Project 8

Determining the neutrino mass with Cyclotron Radiation Emission Spectroscopy

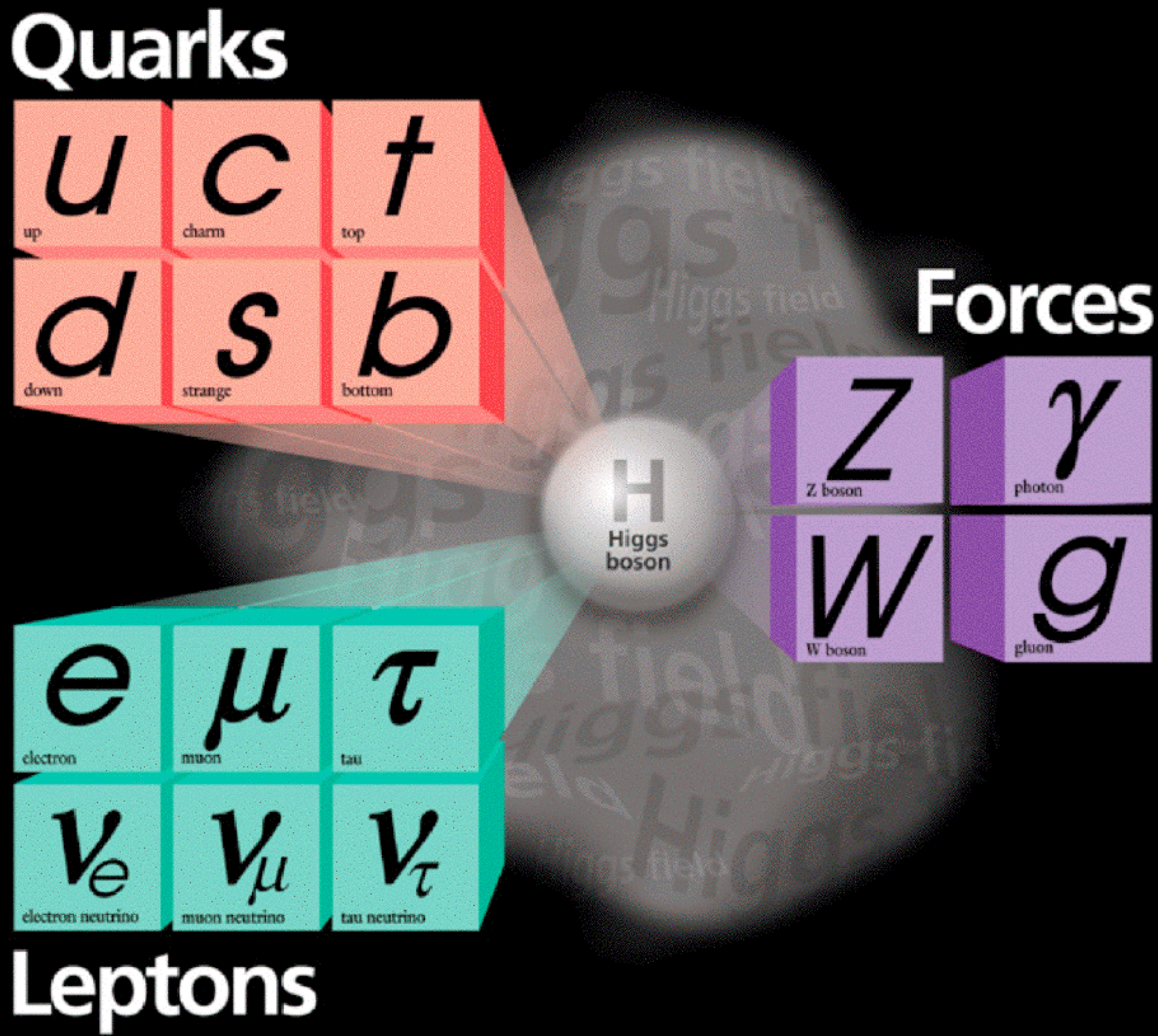
J. A. Formaggio
MIT
for the Project 8 Collaboration

An Admiral
Stockdale
Moment...

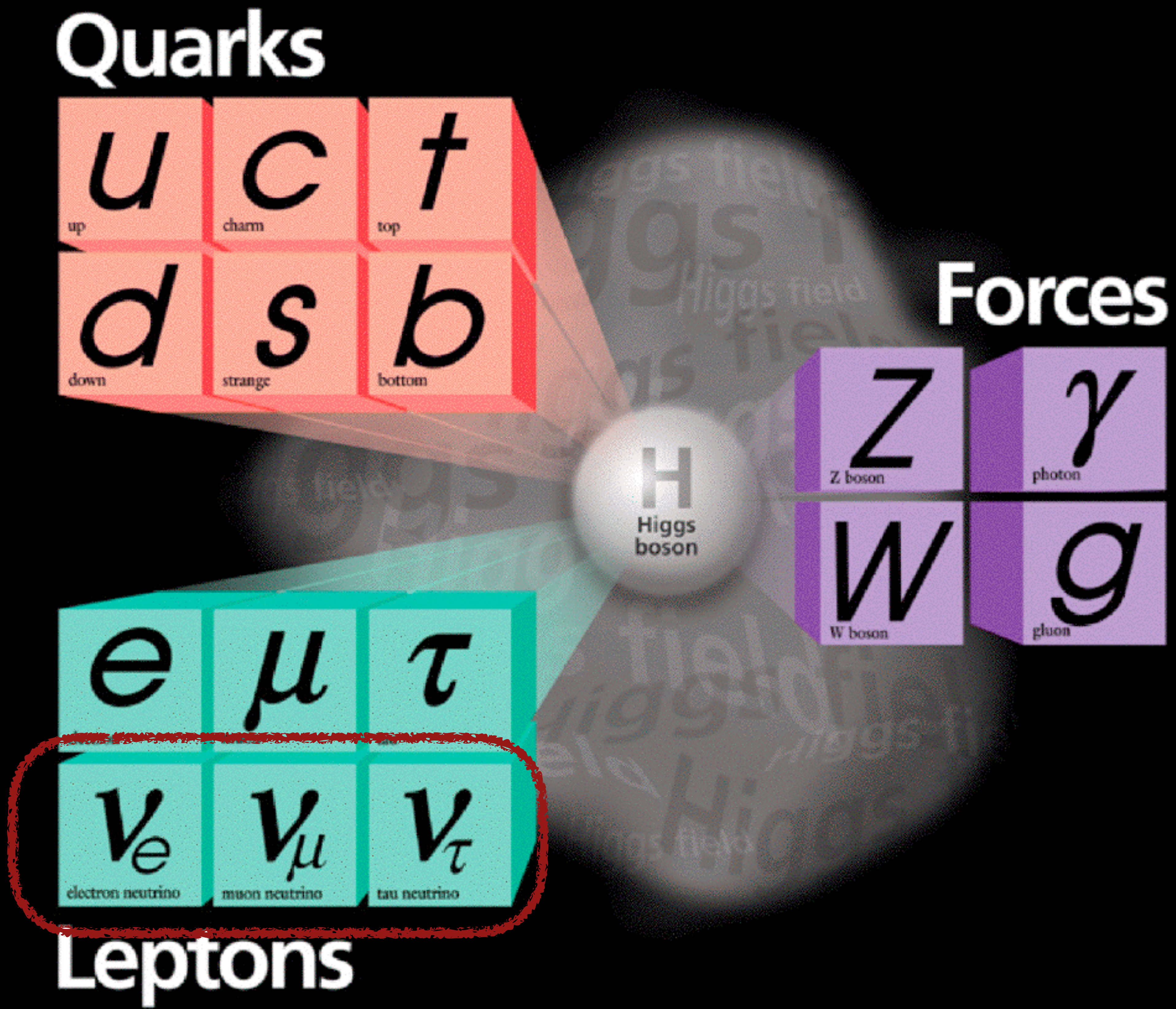
An Admiral Stockdale Moment…

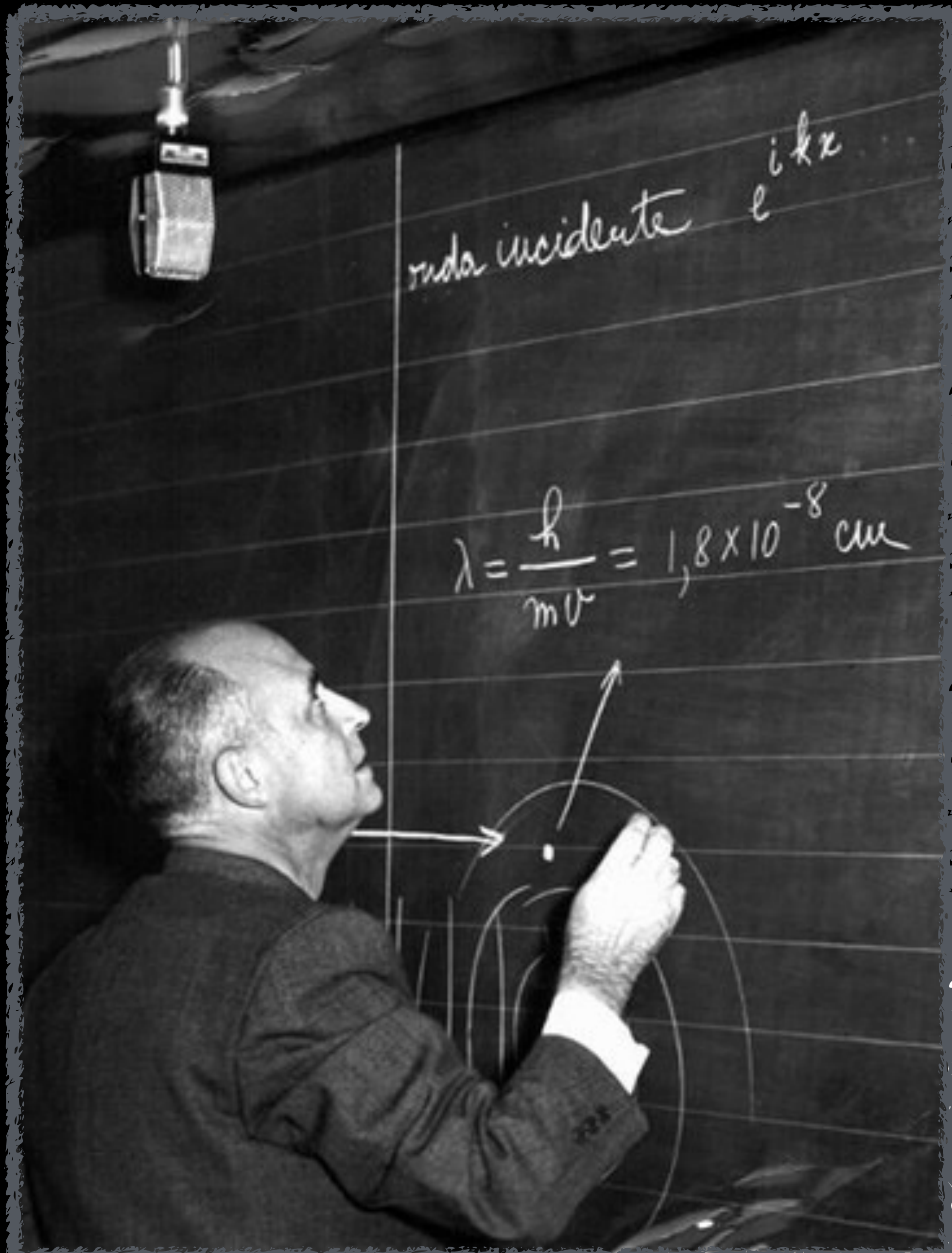
"Who am I? Why am I here?"

