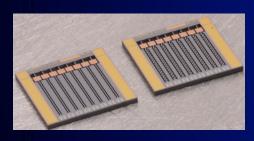# Direct Neutrino Mass Measurements

Diana Parno

Center for Experimental Nuclear Physics and Astrophysics

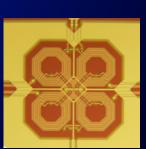*University of Washington*
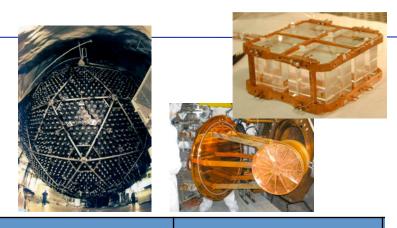

Symmetry Tests in Nuclei and Atoms – KITP – September 20, 2016

Outline

✦ **Probes of neutrino mass: An introduction**

✦ How to measure a spectrum

✦ Theoretical challenges

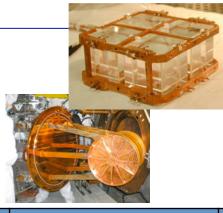✦ A few experimental challenges

✦ Light neutrino, bright future

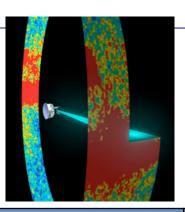# Probes of Neutrino Mass

	ν oscillation
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$
Present knowledge	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\text{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\text{eV}^2$
Next generation	
Model dependence of mass extraction	No mass-scale information

Probes of Neutrino Mass

	ν oscillation	0νββ
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$	$m_{\beta\beta}^2 = \left| \sum_i U_{ei}^2 m_i \right|^2$
Present knowledge	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\mathrm{eV}^2$	$m_{\beta\beta} < (0.2 - 0.4)\ \mathrm{eV}$
Next generation		0.01 – 0.05 eV
Model dependence of mass extraction	No mass-scale information	• δ_1, δ_2 phases • Nucl. matrix elements • Requires LNV

Probes of Neutrino Mass
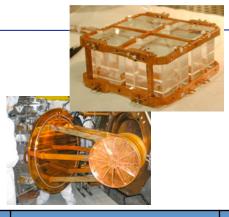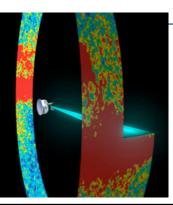
	ν oscillation	0νββ	Cosmology
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert^2$	$M_\nu = \sum_i m_i$
Present knowledge	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\mathrm{eV}^2$	$m_{\beta\beta} < (0.2 - 0.4)\ \mathrm{eV}$	$M_\nu < (0.12 - 1)\ \mathrm{eV}$
Next generation		0.01 – 0.05 eV	0.01 – 0.05 eV
Model dependence of mass extraction	No mass-scale information	• δ_1, δ_2 phases • Nucl. matrix elements • Requires LNV	ΛCDM • Many parameters • H_0 tension

Probes of Neutrino Mass
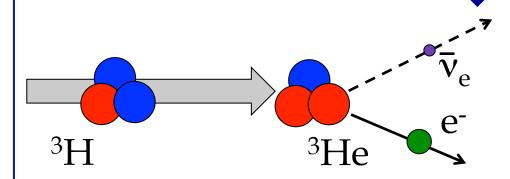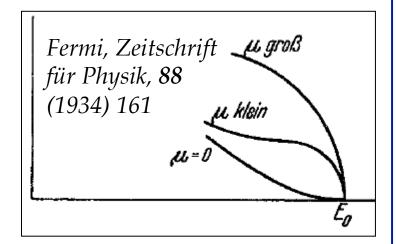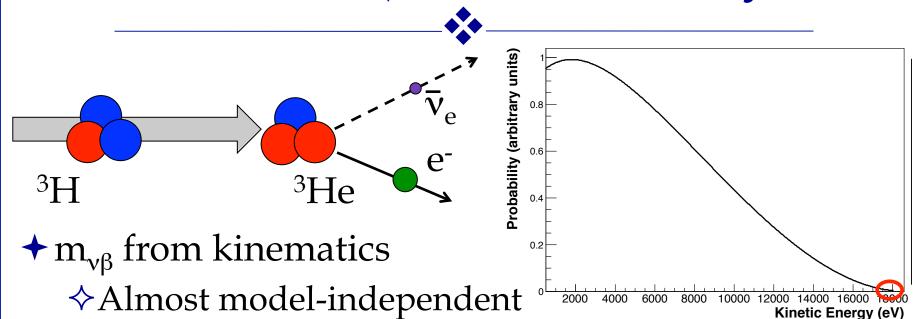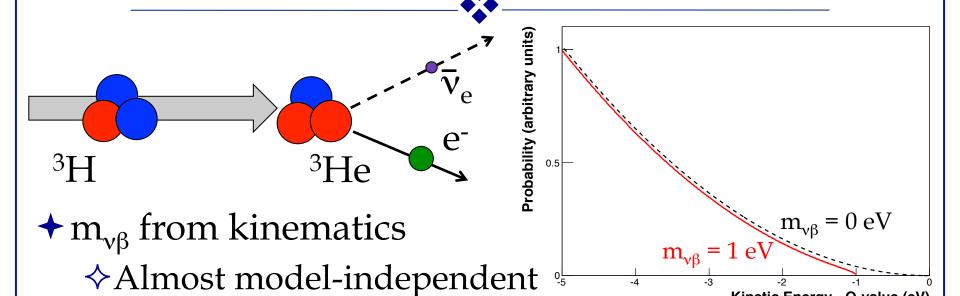
	ν oscillation	0νββ	Cosmology	Decay kinematics
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$	$m_{\beta\beta}^2 = \left\| \sum_i U_{ei}^2 m_i \right\|^2$	$M_\nu = \sum_i m_i$	$m_{\nu\beta}^2 = \sum_i \left\| U_{ei}^2 \right\| m_i^2$
Present knowledge	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\text{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\text{eV}^2$	$m_{\beta\beta} < (0.2 - 0.4)\,\text{eV}$	$M_\nu < (0.12 - 1)\,\text{eV}$	$m_{\nu\beta} < 2\,\text{eV}$
Next generation		0.01 – 0.05 eV	0.01 – 0.05 eV	0.2 eV
Model dependence of mass extraction	No mass-scale information	• δ_1, δ_2 phases • Nucl. matrix elements • Requires LNV	ΛCDM • Many parameters • H_0 tension	• Energy conservation

Direct m_ν from β^- Decay

^{3}H $\rightarrow$ ^{3}He

$\bar{\nu}_e$

e^-

Fermi, Zeitschrift für Physik, 88 (1934) 161

μ groß

μ klein

$\mu = 0$

E_0

✦ $m_{\nu\beta}$ from kinematics

✧ Almost model-independent

Direct m$_\nu$ from β⁻ Decay

^{3}H ^{3}He $\overline{\nu}_e$ e⁻

✦ m$_{\nu\beta}$ from kinematics

✧ Almost model-independent

Direct m_ν from β^- Decay

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

$m_{\nu\beta} = 0$ eV

$m_{\nu\beta} = 1$ eV

Probability (arbitrary units)
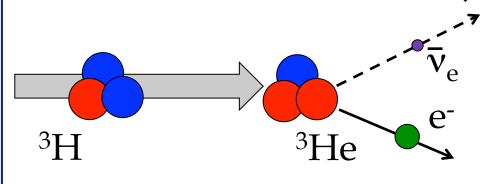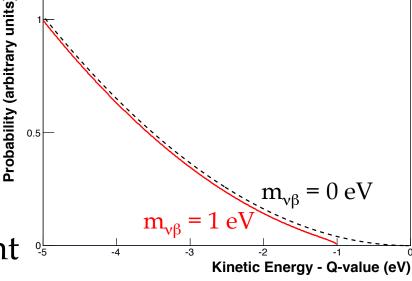
Kinetic Energy - Q-value (eV)

✦ $m_{\nu\beta}$ from kinematics

◇ Almost model-independent

✦ Extract $m_{\nu\beta}$ from spectral shape near endpoint

Direct m_ν from β^- Decay

$\overline{\nu}_e$

e^-

^3H ^3He

✦ $m_{\nu\beta}$ from kinematics
  ◇ Almost model-independent
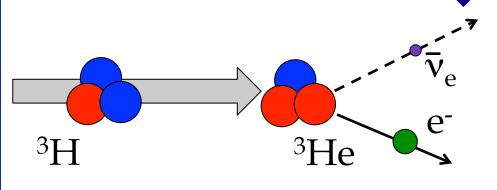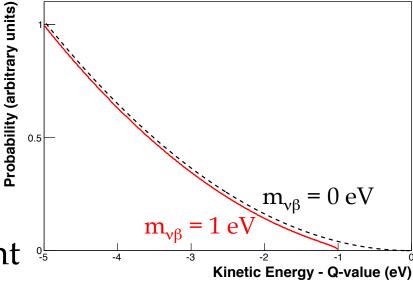
✦ Extract $m_{\nu\beta}$ from spectral shape near endpoint

