Direct Neutrino Mass Measurement in the Project 8 Experiment

PNNL-SA-118235

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Richland, WA

Introduction/Overview

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- Direct neutrino mass measurements after KATRIN
  - why?
  - how?
- Project 8 concept
  - Cyclotron Radiation Emission Spectroscopy (CRES)
  - Atomic Tritium
- Project 8 results and future prospects
  - first demonstration of CRES with **new results**
  - Conceptual design for sensitivity $m_{\nu e} < 2$ eV
  - Prospects for inverted hierarchy sensitivity ($m_{\nu e} < 50$ meV*)

* My "meV"s are lowercase – *i.e.*, milli, 10^{-3}!

The next generation direct mass measurement should probe the inverted hierarchy.

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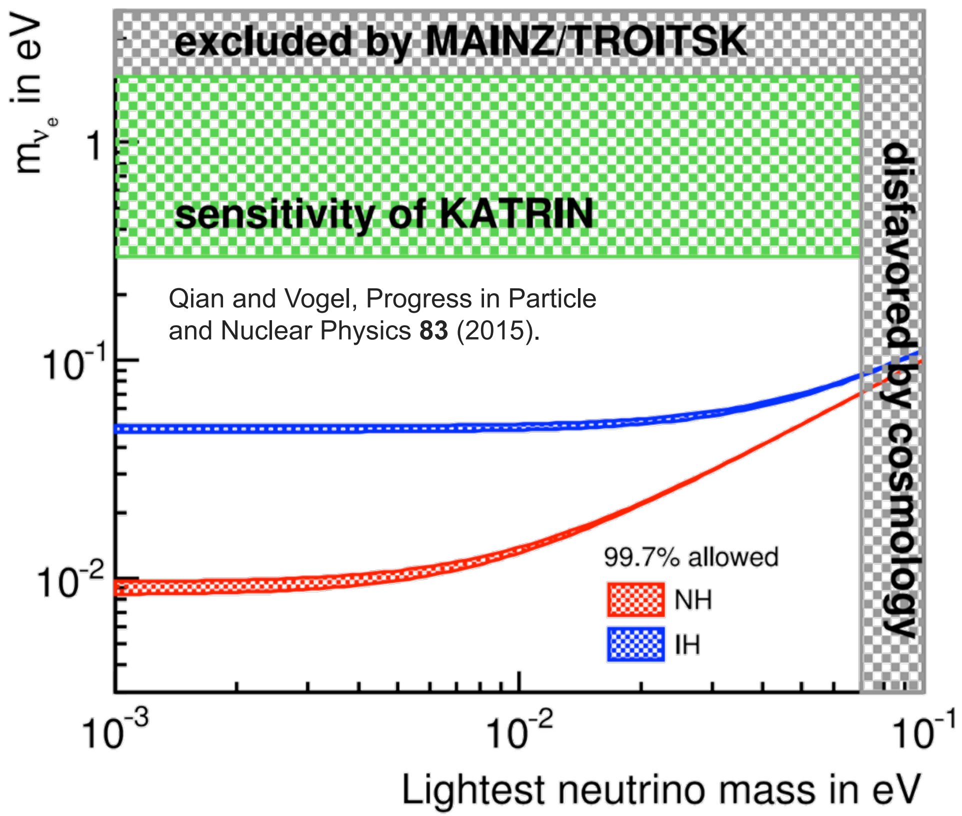

- KATRIN will exhaust the degenerate mass regime ($(\Delta m_{ij}^2)^{1/2} << m_1 \approx m_2 \approx m_3$).
- The next generation experiment should probe the bottom inverted hierarchy, $m_{\nu e} \approx 50$ meV.
- Cosmological limits will be able to exclude inverted hierarchy if observation still favors $m_{\nu e} = 0$.

Sensitivity in cosmology is driven by resolution of small-scale (high-multipole) structure.