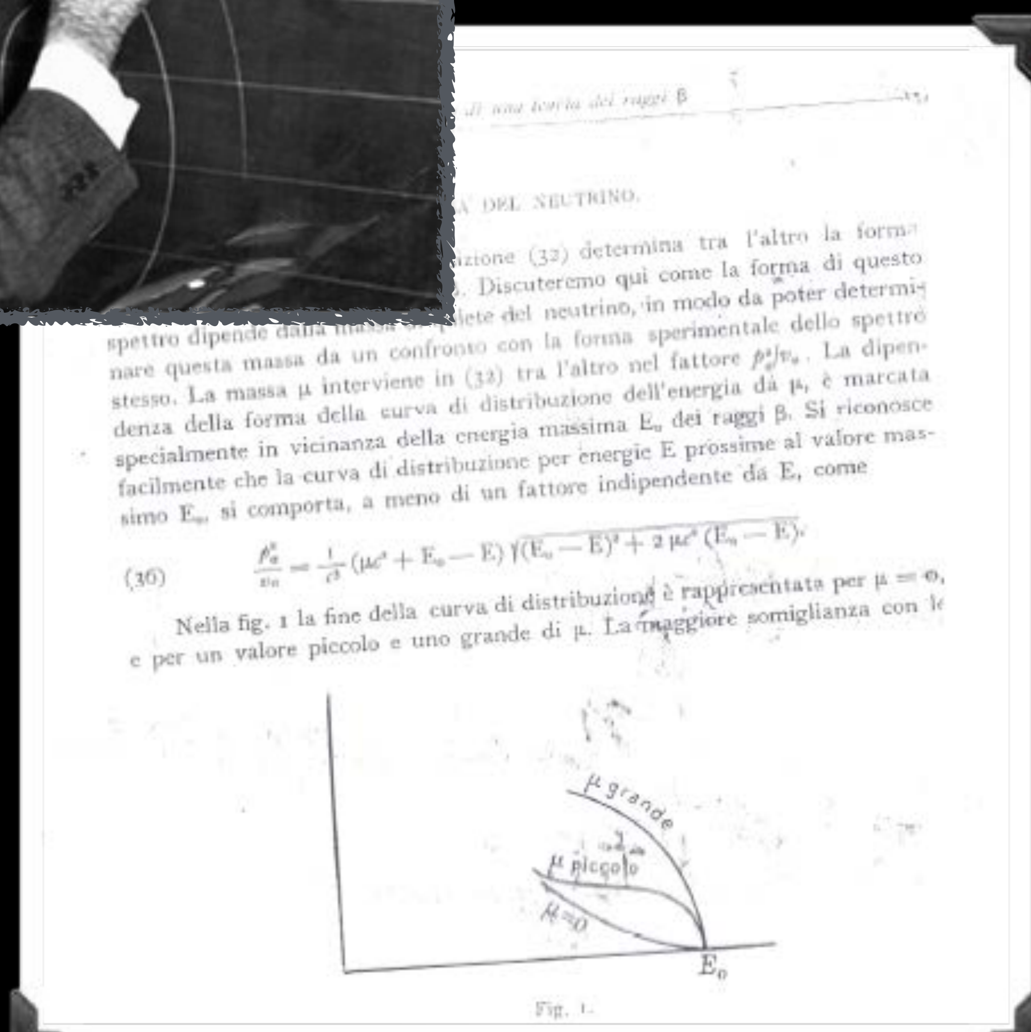
Our "Periodic" Table...



Our "Periodic" Table...







...di una teoria dei raggi β

...A DEL NEUTRINO.

...zione (32) determina tra l'altro la forma ... Discuteremo qui come la forma di questo spettro dipende dalla massa ... del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_ν^2/v_ν. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

(36) $$\frac{p_\nu^2}{v_\nu} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

Since the beginning, the neutrino was an odd one...

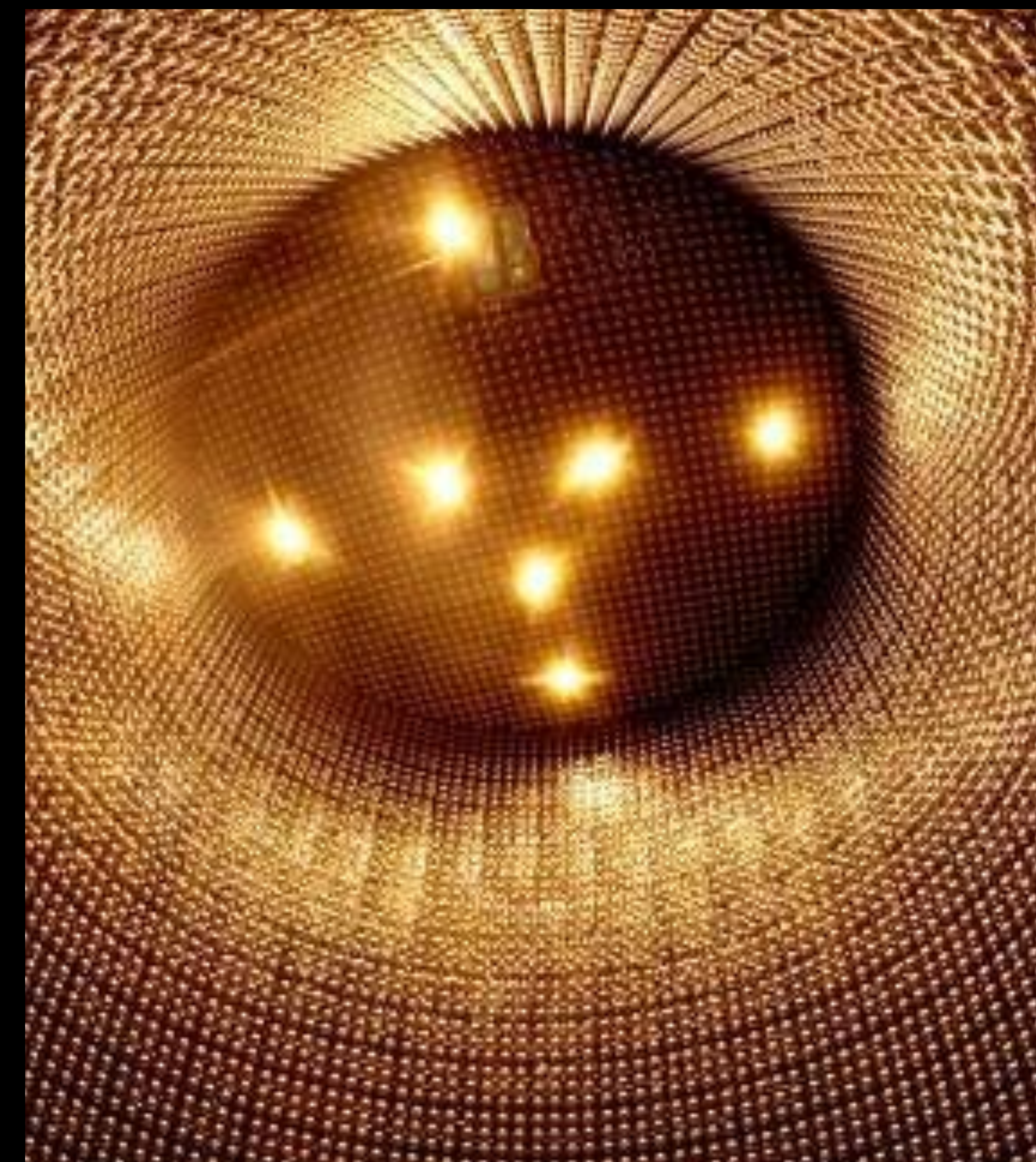
Neutrino mass measurements have a long history in physics, predating the Standard Model itself.

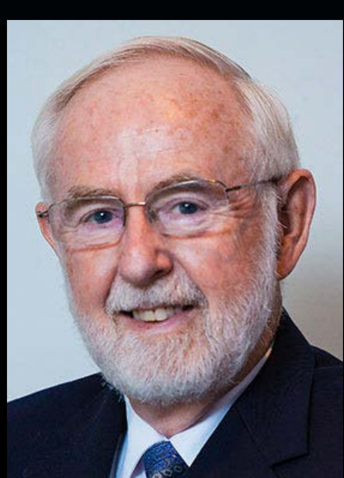
It should therefore be no surprise that our quest to understand this fundamental property continues; both for its own right as well as its theoretical implications.

With oscillations firmly in place, we at least understand that the neutrino has a mass

As such, oscillation measurements place a lower limit on the neutrino mass scale.