^3H (tritium)
Q = 18.6 keV
$t_{1/2}$ = 12.3 yrs
Super-allowed

$m_{\nu\beta}$ = 0 eV

$m_{\nu\beta}$ = 1 eV

Probability (arbitrary units)

Kinetic Energy - Q-value (eV)

Direct m_ν from β^- Decay

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

★ $m_{\nu\beta}$ from kinematics

    ✧ Almost model-independent

★ Extract $m_{\nu\beta}$ from spectral shape near endpoint

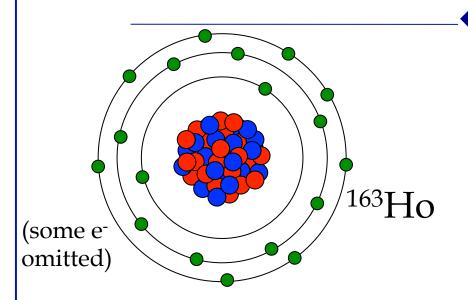| ^3H (tritium)	^{187}Re	^{115}In to $^{115}Sn^*$
Q = 18.6 keV	Q = 2.47 keV	Q = 0.173 keV
$t_{1/2}$ = 12.3 yrs	$t_{1/2}$ = 4.5 x 10^9 yrs	$t_{1/2}$ = 4.4 x 10^{20} yrs
Super-allowed	Forbidden	Forbidden

Direct m$_\nu$ from Electron Capture

^{163}Ho

(some e$^-$
omitted)

Direct m$_\nu$ from Electron Capture

^{163}Ho

(some e$^-$ omitted)

Direct m_ν from Electron Capture

^{163}Ho

(some e⁻ omitted)

Direct m$_\nu$ from Electron Capture

^{163}Ho

^{163}Dy*

ν_e

(some e$^-$ omitted)

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Direct m$_\nu$ from Electron Capture

^{163}Ho

ν_e

^{163}Dy*

(some e$^-$ omitted)

Direct m$_\nu$ from Electron Capture

^{163}Ho

^{163}Dy*

ν_e

(some e⁻ omitted)

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

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

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Direct m$_\nu$ from Electron Capture

(some e⁻ omitted)

^{163}Ho

^{163}Dy*

ν_e

✦ Capture de-excitation energy in ^{163}Ho $\longrightarrow$ ^{163}Dy* + ν_e
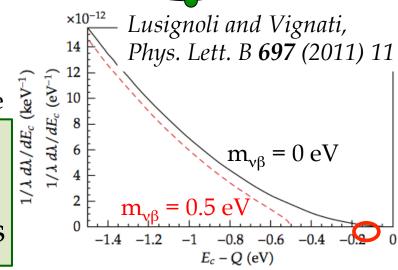
*De Rújula and Lusignoli, Phys. Lett. B **118** (1982) 429*

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

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

$m_{\nu\beta}$ = 0 eV

$m_{\nu\beta}$ = 0.5 eV

CENPA
Center for Experimental Nuclear Physics and Astrophysics

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**

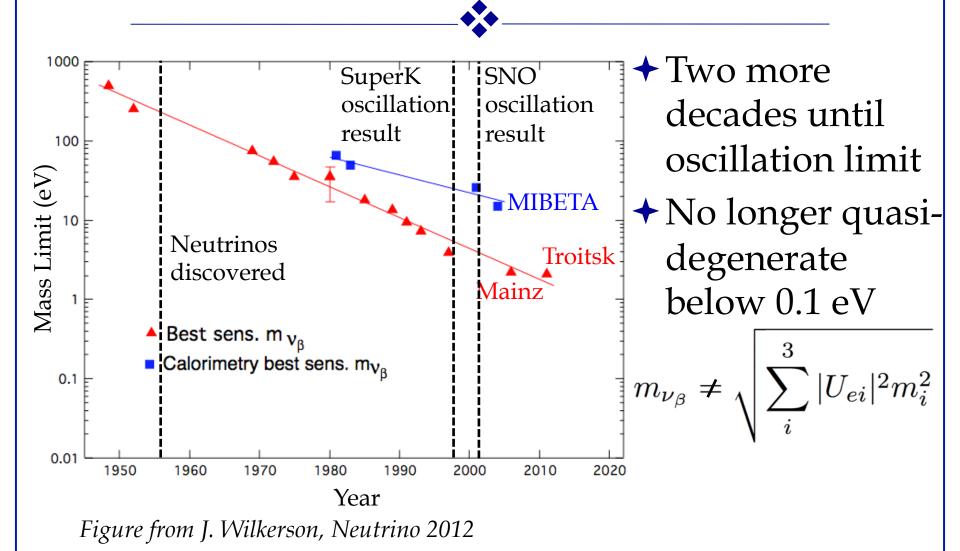$$m_{\nu_\beta} \neq \sqrt{\sum_i^3 |U_{ei}|^2 m_i^2}$$

The State of the Art

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

$$m_{\nu_\beta} \neq \sqrt{\sum_i^3 |U_{ei}|^2 m_i^2}$$
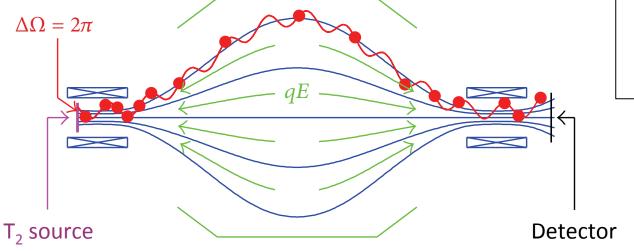
Figure from J. Wilkerson, Neutrino 2012

Outline

- Probes of neutrino mass: An introduction
- **How to measure a spectrum**
- Theoretical challenges
- A few experimental challenges
- Light neutrino, bright future

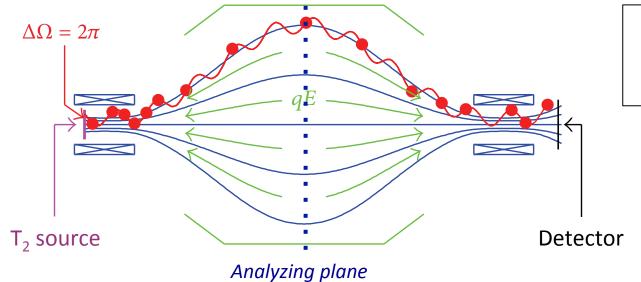# T$_2$ Spectroscopy: MAC-E Filter

✦ Measure integral spectrum with moving threshold

✦ **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter

$\Delta\Omega = 2\pi$

qE

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

T$_2$ source

Detector

T_2 Spectroscopy: MAC-E Filter

✦ Measure integral spectrum with moving threshold

✦ **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter

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

$\Delta\Omega = 2\pi$

qE

Analyzing plane

T_2 source

Detector

$\hat{p}_e$ (without E field)

T$_2$ Spectroscopy: MAC-E Filter

✦ Measure integral spectrum with moving threshold

✦ **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter
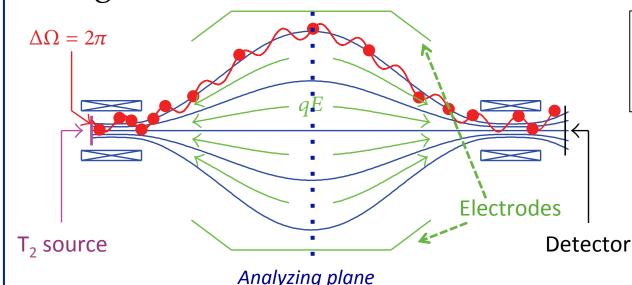
$$\mu = \frac{E_\perp}{B} = \text{const}$$

