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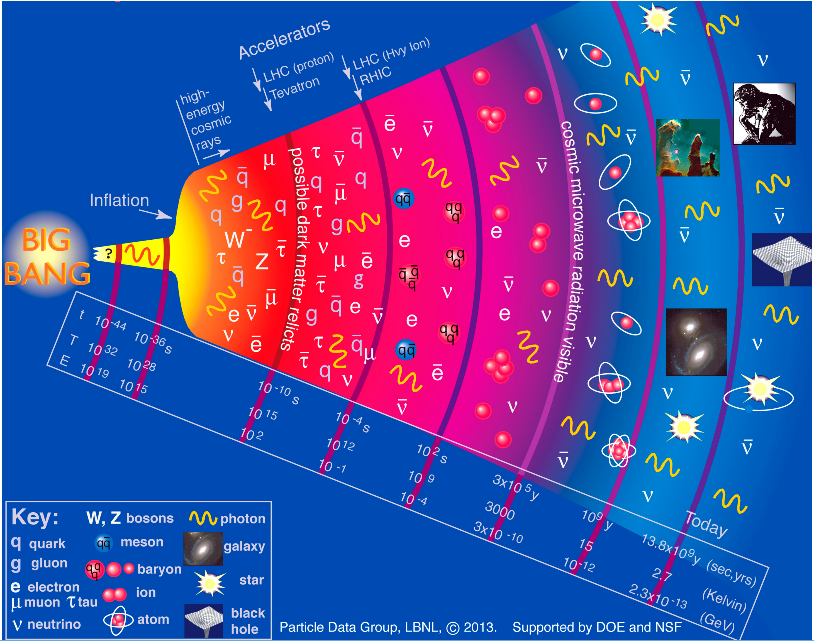
Neutrino physics with the PTOLEMY project

16th MultiDark Consolider Workshop, 25–27/09/2019

History of the universe



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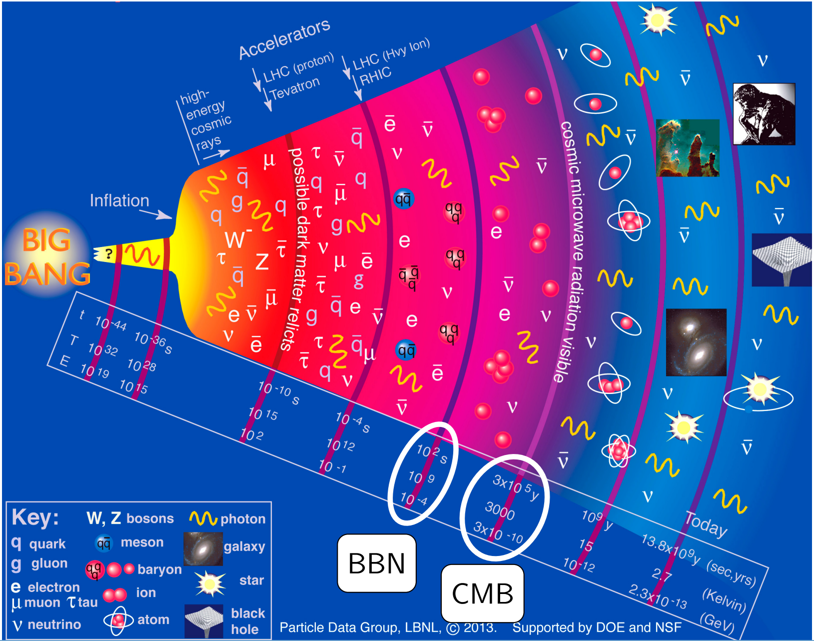
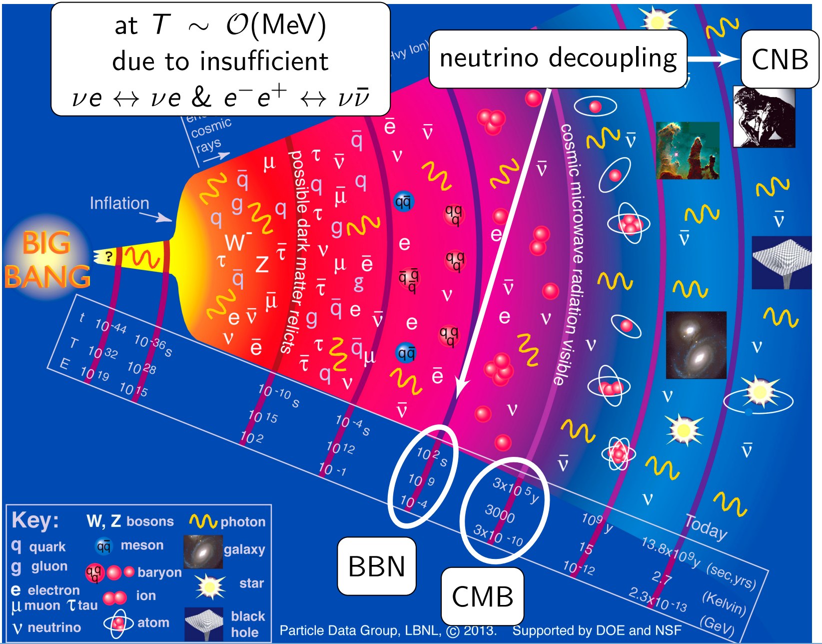


