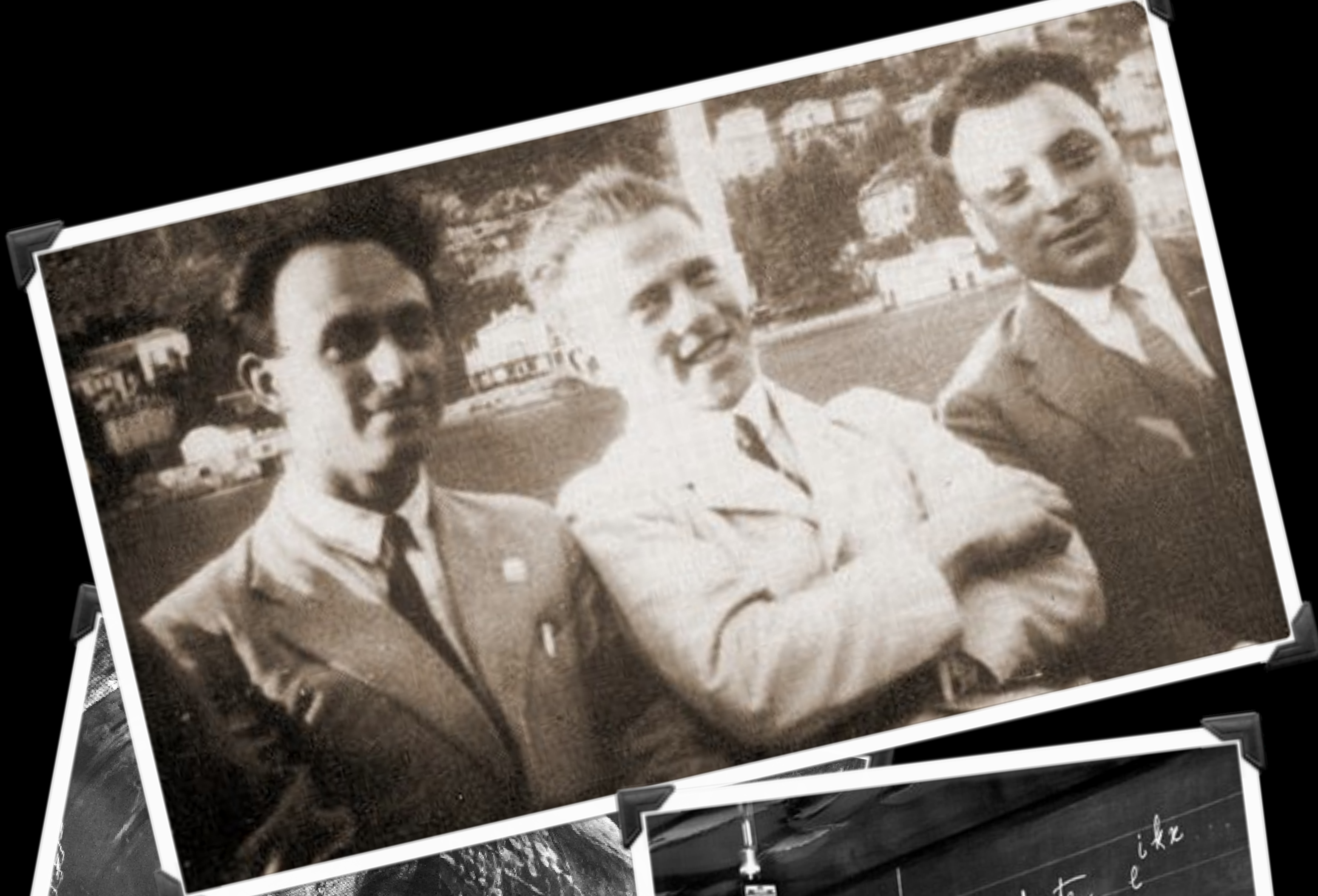



onda incidente e^{ikx}
$\lambda = \frac{h}{mv} = 1,8 \times 10^{-8}$ cm

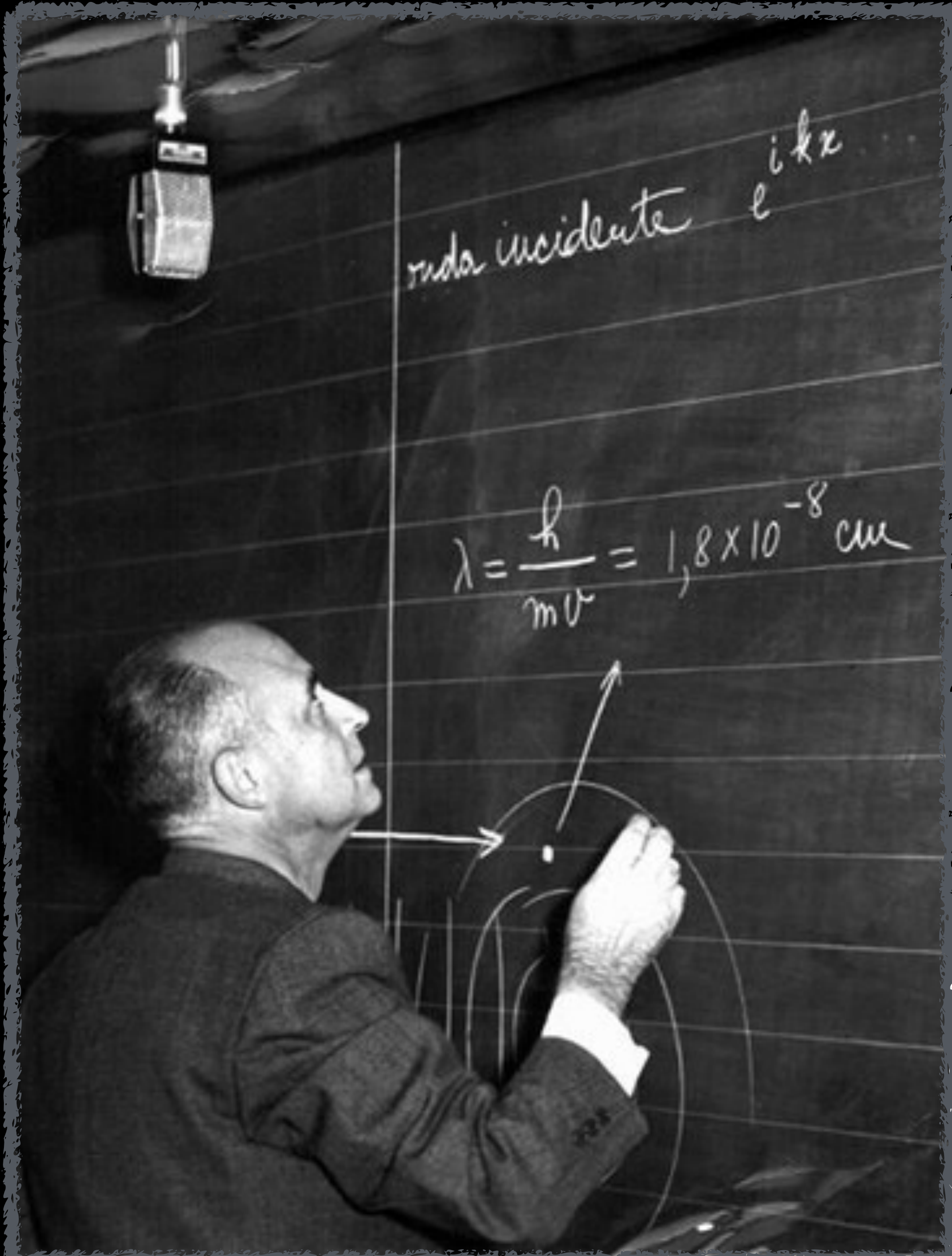
Weighting Neutrinos

Division of Particles and Fields Meeting
Ann Arbor, MI

August 7th 2015

Joseph A. Formaggio
MIT

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



80 a. – 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 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_0^2/v_0. 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

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

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

Fig. 1.

$$\frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

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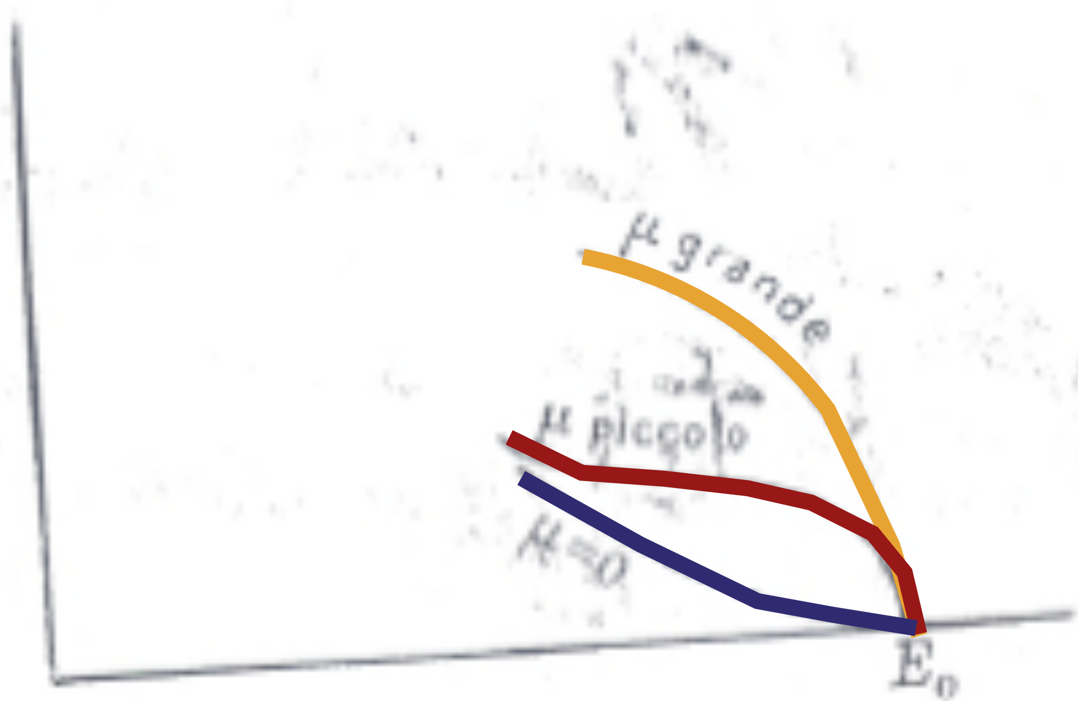

Fig. 1.

We have learned one thing in this time.

"Grande" is ruled out.

And so is "Zero".

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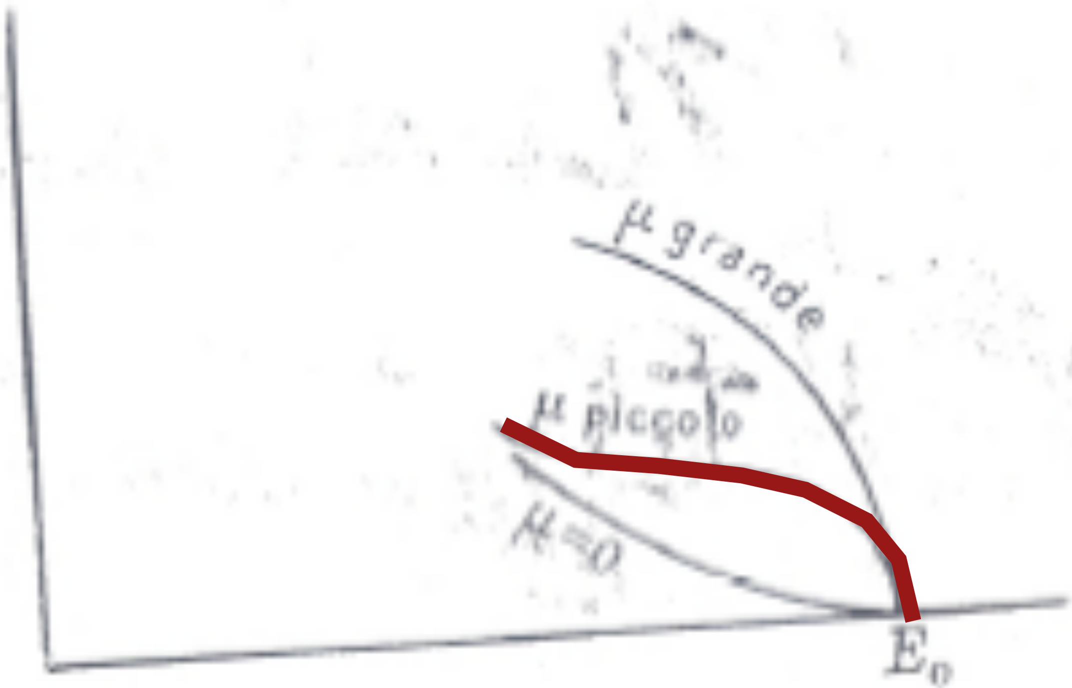


Fig. 1.

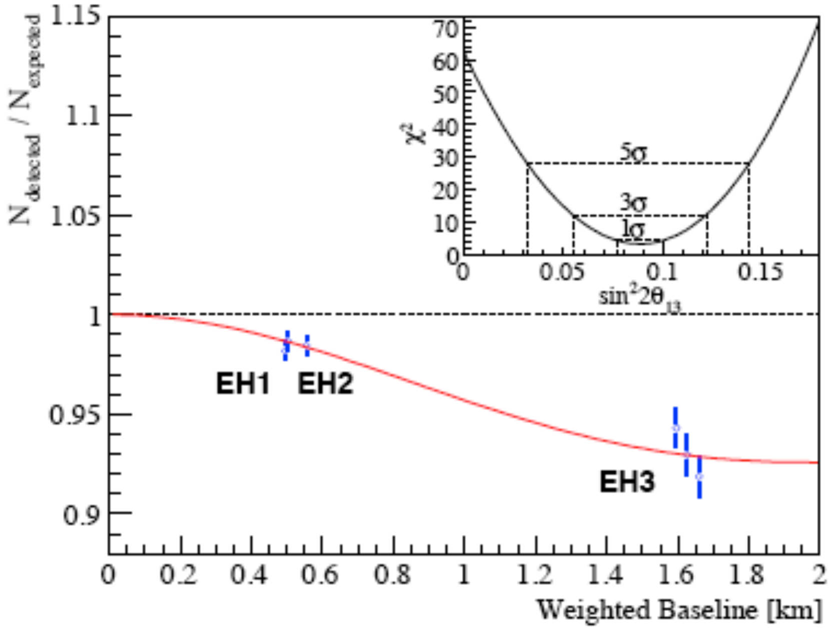
We have learned one thing in this time.

"Grande" is ruled out.

And so is "Zero".

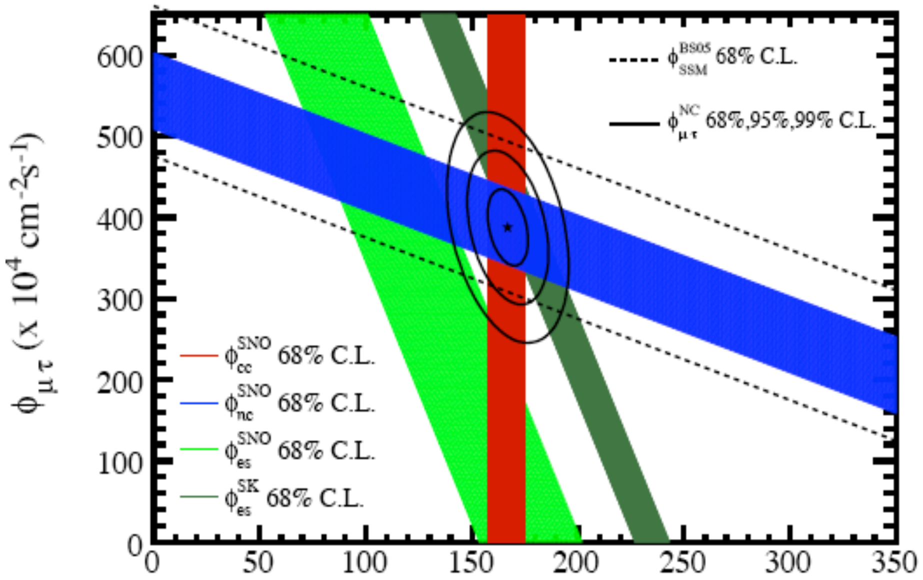
With oscillations firmly in place, we at least understand that the neutrino has a mass

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



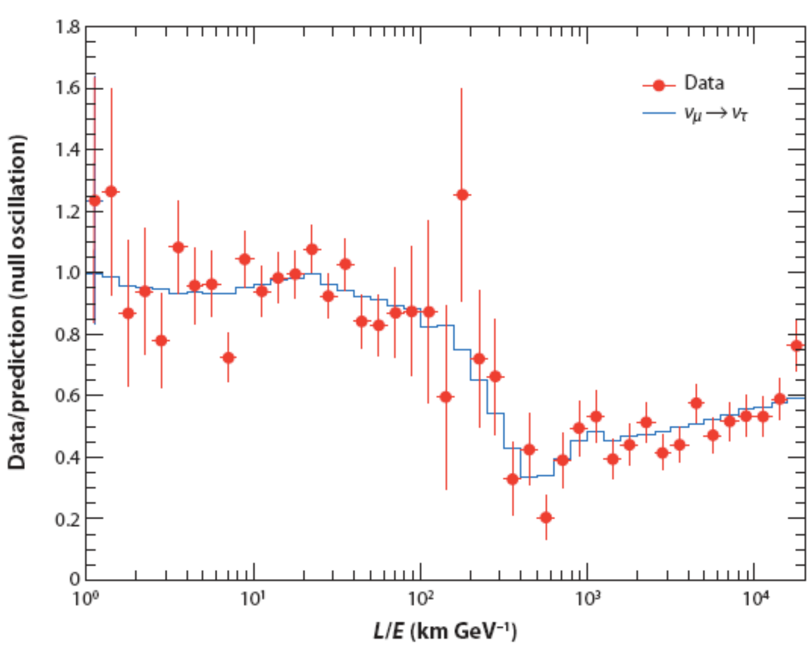
$$\sin^2(2\theta_{13}) = 0.093 \pm 0.008$$

Reactor & Long Baseline



$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$

Solar



$$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$$
$$\Delta m^2_{32} = 0.00244 \pm 0.00006\ \mathrm{eV}^2$$

Atmospheric

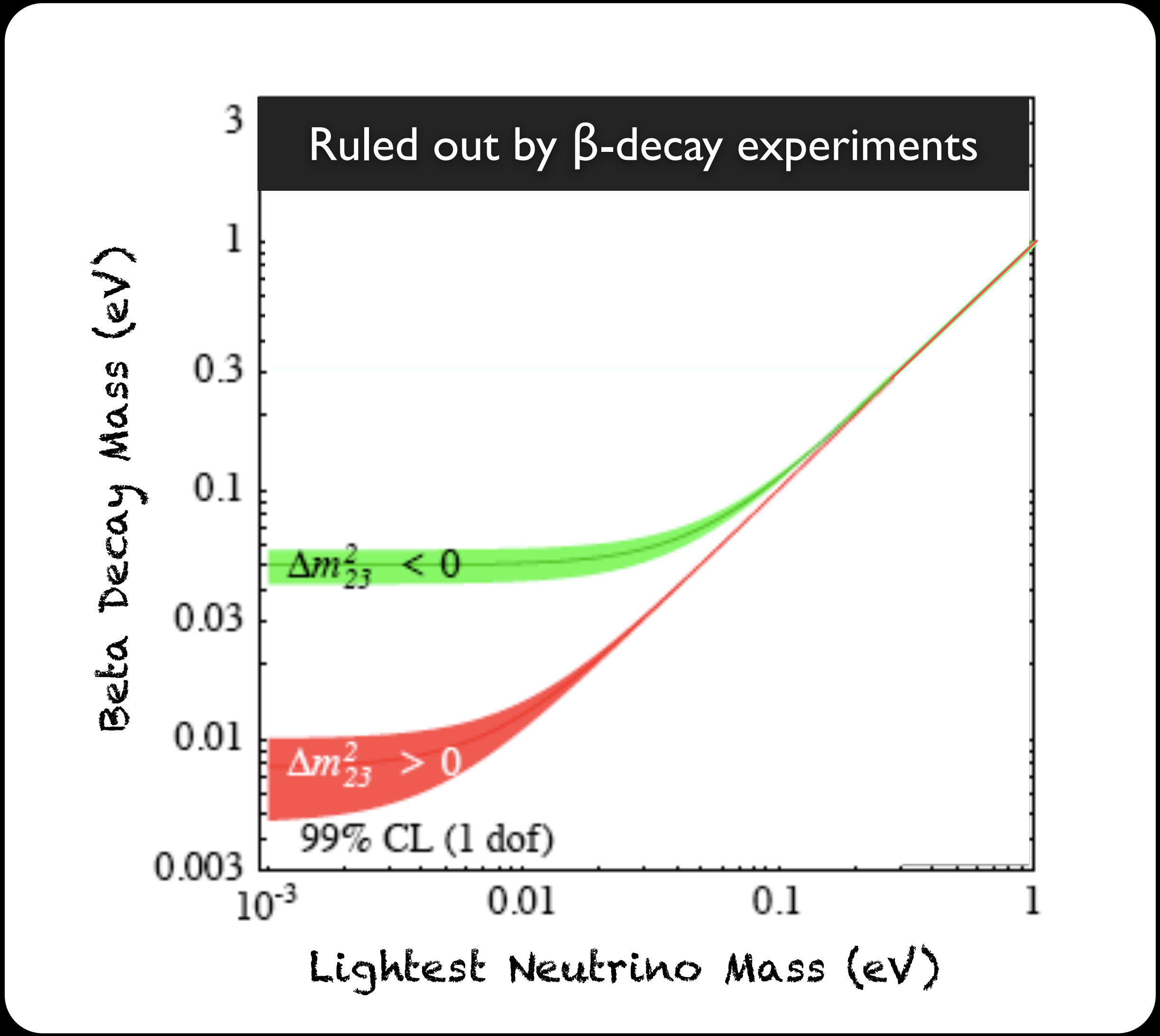
Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).
Fogli et al, arXiv:1205.5254 (hep-ph)

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

Oscillations now make a prediction upon other measurements.



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

Cosmological Measurements

$$\langle m^2_{\beta\beta} \rangle = \left| \sum_i^{n_\nu} U^2_{ei} m_{\nu,i} \right|^2$$

0νββ Measurements

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

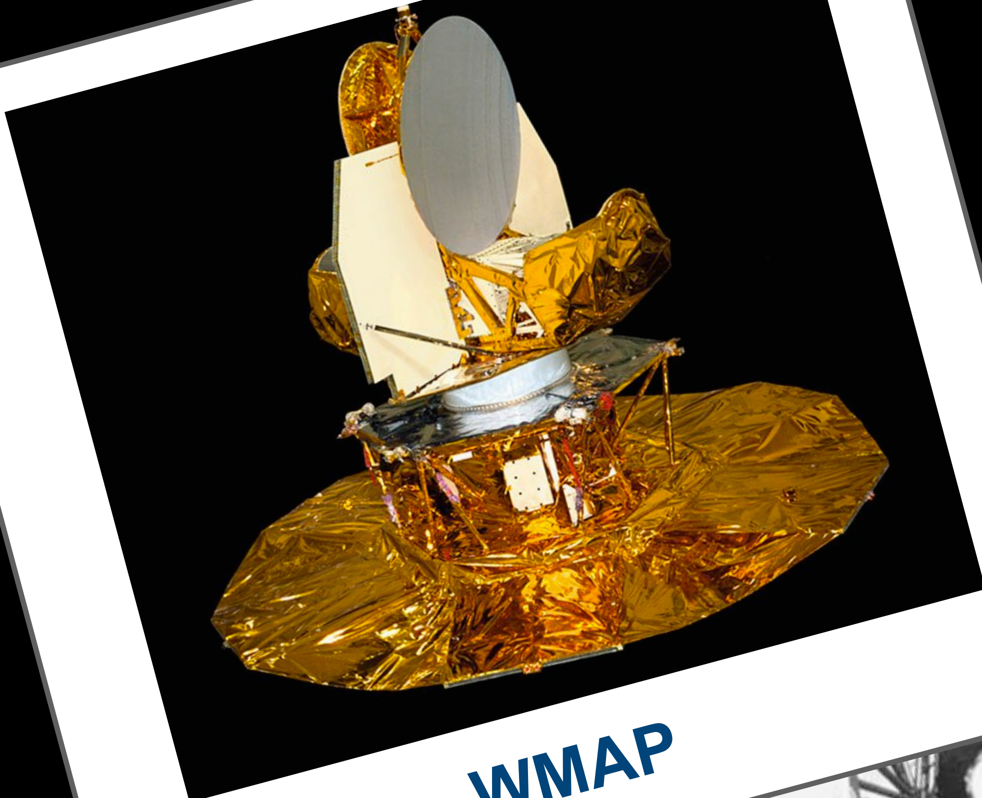
Beta Decay Measurements

Wilson & Penzias

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

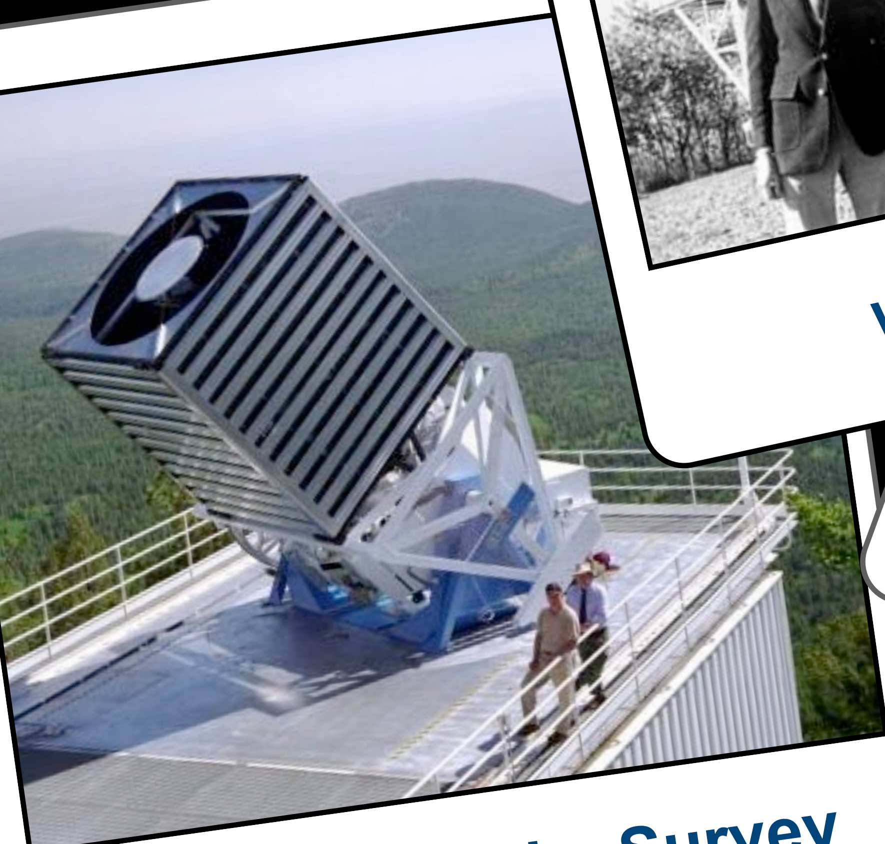
Cosmological Measurements

The Era of Precision Cosmology



WMAP

Wil



Sloan Digital Sky Survey

Atacama Cosmology Telescope

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

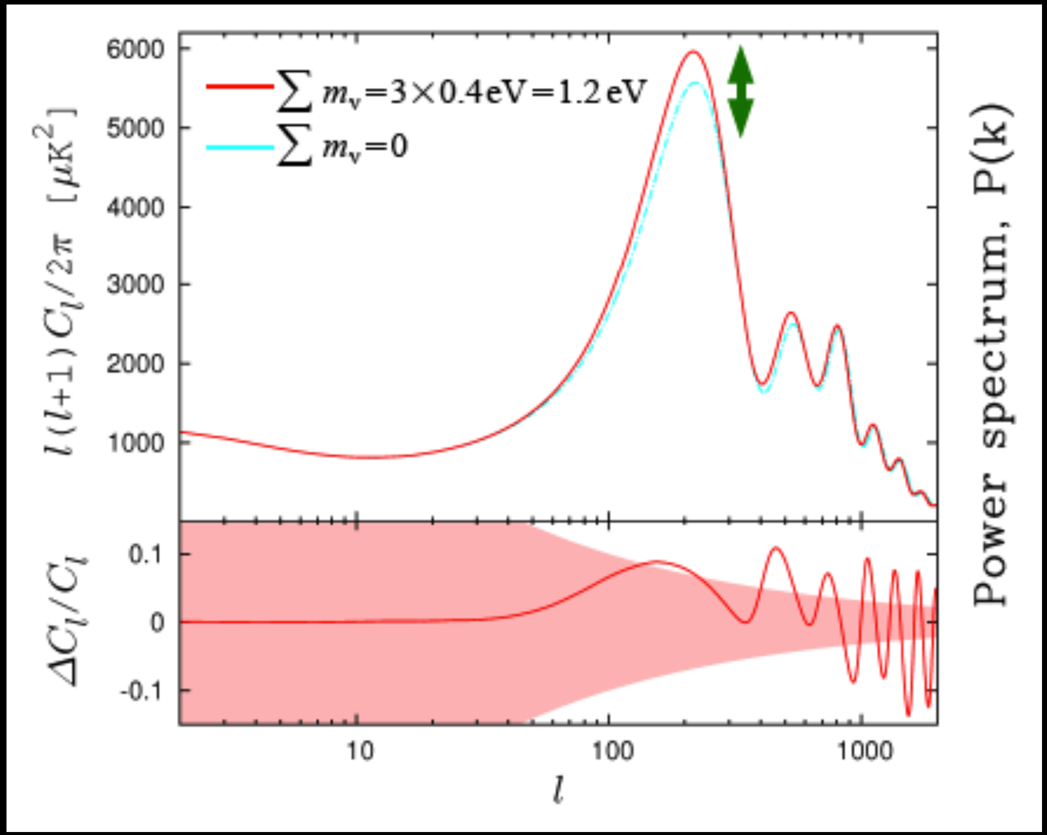
Neutrino Physics & Cosmology

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

    (1) Number of neutrino species

    (2) Sum of neutrino masses

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



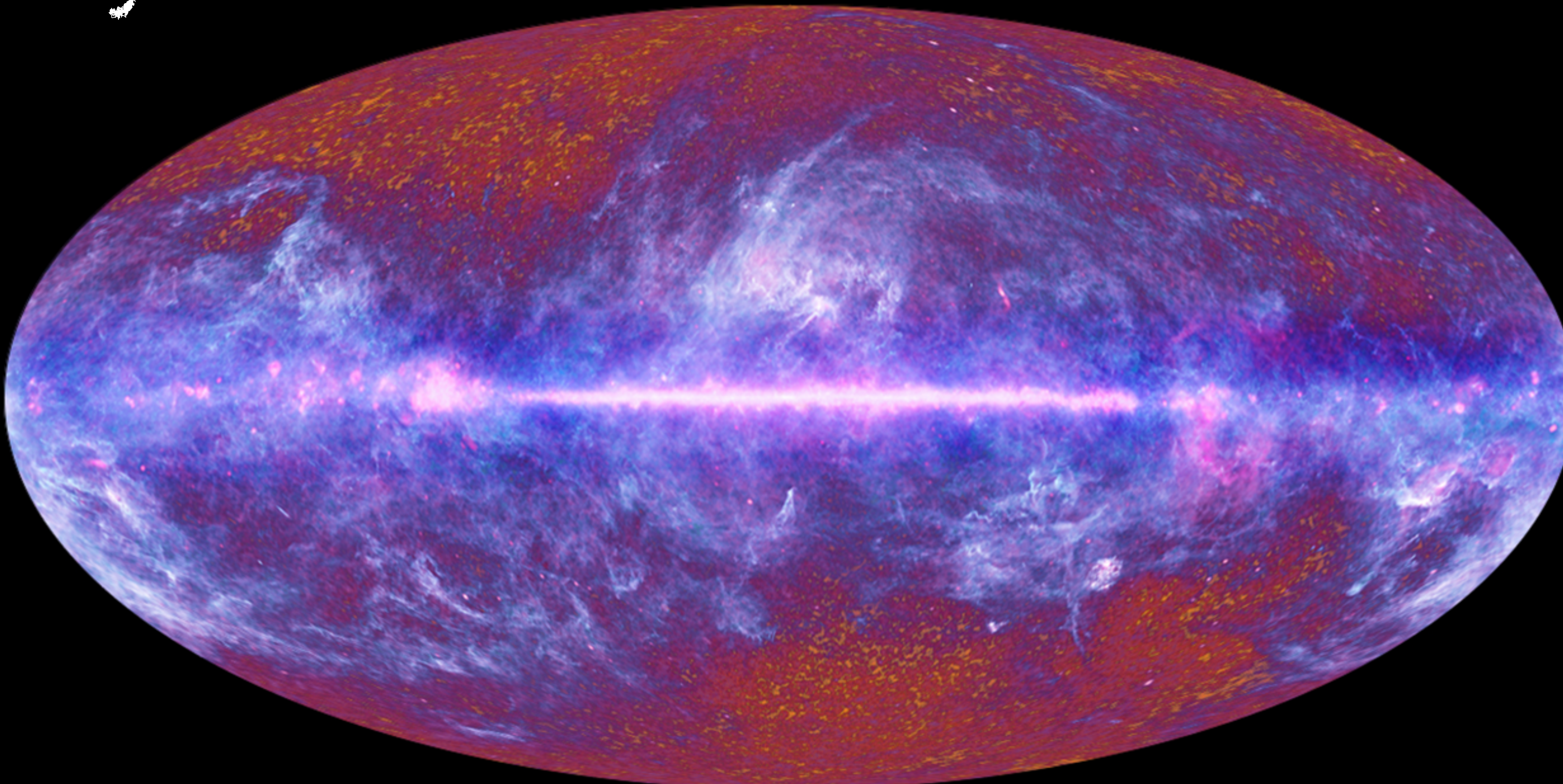
$$\Omega_R h^2 = [1 + N_{\text{eff}}\frac{7}{8}(\frac{4}{11})^{\frac{4}{3}}]\Omega\gamma h^2$$

