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Neutrino clustering and CNB detection techniques

including details on PTOLEMY

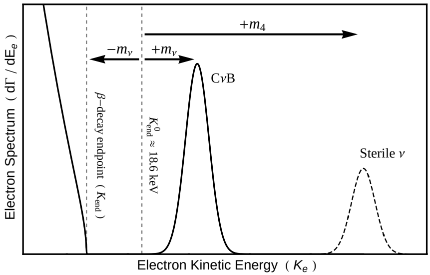
EuCAPT Astroneutrino Theory Workshop 2021, Prague (CZ) / online, 23/09/2021

D Direct detection of relic neutrinos

Proposed methods and their pros/cons

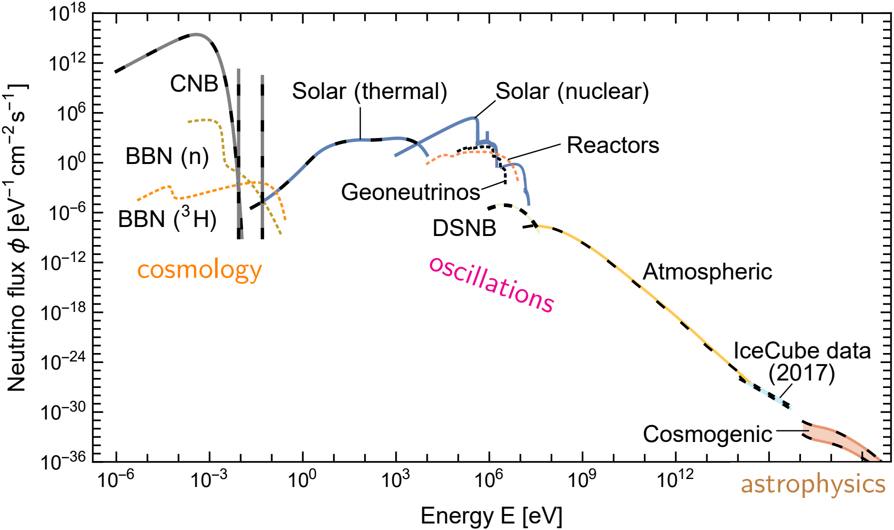
Based on:

- Cocco+, JCAP 06 (2007) 015
- Long+, JCAP 08 (2014) 038



Neutrino spectrum

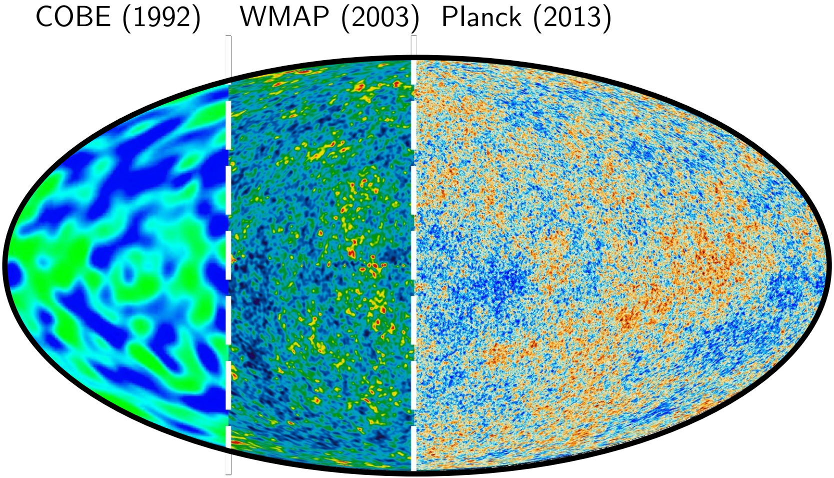
[Vitagliano+, RMP 92 (2020)]



CNB neutrinos have extremely small energy!

The oldest picture of the Universe

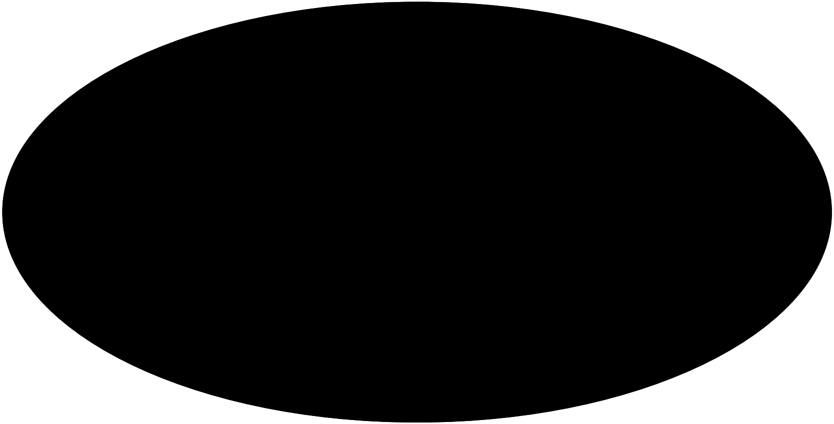
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years



The oldest picture of the Universe

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

$\ldots \rightarrow 2021 \rightarrow \ldots$



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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↓

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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

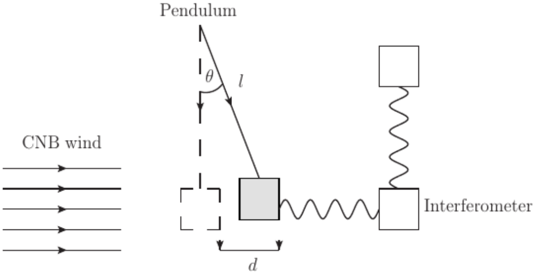
At interferometers?

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



At interferometers?

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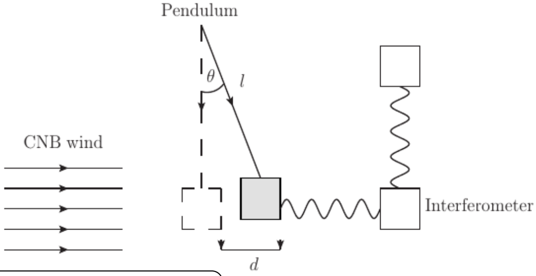
[Domcke et al., 2017]

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

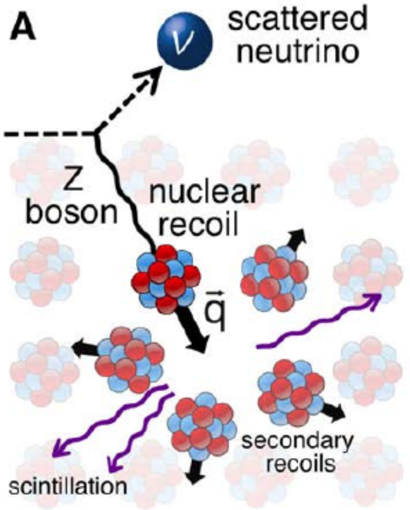


expected $10^{-33} \lesssim a_\nu/(\mathrm{cm/s^2}) \lesssim 10^{-27}$ $\longleftrightarrow$ $a_{\mathrm{LIGO/Virgo}} \simeq 10^{-16}\ \mathrm{cm/s^2}$

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, arxiv:2109.07482]

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

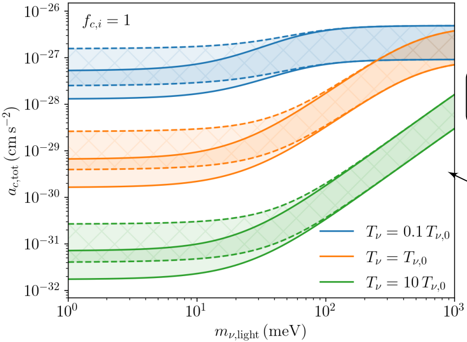
elastic scattering where ν interacts with nucleous "as a whole"

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

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

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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"

Neutrino capture (II) - a viable method

[Long+, JCAP 08 (2014) 038]

How to directly detect non-relativistic neutrinos?