History of the universe

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

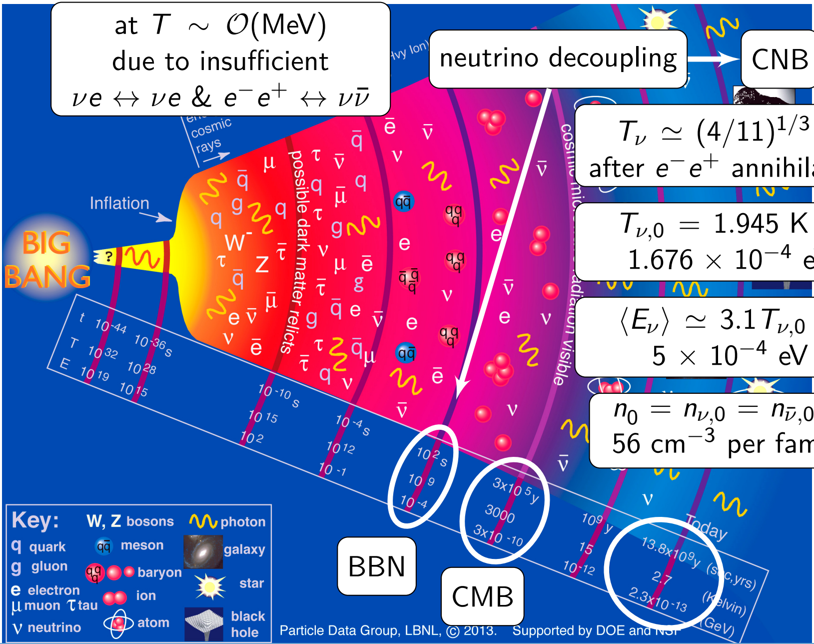
neutrino decoupling → CNB



BBN

CMB

History of the universe



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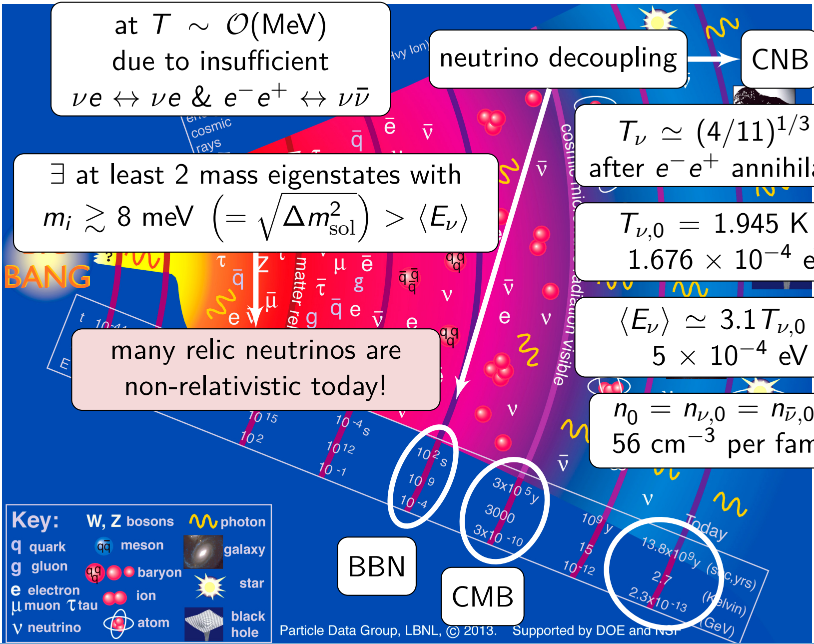
$T_\nu \simeq (4/11)^{1/3} T_\gamma$
after $e^- e^+$ annihilation

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

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

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

History of the universe



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after $e^- e^+$ annihilation

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

$T_{\nu,0} = 1.945\text{ K} \simeq$
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many relic neutrinos are
non-relativistic today!

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq$
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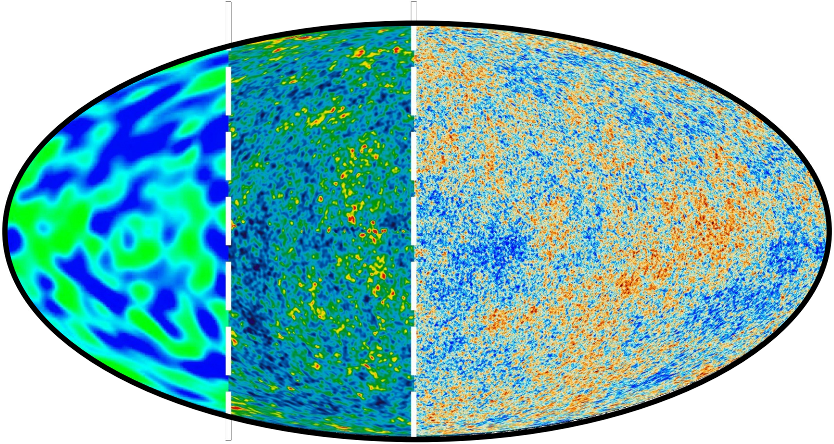
The oldest picture of the Universe

