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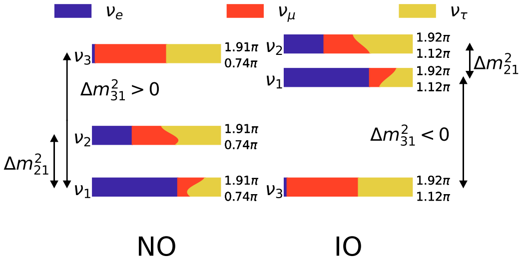
Relic neutrinos: decoupling and direct detection perspectives

Neutrino Frontiers: Focus week. GGI, Firenze, 01–05/07/2024

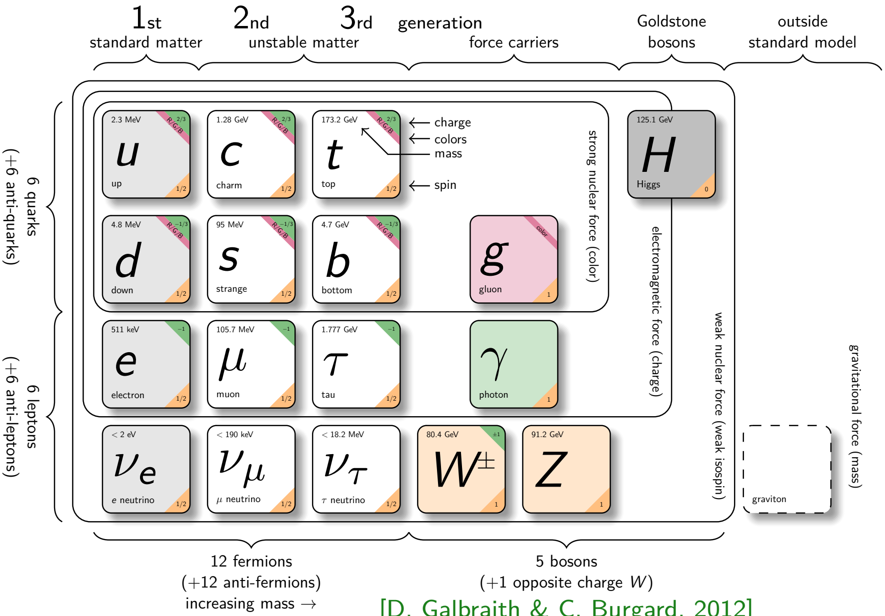
N Neutrinos

Based on:

- JHEP 02 (2021) 071 and update



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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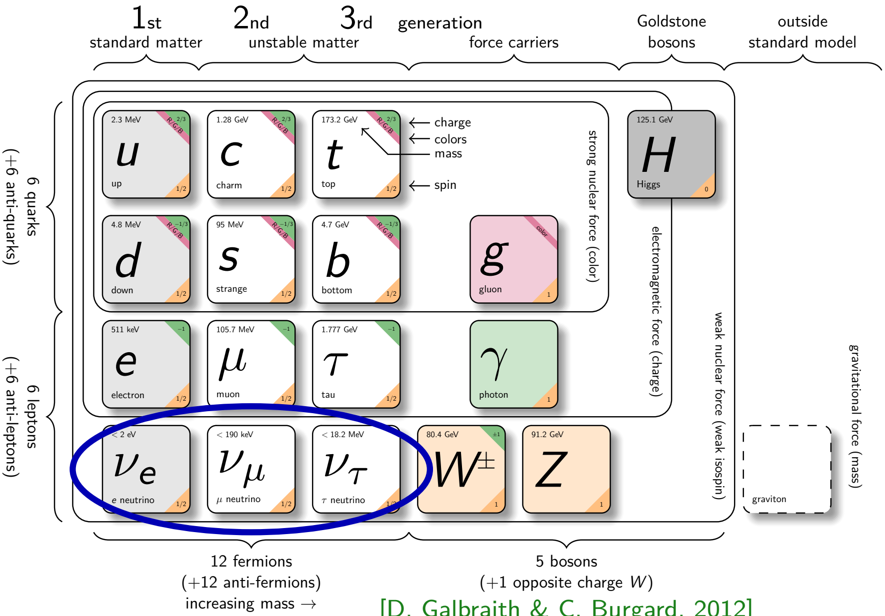
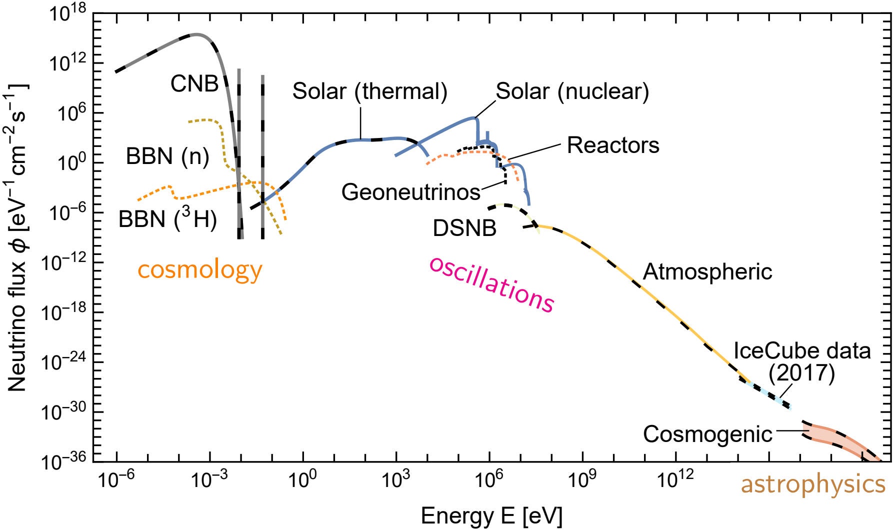


[D. Galbraith & C. Burgard, 2012]

Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]



neutrinos at all energies provide valuable information!

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

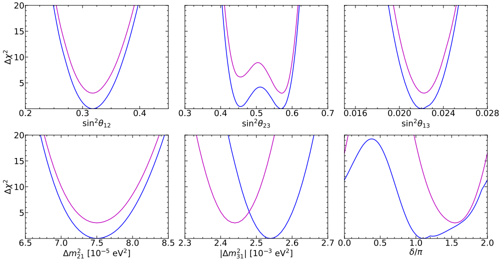
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

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

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

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



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)

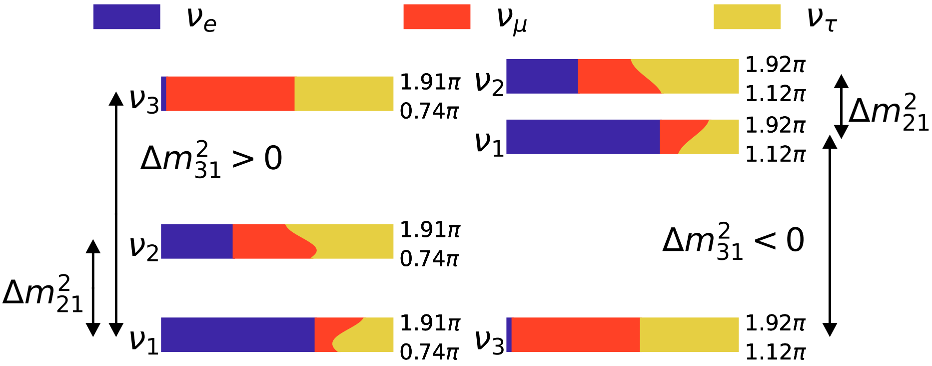
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV



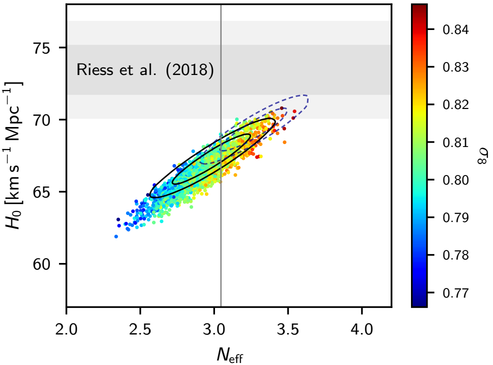
Absolute scale unknown!

