Experimental Neutrino Physics II: The Nature of Neutrinos

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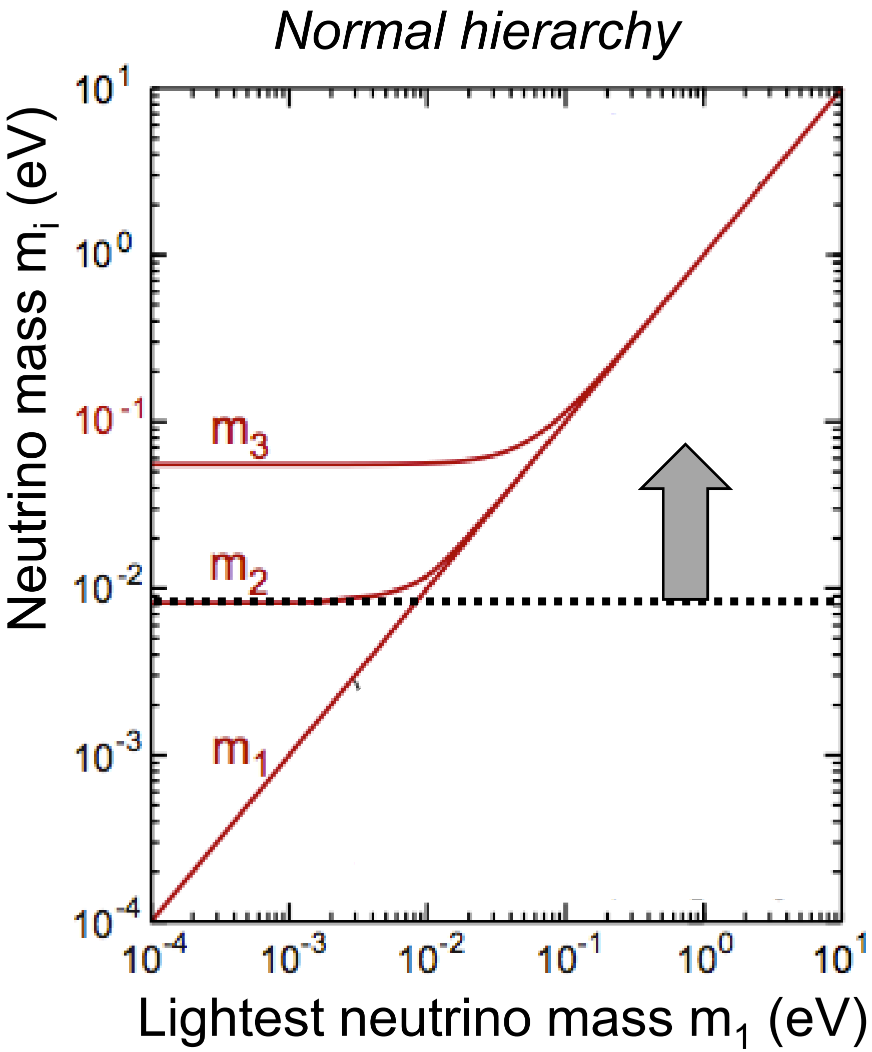
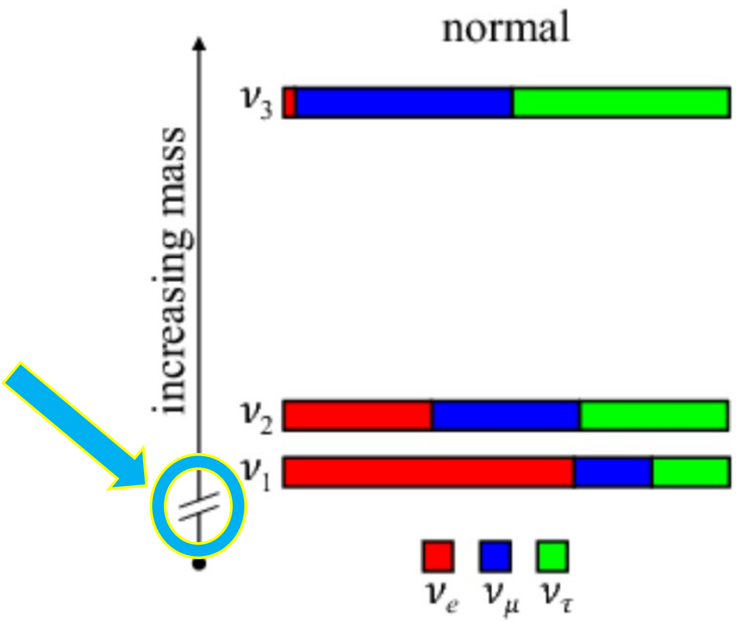
Outline

- The absolute neutrino-mass scale
  - In the lab, and elsewhere
  - How to measure a (low-energy) spectrum
  - Snapshot: Complex spectra
  - Recent commissioning progress
- Searching for Majorana neutrinos

Neutrino Mass Scale

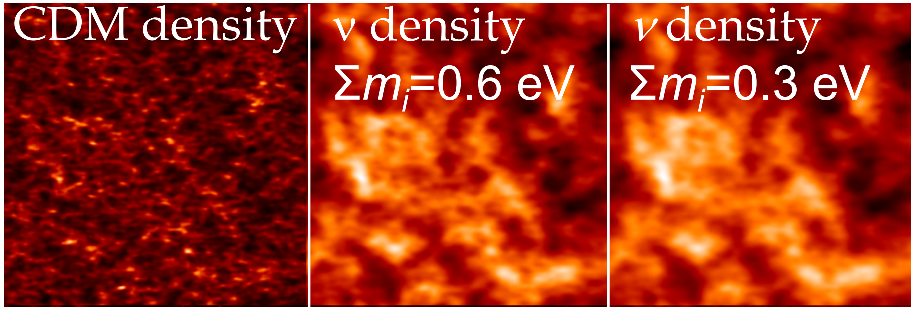


- Oscillation experiments give a lower limit on the two heavier neutrino-mass states
- What can we say about the offset of the lightest mass from zero?



Neutrino Mass from Cosmology...

- Most abundant matter particle in universe
  - Neutrino mass affects structure formation, CMB



J. Brandbyge et al., JCAP ***2008*** *(2008) 020*

$$\sum_i m_i < 0.72 \text{ eV}$$ *PlanckTT + lowP*

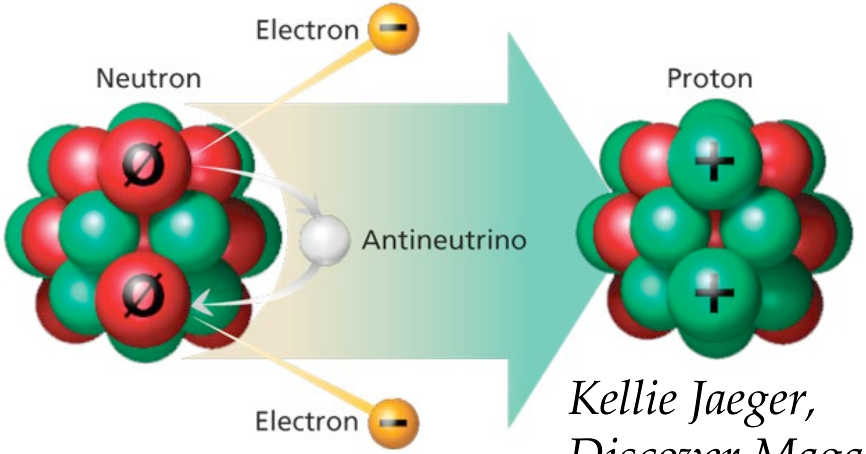
$$\sum_i m_i < 0.21 \text{ eV}$$ *PlanckTT + lowP + BAO*

Planck collaboration, arXiv:1502.01589

- CMB ν-mass limits degenerate with H_0 , σ_8
- Tension with cluster counts
- Better m_ν from lab can disentangle ΛCDM inputs

.. or 0νββ ...

- If neutrinos are Majorana instead of Dirac, then:
  - Lepton number violation
  - Possible baryogenesis explanation
  - Neutrinoless double beta decay 0νββ
    - More on this later in the lecture ...



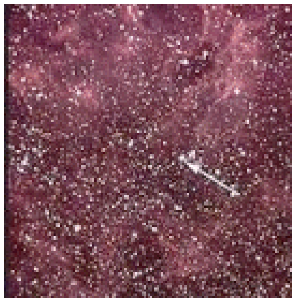
Kellie Jaeger, Discover Magazine

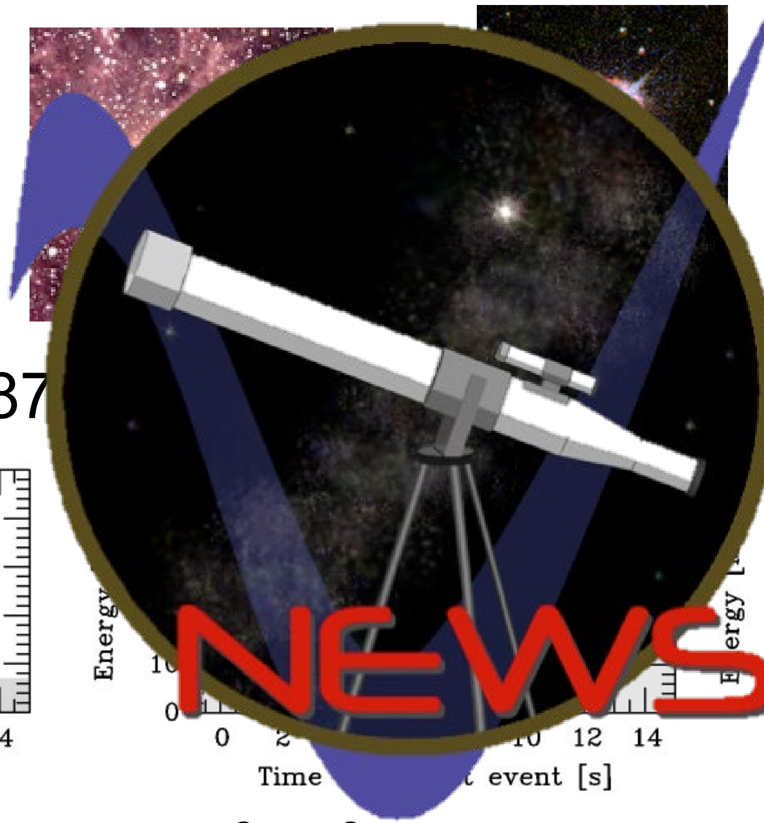
$$\Gamma^{0\nu} = G^{0\nu} \left|M^{0\nu}\right|^2 \underbrace{\left|\sum_i U_{ei}^2 m_i e^{i\alpha_i}\right|^2}_{\langle m_{\beta\beta}\rangle^2}$$

- Better m_ν from lab gets the most of data

...or Supernovae?

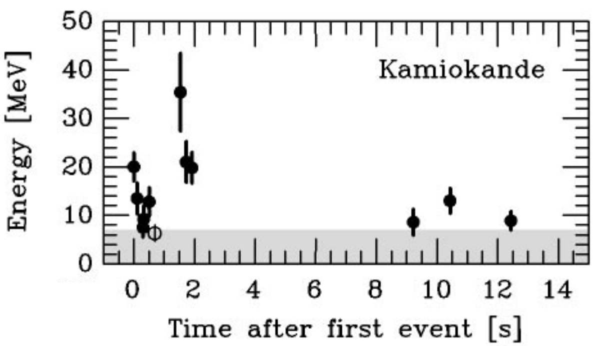
- Supernova 1987a in light

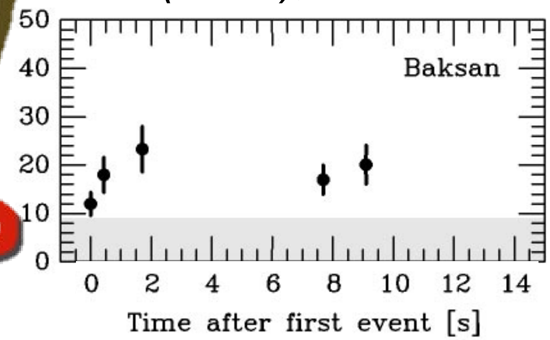




- Supernova 1987

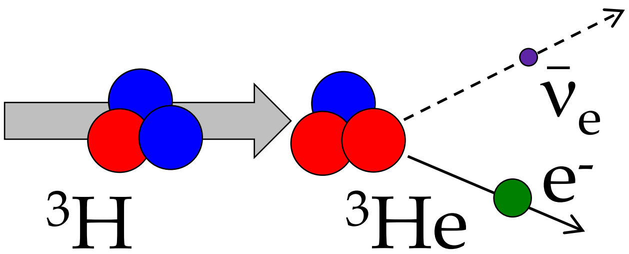
Raffelt, Annu. Rev. Nucl. Sci. ***49*** *(1999), 163*

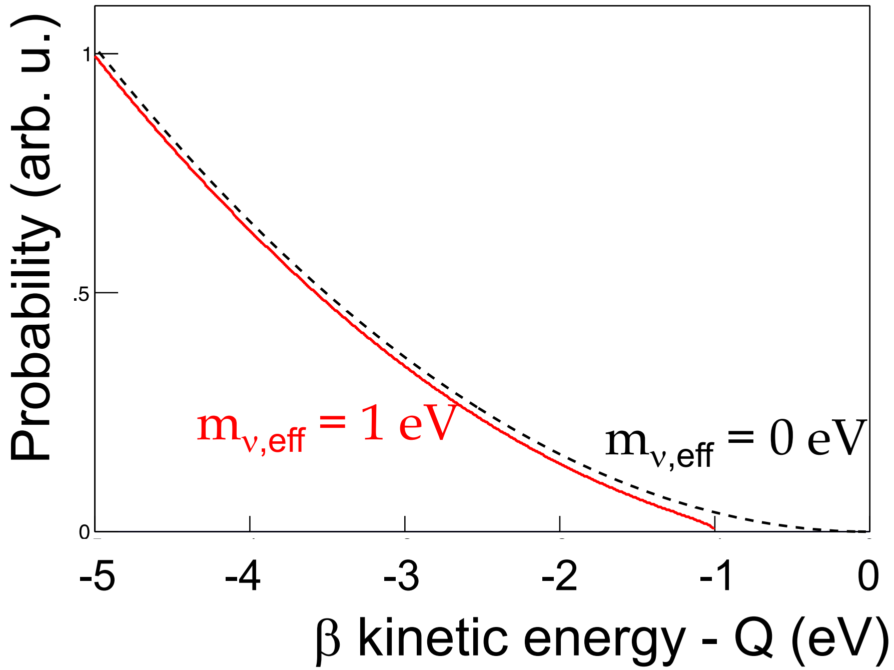




- Time delay goes as m_ν^2/E_ν^2
- From absence of dispersion, $m_\nu < 5.8$ eV

Direct m_ν from β decay





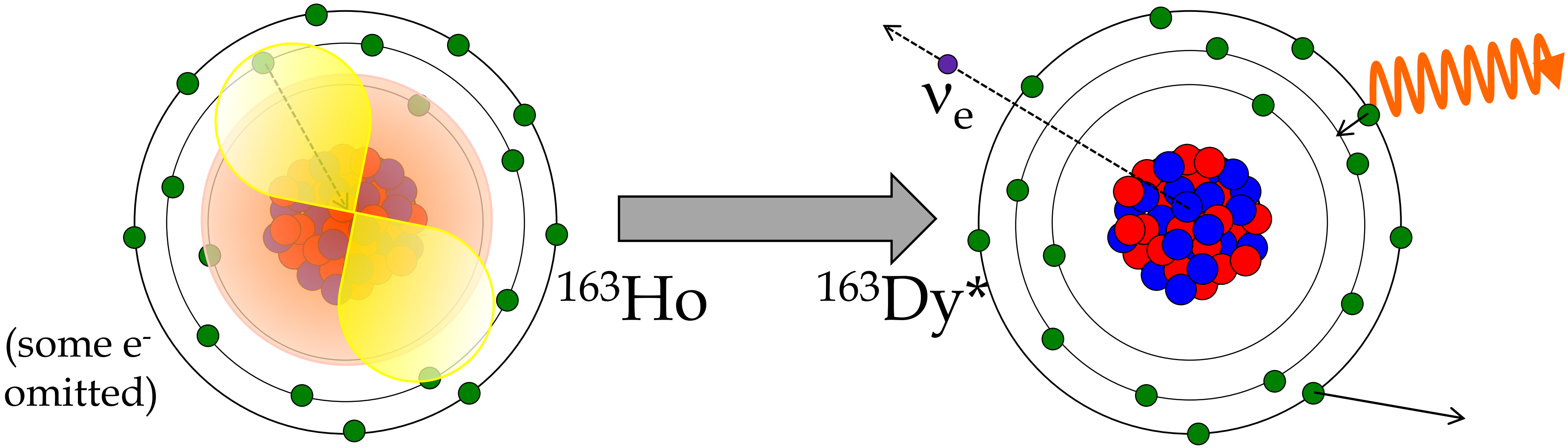
- Extract effective neutrino mass from spectral shape near endpoint

$$m^2_{\nu,eff} = \sum_i^3 |U_{ei}|^2 m_i^2$$

$$\approx m_\nu^2$$ *(quasi-degenerate regime)*

^{3}H (tritium)	^{187}Re	^{115}In to ^{115}Sn*
Q = 18.6 keV	Q = 2.47 keV	Q = 0.173 keV
$t_{1/2}$ = 12.3 years	$t_{1/2}$ = 4.5 x 10^9 yrs	$t_{1/2}$ = 4.4 x 10^{20} yrs
Super-allowed	Forbidden	Forbidden

