Weighting Neutrinos

SLAC Summer Institute

August 14th 2015

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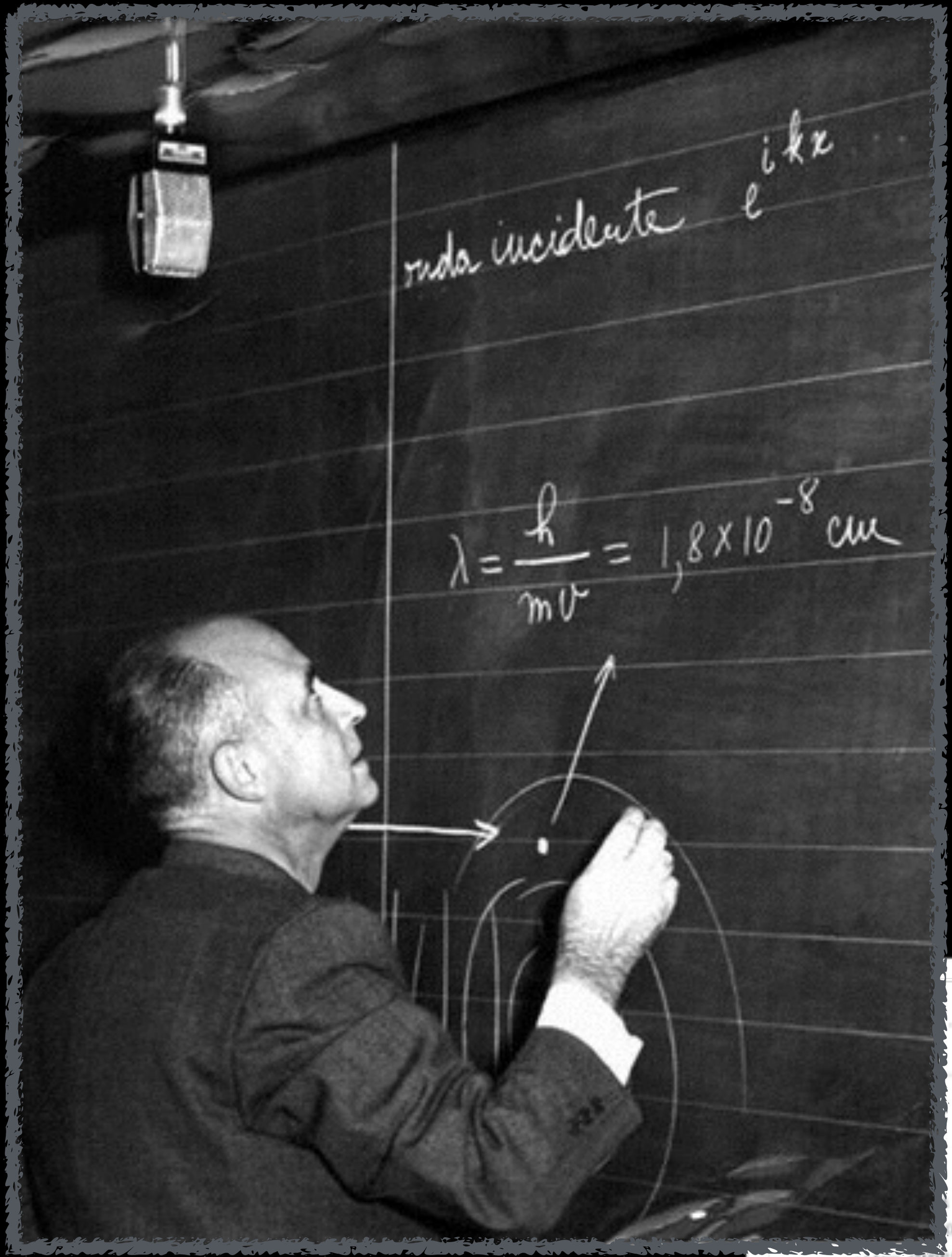
MIT



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
o 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_σ^2/v_σ. 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

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

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

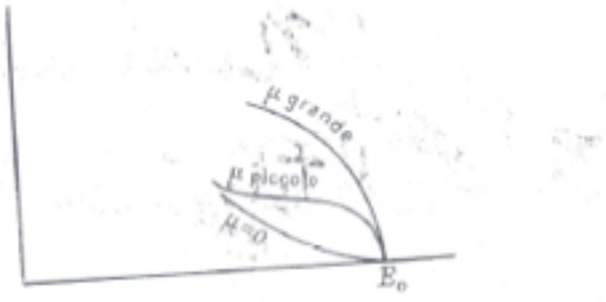
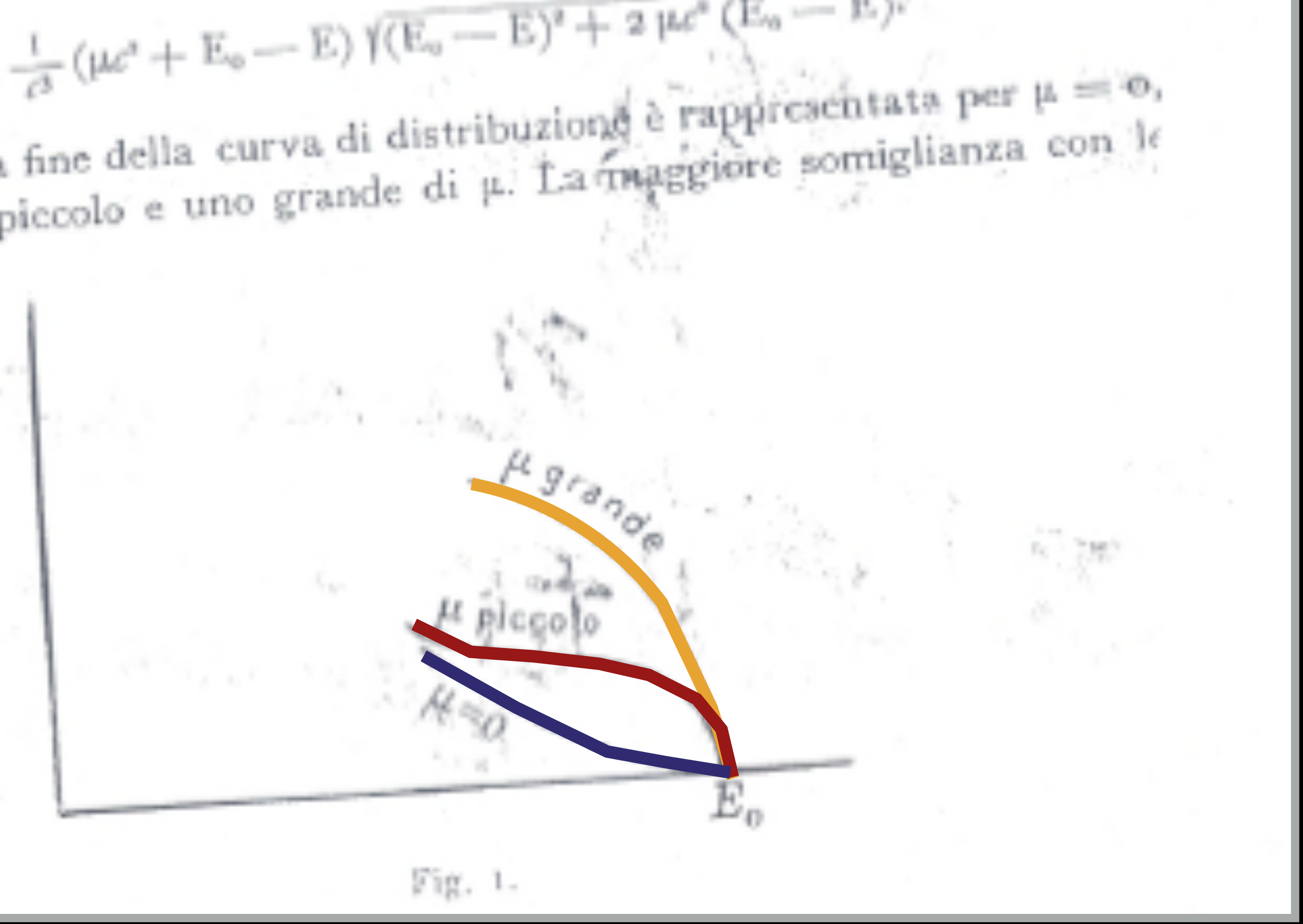


Fig. 1.



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

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

Fig. 1.

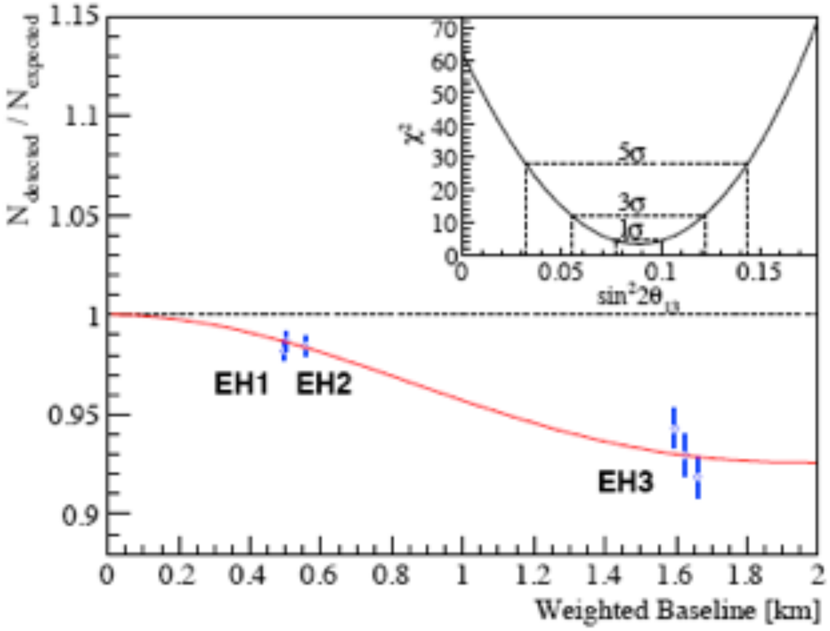
We have learned one thing
in this time.

"Grande" is ruled out.

And so is "Zero".

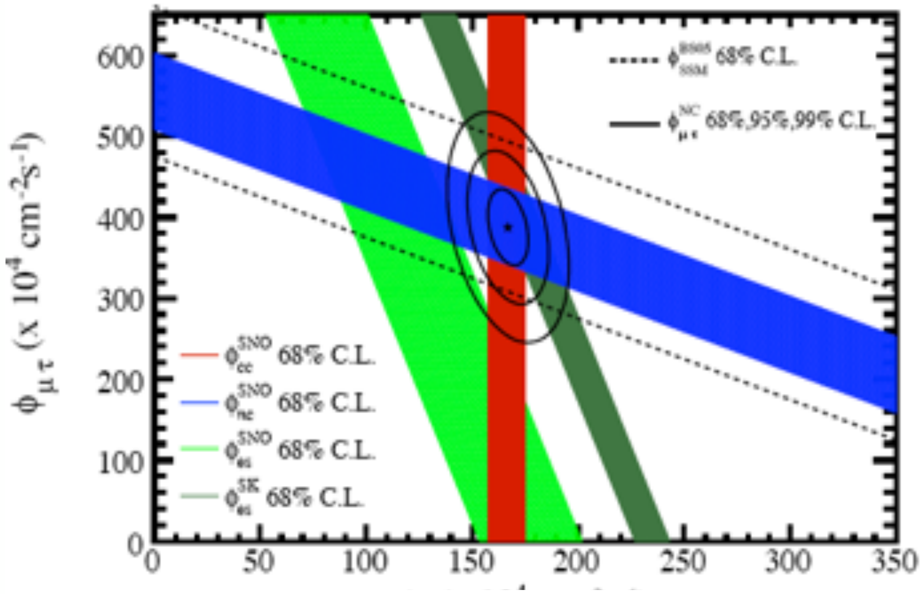
With oscillations firmly in place, we at least understand that the neutrino has a mass

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



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

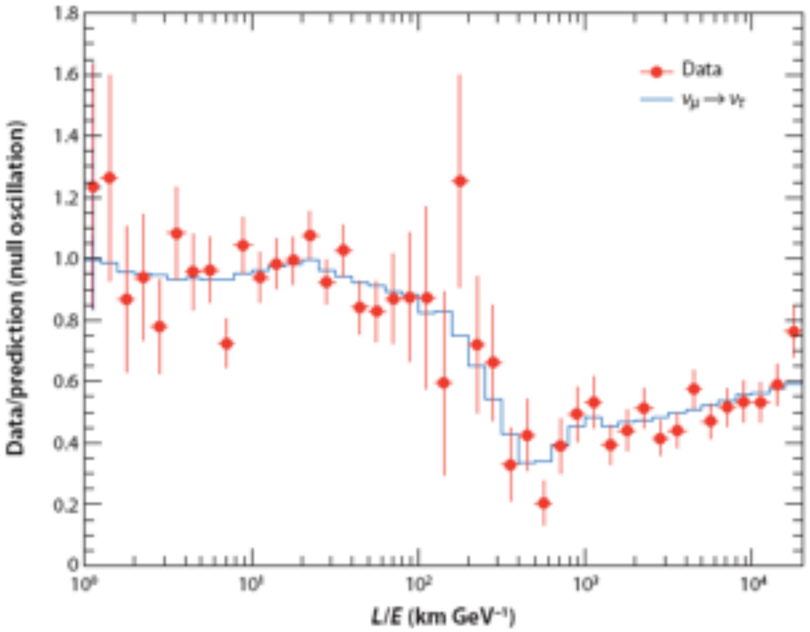
Reactor & Long Baseline



$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$

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

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

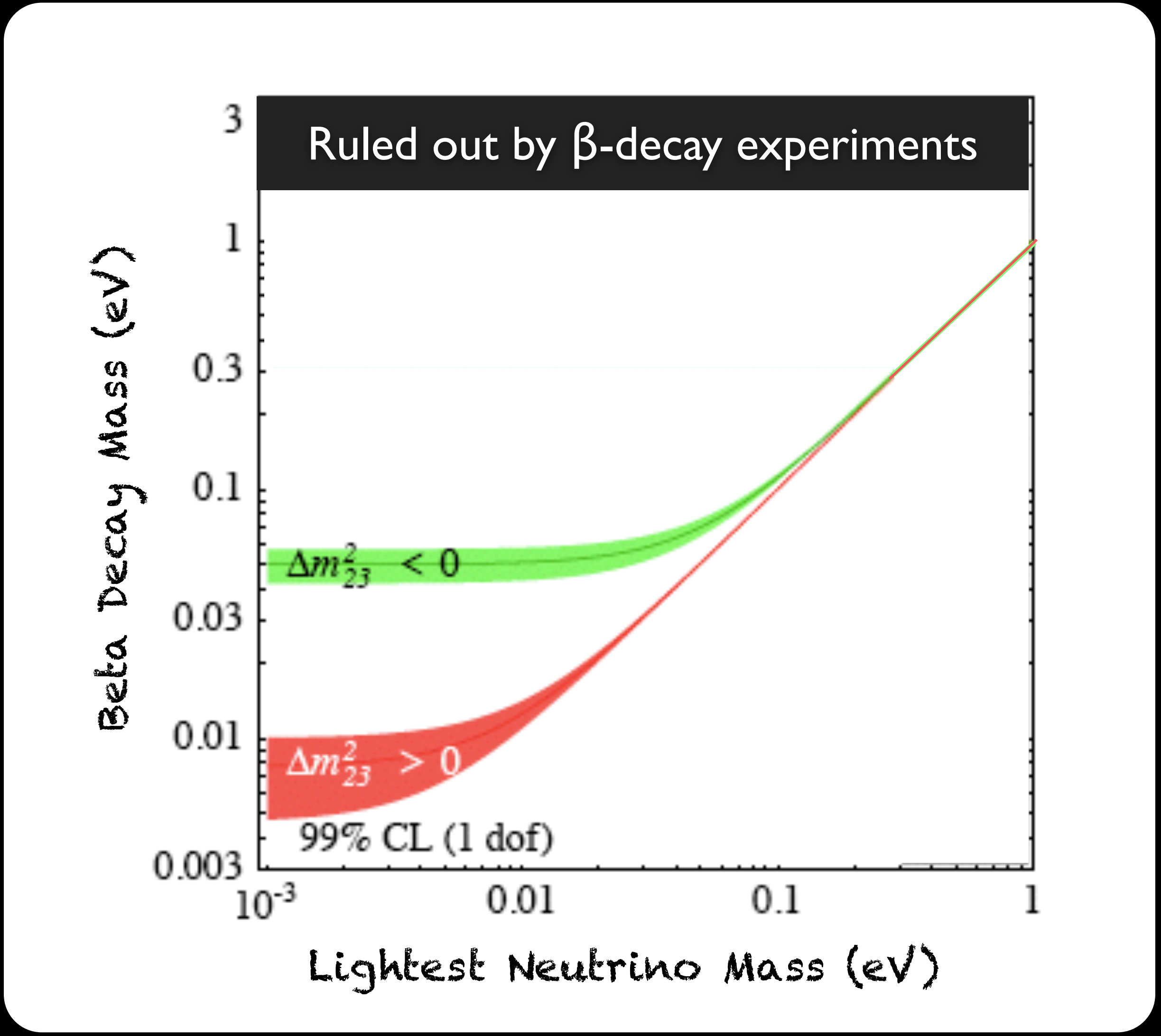
Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).
Fogli et al, arXiv:1205.5254 (hep-ph)

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

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

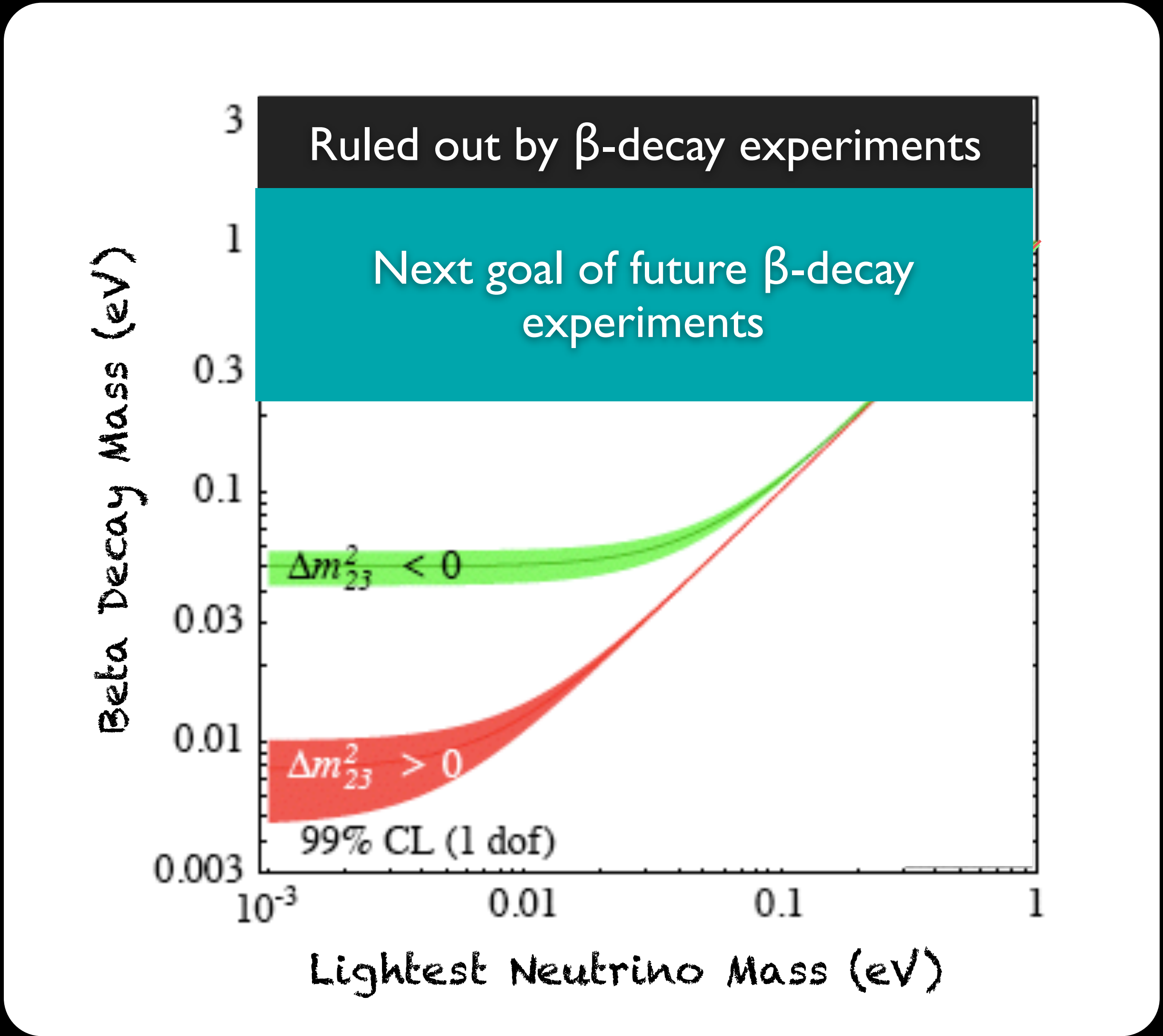
0νββ Measurements

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

Beta Decay Measurements

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.



$m_\nu > 2$ eV (eV scale, current)

Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)

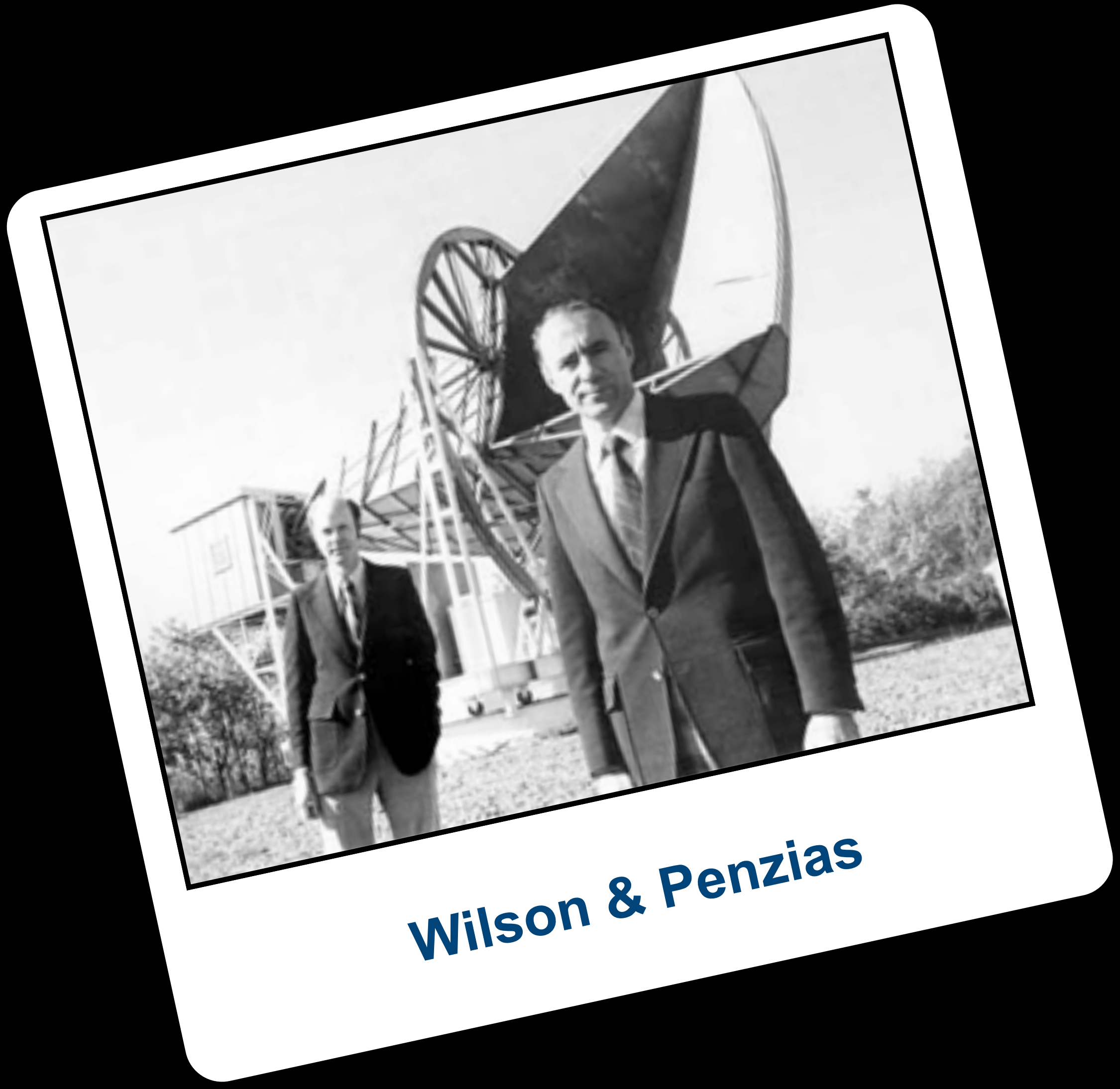
Impact on cosmology and $0\nu\beta\beta$ reach

$m_\nu > 0.05$ eV (inverted hierarchy)

Resolve hierarchy if null result

$m_\nu > 0.01$ eV (normal hierarchy)

Oscillation limit; possible CνB detection

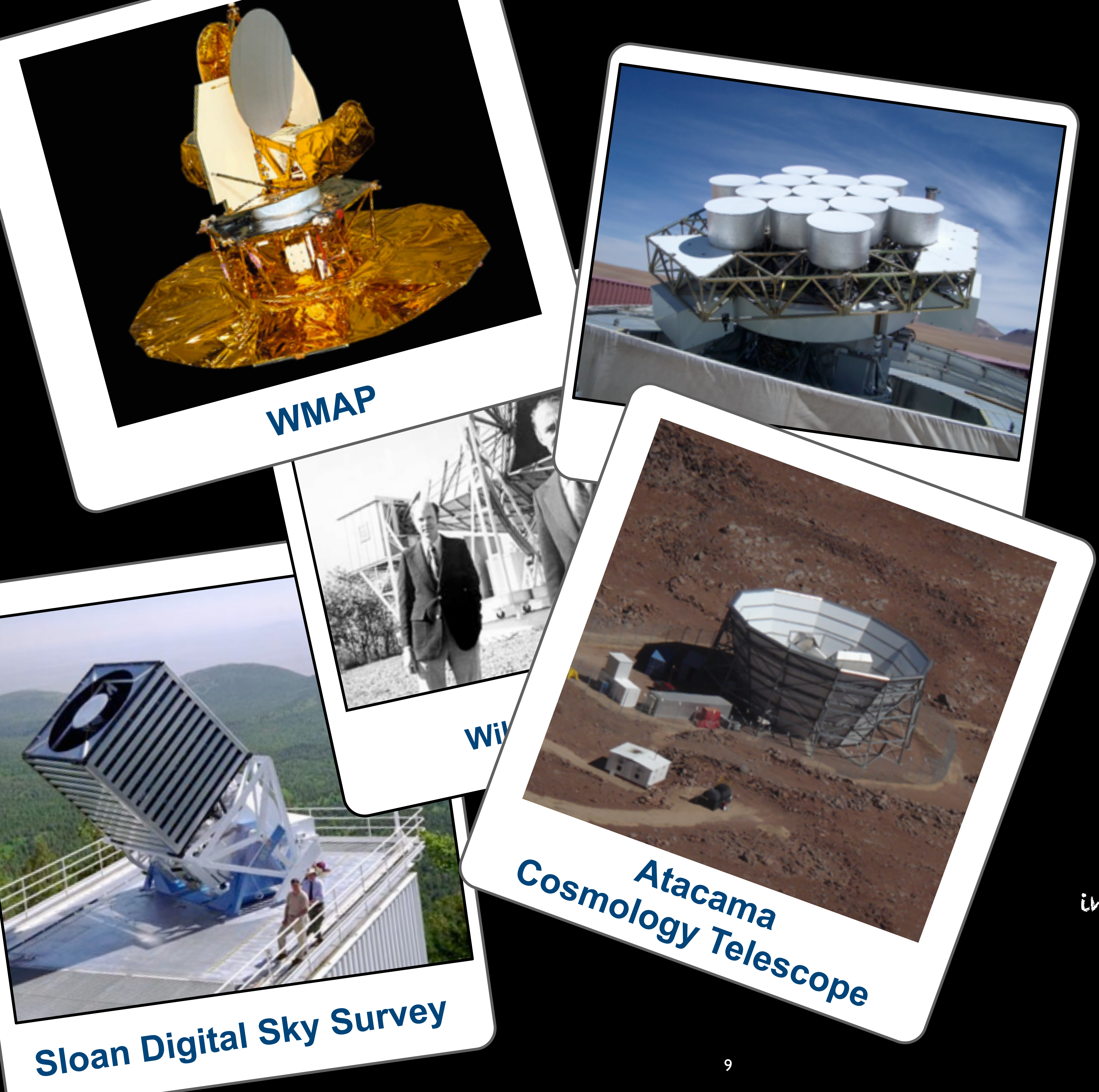


Wilson & Penzias

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

Cosmological Measurements

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

Microwave Background

400 kyr
$z = 1100$

Nucleosynthesis

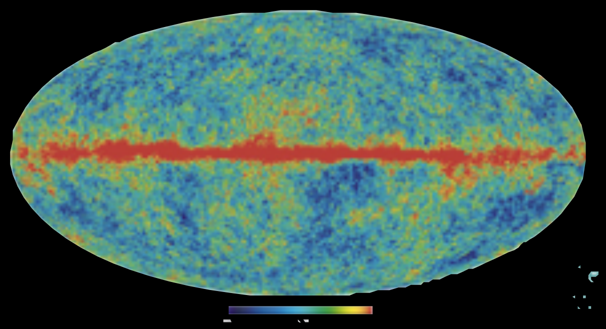
3-30 min
$z = 5 \times 10^8$

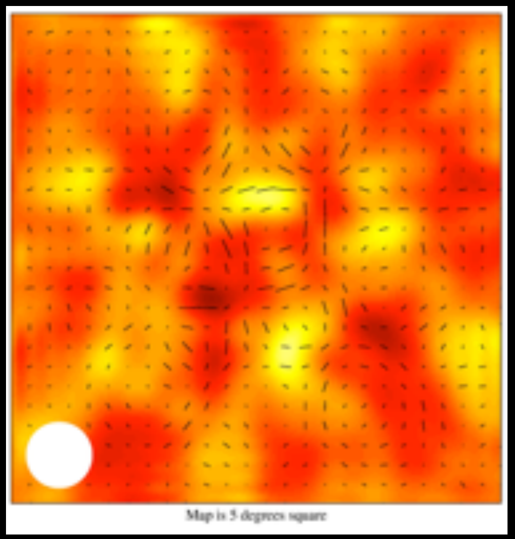
Relic Neutrinos

0.18 s
$z = 1 \times 10^{10}$

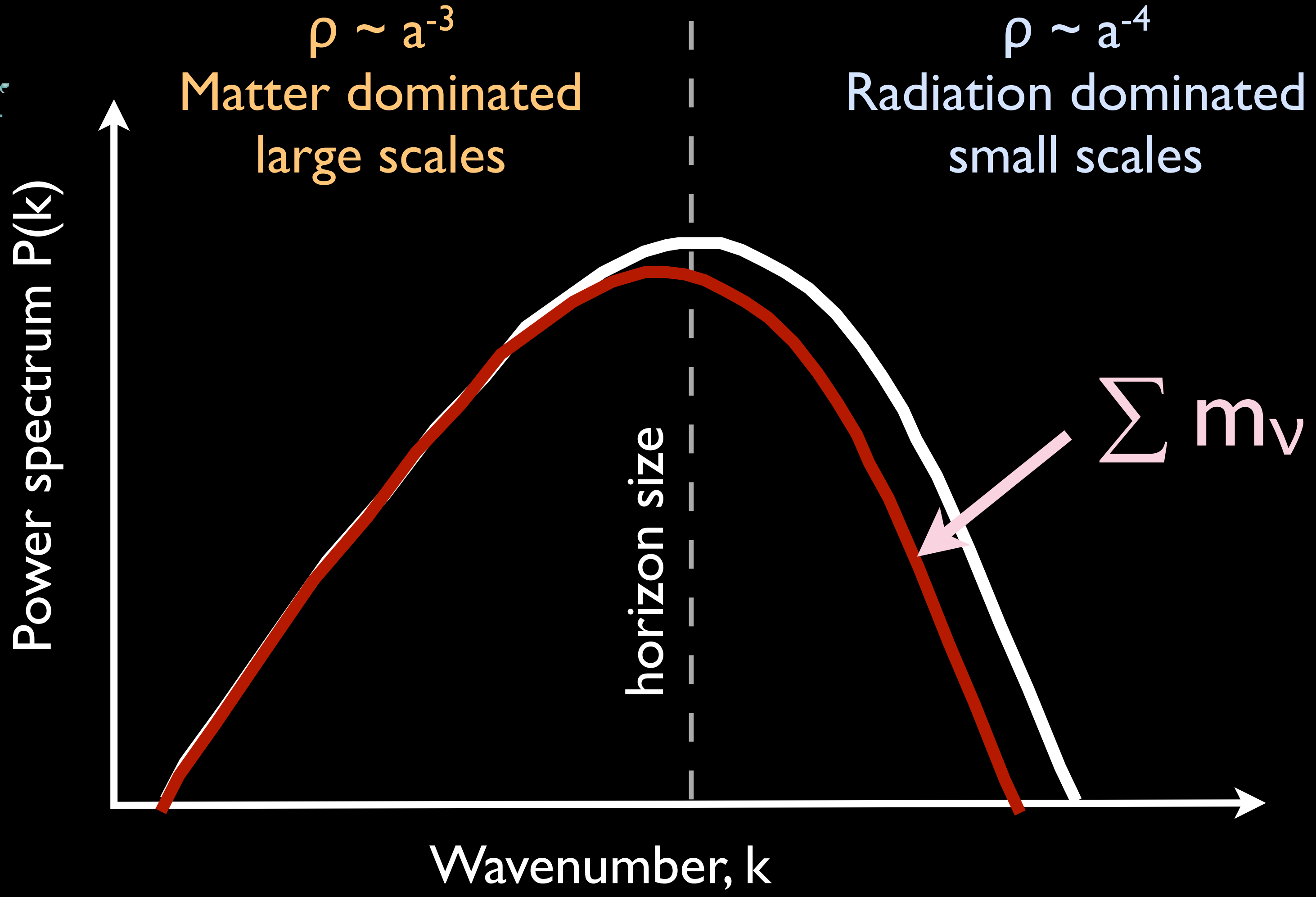
The Strategy
(a naive view)

