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Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

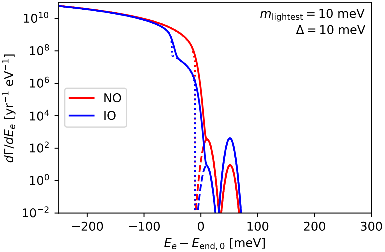
Neutrino physics with the PTOLEMY project

General meeting of the Fellini programme, 30–31/05/2022

1 Direct detection of relic neutrinos

2 PTOLEMY

3 Conclusions: ATM



Neutrino capture

[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

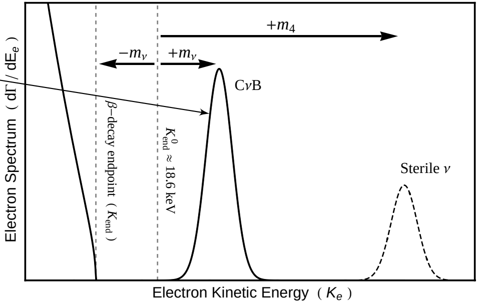
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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 ($\rightarrow$ event rate) is higher

β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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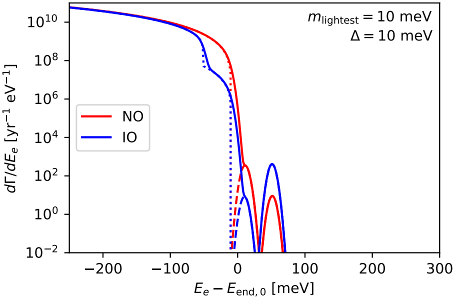
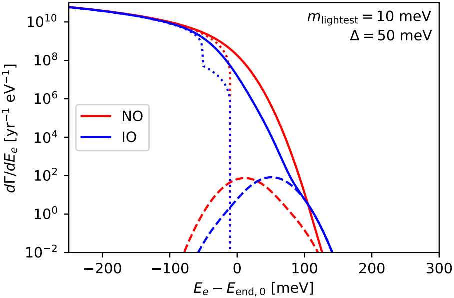
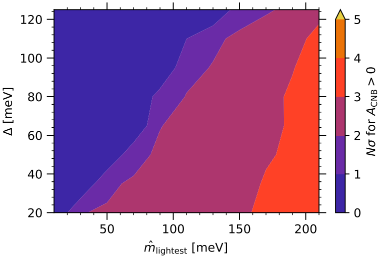




1 *Direct detection of relic neutrinos*

2 ***PTOLEMY***

3 *Conclusions: ATM*



PTOLEMY

[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

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

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

(without clustering)

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ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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PTOLEMY proposal as of 2022

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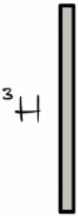

[Courtesy A. Esposito]

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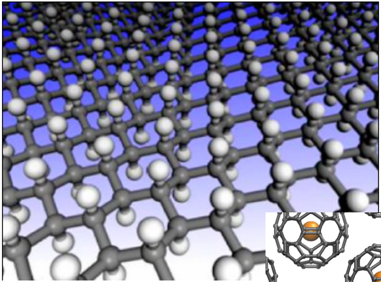
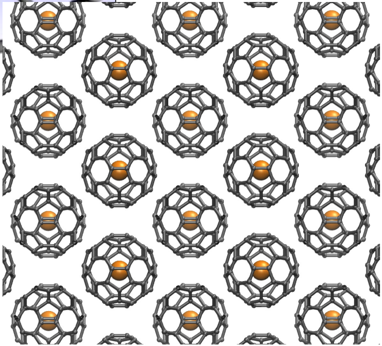


tritium on graphene?

tritium on fullerene?



