



Horizon 2020  
European Union funding  
for Research & Innovation

# Stefano Gariazzo

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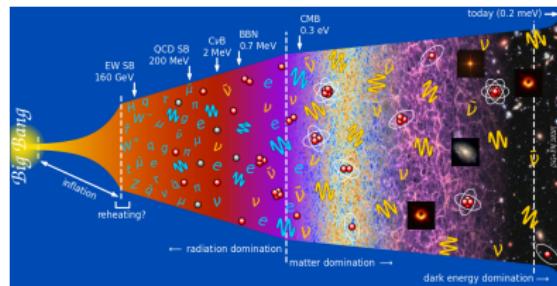
## Neutrino physics with the PTOLEMY project

## 1 Cosmic Neutrino Background

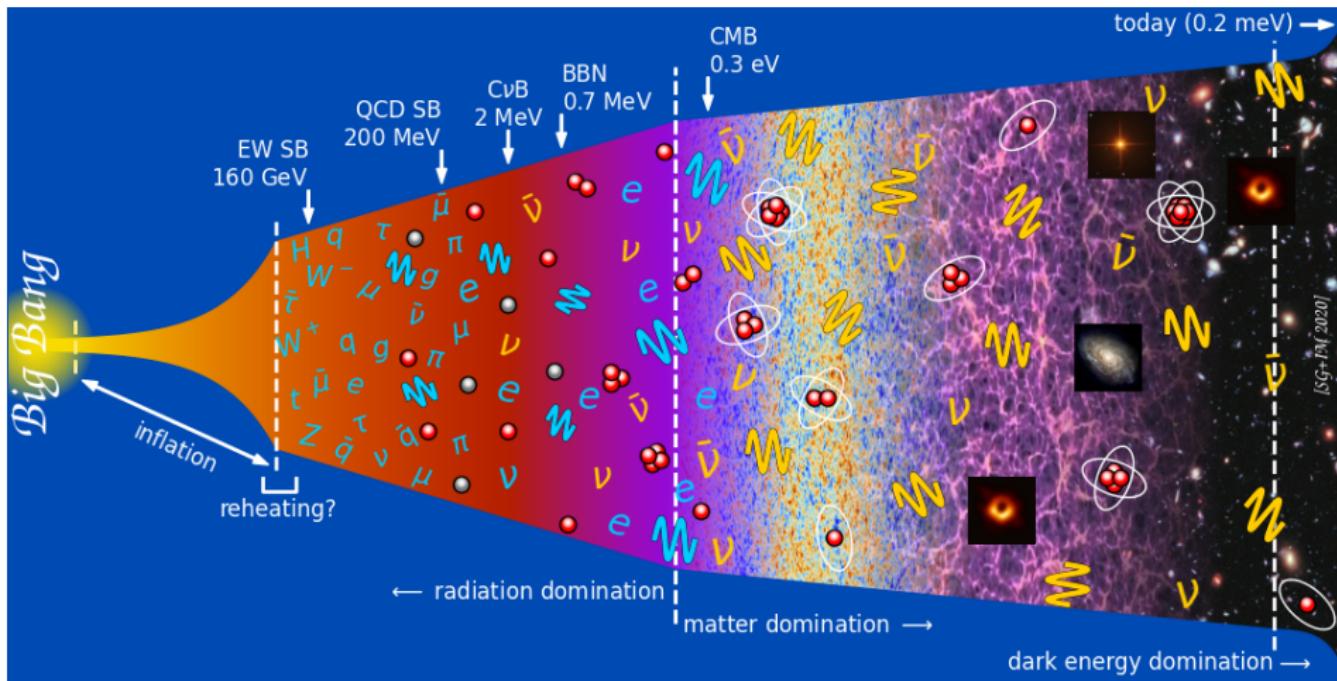
## 2 Direct detection of relic neutrinos