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

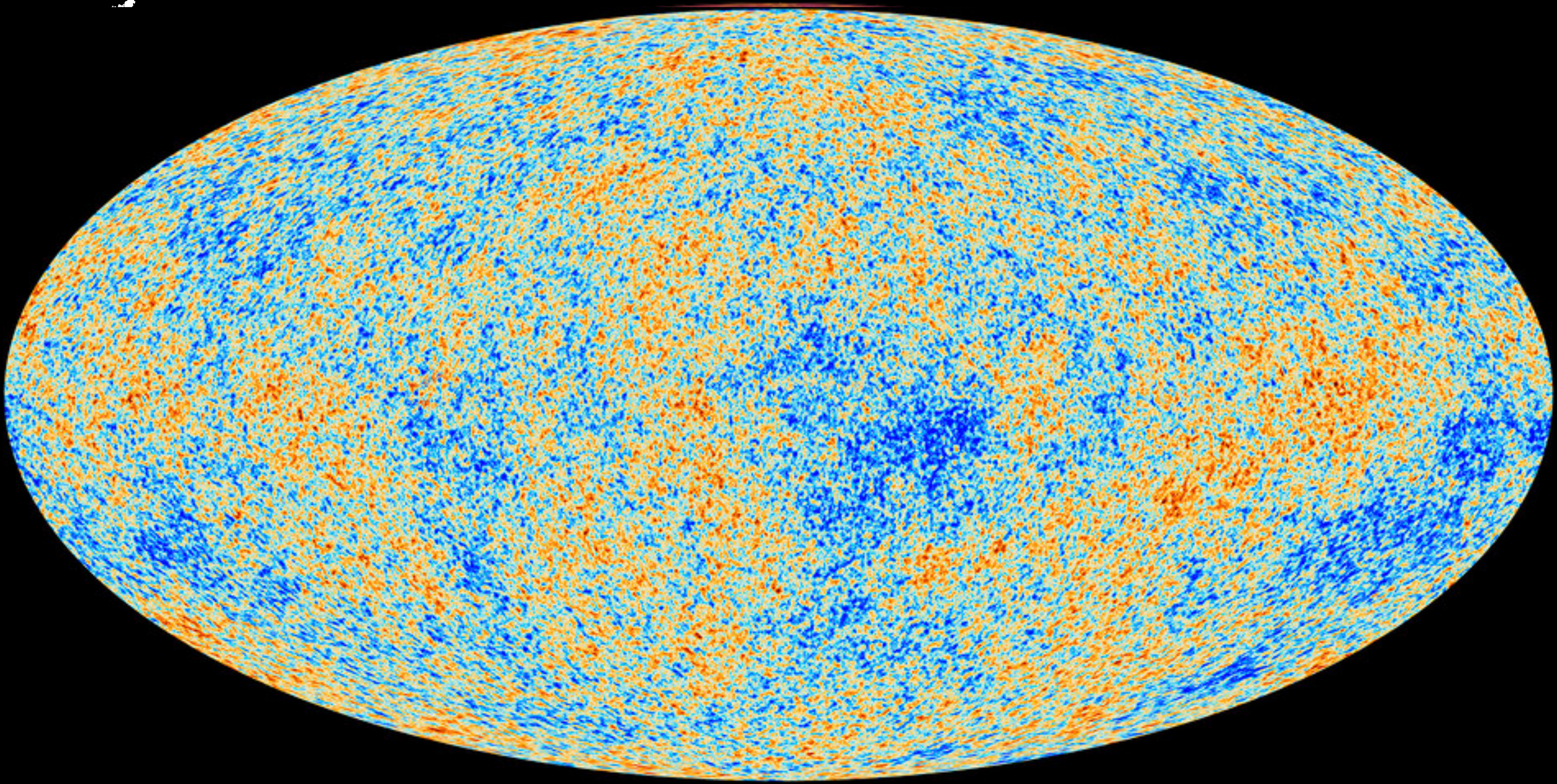
Planck Satellite:

Launched May 14th, 2009

The Microwave sky...



The Microwave sky...

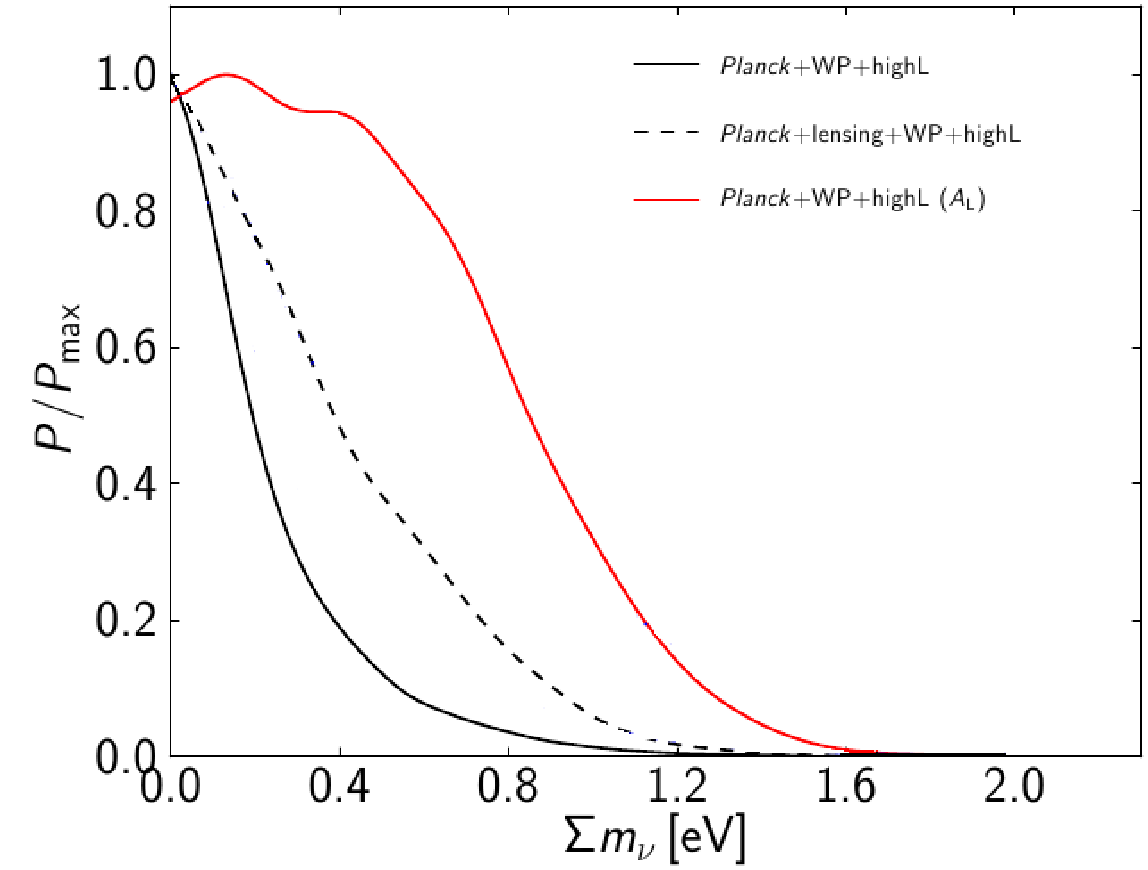


PLANCK Results

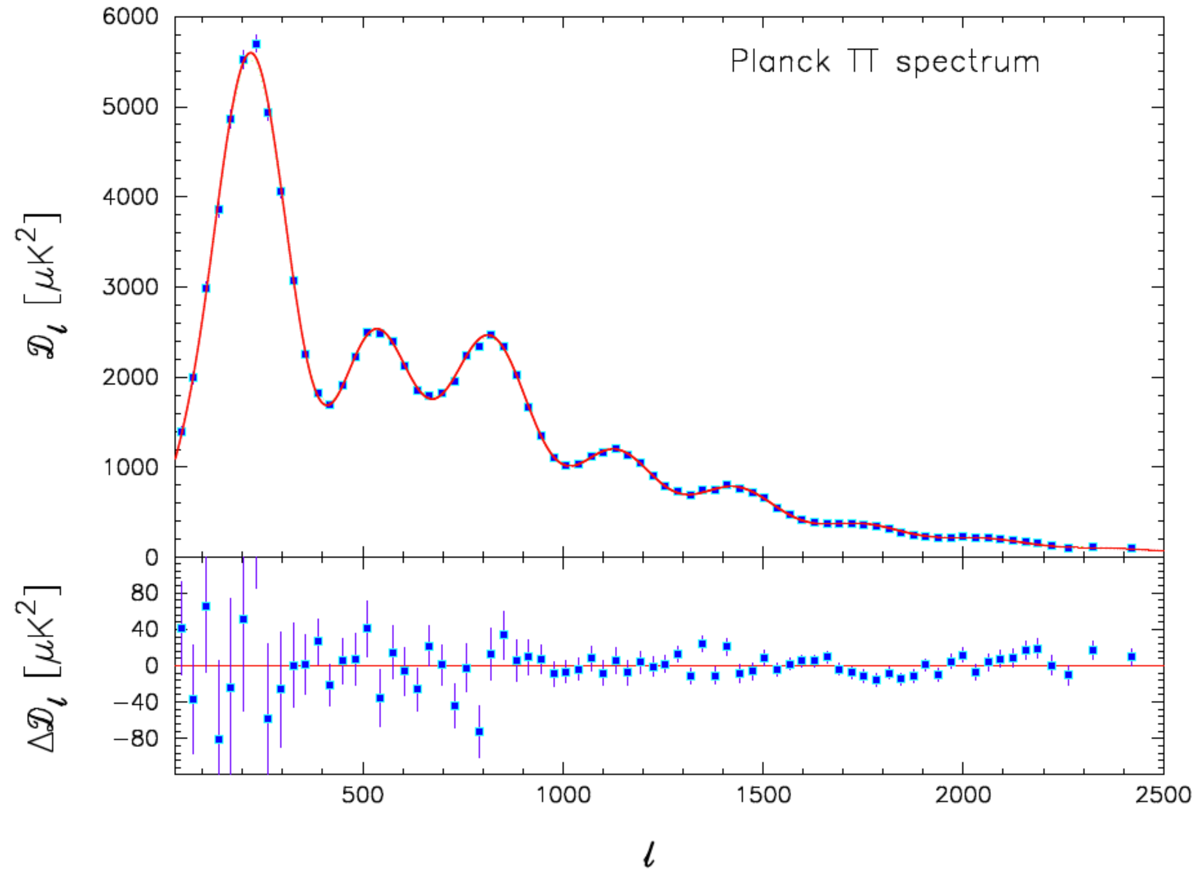
- The basic PLANCK analysis looks at 6 main cosmological parameters. Neutrino masses are added as extensions to that model.

- 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.



Source: Planck *Results XVI*



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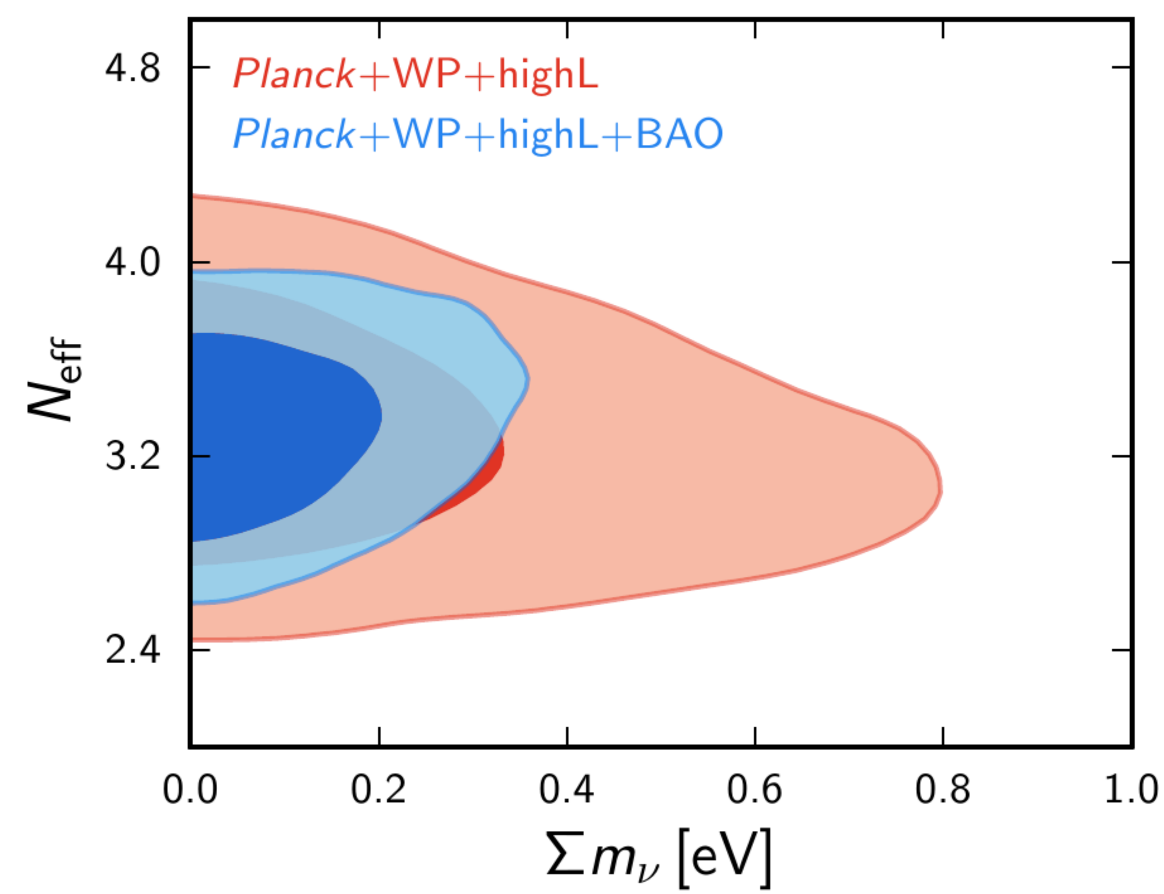

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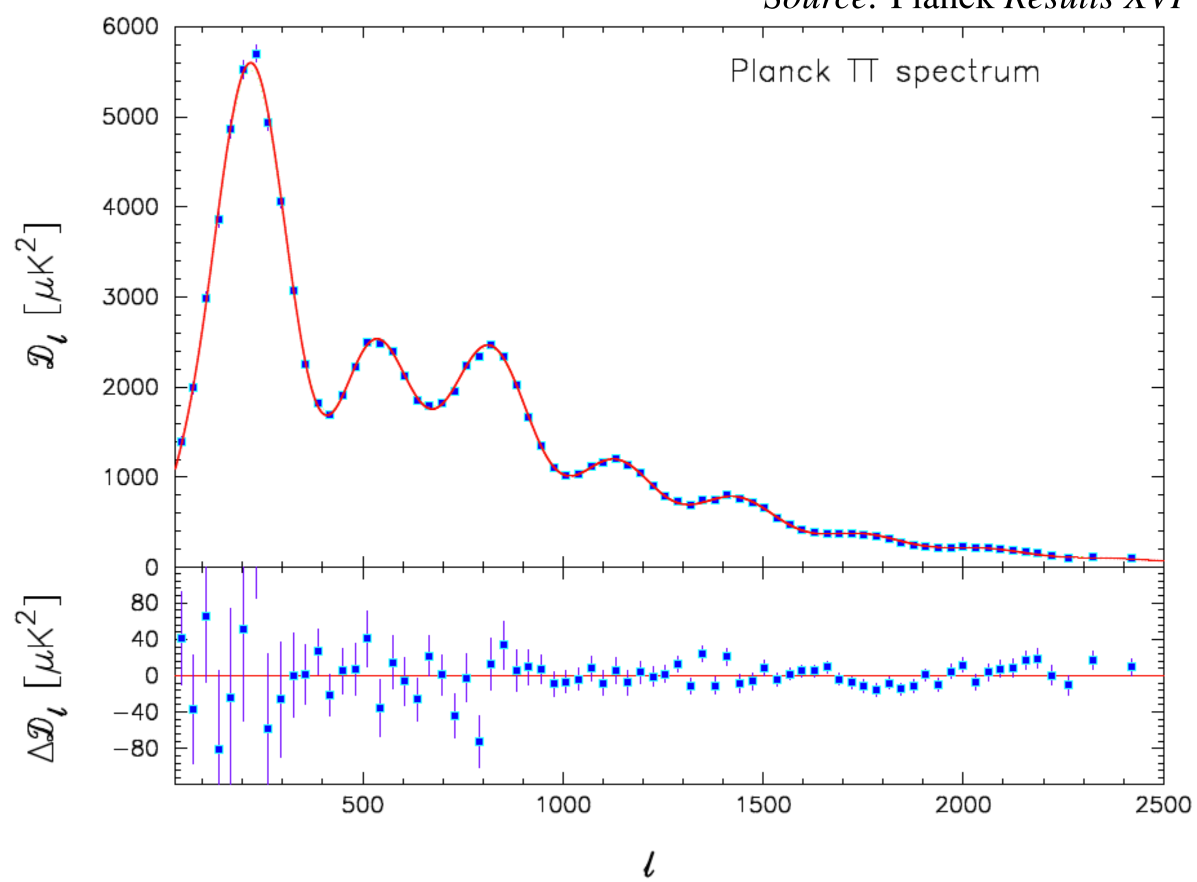
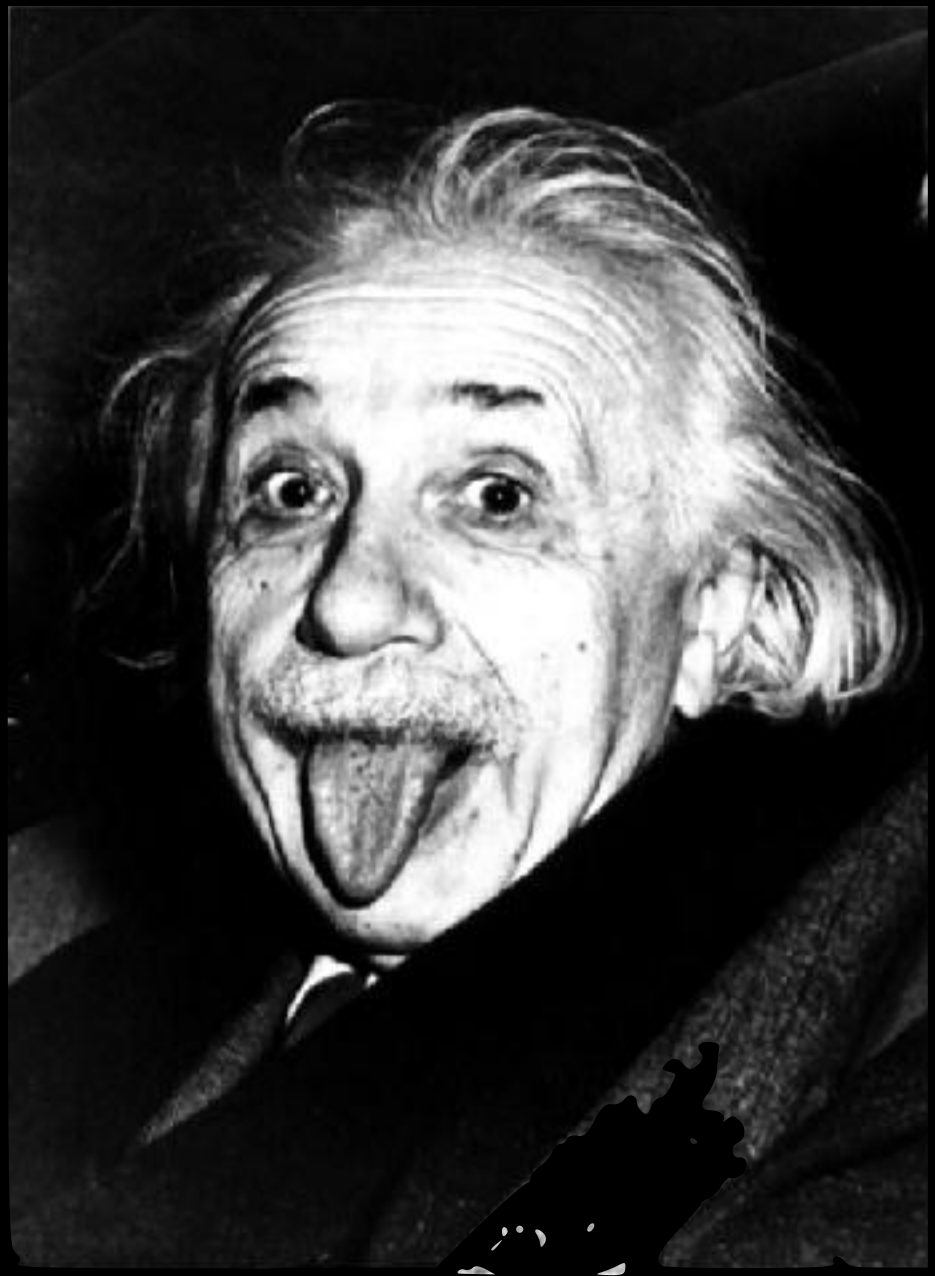
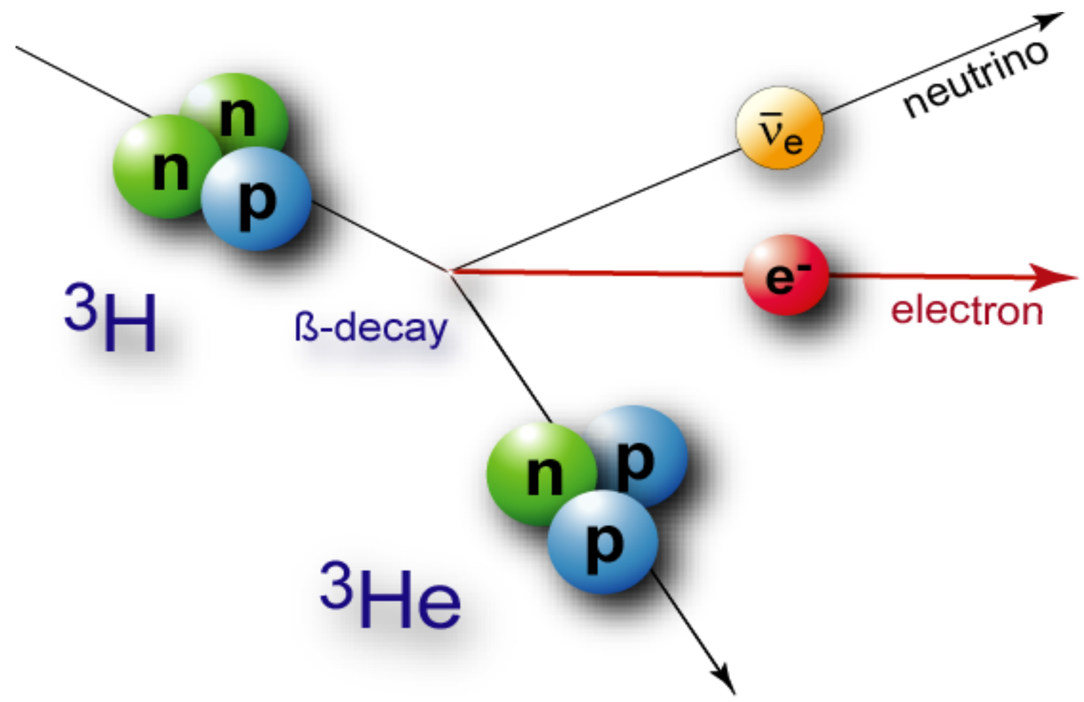




$$\langle m_\beta \rangle^2 = \sum_i^{n_\nu} | U_{ei} |^2 \, m_{\nu,i}^2$$

Beta Decay Measurements

Direct Probes



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

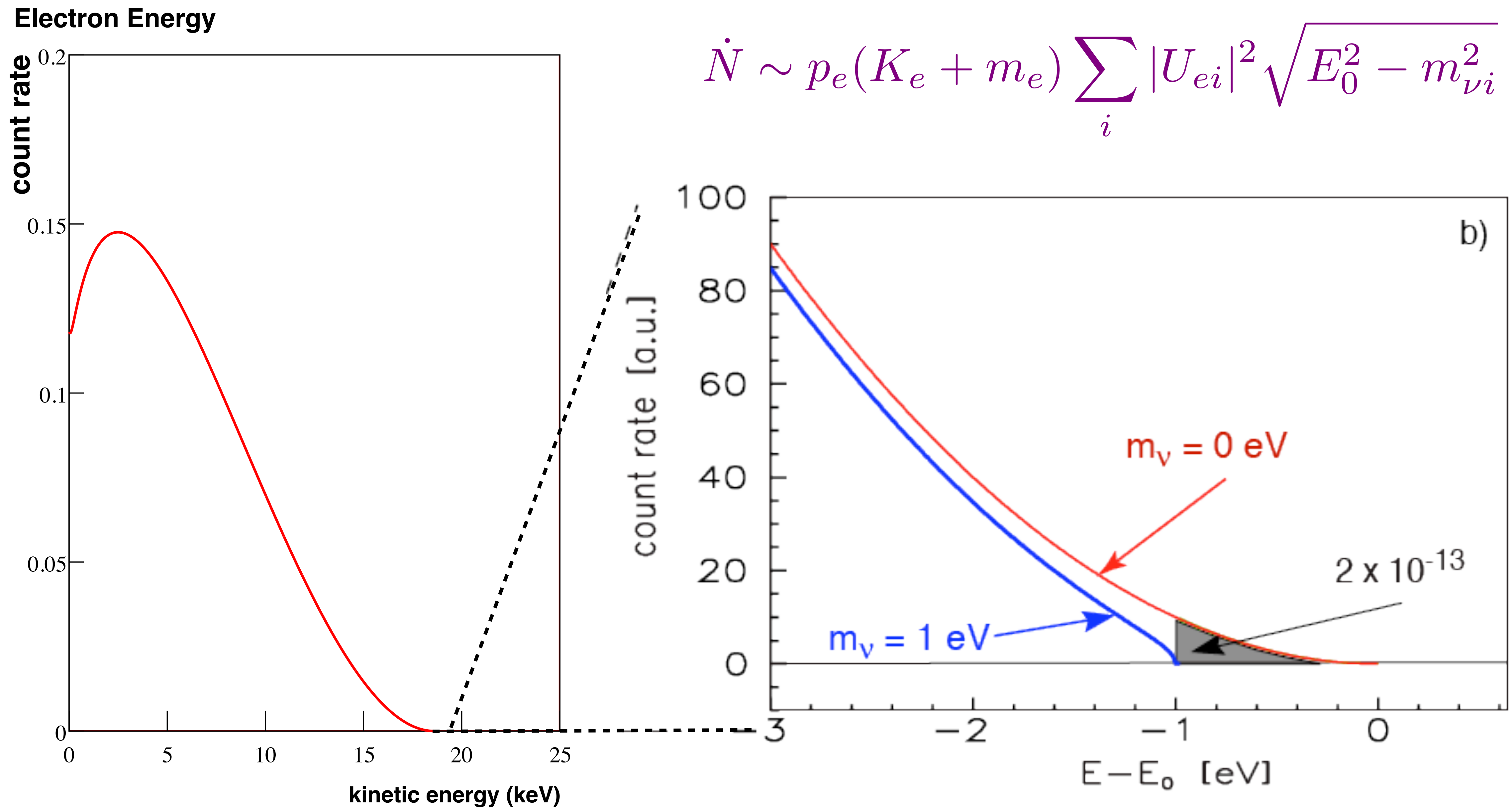
Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Direct Probes

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



Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Current Techniques

Spectroscopy (KATRIN)

Magnetic Adiabatic Collimation with Electrostatic Filtering

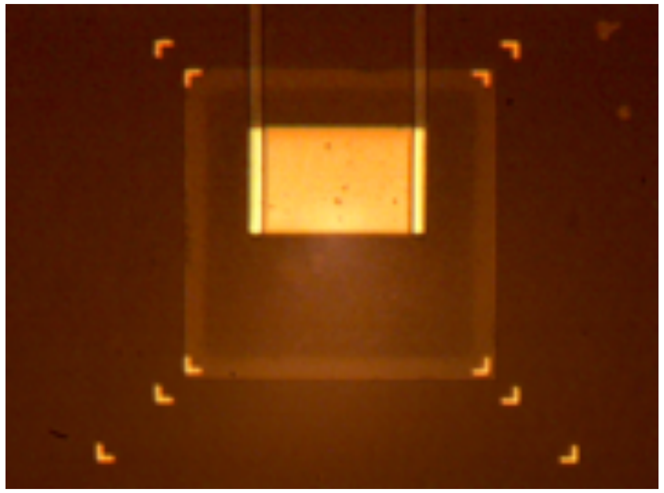
State-of-the-Art technique

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

Calorimetry (HOLMES, ECHO & NUMECS)

Technique highly advanced.