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

$\Delta\Omega = 2\pi$

qE

Electrodes

T$_2$ source

Detector

Analyzing plane

$\hat{p}_e$ *(without E field)*

T$_2$ Spectroscopy: MAC-E Filter

✦ Measure integral spectrum with moving threshold

✦ **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter

$\Delta\Omega = 2\pi$

T$_2$ source

qE

Electrodes
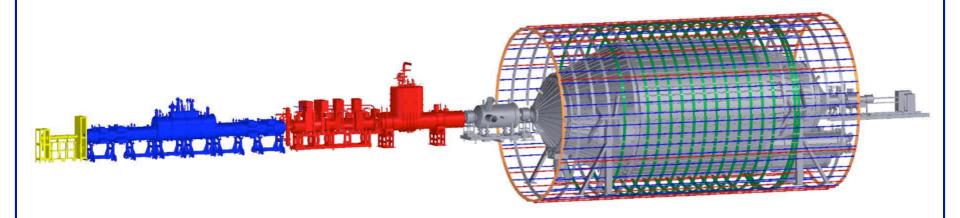
Detector

Analyzing plane

$\hat{p}_e$ *(without E field)*

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

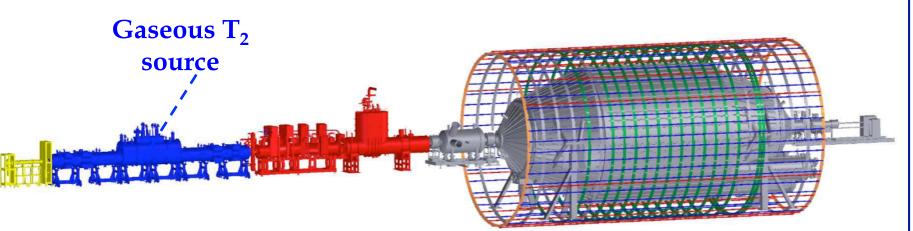$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

Mainz

Troitsk (at INR)
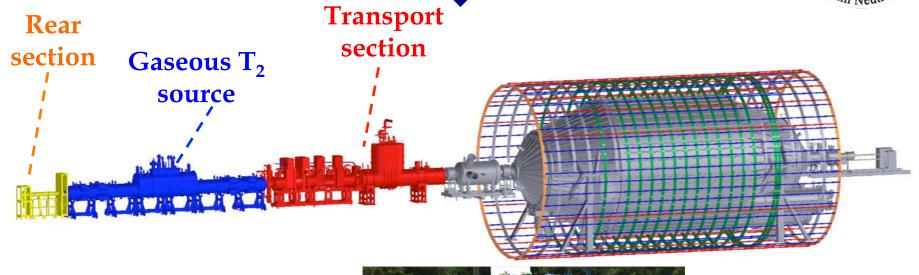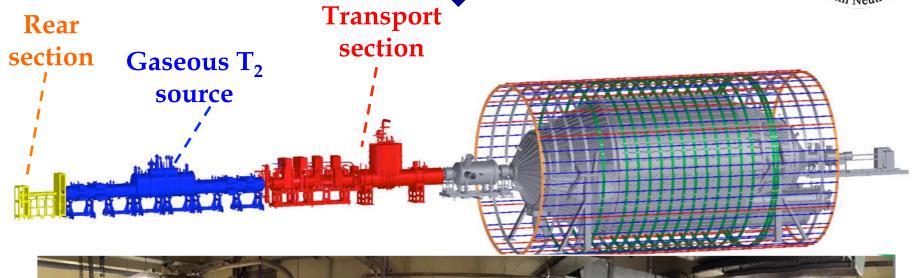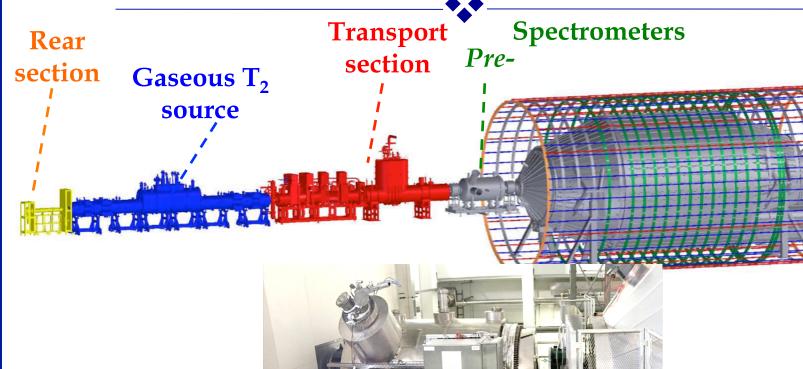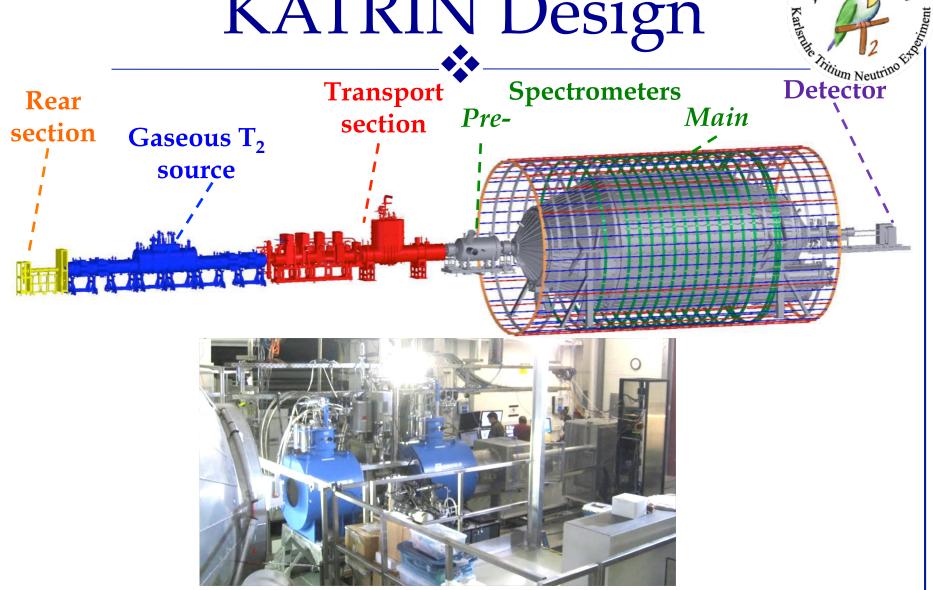
CENPA
Center for Experimental Nuclear Physics and Astrophysics

KATRIN
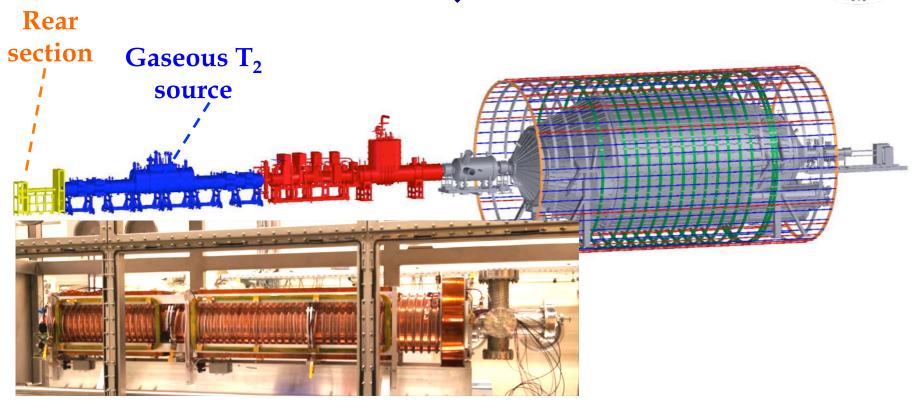Karlsruhe Tritium Neutrino Experiment

KATRIN Design

KATRIN Design

Gaseous T$_2$ source

KATRIN Design

Rear section

Gaseous T_2 source

KATRIN Design

Rear section

Gaseous T_2 source

Transport section

KATRIN Design

Rear section

Gaseous T_2 source

Transport section

KATRIN Design

Rear section

Gaseous T_2 source

Transport section

Pre-

Spectrometers

KATRIN Design

Rear section

Gaseous T$_2$ source

Transport section

Spectrometers

Pre-

Main

LFCS
low-field fine-tuning

EMCS
earth field compensation

main spectrometer vessel

Ø = 12.7 m

KATRIN Design

Rear section

Gaseous T_2 source

Transport section

Spectrometers
Pre-   *Main*

Detector

CENPA
Center for Experimental Nuclear Physics and Astrophysics

KATRIN

❖

- **KA**rlsruhe **TRI**tium **N**eutrino experiment
- Magnetic field range 3 – 60,000 G
- Design resolution 0.93 eV
- 10^{11} decays/sec
- 10^{14} T reduction, source to spec
- Design $m_{\nu\beta}$ sensitivity: **0.2 eV at 90% confidence level**
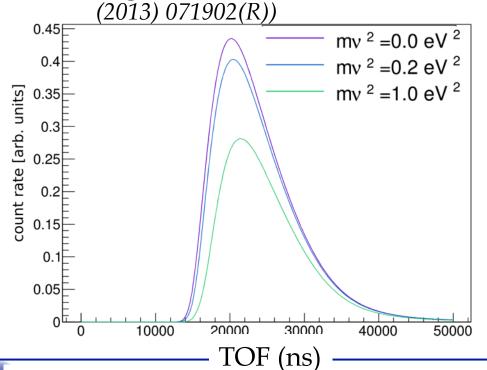
Leopoldshafen November 2006

CENPA
Center for Experimental Nuclear Physics and Astrophysics

KATRIN Bonus Material

★ Any precision beta spectrum is sensitive to new physics ...