[Courtesy V. Tozzini]

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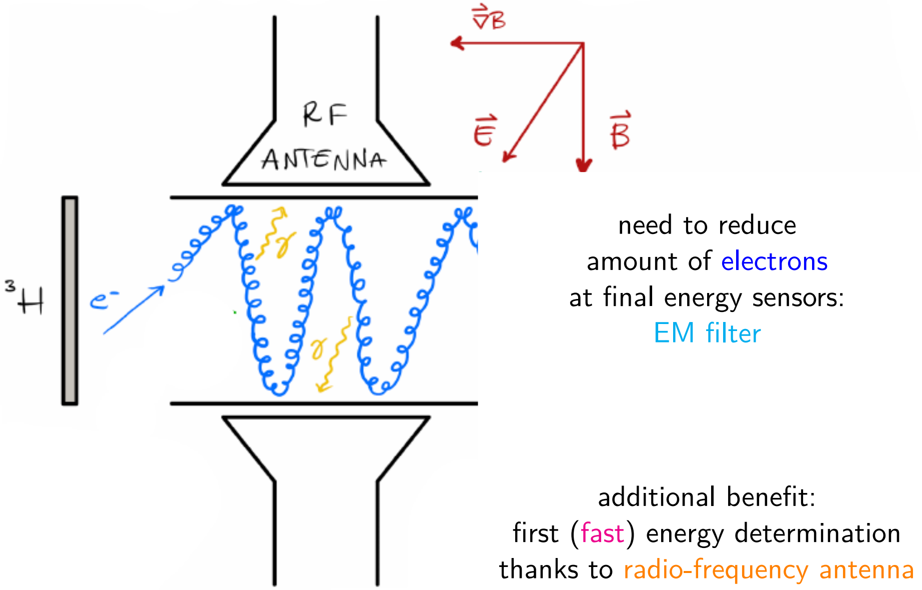

need to reduce
amount of electrons
at final energy sensors:
EM filter

additional benefit:
first (fast) energy determination
thanks to radio-frequency antenna

[Courtesy A. Esposito]

PTOLEMY proposal as of 2022

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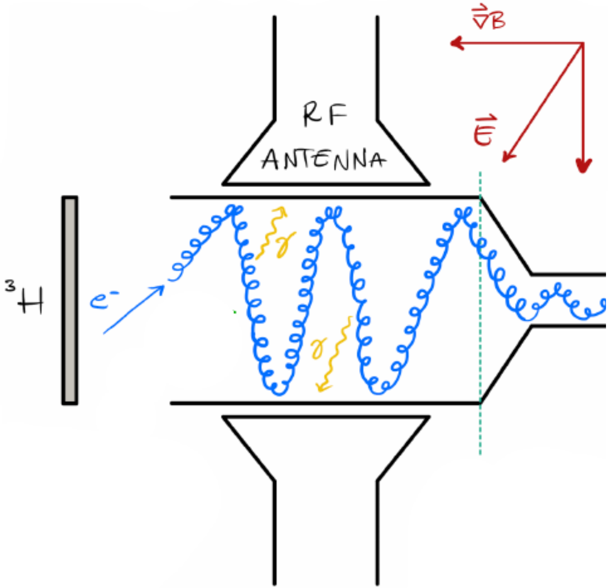

filter only events
close to endpoint
$(E \gtrsim E_0 - 10\text{ eV})$

[Courtesy A. Esposito]

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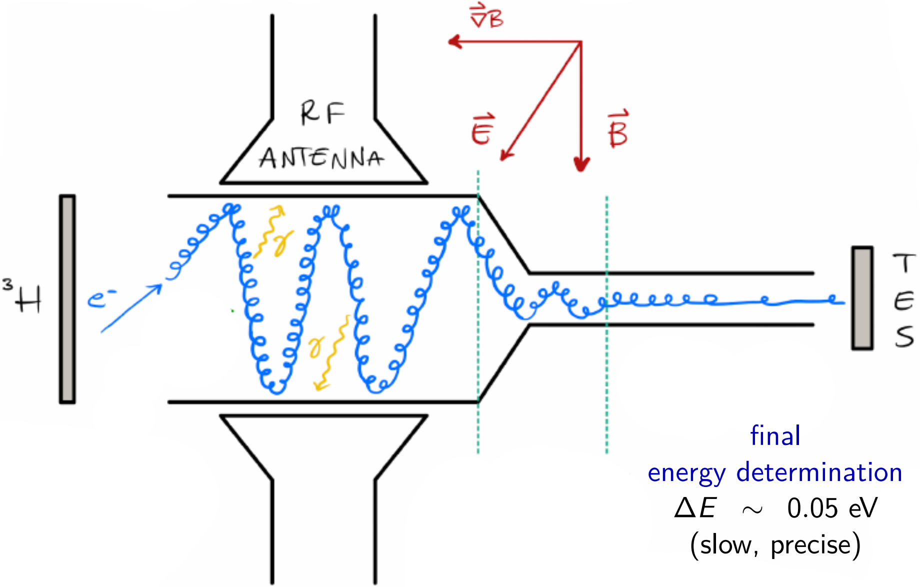

