"la Caixa" Foundation
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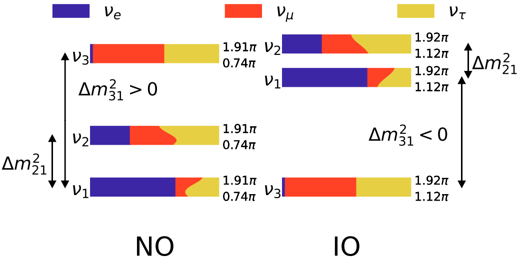
Relic neutrinos: decoupling and direct detection perspectives

CRAG Seminar, University of Sheffield, 08/03/2024

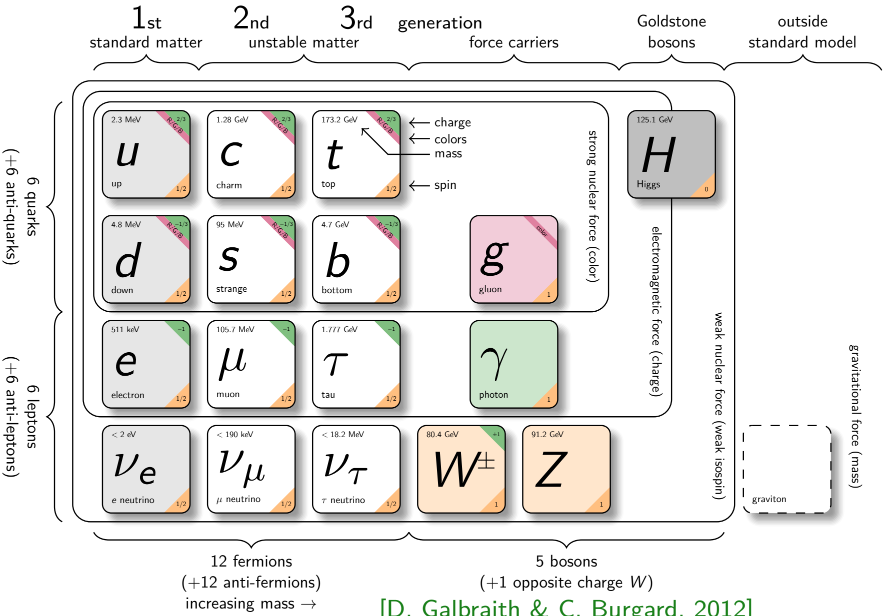
N Neutrinos

Based on:

- JHEP 02 (2021) 071 and update



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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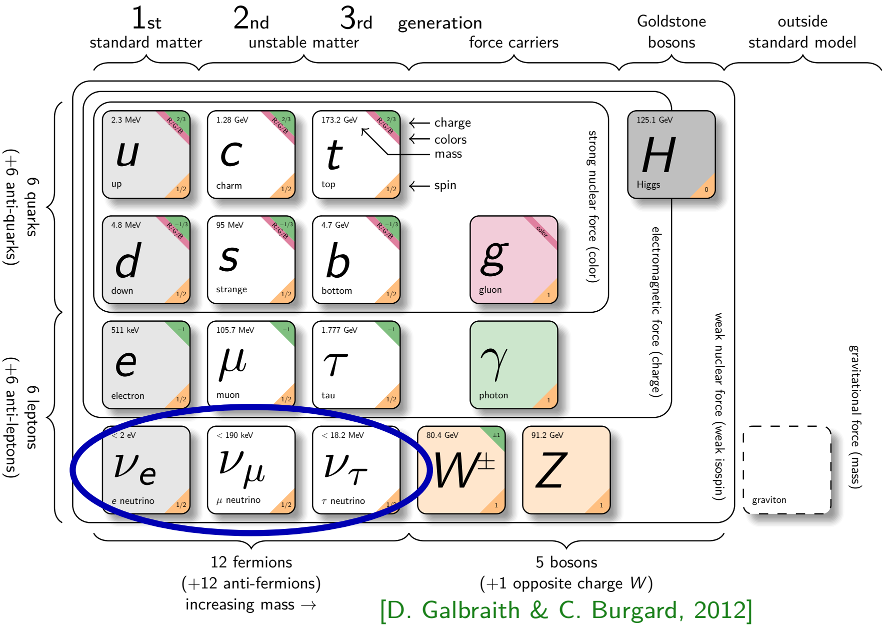
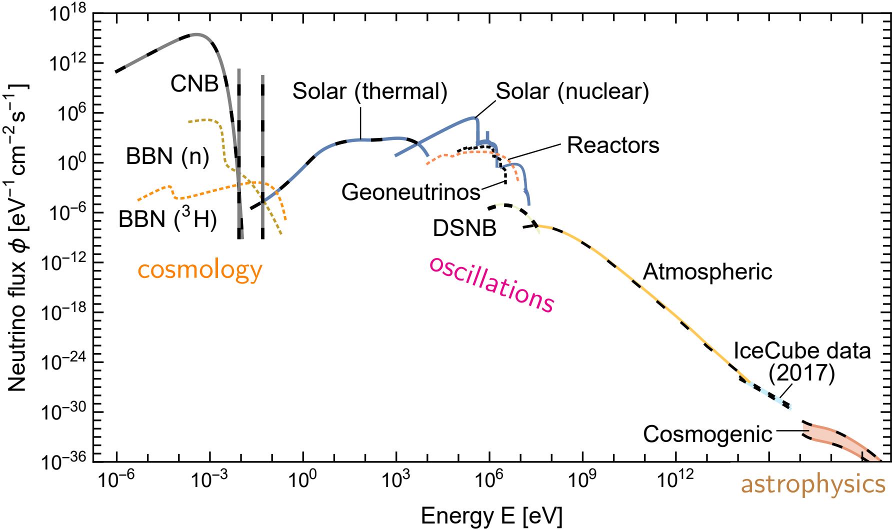


[D. Galbraith & C. Burgard, 2012]

Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]

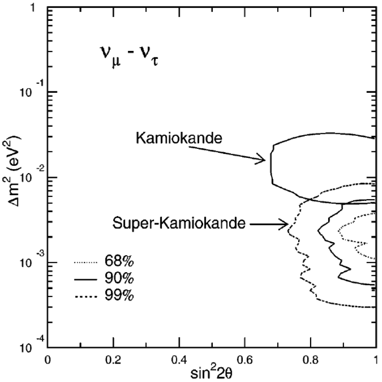


neutrinos at all energies provide valuable information!

Neutrino oscillations

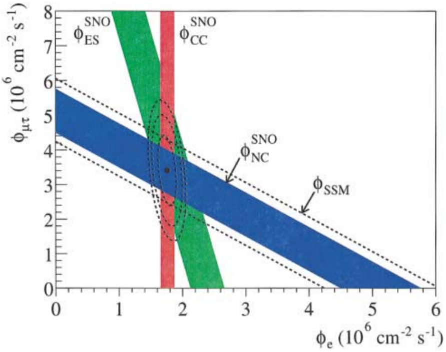
Major discoveries:

[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

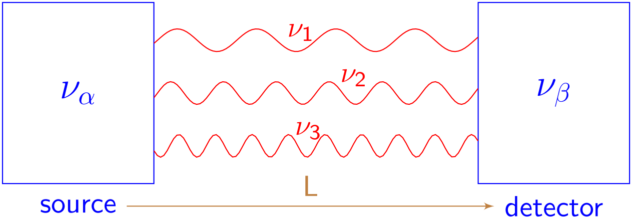
Two neutrino bases

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 ⟶ $t = L$

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

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

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

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

mainly atmospheric and LBL accelerator disappearance

mainly LBL reactors and LBL accelerator appearance

mainly solar and VLBL reactors

Majorana phases irrelevant for oscillation experiments

Relevant for example in neutrinoless double-beta decay

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

LBL = long baseline; VLBL = very long baseline;

Three Neutrino Oscillations

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

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

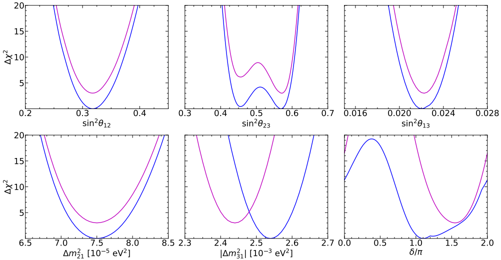
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.54 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.44 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$10\sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2\sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\mathrm{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO})$$
$$10\sin^2(\theta_{23}) = 4.55 \pm 0.13 U 5.71 \pm 0.12\ (\mathrm{NO})$$
$$= 5.71^{+0.14}_{-0.17}\ (\mathrm{IO})$$

$$\delta/\pi = 1.10^{+0.27}_{-0.12}\ (\mathrm{NO})$$
$$= 1.54 \pm 0.14\ (\mathrm{IO})$$



mass ordering still unknown

δ still unknown

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

Neutrinos and their masses

[de Salas+, Frontiers 5 (2018) 36]

Normal ordering (NO)

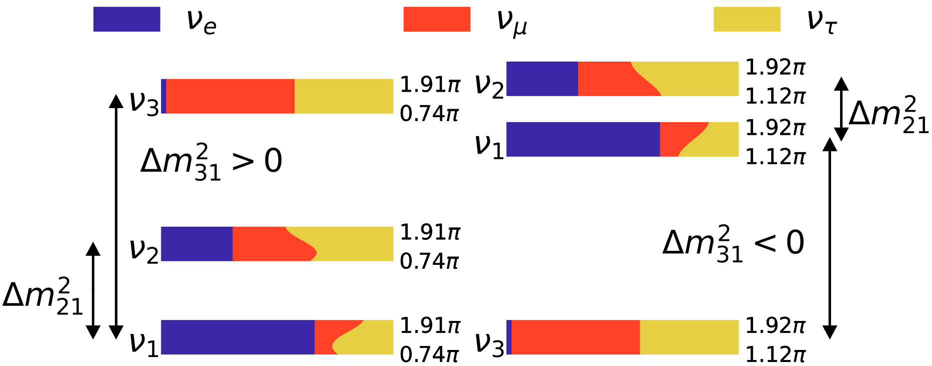
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV



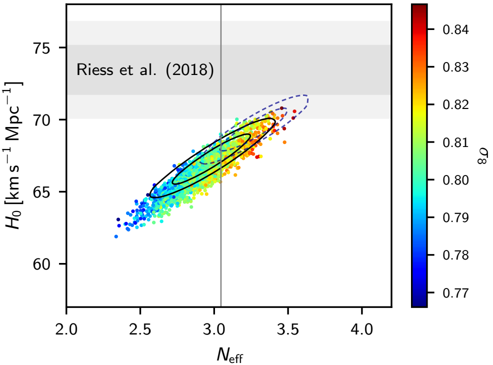
Absolute scale unknown!

Can we constrain the mass ordering using bounds on $\sum m_\nu$?

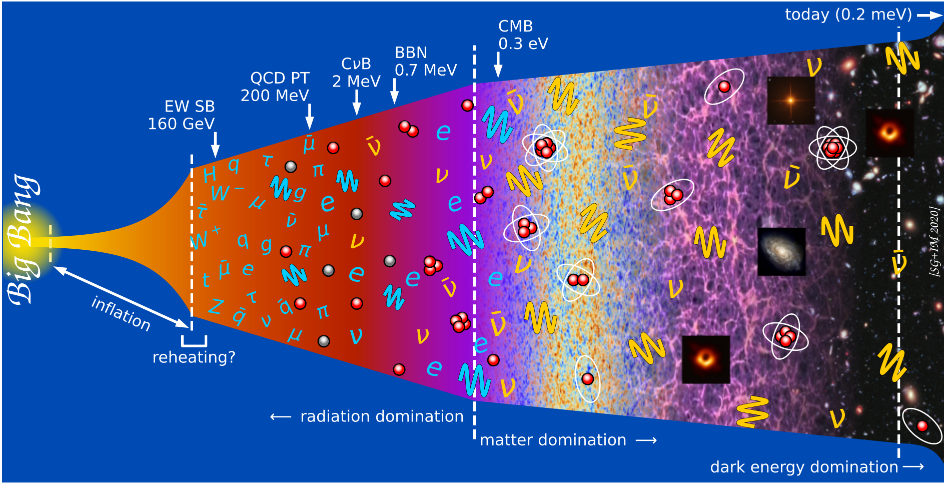
E Neutrinos in the Early Universe

Based on:

