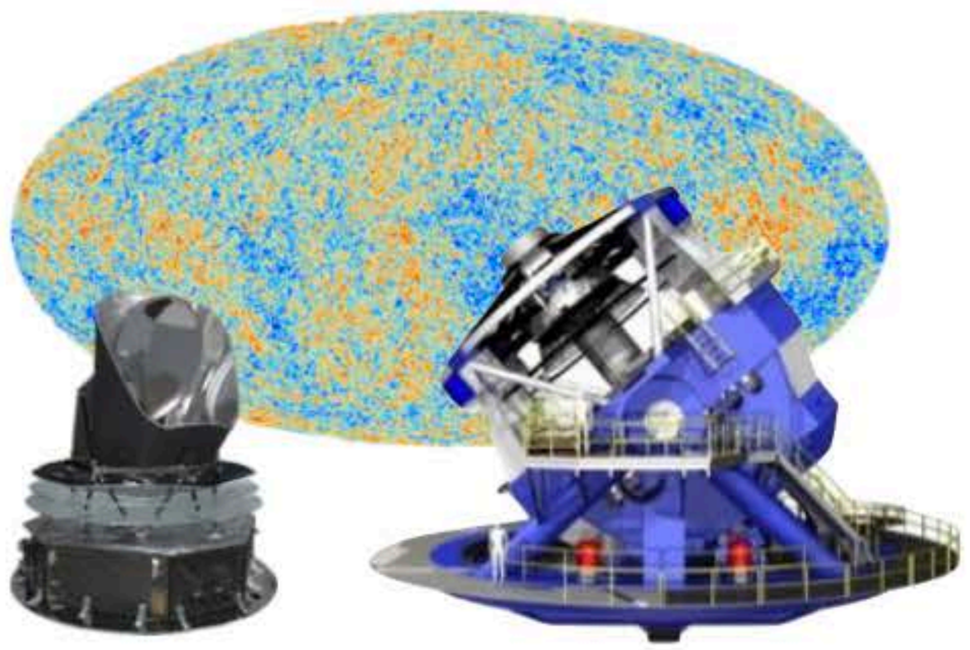
Project 8 and Neutrino Mass

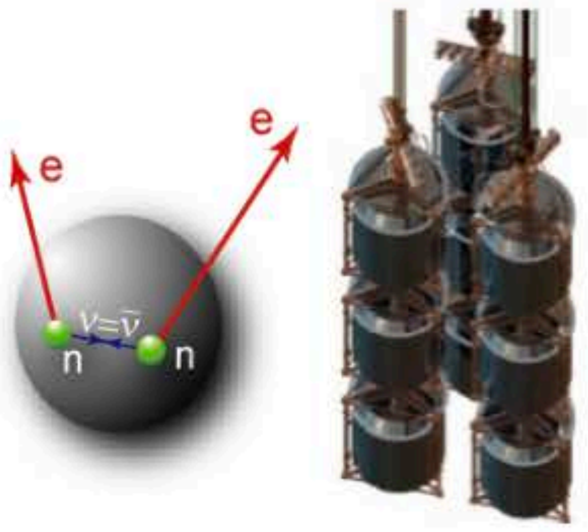
A frequency based approach to measure the neutrino mass

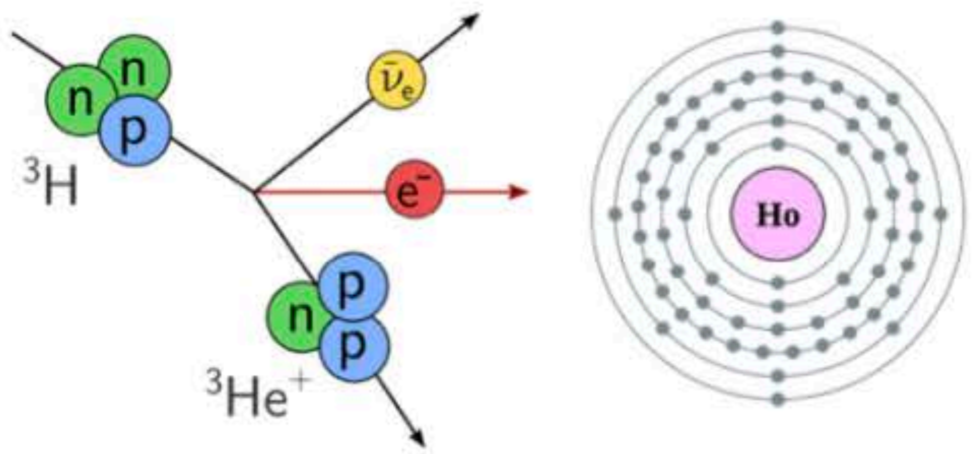
Karsten M. Heeger
Yale University

CERN October 2019

Paths to the Neutrino Mass Scale







	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Present upper limit	~0.1 – 0.6 eV	~0.1 – 0.4 eV	2 eV
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

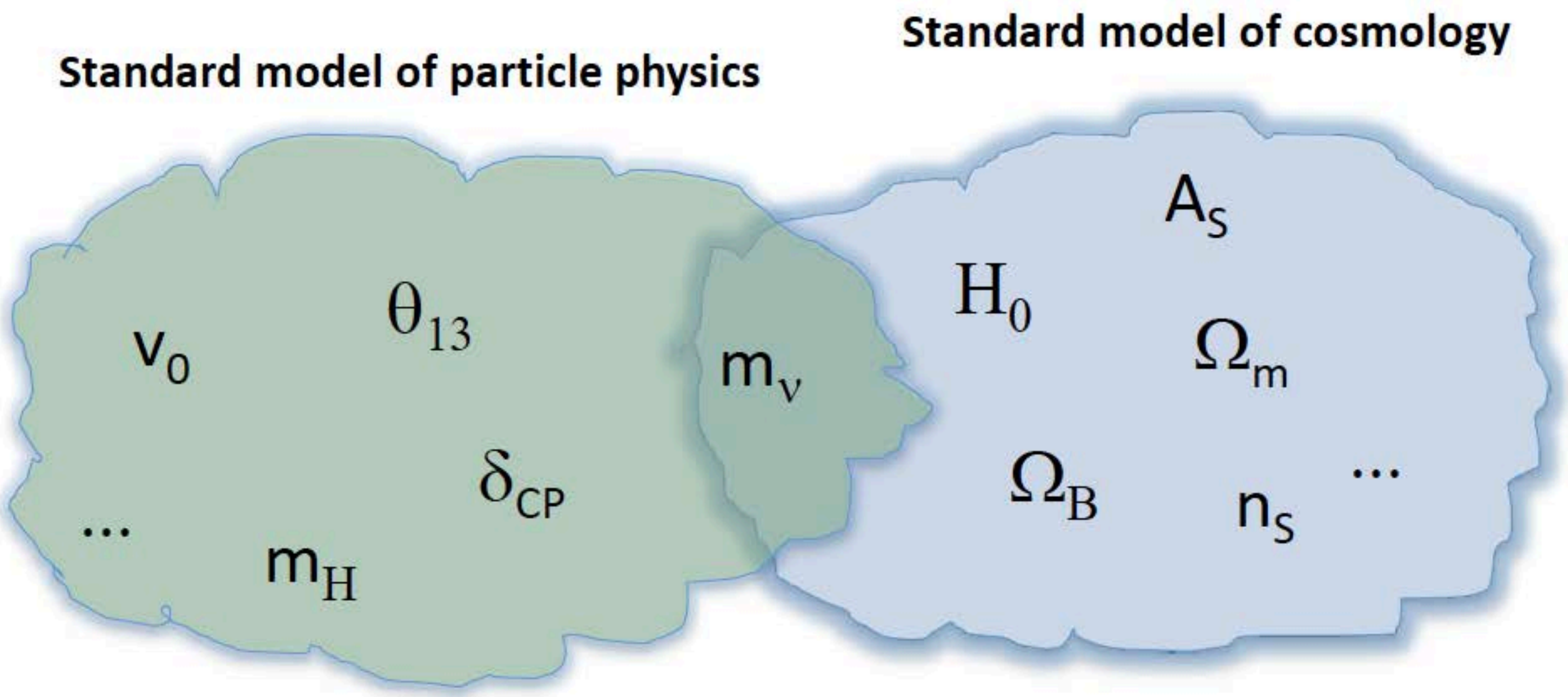
Valerius

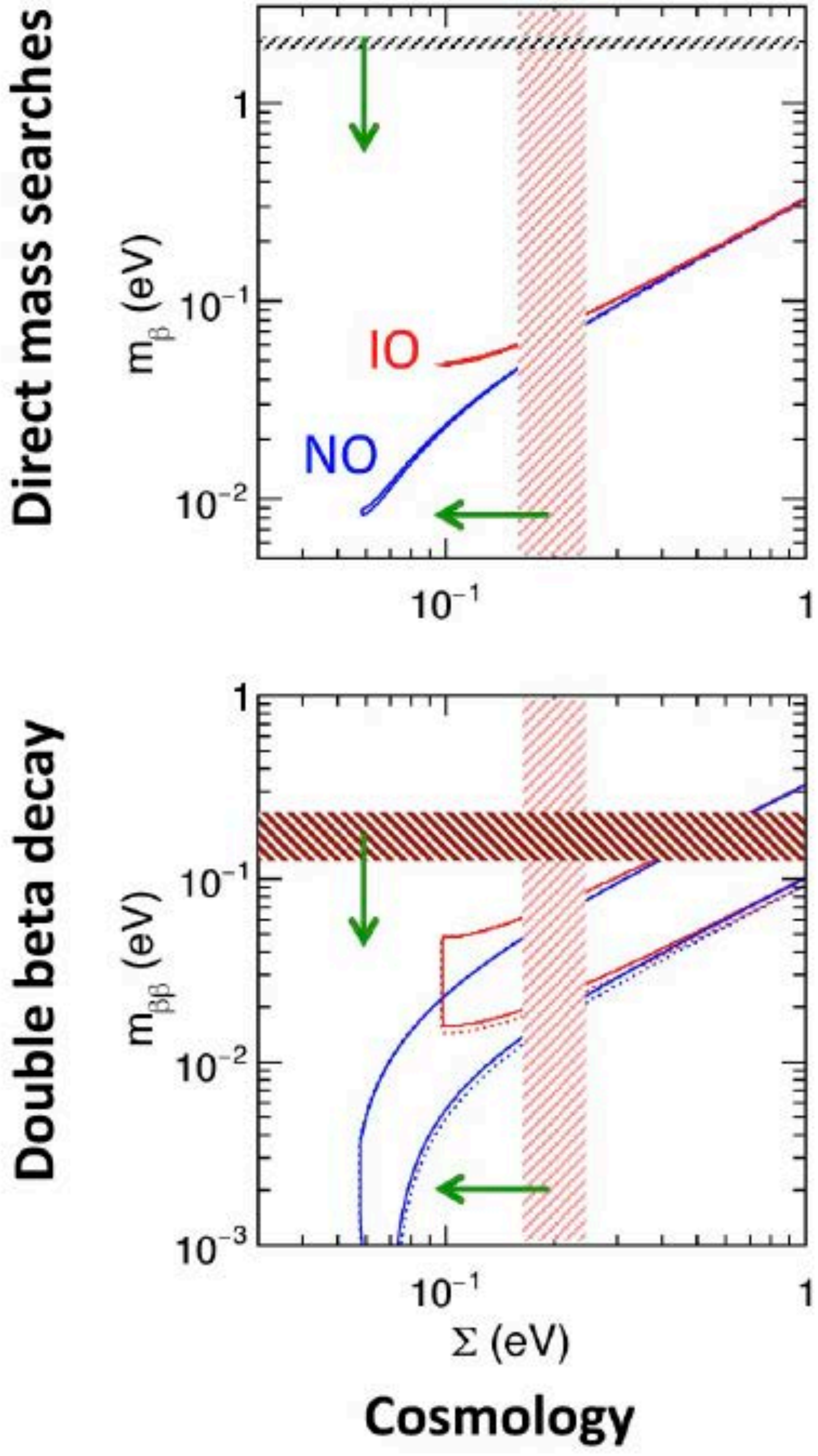
Neutrino Mass Constraints

Cosmology measures	$\sum_i m_i$
Double beta decay measures	$\left\|\sum_i U_{ei}^2\, m_i\right\|$
Direct searches measure	$\left(\sum_i \|U_{ei}^2\|\, m_i^2\right)^{1/2}$

m_ν measurable both by laboratory experiments and cosmology

a critical test of consistency





Mezetto

Neutrino Mass Constraints

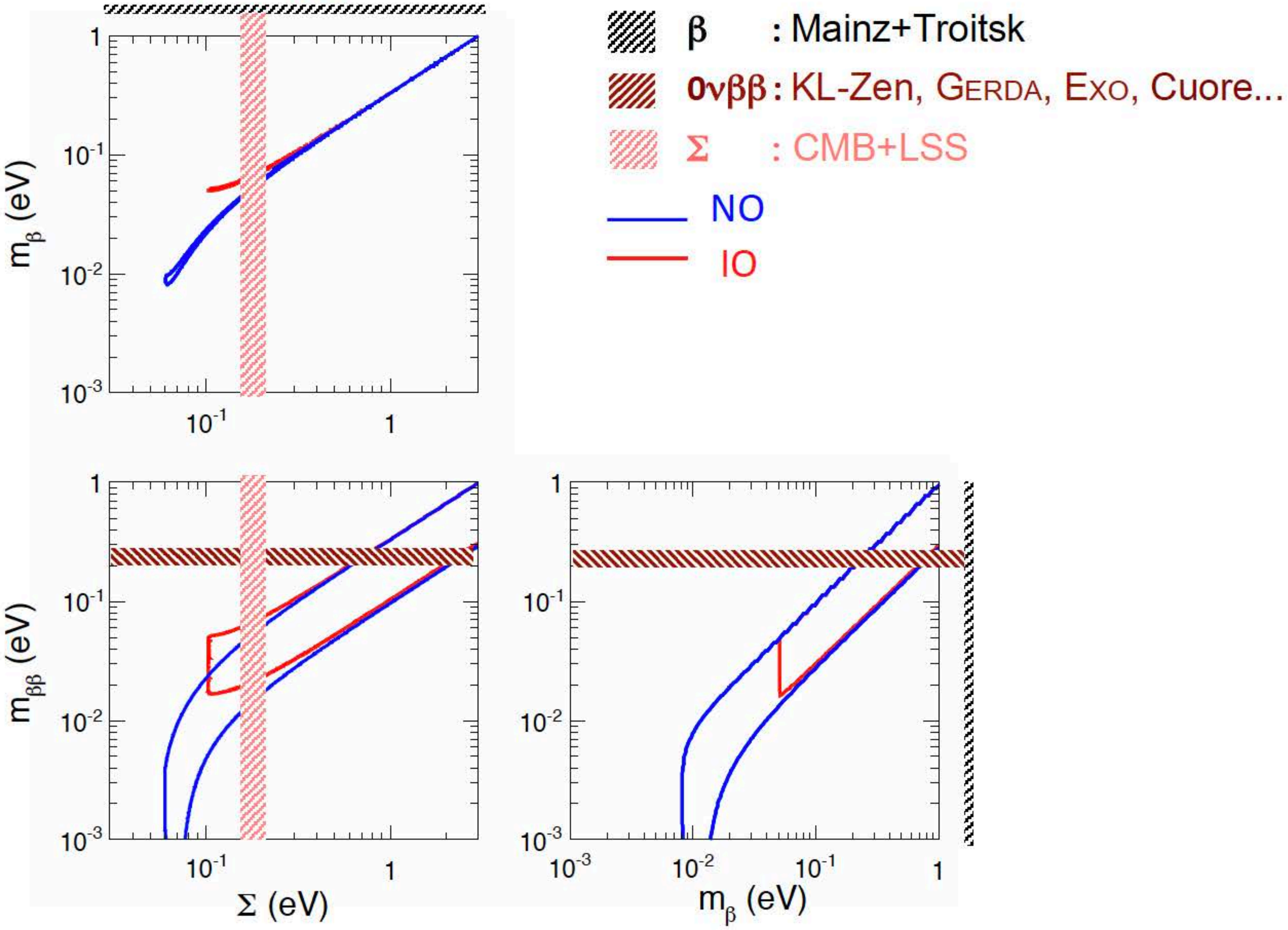
Cosmology measures $\sum_i m_i$

Double beta decay measures $\left|\sum_i U_{ei}^2\, m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2|\, m_i^2\right)^{1/2}$

m_ν measurable both by laboratory experiments and cosmology

a critical test of consistency



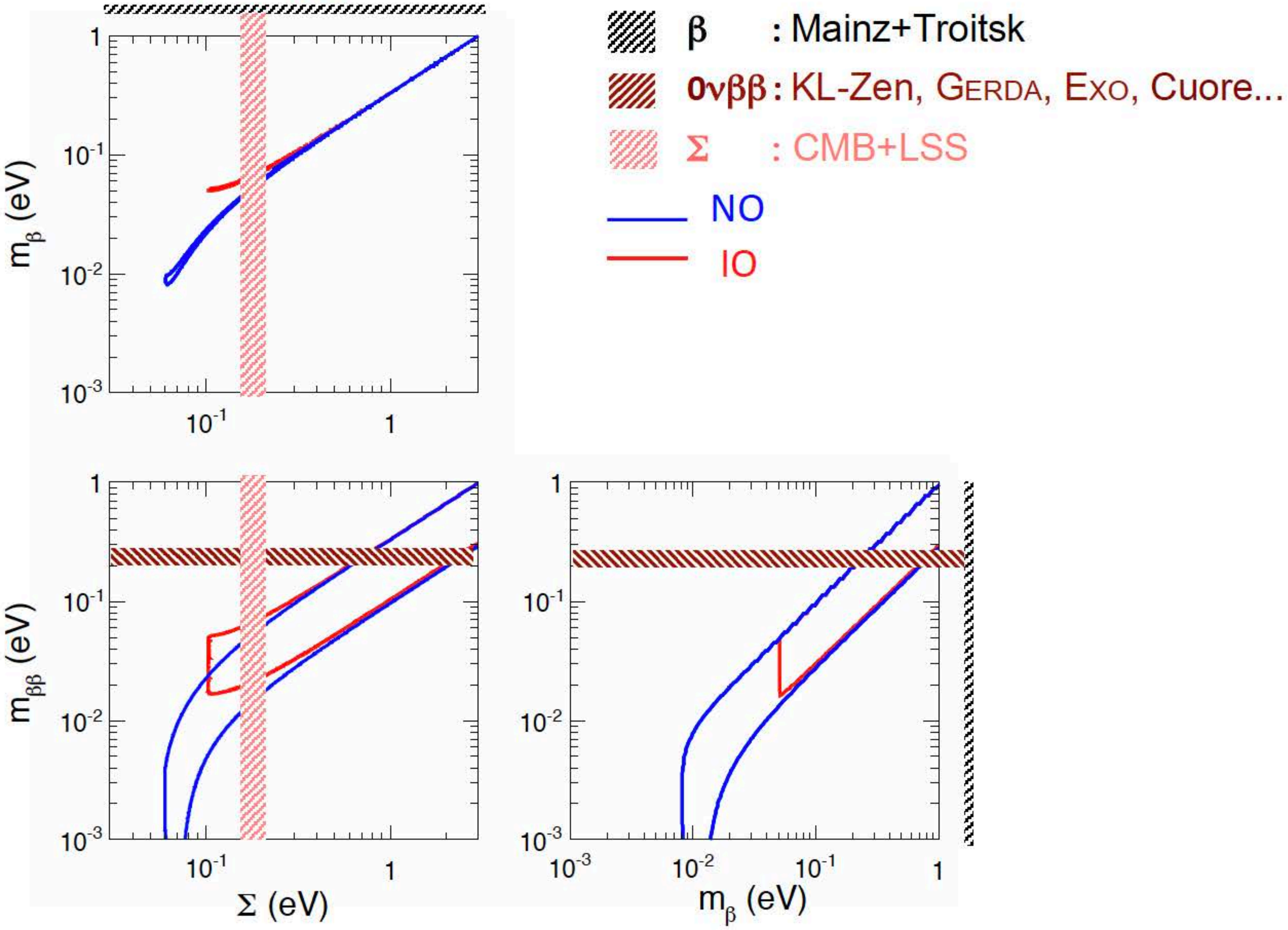
Mezetto

Neutrino Mass Constraints

Cosmology measures $\sum_i m_i$

Double beta decay measures $\left|\sum_i U_{ei}^2 m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2| m_i^2\right)^{1/2}$



m_ν measurable both by laboratory experiments and cosmology

a critical test of consistency

"consistency would be spectacular confirmation!"

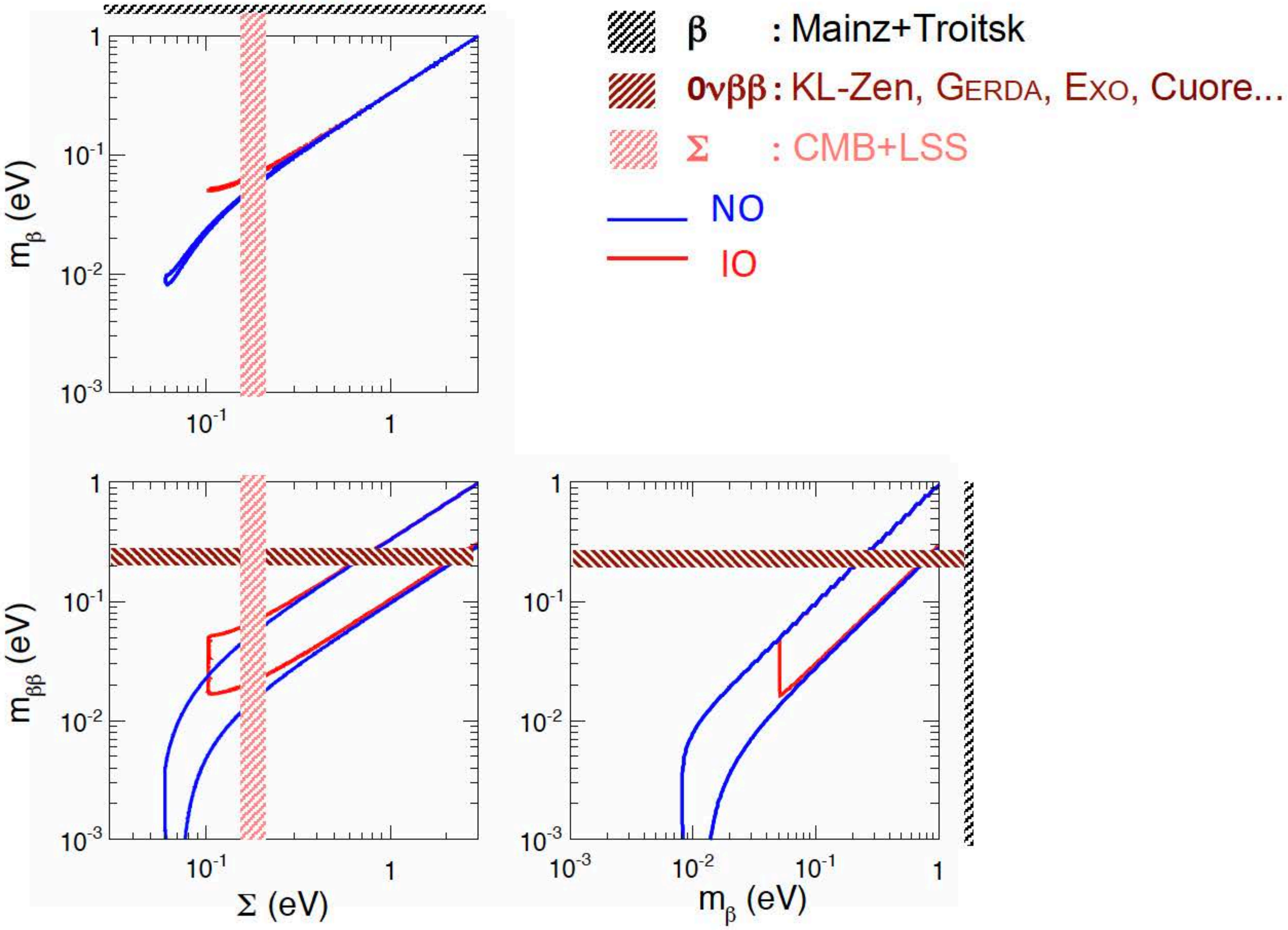
Mezetto

Neutrino Mass Constraints

Cosmology measures $\sum_i m_i$

Double beta decay measures $\left|\sum_i U_{ei}^2\, m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2|\, m_i^2\right)^{1/2}$



m_ν measurable both by laboratory experiments and cosmology

a critical test of consistency

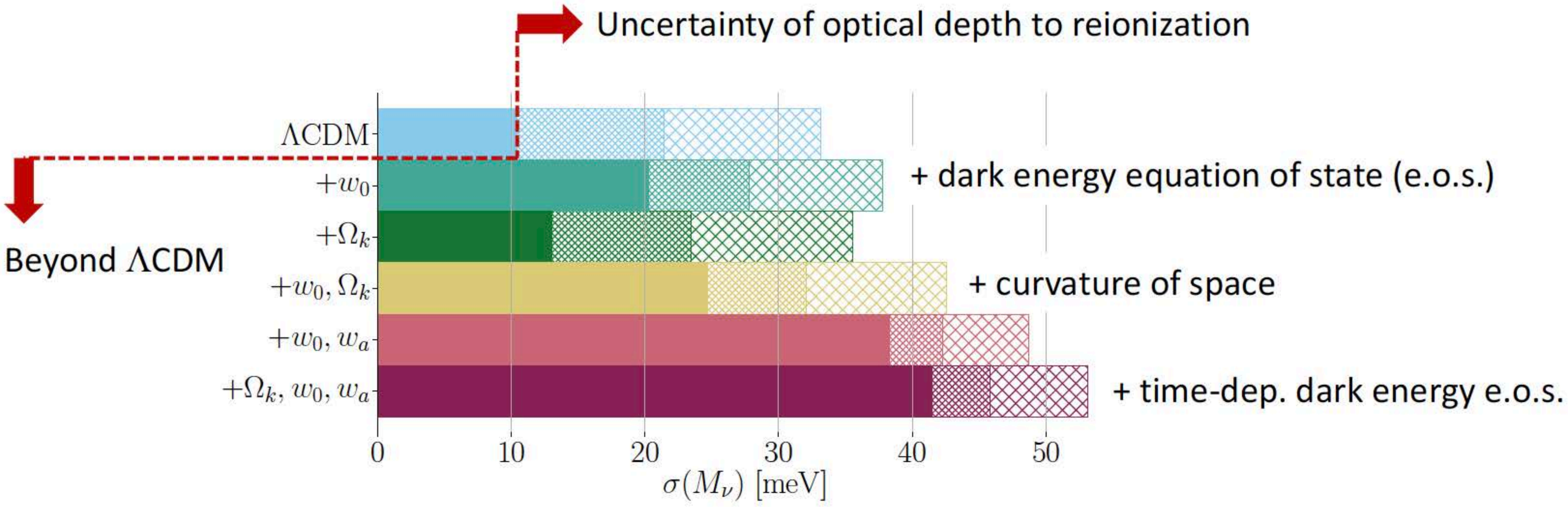
"inconsistency would be major discovery"

Mezetto

Future of Cosmological Neutrino Bounds

Example Forecast:

EUCLID + Planck + Simon's Observatory



Uncertainty of optical depth to reionization

Beyond ΛCDM

+ dark energy equation of state (e.o.s.)

