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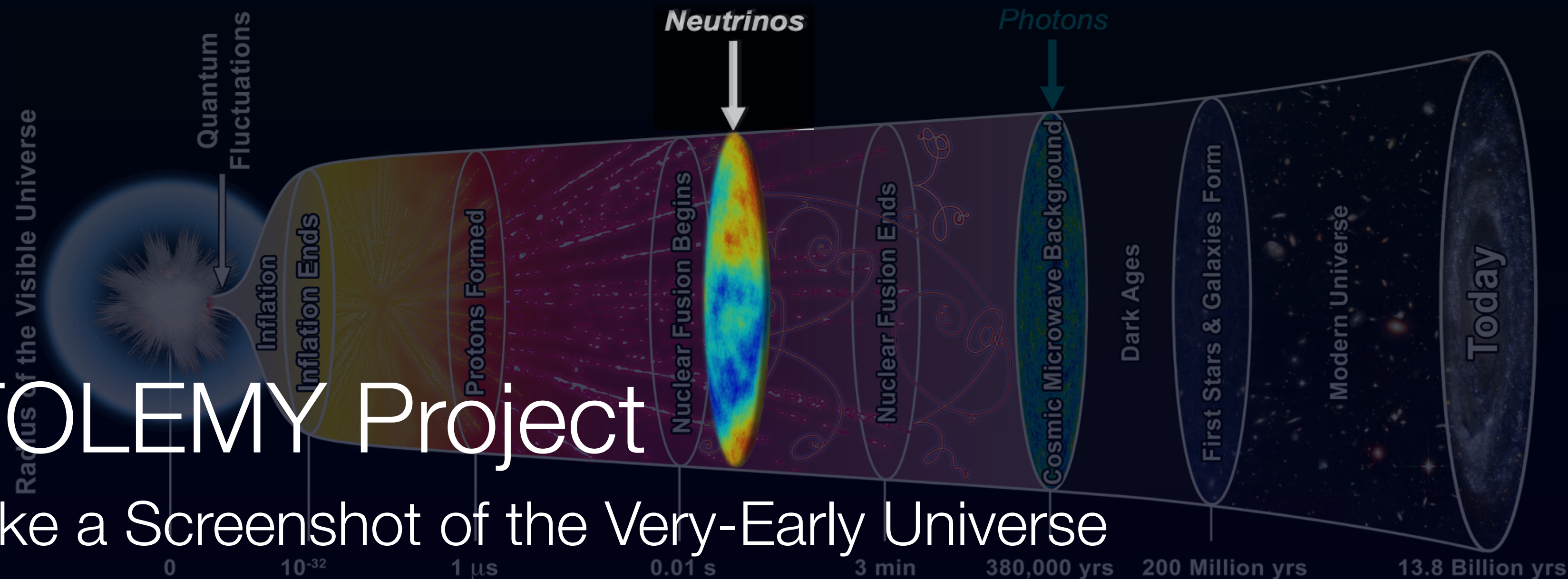


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The PTOLEMY Project

How to Make a Screenshot of the Very-Early Universe



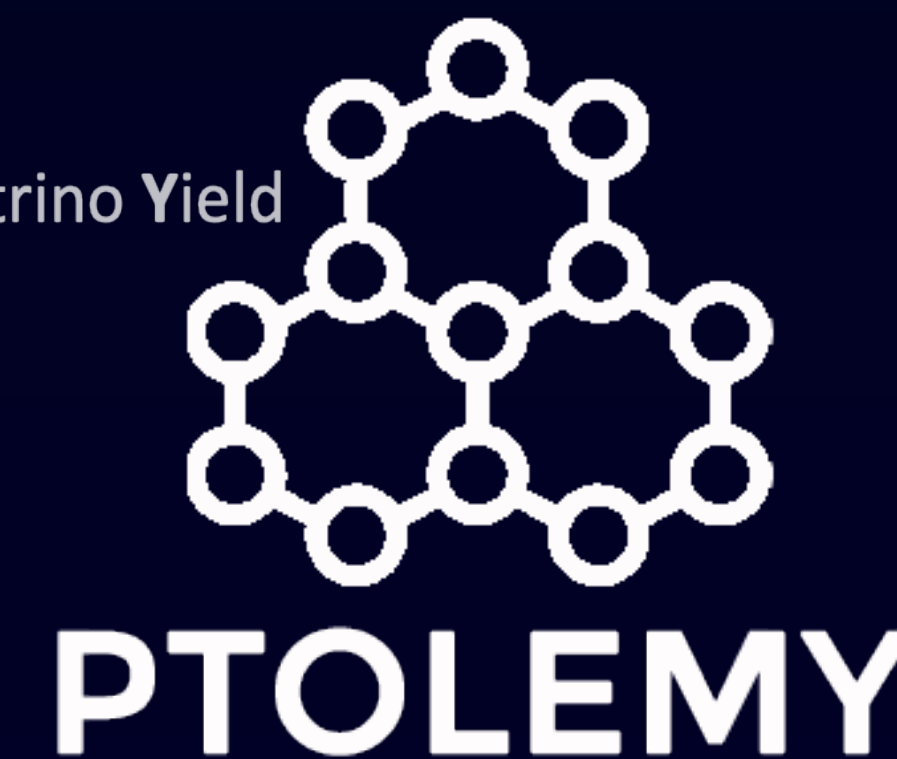
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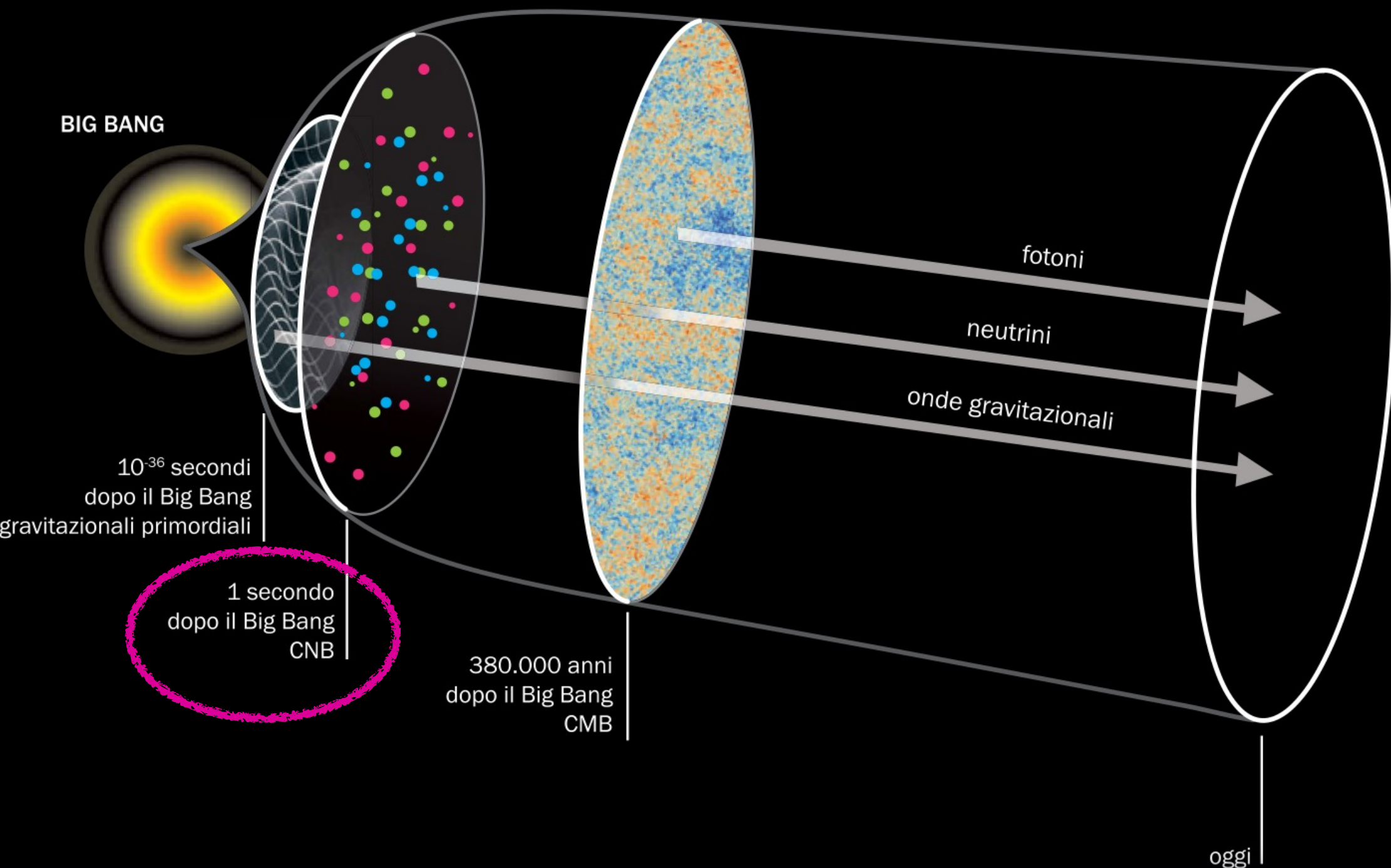
Presentation for Dark Matter and Neutrinos - Institut Henri Poincaré, Paris, 07 May 2025

Francesca Maria Pofi on the behalf of the PTOLEMY collaboration

PonTecorvo / PrinceTon Observatory for Light Early-universe Massive-neutrino Yield

