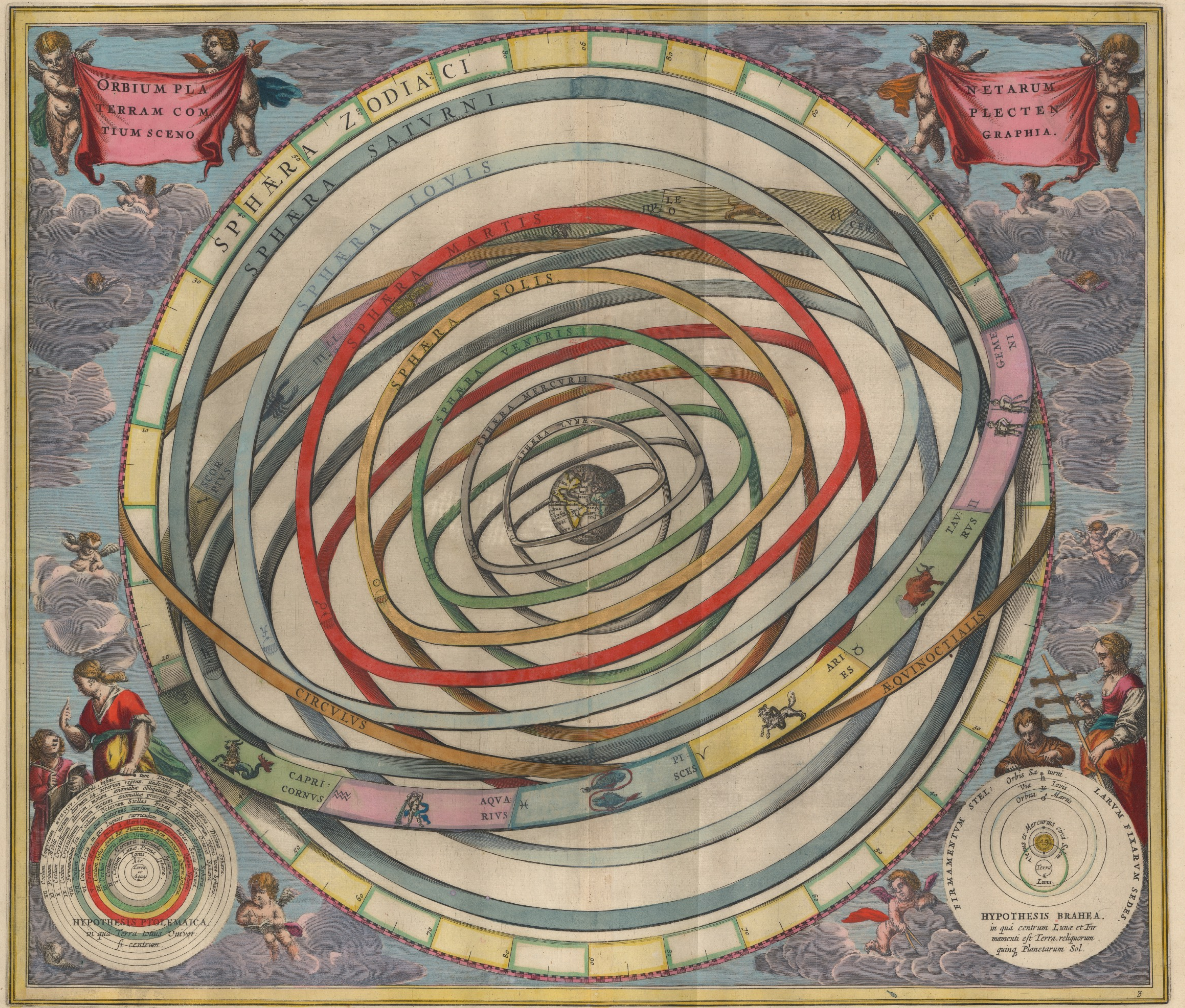
Reconciling the Neutrino Universe



May 30th, 2025
Open Questions in the
Invisible Universe

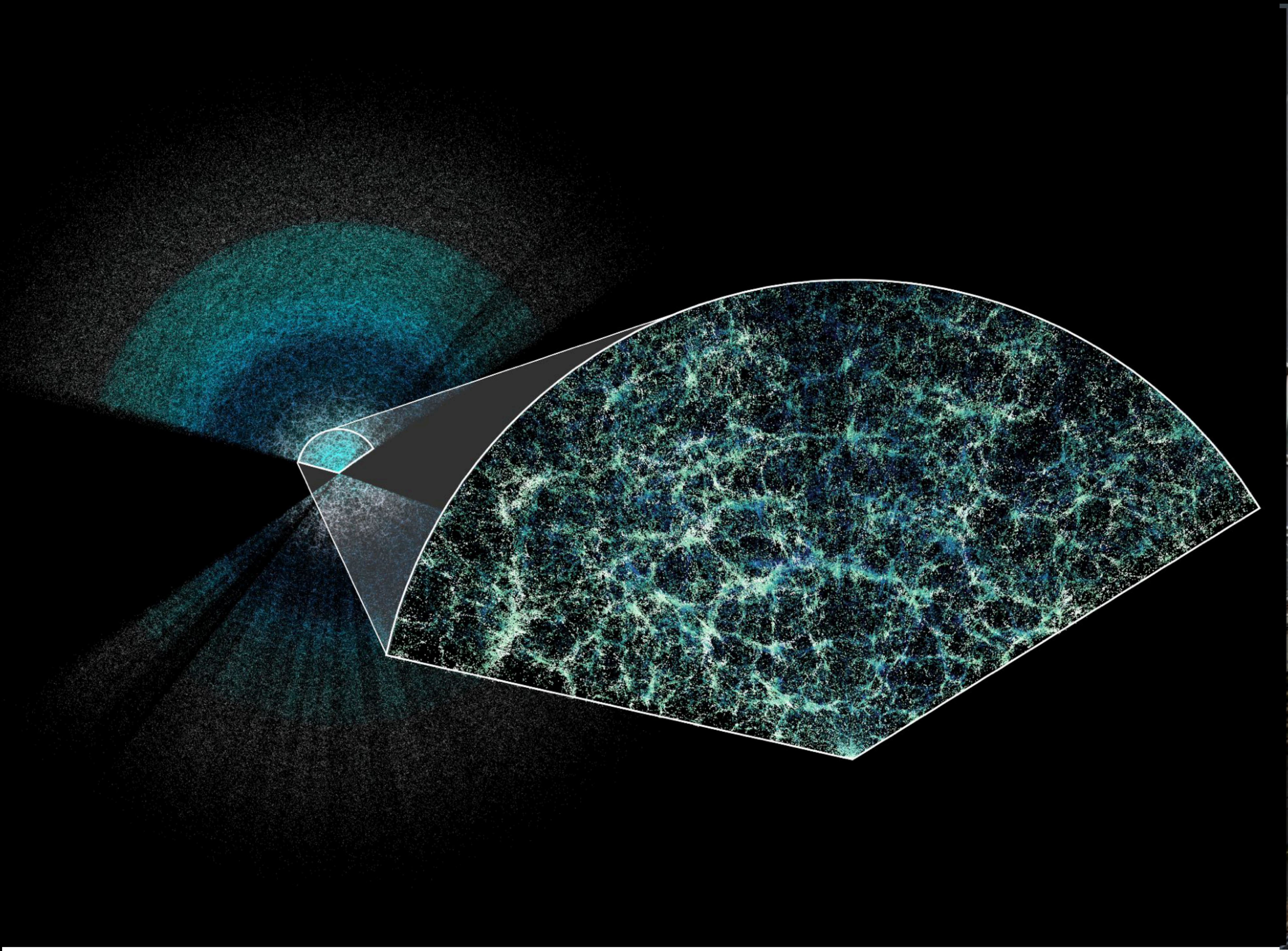
Joseph A. Formaggio
MIT

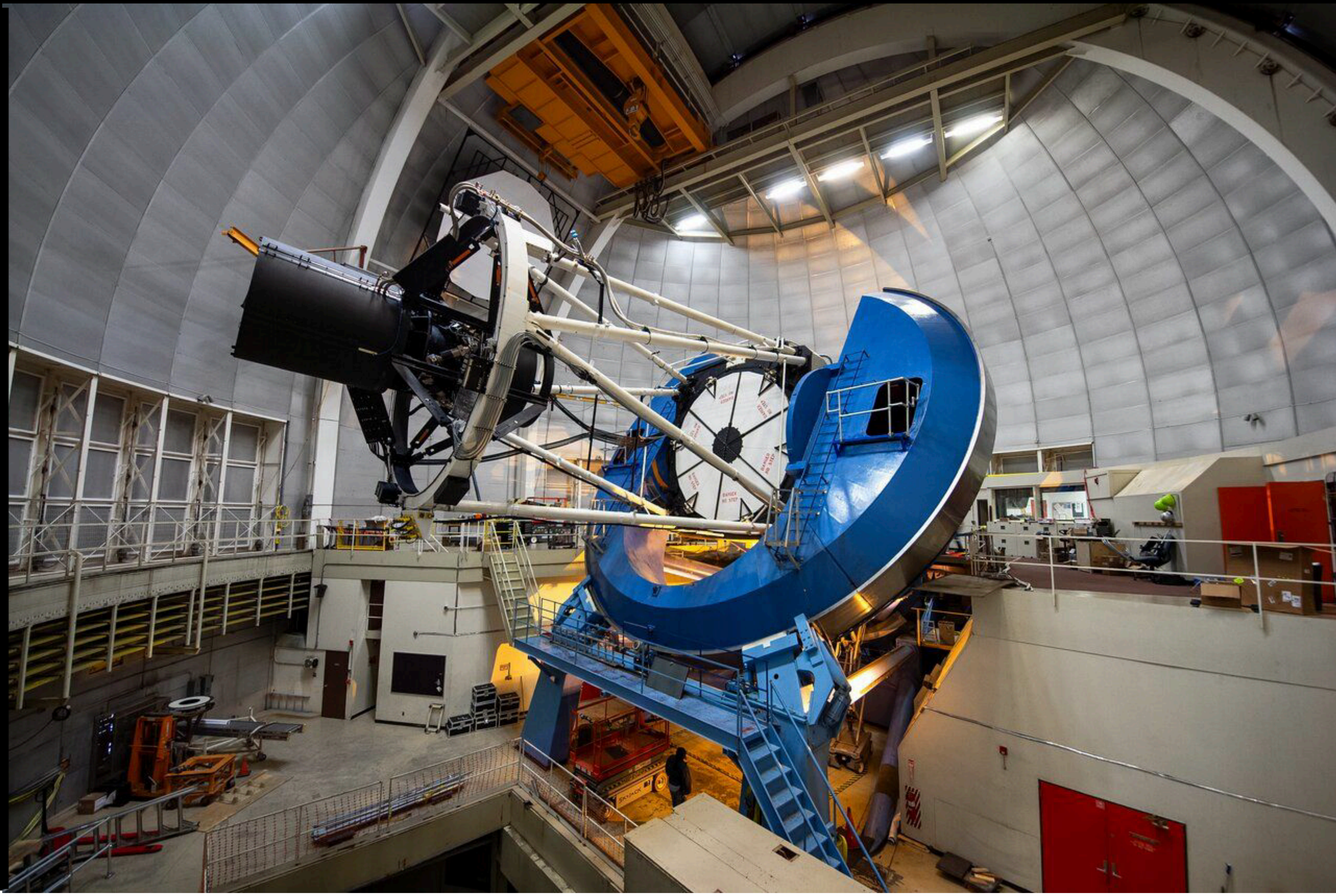
Hypothesis

Ptolemaica...

Reconciling neutrino masses

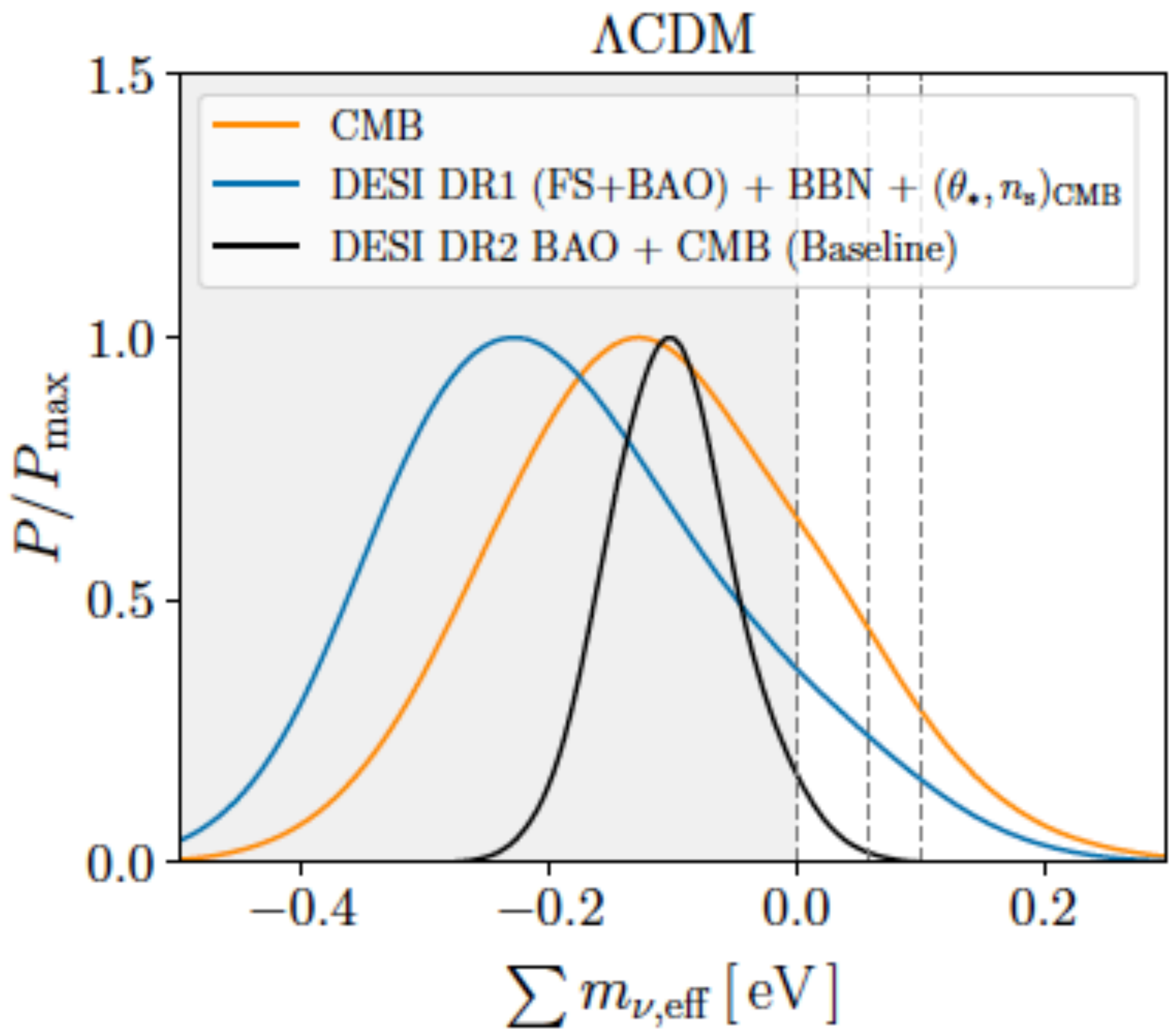
with cosmology

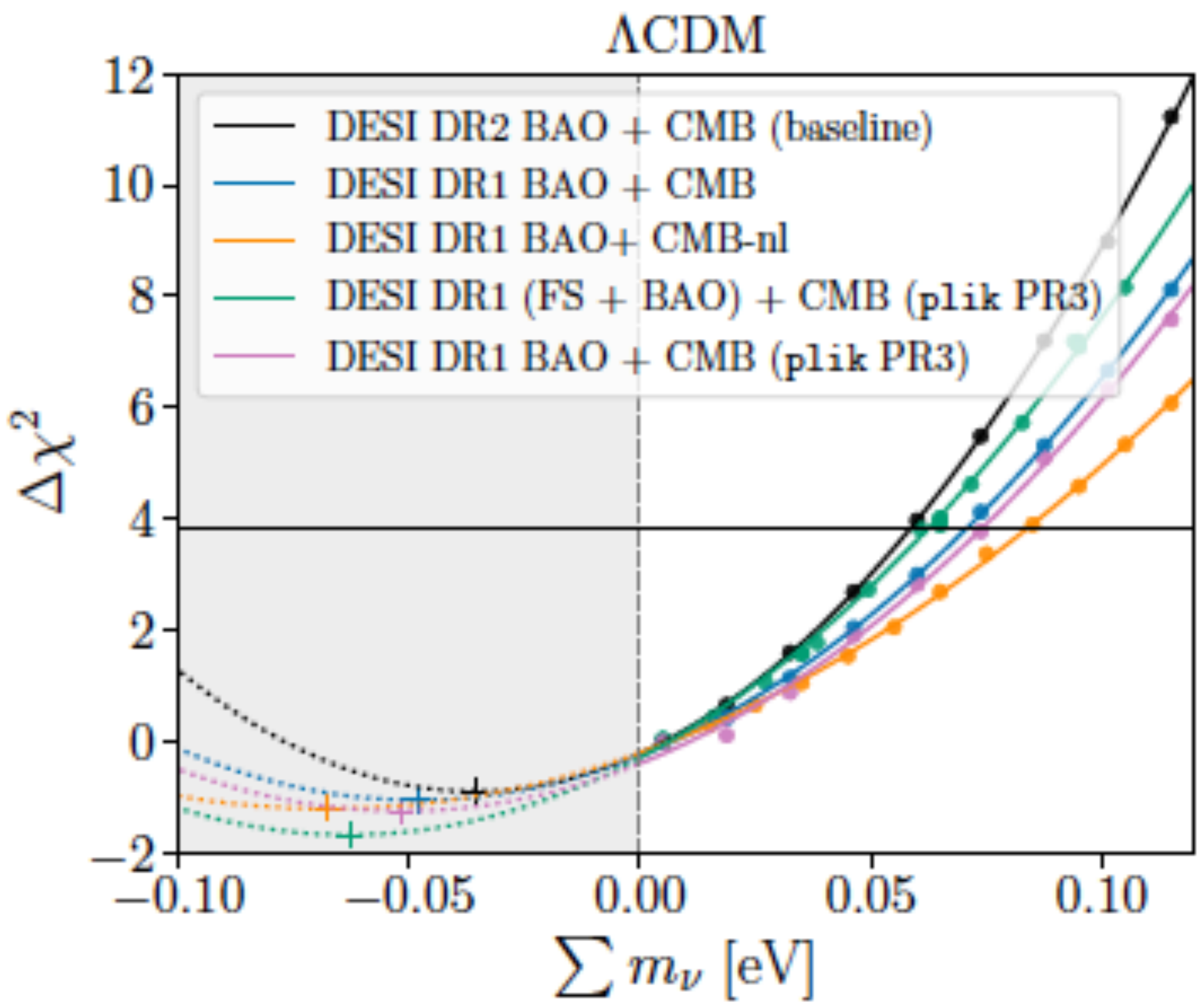




- New results from the DESI all Sky survey.
- Precision measurement of Baryon Acostic Oscillations (BAO).
- Best fit points to negative neutrino masses (starts to rule out oscillations near 4σ)

Willem Elbers, Neutrino 2024
arXiv:2503.14744v2





Serious tension with neutrino oscillation results.