final
energy determination
$\Delta E \sim 0.05$ eV
(slow, precise)

[Courtesy A. Esposito]

Heisenberg uncertainty?

[PTOLEMY, arxiv:2203.11228]

Quantum mechanics complicates the T-on-graphene case

spatially localized T → uncertainty on T momentum [Cheipesh+, PRD 2021] → spread in final e energy

$$\Delta K_\beta = \left|\frac{\vec{p}_e \cdot \Delta\vec{p}_{\mathrm{T}}}{E_{^3\mathrm{He}}}\right| \simeq \frac{p_e}{m_{^3\mathrm{He}}}\frac{1}{\Delta x_{\mathrm{T}}}$$

↳ spread of initial T wave function

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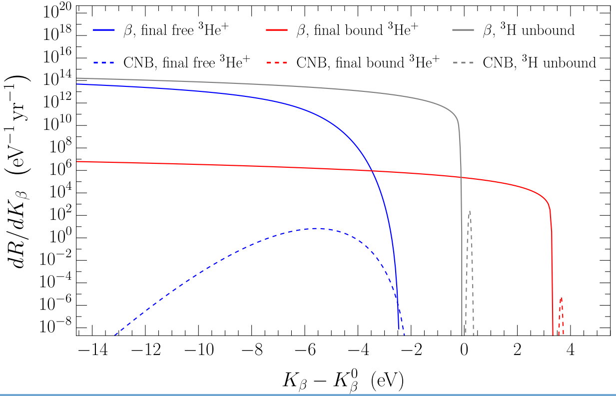

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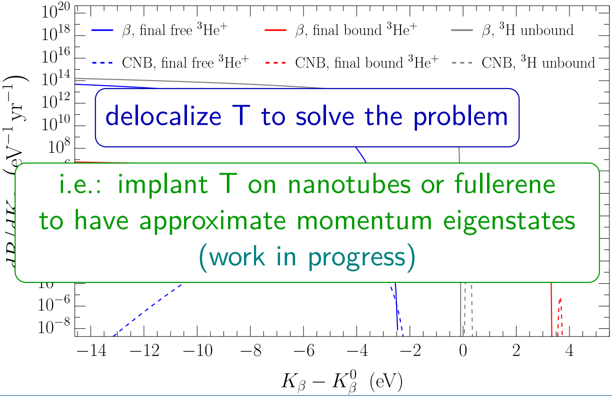

delocalize T to solve the problem

i.e.: implant T on nanotubes or fullerene
to have approximate momentum eigenstates
(work in progress)

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

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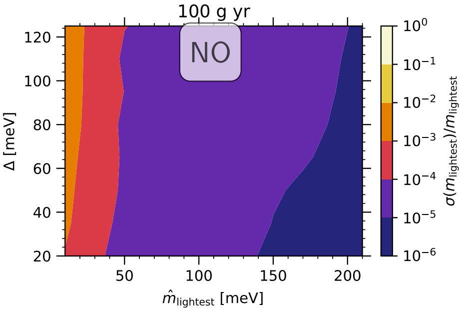

wonderful precision in determining the neutrino mass

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

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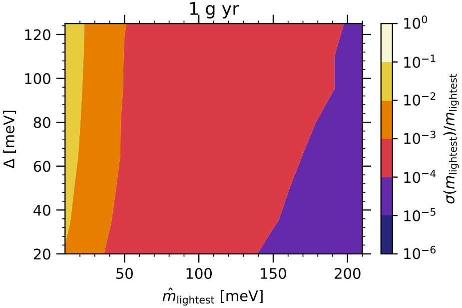

