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Future Tritium Endpoint Experiments

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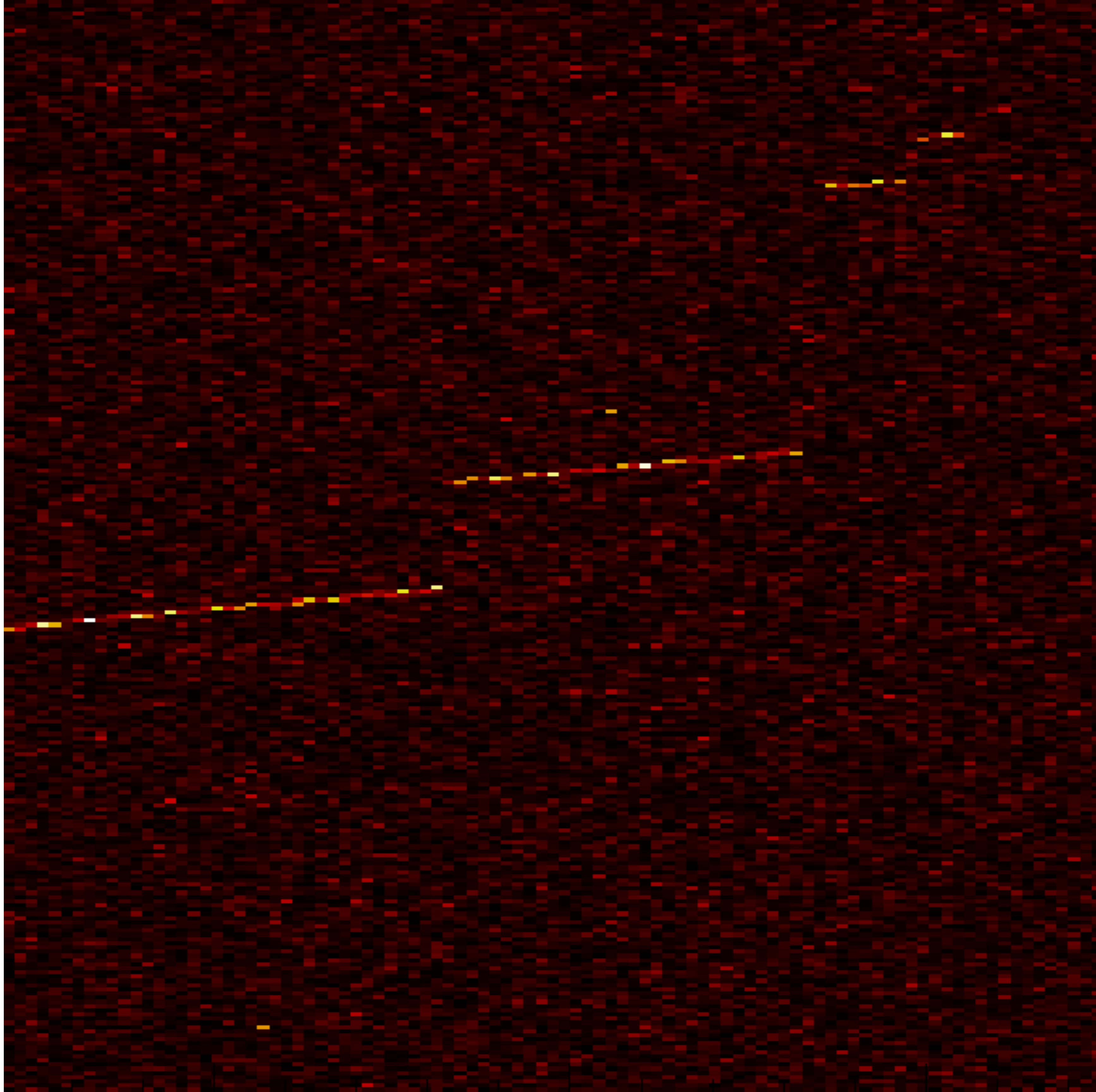


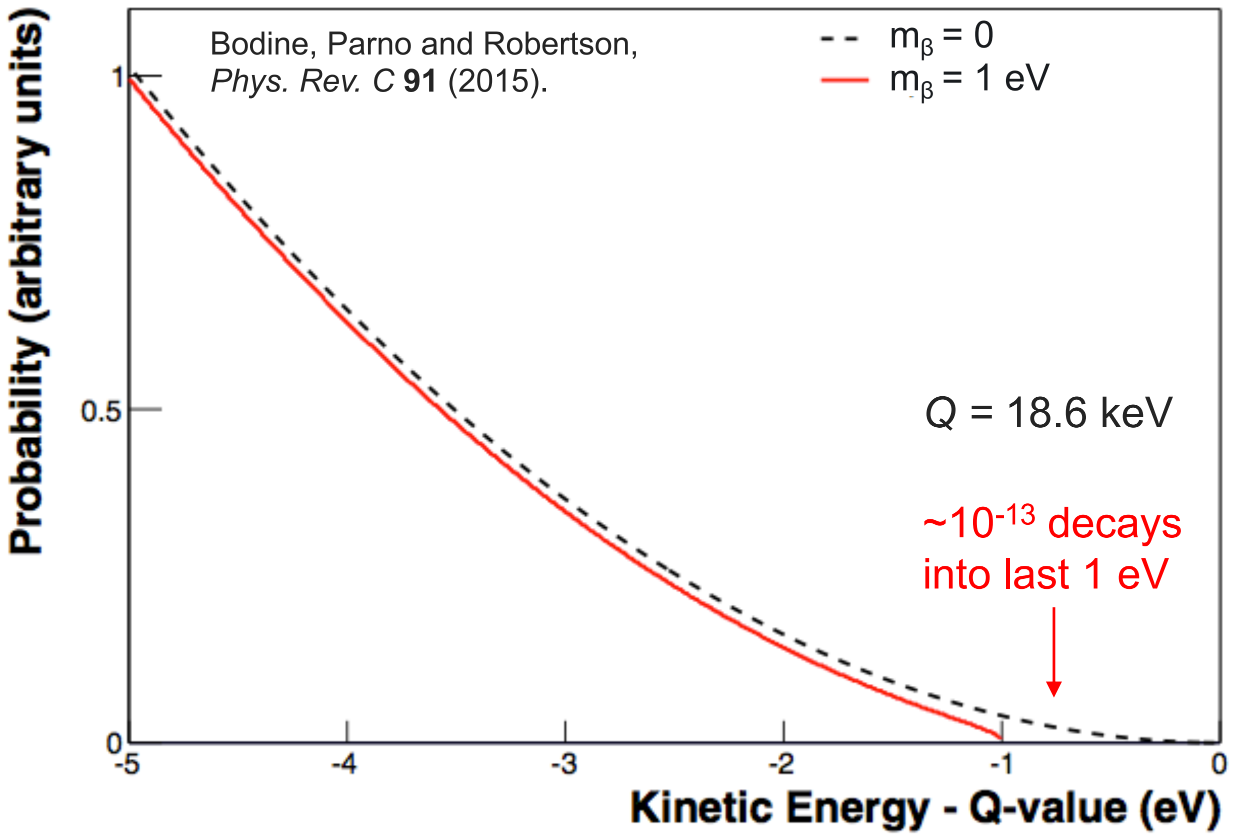
Outline

- The tritium endpoint method
- Milestones in neutrino mass phase space
- The need for new spectroscopy and source technologies
- Cyclotron Radiation Emission Spectroscopy (CRES) for improved statistical sensitvity
- Atomic Tritium (T) for improved systematic sensitivity
- Concept for the Project 8 experiment

The Tritium Endpoint Method to Determine the Absolute Neutrino Mass Scale

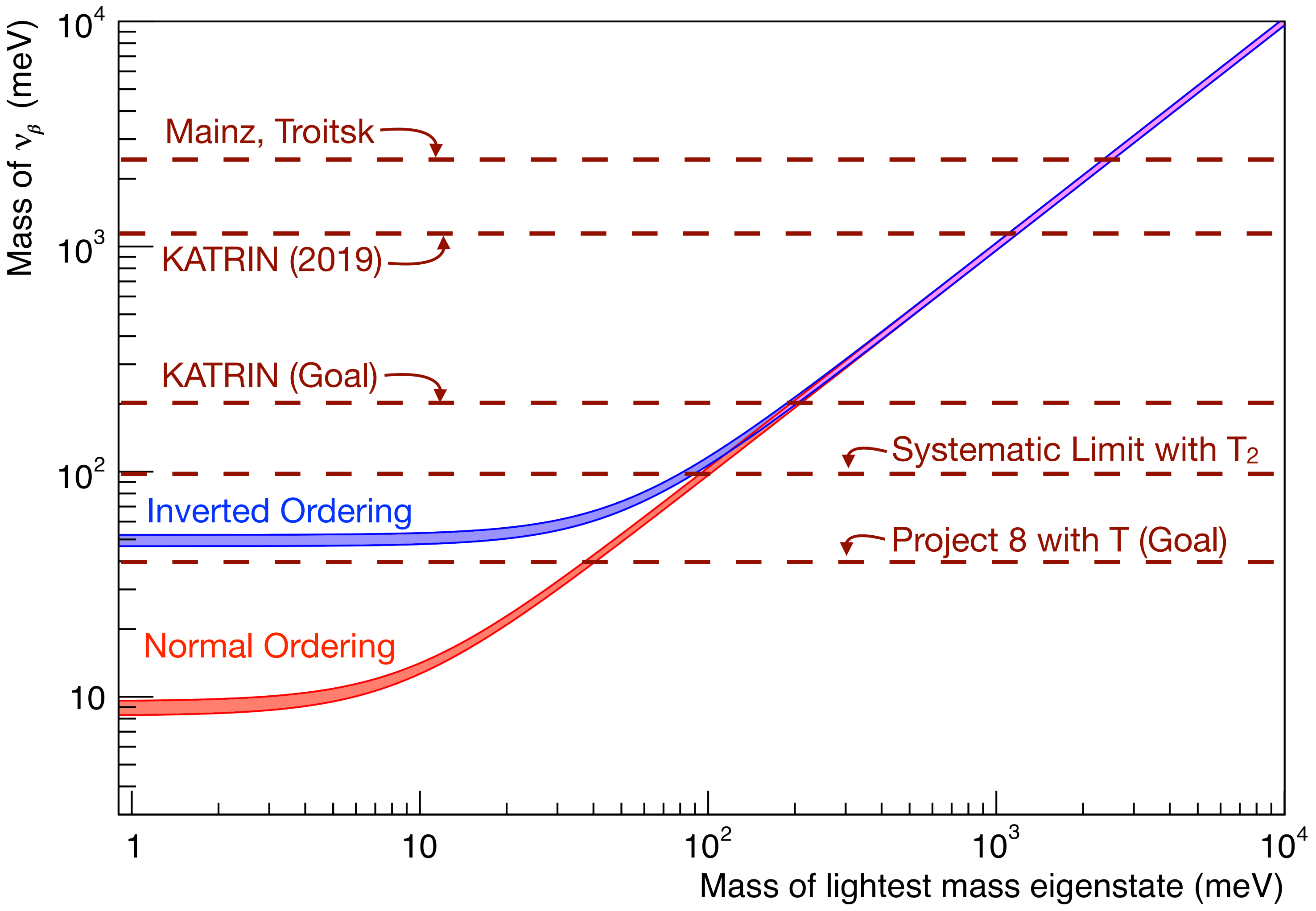
- Tritium Beta Decay: $^3\mathrm{H} \rightarrow\ ^3\mathrm{He} + e^- + \bar{\nu}_e$
- High-precision spectroscopy on the e^-
- Neutrino mass manifests as a deviation at the energy endpoint
- Fit the spectral shape with m_β^2 as a free parameter:

$$m_\beta^2 \equiv \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$



- Only a tiny fraction of decays near the endpoint are sensitive to m_β
- Statistical sensitivity of m_β^2 is roughly $\sim 1/N^{1/2}$, so that of m_β is $\sim 1/N^{1/4}$
- Each generation of tritium endpoint experiment must accommodate *much* more intense tritium source than the last, *and* reduce systematics accordingly

Milestones in Neutrino Mass Phase Space

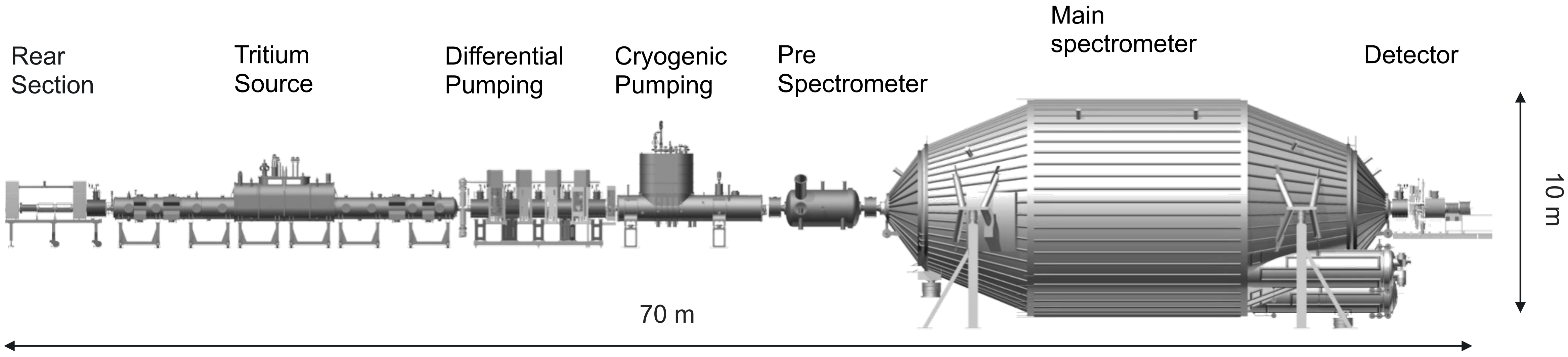


- Current best limit is from KATRIN: 1.1 eV (90% C.L.) [1].
- KATRIN's goal is 0.2 eV limit (90% C.L.), covering the rest of the quasi-degenerate mass possibilities.
- Uncertainty in molecular tritium (T_2) final states sets a systematic floor at about 0.1 eV.
- The next milestone is to cover the possibilities of the Inverted Ordering, down to a lower limit of 48 meV (95% C.L.) [2].
- Project 8 estimates 40 meV sensitivity can be attained using Cyclotron Radiation Emission Spectroscopy and an atomic tritium (T) source [3].

[1] Aker *et al.* (KATRIN), Phys. Rev. Lett. **123** 221802 (2019).
[2] Doe *et al.* (Project 8), arXiv:1309.7093 (2013).
[3] Zyla *et al.* (PDG), Progr. Theor. Exp. Phys. 083C01 (2020).

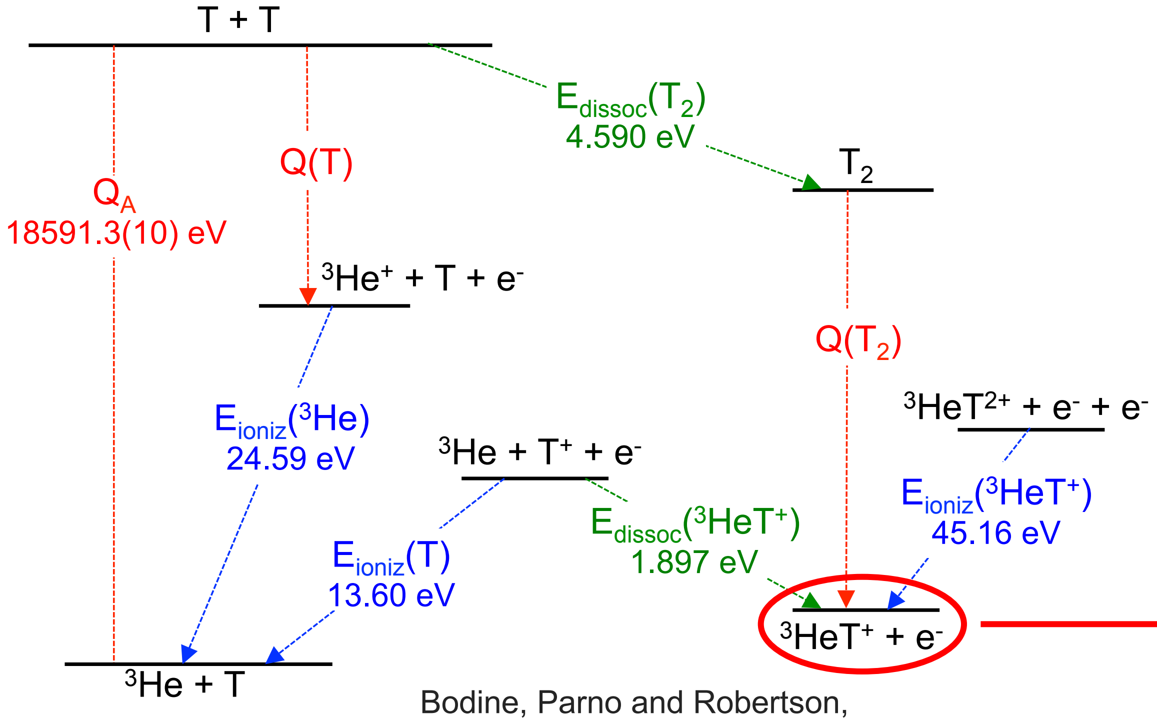
The Quest for Statistical Sensitivity to Neutrino Mass

Karlsruhe Tritium Neutrino (KATRIN) Experiment



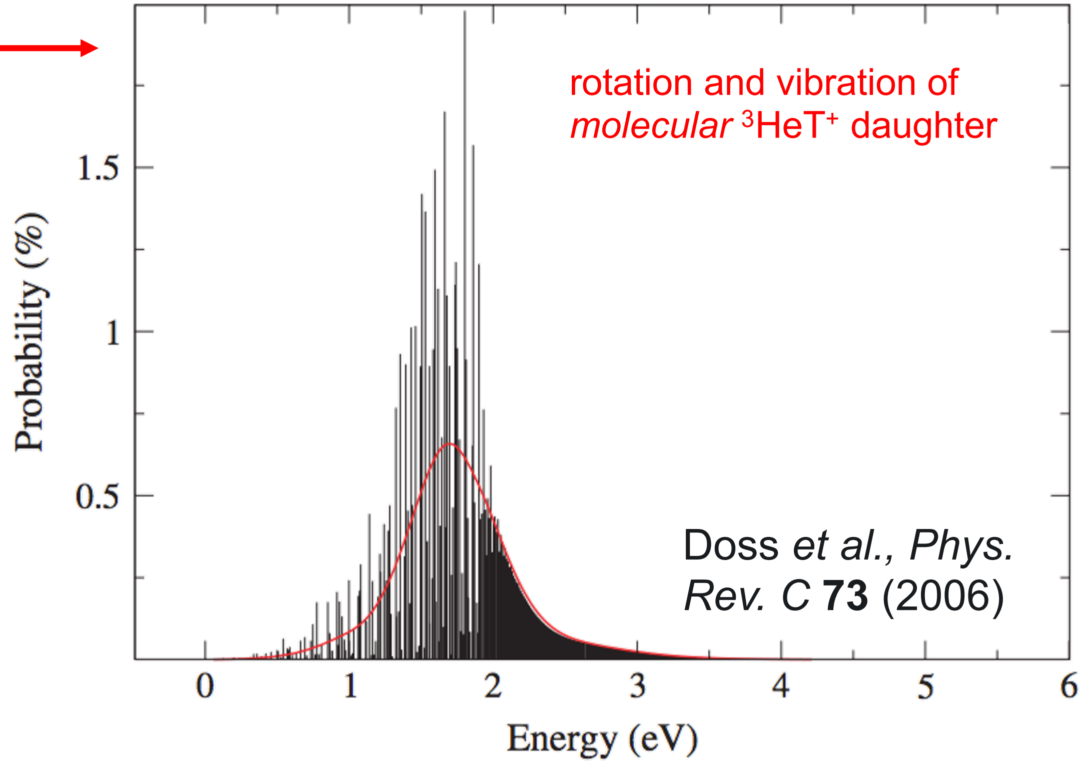
- KATRIN uses the maximum possible source column density – statistical sensitivity can only improve by expanding the source radially.
  - The spectrometer(s) must expand proportionally.
  - Sensitivity to inverted hierarchy m_β required ~100s of meters diameter!
  - KATRIN is already the best possible experiment of its kind! It will determine m_β < 0.2 eV/c^2 (90% c.l.).
- Improvement in neutrino mass statistical sensitivity will require a spectrometer with a better source scaling relation.

