# Stefano Gariazzo

*IFIC, Valencia (ES)*
*CSIC – Universitat de Valencia*

gariazzo@ific.uv.es
http://ific.uv.es/~gariazzo/



Horizon 2020
European Union funding
for Research & Innovation


# Neutrino physics with the PTOLEMY project

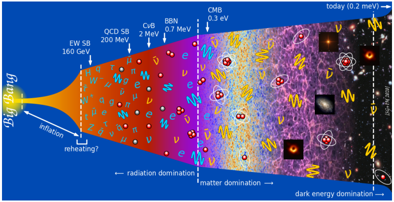
ICHEP 2020, 28/07–06/08/2019

1 ***Cosmic Neutrino Background***

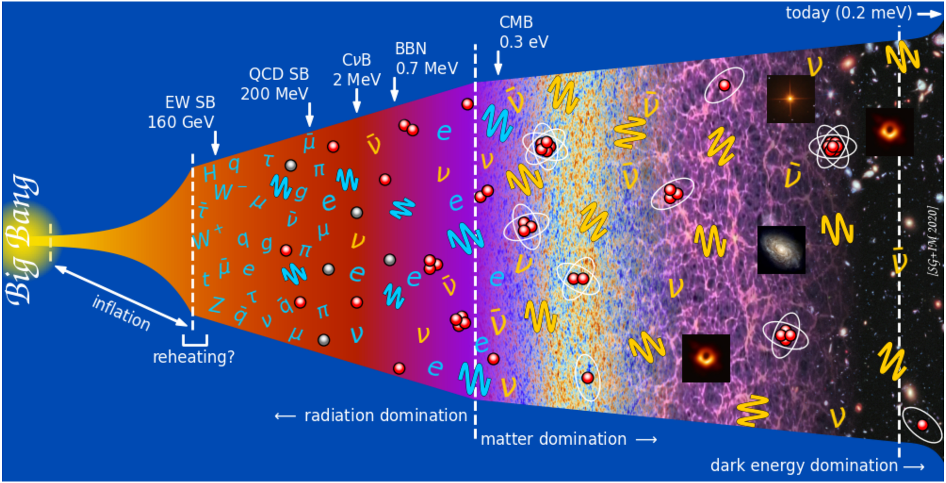
2 *Direct detection of relic neutrinos*

3 *PTOLEMY*