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

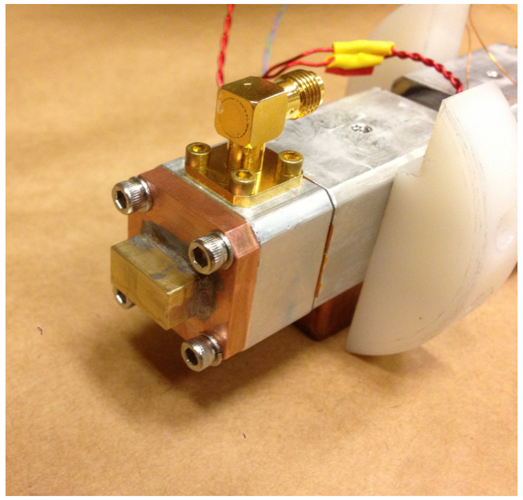


$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

R&D phase (new results)



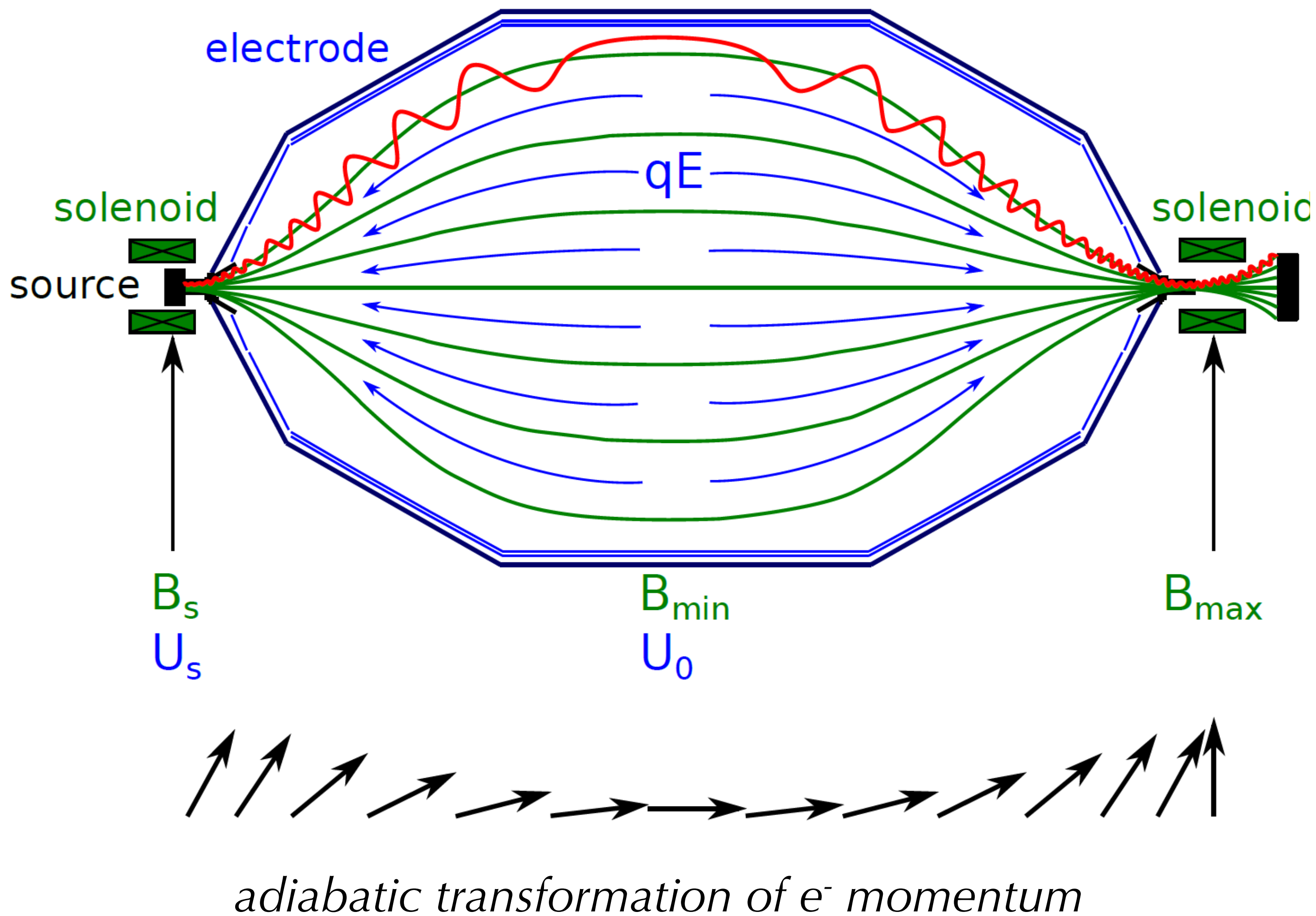
$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

MAC-E Filter Technique

KATRIN

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

Spectroscopic: MAC-E Filter



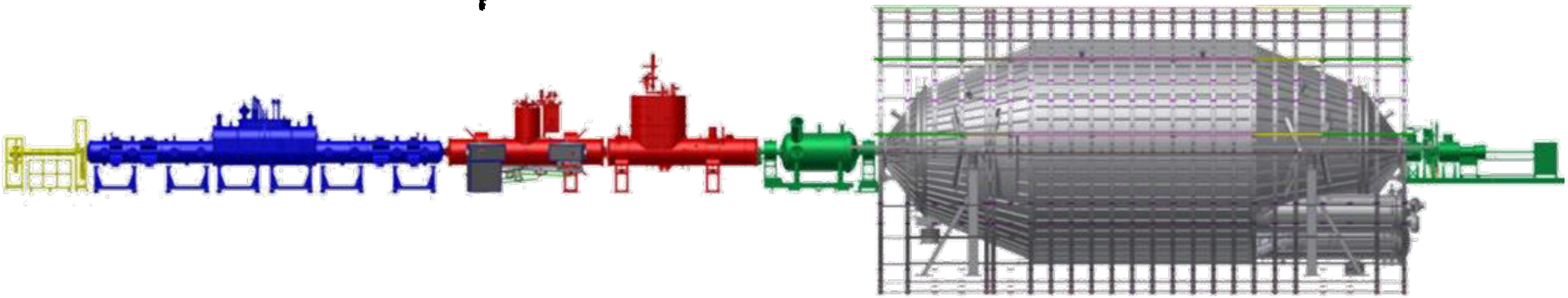
Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

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

The KATRIN Setup



10^{11} e^- / second

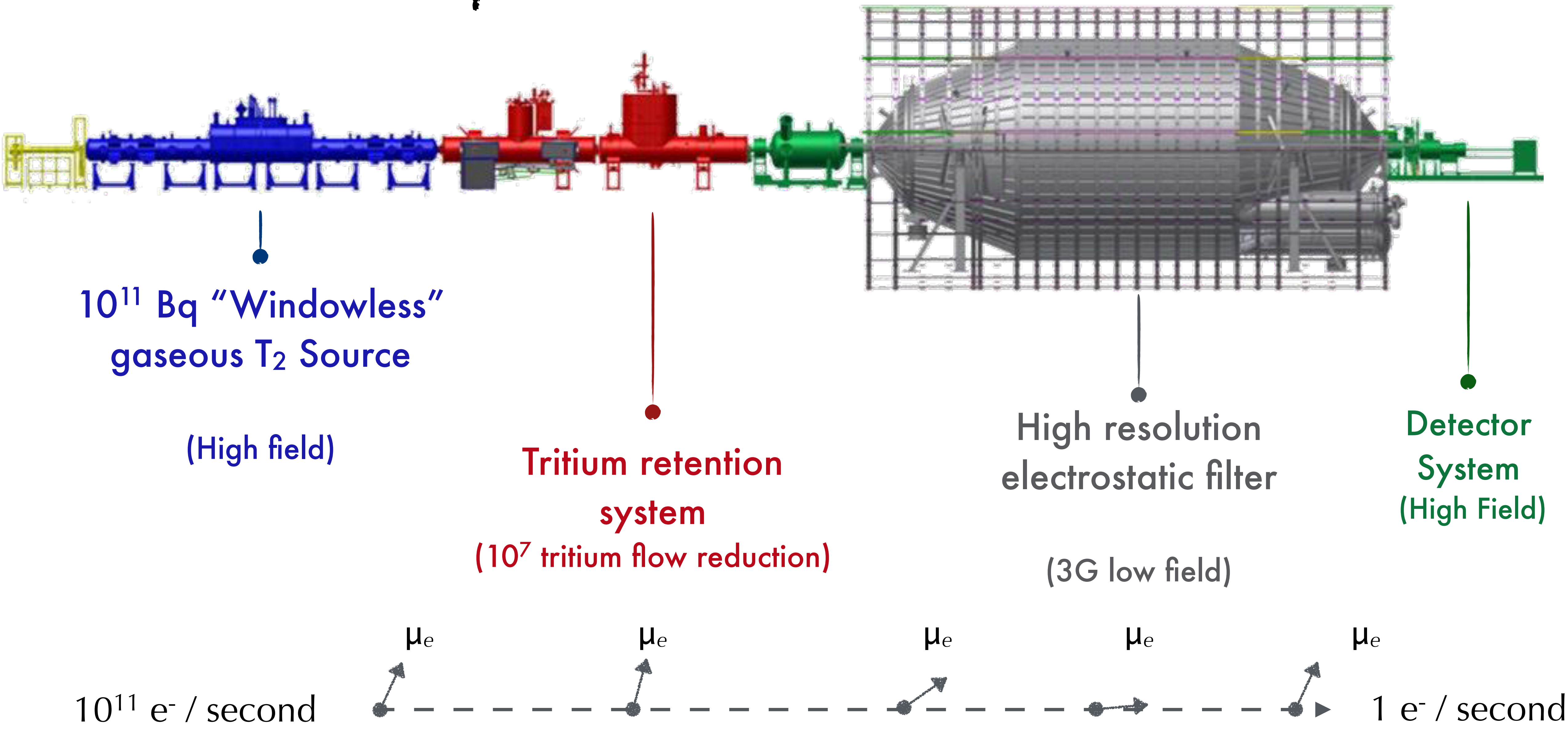
1 e^- / second

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

The KATRIN Setup



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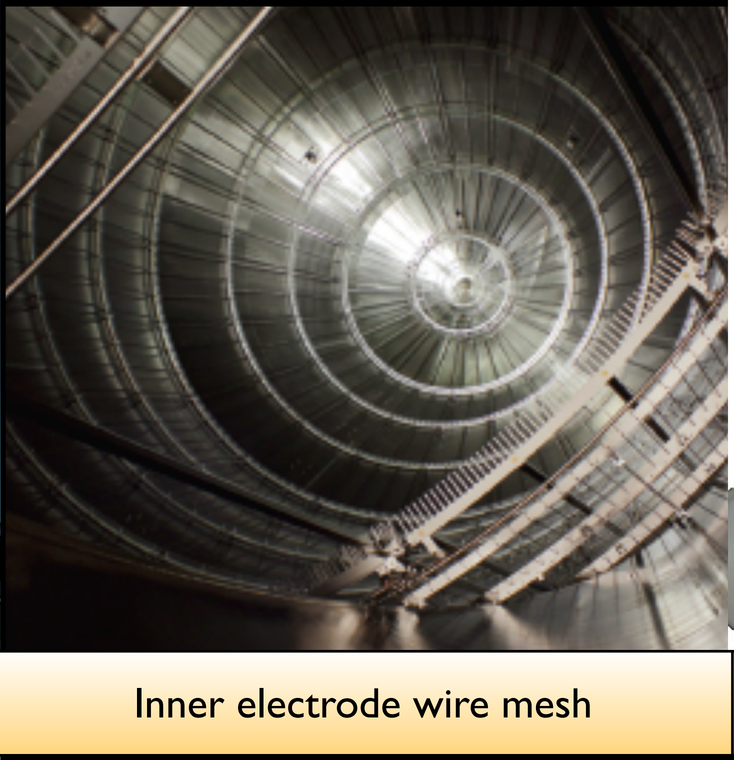
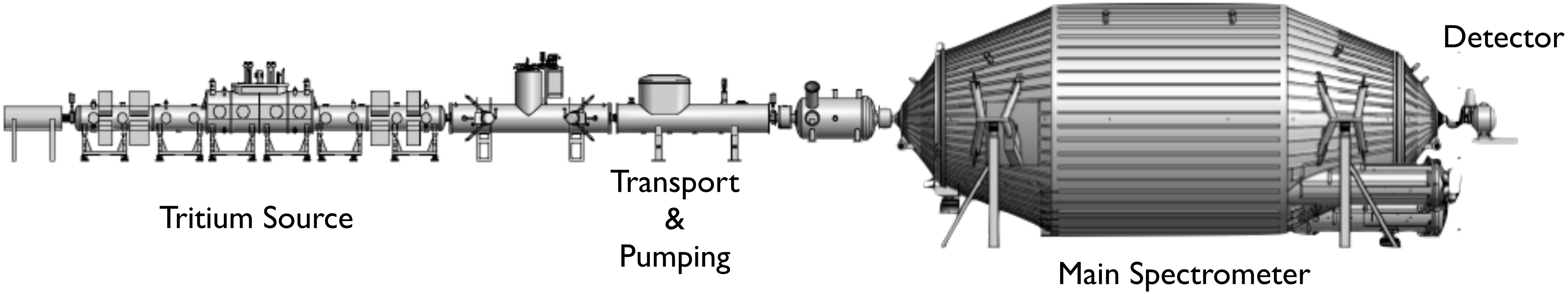
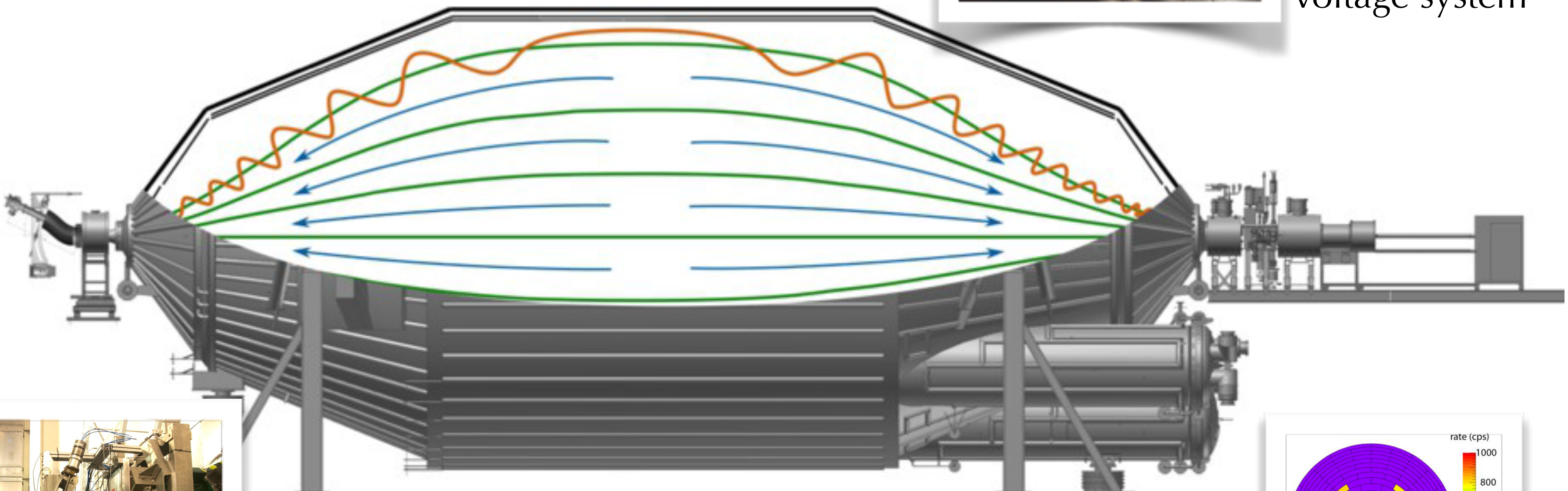


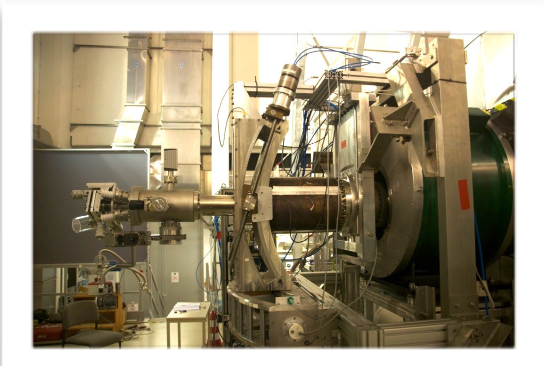
- A 10 m diameter analyzing spectrometer with 1:2000 energy resolution (0.93 eV)
- Extremely stable high voltage of main vessel.
- Few ~ppm precision divider and monitoring spectrometer.



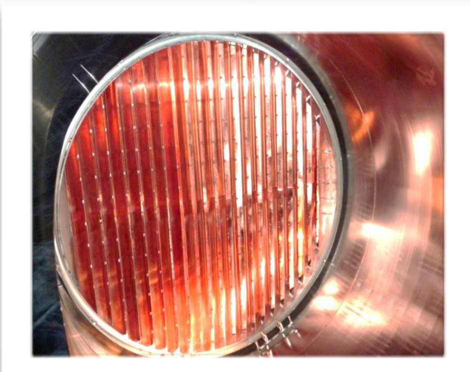
Spectrometer Commissioning

Precision high voltage system

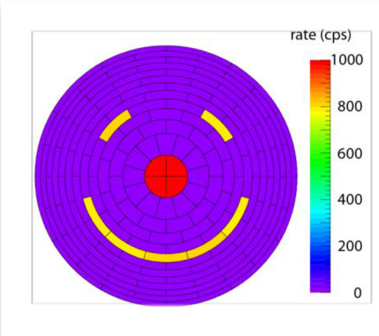




High precision electron gun



Ultra high vacuum system



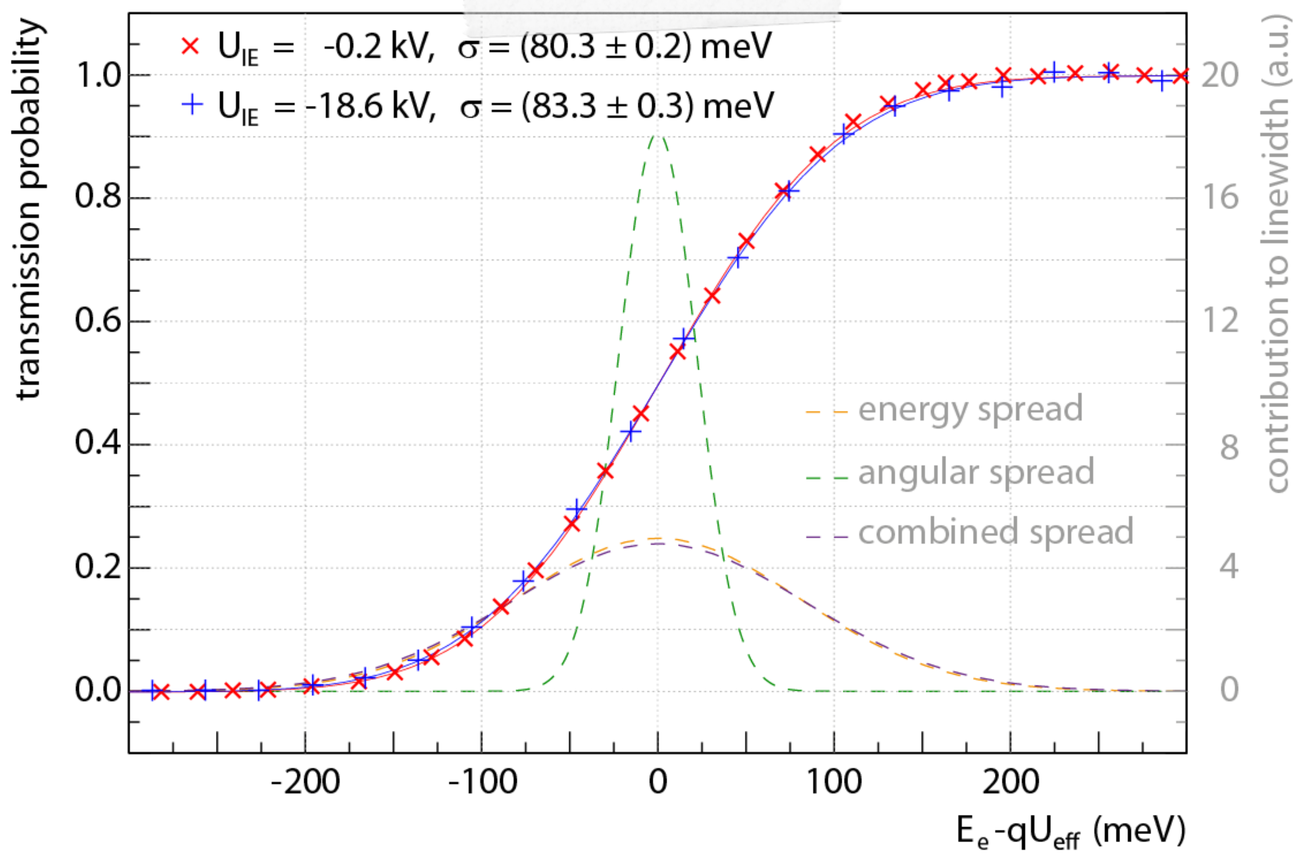
Full detector system

Summer 2013 saw "first light" from the KATRIN.

Spectrometer and detector system fully integrated.

Allowed for test of transmission function and background levels.

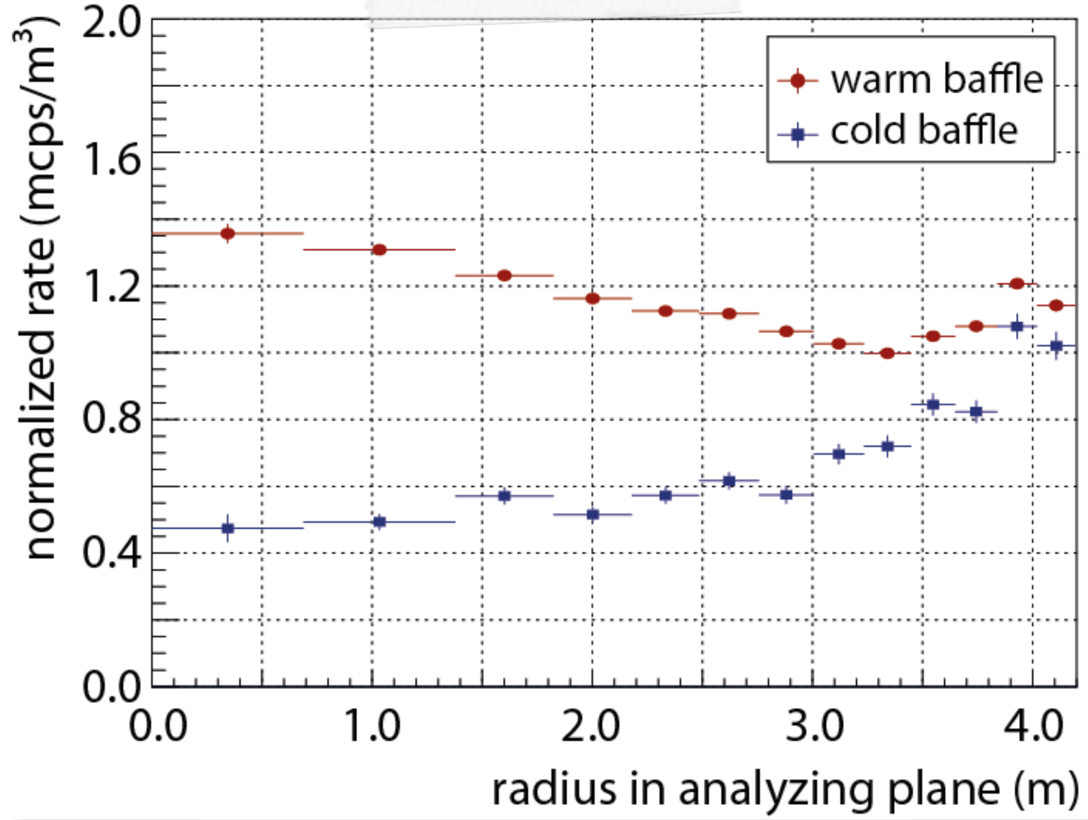
Transmission Function



At -18.6 keV, better than 100 meV resolution

Sharpest transmission function for a MAC-E filter

Background Rates



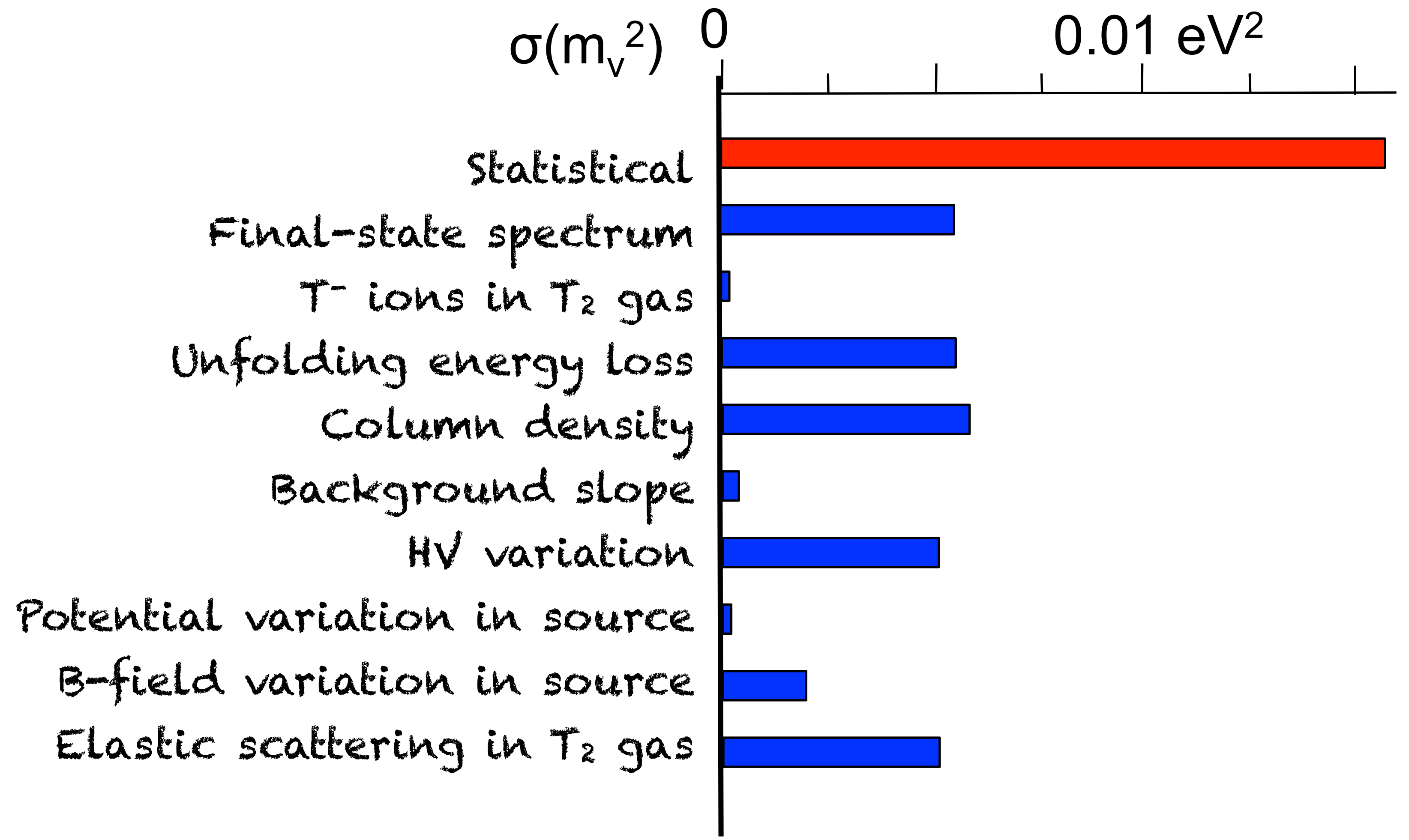
Background rate of order Hz (radon-dominated)

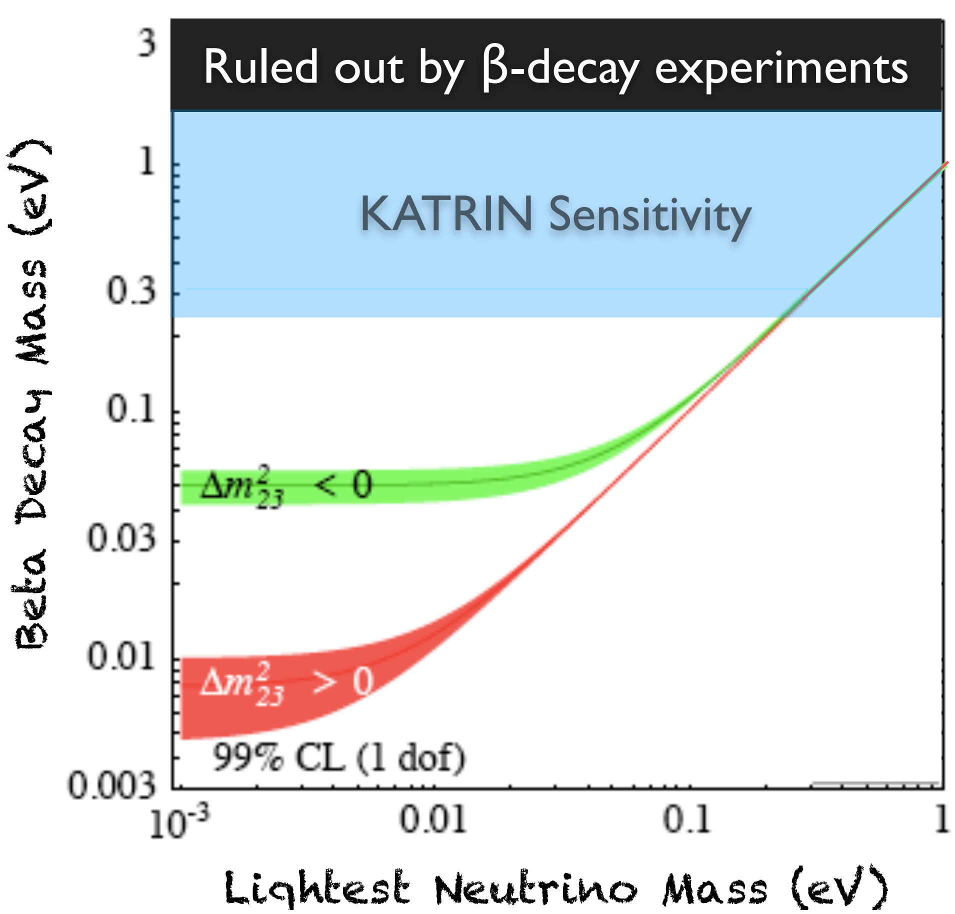
Greater reduction of backgrounds to come

Commissioning showed excellent behavior of MAC-E Filter response.

