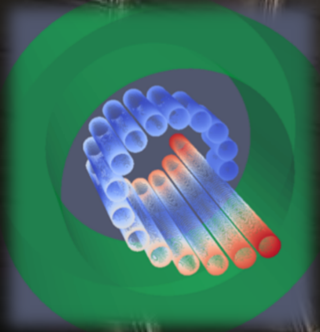
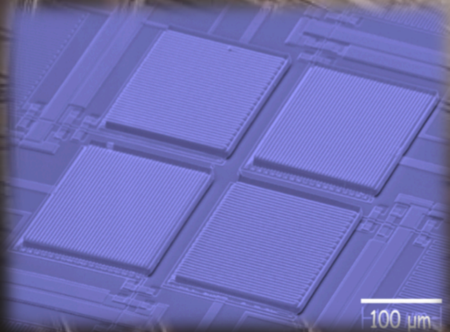
Direct Neutrino Mass Measurements

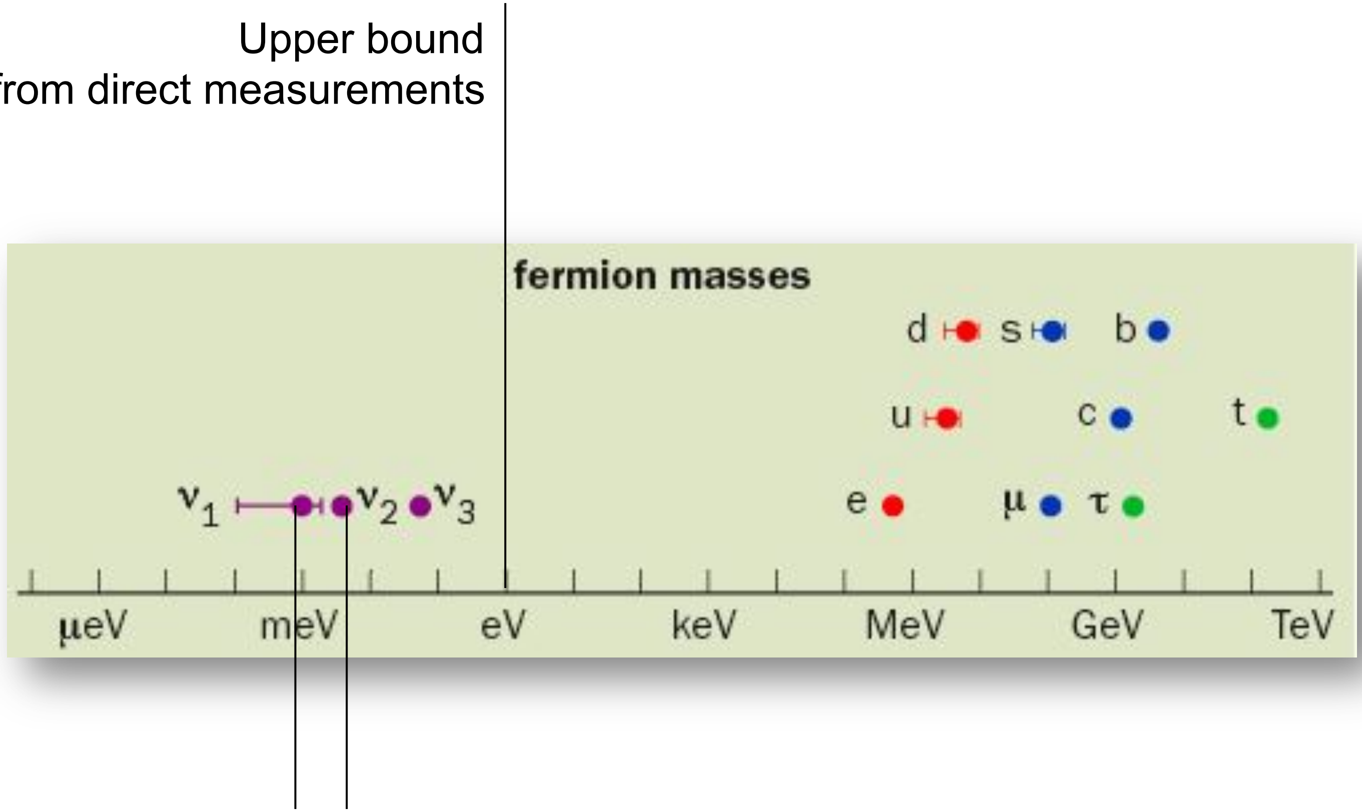
Susanne Mertens
Invisibles 2015

Unterstützt von / Supported by Alexander von Humboldt Stiftung / Foundation
HELMHOLTZ ASSOCIATION
KIT Karlsruhe Institute of Technology
BERKELEY LAB

Neutrino mass

Upper bound
from direct measurements



Lower bound
from oscillation experiments

Neutrino mass

Cosmology

model-dependent
potential: Σm_i = 20-50 meV
e.g. Planck

Search for 0νßß

model-dependent
potential: $m_{ßß}$ = 20-50 meV
e.g. MAJORANA

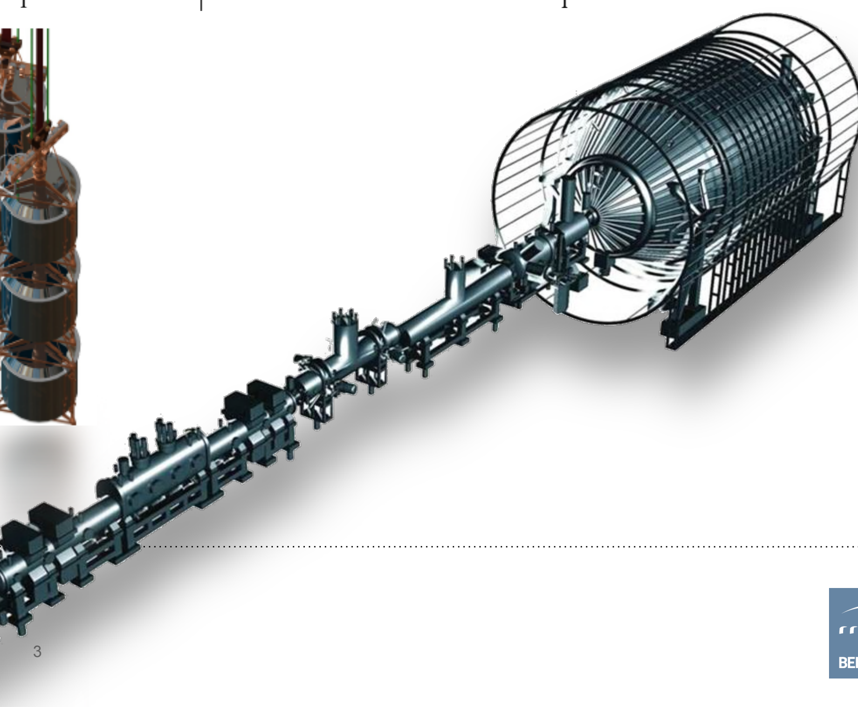
Kinematics of ß-decay

model-independent
potential: m_ν = 200 meV
e.g. KATRIN

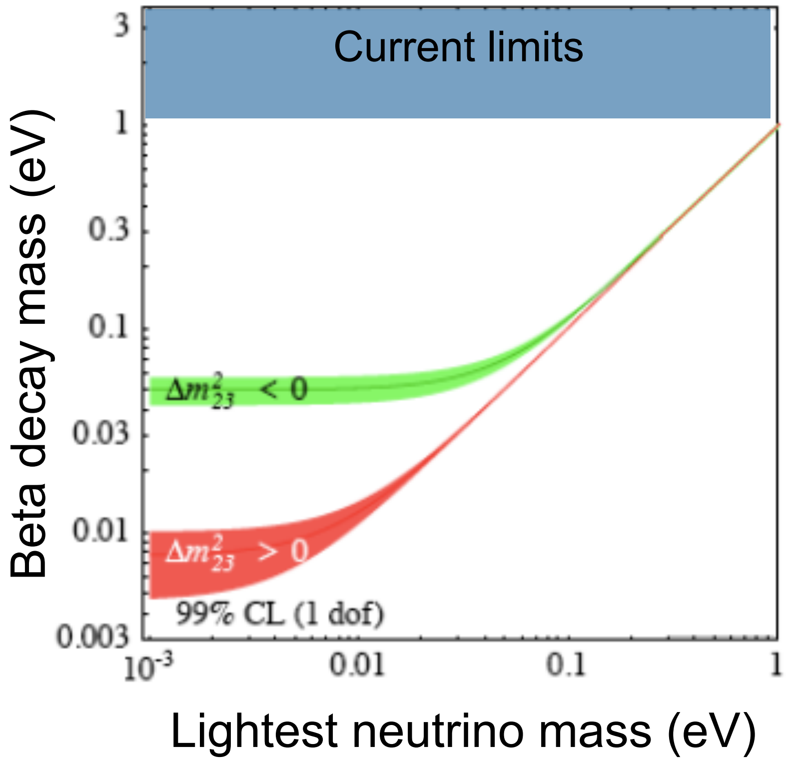
$$m_\nu = \sum_i m_i$$

$$m_{\beta\beta} = \left| \sum_{\rm i} U_{\rm ei}^2 \cdot m_{\nu_{\rm i}} \right|$$

$$m_{\nu_{\rm e}}^2 = \sum_{\rm i} |U_{\rm ei}|^2 \cdot m_{\nu_{\rm i}}^2$$



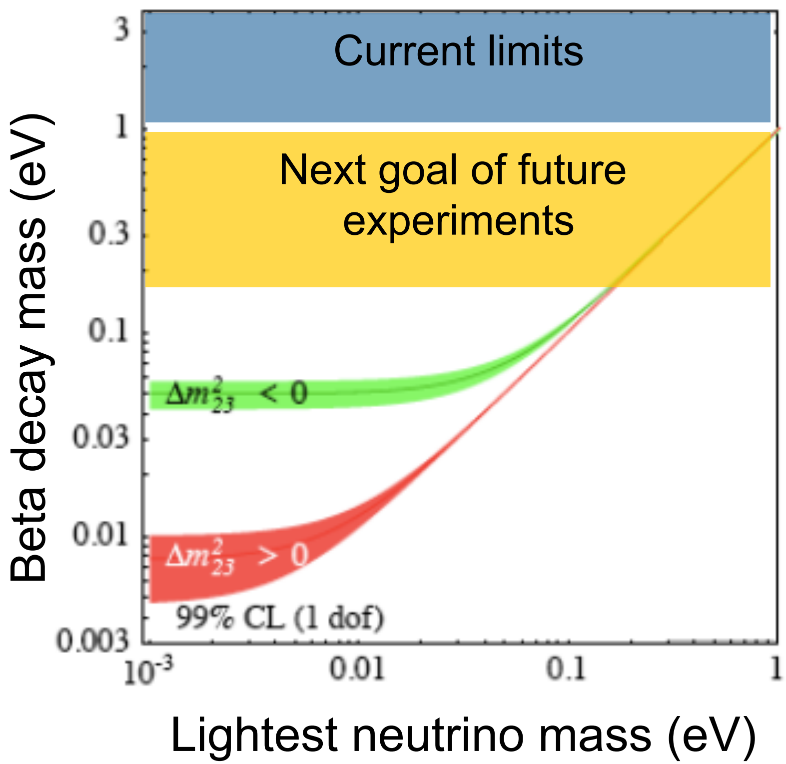
Neutrino mass



- Neutrinos excluded as Dark Matter

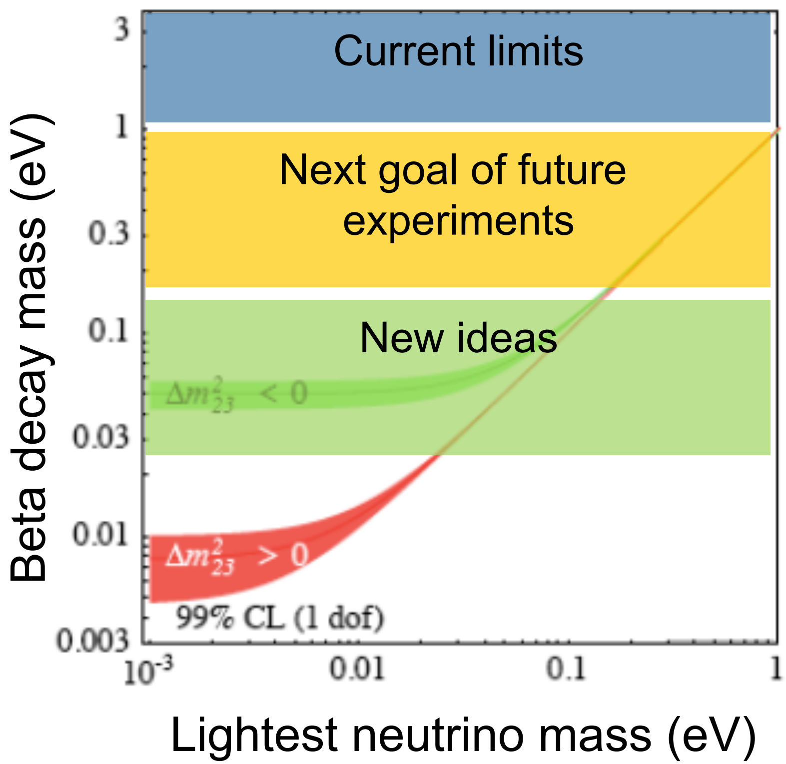
V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

Neutrino mass



- Neutrinos excluded as Dark Matter
- Distinquish between hierarchical and degenerate scenario, impact on structure formation

