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

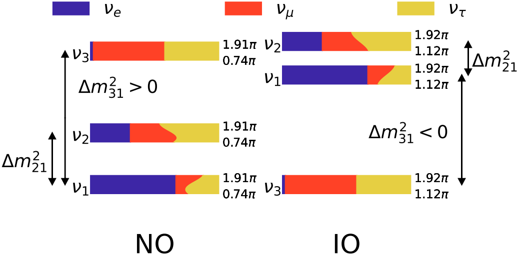
Universidad Tecnica Federico Santa Maria, Santiago de Chile, 28/03/2024

N

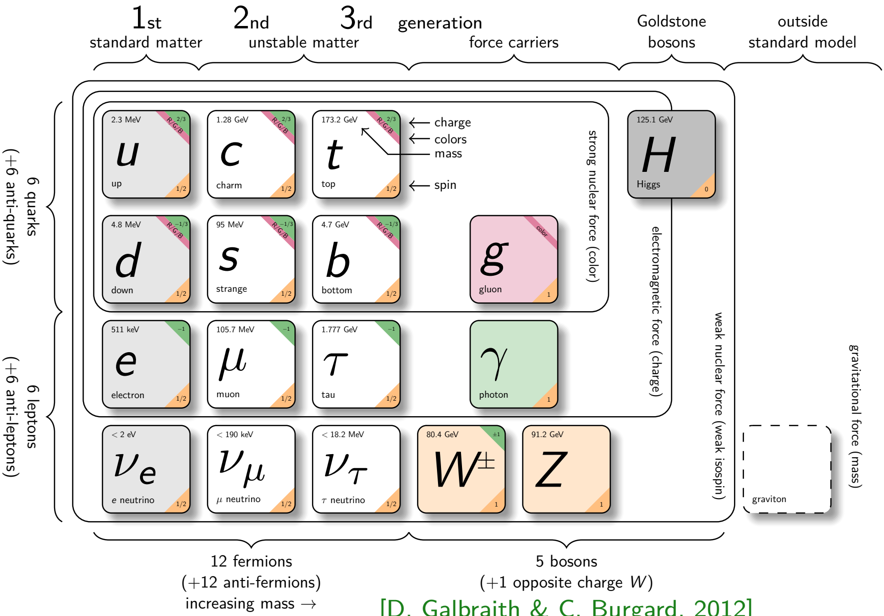
Neutrinos

Based on:

- JHEP 02 (2021) 071 and update



The Standard Model of Particle Physics



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		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

[D. Galbraith & C. Burgard, 2012]

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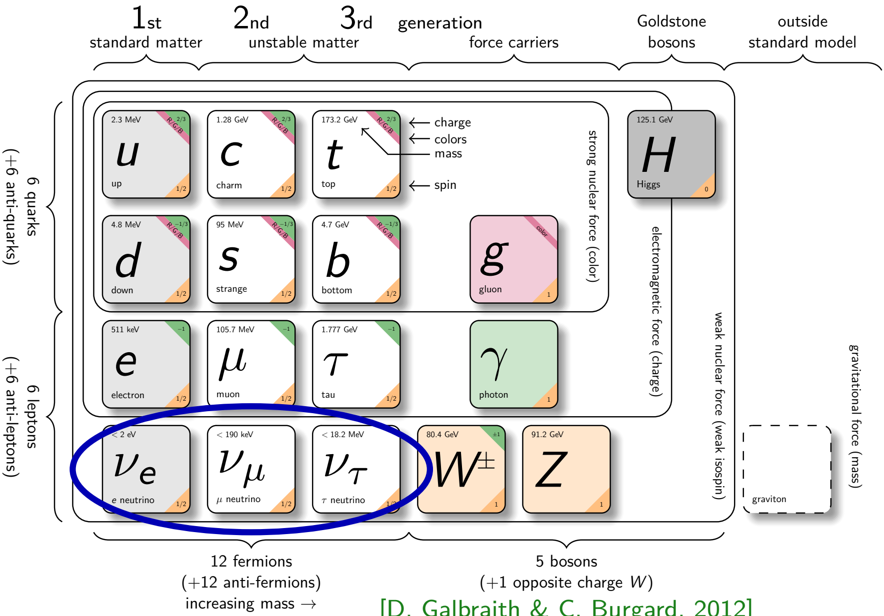
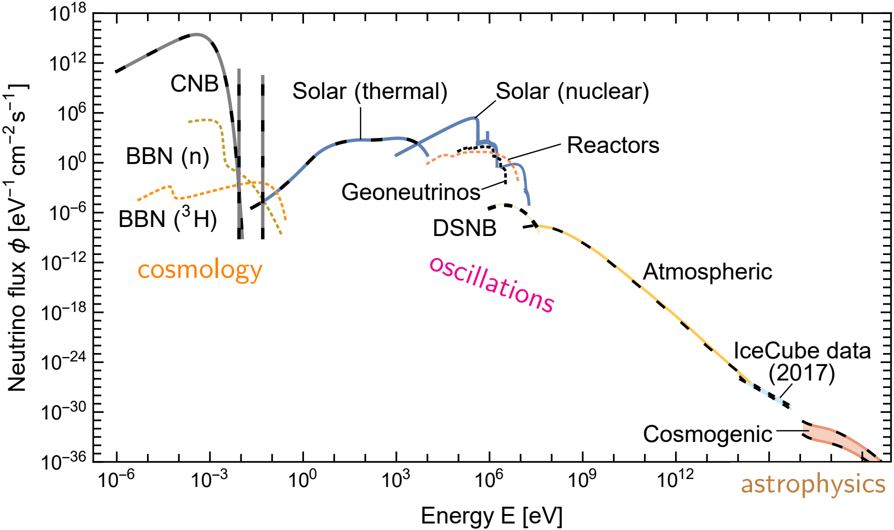


[D. Galbraith & C. Burgard, 2012]

Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]

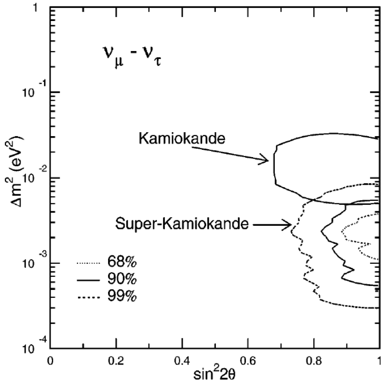


neutrinos at all energies provide valuable information!

Neutrino oscillations

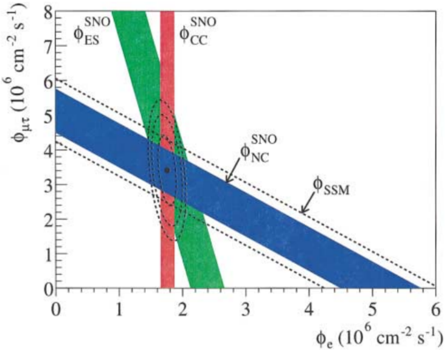
Major discoveries:

[SuperKamiokande, 1998]



first discovery of $\nu_\mu \rightarrow \nu_\tau$ 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

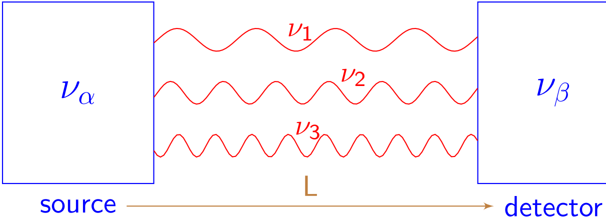
Two neutrino bases

flavor neutrinos ν_α

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

massive neutrinos ν_k

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



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

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

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

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

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

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

Majorana phases irrelevant for oscillation experiments

Relevant for example in neutrinoless double-beta decay

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

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

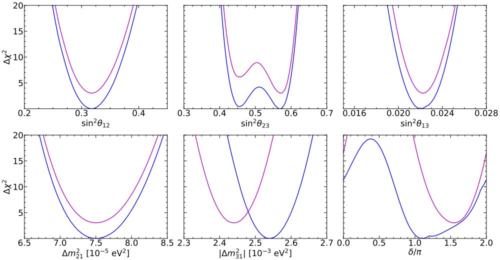
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

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

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

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



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)

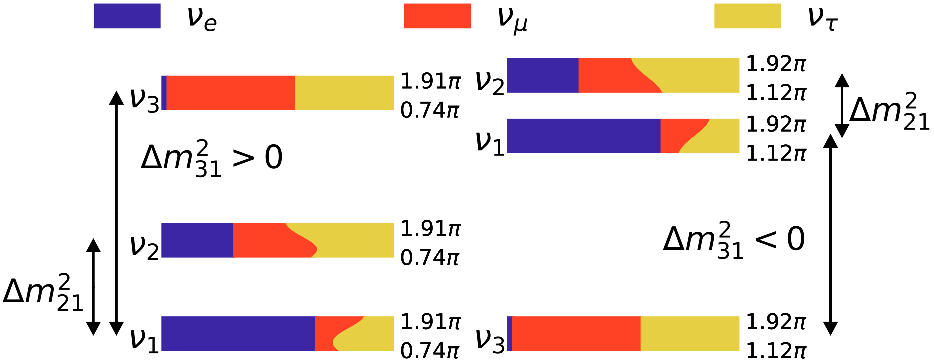
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV



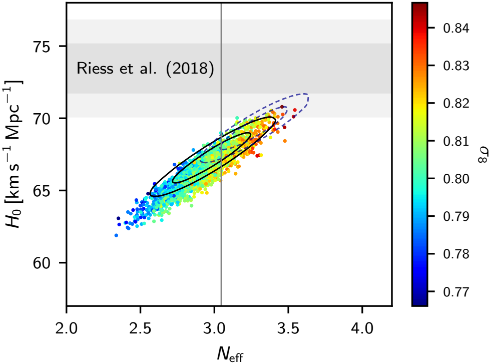
Absolute scale unknown!

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

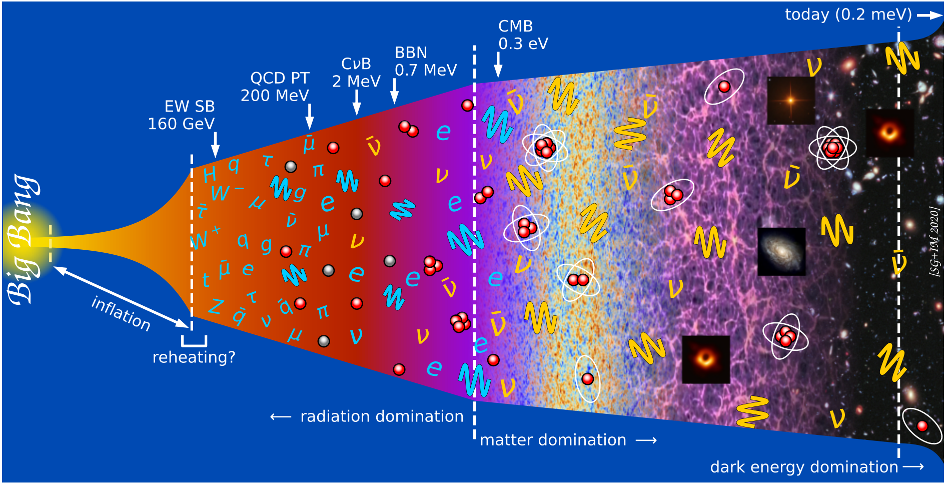
E Neutrinos in the Early Universe

Based on:

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



History of the universe



[SG+IM 2020]

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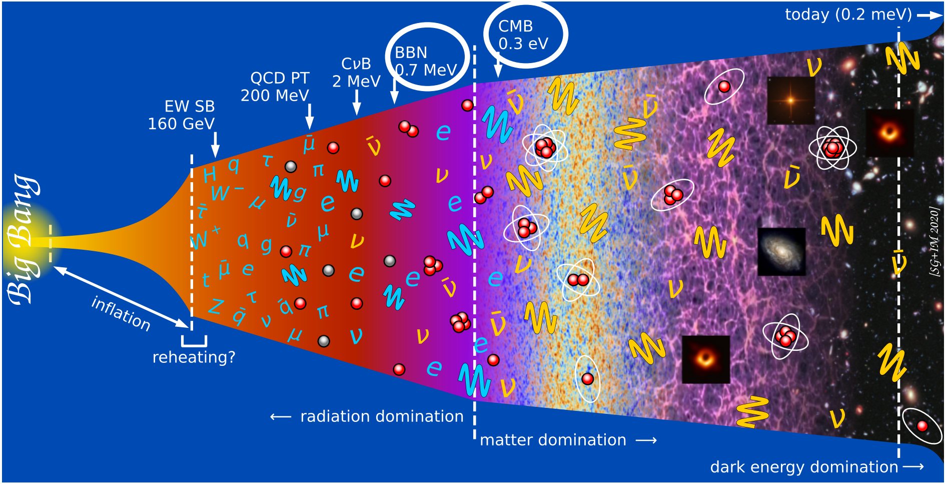
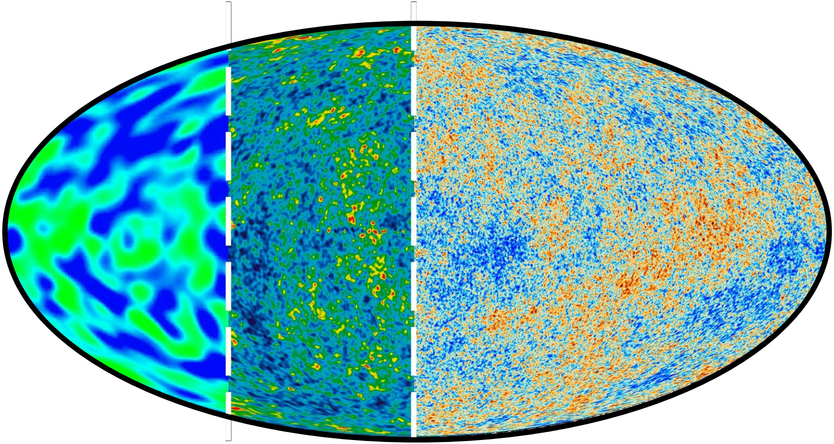