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

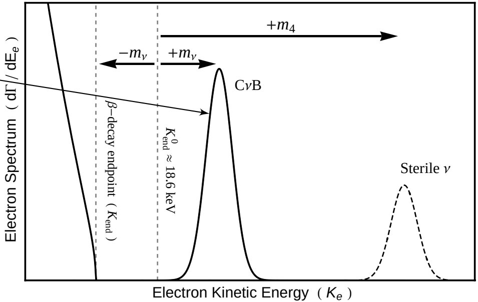
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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

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

only with a lot of material

need a very good energy resolution



What material?

[Cocco+, JCAP 06 (2007) 015]

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

to minimize contamination from β decay background

Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^{8}	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^{9}	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^{7}	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^{3}	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^{2}	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^{2}	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^{3}	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
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^{3}H better because the cross section ($\to$ event rate) is higher

β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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

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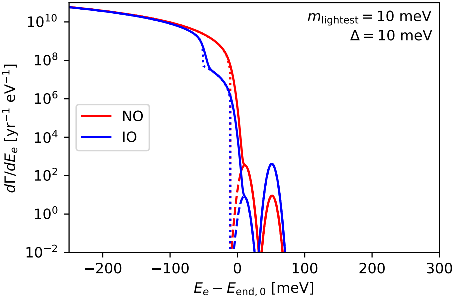
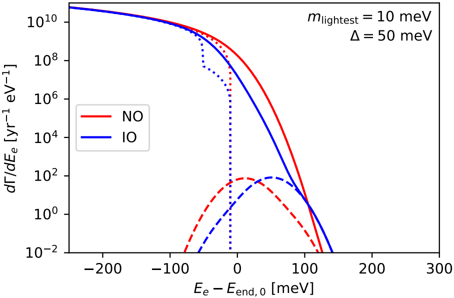




Time variations of ν capture rates

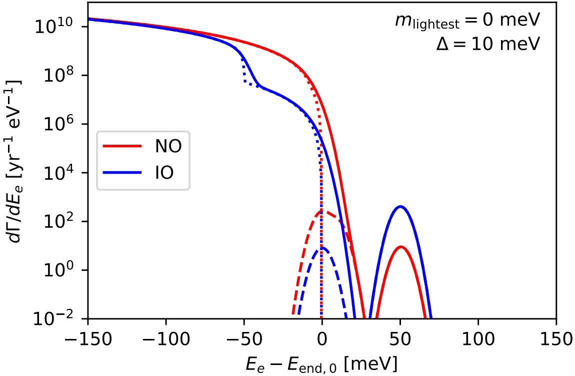
[Akhmedov, JCAP 2019]

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

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

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

rates in the bin Δ on the endpoint



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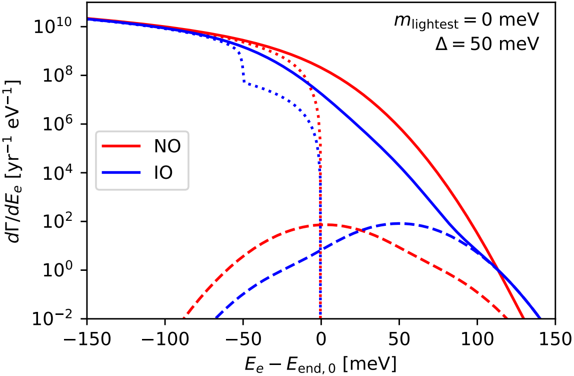

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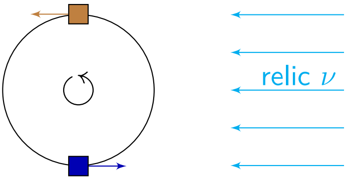

can be daily or annual modulation!

only for ν capture (no β-decay)

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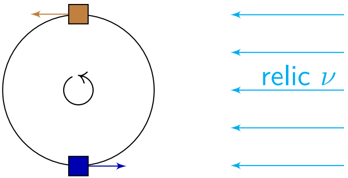

can be daily or annual modulation!

only for ν capture (no β-decay)

Problem:

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

Must use powerful technique for signal/noise separation

Fourier analysis and frequency filtering may be sufficient

no m_ν information in this way!

PTOLEMY

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

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

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

built mainly for CNB

$M_T = 100$ 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)

[PTOLEMY LoI, arxiv:1808.01892]

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ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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Dirac and Majorana neutrinos

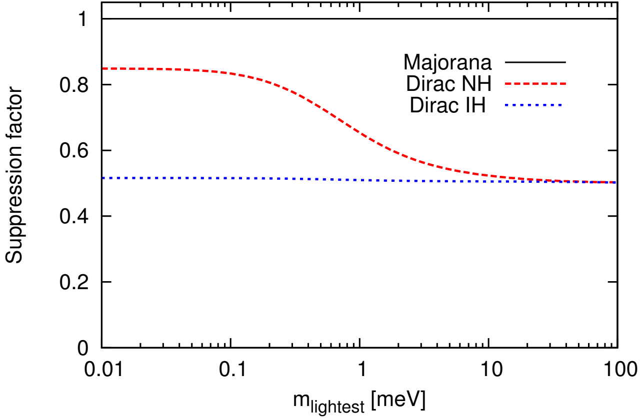
[Roulet+, JCAP 10 (2018) 049]

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

↓

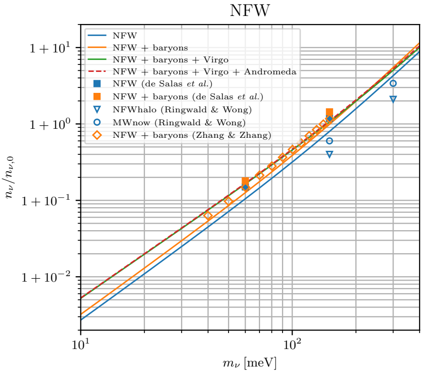
almost indistinguishable from **Majorana**

C Relic neutrino clustering

What about the local relic density of the CNB?

Based on:

- JCAP 09 (2017) 034
- JCAP 01 (2020) 015



ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

$f_c(m_i) = n_i/n_{i,0}$ 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!)

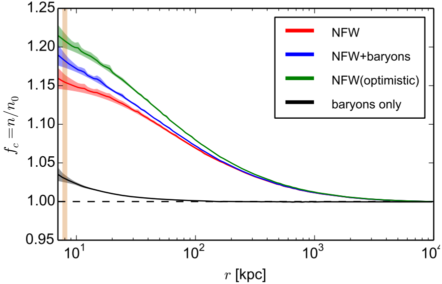
given N ν:

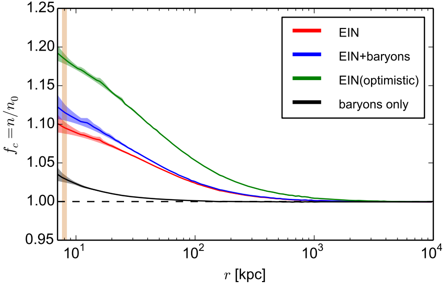
→ weigh each neutrinos

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

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

[JCAP 09 (2017) 034]





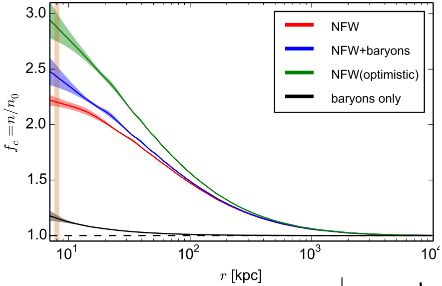
masses	ordering	matter halo	overdensity f_c: $f_1 \simeq f_2$	overdensity f_c: f_3	Γ_{tot} (yr^{-1})
any	any	any	no clustering		4.06
$m_3 = 60$ meV	NO	NFW(+bar)	$\sim$1	1.15 (1.18)	4.07 (4.08)
		NFW optimistic		1.21	4.08
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)
		EIN optimistic		1.18	4.08
$m_1 \simeq m_2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

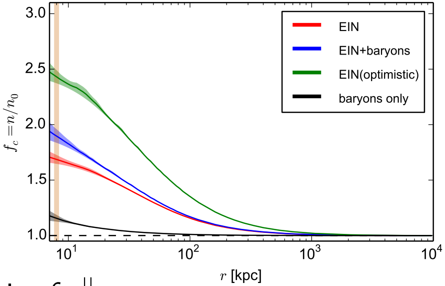
ordering dependence from $\Gamma_{\text{CNB}} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \left[n_i(\nu_{h_R}) + n_i(\nu_{h_L})\right] N_T\, \bar{\sigma}$

