



# ***Direct Neutrino-Mass Measurements***

**Diana Parno, Carnegie Mellon University**

***17<sup>th</sup> International Neutrino Physics Summer School / Santa Barbara, CA / July 8, 2026***



# The Plan

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- ◆ Accessing the neutrino-mass scale
- ◆ How to search for  $m_\nu$  directly
- ◆ Nitty, gritty systematics
- ◆ Microcalorimetry basics ( $^{163}\text{Ho}$ )
- ◆ HOLMES
- ◆ ECHo
- ◆ Beta-spectroscopy basics ( $^3\text{H}$ )
- ◆ KATRIN
- ◆ Project 8
- ◆ Next-generation tritium R&D
- ◆ Sterile neutrinos and bonus physics
- ◆ Alternate measurement ideas

*Approximate break between  
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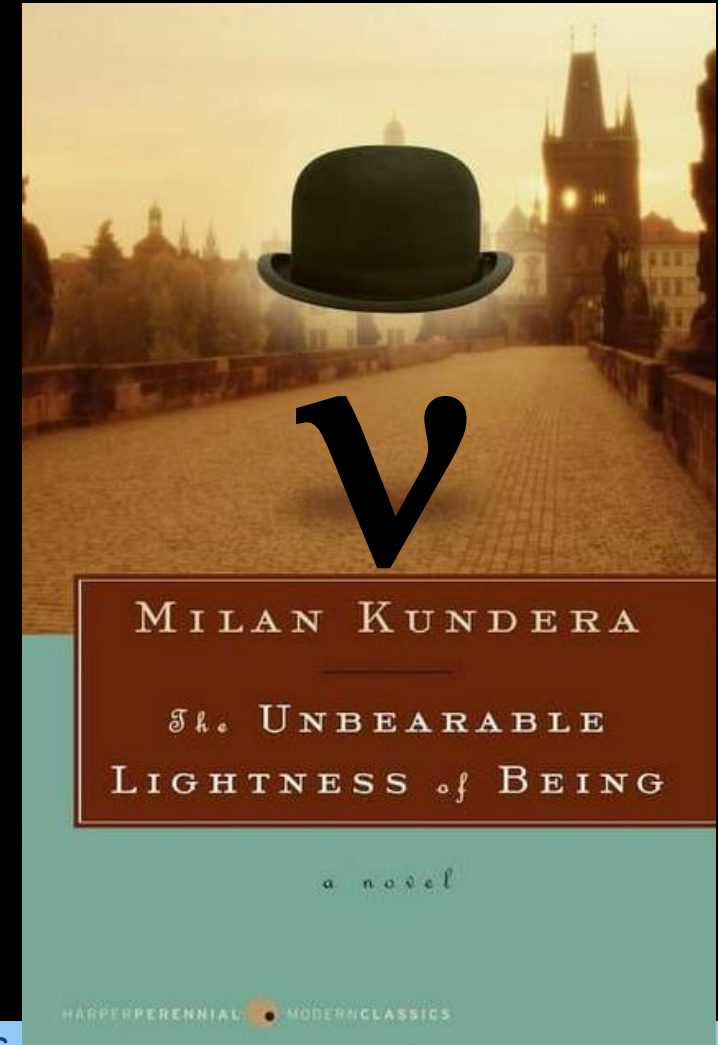
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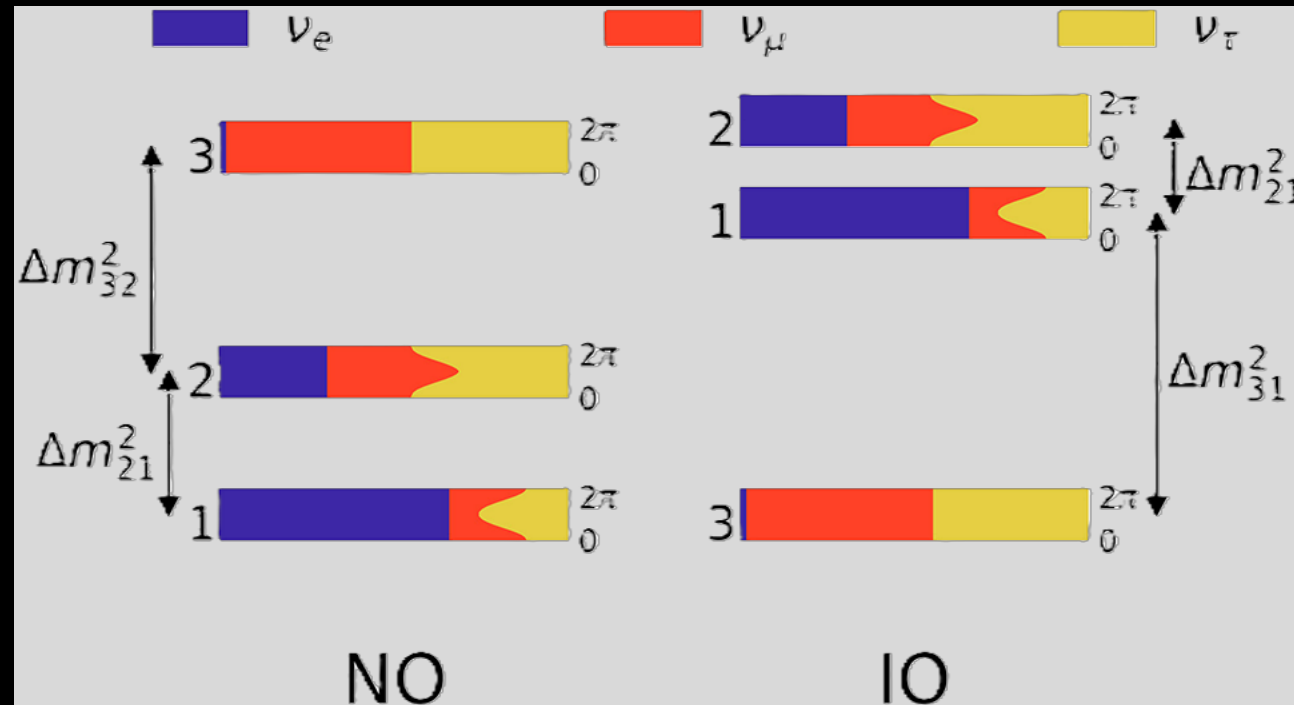
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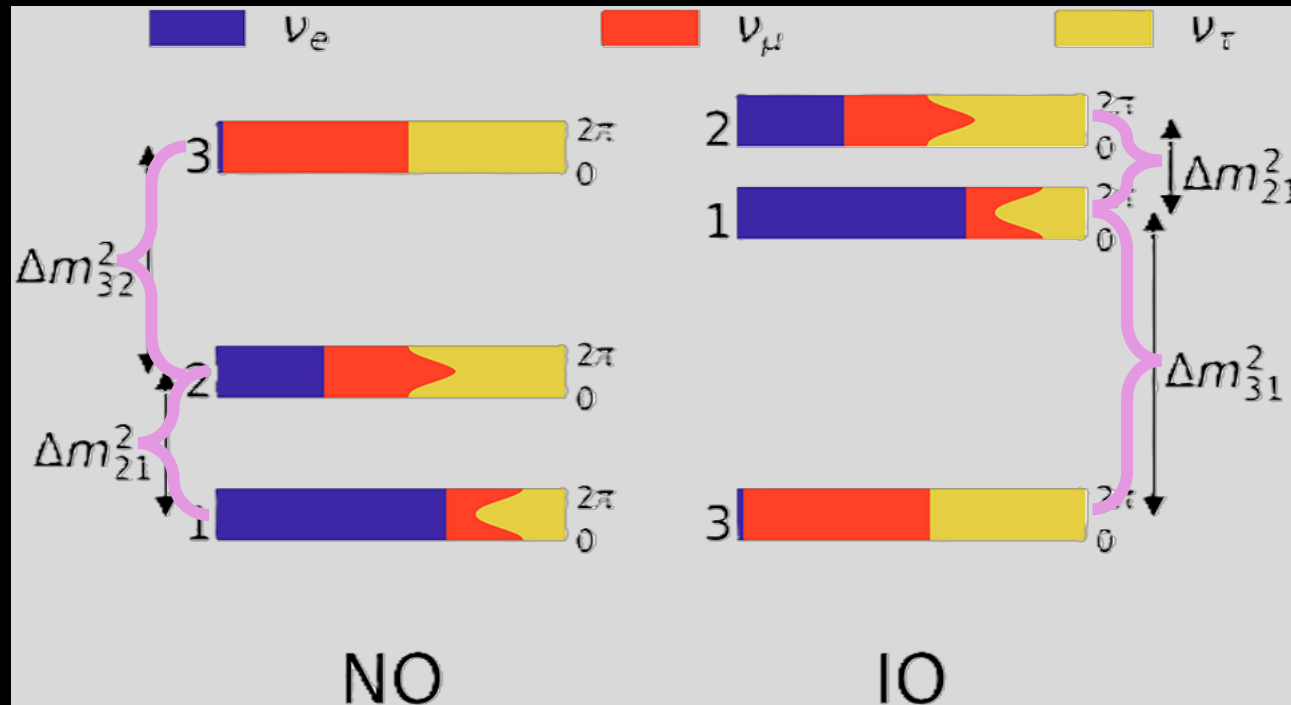
# Mass Picture from Oscillations



de Salas et al., *Front. Astron. Space Sci.* 5 (2018) 36

# Mass Picture from Oscillations

- ◆ Neutrino oscillation means there are 3 distinct neutrino-mass values
- ◆ Oscillation experiments give **splittings between mass states**

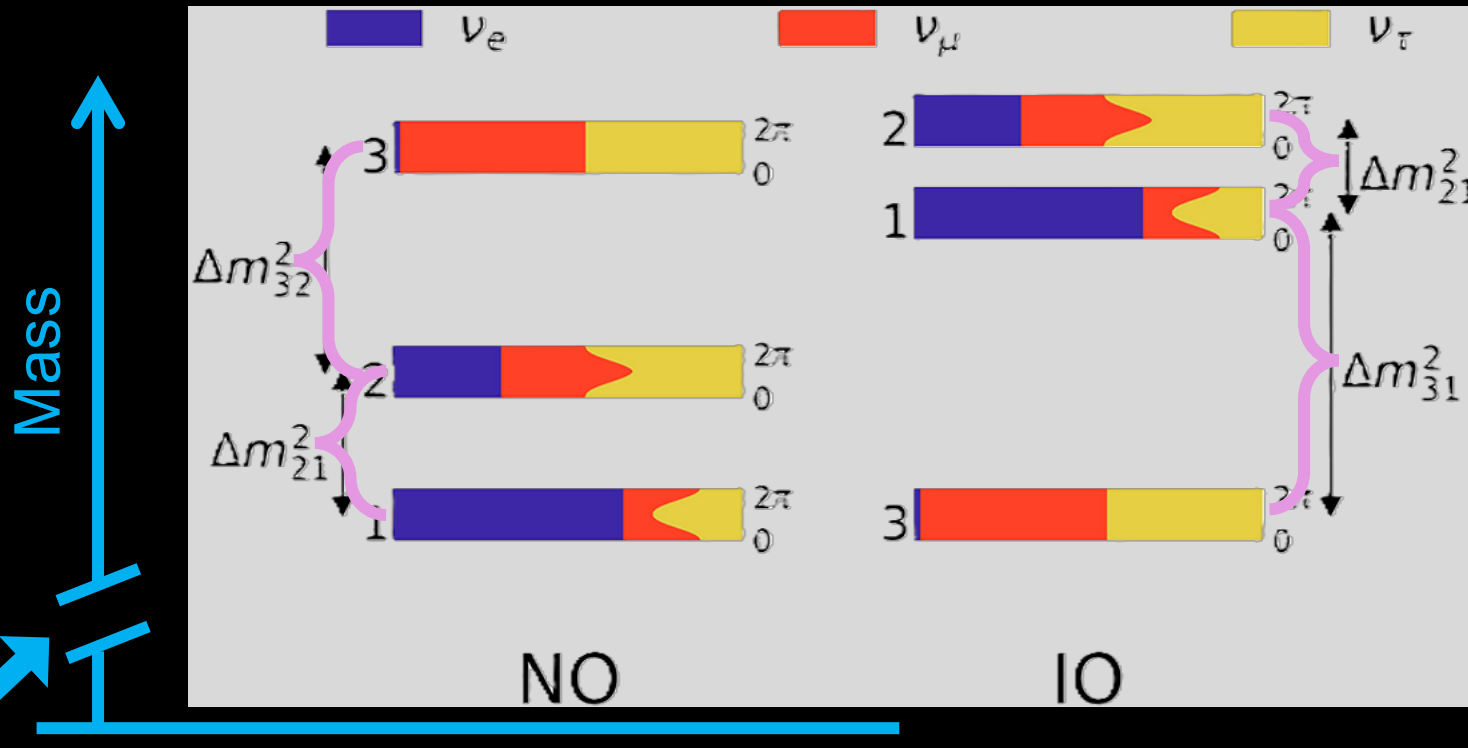


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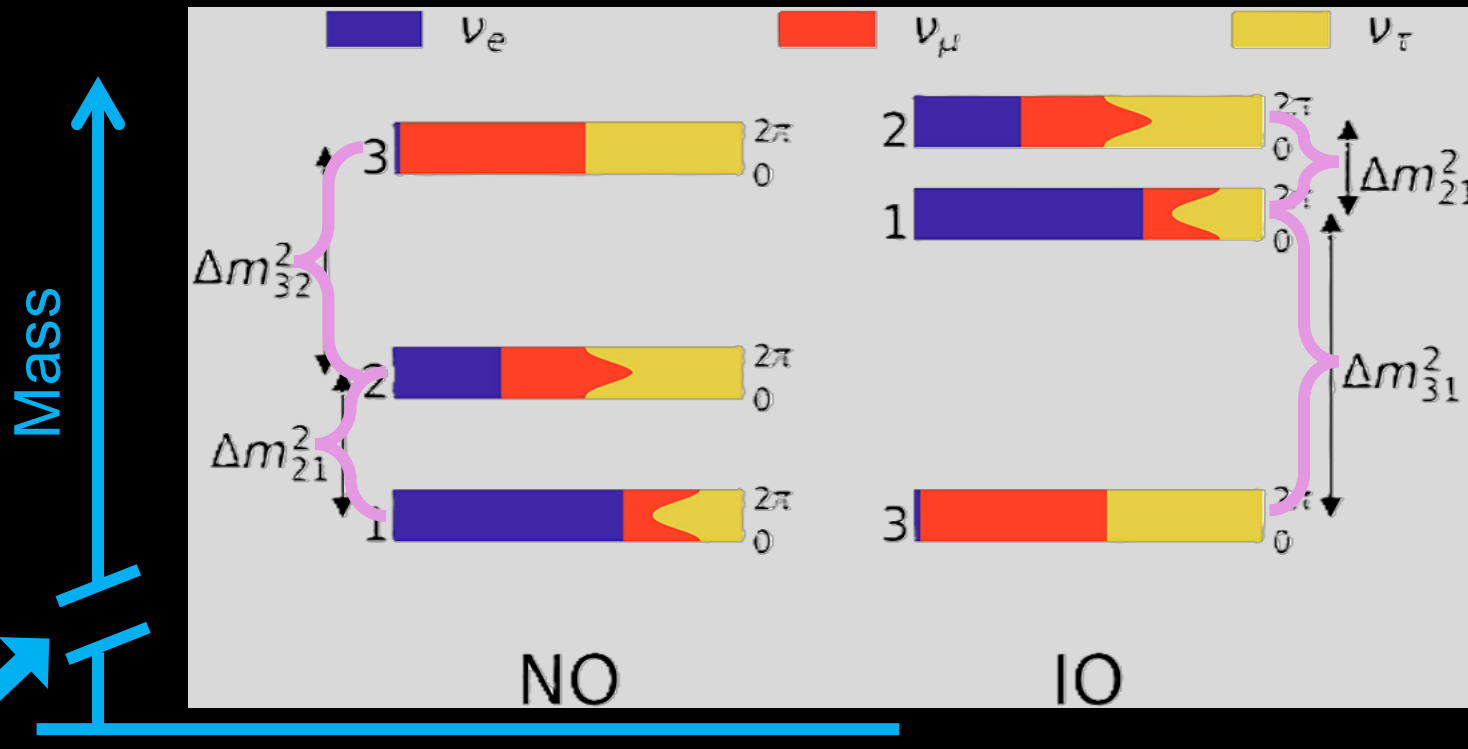


- ◆ We need another probe to access the **offset of the lightest mass from zero**
- ◆ That offset relates to the overall **neutrino-mass scale** on which the splittings sit

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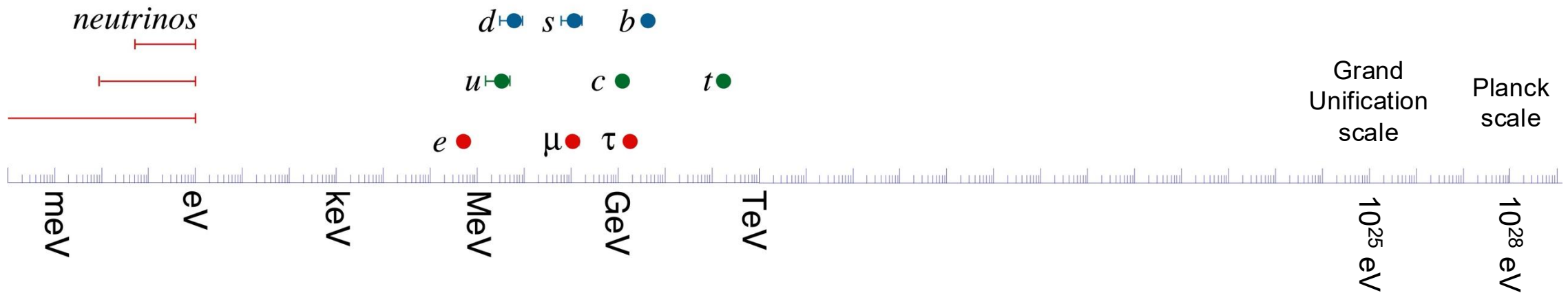


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# Massive Questions

More details later

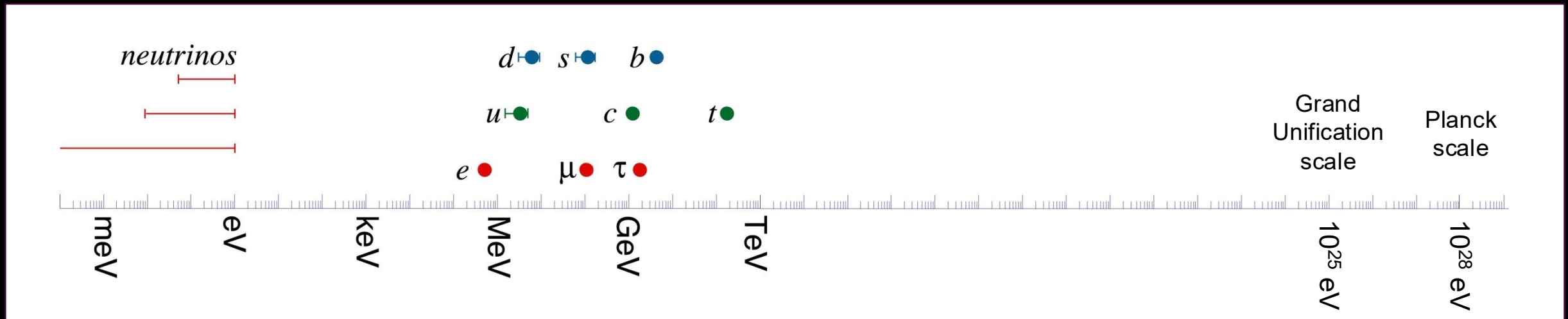




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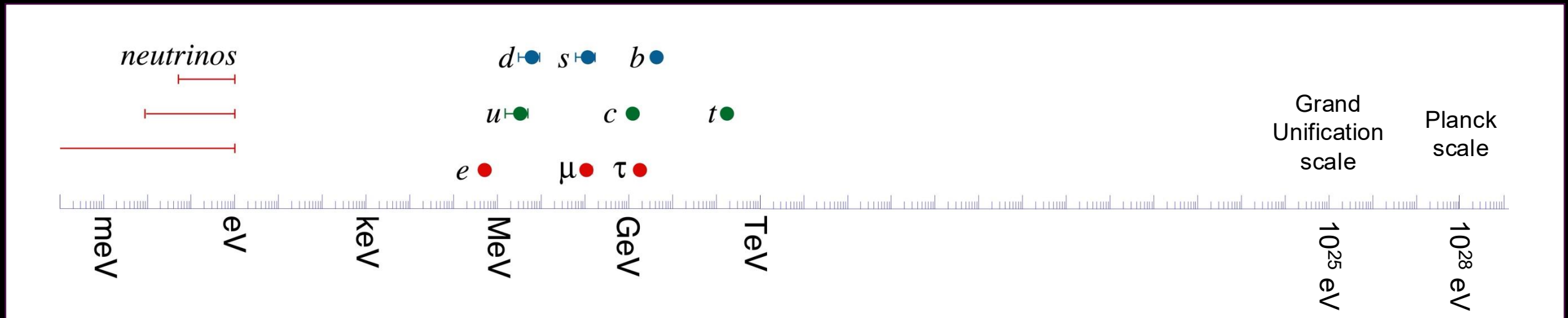
- ◆ We already know the mass scale is much lighter than an eV
- ◆ Why are neutrinos\* so much lighter than every other fundamental, massive particle?
  - ◆ \*Let's assume CPT symmetry: Neutrinos and antineutrinos have the same mass.
- ◆ How do they acquire mass when the Higgs mechanism flips helicity?
- ◆ How do neutrinos affect cosmology?
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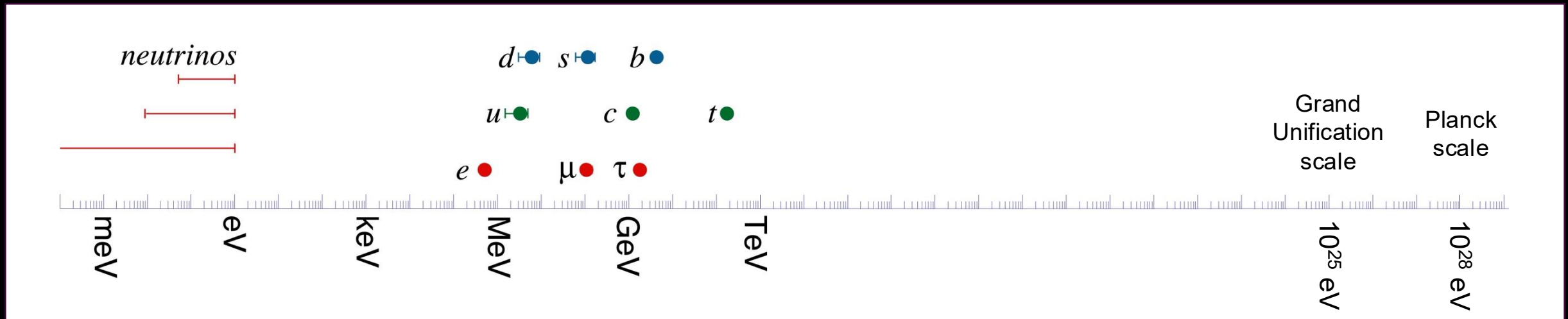
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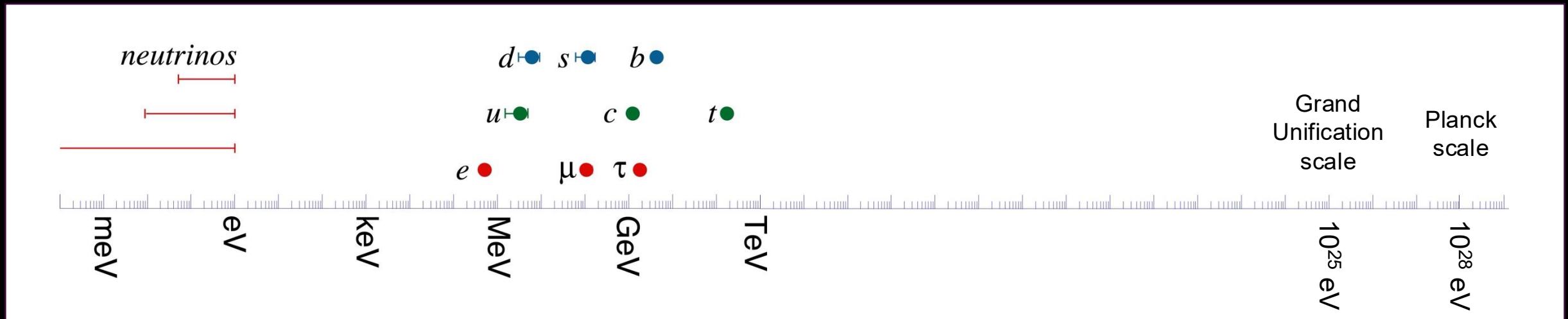
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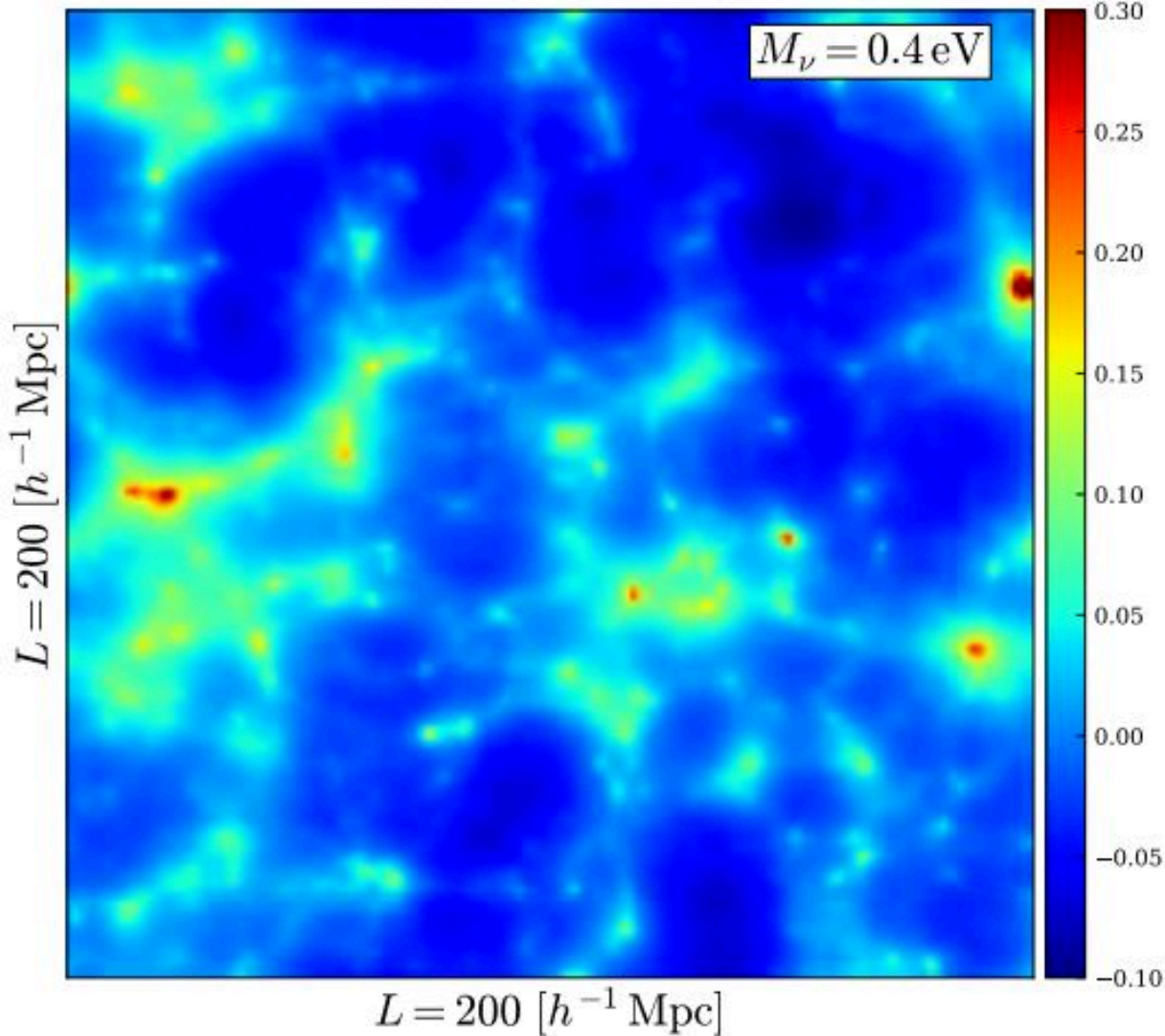
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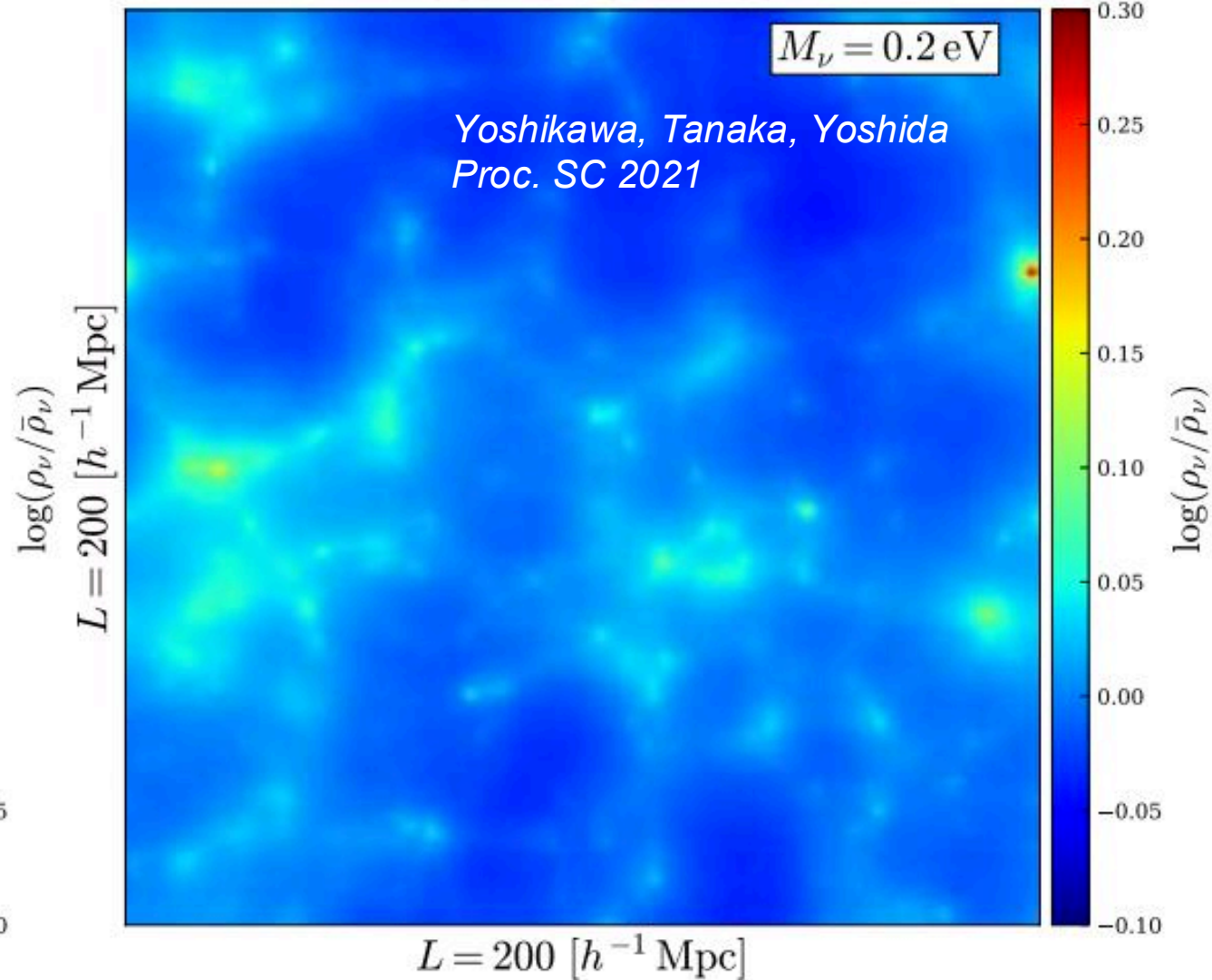




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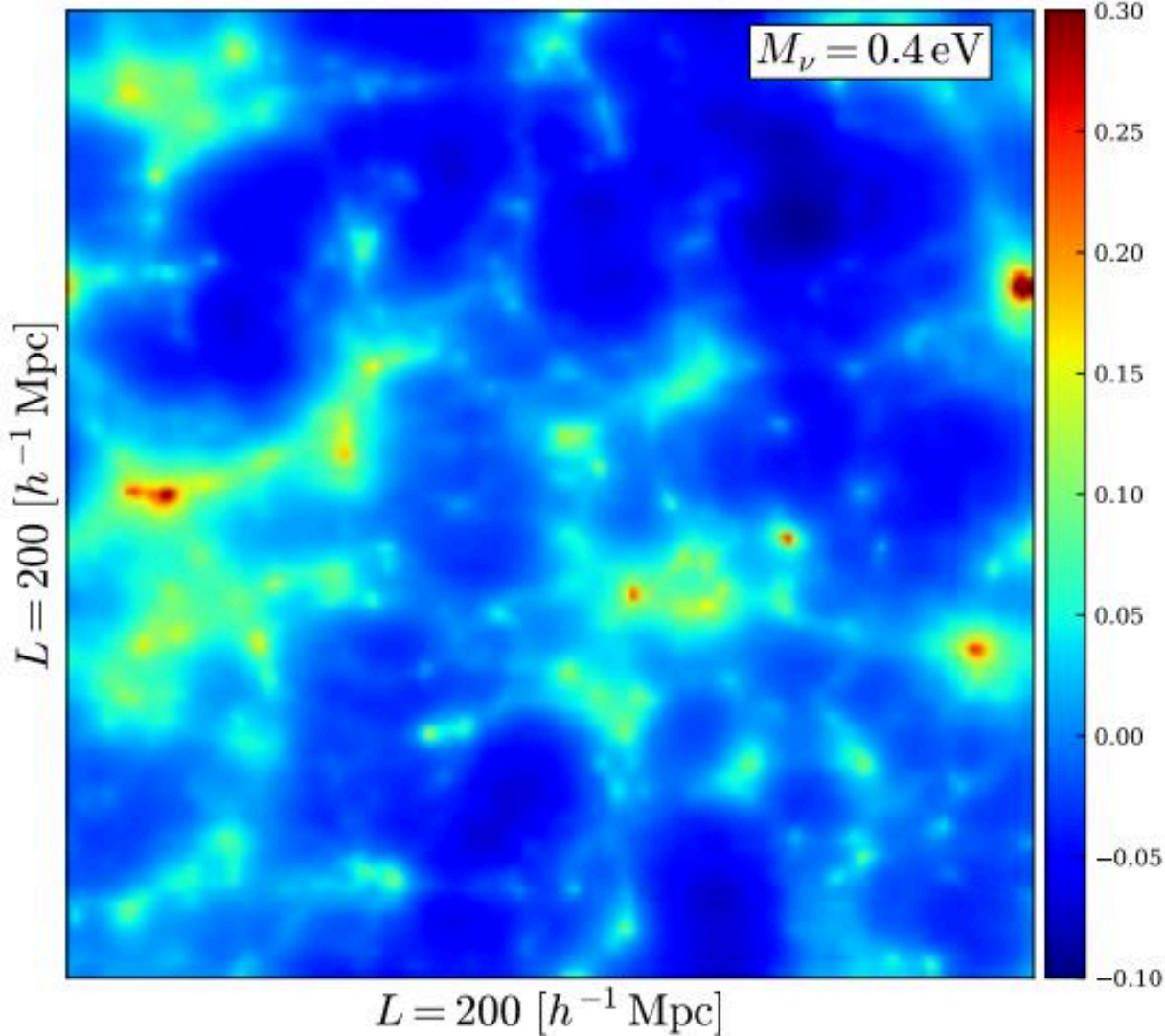


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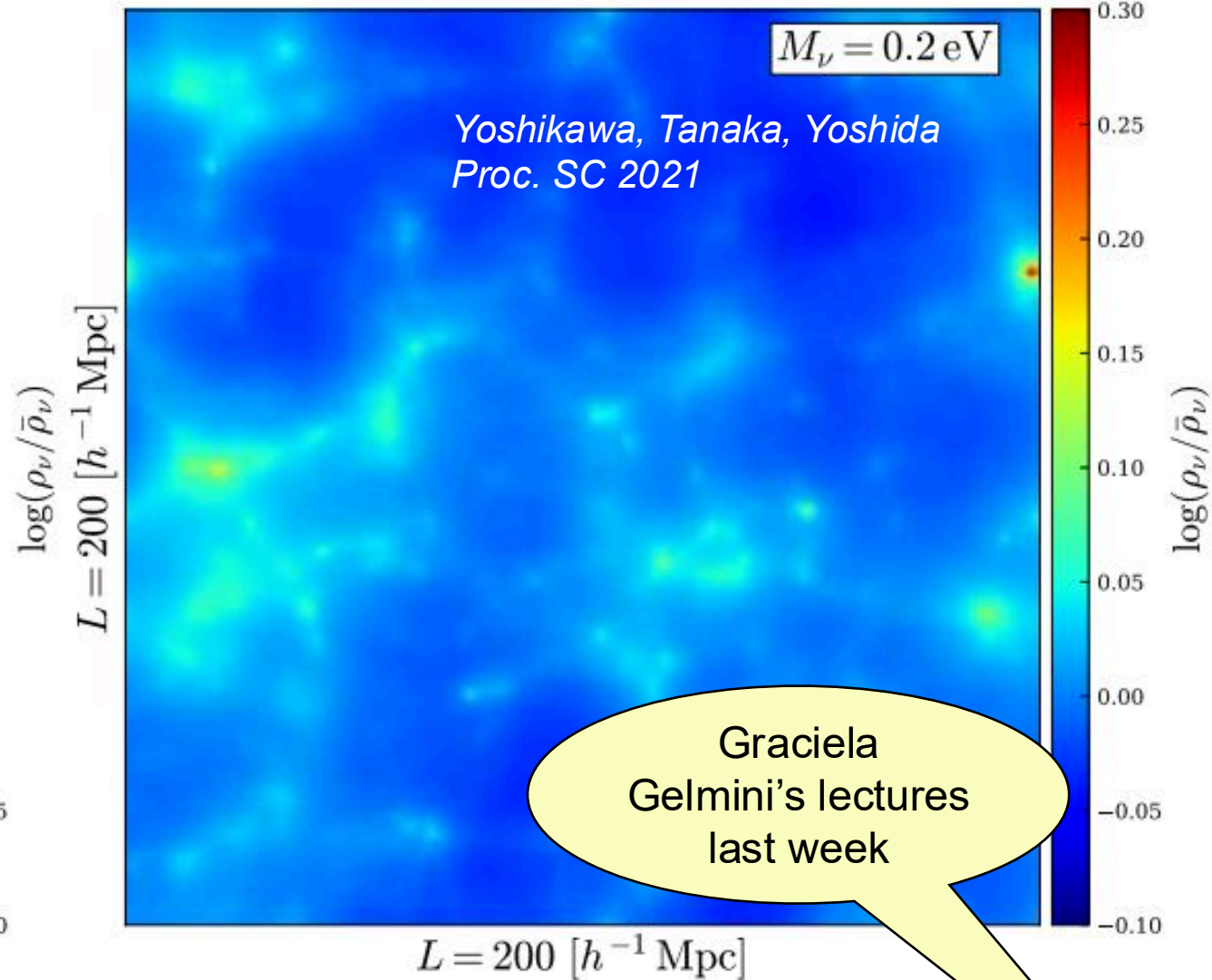


- ◆ The signature of neutrino mass should be imprinted on the universe
- ◆ Neutrino mass ( $\sum m_i$ ) affects the way structures form at different scales
- ◆ Infer from CMB + BAO + lensing data

massive neutrinos



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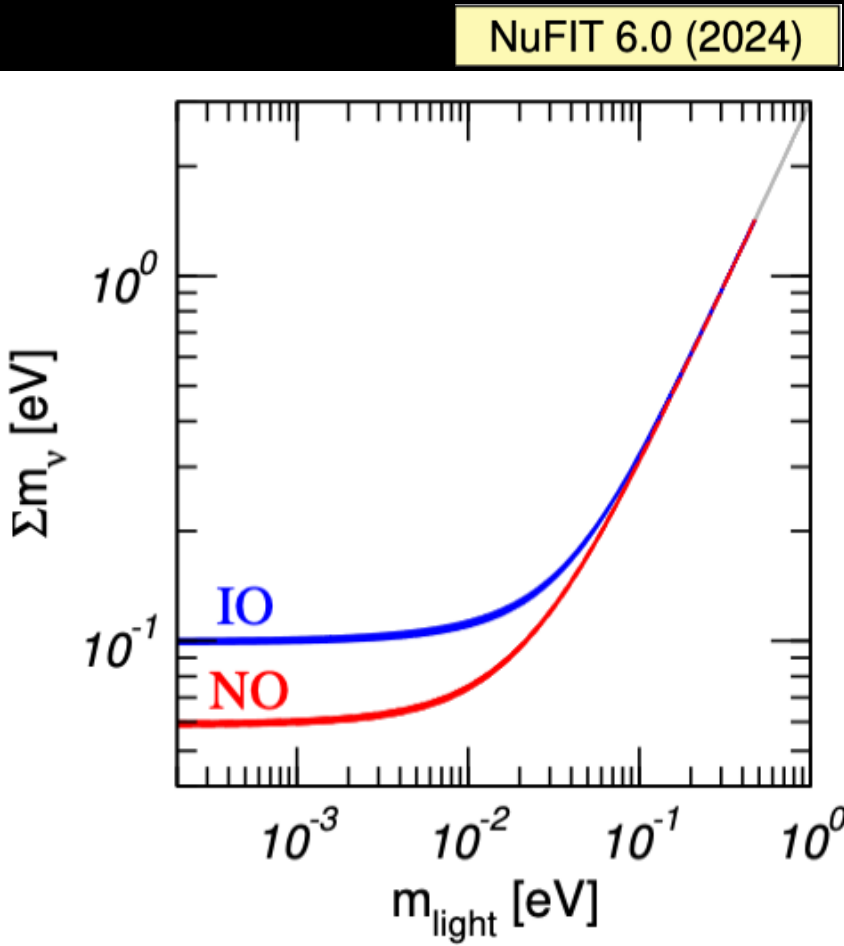


Graciela  
Gelmini's lectures  
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# Mass Scale from Cosmology

- ◆  $m_{\text{light}}$  is the offset from 0 (lightest neutrino mass value)

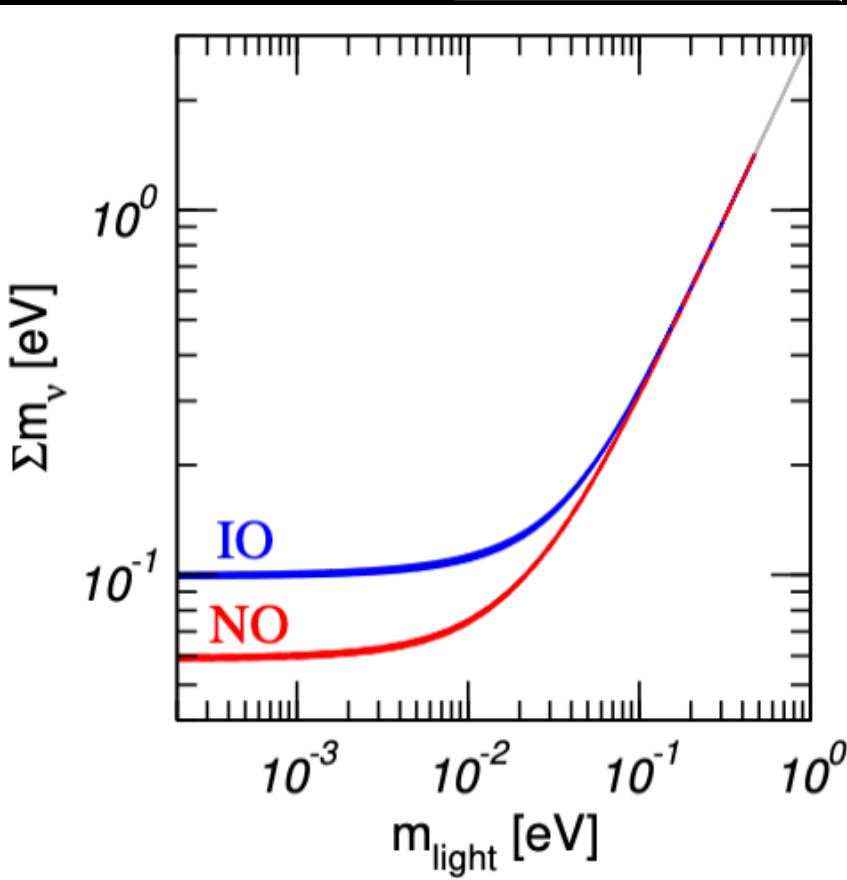


Esteban et al., JHEP 12 (2024) 216

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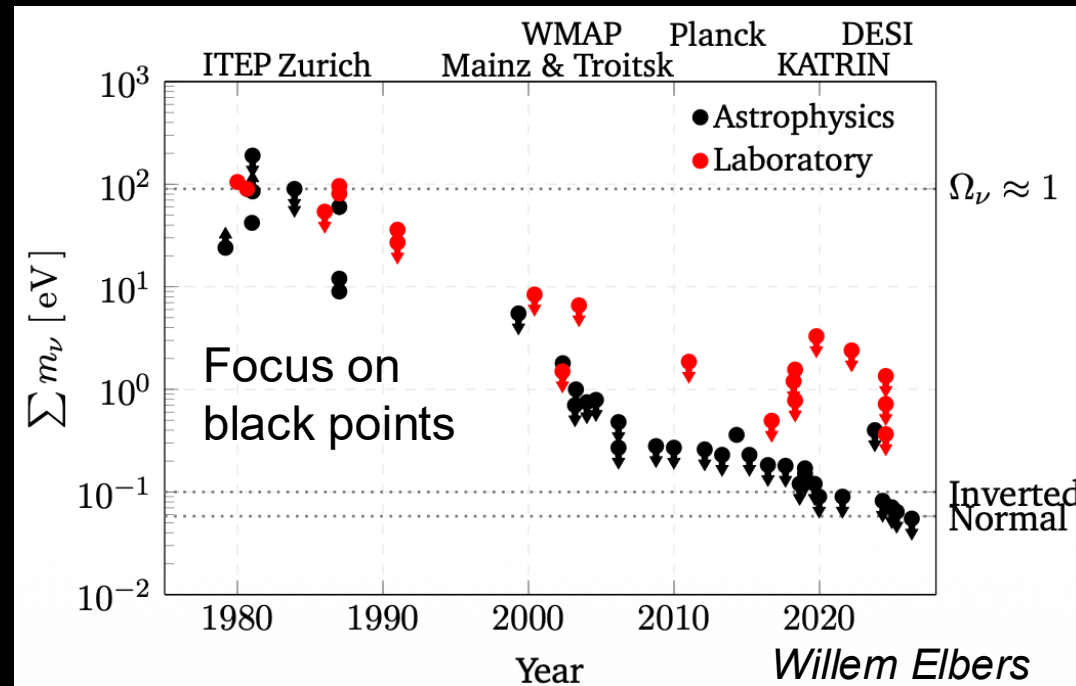
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NuFIT 6.0 (2024)



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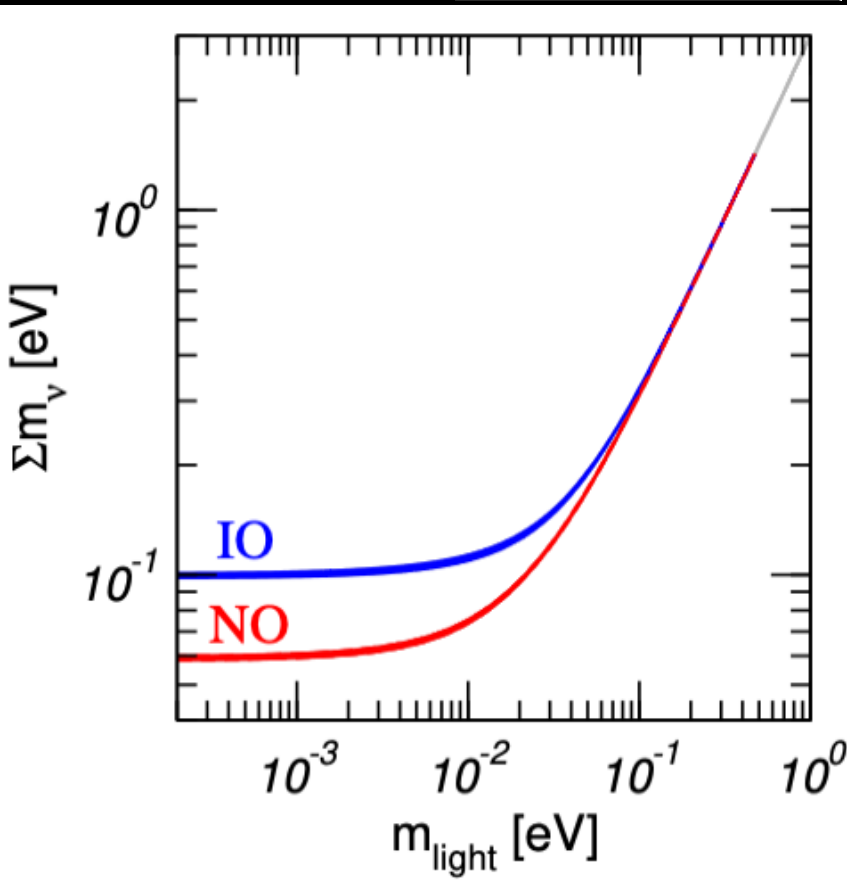




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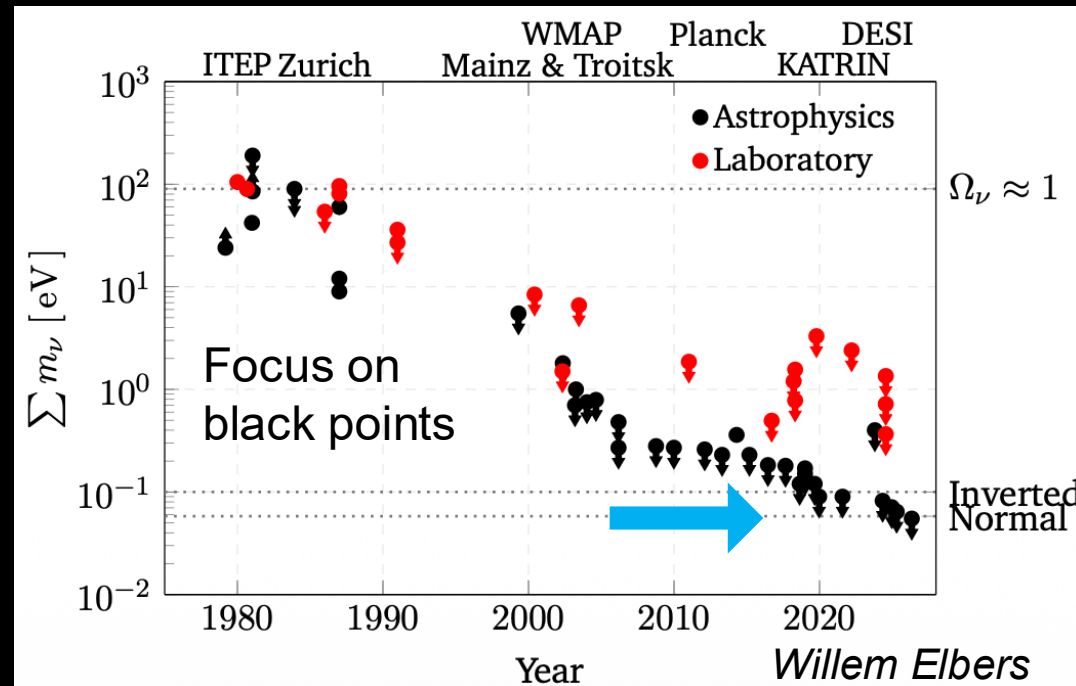
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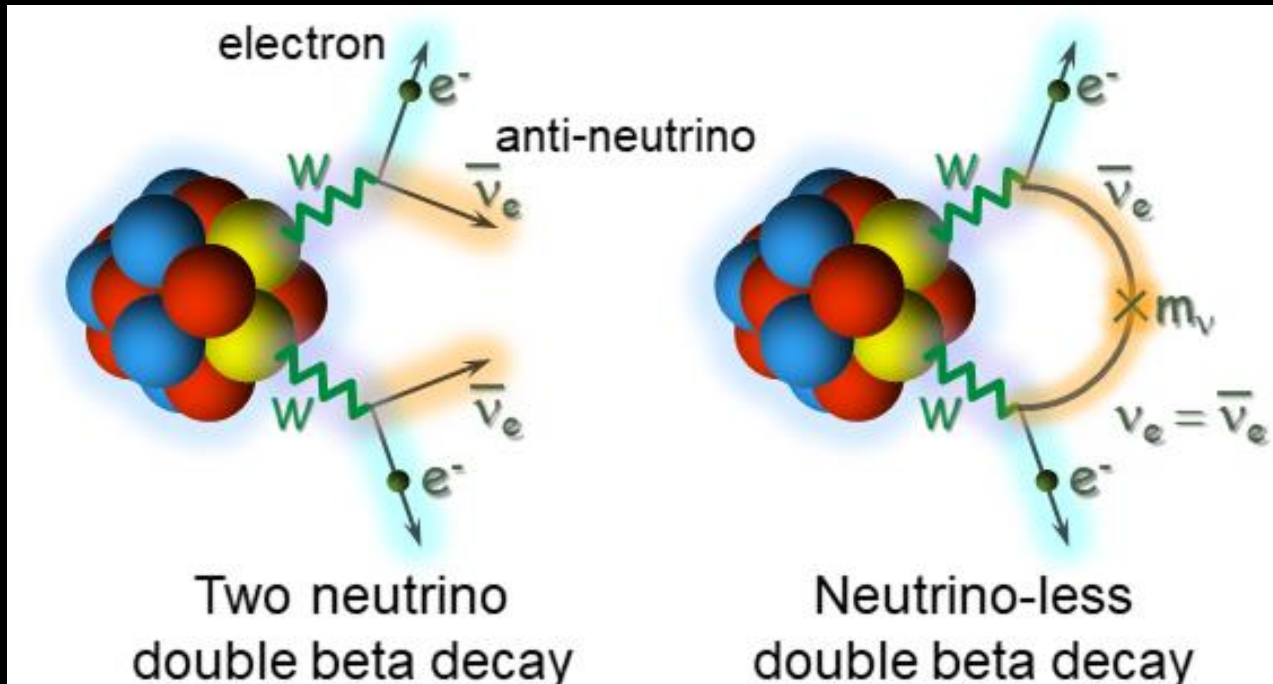
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- ◆ Cosmological mass limits in some tension with floor from oscillation data

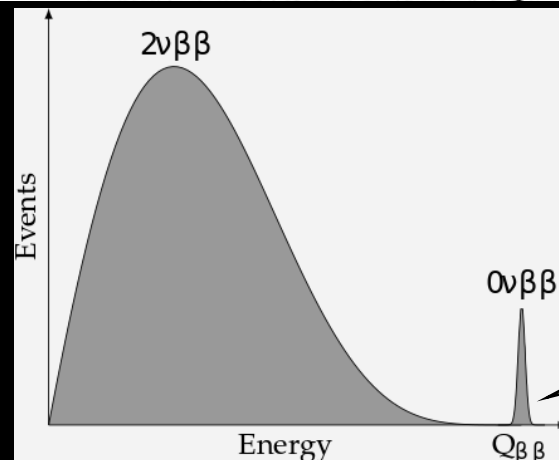


# Neutrinoless Double Beta Decay



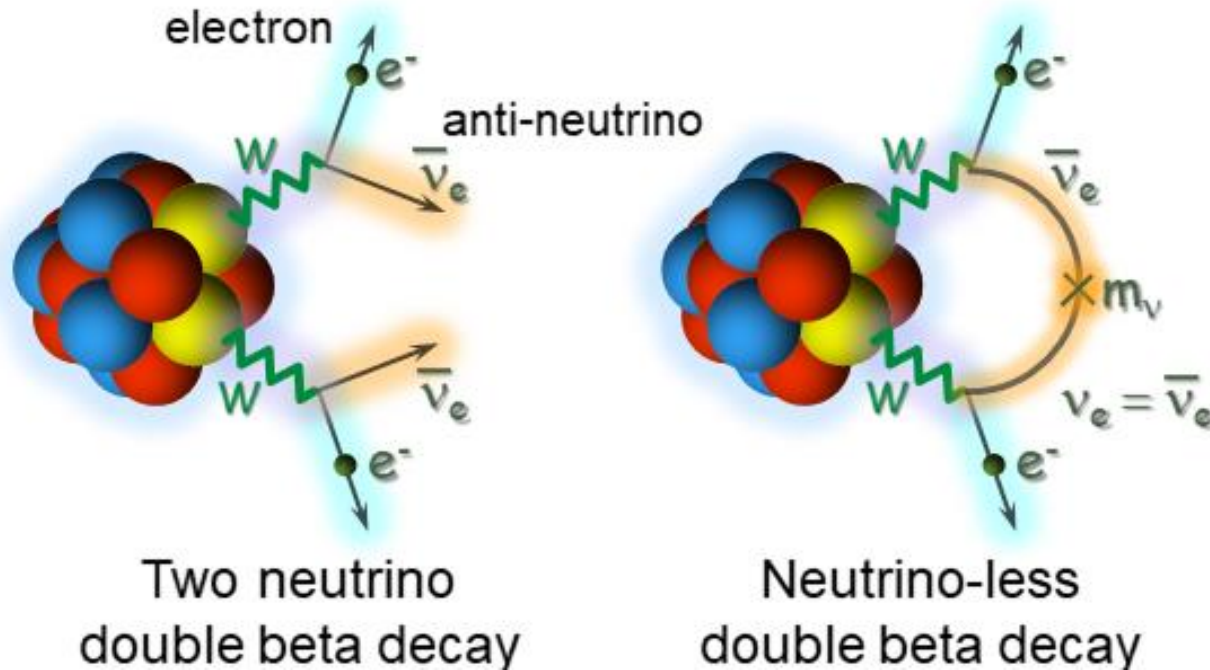
CANDLES collaboration

Giorgio Gratta's  
lectures today  
and tomorrow



Exaggerated  
rate

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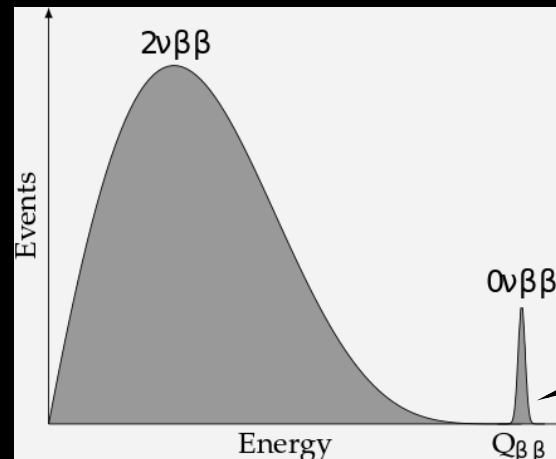


CANDLES collaboration

- ◆ This decay mode may not have any neutrinos, but it would have mass information
- ◆ If the decay occurs, *and* the primary mechanism is light neutrino exchange, then the decay rate is proportional to

$$m_{\beta\beta} = \sum_{i=1}^3 (U_{ei})^2 m_i$$

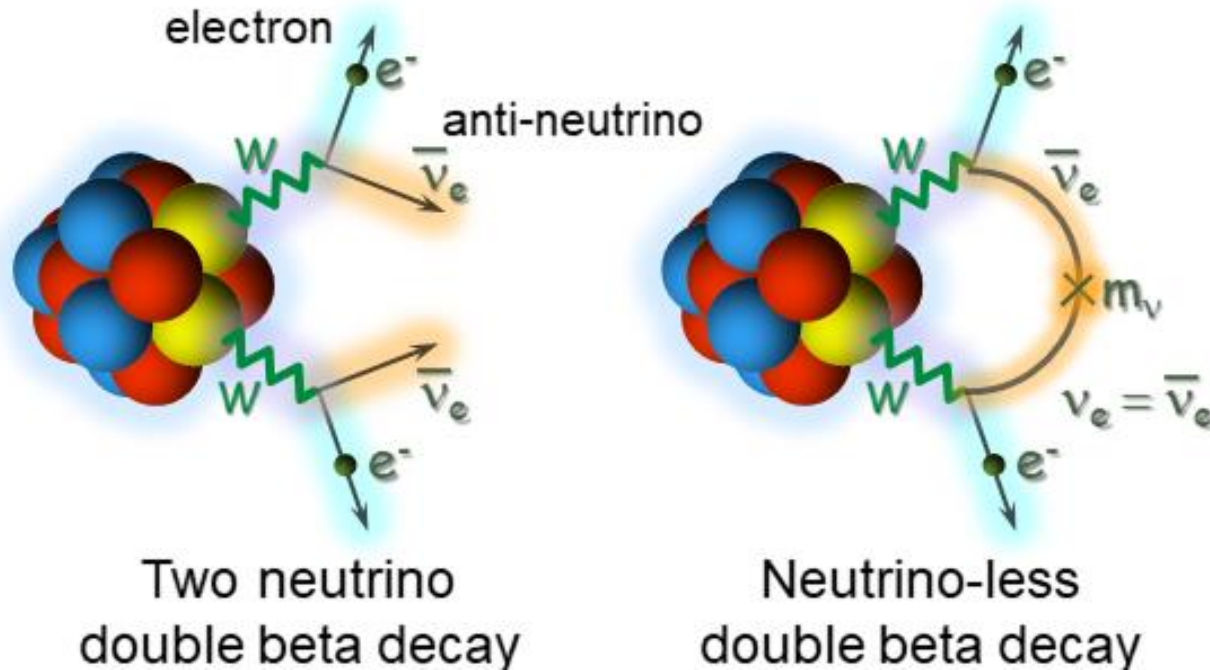
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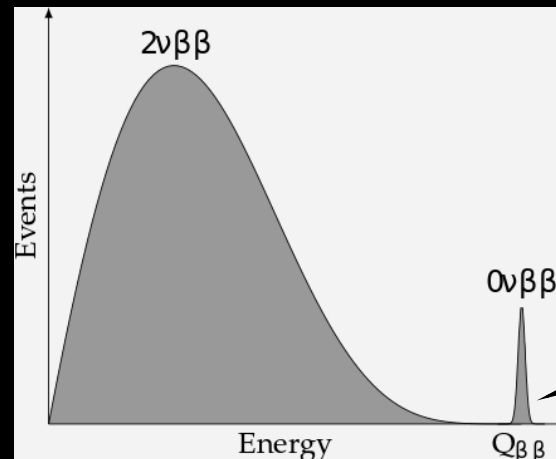