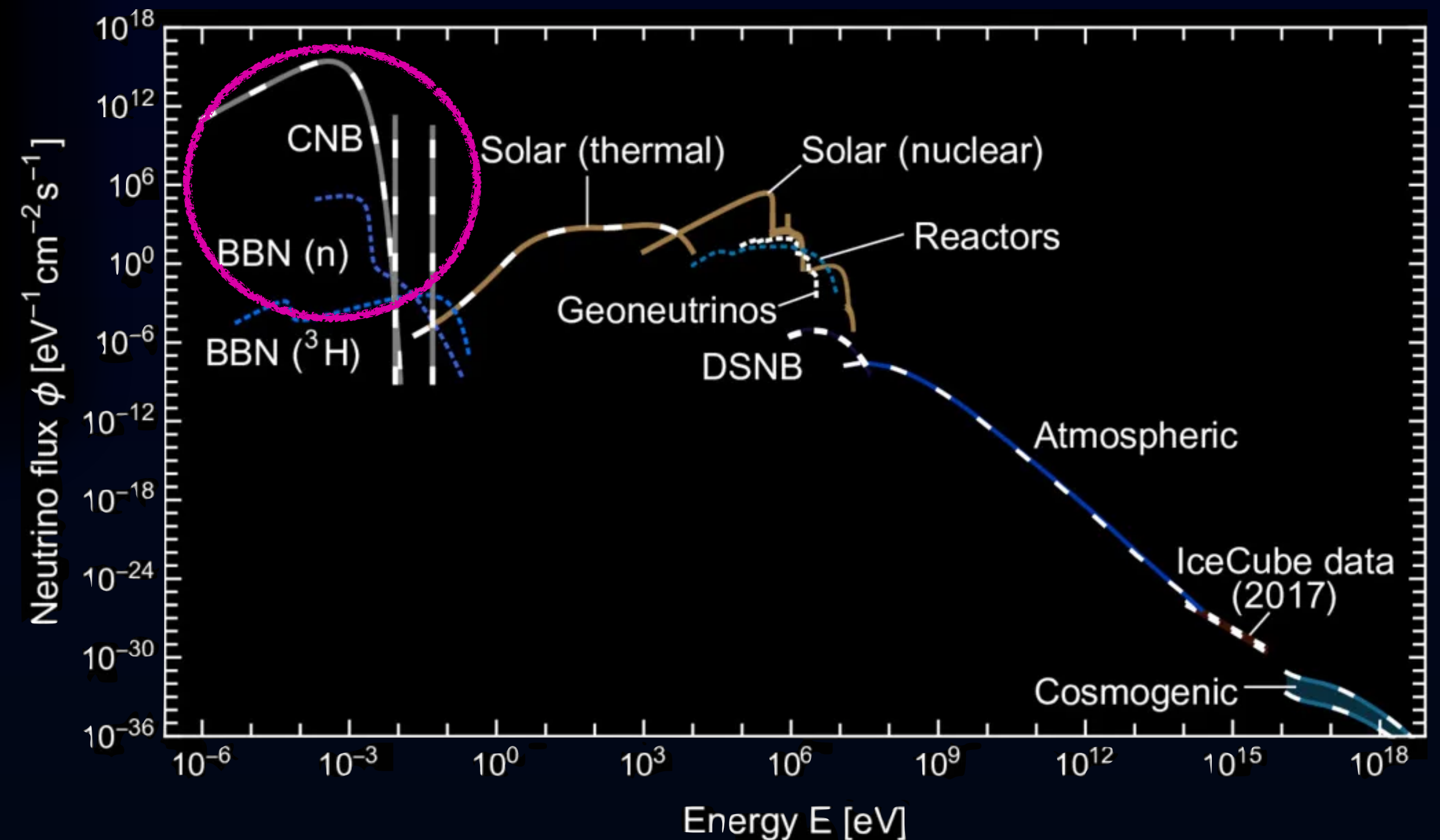
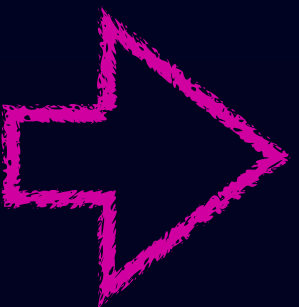


A Sea of 'Still' Neutrinos



Cosmic Neutrino Background (CNB)

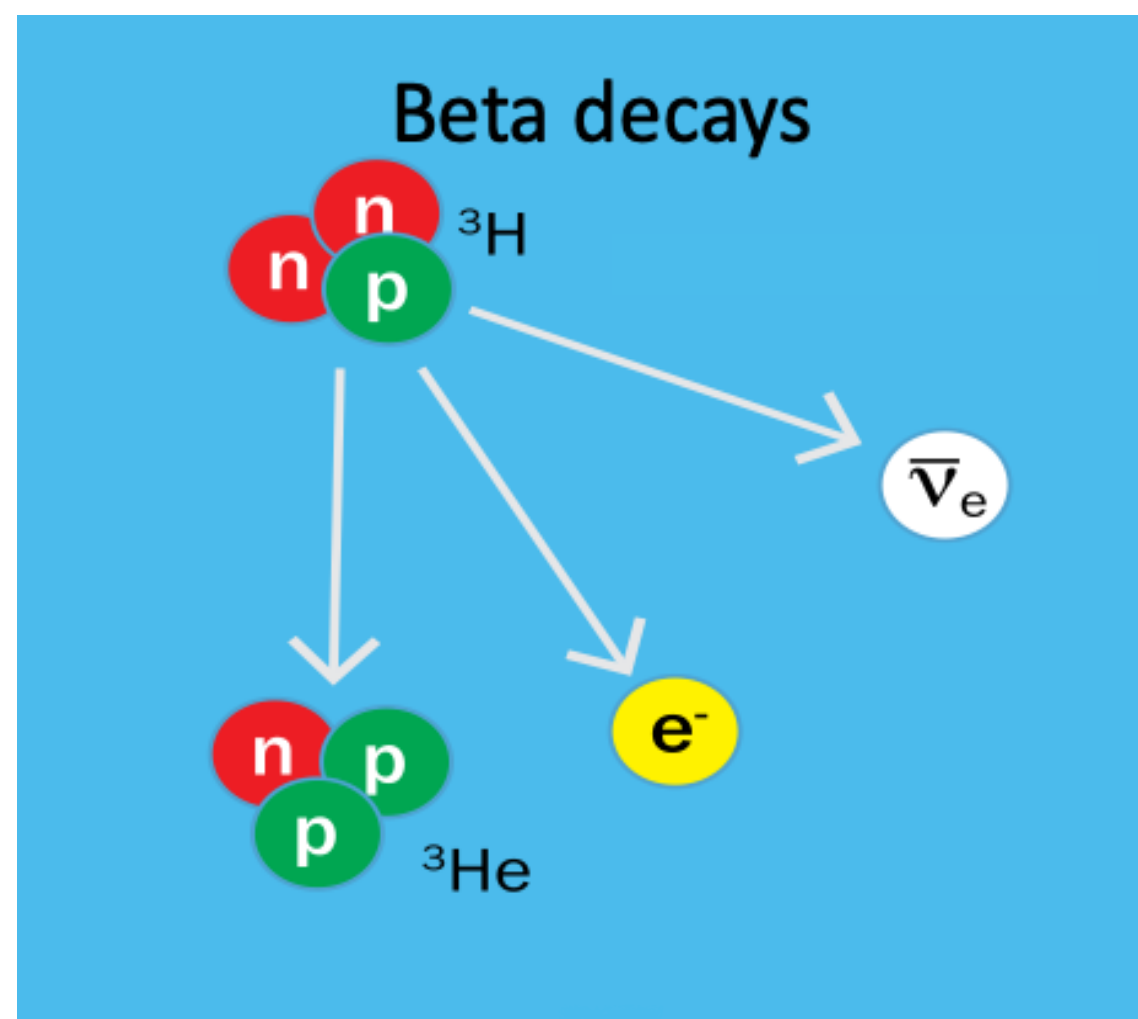
- Identikit:**
- ◆ Decoupling 1 sec after Big Bang
 - ◆ Density $n_\nu \simeq 300/\text{cm}^3$
 - ◆ Temperature $T_\nu \simeq 1.95 \text{ K}$



- ◆ Most abundant neutrinos' source
- ◆ Extremely low energy $E_\nu \simeq 10^{-4} \text{ eV}$
- ➔ Challenging detection: non-threshold reaction needed

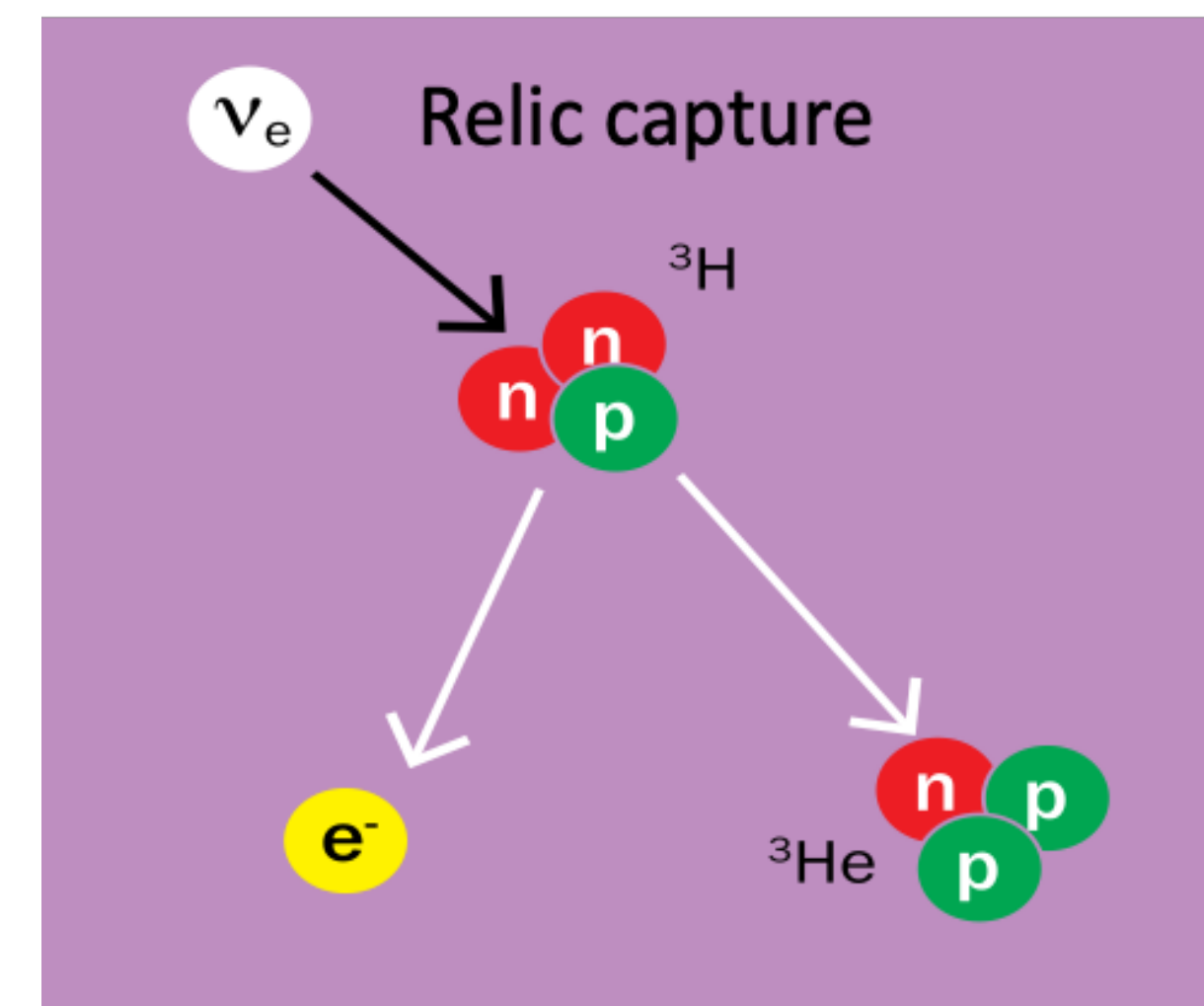
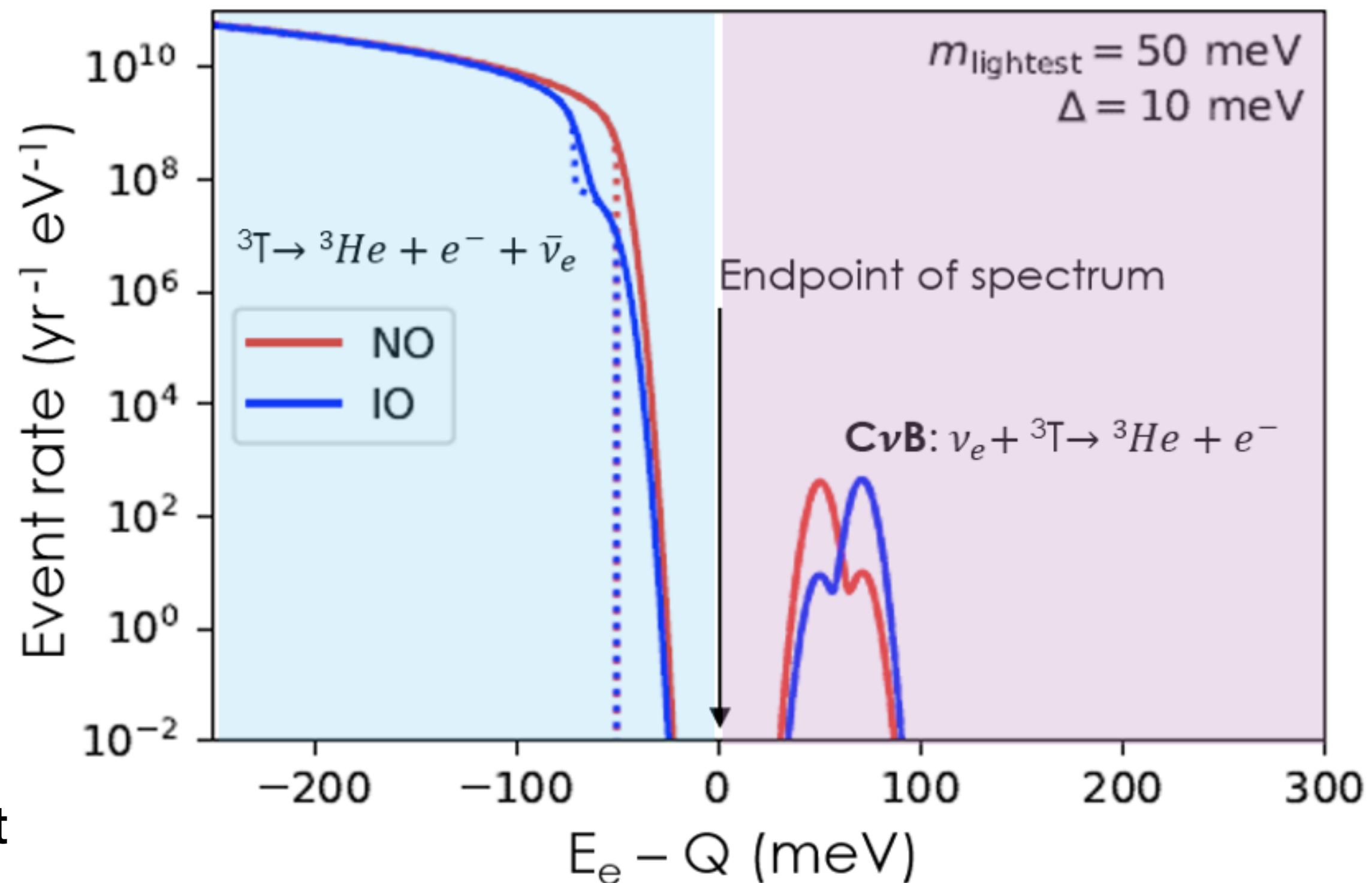
Two Measurements with One Observable