Molecular Tritium and Systematic Sensitivity



Bodine, Parno and Robertson, *Phys. Rev. C* **91** (2015).

- Any experiment with a *molecular* tritium (T_2) source will have a systematic penalty associated with *uncertainty* in the width of rotational and vibrational states of the daughter $^3HeT^+$ populated in the decay.
- KATRIN, e.g., requires 1% in its uncertainty budget [1].



Doss *et al.*, *Phys. Rev. C* **73** (2006)

- An experiment that uses T_2 can be, at best, marginally more sensitive than KATRIN.
- Project 8 will use *atomic* tritium (T) to probe past the floor of the inverted ordering, to 40 meV.

[1] Angrik *et al.*, FZKA-7090

Systematics in the Tritium Endpoint Method [1]

- "Four major effects produce results indistinguishable, to first order, from a neutrino mass:"
  - **Final states**
  - **Resolution function**
  - **Energy loss in the source**
  - **Background**

- "In general, an error in the width of any of these distributions will generate an error of the same sign in the derived neutrino mass without any effect on the quality of the fit"

Example: T_2 spectrum w/ massless neutrinos, molecular final states V_i.

$$\frac{dN}{dE} \propto E(E_0 - E - \langle V_i \rangle)^2 \left(1 + \frac{\langle V_i^2 \rangle - \langle V_i \rangle^2}{(E_0 - E - \langle V_i \rangle)^2}\right)$$

- Looks like a tritium spectrum with:

$$\text{Endpoint} = E_0 - \langle V_i \rangle$$

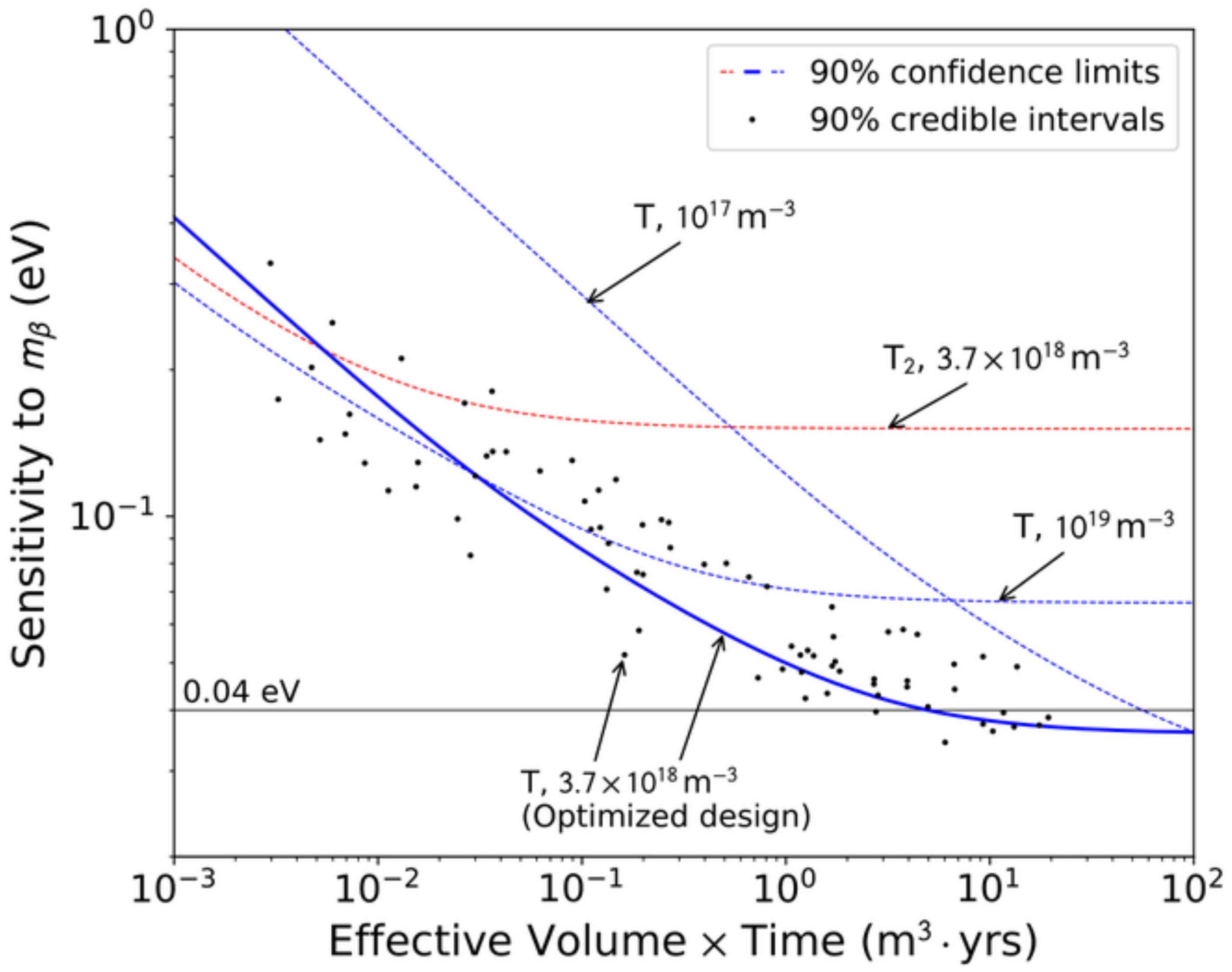
$$m_\beta^2 = -2\left(\langle V_i^2 \rangle - \langle V_i \rangle^2\right) \equiv -2\sigma^2$$

- Additionally, if the variance σ is unknown by $\Delta\sigma$, that contributes an additional

$$\Delta m_\beta^2 \approx 4\sigma\Delta\sigma$$

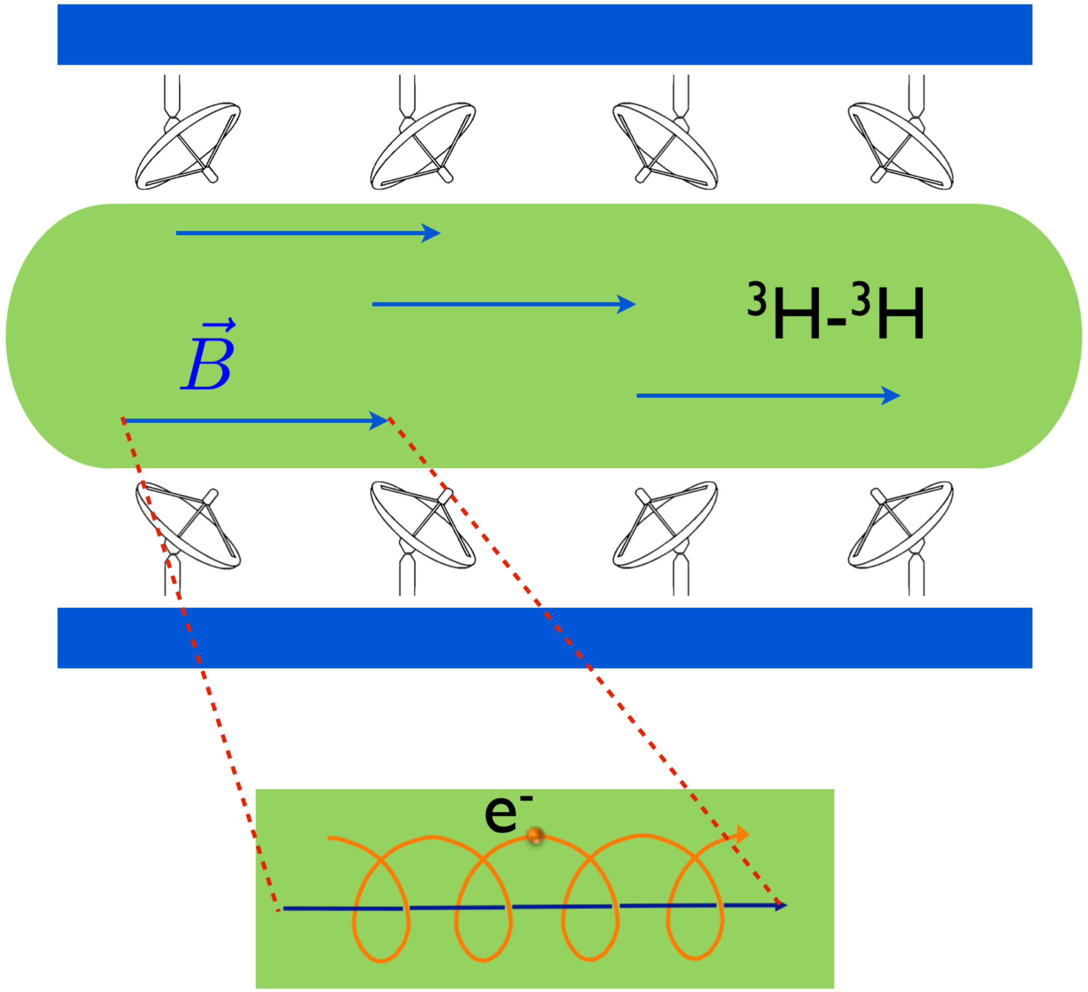
[1] Robertson and Knapp, Ann. Rev. Nucl. Part. Sci. **38** 1988

