gluon 1		
511 keV −1 e electron 1/2	105.7 MeV −1 μ muon 1/2	1.777 GeV −1 τ tau 1/2	γ photon 1		
< 2 eV ν_e e neutrino 1/2	< 190 keV ν_μ μ neutrino 1/2	< 18.2 MeV ν_τ τ neutrino 1/2	80.4 GeV ±1 $W^\pm$ 1 91.2 GeV Z 1		graviton

6 quarks (+6 anti-quarks)

6 leptons (+6 anti-leptons)

strong nuclear force (color)

electromagnetic force (charge)

weak nuclear force (weak isospin)

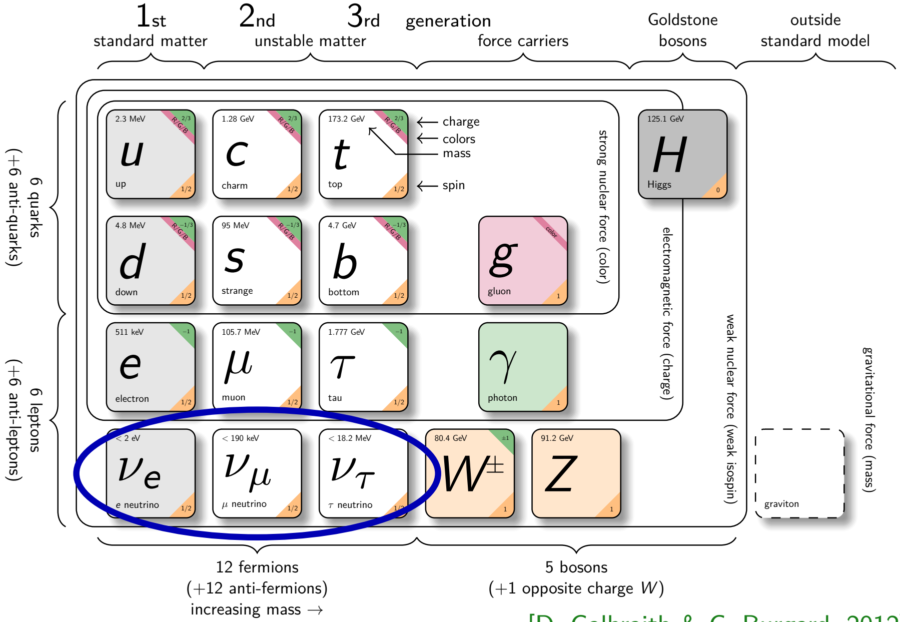
gravitational force (mass)

12 fermions
(+12 anti-fermions)
increasing mass →

5 bosons
(+1 opposite charge W)

[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics

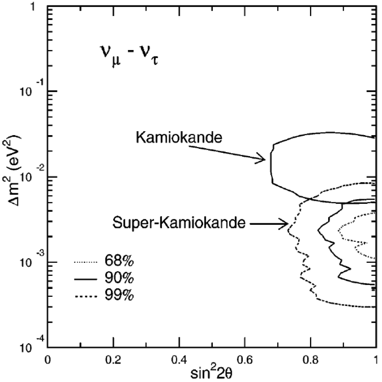


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

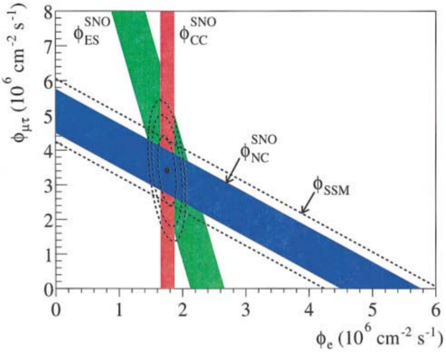
Major discoveries:

[SuperKamiokande, 1998]



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

[SNO, 2001-2002]



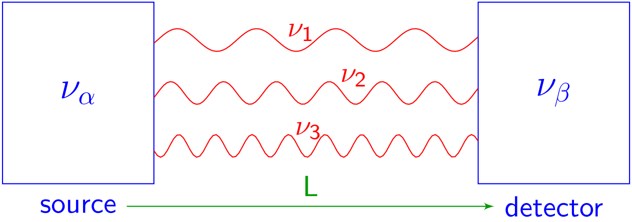
first discovery of $\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations from solar ν

Nobel prize in 2015

Two neutrino bases

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

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



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

$$E_k^2 = p^2 + m_k^2 \xleftarrow{\quad} \text{define} \xrightarrow{\quad} t = L$$

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

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

The mixing matrix

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

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

Majorana phases irrelevant for oscillation experiments ←

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: [de Salas et al. (2018)]

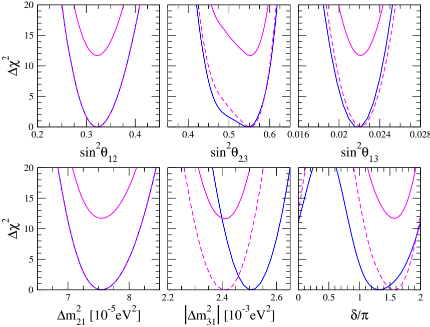
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\begin{aligned}
\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\
&= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})
\end{aligned}$$

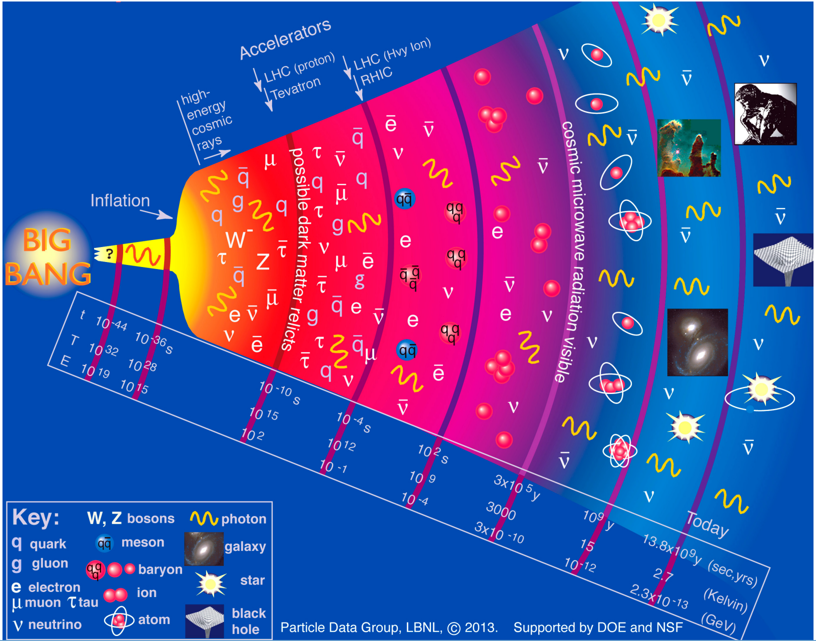
$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\
&= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\
\sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\
&= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})
\end{aligned}$$

First hints for $\delta \simeq 3/2\pi$



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

History of the universe



Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

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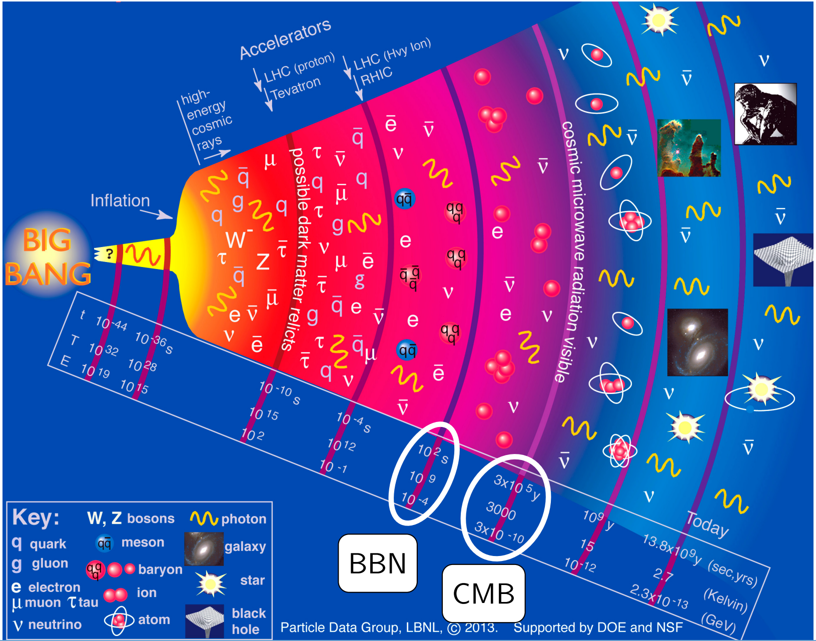

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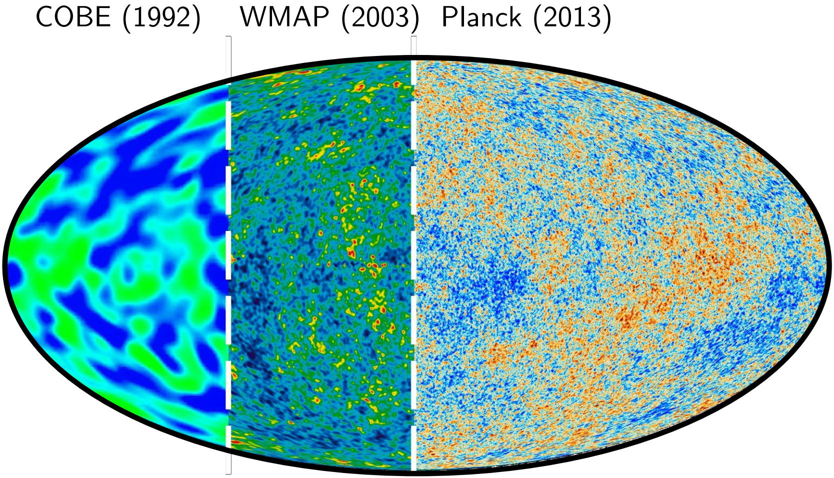
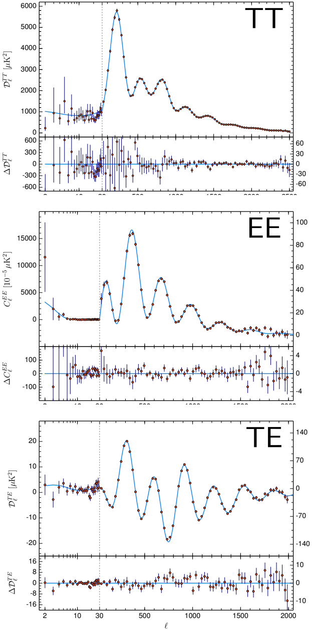
The oldest picture of the Universe

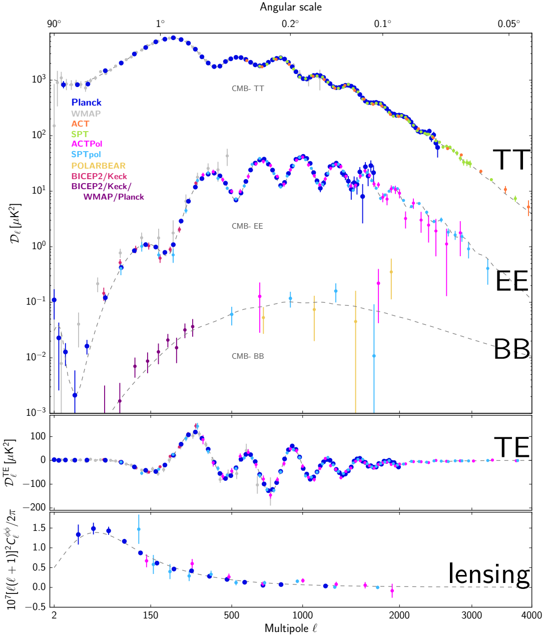
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years



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

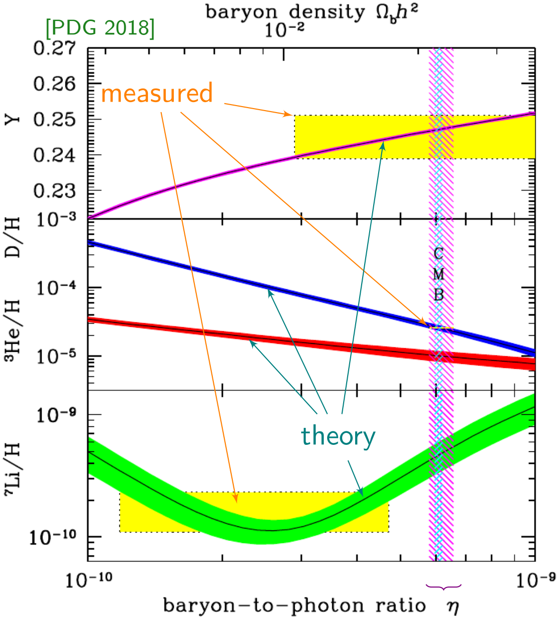
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