WMAP Temperature Map





CMB Polarization



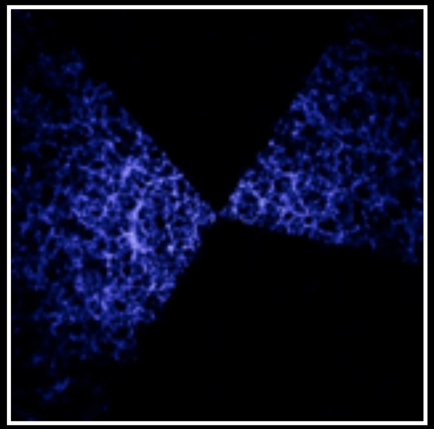
$$\delta(x) = (\rho(x) - \bar{\rho})/\bar{\rho}$$

Neutrinos come to affect the power spectrum,

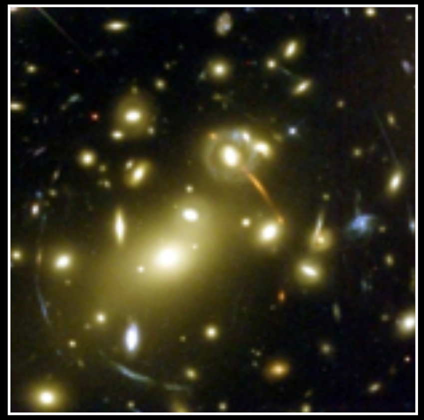
particularly at small distance scales

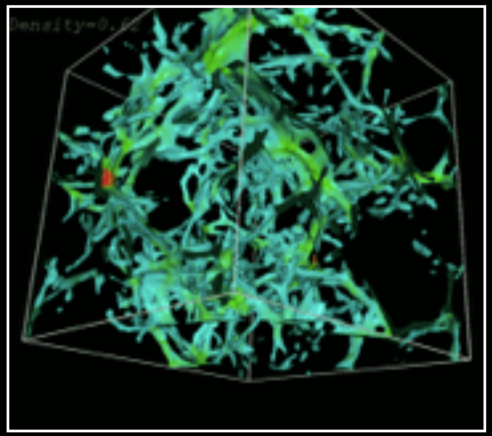
$$P(k) = \langle |\delta(k)|^2 \rangle$$

Galaxy Surveys



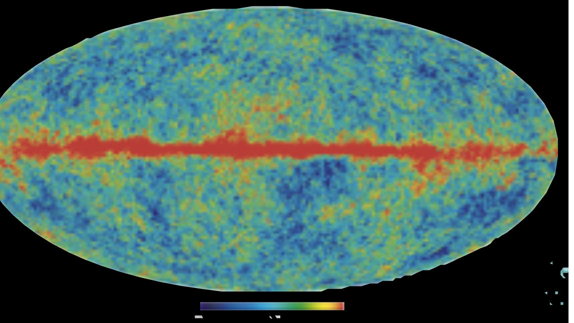
Weak lensing

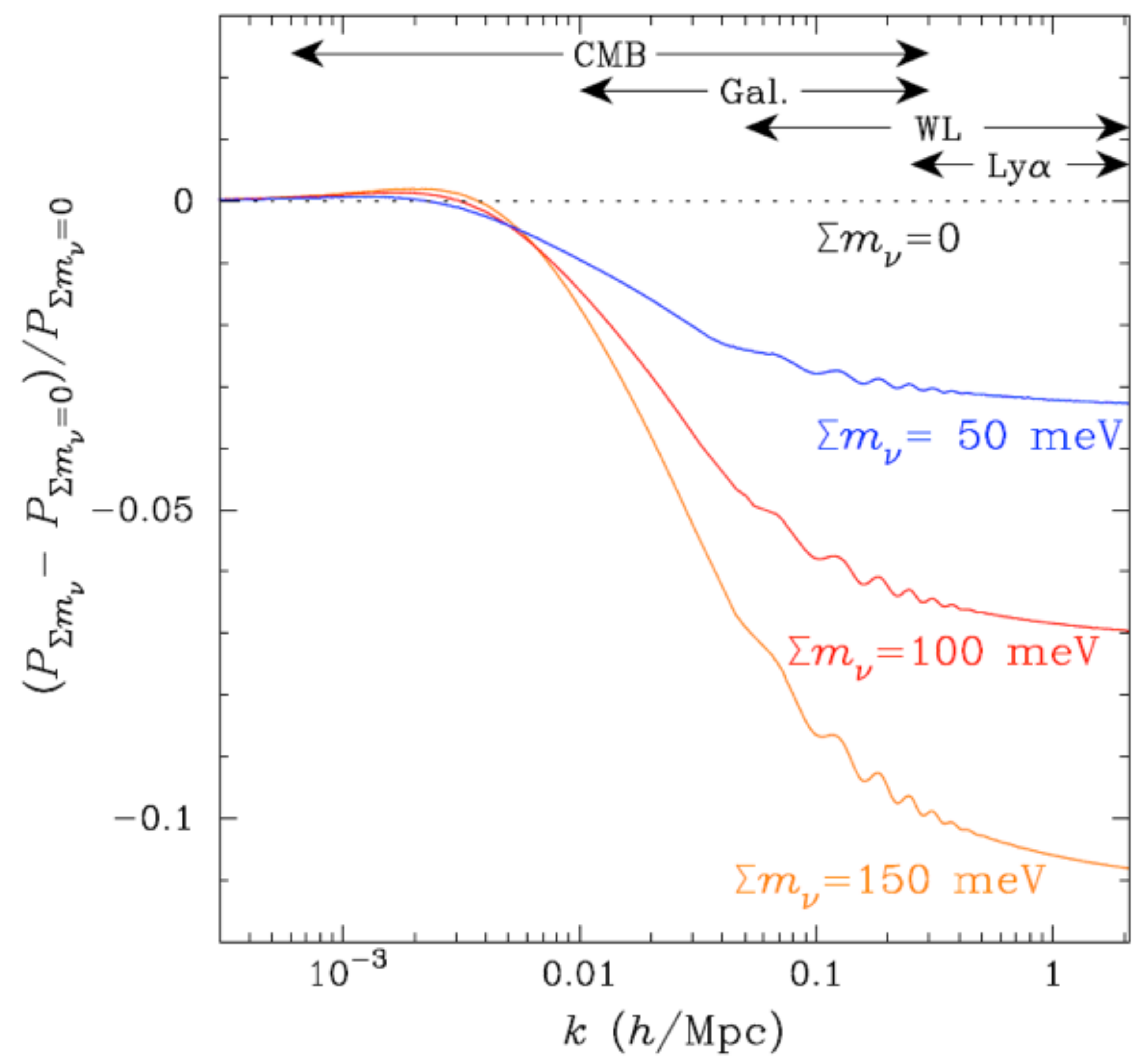




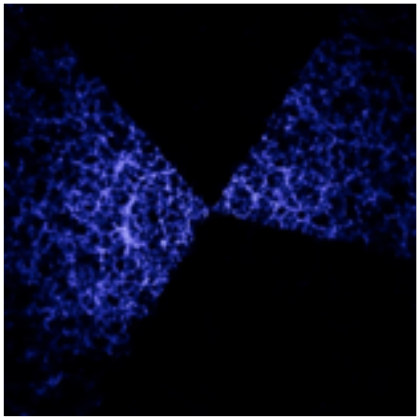
Lyman α

Temperature Map

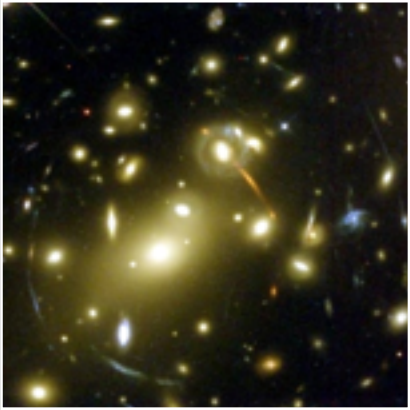


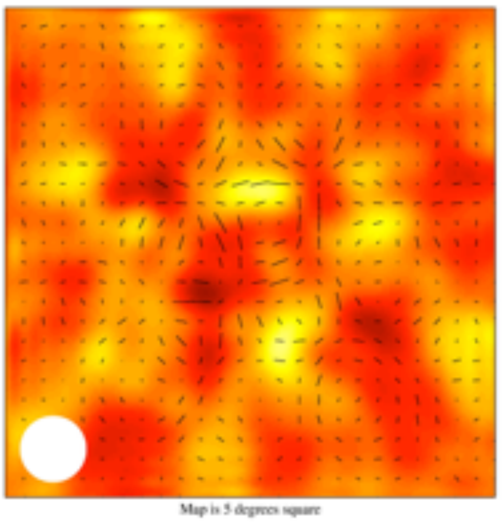


Galaxy Surveys

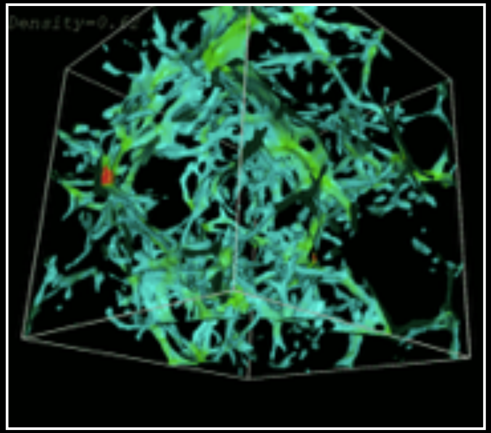


Weak lensing





CMB Polarization



Lyman α

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

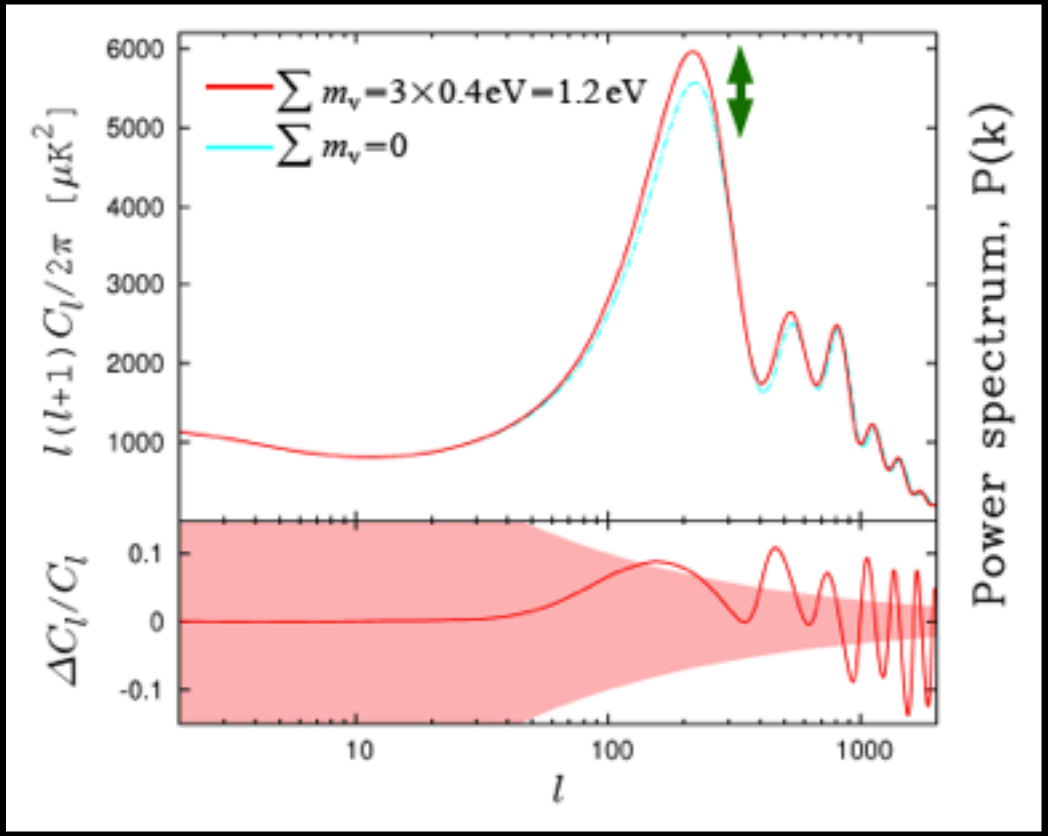
Neutrino Physics & Cosmology

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

  (1) Number of neutrino species

  (2) Sum of neutrino masses

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



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

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

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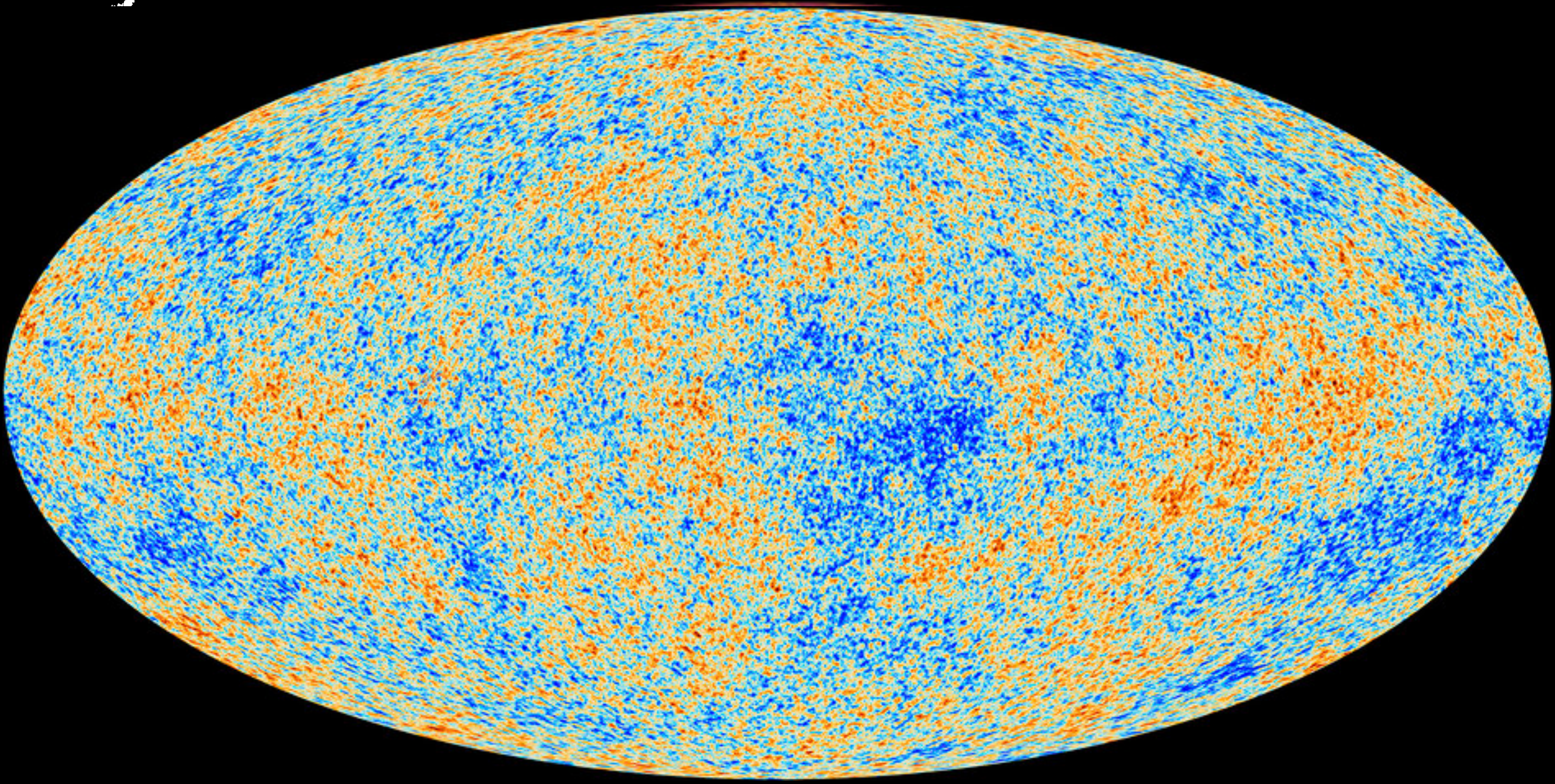
Planck Satellite:

Launched May 14th, 2009

The Microwave sky...

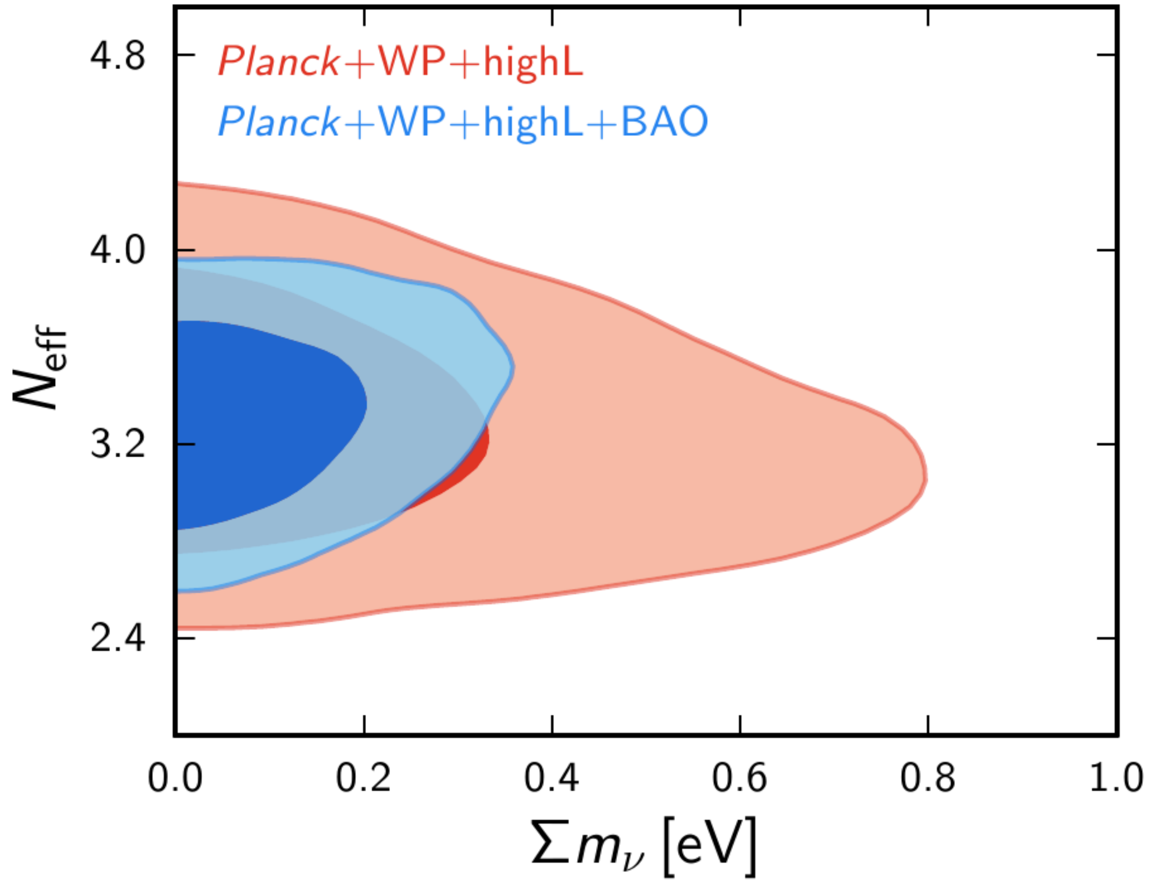


PLANCK Results

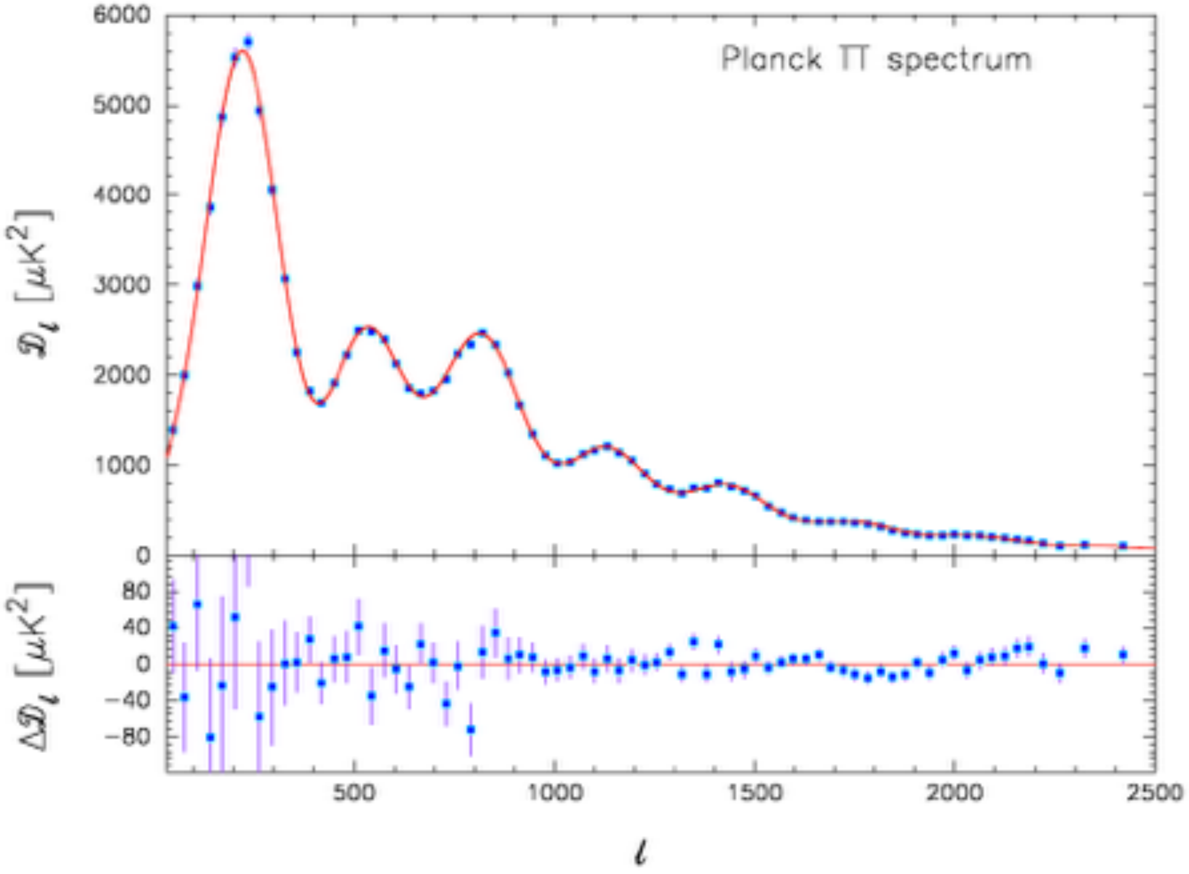
- The basic PLANCK analysis looks at 6 main cosmological parameters. Neutrino masses are added as extensions to that model.

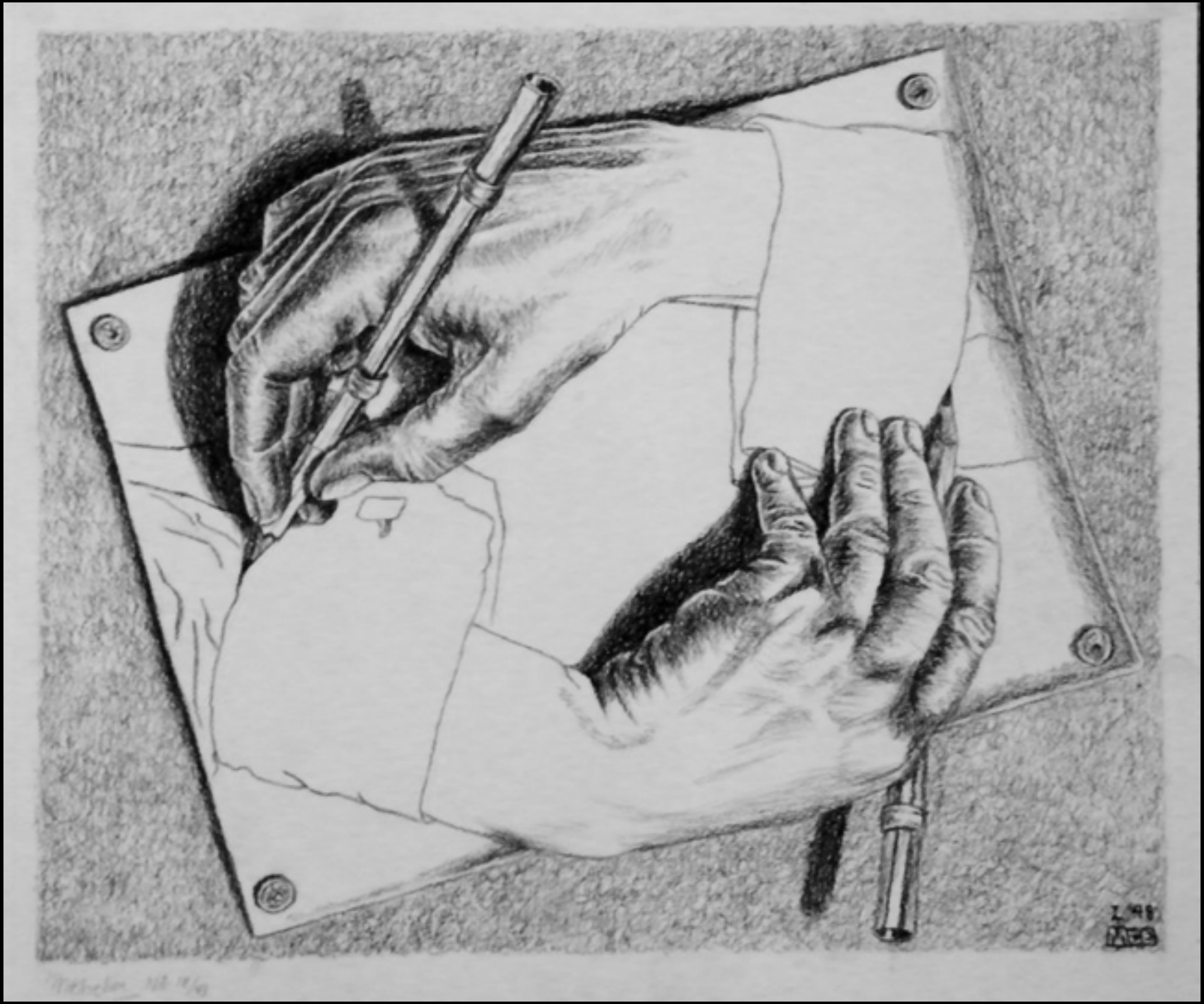
- Most conservative data combinations see no evidence for neutrino masses.

