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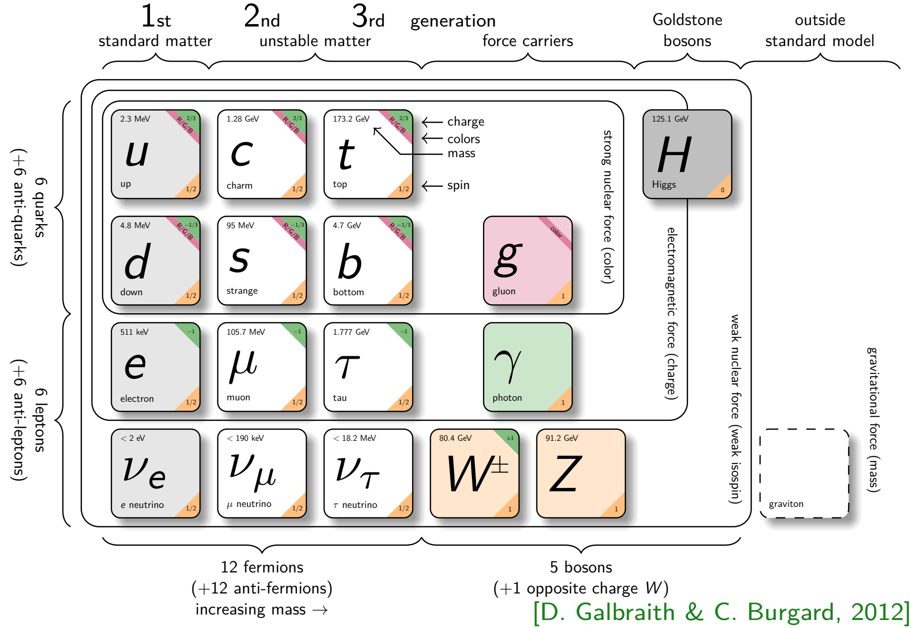
Relic neutrinos and the PTOLEMY project

RWTH Aachen, Particle and Astroparticle Physics Colloquium, 2/04/2019

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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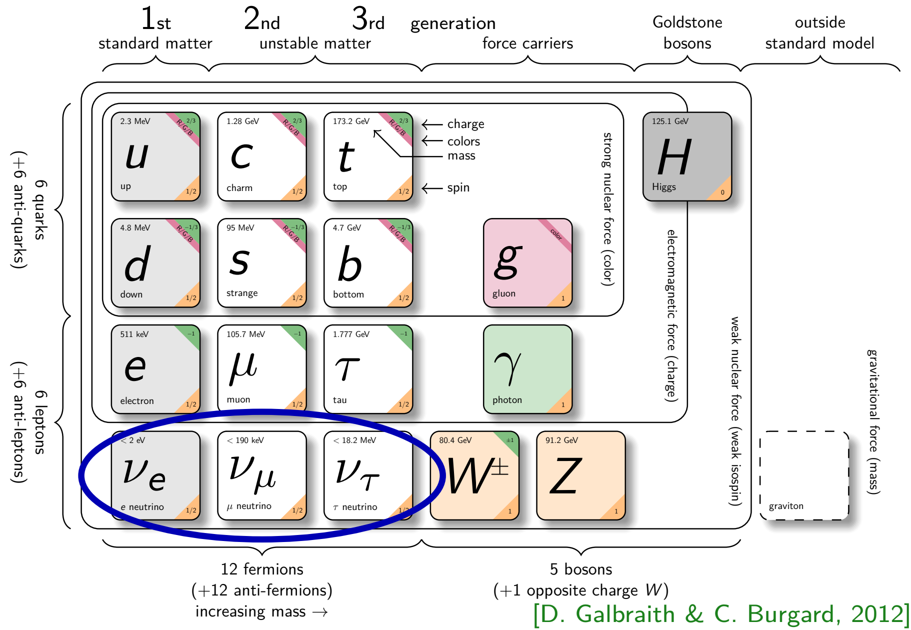

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Three Neutrino Oscillations

Analogous to CKM mixing for quarks:

[Pontecorvo, 1968]
[Maki, Nakagawa, Sakata, 1962]

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

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

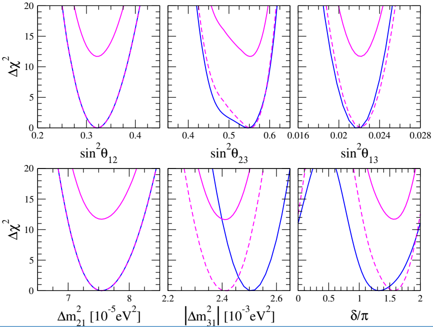
Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

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

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

First hints for $\delta_{CP} \simeq 3/2\pi$



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$|\Delta m^2_{31}| = (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2$ (NO)

$= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}$ …

$\sin^2(\theta_{12})$ [illegible]

$\sin^2(\theta_{13})$ [illegible]$^{+0.008}_{-0.007}$ (NO)

$= 0.0222^{+0.007}_{-0.008}$ (IO)

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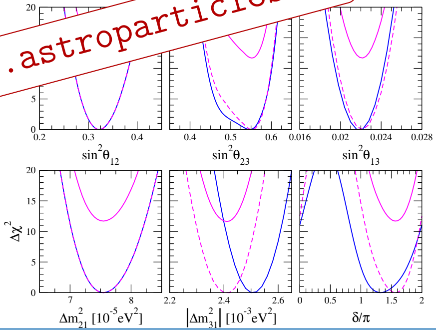


see also: http://globalfit.astroparticles.es

Neutrinos and their masses

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

Normal ordering (NO)

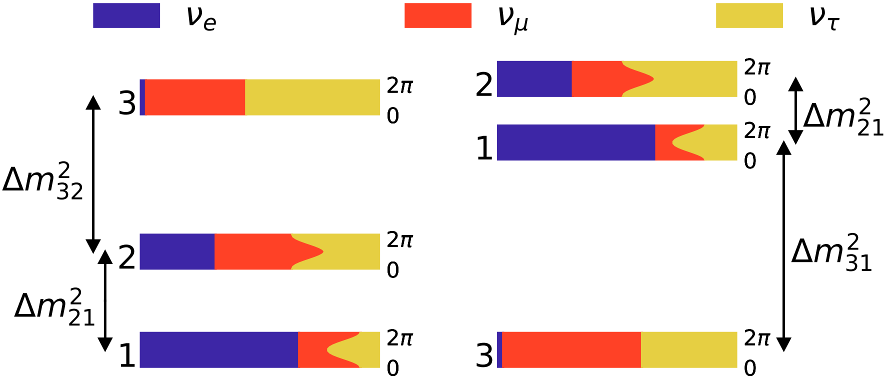
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

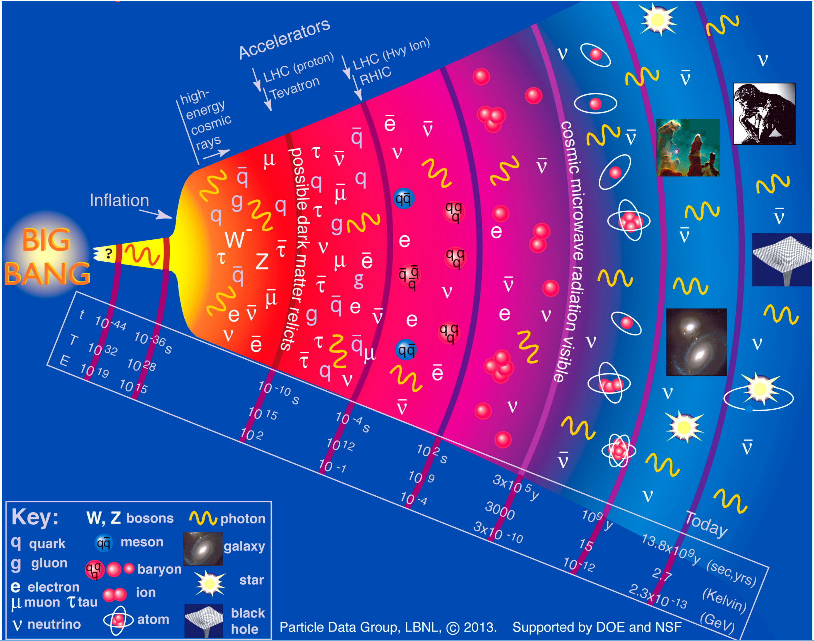
$\sum m_k \gtrsim 0.1$ eV



Absolute scale unknown!

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

History of the universe



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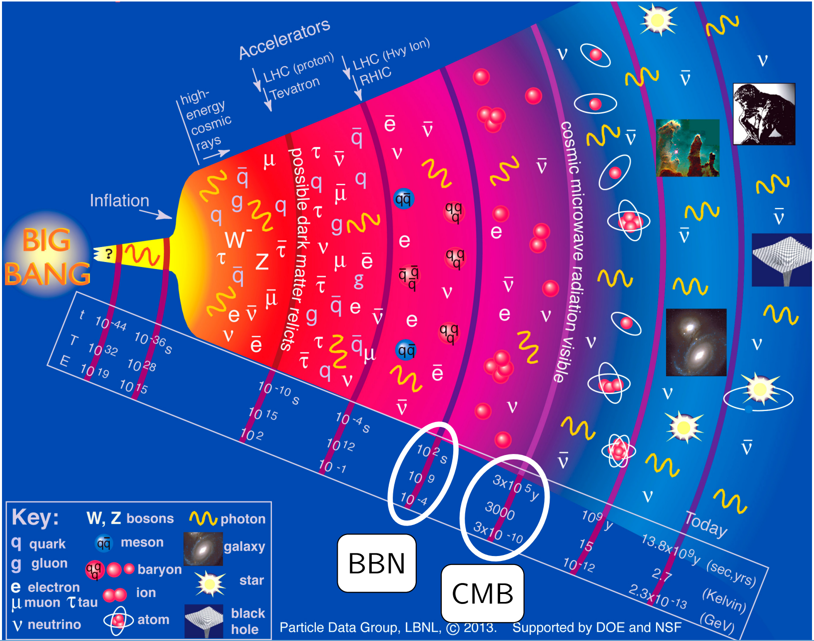