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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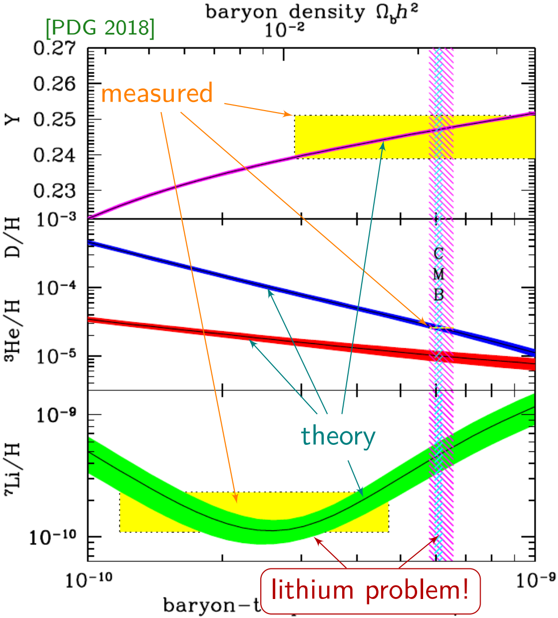


measured

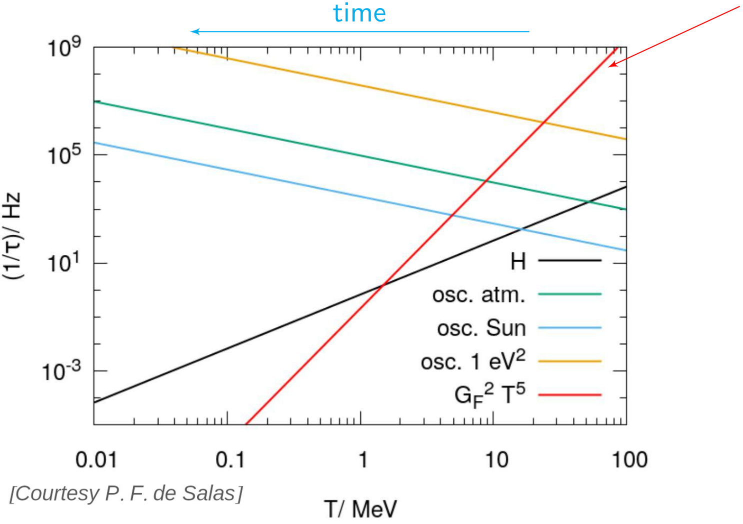
theory

lithium problem!

BBN concordance

Neutrinos in the early Universe

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



[Courtesy P. F. de Salas]

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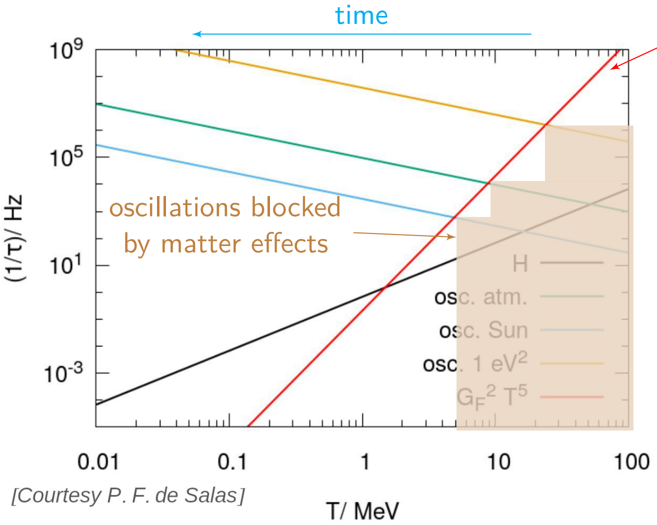

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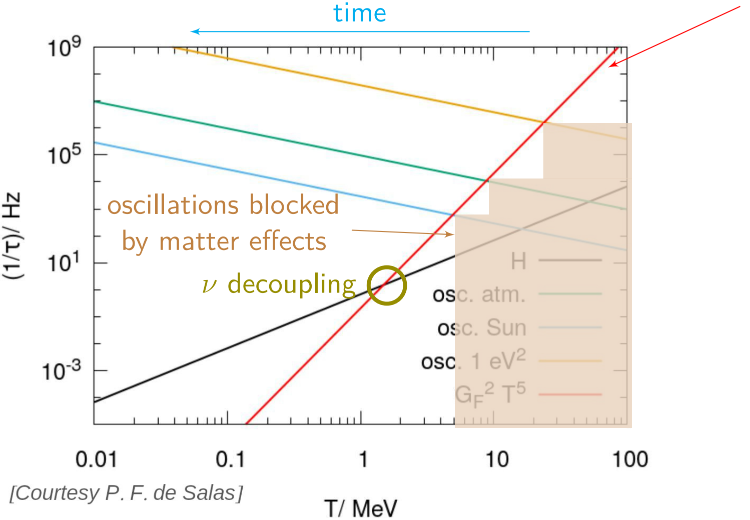

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ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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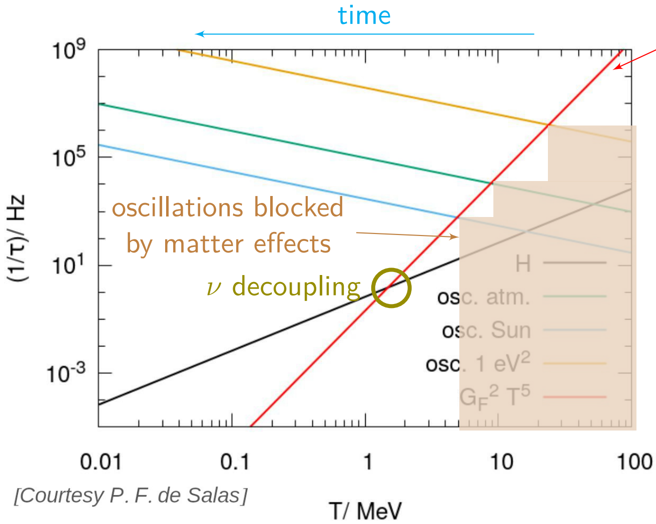
time

oscillations blocked by matter effects

ν decoupling

[Courtesy P. F. de Salas]

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

f_ν: frozen Fermi-Dirac distribution

Today:

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

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

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

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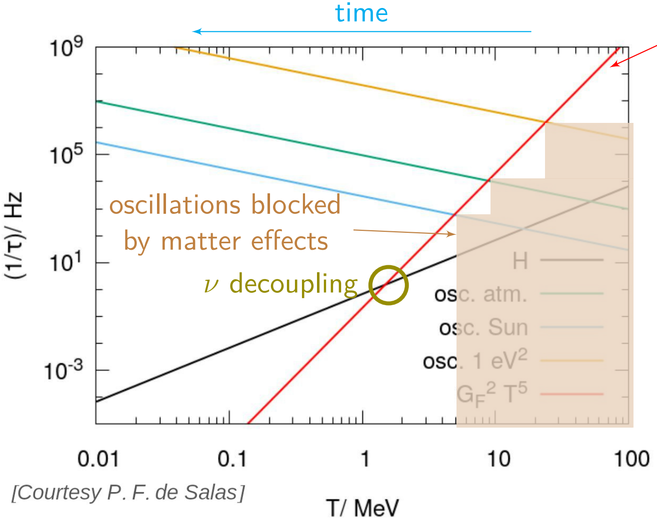

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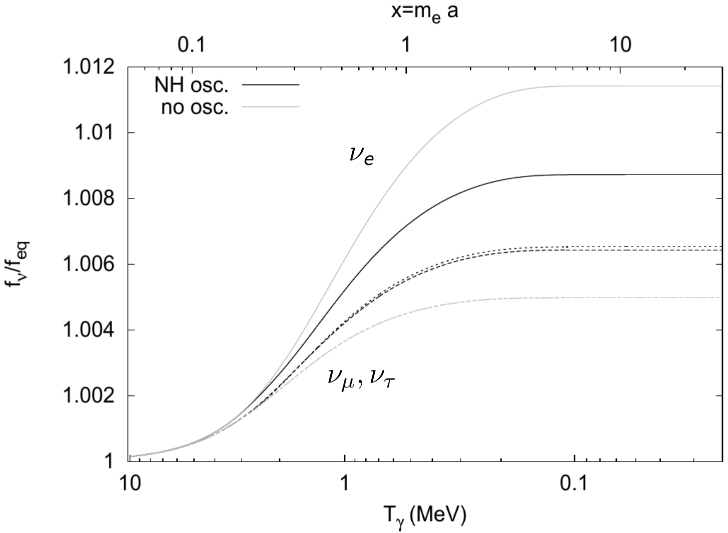
actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

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

[deSalas+, 2016]

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



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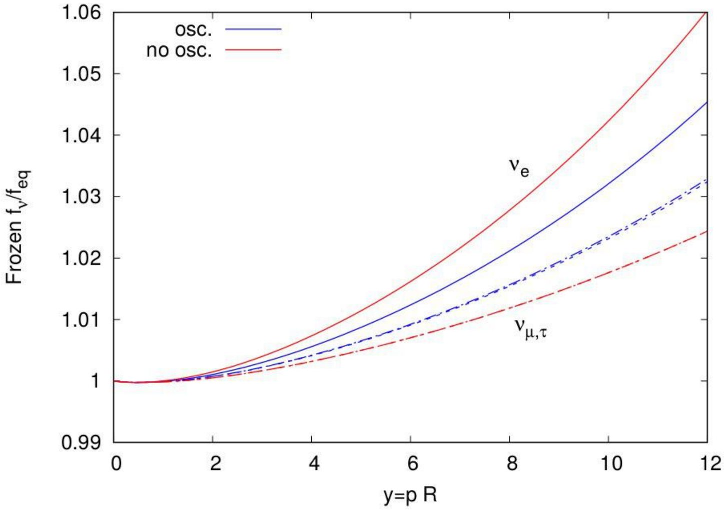
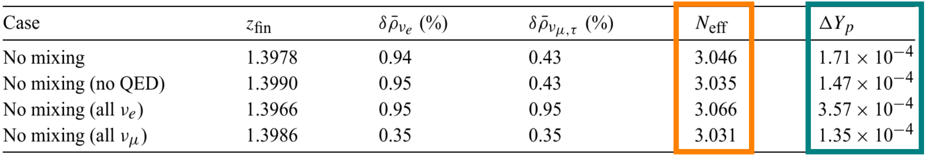


Neutrino momentum distribution and $N_{\rm eff}$

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

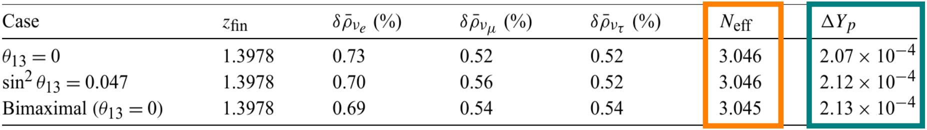
[Mangano+, 2005]

two-neutrino approximation:



Case	$z_{\rm fin}$	$\delta\bar\rho_{\nu_e}$ (%)	$\delta\bar\rho_{\nu_{\mu,\tau}}$ (%)	$N_{\rm eff}$	ΔY_p
No mixing	1.3978	0.94	0.43	3.046	1.71×10^{-4}
No mixing (no QED)	1.3990	0.95	0.43	3.035	1.47×10^{-4}
No mixing (all ν_e)	1.3966	0.95	0.95	3.066	3.57×10^{-4}
No mixing (all ν_μ)	1.3986	0.35	0.35	3.031	1.35×10^{-4}

full three-neutrino results (with oscillations):



Case	$z_{\rm fin}$	$\delta\bar\rho_{\nu_e}$ (%)	$\delta\bar\rho_{\nu_\mu}$ (%)	$\delta\bar\rho_{\nu_\tau}$ (%)	$N_{\rm eff}$	ΔY_p
$\theta_{13}=0$	1.3978	0.73	0.52	0.52	3.046	2.07×10^{-4}
$\sin^2\theta_{13}=0.047$	1.3978	0.70	0.56	0.52	3.046	2.12×10^{-4}
Bimaximal ($\theta_{13}=0$)	1.3978	0.69	0.54	0.54	3.045	2.13×10^{-4}

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

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

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[SG+, 2019]: $N_{\rm eff} = 3.044$ `FortEPiaNO` code	more efficient and precise code, $N > 3$ neutrinos allowed, minor differences in numerical integrals

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[Bennett+, 2019]: $N_{\rm eff} = 3.043$	finite-T QED corrections at $\mathcal{O}(e^3)$! further terms should be negligible

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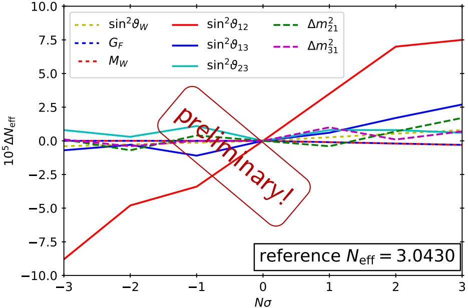
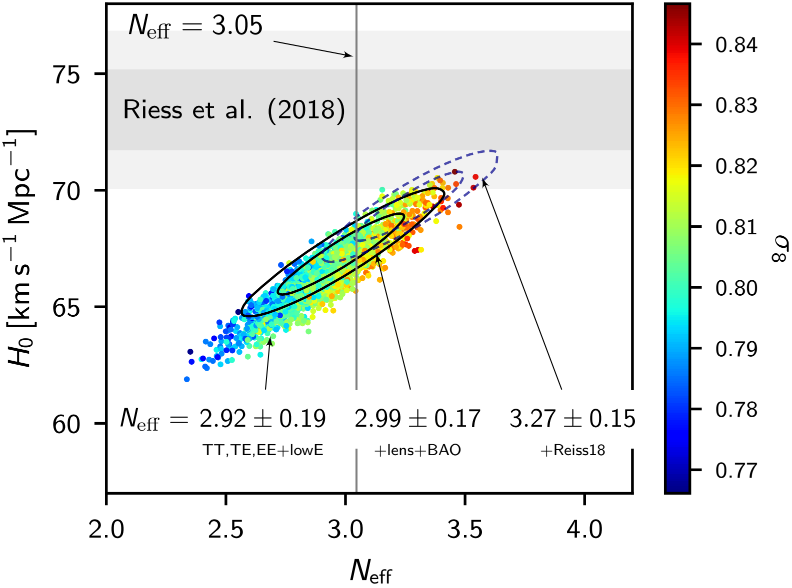
[in preparation]:
uncertainty from neutrino mixing and other parameters?