- New results from the DESI all Sky survey.
- Precision measurement of Baryon Acostic Oscillations (BAO).
- Best fit points to negative neutrino masses (starts to rule out oscillations near 4σ)

Willem Elbers, Neutrino 2024
arXiv:2503.14744v2

Ideally, one would like to make measurements that either

constrain cosmological parameters (difficult), or...

make independent measurements of the cosmic neutrino background.

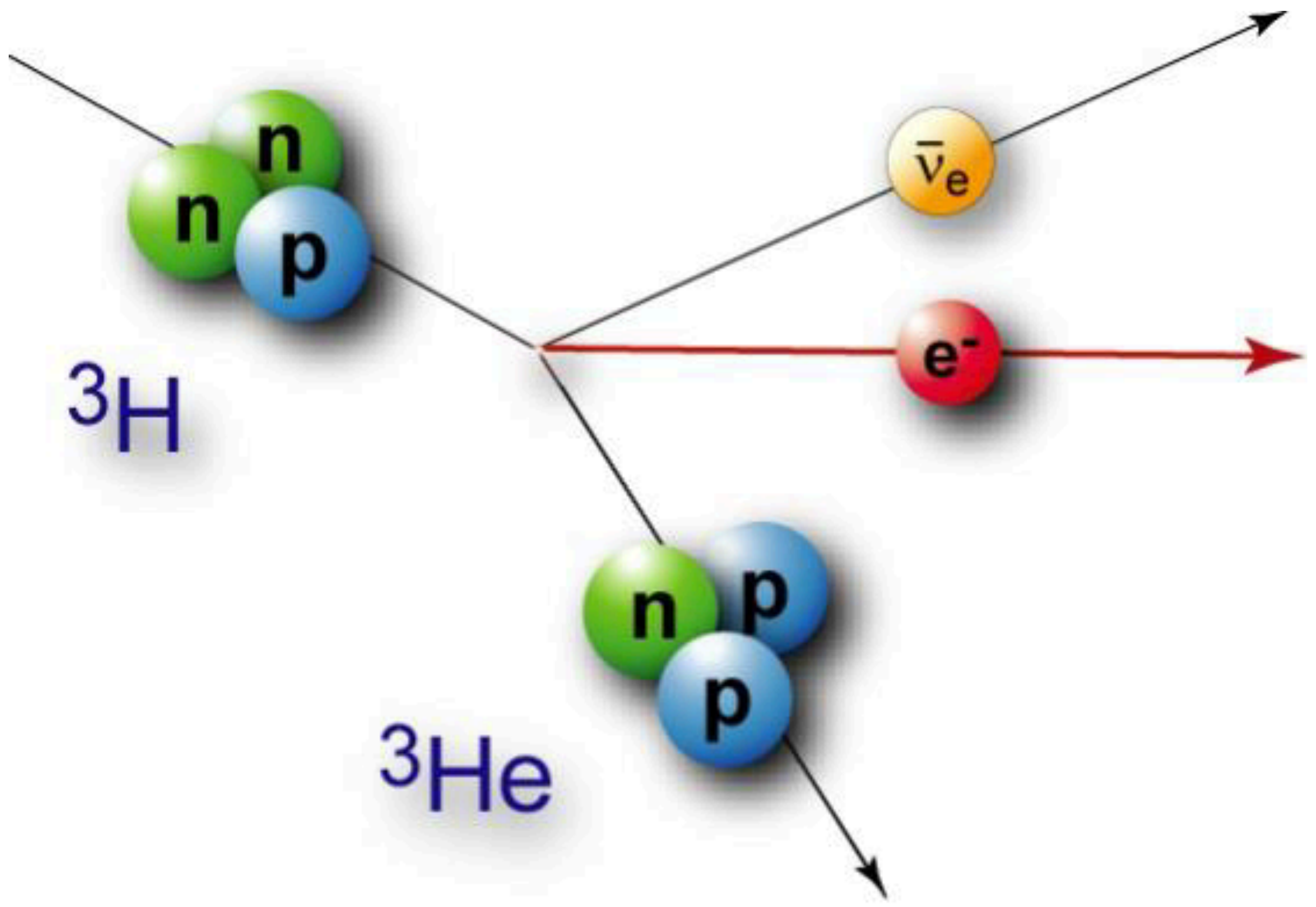
Terrestrial neutrino measurements can provide a path forward.

Terra Cognita…

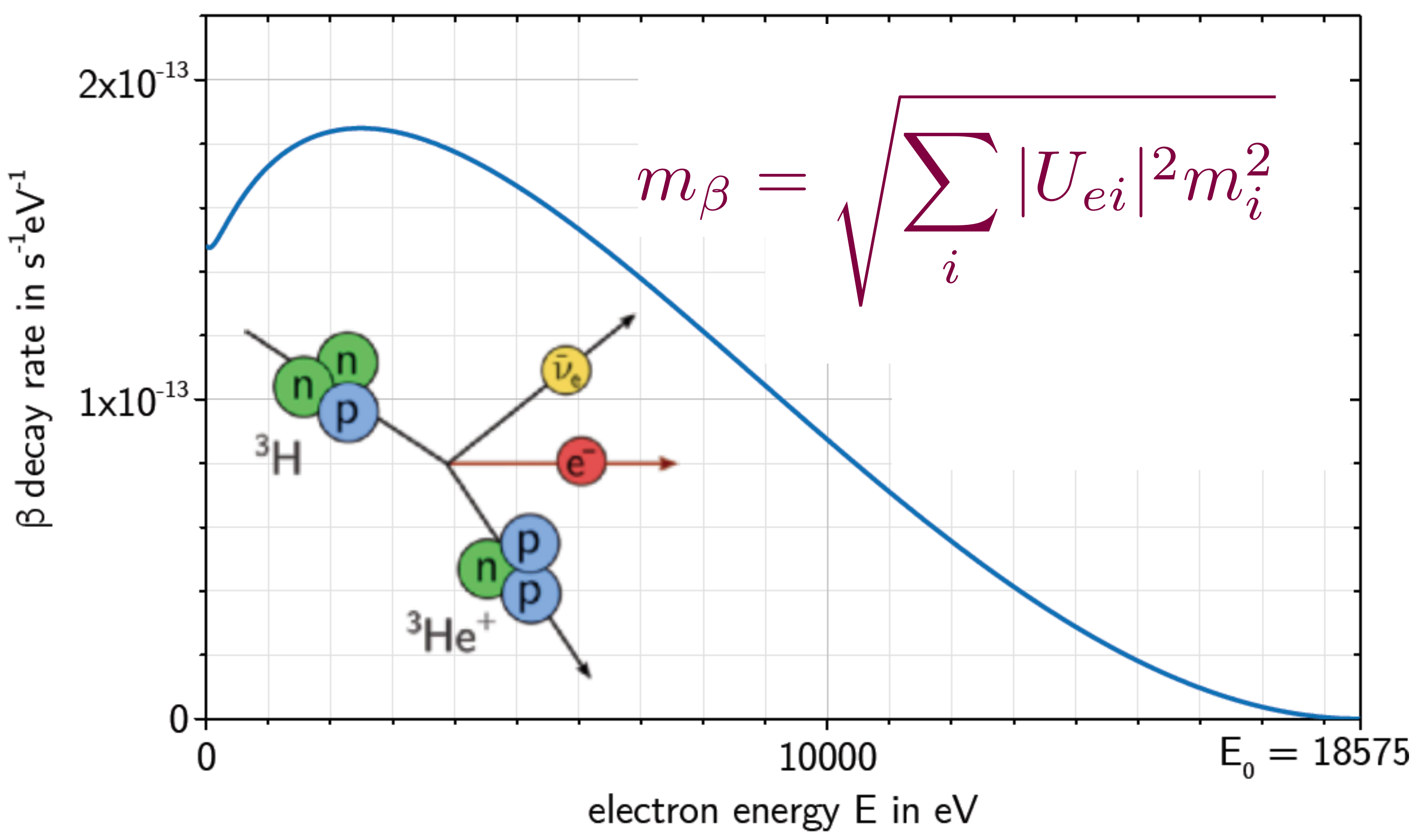
Known techniques:

KATRIN

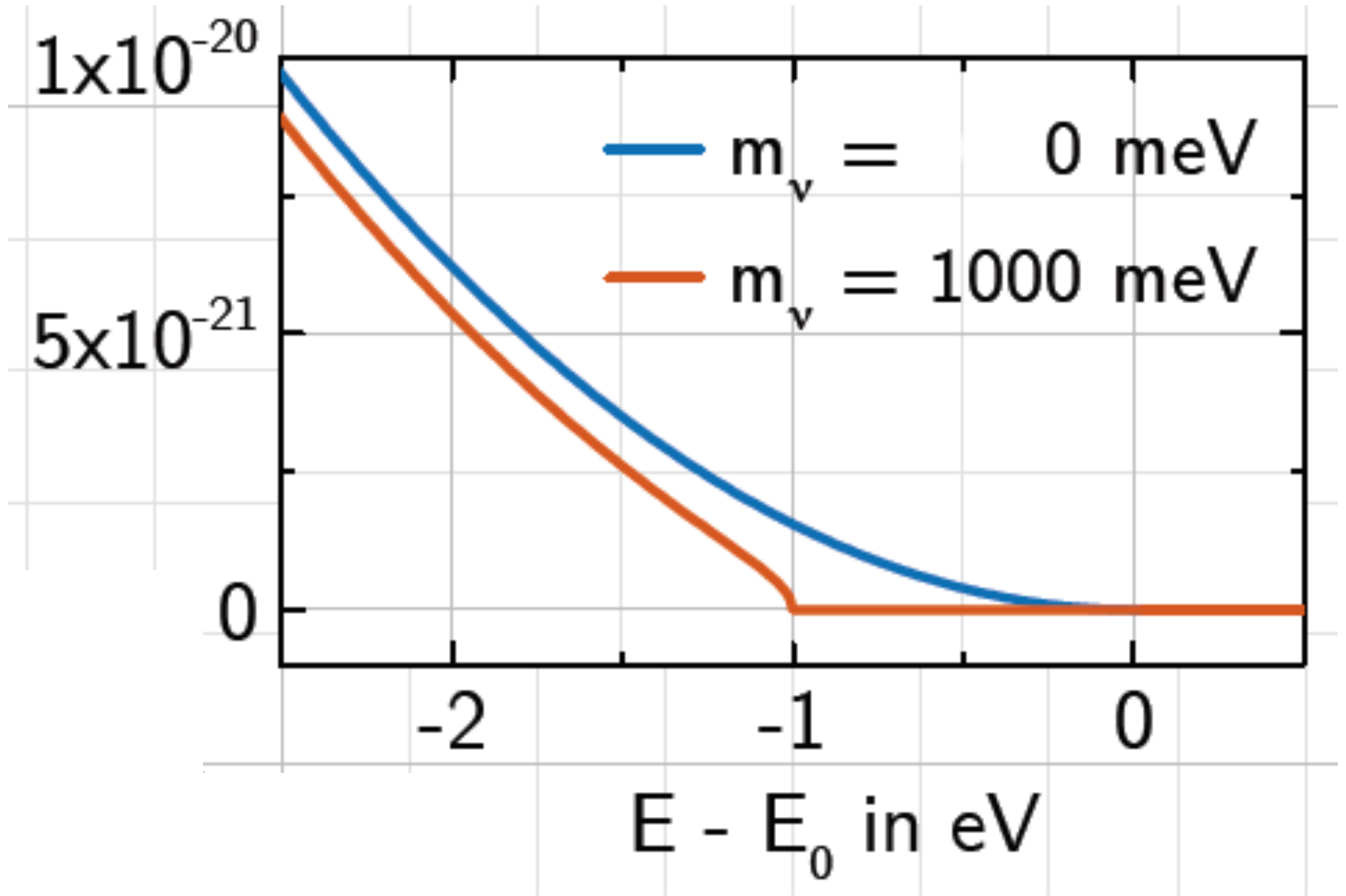
The Basic Idea…



Start with a radioactive isotope (e.g., tritium)



Then measure the outgoing electron's energy



Really zoom in at its maximum energy

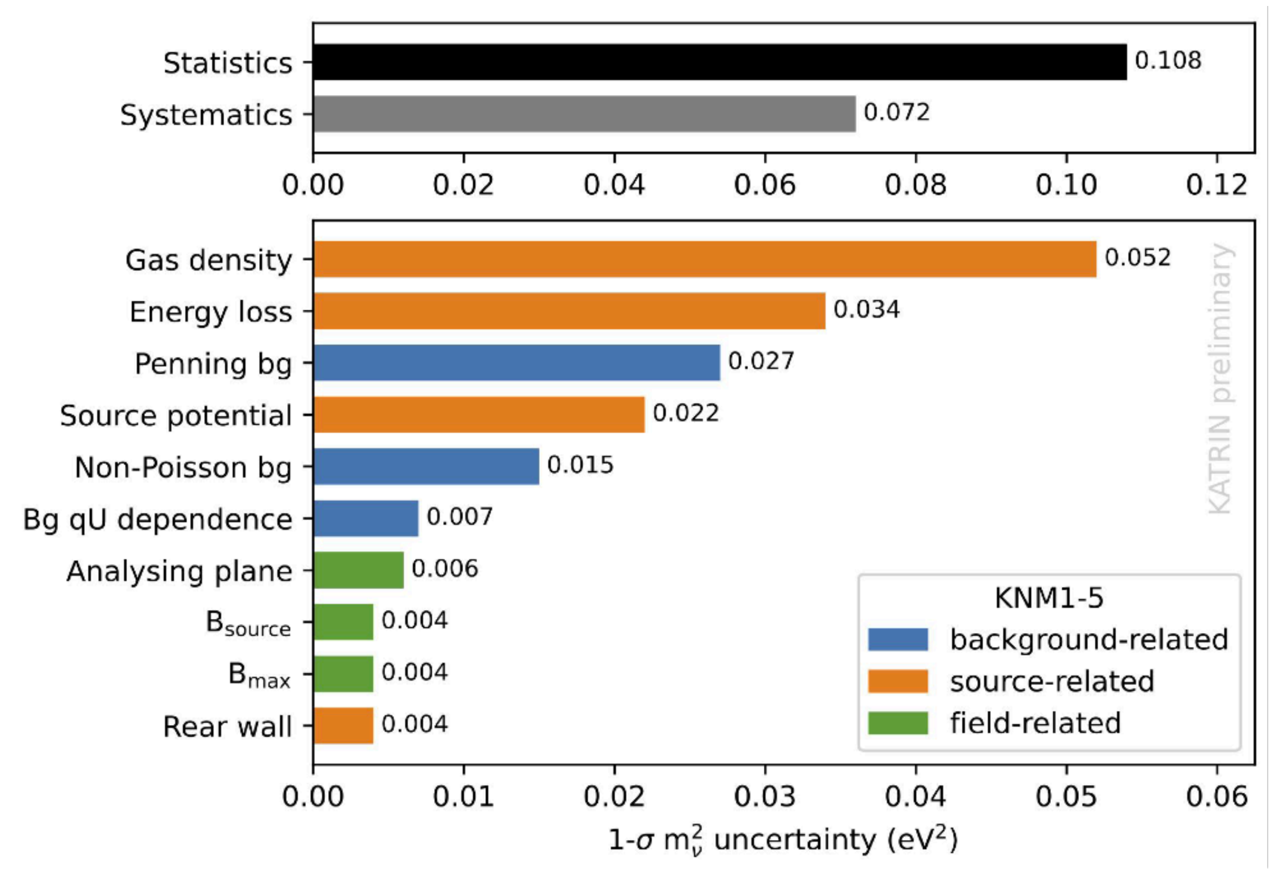
The information about the neutrino mass comes from the distortion of the decay energy spectrum.

High Magnetic Field (Bs)

Low Field B_A

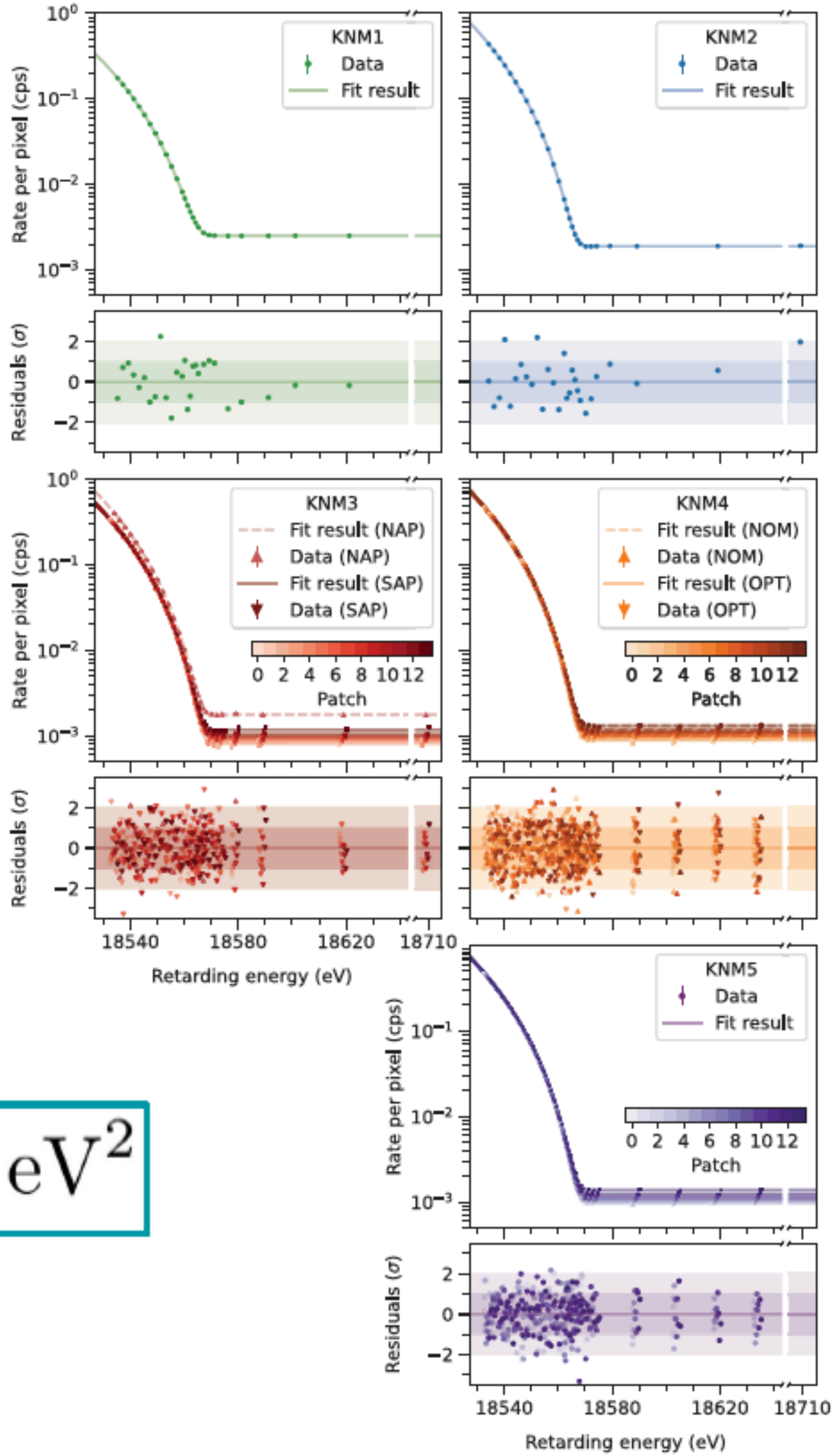
High Magnetic Field (Bs)

Magnetic Adiabatic Collimation w/ Electrostatic Filtering



KATRIN Collaboration et al., Science 388, 180–185 (2025)

$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$



KATRIN

- **KATRIN** releases results from combined KNM1-5 data (about 20% of final projected dataset).
- Strong control of systematics (with gas density and energy loss largest components). Reduction of impact from molecular final states.
- New limit at $\mathbf{m_\beta \leqq 450\ meV/c^2}$ (90% C.L.)
- Data collection to end by 2025 (1000 days). Well-poised to hit final sensitivity of 300 meV/c².
- Ultimately limited by molecular source.

