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Overview on direct neutrino mass measurements

NNN2025, Sudbury, Canada

Outline

- Theoretical considerations
- Fist indirect evidences of neutrino mass
- Direct neutrino mass search
- Current project on direct neutrino mass search
- Prospects

how to measure neutrino mass

- ⭐ **kinematics** (Pauli 1930) neutrino versus photon race / *time of flight* measurement
- ⭐ **spectral distortions** (Fermi 1933) *end-point* of electron spectrum in the β decay
- ⭐ **neutrinoless $\beta\beta$ decay** (Furry; Grueling Whitten 1939-60) *Majorana neutrino* & $\mathbf{\Delta L = 2}$
- ⭐ **neutrino transmutation** (Pontecorvo; Sakata et al 1957-1967) "*oscillations*"
- ⭐ **observational cosmology** (Gershtein Zeldovich 1966) *distortions* of the cosmic distributions
- ⭐ **neutrino capture** (Cocco, Mangano, Messina 2007) direct observation of *big-bang neutrinos*

the 4th method has provided results, proving that the SM is incomplete

F. Vissani Hands On School at GS

Understanding neutrino mass

It is a natural way to open a Window on a model beyond Standard Model of particle physics

In the SM, the masses of the fermions are generated by means of a Yukawa coupling of the scalar Higgs doublet ϕ with a fermion right-handed and left-handed component. The former is an SU(2)L singlet, the latter is part of a doublet. For leptons, we can build such a term coupling the left-handed lepton doublets L_L with the right-handed charged lepton fields E_R

$$-L_{Yukawa,lep} = Y^l_{ij}\bar{L}_L \Phi E_{Rj} + h.c.$$

After spontaneous symmetry breaking this term give the mass term $m^l_{ij} = Y^l_{ij}\frac{v}{\sqrt{2}}$ where v is the v.e.v. of Higgs field. Since in the SM there

Since in the SM There right-handed neutrino is missing we can’t build Yukawa interaction for neutrinos and consequently they are massless. With the particle content of the SM the only possible neutrino mass term that could be constructed is the bilinear operator $\bar{L}_L L^c_L$, but this term is forbidden in the SM because it violates the accidental symmetry and so conservation law of total lepton number, furthermore violates the actual SM symmetry that brings to the B-L conservation.

To extend the Standard Model to introduce neutrino mass

See-Saw mechanism

$$-L_{M_\nu} = M_{D_{ij}} \bar{\nu}_{si} \nu_{Lj} + \frac{1}{2} M_{N_{ij}} \bar{\nu}_{si} \nu^c_{sj} + h.c.$$

$$-L_{M_\nu} = \frac{1}{2} \begin{pmatrix} \overline{\vec{\nu}^c_L}, & \overline{\vec{\nu}_s} \end{pmatrix} \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix} \begin{pmatrix} \overline{\vec{\nu}^c_L} \\ \overline{\vec{\nu}_s} \end{pmatrix} + h.c.$$

$$-L_{M_\nu} = \frac{1}{2} \bar{\nu}_l M^l \nu_l + \frac{1}{2} \bar{N} M^h N$$

$$M^l \simeq -V_l^T M_D^T M_D^{-1} M_D V_l \qquad M^h \simeq V_h^T M_N V_h$$

$$V^\nu = \begin{bmatrix} (1 - \frac{1}{2} M_D^\dagger M_N^{*-1} M_N^{-1} M_D) V_l & M_D^\dagger M_N^{*-1} V_h \\ -M_N^{-1} M_D V_l & (1 - \frac{1}{2} M_N^{-1} M_D M_D^\dagger M_N^{*-1}) V_h \end{bmatrix}$$

Neutrino oscillations I

First indirect evidence of neutrino mass.

For the case of 3+m neutrinos the Lagrangian of the leptonic CC interaction in the mass basis takes the form:

$$-L_{CC} = \frac{g}{\sqrt{2}} \left(\bar{e}_L, \quad \bar{\mu}_L \quad \bar{\tau}_L \right) \gamma^\mu U \begin{pmatrix} \nu^1 \\ \nu^2 \\ \nu^3 \\ \vdots \\ \nu_n \end{pmatrix}$$

Where the Pontecorvo-Maki-Nagakawa-Sakata matrix describe the linear combination between flavour and mass eigenstates of the three SM neutrinos.

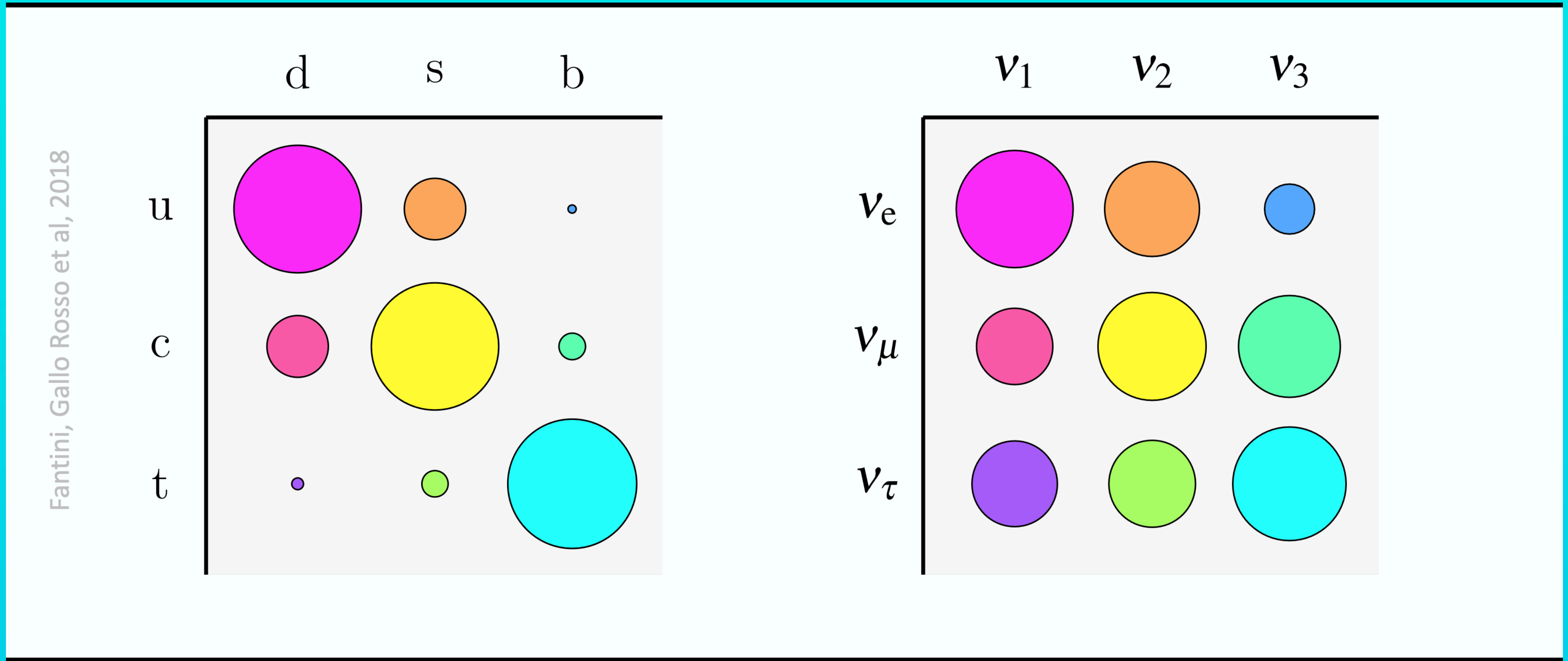
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino oscillations II

First indirect evidence of neutrino mass.

For sake of simplicity we report only the two neutrino oscillation phases formula

$$P_{ij} = \sin^2 2\theta_{ij} \sin\left(1.27 \cdot \frac{m_i^2 - m_j^2}{eV^2} \frac{L}{E} \frac{GeV}{Km}\right)$$



areas of the circles $\propto |V_{qq'}|$ **&** $|U_{\ell i}|$

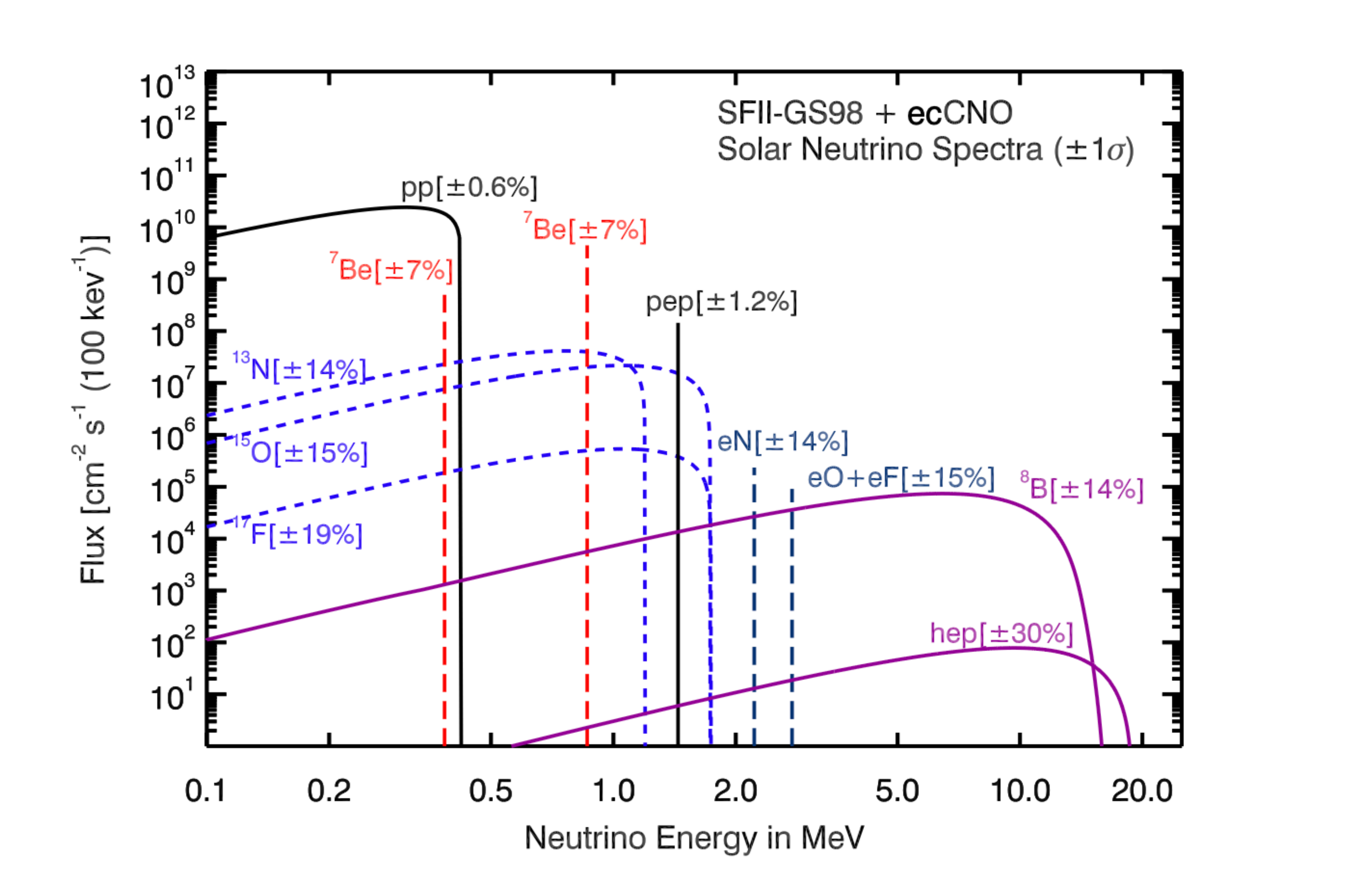
Neutrino oscillations III

First indirect evidence of neutrino mass.

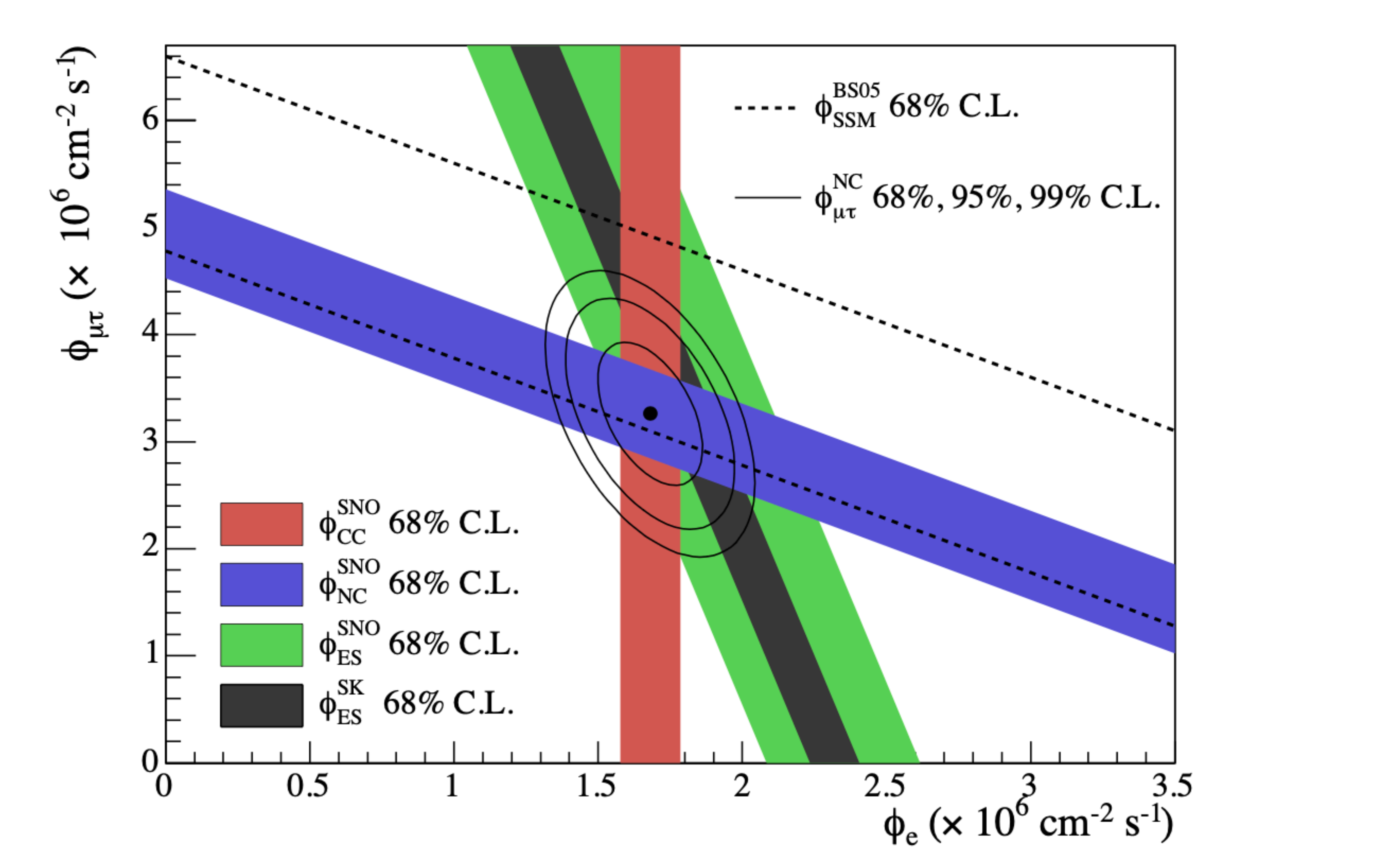
This phenomenon has been tested with different neutrino sources.

Experiment		L (m)	E (MeV)	$\|\Delta m^2\|$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	VSBL–SBL–MBL	$10 - 10^3$	1	$1 - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

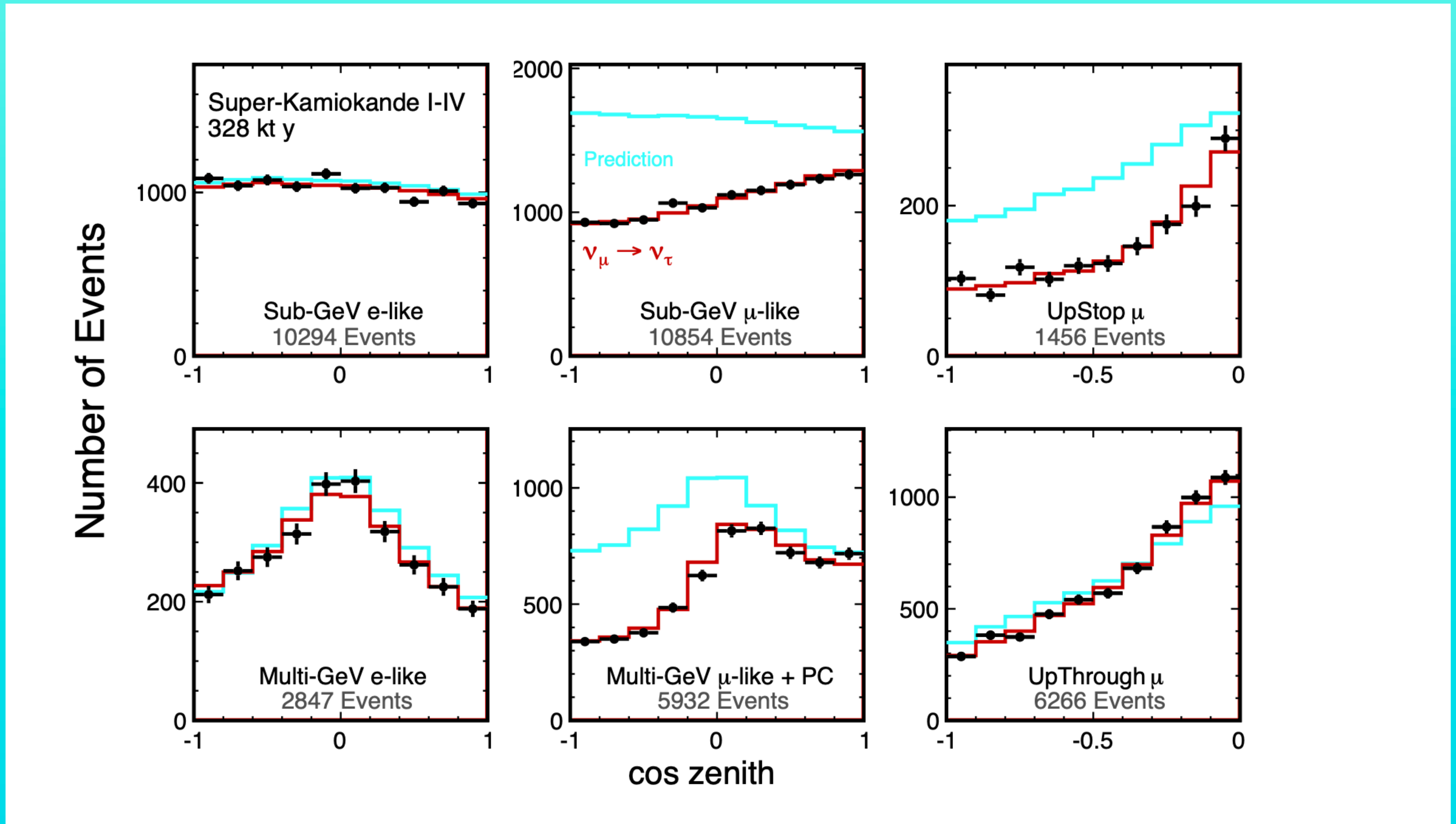
Solar neutrino oscillations



Name	Target material	Energy threshold (MeV)	Mass (ton)	Years
Homestake	C_2Cl_4	0.814	615	1970–1994
SAGE	Ga	0.233	50	1989–
GALLEX	$GaCl_3$	0.233	100 [30.3 for Ga]	1991–1997
GNO	$GaCl_3$	0.233	100 [30.3 for Ga]	1998–2003
Kamiokande	H_2O	6.5	3,000	1987–1995
Super-Kamiokande	H_2O	3.5	50,000	1996–
SNO	D_2O	3.5	1,000	1999–2006
KamLAND	Liquid scintillator	0.5/5.5	1,000	2001–
Borexino	Liquid scintillator	0.19	300	2007–2021



Atmospheric Neutrino oscillations



Super-Kamiokand

OPERA

IceCube

Antares

Iper-Kamiokande (future)

DUNE (future)

Accelerator Neutrino oscillations

Long and Short baseline

Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion hybrid	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–
DUNE	LBNF	Liquid argon TPC	1300	2–3	
Hyper-Kamiokande	J-PARC	Water Cherenkov	295	0.6	

LSND
KARMEN
MiniBoone
MicroBoone

Reactor anti-Neutrino oscillations

Name	Reactor power (GW_{th})	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–2020
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	

What we can conclude from Neutrino Oscillations

with SK atmospheric data	Normal Ordering (best fit) bfp $\pm 1\sigma$	Normal Ordering (best fit) 3σ range	Inverted Ordering ($\Delta\chi^2 = 6.4$) bfp $\pm 1\sigma$	Inverted Ordering ($\Delta\chi^2 = 6.4$) 3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

Spectrum with Normal ordering (NO) $\Rightarrow m_1 < m_2 < m_3$

Spectrum with Inverted ordering (IO) $\Rightarrow m_3 < m_1 < m_2$

$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

Δm^2_{21} Always smallest mass splitting

$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$ Largest mass splitting in NO

Δm^2_{32} Largest mass splitting in IO

NO $\Rightarrow m_2 = \sqrt{\Delta m^2_{21}} \sim 8.6 \times 10^{-3}\ eV, m_3 \simeq \sqrt{\Delta m^2_{32} + \Delta m^2_{21}} \sim 0.05\ eV$

IO $\Rightarrow m_1 \simeq \sqrt{\Delta m^2_{32} + \Delta m^2_{21}} \sim 0.0492\ eV, m_2 \simeq \sqrt{\Delta m^2_{32}} \sim 0.05\ eV$

