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European Commission
Horizon 2020
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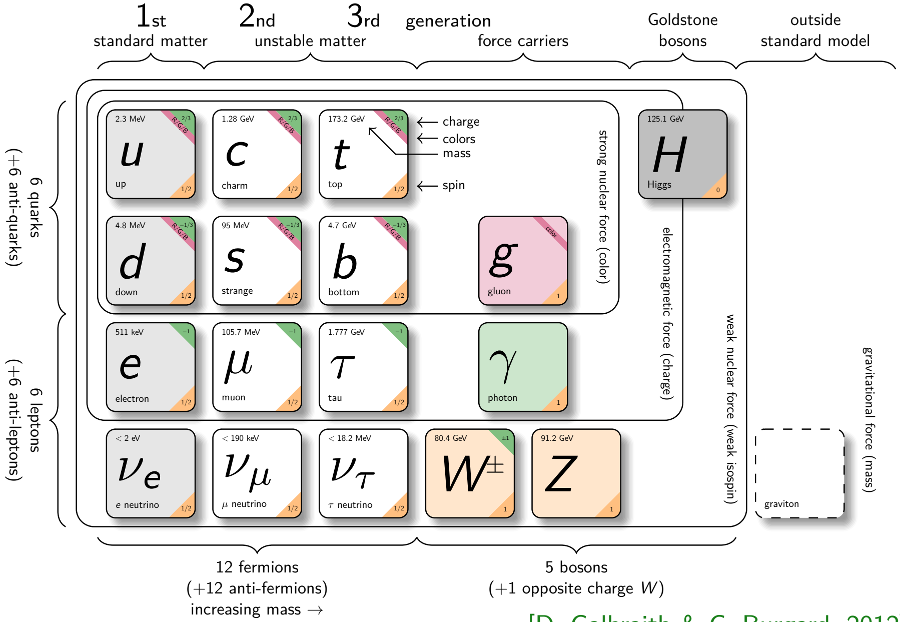
for Research & Innovation

Direct detection of relic neutrinos with PTOLEMY

A focus on the PTOLEMY proposal

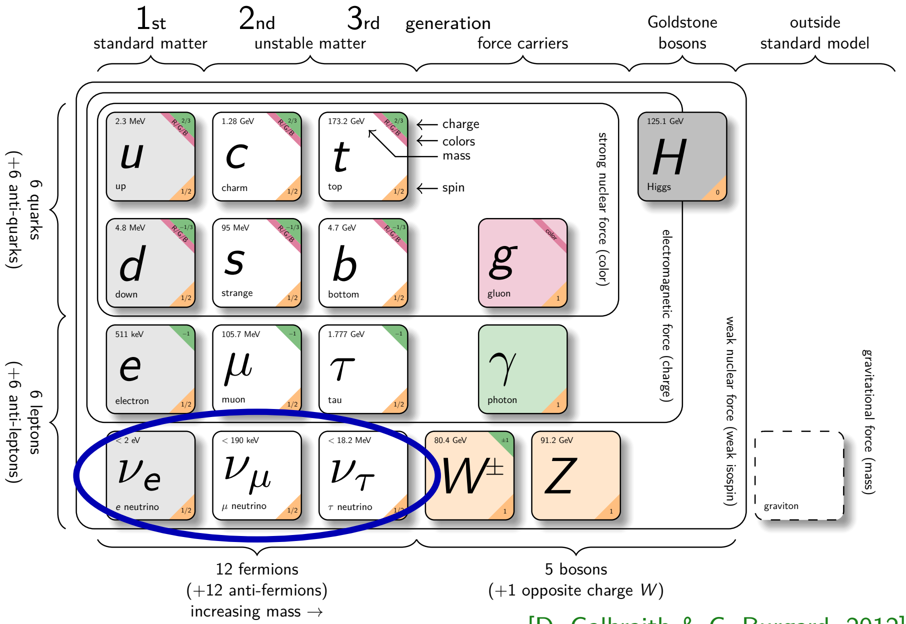
26/04/2018 - Seminar at Max-Planck-Institut für Physik - München (DE)

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

Neutrinos and their masses

Normal ordering (NO)

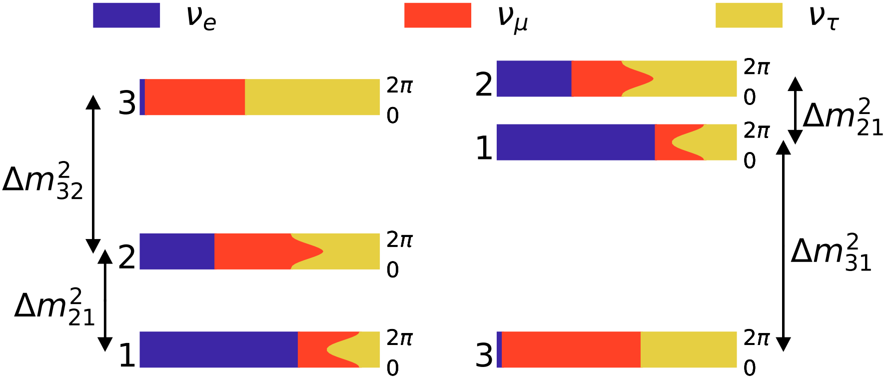
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

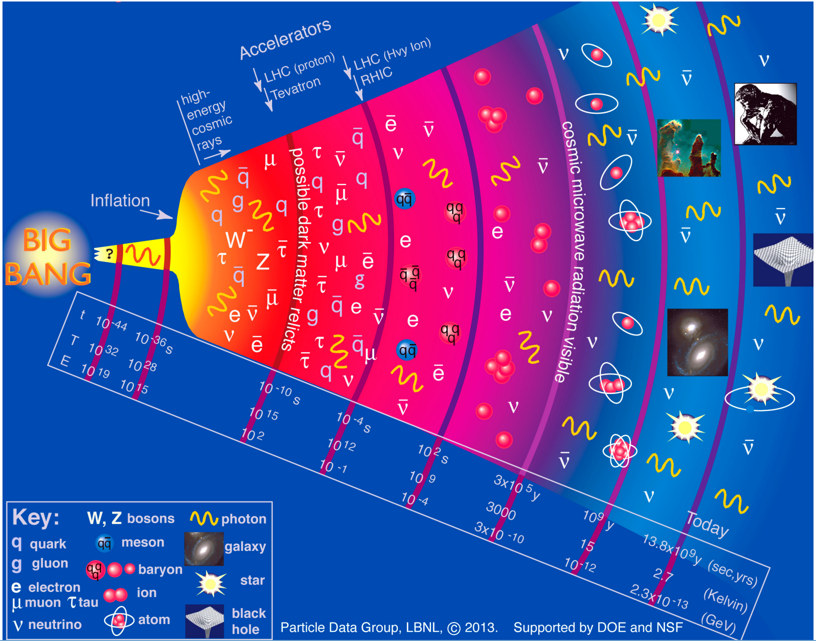
$\sum m_k \gtrsim 0.1$ eV



Absolute scale unknown!