The Cosmic Microwave Background, generated at $t \simeq 1 \times 10^{13}$ s

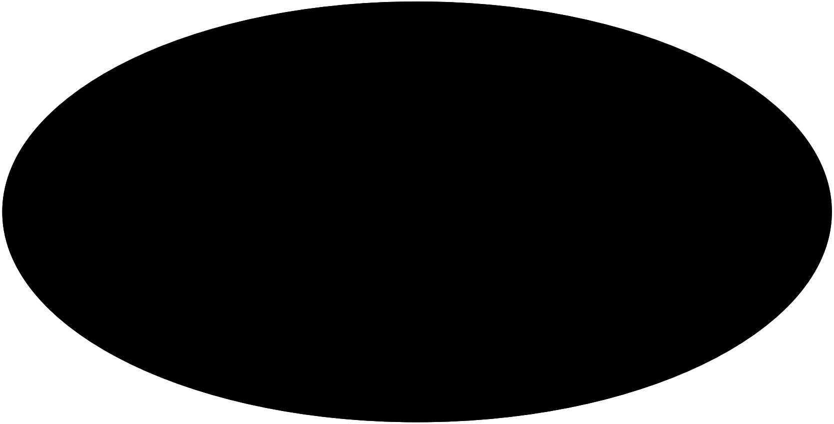
COBE (1992) WMAP (2003) Planck (2013)



The oldest picture of the Universe

The Cosmic Neutrino Background, generated at $t \simeq 100$ s

$2019 \to \dots$



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!

$\gg 10\sigma$!

1 *Cosmic Neutrino Background*

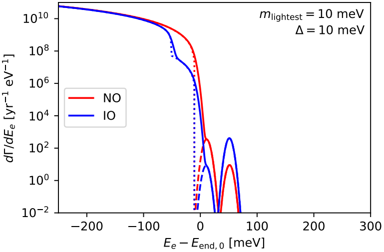
2 ***Direct detection of relic neutrinos***

- Some proposed methods
- Neutrino capture

3 *PTOLEMY*

- The experiment
- Simulations
- Perspectives

4 *Conclusions*



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

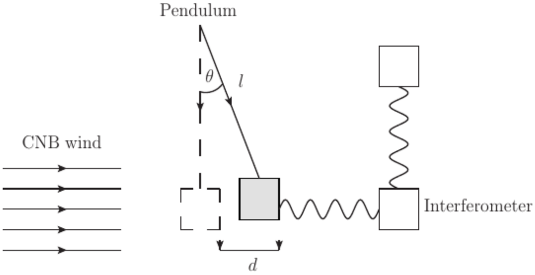
Direct detection - proposed methods - at interferometers

How to directly detect non-relativistic neutrinos?

At interferometers

[Domcke et al., 2017]

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



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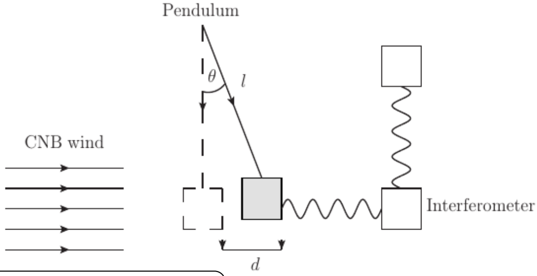


expected $10^{-33} \lesssim a_\nu/(\mathrm{cm/s^2}) \lesssim 10^{-27}$ ↔ $a_{\mathrm{LIGO/Virgo}} \simeq 10^{-16}\ \mathrm{cm/s^2}$

A viable method - neutrino capture

[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

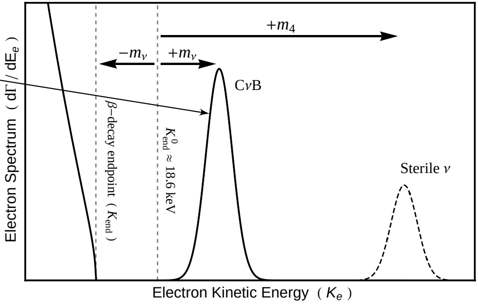
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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

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}
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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]

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

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

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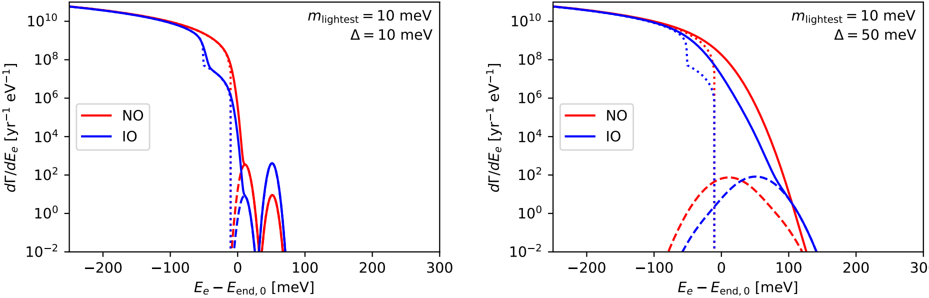

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PTOLEMY

[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

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

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

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

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)

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ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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- Simulations
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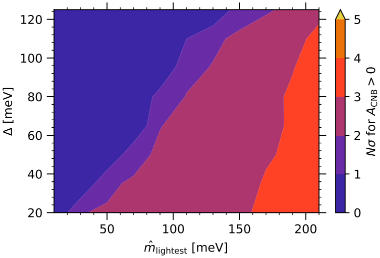