Quasidegenerate case $m_1 \simeq m_2 \simeq m_3 \gg \sqrt{\Delta m^2_{32}}$

A closer look at the direct mass measurement

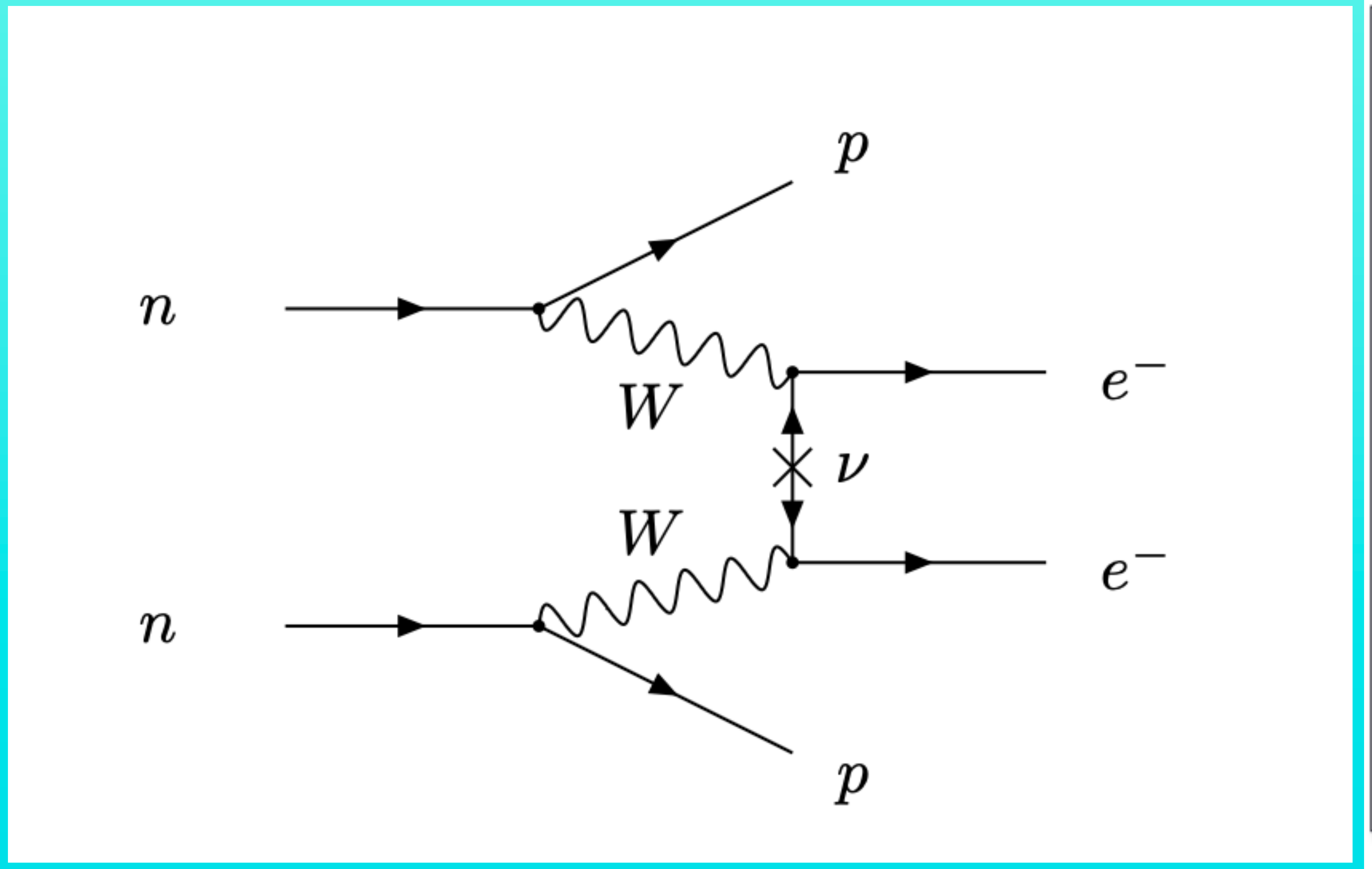
Mass parameters:

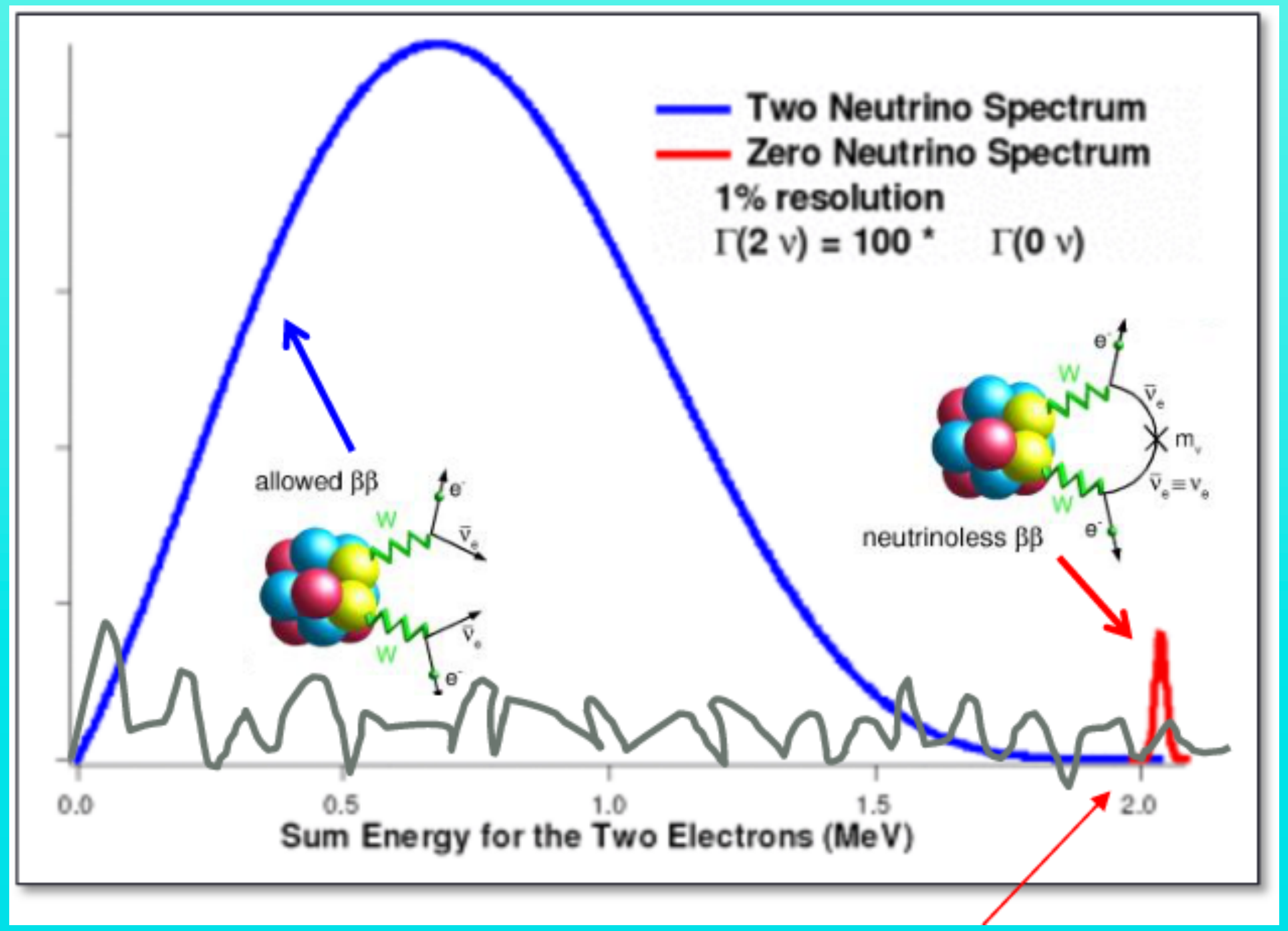
$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2$ Beta decay

$m_{\beta\beta} = |\Sigma_i U_{ei}^2 m_i|$ Neutrinoless double beta decay

$m_{sum} = \Sigma_i m_i$ Cosmology

$0\nu 2\beta$ one more laboratory on masses



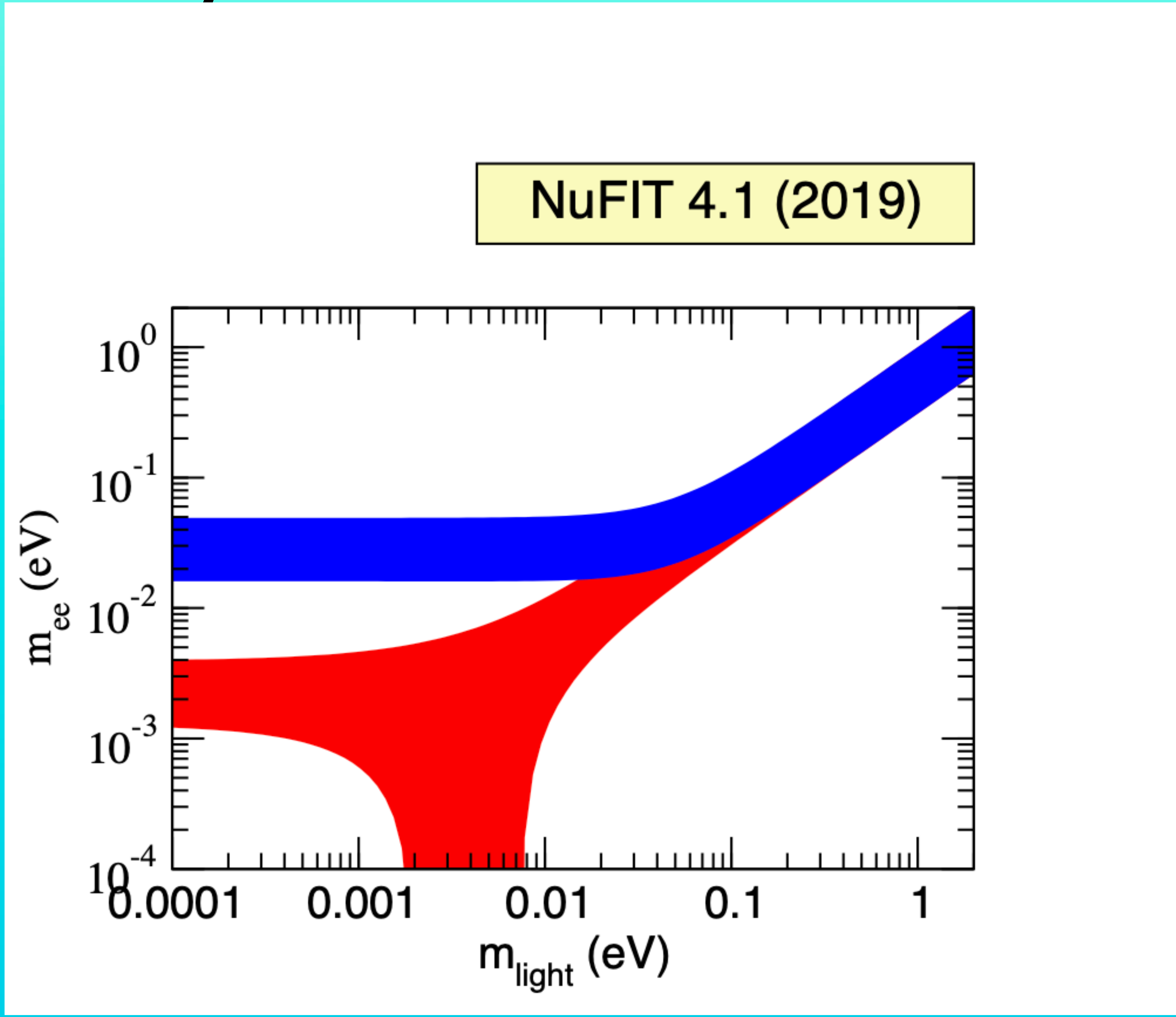


$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{m_{ee}}{m_e}\right)^2$$

$$m_{ee} = \left|\sum_i m_i U_{ei}^2\right|$$

$$= \begin{cases} \left|m_0 c_{12}^2 c_{13}^2 + \sqrt{\Delta m_{21}^2 + m_0^2}\, s_{12}^2 c_{13}^2 e^{2i(\eta_2-\eta_1)} + \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_0^2}\, s_{13}^2 e^{-2i(\delta_{\rm CP}+\eta_1)}\right| & \text{in NO} \\ \left|m_0 s_{13}^2 + \sqrt{m_0^2 - \Delta m_{32}^2}\, s_{12}^2 c_{13}^2 e^{2i(\eta_2+\delta_{\rm CP})} + \sqrt{m_0^2 - \Delta m_{32}^2 - \Delta m_{21}^2}\, c_{12}^2 c_{13}^2 e^{2i(\eta_1+\delta_{\rm CP})}\right| & \text{in IO ,} \end{cases}$$

$0\nu2\beta$ one more laboratory on masses



KamLAND-Zen (^{136}Xe)

$$T_{1/2} < 3.8 \times 10^{26}\ y$$

$$m_{ee} < 28 - 122\ meV$$

LEGEND-200 (^{76}Ge)

$$T_{1/2} < 1.9 \times 10^{26}\ y$$

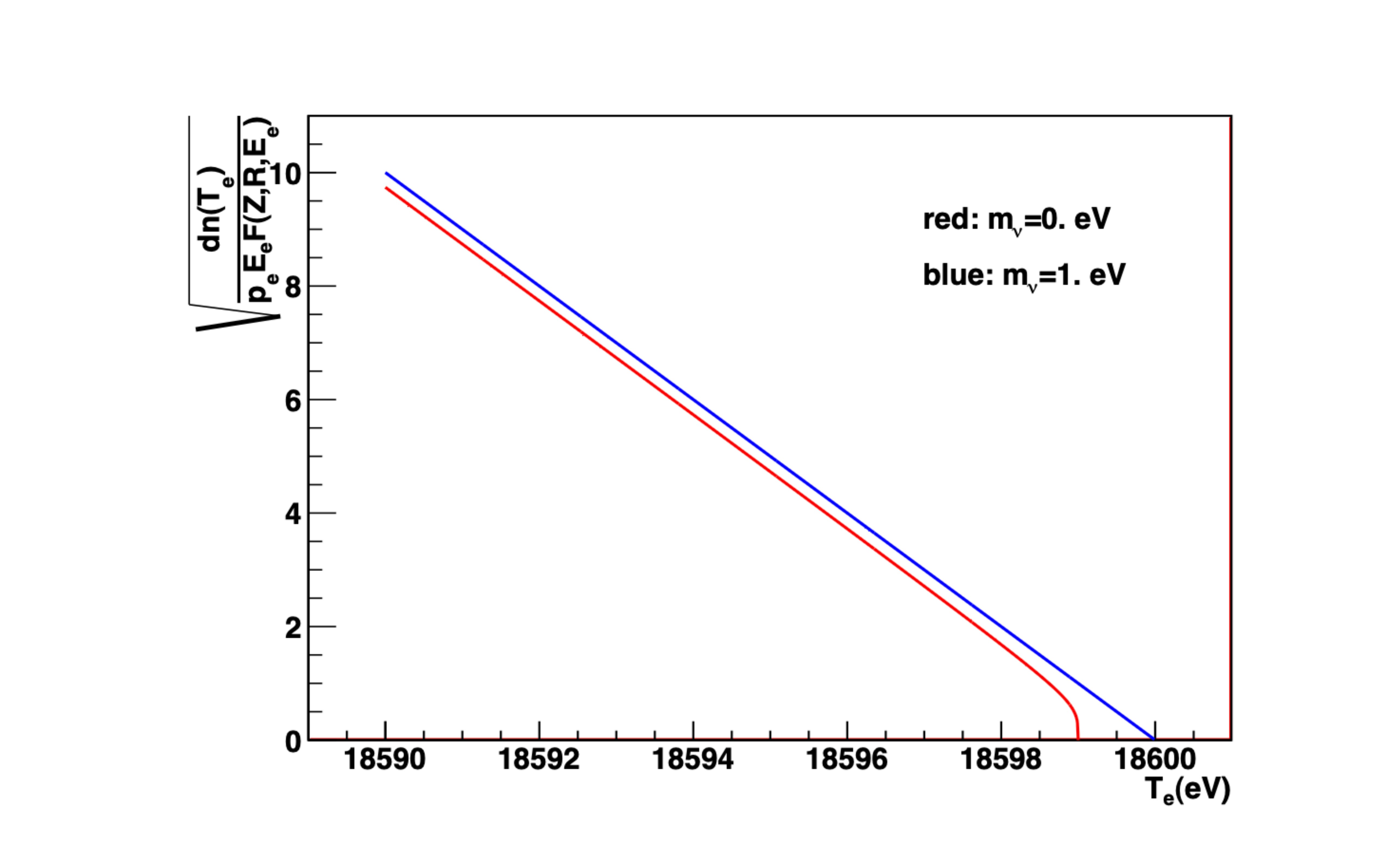
$$m_{ee} < 79 - 180\ meV$$

BETA DECAYS AS A NATURAL WAY TO MEASURE NEUTRINO MASS EIGENSTATE

Constraints from Kinematics of weak decays

$$\frac{dN}{dE} = CpE(Q-T)F(E)\sqrt{(Q-T)^2 - (m^{eff}_{\nu_e})^2}$$

Fermi proposed to exploit ${}^3H \rightarrow {}^2He + e^- + \bar{\nu}_e$



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

$$Event_{ROI} \propto \left(\frac{\Delta E}{Q}\right)^3$$

BETA DECAYS AS A NATURAL WAY TO MEASURE NEUTRINO MASS EIGENSTATE

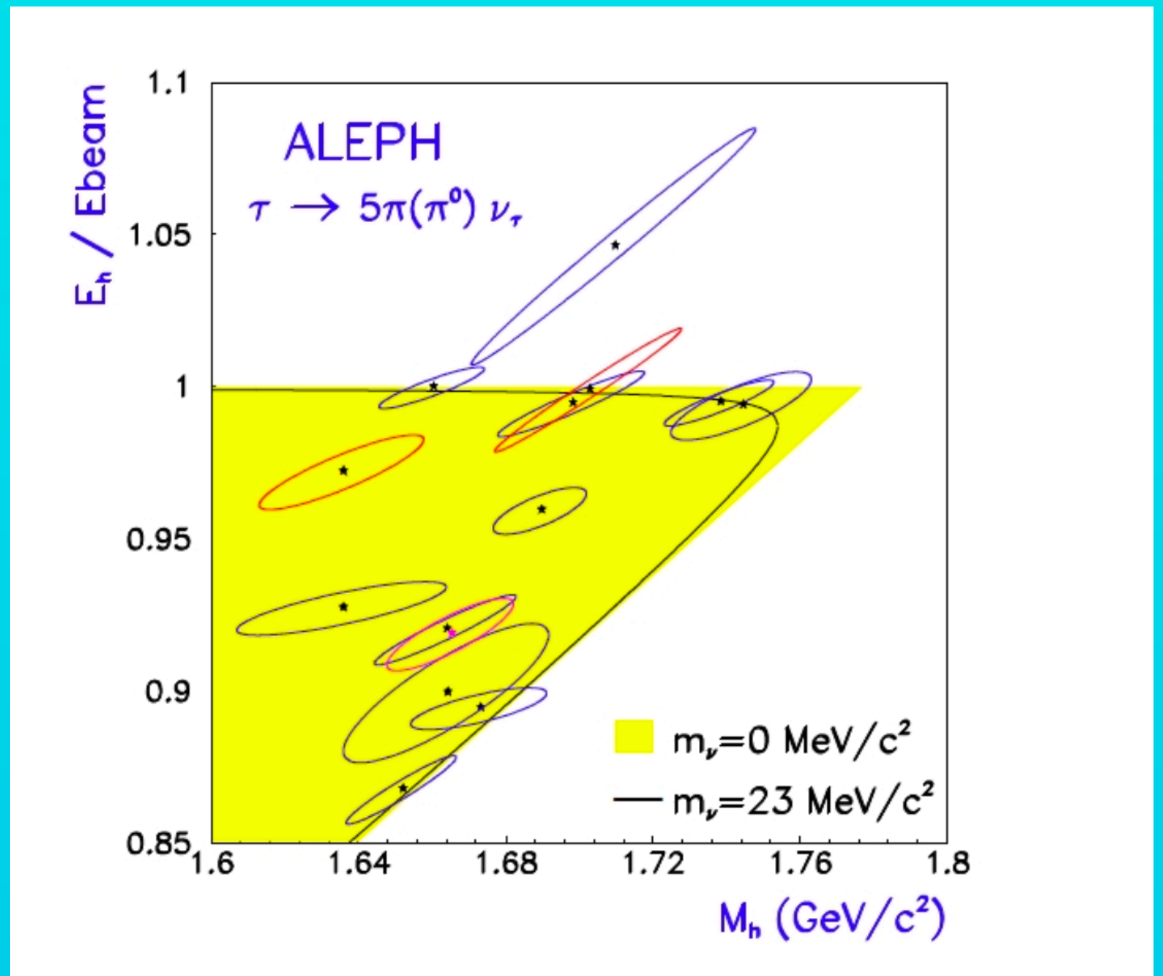
Constraints from Kinematics of weak decays

$\pi \to \mu + \nu_\mu$

$$m_\pi^2 =$$
$$m_\mu^2 + m_\nu^2 + 2p^2 + 2E_\mu E_\nu =$$
$$m_\mu^2 + m_\nu^2 + 2E_\mu^2 - 2m_\mu^2 + 2E_\mu E_\nu =$$
$$-m_\mu^2 + m_\nu^2 + 2E_\mu(E_\mu + E_\nu) \Rightarrow$$
$$m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi E_\mu$$

$m_{\nu_\mu}^{eff} < 190\ keV$ @ 95 C.L.

$\tau \to hadrons + \nu_\tau$



$m_{\nu_\tau}^{eff} < 18.2\ MeV$ @ 95 C.L.

Experiments exploiting tritium

INTRODUCTION

The most sensitive, direct method to search for the mass m_ν of the electron neutrino is a careful measurement of the shape of the tritium β-spectrum. With 'direct' we mean that basically only the kinematics of the 3-body decay enters the analysis. Unknown neutrino properties as for instance whether the neutrino is its own antiparticle or not or whether there is lepton number violation of some kind are not required. These are of course very interesting questions but are addressed by other types of experiments like $\beta\beta$-decay.

In principle any β-spectrum has the signature of a finite neutrino mass. (For short we use neutrino for electron antineutrino.) We choose tritium simply because it is the best case. This was recognized very early. Already in 1948 Curran, Angus, and Cockroft [1] and Hanna and Pontecorvo [2] derived an upper limit of 1 keV for m_ν using proportional counters with a small amount of tritium mixed into the counting gas. In 1952 a 250 eV limit was placed by Hamilton, Alford, and Gross [3] using an electrostatic and by Langer and Moffad [4] using a magnetic spectrometer. At that time apparently most physicists were convinced that the neutrino mass is likely to be zero and not much happened for some time. The situation changed as the muon neutrino was discovered and found to be different from the electron neutrino. If there are different neutrino types should they not have different and thus nonzero masses? Several tritium experiments were started in the 60's from which Bergkvist's work has become a classic in this field. Even from a present point of view Bergkvist considered all sources of potential systematic errors and investigated them carefully. In his paper from 1972 [5] he derived an upper limit of 55 eV (90% CL). This work was certainly discouraging for other groups not only because of its high standard it set but also because of the problem of the final electronic states. Bergkvist recognized that the decay product $^3He^+$ may be left in some excited electronic final state with the consequence that the emitted β-particle must have lost an energy corresponding to the excitation energy. This causes a broadening

of the measured spectrum. He corrected the effect assuming a free atom but it was clear that further progress would require very complicated calculations for realistic sources.

Great excitement was caused in 1980 by the result of a group at the Institute of Theoretical and Experimental Physics (ITEP) in Moscow reporting for the first time a measured finite neutrino mass of 35 eV [6]. With 99 % confidence the mass was reported to be between 26 and 46 eV.