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

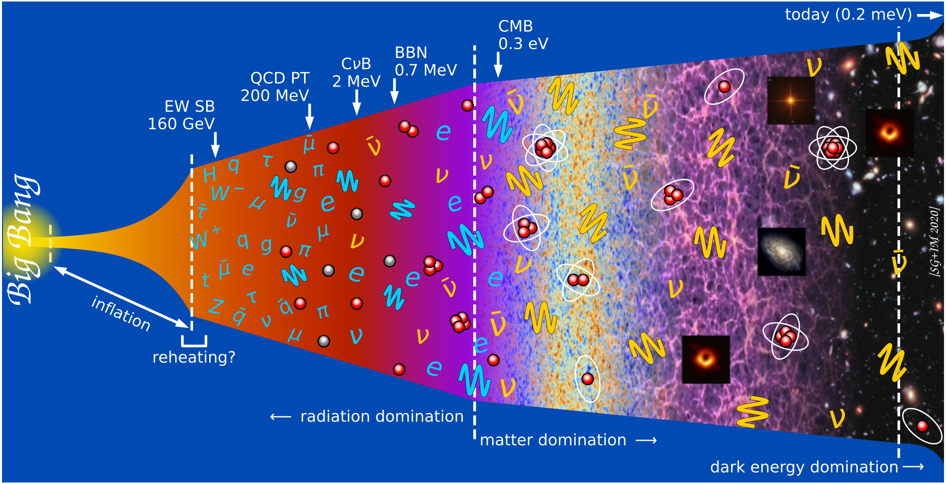
E Neutrinos in the Early Universe

Based on:

- Planck 2018
- JCAP 04 (2021) 073



History of the universe



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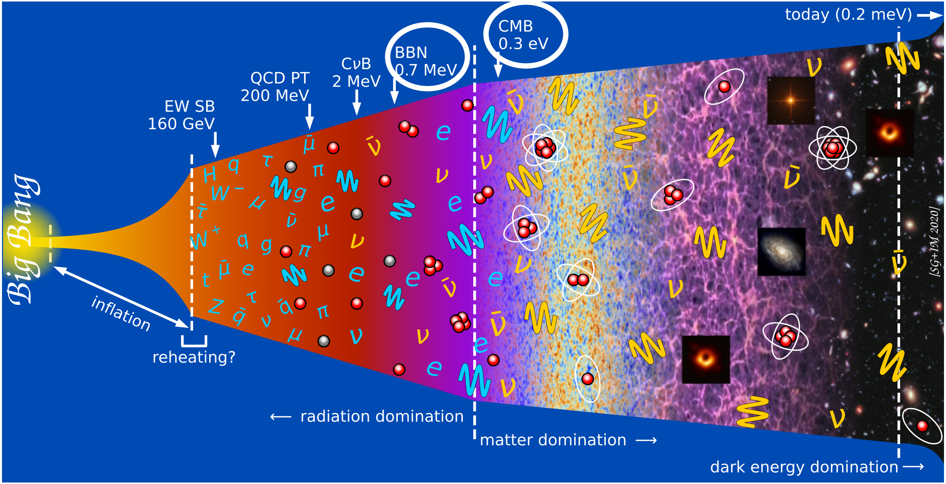
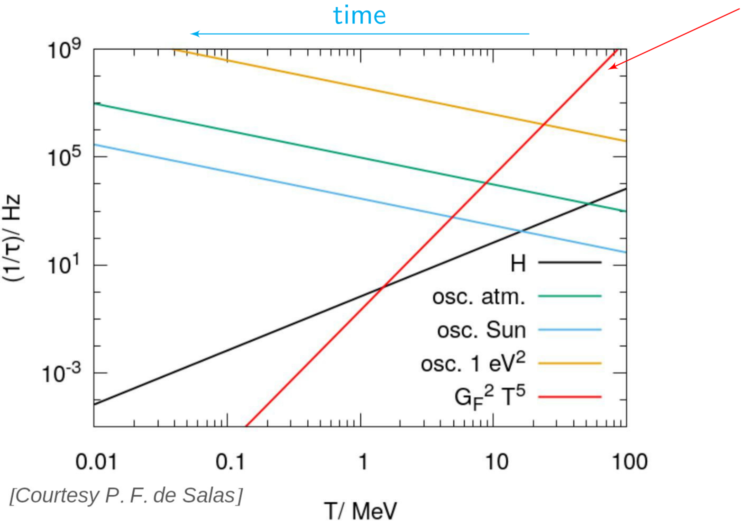


Neutrinos in the early Universe

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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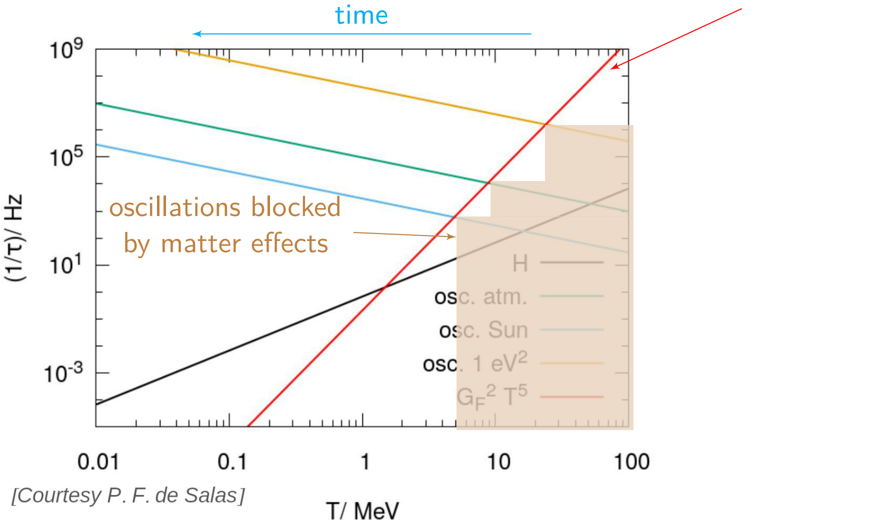

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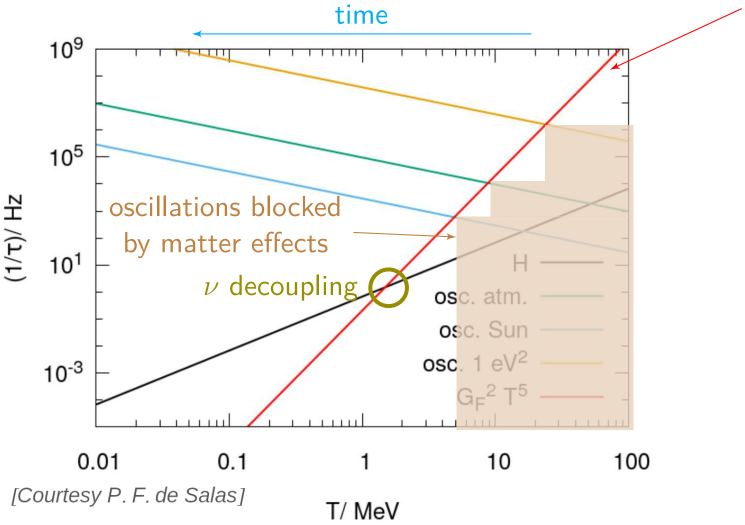

ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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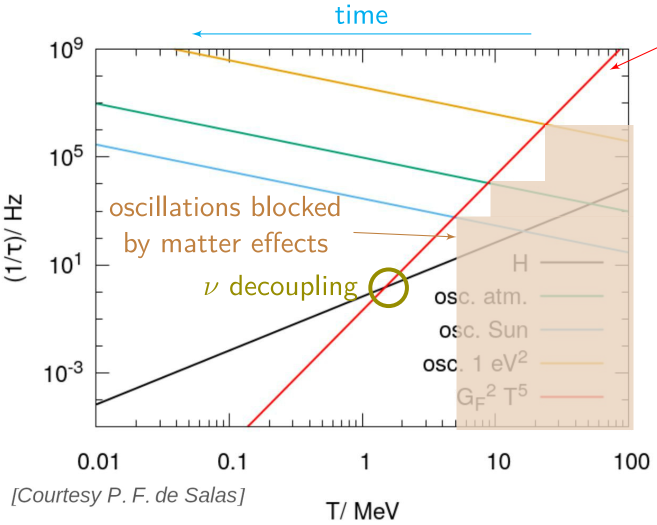

[Courtesy P. F. de Salas]

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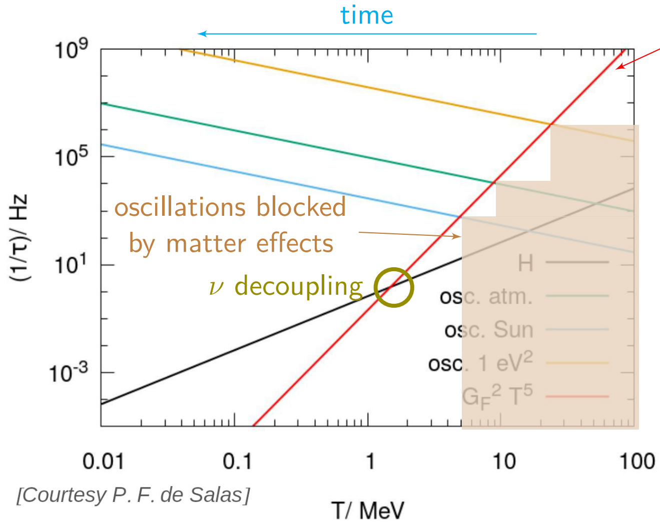

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actually, the decoupling T is momentum dependent!

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

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 $x\dfrac{\mathrm{d}\rho(x)}{\mathrm{d}x} = \rho - 3P$

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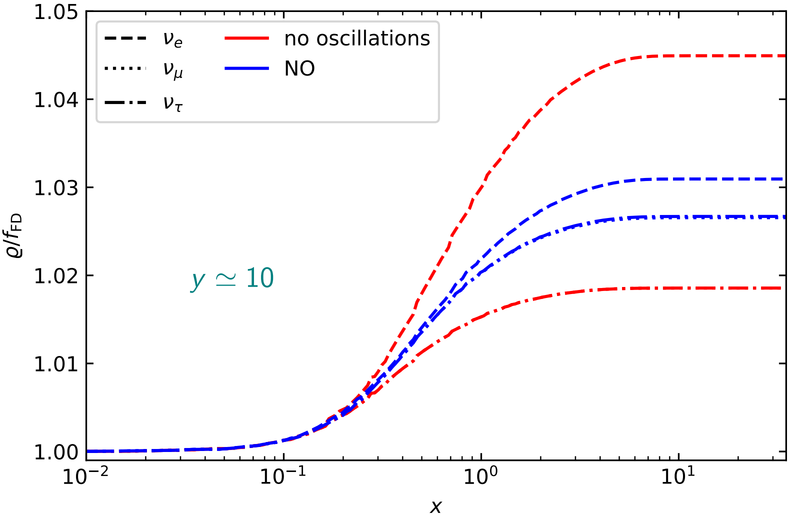
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



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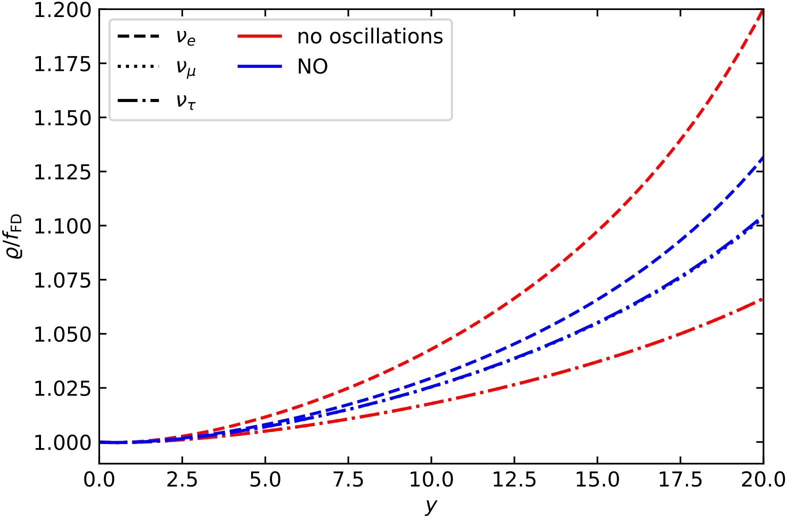
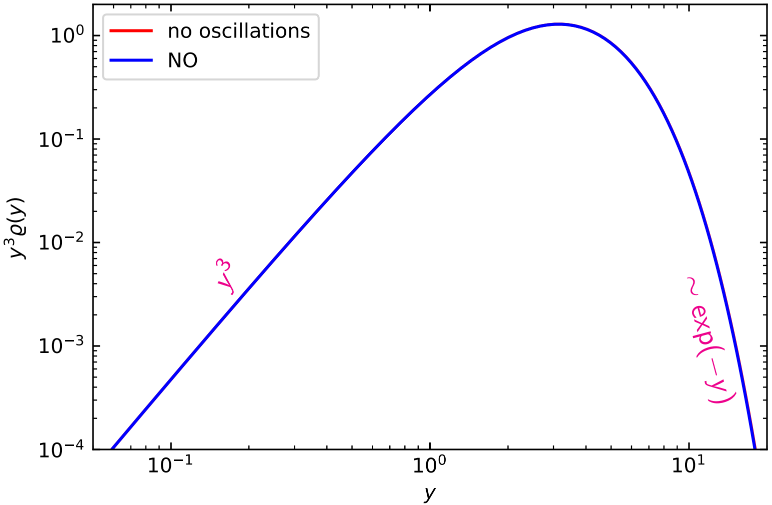


Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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