[SG+IM 2020]

The oldest picture of the Universe

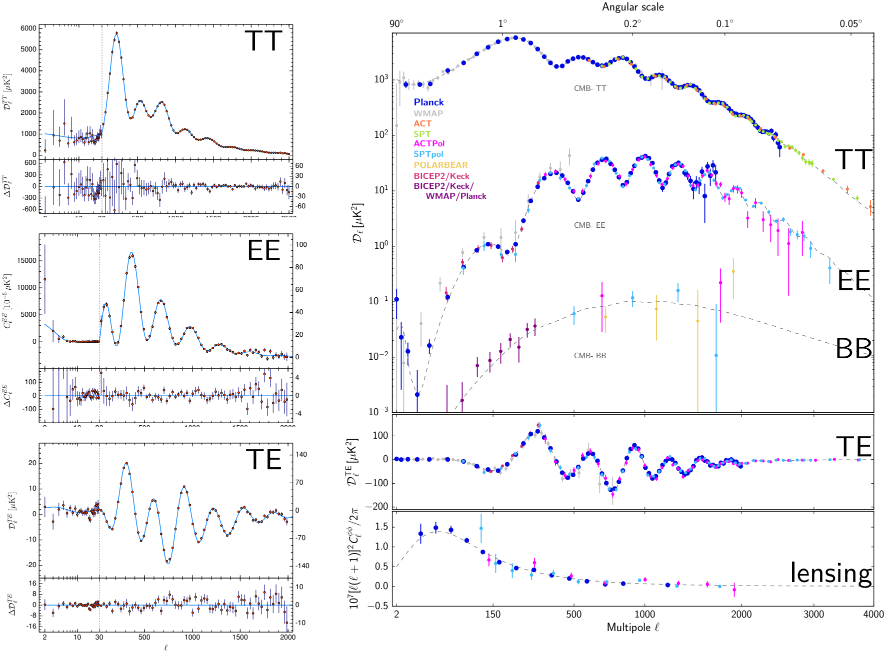
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years

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



CMB spectra as of 2018

[Planck Collaboration, 2018]



Big Bang Nucleosynthesis (BBN)

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

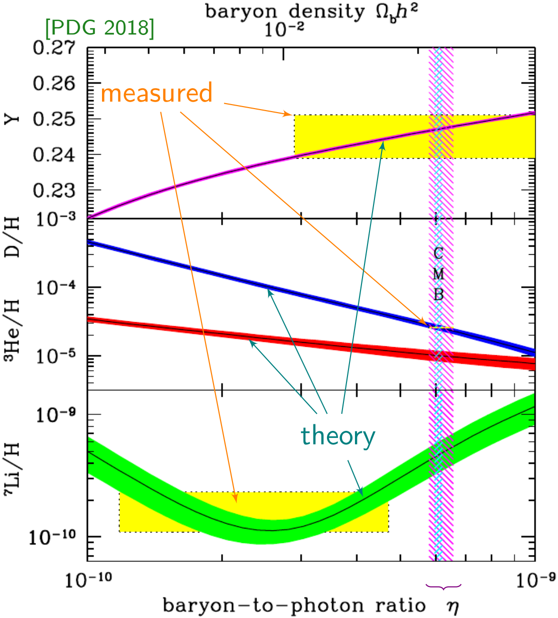
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

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]

measured

theory

BBN concordance

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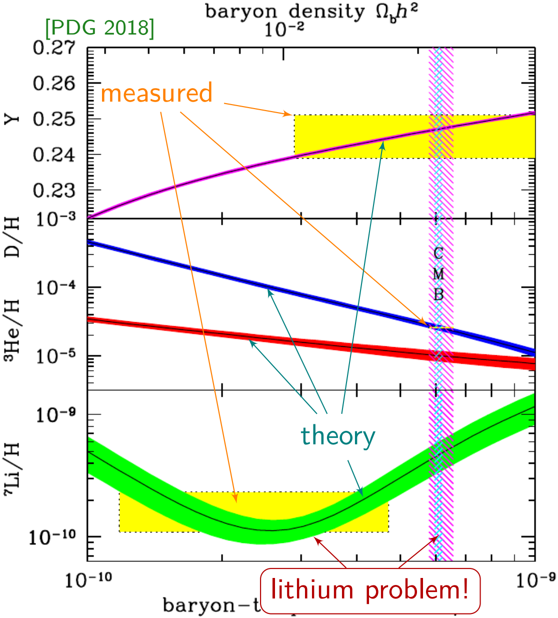

measured

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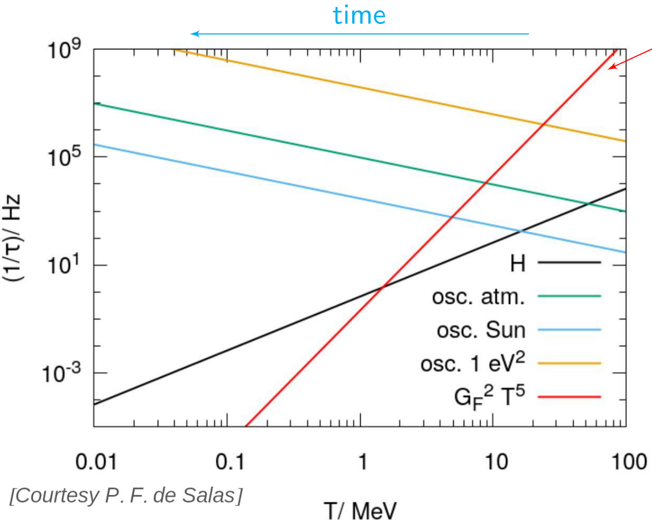
lithium problem!

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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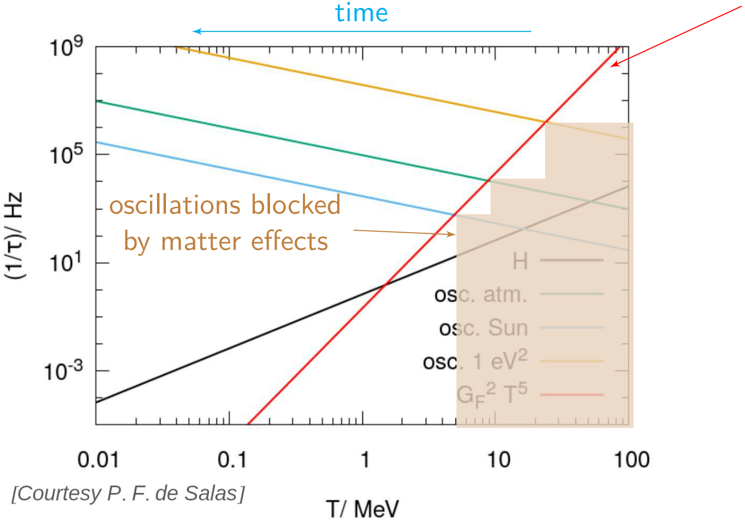

oscillations blocked by matter effects

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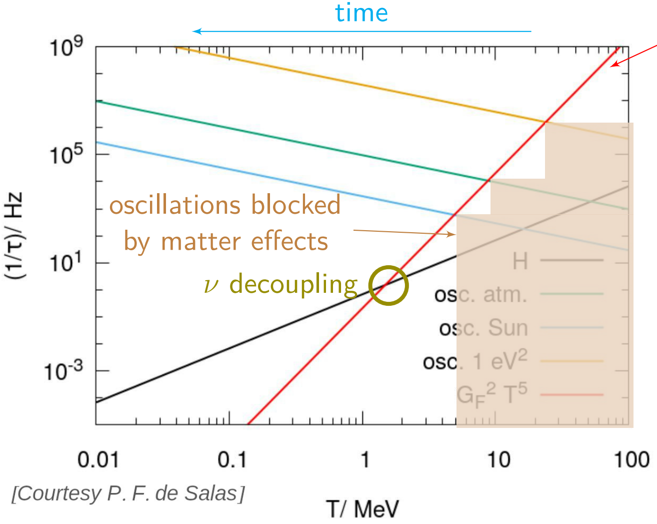

oscillations blocked by matter effects

ν decoupling

[Courtesy P. F. de Salas]

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

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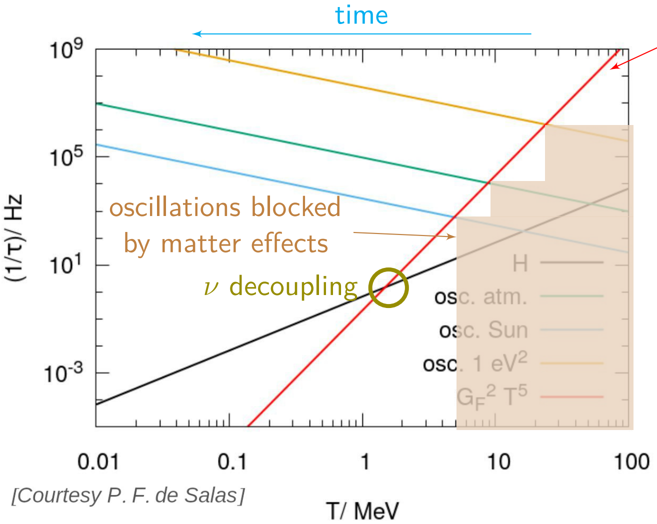

[Courtesy P. F. de Salas]

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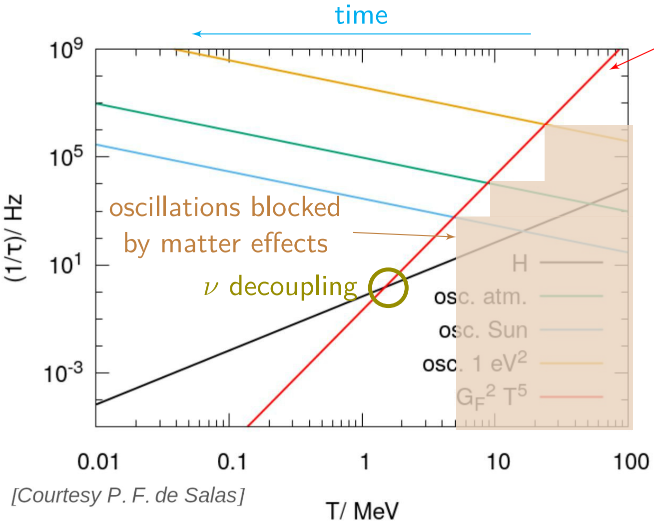

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actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

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

$\propto \langle a^\dagger_j(p,t)\, a_i(p,t) \rangle$

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

$$\boxed{\varrho \text{ evolution from } xH\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = -ia[\mathcal{H}_{\text{eff}}, \varrho] + b\mathcal{I}}$$

H Hubble factor → expansion (depends on universe content)