Sensitivity of Project 8: CRES w/ an Atomic Tritium Source



- Project 8 calculates m_β sensitivity of 40 meV (90% credible interval) w/:
  - Optimized density 3.7×10^{18} atoms/m^3
  - Exposure 5 m^{3}y
  - Resolution 115 ± 2 meV
  - Magnetic field uniformity ~0.1 ppm
- Full Bayesian analysis for m_β near zero
- Effective volume is (physical volume)×efficiency, where efficiency may be only $\lesssim$10%
- Solid blue curve is optimum design scenario, other curves show:
  - Too little or too much T (blue dashed)
  - Molecular final states (red dashed)

Cyclotron Radiation Emission Spectroscopy (CRES)

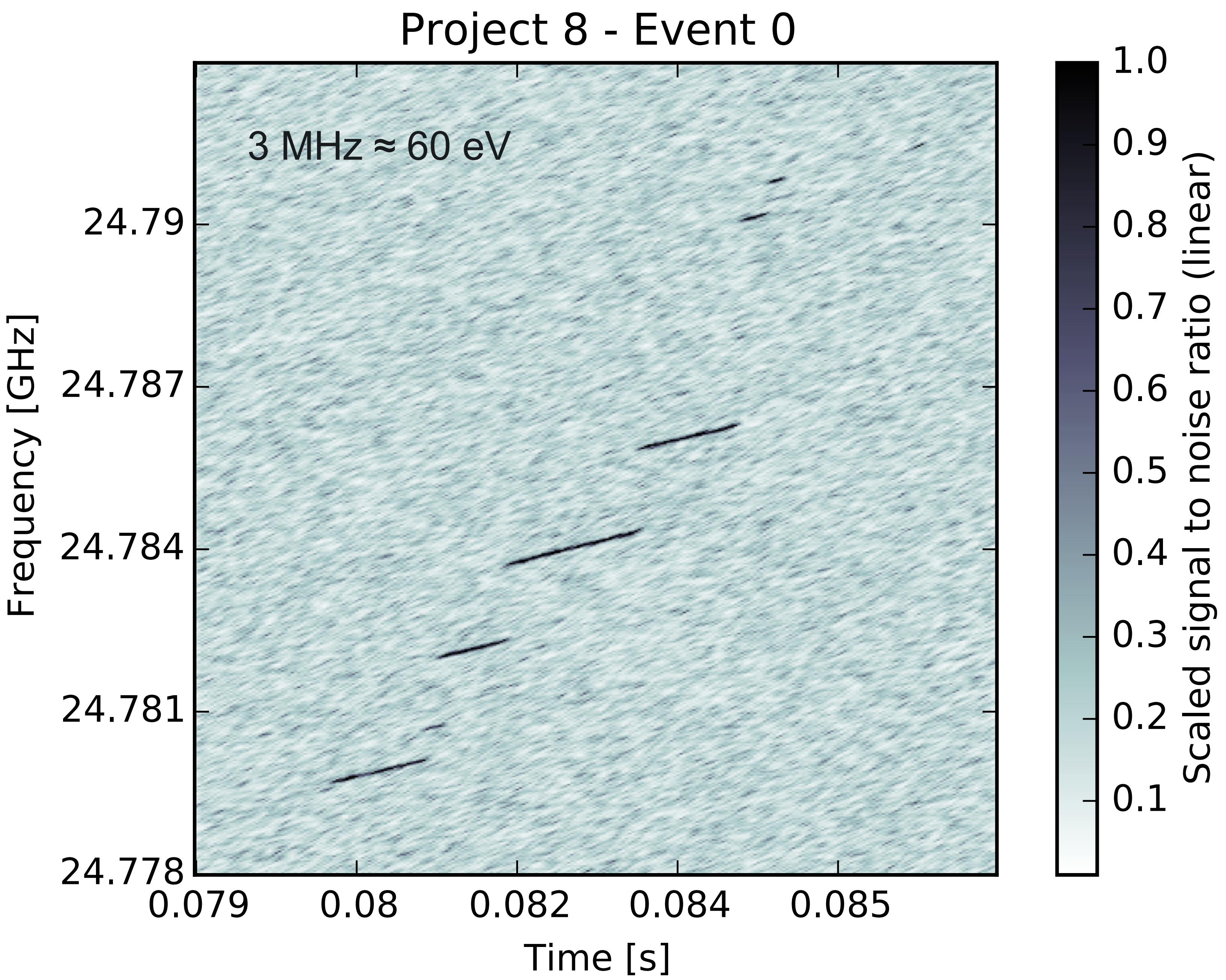


- Project 8 will use CRES [1]:
  - Detect microwave cyclotron radiation from electrons in a magnetic field
  - Tritium source is transparent to microwaves. Directly instrument the source region and avoid electron transport → improved scaling with volume.
  - Nondestructive frequency domain technique – extreme precision w/ absolute standards.
  - Very low expected backgrounds
  - Differential measurements avoids systematics associated w/ tritium source stability
  - Tritium endpoint electrons (E_0 = 18.6 keV) emit $P \approx 1$ fW at $f \approx 27$ GHz in a 1 T *B*-field.

$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E/c^2}$$

[1] Monreal and Formaggio, *Phys. Rev. D* **80** (2009)

A Typical CRES Event*



* Also happens to be the first one ever observed

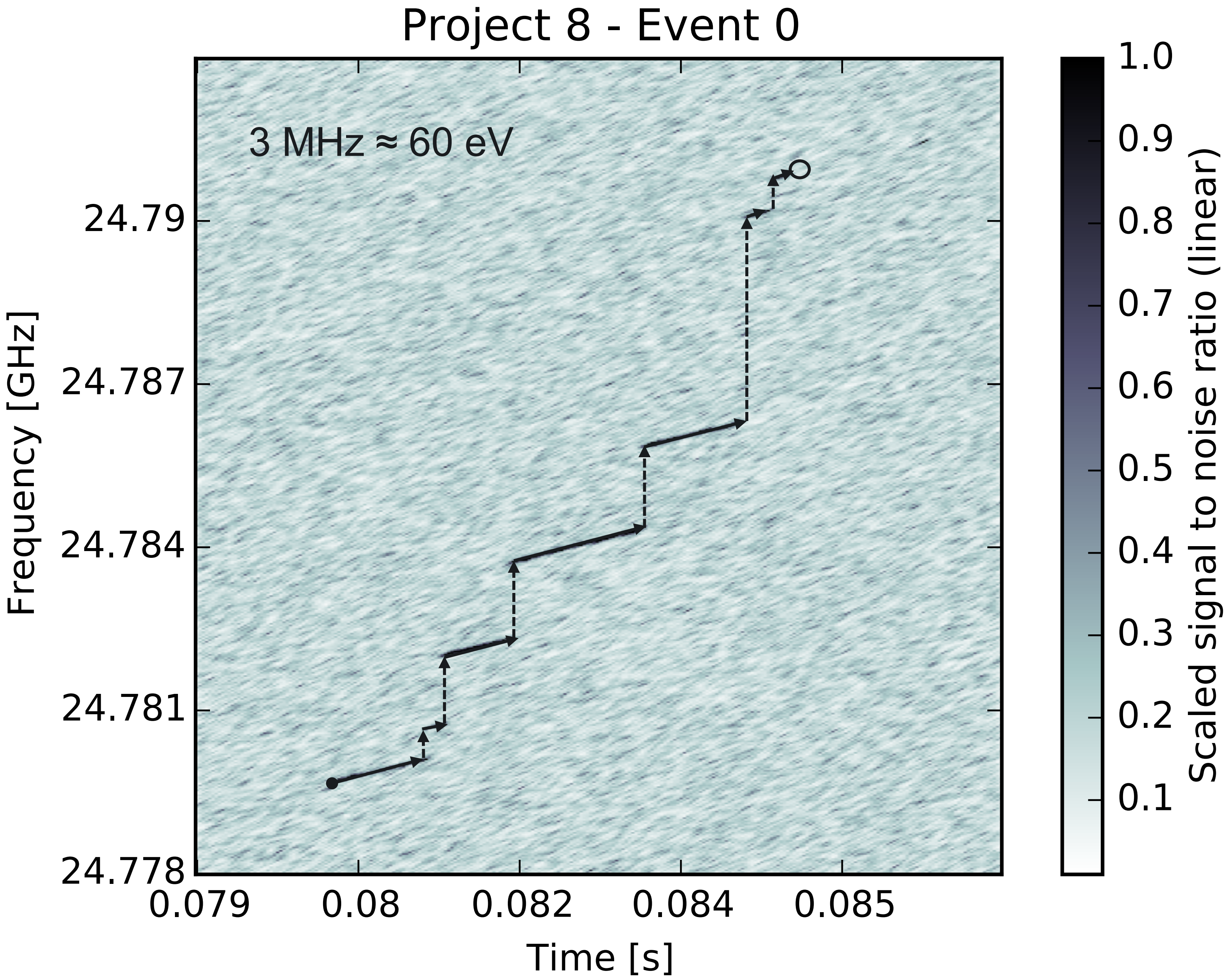
A Typical CRES Event*

Start frequency of the first track gives kinetic energy.