$\Delta N_{\mathrm{eff}} \simeq 10^{-4}$ at most



N_{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:

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

$$\downarrow$$

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

enters

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

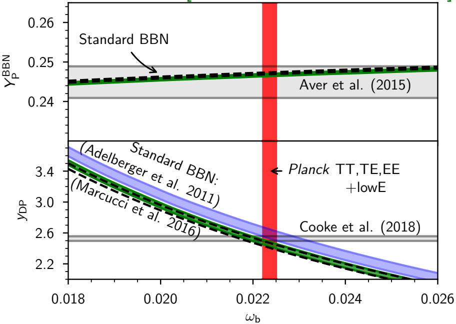
which controls element abundances

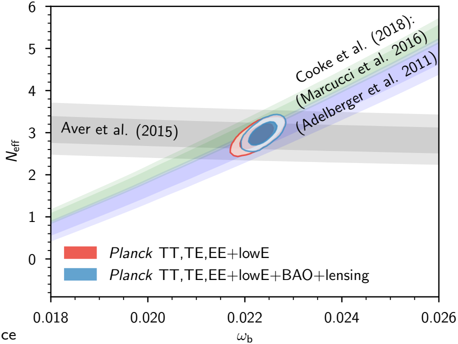
$\boxed{g_\star \text{ depends on } N_{\rm eff}}$

$$\downarrow$$

abundances depend on $N_{\rm eff}$

[Planck Collaboration, 2018]





G_F Fermi constant

G_N Newton constant

n, p: neutron, proton density number

$Q = 1.293$ MeV neutron–proton mass difference

$N_{\rm eff}$ and BBN

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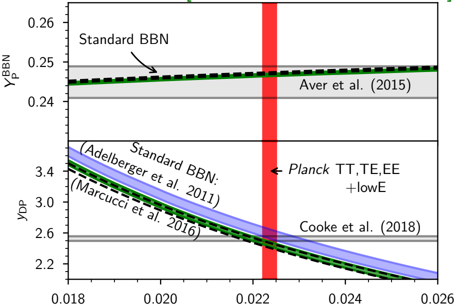
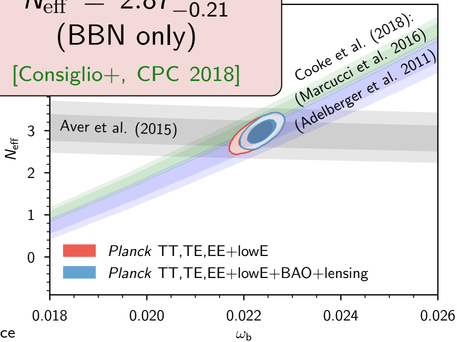


$N_{\rm eff} = 2.87^{+0.24}_{-0.21}$
(BBN only)
[Consiglio+, CPC 2018]



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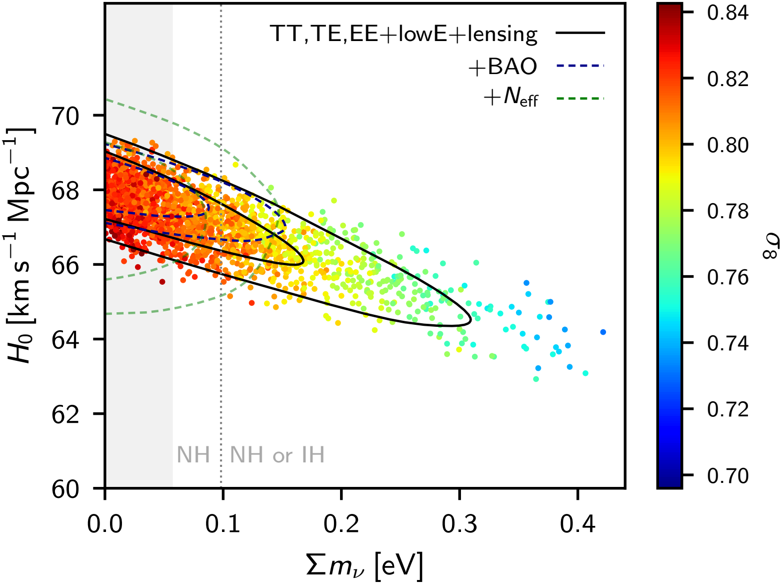
Σm_ν and CMB

[Planck Collaboration, 2018]



Ordering of ν masses

[de Salas+, Frontiers 5 (2018) 36]
http://globalfit.astroparticles.es/

Bayes theorem for models:

$$\boxed{p(\mathcal{M}|d) \propto Z_{\mathcal{M}}\pi(\mathcal{M})}$$

Bayesian evidence:

$$\boxed{Z_{\mathcal{M}} = \int_{\Omega_{\mathcal{M}}} \mathcal{L}(\theta)\,\pi(\theta)\,d\theta}$$

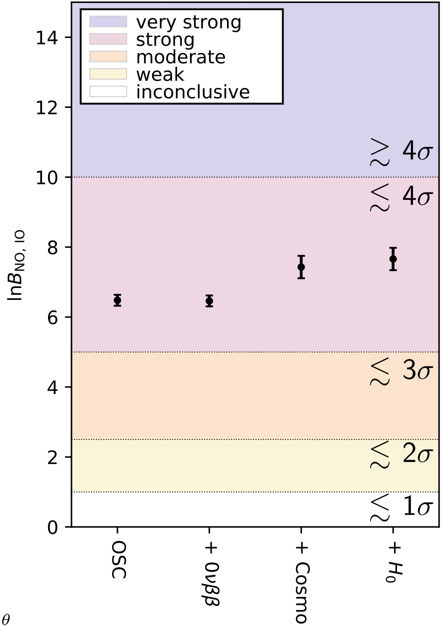
Bayes factor NO vs IO:

$$\boxed{B_{\mathrm{NO,IO}} = Z_{\mathrm{NO}}/Z_{\mathrm{IO}}}$$

Posterior probability:

$$\boxed{\begin{aligned} P_{\mathrm{NO}} &= B_{\mathrm{NO,IO}}/(B_{\mathrm{NO,IO}}+1) \\ P_{\mathrm{IO}} &= 1/(B_{\mathrm{NO,IO}}+1) \end{aligned}}$$

$N\sigma$ from $P_{\mathrm{NO}} = \mathrm{erf}(N/\sqrt{2})$



$\pi(\mathcal{M})$ model prior
$p(\mathcal{M}|d)$ model posterior
$\mathcal{L}(\theta)$ likelihood
$\Omega_{\mathcal{M}}$ parameter space, for parameters θ

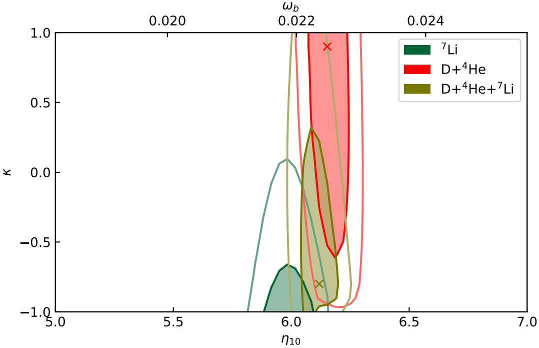
B

Bosonic neutrinos

(?!? what?)

Based on:

- JCAP 03 (2018) 050



Motivation

Neutrinos are fermions ⟶ they obey Fermi-Dirac statistics

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

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

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

"mixed"
distribution!

BE ← $\kappa_\nu = -1$ $\xleftrightarrow[\text{MB}]{\kappa_\nu = 0}$ $\kappa_\nu = +1$ → FD

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

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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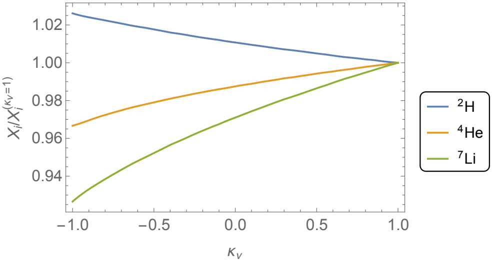
$\downarrow$

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

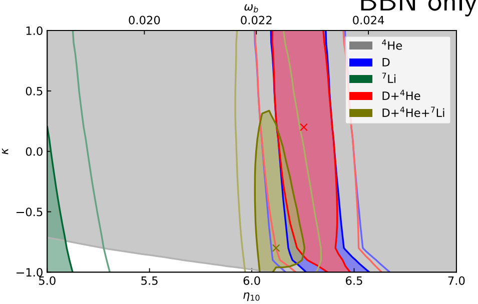
He or D alone cannot constrain κ_ν

Li problem drives ω_b down

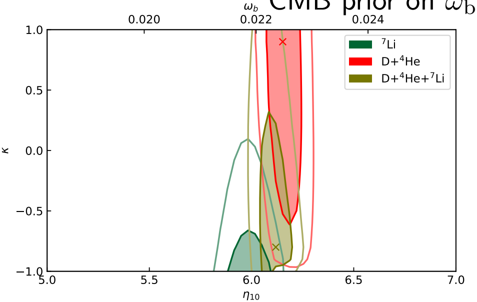
and κ_ν to -1

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]

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

κ_ν affects background evolution:

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

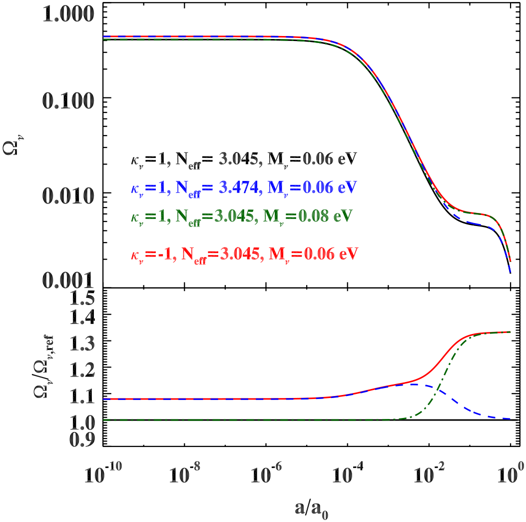
bosons: $\frac{\pi^2}{30} g_i\ T^4$

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

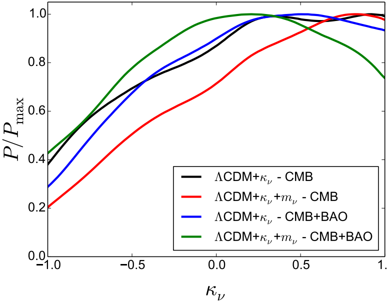
adding radiation (through κ_ν) and Ω_Λ alters H_0 and compensates a bit the larger mass

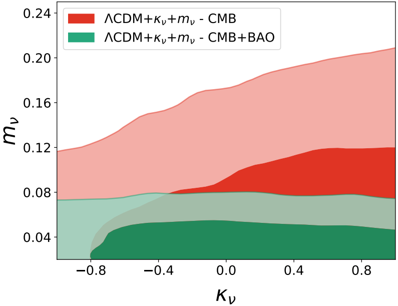
bounds: $\kappa_\nu \gtrsim -0.1$ at 68%

$-1 \leq \kappa_\nu \leq 1$ 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



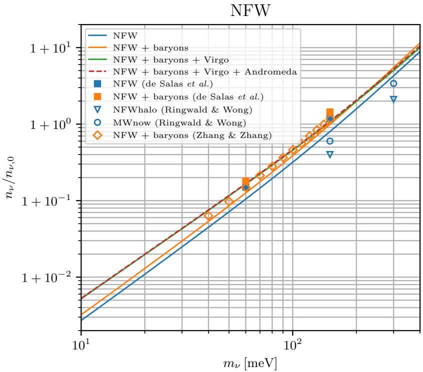


C Clustering in the local Universe

in collaboration with G. Parimbelli, from SISSA!

