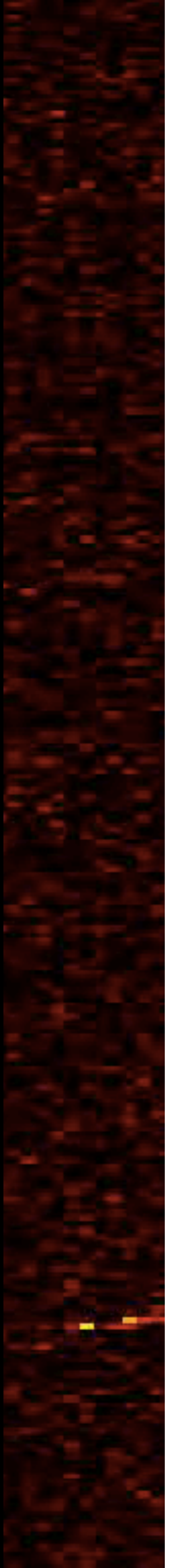
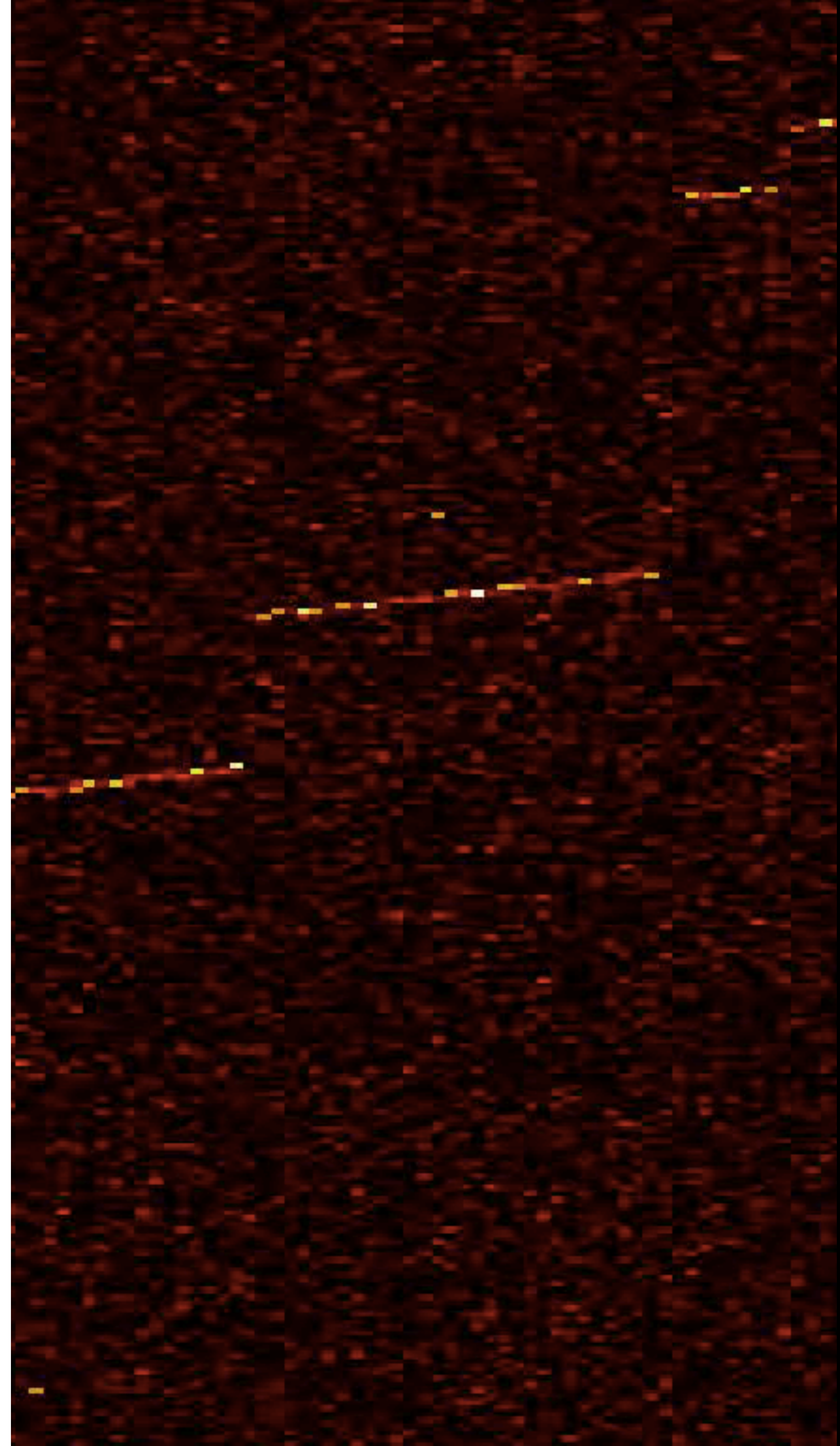


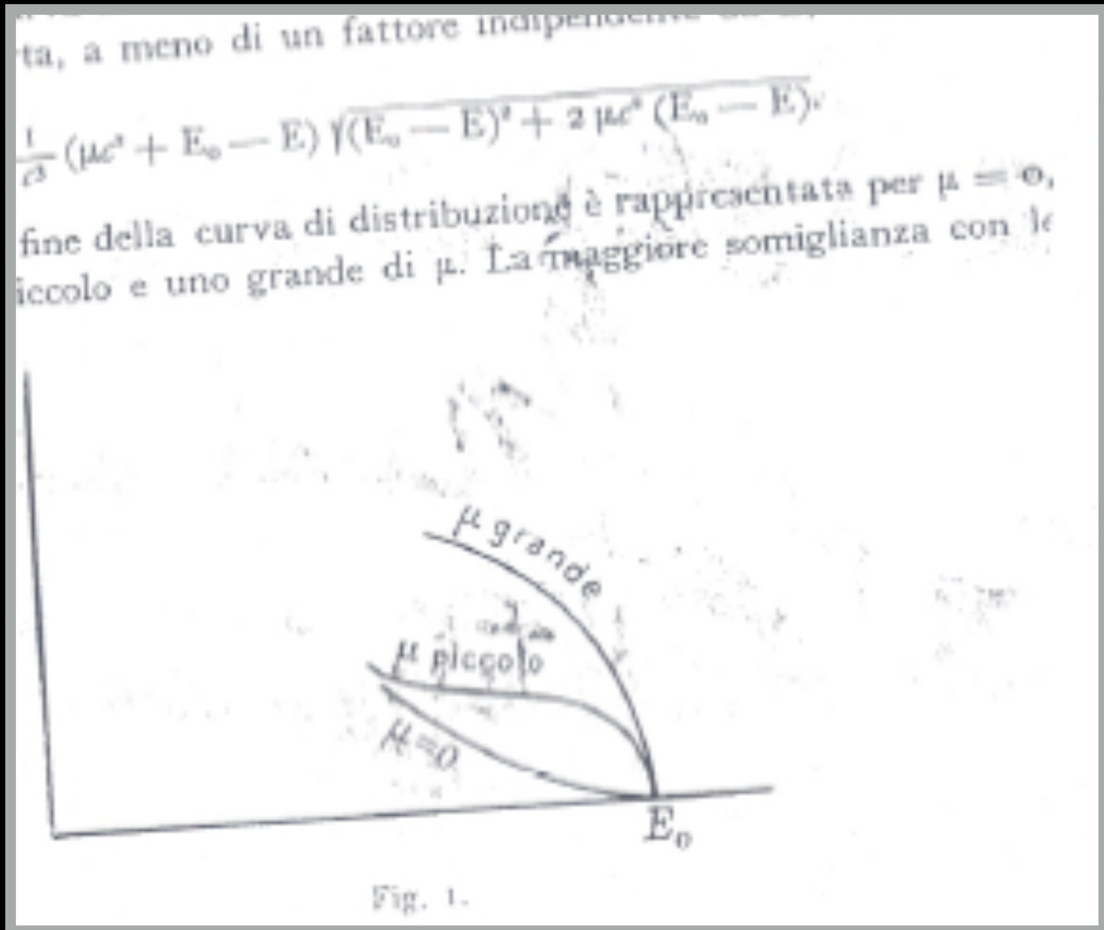
The Project 8 Neutrino Experiment

ν INFN-Roma *Workshop 2020

July 8th 2020

Joseph A. Formaggio
MIT





ta, a meno di un fattore

$$\frac{1}{c^5}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

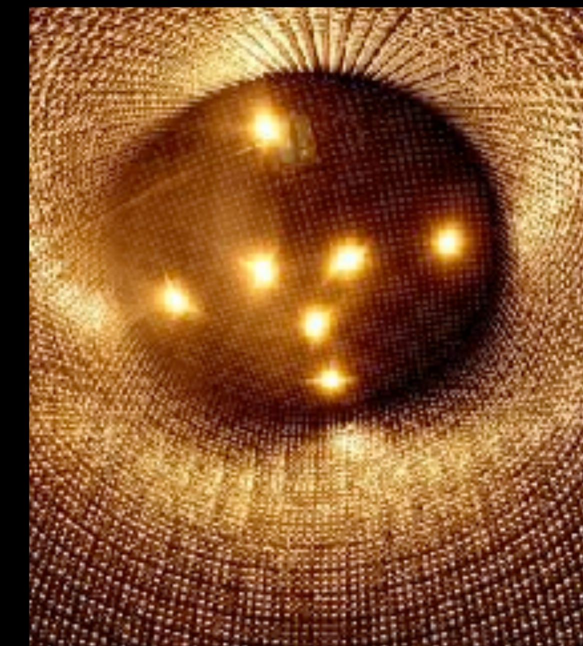
fine della curva di distribuzione è rappresentata per $\mu = 0$,
iccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

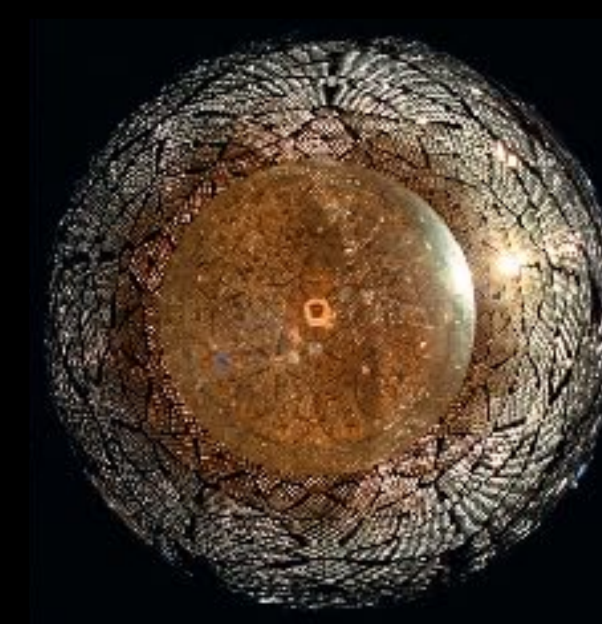
We have made a very important advance over the past century. Neutrinos have mass.

That means that the mechanism by which neutrinos gain mass is different from the other fermions.

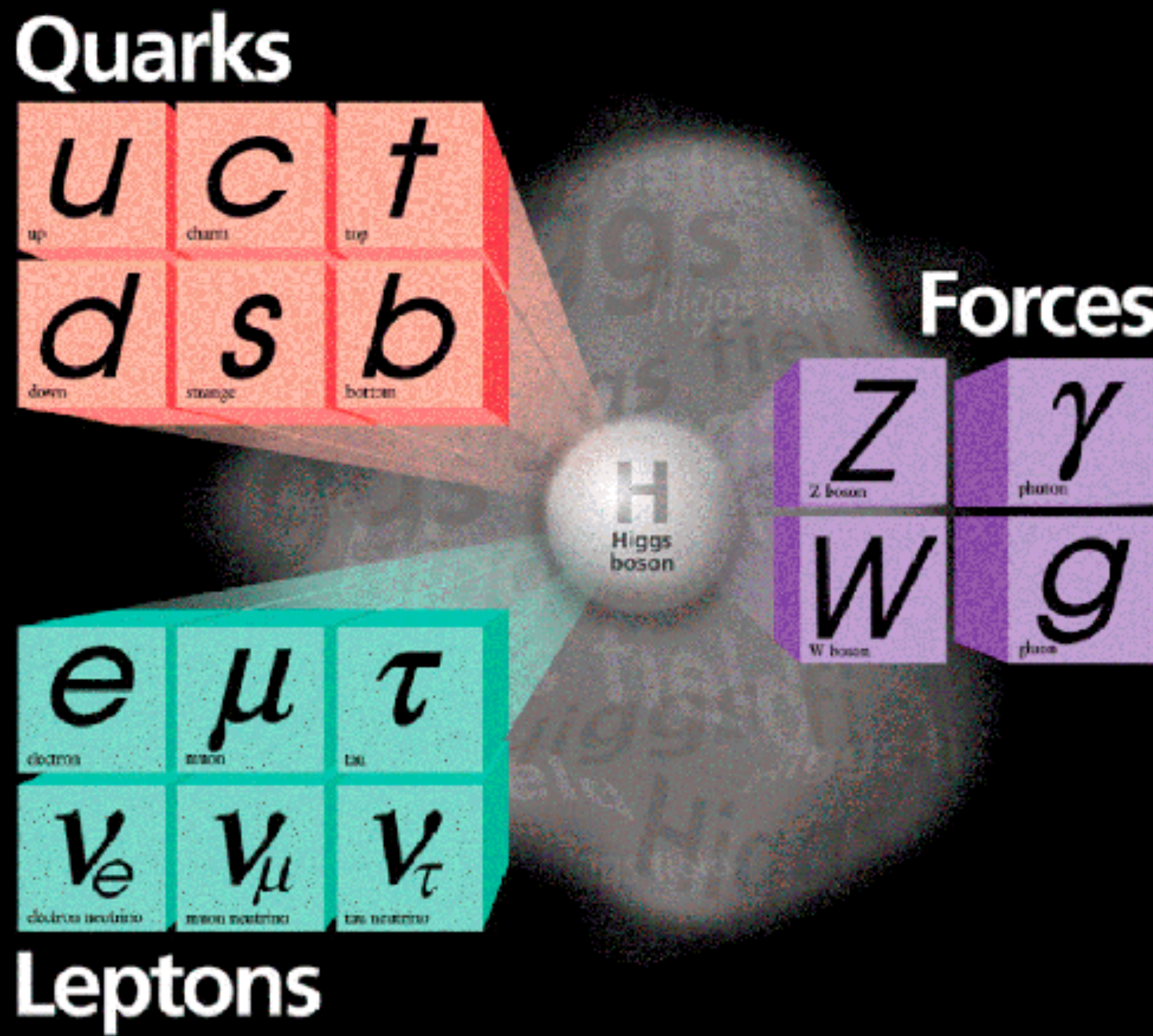
This discovery leads to specific predictions...



Takaaki Kajita
(Super-Kamiokande)



Arthur B. McDonald
(Sudbury Neutrino Observatory)



Quarks
u
c
t
up
charm
top
d
s
b
down
strange
bottom
Higgs boson
H
Forces
Z
γ
Z boson
photon
W
g
W boson
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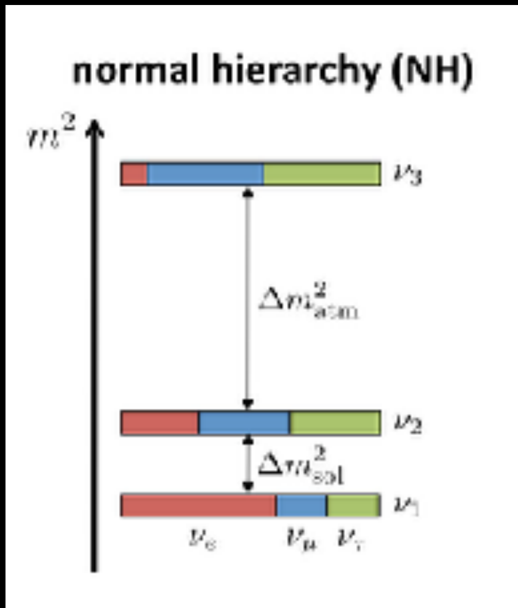
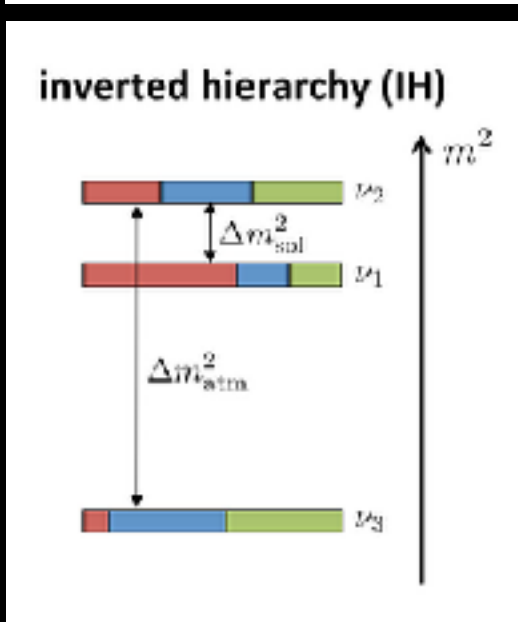
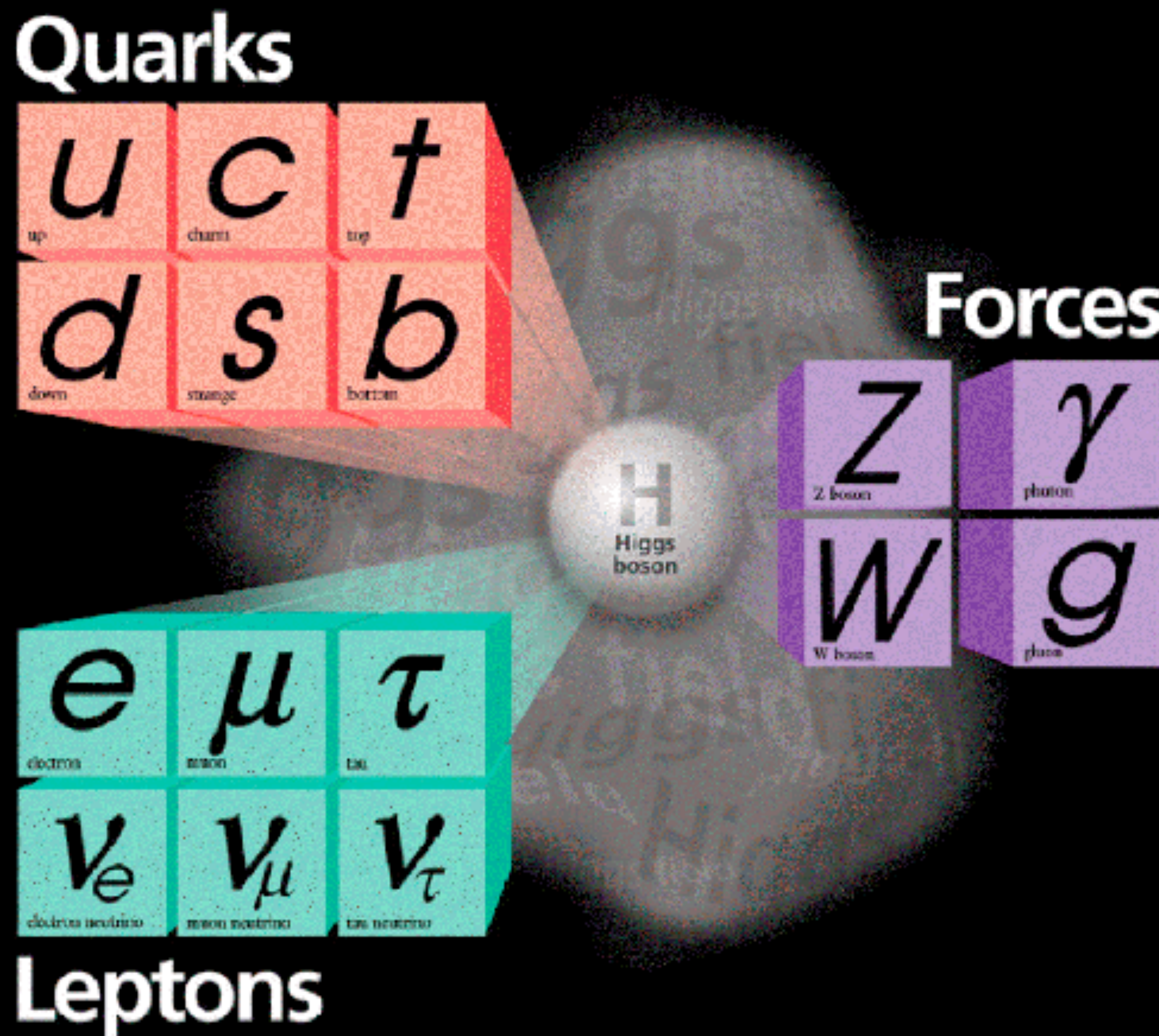
electron
muon
tau
νe
νμ
ντ
electron neutrino
muon neutrino
tau neutrino
Leptons



