Beta Decay & The Path to Neutrino Masses

Fermilab Neutrino Seminar Series
March 12th 2015

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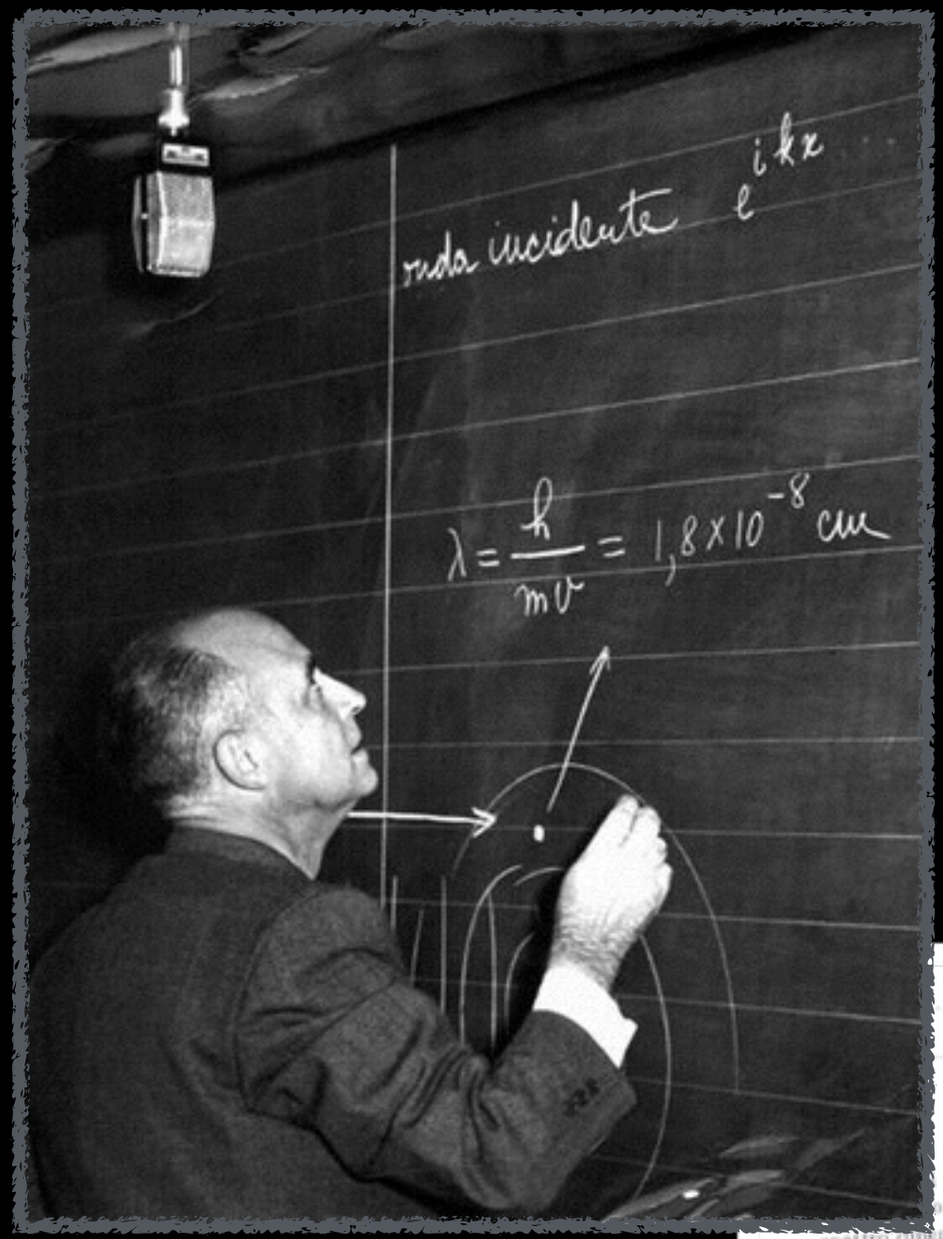
MIT



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.

50 a. 2. Tentativo di una teoria dei raggi β

LA MASSA DEL NEUTRINO.

probabilità di transizione (32) determina tra l'altro la forma
continuo dei raggi β. Discuteremo qui come la forma di questo
spettro dipende dalla massa di quiete del neutrino, in modo da poter determi-
nare questa massa da un confronto con la forma sperimentale dello spettro
stesso. La massa μ interviene in (32) tra l'altro nel fattore p_0^2/v_0. La dipen-
denza 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 mas-
simo E_0, si comporta, a meno di un fattore indipendente da E, come

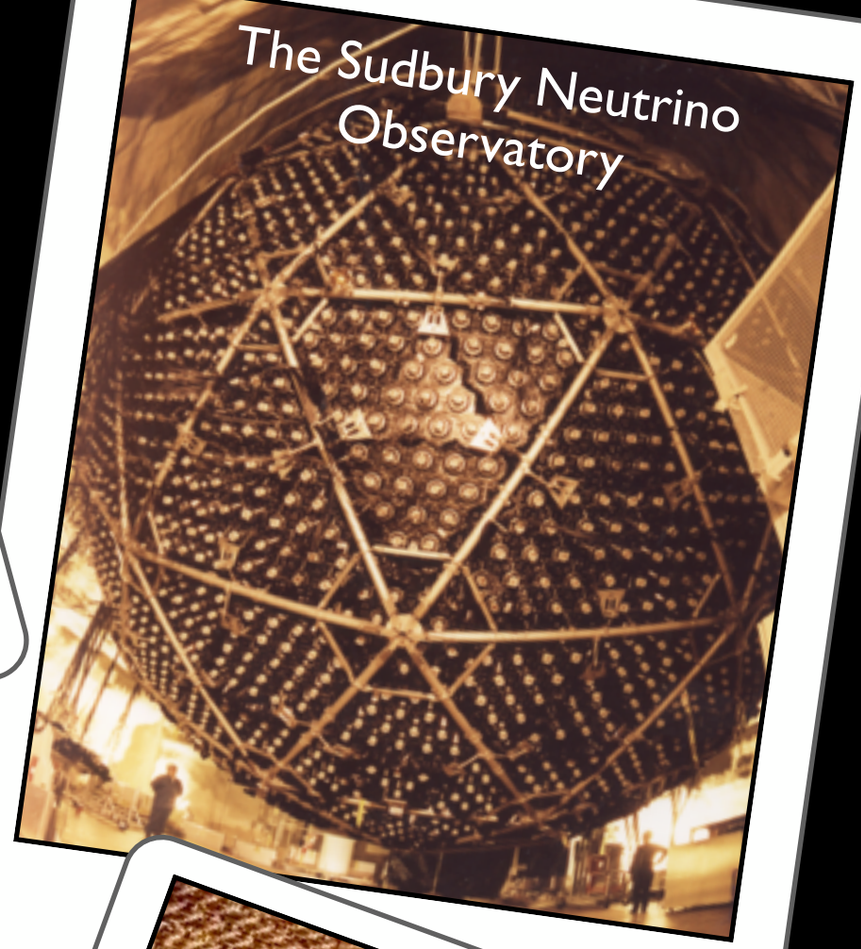
$$\frac{p_0^2}{v_0} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \tag{36}$$

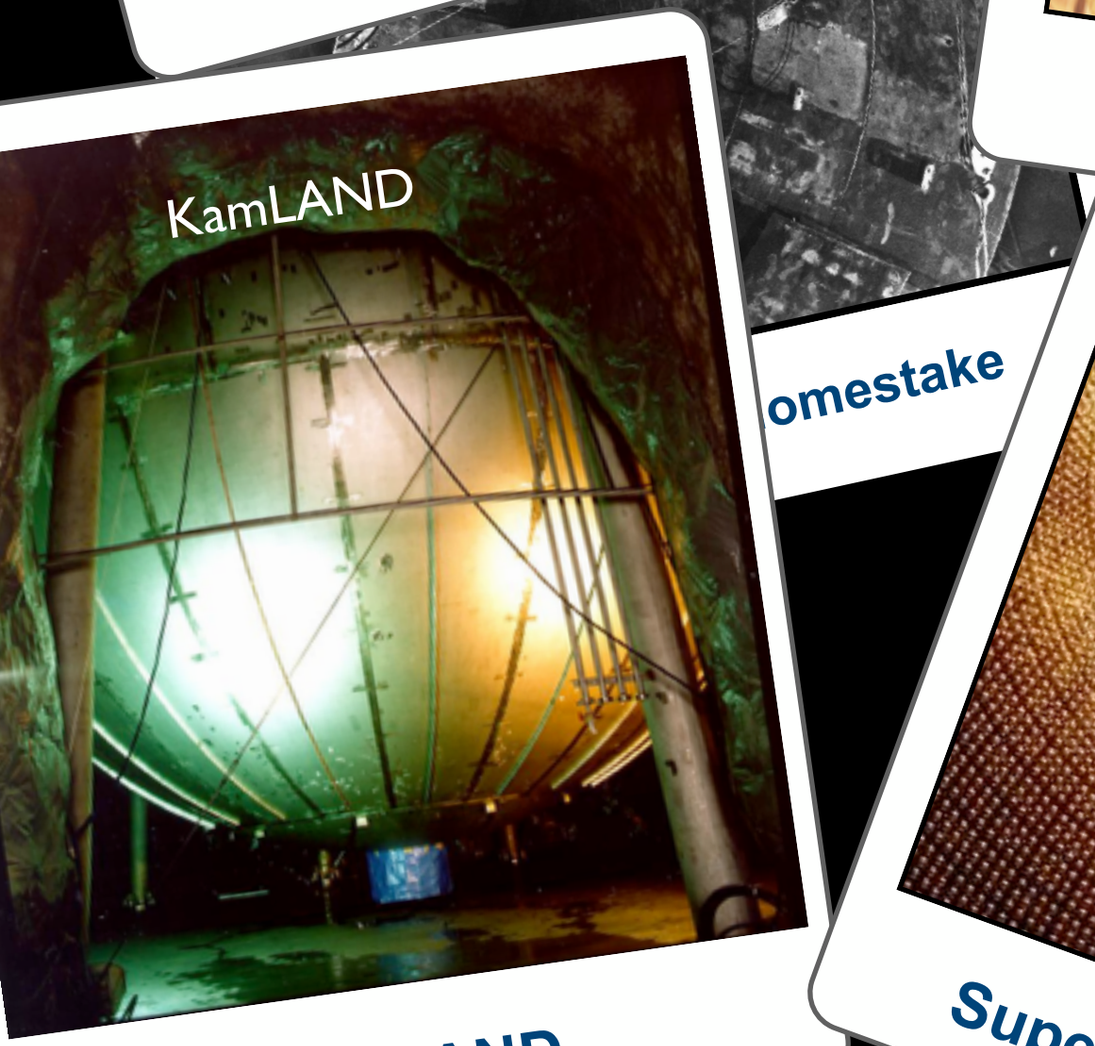
Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0,
e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

Ray Davis Jr., Homestake

MINOS





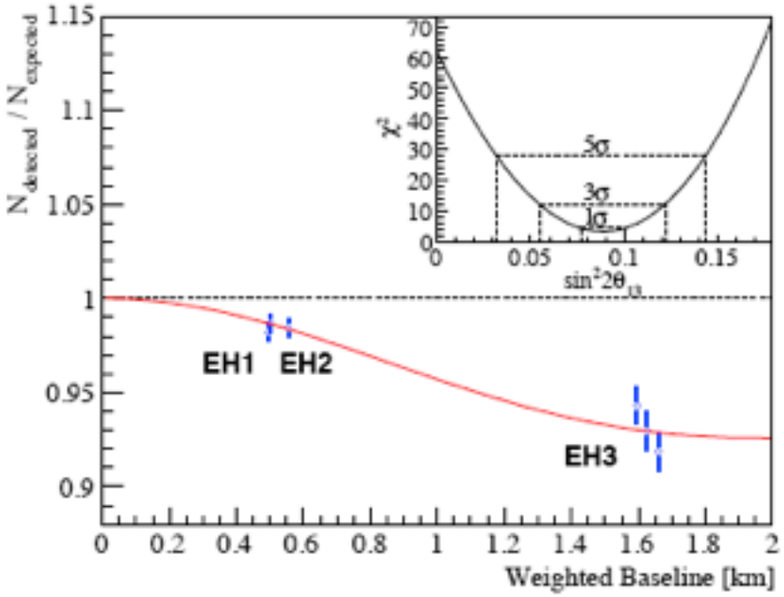
omestake

KamLAND

Super-Kami

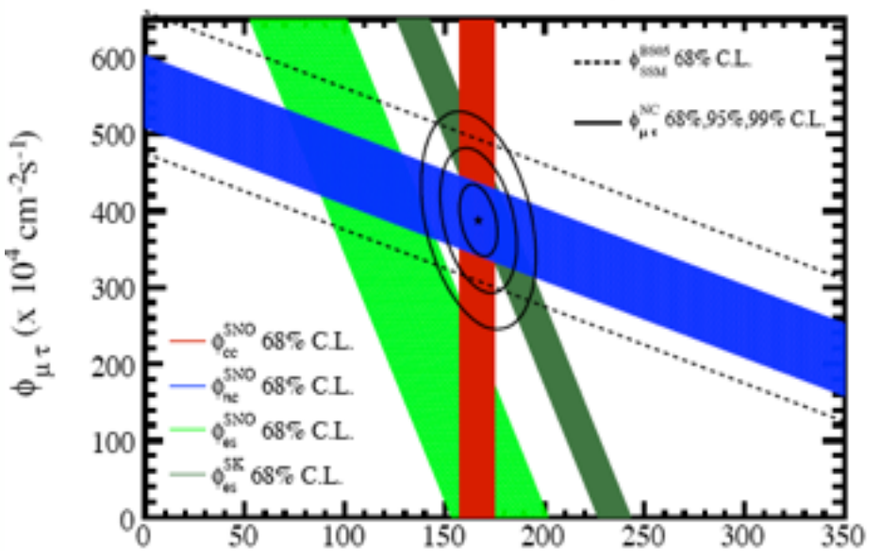
With oscillations firmly in place, we at least understand that the neutrino has a mass

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



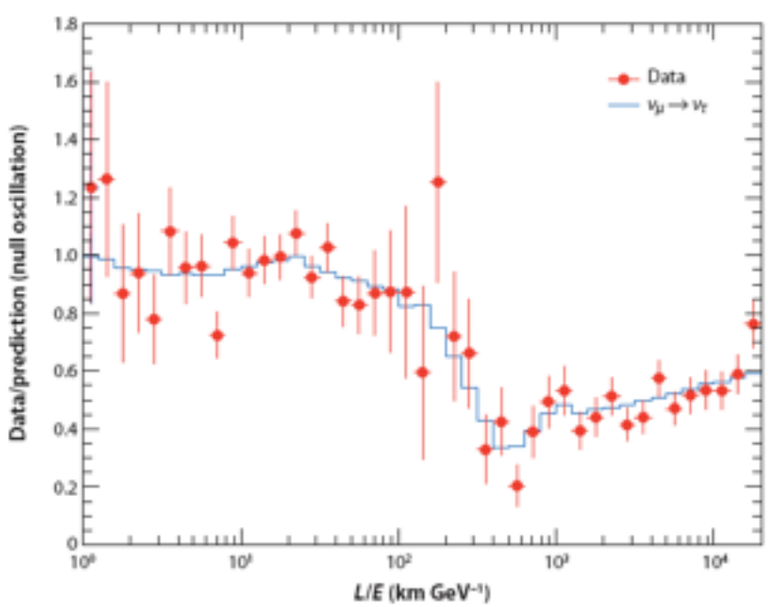
$$\sin^2(\theta_{13}) = 0.0241 \pm 0.0025$$

Reactor & Long Baseline



$$\sin^2(\theta_{12}) = 0.307 \pm 0.016$$
$$\Delta m^2_{12} = (7.54 \pm 0.26) \times 10^{-5}\ \mathrm{eV}^2$$

Solar



$$\sin^2(\theta_{23}) = 0.386 \pm 0.022$$
$$\Delta m^2_{23} = (2.43 \pm 0.09) \times 10^{-3}\ \mathrm{eV}^2$$

Atmospheric

Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).
Fogli et al, arXiv:1205.5254 (hep-ph)

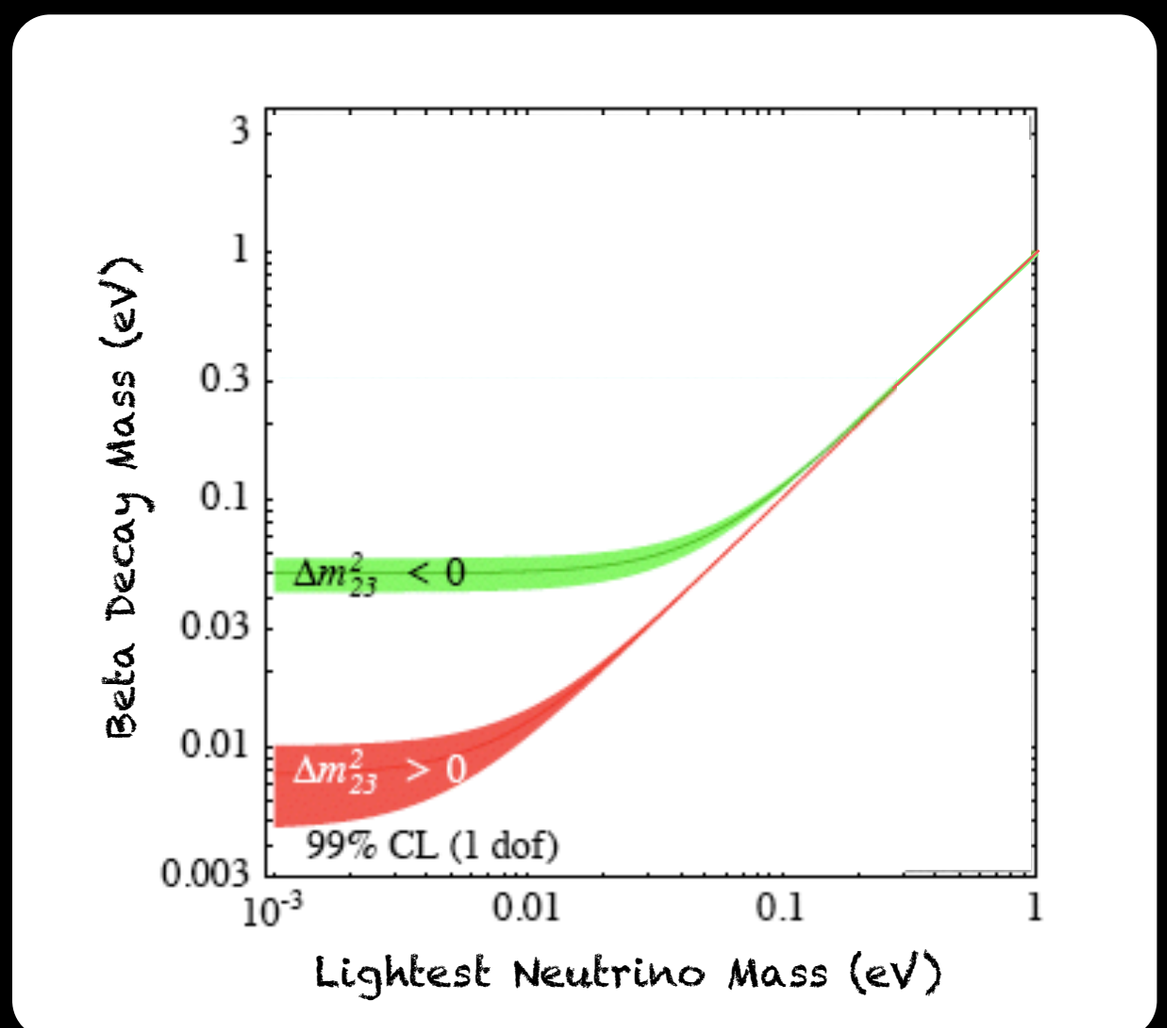
With oscillations firmly in place, we at least understand that the neutrino has a mass

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

Measuring Neutrino Masses

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

Cosmological Measurements



$$\langle m^2_{\beta\beta} \rangle = \mid \sum_{i}^{n_\nu} U^2_{ei} m_{\nu,i} \mid^2$$

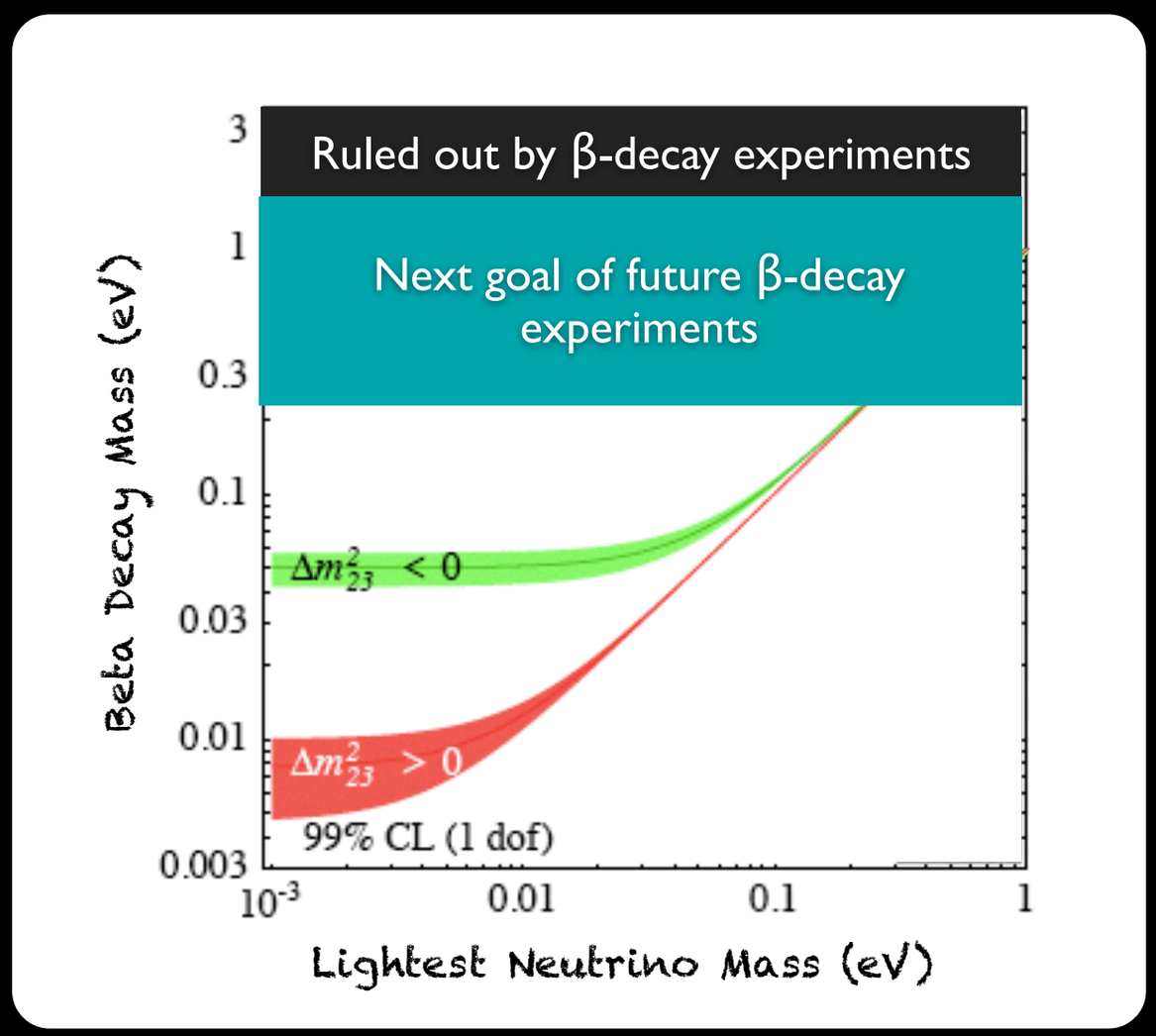
0νββ Measurements

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

Beta Decay Measurements

The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.
- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.



m_ν > 2 eV (eV scale, current)
Neutrinos ruled out as dark matter

m_ν > 0.2 eV (degeneracy scale)
Impact on cosmology and $0\nu\beta\beta$ reach

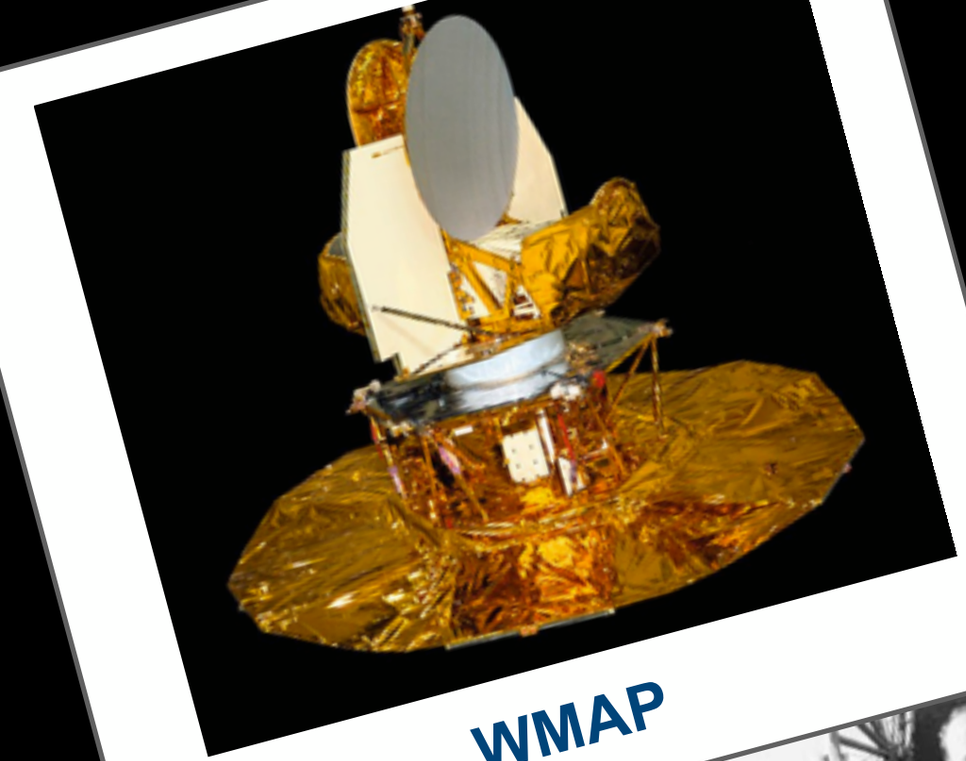
m_ν > 0.05 eV (inverted hierarchy)
Resolve hierarchy if null result

m_ν > 0.01 eV (normal hierarchy)
Oscillation limit; possible $C\nu B$ detection

The Era of Precision Cosmology

Cosmology has had a similar trajectory as neutrino physics, from inception to present day

The Era of Precision Cosmology



WMAP

Wil

Atacama Cosmology Telescope

Sloan Digital Sky Survey

Cosmology has had a similar trajectory as neutrino physics, from inception to present day

The Triumph of Cosmology

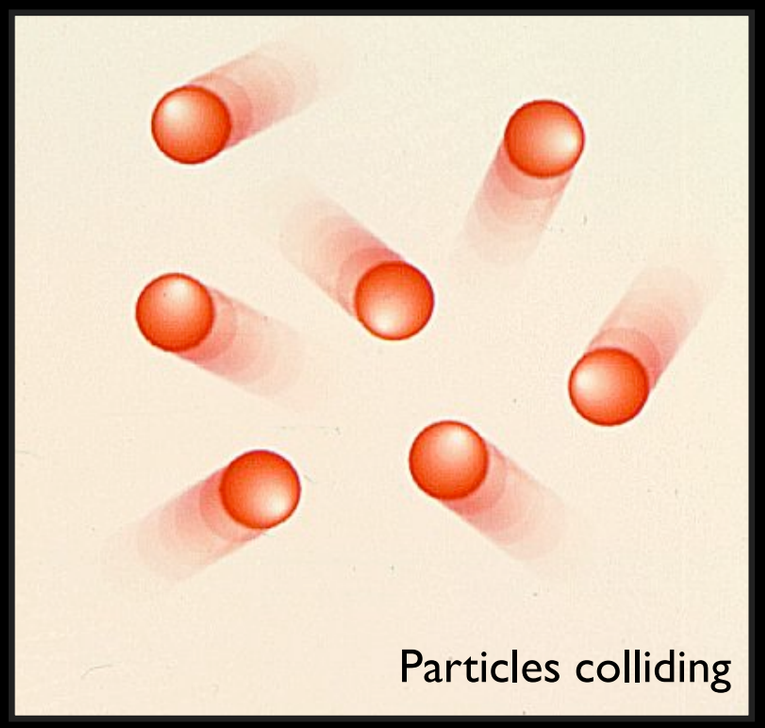
- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.