2015 Nobel Prize in Physics

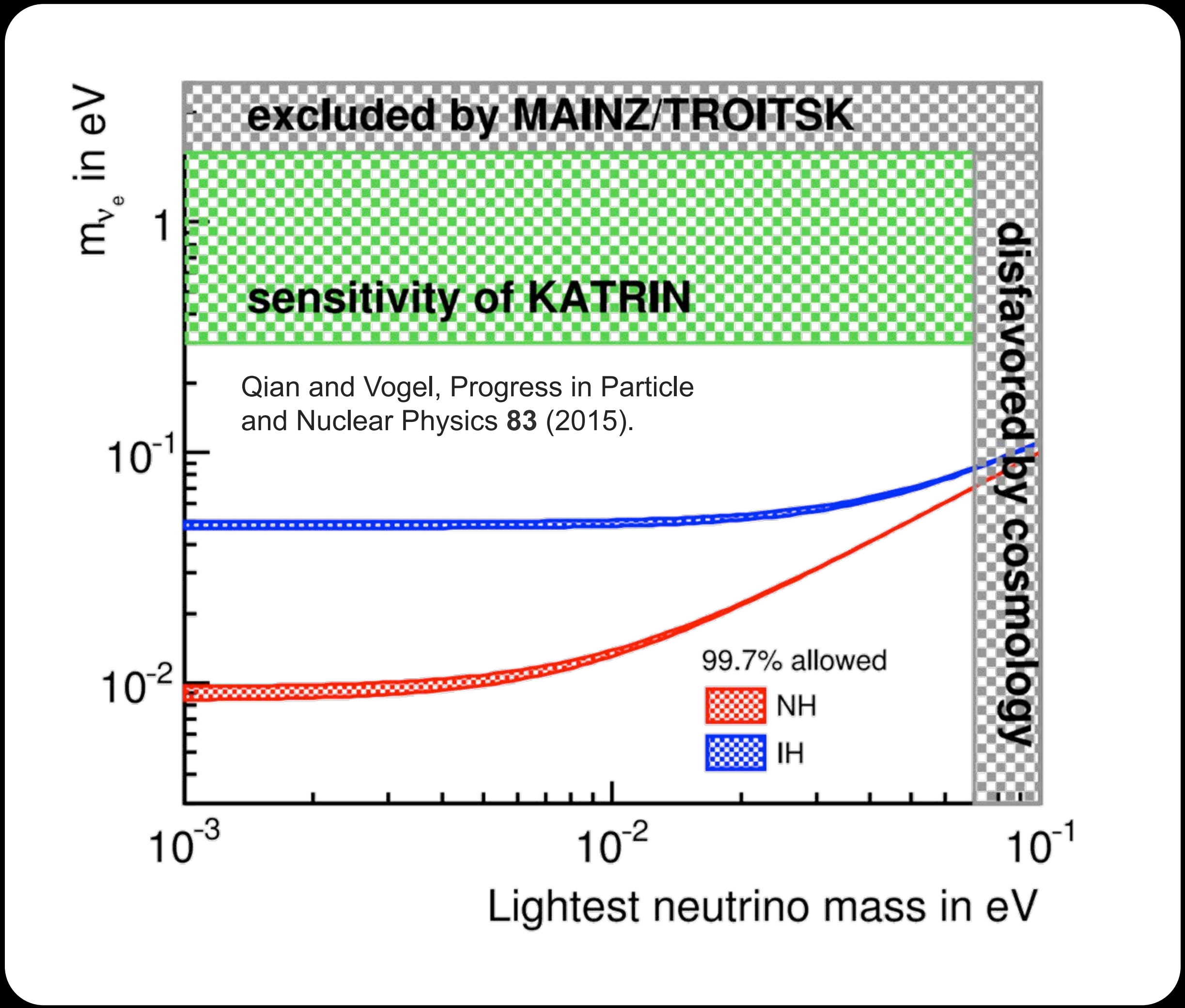




Arthur B. McDonald
(Sudbury Neutrino Observatory)

Takaaki Kajita
(Super-Kamiokande)

The legacy...



$$M = \sum_{i}^{n_\nu} m_{\nu,i}$$

Cosmological Measurements

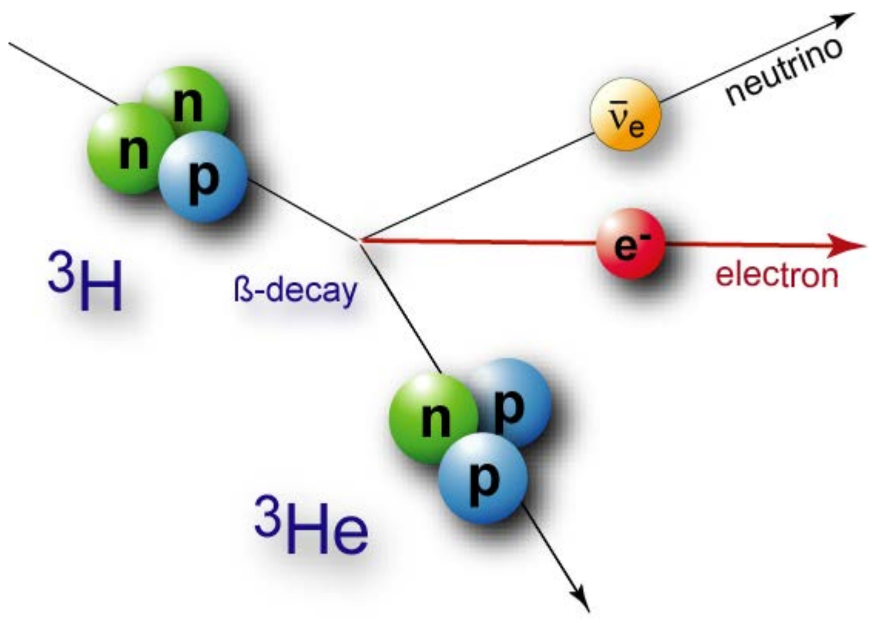
$$\langle m_{\beta\beta}^2 \rangle = \left| \sum_{i}^{n_\nu} U_{ei}^2 m_{\nu,i} \right|^2$$

0νββ Measurements

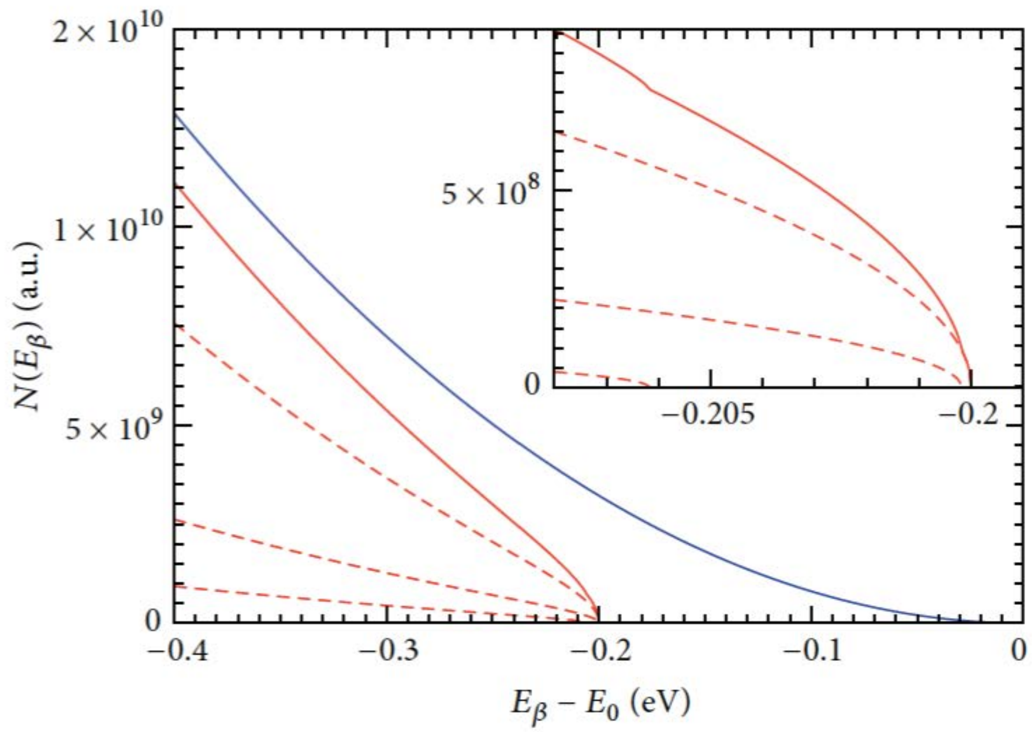
$$\langle m_\beta \rangle^2 = \sum_{i}^{n_\nu} | U_{ei} |^2 \, m_{\nu,i}^2$$

Beta Decay Measurements

$$\dot{N} \sim p_e(K_e + m_e) \sum_i |U_{ei}|^2 \sqrt{E_0^2 - m_{\nu i}^2}$$



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



Look for a kink in the electron spectrum

Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Project 8

Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

PROJECT 8

Frequency Approach

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

"If you are going to measure anything with precision, measure frequency ! "

A. L. Schawlow

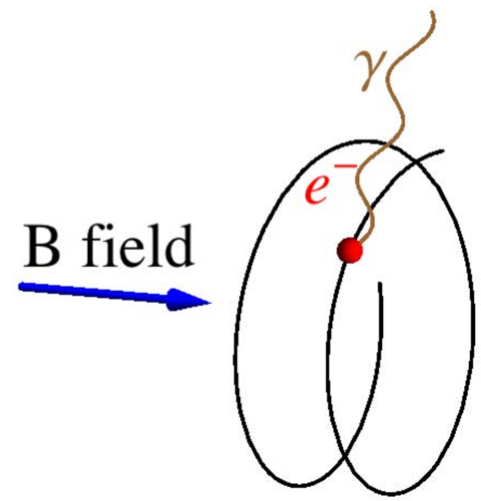
CRES Technique

Novel technique of Cyclotron Radiation Emission Spectroscopy (CRES):

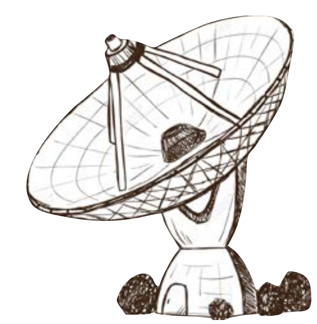
- Cyclotron radiation from single e^- in magnetic field
- Source gas transparent to microwave radiation
- No e^- transport from source to detector (gas scattering)
- Highly precise frequency measurement

"If you are going to measure anything with precision, measure frequency ! "

A. L. Schawlow



$$f_c = \frac{1}{2\pi} \frac{eB}{m_e + K/c^2}$$



For 1 T field, emission is at 26 GHz.