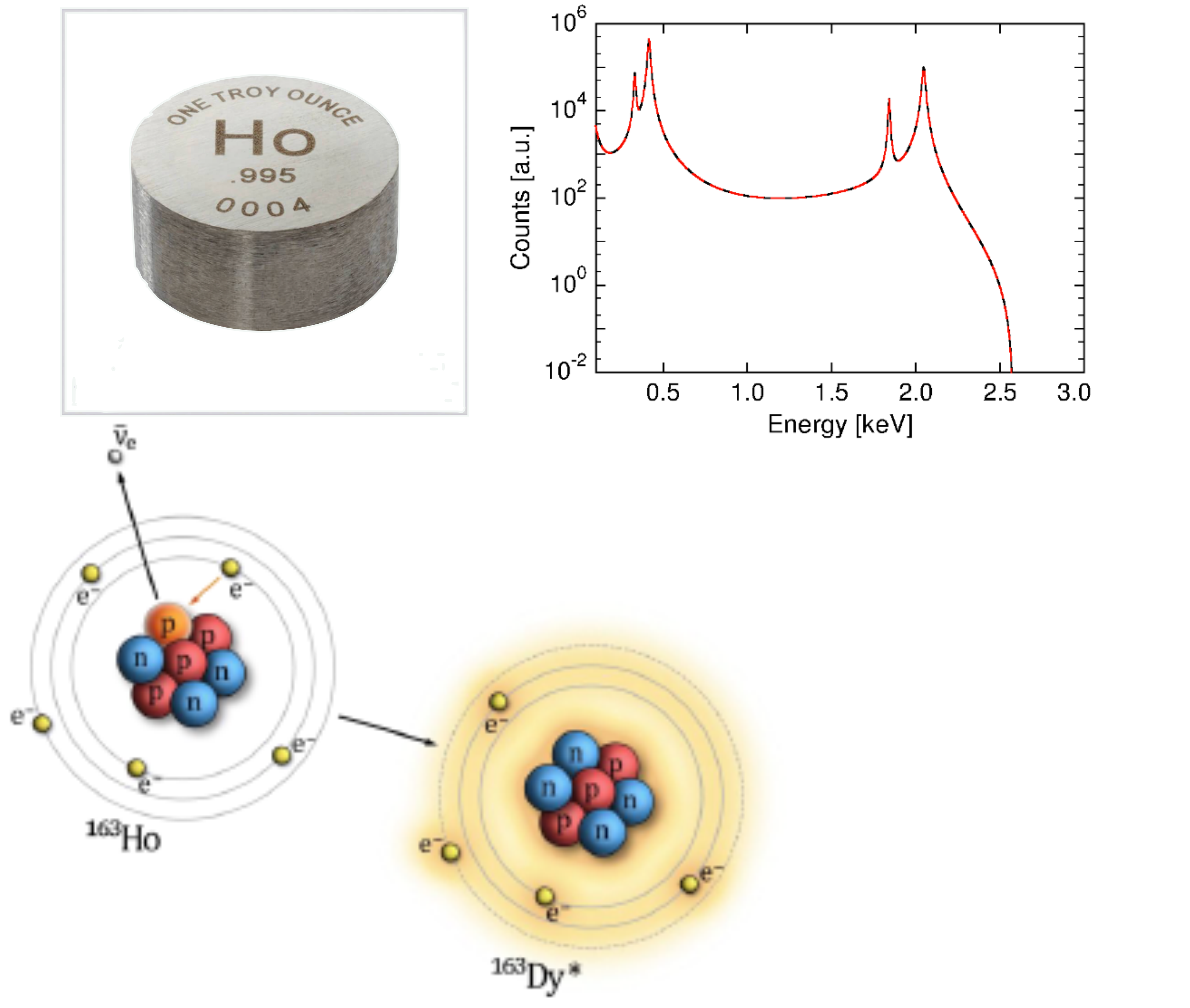
Alexey Lokhov, Neutrino 2024

Sphara Solis

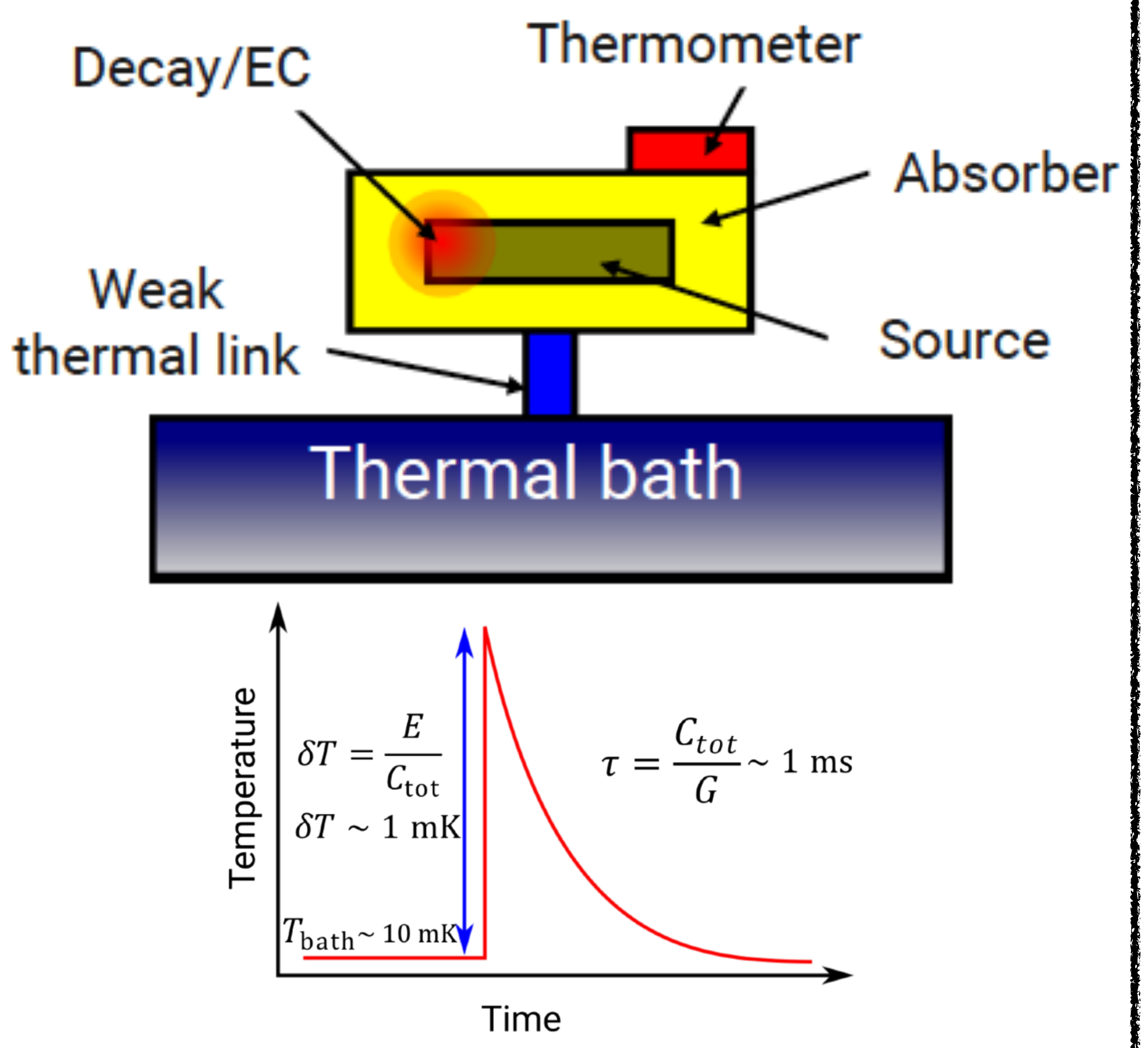
New Techniques:

Calorimetry & CRES

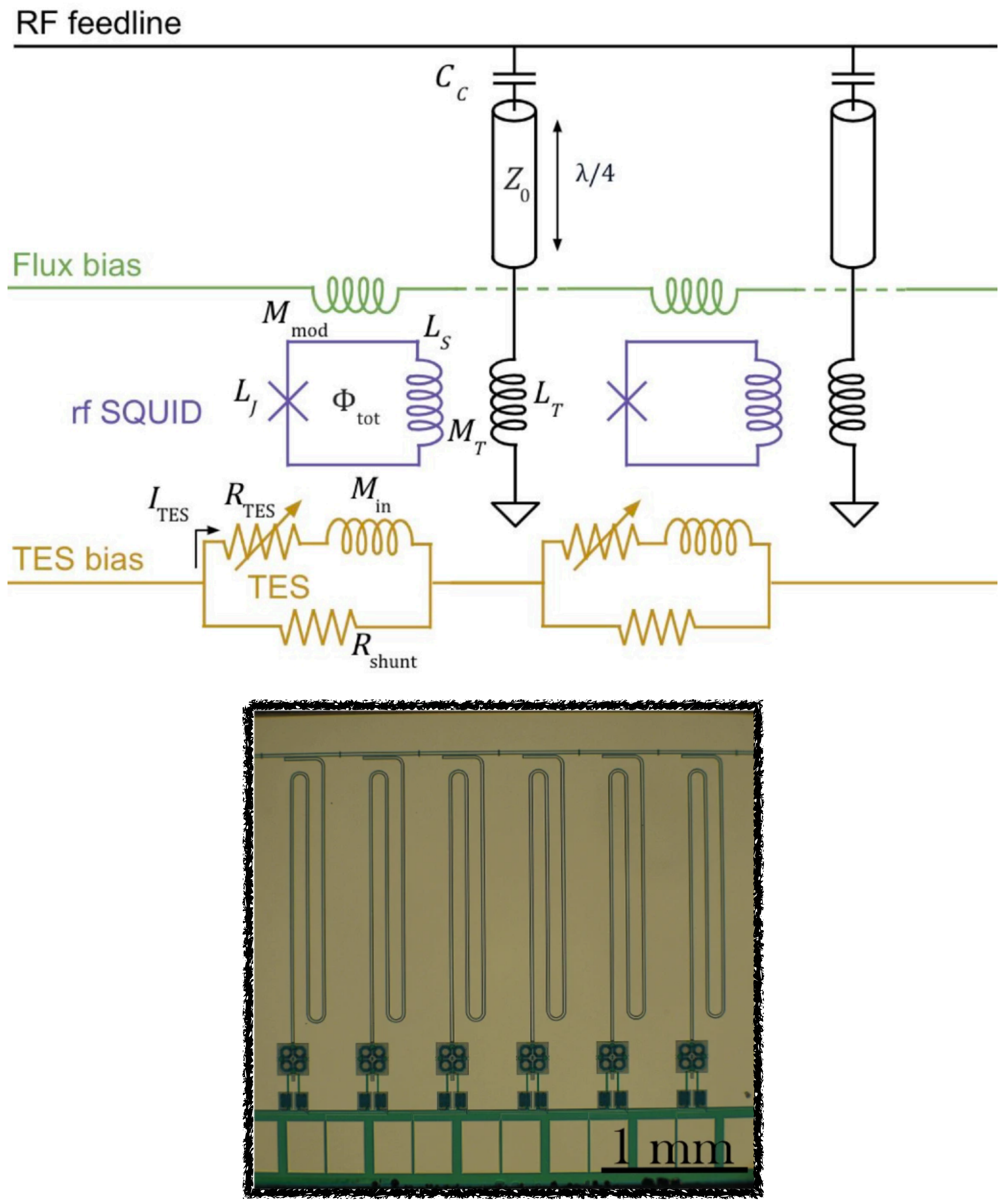
Electron Capture



μ-calometer



Multiplexing



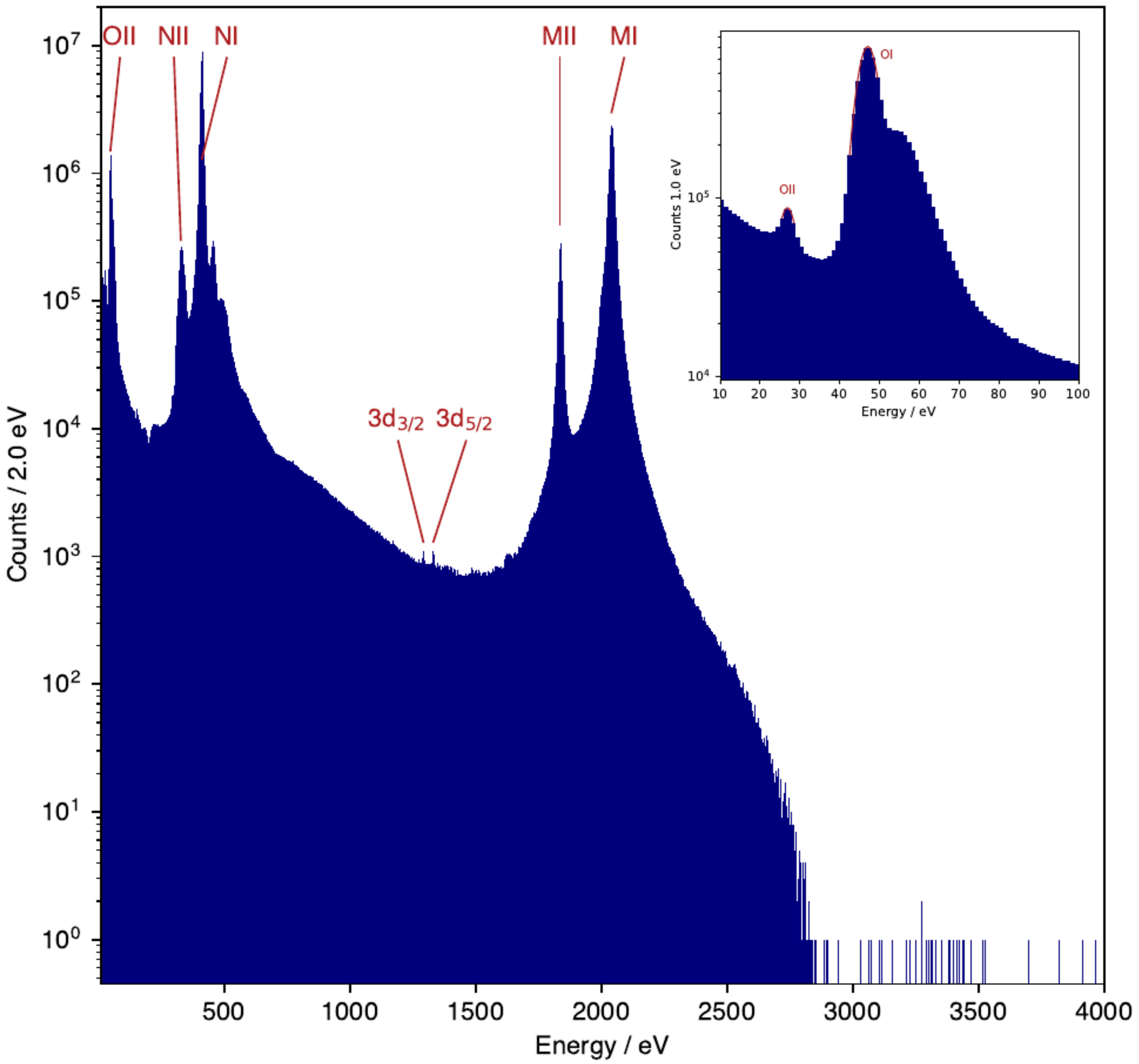
Orthogonal neutrino mass measurement...