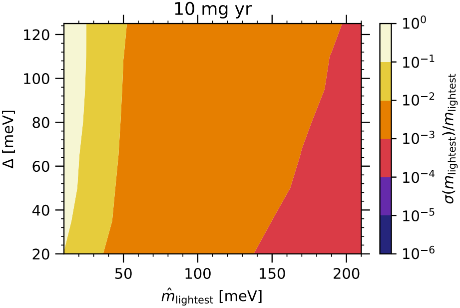

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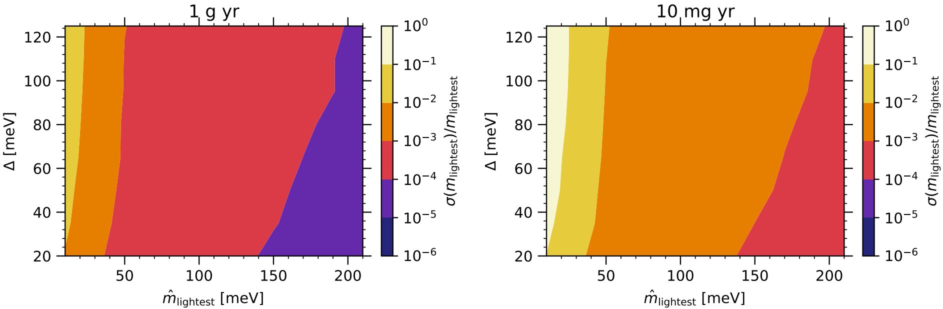

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Δ has almost no impact

Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

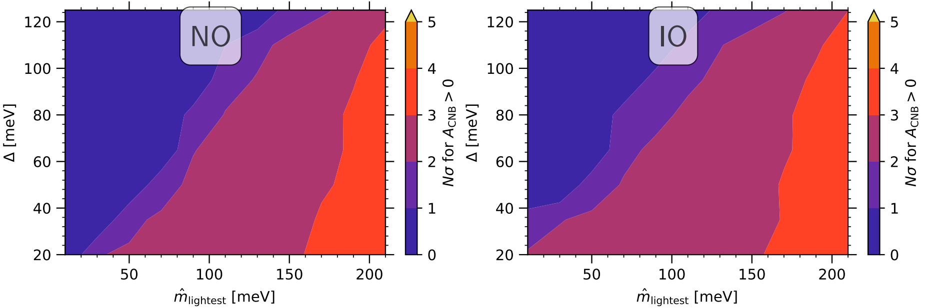
using the definition:

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

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



PTOLEMY and the ν_4

[PTOLEMY, JCAP 07 (2019) 047]

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

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

[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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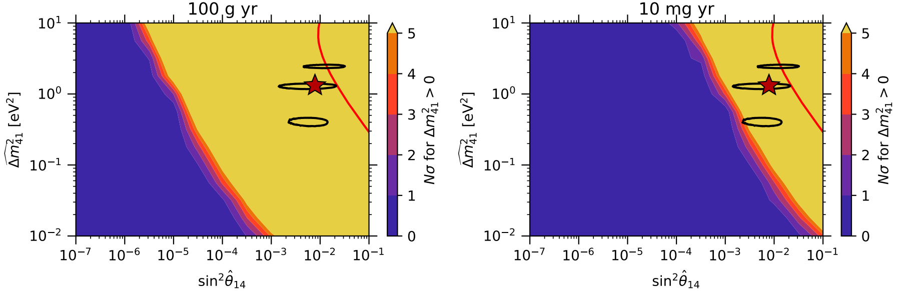
Still possible to measure mass/mixing through β spectrum



black: DANSS+NEOS 3σ (2018)

red: KATRIN 90% forecast

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?	!!	!!	!!
... light ν_s?	✓	✓	∼
... keV ν_s?	?? work in progress		