Frequency chirps linearly, corresponding to ~1 fW radiative loss.

Electron scatters inelastically, losing energy and changing pitch angle.

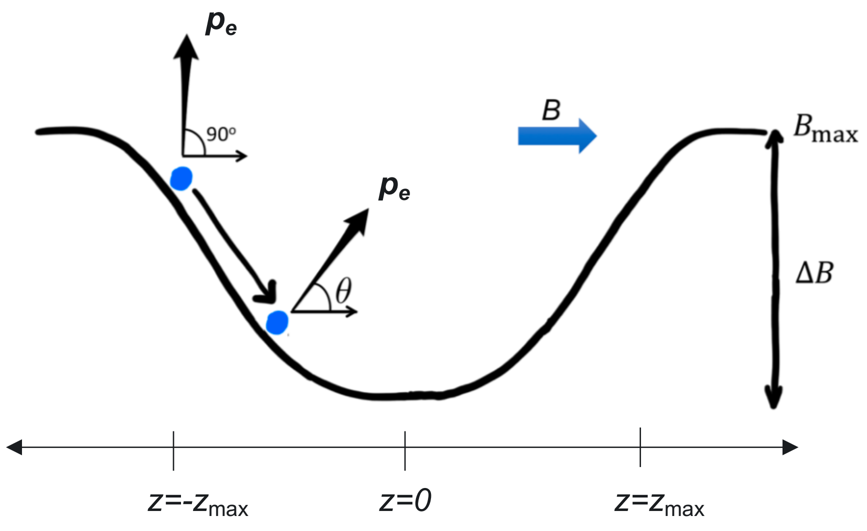
Eventually, scatters out of trapped phase space.



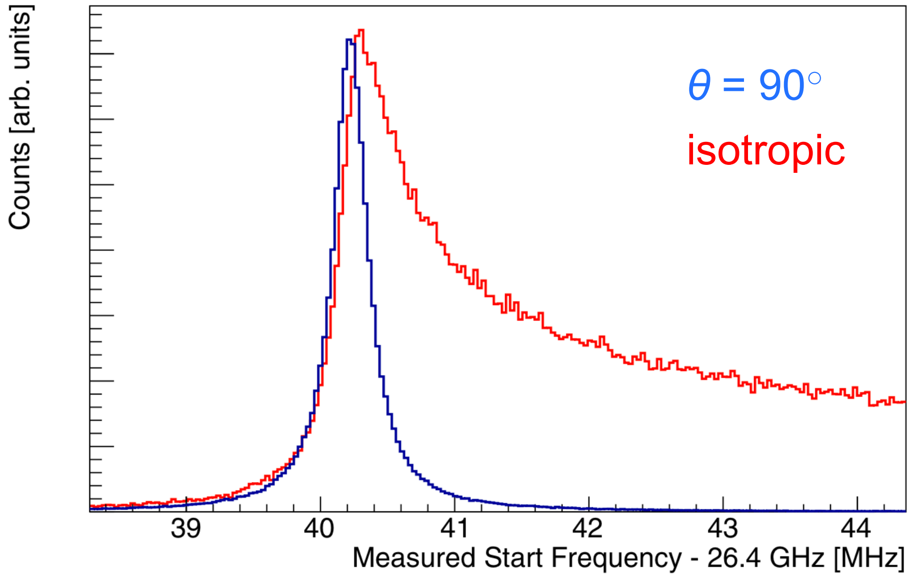
* It also happens to be the first one ever observed.

Cyclotron Radiation Emission Spectroscopy (CRES)

- Real experiments must confine electrons in a magnetic trap for sufficient observation time.
- Trapping leads to modifications of the "naïve" cyclotron formula* of slide 7:
  - *B* is the average field sampled by the electron in an observation time window.
  - Introduces pitch angle (θ) dependence as electrons explore different ranges of *z.*
  - Results in a high-frequency (i.e., an apparent low-energy) tail.
- Along with scattering (slide 13) this contributes to a CRES linshape that is the resolution function discussed above (slide 7).