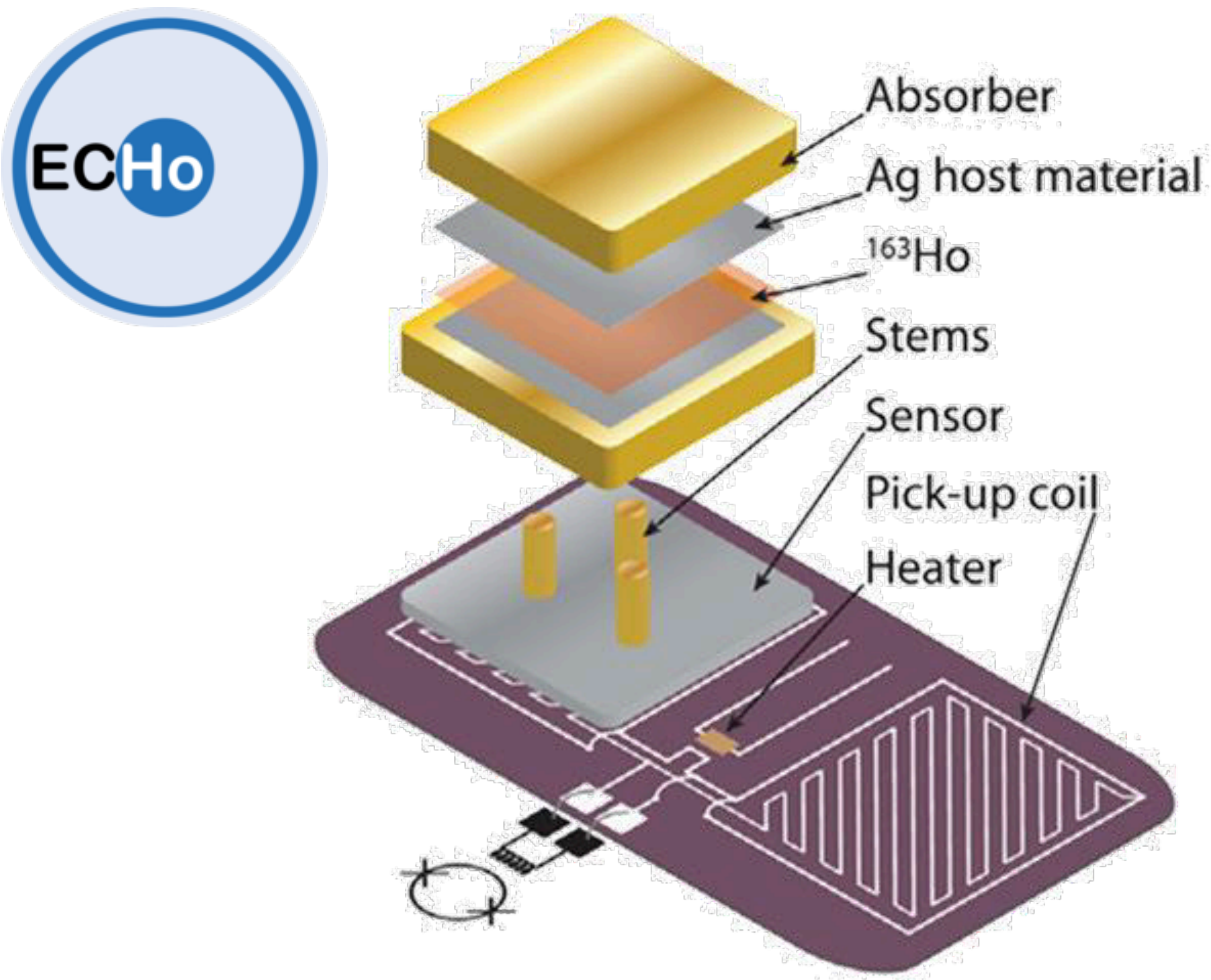
Electron capture (vs beta decay)

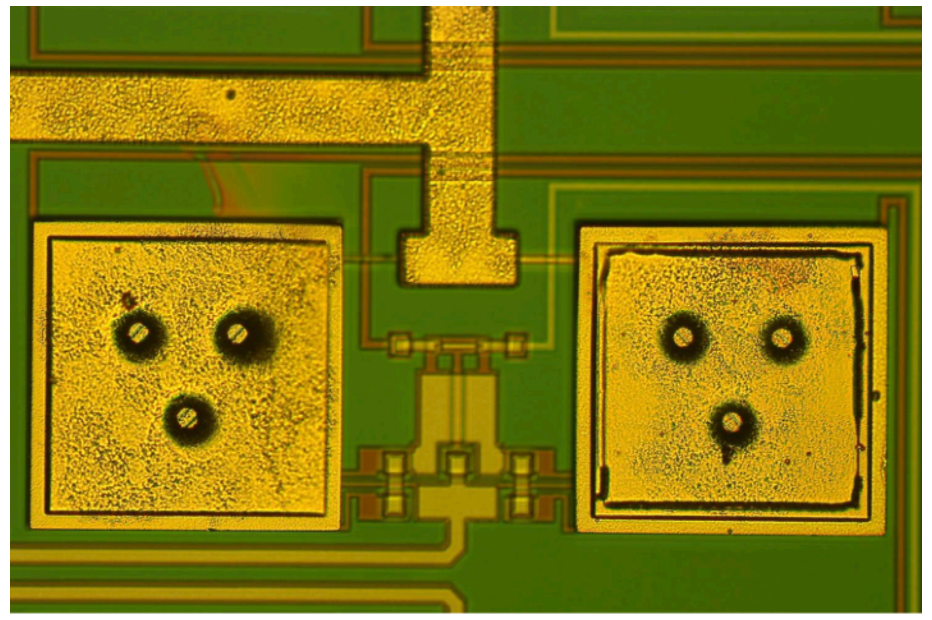
Micro-bolometers

Multiplexed detectors

ECHO Spectrum







ECHO

^{163}Ho implantation on multiplexed detectors

2 x 64 detector modules with Au and Ag host material

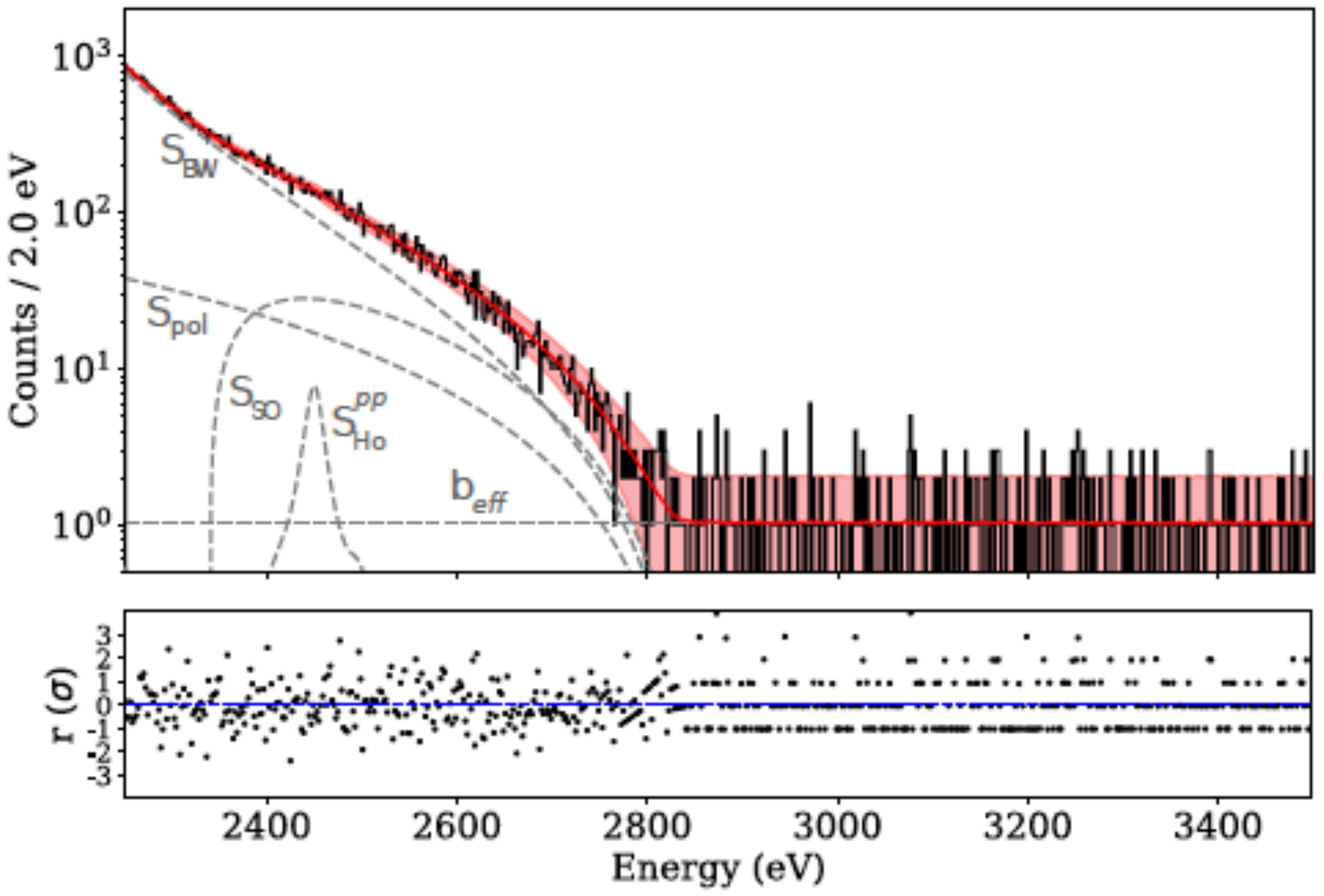
Preliminary limits:

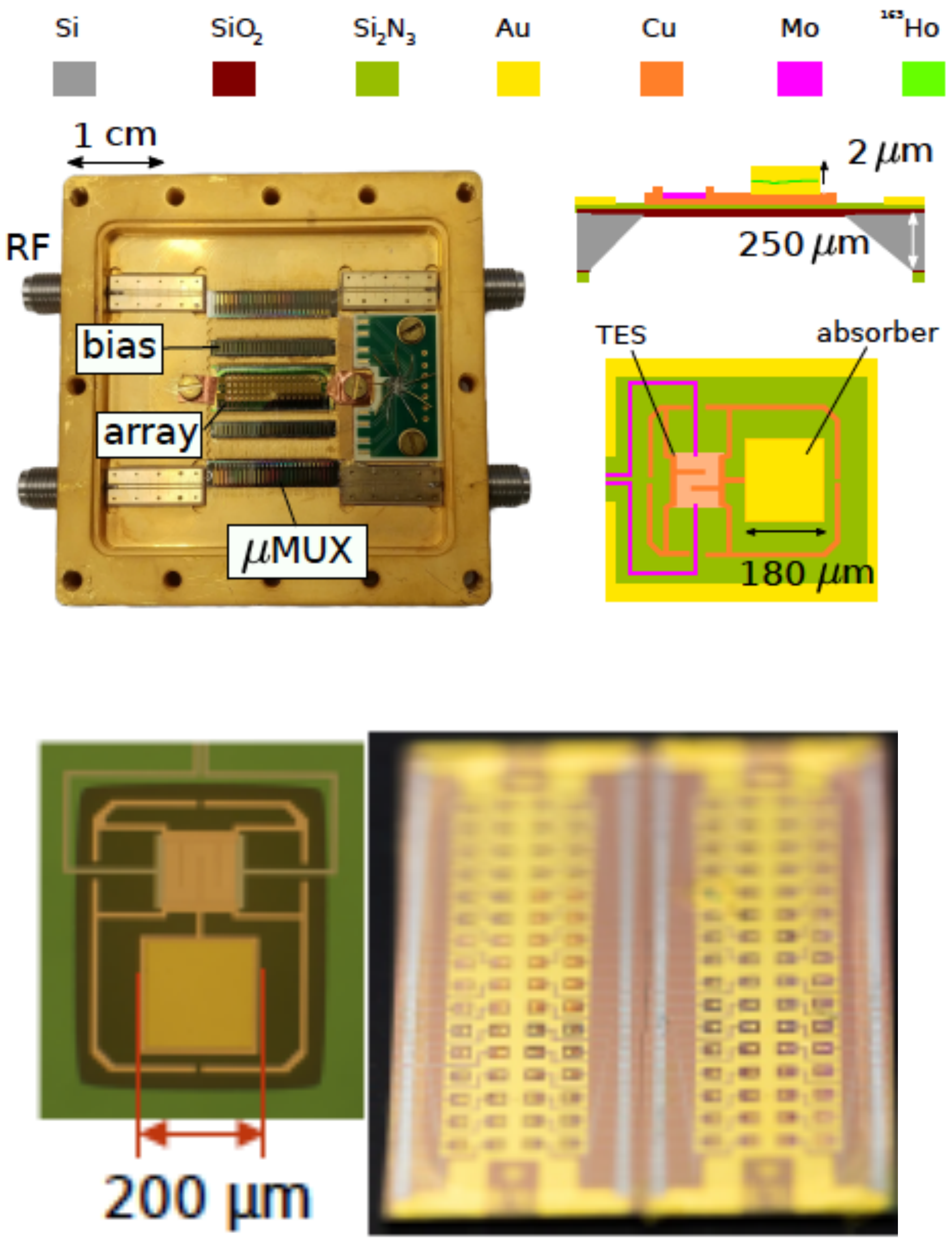
ECHO

m_β < 19 eV @ 90% C.L.
Q = (2862.1 ± 1.7) eV

Orthogonal neutrino mass measurement...

Electron capture (vs beta decay)
Micro-bolometers
Multiplexed detectors





HOLMES

^{163}Ho implantation on multiplexed detectors

48 detectors w/ ~0.3 Bq/pixel.

Preliminary limits:

HOLMES

m_β < 28 eV @ 90% C.L.

Q = 2848^{+11}_{-6} eV

However, *Caveat Emptor*…

Quote: "Experimental electron capture spectrum deviates from all theoretical predictions…"

Need to resort to a phenomenological description of the EC spectrum.

Bottom Line: Ultimately need a decay spectrum that is easily understood.

Cyclotron Radiation Emission Spectroscopy (CRES)

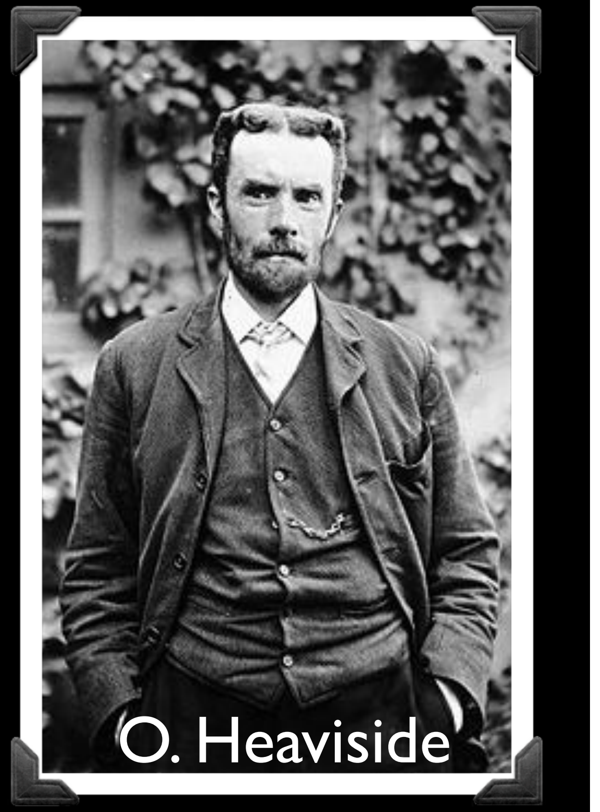
Use radiation from cyclotron motion to measure energy of electron.

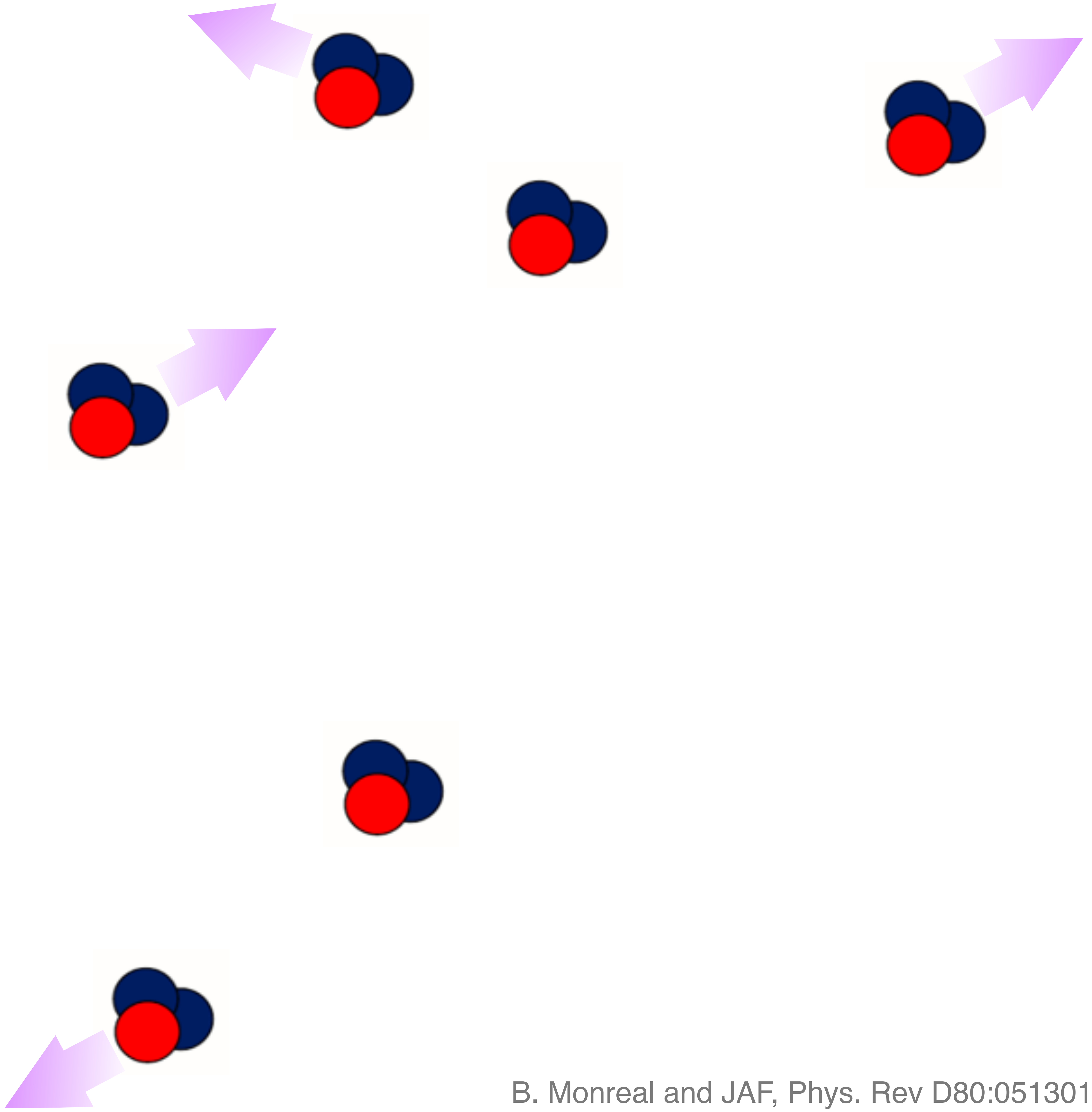
Frequency of radiation

↓

Kinetic energy

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$





B. Monreal and JAF, Phys. Rev D80:051301

Cyclotron Radiation Emission Spectroscopy (CRES)

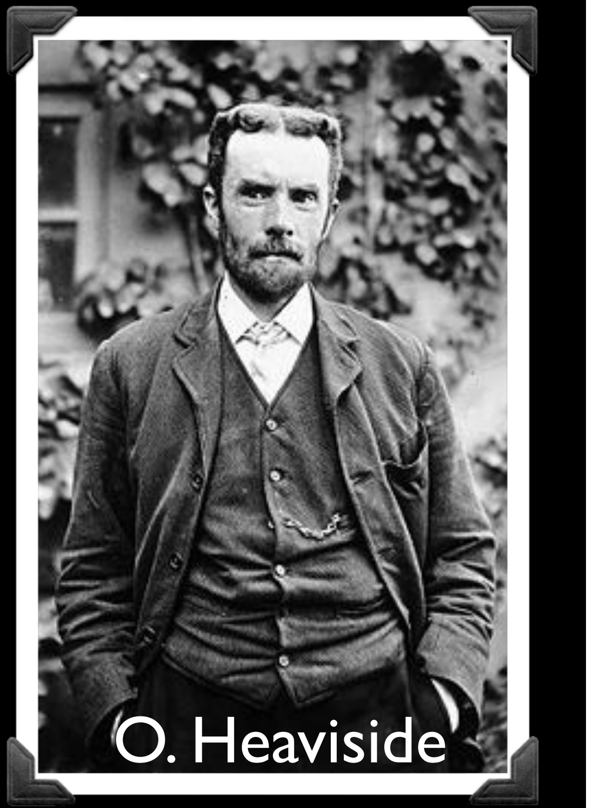
Use radiation from cyclotron motion to measure energy of electron.