- Observation of the cosmological neutrinos would then provide a window into the 1st second of creation

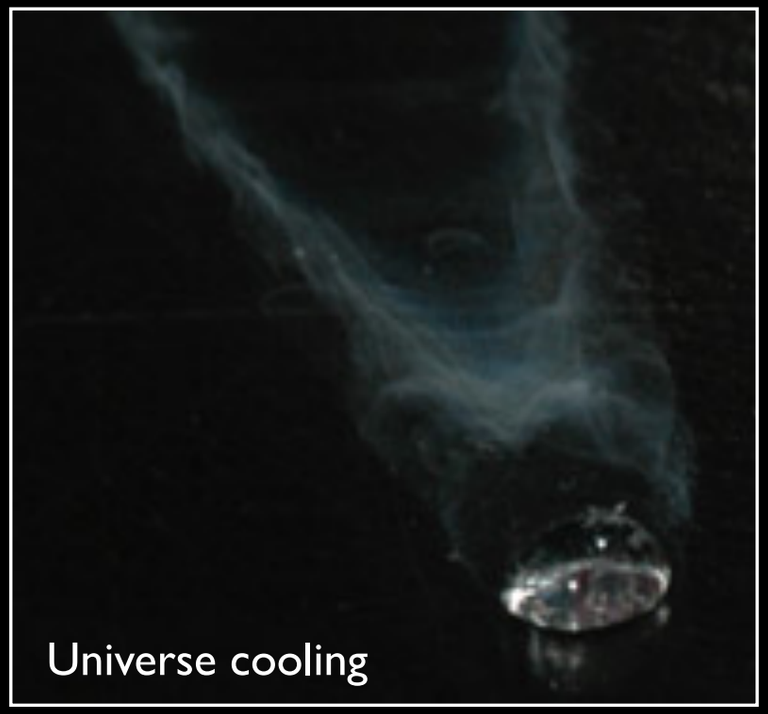
Neutrino Decoupling

- Inference about the existence of the relic neutrino background comes from knowledge of the primordial photon background.

- As the universe expands (cools), neutrinos transition from a state where they are in thermal equilibrium with electrons, to one where they are decoupled from them.


Particles colliding

Neutrino decoupling occurs when two rates are equal.


Universe cooling

$$\Gamma = < \sigma \; n \; v > \simeq \frac{16 G_F^2}{\pi^3} \; (g_L^2 + g_R^2) \; T^5$$

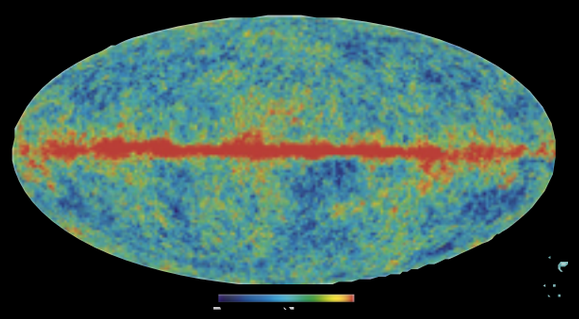
Annihilation Rate

$$H(t) = 1.66 g_*^{1/2} \frac{T^2}{m_{\rm Planck}}$$

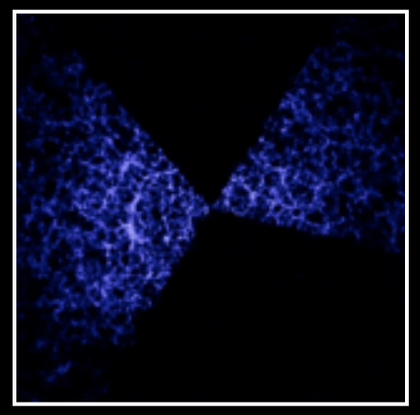
Expansion Rate

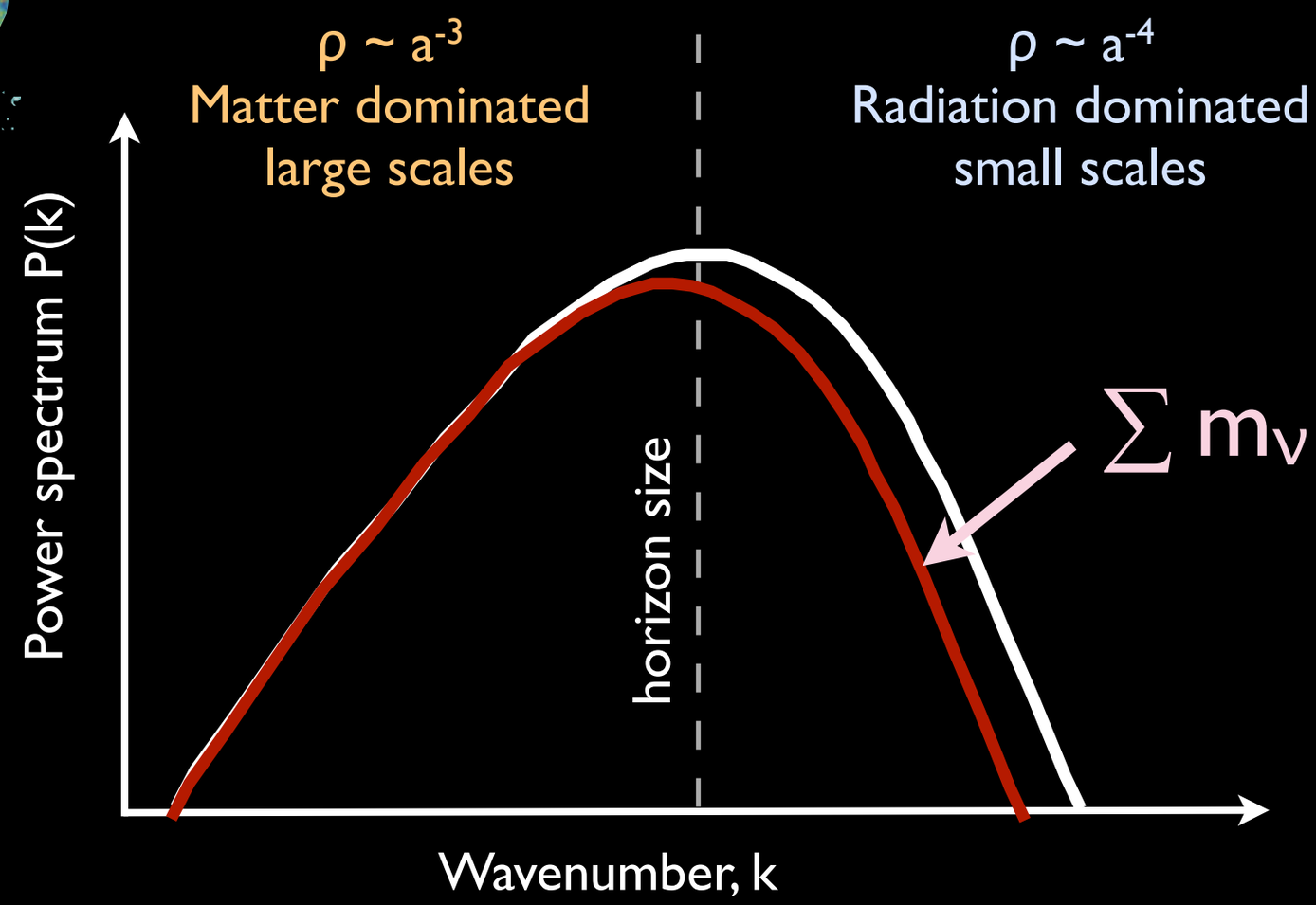
The Strategy
(a naive view)

WMAP Temperature Map

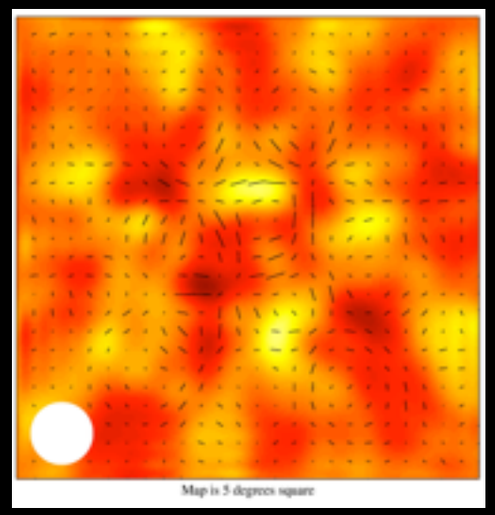


Galaxy Surveys





Weak lensing



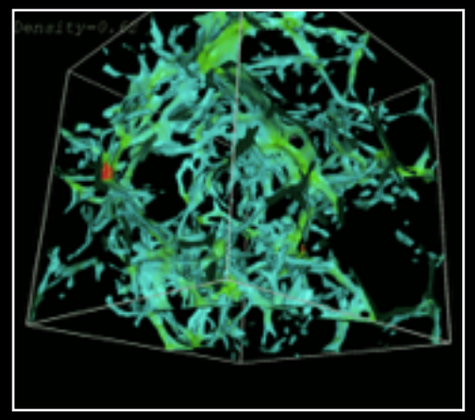
CMB Polarization

$$\delta(x) = (\rho(x) - \bar{\rho})/\bar{\rho}$$

Neutrinos come to affect the power spectrum,

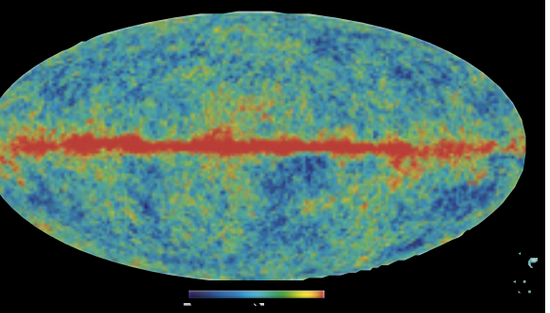
particularly at small distance scales

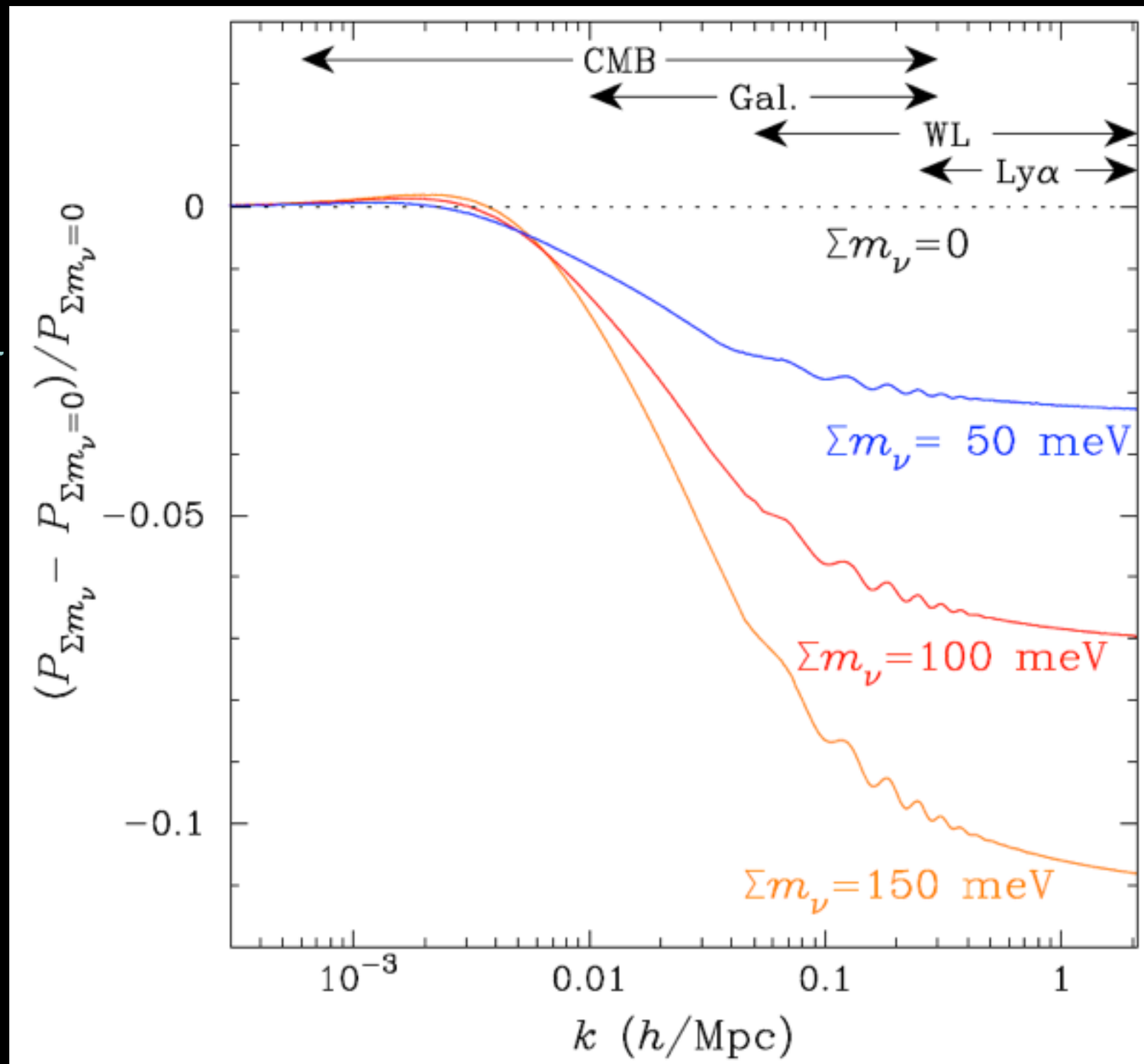
$$P(k) = \langle |\delta(k)|^2 \rangle$$



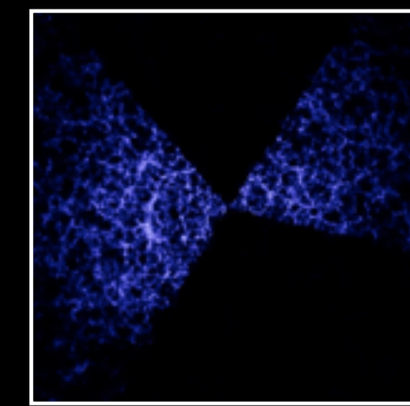
Lyman α

Temperature Map

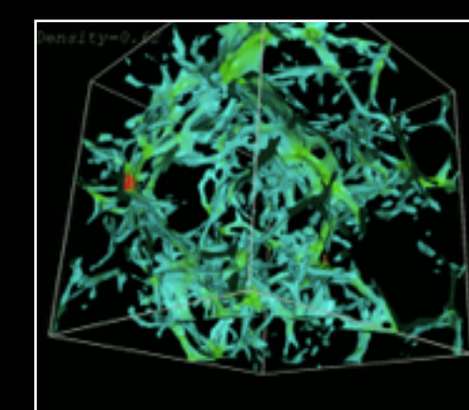




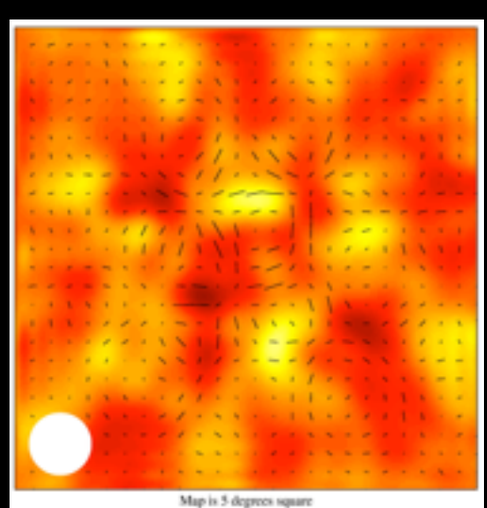
Galaxy Surveys



Weak lensing



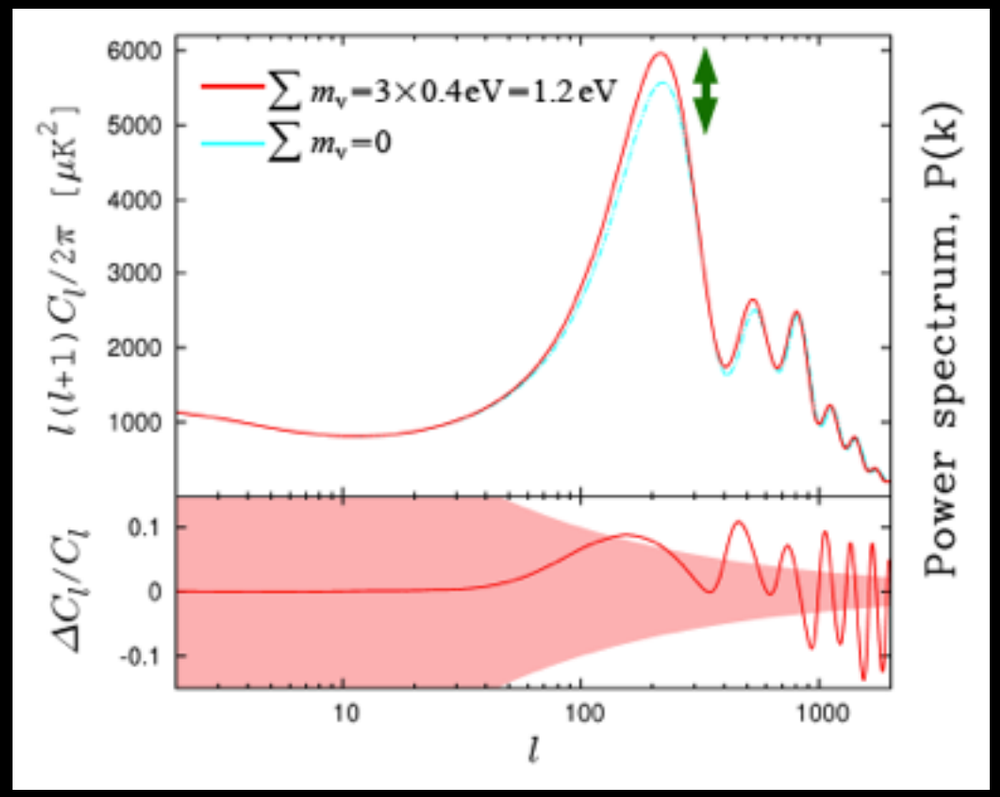
Lyman α



CMB Polarization

Large scale structure tends to weaken power spectrum at small wavelengths...

Neutrino Physics & Cosmology



- Two primary cosmology measurements that link directly to neutrino physics:

  (1) Number of neutrino species

  (2) Sum of neutrino masses

$$\Omega_R h^2 = [1 + N_{\text{eff}} \frac{7}{8} (\frac{4}{11})^{\frac{4}{3}}] \Omega\gamma h^2$$

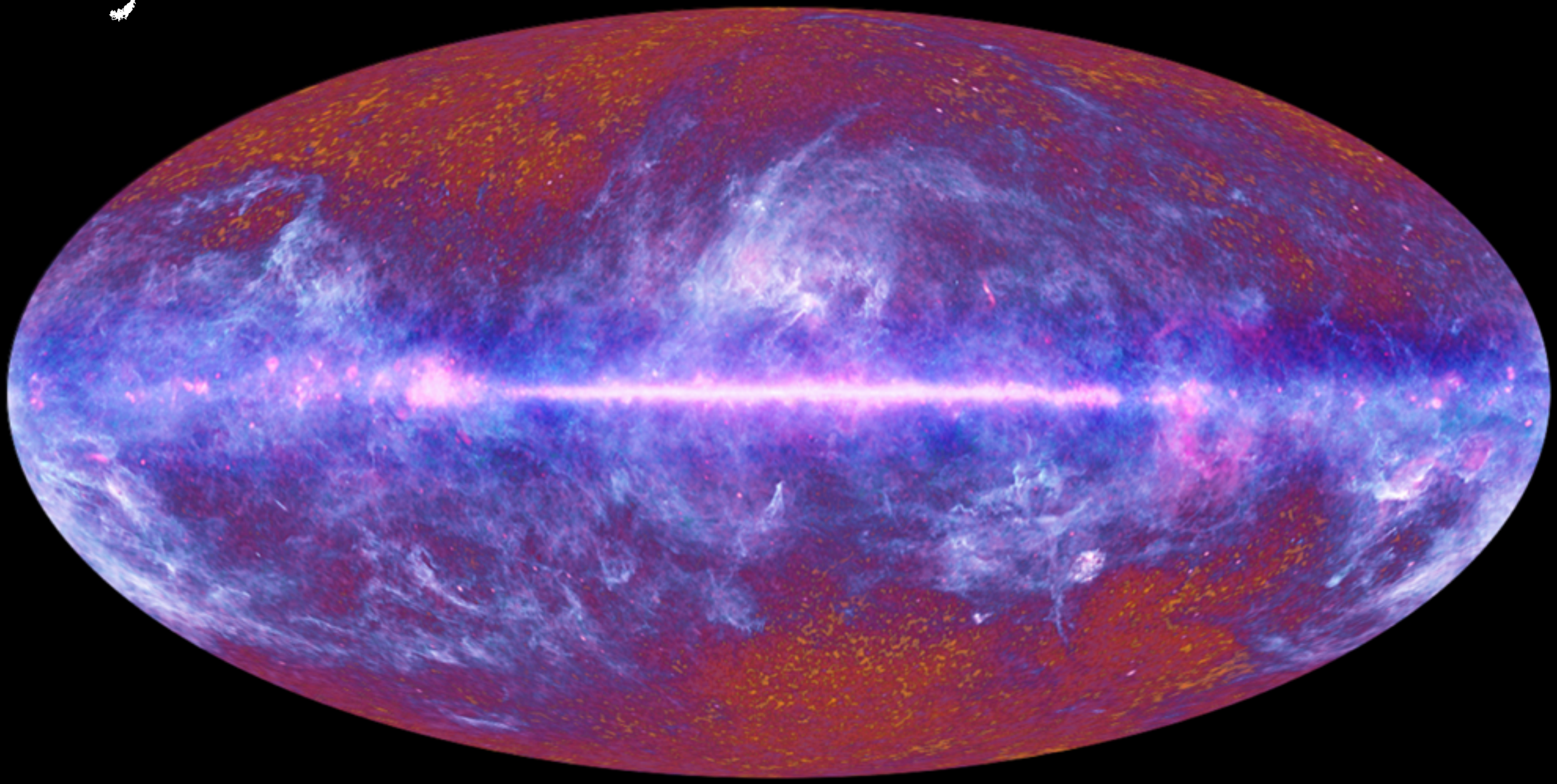
- Both large scale structure (LSS) and CMB anisotropies (CMB), particularly CMB gravitational lensing, can be used to measure these quantities.

$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i^{n_\nu} m_{\nu,i}}{\rho_{\text{critical}}}$$

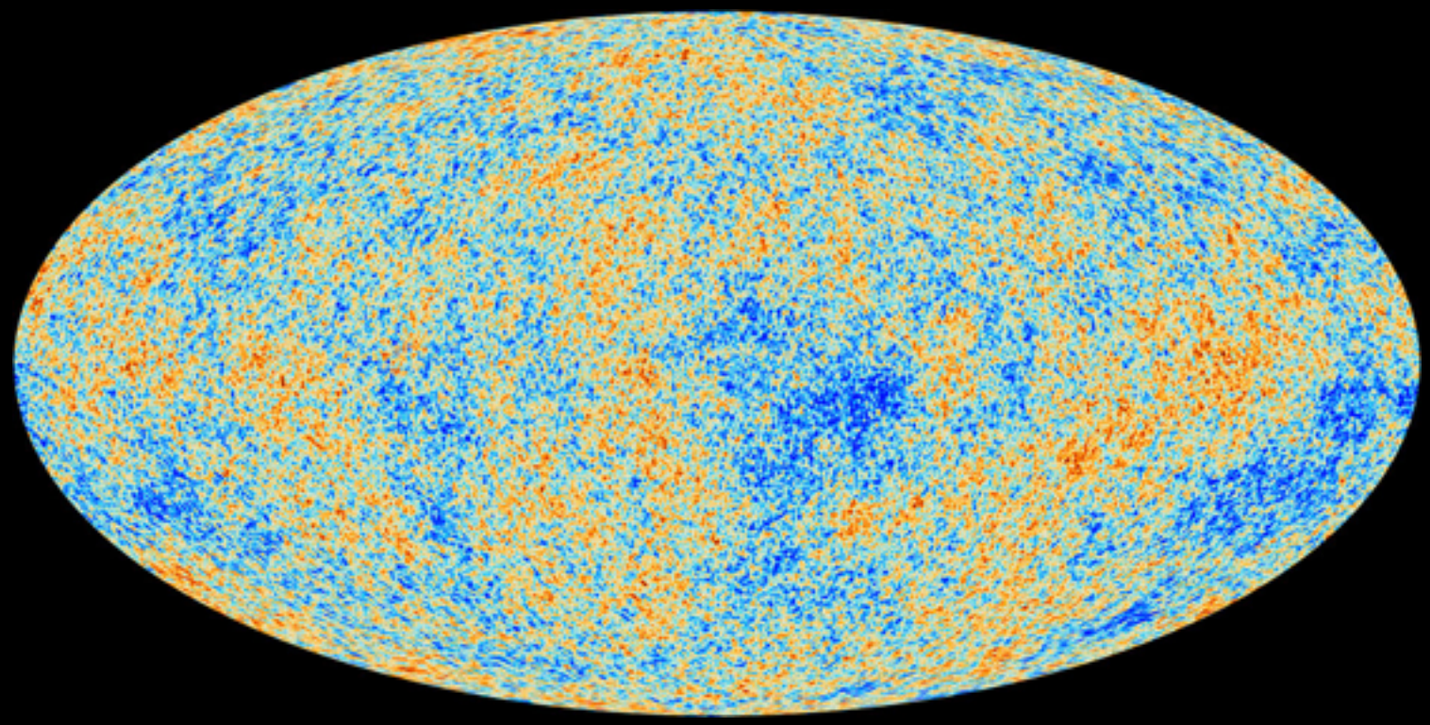
Planck Satellite:

Launched May 14th, 2009

The Microwave sky...



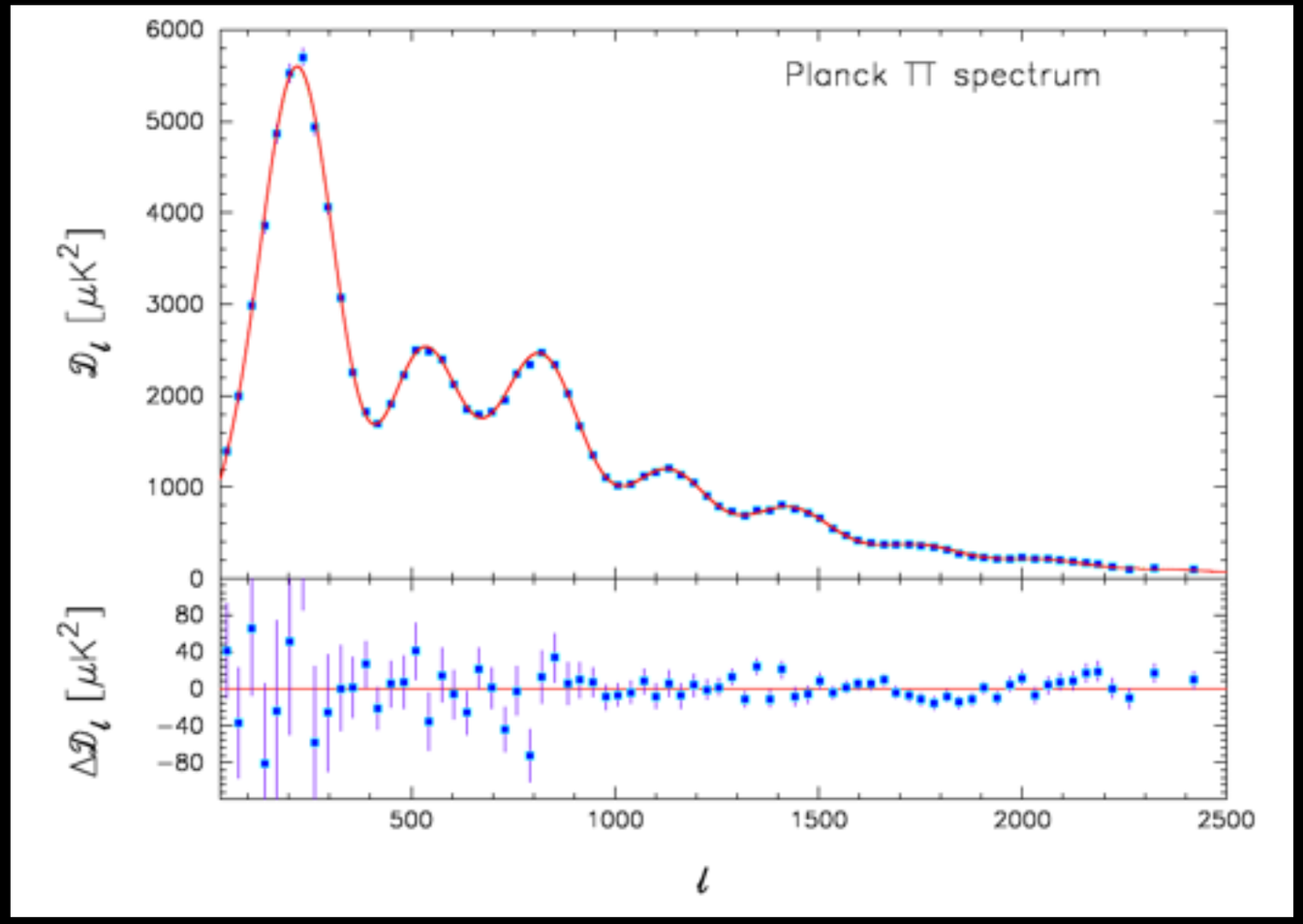
PLANCK Results



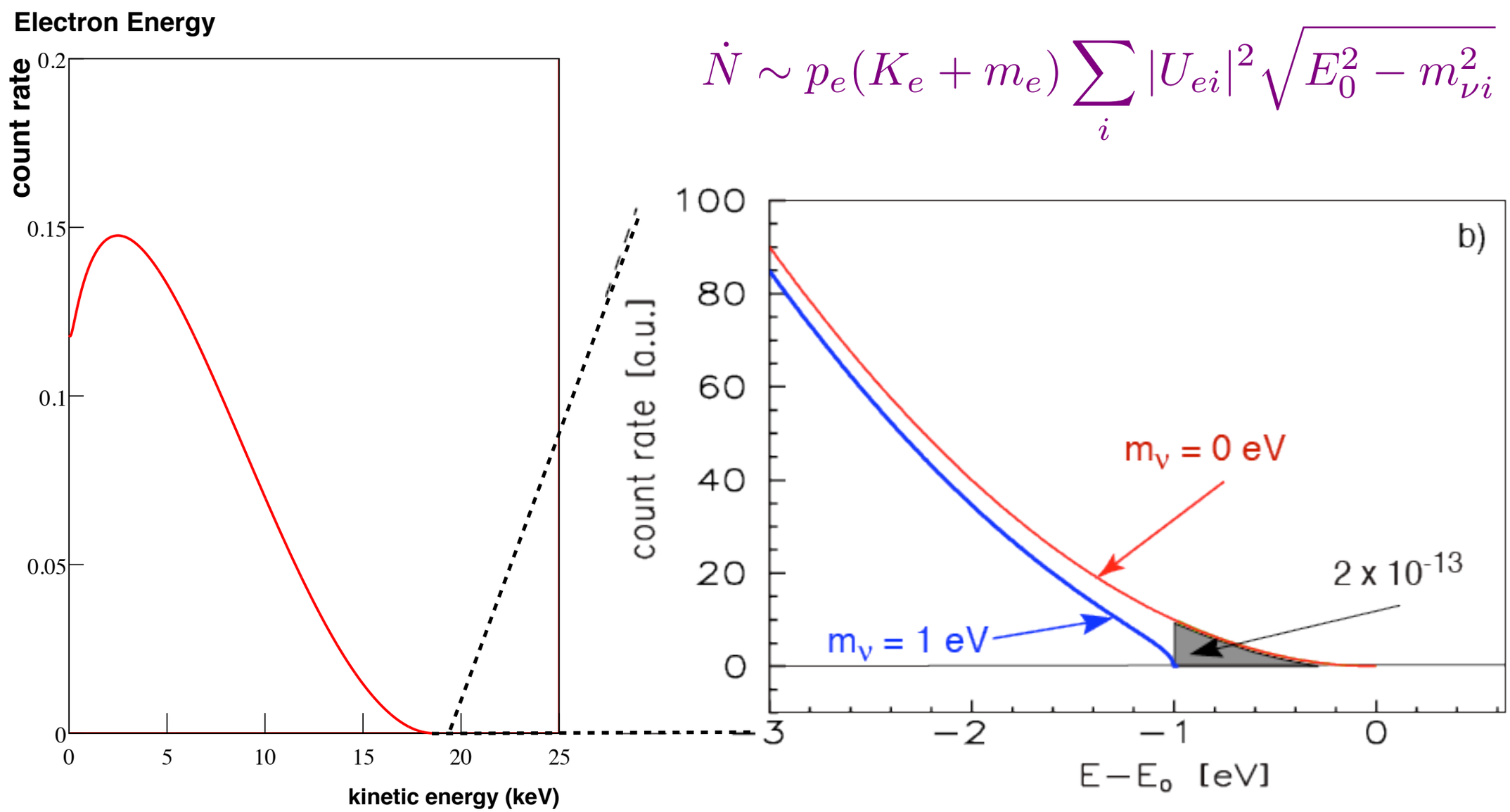
- The basic PLANCK analysis looks at 6 main cosmological parameters. Neutrino masses are added as extensions to that model.