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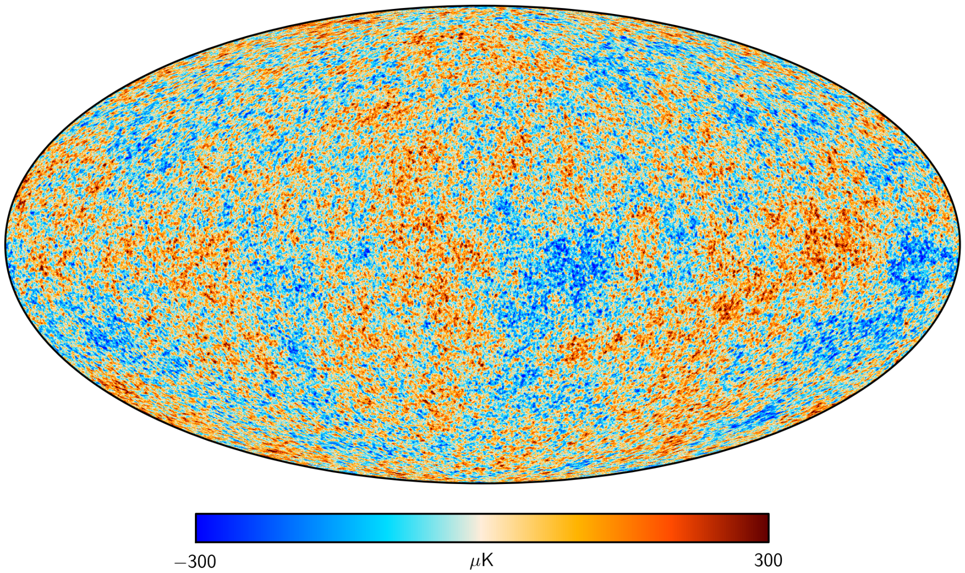
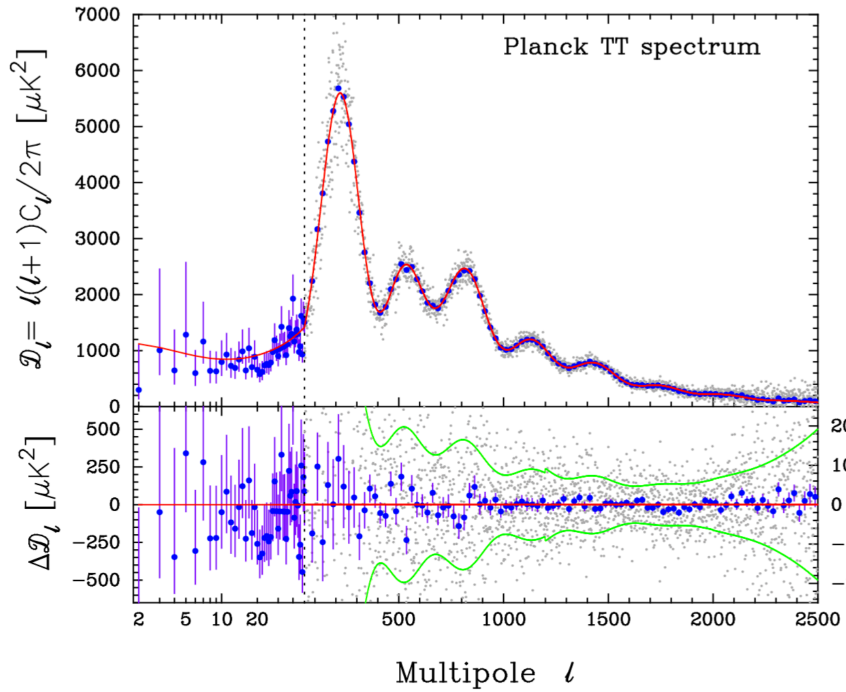
Cosmic Microwave Background Temp.
Planck Legacy Archive [A&A **571** A16 (2014)]





- increasing Σm_i moves power from high to low multipole *l.*
- Planck + WMAP polarization: $\Sigma m_i < 0.66$ eV (95% C.L.).
- Add gravitational lensing: $\Sigma m_i < 0.85$ eV (95% C.L.).
- Tension and model-dependence in cosmological data.
- A direct neutrino mass measurement, or even a more restrictive limit is preferred.

The Tritium Endpoint Method

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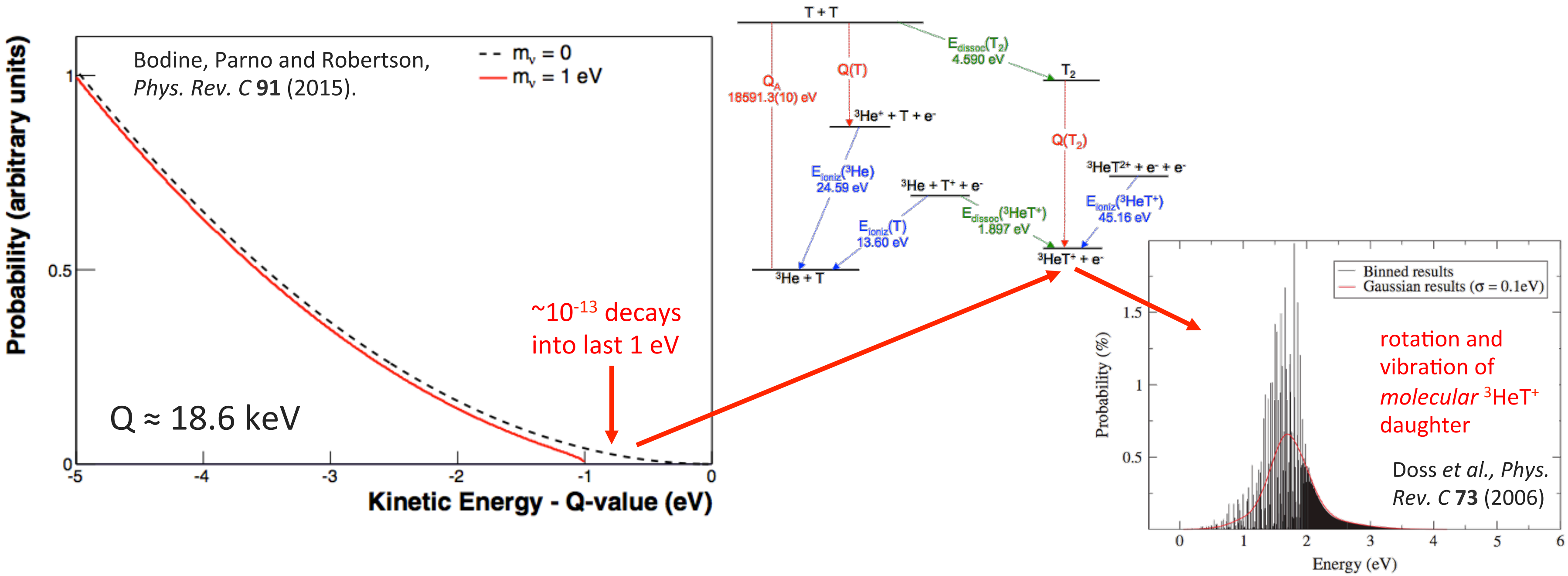
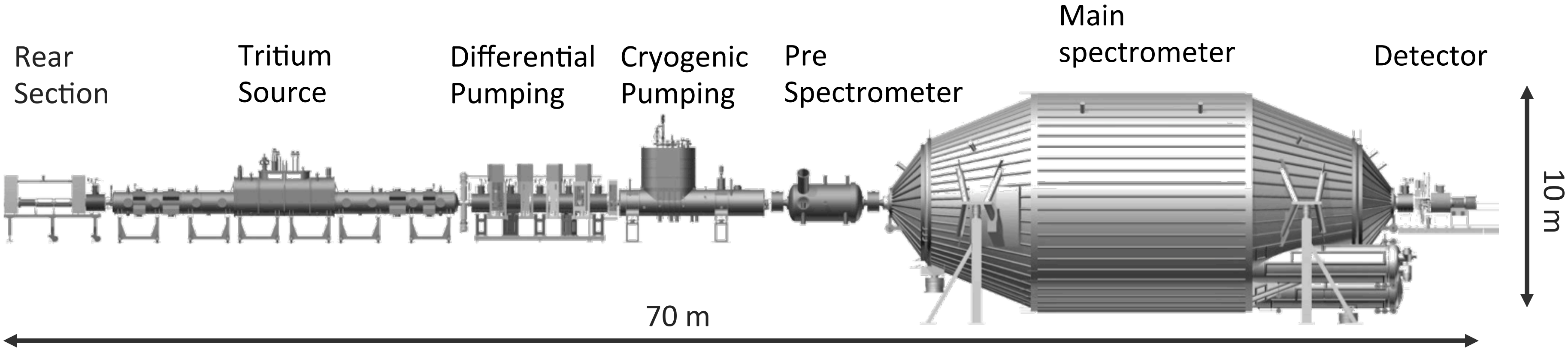