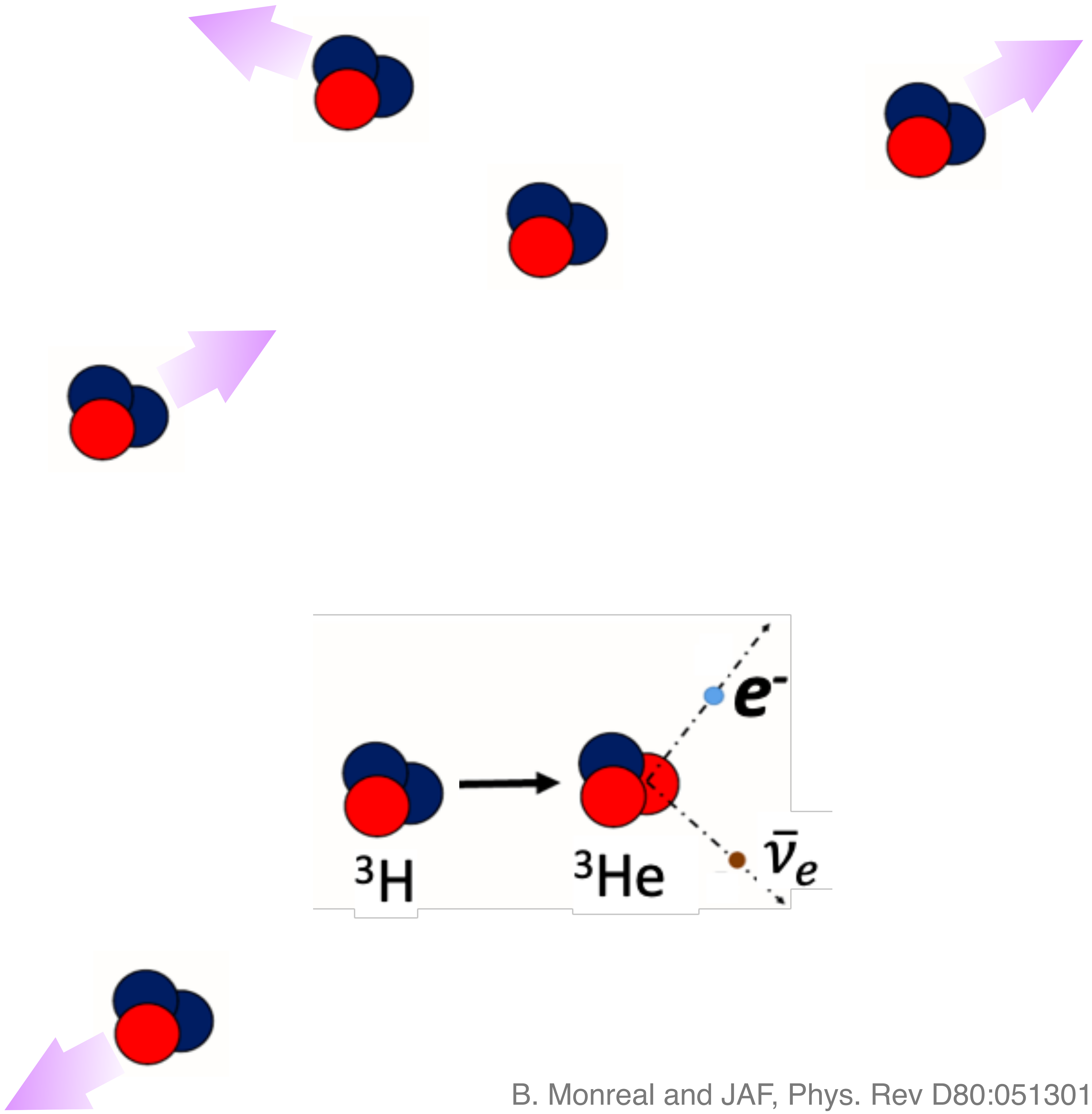
Frequency of radiation

↓

Kinetic energy

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$





B. Monreal and JAF, Phys. Rev D80:051301

Cyclotron Radiation Emission Spectroscopy (CRES)

Use radiation from cyclotron motion to measure energy of electron.

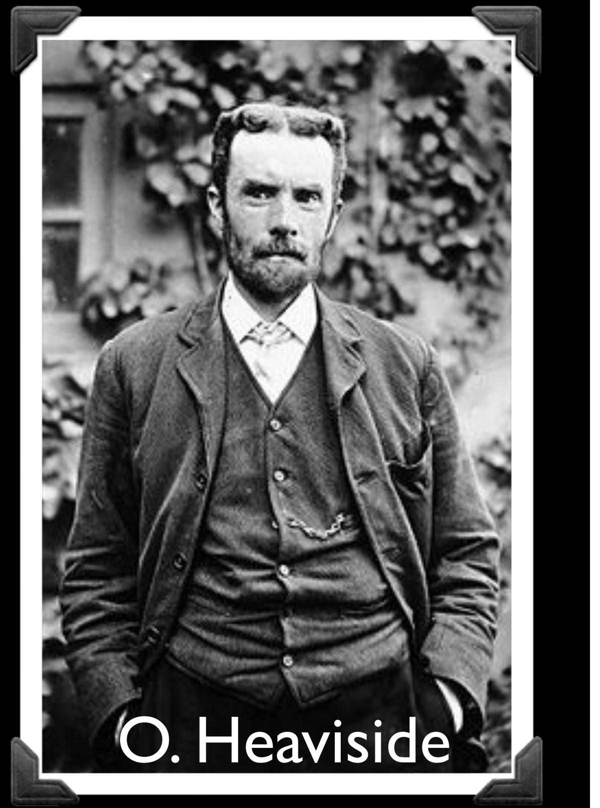
Frequency of radiation

↓

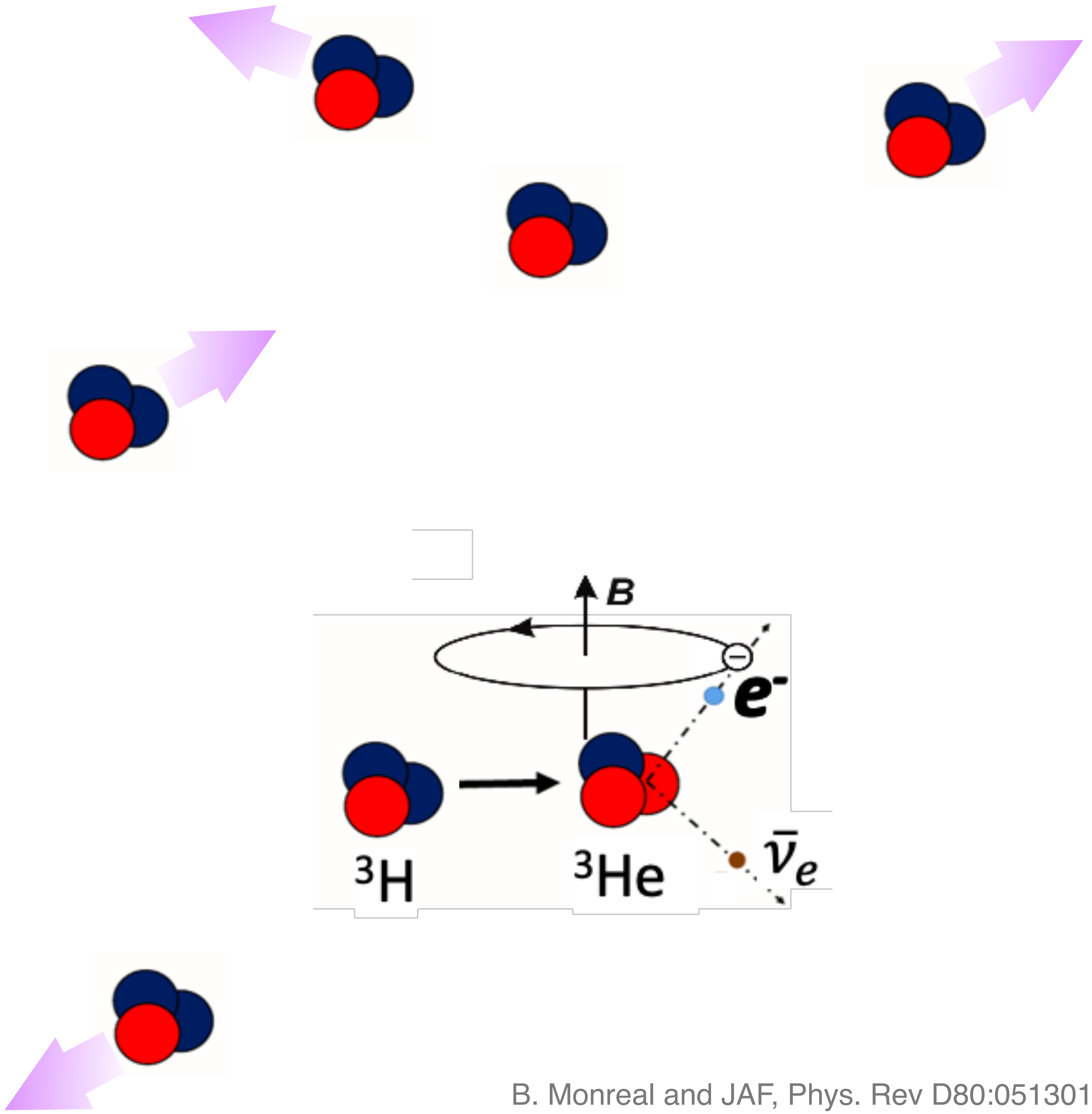
Kinetic energy

A. L. Schawlow

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$



O. Heaviside



B. Monreal and JAF, Phys. Rev D80:051301

Cyclotron Radiation Emission Spectroscopy (CRES)

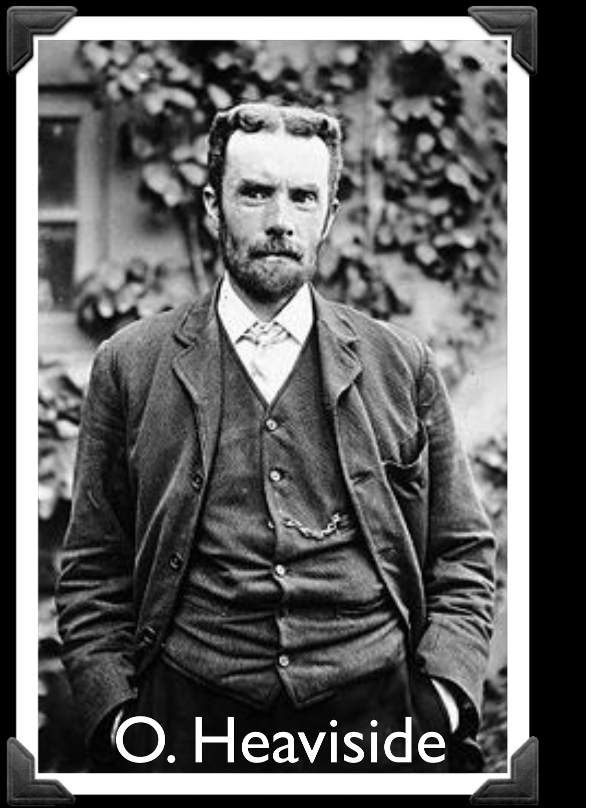
Use radiation from cyclotron motion to measure energy of electron.

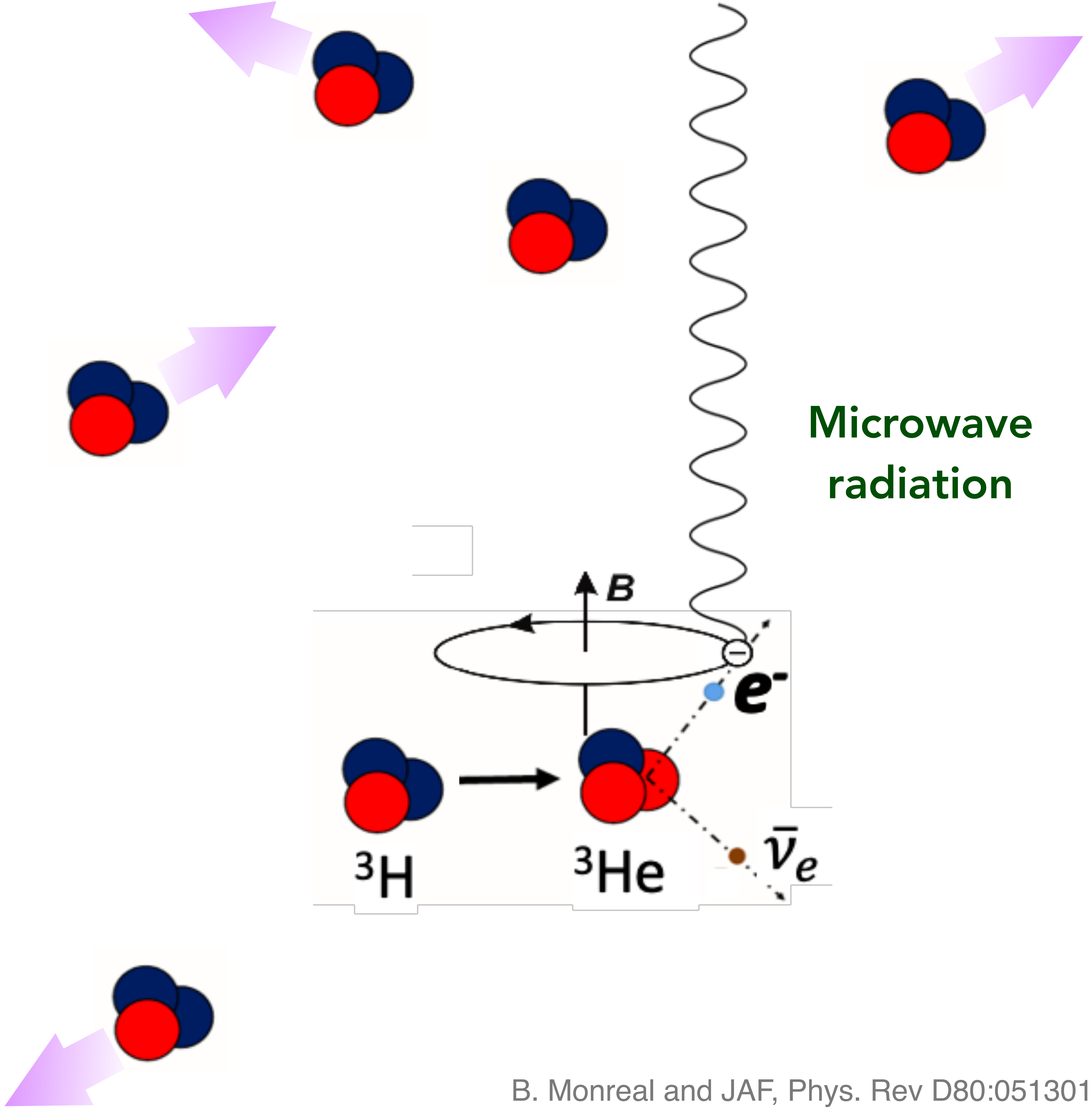
Frequency of radiation

↓

Kinetic energy

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\rm kin}/c^2}$$





B. Monreal and JAF, Phys. Rev D80:051301

Cyclotron Radiation Emission Spectroscopy (CRES)

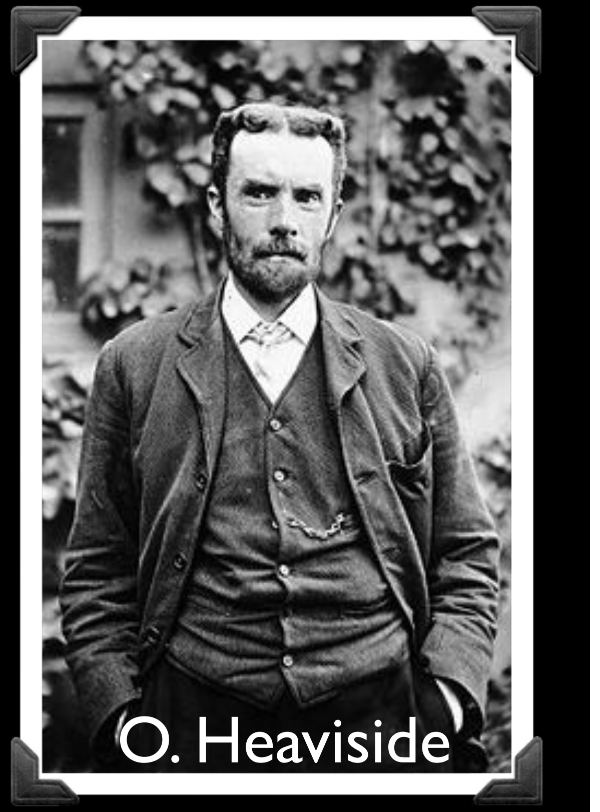
Use radiation from cyclotron motion to measure energy of electron.