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: $m_1 \simeq m_2 \simeq m_3 \Longrightarrow f_1 \simeq f_2 \simeq f_3$

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 $\Delta N_{\rm eff}$)

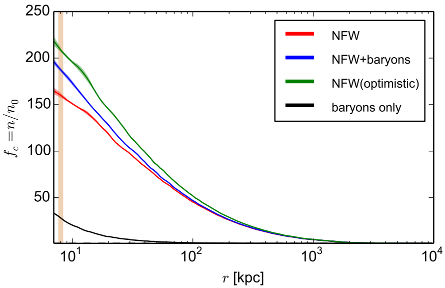
$$\Gamma_4 \simeq |U_{e4}|^2\,\Delta N_{\rm eff}\, f_c(m_4)\,\Gamma_{\rm C\nu B}$$

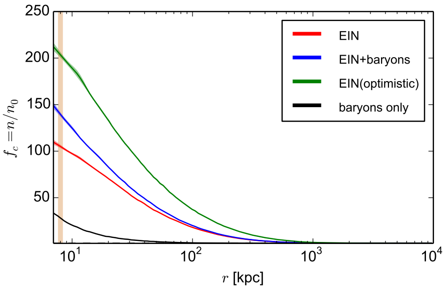
(from global fit [SG+, 2017]: $m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$)

Overdensity of a sterile neutrino

[JCAP 09 (2017) 034]

$\Gamma_4 \simeq \Delta N_{\rm eff} \, |U_{e4}|^2 \, f_c(m_4) \, \Gamma_{\rm C\nu B}$ $\qquad m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$

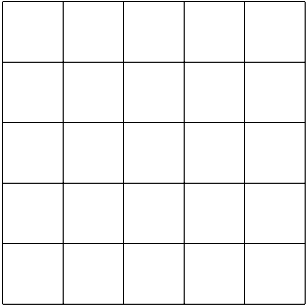


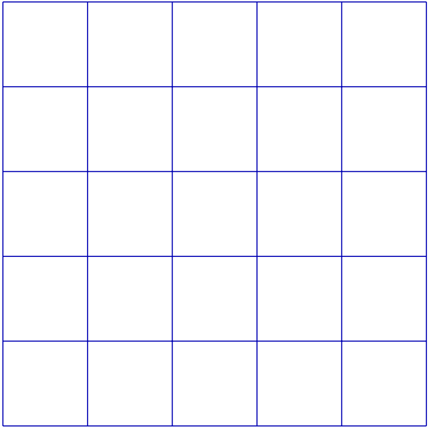


matter halo	overdensity f_4	$\Delta N_{\rm eff}$	$\Gamma_{\rm tot}$ (yr^{-1})
NFW(+bar)	159.9 (187.3)	0.2	2.6 (3.0)
		1.0	13.0 (15.2)
NFW optimistic	208.6	0.2	3.4
		1.0	16.9
EIN(+bar)	105.1 (139.5)	0.2	1.7 (2.3)
		1.0	8.5 (11.3)
EIN optimistic	203.5	0.2	3.3
		1.0	16.5

Forward-tracking and back-tracking

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





final phase space, $z = 0$

Forward-tracking and back-tracking

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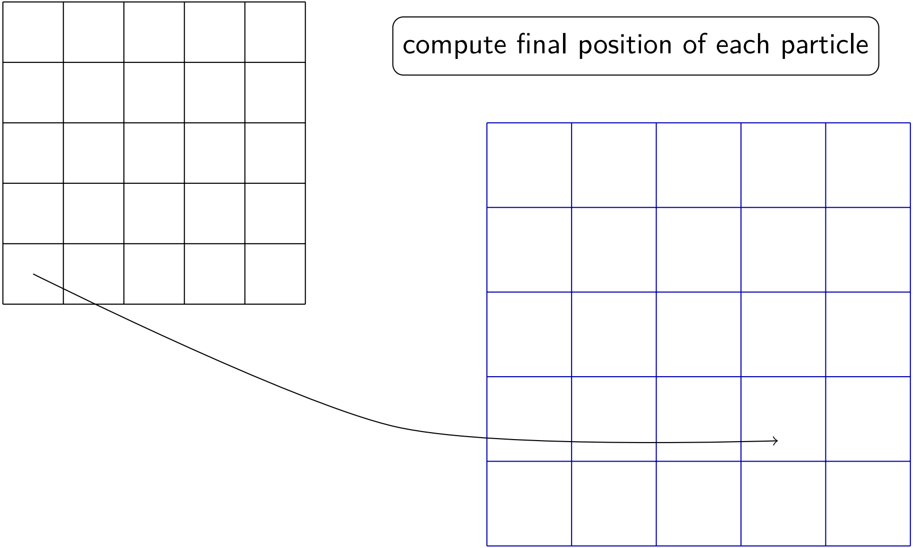
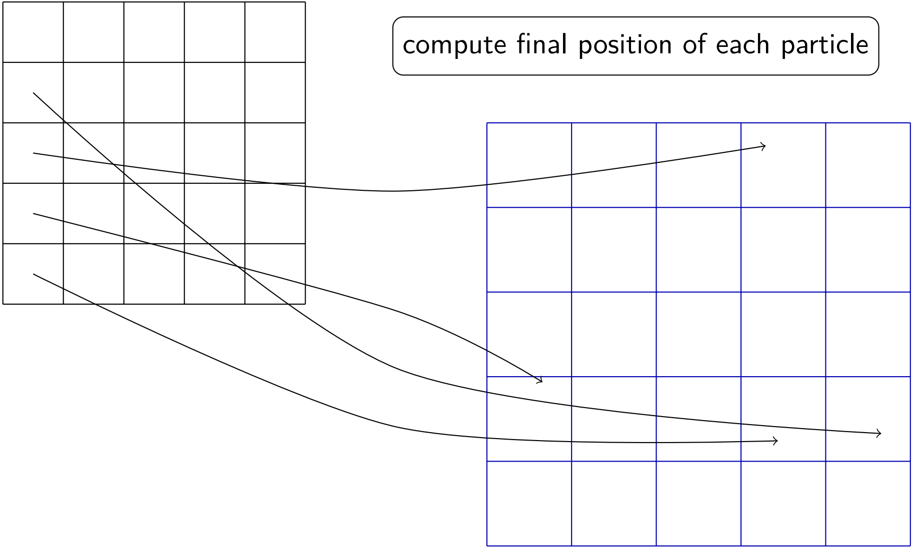


final phase space, $z = 0$

Forward-tracking and back-tracking

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

compute final position of each particle



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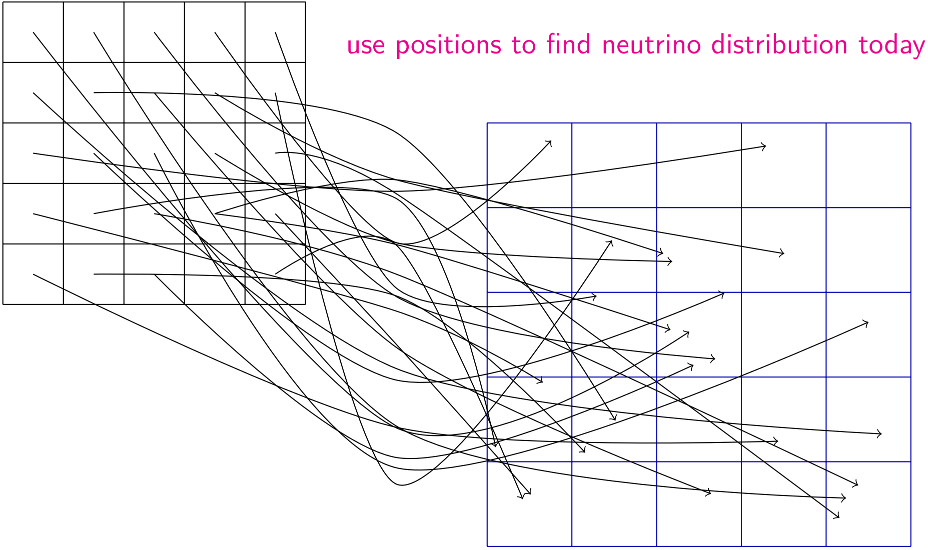

