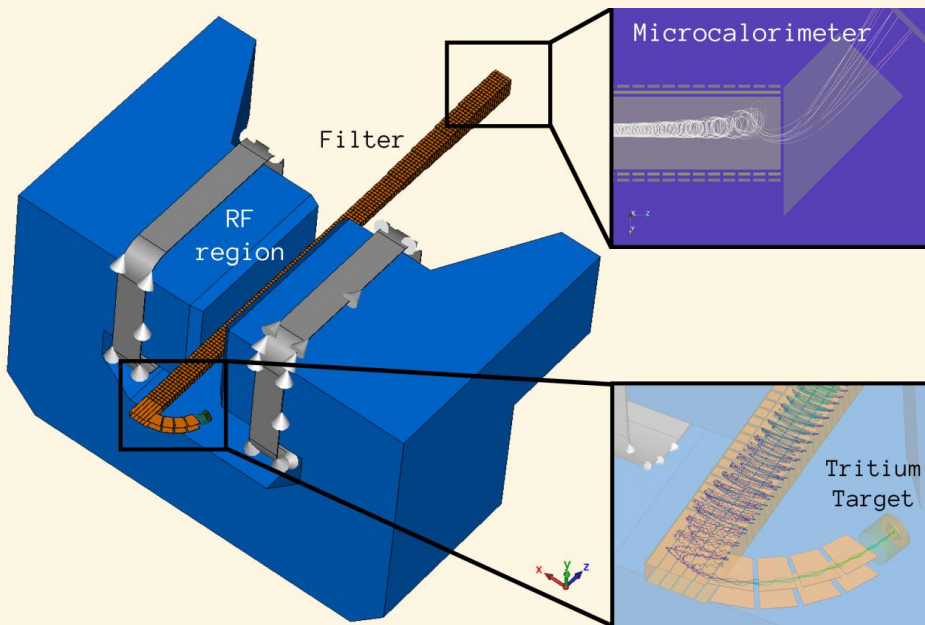


The PTOLEMY Experiment

Quantum-Engineering Material Gaps for the Neutrino Mass Measurement



Wonyong Chung
Princeton University



March 2026
Lake Louise Winter Institute

The Neutrino Mass Hierarchy and the quasi-degenerate mass regime

- The effective electron neutrino mass observable:

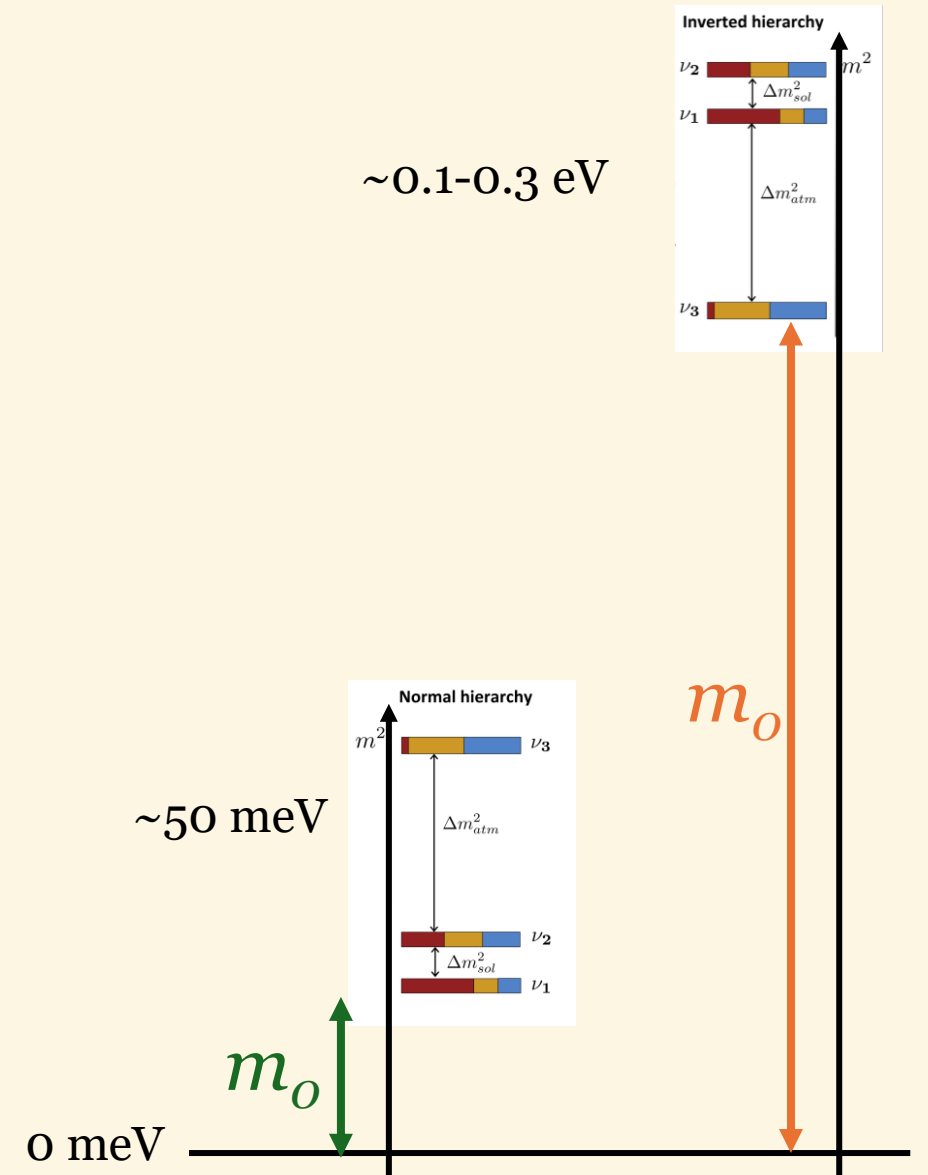
$$m_{\beta}^2 = \sum_i |U_{ei}|^2 m_i^2$$

- Mass-squared differences from oscillation experiments:

$$\sqrt{\Delta m_{21}^2} \approx 8.7 \text{ meV} \quad \sqrt{|\Delta m_{31}^2|} \approx 50 \text{ meV}$$

- KATRIN (2025) 450 meV (90% C.L.) upper limit
 - Now in regime where m_{β} becomes sensitive to ordering