☑ Let's take a β -unstable nucleus eg Tritium (${}^3\text{H}$) \longrightarrow What can we obtain *for free*?



Neutrino Mass Measurement
from endpoint distortion

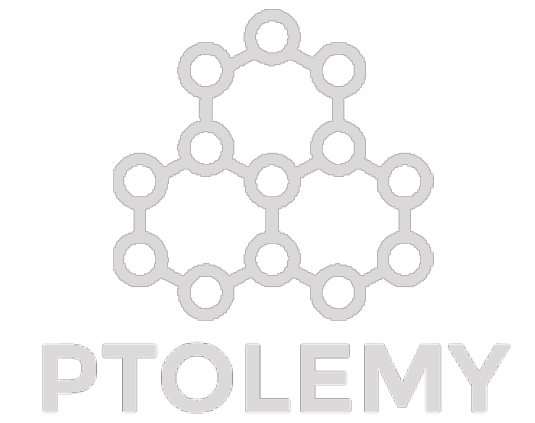
(1^o goal)



First
Relic Neutrinos Detection

(Final goal)

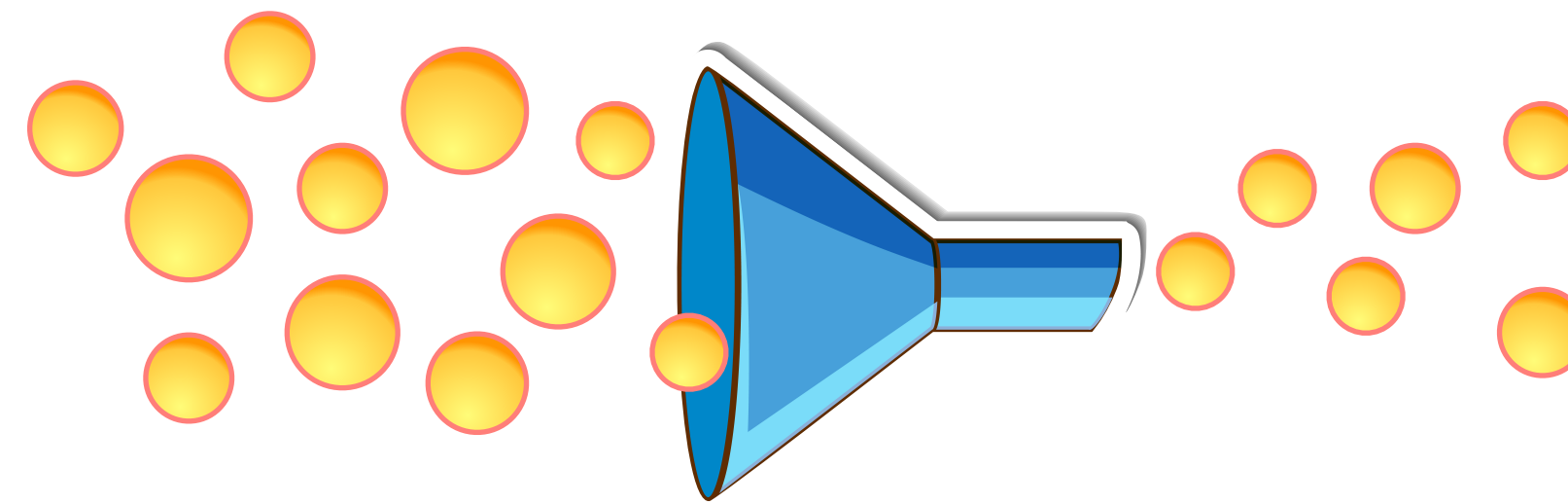
PTOLEMY Ingredients



✓ Extremely accurate measurement of electron energy

- $\mathcal{O}(50 \text{ meV})$ resolution

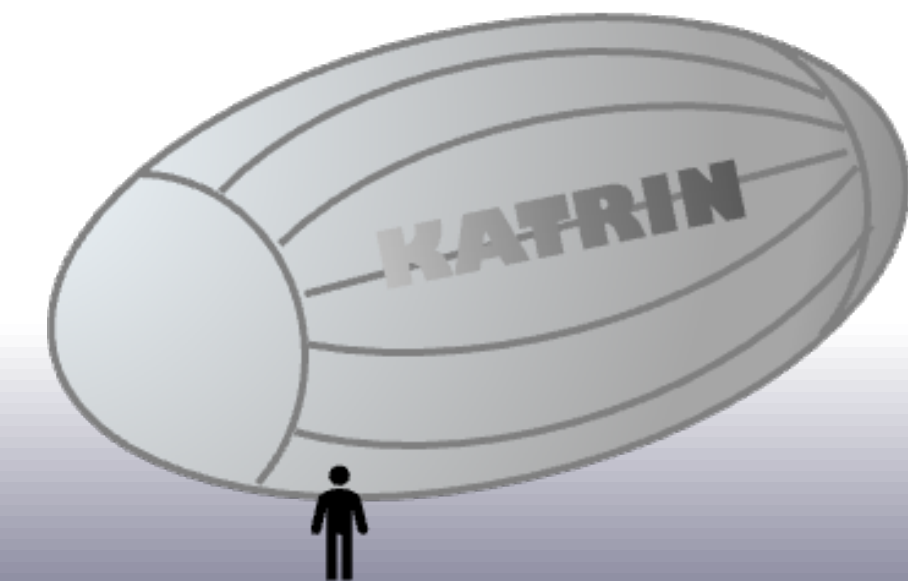
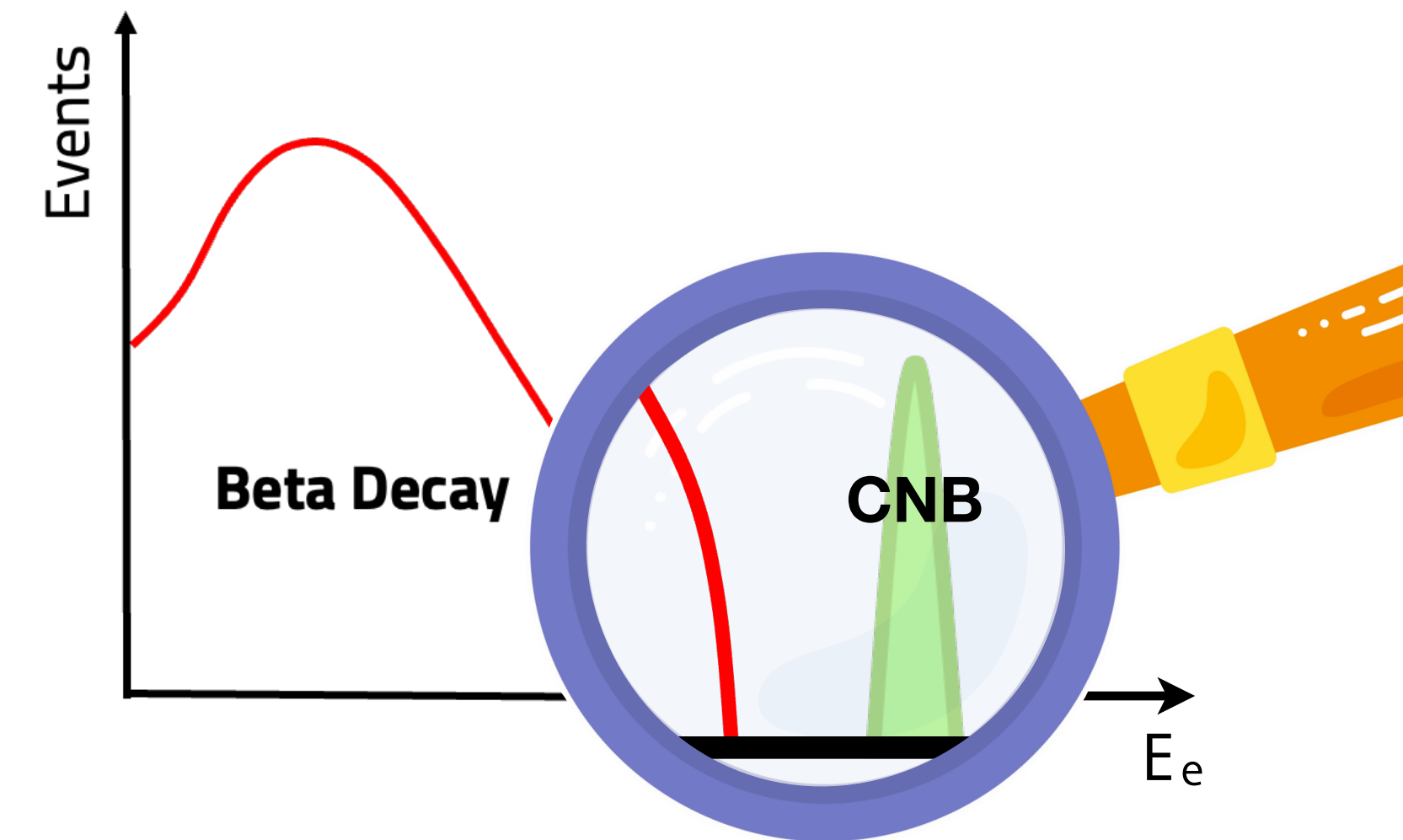
✓ Electron filtering