Model independent upper bound (β decay, Mainz/Troitsk): $m_{\nu_e} \lesssim 2$ eV

History of the universe



Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

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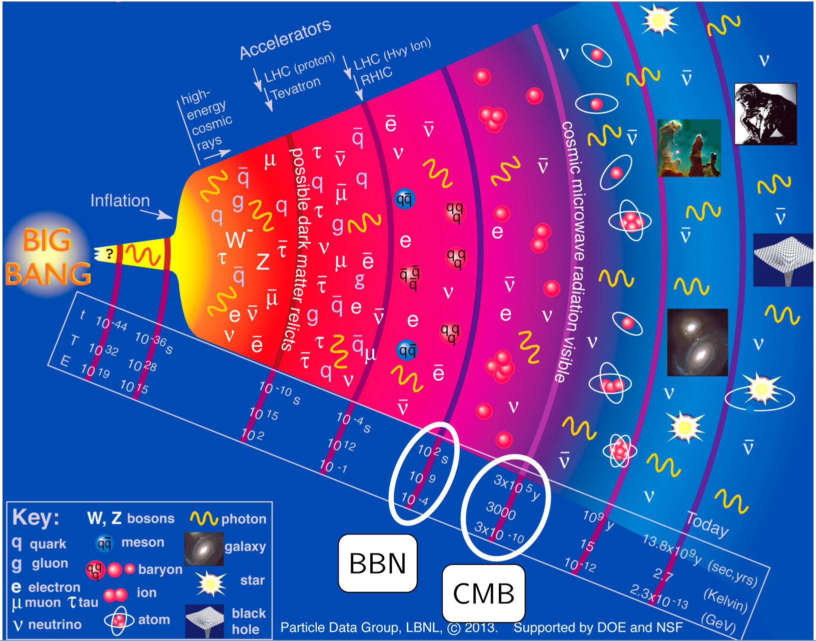

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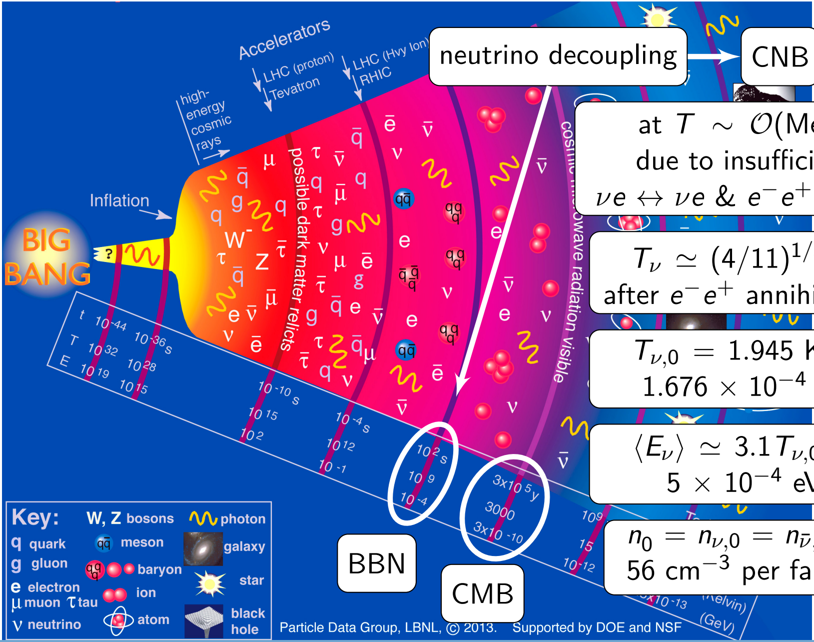


neutrino decoupling → CNB

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

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

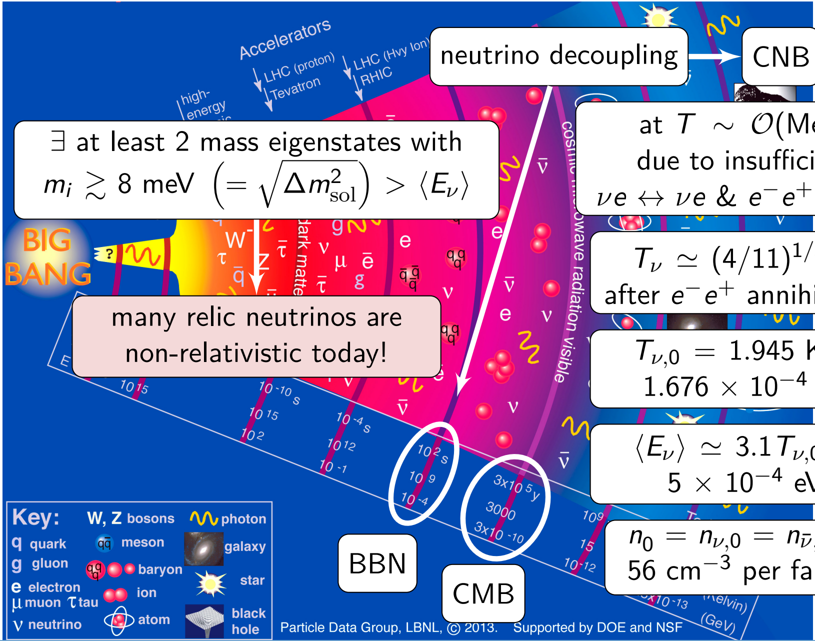
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq$
5×10^{-4} eV

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

BBN

CMB

History of the universe



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

$T_\nu \simeq (4/11)^{1/3}\, T_\gamma$
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Relic neutrinos in cosmology: $N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

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

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

- $N_{\rm eff} \rightarrow$ 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: $N_{\rm eff} \simeq 3.04 \pm 0.2$ [Planck 2015]
Indirect probe of cosmic neutrino background!

Cosmological mass bounds

Cosmology can constrain also $M_\nu = \sum m_\nu$

standard

based on ΛCDM model

[Planck Collaboration 2015, AA594 (2016) A13]

95%

$M_\nu < 0.72$ eV (PlanckTT+lowP)

$M_\nu < 0.21$ eV (+BAO)

$M_\nu < 0.49$ eV (PlanckTTTEEE+lowP)

$M_\nu < 0.17$ eV (+BAO)

see also:

[Vagnozzi et al., PRD96 (2017) 123503]

[Planck Collaboration 2016, AA596 (2016) A107]

95%

$M_\nu < 0.59$ eV (PlanckTT+`SimLow`)

$M_\nu < 0.17$ eV (+BAO)

$M_\nu < 0.34$ eV (PlanckTTTEEE+`SimLow`)

$M_\nu < 0.14$ eV (+BAO)

(`SimLow` not public yet)

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Modified gravity?

[Barreira et al., 2014]:

νGalileon

68%

$M_\nu = 0.98 \pm 0.24$ eV (CMB)

$M_\nu = 0.65 \pm 0.11$ eV (CMB+BAO)

[Bellomo et al., 2016]:

95%

Horndeski scalar-tensor

$M_\nu < 0.76$ eV

[Dirian, 2017]:

68%

nonlocal gravity

$M_\nu = 0.21 \pm 0.08$ eV

[Peirone et al, 2017]:

68%

Covariant Galileon

$M_\nu = 0.8 \pm 0.1$ eV

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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torque on e^- in lab rest frame

↓

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↓

measure torque with a torsion balance

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

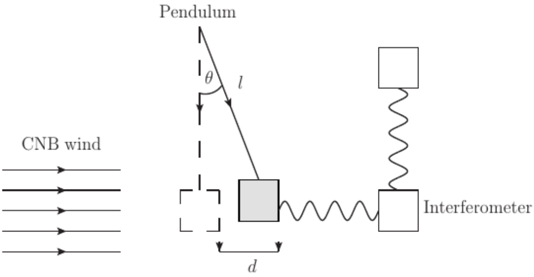
Direct detection - proposed methods - at interferometers

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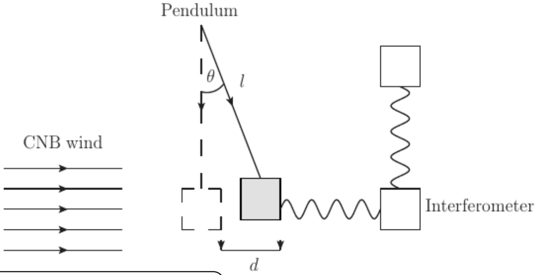
coherent scattering of relic ν on a pendulum $\longrightarrow$ measure oscillations at interferometers



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

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

→

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)

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

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

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

specific energy conditions required

but

Q value depends on ionization fraction!