- Planck 2018
- JCAP 04 (2021) 073
- PRD 106 (2022) 043540



History of the universe



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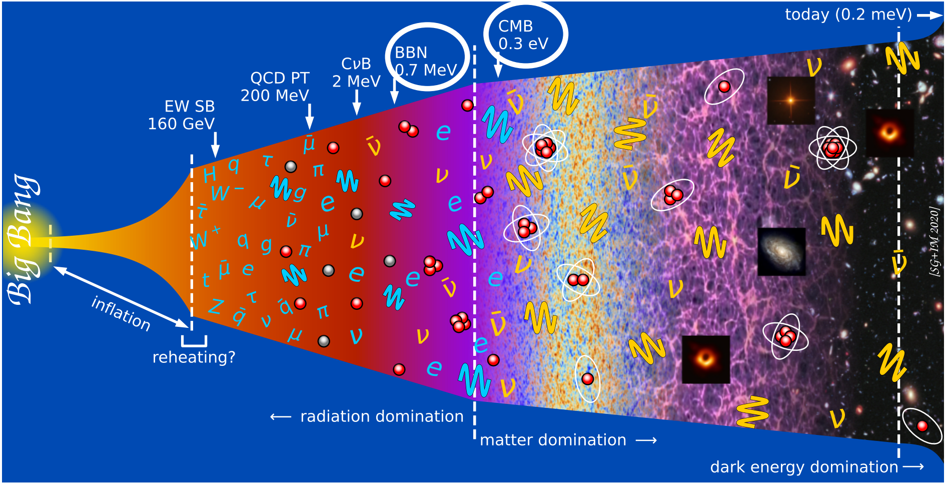
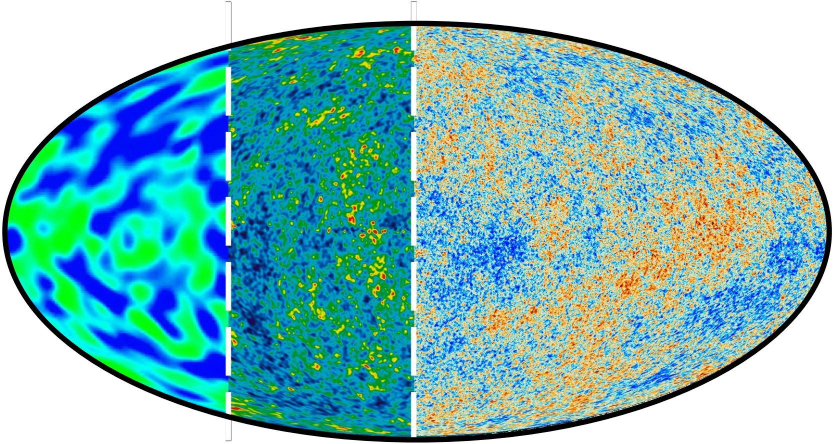


The oldest picture of the Universe

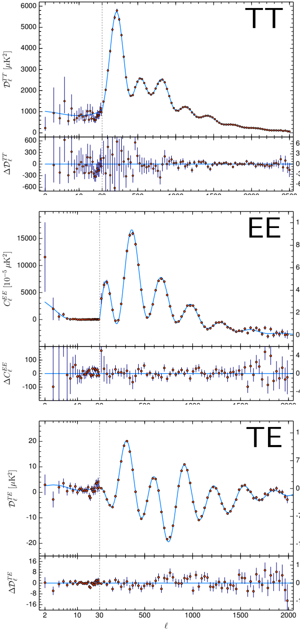
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

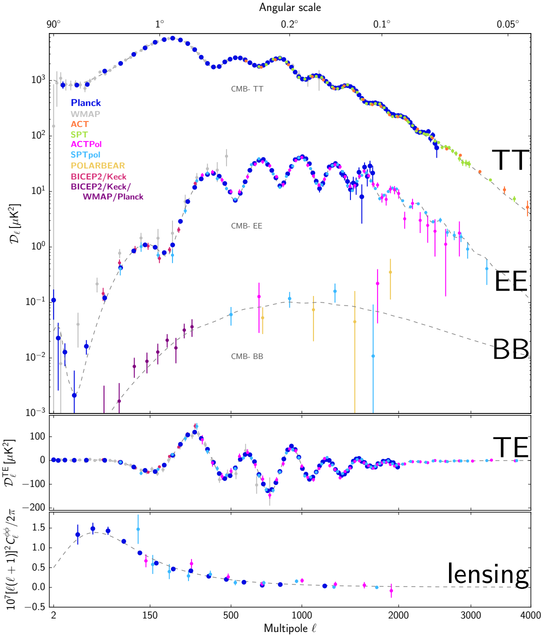
COBE (1992) WMAP (2003) Planck (2013)



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

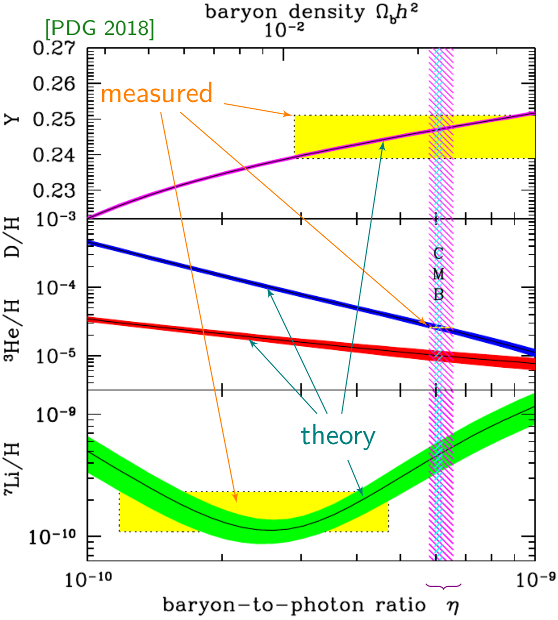
much earlier than CMB!

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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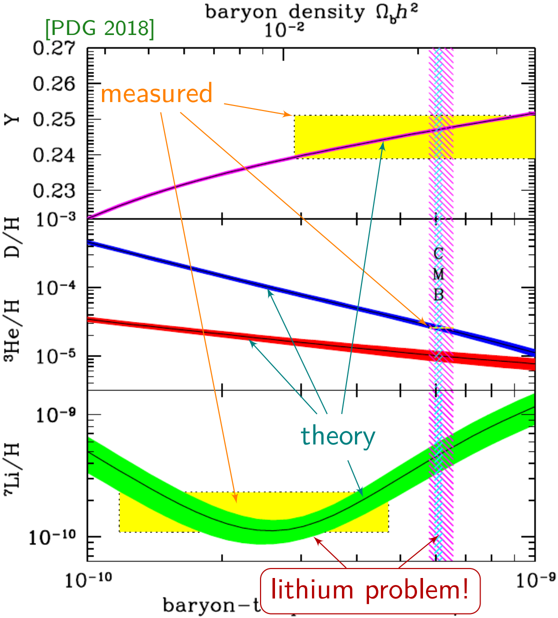
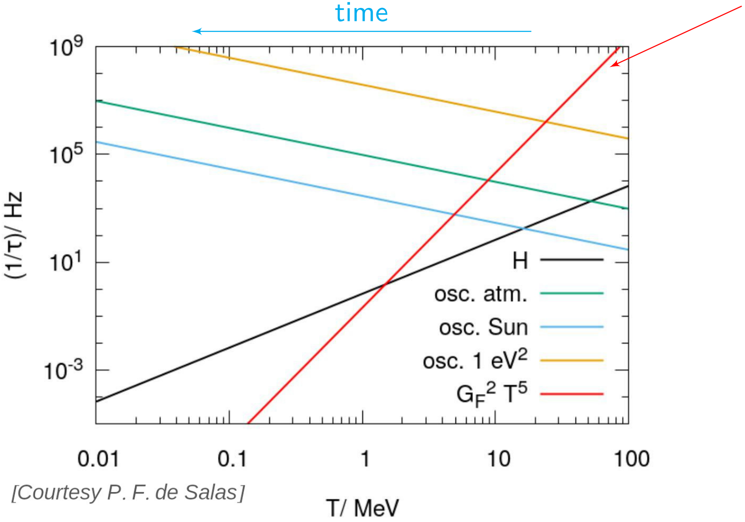


BBN concordance

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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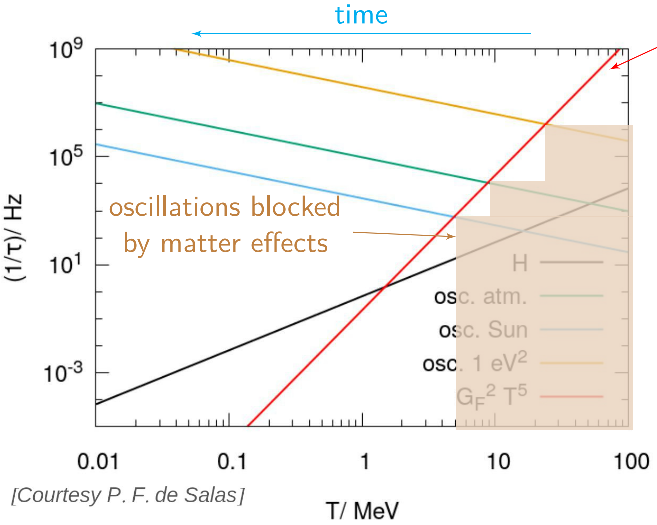

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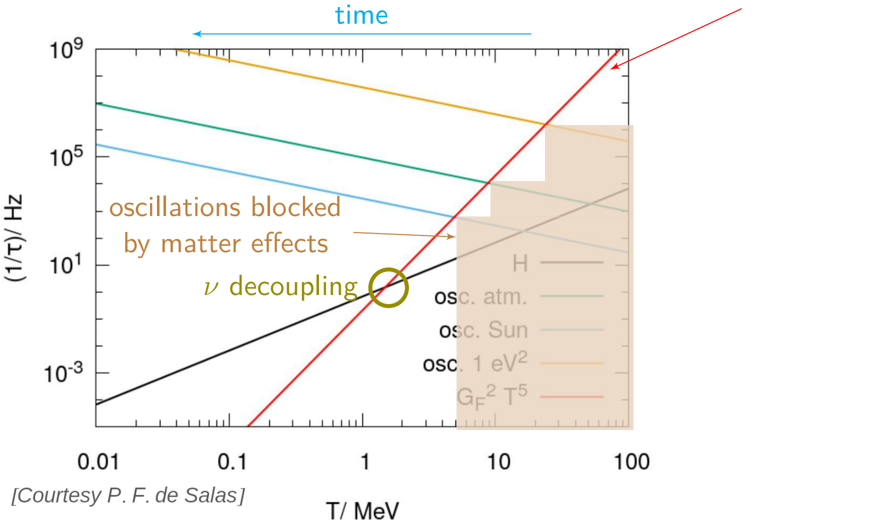

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ν decouple mostly before $e^+ e^- \to \gamma\gamma$ annihilation!

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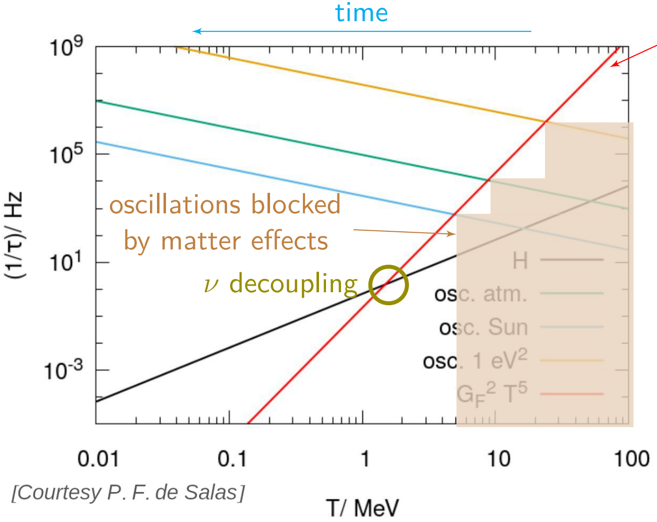

[Courtesy P. F. de Salas]

$T_\nu \simeq (4/11)^{1/3} T_\gamma$ 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

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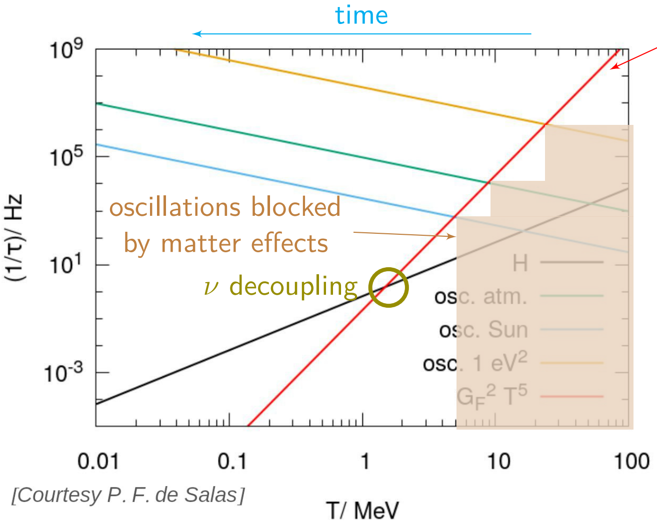

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actually, the decoupling T is momentum dependent!

distortions to equilibrium f_ν!