✓ Electron slowdown

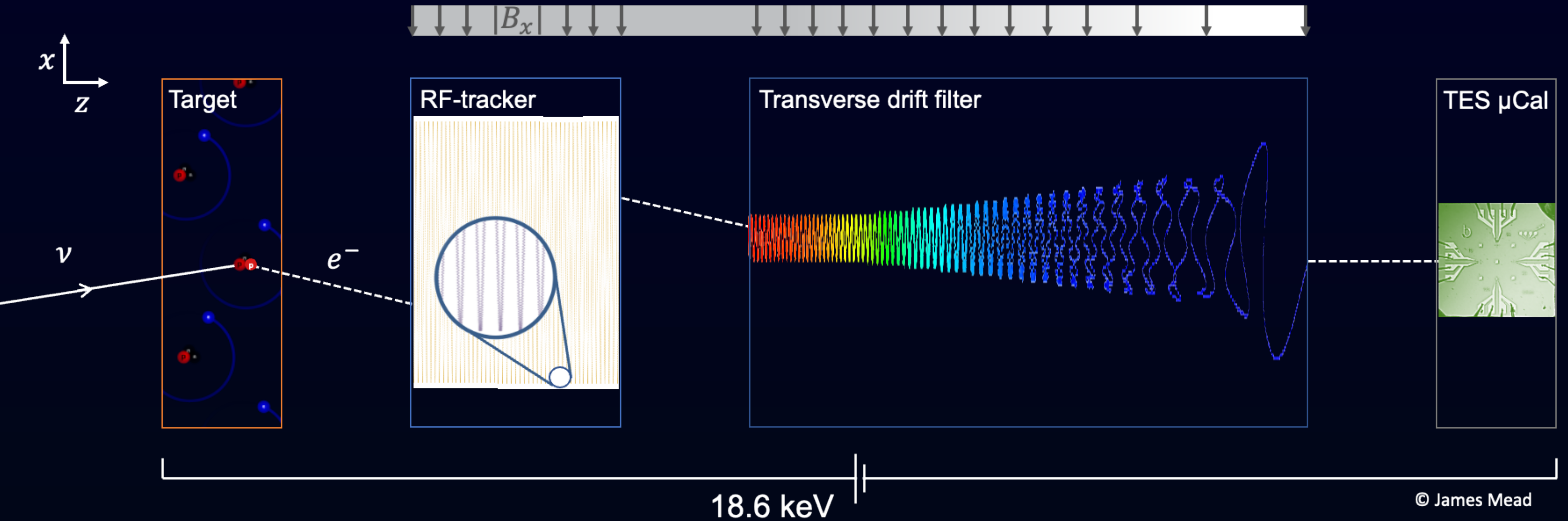


✓ Large target mass ($\mathcal{O}(10 \text{ events/year})$ CNB per 100 grams ^3H)



A Multi-Disciplinary Detector

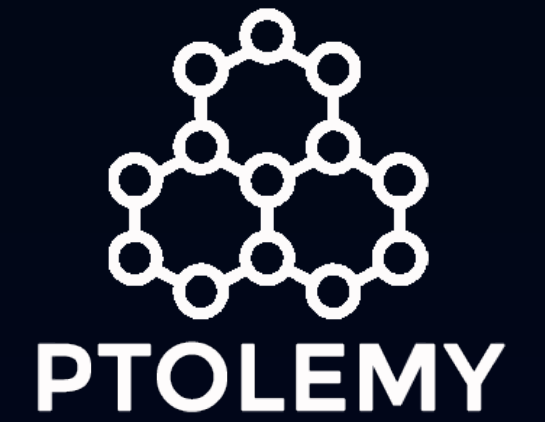
PonTecorvo / PrinceTon Observatory for Light Early-universe Massive-neutrino Yield



© James Mead

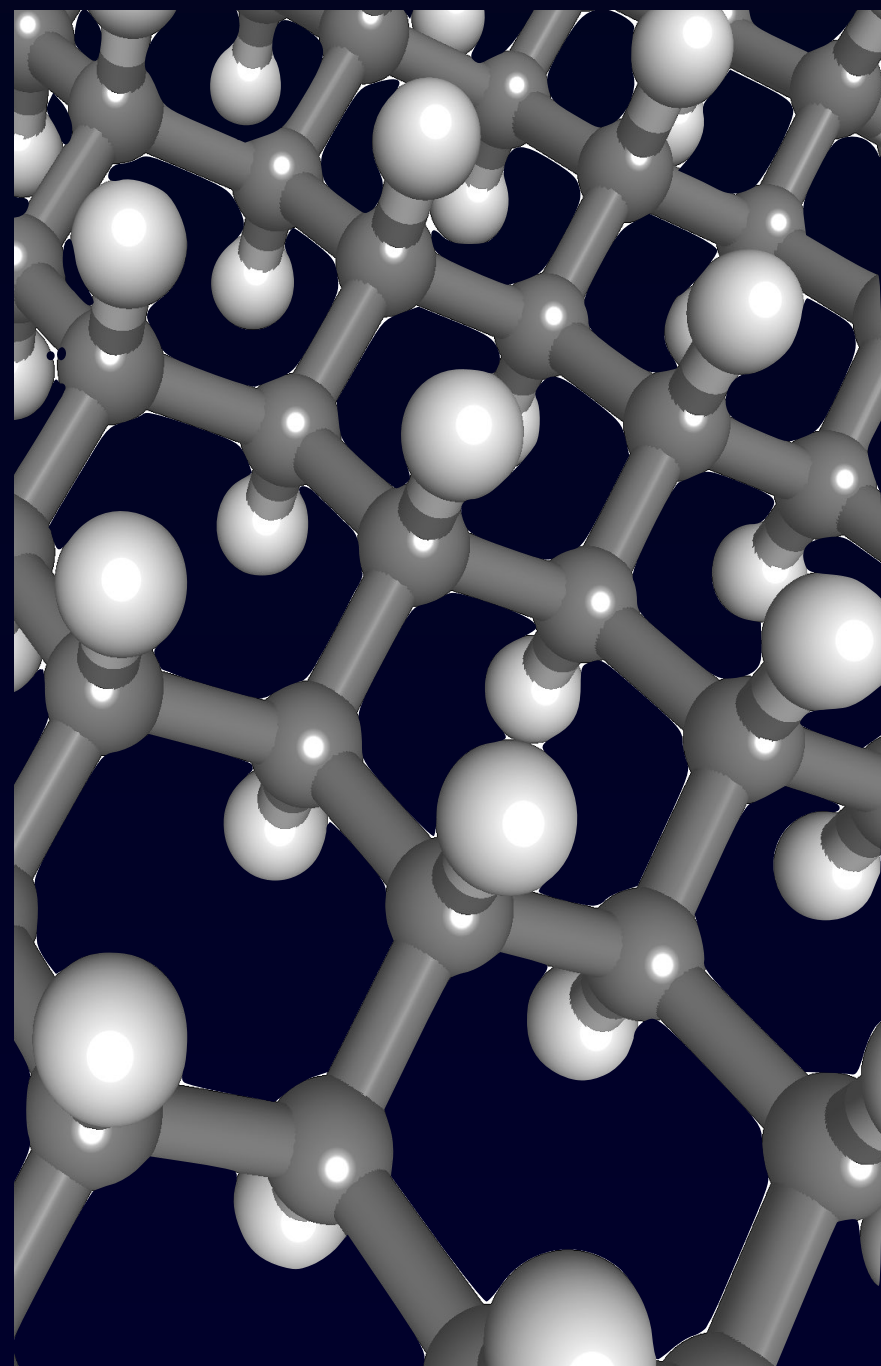
$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

Compact Atomic Tritium



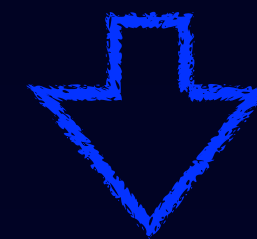
REQUIREMENTS:

- ✓ Minimize β electrons - target interactions \leftrightarrow electron energy conserved
- ✓ Atomic Tritium \leftrightarrow simpler spectrum, less energy uncertainty