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

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

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

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`

vacuum oscillations ← → matter effects

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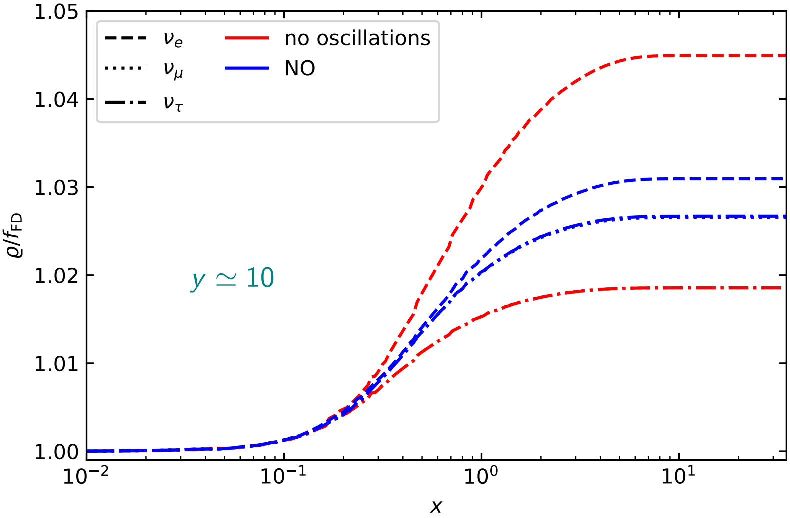
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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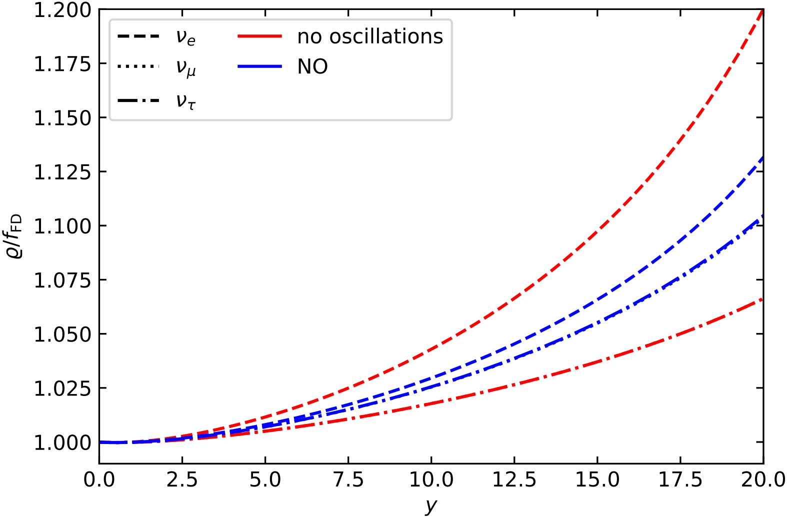
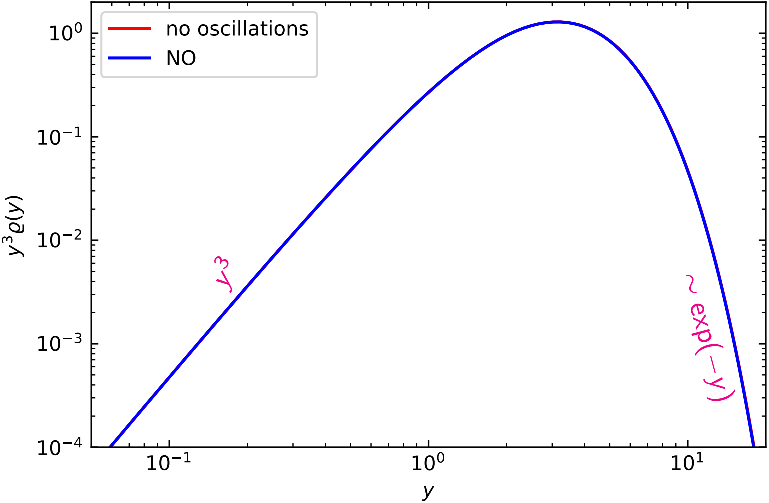


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

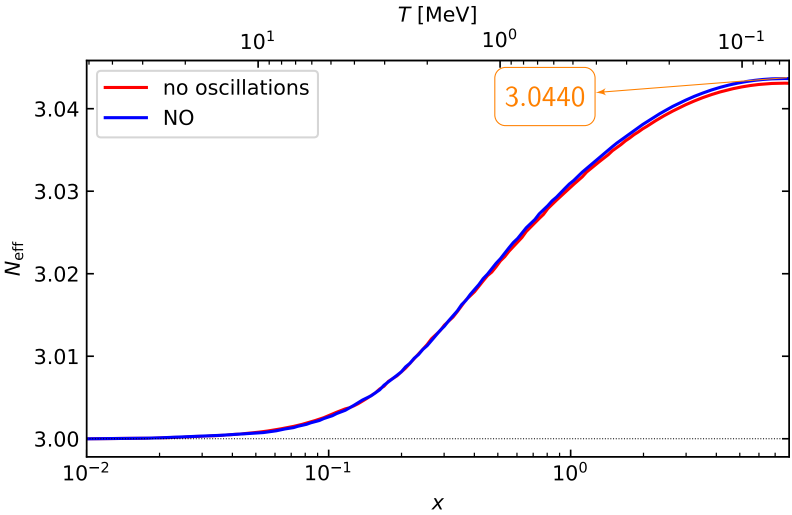
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



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

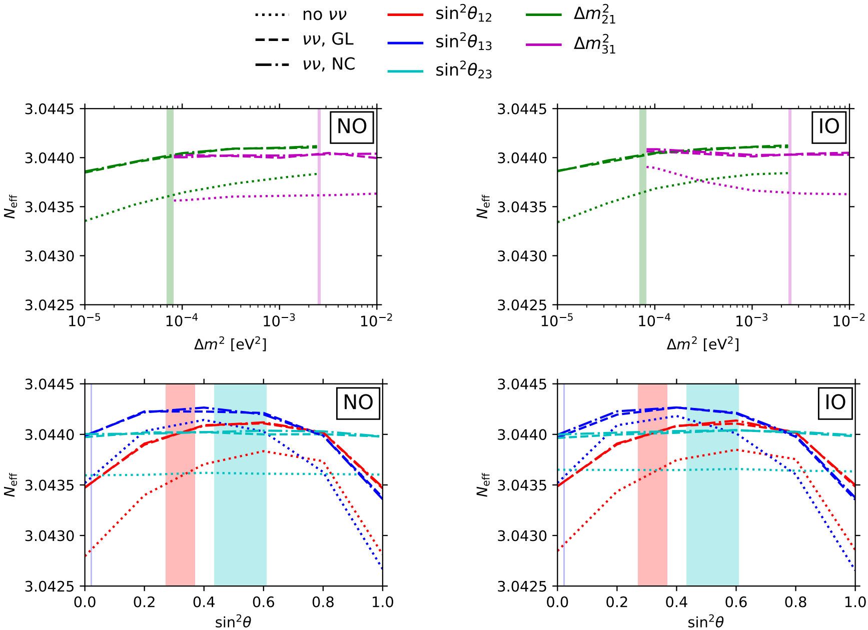
$$N_{\rm eff}^{\text{any time}} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4 \frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7}\left(\frac{T_\gamma}{T_\nu}\right)^4 \frac{1}{\rho_\gamma}\sum_i g_i \int \frac{d^3p}{(2\pi)^3} E(p)\, f_{\nu,i}(p)$$



3.0440

Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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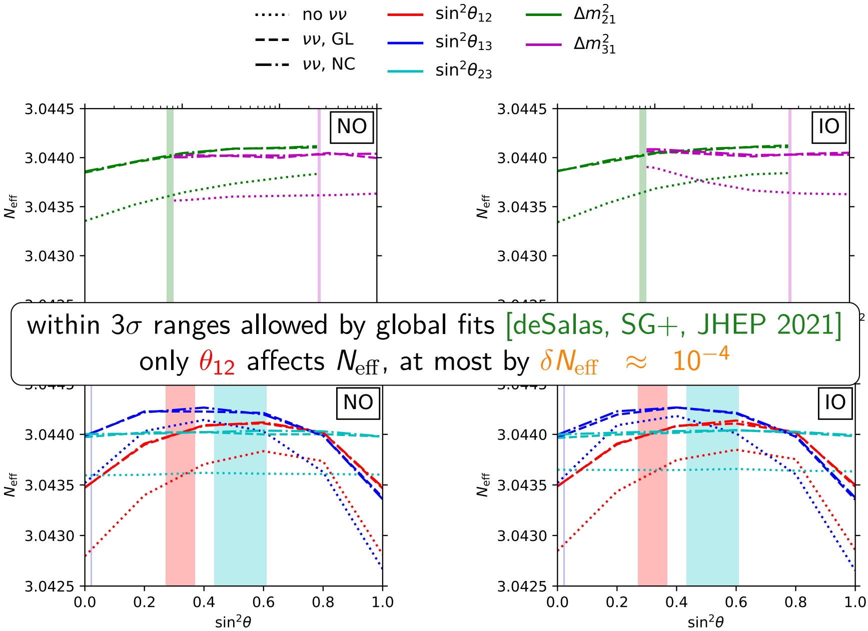
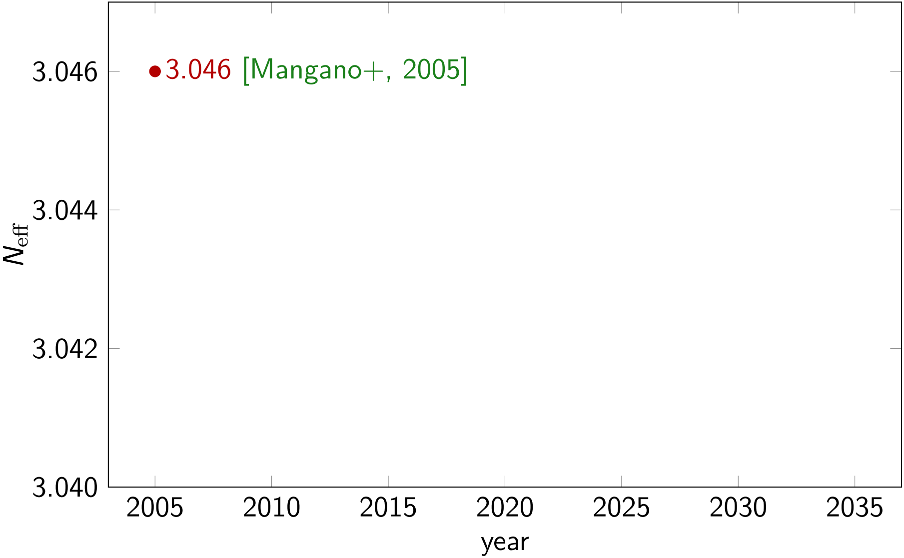


within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]
only θ_{12} affects $N_{\rm eff}$, at most by $\delta N_{\rm eff} \approx 10^{-4}$

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

Full 3ν mixing results:



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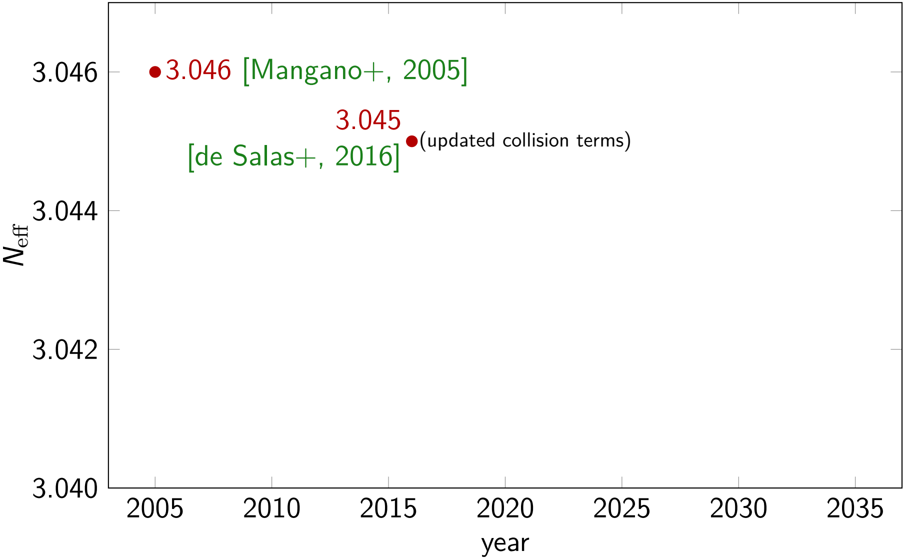

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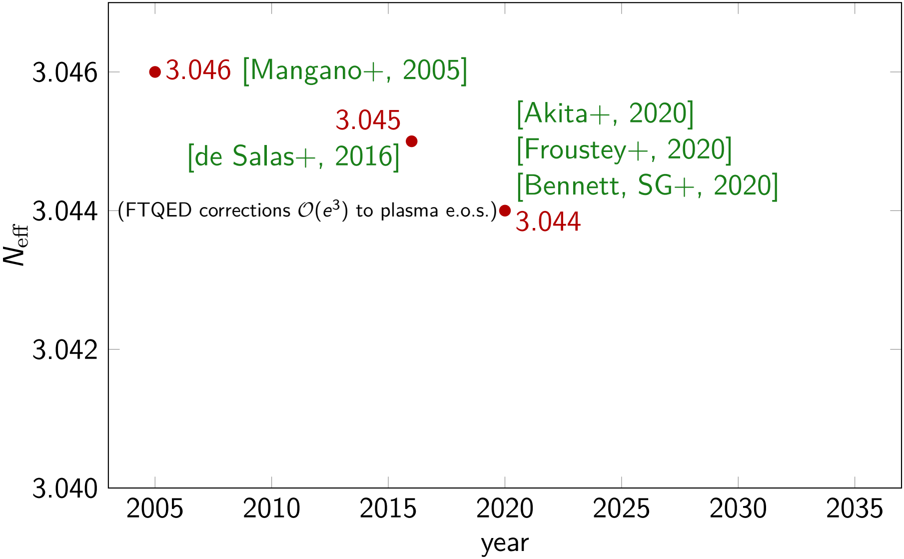

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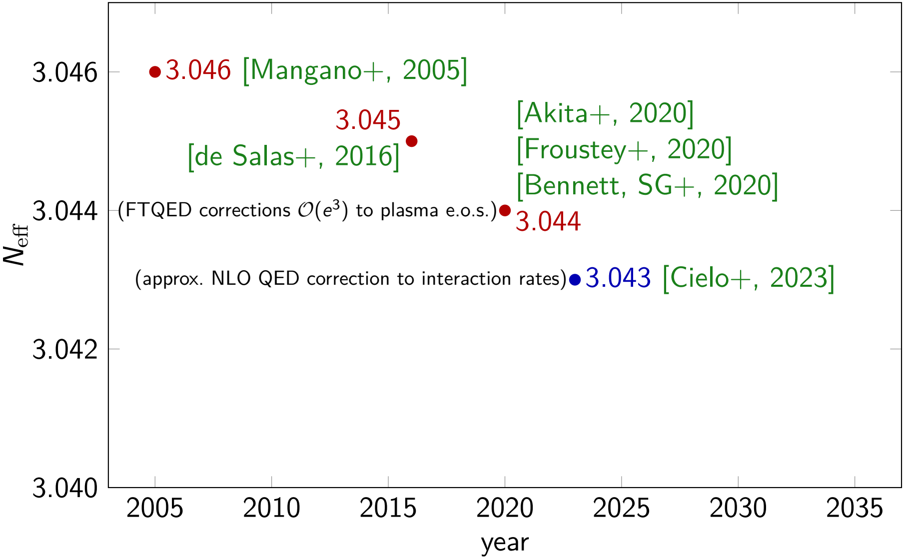