+ curvature of space

+ time-dep. dark energy e.o.s.

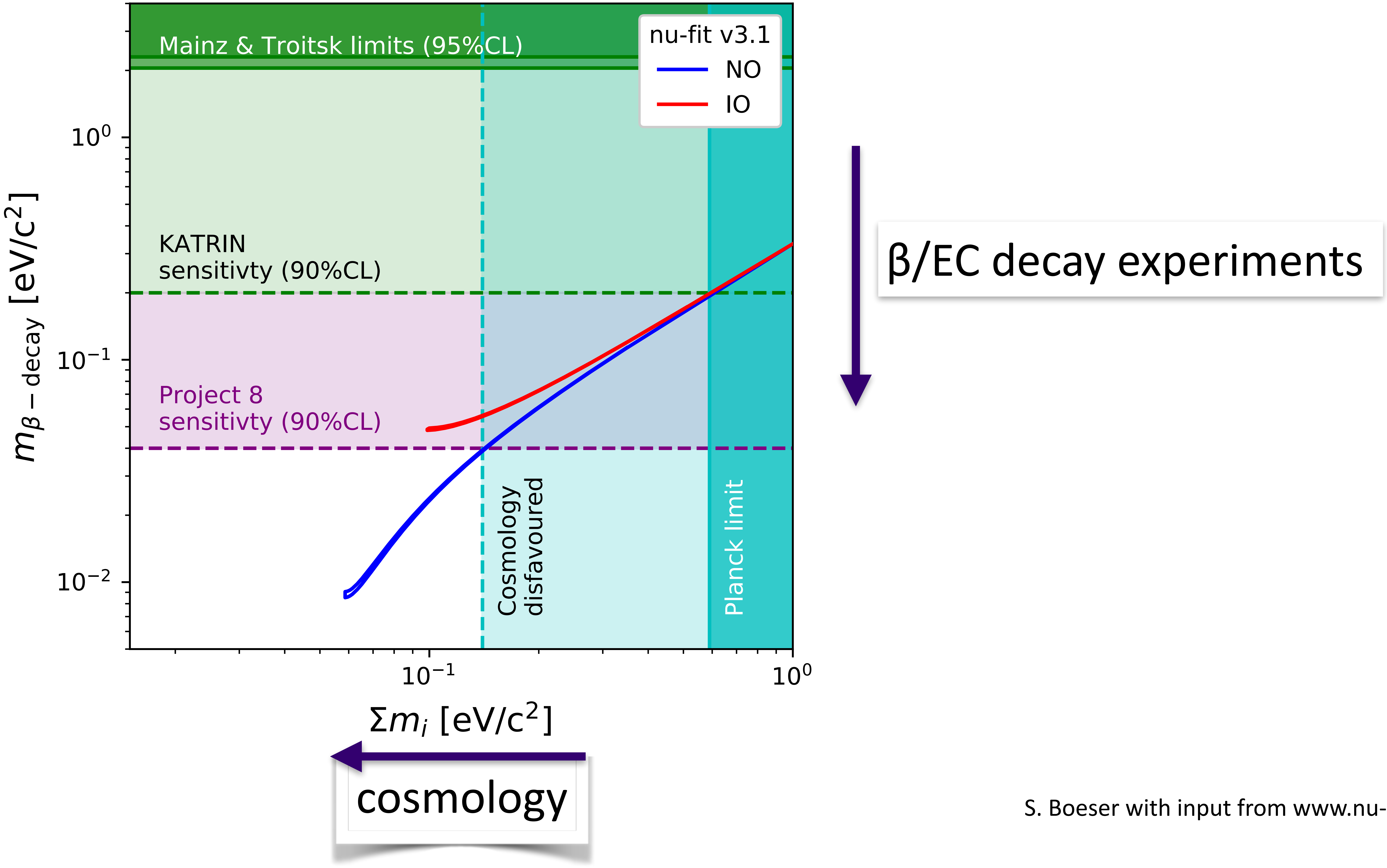
A. Boylea, E. Komatsua, JCAP 2018

Mertens

Complementary Neutrino Mass Limits

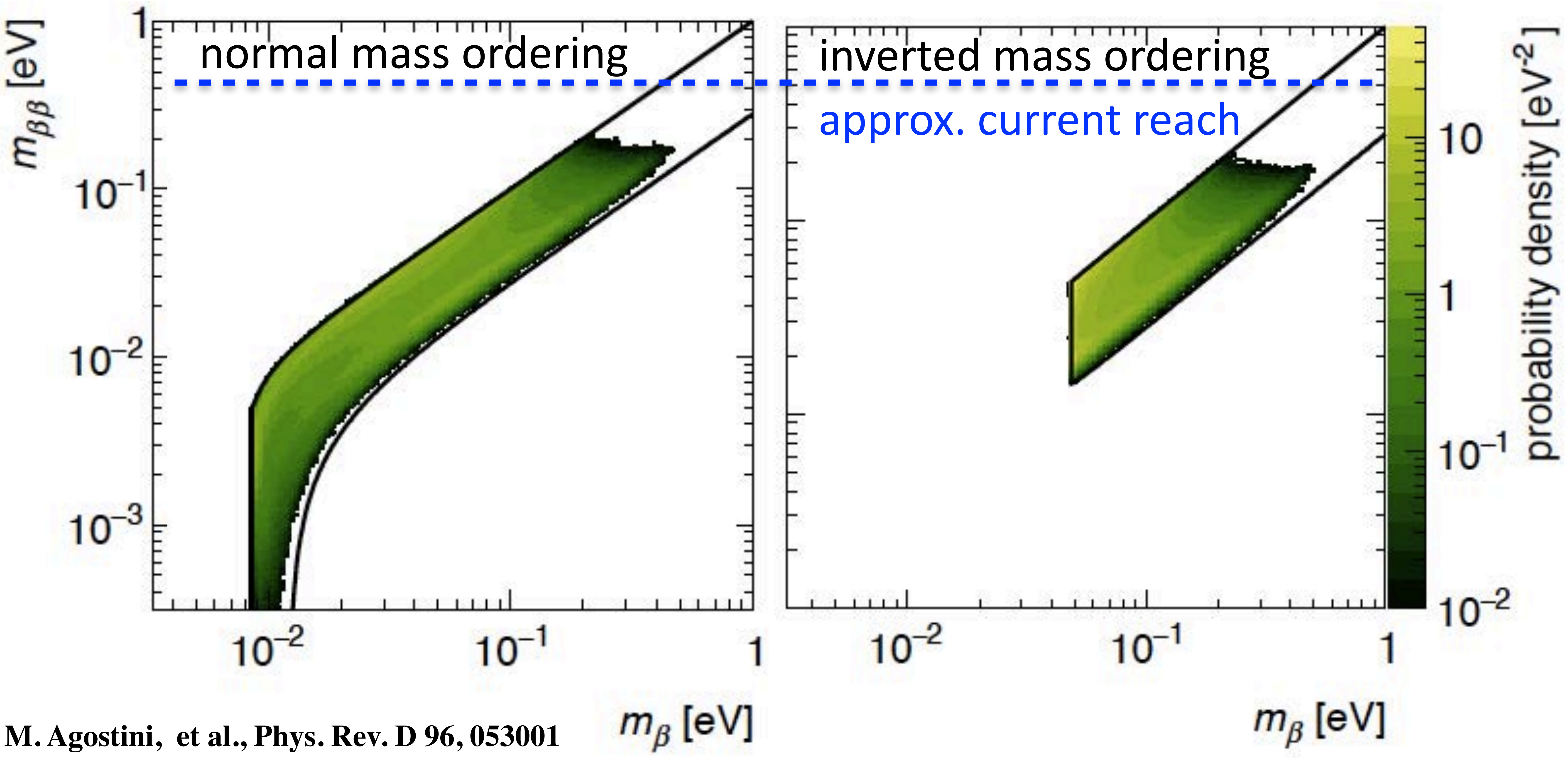
inverted mass ordering

normal mass ordering



S. Boeser with input from www.nu-fit.org

Complementary Neutrino Mass Limits



M. Agostini, et al., Phys. Rev. D 96, 053001

0νββ decay experiments

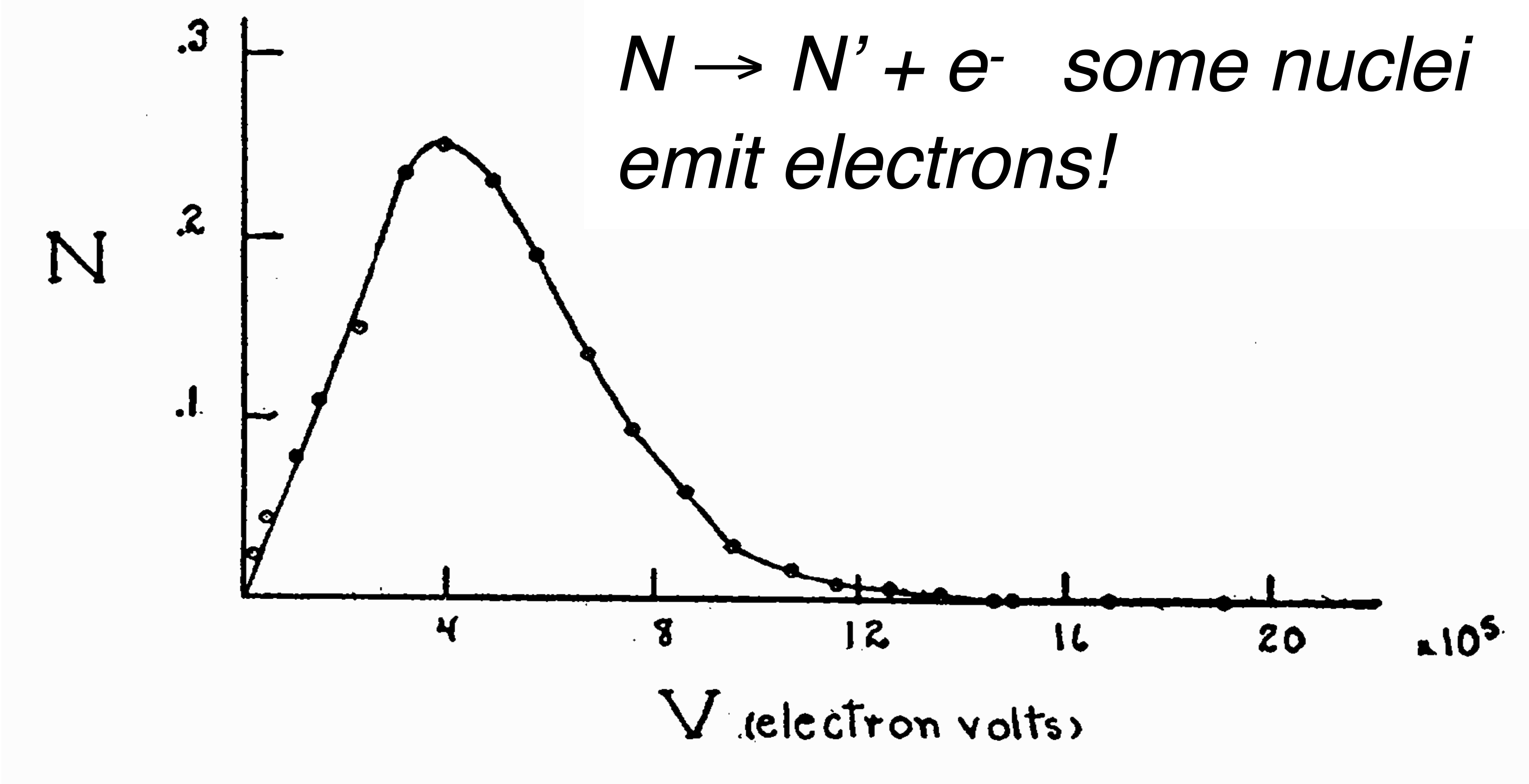
β-decay/EC experiments

β/EC decay experiment limits correlate with the exposure scale required for a definite observation of 0νββ in IMO scenario.

Neutrinos and Beta Spectrum

first evidence of neutrino from
continuous beta spectrum

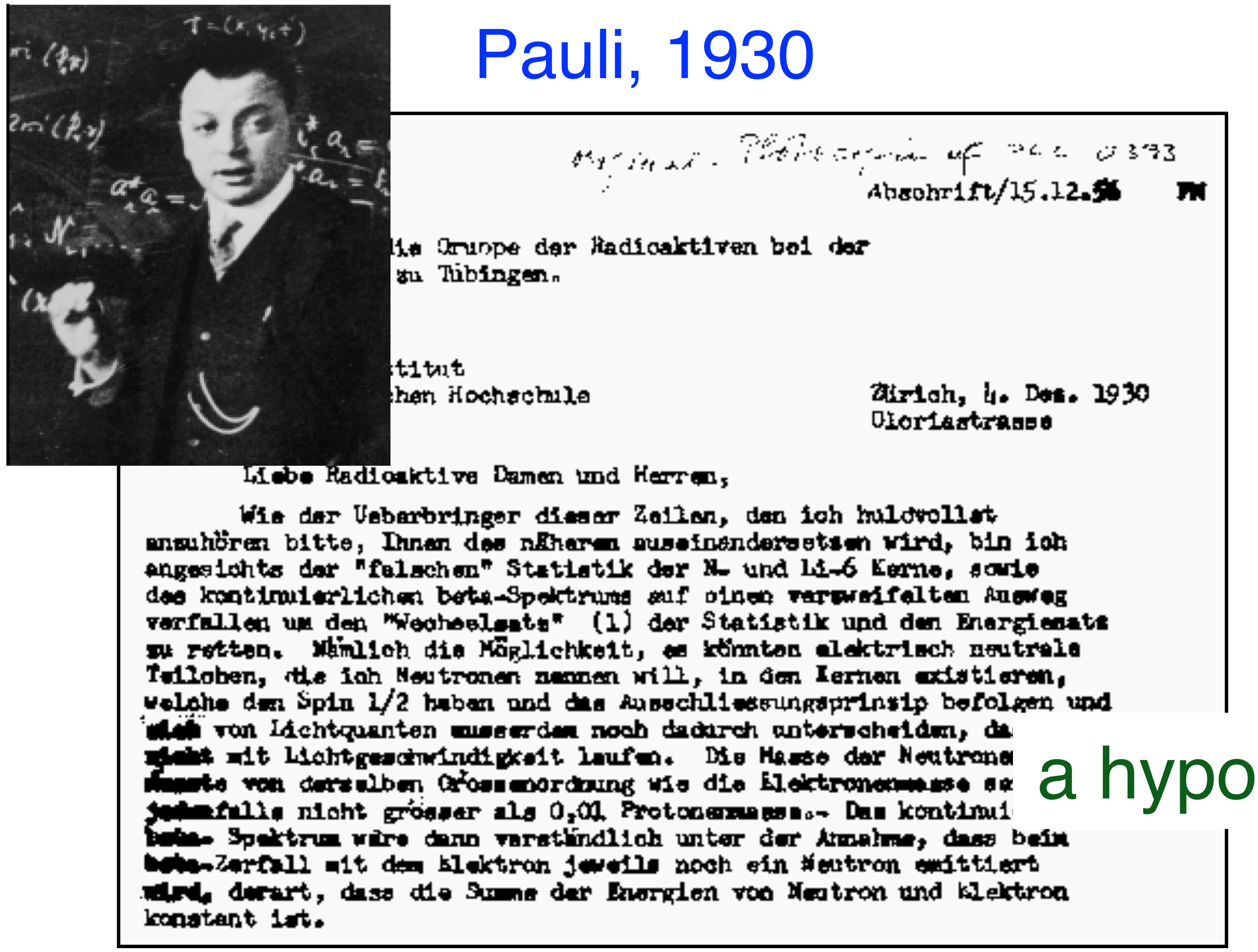
Chadwick, 1914



N → N' + e^- some nuclei emit electrons!

FIG. 5. Energy distribution curve of the beta-rays.

Pauli, 1930



[illegible]
Abschrift/15.12.56 PM

ie Gruppe der Radioaktiven bei der
zu Tübingen.

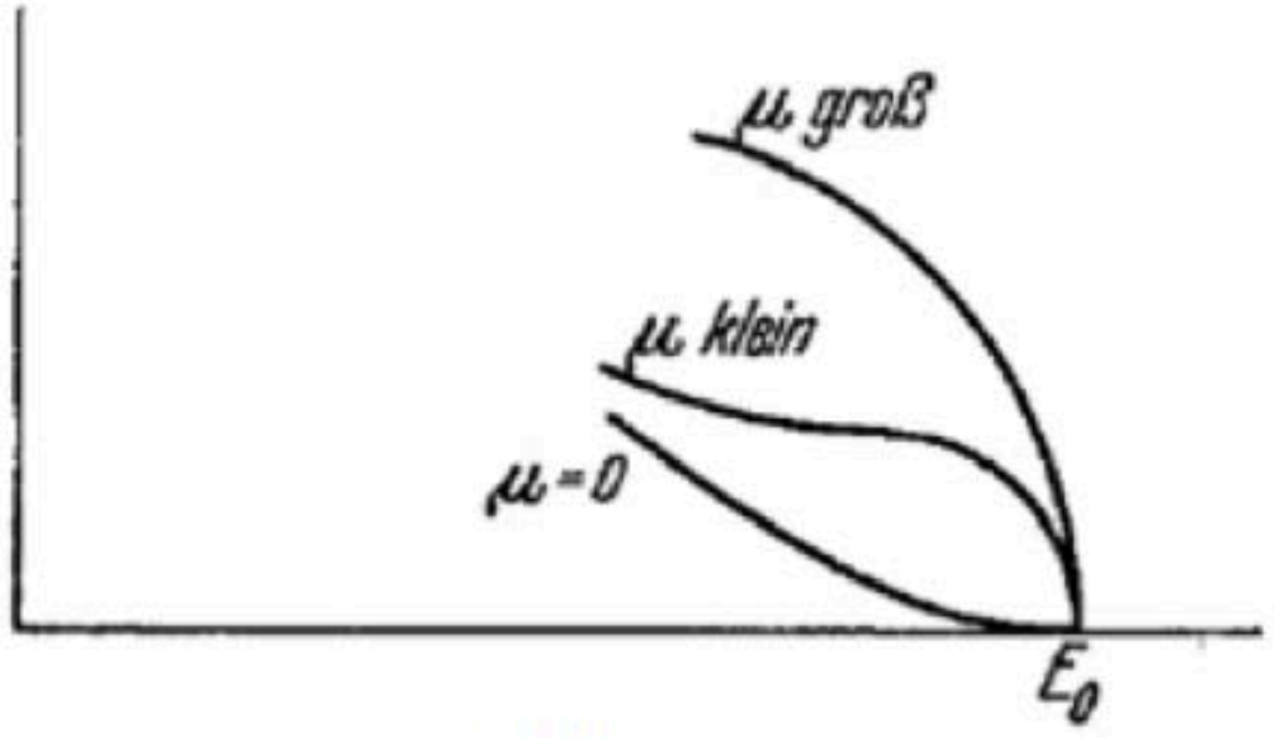
titut
hen Hochschule

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, da nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutrone müsste von derselben Grossenordnung wie die Elektronenmasse se jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinui beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

a hypothesis



β Energy

E. Fermi, Zeitschrift fur Physik 1934

Neutrino Mass and Tritium Beta Decay Endpoint

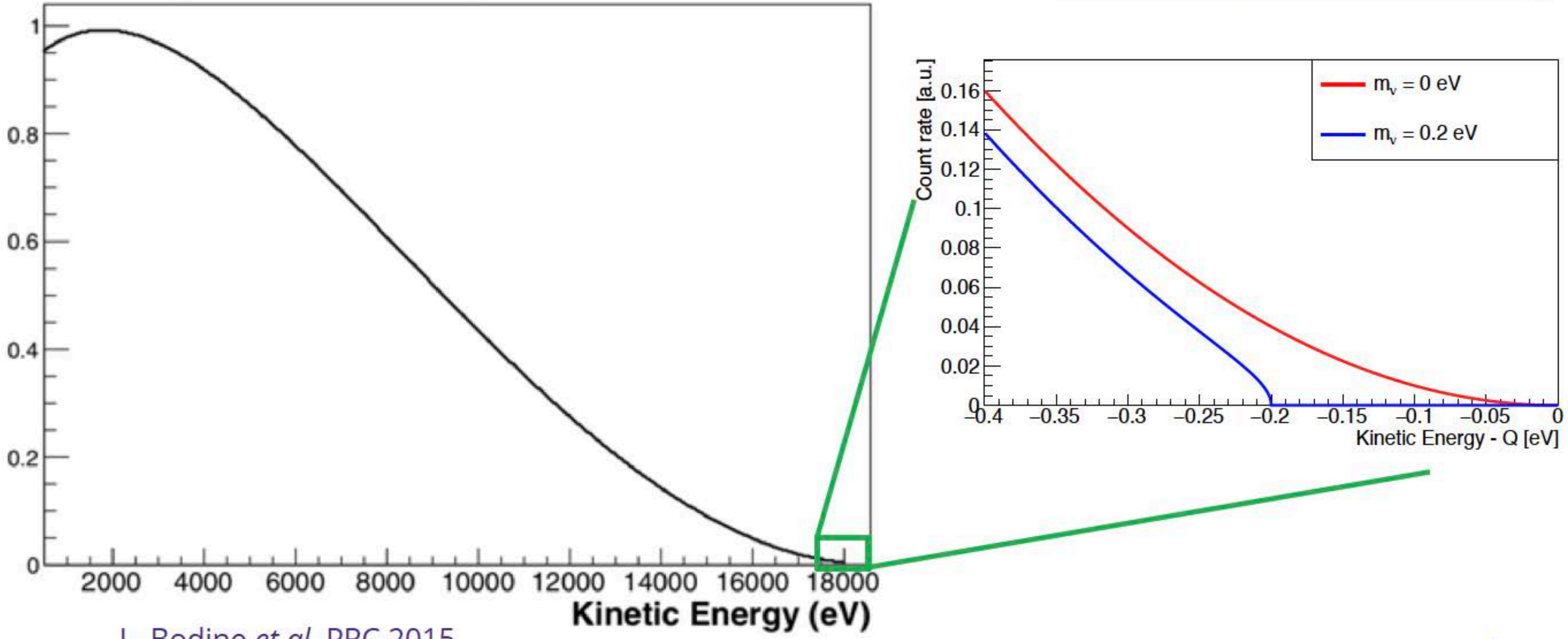
Finite neutrino mass modifies the decay electron spectrum!