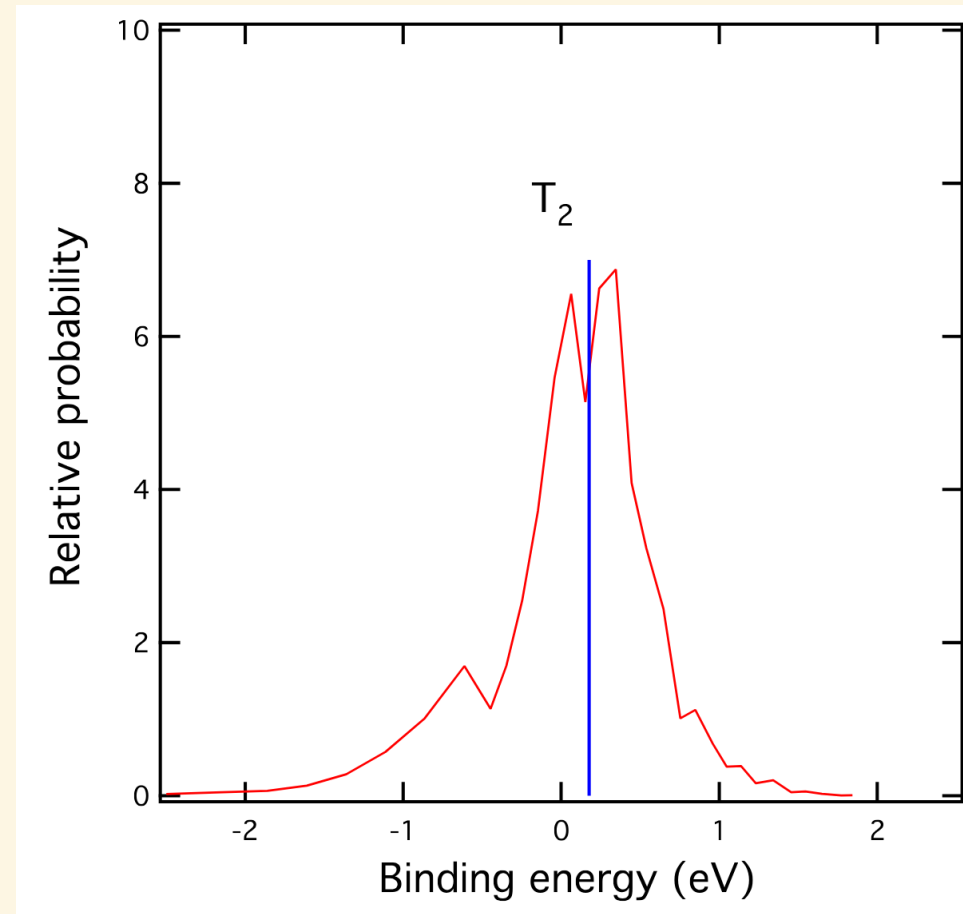
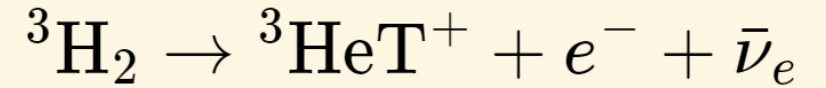
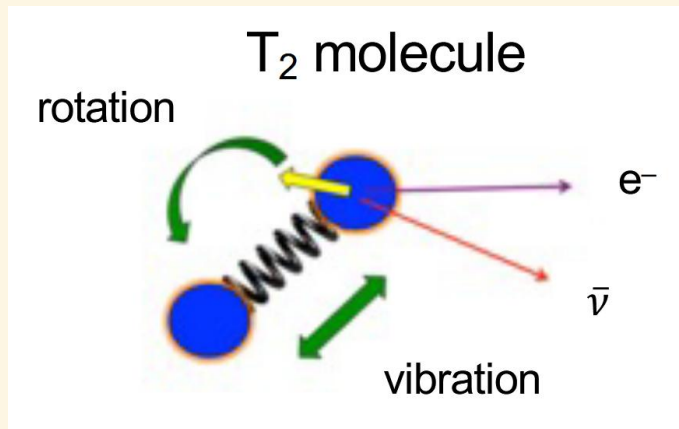
$$m_1 \approx m_2 \approx m_3 \gg \sqrt{|\Delta m_{31}^2|}$$



Molecular Smearing in Diatomic Tritium

[Bodine, Parno, Robertson; [Phys.Rev.C 91 \(2015\), 035505](#)]

- Ground-state electronic manifold spans $\sim 0-4$ eV in rovib. excitations
 - $\sim 57\%$ of decays remain in electronic ground state
 - $O(\text{meV})$ rotational; $O(0.3-0.5 \text{ eV})$ vibrational
 - “Fundamental limit”
- In quasi-degen regime, convolve broadening of final-state distribution (FSD) with ideal spectrum and fit – absorb into systematic budget

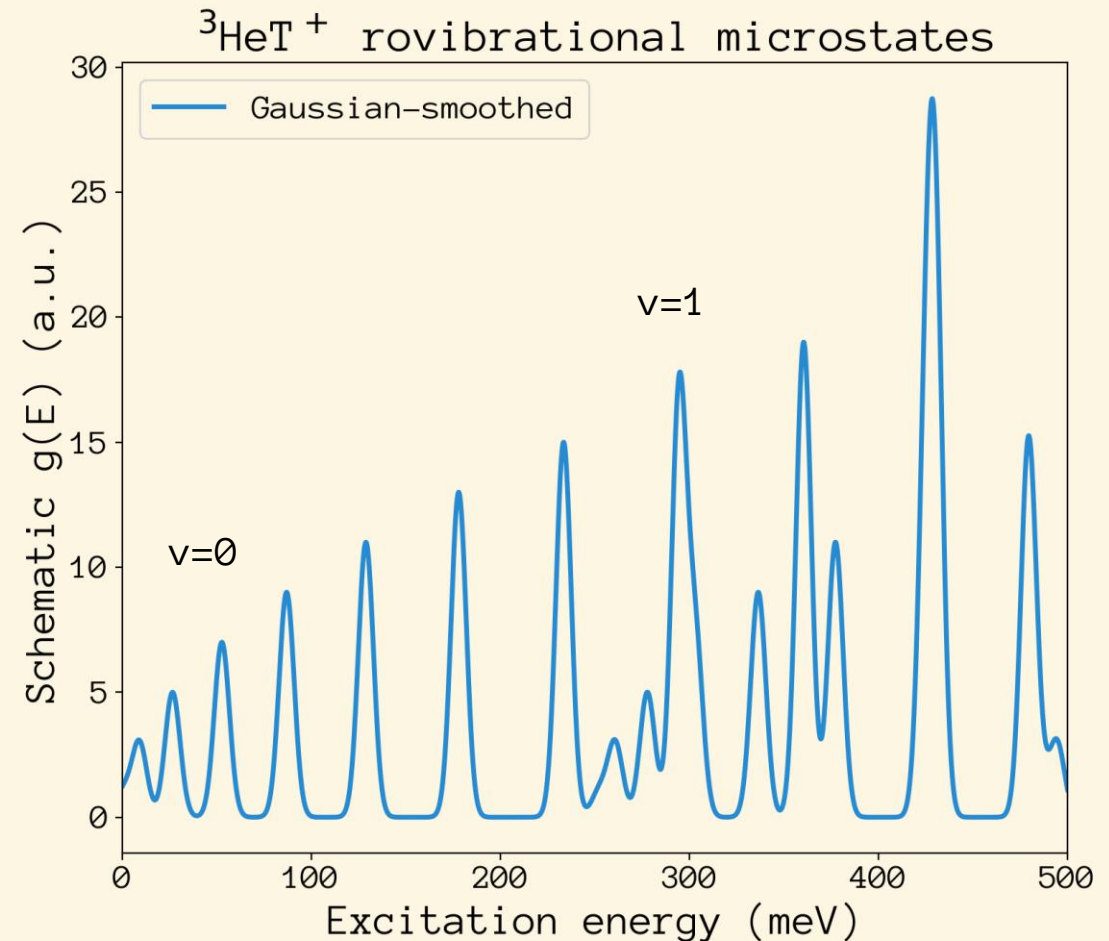
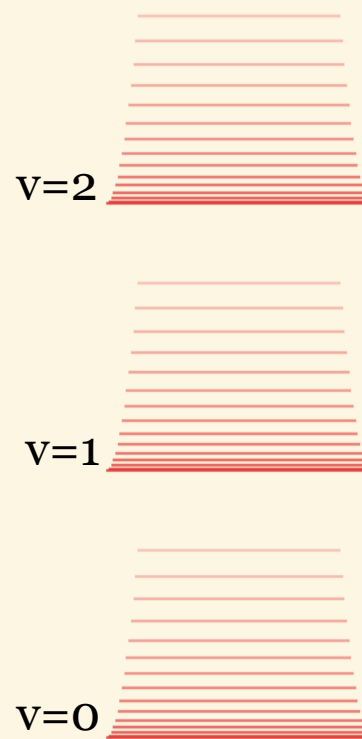