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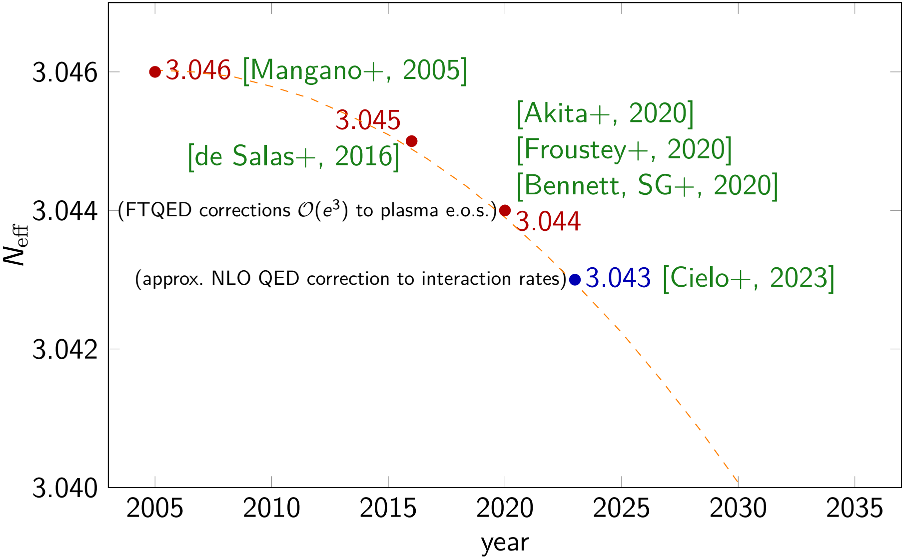

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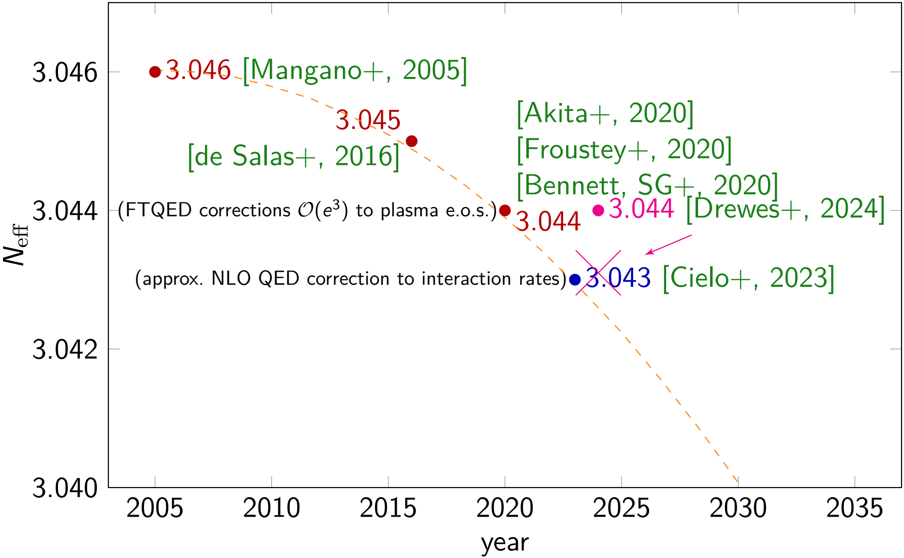
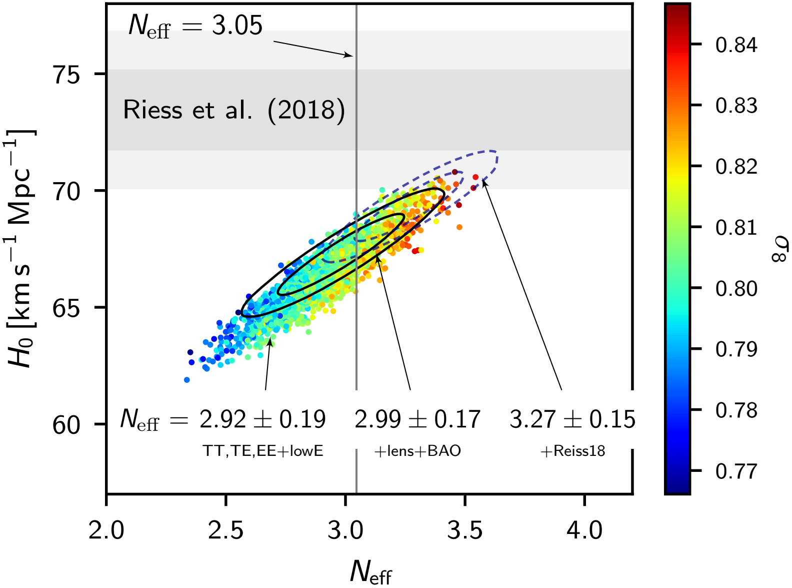


$N_{\rm eff}$ and CMB

[Planck Collaboration, 2018]



$N_{\rm eff}$ and BBN

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

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

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

$$\downarrow$$

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

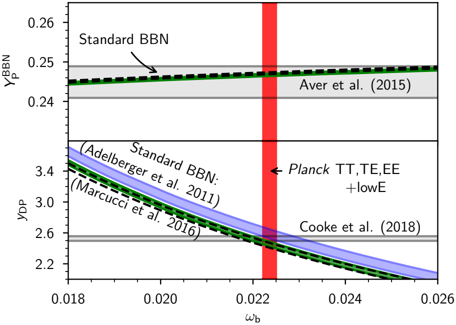
enters
$n/p = \exp(-Q/T_{fr})$
which controls element abundances

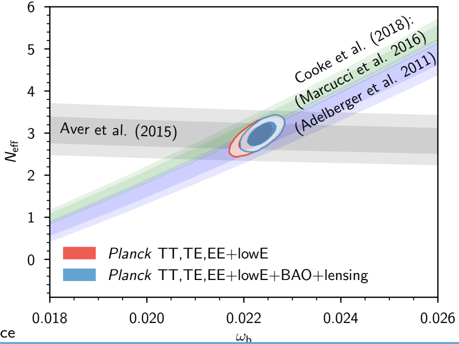
$$\boxed{g_\star \text{ depends on } N_{\rm eff}}$$

$$\downarrow$$

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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at $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

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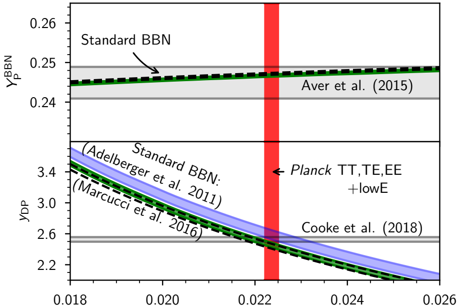
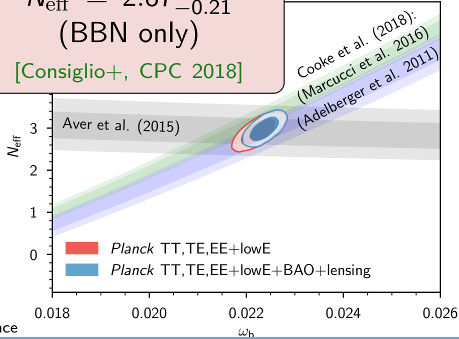


$N_{\rm eff} = 2.87^{+0.24}_{-0.21}$
(BBN only)
[Consiglio+, CPC 2018]



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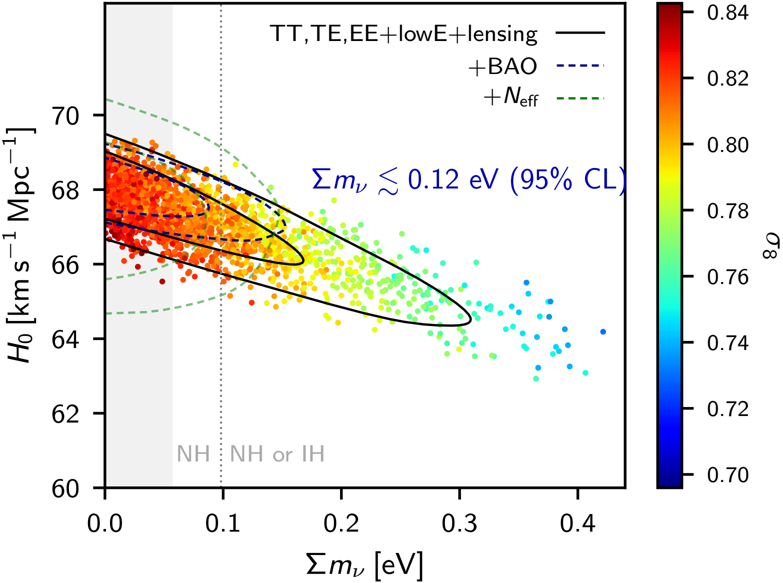
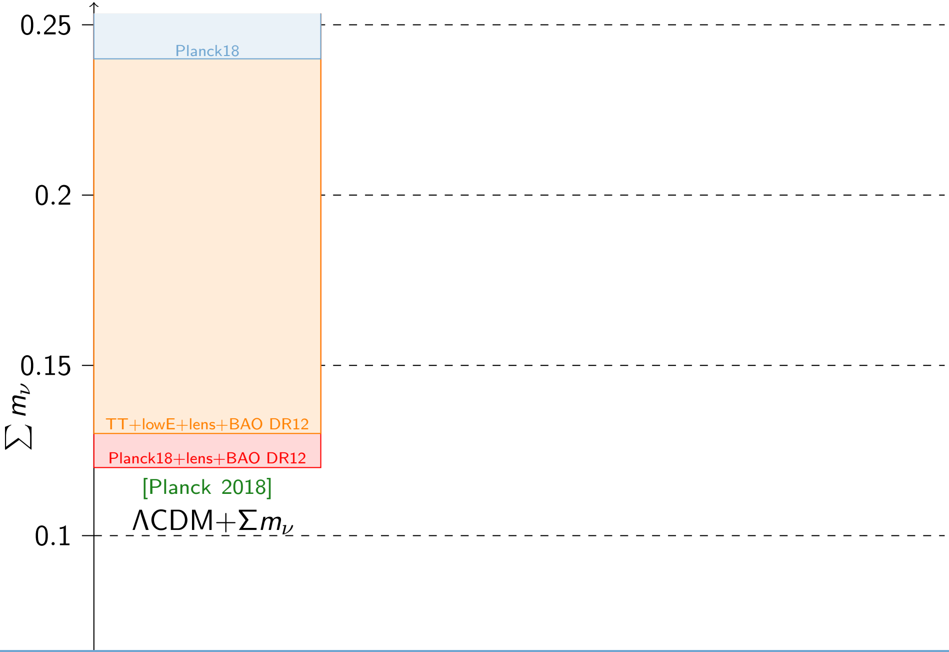
Σm_ν and CMB

[Planck Collaboration, 2018]



Cosmological neutrino mass bounds (95% CL)



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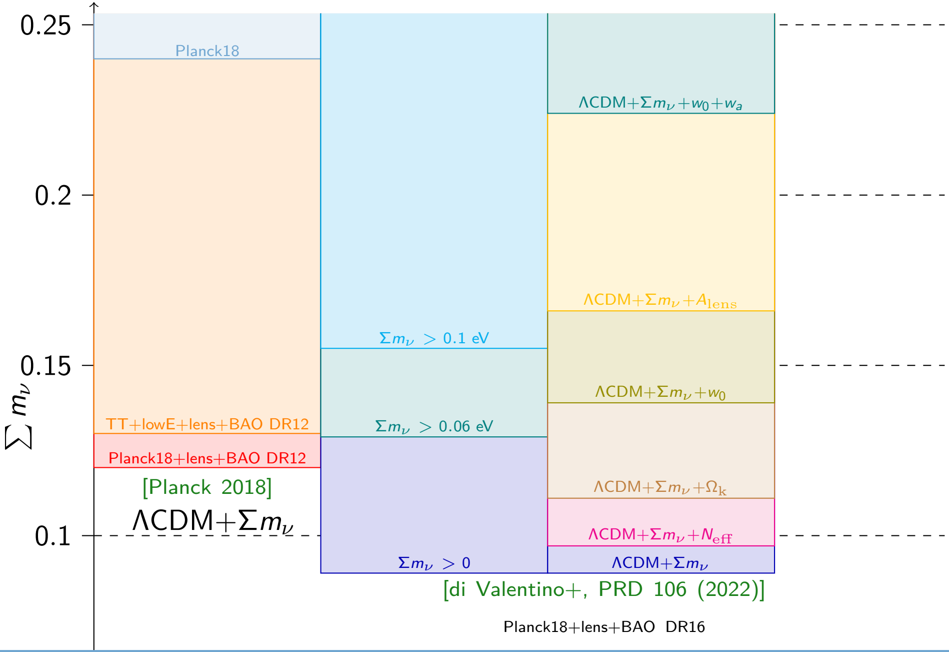