Based on:

- JCAP 09 (2017) 034
- arxiv:1910.13388



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 ⟶ How to compute it?

Idea from [Ringwald & Wong, 2004] ⟶ N-one-body= N × single ν simulations

→ each ν evolved from initial conditions at $z = 3$

→ spherical symmetry, coordinates $(r,\ \theta,\ p_r,\ l)$

→ 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"?

→ must sample all possible r, p_r, l

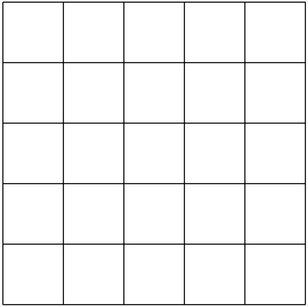
→ must include all possible νs that reach the MW (fastest ones may come from several (up to $\mathcal{O}(100)$) Mpc!)

given N ν:

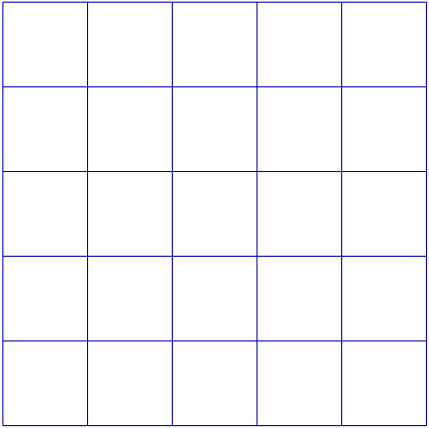
→ weigh each neutrinos

→ reconstruct final density profile with kernel method from [Merritt&Tremblay, 1994]

Forward-tracking and back-tracking



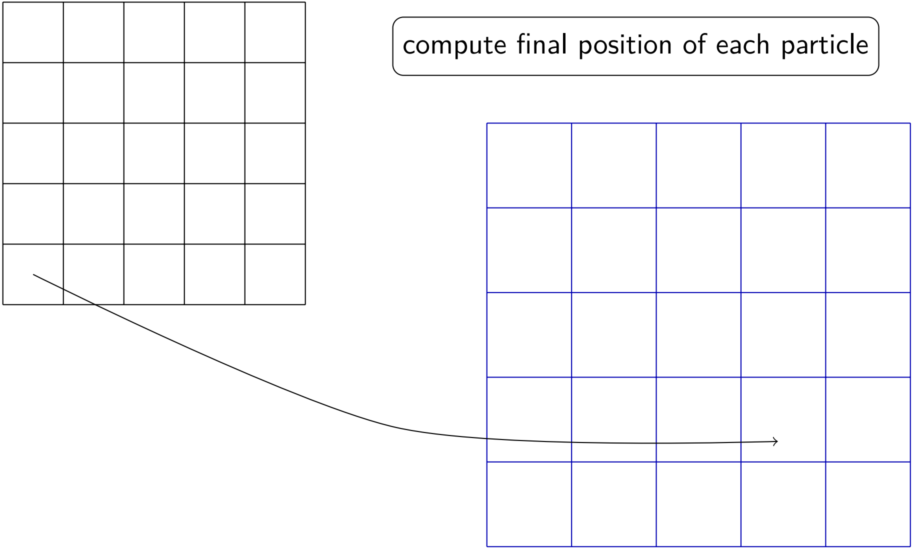
initial phase space, $z = 4 \longrightarrow$ homogeneous Fermi-Dirac distribution



final phase space, $z = 0$

Forward-tracking and back-tracking

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



compute final position of each particle

final phase space, $z = 0$

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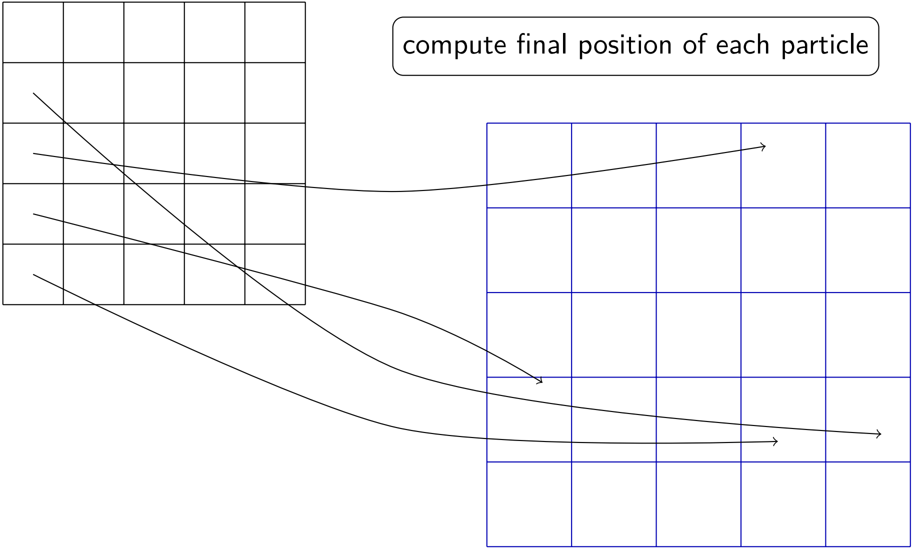
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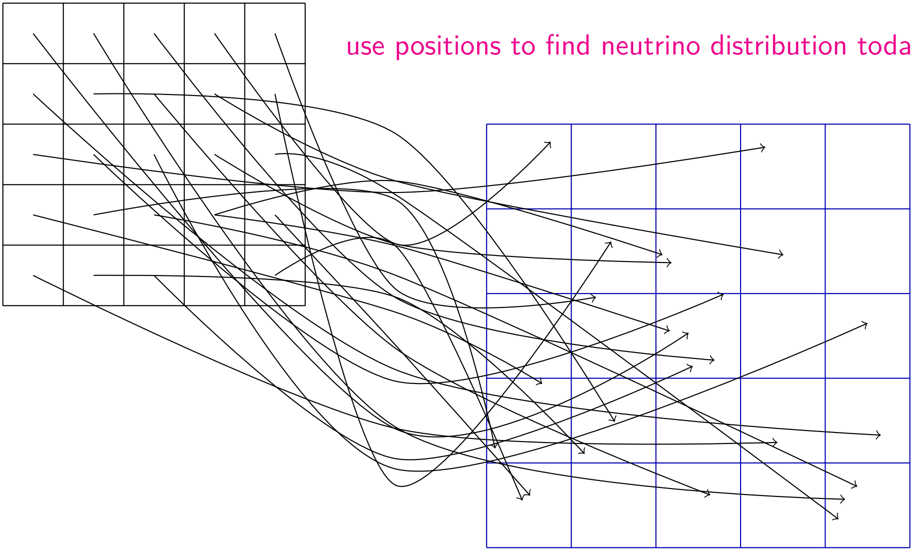

use positions to find neutrino distribution today

final phase space, $z = 0$

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!

final phase space, $z = 0$

Forward-tracking and back-tracking

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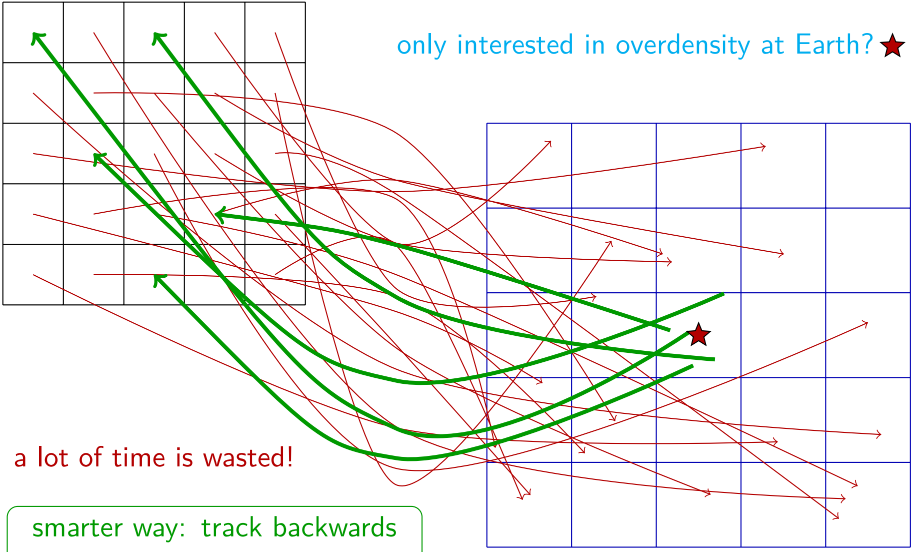

only interested in overdensity at Earth? ★

a lot of time is wasted!

smarter way: track backwards
only interesting particles!

final phase space, $z = 0$

Advantages of tracking back

[arxiv:1910.13388]

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

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[arxiv:1910.13388]

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

Second advantage: no need to use spherical symmetry!

Forward-tracking

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

with full grid would require 3+3 dimensions!

Impossible to relax
spherical symmetry!

Back-tracking

"Initial" conditions only described
by 3D in momentum

(position is fixed, apart for checks)

can do the calculation with
any astrophysical setup

Advantages of tracking back

[arxiv:1910.13388]

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

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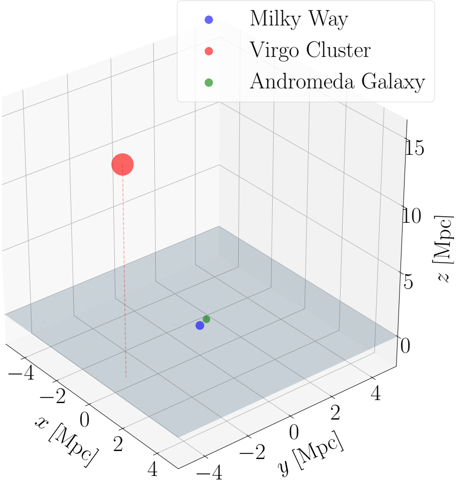
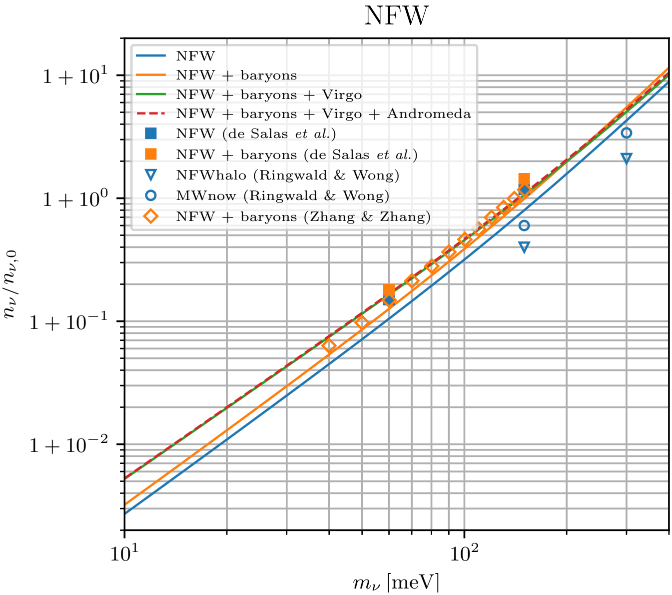


Clustering results with back-tracking

[arxiv:1910.13388]

In comparison with previous results:



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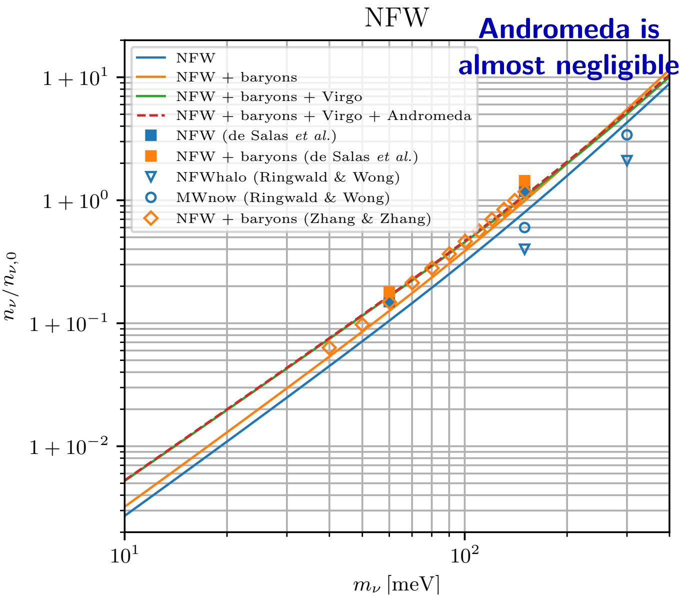

Andromeda is almost negligible

Clustering results with back-tracking

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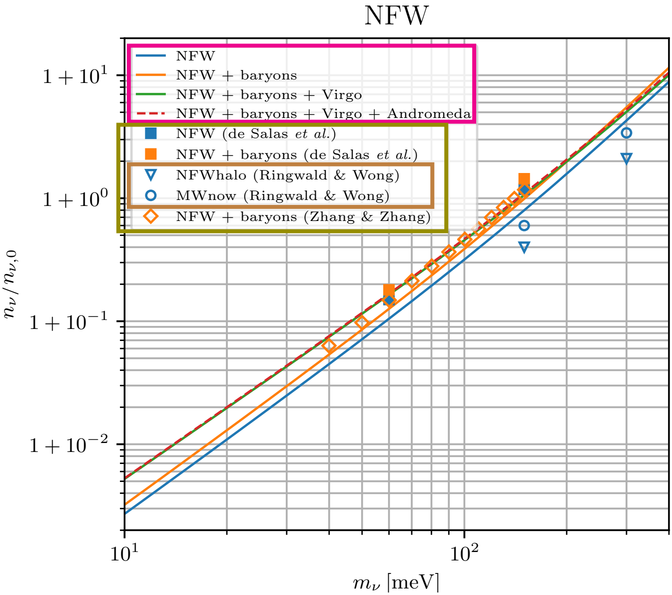

Warning: NFW is not the same for all the cases!