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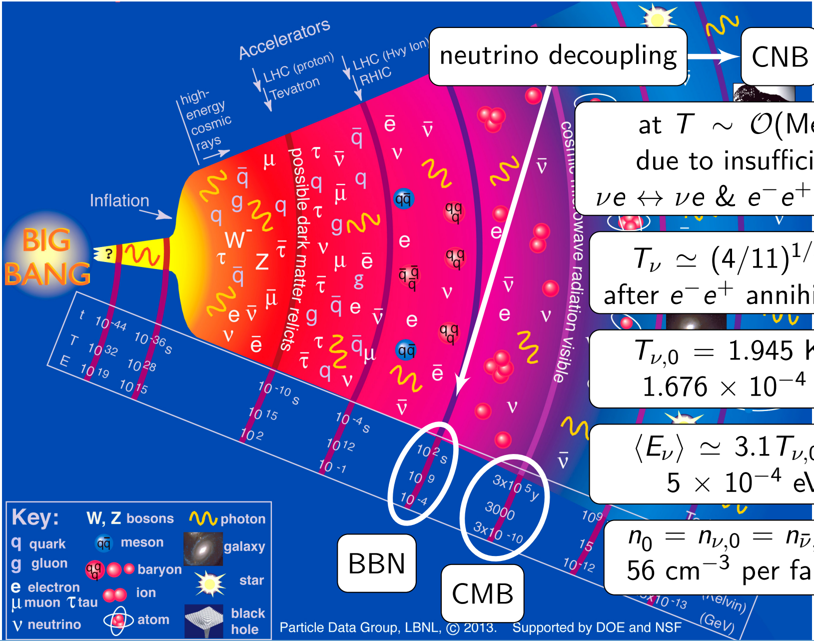


neutrino decoupling → CNB

at $T \sim \mathcal{O}(\mathrm{MeV})$ due to insufficient $\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

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

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

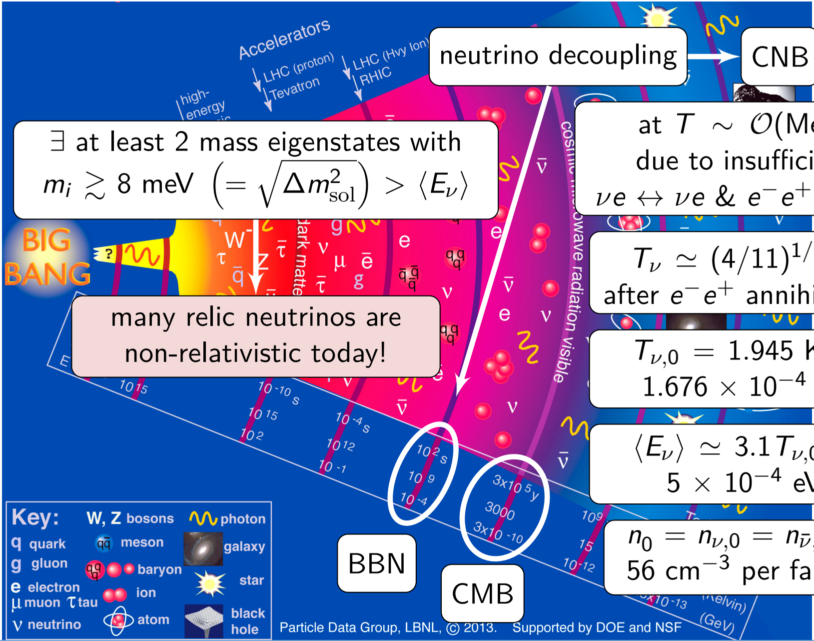
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}\ \mathrm{eV}$

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

BBN

CMB

History of the universe



neutrino decoupling → CNB

∃ at least 2 mass eigenstates with $m_i \gtrsim 8$ meV $\left(= \sqrt{\Delta m^2_{\rm sol}}\right) > \langle E_\nu \rangle$

many relic neutrinos are non-relativistic today!

at $T \sim \mathcal{O}$(MeV) due to insufficient $\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

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Relic neutrinos in cosmology: $N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = [1 + 0.2271 N_{\rm eff}]\,\rho_\gamma$$

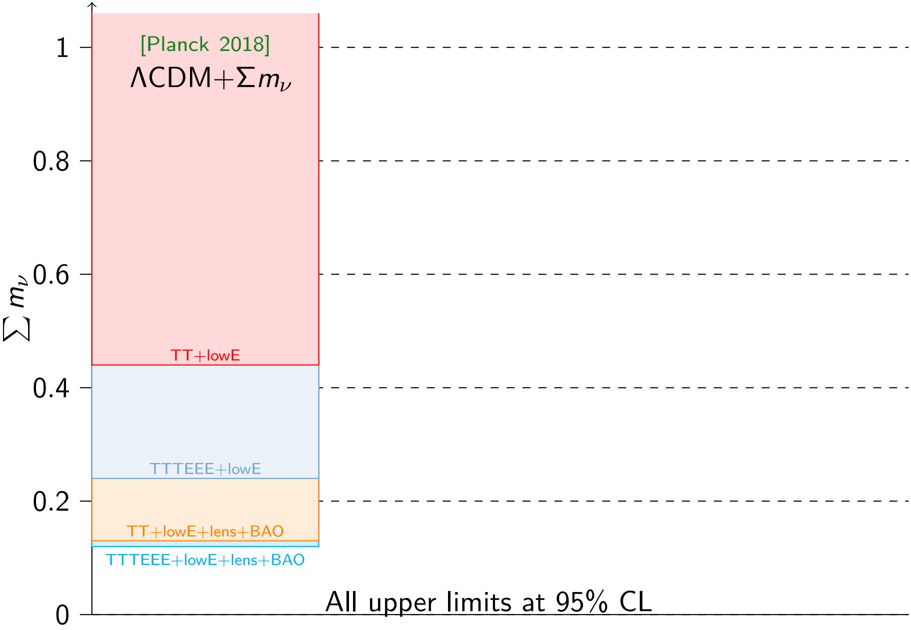
ρ_γ photon energy density, $7/8$ is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \to$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos:
  $N_{\rm eff} = 3.046$ [Mangano et al., 2005] (damping factors approximations) $\sim$
  $N_{\rm eff} = 3.045$ [de Salas et al., 2016] (full collision terms)
  due to not instantaneous decoupling for the neutrinos
- $+$ Non Standard Interactions: $3.040 < N_{\rm eff} < 3.059$ [de Salas et al., 2016]

Observations: $N_{\rm eff} \simeq 3.0 \pm 0.2$ [Planck 2018]
Indirect probe of cosmic neutrino background!

$\gg 10\sigma$!

Cosmological neutrino mass bounds



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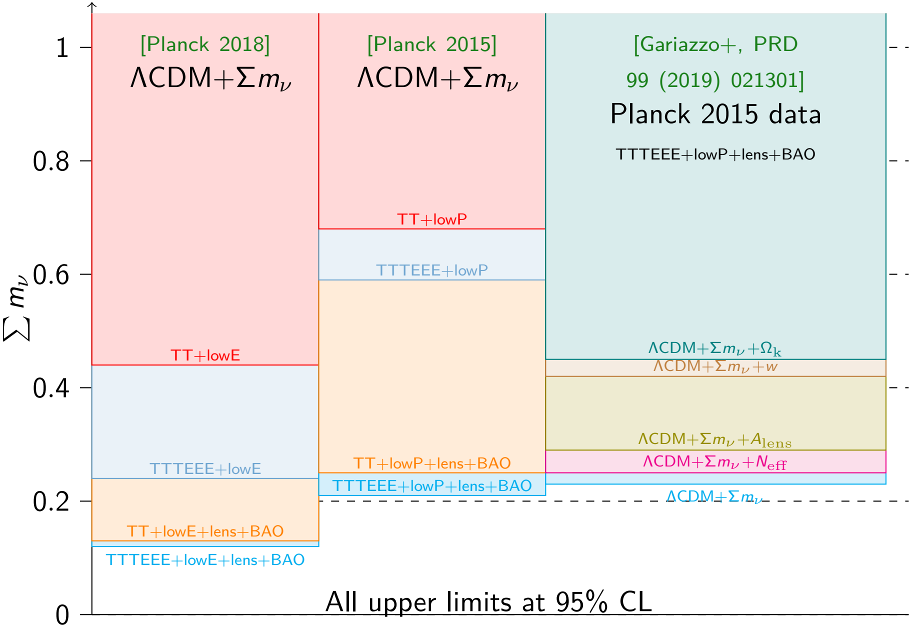

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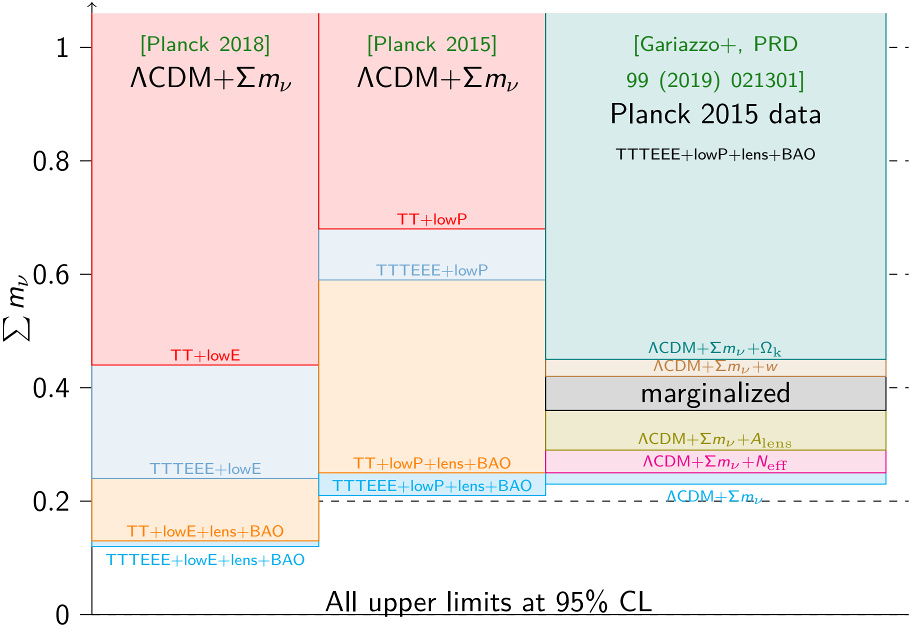

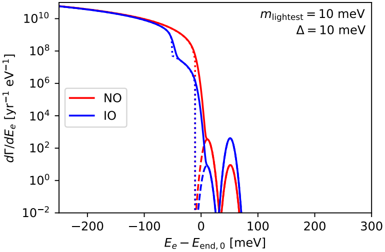
$m_{\rm lightest} = 10$ meV
$\Delta = 10$ meV
NO
IO
$d\Gamma/dE_e$ [yr^{-1} eV^{-1}]
$E_e - E_{\rm end,0}$ [meV]
10^{10}
10^8
10^6
10^4
10^2
10^0
10^{-2}
−200
−100
0
100
200
300

Direct detection - proposed methods - Stodolsky effect

How to directly detect non-relativistic neutrinos?