Direct m_ν from Electron Capture

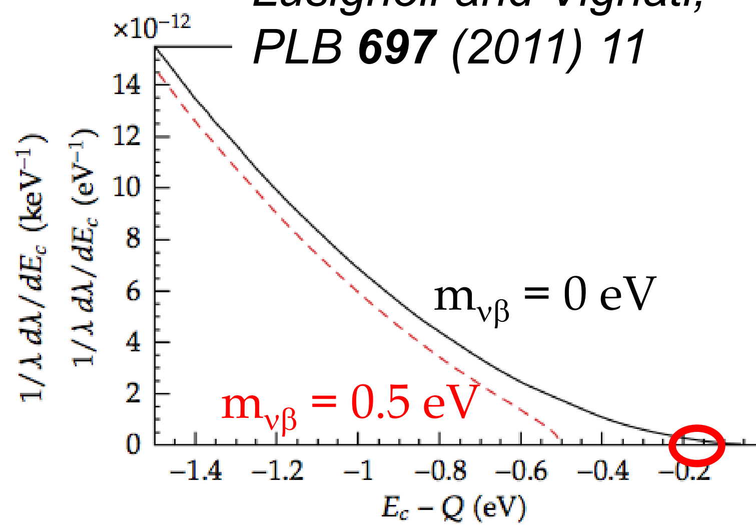


- Capture de-excitation energy in $^{163}\text{Ho} \longrightarrow {}^{163}\text{Dy}^* + \nu_e$

De Rújula and Lusignoli, PLB ***118*** *(1982) 429*

^{163}Ho
Q = 2.83 keV
$t_{1/2}$ = 4750 years

Lusignoli and Vignati, PLB ***697*** *(2011) 11*



The State of the Art

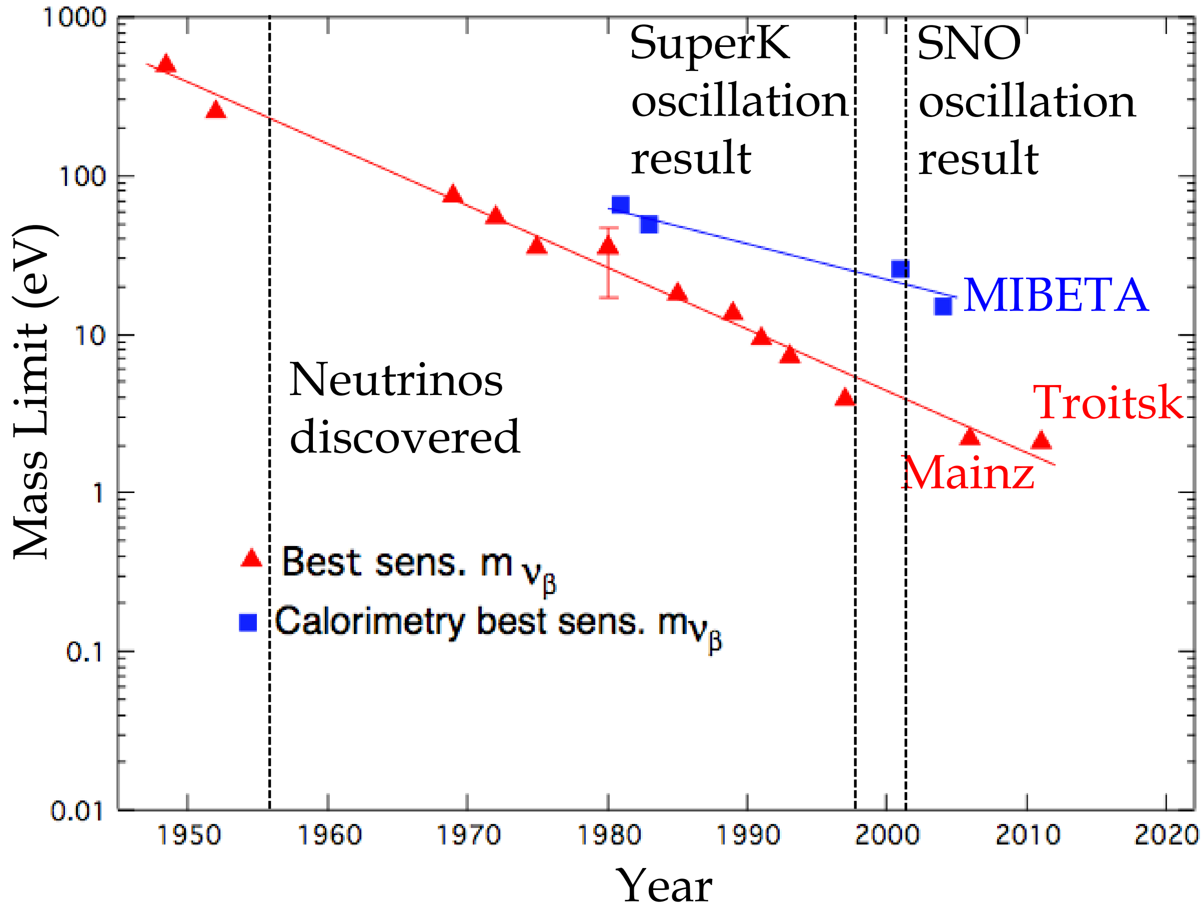


Figure from J. Wilkerson, Neutrino 2012

- Two more decades until oscillation limit
- No longer quasi-degenerate below 0.1 eV

$$m_{\nu_\beta} \neq \sqrt{\sum_i^3 |U_{ei}|^2 m_i^2}$$

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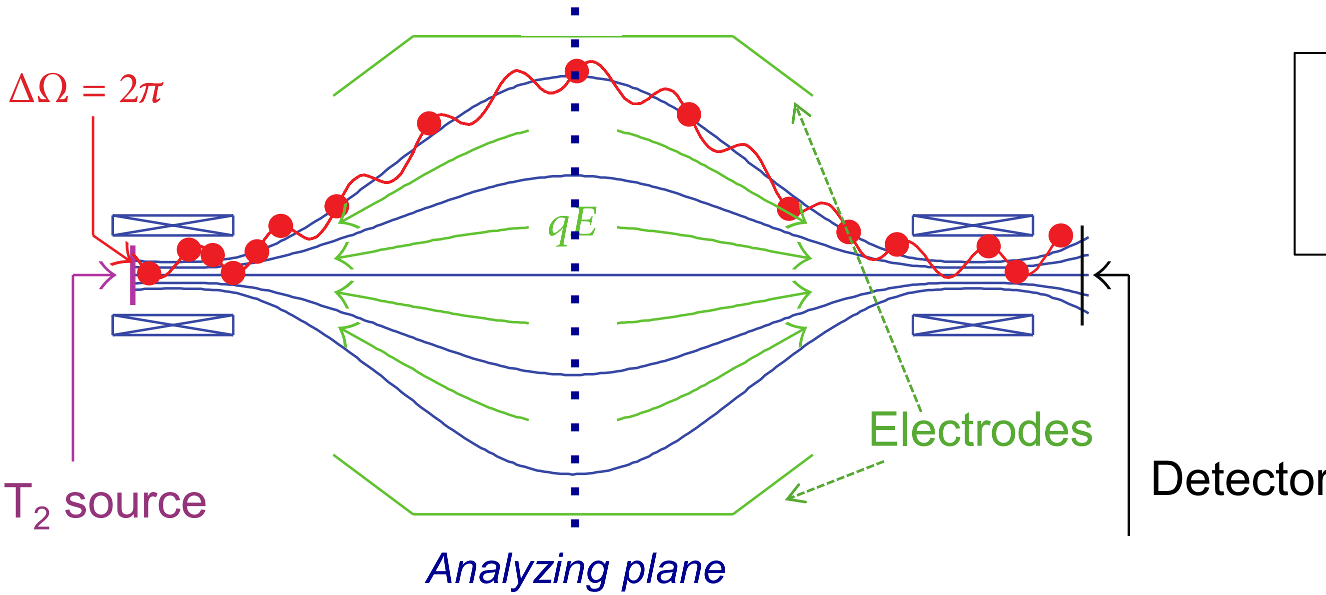
The MAC-E Filter

- Measure integral spectrum with moving threshold
- **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter



$$\mu = \frac{E_\perp}{B} = \mathrm{const}$$

$$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

Detailed application to KATRIN: Kleesiek et al., arXiv:1806.00369

KATRIN

- 10^{11} tritium decays/s
- B-field range 3 - 60000 G
- ΔE = 0.93 eV
- Design sensitivity: 0.2 eV @ 90% CL

Cyclotron Radiation Emission Spectroscopy

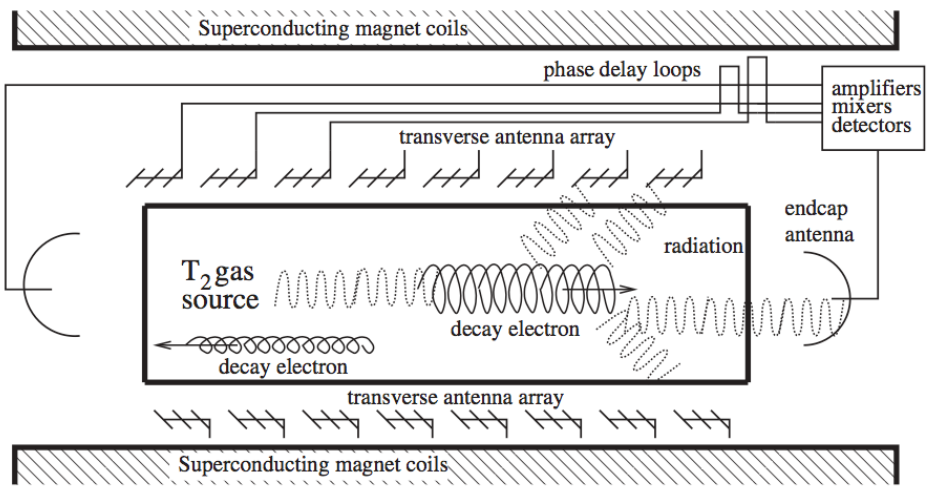
Never measure anything but frequency.

-- Arthur Schawlow

- An electron in a magnetic field will radiate at

$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi} \frac{1}{m_e + \frac{1}{c^2} E_\beta}$$

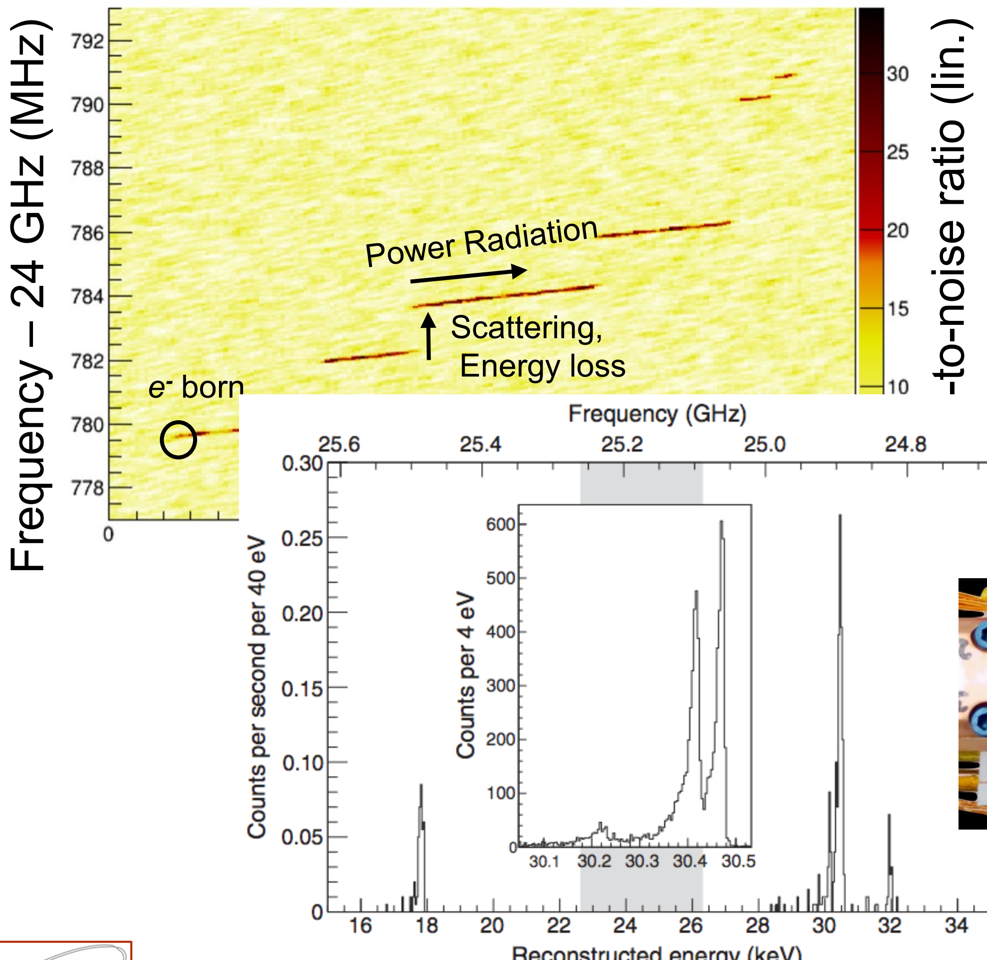
- No need to transport βs away from source
- But ... ppm frequency sensitivity needs Δt = 20 μs at 18 keV
  - Must follow β for 1.4 km!
  - Need a magnetic trap