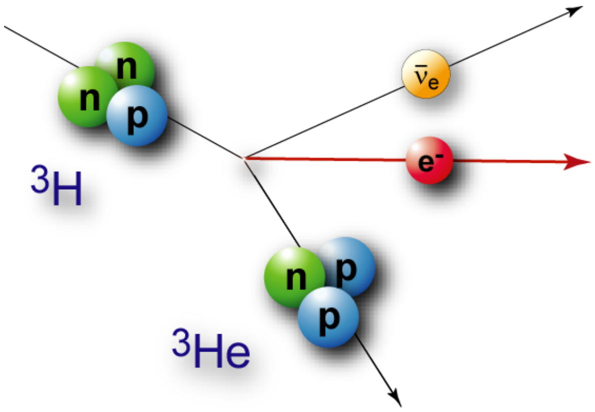
Neutrino mass

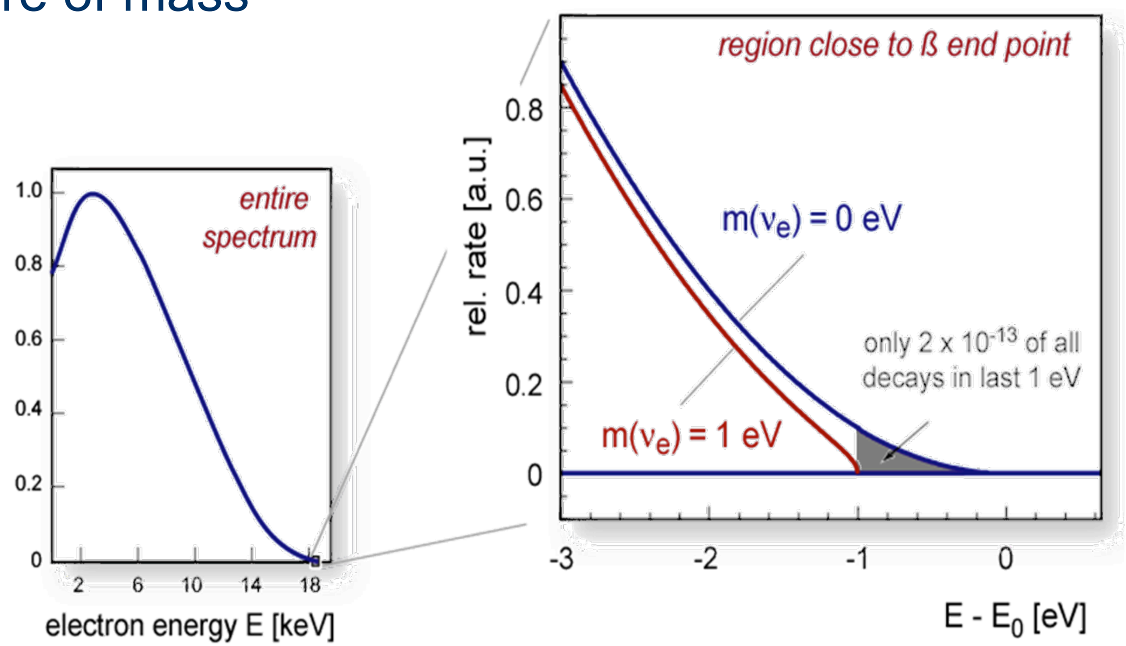


- Neutrinos excluded as Dark Matter
- Distinquish between hierarchical and degenerate scenario, impact on structure formation
- Resolve neutrino mass hierarchy

General Idea

- A kinematic determination of the neutrino mass
- No model dependence on cosmology or nature of mass

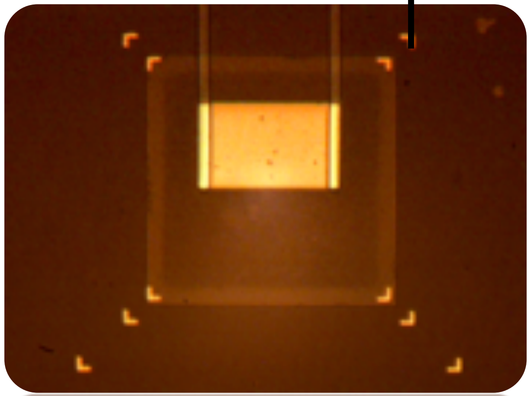




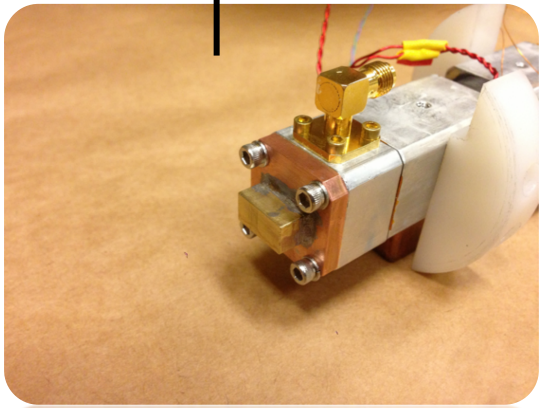
3 Experimental Efforts

Spectroscopy
(KATRIN)

Calorimetry
(HOLMES, ECHO
&NUMECS)



Frequency
(Project 8)



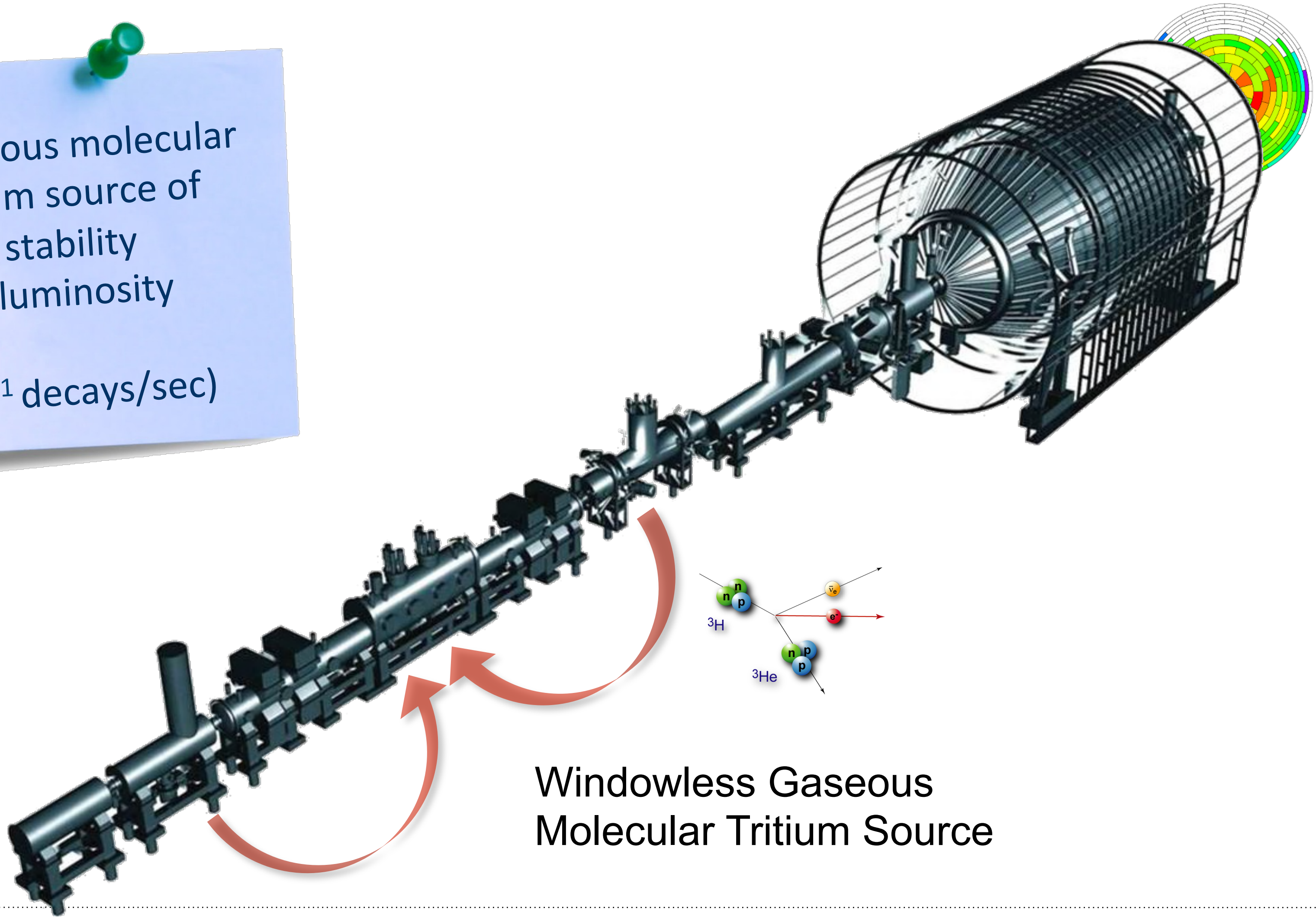
Karlsruhe Tritium Neutrino Experiment

- International Collaboration: 120 members
- 15 institutions in 5 countries: D, US, UK, CZ, RUS
- Reference ν-mass sensitivity: $m(\nu_e)$ = 200 meV, after 3 years

KATRIN Overview

Gaseous molecular tritium source of high stability and luminosity

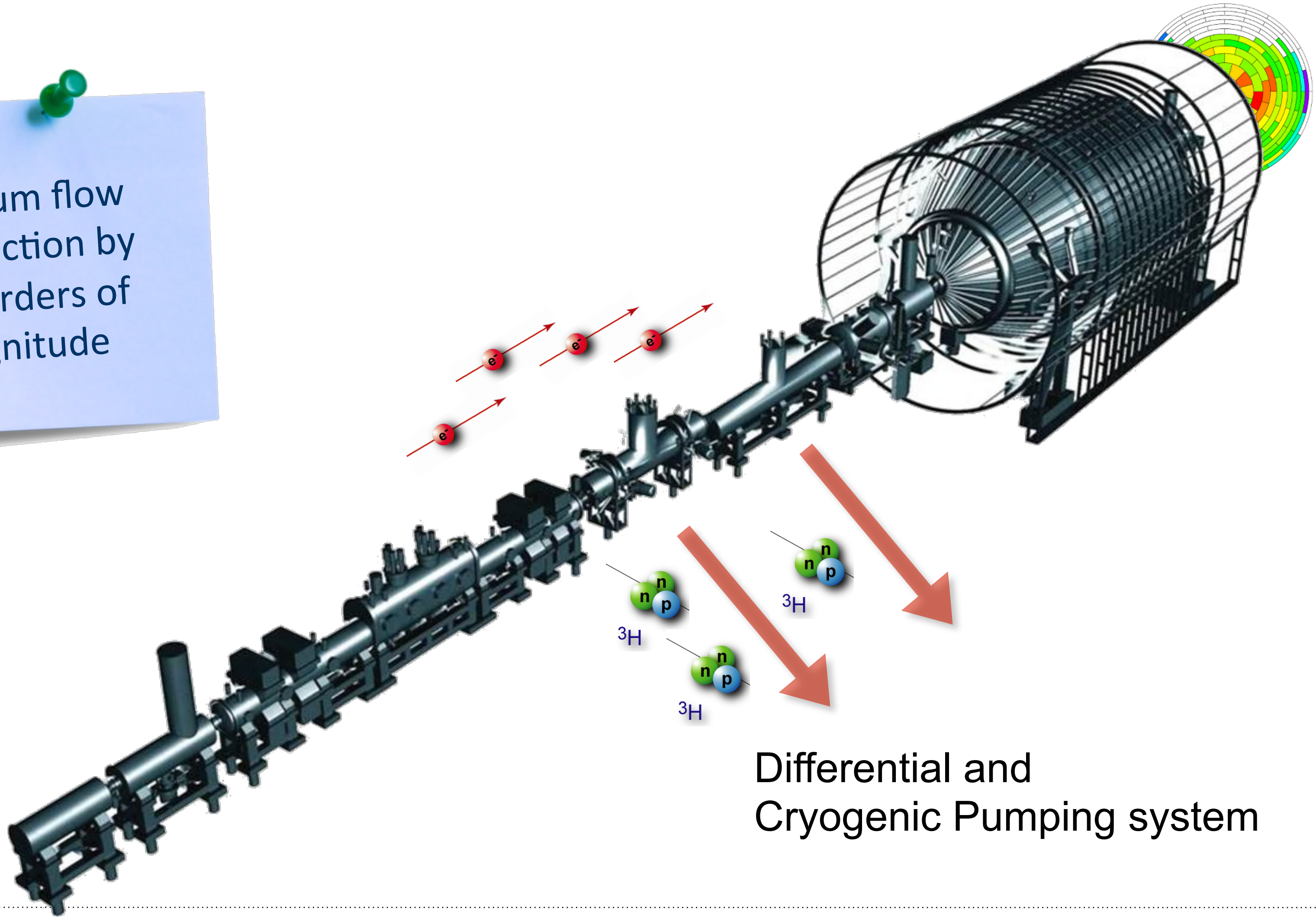
(10^{11} decays/sec)