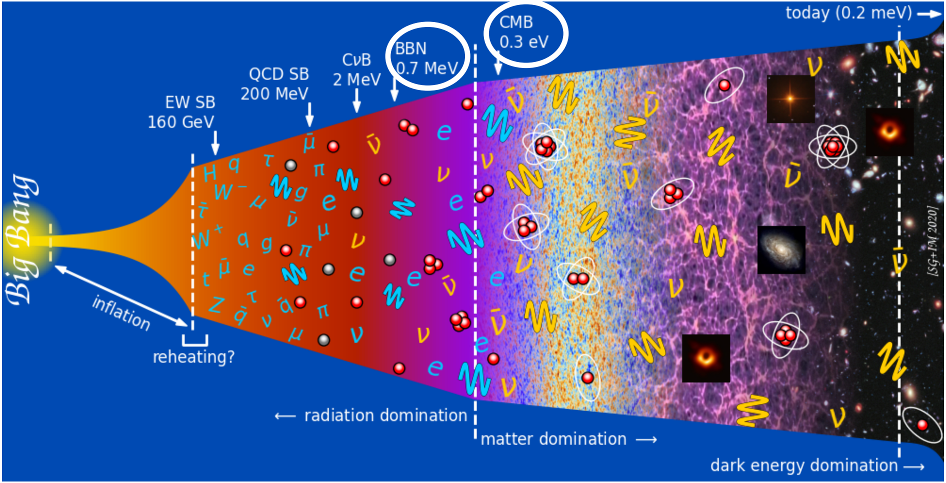
4 *Conclusions*



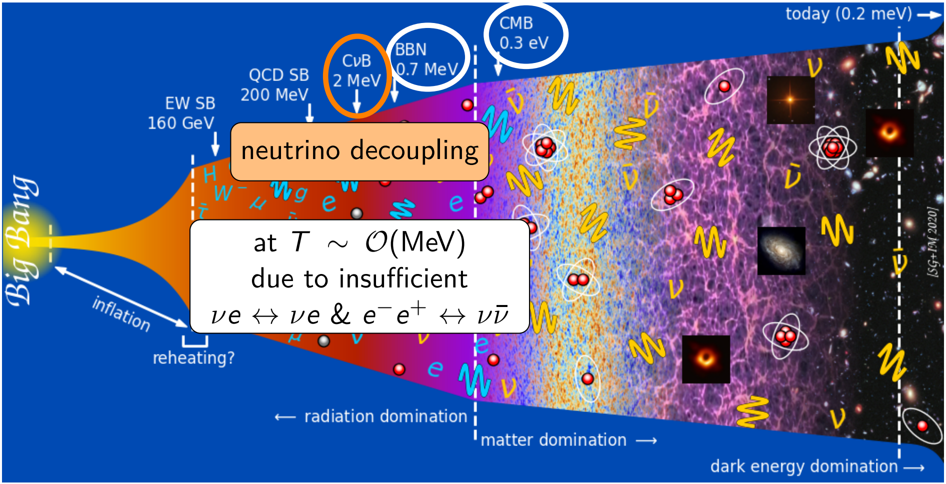
# History of the universe



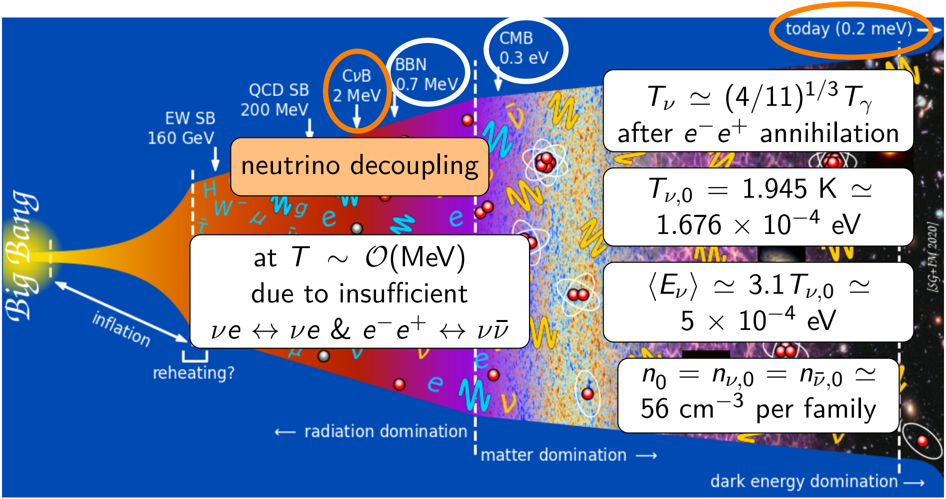
# History of the universe



# History of the universe



# History of the universe




neutrino decoupling

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

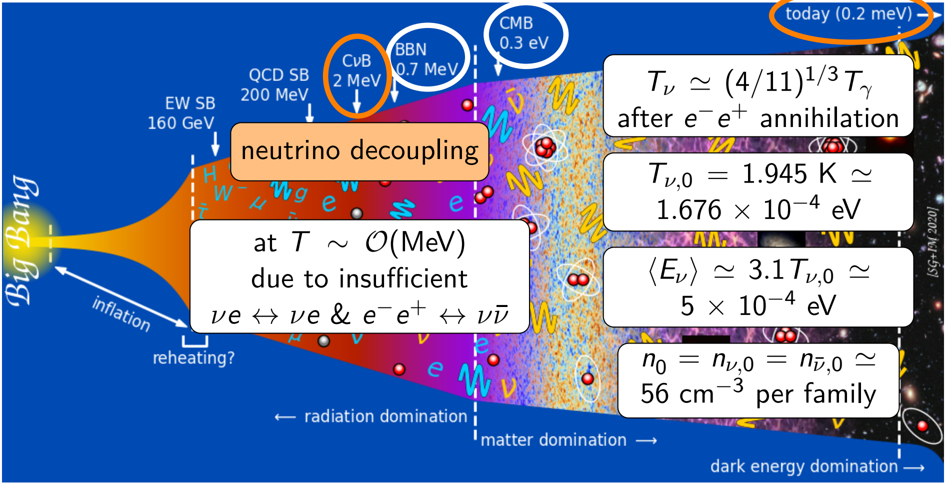
$T_\nu \simeq (4/11)^{1/3} T_\gamma$
after $e^- e^+$ annihilation