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



Source: Planck *Results XVI*

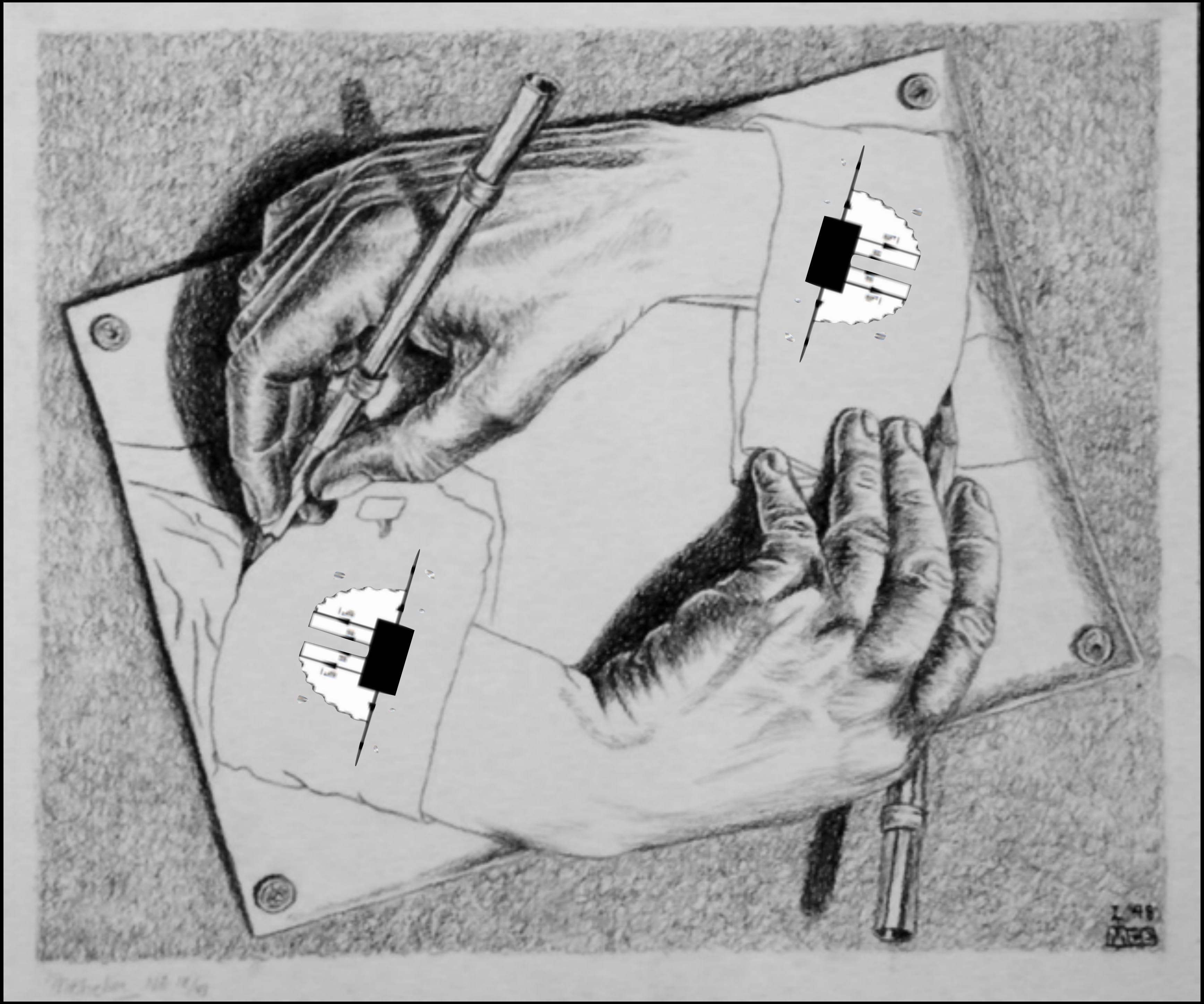




Neutrinoless Double Beta Decay

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

0νββ Measurements



What would a positive signal mean?

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

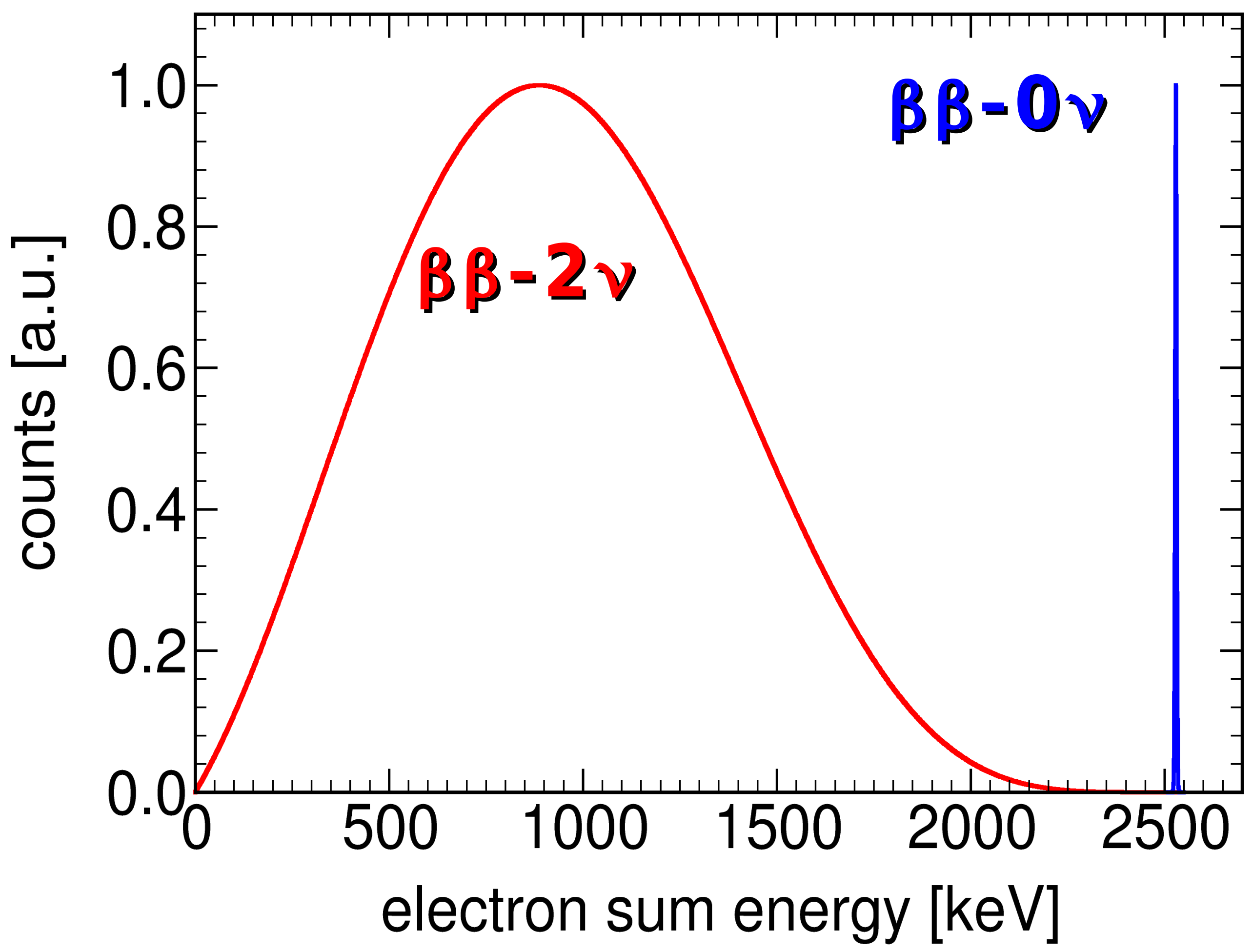
- Demonstrate that neutrinos are Majorana fermions.
- Shed light on the neutrino mechanism
- Probe into the causes for the matter anti-matter asymmetry in the universe

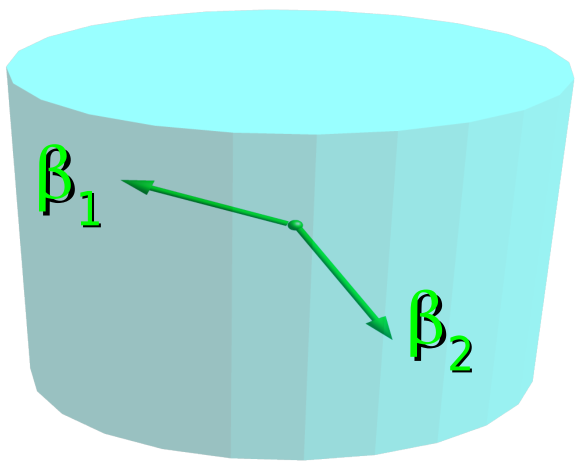
$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

$$\Delta L = 2$$

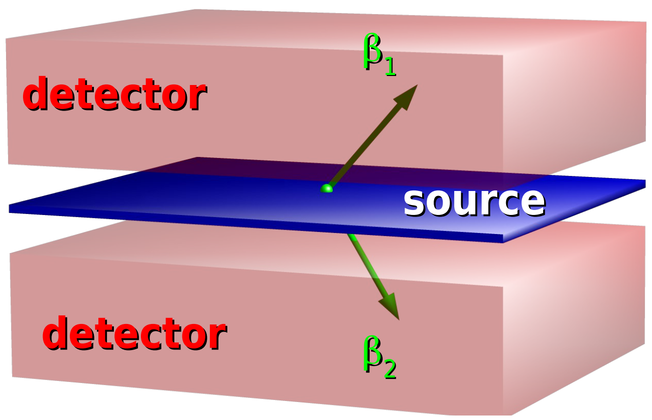
Simple in principle...

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





Source = detector

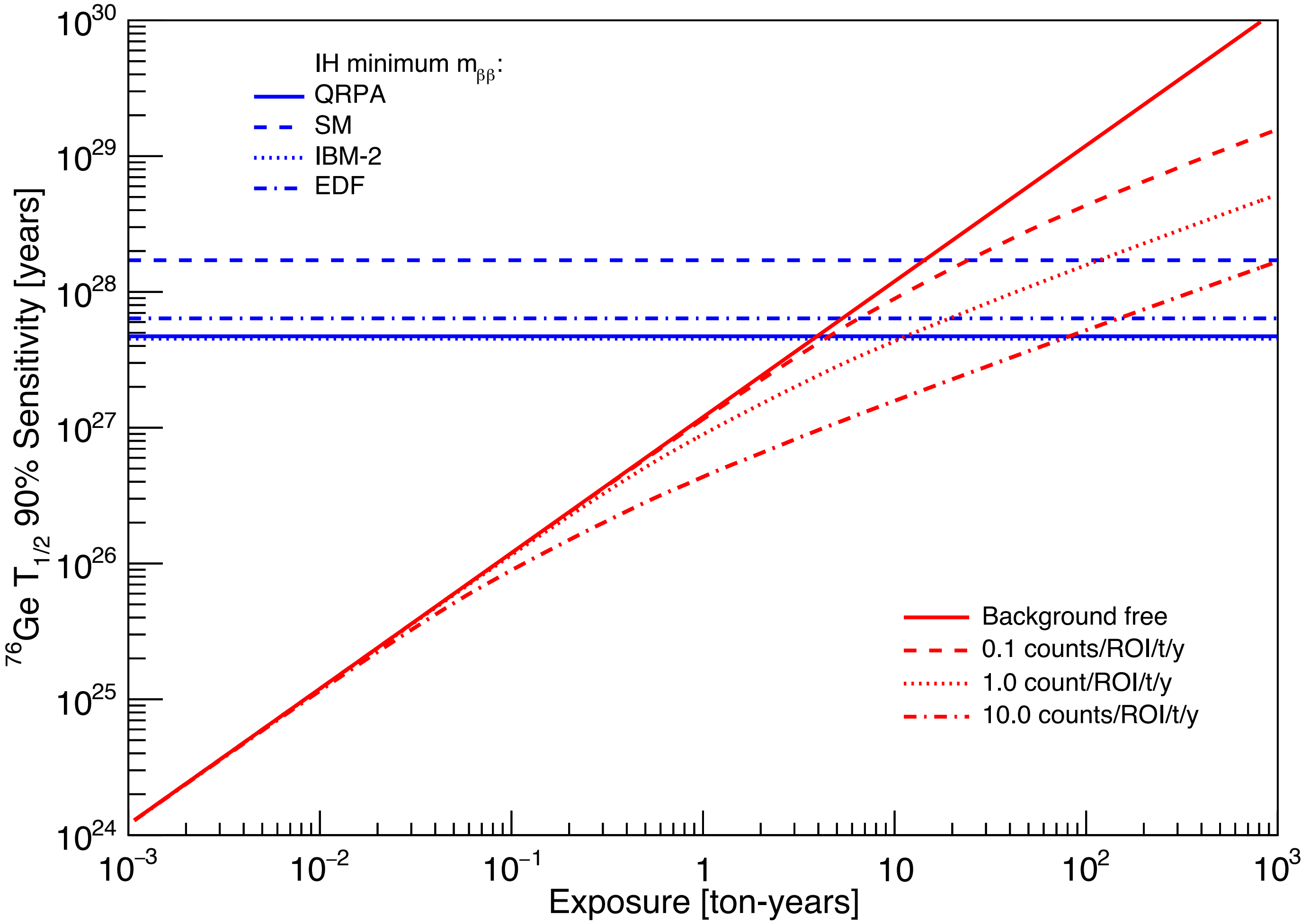


Source ≠ detector

...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



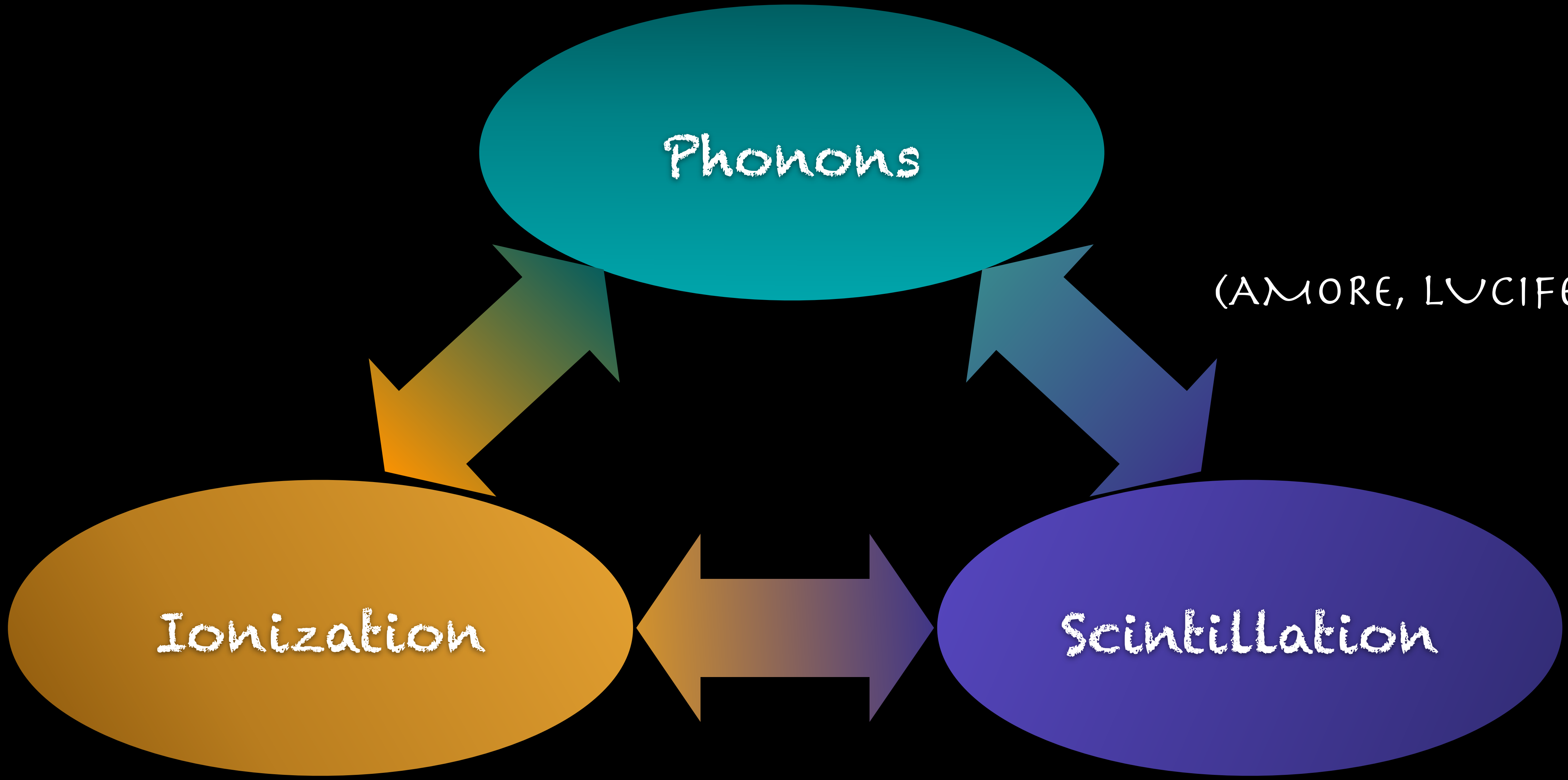
^{76}Ge example, but similar sensitivities for other $0\nu\beta\beta$ isotopes.

Background free

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

Background limited

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



CUORE

Phonons

(AMORE, LUCIFER)

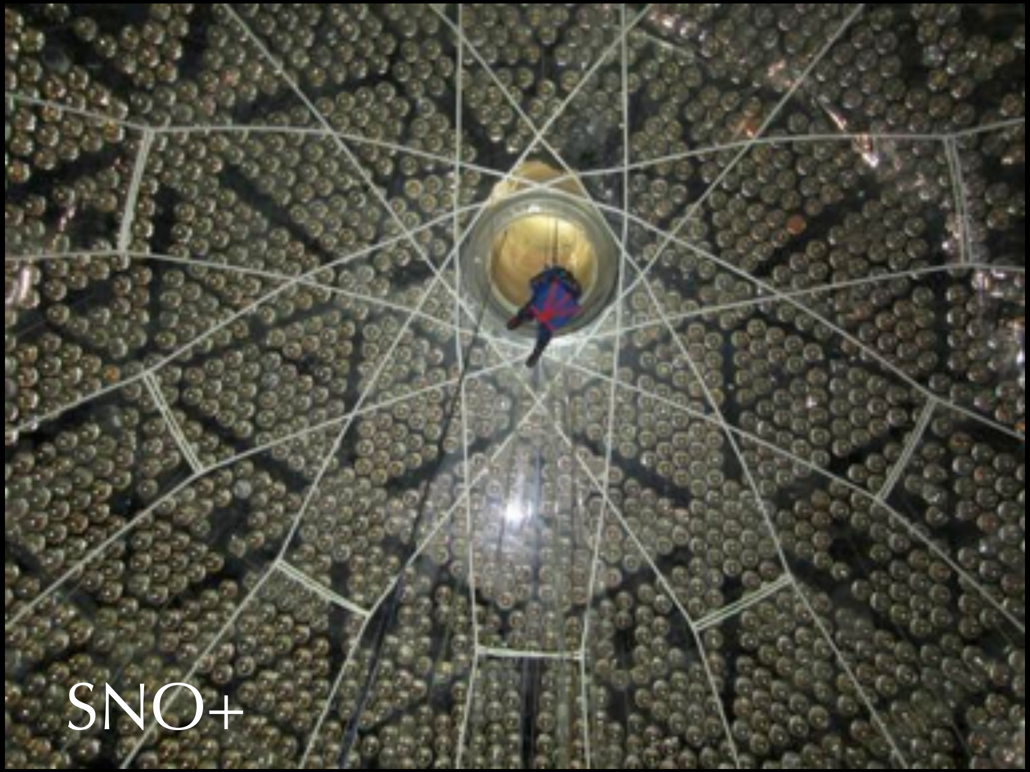
Ionization

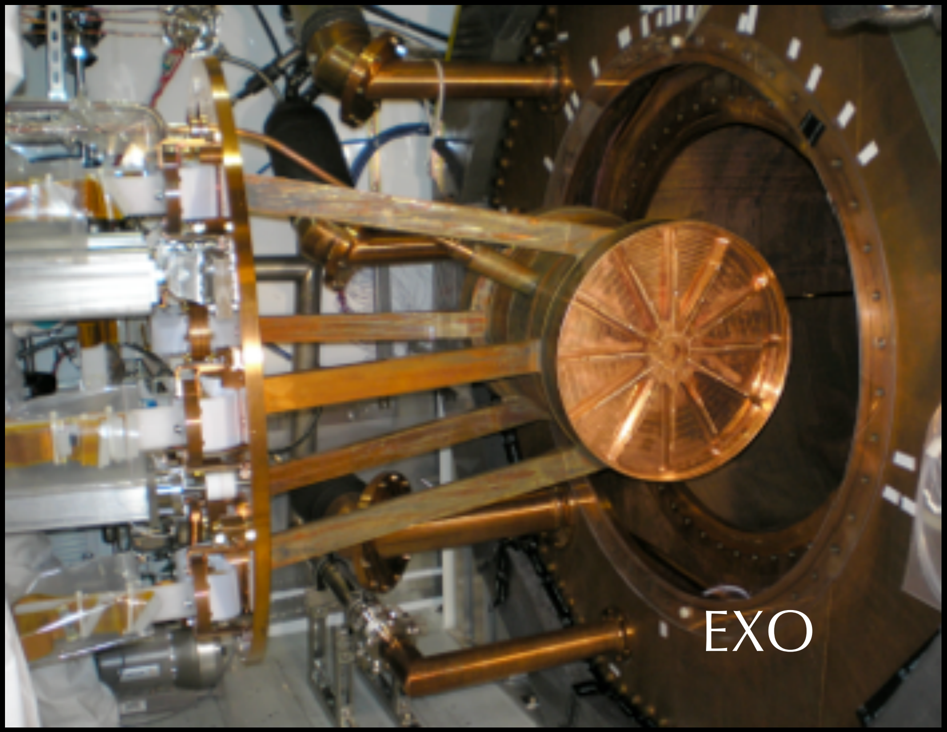
Scintillation

GERDA,
MAROJANA,
SUPERNEMO

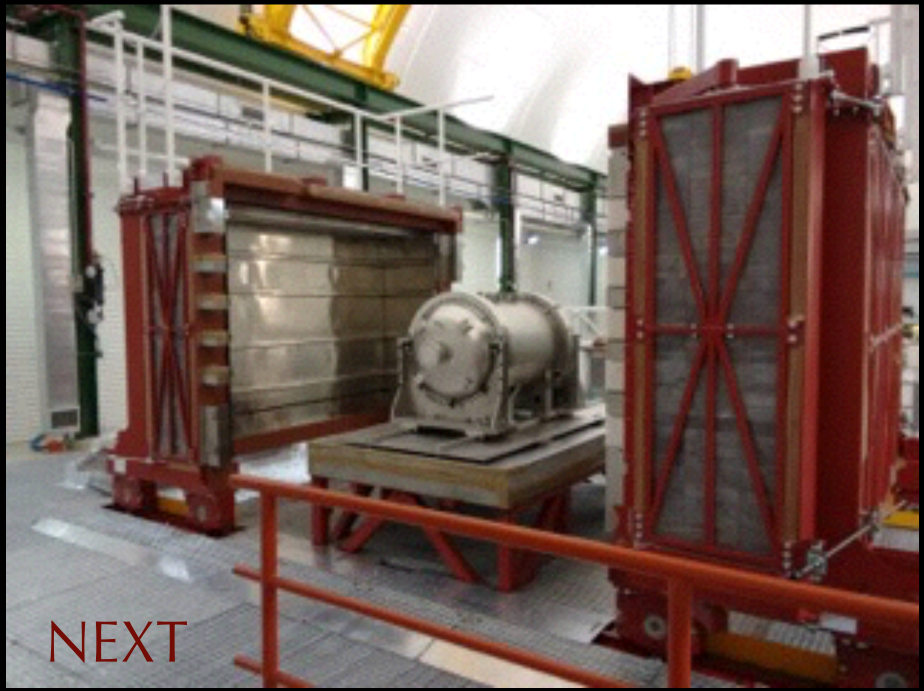
(EXO, NEXT)

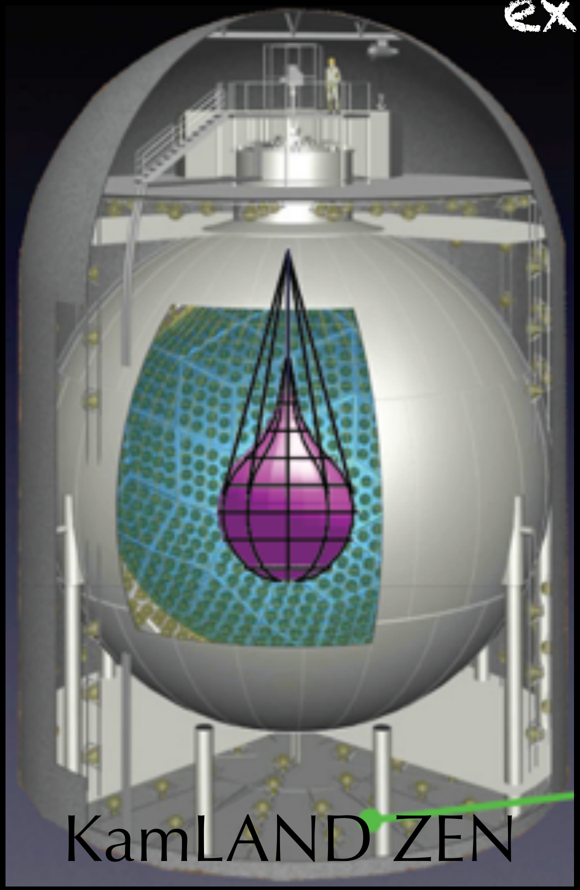
SNO+
KAMLAND ZEN
CANDLES

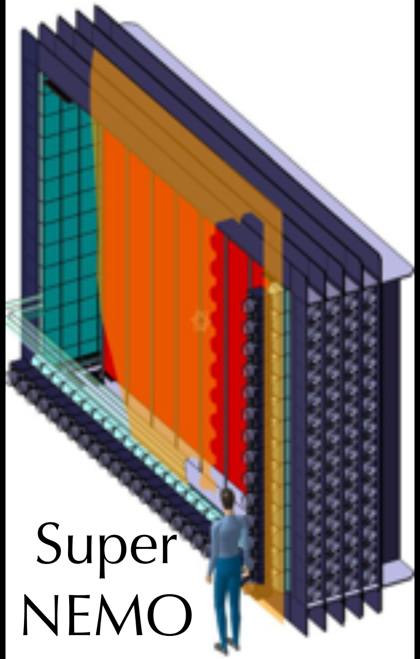




Many,
many
experiments...







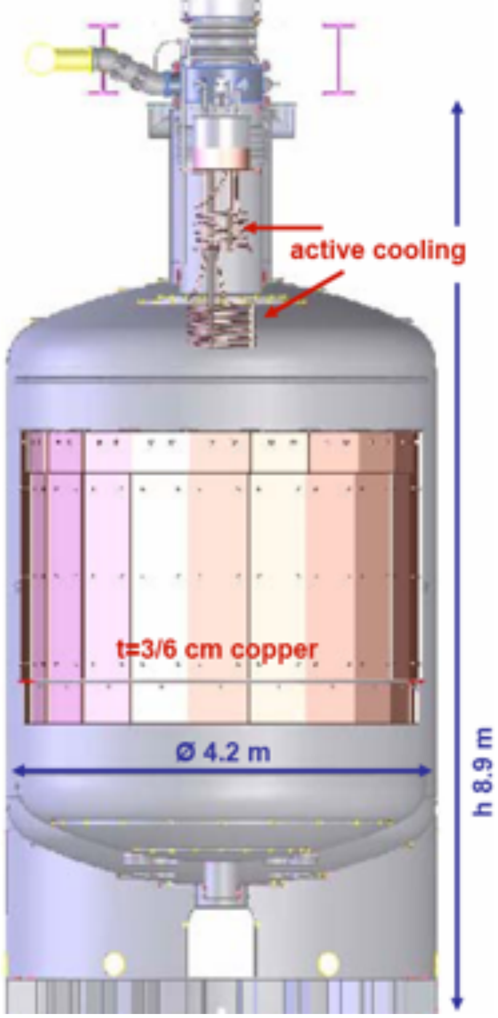
With so many choices, how does any one experiment stand out !?