*Monreal and Formaggio, PRD **80** (2009) 051301(R)*

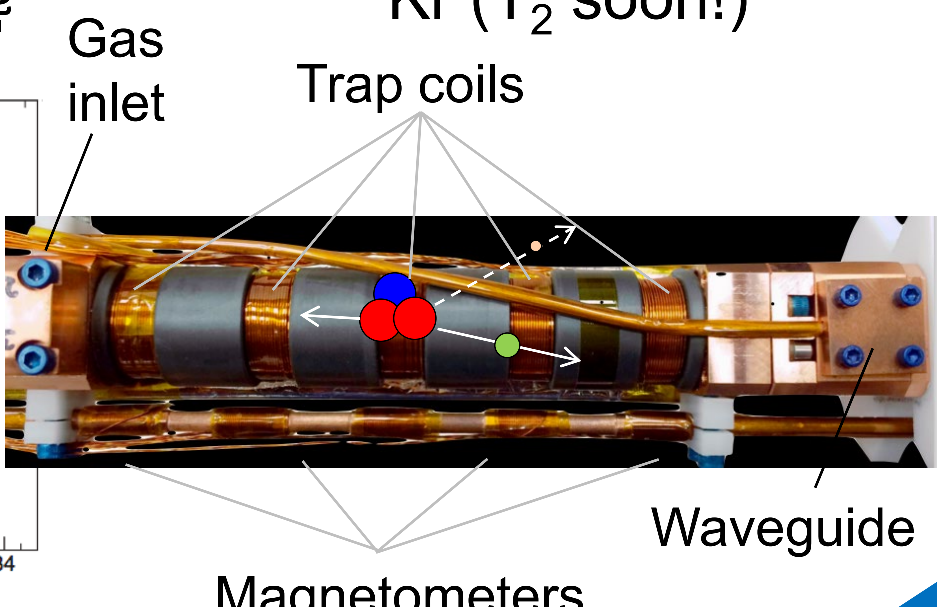
Project 8

- ^{83m}Kr events from first prototype



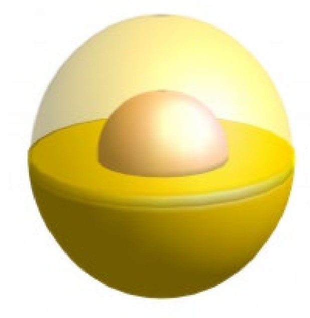
Asner et al., PRL ***114*** *(2015) 162501*

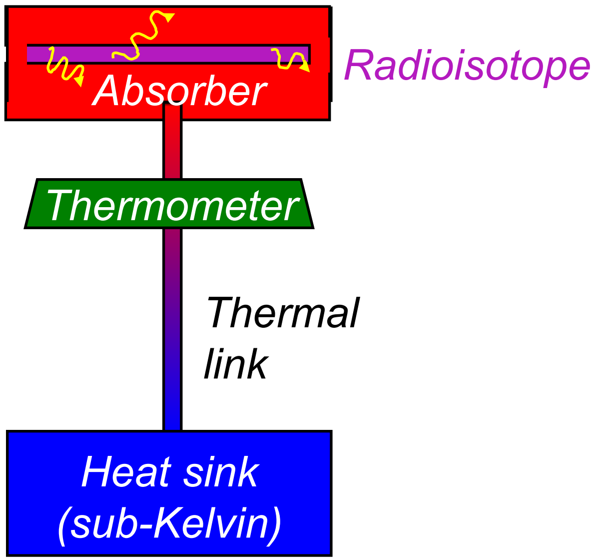
- New tritium-capable cell
  - More versatile trap-coil setup
  - Better coupling to waveguide
  - Commissioning with ^{83m}Kr (T_2 soon!)



Microcalorimetry

- ^{163}Ho EC decays are different from ^{3}H β decays:
  - Small, distributed energy deposits
  - Low total energy ΣE = 2.8 keV
  - Need 4π encapsulation





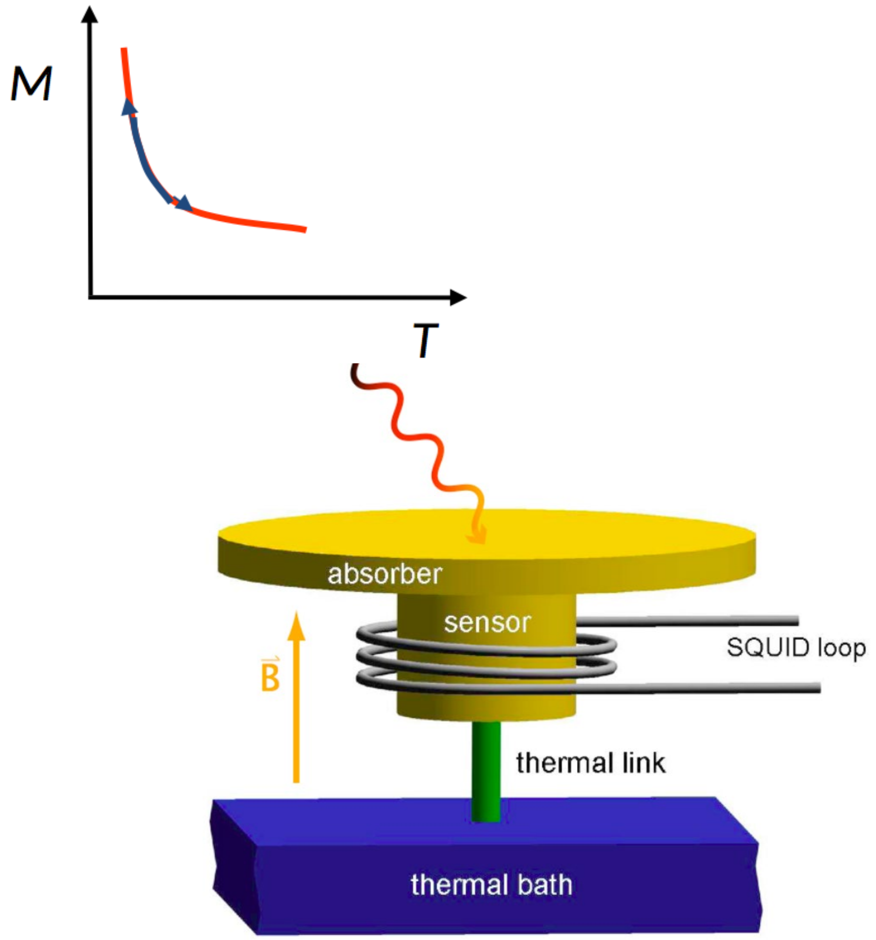
- Absorber
  - Sandwich ^{163}Ho inside
  - Convert energy to heat
  - Need very low heat capacity *C*

$$\Delta T \approx \frac{\Delta E}{C}$$

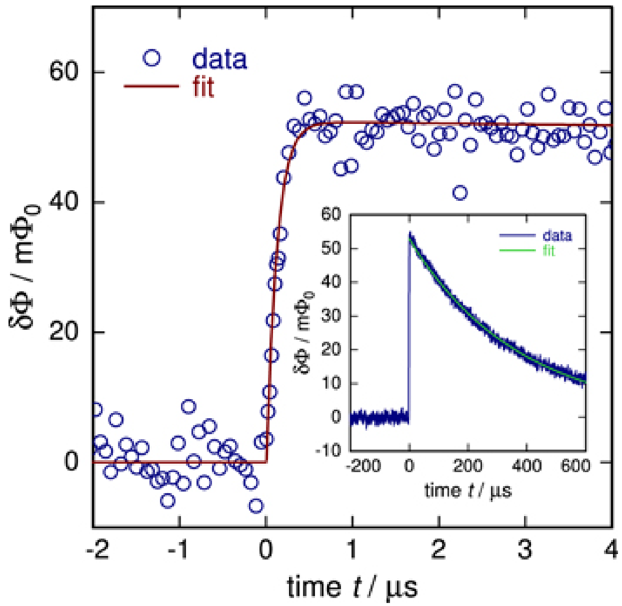
- Thermometer
  - Small $\Delta T \longrightarrow$ big $\Delta\Phi$
  - SQUID readout

ECHo: Metallic Magnetic Calorimeter

- Paramagnetic Au:Er sensor – heat disturbs magnetization



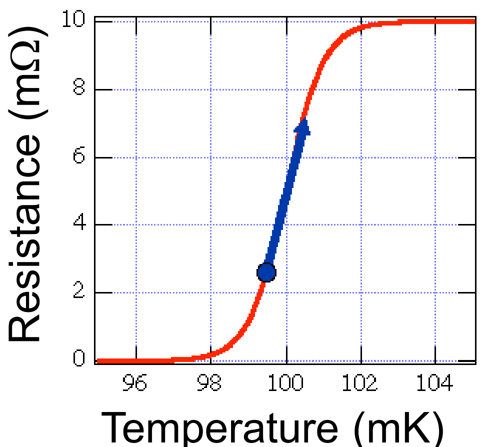
- Rise time $\tau = \mathcal{O}(100\text{ ns})$
- $\Delta E_{FWHM} = \mathcal{O}(1\text{ eV})$



Kempf et al., Supercond. Sci. Tech. ***30*** *(2017) 065002*

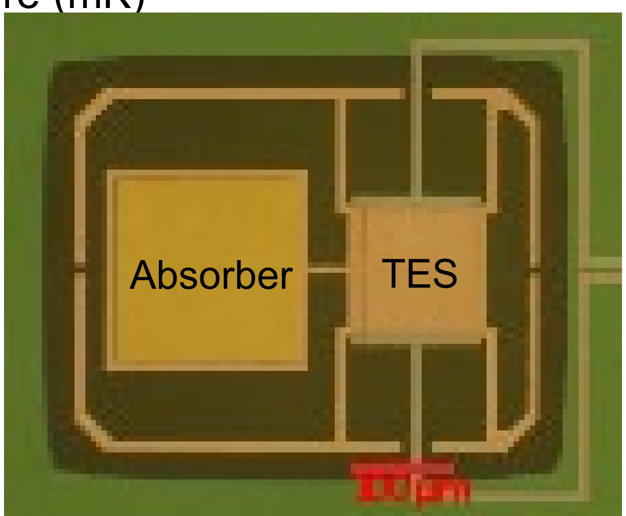
HOLMES: Transition-Edge Sensor

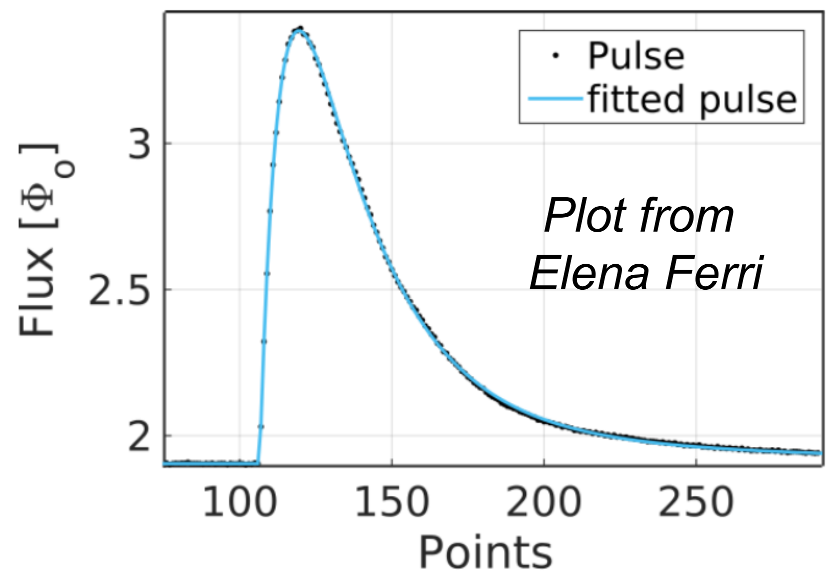
- Mo/Cu film near superconducting T_c – R depends on T in transition region



- Rise time $\tau \sim 20\ \mu$s
  - Slowed for bandwidth reasons
- $\Delta E_{FWHM} = \mathcal{O}(1\ \text{eV})$

*Giachero et al. JINST **12** (2017) C02046*





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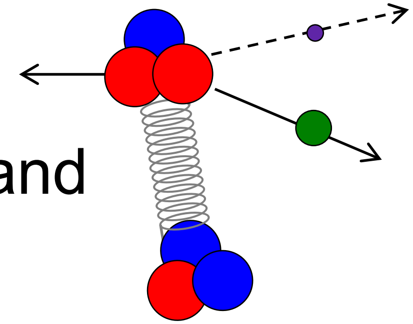
Molecular Tritium

*Bodine, DSP, Robertson, PRC **91** (2015) 035505*

- Simpler to use a T_2 source – not just T

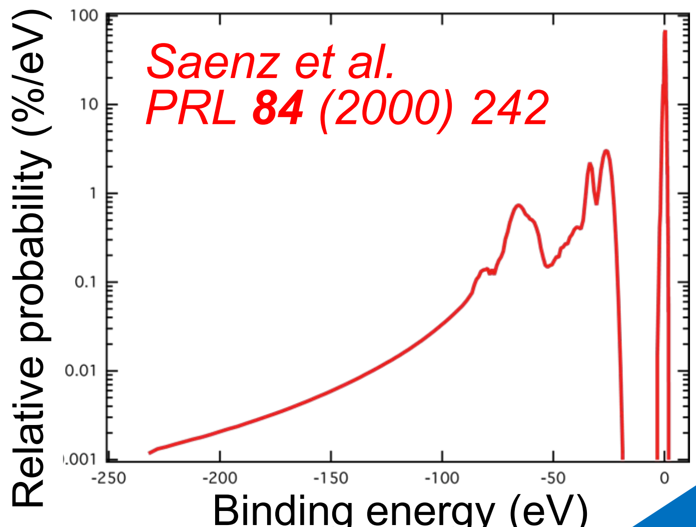


- β spectrum depends on excitation energies V_k and probabilities P_k – need 1% accuracy

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\text{nuc}}|^2 F(Z, E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\max} - E_e - V_k)$$

$$\times \sqrt{(E_{\max} - E_e - V_k)^2 - m_{\nu i}^2} \times \Theta(E_{\max} - E_e - V_k - m_{\nu i})$$

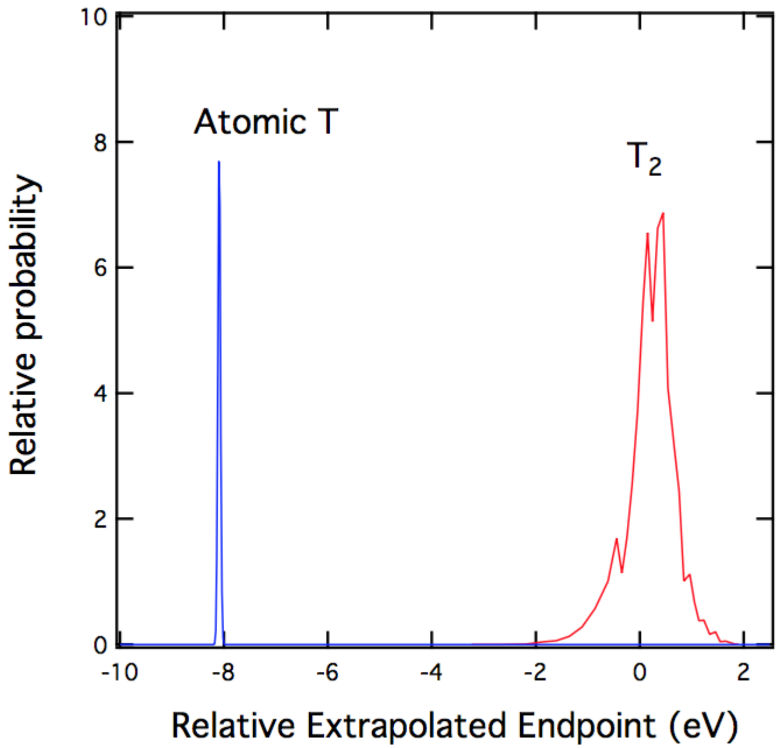
- Approaches to control uncertainty:
  - Ongoing improvement in calculations
  - Characterization of initial T_2 state
  - TRIMS experiment to re-check predicted observable

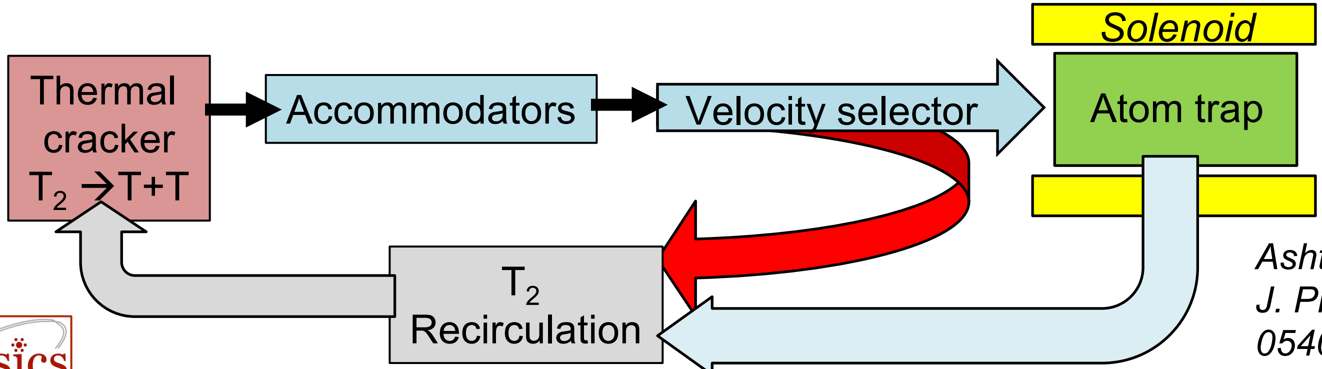


Atomic T Source?