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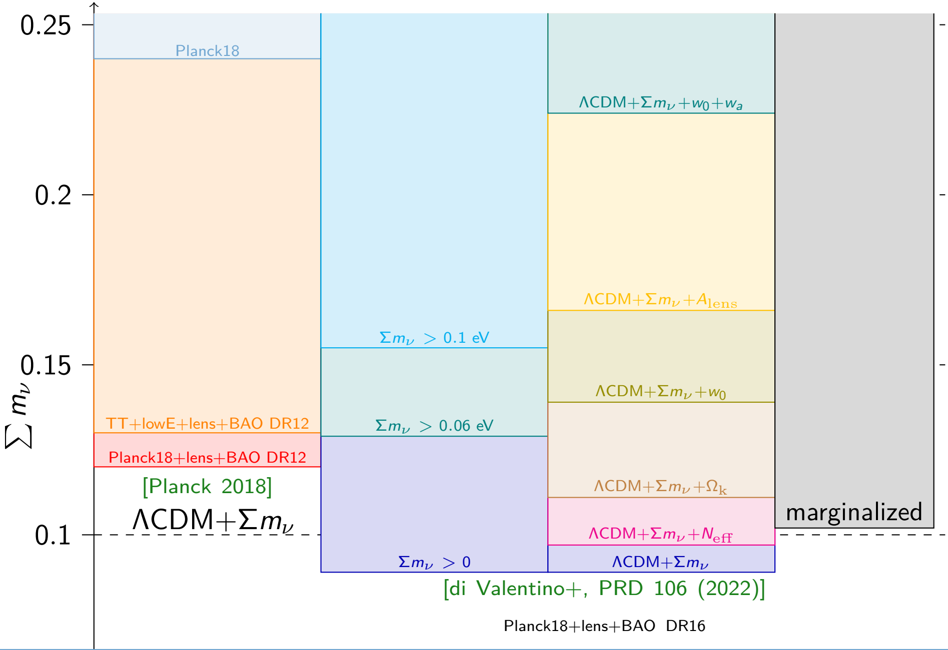


Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

standard factor

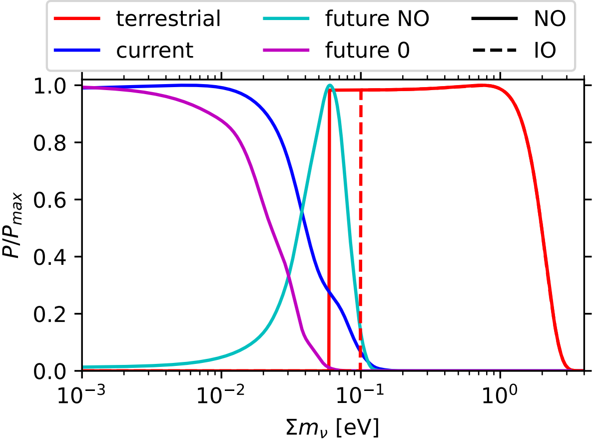
Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\text{ eV})$

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

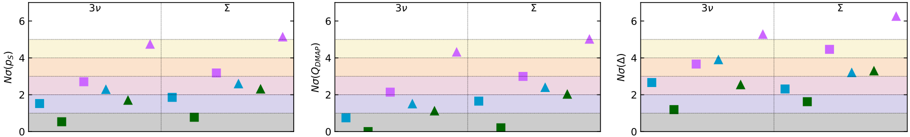
Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu / (94.12\text{ eV})$

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

Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

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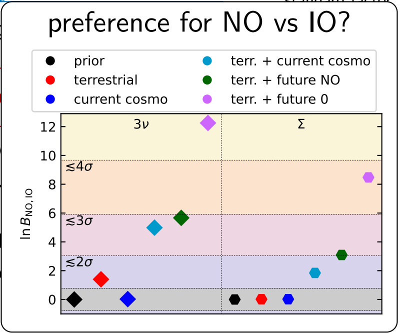
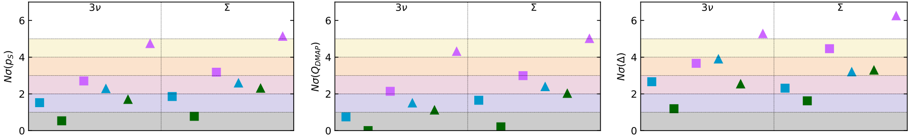
$\Sigma m_\nu = 0.00 \pm 0.02$ eV (1σ)	●	future 0	


preference for NO vs IO?



currently only mild tension between cosmology and oscillations

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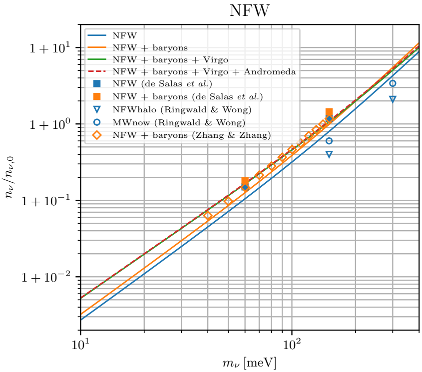
C Clustering in the local Universe

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!)

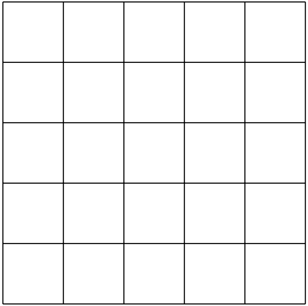
given N ν:

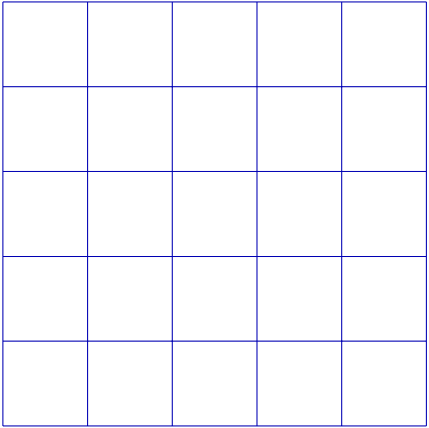
→ weigh each neutrinos

→ 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

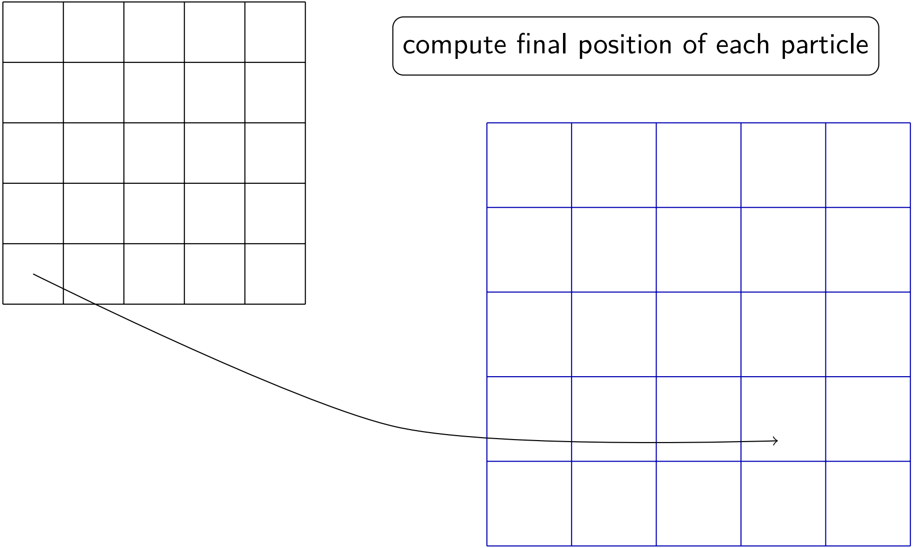




final phase space, $z = 0$

Forward-tracking and back-tracking

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



compute final position of each particle

final phase space, $z = 0$

Forward-tracking and back-tracking

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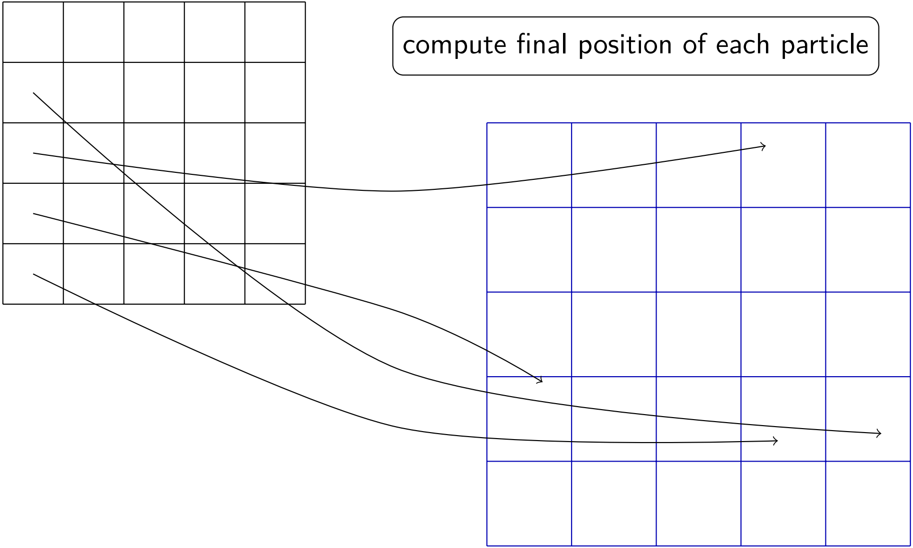

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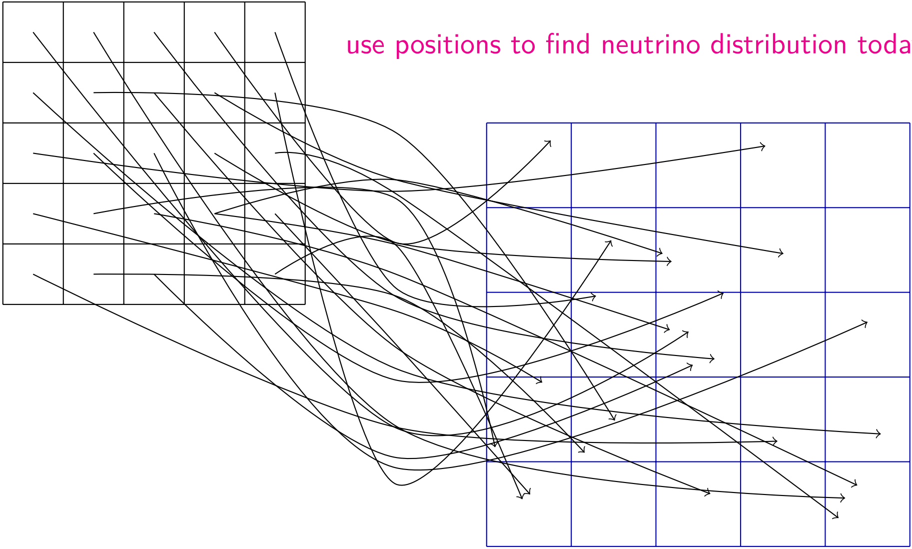

use positions to find neutrino distribution today

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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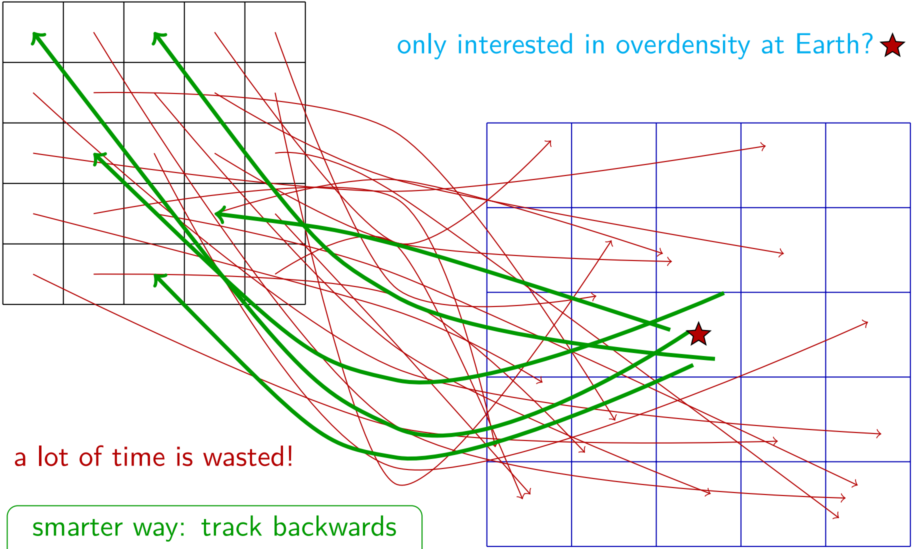


only interested in overdensity at Earth? ★

a lot of time is wasted!

smarter way: track backwards
only interesting particles!

final phase space, $z = 0$

Advantages of tracking back

[JCAP 01 (2020) 015]

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

Advantages of tracking back

[JCAP 01 (2020) 015]

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

Second advantage: no need to use spherical symmetry!