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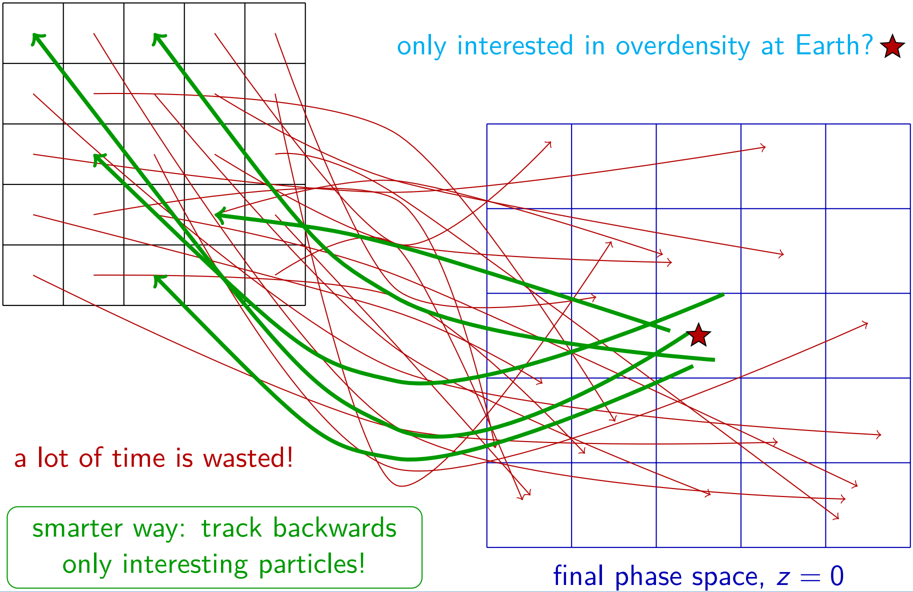


Advantages of tracking back

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

Advantages of tracking back

[JCAP 01 (2020) 015]

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

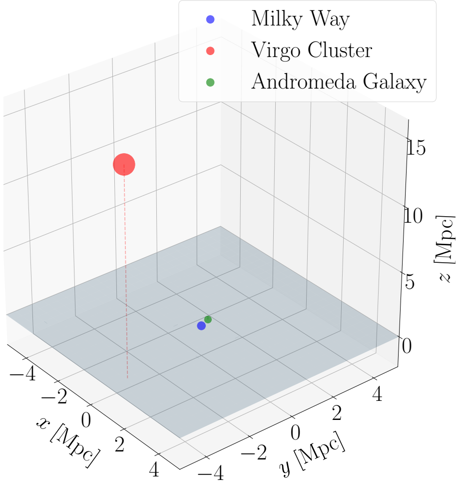
Second advantage: no need to use spherical symmetry!

Forward-tracking	Back-tracking
initial conditions need to sample 1D for position + 2D for momentum when using spherical symmetry	"Initial" conditions only described by 3D in momentum
with full grid would require 3+3 dimensions!	(position is fixed, apart for checks)
Impossible to relax spherical symmetry!	can do the calculation with any astrophysical setup

Advantages of tracking back

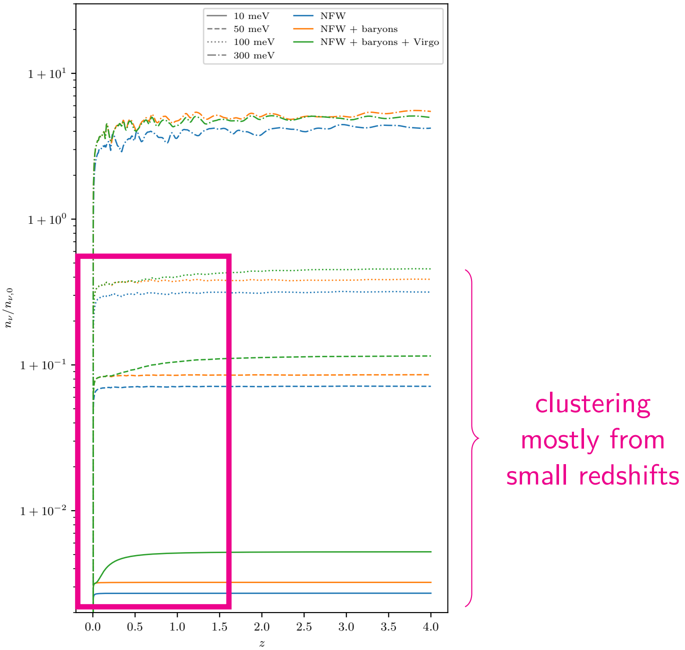
First advantage is in computational terms: much less points to compute

Second advantage: no need to use spherical symmetry!



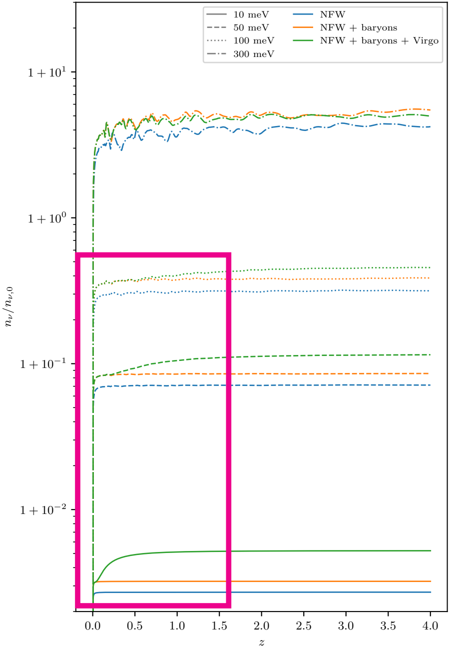
Backtracking. . . until when?

[JCAP 01 (2020) 015]



Backtracking. . . until when?

[JCAP 01 (2020) 015]



for $m \gtrsim 0.3$ eV, trapped orbits already at $z = 4$!

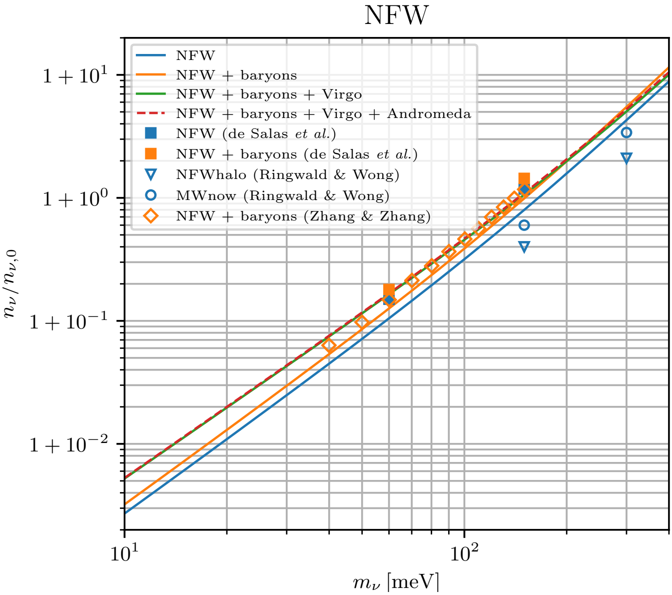
cannot assume homogeneous initial conditions at $z = 4$

clustering mostly from small redshifts

Clustering results with back-tracking

[JCAP 01 (2020) 015]

In comparison with previous results:



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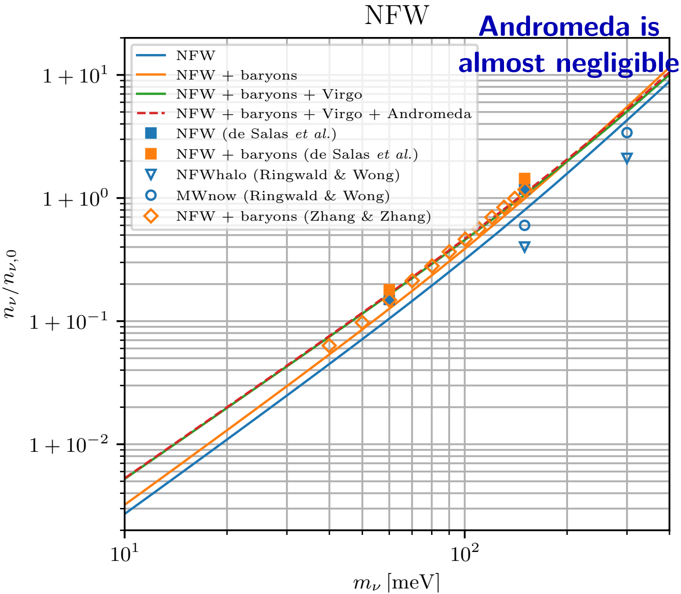

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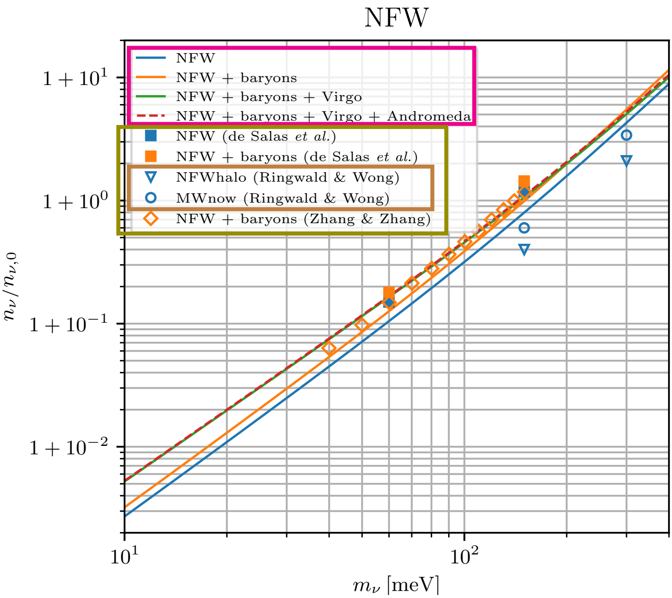

Warning: NFW is not the same for all the cases!

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

[Ringwald&Wong, 2004] uses old parameters

Clustering results with back-tracking

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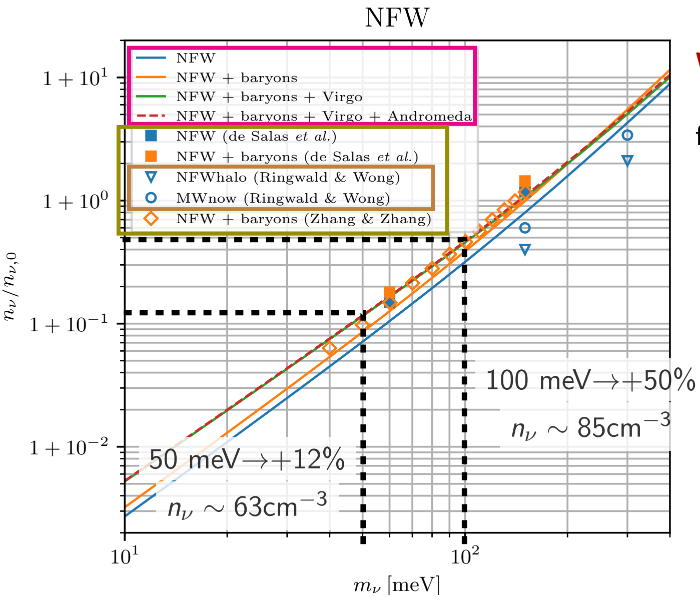

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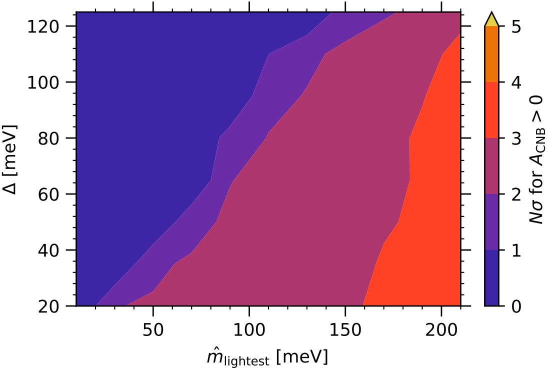
P PTOLEMY

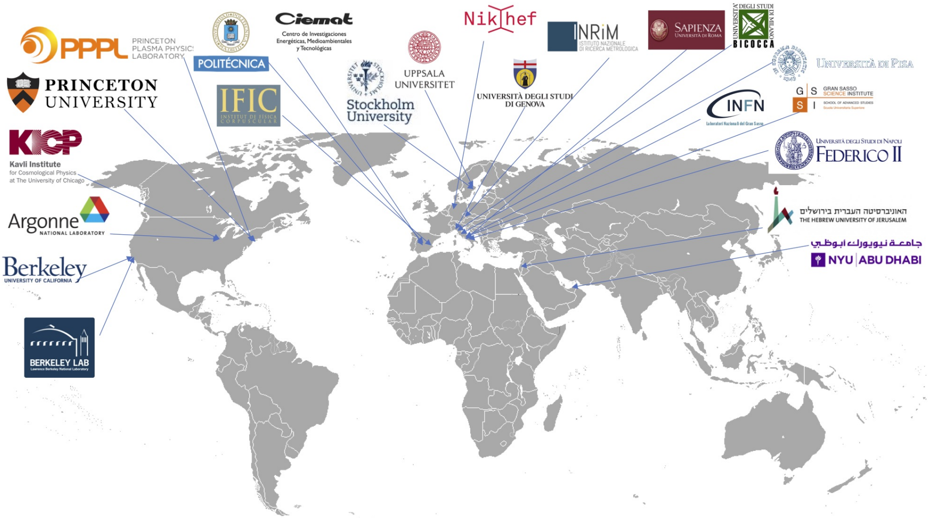
Short description of the experiment and its possibilities

Based on:

- PTOLEMY LoI, arxiv:1808.01892
- PTOLEMY, JCAP 07 (2019) 047



PTOLEMY collaboration

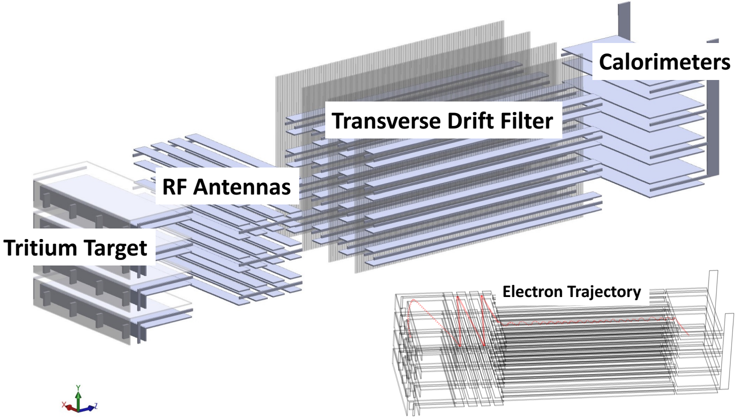


PTOLEMY pipeline

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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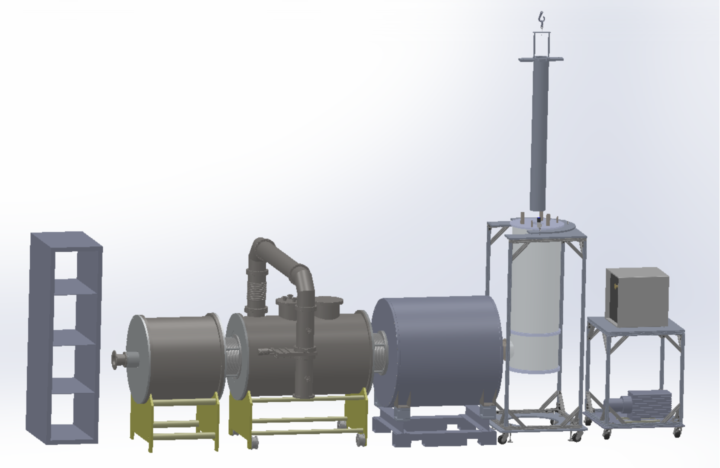