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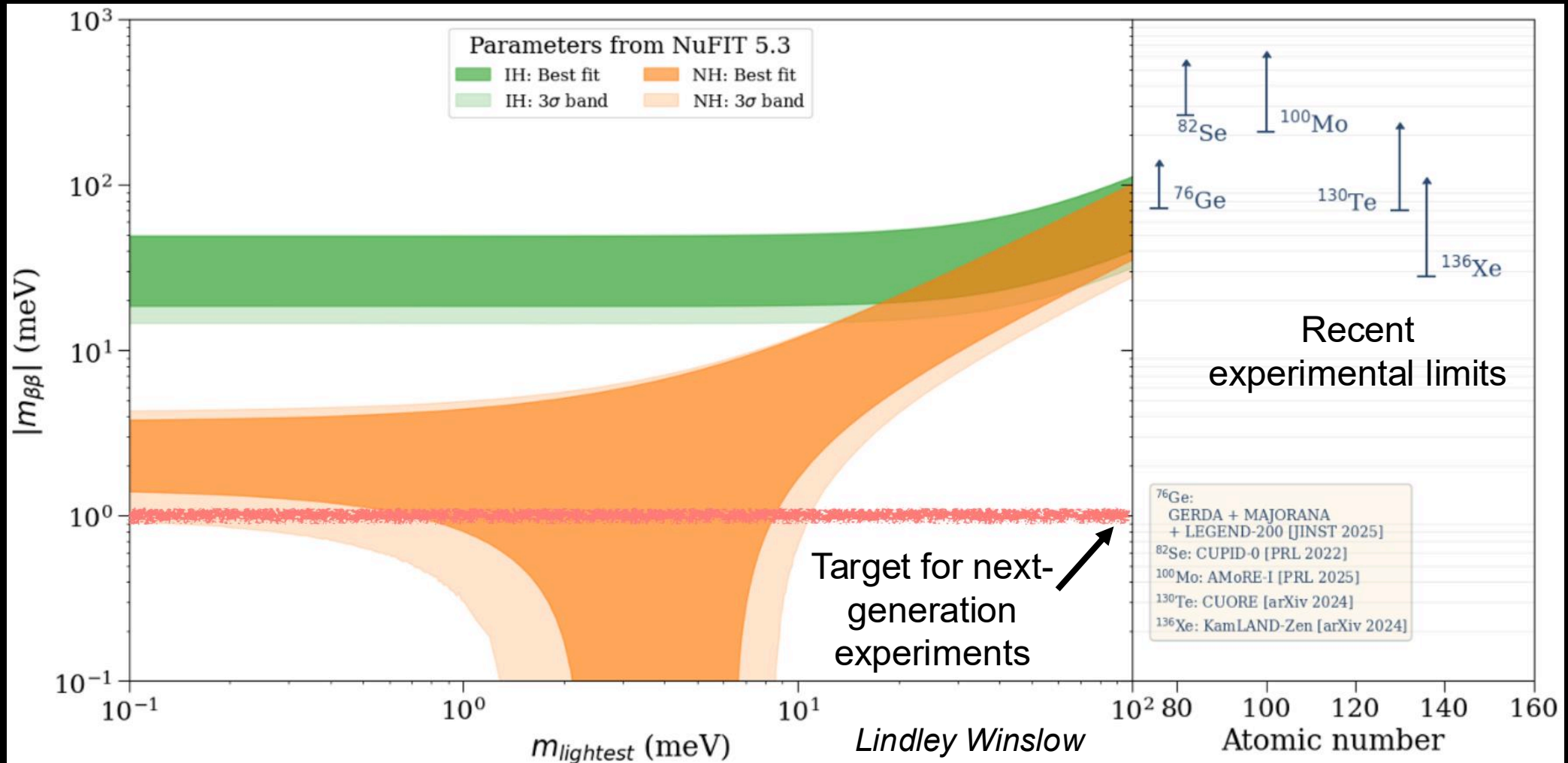


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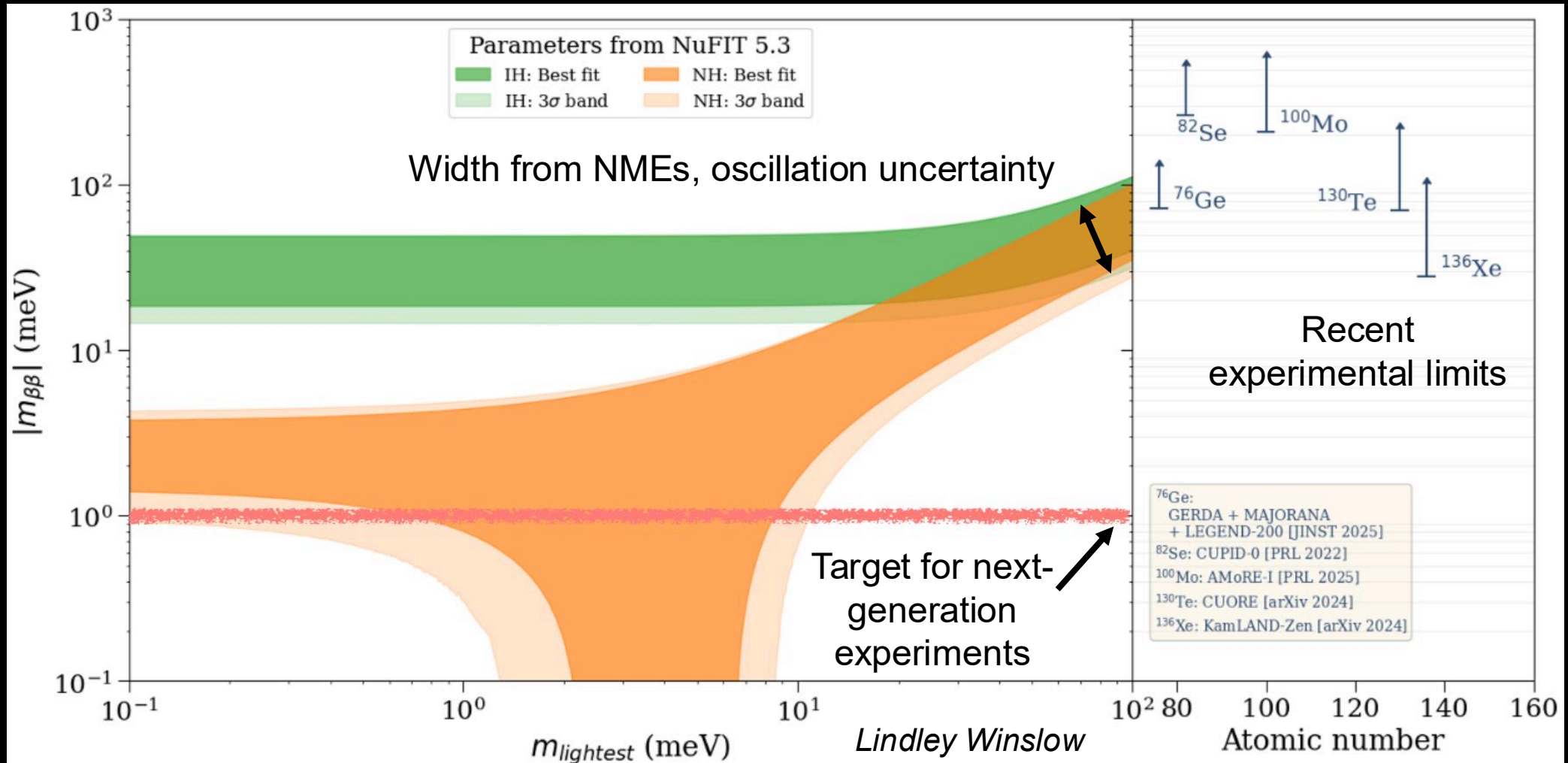
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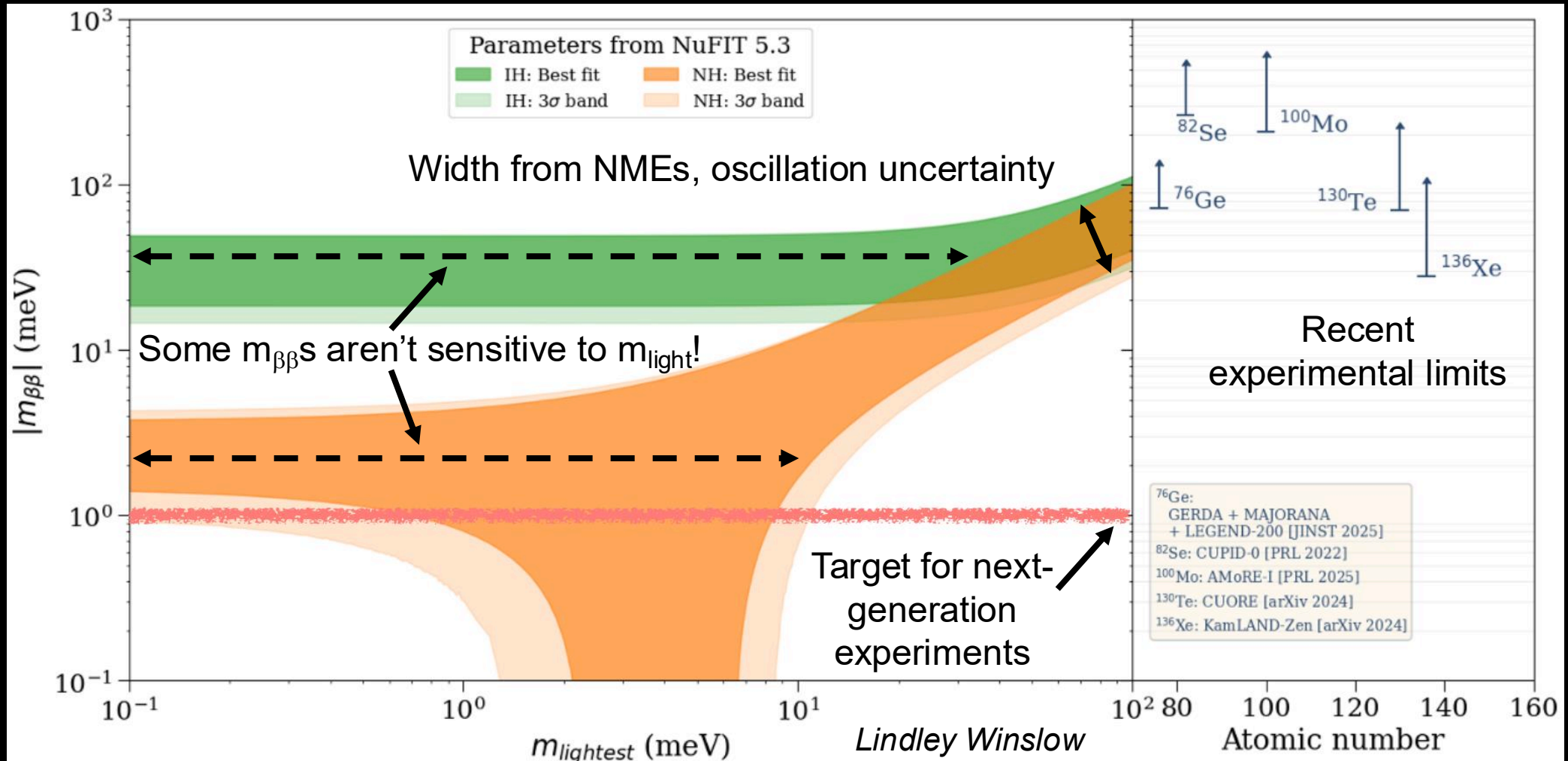
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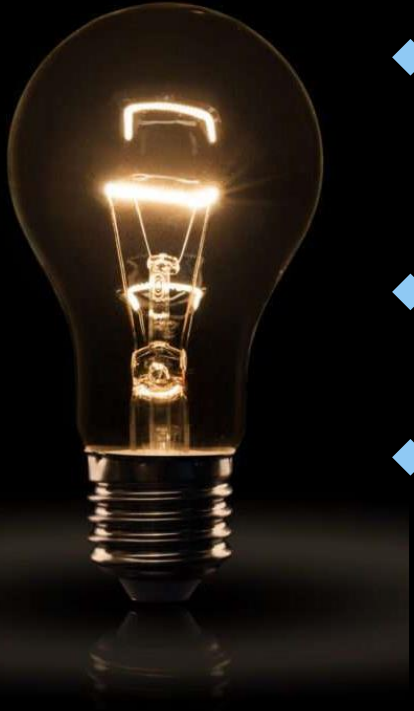


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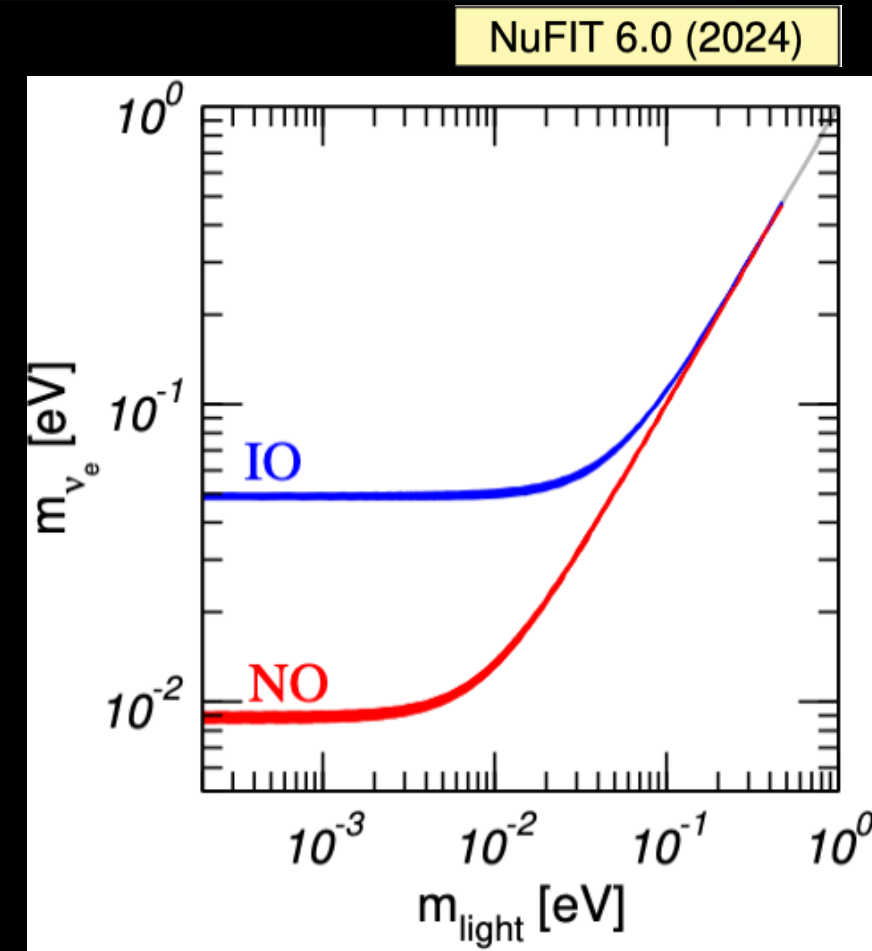
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# Minimizing Model Dependence?

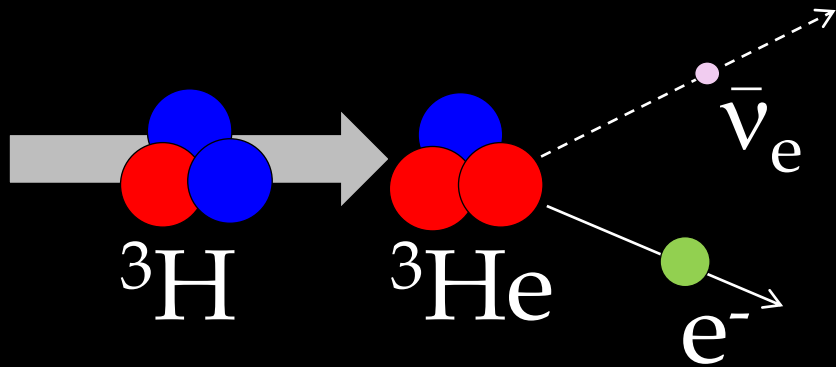


- ◆ Maybe we can make a clean laboratory test of particle theory *and* cosmology at the same time
- ◆ “Direct” neutrino-mass measurements rely on kinematics
- ◆ Only fundamental model dependence: conservation of energy



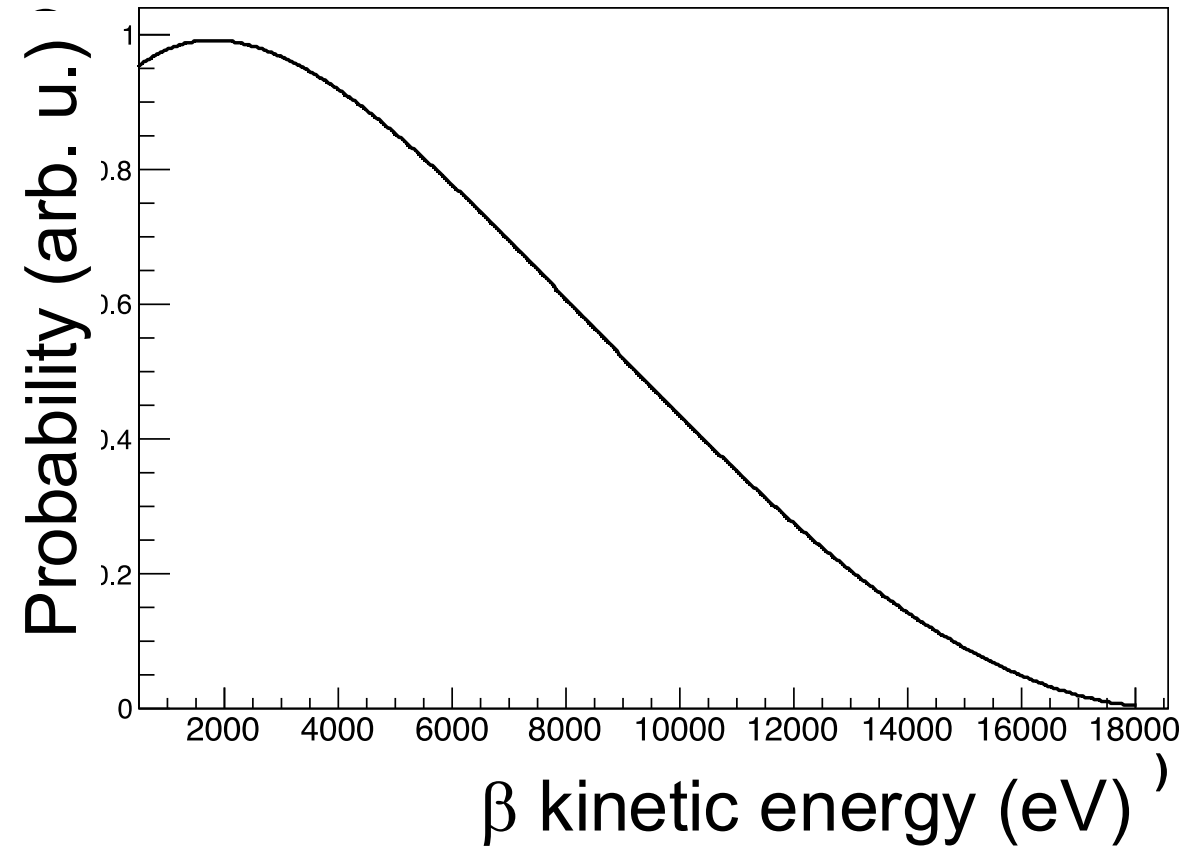
Esteban et al., JHEP 12 (2024) 216

# Direct Mass Probe Through $\beta$ Decay

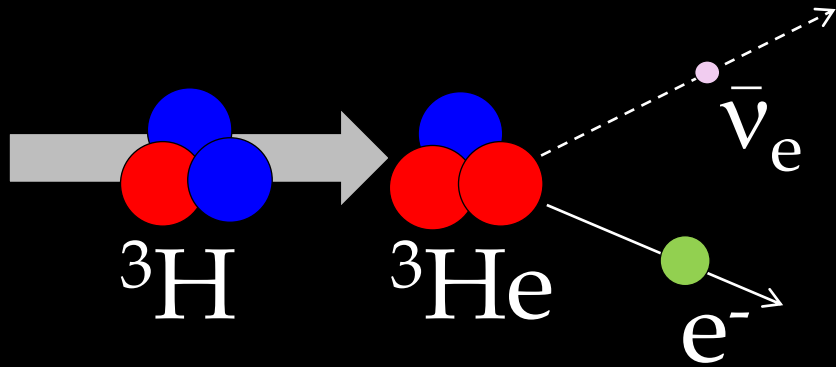


- ◆ Extract effective neutrino mass from spectral shape near endpoint

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 \\ \approx m_\nu^2$$

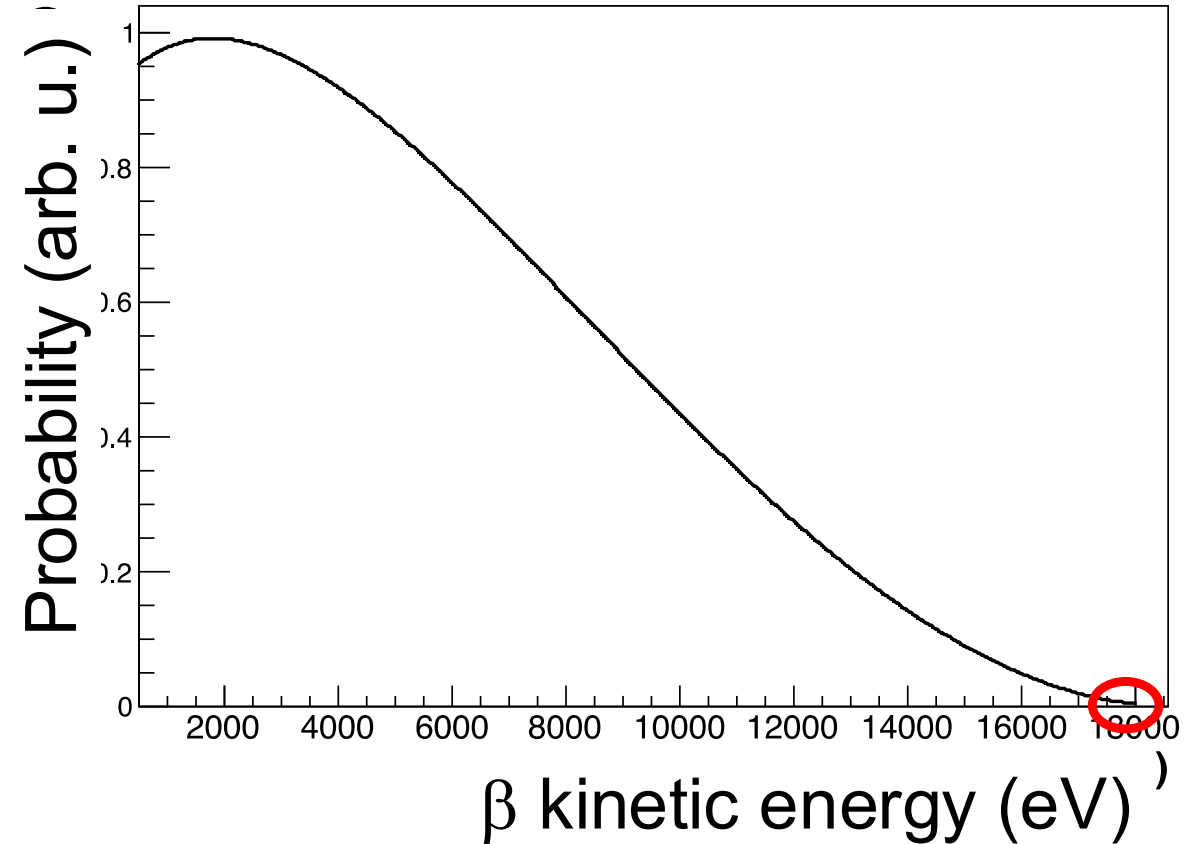


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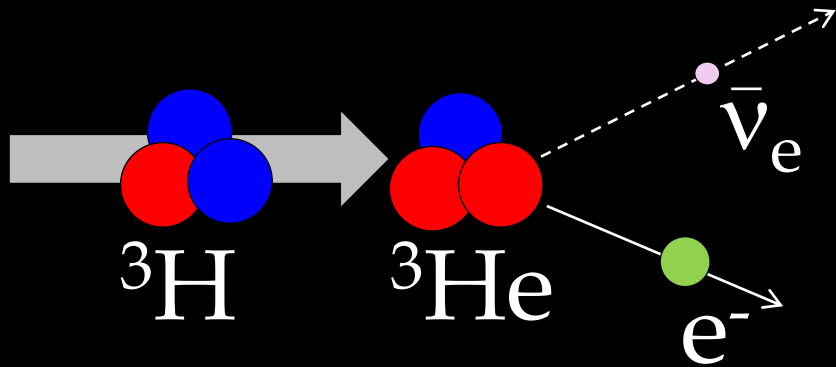


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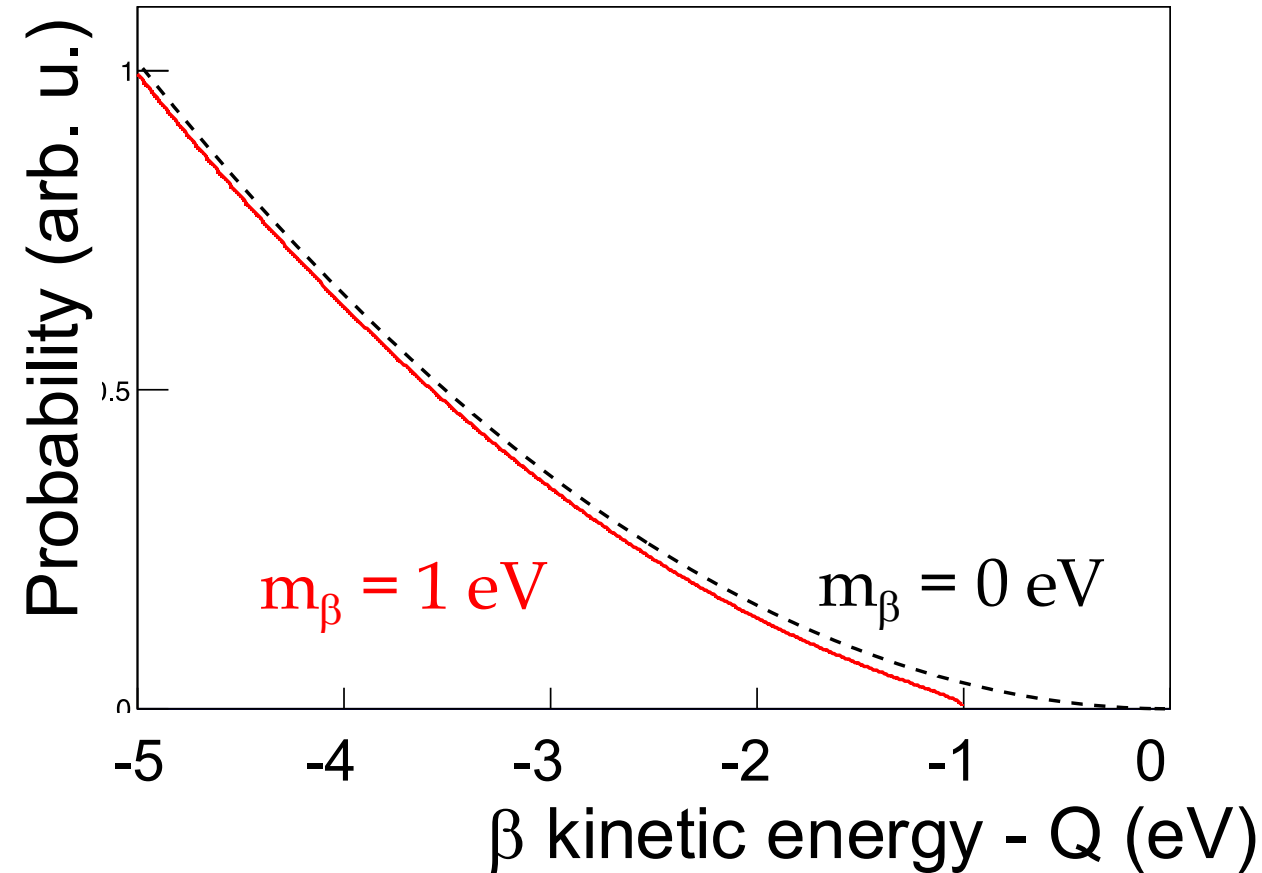


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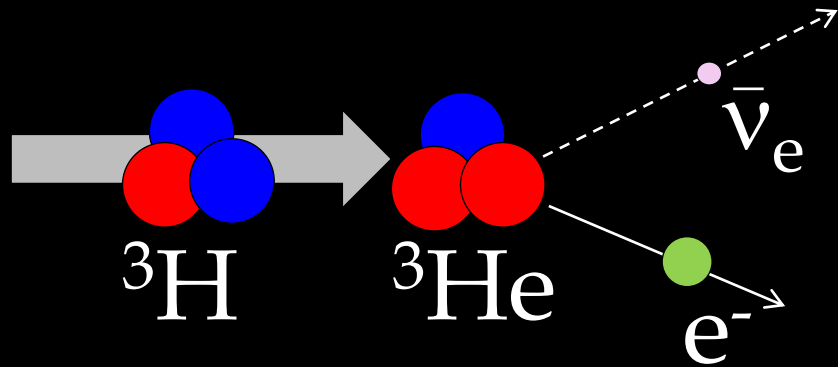
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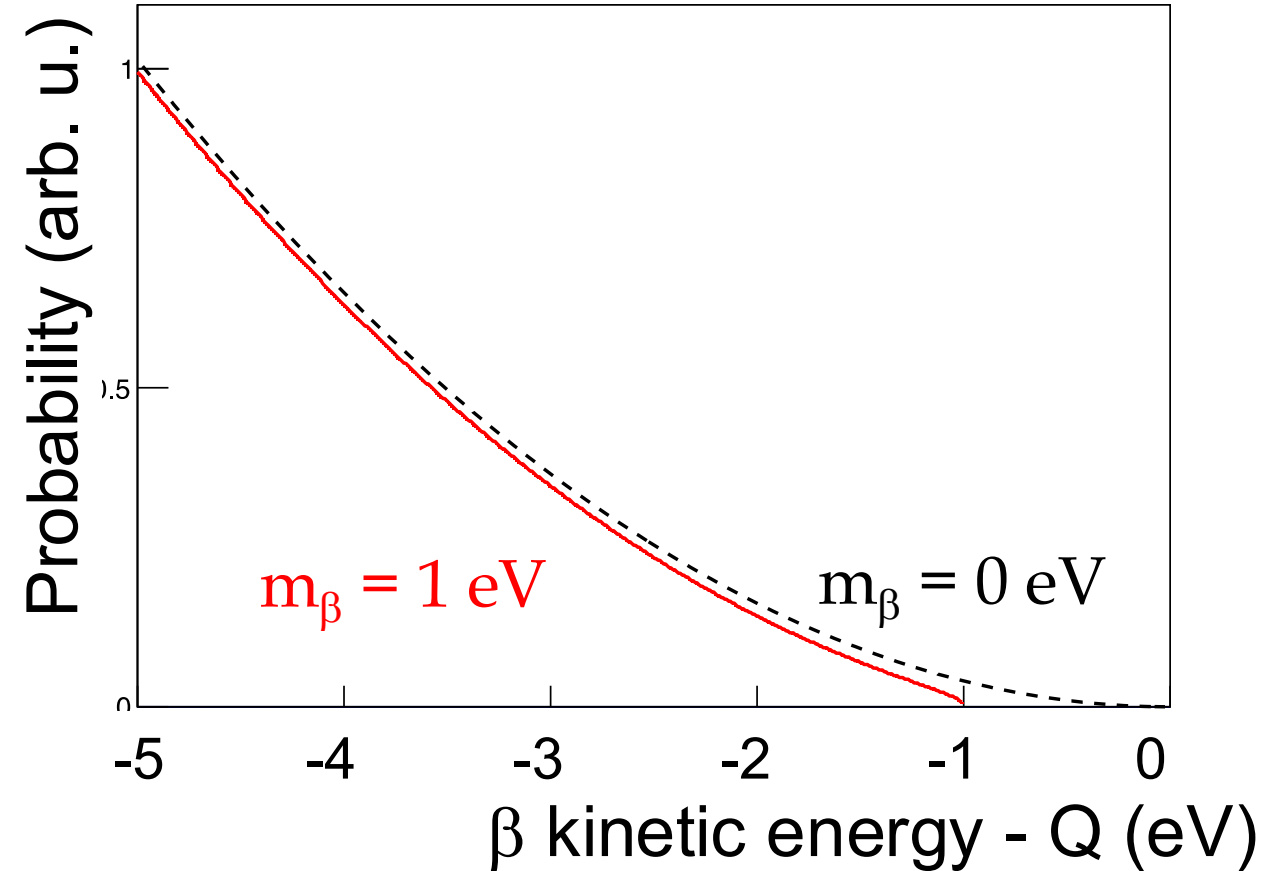
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$^3\text{T}$

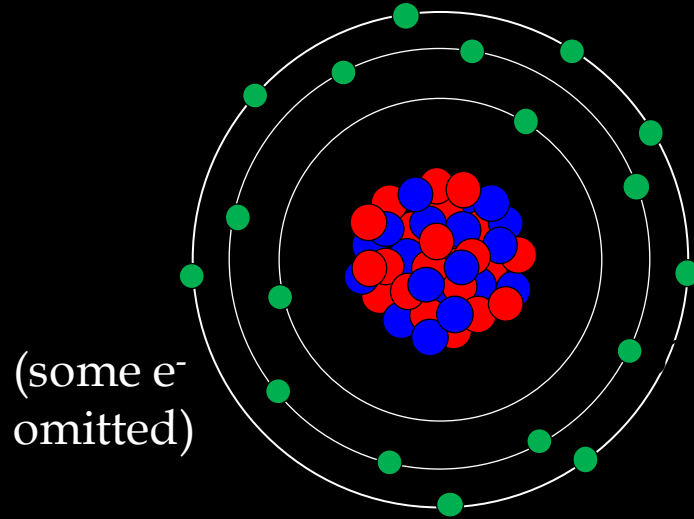
$Q = 18.6 \text{ keV}$

$t_{1/2} = 12.3 \text{ years}$



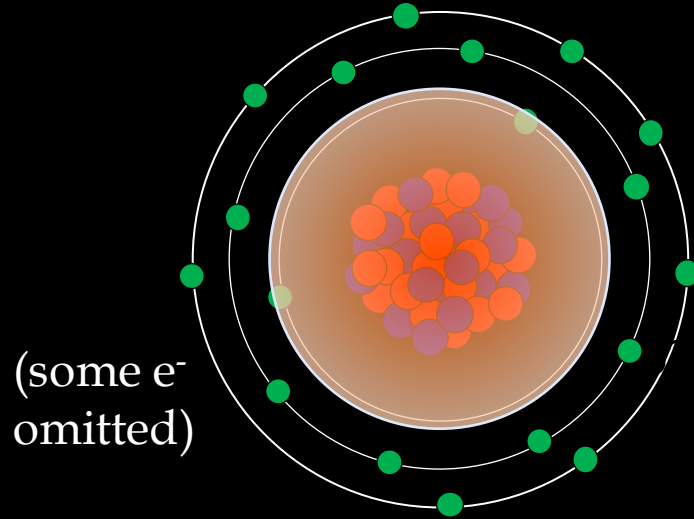
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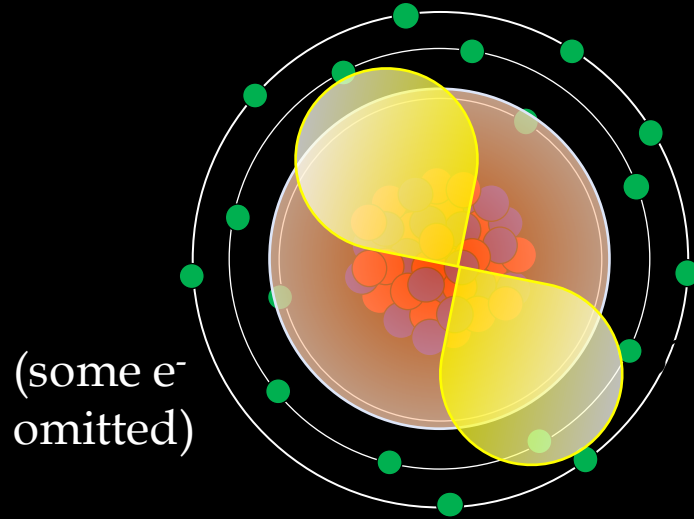
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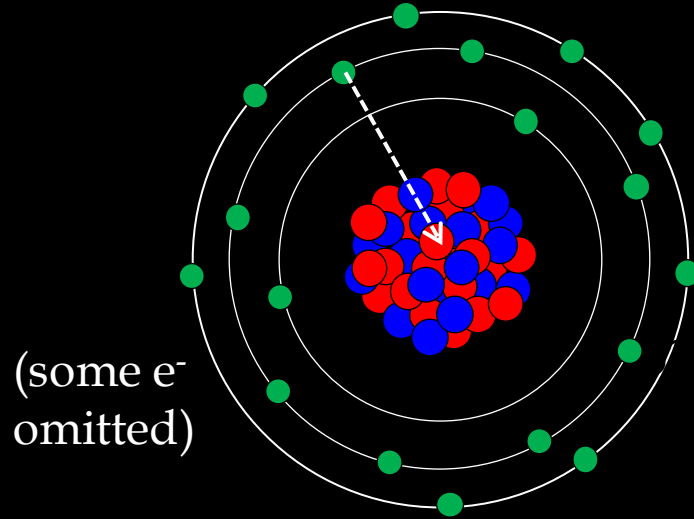
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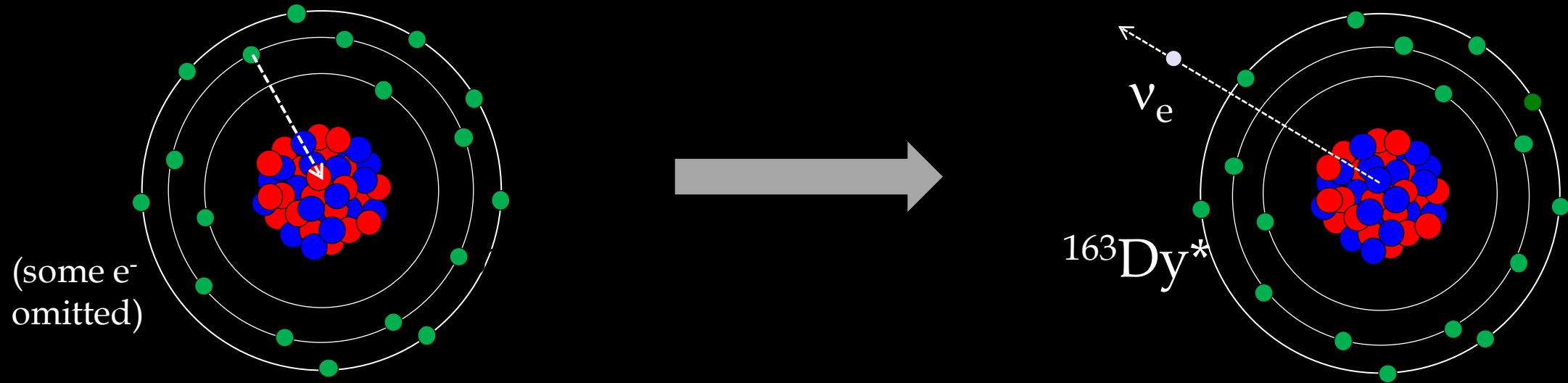
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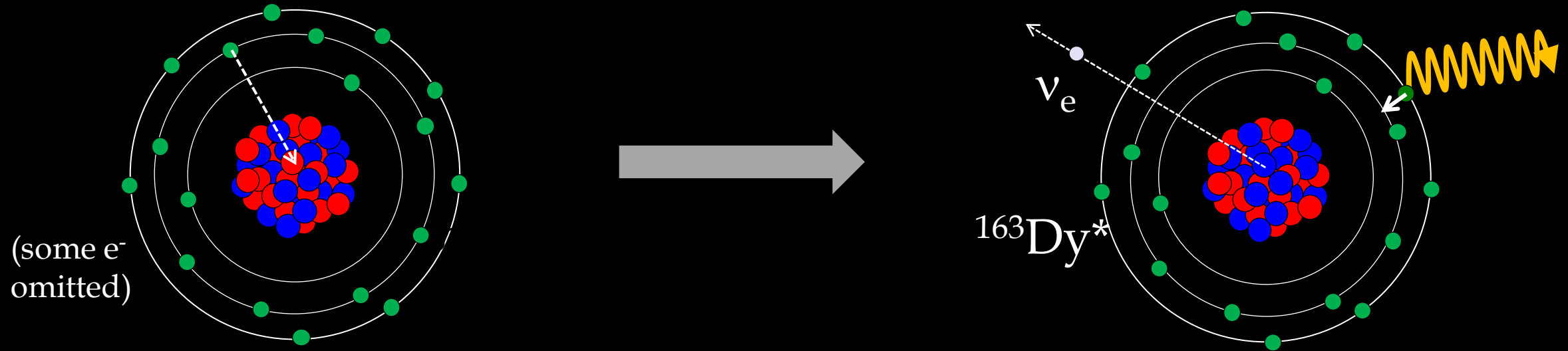




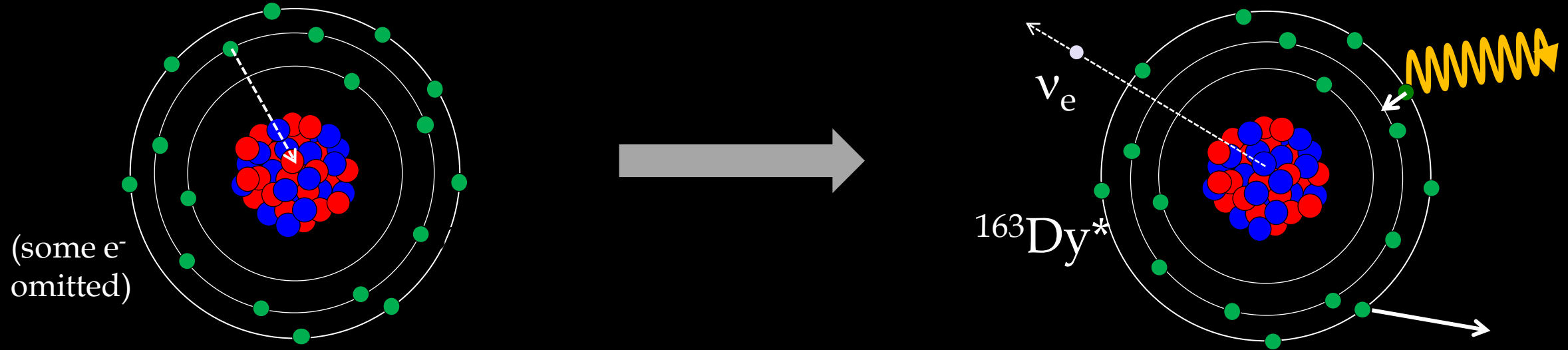
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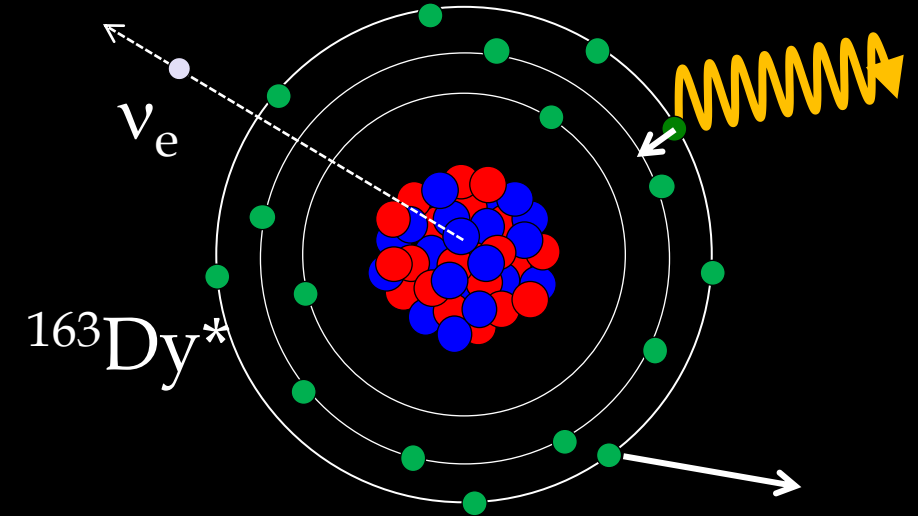
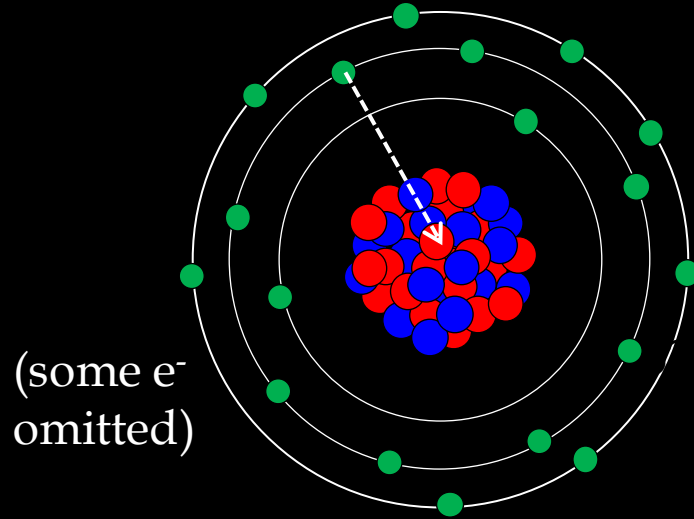
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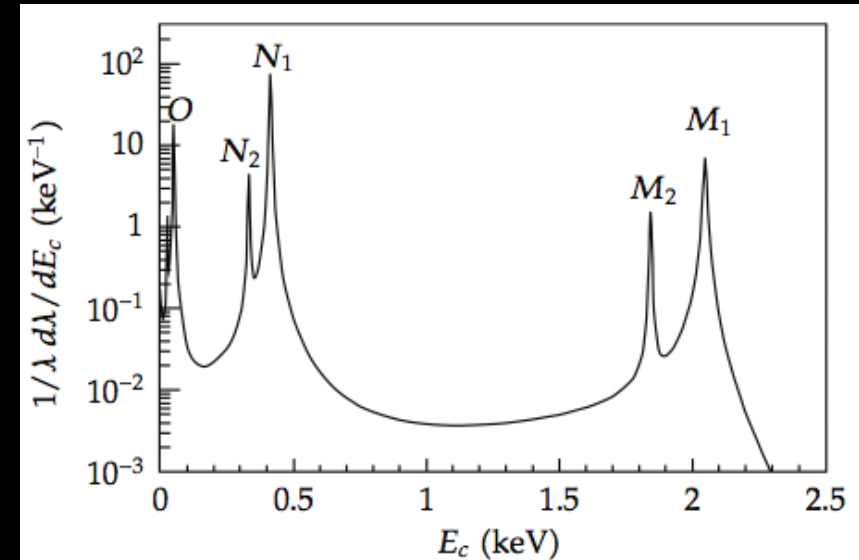


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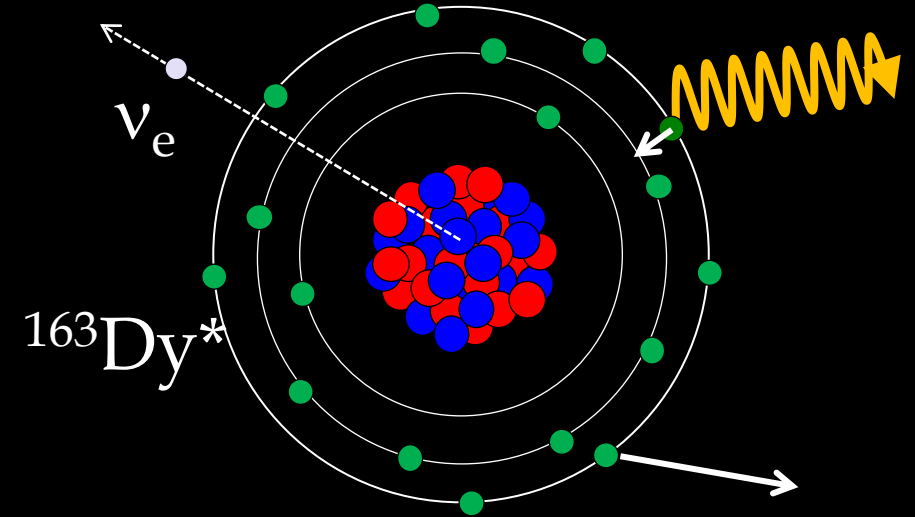
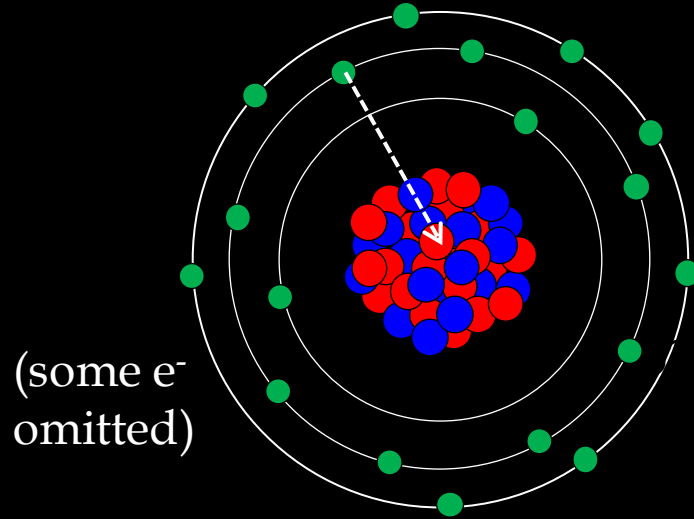


- ◆ Capture de-excitation energy in  $^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$

*Lusignoli and Vignati, Phys. Lett. B 697 (2011) 11*

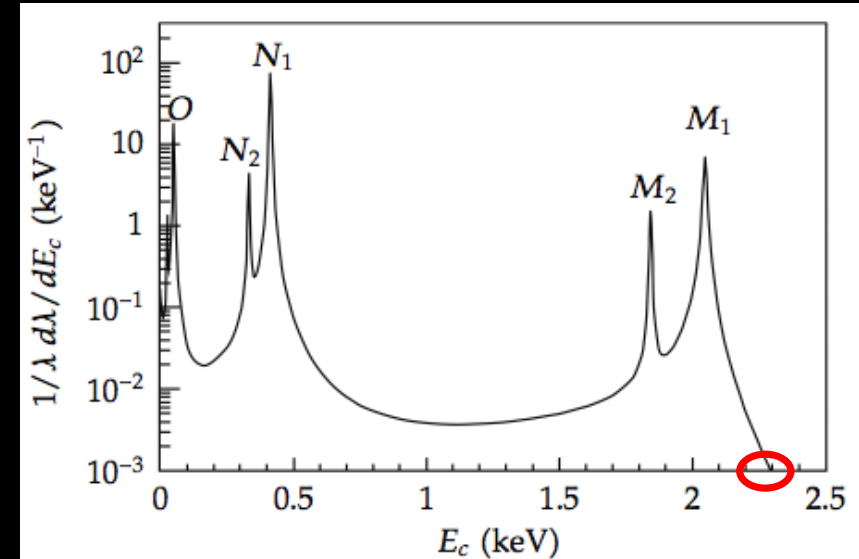


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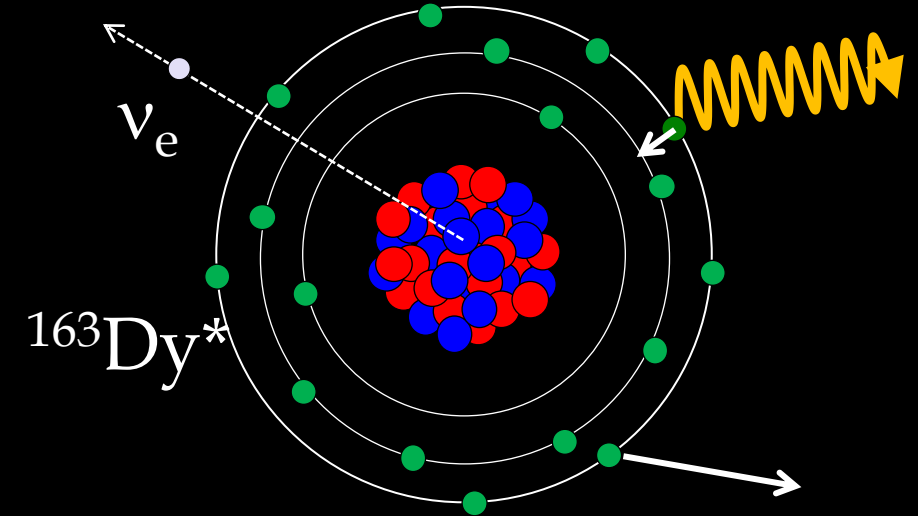
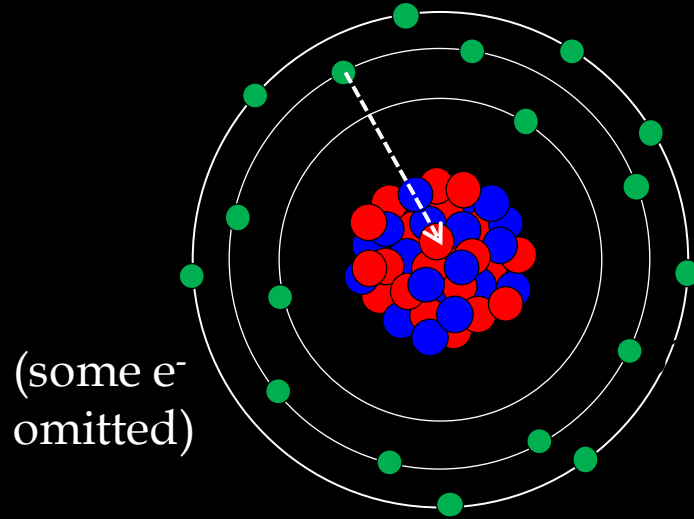


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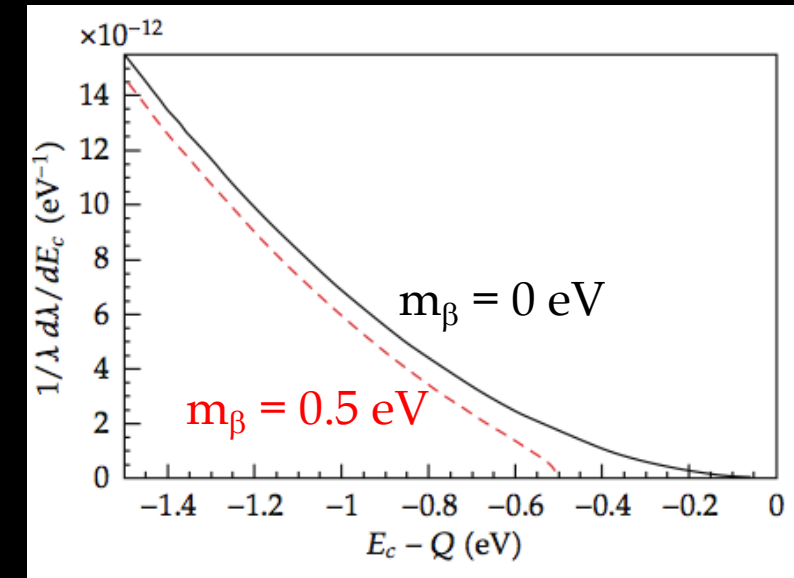
*De Rújula and Lusignoli, Phys. Lett. B*  
**118** (1982) 429

**$^{163}\text{Ho}$**

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*Lusignoli and Vignati, Phys. Lett. B* **697** (2011) 11

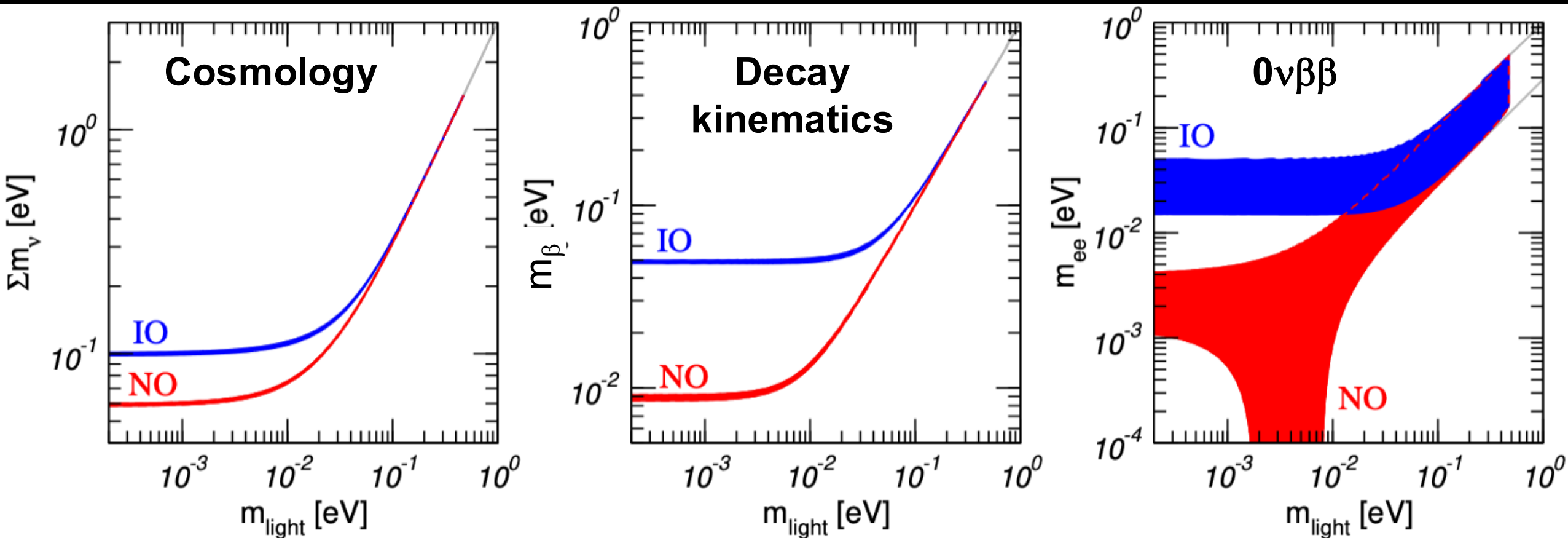




# All the Observables Together

- ◆ If all the models work as advertised, each observable is related to  $m_{\text{light}}$  (and to the others) by the oscillation parameters

NuFIT 6.0 (2024)



# Is Nuclear Decay the Only Kinematic Path?

- ◆ Some neutrino trajectories are really long!
- ◆ Mass makes a difference in kinematics
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DC Comics

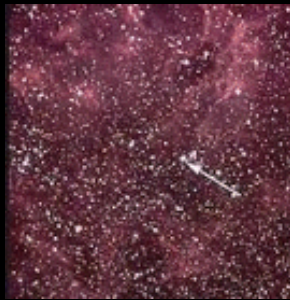


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before

*Anglo-Australian Observatory*



during



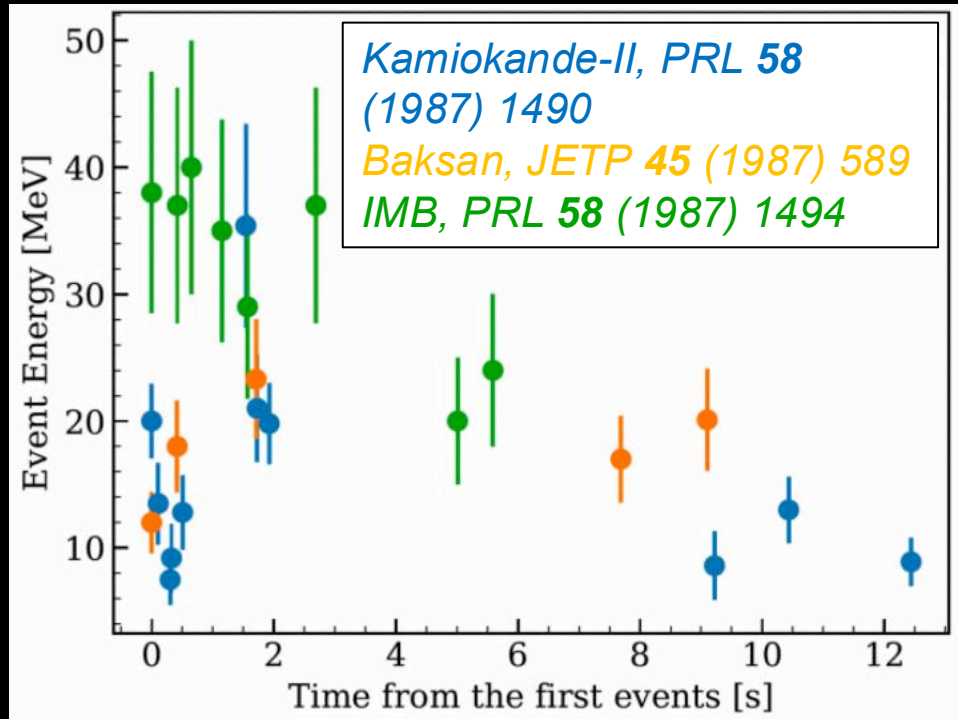
after

*ESA/Hubble*



# Supernova Neutrino Kinematics

- ◆ Possibly the most widely cited neutrinos ever



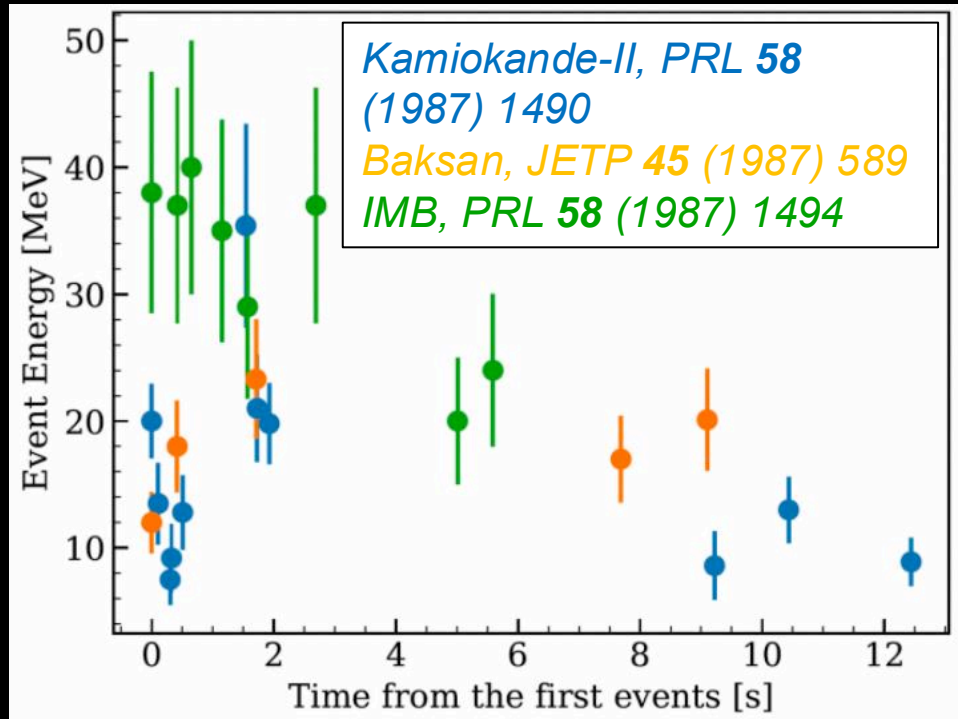
Plot from Masamitsu Mori via Roger Wendell



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- ◆ Time-of-flight delay for massive - massless  $\nu$

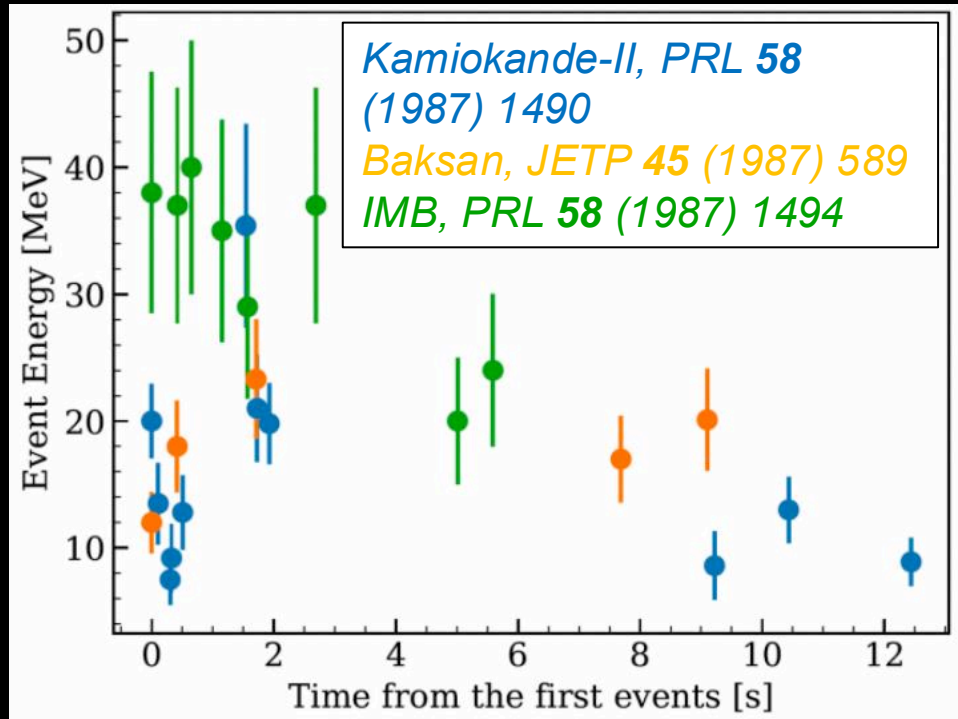
$$\Delta t = D \left( \frac{m^2}{2E^2} \right) = 25.7 \text{ms} \times \left( \frac{D}{50 \text{ kpc}} \right) \left( \frac{m}{\text{eV}} \right)^2 \left( \frac{10 \text{ MeV}}{E} \right)^2$$



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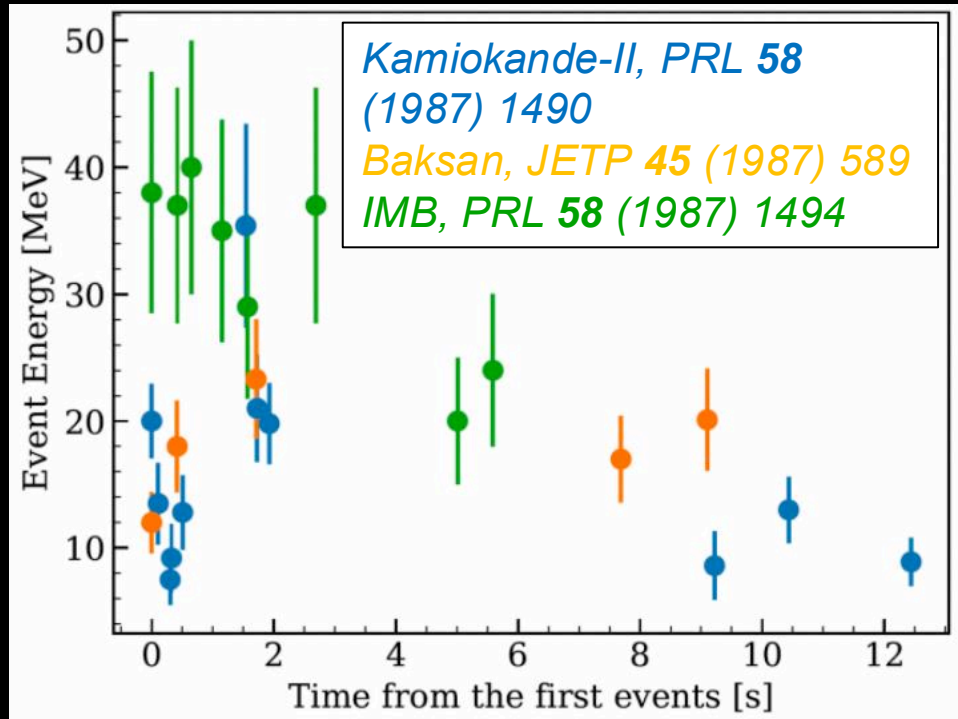
- ◆ In absence of  $t_0$ , look for dispersion among neutrinos with different energies
- ◆ But ... the neutrinos aren't emitted at the same time! What if that's different with energy, too?
  - ◆ Sensitivity depends on core-collapse SN model
  - ◆  $m_\nu < 5.7 \text{ eV}$  (95% C.L.)