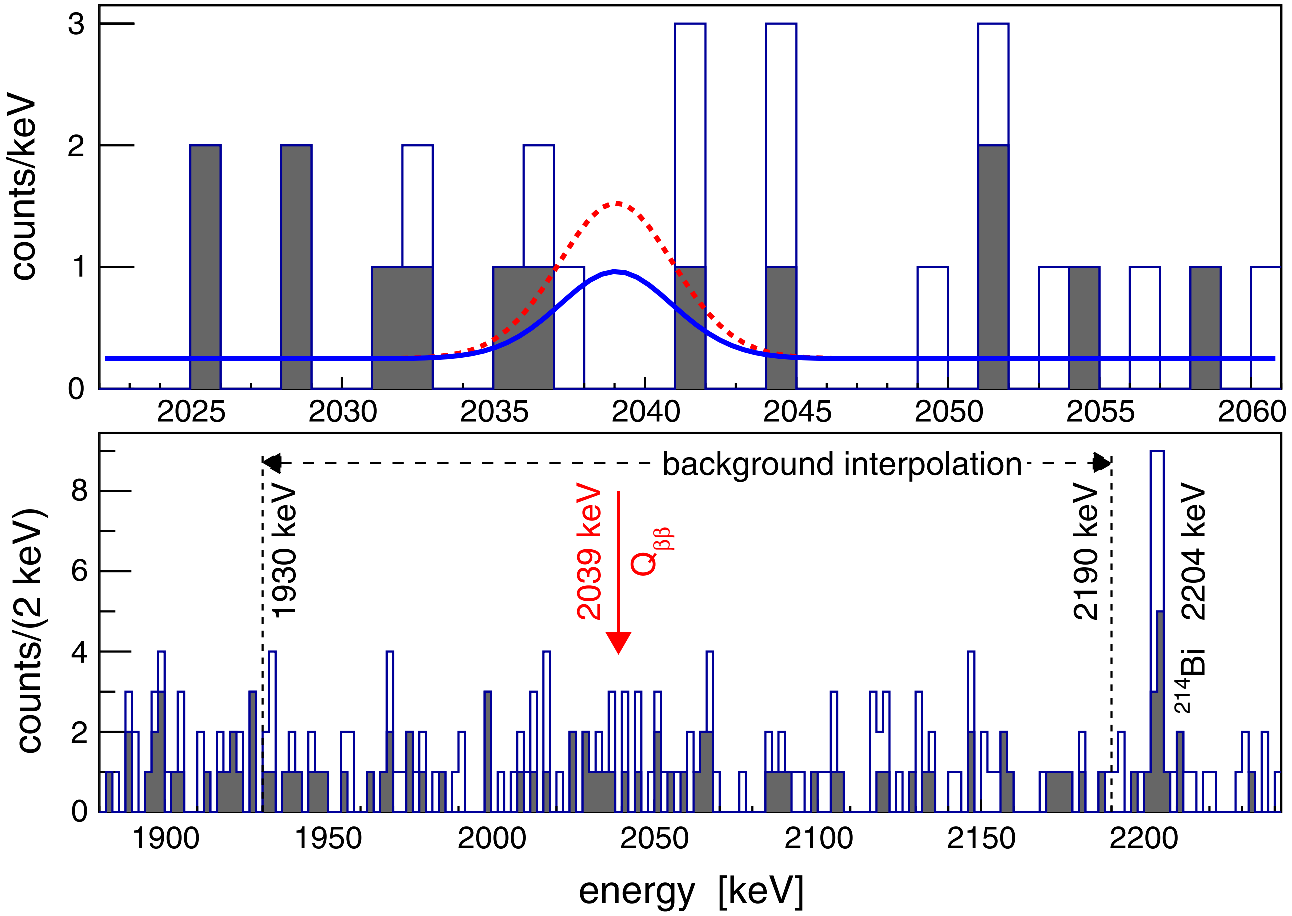
Ionization: GERDA

others ionization detectors:
MAJORANA, SuperNEMO

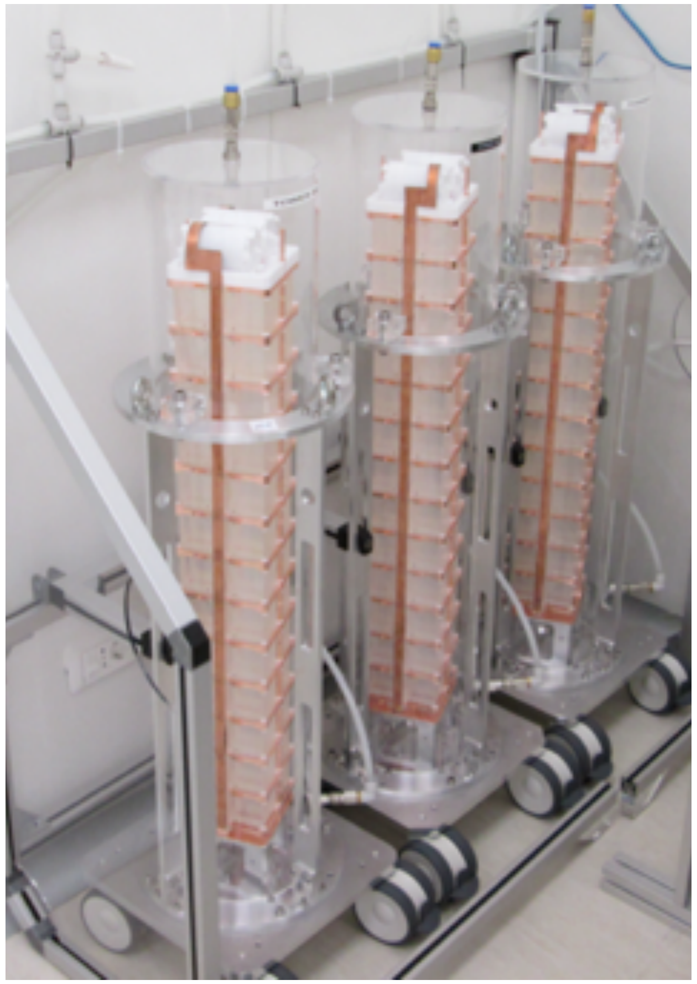
- 87% enriched ^{76}Ge detectors (crystals) in liquid argon
- 14.6 kg of 86% enriched ^{76}Ge (6 p-type semi-coax detectors from H-M & IGEX). (4.8 keV FWHM @ $Q_{\beta\beta}$)
- 3 kg of 87% enriched BEGe enriched detectors (5 detectors)
- Single-site, multi-site pulse shape discrimination

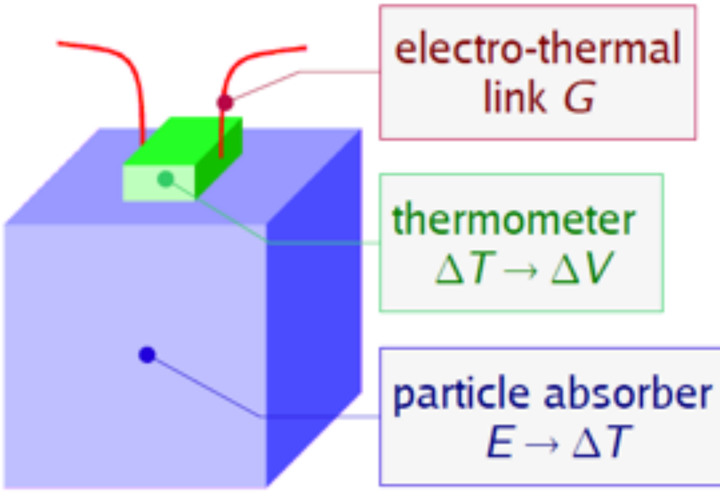
$T_{1/2} > 2.1 \times 10^{25}$ y (90% CL) ^{76}Ge





Phonons:
CUORE



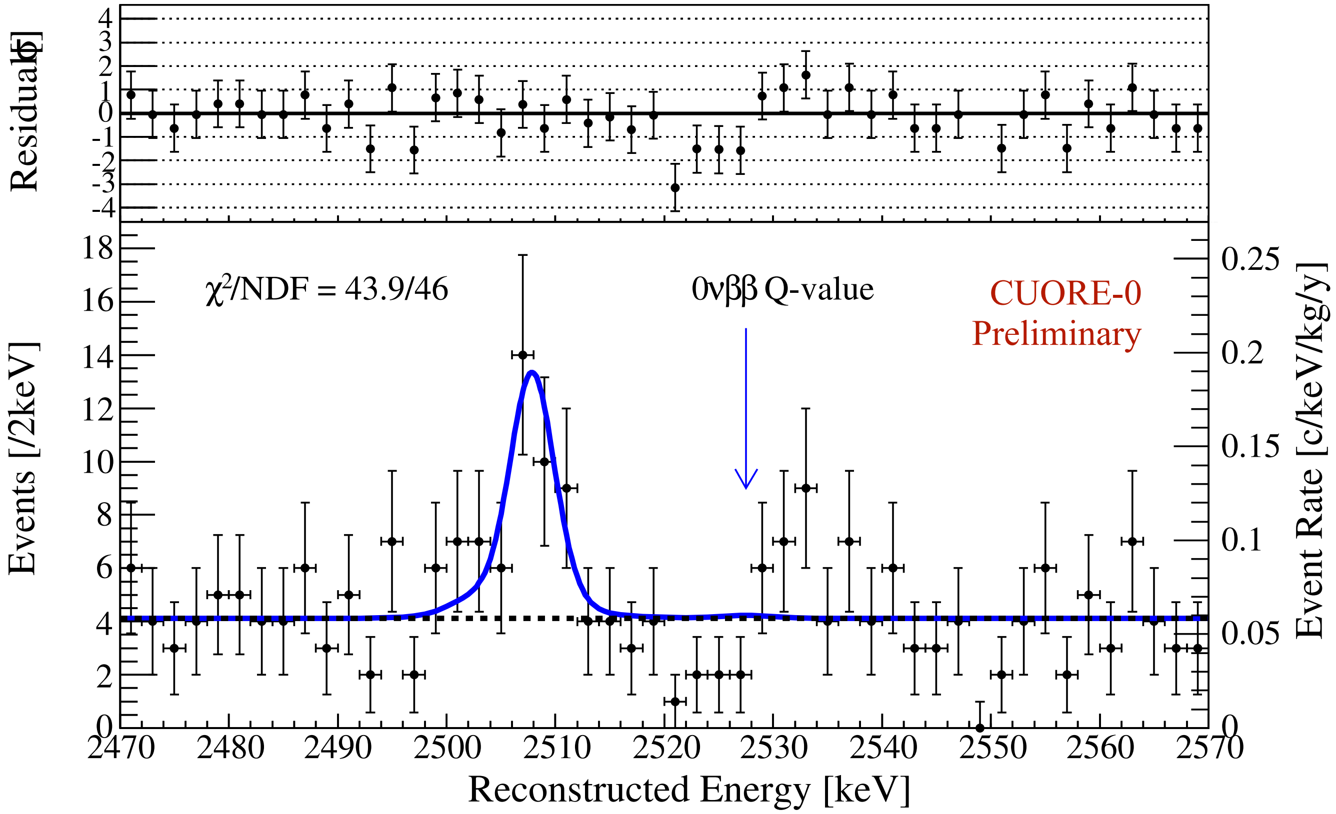


electro-thermal link G

thermometer $\Delta T \rightarrow \Delta V$

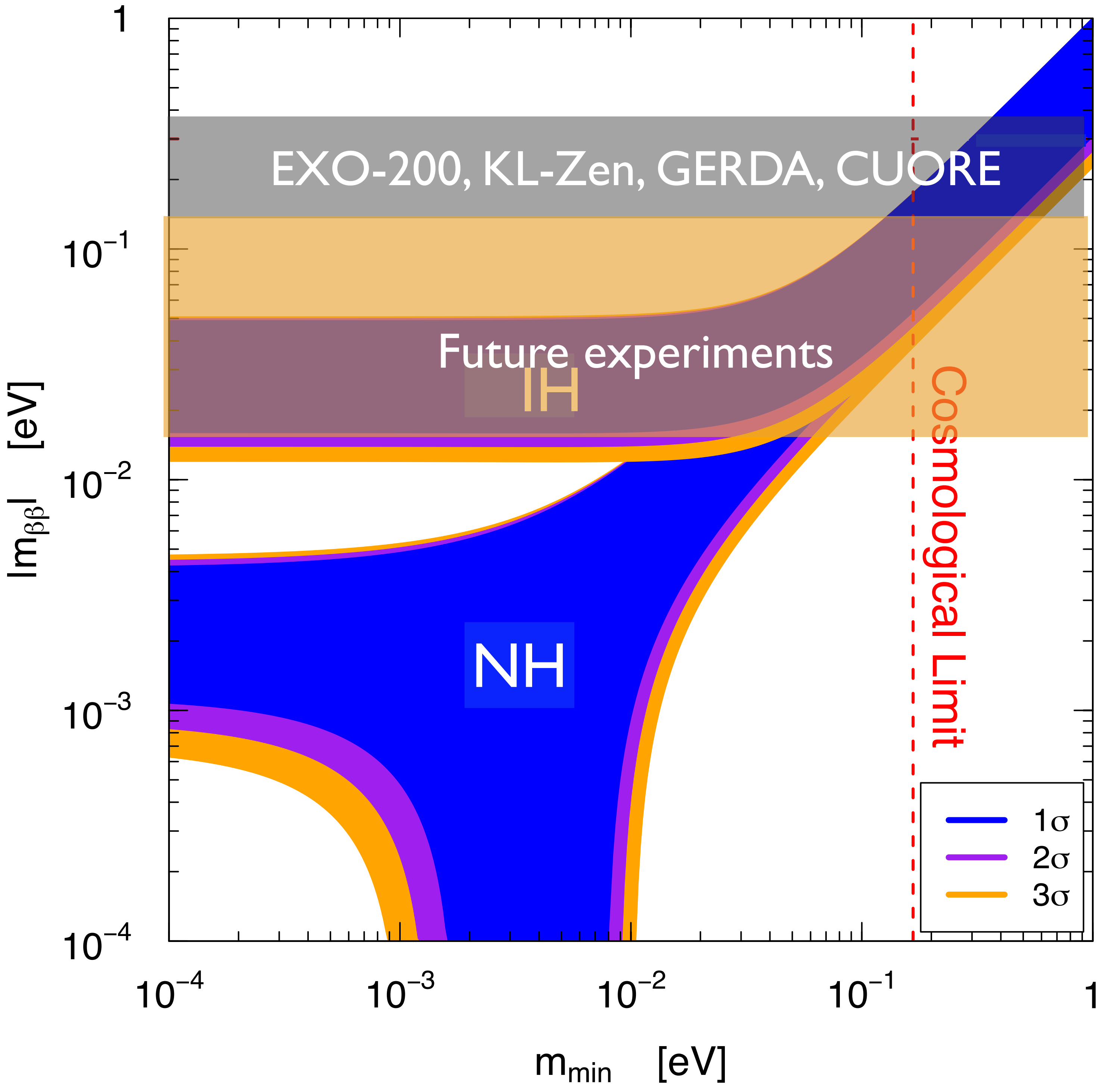
particle absorber $E \rightarrow \Delta T$

- 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



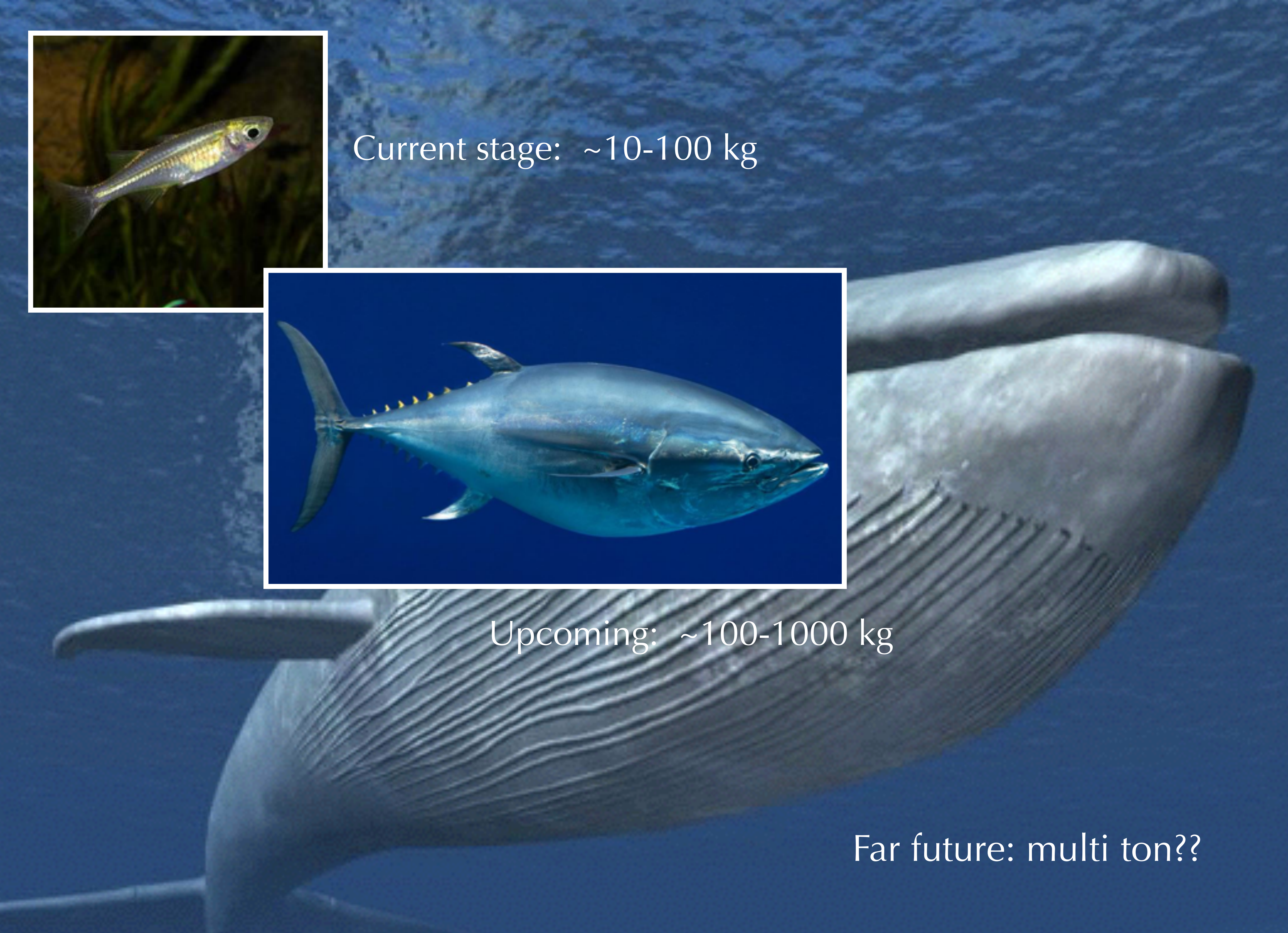
$T_{1/2} > 4.0 \times 10^{24}$ y (90% CL) ^{130}Te

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.

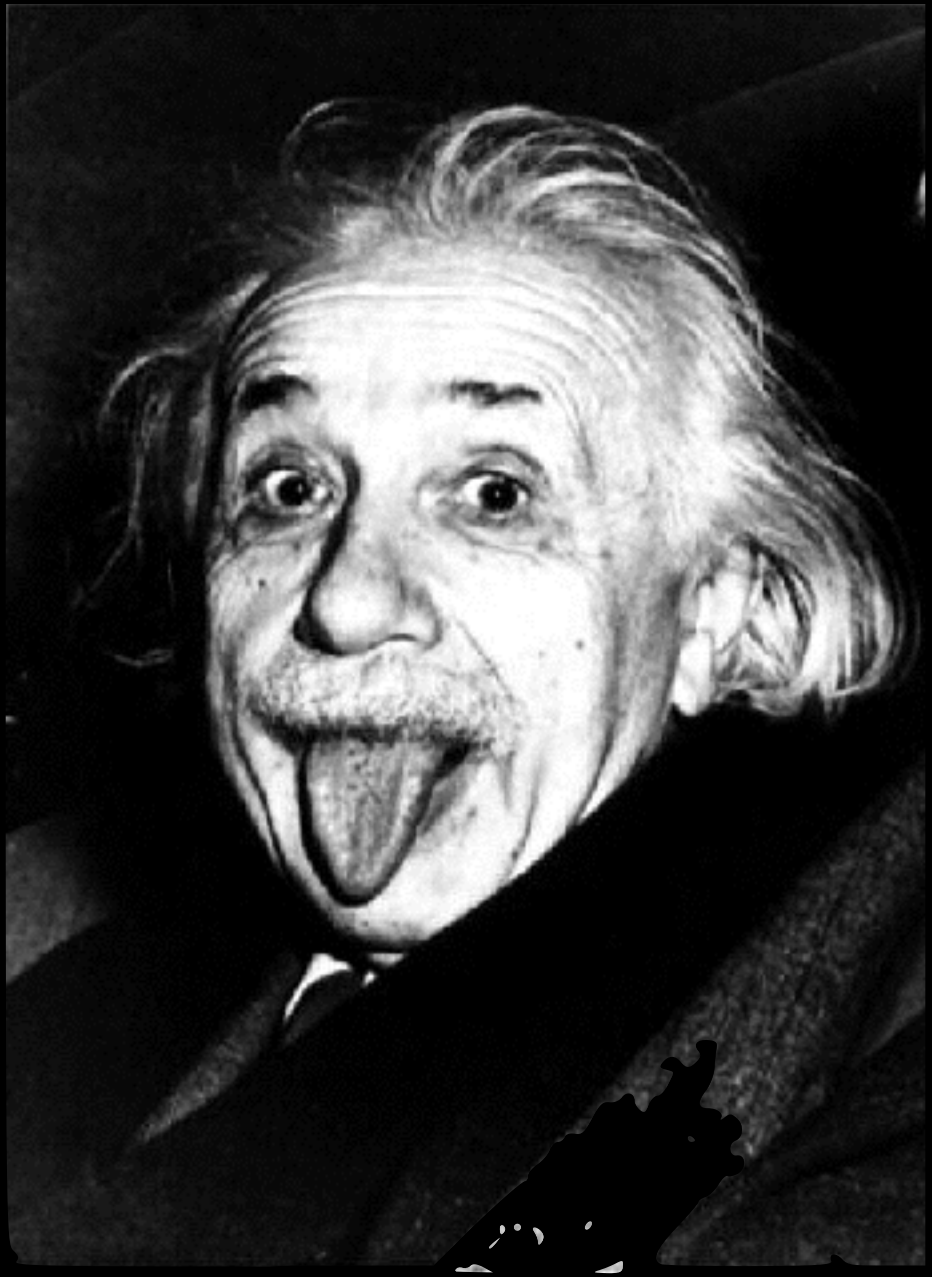
Next generation will push into the inverted Sacle



Current stage: ~10-100 kg

Upcoming: ~100-1000 kg

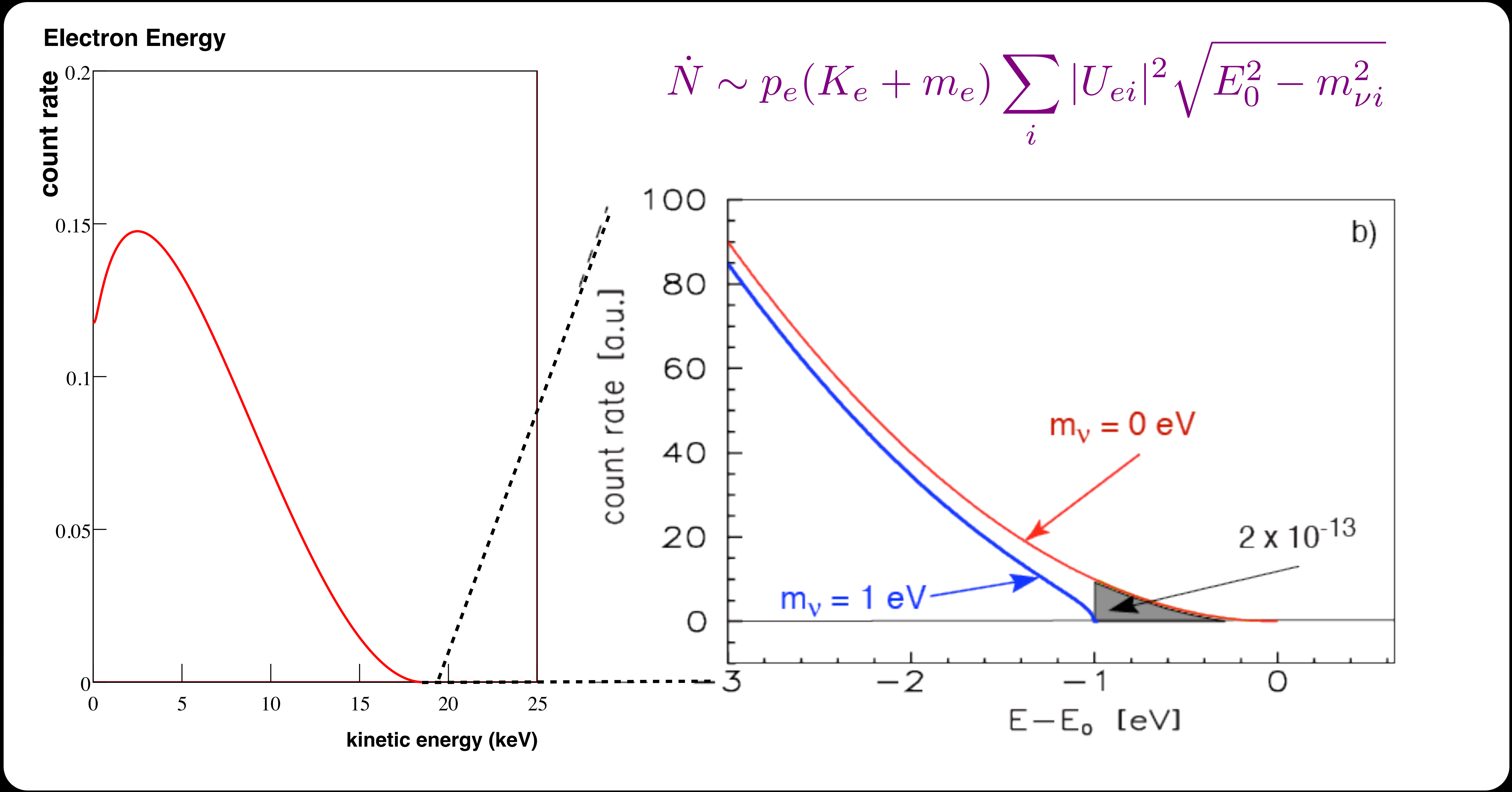
Far future: multi ton??



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

Beta Decay Measurements

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

Neutrinos from Radioactivity

- The phase space of the decay (i.e. how many different states can occupy a particular momentum).
- Corrections due to the Coulomb field, or Fermi function.
- The matrix element related to the initial and final states of the decay.

Transition	ΔI	Parity change?
Superallowed	0, ± 1	No
Allowed	0, ± 1	No
1st Forbidden	0, ± 1	Yes
Unique 1st Forbidden	± 2	Yes
2nd Forbidden	± 2	No
3rd Forbidden	± 3	Yes

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

Fermi Function

$$\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

Matrix Element

Phase space

The π√2 Magnetic Spectrometer

- Bergkvist constructs first tritium source experiment in Stockholm.
- Double focusing spectrometer; first to fully tackle energy resolution, energy loss and final states coherently.
- Achieved best limit of the time (m_ν < 55 eV).

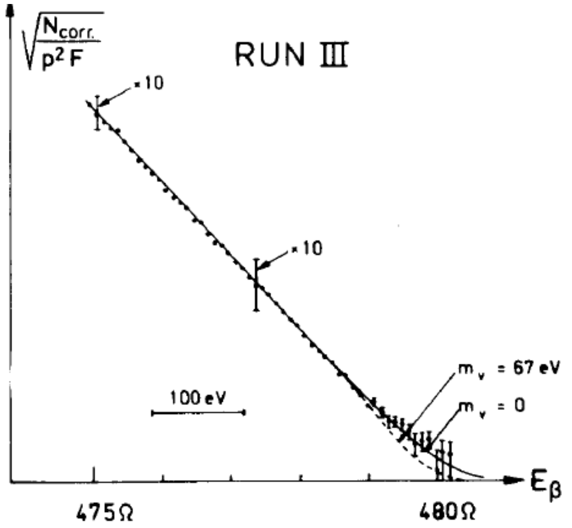
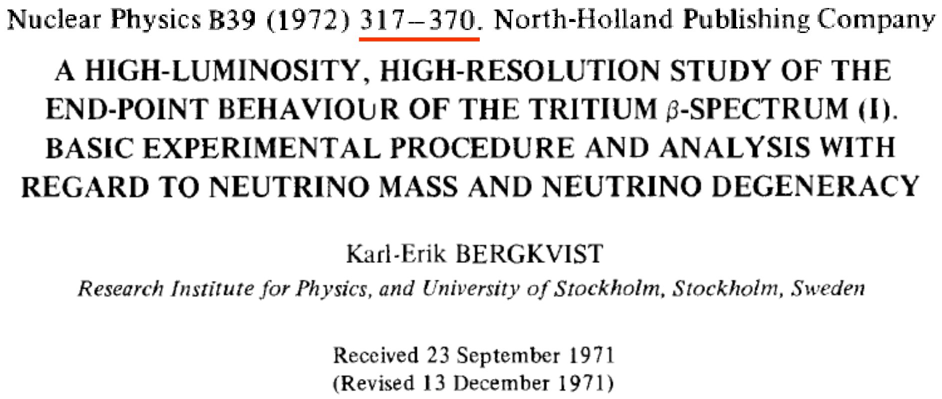


Fig. 20. Kurie plots of data from runs I–III. The data exhibited have been subjected to a very slight correction for distortion in the measured spectrum. The theoretical curves have been fitted to the data in the way discussed in connection with fig. 18.



Nuclear Physics B39 (1972) 317–370. North-Holland Publishing Company

A HIGH-LUMINOSITY, HIGH-RESOLUTION STUDY OF THE END-POINT BEHAVIOUR OF THE TRITIUM β-SPECTRUM (I). BASIC EXPERIMENTAL PROCEDURE AND ANALYSIS WITH REGARD TO NEUTRINO MASS AND NEUTRINO DEGENERACY

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Received 23 September 1971
(Revised 13 December 1971)

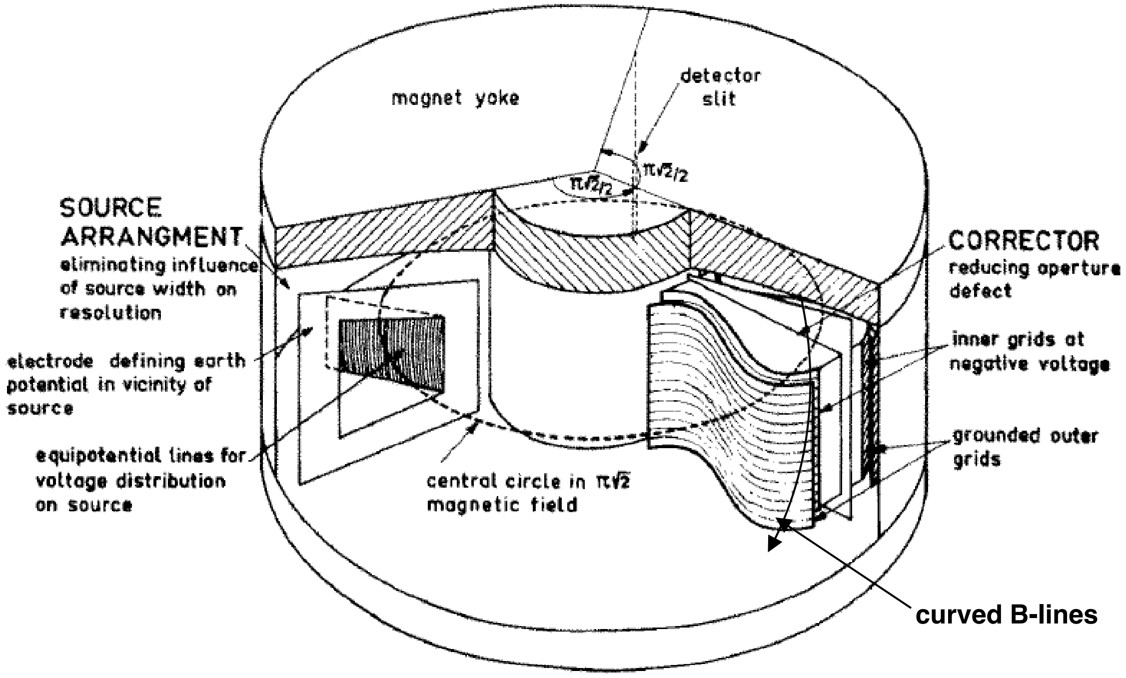
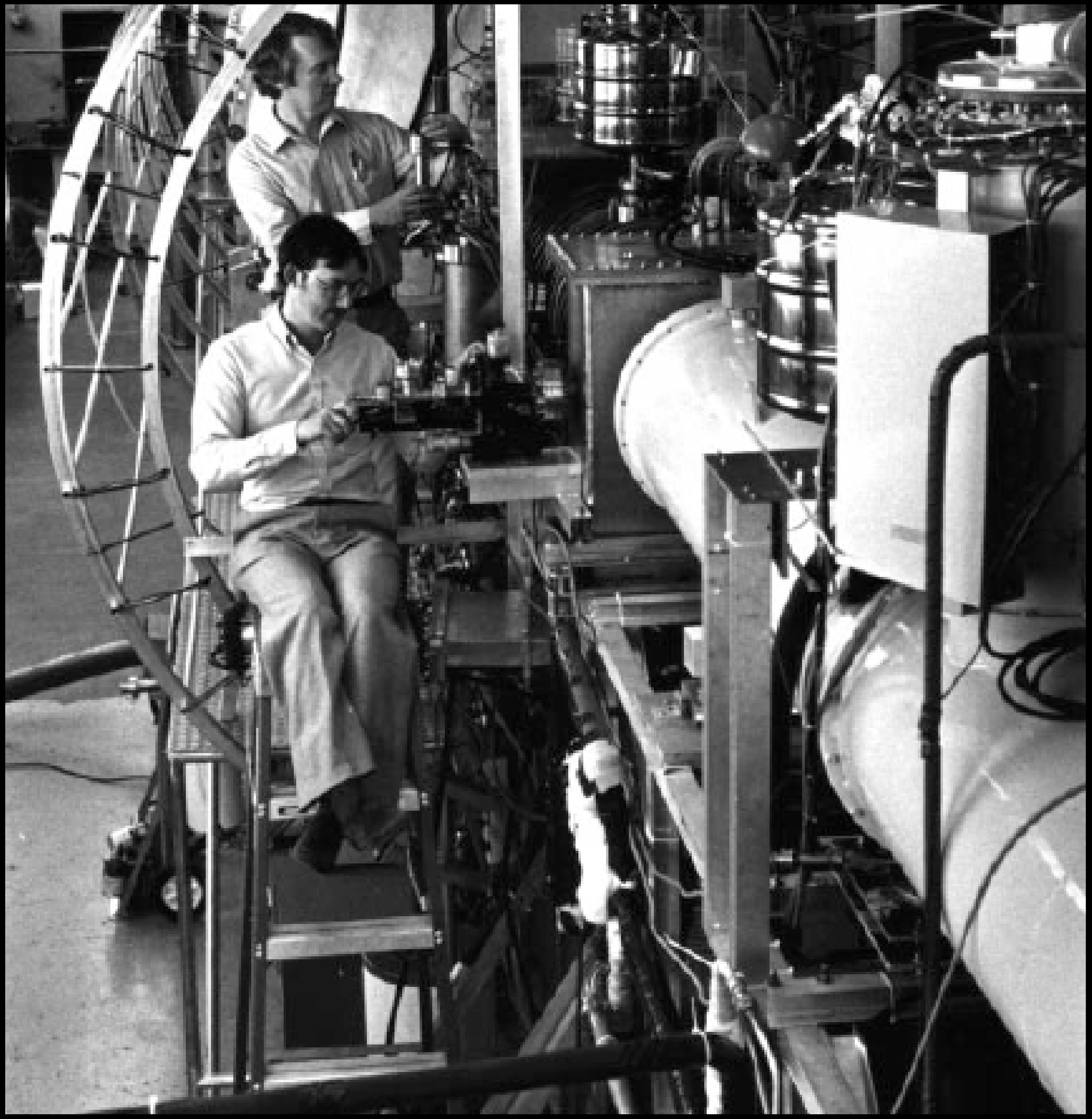


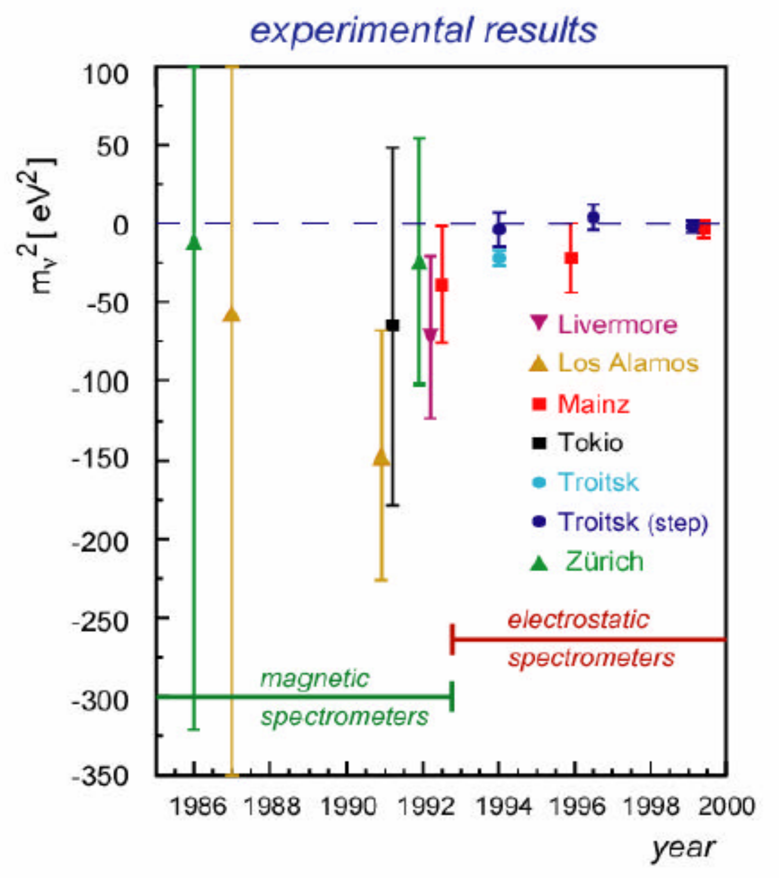
Fig. 3. Basic components of electrostatic-magnetic spectrometer employed in the present investigation of the end-point region of the tritium β-spectrum.