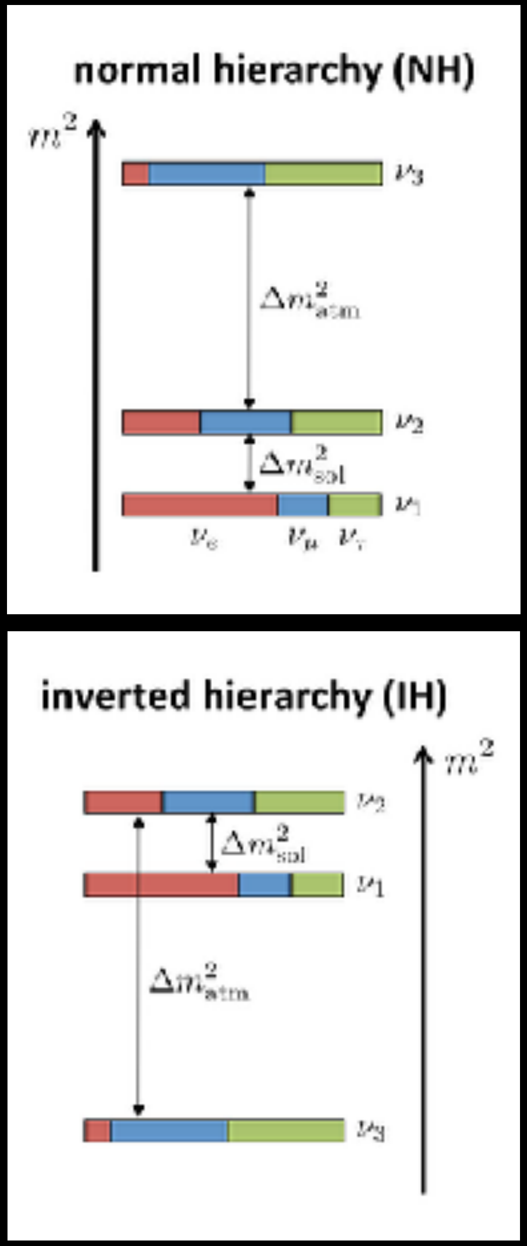


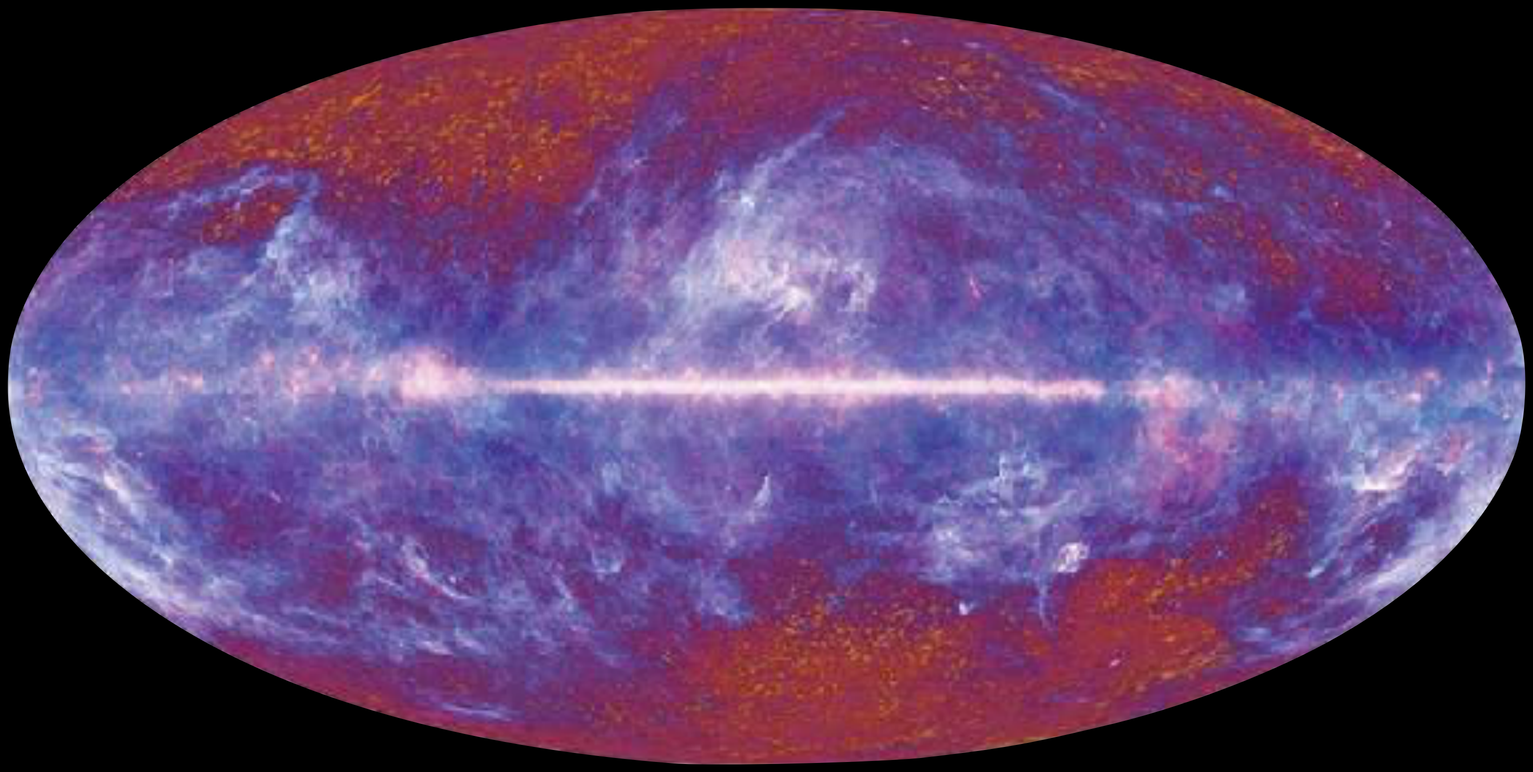


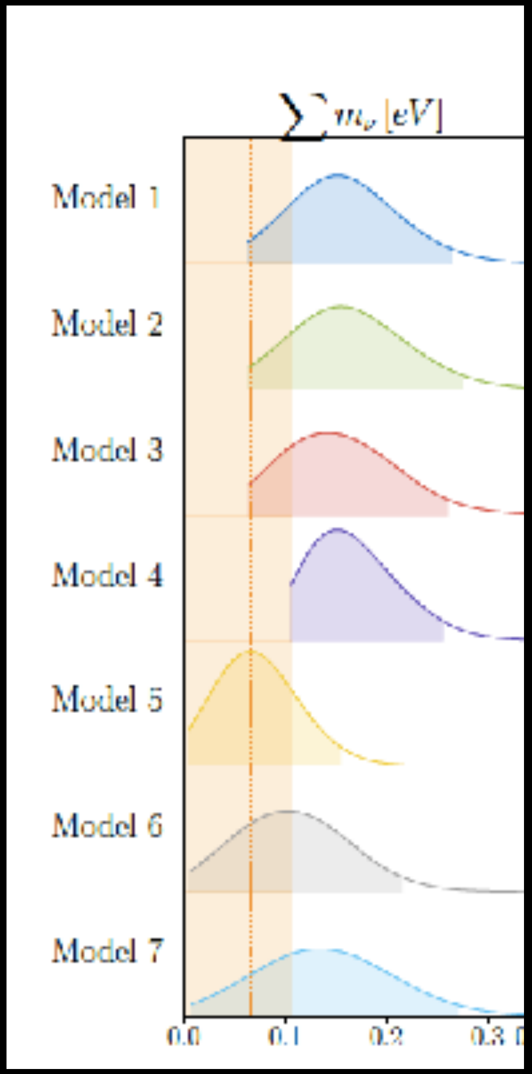
The Origin of Mass

The mechanism by which particles gain mass in the Standard Model may not apply for neutrinos.

The neutrino mass mechanism remains unknown.







The Origin of Mass

The mechanism by which particles gain mass in the Standard Model may not apply for neutrinos.

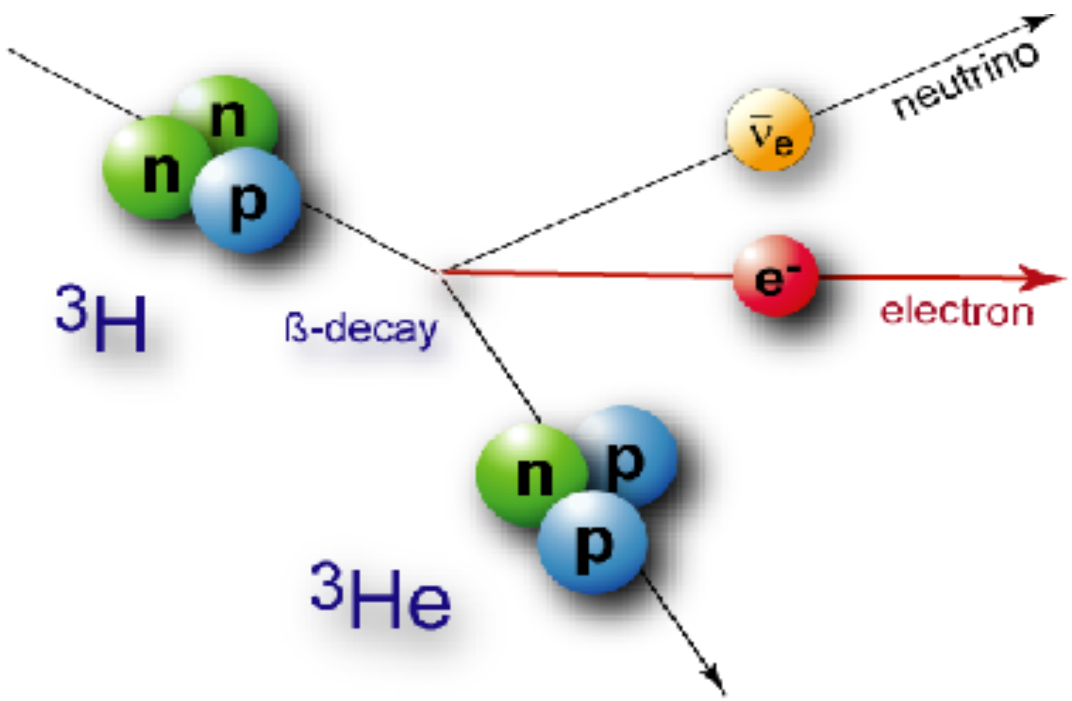
The neutrino mass mechanism remains unknown.

Impact on Cosmology

Given the primordial abundance of neutrinos, even a small finite mass has a measurable impact on cosmic evolution.

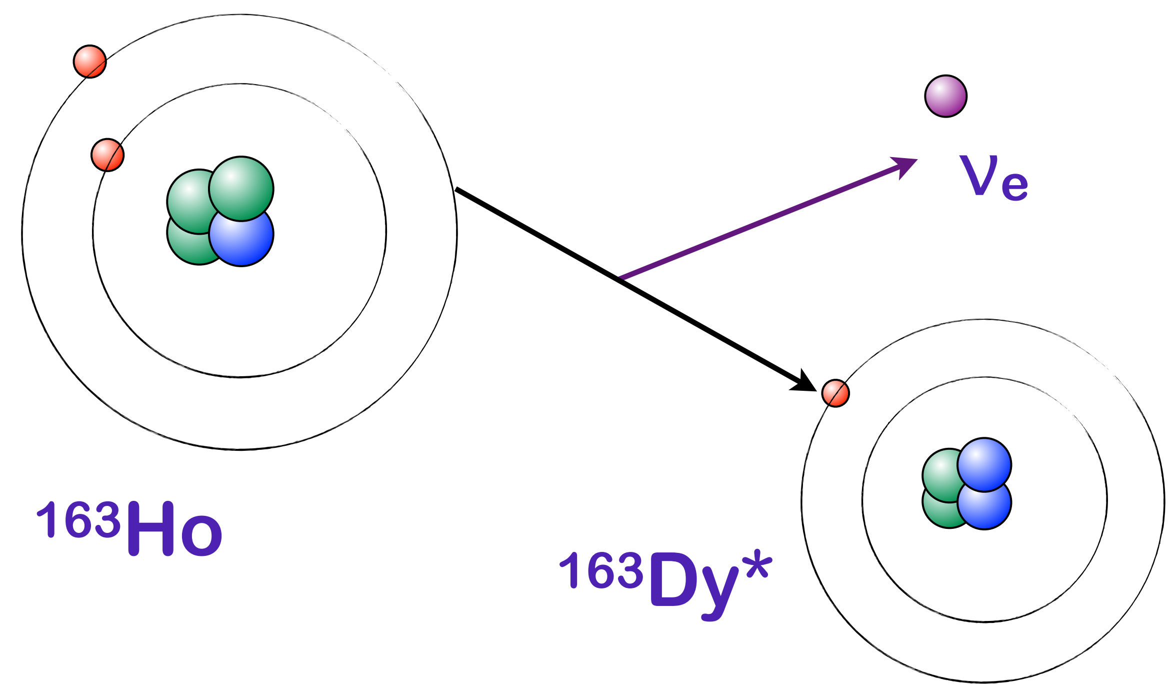
Measurable in next generation of experiments.

Tritium beta decay



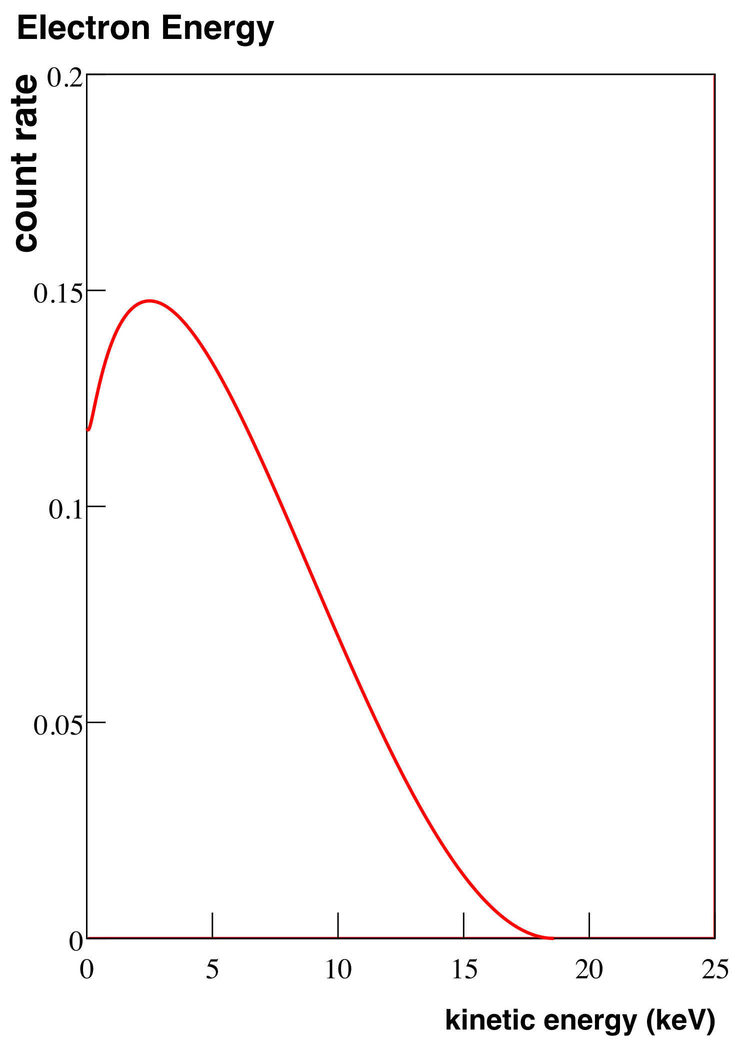
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Holmium electron capture



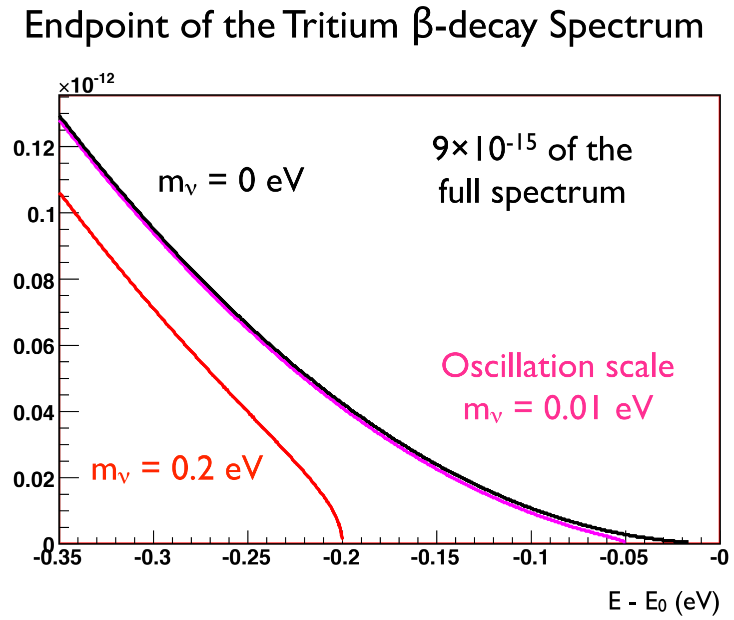
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

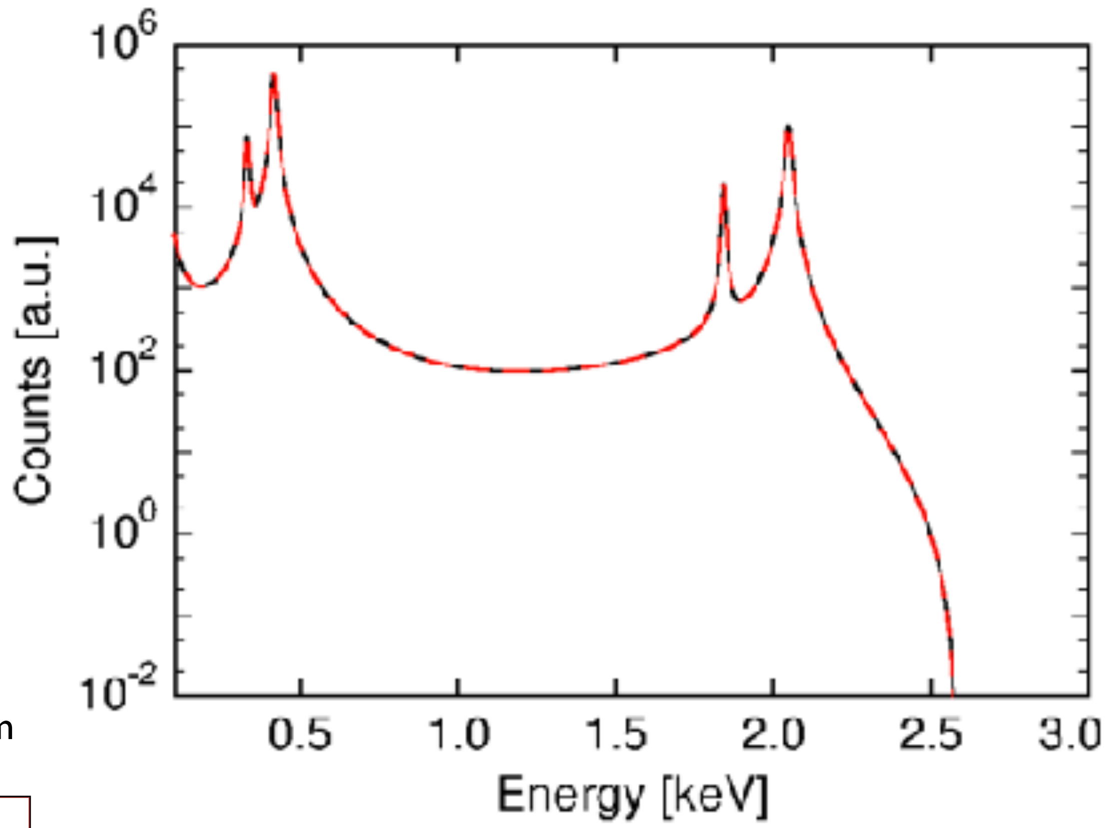
Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.



$$\dot{N} \propto p_\nu E_\nu$$

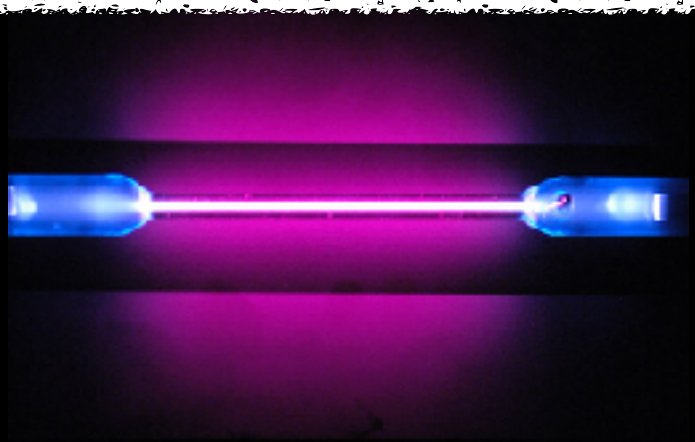
In both cases, differential spectrum depends on the neutrino momentum.





$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu i}^2$$

Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.



^{3}H

18.5 keV

$\tau_{1/2}$ 12.3 yrs

^{163}Ho

2.83 keV

$\tau_{1/2}$ 4570 yrs

^{187}Re

2.5 keV

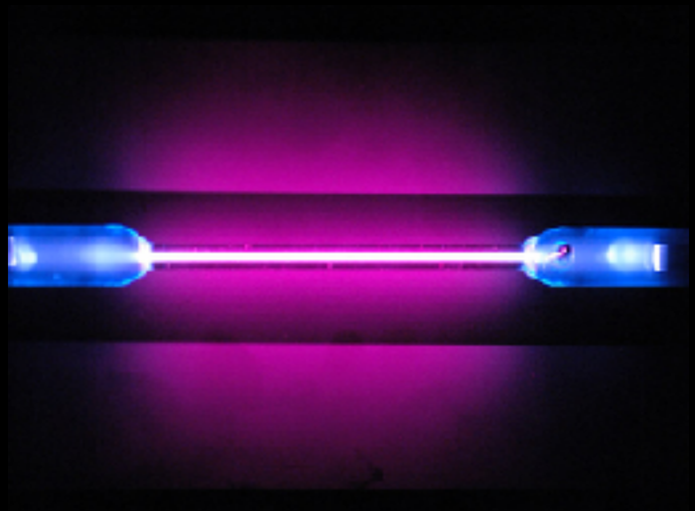
$\tau_{1/2}$ 4.5 Gyrs

^{115}In

155 eV

$\tau_{1/2}$ 4.1×10^{20} yrs

First,
pick a source...



^{3}H

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^{187}Re

2.5 keV

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^{115}In

155 eV

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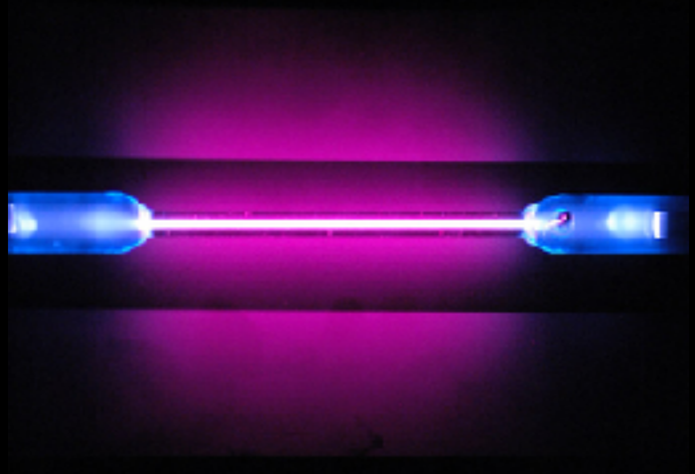


^{3}H

18.5 keV

$\tau_{1/2}$ 12.3 yrs

Electromagnetic/ Frequency

KATRIN - Project 8

^{163}Ho

2.83 keV

$\tau_{1/2}$ 4570 yrs

Calorimetric

ECHO - HOLMES

^{187}Re

2.5 keV

$\tau_{1/2}$ 4.5 Gyrs

MARE (ended)

^{115}In

155 eV

$\tau_{1/2}$ 4.1×10^{20} yrs

No experiment yet

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Use photon spontaneous emission from electron in magnetic field.

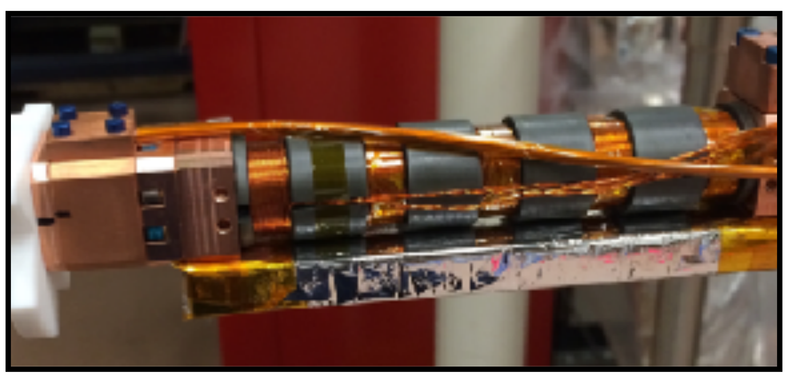
Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based

(Cyclotron Radiation Emission Spectroscopy)

Cyclotron Radiation Emission Spectroscopy (CRES)

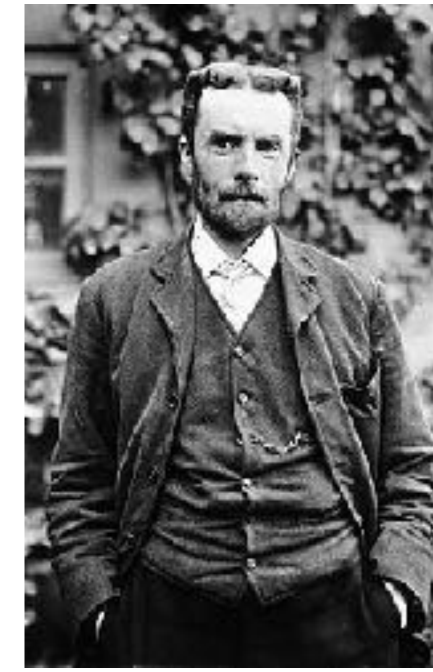


PROJECT 8

Frequency Approach

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

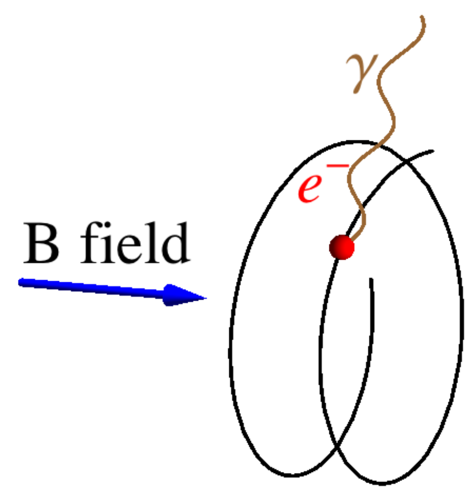
"Never measure anything but frequency."