Stodolsky effect

[Stodolsky, 1974][Duda et al., 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

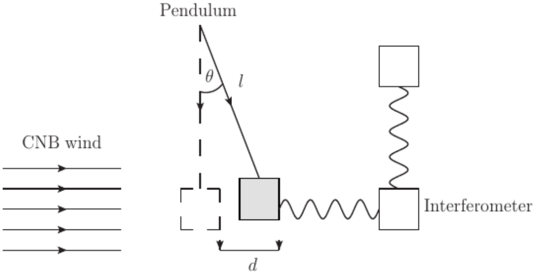
Direct detection - proposed methods - at interferometers

How to directly detect non-relativistic neutrinos?

At interferometers

[Domcke et al., 2017]

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



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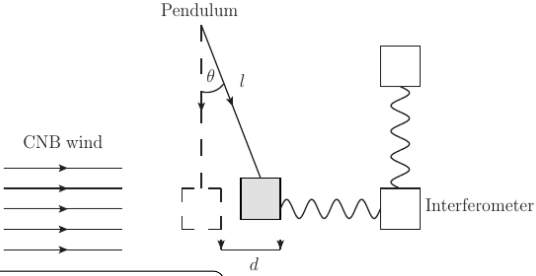

expected $10^{-33} \lesssim a_\nu/(\mathrm{cm/s^2}) \lesssim 10^{-27}$ ↔ $a_{\mathrm{LIGO/Virgo}} \simeq 10^{-16}\ \mathrm{cm/s^2}$

Direct detection - proposed methods - Capture (I)

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

(anti)neutrino capture on electron-capture-decaying nuclei

[Cocco et al., 2009]

electron capture (EC): $e^- + A^+ \to \nu_e + B^*$

(e^- from inner level)

$$\bar{\nu}_e + A \to B^- + e^+$$

must have very specific Q value in order to avoid EC background and have no threshold

$$\bar{\nu}_e + e^- + A^+ \to B$$

specific energy conditions required

but Q value depends on ionization fraction!

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but Q value depends on ionization fraction!

process useful only "if specific conditions on the Q-value are met or significant improvements on ion storage rings are achieved"

A viable method - Capture (II)

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

How to directly detect non-relativistic neutrinos?

Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today $\longrightarrow$ a process without energy threshold is necessary

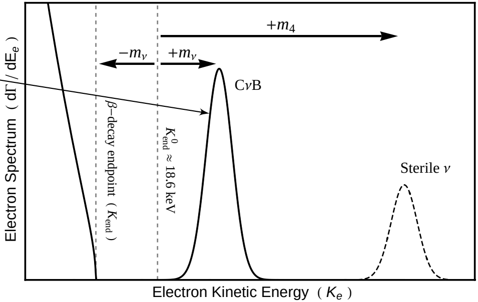
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

Main background: β decay $n \to p + e^- + \bar{\nu}$!

signal is a peak at $2m_\nu$ above β–decay endpoint

only with a lot of material

need a very good energy resolution



What material?

[Cocco et al., 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}
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^{3}H better because the cross section ($\rightarrow$ event rate) is higher

β and Neutrino Capture spectra

[PTOLEMY, arxiv:1902.05508]

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

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

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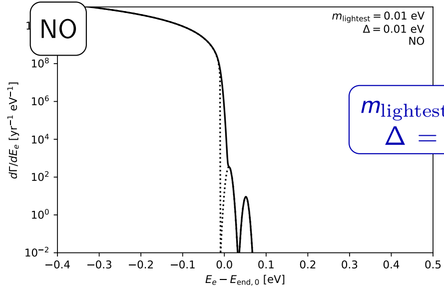
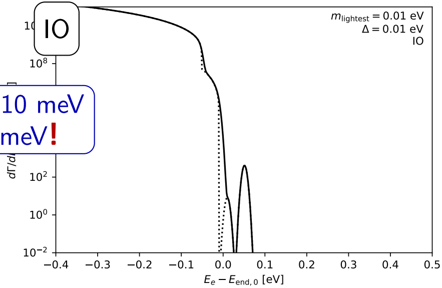


$m_{\rm lightest} = 10$ meV
$\Delta = 10$ meV**!**



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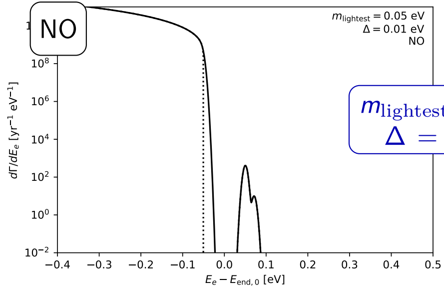

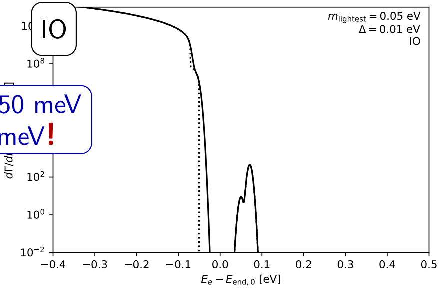

$m_{\rm lightest} = 50$ meV
$\Delta = 10$ meV**!**

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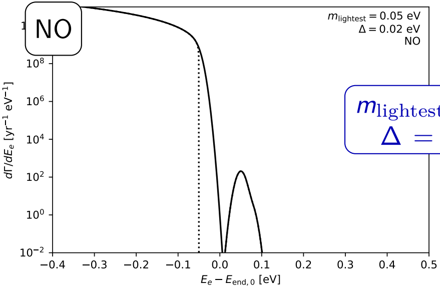
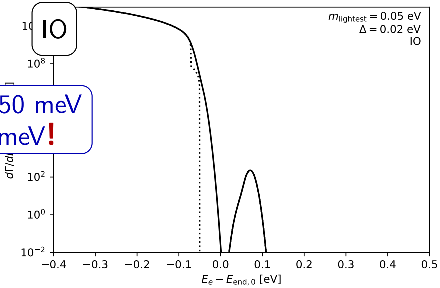




$m_{\rm lightest} = 50$ meV
$\Delta = 20$ meV!

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

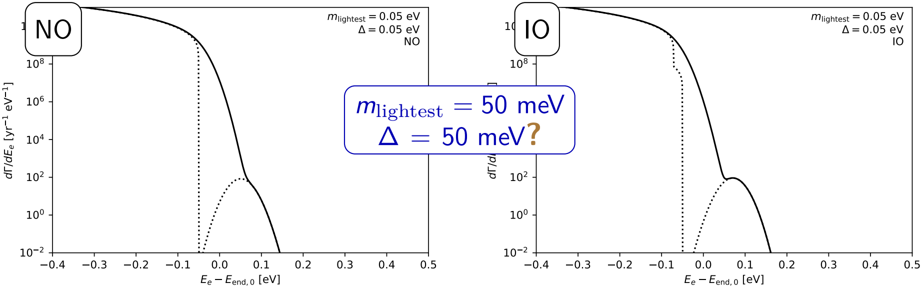
β and Neutrino Capture spectra

[PTOLEMY, arxiv:1902.05508]

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

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

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



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$\Delta = 50$ meV?

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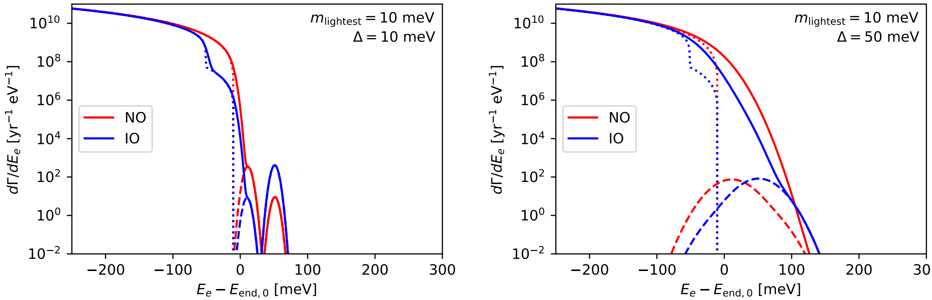

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PTOLEMY

[Long et al., JCAP 08 (2014) 038]
[Betts et al., arxiv:1307.4738]
[PTOLEMY LoI, arxiv:1808.01892]

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

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

built mainly for CNB

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

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

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

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

[Long et al., JCAP 08 (2014) 038]
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$M_T = 100$ g of atomic ^{3}H

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

ehnancement from other effects?

ehnancement from ν clustering in the galaxy?

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

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

(without clustering)

Dirac and Majorana neutrinos

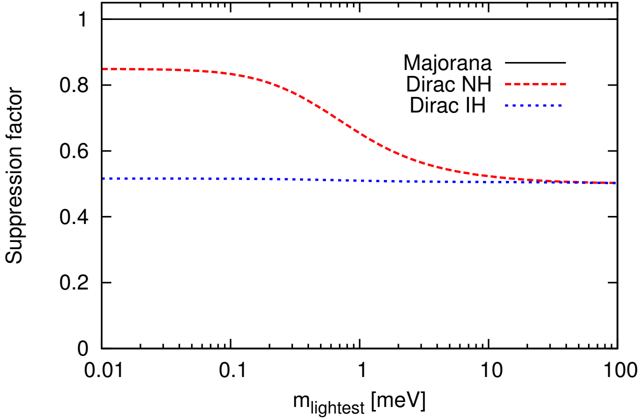
[Roulet+, JCAP 10 (2018) 049]

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

only neutrinos with correct chirality can be detected!

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

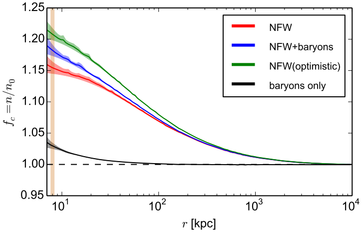
expect more events for the **Majorana** than for Dirac case



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

↓

almost indistinguishable from **Majorana**



NFW
NFW+baryons
NFW(optimistic)
baryons only
$f_c = n/n_0$
r [kpc]
1.25
1.20
1.15
1.10
1.05
1.00
0.95
10^1
10^2
10^3
10^4

ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

$$\Gamma_{\rm CNB} = \sum_{i=1}^{3} |U_{ei}|^2 f_c(m_i) \left[n_{i,0}(\nu_{h_R}) + n_{i,0}(\nu_{h_L})\right] N_T \bar\sigma$$

$f_c(m_i) = n_i/n_{i,0}$ clustering factor ⟶ How to compute it?

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

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

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

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

Assumptions:

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

how many νs is "N"?