The Rovibrational Forest

- In the regime where ordering matters
- Rotational excitations – dense ladder of thresholds at O(meV)

$$E_J = B_v \cdot J(J + 1)$$

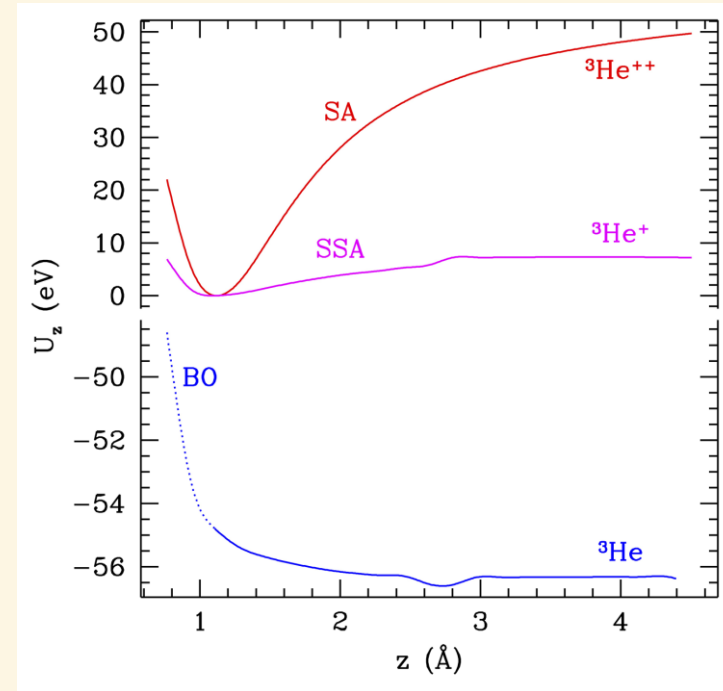
- Degeneracy grows as $(2J+1)$
- Vibrational spacing $\sim 0.2-0.3$ eV
- Parameter-degeneracy between:
 - Endpoint phase-space suppression
 - Low-energy support of FSD
- Each final state has its own endpoint



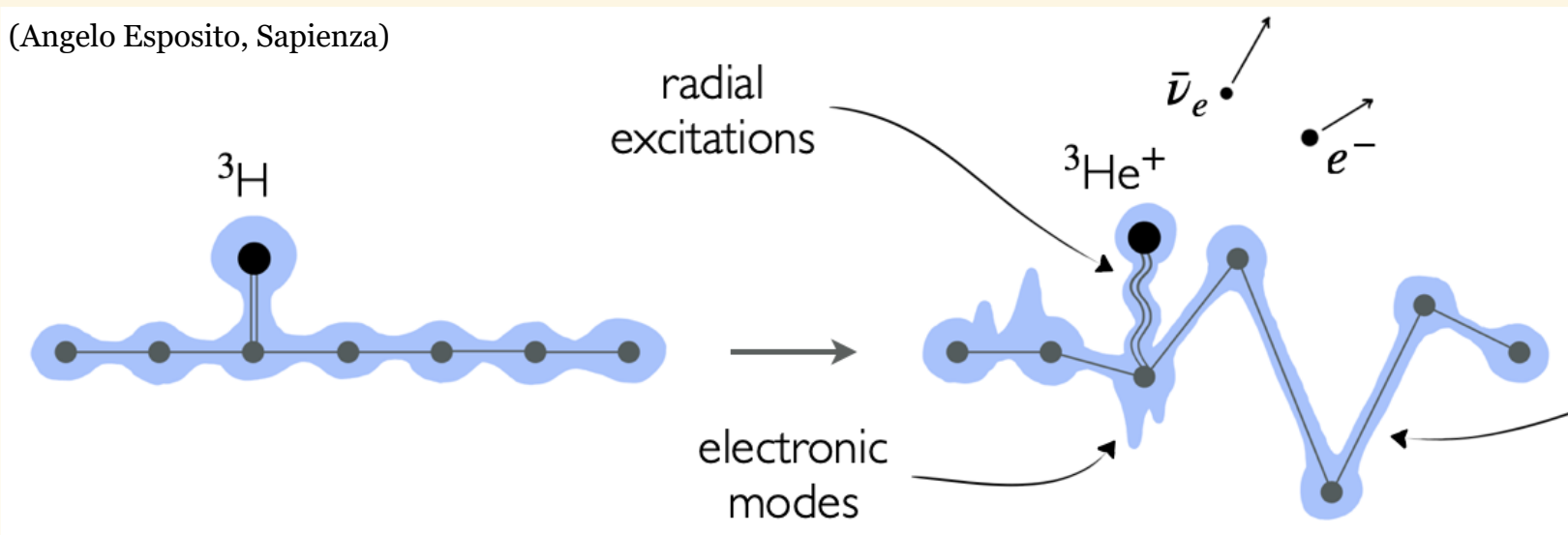
Theory Frontier: Tritiated Graphene

- Atomic tritium on graphene: localized by lattice
- After beta-decay, ${}^3\text{He}^+$ is bound/unbound in local potential well
 - Models: sudden, semi-sudden, adiabatic (Born-Oppenheimer)
- 1st excited bound state of ${}^3\text{He}^+$ at ~ 0.2 eV
- “3D harmonic oscillator” – nominal shifts of ${}^3\text{He}^+$ position
 - Confined by lattice, no rotational ladder of states