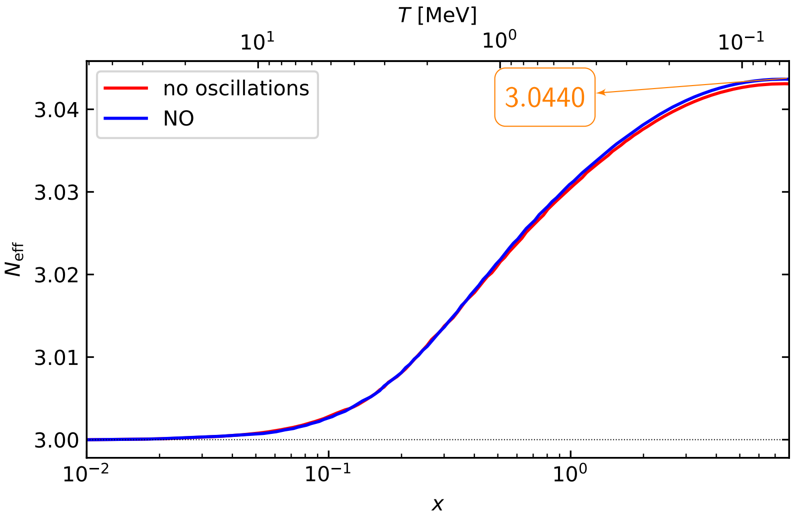
$(11/4)^{1/3} = (T_\gamma/T_\nu)^{\rm fin}$

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



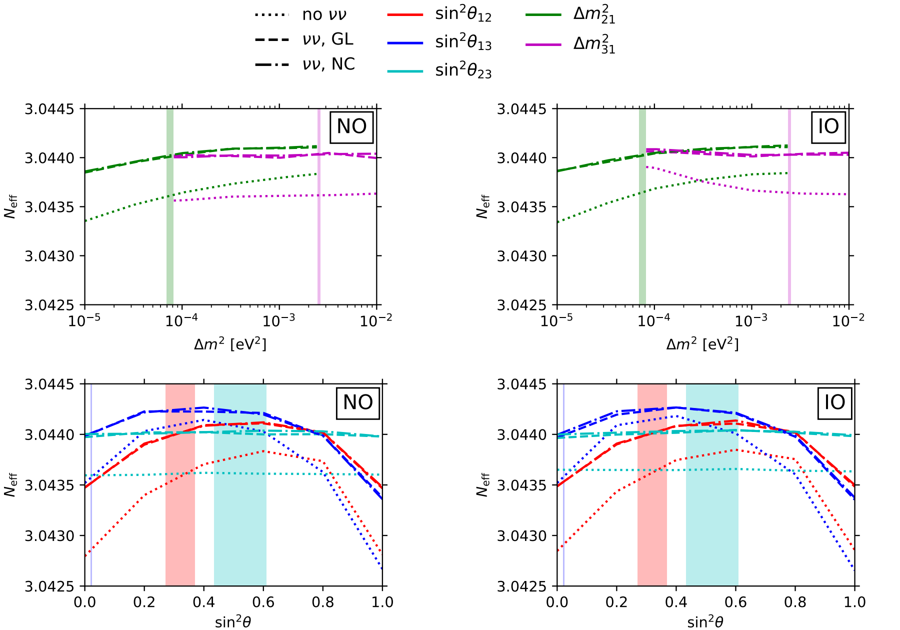
Neutrino momentum distribution and $N_{\rm eff}$ [Bennett, SG+, JCAP 2021]

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



Effect of neutrino oscillations

[Bennett, SG+, JCAP 2021]



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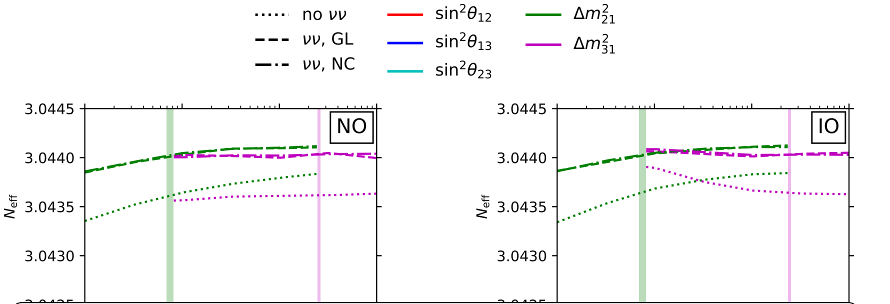
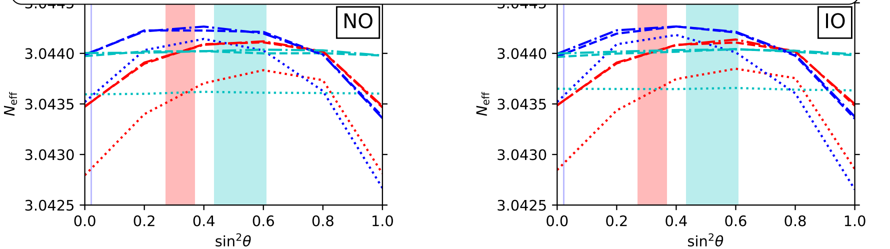


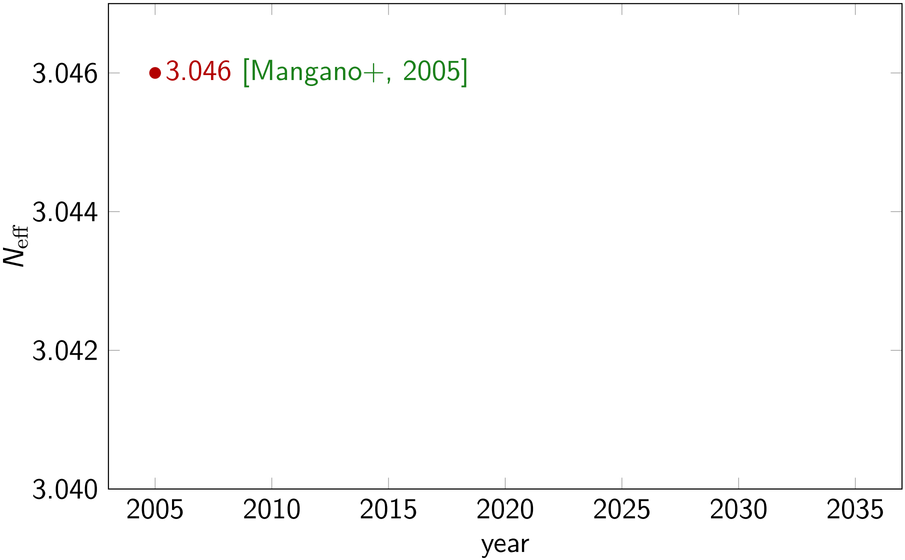
within 3σ ranges allowed by global fits [deSalas, SG+, JHEP 2021]

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



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

Full 3ν mixing results:



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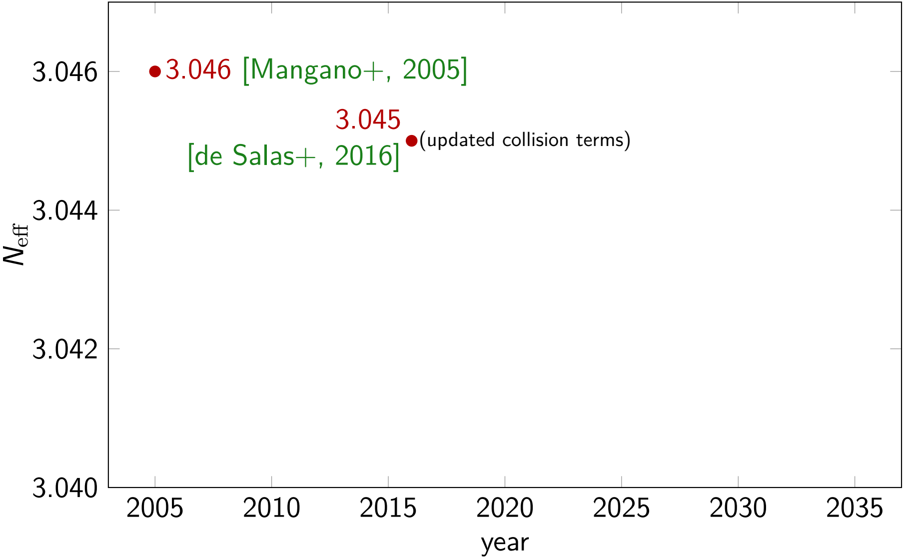