Techniques common to radio astronomy can be used for signal detection.

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

Long Time Prediction...

The idea that accelerating electrons emit radiation dates back to 1897 (Larmor)

The Radiation from an Electron describing a Circular Orbit.

THE complete formula for the radiation may be useful to some of those who are now indulging in atomic speculations. It is derived from the general formula I gave a year ago in NATURE (October 30, 1902), expressing the electromagnetic field everywhere due to an electron moving anyhow. Put in the special value of R required, which is a matter of elementary geometry, and the result is the complete finite formula. But only the part depending on R^{-1} is required for the radiation; and, in fact, we only want the r^{-1} term (if r = distance from the centre of the orbit), if the ratio of the radius of the orbit to the distance is insensible, and that, of course, is quite easy, on account of the extreme smallness of electronic orbits. The magnetic force is given by

$$H_\phi = \frac{Qun}{4\pi r v}\alpha^3 \cos\theta \cos\phi_1, \qquad (1)$$

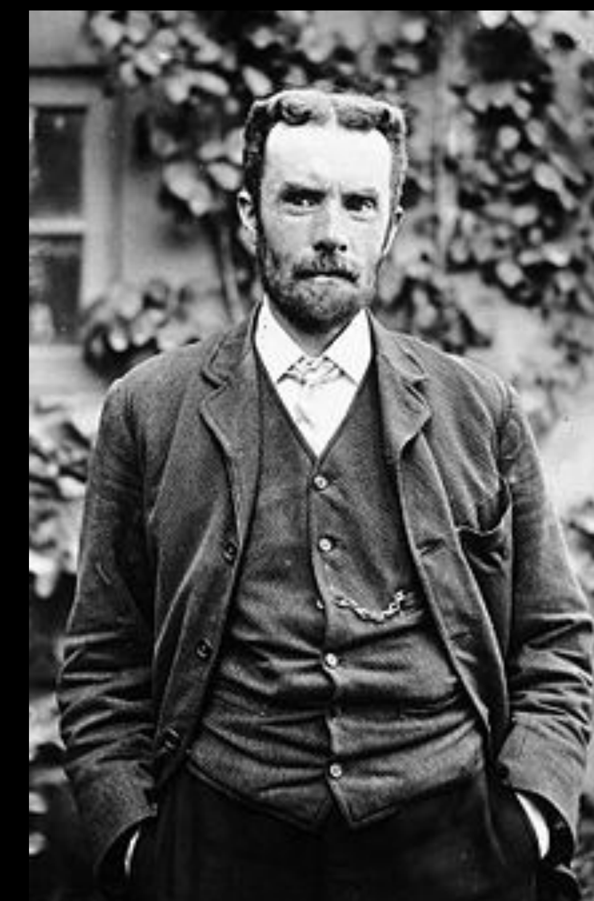
$$H_\theta = \frac{Qun}{4\pi r v}\alpha^3(\sin\phi_1 - \beta), \qquad (2)$$

subject to

$$\alpha = \frac{1}{1-\beta\sin\phi_1}, \quad \beta = \frac{u}{v}\sin\theta, \qquad (3)$$

$$\phi_0 = \phi_1 + \beta\cos\phi_1 = \phi - nt + nr/v. \qquad (4)$$

There is no limitation upon the size of u/v, save that it must be less than 1. But there is a limitation regarding



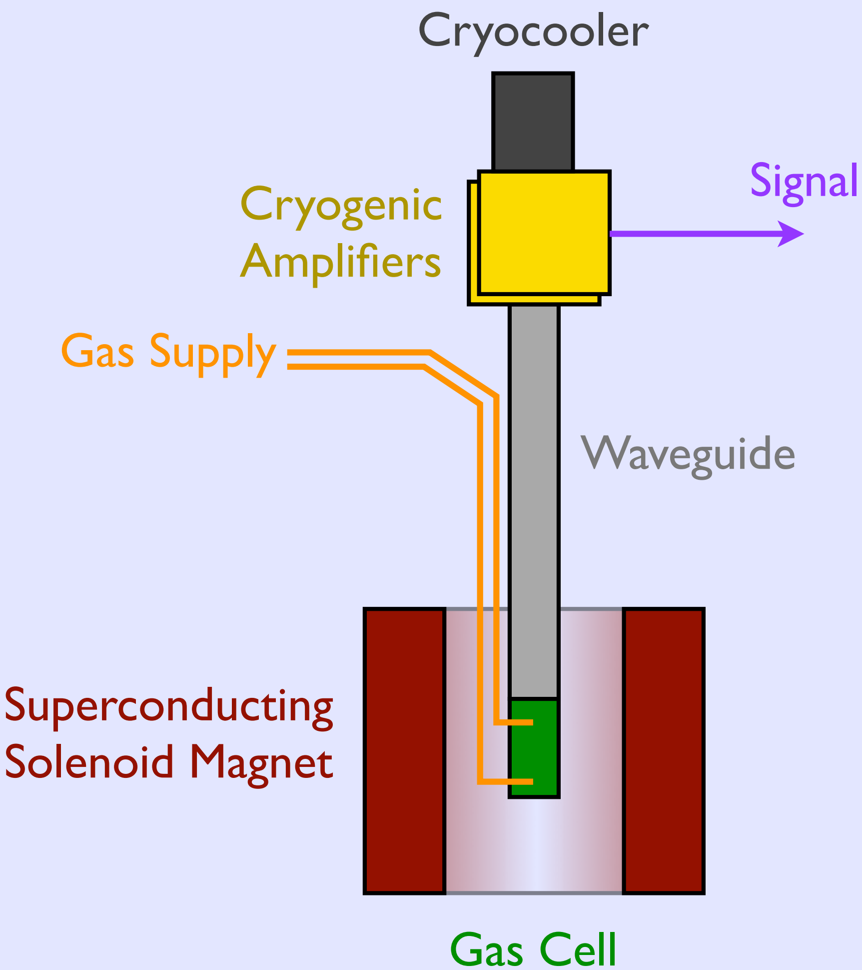
Cyclotron emission itself can be traced back to O. Heaviside (1904). Yet, single electron detection had not been exploited.

Basic Layout of Our Prototype

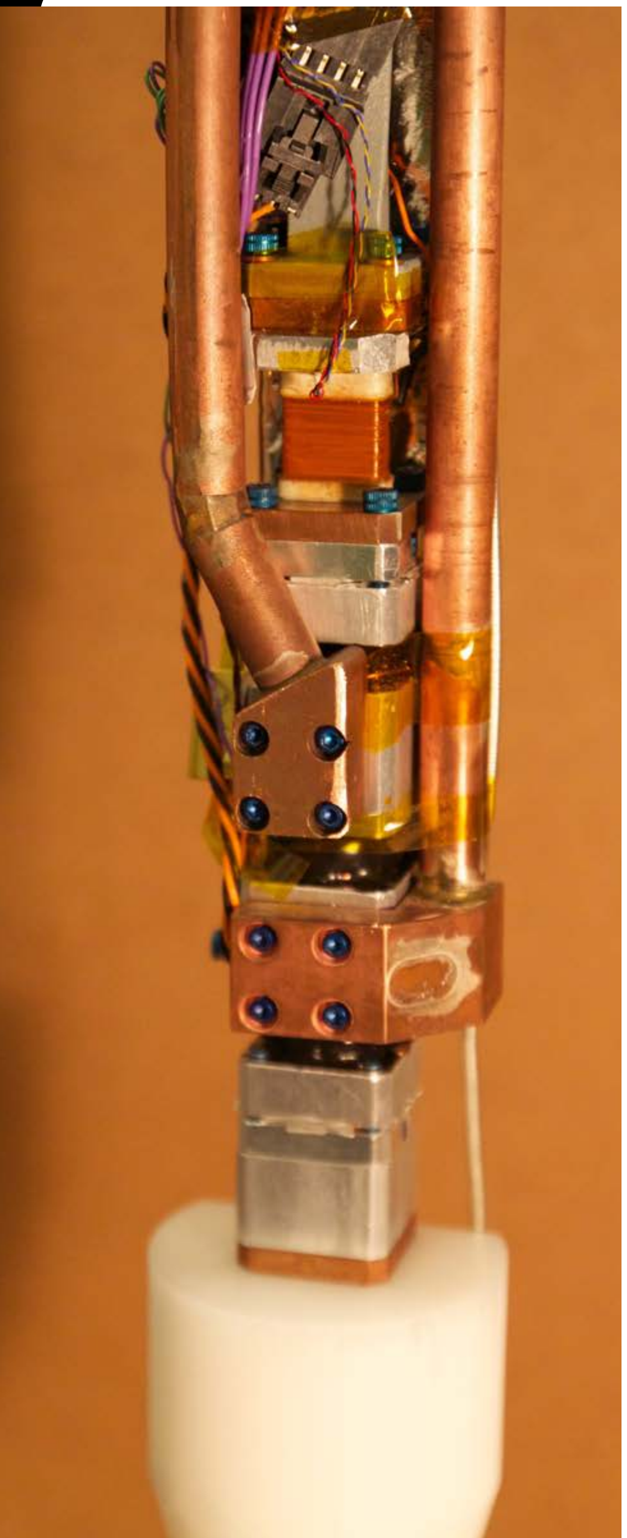
- **Gas/Electron System**
  Provides mono-energetic electrons for signal detection.