A. L. Schawlow

O. Heaviside

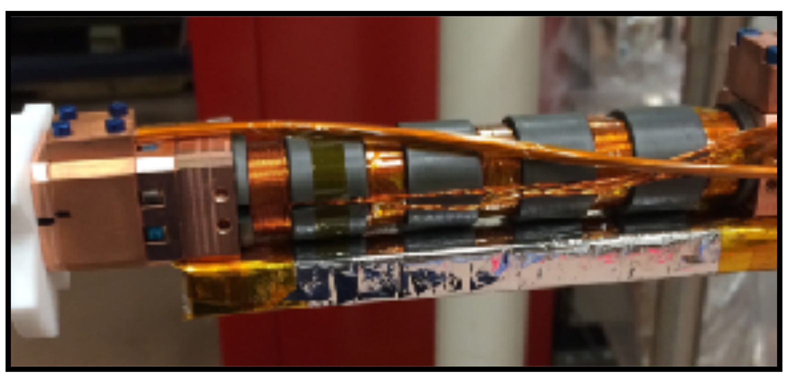
Use frequency measurement of cyclotron radiation from single electrons:



- *Source transparent to microwave radiation*
- *No e- transport from source to detector*
- *Leverages precision inherent in frequency techniques*

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

Cyclotron Radiation Emission Spectroscopy (CRES)



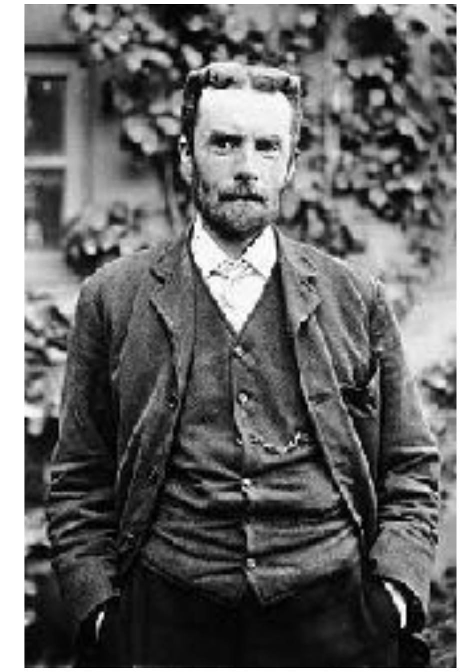
PROJECT 8

Frequency Approach

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

A. L. Schawlow

"Never measure anything but frequency."



O. Heaviside

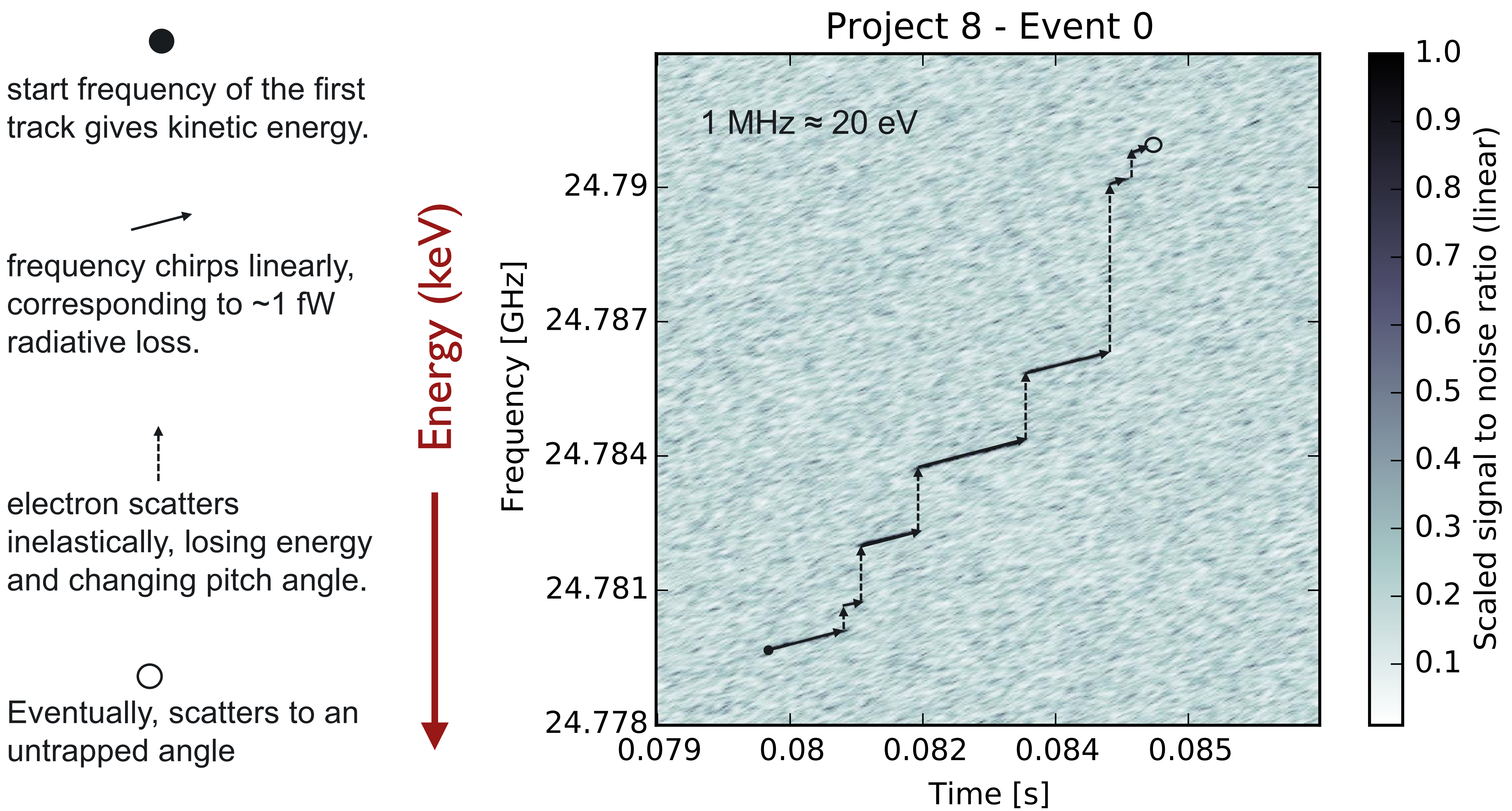
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$

$$f_{c,0} = 27.992\ 491\ 10(6)\ \mathrm{GHz\ T^{-1}}$$

- *Narrow band region of interest (@26 GHz).*
- *Small, but detectable power emitted.*

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

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



A *"typical"* event

(actually, this was our first event)

A Phased Approach

Phase I:

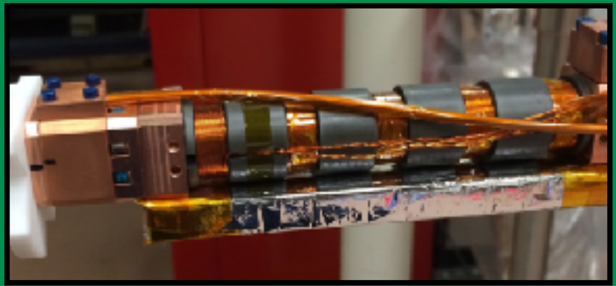
Demonstrate CRES technique on ^{83m}Kr mono-energetic electrons.

Status: Complete! Technique demonstrated.

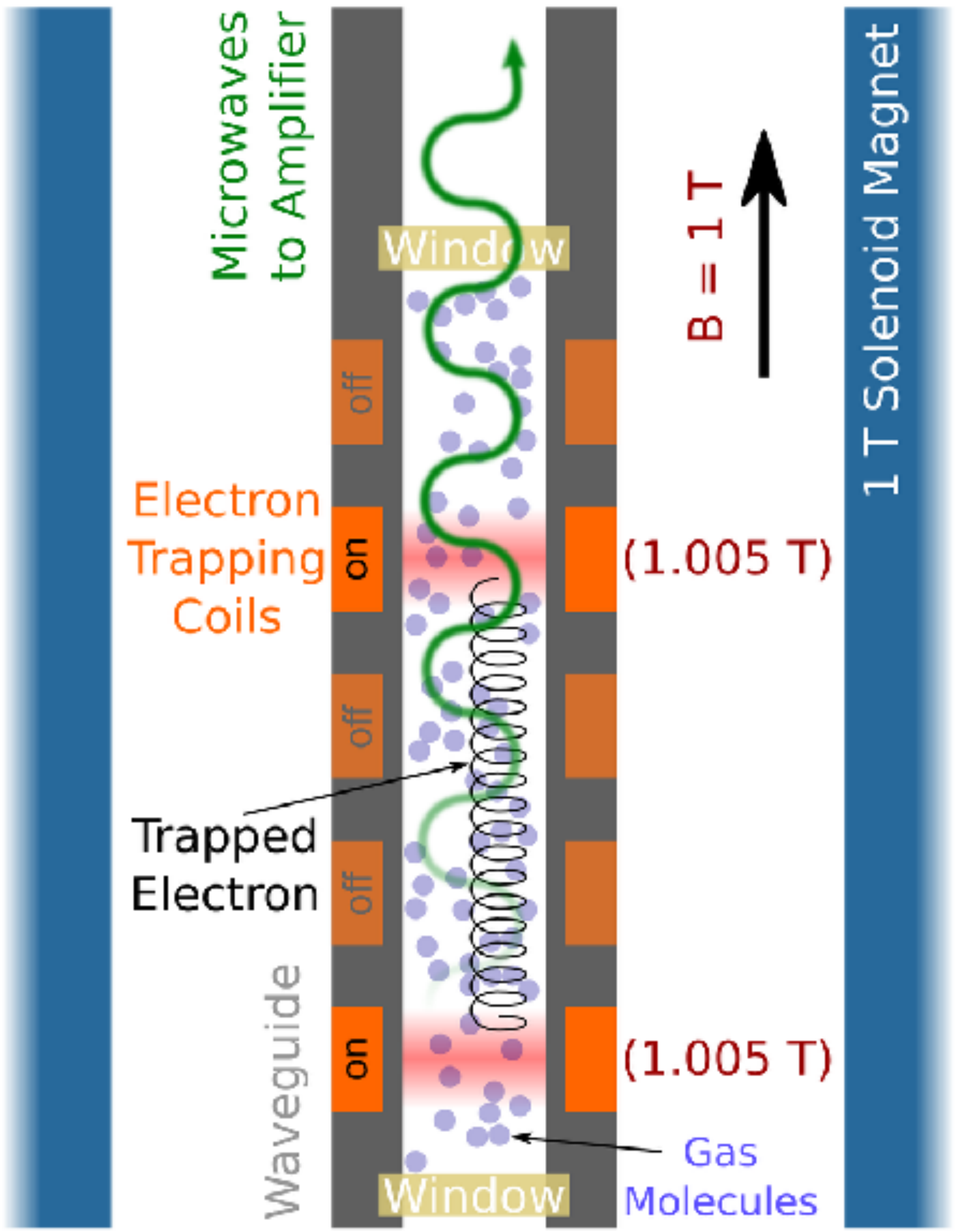
Phase II:

First T_2 spectrum. Extract endpoint. Study systematics and backgrounds.

Status: Ongoing until beginning of 2020.

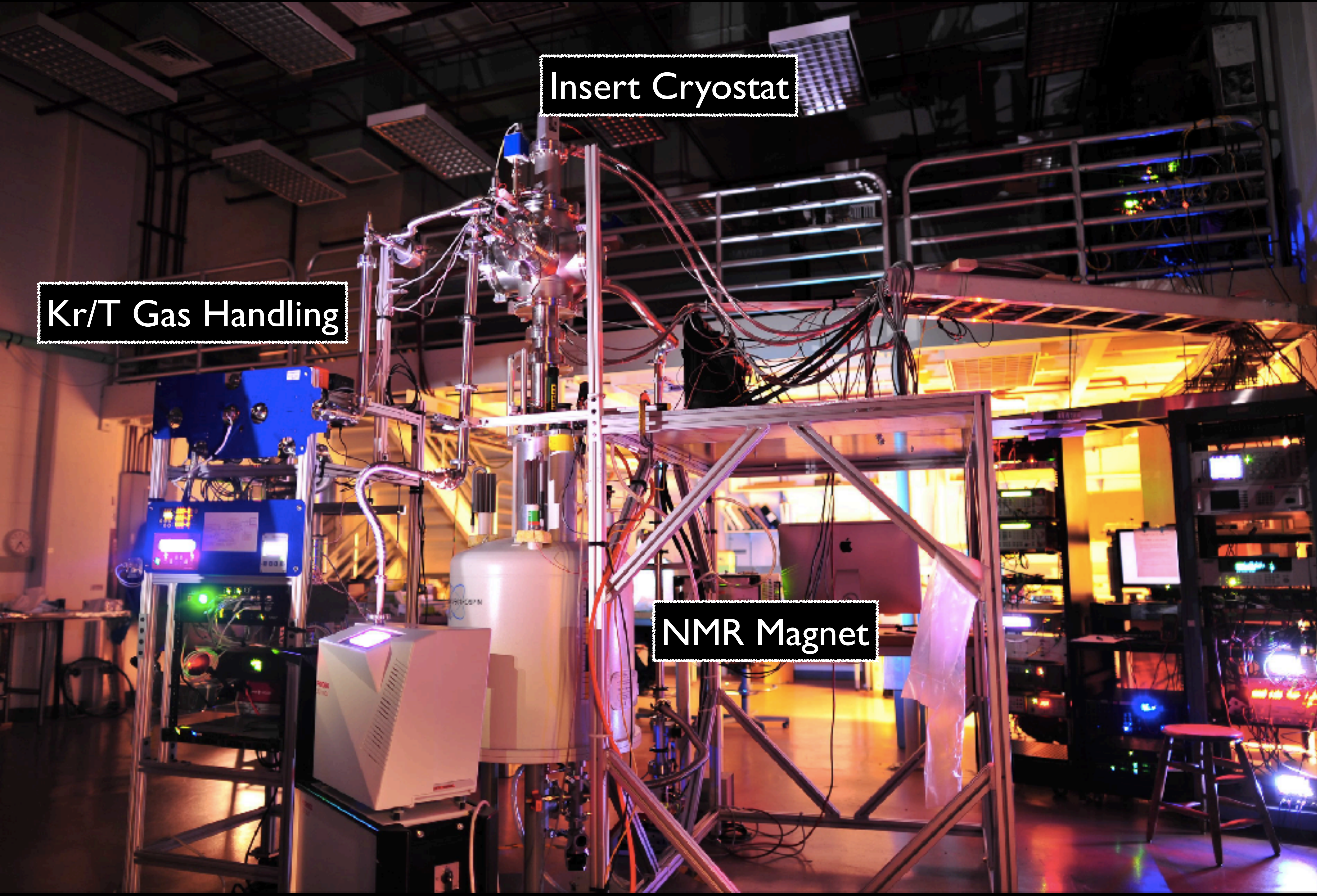


- Trapping coils arranged to provide deep and shallow traps.
- Commissioned using krypton gas, but optimized for tritium gas flow.

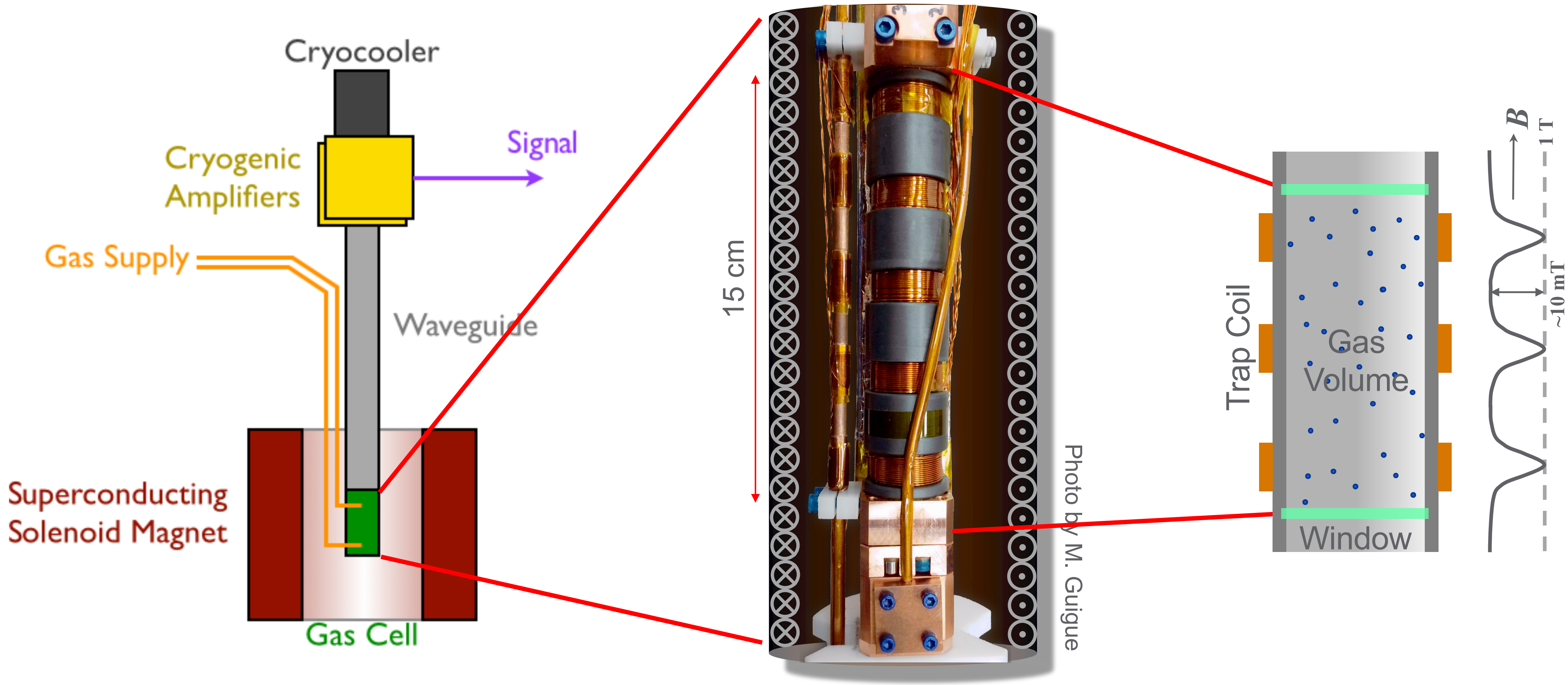


The Phase II Tritium Insert

Goal: Provide a first demonstration of CRES technique using tritium.