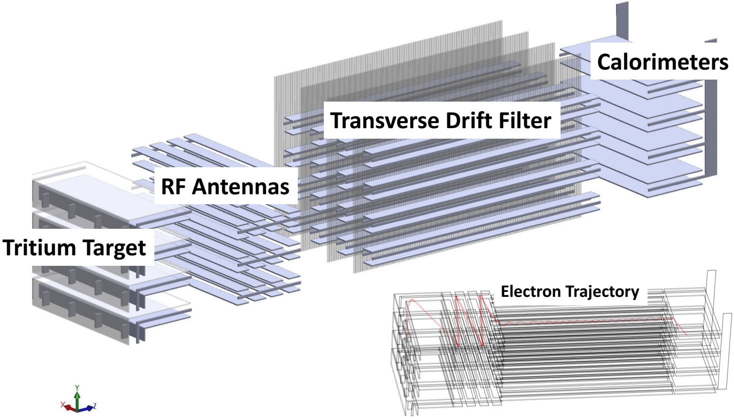
PTOLEMY pipeline

scope of PTOLEMY:

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

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

[PTOLEMY, PPNP 106 (2019) 120]



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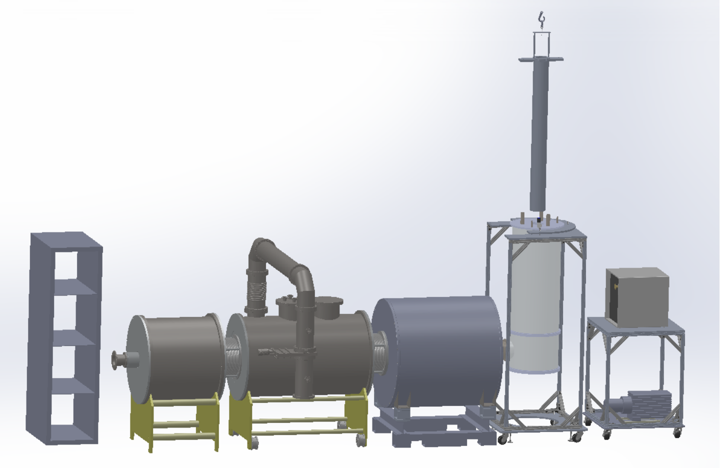

[PTOLEMY, arxiv:1808.01892]

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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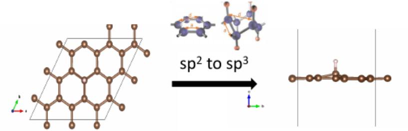
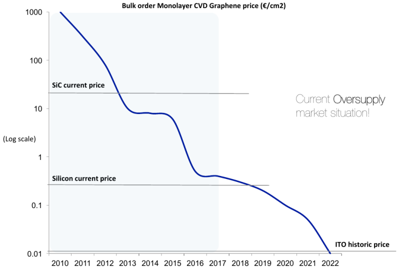
partially existing technology: hydrogenated graphene

layers

Graphene layers are cheap
(commercial use in displays)

hydrogenation under study
at Princeton





[courtesy A.Zurutuza (Graphenea)]

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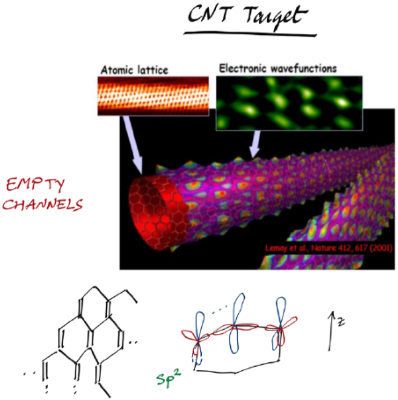
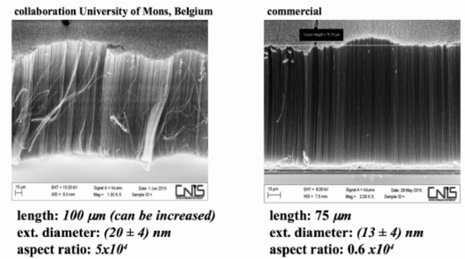
nanotubes



[courtesy G.Cavoto]

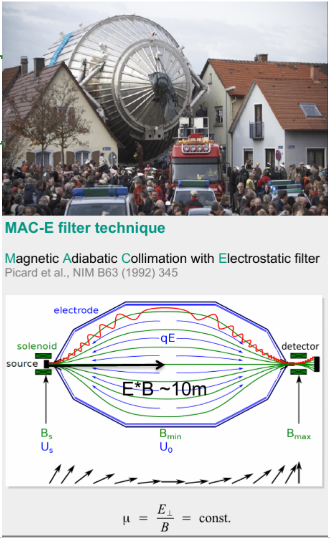


MAC-E filter

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

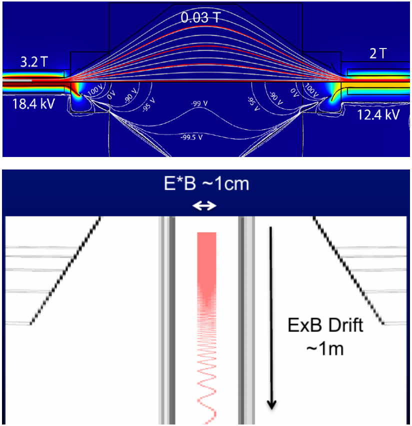
Magnetic Adiabatic Collimation with Electrostatic filter

[KATRIN]



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

see also [PTOLEMY, PPNP 106 (2019) 120]



[courtesy C.Tully]