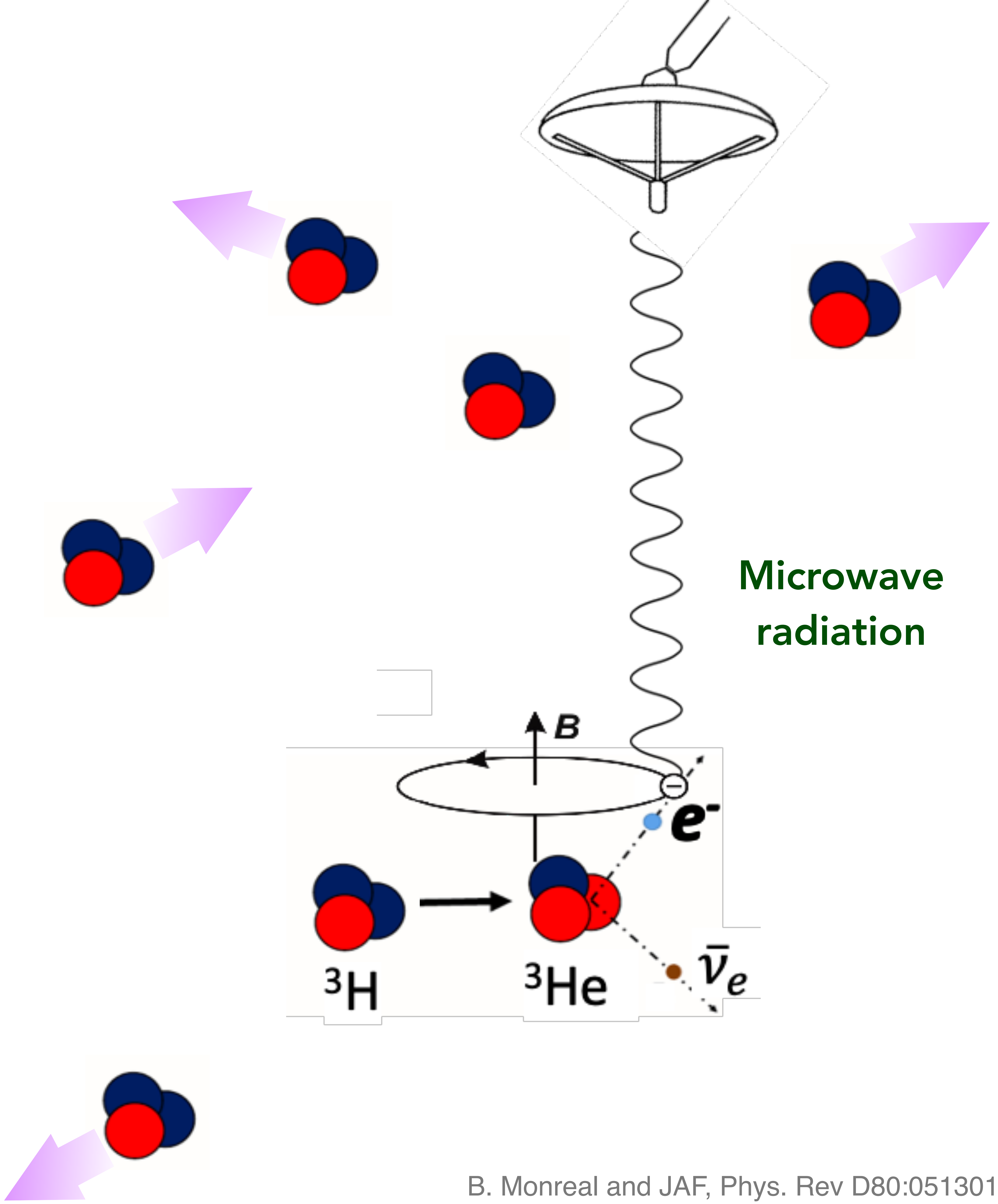
Frequency of radiation

↓

Kinetic energy

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$





B. Monreal and JAF, Phys. Rev D80:051301

Advantages of CRES

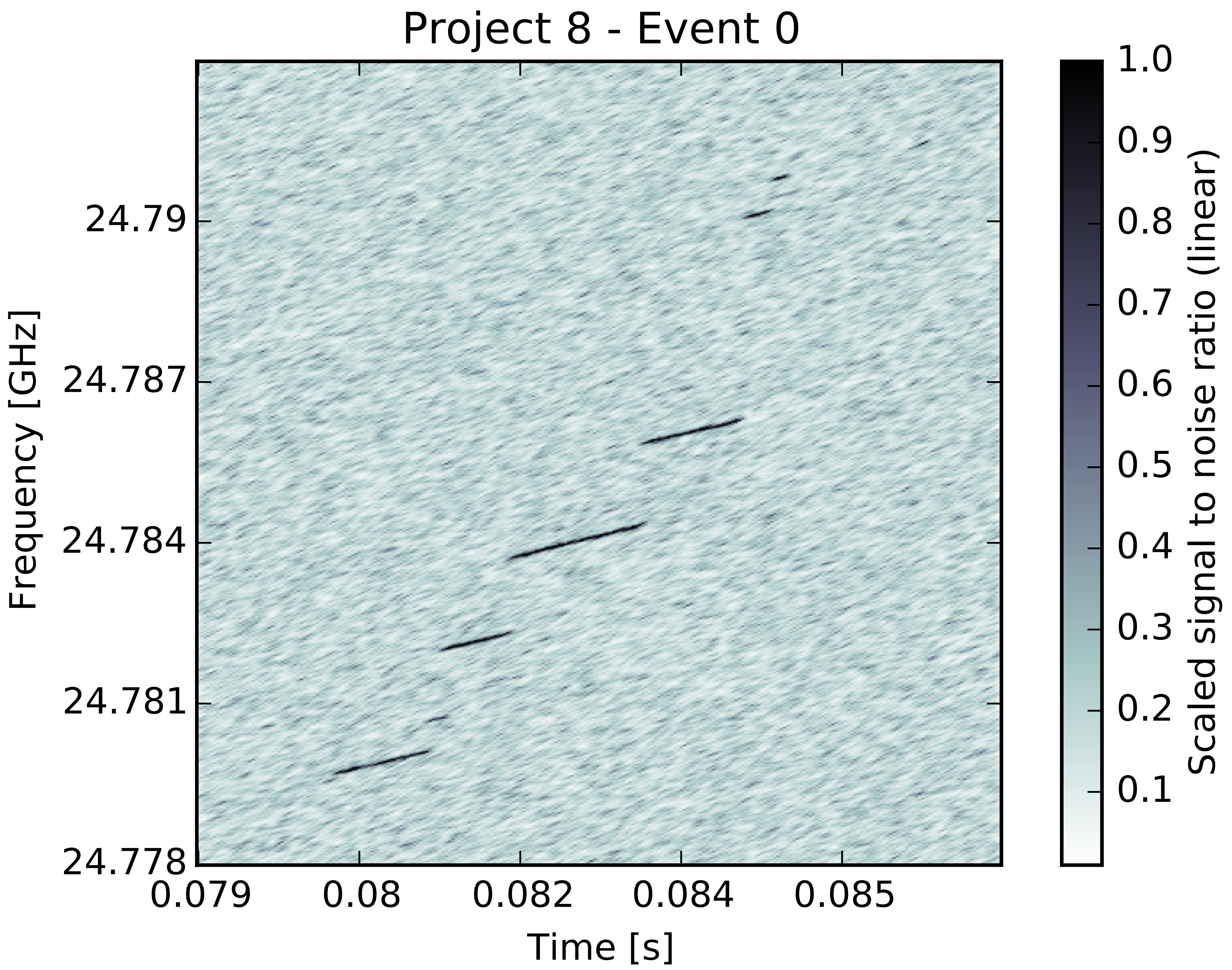
Frequency measurement

Transparancy to microwaves

Differential spectrometer

Low background

Compatible with atomic tritium



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\rm kin}}$$

Advantages of CRES

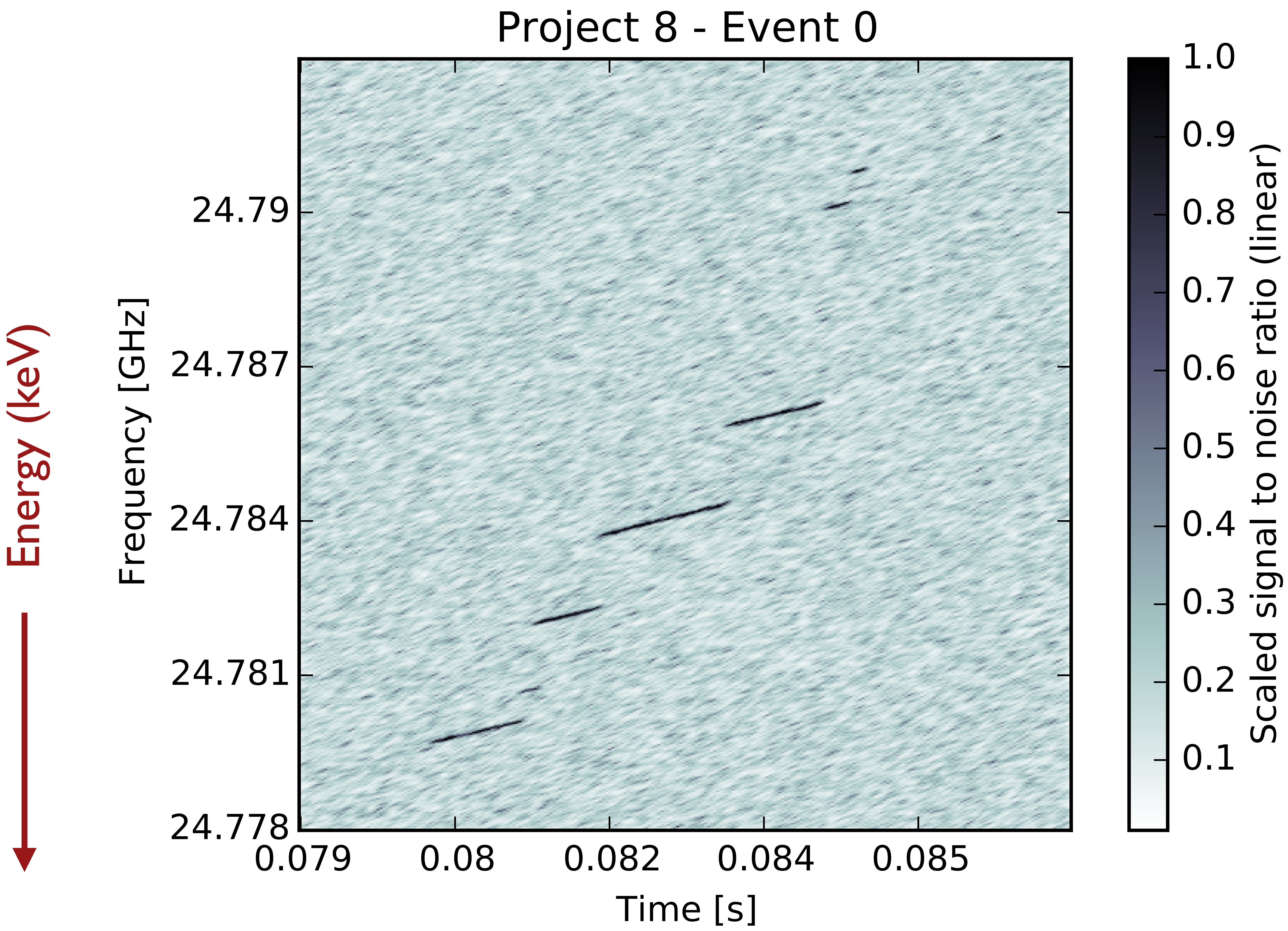
Frequency measurement

Transparancy to microwaves

Differential spectrometer

Low background

Compatible with atomic tritium



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\text{kin}}}$$

Advantages of CRES

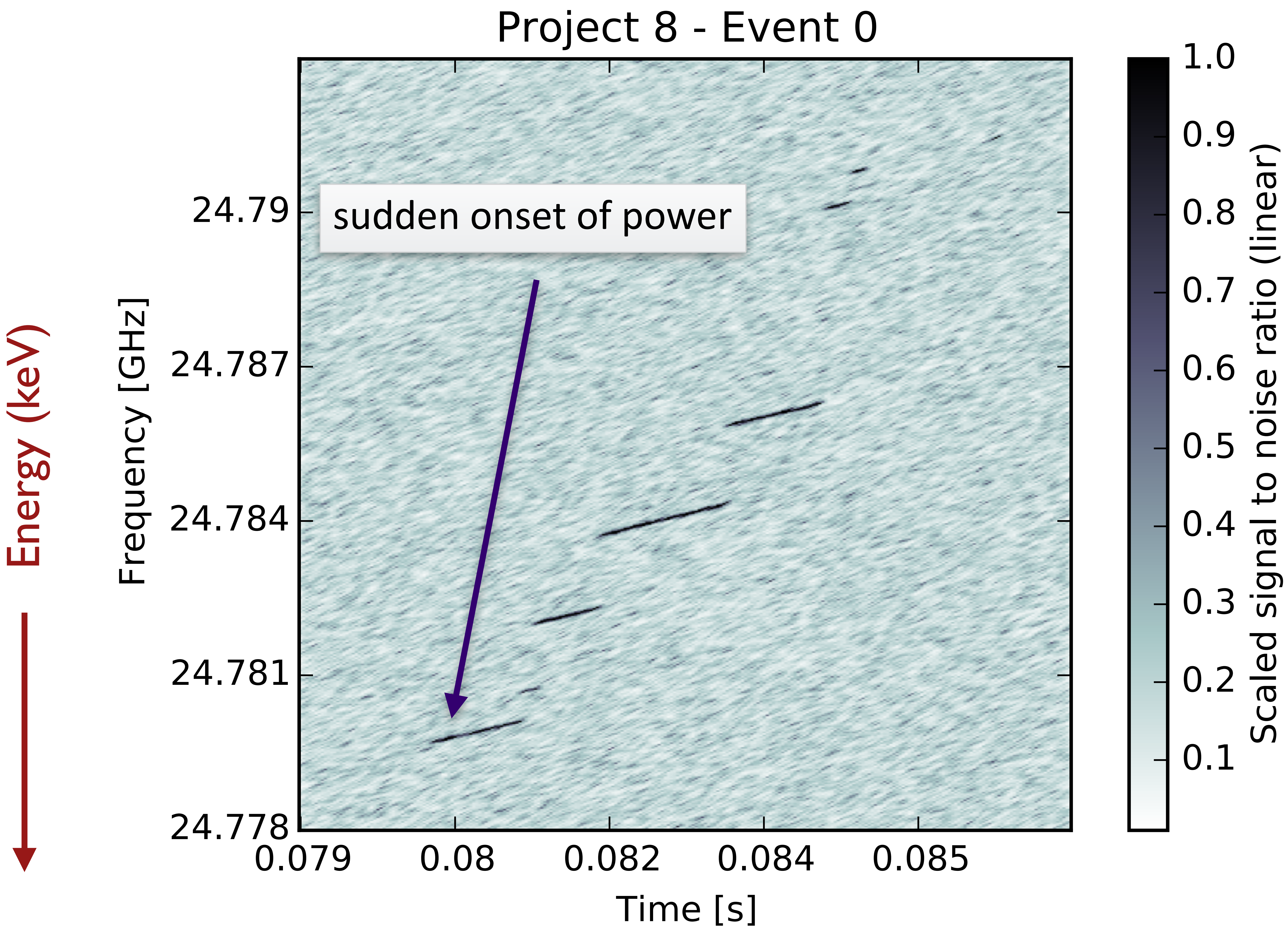
Frequency measurement

Transparancy to microwaves

Differential spectrometer

Low background

Compatible with atomic tritium



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\text{kin}}}$$

Advantages of CRES

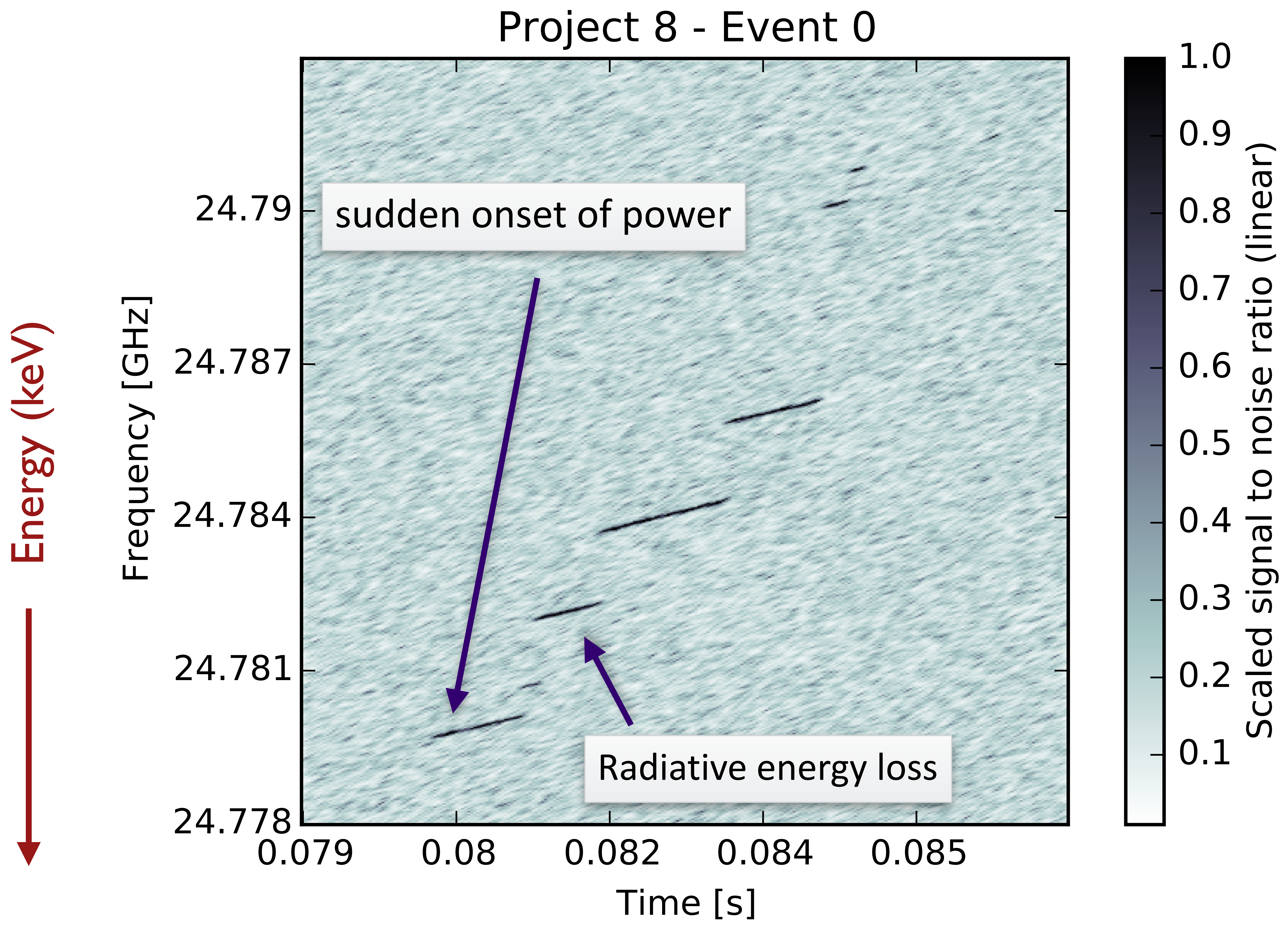
Frequency measurement

Transparancy to microwaves

Differential spectrometer

Low background

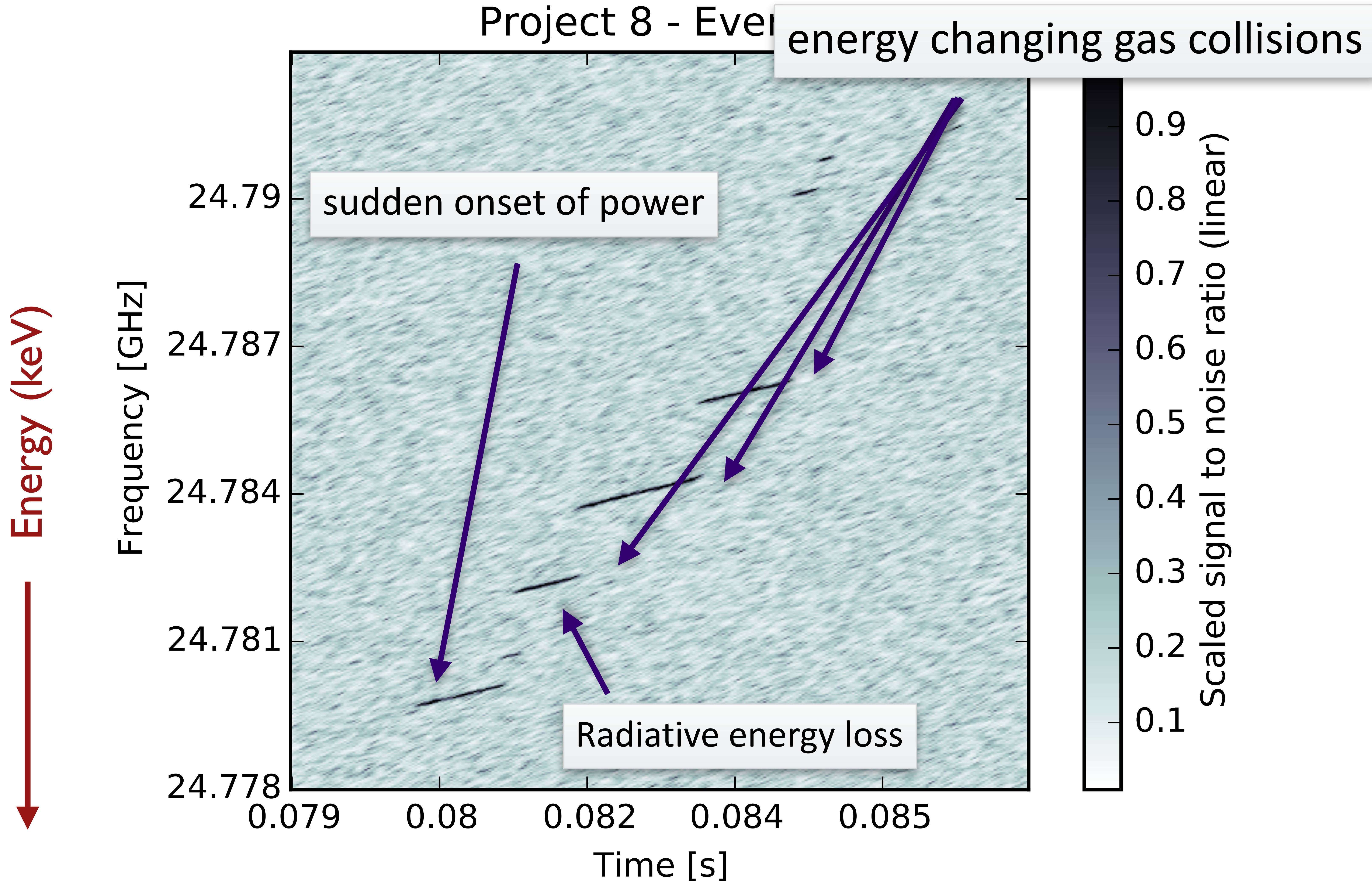
Compatible with atomic tritium



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\text{kin}}}$$

Advantages of CRES

- Frequency measurement
- Transparancy to microwaves
- Differential spectrometer
- Low background
- Compatible with atomic tritium