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

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

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

# History of the universe




neutrino decoupling

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

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

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

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

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

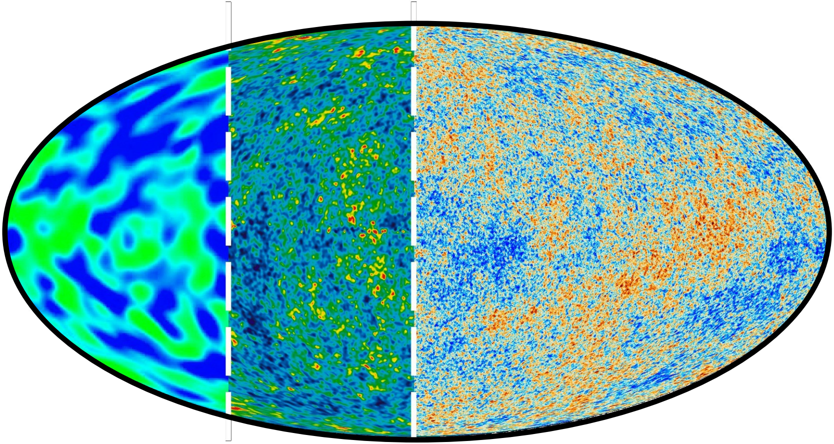
∃ at least 2 mass eigenstates with
$m_i \gtrsim 8$ meV $\left(= \sqrt{\Delta m^2_{\rm sol}}\right) > \langle E_\nu \rangle$

→ many relic neutrinos are non-relativistic today!

# The oldest picture of the Universe

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

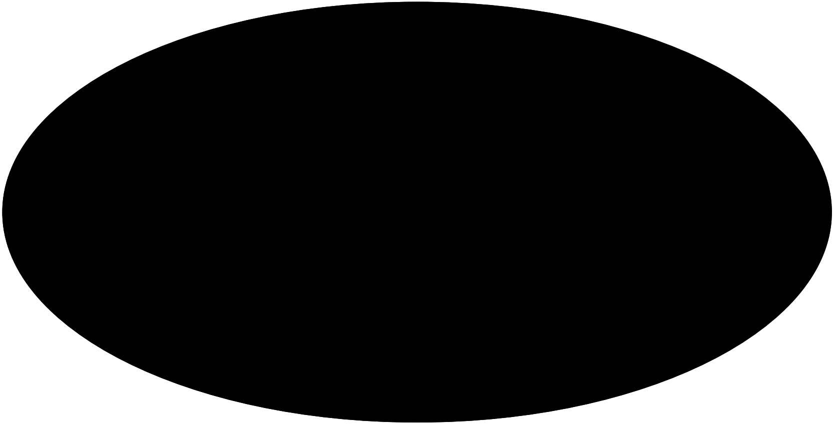
COBE (1992) WMAP (2003) Planck (2013)



# The oldest picture of the Universe

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

$\ldots \to 2019 \to \ldots$



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

Radiation energy density $\rho_r$ in the early Universe:

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

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

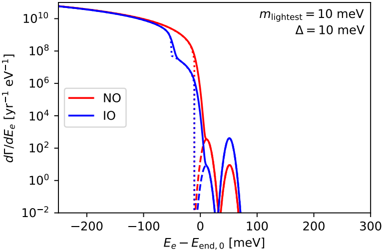
- $N_{\rm eff} \to$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos:
  $N_{\rm eff} = 3.046$ [Mangano et al., 2005] (damping factors approximations) $\sim$
  $N_{\rm eff} = 3.045$ [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***




3 *PTOLEMY*

4 *Conclusions*

# 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

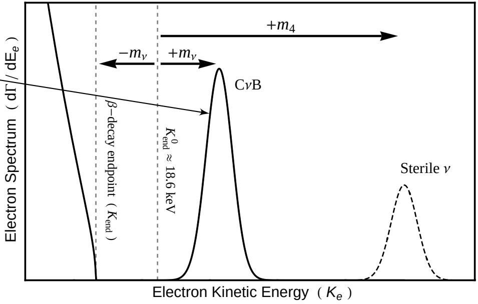
[Weinberg, 1962]: neutrino capture in $\beta$–decaying nuclei $\nu + n \to p + e^-$