- Most conservative data combinations see no evidence for neutrino masses.

- Certainly tension exists with certain parameters (SZ clusters, Hubble constant, BICEP2) that alter the fits or in some cases favor finite masses.



Direct Probes



Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Techniques for the 21st Century

Spectroscopy (KATRIN)

Magnetic Adiabatic Collimation with Electrostatic Filtering

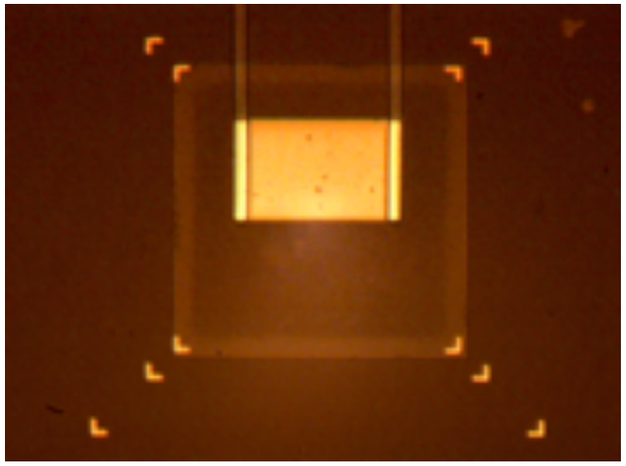
State-of-the-Art technique

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Calorimetry (HOLMES, ECHO & NUMECS)

Technique highly advanced.

New experiment(s) planned to reach ~eV scale.

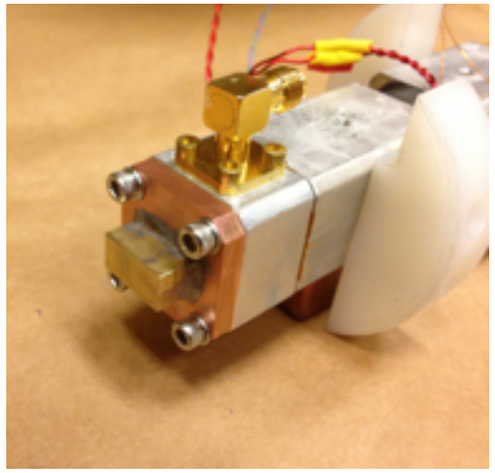


$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

R&D phase (new results)



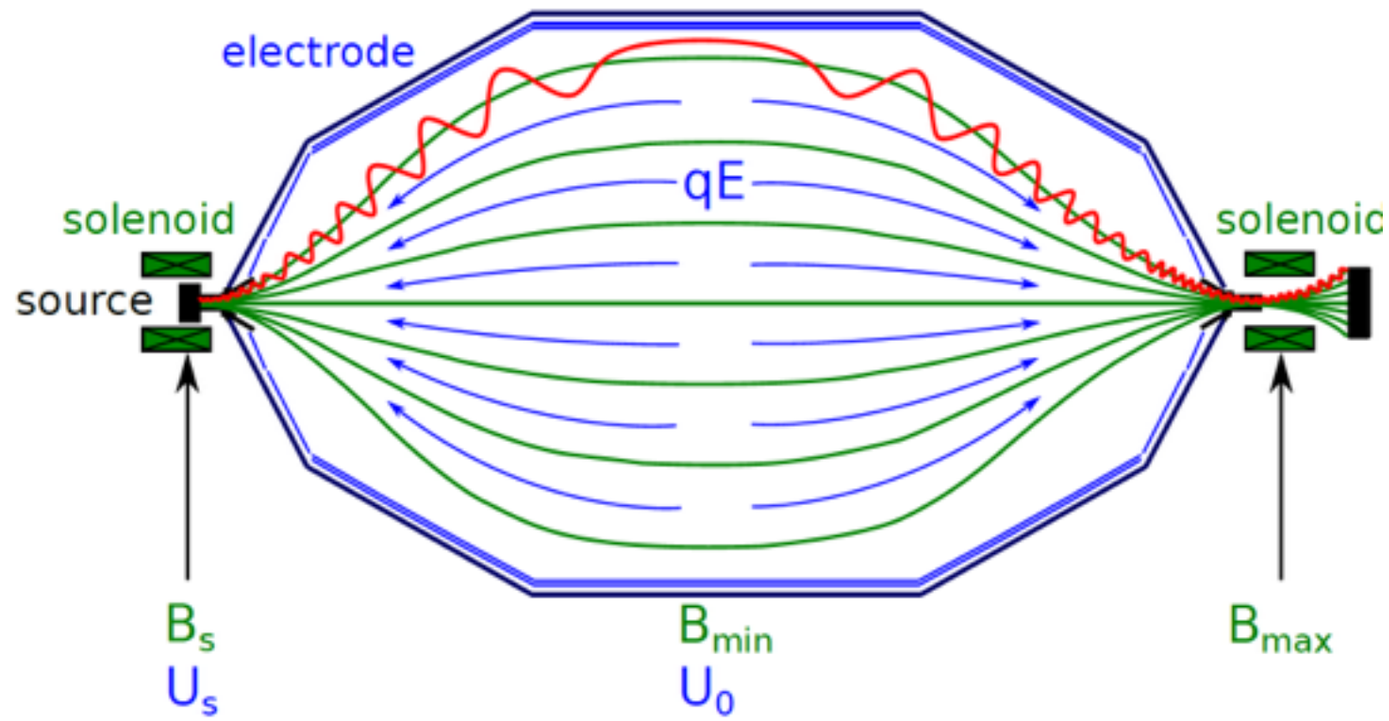
$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

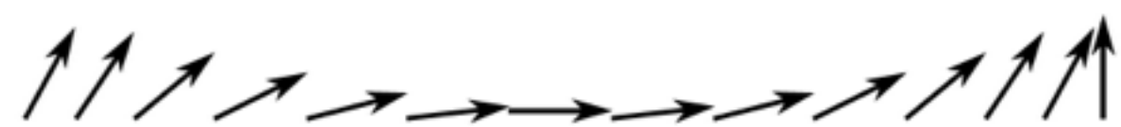
MAC-E Filter Technique

KATRIN

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Spectroscopic: MAC-E Filter





adiabatic transformation of e^- momentum

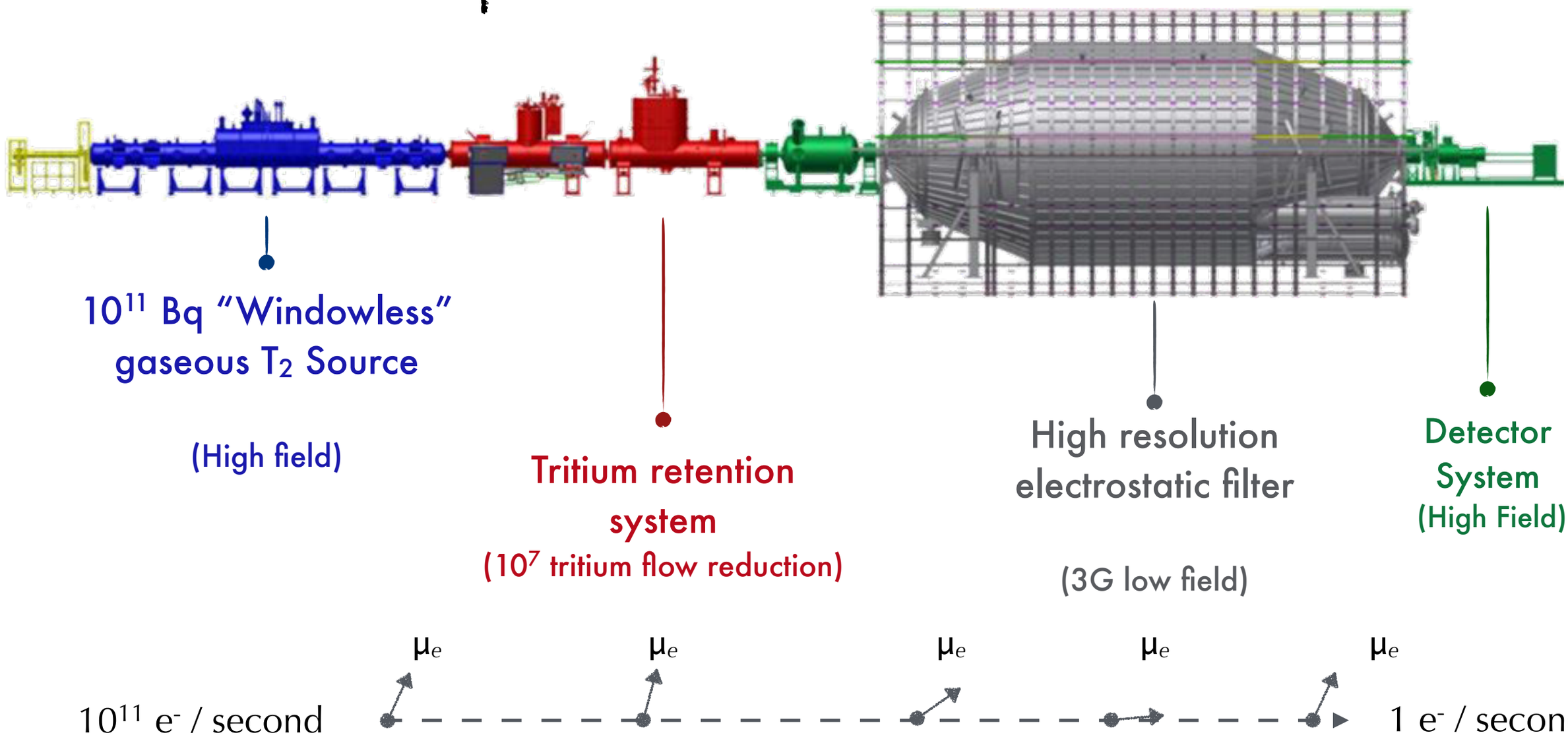
Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

($\Delta E/E = B_{min}/B_{max} = 0.93$ eV)

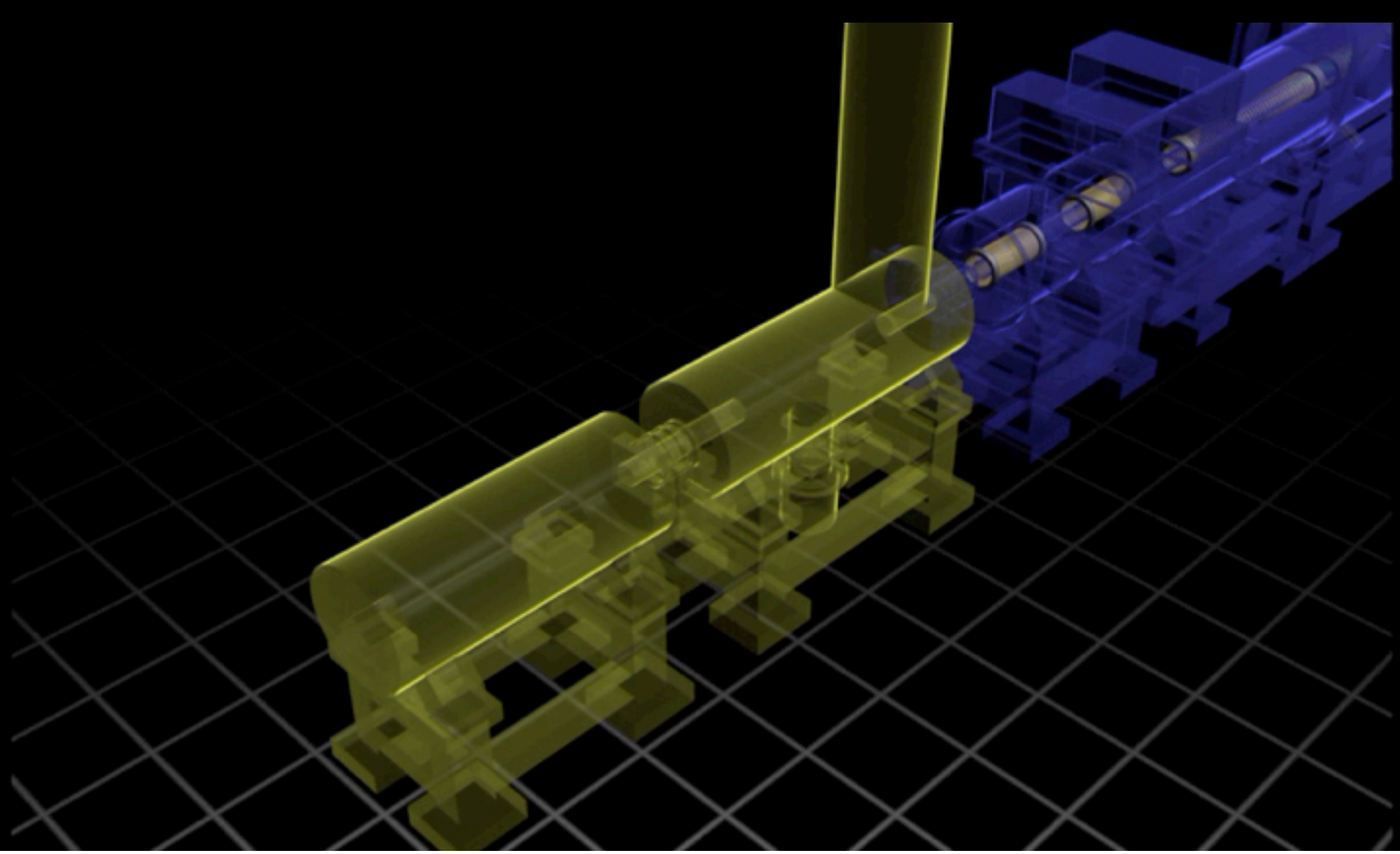
The KATRIN Setup



Adiabatic transport ensures high retention of phase space for decay

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \rightarrow 0.93 \text{ eV}$$

Energy resolution scales as the ratio of minimum / maximum fields

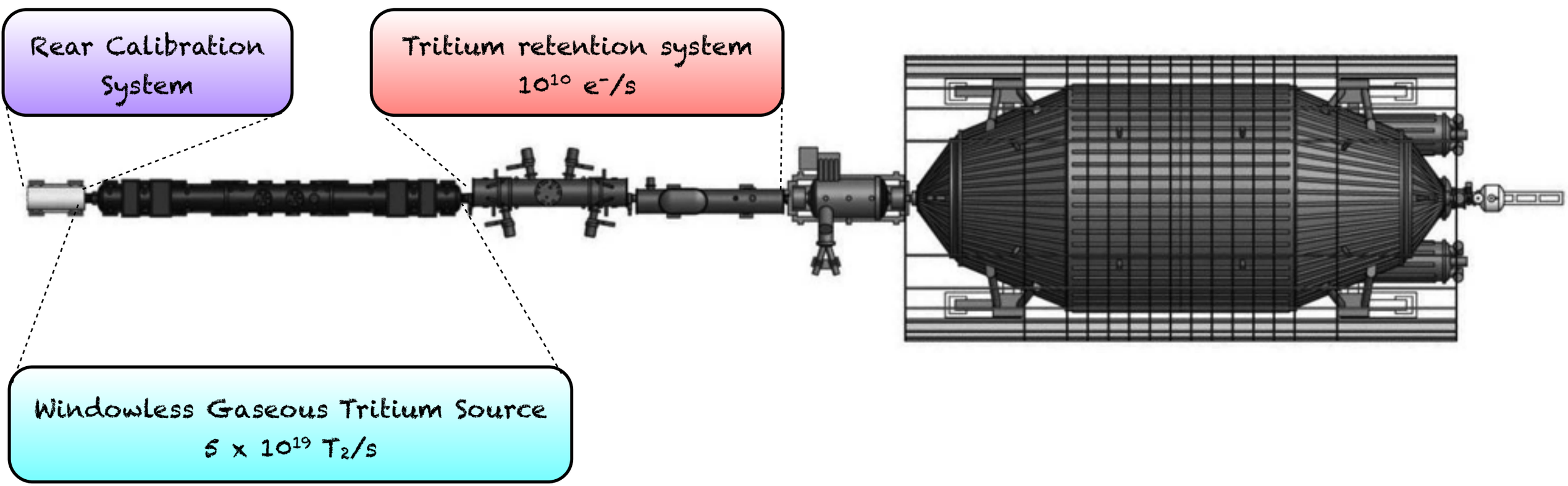


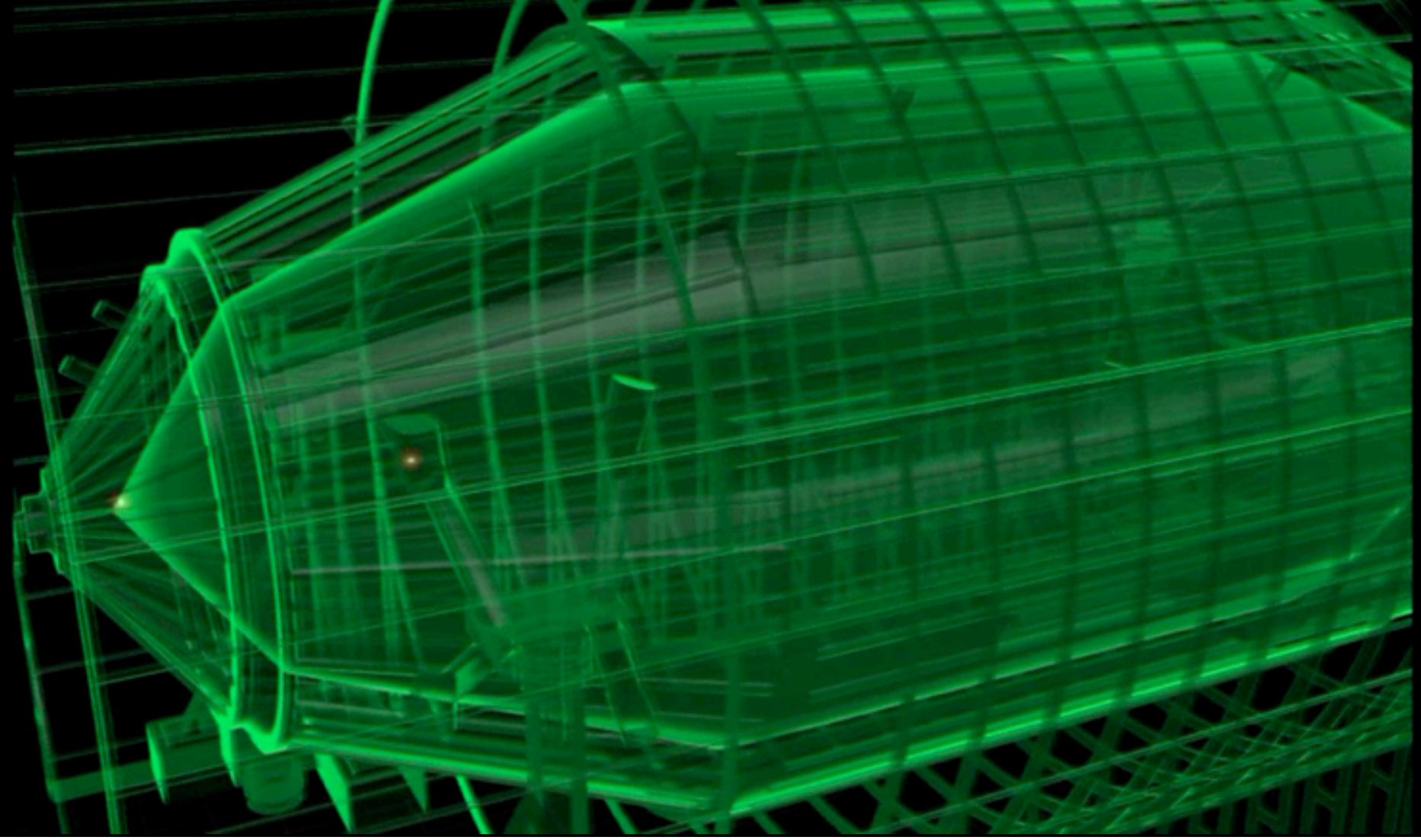
WGTS:

- Injected tritium source with ~few Curie activity.
- Extremely stable pressure/temperature

Tritium Retention System:

- Designed to reduce tritium flow by 10^{14}



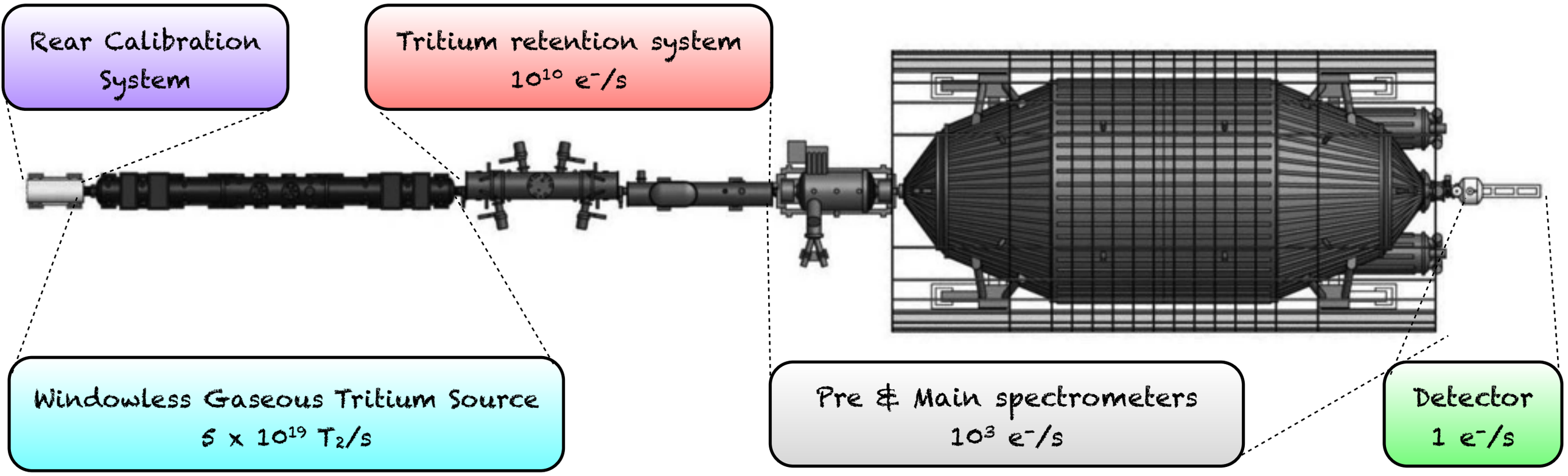


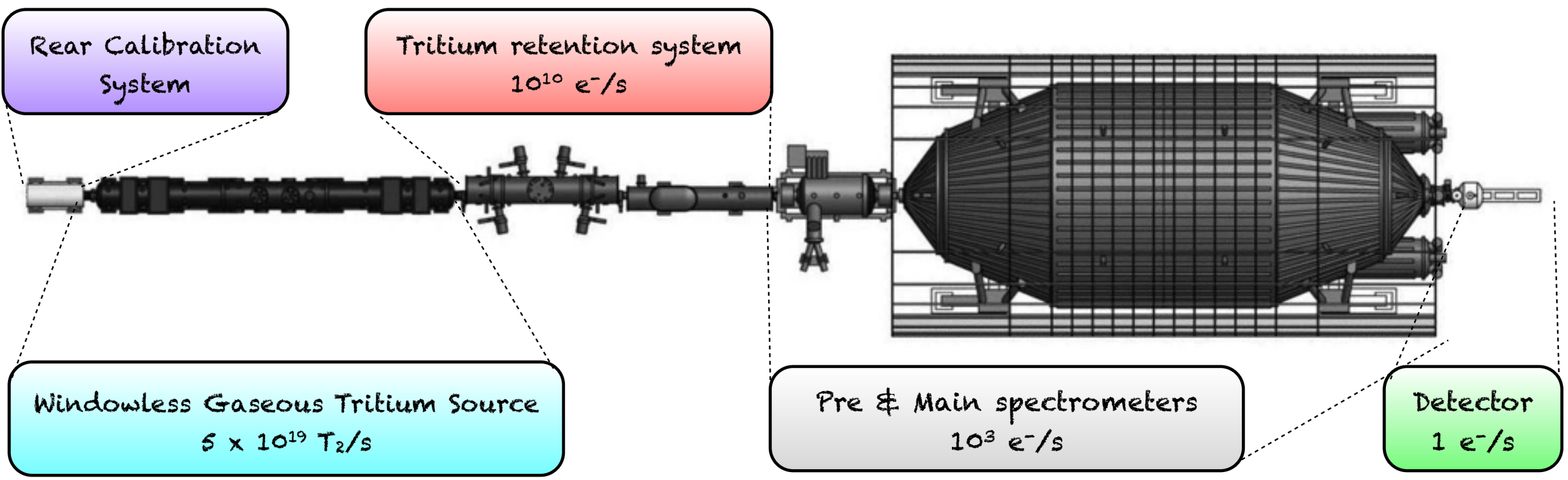
Spectrometers:

- 1 eV resolution transmission function.
- Inner wire electrodes for background reduction.
- Coils to shape low field region.