With Coulomb distortion for T$_{nuc}$ and neutrino mixing:

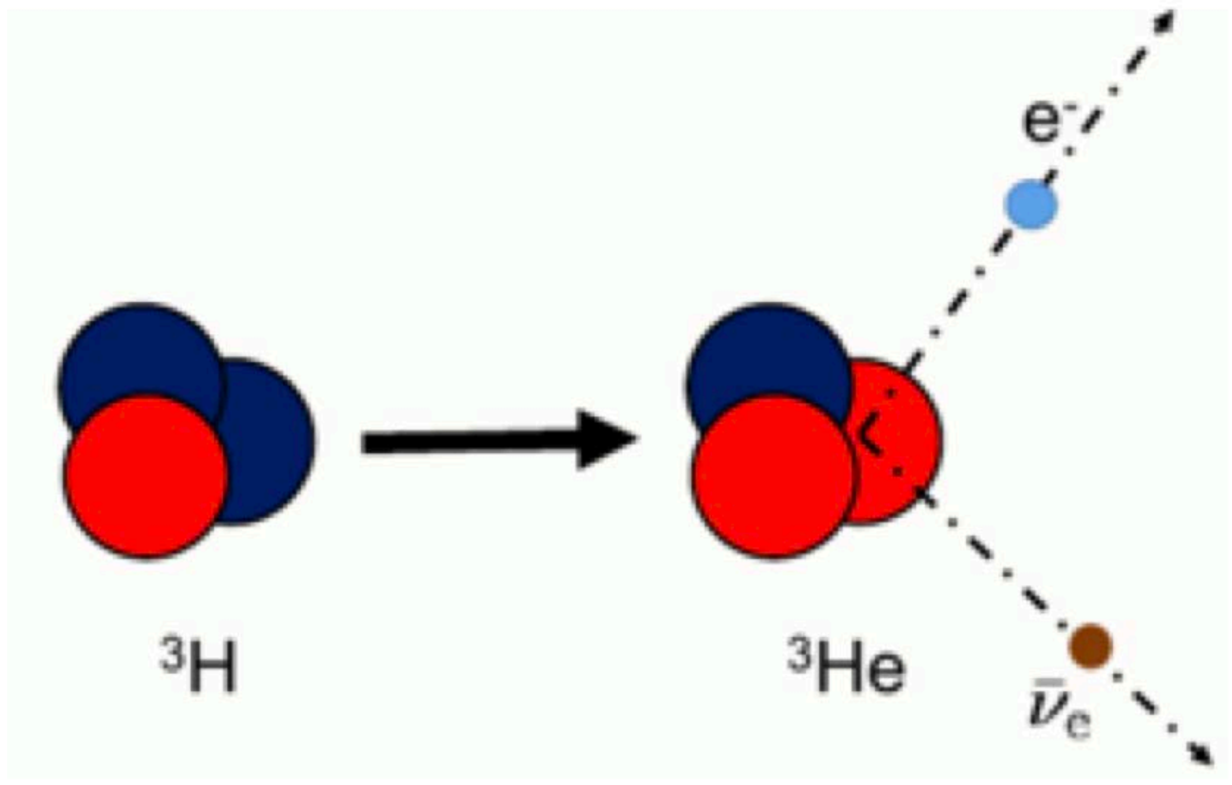
$$\frac{dN}{dE_e} = \boxed{\frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7}} \boxed{|M_{nuc}|^2} \underline{F(Z,E_e)}\, \underline{p_e(E_e+m_e)} \boxed{\sum_i |U_{ei}|^2} \underline{(E_{max}-E_e)}$$
$$\times \sqrt{(E_{max}-E_e)^2 - m_{\nu i}^2}\cdot \underline{\Theta(E_{max}-E_e-m_{\nu i})}$$

Idealized situation:

1. Super-allowed β⁻-decay of ***isolated*** atom
2. Single neutrino mass state



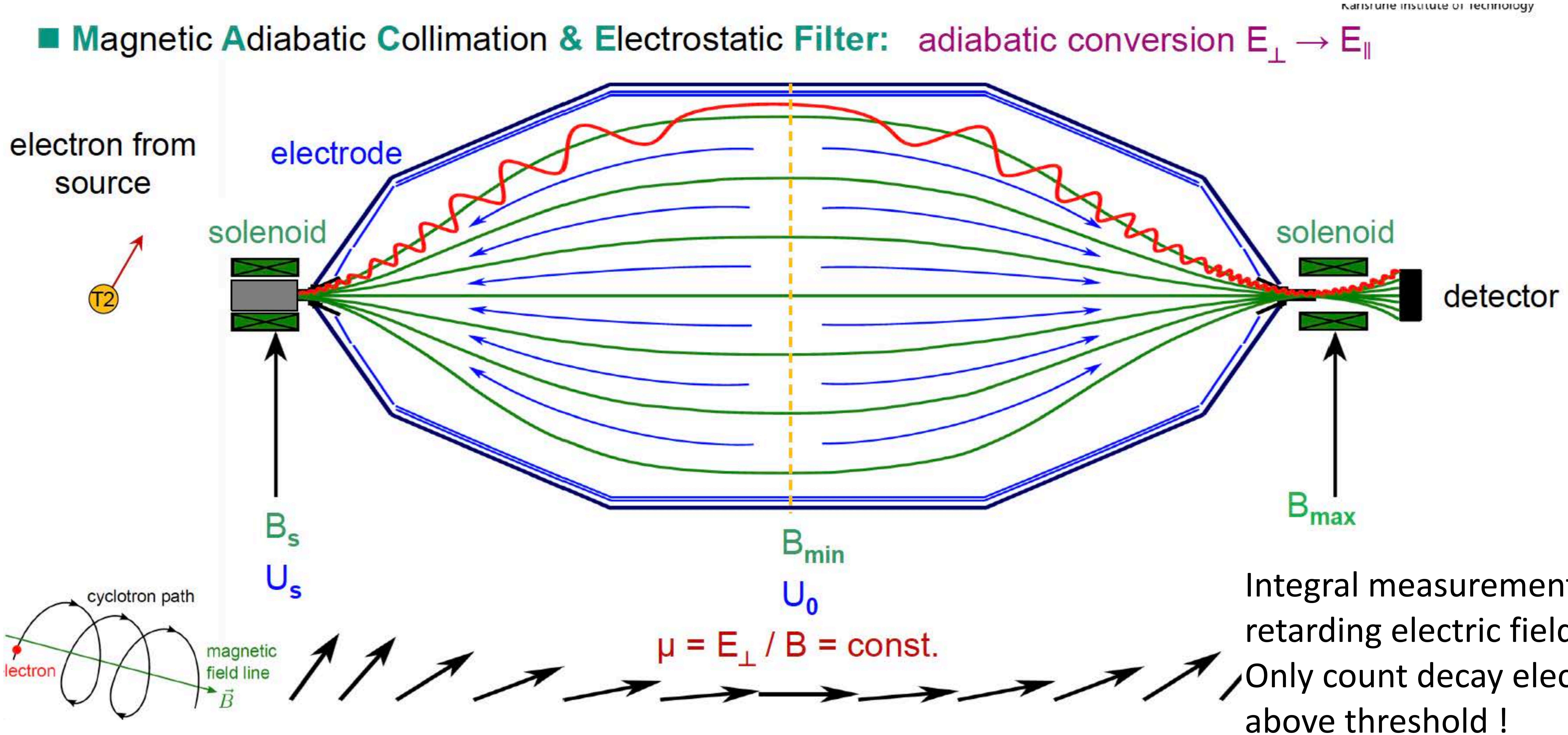
L. Bodine *et al*. PRC 2015



State-of-the-art Technology for T2: MAC-E filter

Magnetic **A**diabatic **C**ollimation with **E**lectrostatic filter

A. Picard et al., Nucl. Instr. Meth. B 63 (1992)



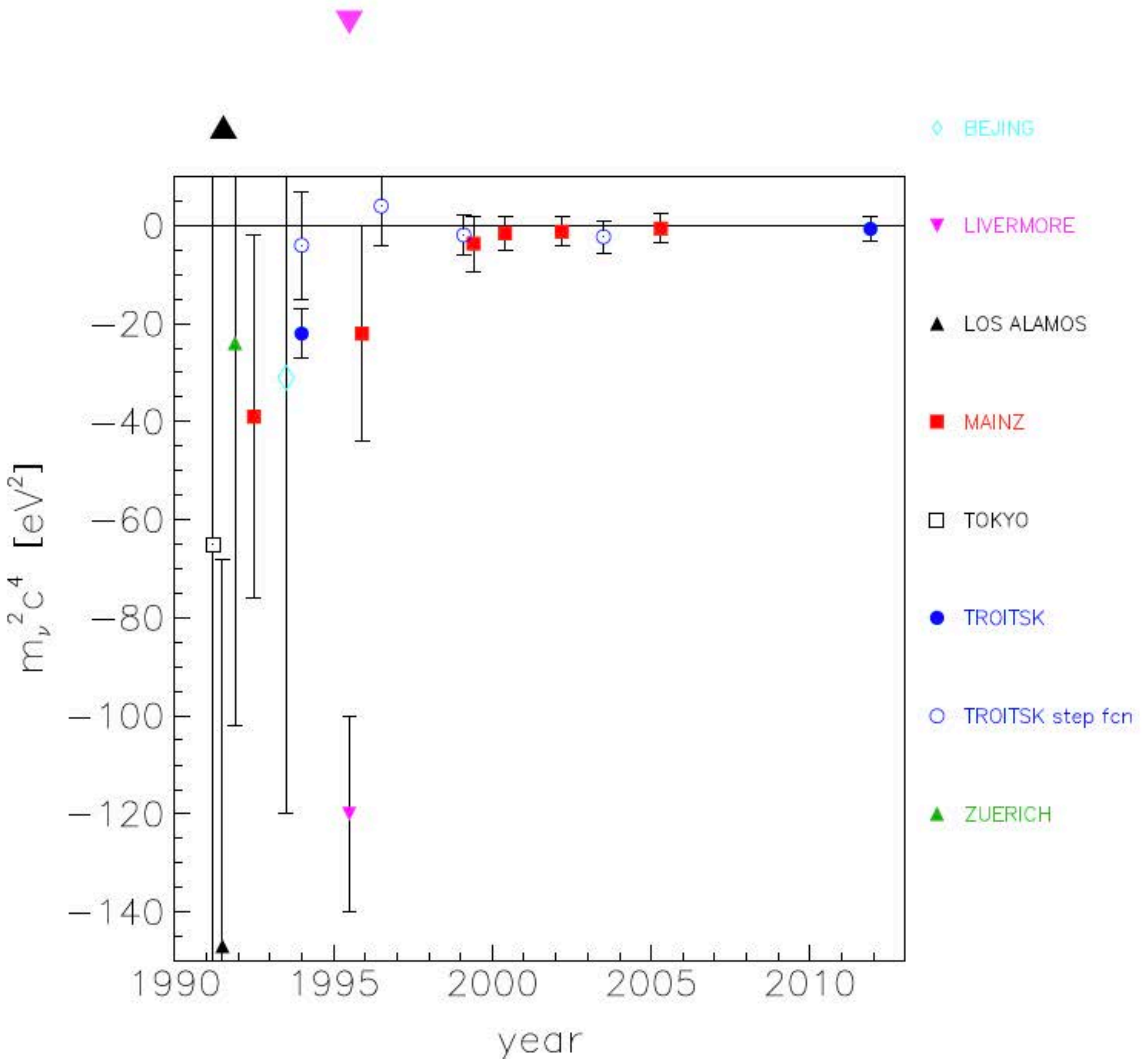
Integral measurement with retarding electric field:
Only count decay electrons above threshold !

Neutrino Mass from Tritium Experiments

Tritium spectrometers have been workhorse of endpoint measurements for decades

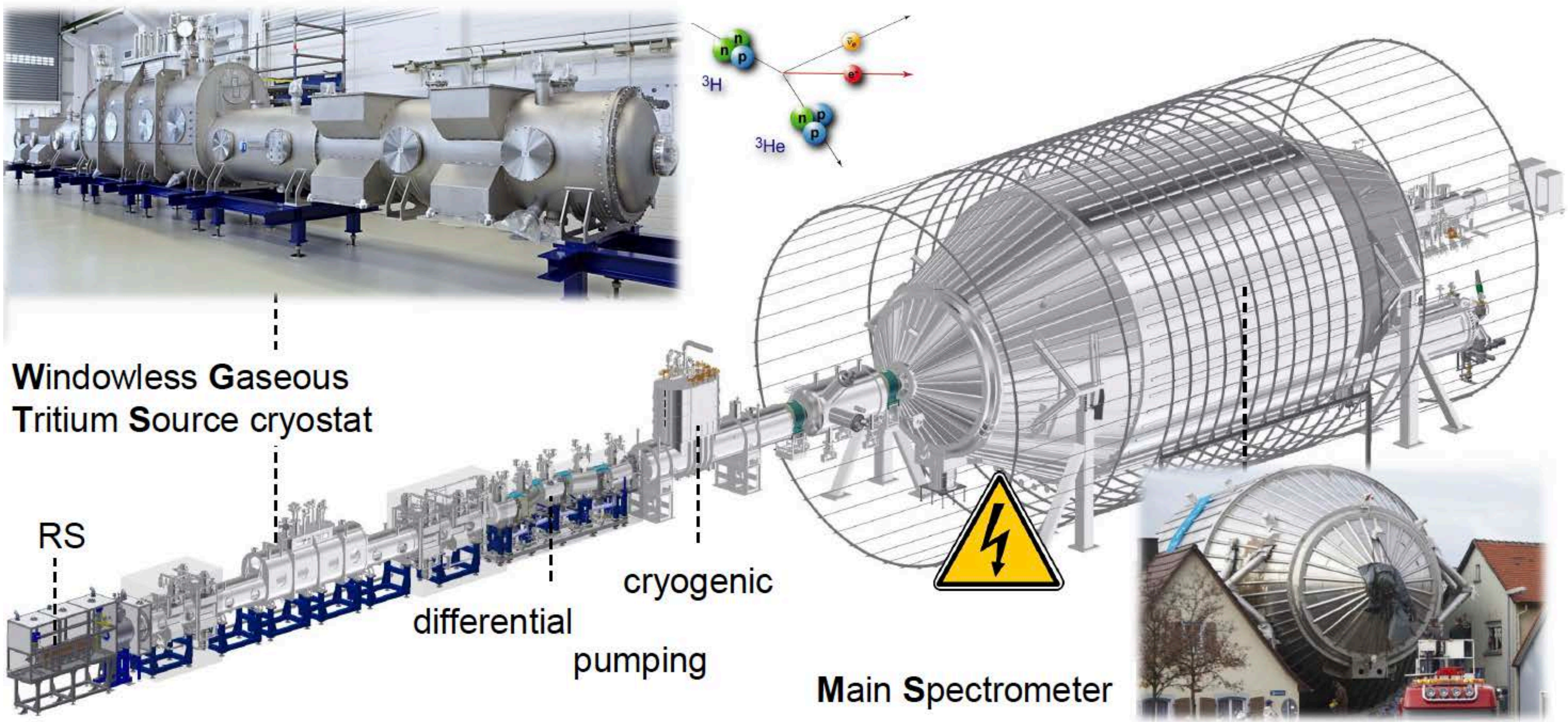
Complicated molecular final states and incomplete de-excitation has yielded non-real mass values

More recent improved theory calculations can correct select previous results



L. Bodine *et al*. PRC **91** 035505 (2015)

KATRIN Overview



Windowless **G**aseous **T**ritium **S**ource cryostat

RS

differential pumping

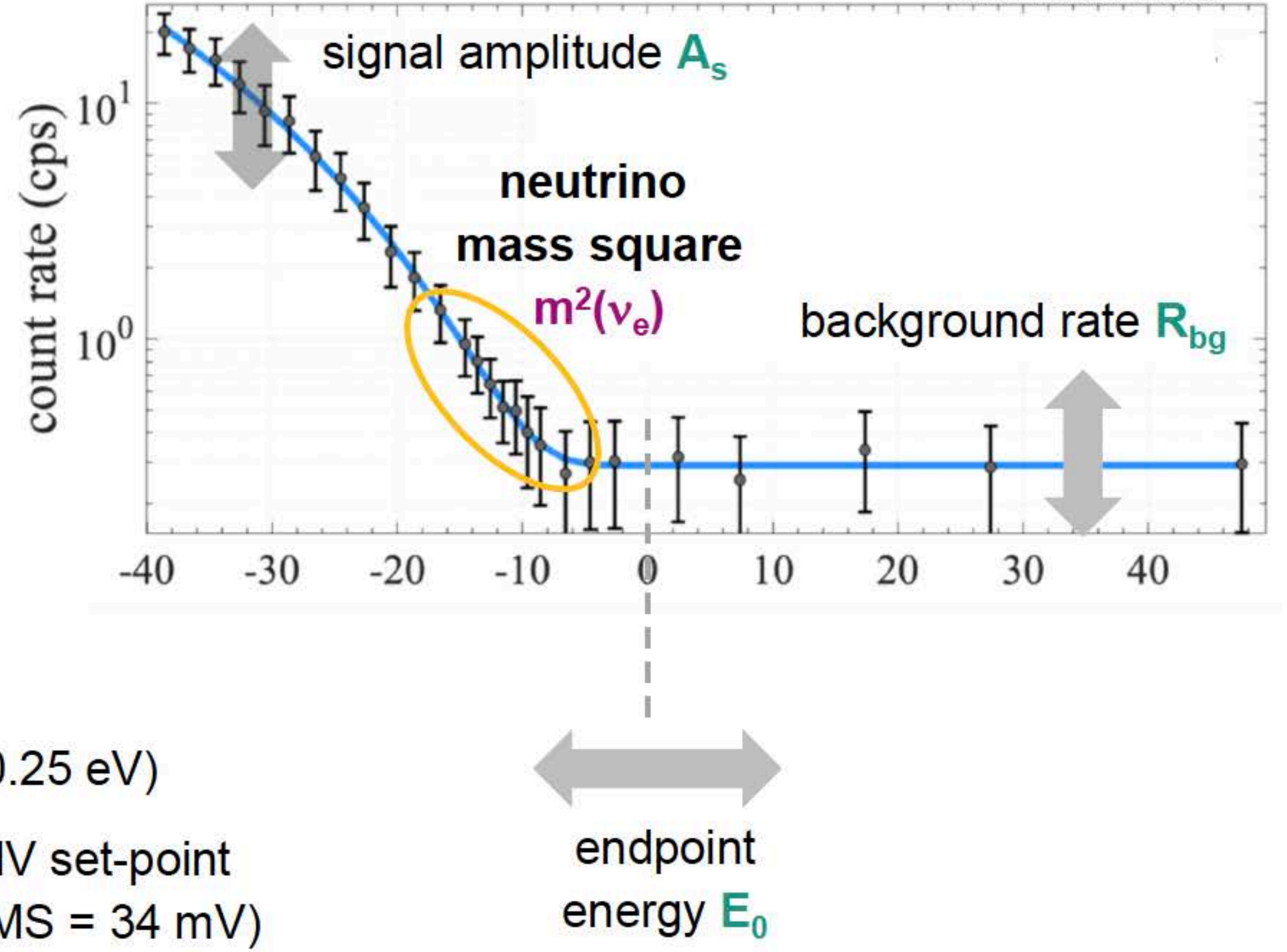
cryogenic

Main **S**pectrometer

KATRIN tritium scanning – fitting of spectrum

- **fit of integrated experimental energy spectrum** to theoretical model with **4 free parameters**
  - leave parameters A_s and E_0 unconstrained ´**shape-only**´ fit
- **merged data set**
  - combine all 274 scans: excellent stability of all fitted ß-decay endpoints E_0 ($\sigma = 0.25$ eV)

  ⇨ “stacking“ of events at mean HV set-point (excellent reproducibility: RMS = 34 mV)

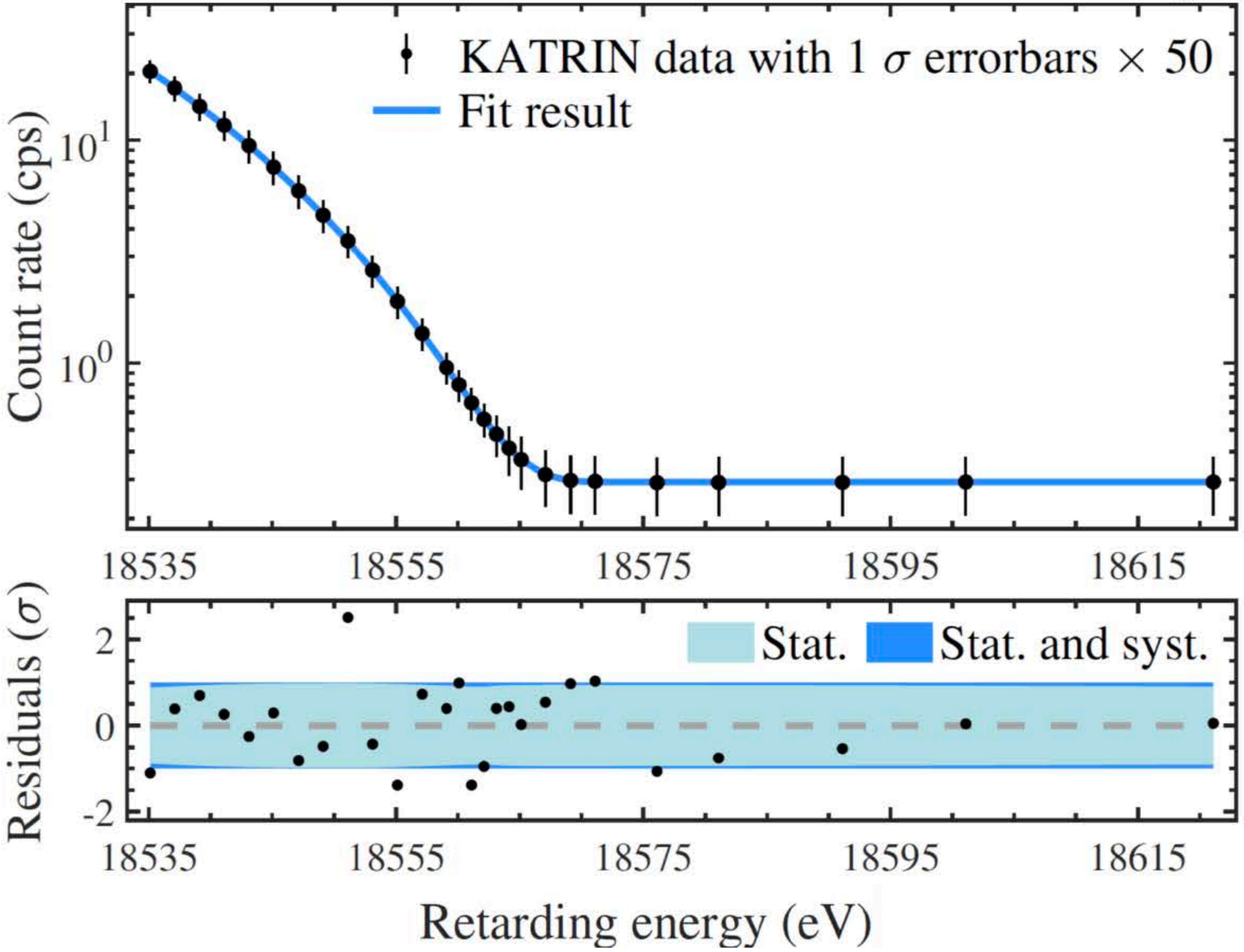


Drexlin, TAUP 2019

KATRIN

Integral tritium ß-decay spectrum

- **High-statistics ß-spectrum**
  - 2 million events in in 90-eV-wide interval (522 h of scanning)
  - excellent goodness-of-fit $\chi^2 = 21.4$ for 23 d.o.f. (p-value = 0.56)



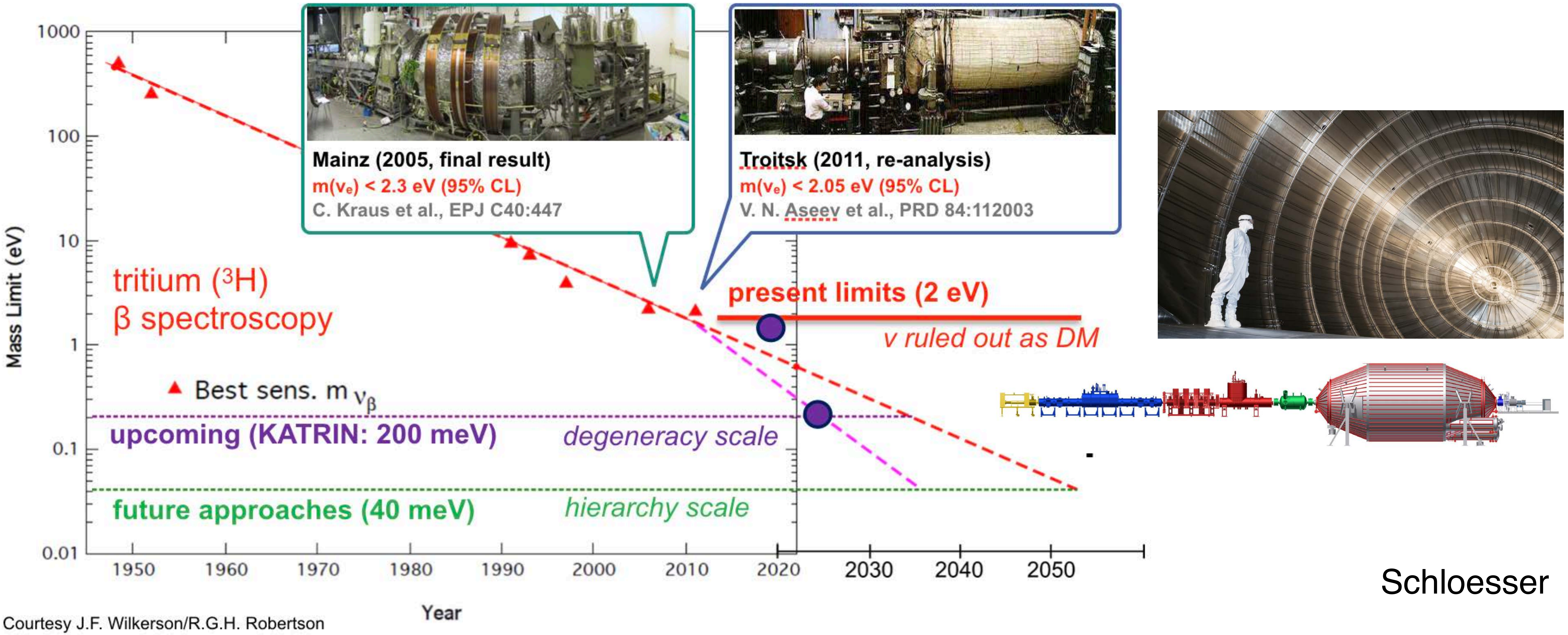
- **bias-free analysis**
  - blinding of FSD
  - full analysis chain first on MC data sets
  - final step: unblinded FSD for experimental data