- Tritium Beta Decay: $^3H \rightarrow {}^3He^+ + e^- + \nu_e + Q$.
- High-precision spectroscopy on the e^-.
- Neutrino mass manifests as a deviation at the energy endpoint.
- Fit the spectral shape with $m_{\nu e}^2$ as a free parameter:

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

Tritium Endpoint Experimental Sensitivity and Size

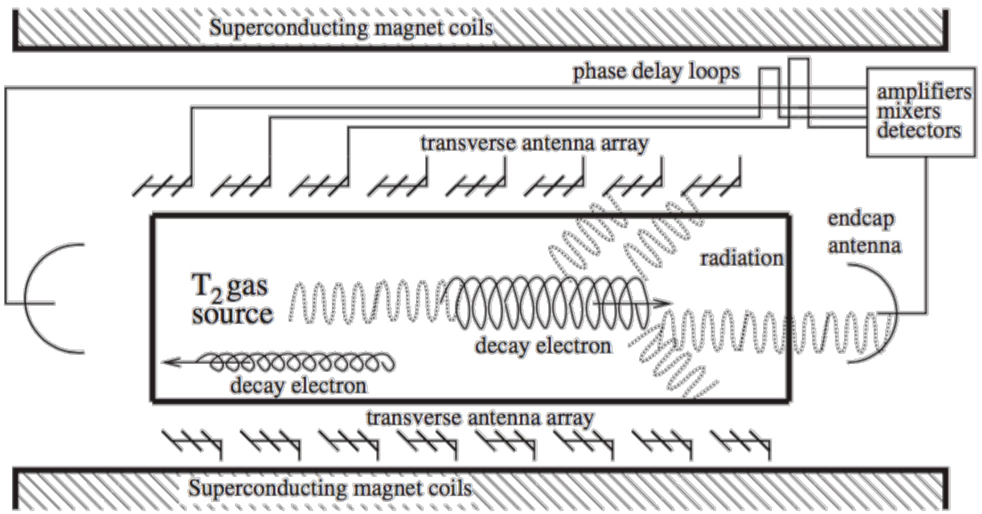
Statistical sensitivity is driven by the intensity of the tritium source. *Size* is driven by how your e^- spectroscopy technique accommodates that intensity.

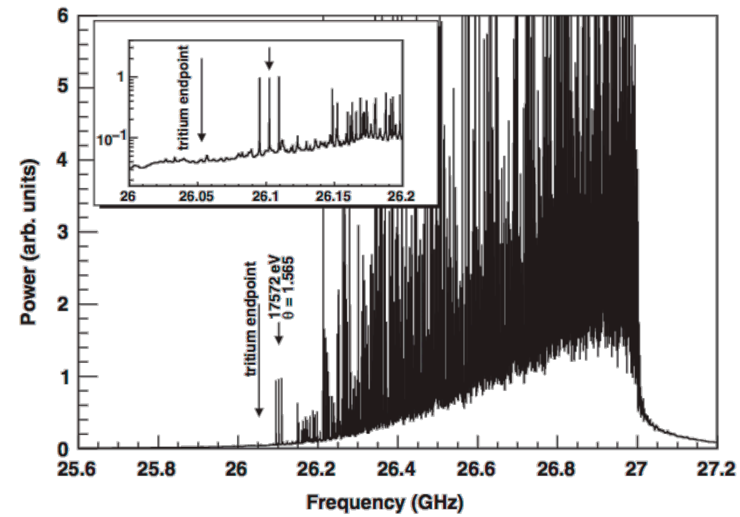


- KATRIN uses the maximum possible source column density – statistical sensitivity can only improve by expanding the source radially.
  - The spectrometer(s) must expand proportionally.
  - Sensitivity to inverted hierarchy $m_{\nu e}$ required ~100s of meters diameter!
  - KATRIN is already the best possible experiment of its kind!

- Improvement in neutrino mass sensitivity will require a spectrometer with a better source scaling relation.
- Sensitivity to inverted hierarchy masses will require an *atomic* tritium source to avoid final-state systematic uncertainty.