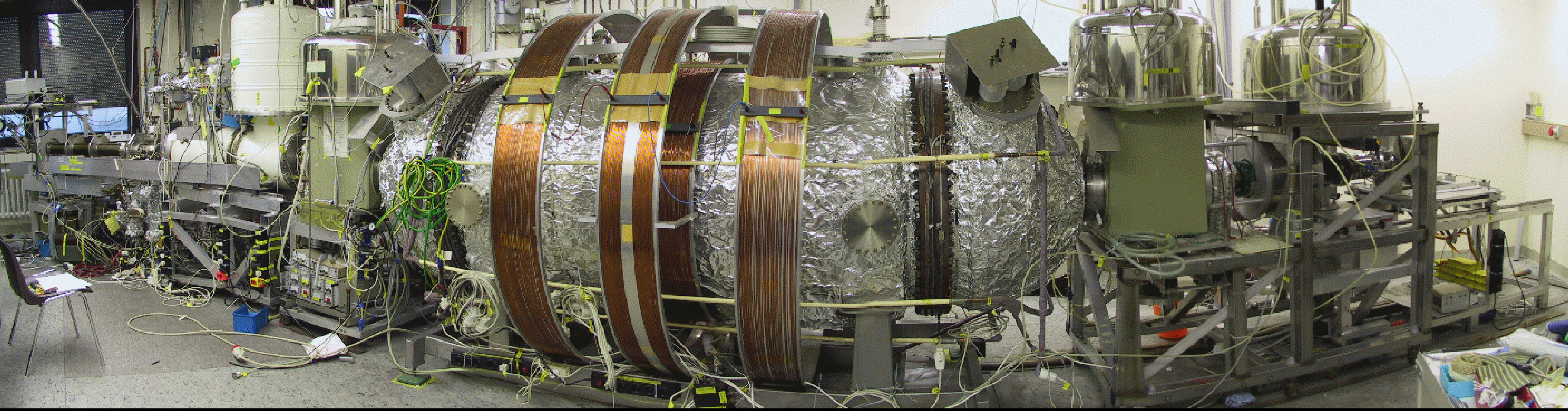
Los Alamos

- Robertson, Bowles, Wilkerson and others at Los Alamos devise the first gaseous tritium source experiment to circumvent earlier issues seen with solid state sources.

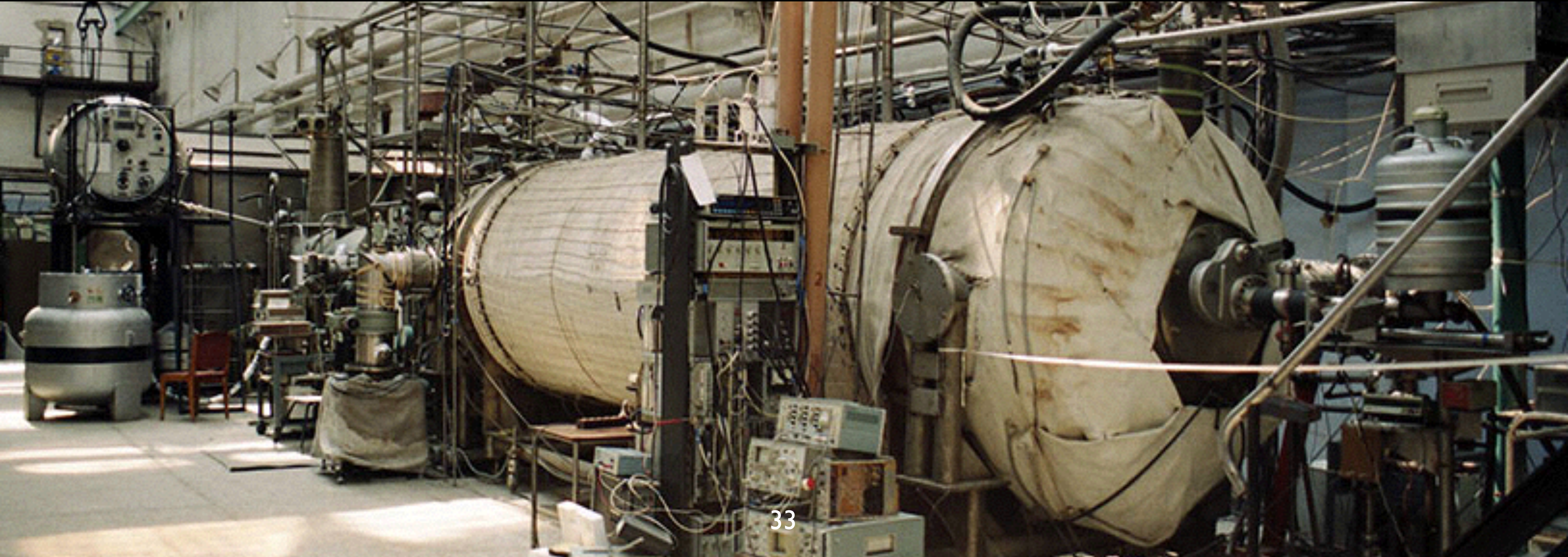
- Their limit of 27 eV rules out a previous signal for neutrino mass. Sets stage for gaseous sources in future designs.







Mainz & Troitsk



Current Techniques

Spectroscopy (KATRIN)

Magnetic Adiabatic Collimation with Electrostatic Filtering

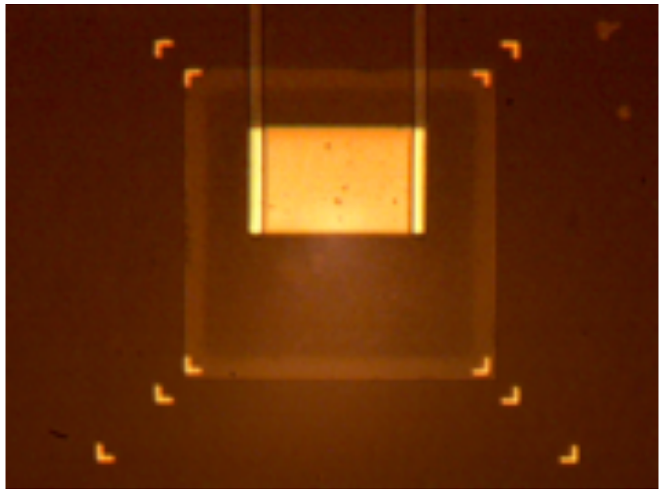
State-of-the-Art technique

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

Calorimetry (HOLMES, ECHO & NUMECS)

Technique highly advanced.

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

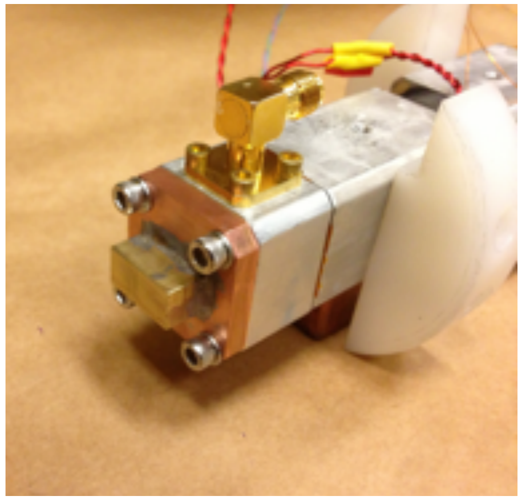


$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

R&D phase (new results)



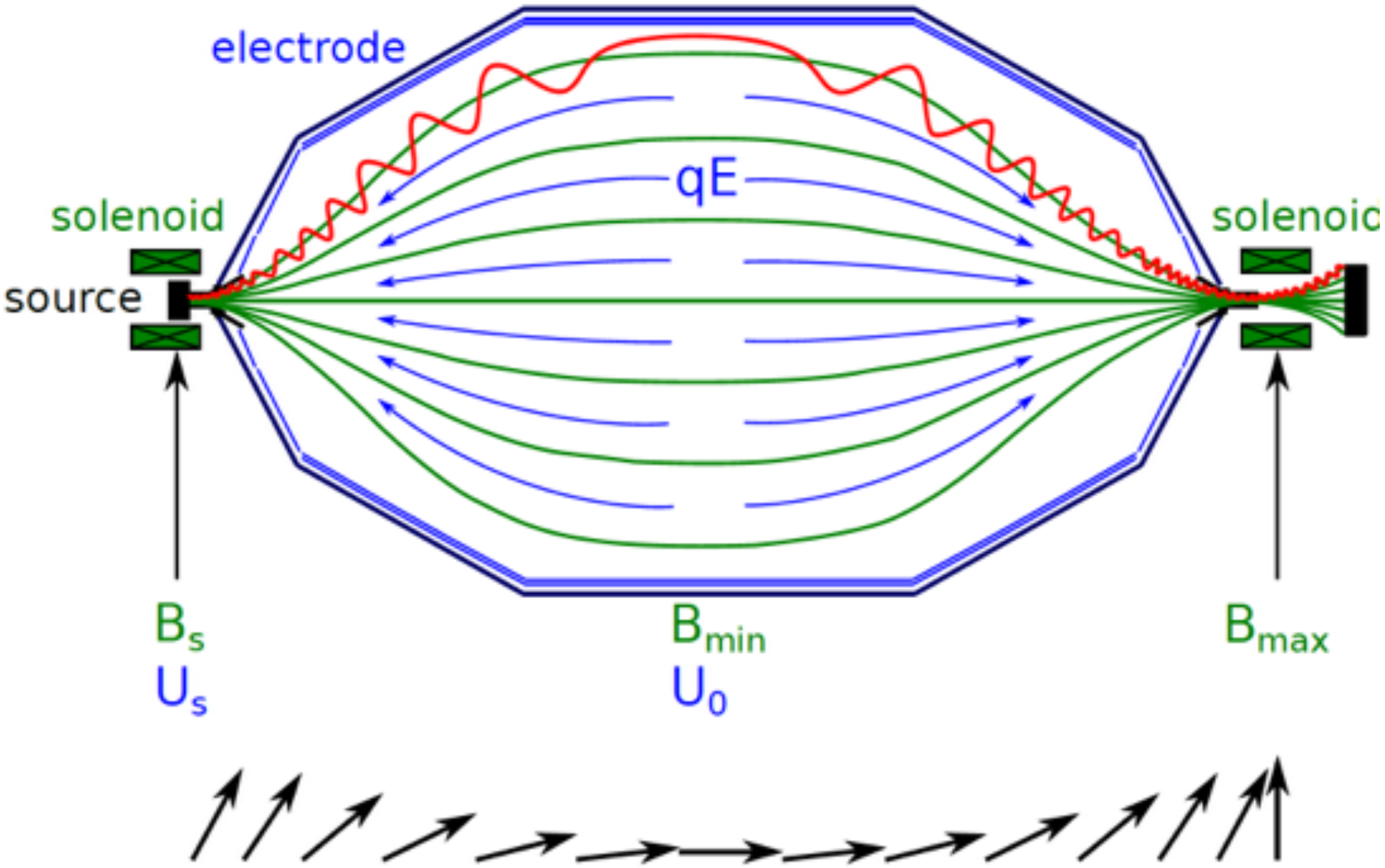
$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

MAC-E Filter Technique

KATRIN

$$\mathrm{T}_2 \rightarrow (\mathrm{T}\cdot\,{}^3\mathrm{He}^+) + \mathrm{e}^- + \bar{\nu}_e$$

Spectroscopic: MAC-E Filter



adiabatic transformation of e⁻ momentum

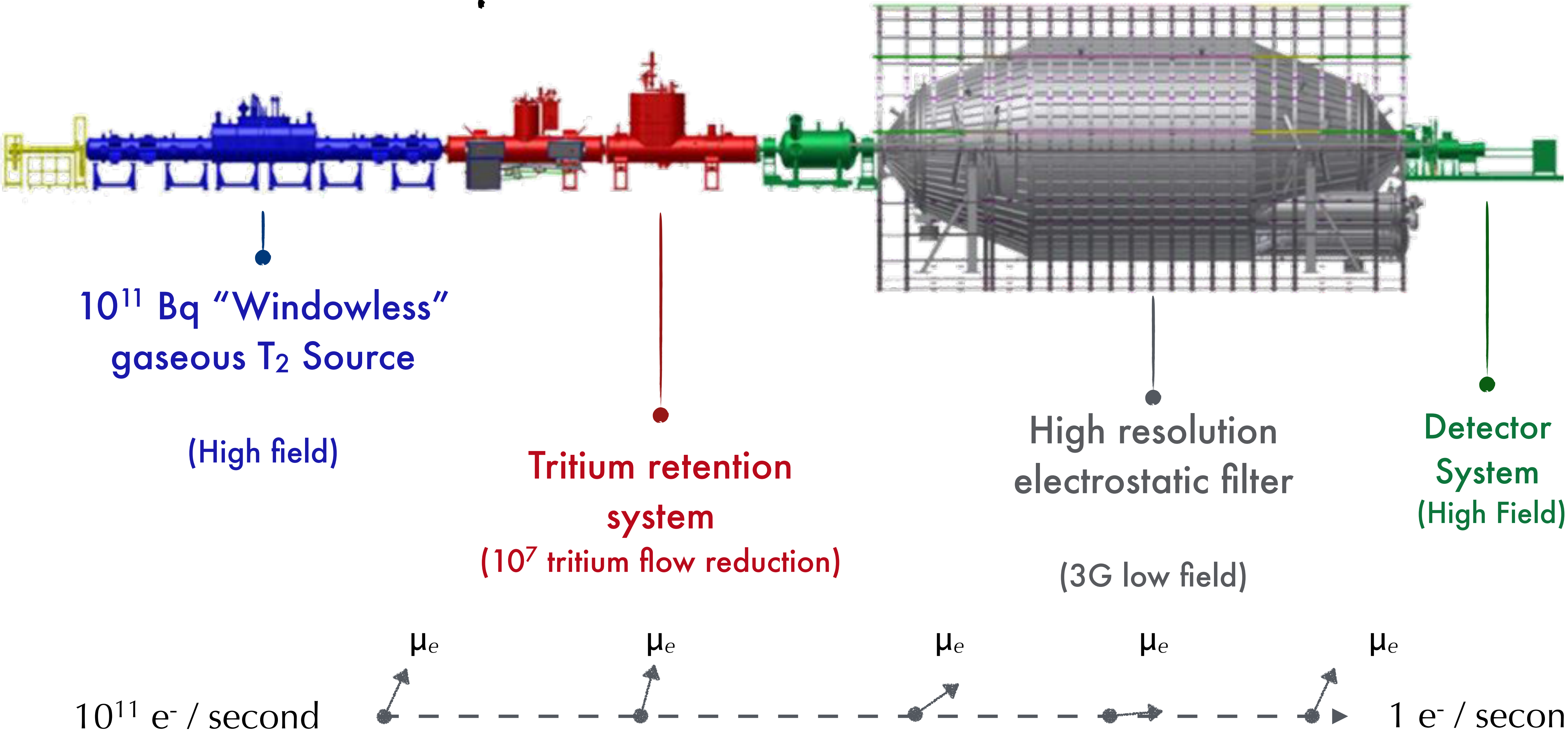
Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

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

The KATRIN Setup



10^{11} Bq "Windowless" gaseous T_2 Source

(High field)

Tritium retention system

(10^7 tritium flow reduction)

High resolution electrostatic filter

(3G low field)

Detector System

(High Field)

10^{11} e$^-$ / second → 1 e$^-$ / second

Adiabatic transport ensures high retention of phase space for decay

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

Energy resolution scales as the ratio of minimum / maximum fields

The Journey...


Belfast
Dublin
IRELAND
Irish Sea
Celtic Sea
UNITED KINGDOM
Isle of Man (U.K.)
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Sea
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
RUSSIA
Vilnius
Mahilyow
Minsk
BELARUS
Hrodna
Homyel'
Gdańsk
Hamburg
Bremen
Berlin
Amsterdam
NETH.
Rotterdam
Essen
Cologne
Bonn
Leipzig
Elbe
Oder
Poznań
Warsaw
Brest
Kiev
POLAND
Łódź
Wrocław
Vistula
Rivne
UKRAINE
Dnipro
Brussels
Lille
BEL.
GERMANY
Frankfurt am Main
Prague
CZECH REPUBLIC
Kraków
L'viv
Chernivtsi
Guernsey (U.K.)
Jersey (U.K.)
Luxembourg
LUX.
Paris
Seine
Brno
SLOVAKIA
CARPATHIAN MTS.
Chişinău
Iaşi
MOLDOVA
Stuttgart
Strasbourg
Rhine
Munich
Danube
Bratislava
Vienna
Budapest
Cluj-Napoca
Nantes
Loire
LIECH.
AUSTRIA
HUNGARY
ROMANIA
Zürich
Bern
Vaduz
SWITZ.
Geneva
ALPS
Bay of Biscay
FRANCE
Ljubljana
SLOVENIA
Zagreb
Bucharest
Lyon
MASSIF CENTRAL
Bordeaux
Milan
Turin
Venice
Po
DINARIC ALPS
CROATIA
BOSNIA AND HERZEGOVINA
Belgrade
Serbia
Varna
BULGARIA
Bilbao
Toulouse
Andorra la Vella
ANDORRA
PYRENEES
Marseille
MONACO
Genoa
Ligurian Sea
Florence
SAN MARINO
APENNINES
Sarajevo
Montenegro
Sofia
Istanbul
Porto
Zaragoza
Corsica
ITALY
Adriatic Sea
Podgorica
Skopje
F.Y.R.O.M.
PORTUGAL
Madrid
Barcelona
Rome
VATICAN CITY
Tirana
ALB.
Thessaloniki
Lisbon
Tagus
SPAIN
Valencia
Balearic Sea
Sardinia
Naples
Tyrrhenian Sea
GREECE
Aegean Sea
TURKEY
İzmir
BALEARIC ISLANDS
Cagliari
Ionian Sea
Athens
Sevilla
Gibraltar (U.K.)
Málaga
Mediterranean Sea
Palermo
Sicily
Rhodes
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Algiers
Melilla (SPAIN)
Oran
Tunis
Crete
Rabat
Casablanca
MOROCCO
ALGERIA
TUNISIA
Valletta
MALTA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
0 300 Kilometers
0 300 Miles
20

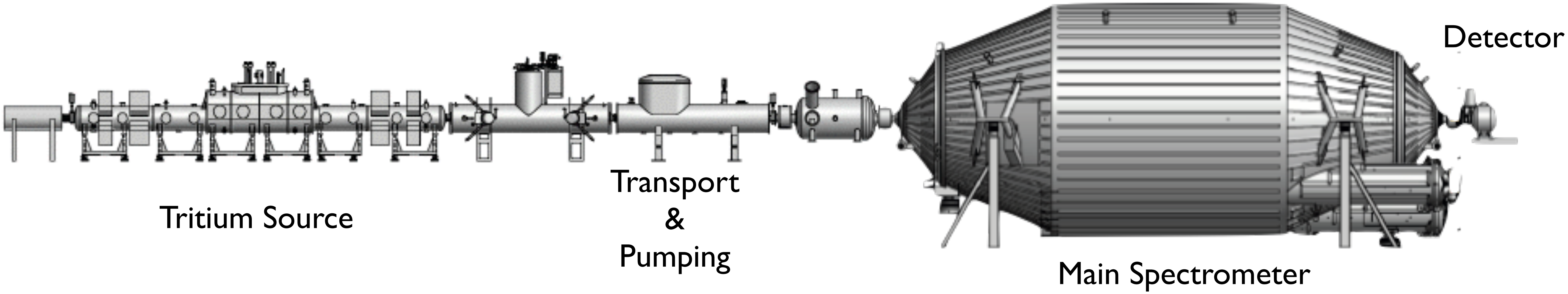
…and the arrival.


Field- Compensation Air Coils

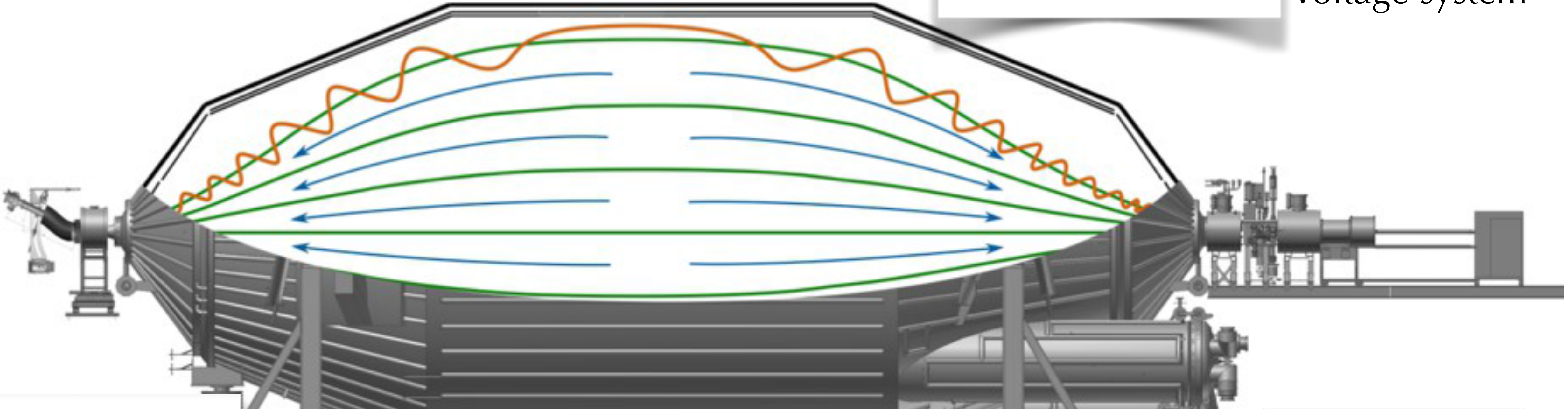

Inner electrode wire mesh


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.



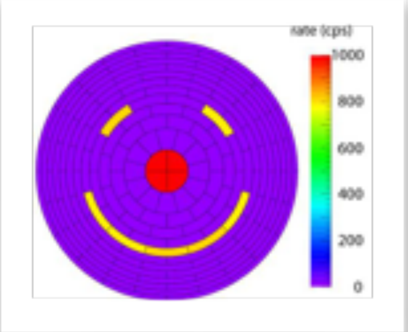
Spectrometer Commissioning



Precision high voltage system

High precision electron gun

Ultra high vacuum system



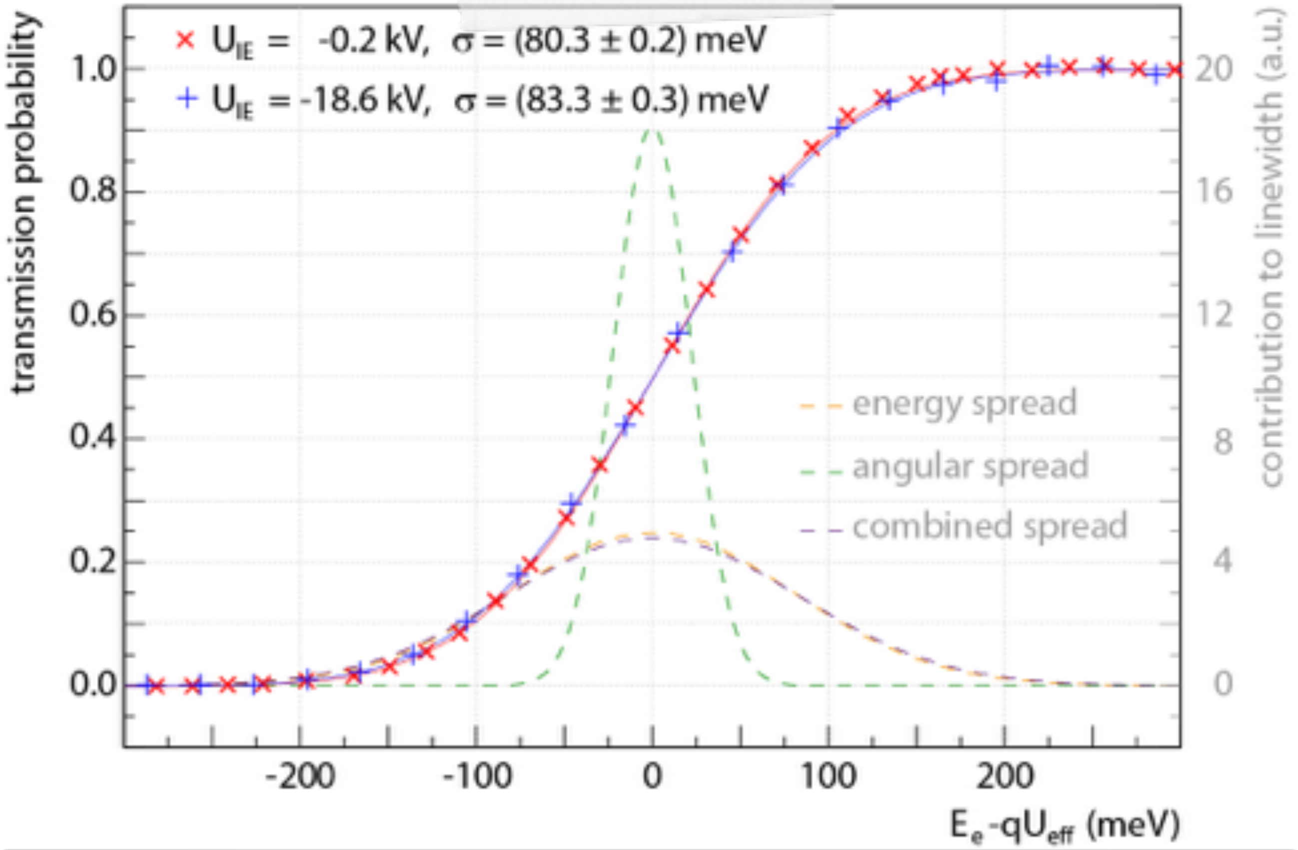
Full detector system

Summer 2013 saw "first light" from the KATRIN.

Spectrometer and detector system fully integrated.

Allowed for test of transmission function and background levels.