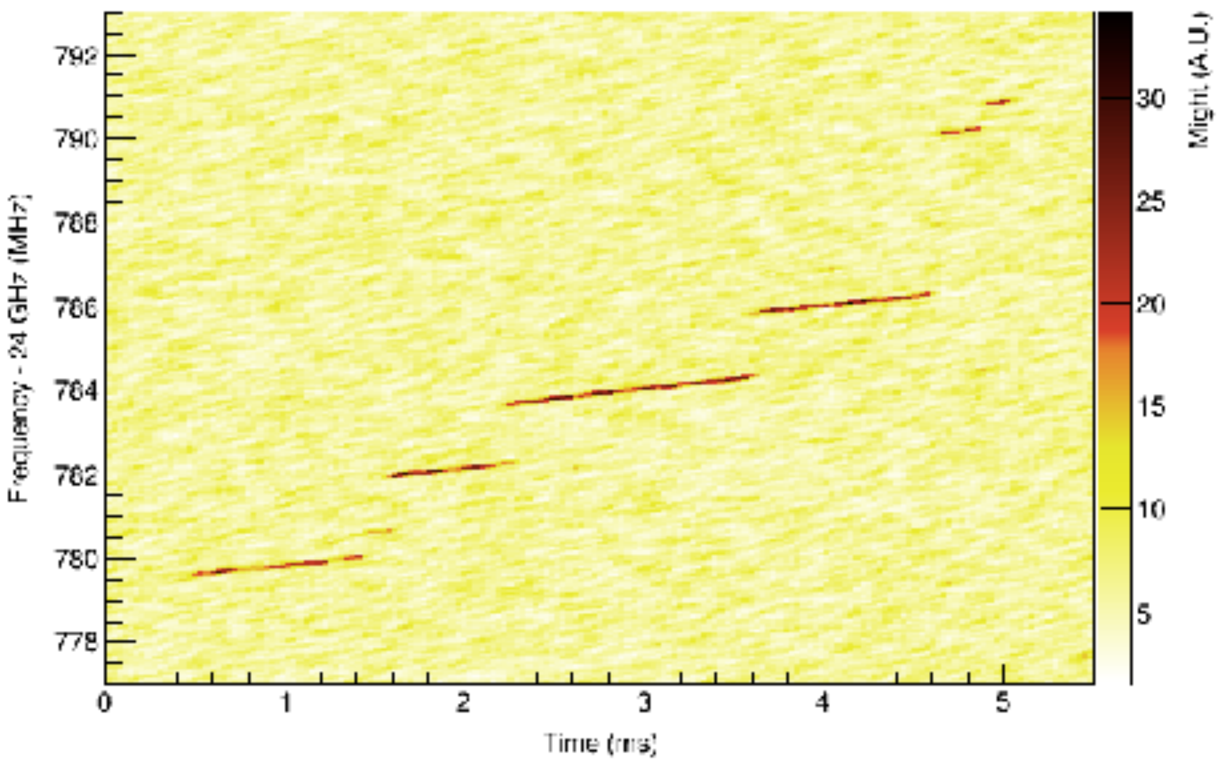

Insert Cryostat
Kr/T Gas Handling
NMR Magnet

Basic Layout

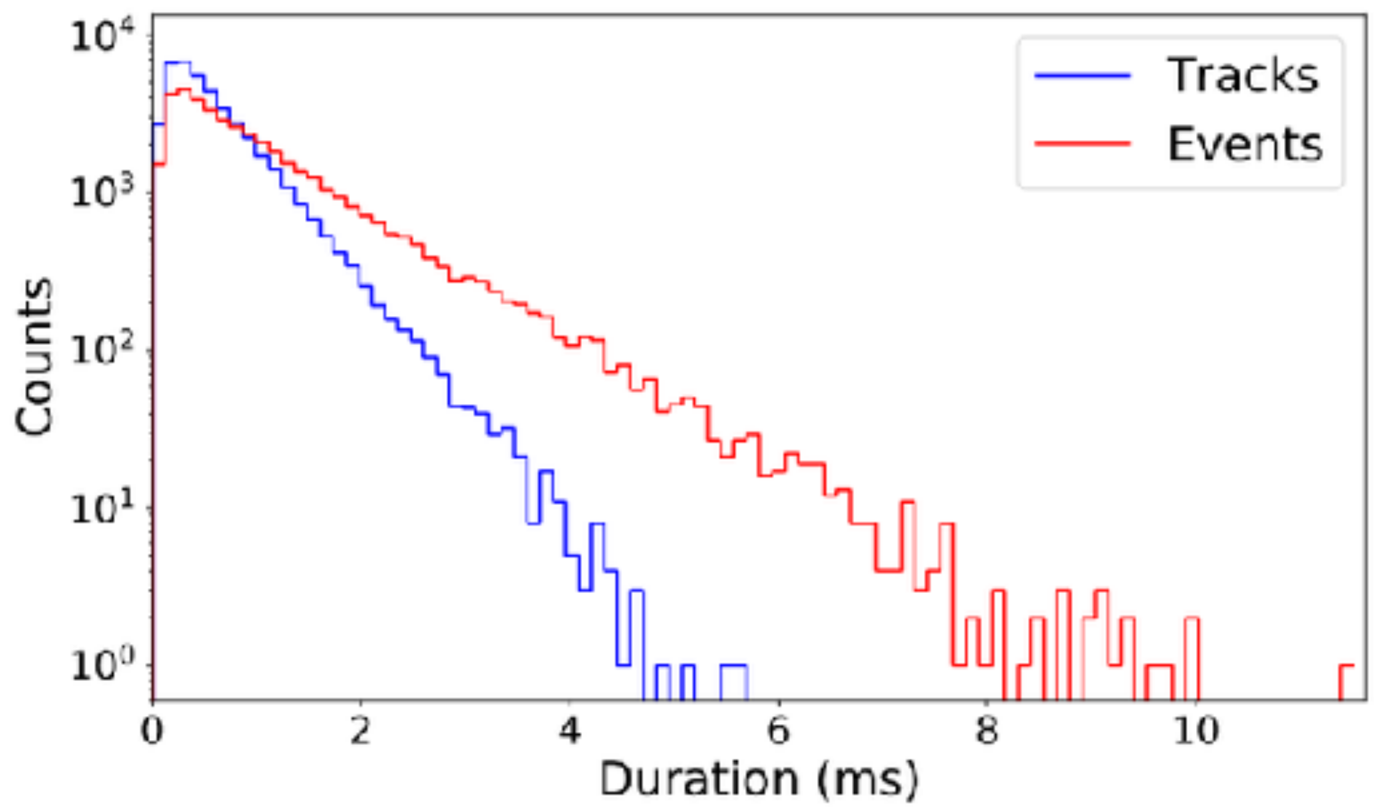


Main system consists of a
waveguide + magnetic trap + gas supply

Reconstructing Events



Power spectrogram



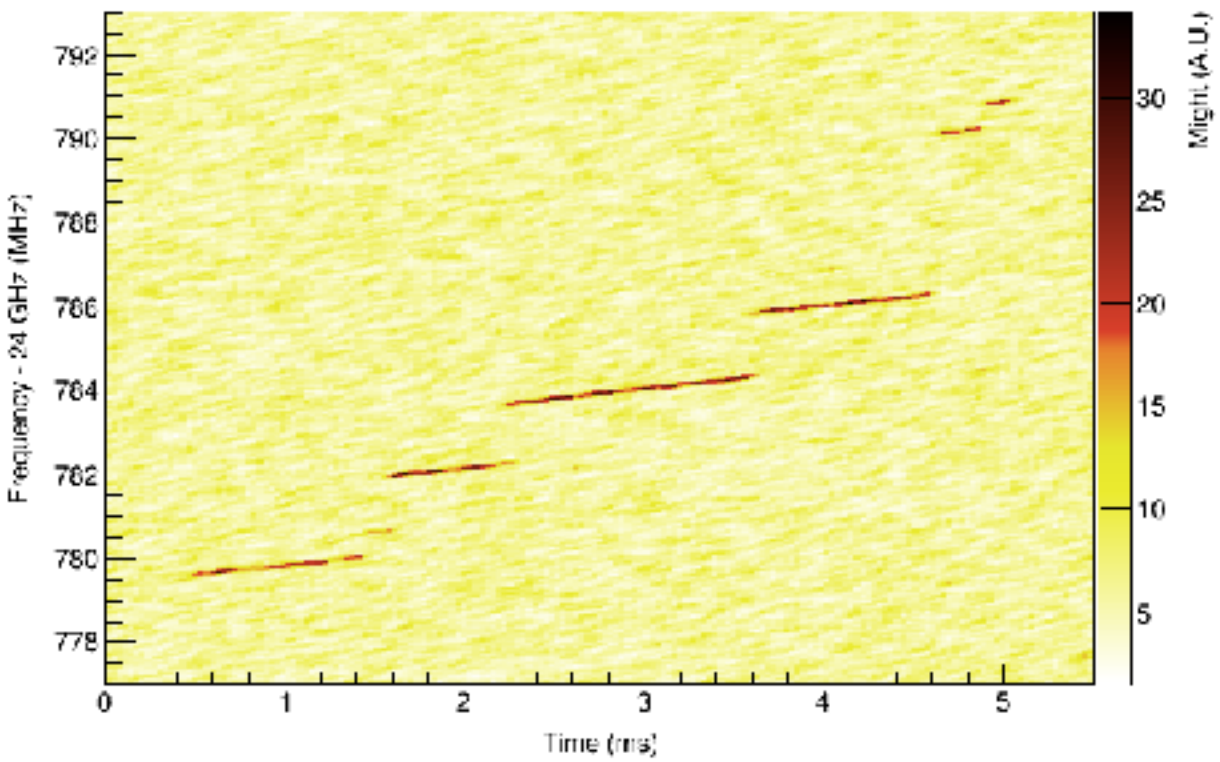
Reconstructed tracks and events

Reconstruction of events extends as short as 120 μs.

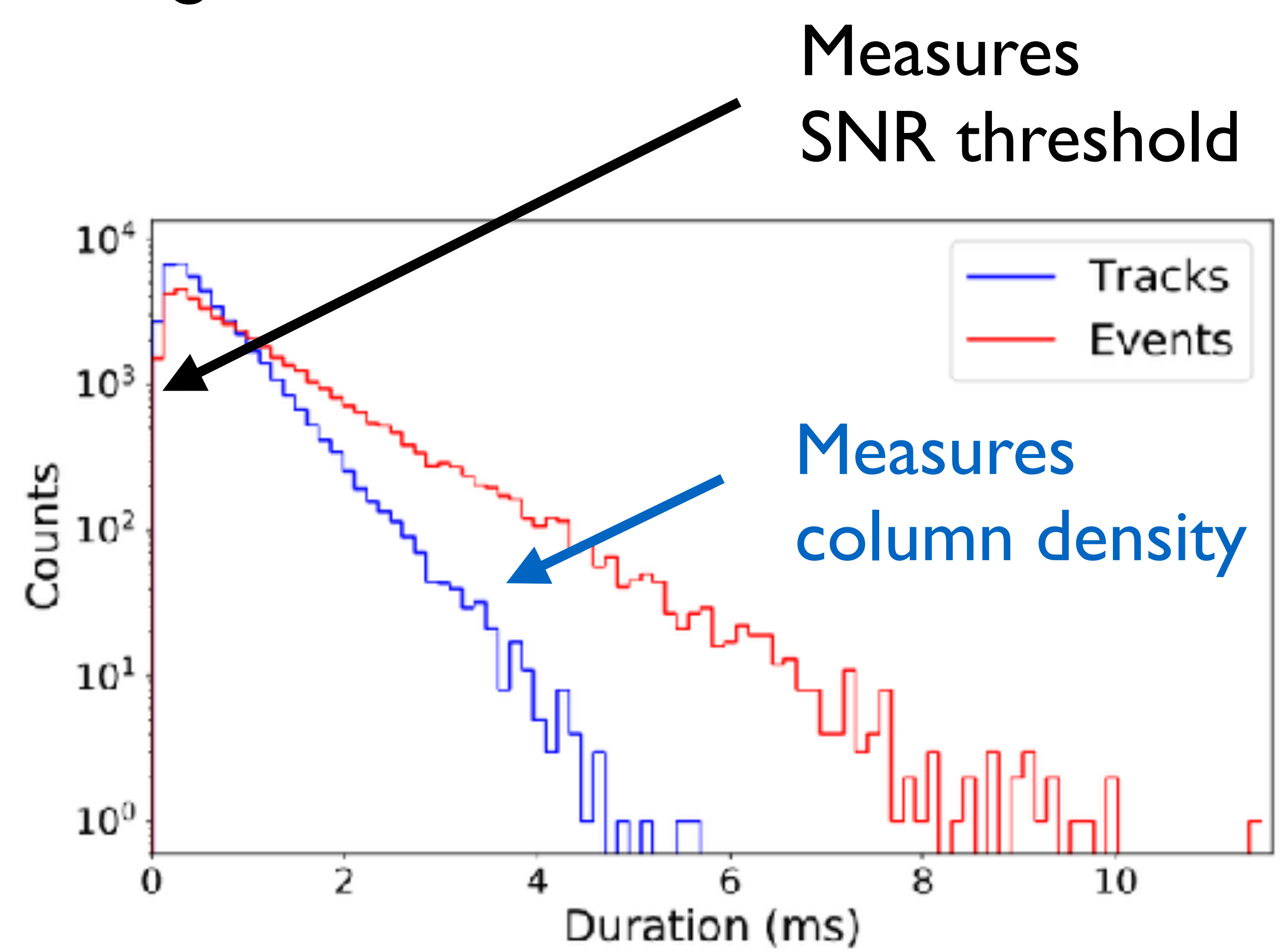
Predicted background from mis-reconstructed noise:

less than 1 event in planned Phase II T_2 data campaign

Reconstructing Events



Power spectrogram



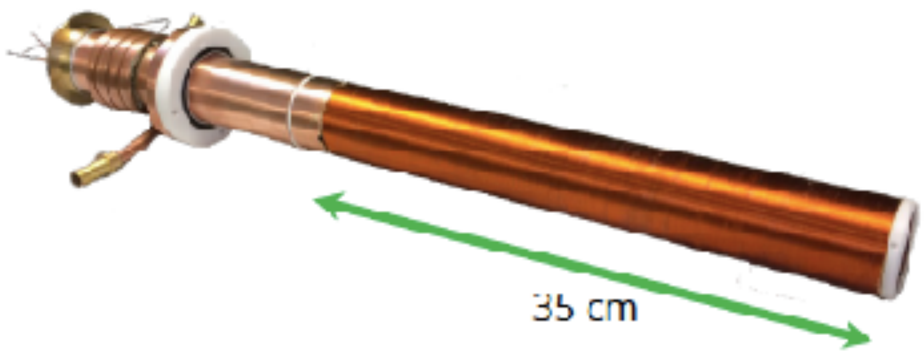
Reconstructed tracks and events

Reconstruction of events extends as short as 120 μs.

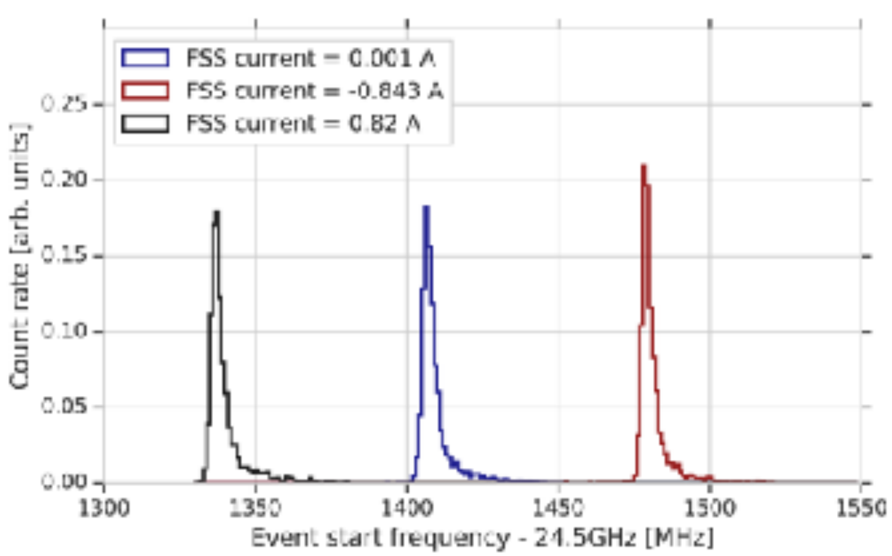
Predicted background from mis-reconstructed noise:

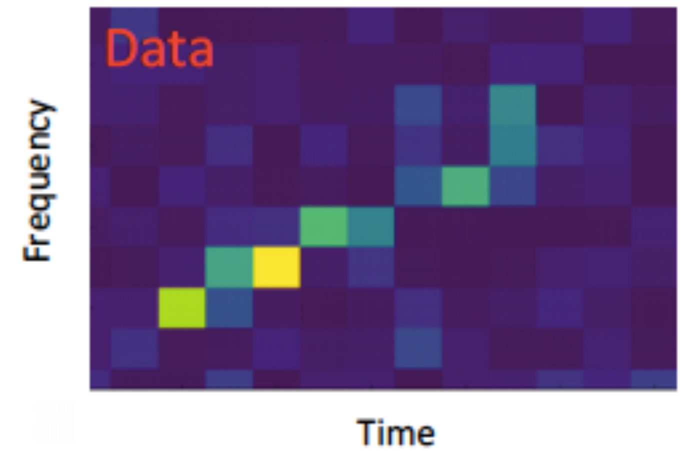
less than 1 event in planned Phase II T_2 data campaign

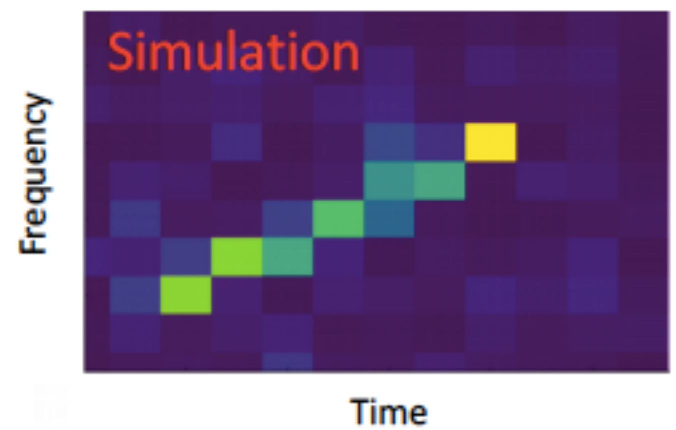
Calibrating Efficiency



Use a *field-shifting solenoid* *to sweep the 17.8 keV ^{83m}Kr conversion line across the frequency region of interest for tritium data to determine SNR vs. frequency*

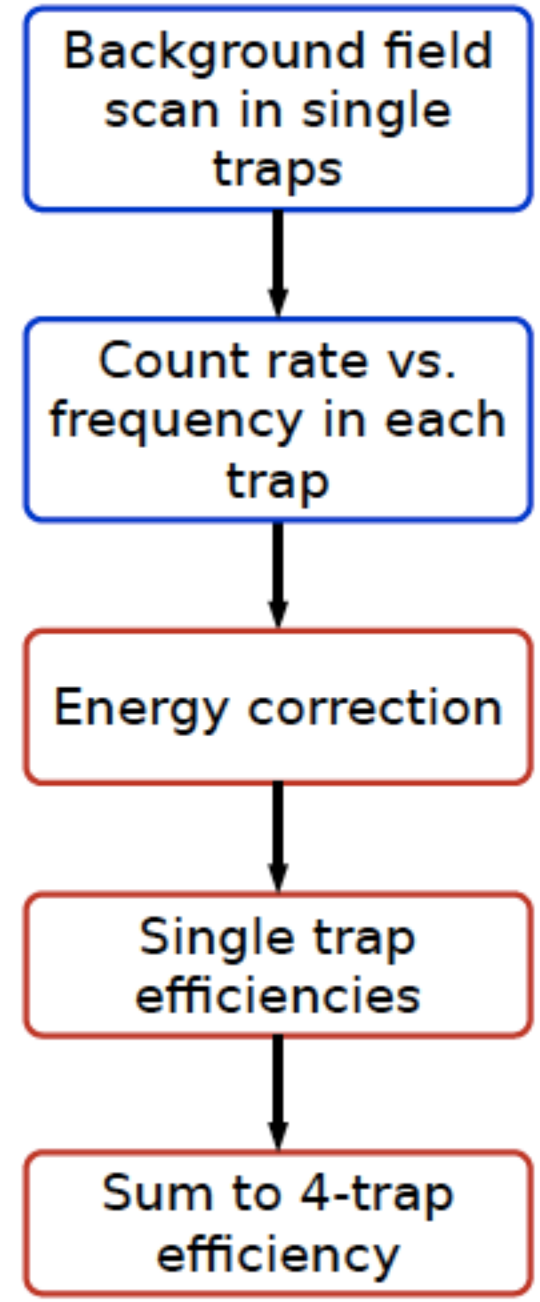




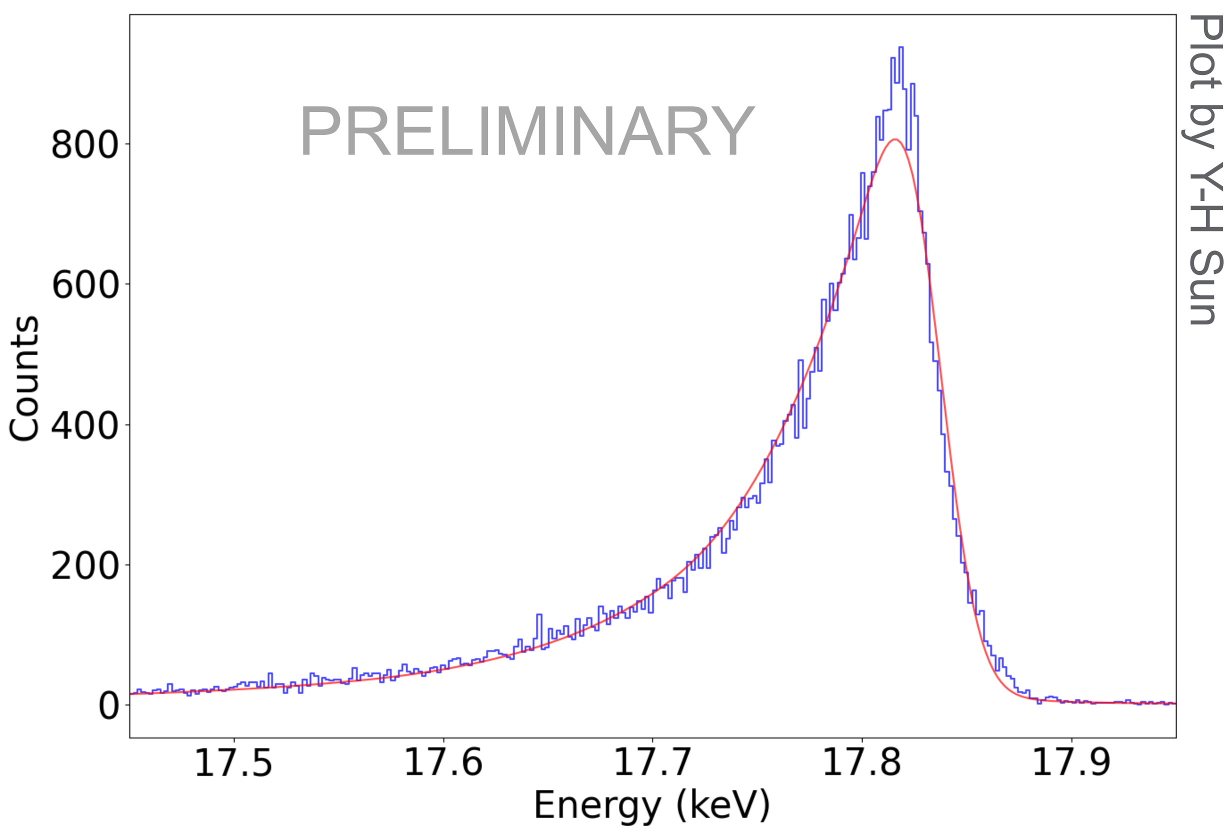


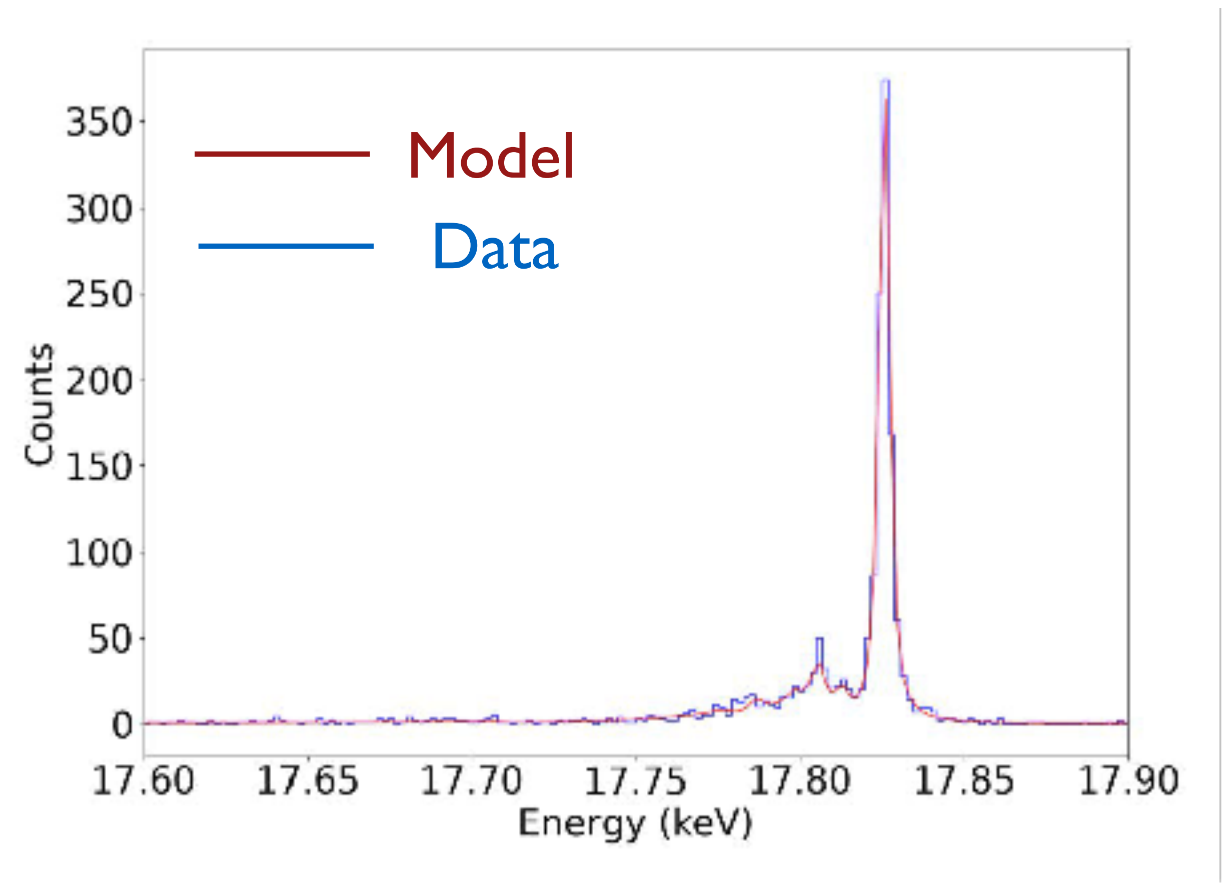
Use detailed Monte Carlo to simulate and study CRES event topologies.