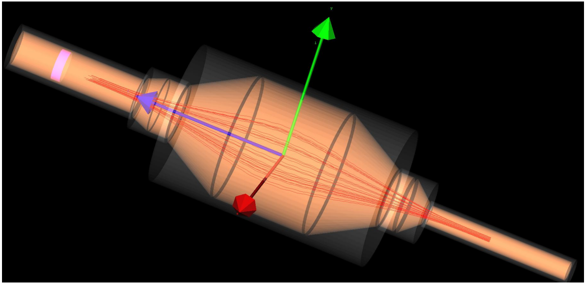
RF tracking

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)

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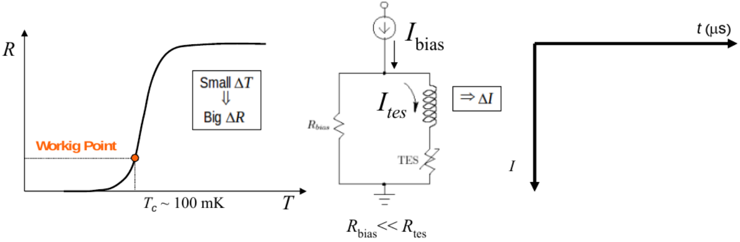
Microcalorimetry with Transition-Edge Sensors

[courtesy M.Ratjeri]



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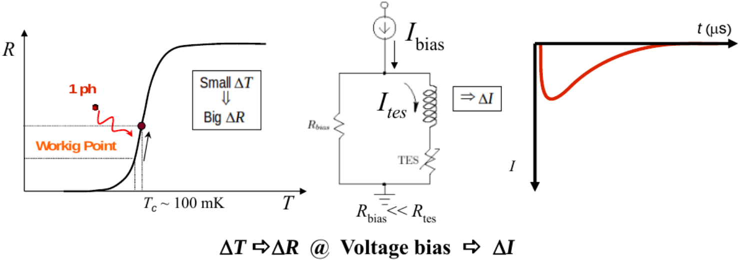

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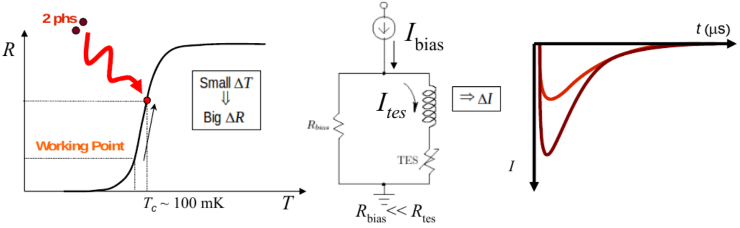

$\Delta T \Rightarrow \Delta R$ @ Voltage bias $\Rightarrow$ ΔI

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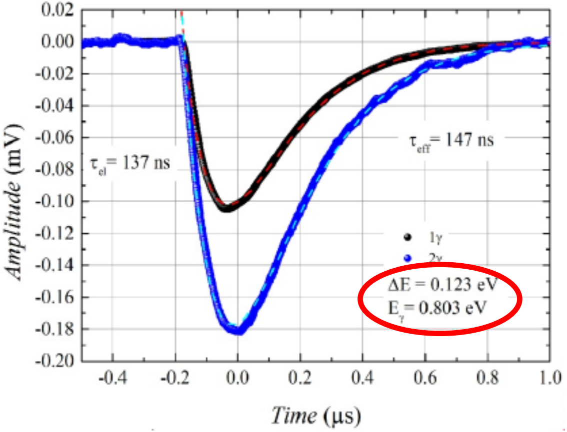


Simulations - I

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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 $\longrightarrow$ $N^i_t = \hat{N}^i + \hat{N}_b$

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**:

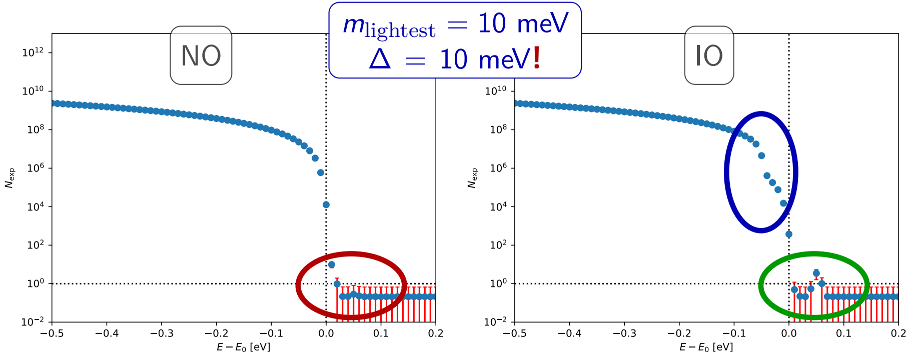
$$N^i_{\rm th}(\boldsymbol{\theta}) = \boldsymbol{A}_\beta N^i_\beta(\hat{E}_{end} + \boldsymbol{\Delta E_{end}}, m_i, U) + \boldsymbol{A}_{\rm CNB} N^i_{\rm CNB}(\hat{E}_{end} + \boldsymbol{\Delta E_{end}}, m_i, U) + N_b$$

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?