♦ e.g. sterile neutrinos (T. Lasserre, yesterday)

♦ e.g. Lorentz-invariance violation *(Díaz et al., Phys. Rev. D **88** (2013) 071902(R))*

★ Meanwhile: R&D for time-of-flight spectrum

♦ Mitigate background

♦ Improve statistics

*Steinbrink et al., N. J. Phys. **15** (2013), 113020*

T$_2$ Spectroscopy: Cyclotron Radiation

Never measure anything but frequency.

-- Arthur Schawlow

✦ An electron in a magnetic field will radiate at

$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi} \frac{1}{m_e + \frac{1}{c^2} E_\beta}$$
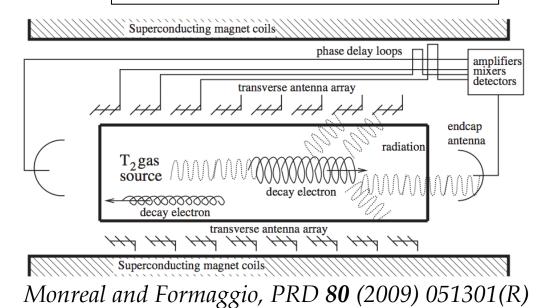
T$_2$ Spectroscopy: Cyclotron Radiation
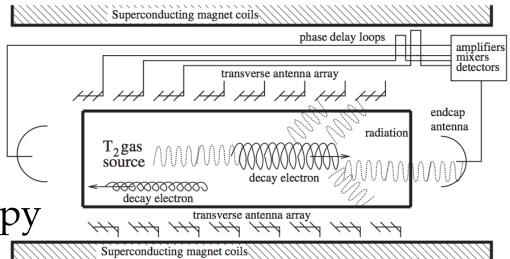
Never measure anything but frequency.

-- Arthur Schawlow

✦ An electron in a magnetic field will radiate at

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

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

Diana Parno -- Direct Neutrino Mass Measurements

T$_2$ Spectroscopy: Cyclotron Radiation

Never measure anything but frequency.

-- Arthur Schawlow

PROJECT 8

✦ An electron in a magnetic field will radiate at
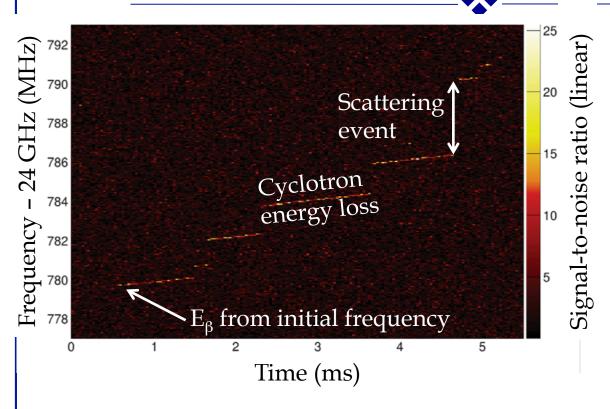
$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi} \frac{1}{m_e + \frac{1}{c^2} E_\beta}$$

✦ Trap electrons

✦ Measure entire beta spectrum at once: **C**yclotron **R**adiation **E**mission **S**pectroscopy

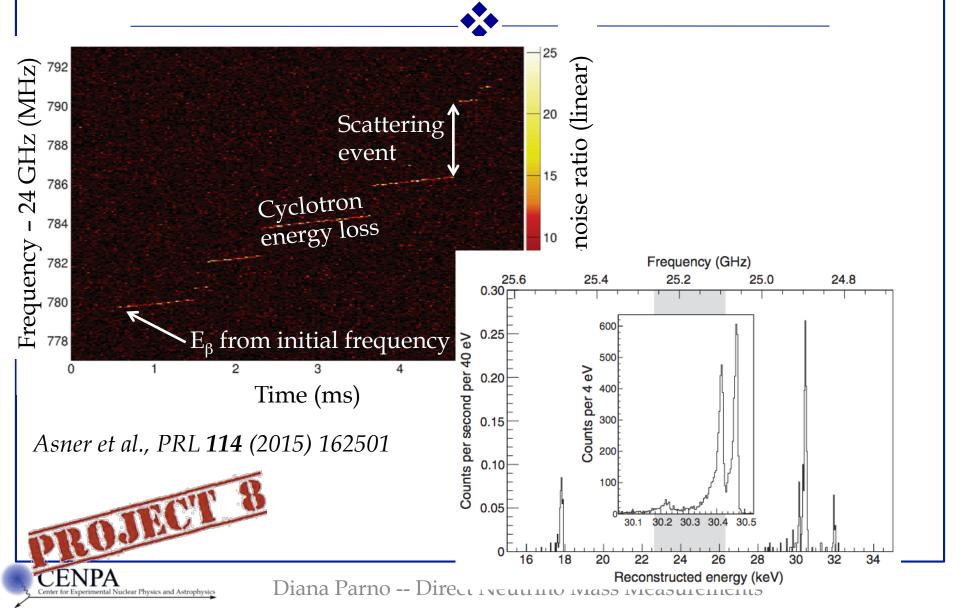*Monreal and Formaggio, PRD **80** (2009) 051301(R)*
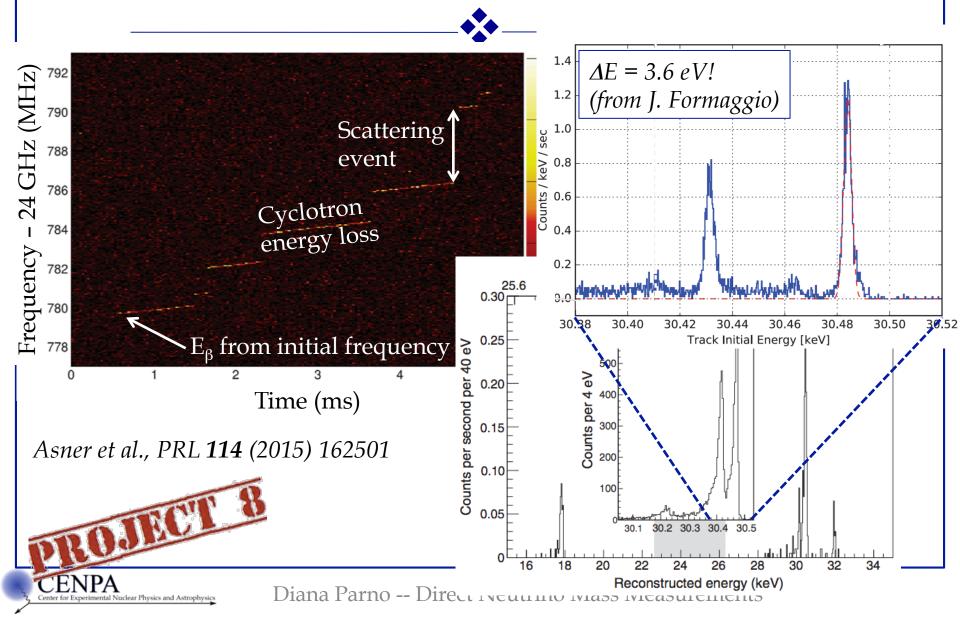
CRES Data from ^{83m}Kr Source

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

CRES Data from ^{83m}Kr Source

Scattering event

Cyclotron energy loss

E_β from initial frequency

Frequency – 24 GHz (MHz)

Time (ms)

noise ratio (linear)

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

PROJECT 8

Frequency (GHz)

Counts per second per 40 eV

Counts per 4 eV

Reconstructed energy (keV)

CRES Data from ^{83m}Kr Source

Frequency – 24 GHz (MHz)

Scattering event

Cyclotron energy loss

E_β from initial frequency

Time (ms)

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

Δ*E = 3.6 eV!*
(from J. Formaggio)

Counts / keV / sec

Track Initial Energy [keV]

Counts per second per 40 eV

Counts per 4 eV

Reconstructed energy (keV)

^{163}Ho: Microcalorimetry

Absorber — *Radioisotope*

Thermometer

Thermal link

Heat sink (sub-Kelvin)