LOCUST: NJP 21 10.1088 (2019)



Trap Configurations





Deep Trap

Shallow Trap

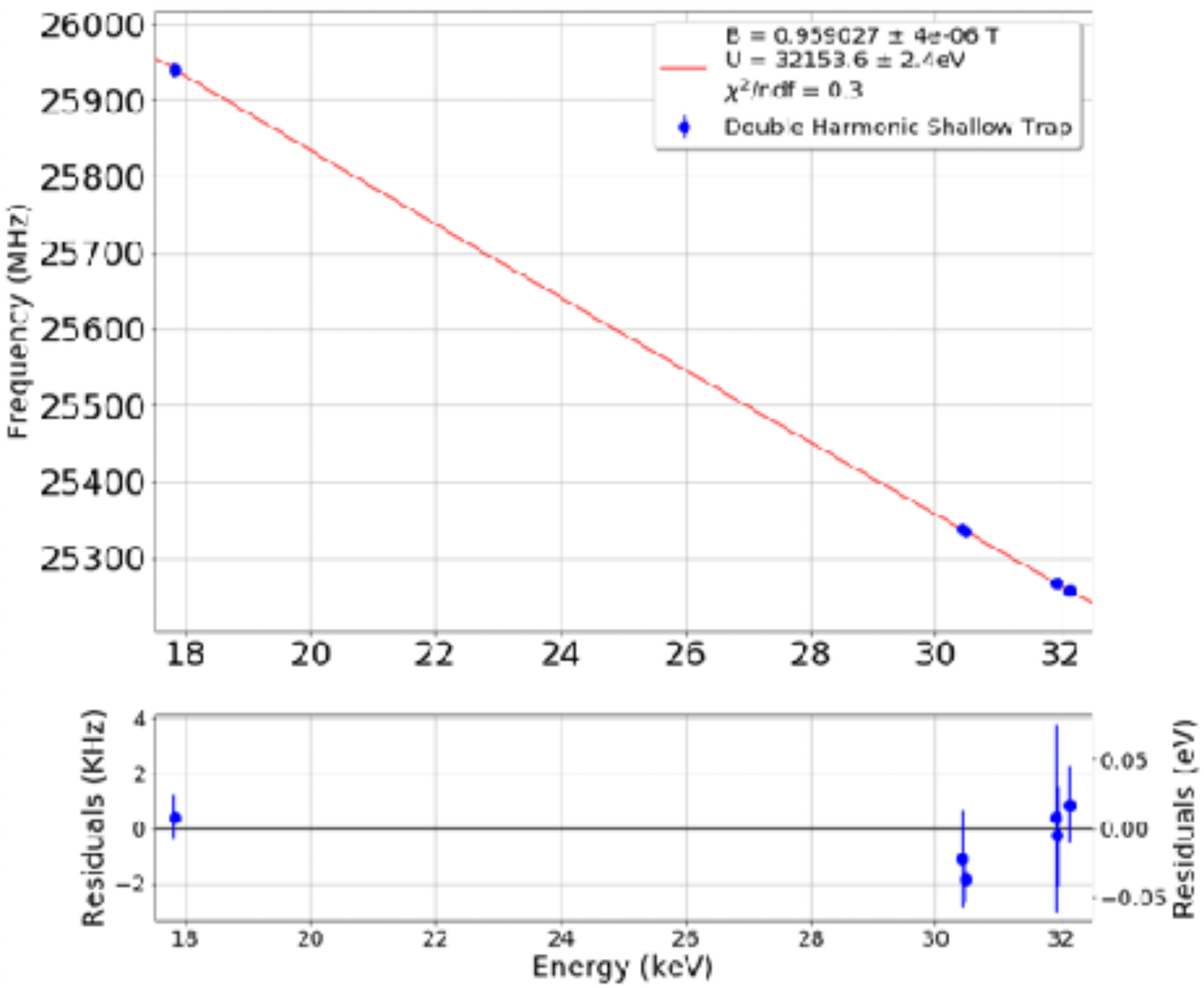
We usually operate in one of two possible configurations:

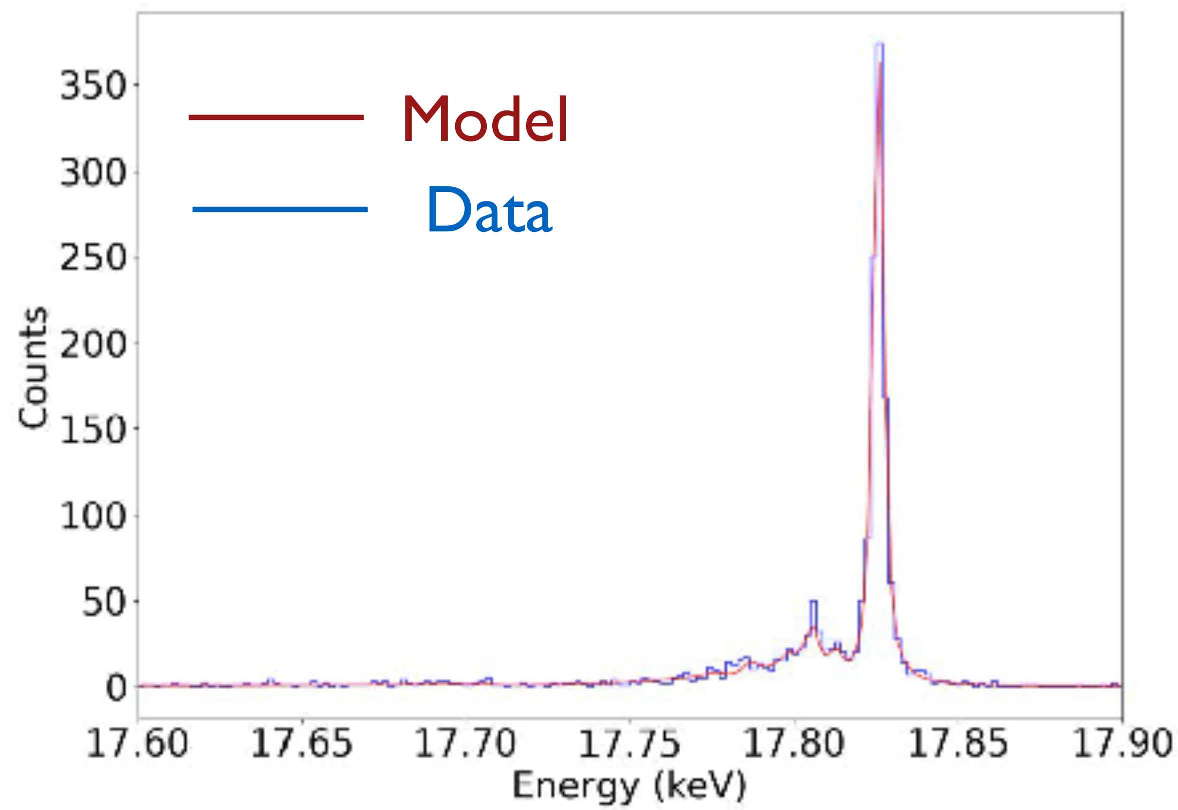
(a) deep trap for high statistics; (b) shallow trap for high precision.

Best demonstrated instrumental width: **2.0 ± 0.1 eV (FWHM)**

(2.8 eV natural line width)

Shallow Trap Linearity Measurements



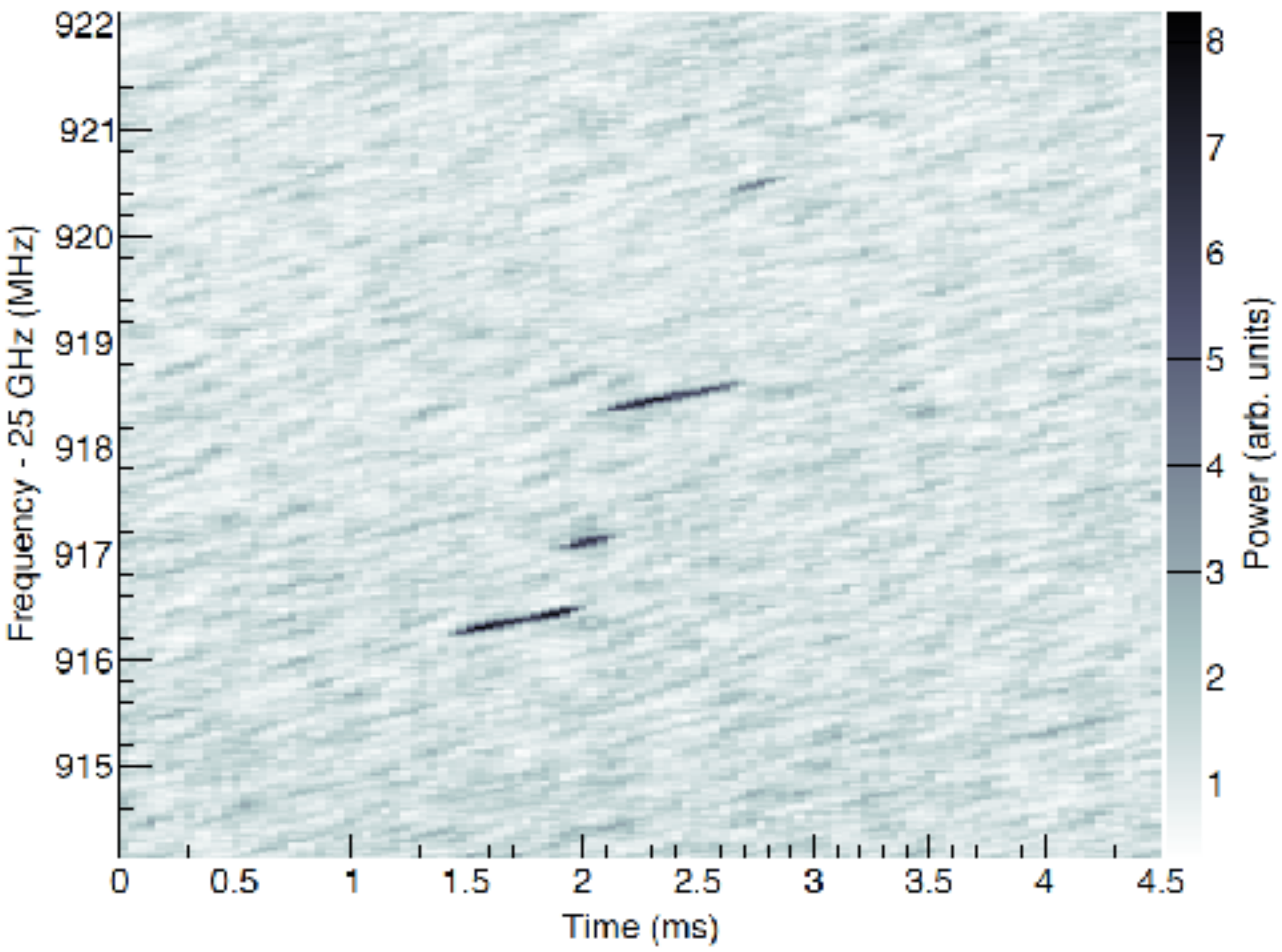


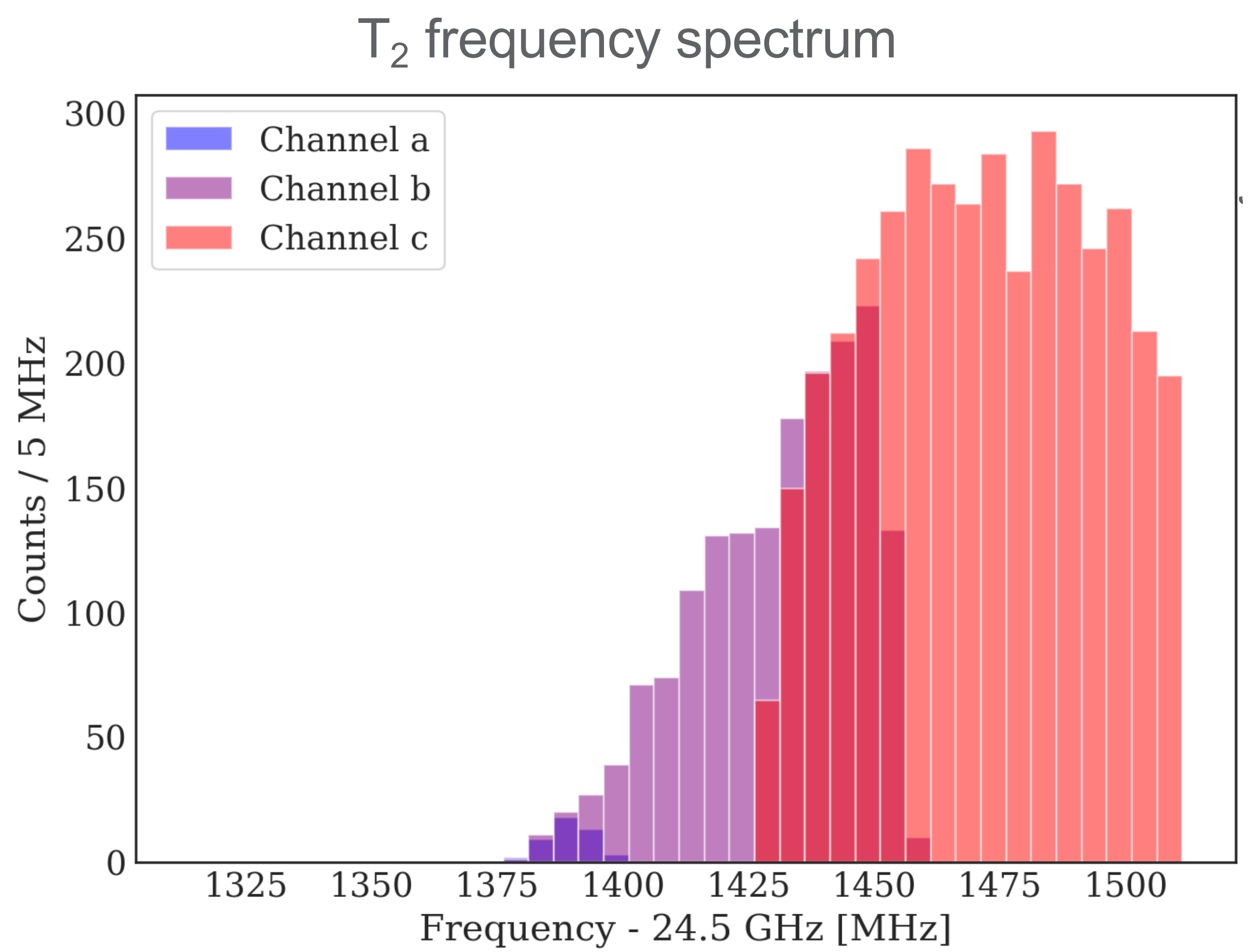
- 32-keV γ energy: (32153.6 ± 2.4) eV
  - Vénos, et al: (32151.7 ± 0.5) eV
    Appl. Radiat. Isot. **63** 323-7 (2005)

We can also test the linearity of the technique by measuring multiple mono-energetic lines from ^{83m}Kr.

Excellent agreement with previous measurements.

First tritium CRES spectrum

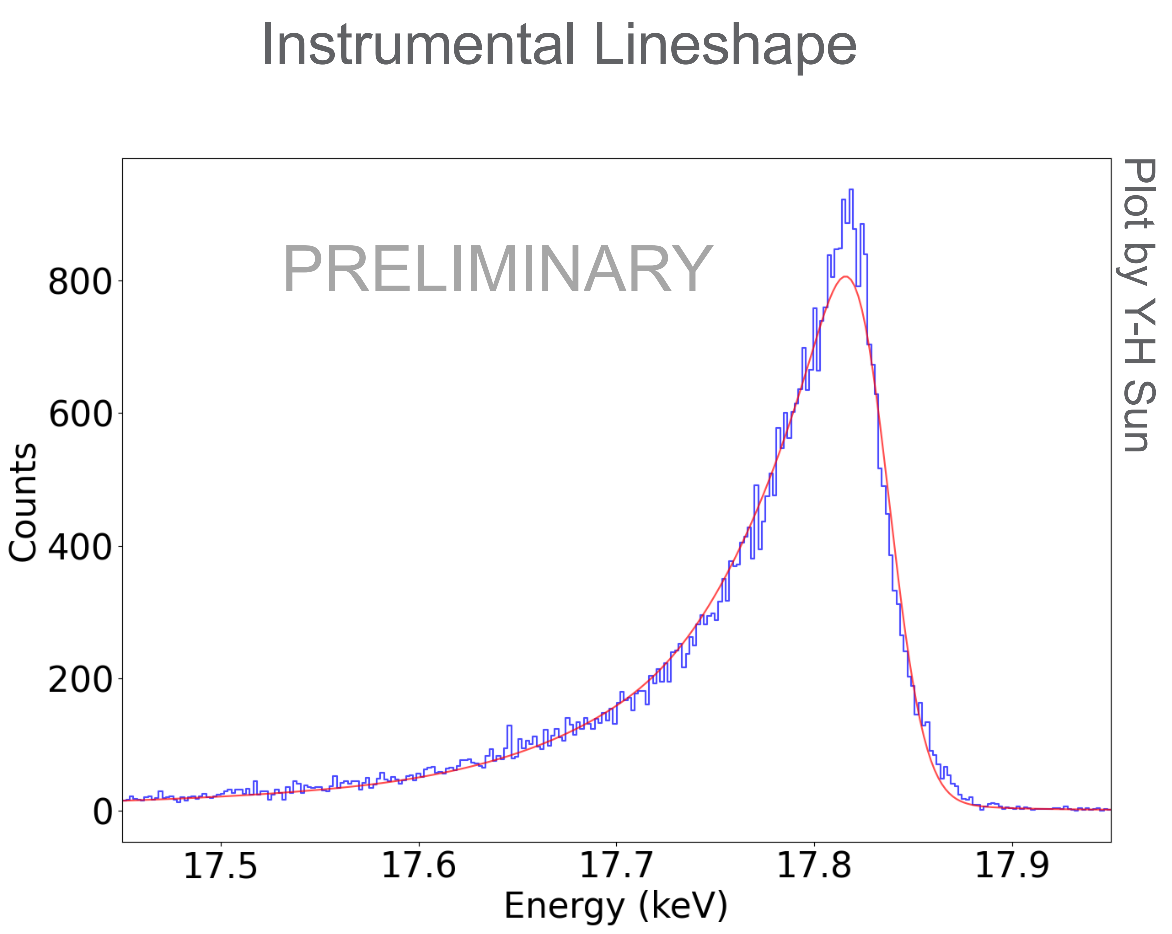


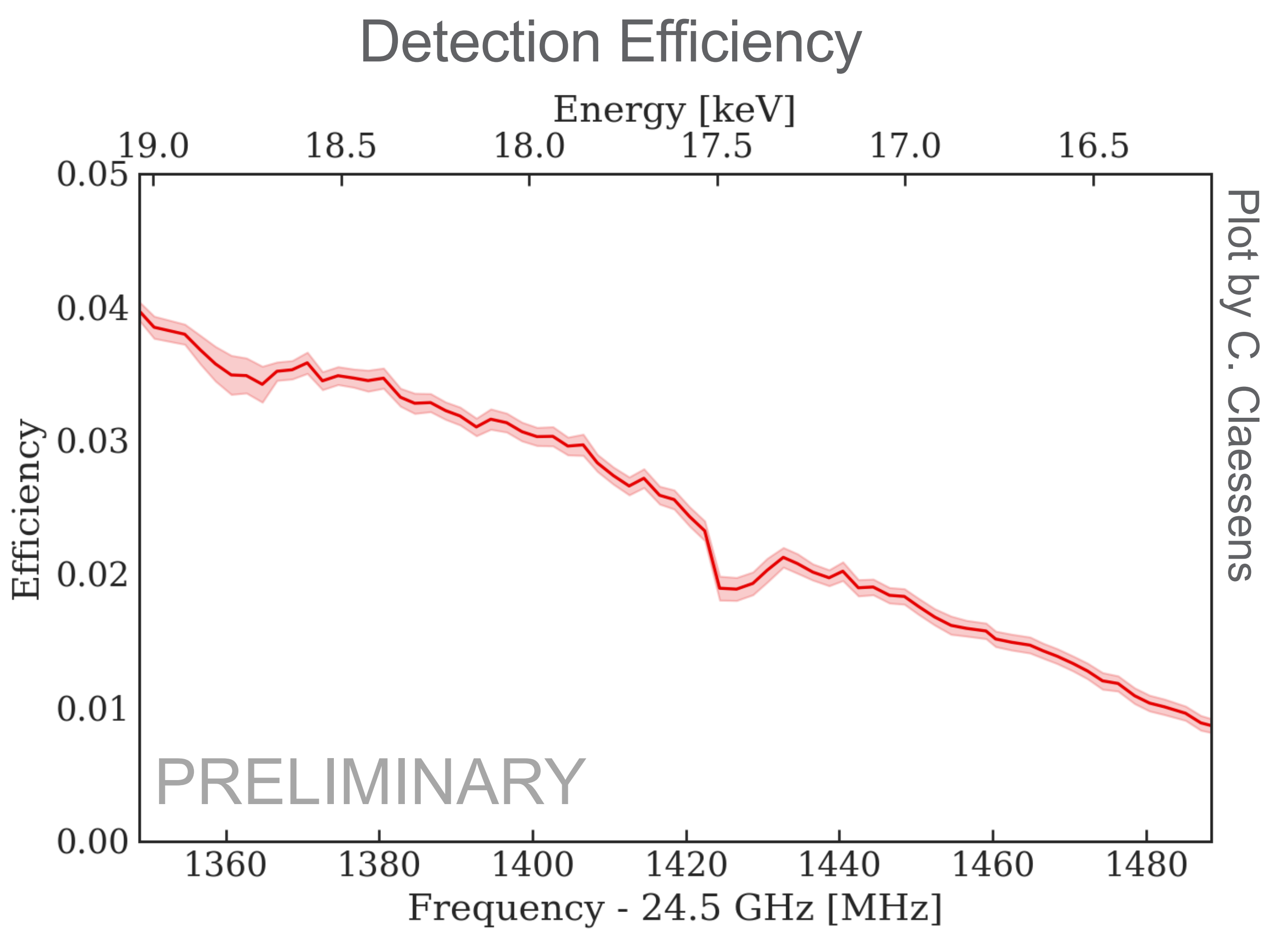


First tritium from Phase 2:

- *Data taken from winter 2019-2020 (82 days of livetime).*
- *Four-coil "deep" trap configuration with 1 mm^3 active volume.*
- *Three overlapping frequency bands which cover 16.2-18.6 keV*
- *3770 unique counts.*

Unfolding Spectrum





First tritium from Phase 2:

- *The krypton data is used to constrain the instrumental energy resolution.*
- *A scan of the krypton 17 keV line provides a measurement of the detector efficiency.*

First tritium CRES spectrum

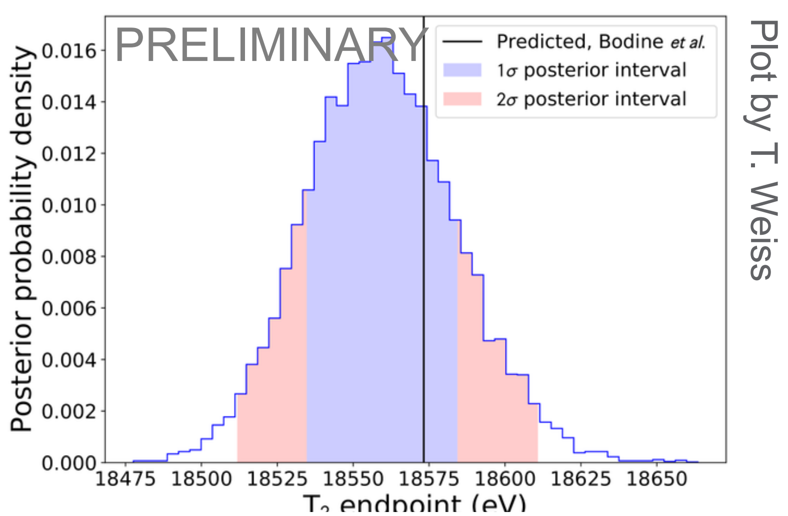
T_2 endpoint result:

$$E_0 = \left(18559.4^{+24.9}_{-24.7}\right)\ \mathrm{eV}$$

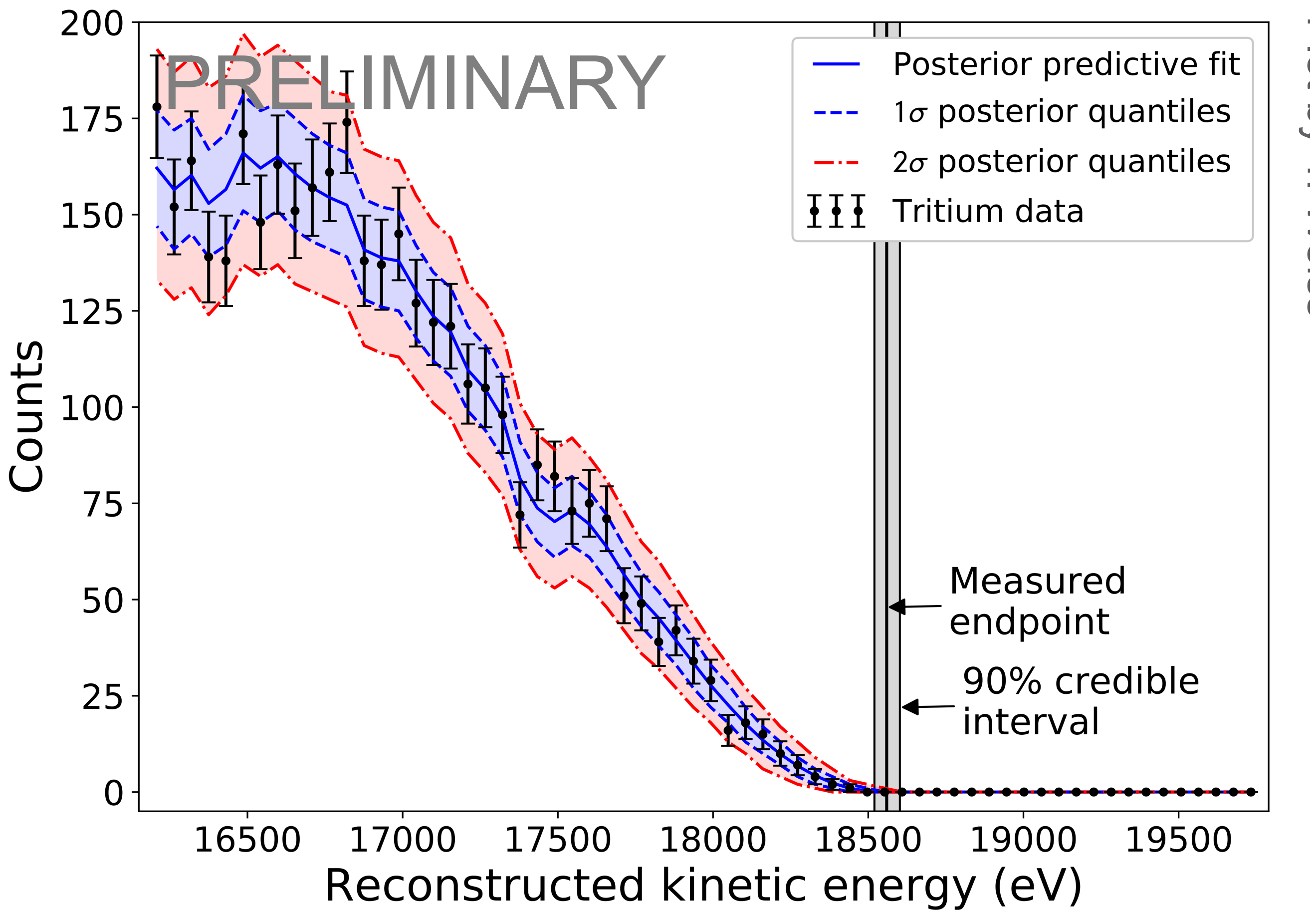
Background rate:

$$\leq 3\times10^{-10}\mathrm{eV}^{-1}\mathrm{s}^{-1}\ (90\%\ \mathrm{C.I.})$$

Posterior distribution



Energy spectrum and posterior fit



We extract a first tritium spectrum using the CRES technique.