Francesca M. Pofi

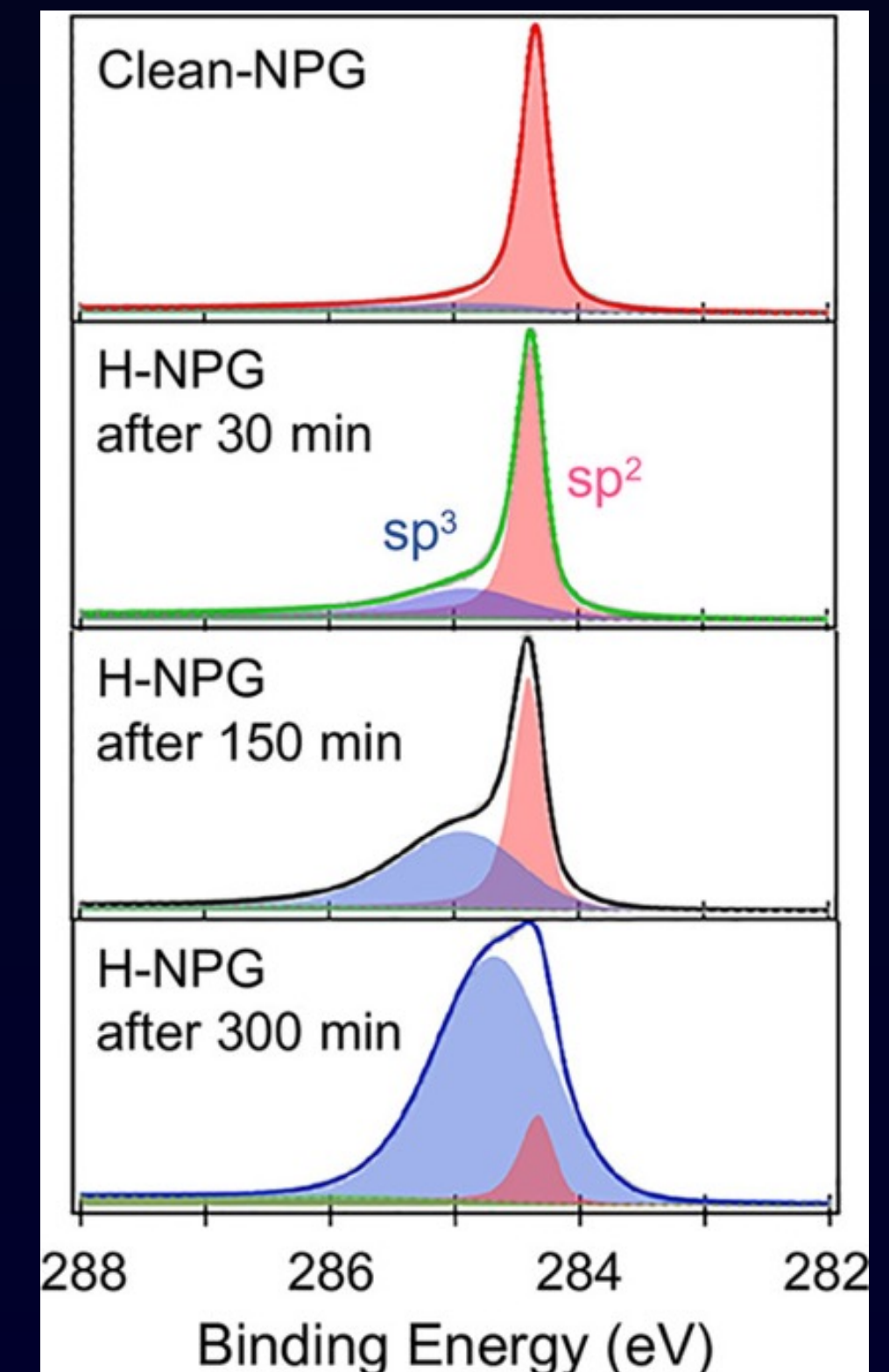
- ✓ Compact \leftrightarrow possibility to store huge quantities
- ✓ Stable \leftrightarrow no tritium released into environment



SOLUTION:

*Atomic tritium chemically bound
on graphene sheets*

~ 100% H loading reached
(1 H for each C)



Trigger with Non-Destructive Energy Measurement

Aim: filter trigger \leftrightarrow determine if β electron energy is near to ${}^3\text{H}$ decay endpoint

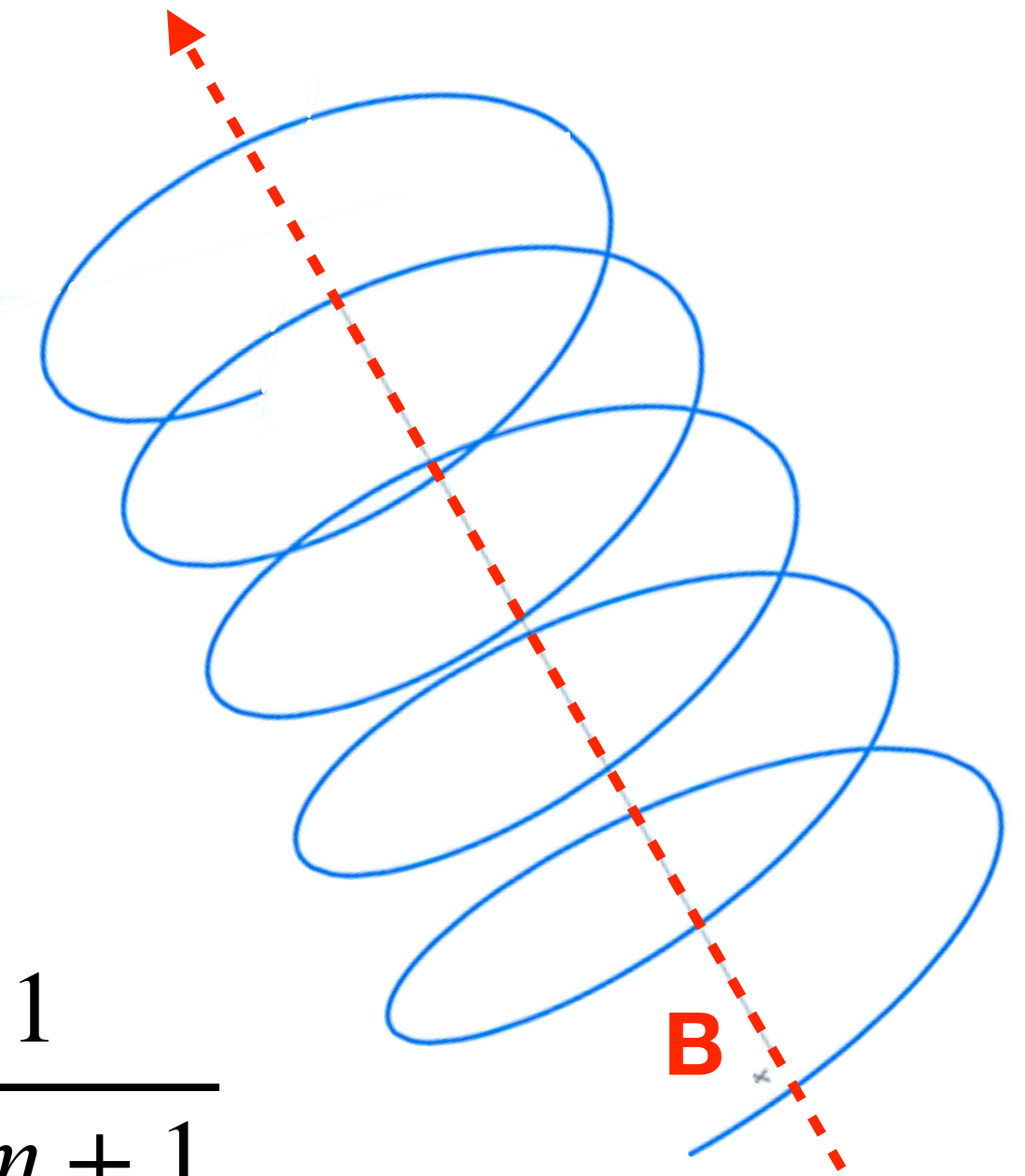
- Fast: $\mathcal{O}(100 \mu\text{s})$
- Raw measurement: $\mathcal{O}(10 \text{ eV})$ resolution
- **Non-destructive:** initial electron energy not modified

How? Cyclotron radiation spectroscopy

uniform B field \rightarrow cyclotron motion \rightarrow **RF radiation** emission

$$\text{power } P(\gamma, \theta) = \frac{1}{4\pi\epsilon_0} \frac{2}{3} \frac{|q|^4 B^2}{m^2 c^3} (\gamma^2 - 1) \sin^2 \theta \quad \text{frequency } f_c = \frac{1}{2\pi} \frac{|q| B}{m} \frac{1}{K/m + 1}$$

θ \downarrow Pitch angle
 K/m \downarrow Electron kinetic energy

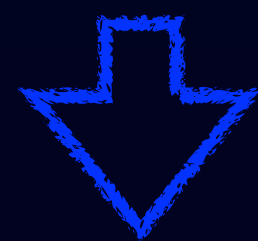
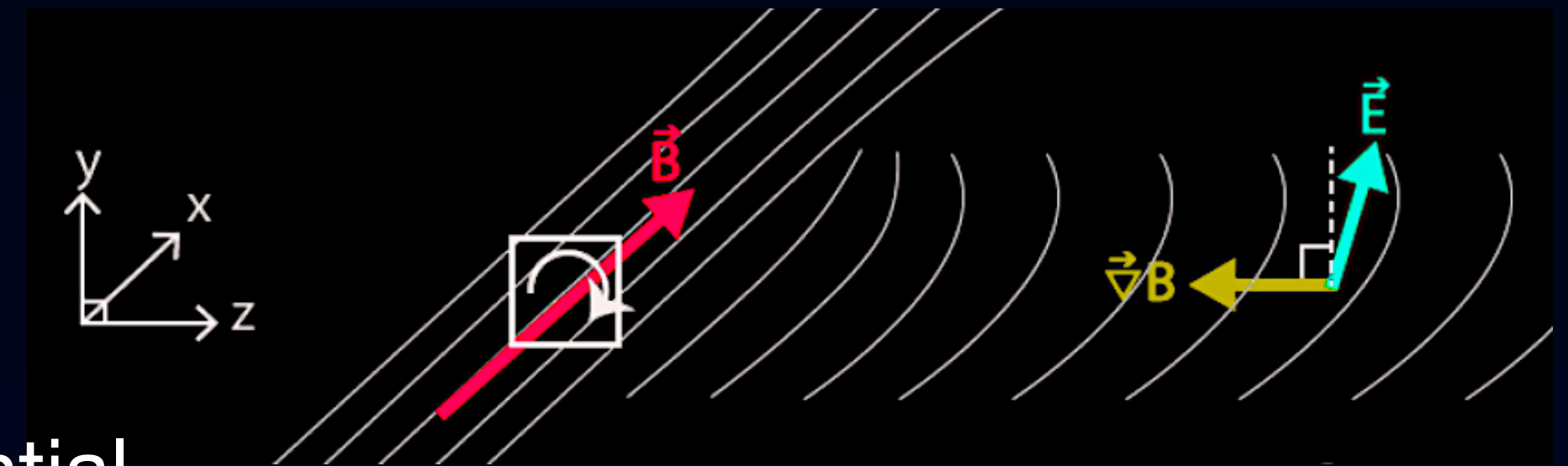


Filter within One Meter

E Field → $\underline{E \times B}$ drift → motion along filter
 → potential hill
 +

B Field → $\underline{\nabla B \times B}$ drift → motion against increasing potential