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)

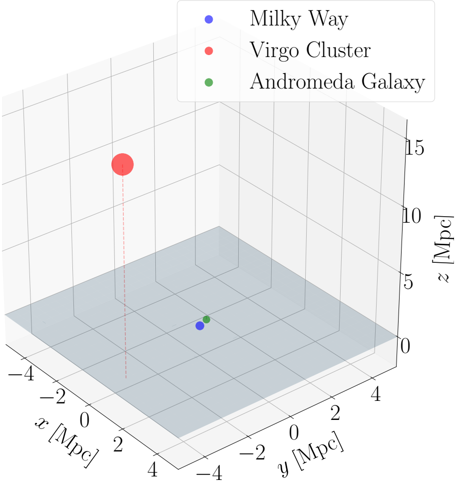
can do the calculation with
any astrophysical setup

Advantages of tracking back

[JCAP 01 (2020) 015]

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

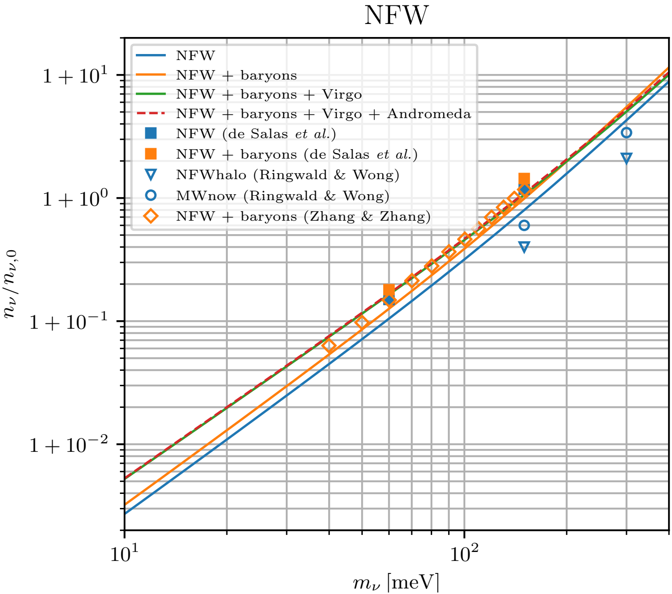
Second advantage: no need to use spherical symmetry!



Clustering results with back-tracking

[JCAP 01 (2020) 015]

In comparison with previous results:



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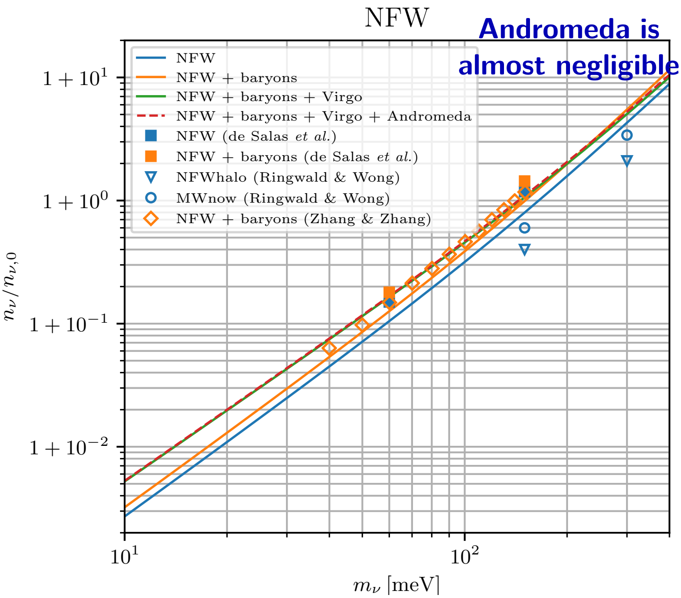
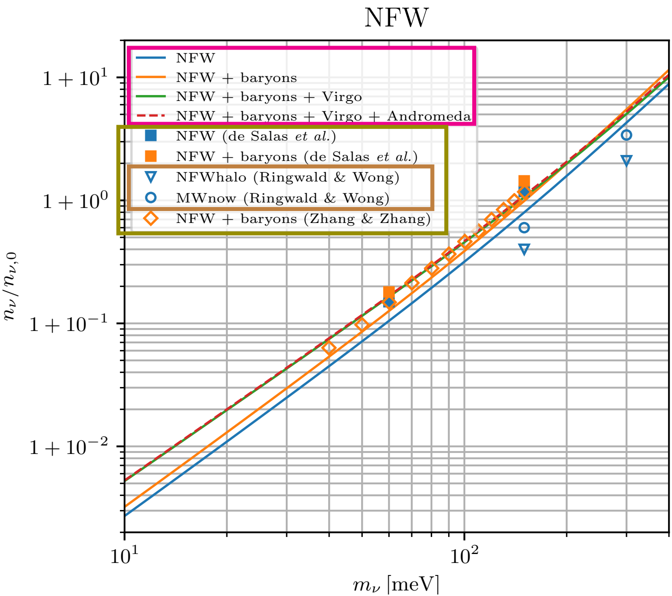


Andromeda is almost negligible

Clustering results with back-tracking

[JCAP 01 (2020) 015]

In comparison with previous results:



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

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

[Ringwald&Wong, 2004] uses old parameters

Clustering results with back-tracking

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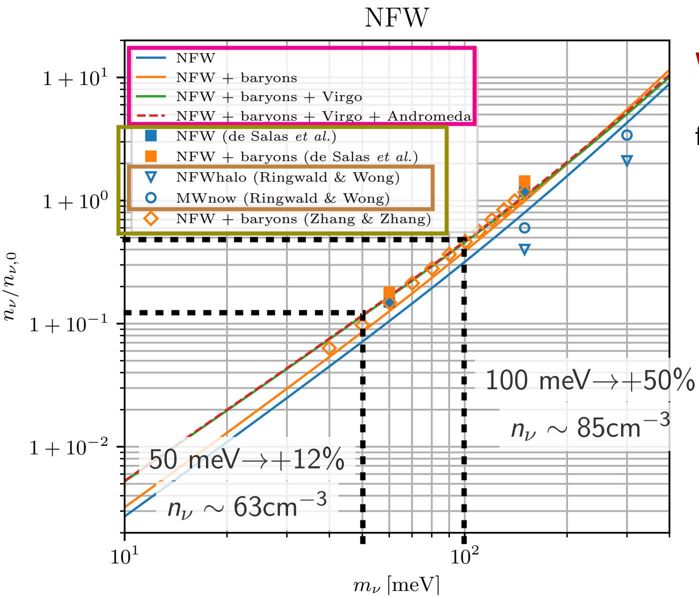

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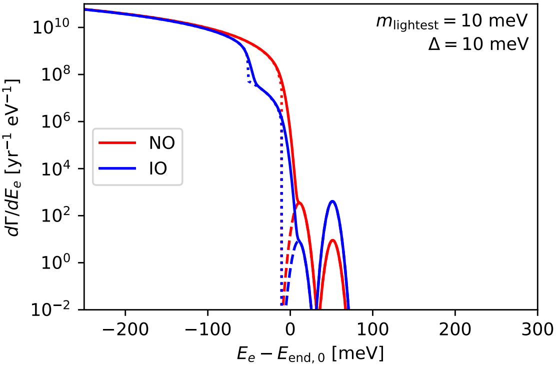
D

Direct detection of relic neutrinos

Based on:

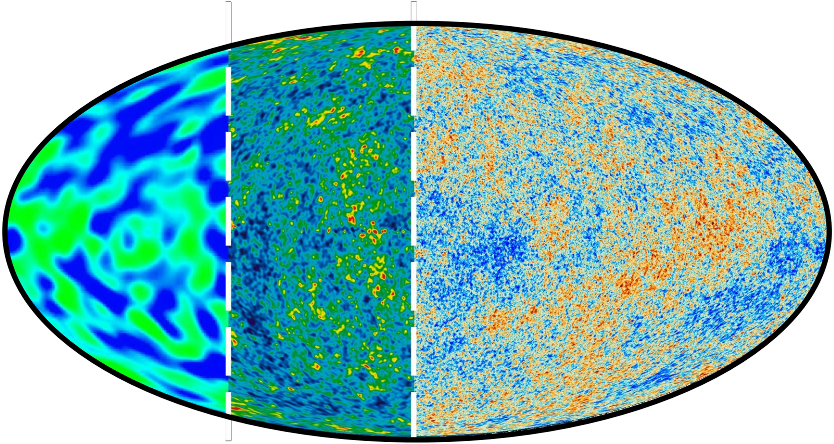
- JCAP 01 (2023) 003
- JCAP 08 (2014) 038
- JCAP 07 (2019) 047



The oldest picture of the Universe

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

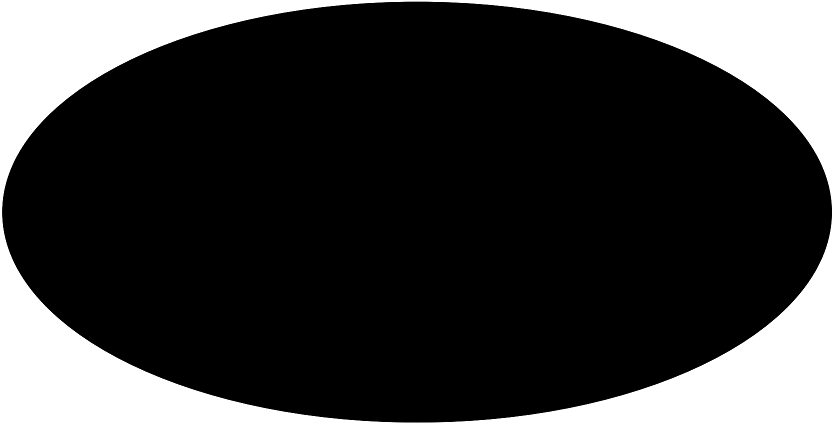
COBE (1992) WMAP (2003) Planck (2013)



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

↓

torque on e^- in lab rest frame

↓

use a ferromagnet to build detector

↓

measure torque with a torsion balance

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[Stodolsky, 1974][Duda+, 2001]

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↓

use a ferromagnet to build detector

↓

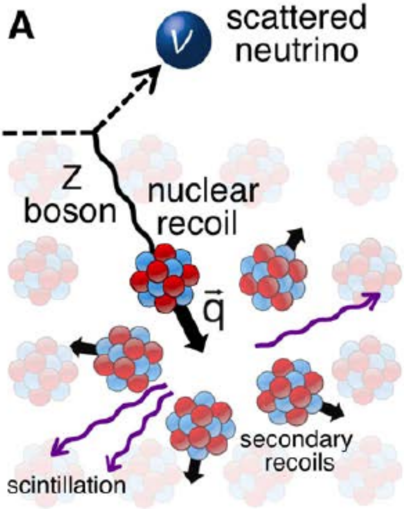
measure torque with a torsion balance

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

[Shergold, JCAP 2021]

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

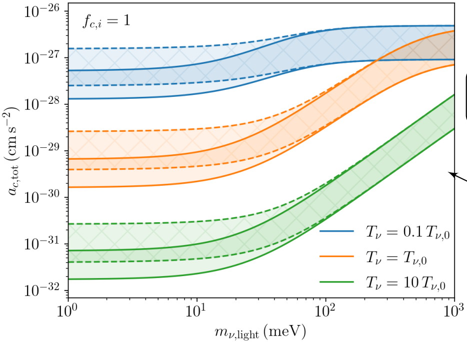
elastic scattering where ν interacts with nucleous "as a whole"

Can we detect relic neutrinos with CEνNS?

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

$\downarrow$

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



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

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

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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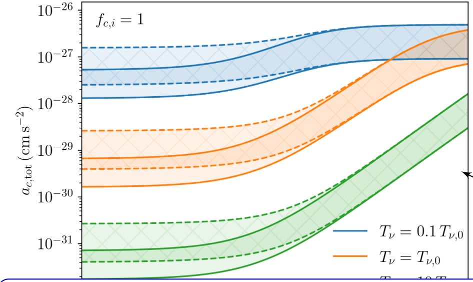

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A, Z mass, atomic numbers
p_ν, E_ν neutrino momentum and energy
Δp_ν net momentum transfer
n_ν neutrino number density
ρ target mass density

unclustered relic νs, $n_\nu = n_0$

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

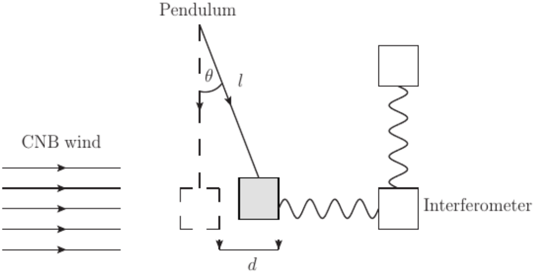
At interferometers?

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



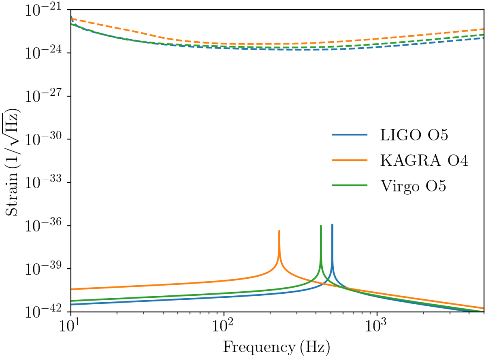
At interferometers?