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

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

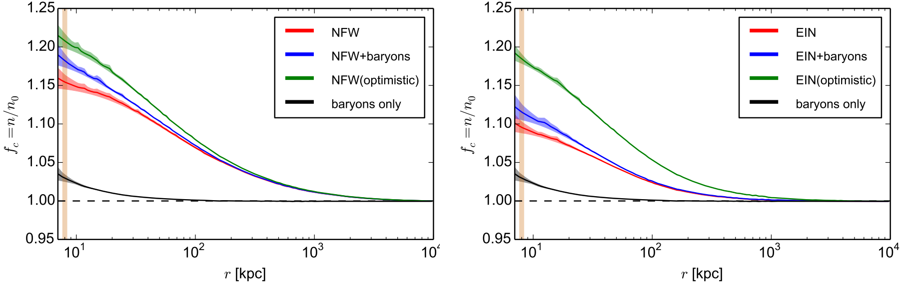
given N ν:

→ weigh each neutrinos

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

Overdensity when $m_{\rm heaviest} \simeq 60$ meV

[JCAP 09 (2017) 034]



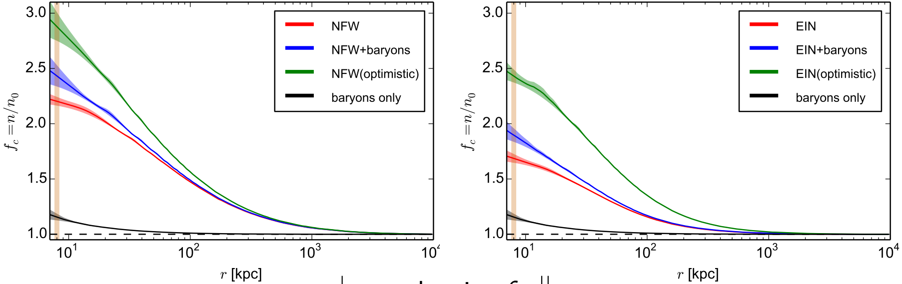
masses	ordering	matter halo	overdensity f_c: $f_1 \simeq f_2$	overdensity f_c: f_3	$\Gamma_{\rm tot}$ (yr^{-1})
any	any	any	no clustering		4.06
$m_3 = 60$ meV	NO	NFW(+bar)	$\sim$1	1.15 (1.18)	4.07 (4.08)
		NFW optimistic		1.21	4.08
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)
		EIN optimistic		1.18	4.08
$m_1 \simeq m_2 = 60$ meV	IO	NFW(+bar)	1.15 (1.18)	$\sim$1	4.66 (4.78)
		NFW optimistic	1.21		4.89
		EIN(+bar)	1.09 (1.12)		4.42 (4.54)
		EIN optimistic	1.18		4.78

ordering dependence from $\Gamma_{\rm CNB} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \, [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] \, N_T \, \bar{\sigma}$

Overdensity when $m_\nu \simeq 150$ meV

[JCAP 09 (2017) 034]

$\Longrightarrow$ minimal mass detectable by PTOLEMY if $\Delta \simeq$ 100–150 meV



matter halo	overdensity f_c $f_1 \simeq f_2 \simeq f_3$	$\Gamma_{\rm tot}$ (yr^{-1})
any	no clustering	4.06
NFW(+bar)	2.18 (2.44)	8.8 (9.9)
NFW optimistic	2.88	11.7
EIN(+bar)	1.68 (1.87)	6.8 (7.6)
EIN optimistic	2.43	9.9

no ordering dependence: $m_1 \simeq m_2 \simeq m_3 \Longrightarrow f_1 \simeq f_2 \simeq f_3$

Additional clustering due to other galaxies

[JCAP 09 (2017) 034]

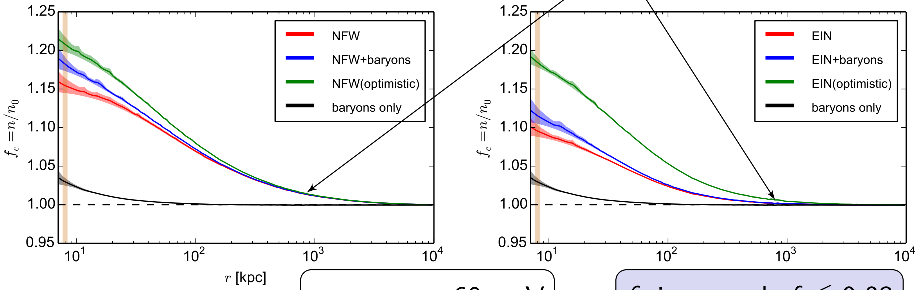
nearest galaxies: various MW satellites

with $M_{\rm sat} \ll M_{\rm MW}$ → negligibly small ν halo

nearest big galaxy:

Andromeda

$M_{\rm Andromeda} = M_{\rm MW} \times \mathcal{O}(1)$ — $d_{\rm Andromeda} \simeq 800$ kpc



$m_{\rm heaviest} \simeq 60$ meV → f_c increased of $\lesssim 0.03$

Additional clustering due to other galaxies

[JCAP 09 (2017) 034]

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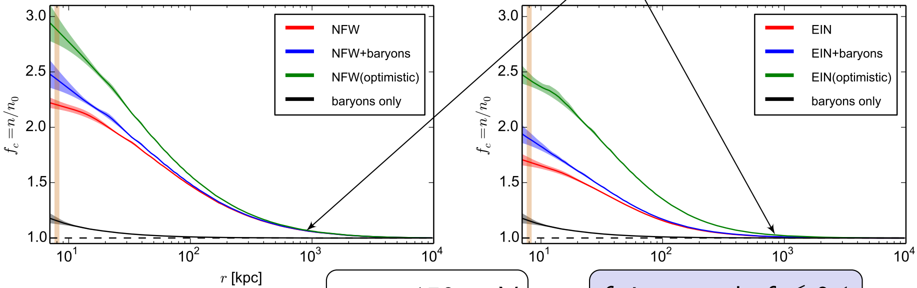


$m_\nu \simeq 150$ meV → f_c increased of $\lesssim 0.1$

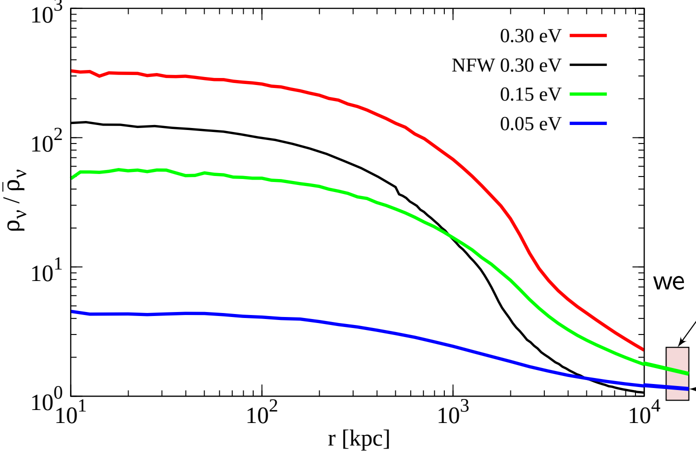
(halo is less diffuse for higher ν masses)

Additional clustering due to Virgo cluster

nearest galaxy cluster:

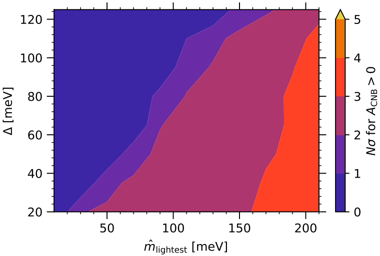
Virgo cluster → very wide ν halo, may reach Earth

$M_{\rm Virgo} = M_{\rm MW} \times \mathcal{O}(10^3)$ — $d_{\rm Virgo} \simeq 16$ Mpc



same amplitude of MW halo?

[Villaescusa-Navarro et al., JCAP 1106 (2011) 027]



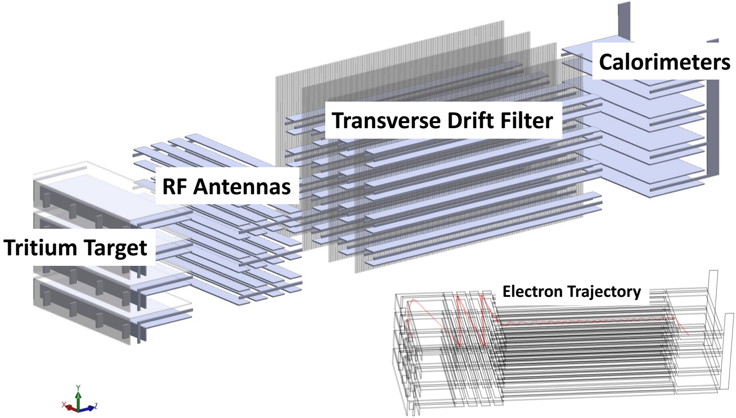
Δ [meV]
120
100
80
60
40
20
50
100
150
200
$\hat{m}_{\rm lightest}$ [meV]
$N\sigma$ for $A_{\rm CNB} > 0$
0
1
2
3
4
5

PTOLEMY pipeline

scope of PTOLEMY:

measure electron spectrum near ^{3}H β-decay endpoint

(same as neutrino mass experiments, e.g. KATRIN)



[PTOLEMY, arxiv:1810.06703]

The source - graphene

source of ^{3}H in gas form (KATRIN-like) has column density $\sim 1\,\mu$g cm^{-2}
source tube is 10 m, for $\sim \mathcal{O}(100)$ μg of ^{3}H

not practical solution for required 100 g of ^{3}H!

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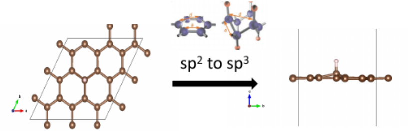
not practical solution for required 100 g of ^{3}H!

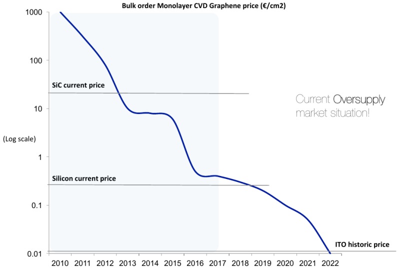
partially existing technology: hydrogenated graphene

layers

Graphene layers are cheap
(commercial use in displays)

hydrogenation under study
at Princeton





[courtesy A.Zurutuza (Graphenea)]

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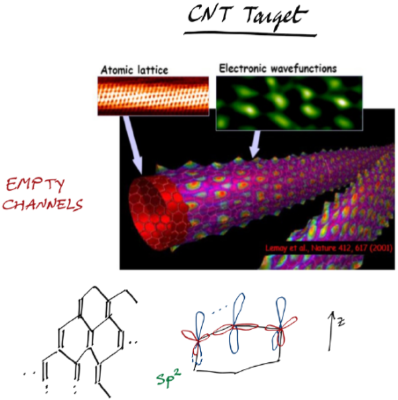
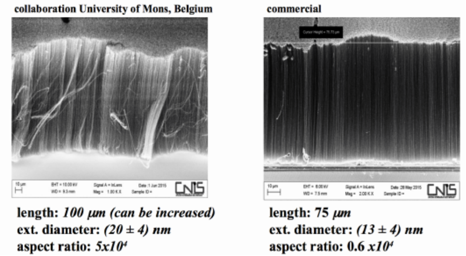
partially existing technology: hydrogenated graphene

→ nanotubes



[courtesy G.Cavoto]



MAC-E filter

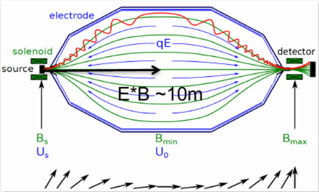
Background flux is too high for microcalorimeter. Must be reduced!