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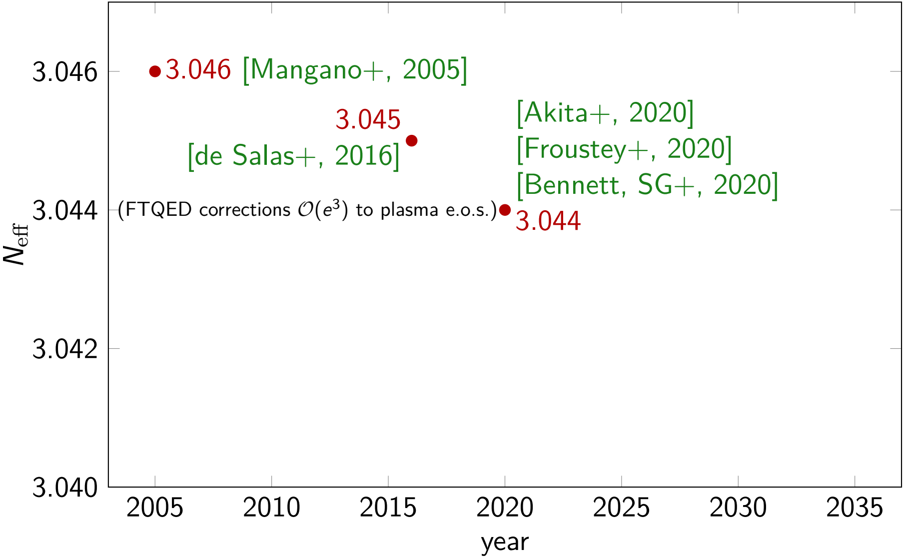

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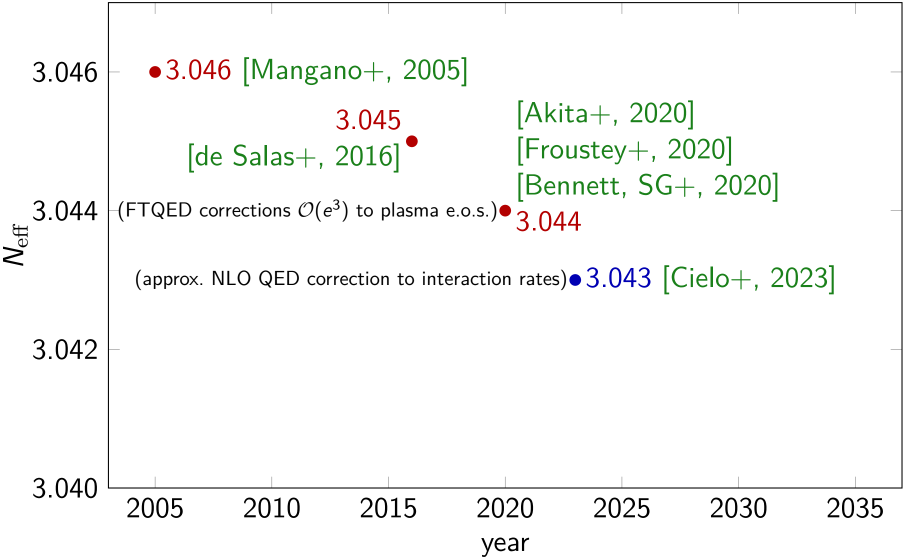

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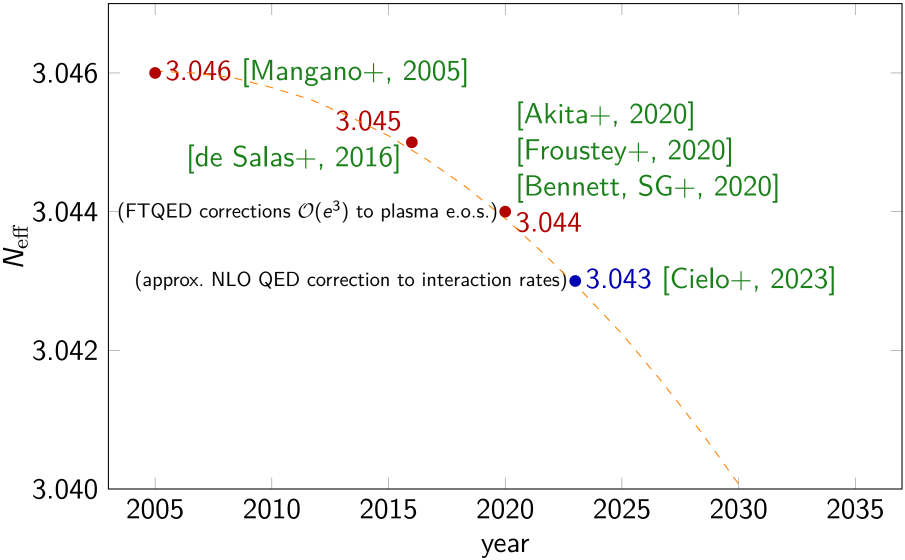

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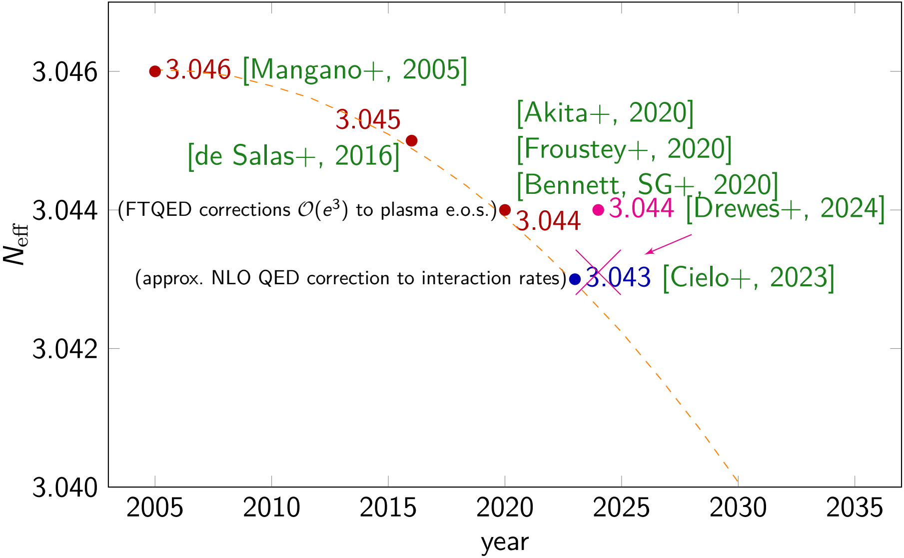
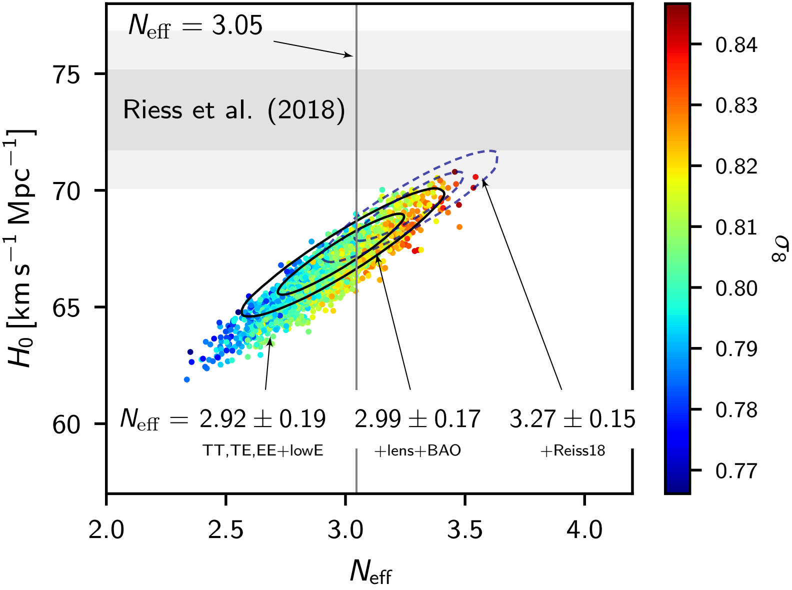