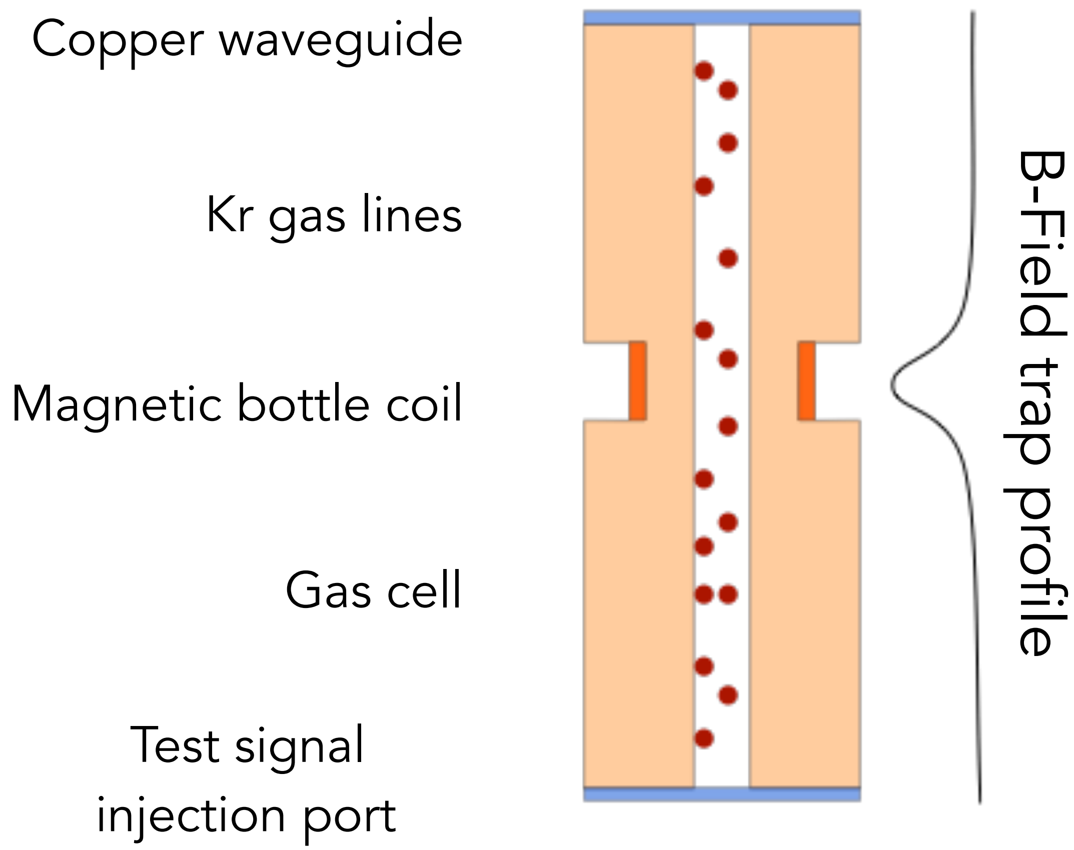
- **Magnet System**
  Provides magnetic field and trapping of electrons.

- **RF Detection/Calibration System**
  Detection of microwave signal.



The Apparatus



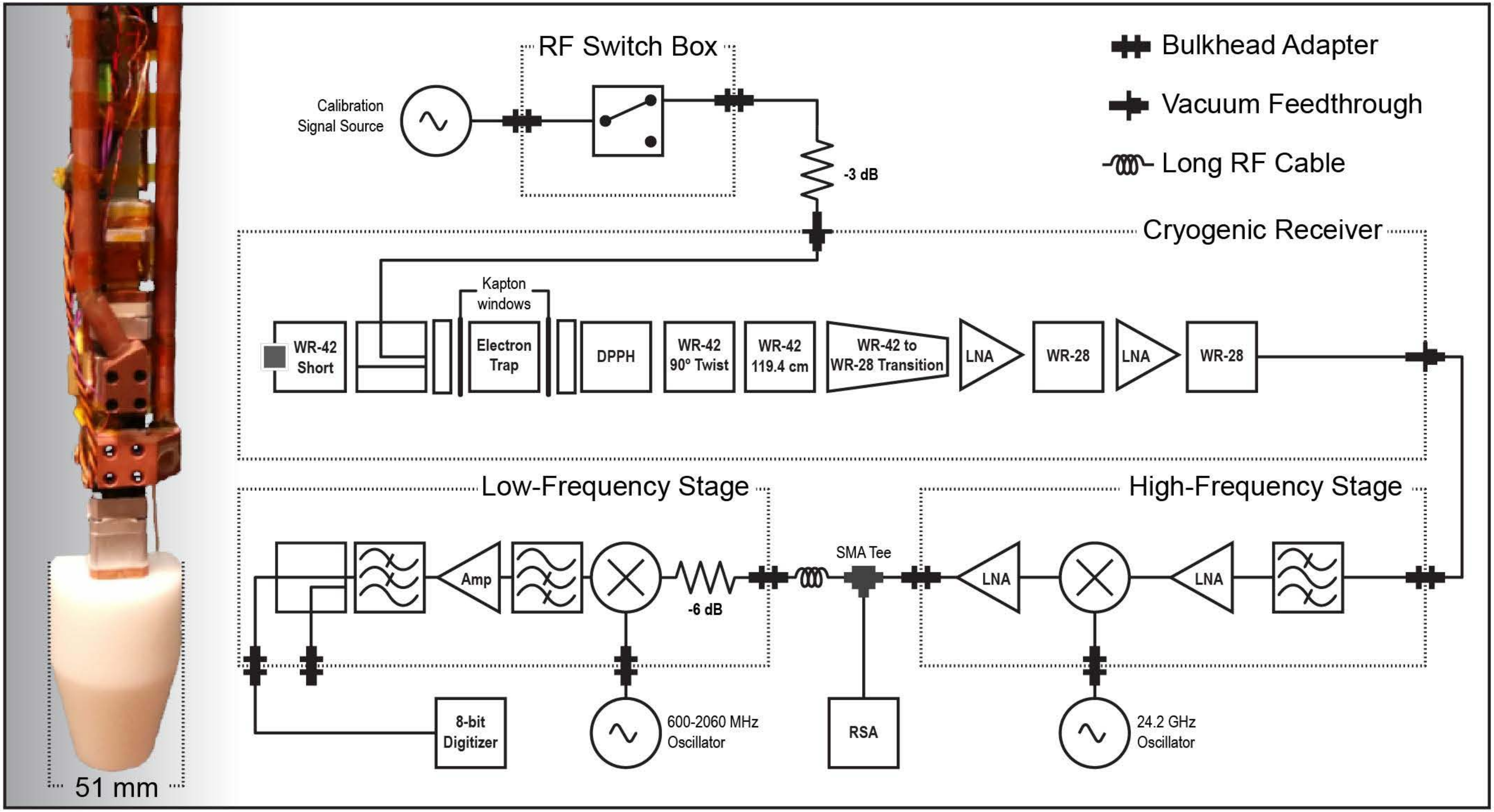


Waveguide Cut-away

Photo of apparatus

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

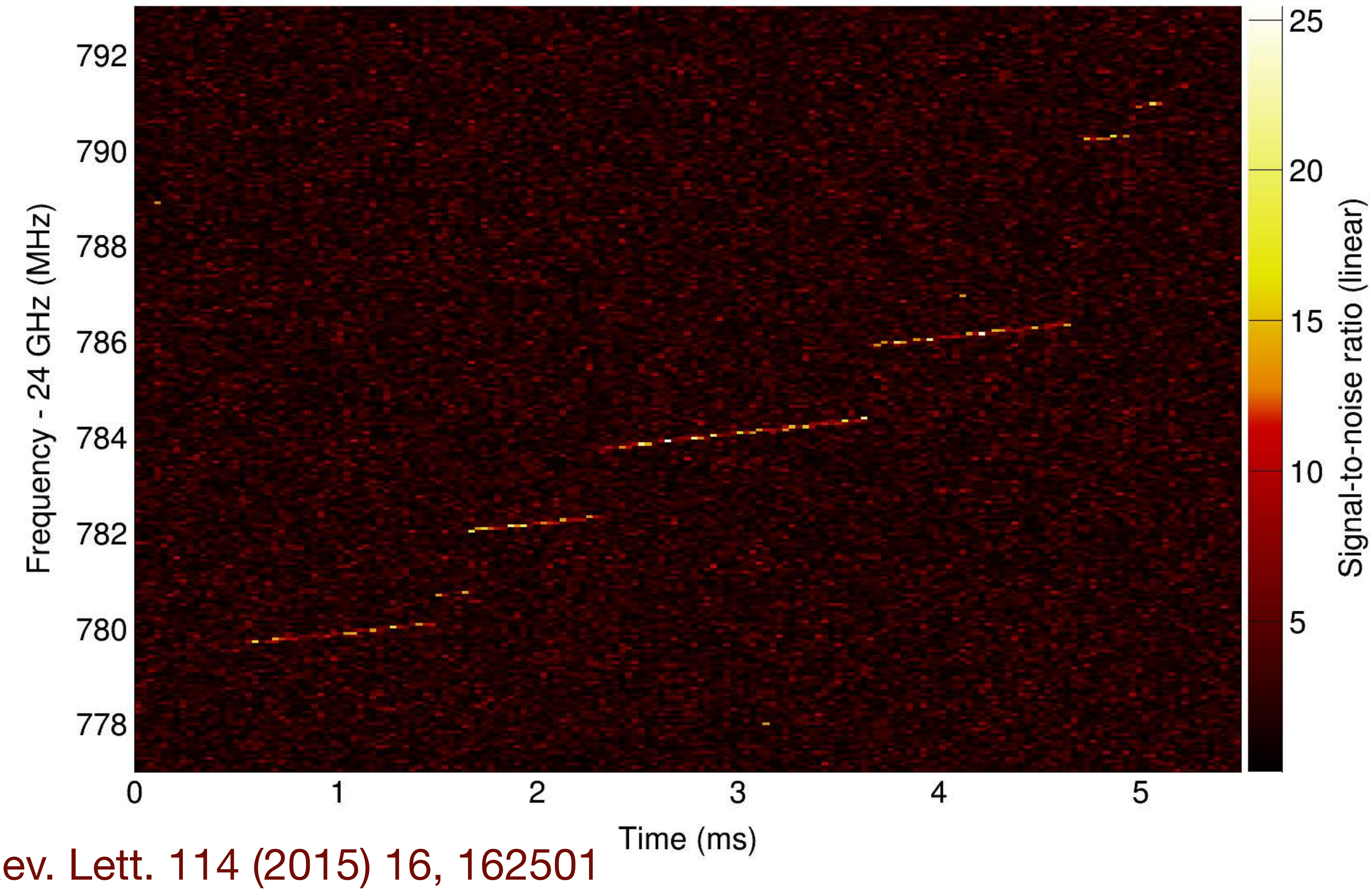
Magnetic bottle allows for trapping of electron within cell for measurement.