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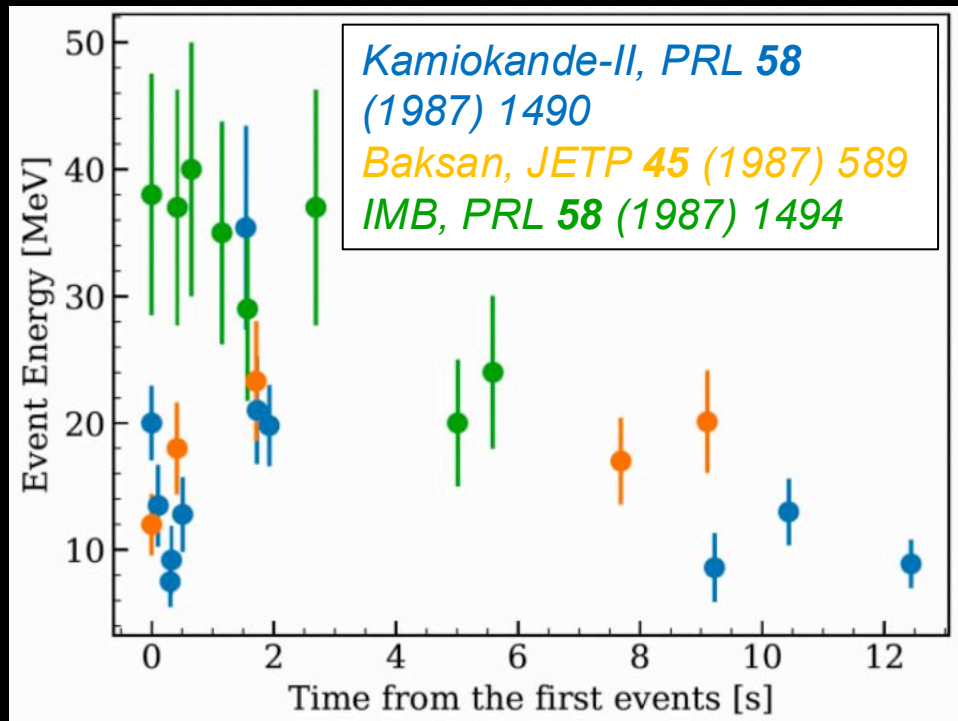
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Loredo and Lamb, *PRD* 65 (2022) 063002

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# The Plan

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- ◆ Accessing the neutrino-mass scale
- ◆ **How to search for  $m_\nu$  directly**
- ◆ Nitty, gritty systematics
- ◆ Microcalorimetry basics ( $^{163}\text{Ho}$ )
- ◆ HOLMES
- ◆ ECHo
- ◆ Beta-spectroscopy basics ( $^3\text{H}$ )
- ◆ KATRIN
- ◆ Project 8
- ◆ Next-generation tritium R&D
- ◆ Sterile neutrinos and bonus physics
- ◆ Alternate measurement ideas

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# The $\beta$ Spectrum in Detail

---

$$\begin{aligned} \frac{d\Gamma}{dE} = & \frac{G_F^2 |V_{ud}|^2}{2\pi^3} |M|^2 F(Z, \beta) \beta (E + m_e)^2 \\ & \times (E_0 - E) \sum_{i=1}^3 |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2} \\ & \times \Theta(E_0 - E - m_i) \end{aligned}$$

$E_0$  = endpoint energy of  
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constants related  
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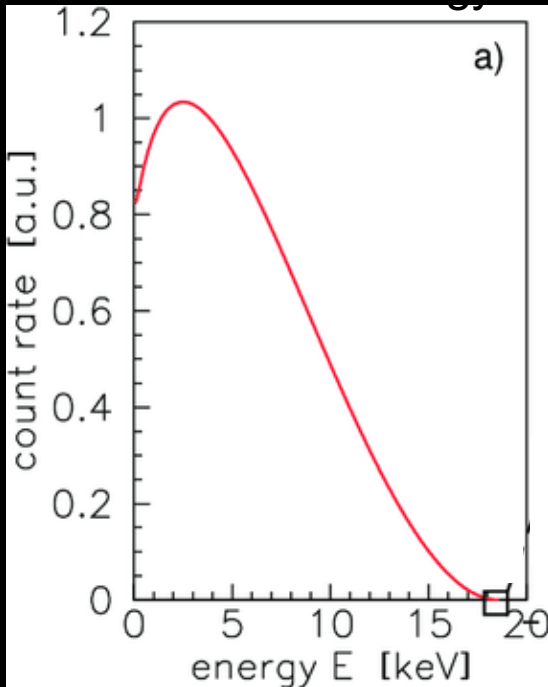
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# Close to $E_0$ (fastest $\beta$ s, slowest $\nu$ s)

Near the endpoint, in the degenerate regime:

$$\frac{d\Gamma}{dE} \simeq 3 \underset{\substack{\text{rate} \\ \swarrow}}{r} (\underset{\substack{\text{endpoint} \\ \downarrow}}{E_0} - \underset{\substack{\text{electron} \\ \swarrow}}{E}) \sqrt{(E_0 - E)^2 - m_\beta^2}$$



Images: KATRIN collaboration

Slide: Elise Novitski

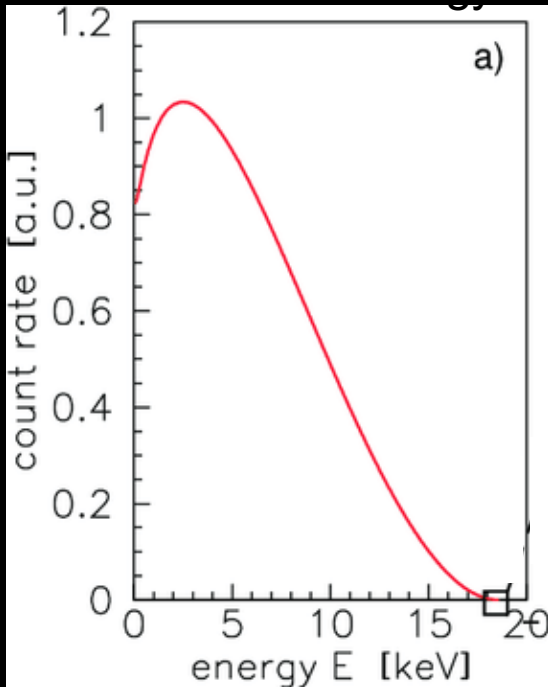
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Observable: electron-weighted effective neutrino mass  $m_\beta$

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$



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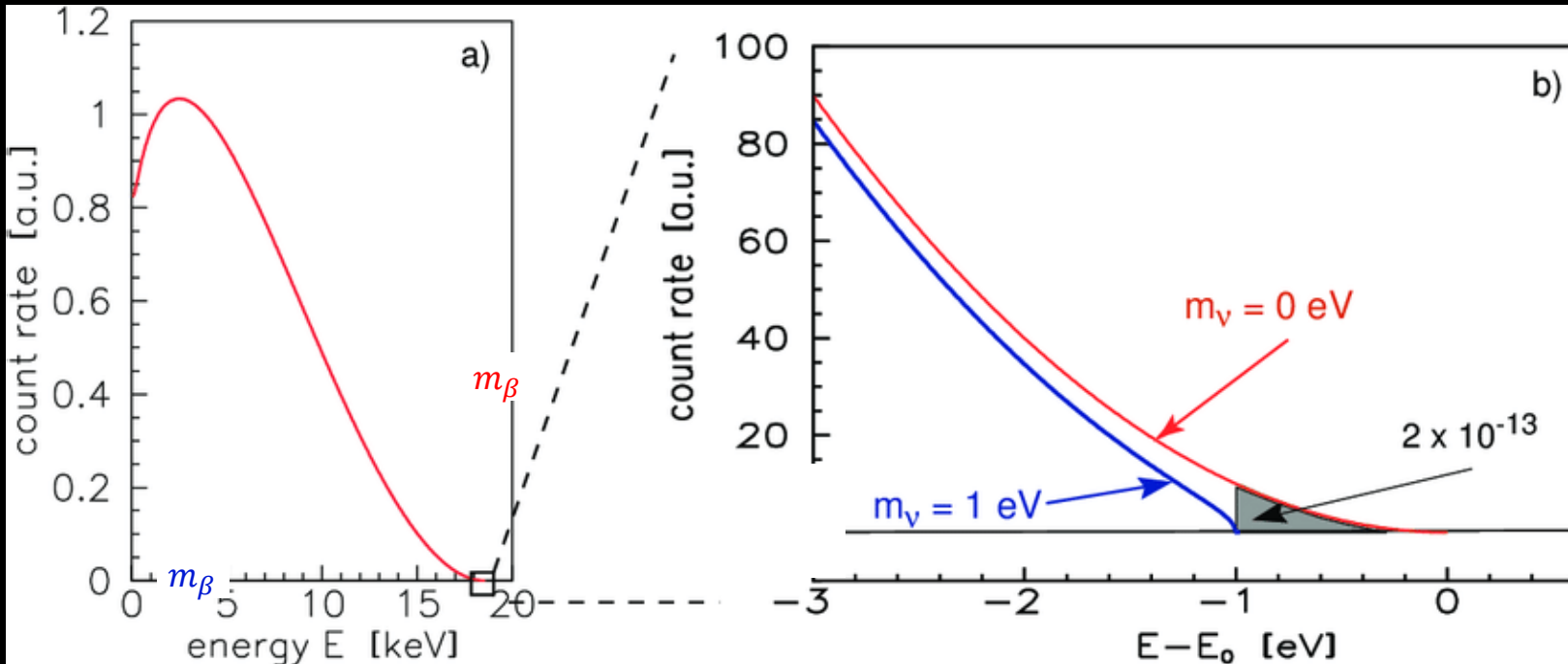
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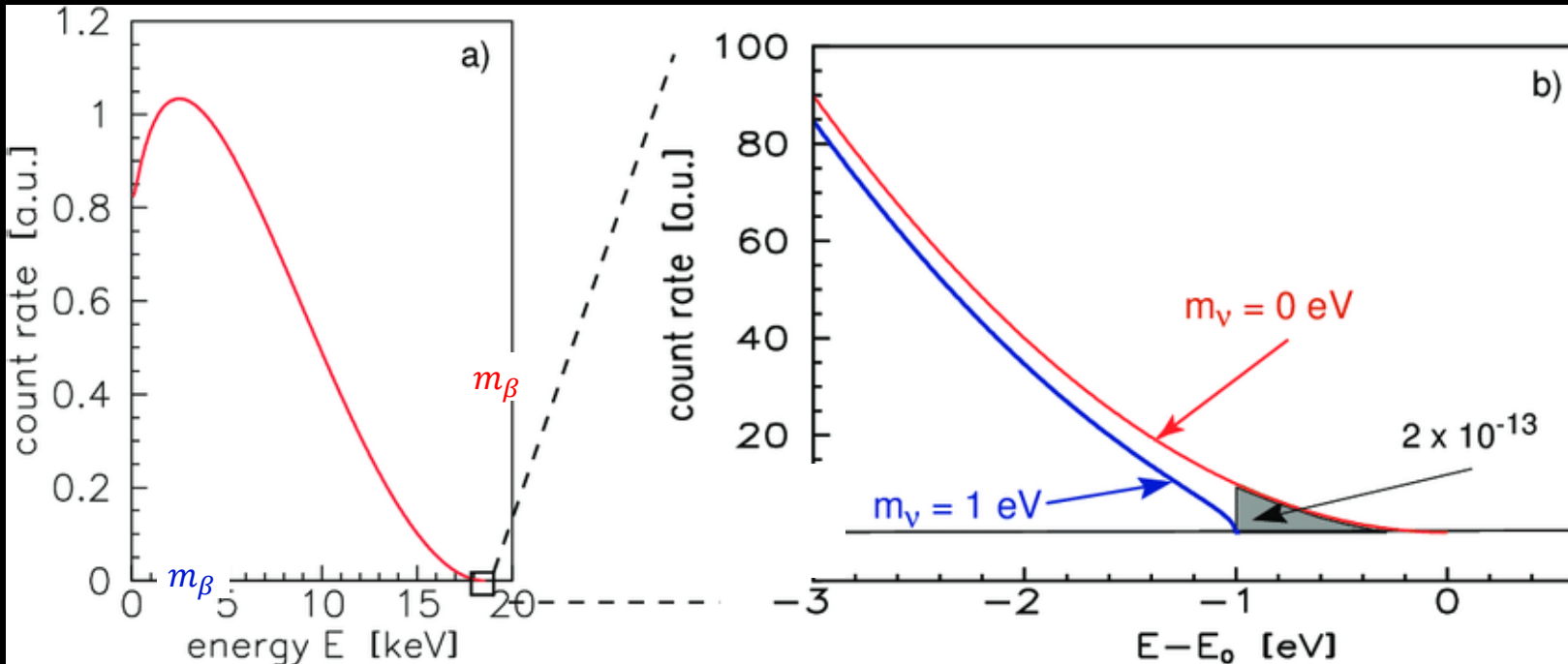
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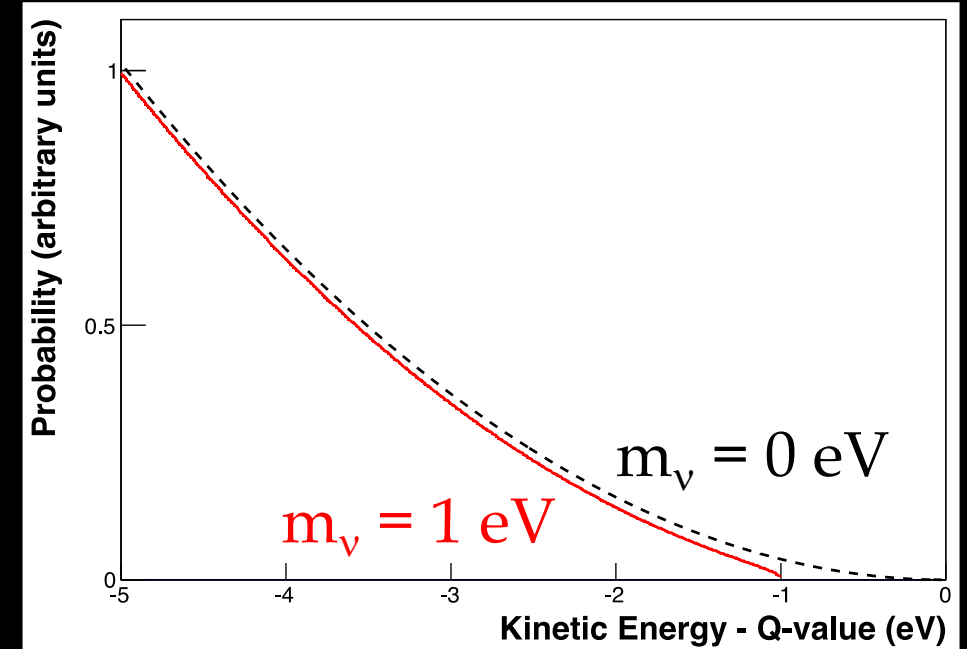
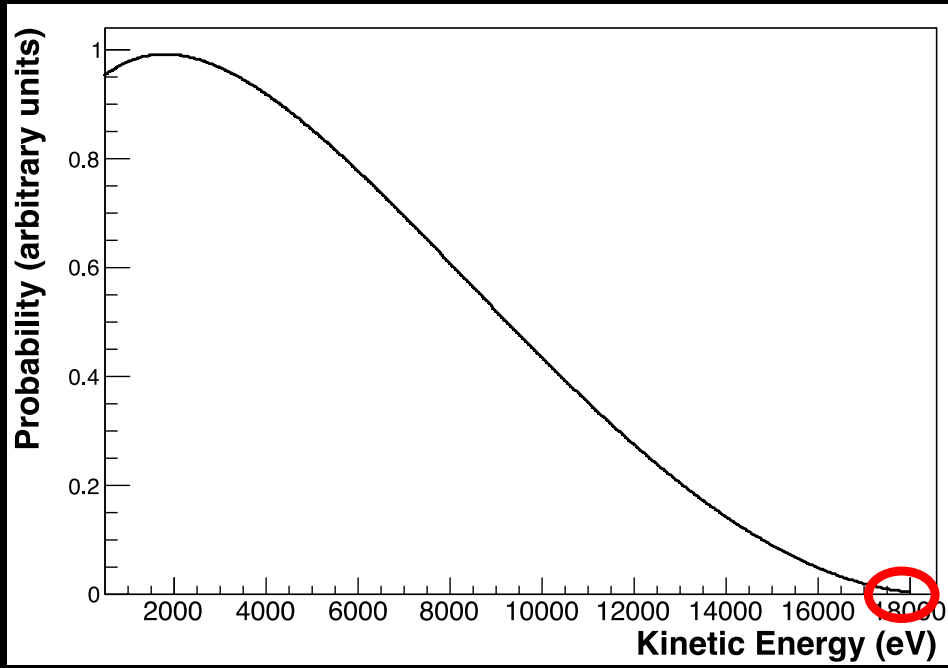
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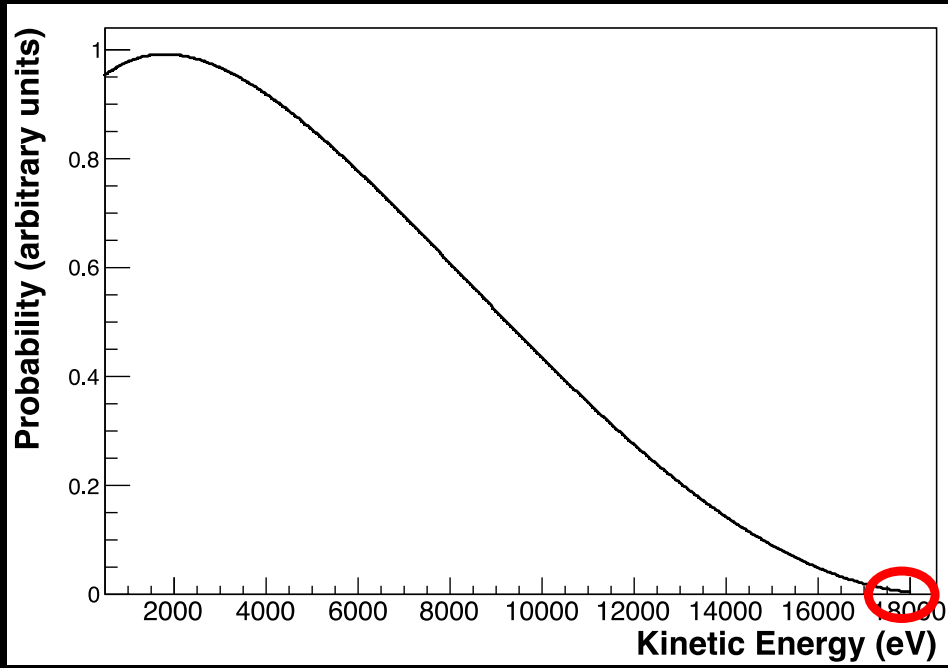


The existence of a nonzero neutrino mass shifts and distorts the endpoint of the spectrum

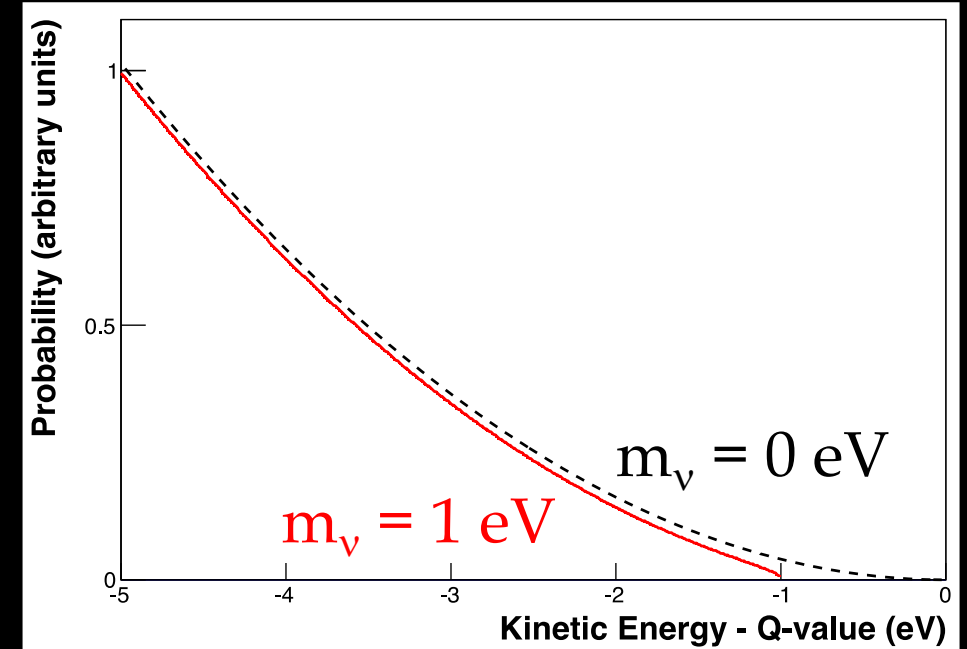
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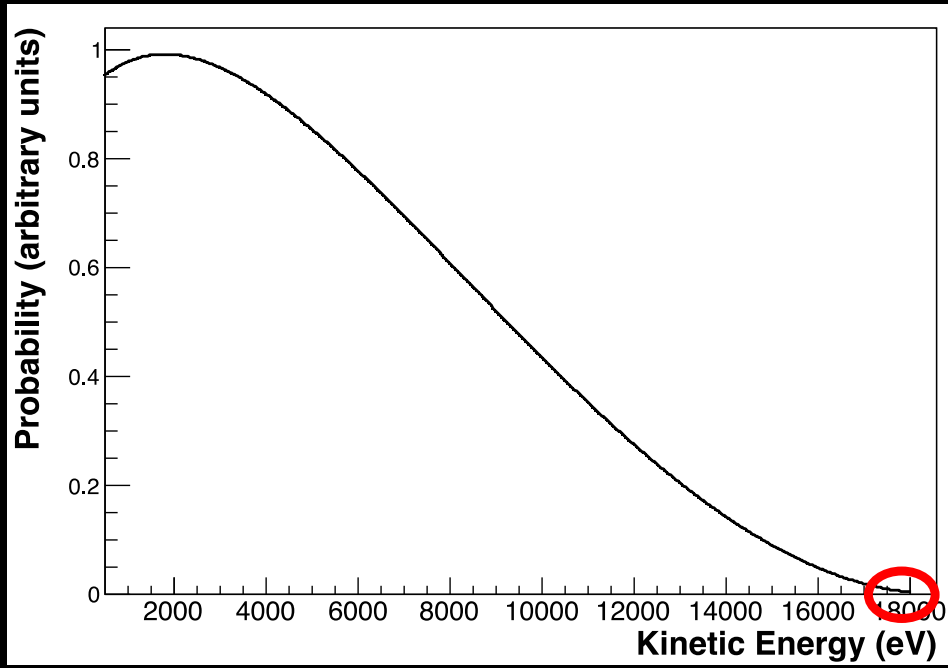


$\sim 10^{-13}$

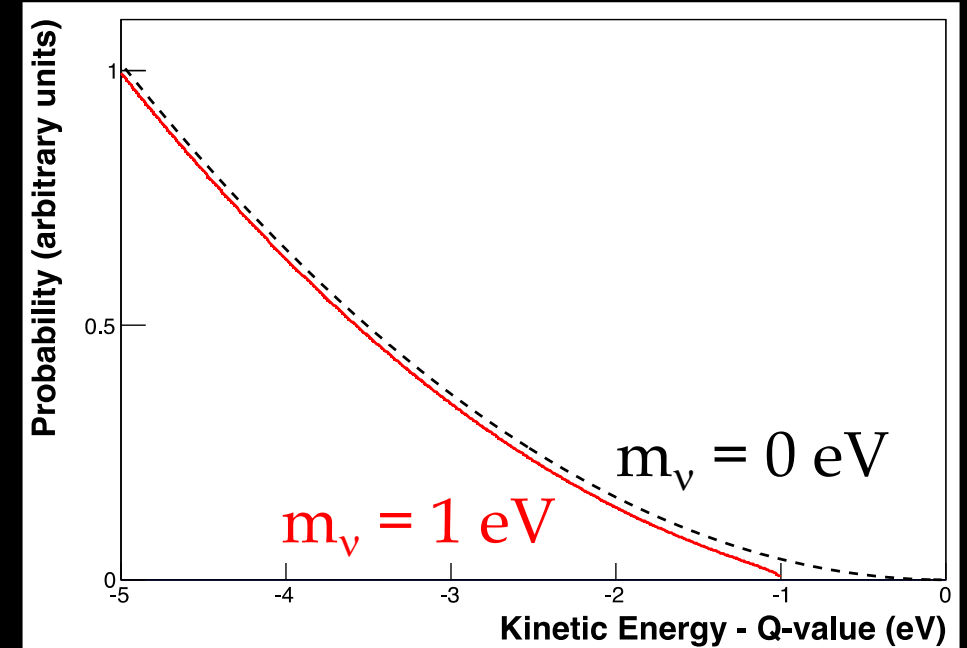




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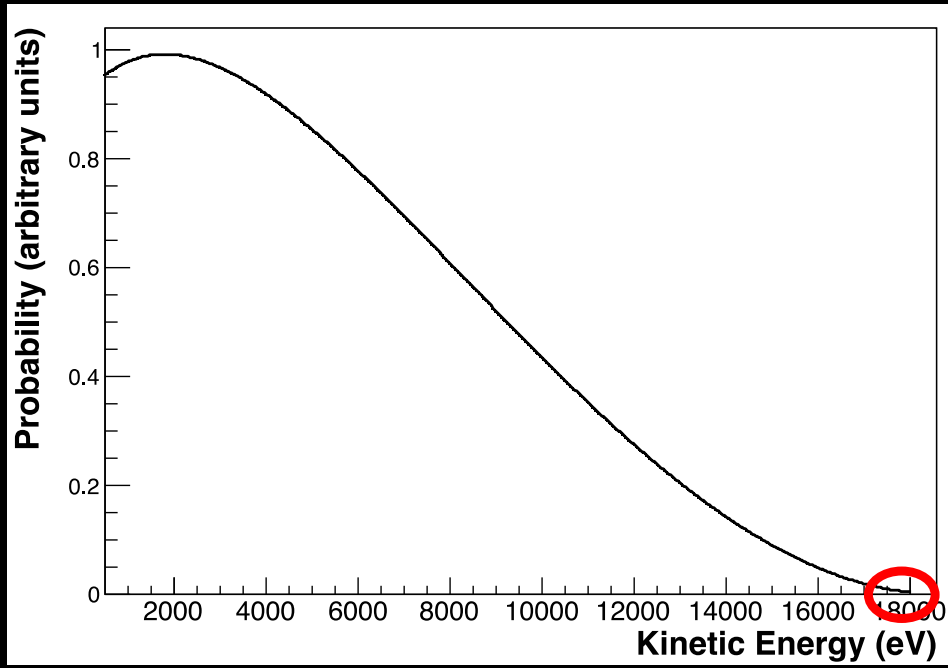


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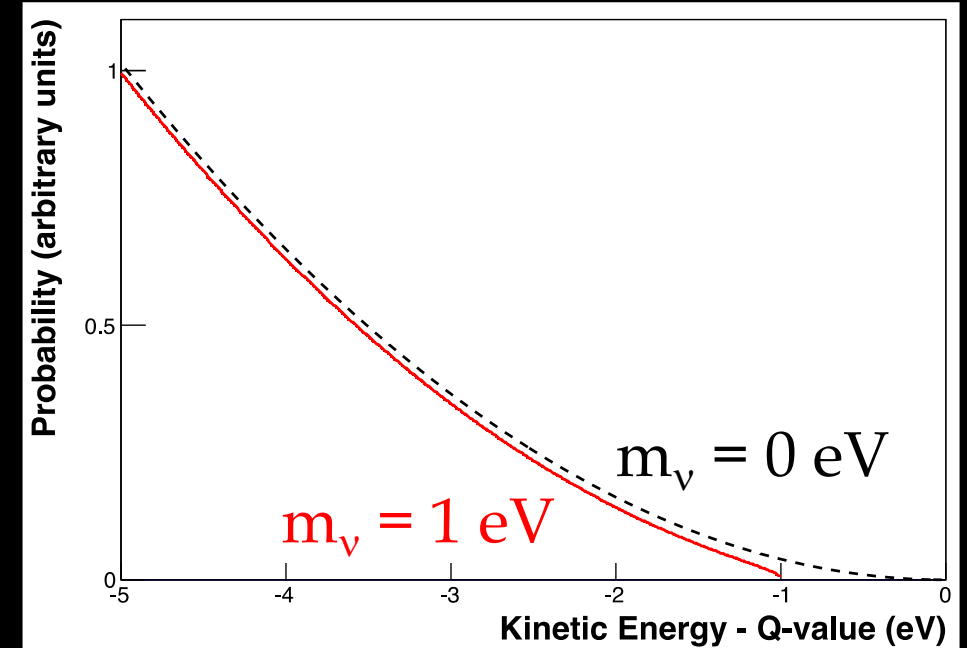


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- ◆ Precisely measure energy, rate near endpoint
- ◆ Somehow ignore all the low-energy decays with no useful information

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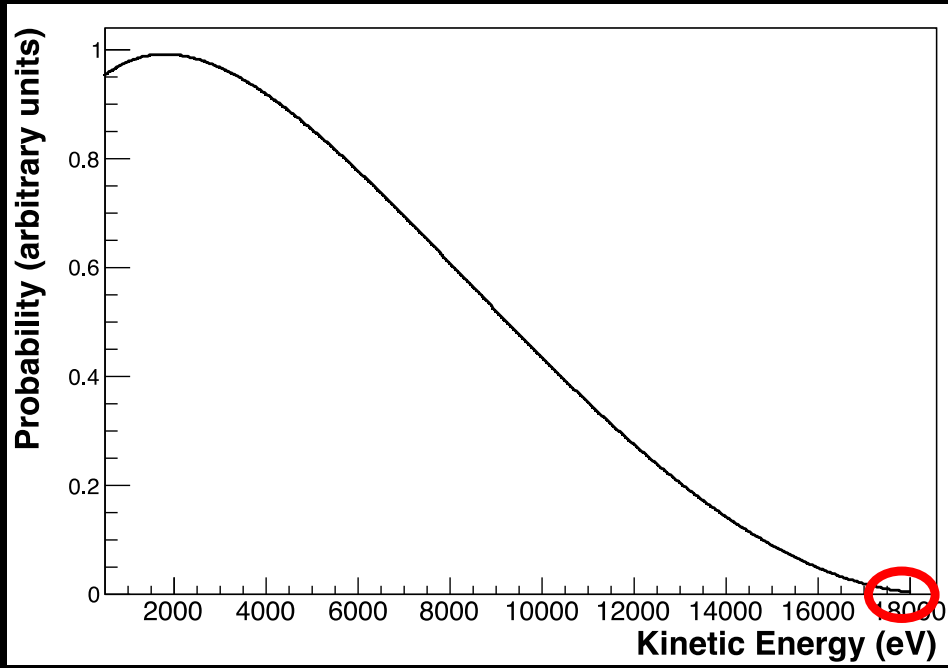


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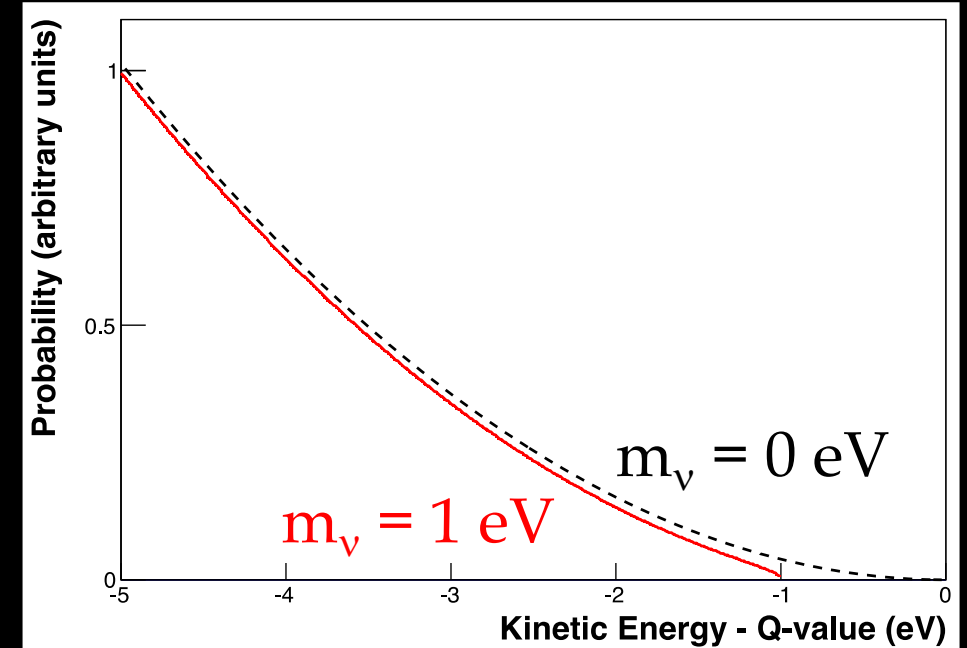


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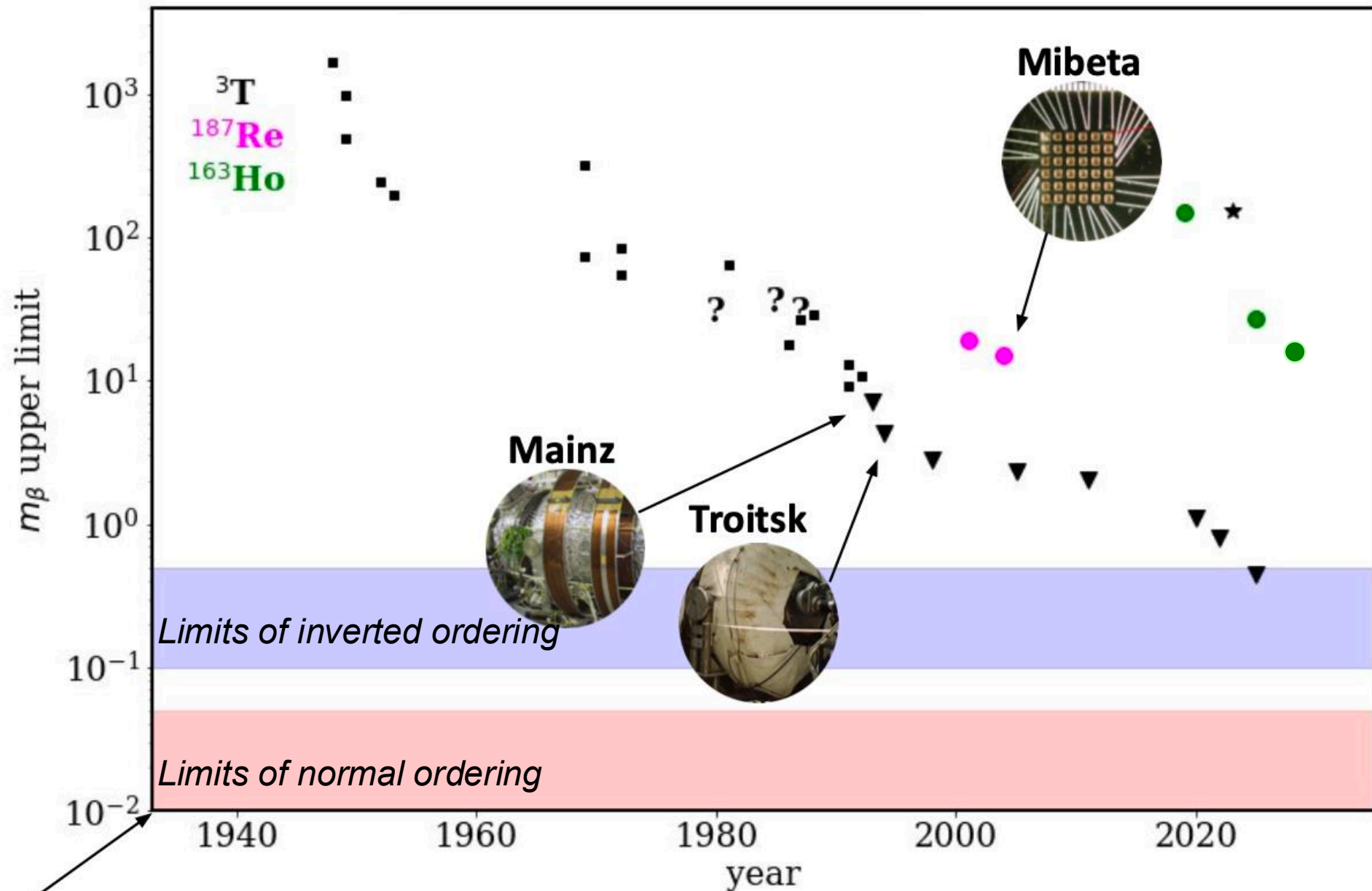


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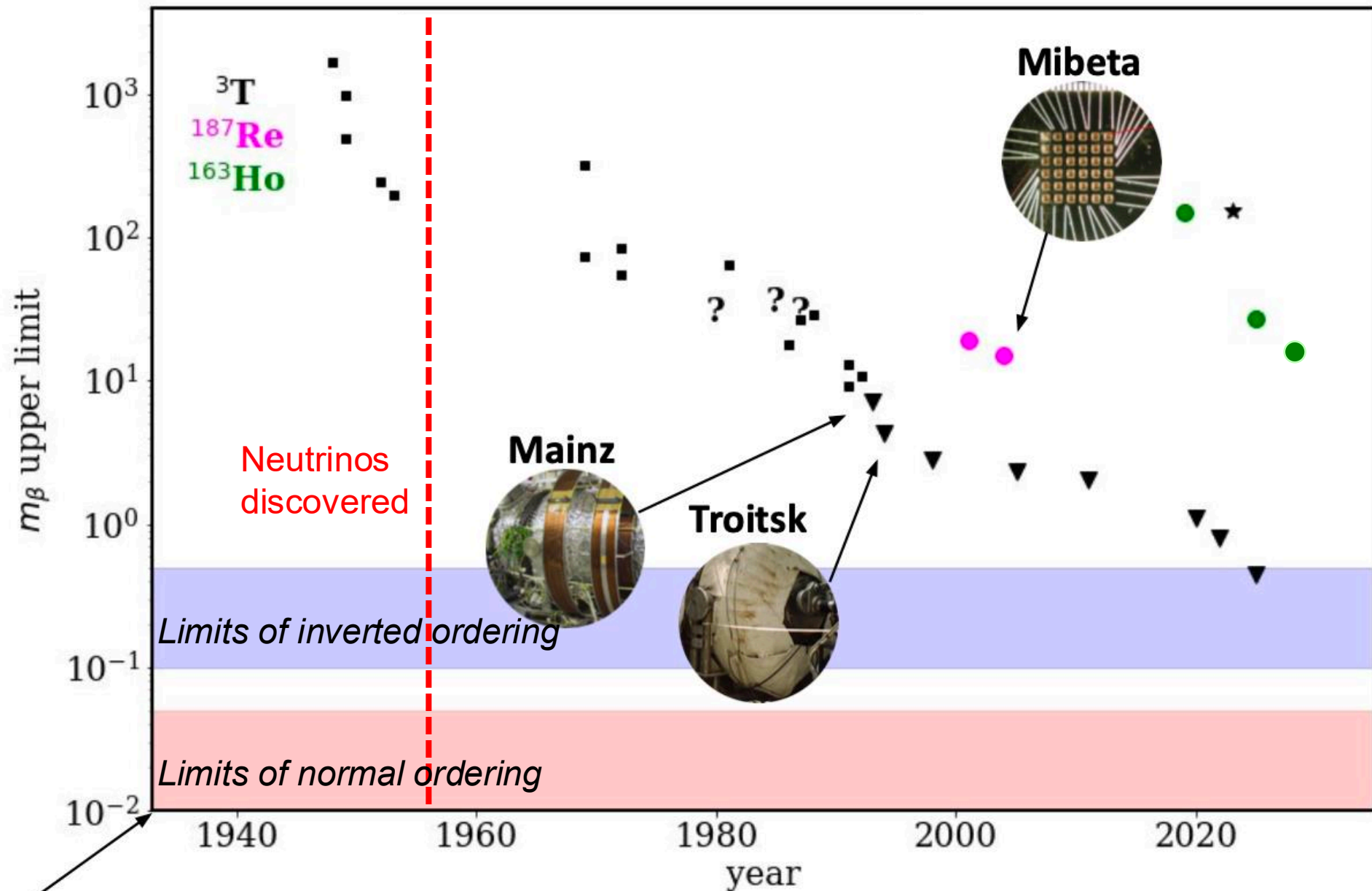
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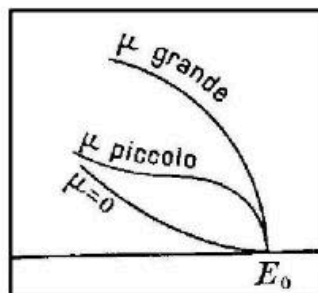


Adapted from Matteo Borghesi

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Perrin-Fermi



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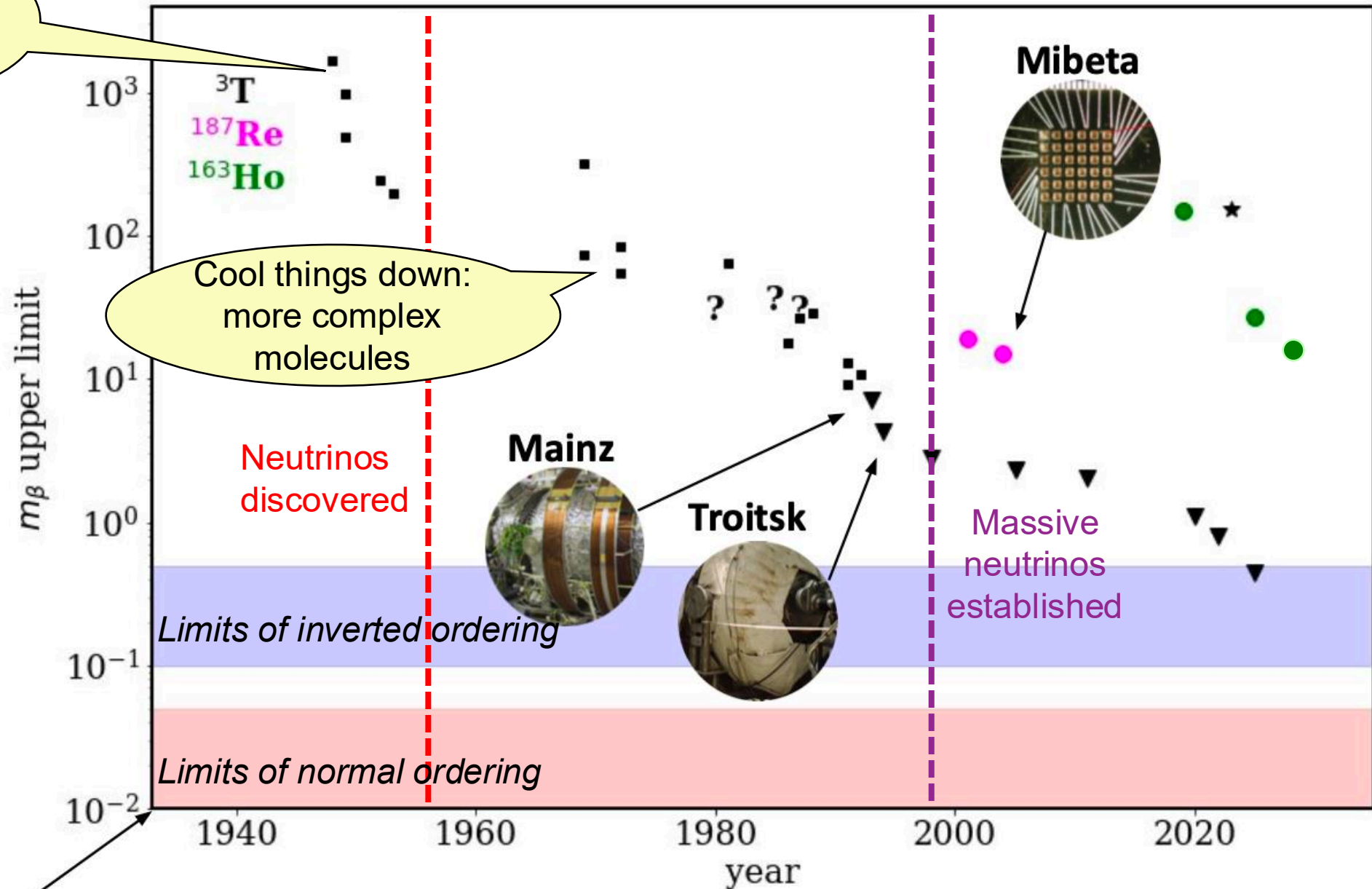






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High-resolution spectrometers

Cool things down: more complex molecules

Mibeta

Neutrinos discovered

Mainz

Troitsk

Massive neutrinos established

Limits of inverted ordering

Limits of normal ordering

$m_\beta$  upper limit

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$10^2$

$10^3$

1940

1960

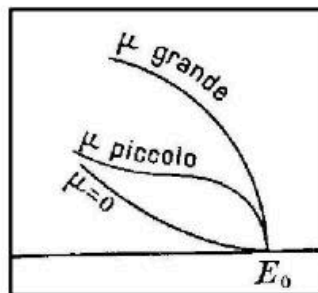
1980

2000

2020

year

Perrin-Fermi



Adapted from Matteo Borghesi

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High-resolution spectrometers

Cool things down: more complex molecules

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These experiments are still running

$m_\beta$  upper limit

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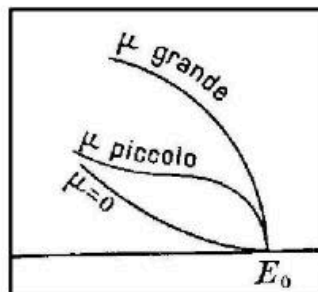
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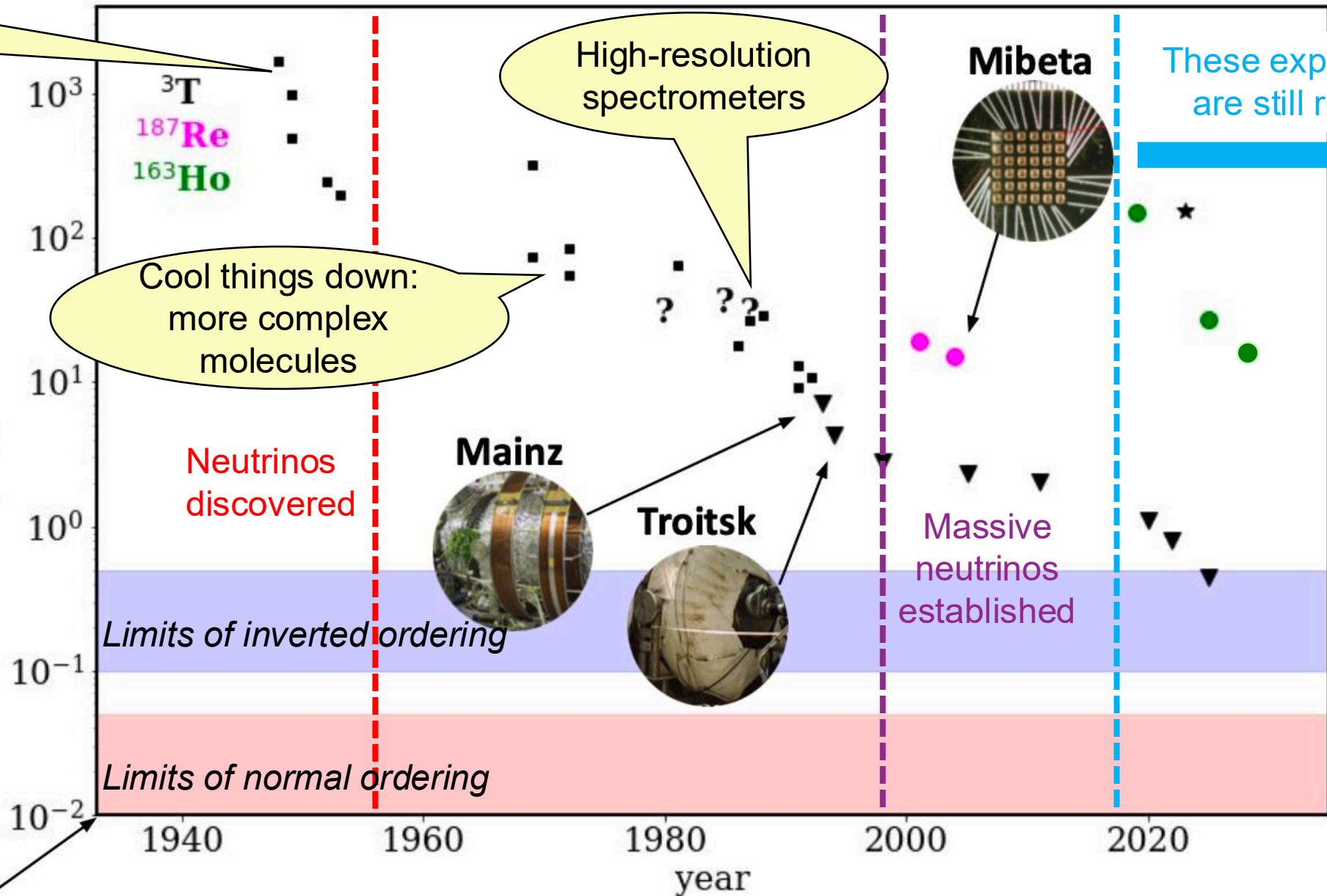
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# What Isotope Is Best?

Total kinetic energy  
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- ◆ Low Q-value
  - ◆ Higher fraction of spectrum gives information about  $m_\beta$
- ◆ Reasonable half-life
  - ◆ Too short: hard to handle during experiment
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# Whatever Happened to $^{187}\text{Re}$ ?



MANU, *Nature* **397** (1999) 6715  
MIBETA, *NIM A* **520** (2004) 125

# Whatever Happened to $^{187}\text{Re}$ ?



- ◆ 15-19 eV sensitivity for MANU and MIBETA
- ◆ R&D by MARE collaboration into 2 detector types:
  - ◆ Metallic Re (superconducting)
    - ◆ Complex thermalization
  - ◆ Dielectric  $\text{AgReO}_4$ 
    - ◆ Long response time
    - ◆ Interference of  $\beta$  with local crystal structure



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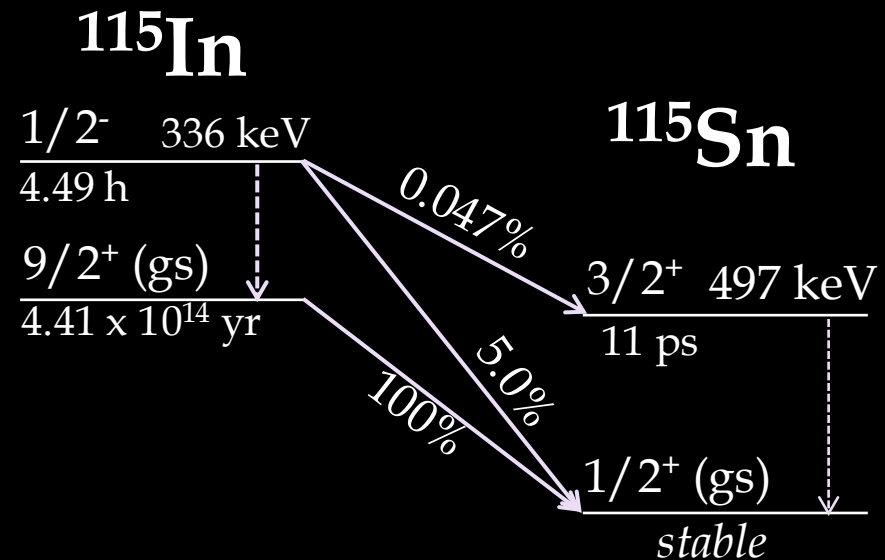


Community has moved on to  $^{163}\text{Ho}$

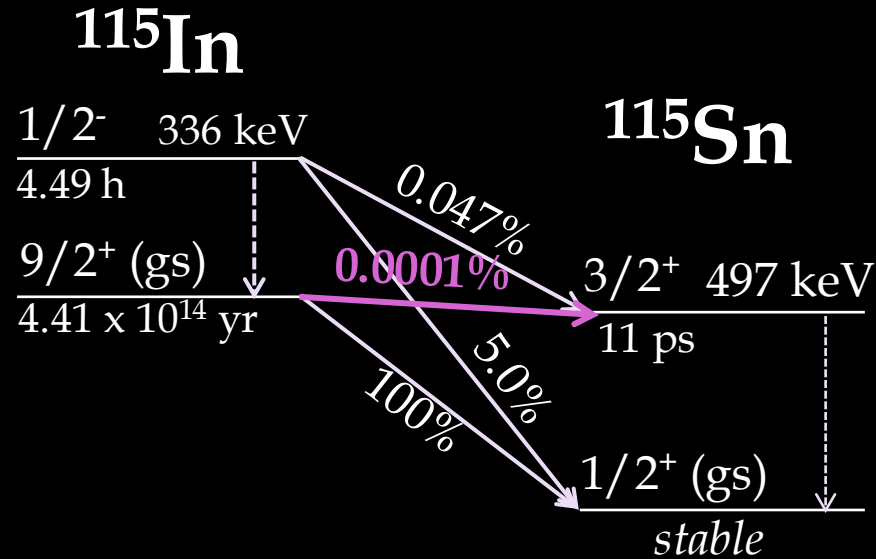
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MIBETA, *NIM A* **520** (2004) 125

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

# $^{115}\text{In}$ : Ultra-Low Q-value



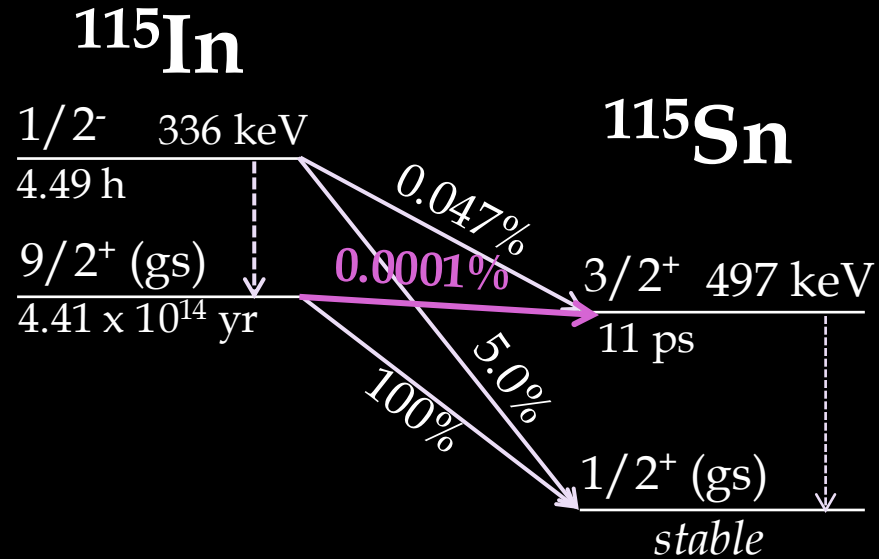
# $^{115}\text{In}$ : Ultra-Low Q-value



- ◆ New decay branch of  $^{115}\text{In}$   $^{115}\text{Sn}$  discovered in 2005 (Cattadori et al., Nucl. Phys. A **748** 333, 2005)
- ◆ Lowest known  $Q_\beta$ -value,  $173 \pm 12$  eV (Urban et al., PRC **94** 011302(R), 2016)
- ◆ But this decay is hidden in a  $Q=497$  keV decay branch

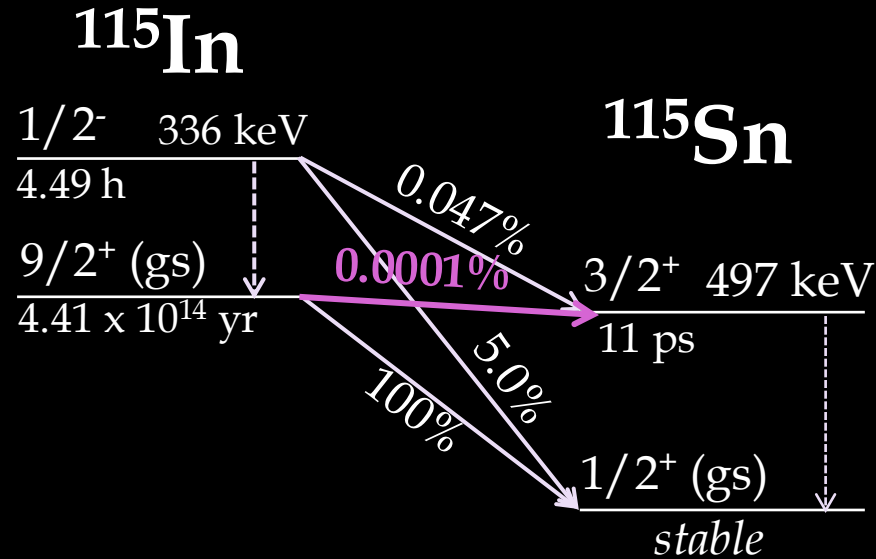


# $^{115}\text{In}$ : Ultra-Low Q-value



- ◆ New decay branch of  $^{115}\text{In}$  to  $^{115}\text{Sn}$  discovered in 2005 (*Cattadori et al., Nucl. Phys. A* **748** 333, 2005)
- ◆ Lowest known  $Q_\beta$ -value,  $173 \pm 12$  eV (*Urban et al., PRC* **94** 011302(R), 2016)
- ◆ But this decay is hidden in a  $Q=497$  keV decay branch

# $^{115}\text{In}$ : Ultra-Low Q-value



- ◆ New decay branch of  $^{115}\text{In} \rightarrow ^{115}\text{Sn}$  discovered in 2005 (Cattadori et al., Nucl. Phys. A **748** 333, 2005)
- ◆ Lowest known  $Q_\beta$ -value,  $173 \pm 12$  eV (Urban et al., PRC **94** 011302(R), 2016)
- ◆ But this decay is hidden in a  $Q=497$  keV decay branch

Measuring the end-point energy region of the electron spectrum for the rare  $\beta$  decay of  $^{115}\text{In}$  constitutes a magnificent challenge.