$N_{\rm eff}$ and CMB

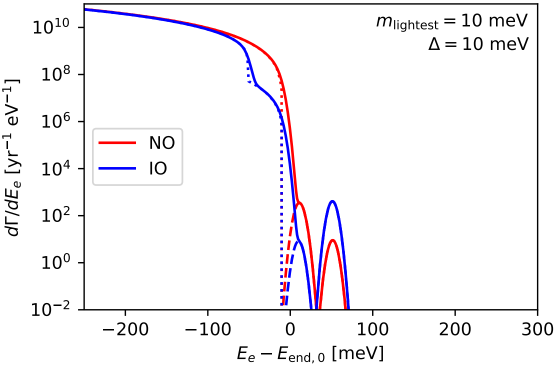
[Planck Collaboration, 2018]



D Direct detection of relic neutrinos

Based on:

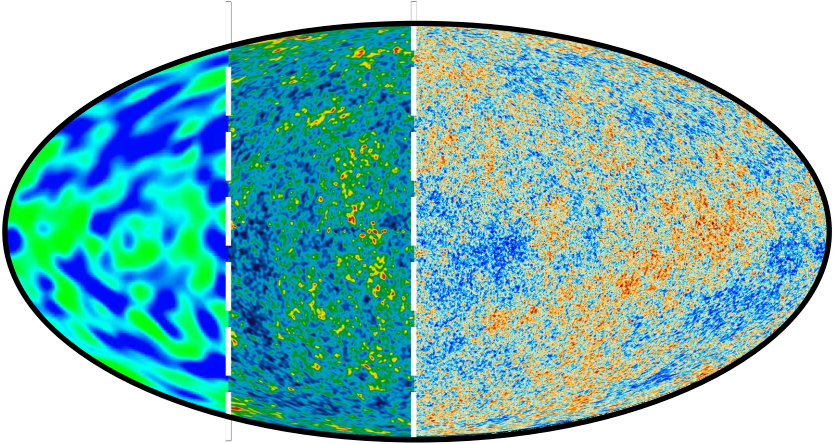
- JCAP 01 (2023) 003
- JCAP 08 (2014) 038
- JCAP 07 (2019) 047



The oldest picture of the Universe

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

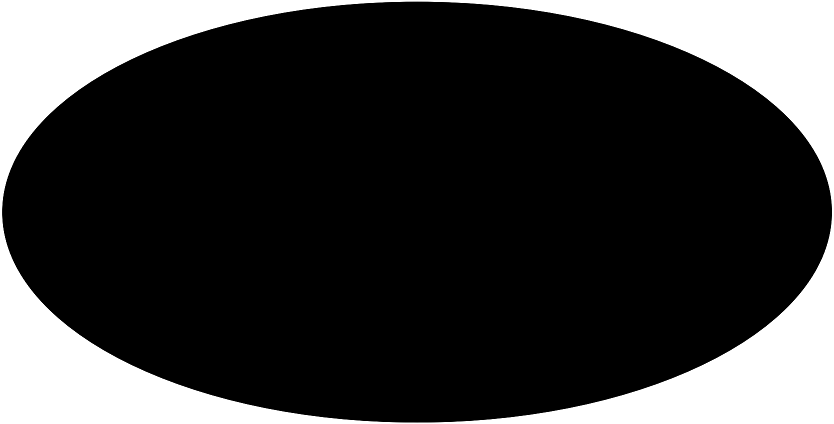
COBE (1992) WMAP (2003) Planck (2013)



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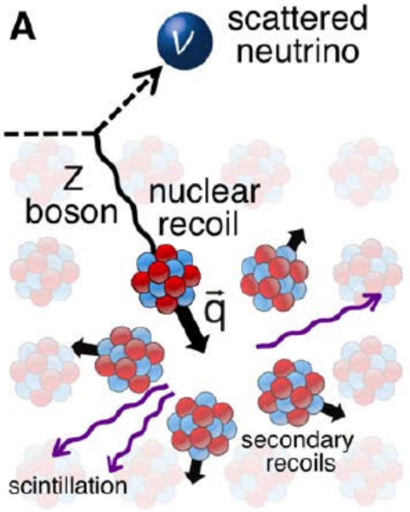
expected $a_\nu \simeq \mathcal{O}(10^{-26})$ cm/s^2 ⟷ $a_{\rm exp} \simeq \mathcal{O}(10^{-12})$ cm/s^2

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?

[Shergold, JCAP 2021]

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

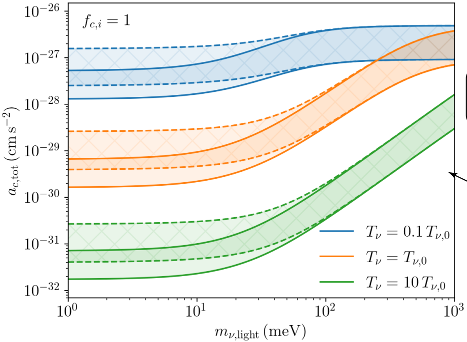
elastic scattering where ν interacts with nucleous "as a whole"

Can we detect relic neutrinos with CEνNS?

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

↓

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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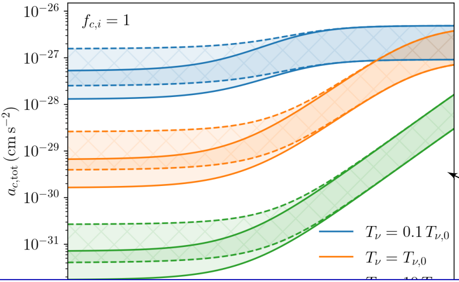

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p_ν, E_ν neutrino momentum and energy

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}

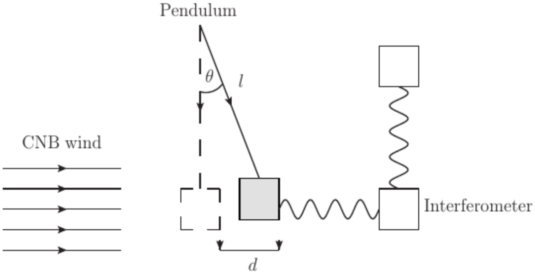
At interferometers?