Next round of commissioning meant to study background levels.

Projected Sensitivity



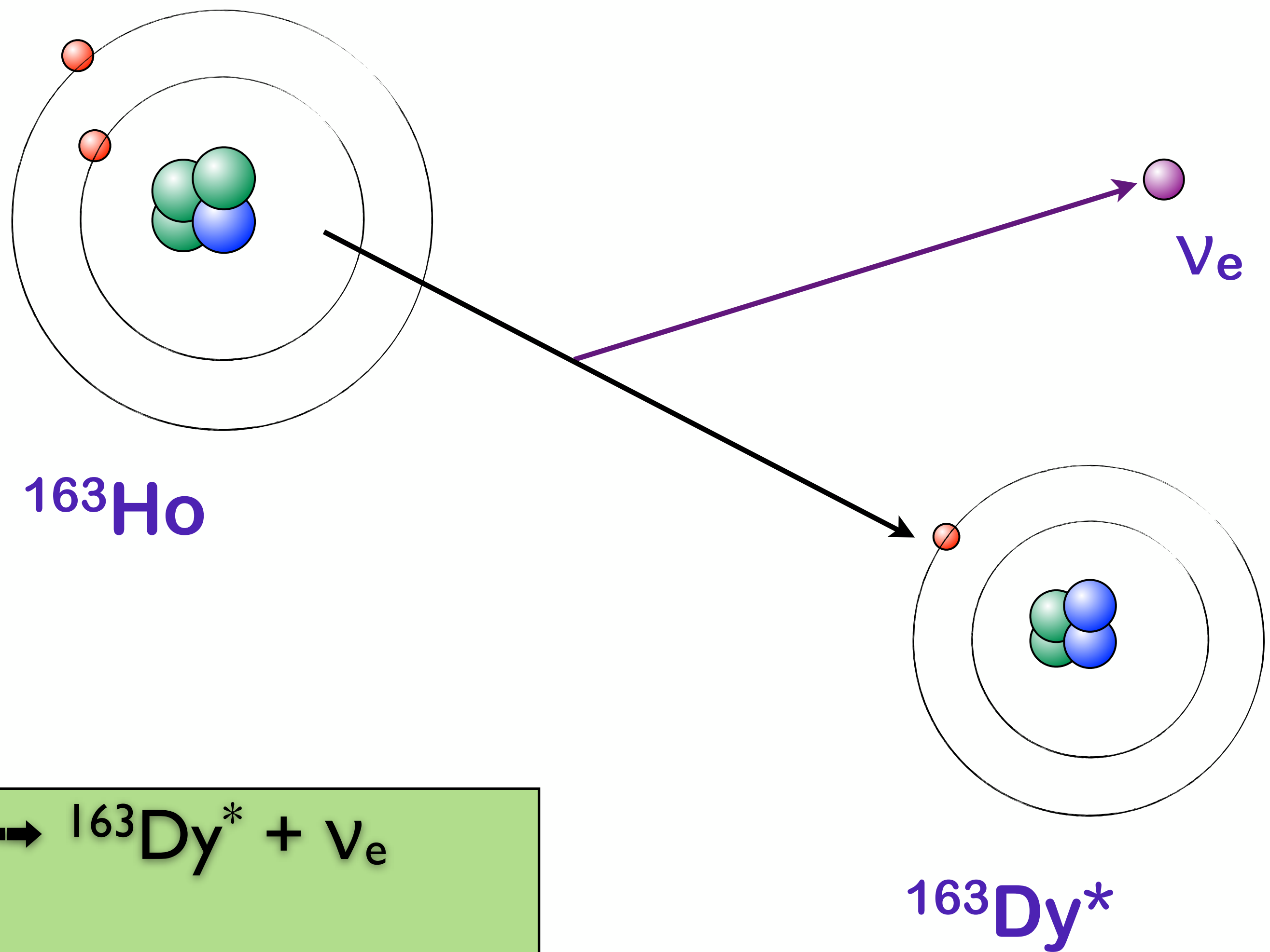


Neutrino Mass Goals

Discovery: 350 meV (at 5σ)

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

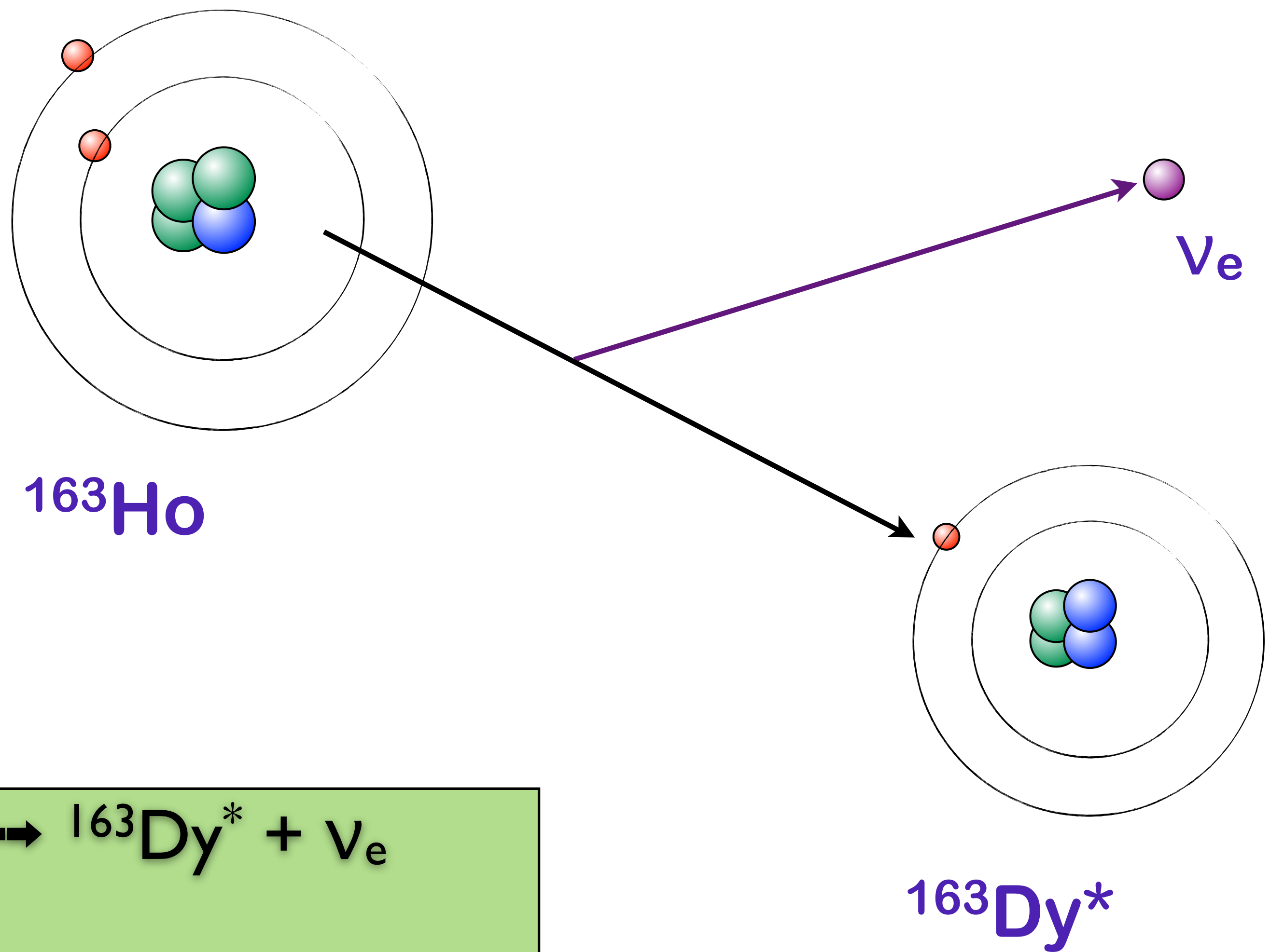
Data taking to commence in 2016.



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

$$^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + \mathrm{E.C.}$$

New kid on the block: Electron Capture



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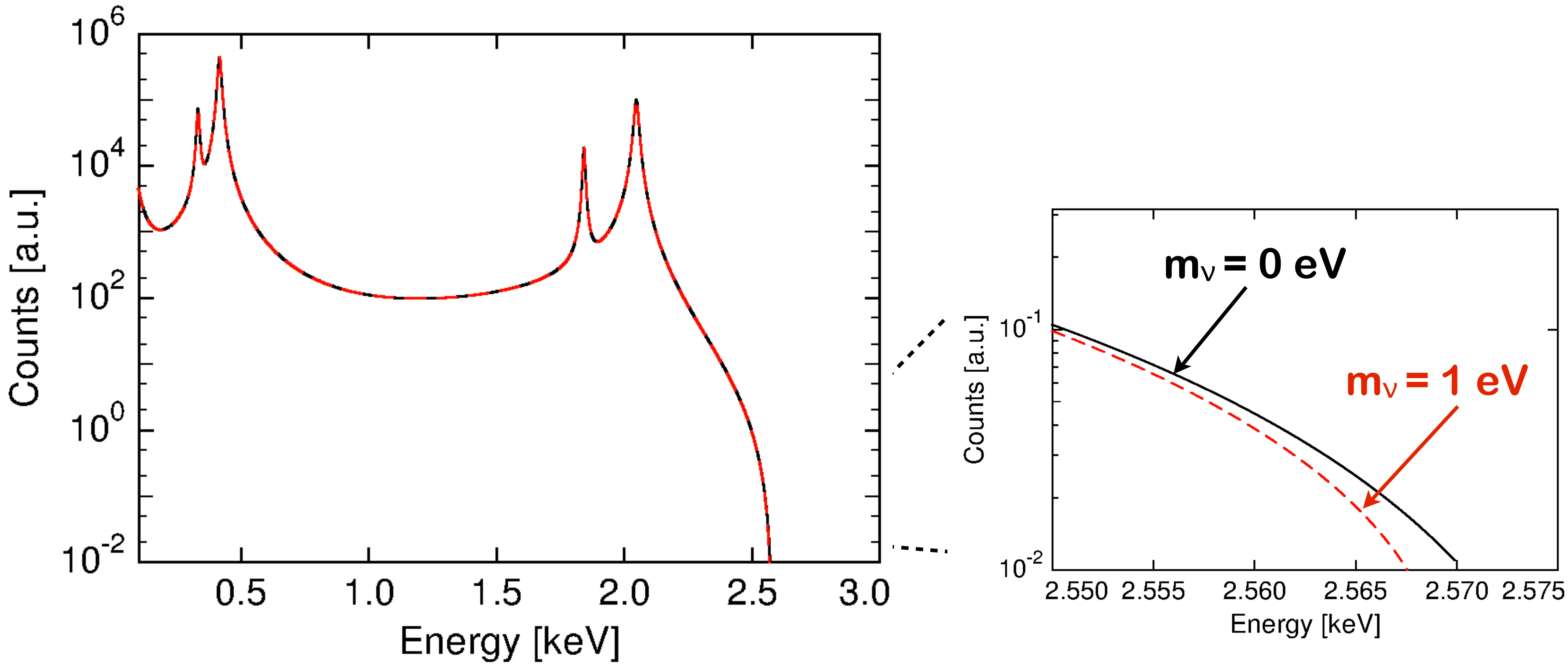
New ~~kid~~ isotope on the block:

Electron Capture

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

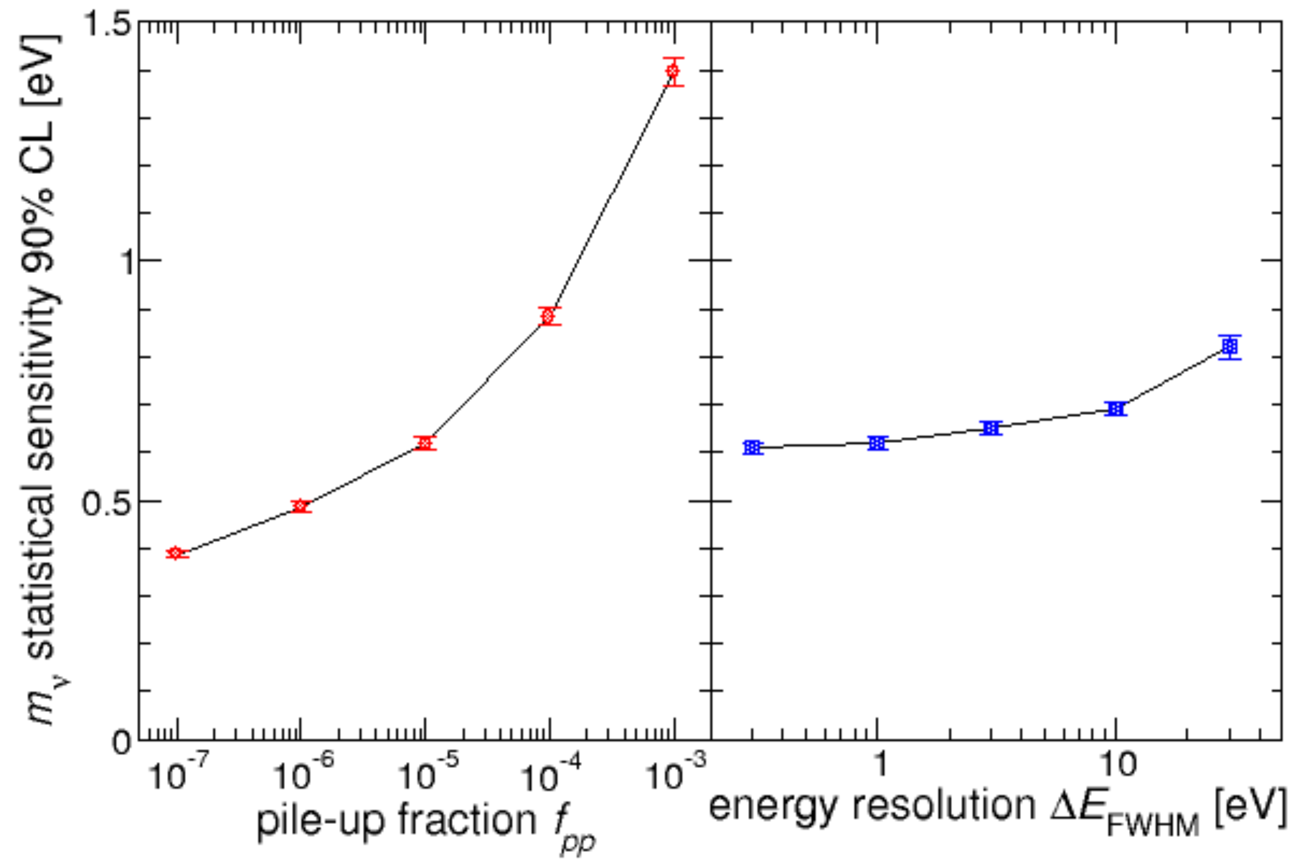


New ~~kid~~ isotope on the block:

Electron Capture

Advantages & Challenges

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

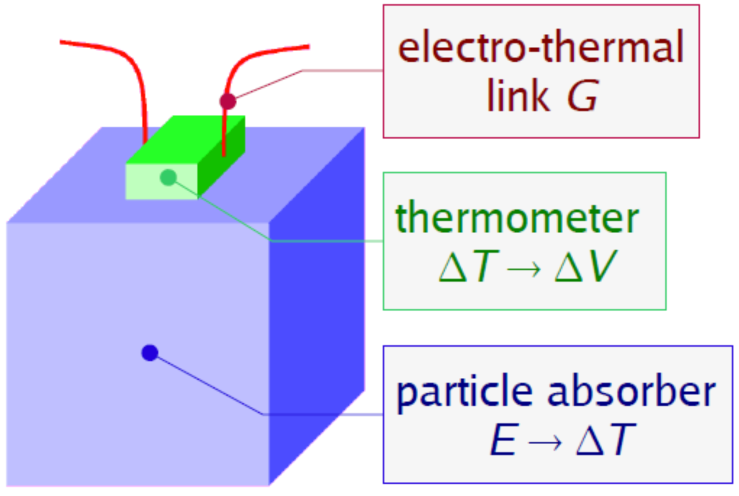
- **Experimental Challenges:**

  Fast rise times to avoid pile-up effects.

  Good energy resolution & linearity

  Sufficient isotope production

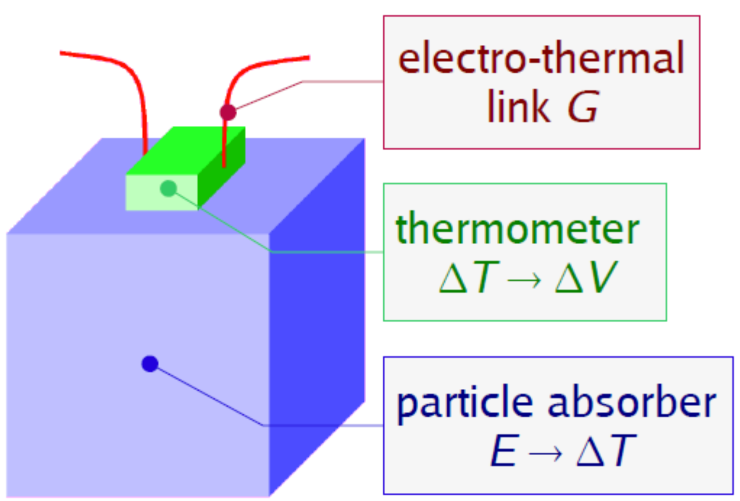
Calorimetry



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

Advantages & Challenges

Calorimetry



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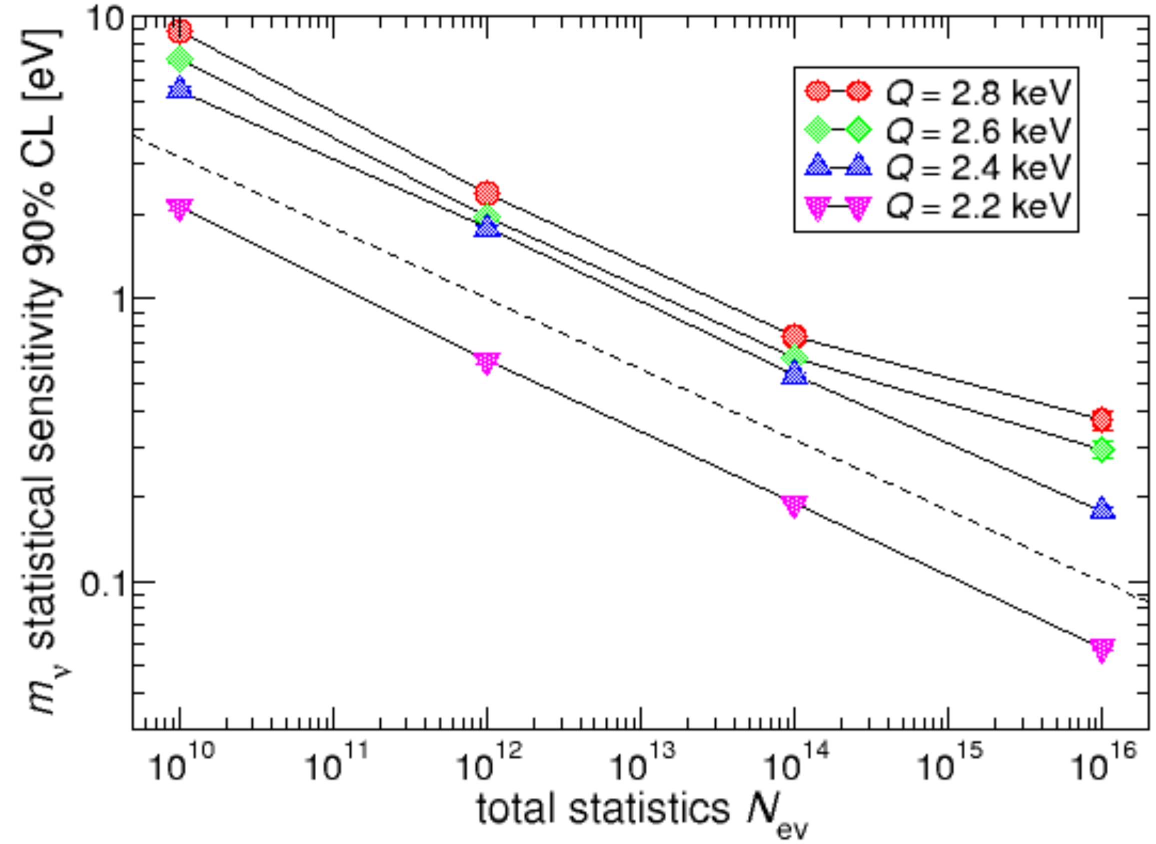
Challenges:



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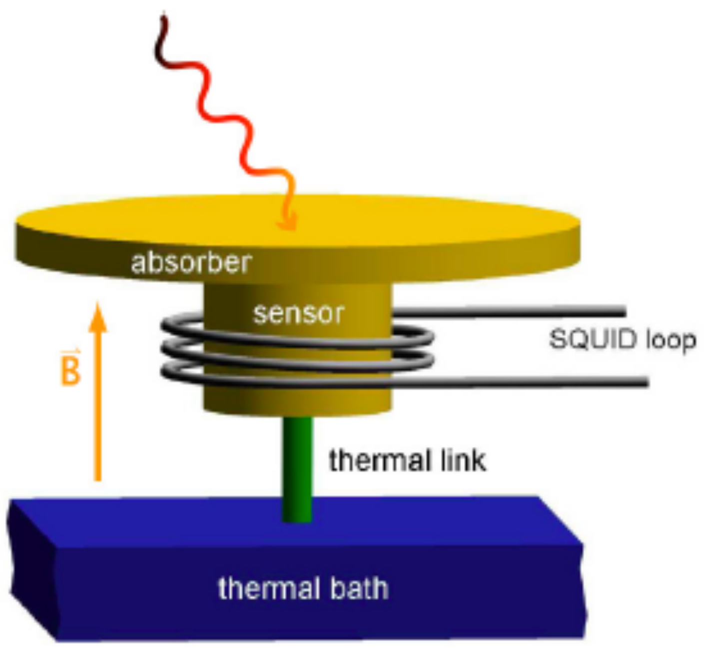
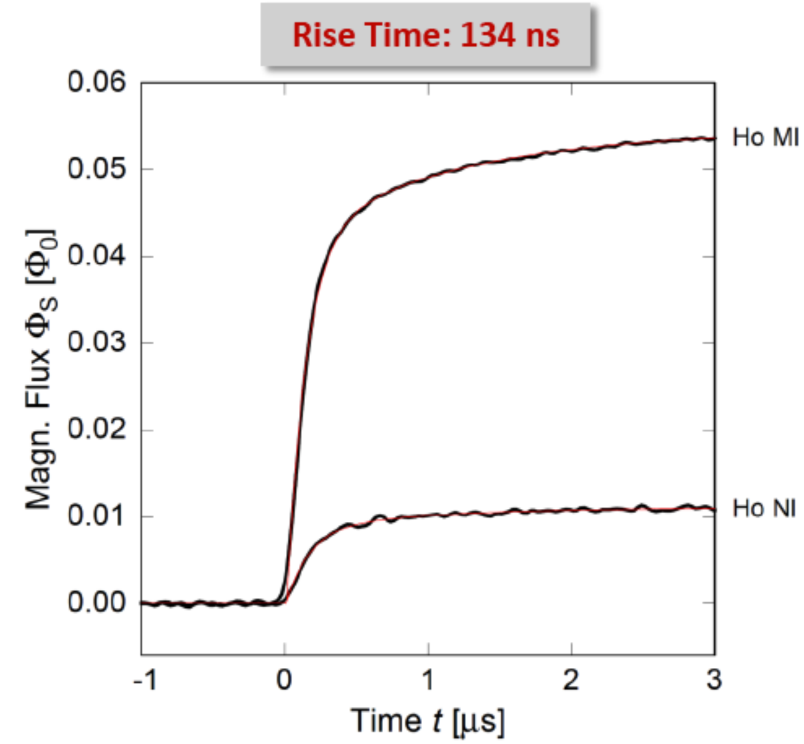
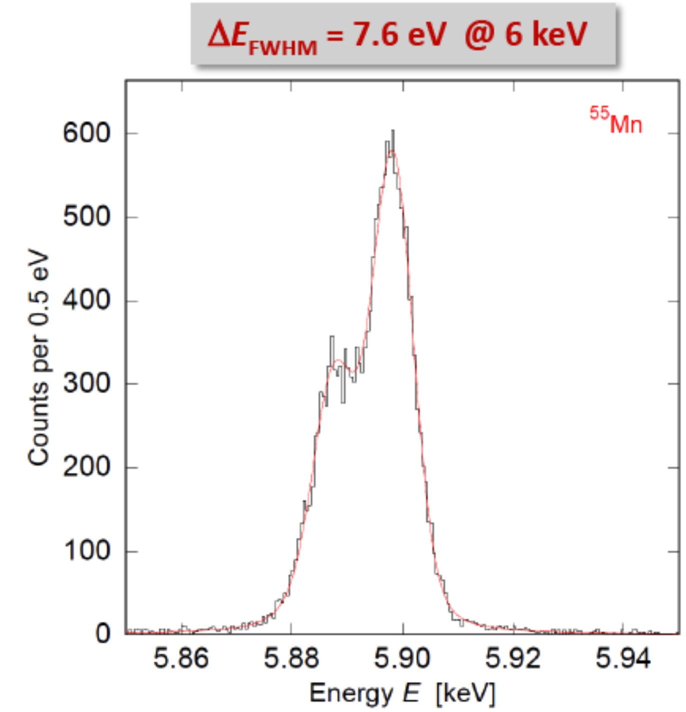
The ECHo Experiment

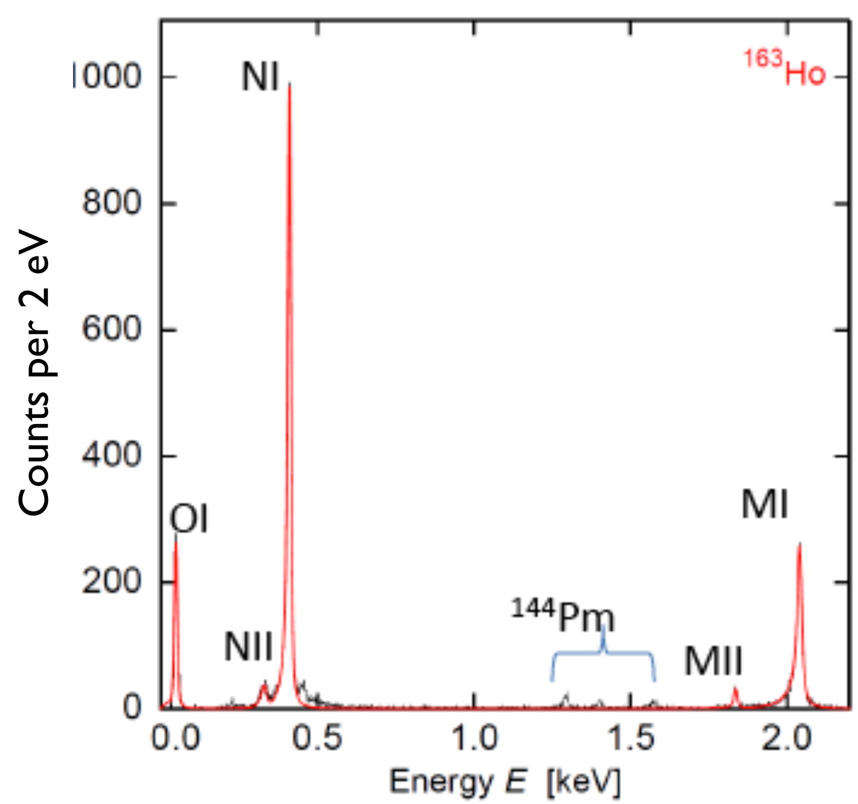
Technology:



Metallic Magnetic Calorimeters



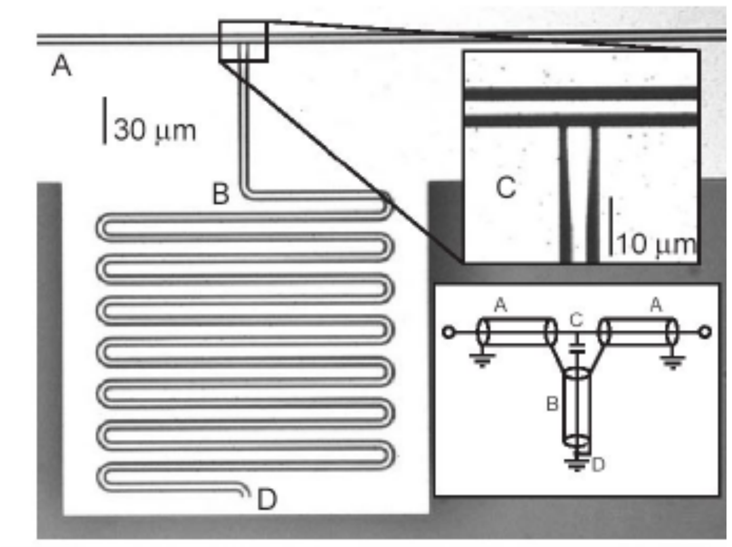




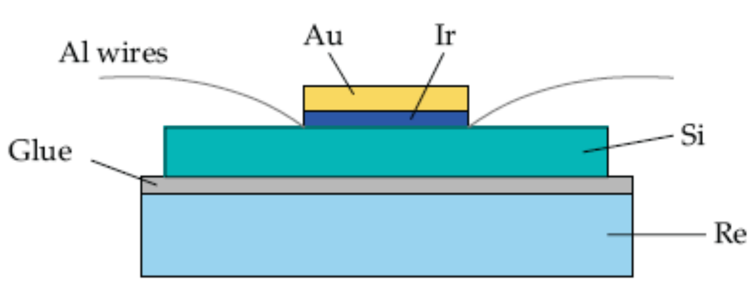
- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

The HOLMES Experiment

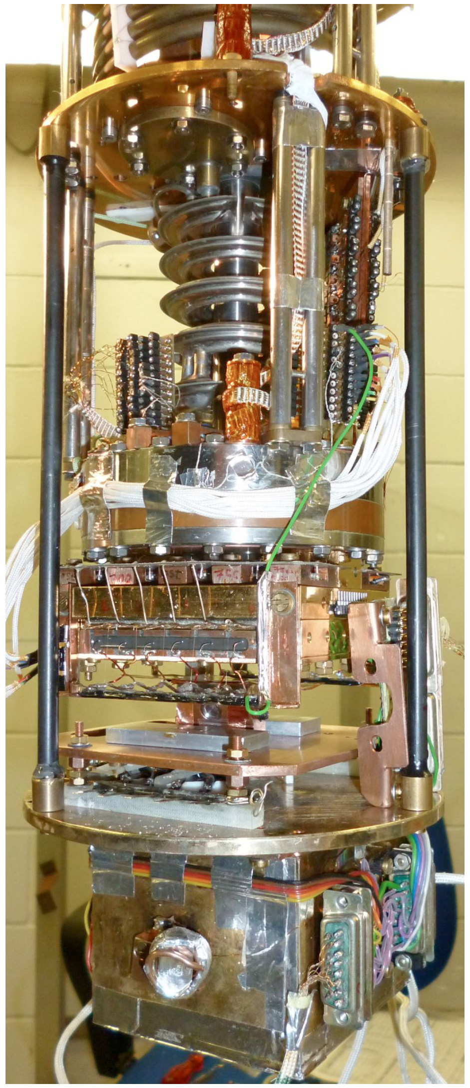
Technologies:



Superconducting Resonators

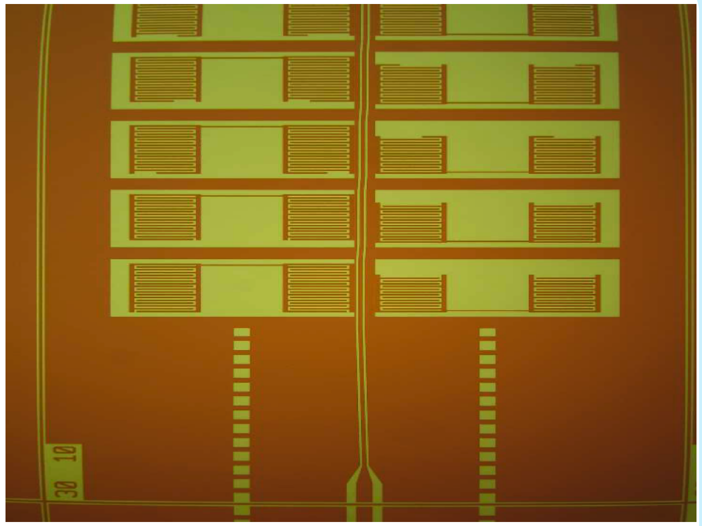


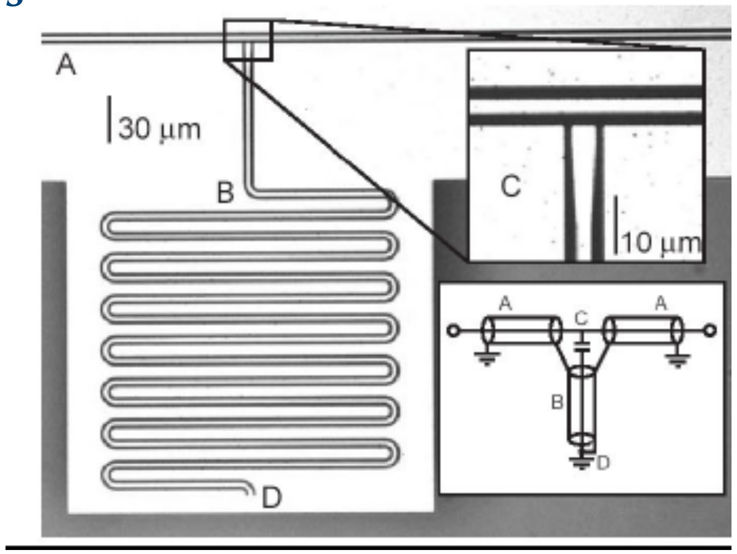
Transition Edge Sensors

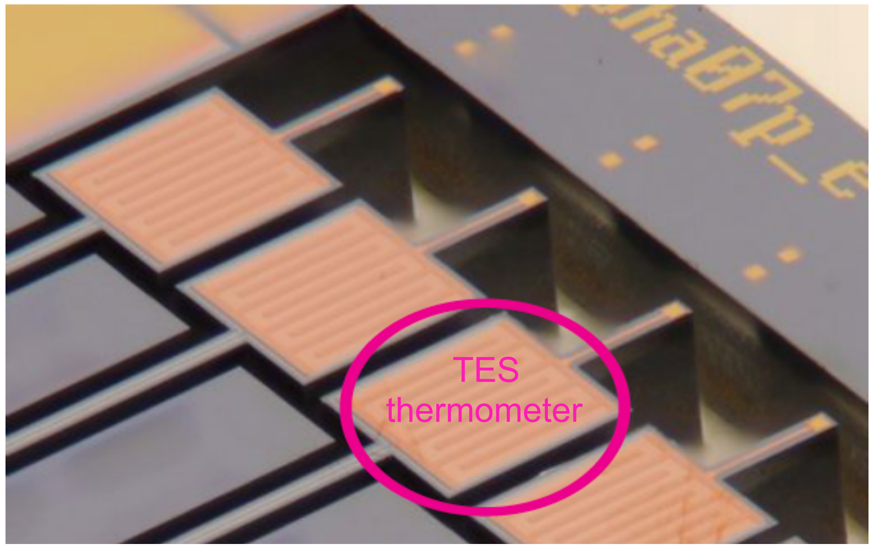


HOLMES (Italy)

transition edge sensors / MKIDs







NuMECS (USA)

transition edge sensors

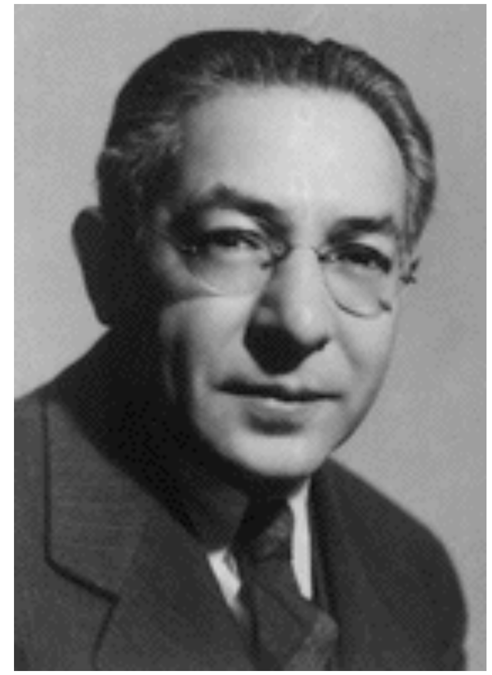
Project 8

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

PROJECT 8

Frequency Approach

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



I. I. Rabi

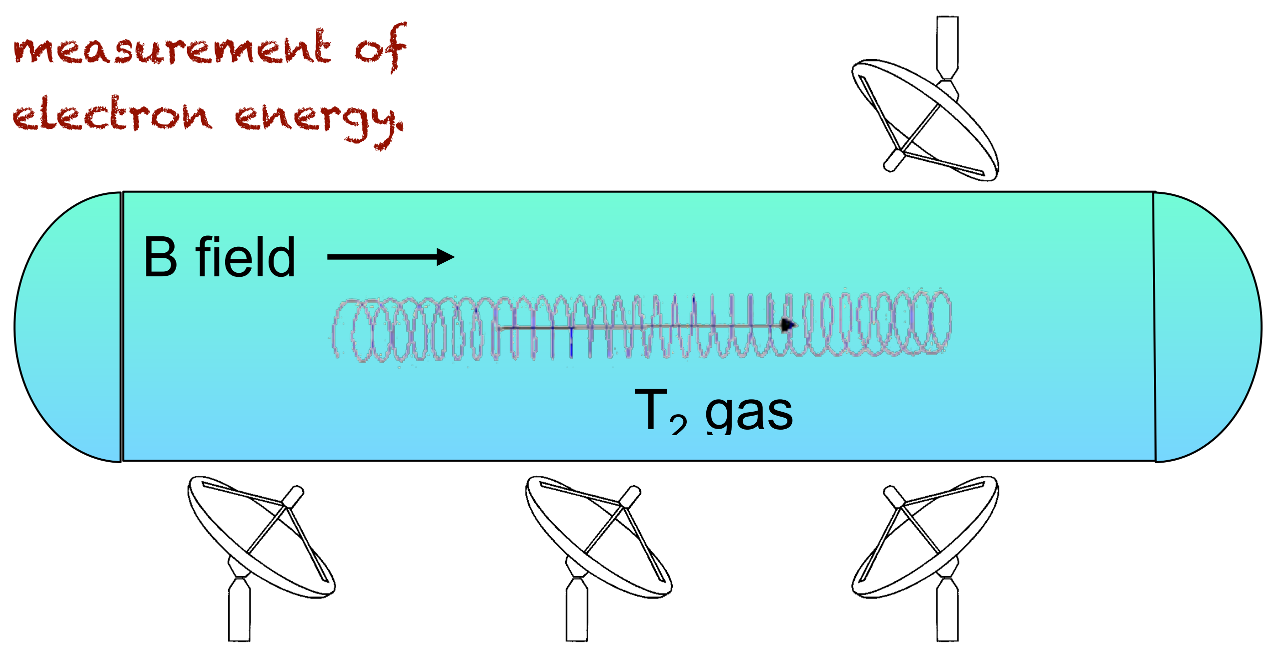
"Never measure anything but frequency."

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.

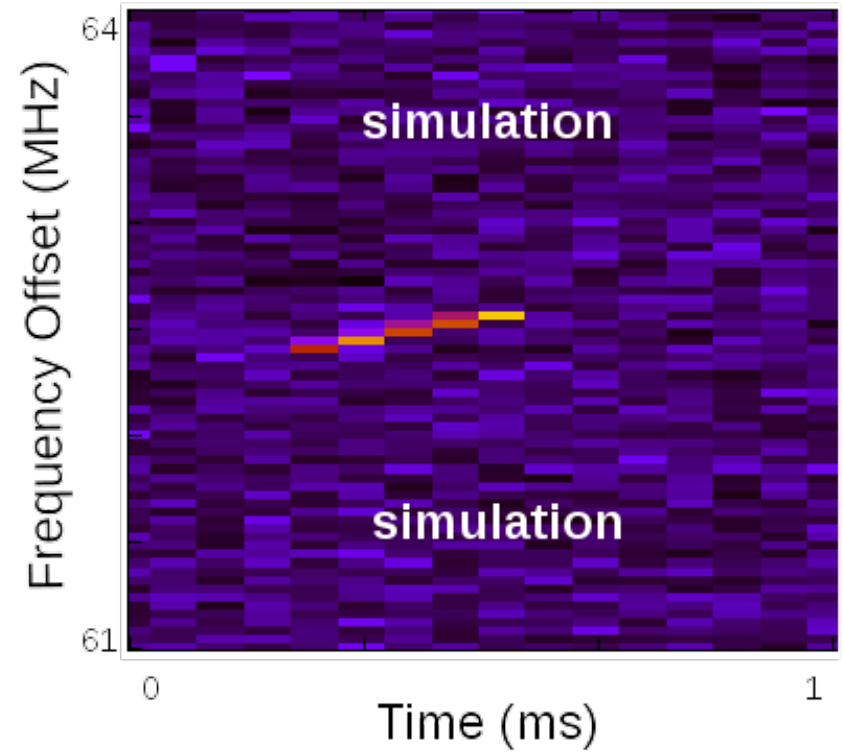


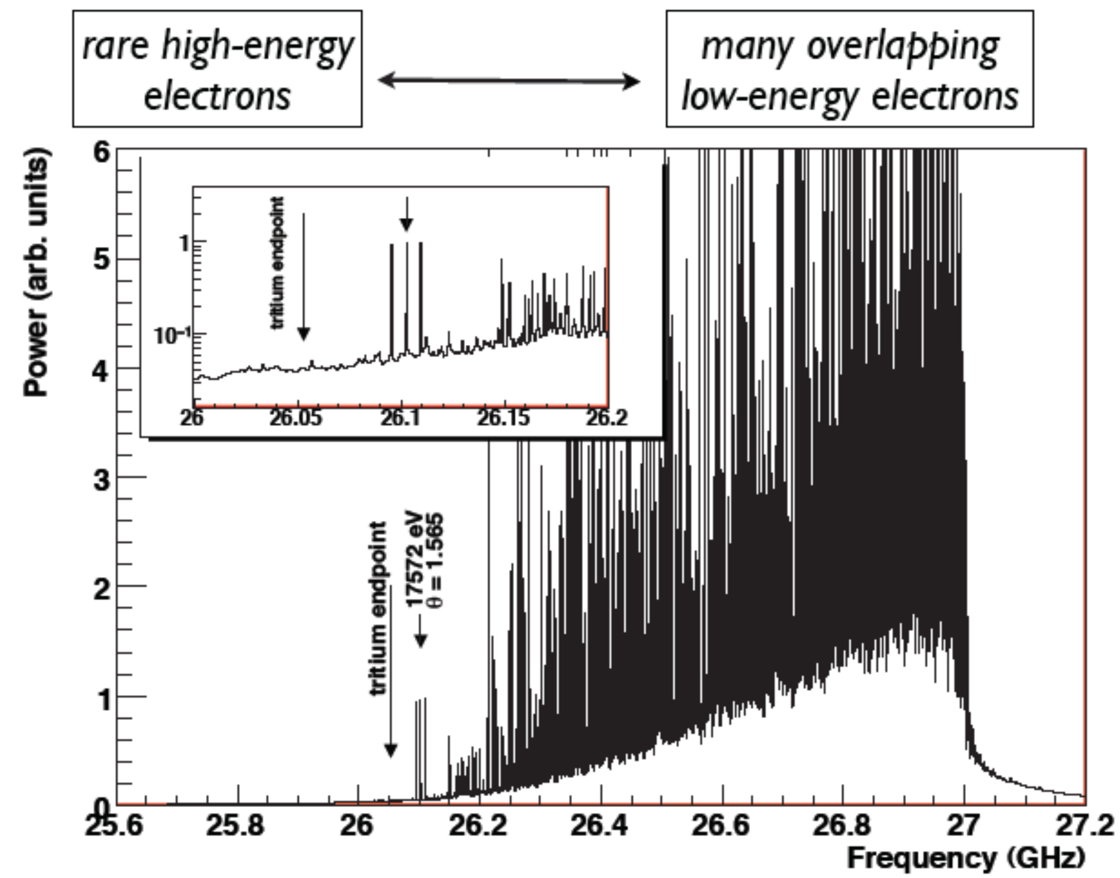
B. Monreal and JAF, Phys. Rev D80:051301

Unique Advantages

- **Source = Detector**
  (no need to extract the electrons from the tritium)
- **Frequency Measurement**
  (can pin electron energies to well-known frequency standards)
- **Full Spectrum Sampling**
  (full spectrum measured at once, large leverage for stability and statistics)

Signal Simulation
Power vs Time, Frequency

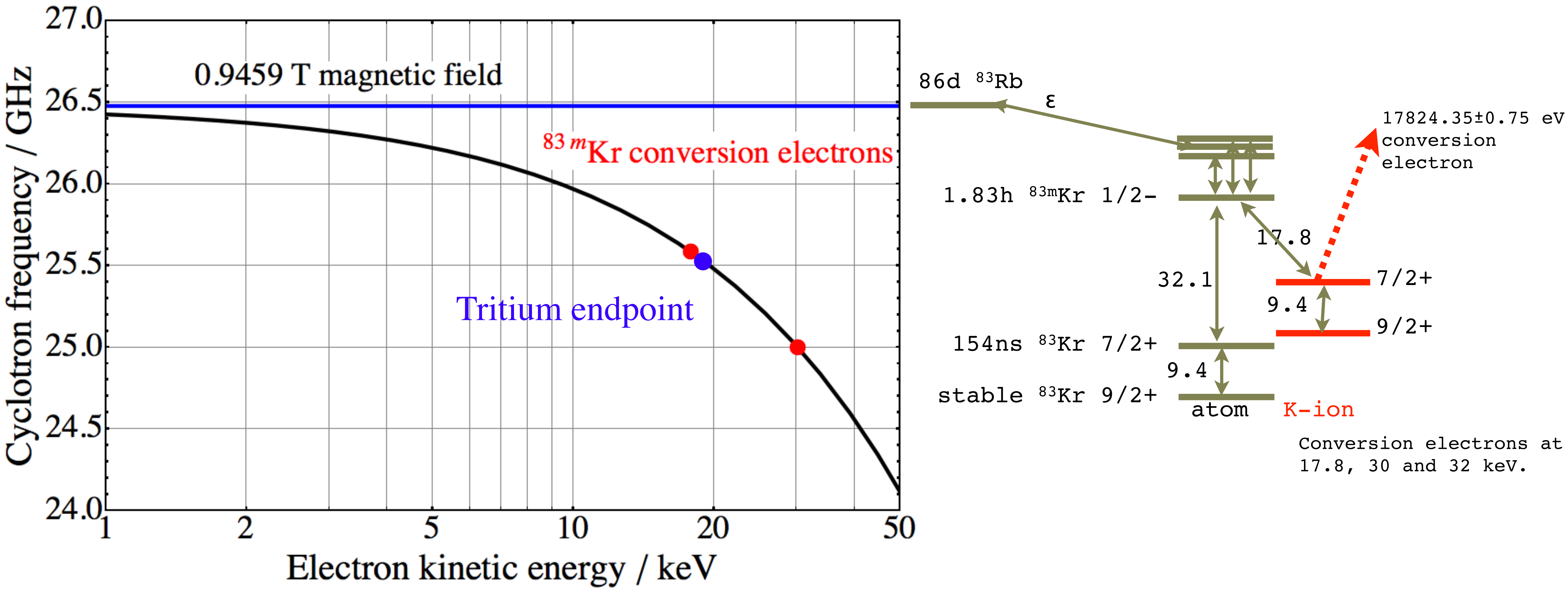




100,000 tritium decays in 30μs

Simulation of beta (frequency) spectrum

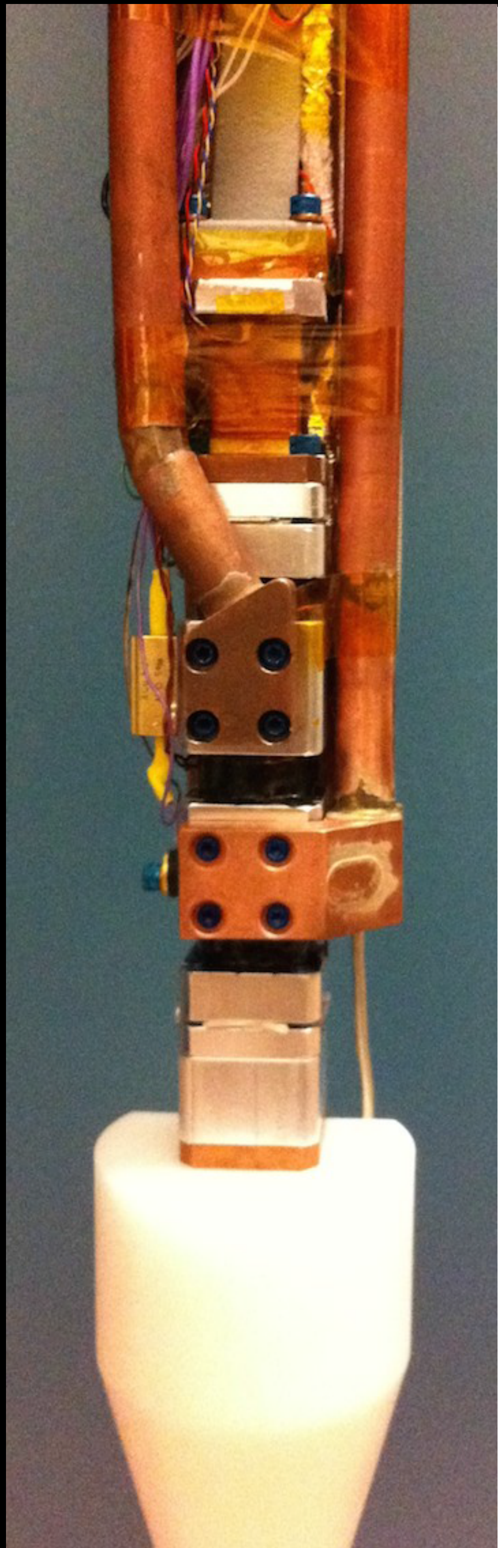
Initial Demonstration: ^{83m}Kr

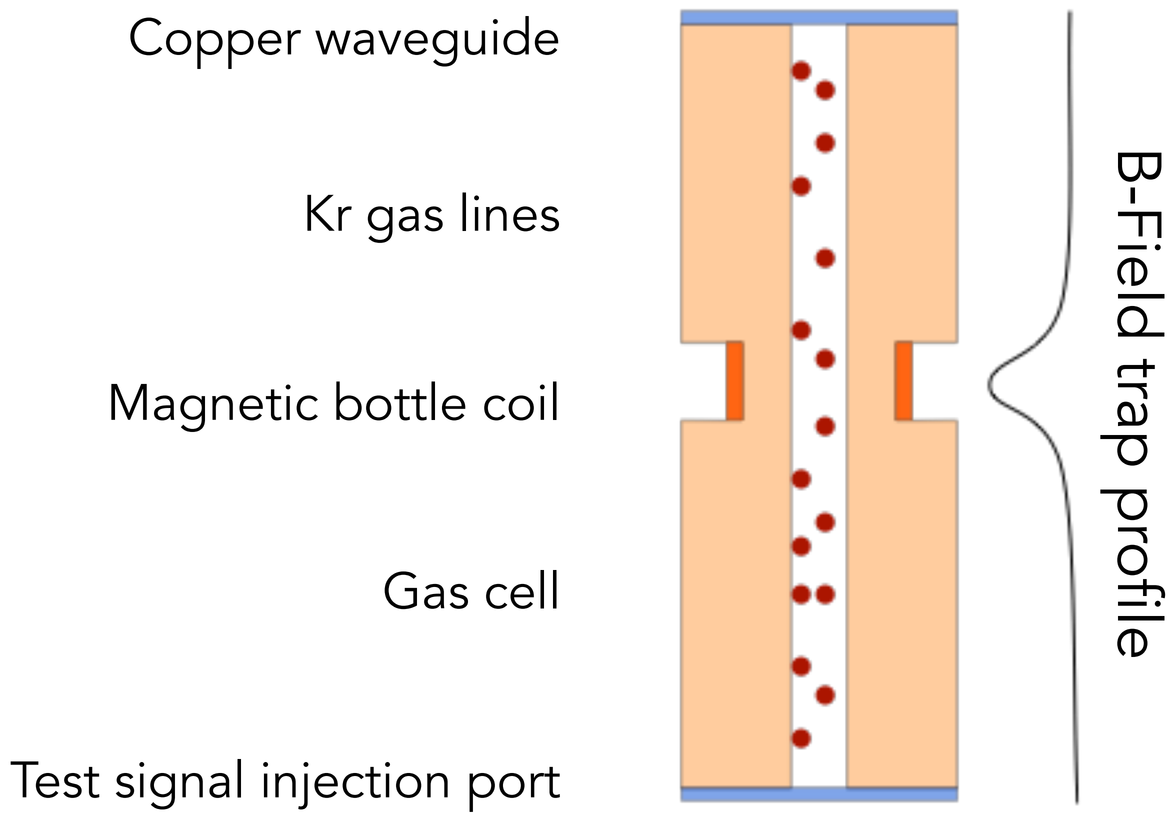


Phase I : Use mono-energetic source to determine single electron detection.

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

The Apparatus





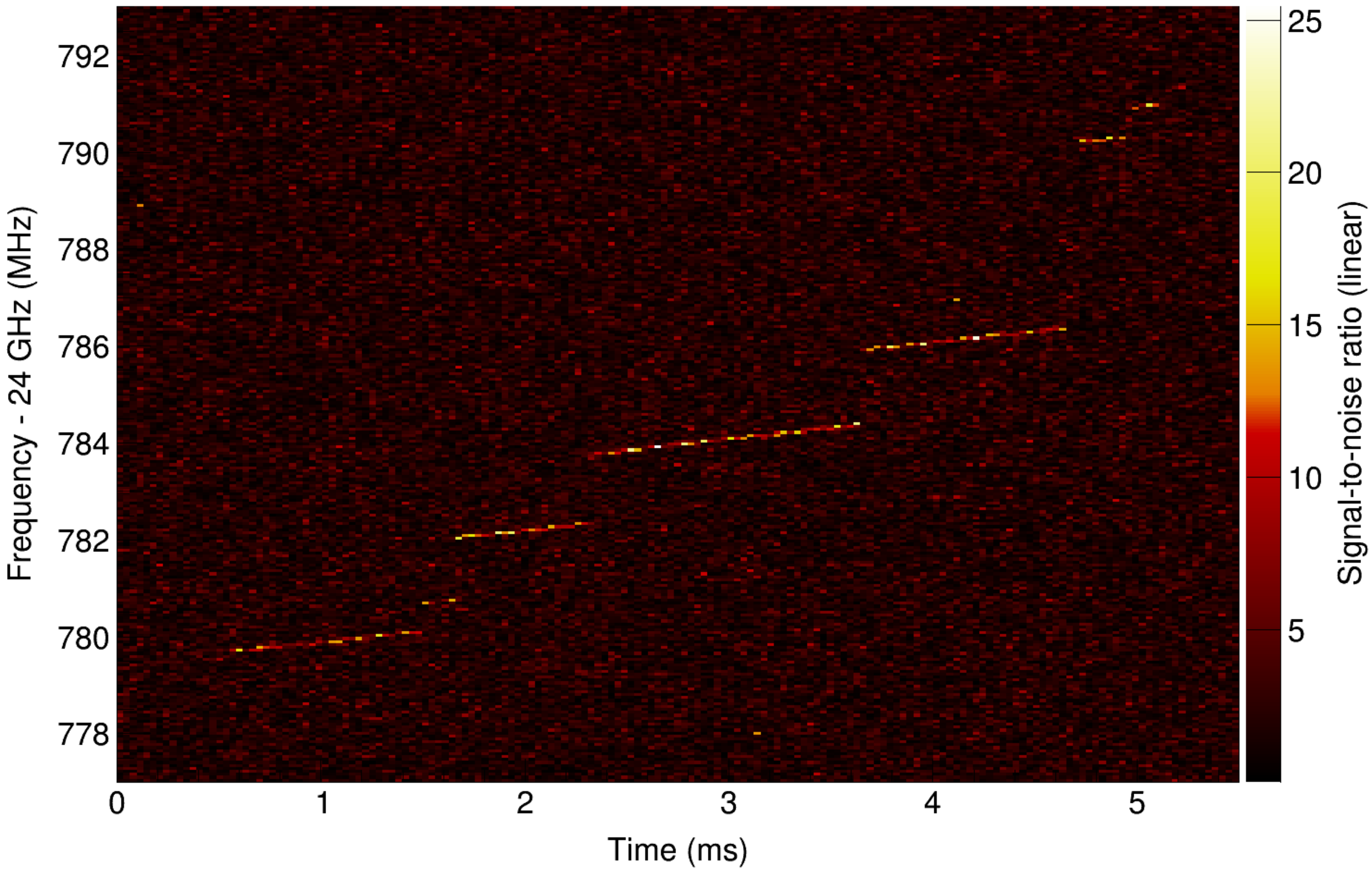
Waveguide Cut-away

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.