PROJECT 8

- Atomic T has less spectral broadening, less uncertainty
- But – recombination is deadly
  - $E_0(T_2) > E_0(T)$
- Project 8 pursuing R&D toward trapped-atom source for ultimate, “Phase IV” stage
  - Mid-2020s?

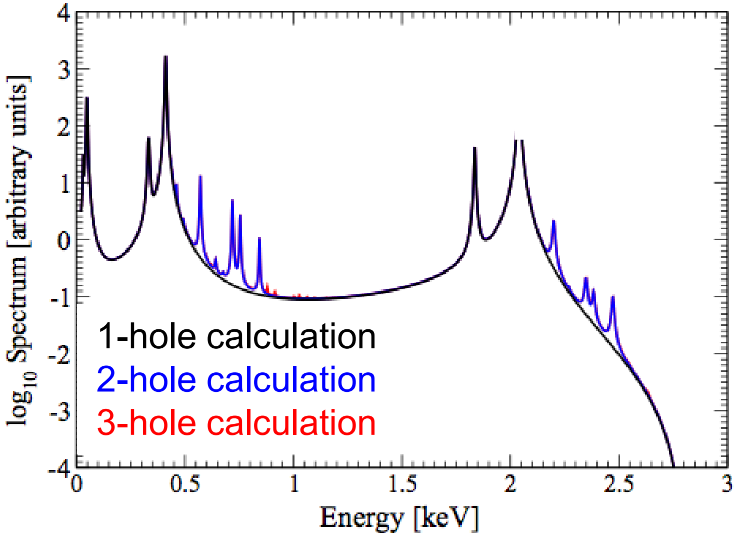




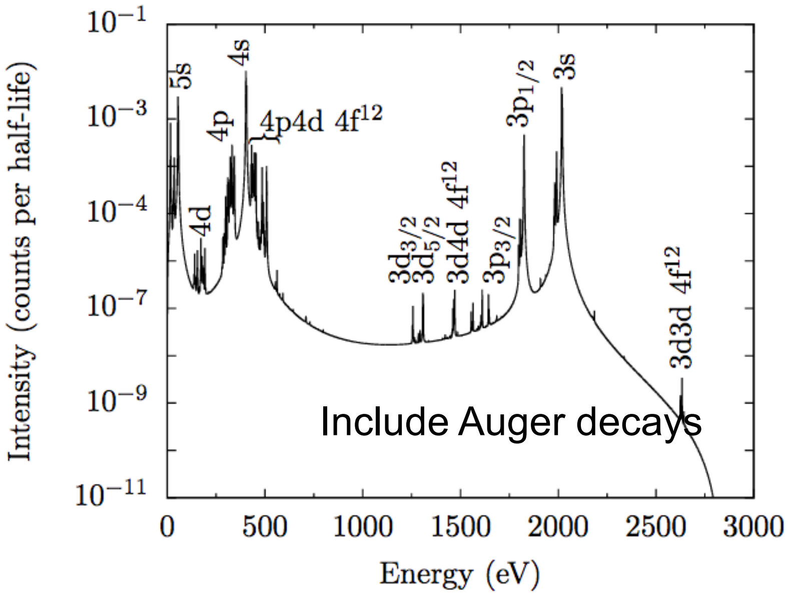
*Ashtari Esfahani et al., J. Phys. G **44** (2017) 054004*

^{163}Ho: Shakeup, Shakeoff, and More

- Precise measurements of *Q* value ongoing
- Daughter ^{163}Dy* is excited!
  - Spectrum modified by shakeup, shakeoff
  - Structure modifies shape near endpoint?
  - Additional effects from embedding in solid absorber



*Faessler et al., PRC **91** (2015) 064302*



Braß et al., arXiv:1711.10309

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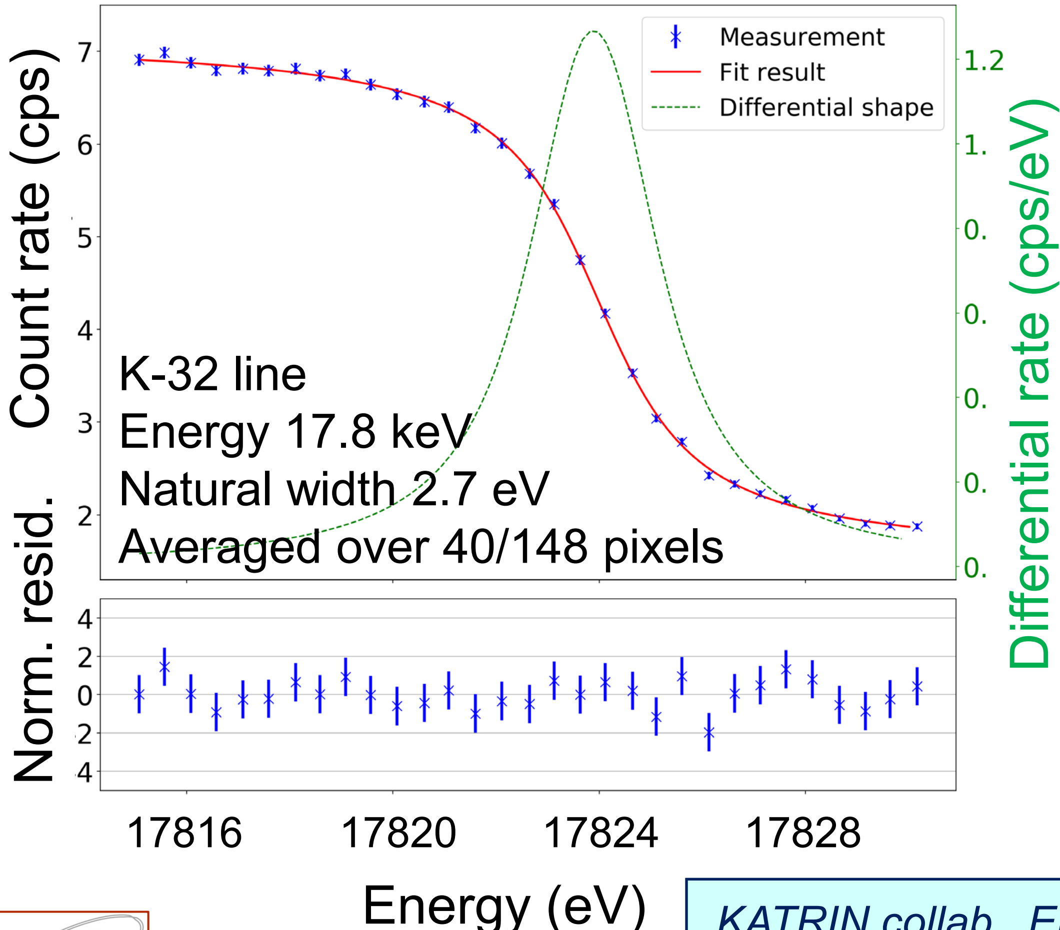
KATRIN: ^{83m}Kr Spectroscopy

- July 2017: Monoenergetic electrons from two beamline ^{83m}Kr sources



- Commissioning with isotropic source
  - Energy scans
  - Demonstrate sub-eV energy resolution
  - Calibration, monitoring equipment

*KATRIN collab., JINST **13** P04020 (2018)*

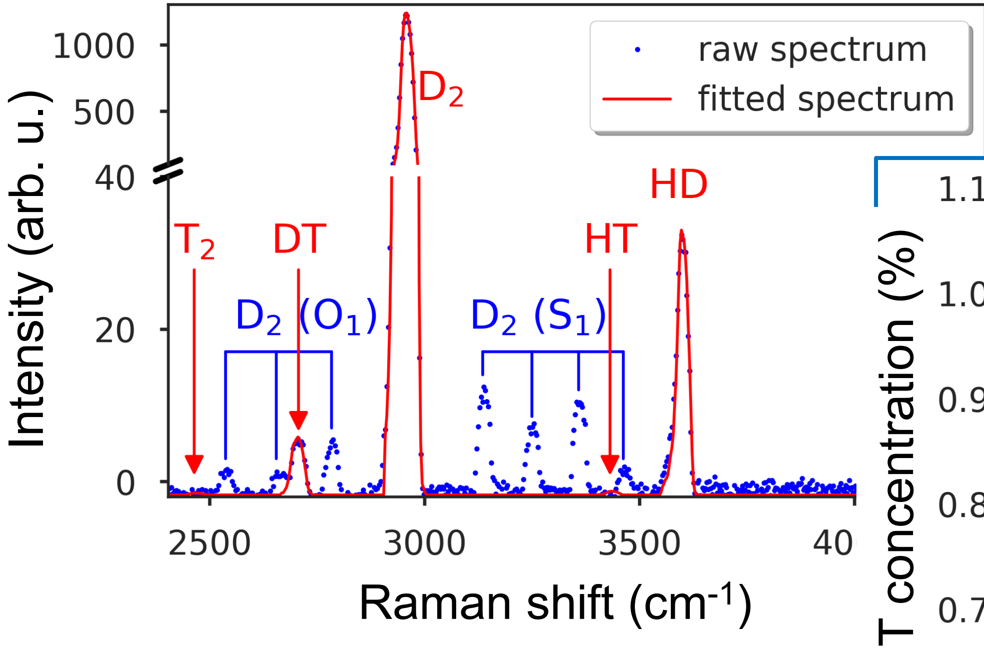
- New method for high-voltage calibration

*KATRIN collab., EPJ C **78** 368 (2018)*

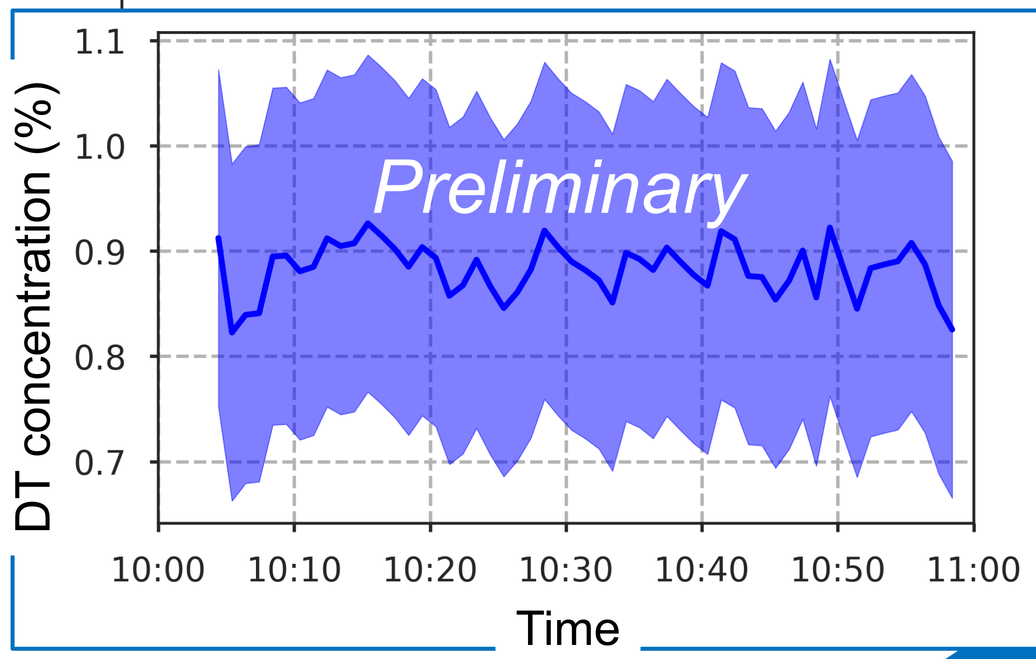
KATRIN: Very First Tritium

- Small amounts of DT introduced in May/June 2018
- Measure tritium concentration with laser Raman spectroscopy

LARA system: Schlösser et al., J. Mol. Spect. ***1044*** *61 (2013)*

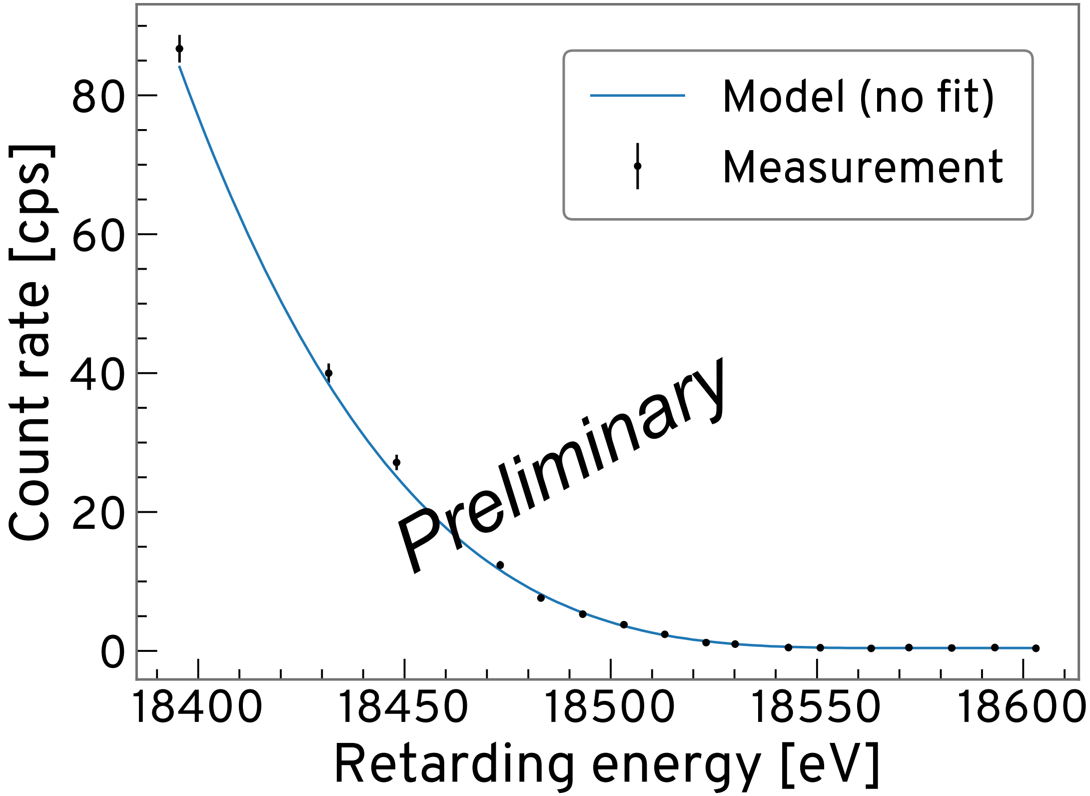


DT conc.: 0.9% (3% variation over scan)