[Phys.Rev.D 106 (2022), 053002]



(Angelo Esposito, Sapienza)



The lattice: soft acoustic phonons

Max $O(70$ meV), but strongly suppressed to below 15 meV (small recoil, weak coupling)

The Graphene Excitation Gap

- 3 spectral regimes near endpoint:

- **0 to ~15 meV: acoustic phonon excitations**

Mild broadening, suppressed due to beta-decay timescale vs. phonon response

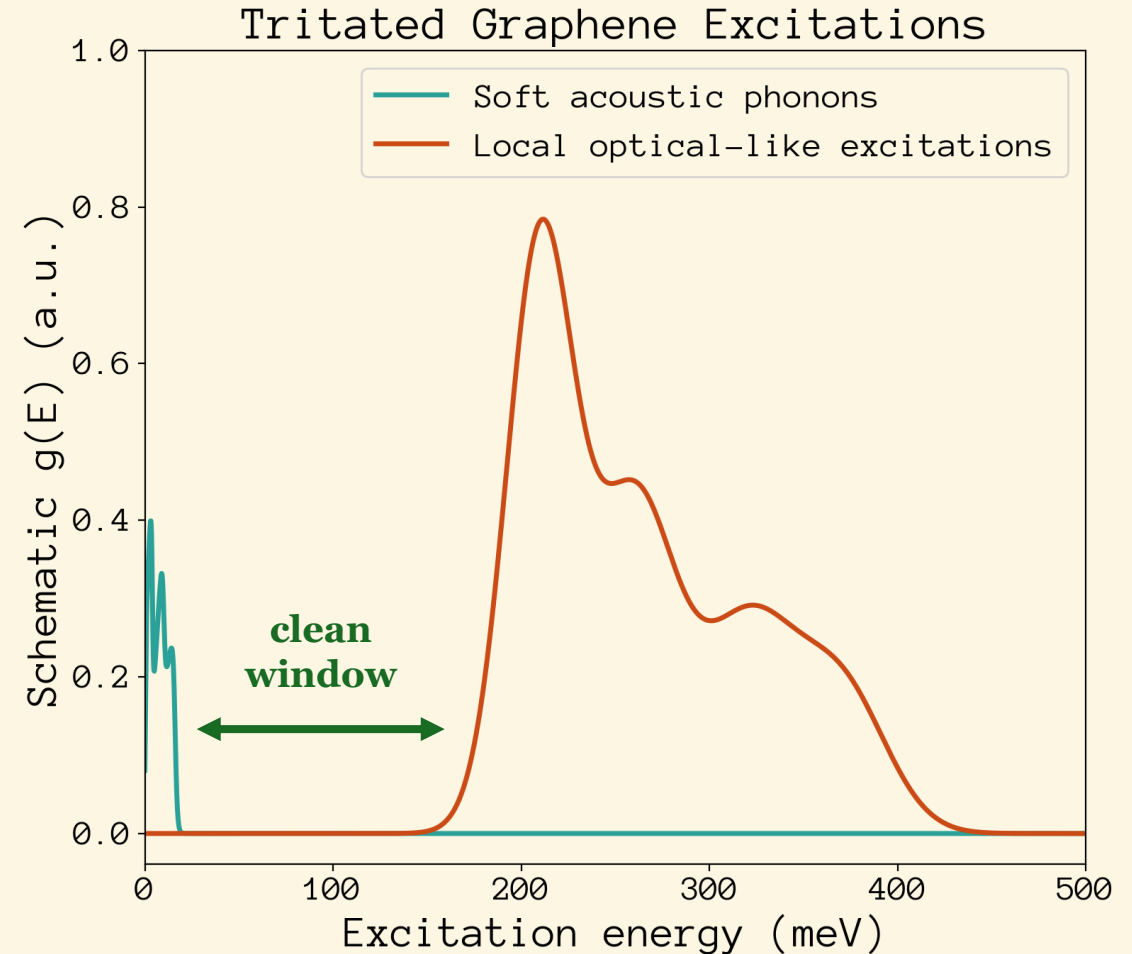
- **~15 meV to ~200 meV: the clean window**

No expected excitations, no rotational ladders, below first bound state of ${}^3\text{He}^+$

- **~200 meV+: mixed excitations**

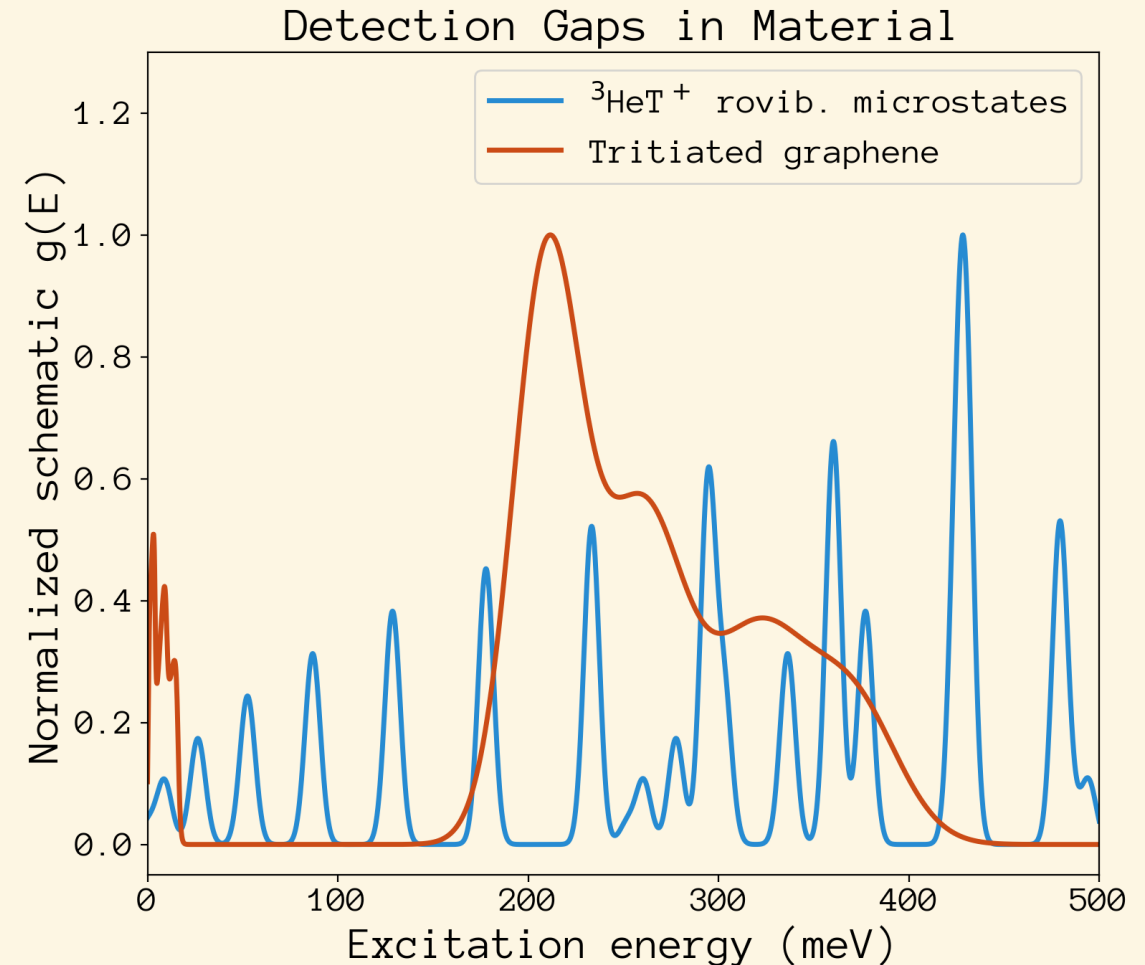
Localized “optical-like” excitations of ${}^3\text{He}^+$ bound states + lattice phonons