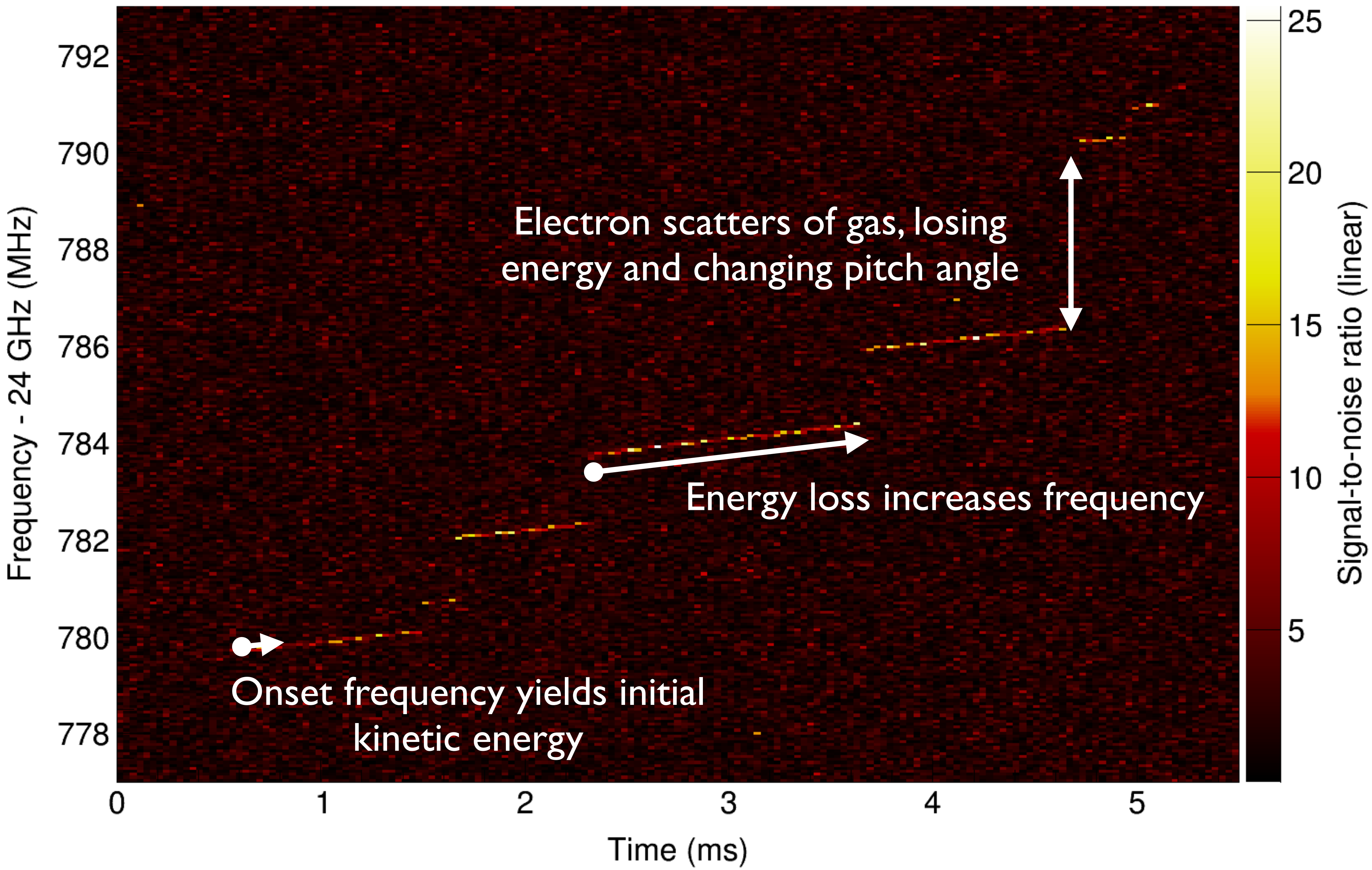
Project 8 "Event Zero"



Clear detection of single electrons from their emitted cyclotron frequency.

All predicted features present (sudden onset, energy loss, scattering loss)

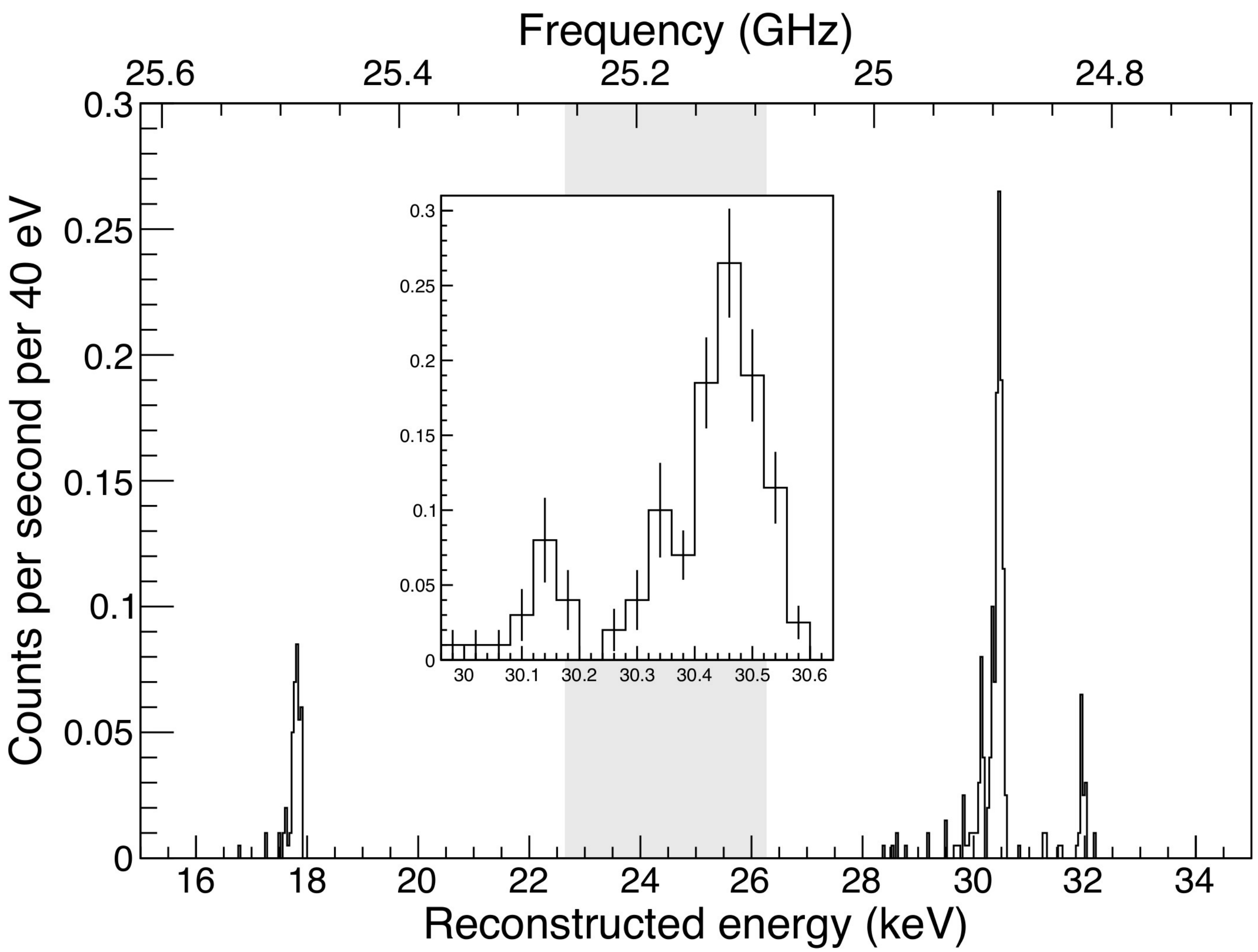
Project 8 "Event Zero"



Clear detection of single electrons from their emitted cyclotron frequency.

All predicted features present (sudden onset, energy loss, scattering loss)

Image Reconstruction & Energy Resolution

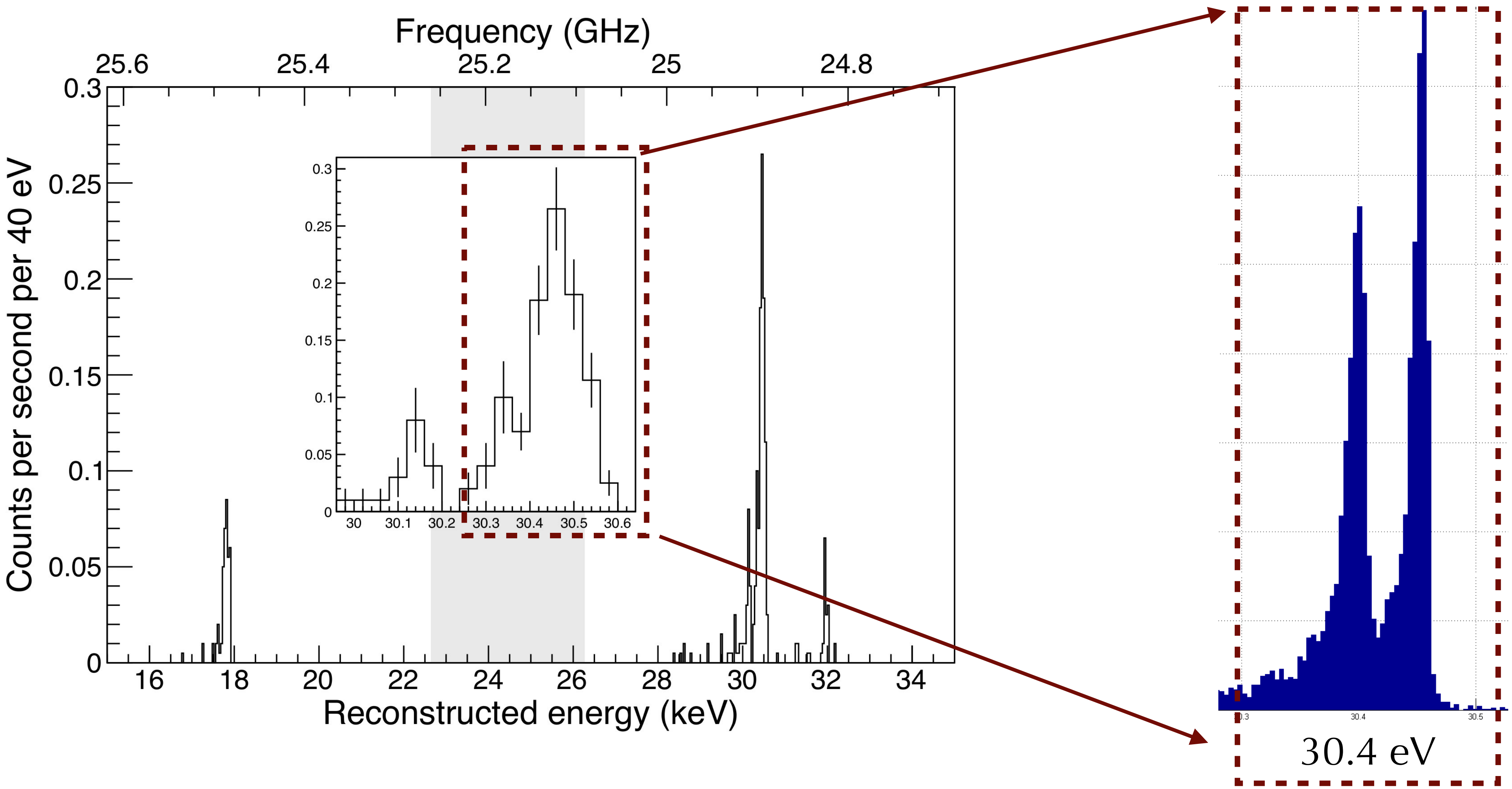


FWHM ~ 140 eV

Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

Image Reconstruction & Energy Resolution

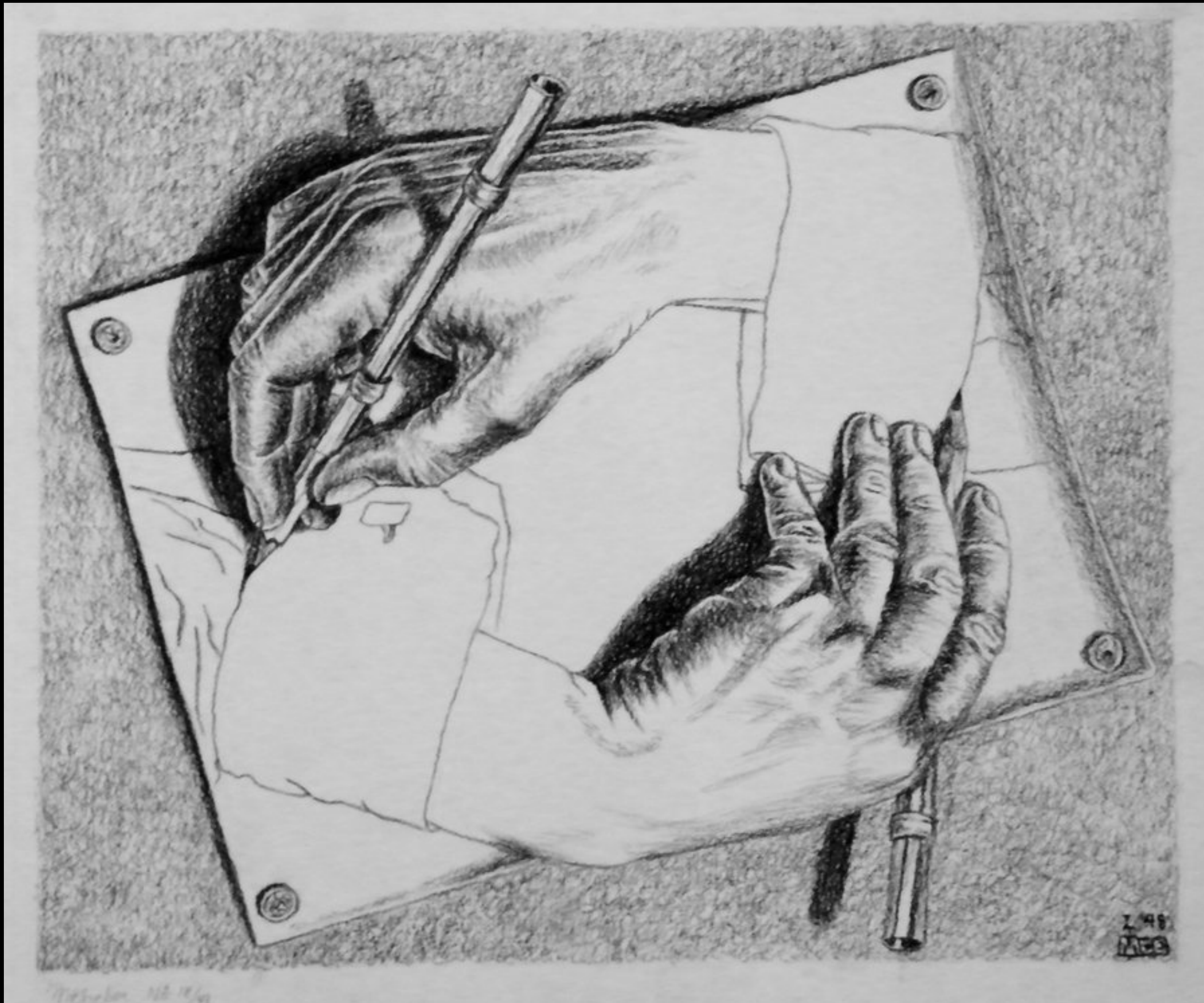


FWHM ~ 140 eV

FWHM ~15 eV
(and improving)

Event reconstruction from image reconstruction allows detailed analysis

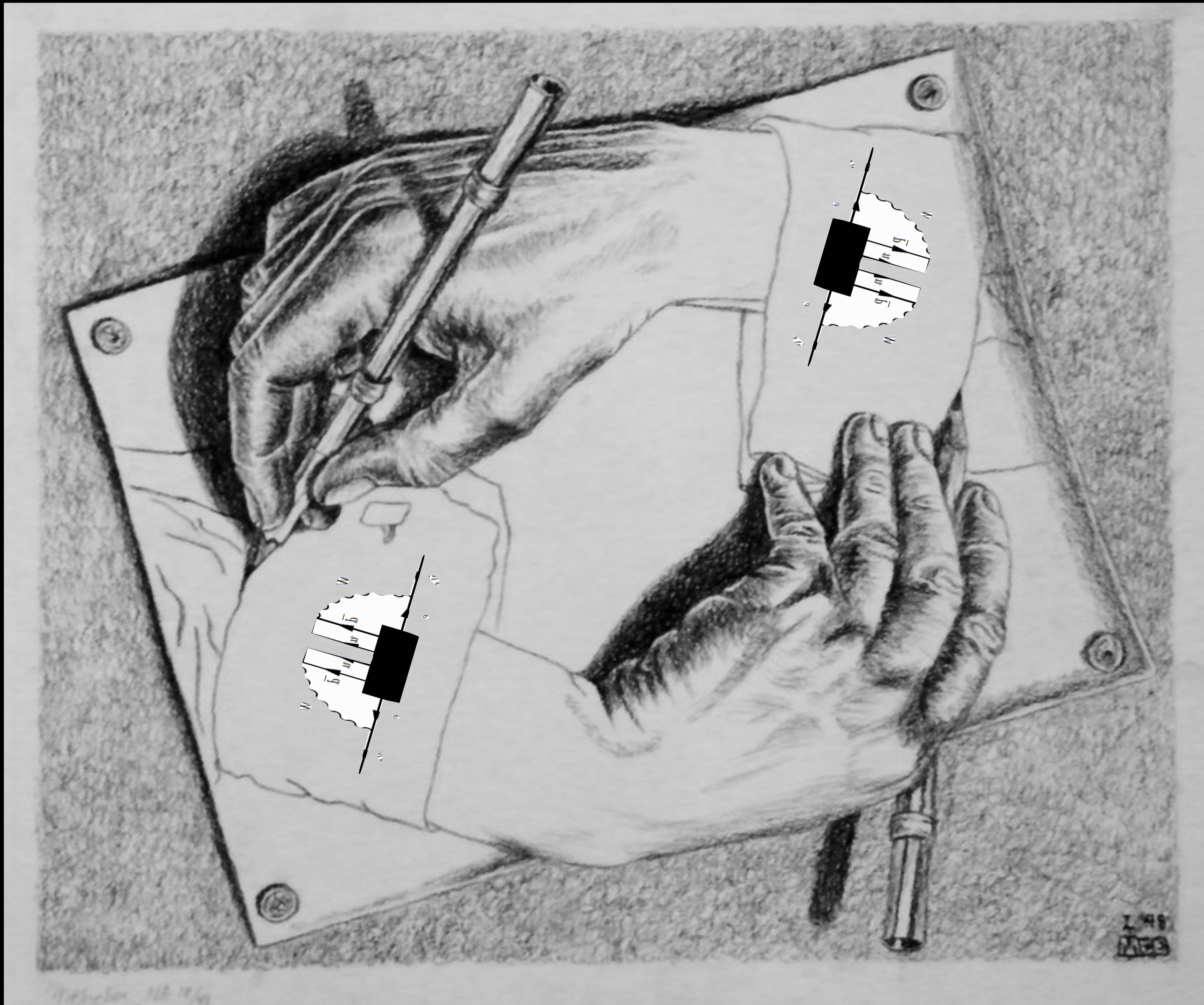
(energy & scattering all extractable)



Neutrinoless Double Beta Decay

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

0νββ Measurements



What would a positive signal mean?

A lot, actually, since the Standard Model conserves B-L.

- Demonstrate that neutrinos are Majorana fermions.
- Shed light on the neutrino mechanism
- Probe into the causes for the matter anti-matter asymmetry in the universe

$$(N, Z) \to (N-2, Z+2) + e^- + e^-$$

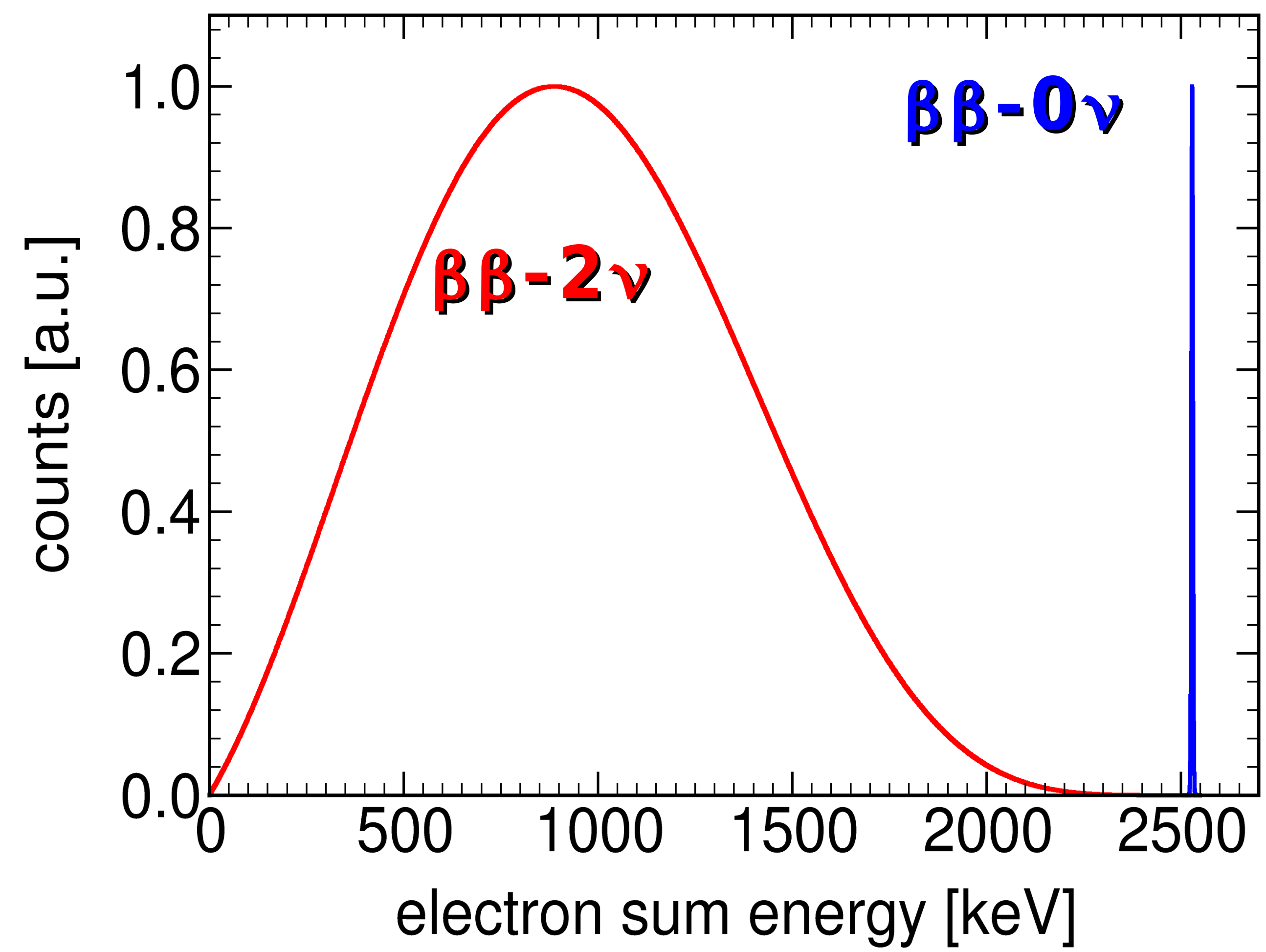
$$\Delta L = 2$$

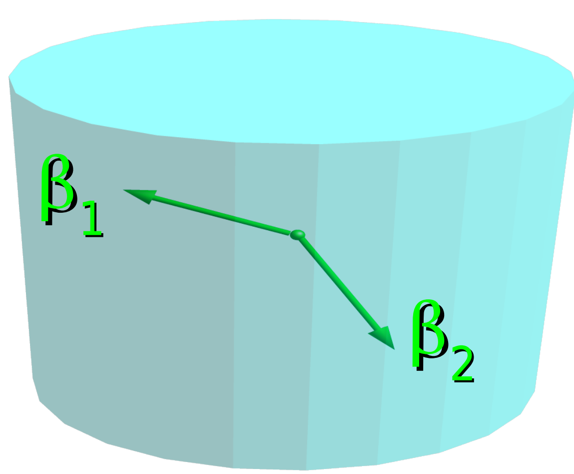
Simple in principle...

- Clean Signature
  Sum of electrons is at a single energy

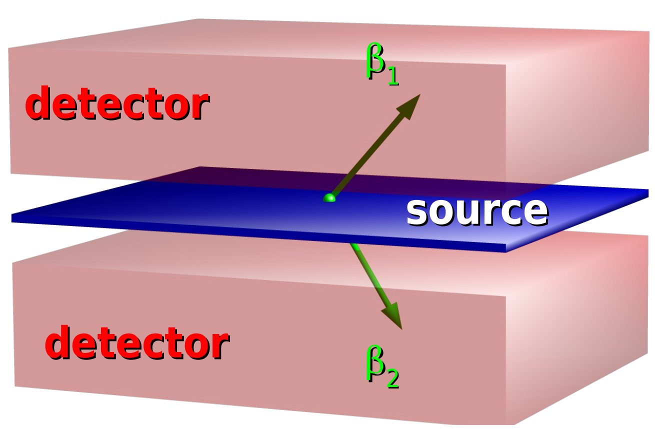
- Know where to look
  Occurs at endpoint of the allowed decay, well-separated from bulk $\beta\beta\nu\nu$.

- Particle detection
  (we know how to detect electrons well)





Source = detector

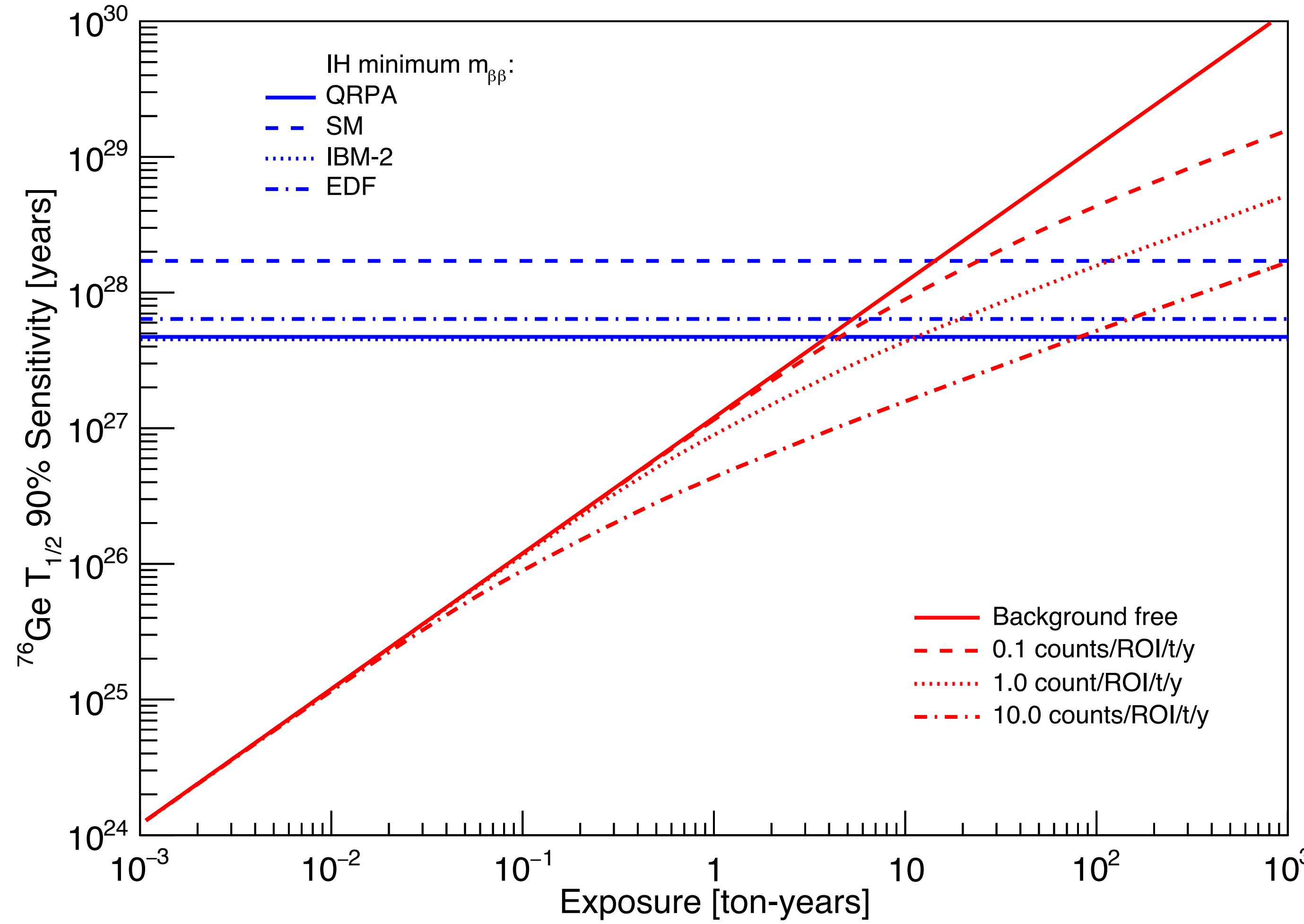


Source ≠ detector

…but not in practice

- Background Suppression
  The key to success in all these experiments is background suppression
- Isotope Abundance
  Often trading high Q value for poor abundance
- Rarity of Process
  Rarest process (yet) to be measured.