- **ν-mass and E_0: best fit results**

$$m^2(\nu_e) = \left(-1.0 \begin{smallmatrix} +\,0.9 \\ -\,1.1 \end{smallmatrix}\right) \mathrm{eV}^2 \; (90\% \; \mathrm{CL})$$

Drexlin, TAUP 2019

Direct Neutrino Mass Searches



Mainz (2005, final result)
$m(\nu_e) < 2.3$ eV (95% CL)
C. Kraus et al., EPJ C40:447

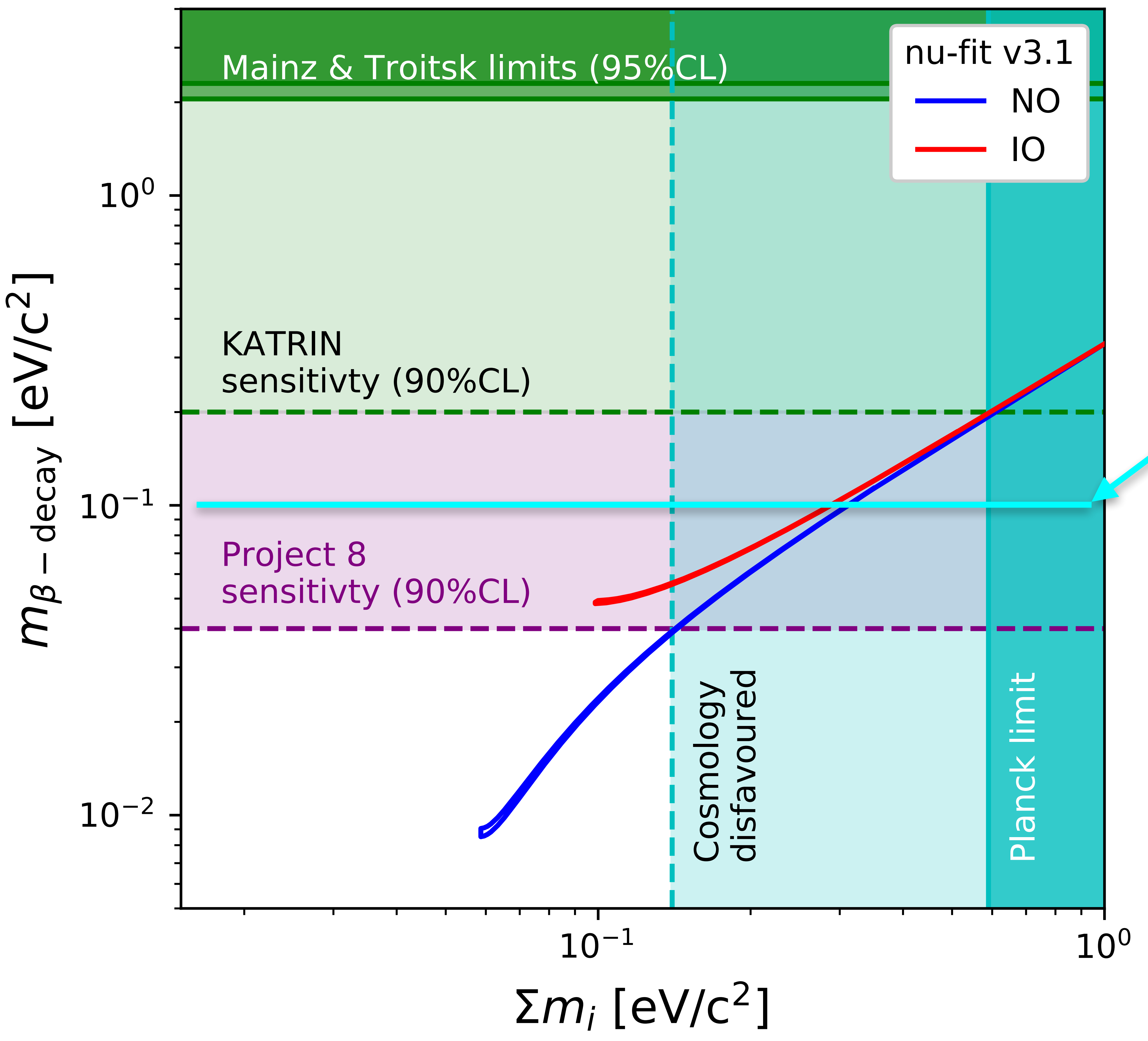
Troitsk (2011, re-analysis)
$m(\nu_e) < 2.05$ eV (95% CL)
V. N. Aseev et al., PRD 84:112003

Courtesy J.F. Wilkerson/R.G.H. Robertson

Schloesser

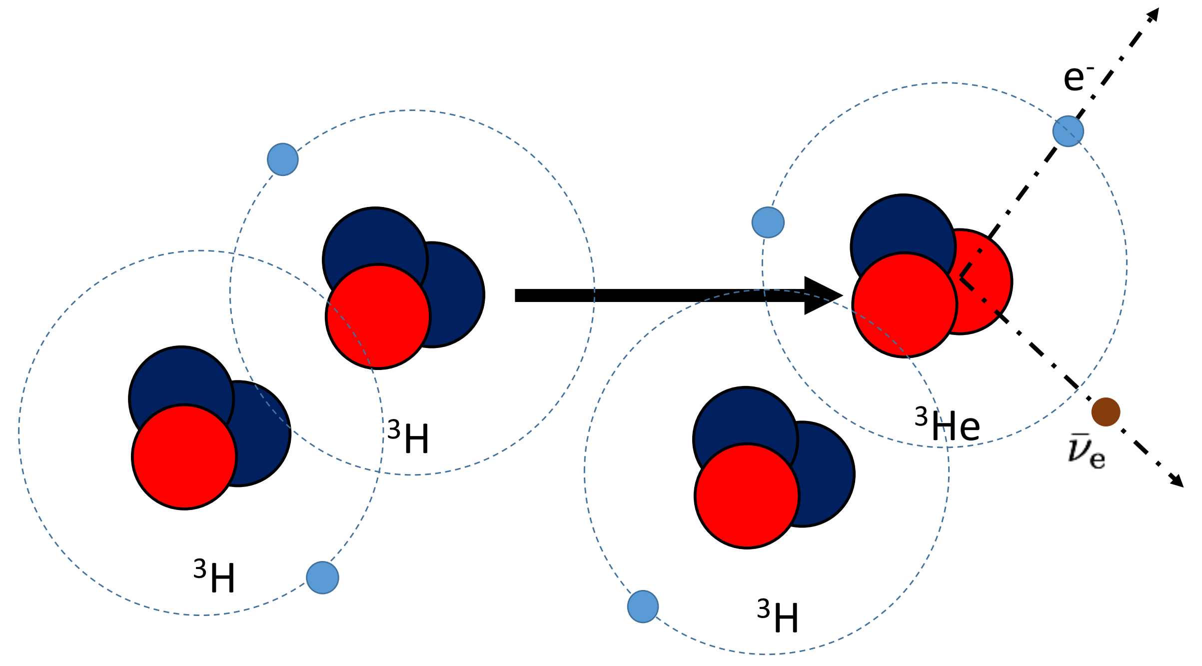
Tritium experiments define the mass limit. Where will we be in 2030?

Challenges for Sensitivity Beyond KATRIN



S. Boeser with input from www.nu-fit.org

Source intrinsic limitation:
Irreducible excitation of ro-vibrational initial and final states of **T_2 molecule**.

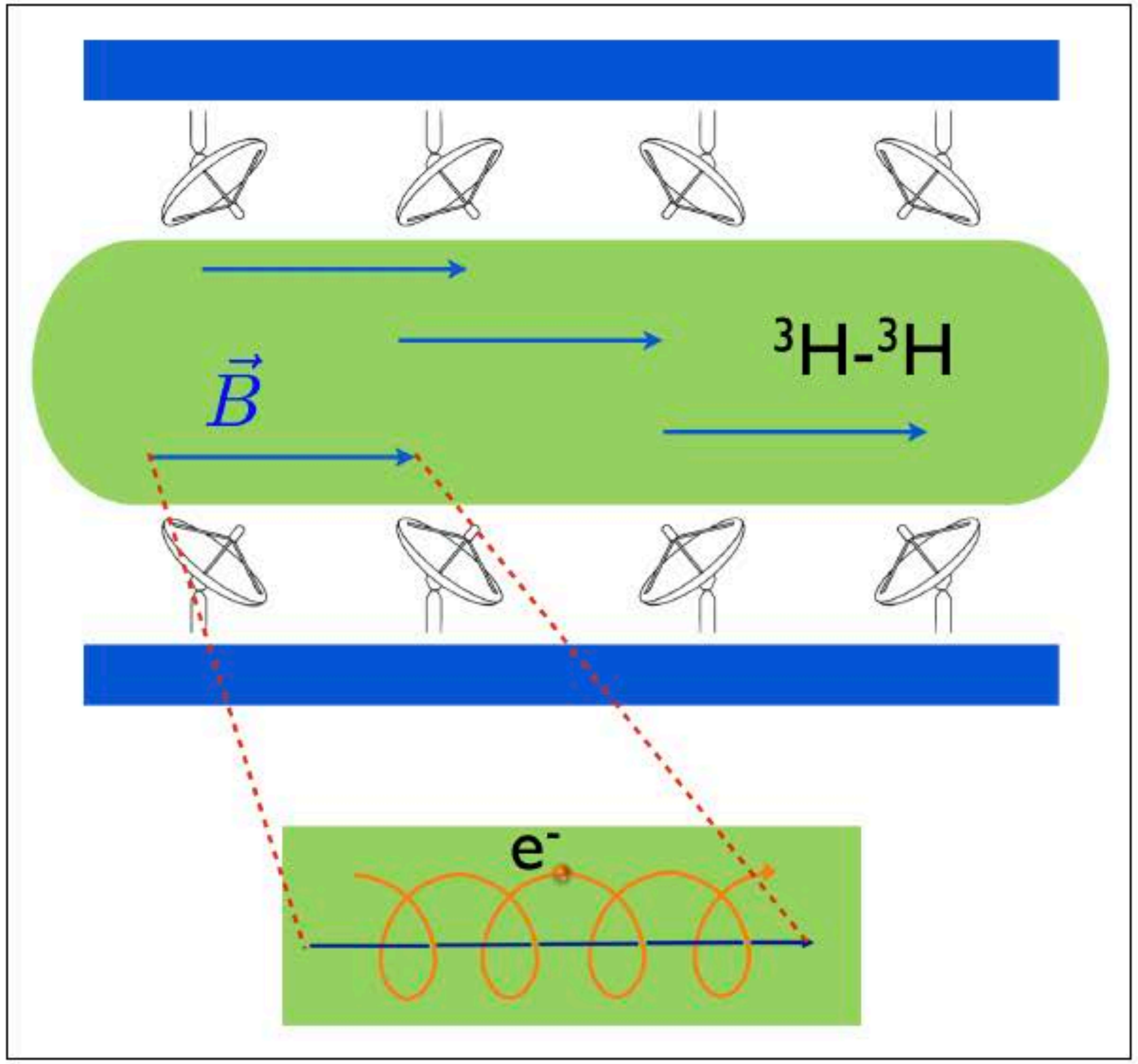


Technical challenges:

1. Statistical nature of e^- scattering in gas column
2. e^- can be scattered into angular acceptance cone of the MAC-E filter
3. Rydberg atoms as background source

Project 8: Cyclotron Radiation Emission Spectroscopy of T2

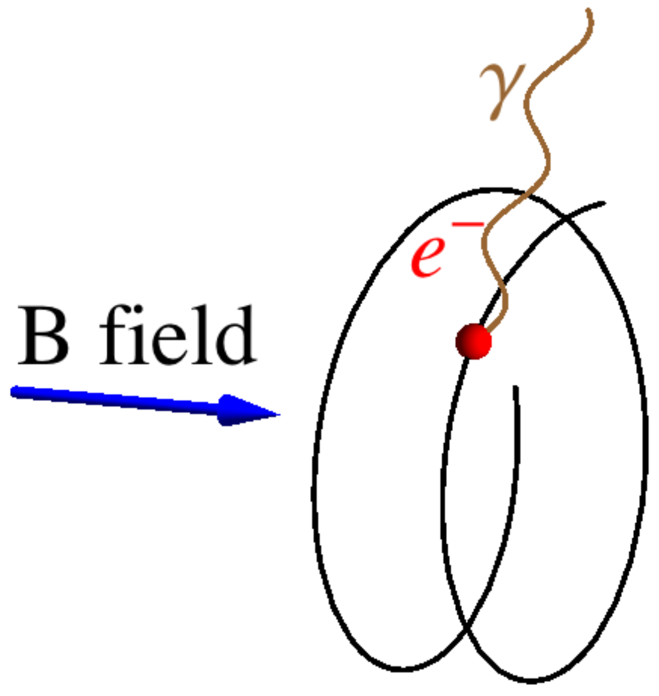
1. Start with an enclosed volume
2. Fill with tritium gas
3. Add a magnetic field



B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

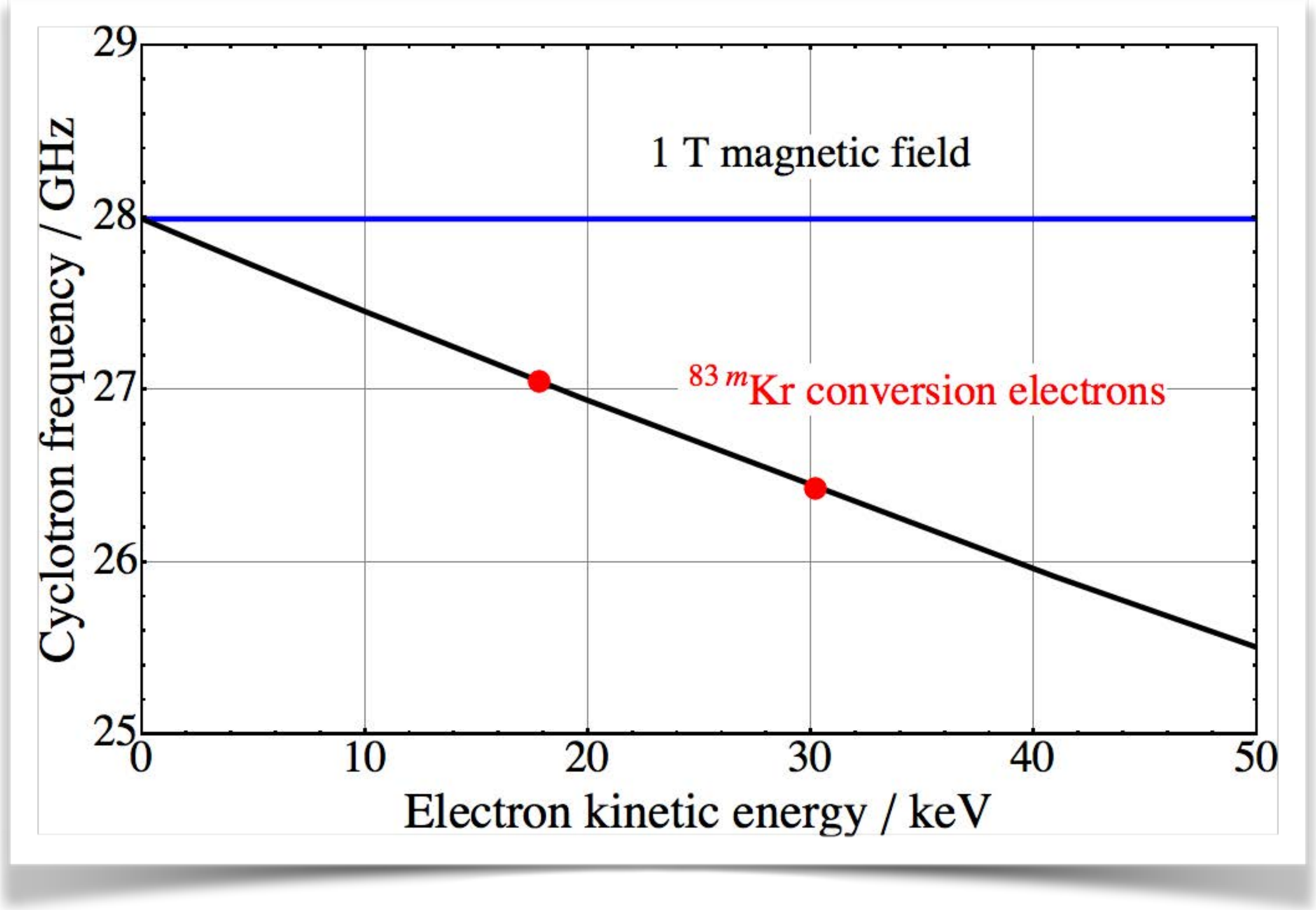
4. Decay electrons spiral around field lines
5. Add antennas to detect the cyclotron radiation

Project 8: Cyclotron Radiation Emission Spectroscopy of T2

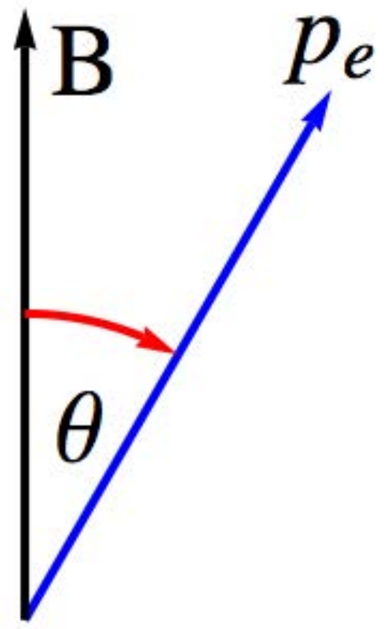


Novel approach: J. Formaggio and B. Monreal, Phys. Rev. D 80:051301 (2009)

- Cyclotron radiation from single electrons
- Source transparent to microwave radiation
- No e- transport from source to detector
- Highly precise frequency measurement



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



$$P\left(E_{\rm kin}, m, \theta\right) = \frac{1}{4\pi\epsilon_0} \frac{2}{3} \frac{e^4}{m^4 c^5} B^2 \left(E_{\rm kin}^2 + 2\, E_{\rm kin}\, m\, c^2\right) \sin^2\theta$$

$$P\left(17.8\,{\rm keV}, 90^\circ, 1\,{\rm T}\right) = 1\,{\rm fW}$$
$$P\left(30.2\,{\rm keV}, 90^\circ, 1\,{\rm T}\right) = 1.7\,{\rm fW}$$

Small but readily detectable with state of the art detectors

Project 8 in a waveguide with magnetic trap

Energy resolution vs. frequency resolution

$$\frac{\Delta E_{\mathrm{kin}}}{E_{\mathrm{kin}}} = \boxed{\left(1+\frac{m_e c^2}{E_{\mathrm{kin}}}\right) \approx 28} \frac{\Delta\nu_c}{\nu_c}$$

for 18.6 keV electron

$$\Delta E_{\mathrm{kin}} \approx 0.2\,\mathrm{eV} \rightarrow \frac{\Delta\nu_c}{\nu_c} \approx 4\times10^{-7}$$

$$\nu_c \approx 27\,\mathrm{GHz} \rightarrow \Delta\nu_c \approx 11\,\mathrm{kHz}$$

Frequency resolution vs. observation time

$$\Delta\nu_c \times t_{\mathrm{obs}} \geq \frac{1}{2\pi} \rightarrow t_{\mathrm{obs}} \geq 14\,\mu\mathrm{s}$$

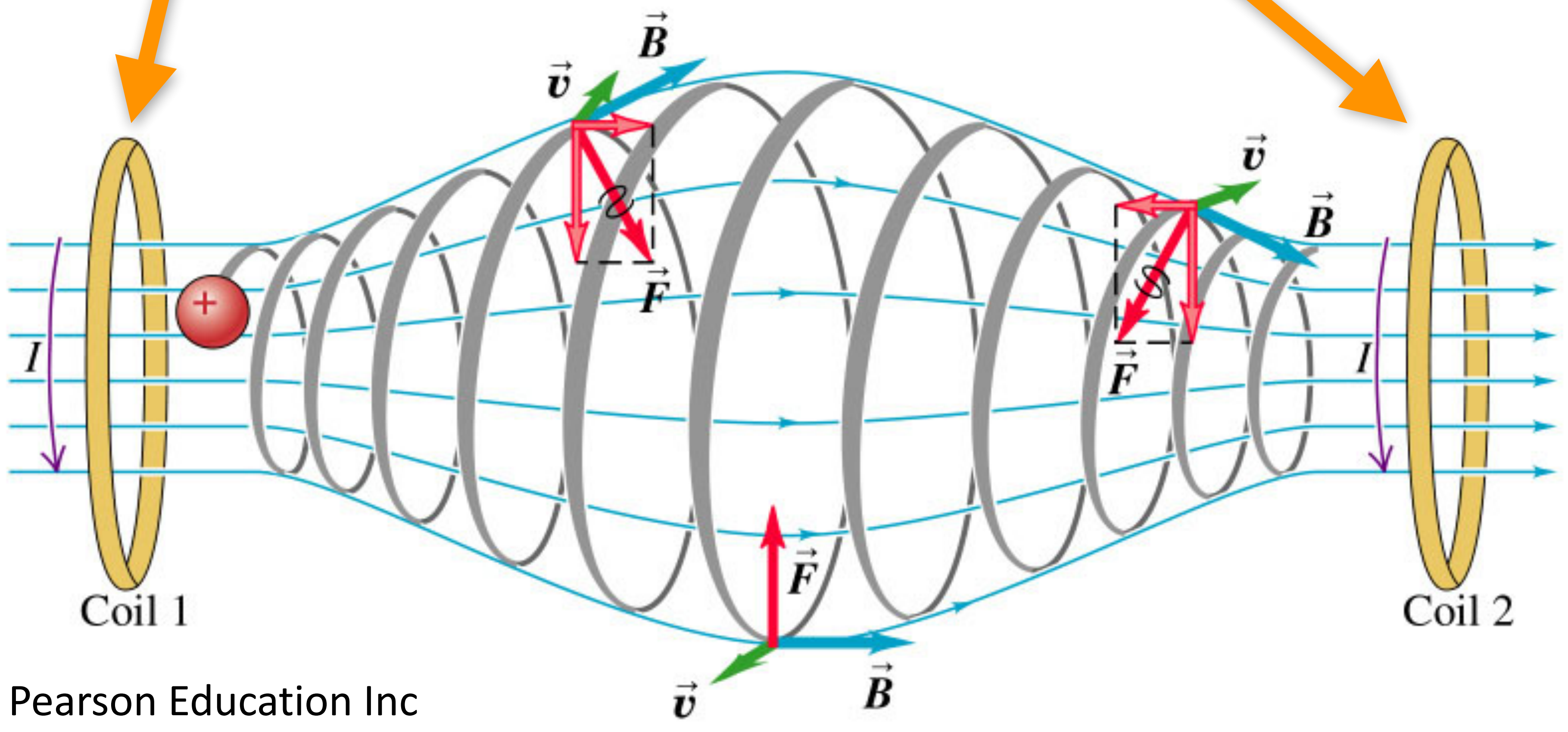
→ **Need for a magnetic (no work) trap!**