KATRIN: First Tritium Scan

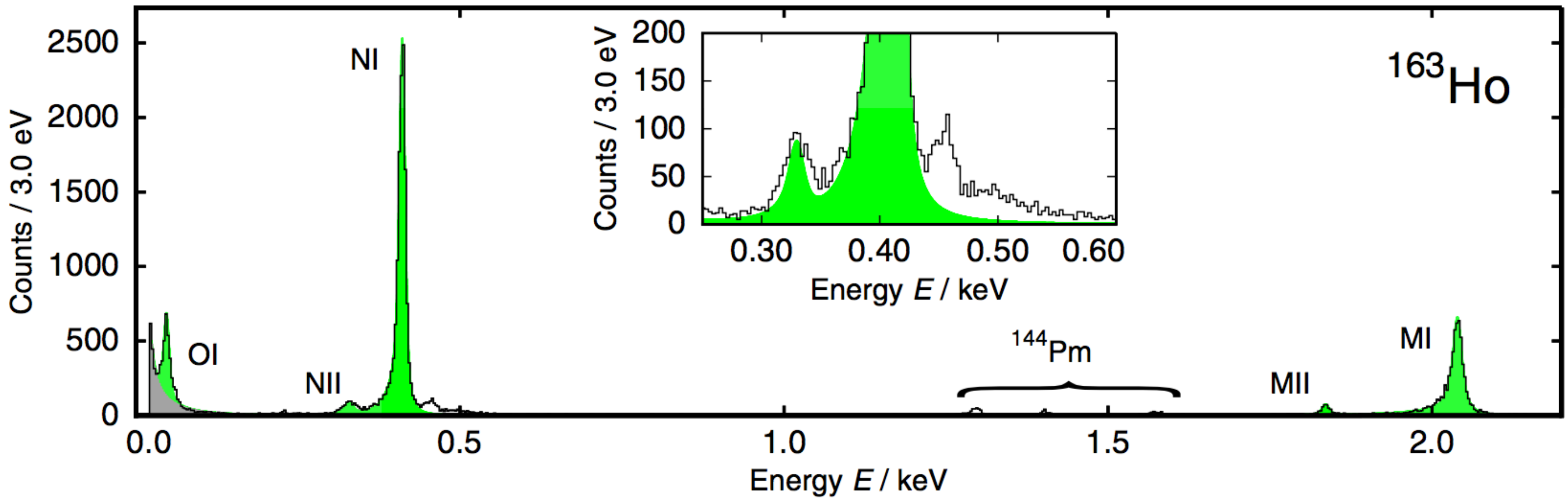
- KATRIN tritium scan #1 (Day 2 of tritium commissioning)
- Immediate comparison of data to model



- Model initialized with system parameters from slow controls
- Very good agreement "out of the box"

ECHo: A Precise Spectrum

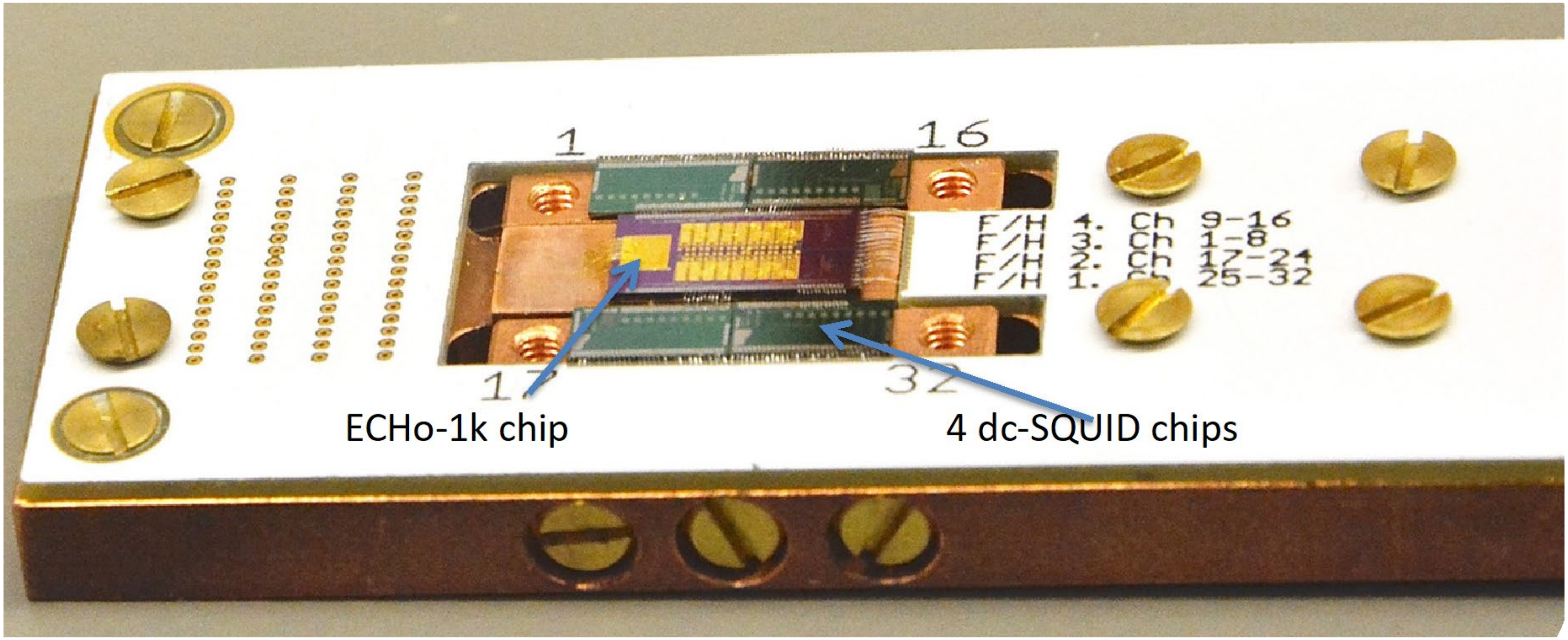
- First calorimetric measurement of OI line!
- Structures not fully explained by 1-vacancy model – Auger decay?



*Ranitzsch et al., PRL **119** (2017) 122501*

ECHo-1k: The Beginning

- First chips for next phase are cooled down and taking data



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- Searching for Majorana neutrinos
  - A fundamental question
  - Designing an experiment
  - Different isotopes, different strategies
  - Present and future

A Majorana Motivation

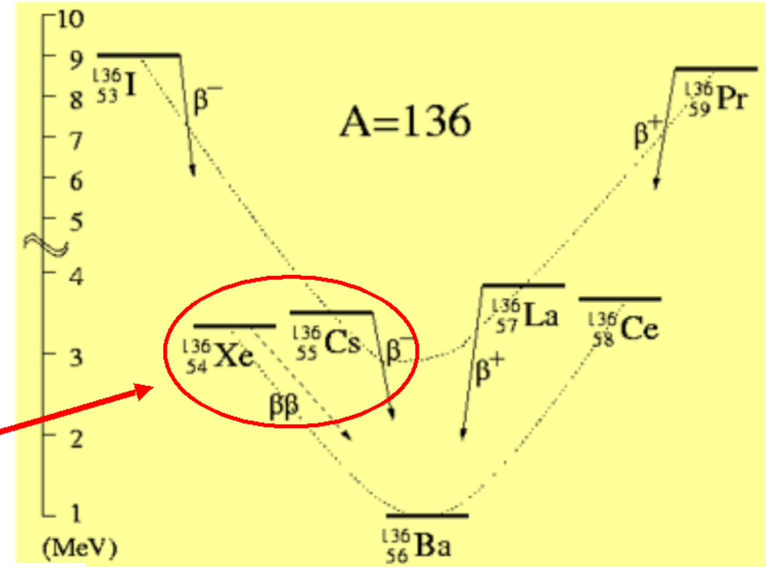
- 1937: Ettore Majorana realizes a neutral, spin-1/2 fermion could in principle be described by a real wave function
- If neutrinos are Majorana particles – instead of Dirac particles – we get an appealing set of models for neutrino mass
  - Bonus: We also get leptogenesis, a model explaining the excess of matter over antimatter in the early universe
  - It also means we violate lepton number ...
- Best (only) prospect for experimental test: neutrinoless double beta decay

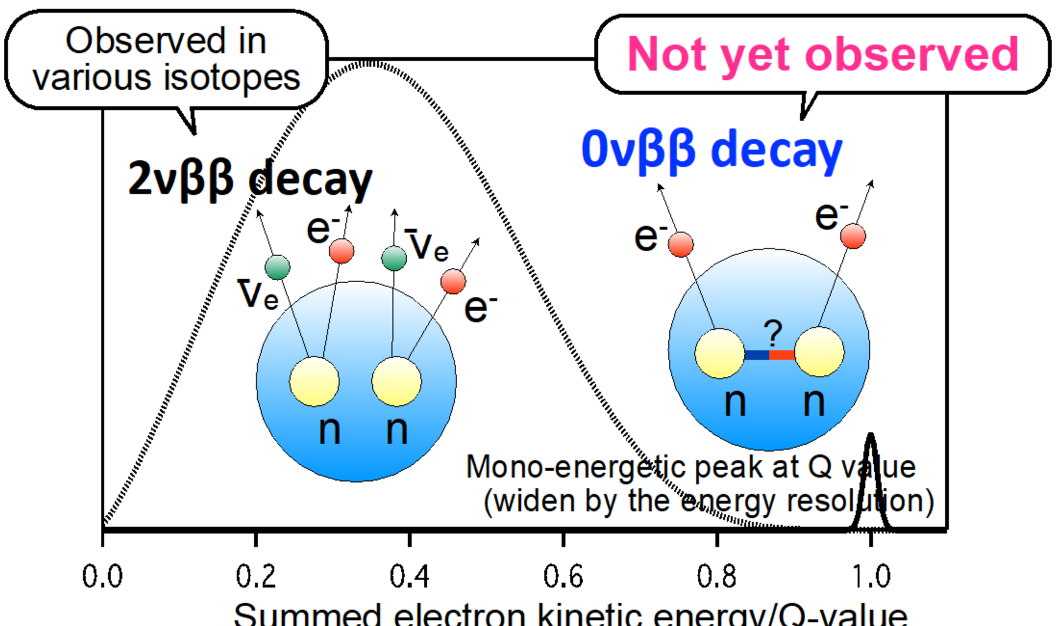
Neutrinoless Double Beta Decay

2νββ first calculated by Maria Goeppert Mayer, 1935

Double-beta decay:

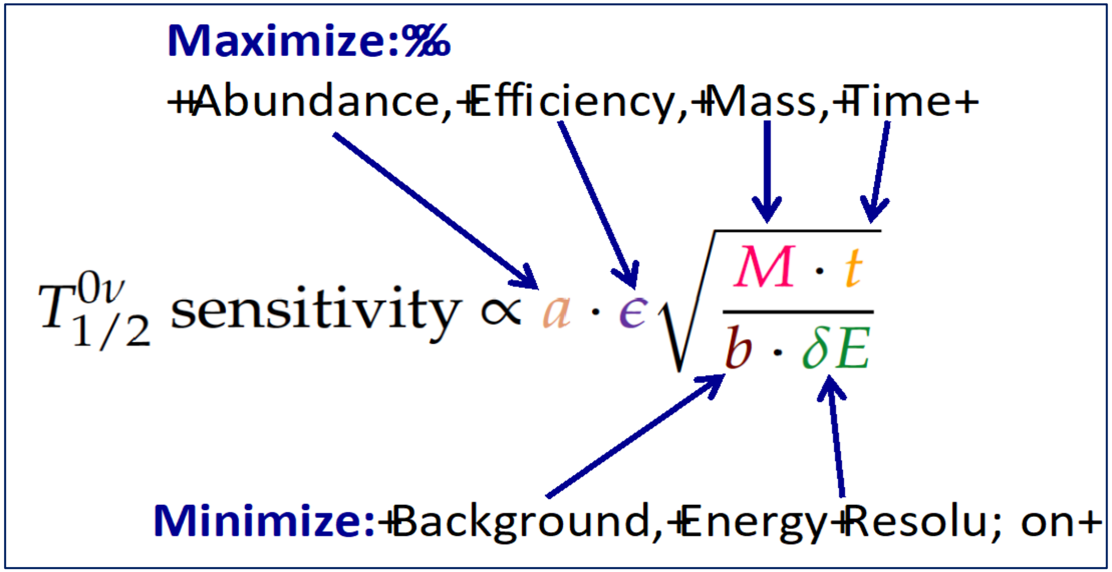
a second-order process only detectable if first order beta decay is energetically forbidden





- 0νββ: simultaneous decay of two nucleons with exchange of light neutrino
- Various possible mechanisms
- *All* necessarily imply a Majorana neutrino

Searching for a Very Rare Decay



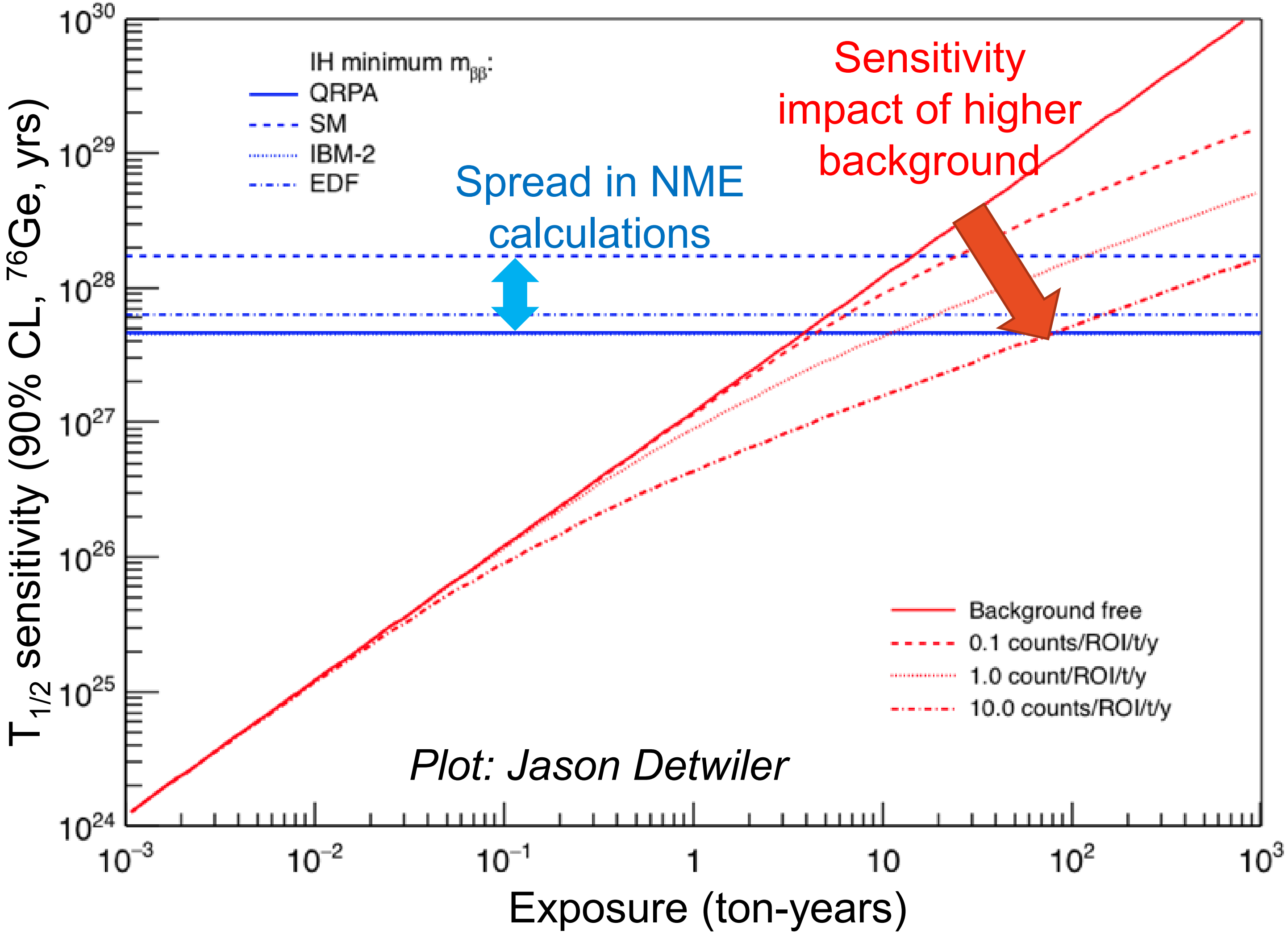
Graphic: Daniel Dwyer

- You need huge amounts of material
  - Cheap enrichment to $0\nu\beta\beta$ isotope/ high natural abundance
- You don't want to miss any event
  - Efficient detector with little downtime
- Must control background