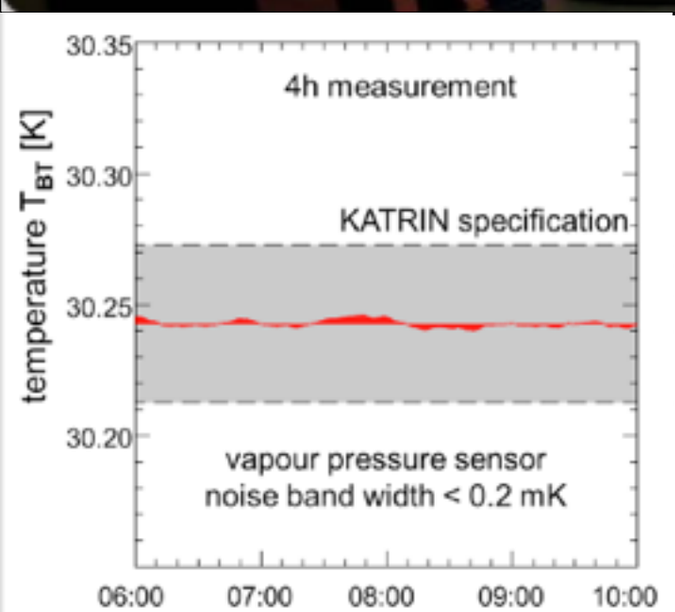
Detector:

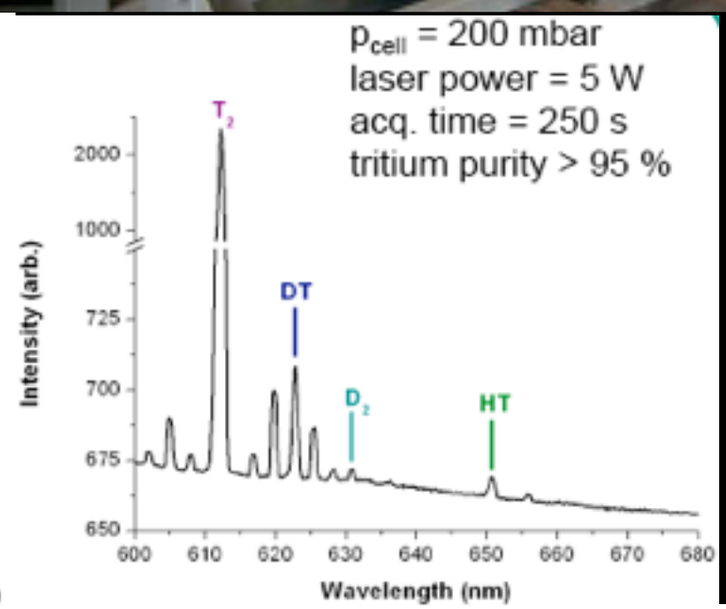
- Position-dependent beta detector.



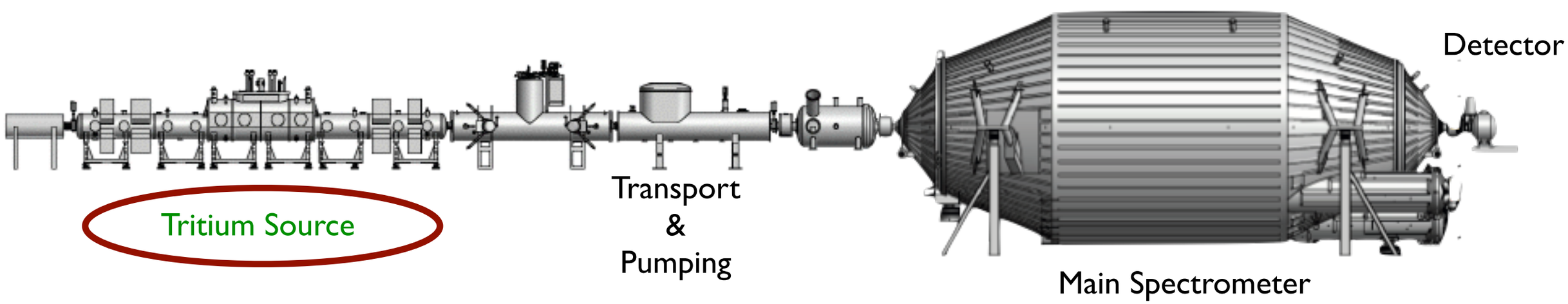

Rear Calibration System
Tritium retention system
10^{10} e^-/s
Windowless Gaseous Tritium Source
5×10^{19} T_2/s
Pre & Main spectrometers
10^3 e^-/s
Detector
1 e^-/s

WGTS Demonstrator





- Provides ~ 2 x 10^{11} Bq of activity (with tritium activity extruded from system).
- Monitoring of tritium purity, pressure & temperature.
- Temperature stability of ±3.6 mK recently achieved (x10 better than specification).

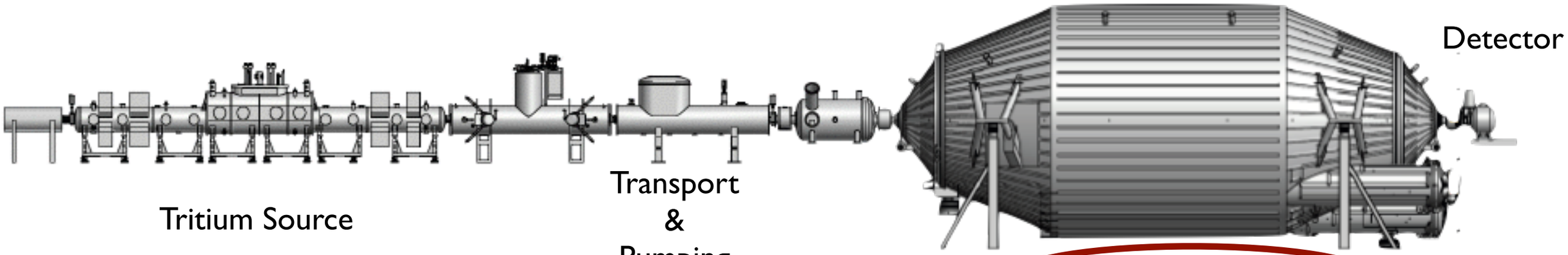


Field- Compensation Air Coils

Inner electrode wire mesh

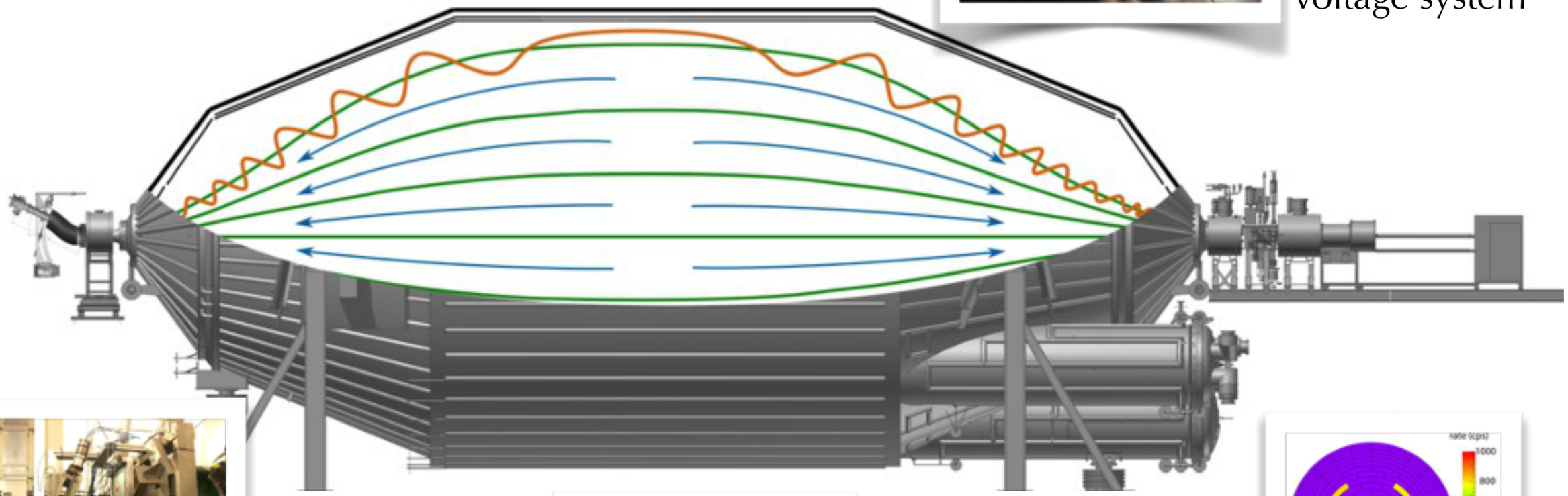
High Voltage Divider

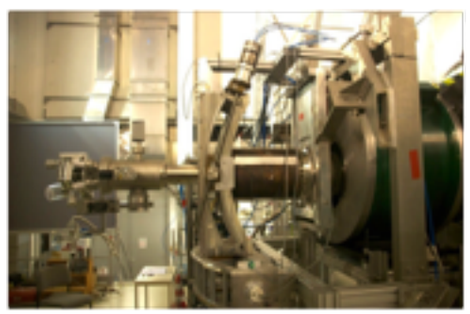
- A 10 m diameter analyzing spectrometer with 1:2000 energy resolution (0.93 eV)
- Extremely stable high voltage of main vessel.
- Few ~ppm precision divider and monitoring spectrometer.



Spectrometer Commissioning

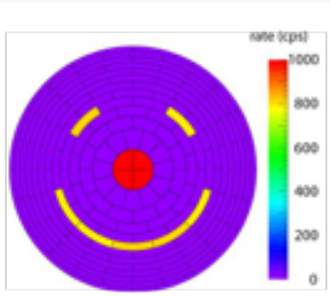
Precision high voltage system





High precision electron gun

Ultra high vacuum system



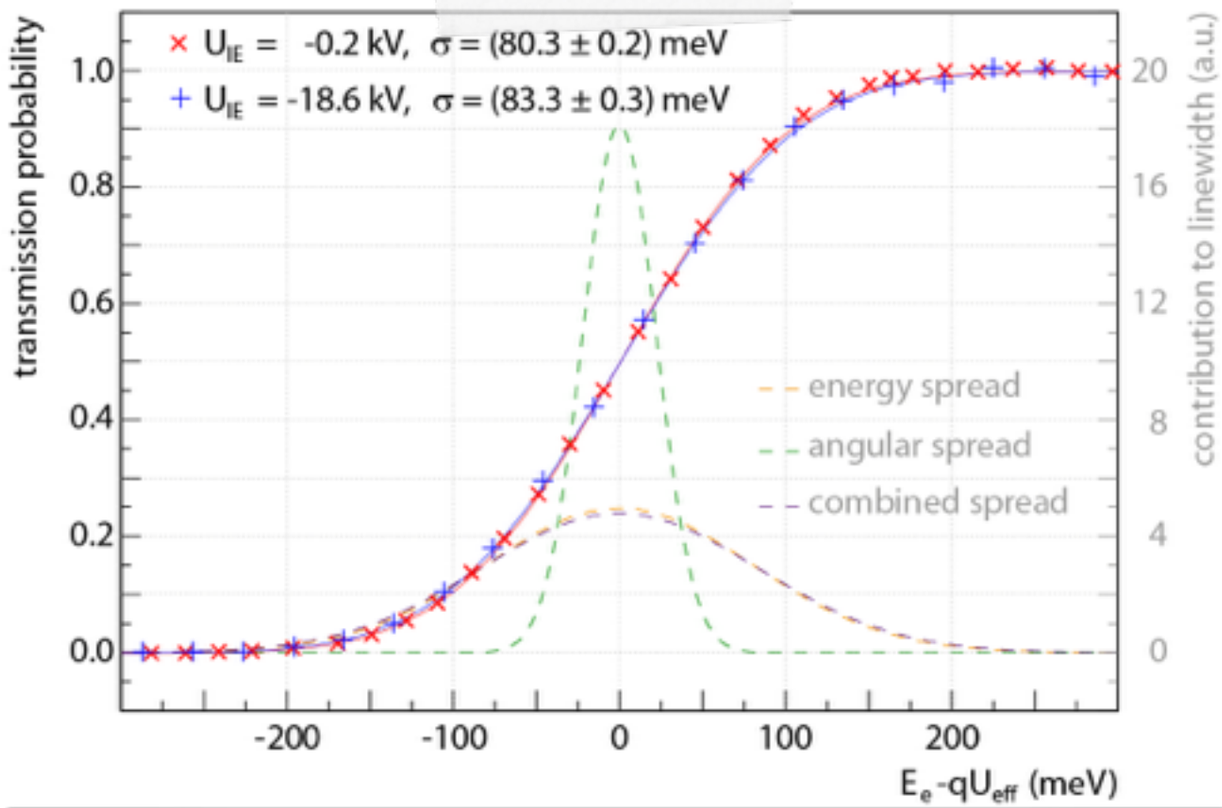
Full detector system

Summer 2013 saw "first light" from the KATRIN.

Spectrometer and detector system fully integrated.

Allowed for test of transmission function and background levels.

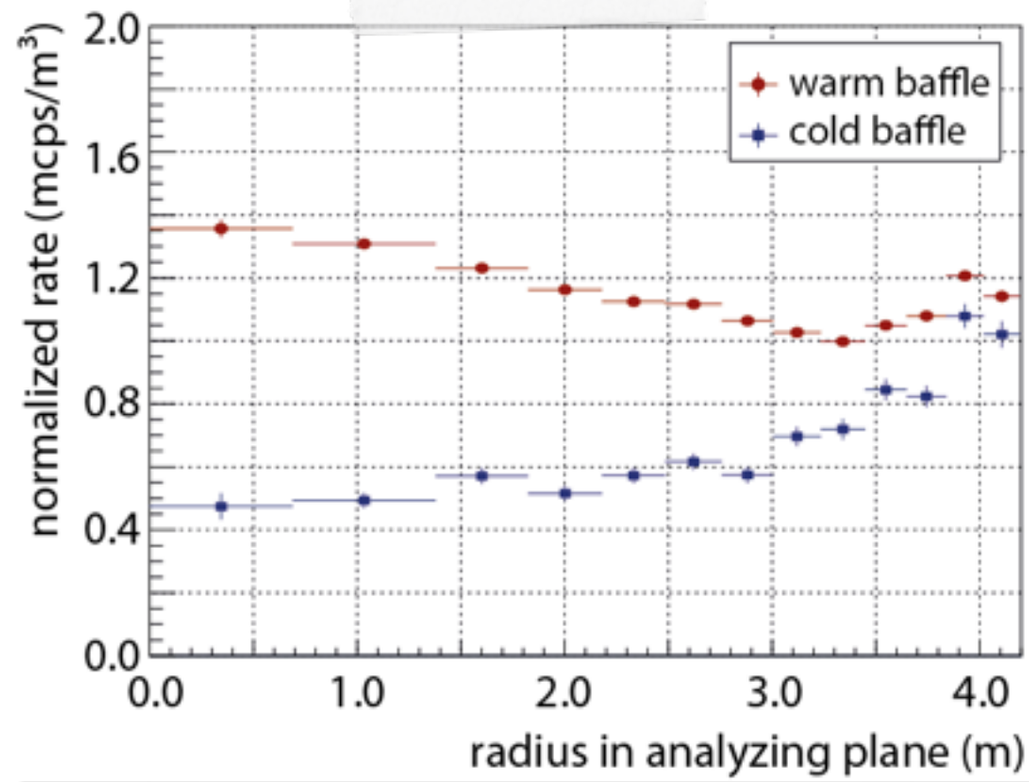
Transmission Function



At -18.6 keV, better than
100 meV resolution

Sharpest transmission function
for a MAC-E filter

Background Rates



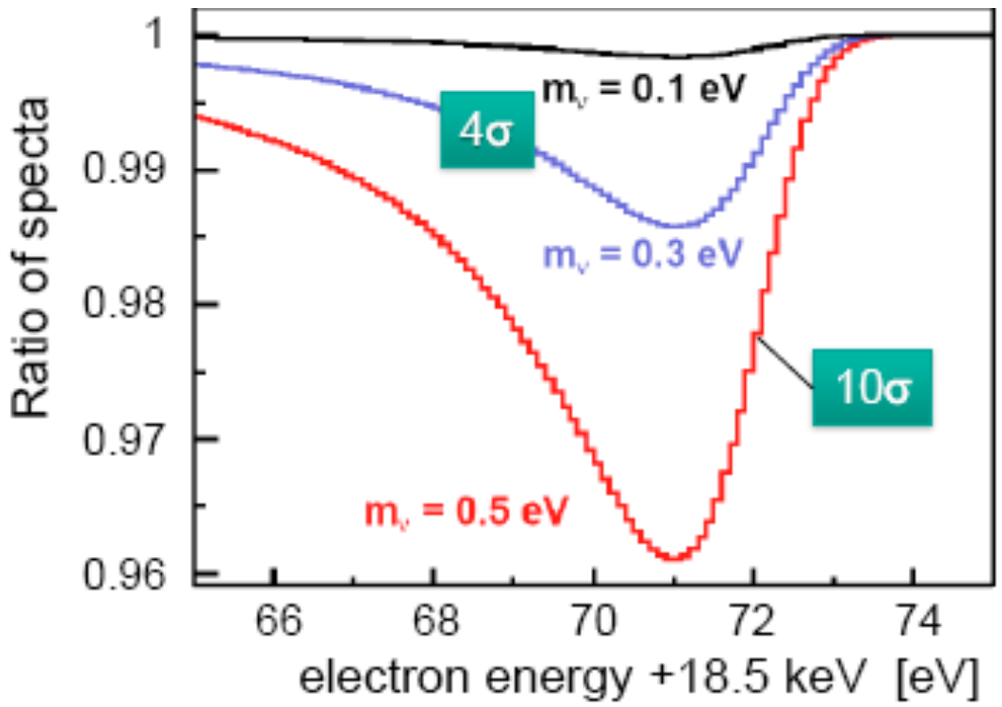
Background rate of order Hz
(radon-dominated)

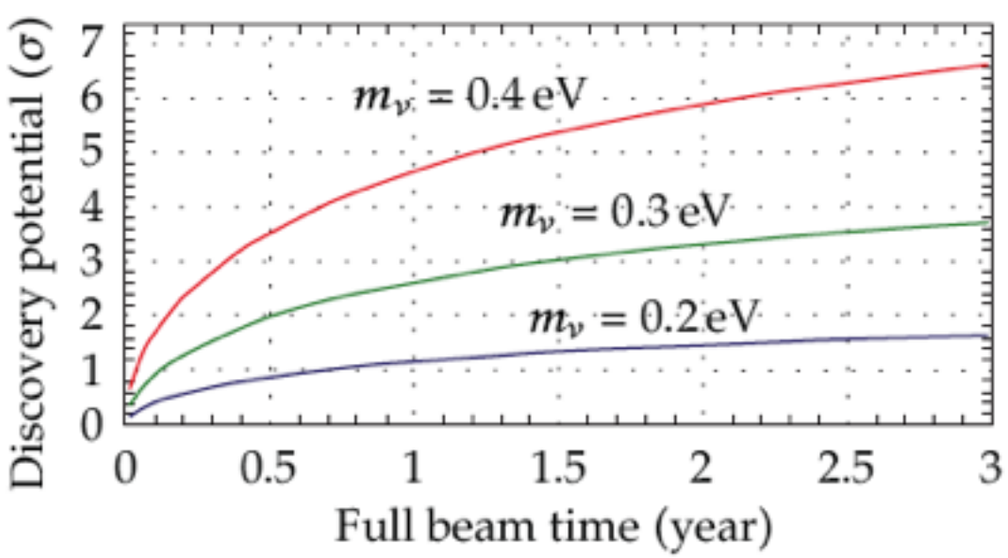
Greater reduction of
backgrounds to come

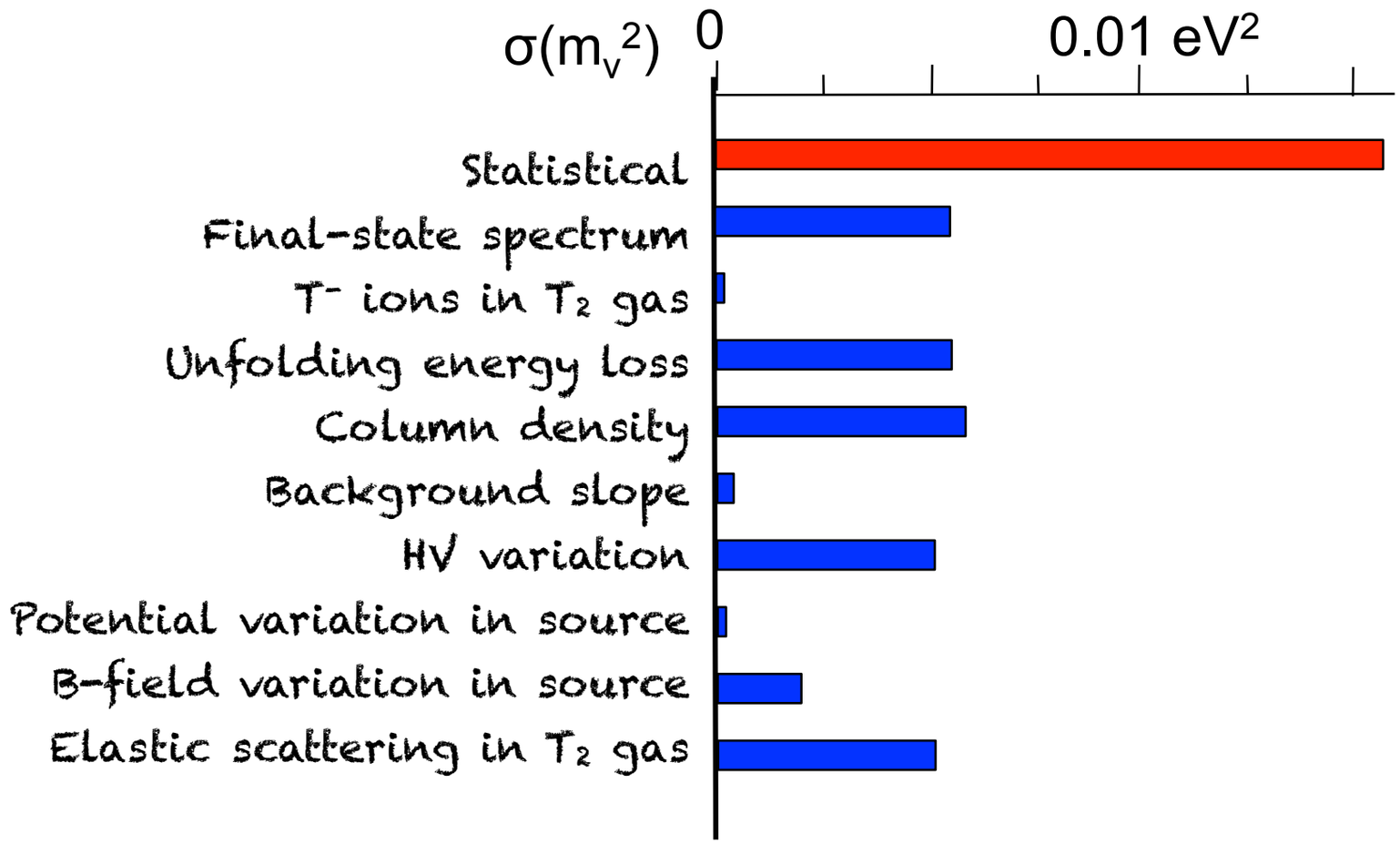
Commissioning showed excellent behavior of MAC-E Filter response.

Next commissioning (now) should show greater background suppression.

Projected Sensitivity







Neutrino Mass Goals

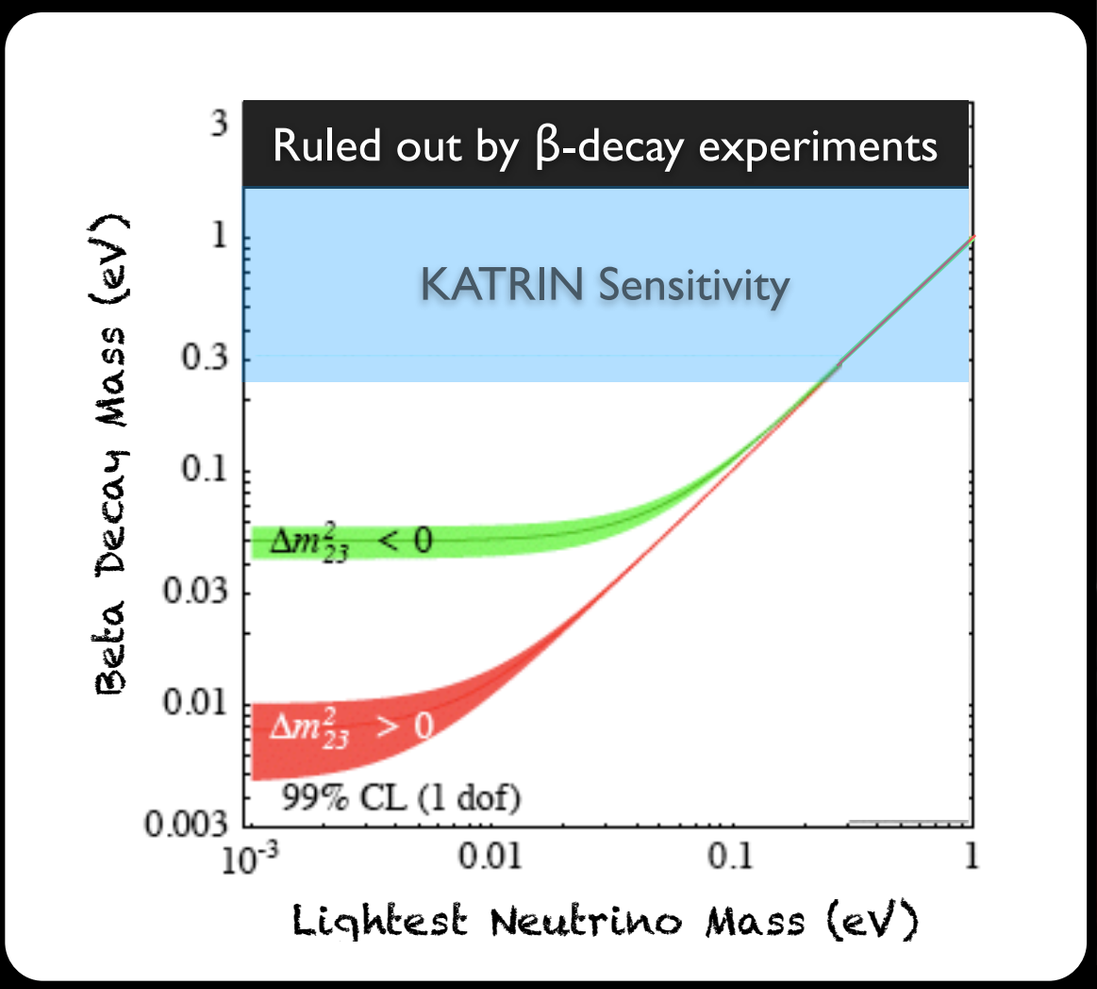
Discovery: 350 meV (at 5σ)

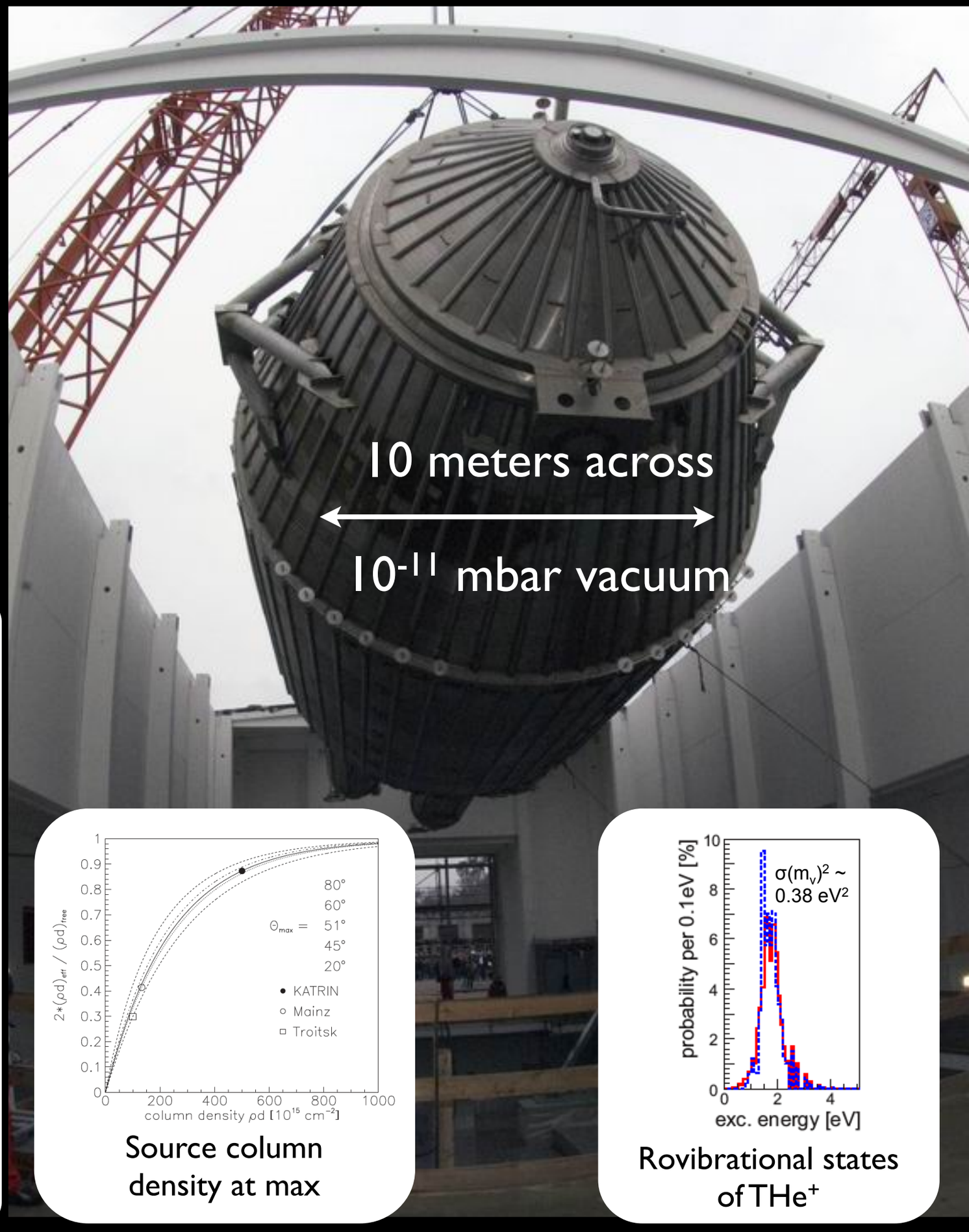
Sensitivity: 200 meV (at 90% C.L.)