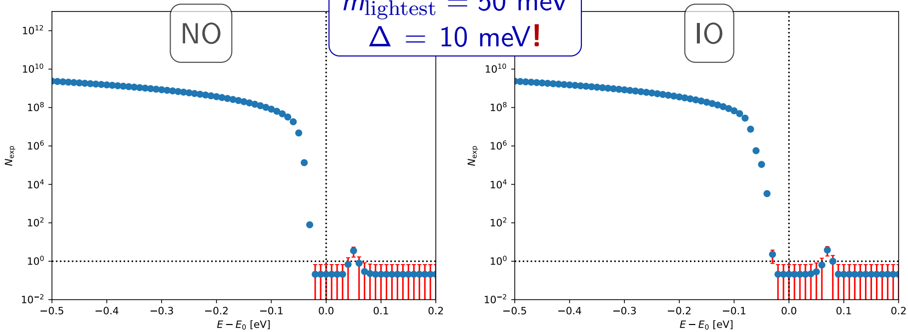


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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

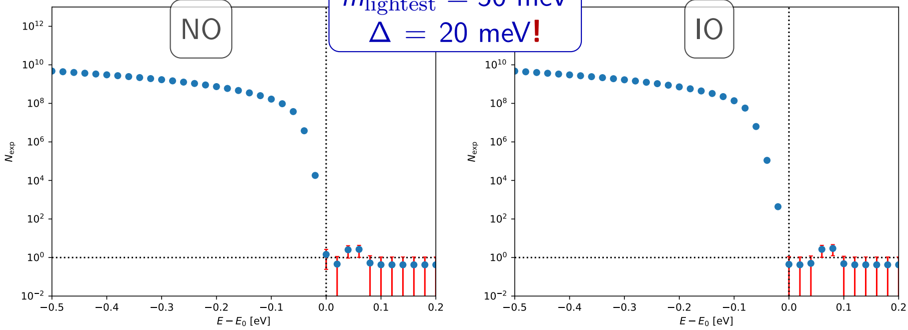


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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

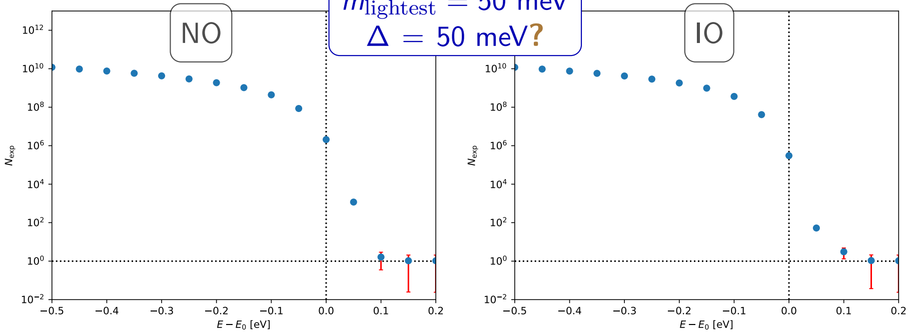


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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



1 year of observation with 100 g of T source

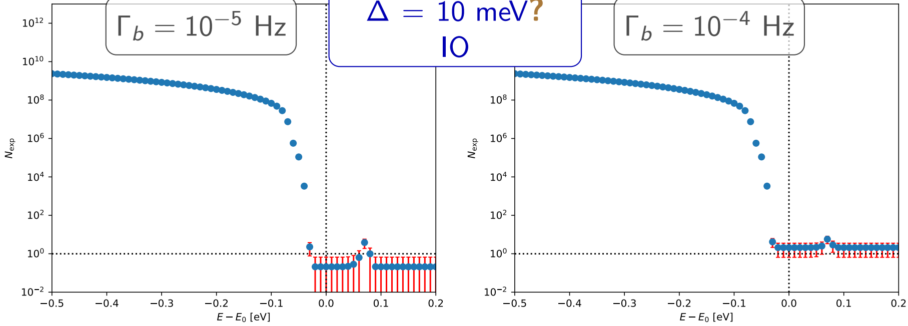
Simulations - II

no random noise?

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

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

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



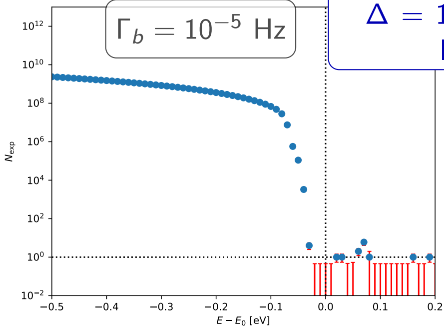
1 year of observation with 100 g of T source

Simulations - II

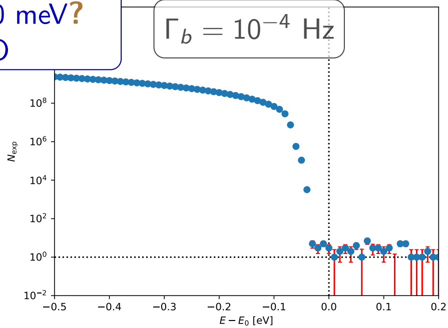
with random noise!