## 3 PTOLEMY

## 4 Conclusions

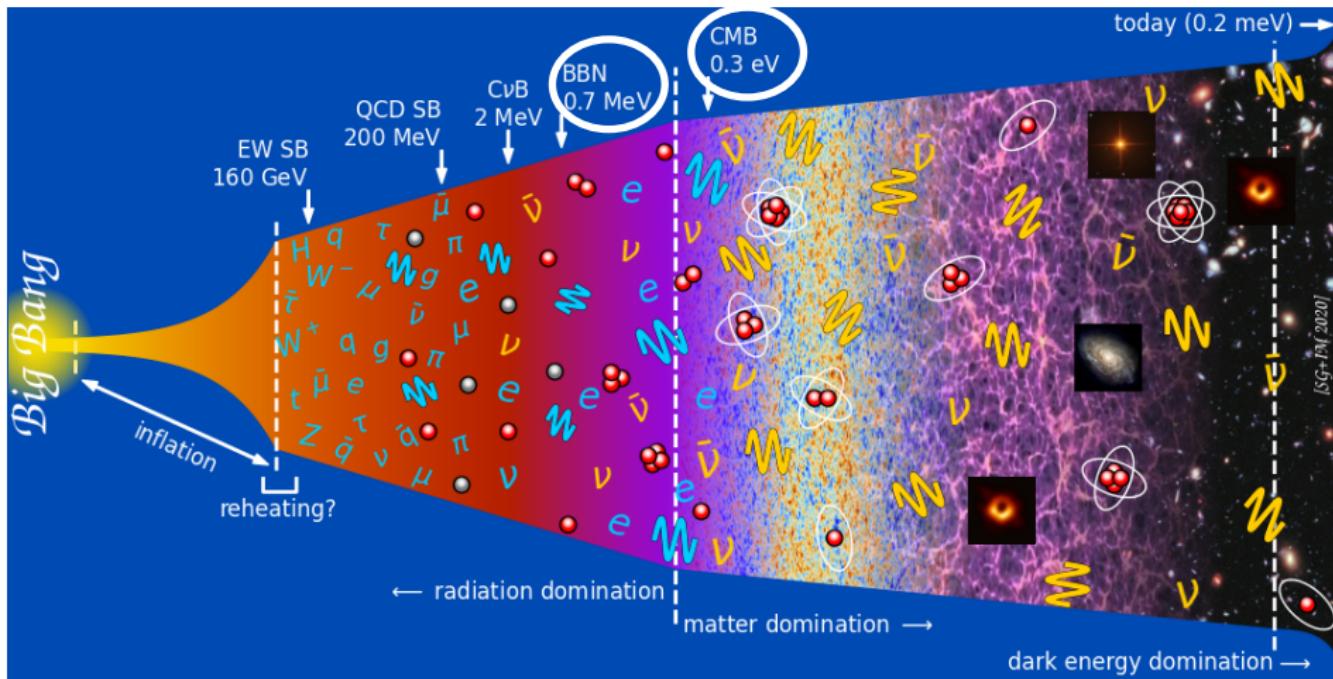


# History of the universe

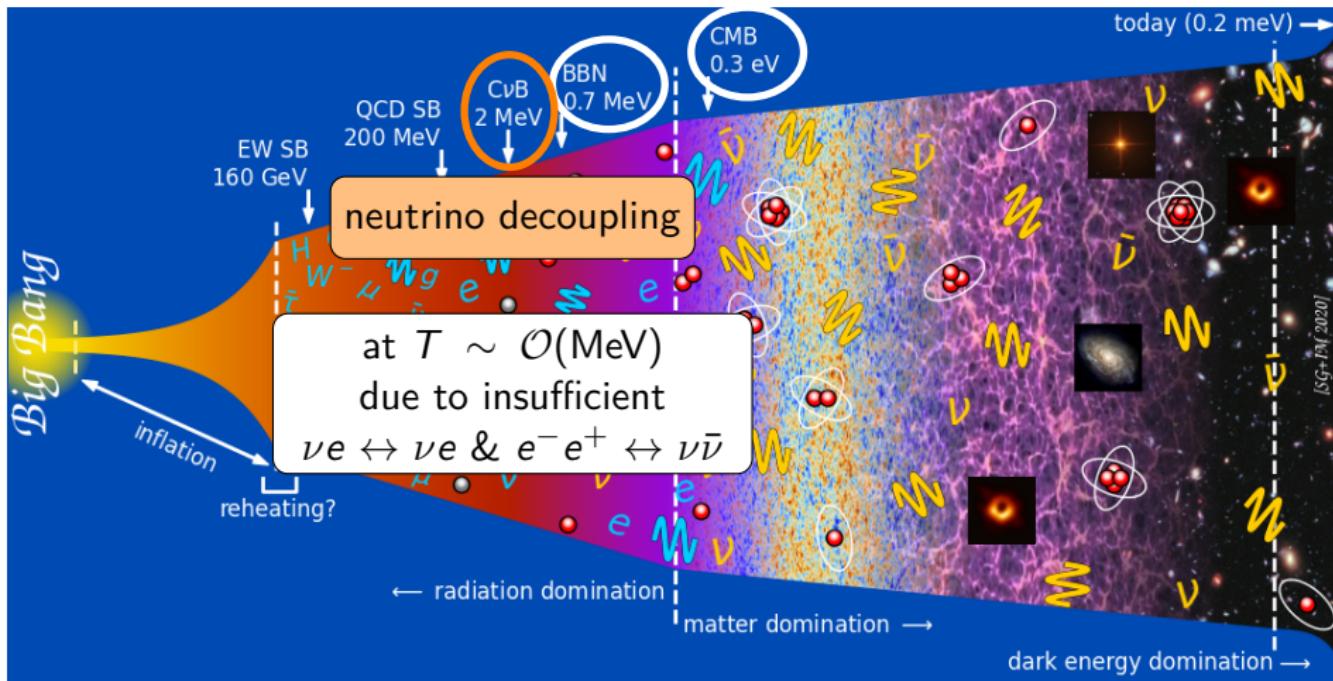


ISG-IAP 2020

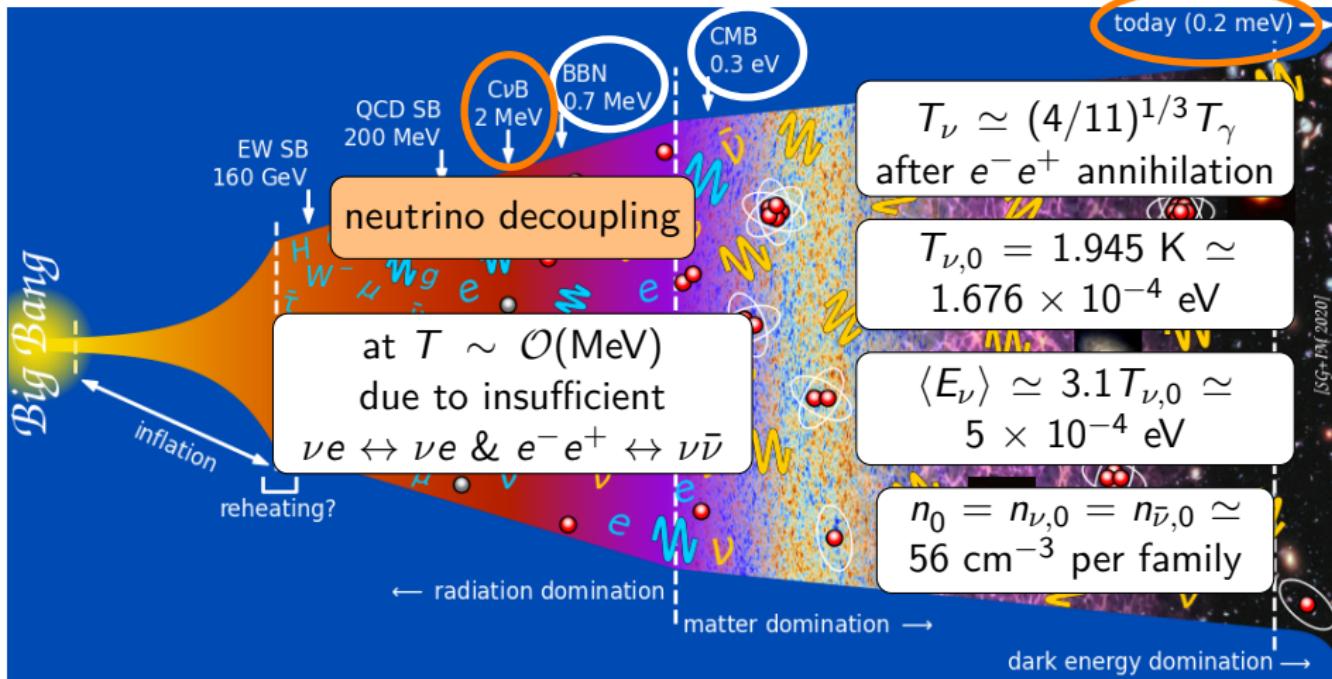
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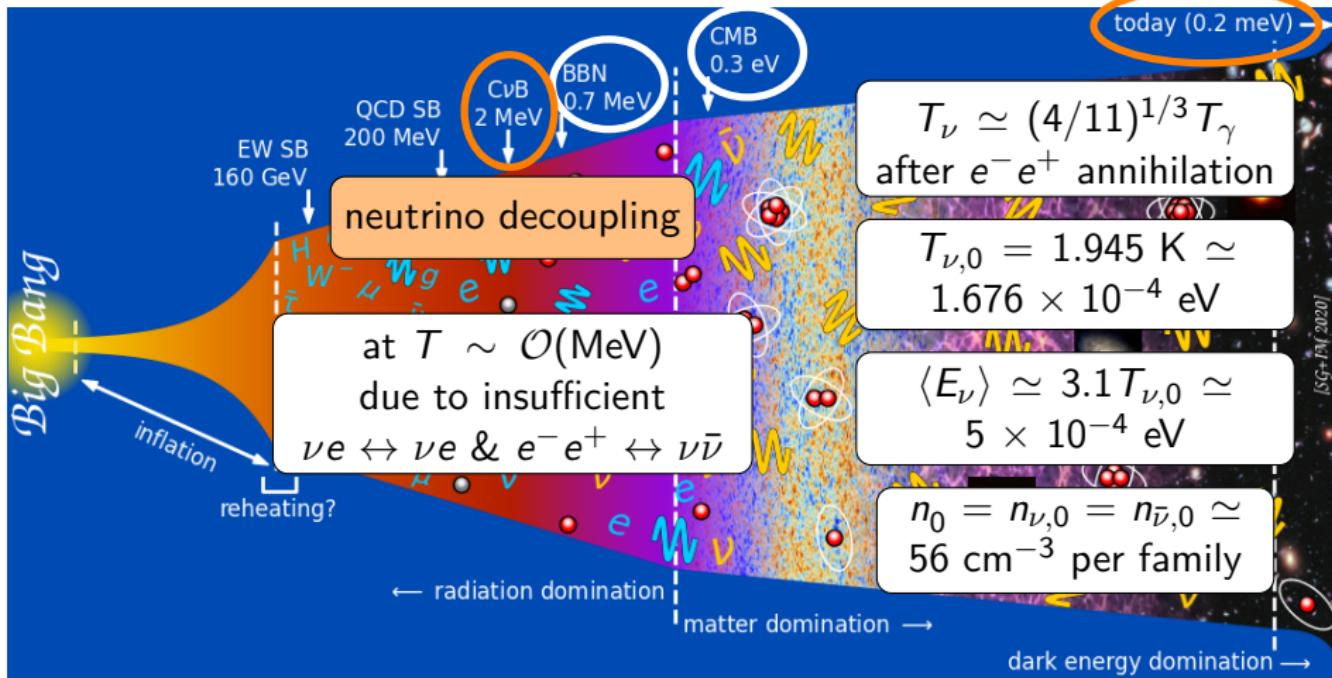
# History of the universe