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

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”

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 ⟶ a process without energy threshold is necessary

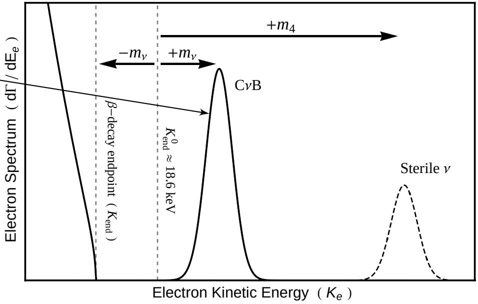
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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

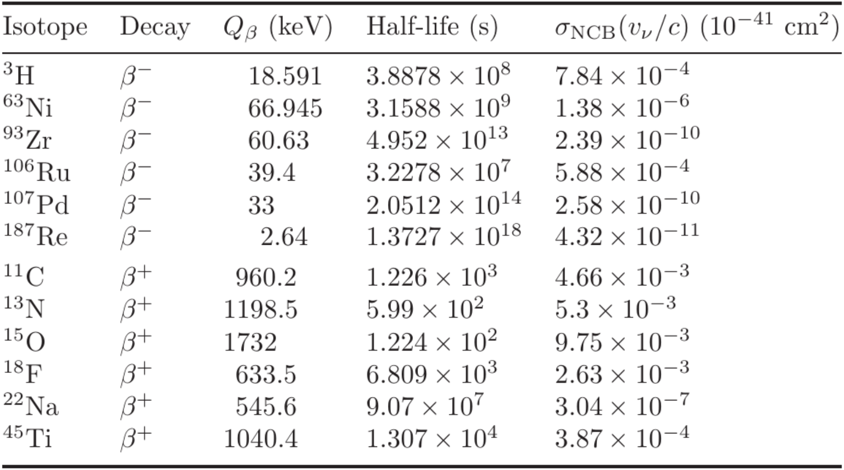


What material?

[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}
^{13}N	β^+	1198.5	5.99×10^{2}	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^{2}	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^{3}	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^{4}	3.87×10^{-4}

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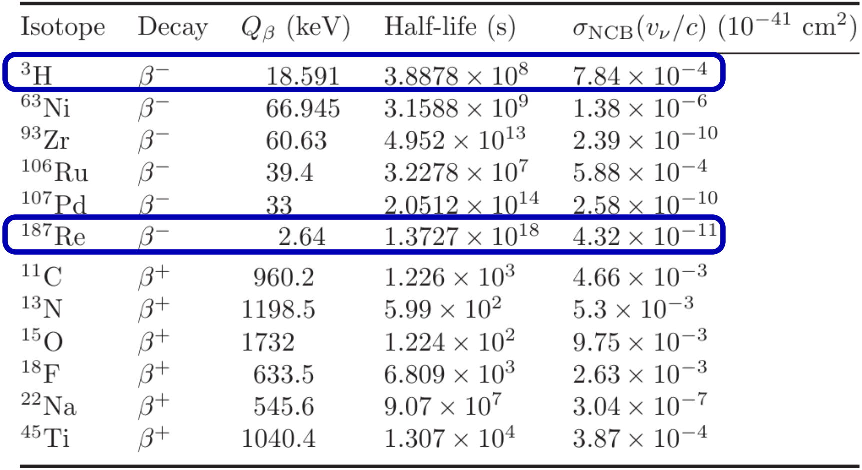

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^{3}H better because the cross section ($\rightarrow$ event rate) is higher

PTOLEMY

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

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

(see later)

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

N_T number of $^3\mathrm{H}$ 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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0.05 eV**?**

built mainly for CNB

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

(see later)

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

ehnancement from
ν clustering in the galaxy?

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

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)

ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

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

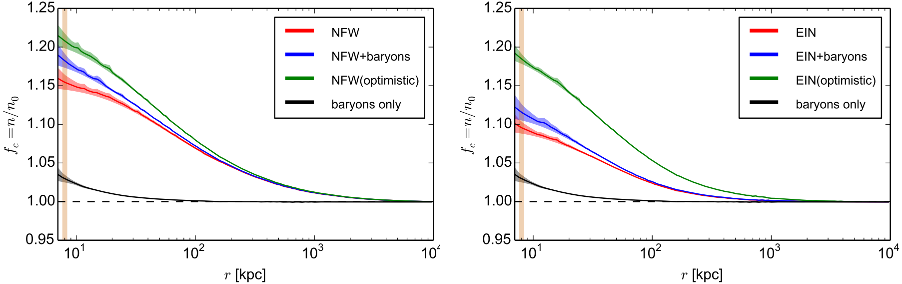
given N ν:

→ weigh each neutrinos

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

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

[JCAP 09 (2017) 034]



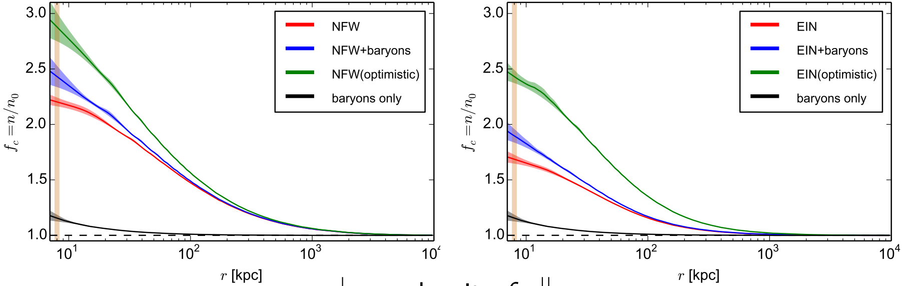
masses	ordering	matter halo	overdensity f_c $f_1 \simeq f_2$	 f_3	Γ_{tot} (yr^{-1})
any	any	any	no clustering		4.06
$m_3 = 60$ meV	NO	NFW(+bar)	$\sim$1	1.15 (1.18)	4.07 (4.08)
		NFW optimistic		1.21	4.08
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)
		EIN optimistic		1.18	4.08
$m_1 \simeq m_2 = 60$ meV	IO	NFW(+bar)	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 $\Gamma_{\mathrm{CNB}} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \left[n_i(\nu_{h_R}) + n_i(\nu_{h_L})\right] N_T \bar{\sigma}$

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

Additional clustering due to other galaxies

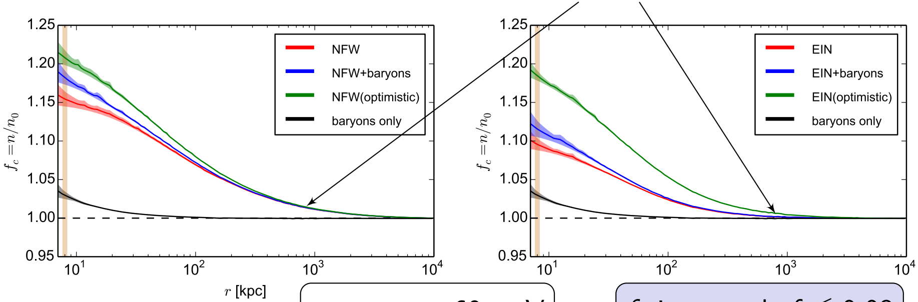
nearest galaxies: various MW satellites

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

nearest big galaxy:

Andromeda

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



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

Additional clustering due to other galaxies

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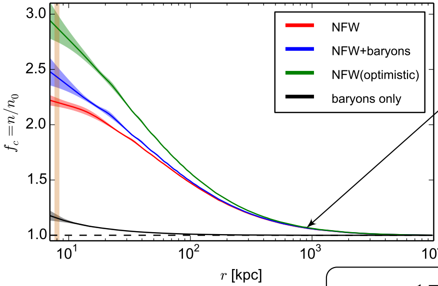
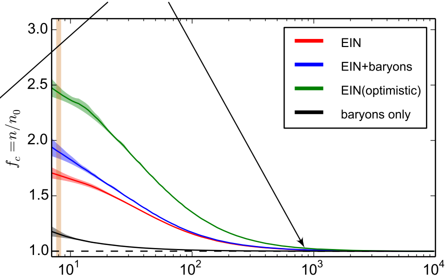


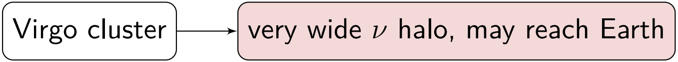


$m_\nu \simeq 150$ meV ⟶ f_c increased of $\lesssim 0.1$

(halo is less diffuse for higher ν masses)

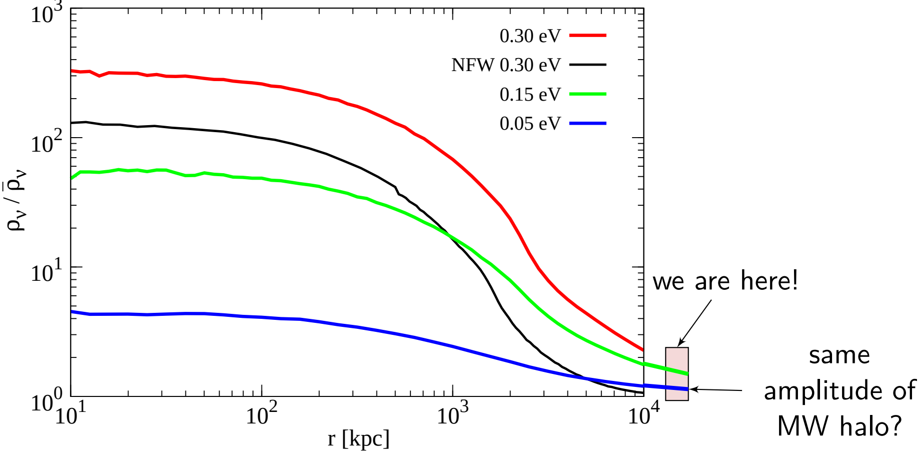
Additional clustering due to Virgo cluster

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



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

Status of PTOLEMY

[Cocco et al., 2007] theoretical basis for the experiment

[Betts et al., arxiv:1307.4738] first proposal – Princeton based

Sept 2017: first Letter of Intent (LoI) submitted to LNGS

11–12 Dec '17: "Kick-off meeting of the PTOLEMY project", at LNGS
`https://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=14222`

summary of current status

reunite interested people
from different communities

Request for approval as experiment at LNGS in April 2018
(LNGS scientific committee meeting)

LNGS = Laboratori Nazionali del Gran Sasso (Gran Sasso National Labs)

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reunite interested people from different communities

Request for approval as experiment at LNGS in April 201
(LNGS scientific committee meeting)

under process

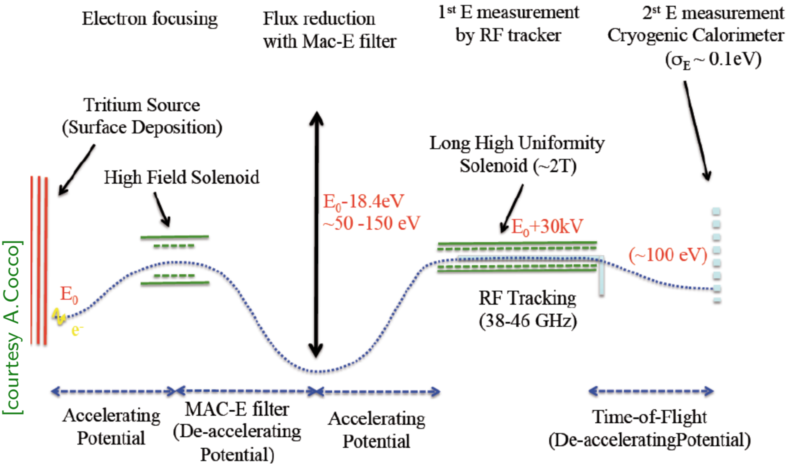
LNGS = Laboratori Nazionali del Gran Sasso (Gran Sasso National Labs)

PTOLEMY pipeline

scope of PTOLEMY:

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

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



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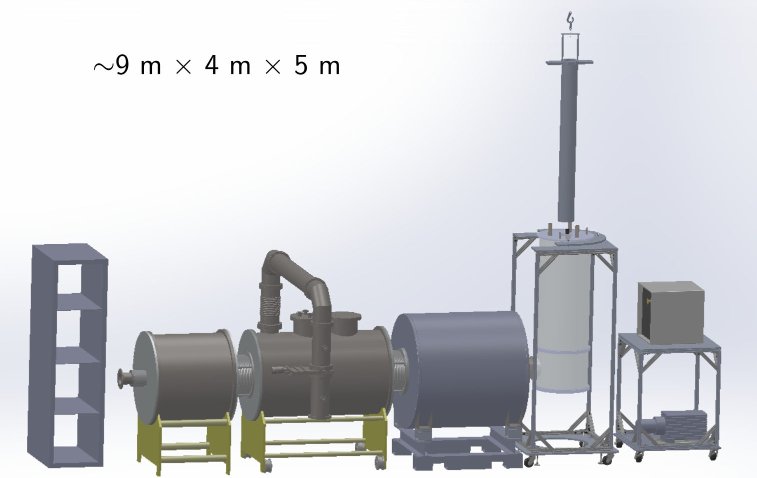

The source - graphene

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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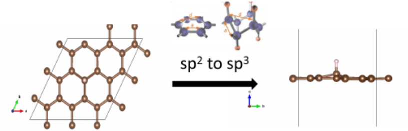
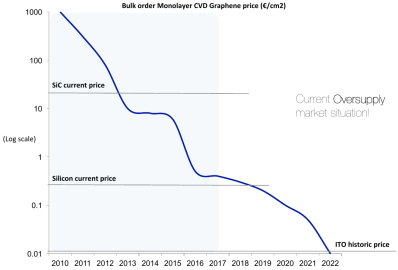
partially existing technology: hydrogenated graphene

layers

Graphene layers are cheap
(commercial use in displays)

hydrogenation under study
at Princeton





[courtesy A.Zurutuza (Graphenea)]

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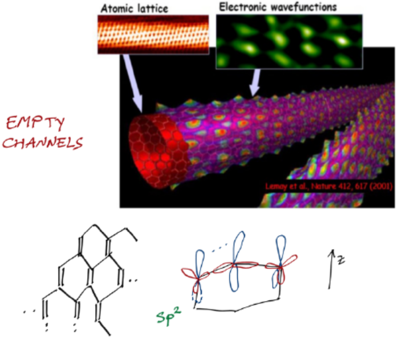
not practical solution for required 100 g of ^{3}H!