Windowless Gaseous Molecular Tritium Source

KATRIN Overview

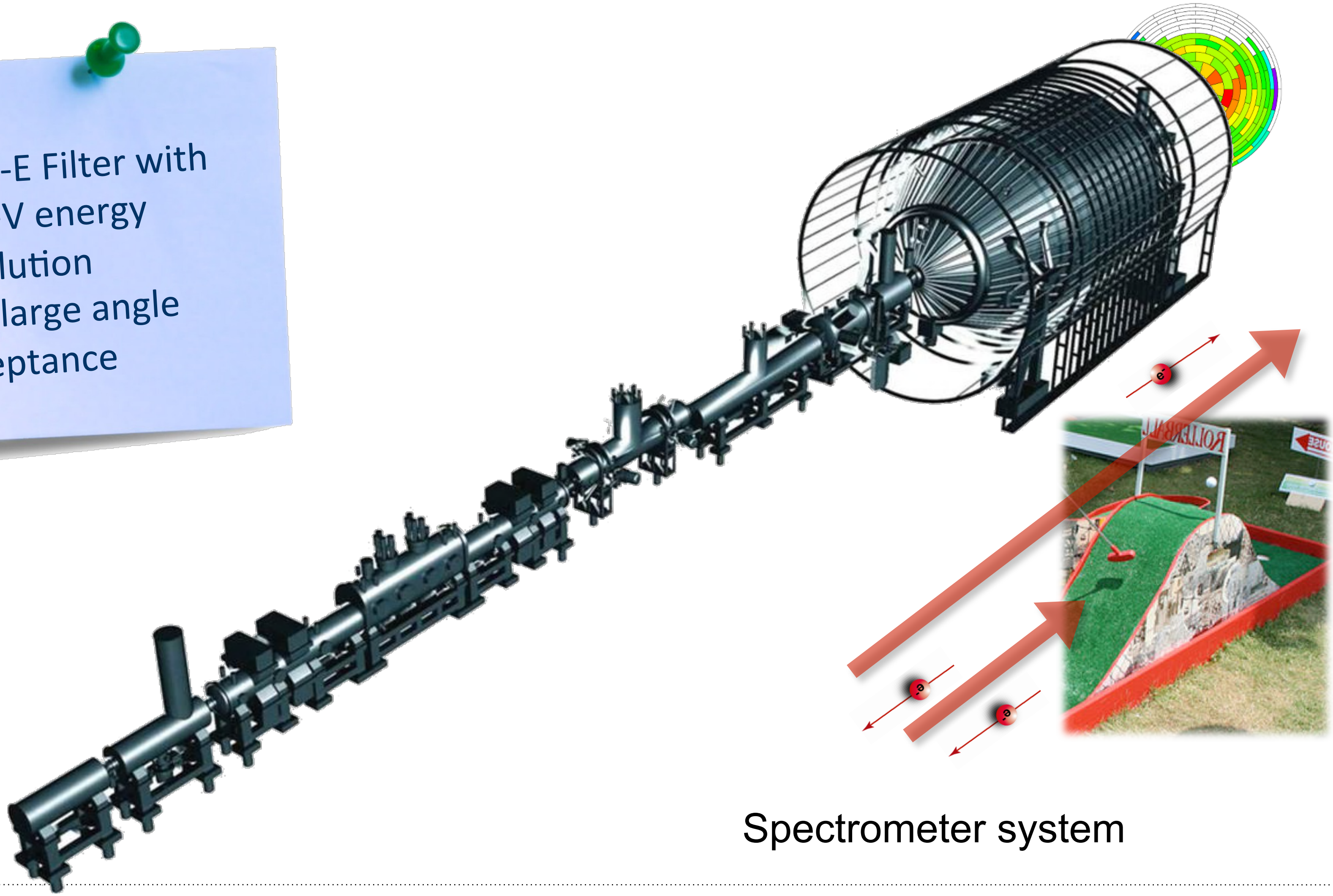
Tritium flow reduction by 14 orders of magnitude



Differential and
Cryogenic Pumping system

KATRIN Overview

MAC-E Filter with
< 1 eV energy
resolution
and large angle
acceptance



Spectrometer system

KATRIN Overview

MAC-E Filter with
< 1 eV energy
resolution
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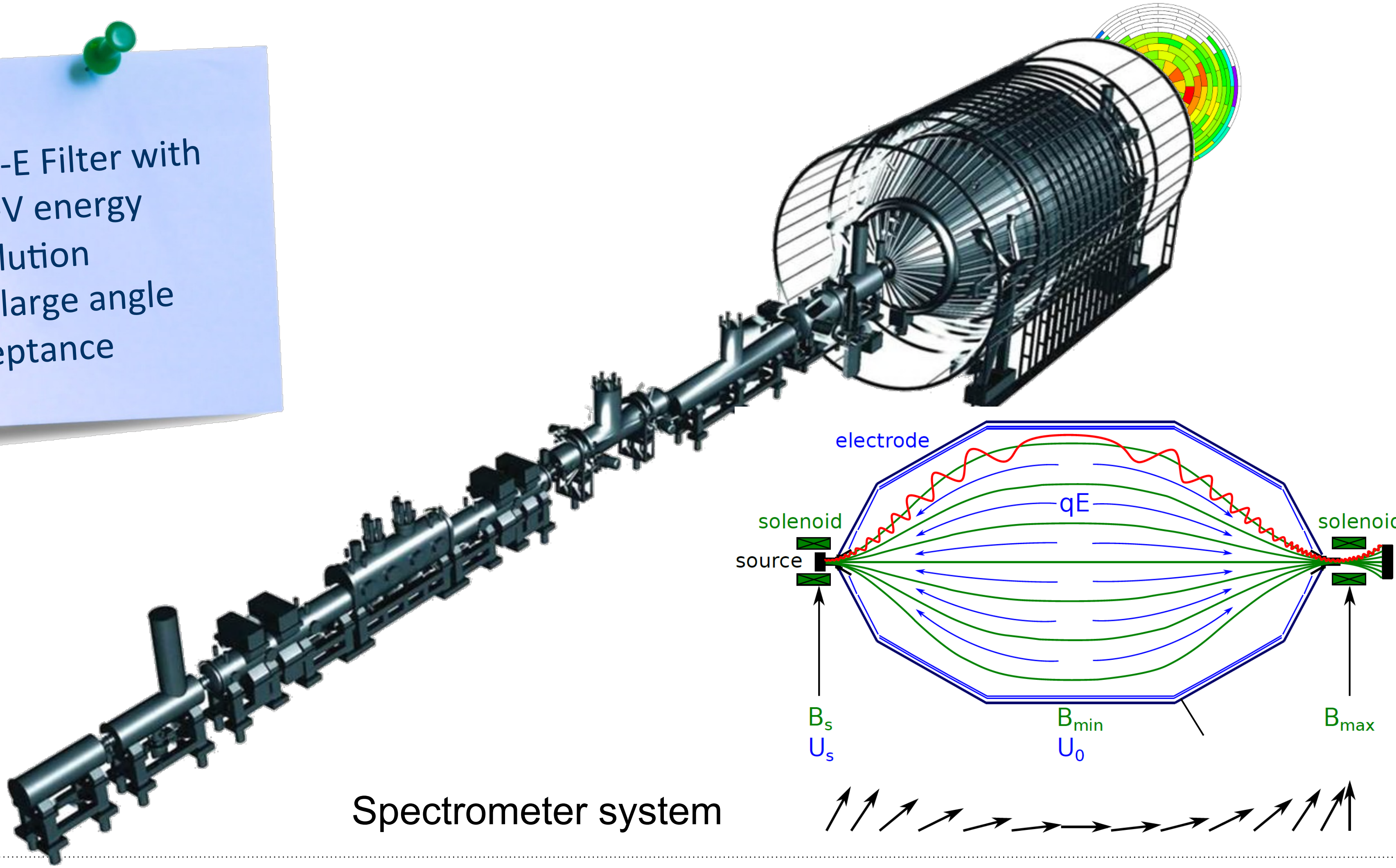
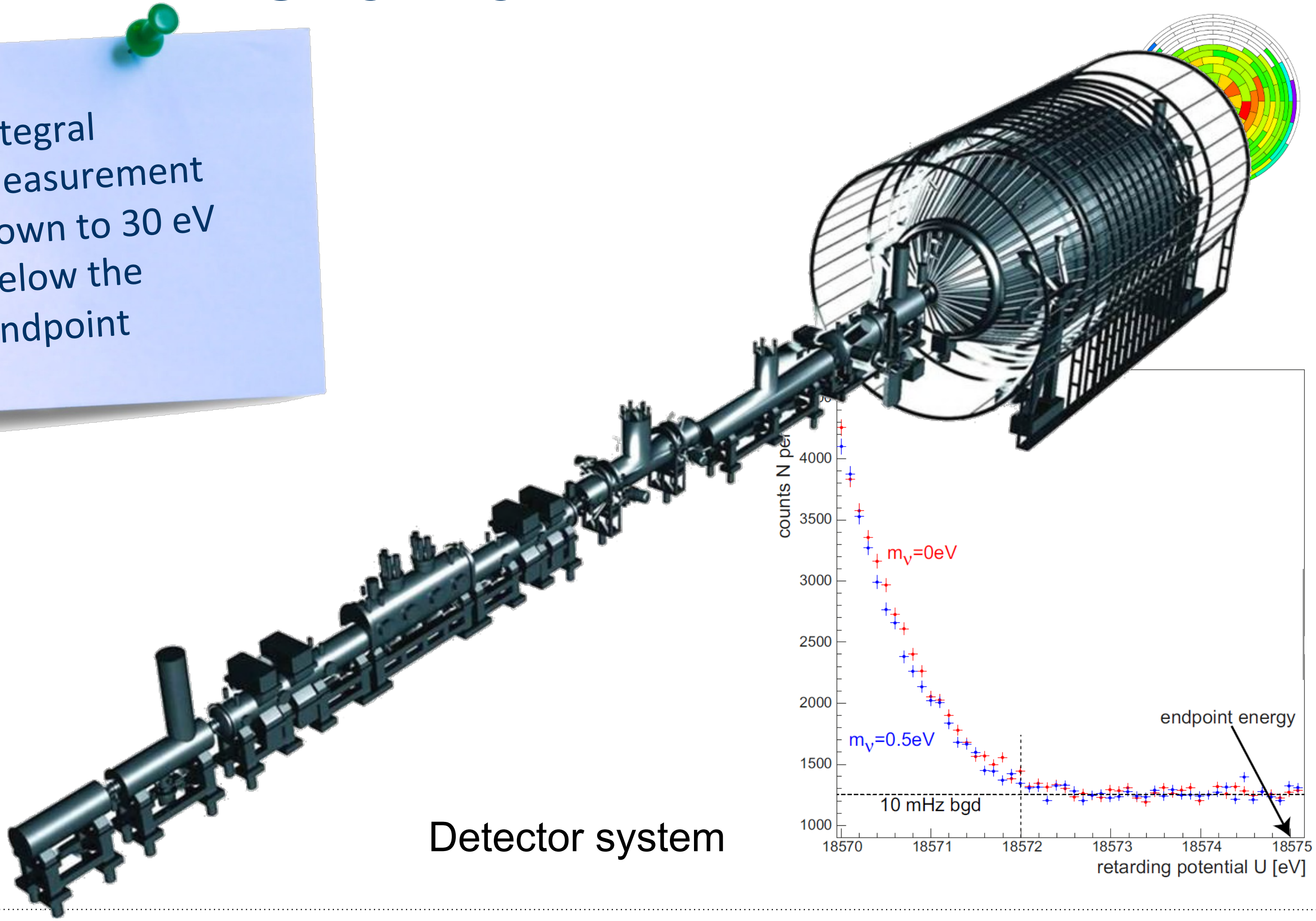
acceptance