✓: no problem here

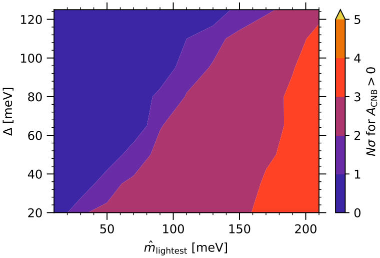
∼: not so strongly required

!!: strongly required

1 Direct detection of relic neutrinos

2 PTOLEMY

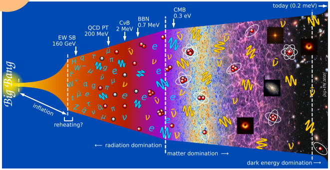
3 **Conclusions: ATM**

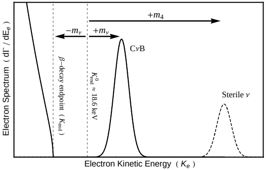


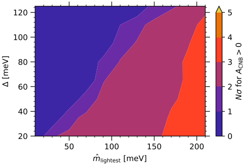
What did we learn on PTOLEMY?

A

Amazing science ahead!

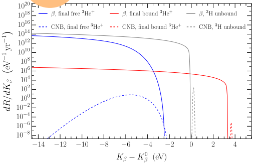


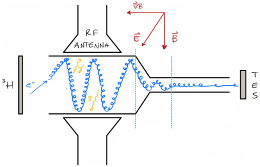


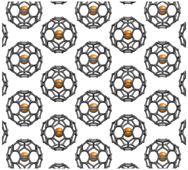


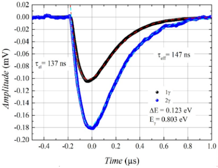
T

Technological challenge!



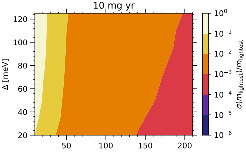


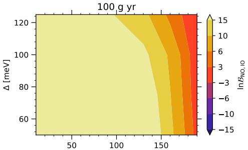


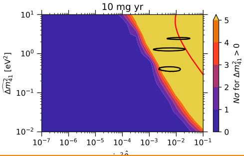


M

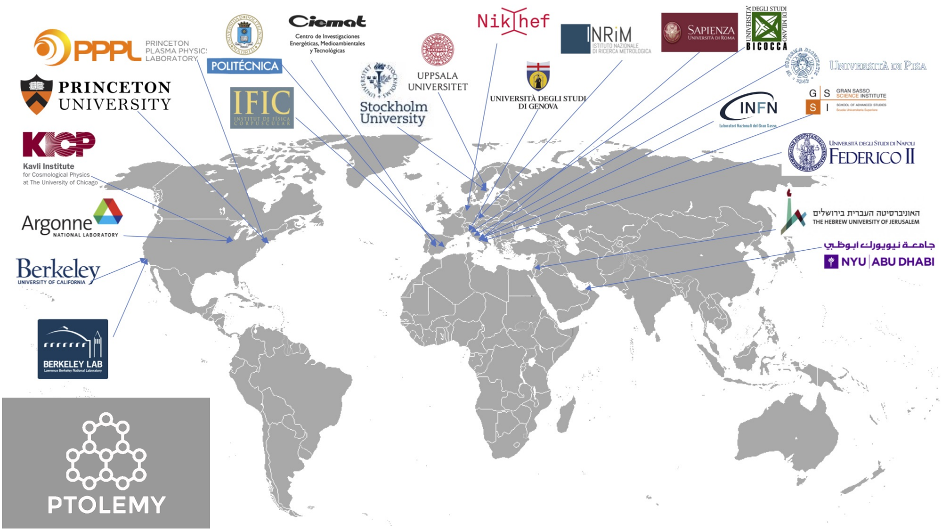
Neutrino Mass results even with prototypes (lower T amount)







PTOLEMY collaboration



Thank you for the attention!