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

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

only with a lot of material

need a very good energy resolution



# $\beta$ and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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

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

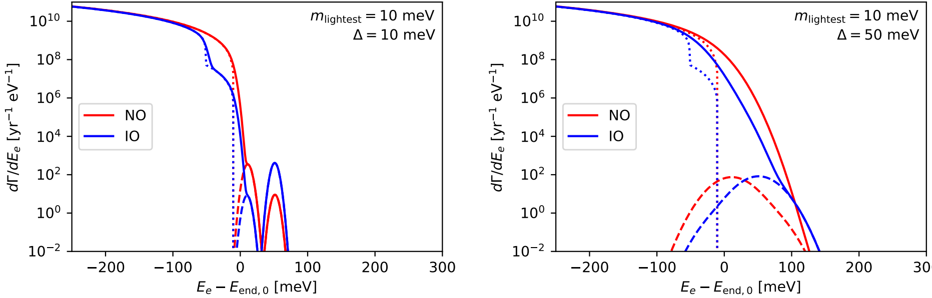
# $\beta$ and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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




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

Pontecorvo Tritium 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

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

$N_T$ 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)

[PTOLEMY LoI, arxiv:1808.01892]

Pontecorvo Tritium 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

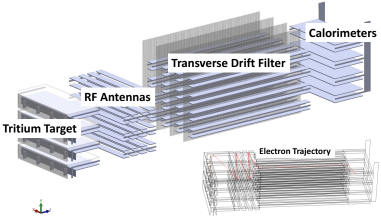
ehnancement from $\nu$ clustering in the galaxy?

ehnancement from other effects?

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

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

(without clustering)



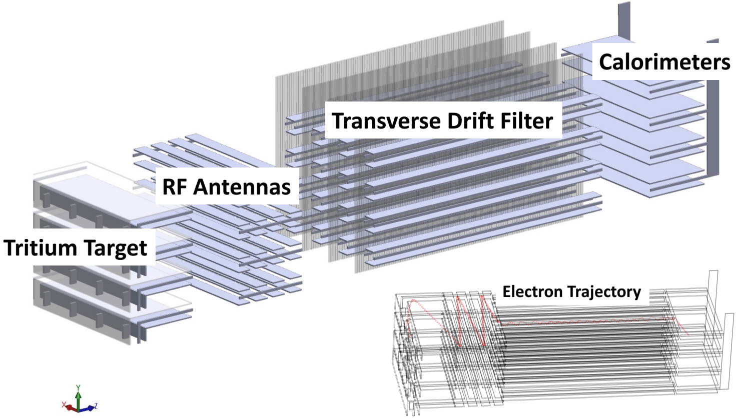
Calorimeters
Transverse Drift Filter
RF Antennas
Tritium Target
Electron Trajectory

# PTOLEMY pipeline

scope of PTOLEMY: see talk by M. Messina!

measure electron spectrum near $^3$H $\beta$-decay endpoint

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




[PTOLEMY, PPNP 106 (2019) 120]

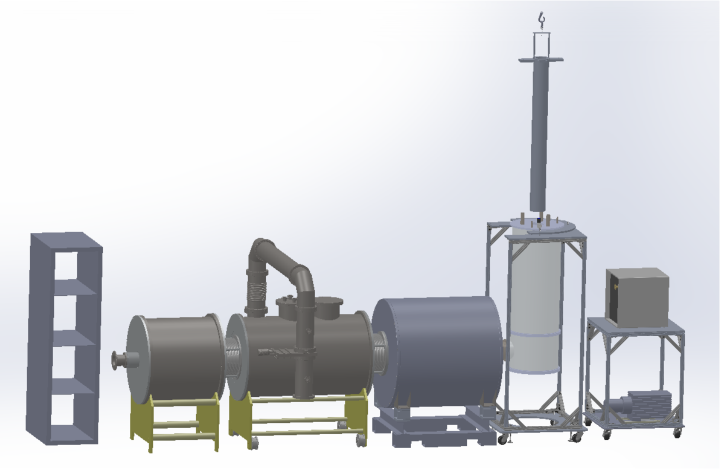
# PTOLEMY pipeline

scope of PTOLEMY: see talk by M. Messina!

measure electron spectrum near $^3$H $\beta$-decay endpoint

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

[PTOLEMY, arxiv:1808.01892]



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

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 – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

# Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

relative error on $m_{\rm lightest}$

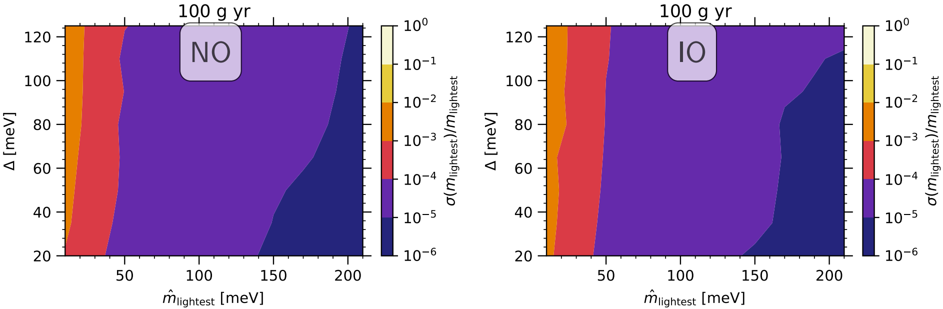
as a function of $\hat{m}_{\rm lightest}$, $\Delta$

# Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

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




wonderful precision in determining the neutrino mass

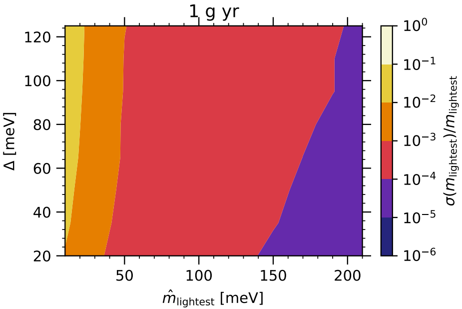
(well, yes, with 100 g of tritium...)

# Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

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




wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

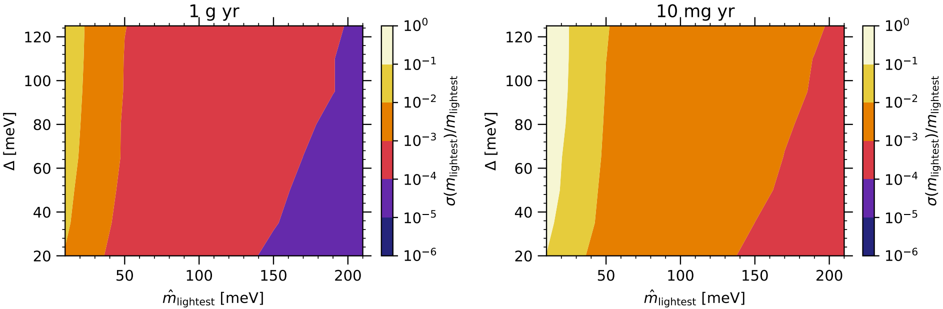
# Neutrino mass determination

[PTOLEMY, JCAP 07 (2019) 047]

statistical only!

relative error on $m_{\rm lightest}$

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




wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

$\Delta$ 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]

**Bayesian method:**

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

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

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

worse fit

better fit

# Neutrino mass ordering

Bayesian method:

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

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

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

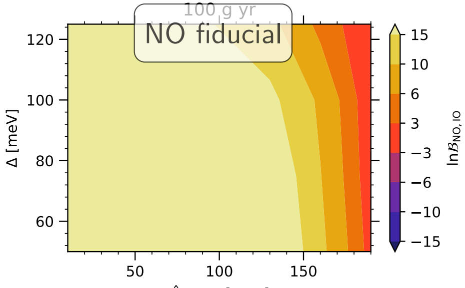
worse fit

better fit

statistical only!

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

NO fiducial




IO fiducial

always strong significance

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

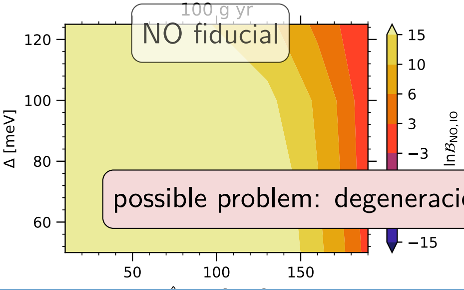
worse fit

better fit

statistical only!