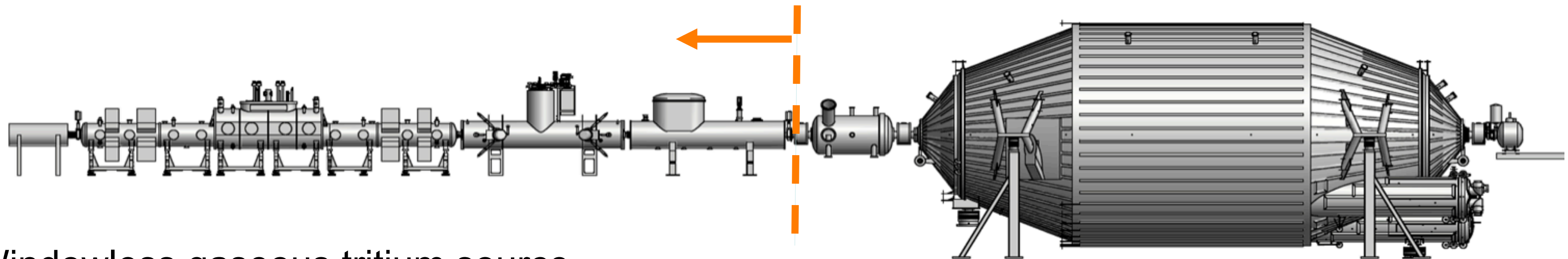
Spectrometer system

KATRIN Overview

Integral measurement down to 30 eV below the endpoint



KATRIN Source Status



Windowless gaseous tritium source

→ delivery this year

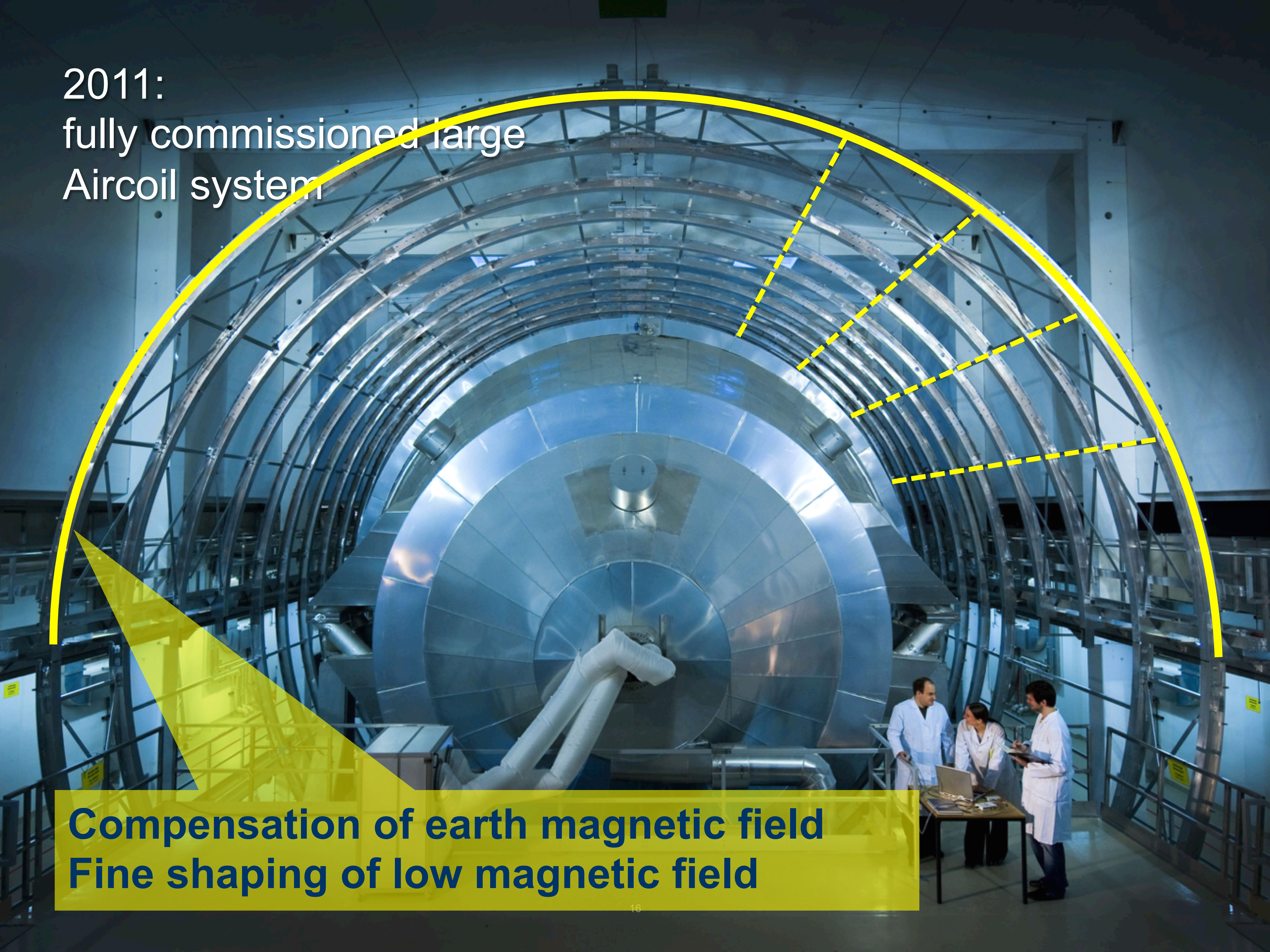
Differential pumping section

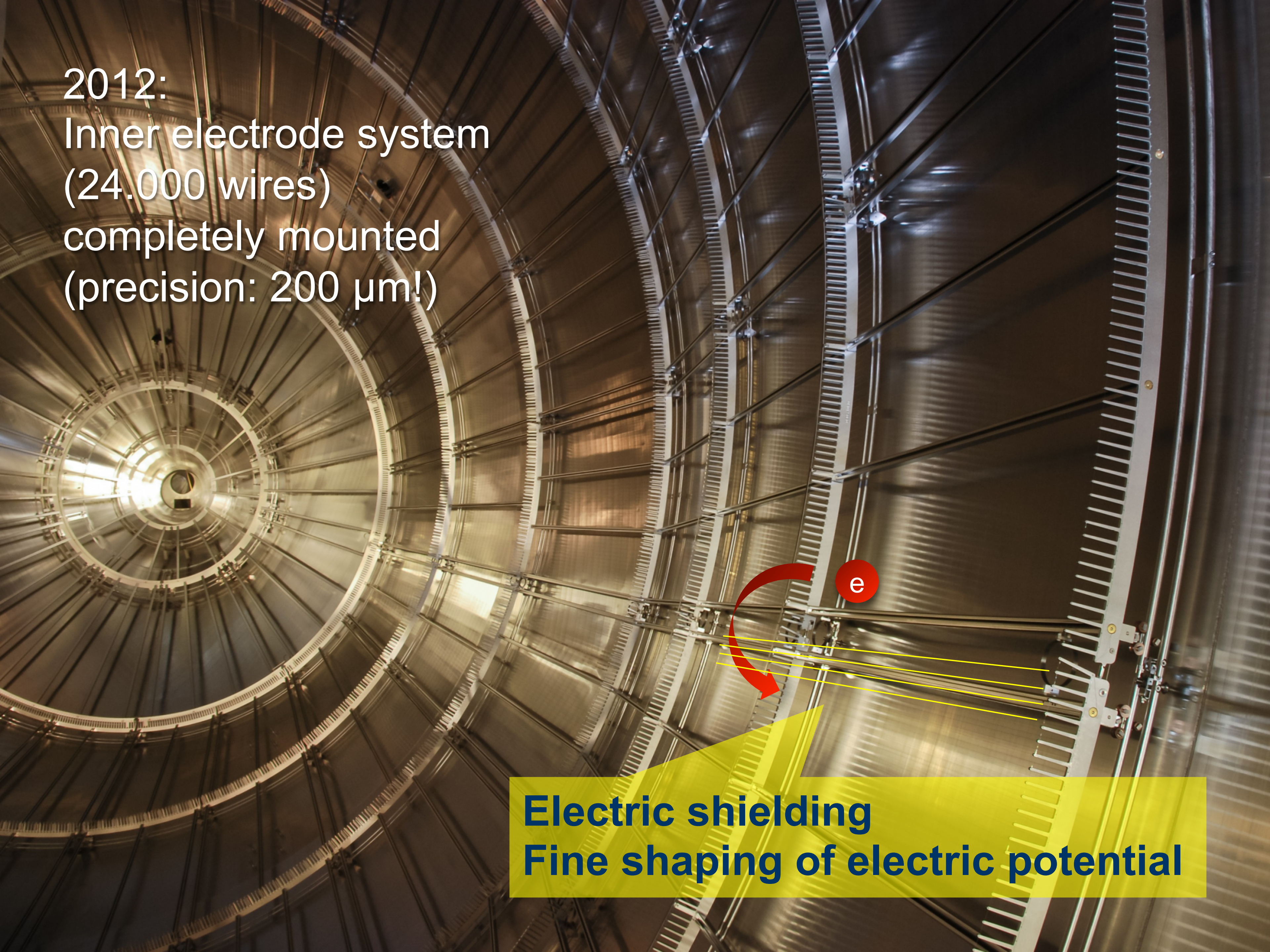
→ Commissioning at KIT

Cryogenic pumping section

→ Delivery this year

Source System integrated in mid-2016


2011:
fully commissioned large
Aircoil system
Compensation of earth magnetic field
Fine shaping of low magnetic field

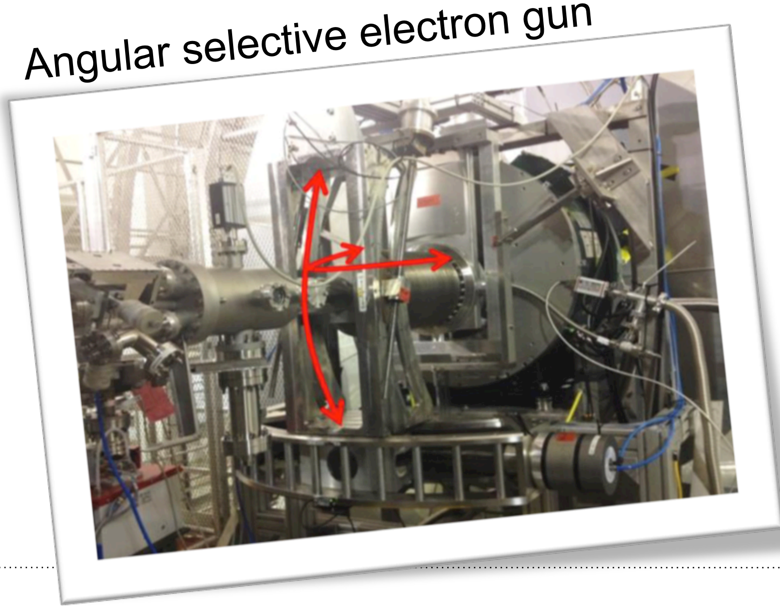

2012:
Inner electrode system
(24.000 wires)
completely mounted
(precision: 200 µm!)
e
Electric shielding
Fine shaping of electric potential

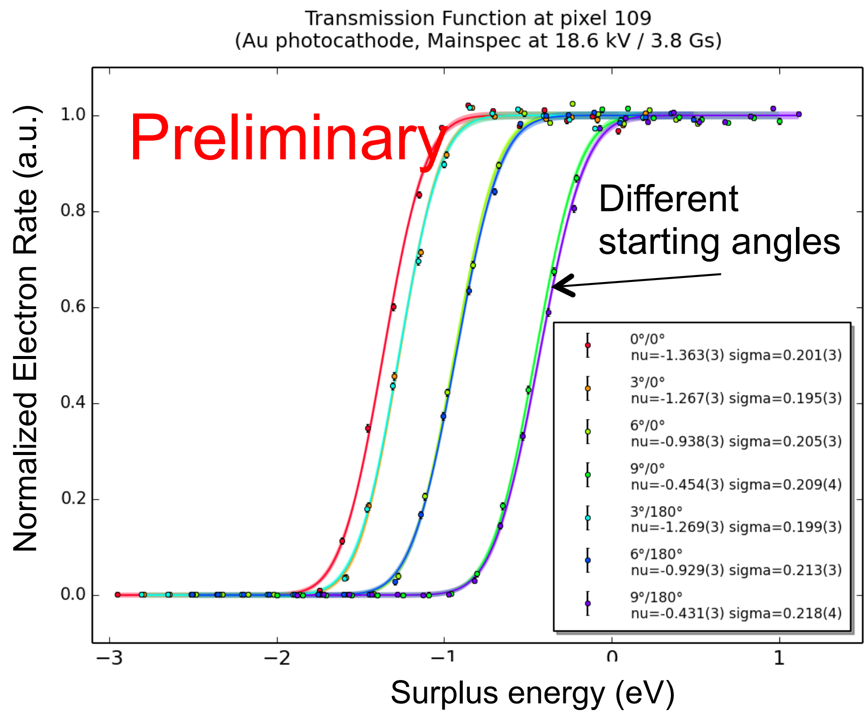
KATRIN Spectrometer Status

2015: 2nd measurement phase completed

- ➢ Spectrometer works as MAC-E Filter

Angular selective electron gun

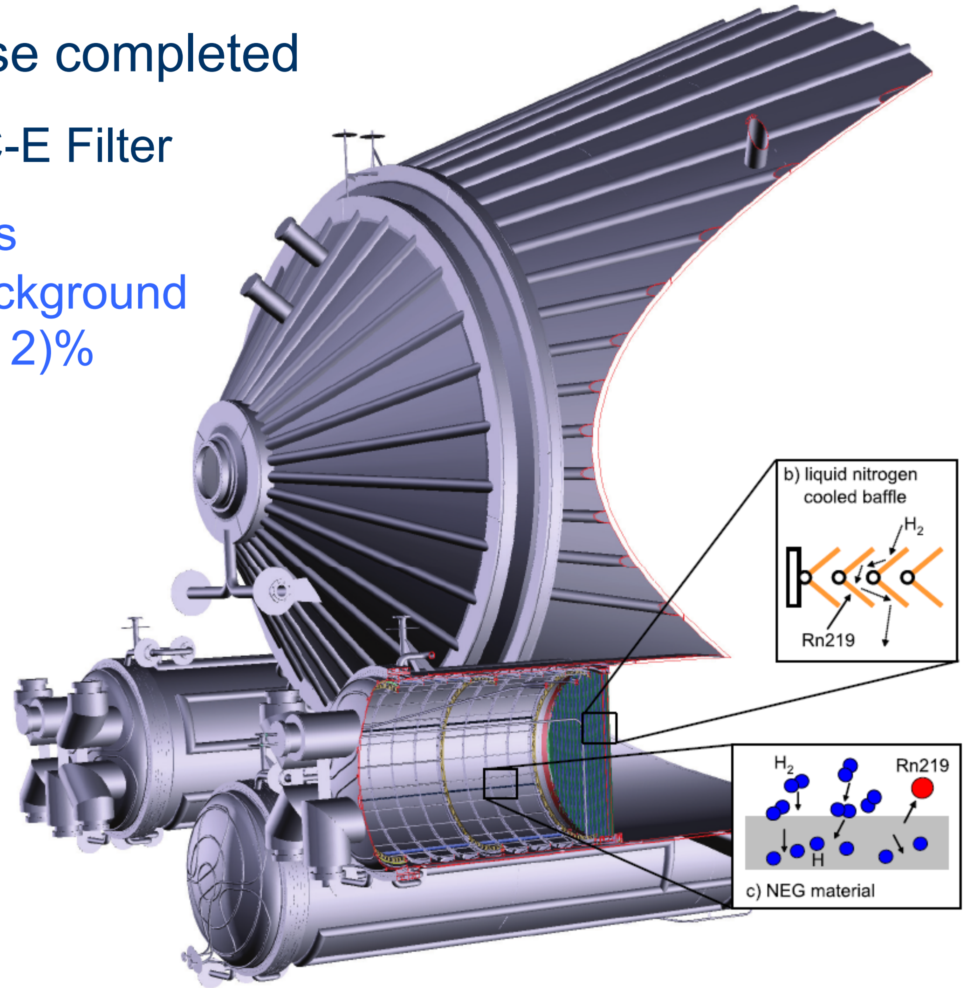




KATRIN Spectrometer Status

2015: 2nd measurement phase completed

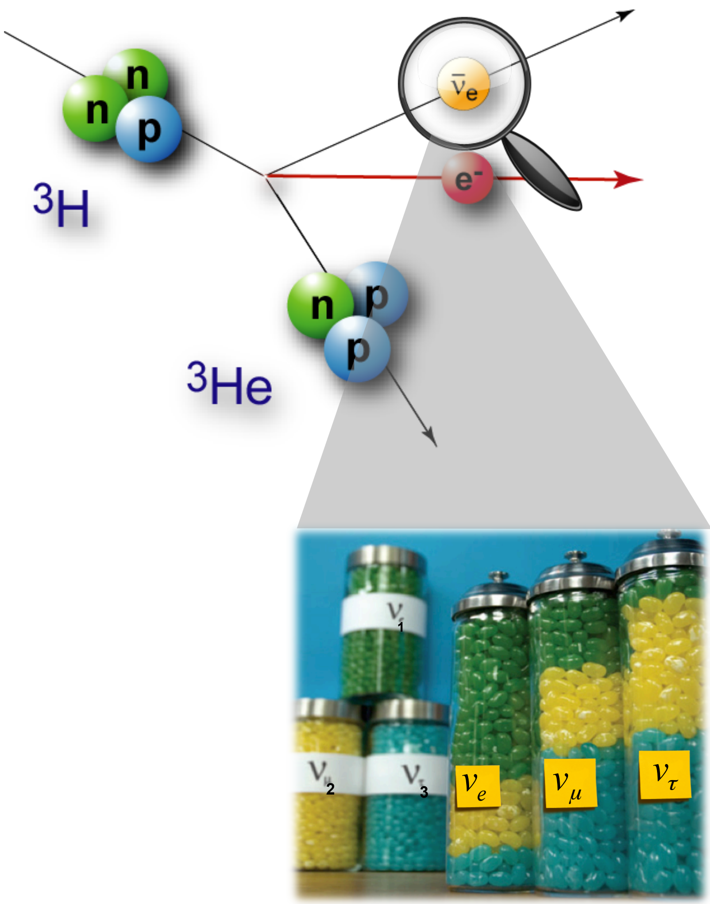
- ➢ Spectrometer works as MAC-E Filter
- ➢ Liquid nitrogen cooled baffles eliminate Radon-induced background with an efficiency of ε = (97± 2)%