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

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



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



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

1 year of observation with 100 g of T source

Neutrino mass determination

statistical only!

relative error on $m_{\rm lightest}$

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

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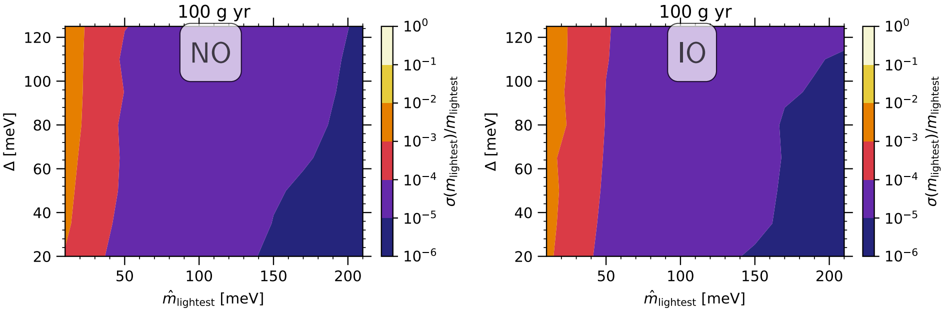


wonderful precision in determining the neutrino mass

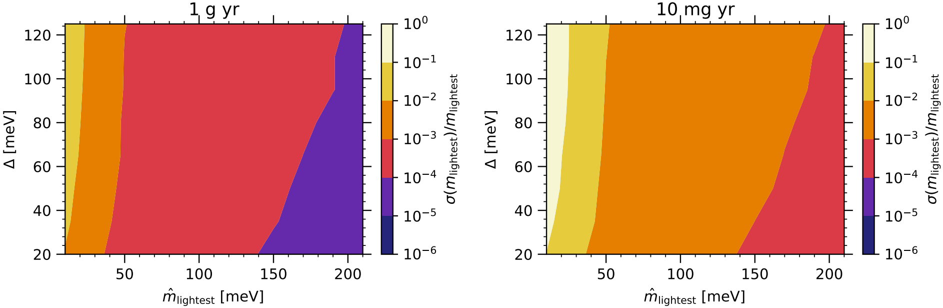
(well, yes, with 100 g of tritium...)

Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

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



wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

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[PTOLEMY, JCAP 07 (2019) 047]

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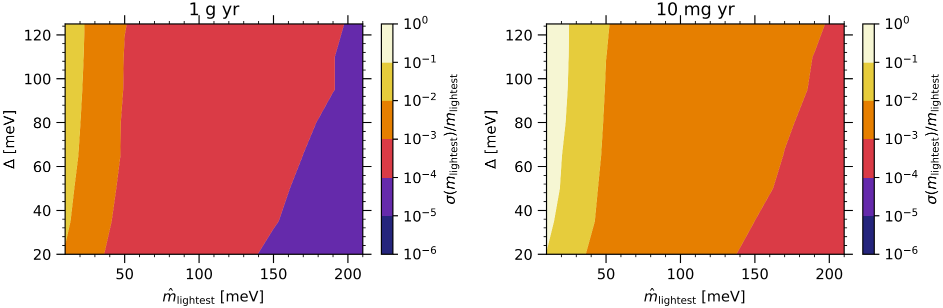

wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

Δ has almost no impact

Neutrino mass ordering

[PTOLEMY, JCAP 07 (2019) 047]

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 $\widehat{\mathrm{IO}}/\mathrm{IO}$

Neutrino mass ordering

[PTOLEMY, JCAP 07 (2019) 047]

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worse fit

better fit

Neutrino mass ordering

[PTOLEMY, JCAP 07 (2019) 047]

Bayesian method:

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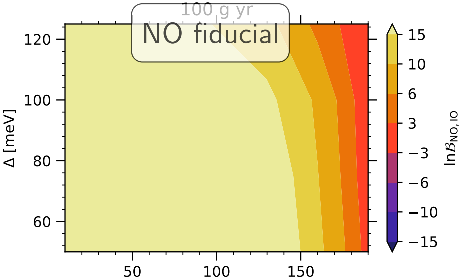
$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$ $\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

worse fit

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

[PTOLEMY, JCAP 07 (2019) 047]

Bayesian method:

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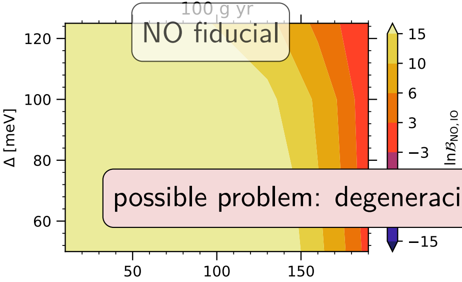
$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$ — $\widehat{\mathrm{IO}}/\mathrm{NO}$ vs $\widehat{\mathrm{IO}}/\mathrm{IO}$

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

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

statistical only!

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



IO fiducial

always strong significance

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

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

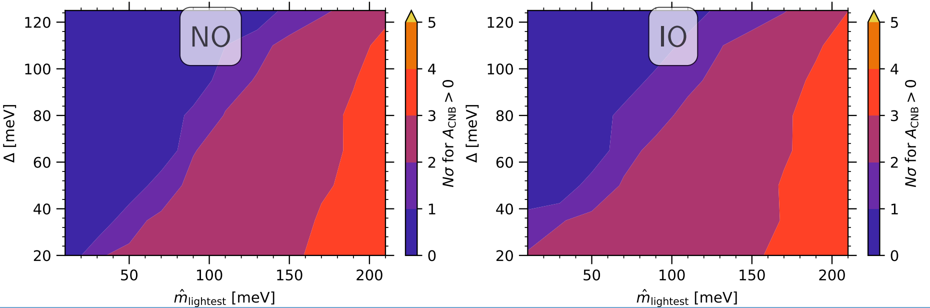
using the definition:

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

if $\boldsymbol{A}_{\rm \bf CNB} > 0$ 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*