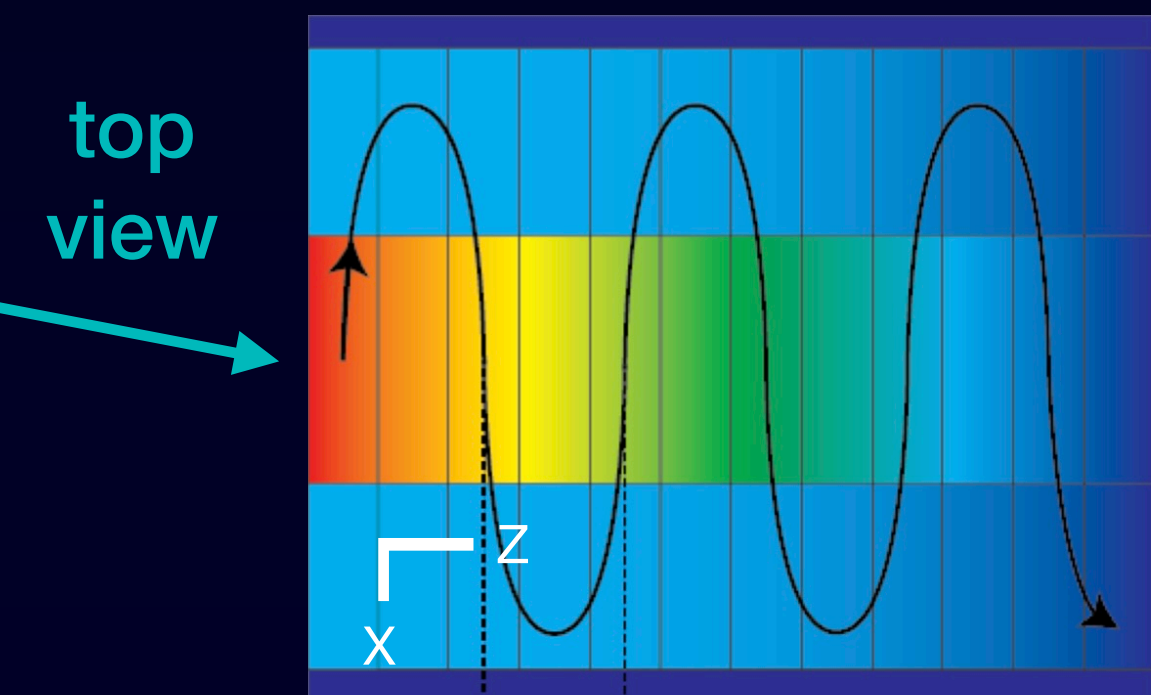
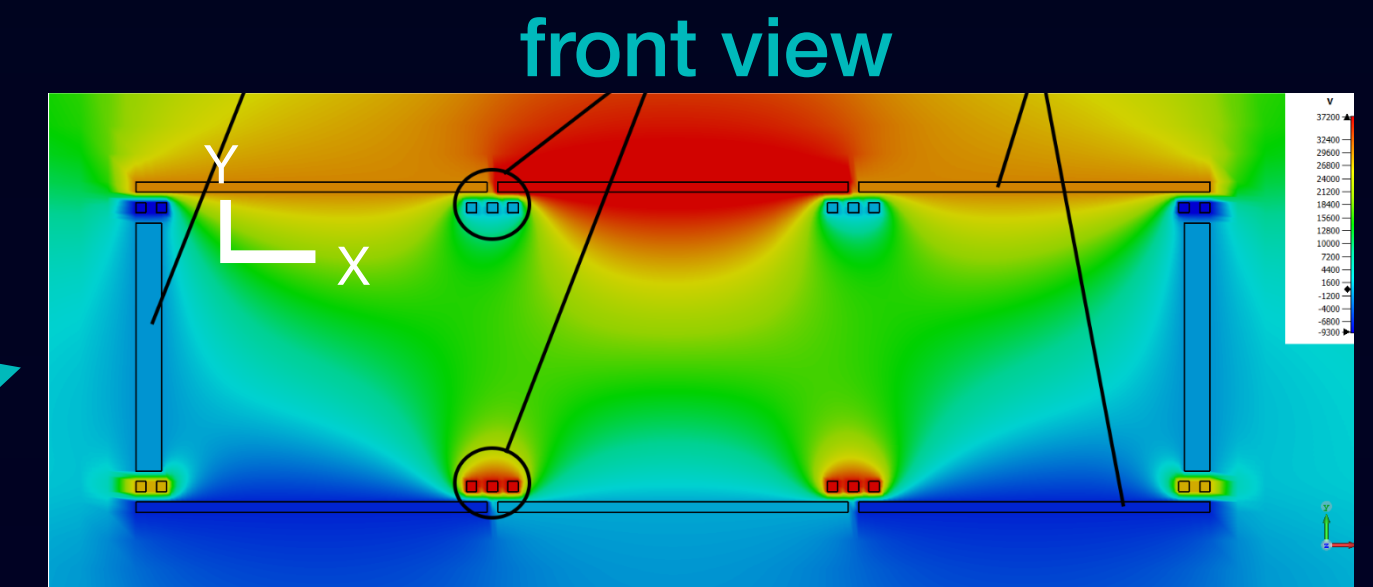
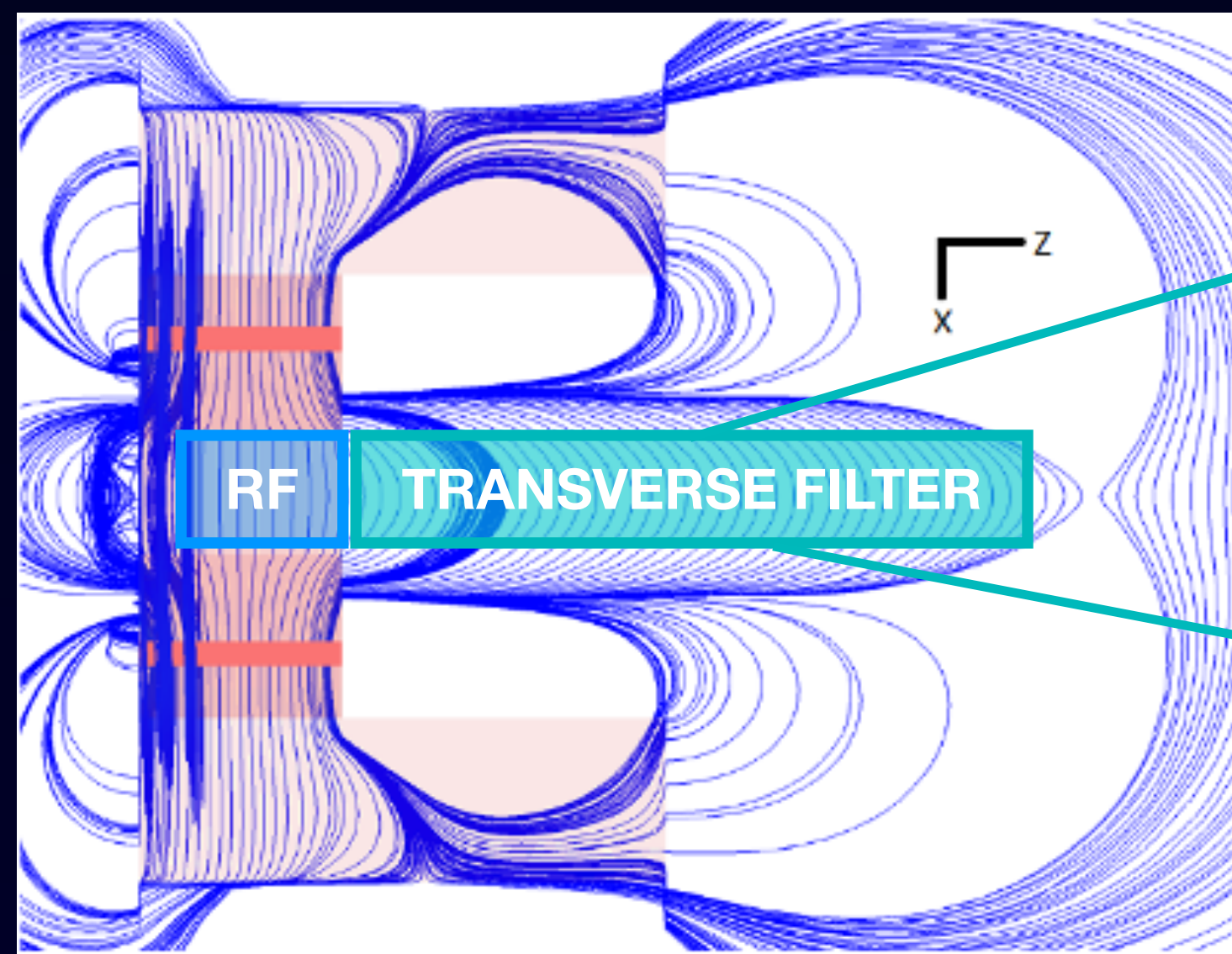
➤ exponential decay @ same rate → lateral drift balancing



FINAL RESULT:

Electrons' slowdown + filtering

- with controlled trajectory
- in short space (~1 m)



Promising Results with TES

R&D: TRANSITION EDGE SENSORS (TES)

- Operation: superconductive film @ critical temperature
 γ absorption \rightarrow small temperature increase \rightarrow huge change in resistance

- Usually employed in photon detection

\rightarrow **< 50 meV resolution on 0.8 eV γ s** (L. Lolli et al. Appl. Phys. Lett. 103 (2013) 041107)

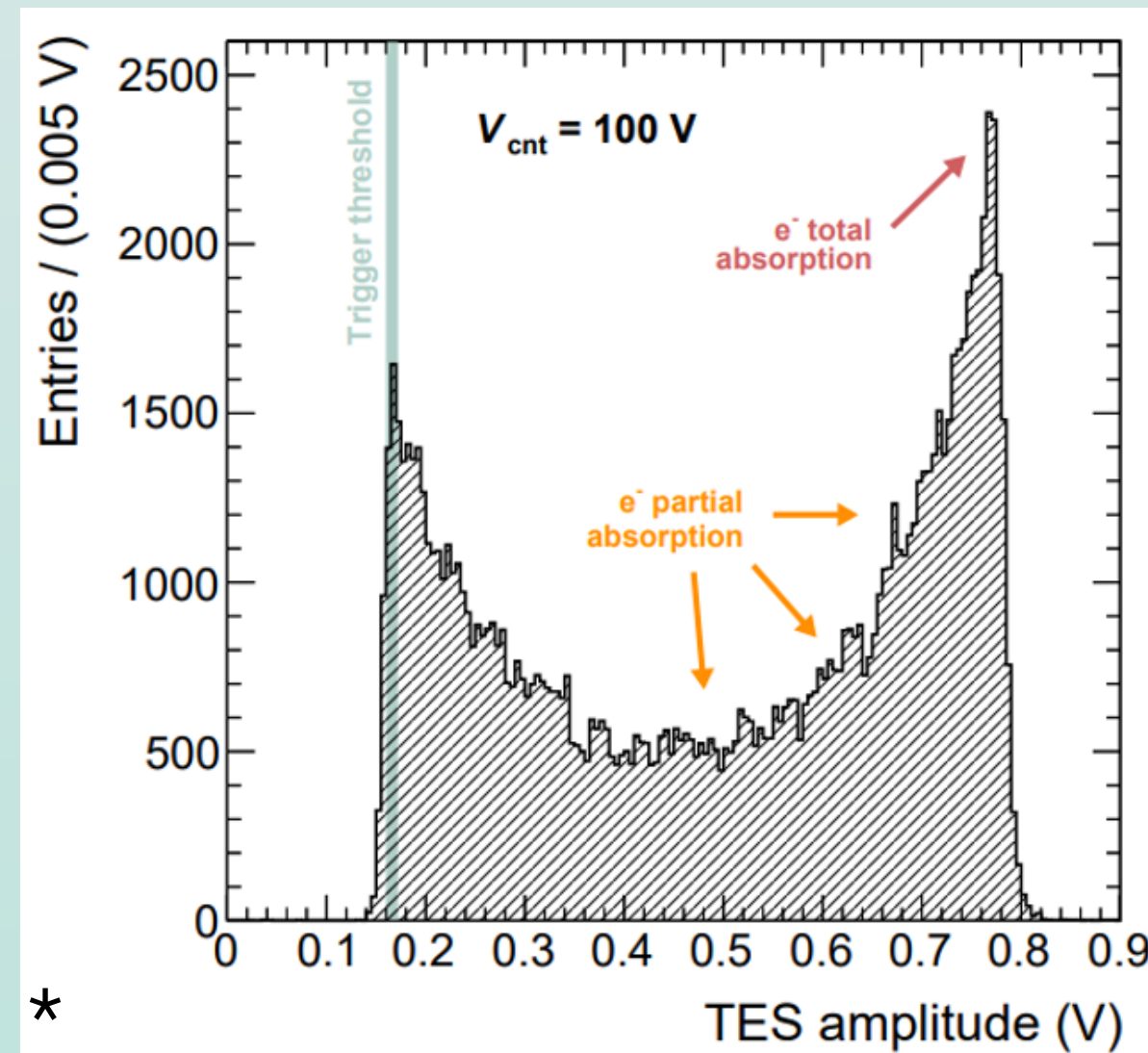
PTOLEMY GOAL!