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

# Other Ultra-Low-Q Decays?



- ◆ Many other ultra-low-Q decays have been suggested
  - ◆ A lot of them turn out not to be kinematically allowed
  - ◆ Systematic nuclear-mass-measurement program in Penning traps

For example

*Gavage et al., PRC 106 (2022) 045503*

*Ruotsalainen et al., PRL 134 (2025) 172501*

*Winter et al., EPJ A 62 (2026) 123*

| Isotope           | Decay type | Q-value (keV) | Half-life (yr)               |
|-------------------|------------|---------------|------------------------------|
| $^3\text{H}$      | $\beta^-$  | 18.57         | 12.3                         |
| $^{75}\text{Se}$  | EC         | 0.64(51)      | 0.3279(1)                    |
| $^{75}\text{Se}$  | EC         | 6.04(41)      | 0.3279(1)                    |
| $^{75}\text{Ge}$  | $\beta^-$  | 6.56(60)      | 0.00015750(8)                |
| $^{115}\text{In}$ | $\beta^-$  | 0.173(12)     | $4.3(5) \times 10^{20}$      |
| $^{135}\text{Cs}$ | $\beta^-$  | 0.440         | $1.33 \times 10^6$           |
| $^{163}\text{Ho}$ | EC         | 2.833(34)     | 4570                         |
| $^{187}\text{Re}$ | $\beta^-$  | 2470(4)       | $4.12(23) \times 10^{10}$ yr |

*Confirmed transitions as of ~2022*

*Snowmass Report of Neutrino Properties Working Group*

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*Gamage et al., PRC 106 (2022) 045503*  
*Ruotsalainen et al., PRL 134 (2025) 172501*  
*Winter et al., EPJ A 62 (2026) 123*

- ◆ So far, experimental complications make them less appealing than  $^3\text{H}$  or  $^{163}\text{Ho}$



- ◆ Low branching fractions compared to higher-Q decays
- ◆ Low isotopic abundance
- ◆ Challenging nuclear physics

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# The Plan

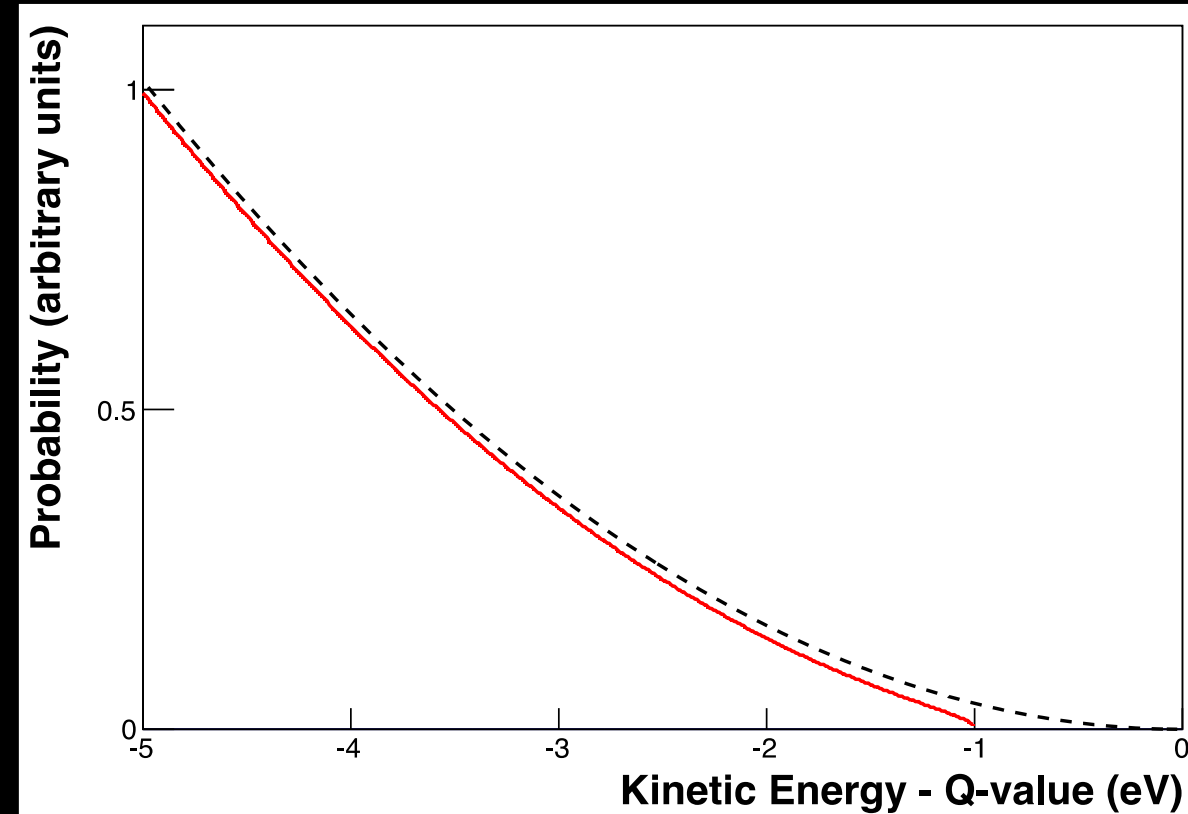
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- ◆ Accessing the neutrino-mass scale
- ◆ How to search for  $m_\nu$  directly
- ◆ **Nitty, gritty systematics**
- ◆ Microcalorimetry basics ( $^{163}\text{Ho}$ )
- ◆ HOLMES
- ◆ ECHo
- ◆ Beta-spectroscopy basics ( $^3\text{H}$ )
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# Systematics

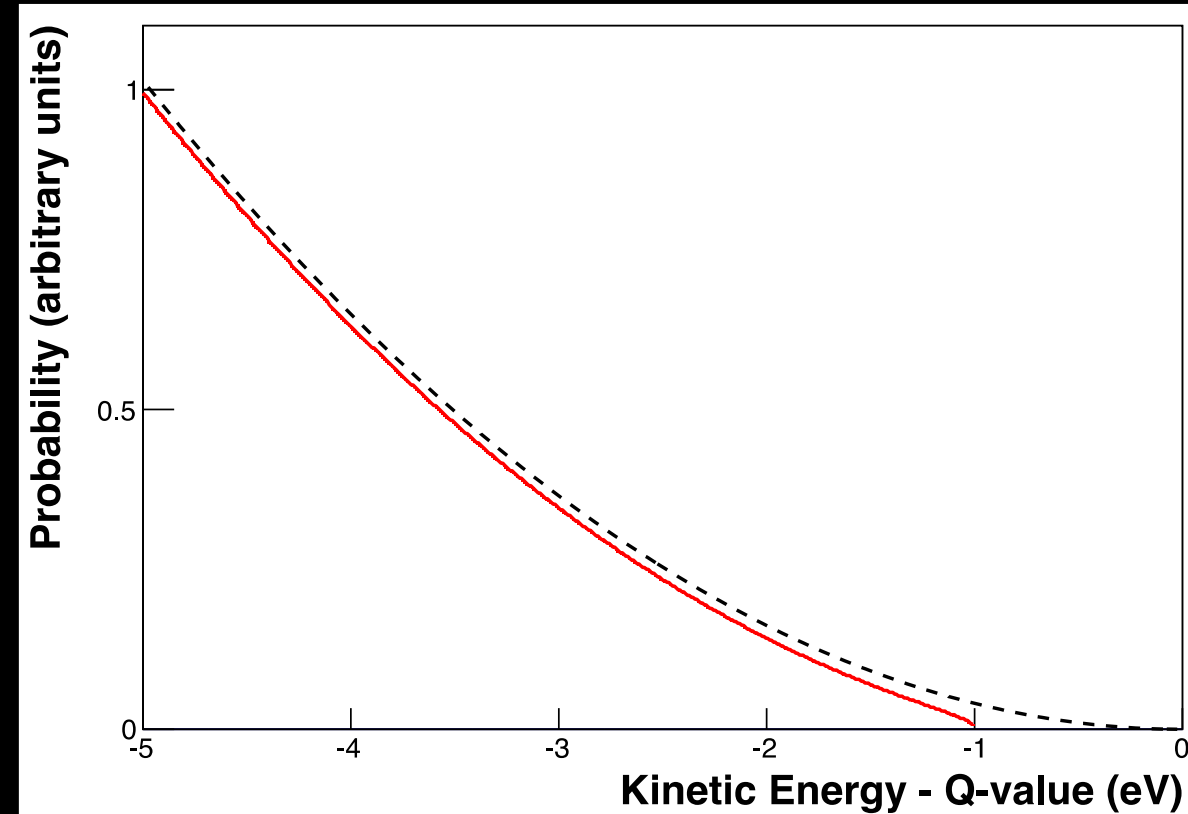


- ◆ Consider a generic systematic effect that changes apparent  $\beta$  energy
  - ◆ High starting rate in low-E bins
  - ◆ Low starting rate in high-E bins



# Systematics

- ◆ Consider a generic systematic effect that changes apparent  $\beta$  energy
  - ◆ High starting rate in low-E bins
  - ◆ Low starting rate in high-E bins



- ◆ Mistaken assignment of a  $\beta$  to a higher-E bin is much more likely than the other way!
- ◆ This shifts the reconstructed  $m_\beta^2$  value to be more negative



# A General Guideline

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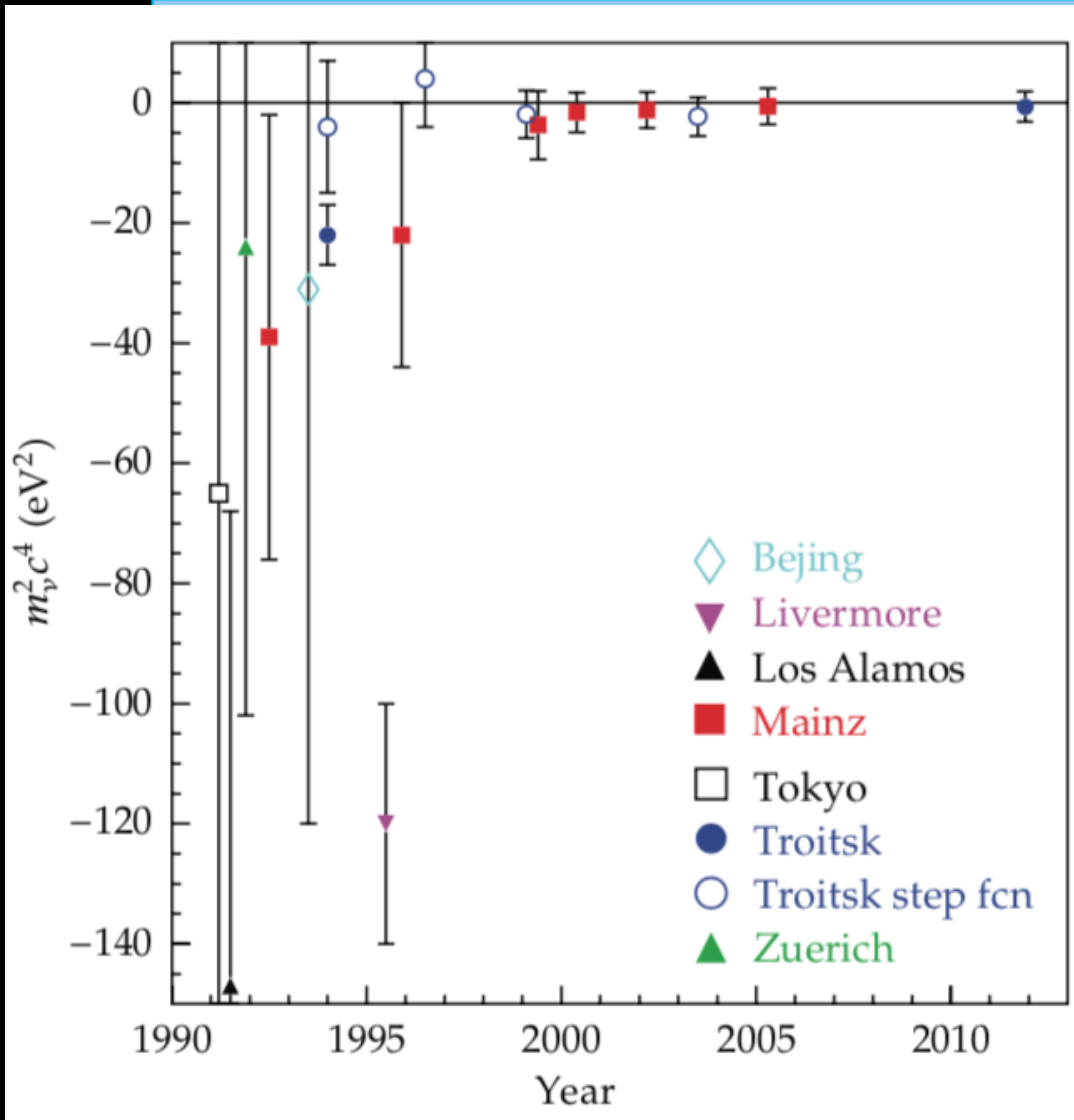
- ◆ Continuous effects (like broadening) are strongly correlated with the effect of a neutrino mass
- ◆ If not accounted for, the penalty is approximately twice the neglected variance of the systematic effect

$$\Delta m_\nu^2 \approx -2\sigma^2$$

*Robertson and Knapp, Annu. Rev. Nucl. Part. Sci. 38 185 (1988)*

- ◆ (*This is a guideline: Actual analysis requires careful quantitative studies.*)

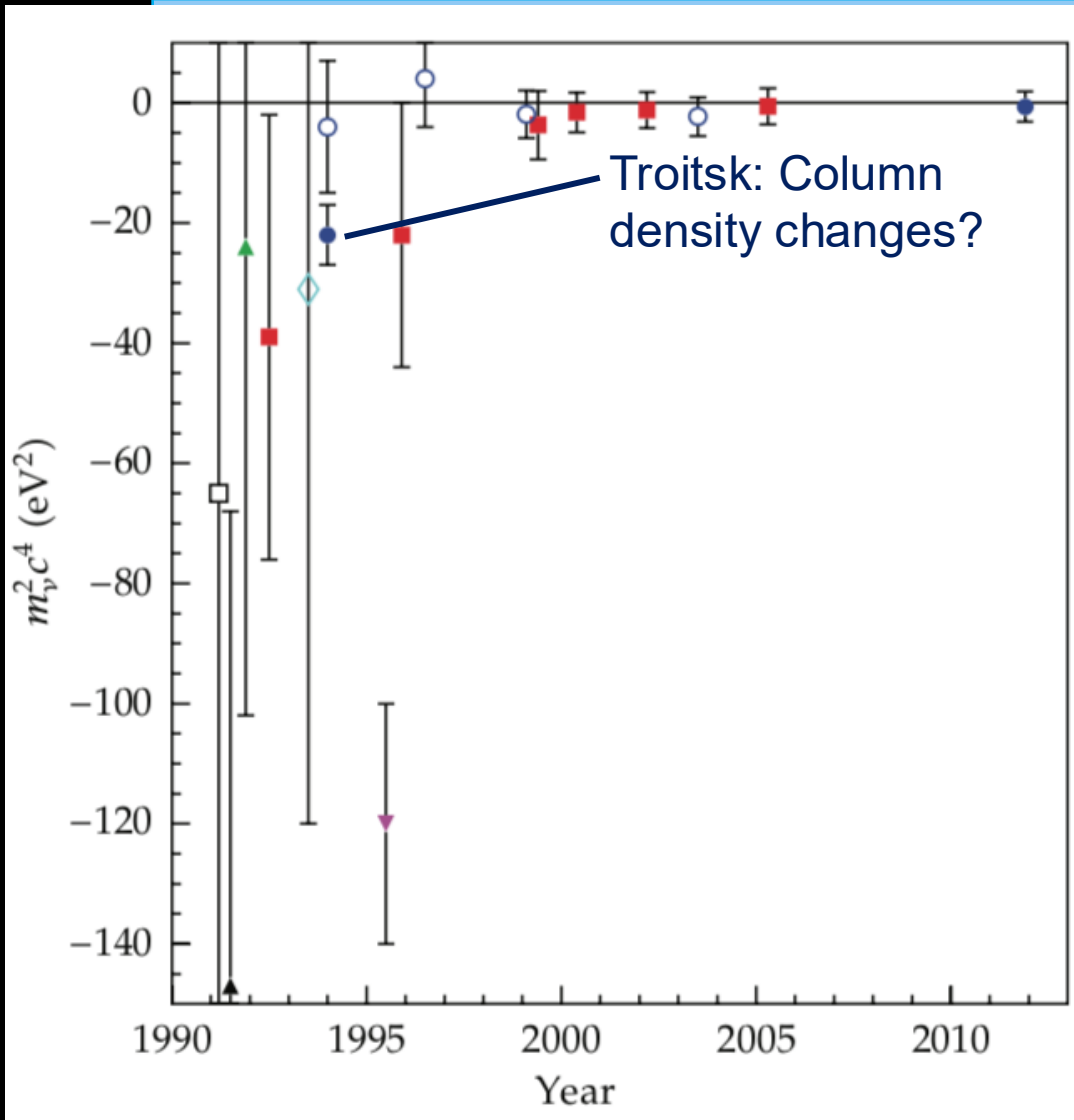
# Paying the Penalty for Systematics



- ◆ Let's look at historical **best-fit** values (rather than upper limits)
- ◆ If you measure a significant  $m_\beta^2 < 0$ :
  - ◆ Tachyonic neutrinos?
  - ◆ Some uncertainty of unexpected nature or size?

*Drexlin et al., Adv. High Energy Phys. 2013 (2013) 293986*

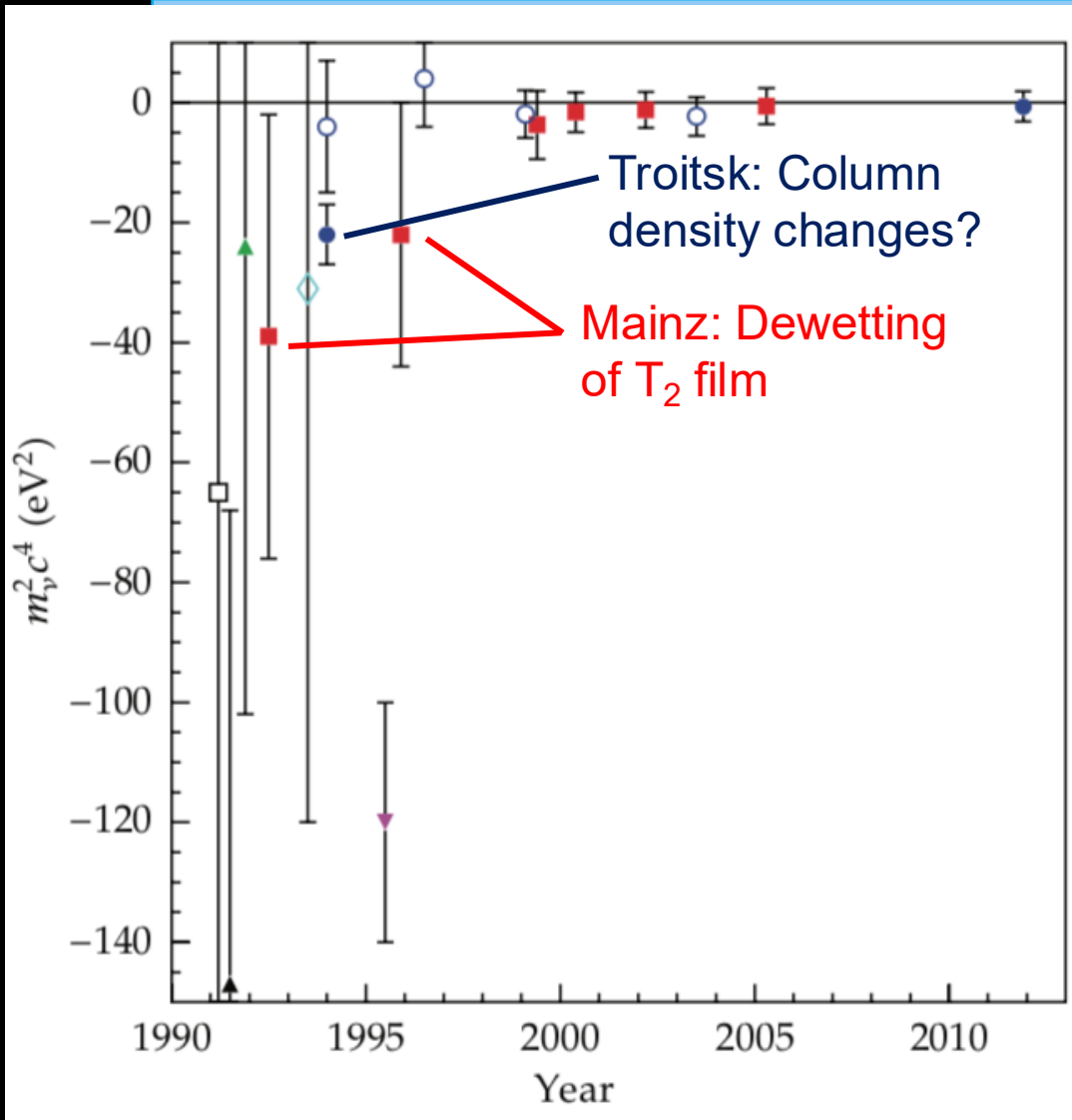
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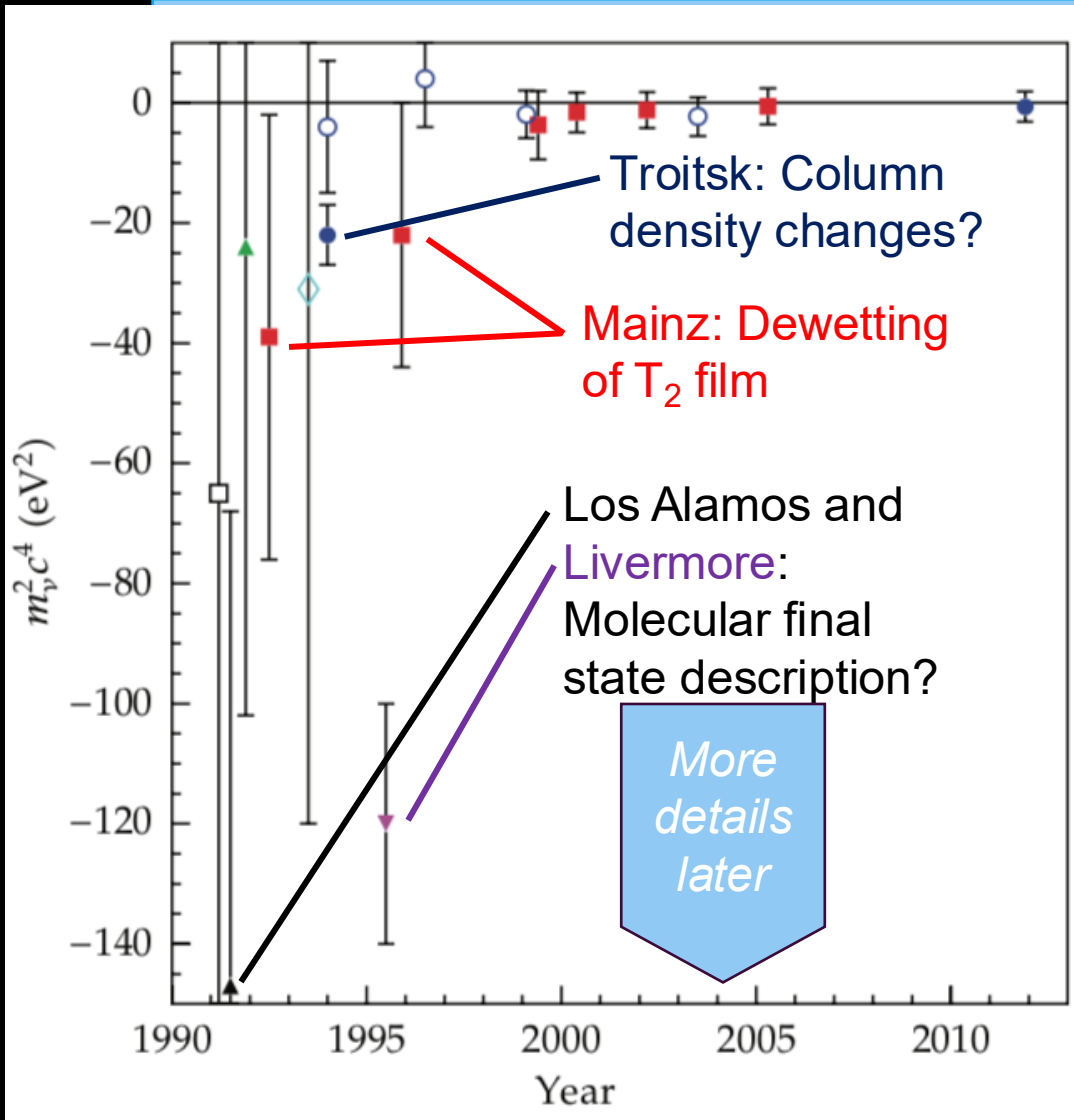
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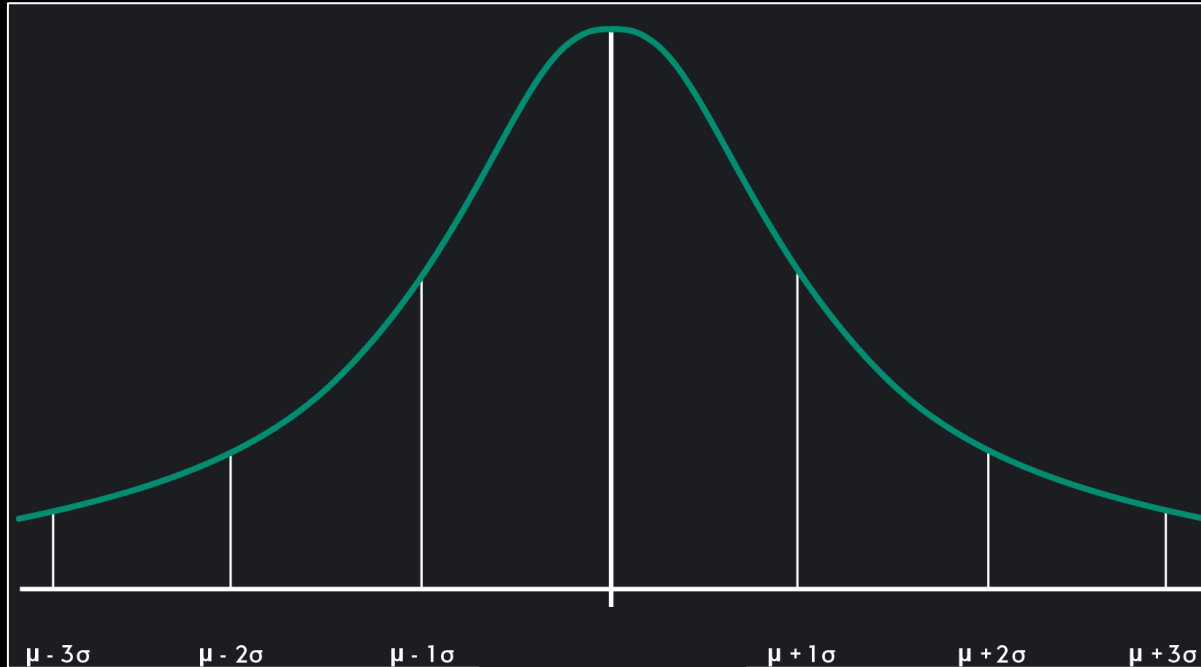
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# “Significantly” Negative?

Alert:  
frequentist  
discussion

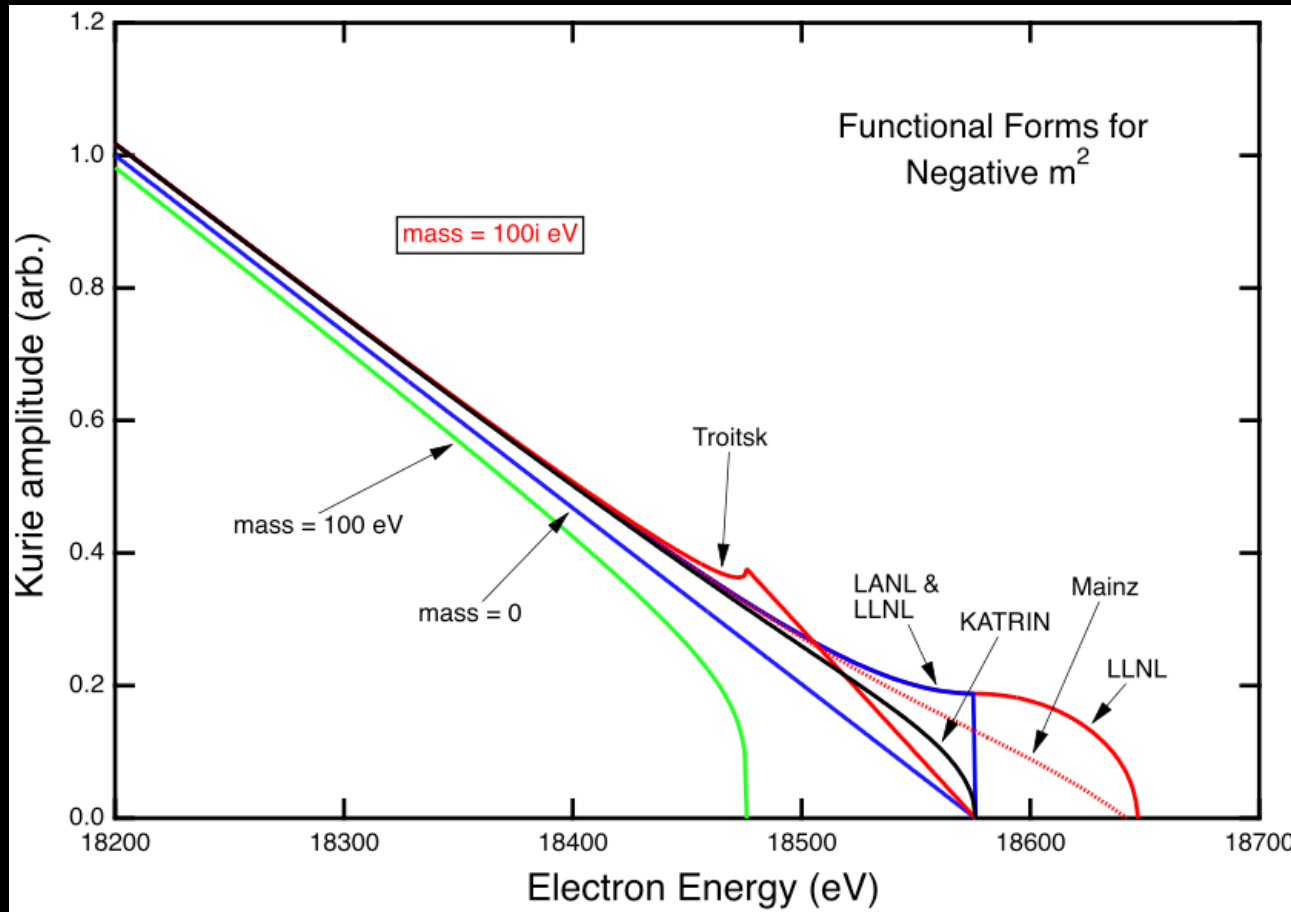
- ◆ Negative  $m_\beta^2$  values can also come from statistics!



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- ◆ If the true  $m_\beta^2$  is below your sensitivity, you're measuring zero
- ◆ Best-fit can fluctuate below that point
- ◆ Spectral model must include the unphysical range for the fit to work well! Consider:
  - ◆ Continuity with physical model
  - ◆ Valid  $\chi^2$  behavior across bound
- ◆ Approaches for setting a limit:
  - ◆ Feldman-Cousins
  - ◆ Lokhov-Tkachov

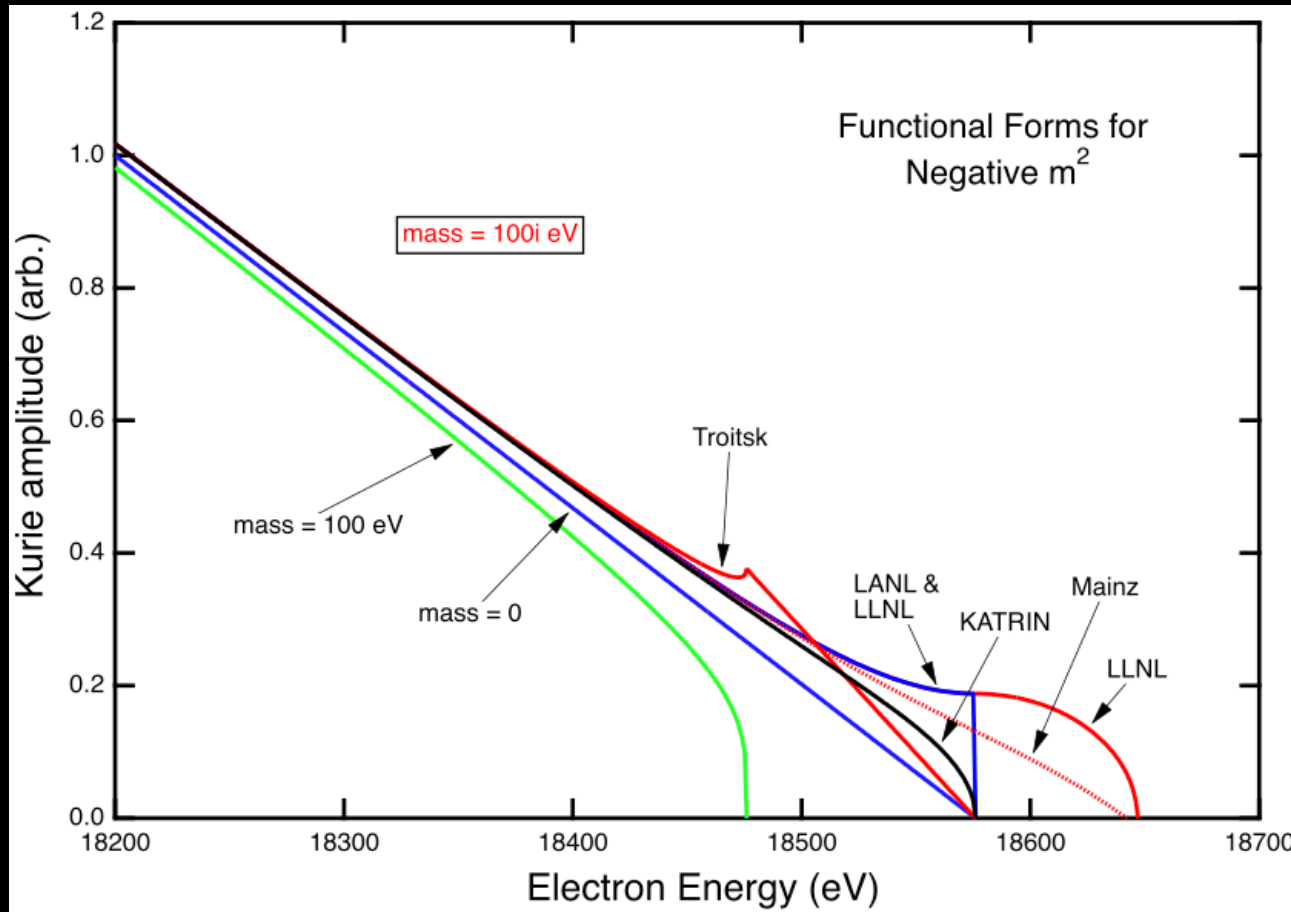
Formaggio, de Gouvêa, and Robertson, *Phys. Rep.* **914** (2021) 1



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More details  
later

Formaggio, de Gouvêa, and Robertson, *Phys. Rep.* **914** (2021) 1

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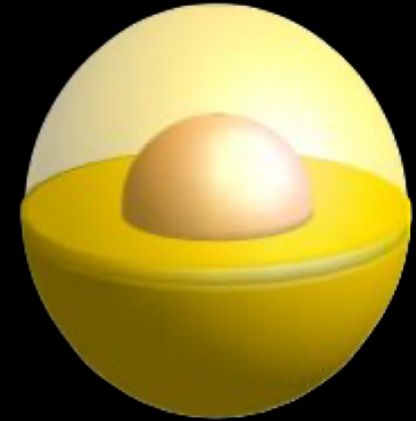
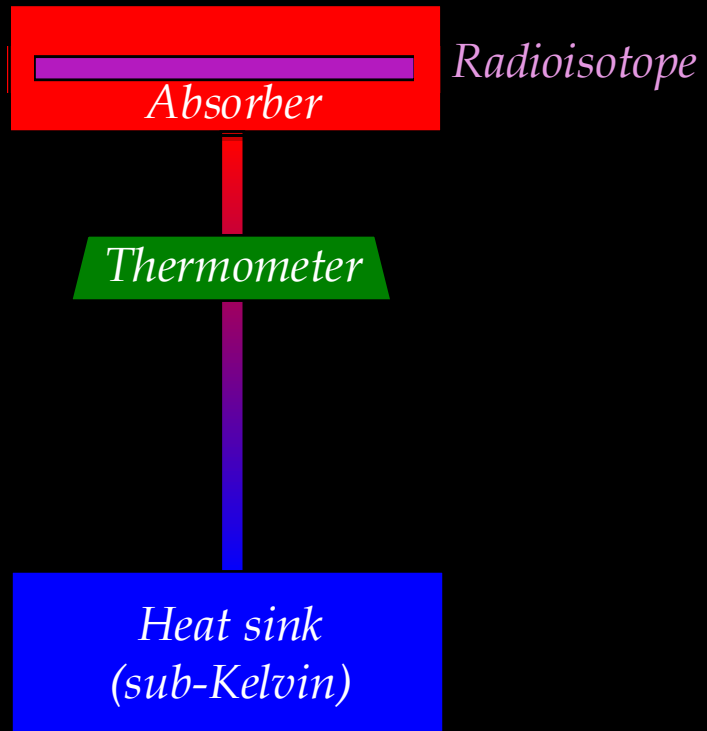
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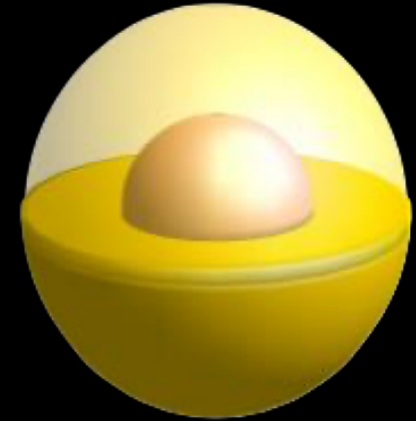
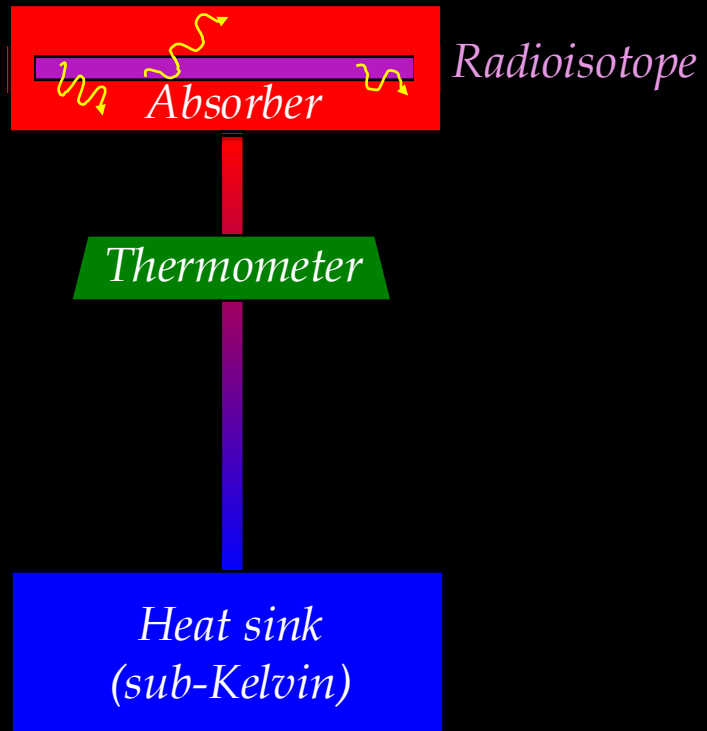
# $^{163}\text{Ho}$ : Microcalorimetry

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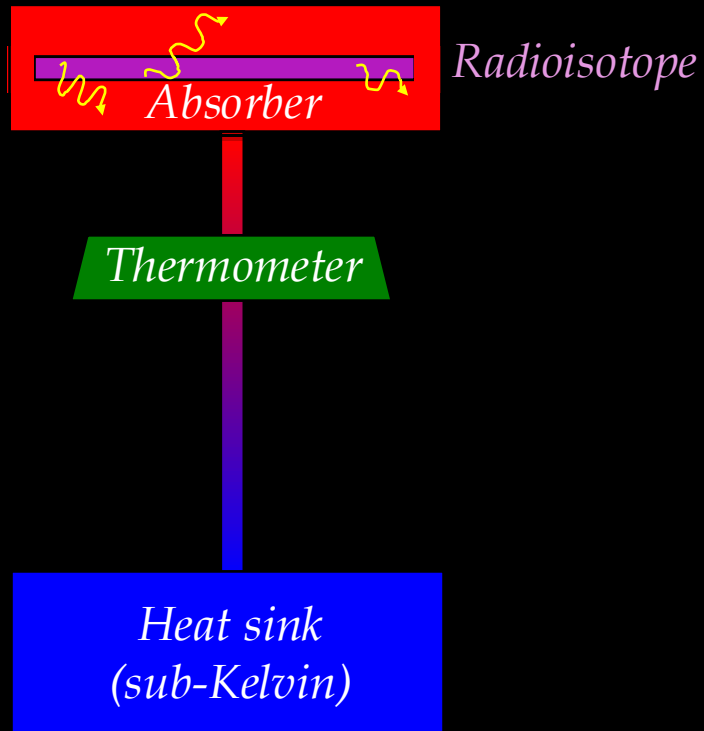


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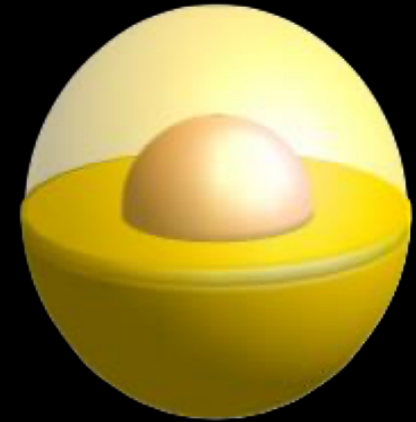
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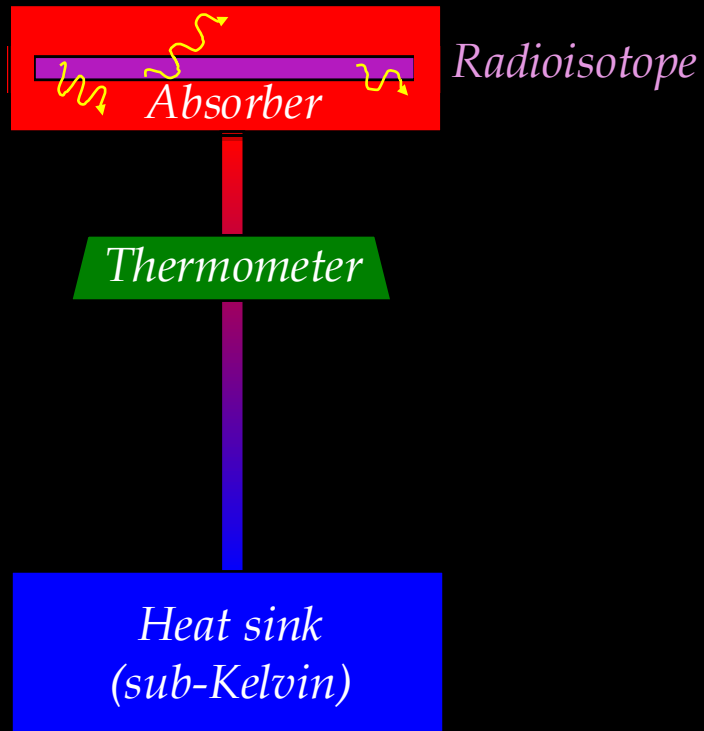
# $^{163}\text{Ho}$ : Microcalorimetry



- ◆ Absorber
  - ◆ Sandwich  $^{163}\text{Ho}$  inside
  - ◆ Convert energy to heat
  - ◆ Very low heat capacity  $C$
- ◆ Thermometer
  - ◆ Small  $\Delta T$       big response



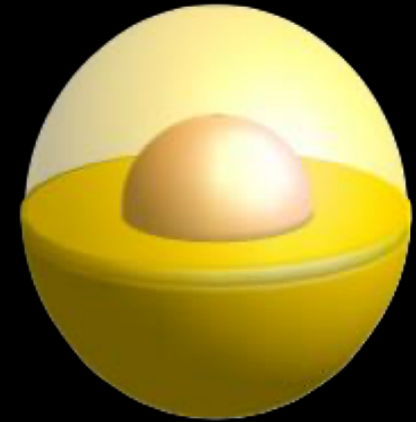
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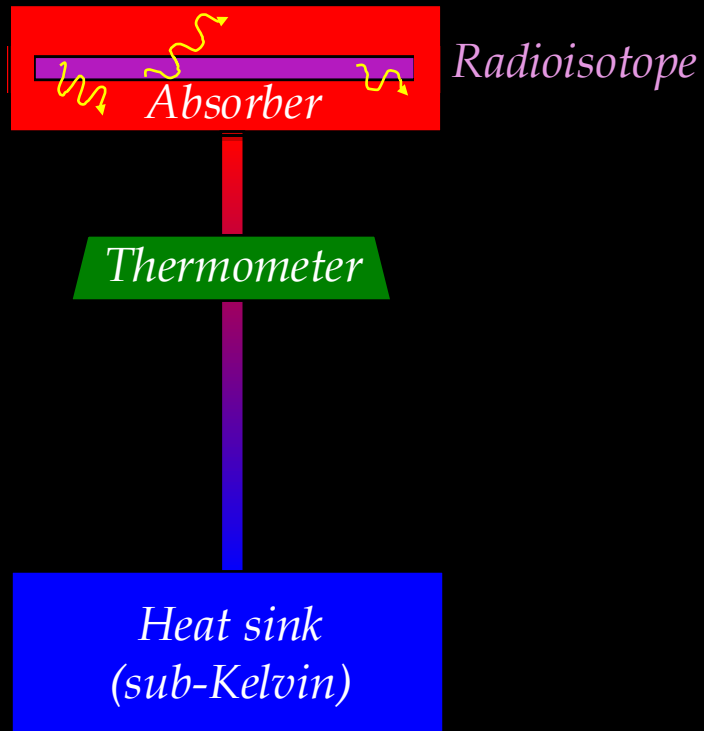
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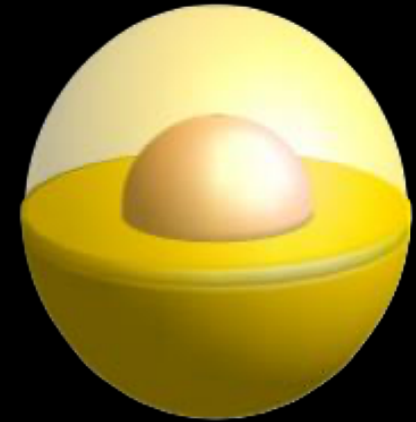
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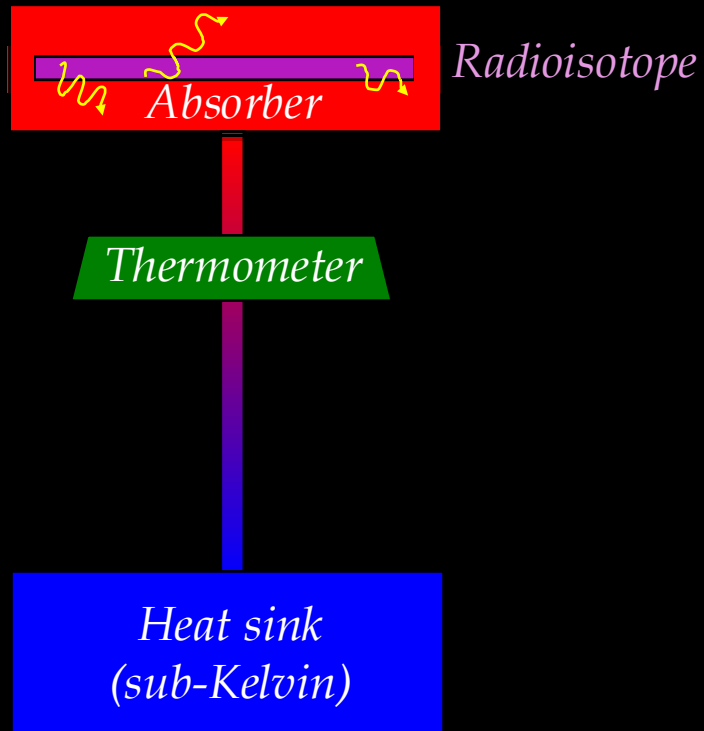
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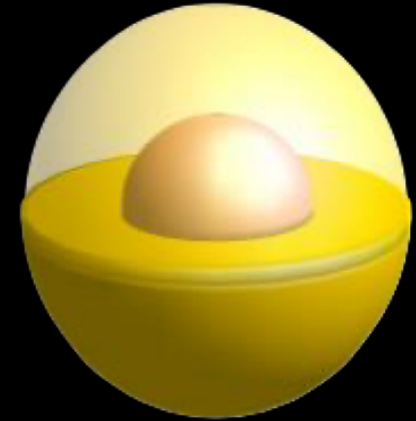
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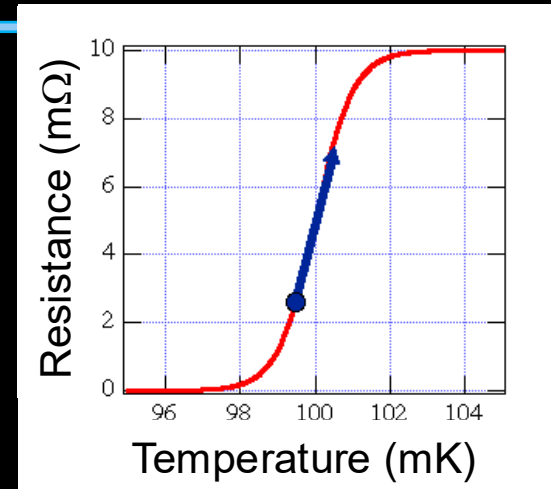
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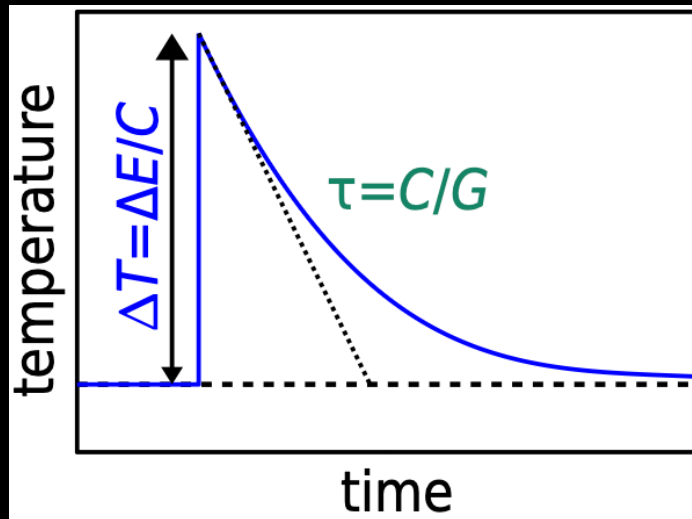
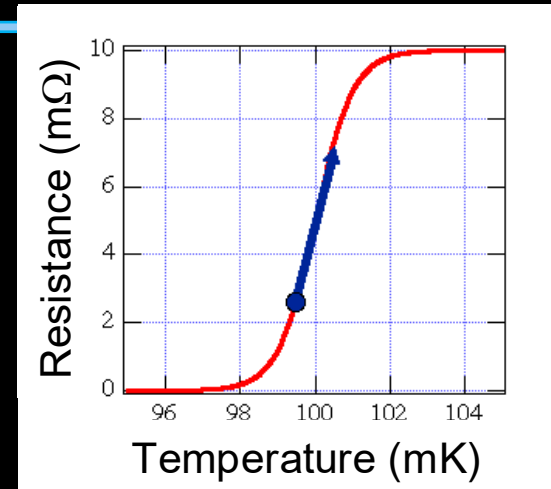
# Thermometer Idea: Transition-Edge Sensor

- ◆ Keep a bilayer film near superconducting  $T_c$ 
  - ◆  $R$  depends on  $T$  in transition region
  - ◆ Couple TES resistance to magnetic flux
  - ◆ Read out changes almost noiselessly with a SQUID



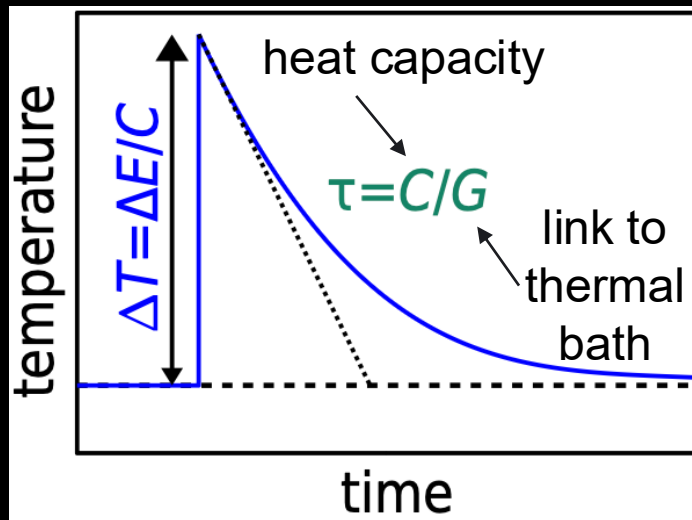
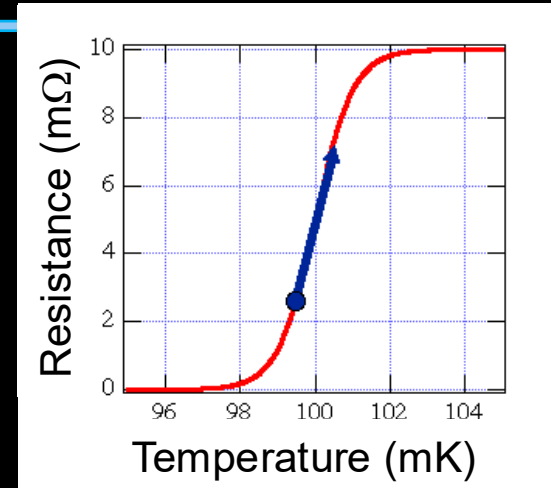
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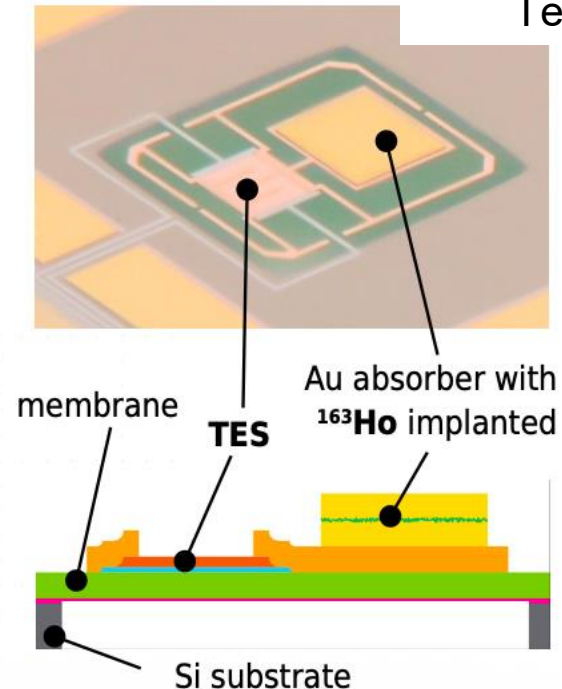
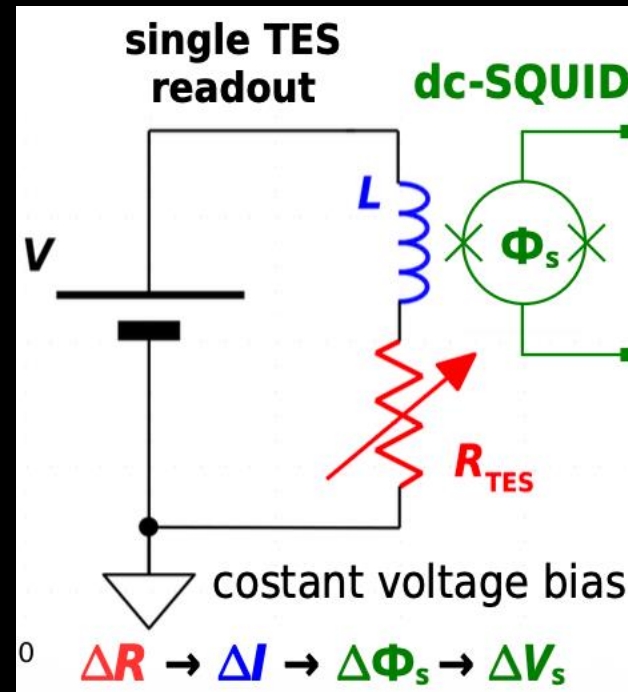
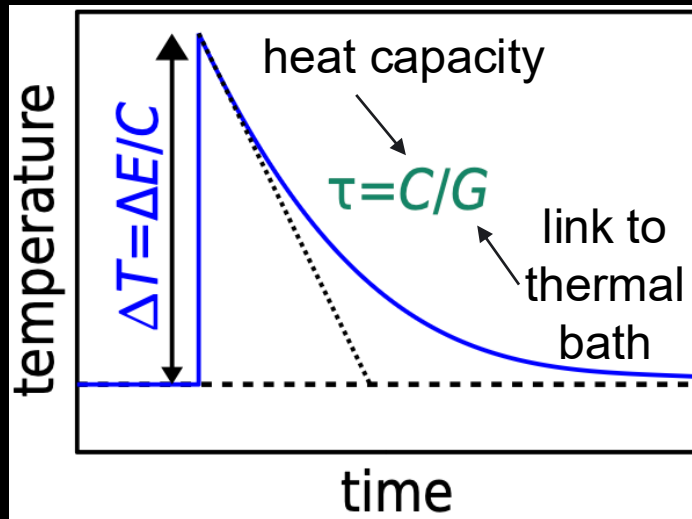
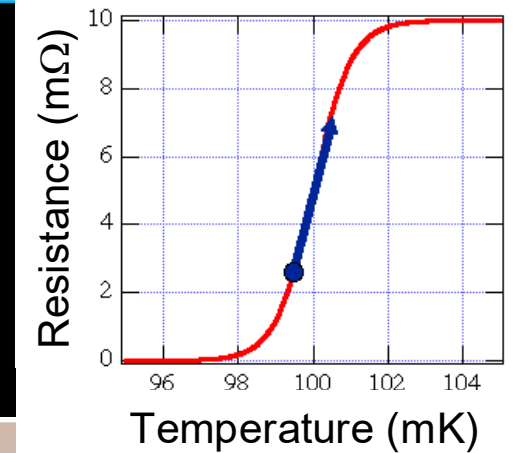
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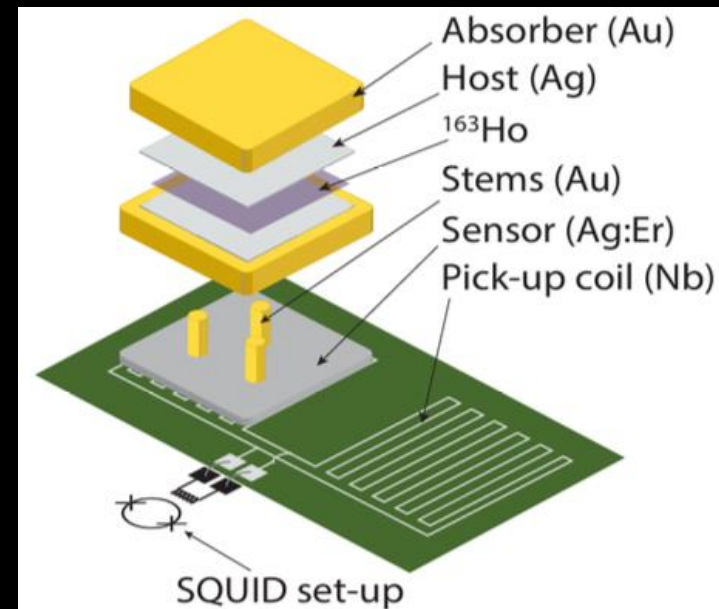
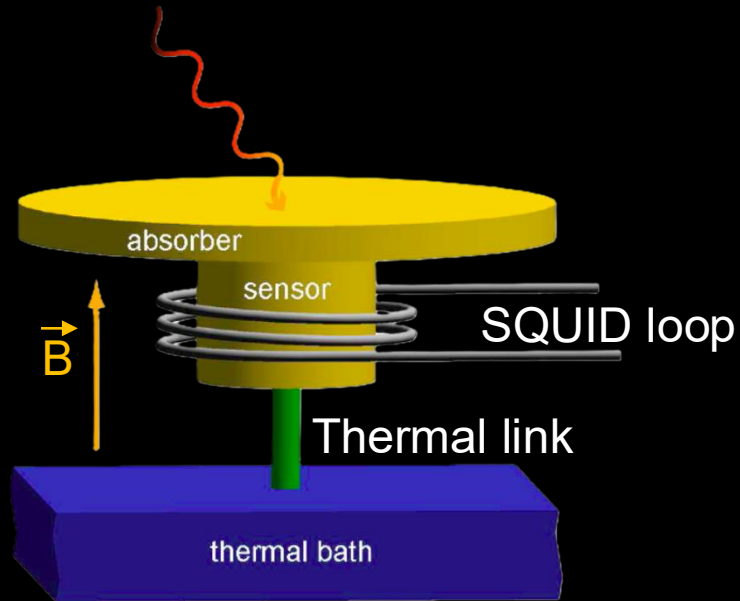
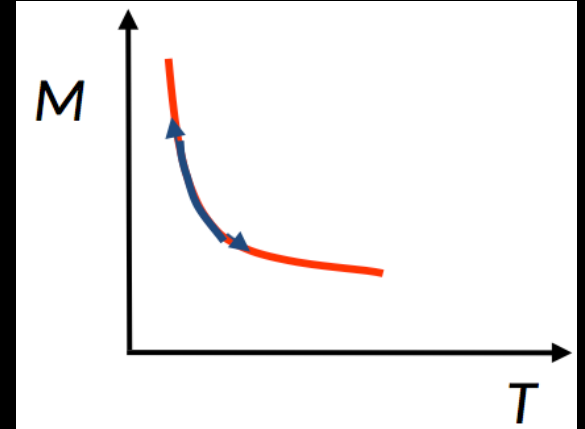
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Angelo Nucciotti

# Thermometer Idea: **M**etallic **M**agnetic **C**alorimeter

- ◆ Use a paramagnetic sensor:
  - ◆ Heat disturbs magnetization
  - ◆ Magnetic flux change read out by SQUID via pick-up coil



*ECHO*, *Phys.Rev.Lett.* **136** (2026) 121801



# How to Get $^{163}\text{Ho}$

---

- ◆ Generated by neutron irradiation
  - ◆  $(n,\gamma)$ -reaction on  $^{162}\text{Er}$
- ◆ Remove  $^{166\text{m}}\text{Ho}$  byproduct by mass separation

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RISIKO @ Institute of Physics, Mainz University

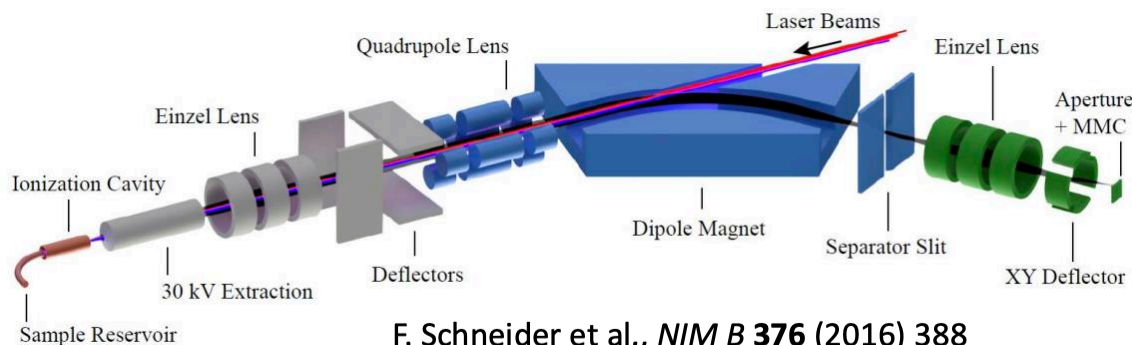
- Resonant laser ion source  $\rightarrow$  efficiency:

$$(69 \pm 5^{\text{stat}} \pm 4^{\text{syst}})\%$$

- Reduction of  $^{166\text{m}}\text{Ho}$  in MMC

$$^{166\text{m}}\text{Ho}/^{163}\text{Ho} < 4(2)10^{-9}$$

Validation via AMS measurement  
@HZDR DREAMS facility



F. Schneider et al., *NIM B* **376** (2016) 388  
T. Kieck et al., *Rev. Sci. Instr.* **90** (2019) 053304  
T. Kieck et al., *NIM A* **945** (2019) 162602