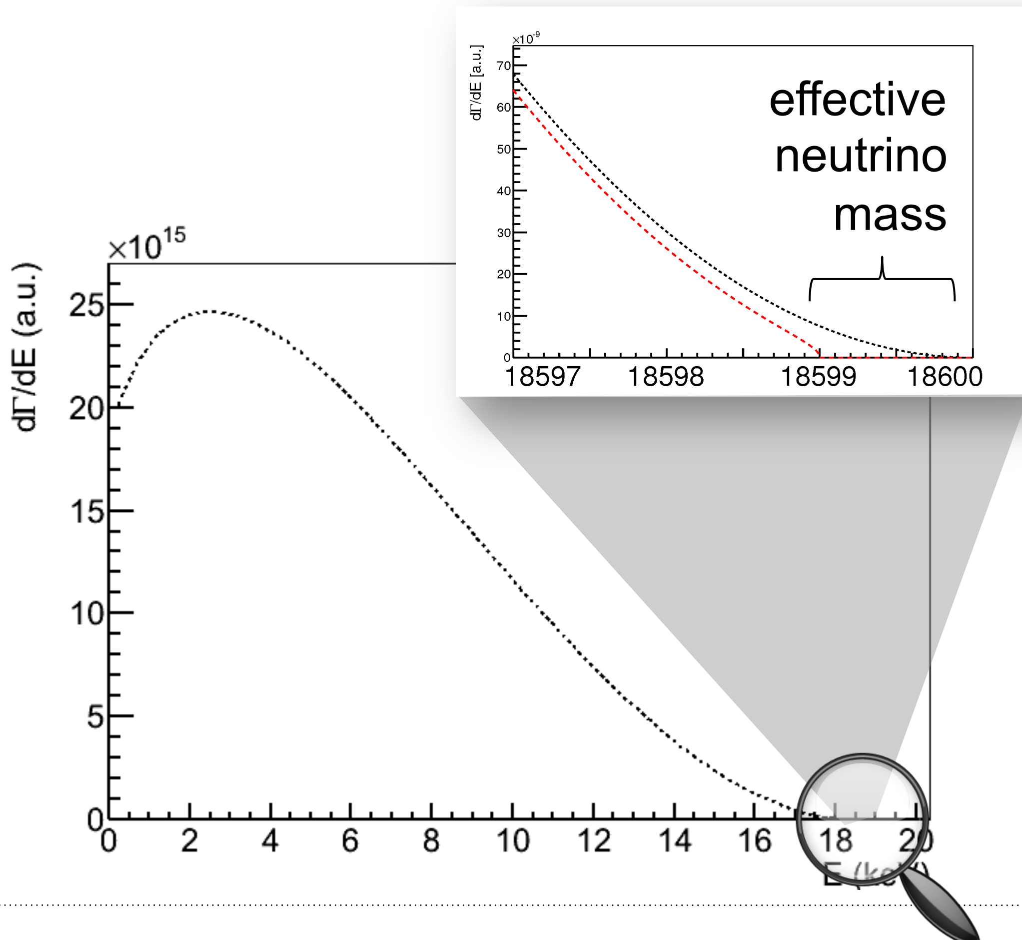


N. Wandkowsky et al., J. Phys. G 40 (2013) 8
S. M. et al., Astropart. Phys. 41 (2013) 52

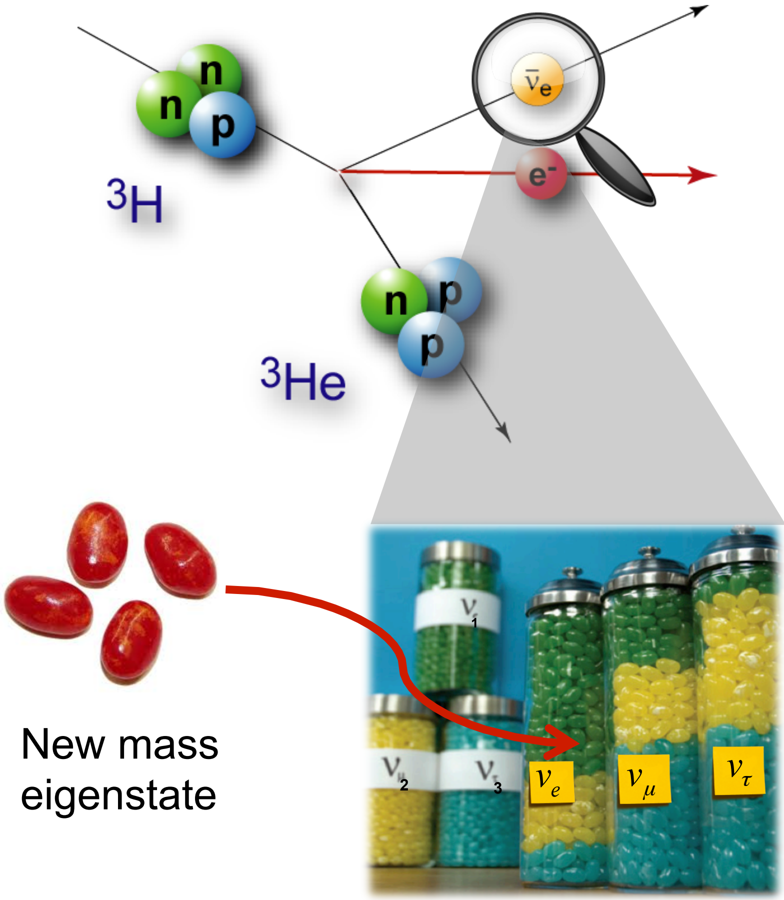
KATRIN and sterile neutrinos

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

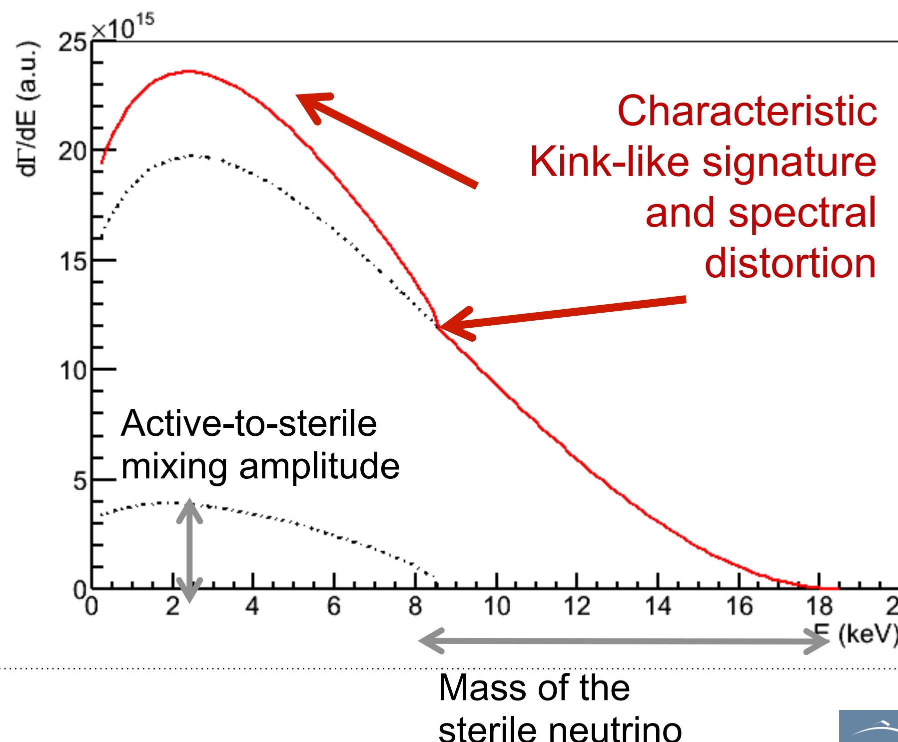




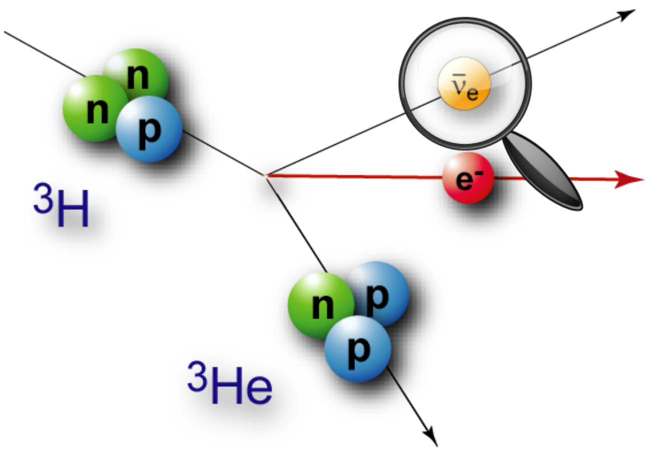
KATRIN and sterile neutrinos



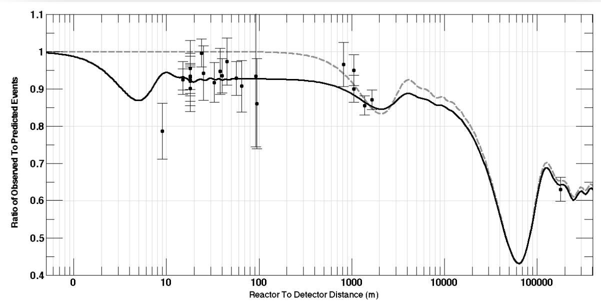
$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\text{light}}) + \sin^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\text{heavy}})$$



KATRIN and sterile neutrinos



eV-sterile neutrinos



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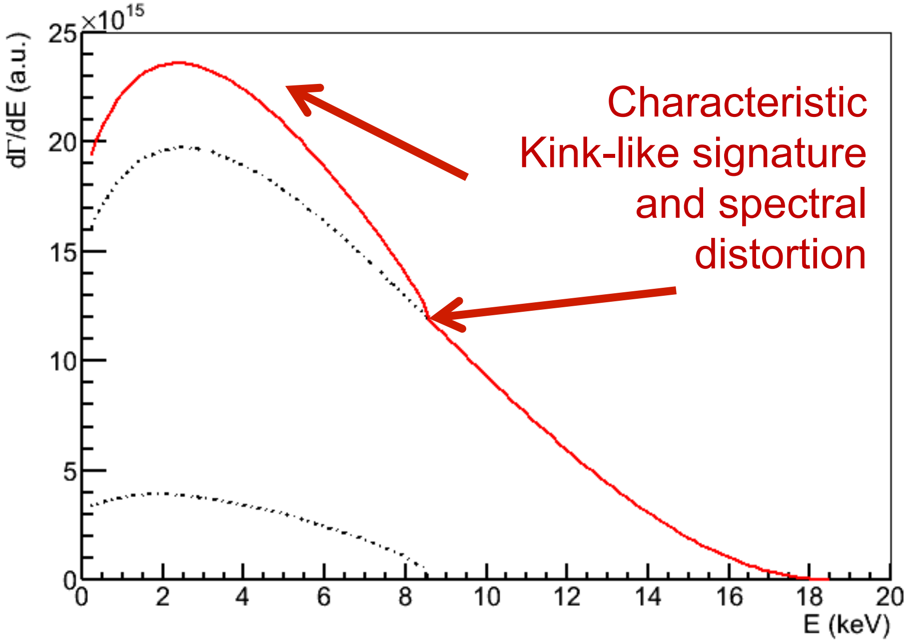
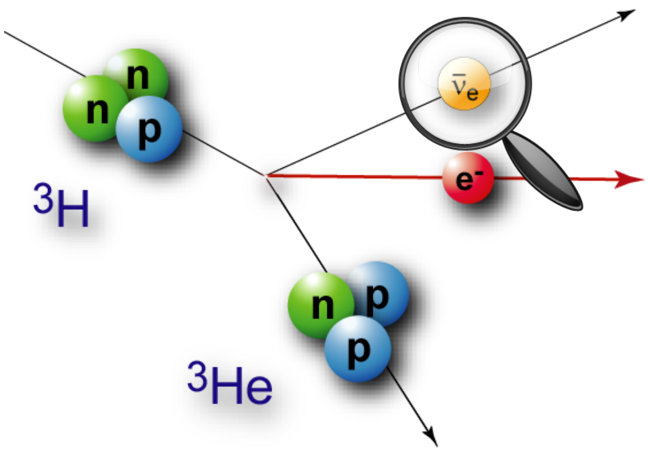