# History of the universe



# History of the universe



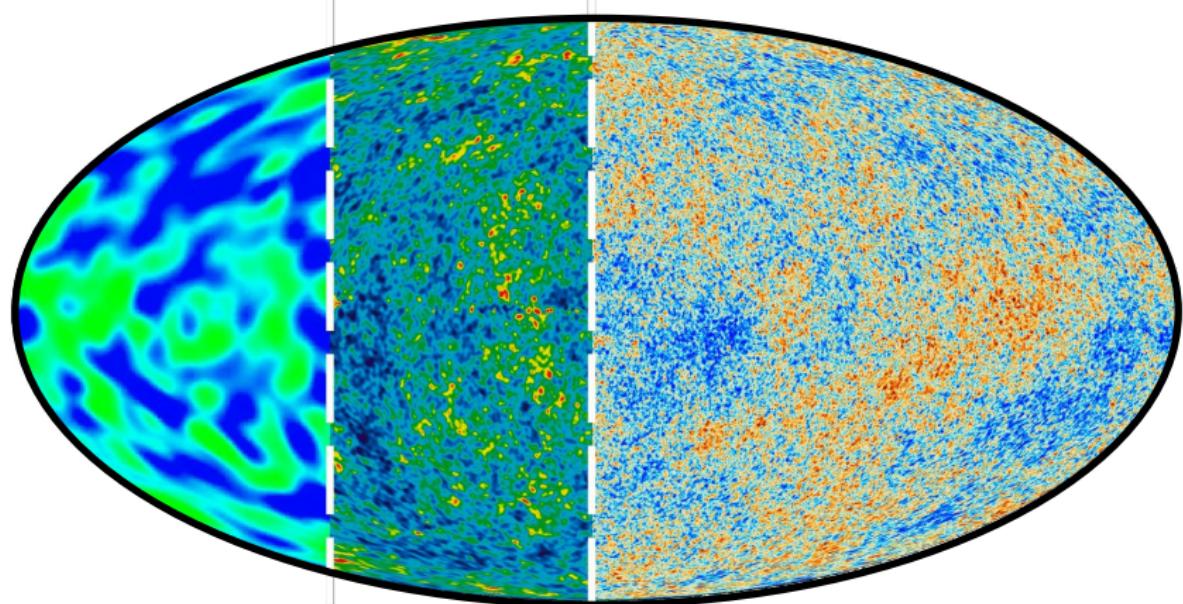
$\exists$  at least 2 mass eigenstates with  
 $m_i \gtrsim 8 \text{ meV}$  ( $= \sqrt{\Delta m_{\text{sol}}^2} > \langle E_\nu \rangle$ )