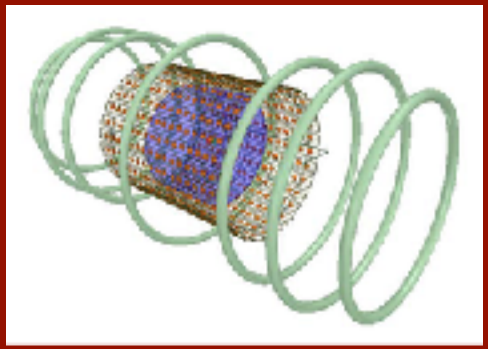
Background levels controlled to better than <0.3 nHz/eV.

Going Forward...

Phase III:

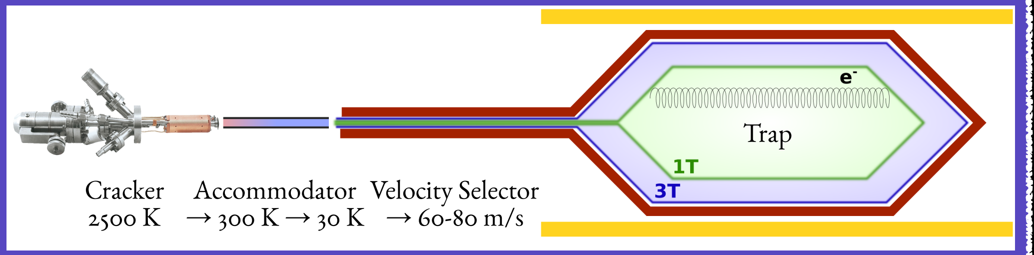
(a) RF Demonstrator (200 cm^3 volume, eV mass sensitivity)

(b) Atomic T Demonstrator (trap atomic tritium at high densities)



Phase IV:

Atomic tritium source. Inverted ordering reach (40 meV)



Wish to transition from small circular waveguide cell to large volume system.

Major new obstacles:

- *Maintaining signal to noise across larger volume*
- *Field homogeneity for energy reconstruction*

Phase III

Goal: Expand technique to large volumes

Wish to transition from small circular waveguide cell to large volume system.

Major new obstacles:

- Maintaining signal to noise across larger volume
- Field homogeneity for energy reconstruction

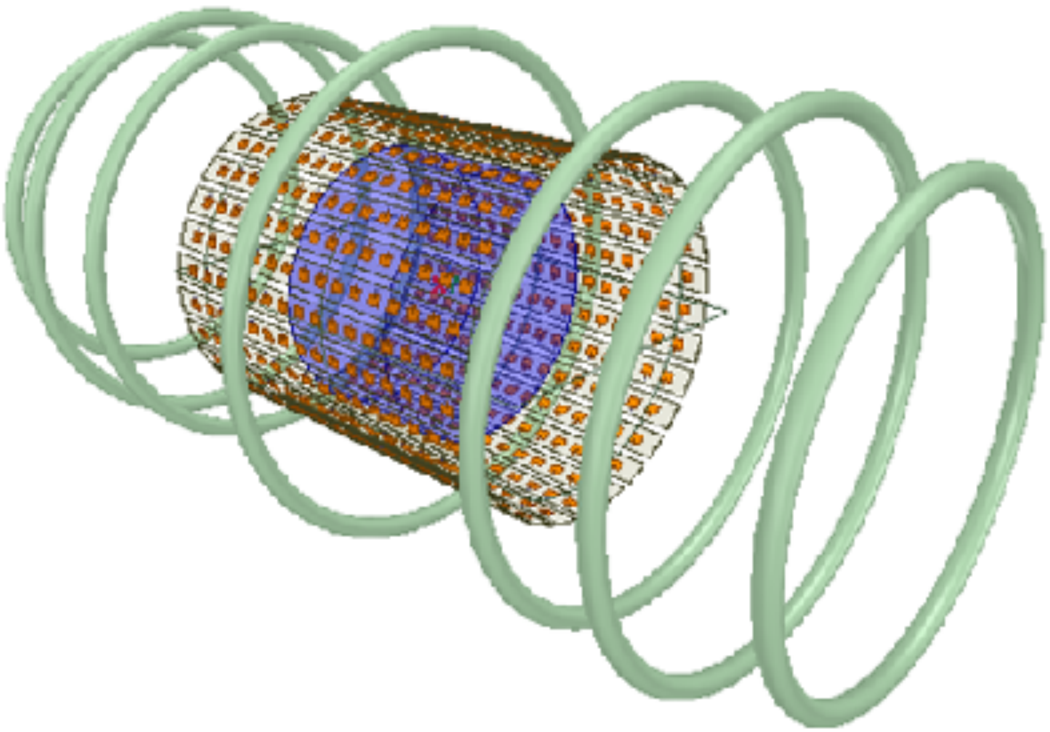
Remedies:

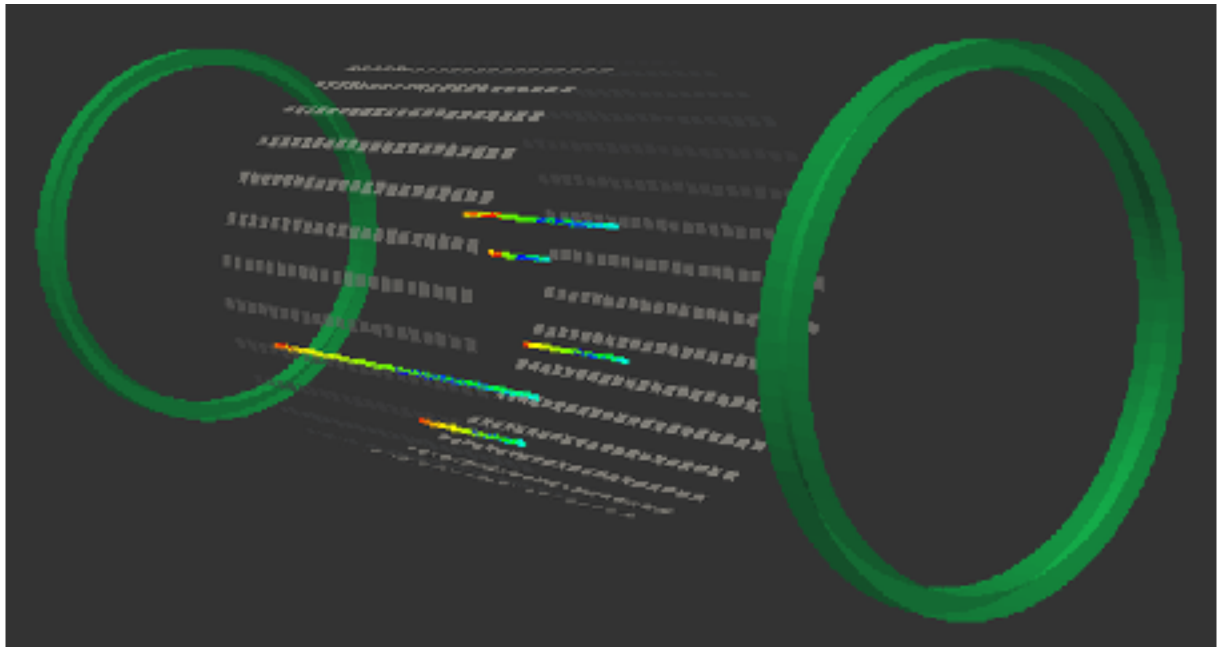
- Switch from single waveguide to patch array system
- Radial reconstruction

Phase III

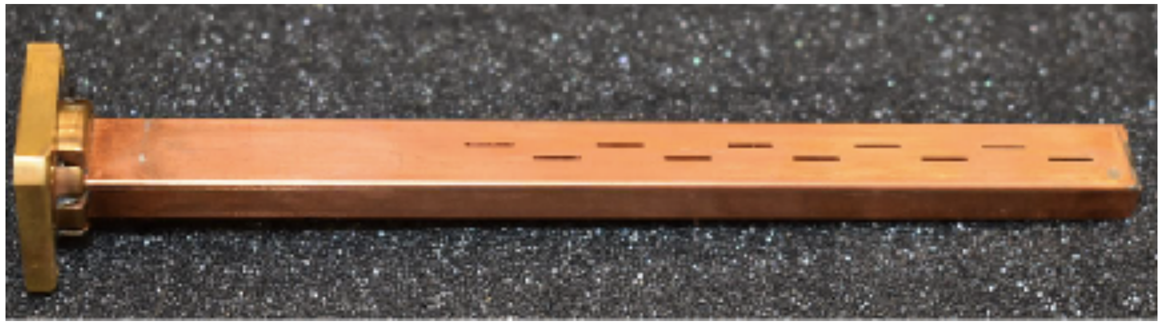
Goal: Expand technique to large volumes

New Antenna Arrays

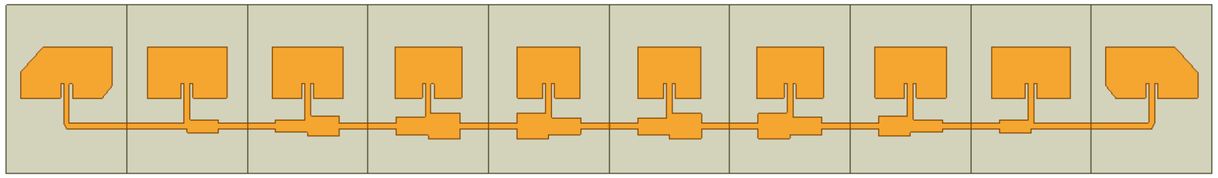




Conceptual design of RF array
design options



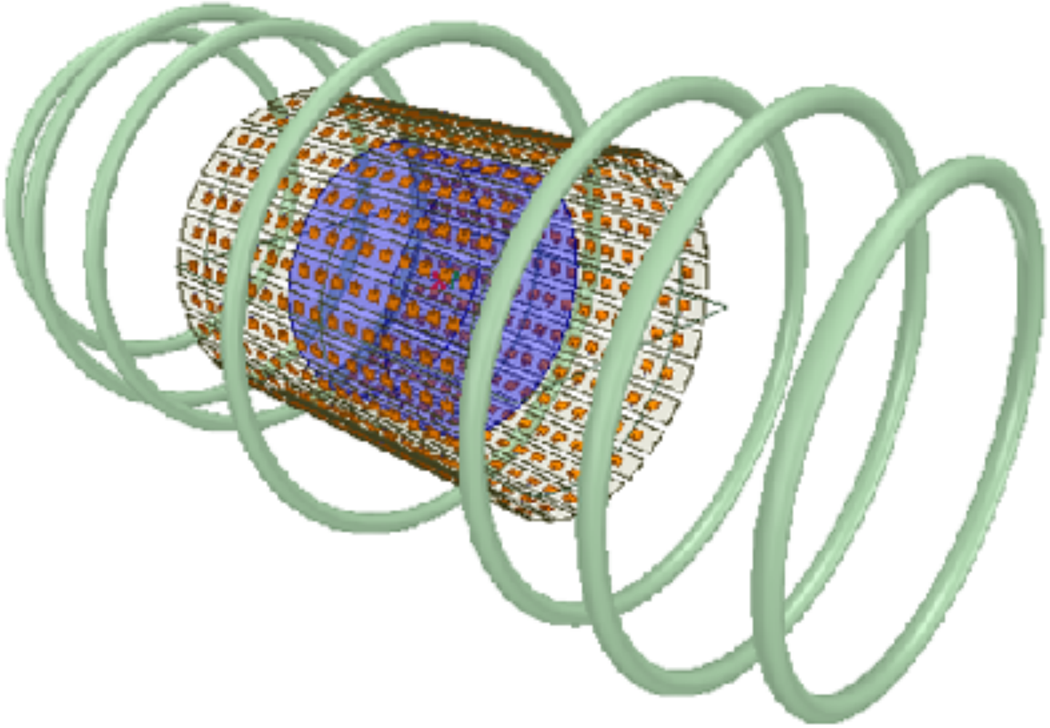
Waveguide Slot Array

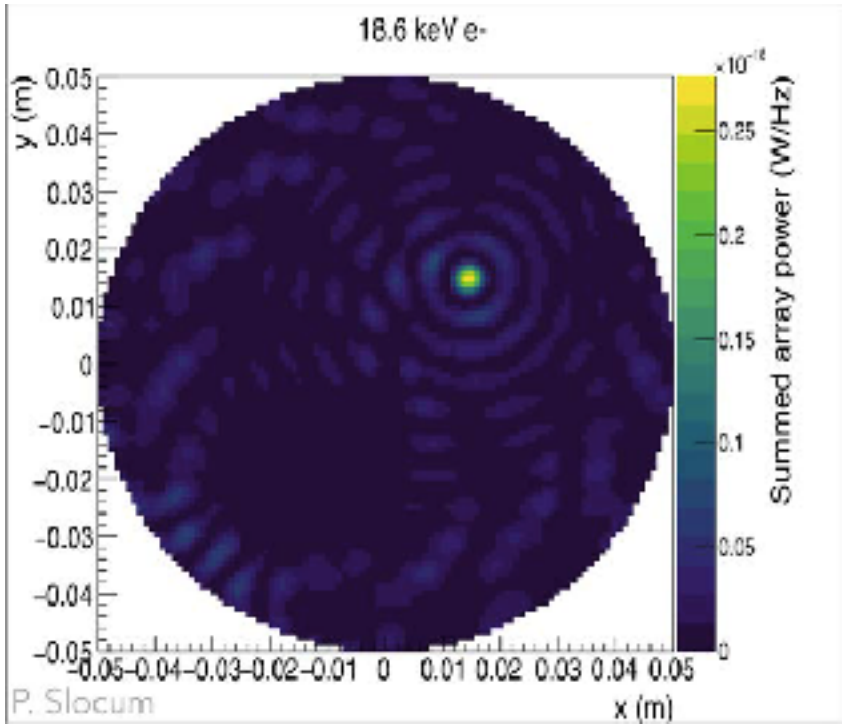


Patch Antenna Array

Full design campaign underway to characterize signal-to-noise and localization expected from new phased antenna array.

New Antenna Arrays





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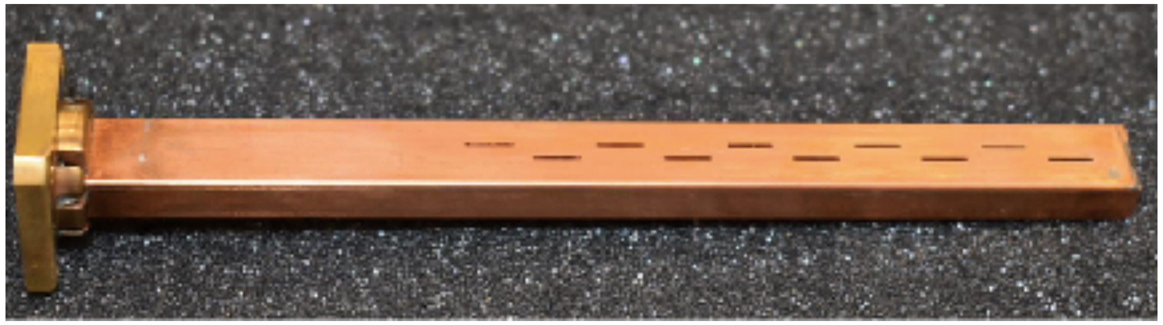

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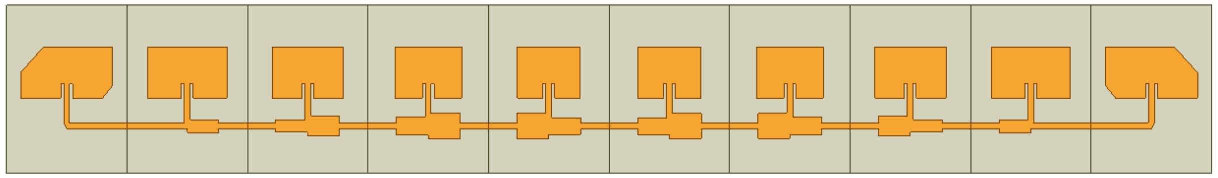

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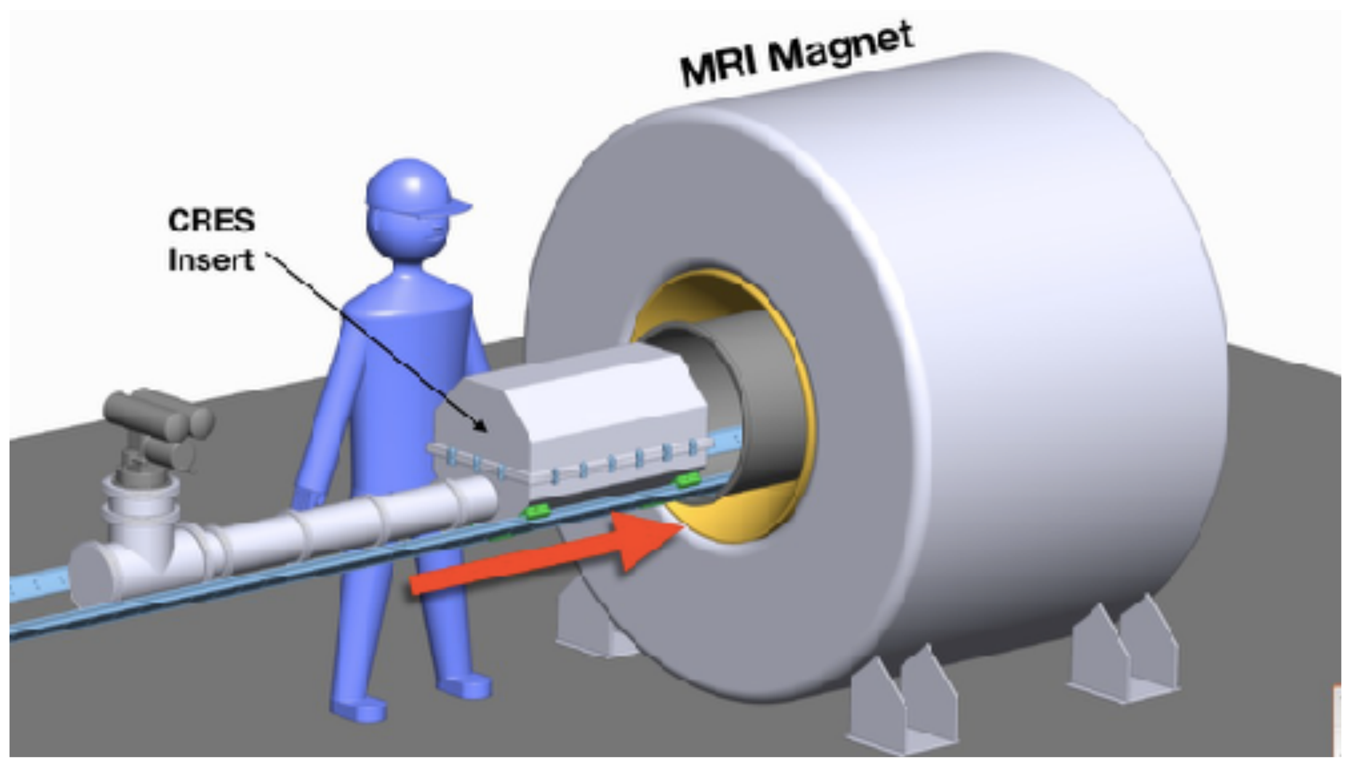


Need 1 T magnetic field.
10-20 cm long (200 cm^3)
magnetic "bathtub" trap.

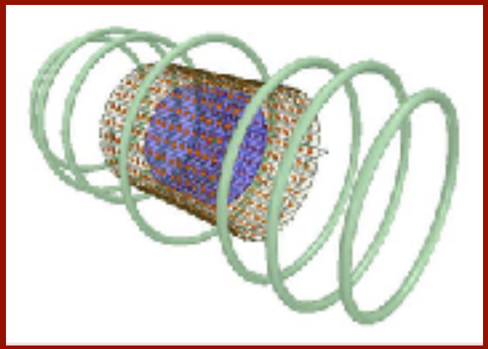
Large bore MRI magnet installed and running

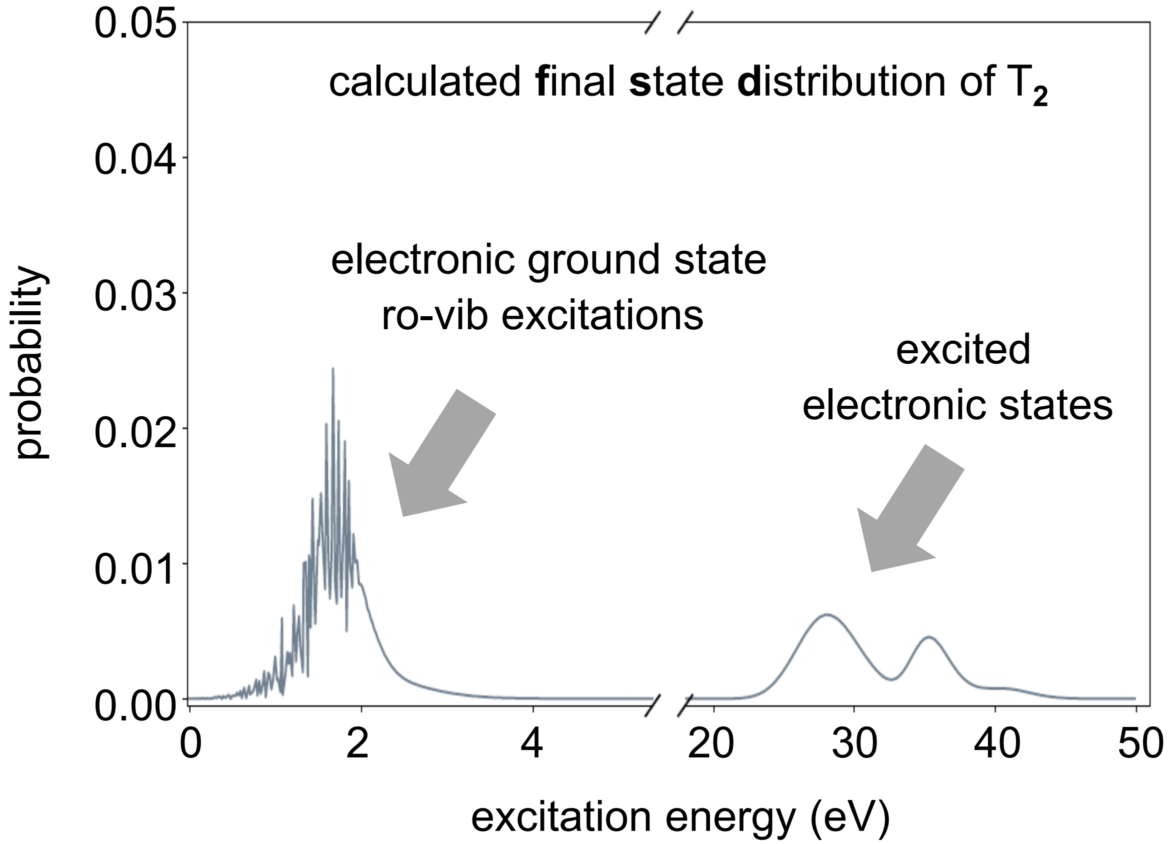
Forward...