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

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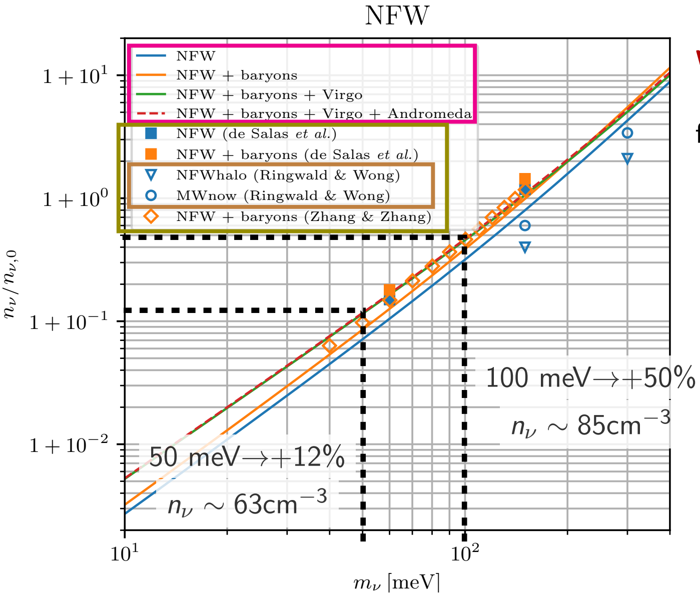

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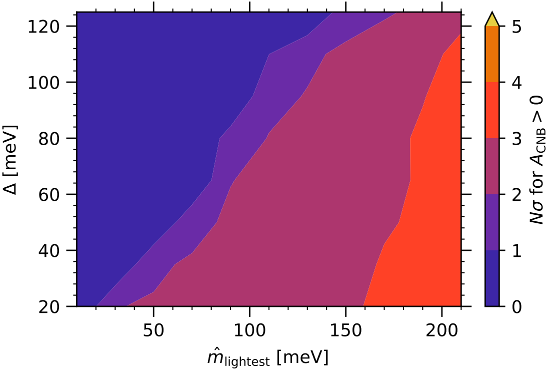
D Direct Detection

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

Based on:

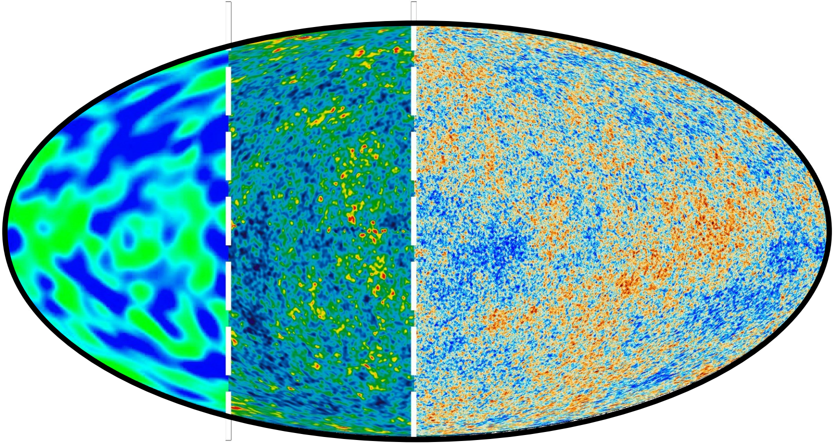
- arxiv:1808.01892
- JCAP 07 (2019) 047



The oldest picture of the Universe

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

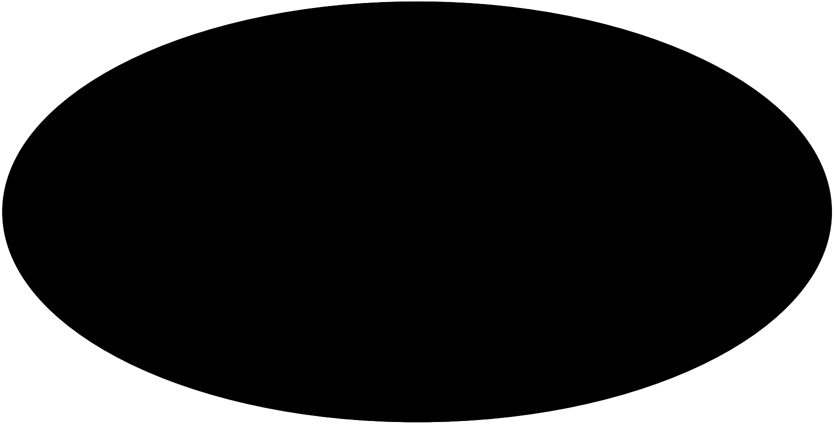
COBE (1992) WMAP (2003) Planck (2013)



The oldest picture of the Universe

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

$\ldots \rightarrow 2019 \rightarrow \ldots$



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

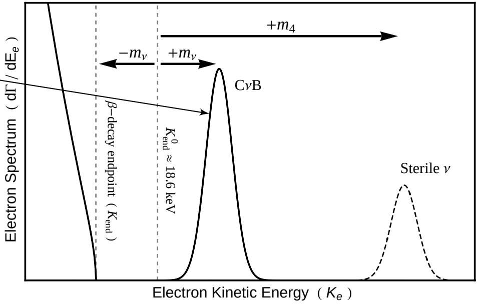
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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]

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

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

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$\bar{\sigma}$ cross section, N_T number of tritium atoms in the source (PTOLEMY: 100 g), $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

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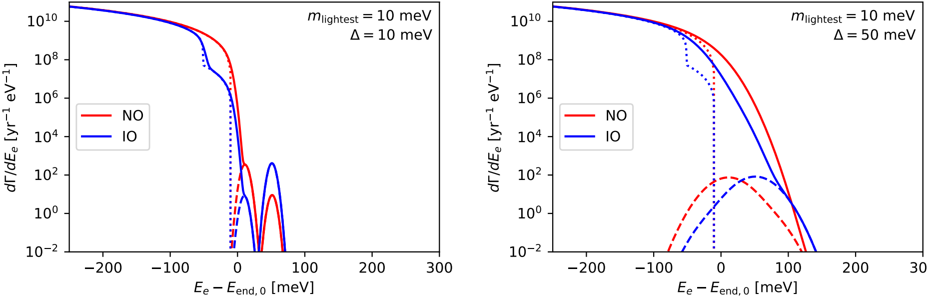

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PTOLEMY

[PTOLEMY LoI, arxiv:1808.01892]

PonTecorvo 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

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

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?

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

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(without clustering)

Dirac and Majorana neutrinos

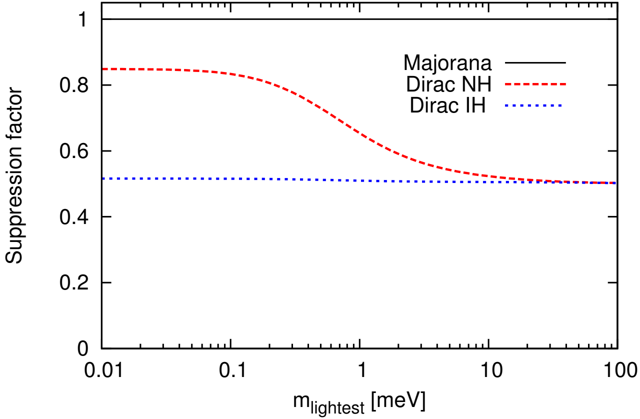
[Roulet+, JCAP 10 (2018) 049]

direct detection through $\nu_e + ^3\mathrm{H} \longrightarrow e^- + ^3\mathrm{He}$

only neutrinos with correct chirality can be detected!

non-relativistic **Majorana** case: ν and $\bar{\nu}$ cannot be distinguished!

expect more events for the **Majorana** than for Dirac case



Dirac normal or inverted ordering differ because lighter ν_1 and ν_2 in NH are relativistic

↓

almost indistinguishable from **Majorana**

Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

relative error on $m_{\rm lightest}$

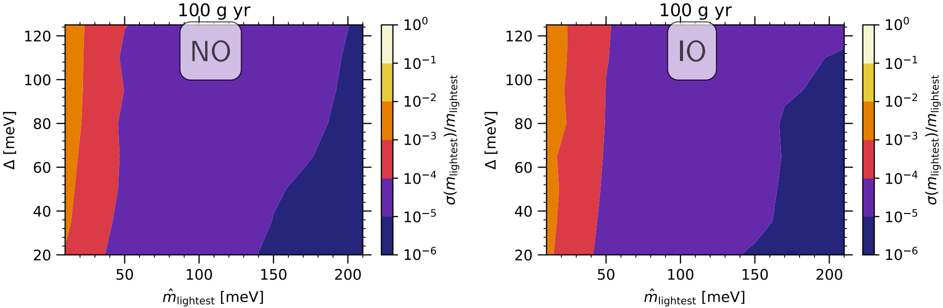
as a function of $\hat{m}_{\rm lightest}$, Δ

Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

relative error on m_lightest
as a function of $\hat{m}_\mathrm{lightest}$, Δ



wonderful precision in determining the neutrino mass

(well, yes, with 100 g of tritium...)

Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

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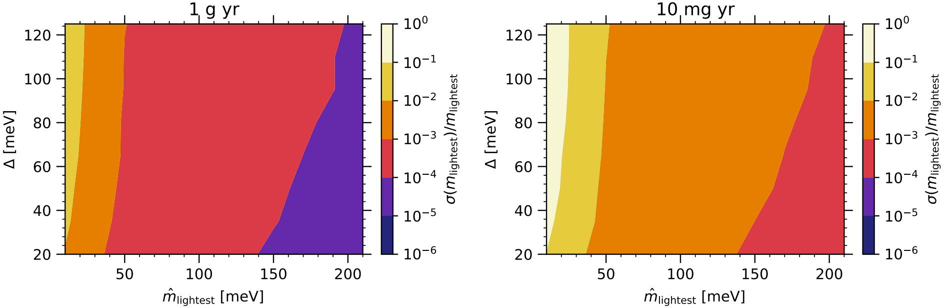

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(mass detection already with 10 mg of tritium!)

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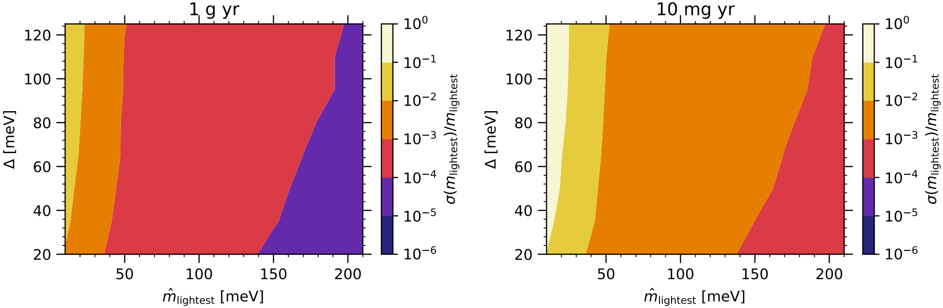


wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

Δ has almost no impact

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

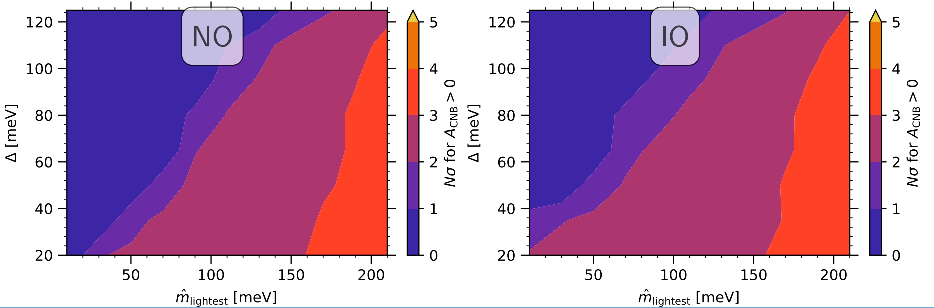
using the definition:

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

if $\boldsymbol{A}_{\bf CNB} > 0$ 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. . .)