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

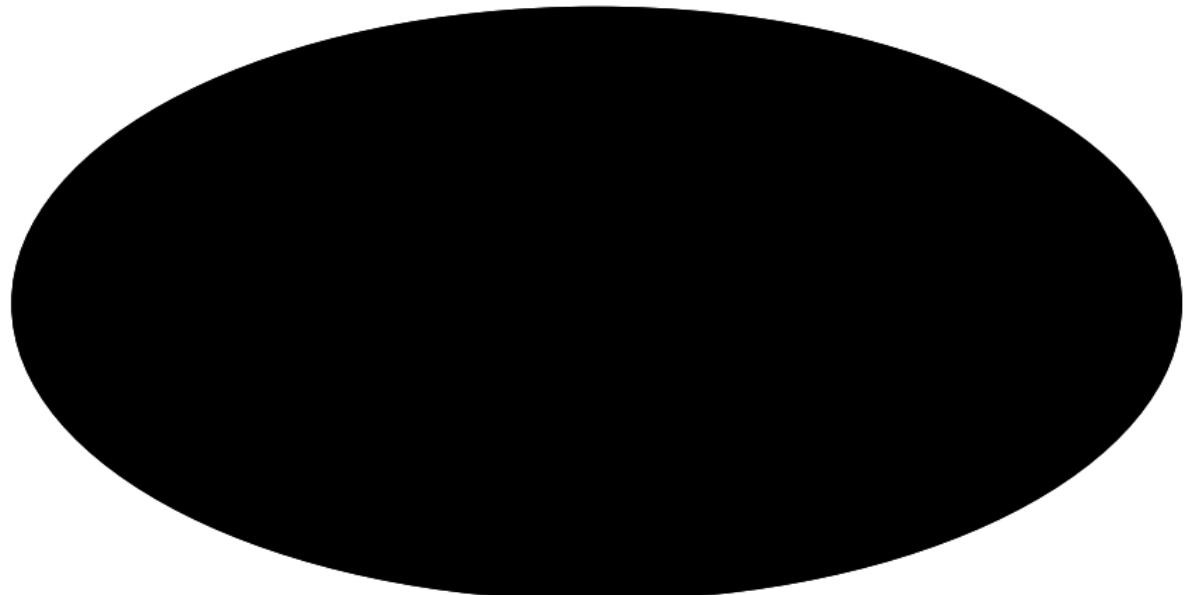
COBE (1992)    WMAP (2003)    Planck (2013)



## The oldest picture of the Universe

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

$\dots \rightarrow 2019 \rightarrow \dots$

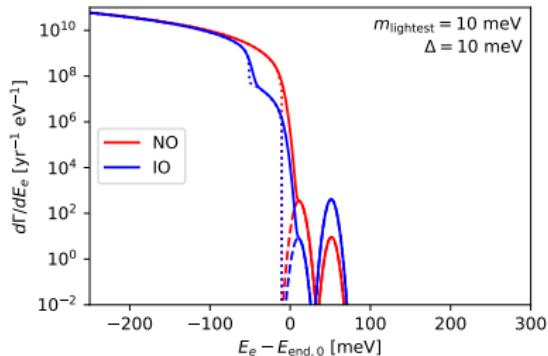


## 1 Cosmic Neutrino Background

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# A viable method - neutrino capture

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

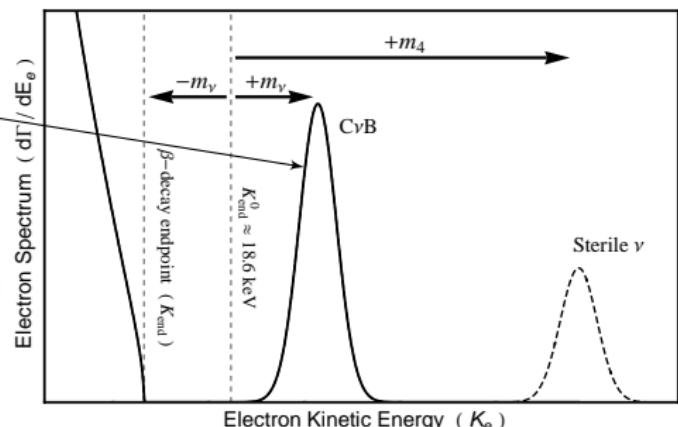
[Weinberg, 1962]: neutrino capture in  $\beta$ -decaying nuclei  $\nu + n \rightarrow p + e^- + \bar{\nu}$

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

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

only with a lot of material

need a very good energy resolution



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

to minimize contamination from  $\beta$  decay background

Isotope	Decay	$Q_\beta$ (keV)	Half-life (s)	$\sigma_{\text{NCB}}(v_\nu/c)$ ( $10^{-41} \text{ cm}^2$ )
$^3\text{H}$	$\beta^-$	18.591	$3.8878 \times 10^8$	$7.84 \times 10^{-4}$
$^{63}\text{Ni}$	$\beta^-$	66.945	$3.1588 \times 10^9$	$1.38 \times 10^{-6}$
$^{93}\text{Zr}$	$\beta^-$	60.63	$4.952 \times 10^{13}$	$2.39 \times 10^{-10}$
$^{106}\text{Ru}$	$\beta^-$	39.4	$3.2278 \times 10^7$	$5.88 \times 10^{-4}$
$^{107}\text{Pd}$	$\beta^-$	33	$2.0512 \times 10^{14}$	$2.58 \times 10^{-10}$
$^{187}\text{Re}$	$\beta^-$	2.64	$1.3727 \times 10^{18}$	$4.32 \times 10^{-11}$
$^{11}\text{C}$	$\beta^+$	960.2	$1.226 \times 10^3$	$4.66 \times 10^{-3}$
$^{13}\text{N}$	$\beta^+$	1198.5	$5.99 \times 10^2$	$5.3 \times 10^{-3}$
$^{15}\text{O}$	$\beta^+$	1732	$1.224 \times 10^2$	$9.75 \times 10^{-3}$
$^{18}\text{F}$	$\beta^+$	633.5	$6.809 \times 10^3$	$2.63 \times 10^{-3}$
$^{22}\text{Na}$	$\beta^+$	545.6	$9.07 \times 10^7$	$3.04 \times 10^{-7}$
$^{45}\text{Ti}$	$\beta^+$	1040.4	$1.307 \times 10^4$	$3.87 \times 10^{-4}$

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

## $\beta$ and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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

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

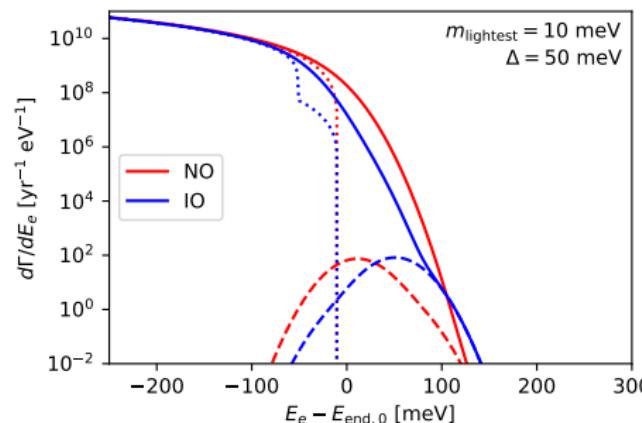
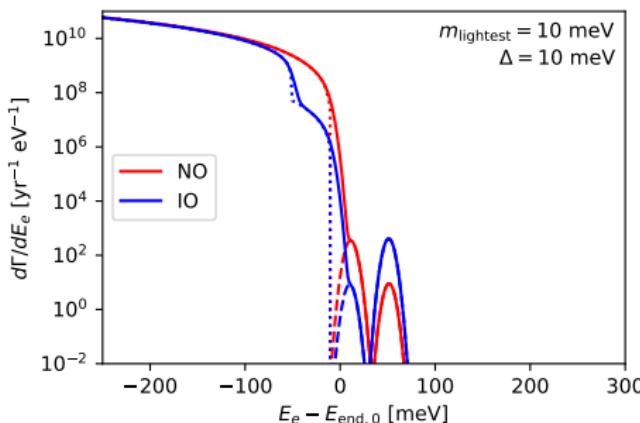
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Pontecorvo Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution  $\Delta \simeq 0.1 \text{ eV}$ ?  
 $0.05 \text{ eV}$ ?

can probe  $m_\nu \simeq 1.4\Delta \simeq 0.1 \text{ eV}$

built mainly for CNB

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

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

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

(without clustering)

$\sim \mathcal{O}(10) \text{ yr}^{-1}$

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enhancement from  
 $\nu$  clustering in the galaxy?

enhancement from  
other effects?