- m_β creates universal, delayed threshold on every excitation
- Non-degenerate with excitation spectrum parameters



The Neutrino Mass Signature

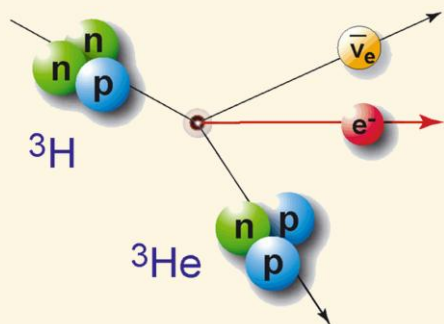
- Substrate effects: from nuisance to feature
 - “Source as detector”
- Instead of minimizing FSD effects, design the material FSD to have a gap in m_β range
- Not searching for a shift buried under background
- Searching for mismatch between predictive spectral model and measured endpoint behavior
- Natural interpretation of any discrepancy in the clean window is the neutrino mass



Joining the likes of scintillators (Stokes shift), silicon detectors (band gap), ionization detectors, bolometers, etc...

The Path to Relic Neutrinos

Neutrino mass is needed first to assess experimental requirements

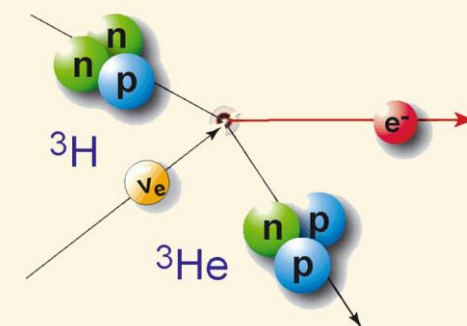
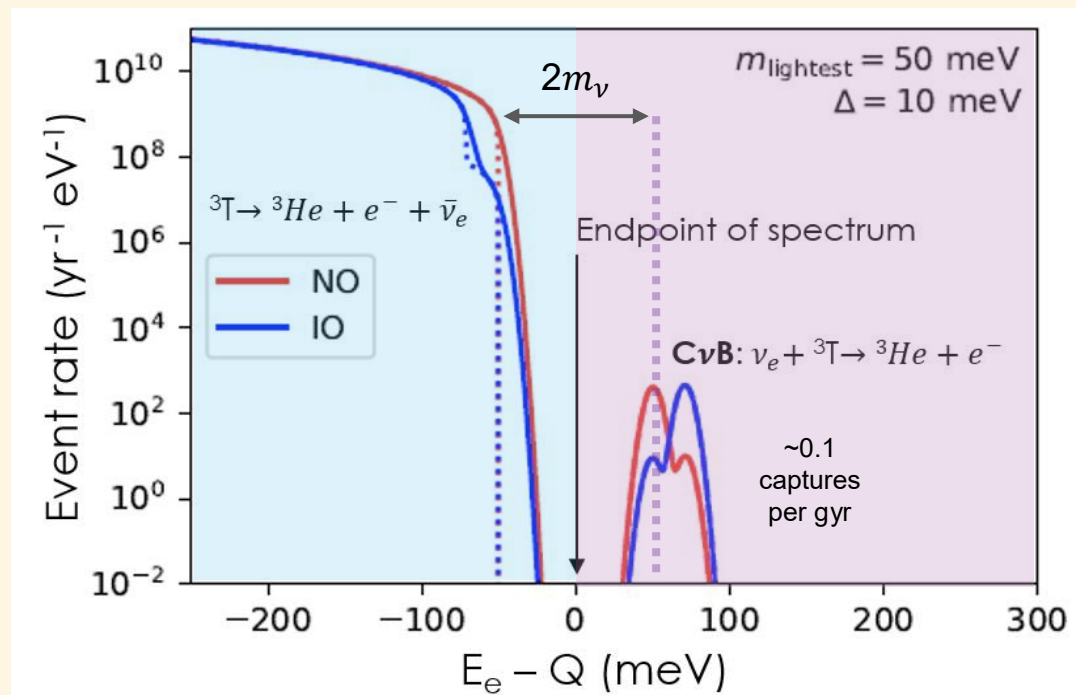


Neutrino mass

$m_\nu < 0.45 \text{ eV}$ [KATRIN 2025]

$\sum m < 0.12 \text{ eV}$ [Planck 2018]

$m_\alpha \geq 0.05 \text{ eV}$ [oscillations]