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

NO fiducial




IO fiducial

always strong significance

possible problem: degeneracies between $m_{\rm lightest}$ and $\Delta m^2_{31}$

# Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

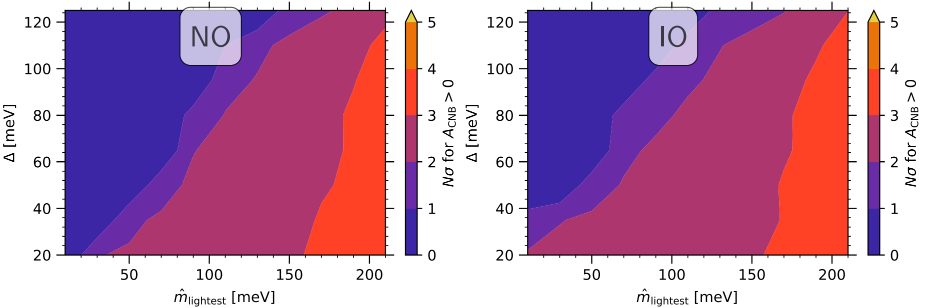
using the definition:

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

if $\boldsymbol{A}_{\rm CNB} > 0$ at $N\sigma$, direct detection of CNB accomplished at $N\sigma$

statistical only!

significance on $A_{\rm CNB} > 0$
as a function of $\hat{m}_{\rm lightest}$, $\Delta$

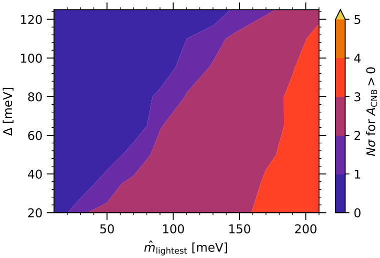


1 *Cosmic Neutrino Background*

2 *Direct detection of relic neutrinos*

3 *PTOLEMY*

4 ***Conclusions***



# Requirements for PTOLEMY discoveries

What do we need to discover...

| | low $\Gamma_b$ | extreme $\Delta$ | a lot of $^3$H |
|---|---|---|---|
| ... $\nu$ masses? | ✗ | ✗ | ? |
| ... $\nu$ mass ordering? | ✗ | ? | ? |
| ... CNB direct detection? | ✓ | ✓ | ✓ |

✓: strongly required

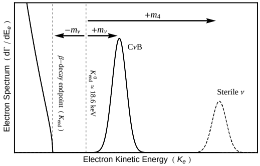
?: not so strongly required

✗: loosely required

# Conclusions

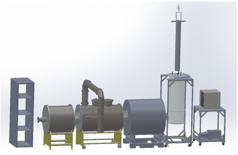
1

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



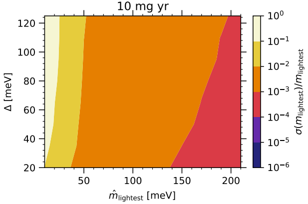

2

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

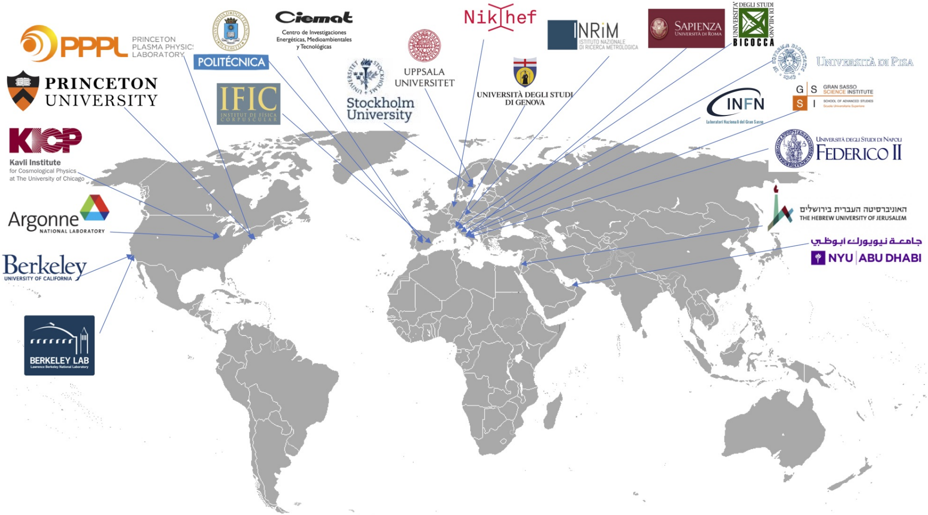


3

amazing results
already achievable
with small tritium amount!



# PTOLEMY collaboration




**Thank you for the attention!**