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

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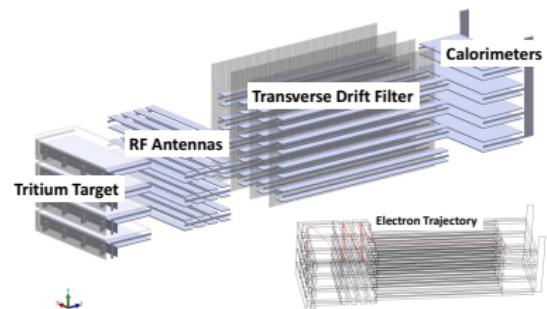
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## 3 PTOLEMY

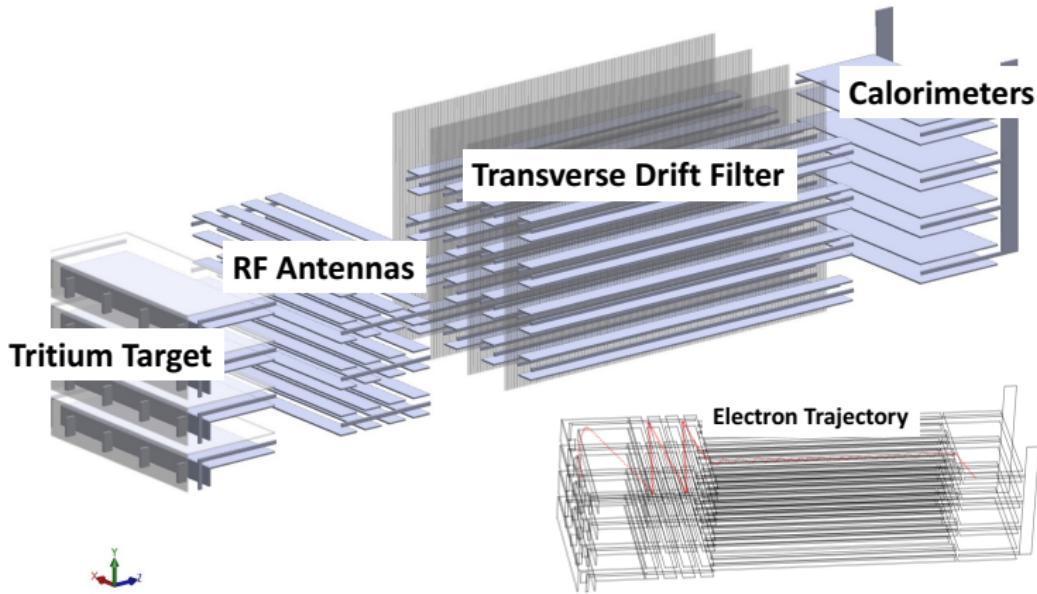
## 4 Conclusions



# PTOLEMY pipeline

scope of PTOLEMY:

measure electron spectrum near  ${}^3\text{H}$   $\beta$ -decay endpoint  
(same as neutrino mass experiments, e.g. KATRIN)

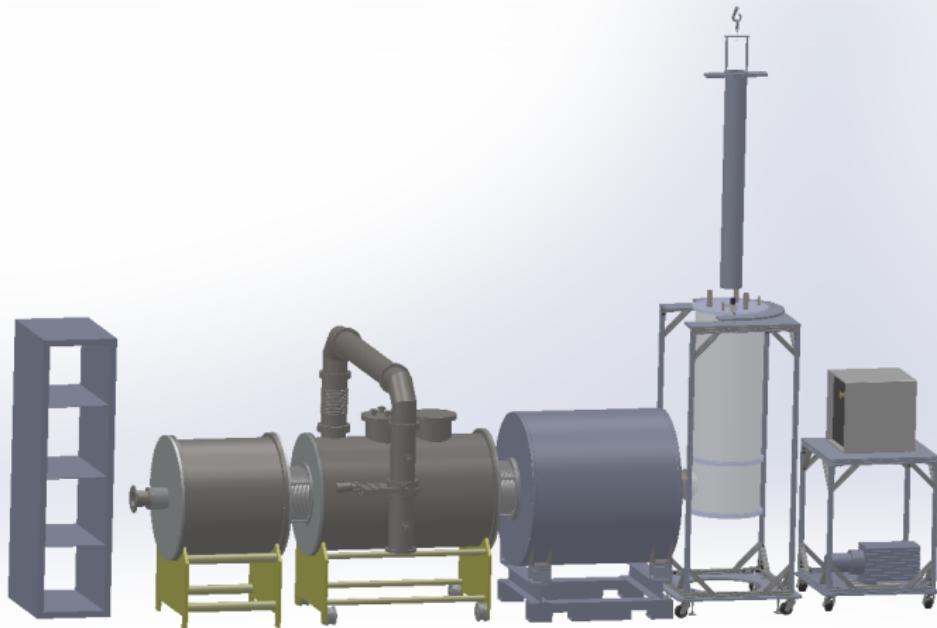


[PTOLEMY, PPNP 106 (2019) 120]

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measure electron spectrum near  ${}^3\text{H}$   $\beta$ -decay endpoint  
(same as neutrino mass experiments, e.g. KATRIN)



[PTOLEMY, arxiv:1808.01892]

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

$$N_\beta^i = T \int_{E_i - \Delta/2}^{E_i + \Delta/2} \frac{d\tilde{\Gamma}_\beta}{dE_e} dE_e$$

$$N_{\text{CNB}}^i = T \int_{E_i - \Delta/2}^{E_i + \Delta/2} \frac{d\tilde{\Gamma}_{\text{CNB}}}{dE_e} dE_e$$