✦ Absorber
  ✦ Sandwich ^{163}Ho inside

^{163}Ho: Microcalorimetry

Absorber

```
┌──────────────────┐
│     Absorber     │  ← Radioisotope
└──────────────────┘
      │
  ┌───────────┐
  │Thermometer│
  └───────────┘
      │
   Thermal
   link
      │
┌──────────────────┐
│    Heat sink     │
│   (sub-Kelvin)   │
└──────────────────┘
```

- ✦ Absorber
  - ✦ Sandwich ^{163}Ho inside
  - ✦ Convert energy to heat
  - ✦ Want low heat capacity C

$$\Delta T \approx \frac{\Delta E}{C}$$
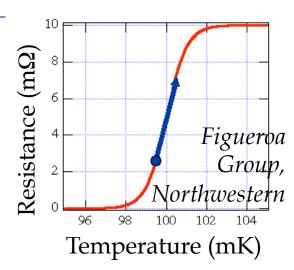
^{163}Ho: Microcalorimetry

Radioisotope

Absorber

Thermometer

Thermal link

Heat sink (sub-Kelvin)

- ✦ Absorber
  - ✦ Sandwich ^{163}Ho inside
  - ✦ Convert energy to heat
  - ✦ Want low heat capacity C

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

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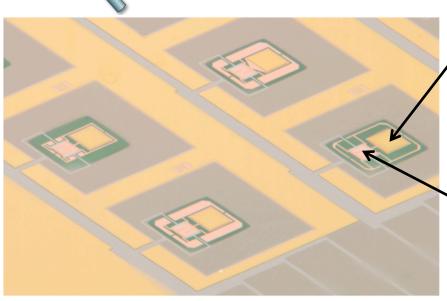 - ✦ SQUID readout

Transition Edge Sensor

- Thin film near superconducting T_c
- R depends strongly on T

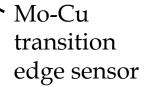*Figueroa Group, Northwestern*

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Transition Edge Sensor

- Thin film near superconducting T_c
- R depends strongly on T

HOLMES
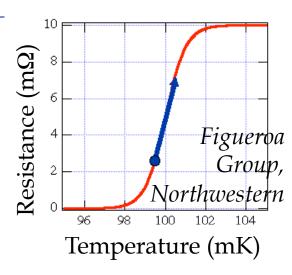
Au absorber with ^{163}Ho filling

Mo-Cu transition edge sensor

Figueroa Group, Northwestern

- Preliminary $\Delta E_{\text{FWHM}} \sim 4$ eV
- $\tau_{\text{rise}} \sim 6$ μs

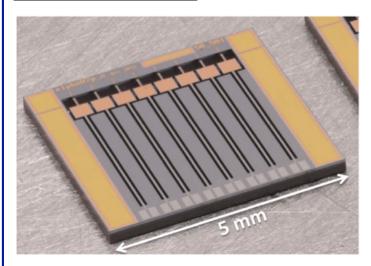*General reference: Alpert et al., Eur. Phys. J. C **75** 112 (2015)*
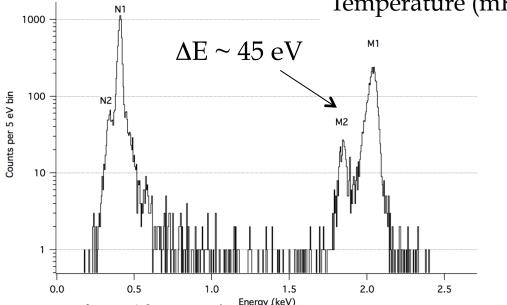
Transition Edge Sensor

❖

✦ Thin film near superconducting T_c
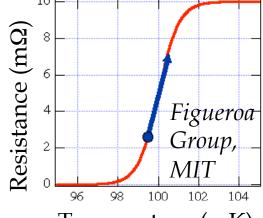
✦ R depends strongly on T

NuMECS

Figueroa Group, MIT

5 mm

$\Delta E \sim 45$ eV
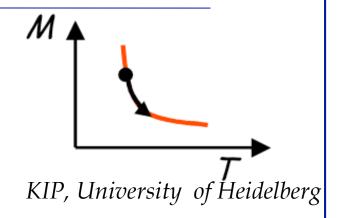
General reference: Croce et al., J. Low Temp. Phys. **184** *958 (2016)*
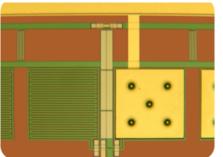
CENPA
Center for Experimental Nuclear Physics and Astrophysics

Magnetic Metallic Calorimeter

✦ Attach metallic paramagnet to absorber

✦ Heat disturbs magnetization

KIP, University of Heidelberg

Magnetic Metallic Calorimeter

M vs T

KIP, University of Heidelberg

✦ Attach metallic paramagnet to absorber

✦ Heat disturbs magnetization

ECHo

✦ Preliminary
$\Delta E_{FWHM} \sim 10$ eV

✦ $\tau_{rise} \sim 0.13$ μs

Two pixels, one day from L. Gastaldo

General reference: Gastaldo et al., J. Low Temp. Phys. 176 876 (2014)

CENPA
Center for Experimental Nuclear Physics and Astrophysics

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
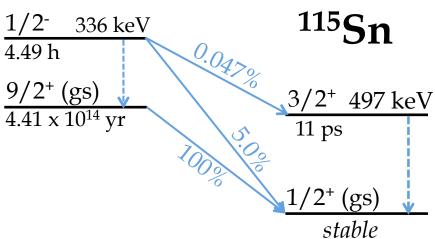- Low specific activity
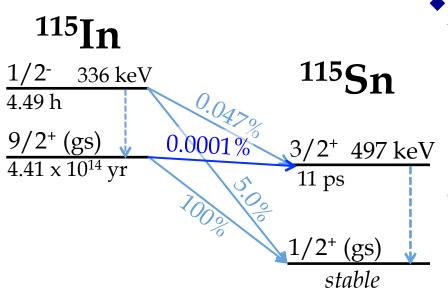
Community has moved on to ^{163}Ho

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

CENPA
Center for Experimental Nuclear Physics and Astrophysics

^{115}In: A Dark Horse Isotope?

^{115}In

1/2⁻   336 keV
4.49 h

9/2⁺ (gs)
4.41 x 10¹⁴ yr

^{115}Sn

0.047%

3/2⁺ 497 keV
11 ps

5.0%

100%

1/2⁺ (gs)
stable

^{115}In: A Dark Horse Isotope?

^{115}In

1/2⁻   336 keV
4.49 h

9/2⁺ (gs)
4.41 x 10¹⁴ yr

0.047 %

0.0001 %

5.0 %

100 %

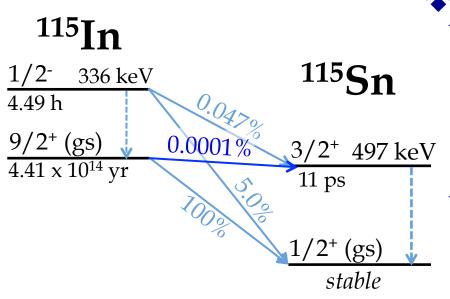**^{115}Sn**

3/2⁺ 497 keV
11 ps

1/2⁺ (gs)
stable

✦ 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)*

^{115}In: A Dark Horse Isotope?

^{115}**In**

1/2⁻   336 keV
4.49 h

9/2⁺ (gs)
4.41 x 10^{14} yr

^{115}**Sn**

0.047%

0.0001%

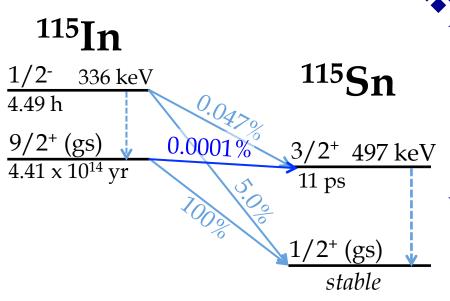3/2⁺   497 keV
11 ps

5.0%

100%

1/2⁺ (gs)
stable

✦ 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

^{115}In: A Dark Horse Isotope?

^{115}In

1/2⁻   336 keV
4.49 h

9/2⁺ (gs)
4.41 x 10^{14} yr

^{115}Sn

0.047%

0.0001%

3/2⁺ 497 keV
11 ps

5.0%

100%

1/2⁺ (gs)
stable

✦ 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.