Relic neutrinos

Neutrino momentum $\sim 0.17 \text{ meV}$

KE ($m_\nu = 50 \text{ meV}$) = 0.3 meV

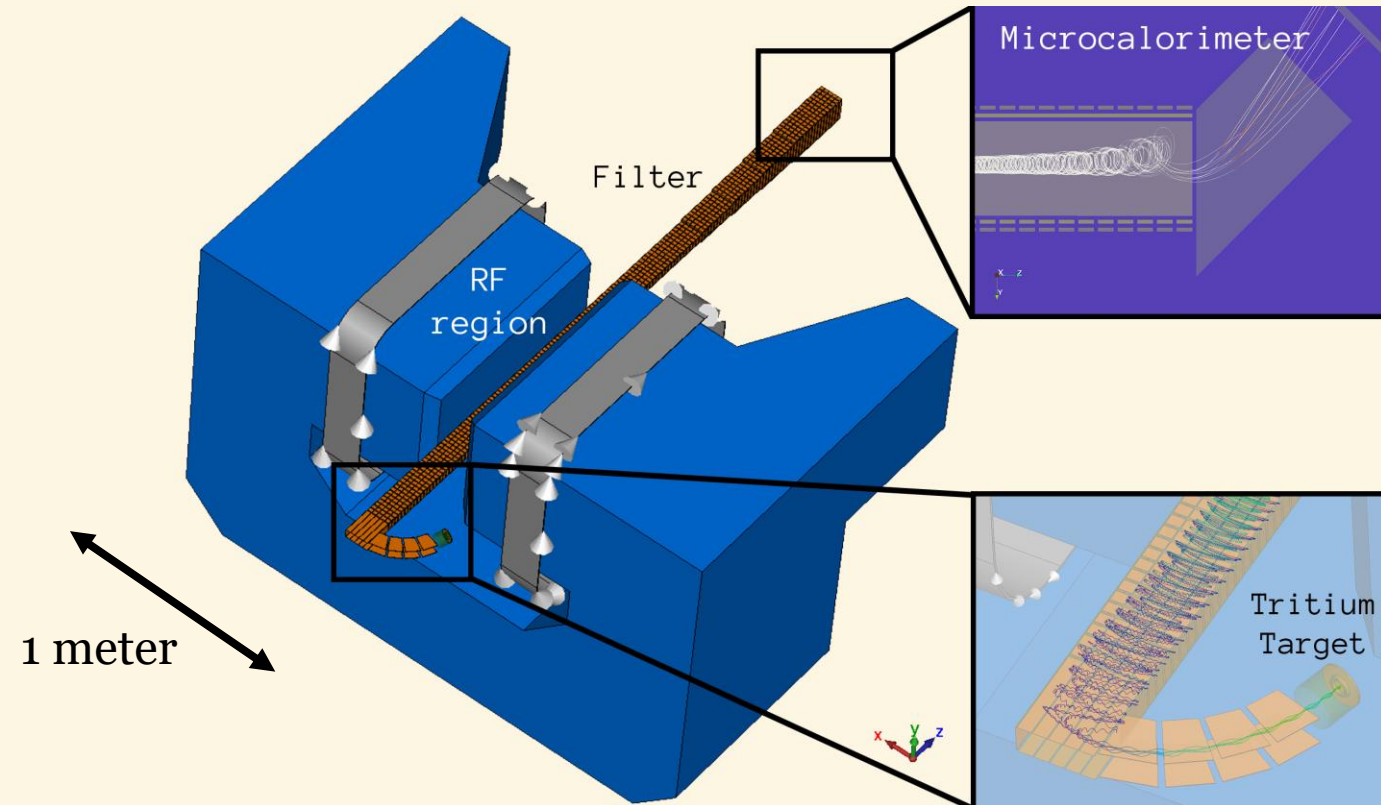
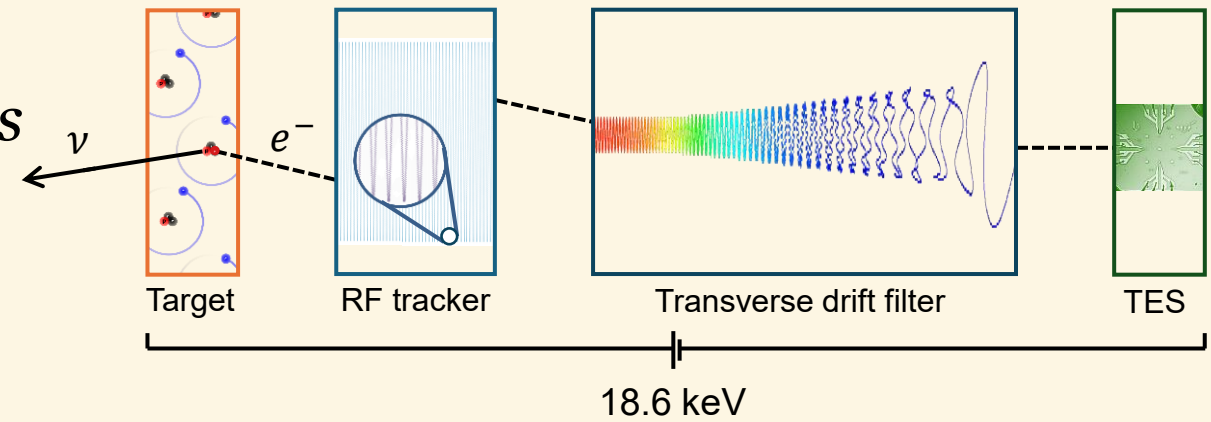
- Zero-point motion in graphene smears the relic capture peak [[Phys.Rev.D 104 \(2021\), 116004](#)]
- Far future: spin-polarized atomic tritium in superfluid 4He films
- Knowing mass first sets resolution, statistics, background requirements

The PTOLEMY Innovation

Phase space expansion via magnetic optics

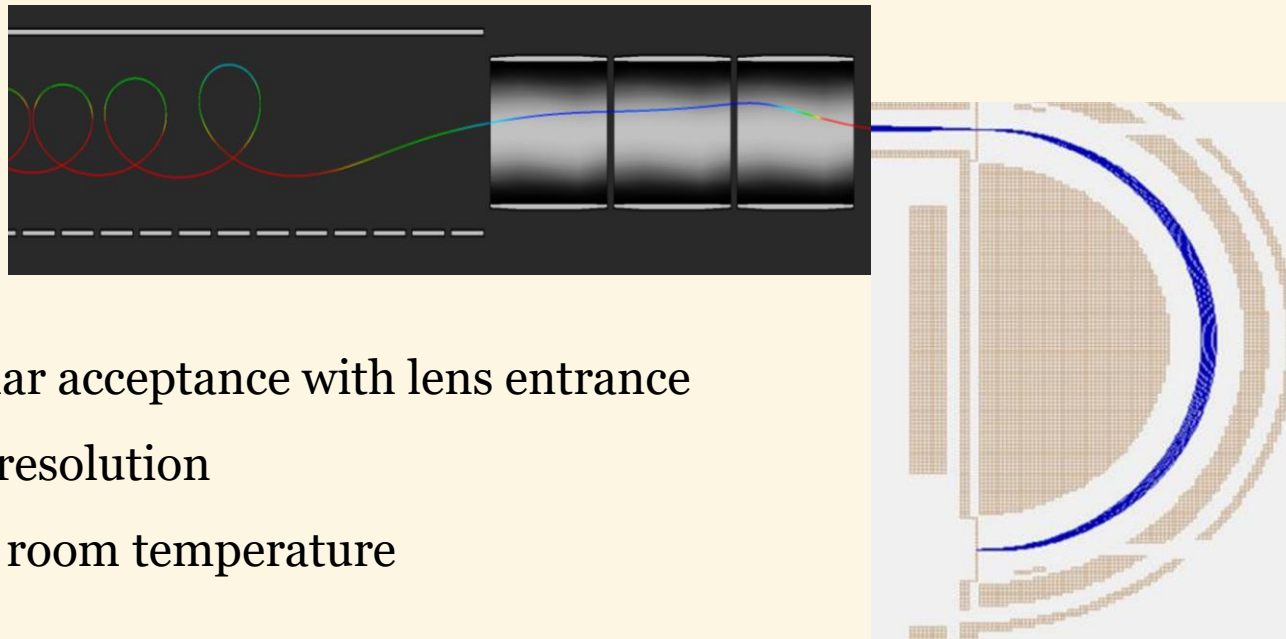
- Decouples large-area source geometries from compact, high-resolution detector
- The systems innovation: new type of EM spectrometer selects slice of phase space instead of transporting full phase space adiabatically
- Arbitrarily large target areas can be expanded into collimating low field then accelerated in transverse momentum into detector, also providing large RF signature
- Efficient MgB₂ conduction-cooled superconducting coils at 20K