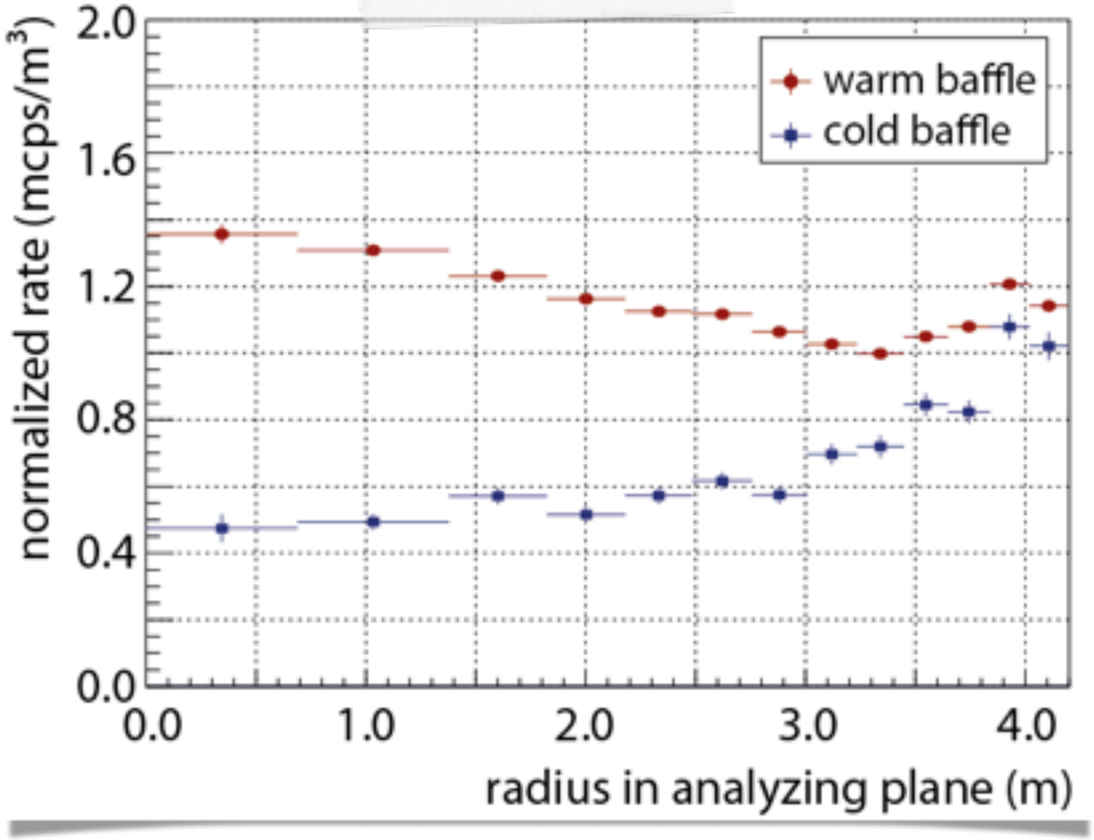
Transmission Function



At -18.6 keV, better than
100 meV resolution

Sharpest transmission function
for a MAC-E filter

Background Rates



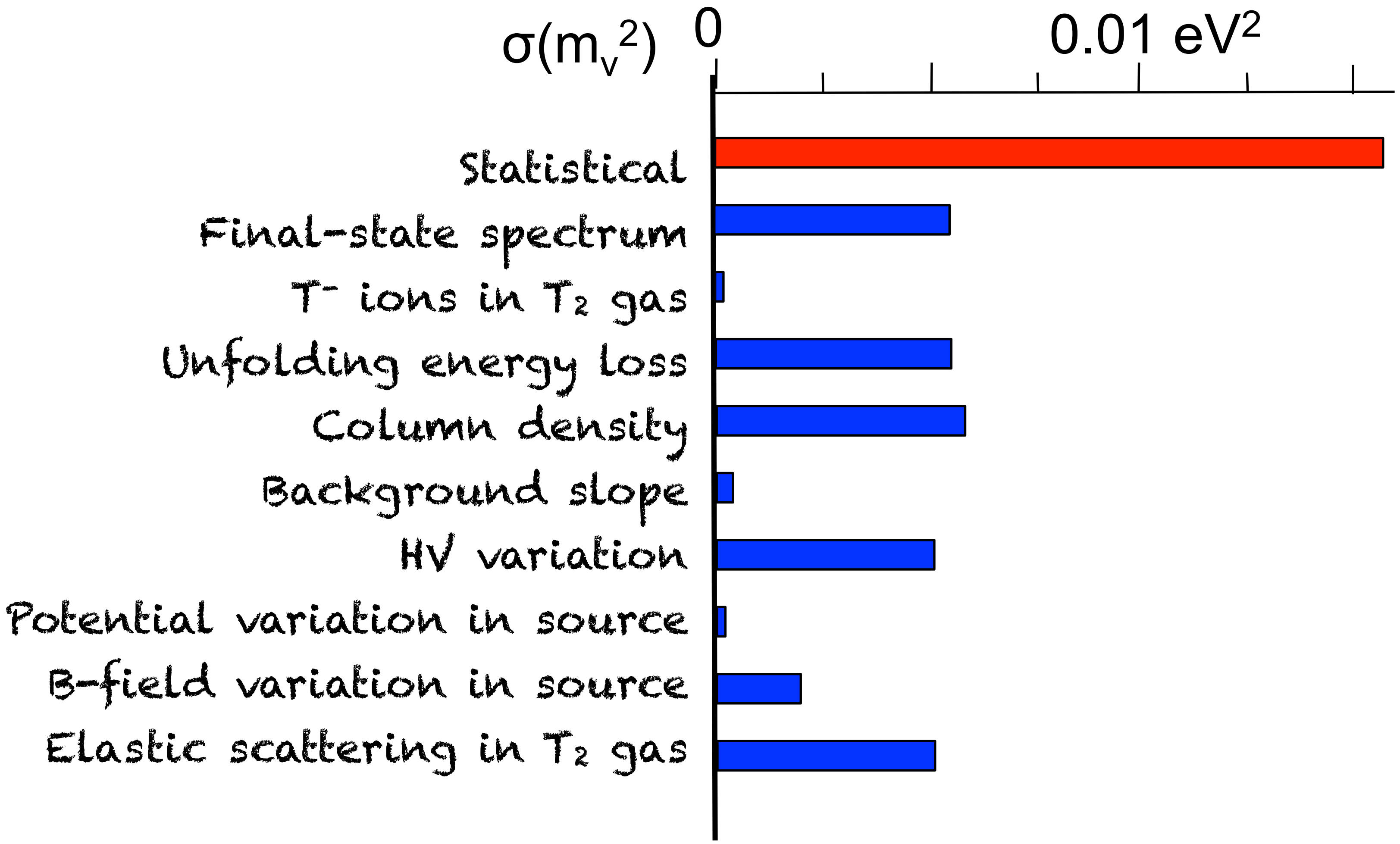
Background rate of order Hz
(radon-dominated)

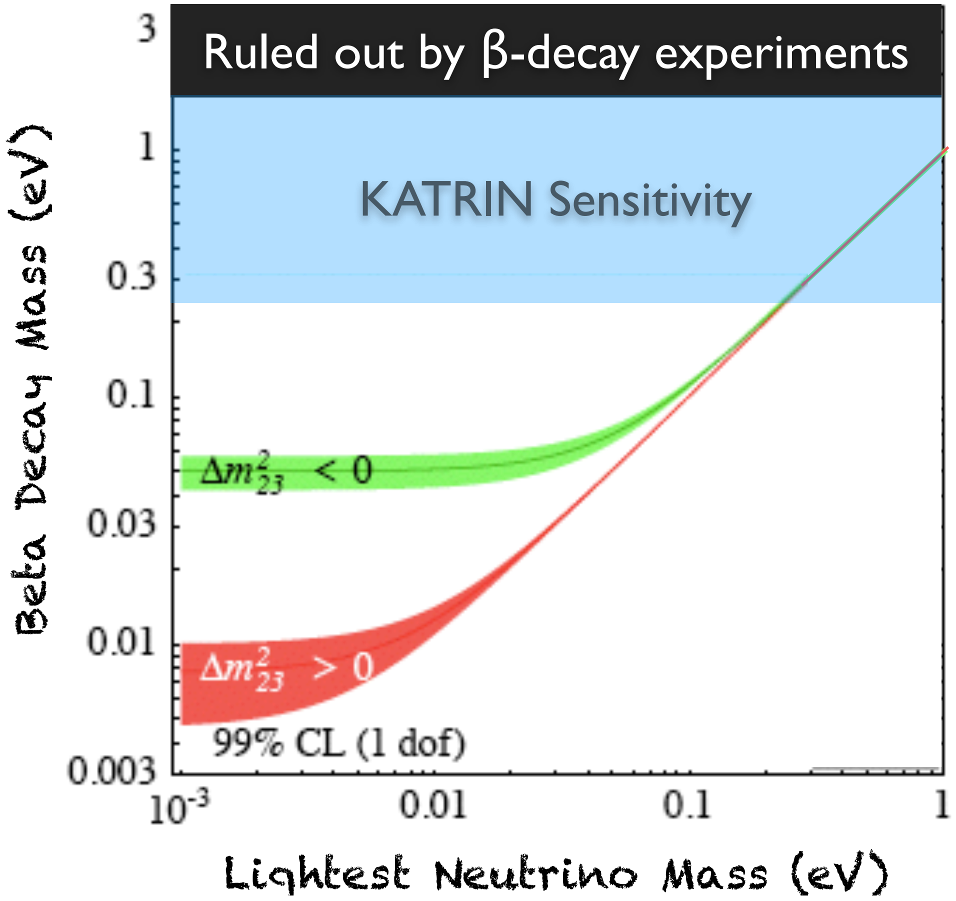
Greater reduction of
backgrounds to come

Commissioning showed excellent behavior of MAC-E Filter response.

Next round of commissioning meant to study background levels.

Projected Sensitivity





Neutrino Mass Goals

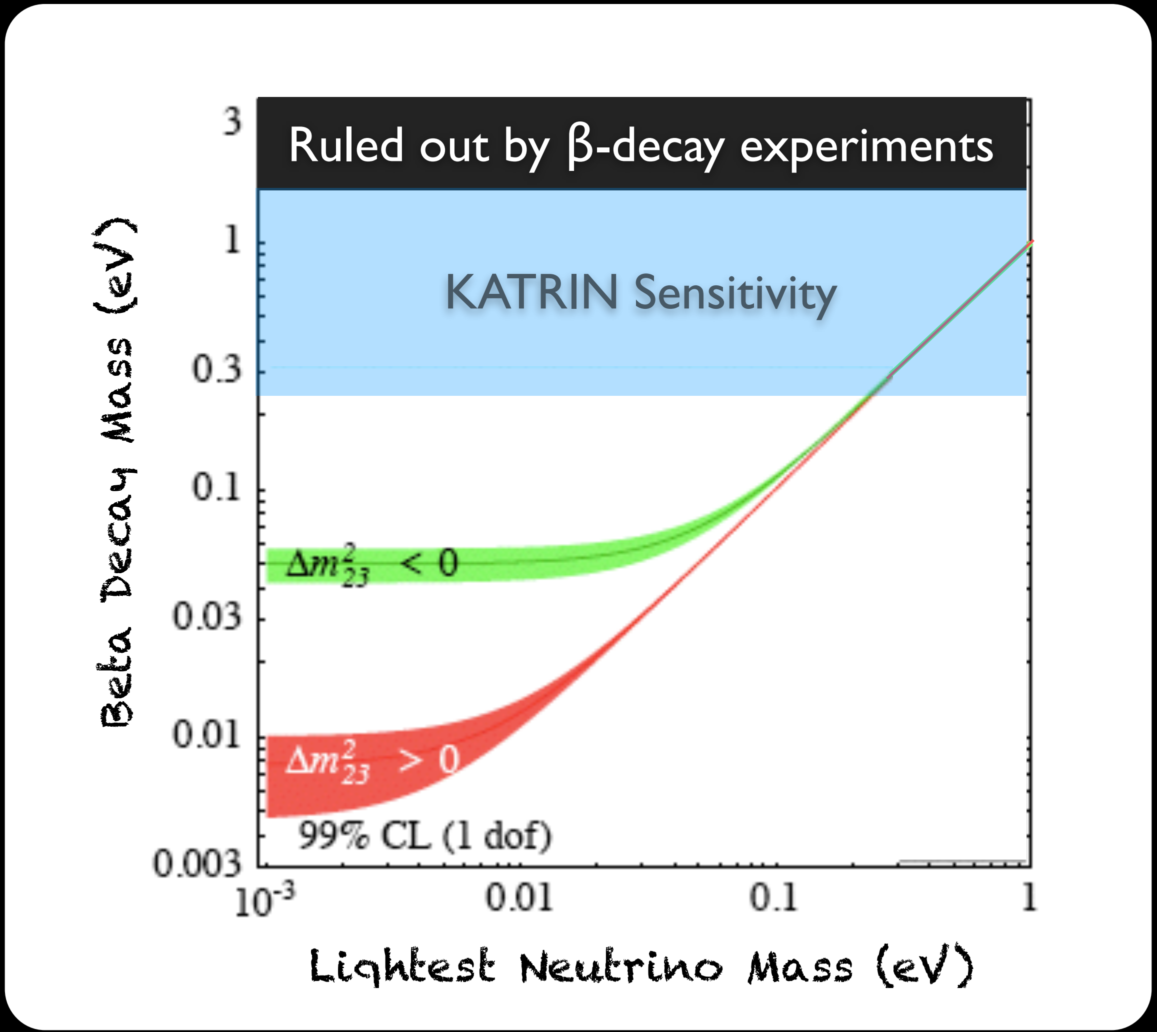
Discovery: 350 meV (at 5σ)

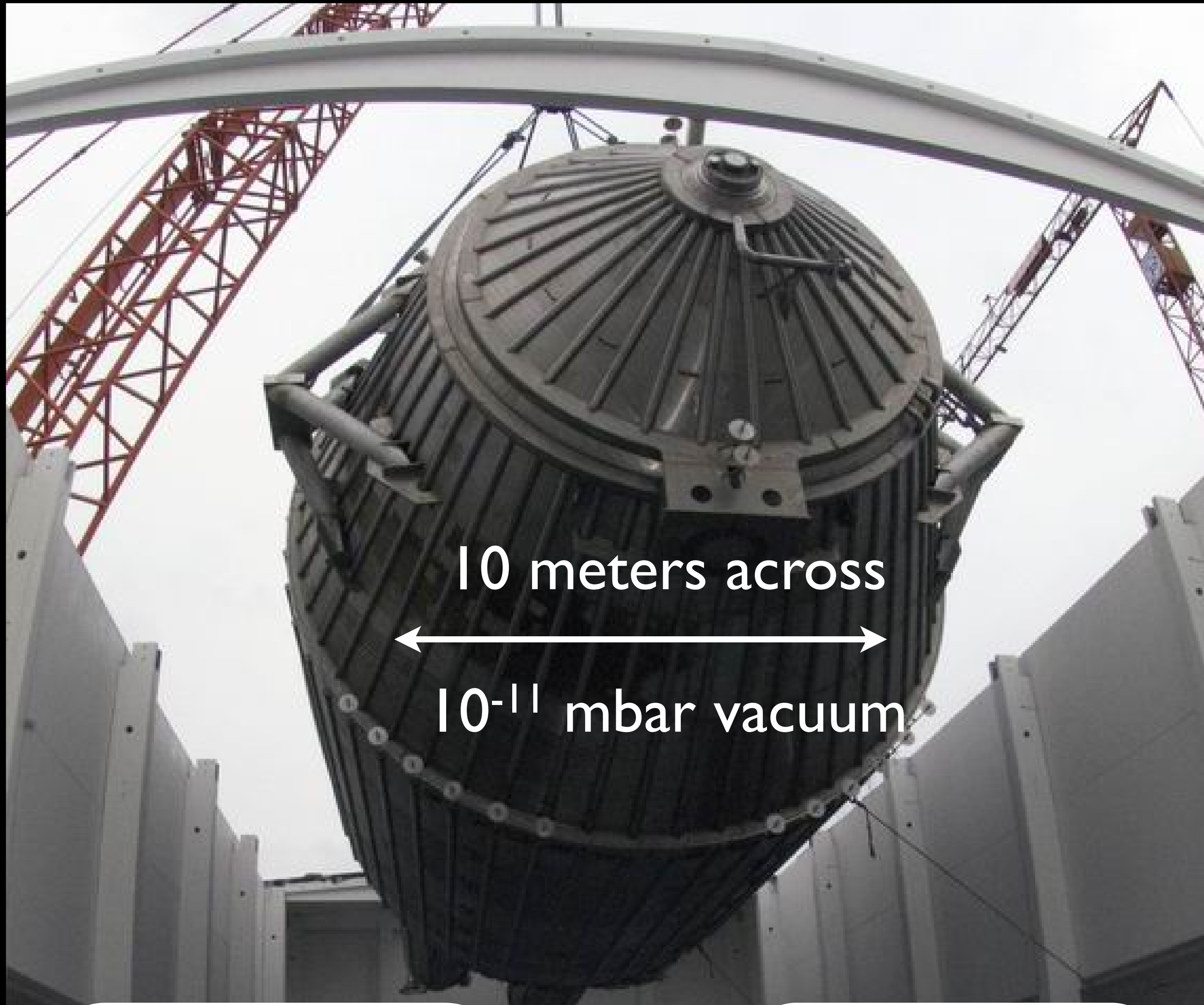
Sensitivity: 200 meV (at 90% C.L.)

Data taking to commence in 2016.

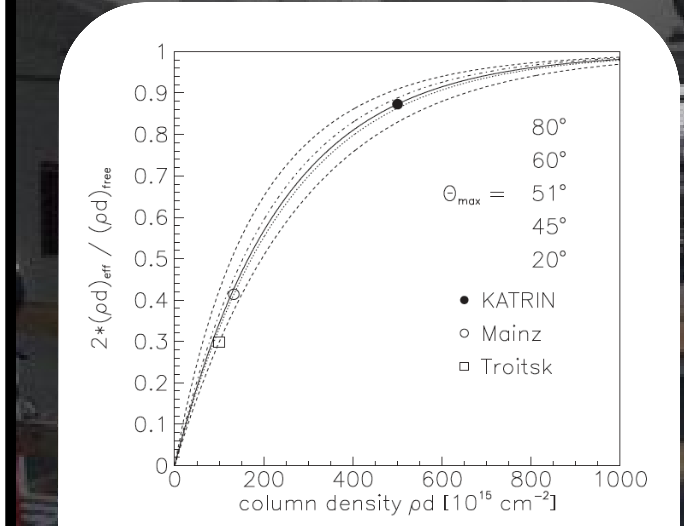
Can we push further?

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

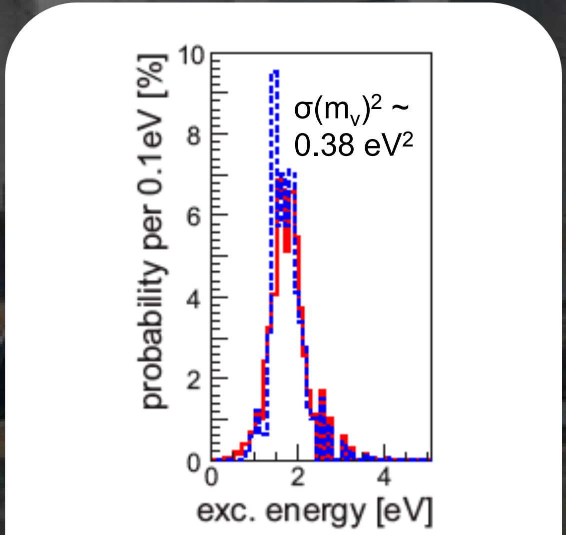



10 meters across

10^{-11} mbar vacuum

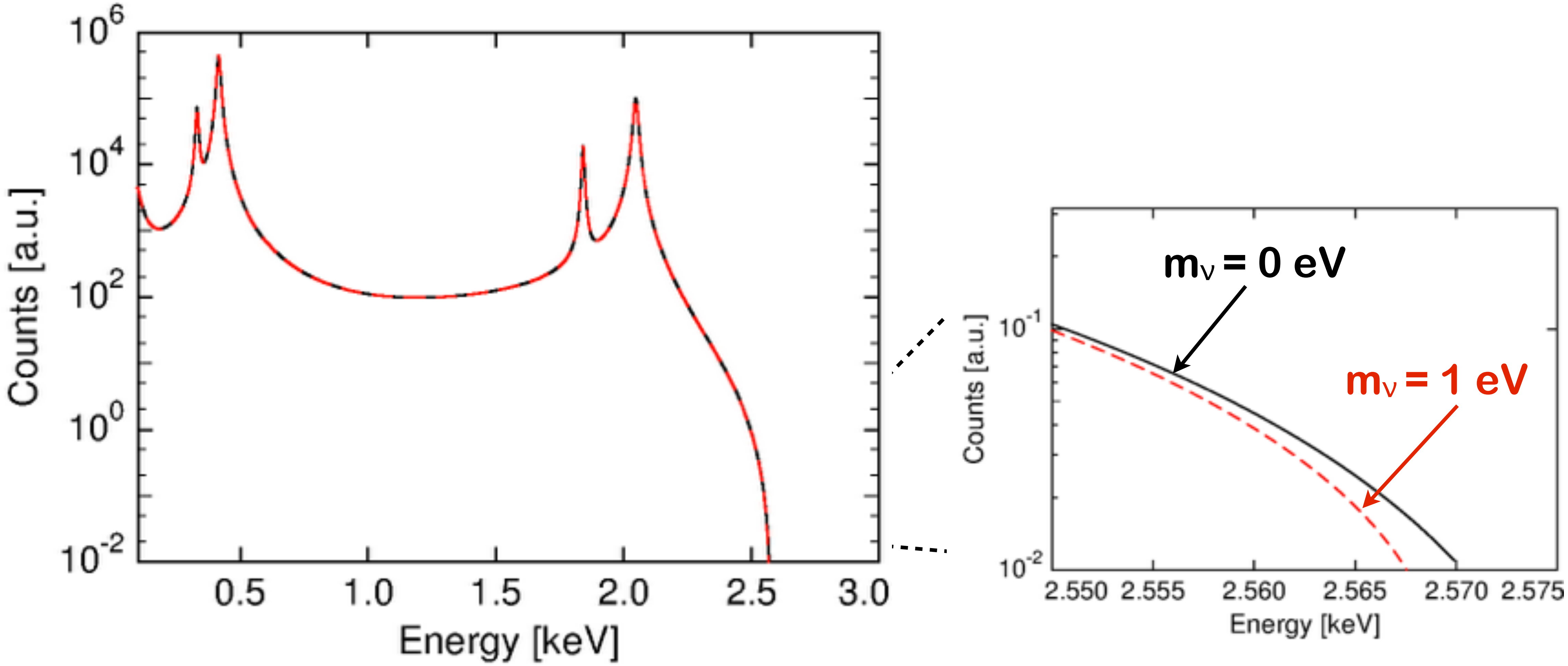


Source column density at max



Rovibrational states of THe^+

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

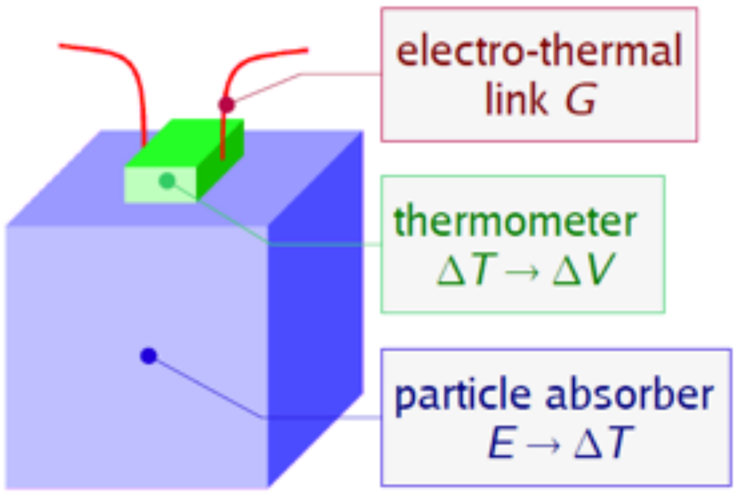


New ~~kid~~ isotope on the block:

Electron Capture

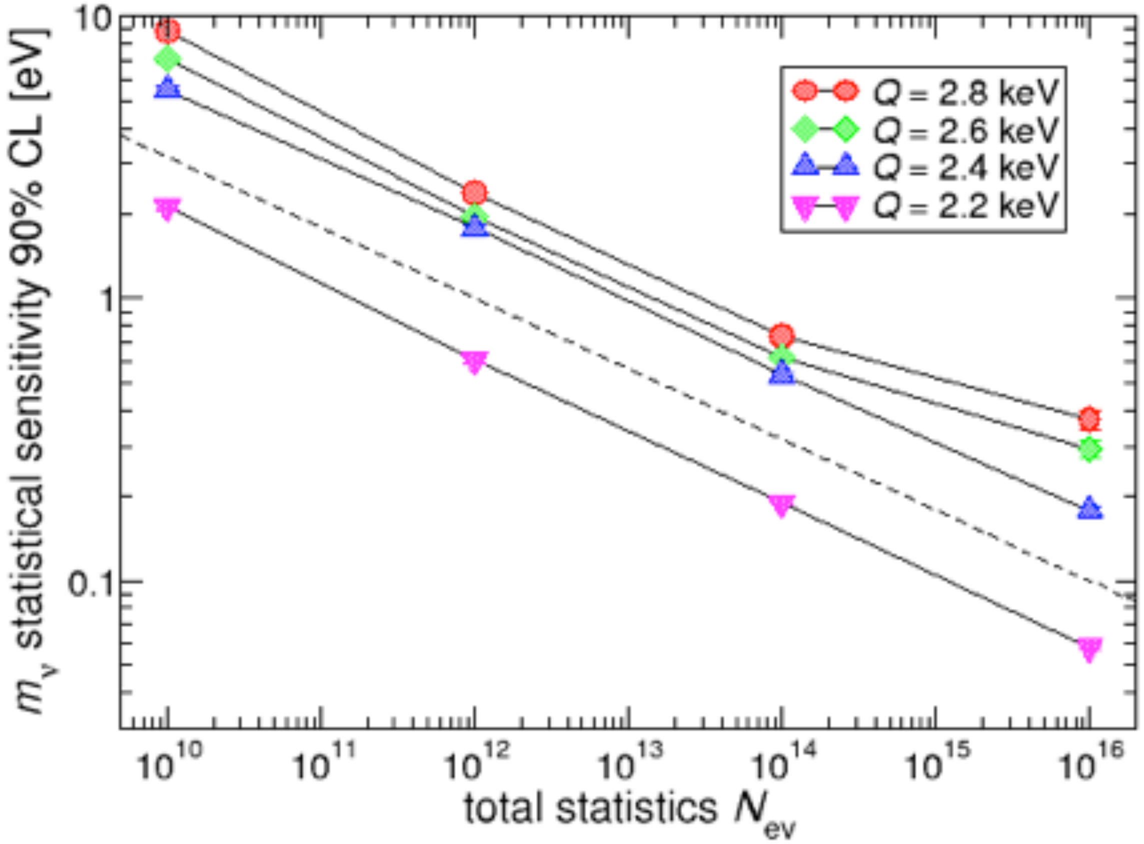
Advantages & Challenges

Calorimetry



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

Challenges:



Source Activity

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

Detector Response

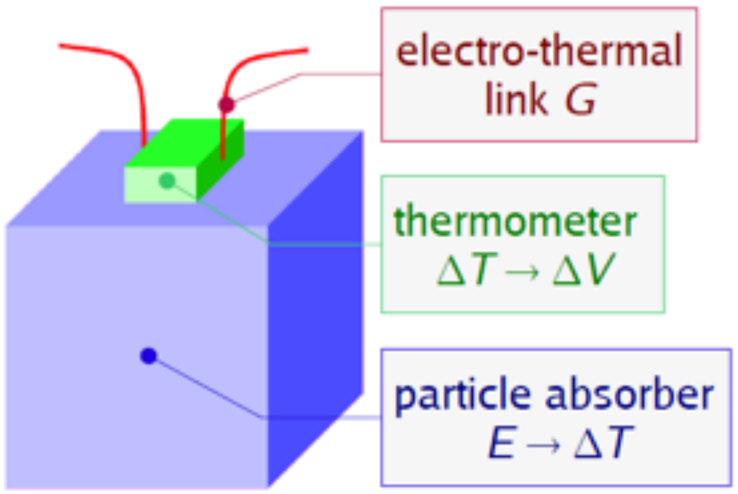
$\Delta E_{FWHM} < 10$ eV
$\tau_{risetime} < 1$ μs

- **Advantages:**
  - Source = detector
  - No backscattering
  - No molecular final state effects.
  - Self-calibrating

- **Experimental Challenges:**
  - Fast rise times to avoid pile-up effects.
  - Good energy resolution & linearity
  - Sufficient isotope production

New results!

Calorimetry



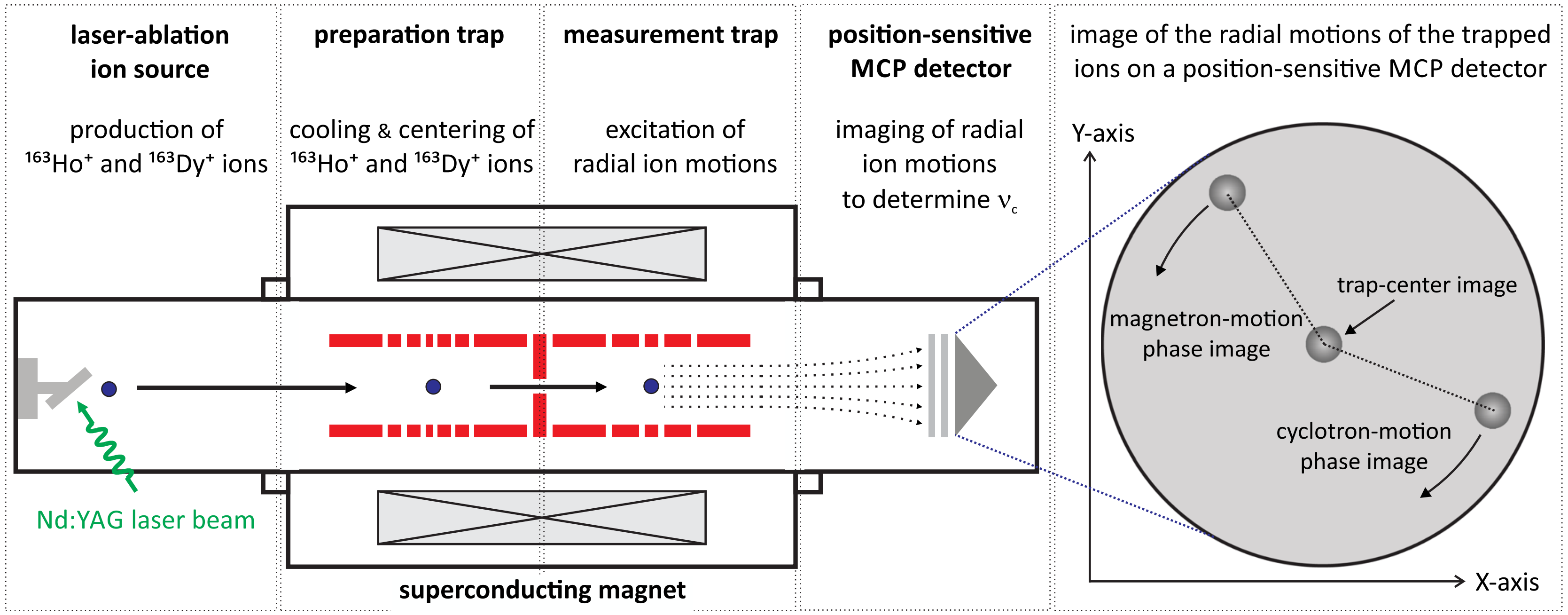
electro-thermal link G

thermometer $\Delta T \rightarrow \Delta V$

particle absorber $E \rightarrow \Delta T$

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

SHIPTRAP



laser-ablation ion source

production of $^{163}\mathrm{Ho}^+$ and $^{163}\mathrm{Dy}^+$ ions

preparation trap

cooling & centering of $^{163}\mathrm{Ho}^+$ and $^{163}\mathrm{Dy}^+$ ions

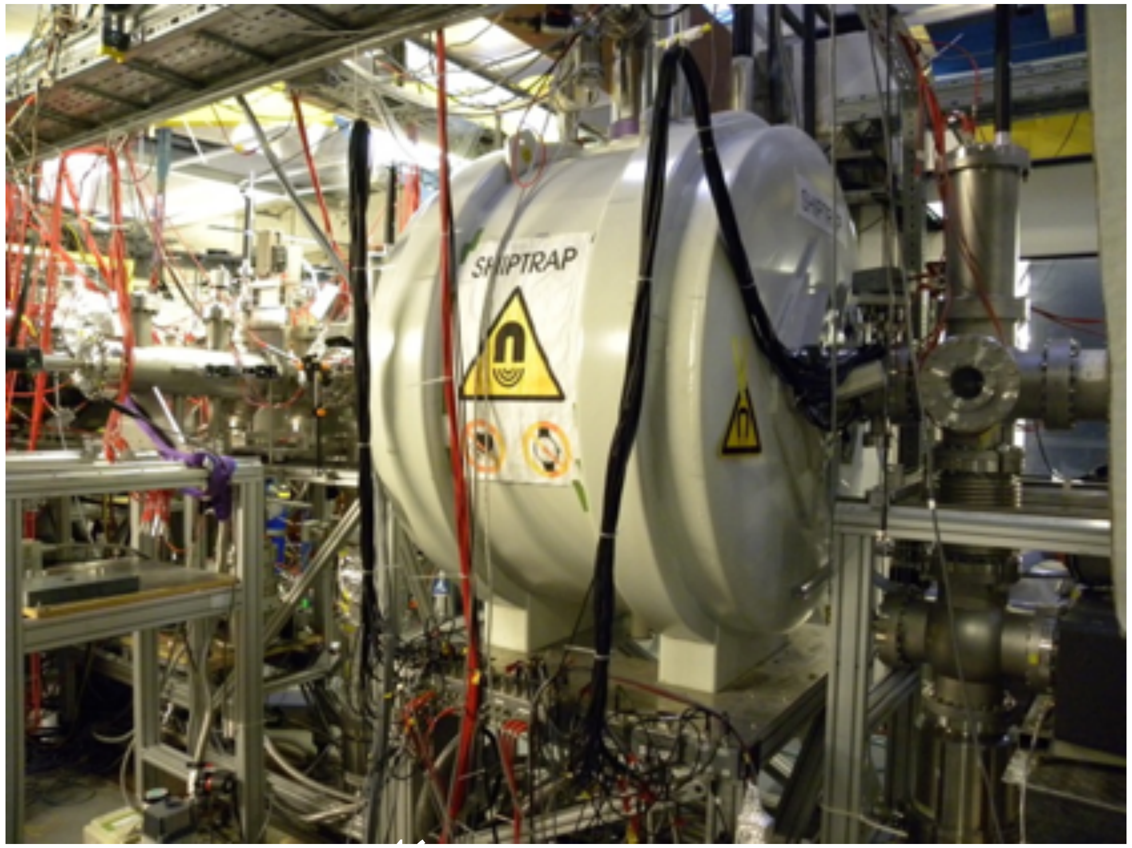
measurement trap

excitation of radial ion motions

position-sensitive MCP detector

imaging of radial ion motions to determine ν_c

image of the radial motions of the trapped ions on a position-sensitive MCP detector



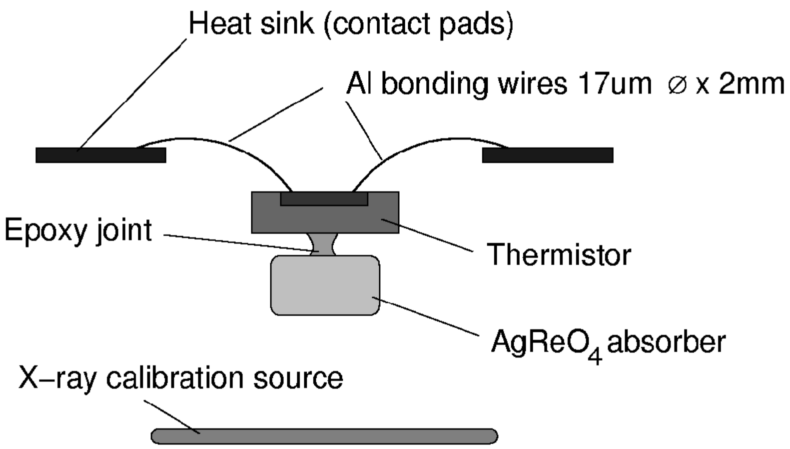
Latest results with Penning traps show improved resolution on the Ho-Dy mass difference.