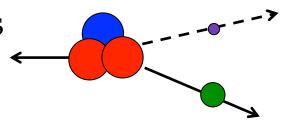*-- Andreotti et al., PRC **84** 044605 (2011)*

Outline

- Probes of neutrino mass: An introduction
- How to measure a spectrum
- **Theoretical challenges**
- A few experimental challenges
- Light neutrino, bright future

T$_2$: Molecular Final-State Distribution

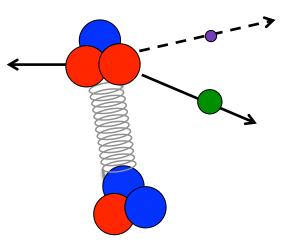✦ Electronic excitations in T atoms

T$_2$: Molecular Final-State Distribution

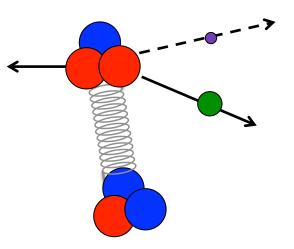- ✦ Electronic excitations in T atoms

- ✦ Excitations in T$_2$ gas
  - ✧ Electronic: 20 eV
  - ✧ Vibrational: ~0.1 eV
  - ✧ Rotational: ~0.01 eV

T_2: Molecular Final-State Distribution

- ✦ Electronic excitations in T atoms

- ✦ Excitations in T_2 gas
    - ✧ Electronic: 20 eV
    - ✧ Vibrational: ~0.1 eV
    - ✧ Rotational: ~0.01 eV

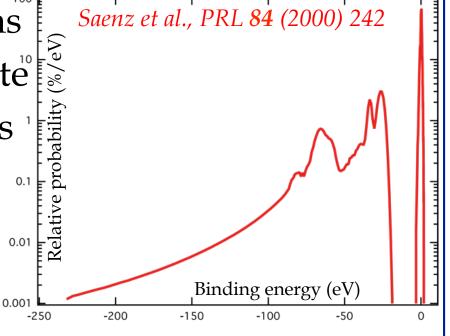- ✦ Beta spectrum depends on excitation energies V_k **and** probabilities P_k

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

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

Describing T$_2$ Final States
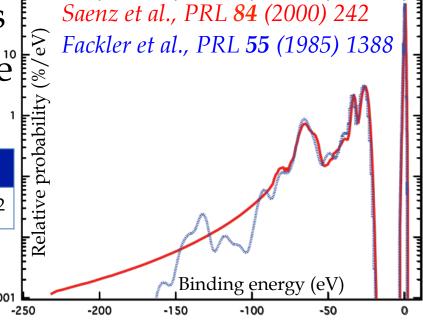
✦ Precise ab initio calculations

✦ Uncertainty hard to estimate

✦ Enters directly into analysis

Saenz et al., PRL 84 (2000) 242

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Describing T$_2$ Final States

✦ Precise ab initio calculations

✦ Uncertainty hard to estimate

✦ Enters directly into analysis

Calculation	LANL m$_\nu^2$	LLNL m$_\nu^2$
1985	-147(79) eV²	-130(25) eV²

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

*Saenz et al., PRL **84** (2000) 242*

*Fackler et al., PRL **55** (1985) 1388*

Relative probability (%/eV)

Binding energy (eV)

Describing T$_2$ Final States

✦ Precise ab initio calculations

✦ Uncertainty hard to estimate

✦ Enters directly into analysis

Calculation	LANL m$_\nu^2$	LLNL m$_\nu^2$
1985	-147(79) eV^2	-130(25) eV^2
2000 (est.)	20(79) eV^2	37(25) eV^2

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

Saenz et al., PRL 84 (2000) 242
Fackler et al., PRL 55 (1985) 1388

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Describing T$_2$ Final States

- Precise ab initio calculations
- Uncertainty hard to estimate
- Enters directly into analysis

Calculation	LANL m$_\nu^2$	LLNL m$_\nu^2$
1985	-147(79) eV^2	-130(25) eV^2
2000 (est.)	20(79) eV^2	37(25) eV^2

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

*Saenz et al., PRL **84** (2000) 242*
*Fackler et al., PRL **55** (1985) 1388*

Relative probability (%/eV) vs Binding energy (eV)
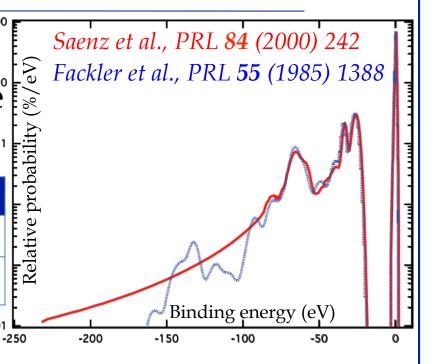
- KATRIN needs σ_{FSD} to 1%
  - New calculations
  - Initial-state source characterization
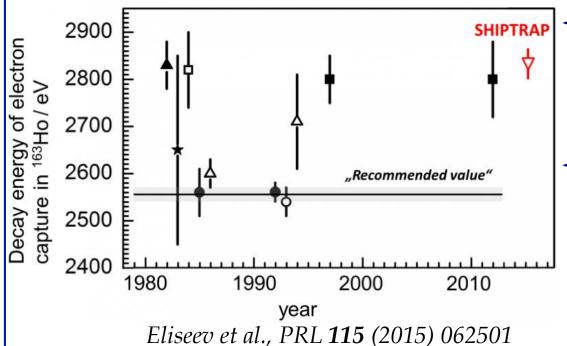- TRIMS experiment to resolve historical discrepancy

Q Value for ^{163}Ho Decay

- *Q* = *A* – *A*′ (ground states)
- For ^{163}Ho and ^{163}Dy, *Q* inferred from spectrum
- Significant disagreements between techniques

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

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Q Value for ^{163}Ho Decay

ECHo

- $Q = A - A'$ (ground states)
- For ^{163}Ho and ^{163}Dy, Q inferred from spectrum
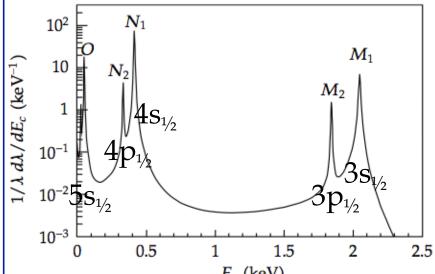- Significant disagreements between techniques

- 2015: dedicated Q measurement with SHIPTRAP
- $Q = 2833(30)(15)$ eV
  - Lower statistics
  - Separated from spectral features

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

CENPA
Center for Experimental Nuclear Physics and Astrophysics
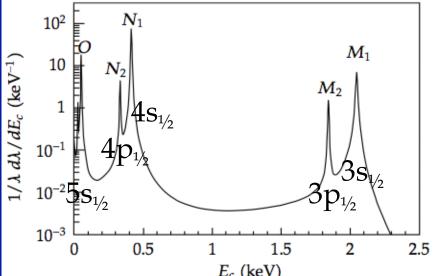
^{163}Ho: Shakeup

✦ Standard spectral calculation assumes 1 e$^-$ vacancy

✦ What about ^{163}Dy* states with two or more holes?

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

^{163}Ho: Shakeup

✦ Standard spectral calculation assumes 1 e⁻ vacancy

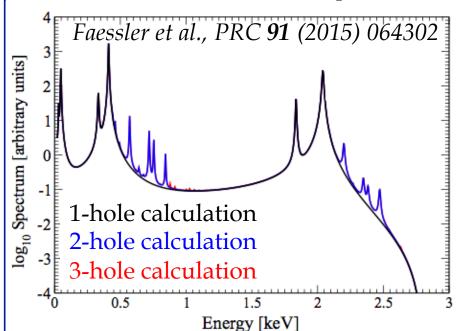✦ What about ^{163}Dy* states with two or more holes?

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

✦ New resonance(s)

✦ Structure near endpoint complicates m_ν^2 extraction

Robertson, PRC **91** *(2015) 035504*
Faessler and Šimkovic, PRC **91** *(2015) 045505*
Faessler et al., PRC **91** *(2015) 064302*

^{163}Ho: Shakeup

- Standard spectral calculation assumes 1 e$^-$ vacancy
- What about ^{163}Dy* states with two or more holes?