Tritium compatible CRES cell

To cryogenic amplifier + heterodyne mixing stage + signal digitizer

^{83m}Kr and T_2 supply line

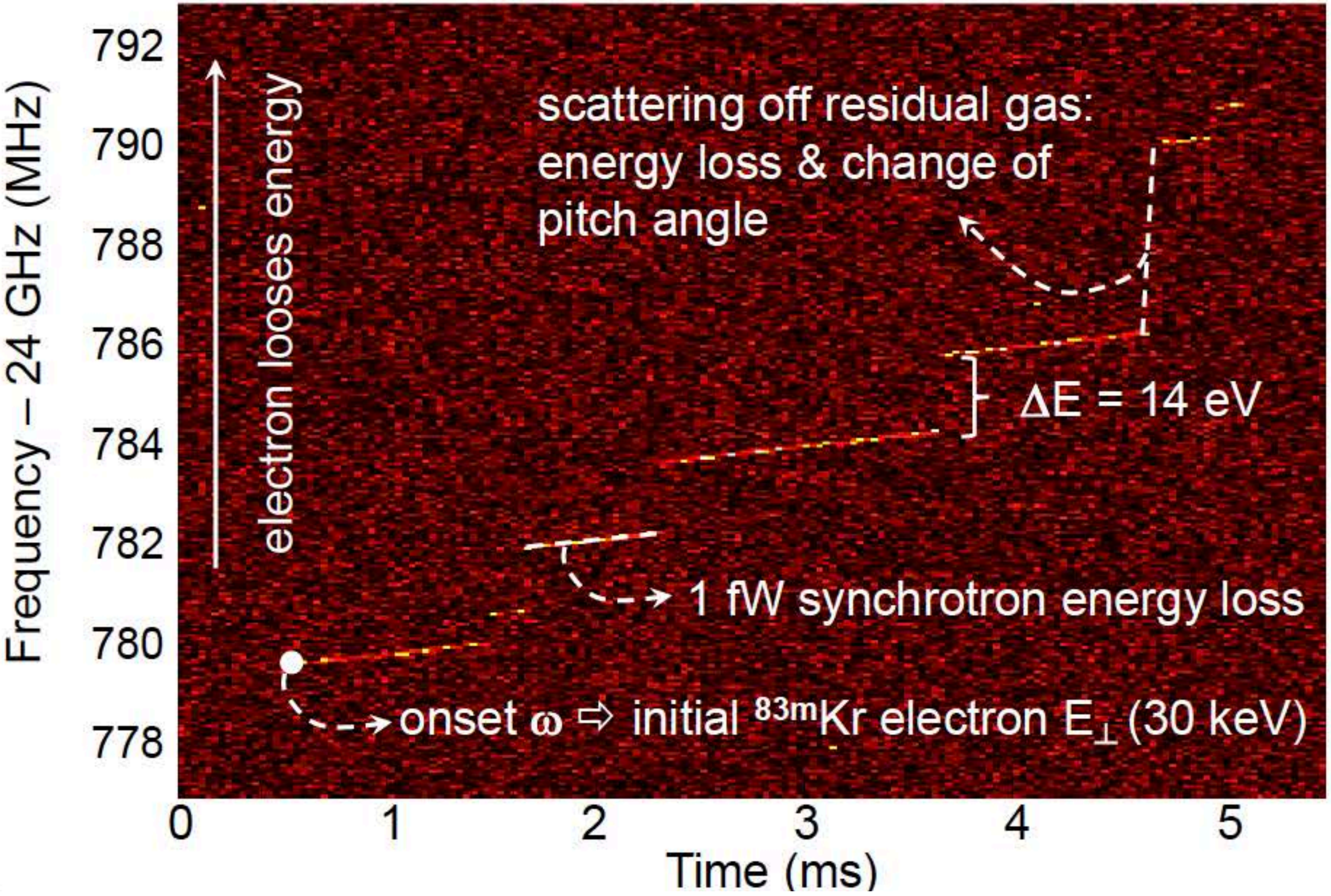
Double magnetic mirror trap

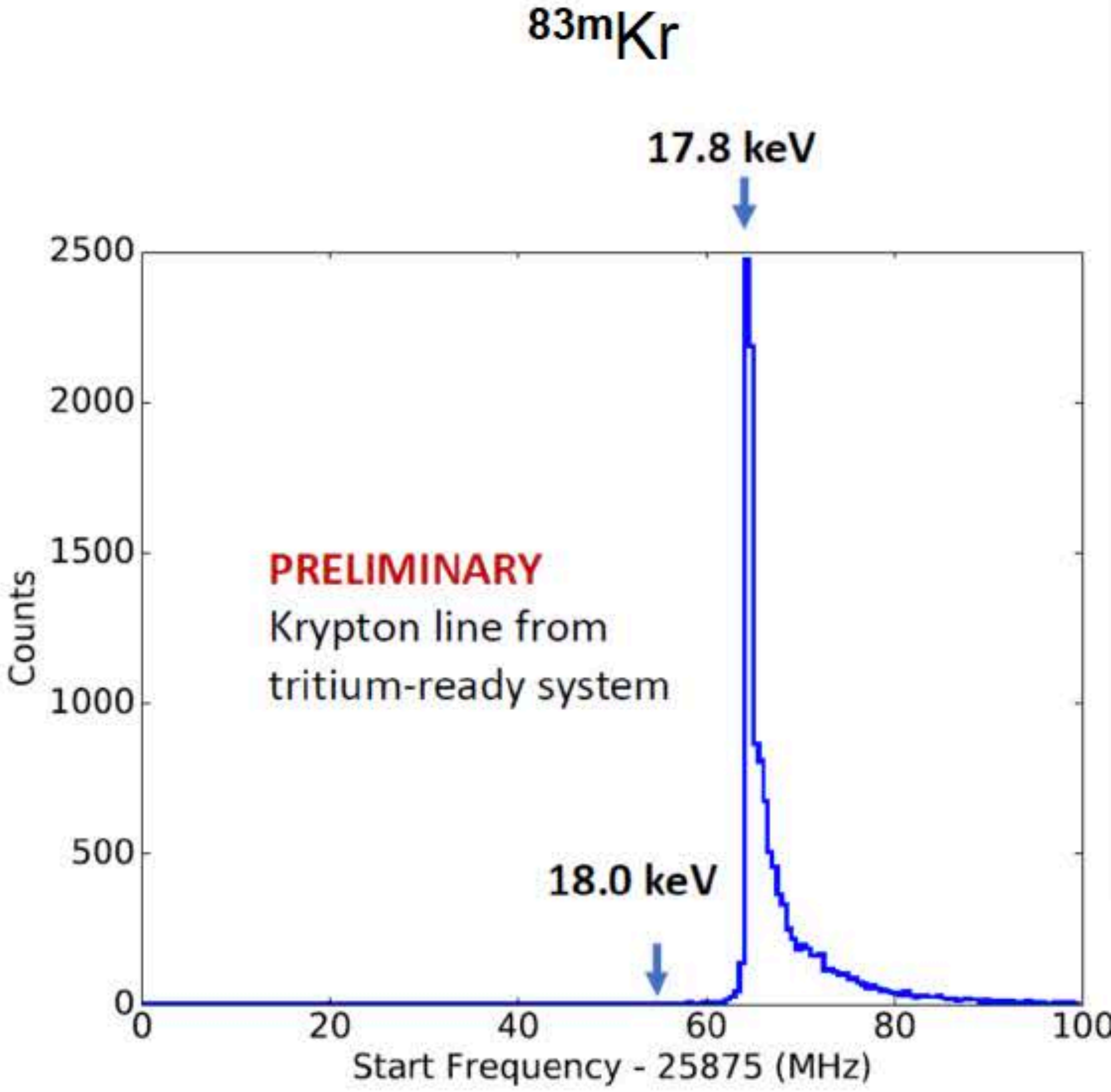


Pearson Education Inc

Project 8: Single Electron Detection

First Detection of Cyclotron Radiation from single keV electron





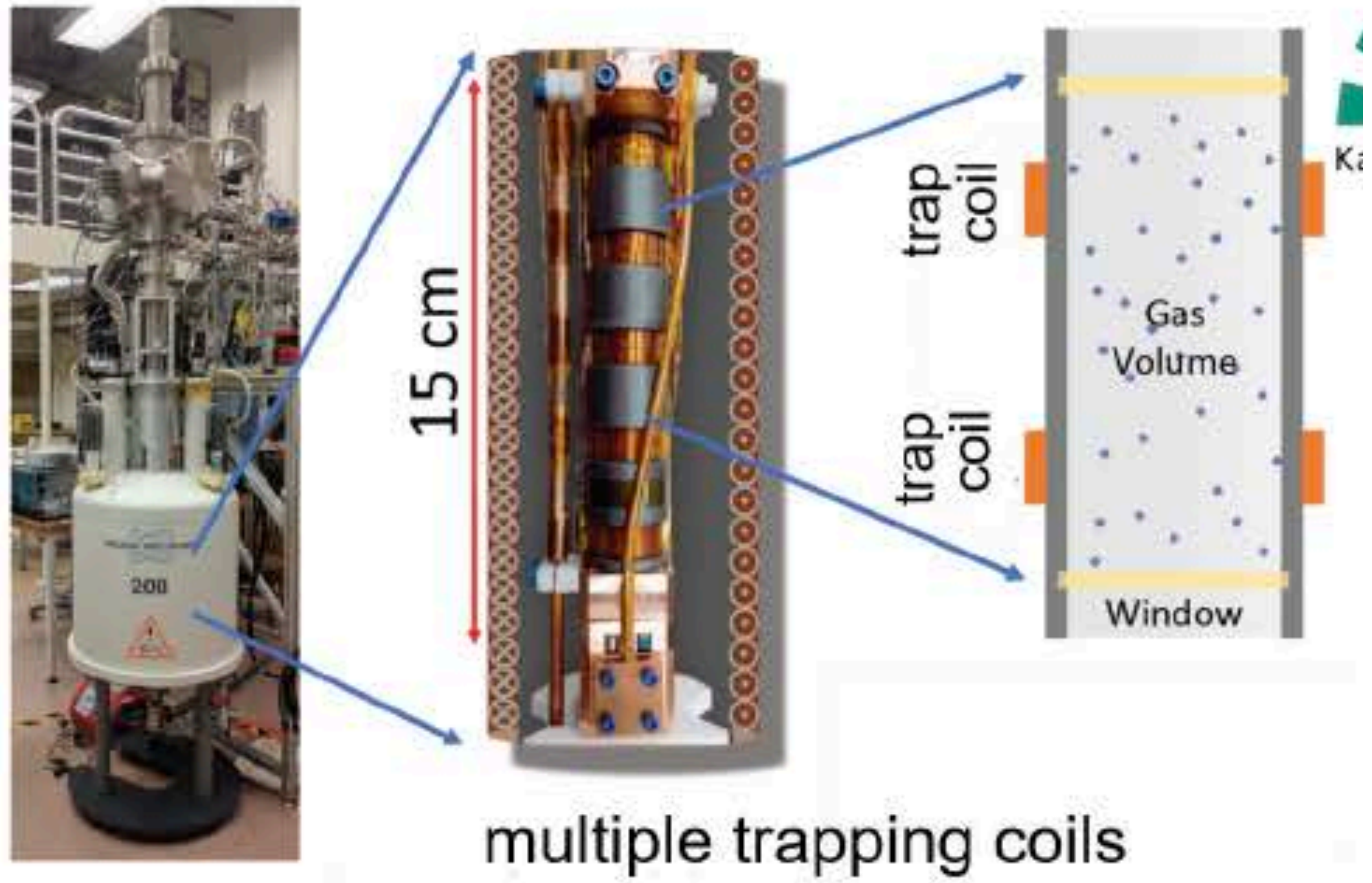
Project 8 - A Staged Approach

❶ Phase – I: 2010-2016 – proof-of-principle
test measurements with ^{83m}Kr
CRES observed for first time

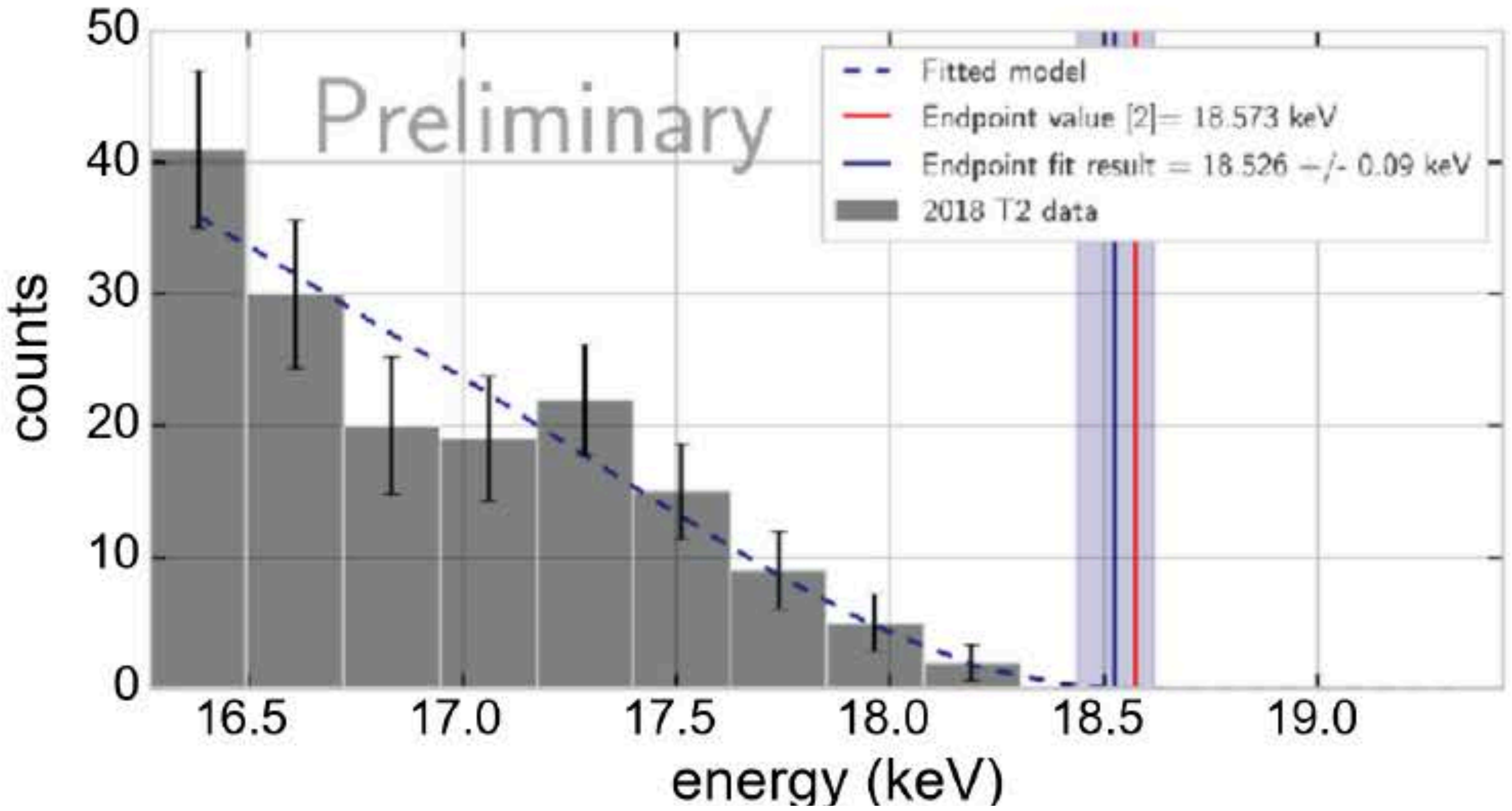
❷ Phase – II: 2015-2019 - tritium
CRES demonstrator
first tritium data 2018
several days of runs

fitted ß-decay endpoint:
E_0 = (18.526 ± 0.09) keV

new 2019 campaign to
begin soon (100 d)



multiple trapping coils



The newly assembled instrument

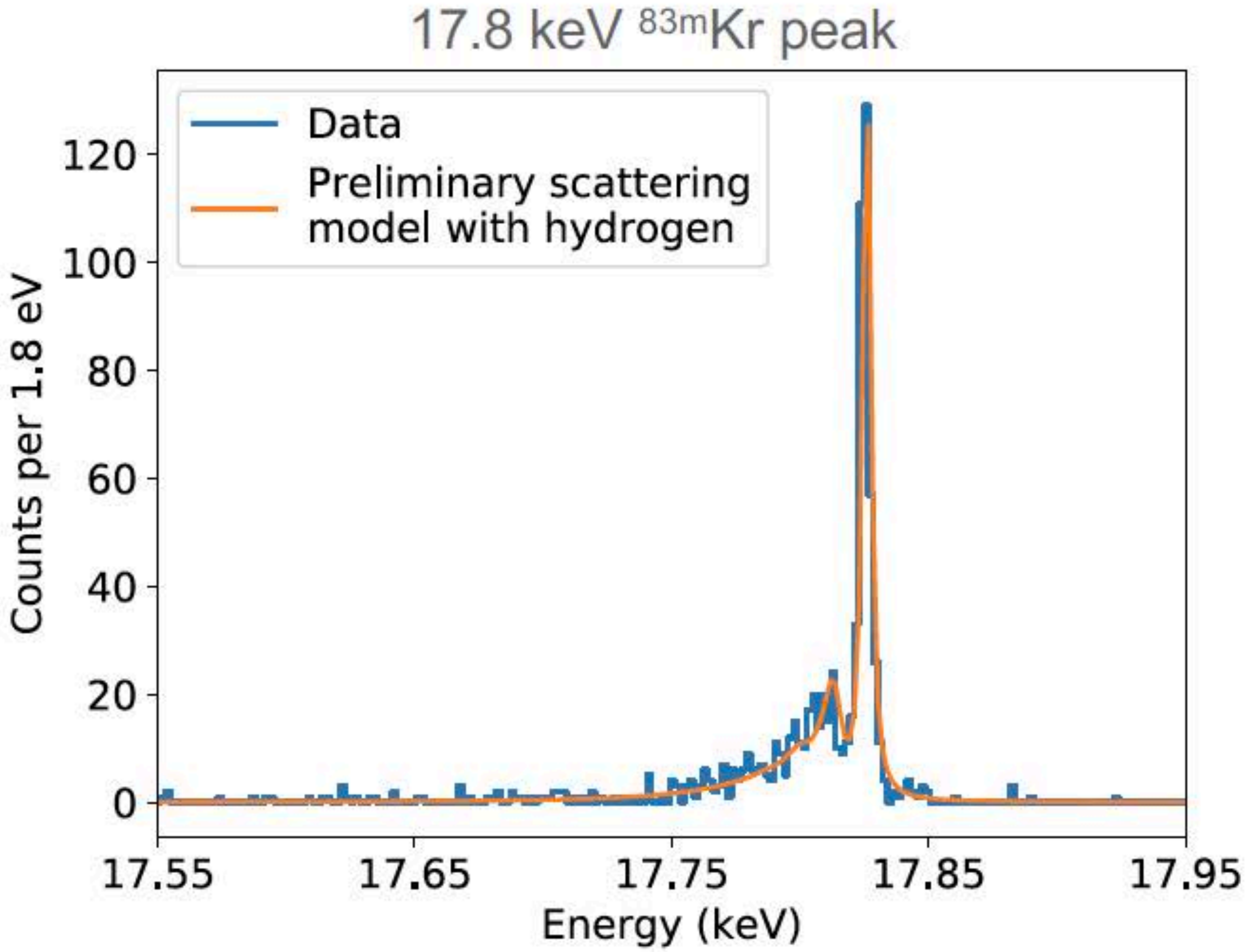
Kr/T_2 gas handling system attached

Insert cryostat

NMR magnet providing background magnetic field

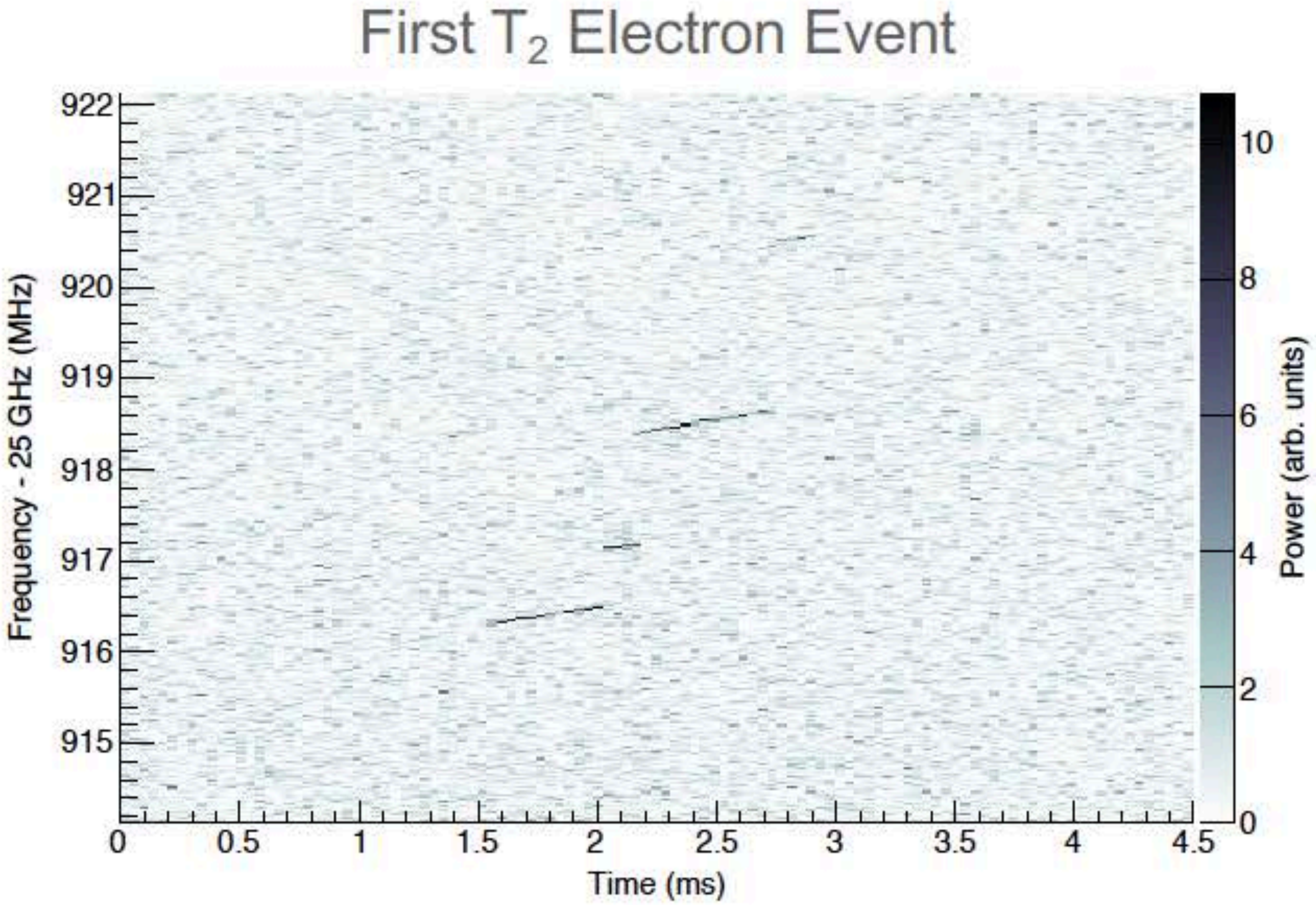
Picture: Alec Lindman

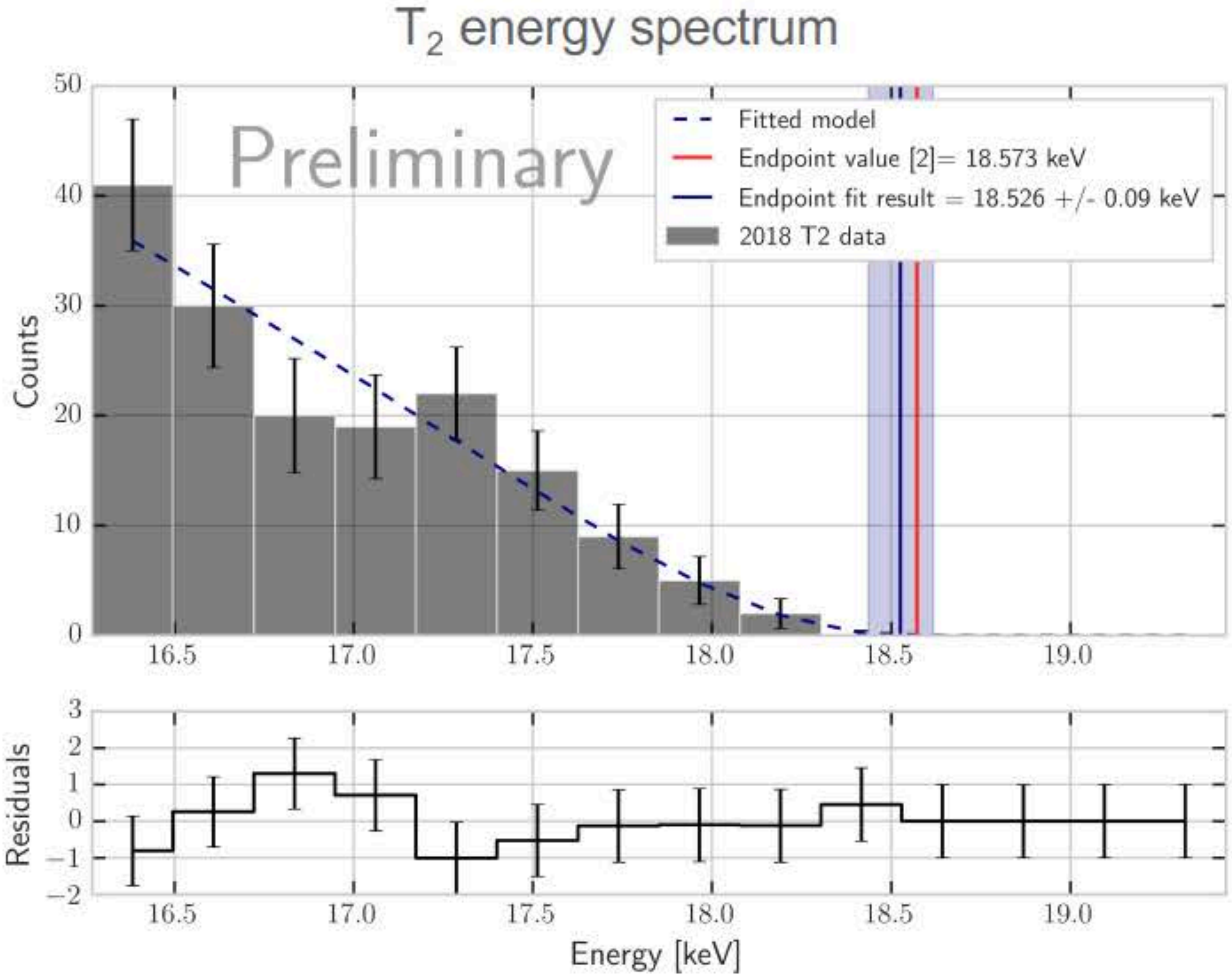
Project 8: A High Precision Measurement



- Preliminary model includes intrinsic line width and Gaussian instrument resolution
- Line width: 2.8 ± 0.1 eV (FWHM)
- Instrumental width: **2.0 ± 0.5 eV** (FWHM)