Physics
Carnegie Mellon University

Sensitivity and Exposure

- Exposure = Mass x Time (t-yr)

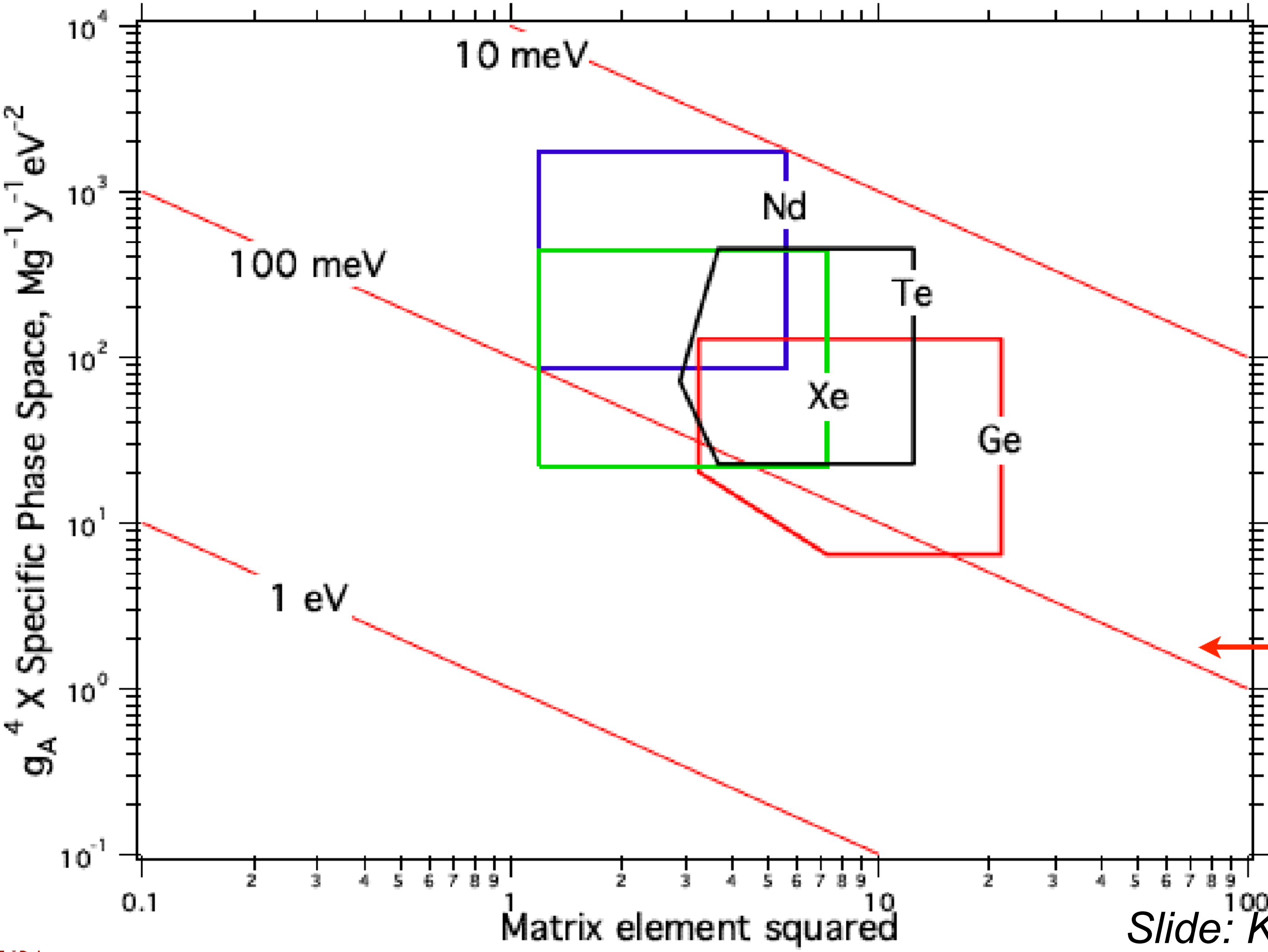


Is One Nuclide Best?

For Ge, Te, Xe, Nd

← uncertainty on NME^2 →

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)



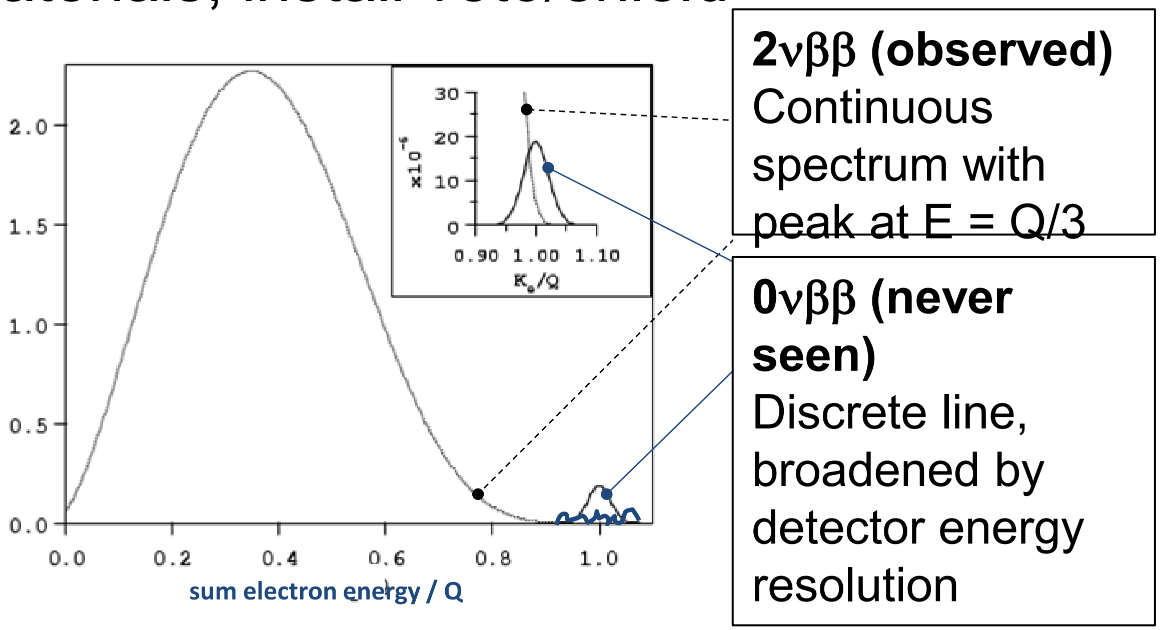
uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

Slide: Krishna Kumar

Background Considerations

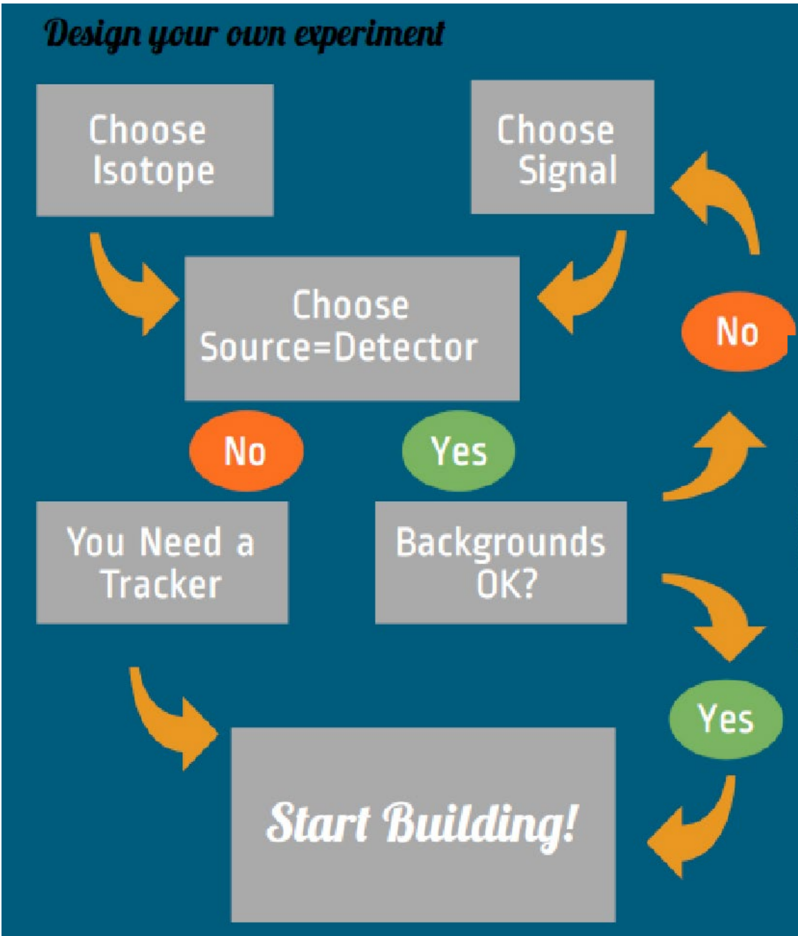
- Must have clean, well-understood spectrum in region of interest (ROI)
  - Go deep underground to avoid cosmic rays
  - Carefully select materials, install veto/shield
- Background from $2\nu\beta\beta$ can only be addressed with very good energy resolution



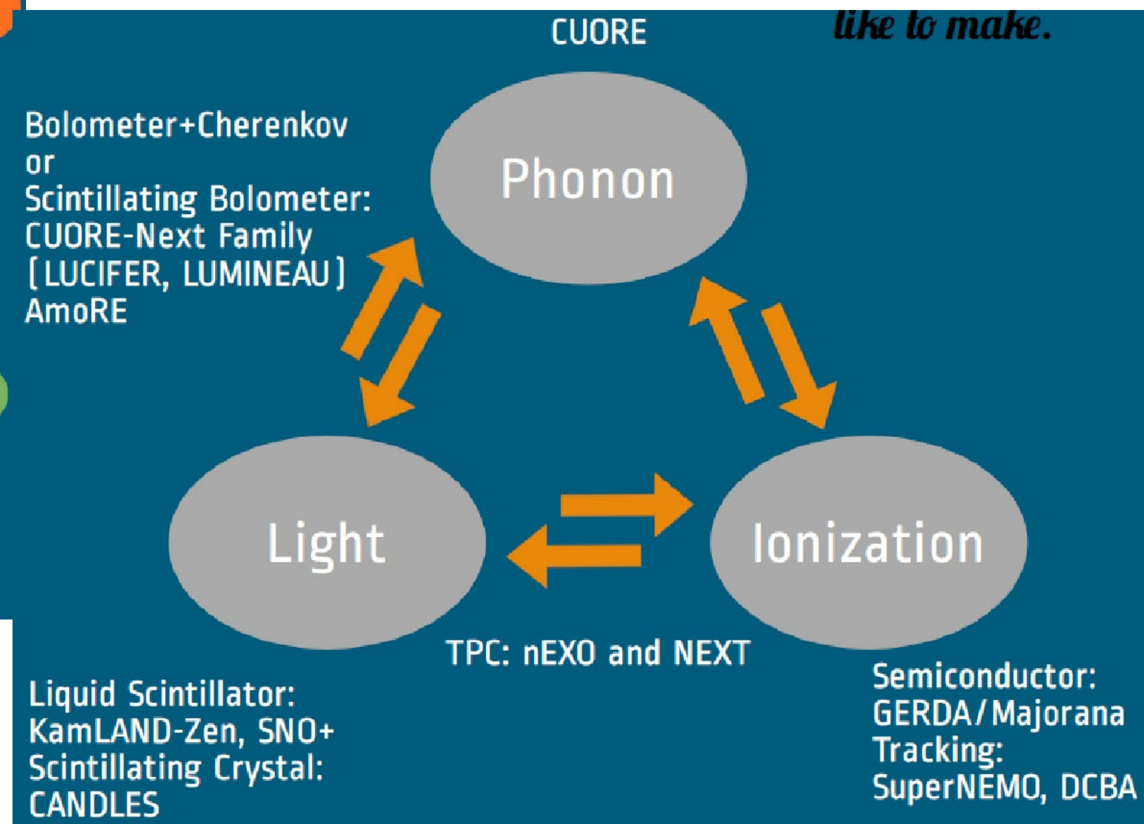
The signal is a **peak (at the Q-value)** over an almost **flat background**

Graphic: Andrea Giuliani

Designing a 0νββ Search



Graphics: *Lindley Winslow*



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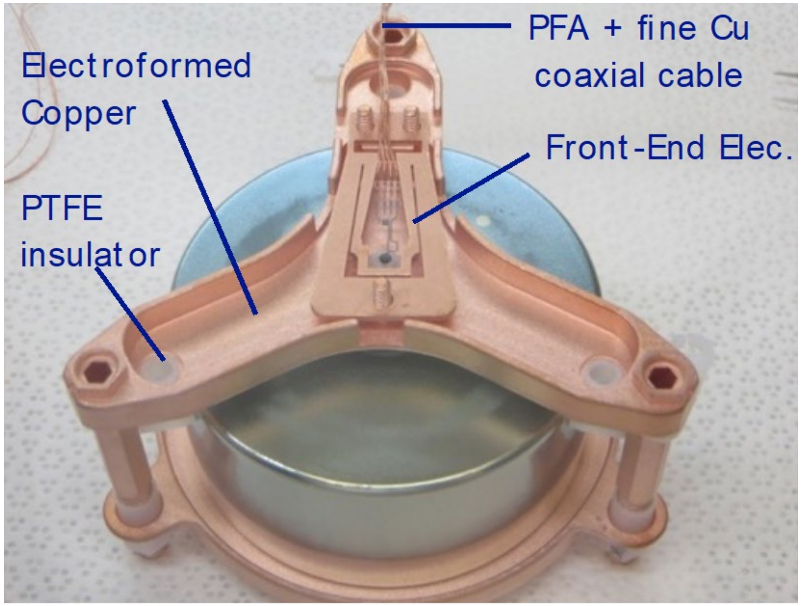
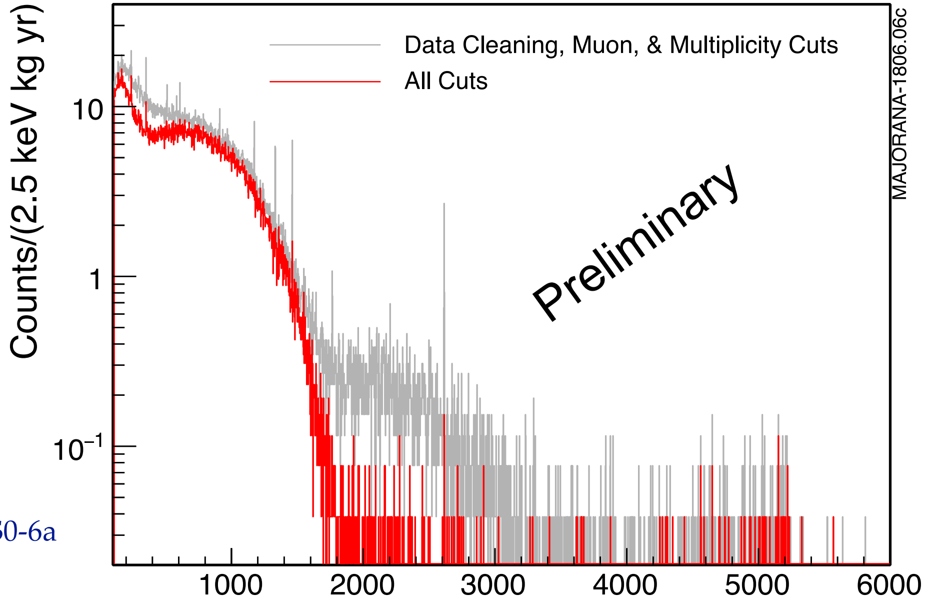
^{76}Ge – Majorana Demonstrator