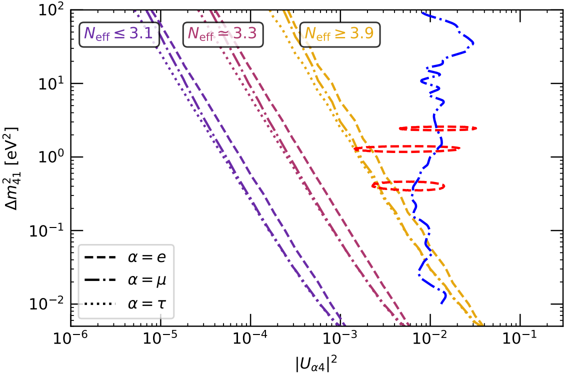
seriously, I cannot go
through the entire alphabet in one hour!

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 (2)
- JCAP 07 (2019) 014
- in preparation (3)
- JCAP 07 (2019) 047



Short Baseline (SBL) anomaly

[SG+, JPG 43 (2016) 033001]

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 $\bar{\nu}_\mu \to \bar{\nu}_e$, 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]

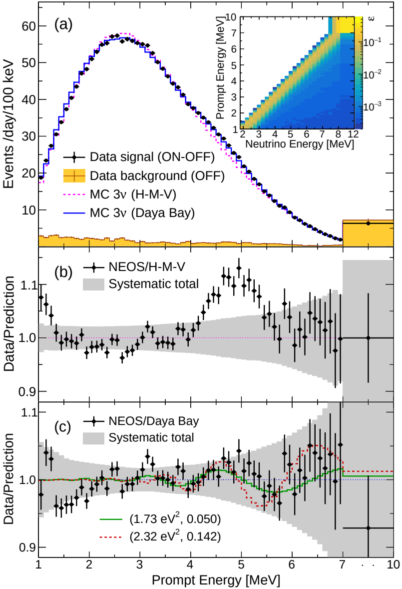
MiniBooNE See next

Possible explanation:

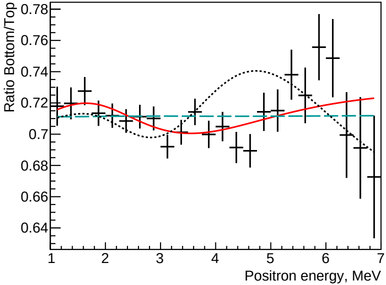
Additional squared mass difference $\Delta m^2_{\text{SBL}} \simeq 1\ \mathrm{eV}^2$

Recent results. . .

[NEOS, PRL 2017]



[DANSS, PLB 2018]

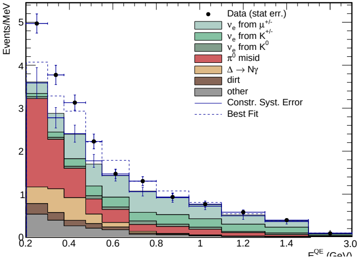


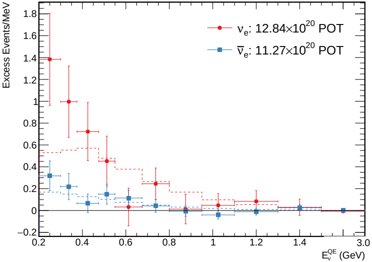
first *model independent* indications in favor of SBL oscillations

DANSS alone gives a $\Delta\chi^2 \simeq 13$ in favor of a light sterile neutrino!

Recent results. . .

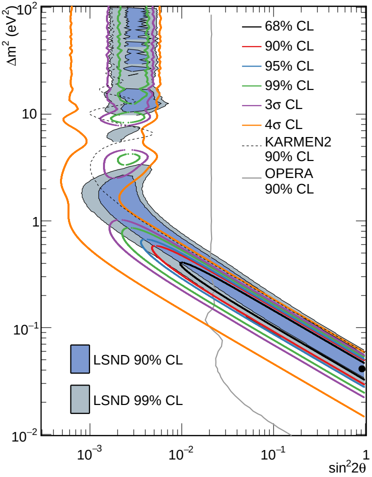
[MiniBooNE, PRL 2018]





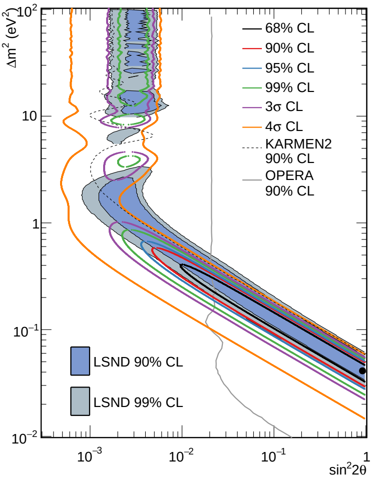
Recent results. . .

[MiniBooNE, PRL 2018]

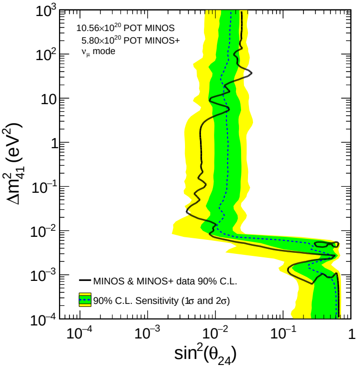


Recent results. . .

[MiniBooNE, PRL 2018]



[MINOS+, PRL 2019]

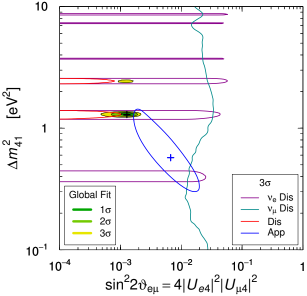


MiniBooNE is incompatible with MINOS+ when combined with NEOS&DANSS

APP – DIS tension in 2019

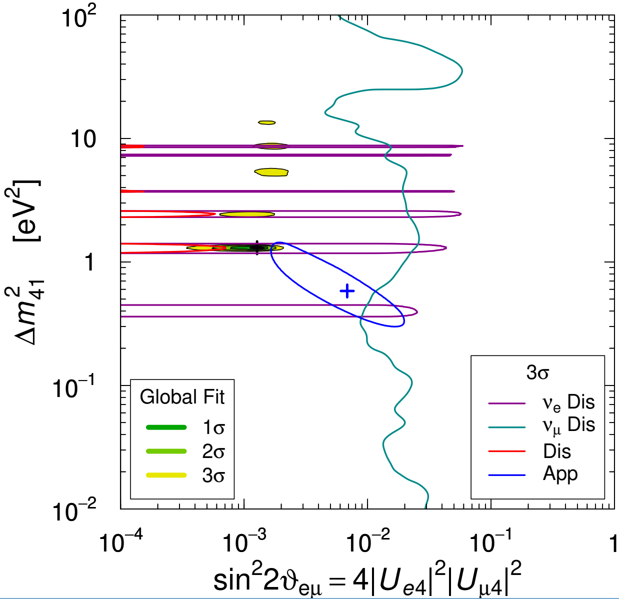
[SG+, in preparation]

Status just after Neutrino 2018:



MINOS+ update, new data including MiniBooNE (all bins)

Status in early 2019



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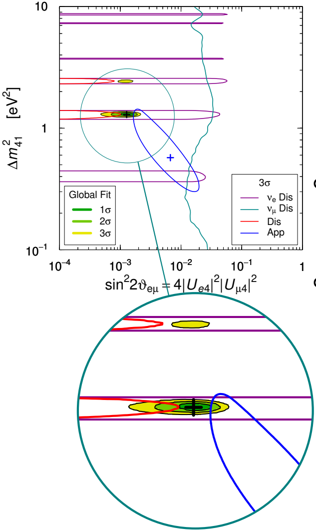

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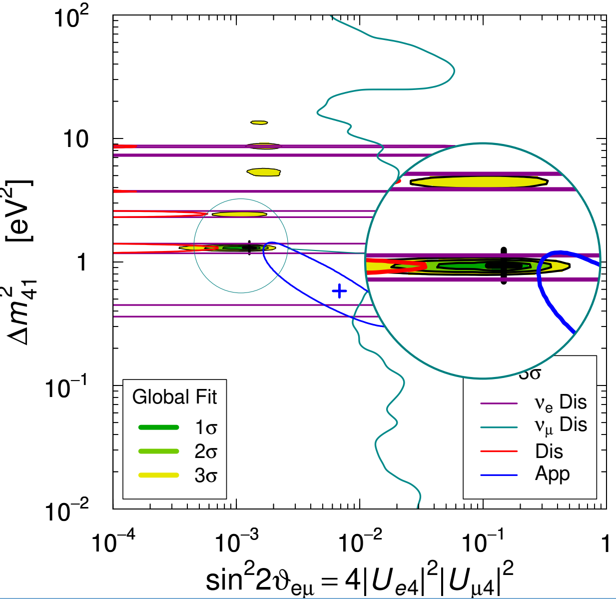

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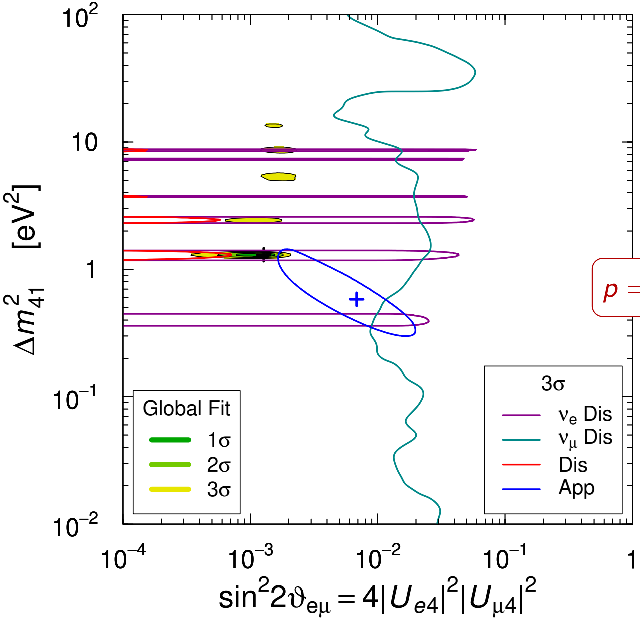
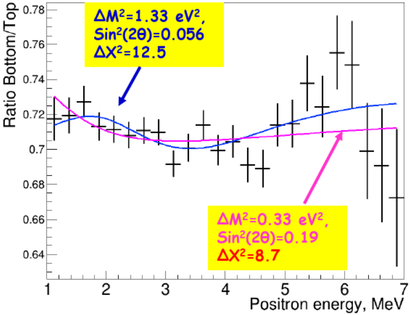


$p = 3 \times 10^{-9}$

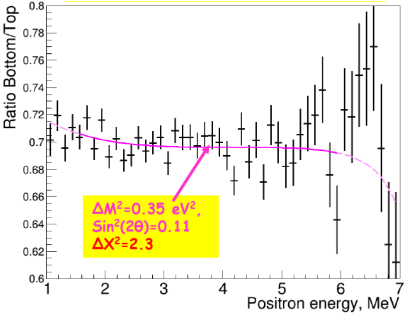
DANSS in 2019

[Danilov@EPS-HEP, 2019]

old data



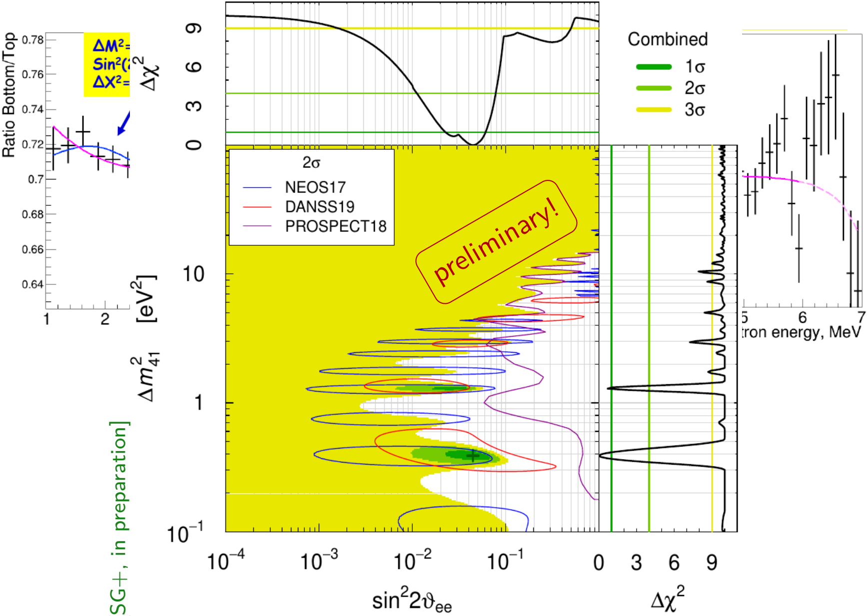
new data



New analysis also considers systematics!