Project 8 Phase II: First Observation of Tritium Events

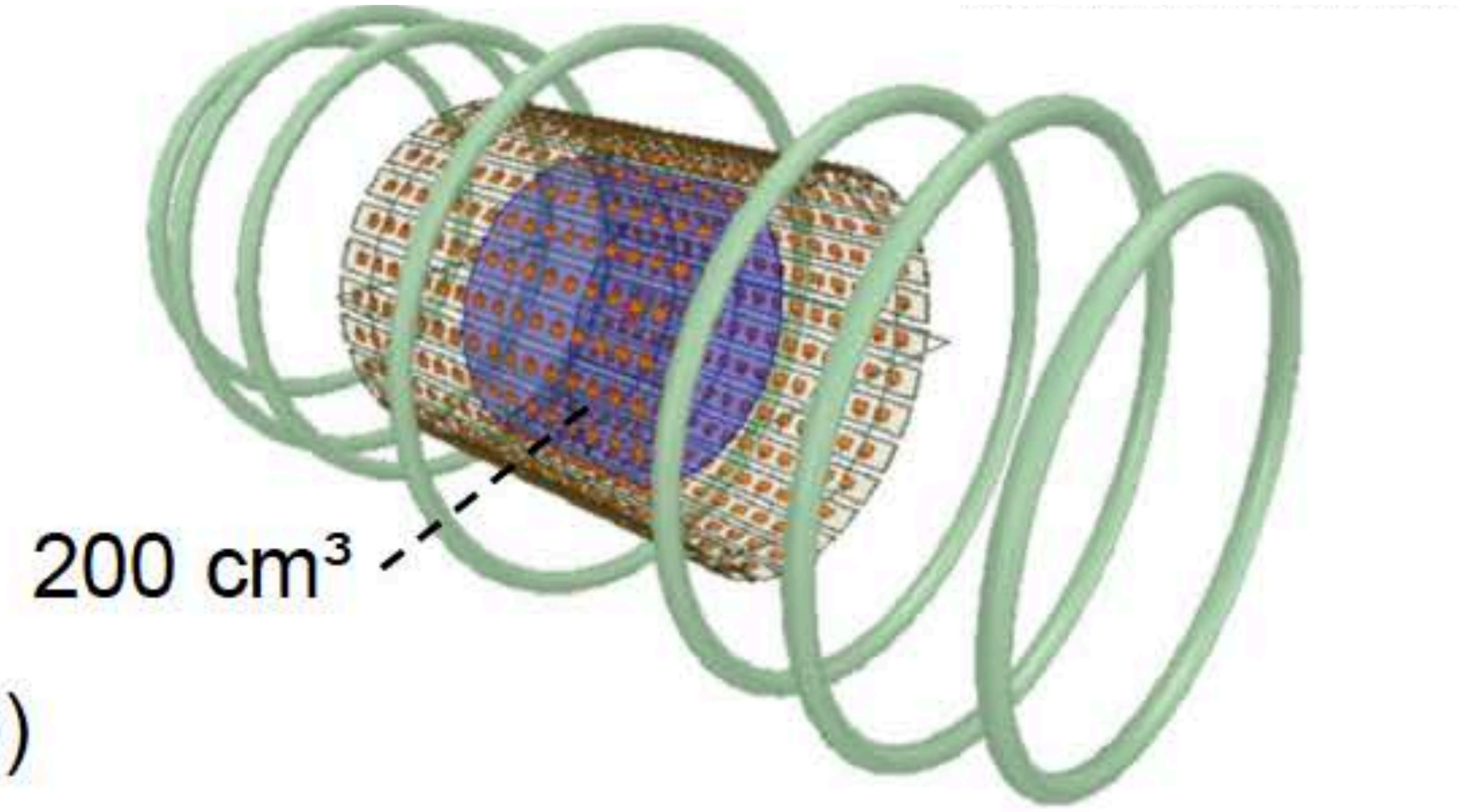


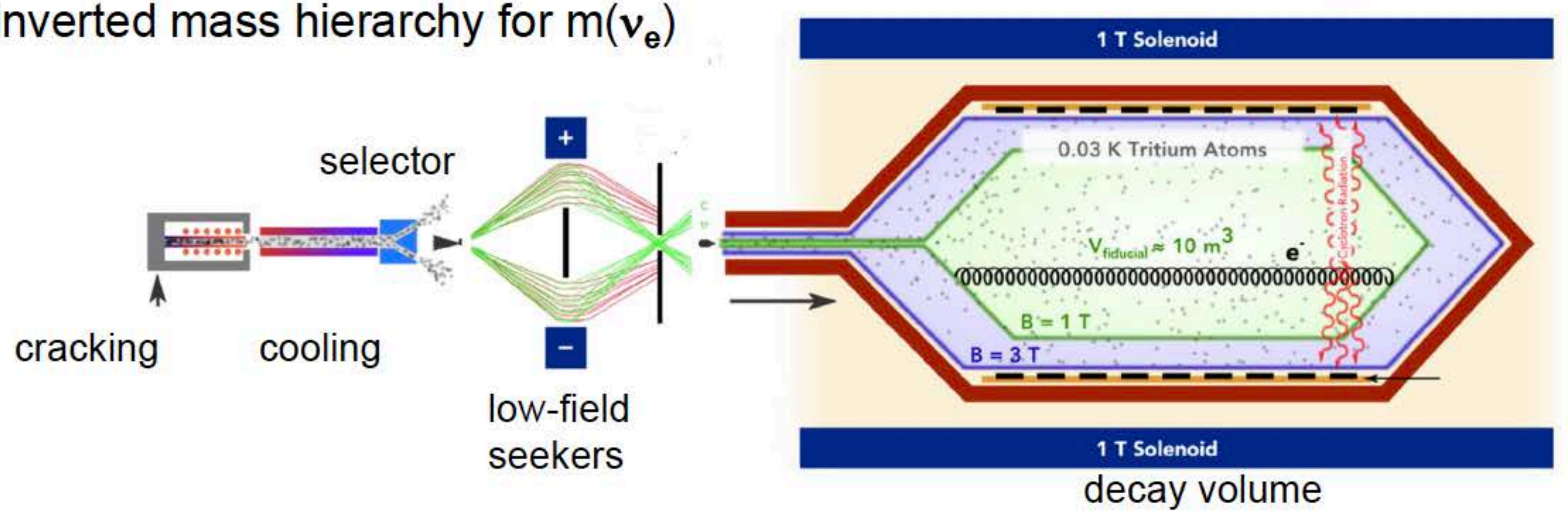


Project 8 - The Future

❸ Phase – III: … – a large volume demonstrator
based on multi-antenna array in MRI
tritium spectrum for $m(\nu_e) \sim 2$ eV

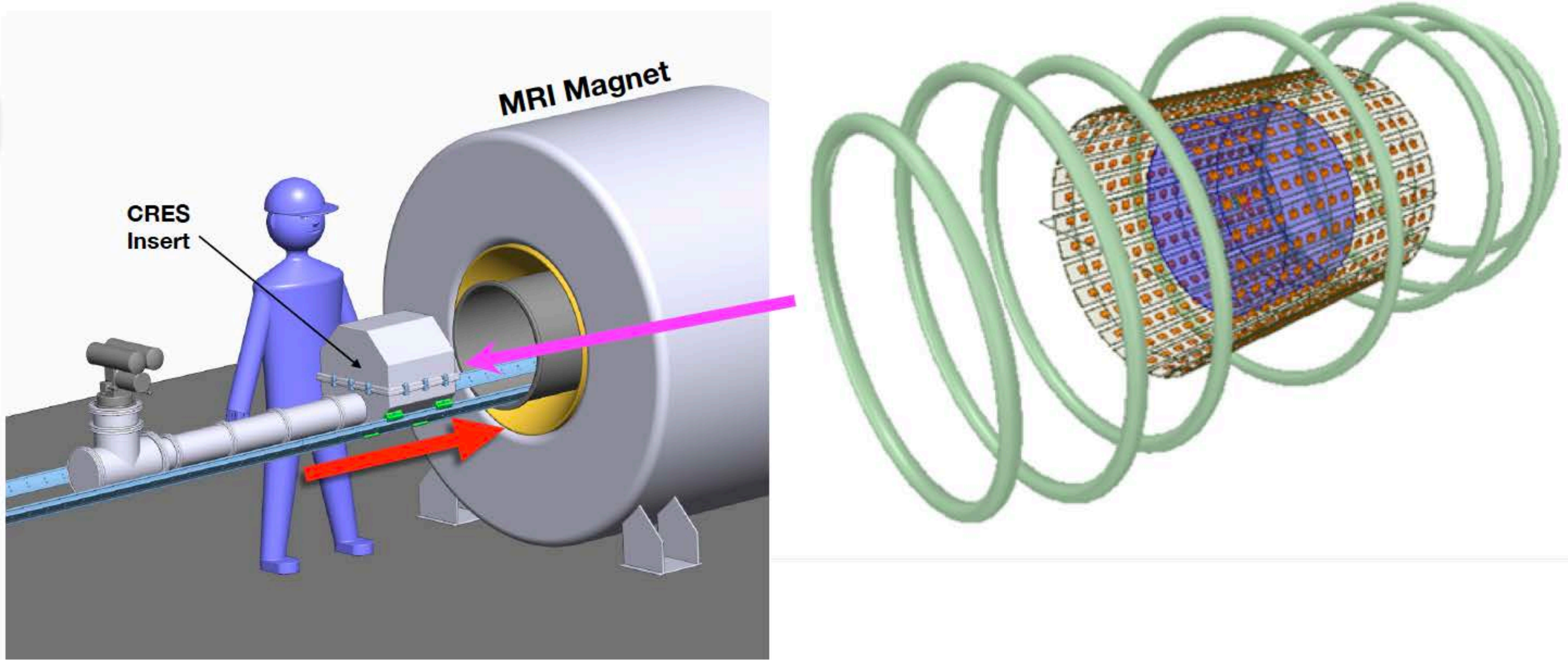
❹ Phase – IV: … – towards an atomic tritium source
R&D for an **atomic tritium source** (Ioffe trap)
goal: inverted mass hierarchy for $m(\nu_e)$





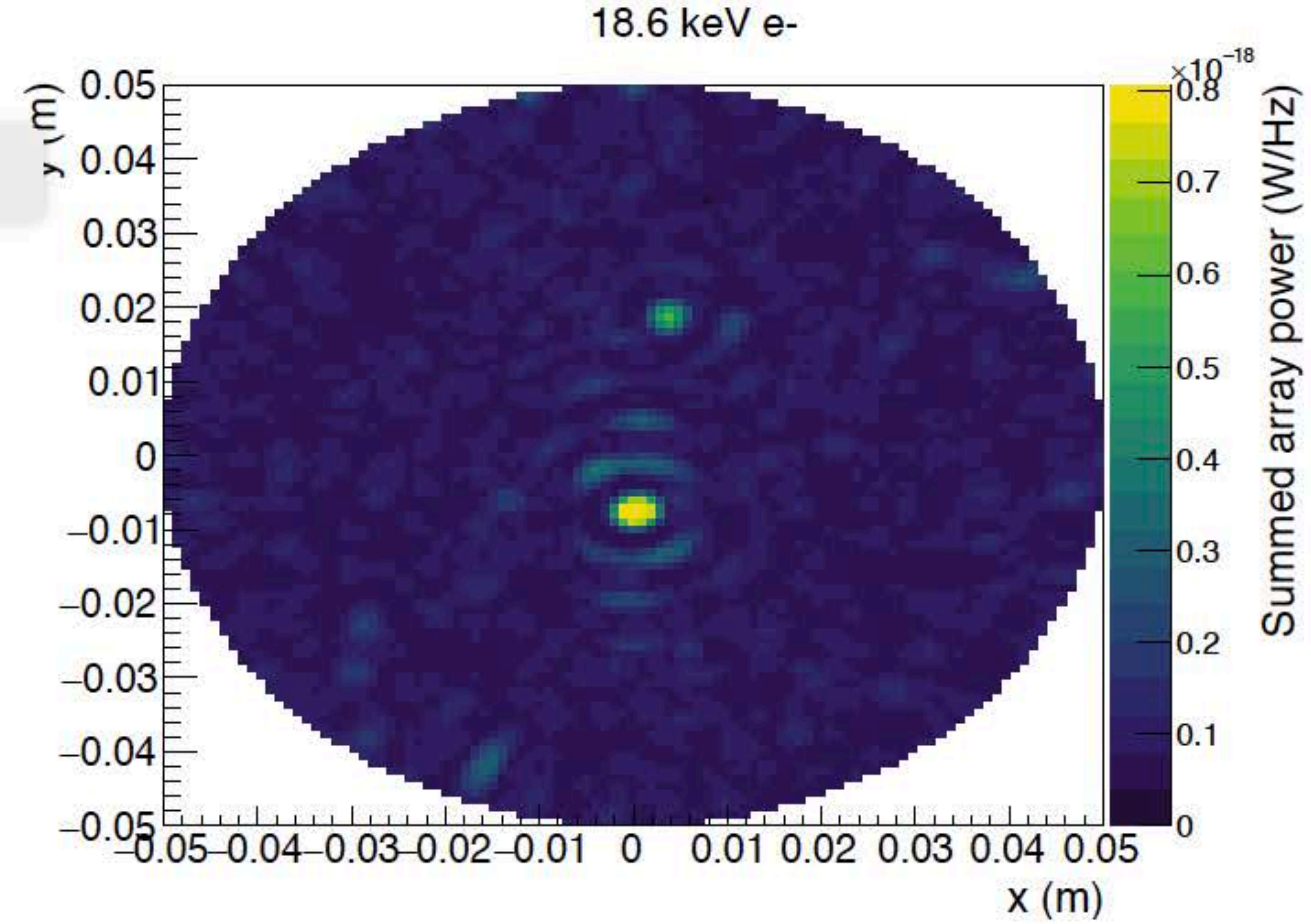
Project 8: Phase III

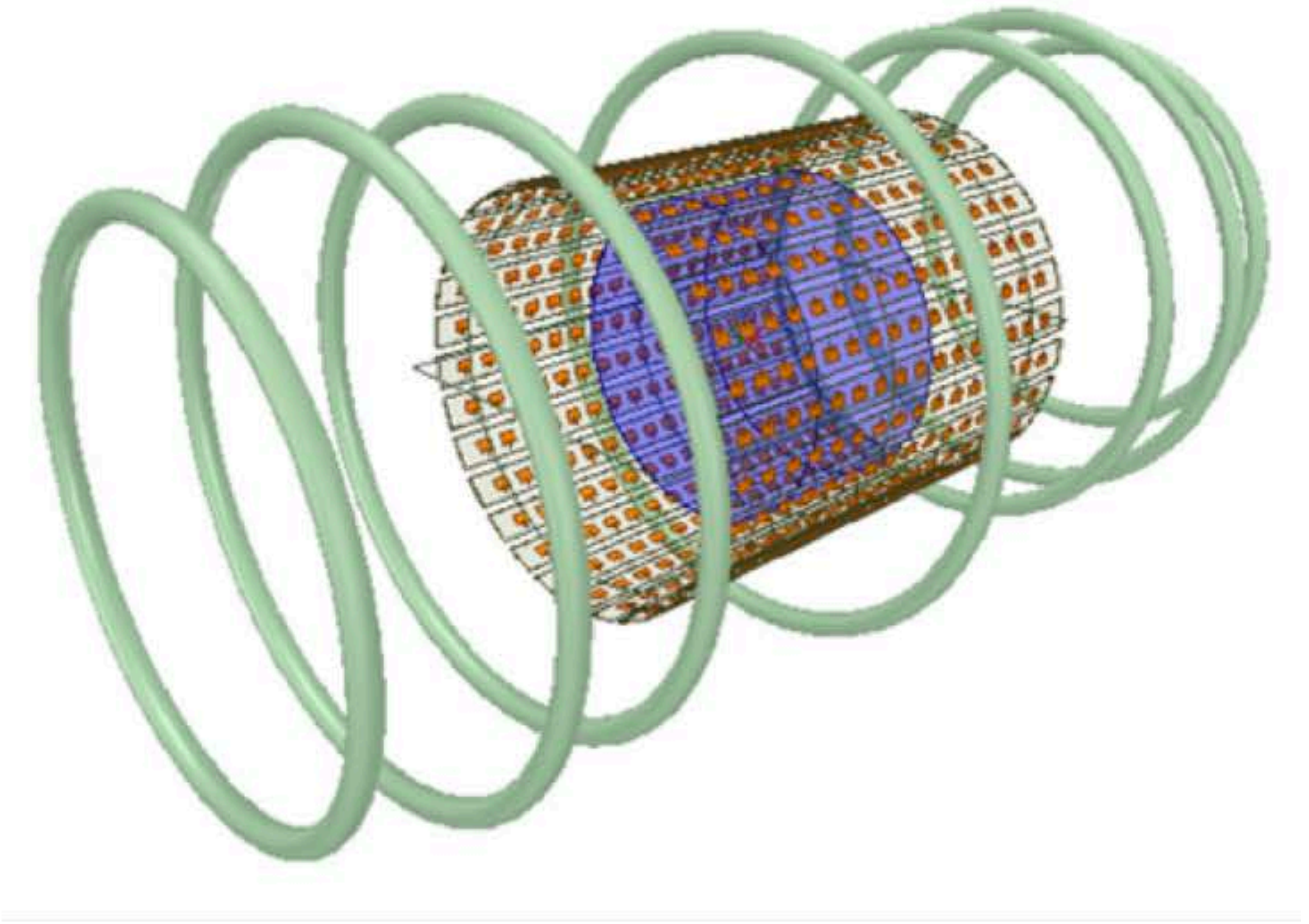
- Inwards-looking antenna array watches electrons radiating cyclotron power in free space