- Cooled, enriched semiconductor detectors
- Excellent energy resolution and tight background control





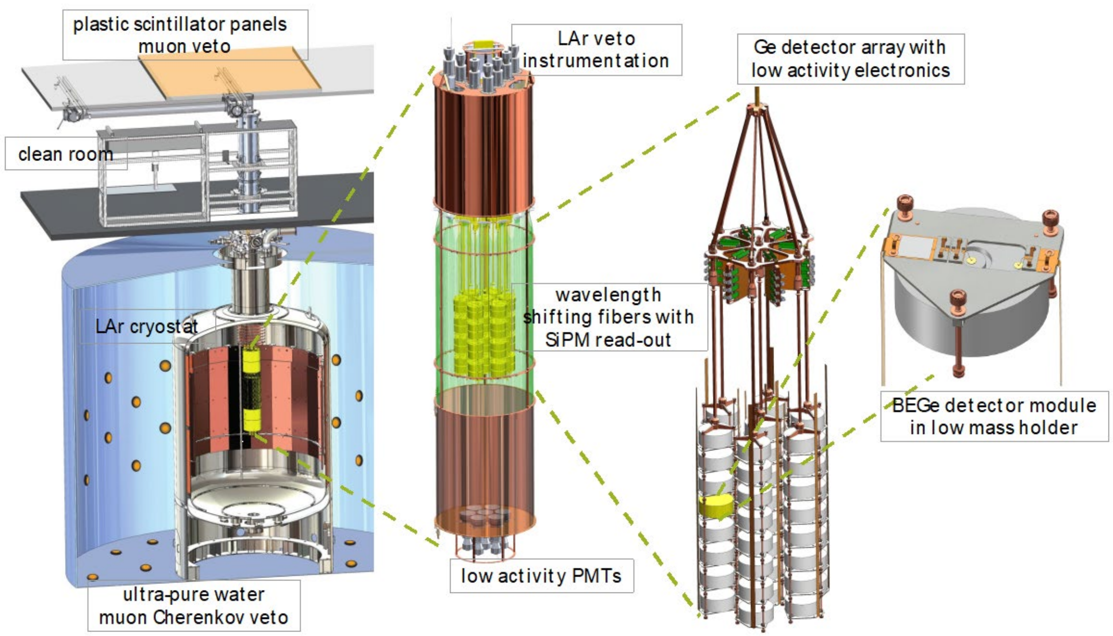
Lowest background configuration

Majorana Demonstrator Collab., Neutrino 2018

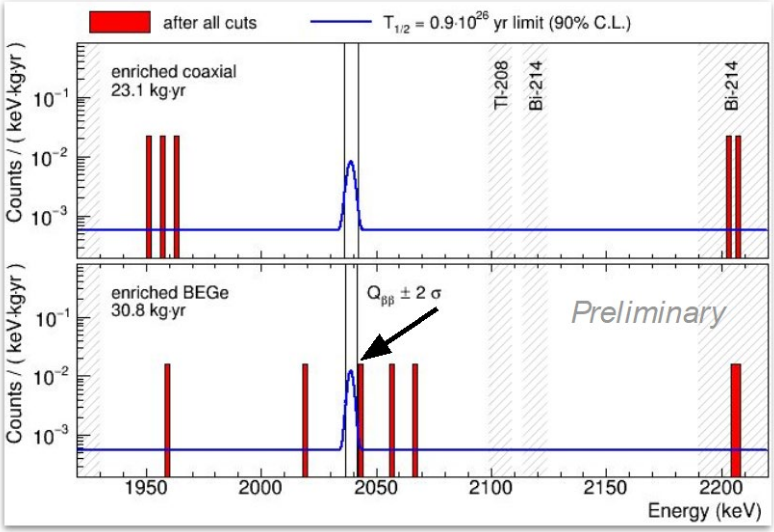
Physics Carnegie Mellon University

^{76}Ge – GERDA

- Embed semiconductor Ge detectors in LAr shield
  - Detect passing muons, etc, to provide veto



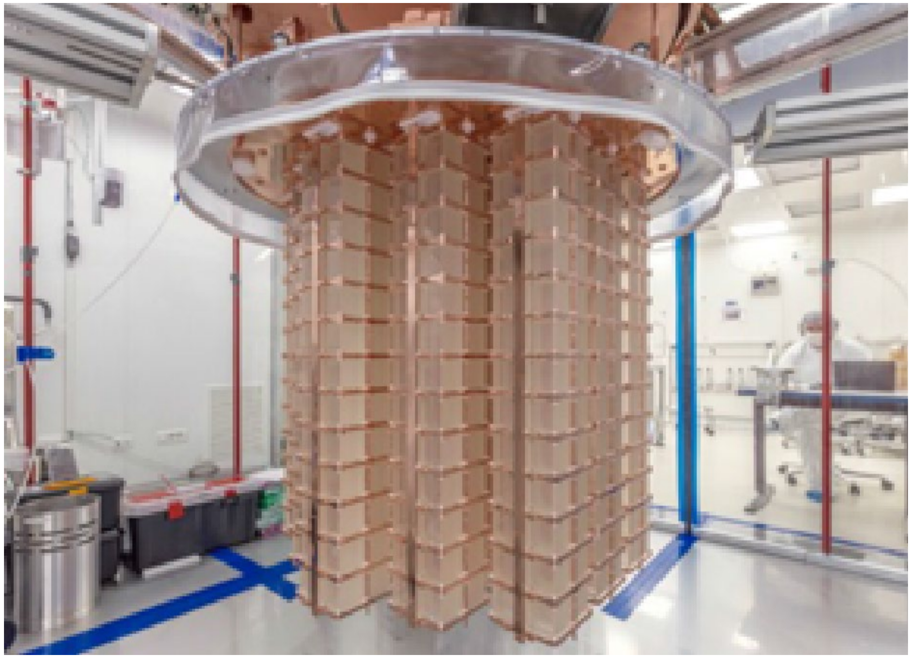
Nature 544 (2017) 47

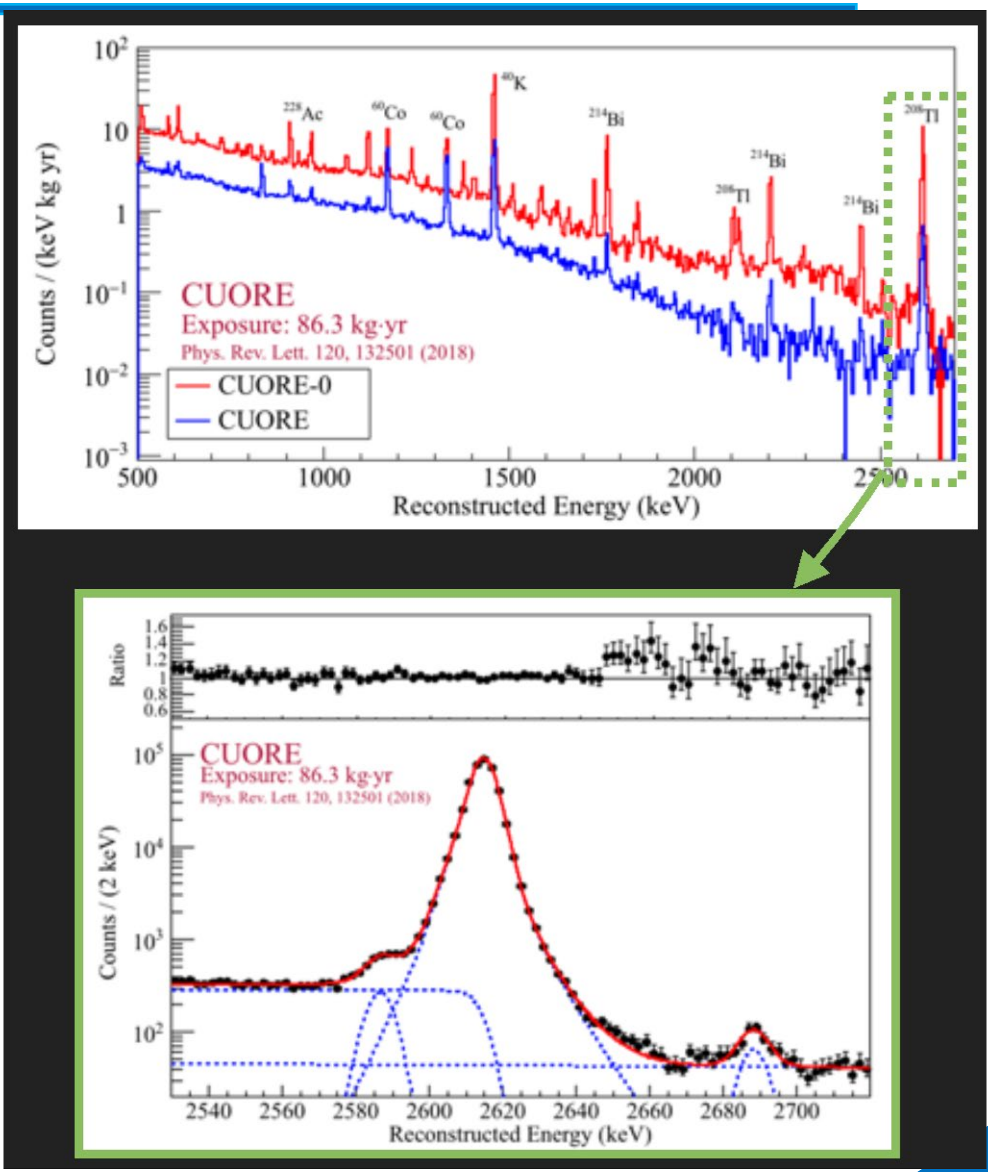


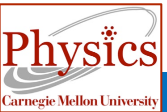
GERDA collab., Neutrino 2018

^{130}Te – CUORE

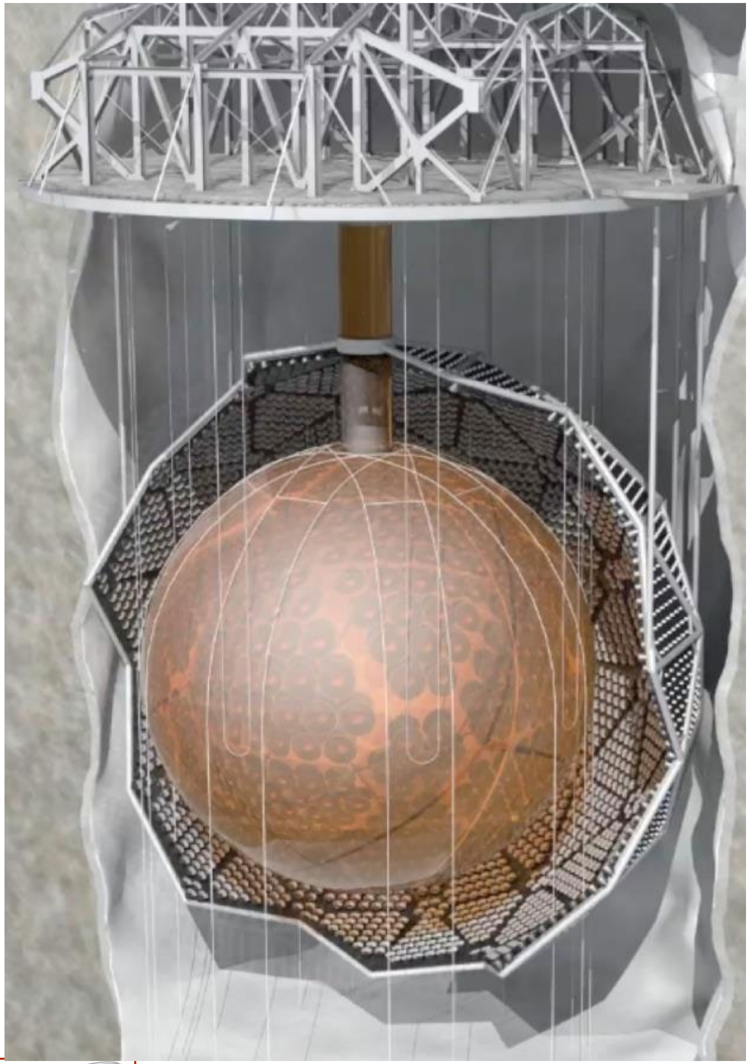
- TeO bolometers – high natural abundance
  - Coldest cubic meter in universe, at 6.3 mK!