Magnetic Adiabatic Collimation with Electrostatic filter

[KATRIN]

MAC-E filter technique

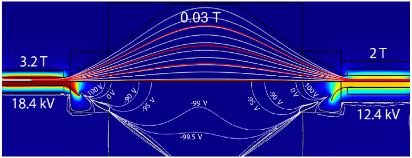
Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345

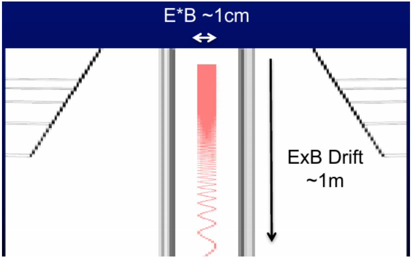


$$\mu = \frac{E_\perp}{B} = \text{const.}$$

[PTOLEMY]: $E \times B$ filter
(must enter in GS labs)

see also [PTOLEMY, arxiv:1810.06703]





[courtesy C.Tully]

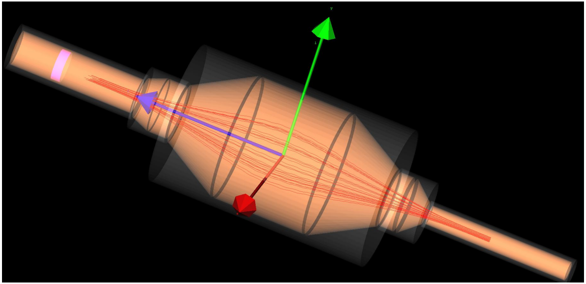
RF tracking

first energy determination with

RadioFrequency trigger, using
Cyclotron Radiation Emission Spectroscopy (CRES)

see also [Project 8, JPG 44 (2017) 054004]

can RF antenna be integrated in the MAC-E filter?



Final energy determination with TES

Final energy determination needs $\sigma_E \simeq 0.1$ eV or less!

Microcalorimetry with Transition-Edge Sensors

TES: "*A microcalorimeter*
made by a superconducting film
operated in the temperature region
between the normal and the superconducting state"

↙ difficult readout

↘ difficult temperature control

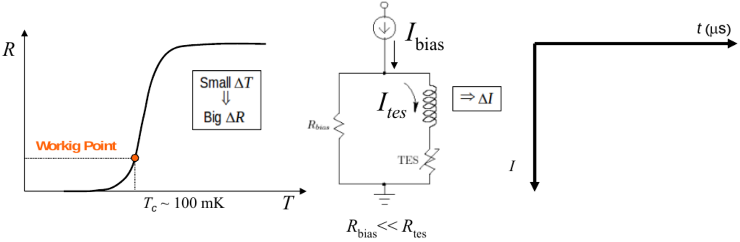
Same technology as in HOLMES experiment (ν masses)

Final energy determination with TES

Final energy determination needs $\sigma_E \simeq 0.1$ eV or less!

Microcalorimetry with Transition-Edge Sensors

[courtesy M.Ratjeri]



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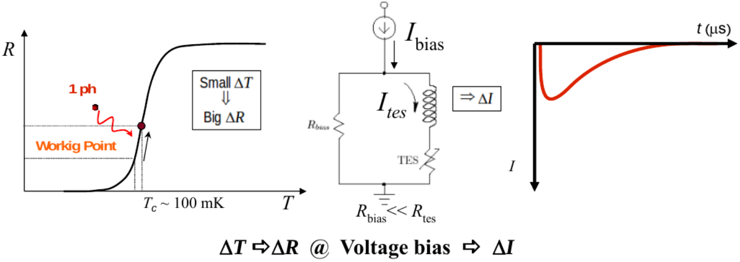
Microcalorimetry with **T**ransition-**E**dge **S**ensors

[courtesy M.Ratjeri]



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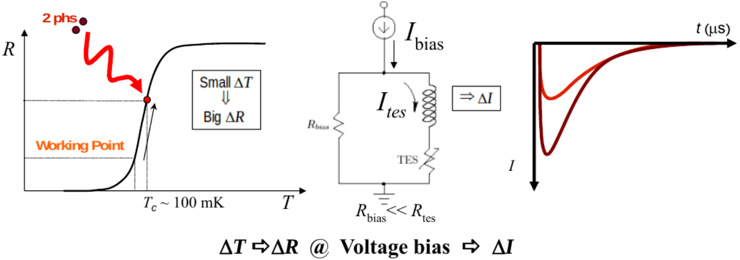

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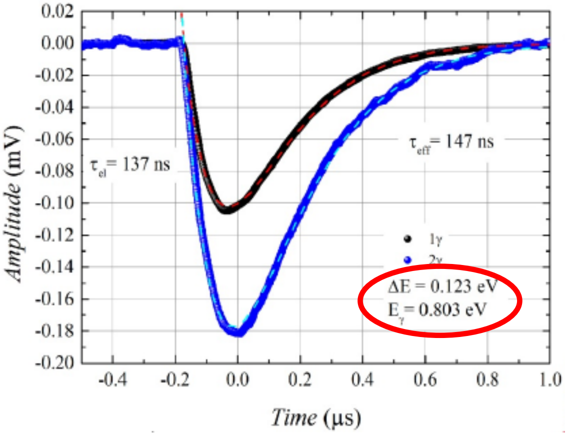

Simulations - I

[PTOLEMY, arxiv:1902.05508]

Events in **bin** i, centered at E_i:

$$N^i_\beta = T \int_{E_i-\Delta/2}^{E_i+\Delta/2} \frac{d\widetilde{\Gamma}_\beta}{dE_e} dE_e \qquad\qquad N^i_{\rm CNB} = T \int_{E_i-\Delta/2}^{E_i+\Delta/2} \frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e} dE_e$$

fiducial number of events: $\hat{N}^i = N^i_\beta(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) + N^i_{\rm CNB}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$

add **background** $\hat{N}_b = \hat{\Gamma}_b T$ with $\hat{\Gamma}_b \simeq 10^{-5}$ Hz $\longrightarrow$ $\boxed{N^i_t = \hat{N}^i + \hat{N}_b}$

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

Simulations - I

[PTOLEMY, arxiv:1902.05508]

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simulated experimental spectrum: $N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) = N^i_t \pm \sqrt{N^i_t}$

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

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[PTOLEMY, arxiv:1902.05508]

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simulated experimental spectrum: $N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) = N^i_t \pm \sqrt{N^i_t}$

repeat for theory spectrum, free **amplitudes** and **endpoint position**:

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

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

Simulations - I

[PTOLEMY, arxiv:1902.05508]

Events in **bin** i, centered at E_i:

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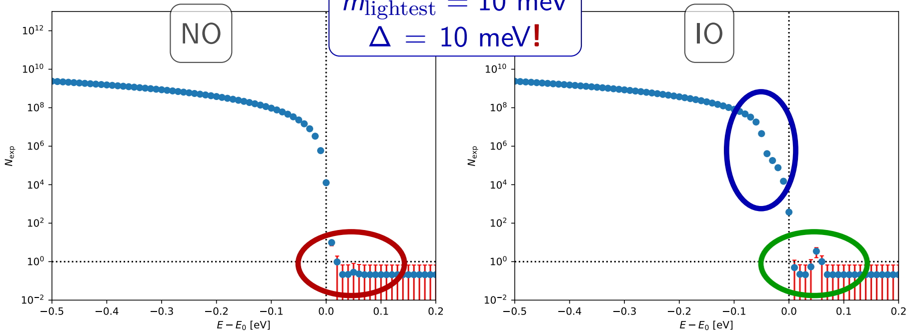
fit $\longrightarrow$ $$\chi^2(\boldsymbol{\theta}) = \sum_i \left(\frac{N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) - N^i_{\rm th}(\boldsymbol{\theta})}{\sqrt{N^i_t}}\right)^2$$ or $\log\mathcal{L} = -\frac{\chi^2}{2}$

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

Simulations - II

no random noise?

$m_{\text{lightest}} = 10$ meV
$\Delta = 10$ meV!

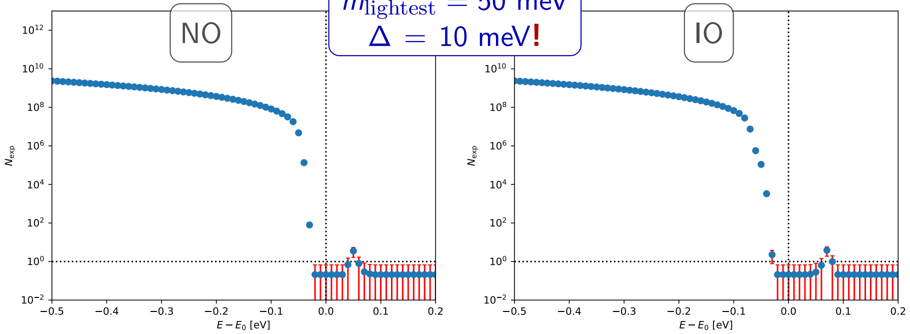


1 year of observation with 100 g of T source

Simulations - II

no random noise?

$m_{\text{lightest}} = 50$ meV
$\Delta = 10$ meV!

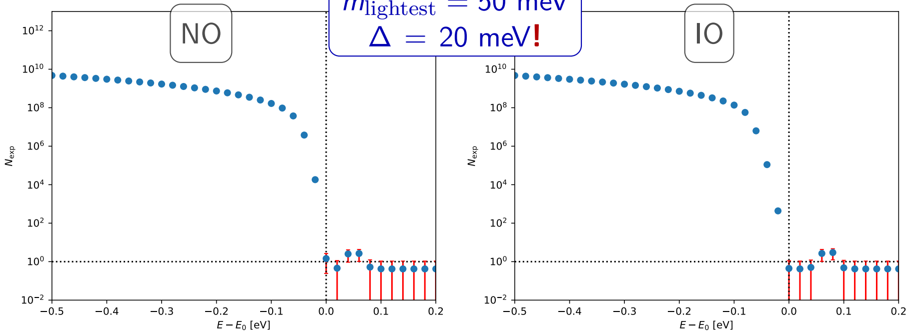


1 year of observation with 100 g of T source

Simulations - II

no random noise?