- Concept also valid for electron detection!

- First results:

$\mathcal{O}(1 \text{ eV})$ resolution on $\sim 100 \text{ eV } e^-$

(*C. Pepe et al., Phys.Rev.Applied 22 (2024) 4)

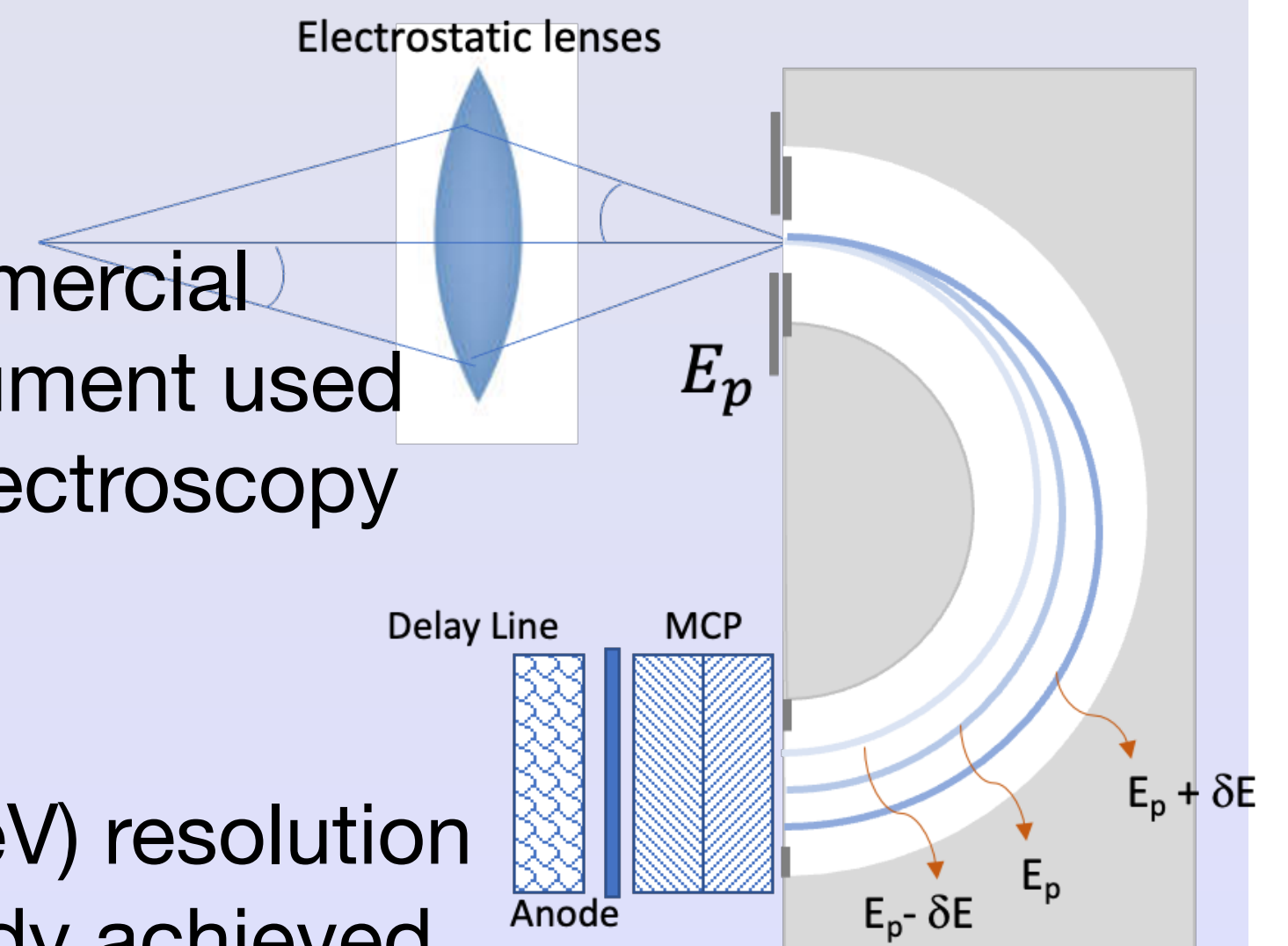


ALTERNATIVE: HEMISPHERICAL ELECTRON ANALYSER

- Operation: hemispherical condenser
 \rightarrow e-path optimized for energy E_p \rightarrow position detection at exit

- Commercial instrument used in spectroscopy

- $\mathcal{O}(\text{meV})$ resolution already achieved



Competitive Sensitivity with Just 1 μg Tritium

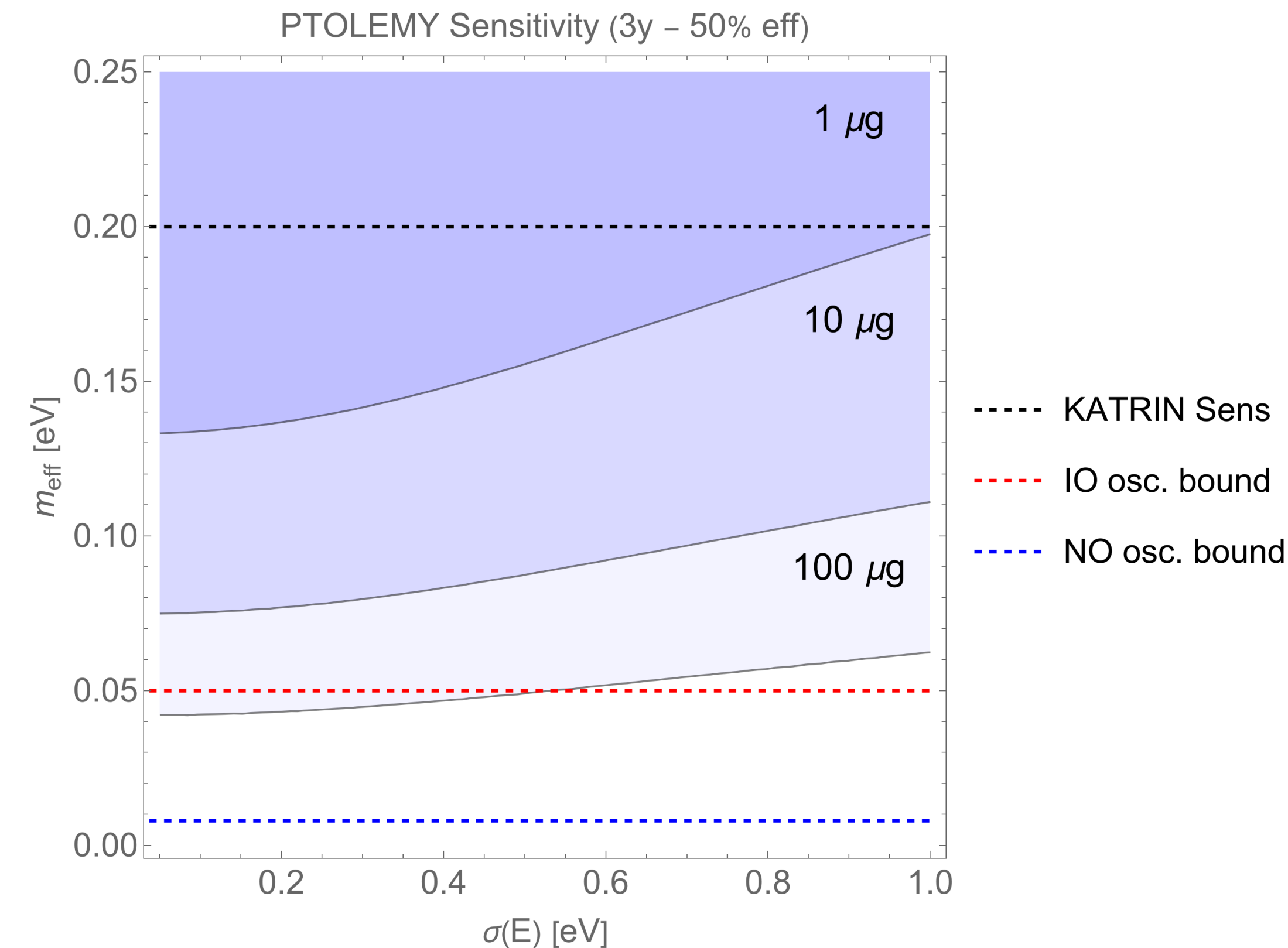
Aim: effective neutrino mass sensitivity study
by varying target mass

How? Toy Monte Carlo + Likelihood profile

➤ sensitivity = alternative hypothesis median exceeding 90% tail of null hypothesis