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

1-hole calculation
2-hole calculation
3-hole calculation

- New resonance(s)
- Structure near endpoint complicates m_ν^2 extraction

*Robertson, PRC **91** (2015) 035504*
*Faessler and Šimkovic, PRC **91** (2015) 045505*
*Faessler et al., PRC **91** (2015) 064302*
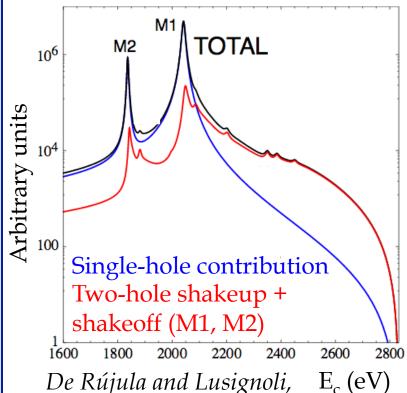
- Looks like a few % effect, separated from endpoint

^{163}Ho: Shakeoff

✦ Electrons can also be excited to the continuum

  ✦ 3-body process, $^{163}\text{Ho} \longrightarrow {}^{163}\text{Dy}[H,H'] + e^- + \nu_e$

^{163}Ho: Shakeoff

✦ Electrons can also be excited to the continuum

    ✦ 3-body process, ^{163}Ho $\longrightarrow$ ^{163}Dy$[H,H']$ + e⁻ + ν_e

        ✦ Recent preliminary calculations near endpoint

Single-hole contribution
Two-hole shakeup + shakeoff (M1, M2)
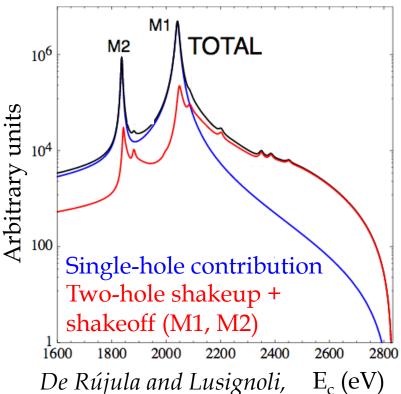
*De Rújula and Lusignoli, JHEP **2016** 15, 2016*

^{163}Ho: Shakeoff

✦ Electrons can also be excited to the continuum

  ✦ 3-body process, ^{163}Ho $\longrightarrow$ ^{163}Dy[*H,H'*] + e⁻ + ν_e

Single-hole contribution
Two-hole shakeup +
shakeoff (M1, M2)

*De Rújula and Lusignoli, JHEP **2016** 15, 2016*

✦ Recent preliminary calculations near endpoint

  ✦ Enhanced statistics (40x near endpoint)

  ✦ Relative pileup contribution reduced

  ✦ More complex analysis?

✦ Ongoing theory work

Outline

❖

✦ Probes of neutrino mass: An introduction

✦ How to measure a spectrum

✦ Theoretical challenges

✦ A few experimental challenges

✦ Light neutrino, bright future

From Proof of Principle to m_ν^2

✦ Further study needed:
  - ✦ Target activity
  - ✦ Homogeneity of magnetic field
  - ✦ Lifetime of e⁻ in trap
  - ✦ Background
    - ✦ Suppressed by design
  - ✦ Molecular final states
    - ✦ Atomic T source?

Phase I (^{83m}Kr)

Phase II (T_2)

Images from Project 8 collaboration

Tritium Challenges

- T_2 is simple in principle, but hard in practice
- Example: Mainz experiment (quench-condensed T_2)
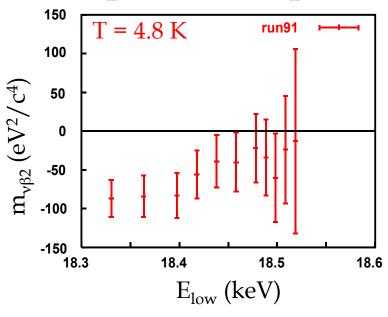

Figure from B. Bornschein

Tritium Challenges

✦ T_2 is simple in principle, but hard in practice

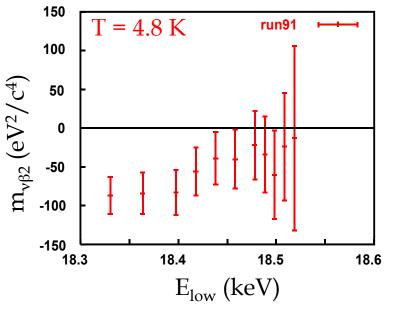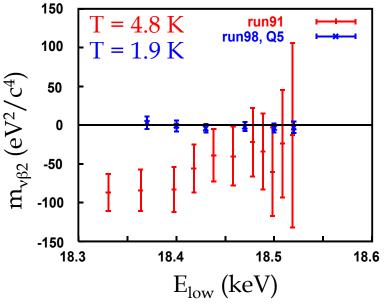✦ Example: Mainz experiment (quench-condensed T_2)

Figure from B. Bornschein

✦ The culprit: Source dewetting over time
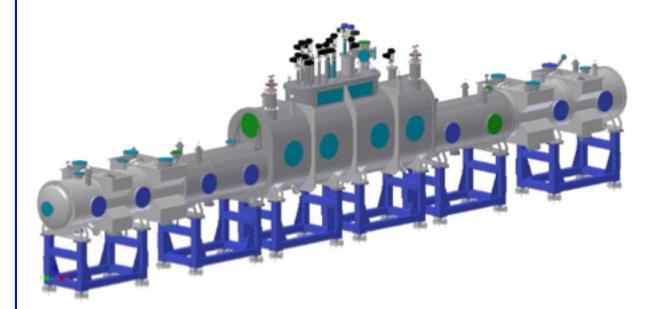
✦ Irregular structure, extra energy loss

*Fleischmann et al., Eur. Phys. J. B **16** (2000) 521*

Tritium Challenges

✦ T_2 is simple in principle, but hard in practice

✦ Example: Mainz experiment (quench-condensed T_2)

T = 4.8 K — run91
T = 1.9 K — run98, Q5

$m_{\nu\beta 2}$ (eV^2/c^4) vs E_{low} (keV)

Figure from B. Bornschein

✦ The culprit: Source dewetting over time

✦ Irregular structure, extra energy loss

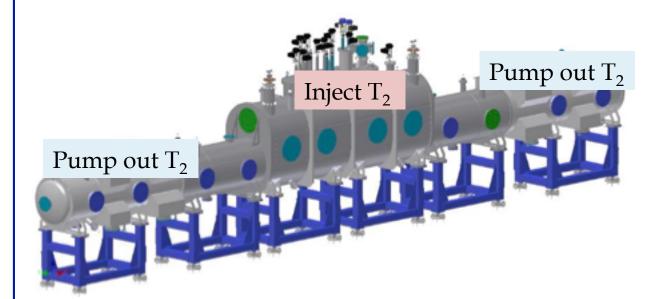*Fleischmann et al., Eur. Phys. J. B **16** (2000) 521*

KATRIN Source

❖

✦ Windowless, gaseous T_2 in 16m cryostat at 30K

KATRIN Source
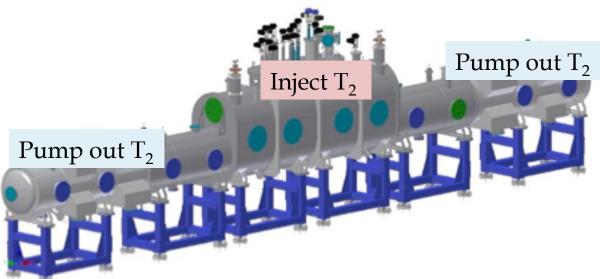
✦ Windowless, gaseous T_2 in 16m cryostat at 30K

KATRIN Source

✦ Windowless, gaseous T_2 in 16m cryostat at 30K

✦ Stability is crucial:

Pump out T_2

Inject T_2

Pump out T_2

✦ Temperature

✦ Inlet/outlet pressure

✦ Isotopic composition

✦ Rate

✦ Scattering
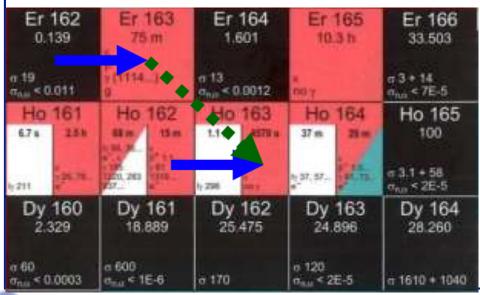
✦ ...