Project 8 and Cyclotron Radiation Emission Spectroscopy (CRES)





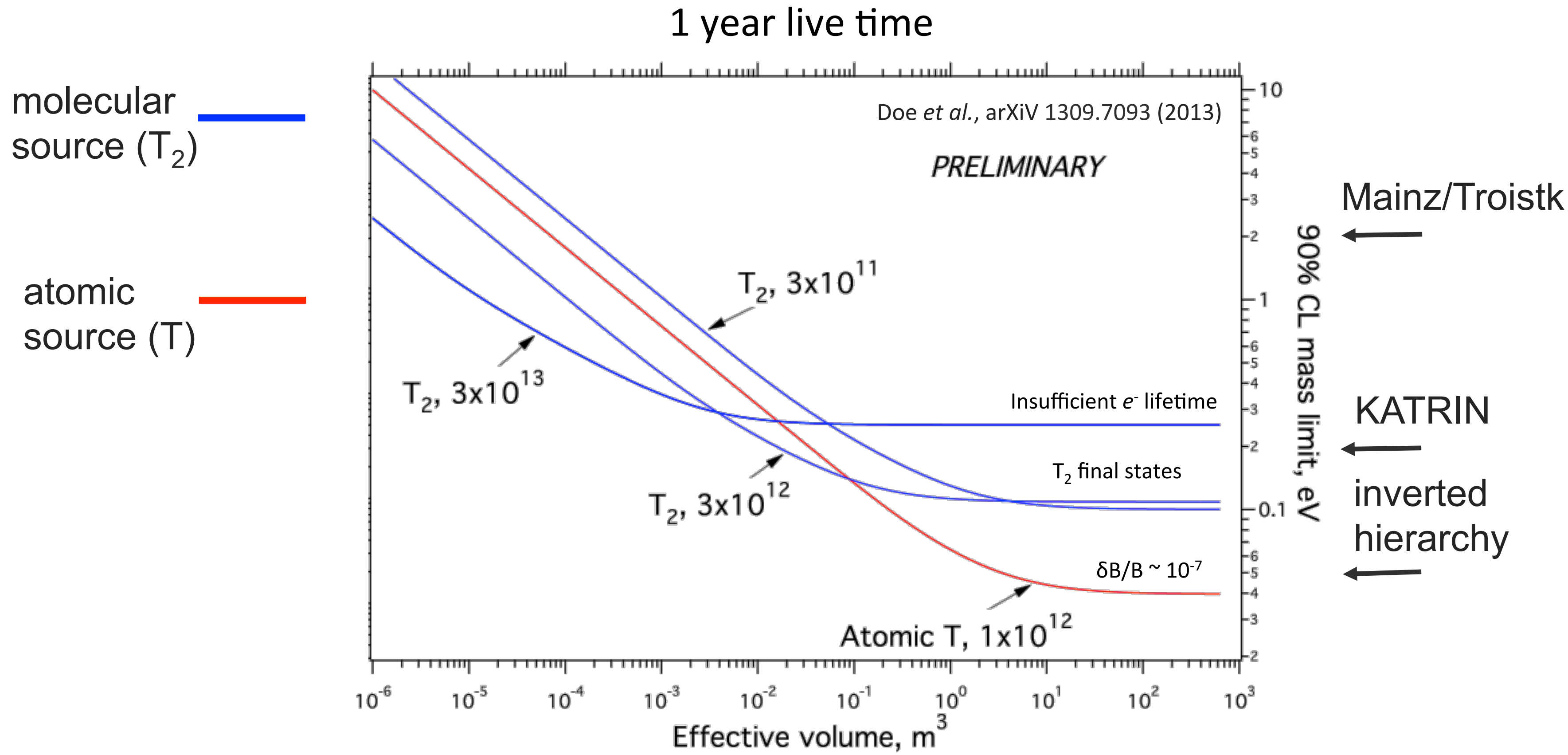
Monreal and Formaggio, *Phys. Rev. D* **80** (2009).

- Project 8 will use CRES:
  - Detect ~fW μwave cyclotron radiation from magnetically trapped electrons.
  - Tritium source is transparent to μwaves → improved scaling ~volume.
  - Nondestructive frequency domain technique – extreme precision w/ absolute standards.

- Kinetic energy and frequency are related by relativistic kinematics:

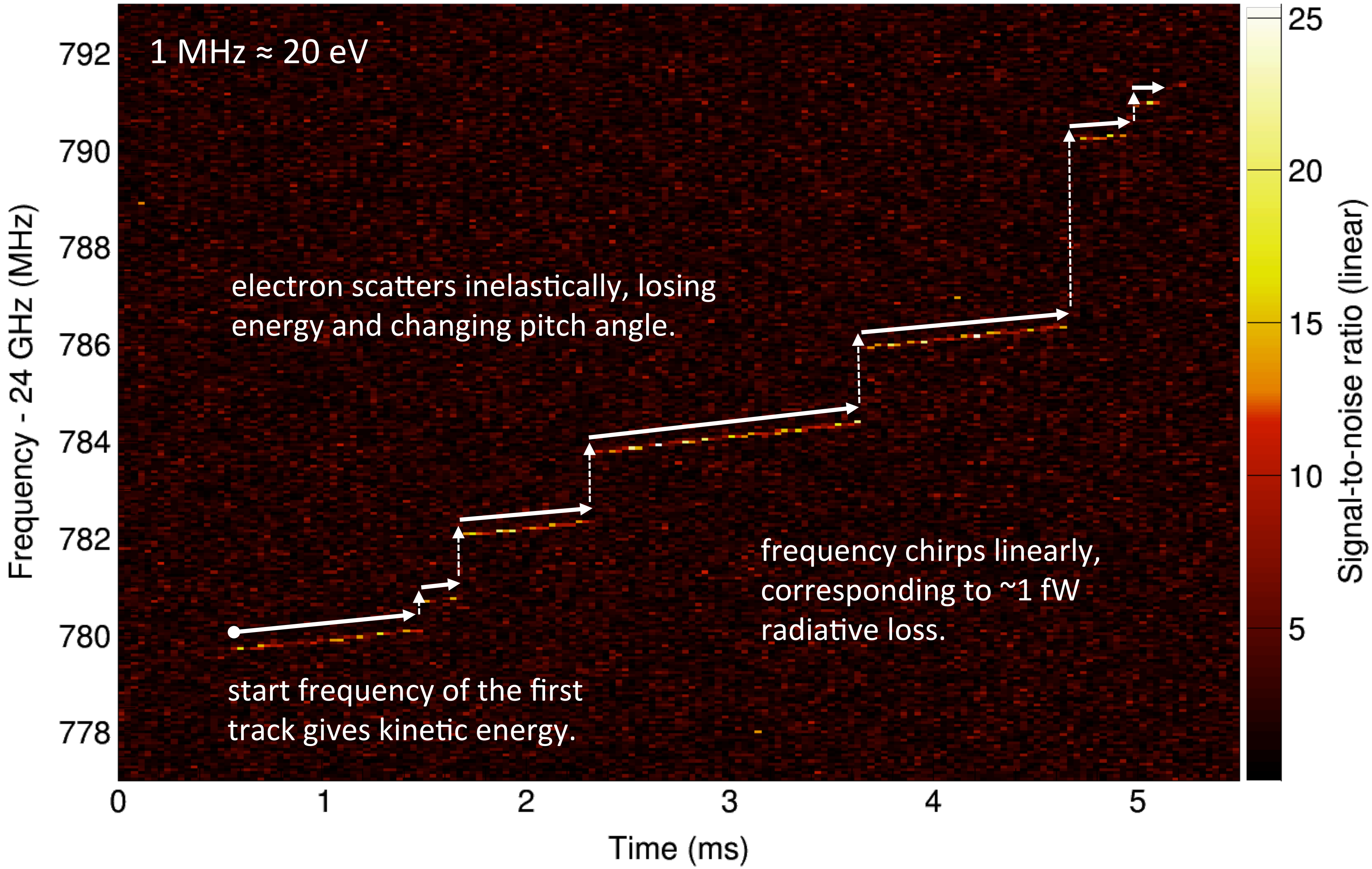
$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E/c^2} \qquad P = \frac{2\pi e^2 f_0^2}{3\varepsilon_0 c}\frac{\beta^2 \sin^2\theta}{1-\beta^2}$$

Project 8 Estimated Sensitivity

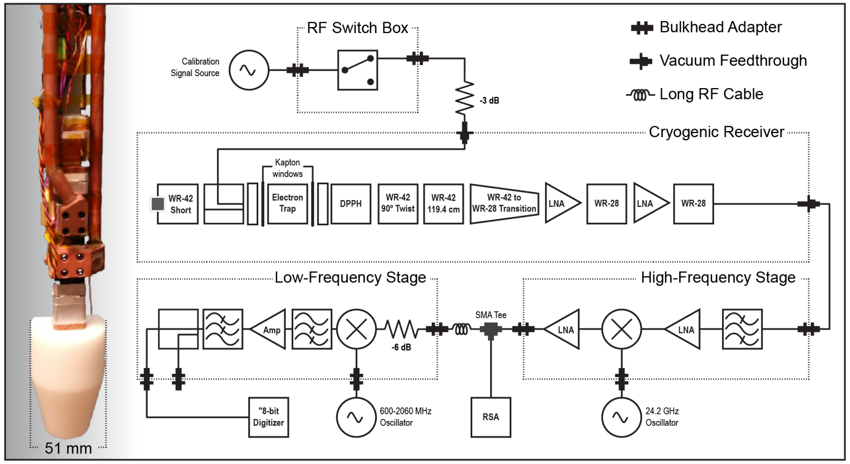


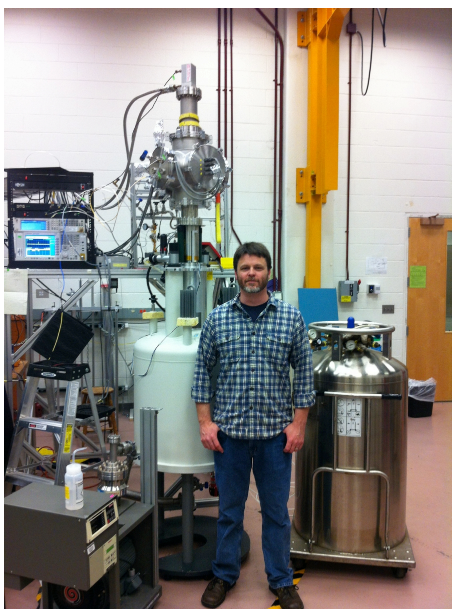
- Sensitivity estimates include: statistics, frequency broadening from finite e^- lifetimes, conservative background estimates, molecular final state systematic and *B*-field variations.
- "Effective volume" is the real instrumented source volume and e^- trap/detection efficiency.
- Most sensitive estimate is $m_{\nu e}$ < 40 meV for an atomic source with 0.1ppm field uniformity.