KATRIN and sterile neutrinos



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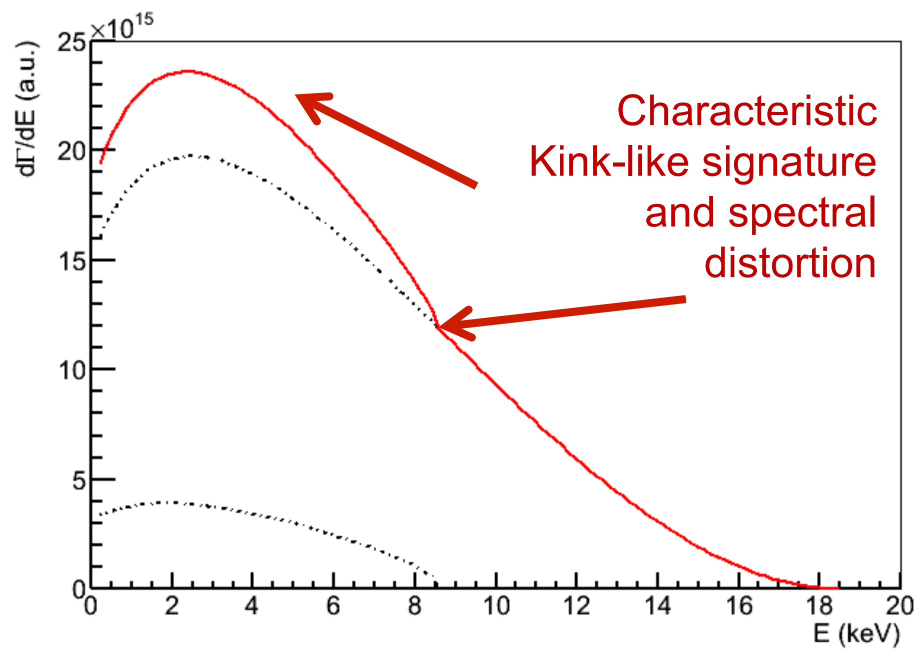
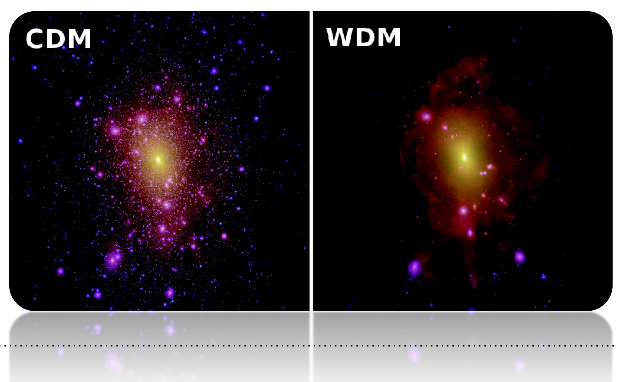
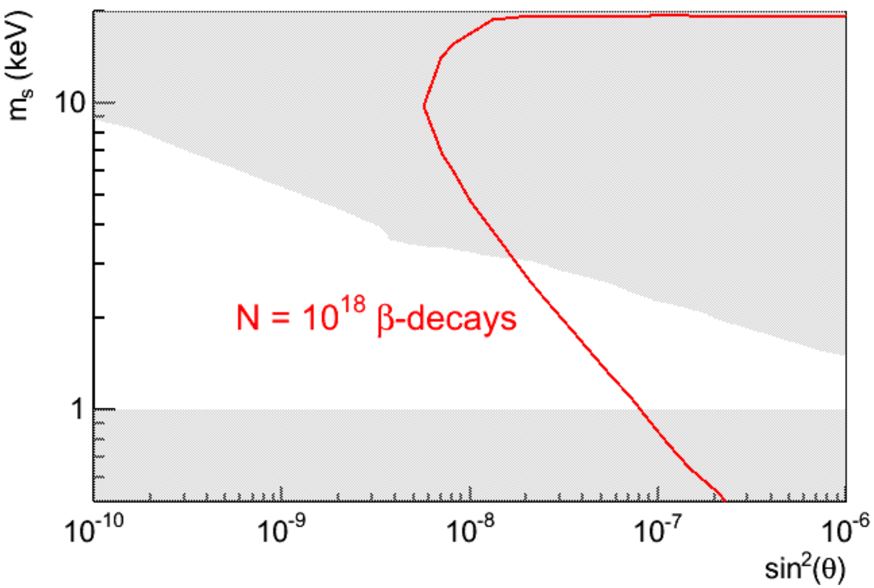


keV-sterile
neutrinos

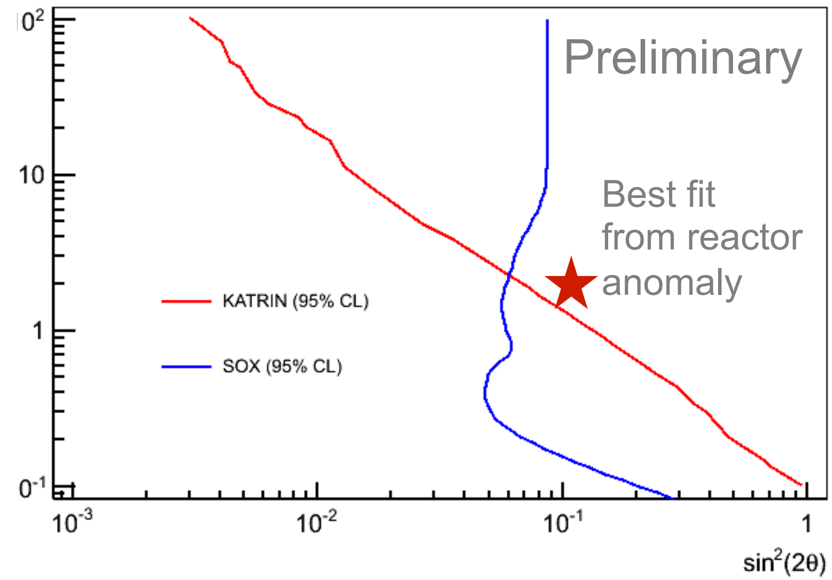


KATRIN and sterile neutrinos

keV-scale sterile neutrinos



eV-scale sterile neutrinos



Upgraded KATRIN provides interesting statistical sensitivity to astrophysically allowed region for dark matter sterile neutrinos

KATRIN **as is** probes the favored parameter space for light sterile neutrinos and is complementary to oscillation experiments

S. M. *et al.* JCAP 1502 (2015) 02, 020,
S. M. *et. al.* Phys.Rev. D91 (2015) 4, 042005,

J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Esmaili, O.L.G. Peres, Phys. Rev. D 85, 117301
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011

3 Experimental Efforts

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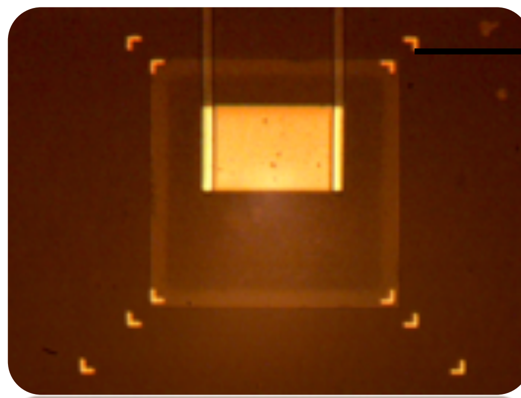
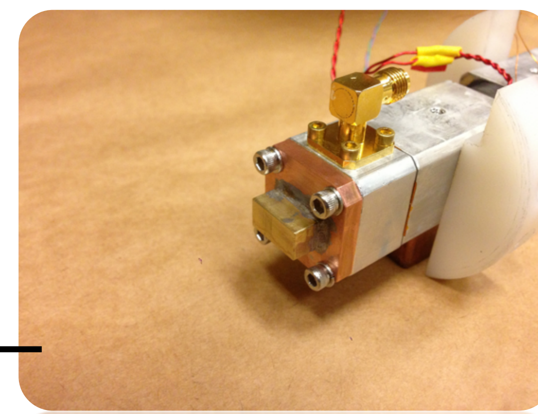
(KATRIN)



Calorimetry
(HOLMES, ECHO
&NUMECS)



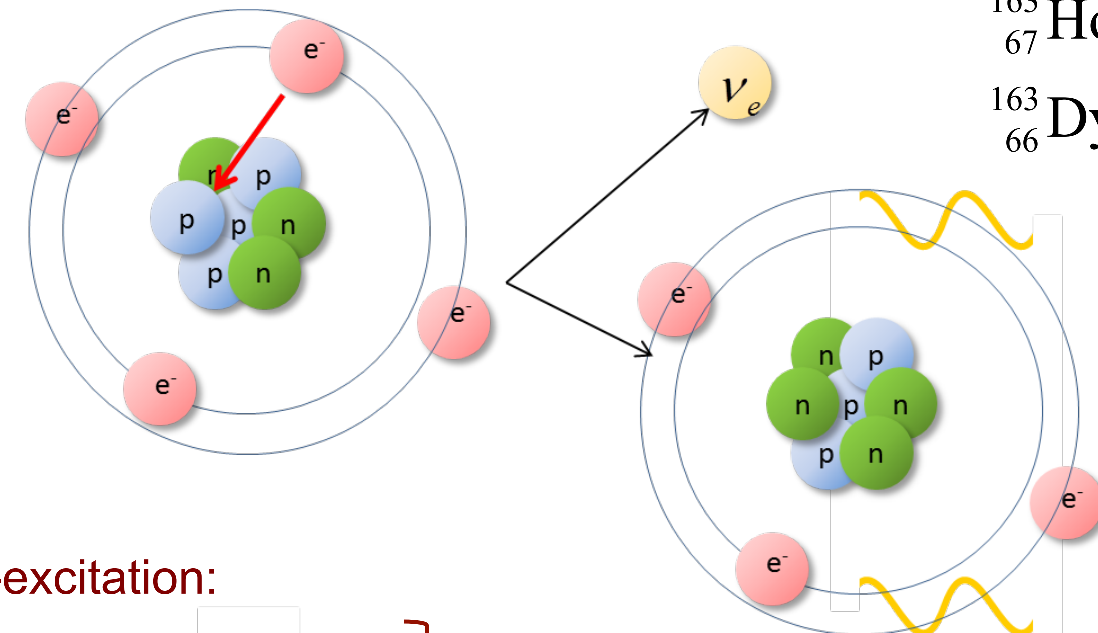
Frequency
(Project 8)

Drexlin, V. Hannen, S. M., C. Weinheimer, Adv. High Energy Physics 2013, Article ID 293986, (2013)