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\text{kin}}}$$

First CRES Limits

Energy resolution on ^{83m}Kr: 1.66 $\pm$ 0.19 eV

(That's a frequency measurement of 3 ppm on total energy)

First CRES mass measurement:

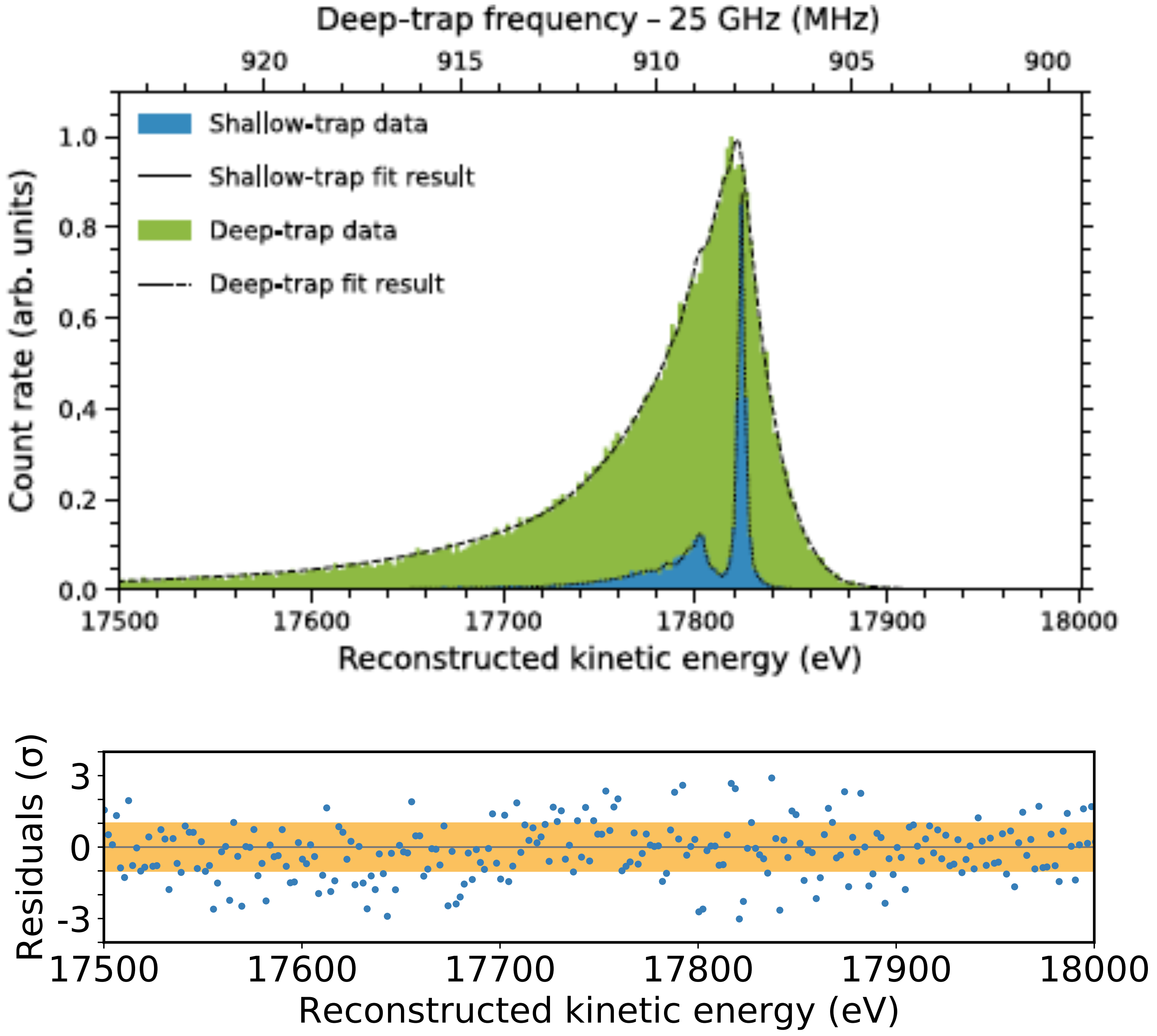
m_β < 155 eV (90% C.L., Bayesian)

m_β < 152 eV (90% C.L., Frequentist)

(And **no** background seen!)

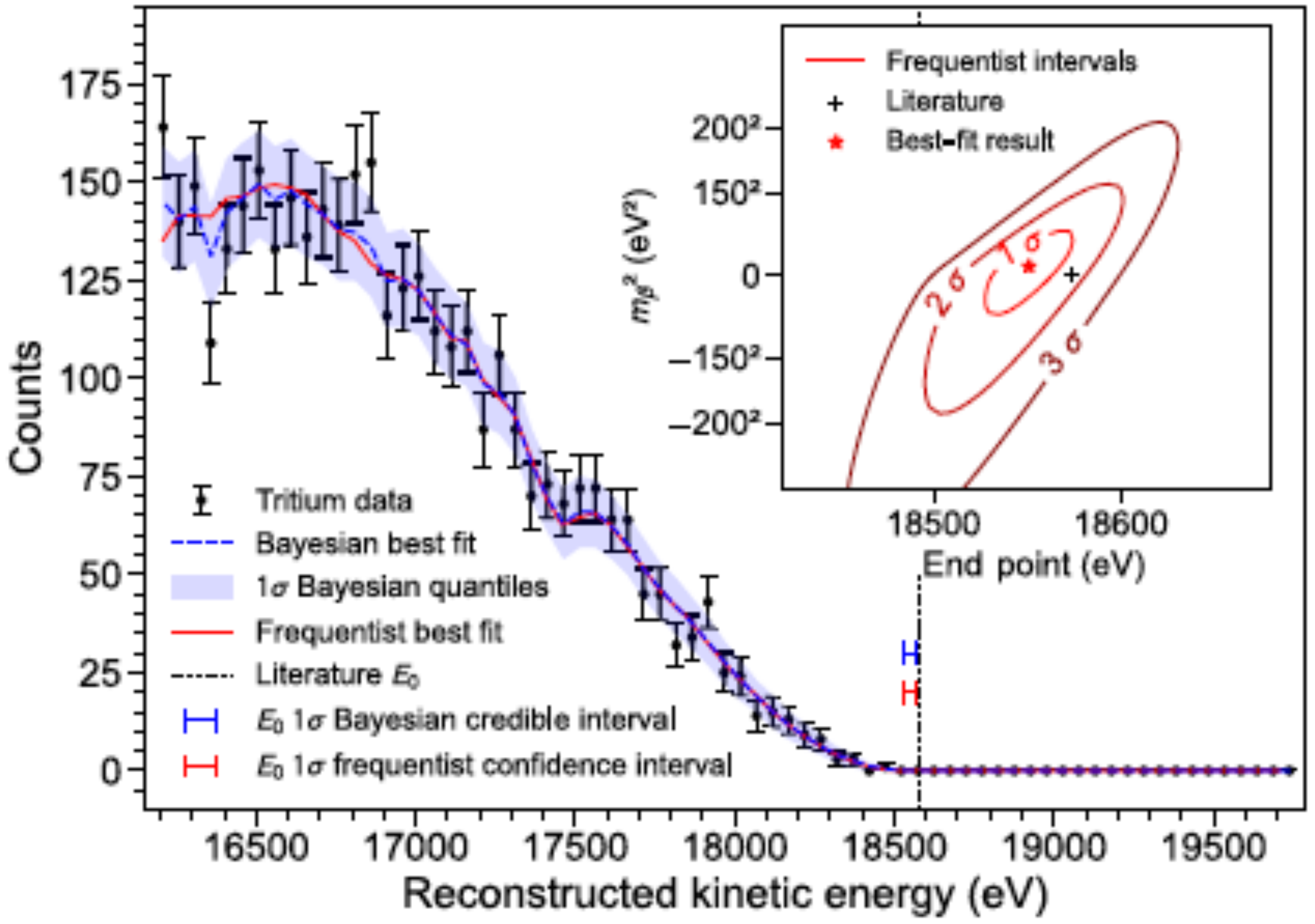
N_b < 3 x 10^{-10} /eV/s (90% C.L.)

^{83m}Kr Spectrum



Ashtari Esfahani et al Phys. Rev. Lett. 131, 102502 (2023)

1st Tritium Spectrum!



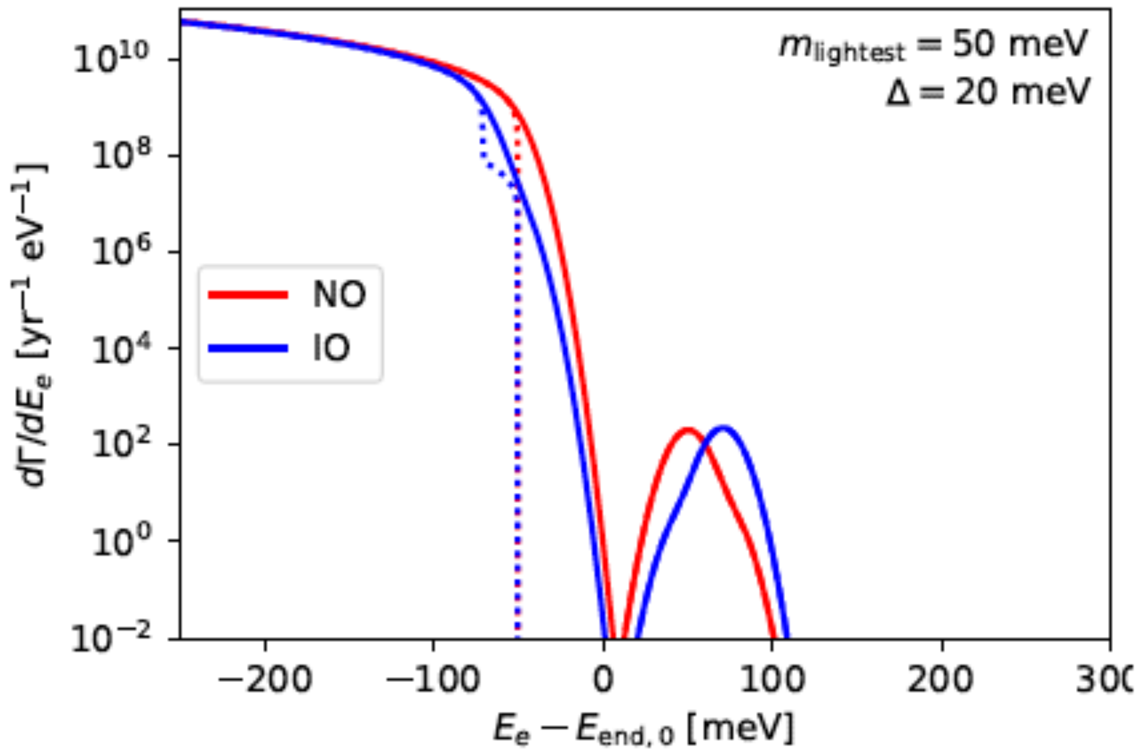
Ashtari Esfahani et al. Phys.Rev.C 3, 035503 (2024)

Sphara Zodiaci

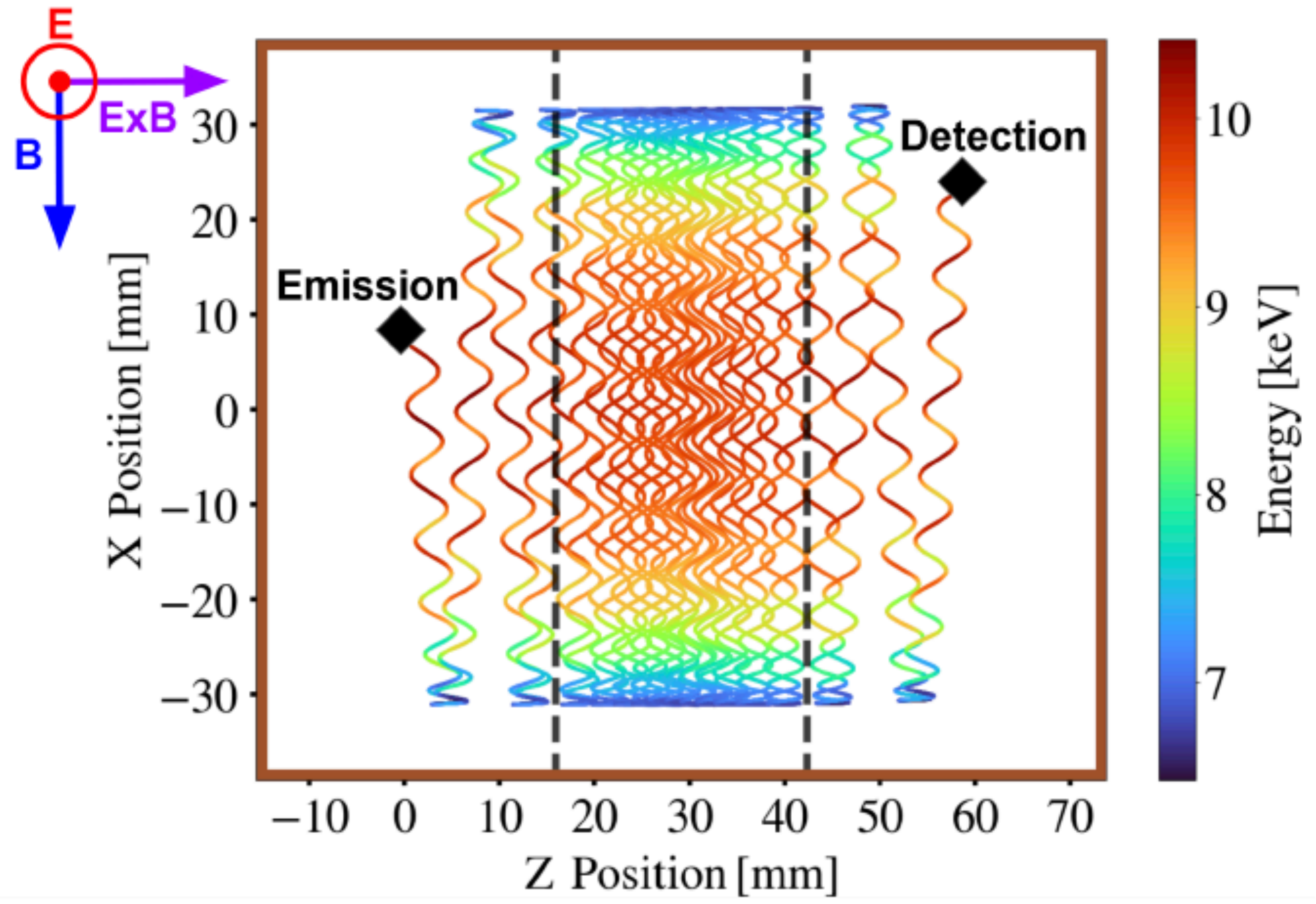
Moving Beyond the Known

PTOLEMY

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

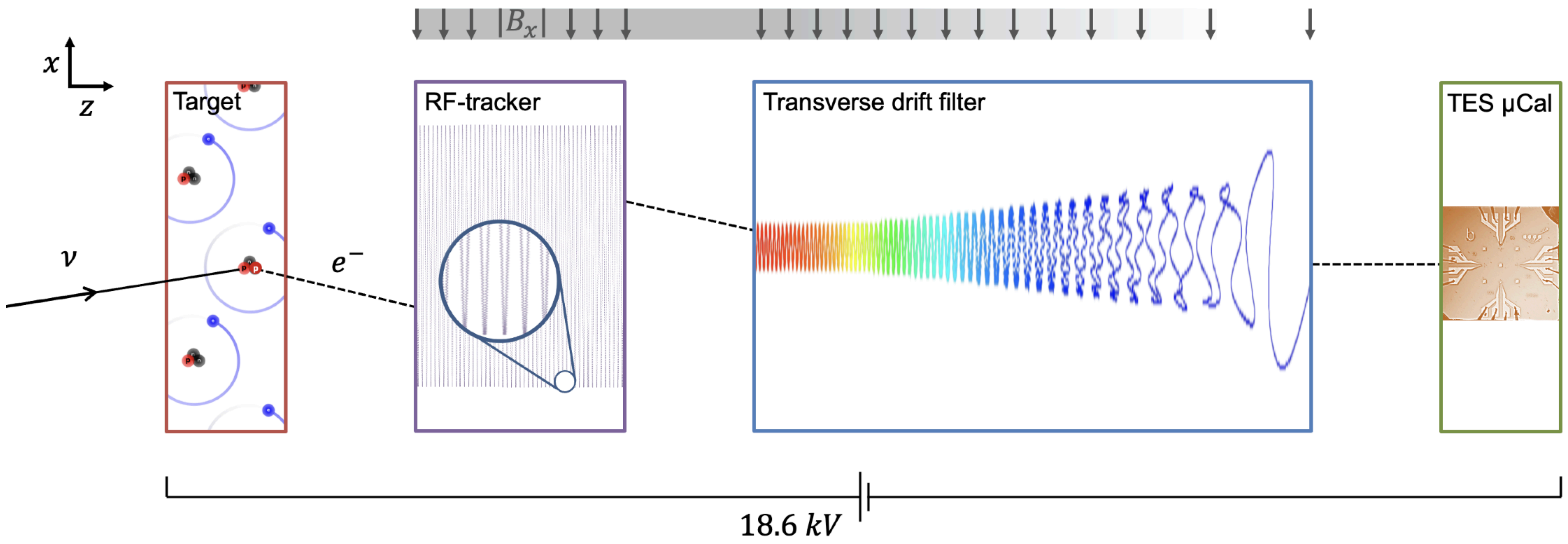


$$^{3}\mathrm{H} + \nu_e \rightarrow {}^{3}\mathrm{He}^{+} + e^{-}$$



$E_{\parallel} \rightarrow E_{\perp}, \quad \Delta E \sim \mathcal{O}(100 meV)$

$\sigma \sim \mathcal{O}(10\ meV)$



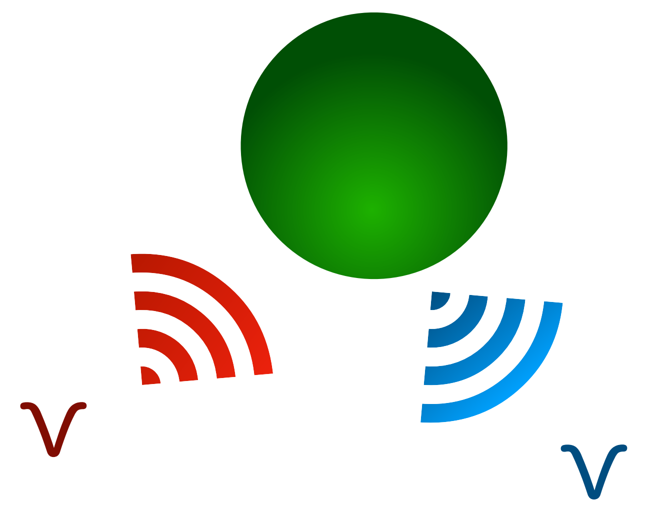
$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