*Babutzka et al., New J. Phys. **14** (2012) 103046*

CENPA
Center for Experimental Nuclear Physics and Astrophysics

^{163}Ho Production

- ✦ Two ways to make ^{163}Ho
  - ✦ Neutron irradiation of $^{162}Er_2O_3$
    - ✦ Large σ, significant radio impurities

Gatti, ν Telescopes 2015 (HOLMES)

^{163}Ho Production
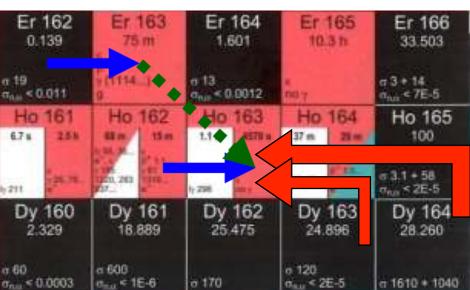
- ✦ Two ways to make ^{163}Ho
  - ✦ Neutron irradiation of $^{162}Er_2O_3$
    - ✦ Large σ, significant radio impurities
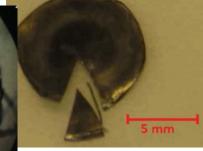 - ✦ Proton irradiation of ^{nat}Dy
    - ✦ Small σ, high purity
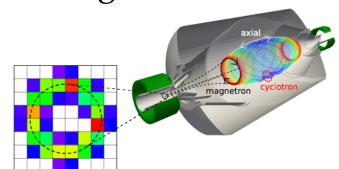
NuMECS

Gatti, ν Telescopes 2015 (HOLMES)

*Croce et al., J. Low Temp. Phys. **184** 958 (2016) (NuMECS)*

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Backgrounds

- m$_\nu^2$ sensitivity goes as sixth root of background rate

- Novel background sources in large MAC-E filter, e.g.

*Wandkowsky et al., J. Phys. G **40** (2013) 085102*

Backgrounds

+ m_ν^2 sensitivity goes as sixth root of background rate

+ Novel background sources in large MAC-E filter, e.g.

*Wandkowsky et al., J. Phys. G **40** (2013) 085102*
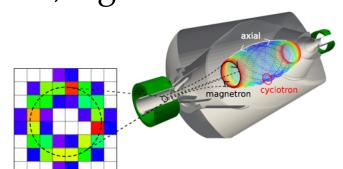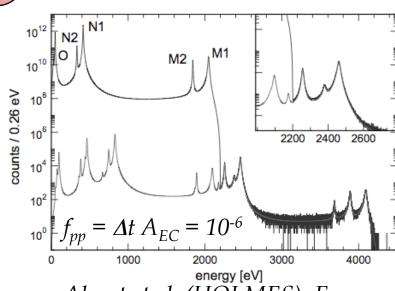
+ Worst "background" source is pileup

+ Limits activity/pixel

$f_{pp} = \Delta t\, A_{EC} = 10^{-6}$

*Alpert et al. (HOLMES), Eur. Phys. J. C **75** (2015) 112*

Acknowledgments

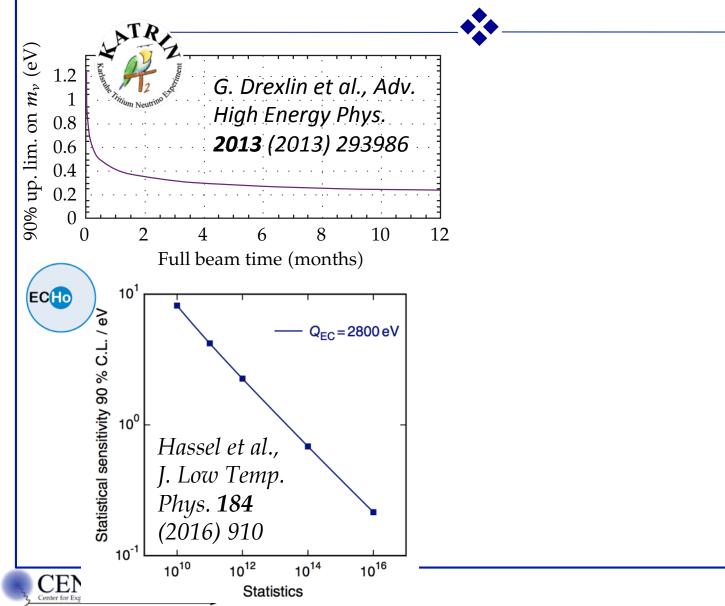*Determination of the absolute (anti)neutrino mass, ECT* workshop, Trento, Italy, April 2016*
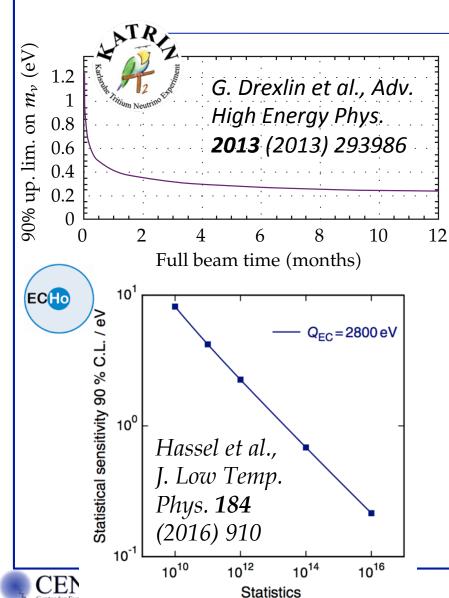
✦ KITP and the organizers

✦ The direct neutrino-mass measurement community
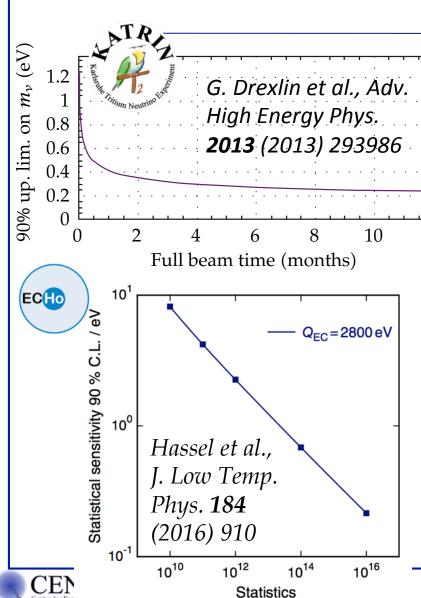
U.S. DEPARTMENT OF ENERGY | Office of Science

The Next Few Years...

90% up. lim. on m_ν (eV)

Full beam time (months)

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

Statistical sensitivity 90 % C.L. / eV

$Q_{EC} = 2800\,\text{eV}$

Statistics

*Hassel et al., J. Low Temp. Phys. **184** (2016) 910*

ECHo

CEN
Center for Exp

The Next Few Years...

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

90% up. lim. on m_ν (eV)

Full beam time (months)

✦ KATRIN "first light"

✦ Final Project 8 ^{83m}Kr spectra

Statistical sensitivity 90 % C.L. / eV

$Q_{EC} = 2800$ eV

Hassel et al., J. Low Temp. Phys. **184** (2016) 910

Statistics

CEN
Center for Exp

The Next Few Years...

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

Hassel et al., J. Low Temp. Phys. **184** (2016) 910

2016

✦ KATRIN "first light"

✦ Final Project 8 ^{83m}Kr spectra

2017

✦ Start of KATRIN T_2 data

✦ HOLMES prototype array

✦ T_2 spectrum from Project 8

The Next Few Years...

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

$Q_{EC} = 2800$ eV

Hassel et al., J. Low Temp. Phys. **184** (2016) 910

2016

✦ KATRIN "first light"

✦ Final Project 8 ^{83m}Kr spectra

2017

✦ Start of KATRIN T_2 data

✦ HOLMES prototype array
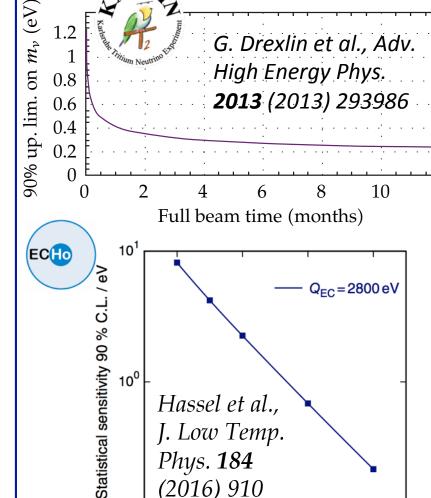
✦ T_2 spectrum from Project 8

2018

✦ Full HOLMES operation

✦ ECHo-1k (1000 Bq) ends

✦ ECHo-1M gets underway

… and Beyond

³H

- ✦ Design **KATRIN** sensitivity ~0.2 eV after 5 yrs
- ✦ Phase III of **Project 8** (2016-2020) targets 2 eV in 1 yr
- ✦ Ultimate Phase IV of **Project 8** could probe hierarchy with atomic tritium

¹⁶³Ho

- ✦ **NuMECS** data will test theory, detector modeling
- ✦ **HOLMES** target: 1.5 eV stat. sensitivity in 3 yrs
- ✦ **ECHo-1M** could reach <1 eV stat. sensitivity by 2021

Thank you!