partially existing technology: hydrogenated graphene

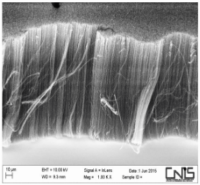
nanotubes

CNT Target



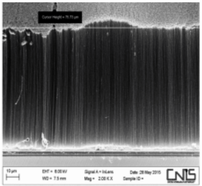
[courtesy G.Cavoto]

collaboration University of Mons, Belgium



length: ***100 μm (can be increased)***
ext. diameter: ***(20 ± 4) nm***
aspect ratio: ***5x10⁴***

commercial



length: 75 ***μm***
ext. diameter: ***(13 ± 4) nm***
aspect ratio: 0.6 ***x10⁴***

MAC-E filter

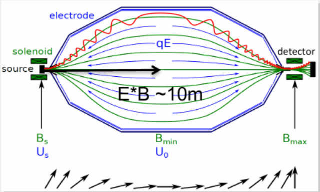
Background flux is too high for microcalorimeter. Must be reduced!

Magnetic Adiabatic Collimation with Electrostatic filter

[KATRIN]

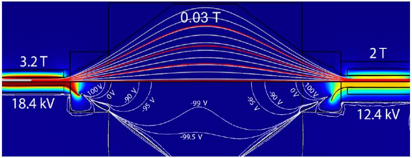
MAC-E filter technique

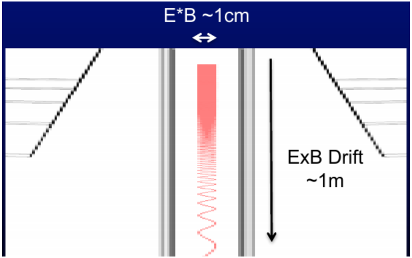
Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345



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

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





[courtesy C.Tully]

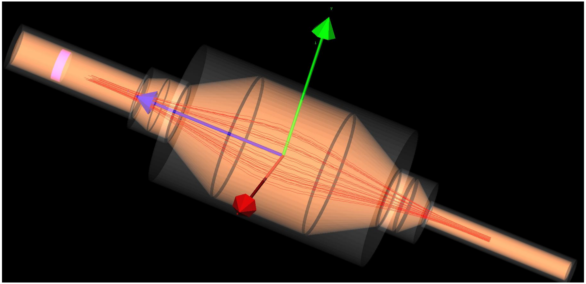
RF tracking

first energy determination with

RadioFrequency trigger, using
Cyclotron Radiation Emission Spectroscopy (CRES)

see also [Project 8, arxiv:1703.02037]

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

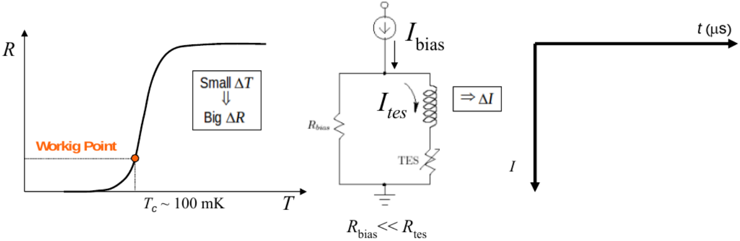
Same technology as in HOLMES experiment (ν masses)

Final energy determination with TES

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

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

[courtesy M.Ratjeri]



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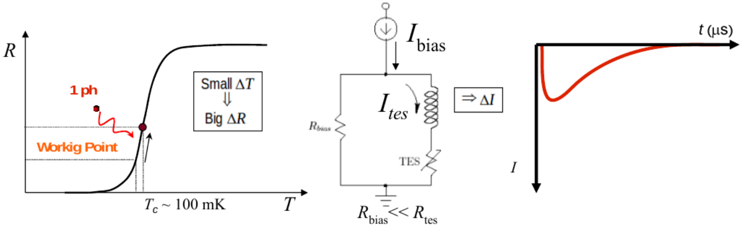

ΔT ⇨ ΔR @ Voltage bias ⇨ ΔI

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Microcalorimetry with Transition-Edge Sensors

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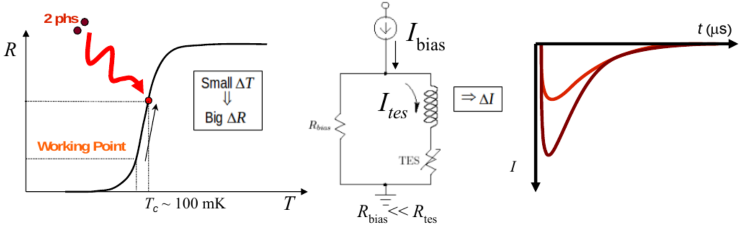

$\Delta T \Rightarrow \Delta R$ @ **Voltage bias** $\Rightarrow \Delta I$

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

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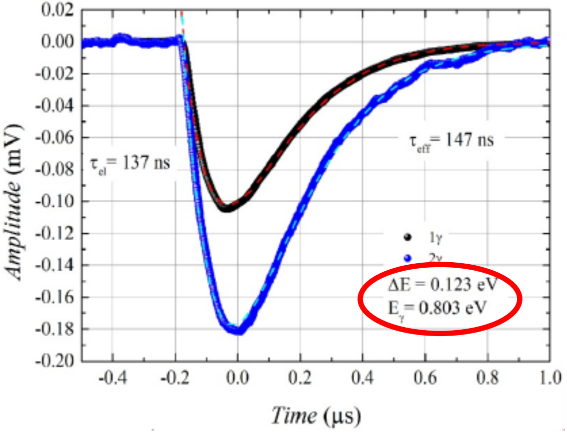

β and Neutrino Capture spectra

[PTOLEMY LoI, in preparation]

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

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

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

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

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[PTOLEMY LoI, in preparation]

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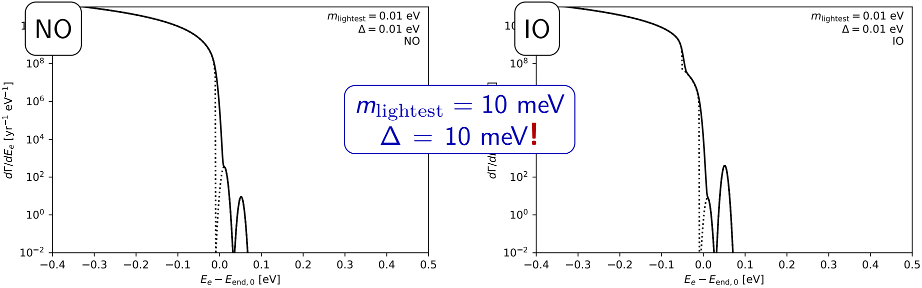

$m_{\rm lightest} = 10$ meV
$\Delta = 10$ meV!