Data taking to commence in 2016.

Can we push further?

- Can direct measurements push to the inverted hierarchy scale?
- To do so, they must have better scaling law.

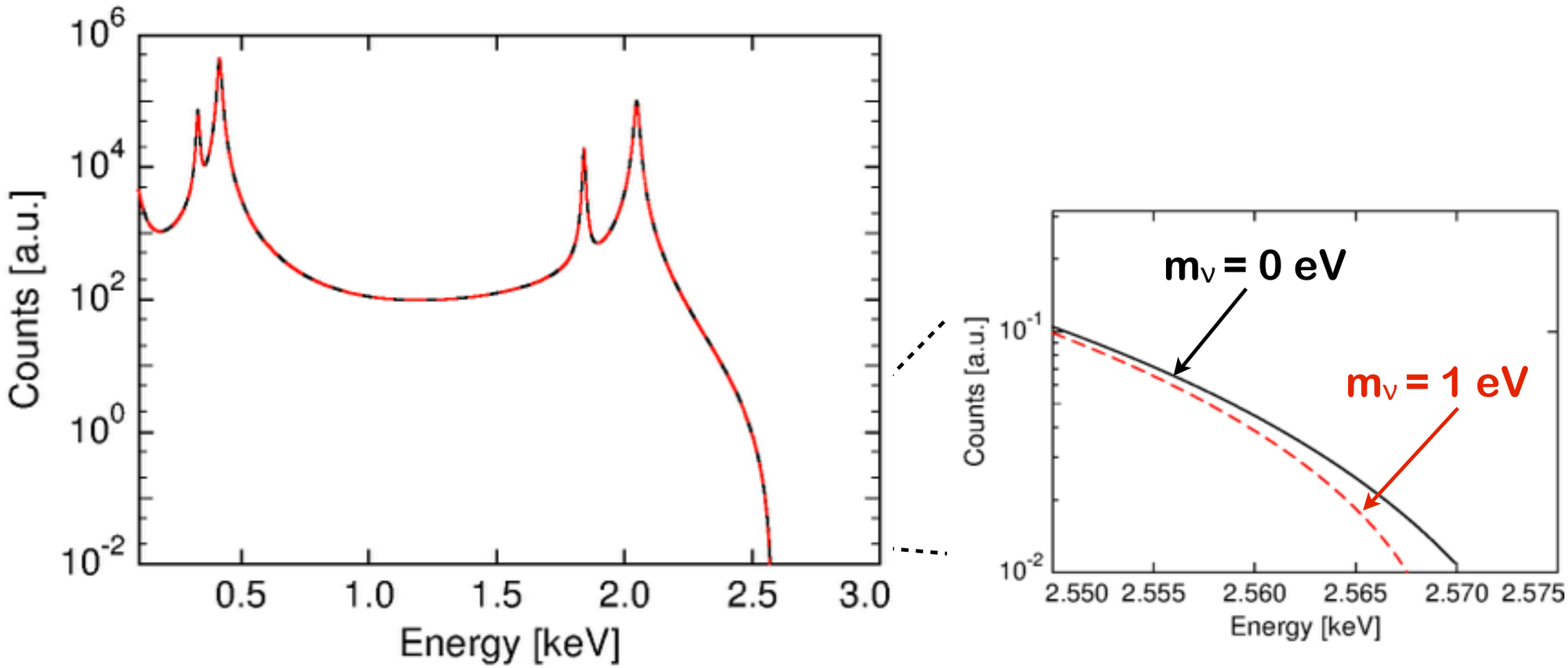




Source column density at max

Rovibrational states of THe^+

$$\dot{N} \sim (Q_{EC} - E_C)^2 \sum_i |U_{ei}|^2 \sqrt{1 - \frac{m_{\nu i}^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \psi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_{EC} - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

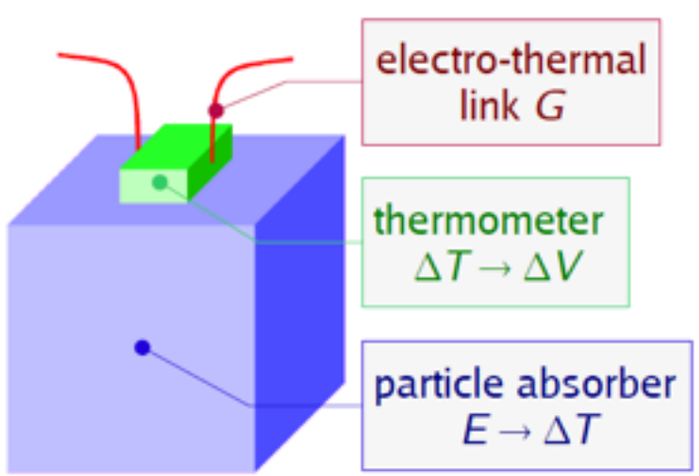


New ~~trick~~ isotope on the block:

Electron Capture

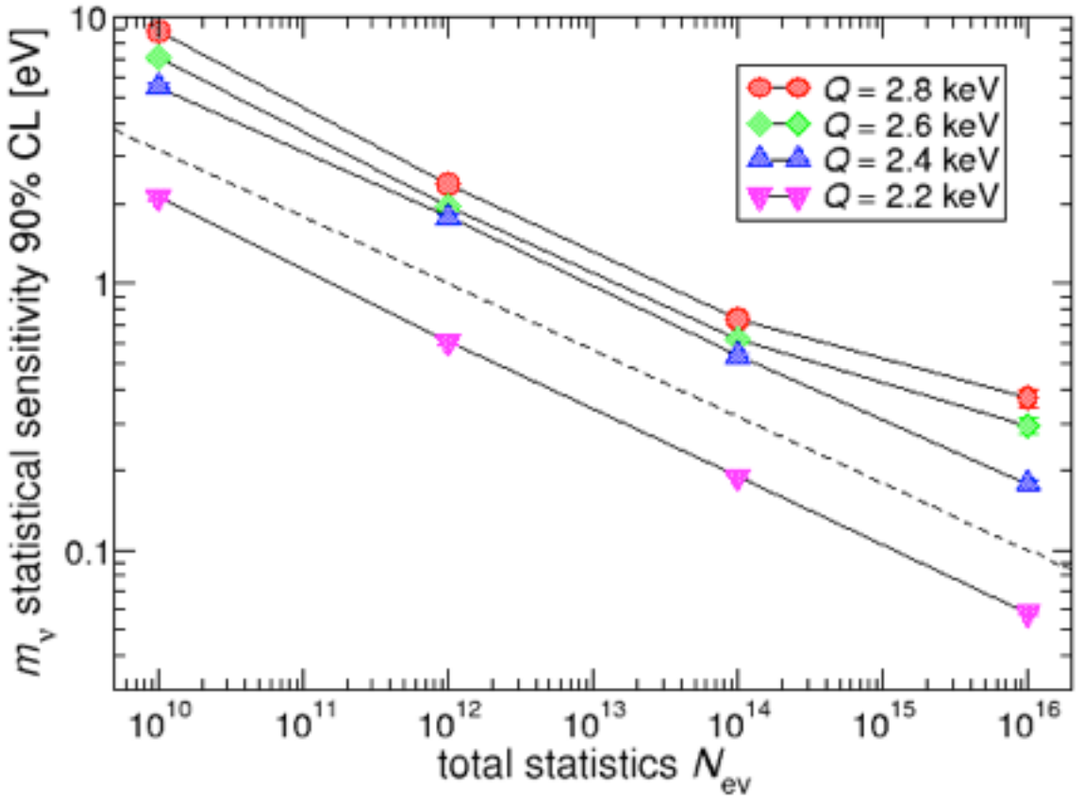
Advantages & Challenges

Calorimetry



$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow {}^{183}\mathrm{Dy}^* + \nu_e$$

Challenges:



Source Activity

$N_{ev} > 10^{14}$ to reach sub-eV level

- **Advantages:**

  Source = detector

  No backscattering

  No molecular final state effects.

  Self-calibrating

Detector Response

$\Delta E_{FWHM} < 10$ eV
$\tau_{risetime} < 1$ µs

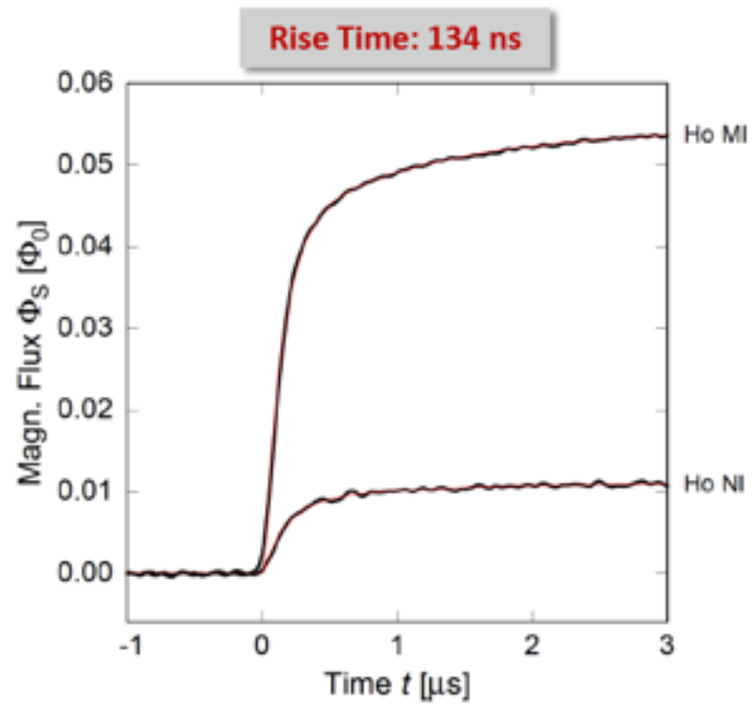
- **Experimental Challenges:**

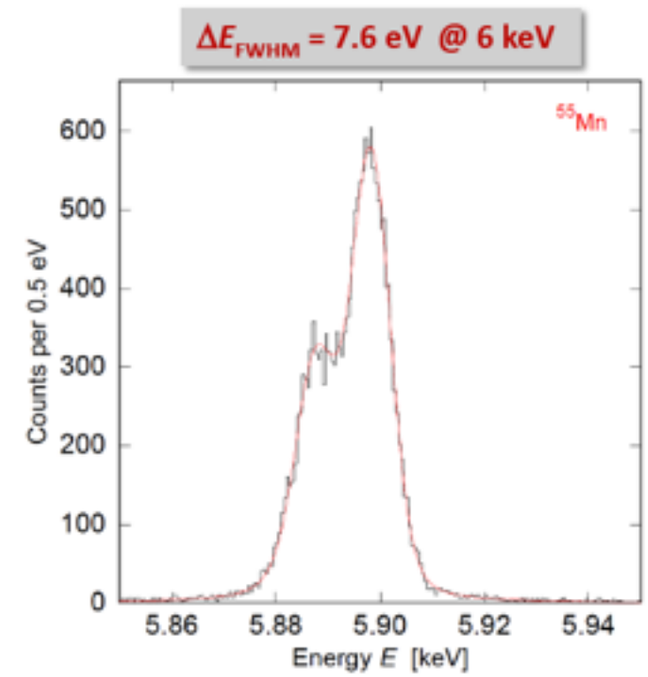
  Fast rise times to avoid pile-up effects.

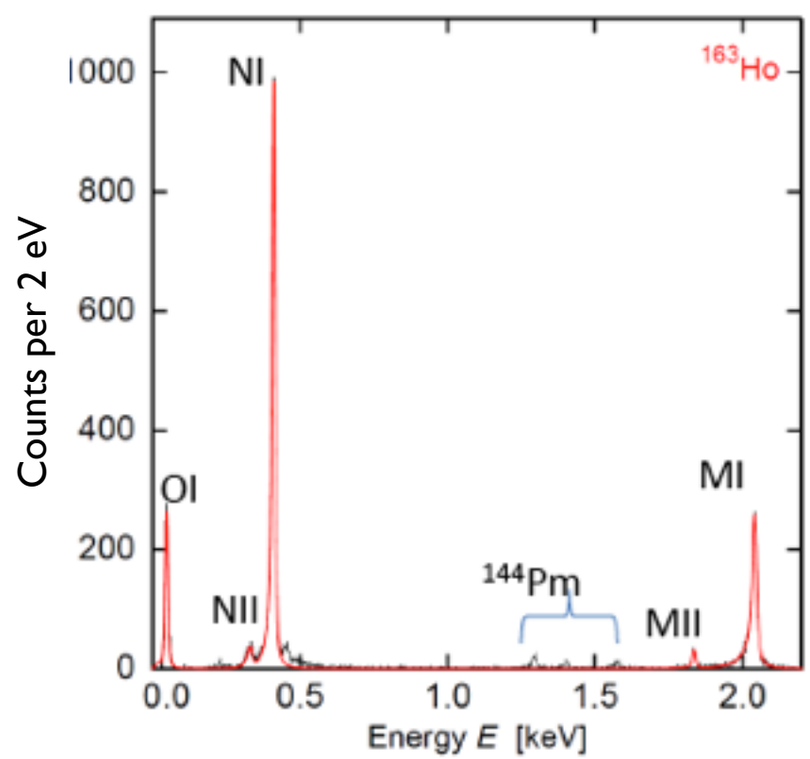
  Good energy resolution & linearity

  Abundant isotope production

The ECHo Experiment

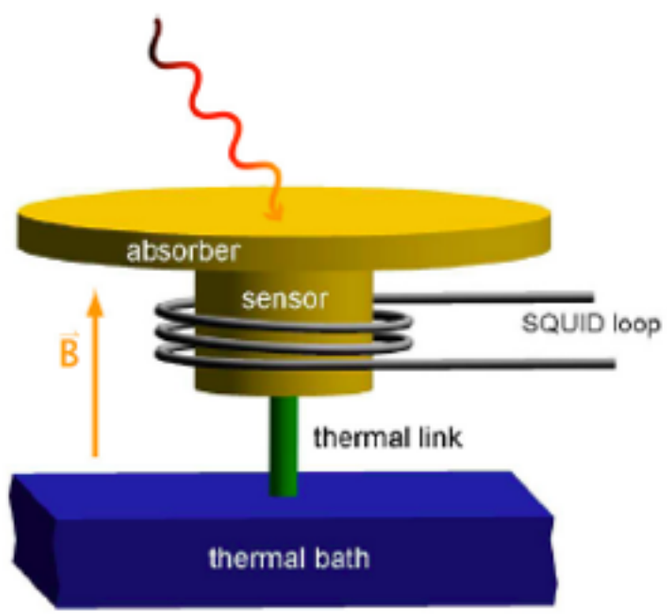






- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

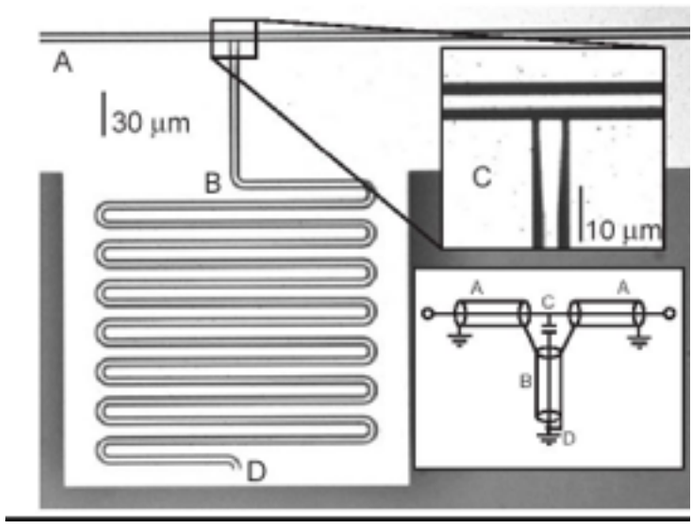
Technology:



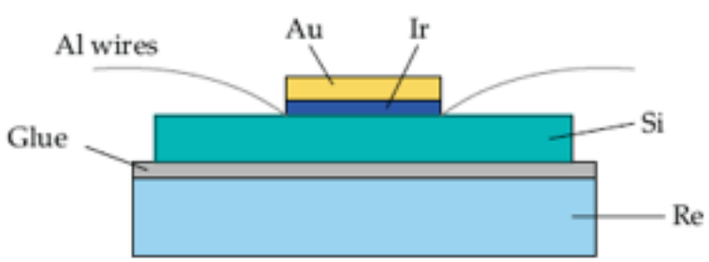
Metallic Magnetic Calorimeters

The HOLMES Experiment

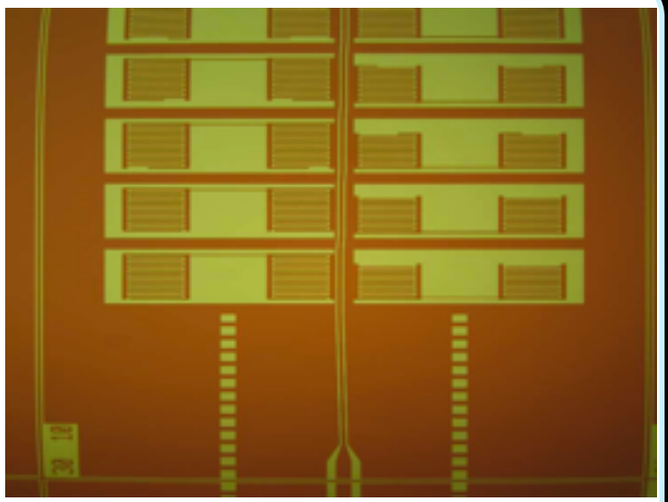
Technologies:

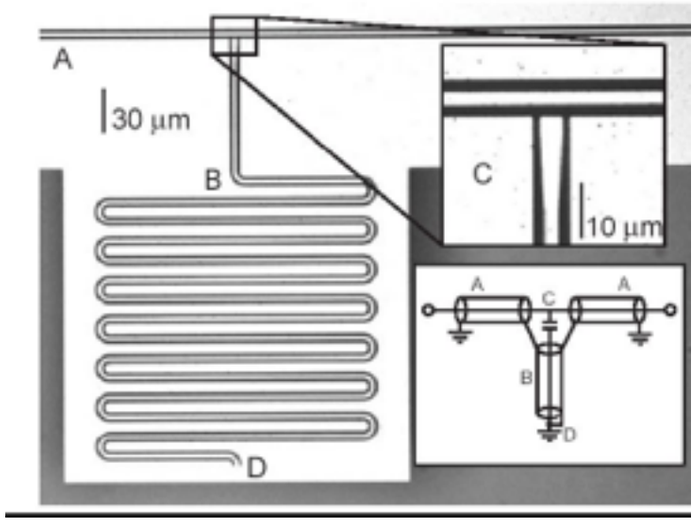


Superconducting Resonators



Transition Edge Sensors





MARE-HOLMES

- MARE (Phase I) explored various technology approaches, such as Transition-Edge Sensors (TES) and Microwave Kinetic Inductance Detectors (MKIDs).
- Successful extraction of Ho^+ ions for metal production and implantation onto detectors.
- Successful funding received for one thousand channel Ho detector experiment (the HOLMES experiment).

Project 8

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

I. I. Rabi

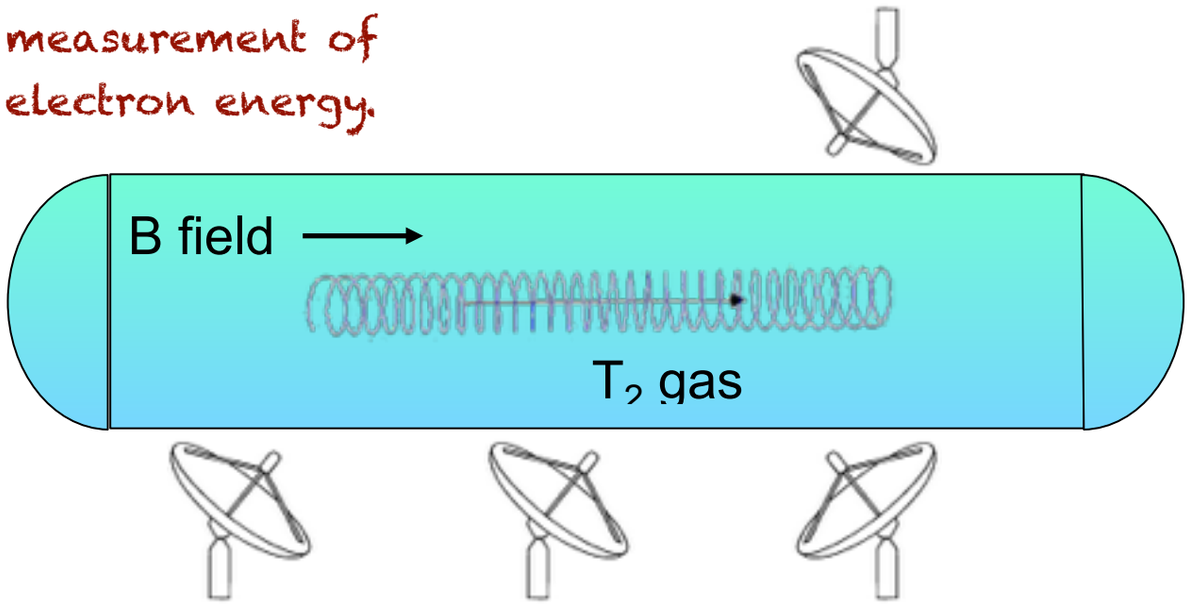
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- Non-destructive measurement of electron energy.



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

PROJECT 8

Frequency Approach

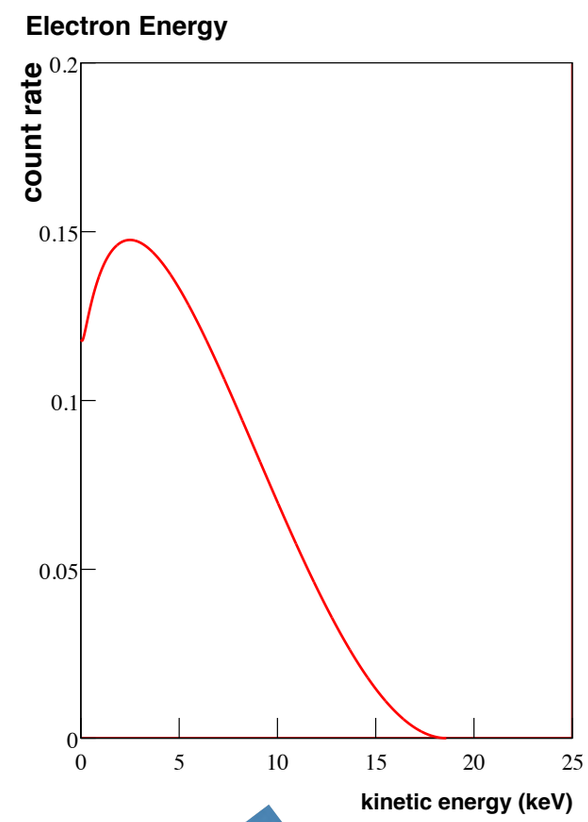
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Unique Advantages

- Source = Detector
  (no need to separate the electrons from the tritium)

- Frequency Measurement
  (can pin electron energies to well-known frequency standards)

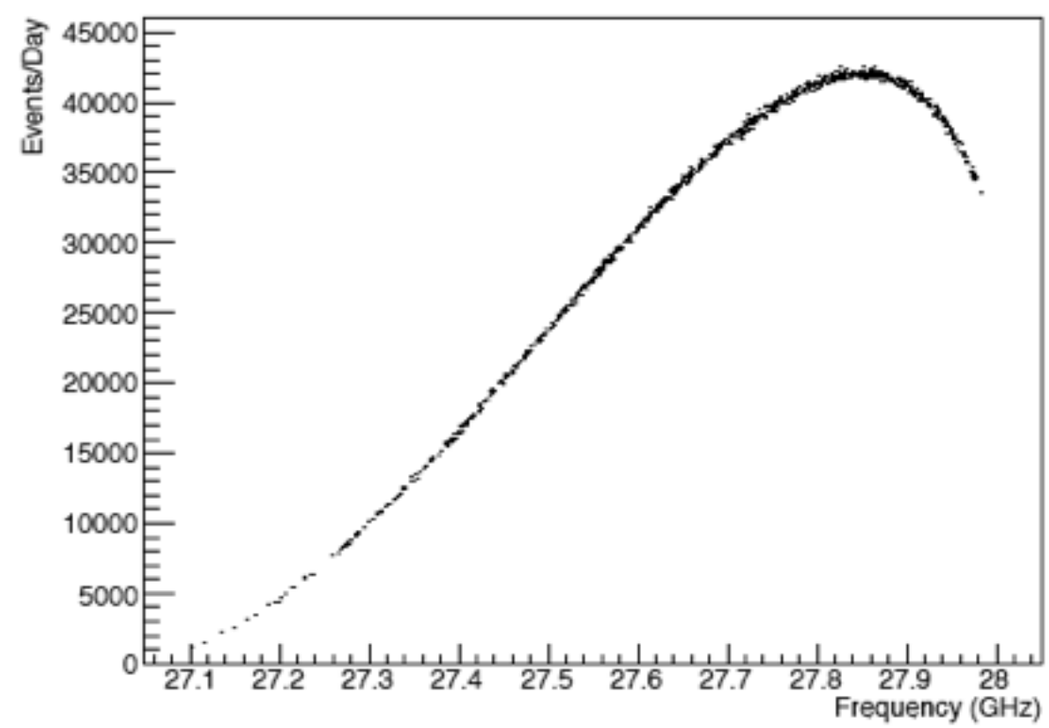
- Full Spectrum Sampling
  (full differential spectrum measured at once, large leverage for stability and statistics)



Beta spectrum

Cyclotron Frequency

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



Beta (frequency) spectrum

...and Challenges

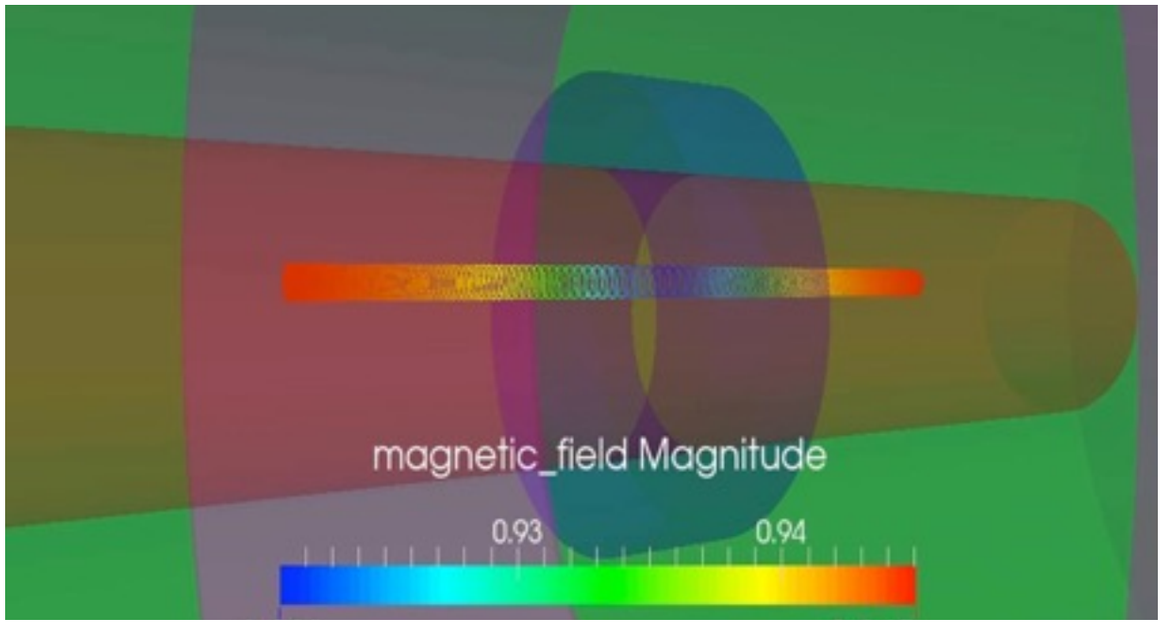
- **Power Emitted**
  Less than 1 fW of power radiated (depends on antenna geometry) is challenging.

- **Confinement Period**
  One needs time to make sufficiently accurate measurement (> 10 μs). Employ magnetic bottle for trapping.