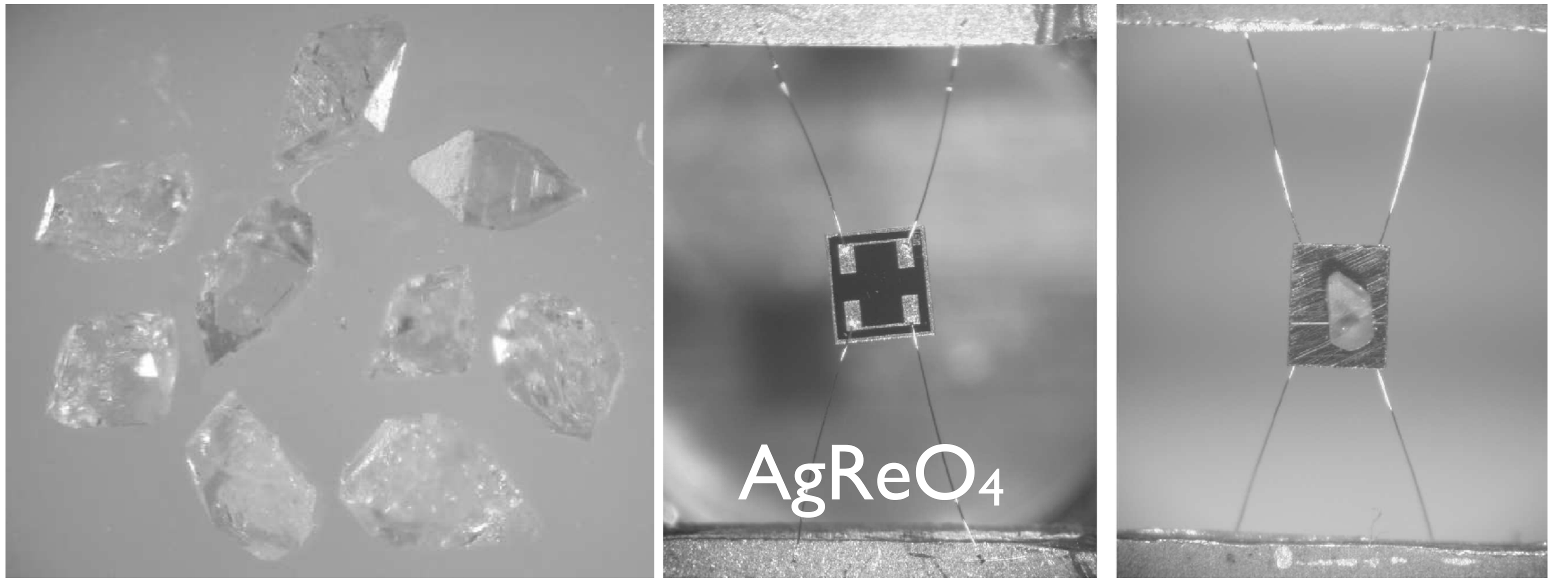
/PhysRevLett.115.062501

Their Predecessor

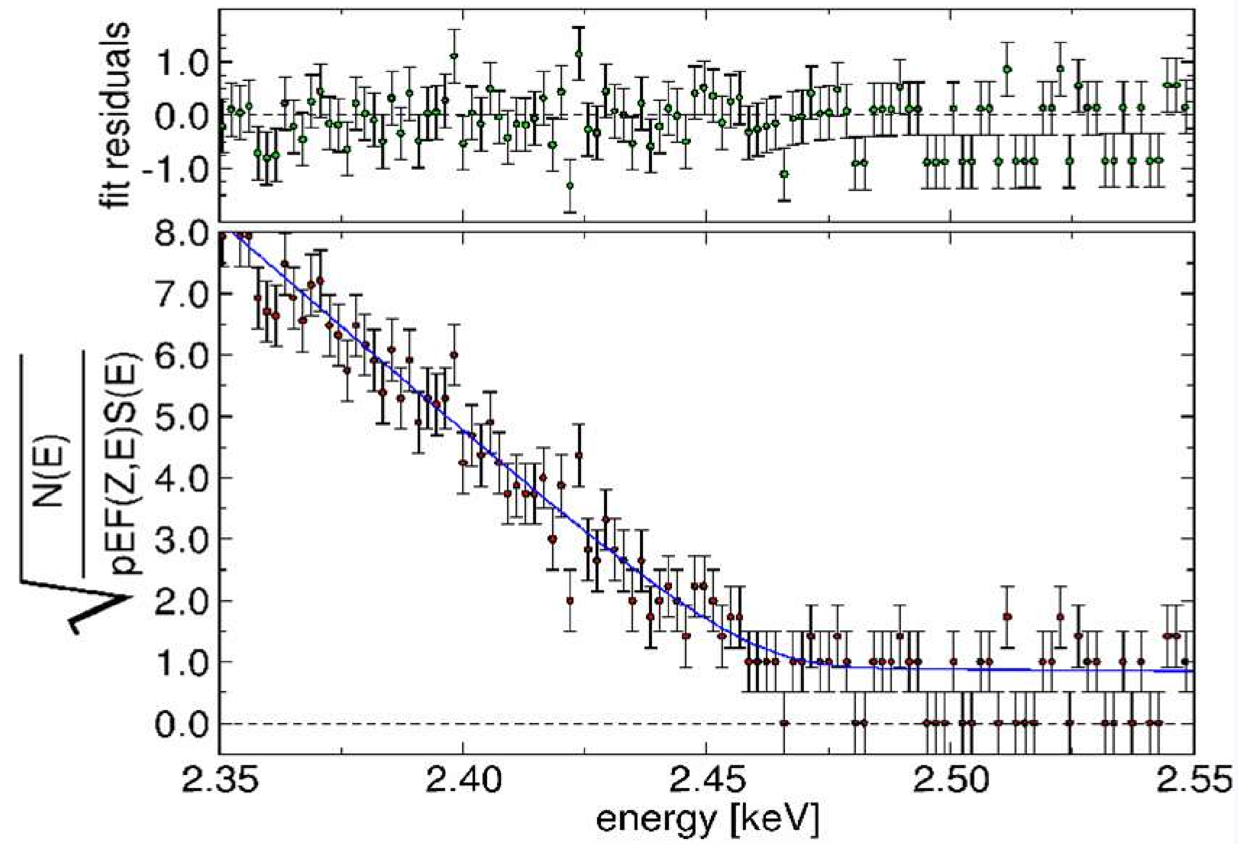
MARE

Calorimetry



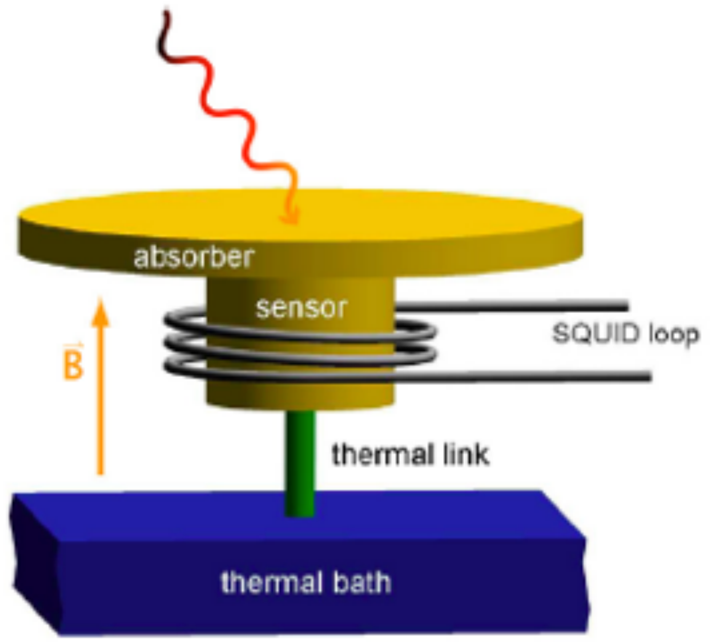


MARE provides the first β decay measurement of ^{187}Re using calorimetry



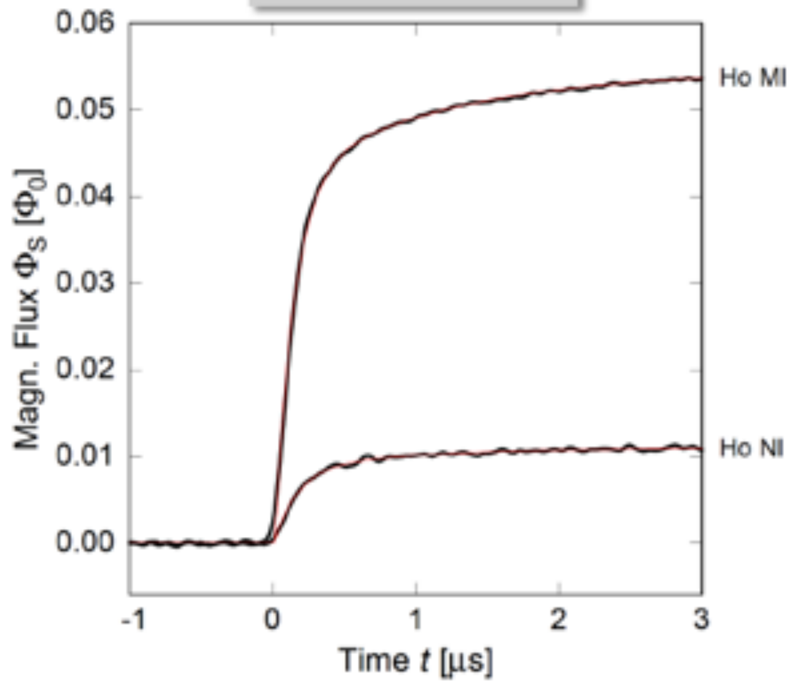
The ECHo Experiment

Technology:

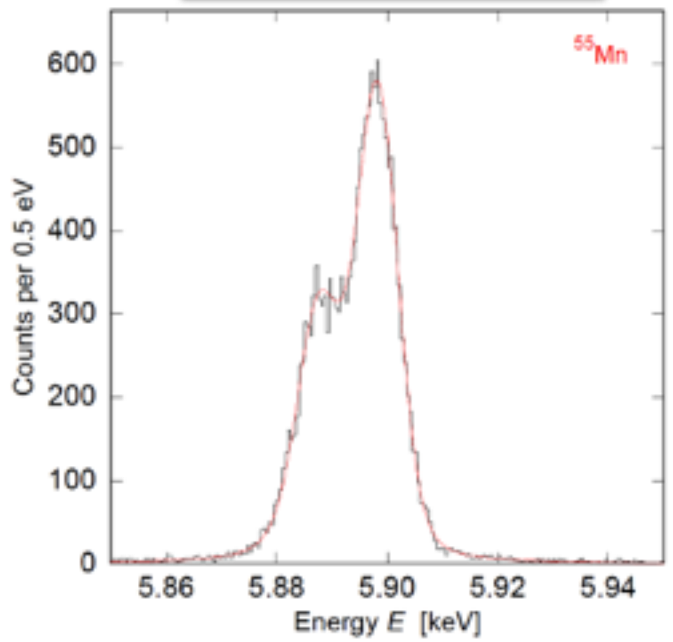


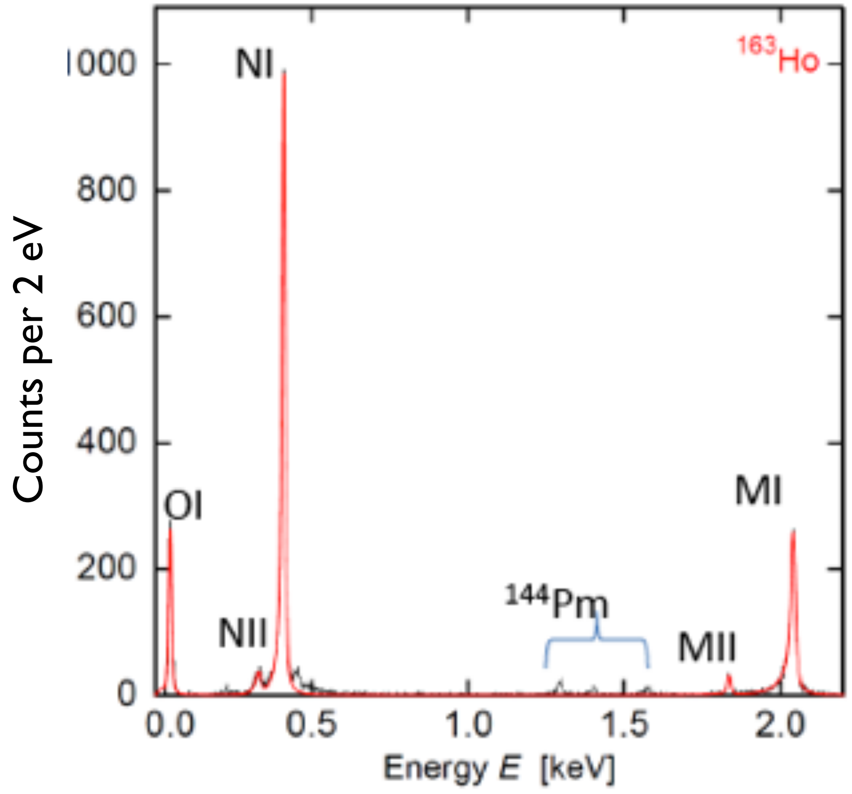
Metallic Magnetic Calorimeters

Rise Time: 134 ns



ΔE_{FWHM} = 7.6 eV @ 6 keV

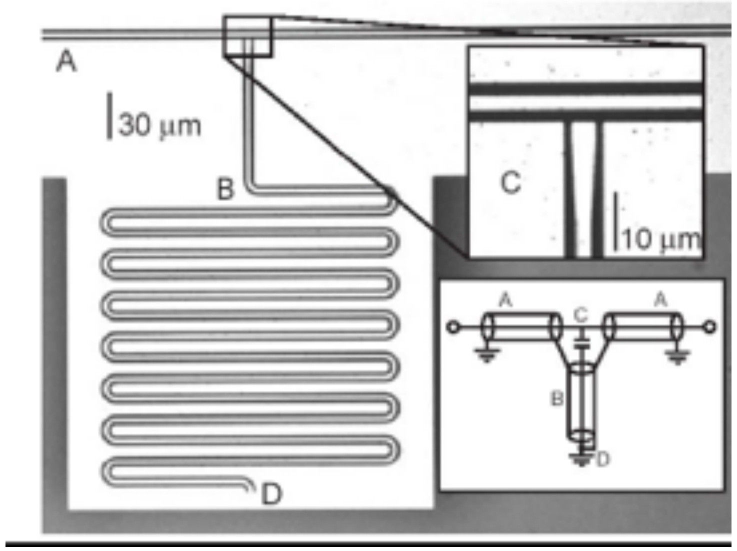




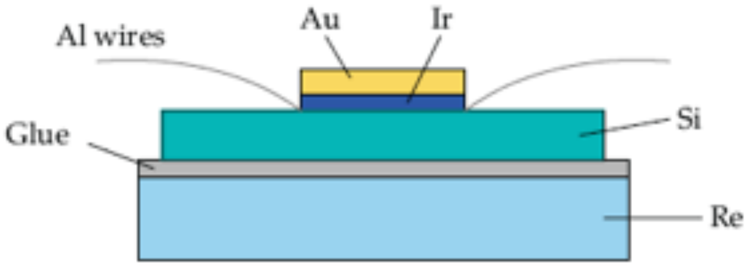
- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

The HOLMES Experiment

Technologies:



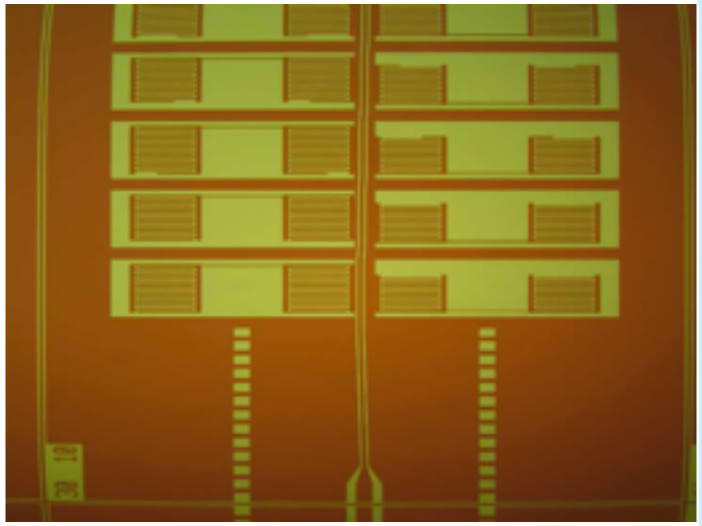
Superconducting Resonators

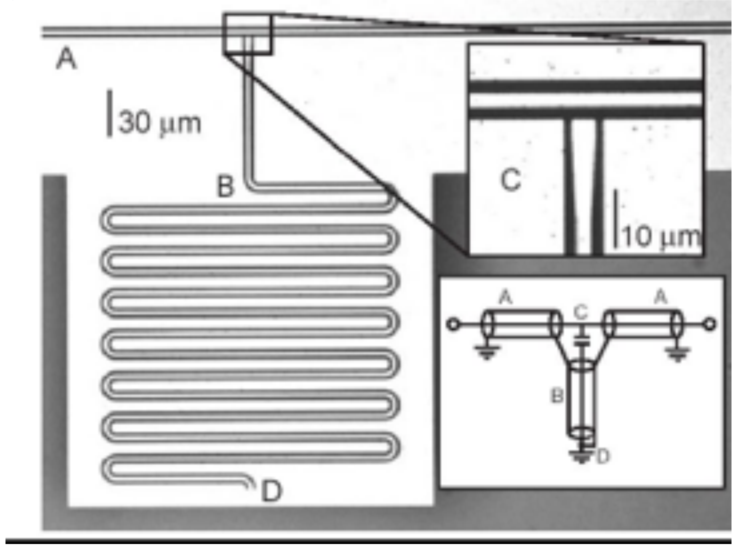


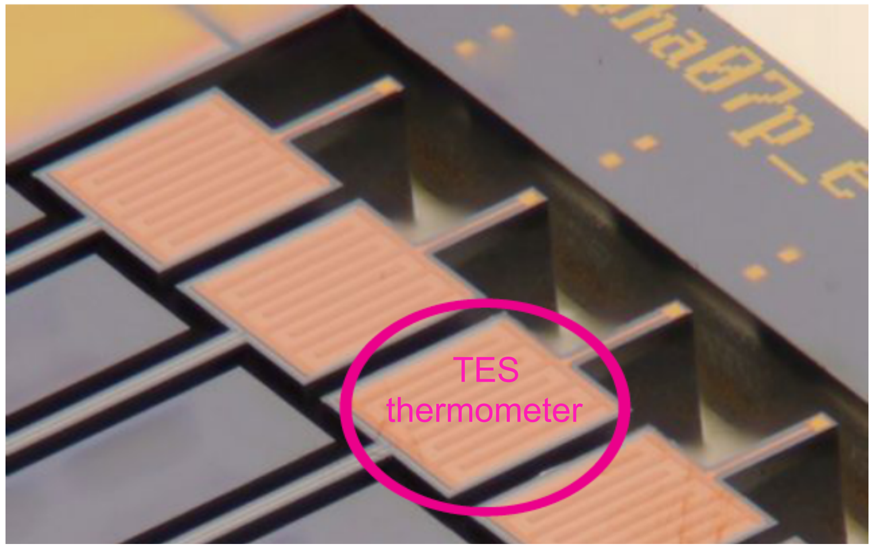
Transition Edge Sensors

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

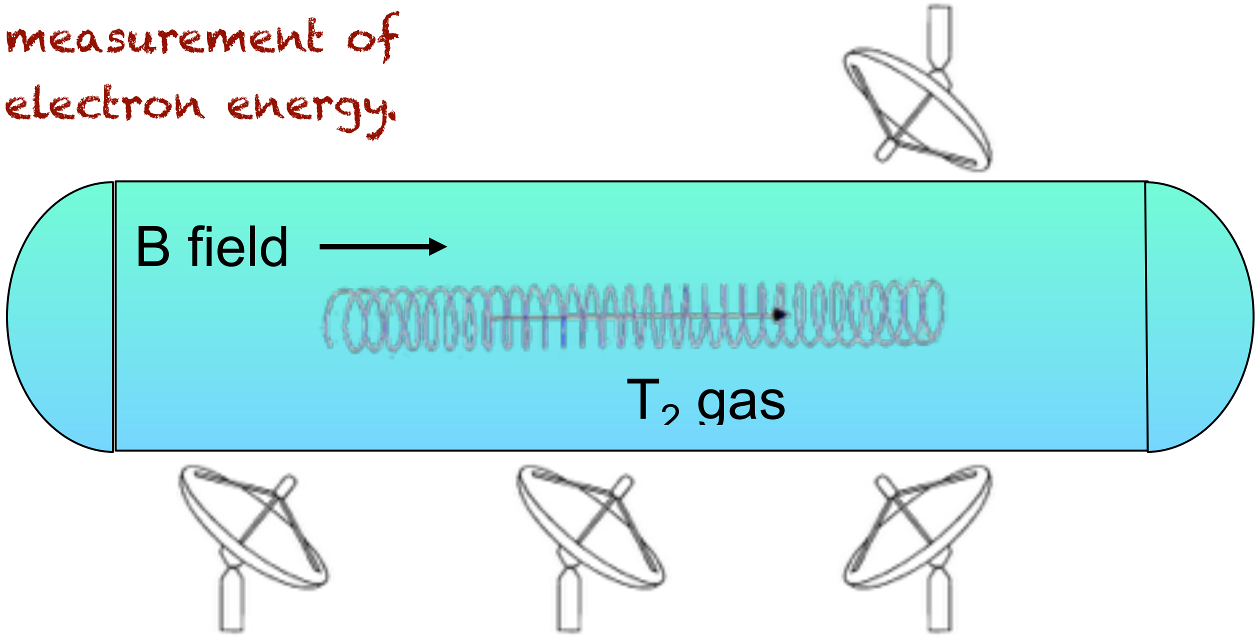
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

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

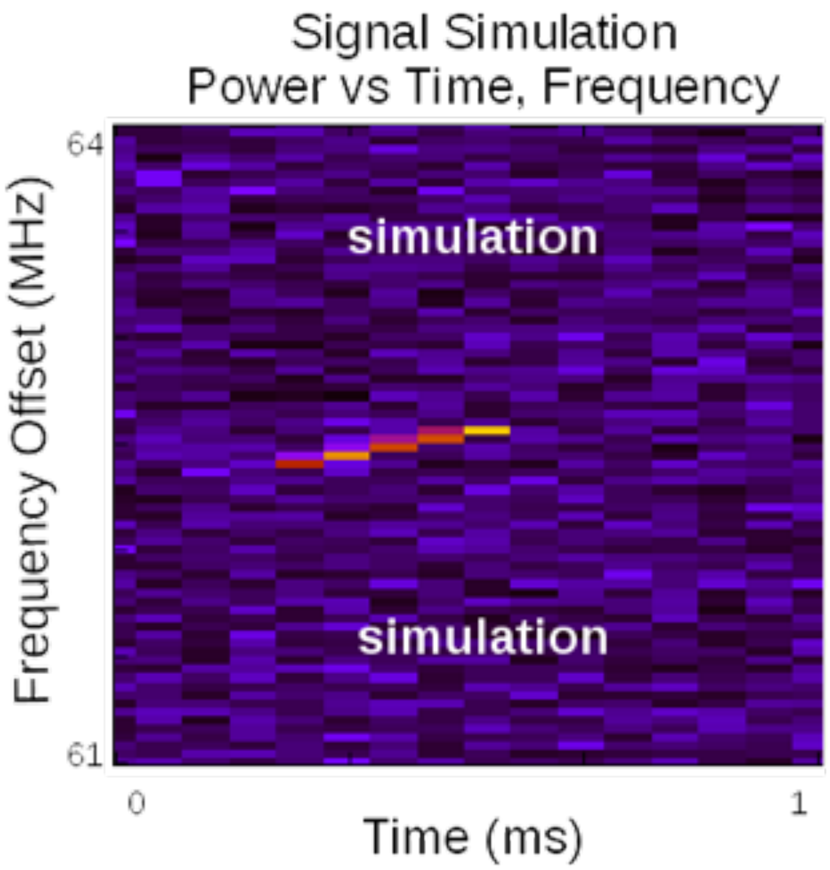
- Non-destructive measurement of electron energy.