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

add **background**  $\hat{N}_b = \hat{\Gamma}_b T$        $\longrightarrow$   $N_t^i = \hat{N}^i + \hat{N}_b$

with  $\hat{\Gamma}_b \simeq 10^{-5}$  Hz

simulated **experimental** spectrum:

$$N_{\text{exp}}^i(\hat{E}_{\text{end}}, \hat{m}_i, \hat{U}) = N_t^i \pm \sqrt{N_t^i}$$

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

$$N_{\text{th}}^i(\theta) = \mathbf{A}_\beta N_\beta^i(\hat{E}_{\text{end}} + \Delta E_{\text{end}}, m_i, U) + \mathbf{A}_{\text{CNB}} N_{\text{CNB}}^i(\hat{E}_{\text{end}} + \Delta E_{\text{end}}, m_i, U) + N_b$$

fit  $\longrightarrow$   $\chi^2(\theta) = \sum_i \left( \frac{N_{\text{exp}}^i(\hat{E}_{\text{end}}, \hat{m}_i, \hat{U}) - N_{\text{th}}^i(\theta)}{\sqrt{N_t^i}} \right)^2$  or  $\log \mathcal{L} = -\frac{\chi^2}{2}$

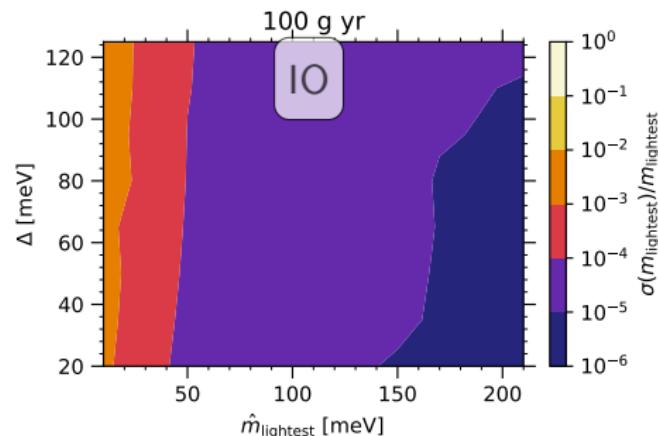
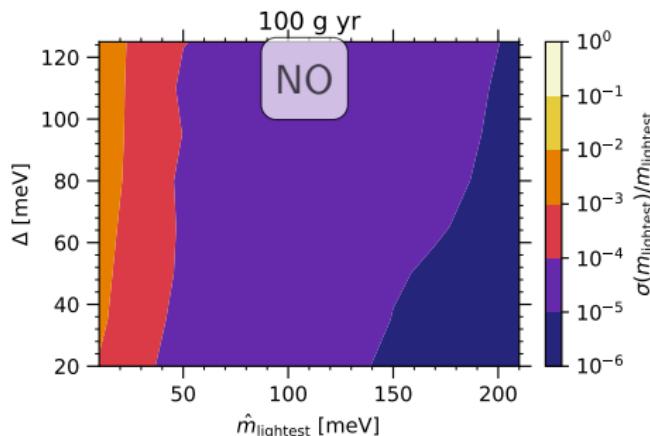
$T$  exposure time –  $(\hat{E}_{\text{end}}, \hat{m}_i, \hat{U})$  fiducial endpoint energy, masses, mixing matrix –  $\theta = (A_\beta, N_b, \Delta E_{\text{end}}, A_{\text{CNB}}, m_i, U)$

statistical only!

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

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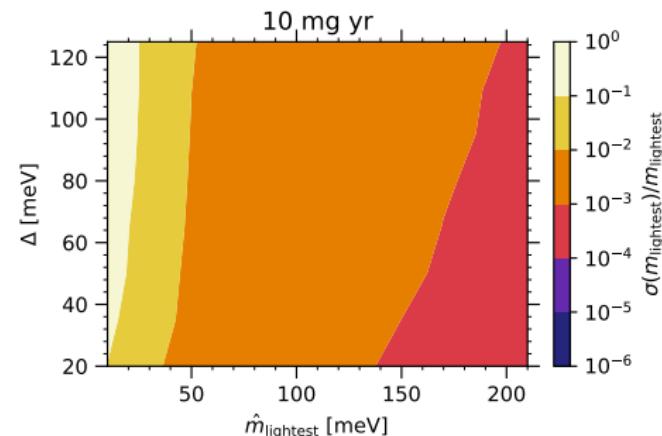
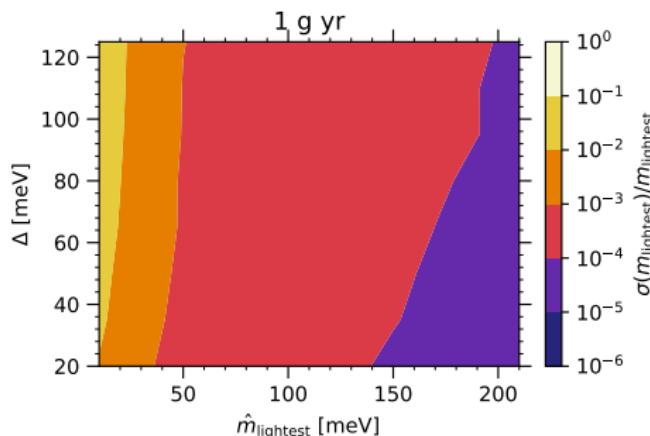


wonderful precision in determining the neutrino mass

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

statistical only!

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

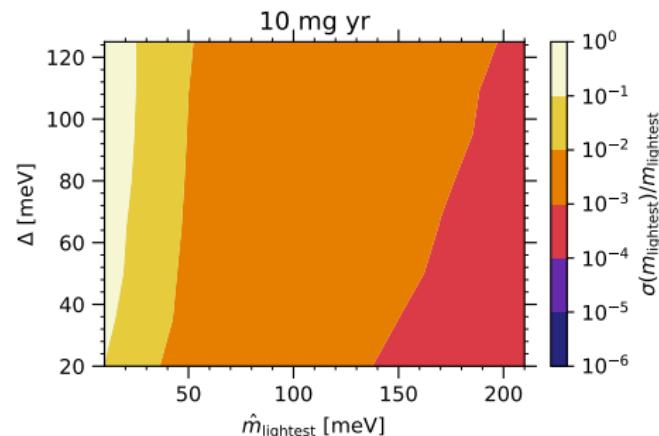
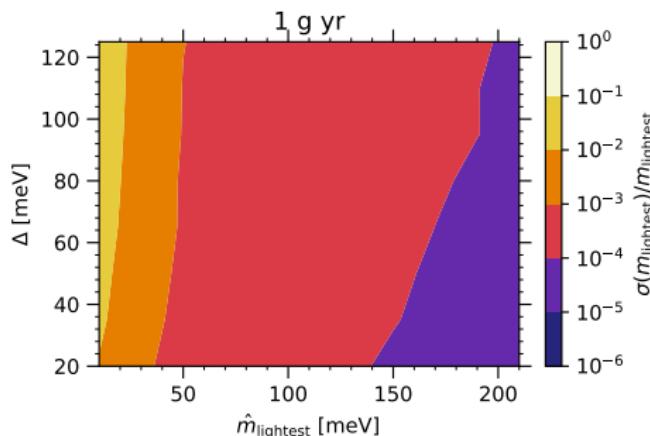


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(mass detection already with 10 mg of tritium!)