ν oscillations in the early universe

[Bennett, SG+, JCAP 2021]
[Sigl, Raffelt, 1993]

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

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

$\propto \langle a_j^\dagger(p,t)\, a_i(p,t) \rangle$

off-diagonals to take into account coherency in the neutrino system

ϱ evolution from $x H \dfrac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = -ia[\mathcal{H}_{\rm eff}, \varrho] + b\mathcal{I}$

H Hubble factor $\rightarrow$ expansion (depends on universe content)

effective Hamiltonian $\mathcal{H}_{\rm eff} = \dfrac{\mathbb{M}_{\rm F}}{2y} - \dfrac{2\sqrt{2} G_{\rm F}\, y\, m_e^6}{x^6} \left(\dfrac{\mathbb{E}_\ell + \mathbb{P}_\ell}{m_W^2} + \dfrac{4}{3}\, \dfrac{\mathbb{E}_\nu}{m_Z^2} \right)$

vacuum oscillations ⟵ ⟶ matter effects

$\mathcal{I}$ collision integrals

take into account ν–e scattering and pair annihilation, ν–ν interactions

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

solve together with z evolution, from $x \frac{\mathrm{d}\rho(x)}{\mathrm{d}x} = \rho - 3P$

ρ, P total energy density and pressure, also take into account FTQED corrections

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

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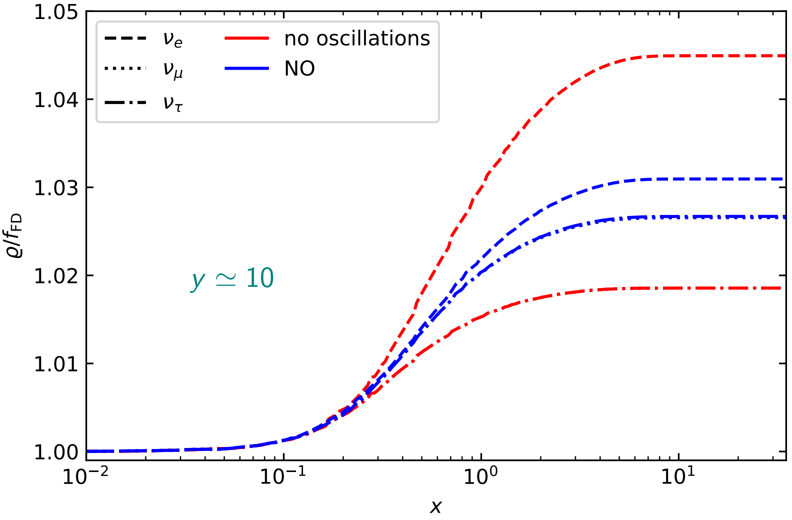
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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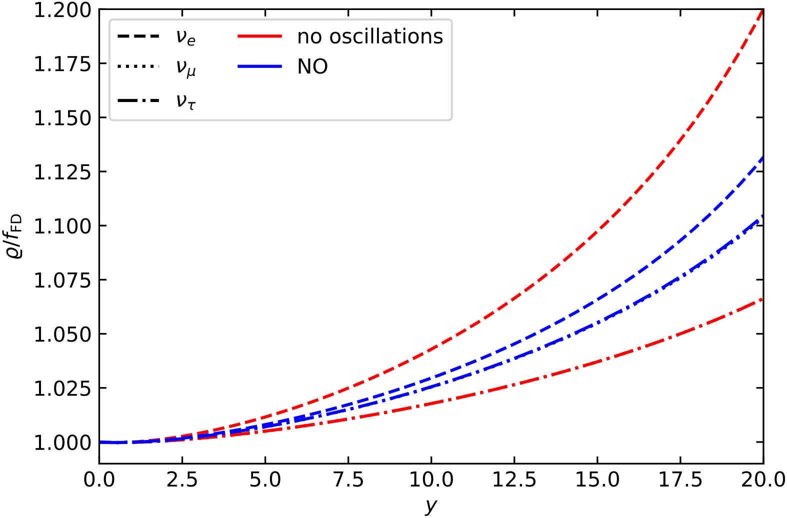
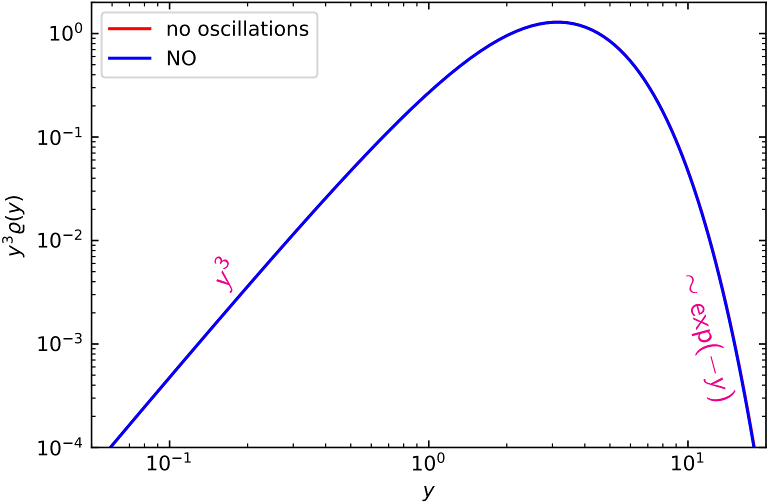


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

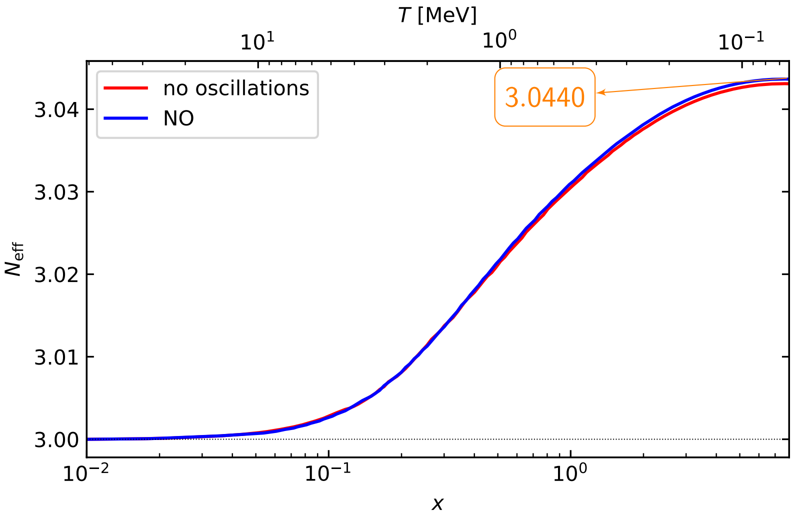
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



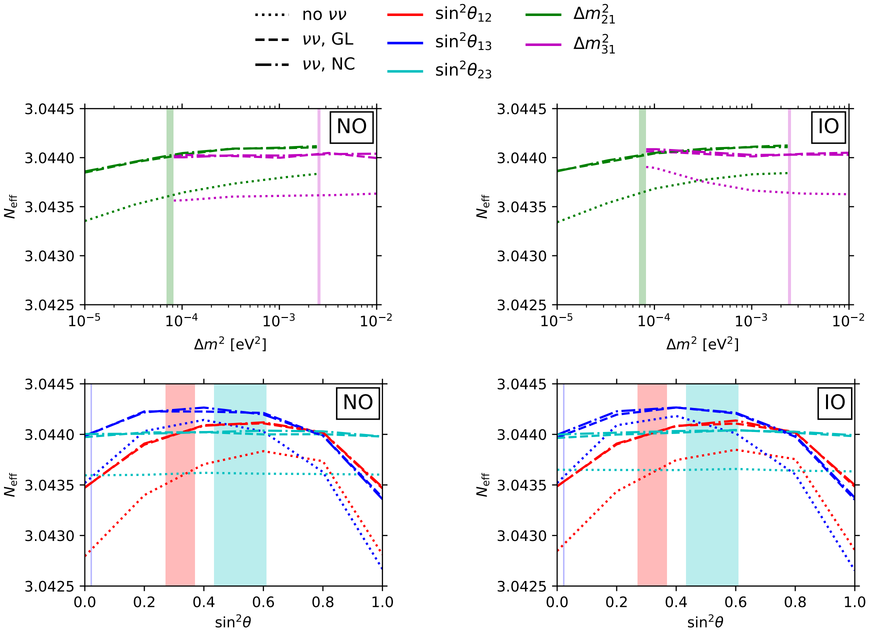
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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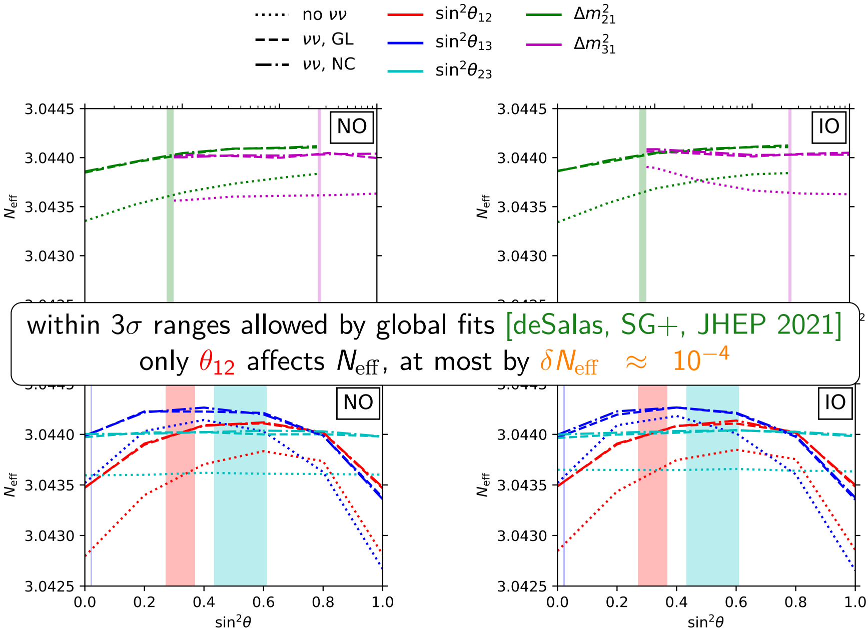
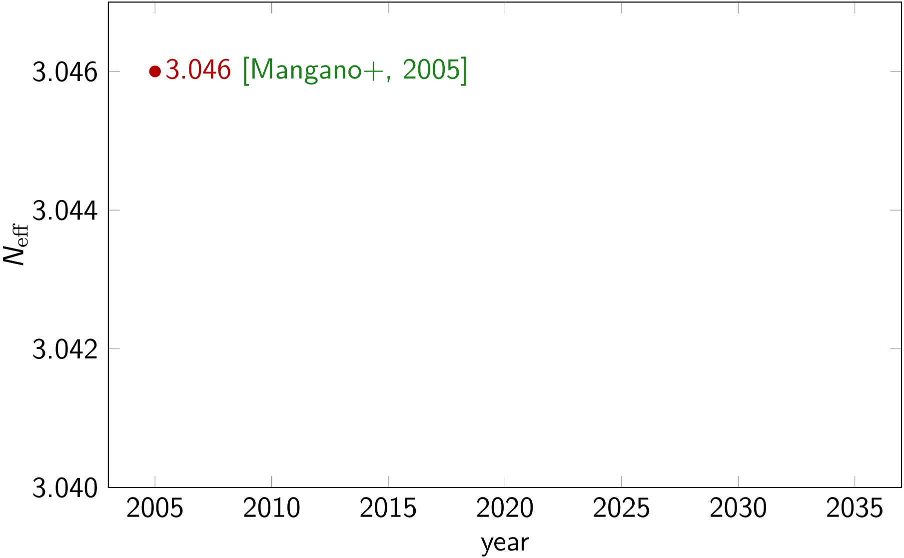


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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

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

Full 3ν mixing results:



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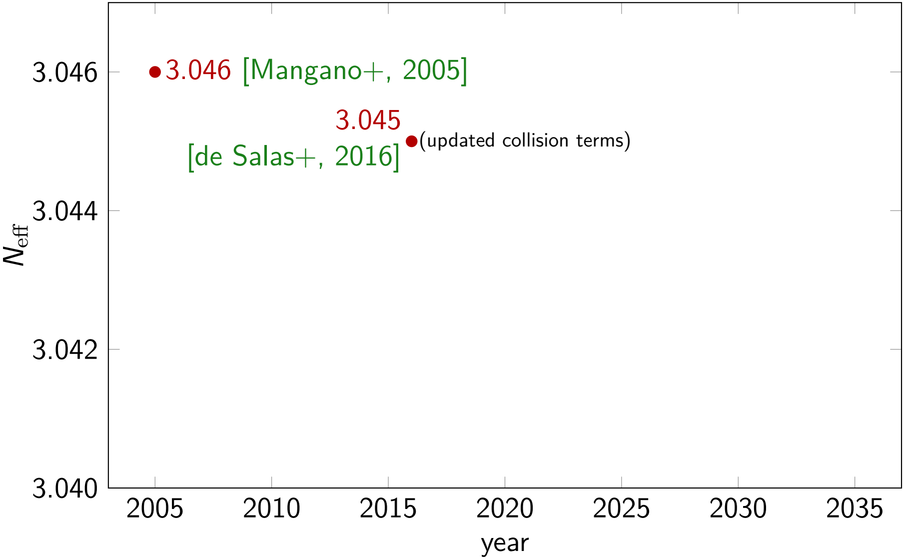