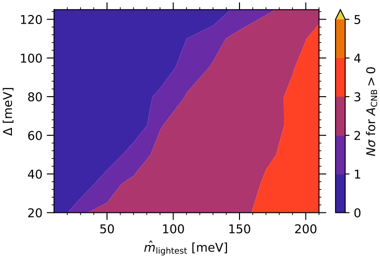
2 *Direct detection of relic neutrinos*

- Some proposed methods
- Neutrino capture

3 *PTOLEMY*

- The experiment
- Simulations
- Perspectives

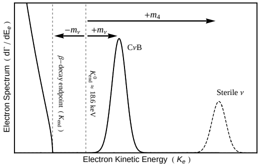
4 ***Conclusions***



Conclusions

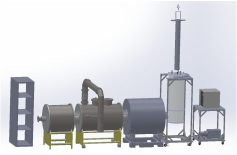
1

amazing (neutrino) science
with direct detection
of relic neutrinos (e.g. PTOLEMY)
[non-relativistic regime, ν masses, ordering, ...]



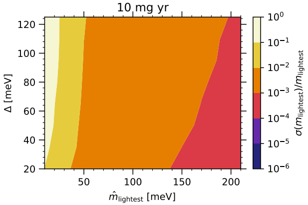
2

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

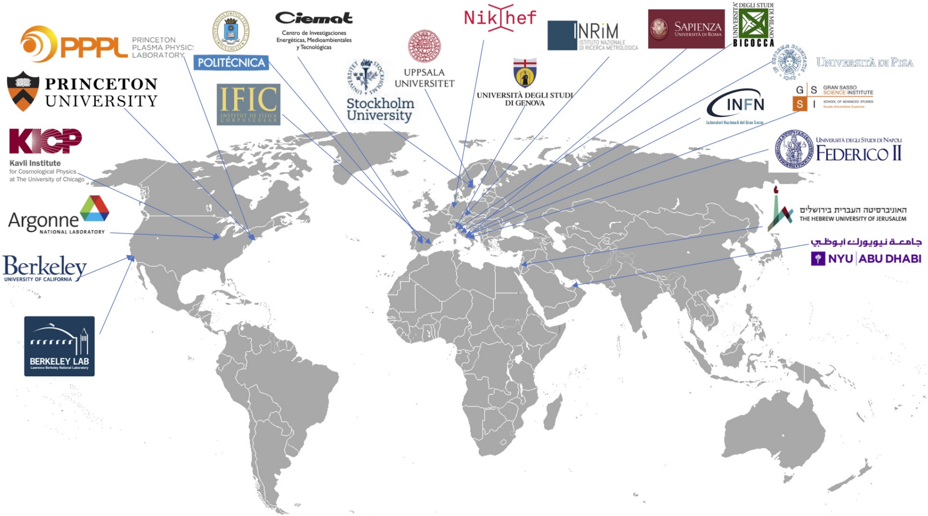


3

amazing results
already achievable
with small tritium amount!



PTOLEMY collaboration



Thank you for the attention!

Time variations of ν capture rates

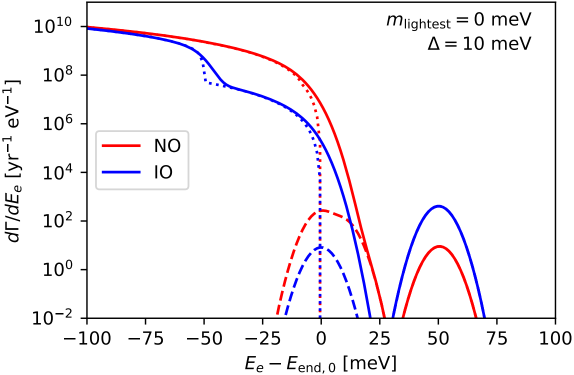
[Akhmedov, arxiv:1905.10207]

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

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

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

rates in the bin Δ on the endpoint



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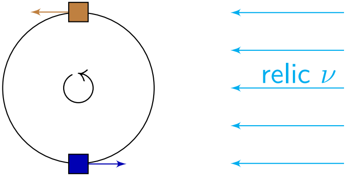

can be daily or yearly modulation!

only for ν capture (no β-decay)

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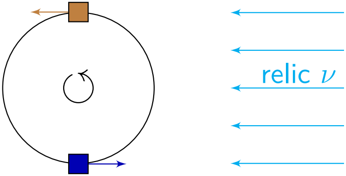


can be daily or yearly modulation!

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!

Dirac and Majorana neutrinos

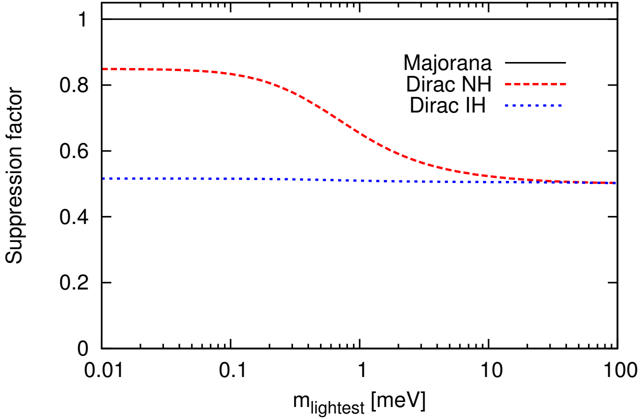
[Roulet+, JCAP 10 (2018) 049]

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**

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): $e^- + A^+ \rightarrow \nu_e + B^*$

(e^- from inner level)

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

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

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

specific energy conditions required

but Q value depends on ionization fraction!

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

specific energy conditions required

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"