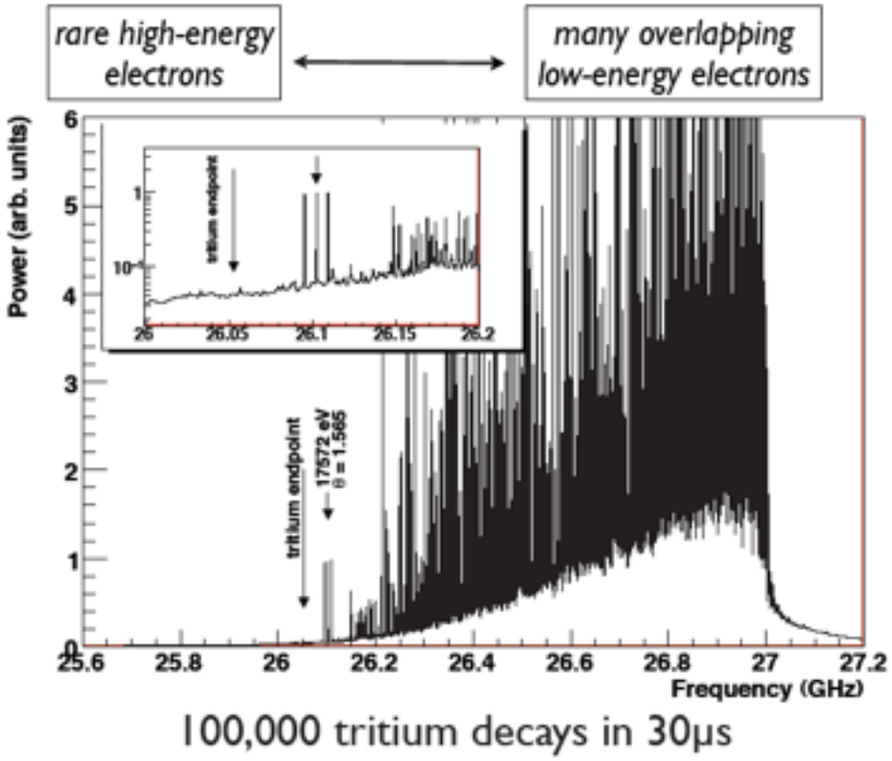
- **Full Spectrum**
  The full spectrum is available. Fortunately, linearity of frequency space helps separate regions of interest.

$$P_{\mathrm{tot}}(\beta_{\|}, \beta) = \frac{1}{4\pi\epsilon_0} \frac{2e^2\omega_0^2}{3c} \frac{\beta_{\|}^2}{1-\beta^2}$$

(Free) Radiative Power Emitted

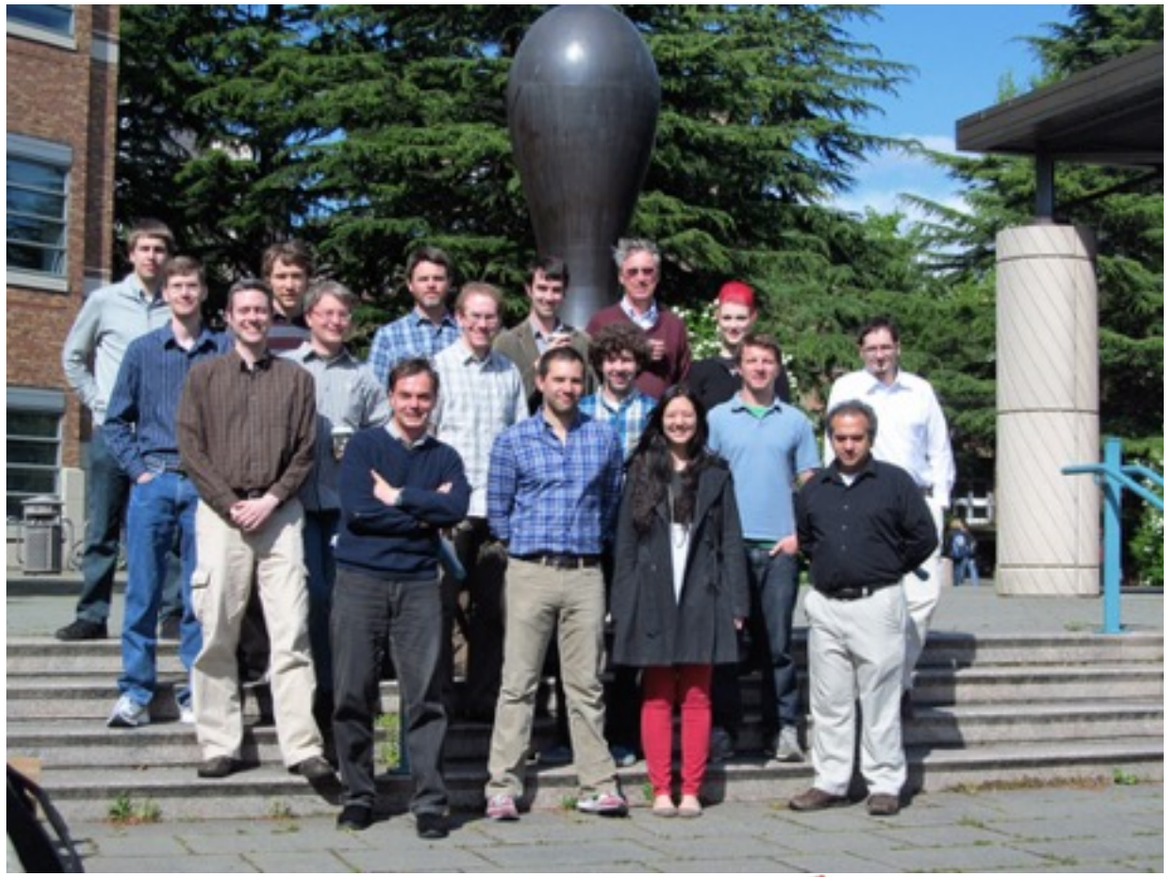


Simulation of electron motion in magnetic bottle



Simulation of beta (frequency) spectrum

Project 8 Collaboration



PROJECT 8

J. Formaggio, D. Furse*, N. Oblath,
P. Monhanmurthy*, D. Rysewyk
Massachusetts Institute of Technology

T. Thuemmler
Karlsruhe Institute of Technology

P. Slocum
Yale University

Shepard Doelman
Haystack Observatories

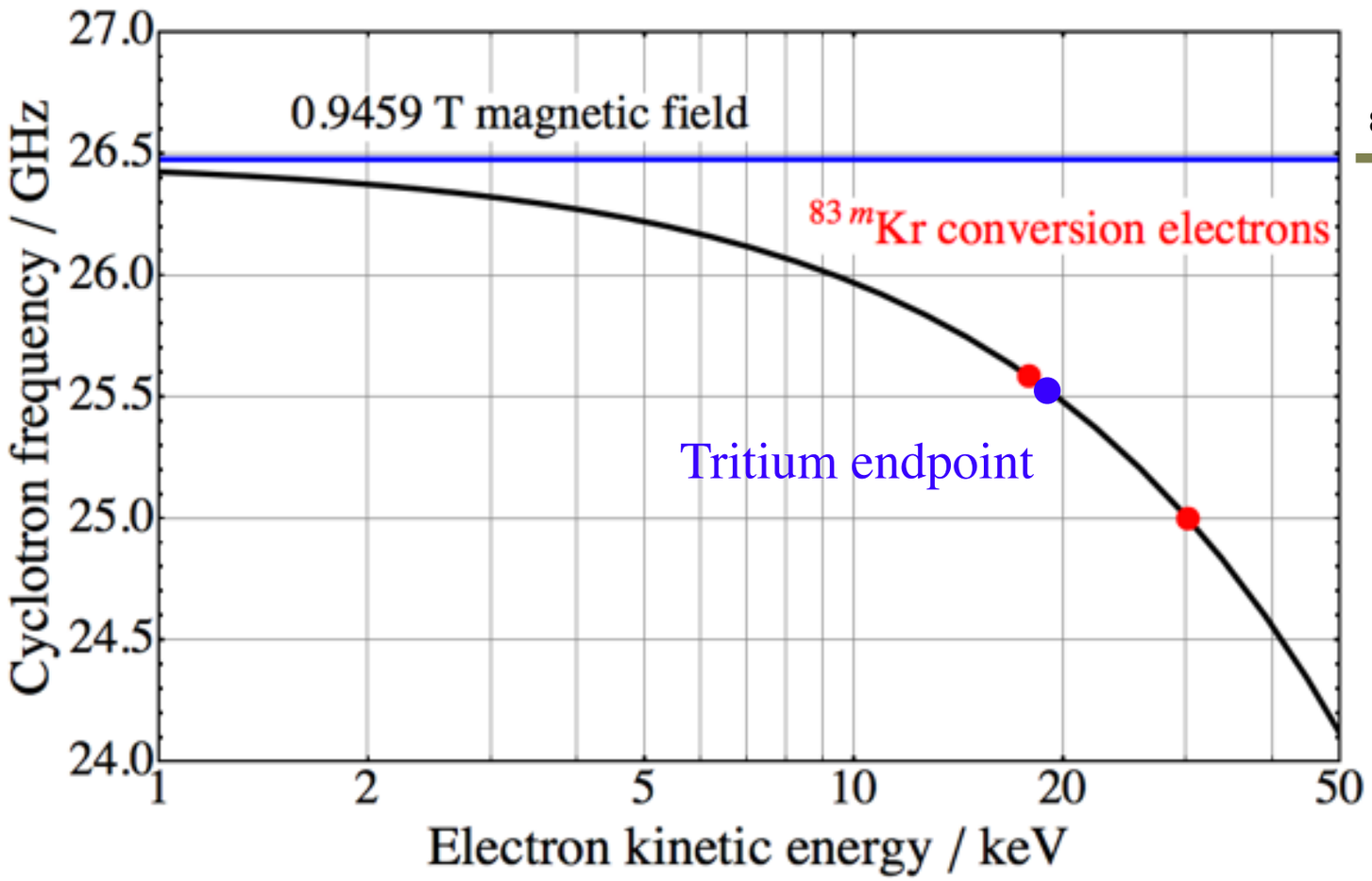
B. LaRoque*, L. de Viverios, B. Monreal
University of California, Santa Barbara

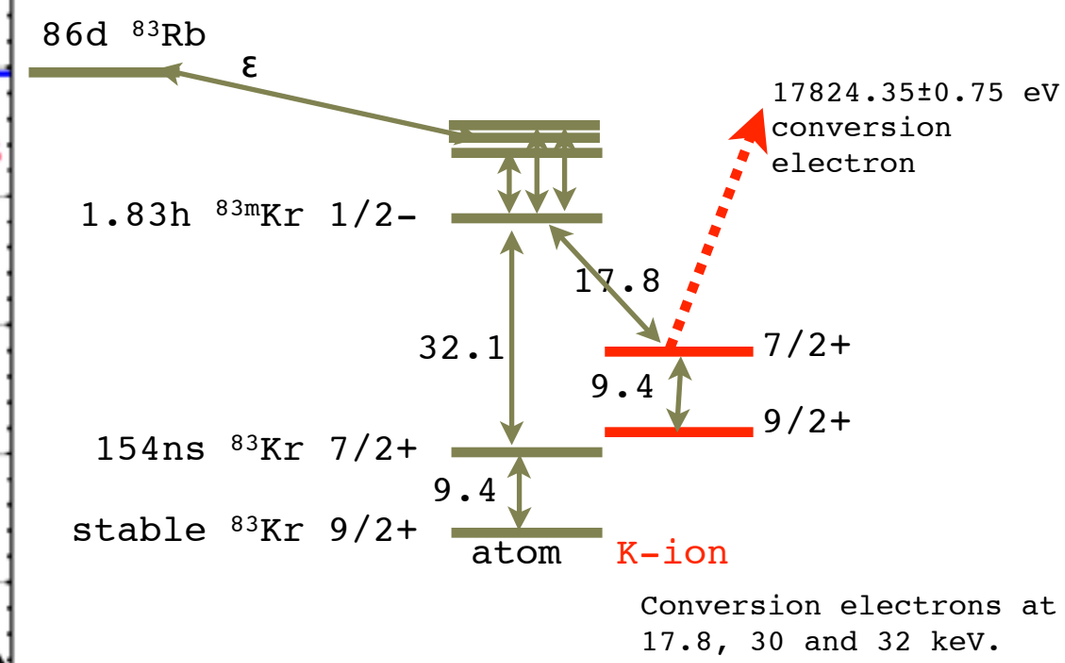
M. Fertl, J. Kofron*, R.G.H. Robertson, L. Rosenberg, G. Rybka, M. Sternberg
University of Washington, Center for Experimental Nuclear Physics and Astrophysics

D.M. Asner, J. Fernandes, A.M. Jones, J.F. Kelly, B.A. VanDevender
Pacific Northwest National Lab

* indicates graduate student

Initial Demonstration: ^{83m}Kr





Phase I : Use mono-energetic source to determine single electron detection.

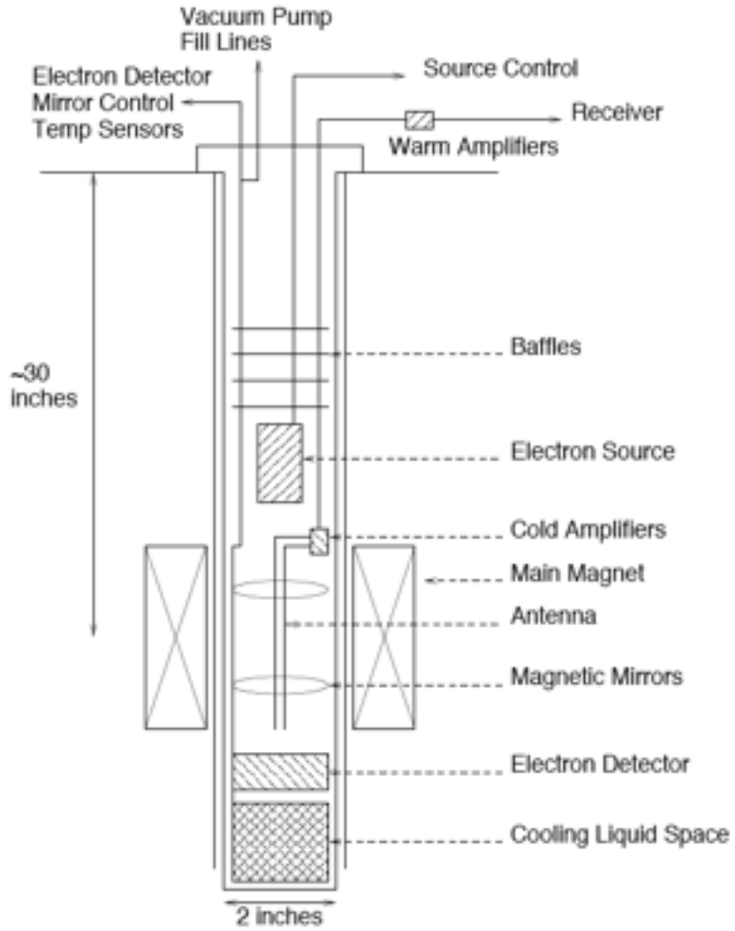
Use of standard gaseous ^{83m}Kr source allows quantification of energy resolution and linearity.

Basic Layout of Phase I

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

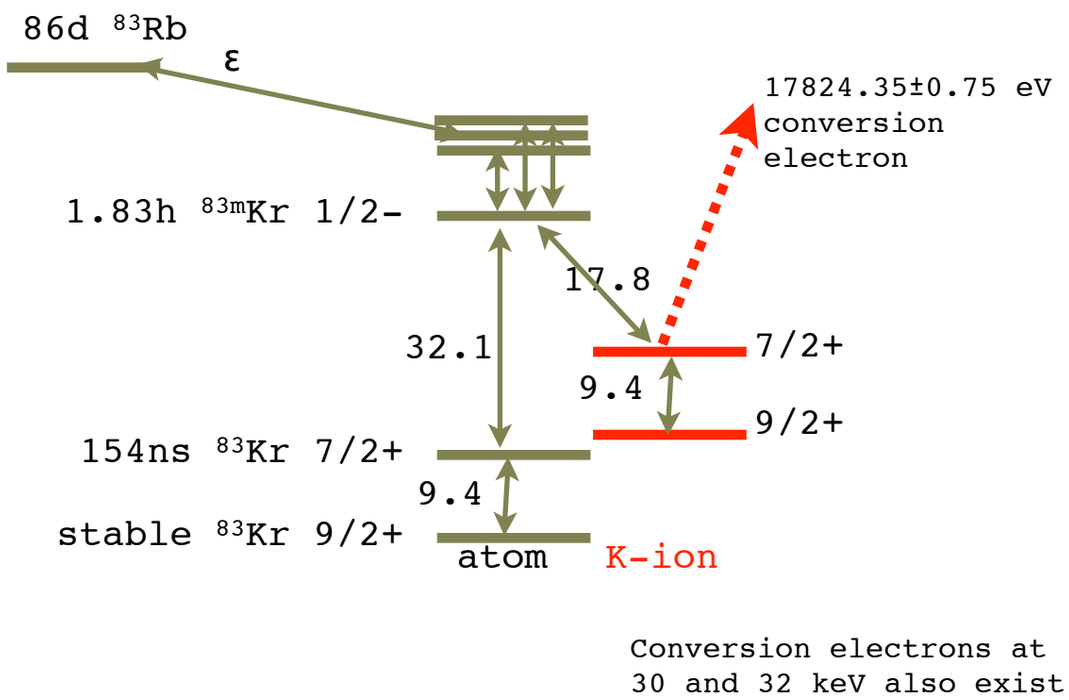
- **Magnet System**
  Provides magnetic field and trapping of electrons.

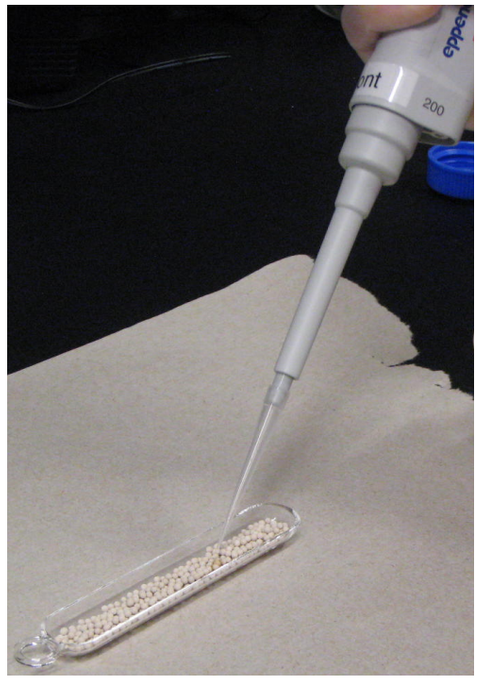
- **RF Detection/Calibration System**
  Detection of microwave signal.



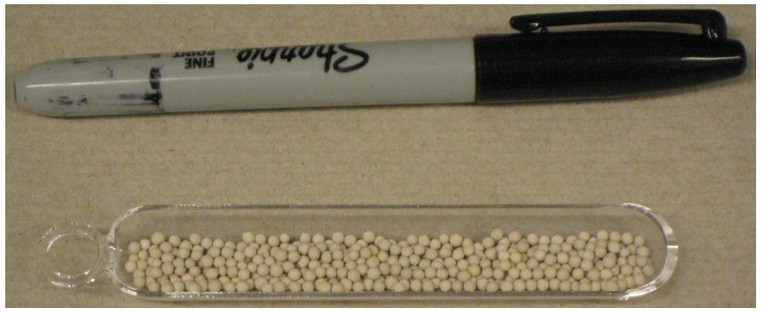
The Electron Source

Initial Demonstration Source: ^{83m}Kr





Zeolite loading

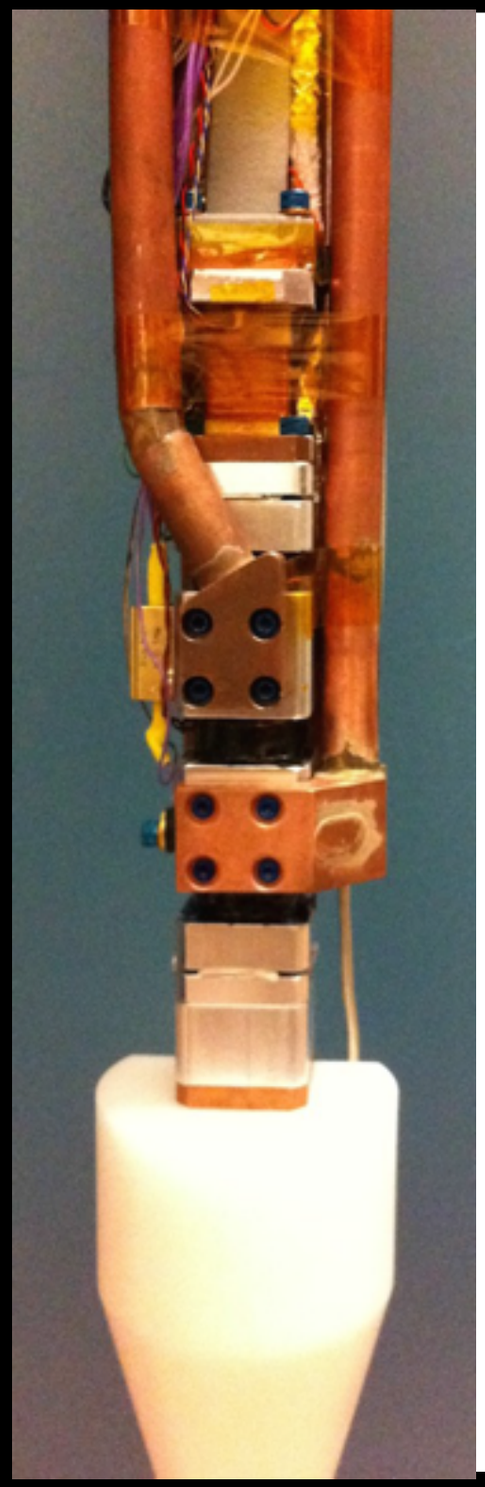


Mono-energetic gaseous electron source

Collaboration taking a phased approach to understand the scaling and systematics of the experiment.

First phase (single electron detection) requires single electron detection.

Using ^{83m}Kr (^{83}Rb implanted in zeolite beads) as source



The Apparatus

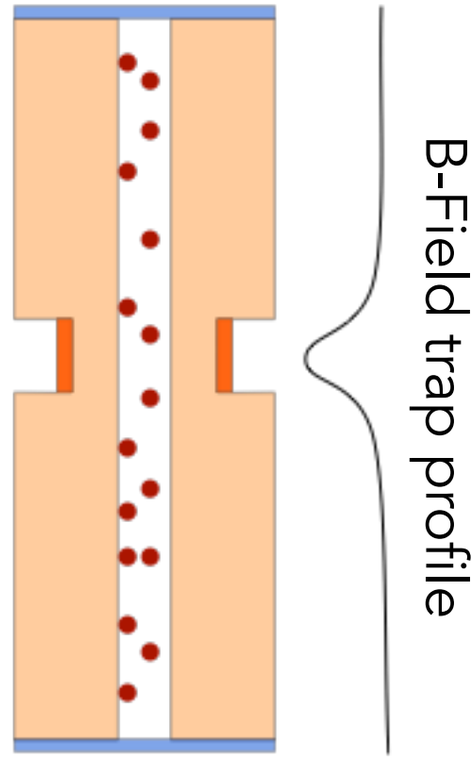
Copper waveguide

Kr gas lines

Magnetic bottle coil

Gas cell

Test signal injection port



Waveguide
Cut-away

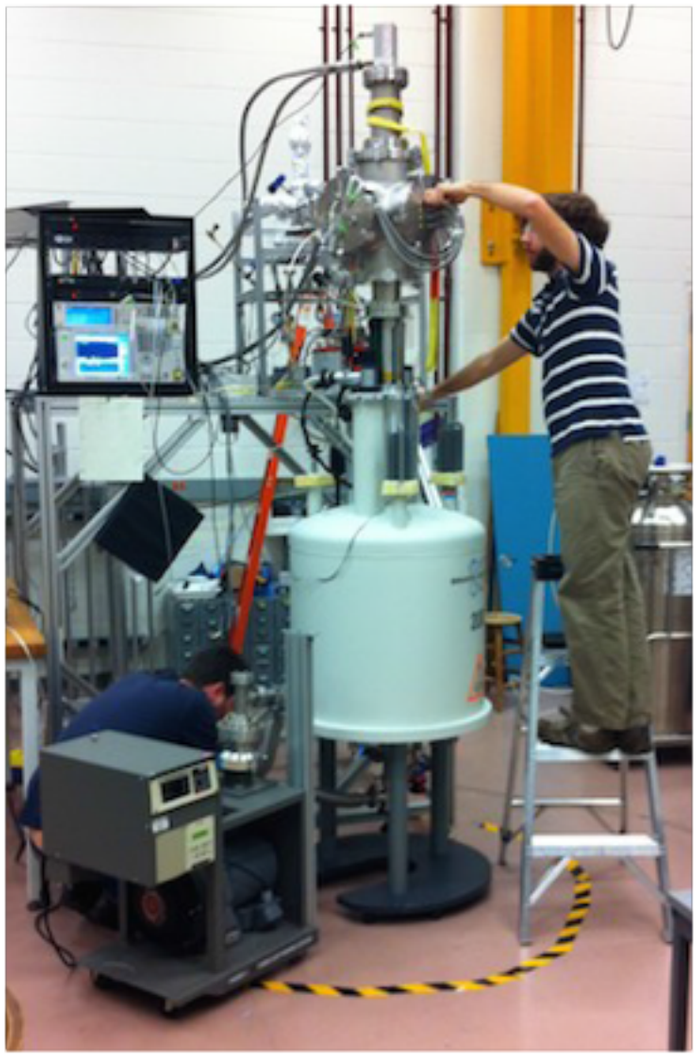
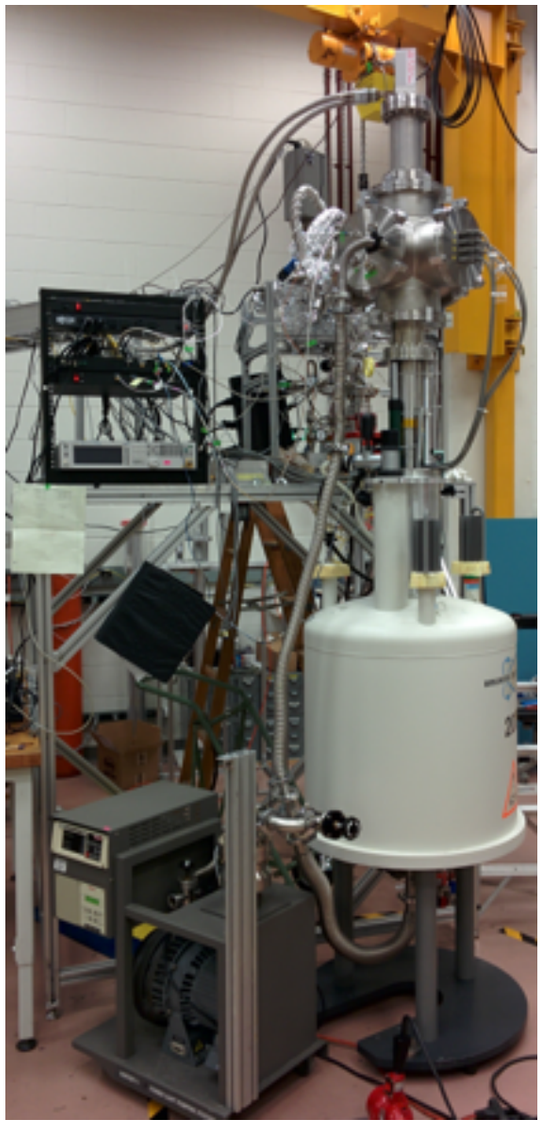


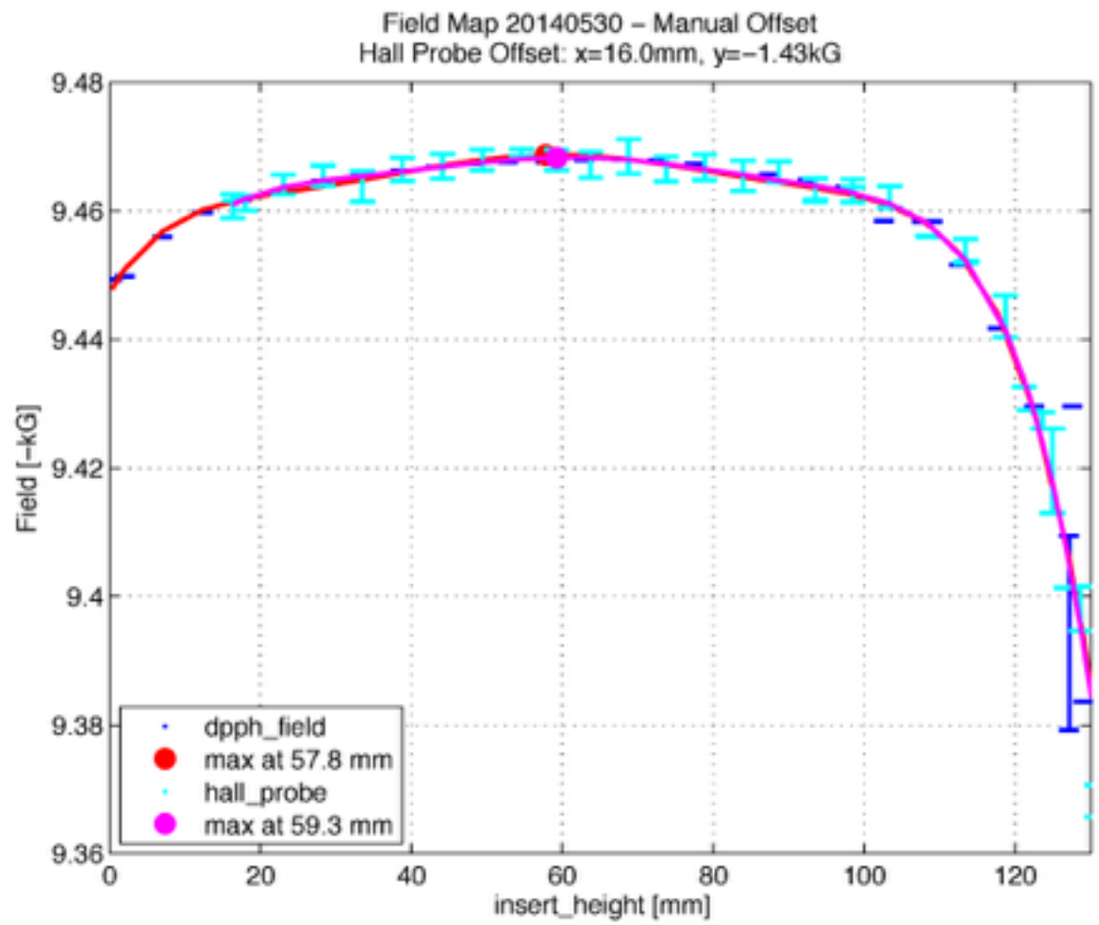
Photo of apparatus

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

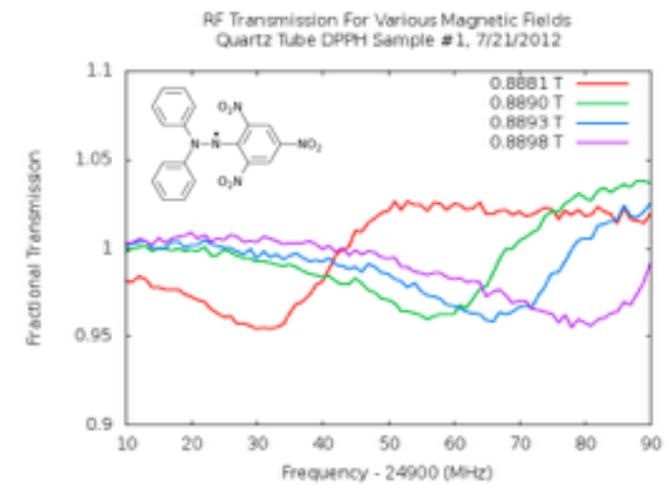
Magnetic bottle allows for trapping of electron within cell for measurement.