🌀 smallest target considered: 1 μg ^3H = 7×7 cm² tritiated graphene

→ $\sim 10^{16}$ events in 3 years with 50% efficiency



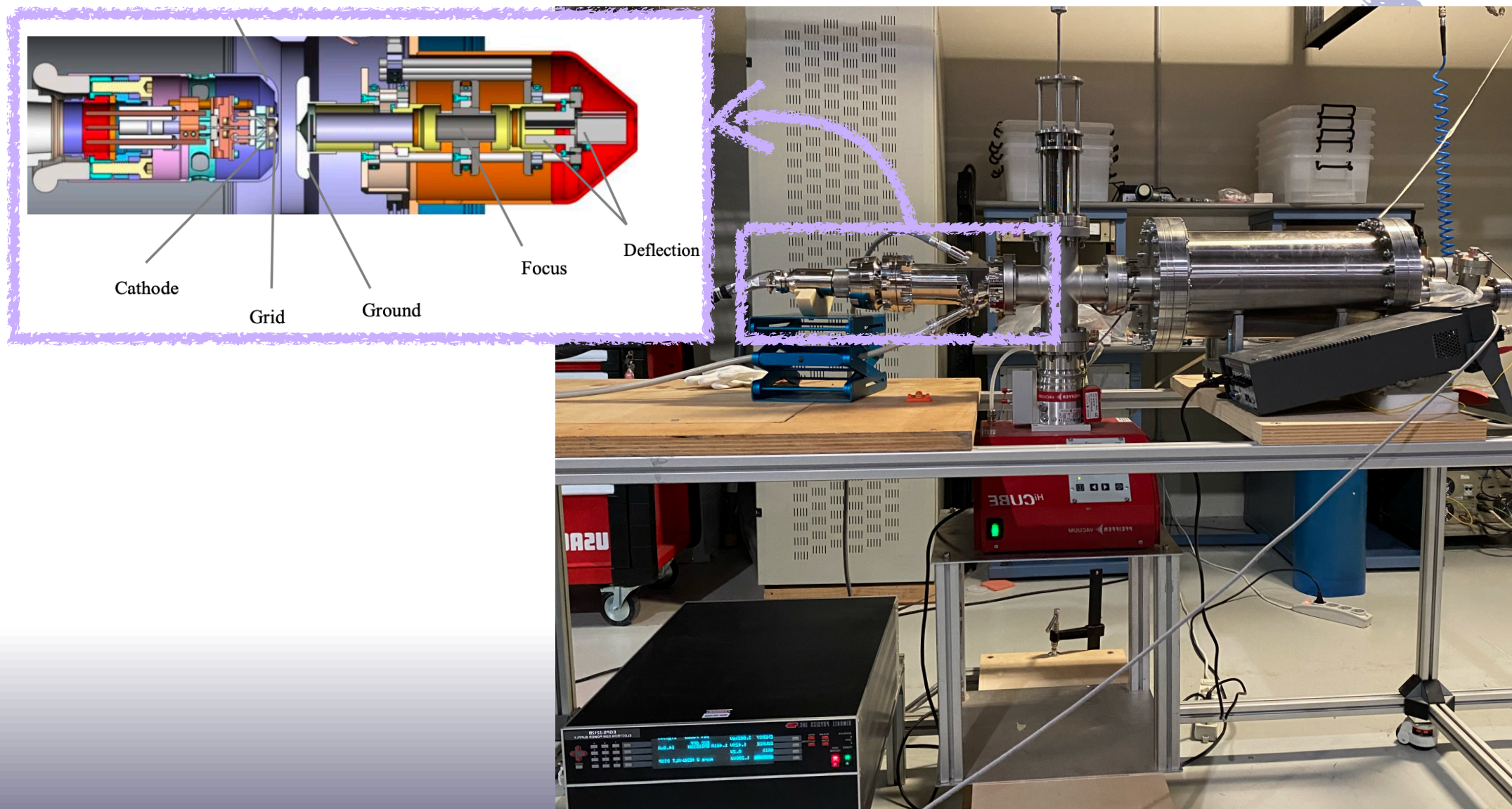
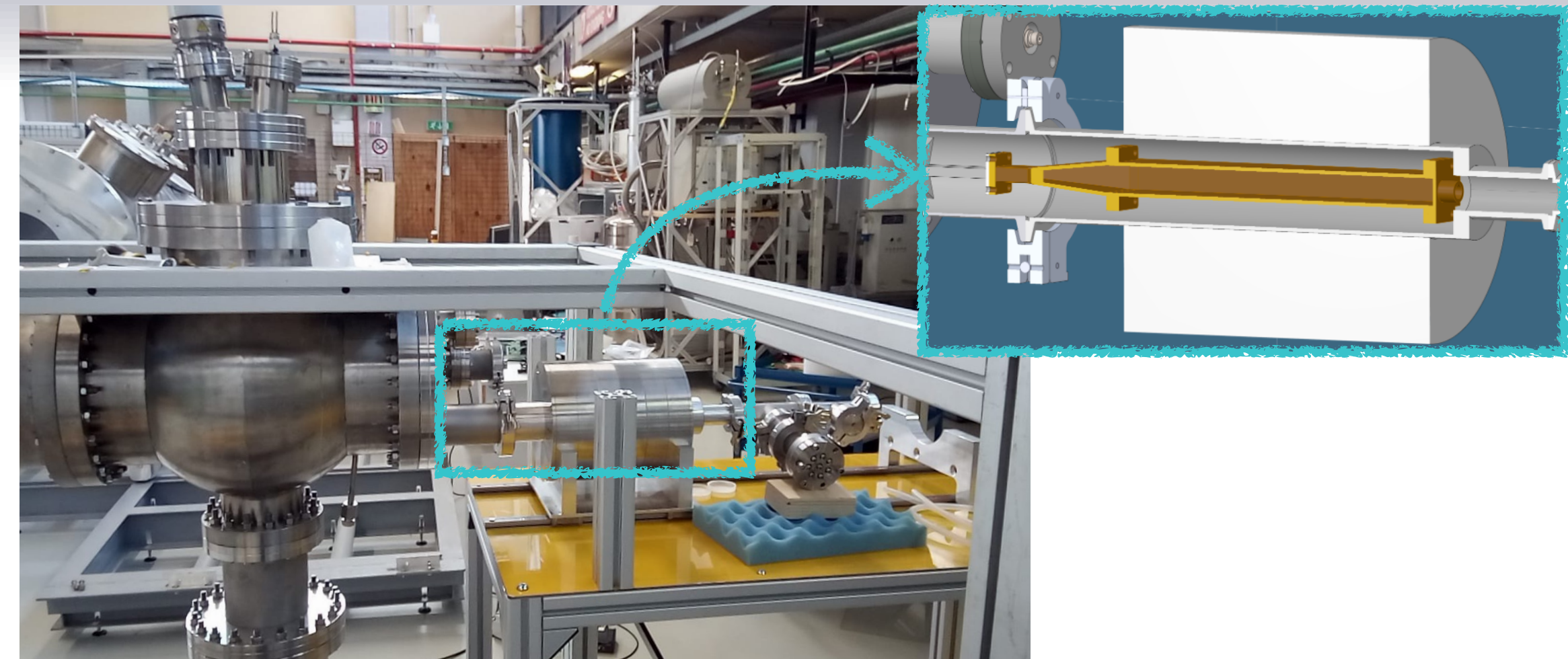
Result: 0.15 eV @ 90% CL sensitivity to neutrino mass with 1 μg Tritium!

➤ Competitive with best current upper limit = 0.45 eV from KATRIN (M. Aker et al., <https://arxiv.org/abs/2406.13516>)

Towards PTOLEMY Demonstrator @ LNGS

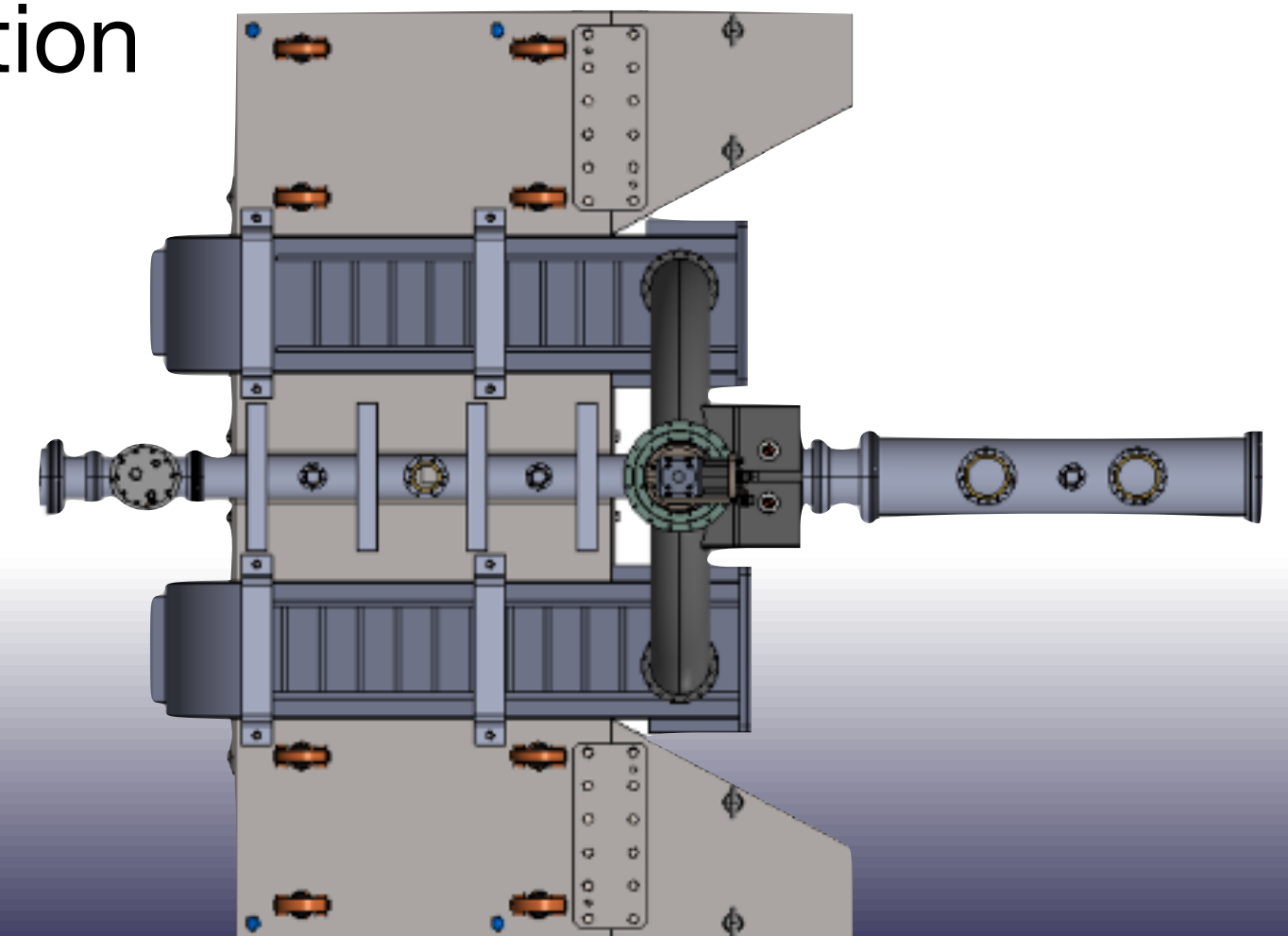
RF detection with ^{83m}Kr injection

High stability HV system



Electron beam for calibration

Magnet for transverse drift filter
in Nov 2025!



Recap & Outlook

- ▶ Challenging project: extremely precise energy measurement with high background
 - ▶ Innovative concept of electromagnetic compact filter
- ▶ Demonstrator under construction @ LNGS from November 2025
- ▶ Competitive on **neutrino mass measurement** with small target

▶ Outlook:

Phase 0: Demonstrator

Phase 1: m_ν Measurement

Phase 2: Upgrade to middle-scale

Phase 3: CNB Detection