$m_{\rm lightest} = 50$ meV
$\Delta = 20$ meV!

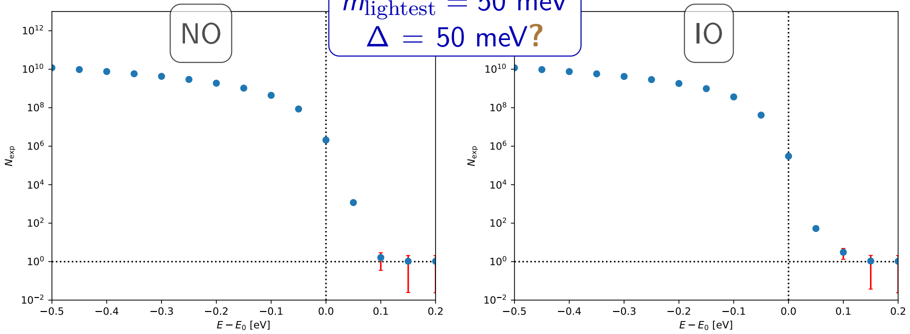


1 year of observation with 100 g of T source

Simulations - II

no random noise?

$m_{\text{lightest}} = 50$ meV
$\Delta = 50$ meV?



1 year of observation with 100 g of T source

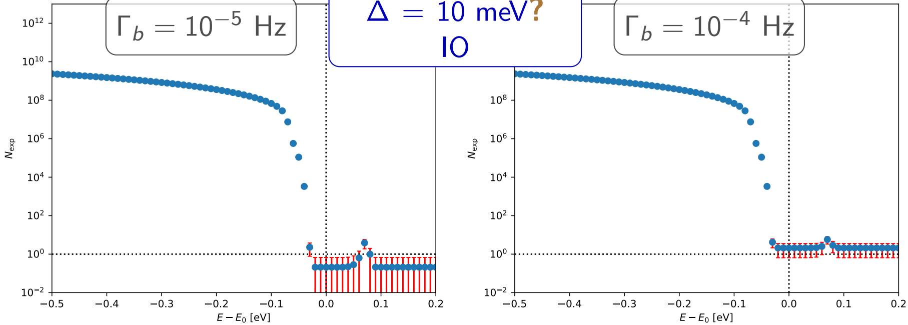
Simulations - II

no random noise?

$m_{\rm lightest} = 50$ meV
$\Delta = 10$ meV?
IO

$\Gamma_b = 10^{-5}$ Hz

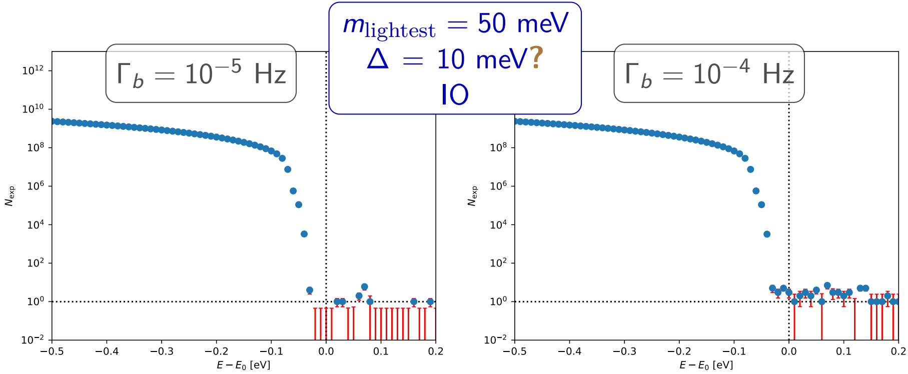
$\Gamma_b = 10^{-4}$ Hz



1 year of observation with 100 g of T source

Simulations - II

with random noise!



things are more complicated in this way...low background needed!

1 year of observation with 100 g of T source

Perspectives for the mass determination [PTOLEMY, arxiv:1902.05508]

statistical only!

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

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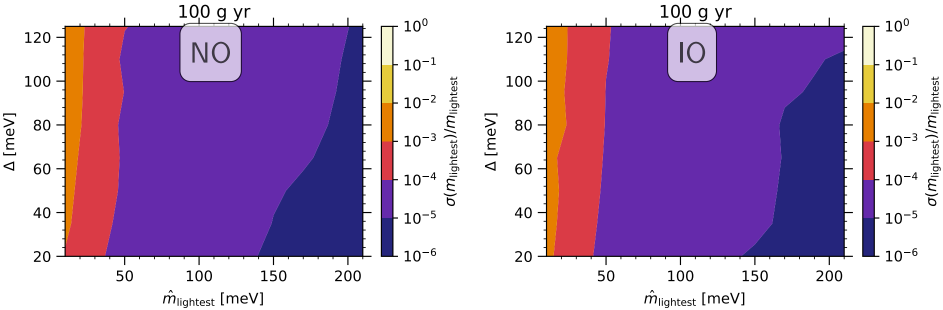


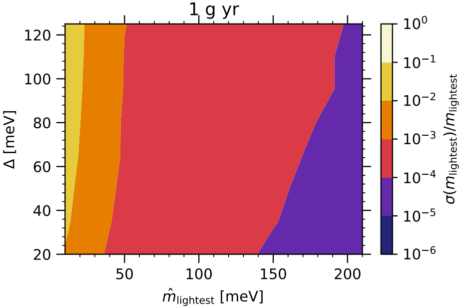
wonderful precision in determining the neutrino mass

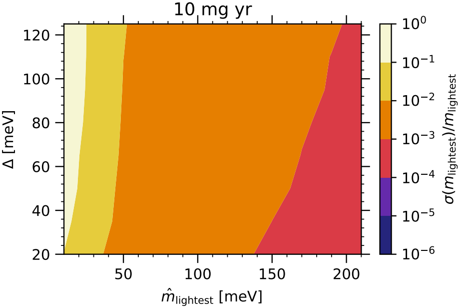
(well, yes, with 100 g of tritium...)

Perspectives for the mass determination [PTOLEMY, arxiv:1902.05508]

statistical only!

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





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(mass detection already with 10 mg of tritium!)

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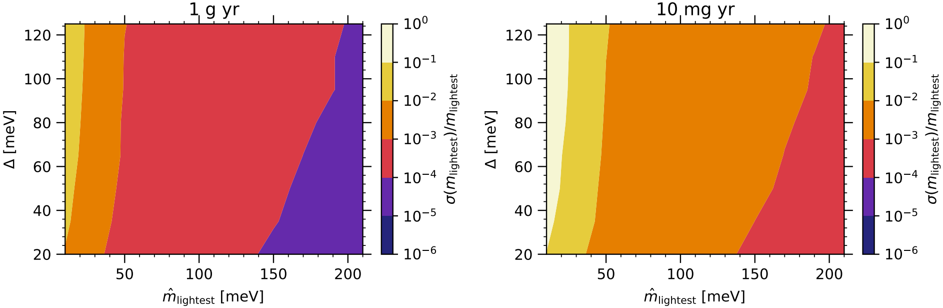

wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

Δ has almost no impact

Neutrino mass ordering

[PTOLEMY, arxiv:1902.05508]

Bayesian method:

Fit fiducial ordering ($\widehat{\rm NO}$ or $\widehat{\rm IO}$) using both correct and wrong ordering

$\widehat{\rm NO}/{\rm NO}$ vs $\widehat{\rm NO}/{\rm IO}$ $\qquad\qquad$ $\widehat{\rm IO}/{\rm NO}$ vs $\widehat{\rm IO}/{\rm IO}$

Neutrino mass ordering

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Bayesian method:

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$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$

$\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit: $\widehat{\mathrm{NO}}/\mathrm{IO}$, $\widehat{\mathrm{IO}}/\mathrm{NO}$

better fit: $\widehat{\mathrm{NO}}/\mathrm{NO}$, $\widehat{\mathrm{IO}}/\mathrm{IO}$

Neutrino mass ordering

[PTOLEMY, arxiv:1902.05508]

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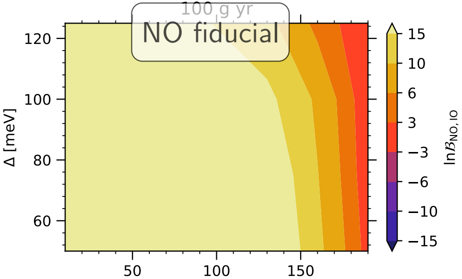
$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$ $\qquad$ $\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit

better fit

statistical only!

(Bayesian) preference on m_{lightest}
as a function of $\hat{m}_{\mathrm{lightest}}$, Δ



IO fiducial

always strong significance

Neutrino mass ordering

Bayesian method:

Fit fiducial ordering ($\widehat{\mathrm{NO}}$ or $\widehat{\mathrm{IO}}$) using both correct and wrong ordering

$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$ — $\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit: $\widehat{\mathrm{NO}}/\mathrm{IO}$, $\widehat{\mathrm{IO}}/\mathrm{NO}$

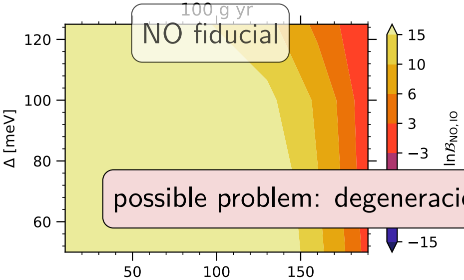
better fit: $\widehat{\mathrm{NO}}/\mathrm{NO}$, $\widehat{\mathrm{IO}}/\mathrm{IO}$

statistical only!