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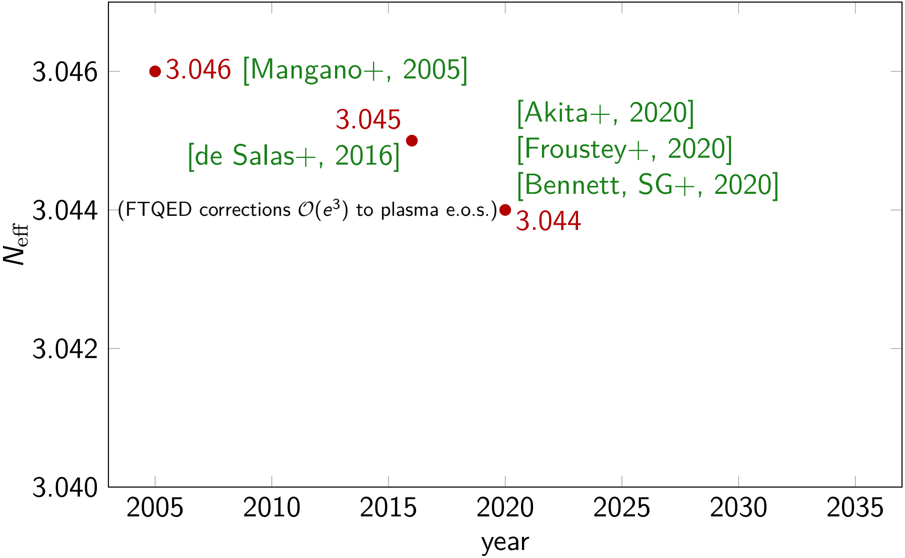

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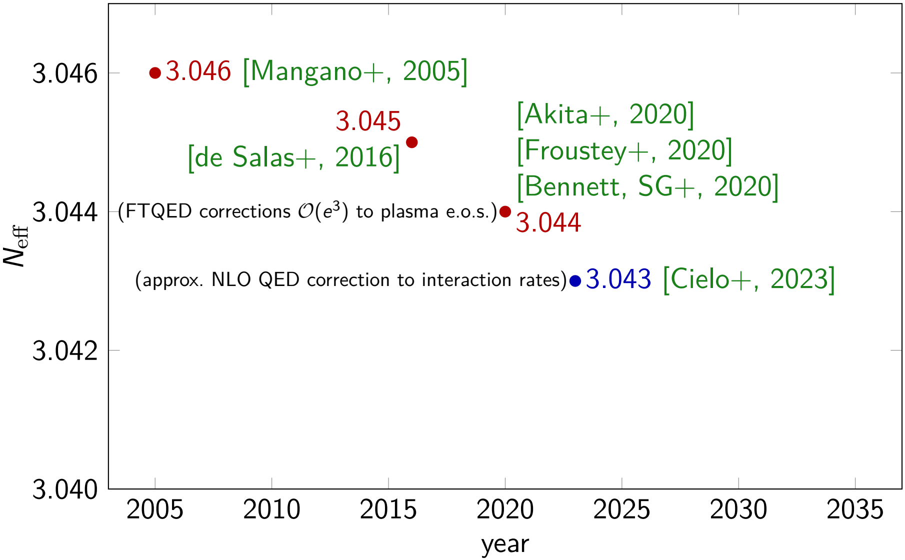

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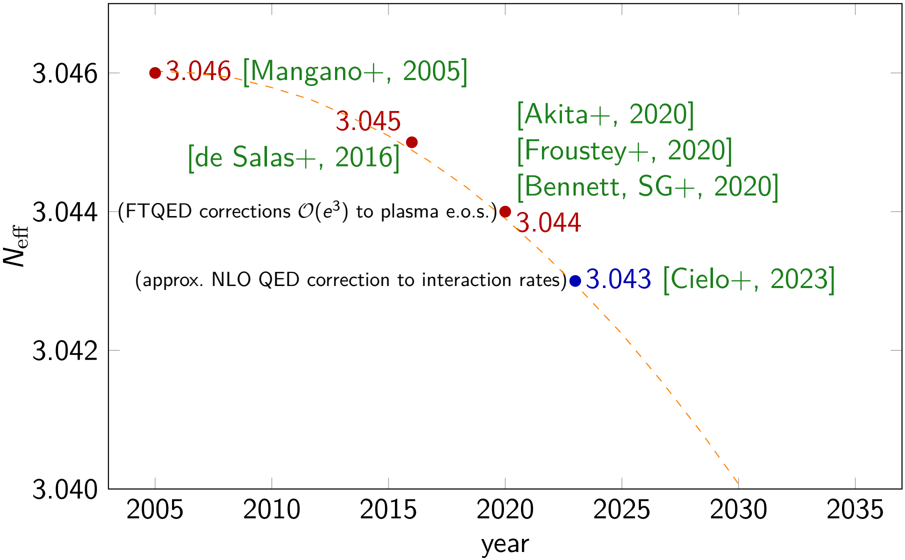

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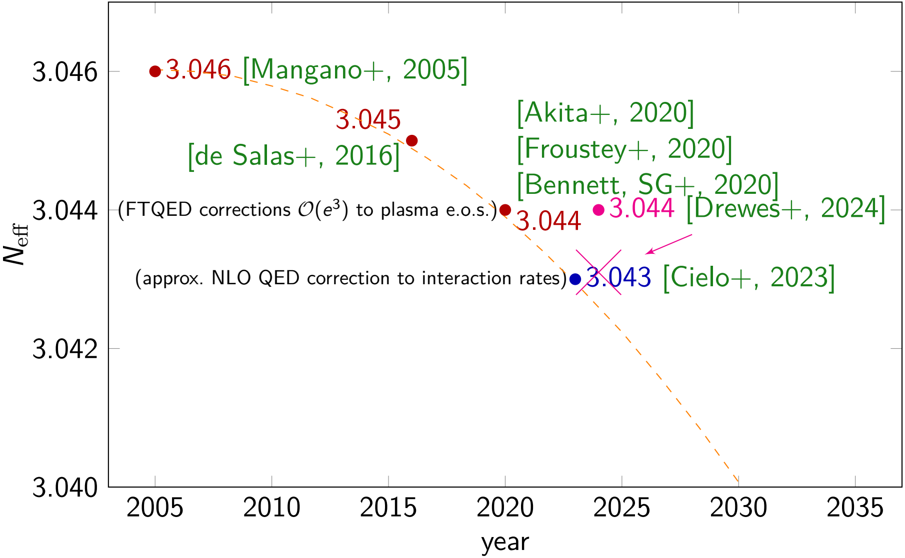
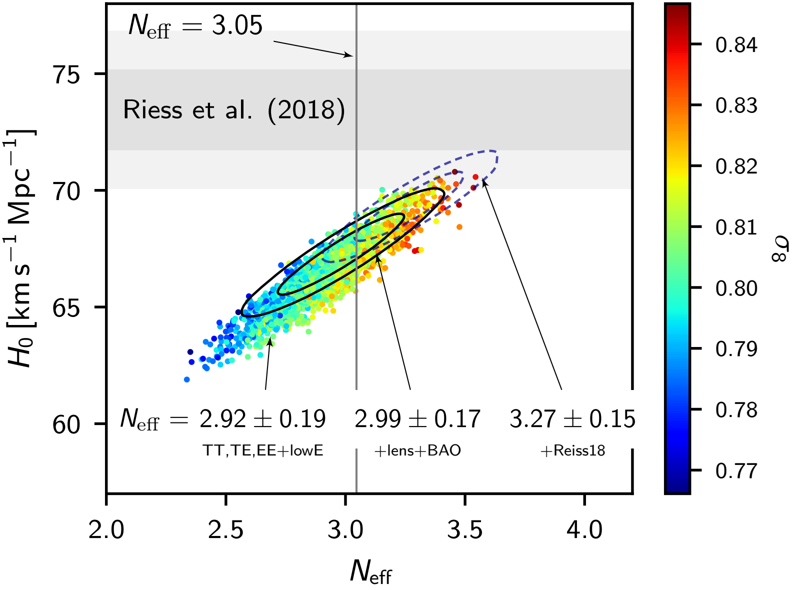


N_{eff} and CMB

[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

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

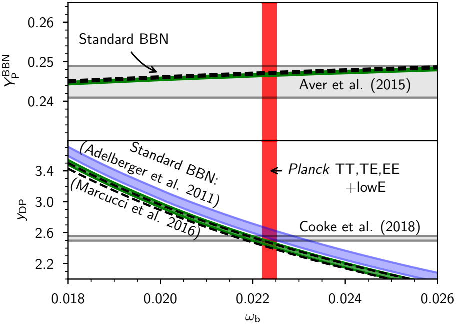
which controls element abundances

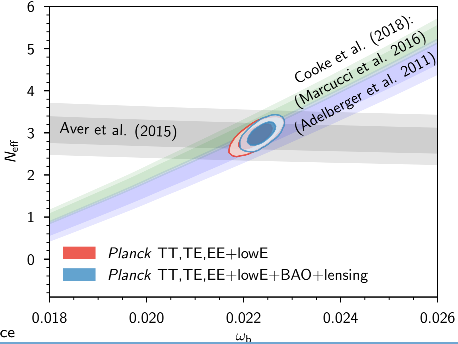
$g_\star$ depends on $N_{\rm eff}$

$$\downarrow$$

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

$N_{\rm eff}$ 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:

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

↓

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

enters

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

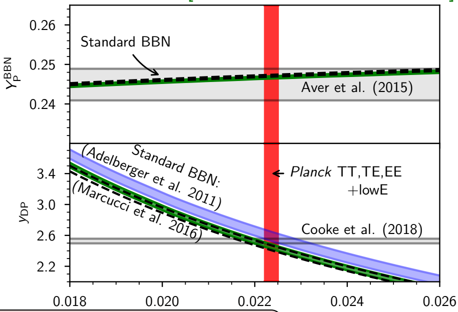
which controls element abundances

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

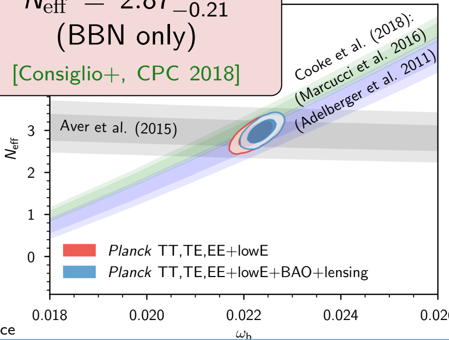
↓

abundances depend on $N_{\rm eff}$

[Planck Collaboration, 2018]



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



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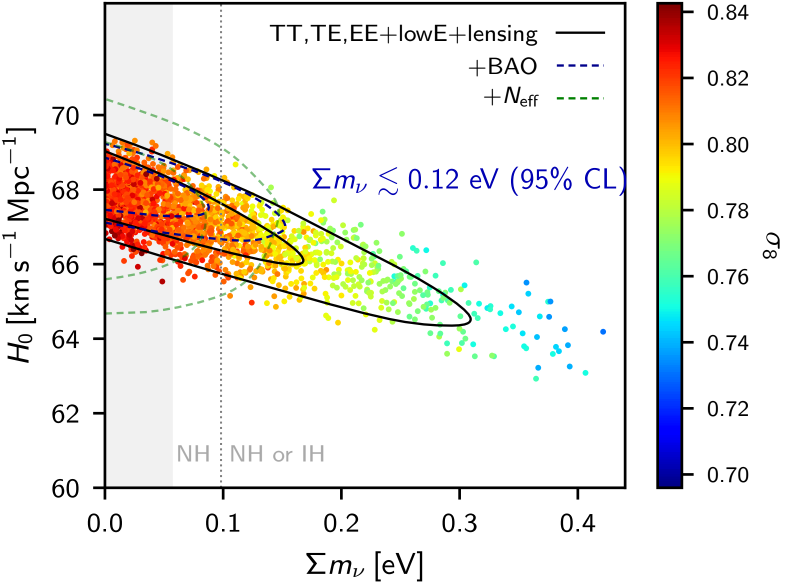
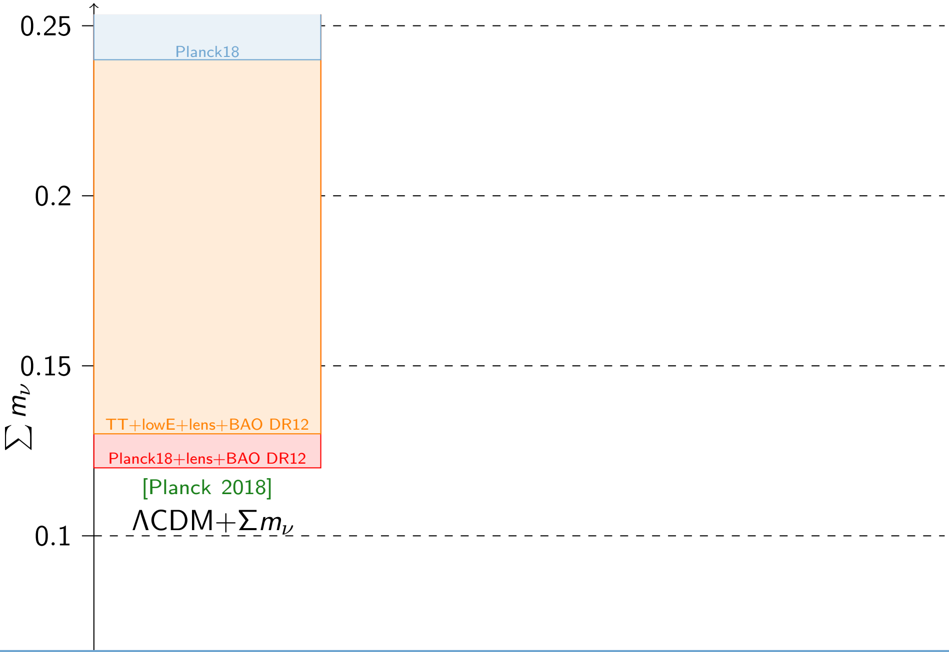
Σm_ν and CMB