DANSS in 2019

[Danilov@EPS-HEP, 2019]

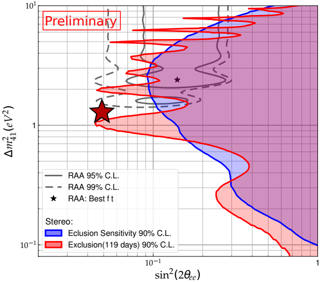


[SG+, in preparation]

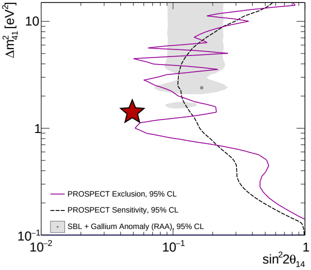
More to come...

★ = 2018 DANSS+NEOS best fit
[SG et al., PLB 782 (2018) 13]

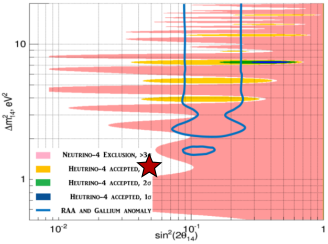
[STEREO, arxiv:1905.11896]



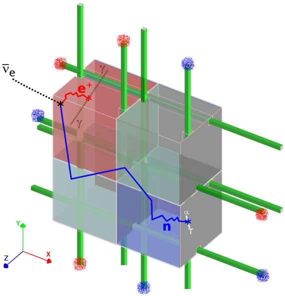
[PROSPECT, PRL 2018]



[Neutrino-4, PZETF 2019]



[SoLiD, JINST 2018]



Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos $\longrightarrow$ new oscillations in the early Universe

sterile $\Longrightarrow$ no weak/em interactions in the thermal plasma

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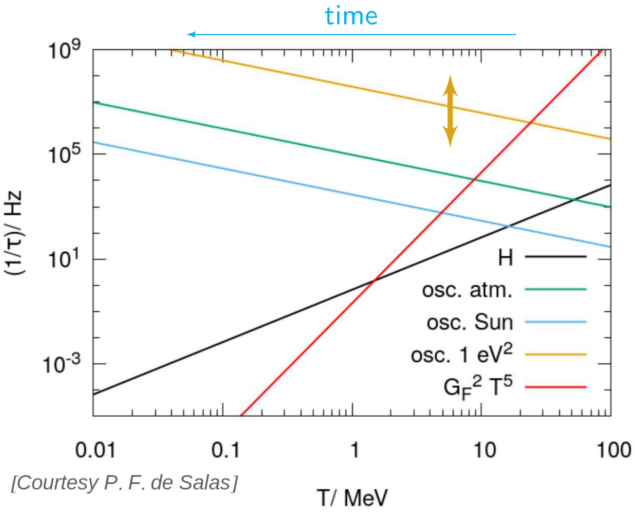

[Courtesy P. F. de Salas]

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

later oscillations

$\Downarrow$

less time before ν decoupling!

Sterile neutrino in the early universe

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Four neutrinos ⟶ new oscillations in the early Universe

sterile ⟹ no weak/em interactions in the thermal plasma

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when are they enough to allow full equilibrium of active-sterile states?

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

no sterile production

active&sterile in equilibrium

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

[Dolgov&Villante, 2004]

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

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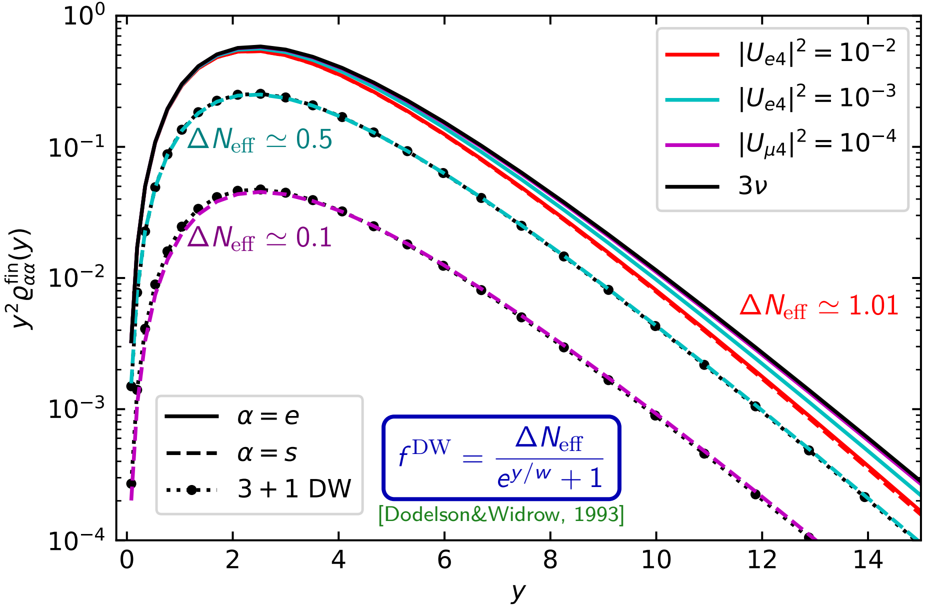
Full calculation: use numerical code!

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

Momentum distributions

[SG+, JCAP 07 (2019) 014]

$\Delta m^2_{41} = 1.29\ \text{eV}^2$, other $|U_{\beta 4}|^2 = 0$, $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm active}$



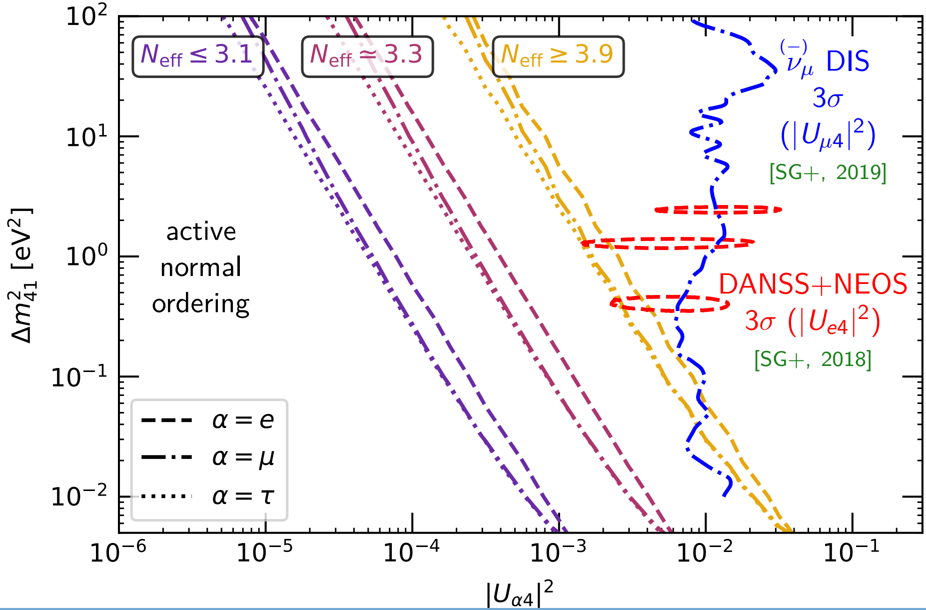
$$\boxed{f^{\rm DW} = \frac{\Delta N_{\rm eff}}{e^{y/w}+1}}$$

[Dodelson&Widrow, 1993]

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

[SG+, JCAP 07 (2019) 014]

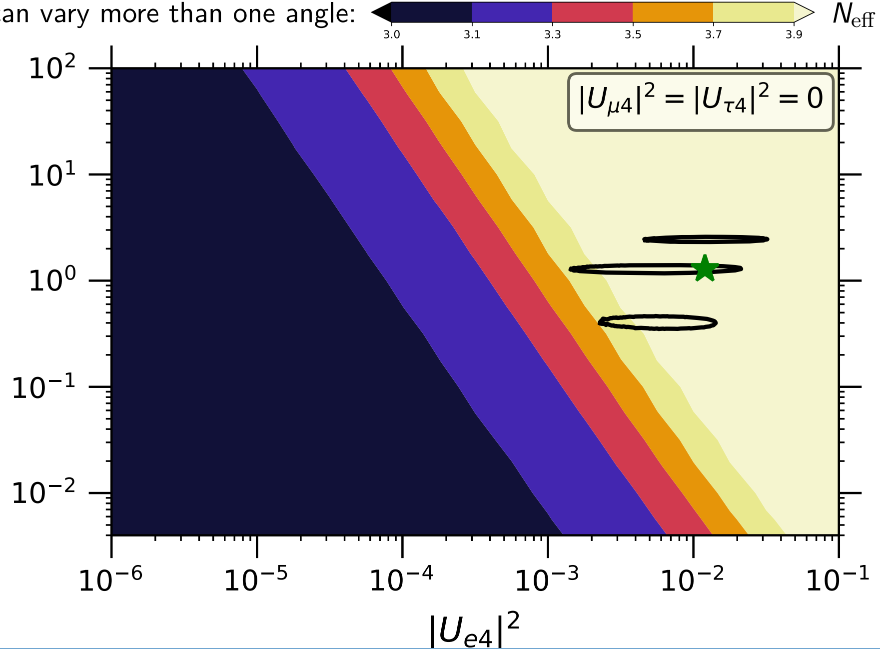
Only vary one angle and fix two to zero: do they have the same effect?



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

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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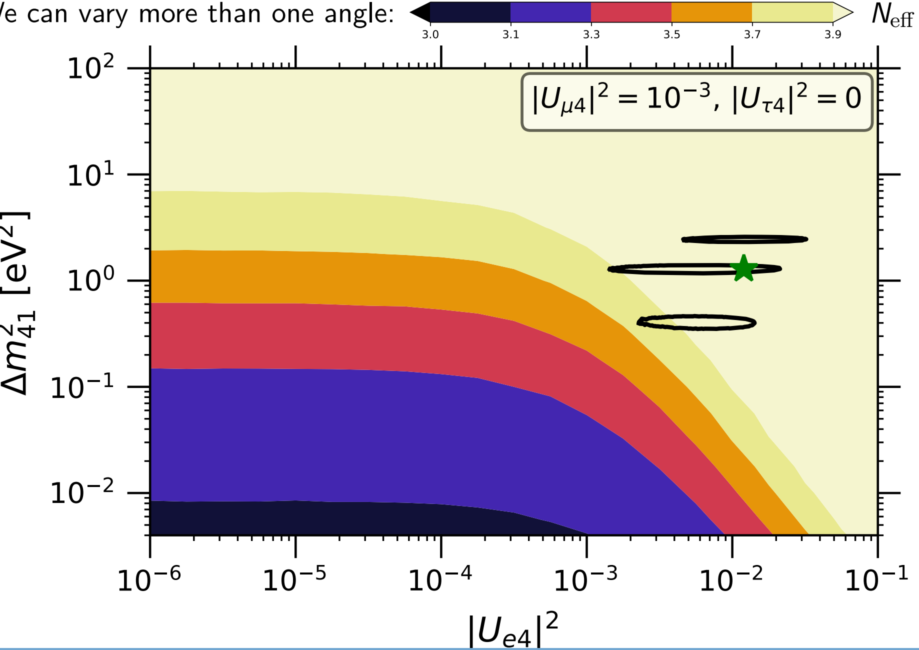