(Bayesian) preference on m_{lightest}
as a function of $\hat{m}_{\mathrm{lightest}}$, Δ

NO fiducial

IO fiducial



always strong significance

possible problem: degeneracies between m_{lightest} and Δm^2_{31}

Detection of the relic neutrinos

[PTOLEMY, arxiv:1902.05508]

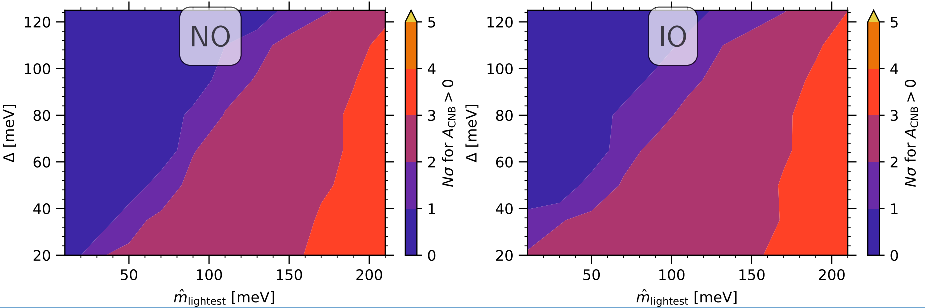
using the definition:

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

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



Requirements for PTOLEMY discoveries

What do we need to discover...

	low Γ_b	extreme Δ	a lot of ^{3}H
... ν masses?	✗	✗	?
... ν mass ordering?	✗	?	?
... CNB direct detection?	✓	✓	✓

✓: strongly required

?: not so strongly required

✗: loosely required

1 Cosmic Neutrino Background

2 Direct detection of relic neutrinos
- Some proposed methods
- Neutrino capture

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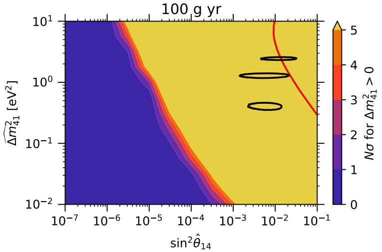
- Results from the Milky Way
- Systematics and future developments

4 PTOLEMY
- The experiment
- Simulations
- Perspectives

5 **Beyond the standard: light sterile neutrinos**

6 Conclusions



Short Baseline (SBL) anomaly

[SG+, JPG 43 (2016) 033001]

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

A short review:

LSND search for $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

Reactor re-evaluation of the expected anti-neutrino flux $\Rightarrow$ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Mention et al, 2011], [Azabajan et al, 2012]

Gallium calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

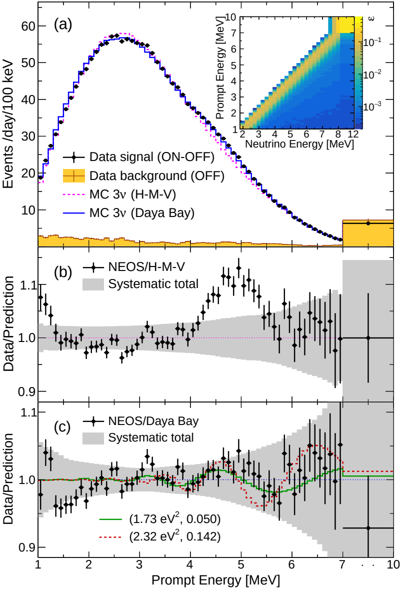
MiniBooNE See next

Possible explanation:

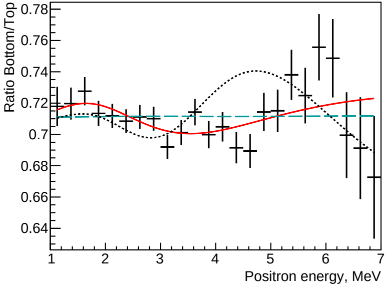
Additional squared mass difference $\Delta m^2_{\text{SBL}} \simeq 1\ \mathrm{eV}^2$

Recent results. . .

[NEOS, PRL 118 (2017) 121802]



[DANSS, PLB 787 (2018) 56]

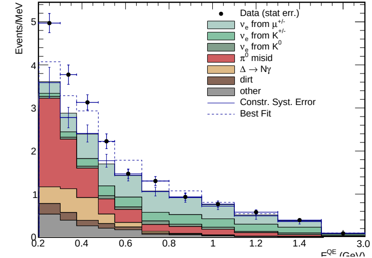


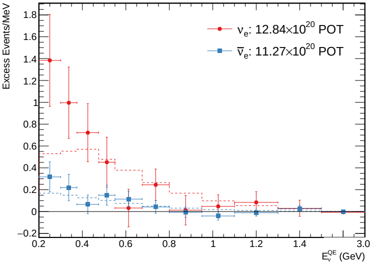
first *model independent* indications in favor of SBL oscillations

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

Recent results. . .

[MiniBooNE, PRL 121 (2018) 221801]





Recent results. . .

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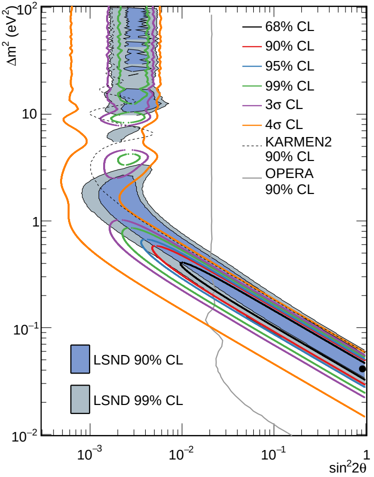

Recent results. . .

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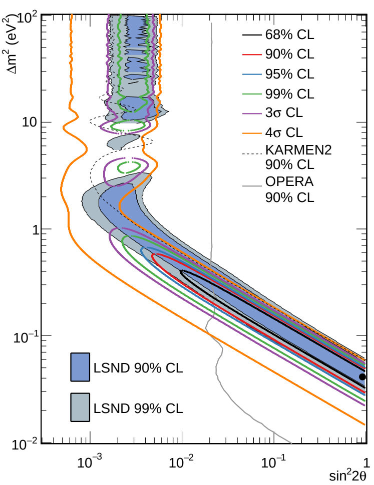
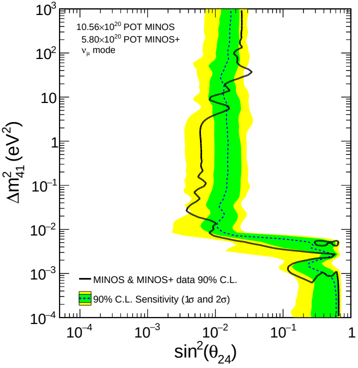


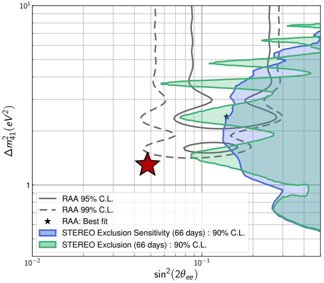
[MINOS+, PRL 122 (2019) 091803]



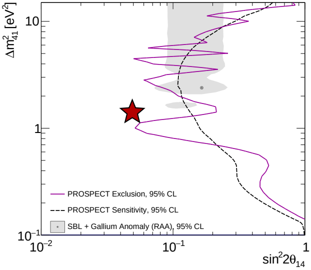
More to come...

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

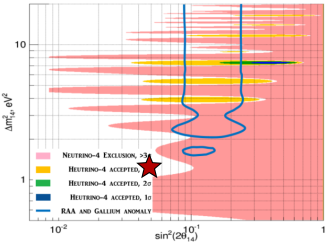
[STEREO, PRL 121 (2018) 161801]



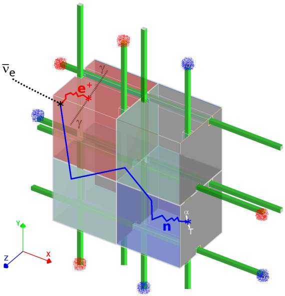
[PROSPECT, PRL 121 (2018) 251802]



[Neutrino-4, arxiv:1809.10561]



[SoLiD, JINST 13 (2018) P09005]



3+1 Neutrino Model

new $\Delta m^2_{\text{SBL}} \Rightarrow$ 4 neutrinos!

↓

ν_4 with $m_4 \simeq 1$ eV,
no weak interactions

↓

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

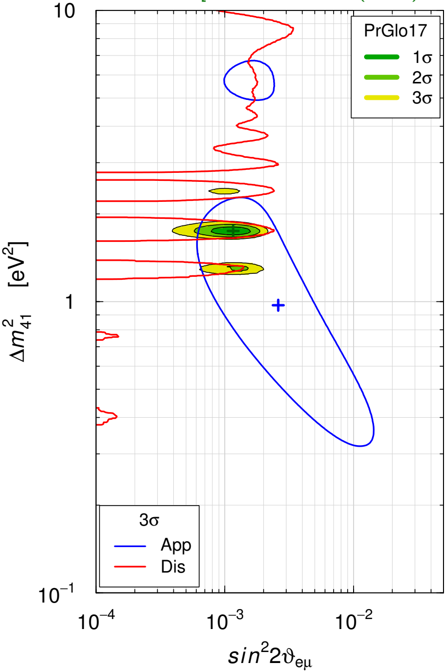
$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau, s)$$

ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\text{SBL}}}$$

assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$

[SG+, JHEP 06 (2017) 135]



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[SG+, work in progress]

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$\downarrow$

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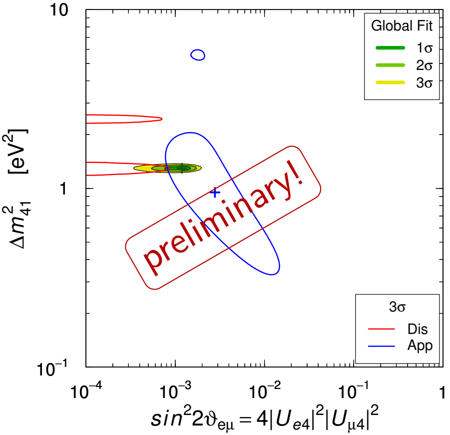

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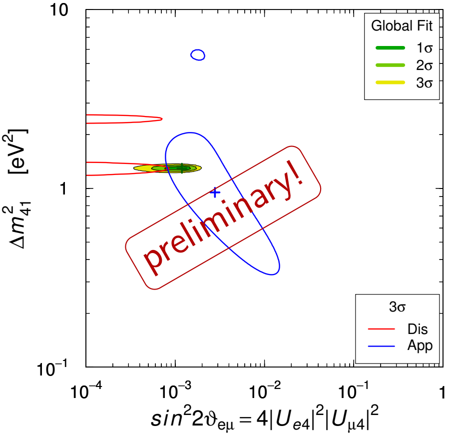
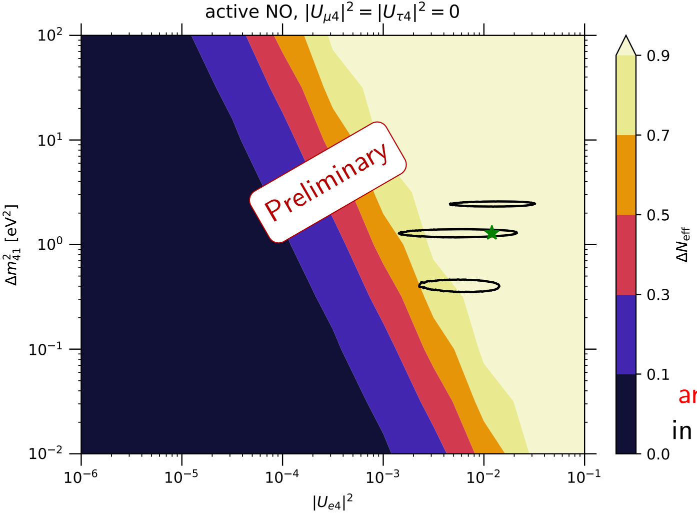


can ν_4 thermalize in the early Universe through oscillations?