We know now that the ITEP-result is wrong. However it had the great virtue prompting many groups around the world to initiate new tritium experiments. In fact as many as some 20 projects were started in the early 80's. The first result of the new experiments was reported in 1986 by the Zurich group [7]. No indication for a nonzero neutrino mass was found and an upper limit of 18 eV (95 % CL) was reported. The result was in clear contradiction to the ITEP-result. We may cite from [7]: 'We see no possible source of error in our experiment large enough to account for the discrepancy'. The reason for this conclusion was that at that time significant progress has been made computing the electronic final states and the Zurich group estimated a corresponding error of about 150 eV^2 for m_ν^2 at 95 % CL. It was clear that the ITEP result should not have been affected any more by the final states. Hence the discrepancy was of order of 1000 eV^2 which could only be caused by experimental problems.

In the following years the Zurich group considerably improved their experiment and has recently published [8] their final result: $m_\nu^2 = -24 \pm 48 \pm 61$ eV^2 (1σ). Also the groups in Tokyo, Los Alamos, and Mainz reported results without any indication for a nonzero neutrino mass and of course also ruling out the ITEP claim. Below we will discuss these experiments in some detail with more weight given to Zurich because of our involvement. We should note here also Stoeffl's experiment in Livermore which is conceptually similar to the Los Alamos design. Although results have been presented at various conferences, to our knowledge no tritium data have been published sofar and we can thus not discuss this interesting experiment here.

Prog. Part. Nucl. Phys., Vol. 32, pp 131-151, 1994

Experiments exploiting tritium

Zurich experiments

Electron Antineutrino Mass from β-Decay

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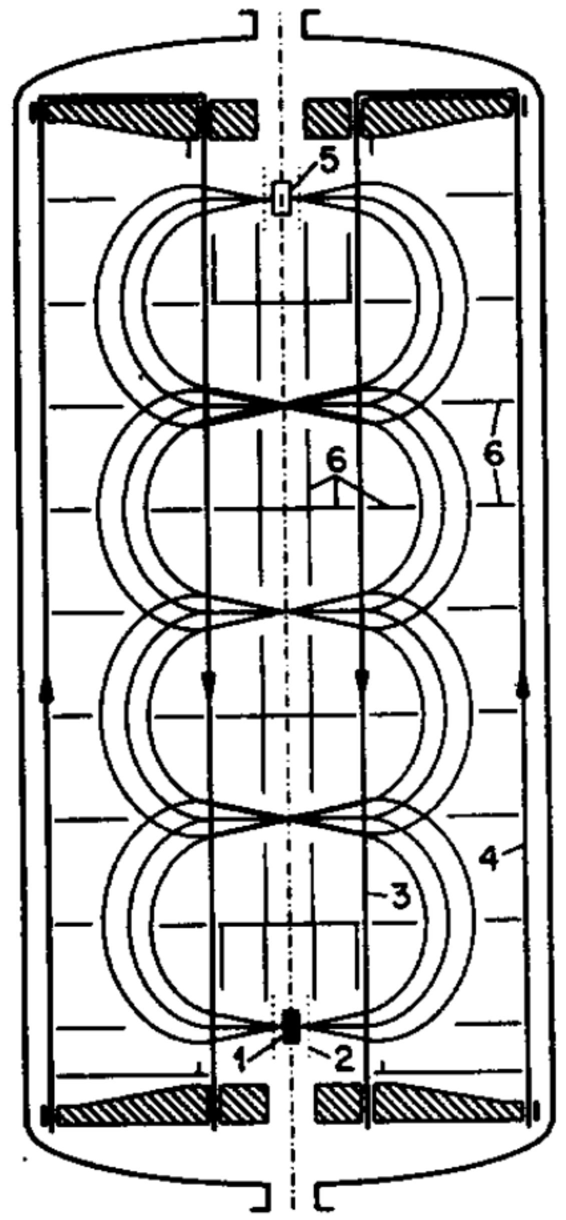


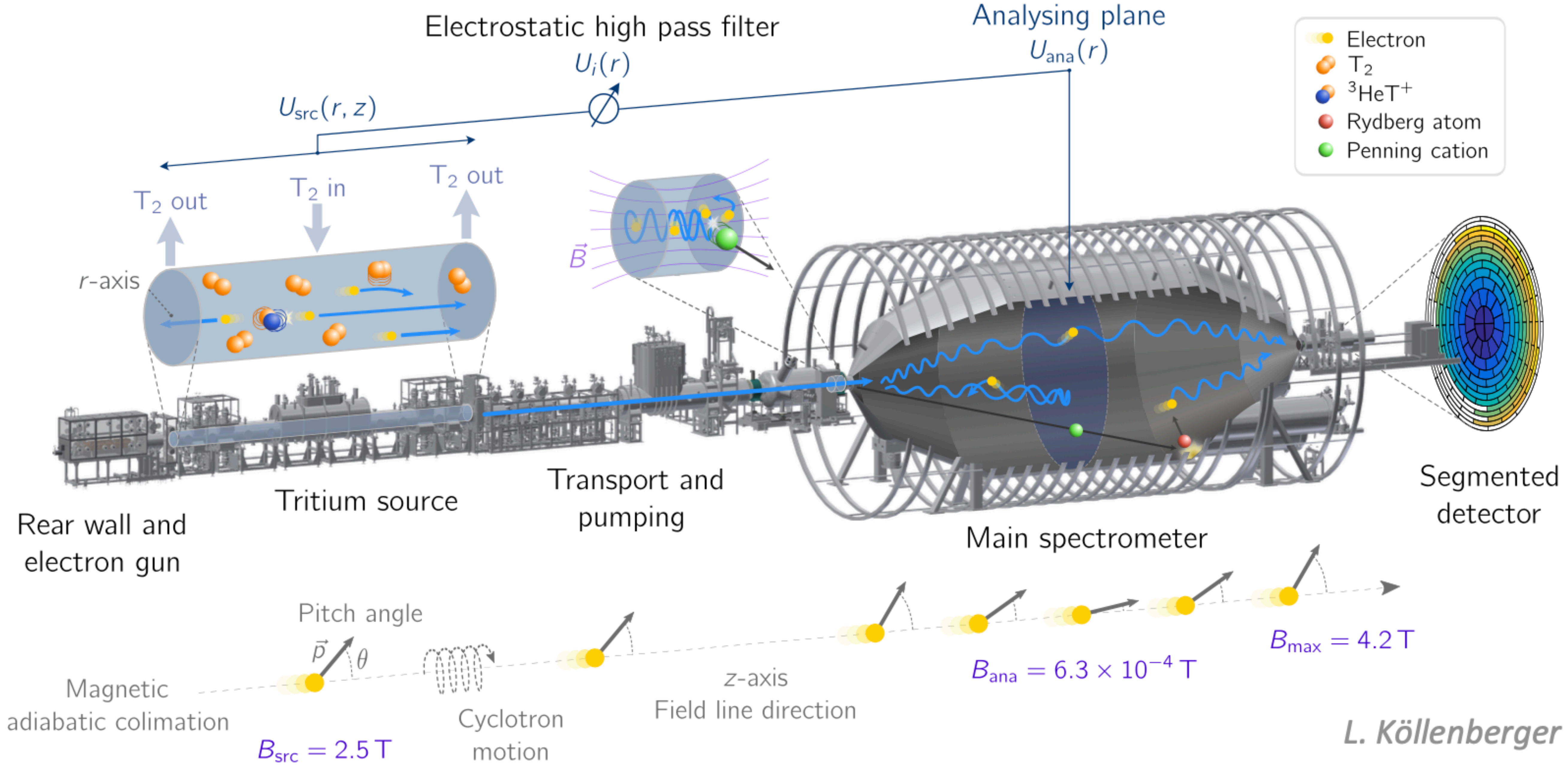
Figure 4: Cross section of the spectrometer (source 1, grid 2, current loops 3,4, detector 5, baffles 6).

This experiment was conceived after the publication of the ITEP results where a neutrino mass of 35 eV evidence "was found".

Introduction - KATRIN

TAUP2025

- World leading experiment in direct measurement of neutrino mass



→ New neutrino mass limit: $m_{\nu_e} \leq 0.45\ \mathrm{eV/c^2}$ @ 90% C.L.

The KATRIN Collaboration, Science 388,180-185(2025)

- Information on neutrino mass inferred from spectral analysis of the tritium beta-decay spectrum

$$T_2 \longrightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$$

- Main features:
  - High luminosity molecular tritium source → 10^{11} decays/s
  - MAC-E filter principle → about 1 eV resolution
  - Silicon p-i-n diode counting detector → energy resolution ~ 1 keV

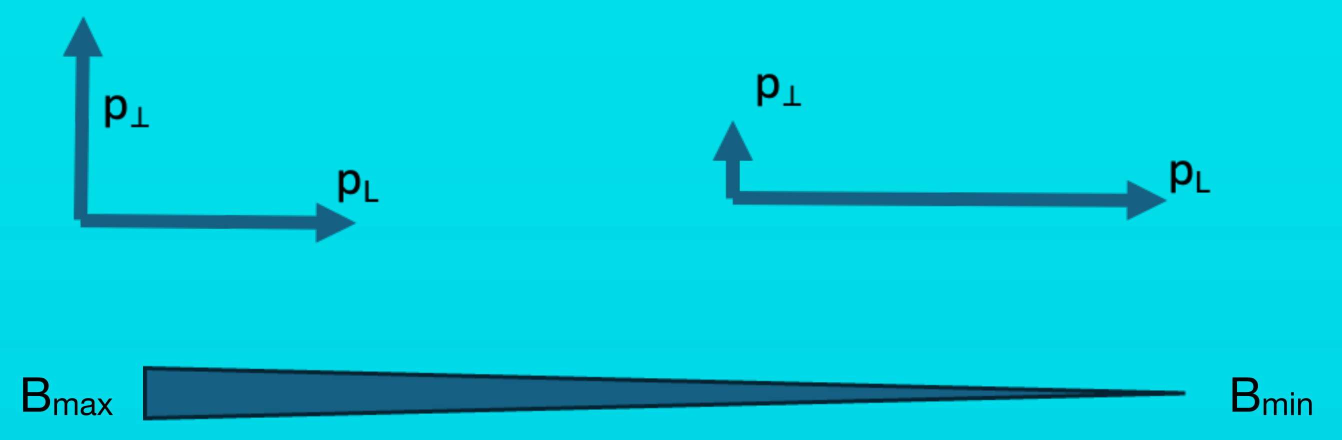
Experiments exploiting tritium

$$\frac{1}{B}\frac{dB}{dt} = \omega << \omega_c$$

Adiabatic condition: B changes as function of time along trajectory must be less than the typical Larmor frequency

In an adiabatic motion not only kinetic energy is conserved but also magnetic moment.

$$\mu = \frac{(p_\perp^{max})^2}{2B_{max}} \rightarrow \frac{(p_\perp^{min})^2}{2B_{min}}$$

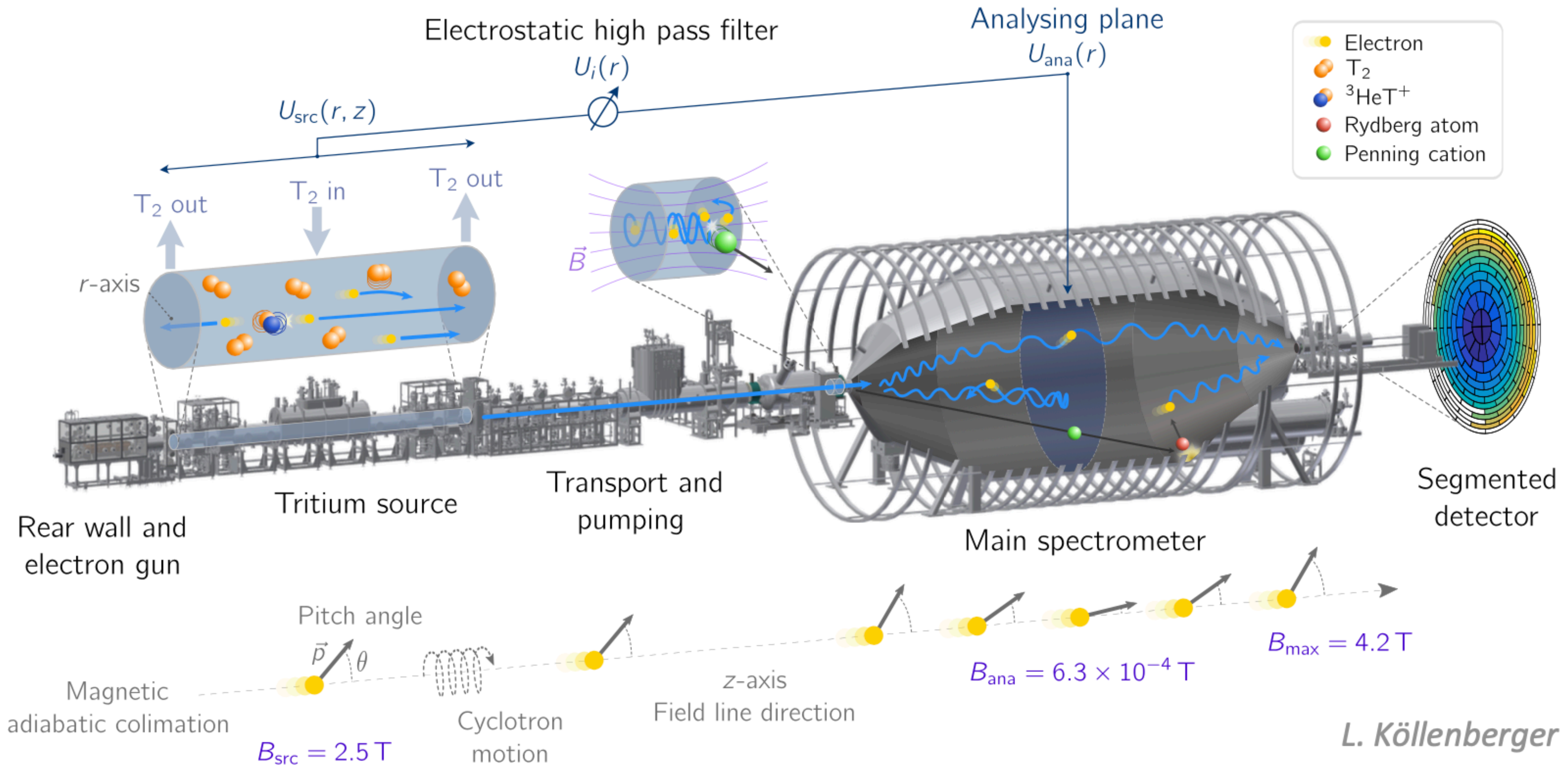


First Lagrange invariant

Introduction - KATRIN

TAUP2025

- World leading experiment in direct measurement of neutrino mass



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The KATRIN Collaboration, Science 388,180-185(2025)

- Information on neutrino mass inferred from spectral analysis of the tritium beta-decay spectrum

$$T_2 \longrightarrow {}^3HeT^+ + e^- + \bar{\nu}_e$$

- Final projected sensitivity:

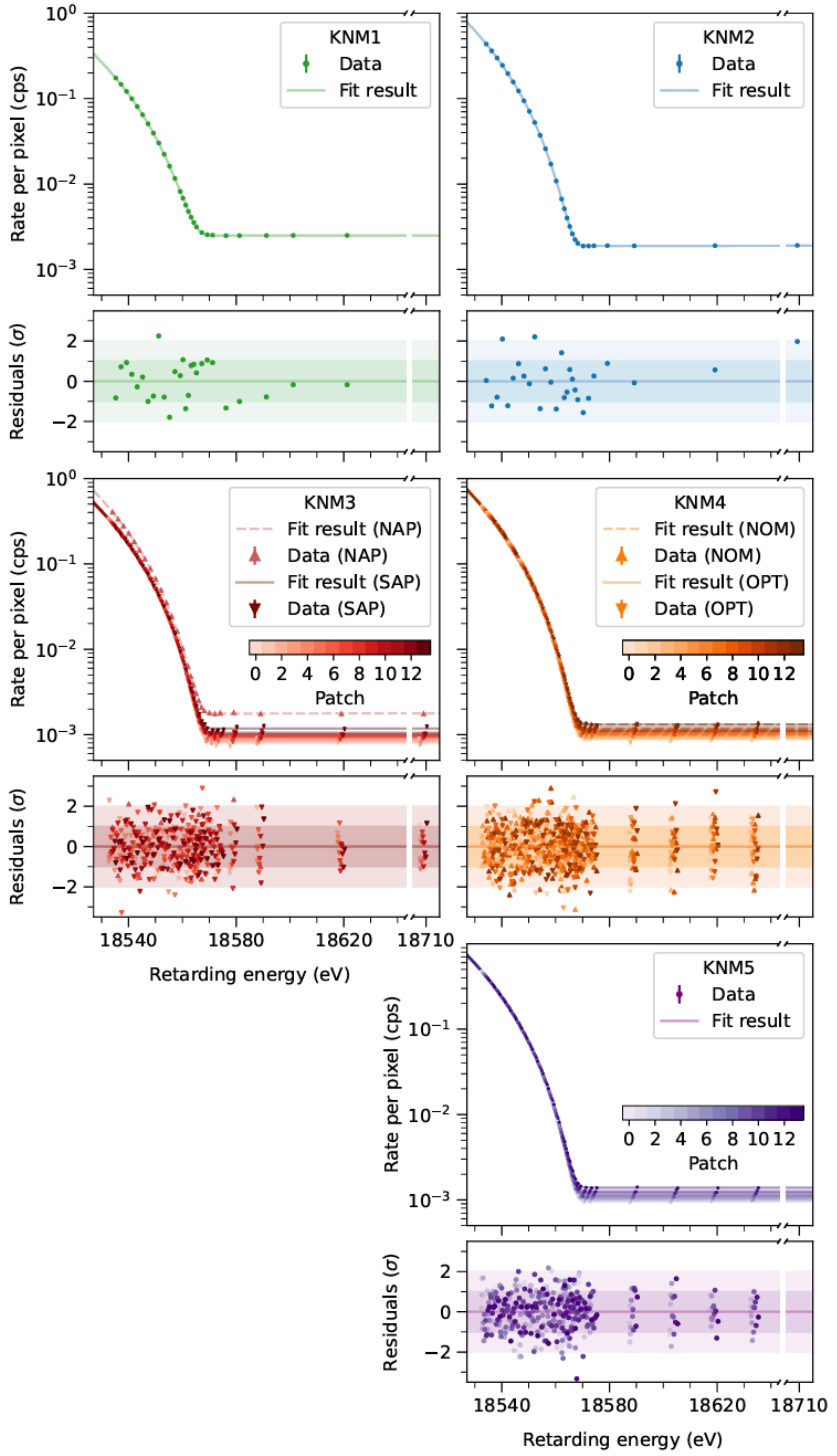
$$m_{\nu_e} \leq 0.3\ eV^2/c^2\ @\ 90\,\%\,C.L.$$

→ After 1000 days of measurement

→ Should be reached at the end of this year!

How can we go beyond?

arXiv:2406.13516



Microcalorimeter technology to measure neutrino mass

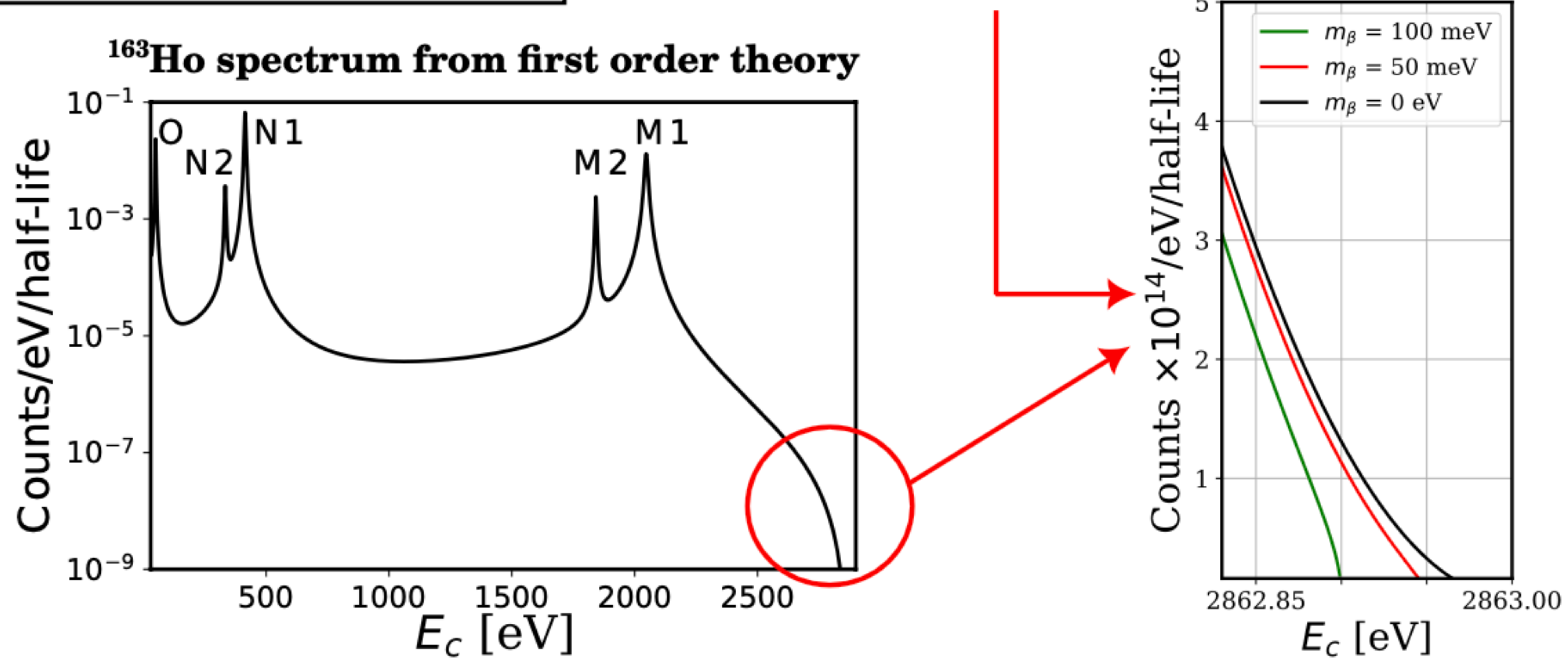
This technology has a long story starting with the MARE project based on Rhenium isotope. Then and ERC gran allowed to start exploiting the Holmium isotope.