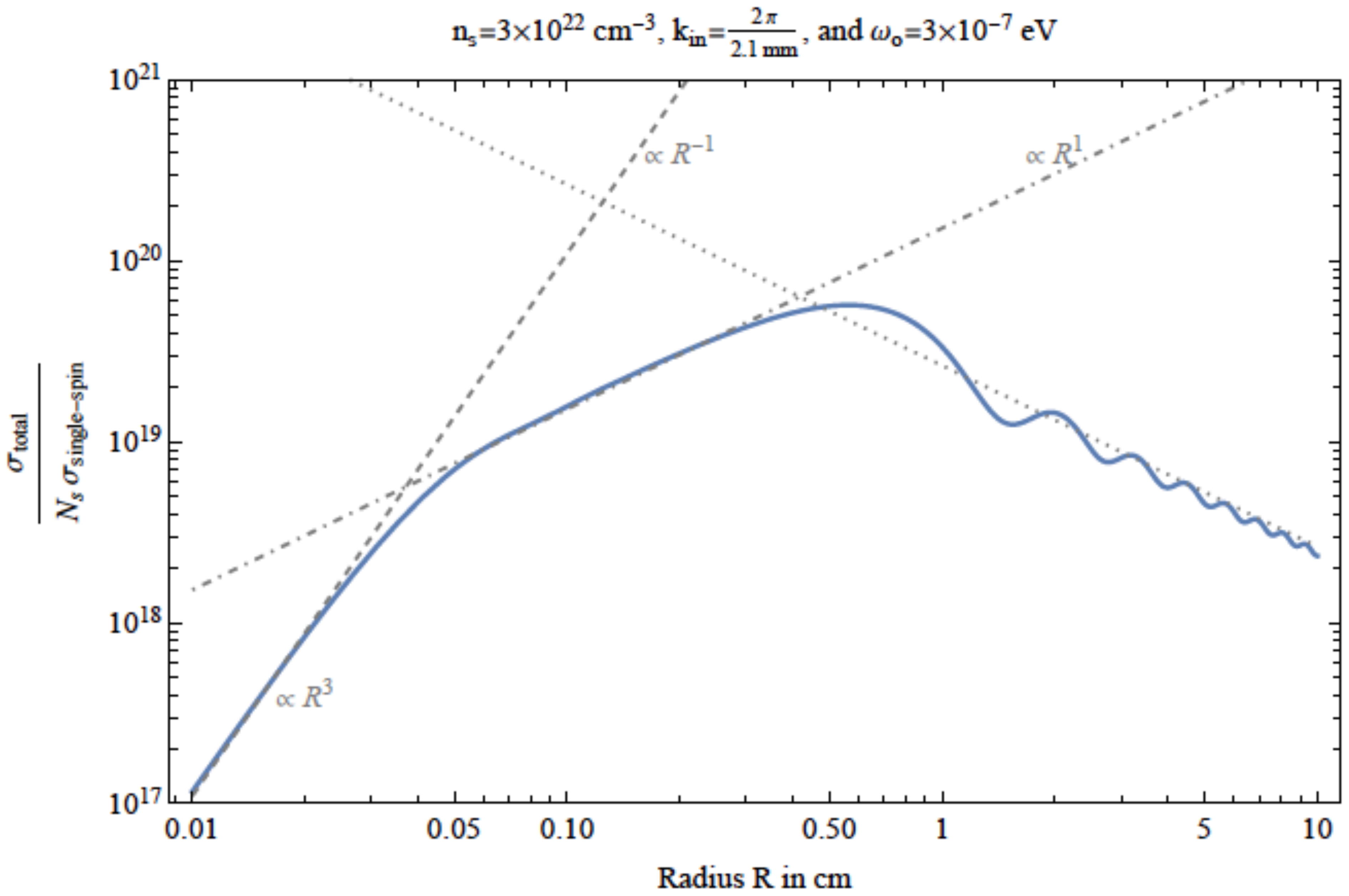
Uses E x B Drift to extract energy of electrons from an embedded tritium source.

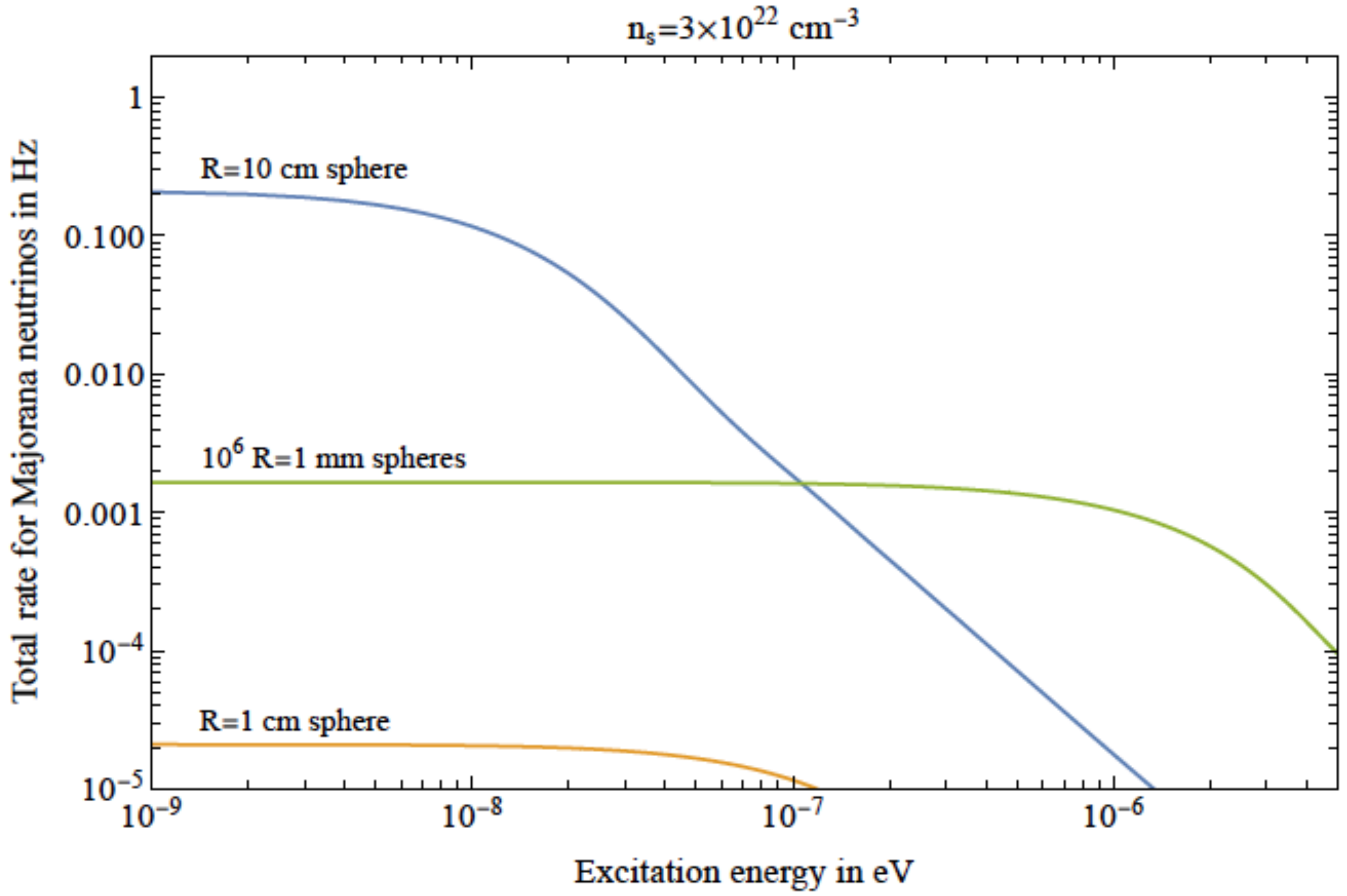
Intended for operation with very high (gram-level) tritium.

Aiming to measure the CvB directly.

Superradiant Interactions







A. Arvanitaki et al. arXiv:2408.04021v2

Interesting proposal by Arvanitaki, Dimopoulos and Galanis

to look for the CvB through superradiant spin interactions, which scale as N^2.

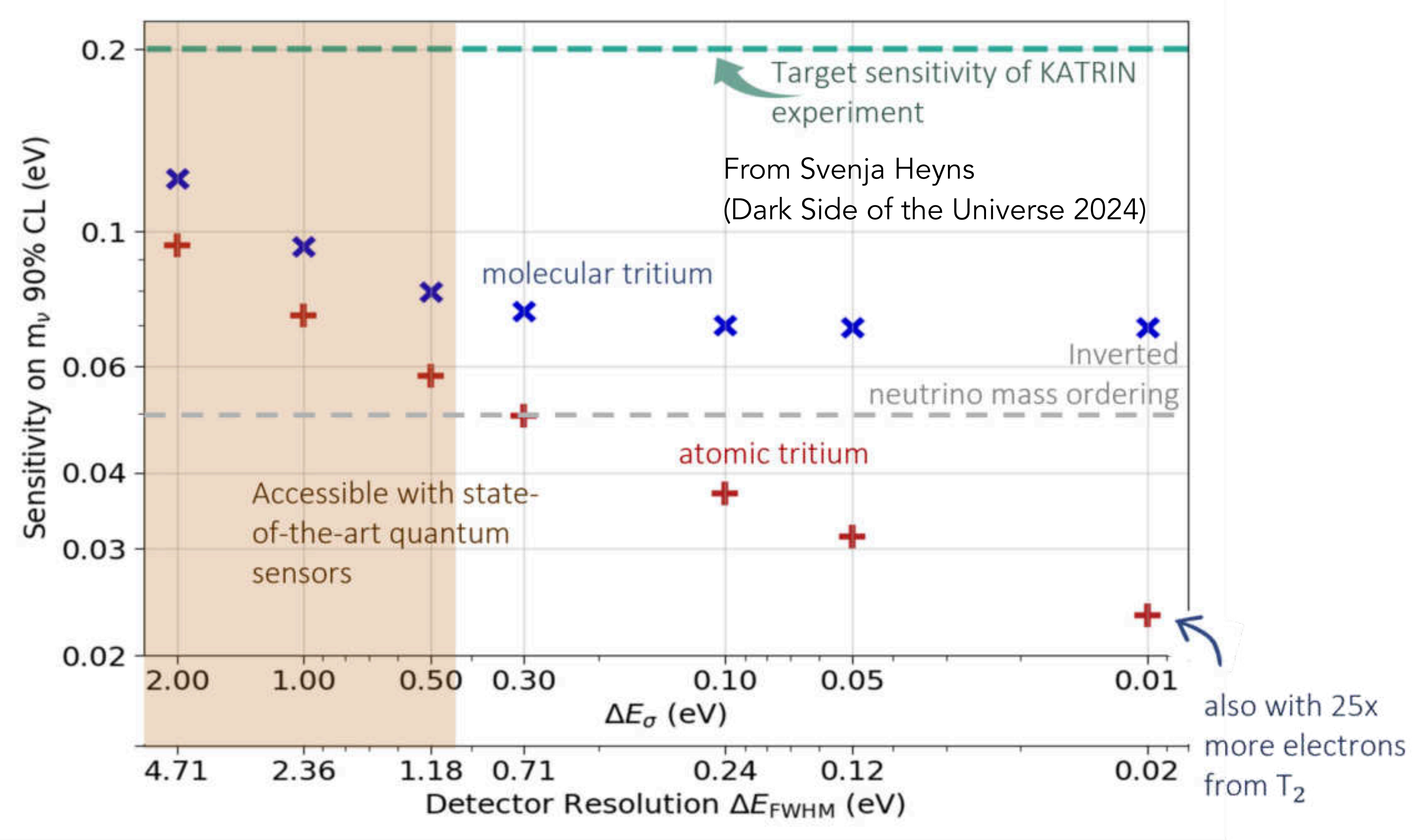
Look at both energy exchanges and “controllable” noise.

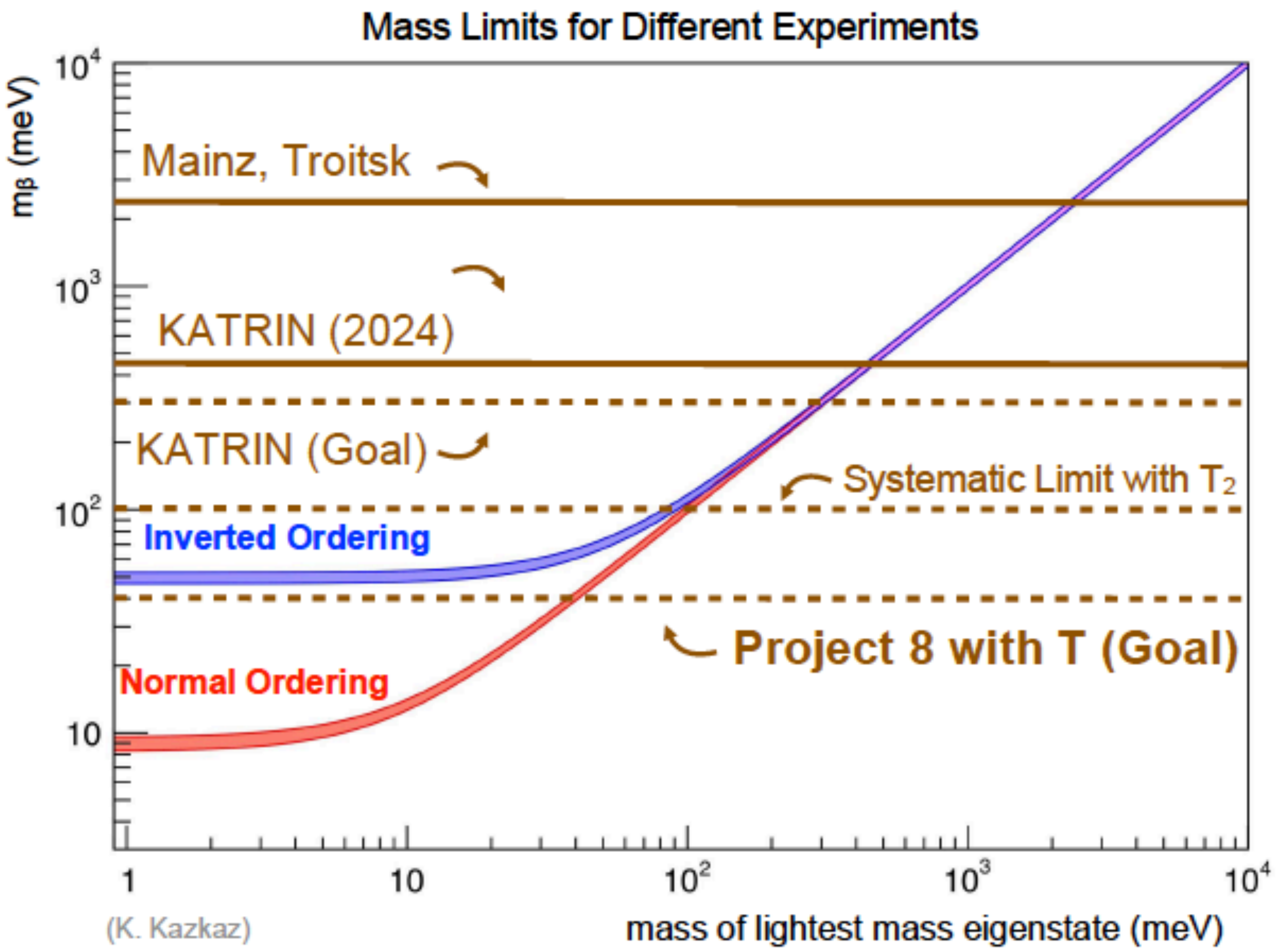
How do we access the next scale of neutrino masses?

General Principles…

- High energy resolution
- Background-free operation
- Better target mass scaling
- Well-understood, highly resolved source

…hence a big push for an atomic tritium source





- **KATRIN++** is exploring the possibility of expanding its tritium program to include an atomic source with a differential spectrometer (quantum-sensor R&D) to probe the inverted ordering.
- **ECHO and HOLMES** released preliminary results from their recent data run using ^{163}Ho implanted bolometers. Combine techniques to look at large-scale holmium efforts for neutrino mass.
- **Project 8** is expanding to an atomic tritium experiment with a projected sensitivity of 40 meV/c^2 using large, low-frequency resonant cavities.
- In the wings, **PTOLEMY, levitating spheres, etc.**

A New Model...

Reconciling cosmological neutrino measurements with terrestrial constraints requires more precise measurements of the neutrino mass scale.

Finer measurements could provide constraints on new cosmological models.

New motivation for terrestrial measurements!

Thank you for your attention!