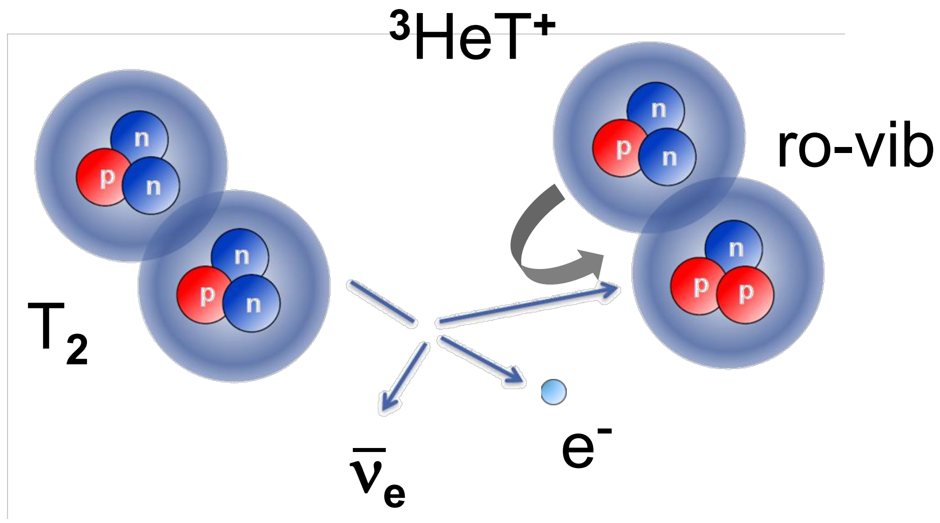
Phase III:

(a) RF Demonstrator (200 cm^3 volume, eV mass sensitivity)

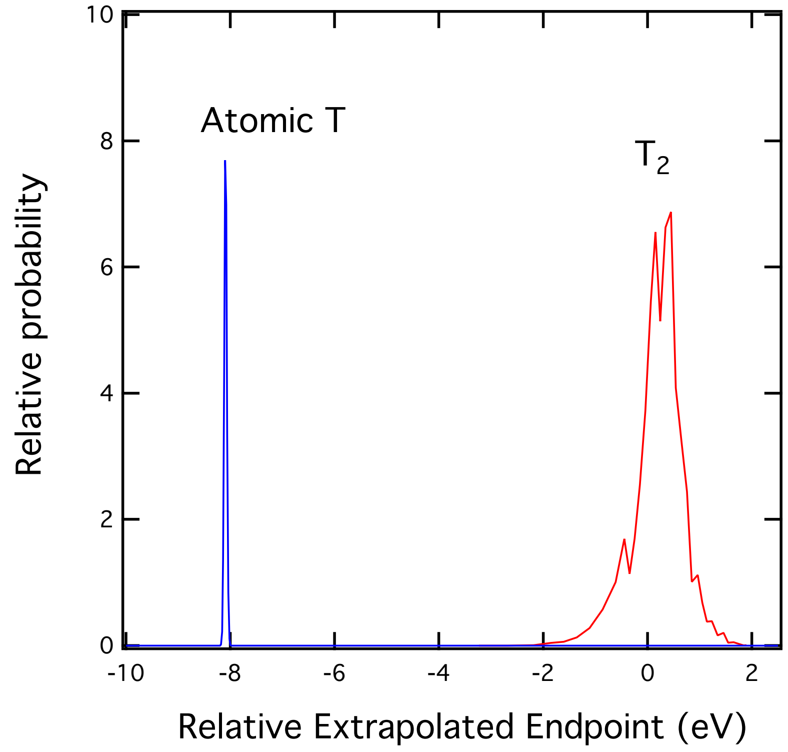
(b) Atomic T Demonstrator (trap atomic tritium at high densities)





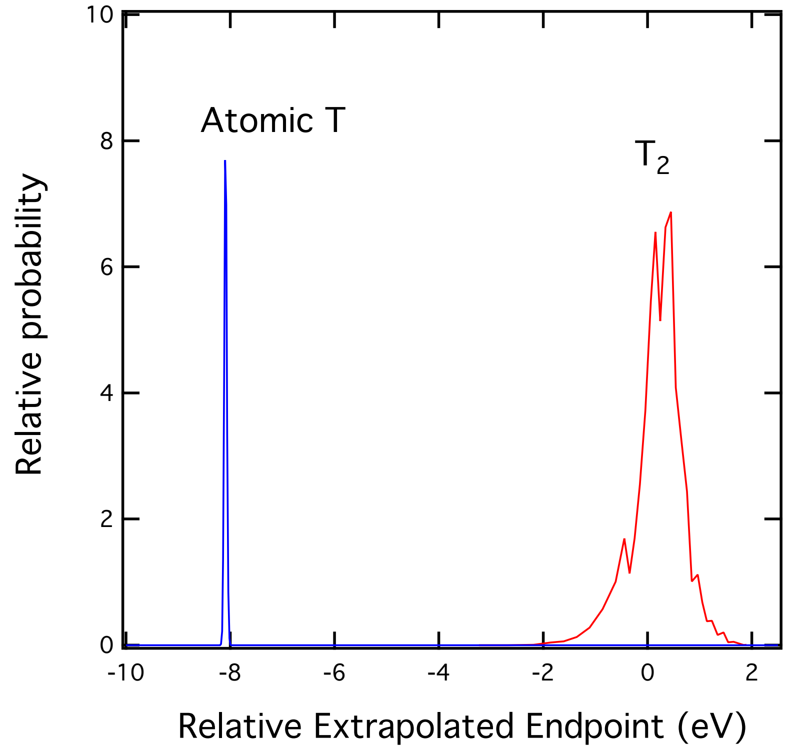


Need to overcome molecular final states to reach "inverted" scale.



Atomic tritium provides a narrower profile, allowing one to access inverted scale.

Need to overcome molecular final states to reach “inverted” scale.



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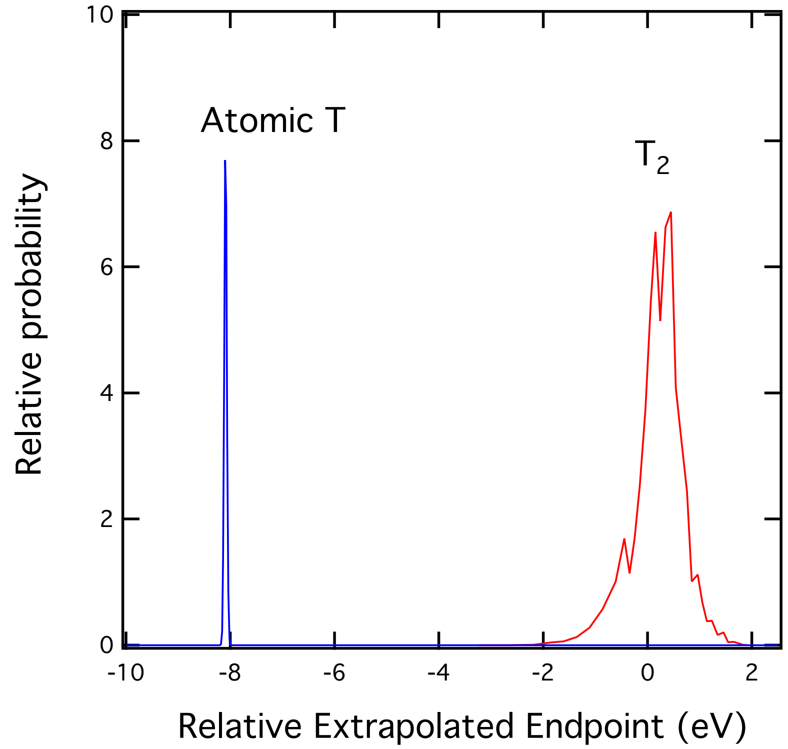
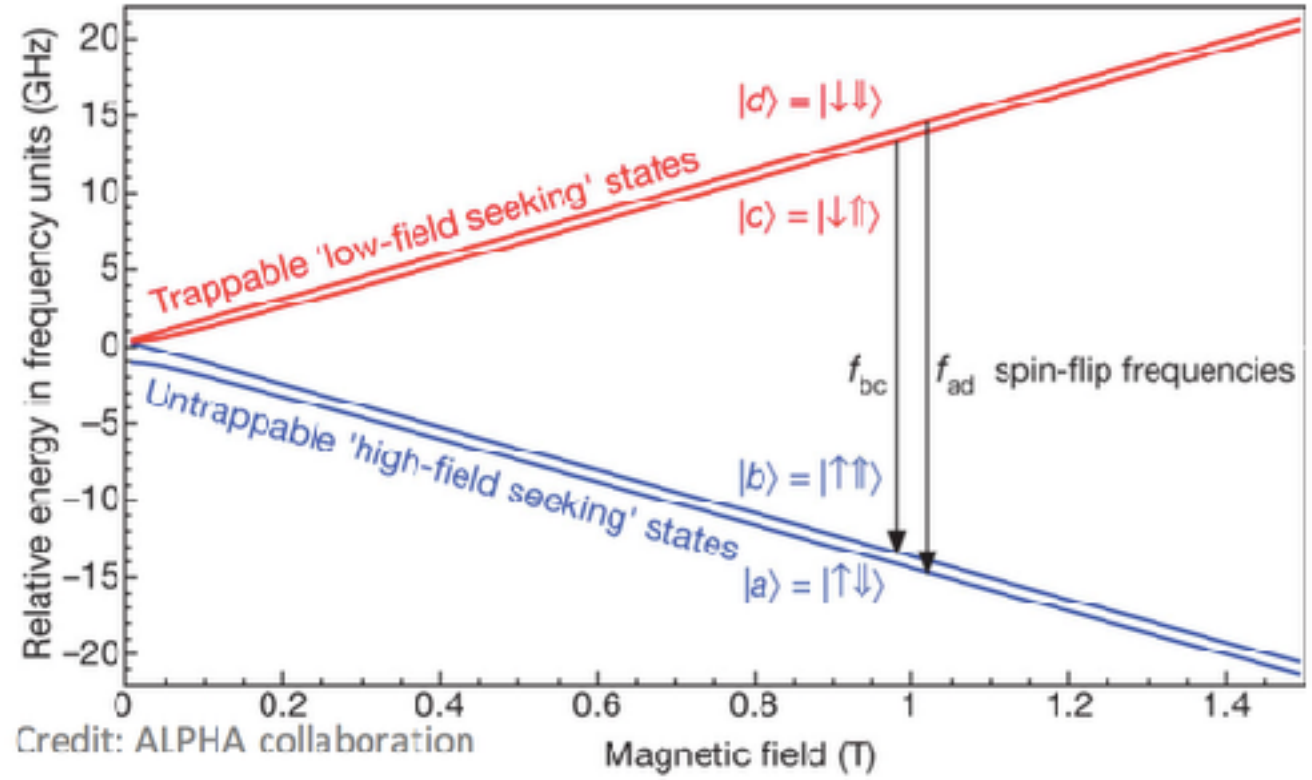
Need to overcome molecular final states to reach “inverted” scale.

Challenges?

How to create?
How to trap?
How to keep purity?





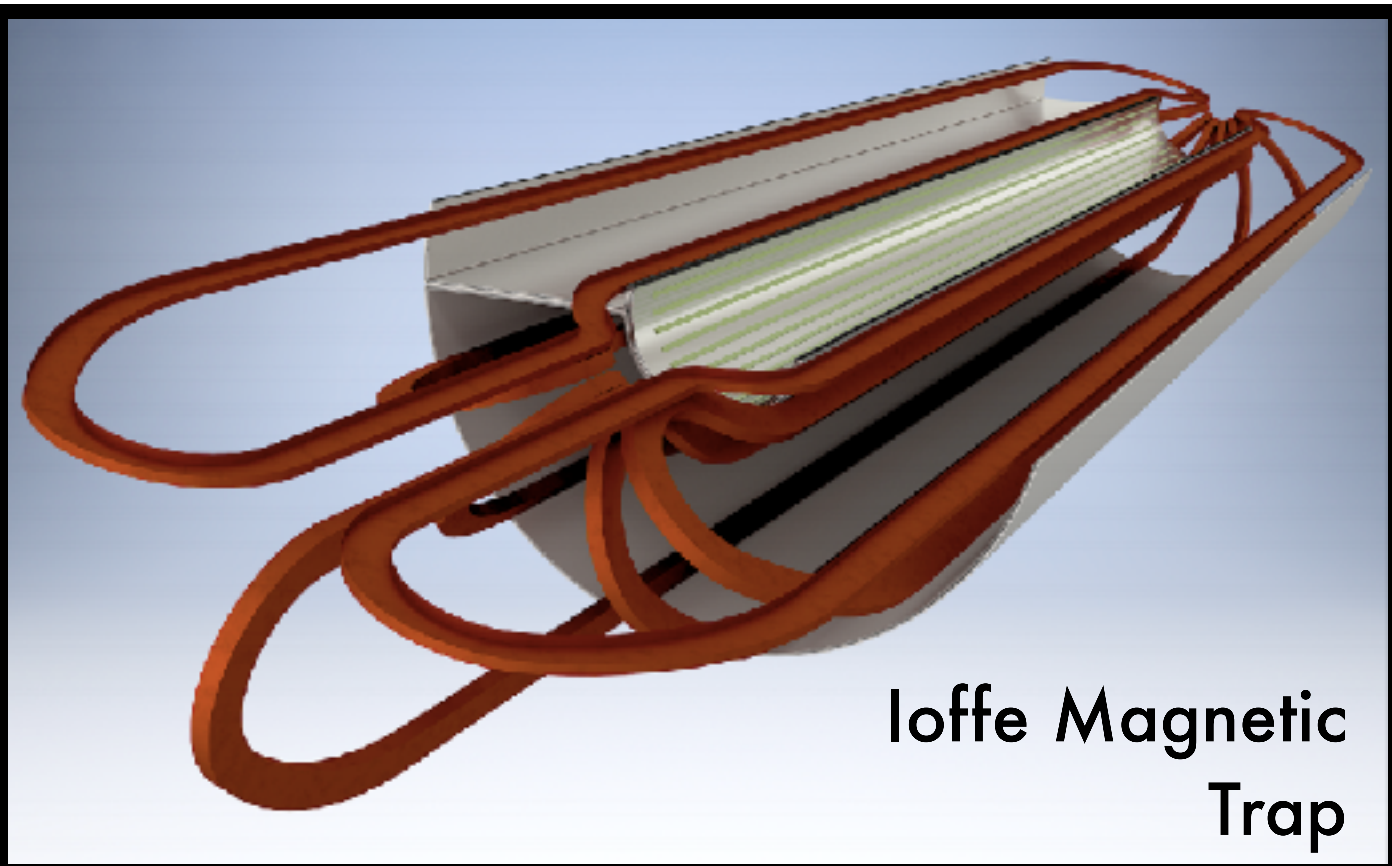
H,D and T have unpaired electrons (non-zero μ)

Atom tend to (anti-)align with B-field if change is adiabatic

Potential energy…

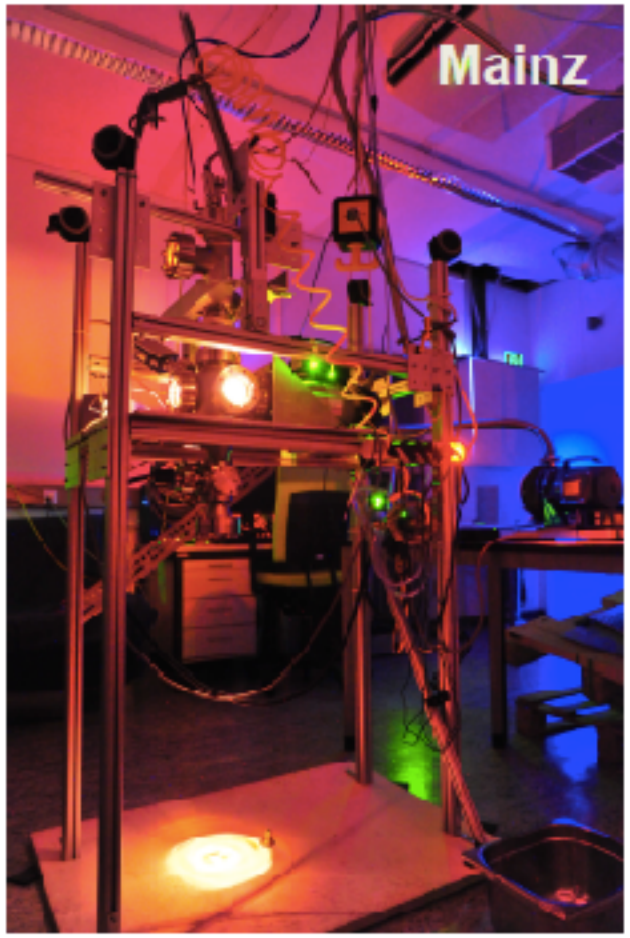
$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

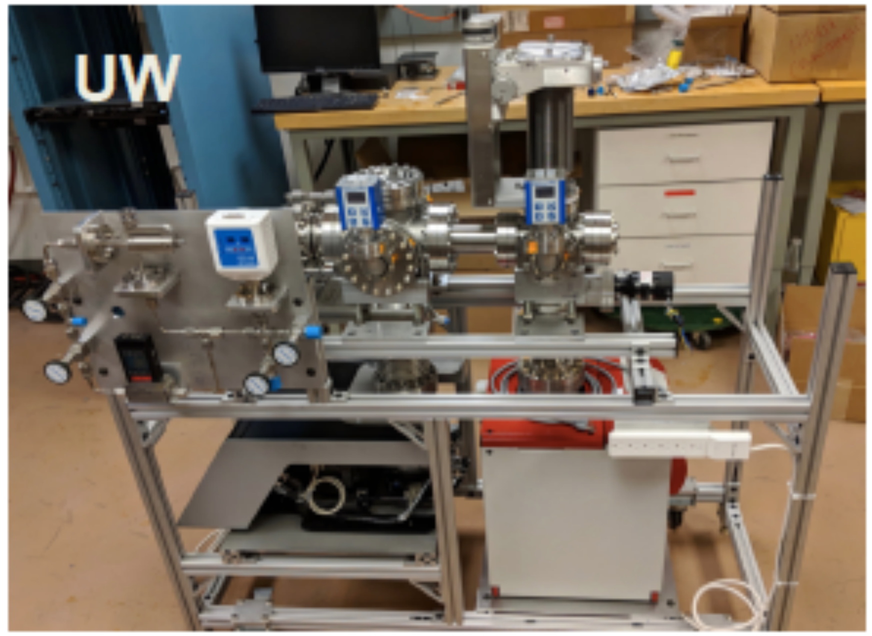
(atoms follow field mimimim)

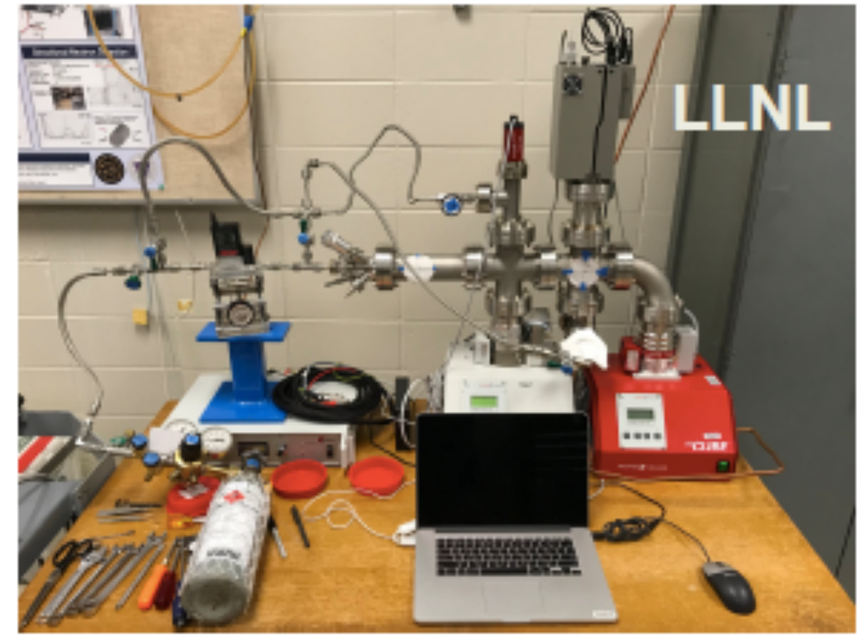


Solution: A large volume magnetic trap for T atoms

Making Atomic Tritium



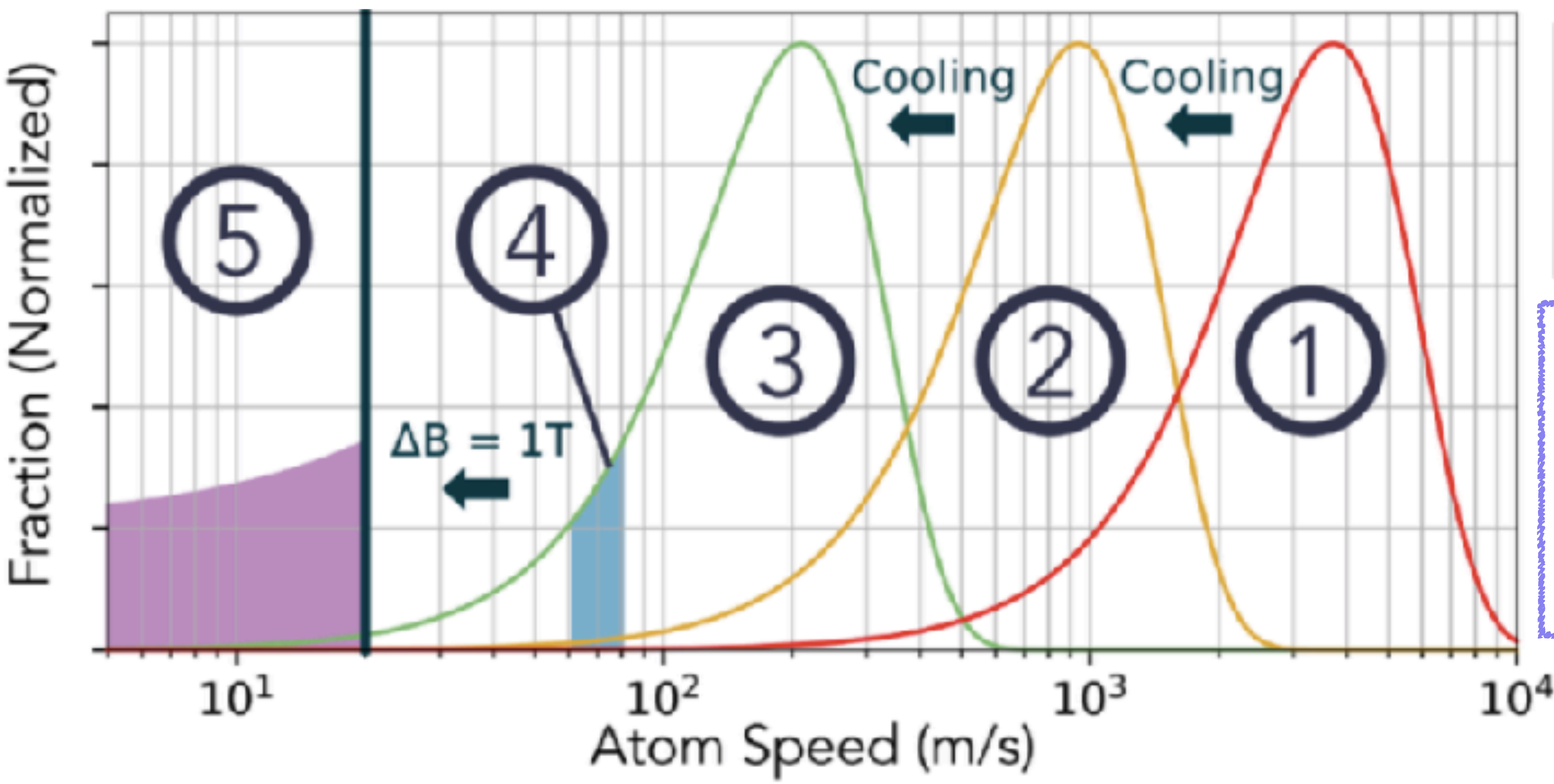




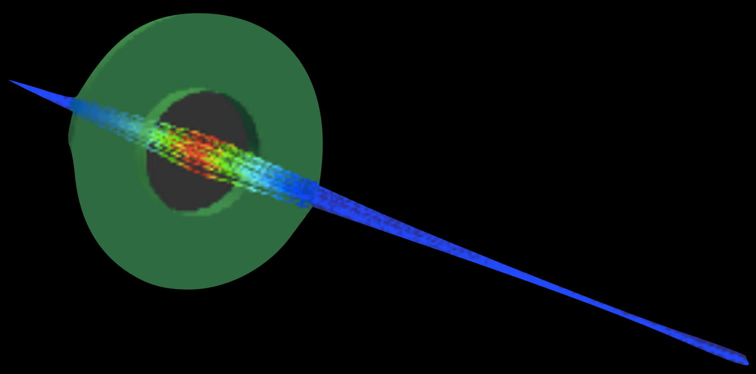
Thermal Cracker

Simultaneous efforts to create large flow of tritium atoms, typically at about 100 times higher than commercial crackers (at high temperatures)