The EC decay of ^{163}Ho

TAUP2025

$$^{163}\mathrm{Ho} + e^- \rightarrow \, ^{163}\mathrm{Dy}^H + \nu_e$$
$$^{163}\mathrm{Dy}^H \rightarrow \, ^{163}\mathrm{Dy} + E_C^H$$

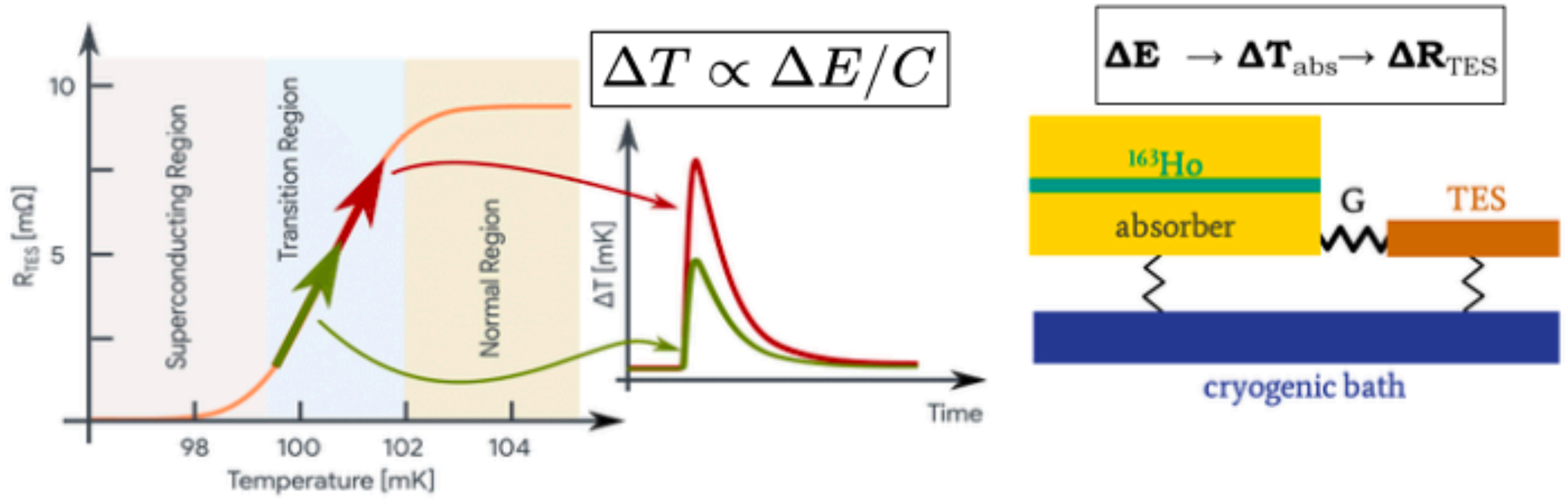
$$N(E_c) = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q - E_c)^2 - \boldsymbol{m}_\beta^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_b(H_i))^2 + \Gamma_{H_i}^2/4}$$

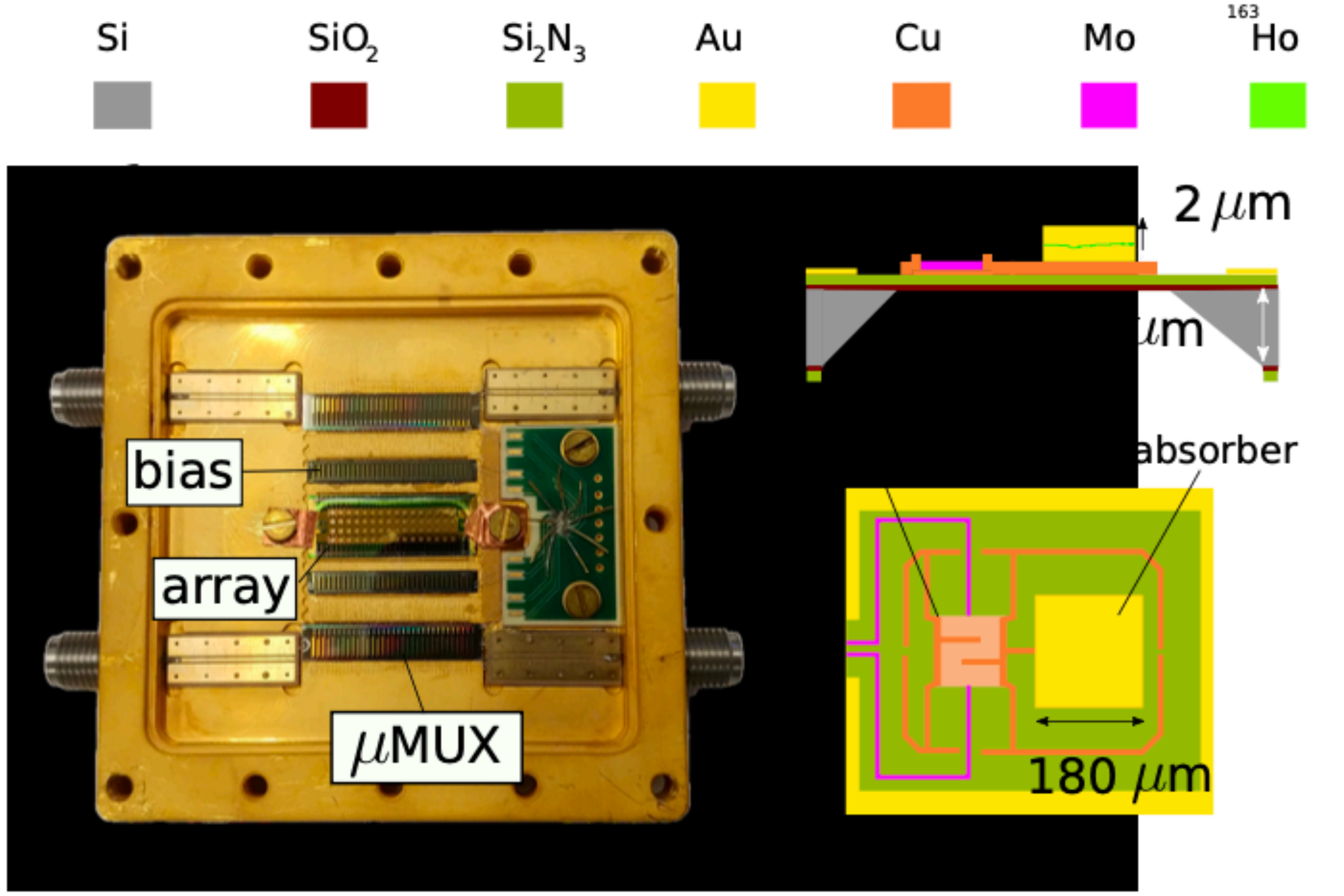


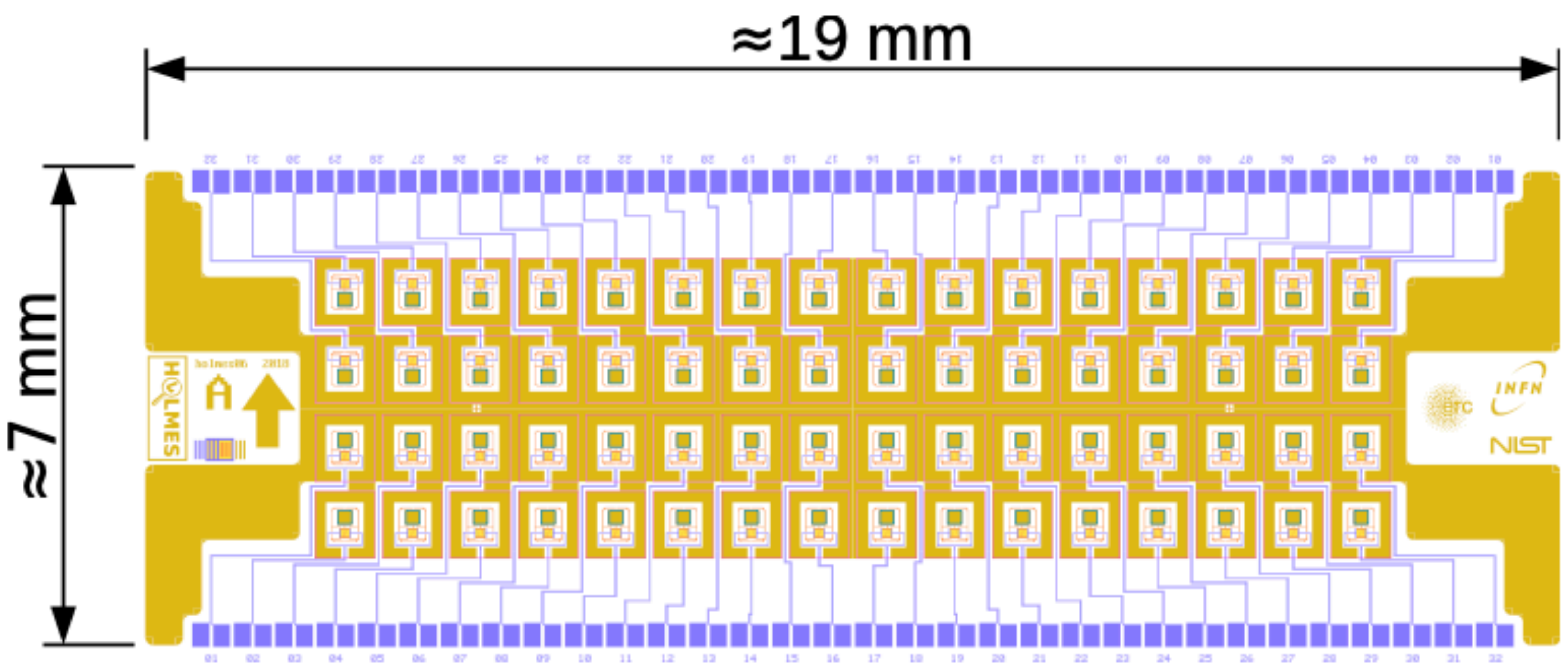
- E_C = atom de-excitation + nuclear recoil;
- Method proposed by *A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429*;
- $Q = 2863.2 \pm 0.6$ eV *Ch. Schweiger et al. Nat. Phys. (2024)*;
- $\tau_{1/2} \sim 4570$ y.

HOLMES detectors

- **Low temperature** (~ 100 mK) **microcalorimeters**;
- ^{163}Ho implanted gold absorbers each coupled to a Cu/Mo **Transition Edge Sensor**;
- 1+1 μm Au thickness for electrons full absorption;
- μMUXed TES 64-pixel array ~0.3 Bq/pixel.

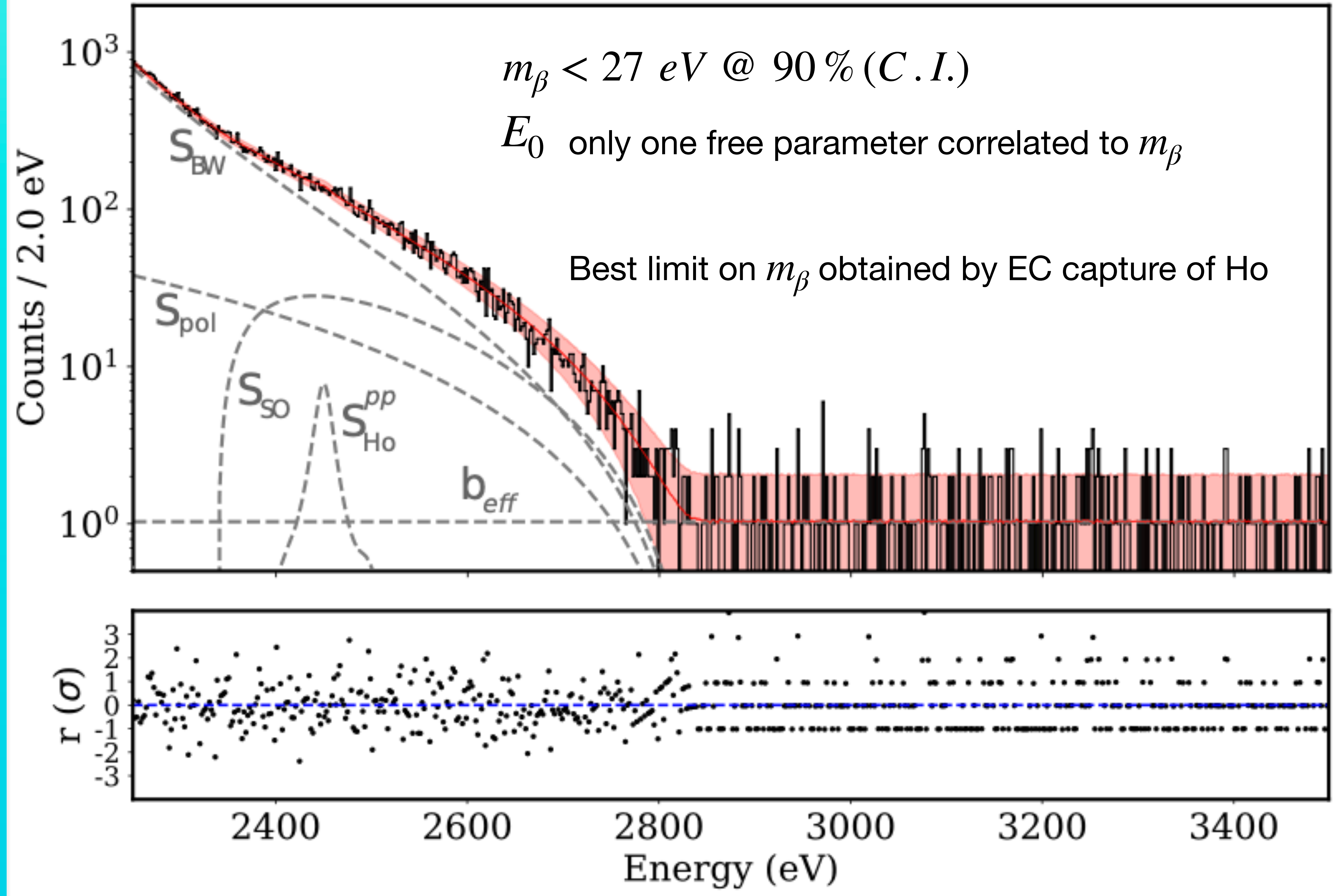






Endpoint analysis

- Bayesian analysis with 13 free parameters:
  - ROI: [2250, 3500] eV;
  - $\Delta E_{FWHM} \sim 6$ eV, $f_{pp} \lesssim 10^{-5}$;
  - spectrum as sum of a few terms.



Spectrum @ ROI [2250,3500] eV:

$$\mathcal{S}_{\exp} = \left[N_{tot}\left(\mathcal{S}_{\text{Ho}} + f^{pp}_{eff}\mathcal{S}^{pp}_{\text{Ho}}\right)\right] * \mathcal{R}_{eff} + b_{eff}$$

N_{tot}: number of events;
$\mathcal{S}_{\text{Ho}}$: Ho real spectrum;
$f^{pp}_{eff}\mathcal{S}^{pp}_{\text{Ho}}$: pile-up fraction and pile-up spectrum;
b_{eff} : flat background;
$\mathcal{R}_{eff}$: detector effective resolution.

$$\mathcal{S}_{\text{Ho}} \approx k_0\left(k_{\text{BW}}\mathcal{S}_{\text{BW}} + k_{\text{SO}}\mathcal{S}_{\text{SO}} + \mathcal{S}_{\text{pol}}\right) \times \mathcal{F}_{\text{PS}}$$

$\mathcal{S}_{\text{BW}}$: M1 peak right tail

$\mathcal{S}_{\text{SO}}$: energy spectrum of shake off de-excitation

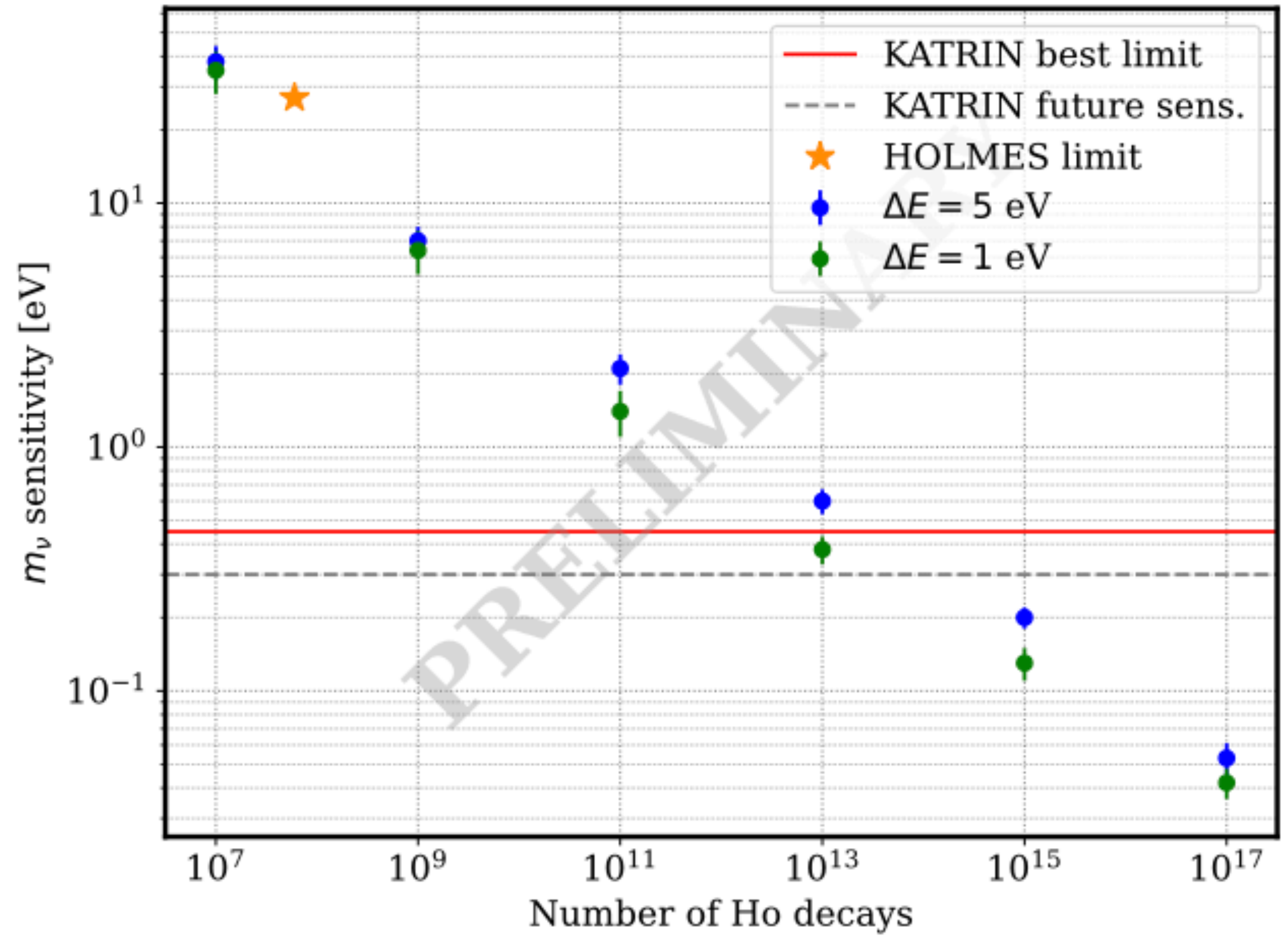
$\mathcal{S}_{\text{pol}}$: tails of other peaks and shake-offs

$\mathcal{F}_{\text{PS}}$: phase space, only term with m_β $\propto (E_0 - E_c)\sqrt{(E_0 - E_c)^2 - m_\beta^2}$

Scan the QR code to read our new article (accepted by PRL):

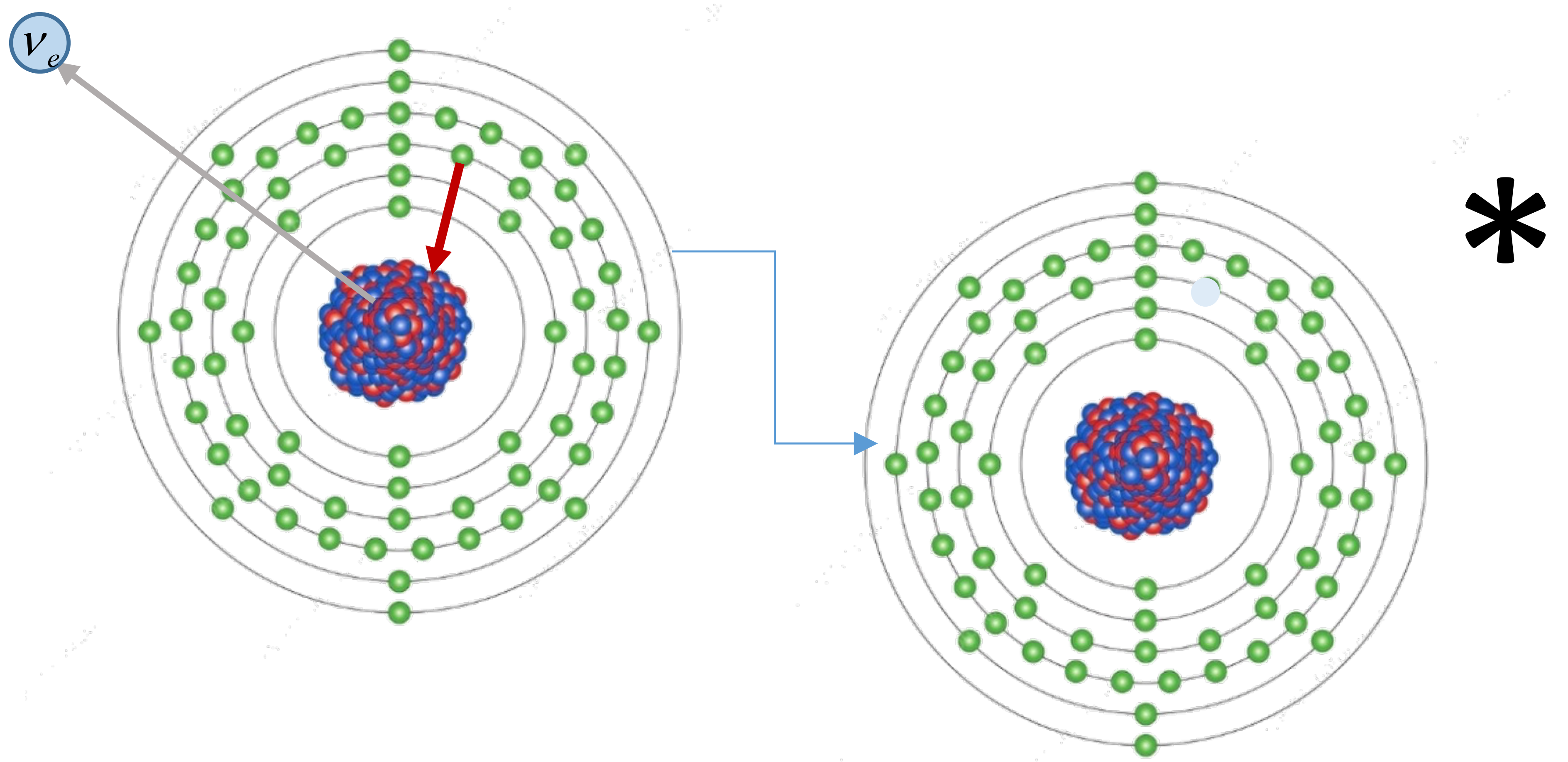
"Most stringent bound on electron neutrino mass obtained with a scalable low temperature micro-calorimeter array"

^{163}Ho future experiment sensitivity (stat. only)



- No background & no pile-up $\Rightarrow$ need to go to 10^{17} events;
- Still need to establish the systematics;
- $\mathcal{O}(150)$ meV: $N_{ev} \sim \mathcal{O}(10^{15})$, $N_{det} \sim \mathcal{O}(10^5)$, $A_{det} \sim \mathcal{O}(10)$ Bq, $T \sim \mathcal{O}(10)$ y;
- $\mathcal{O}(50)$ meV: $N_{ev} \sim \mathcal{O}(10^{17})$, $N_{det} \sim \mathcal{O}(10^7)$, $A_{det} \sim \mathcal{O}(10)$ Bq, $\Delta E_{FWHM} \sim \mathcal{O}(1)$ eV, $T \sim \mathcal{O}(10)$ y.