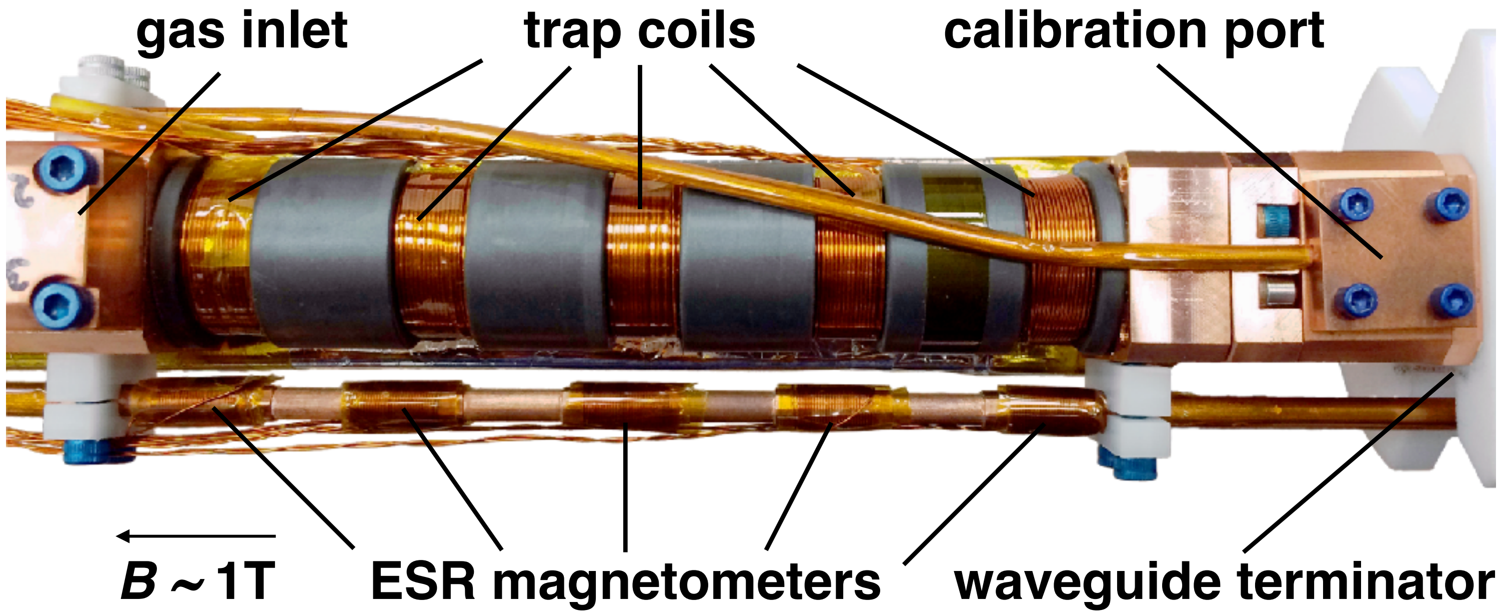
4 mT harmonic trap response

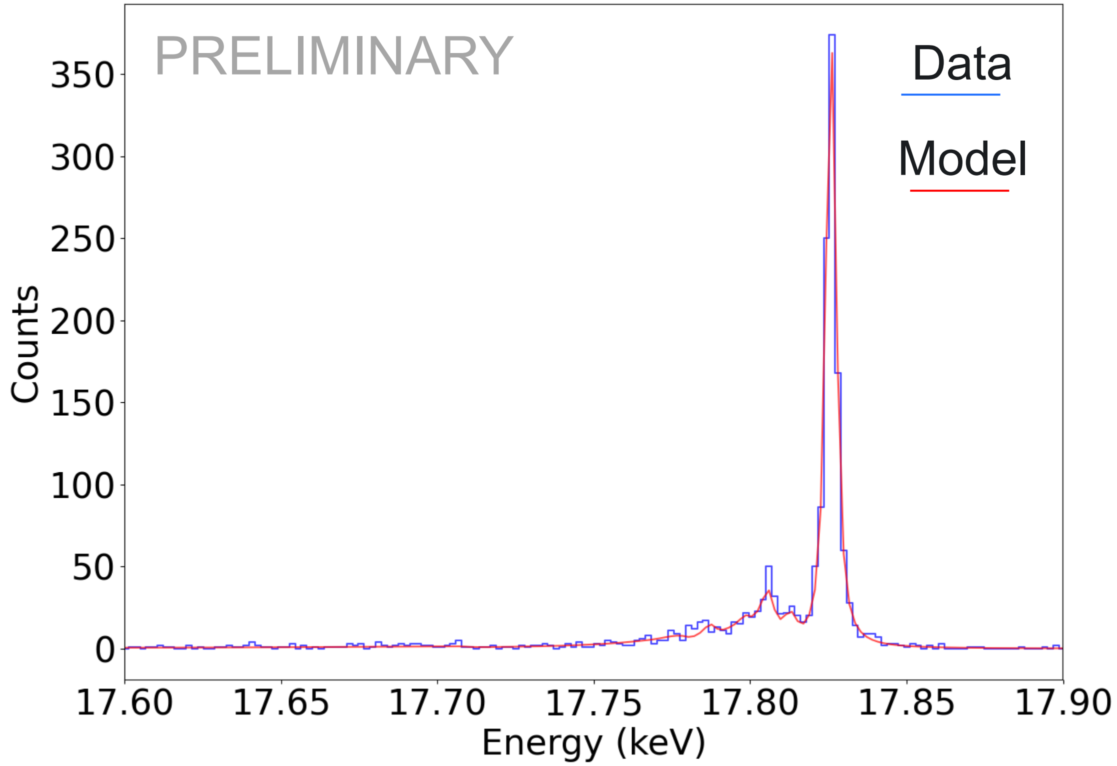


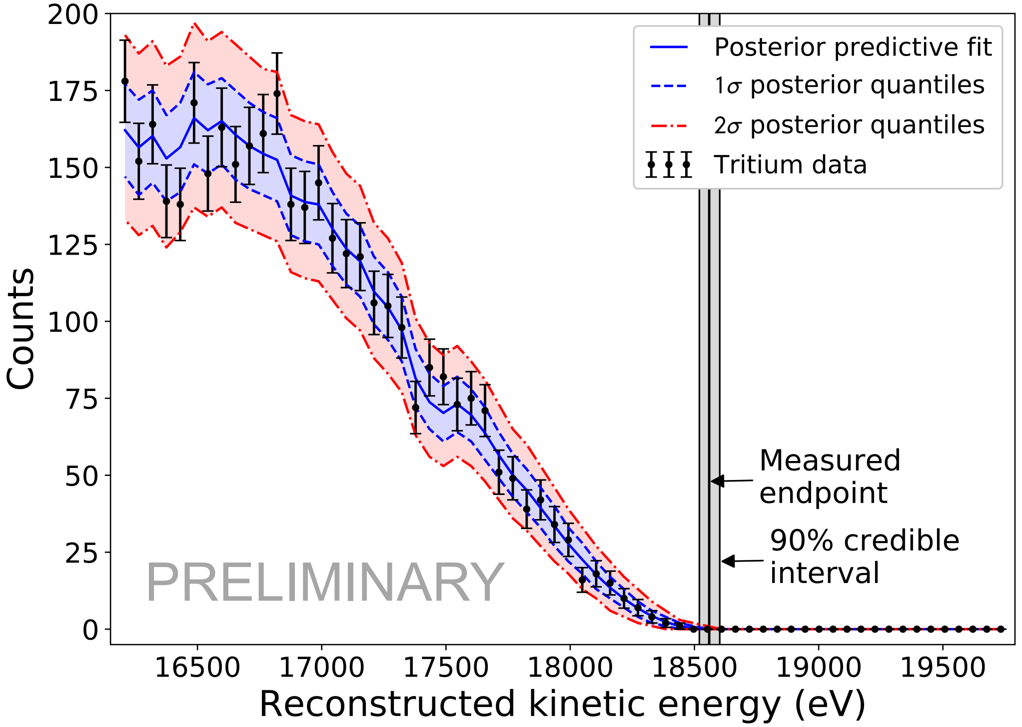
[1] Ashtari Esfahani *et al.*, Phys. Rev. C **99** (2019)

* The "naïve" cyclotron formula is: $f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E/c^2}$

CRES Prototype Measurements (Phase II)

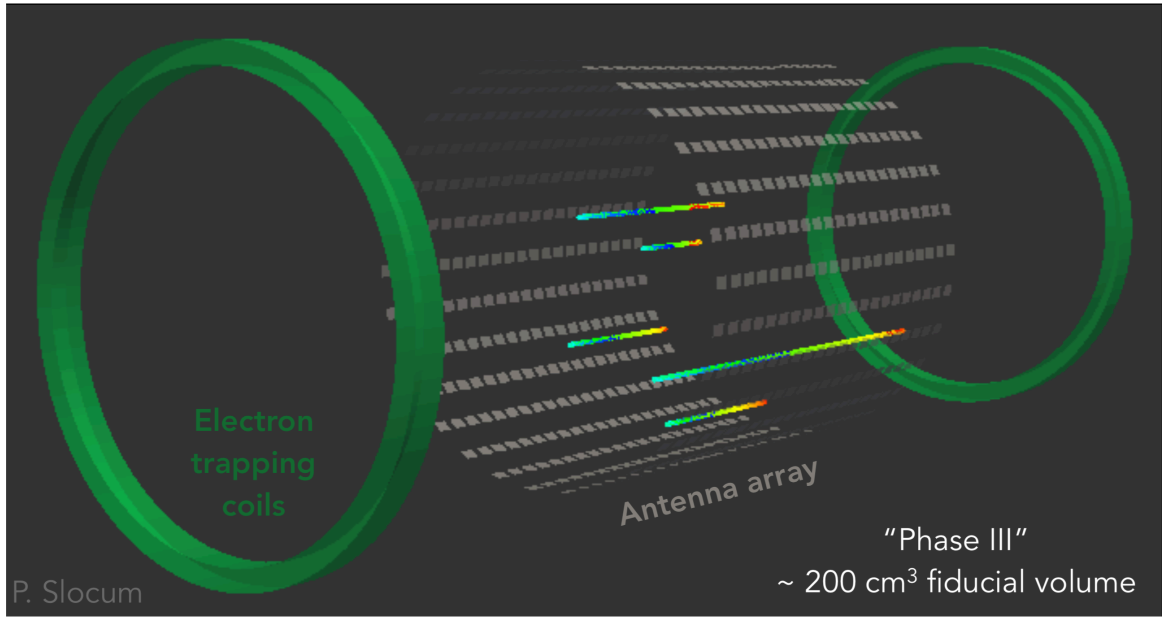




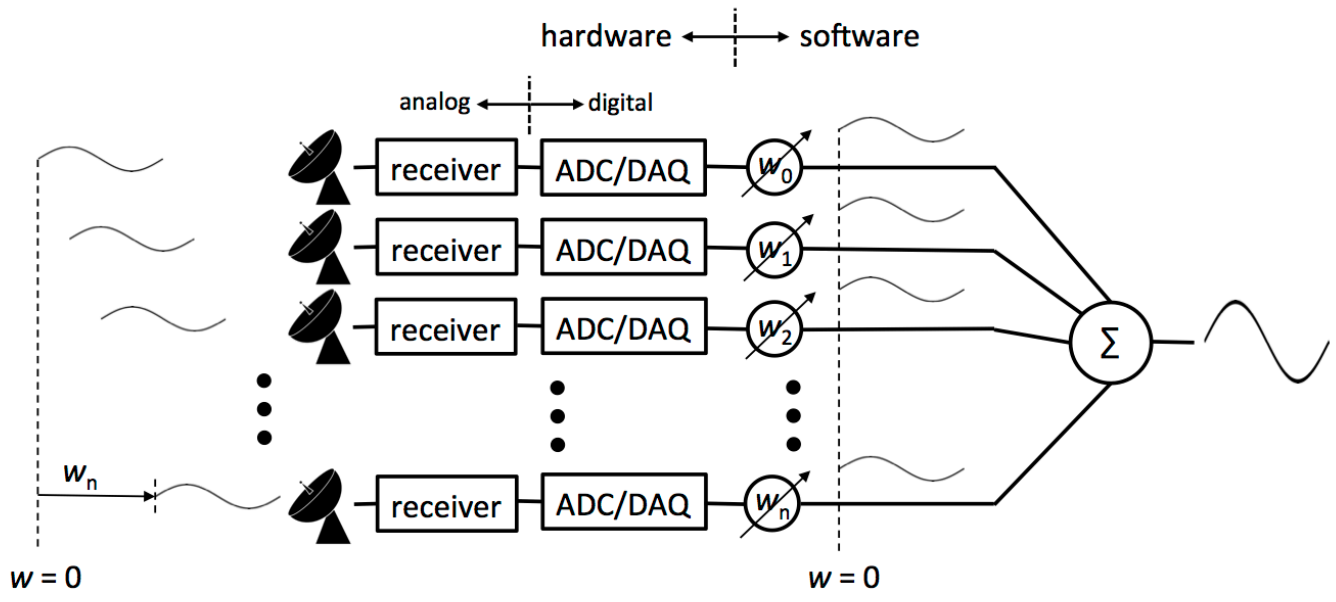


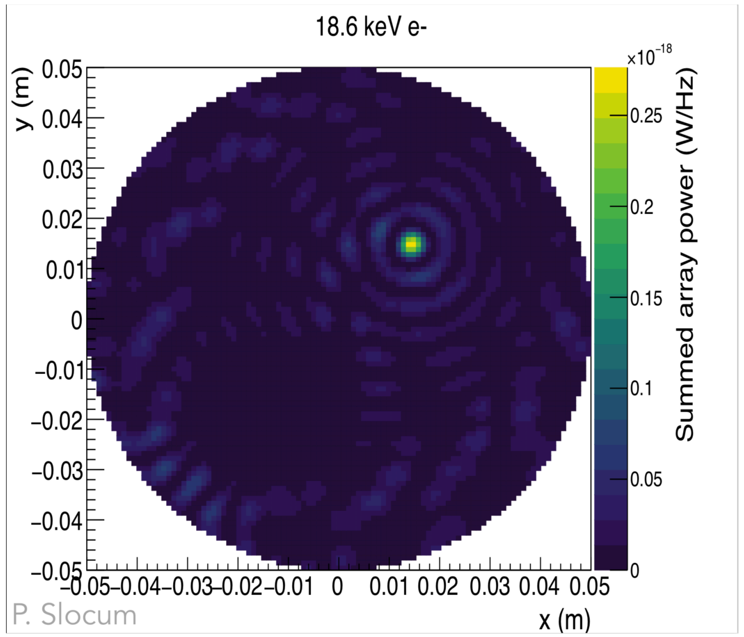
- Phase II CRES instrument provides V_{eff} ~1 mm^3 inside waveguide
- Permits measurements of ^{83m}Kr and T_2
- Shallow trap configurations sacrifice efficiency for instrumental resolution, as good as 2.0 ± 0.1 eV (^{83m}Kr, above)
- First T_2 measurement (left) yields correct endpoint: E_0 = 18559 ± 25 eV
- Backgrounds less than 3×10^{-10} (eV•s)$^{-1}$ (90% C.L.)