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

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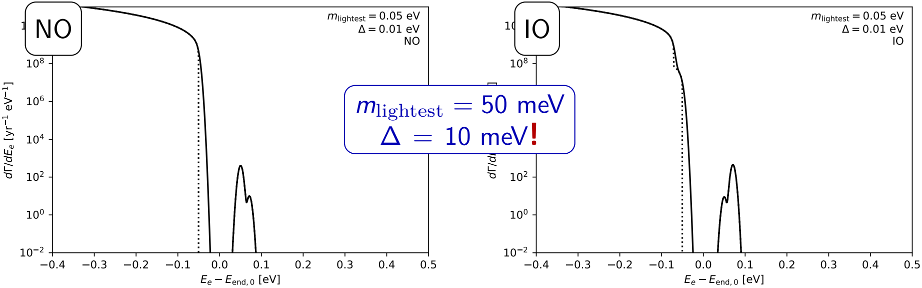

$m_{\rm lightest}=50$ meV
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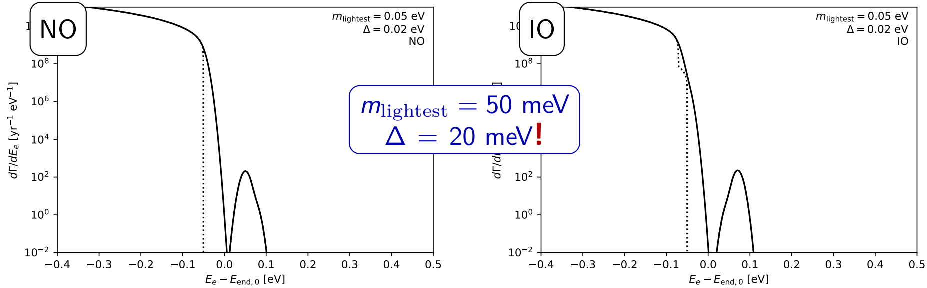

$m_{\rm lightest} = 50$ meV
$\Delta = 20$ meV**!**

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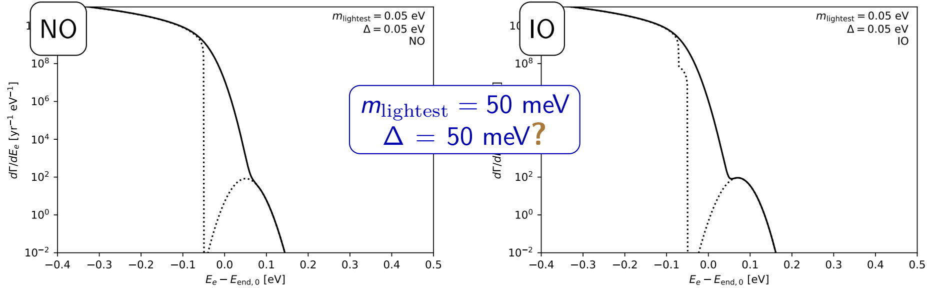

$m_{\rm lightest} = 50$ meV
$\Delta = 50$ meV?

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

Simulations - I

[PTOLEMY LoI, in preparation]

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

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

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

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

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$$\xrightarrow{\qquad} \boxed{N^i_t = \hat{N}^i + \hat{N}_b}$$

simulated experimental spectrum:

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

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

Simulations - I

[PTOLEMY LoI, in preparation]

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

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

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

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

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 LoI, in preparation]

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

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

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

fit

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

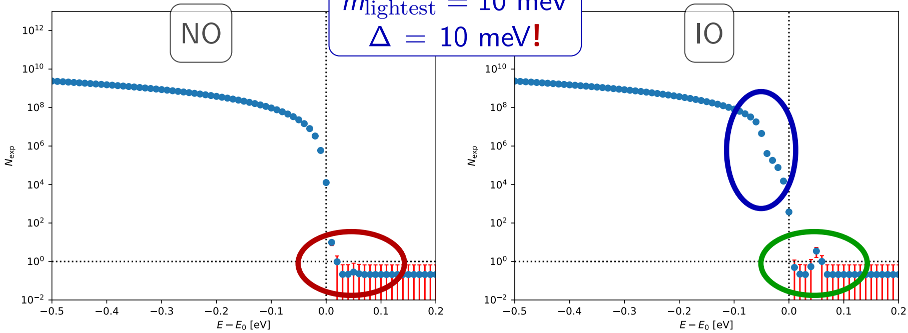
T exposure time – $(\hat{E}_{\mathrm{end}}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\mathrm{CNB}}, m_i, U)$

Simulations - II

[PTOLEMY LoI, in preparation]

no random noise?

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

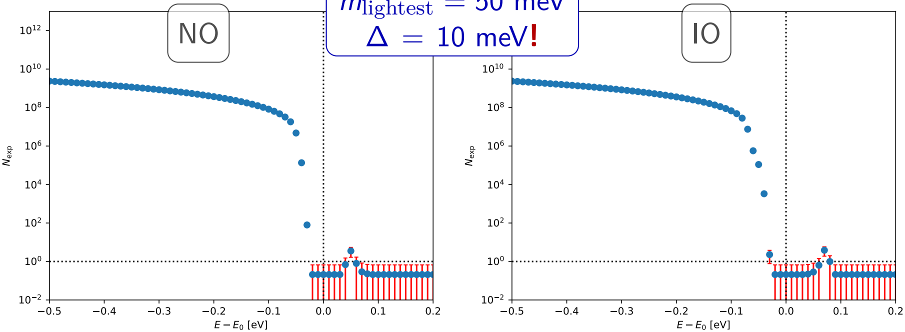


Simulations - II

[PTOLEMY LoI, in preparation]

no random noise?

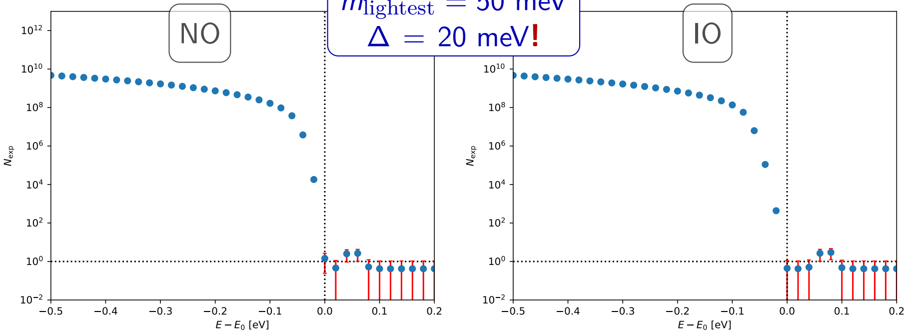
$m_{\rm lightest} = 50$ meV
$\Delta = 10$ meV!



Simulations - II

[PTOLEMY LoI, in preparation]

no random noise?

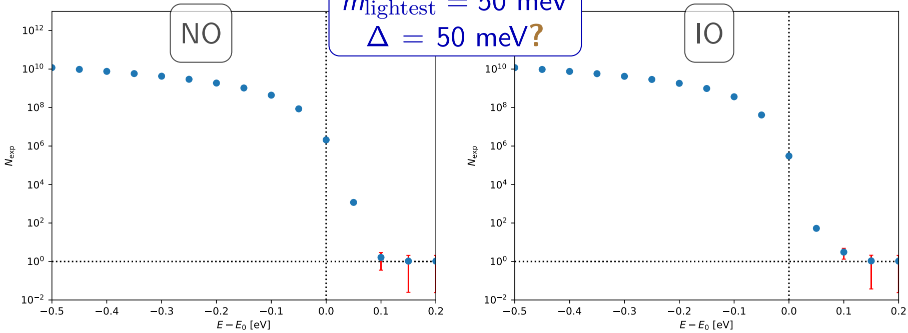


$m_{\mathrm{lightest}} = 50$ meV
$\Delta = 20$ meV!

Simulations - II

[PTOLEMY LoI, in preparation]

no random noise?