HECo experiment: Electron capture on ^{163}Ho

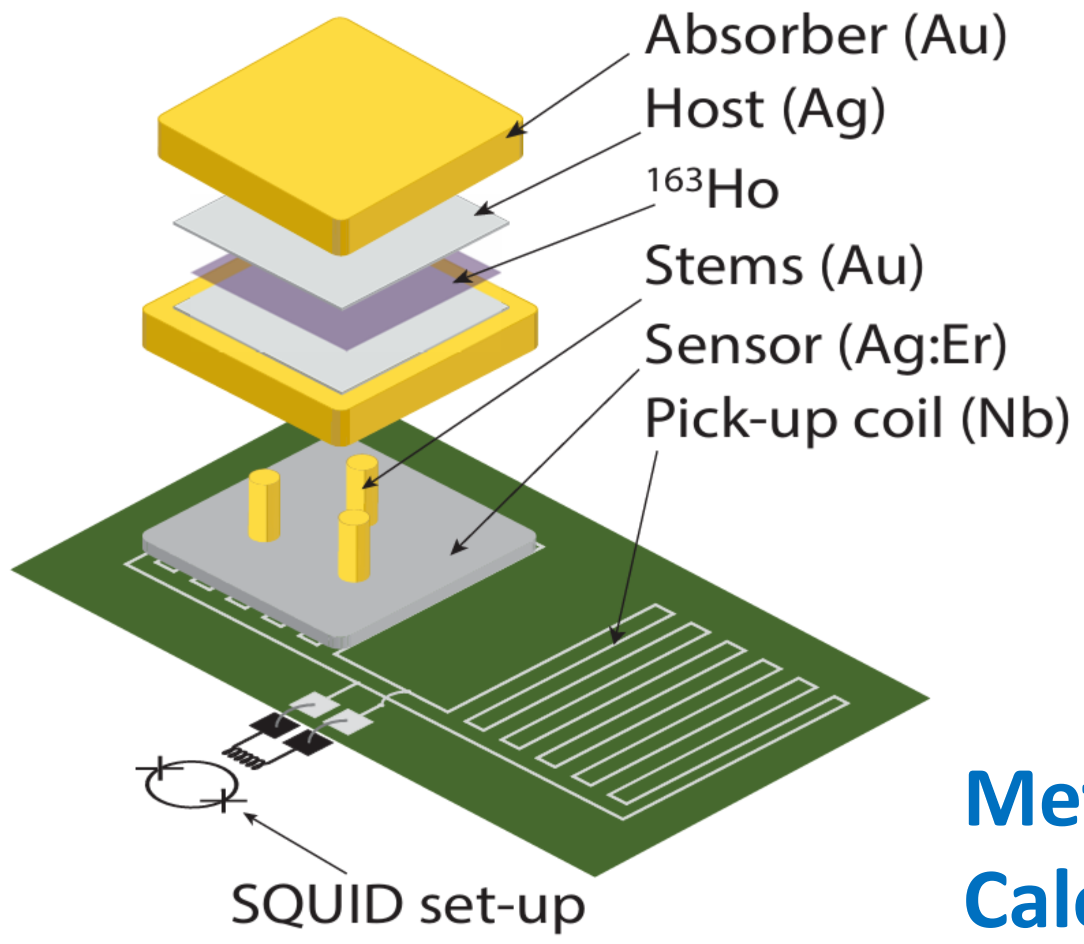


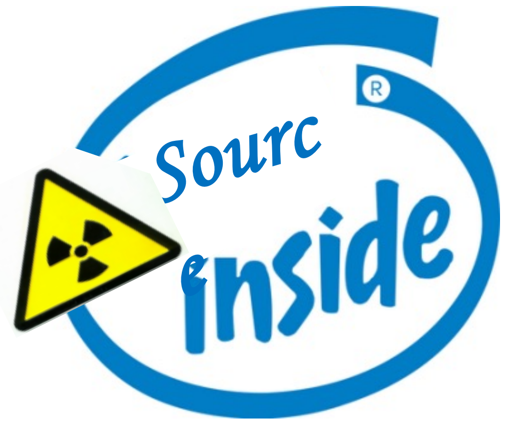
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

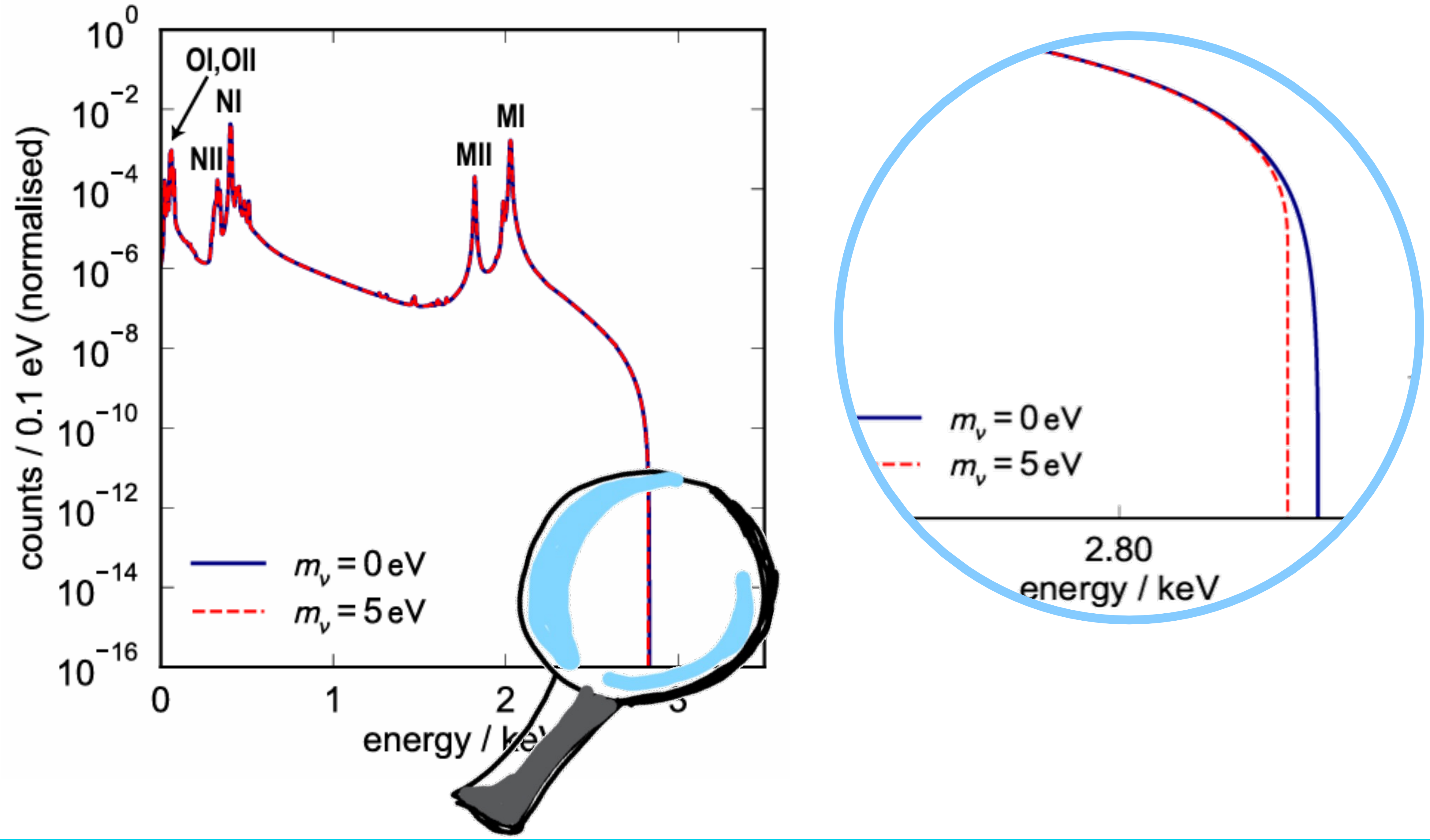
- $\tau_{1/2} \cong 4570$ years ($2*10^{11}$ atoms for 1 Bq)
- $Q_{EC} = (2863.2 \pm 0.6)$ eV

Ch. Schweiger et al., *Nat. Phys.* **20**, 921–927 (2024)





Metallic Magnetic Calorimeters (MMC)



Calorimetric measurement

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

ECHo-1k results

2×10^8 ^{163}Ho events

ΔE_{FWHM} = 6.59(16) eV @ 1.8 keV

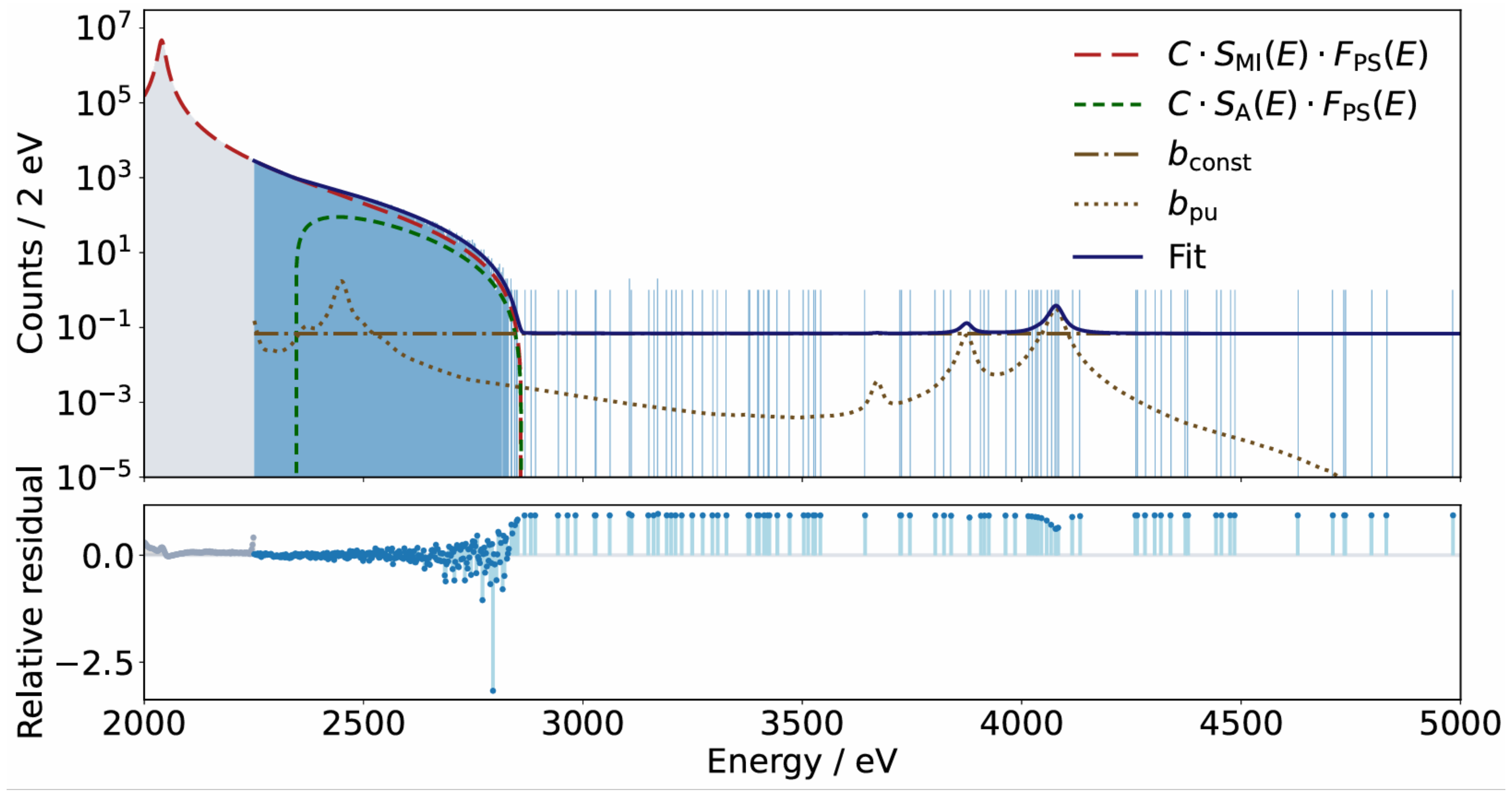
B = 9.1(1.3)×10^{-6}/eV/pixel/day

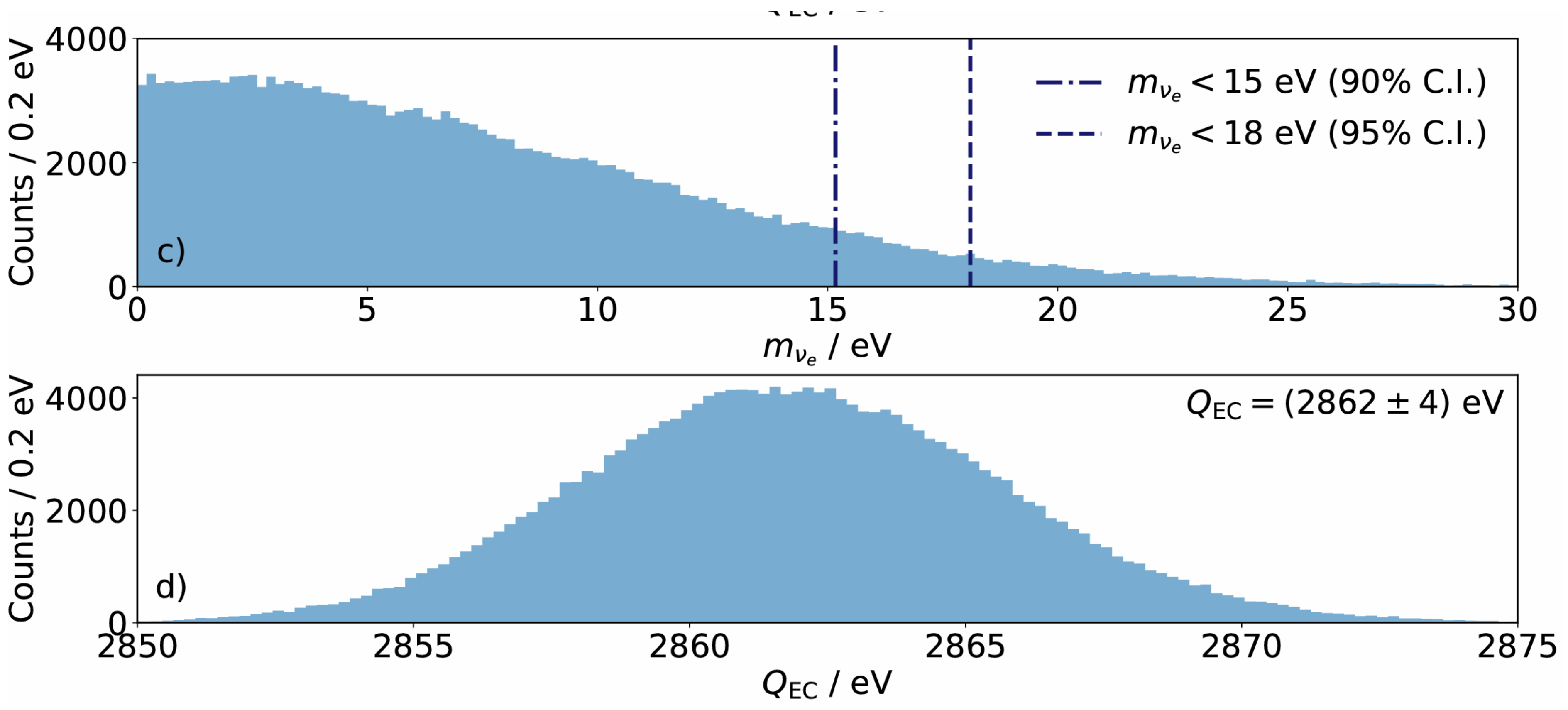
Endpoint region

$$\frac{dN}{dE} = C\times[A(E)\times F_{PS}(Q,E)] \otimes g(E,\sigma) + b(E)$$

$$F_{PS} = (Q-E)\sqrt{(Q-E)^2 - m_\beta^2}$$

- No analytical function is available to describe $A(E)$, the probability to create excited states with a given energy in the ^{163}Dy atom
- In M. Braß et al., New J. Phys. 22 (2020) 093018 it is stated that $A(E)$ is very smooth
- Test of different functions has been performed





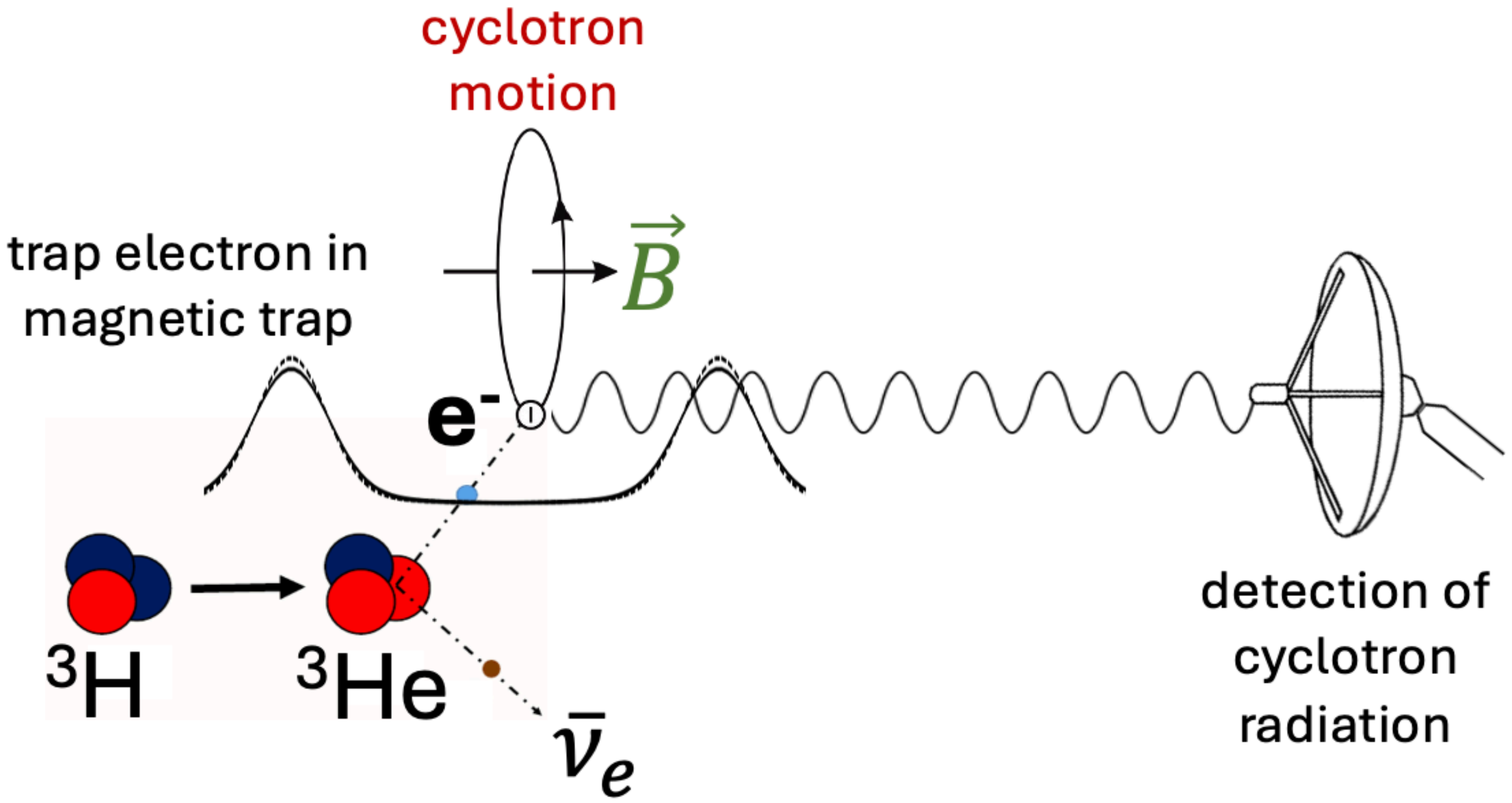
Q = 2862(4) eV

$m_\nu < 15$ eV/c^2 (90% C.I.)