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

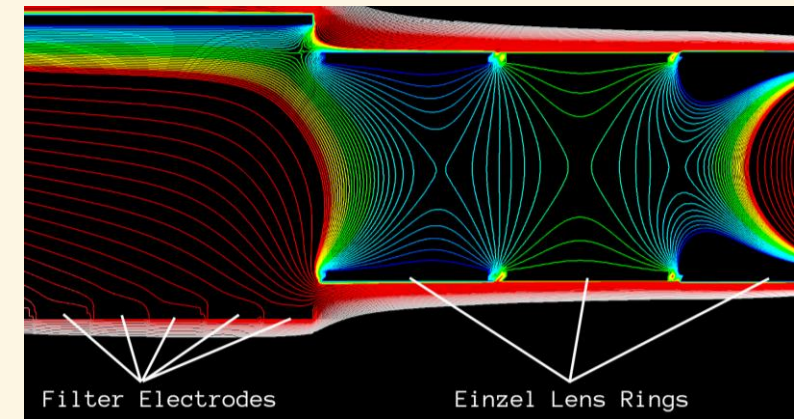
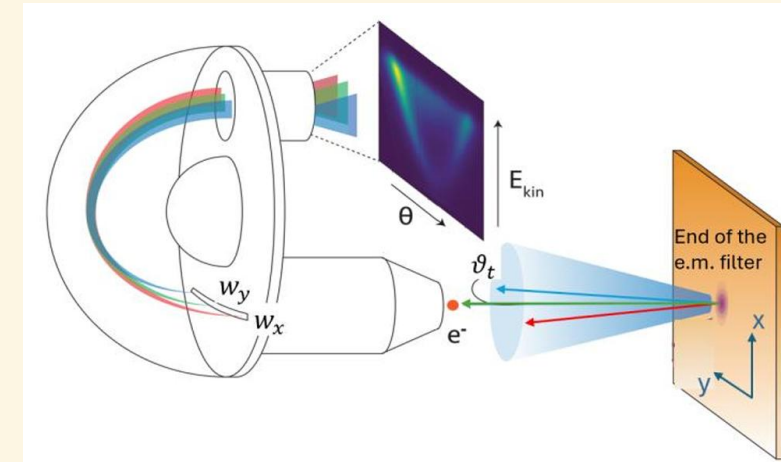


Zero-Field Precision Measurement

- PTOLEMY magnet design produces zero-field saddle region at end of filter
- Hemispherical electrostatic analyzer (HSA): commercial instrument widely used in ARPES, XPS, EELS
- Mature, commercially available, decades of experience in condensed matter