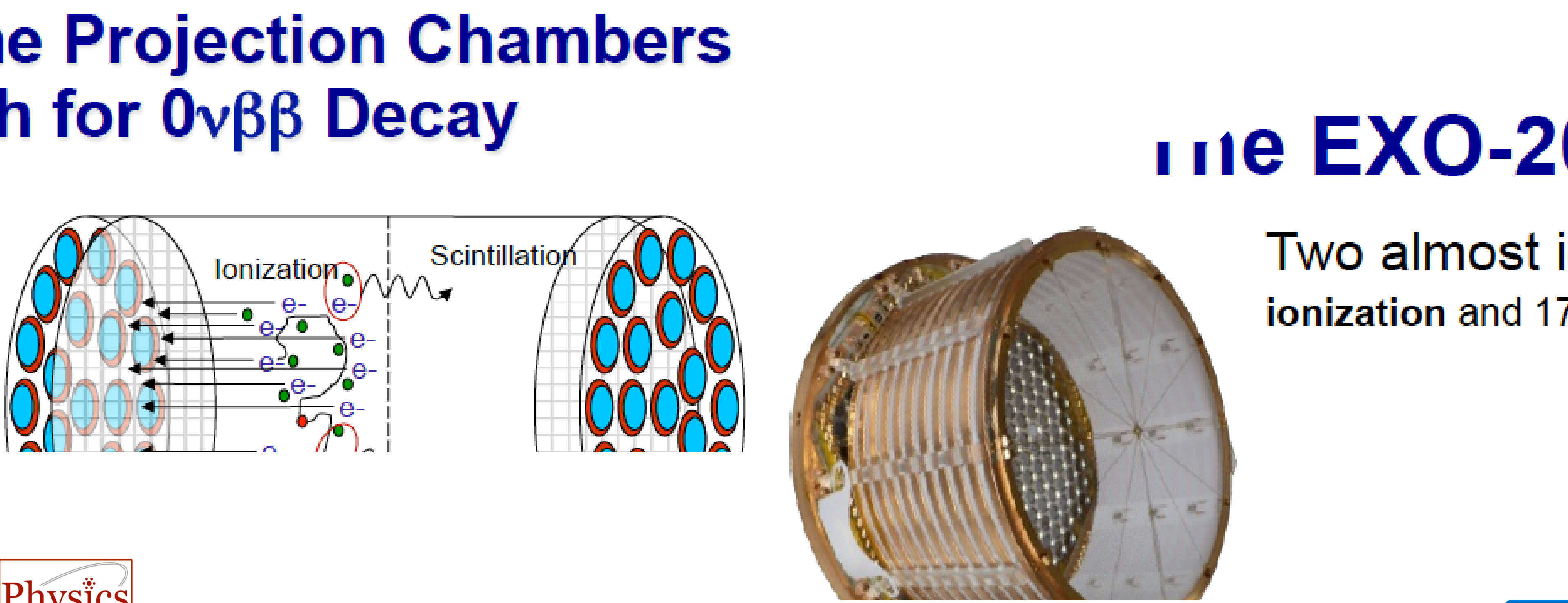
^{130}Te – SNO+



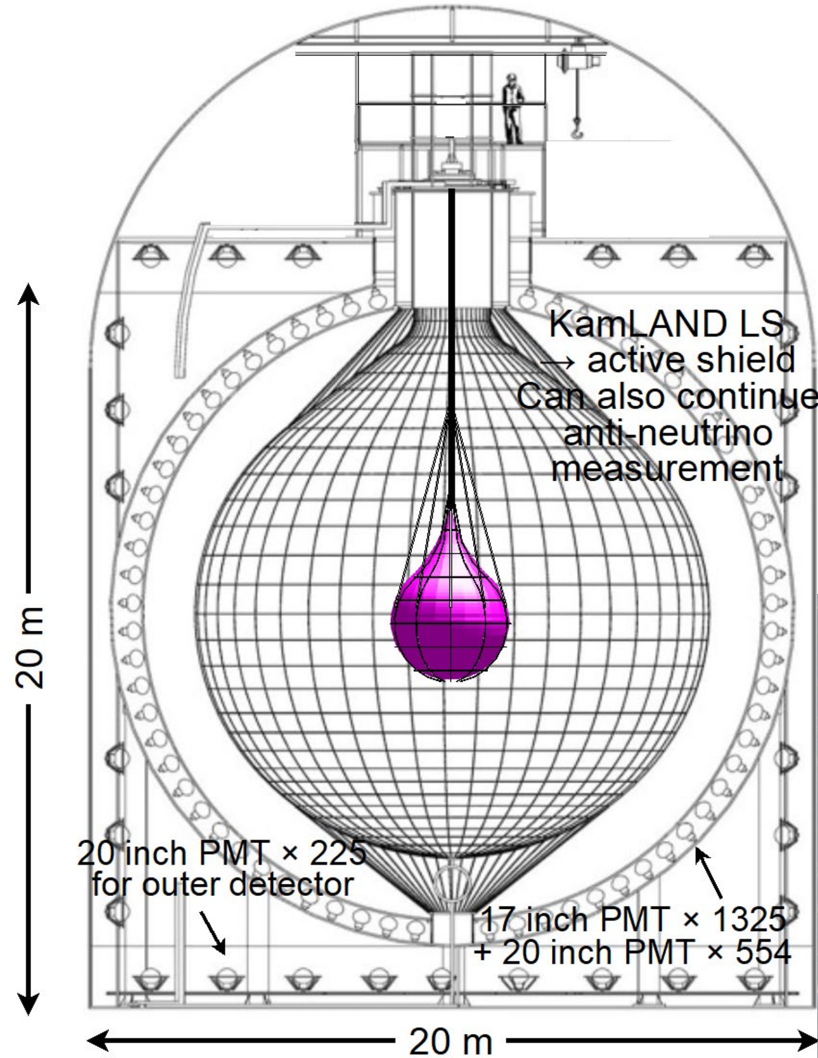
- Upgraded SNO detector, now to be filled with liquid scintillator and doped with ^{130}Te
- Underground purification plants
- Should start $0\nu\beta\beta$ search next year

^{136}Xe – EXO

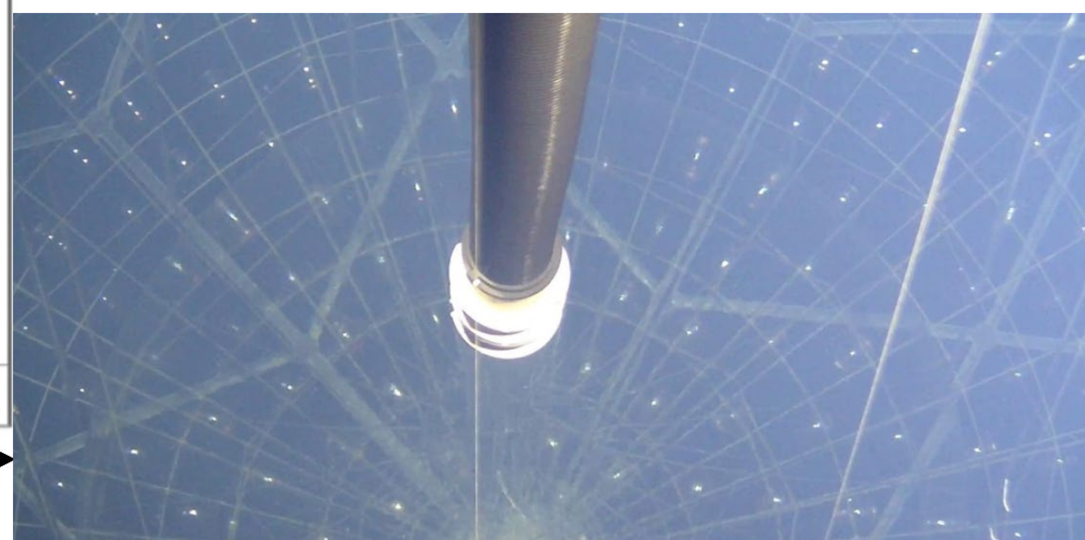
- EXO-200 [kg]: Liquid Xe Time Projection Chamber
  - Simultaneously collect scintillation, ionization signals
- nEXO proposal for next generation
  - Reduce background by tagging Ba daughters?



^{136}Xe – KamLAND-Zen



- Upgrade to KamLAND neutrino-oscillation detector
- Internal balloon contains liquid scintillator, ^{136}Xe
- Poor energy resolution compensated by large size

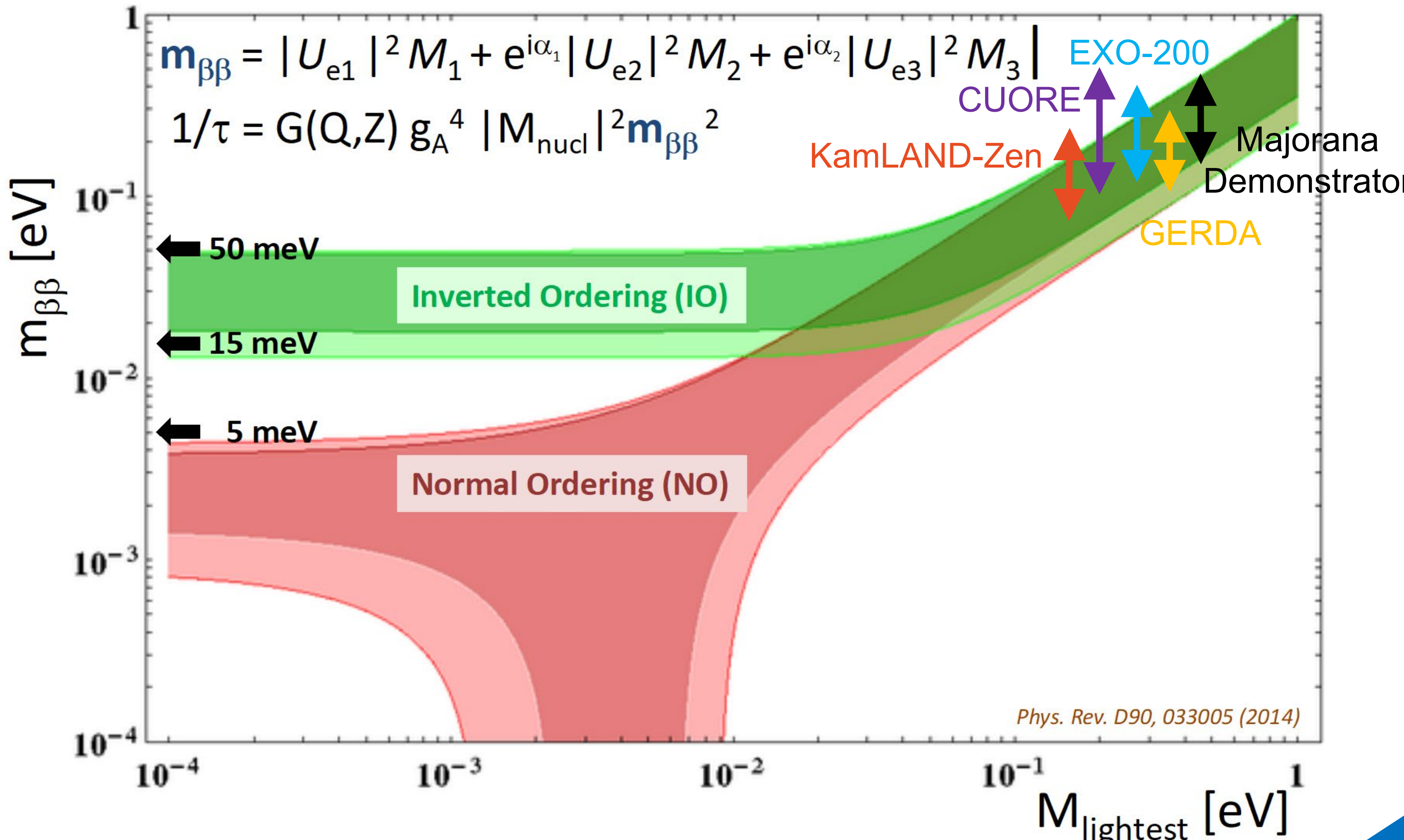


Outline

- The absolute neutrino-mass scale
- Searching for Majorana neutrinos
  - A fundamental question
  - Designing an experiment
  - Different isotopes, different strategies
  - Present and future

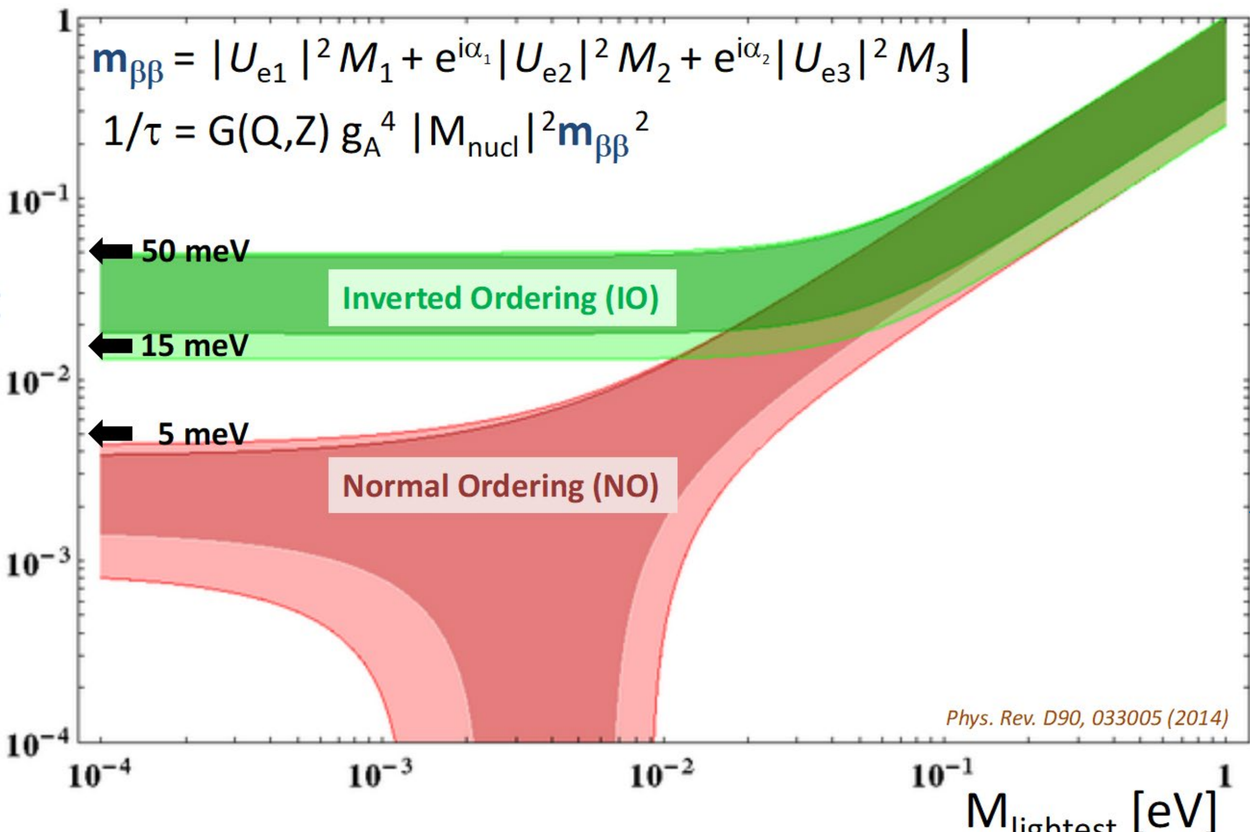
0νββ: Current Status

- Latest limits as reported at Neutrino 2018 two weeks ago



Toward Ton-Scale

- At about 1 ton of isotope, we can probe to the bottom of the inverted-hierarchy band
- Theory effort needed to better understand quenching of gA coupling constant, nuclear matrix elements



- Community R&D over next few years, preparing for selection of isotope and project
- Next-generation experiment high priority for nuclear physics

A Shameless Advertisement, Again

- My group is hiring a postdoc to work on:
  - KATRIN
    - Direct measurement of neutrino mass
  - COHERENT
    - CEvNS measurements on multiple nuclei
- Apply on Interfolio by July 17 for full consideration:
  - https://apply.interfolio.com/5143

Backup

Whatever Happened to ^{187}Re?

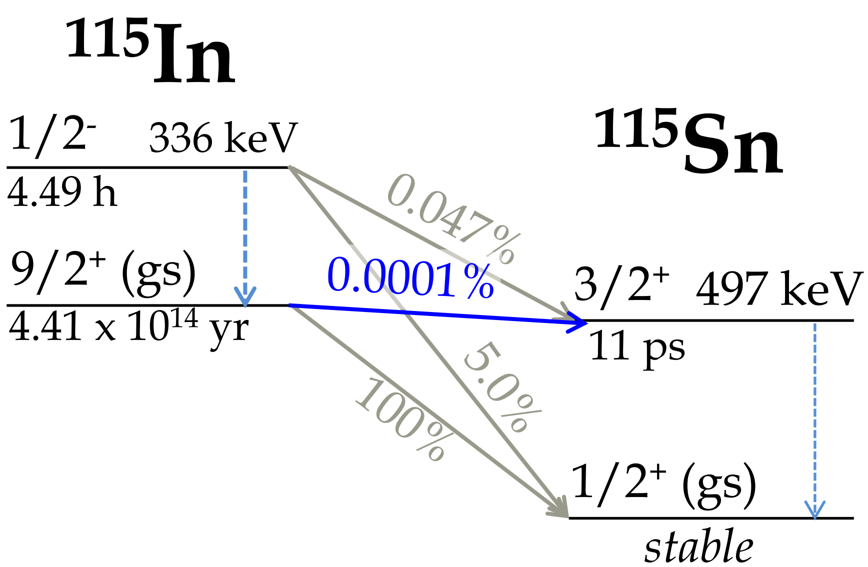
- ~15 eV sensitivity for MIBETA (2004)
- R&D by MARE collaboration

- Metallic Re (superconducting)
  - Complex thermalization
- Dielectric $AgReO_4$
  - Long response time
- Low specific activity

Community has moved on to ^{163}Ho

Nucciotti, Adv. High Energy Phys. ***2016*** *9153024*

^{115}In: A Dark Horse Isotope?



- New decay branch of ^{115}In ⟶ ^{115}Sn discovered in 2005 (*Cattadori et al., Nucl. Phys. A **748** 333, 2005*)
- Lowest known Q_β-value, 173±12 eV *(Urban et al., PRC **94** 011302(R), 2016)*

✦ Low-Q decay hidden in Q=497 keV decay branch

> Measuring the end-point energy region of the electron spectrum for the rare β decay of ^{115}In constitutes a magnificent challenge.

*-- Andreotti et al., PRC **84** 044605 (2011)*

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