The source - graphene

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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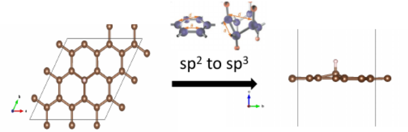
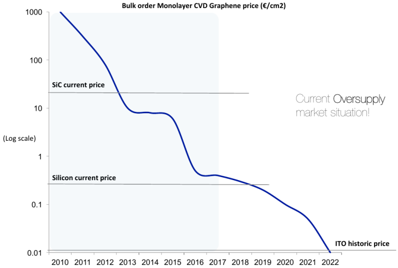
partially existing technology: hydrogenated graphene

layers

Graphene layers are cheap
(commercial use in displays)

hydrogenation under study
at Princeton





[courtesy A.Zurutuza (Graphenea)]

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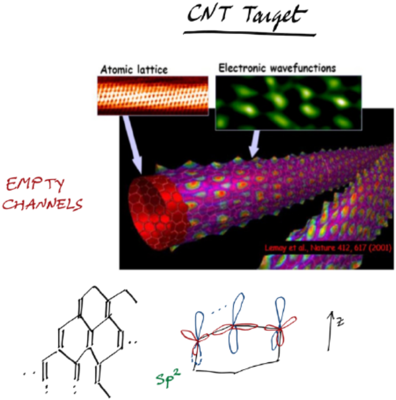
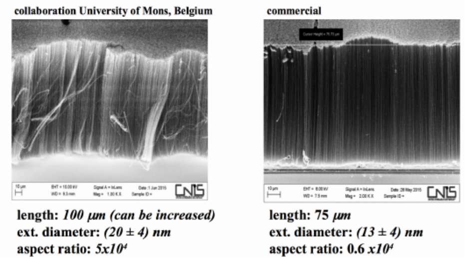


[courtesy G.Cavoto]

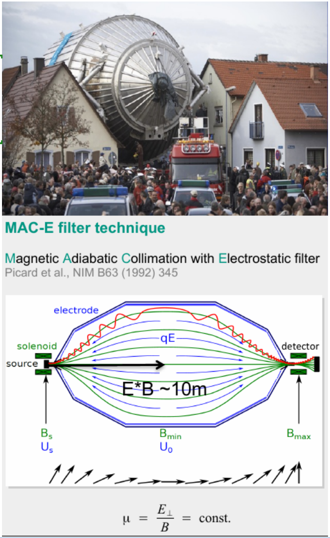


MAC-E filter

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

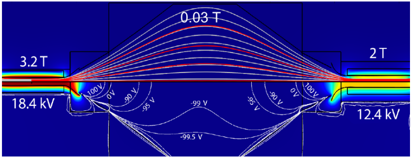
Magnetic Adiabatic Collimation with Electrostatic filter

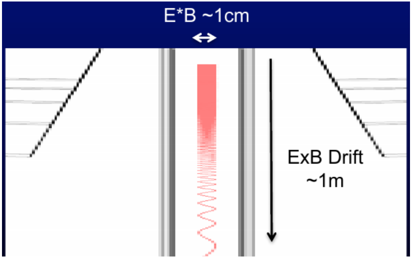
[KATRIN]



see also [PTOLEMY, arxiv:2108.10388]

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





[courtesy C.Tully]

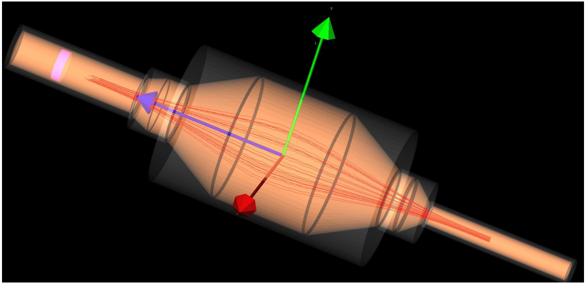
RF tracking

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

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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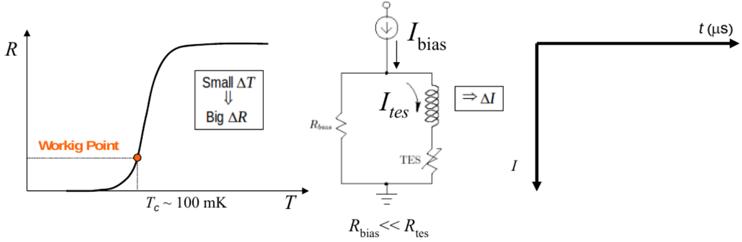
Microcalorimetry with Transition-Edge Sensors

[courtesy M.Ratjeri]



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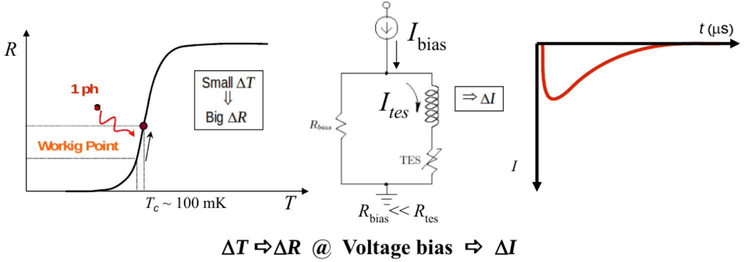

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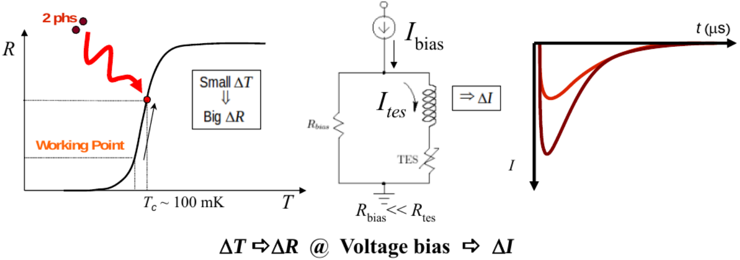

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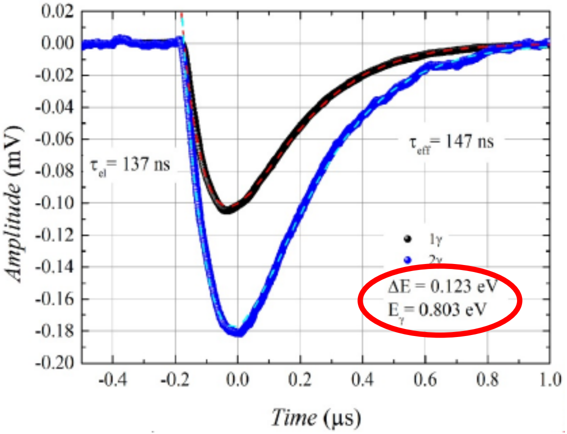

Simulations - theory

[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

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

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, JCAP 07 (2019) 047]

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

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

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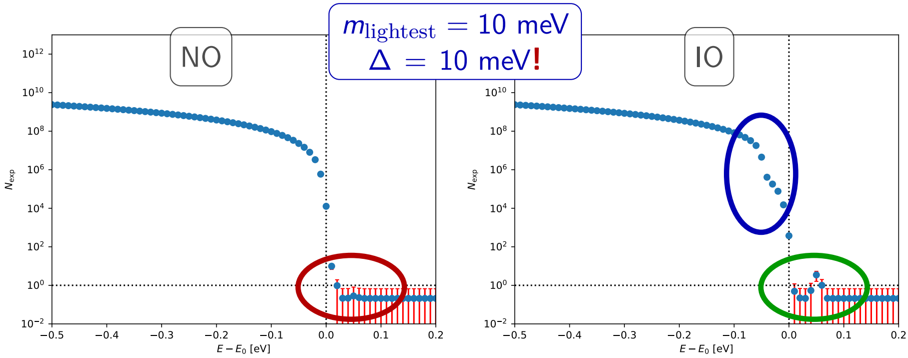
fit ⟶ $$\chi^2(\boldsymbol{\theta}) = \sum_i\left(\frac{N^i_{\rm exp}(\hat{E}_{\rm end},\hat{m}_i,\hat{U}) - N^i_{\rm th}(\boldsymbol{\theta})}{\sqrt{N^i_t}}\right)^2$$ or $\log\mathcal{L} = -\frac{\chi^2}{2}$

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?