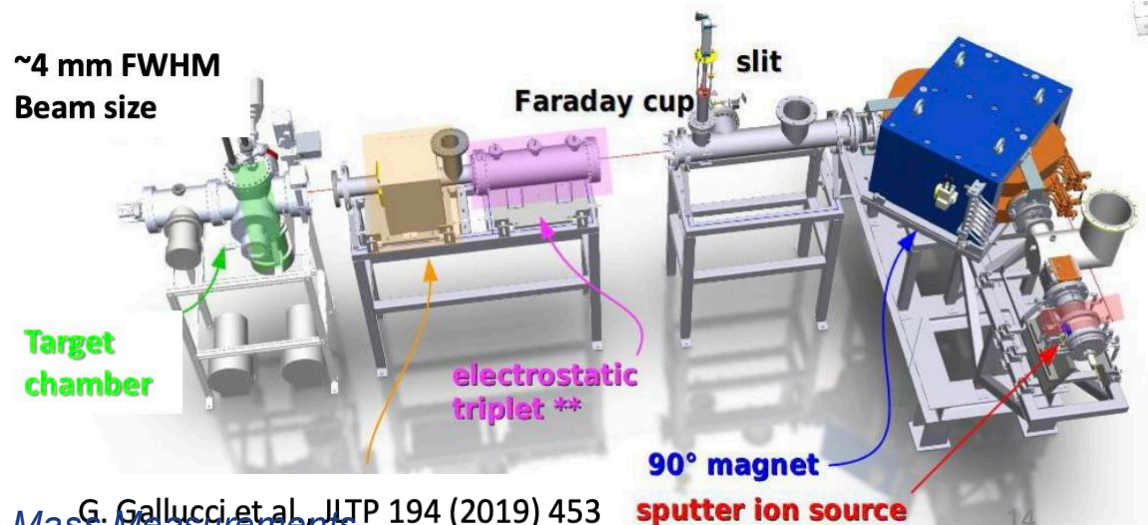
Loredana Gastaldo

Mass separator and implanter installed @ Physics Department, Genoa University

- Beam source: Argon sputter ion source
- Acceleration section  $\rightarrow$  up to 50 kV
- Demonstrated current stability for  $^{165}\text{Ho}$  beam using a sintered target



$\sim 4$  mm FWHM  
Beam size



G. Gallucci et al., *IJTP* **194** (2019) 453

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*Nature does not care what labels we put on our science.*

RISIKO @ Institute of Physics, Mainz University

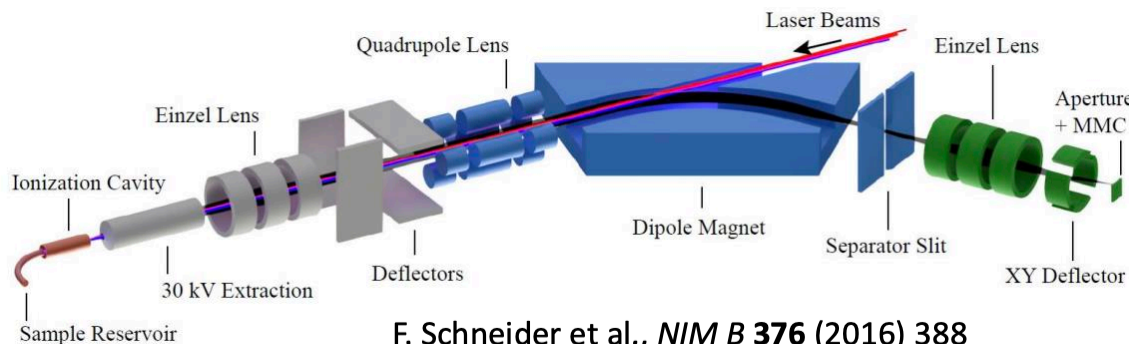
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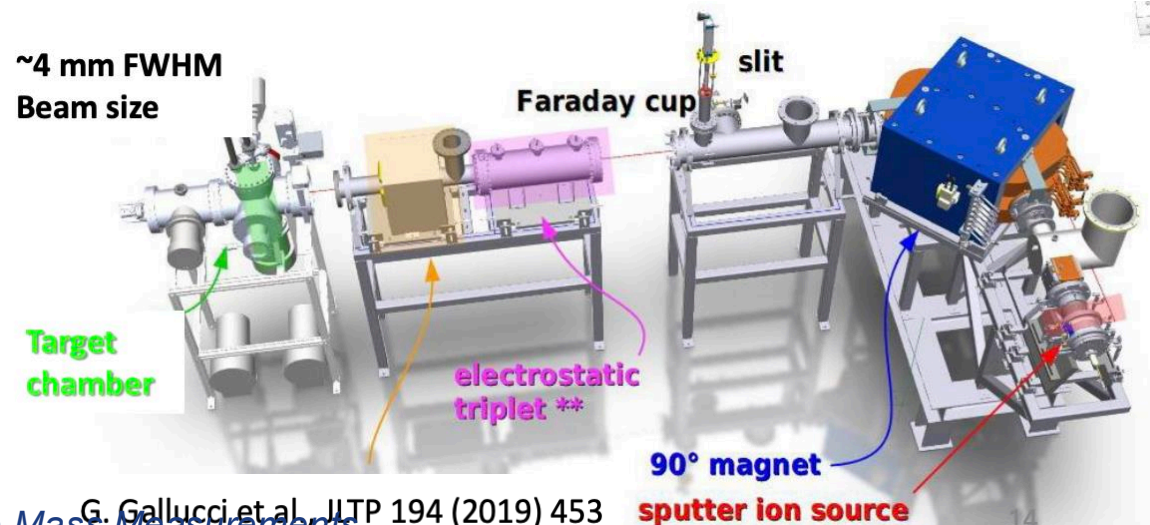
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$\sim 4$  mm FWHM  
Beam size

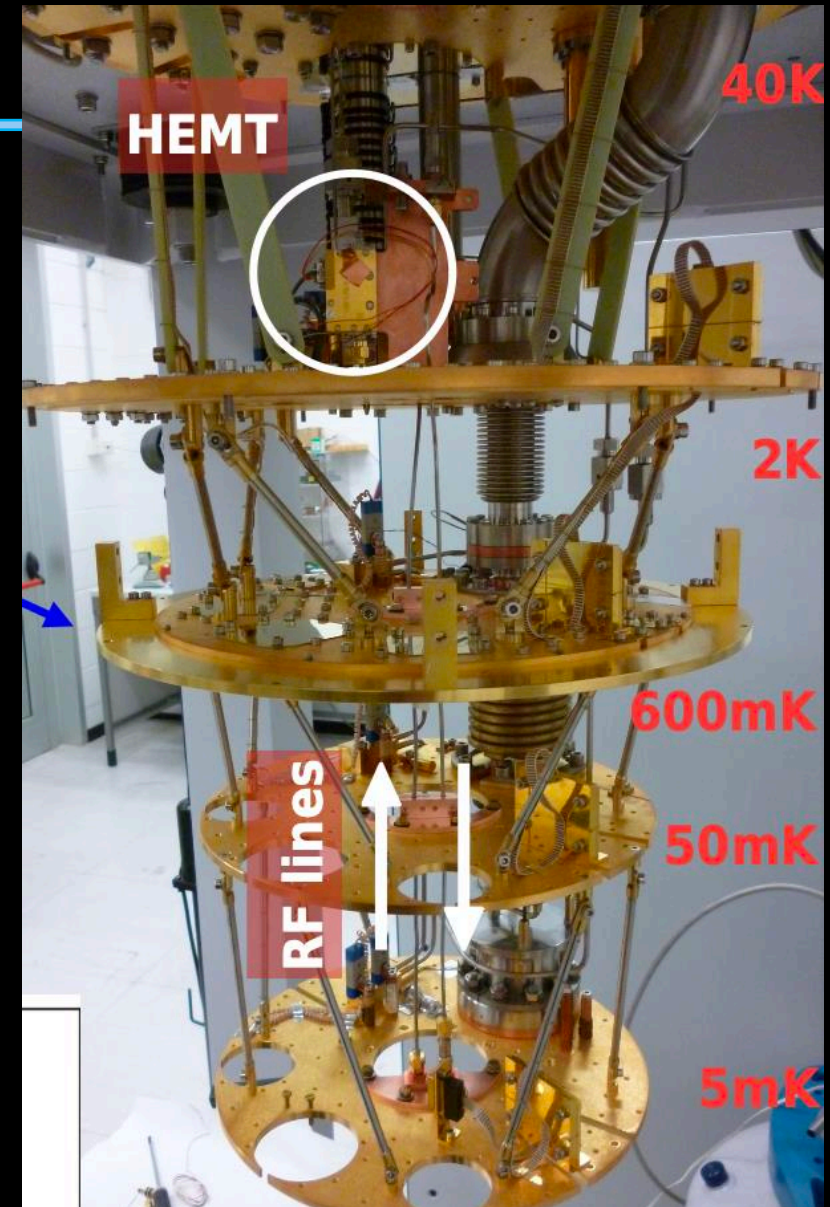


G. Gallucci et al., *IJTP* **194** (2019) 453

# The Readout Challenge

- ◆ 1,000-12,000 tiny sensors, plus a cryogenic platform with limited cooling capacity ( $\mu\text{W}$ - $\text{mW}$  heat loads)
  - ◆ Must use special materials
  - ◆ Can't have too much cold electronics
  - ◆ Can't connect lots of cables directly from room temperature

**Need microwave multiplexing**

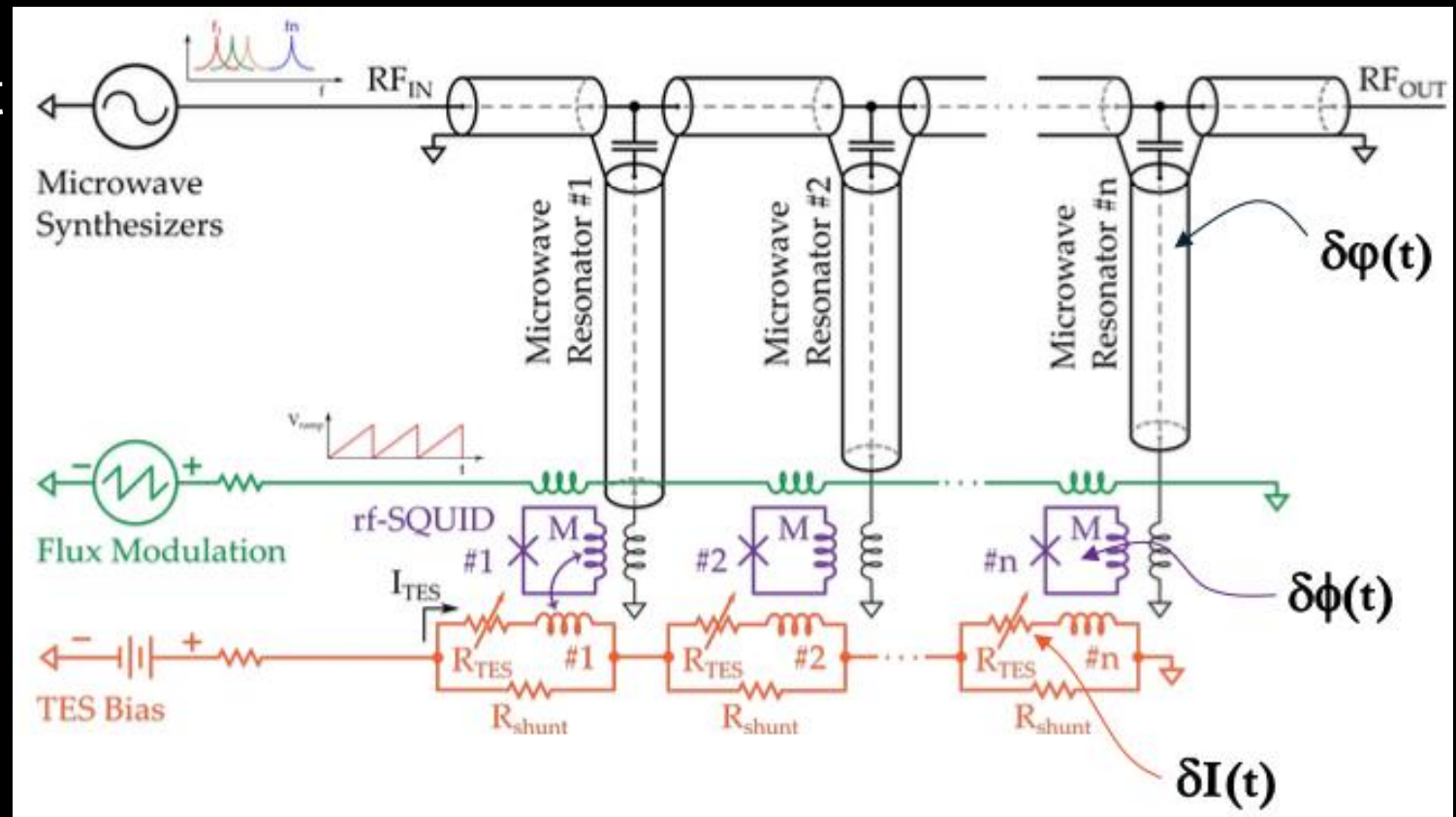


*Slide adapted from Elise Nowitzki*



# Microwave Multiplexing Example

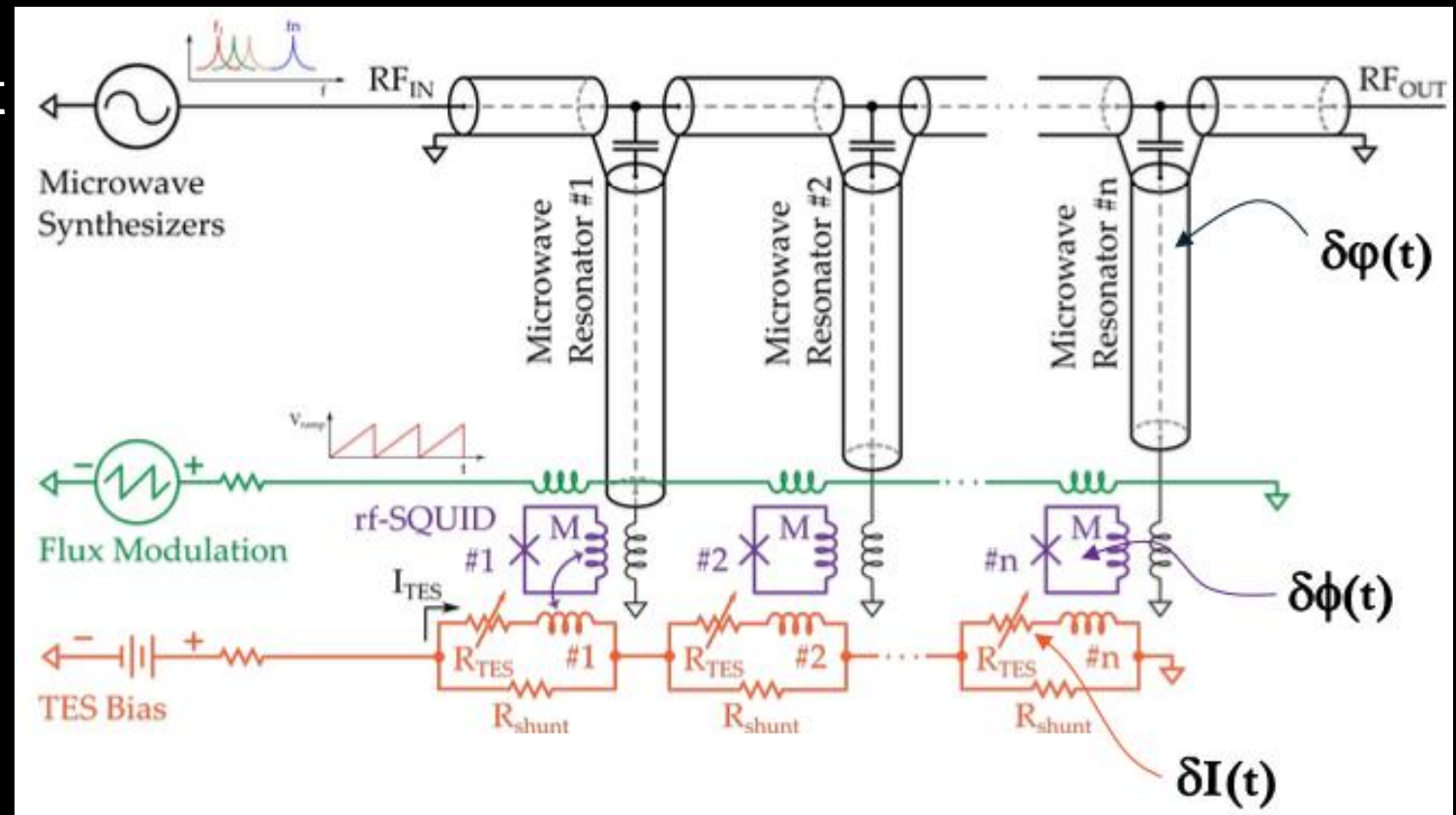
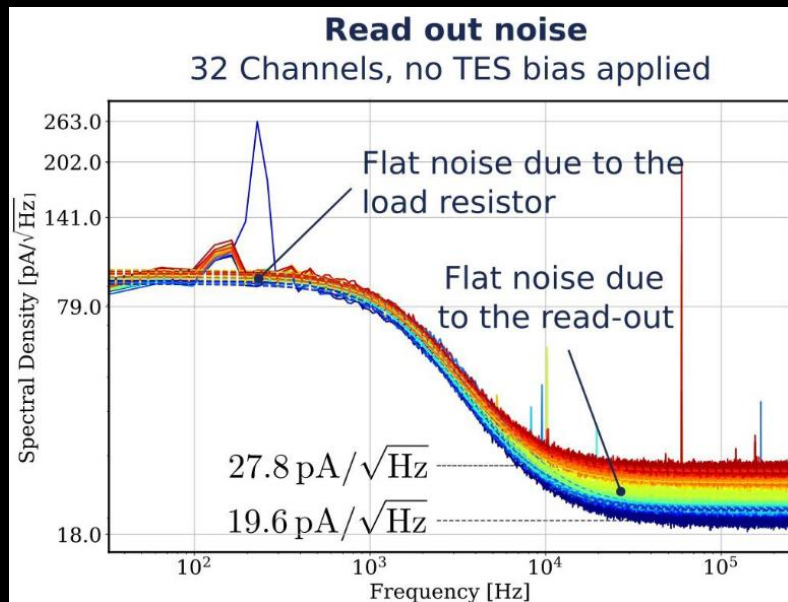
- ◆ Apply a periodic ramp to the SQUIDs
- ◆ Microwave resonator frequencies oscillate continuously
- ◆ Signals from different channels naturally spread out in frequency



M. Faverzani

# Microwave Multiplexing Example

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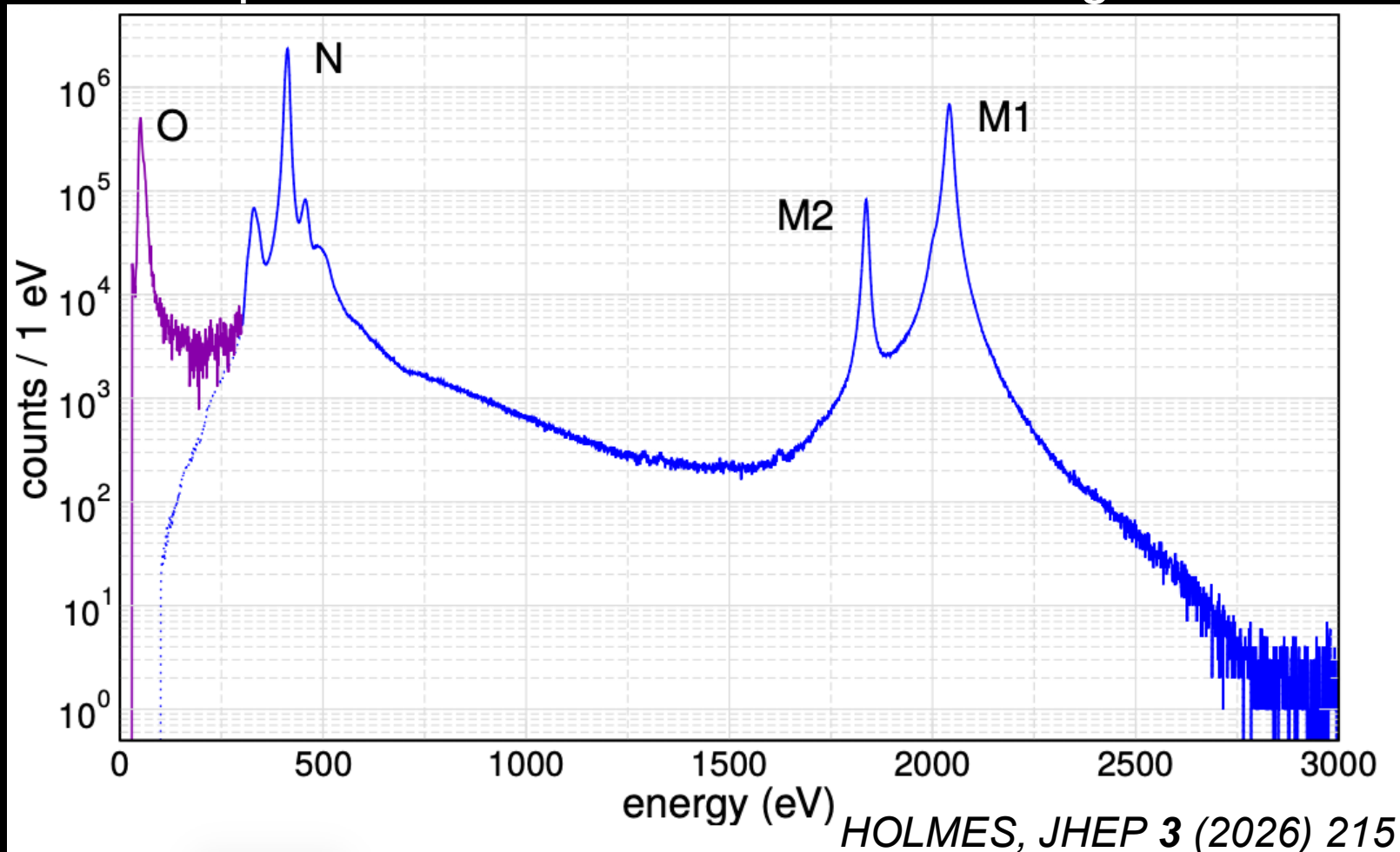


*M. Faverzani*

Diana Parno - Direct Neutrino-Mass Measurements

# The Spectral Challenge (I)

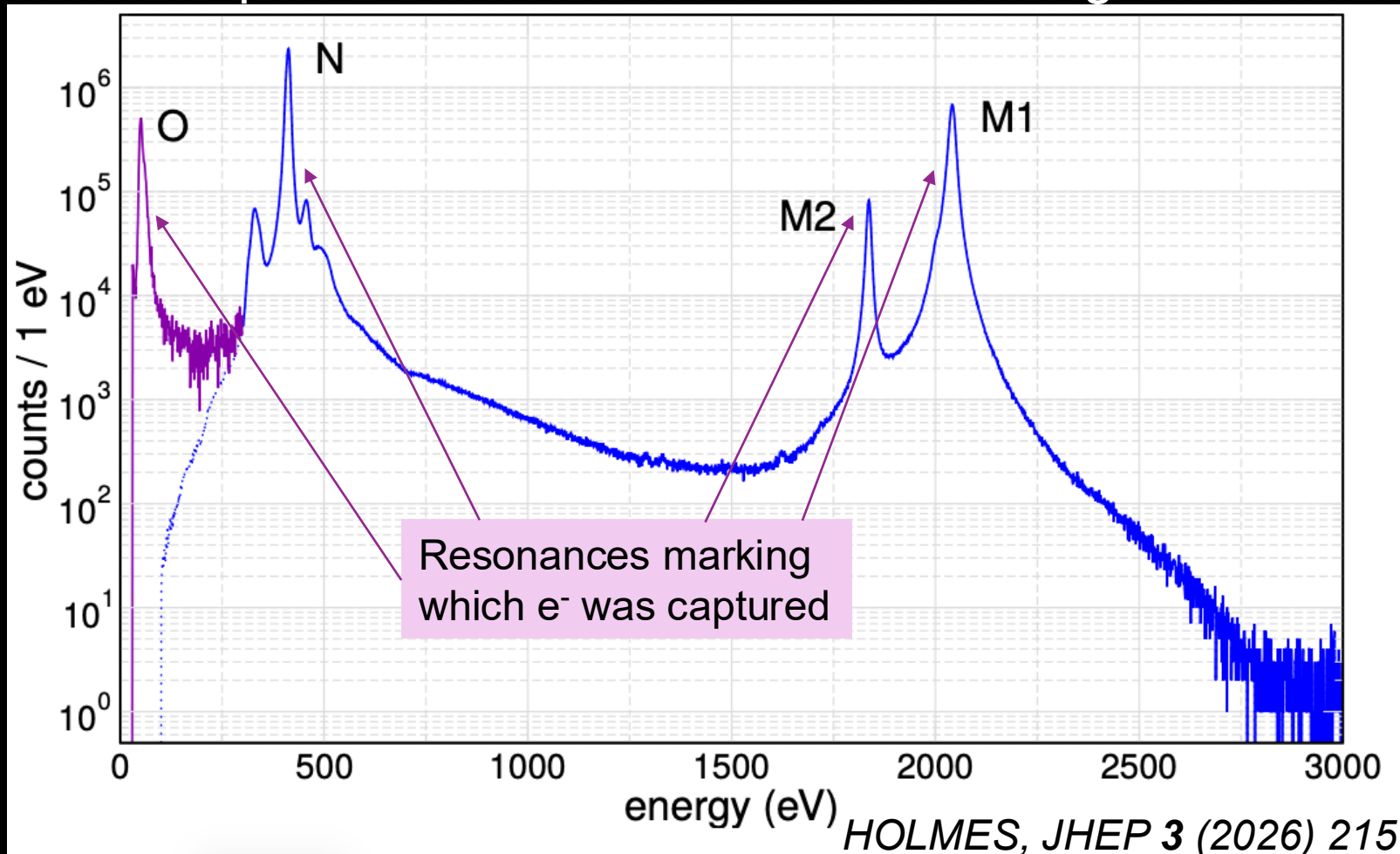
- ◆ Electron-capture spectra aren't smooth like a  $\beta^-$  spectrum!
- ◆ Structures near endpoint could mask neutrino-mass signal





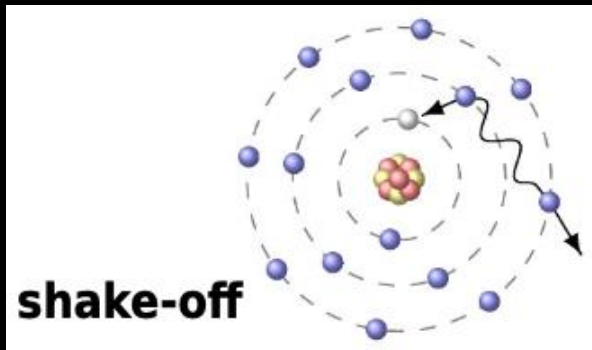
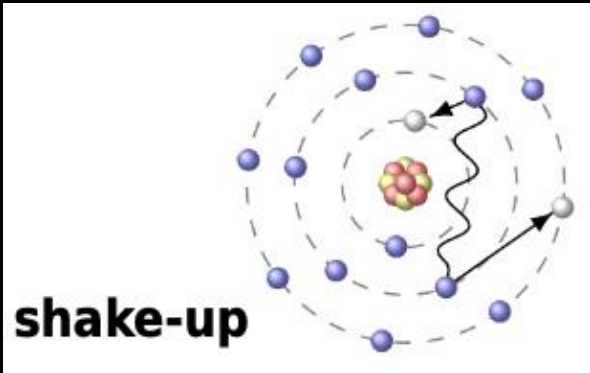
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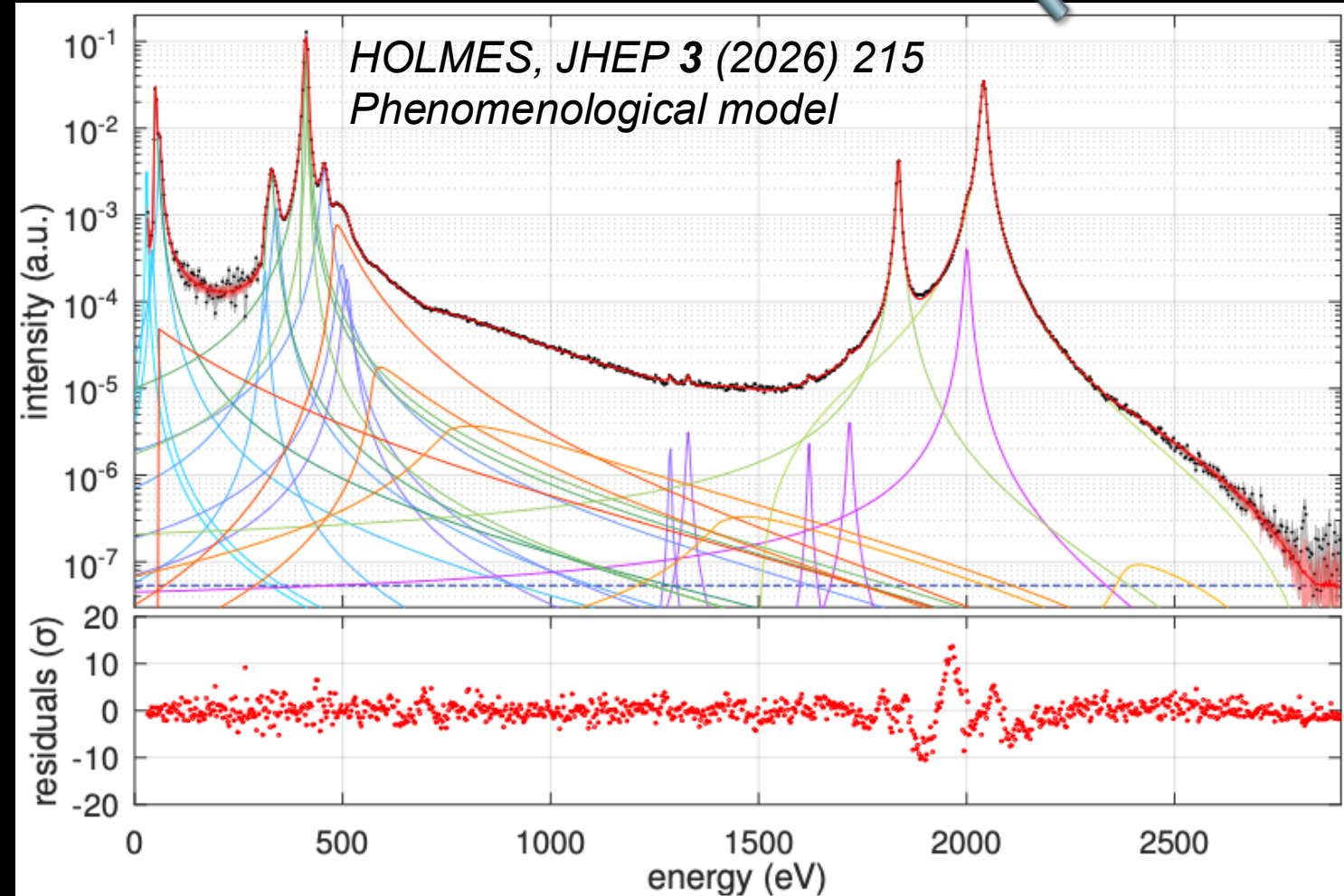
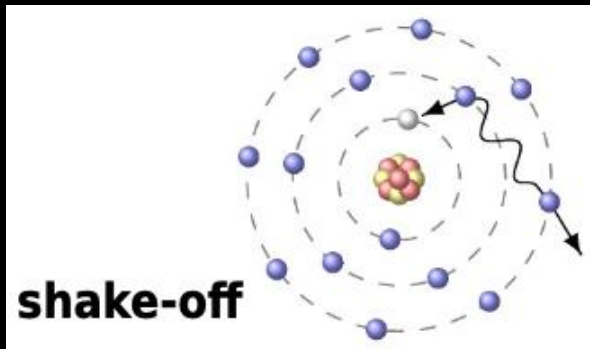
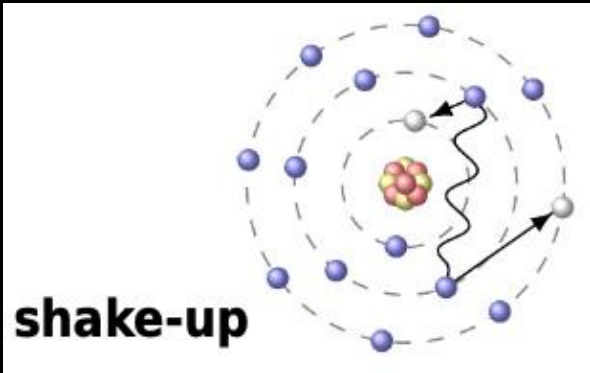
# The Spectral Challenge (II)

- ◆ The  $^{163}\text{Dy}$  decay product is highly excited!
- ◆ Each type of energy loss has a signature on the spectrum



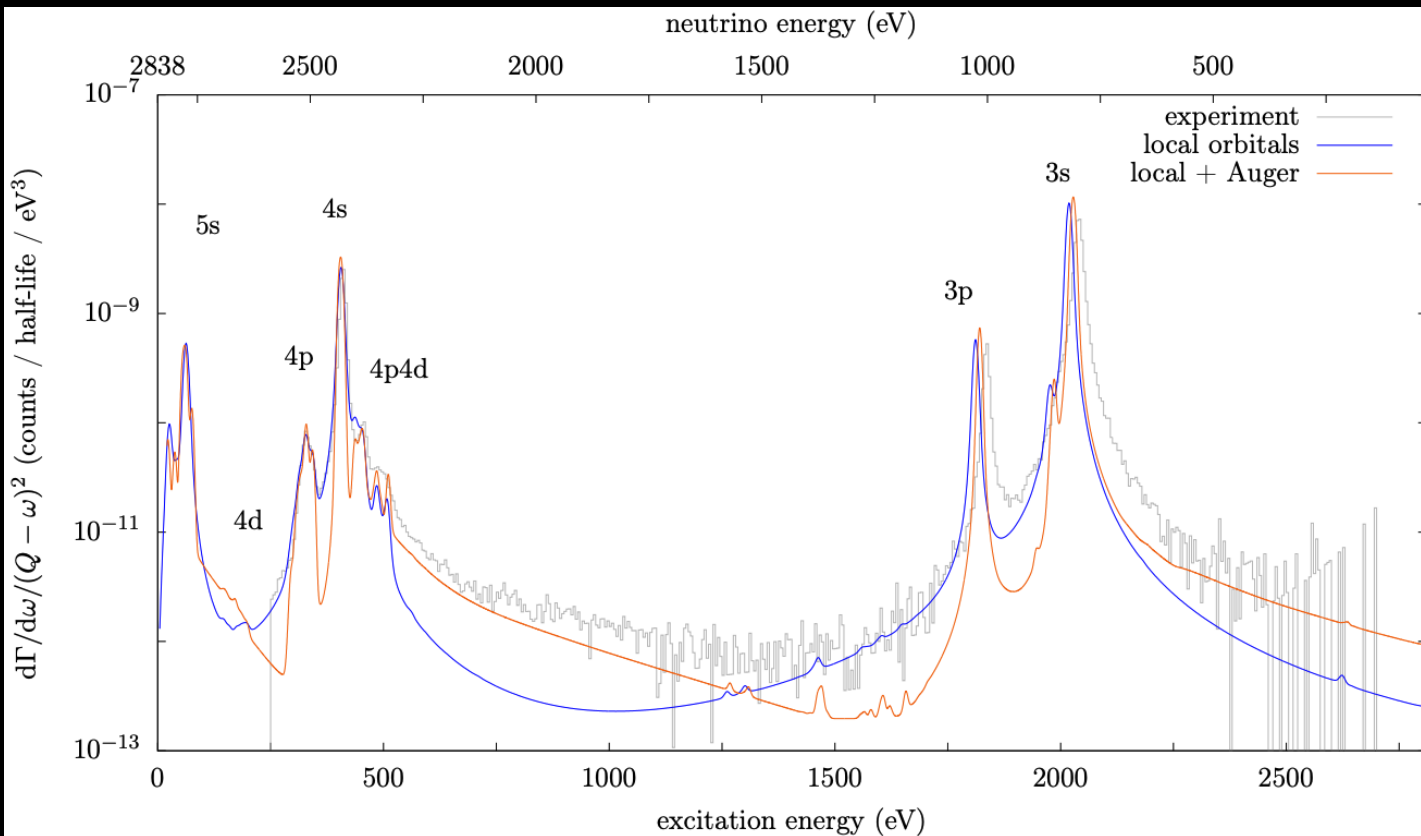
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# The Spectral Challenge (III)

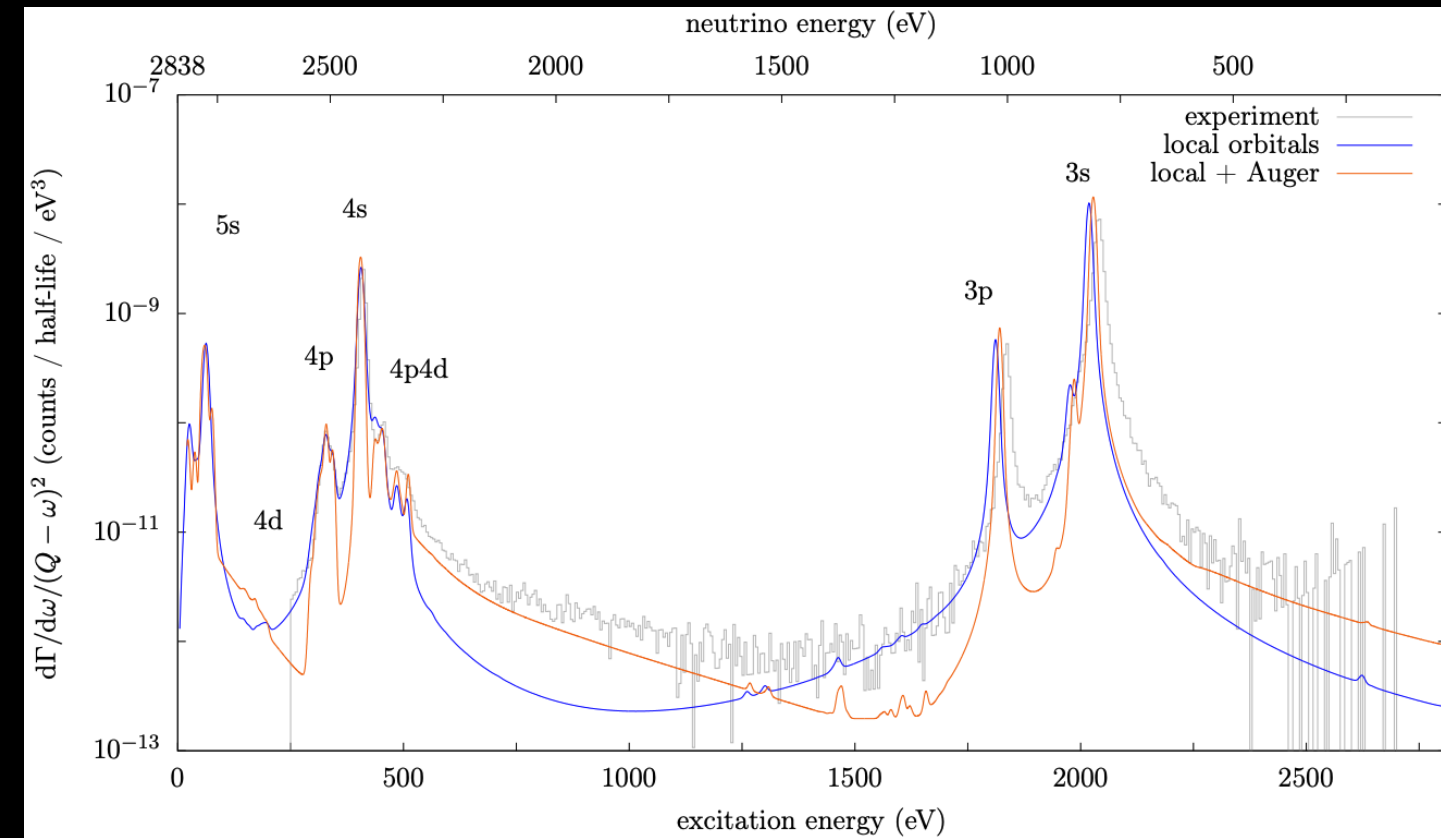
- ◆ Overall sense of experimental spectrum is captured by many-body theory
- ◆ Discrepancies in line positions, broadening may be due to more complex final states



*Braß and Haverkort, New J. Phys. 9 (2020) 093018*

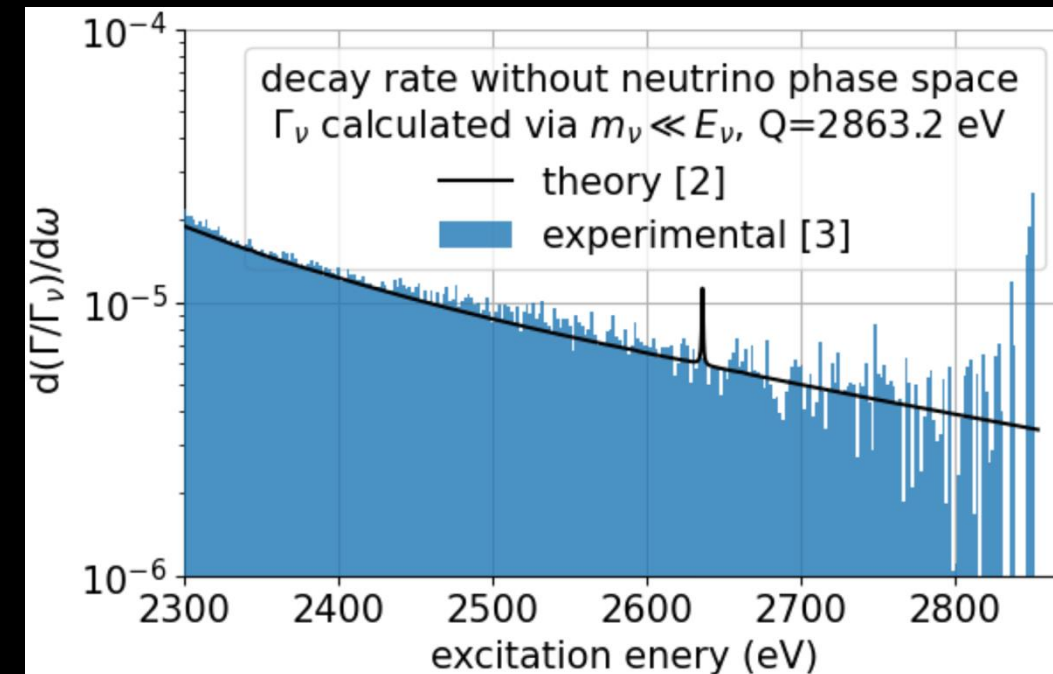
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Braß and Haverkort, *New J. Phys.* **9** (2020) 093018

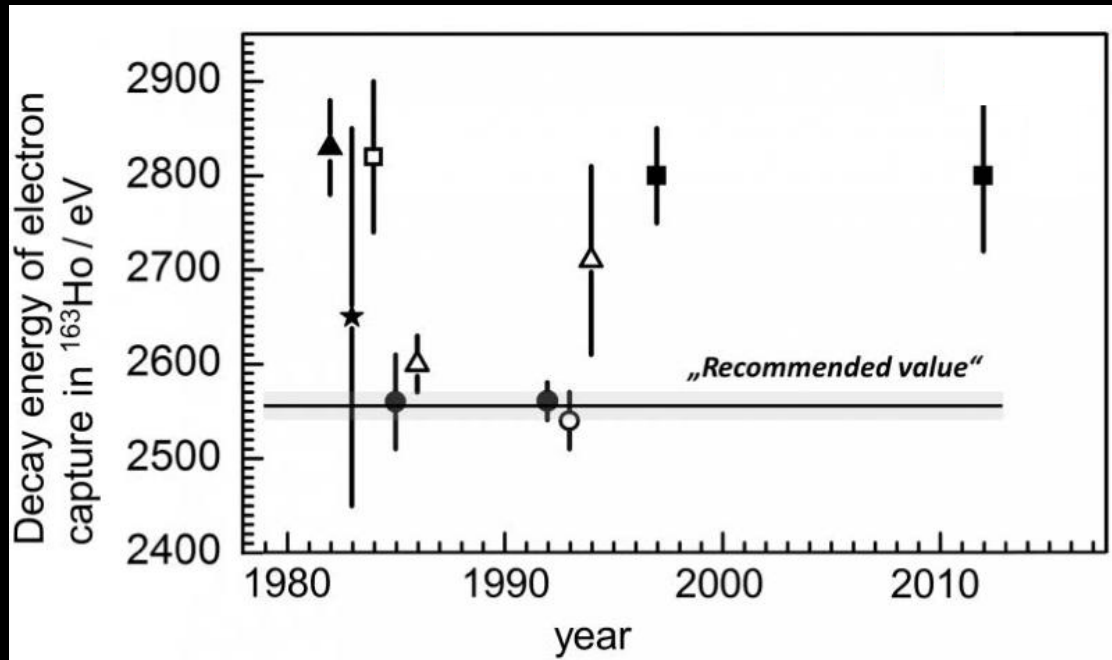
- ◆ Endpoint region is well described



ECHo, *PRL* **136** (2026) 121801

# The Q-Value Challenge (I)

- ◆ For tritium: straightforward fit parameter; systematics test
- ◆ For holmium: affects rate and spectral shape at endpoint
  - ◆ How close is  $E_0$  to which resonance?

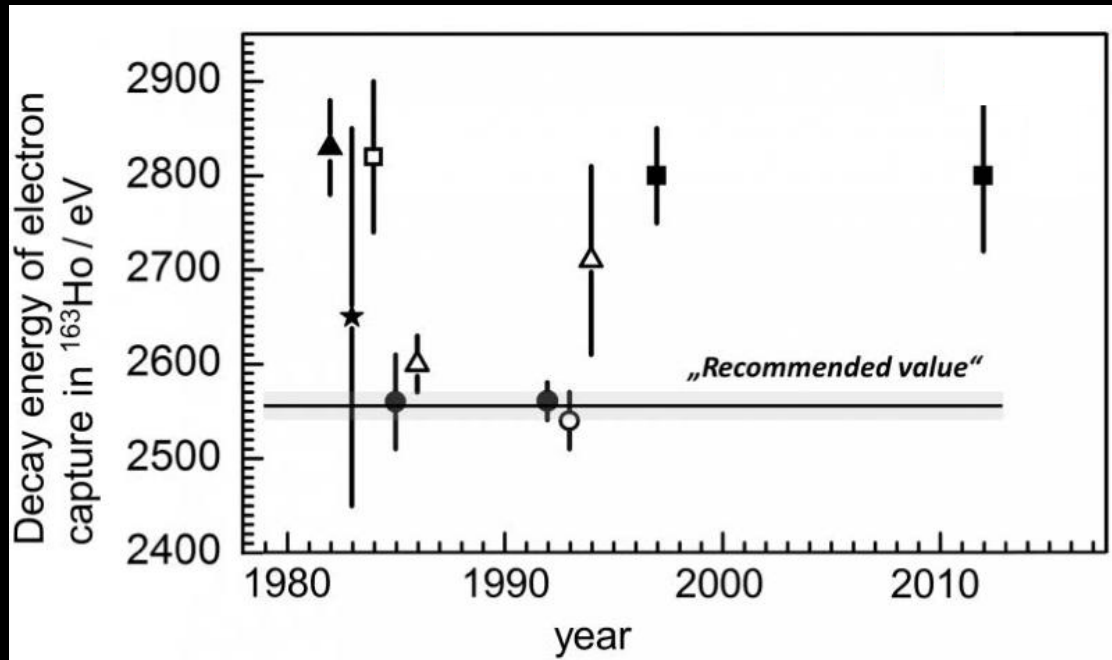


*Eliseev et al., PRL 115 (2015) 062501*



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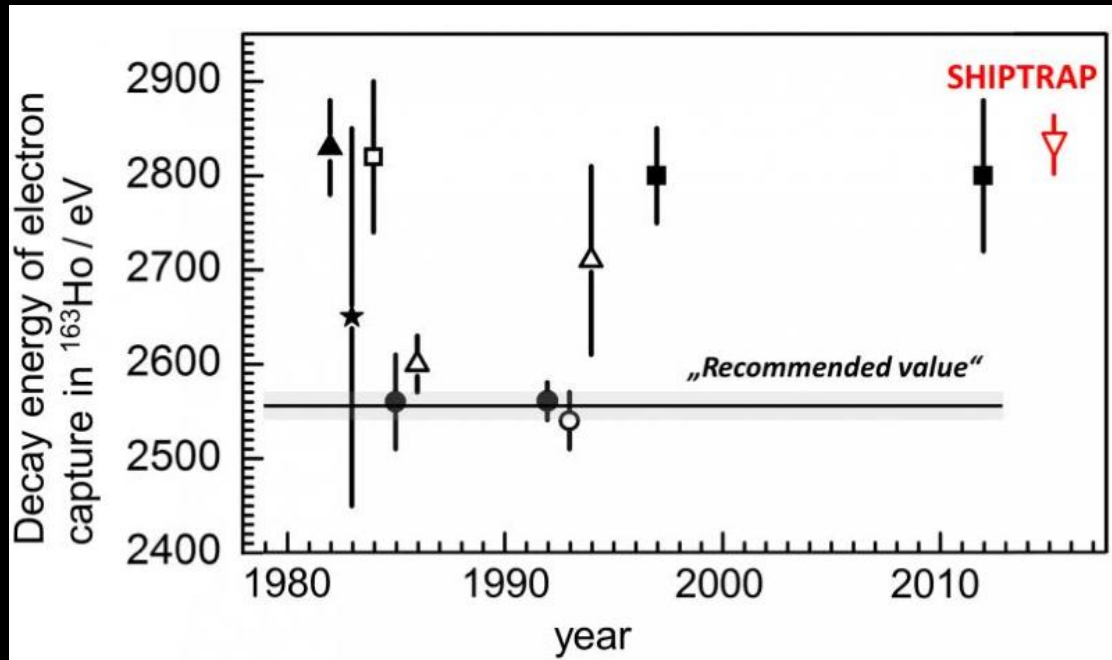
*Eliseev et al., PRL 115 (2015) 062501*

- ◆ Lots of historical scatter in measurements from decay spectra
- ◆ Motivates dedicated measurements
  - ◆ Highly ionize the relevant nuclides ( $^{163}\text{Ho}$ ,  $^{163}\text{Dy}$ )
  - ◆ Confine them in a Penning trap
  - ◆ Measure ratio of cyclotron frequencies to extract mass difference



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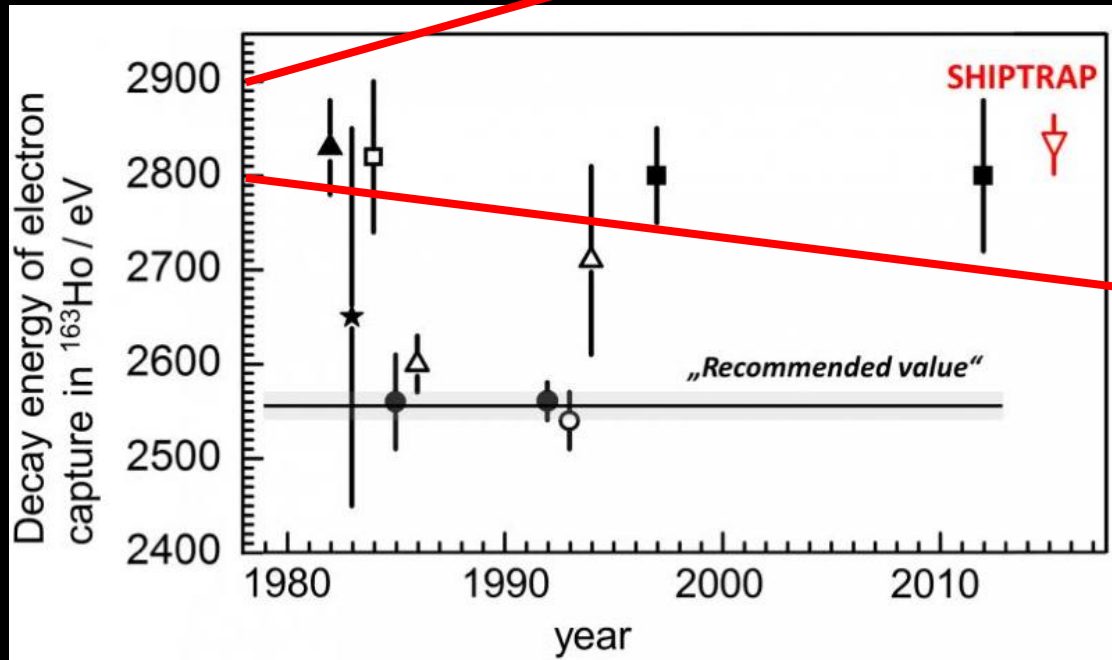


*Eliseev et al., PRL 115 (2015) 062501*

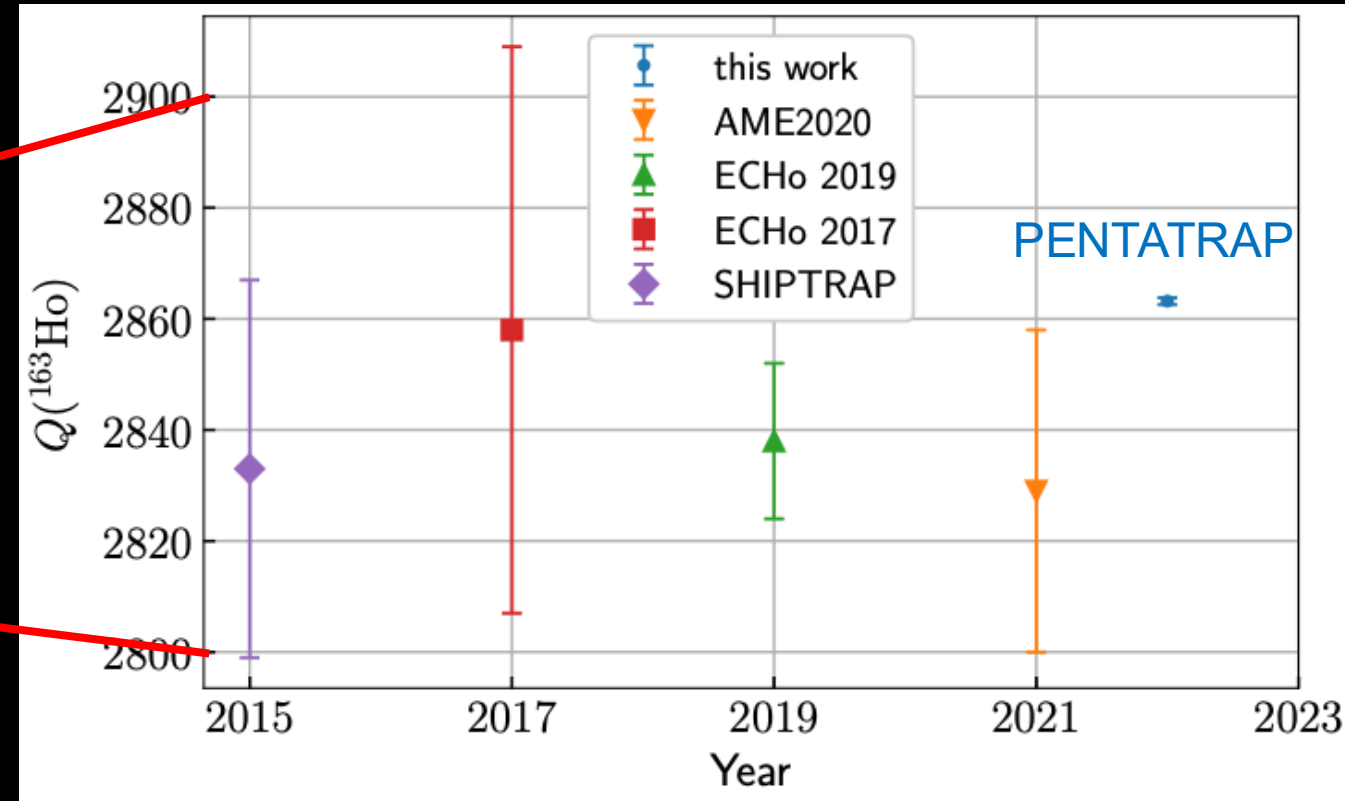
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# The Q-Value Challenge (II)

- ◆ Penning-trap advances improved uncertainty 50x, to 0.6 eV
- ◆ Endpoint rate is resonantly enhanced



*Eliseev et al., PRL 115 (2015) 062501*



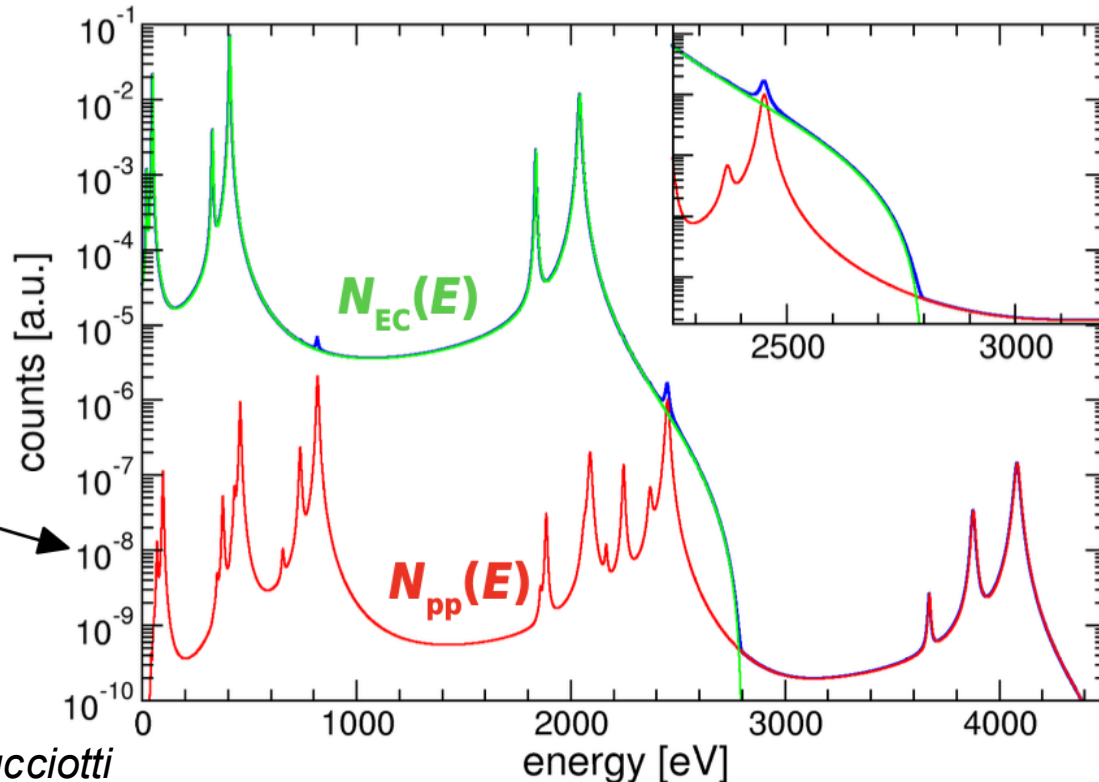
*Schweiger et al., Nat. Phys. 20 (2024) 921*

# The Pileup Challenge

- ◆ When two events in the same detector arrive close in time, they may register as one event with a higher energy

►  $N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$  with  $f_{pp} \approx A_{EC} \tau_R$

$A_{EC}$  EC activity per detector  
 $\tau_R$  time resolution ( $\approx$  rise time)



$Q = 2.8 \text{ keV}$

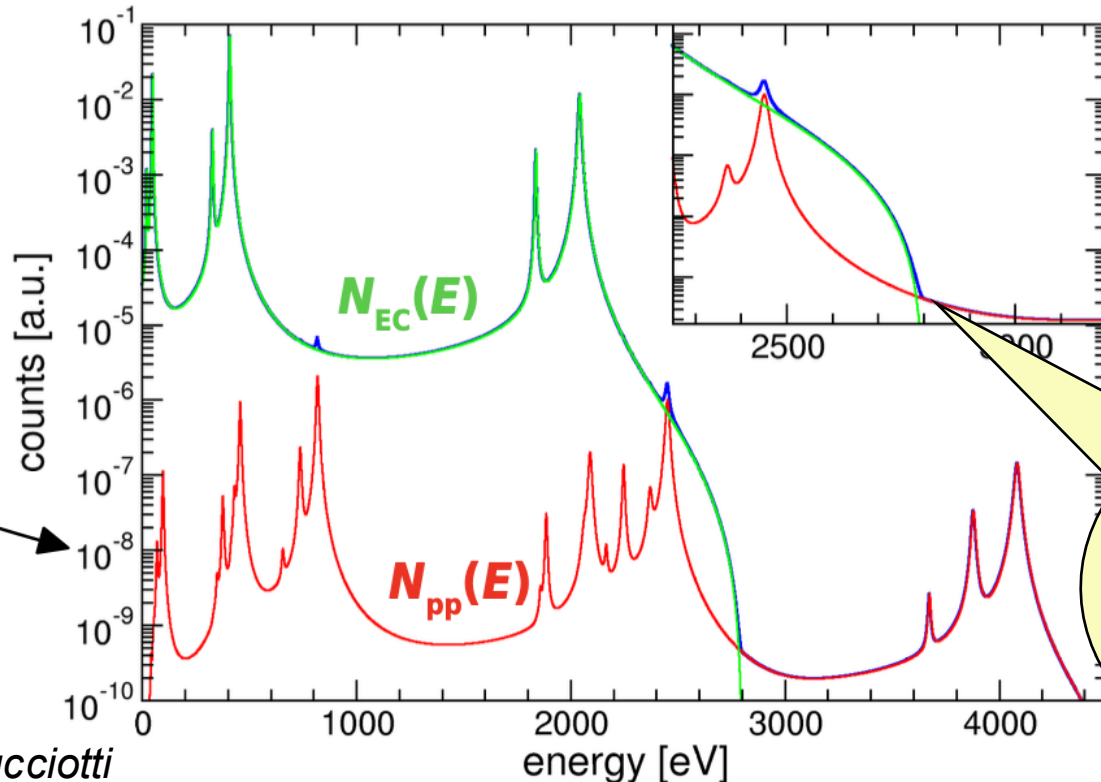
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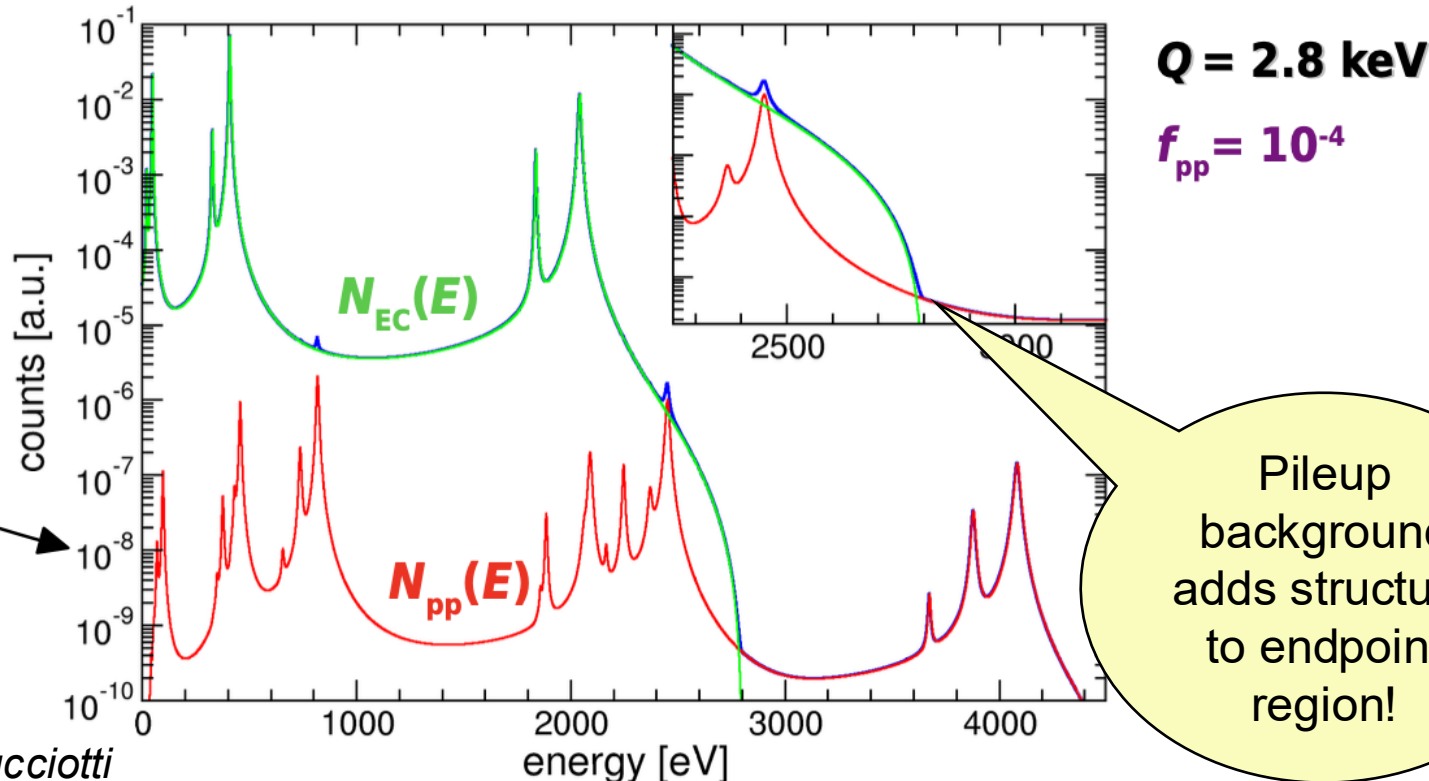
Pileup  
background  
adds structure  
to endpoint  
region!