Scaling CRES to Larger Volumes (i.e., More Intense Tritium Sources)



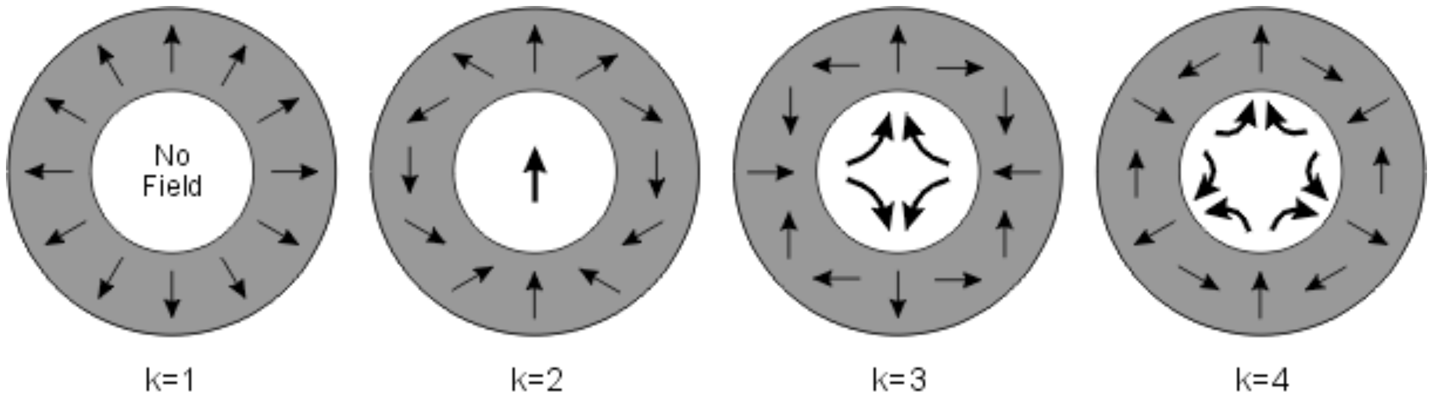
- CRES must be scaled to much larger volumes ~1 $mm^3 \rightarrow$ ~10 m^3
- Must leave waveguide for free space observed with antennas (left)
- Active signal processing techniques (below left) focus and fiducialize source volume (below right)
  - Permits simultaneous electron events
  - Confines *B*-field uniformity requirement to single voxels



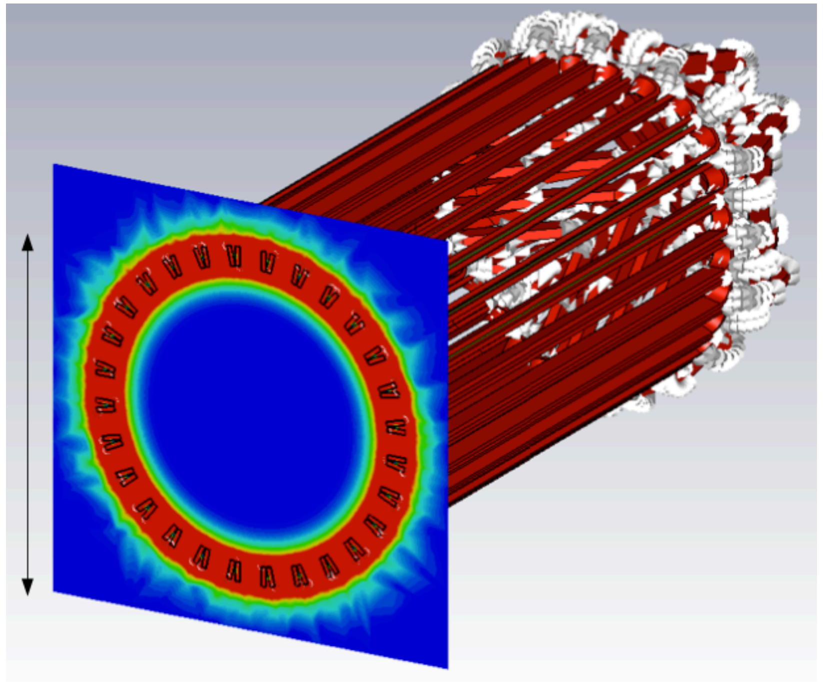


Atomic Tritium Source

- T_2 endpoint is 8 eV higher than that of T, and is therefore a potential background. Requires purity $T_2/T \lesssim 10^{-6}$.
- At $\rho \sim 10^{18}$ m^{-3} recombination $2T \rightarrow T_2$ happens on vessel walls. T requires a *magnetic* trap. T_2 w/ negligible magnetic moment evaporates away.
- Ioffe traps and Halbach arrays can have large fields near surfaces, with a large uniform region in the center suitable for CRES.

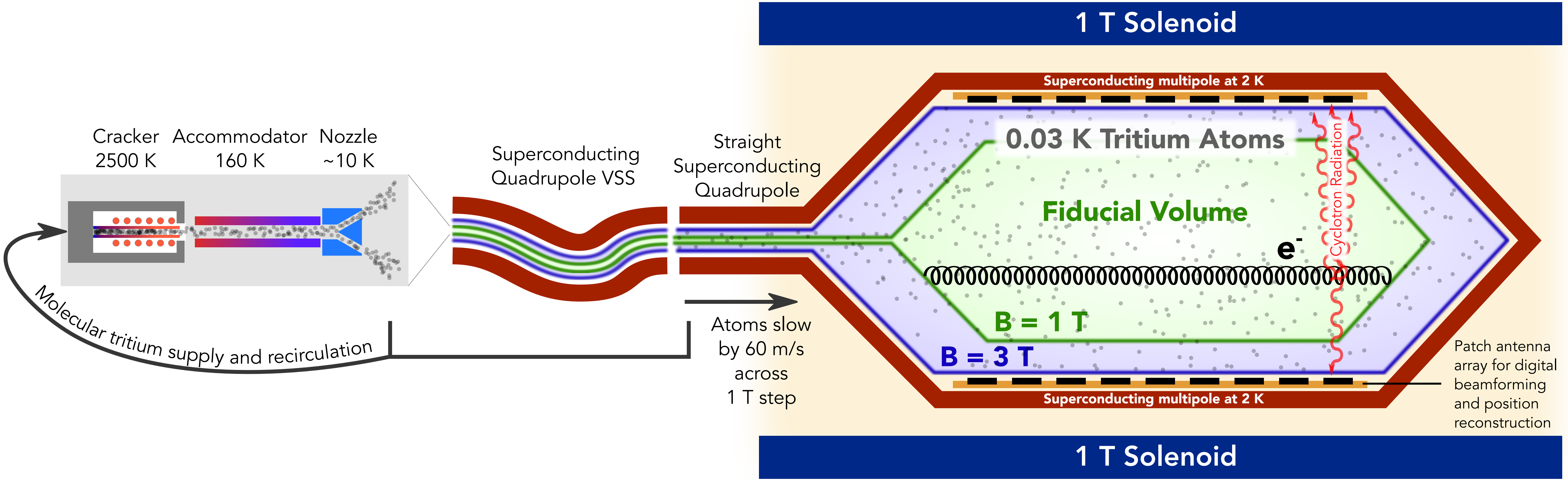


Cylindrical Halbach Arrays



Ioffe trap field profile

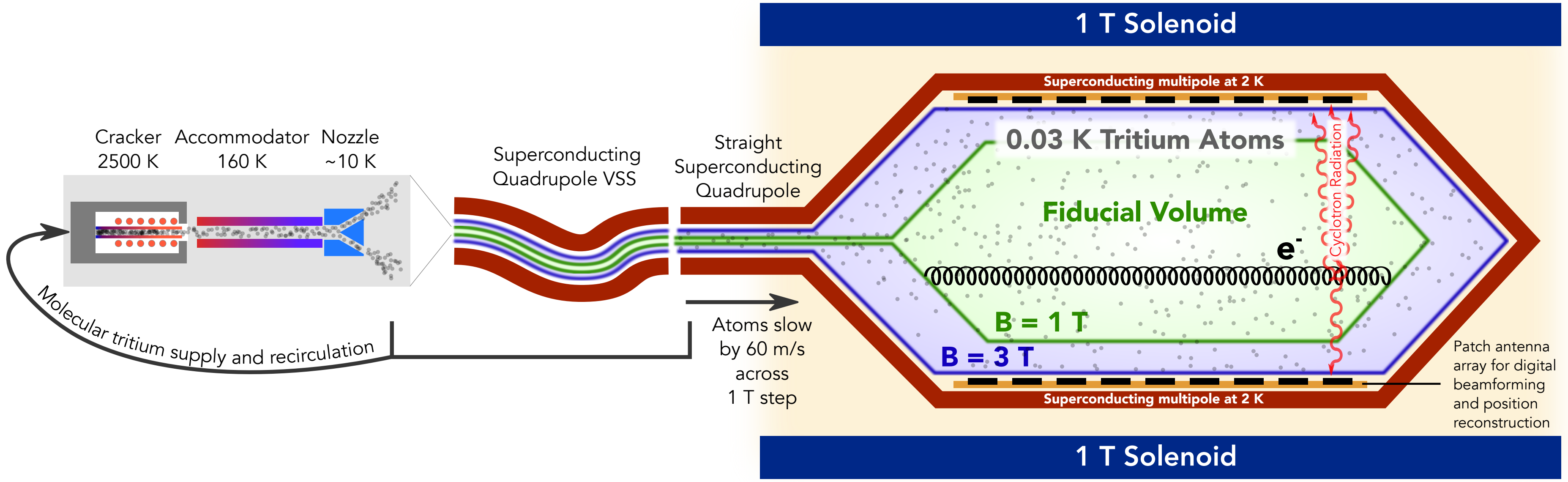
Project 8 Phase IV Concept



- The ultimate Project 8 experiment, with sensitivity to all possible Inverted Ordering masses, must integrate:
  - The conversion $T_2 \rightarrow T$.
  - Transport and cooling of T.
  - Magnetic trapping of T (Ioffe, Halbach…).
  - CRES antenna array.
- Current Project 8 R&D effort (Phase III) focused on developing these required technologies.