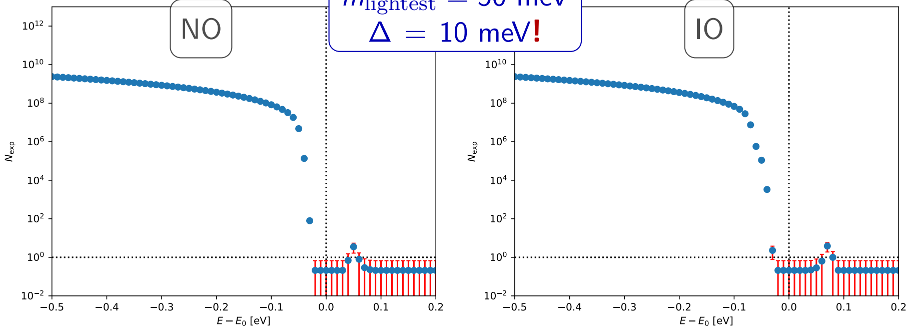


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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

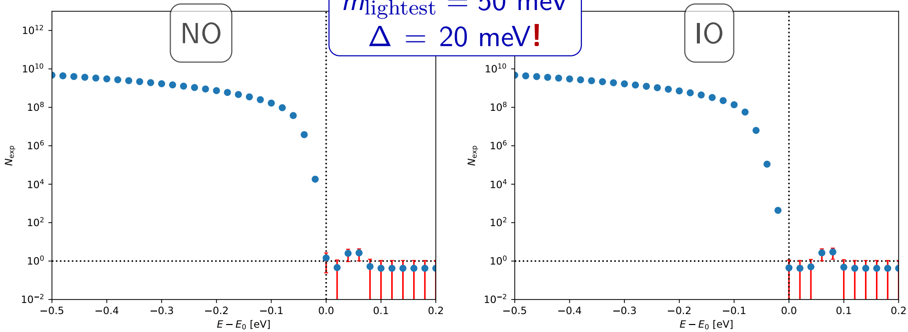


1 year of observation with 100 g of T source

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

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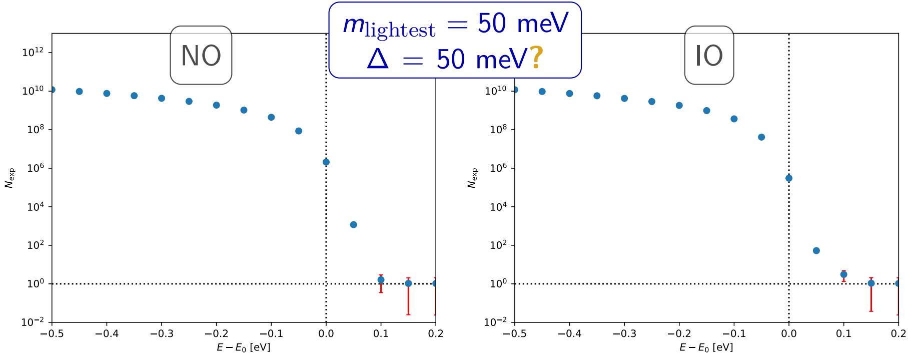

1 year of observation with 100 g of T source

Simulations - II

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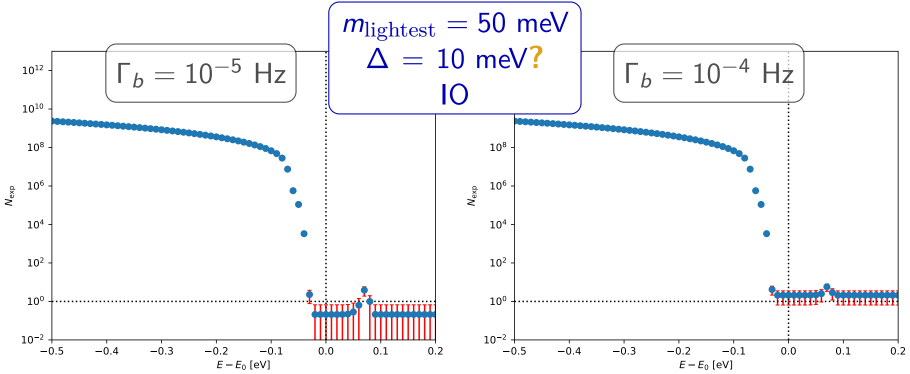


1 year of observation with 100 g of T source

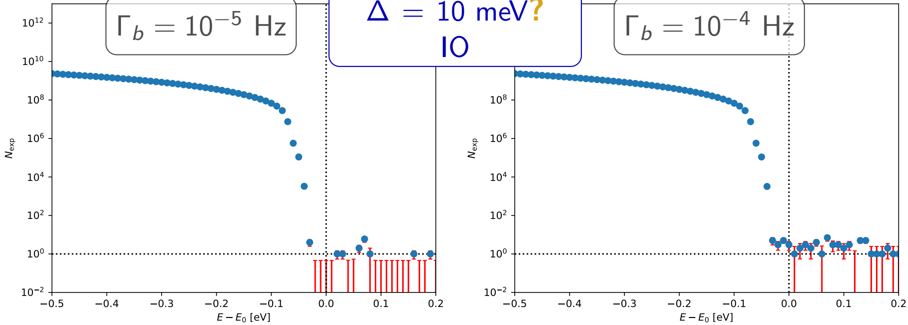
Simulations - II

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

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

relative error on $m_{\rm lightest}$

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

Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

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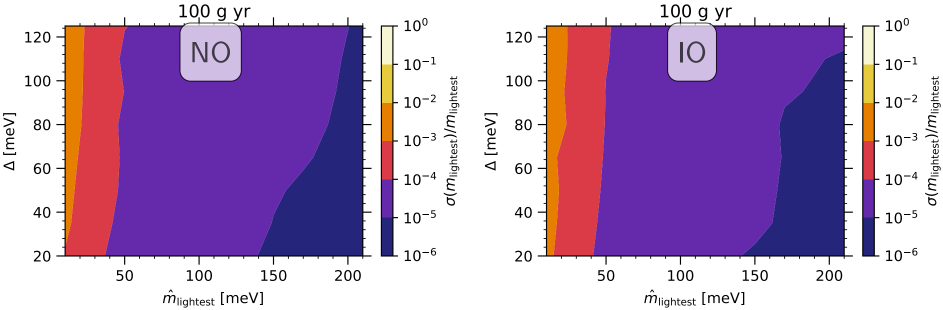

wonderful precision in determining the neutrino mass

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

Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

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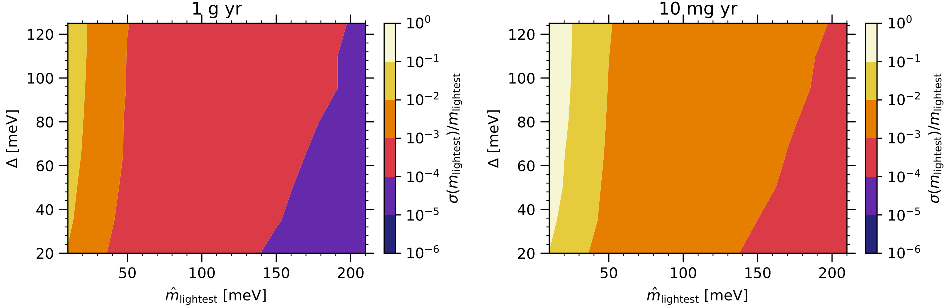

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(mass detection already with 10 mg of tritium!)