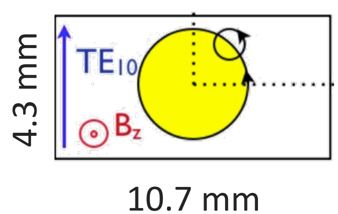
Typical CRES event

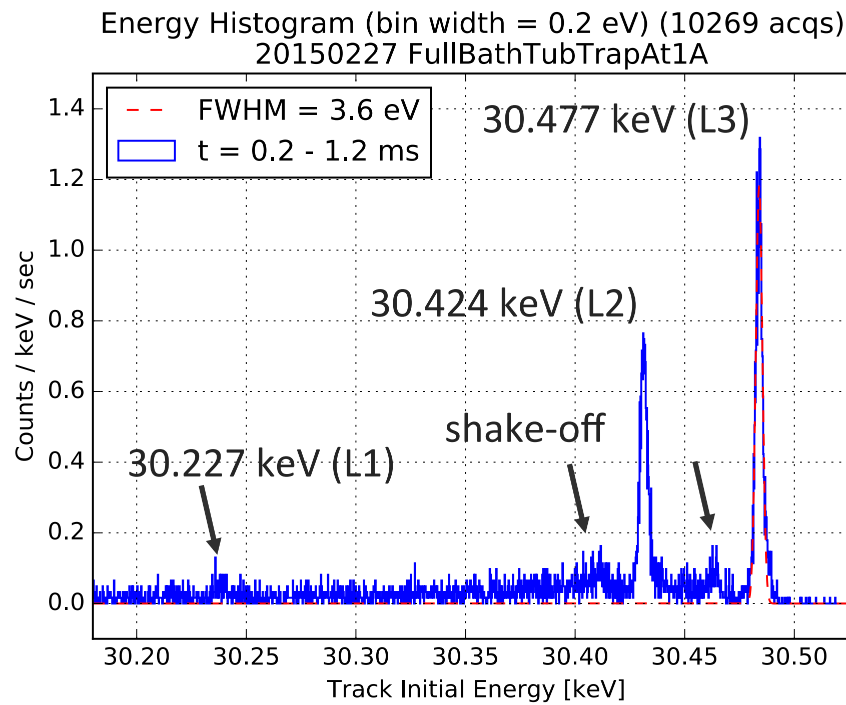


CRES ^{83m}Kr Prototype Demonstration (Phase I)









- Published* 15 eV FWHM resolution w/ harmonic ($B \sim z^2$) trap.
- Recently obtained 3.6 eV FWHM w/ more uniform "bathtub."
- 2.1 eV FWHM from same data w/ high-power cut.
- Resolution is understood to follow from *B*-field variations.

*Asner *et al.*, *Phys. Rev. Lett.* **114** (2015).

First CRES Measurement of Tritium Endpoint (Phase II)

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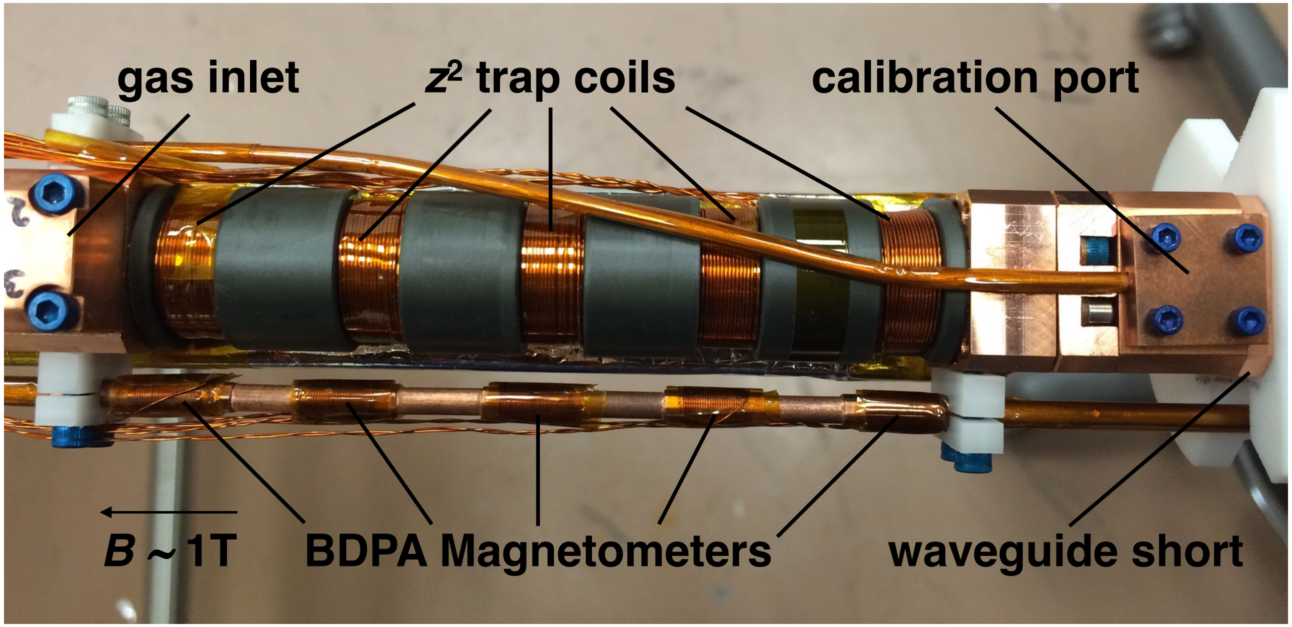
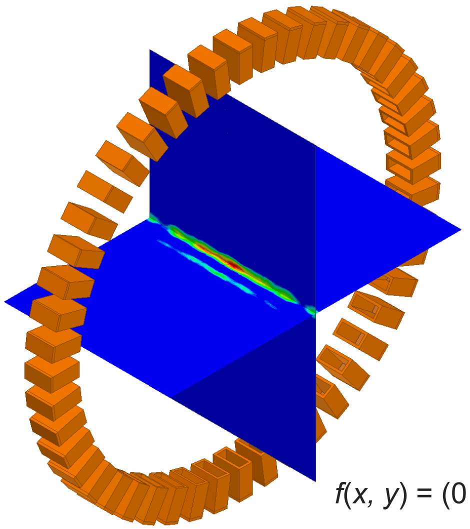
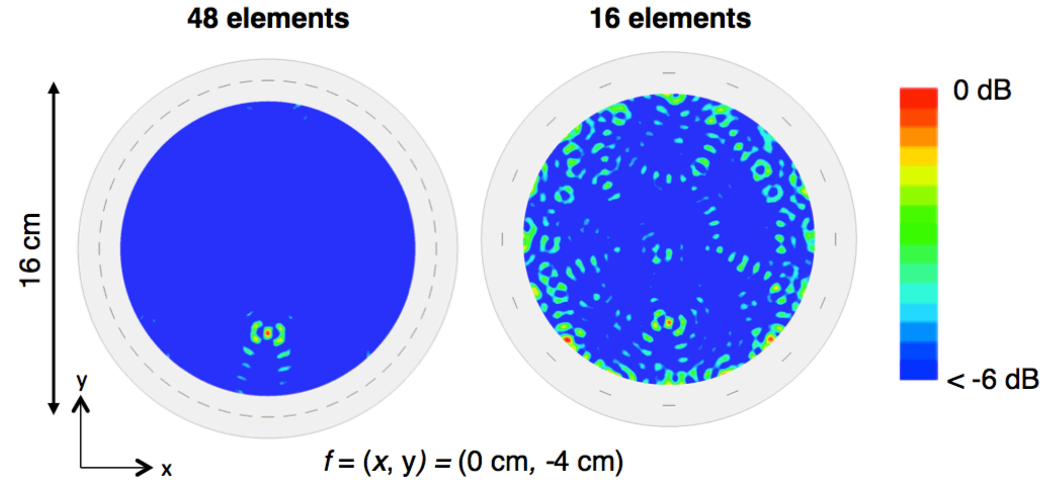