[Planck Collaboration, 2018]



Cosmological neutrino mass bounds (95% CL)



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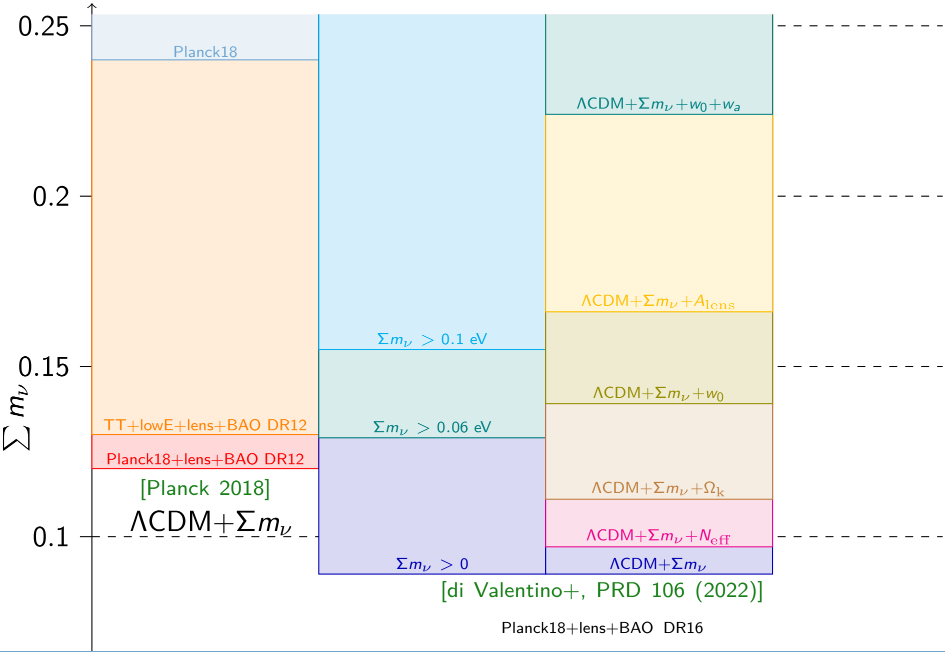

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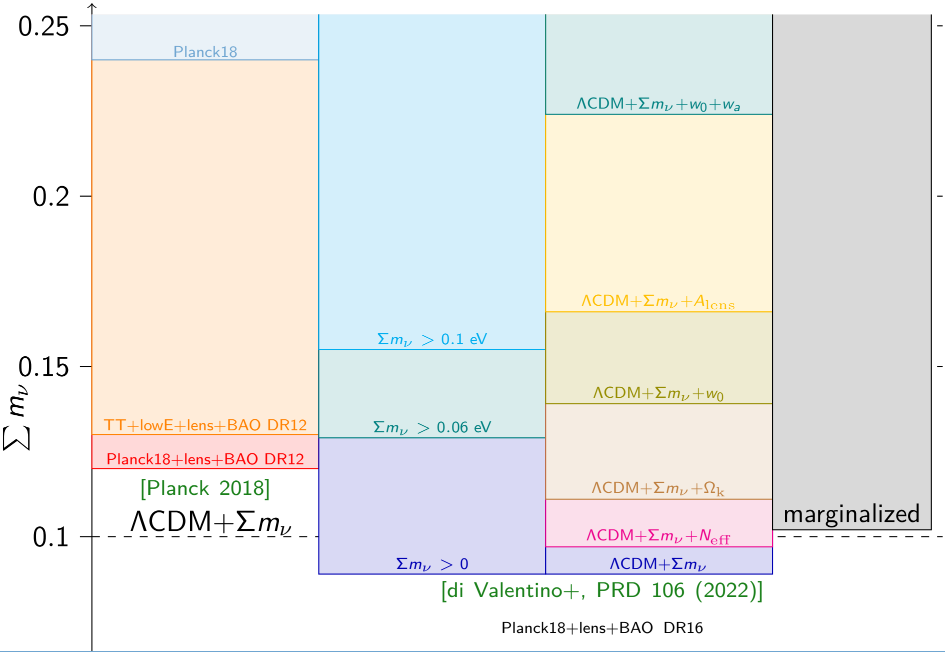


Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

standard factor

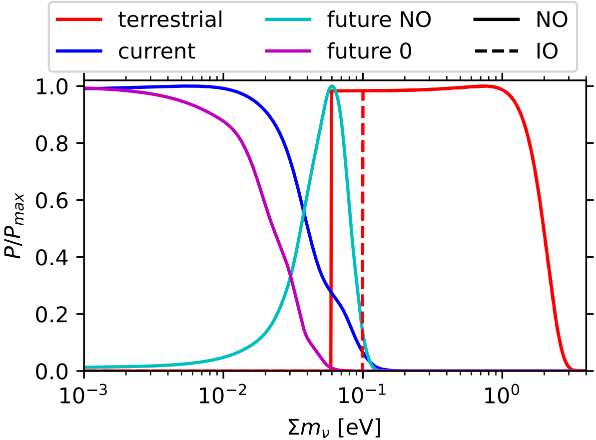
Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\ \text{eV})$

NO: $\Sigma m_\nu \gtrsim 0.06$ eV Current: $\Sigma m_\nu \lesssim 0.1$ eV (95%) IO: $\Sigma m_\nu \gtrsim 0.1$ eV

Future sensitivity: $\sigma(\Sigma m_\nu) \simeq 0.02$ eV

Still preferring $\Sigma m_\nu = 0$? Will measure e.g. $\Sigma m_\nu = 0.06$ eV?

tension even with NO!



confirm NO, disfavor IO

Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

standard factor

Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\text{ eV})$

Is there a tension between cosmology and oscillations?

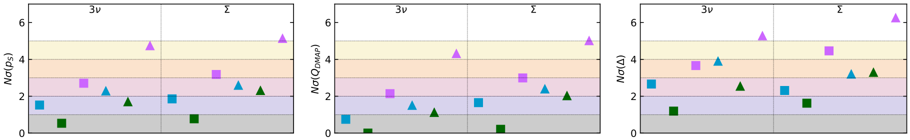
or will there be a tension?

several possible tests can be considered, similar results

$\Sigma m_\nu \lesssim 0.1$ eV (95%) ● current ■ NO

$\Sigma m_\nu = 0.06 \pm 0.02$ eV (1σ) ● future NO ▲ IO

$\Sigma m_\nu = 0.00 \pm 0.02$ eV (1σ) ● future 0



currently only mild tension between cosmology and oscillations

future NO can be at $\sim 2\sigma$ tension with IO

future 0 can be at $\sim 2-3\sigma$ tension with NO, $\gtrsim 4\sigma$ with IO

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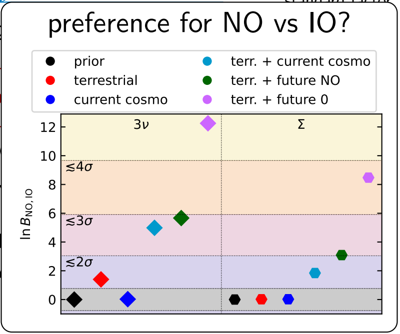

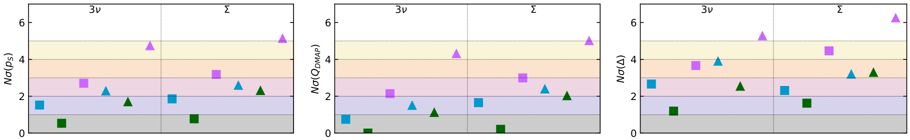

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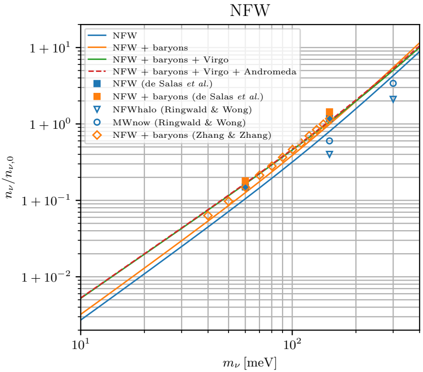
C Clustering in the local Universe

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 ⟶ 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, θ, 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!)

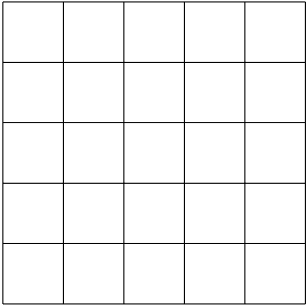
given N ν:

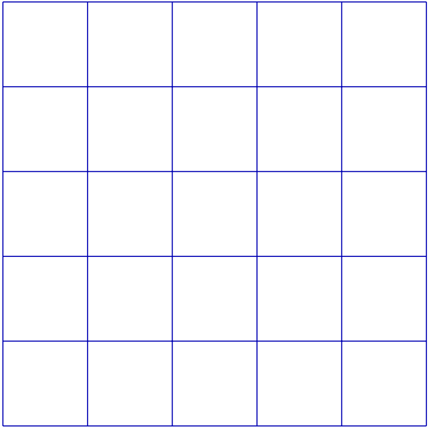
→ weigh each neutrinos

→ 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



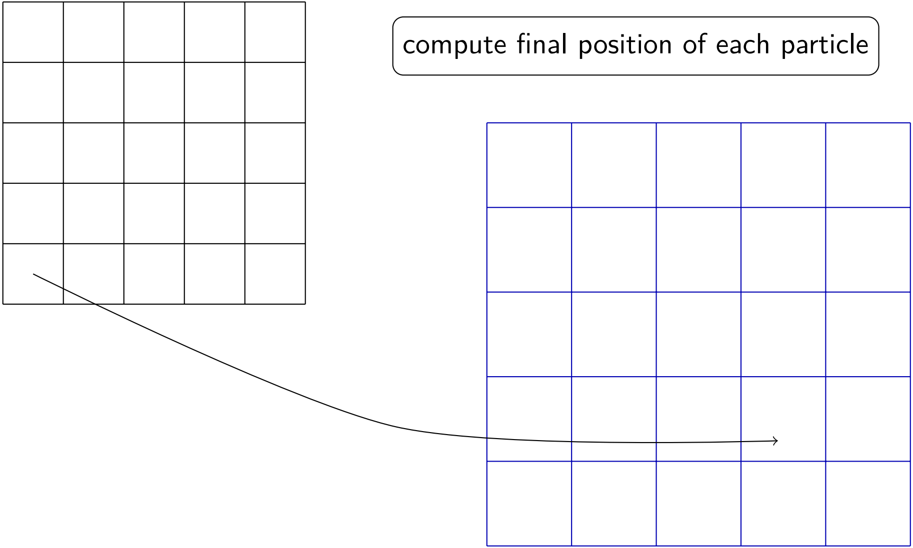


final phase space, $z = 0$

Forward-tracking and back-tracking

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

compute final position of each particle



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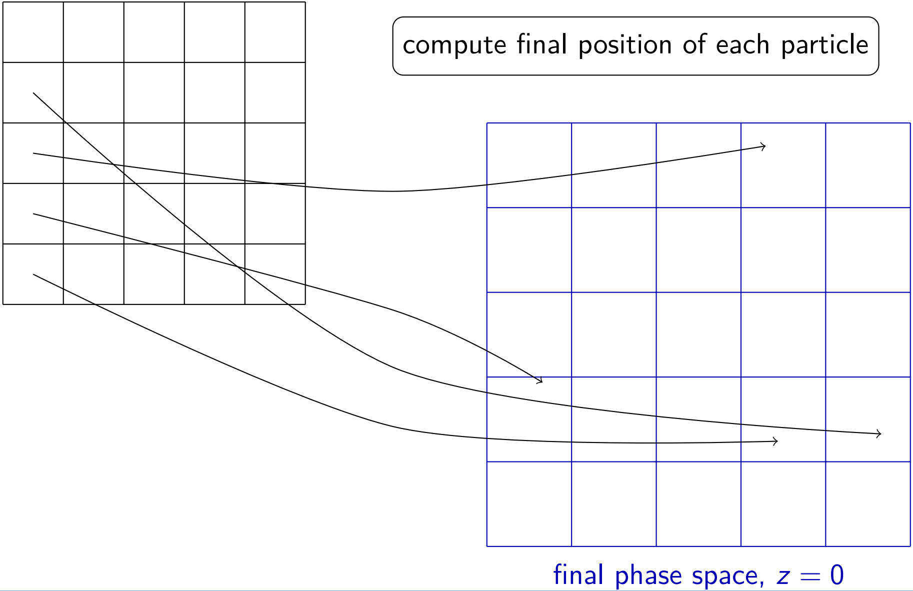