LSν thermalization

Compute oscillations in early universe,
varying Δm^2_{41}, $|U_{e4}|^2$, here fix $|U_{\mu 4}|^2 = |U_{\tau 4}|^2 = 0$:

[SG+, in preparation]



black line, green star: 3σ region and best fit from DANSS+NEOS

[Gariazzo+, 2018]

Note:
the three $|U_{\alpha 4}|^2$ are NOT equivalent in the thermalization process!

LSν thermalization

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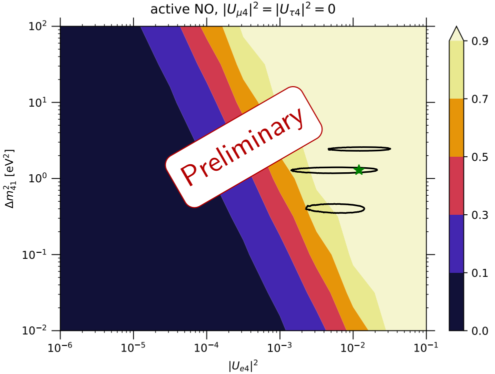
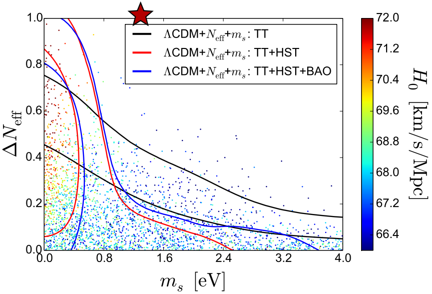
[SG+, in preparation]



[Archidiacono+, JCAP 08 (2016) 067]

but cosmological fits give:



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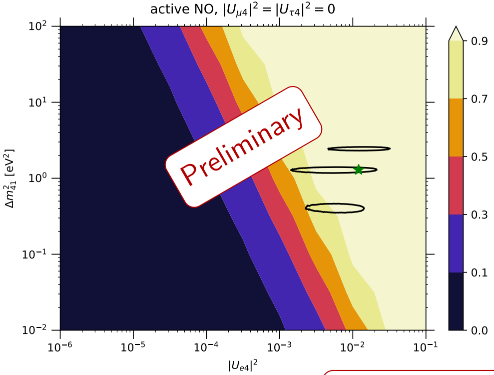

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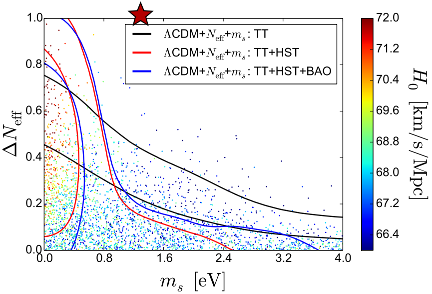


$\Delta N_{\rm eff} = 1$ disfavoured!

if LSν confirmed, we need new physics to reduce $N_{\rm eff}$

Assumptions and useful equations

[JCAP 09 (2017) 034]

We assume possible incomplete thermalization

(due to some unknown new physics)

$$f_4(p) = \frac{\Delta N_{\rm eff}}{e^{p/T_\nu}+1} = \Delta N_{\rm eff}\, f_{\rm active}(p)$$

$$\Delta N_{\rm eff} = \left[\frac{1}{\pi^2}\int dp\; p^3 f_4(p)\right] \Big/ \left[\frac{7}{8}\frac{\pi^2}{15}\, {T_\nu}^4\right]$$

$$\bar{n}_4 = \frac{g_4}{(2\pi)^3}\int f_4(p)\, p^2\, dp = n_0\, \Delta N_{\rm eff}$$

$$n_4 = n_0\, \Delta N_{\rm eff}\, f_c(m_4)$$

($f_c(m_4)$ is independent of $\Delta N_{\rm eff}$)

$$\Gamma_4 \simeq |U_{e4}|^2\, \Delta N_{\rm eff}\, f_c(m_4)\, \Gamma_{\rm C\nu B}$$

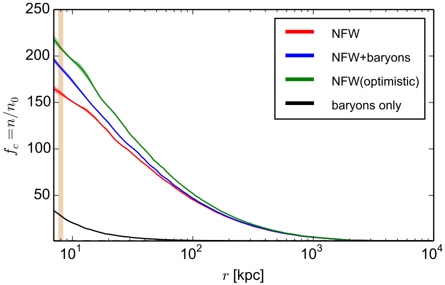
(from global fit [SG et al., 2017]: $m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$)

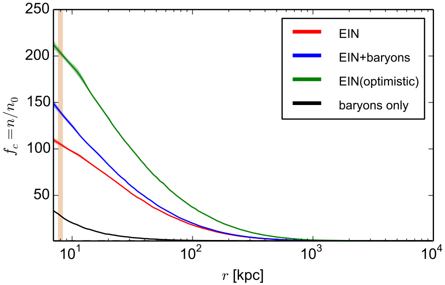
Overdensity of a sterile neutrino

[JCAP 09 (2017) 034]

$\Gamma_4 \simeq \Delta N_{\rm eff} \, |U_{e4}|^2 \, f_c(m_4) \, \Gamma_{C\nu B}$

$m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$





matter halo	overdensity f_4	$\Delta N_{\rm eff}$	$\Gamma_{\rm tot}$ (yr^{-1})
NFW(+bar)	159.9 (187.3)	0.2	2.6 (3.0)
		1.0	13.0 (15.2)
NFW optimistic	208.6	0.2	3.4
		1.0	16.9
EIN(+bar)	105.1 (139.5)	0.2	1.7 (2.3)
		1.0	8.5 (11.3)
EIN optimistic	203.5	0.2	3.3
		1.0	16.5

PTOLEMY and the ν_4

[PTOLEMY, arxiv:1902.05508]

$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \mathcal{O}(10)/\mathrm{yr}$

$$\Gamma_4 \simeq \Delta N_{\mathrm{eff}}\, |U_{e4}|^2\, f_c(m_4)\, \Gamma_{\mathrm{CNB}}$$

[SG+, PLB 782 (2018)]

$m_4 \simeq 1.15$ eV

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

$\Delta N_{\mathrm{eff}} =$ **??**

[de Salas+, 2017]

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

Γ_4 depends probably on new physics!

PTOLEMY and the ν_4

[PTOLEMY, arxiv:1902.05508]

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[SG+, PLB 782 (2018)]

$m_4 \simeq 1.15$ eV

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

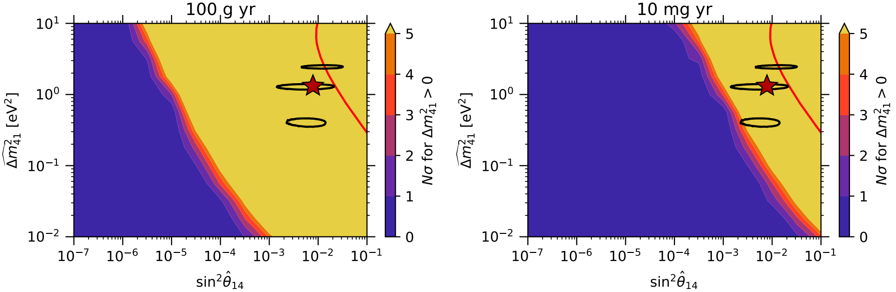
$\Delta N_{\rm eff} =$ **??**

[de Salas+, 2017]

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

Γ_4 depends probably on new physics!

Still possible to measure mass/mixing through β spectrum



black: DANSS+NEOS 3σ red: KATRIN 90% forecast

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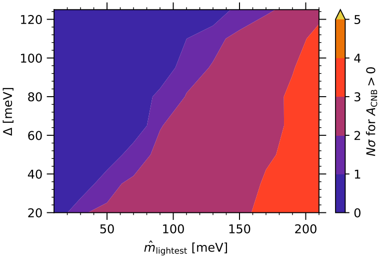
5 *Beyond the standard: light sterile neutrinos*

6 ***Conclusions***



Conclusions

1

amazing (neutrino) science
with direct detection
of relic neutrinos (e.g. PTOLEMY)
[non-relativistic regime, masses, ordering?, MW structure?, Dirac/Majorana?, ...]

2

But it will be a technological challenge!
(^3H amount, low background, energy resolution, ...)

3

possible event rate enhancement
due to clustering in the Milky Way:
should also include nearby galaxies/clusters!

Conclusions

1

amazing (neutrino) science
with direct detection
of relic neutrinos (e.g. PTOLEMY)
[non-relativistic regime, masses, ordering?, MW structure?, Dirac/Majorana?, ...]

2

But it will be a technological challenge!
(^{3}H amount, low background, energy resolution, ...)

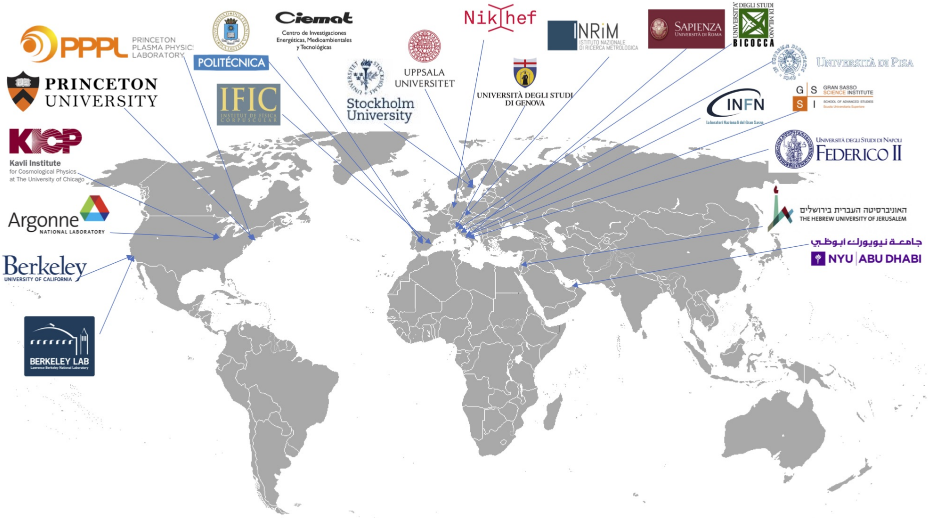
3

possible event rate enhancement
due to clustering in the Milky Way:
should also include nearby galaxies/clusters!

+1

light sterile neutrino ($m_4 \simeq 1.15$ eV) **??**
possible detection thanks to β decay spectrum

PTOLEMY collaboration



Thank you for the attention!