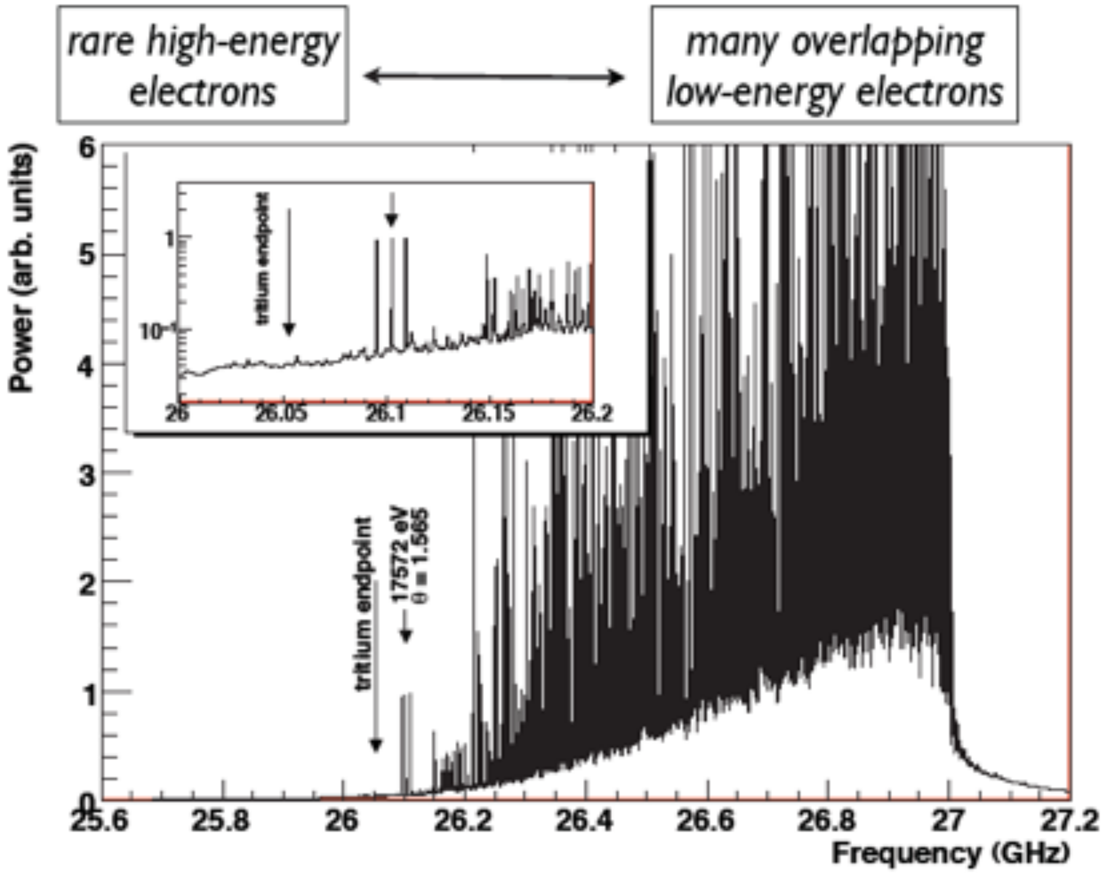
B. Monreal and JAF, Phys. Rev D80:051301

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)



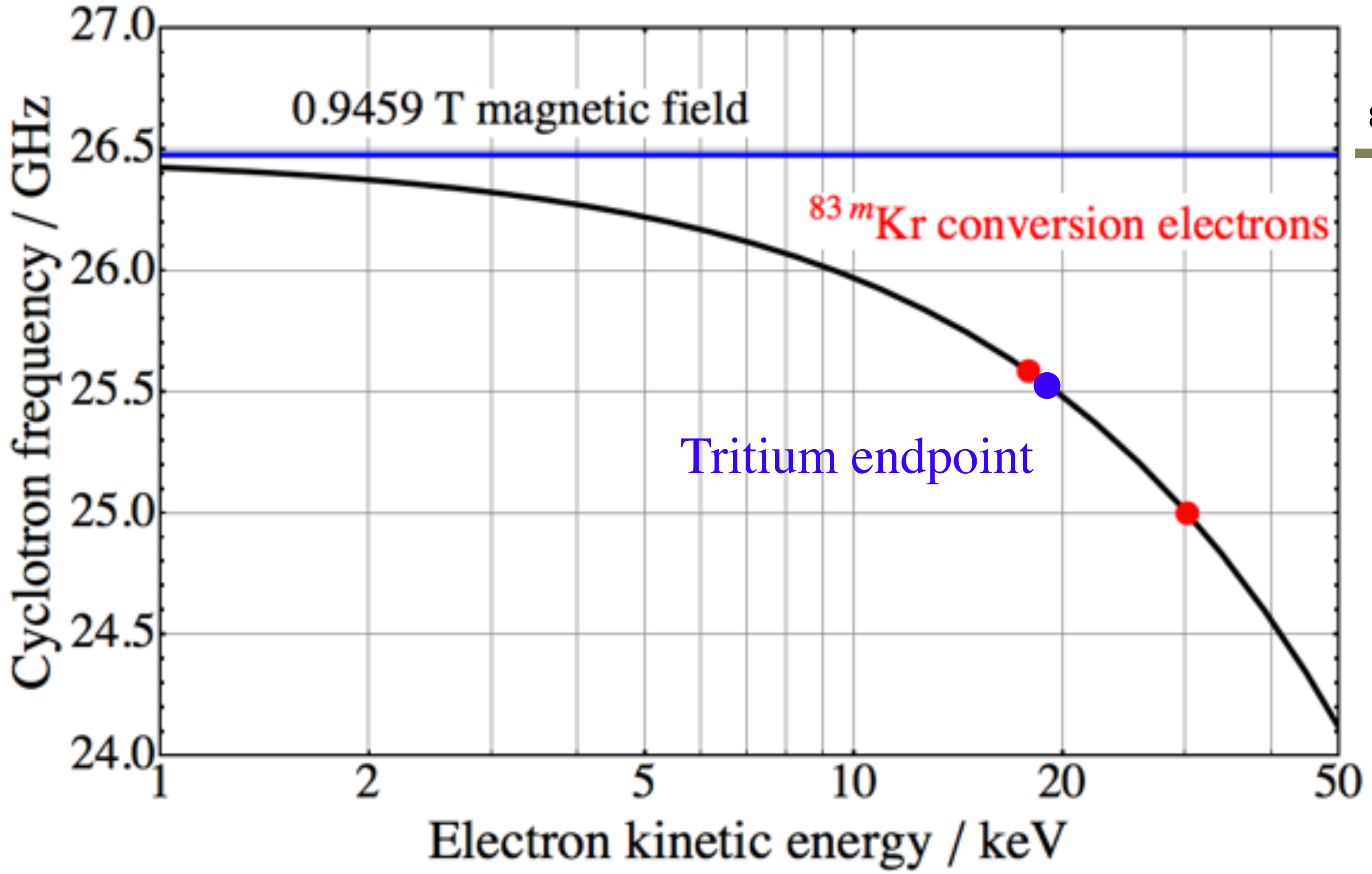
Signal Simulation
Power vs Time, Frequency

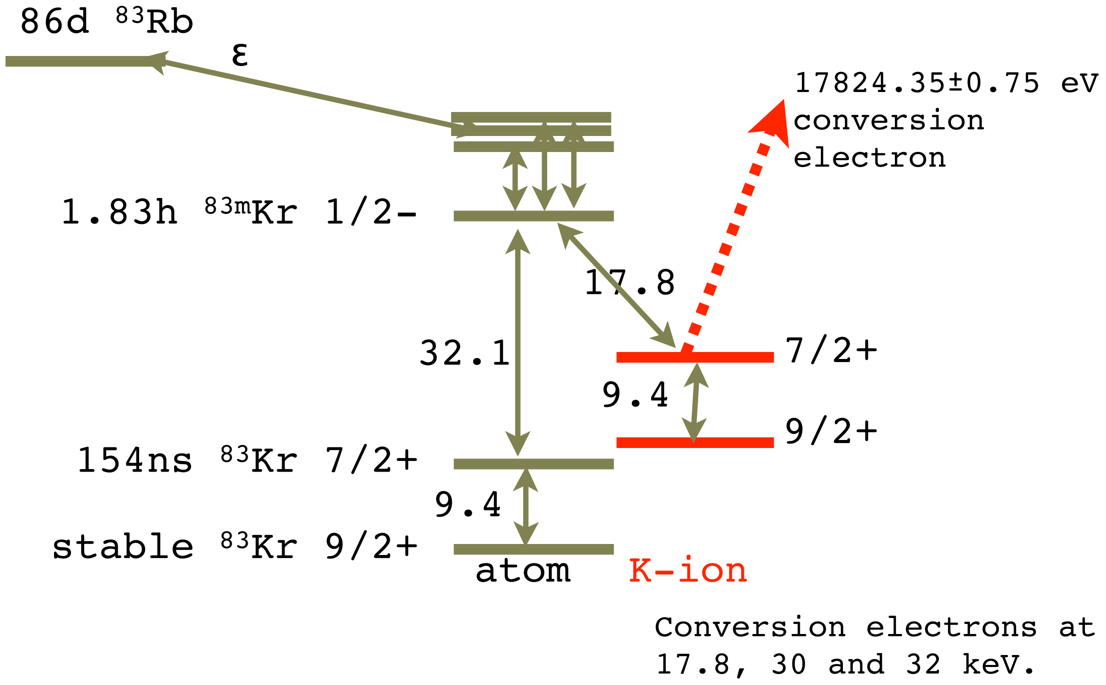


100,000 tritium decays in 30μs

Simulation of beta (frequency) spectrum

Initial Demonstration: ^{83m}Kr





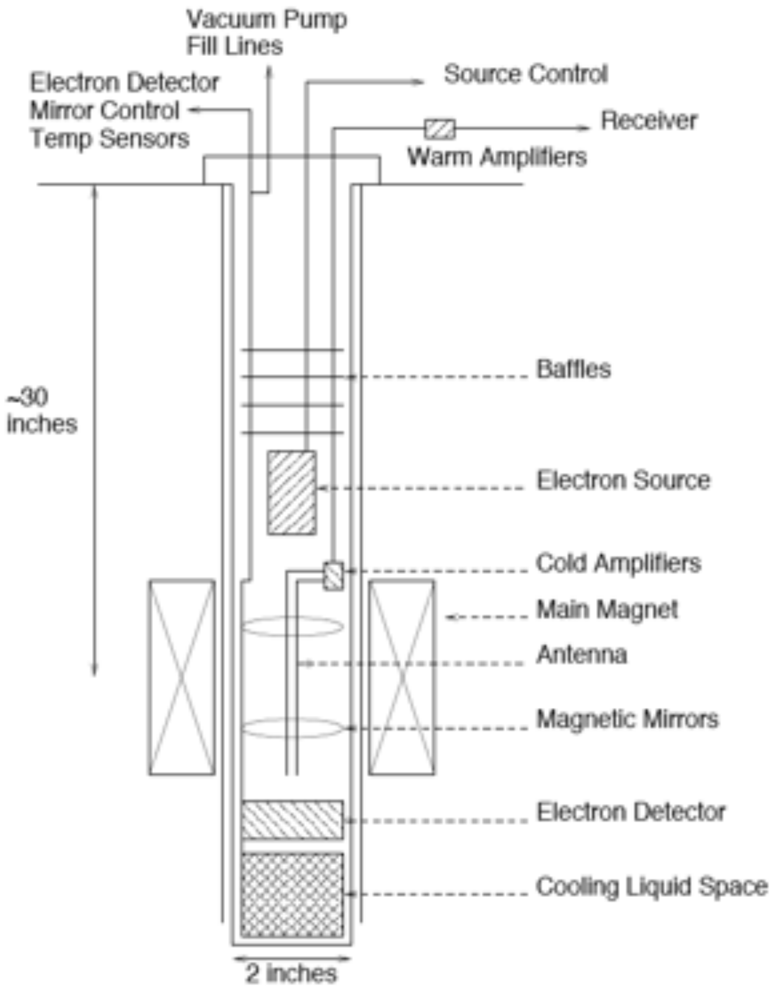
Conversion electrons at 17.8, 30 and 32 keV.

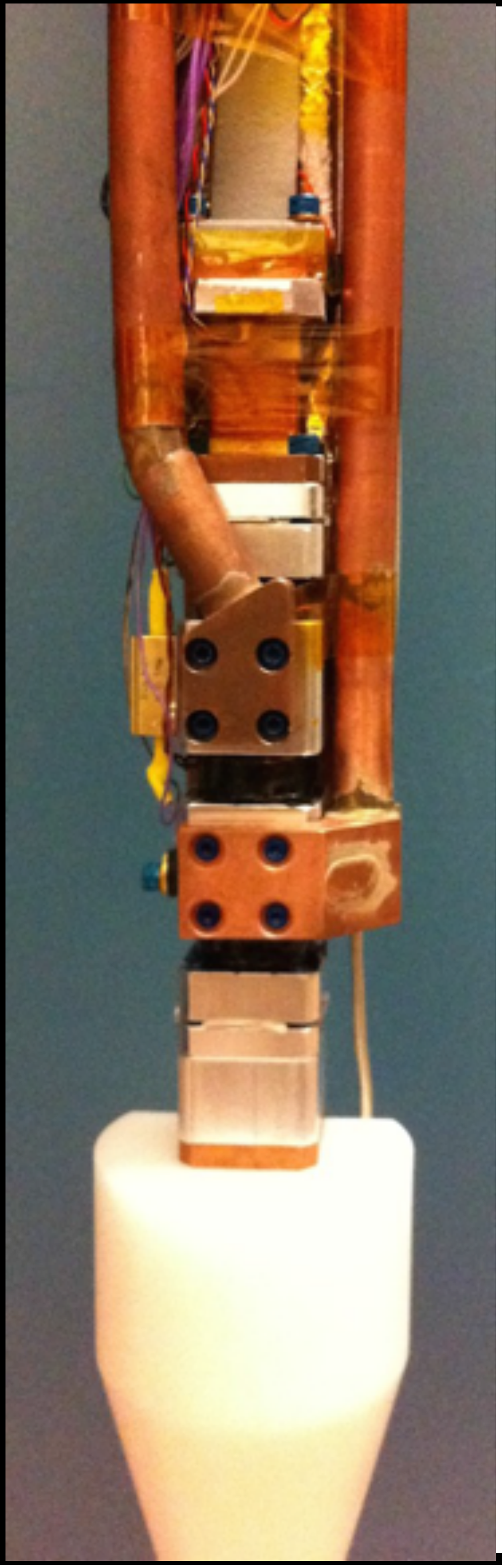
Phase I : Use mono-energetic source to determine single electron detection.

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

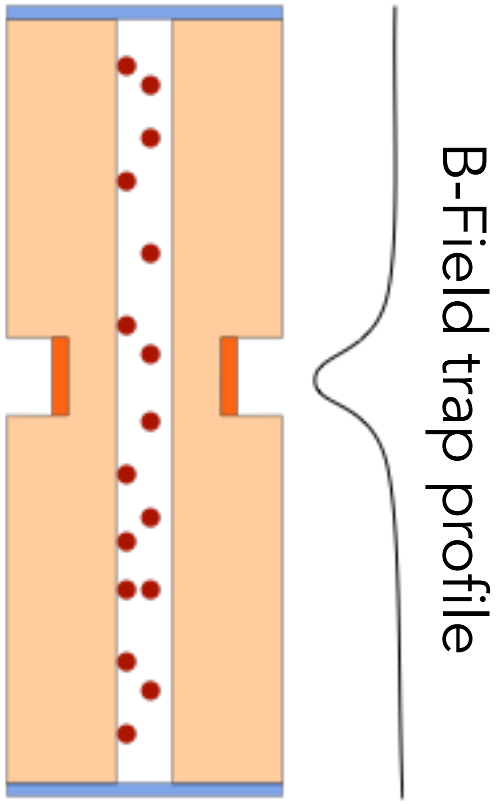
Basic Layout of Phase I

- **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 Apparatus



Copper waveguide

Kr gas lines

Magnetic bottle coil

Gas cell

Test signal injection port

Waveguide
Cut-away

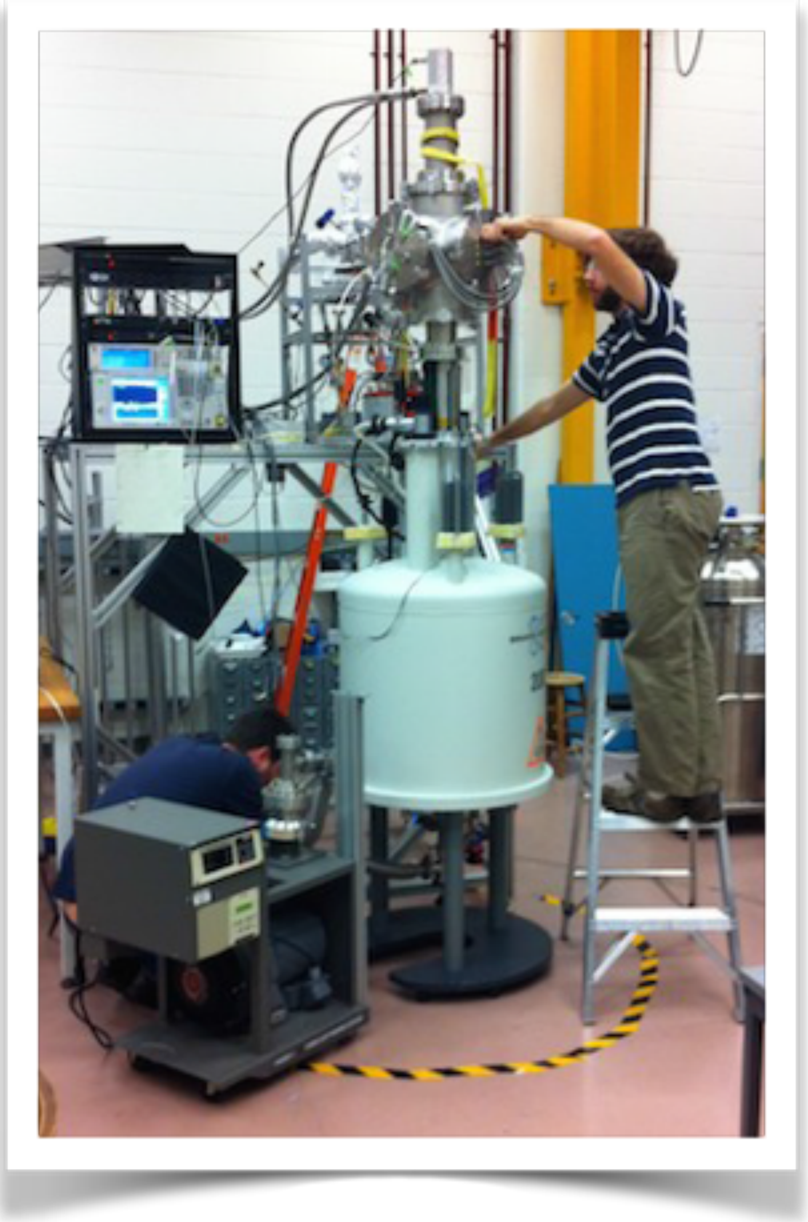
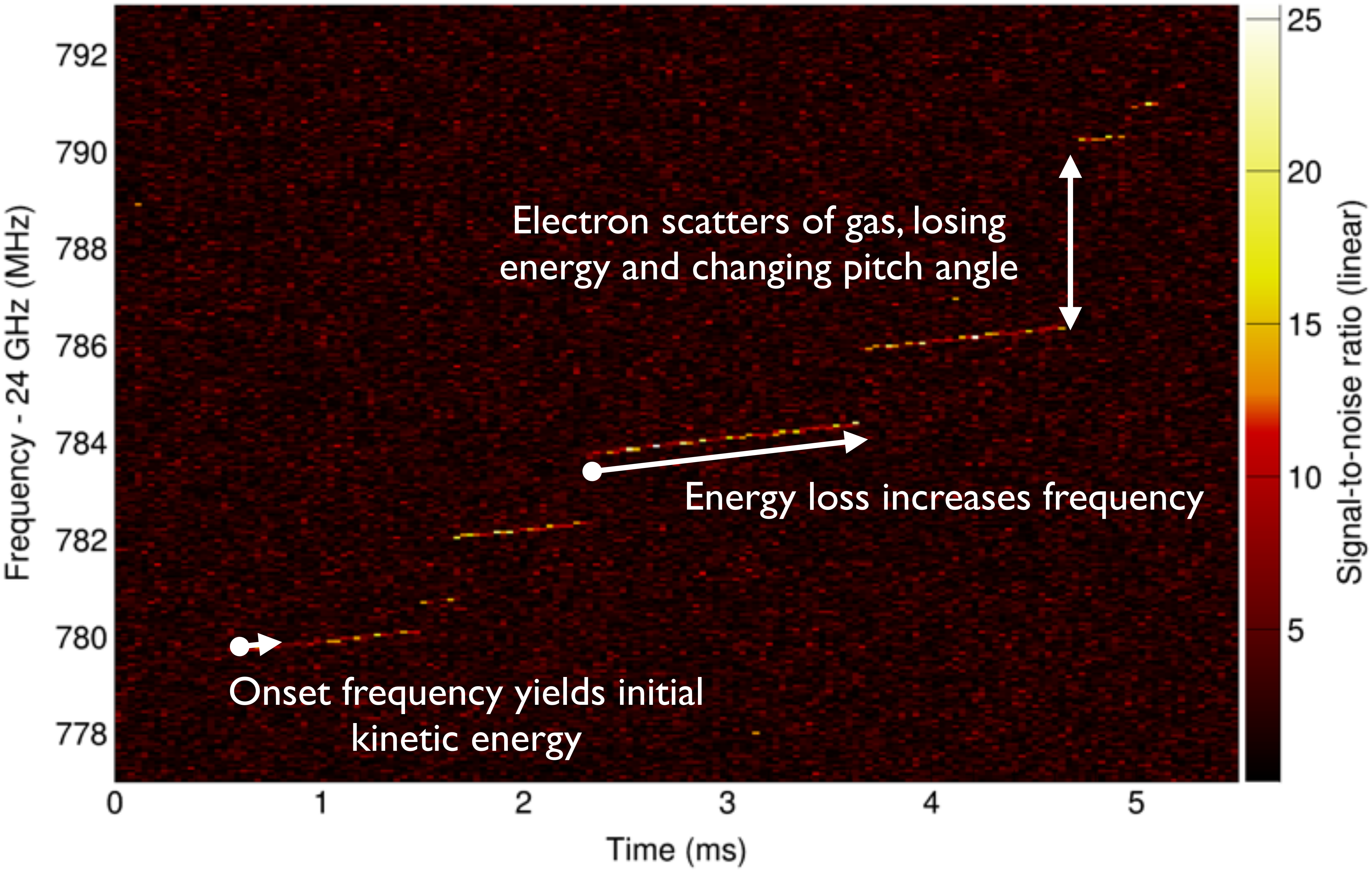


Photo of apparatus

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.

Project 8 "Event Zero"



Electron scatters of gas, losing energy and changing pitch angle

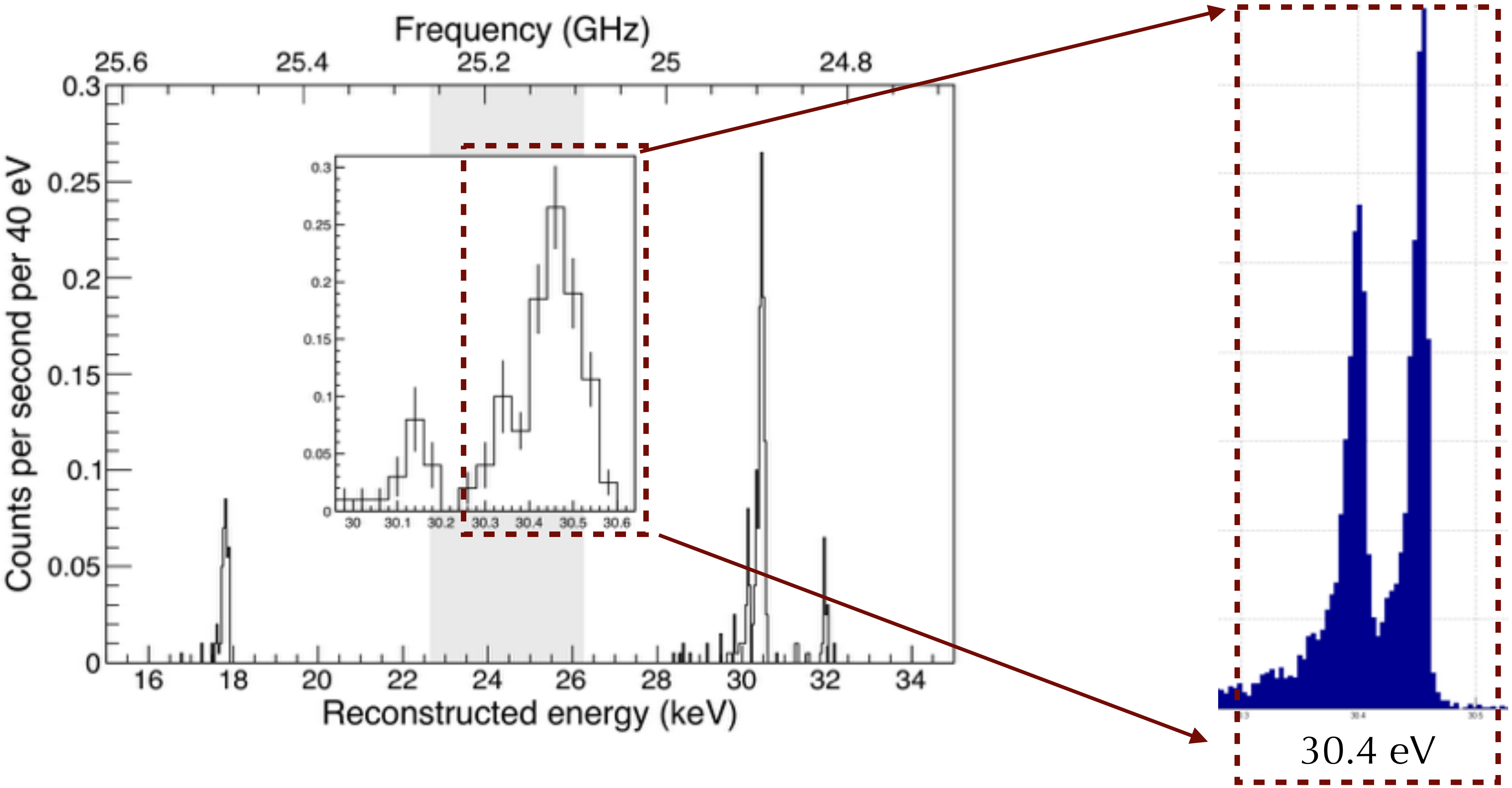
Energy loss increases frequency

Onset frequency yields initial kinetic energy

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

FWHM ~15 eV
(and improving)

Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

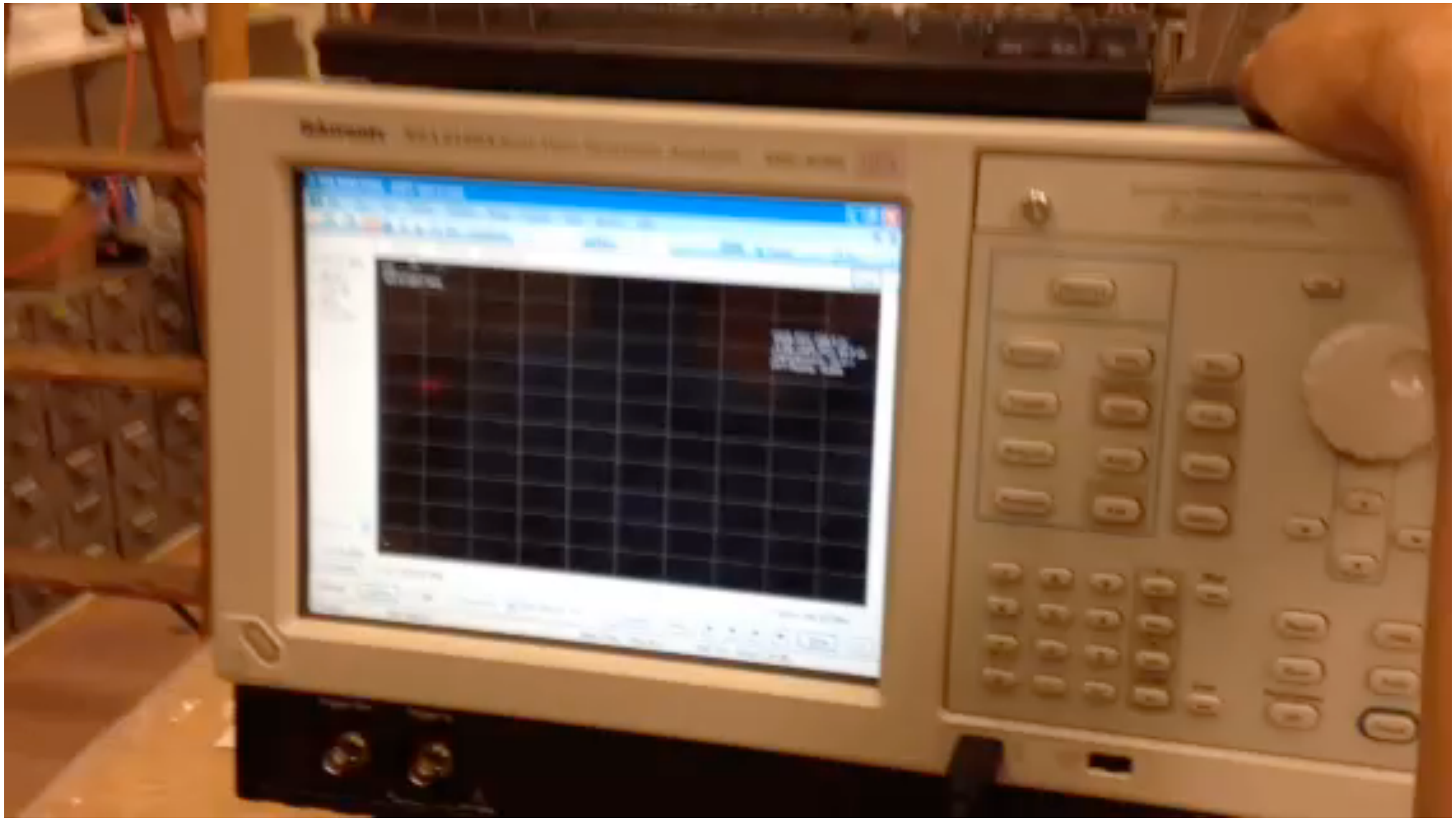
- The quest for neutrino mass has a long and very rich history, filled with remarkable people possessing remarkable ingenuity.
- We are by no means done. Oscillations provide a prediction that can and should be tested.
- Frontiers in beta decay, neutrinoless double beta decay and cosmology can now all feed into this remarkable measurement.

Thank you for
your attention

I'm sorry, we are out of time

(Backup slides)

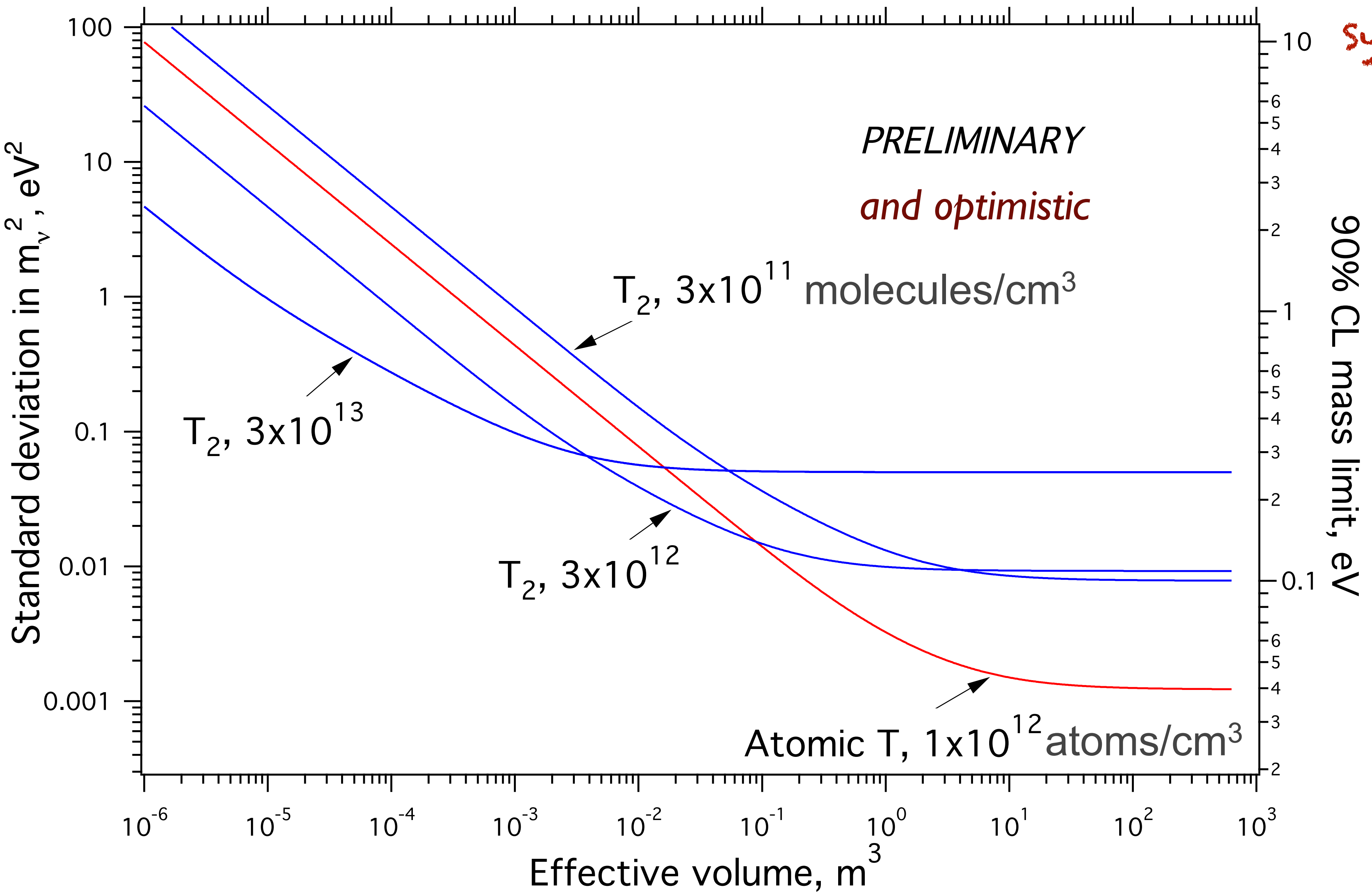
Eureka moment



First detection of single-electron cyclotron radiation.

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

Projected Sensitivity (Molecular & Atomic)



Systematics include:

Statistical uncertainties
(1 year run)

Final state interactions

Thermal broadening

Volume ≈ 0.05 m^3
(≈ 70 mCi)

Scattering

Background

Volume ≈ 5 m^3
(0.25 Ci)

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	
GERDA I	^{76}Ge	16/13	40	4 keV ROI	
KamLAND-Zen (Phase 2)	^{136}Xe	383/88	210 per t(Xe)	400 keV ROI	
CUORE	^{130}Te	600/206	50	5 keV ROI	Projected
GERDA II	^{76}Ge	35/27	4	4 keV ROI	
MAJORANA DEMONSTRATOR	^{76}Ge	30/24	4	4 keV ROI	
NEXT 100	^{136}Xe	100/80	9	17 keV ROI	
SNO+	^{130}Te	2340/160	45 per t(Te)	240 keV ROI	

* FV = $0\nu\beta\beta$ isotope mass in fiducial volume (includes enrichment factor)
† Region of Interest (ROI) can be single or multidimensional (E, spatial, …)