Magnetic Environment





Main field measurement



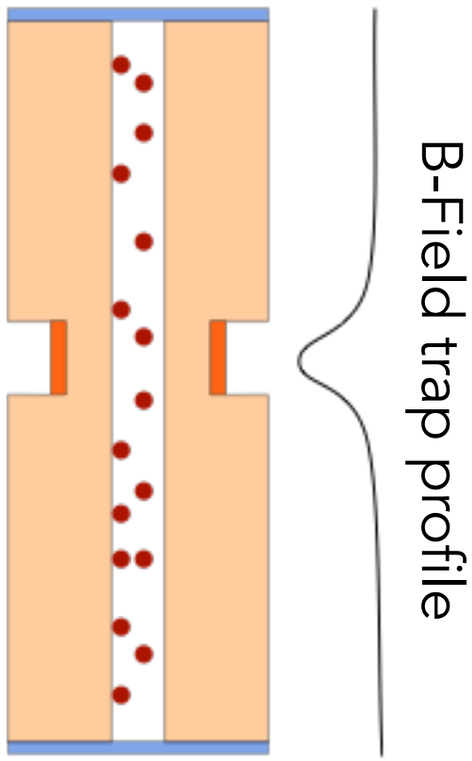
ESR Measurement

A normal-conducting coil provides a trapping potential for high pitch electrons (magnetic bottle).

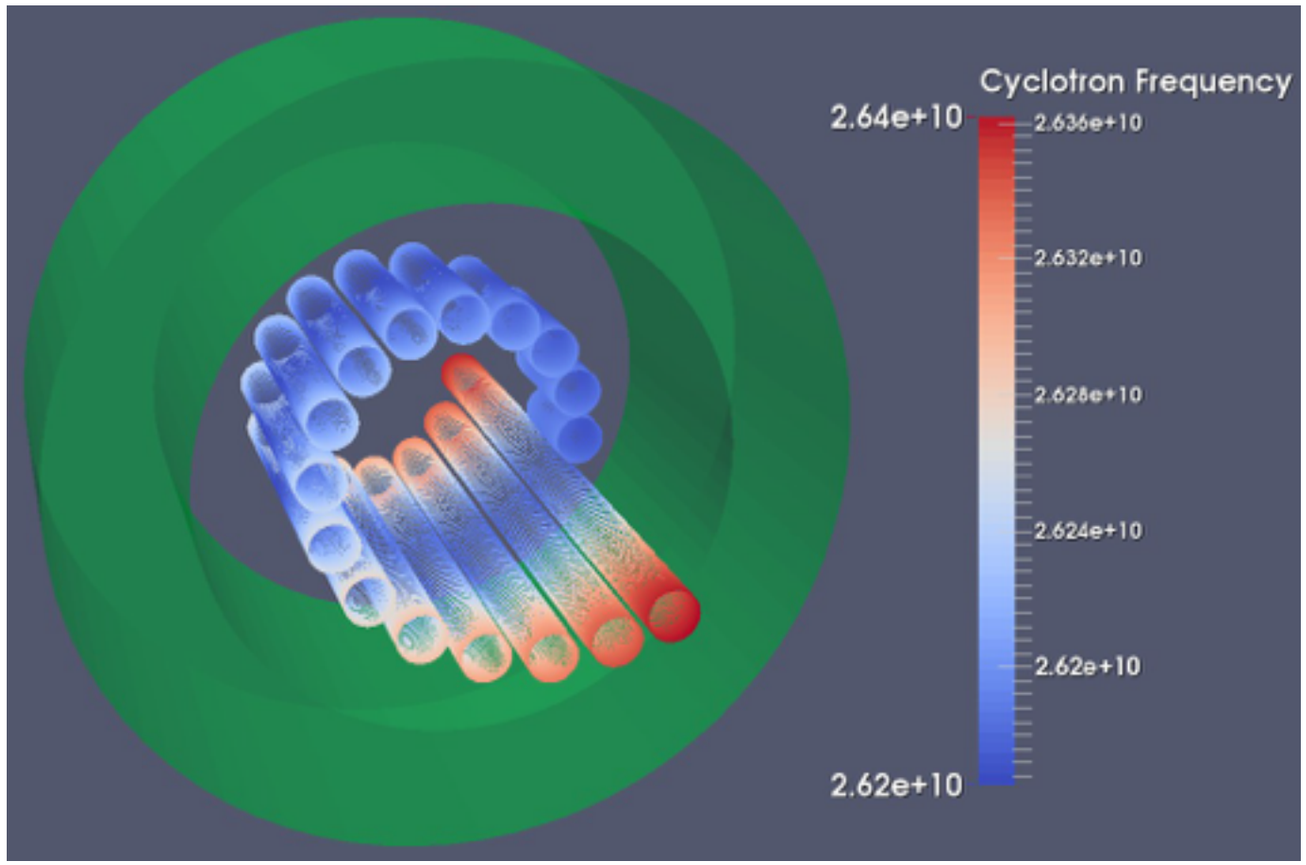
Up to 8 mT trapping potential in an overall 1 Tesla field.

Trapped can be turned "on" and "off" for noise studies.

Magnetic Environment



Magnetic bottle cut-away



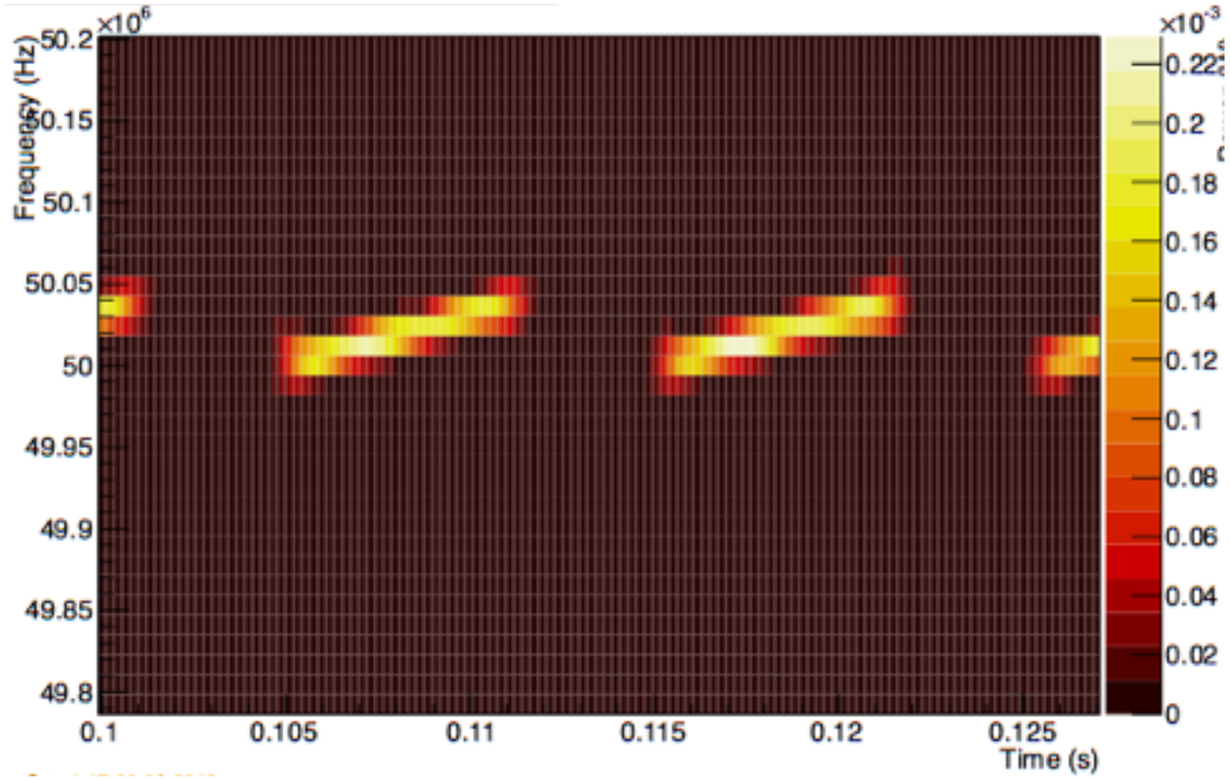
Simulation of trapped electrons (using our own Kassiopeia software)

A normal-conducting coil provides a trapping potential for high pitch electrons (magnetic bottle).

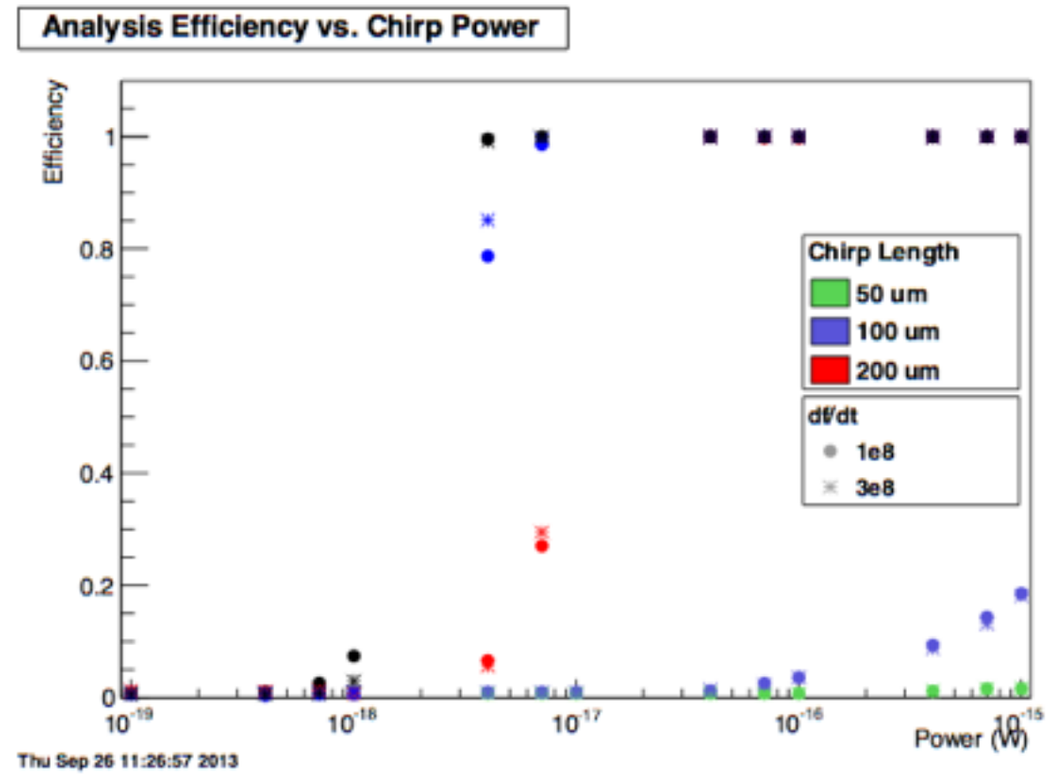
Up to 8 mT trapping potential in an overall 1 Tesla field.

Trapped can be turned "on" and "off" for noise studies.

What Does a Signal Look Like?



Simulated "Chirp" Signal



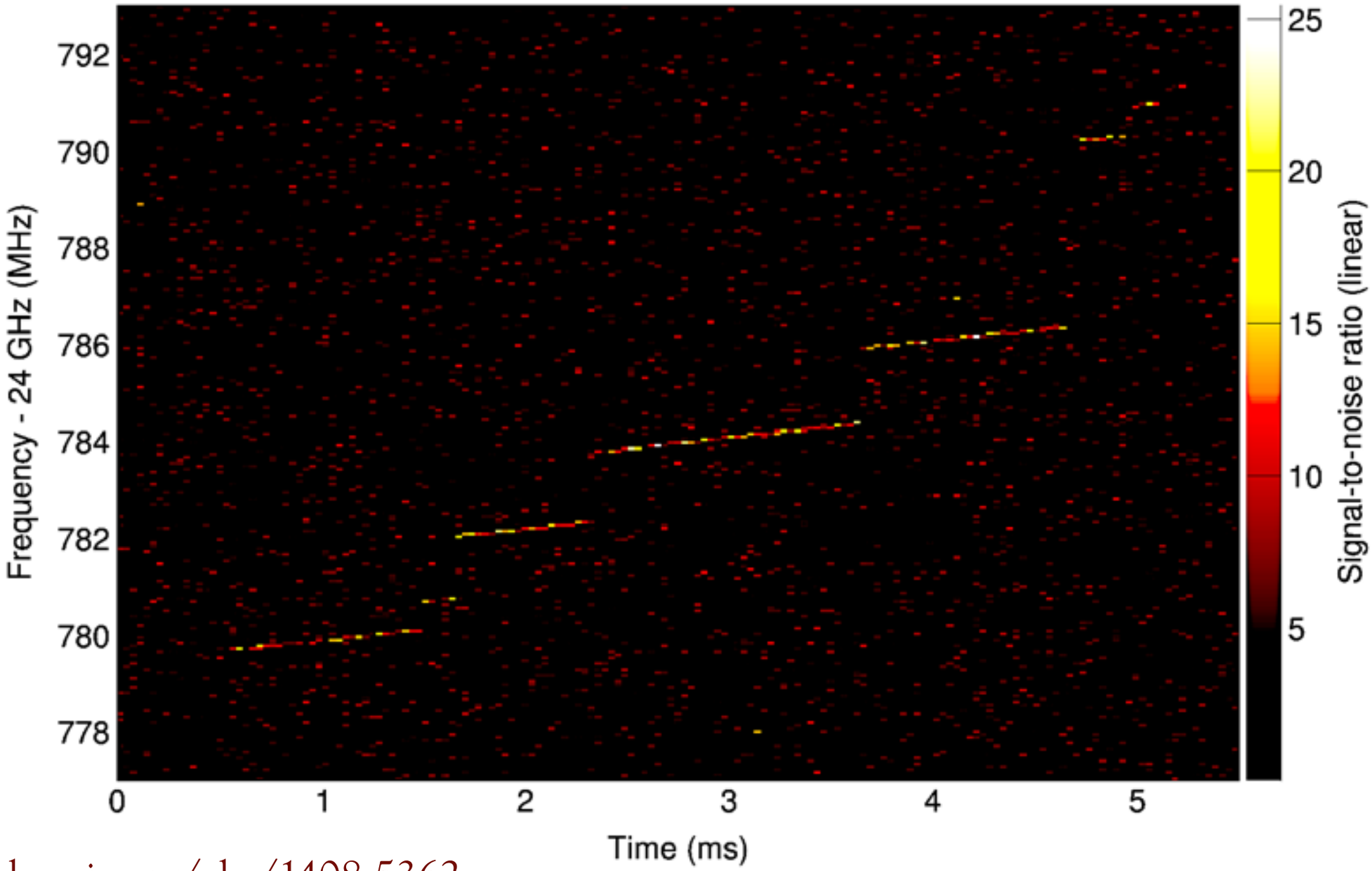
Efficiency for finding candidates

Signal exhibits itself as a short duration pulse ("chirp") in frequency.

Signal is digitized in frequency/time space and scanned for clusters.

Sensitivity studies demonstrate excellent efficiency down to 10^{-17} fW for 50 μs signals.

Project 8 "Event Zero"

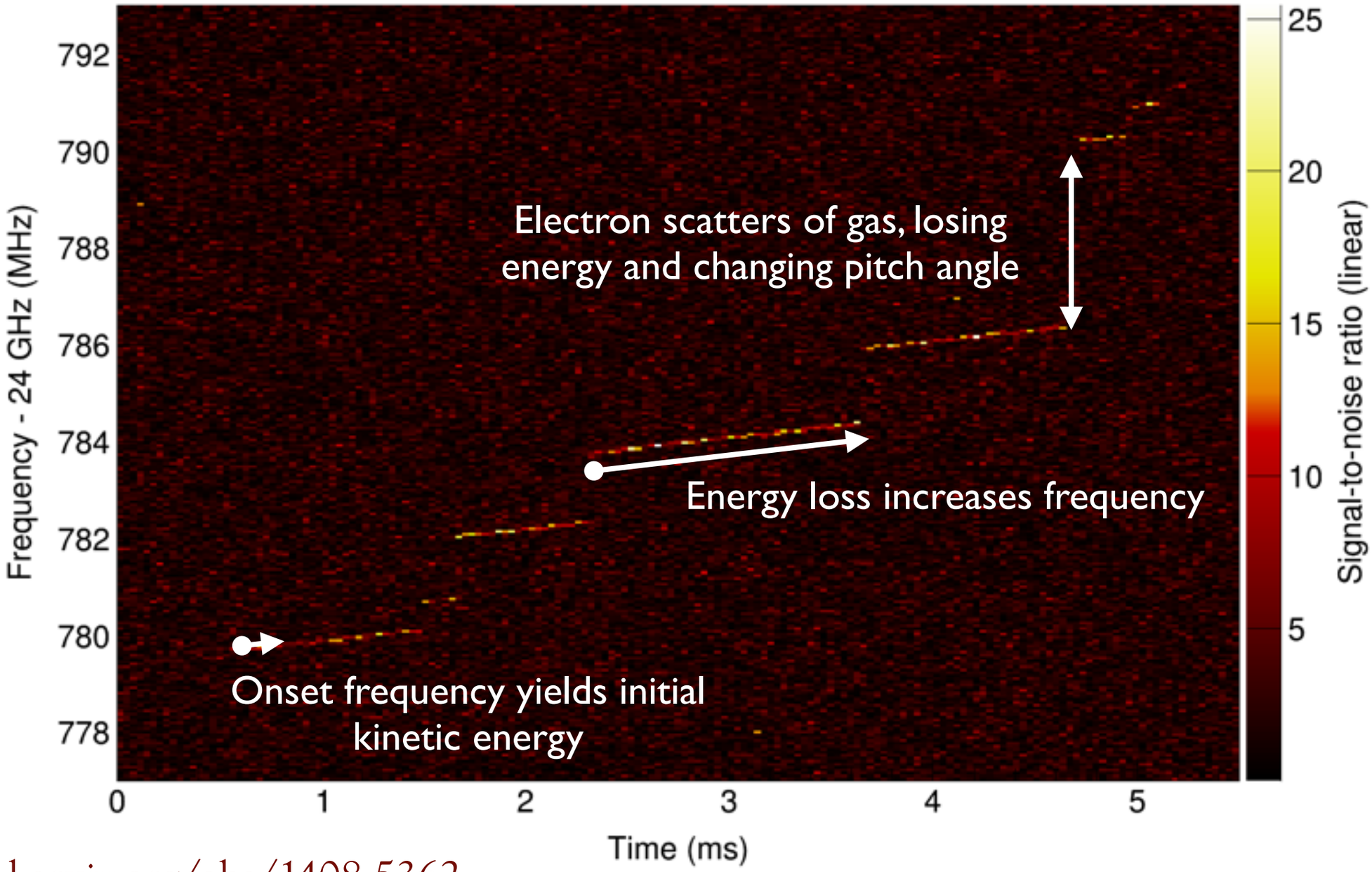


http://lanl.arxiv.org/abs/1408.5362

First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

Project 8 "Event Zero"