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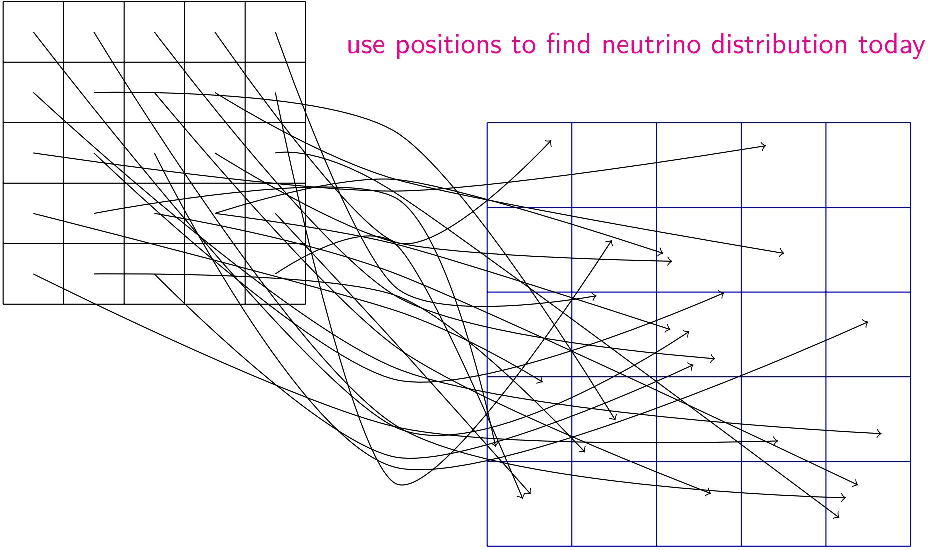

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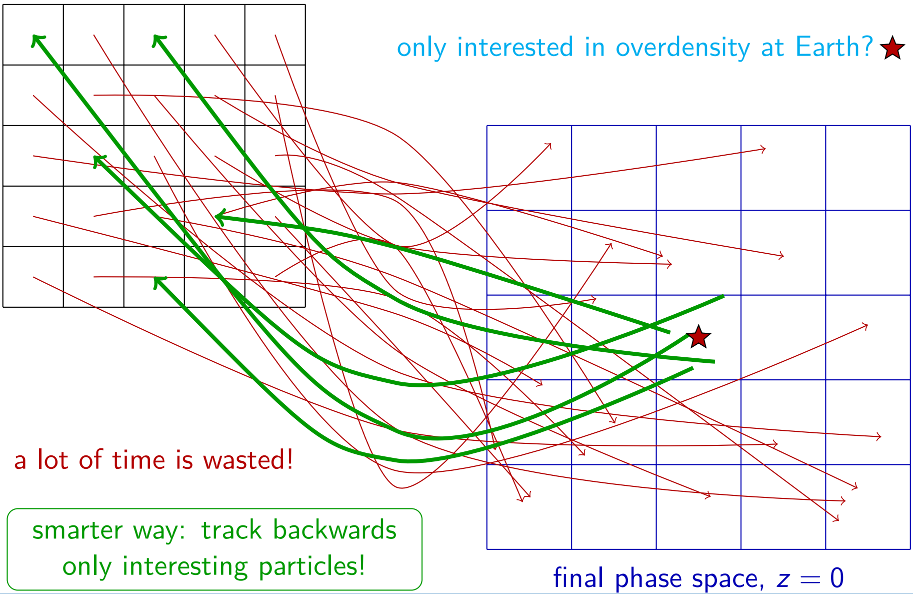

Advantages of tracking back

[JCAP 01 (2020) 015]

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

Advantages of tracking back

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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

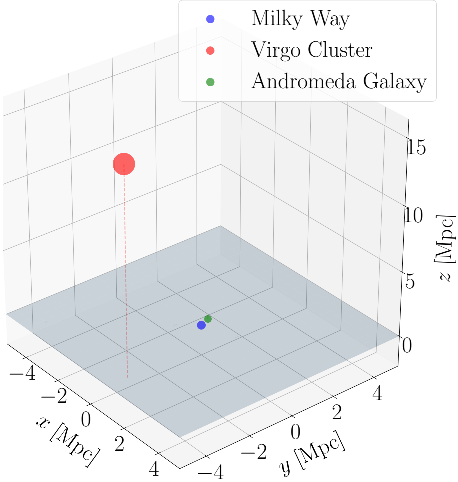
(position is fixed, apart for checks)

can do the calculation with any astrophysical setup

Advantages of tracking back

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

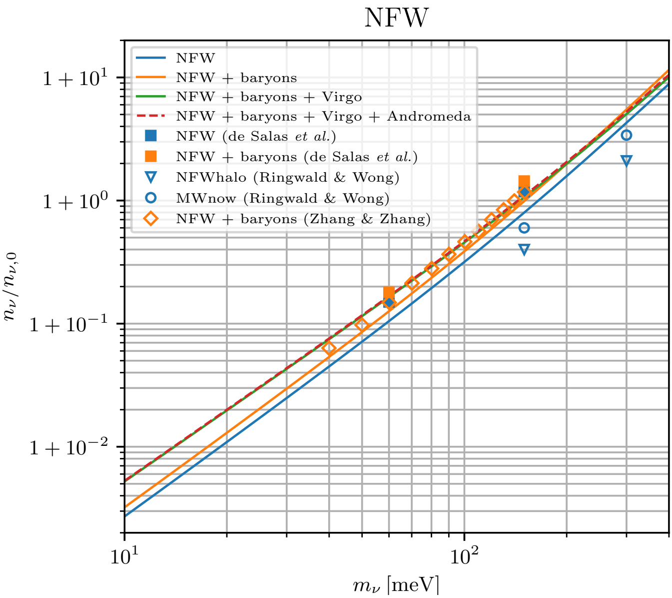
Second advantage: no need to use spherical symmetry!



Clustering results with back-tracking

[JCAP 01 (2020) 015]

In comparison with previous results:



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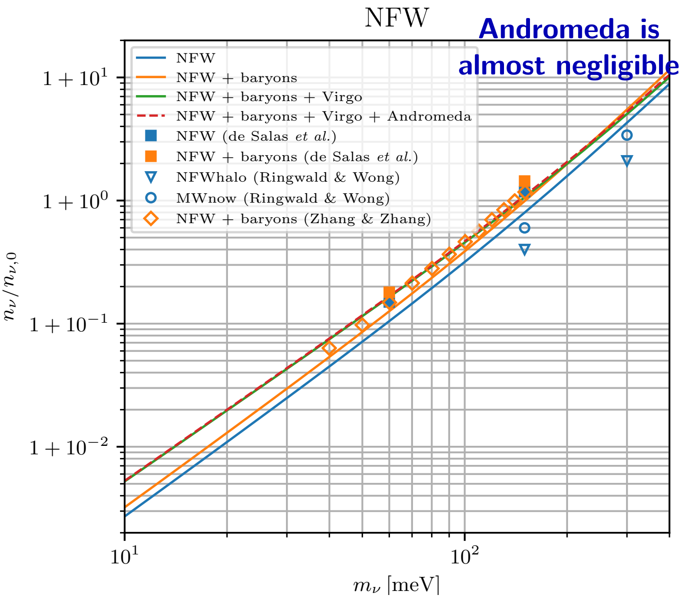

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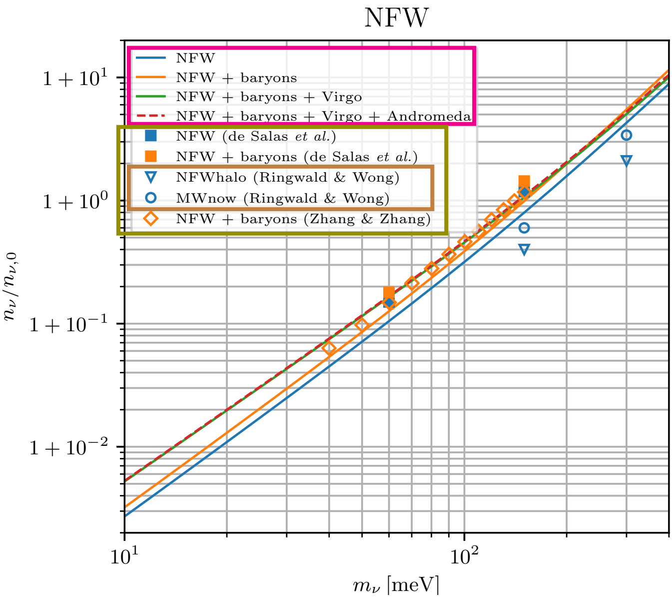

Warning: NFW is not the same for all the cases!

[de Salas+, 2017] and [Zhang², 2018] use $\gamma \neq 1$, now we have $\gamma = 1$

[Ringwald&Wong, 2004] uses old parameters

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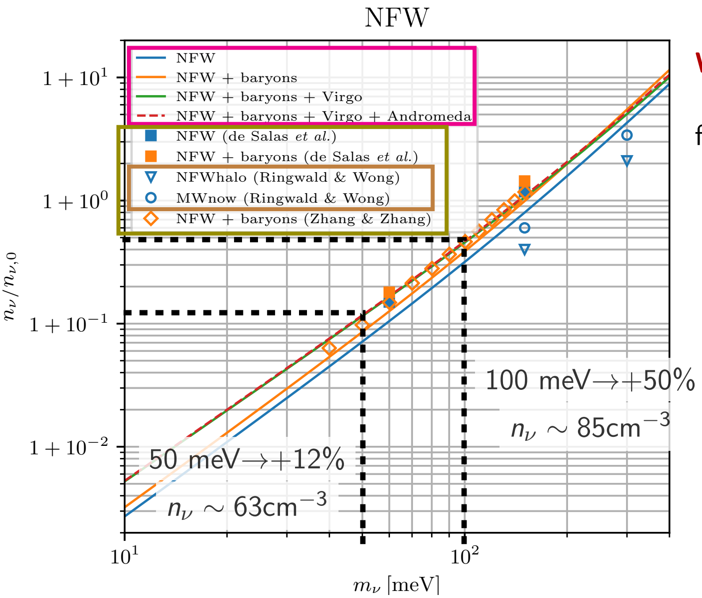

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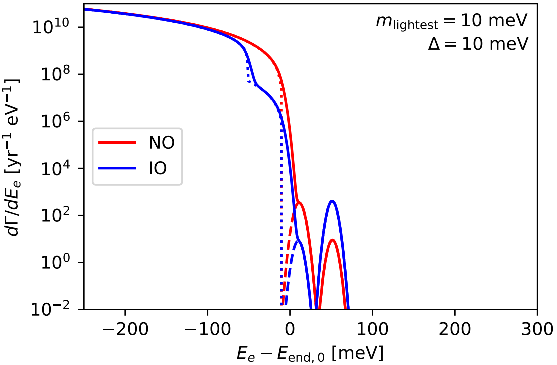
D Direct detection of relic neutrinos

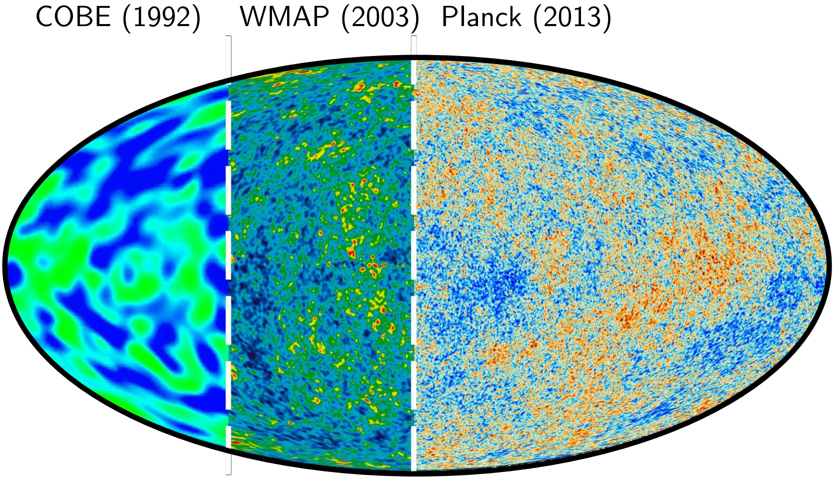
Based on:

- JCAP 01 (2023) 003
- JCAP 08 (2014) 038
- JCAP 07 (2019) 047



The oldest picture of the Universe

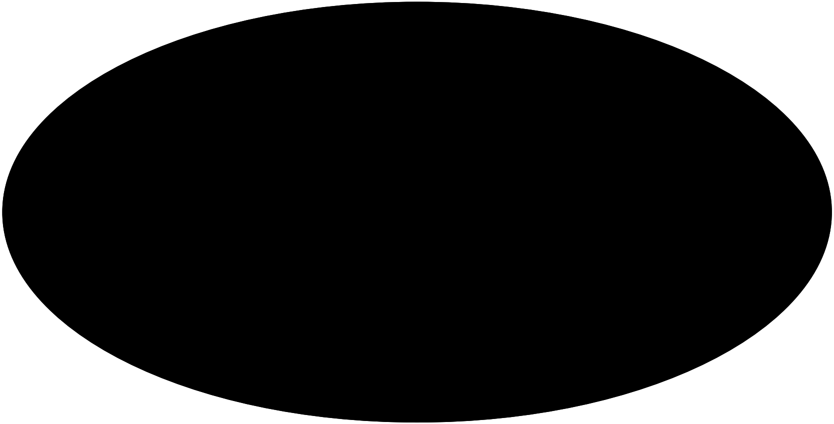
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years



The oldest picture of the Universe

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

$\ldots \rightarrow 2024 \rightarrow \ldots$



$T_\nu \sim 10^{-4}$ eV, $E_\nu \sim 5 \times 10^{-4}$ eV today!