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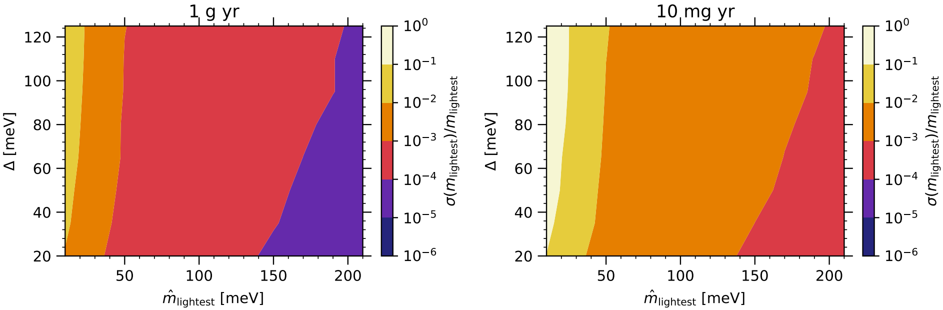

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(mass detection already with 10 mg of tritium!)

Δ has almost no impact

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

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worse fit

better fit

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[PTOLEMY, JCAP 07 (2019) 047]

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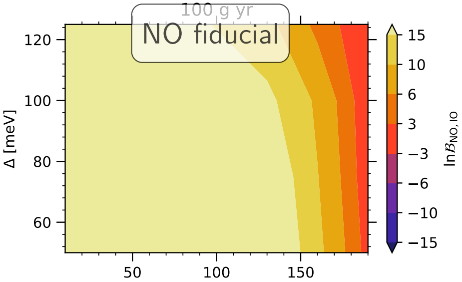
(Bayesian) preference on m_{lightest}
as a function of $\hat{m}_{\mathrm{lightest}}$, Δ



IO fiducial

always strong significance

Neutrino mass ordering

[PTOLEMY, JCAP 07 (2019) 047]

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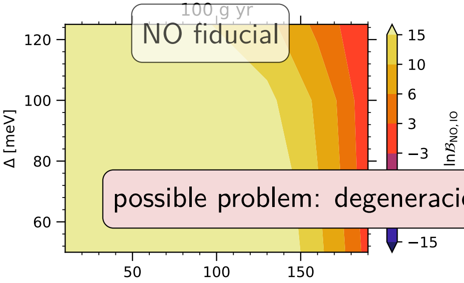

NO fiducial

IO fiducial

always strong significance

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

PTOLEMY and the ν_4

[PTOLEMY, JCAP 07 (2019) 047]

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

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

[SG+, PLB 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!

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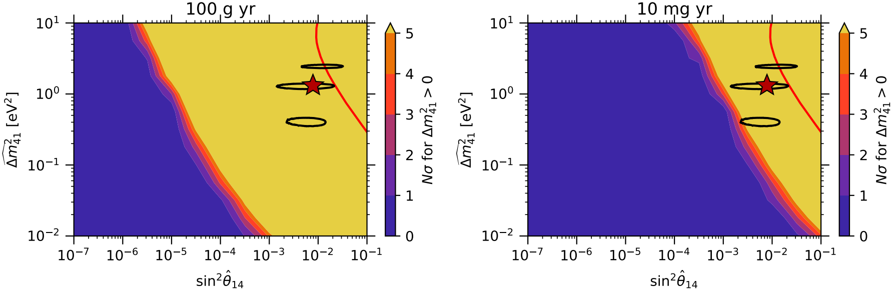
Γ_4 depends probably on new physics!

Still possible to measure mass/mixing through β spectrum



black: DANSS+NEOS 3σ (2018)

red: KATRIN 90% forecast

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

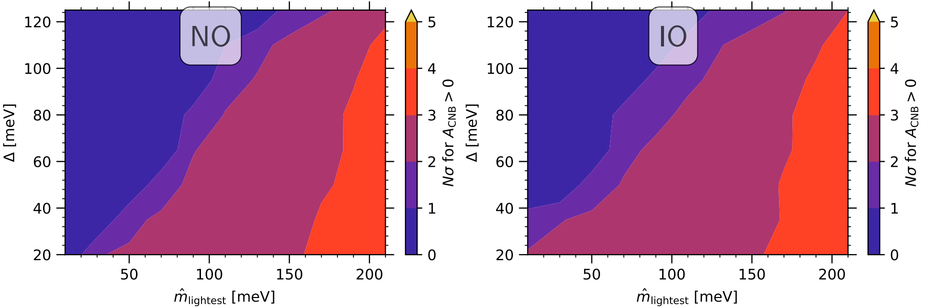
using the definition:

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

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



Tritium mass and PTOLEMY reach

[PTOLEMY, JCAP 07 (2019) 047]

PTOLEMY can do interesting physics
even with **a small amount of Tritium**

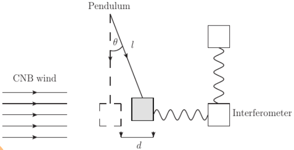
given T mass:	10 mg	1 g	100 g
can we do. . . ν masses?	✓ $m_{\rm lightest} < 7$ meV	✓ $m_{\rm lightest} < 2$ meV	✓ $m_{\rm lightest} < 0.5$ meV
(eV) sterile neutrino?	✓ ($\sim 5\sigma$)	✓ ($\gg 5\sigma$)	✓ ($\gg 5\sigma$)
mass ordering?	? (not studied yet)	? (not studied yet)	✓
direct detection?	✗	✗	✓ (favorable m_ν)

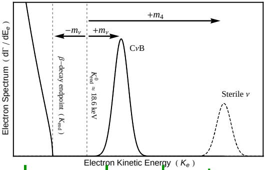
S Summary

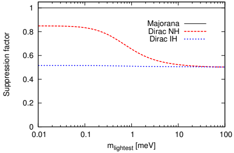
What did we learn about direct detection of the CNB?

D

Direct detection is hard! but not impossible

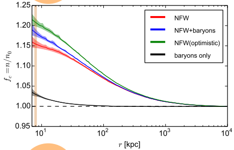


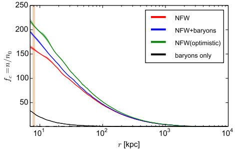


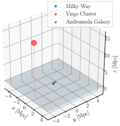


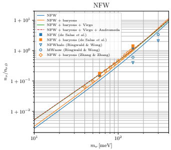
C

Clustering may let us learn also about our neighborhood



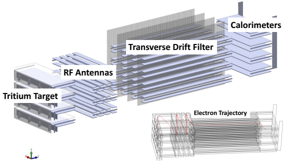


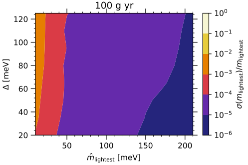


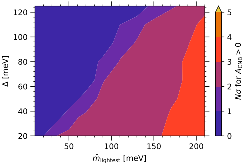


P

PTOLEMY is on the way (a long way)







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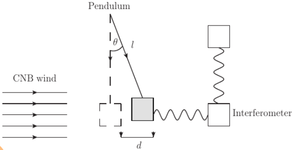

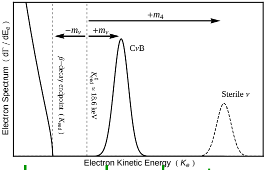

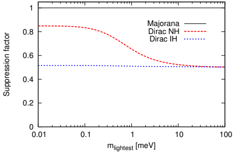

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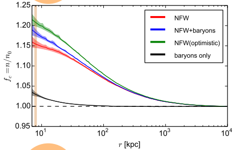

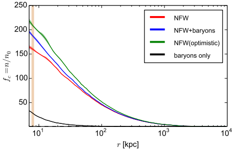

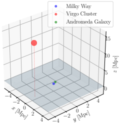

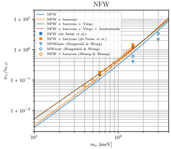

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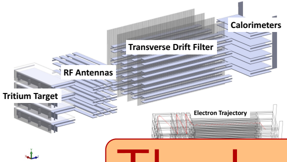

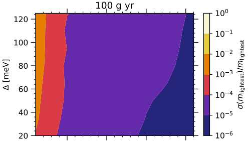

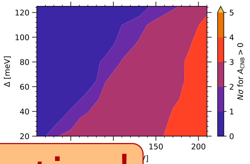

Thanks for your attention!