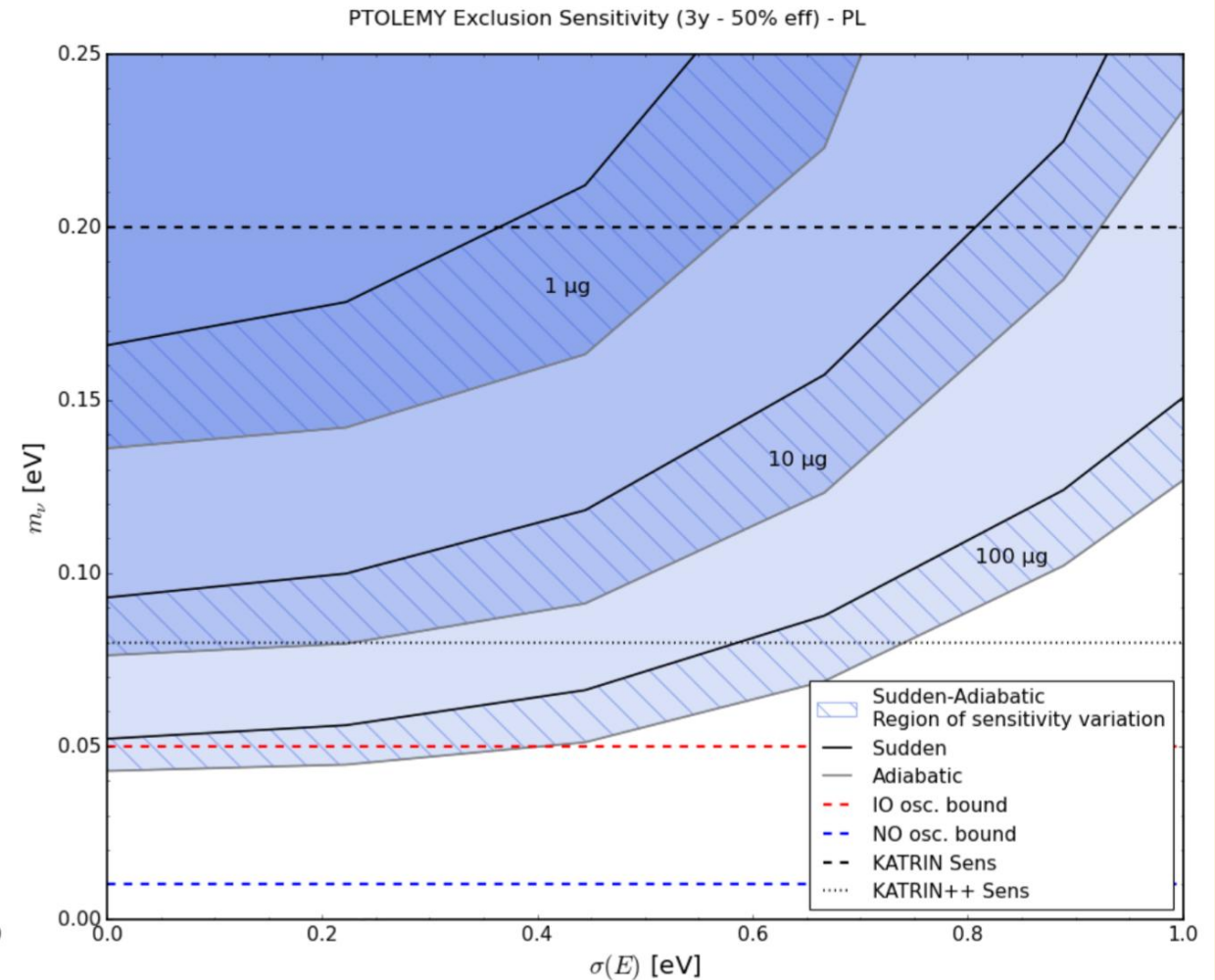
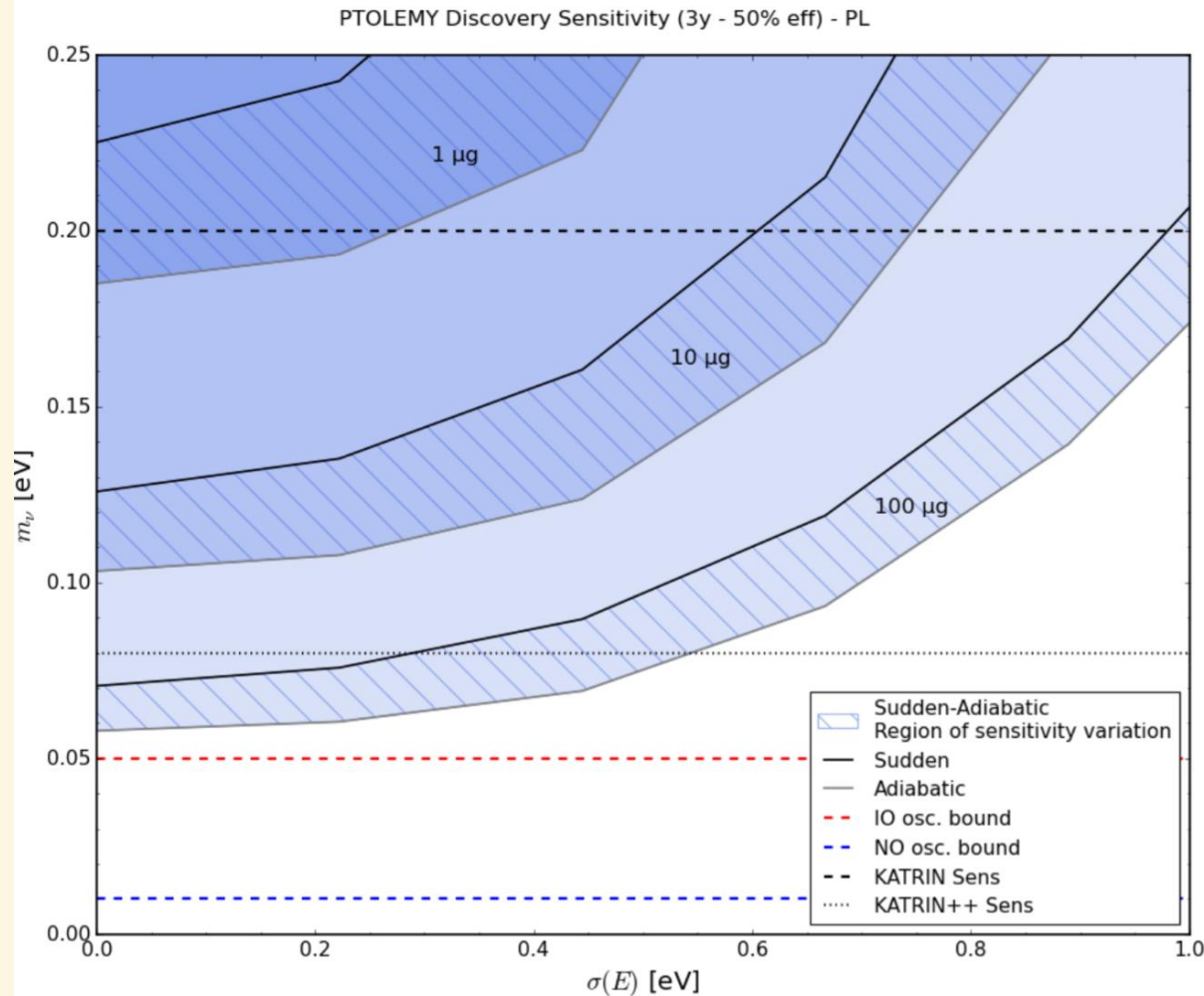


- Large angular acceptance with lens entrance
- 10-50 meV resolution
- Operates at room temperature



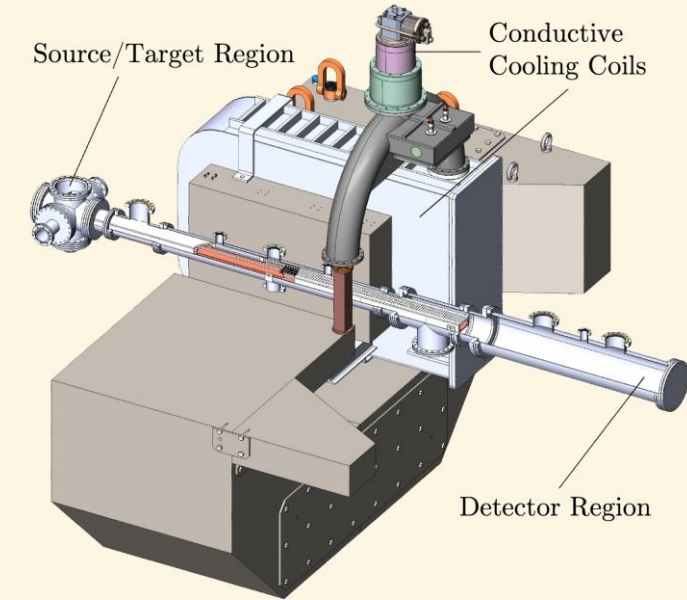
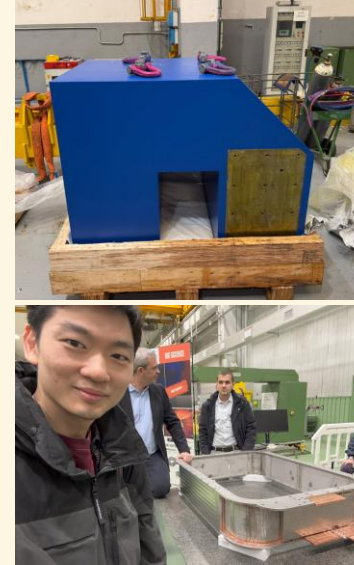
Sensitivity to the Neutrino Mass

- 3-yr run with 1 μg : ~ 150 meV exclusion @ 90% CL, 50 meV resolution
- No systematics included – likely 2x optimistic
- Sensitivity band reflects theory model variation



LNGS Demonstrator

- **Phase-0 (now-2027): Technology validation**
 - LNGS demonstrator (now under construction)
 - Magnet en route to CERN for field mapping, at LNGS later this year
 - Conceptual Design Report



- **Phase-1 (2027-): Neutrino mass measurement proposal**

- 3-yr physics run, 1-10 ug tritium
- 10-50 meV resolution
- 150 meV sensitivity