https://arxiv.org/abs/2509.03423

PROJECT 8

Cyclotron radiation emission spectroscopy (CRES): A different technique



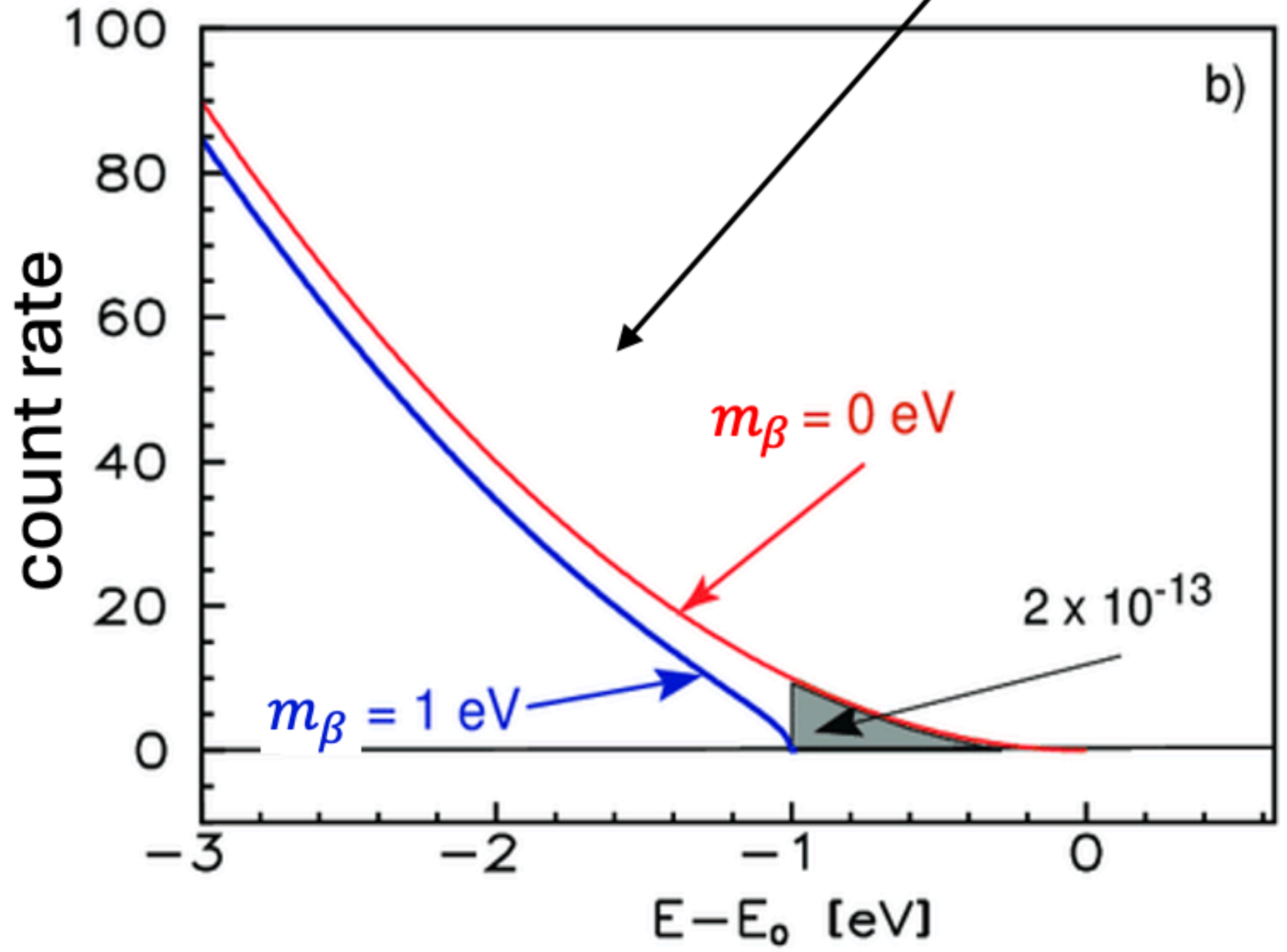
to measure

$$f_c = \frac{1}{2\pi} \frac{e\,\langle B \rangle}{m_e + E_{kin}/c^2}$$

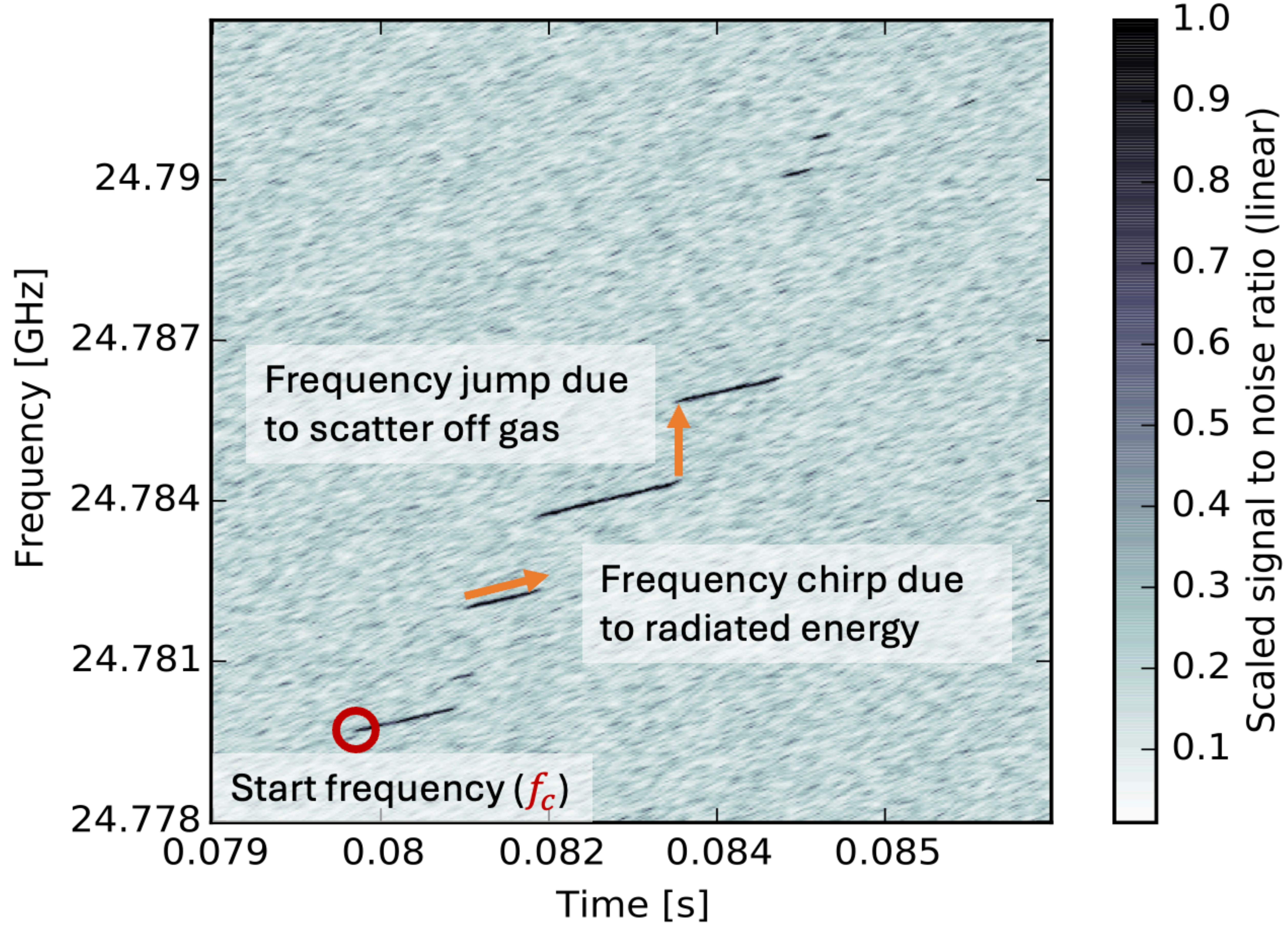
cyclotron frequency

average magnetic field experienced by electron

kinetic energy



Anatomy of a CRES event

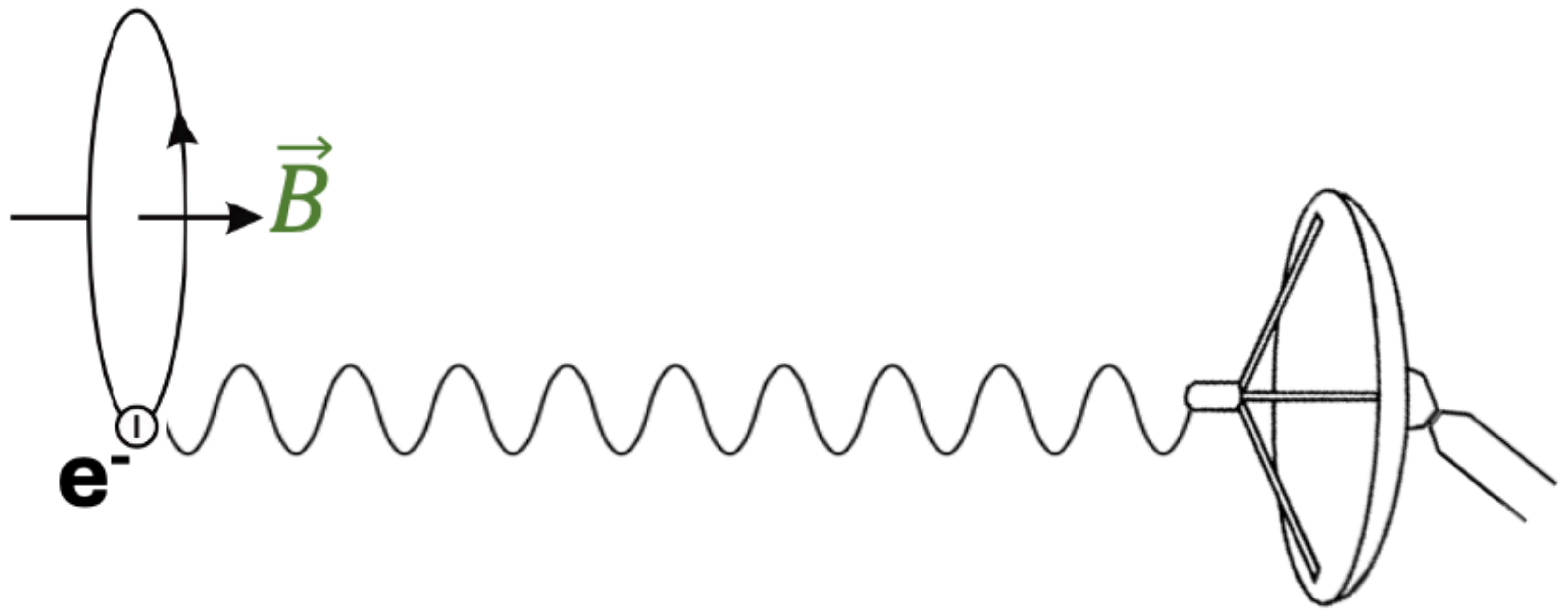


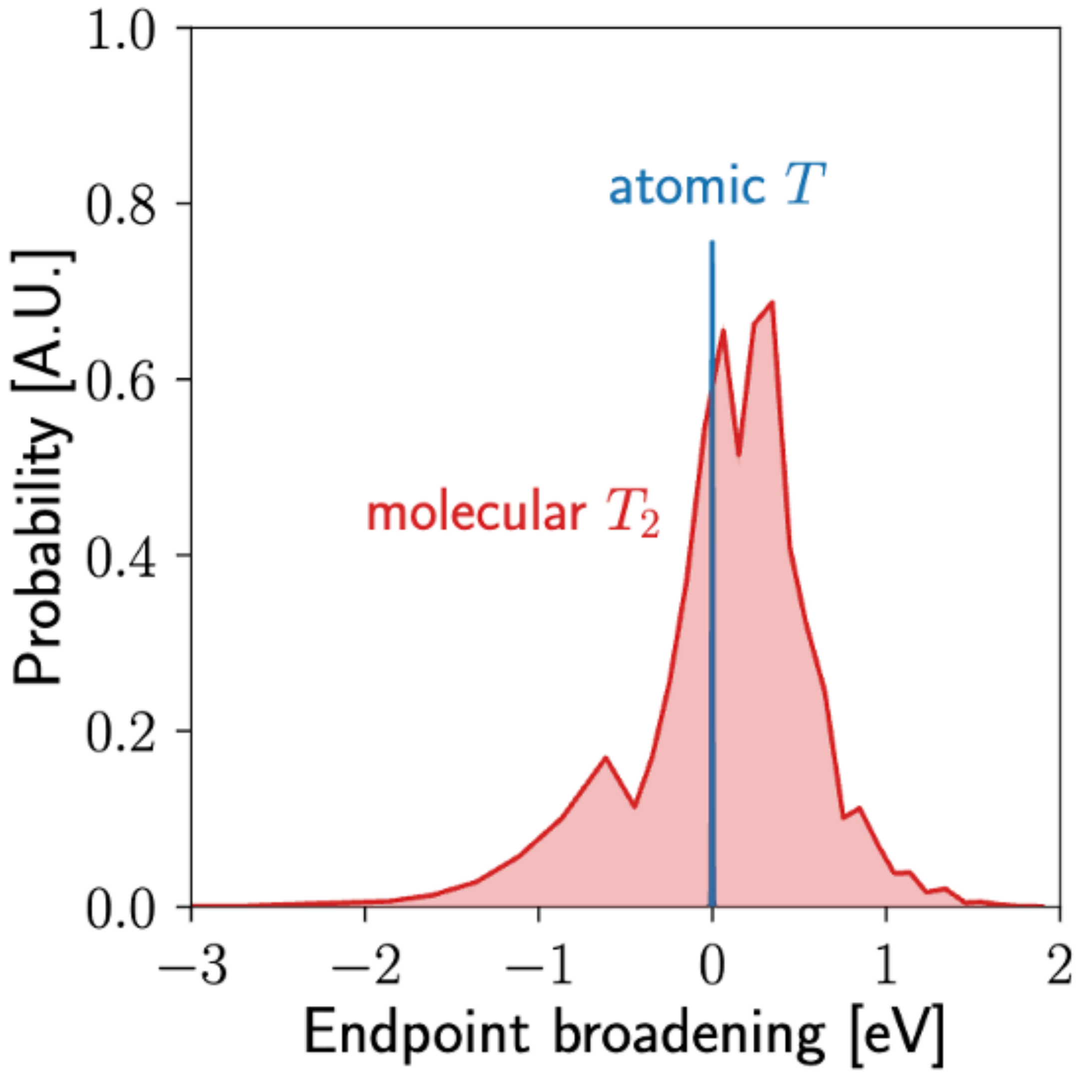
$$f_c = \frac{1}{2\pi} \frac{e\langle B \rangle}{m_e + E_{kin}/c^2}$$

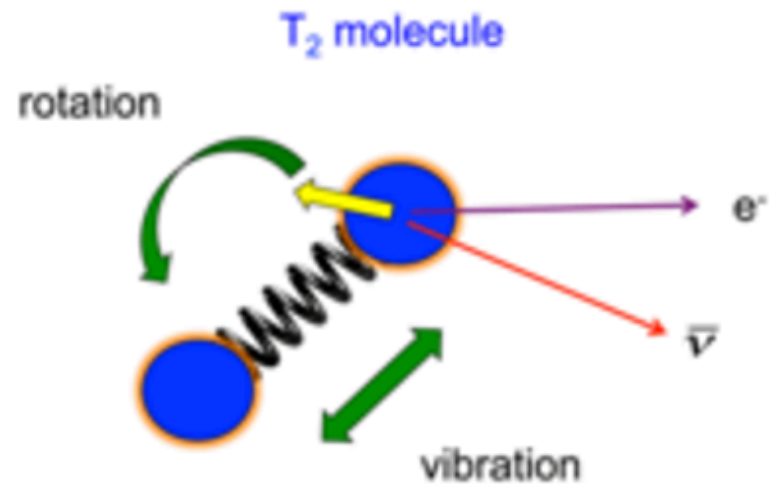
Project 8 Collaboration, Phys. Rev. Lett. (2023)
Project 8 Collaboration, Phys. Rev. C (2024)

Advantages of CRES

- It's a frequency measurement!
- Don't need to transport electrons from source to measure their energy
- Differential spectrometry
- Very low background
- Compatible with atomic tritium







Ideas for Future experiments

KATRIN++

QTNM

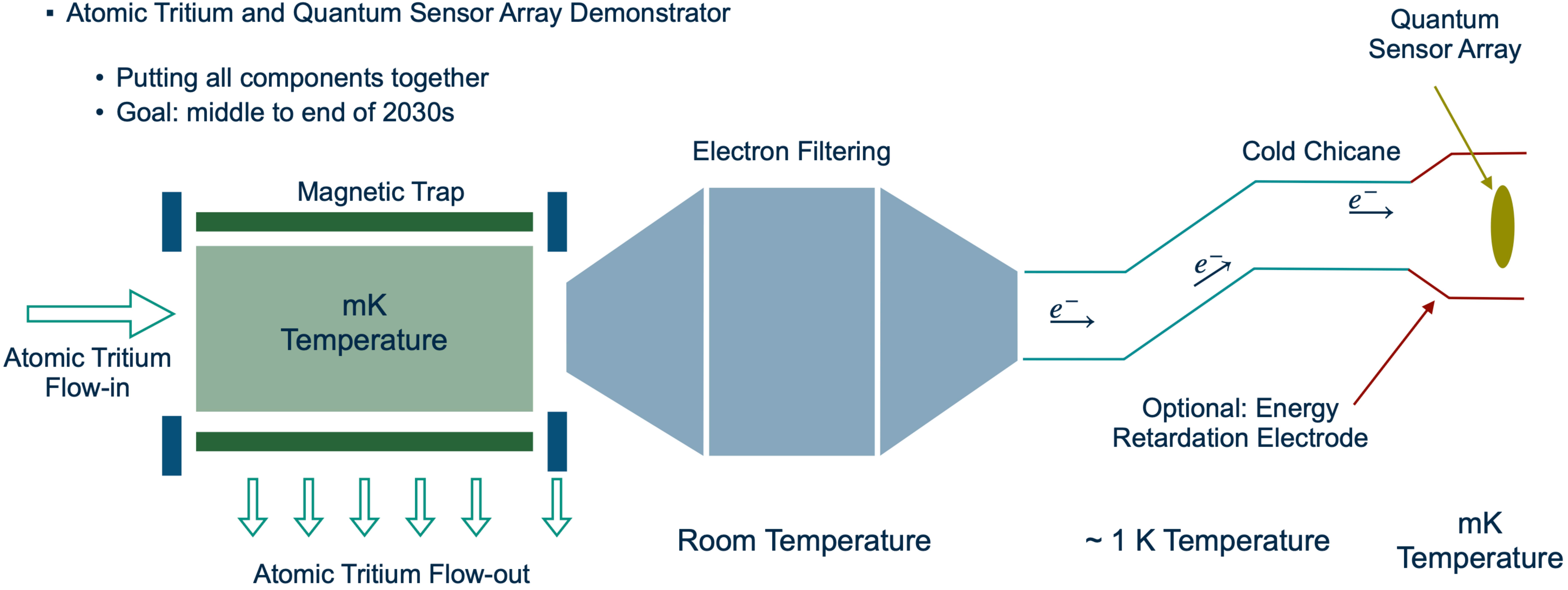
PTOLEMY

KATRIN++ - Final R&D Goal

TAUP2025

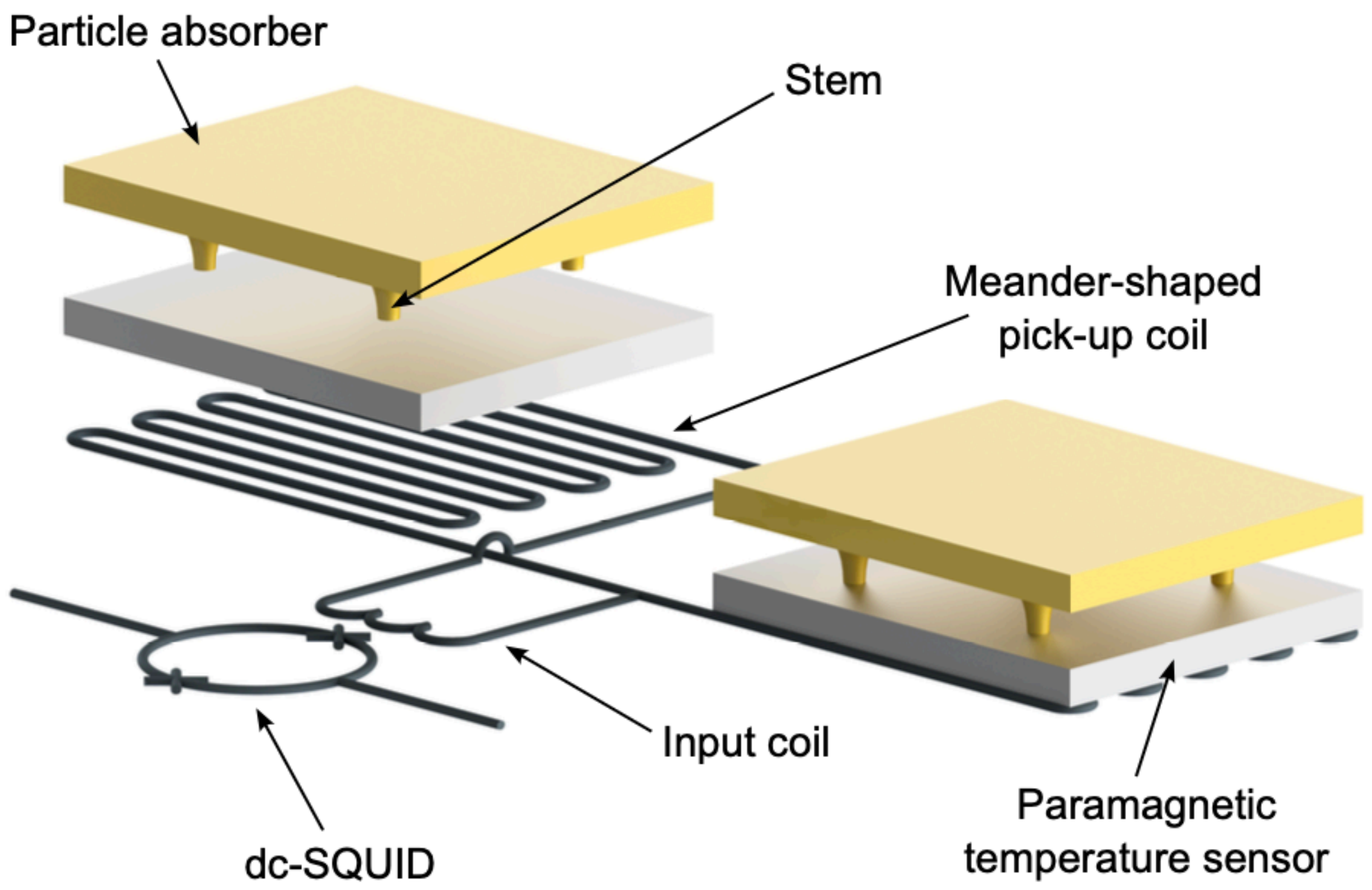
Very Rough Sketch!