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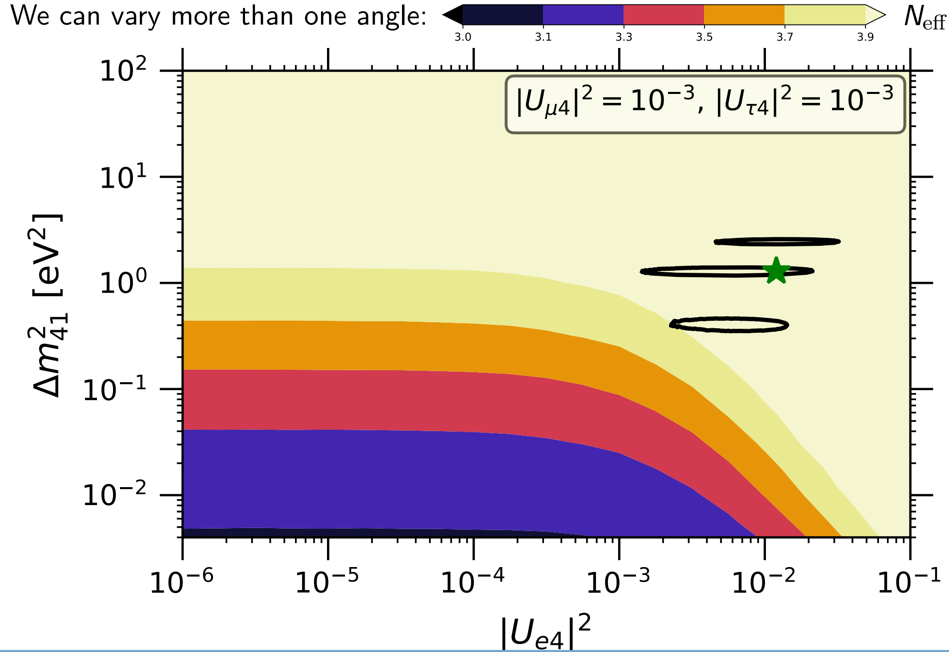
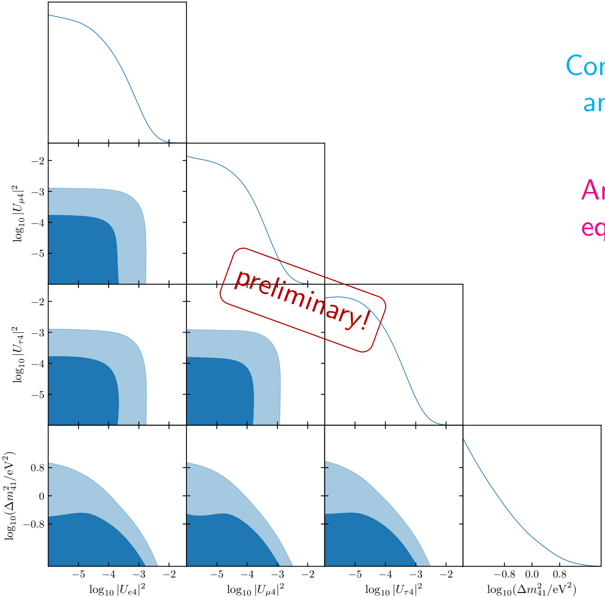


Cosmological constraints on $|U_{\alpha4}|^2$

[in preparation]

Use multi-angle results from `FortEPiaNO` to derive constraints on $|U_{\alpha4}|^2$:



Constraints come from N_{eff}
and late-time density Ω_s

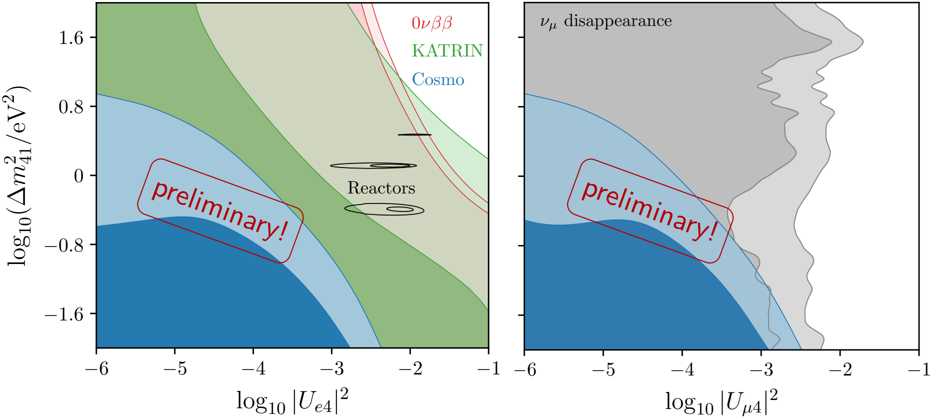
Angles $|U_{\alpha4}|^2$ are almost
equivalent for cosmology

Comparing constraints

[in preparation]

Cosmological constraints are stronger than most other probes

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



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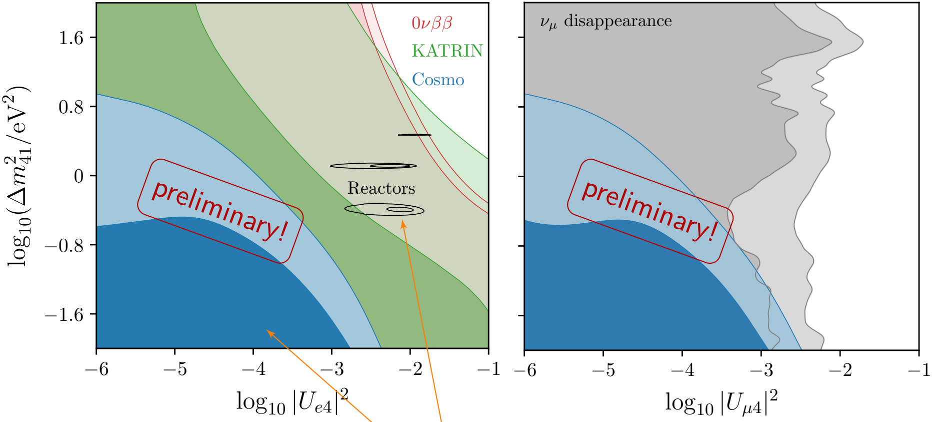


Warning: tension between reactor experiments and CMB bounds!

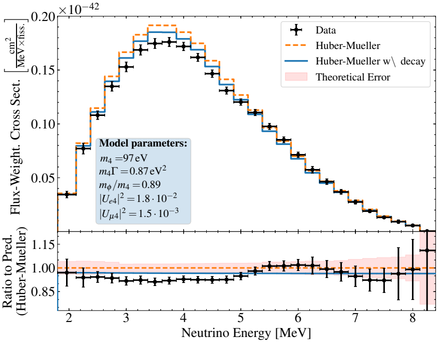
Can new physics solve the anomalies and tensions?

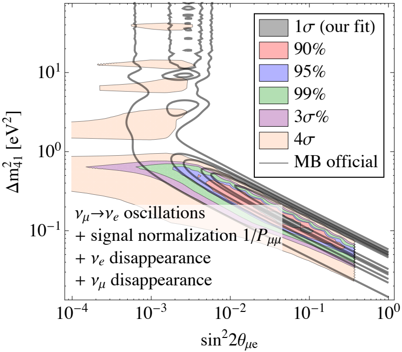
Many attempts to explain LSND/MiniBooNE anomalies,
APP vs DIS, oscillations vs cosmo tensions with new physics

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 $m_\phi \lesssim m_4$

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





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

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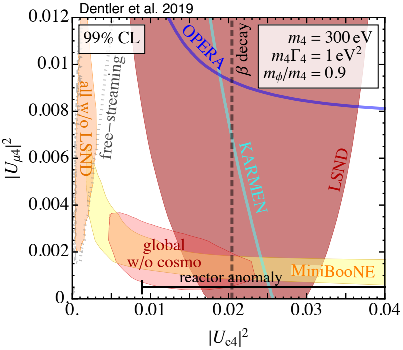

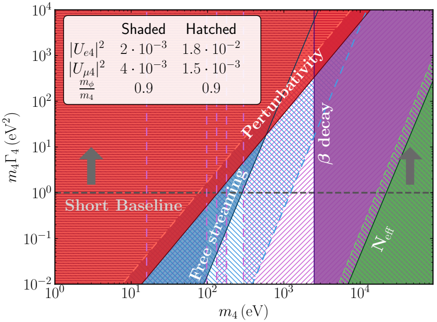

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$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2} G_F \epsilon^{fC}_{\alpha\beta} [\overline{\nu_\alpha} \gamma^\rho P_L \nu_\beta] \left[\bar{f} \gamma_\rho P_C f\right]$$

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

Non-standard interactions (NSI) involving ν_s

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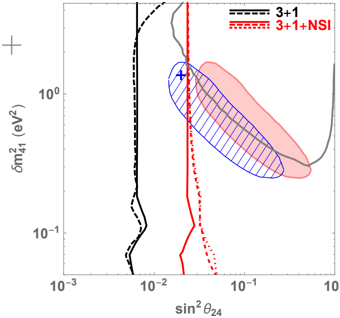
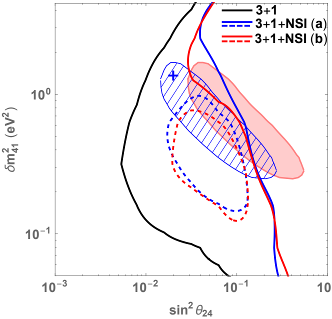
Non-standard interactions (NSI) involving ν_s

MINOS+
vs APP





IceCube/
DeepCore
vs APP

PTOLEMY and the ν_4

[PTOLEMY, JCAP 07 (2019) 047]

$$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \mathcal{O}(10)/\mathrm{yr} \qquad \boxed{\Gamma_4 \simeq \Delta N_{\rm eff}\, |U_{e4}|^2\, f_c(m_4)\, \Gamma_{\rm CNB}}$$

[SG+, PLB 2018]

$$m_4 \simeq 1.15\ \mathrm{eV}$$

$$|U_{e4}|^2 \simeq 0.01$$

$$\Delta N_{\rm eff} = ??$$

[de Salas+, 2017]

$$f_c(m_4) = \mathcal{O}(10^2)$$

Γ_4 depends probably on new physics!

PTOLEMY and the ν_4

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$m_4 \simeq 1.15$ eV

$|U_{e4}|^2 \simeq 0.01$

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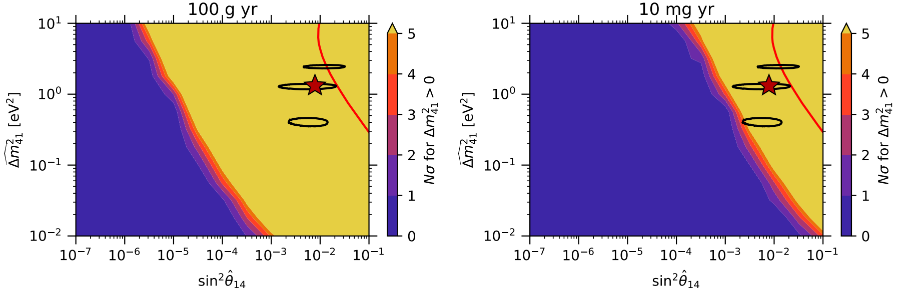
[de Salas+, 2017]

$f_c(m_4) = \mathcal{O}(10^2)$

$\boxed{\Gamma_4 \text{ depends probably on new physics!}}$

$\boxed{\text{Still possible to measure mass/mixing through } \beta \text{ spectrum}}$



black: DANSS+NEOS 3σ (2018)

red: KATRIN 90% forecast

Z Conclusions

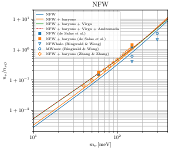
almost there!

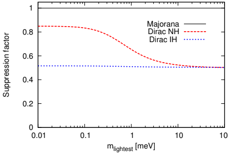
©Barbara Cesanelli

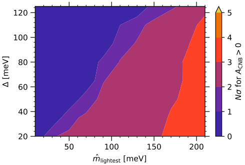
What do we learn from relic neutrinos?

D

Direct detection - wonderful opportunities for the future

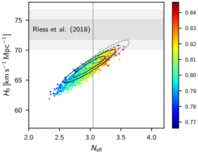


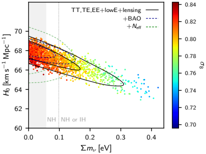


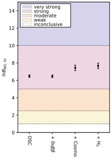


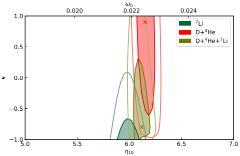
I

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



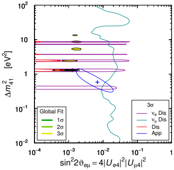


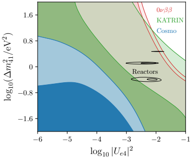


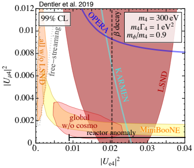


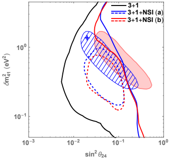
N

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





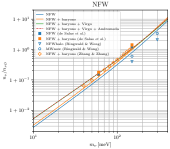


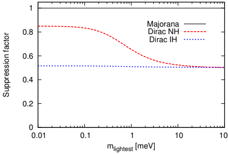


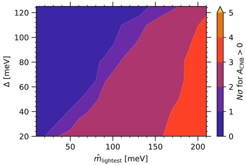
What do we learn from relic neutrinos?

D

Direct detection - wonderful opportunities for the future

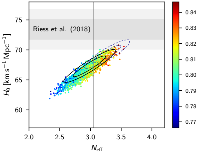


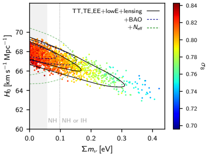


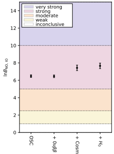


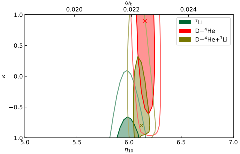
I

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









N

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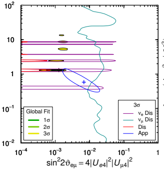

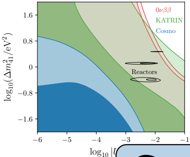

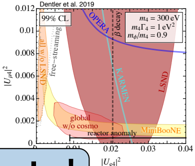

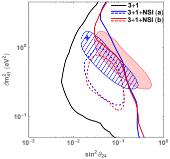

G

Grazie!