Project 8: Phase III

> **Single electrons resolvable in simulation**

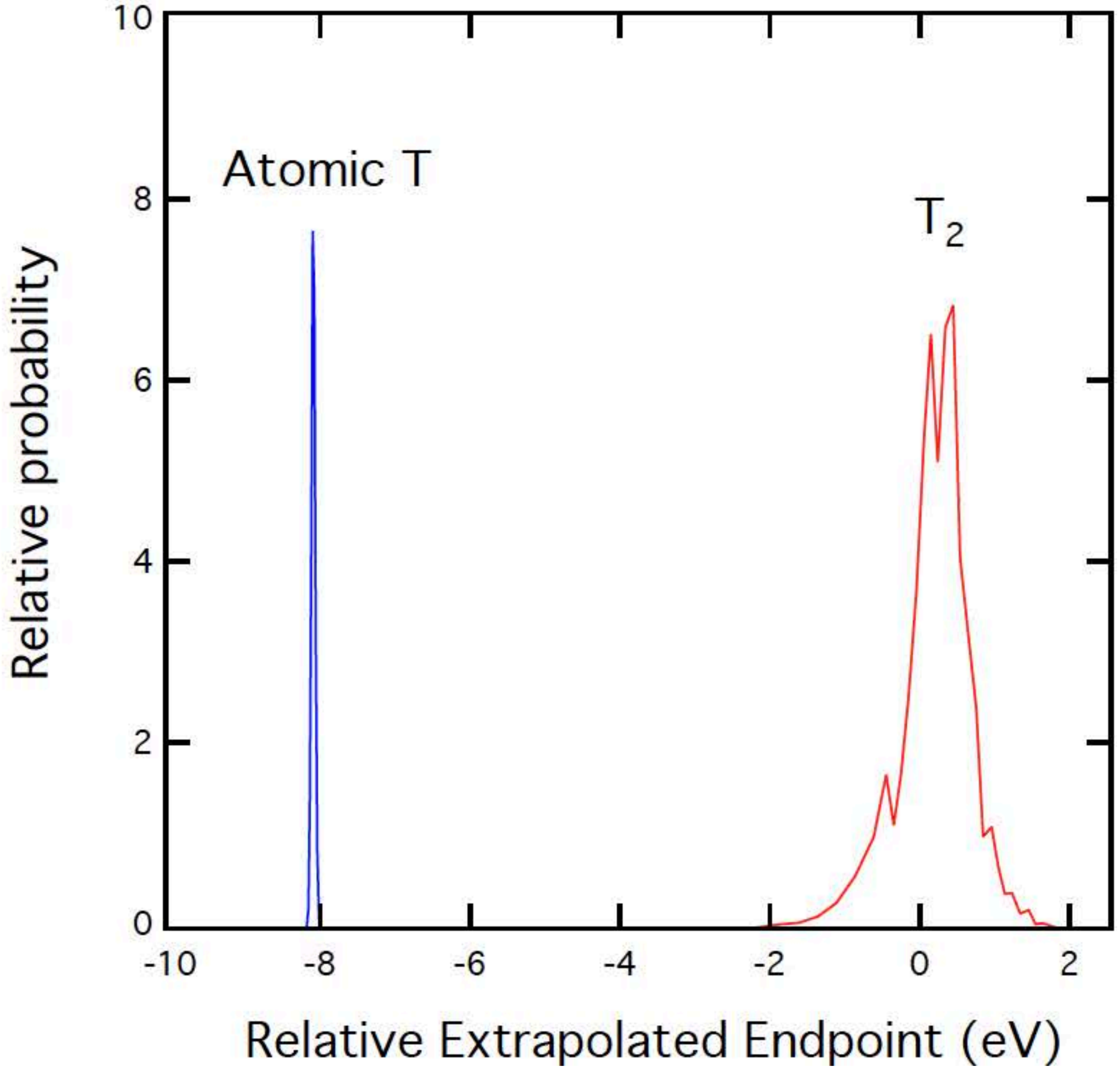


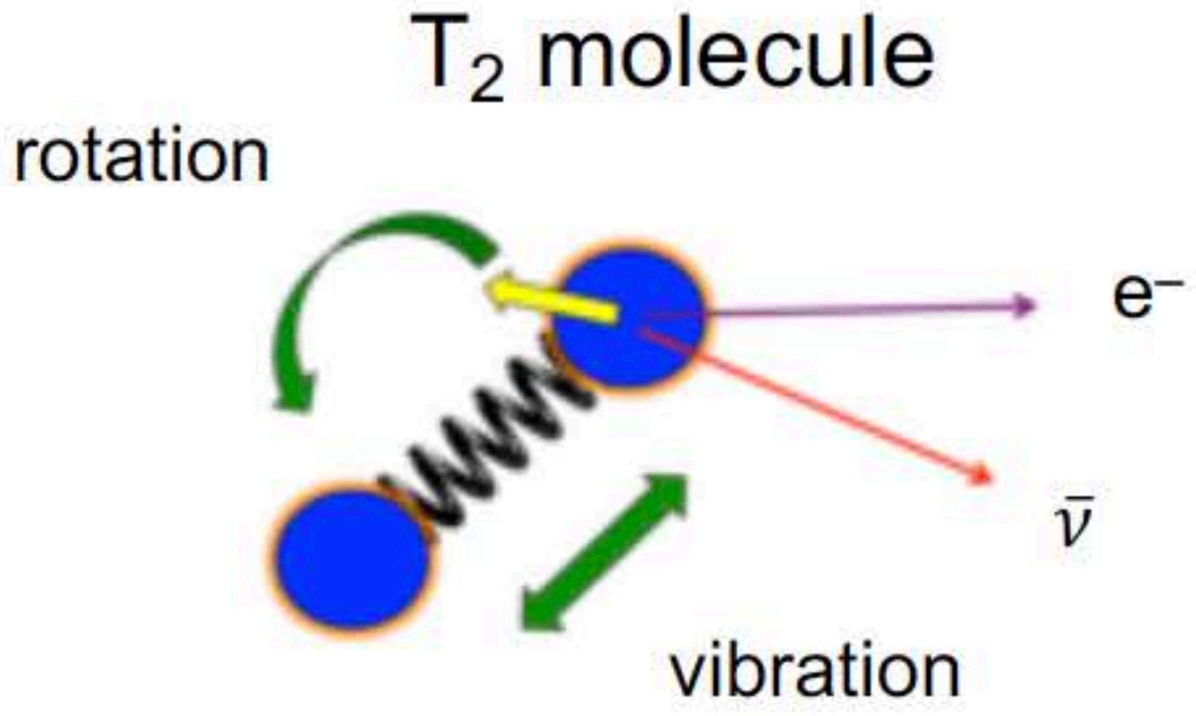


see also:
A. Ashtari Esfahani *et al.*
arXiv:1907.11124

Atomic Tritium

- Sensitivity beyond inverted hierarchy requires atomic tritium

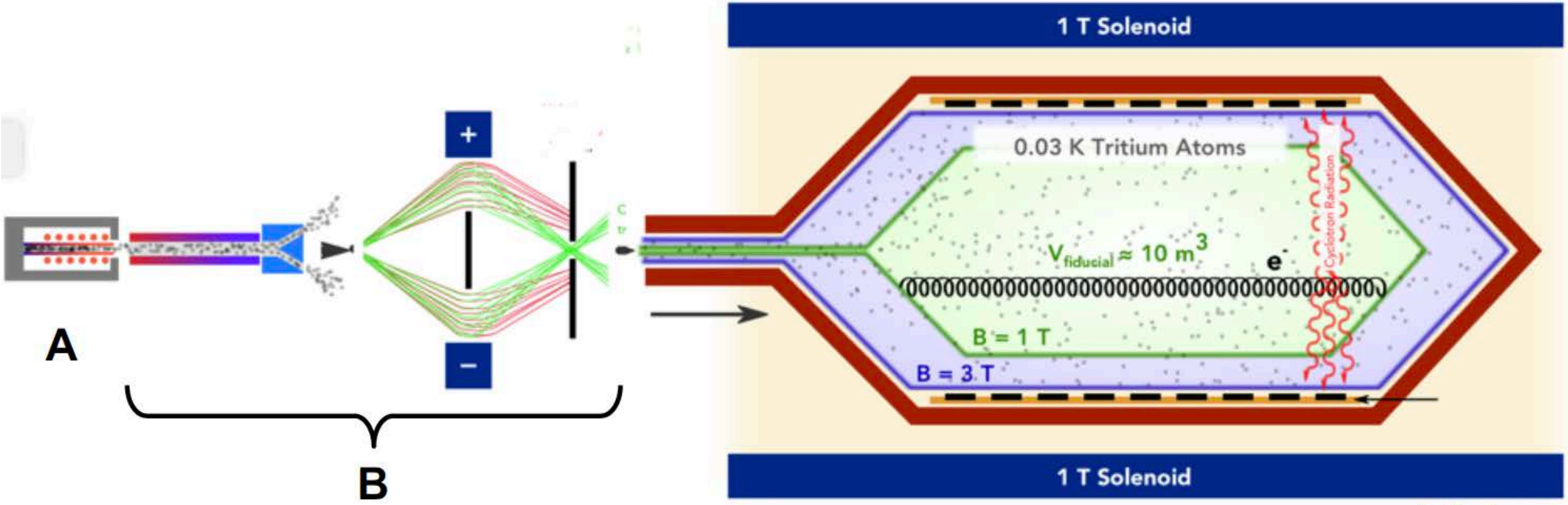




H. Robertson

Phase IV Concept

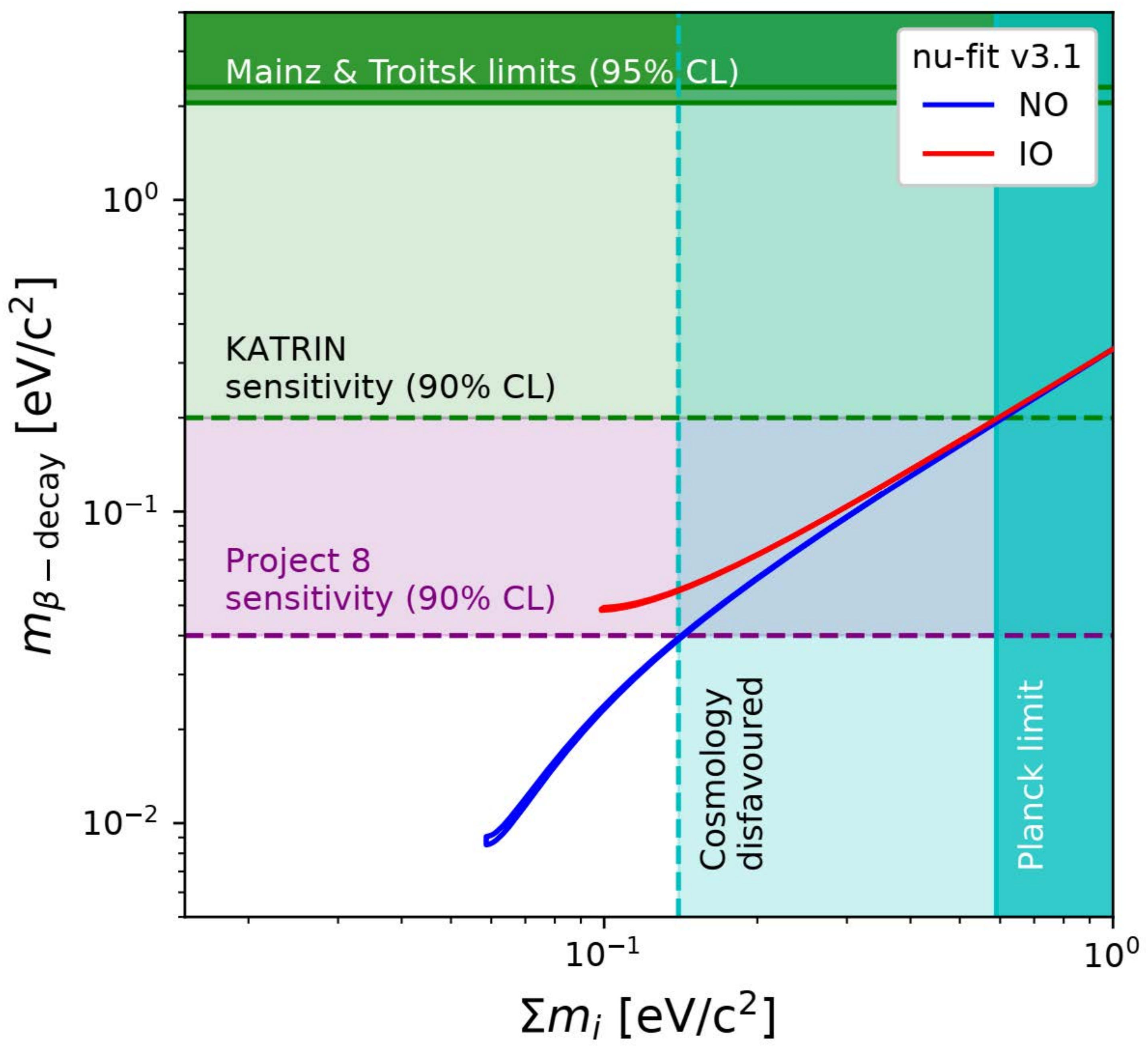
- **Use magnetic moment of atomic species to guide and trap**
  - Unpaired electron of atomic T (or H, D) gives it magnetic moment

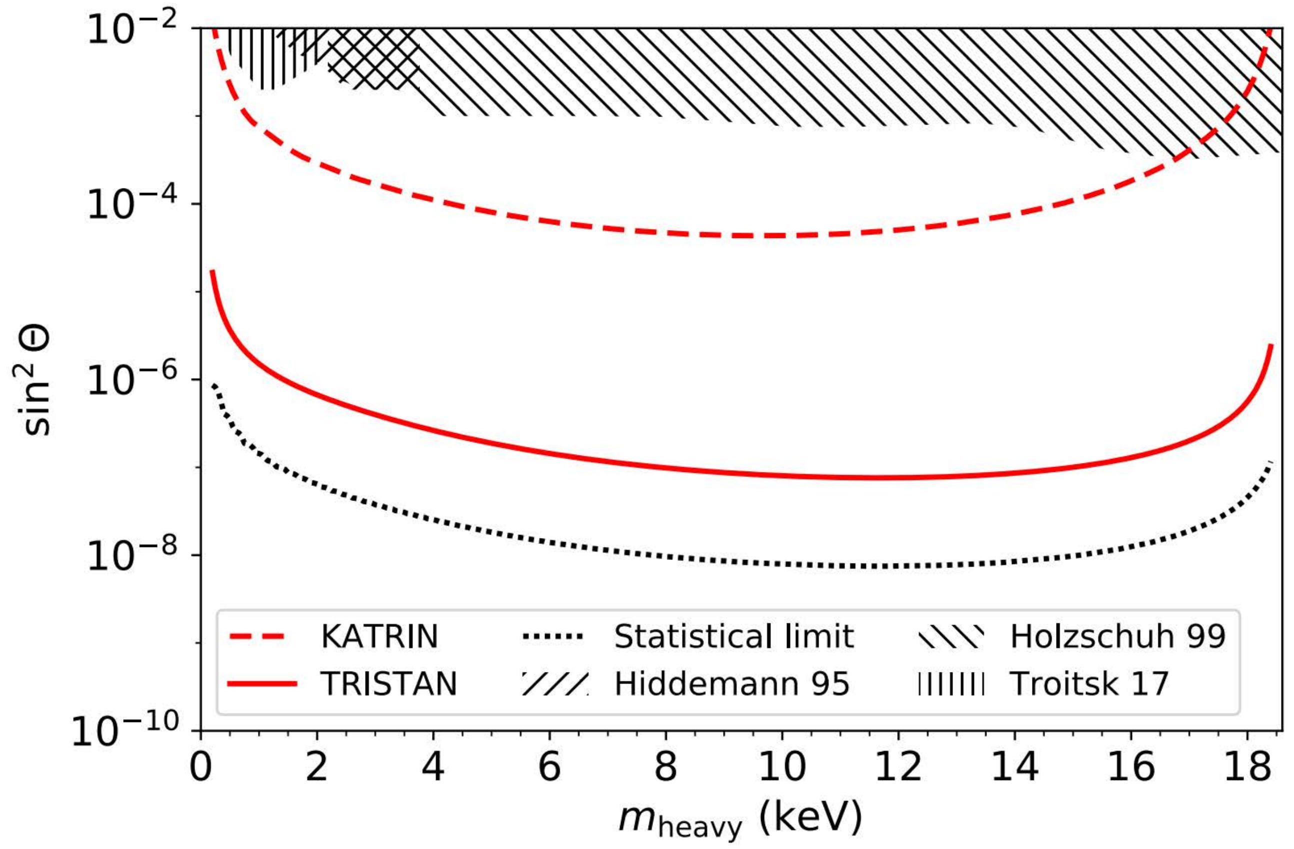


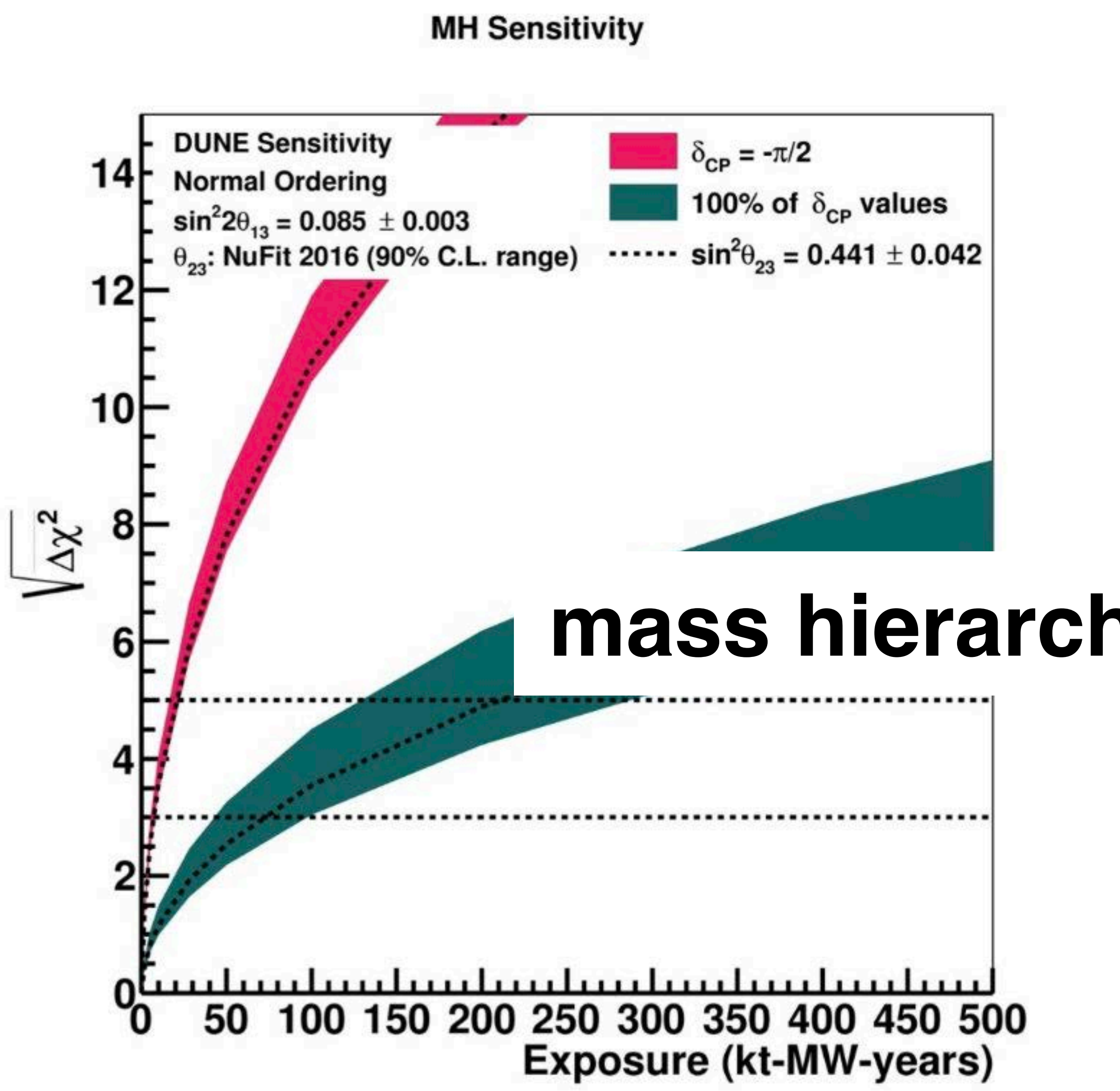
A. Lindman

A: Atomic tritium production
B: Transport and preparation
C: Trapping and measurement