Electron Capture on Holmium

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{EC}}$$

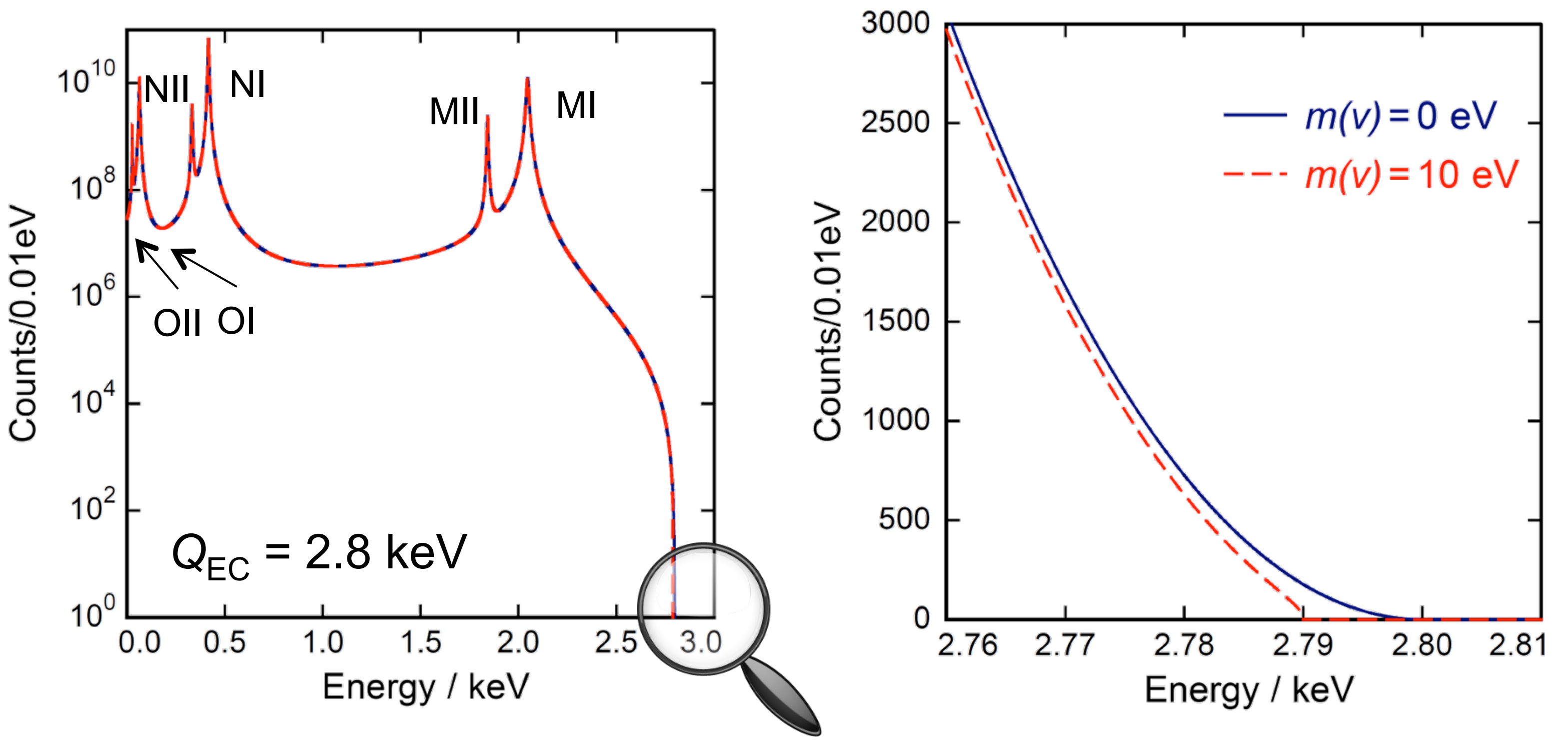


Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

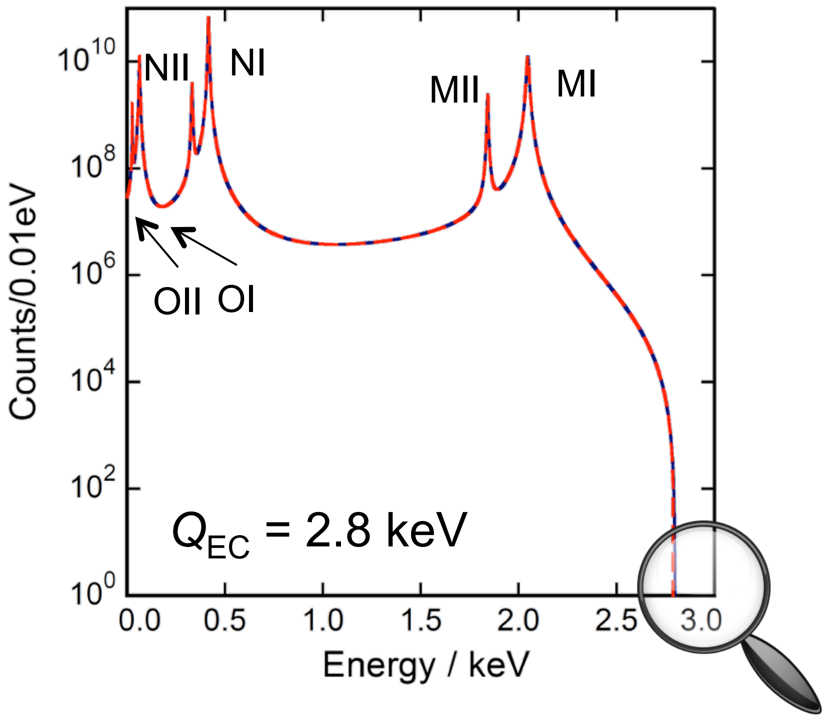
} Calorimetric measurement

Holmium spectrum



- Endpoint: 2.3 – 2.8 keV (small endpoint preferred)
- Half live: 4500 years

Endpoint of Holmium spectrum



- Endpoint: 2.3 – 2.8 keV
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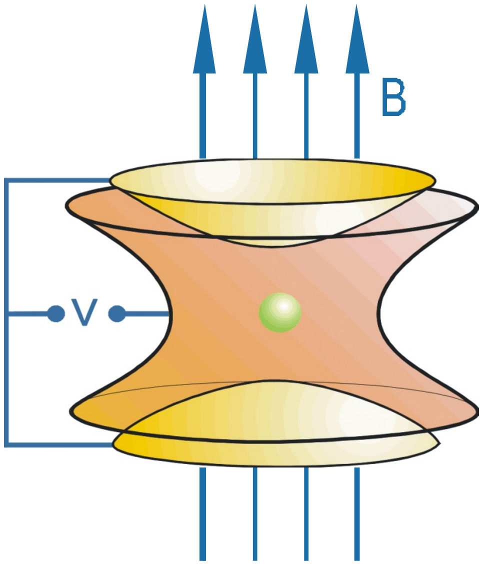
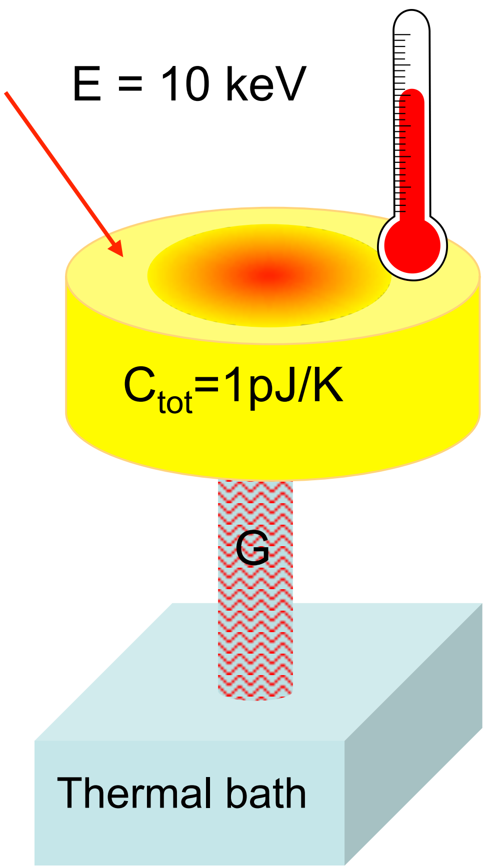
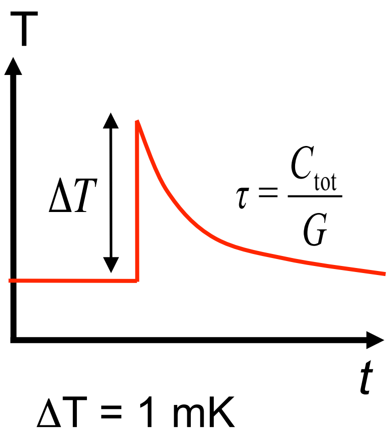
➢ Penning trap mass spectroscopy at PENTATRAP (MPIK HD)

➢ Precise measurement of the ^{163}Ho and ^{163}Dy atomic mass



Calorimetric measurement





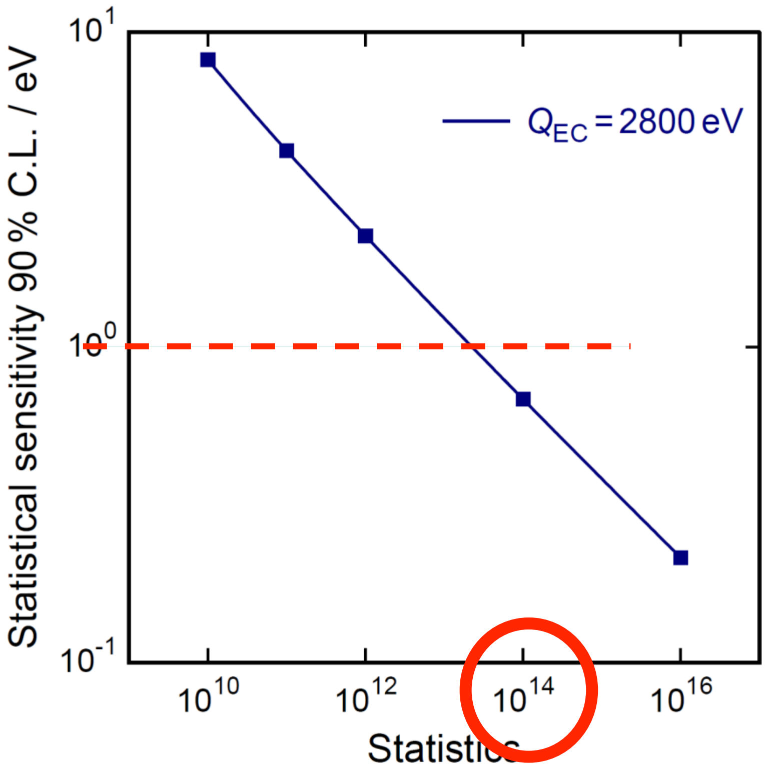
Advantages:

- Source = detector
- All energy is detected

Challenges:

- ΔE_{FWHM} < 10 eV
- $\tau_{risetime}$ < 1 μs to avoid background due to pile-up
- Sufficient isotope production

Calorimetric measurement



10^{14} decays in 1 year
100 Bq per pixel → 10^5 detectors

Advantages:

- Source = detector
- All energy is detected

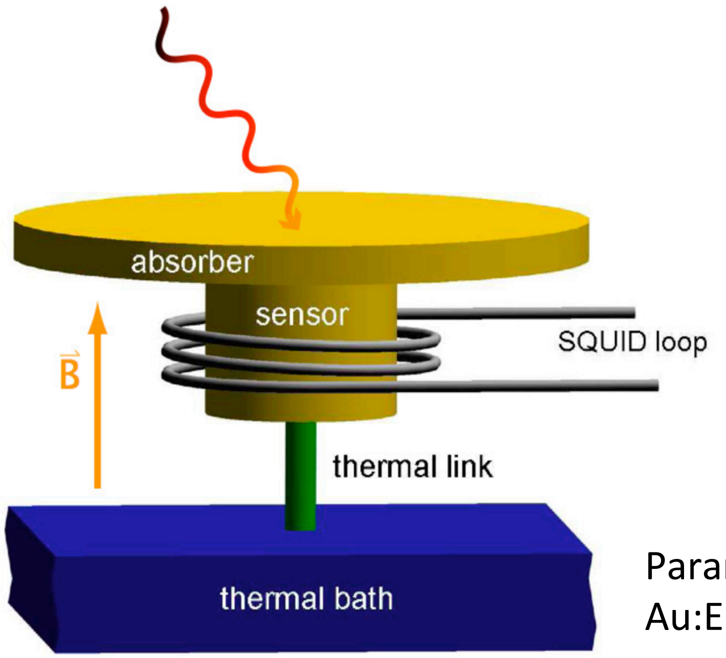
Challenges:

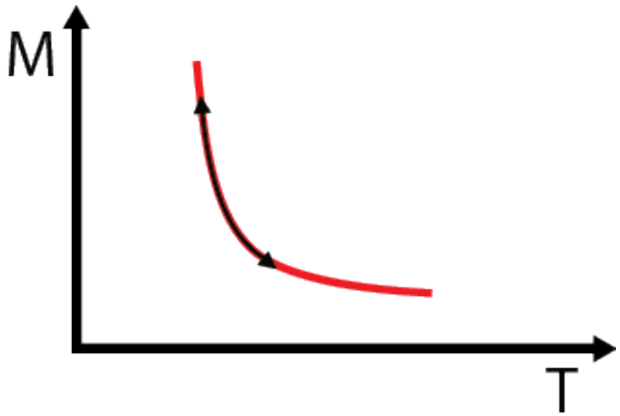
- $\Delta E_{FWHM} < 10$ eV
- $\tau_{risetime} < 1$ μs to avoid background due to pile-up
- Sufficient isotope production
- Scalability

The ECHo Experiment

Heidelberg (Univ., MPI-K),
U Mainz, U Tübingen, TU Dresden
U Bratislava, INR Debrecen,
ITEP Moscow, PNPI St Petersburg,
IIT Roorkee, Saha Inst. Kolkata

- Metallic magnetic calorimeters (MMC)



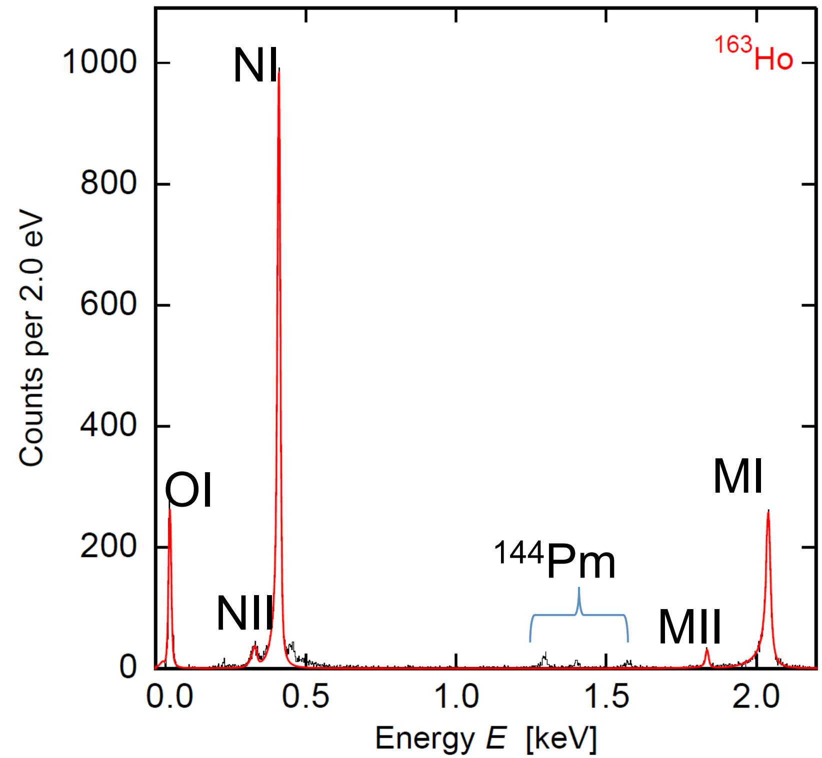


Paramagnetic sensor
Au:Er @ 30 mK

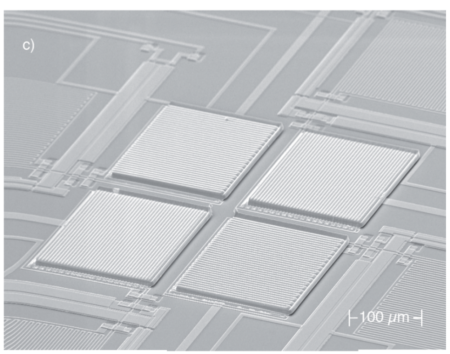
A. Fleischmann et al., *AIP Conf. Proc.* 1185, 571, (2009)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
P. C.-O. Ranitzsch et al., JLTP 167, 1004 (2012)
S. Kempf et al, JLTP *10.1007/s10909-013-1041-0*