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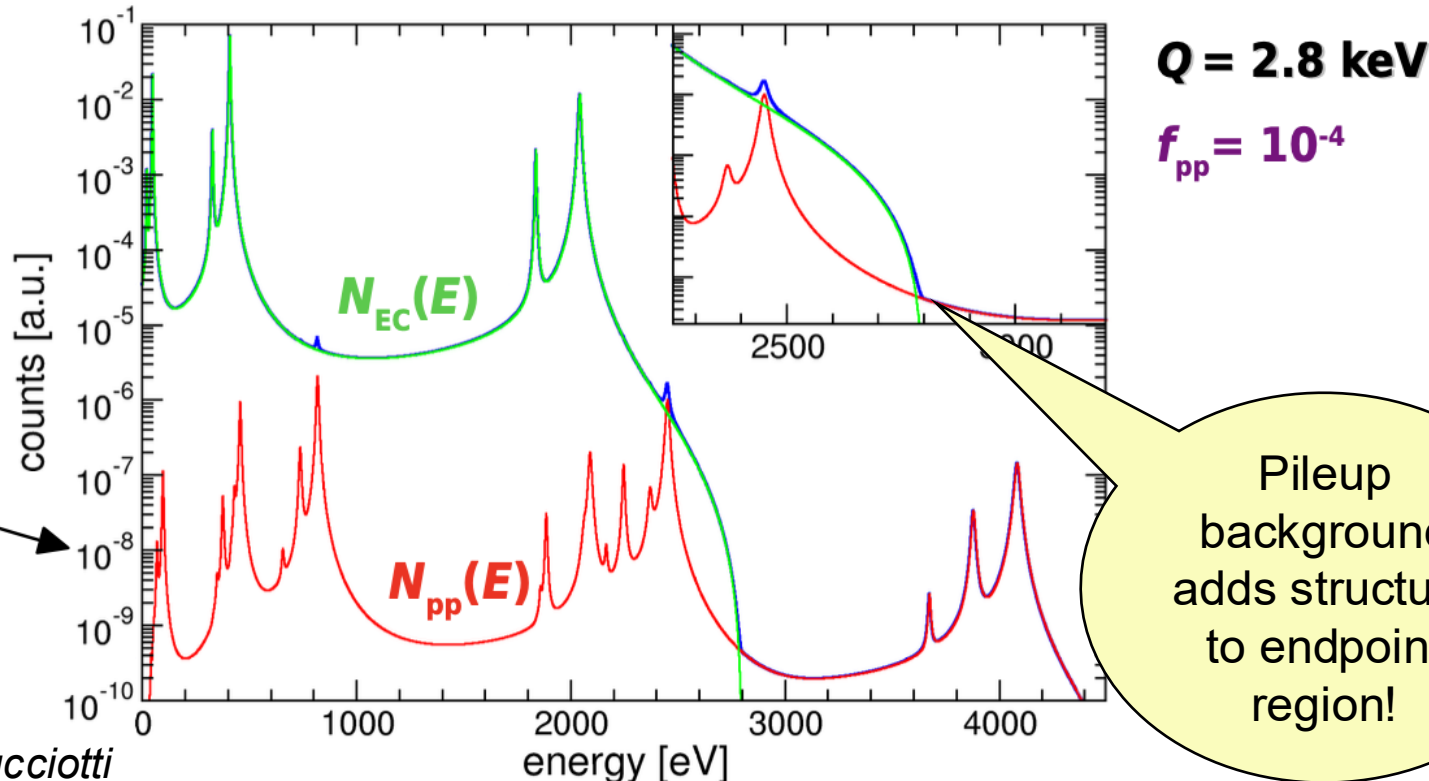
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→ faster recovery
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- ◆ Spread out smaller activities among more sensors

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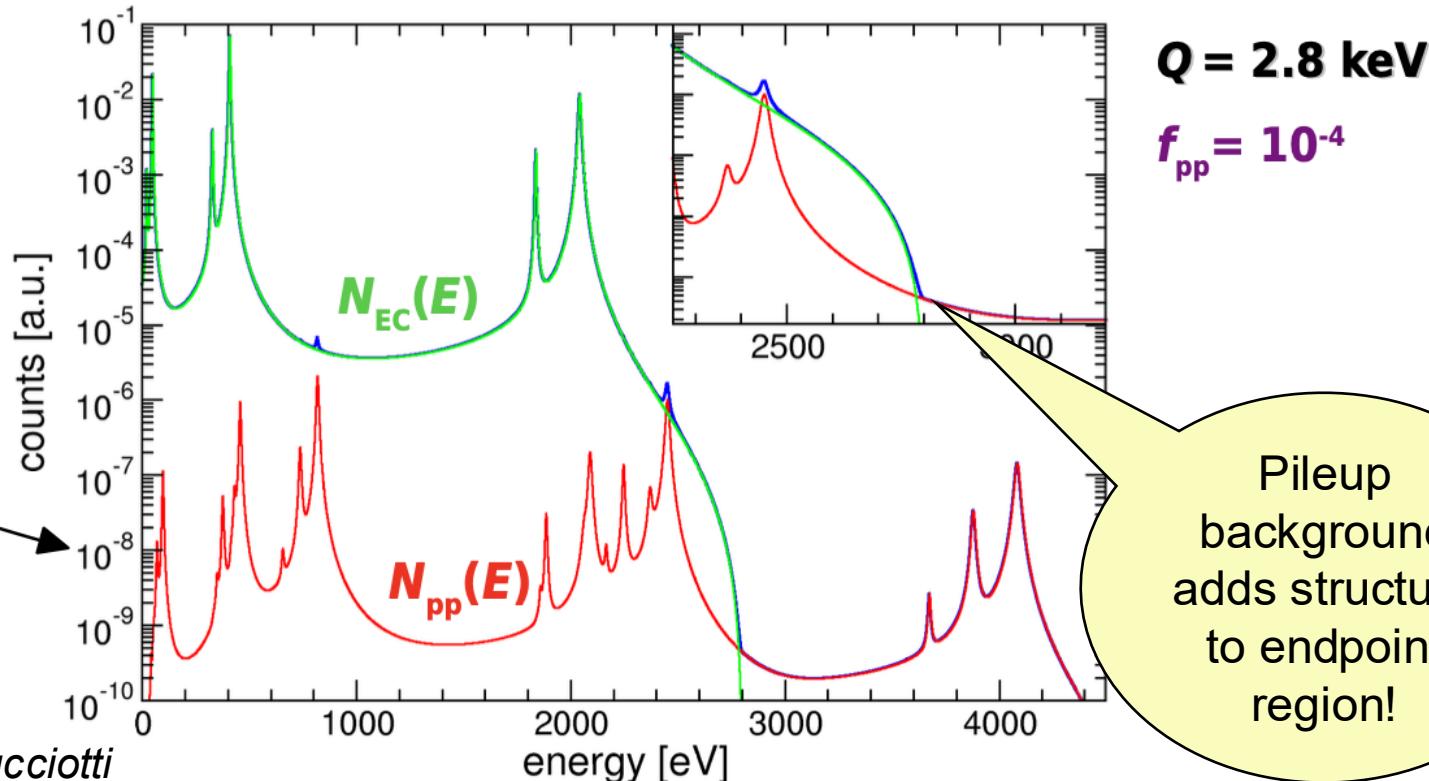


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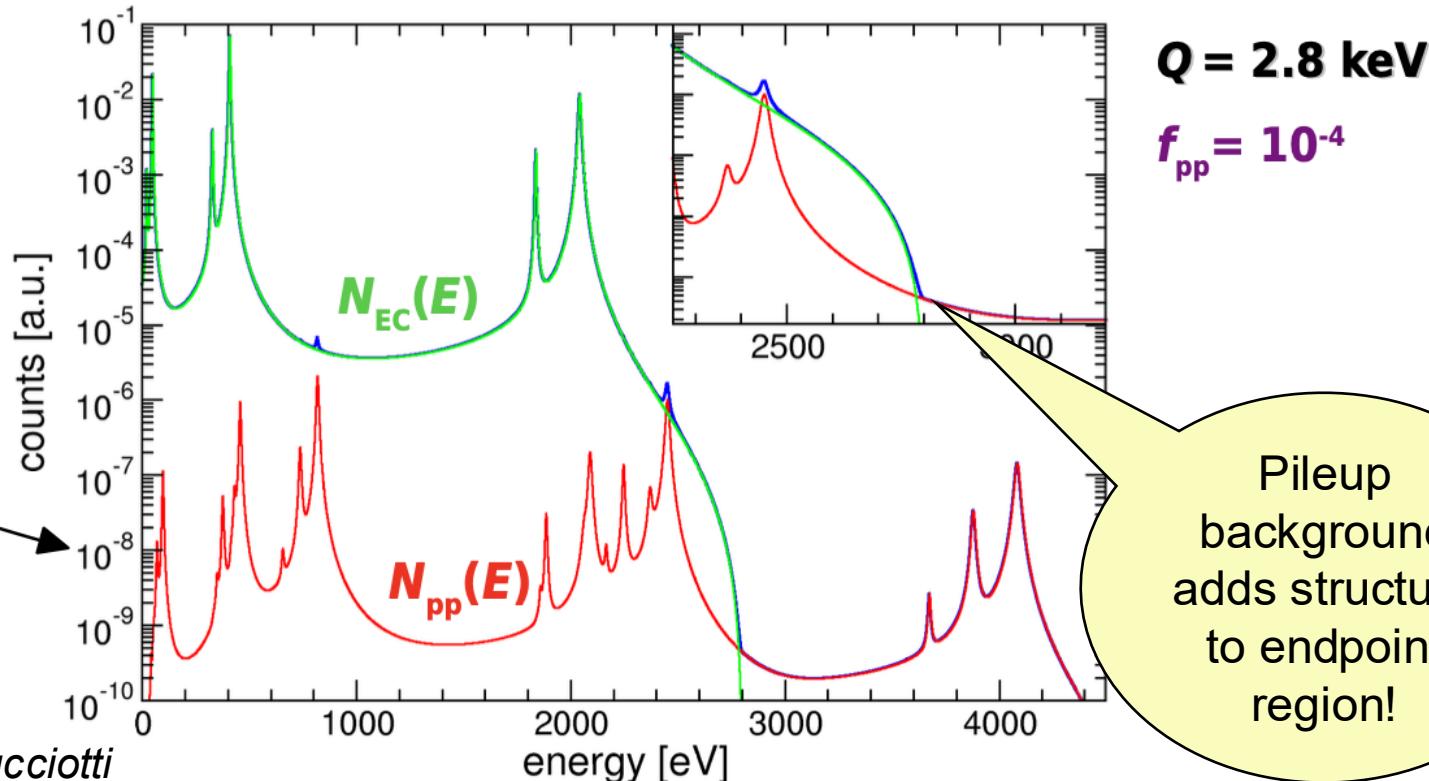


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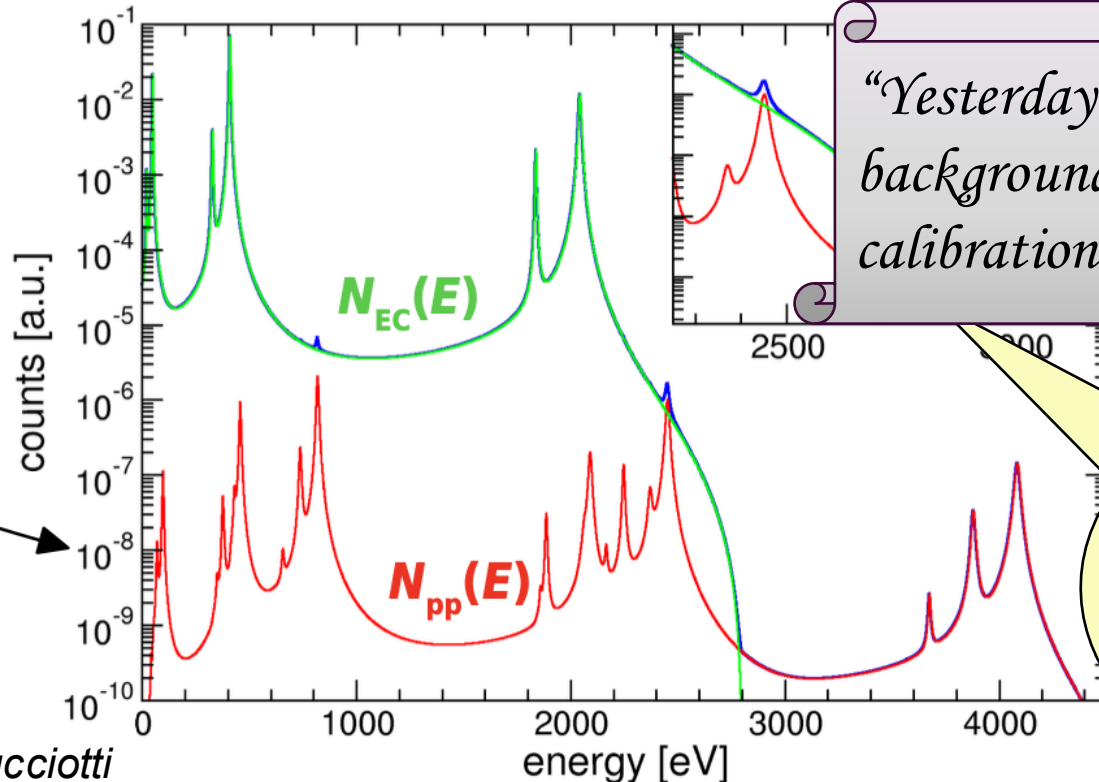
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*"Yesterday's signal is today's background and tomorrow's calibration."*

Pileup background adds structure to endpoint region!

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# The Plan

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- ◆ Accessing the neutrino-mass scale
- ◆ How to search for  $m_\nu$  directly
- ◆ Nitty, gritty systematics
- ◆ Microcalorimetry basics ( $^{163}\text{Ho}$ )
- ◆ **HOLMES**
- ◆ **ECHo**
- ◆ Beta-spectroscopy basics ( $^3\text{H}$ )
- ◆ KATRIN
- ◆ Project 8
- ◆ Next-generation tritium R&D
- ◆ Sterile neutrinos and bonus physics
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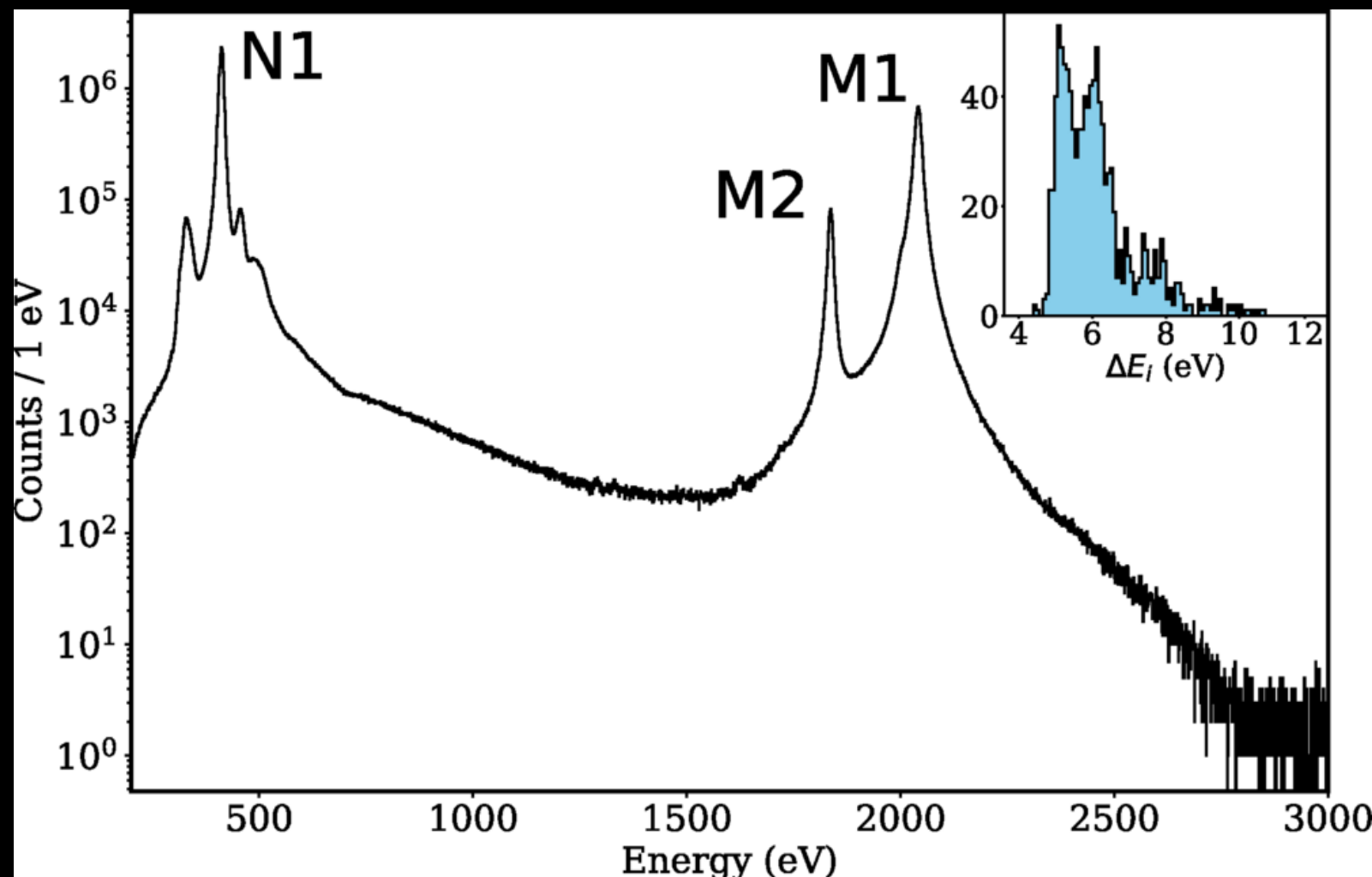
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# New Results: HOLMES!

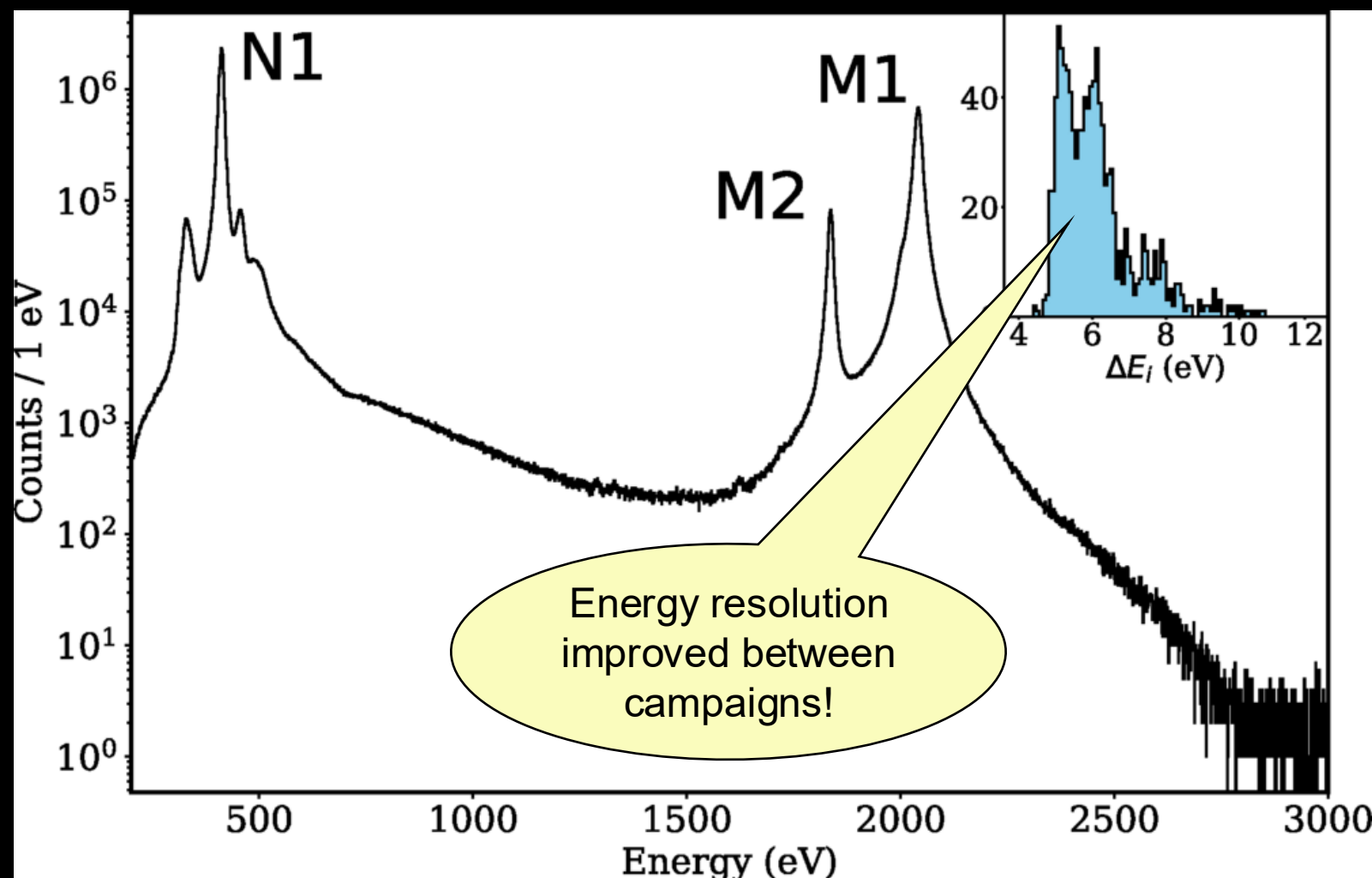
- ◆ TES readouts
- ◆  $\Delta E_{\text{FWHM}} \approx 7$  eV
- ◆  $\sim 0.3$  Bq per detector
- ◆ 64-pixel array
- ◆  $E_0 = 2848^{+7}_{-6}$  eV
- ◆  $m_\beta < 27$  eV @ 90% CI



HOLMES, PRL 135 (2025) 141801

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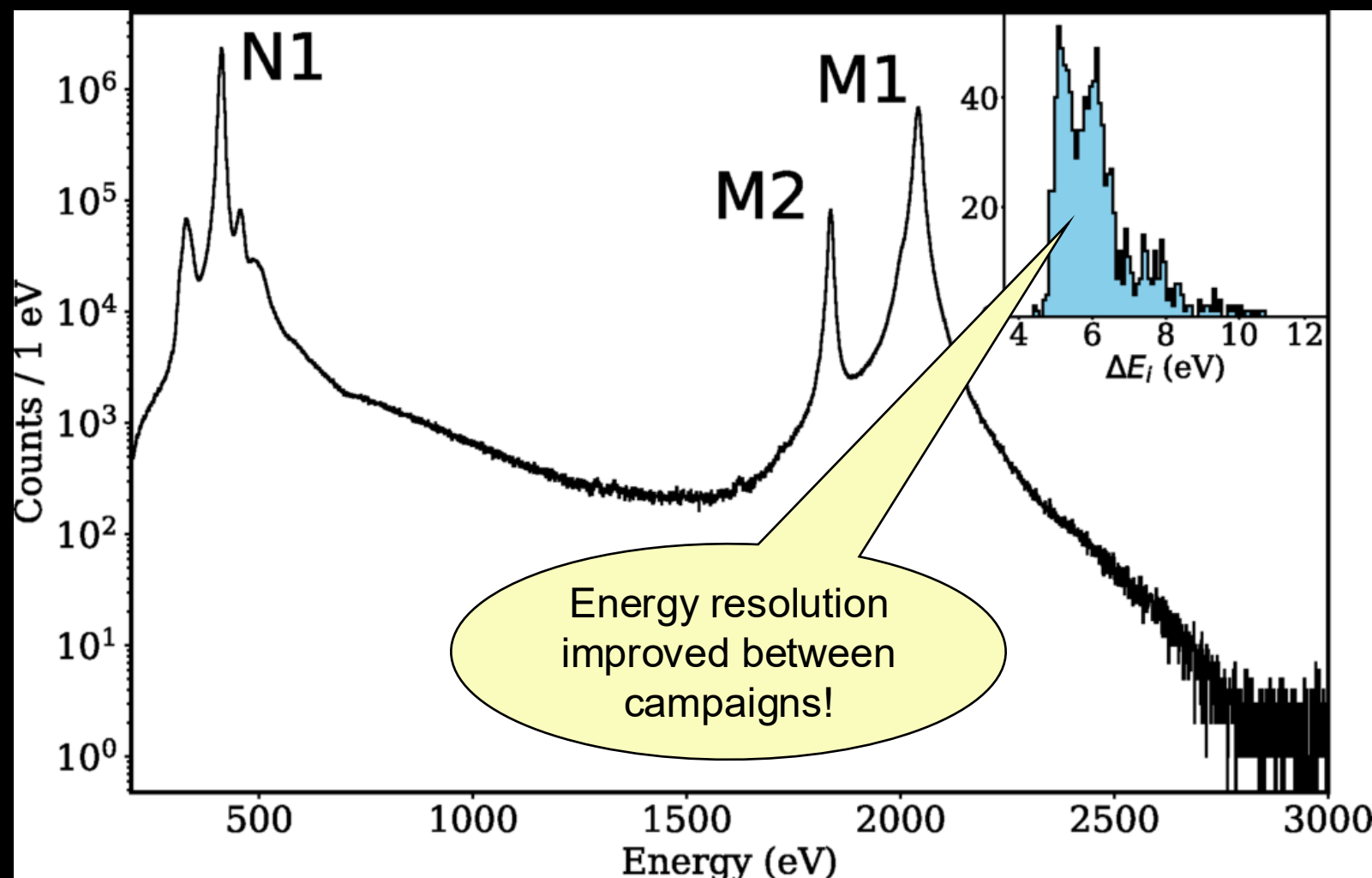
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HOLMES, PRL 135 (2025) 141801



# HOLMES's Future Plans

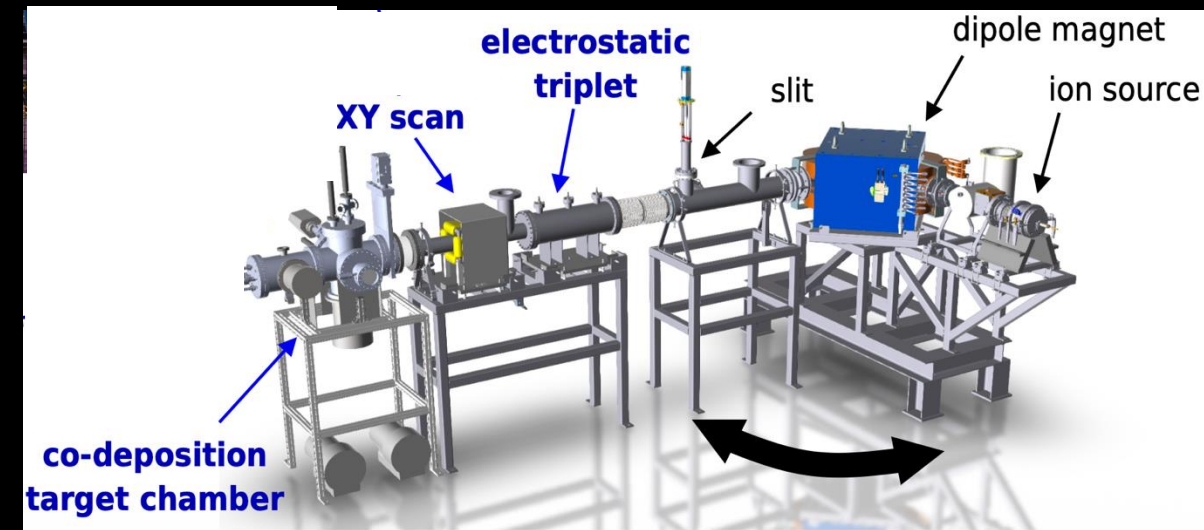
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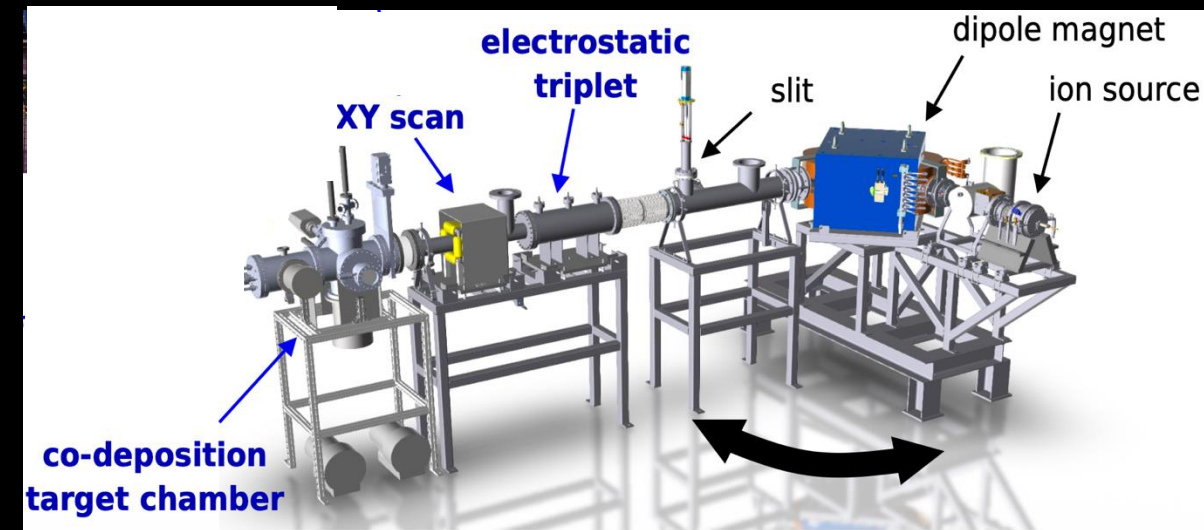
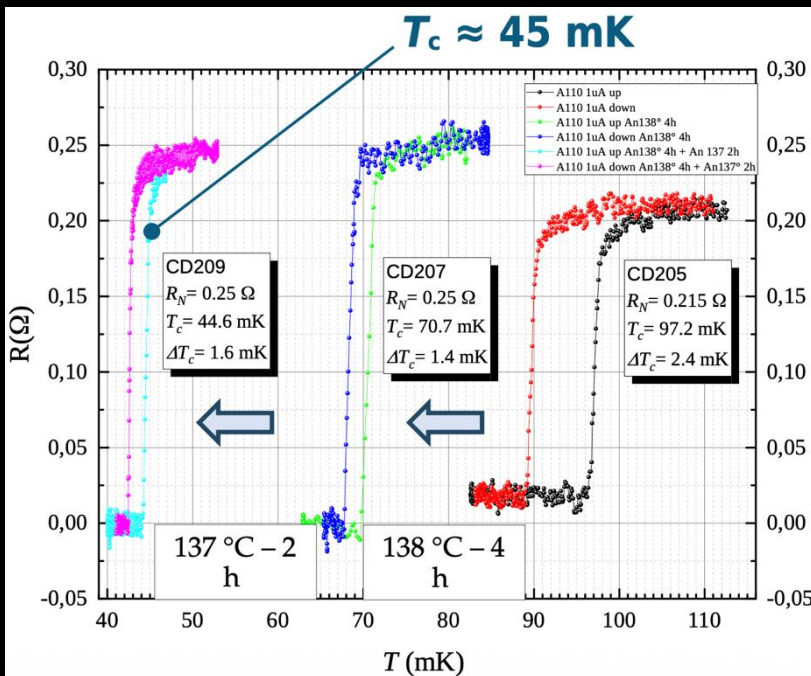
- ◆ Improve sensitivity via 3 main R&D thrusts:
  - ◆ Upgraded ion implanter
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  - ◆ Reduced DAQ/readout cost



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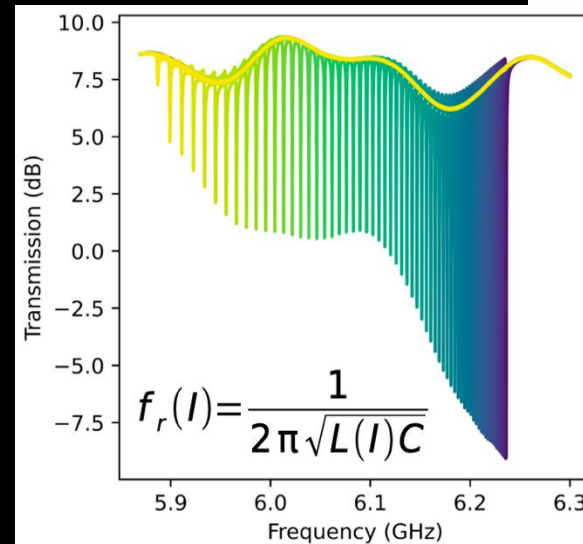
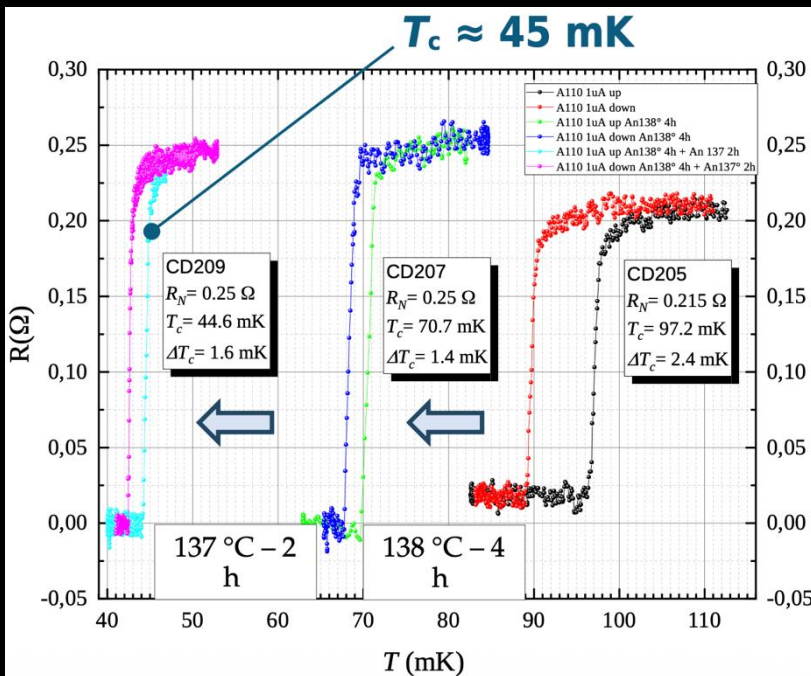
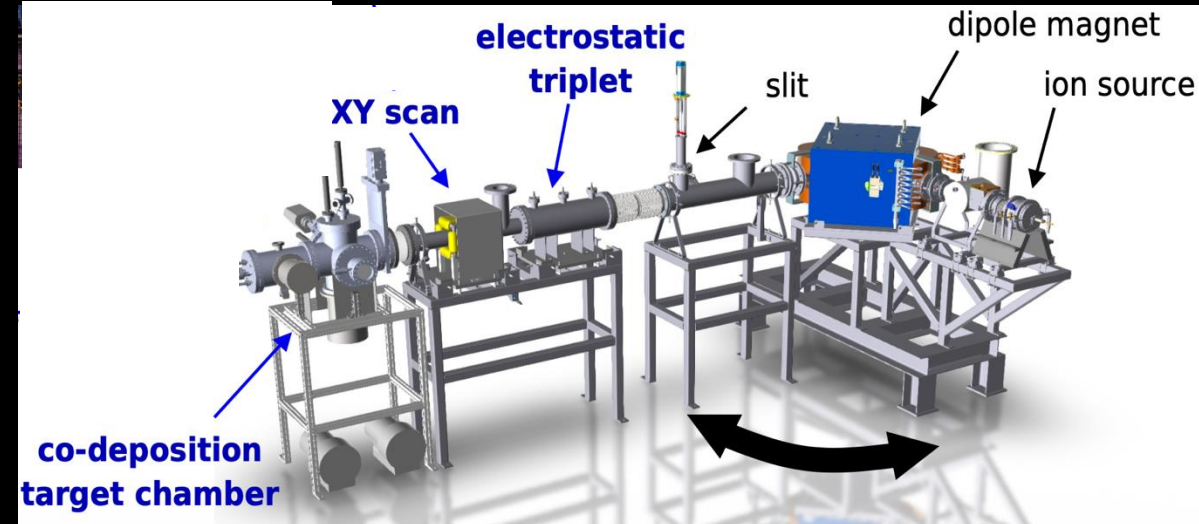


**Angelo Nucciotti**

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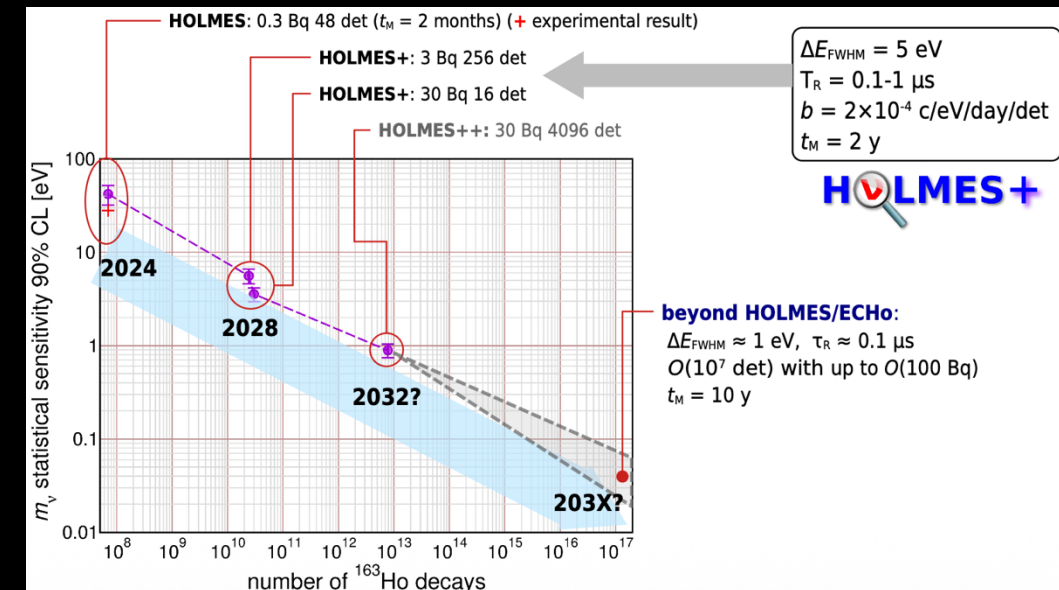
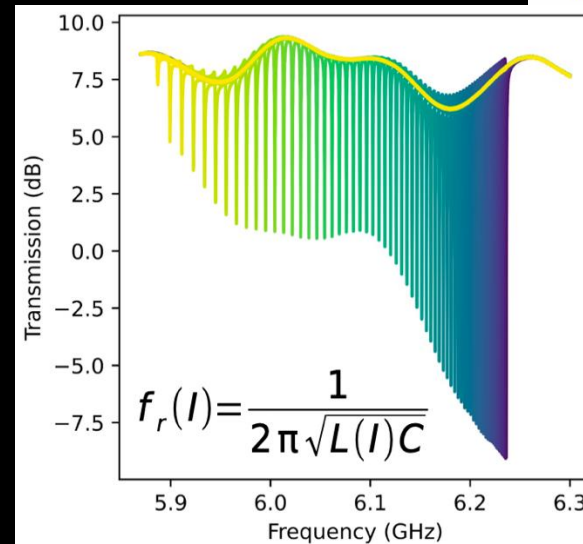
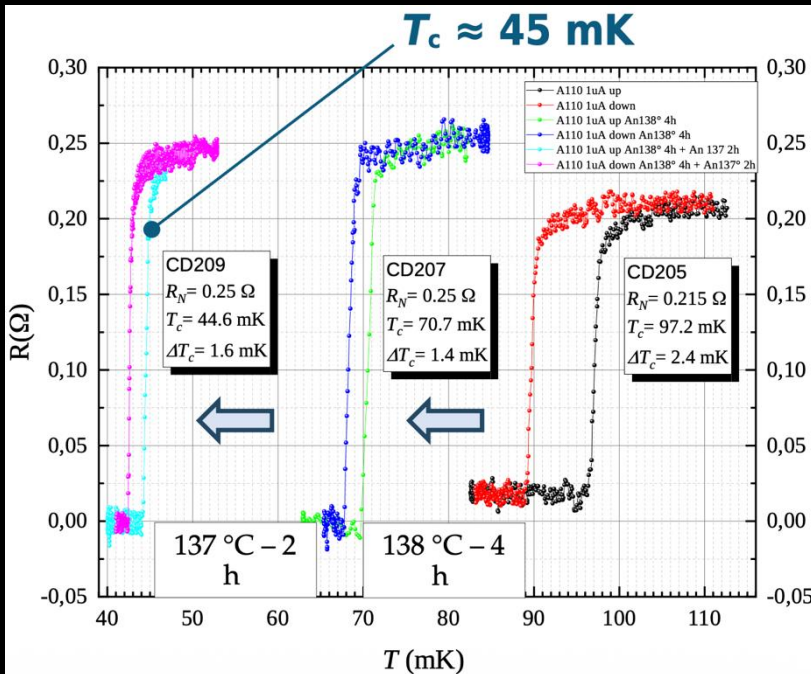
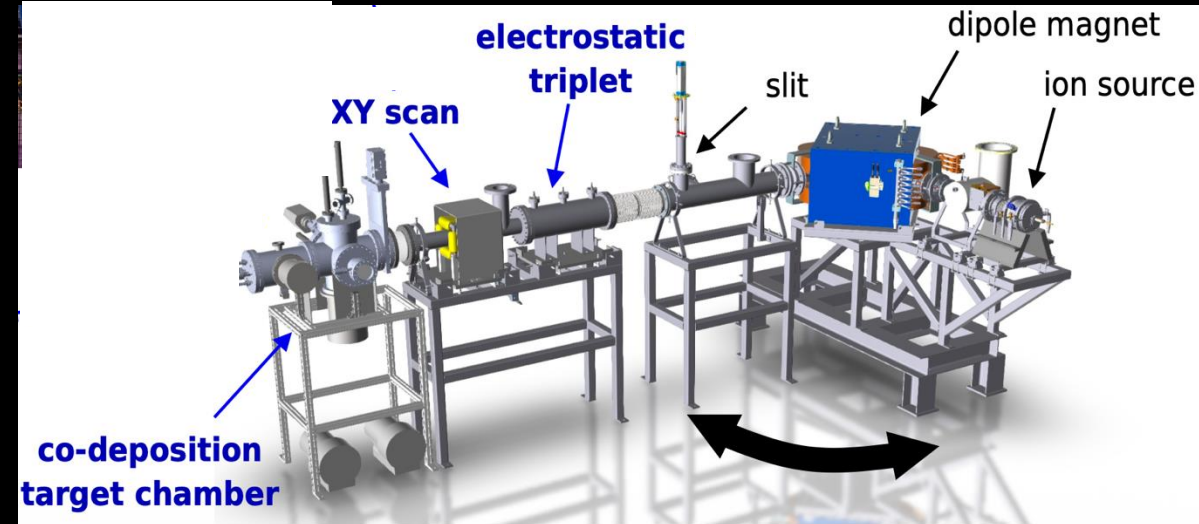
**Angelo Nucciotti**



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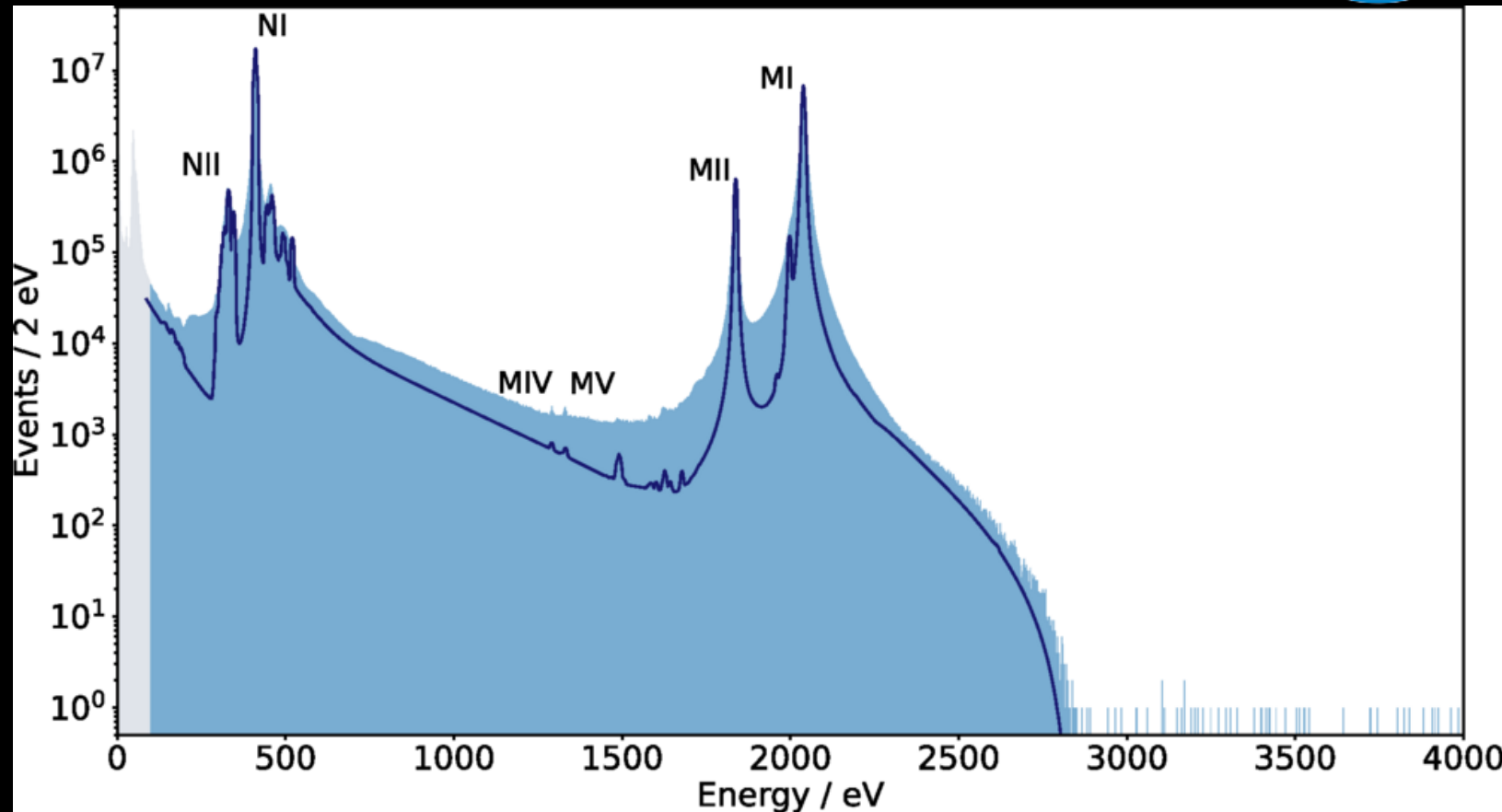


Angelo Nucciotti

# New Results: ECHo!

ECHo

- ◆ MMC readouts
- ◆ 57 pixels
- ◆ 46 Bq total  $^{163}\text{Ho}$  activity
- ◆ 9 background pixels
- ◆ 6 months' run
- ◆  $Q = 2862(4) \text{ eV}$
- ◆  $m_\nu < 15 \text{ eV}/c^2$  (90% C.I.)



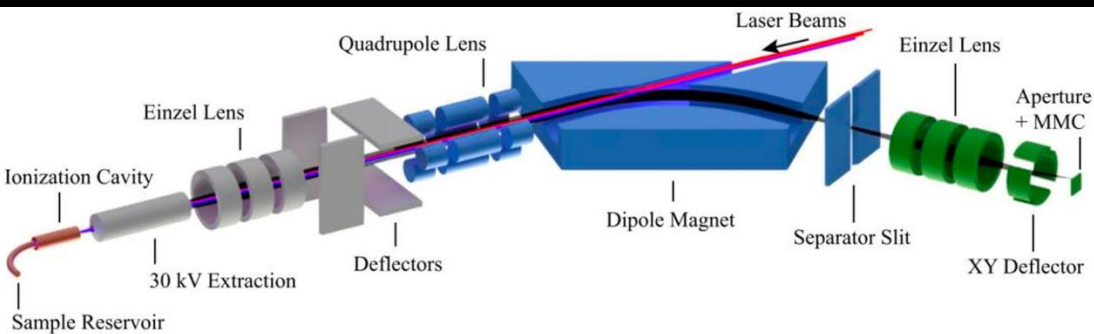
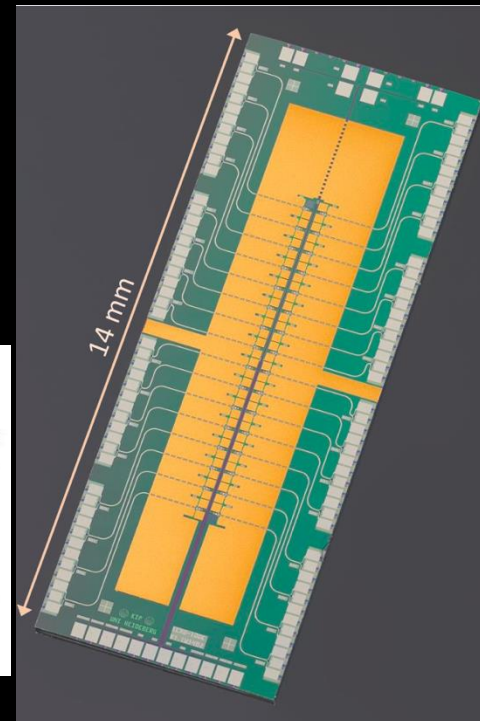
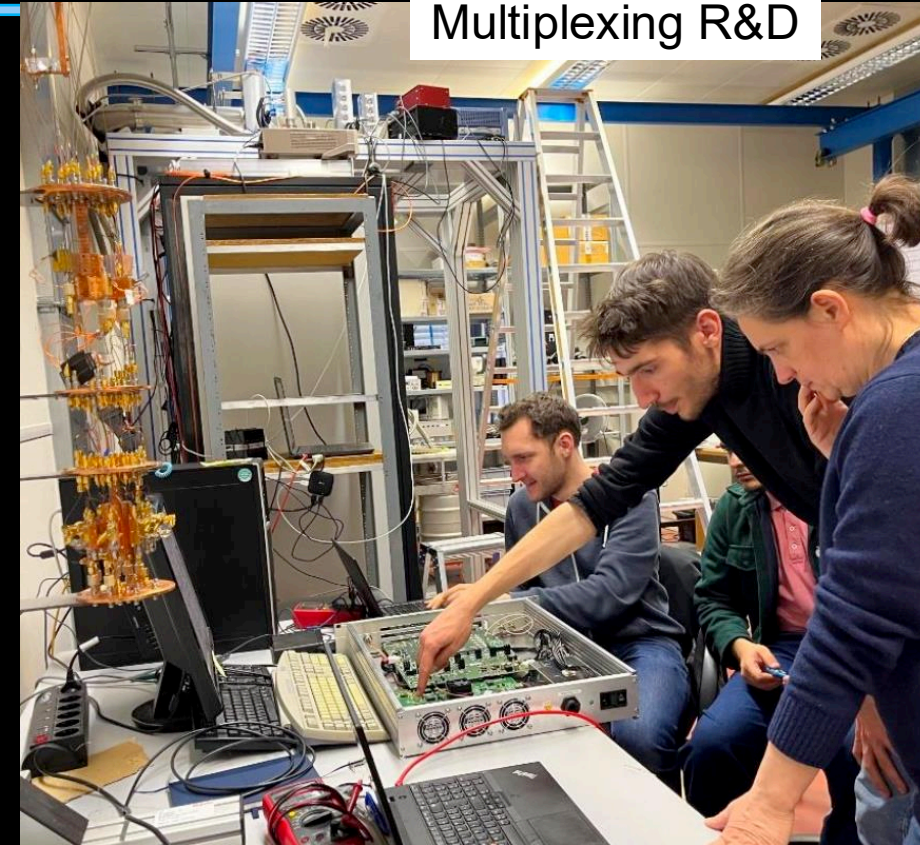
*ECHo, PRL 136 (2026) 121801*

# ECHo's Future Plans



- ◆ ECHo-LE (2026 - 2030) targets:
  - ◆ Activity per pixel  $\sim 10$  Bq/pixel
  - ◆ Number of detectors: 20000
    - ◆ do it all with 25 cryo readout lines!
  - ◆  $\Delta E_{\text{FWHM}} < 5$  eV
  - ◆  $f_{\text{pu}} < 10^{-6}$
  - ◆  $b < 10^{-6}$  /eV/detector/day

Multiplexing R&D



**Loredana Gastaldo**

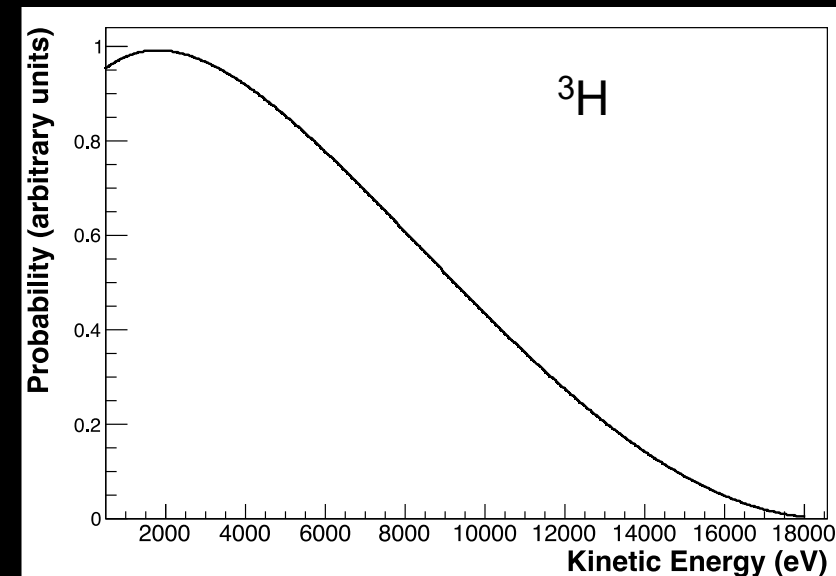
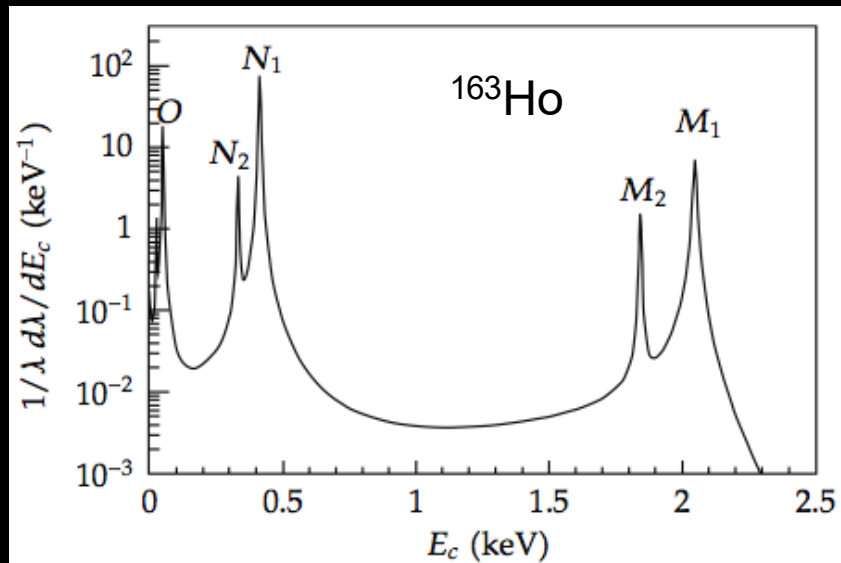


# The Plan

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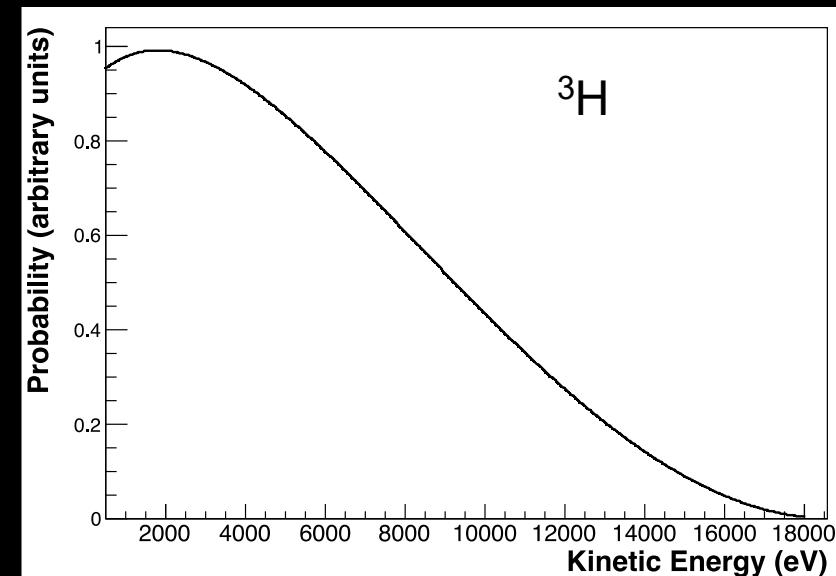
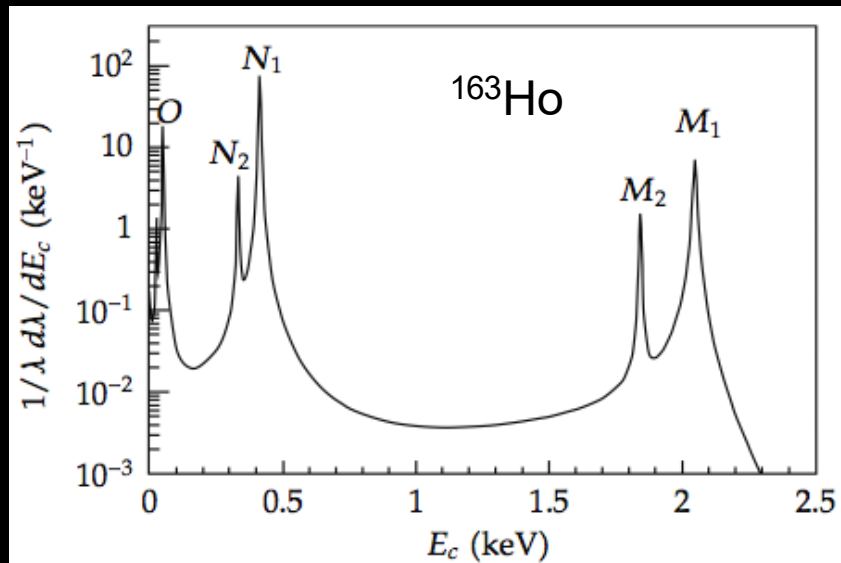
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# What Makes $^3\text{H}$ Different from $^{163}\text{Ho}$ ?



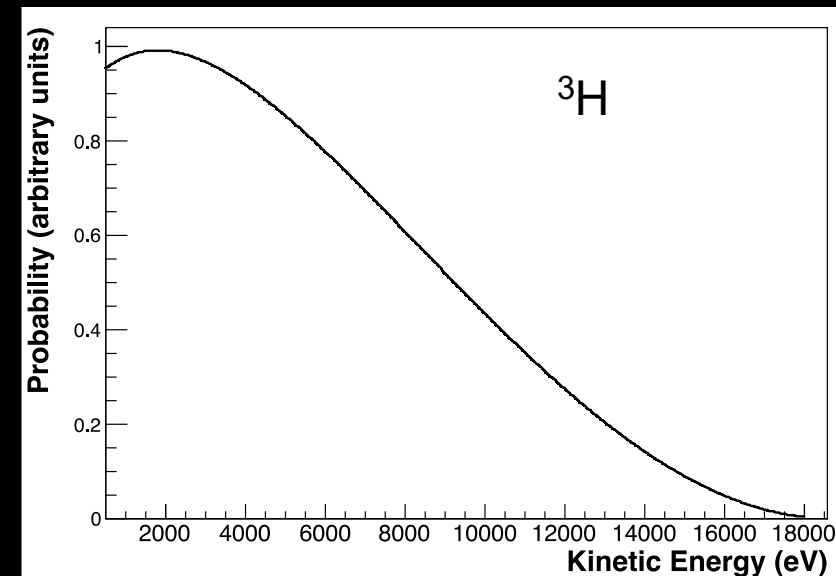
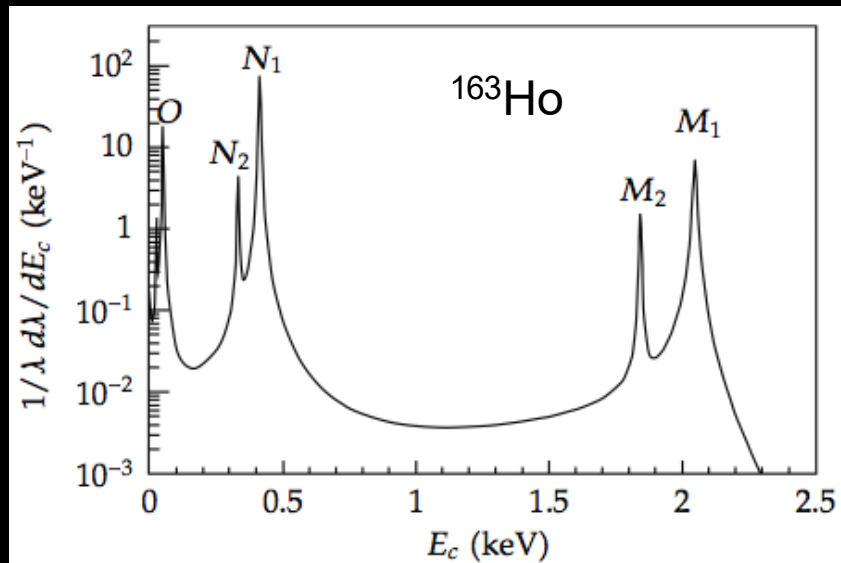
# What Makes $^3\text{H}$ Different from $^{163}\text{Ho}$ ?