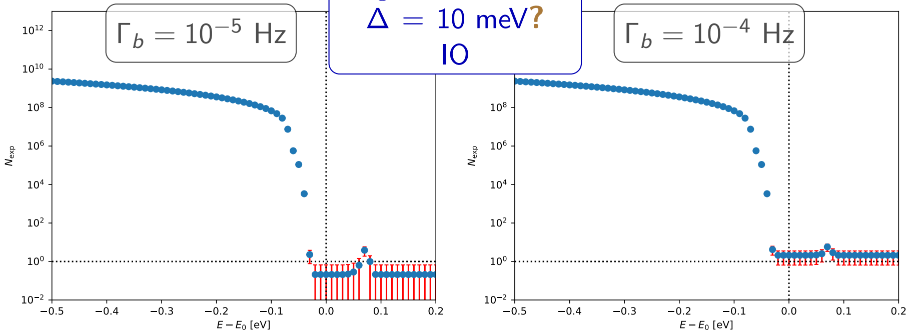
$m_{\text{lightest}} = 50$ meV

$\Delta = 50$ meV?

Simulations - II

[PTOLEMY LoI, in preparation]

no random noise?



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

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

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

Simulations - II

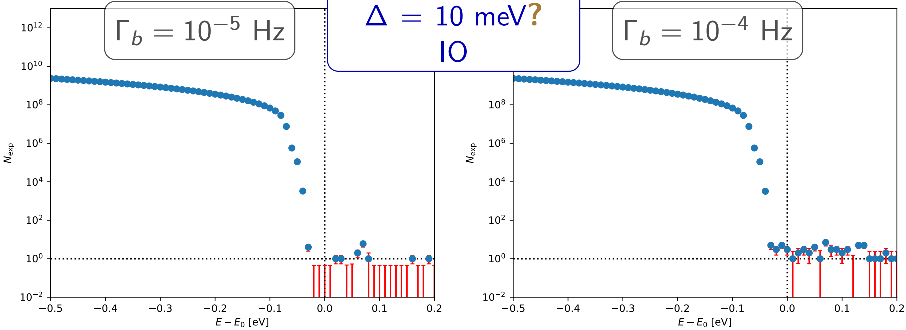
[PTOLEMY LoI, in preparation]

with random noise!

$m_{\rm lightest} = 50$ meV

$\Delta = 10$ meV?

IO



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

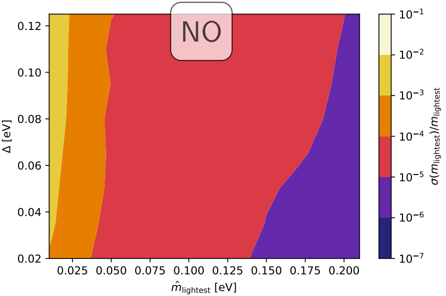
Perspectives for the mass determination

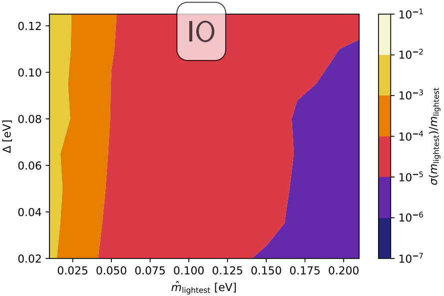
[PTOLEMY LoI, in preparation]

statistical only!

relative error on $m_{\rm lightest}$

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





wonderful precision in determining the neutrino mass

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

Δ has almost no impact

Detection of the relic neutrinos

[PTOLEMY LoI, in preparation]

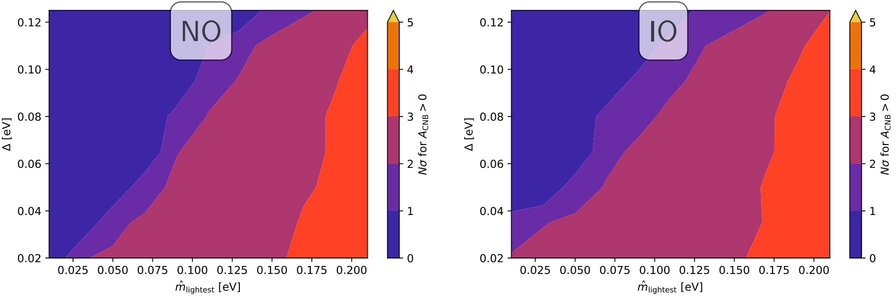
using the definition:

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

if $\boldsymbol{A}_{\mathbf{CNB}} > 0$ 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



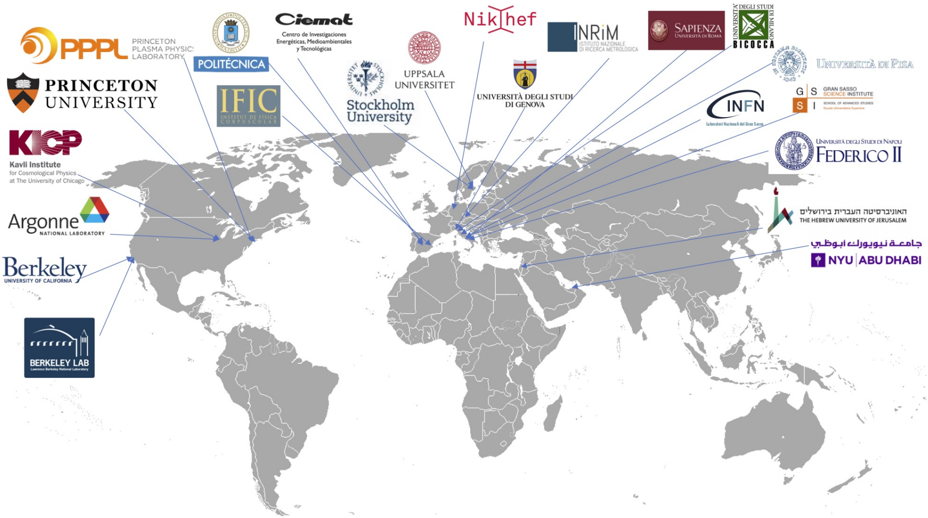
Requirements for PTOLEMY discoveries

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

PTOLEMY collaboration



Short Baseline (SBL) anomaly

[SG et al., JPG 43 (2016) 033001]

Problem: anomalies in SBL experiments $\Rightarrow \begin{cases} \text{errors in flux calculations?} \\ \text{deviations from 3-}\nu\text{ description?} \end{cases}$

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 ⇒ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [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	(inconclusive) search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No ν_e excess detected, but $\bar{\nu}_e$ excess observed at 2.8σ [MiniBooNE Collaboration, 2013]

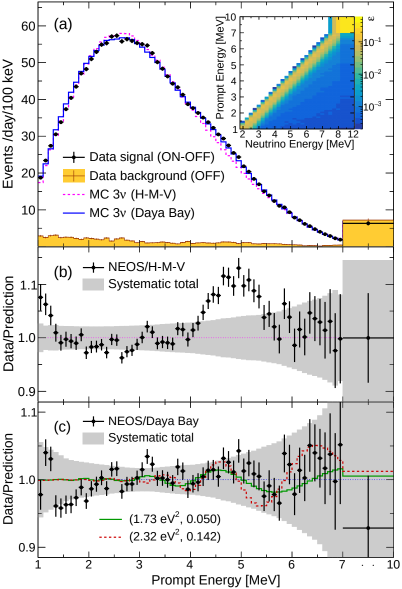
Possible explanation:

Additional squared mass difference

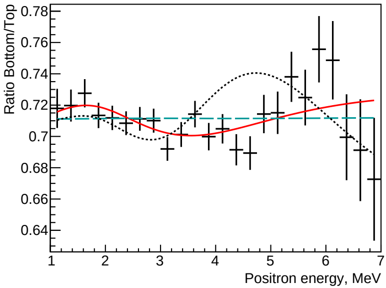
$$\Delta m^2_{\text{SBL}} \simeq 1\ \mathrm{eV}^2$$

More recently...