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



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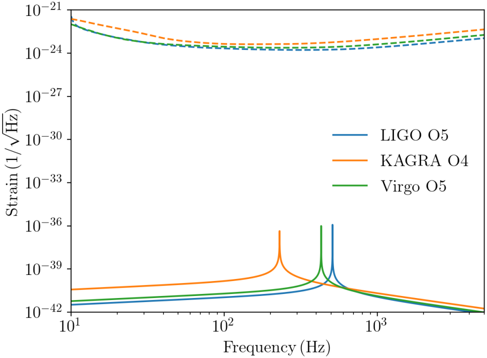


Sensitivity

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

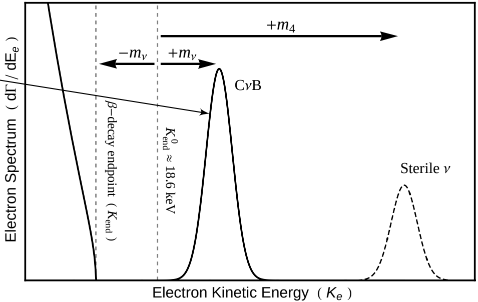
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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

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

β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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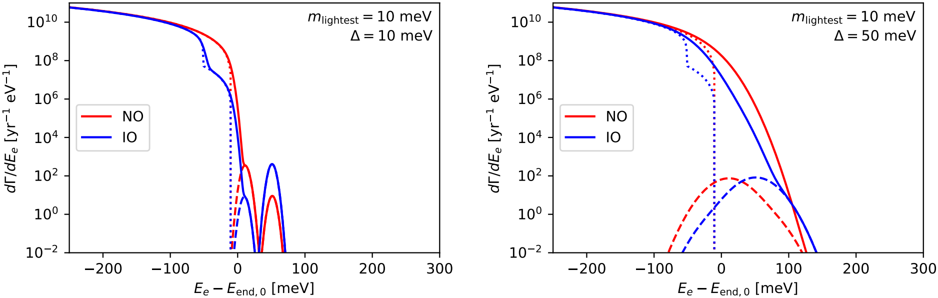

[PTOLEMY LoI, arxiv:1808.01892]

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

built mainly for CNB

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

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

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

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

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

(without clustering)

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

ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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

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PTOLEMY proposal as of 2022

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[Courtesy A. Esposito]

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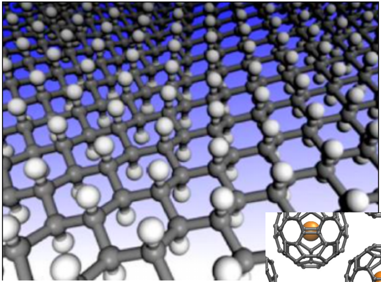
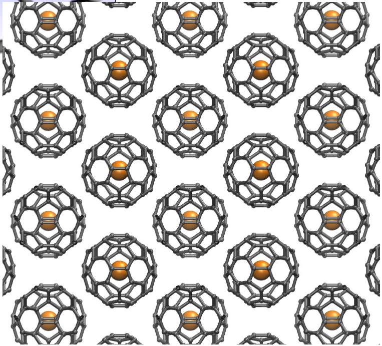


tritium on graphene?

tritium on fullerene?



[Courtesy A. Esposito]

[Courtesy V. Tozzini]

PTOLEMY proposal as of 2022

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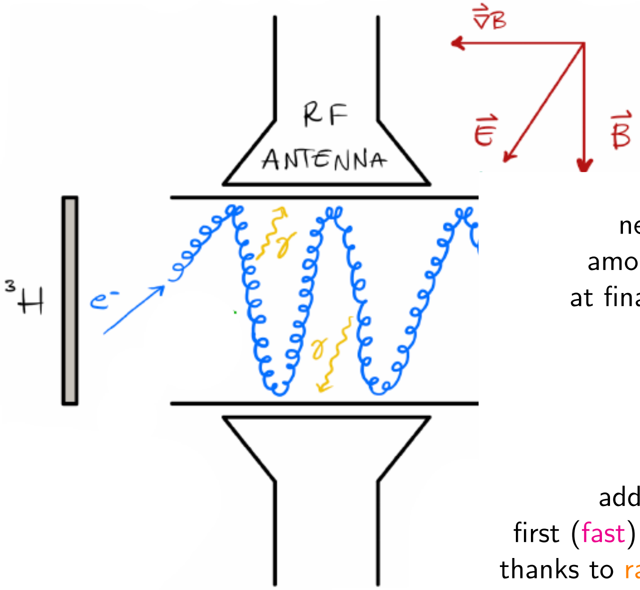


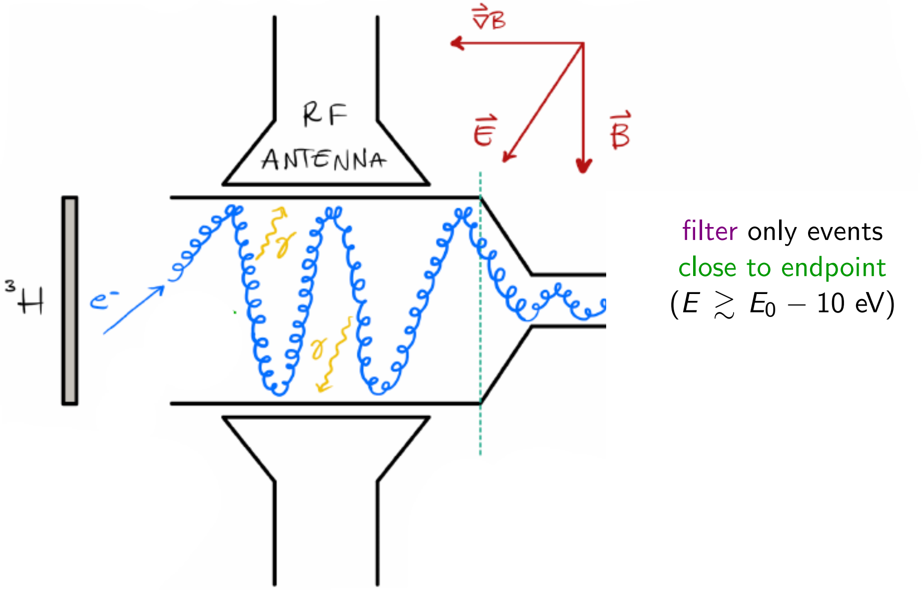
need to reduce
amount of electrons
at final energy sensors:
EM filter

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

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]

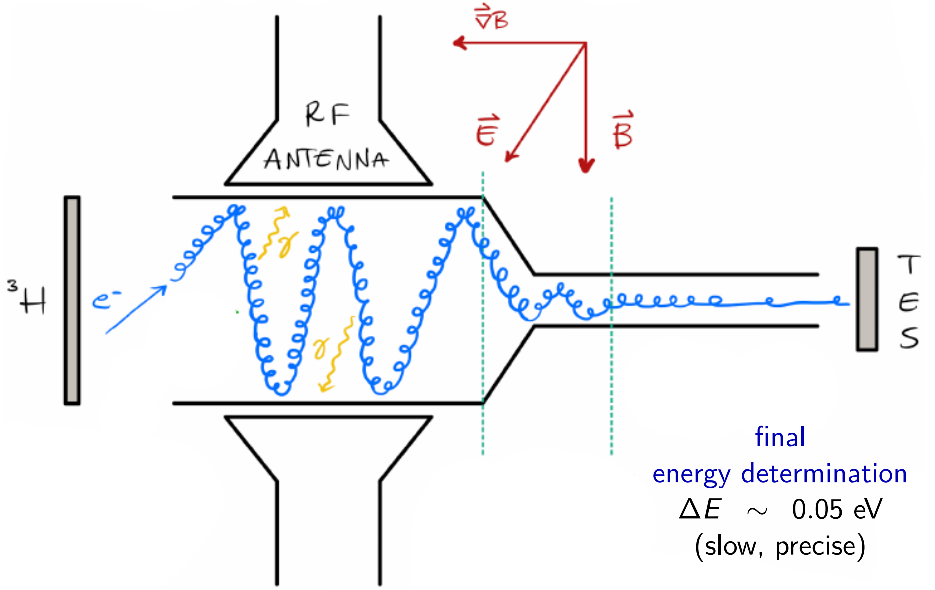


filter only events close to endpoint ($E \gtrsim E_0 - 10$ eV)