How to directly detect non-relativistic neutrinos?

At interferometers

[Domcke+, 2017] [Shergold, 2021]

coherent scattering of relic ν on a pendulum $\longrightarrow$ measure oscillations at interferometers



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 ⟶ a process without energy threshold is necessary

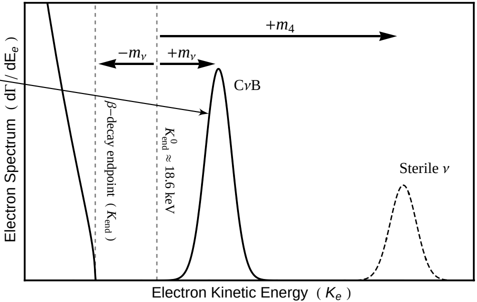
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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

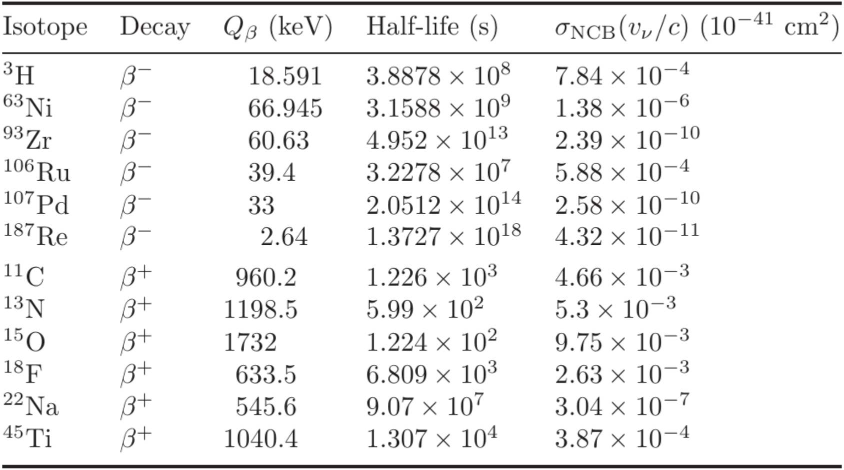


What material?

[Cocco+, JCAP 06 (2007) 015]

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

to minimize contamination from β decay background



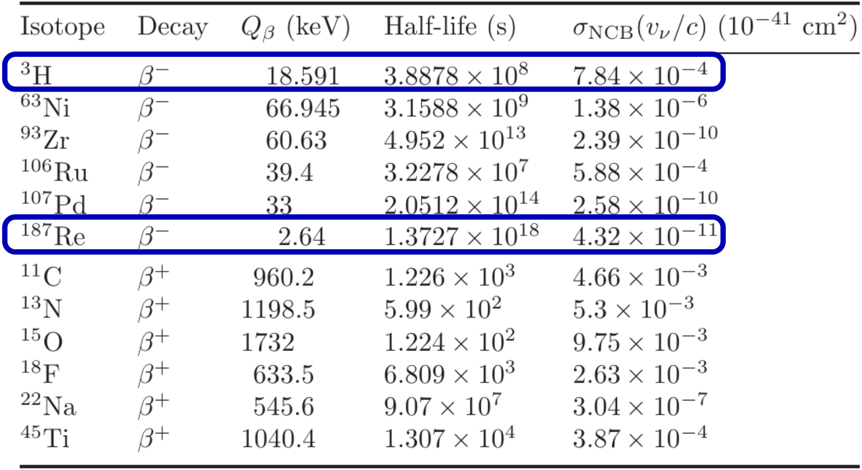
Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{\mathrm{NCB}}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{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}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

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



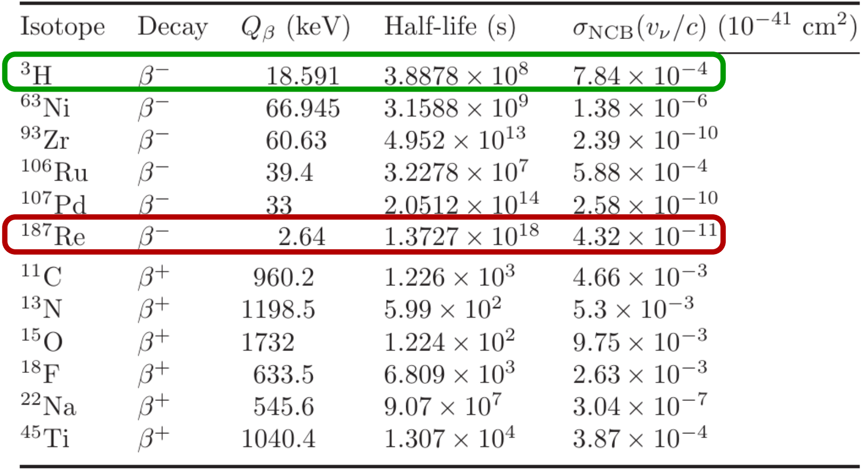
Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^{8}	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^{9}	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^{7}	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{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}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^{4}	3.87×10^{-4}

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



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^{3}H better because the cross section (→ event rate) is higher

At accelerator facilities?

[Bauer+, PRD 2021]

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

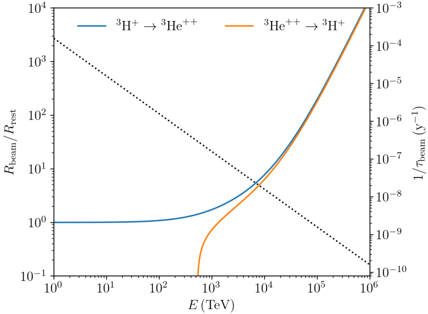
Large background due to tritium beta decay...

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

$$\begin{tikzcd}
P \arrow[r, shift left, "\mathrm{RB}\beta"] & D \arrow[l, dashed, shift left, "\mathrm{EC}"]
\end{tikzcd}$$

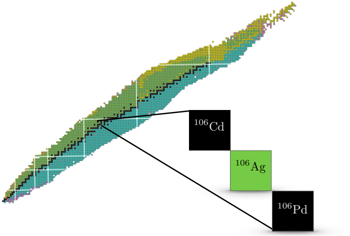
Max event rate at equilibrium limits
information on RBβ rate when running a long experiment

better: try to measure final stable state F in

3-state

$$\begin{tikzcd}
 & & F^+ \\
P \arrow[r, shift left, "\mathrm{RB}\beta"] & D \arrow[l, dashed, shift left, "\mathrm{EC}"] \arrow[ur, dotted, "\mathrm{C}\beta"] \arrow[dr, "\mathrm{B}\beta"'] & \\
 & & F
\end{tikzcd}$$

e.g.



At accelerator facilities?

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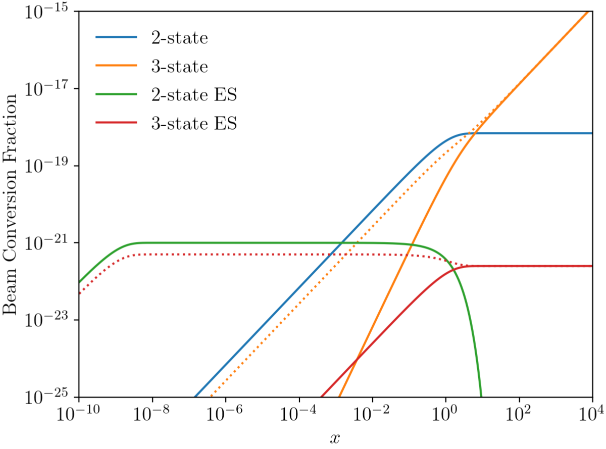

2-state

$$\begin{tikzcd} P \arrow[r, shift left, "\mathrm{RB}\beta"] & D \arrow[l, shift left, dashed, "\mathrm{EC}"] \end{tikzcd}$$

3-state

$$\begin{tikzcd} & & F^{+} \\ P \arrow[r, shift left, "\mathrm{RB}\beta"] & D \arrow[l, shift left, dashed, "\mathrm{EC}"] \arrow[ur, dotted, "\mathrm{C}\beta"] \arrow[dr, "\mathrm{B}\beta"'] & \\ & & F \end{tikzcd}$$

excited states
also possible

β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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

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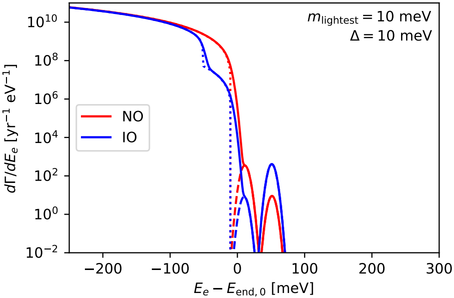

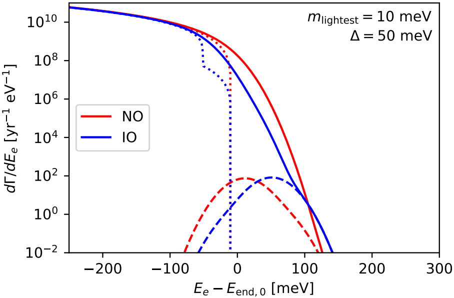

PTOLEMY

[PTOLEMY LoI, arxiv:1808.01892]

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

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

built mainly for CNB

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)

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

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

ehnancement from
ν clustering in the galaxy?

ehnancement from
other effects?

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

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PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]

[Courtesy A. Esposito]

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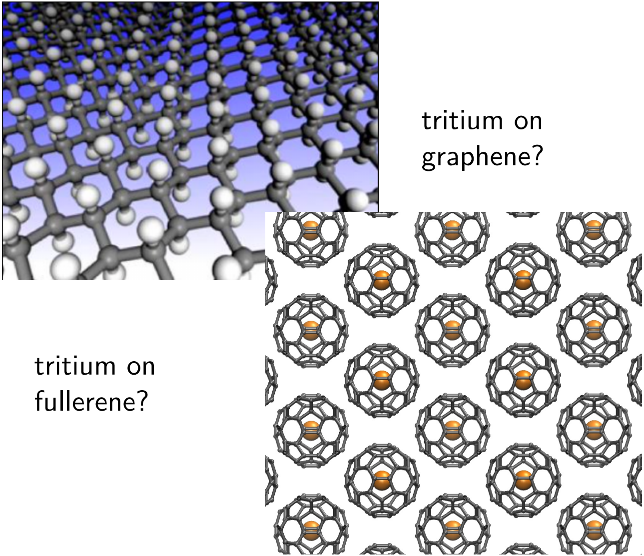


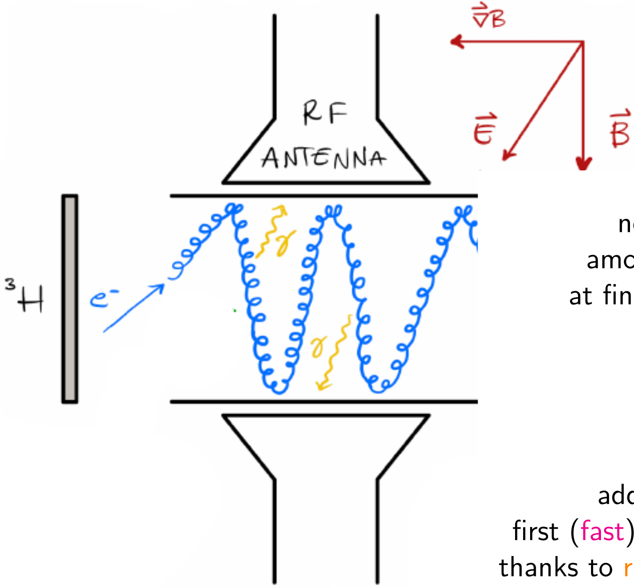
tritium on graphene?

tritium on fullerene?