Cooling Atomic Tritium



(1) Cracker
(2) Accommodator
(3) Nozzle
(4) Velocity/State Selector
(5) Magnetic Well

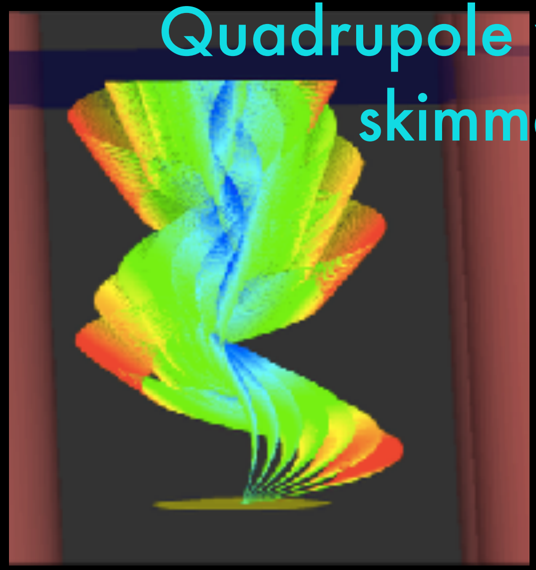


Magnetic lens

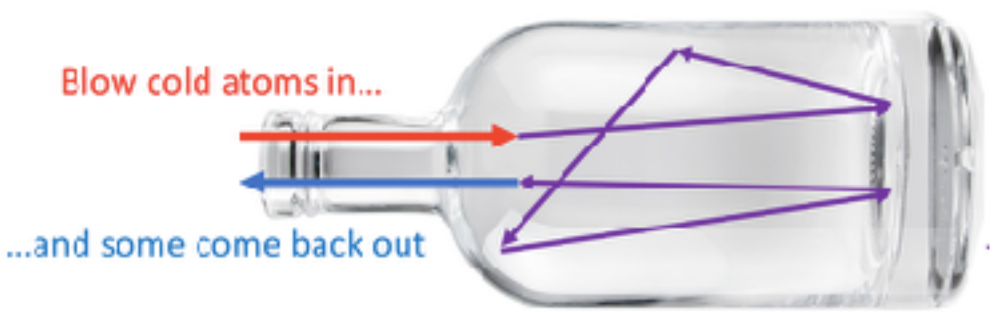
Need to reach sub-kelvin temperatures to trap atomic tritium (from very high cracking temperatures).

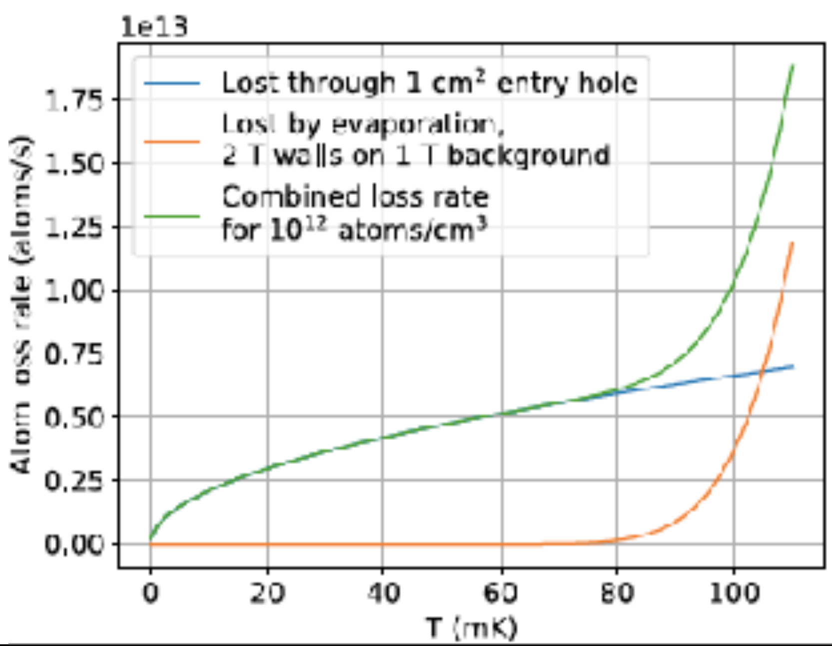
R&D for velocity/state selector

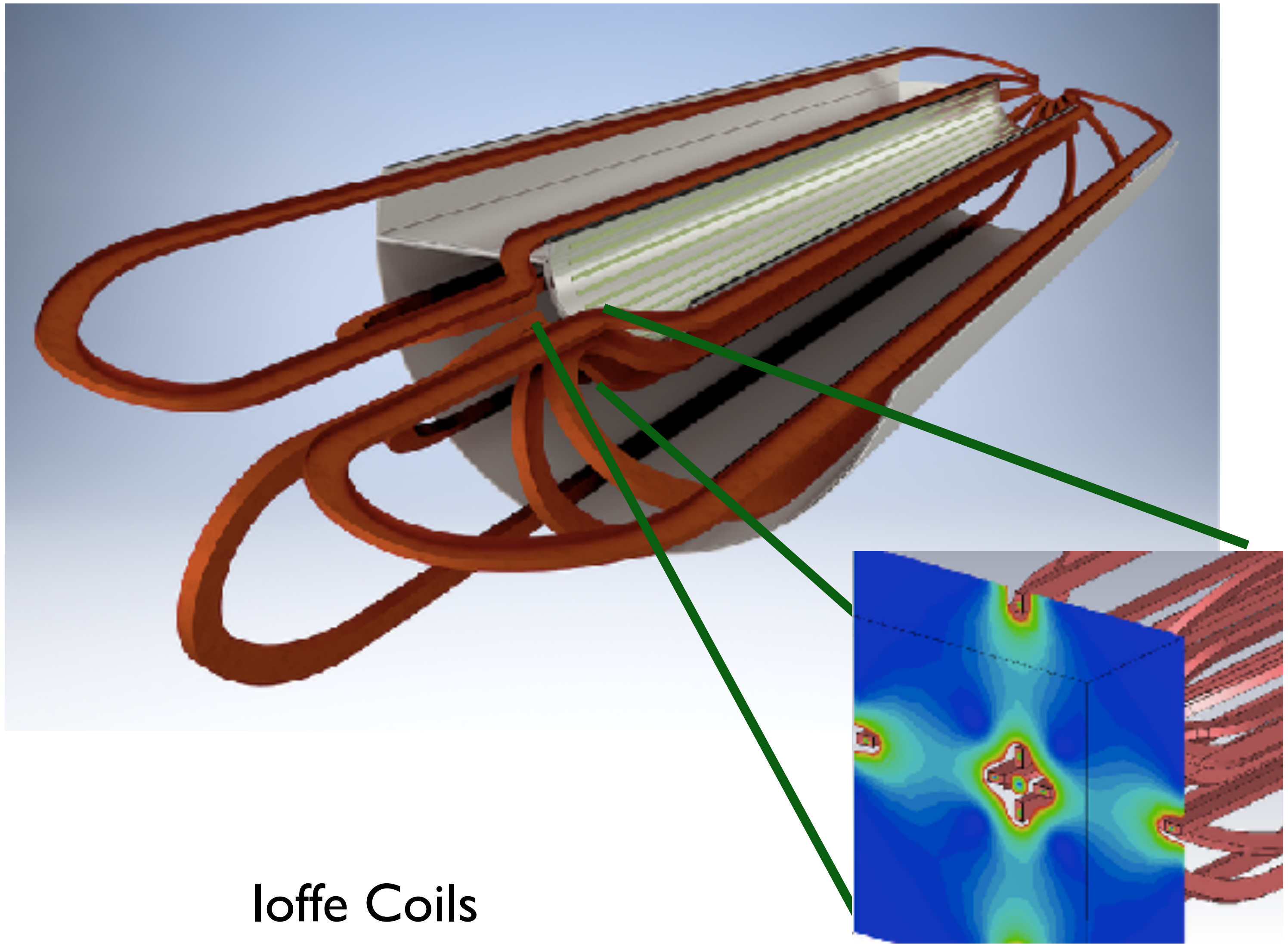
Quadrupole w/ skimmers



Trapping Atomic Tritium



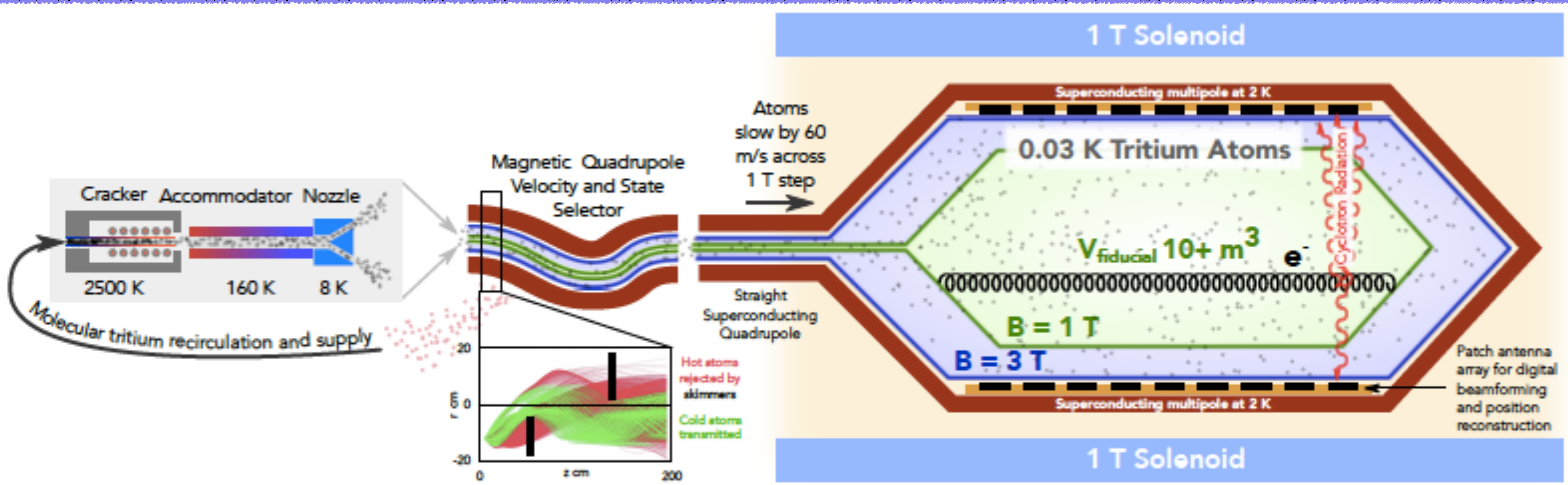




Pursuing an open Ioffe trap to contain tritium atoms at cold temperatures.

(Also exploring Halbach configuration for atom trapping)

Phase IV

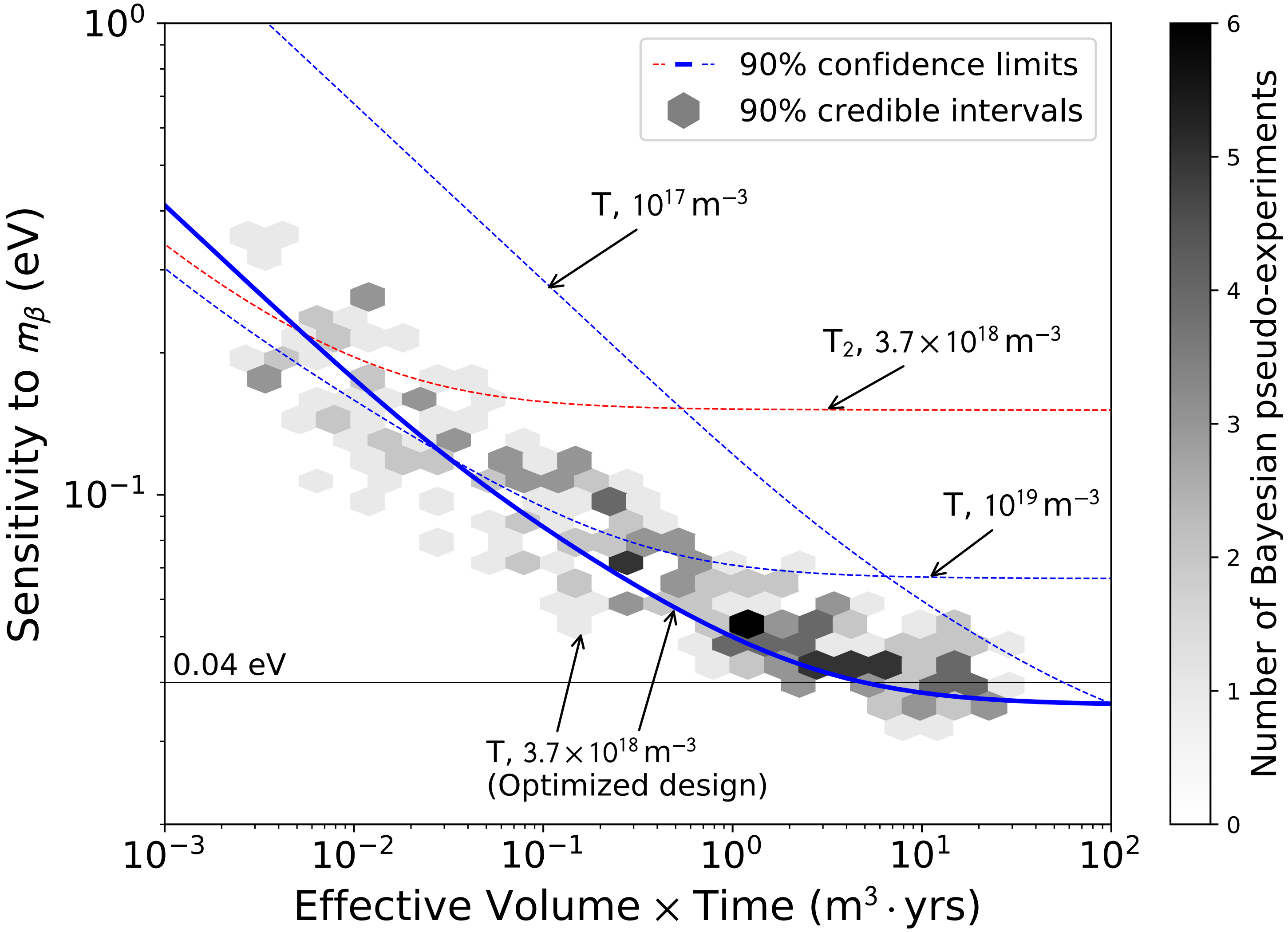


Ultimate atomic tritium experiment combines R&D from Phase III into large RF array tritium trap.

Atomic source, transport, and trap combined for large (m^3) instrumented volume.

Target Mass Sensitivity

m_β < 40 meV



Systematics and Sensitivity

Optimized density of 3.7×10^{18} atoms/m^3

Assume exposure of 5 m^3 y

Full Bayesian analysis

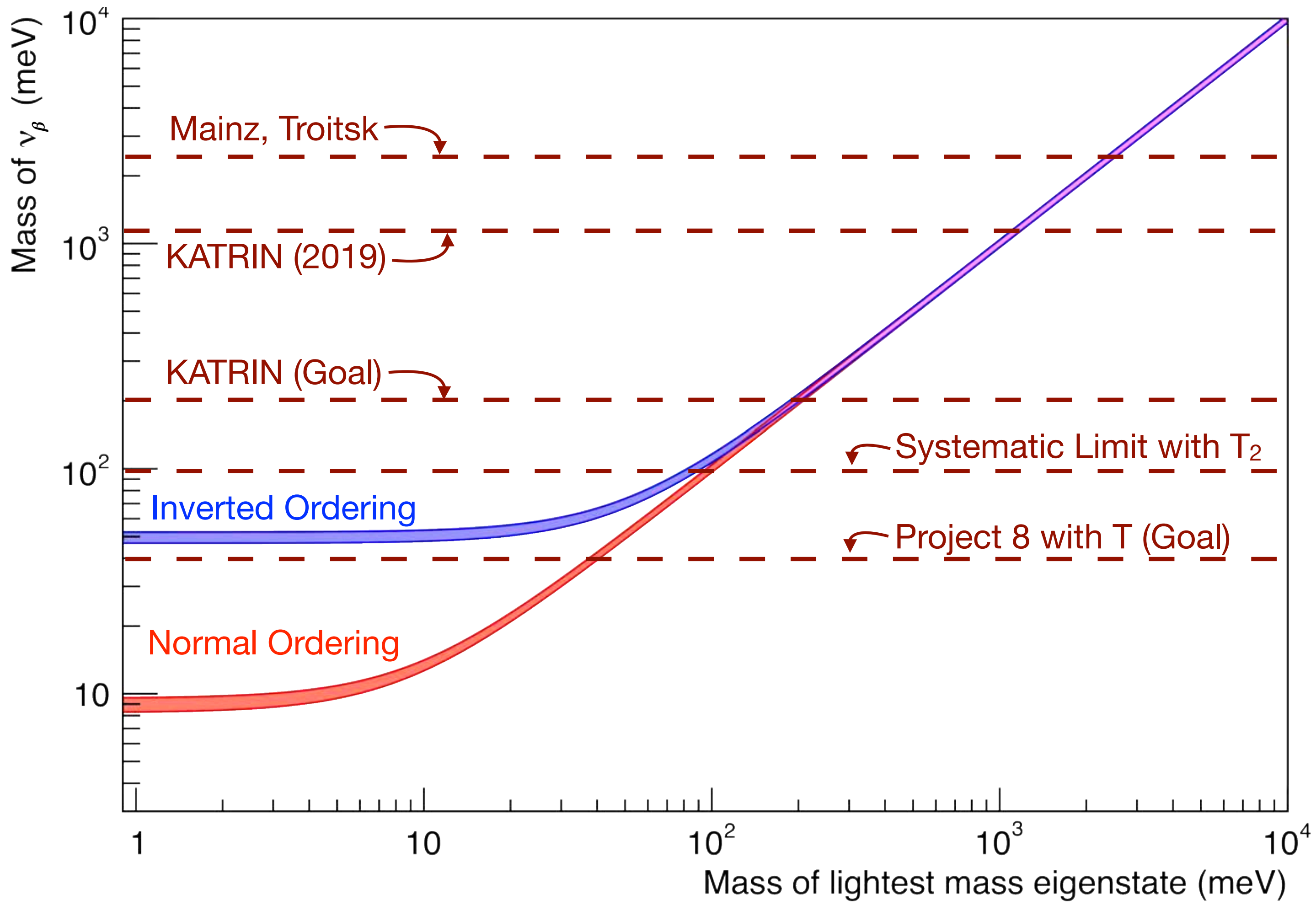
Magnetic field uniformity of 0.1 ppm

Optimal energy resolution:

$$\sigma_E \cong (115 \pm 2)\ \text{meV}.$$

Phase IV

Goal: Break into the inverted neutrino mass scale



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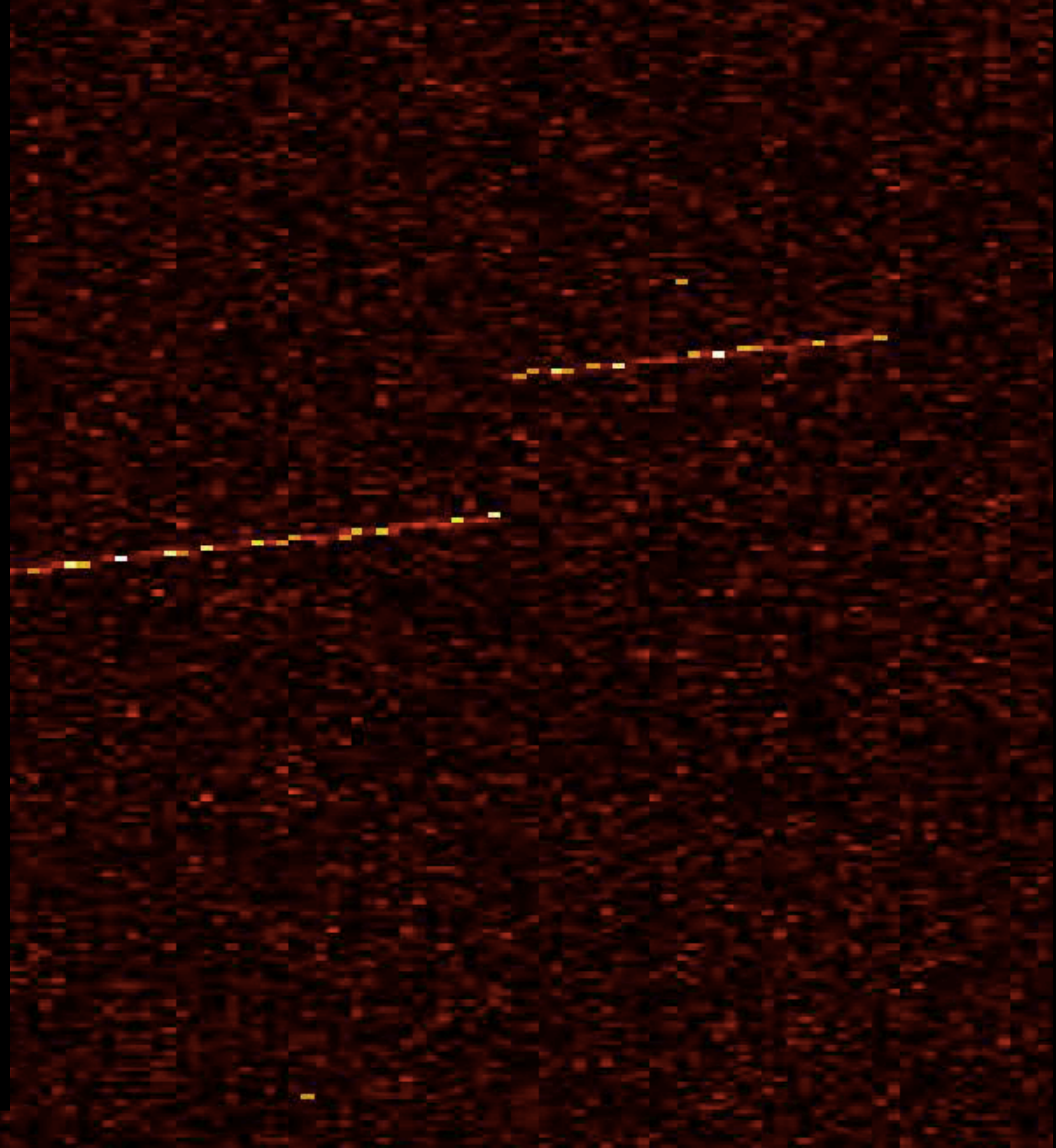
A Quick Summary

CRES can now be added as a demonstrated technique for studying beta decay.

Phase II has been completed, with better understanding on systematics.

CRES continues to expand, with the eventual target of using an atomic tritium source.



Thanks for
your attention!