[NEOS, PRL 118 (2017) 121802]



[DANSS, arxiv:1804.04046]



3+1 Neutrino Model

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

$\downarrow$

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

$\downarrow$

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

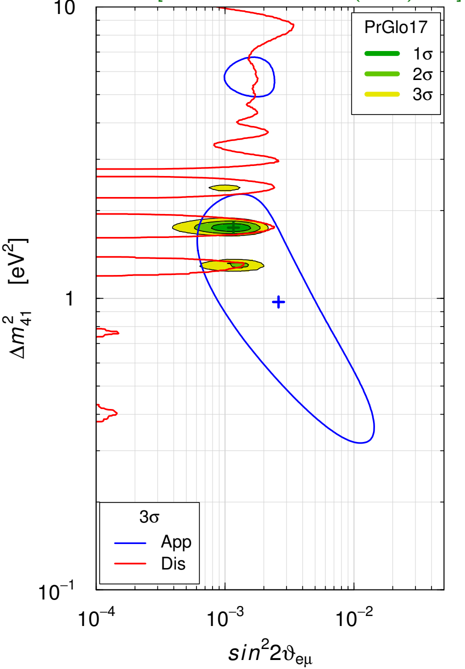
$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau, s)$$

ν_s is mainly ν_4:

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

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

[SG et al., JHEP 06 (2017) 135]



3+1 Neutrino Model

[SG et al., arxiv:1801.06467]

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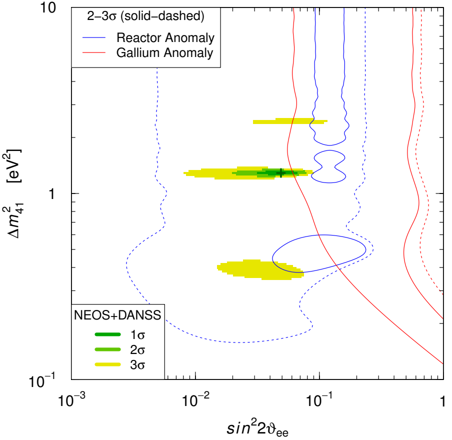

3+1 oscillations favored

$(\Delta\chi^2 \gtrsim 14,\ 3.4\sigma)$

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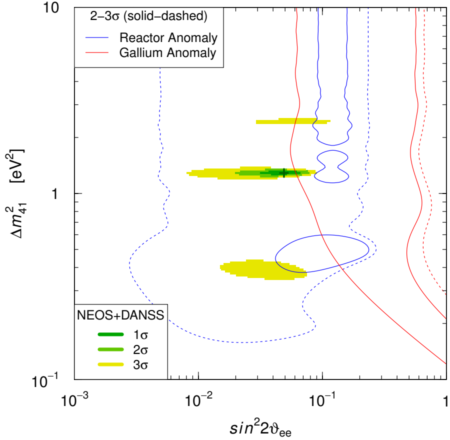


3+1 oscillations favored

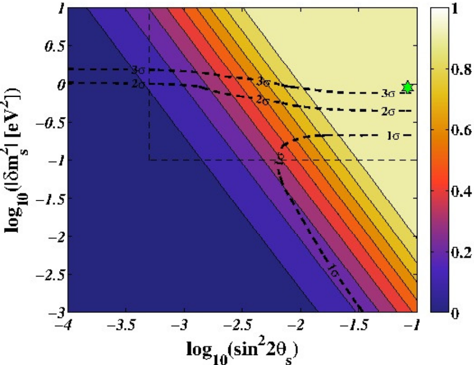
$(\Delta\chi^2 \gtrsim 14,\ 3.4\sigma)$

can ν_4 thermalize in the early Universe through oscillations?

LSν thermalization

Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

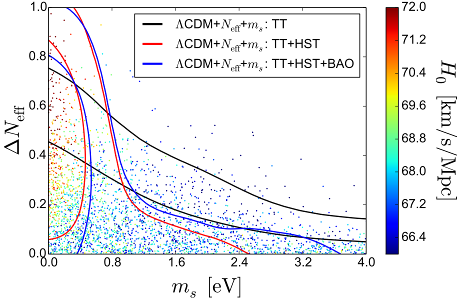
[Hannestad et al., JCAP 1207 (2012) 025]



(colors coding ΔN_{eff})

[Archidiacono, SG et al., JCAP 08 (2016) 067]

but cosmological fits give:



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

ΔN_{eff} should be $\simeq 1$, but it is disfavoured! (new physics?)

[to be precise: ΔN_{eff} is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

Assumptions and useful equations

[JCAP 09 (2017) 034]

We assume possible incomplete thermalization

(due to some unknown new physics)

→

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

↓

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

↙

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

↓

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

($f_c(m_4)$ is independent of ΔN_{eff})

↓

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

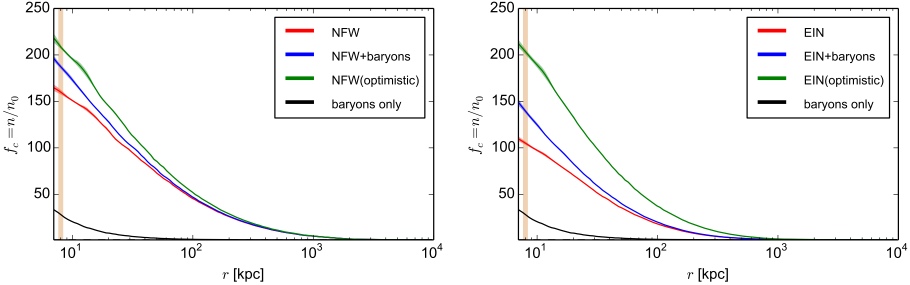
(from global fit [SG et al., 2017]: $m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$)

Overdensity of a sterile neutrino

[JCAP 09 (2017) 034]

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

$m_4 \simeq 1.3$ 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 LoI, in preparation]

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

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

[SG et al., 1801.06467]

$m_4 \simeq 1.15$ eV

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

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

[SG et al., 2017]

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

Γ_4 probably too small to be measured!

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[SG et al., 1801.06467]

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

[SG et al., 2017]

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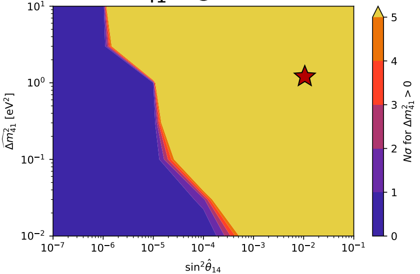
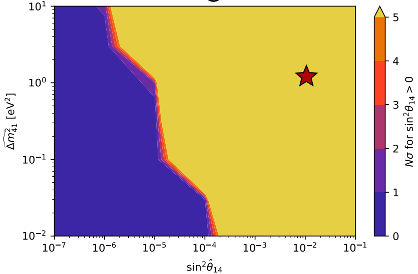
Γ_4 probably too small to be measured!

Still possible to measure mass/mixing through β spectrum

Δm^2_{41} significance



$\sin^2\theta_{14}$ significance



Conclusions

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

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

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

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+1

light sterile neutrino ($m_4 \simeq 1.15$ eV) **?**
possible detection thanks to large clustering

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Thank you for the attention!