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wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

$\Delta$  has almost no impact

Bayesian method:

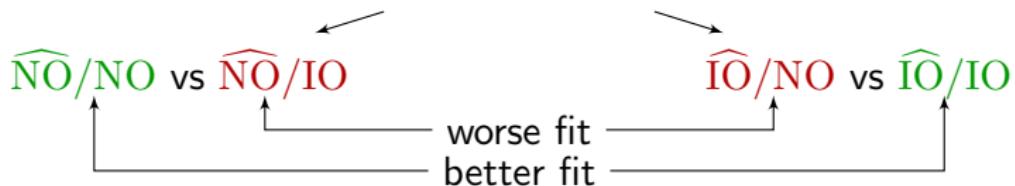
Fit fiducial ordering ( $\widehat{\text{NO}}$  or  $\widehat{\text{IO}}$ ) using both **correct** and **wrong** ordering

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

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

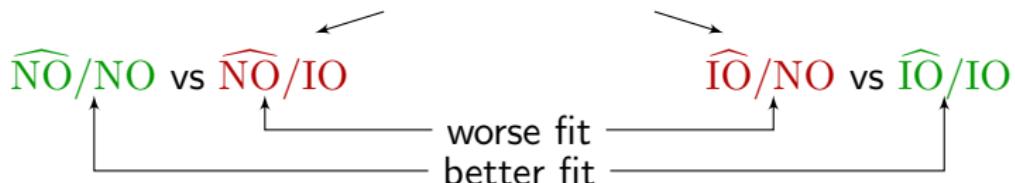
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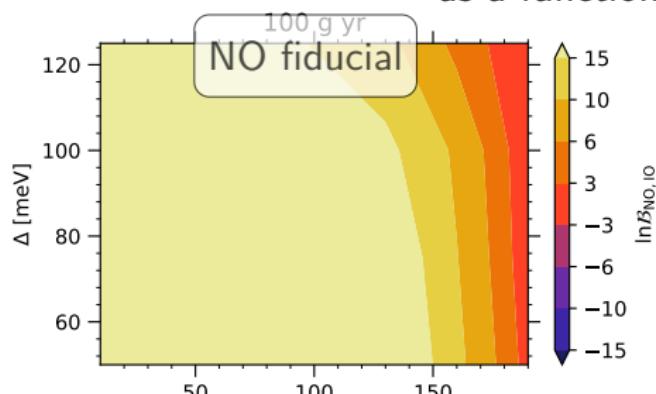
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statistical only!

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

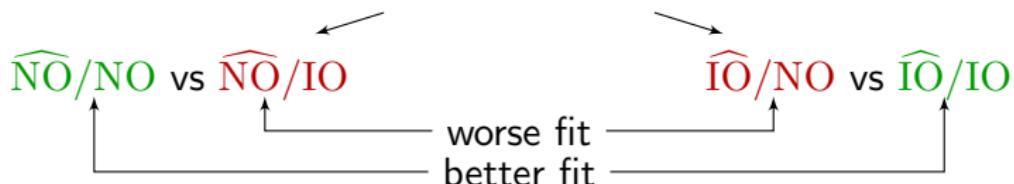


IO fiducial

always strong significance

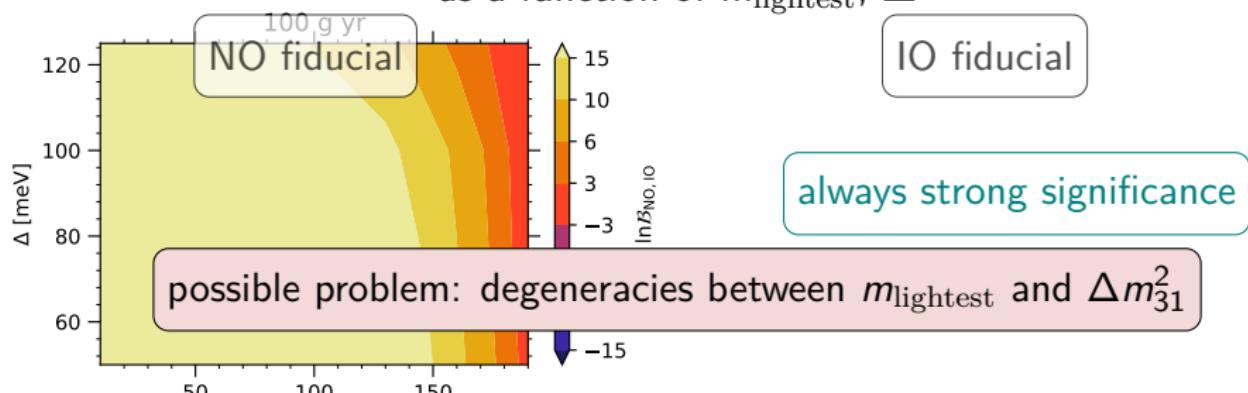
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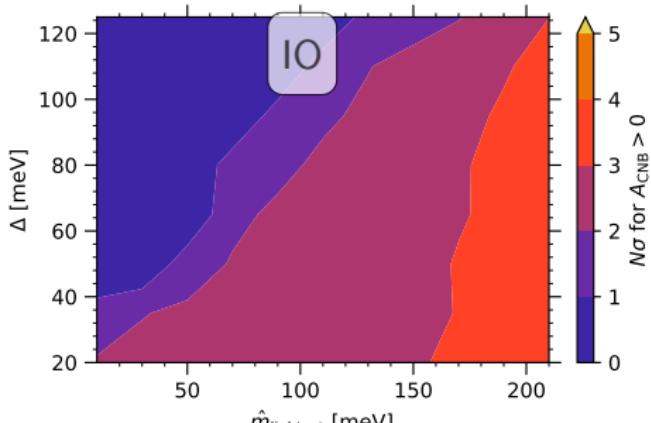
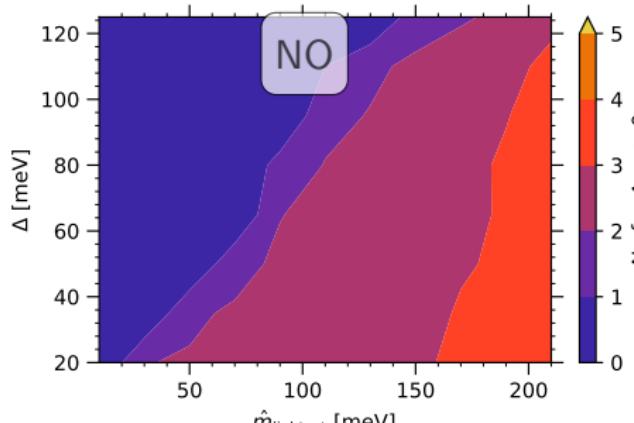
using the definition:

$$N_{\text{th}}^i(\theta) = A_\beta N_\beta^i(\hat{E}_{\text{end}} + \Delta E_{\text{end}}, m_i, U) + A_{\text{CNB}} N_{\text{CNB}}^i(\hat{E}_{\text{end}} + \Delta E_{\text{end}}, m_i, U) + N_b$$

if  $A_{\text{CNB}} > 0$  at  $N\sigma$ , direct detection of CNB accomplished at  $N\sigma$

statistical only!

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

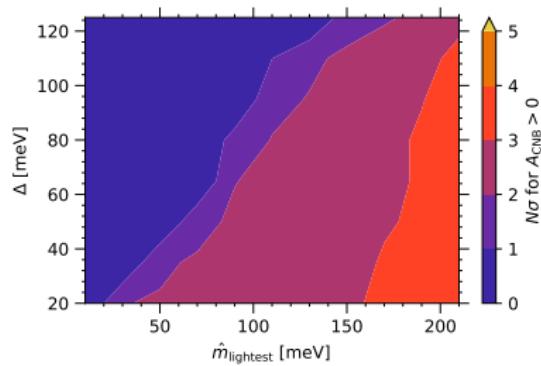


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# ■ Requirements for PTOLEMY discoveries

What do we need to discover...

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

✓: strongly required

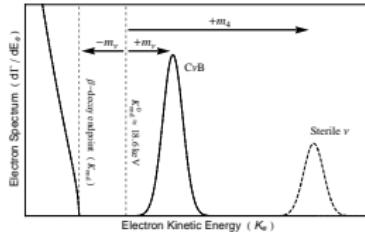
? : not so strongly required

✗: loosely required

# Conclusions

1

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



2

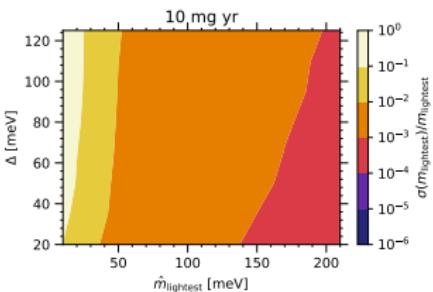
But it will be a technological challenge!

[ ${}^3\text{H}$  amount, low background, energy resolution, ...]

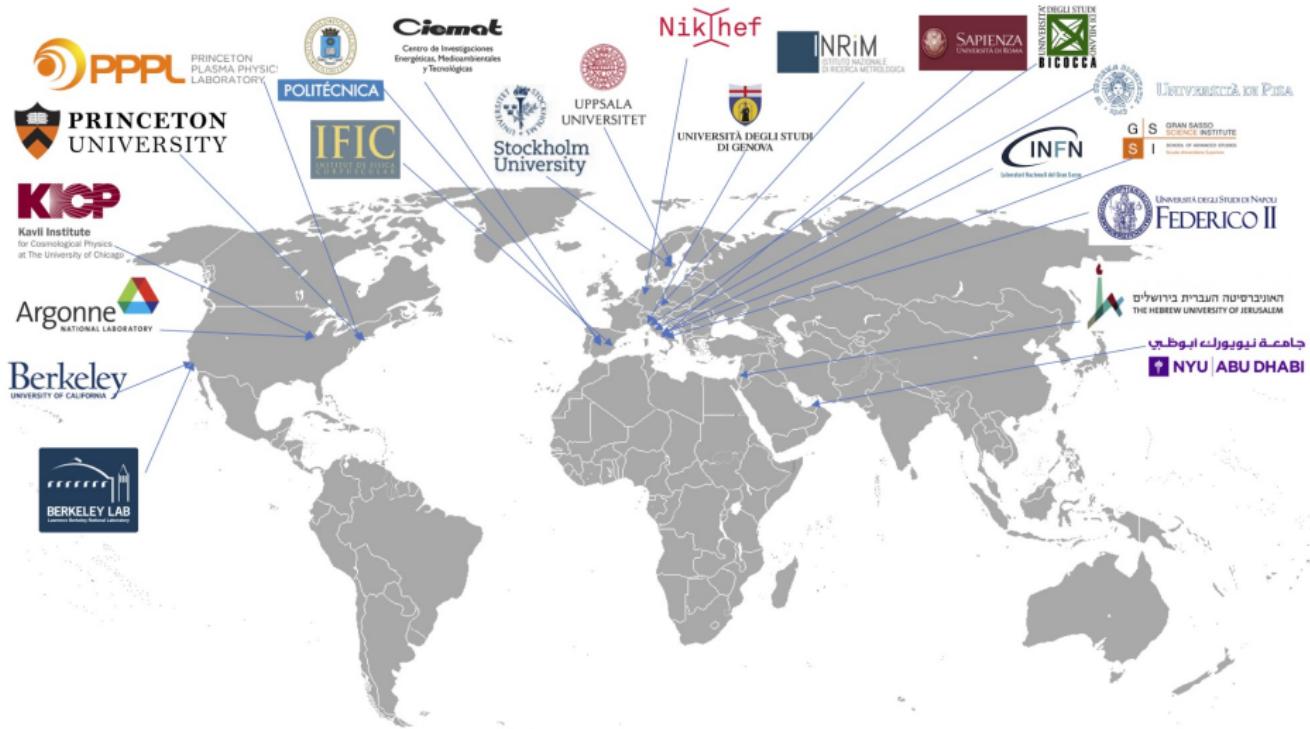


3

amazing results  
already achievable  
with small tritium amount!



# PTOLEMY collaboration



Thank you for the attention!