We need thresholdless detection process... How do we get them?

Stodolsky effect?

How to directly detect non-relativistic neutrinos?

Stodolsky effect

[Stodolsky, 1974][Duda+, 2001]

(only if there is lepton asymmetry)

energy splitting of e^- spin states due to coherent scattering with relic neutrinos

$\downarrow$

torque on e^- in lab rest frame

$\downarrow$

use a ferromagnet to build detector

$\downarrow$

measure torque with a torsion balance

Stodolsky effect?

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[Stodolsky, 1974][Duda+, 2001]

(only if there is lepton asymmetry)

energy splitting of e^- spin states due to coherent scattering with relic neutrinos

↓

torque on e^- in lab rest frame

↓

use a ferromagnet to build detector

↓

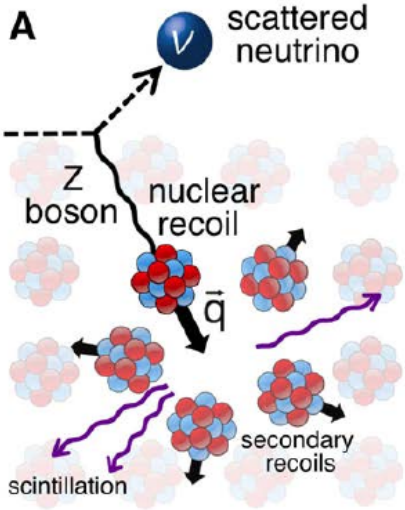
measure torque with a torsion balance

expected $a_\nu \simeq \mathcal{O}(10^{-26})$ cm/s^2 ⟷ $a_{\rm exp} \simeq \mathcal{O}(10^{-12})$ cm/s^2

CEνNS?

First of all: what's Coherent Elastic ν-Nucleous Scattering?

elastic scattering where ν interacts with nucleous "as a whole"



Predicted for $|\vec{q}|R \lesssim 1$
by [Freedman, PRD 1974]

small recoil energies! $\lesssim$ 10 keV...
difficult to measure

$$\frac{d\sigma}{dT}(E_\nu, T) \sim \frac{G_F^2 M}{4\pi} N^2$$

[Drukier, Stodolsky, PRD 1984]

enhancement N^2 because
ν interacts
coherently with all nucleons

may give huge cross
section enhancement

CEνNS?

First of all: what's Coherent Elastic ν-Nucleous Scattering?

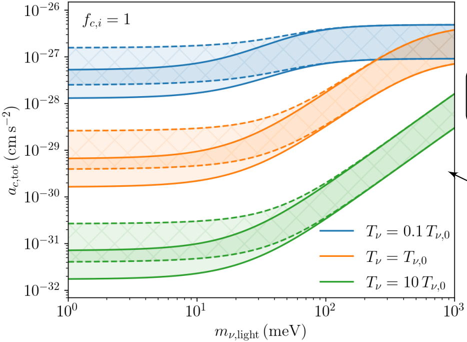
elastic scattering where ν interacts with nucleous "as a whole"

Can we detect relic neutrinos with CEνNS?

relic neutrinos have de Broglie length $\lambda \sim 2\pi/p_\nu$

↓

enhancement in interactions due to coherence with nuclei in volume λ^3



Acceleration induced by CEνNS of relic ν on test mass M:

$$a^N \propto ((A-Z)/A)^2 E_\nu / p_\nu^2 \Delta p_\nu n_\nu \rho$$

A, Z mass, atomic numbers
p_ν, E_ν neutrino momentum and energy
Δp_ν net momentum transfer
n_ν neutrino number density
ρ target mass density

unclustered relic νs, $n_\nu = n_0$
a^N of atoms in silicon target

CEνNS?

[Shergold, JCAP 2021]

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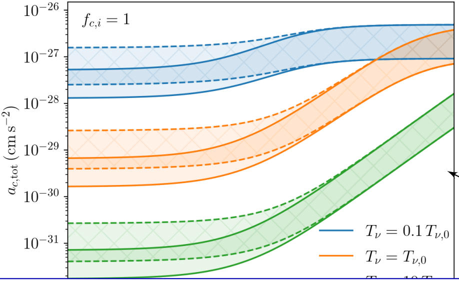

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Δp_ν net momentum transfer

n_ν neutrino number density

ρ target mass density

unclustered relic νs, $n_\nu = n_0$

proposed torsion balances can most optimistically reach $a \sim 10^{-23}$ cm s^{-2}

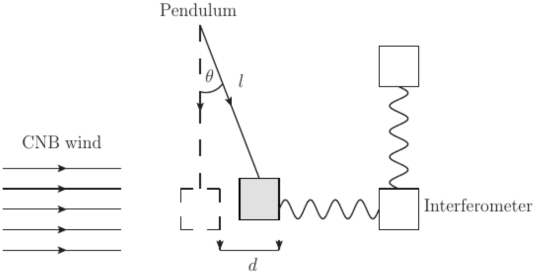
At interferometers?

How to directly detect non-relativistic neutrinos?

At interferometers

[Domcke+, 2017] [Shergold, 2021]

coherent scattering of relic ν on a pendulum → measure oscillations at interferometers



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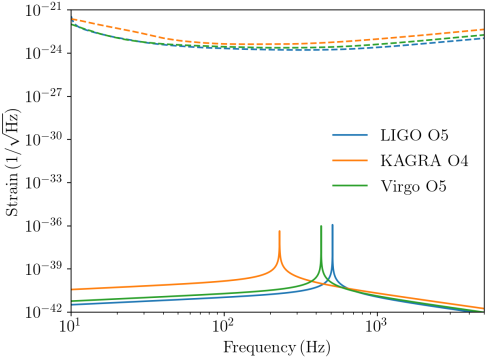


Sensitivity

Example signal $m_\nu = 0.8$ eV

Neutrino capture

[Long+, 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

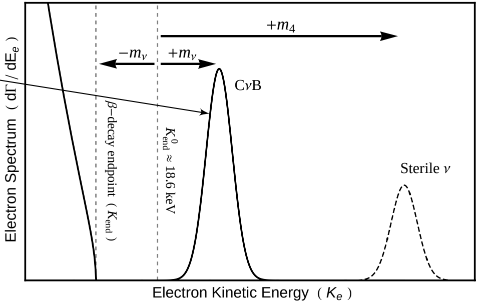
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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



What material?

[Cocco+, JCAP 06 (2007) 015]

best element has highest $\sigma_{\rm NCB}(v_\nu/c)\cdot t_{1/2}$

to minimize contamination from β decay background

Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
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^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
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^{3}H better because the cross section ($\rightarrow$ event rate) is higher

At accelerator facilities?

[Bauer+, PRD 2021]

What if we consider accelerated tritium ions, ${}^3H^+ + \nu_e \to {}^3He^{++} + e^-$?

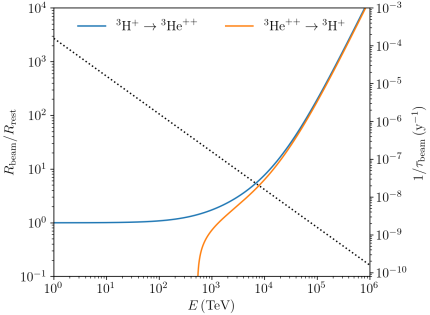
Large background due to tritium beta decay...

Inverse process ${}^3He^{++} + \bar{\nu}_e \to {}^3H^+ + e^+$ would require energy threshold

Match threshold in beam rest frame: $\tilde{E}_\nu = \frac{m_\nu}{M} E \geq Q$
with M, E ion mass, energy in lab frame

Even better:
resonant
${}^3He^{++} + \bar{\nu}_e + e^-$ (bound) $\to {}^3H^+$
can have many orders of magnitude larger cross-section
(which still scales with G_F^2)

but also **large background**...need huge E to overcome it



At accelerator facilities?

[Bauer+, PRD 2021]

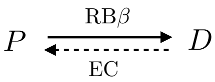
All mentioned cross sections scale with G_F^2

resonant bound beta decay (RBβ): ${}^A_Z P + \nu_e \to {}^{A}_{Z+1} D + e^-$ (bound)

at resonance, G_F^2 suppression is lost in favor of Q^2 suppression!

problem: final state D is converted back to P through electron capture (EC)!

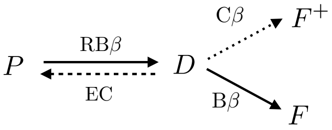
2-state



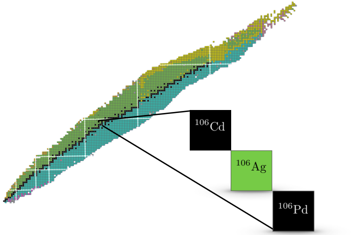
Max event rate at equilibrium limits information on RBβ rate when running a long experiment

better: try to measure final stable state F in

3-state



e.g.



At accelerator facilities?

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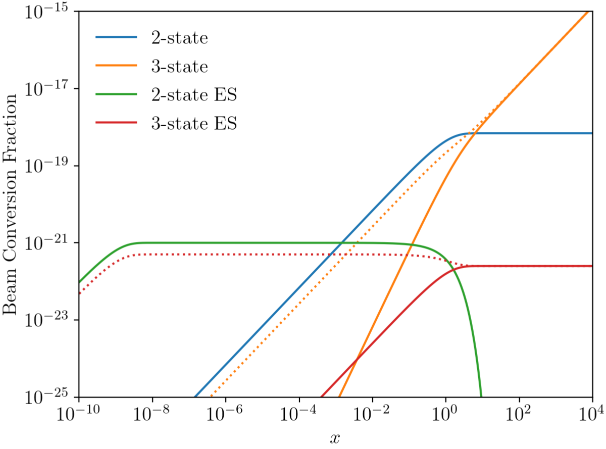
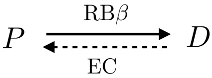
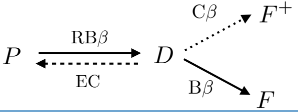


2-state



3-state



excited states
also possible

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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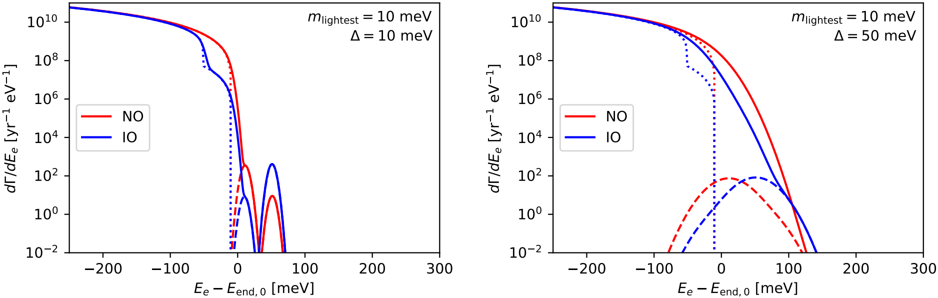

Pontecorvo Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq 0.1$ eV? 0.05 eV? ⟷ built mainly for CNB

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

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

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

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)

[PTOLEMY LoI, arxiv:1808.01892]

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

built mainly for CNB

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

ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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

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PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]

[Courtesy A. Esposito]

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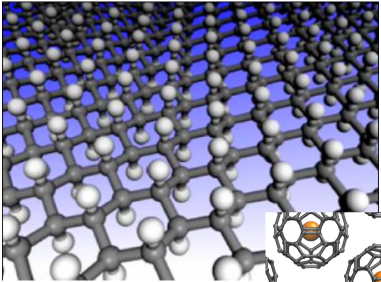
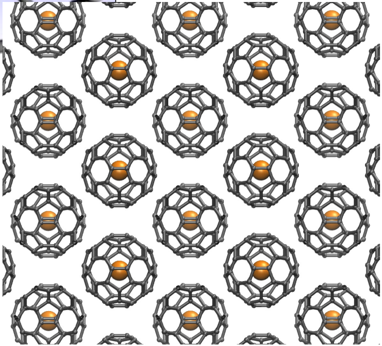


tritium on graphene?

tritium on fullerene?