Summary, Conclusions, and Outlook

- Any tritium endpoint experiment will be hyper-sensitive to uncontrolled systematics.
- Tritium endpoint experiments after KATRIN will need a new spectroscopy technique and an atomic tritium source.
- Project 8 is developing CRES and atomic tritium trapping demonstrators now as candidate technologies.



The Project 8 Collaboration

Case Western Reserve University
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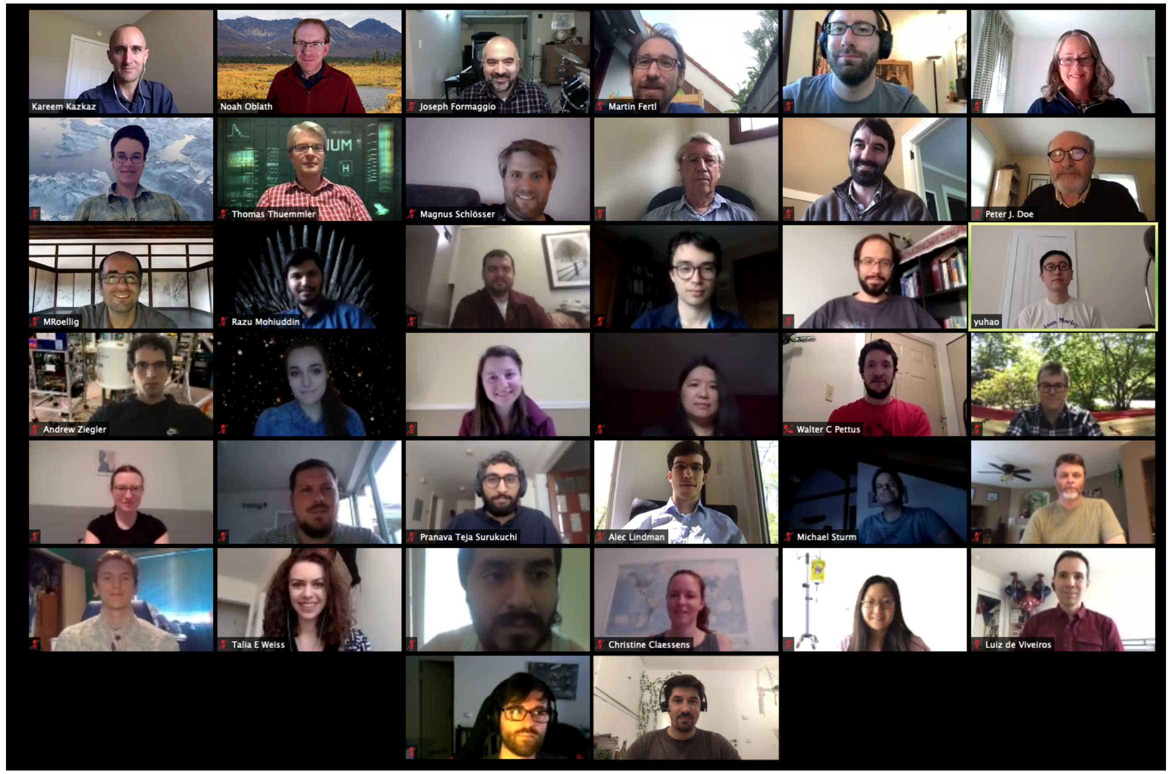
www.project8.org



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Supplemental Slides

Relationship Between Cosmological Fits and Direct Measurements

Cosmology

- Sum of the three eigenvalues
- Depends on cosmological model and number of free parameters

$$\Sigma \equiv \sum_{i=1}^{3} m_i$$

Beta decay / electron capture

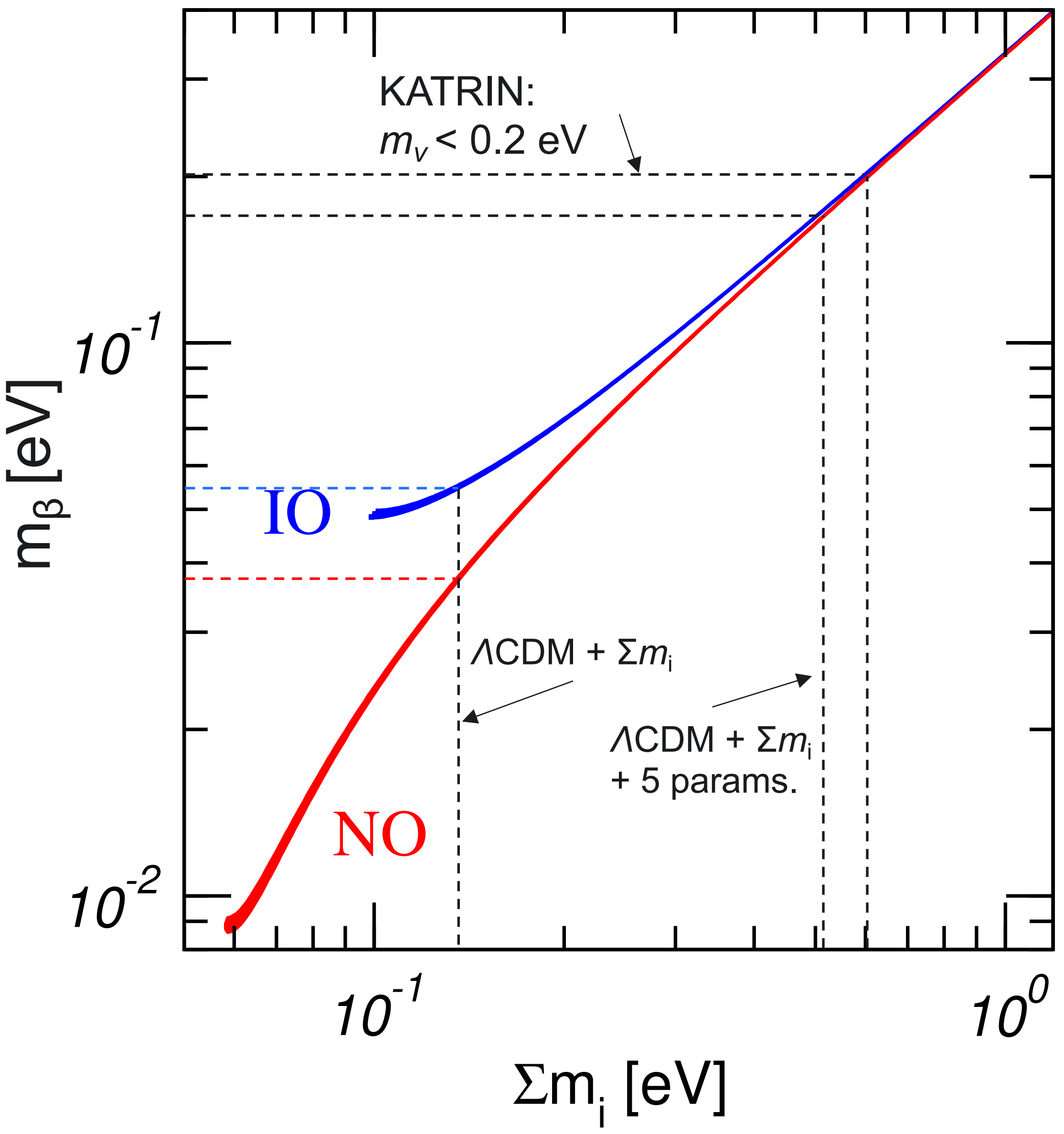
- Direct, model independent
- Focus of this talk

$$m_\beta^2 \equiv \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

	Model	95% CL (eV)
CMB alone		
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26
CMB + probes of background evolution		
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515

Zyla *et al.* (PDG), Progr. Theor. Exp. Phys. 083C01 (2020).

NuFIT 4.1 (2019) www.nu-fit.org, Esteban *et* al., JHEP 106 (2019).



Relationship Between 0vββ Mass and Direct Measurements

Neutrinoless double-beta decay

- Coherent sum over eigenstates, possible phase cancellation
- Observable only as a product with hugely uncertain nuclear matrix element

Experiment	Iso	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]
LEGEND 200 [62,63]	^{76}Ge	8.4×10^{26}	40–73
LEGEND 1k [62,63]	^{76}Ge	4.5×10^{27}	17–31 ←
SuperNEMO [69,70]	^{82}Se	6.1×10^{25}	82–138
CUPID [59,60,72]	^{82}Se	1.8×10^{27}	15–25 ←
CUORE [53,54]	^{130}Te	5.4×10^{25}	66–164
CUPID [59,60,72]	^{130}Te	2.1×10^{27}	11–26 ←
SNO+ Phase I [67,73]	^{130}Te	1.1×10^{26}	46–115
SNO+ Phase II [68]	^{130}Te	4.8×10^{26}	22–54
KamLAND-Zen 800 [61]	^{136}Xe	1.6×10^{26}	47–108
KamLAND2-Zen [61]	^{136}Xe	8.0×10^{26}	21–49
nEXO [74]	^{136}Xe	4.1×10^{27}	9–22 ←
NEXT 100 [65,75]	^{136}Xe	5.3×10^{25}	82–189
NEXT 1.5k [76]	^{136}Xe	7.9×10^{26}	21–49
PandaX-III 200 [66]	^{136}Xe	8.3×10^{25}	65–150
PandaX-III 1k [66]	^{136}Xe	9.0×10^{26}	20–46

Agostini, Benato and Detwiler, Phys. Rev. D **96** 053001 (2017)

$$m_{\beta\beta}^2 \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

Dolinski, Poon and Rodejohann, Ann. Rev. Nucl. Part. Sci. **69** 219 (2019)