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

[PTOLEMY LoI, arxiv:1808.01892]



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

[Courtesy A. Esposito]

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

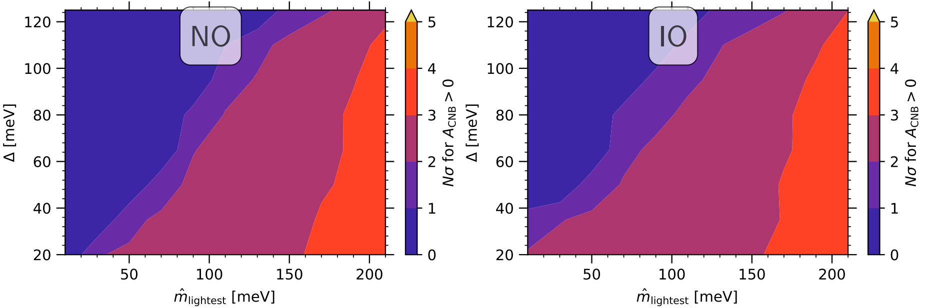
using the definition:

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

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



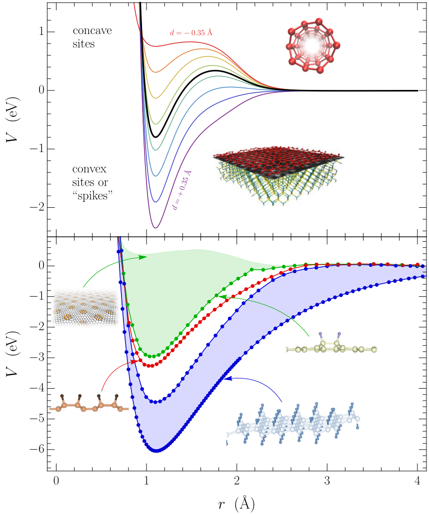
Quantum uncertainty and PTOLEMY

[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

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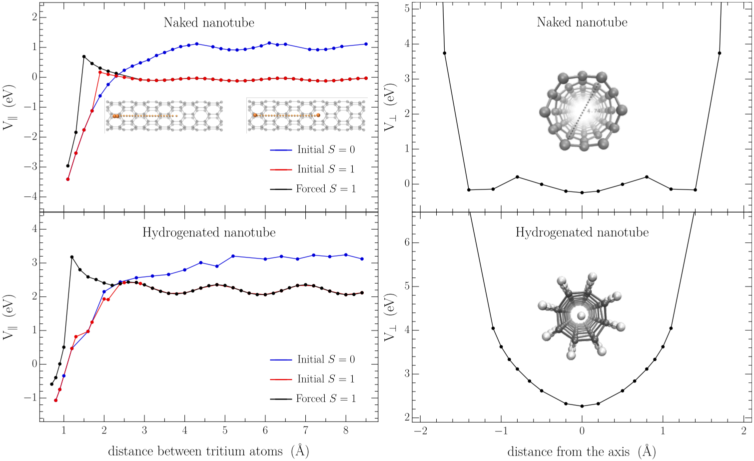

Nanotube configurations have flat potential parallel to nanotube axis

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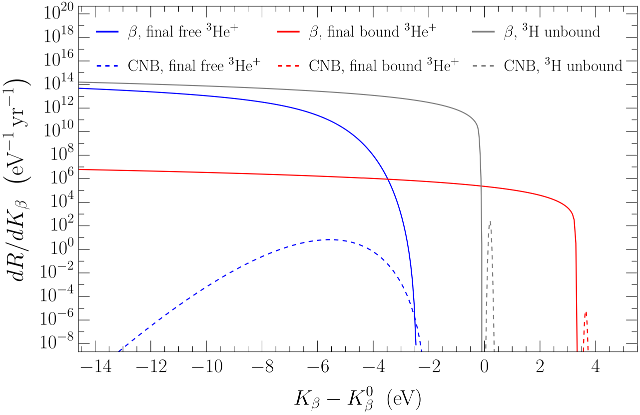


Graphene configuration can make observation range from

completely impossible or suppressed but possible

Z

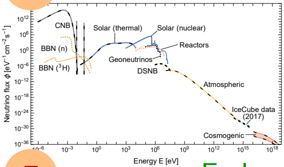
Conclusions

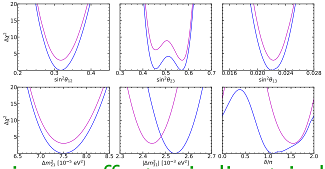
almost there!

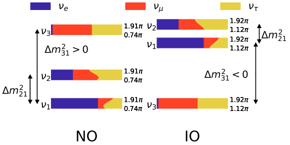
What do we learn from relic neutrinos?

N

Neutrinos: precision era (many sources)

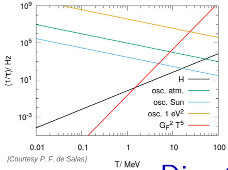


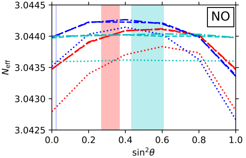


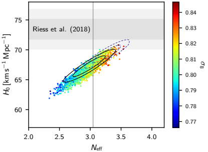


E

Early universe effects: indirect indications

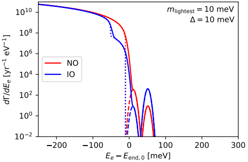


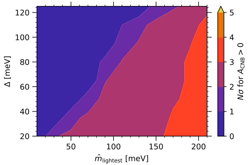


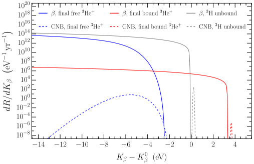


D

Direct detection: still long to go







What do we learn from relic neutrinos?

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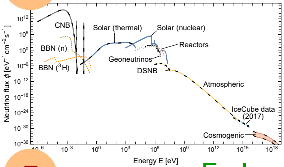

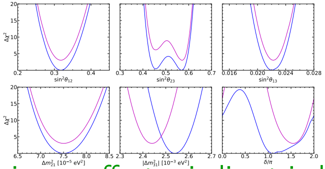

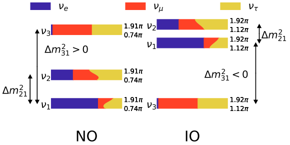

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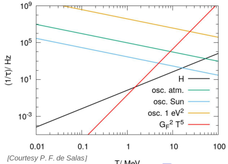

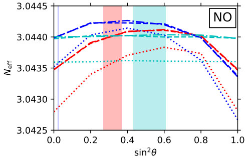

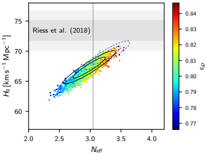

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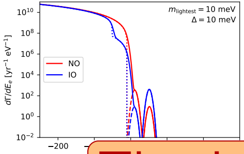

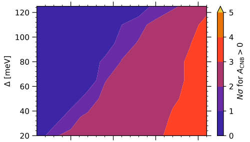

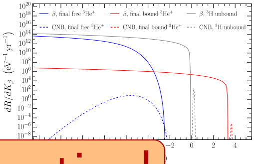

Thanks for your attention!