- Five harmonic ($B \sim z^2$) traps w/ ESR magnetometers → longer bathtub.
- Circular waveguide → reclaim 3 dB signal from circularly polarized signal.
- Colder amplifiers w/ improved termination → lower noise/higher gain.
- First ^{83m}Kr conversion electrons last Thursday!
- Expect tritium data this calendar year → $m_{\nu e}$ < 10—100 eV.

First Competitive Mass Limit – $m_{\nu e}$ < 2 eV (Phase III)

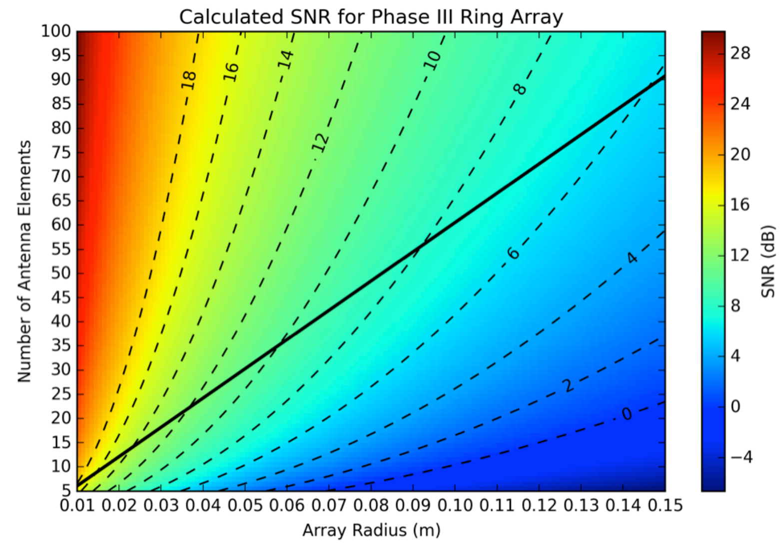


f(*x*, *y*) = (0 cm, 0 cm)



f = (*x*, *y*) = (0 cm, -4 cm)

- Phase III moves waveguide → free space to accommodate more tritium volume.
- Working concept is for two 10-cm diameter 30-element ring arrays with digital beam forming:
  - CRES SNR > 10 dB.
  - fiducial volume ≈ 200 cm^3.
  - New-to-us large-bore MRI magnet already obtained.
- $m_{\nu e}$ < 2 eV will take one year starting ca. 2019 or 2020.



Inverted Hierarchy Sensitivity (Phase IV)

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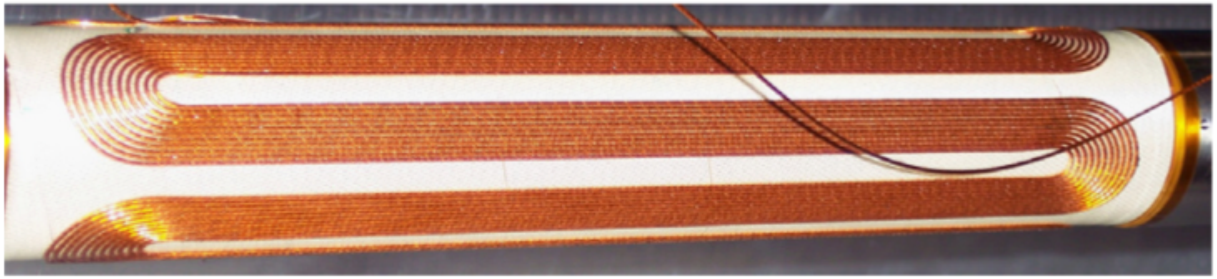
- Phase IV adds more instrumented tritium volume and switches to *atomic* tritium:
  - Tritium atoms trapped via magnetic moment in a Ioffe trap to prevent recombination at the walls.
  - Decay and scattering heat removed by thermal exchange with ^{4}He in contact with the physical vessel.
  - Antenna array engineered to coexist with Ioffe trap on the inner walls of the physical vessel.