- ◆  $\beta^-$  spectrum shape simpler than electron-capture spectrum
- ◆ At spectral tail, almost all energy is in motion of  $\beta$
- ◆ Shorter half-life
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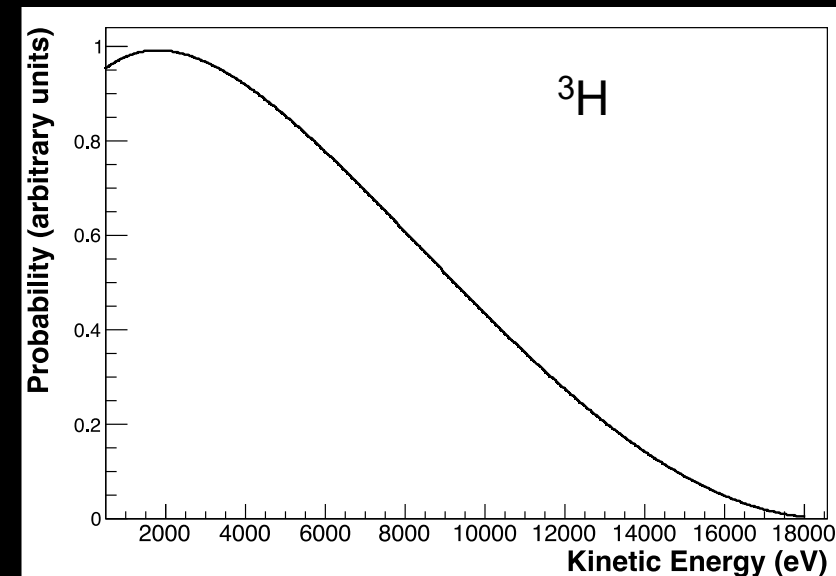
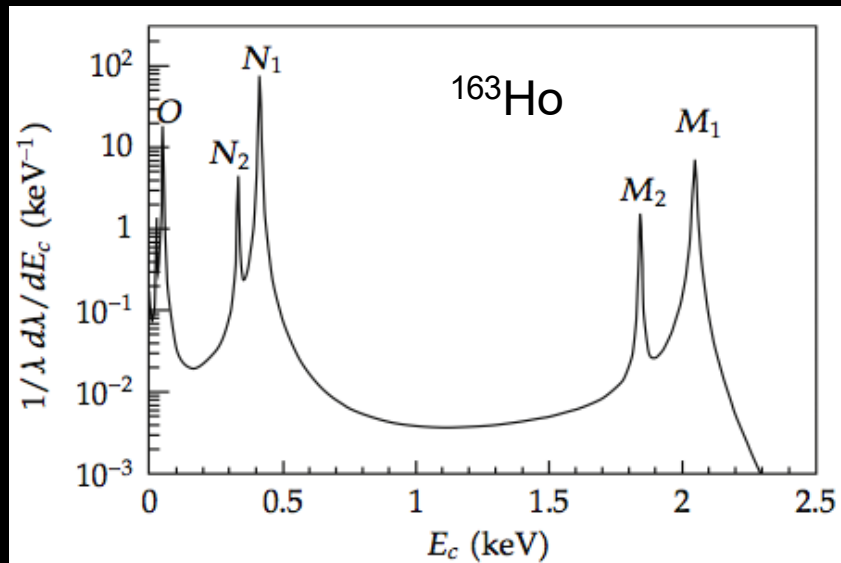
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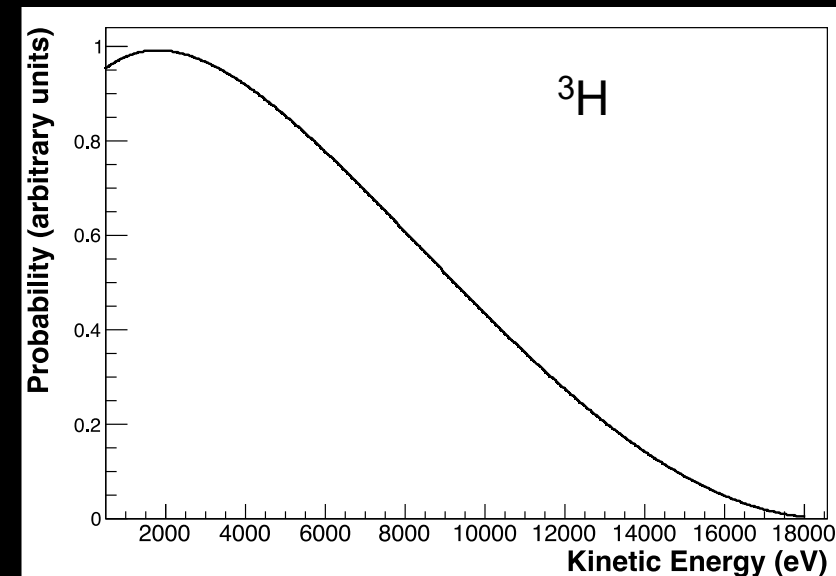
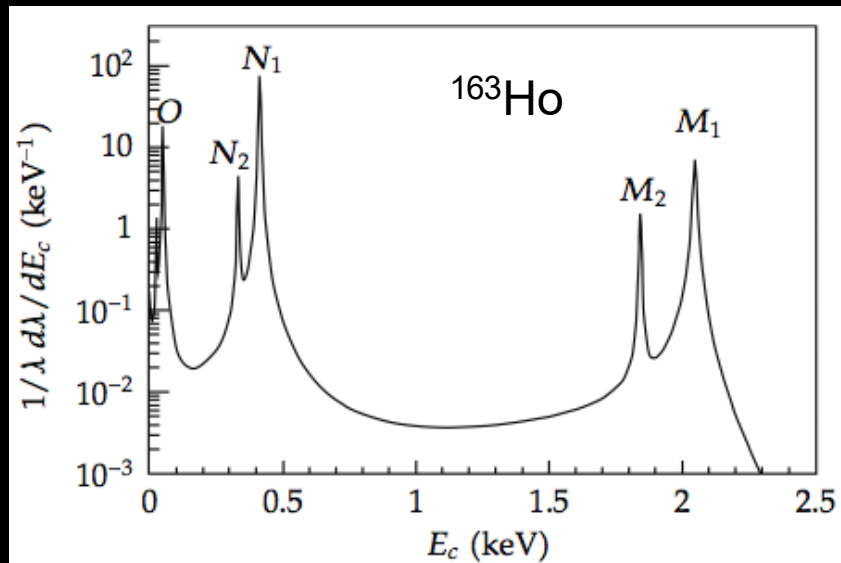
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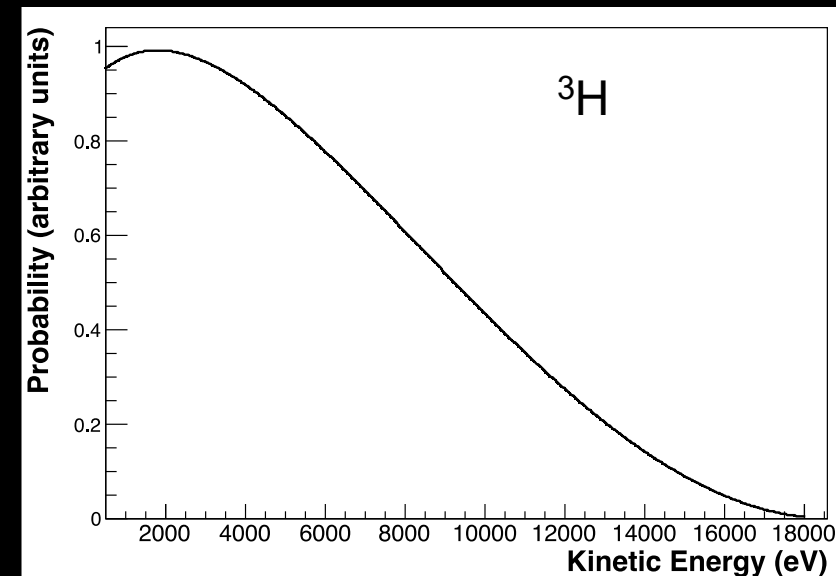
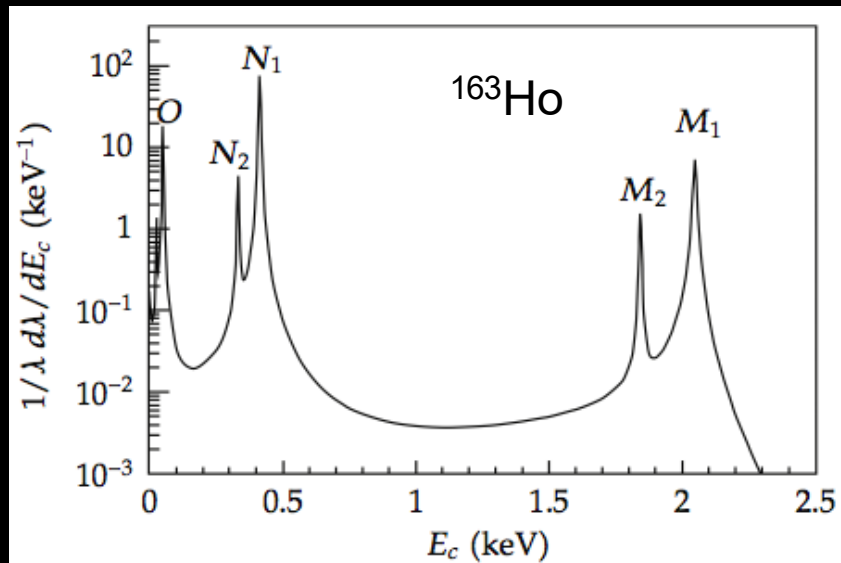
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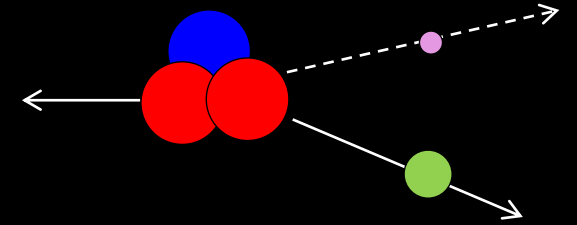
# Developing a Tritium Source

| Group              | Date | Source           |
|--------------------|------|------------------|
| Curran et al.      | 1948 | T <sub>2</sub>   |
| Hanna & Pontecorvo | 1949 | T <sub>2</sub>   |
| Curran et al.      | 1949 | T <sub>2</sub>   |
| Langer & Moffat    | 1952 | T:Succinic acid  |
| Hamilton et al.    | 1953 | T:Zr             |
| Salgo & Staub      | 1969 | T <sub>2</sub> O |
| Daris & St. Pierre | 1969 | T:Al             |
| Bergkvist          | 1972 | T:Al             |
| Röde & Daniel      | 1972 | T:Polystyrene    |
| ITEP               | 1980 | T:Valine         |
| Simpson            | 1981 | T:Si             |
| ITEP               | 1985 | T:Valine         |
| Zurich             | 1986 | T:C              |
| ITEP               | 1987 | T:Valine         |
| LANL               | 1987 | T <sub>2</sub>   |
| INS Tokyo          | 1988 | T:CdArachidate   |
| INS Tokyo          | 1991 | T:CdArachidate   |
| LANL               | 1991 | T <sub>2</sub>   |
| Zurich             | 1992 | T:C              |
| Mainz              | 1993 | T <sub>2</sub>   |
| Troitsk            | 1994 | T <sub>2</sub>   |

- ◆ Embedding decaying tritium in a metal or a large molecule makes it easier to work with
- ◆ Eventually, molecular physics around the decaying nucleus becomes important
- ◆ Drive toward simple molecules!

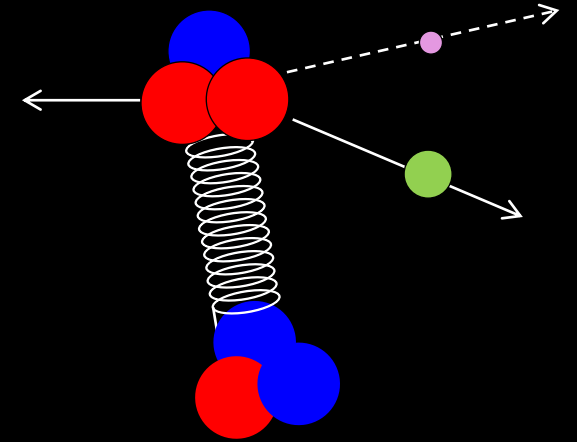
# Molecular Final-State Distribution

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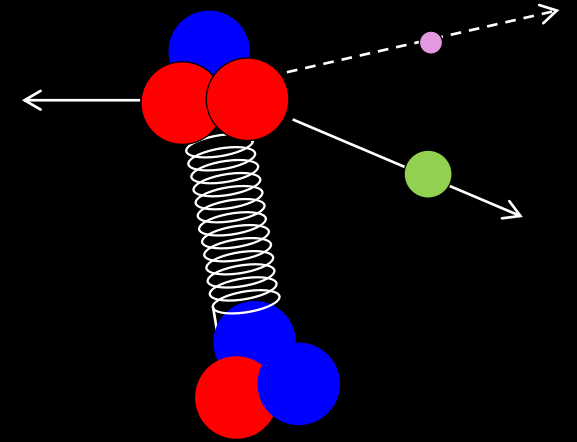
# Molecular Final-State Distribution

- ◆ Electronic excitations in T atoms
- ◆ Excitations in T<sub>2</sub> gas
  - ◆ Electronic: 20 eV
  - ◆ Vibrational: ~0.1 eV
  - ◆ Rotational: ~0.01 eV
- ◆ Beta spectrum depends on excitation energies  $V_k$  and probabilities  $P_k$



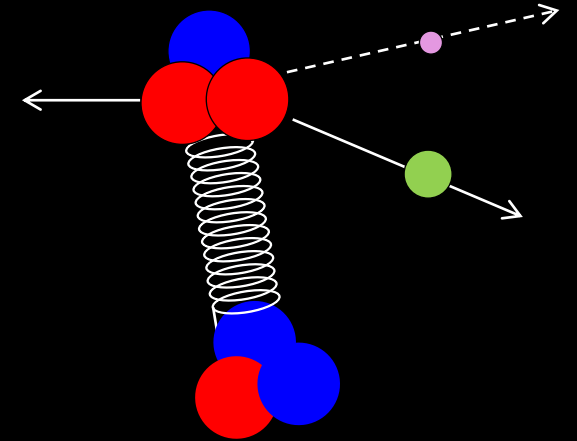
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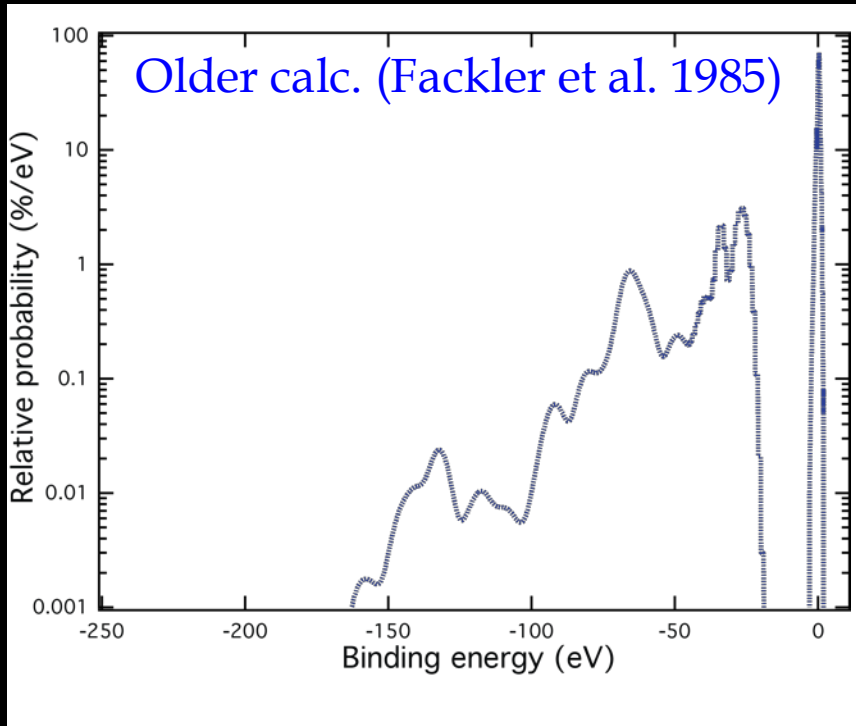
$$\frac{d\Gamma}{dE} = \frac{G_F^2 |V_{ud}|^2}{2\pi^3} |M|^2 F(Z, \beta) \beta(E + m_e)^2 (E_0 - E) \times \sum_{i=1}^3 \sum_{k=1} |U_{ei}|^2 P_k \sqrt{(E_0 - E - V_k)^2 - m_i^2} \times \Theta(E_0 - E - V_k - m_i)$$

# LANL, LLNL and the FSD

- ◆ Any mistake in the FSD variance will shift the mass observable:

$$\Delta m_\nu^2 \approx -2\sigma^2$$

*Robertson and Knapp, Annu. Rev. Nucl. Part. Sci 38, 185 (1988)*

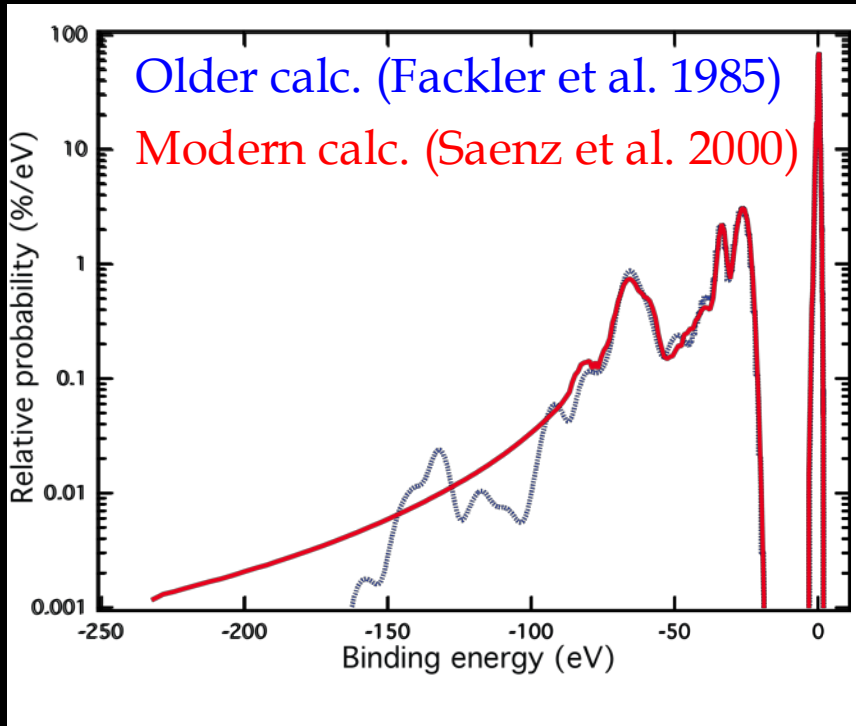


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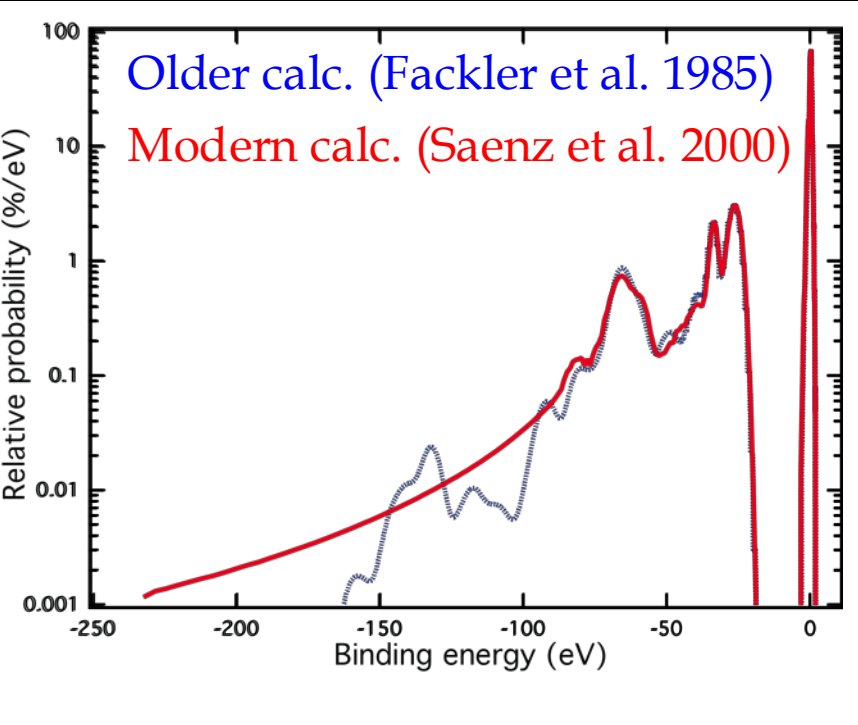


TABLE IX. Atomic mass difference and neutrino mass squared extracted from two experiments, in one case with the original 1985 theoretical calculations of the FSD and in the second case with a more modern calculation.

|                                                         | LANL [15]    | LLNL [16]    |
|---------------------------------------------------------|--------------|--------------|
| <b>As published.</b> Theory: Fackler <i>et al.</i> [59] |              |              |
| $\Delta_{00}$ (eV)                                      | 18 570.5(20) | 18 568.5(20) |
| $Q_A$ (eV)                                              | 18 588.6(20) | 18 586.6(25) |
| $m_\nu^2$ (eV <sup>2</sup> )                            | −147(79)     | −130(25)     |
| <b>Re – evaluated.</b> Theory: Saenz <i>et al.</i> [8]  |              |              |
| $\Delta_{00}$ (eV)                                      | 18 571.2(20) | 18 569.2(20) |
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Bodine, DP, Robertson, *Phys. Rev. C* **91**, 035505 (2015)

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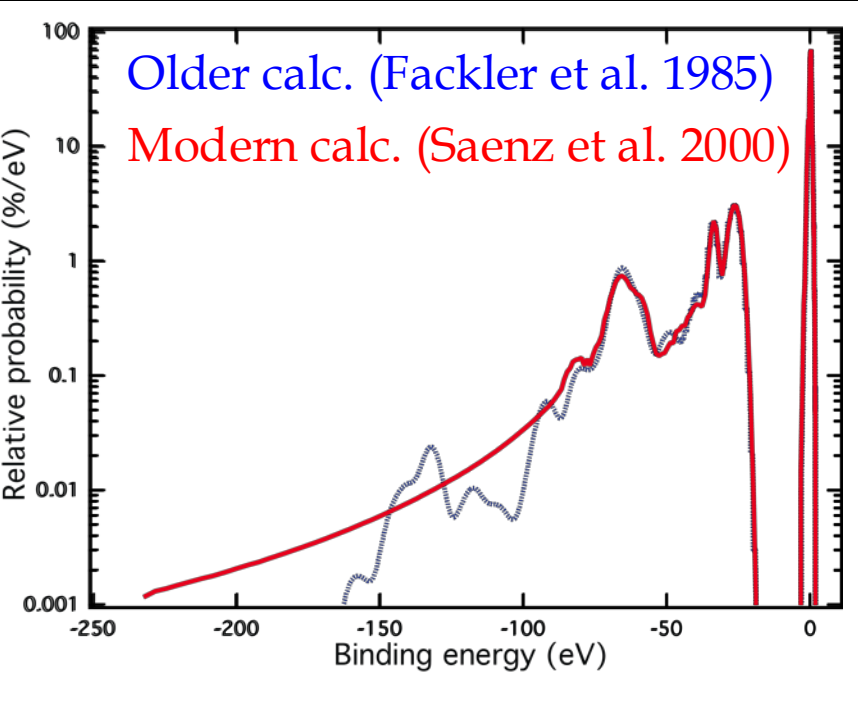


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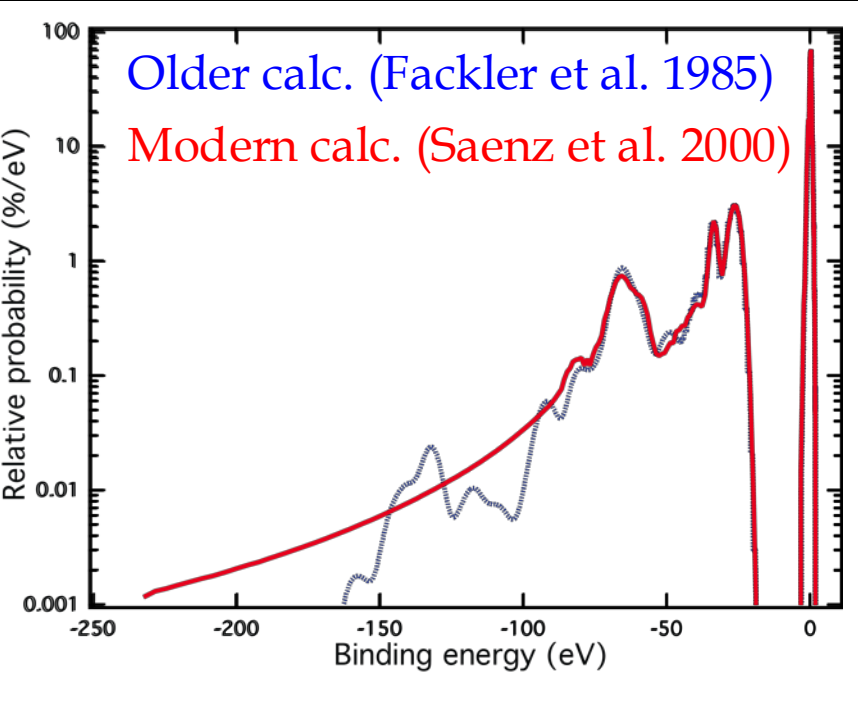


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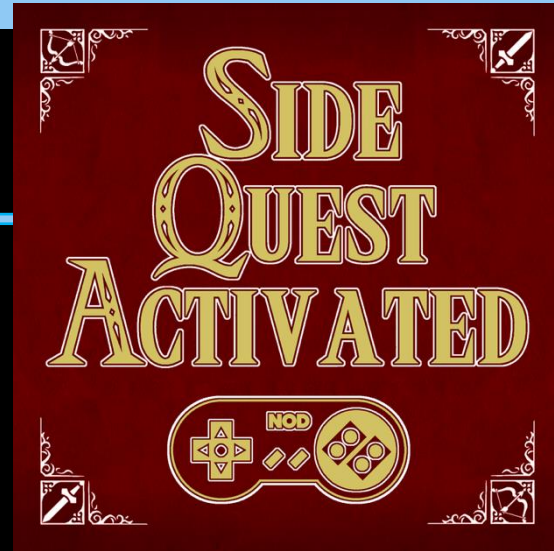
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# Is the Newer Theory Right?

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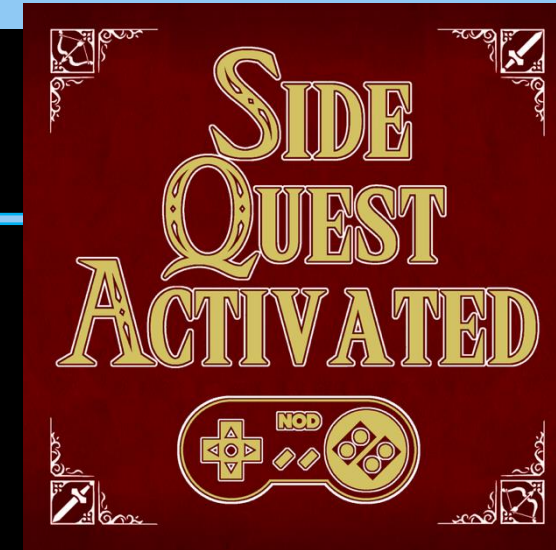
*Schneidewind et al., Eur. Phys. J. C 84 (2024) 494*



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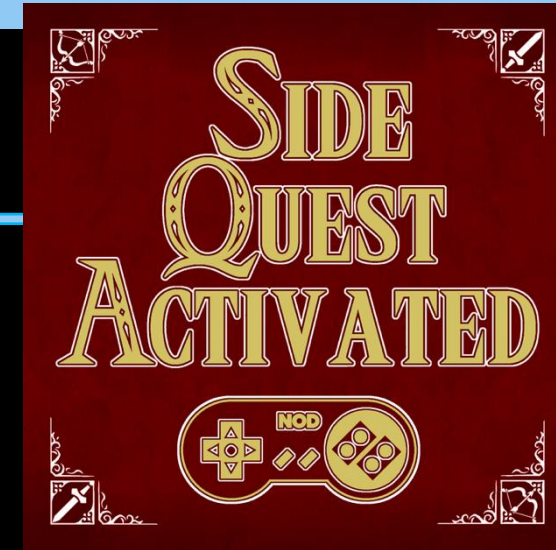
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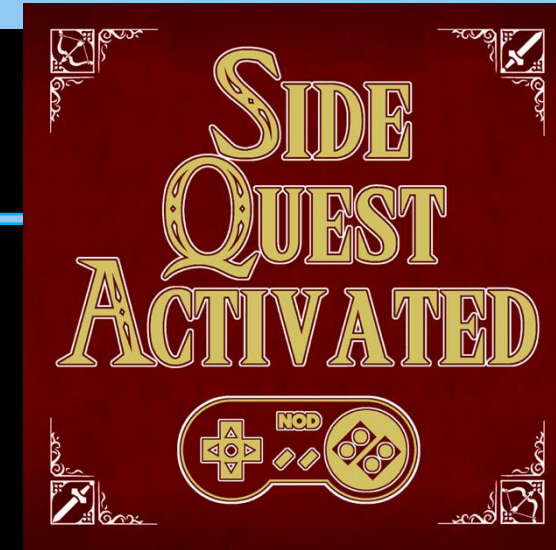
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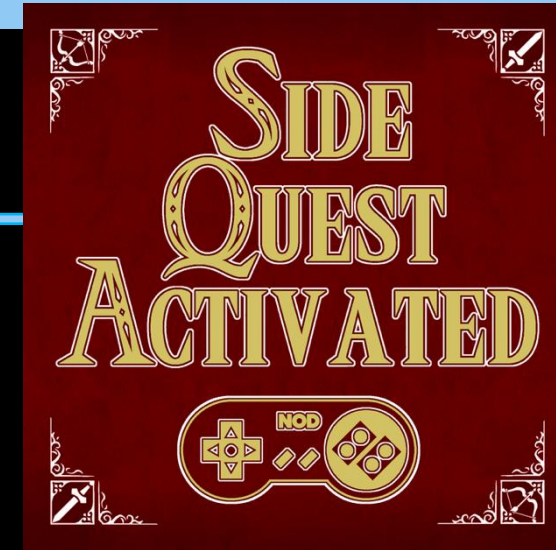




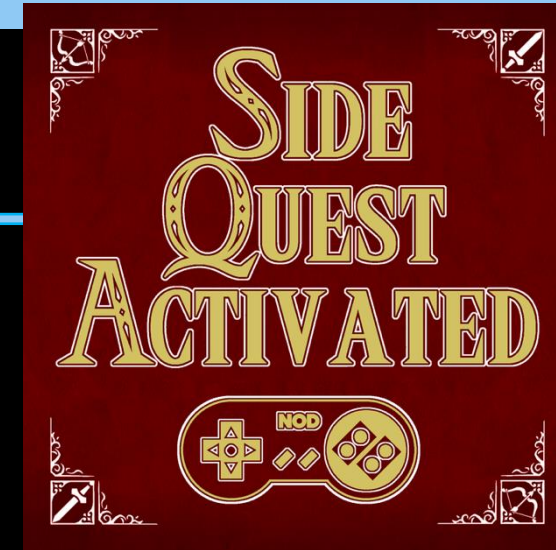
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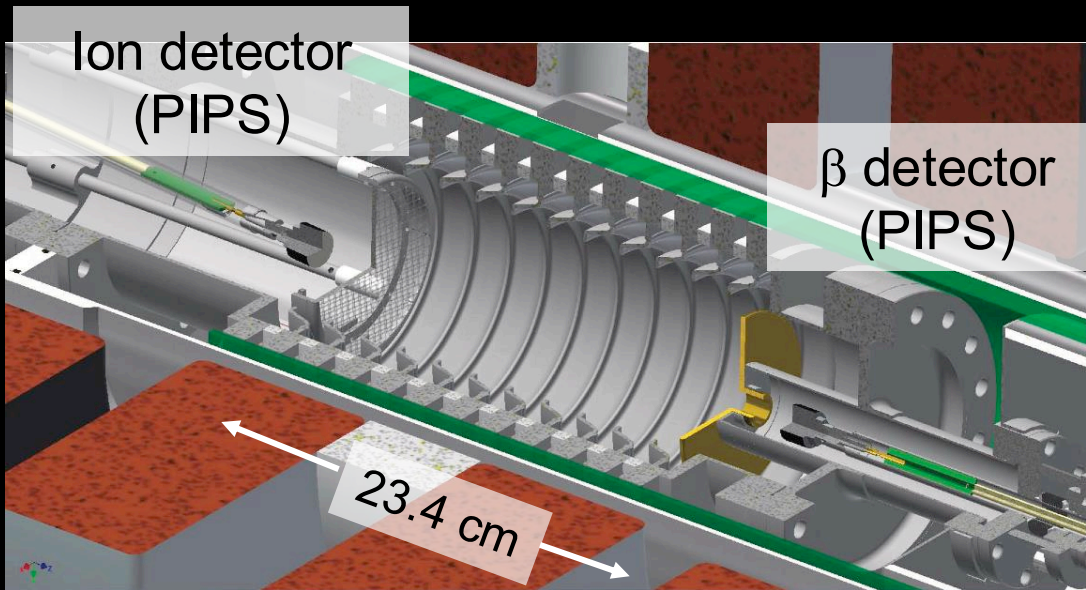
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|                | Theory                                                     | Snell Experiment*                                                             | Wexler Experiment*                                    |
|----------------|------------------------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------|
| HT             | 0.55 – 0.57                                                | $0.932 \pm 0.019$                                                             | $0.895 \pm 0.011$                                     |
| T <sub>2</sub> | 0.39 – 0.57                                                |                                                                               | $0.945 \pm 0.006$                                     |
|                | <i>Jonsell, Saenz, Froelich,<br/>PRC 60, 034601 (1999)</i> | <i>Snell, Pleasanton, Leming,<br/>J. Inorg. Nucl. Chem. 5, 112<br/>(1957)</i> | <i>Wexler, J. Inorg. Nucl.<br/>Chem. 10, 8 (1958)</i> |

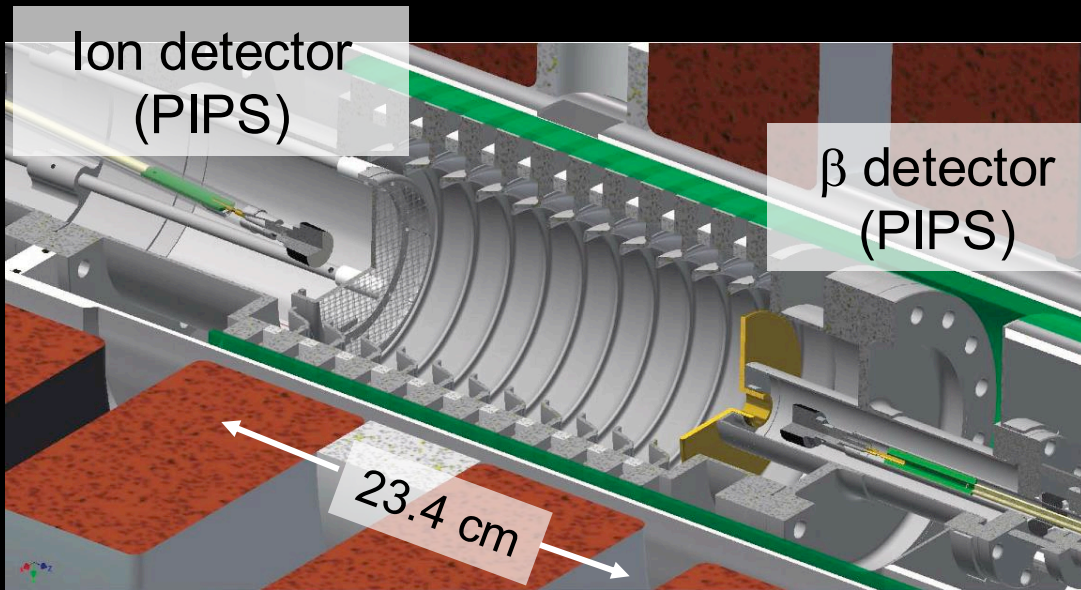
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- Coincidence detection of  $\beta$ , ion
- Uniform acceleration gradient and guiding 0.2 T magnetic field
- Pressure  $\sim 3 \times 10^{-8}$  mbar to avoid charge exchange and recombination
- Ion-mass measurement through kinematics



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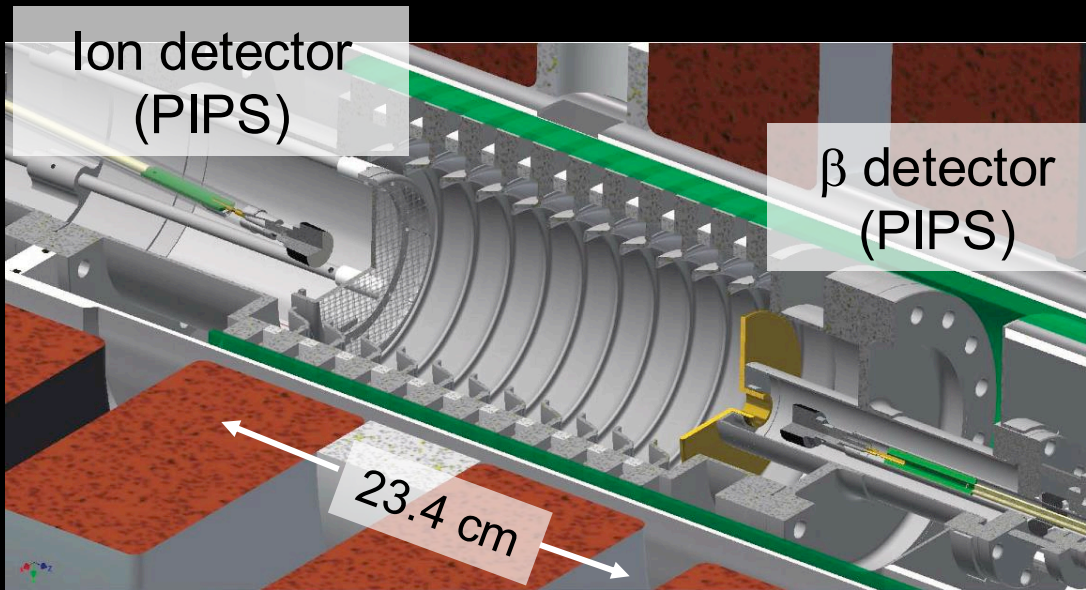


$$\frac{m}{q^2} = t^2 \frac{E^2}{2K_{ion}}$$



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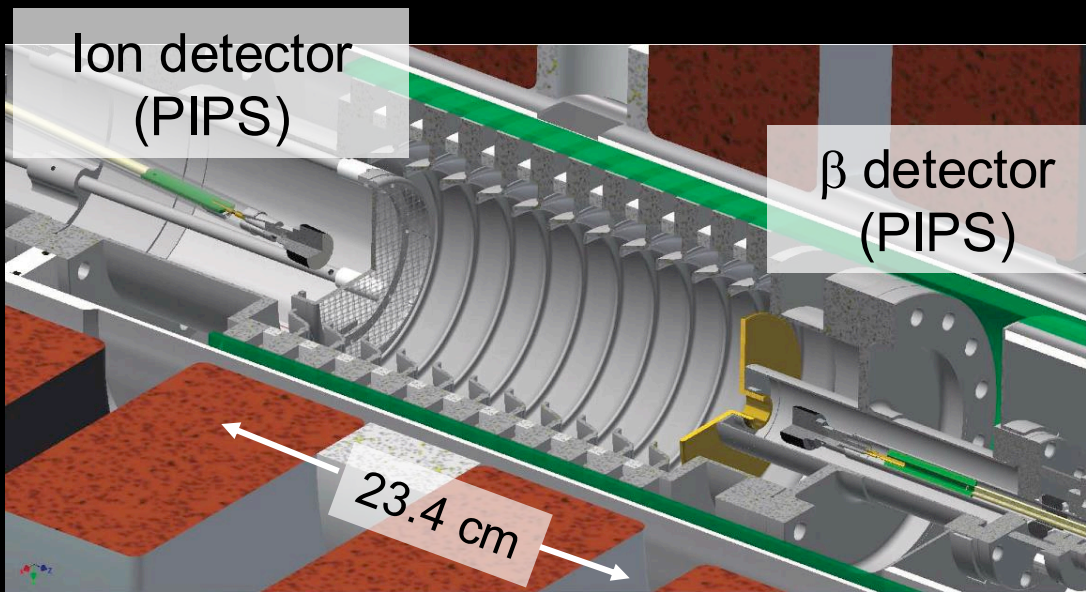
Ion mass

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Ion charge

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Ion mass

Ion time of flight (relative to  $\beta$ )

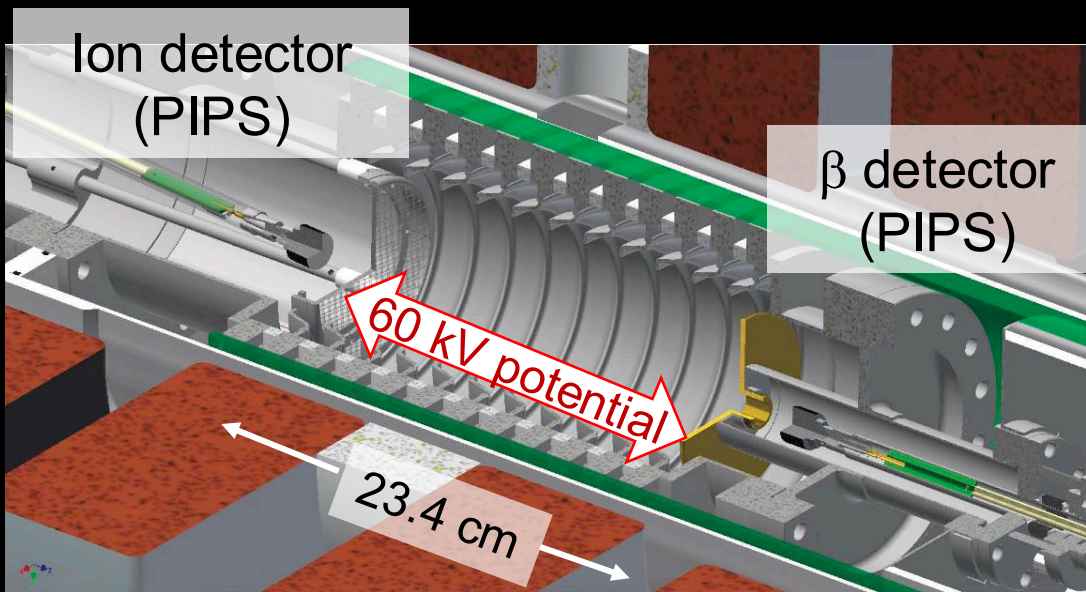
Ion charge

Final ion kinetic energy

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Ion mass

Ion time of flight (relative to  $\beta$ )

Uniform electric field

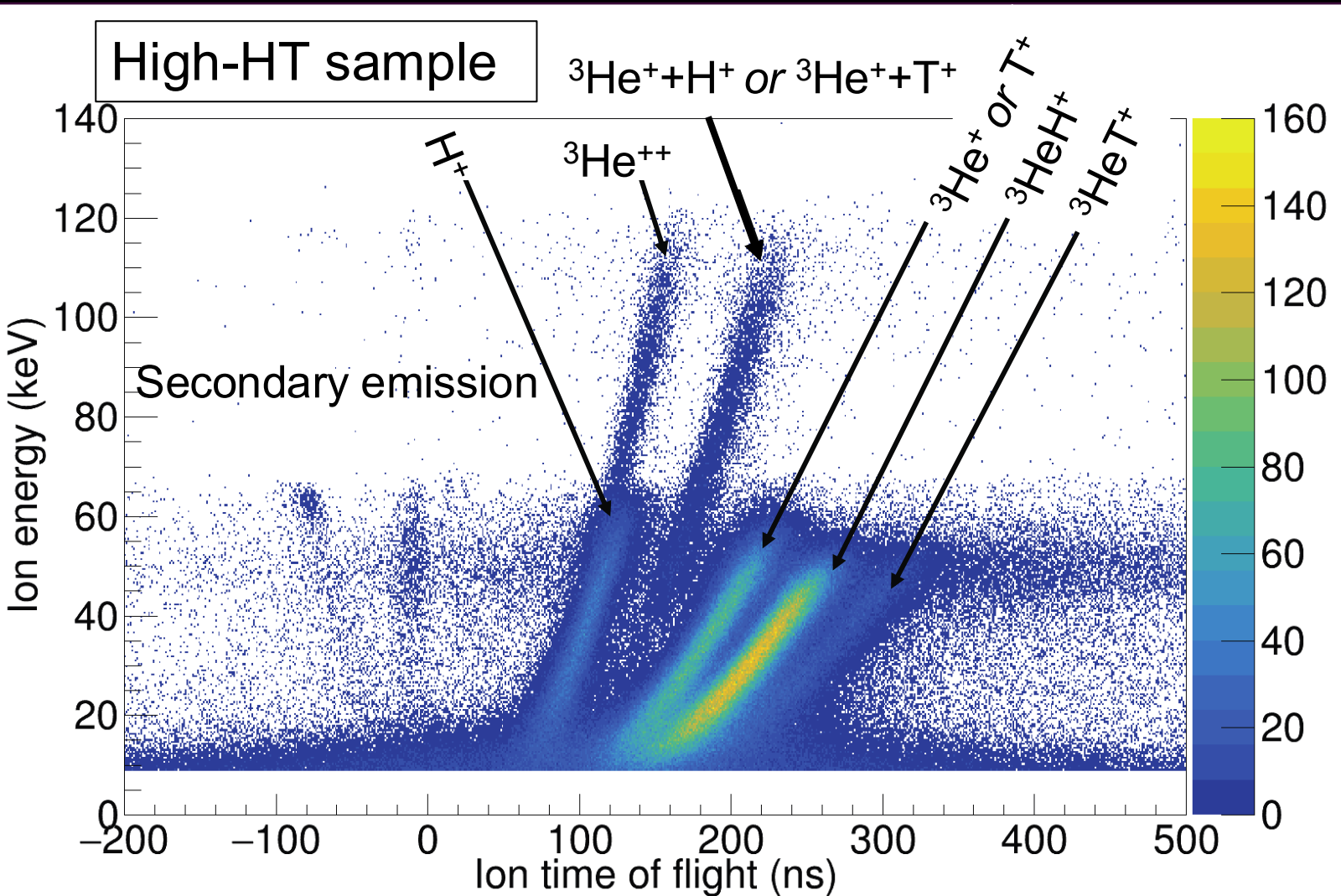
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# TRIMS Results Support Theory

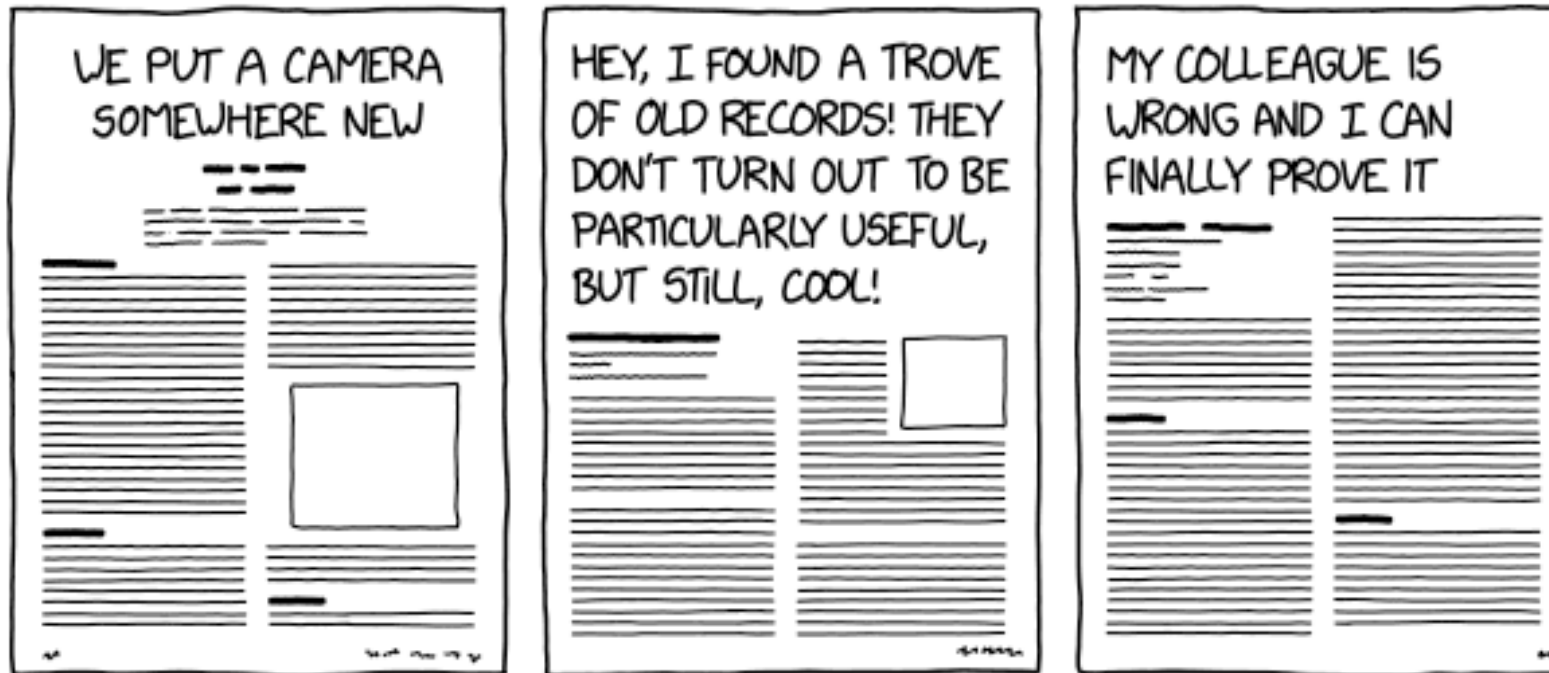


- ◆ Theory for HT and  $T_2$  is the same
- ◆ Even by eye you can see the bound molecule is much closer to 50% than 90%
- ◆ (Final analysis, especially of  $T_2$  data set, is still ongoing)

Lin et al., PRL 124, 222502 (2020)

# What Went Wrong in the 1950s?

## TYPES OF SCIENTIFIC PAPER

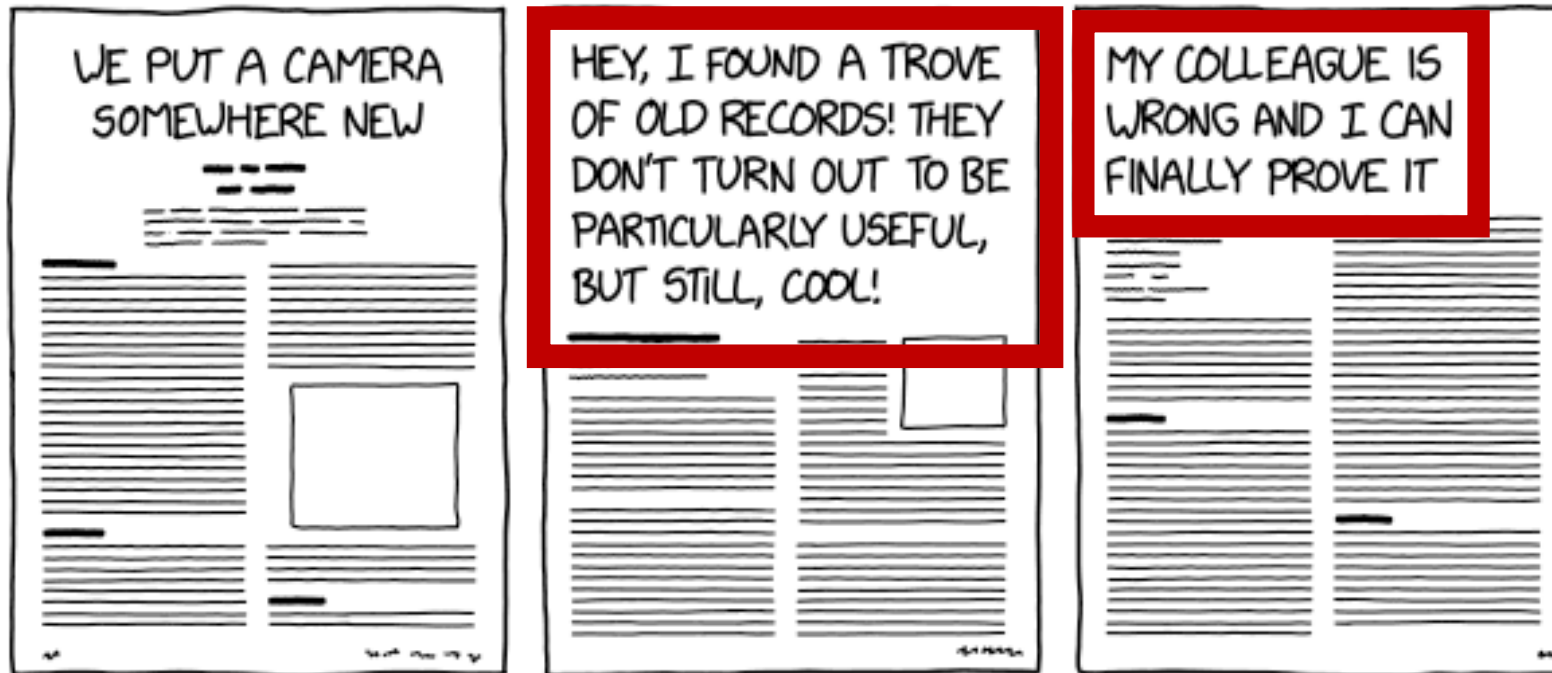


*xkcd*



# What Went Wrong in the 1950s?

## TYPES OF SCIENTIFIC ~~PAPER~~ TALK



xkcd



# It Isn't Only HT and TT

- ◆ Other measurements by Snell, Pleasanton and Wexler, where theory predictions now exist





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- ◆ Other measurements by Snell, Pleasanton and Wexler, where theory predictions now exist



| Parent                            | Decay Product                                        | Exp. $P_{\text{bound}}$ | Th. $P_{\text{g.s.}}$  |
|-----------------------------------|------------------------------------------------------|-------------------------|------------------------|
| HT                                | ${}^3\text{HeH}^+$                                   | 0.932(19)<br>0.895(11)  | 0.55-0.57              |
| TT                                | ${}^3\text{HeT}^+$                                   | 0.945(6)                | 0.39-0.57              |
| $\text{CH}_3\text{T}$             | $\text{CH}_3^+$                                      | 0.833(15)               | 0.62<br>0.578<br>0.616 |
| ${}^{14}\text{CO}_2$              | $\text{NO}_2^+$                                      | 0.814(6)                | 0.6715                 |
| p- $\text{C}_3\text{H}_7\text{T}$ | $\text{C}_3\text{H}_7^+$<br>$\text{C}_3\text{H}_5^+$ | 0.410(8)<br>0.290(14)   | 0.32<br>0.21           |
| s- $\text{C}_3\text{H}_7\text{T}$ | $\text{C}_3\text{H}_7^+$<br>$\text{C}_3\text{H}_5^+$ | 0.560(11)<br>0.070(7)   | 0.47<br>0.05           |

| Parent                                    | Decay Product            | Exp. $P_{\text{bound}}$ | Th. $P_{\text{g.s.}}$ |
|-------------------------------------------|--------------------------|-------------------------|-----------------------|
| o- $\text{C}_6\text{H}_4\text{TCH}_3$     | $\text{C}_7\text{H}_7^+$ | 0.78                    | 0.54                  |
| m- $\text{C}_6\text{H}_4\text{TCH}_3$     | $\text{C}_7\text{H}_7^+$ | 0.79                    | 0.54                  |
| p- $\text{C}_6\text{H}_4\text{TCH}_3$     | $\text{C}_7\text{H}_7^+$ | 0.76                    | 0.54                  |
| $\text{C}_6\text{H}_5\text{CH}_2\text{T}$ | $\text{C}_7\text{H}_7^+$ | 0.79                    | 0.52                  |

# It Isn't Only HT and TT

- ◆ Other measurements by Snell, Pleasanton and Wexler, where theory predictions now exist

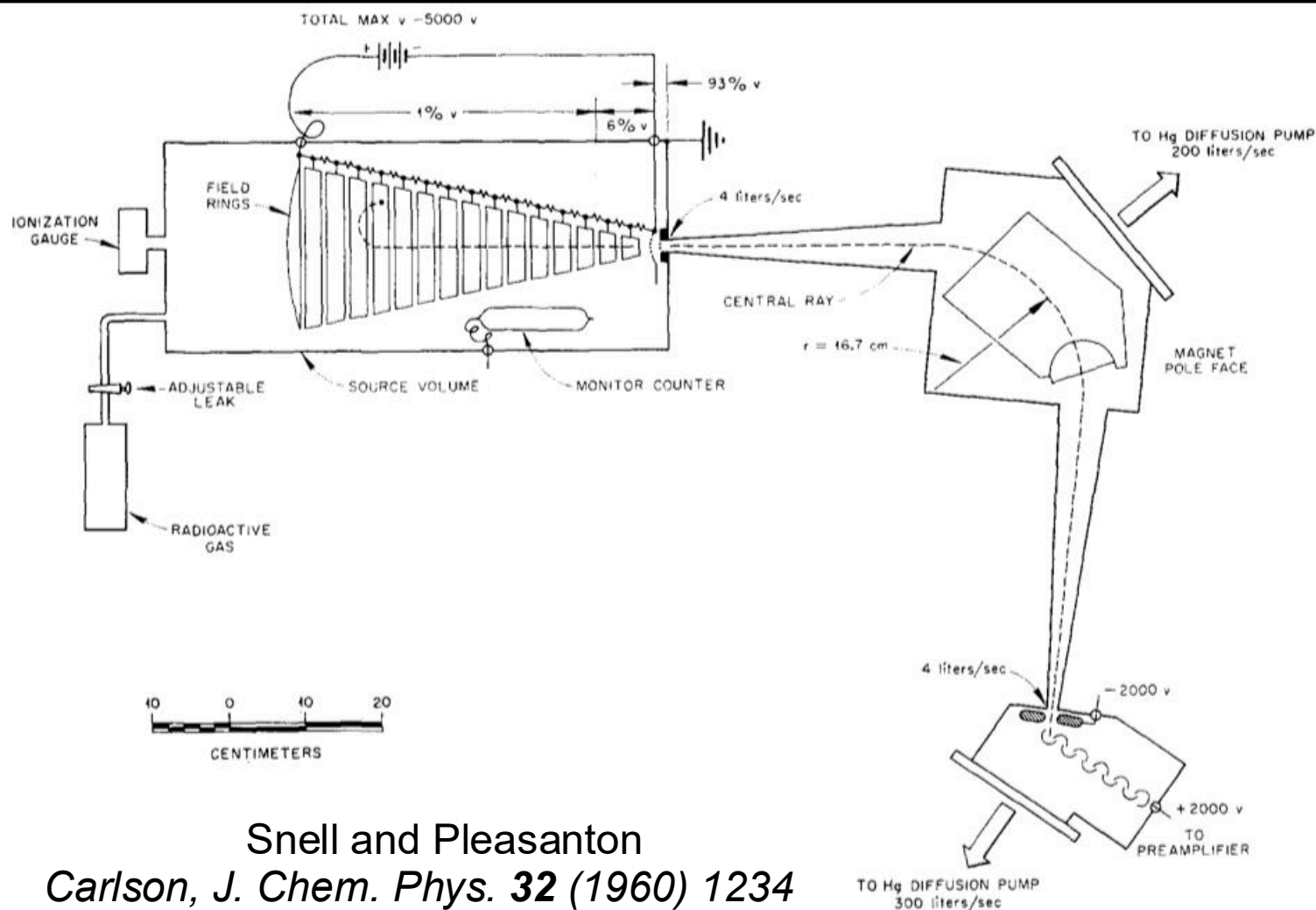


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| s- $\text{C}_3\text{H}_7\text{T}$ | $\text{C}_3\text{H}_7^+$<br>$\text{C}_3\text{H}_5^+$ | 0.560(11)<br>0.070(7)   | 0.47<br>0.05           |

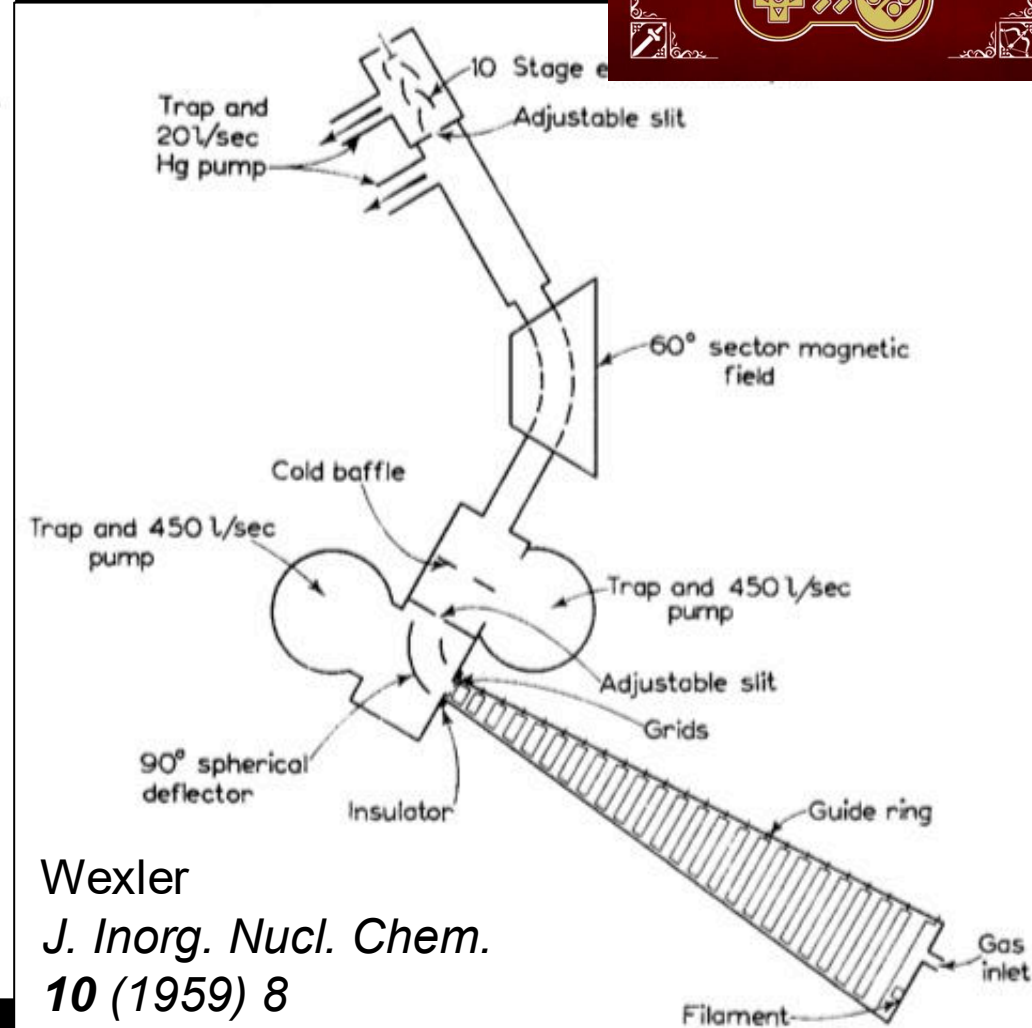
Theory predicts  $P_{\text{bound}}$

| Parent                                    | Decay Product            | Exp. $P_{\text{bound}}$ | Th. $P_{\text{g.s.}}$ |
|-------------------------------------------|--------------------------|-------------------------|-----------------------|
| o- $\text{C}_6\text{H}_4\text{TCH}_3$     | $\text{C}_7\text{H}_7^+$ | 0.78                    | 0.54                  |
| m- $\text{C}_6\text{H}_4\text{TCH}_3$     | $\text{C}_7\text{H}_7^+$ | 0.79                    | 0.54                  |
| p- $\text{C}_6\text{H}_4\text{TCH}_3$     | $\text{C}_7\text{H}_7^+$ | 0.76                    | 0.54                  |
| $\text{C}_6\text{H}_5\text{CH}_2\text{T}$ | $\text{C}_7\text{H}_7^+$ | 0.79                    | 0.52                  |