Waveguide Detector

Phase I setup is a waveguide setup for single electron detection (about 1 fW power emission)

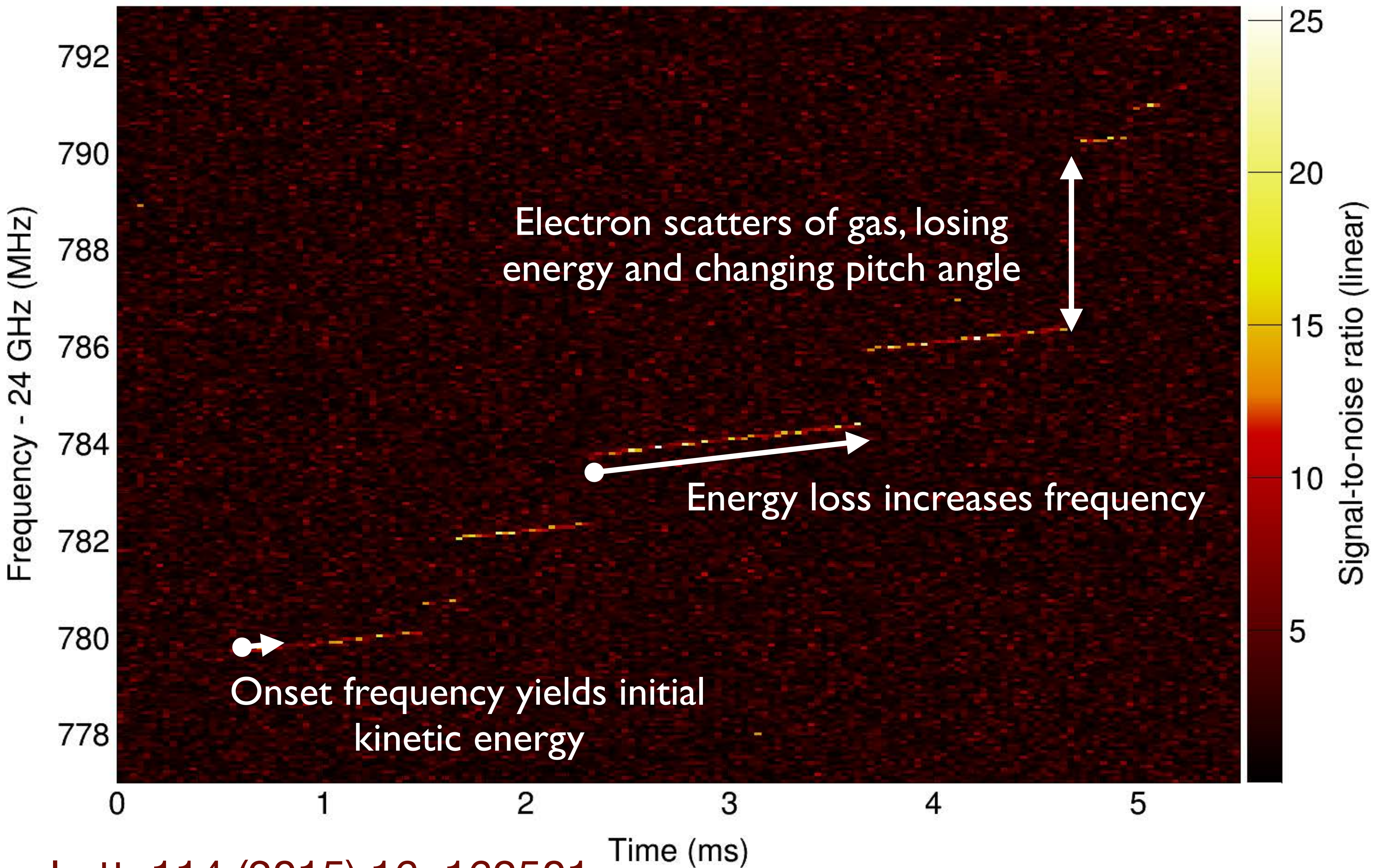
Project 8's "Event Zero"



Phys. Rev. Lett. 114 (2015) 16, 162501

Cyclotron Radiation Emission Spectroscopy (CRES) for single relativistic electrons now experimentally demonstrated.

Project 8's "Event Zero"

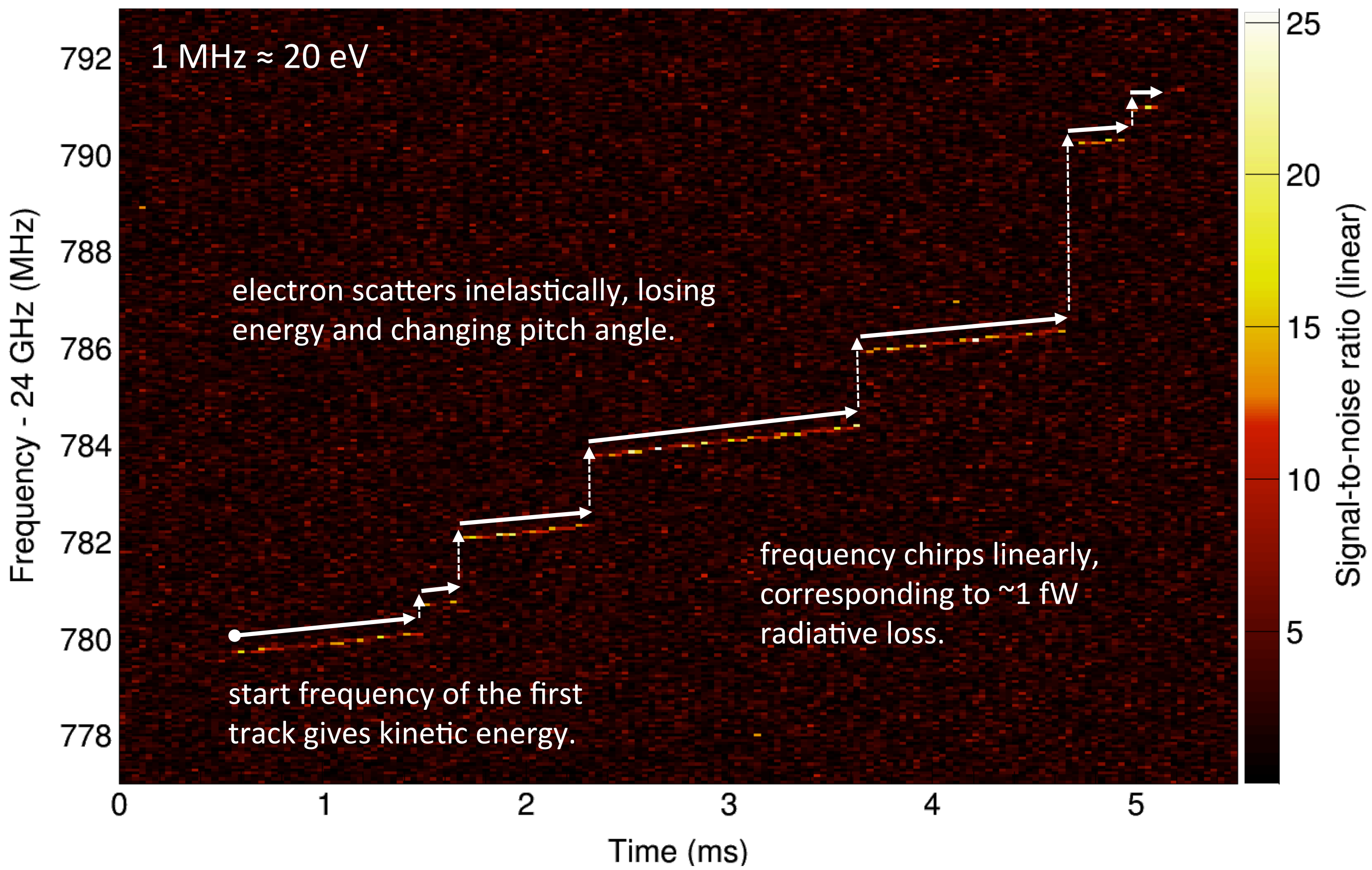


Phys. Rev. Lett. 114 (2015) 16, 162501

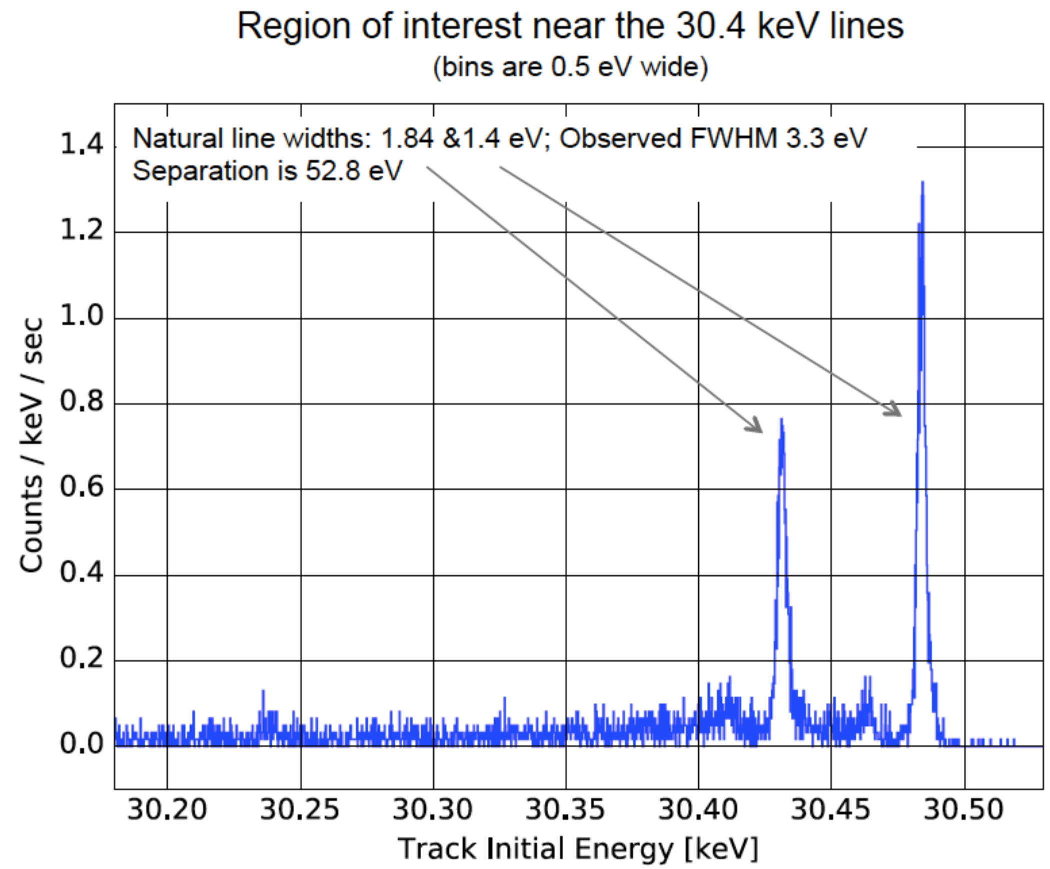
Exhibits all predicted characteristics:

- Onset frequency
- Energy loss due to cyclotron radiation
- Quantum jumps due to inelastic scattering

High Resolution Achieved



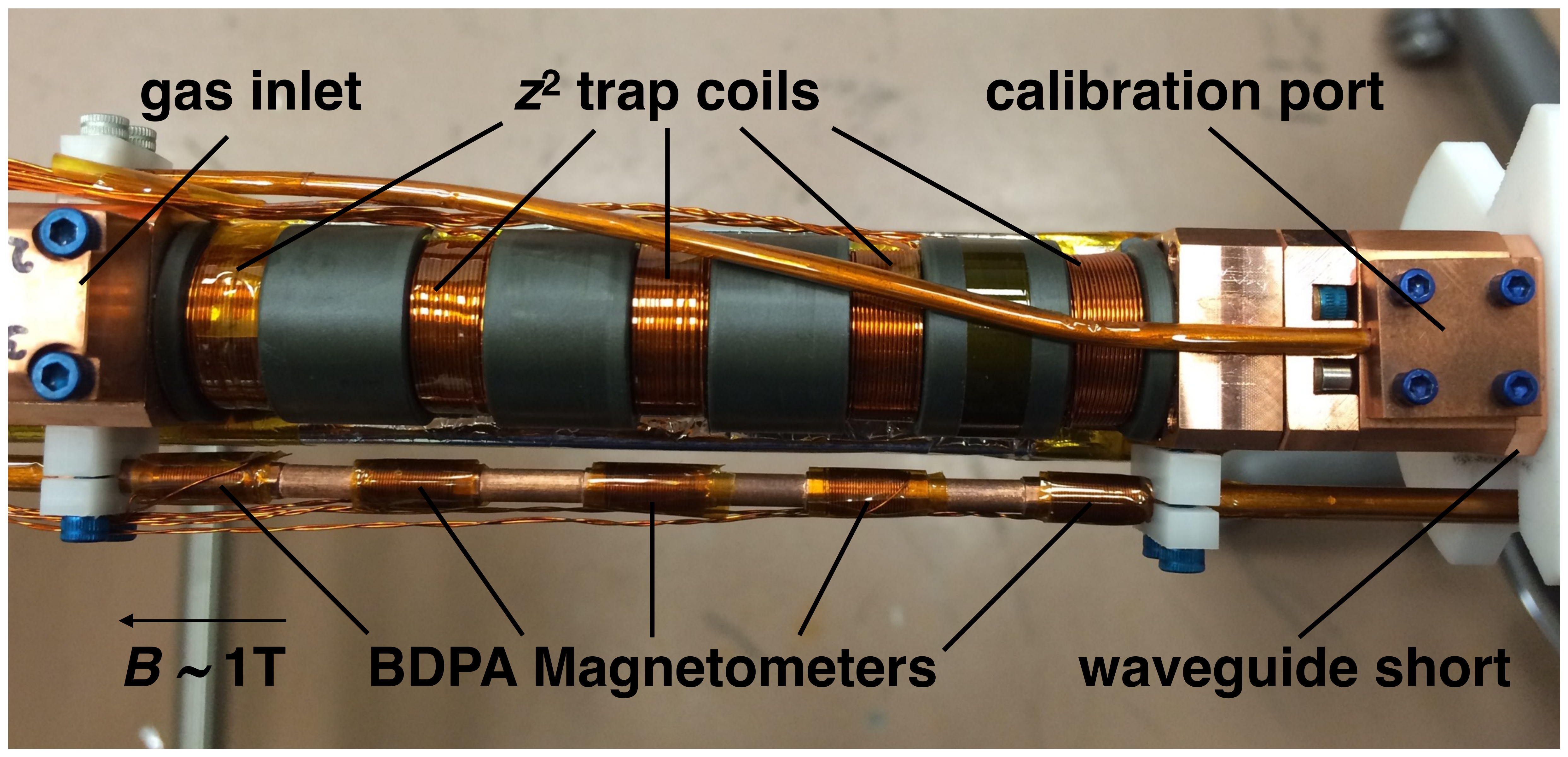
Imaging of single electrons, including scattering



Improved resolution (~3.6 eV at 30 keV)

Imaging of mono-energetic electrons show excellent precision and resolution of expected electron lines (about 3.6 eV FWHM).

Shown to be a powerful spectroscopic tool for radioactive gasses.

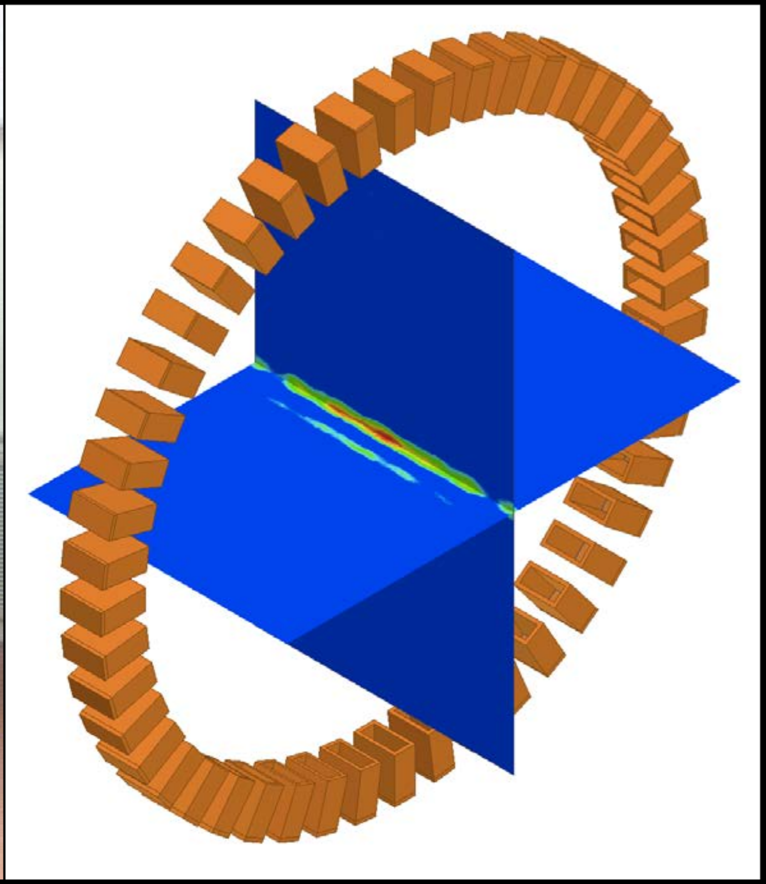


We are now moving toward a competitive neutrino mass measurement using this technique.

Next Stage:
Phase II
(Tritium Cell)

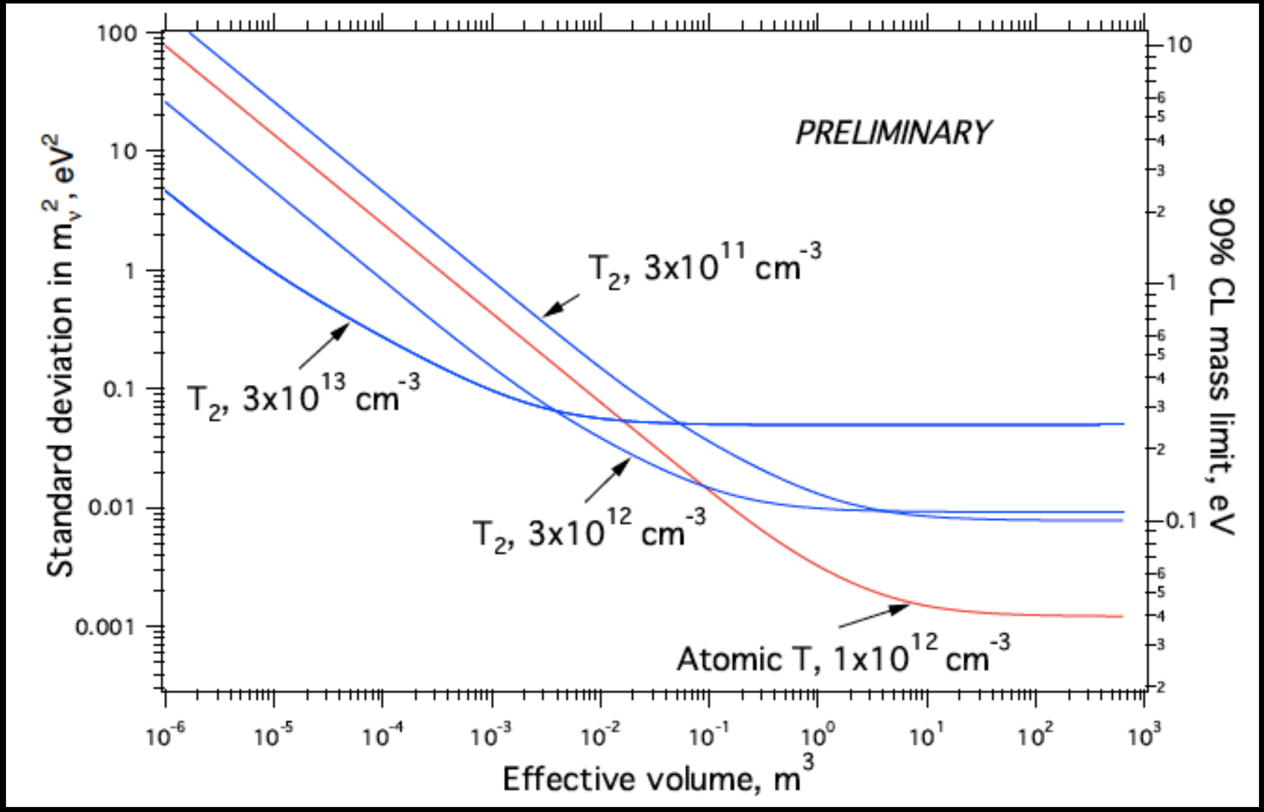
First tritium run starts this year.