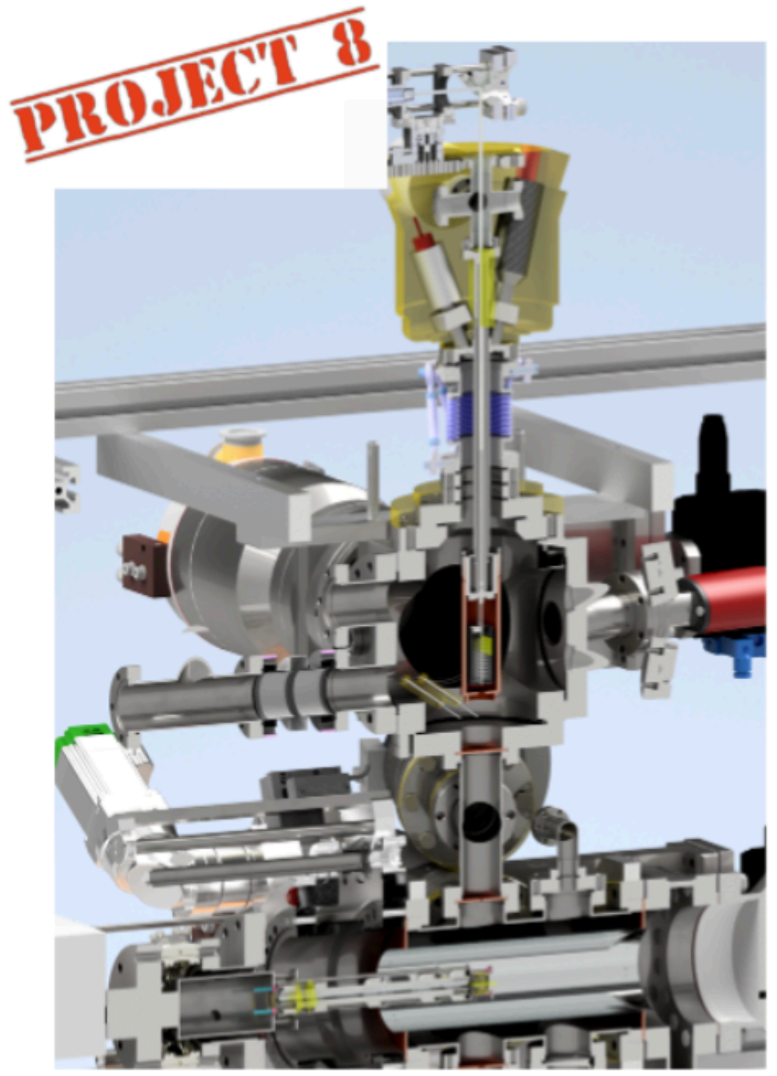
- Atomic Tritium and Quantum Sensor Array Demonstrator
  - Putting all components together
  - Goal: middle to end of 2030s



Future project of the KATRIN collaboration

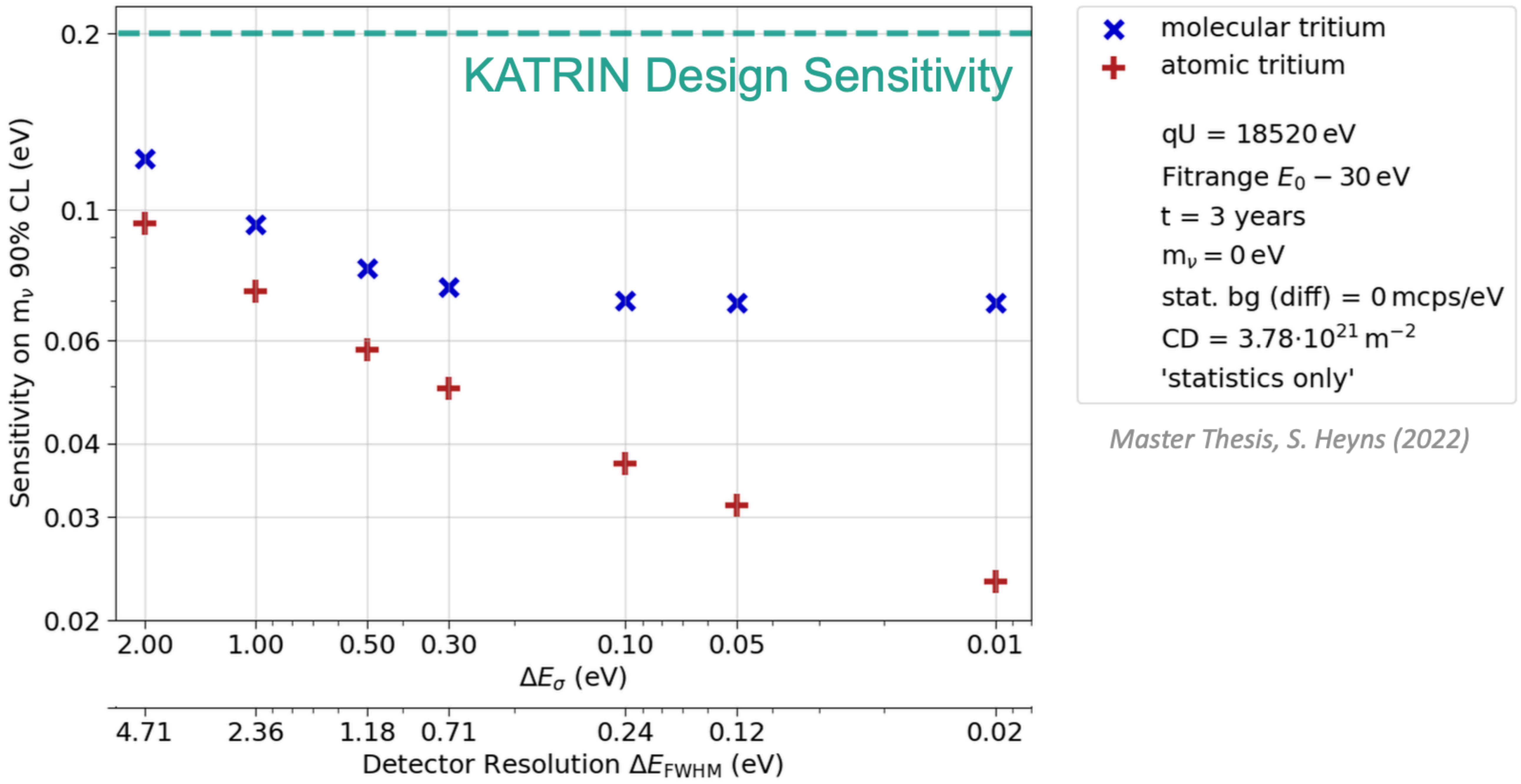
- Going beyond the final KATRIN sensitivity is an extremely challenging endeavor!
- It requires paradigm shift in measurement principles
    - Differential measurement method will allow us to probe sub-100 meV region of the neutrino mass!
    - High luminosity atomic tritium source will allow us to go even further, beyond the invert mass ordering!
- Currently ongoing R&D projects under KATRIN++ umbrella:
    - Development of large area quantum sensor arrays for ultra-high resolution electron spectroscopy
    - Development of single-electron tagger for a time-of-flight measurement
    - Development of atomic tritium source





Going Beyond KATRIN

- Going beyond KATRIN final sensitivity requires paradigm shift in measurement approach



Master Thesis, S. Heyns (2022)

- Two directions forward:
  - Differential measurement mode:
    - → Significant increase in statistics
    - → Reduction of backgrounds
    - → Increase in energy resolution
  - Change from molecular tritium source to an atomic one:
    - → Eliminate effects due to molecular final states

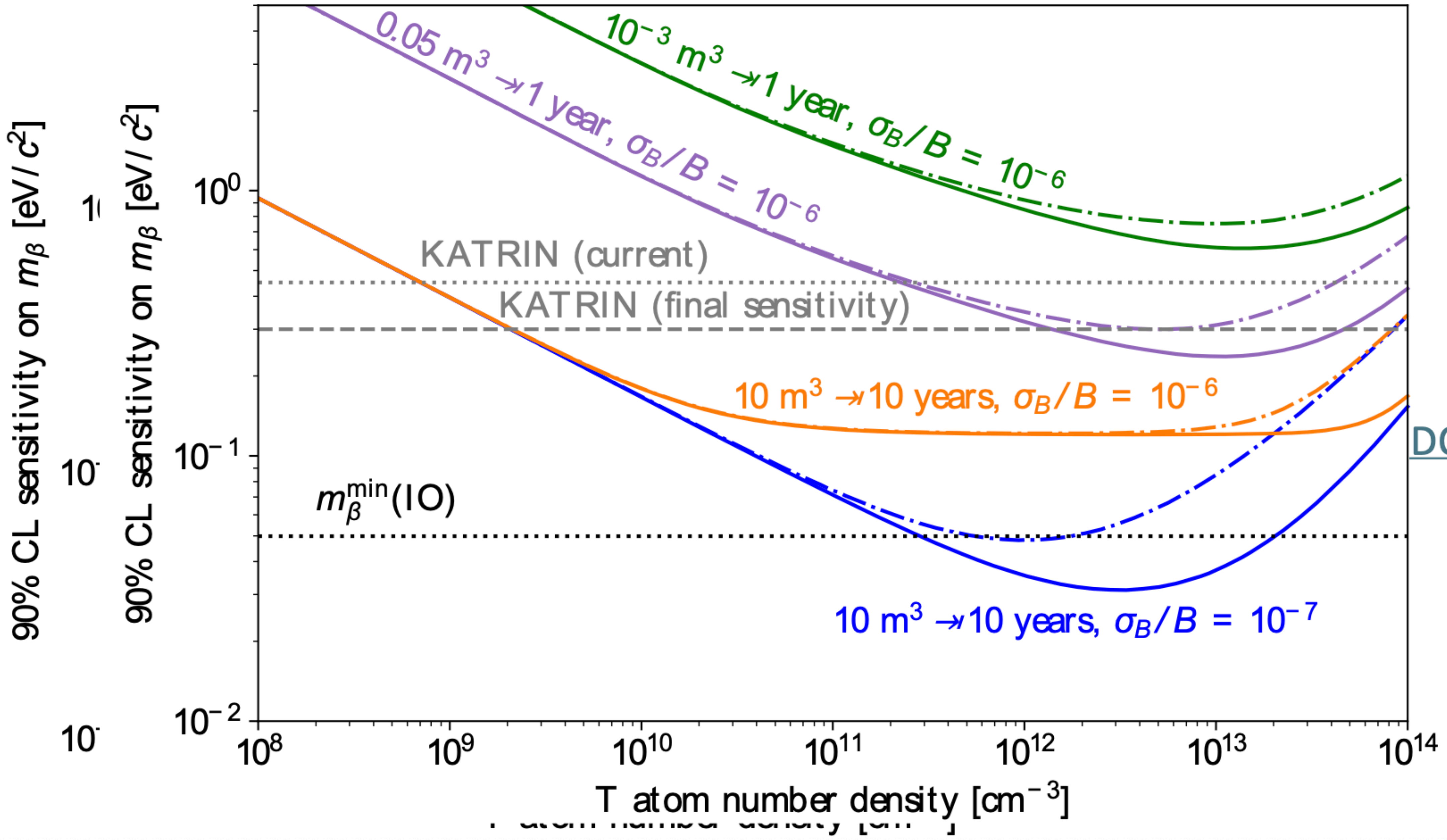
QTNM
Quantum Technologies for Neutrino Mass

UCL · University of Oxford · Queen Mary University of London · NPL National Physical Laboratory · Warwick The University of Warwick · Prifysgol Abertawe Swansea University

Funded as part of the **Quantum Technologies for Fundamental Physics** programme

Physics Goal

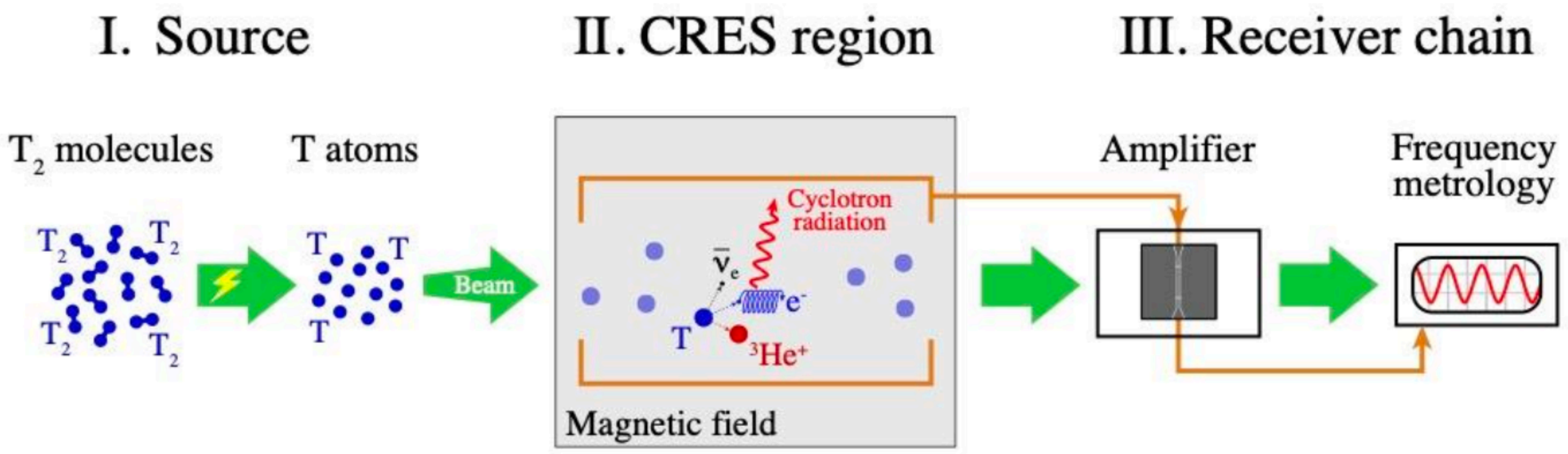
Neutrino mass measurement from atomic ^{3}H β-decay via Cyclotron Radiation Emission Spectroscopy using latest advances in quantum technologies.

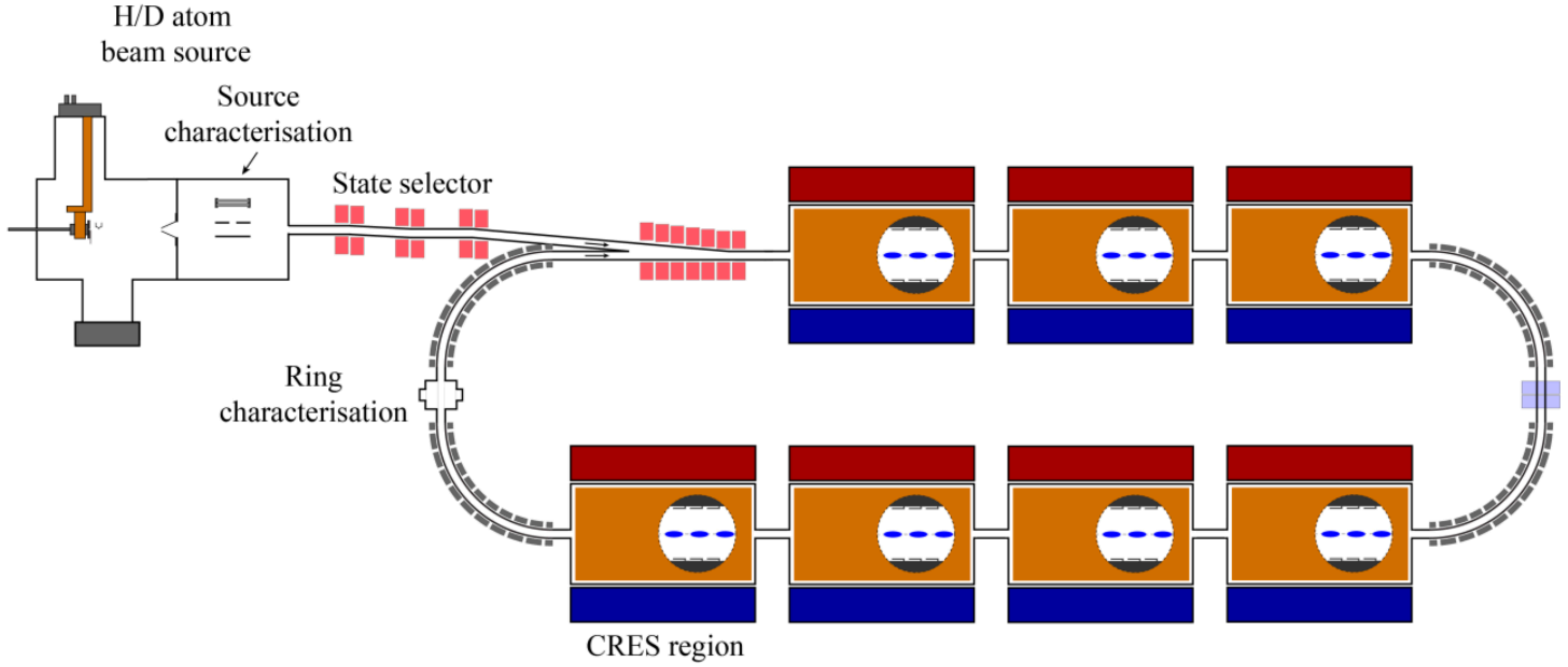


arXiv:2412.06338

DOI 10.1088/1367-2630/adc624

QTNM Schematics and Scalability



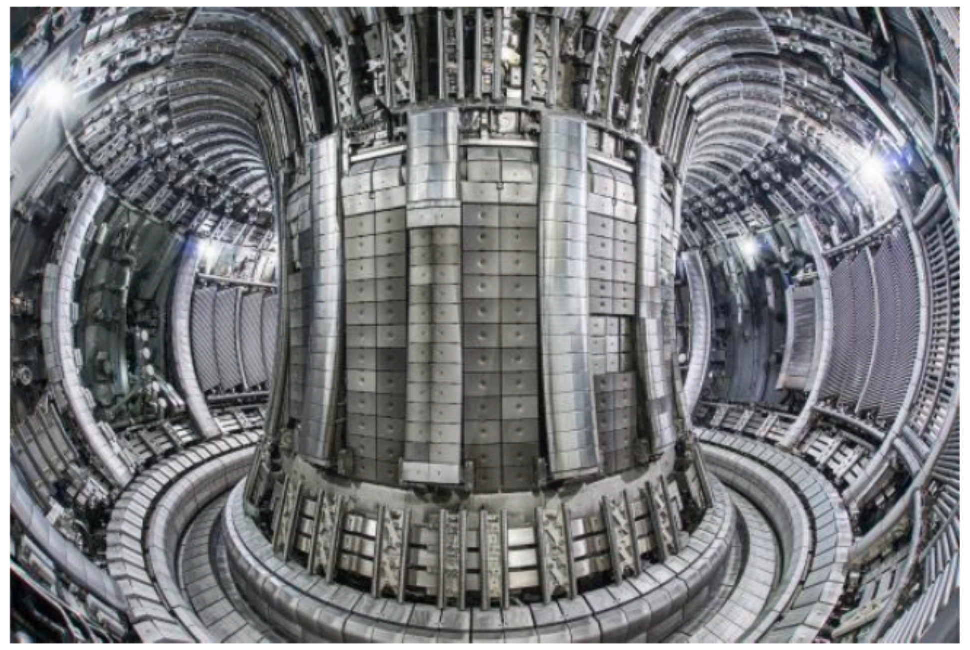


Technology Demonstration (2021-2025):
CRESDA-0 = CRES Demonstration Apparatus

- **Quantum** noise limited microwave **sensors** at high TRL for CRES at ~18GHz (corresponding to 0.7T field)
- 3D B-field mapping with $\lesssim 1\ \mu T$ precision, using H-atoms as **quantum sensors** (Rydberg Magnetometry)
- Production and confinement of **H-atoms**, $\geq 10^{12}\ cm^{-3}$
- Modelling tools for CRES and neutrino mass

Preferred Location:

Culham Centre for Fusion Energy



Project Phases

<u>CRESDA0</u> → CRESDA+Tritium → 100 meV → 50 meV → 10 meV

Current (2021-2025)

2026-2030

2030……………………………………..2040

Ultimate experiment by international collaboration

Mass measurement while detecting Relic Neutrinos

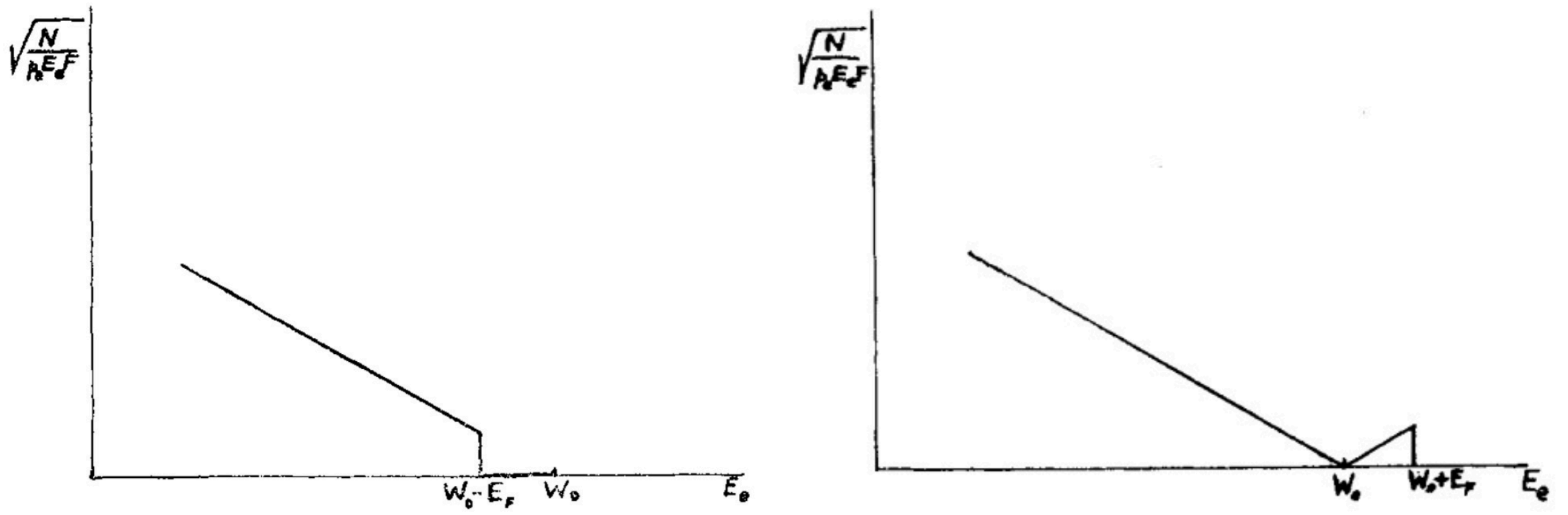
Weinberg, 1962

Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

Modern cosmological theories imply that the universe is filled with a shallow degenerate Fermi sea of neutrinos. In the steady state and oscillating models (and perhaps also the "big bang" theories) it can be shown rigorously that the proportion of filled neutrino levels (plus the proportion of filled antineutrino levels) is precisely one up to a finite Fermi energy E_F. The proof takes into account both absorption and the repressive effects of already filled levels on neutrino emission. Experiment shows that $E_F \lesssim 200$ eV for antineutrinos and $E_F \lesssim 1000$ eV for neutrinos. The degenerate neutrinos could be observed (if $E_F > 10$ eV) by looking for apparent violations of energy conservation in β^- decay. In the steady state and evolutionary cosmologies E_F is much too low to ever be observed, but in the oscillating cosmologies $E_F \simeq 5R_c$ MeV, where R_c is the minimum radius of the universe in units of its present radius; thus experiment already shows that the universe will contract by a factor over 10^3, if at all. Astronomical evidence plus Einstein's field equation (without cosmological constant) require in an oscillating cosmology that $E_F < 2\times10^{-3}$ eV (so $R_c < 10^{-9}$) and suggest that higher energy neutrinos may represent the bulk of the energy of the universe. A model universe incorporating this idea is constructed.