J. Detwiler



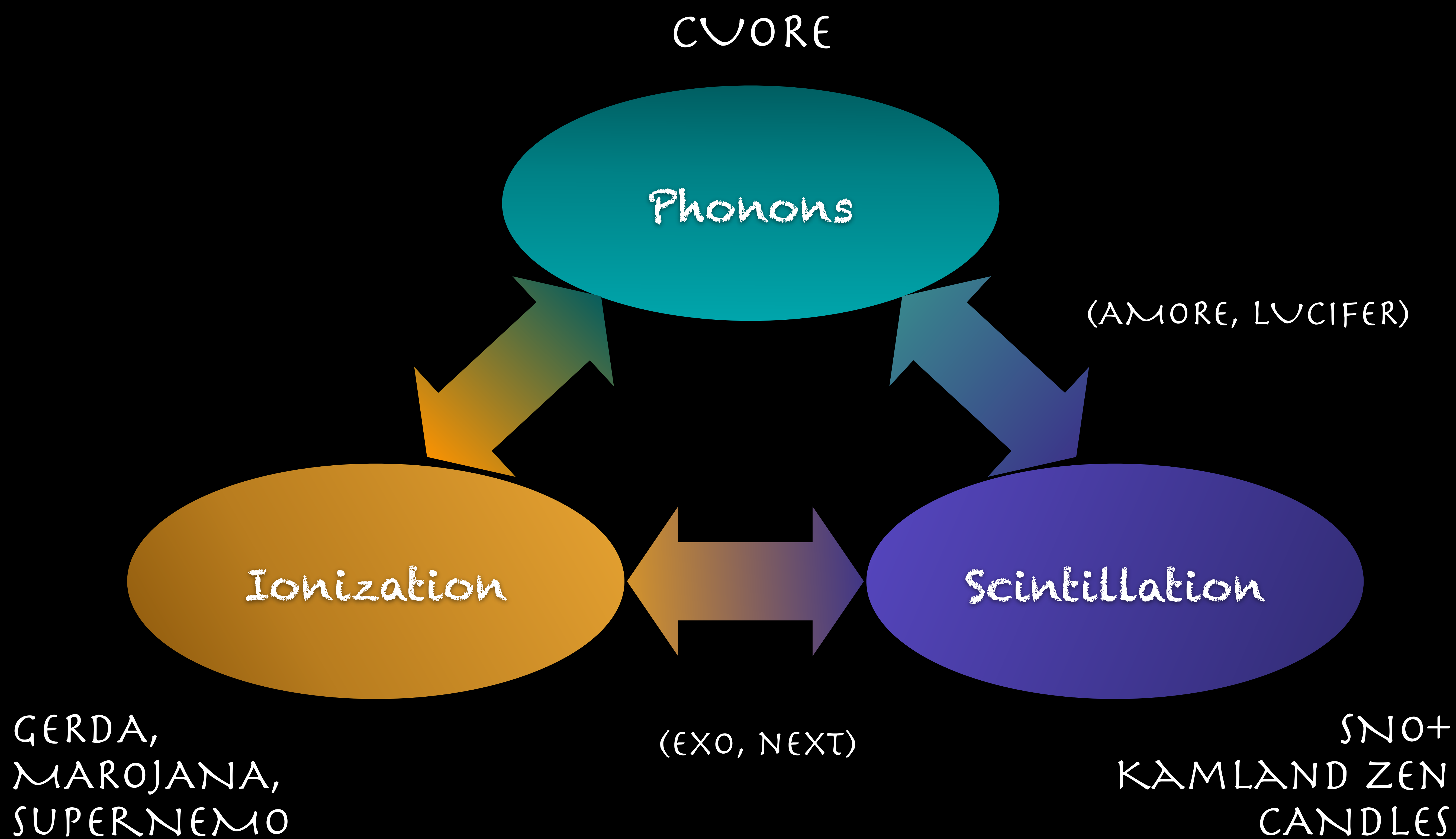
^{76}Ge example, but similar sensitivities for other $0\nu\beta\beta$ isotopes.

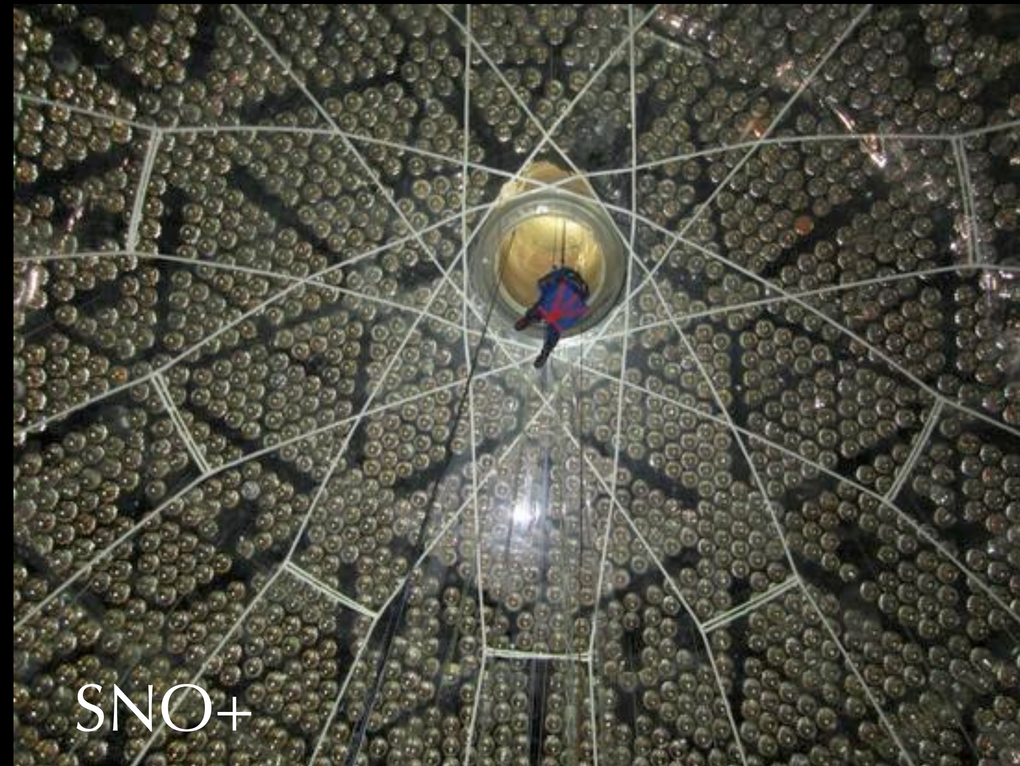
Background free

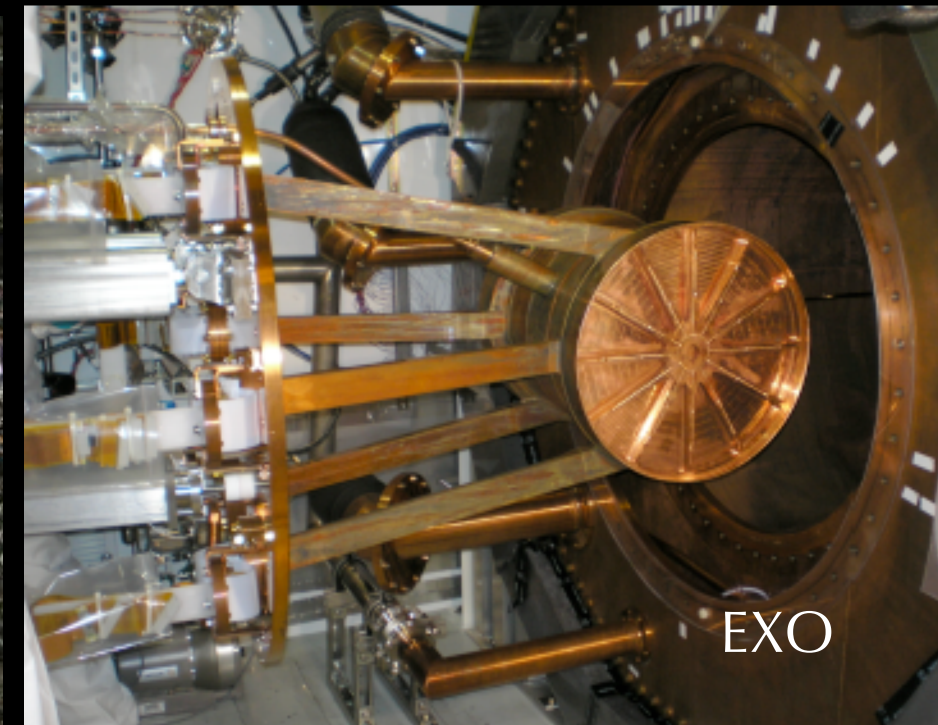
$$\left[T^{0\nu}_{1/2}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

Background limited

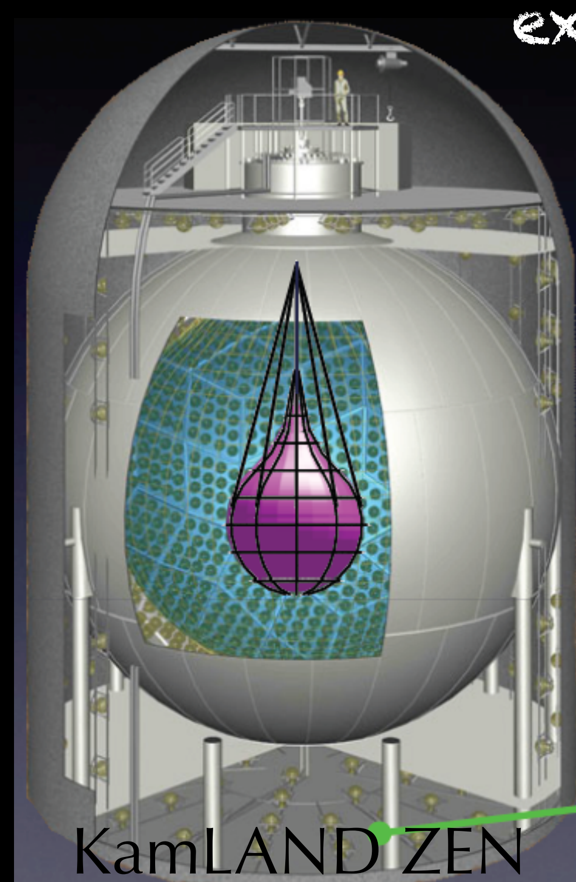
$$\left[T^{0\nu}_{1/2}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

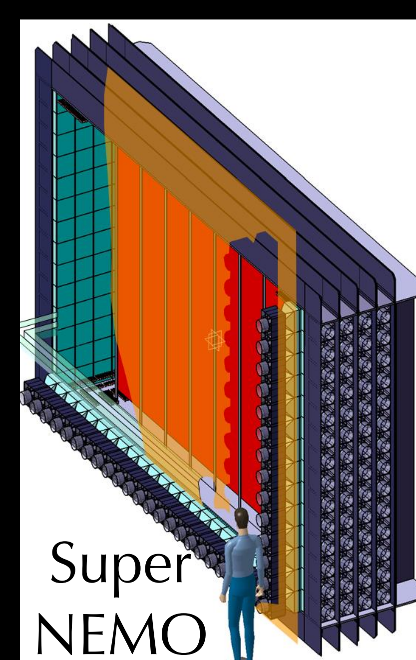

CUORE
Phonons
(AMORE, LUCIFER)
Ionization
Scintillation
GERDA,
MAROJANA,
SUPERNEMO
(EXO, NEXT)
SNO+
KAMLAND ZEN
CANDLES





Many,
many
experiments...





With so many choices, how does any one experiment stand out !?

With so many choices, how does any one experiment stand out !?

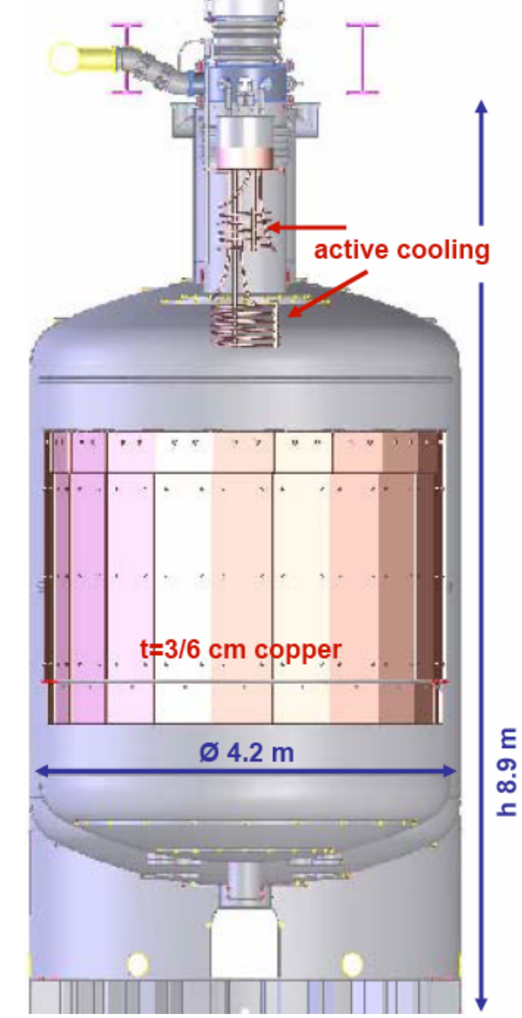
With so many choices, how does any one experiment stand out !?

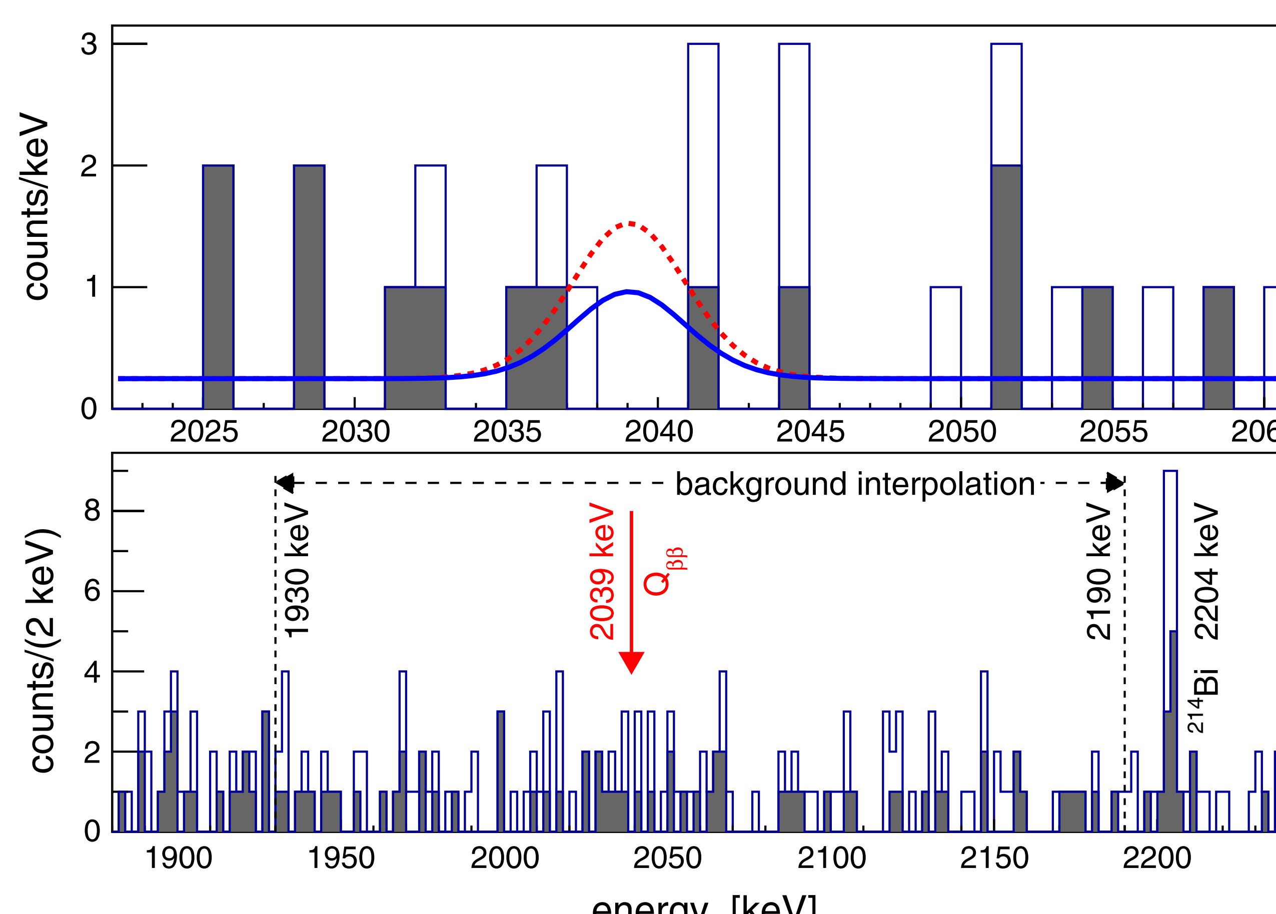
(since I cannot do justice to all of them, I will highlight only a few)

Ionization: GERDA

others ionization detectors: MAJORANA, SuperNEMO

- 87% enriched ^{76}Ge detectors (crystals) in liquid argon
- 14.6 kg of 86% enriched ^{76}Ge (6 p-type semi-coax detectors from H-M & IGEX). (4.8 keV FWHM @ $Q_{\beta\beta}$)
- 3 kg of 87% enriched BEGe enriched detectors (5 detectors)
- Single-site, multi-site pulse shape discrimination





$T_{1/2} > 2.1 \times 10^{25}$ y (90% CL) ^{76}Ge

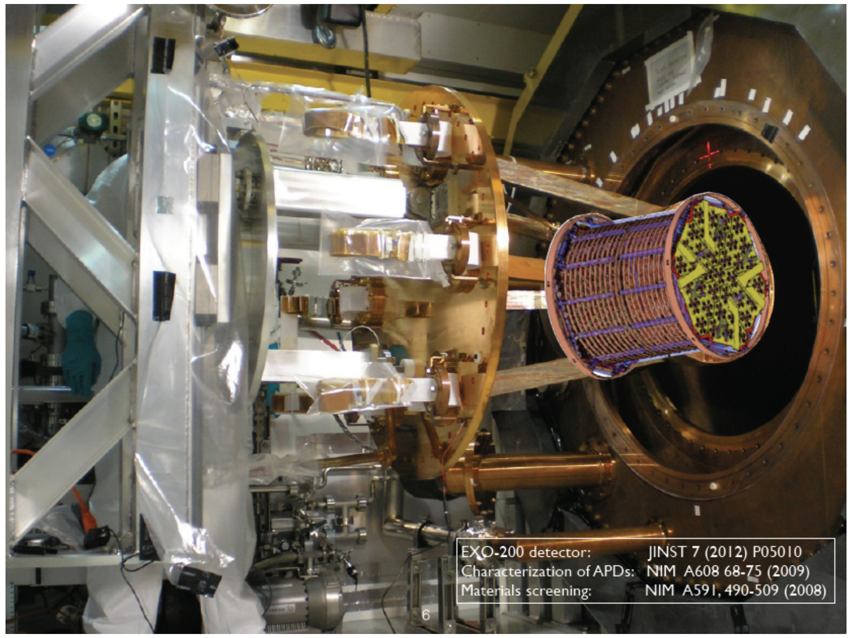
Tracking: EXO-200

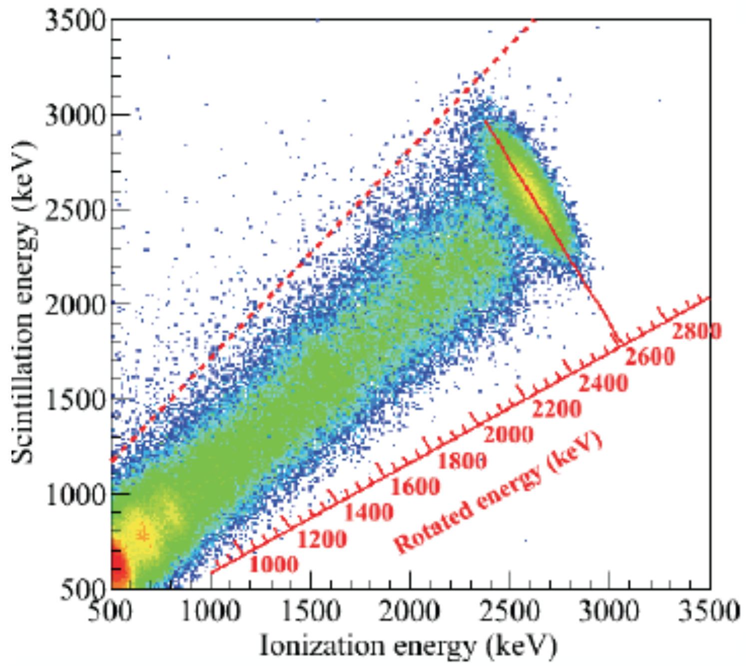
others tracking/TPCs:
NEXT, SuperNEMO, nEXO

- Enriched Liquid Xe in TPC
  - 200 kg of 80.6 % enriched ^{136}Xe, 75.6 kg fiducial mass,
  - 100 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ $Q_{\beta\beta}$)
  - Single site - Multisite discrimination

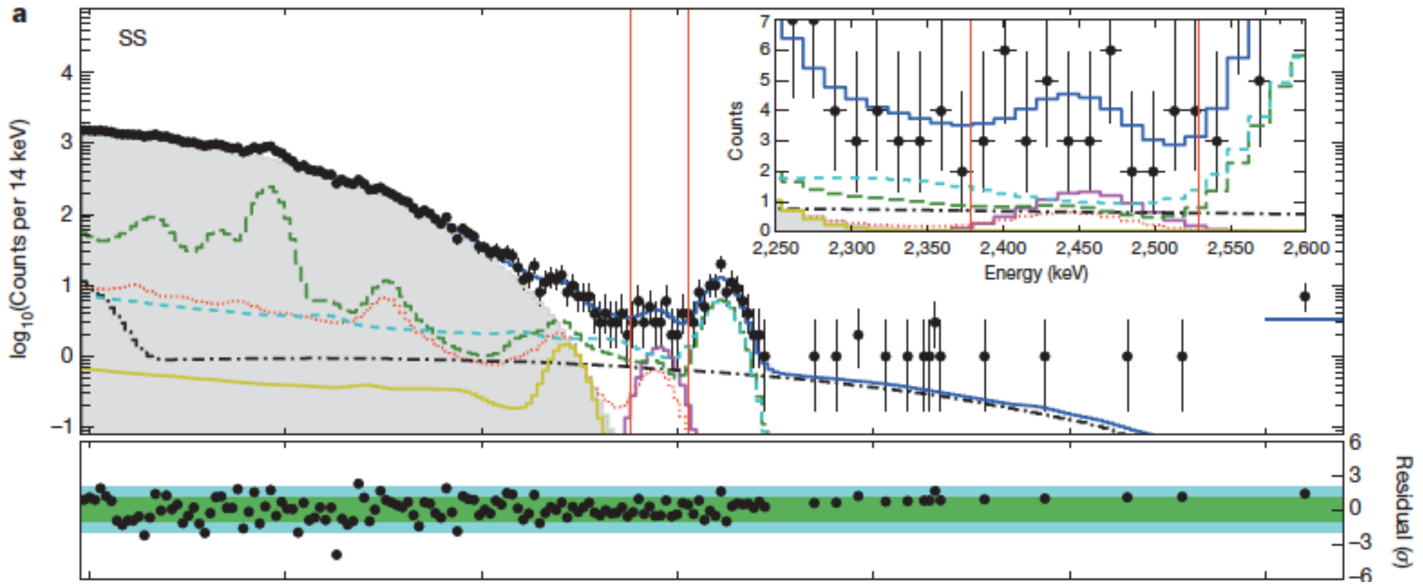
$T_{1/2} > 1.1 \times 10^{25}$ y (90% CL) ^{136}Xe

EXO-200 TPC





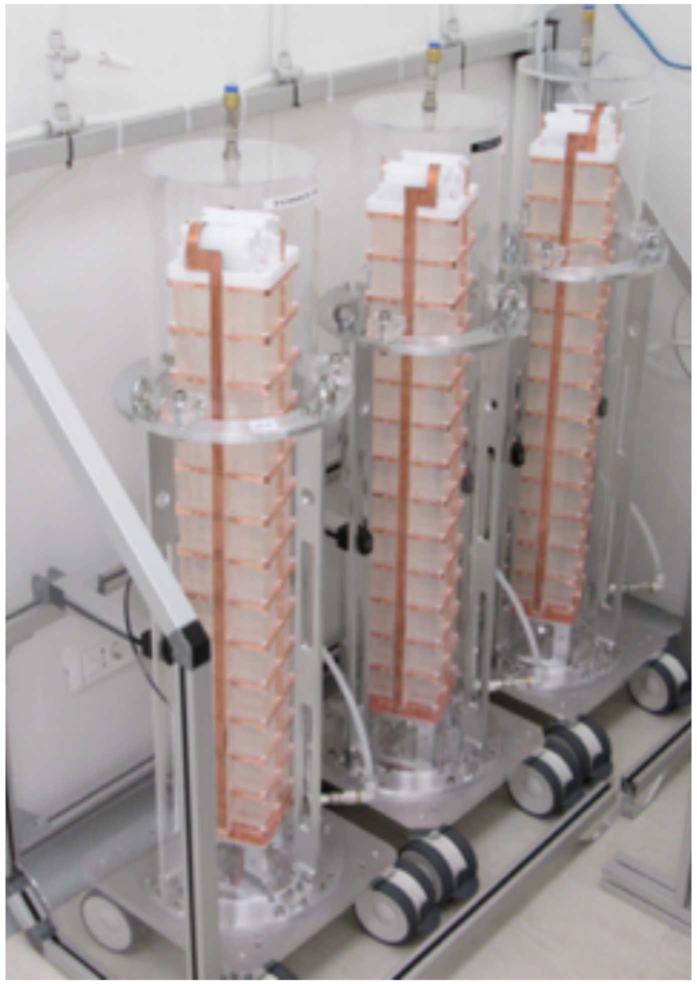
Ionization/
Scintillation

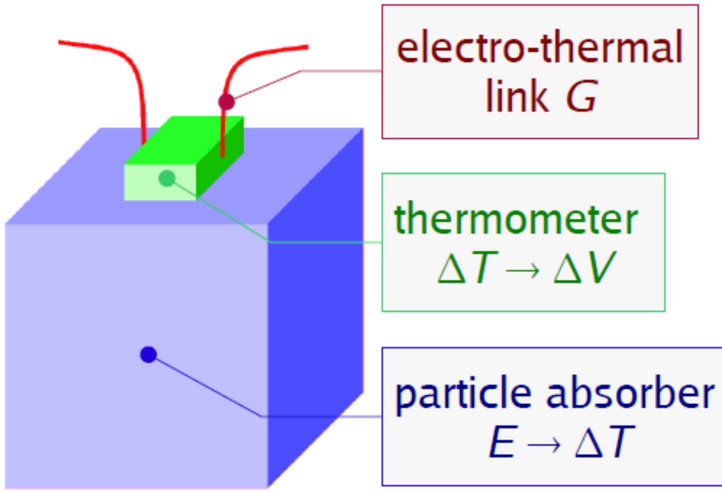


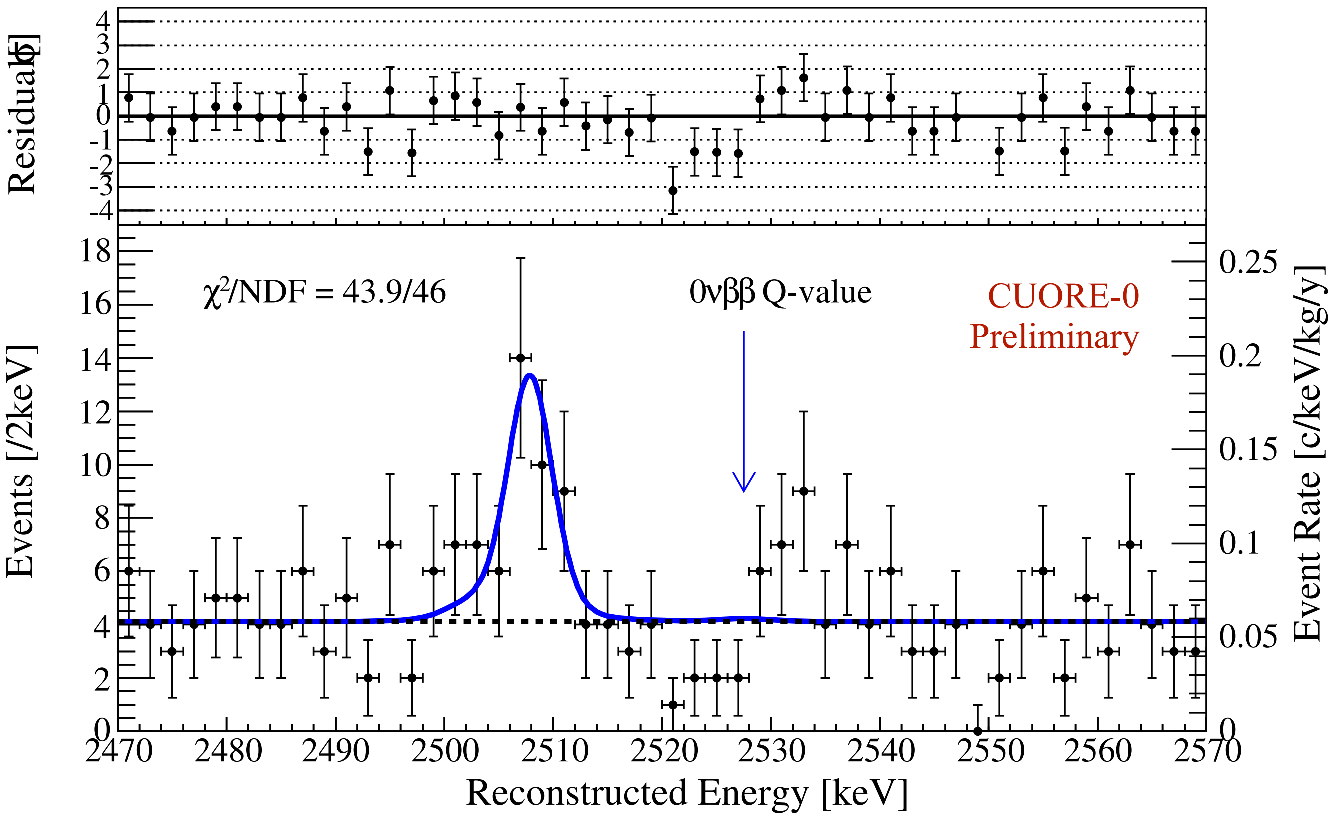
Background & Signal

Phonons: CUORE

- Towers of 11 kg of ^{130}Te (34% nat.) bolometers
- Array of 52 5x5x5 cm^3 TeO_2 crystals held at 10 mK
- FWHM of 5.1 keV