Atomic tritium source design constraints

Parameter	Value	Comments
T density	$10^{12}\,\mathrm{cm}^{-3}$	statistical sensitivity of Figure 4
T temperature	130–170 mK	prevents evaporation for Ioffe trap
T_2/T concentration	$\lesssim 10^{-6}$	limits background from T_2 spectrum
$\delta B/B$	$\sim 10^{-7}$	uniform field for CRES energy resolution
Ioffe trap depth	5 T	confines atomic tritium
Ioffe trap symmetry	20-fold (50-fold)	48% (75%) usable fiducial volume
smallest dimension	50–100 cm	1–2 mean free paths for thermalization



ALPHA atomic anti-hydrogen Ioffe trap
[Amole *et al.*, NIM A **735** (2014)]

Conclusions and Outlook for Project 8

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Phases and Goals of Project 8

Phase	Timeline	Source	R&D Milestones	Science Goals
I	2010–2016	^{83m}Kr	single electron detection proof of concept	conversion electron spectrum of ^{83m}Kr
II	2015–2017	T_2	Kurie plot systematic studies	Final-state spectrum test, ^{3}H–^{3}He mass difference, $m_\nu \lesssim 10$–$100\,\mathrm{eV}/c^2$
III	2016–2020	T_2	high-rate sensitivity B field mapping	$m_\nu \lesssim 2\,\mathrm{eV}/c^2$
IV	2017...	T	atomic tritium source	$m_\nu \lesssim 40\,\mathrm{meV}/c^2$ measure m_ν *or* determine normal hierarchy

- Project 8 plan is organized into four phases, executed in parallel:
  - Phase I – First results are published with new and improved results to be published soon.
  - Phase II – first data with ^{83m}Kr last week, first tritium data this Fall.
  - Phase III – Quantitative conceptual design for a receiver array that could compete with current m_{ve} < 2 eV sensitivity in a year.
  - Phase IV – Design constraints required by inverted hierarchy sensitivity are derived. Quantitative conceptual design of atomic tritium source beginning now.

Conclusions and Outlook for Direct Mass Measurements

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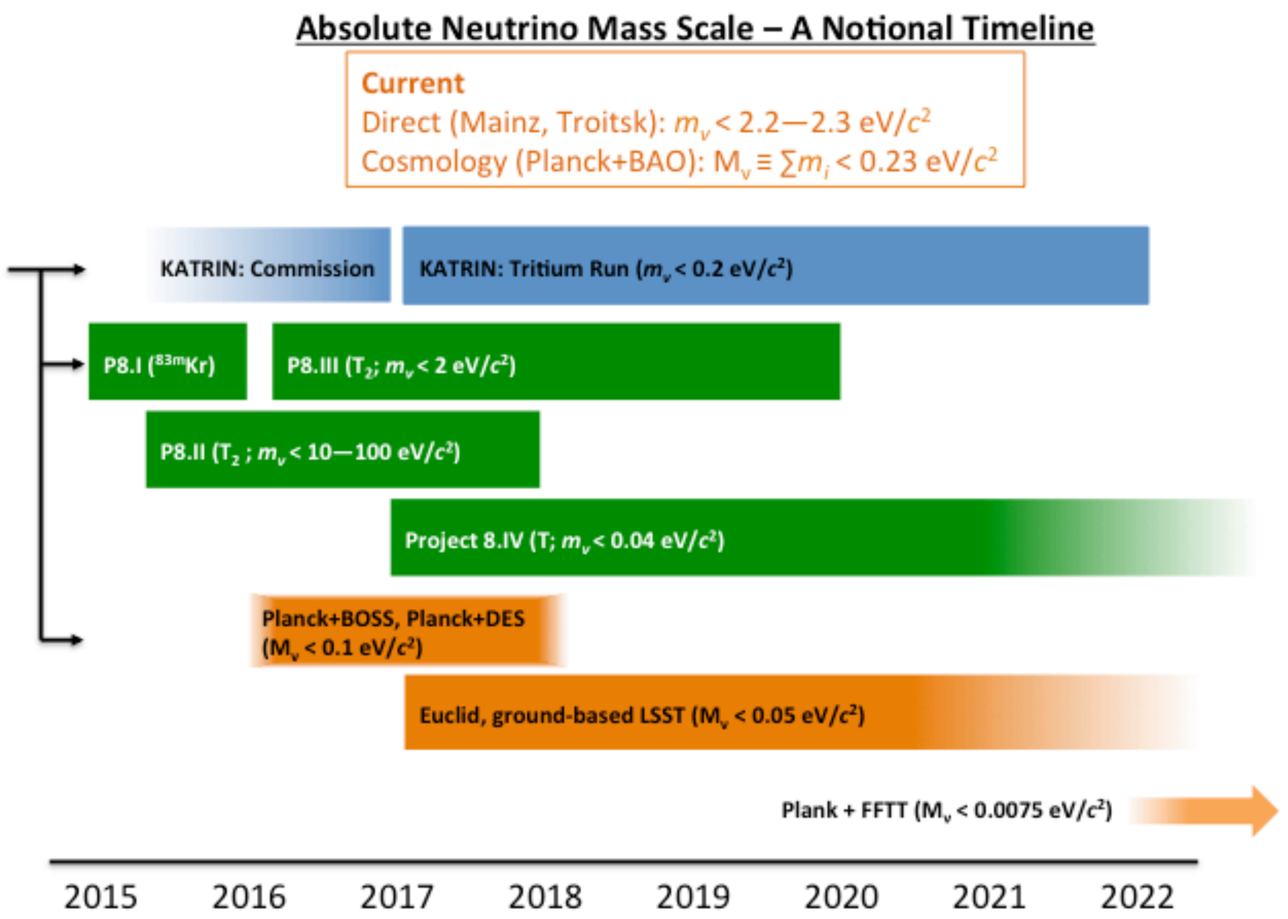

Project 8 Collaboration

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