[Phys. Rev. 128, 1457]



Deviation from the energy conservation at the end point of the β^+/β^- due to the interaction with massless relic neutrino background

Cocco, Messina & Mangano, 2007

Probing Low Energy Neutrino Backgrounds with Neutrino Capture on Beta Decaying Nuclei

A. G. Cocco[1], G. Mangano[1] and M. Messina[2]
[1] Istituto Nazionale di Fisica Nucleare - Sezione di Napoli - Complesso Universitario di Monte S.Angelo, I-80126, IT
[2] Laboratorium für Hochenergiephysick - Universität Bern - Sidlerstrasse 5, CH-3012 Bern, CH
E-mail: marcello.messina@cern.ch

Abstract. In this paper we investigate the possibility to detect Cosmological Relic Neutrinos, the oldest (after the Cosmological Microwave Background) particles produced after the Big Bang. In this paper we make a short overview of the methods proposed so far and we propose a new method that allows the CRN detection based on beta decaying target nuclei. The most important features of this process is that it does not require any minimum energy in order the neutrino interacts with nucleus. A detailed calculation of the cross section of the neutrino interaction on beta decaying nuclei is shown. The quoted value of the cross section times the neutrino velocity is of the order of $10^{-42} cm^2 \cdot c$.

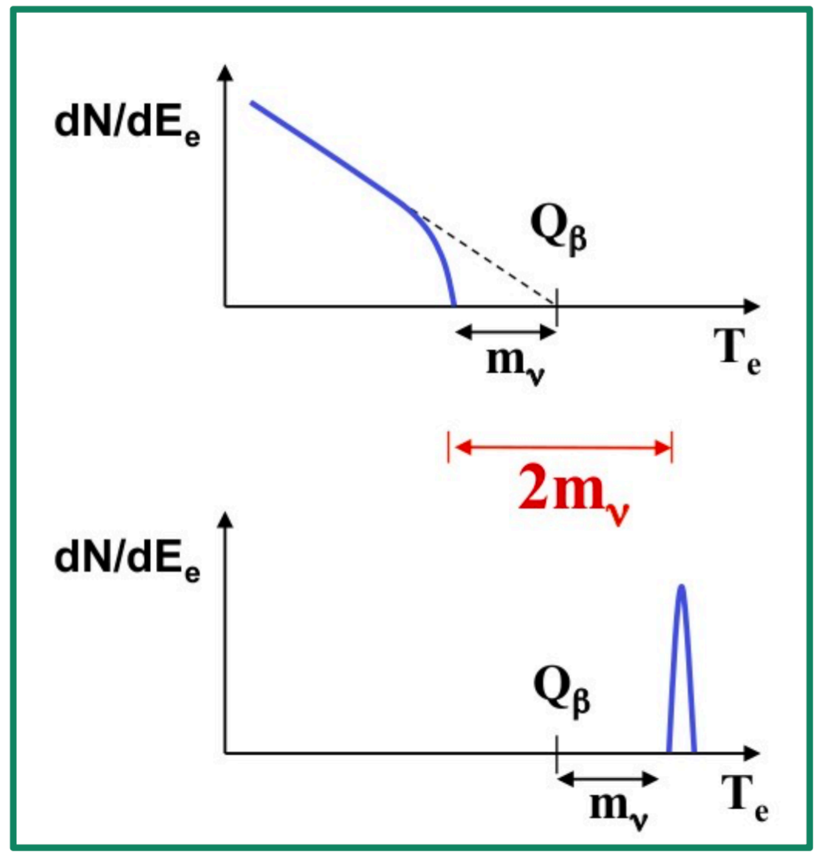
[AG.Cocco, G.Mangano, M.Messina JCAP 06(2007)015]

★ Threshold-less

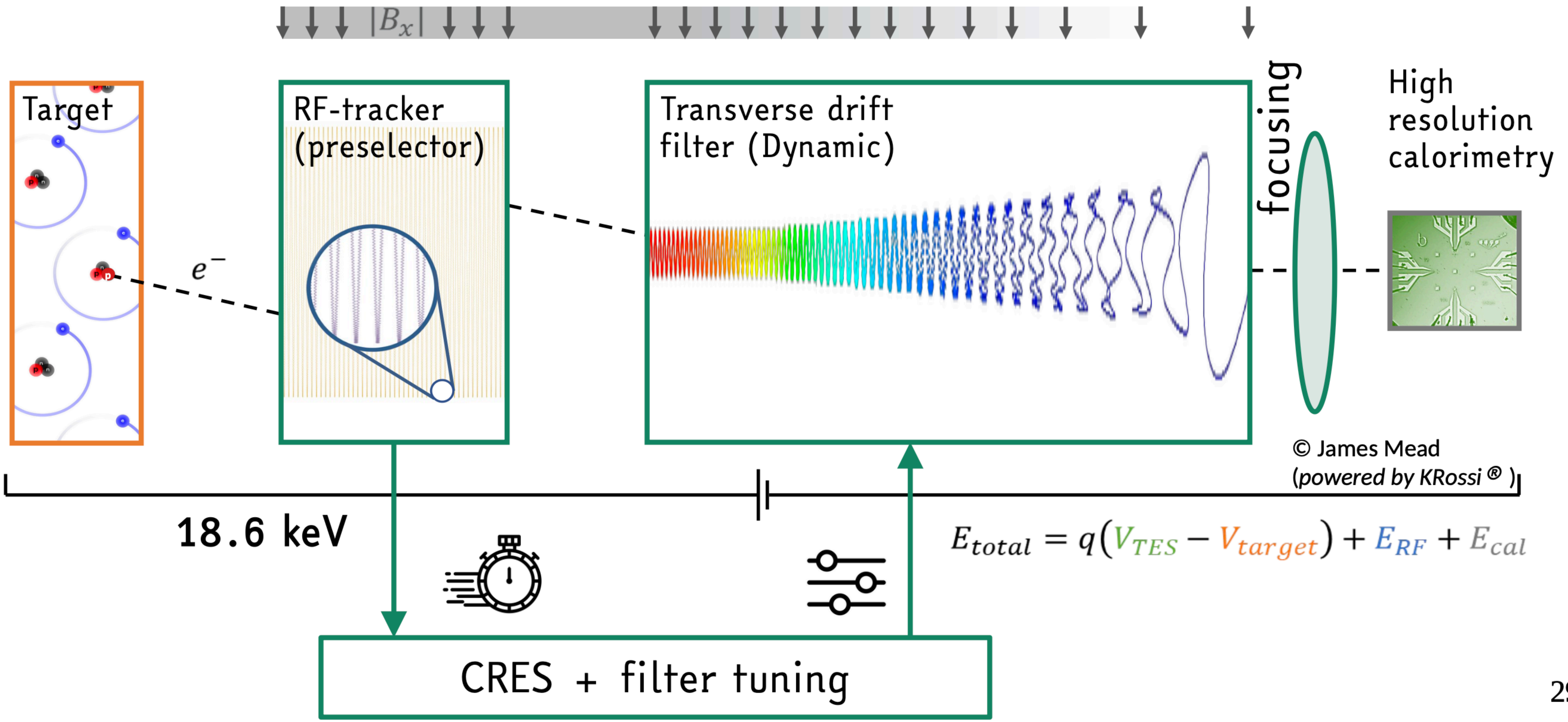
$$\nu_e + (A,Z) \to (A,Z+1) + e^-$$

★ Monochromatic peak at Q+m

★ Neutrino mass as by-product



PTOLEMY detection concept



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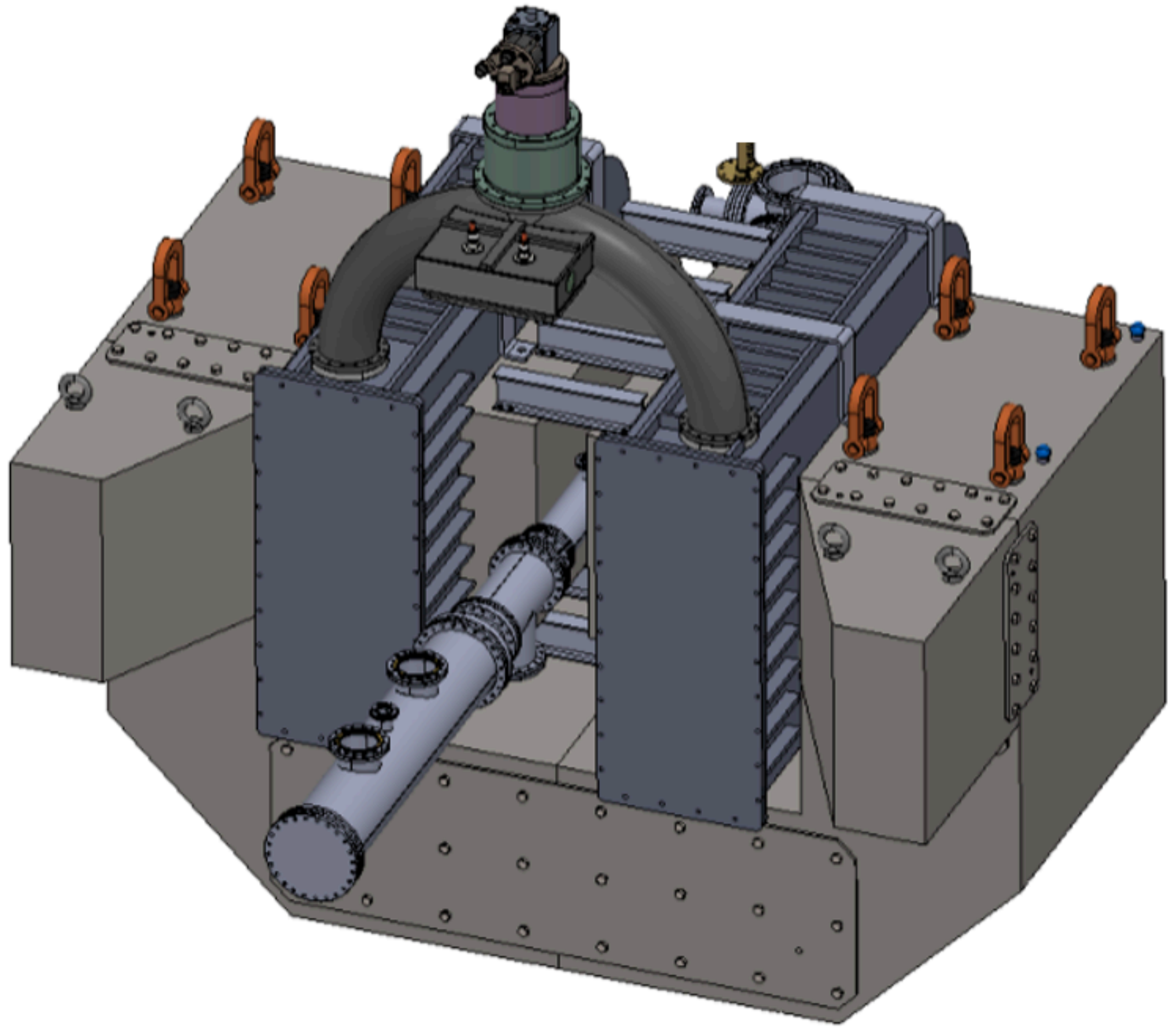
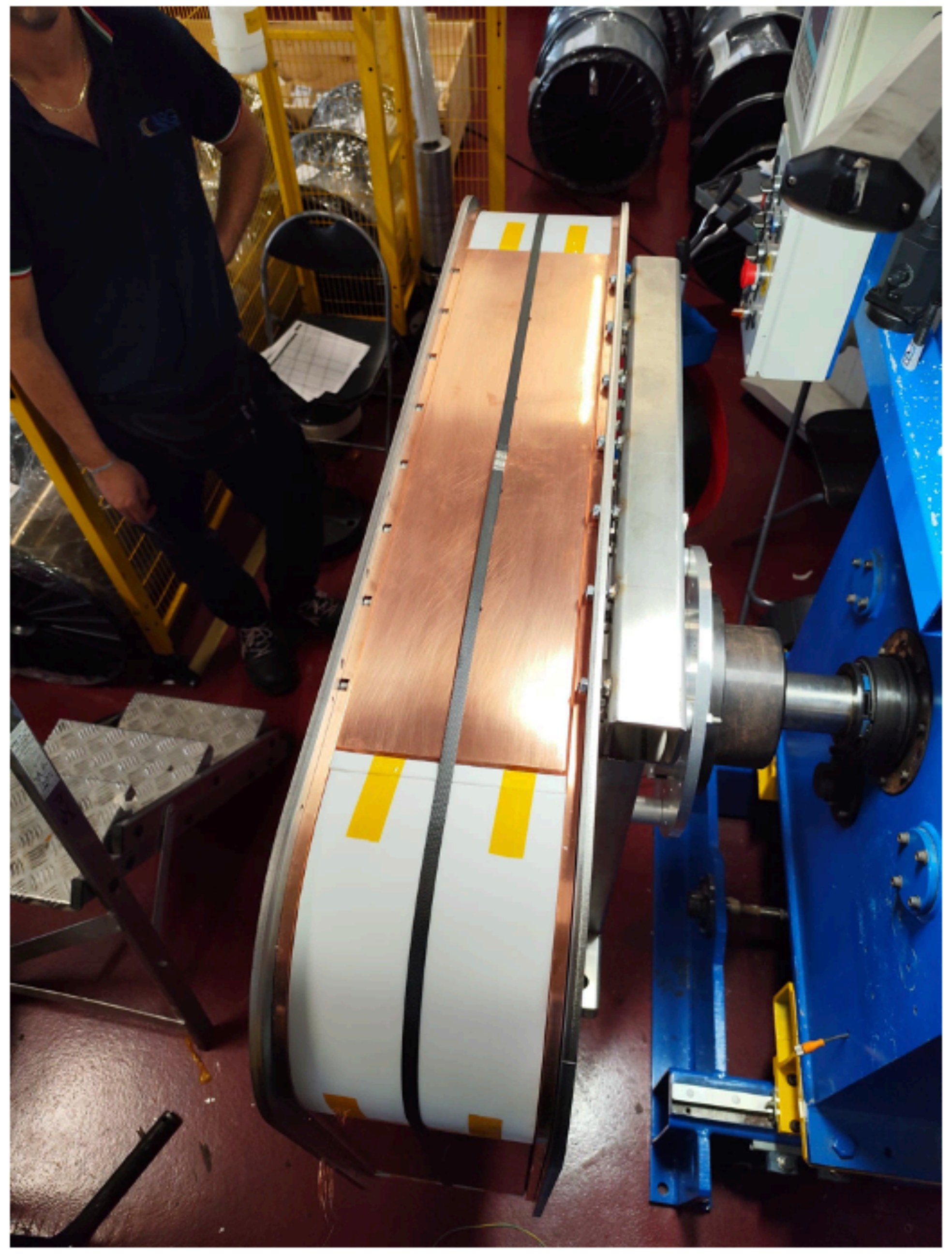
Superconductive magnet



★ **Uniform region:**
~10 x 10 x 80 cm
★ **ΔB/B (1T) ~ 10^{-4}**



@ASG, Genova, Italy

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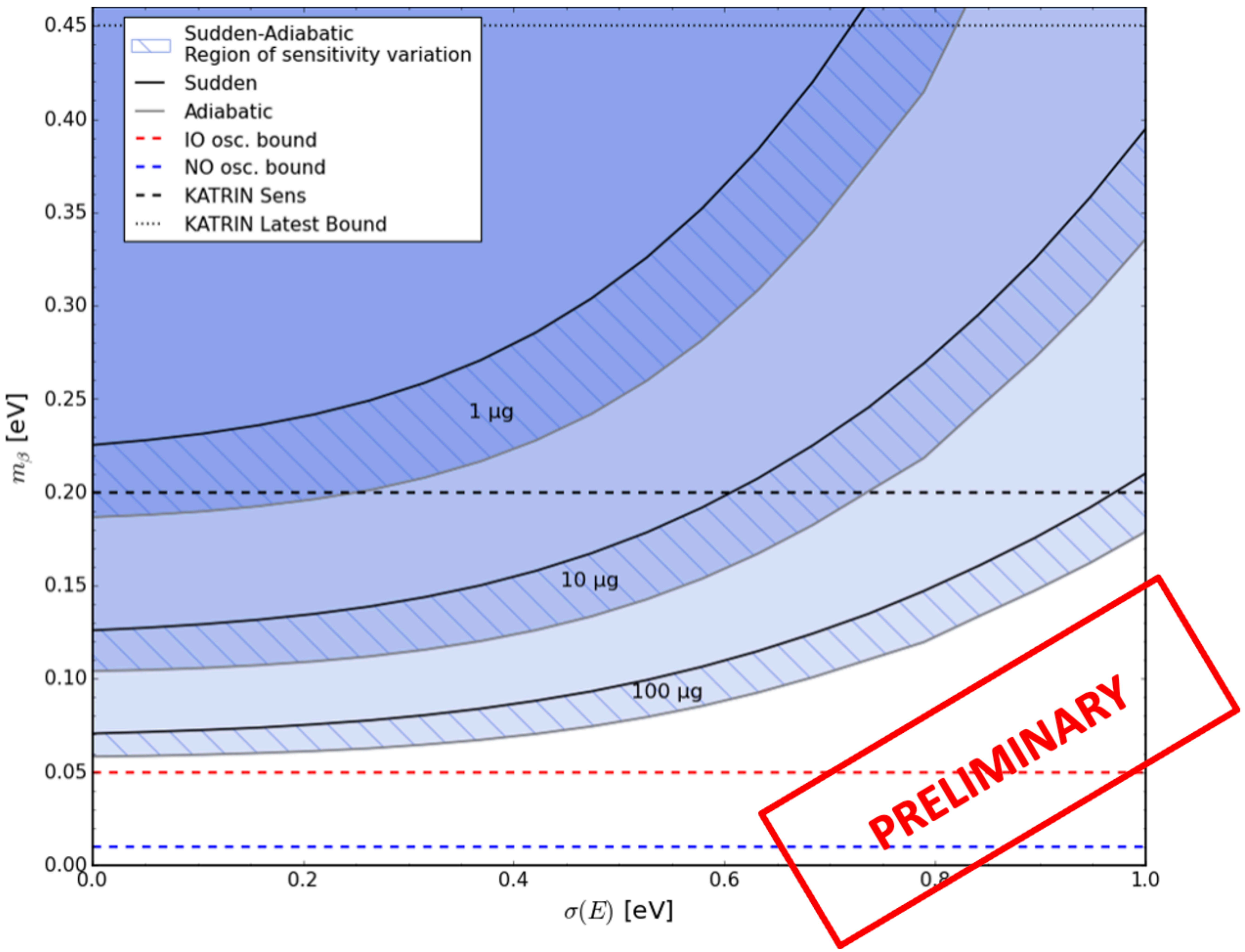
Realistic sensitivity

From profile likelihood



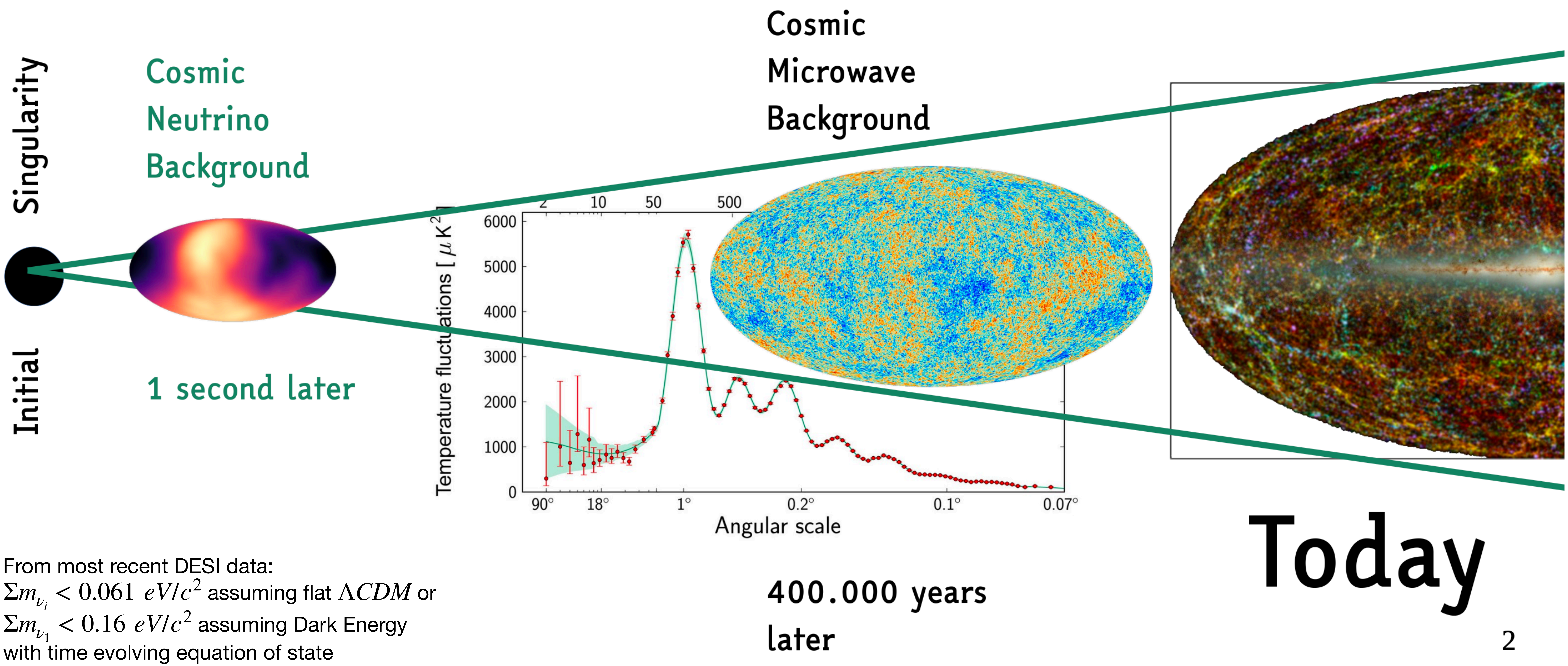
★ Weakly dependent upon energy resolution (>400meV)

★ 1 μg: competitive with the forthcoming generation

★ 100 μg (0.5 m²) close to probe the IO scenario

55

Neutrino mass hints from Cosmology



From most recent DESI data:
$\Sigma m_{\nu_i} < 0.061\ eV/c^2$ assuming flat ΛCDM or
$\Sigma m_{\nu_1} < 0.16\ eV/c^2$ assuming Dark Energy with time evolving equation of state

Conclusion

- From beta decays measurements the most stringent limits give us: m_β< 0.45 eV/c^2 (m_β< 0.31 eV/c^2)
- From Cosmology $\Sigma m_{\nu_i} < 0.061 eV/c^2$ assuming ΛCDM or $\Sigma m_{\nu_1} < 0.16 eV/c^2$ assuming Dark Energy
- Neutrino Oscillation " m_{ν_e}"$> 0.050\ eV/c^2$ (IO) or "m_{ν_e}" $> 0.009\ eV/c^2$ (NO)

In the next 10 years we might be hitting the 50 meV/c^2 mass sensitivity