Final Goals



Phase III

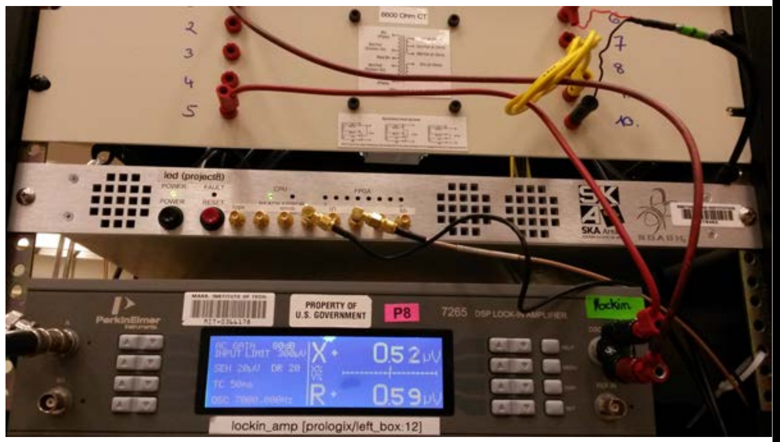
- Multiple antennas to provide detection in large volume.
- Sensitivity goal of ~ 2 eV.



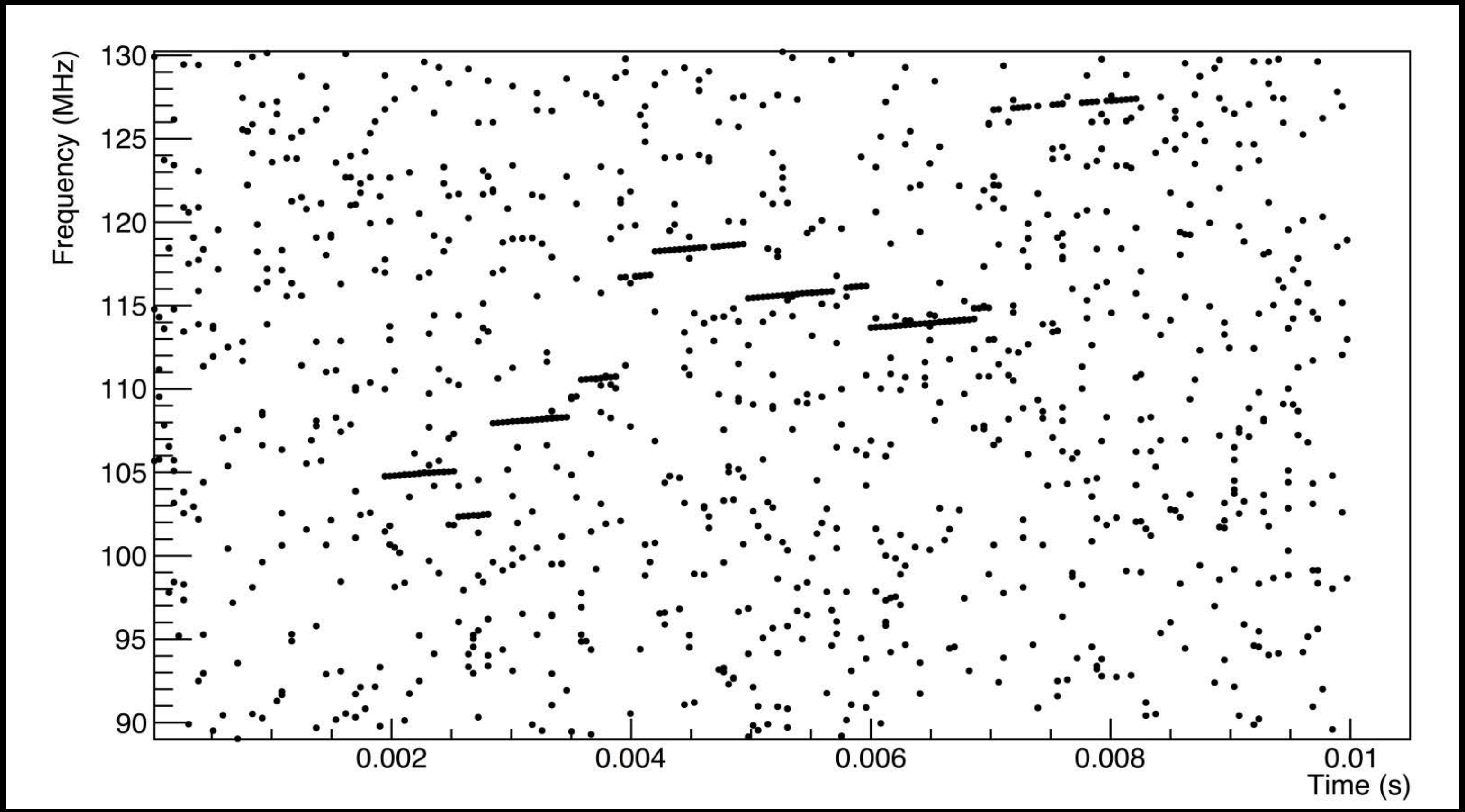
Phase IV

- Move to large volume (m^3) atomic tritium target.
- Goal to reach inverted mass ordering scale.

The Radio Astronomy Overlap



ROACH2 planned for Phase II data taking



Complex frequency event reconstruction, multiple antennas.

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Sebastian Boser, Christine Claessens, Alec Lindman

Karlsruhe Institute of Technology

Thomas Thummler

Lawrence Livermore National Laboratory

Kareem Kazkaz

Massachussetts Institute of Technology

Joseph Formaggio, Evan Zayas

Pacific Northwest National Laboratory

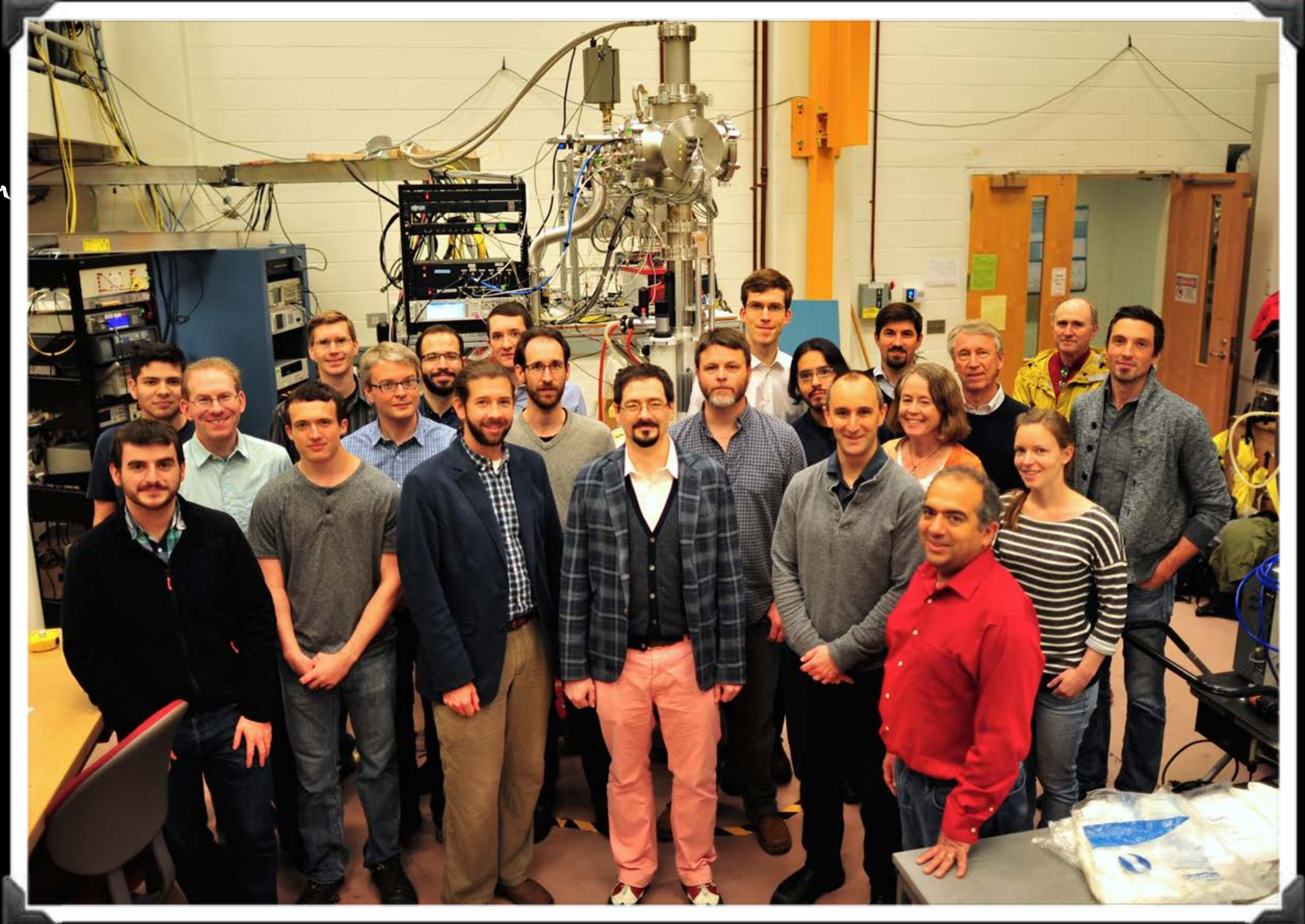
Erin Finn, Mathieu Guigue, Mark Jones, Noah Oblath, Jonathan Tedeschi, Brent VanDevender

Smithsonian Astrophysical Observatory

Shep Doeleman, Jonathan Weintroub, Andre Young

University of California, Santa Barbara

Luiz de Viveiros, Benjamin LaRoque, Benjamin Monreal



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