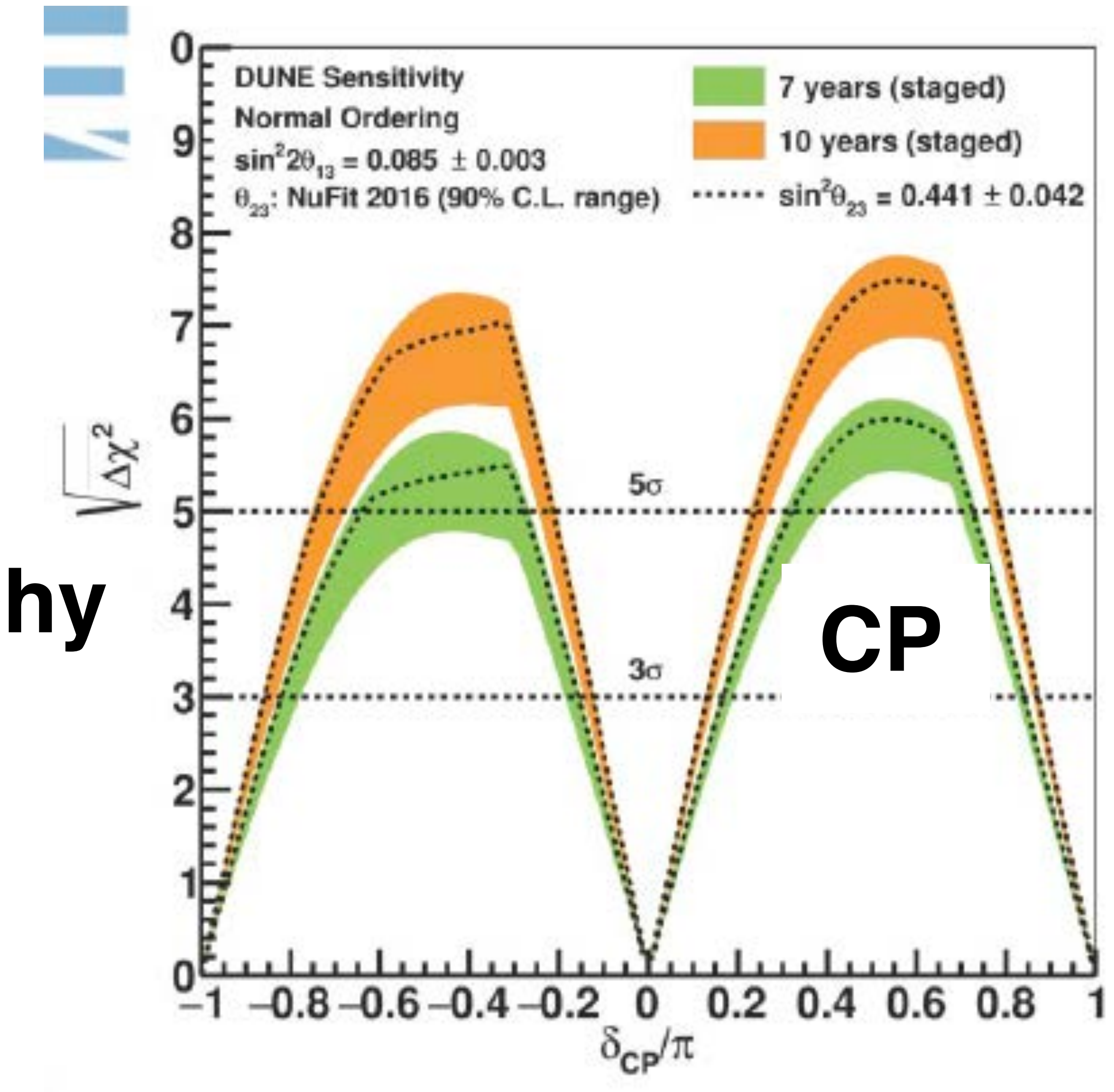
Towards the Future - Next Discoveries



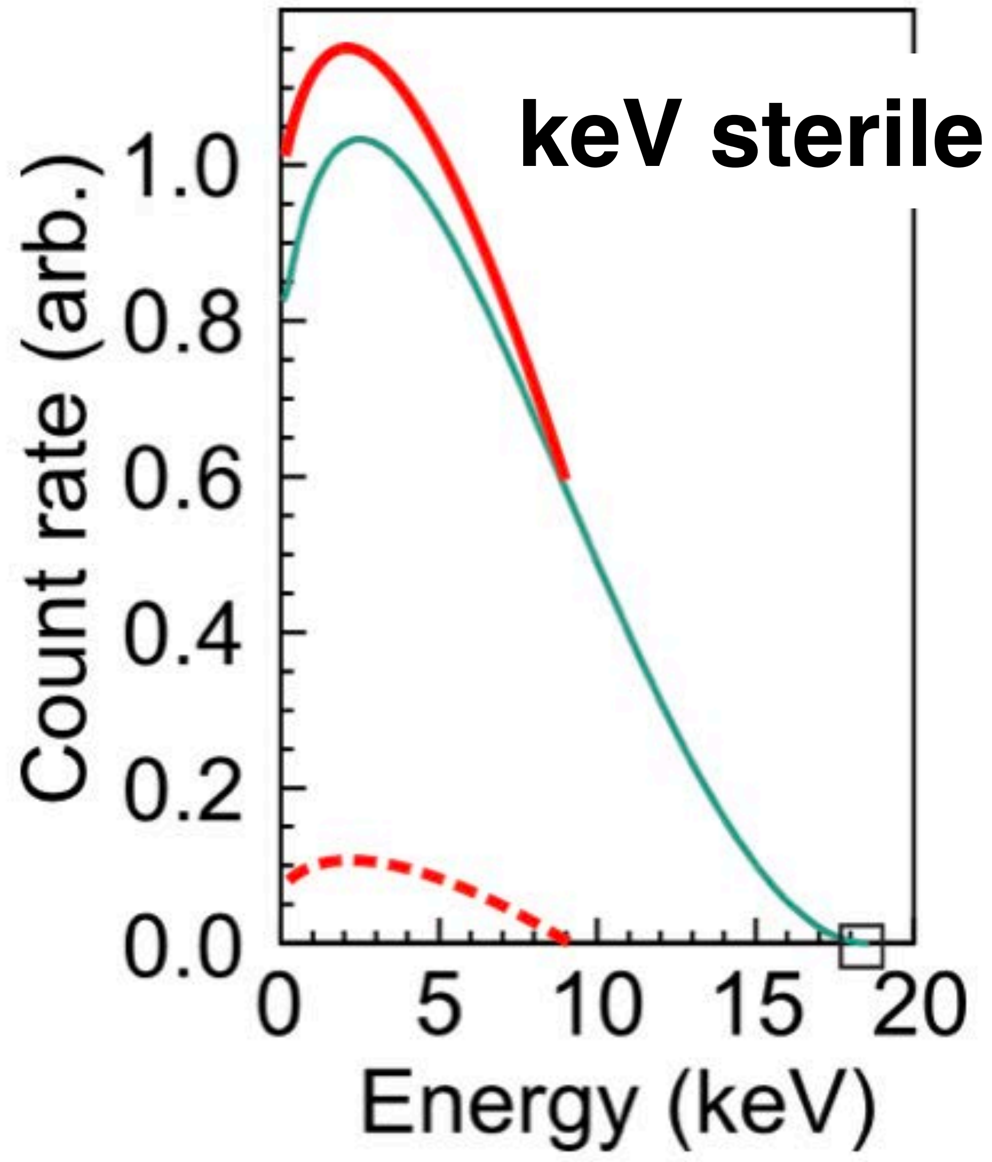




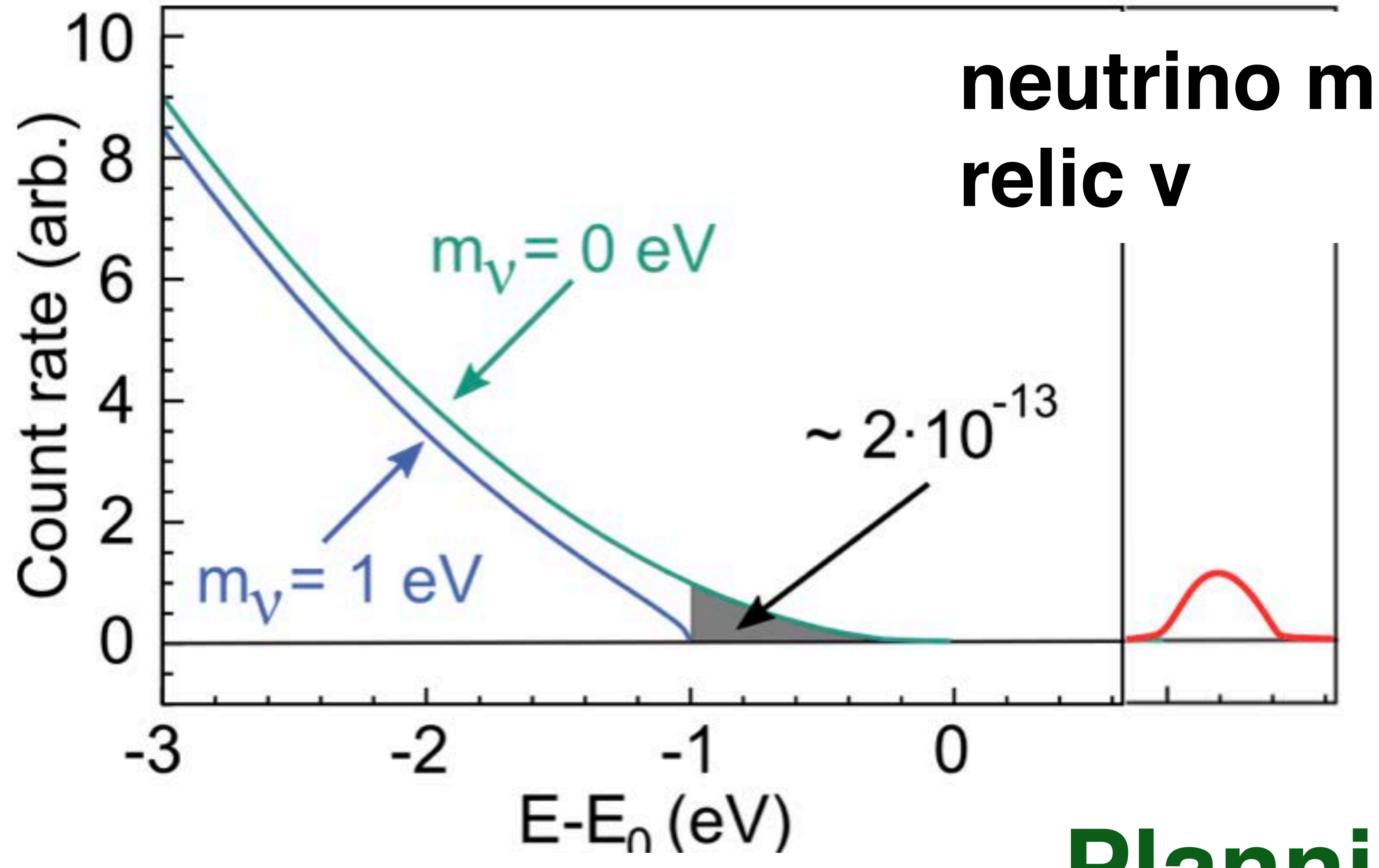
mass hierarchy



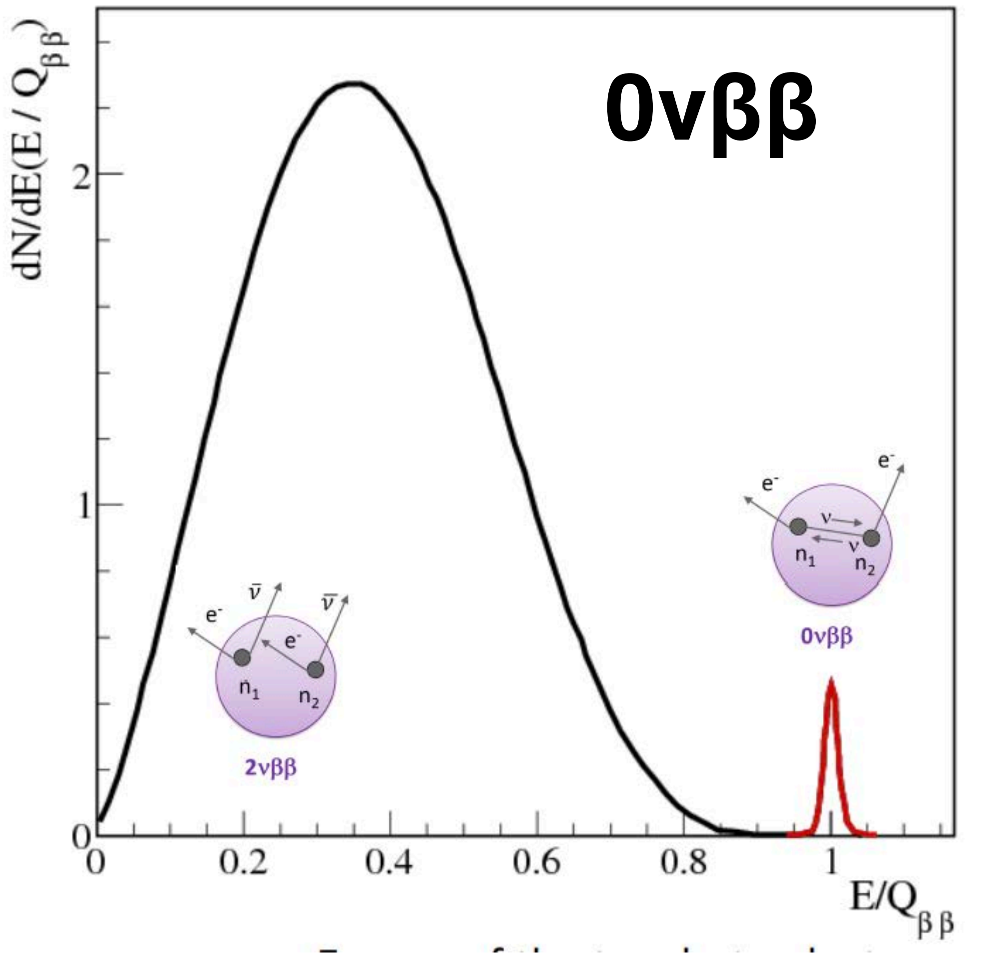
CP



keV sterile ν



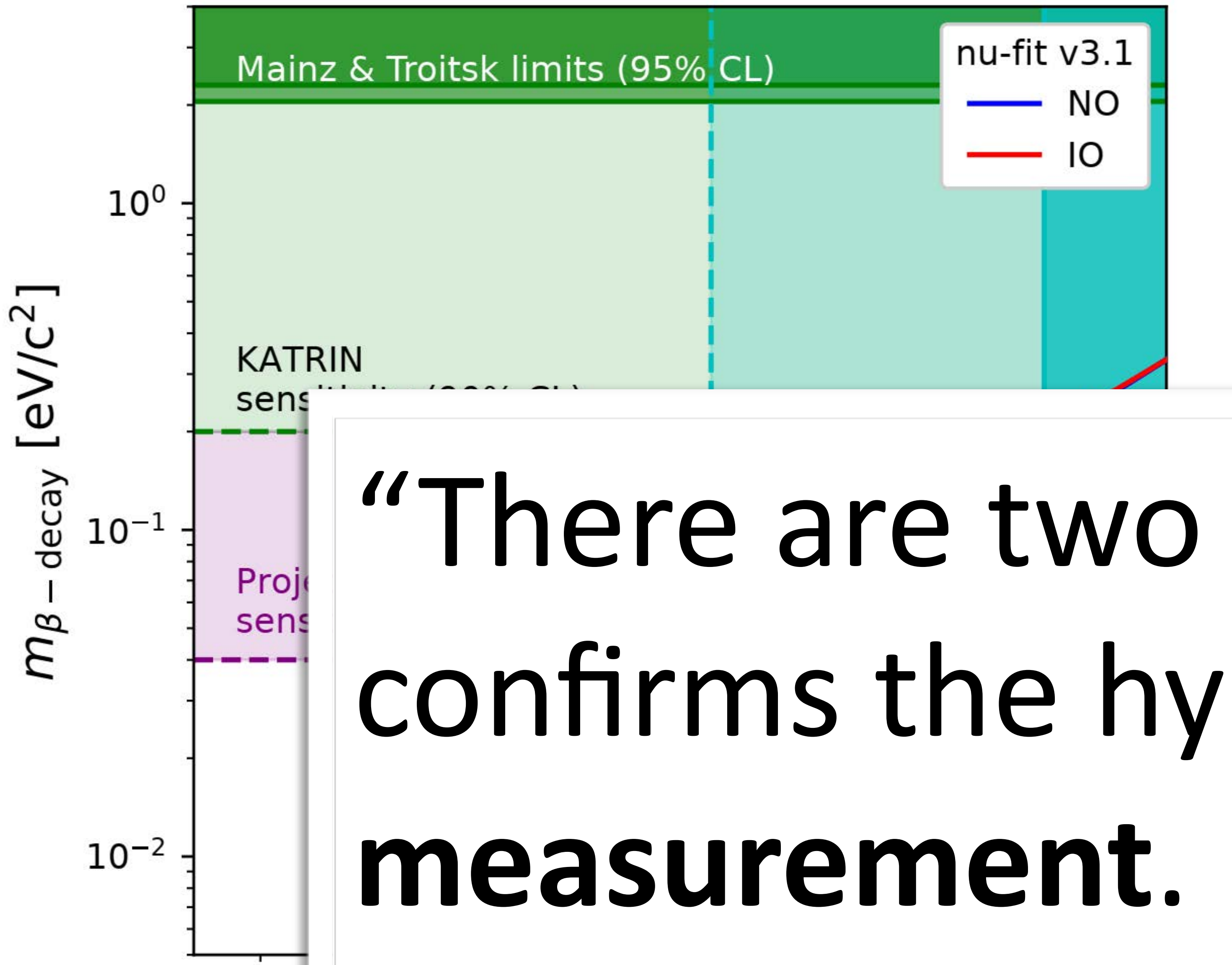
neutrino mass
relic ν

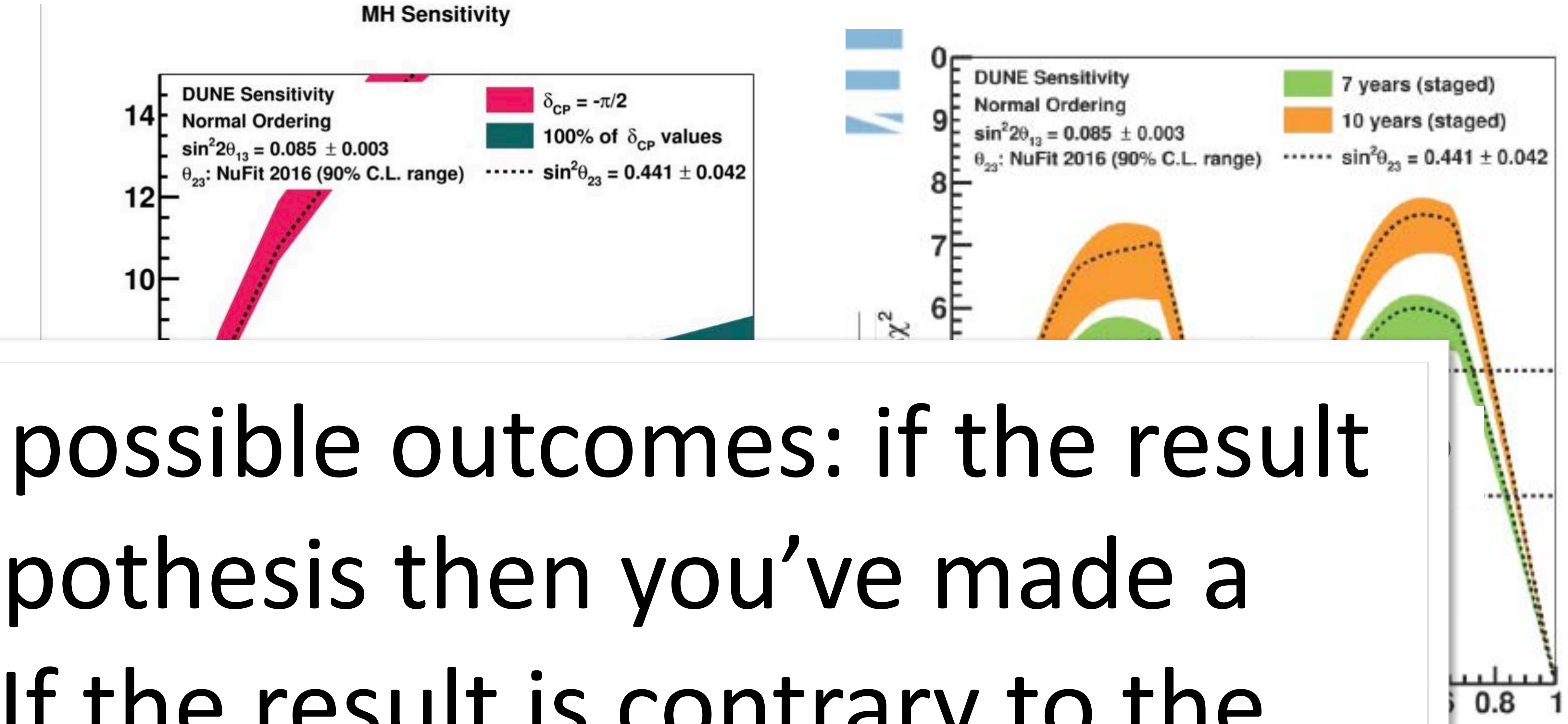


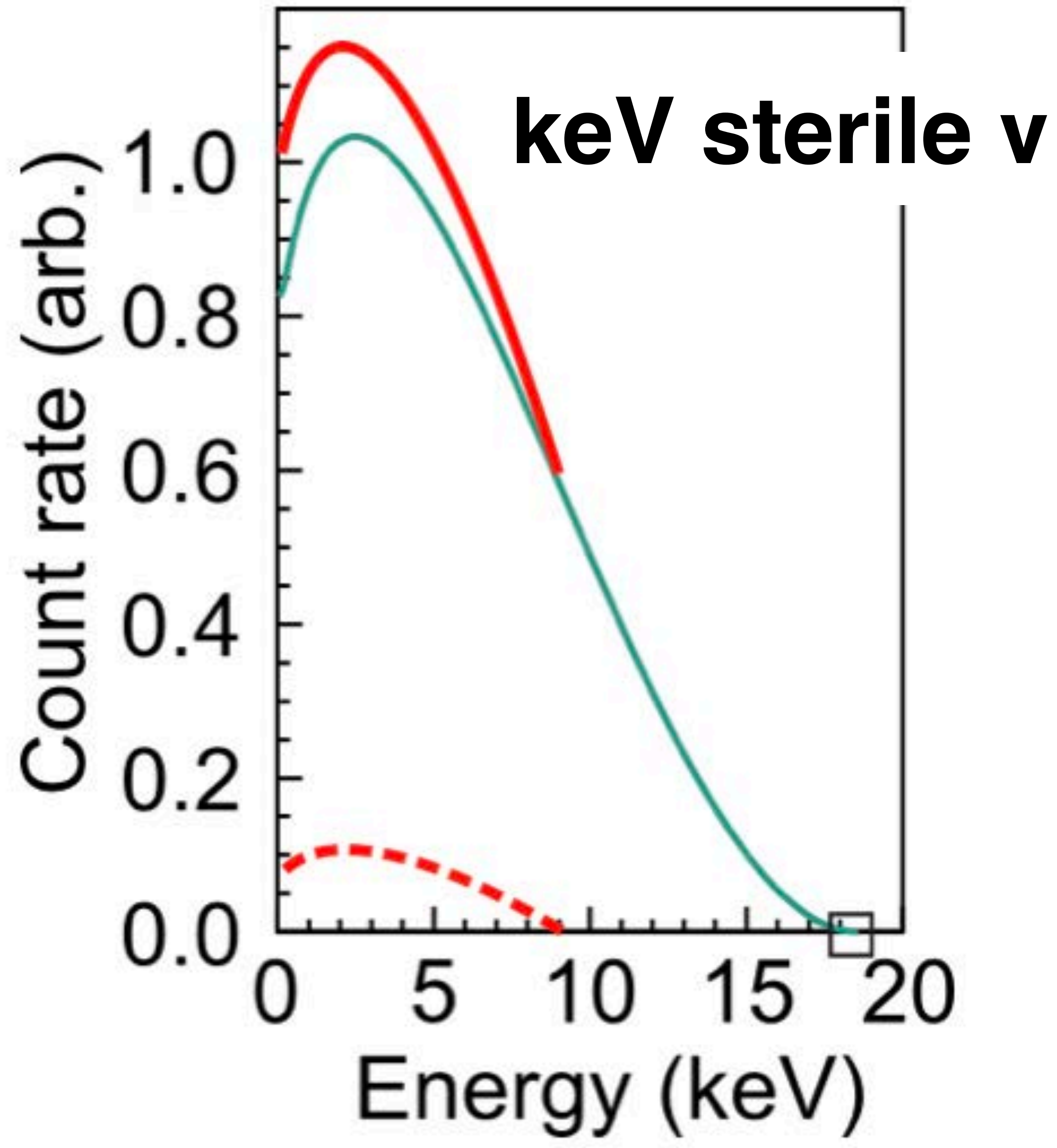
0νββ

Planning for discovery experiments!

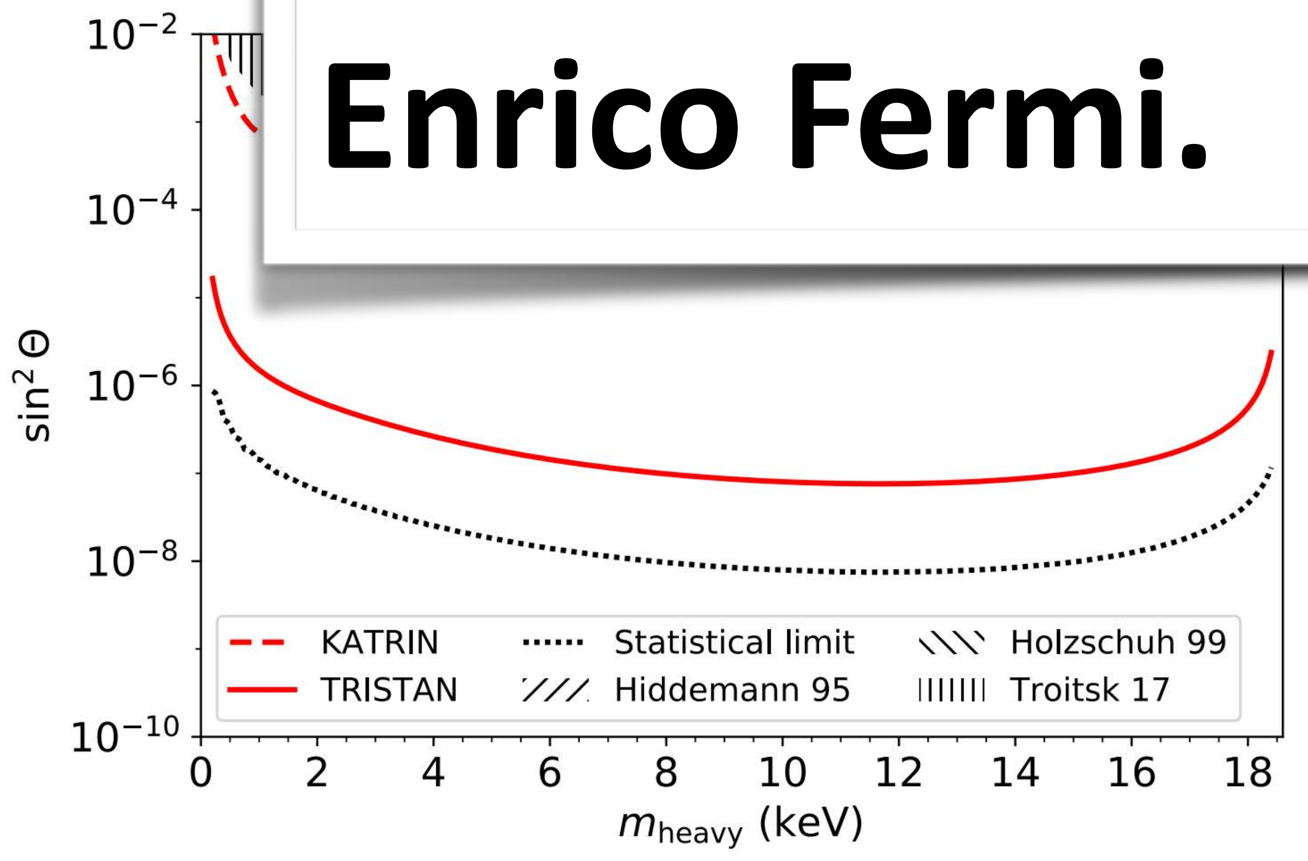
Towards the Future - Next Discoveries

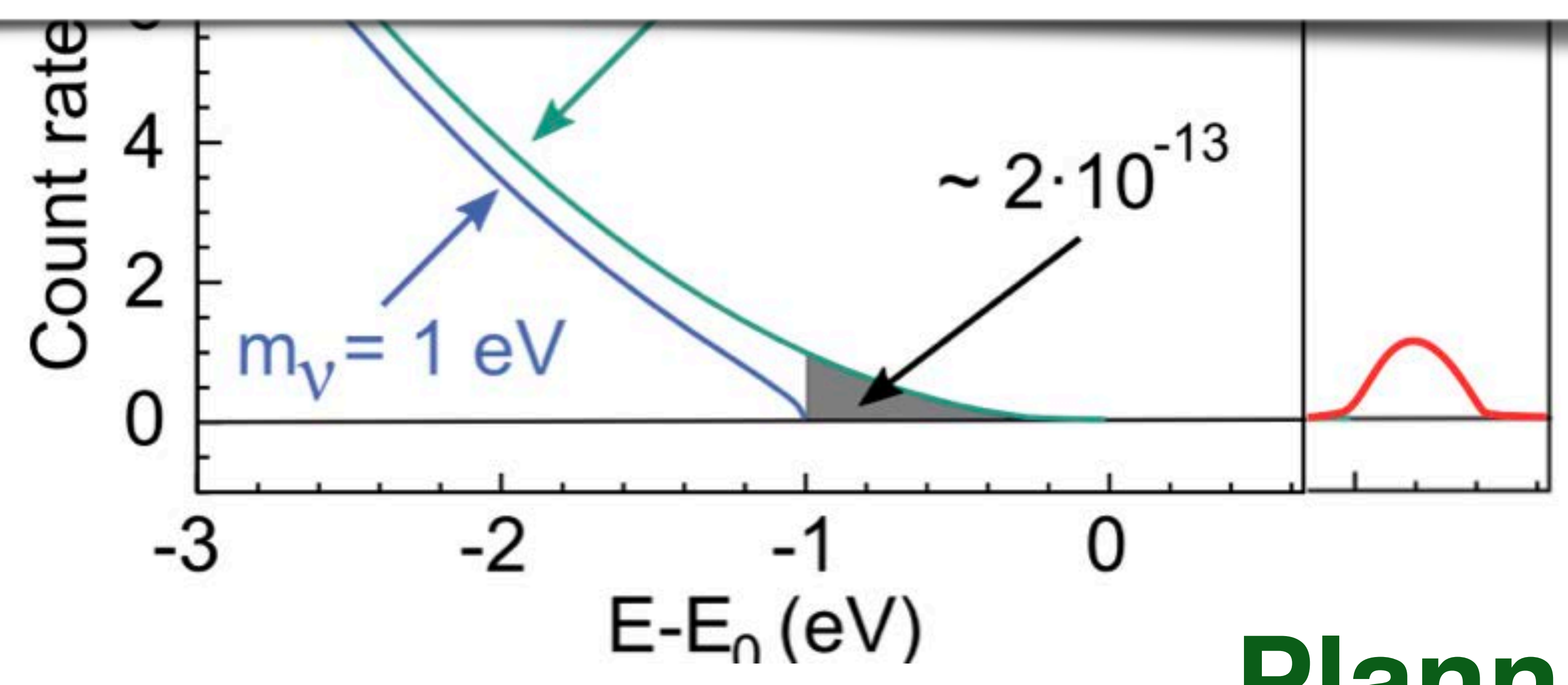


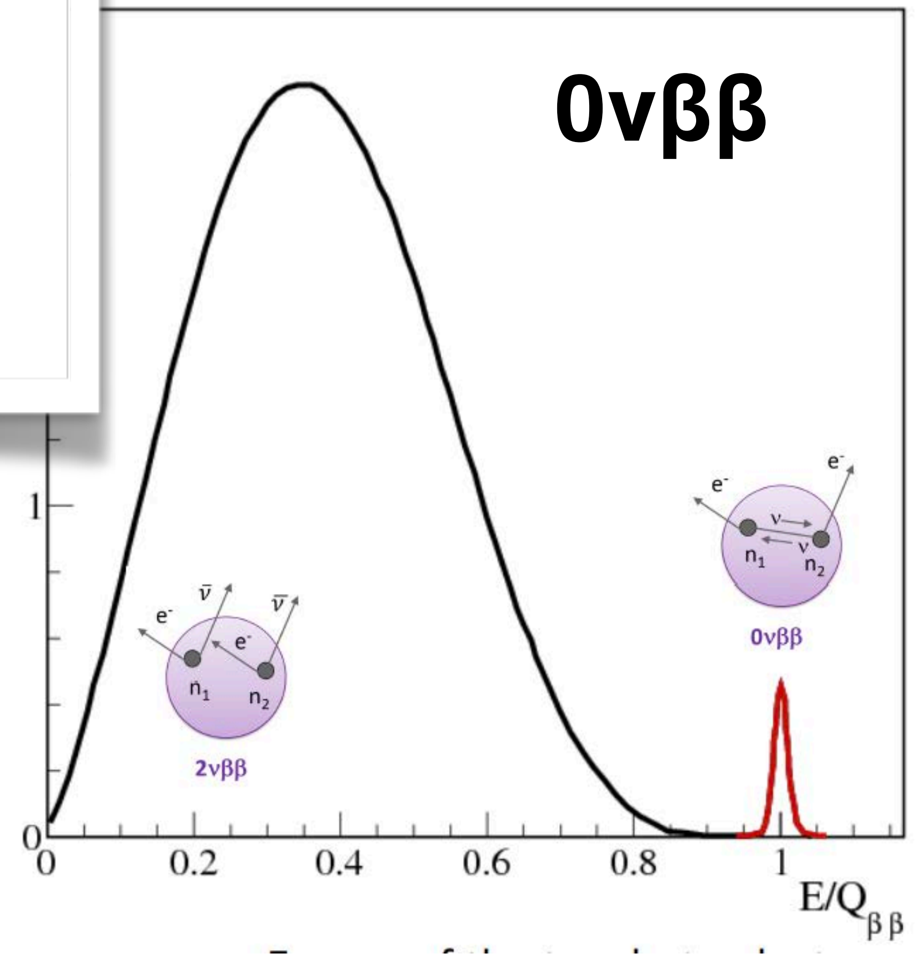




> “There are two possible outcomes: if the result confirms the hypothesis then you’ve made a **measurement**. If the result is contrary to the hypothesis then you’ve made a **discovery**”,
> **Enrico Fermi.**







Planning for discovery experiments!

Summary

We have demonstrated Cyclotron Radiation Emission Spectroscopy as a novel technique with a promising future in a next-generation neutrino mass experiment

Phase I achieved few-eV resolution of ^{83m}Kr spectrum

- Approaching natural linewidth of ^{83m}Kr source

– **Phase II tritium** data taking ongoing

- Challenges of continuous spectrum measurement being met

R&D underway towards scaling CRES technique, atomic tritium for next generation endpoint measurement

Project 8 Collaboration

Case Western Reserve University
- Laura Gladstone, Benjamin Monreal, Yu-Hao Sun

Harvard-Smithsonian Center for Astrophysics
- Sheperd Doeleman, Jonathan Weintroub, André Young

Johannes Gutenberg-Universität Mainz
- Sebastian Böser, Christine Claessens, Martin Fertl, Michael Gödel, Alec Lindman

Karlsruher Institut für Technologie
- Thomas Thümmler

Lawrence Livermore National Laboratory
- Kareem Kazkaz, Lucie Tvrznikova

Massachusetts Institute of Technology
- Zachary Bogorad, Nicholas Buzinsky, Joseph Formaggio, Evan Zayas

Pacific Northwest National Laboratory
- Mathieu Guigue, Mark Jones, Benjamin LaRoque, Erin Morrison, Noah Oblath, Malachi Schram, Jonathan Tedeschi, Brent VanDevender, Mathew Thomas, Maurio Grando

Pennsylvania State University
- Luiz de Viveiros, Timothy Wendler, Andrew Ziegler

University of Washington
- Ali Ashtari Esfahani, Raphael Cervantes, Peter Doe, Eric Machado, Elise Novitski, Walter Pettus, Hamish Robertson, Leslie Rosenberg, Gray Rybka

Yale University
- Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Surukuchi, Arina Telles

This work was supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all collaborating institutions

P8 slides on behalf of collaboration