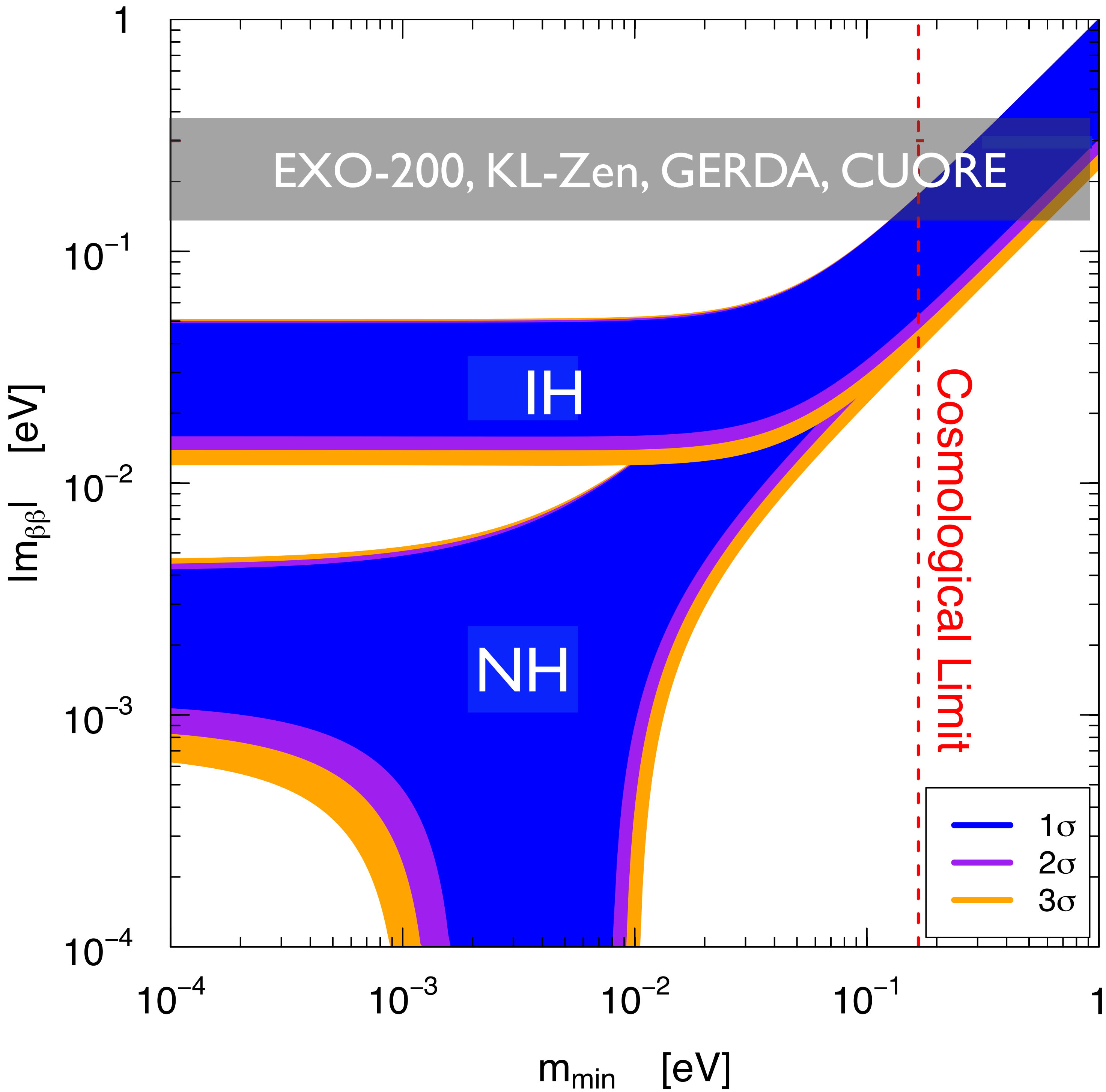






$T_{1/2} > 4.0 \times 10^{24}$ y (90% CL) ^{130}Te

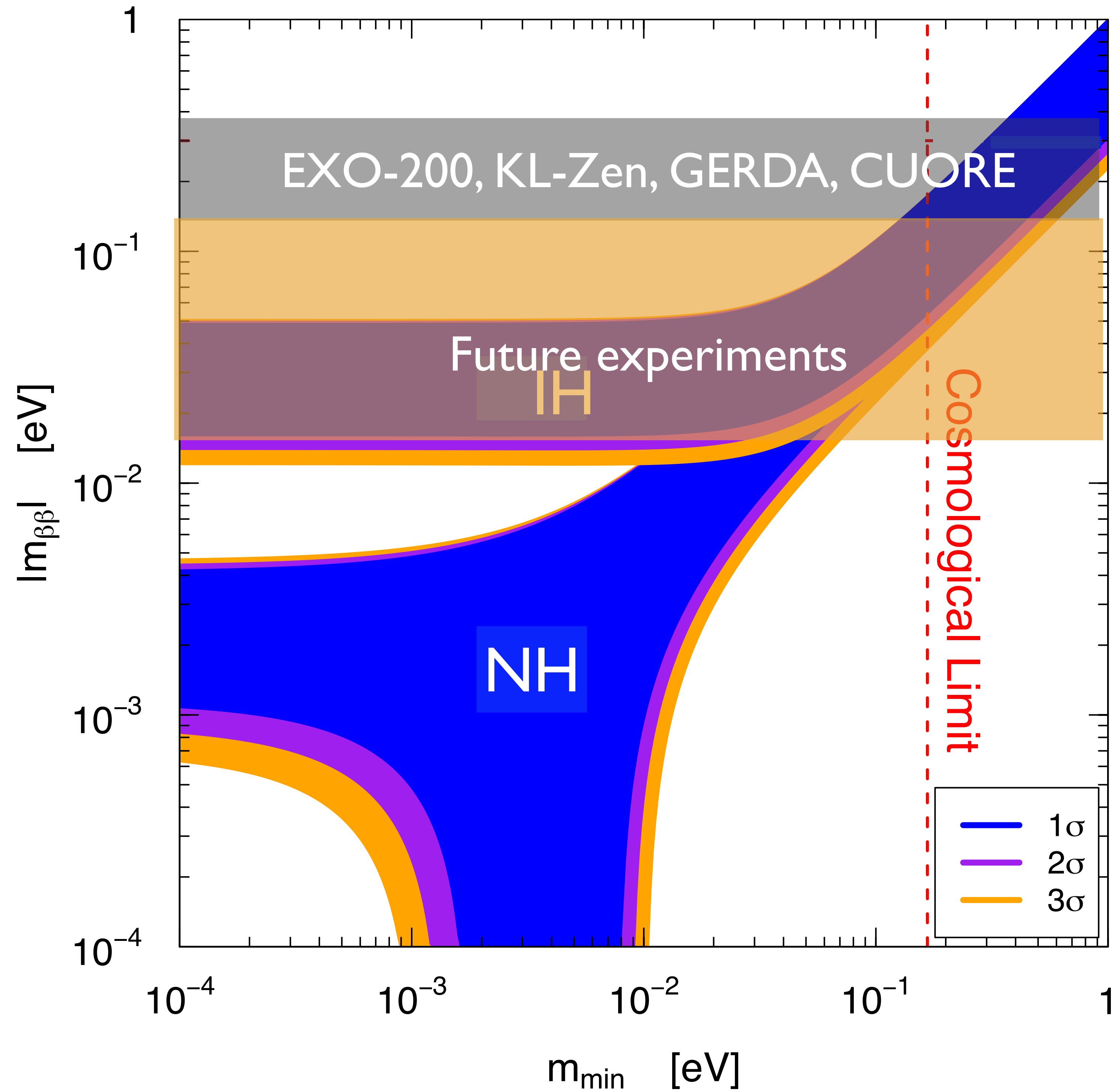
S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A 27, 1230015 (2012)



Current limits essential rule out long-standing claim for observation of the neutrinoless decay mode in ^{76}Ge.

Next generation will push into the inverted Sacle

S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A 27, 1230015 (2012)



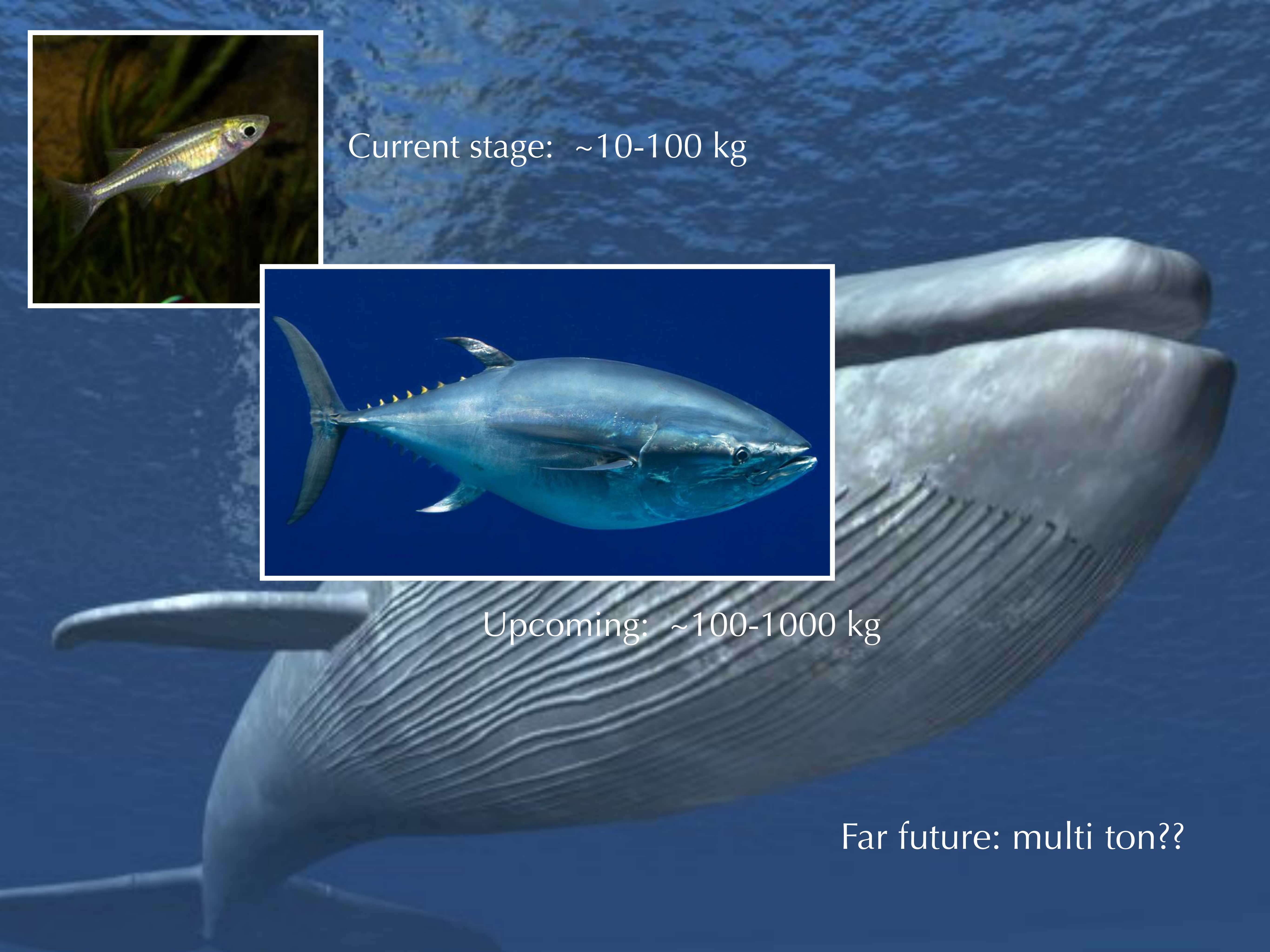
Current limits essential rule out long-standing claim for observation of the neutrinoless decay mode in ^{76}Ge.

Next generation will push into the inverted Sacle

Current stage: ~10-100 kg

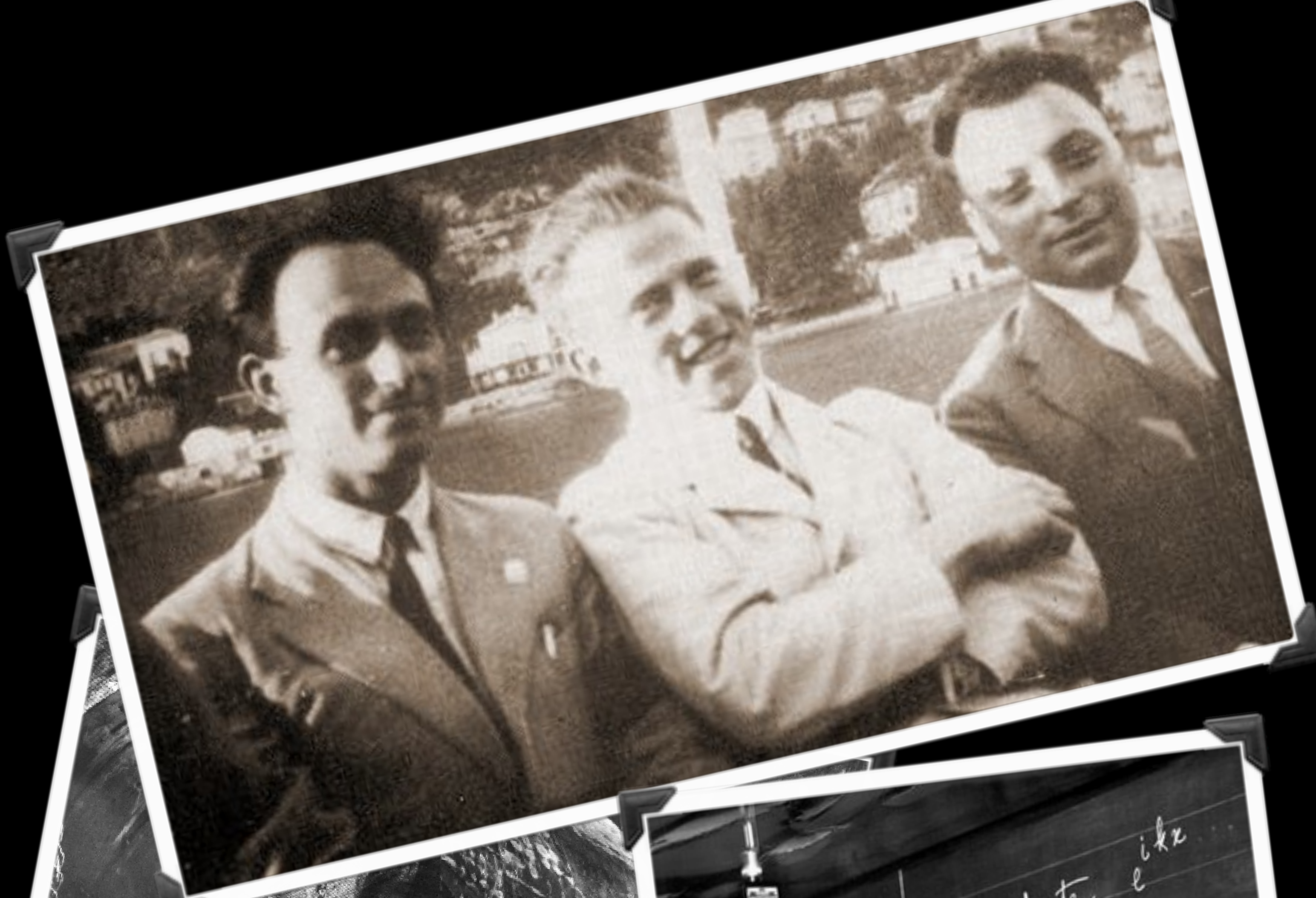
Current stage: ~10-100 kg

Upcoming: ~100-1000 kg


Current stage: ~10-100 kg
Upcoming: ~100-1000 kg
Far future: multi ton??

Special thanks to J. Wilkerson and many others for their help.

Apologies for not covering all experiments.

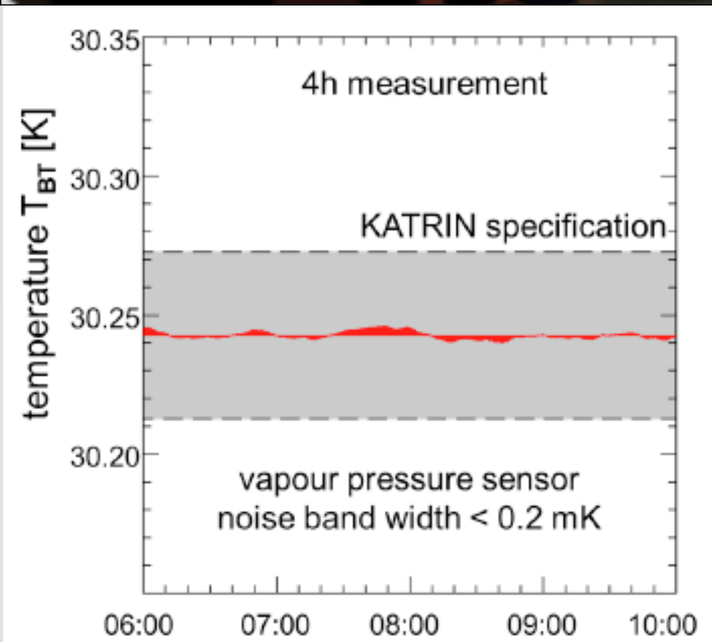


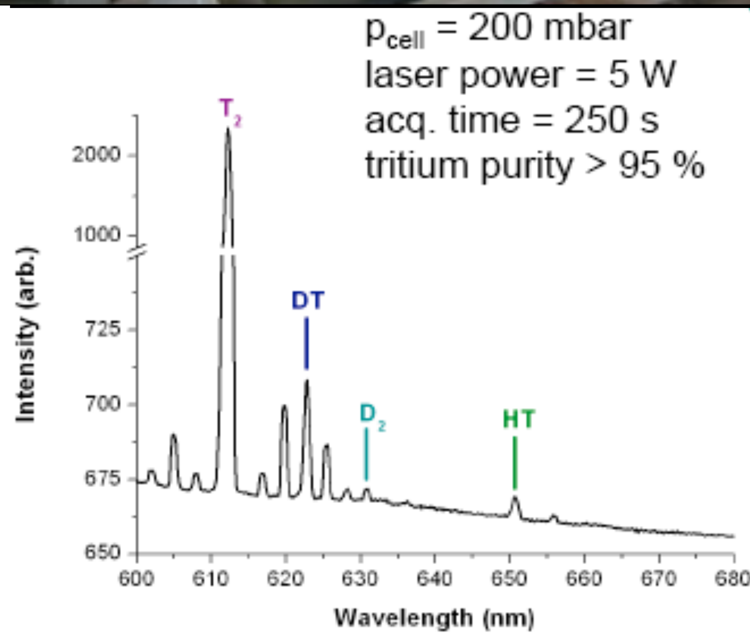
And thank you for your attention

I’m sorry, we are out of time

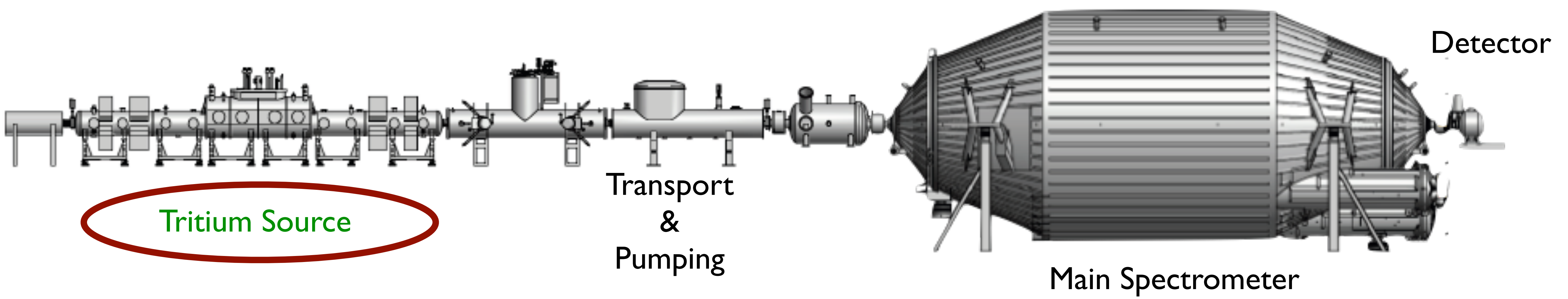
(Backup slides)

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 $\pm$3.6 mK recently achieved (x10 better than specification).



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

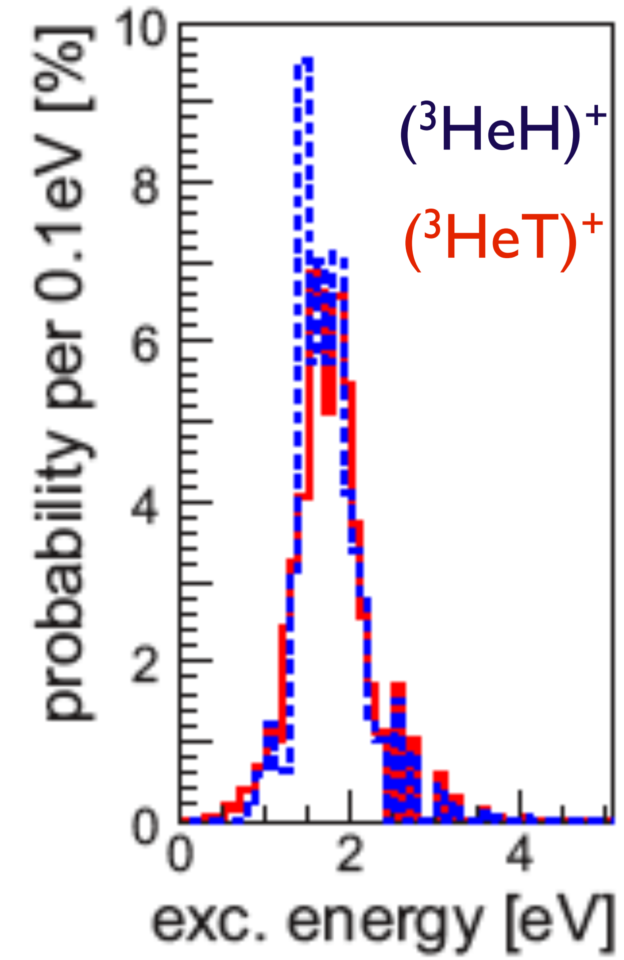
Moving Beyond the Degeneracy Scale

- 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)

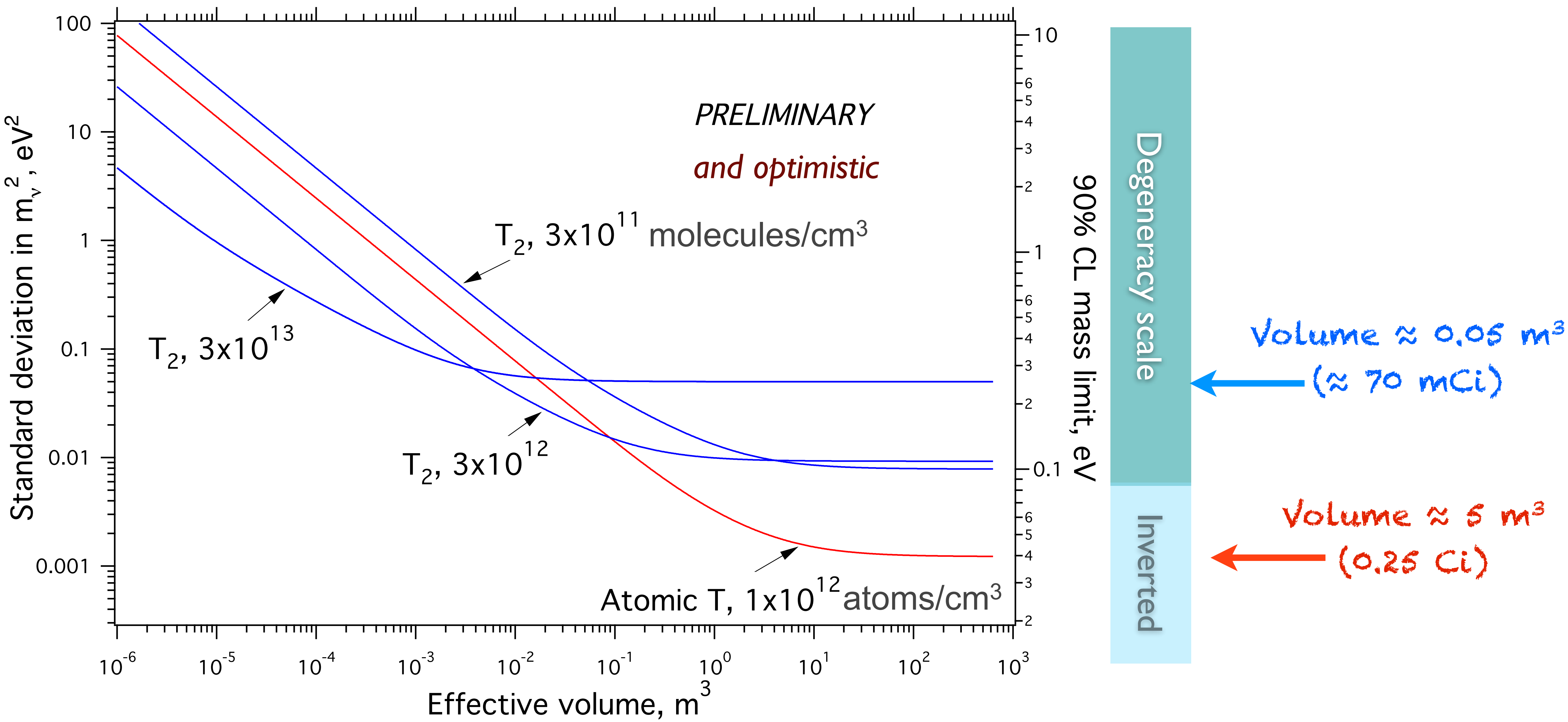
rotational

vibrational

Inherent 0.36 eV final state smearing

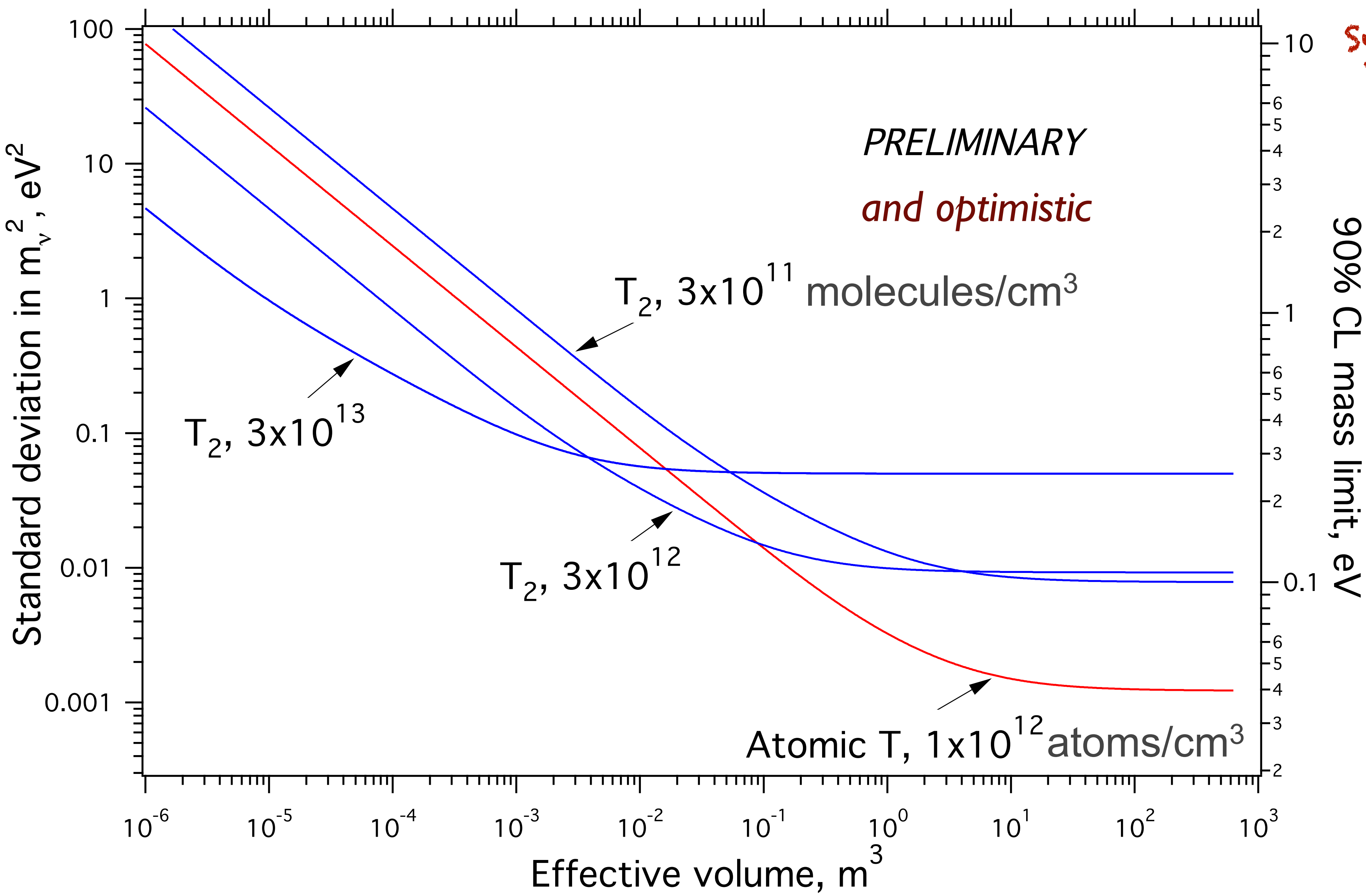


Projected Sensitivity (Molecular & Atomic)



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

Projected Sensitivity (Molecular & Atomic)



Systematics include:

Statistical uncertainties (1 year run)

Final state interactions

Thermal broadening

Scattering

Background

Field inhomogeneity

1% uncertainty in resolution distribution

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

Backgrounds in experiments

Experiment		Mass [kg] (total/FV*)	Bkg (cnts/ROI -t-y)†	Width (FWHM)	
CUORE0	^{130}Te	32/11	300	5.1 keV ROI	Measured
EXO-200	^{136}Xe	170/76	130	88 keV ROI	Measured
GERDA I	^{76}Ge	16/13	40	4 keV ROI	Measured
KamLAND-Zen (Phase 2)	^{136}Xe	383/88	210 per t(Xe)	400 keV ROI	Measured
CUORE	^{130}Te	600/206	50	5 keV ROI	Projected
GERDA II	^{76}Ge	35/27	4	4 keV ROI	Projected
MAJORANA DEMONSTRATOR	^{76}Ge	30/24	4	4 keV ROI	Projected
NEXT 100	^{136}Xe	100/80	9	17 keV ROI	Projected
SNO+	^{130}Te	2340/160	45 per t(Te)	240 keV ROI	Projected

* FV = $0\nu\beta\beta$ isotope mass in fiducial volume (includes enrichment factor)

† Region of Interest (ROI) can be single or multidimensional (E, spatial, …)