# Mass-Spectrometer Design



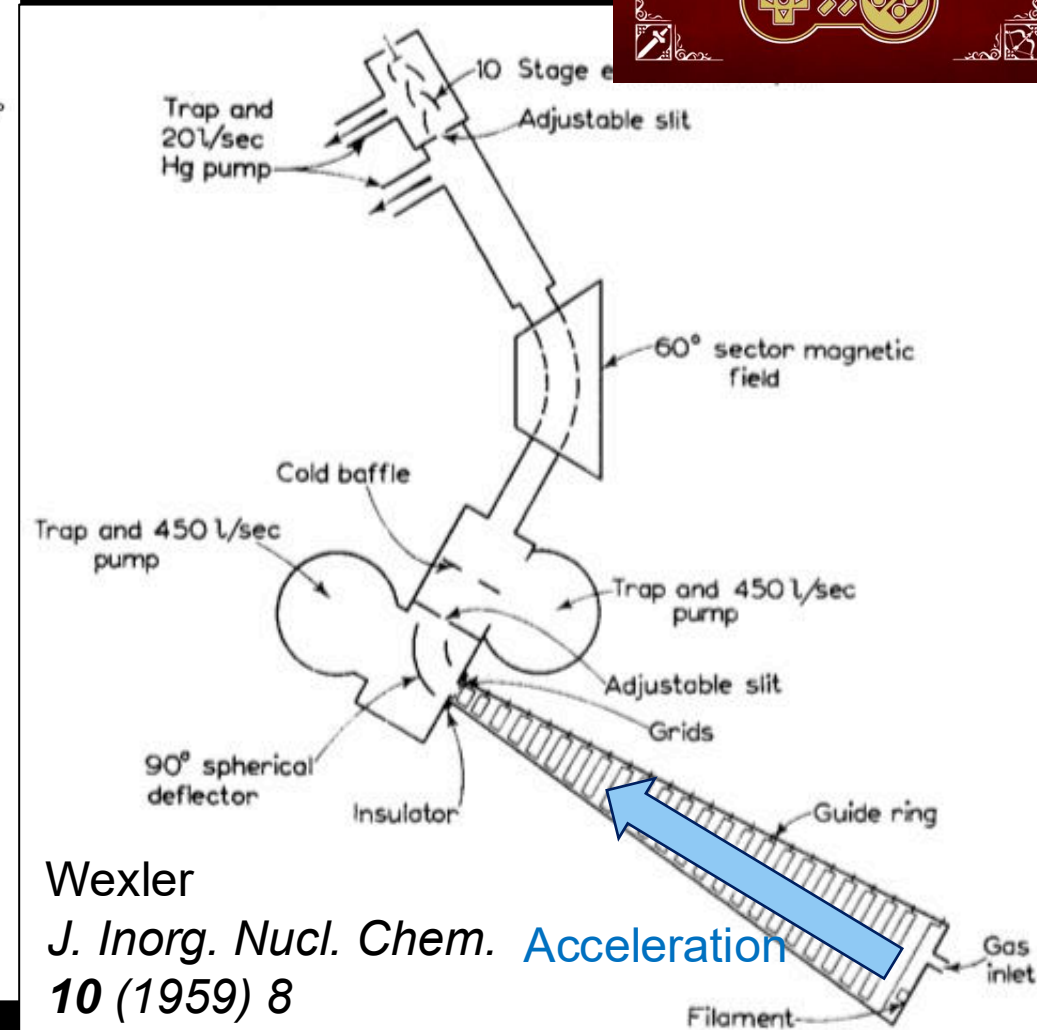
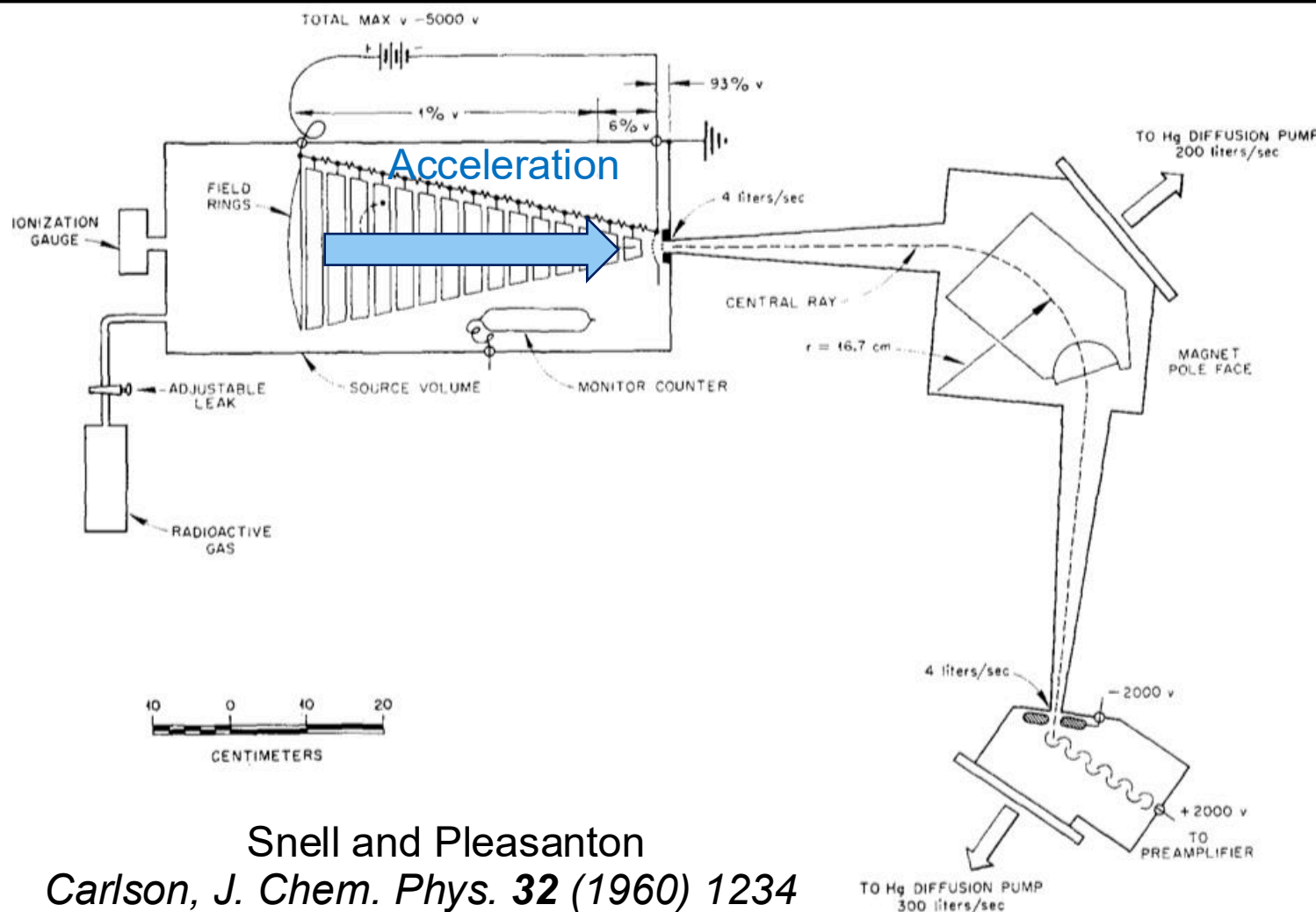
Snell and Pleasanton  
 Carlson, *J. Chem. Phys.* **32** (1960) 1234



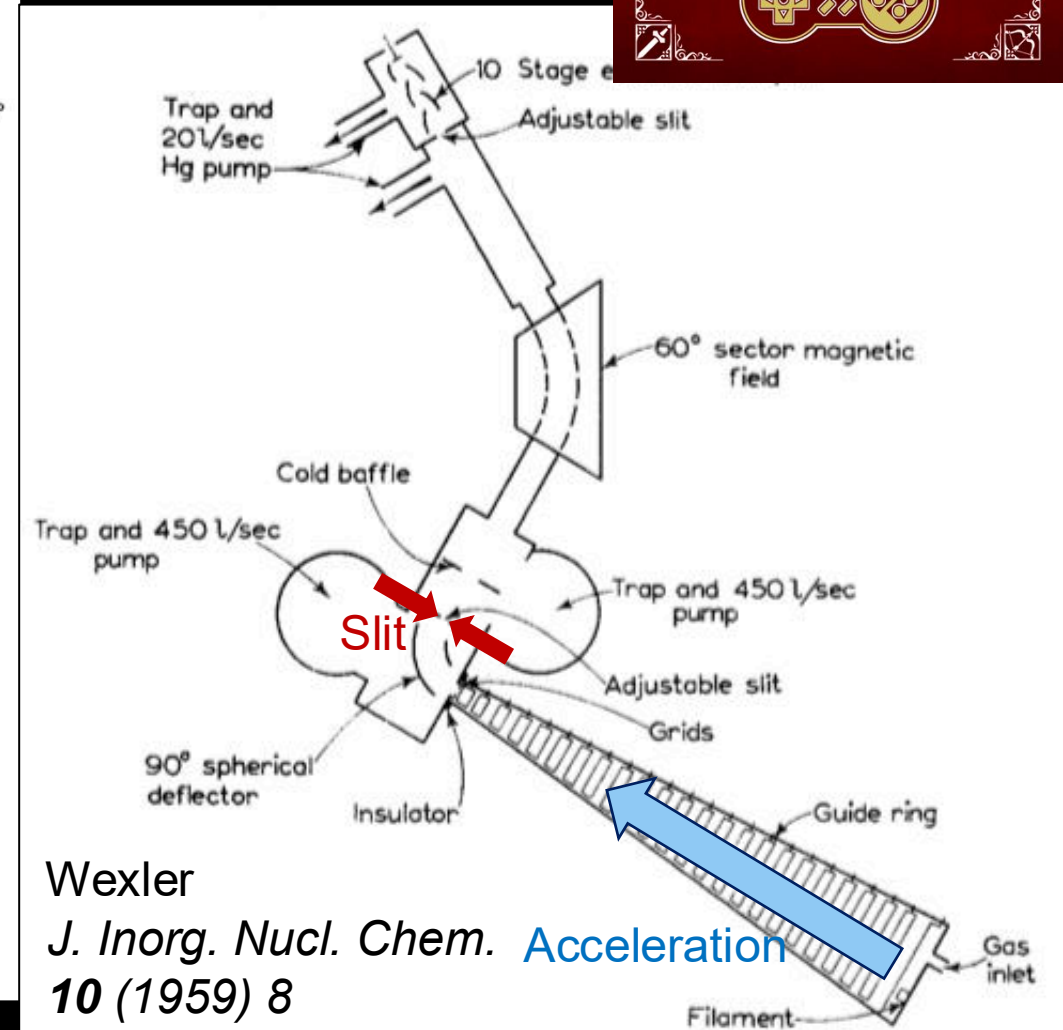
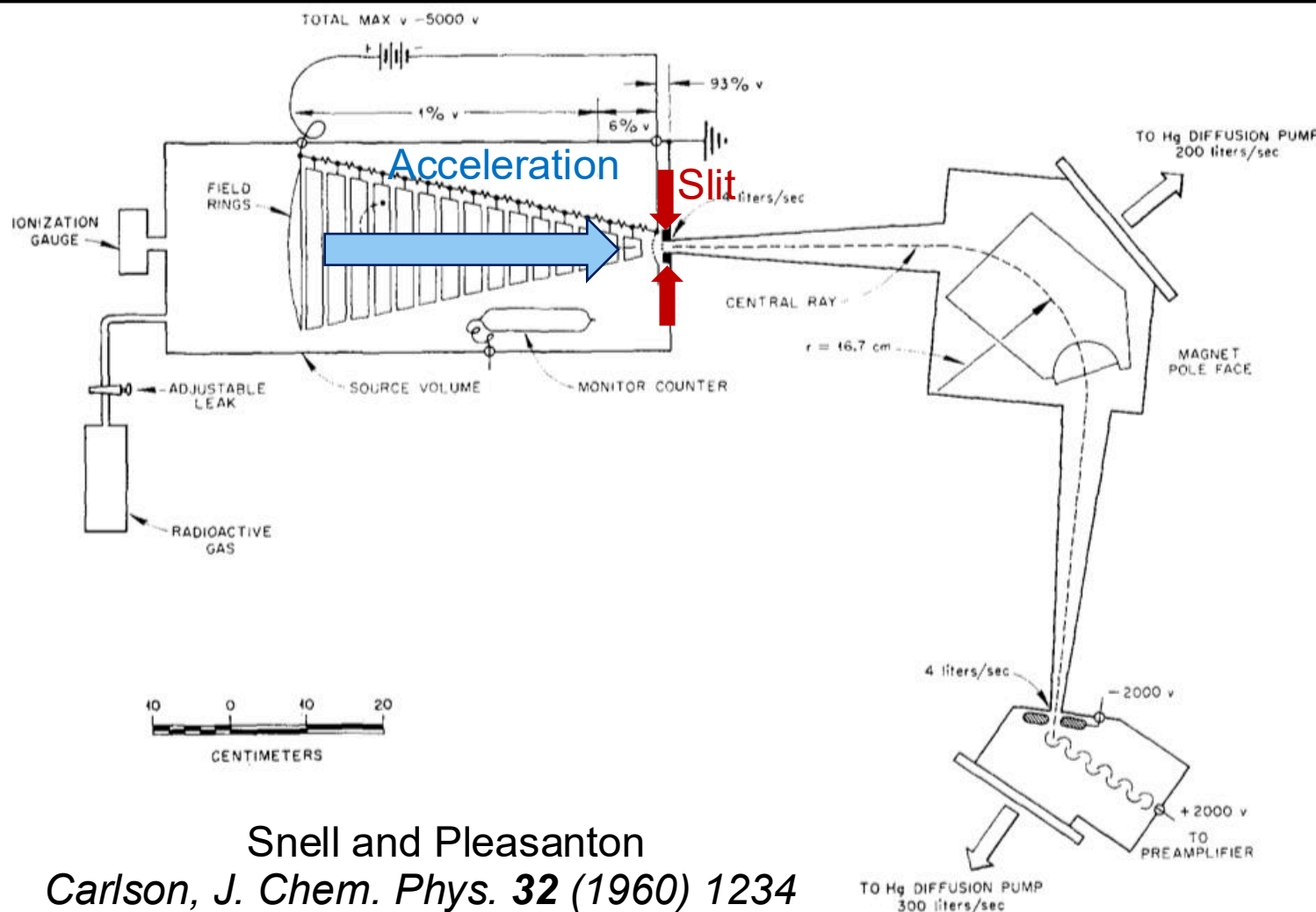
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**10** (1959) 8



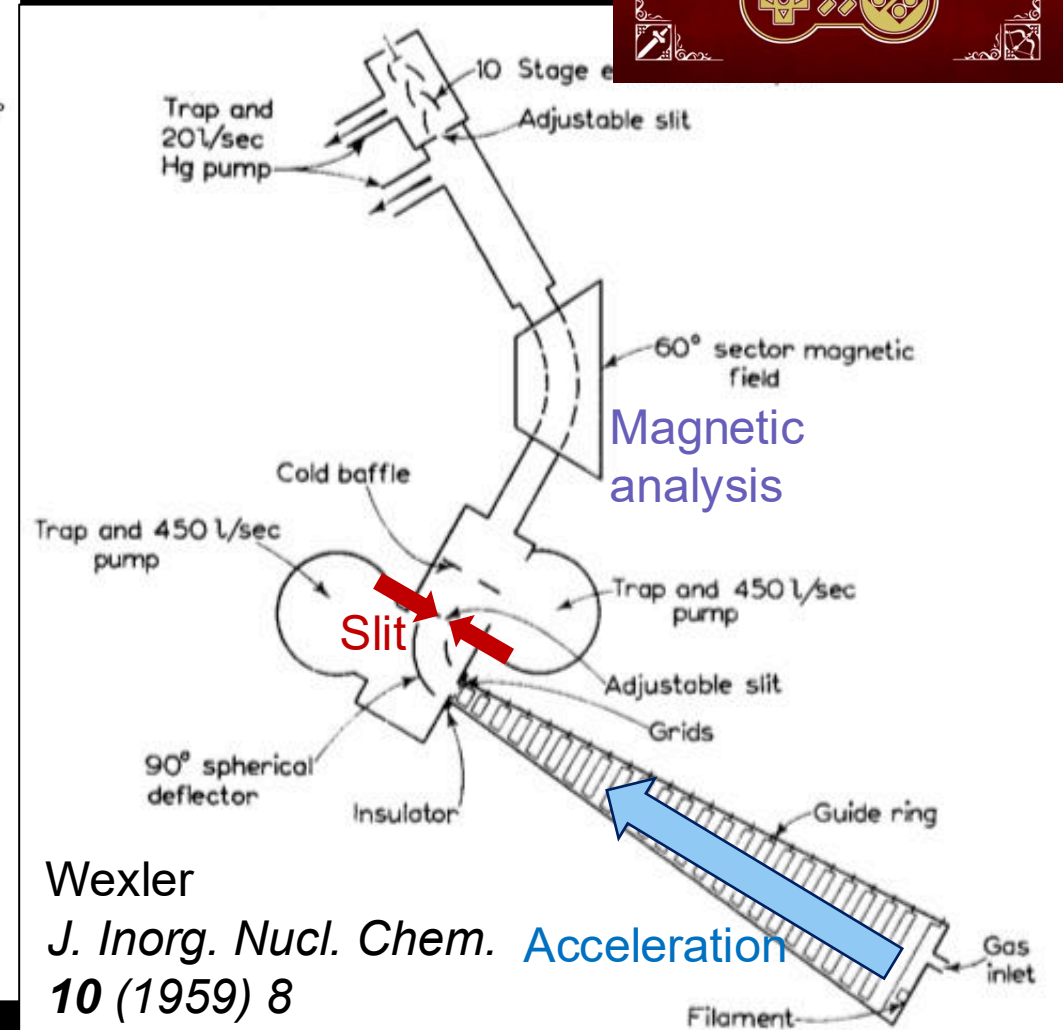
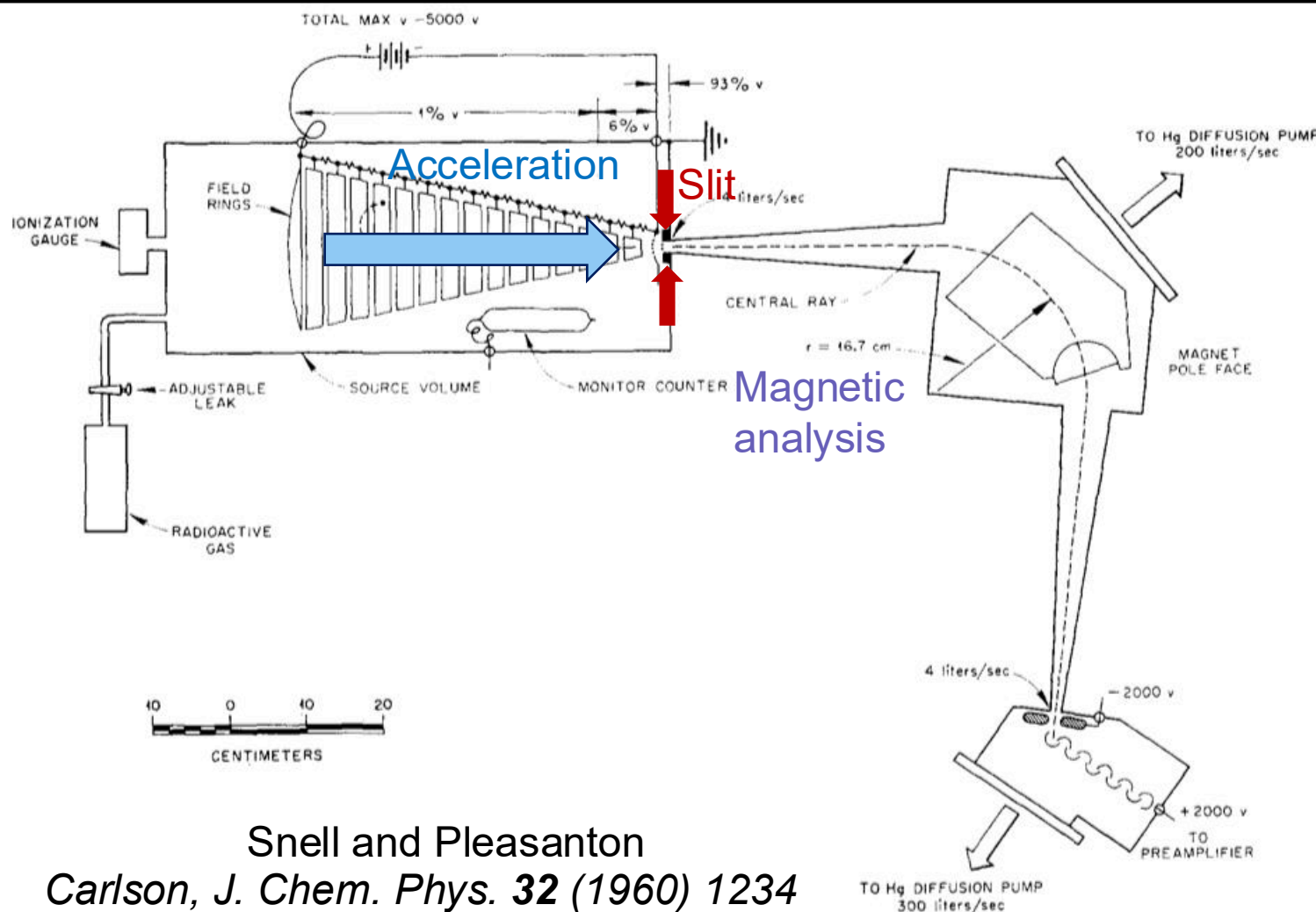
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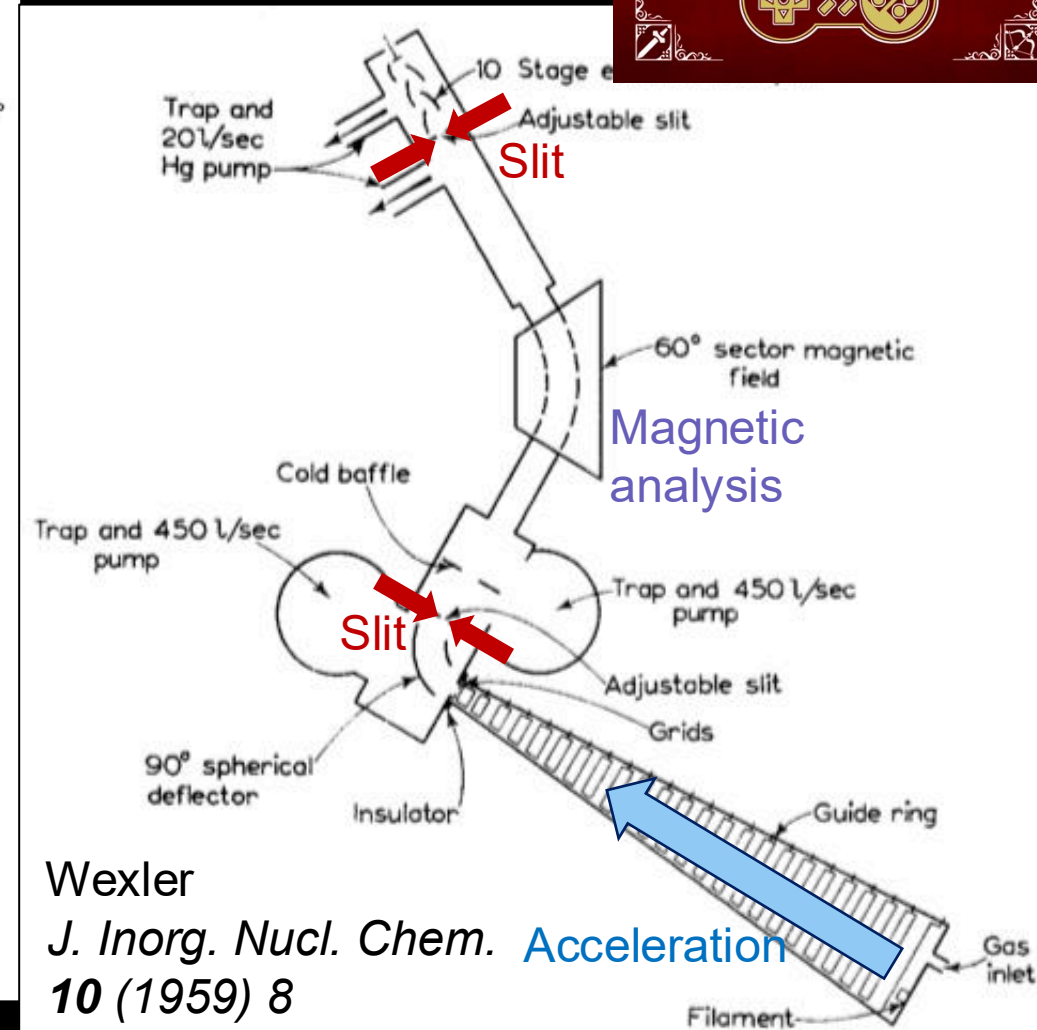
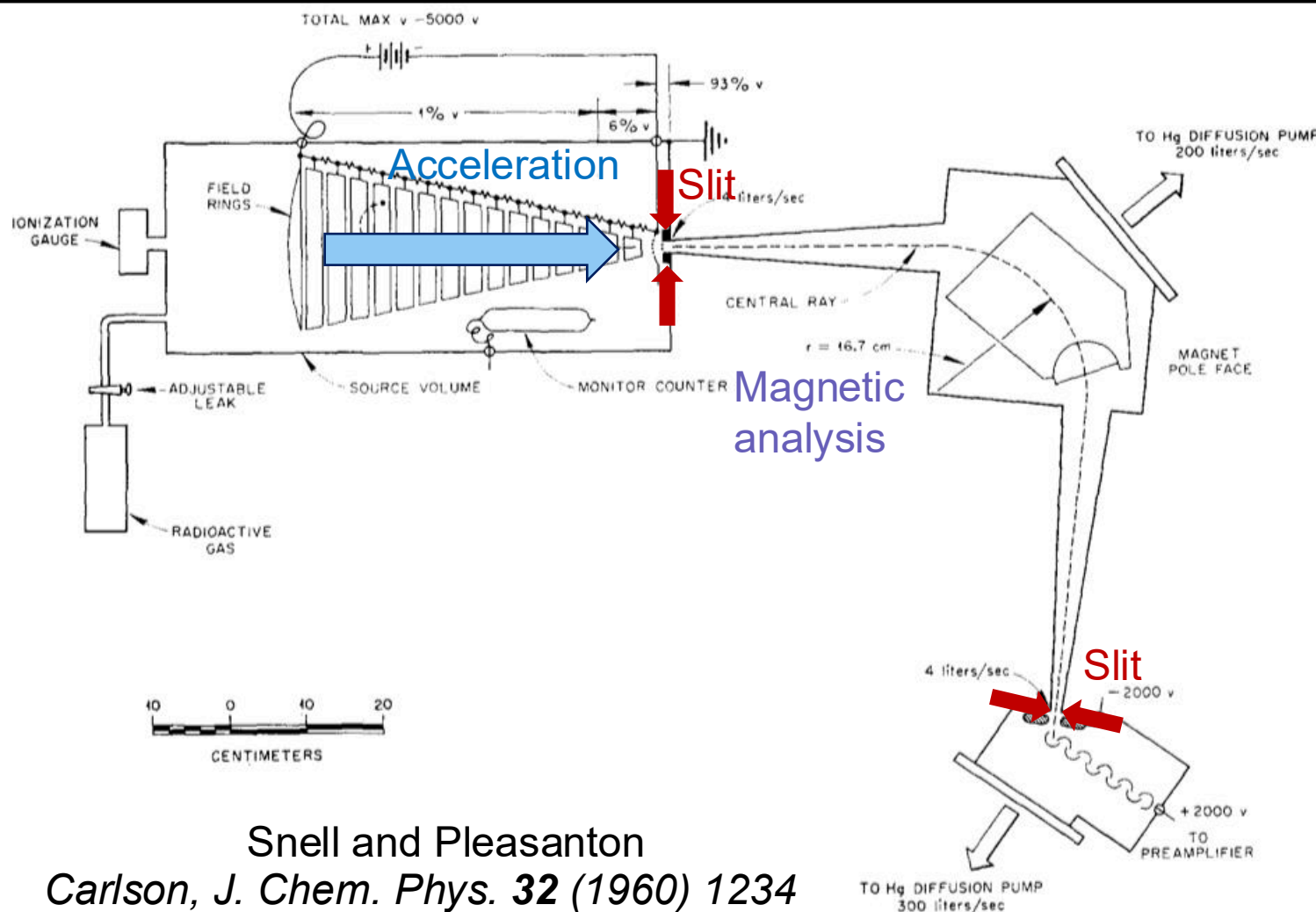


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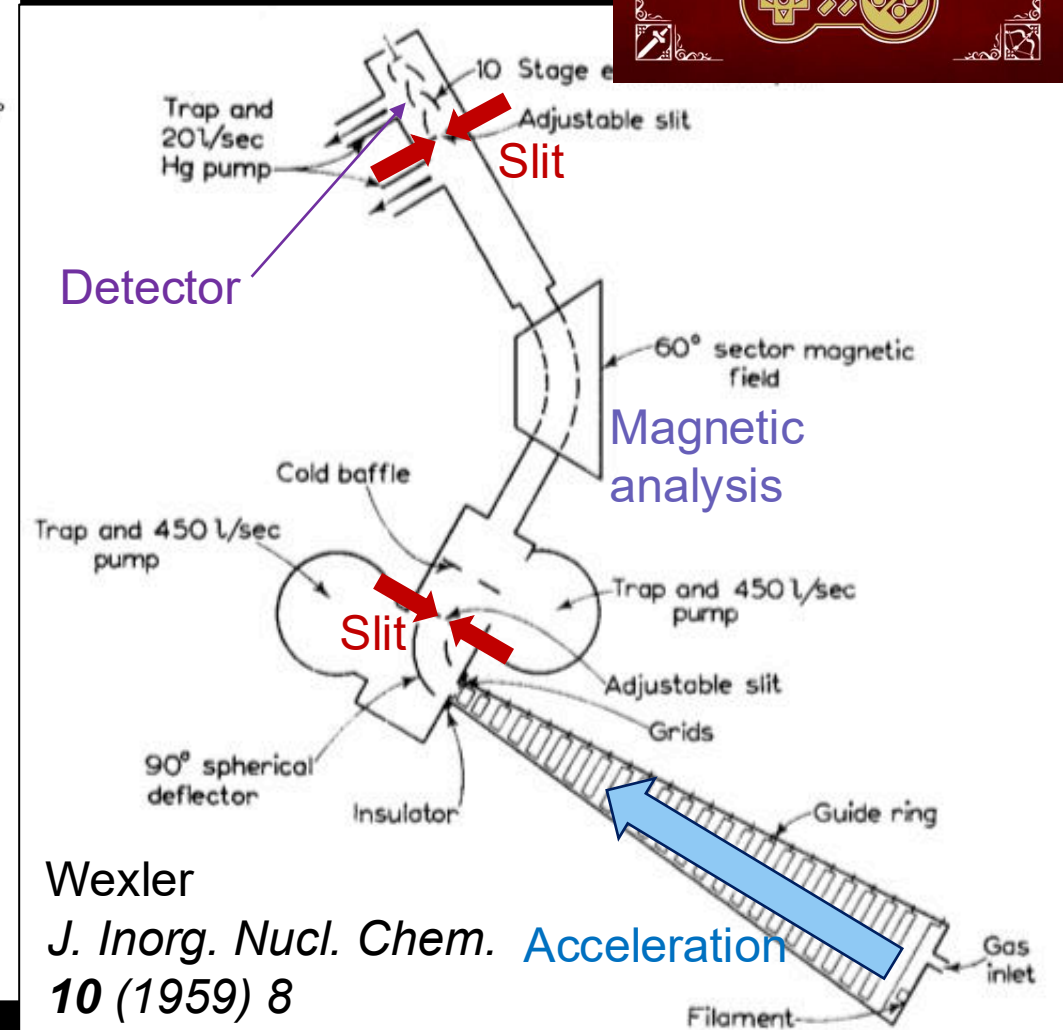
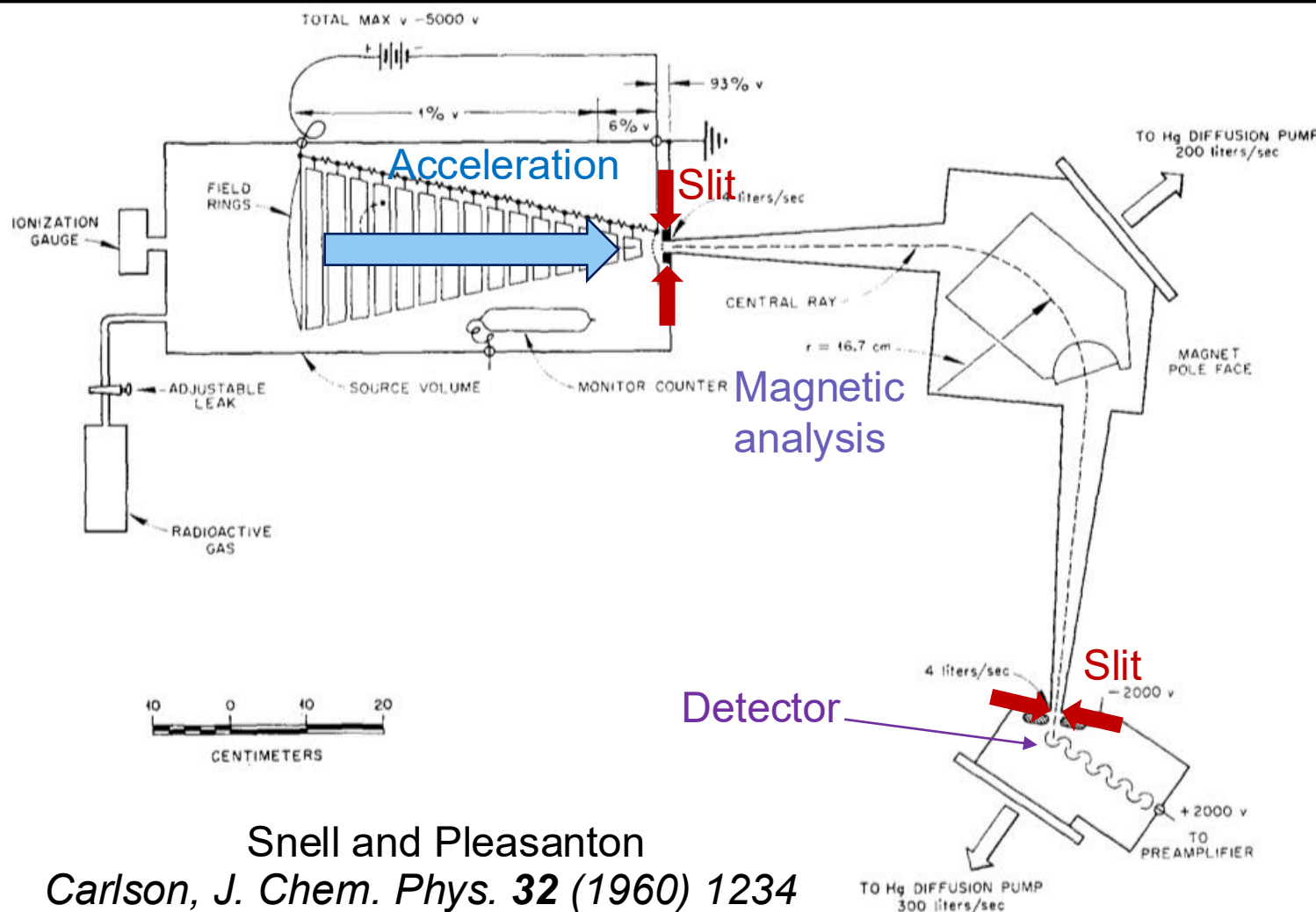




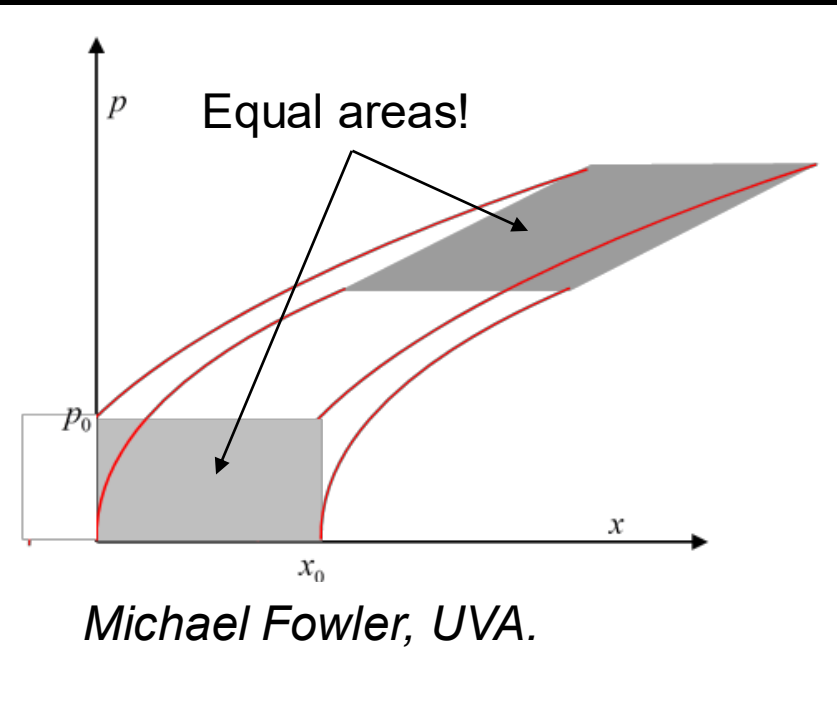
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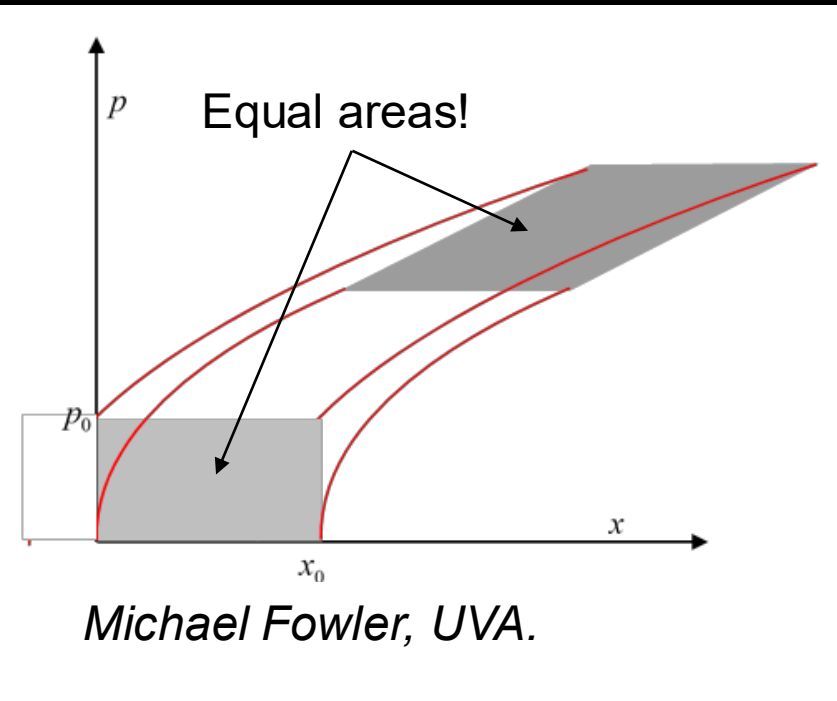
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# Liouville's Theorem



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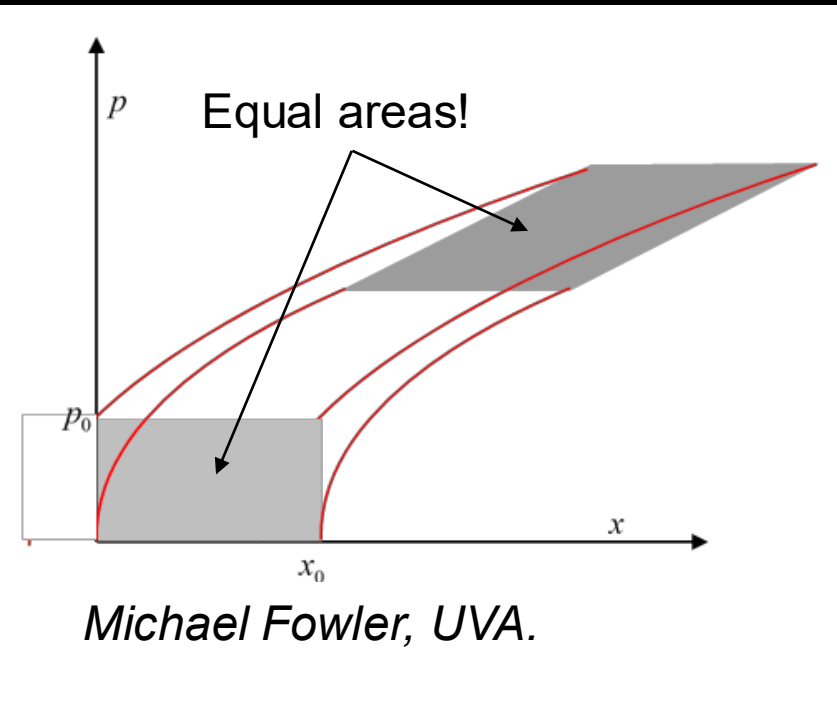


Michael Fowler, UVA.

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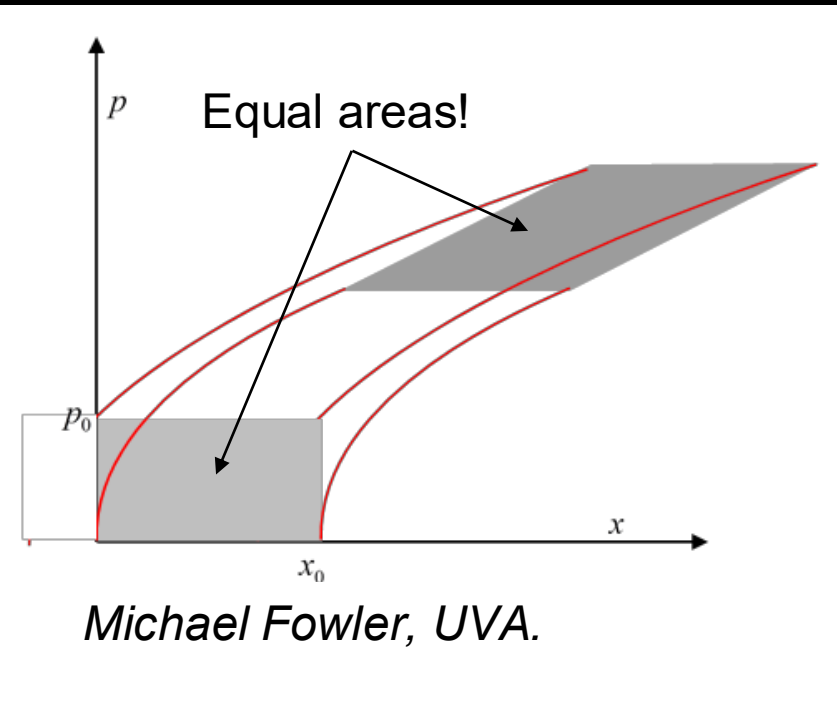


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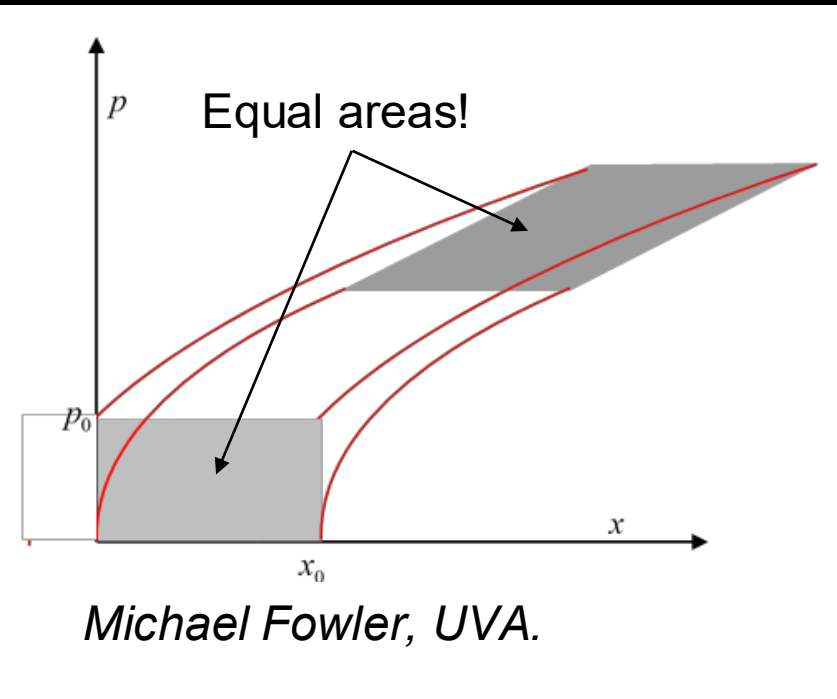
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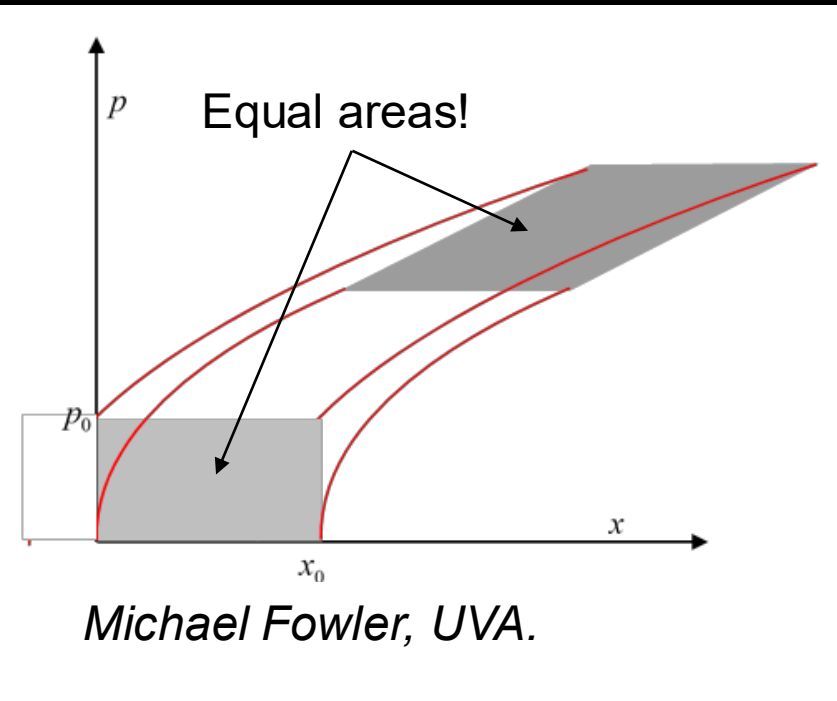
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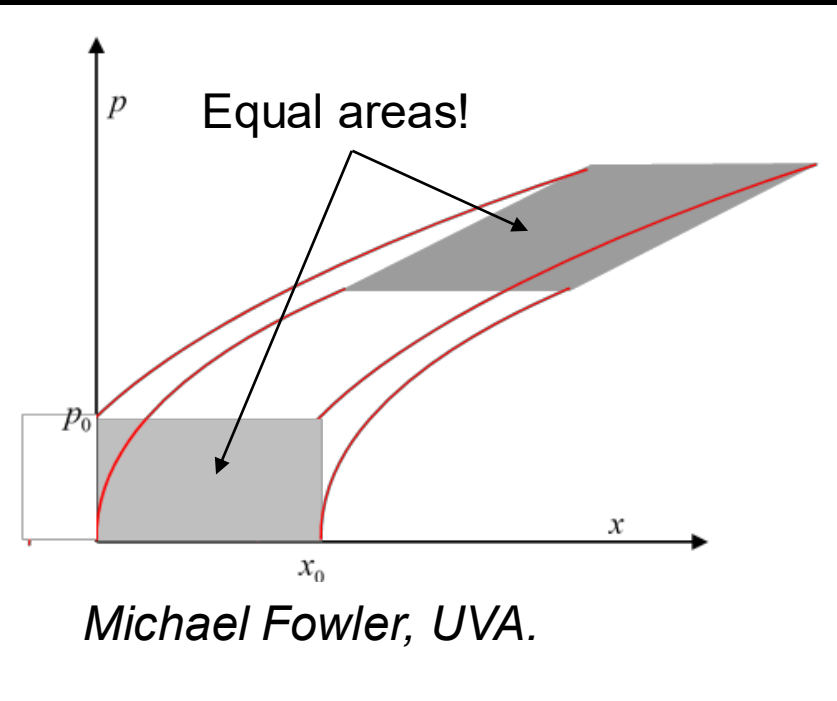
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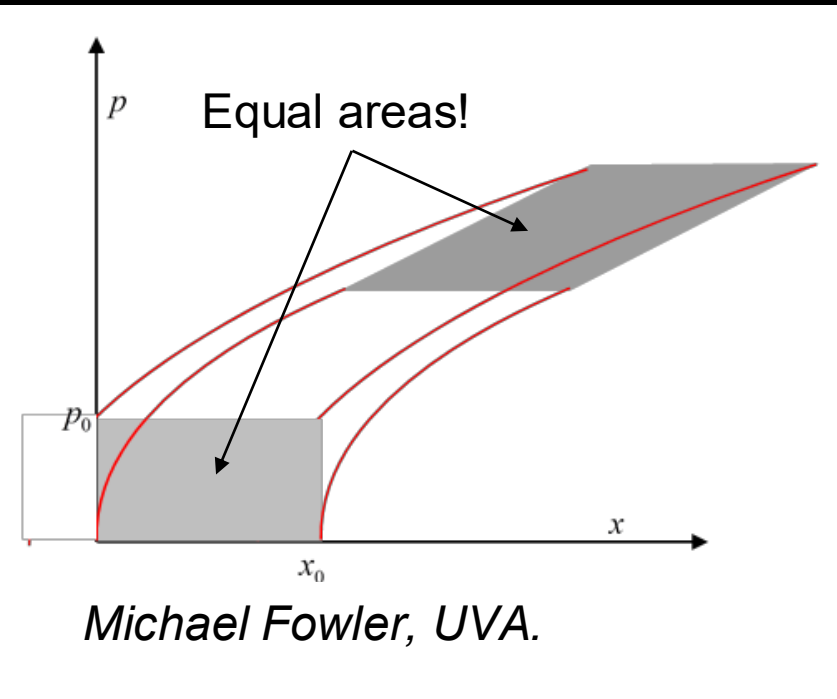
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# Liouville, Quantitatively

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- ◆ Calculate recoil energies for each branch based on lepton momentum and FSD theory for that branch
- ◆ Weight energy for each ion species by probability of branch (from TRIMS)
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$$\frac{\omega_3}{\omega_4} = \left( \frac{m_4}{m_3} \right)^2 \left( \frac{E_4}{\bar{E}_3} \right)^{3/2} = 0.126$$

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$$P'_{\text{bound}} = \frac{P_4^{\text{TRIMS}}}{\frac{\omega_1}{\omega_4} P_1^{\text{TRIMS}} + \frac{\omega_3}{\omega_4} P_3^{\text{TRIMS}} + P_4^{\text{TRIMS}}}$$



# Reconciling TRIMS and History

Preliminary



| Branch                        | $P_{\text{TRIMS}}$ | $P'_{\text{TRIMS}}$ | $P_{\text{W}}$ | $P_{\text{S\&P}}$ |
|-------------------------------|--------------------|---------------------|----------------|-------------------|
| ${}^3\text{HeH}^+$ (HT decay) | 0.565(55)          | <b>0.851</b>        | 0.895(11)      | 0.932(19)         |
| ${}^3\text{HeT}^+$ (TT decay) | 0.50(2)            | <b>0.931</b>        | 0.945(6)       | -----             |

# Reconciling TRIMS and History

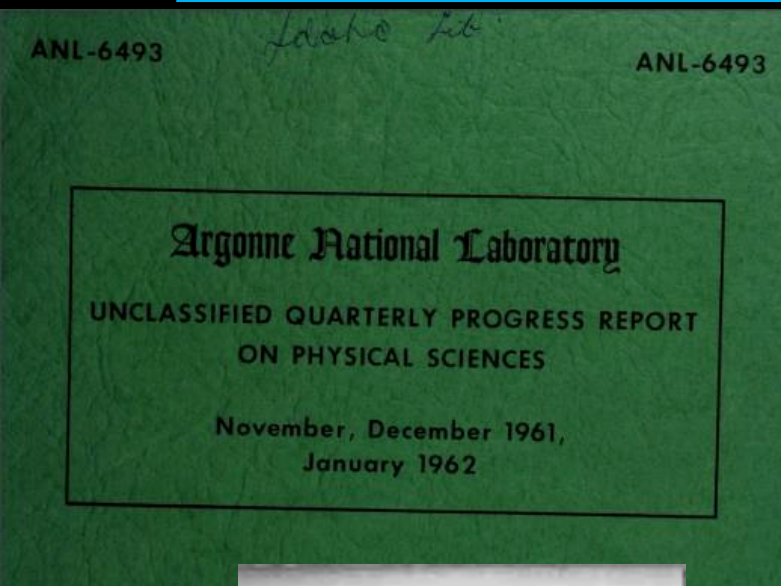
Preliminary



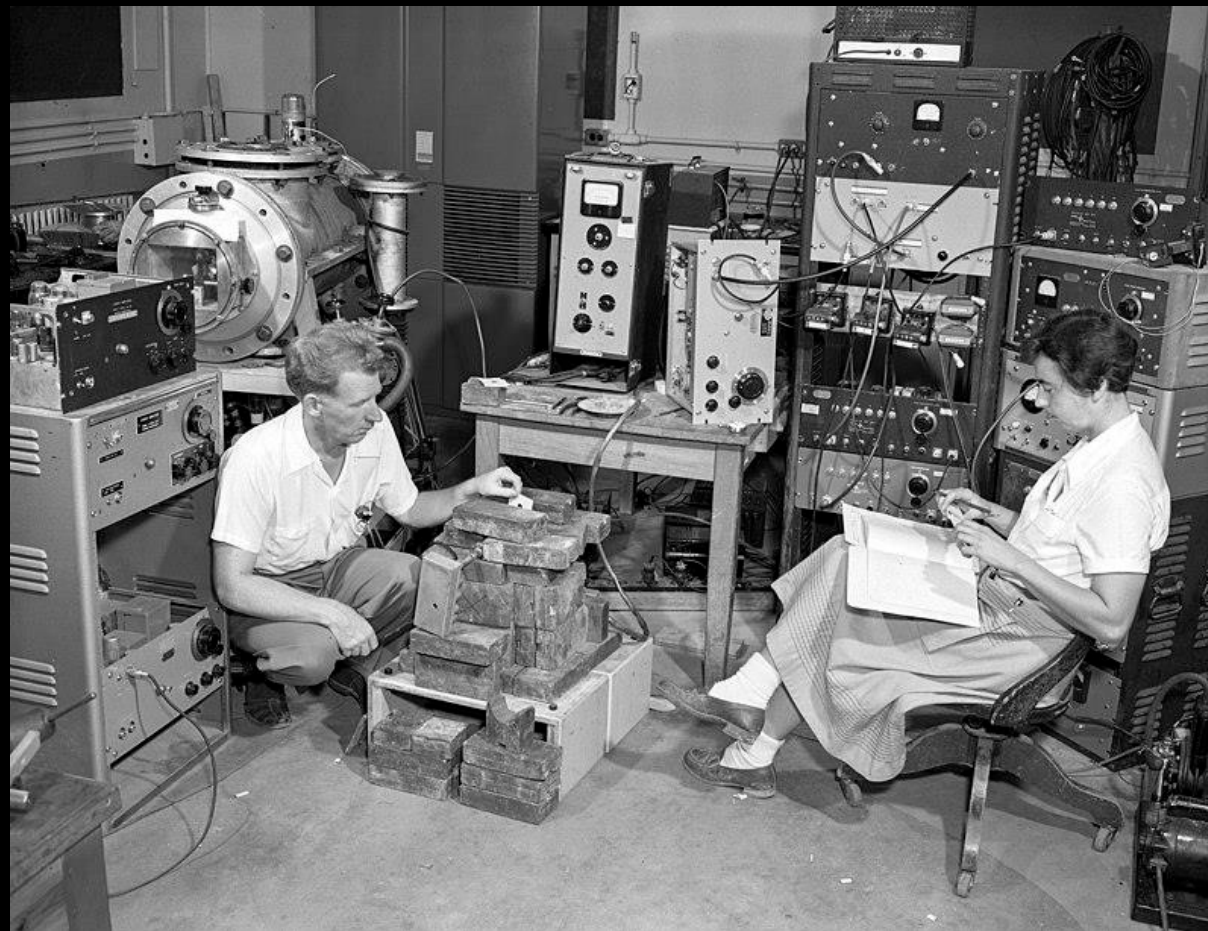
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- ◆ Phase-space effects are large enough to quantitatively reconcile TRIMS measurements with those of Wexler, Snell & Pleasanton!
- ◆ Experiment and theory are fully consistent
- ◆ ... what went wrong here?

# Traveling Back in Time...



Solomon Wexler, ANL  
(1919-1996)



# They Understood the Problem!

---



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... so far we have made **no allowance for the variation of the collecting efficiency of the apparatus with the kinetic energy of the molecular fragments**. Accordingly, if the molecular dissociations to be described are importantly accompanied by the release to the fragments of kinetic energy in the amount of one or more electron volts, **the figures to be given will be subject to modification** when the appropriate information becomes available.

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However, this value of the yield may be considered as **only an upper limit** ... Since **mass spectrometers strongly discriminate against ions with appreciable translational energy**, the measured yields of the atomic fragments would be too low and, accordingly, that of the bound molecular ion too high.

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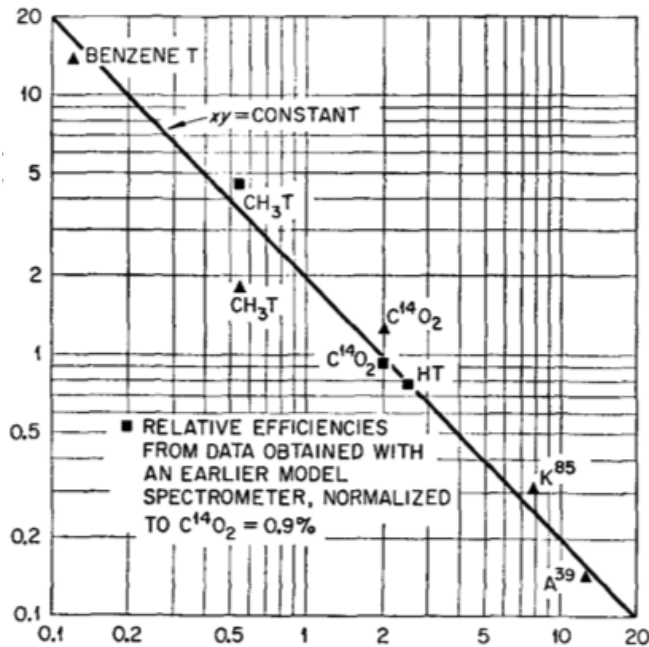
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**Studies which may be in considerable error, however, are those on HT, TT, and  $^{14}\text{CO}_2$  where the daughter ions will carry off a sizable fraction of the kinetic energy...**

-- Carlson, J. Chem. Phys. **32** (1960) 1234





# Yet This Was Mostly Forgotten...

- ◆ Results are quoted in a huge range of fields
  - ◆ Organic chemistry methods (theoretical and experimental)
  - ◆ Biological damage from medical radioisotopes
  - ◆ Absolute radiocarbon dating
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Since the **translational energies of the dissociation fragments from the excited states are 8 to 26 eV, and from the ground state 0 to 3 eV**, we find this explanation plausible.

-- Jonsell, Saenz, and Froehlich, PRC **60** (1999) 034601

# Unquantifiable Uncertainties

---



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- ◆ What do you do when the correct interpretation of your results needs theoretical calculations that do not yet exist?
  - ◆ Don't publish experiment?
  - ◆ Push for theory progress?
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TABLE 1.—DISSOCIATION OF TH AND TT BY  $\beta$ -DECAY

| Molecule | Ion fragment                                     | Probability of occurrence (%) |                                    |
|----------|--------------------------------------------------|-------------------------------|------------------------------------|
|          |                                                  | This work                     | SNELL <i>et al.</i> <sup>(1)</sup> |
| TH       | (He <sup>3</sup> H) <sup>+</sup>                 | 89.5 $\pm$ 1.1                | 93.2 $\pm$ 1.9                     |
|          | (He <sup>3</sup> ) <sup>+</sup>                  | 8.2 $\pm$ 1.0                 | 5.1 $\pm$ 0.3                      |
|          | H <sup>+</sup>                                   | 2.3 $\pm$ 0.4                 | 1.55 $\pm$ 0.16                    |
|          | (He <sup>3</sup> ) <sup>++</sup>                 |                               | 0.14 $\pm$ 0.01                    |
| TT       | (THe <sup>3</sup> ) <sup>+</sup>                 | 94.5 $\pm$ 0.6                |                                    |
|          | T <sup>+</sup> + (He <sup>3</sup> ) <sup>+</sup> | 5.5 $\pm$ 0.6                 |                                    |

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|          | (He <sup>3</sup> ) <sup>+</sup>                  | 8.2 $\pm$ 1.0                 | 5.1 $\pm$ 0.3                      |
|          | H <sup>+</sup>                                   | 2.3 $\pm$ 0.4                 | 1.55 $\pm$ 0.16                    |
|          | (He <sup>3</sup> ) <sup>++</sup>                 |                               | 0.14 $\pm$ 0.01                    |
| TT       | (THe <sup>3</sup> ) <sup>+</sup>                 | 94.5 $\pm$ 0.6                |                                    |
|          | T <sup>+</sup> + (He <sup>3</sup> ) <sup>+</sup> | 5.5 $\pm$ 0.6                 |                                    |

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# Unquantifiable Uncertainties



- ◆ What do you do when the correct interpretation of your results needs theoretical calculations that do not yet exist?
  - ◆ Don't publish experiment?
  - ◆ Push for theory progress?
  - ◆ Asterisk on table values?
  - ◆ Report values as upper limits?
  - ◆ Estimate quantitative size of problem?
    - ◆ Treat cases? 0.1 eV, 1 eV, 10 eV...
- ◆ There may not be one best answer ... but even very clear statements in text are not enough

TABLE 1.—DISSOCIATION OF TH AND TT BY  $\beta$ -DECAY

| Molecule | Ion fragment                                     | Probability of occurrence (%) |                                    |
|----------|--------------------------------------------------|-------------------------------|------------------------------------|
|          |                                                  | This work                     | SNELL <i>et al.</i> <sup>(1)</sup> |
| TH       | (He <sup>3</sup> H) <sup>+</sup>                 | 89.5 $\pm$ 1.1                | 93.2 $\pm$ 1.9                     |
|          | (He <sup>3</sup> ) <sup>+</sup>                  | 8.2 $\pm$ 1.0                 | 5.1 $\pm$ 0.3                      |
|          | H <sup>+</sup>                                   | 2.3 $\pm$ 0.4                 | 1.55 $\pm$ 0.16                    |
|          | (He <sup>3</sup> ) <sup>++</sup>                 |                               | 0.14 $\pm$ 0.01                    |
| TT       | (THe <sup>3</sup> ) <sup>+</sup>                 | 94.5 $\pm$ 0.6                |                                    |
|          | T <sup>+</sup> + (He <sup>3</sup> ) <sup>+</sup> | 5.5 $\pm$ 0.6                 |                                    |

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