[Courtesy V. Tozzini]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]



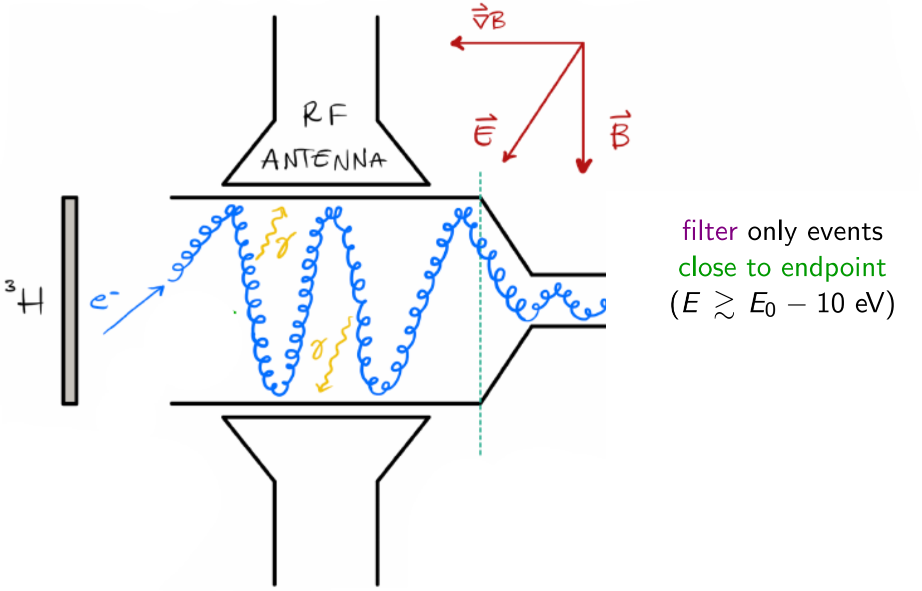
need to reduce
amount of electrons
at final energy sensors:
EM filter

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

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]

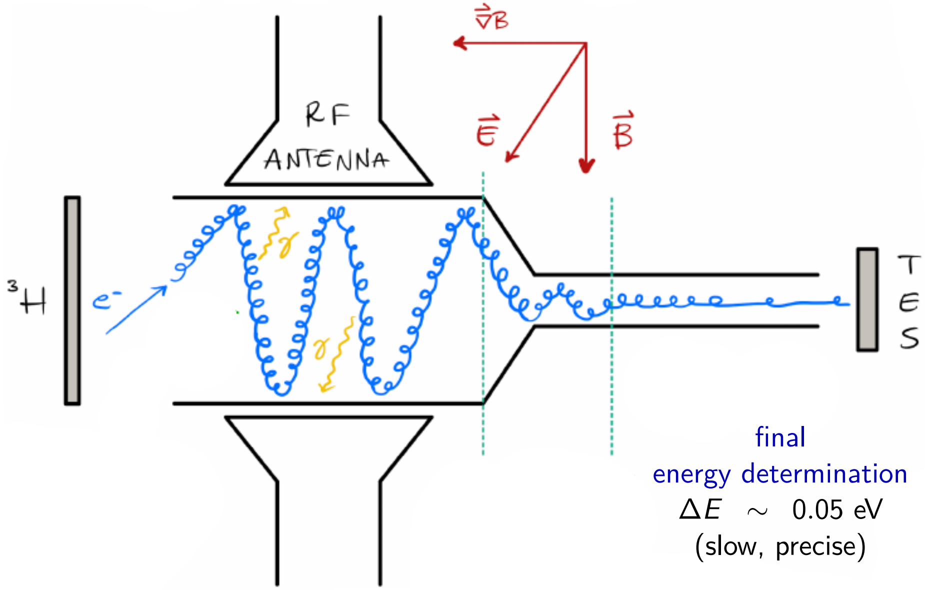


filter only events
close to endpoint
($E \gtrsim E_0 - 10$ eV)

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]



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

[Courtesy A. Esposito]

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

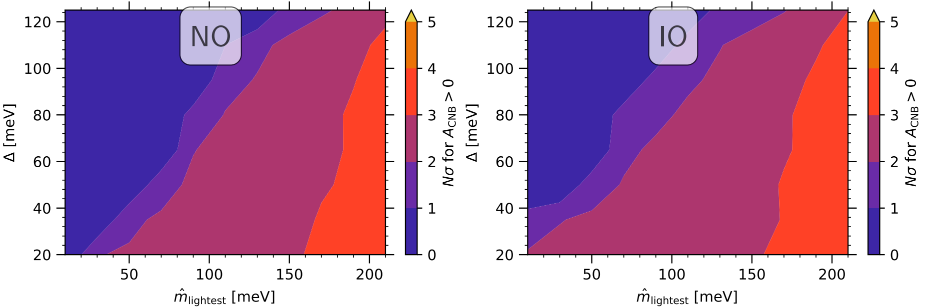
using the definition:

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

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



Time variations of ν capture rates

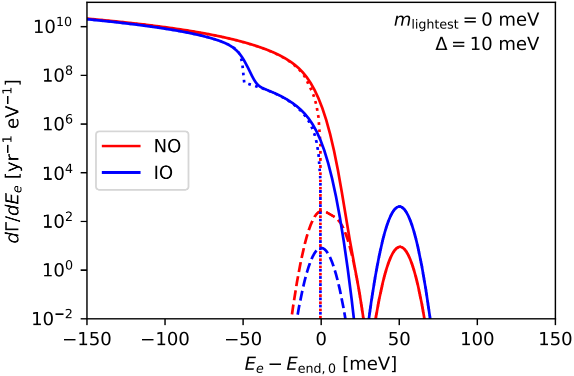
[Akhmedov, JCAP 2019]

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

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

$$\frac{\nu\text{ capture rate}}{\beta\text{ decay rate}} = \frac{\Gamma_{\rm NC}}{\Gamma_\beta} \simeq \frac{n_\nu}{56\text{ cm}^{-3}}\frac{2.54\times10^{-11}}{(\Delta/\text{eV})^3}$$

rates in the bin Δ on the endpoint



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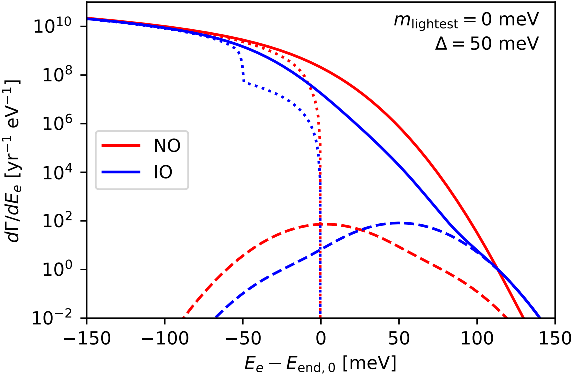

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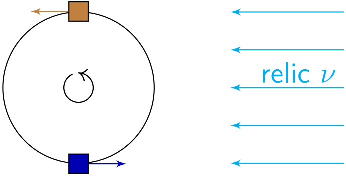

can be daily or annual modulation!

only for ν capture (no β-decay)

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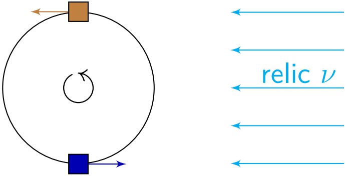


can be daily or annual modulation!

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!

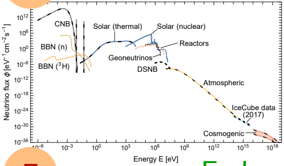
Z Conclusions

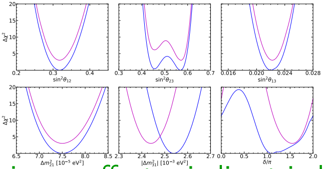
almost there!

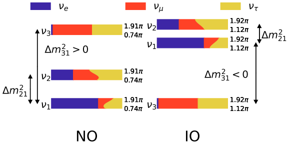
What do we learn from relic neutrinos?

N

Neutrinos: precision era (many sources)

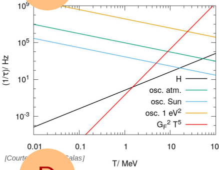


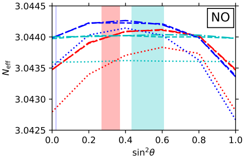


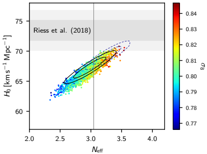


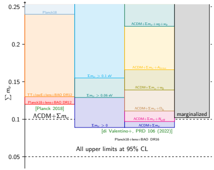
E

Early universe effects: indirect indications



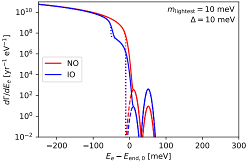


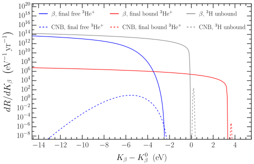


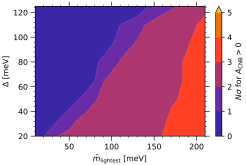


D

Direct detection: still long to go







What do we learn from relic neutrinos?

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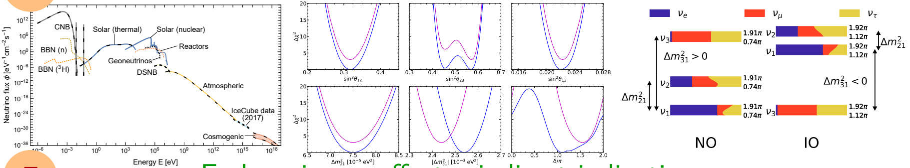
Neutrinos: precision era (many sources)



E

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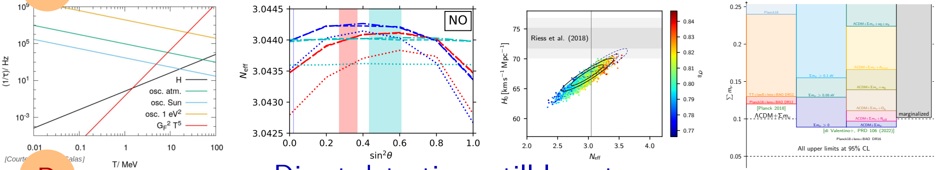

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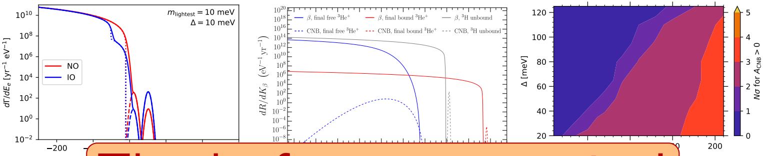


Thanks for your attention!

6 Appendix

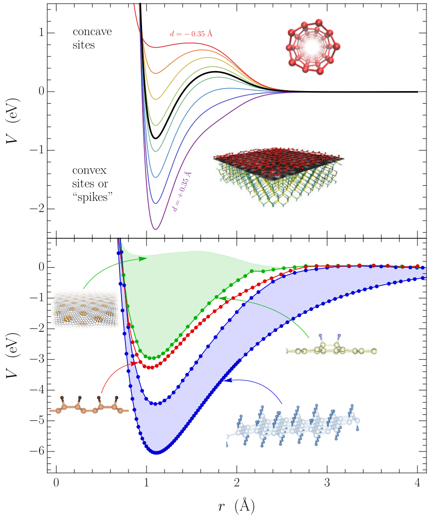
Quantum uncertainty and PTOLEMY

[PTOLEMY, PRD 106 (2022)]

Tritium atoms will be attached to graphene sheets

↓

Quantum uncertainty on electron energy due to condensed matter state



Binding potential depends on distance graphene-tritium and graphene sheet configuration

Concave sites behave differently than convex ones

Hydrogen coverage (amount of H atoms in the graphene sheet) is also important

Quantum uncertainty and PTOLEMY

[PTOLEMY, PRD 106 (2022)]

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↓

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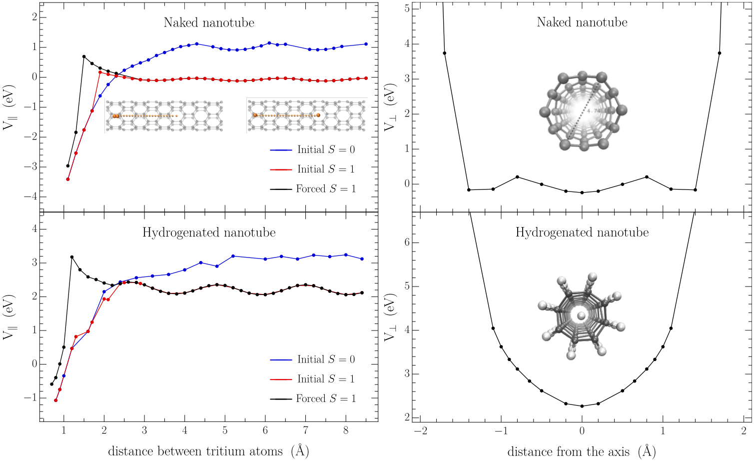

Nanotube configurations have flat potential parallel to nanotube axis

Quantum uncertainty and PTOLEMY

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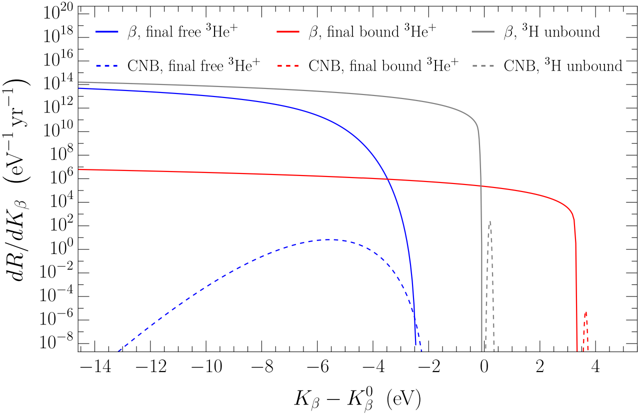


Graphene configuration can make observation range from completely impossible or suppressed but possible

Dirac and Majorana neutrinos

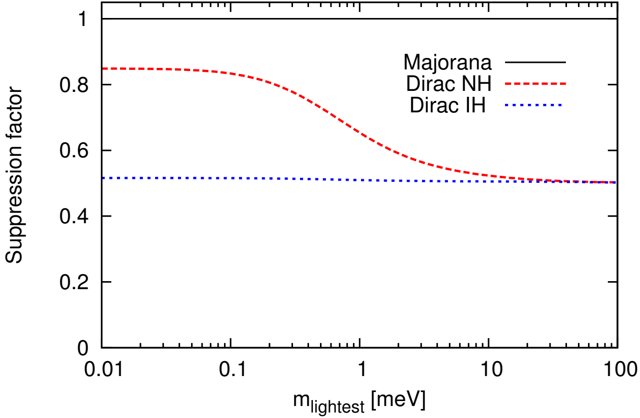
[Roulet+, JCAP 10 (2018) 049]

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**