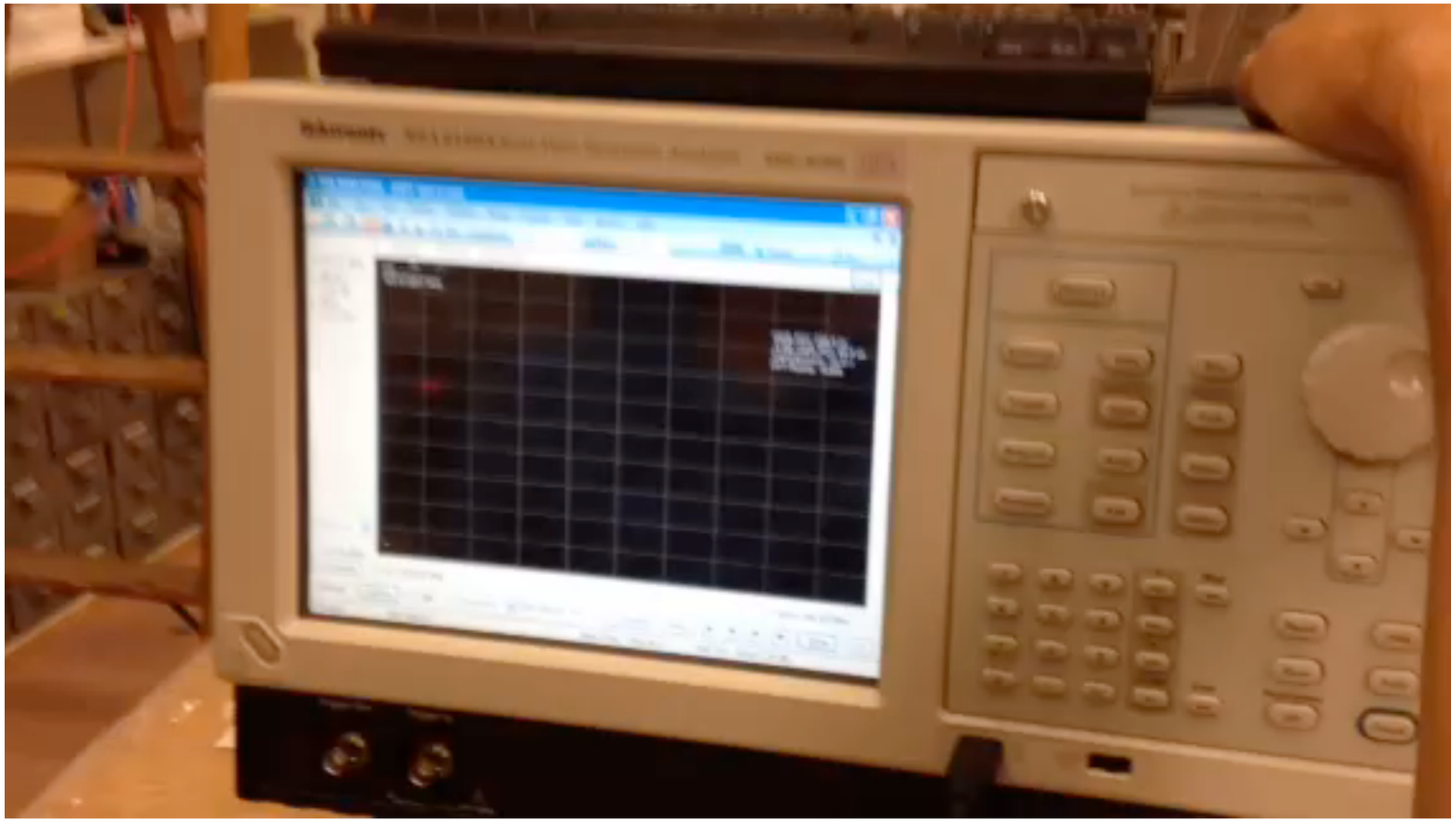


http://lanl.arxiv.org/abs/1408.5362

First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

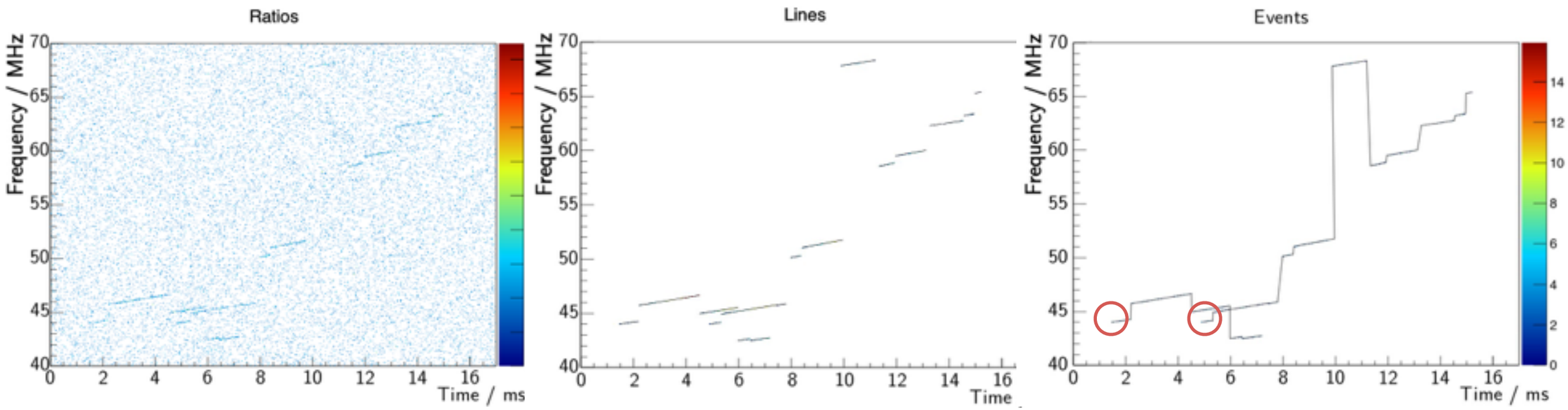
Eureka moment



First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

Image Reconstruction & Energy Resolution

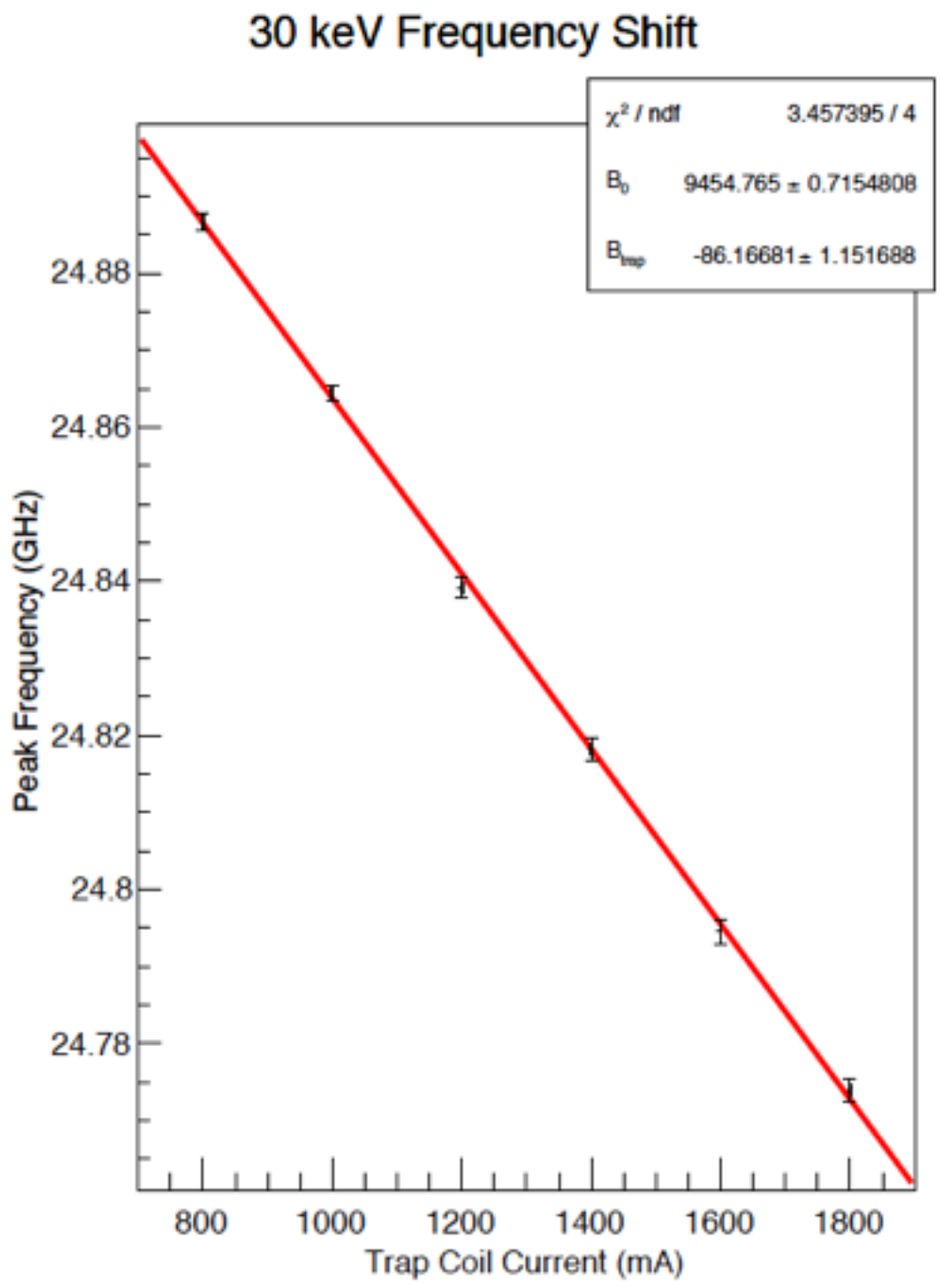


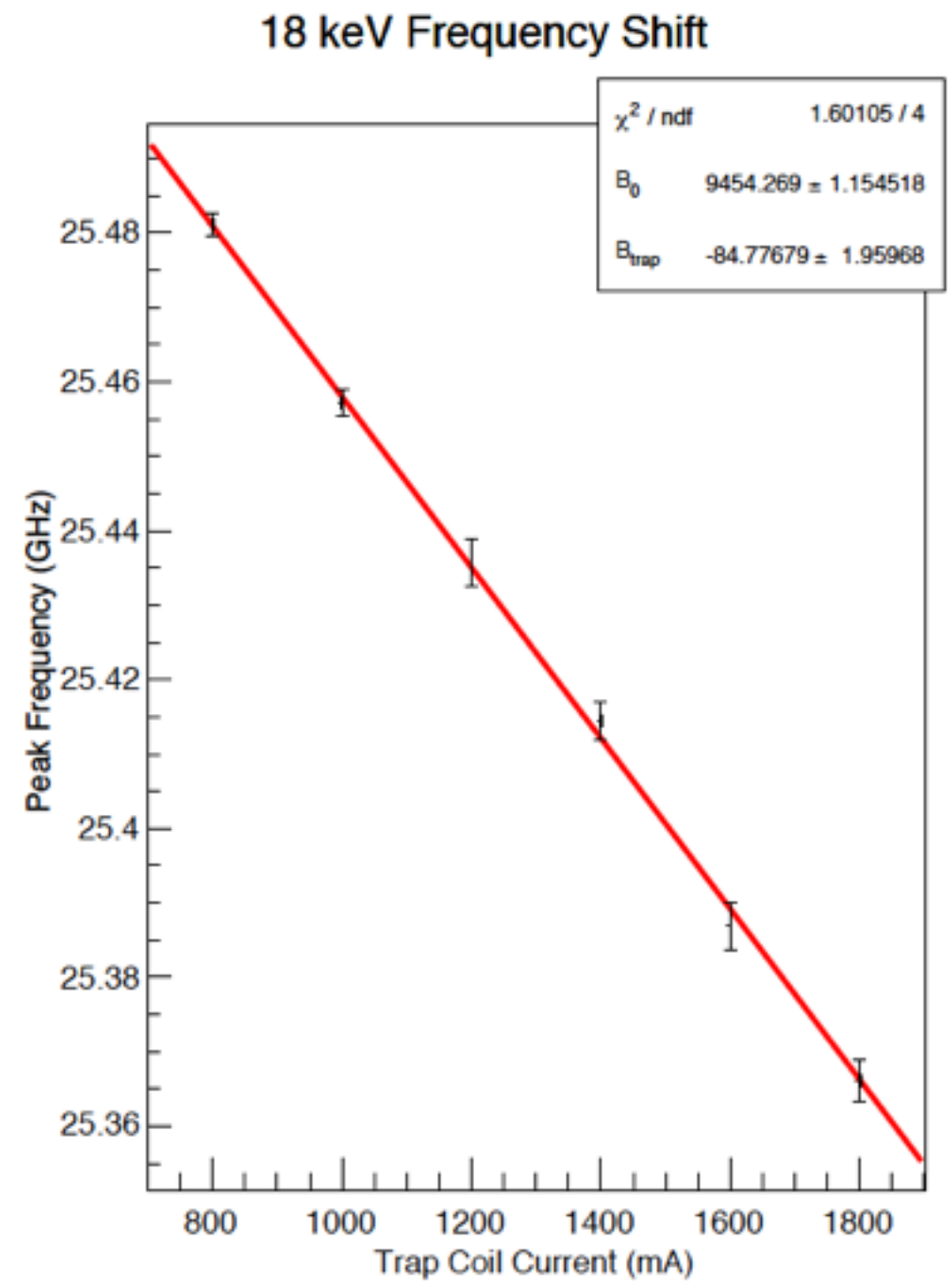
clusters above threshold turn into… tracks, which in turn become… …events

Cyclotron Radiation Emission Spectroscopy (CRES) allows extraction of many details from trapped electrons (energy, resolution, confinement time, etc.)

Reduces to an image analysis for event characterization.

Trap Dependence

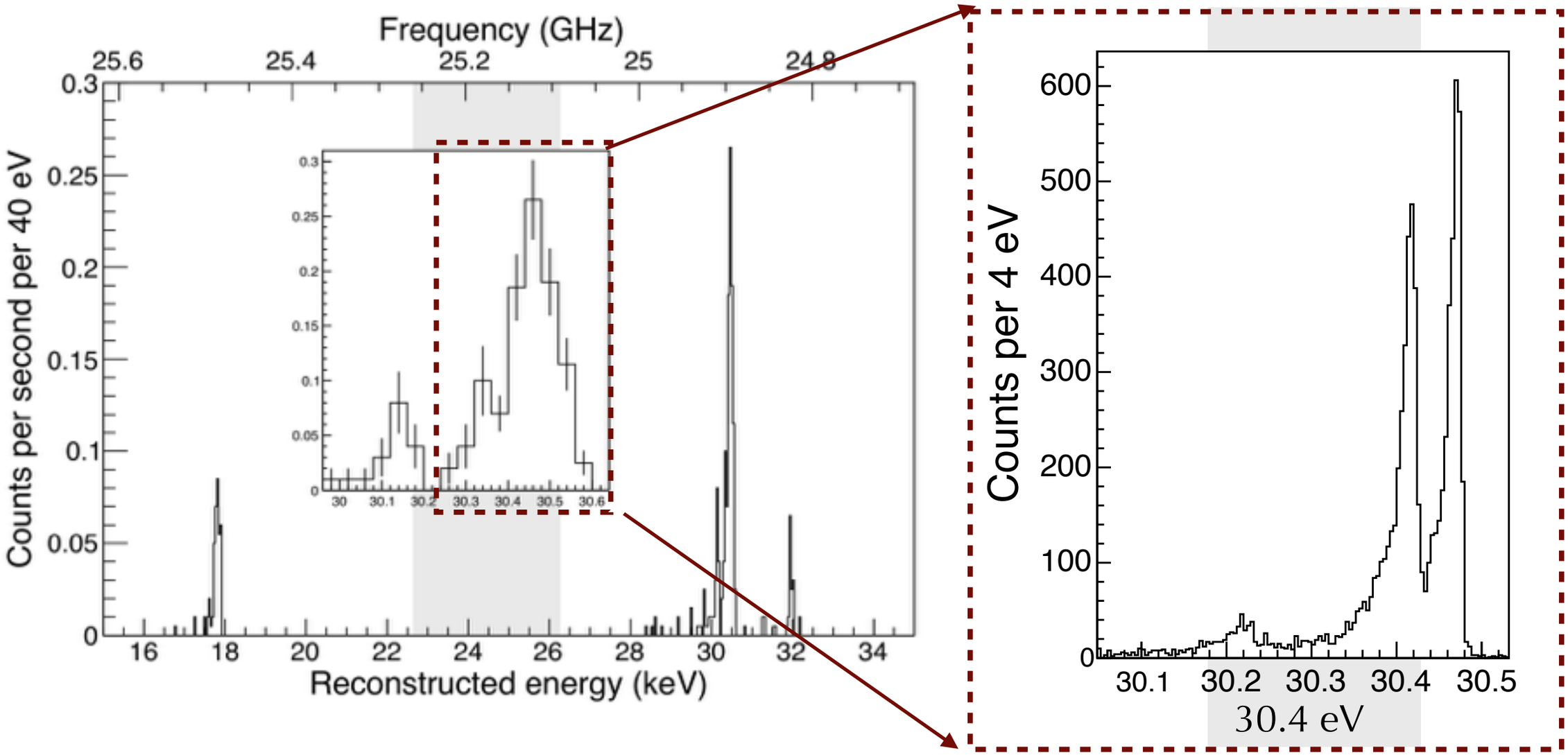




Dependence on trap parameters well understood.

Can be used to determine baseline field strength.

Image Reconstruction & Energy Resolution



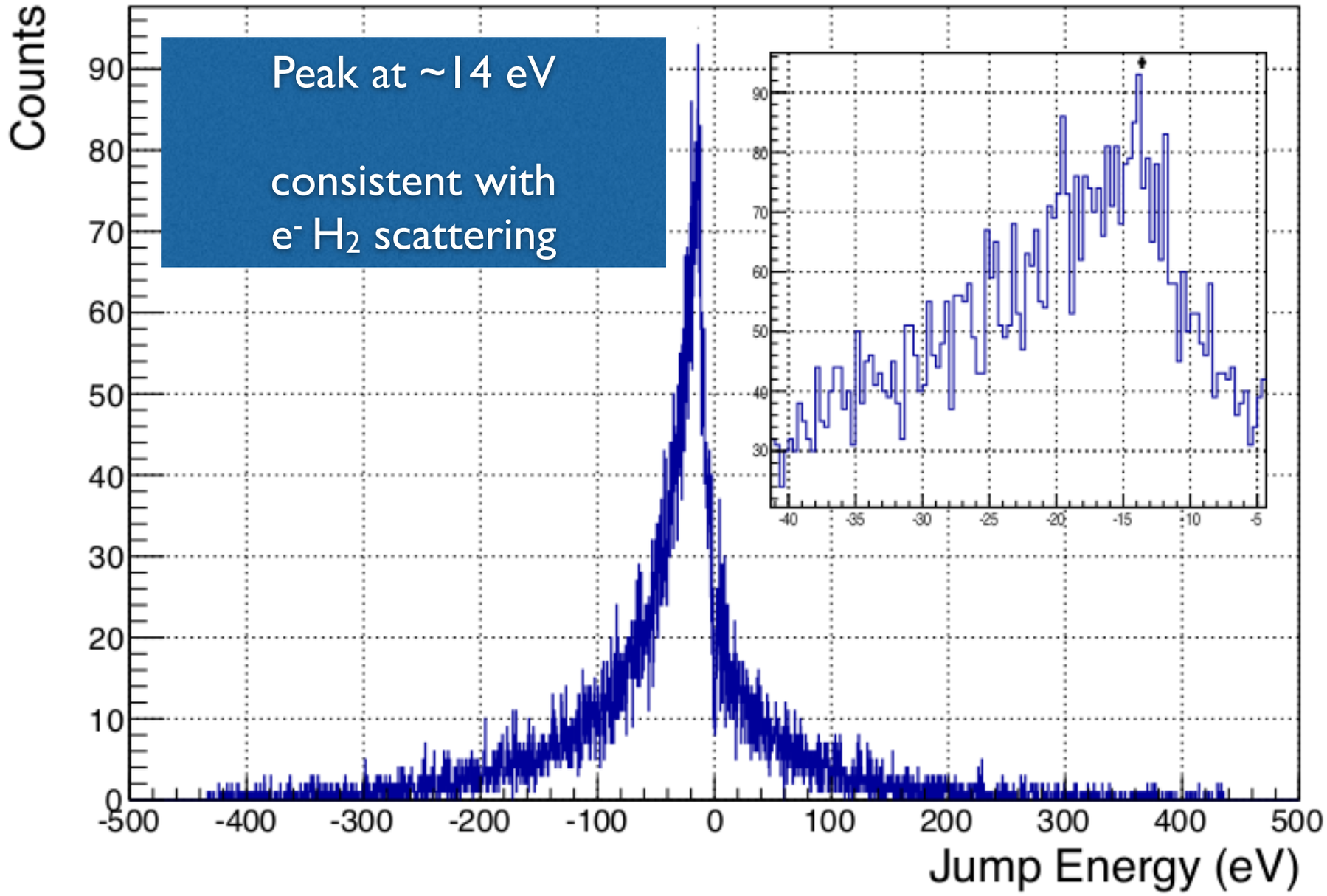
FWHM ~ 140 eV

Already improving…
(FWHM ~15 eV)

Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

Image Reconstruction & Energy Resolution



Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

Attempting to
see the
inverted
scale...

A Phased Approach

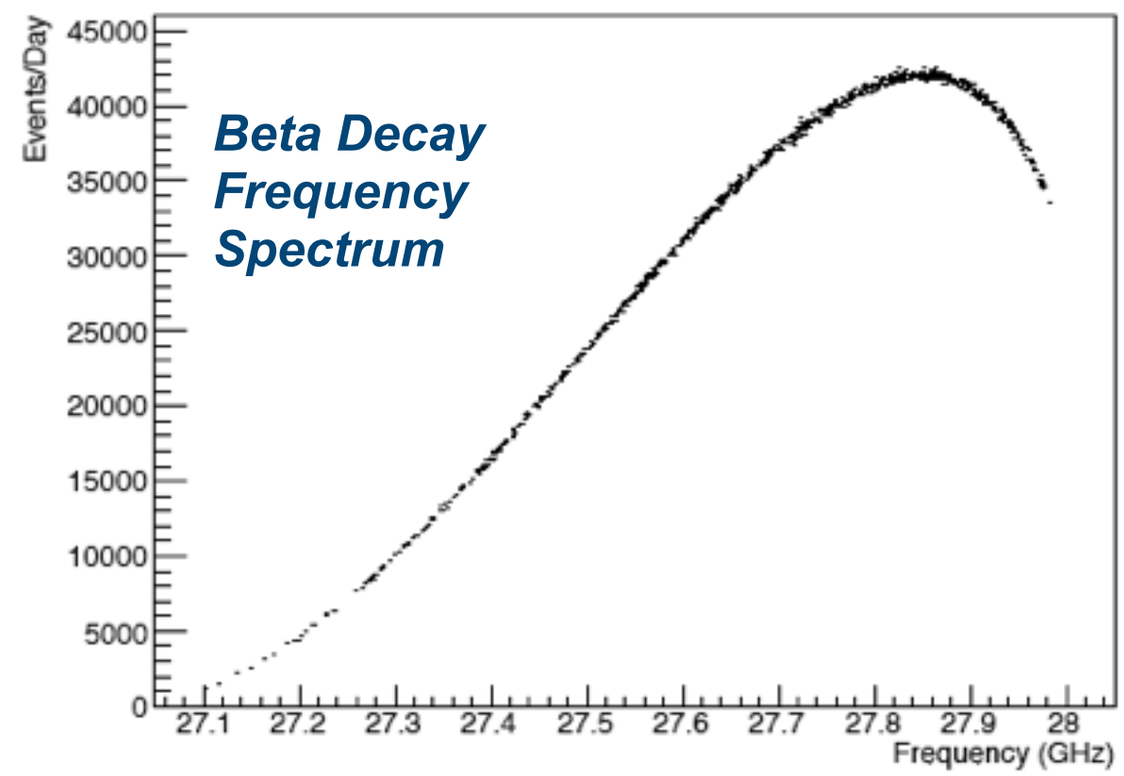
Given the novelty of the project, we are pursuing a phased approach toward neutrino mass measurements:

	Timeline	Scientific Goal	Source	R&D Milestone
Phase I	2010-2014	Proof of principle; Kr spectrum	^{83m}Kr	Single electron detection
Phase II	2014-2016	T-He mass difference	T_2	Tritium spectrum; calibration and error studies
Phase III	2016-2018	0.2 eV scale	T_2	
Phase IV	2018+	0.05 eV scale	T	High rate sensitivity

We have commenced Phase I, we are designing Phase II

Sensitivity to Neutrino Masses

- There are distinct advantages that are specific to frequency-based measurements:
- You get the entire spectrum (and background) at once.
- The background is extremely small:
  - There is no detector.
  - There might not even be any surfaces.
  - Cosmic ray interactions and radioactive backgrounds are interacting with a gas, very little target material.



$$\frac{dN}{dE_e} = 3rt(E_0 - E_e)[(E_0 - E_e)^2 - m_\nu^2]^{1/2}$$

Mass sensitivity depends on:

Target activity (volume x density)

Background

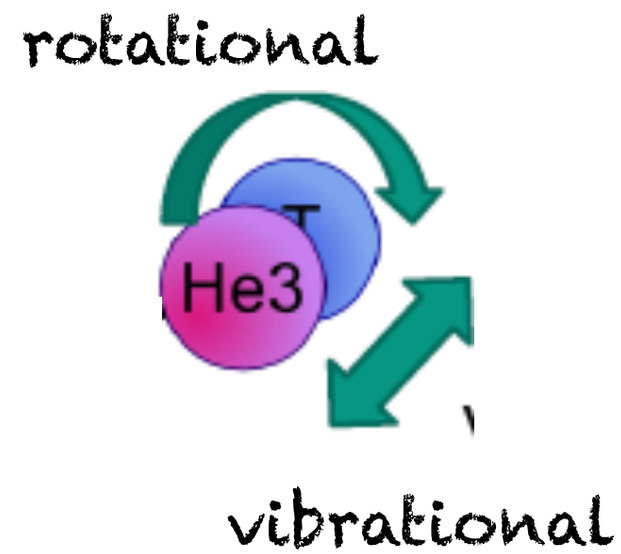
Field homogeneity

Lifetime of electron in trap (density)

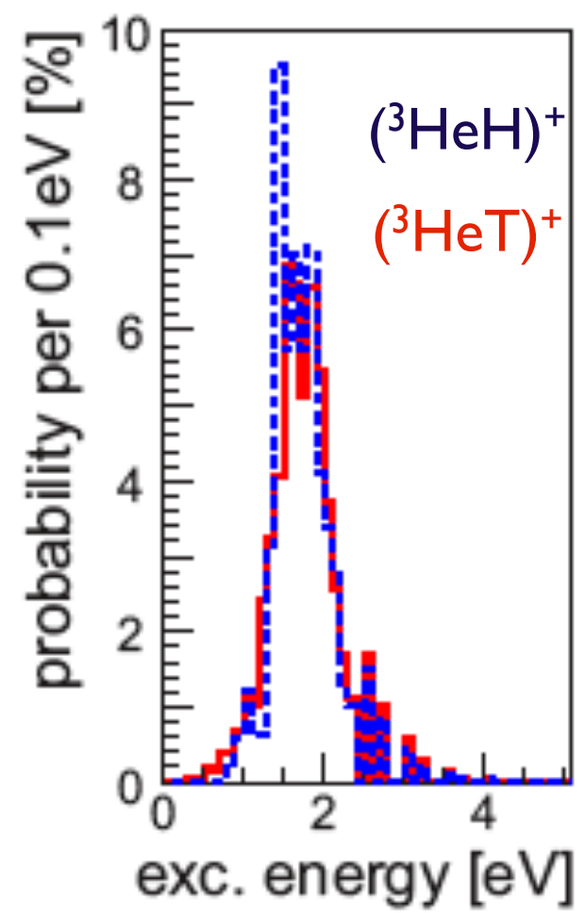
Final states, doppler shifts, temperature

Moving Beyond the Degeneracy Scale

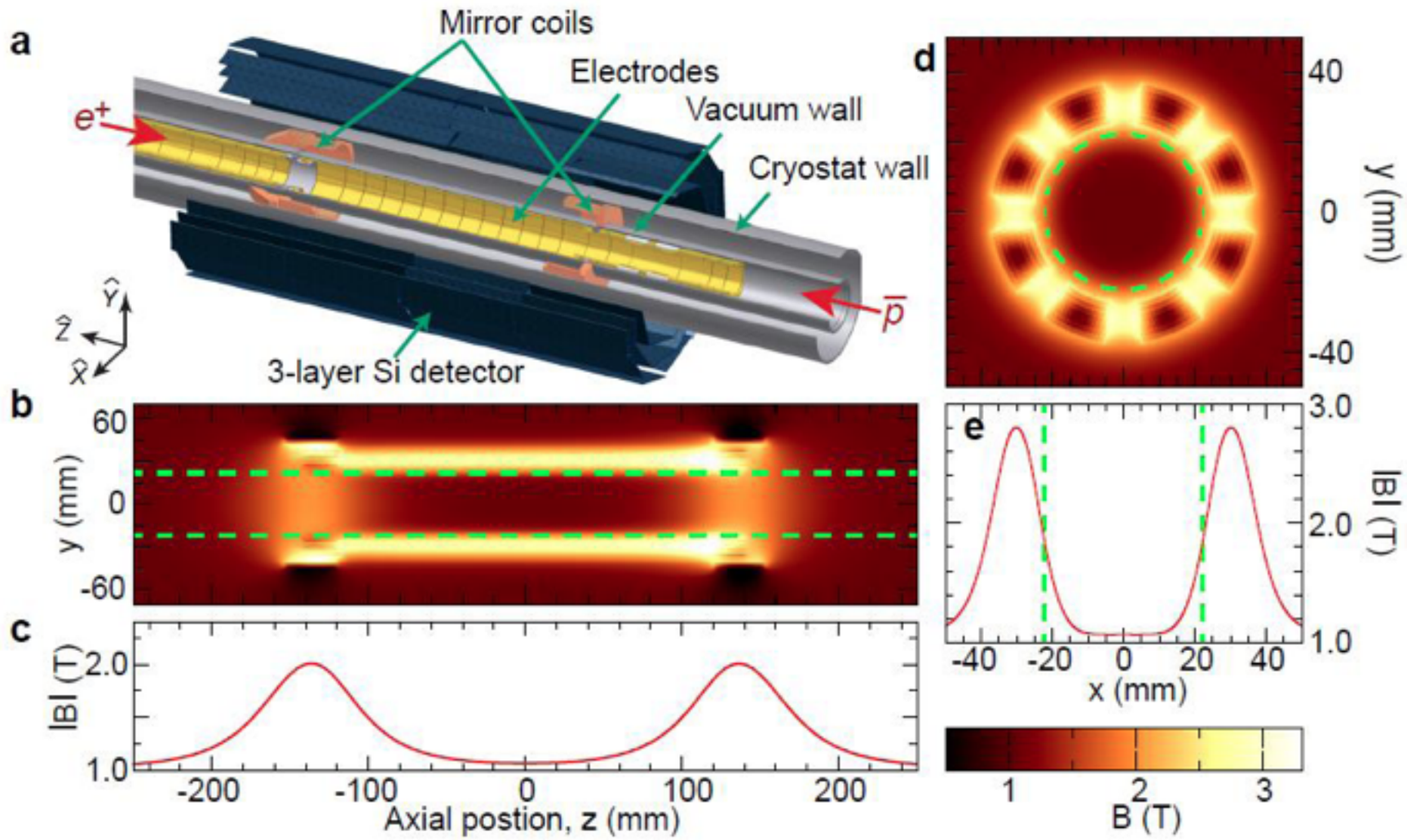
- Most effective tritium source achieved so far involves the use of gaseous molecular tritium.
- Method will eventually hit a resolution "wall" which is dictated by the rotational-vibrational states of T_2. This places a resolution limit of 0.36 eV.
- One needs to either switch to (extremely pure) atomic tritium or other isotope with equivalent yield.
- The trapping conditions necessary for electrons also lends itself for atomic trapping of atomic tritium (R. G. H. Robertson)



Inherent 0.36 eV final state smearing



Trapping of Atomic Tritium



ALPHA Collaboration: Nature Phys.7:558-564,2011; arXiv 1104.4982

Similar design to anti-hydrogen trapping:

Solenoidal field for uniformity

Pinch coils for axial confinement

Ioffe multipoles for radial confinement

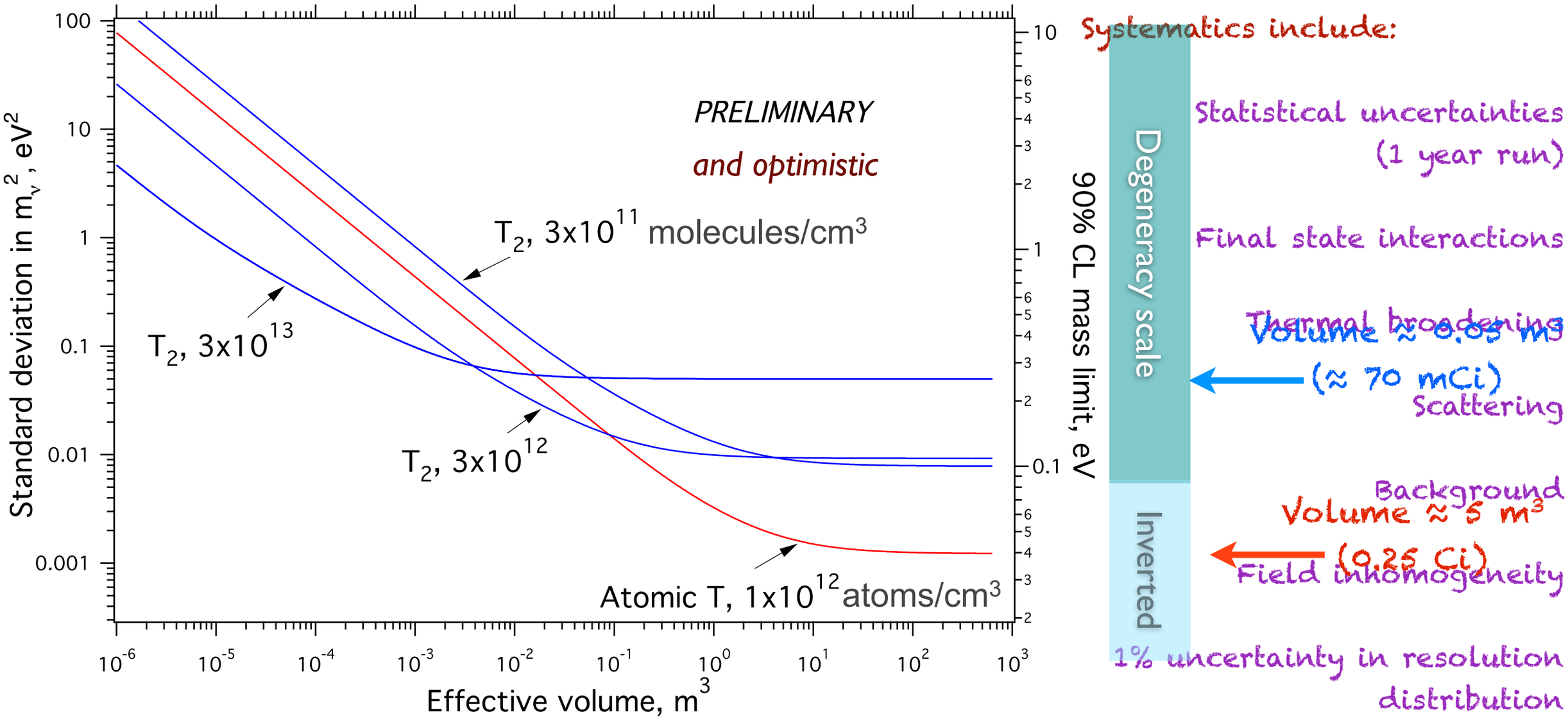
Cooling polarized tritium down to ~ 1K is necessary (and the main challenge)

In order to achieve atomic tritium purity, it is necessary to cool and trap polarized atomic tritium in both a radial and axial magnetic trap (Ioffe-Pritchard traps).

Technique quite similar to hydrogen BEC (MIT) and anti-hydrogen trapping (ALPHA).

Densities low, so recombination is highly suppressed.

Projected Sensitivity (Molecular & Atomic)



Systematics include final state interactions, thermal broadening, statistical uncertainties, and scattering.

See position paper (link here) for details.

Direct probes on neutrino mass measurements may provide a robust test of cosmology (and vice-versa).

New results to come; new techniques come to the fold.

Let's see what the next decade brings.

Thanks for your attention!