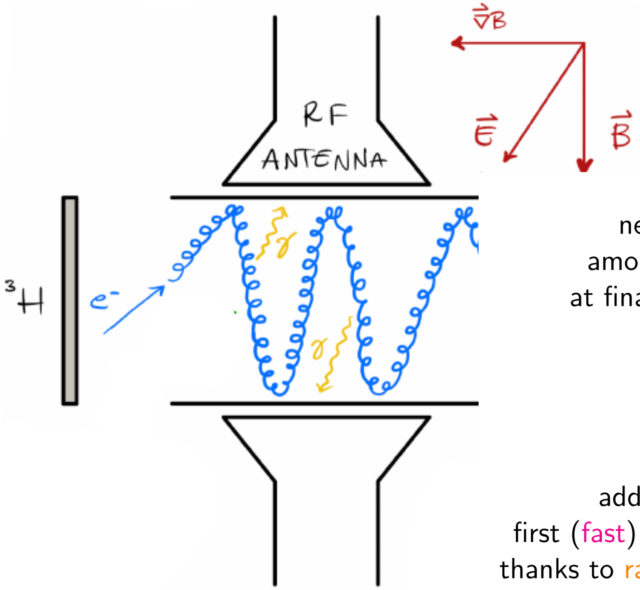


[Courtesy A. Esposito]

[Courtesy V. Tozzini]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]



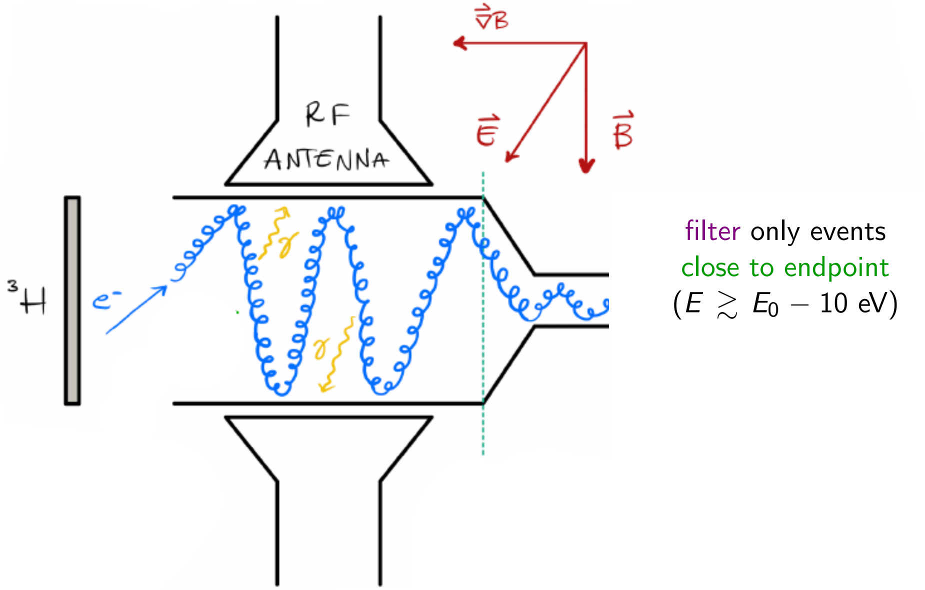
need to reduce
amount of electrons
at final energy sensors:
EM filter

additional benefit:
first (fast) energy determination
thanks to radio-frequency antenna

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]

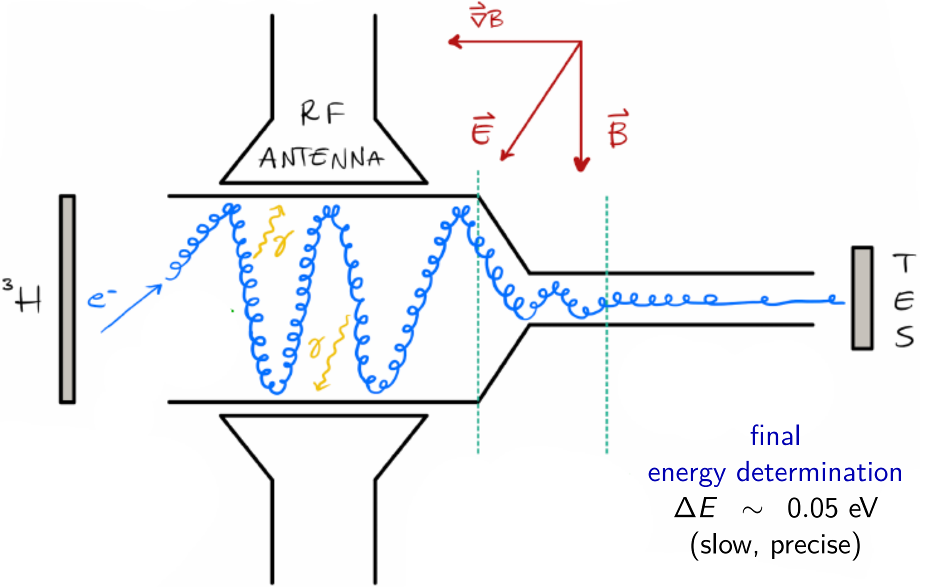


filter only events
close to endpoint
$(E \gtrsim E_0 - 10\ \text{eV})$

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]



final
energy determination
$\Delta E \sim 0.05$ eV
(slow, precise)

[Courtesy A. Esposito]

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

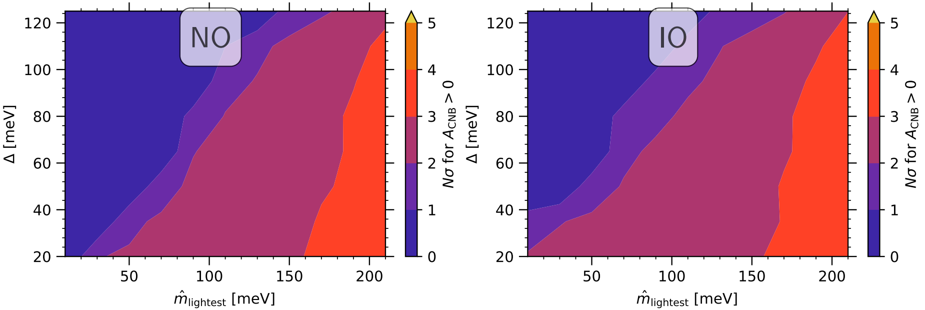
using the definition:

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

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



Time variations of ν capture rates

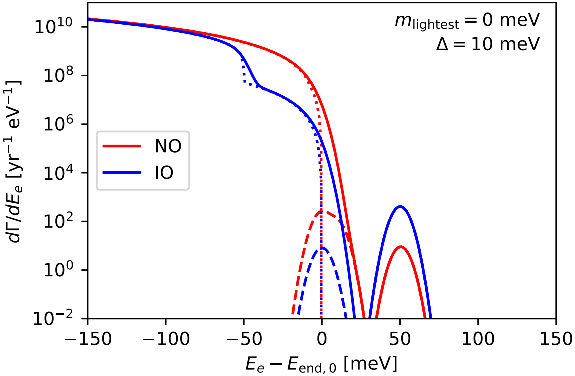
[Akhmedov, JCAP 2019]

What if the lightest neutrino is massless and Δ cannot be small enough?

single NC events cannot be distinguished by the background (β-decay)!

$$\frac{\nu \text{ capture rate}}{\beta \text{ decay rate}} = \frac{\Gamma_{\rm NC}}{\Gamma_\beta} \simeq \frac{n_\nu}{56\ \text{cm}^{-3}} \frac{2.54 \times 10^{-11}}{(\Delta/\text{eV})^3}$$

rates in the bin Δ on the endpoint



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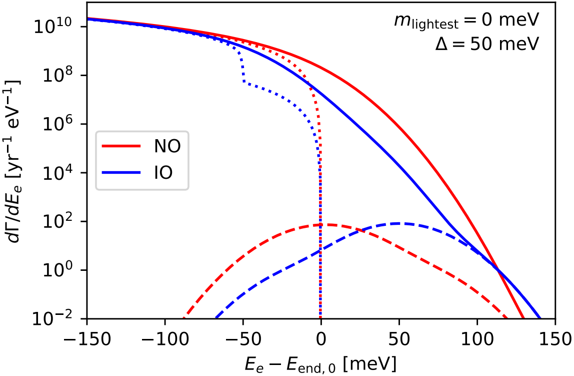

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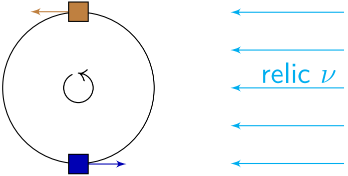

can be daily or annual modulation!

only for ν capture (no β-decay)

Time variations of ν capture rates

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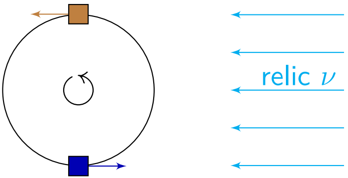


can be daily or annual modulation!

only for ν capture (no β-decay)

Problem:

Expected daily modulation is $\sim$ 1% of the signal!!

Must use powerful technique for signal/noise separation

Fourier analysis and frequency filtering may be sufficient

no m_ν information in this way!

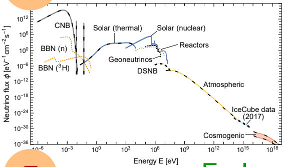
Z Conclusions

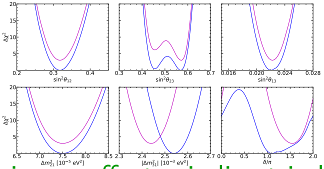
almost there!

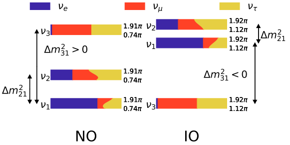
What do we learn from relic neutrinos?

N

Neutrinos: precision era (many sources)

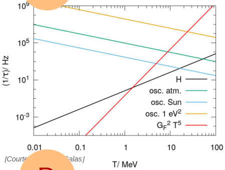


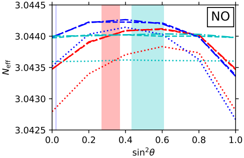


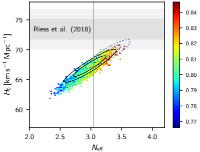


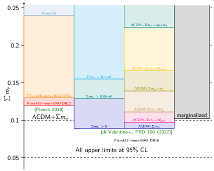
E

Early universe effects: indirect indications



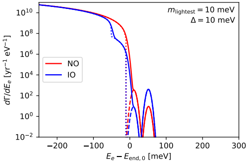


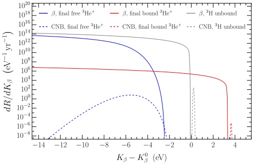


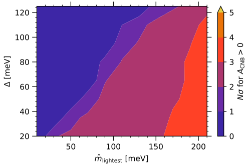


D

Direct detection: still long to go







What do we learn from relic neutrinos?

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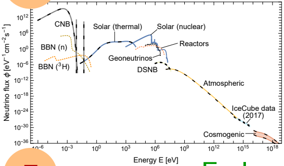
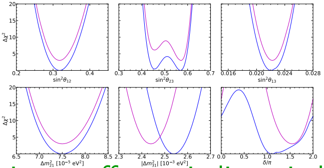
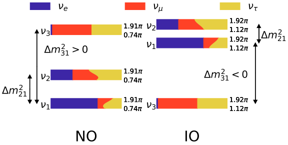
Neutrinos: precision era (many sources)







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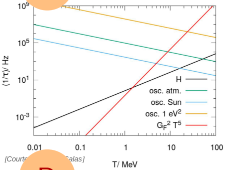

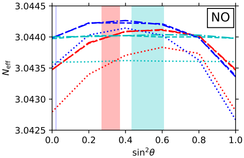

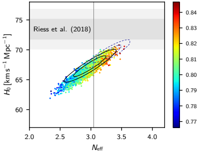

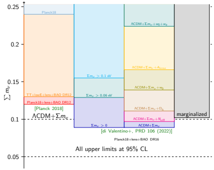

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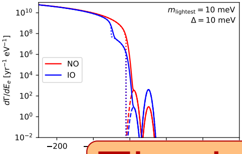

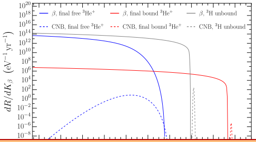

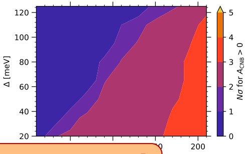

Thanks for your attention!