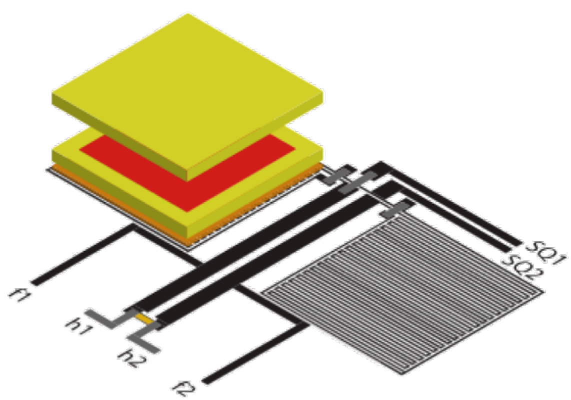
The ECHo Experiment

- Metallic magnetic calorimeters (MMC)
- Fast rise times (τ = 130 ns), good energy resolutions (7.6 eV @ 6keV), and linearity (1%) demonstrated



ECHO first prototype





A. Fleischmann et al., *AIP Conf. Proc.* 1185, 571, (2009)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
P. C.-O. Ranitzsch et al., JLTP 167, 1004 (2012)
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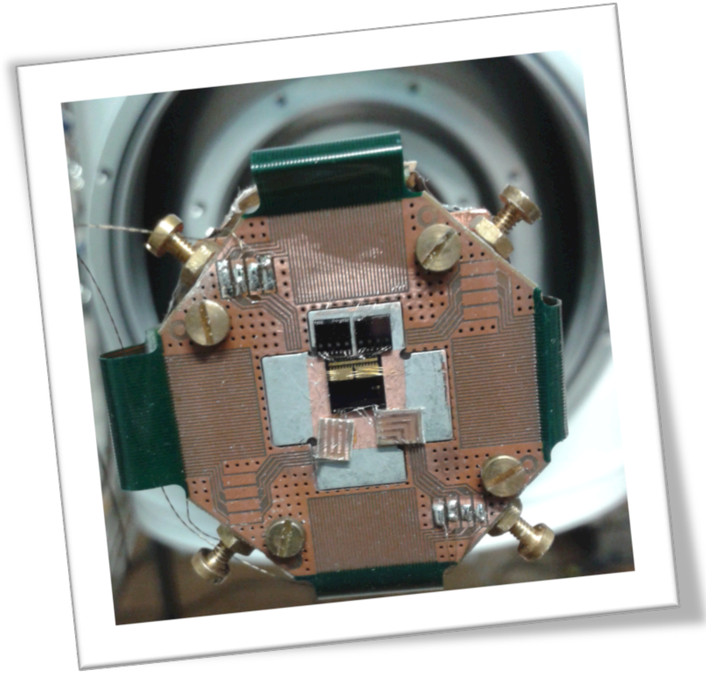
- 2 new chips, each with 16 pixel detector arrays, started test 4 weeks ago



✓ High purity ^{163}Ho source
✓ Increase activity per pixel (0.2 Bq)
✓ Better understanding of line-shapes

A. Fleischmann et al., *AIP Conf. Proc.* 1185, 571, (2009)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
P. C.-O. Ranitzsch et al., JLTP 167, 1004 (2012)
S. Kempf et al, JLTP *10.1007/s10909-013-1041-0*

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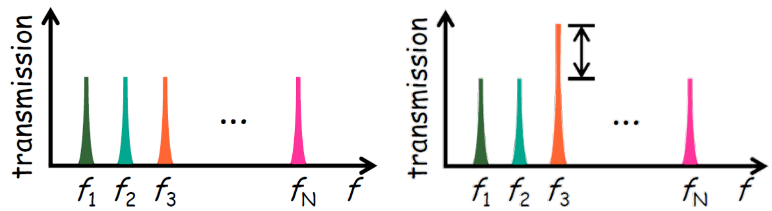
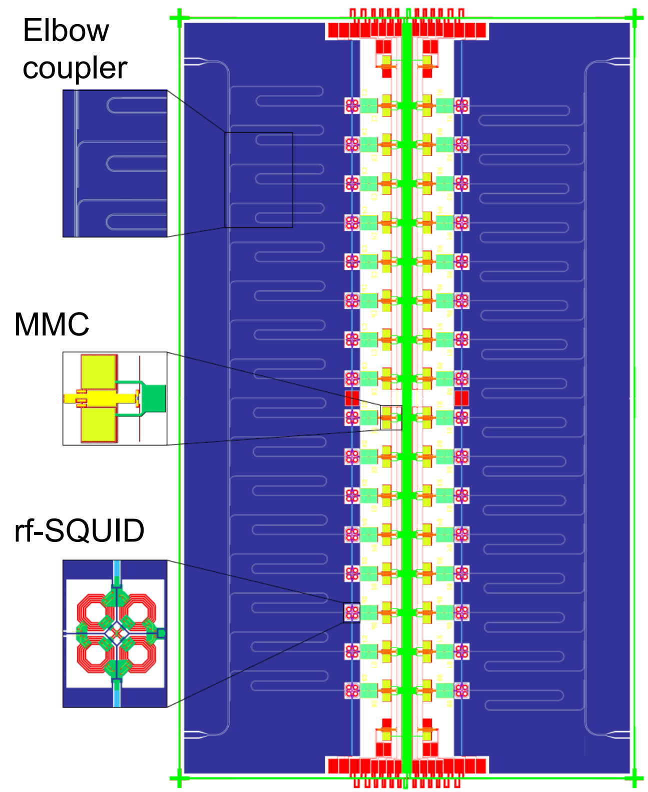
- Fast rise times (τ = 130 ns), good energy resolutions (7.6 eV @ 6keV), and linearity (1%) demonstrated
- 2 new chips, each with 16 pixel detector arrays, started test 4 weeks ago
- Microwave Multiplexing techniques (RF-SQUID)



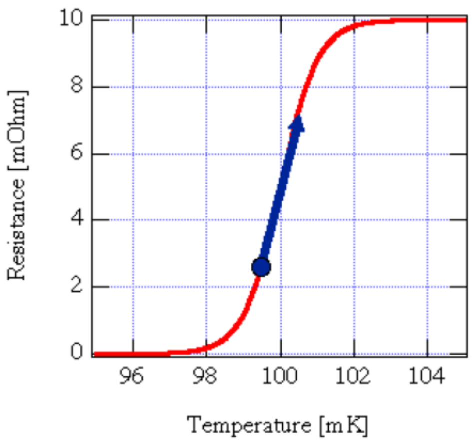


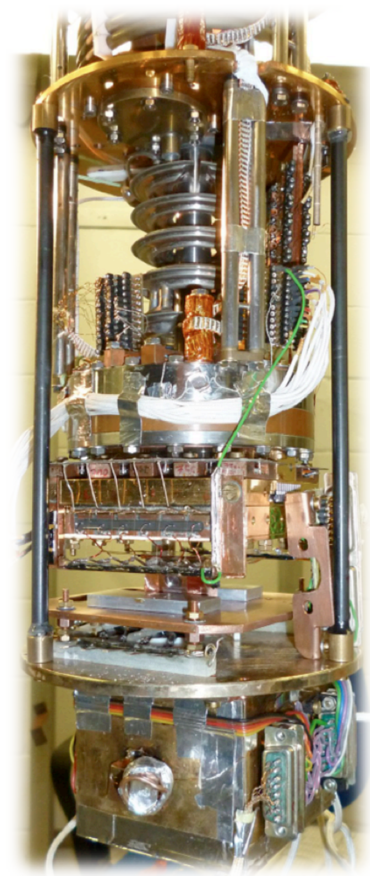
A. Fleischmann et al., *AIP Conf. Proc.* 1185, 571, (2009)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
P. C.-O. Ranitzsch et al., JLTP 167, 1004 (2012)
S. Kempf et al, JLTP *10.1007/s10909-013-1041-0*

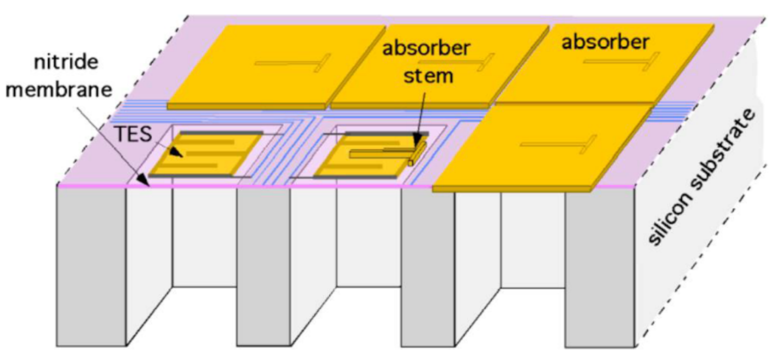
The HOLMES Experiment

U Milano-Bicocca,
INFN Milano/Genova/Roma,
U Lisboa, U Miami,
NIST, JPL

- Transition-Edge Sensors (TES)
- Microwave Multiplexing with Kinetic Inductance Detectors (MKIDs).
- Successful funding received for one thousand channel Ho detector experiment







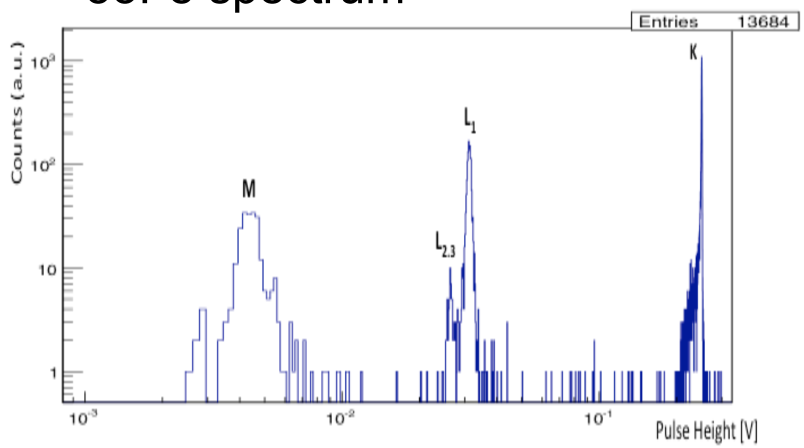
M. Ribeiro Gomes et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

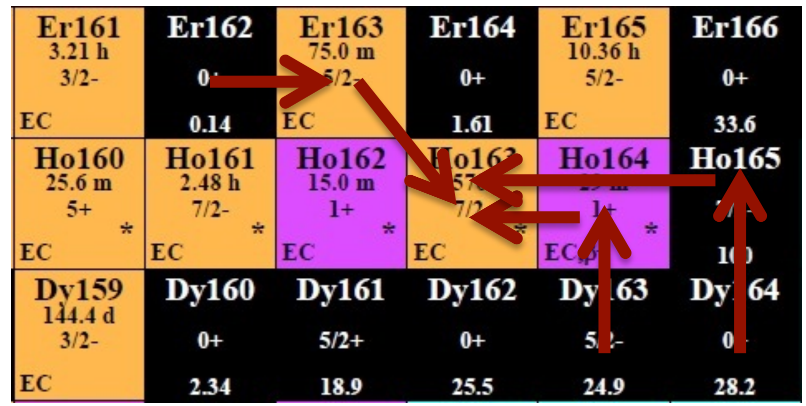
The NuMecs Experiment

Los Alamos,
NIST,
U Madison
and others

- Transition-Edge Sensors (TES)
- Good energy resolution (6 eV @ 6 keV with 55Fe surrogate) demonstrated.
- Focus on high purity ^{163}Ho production – proton activation of dysprosium

55Fe spectrum

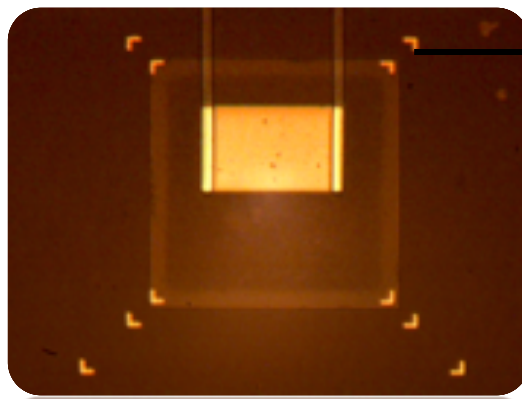




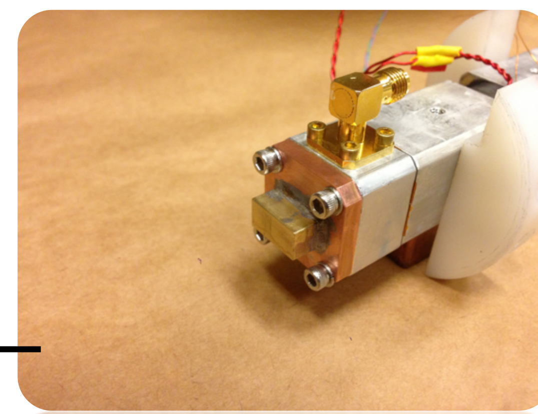
J.W. Engle et al. NIM B 311 (2013) 131–138
http://fsnutown.phy.ornl.gov/fsnufiles/positionpapers/FSNu_Project8.pdf

3 Experimental Efforts

Spectroscopy
(KATRIN)



Calorimetry
(HOLMES, ECHO
&NUMECS)



Frequency
(Project 8)

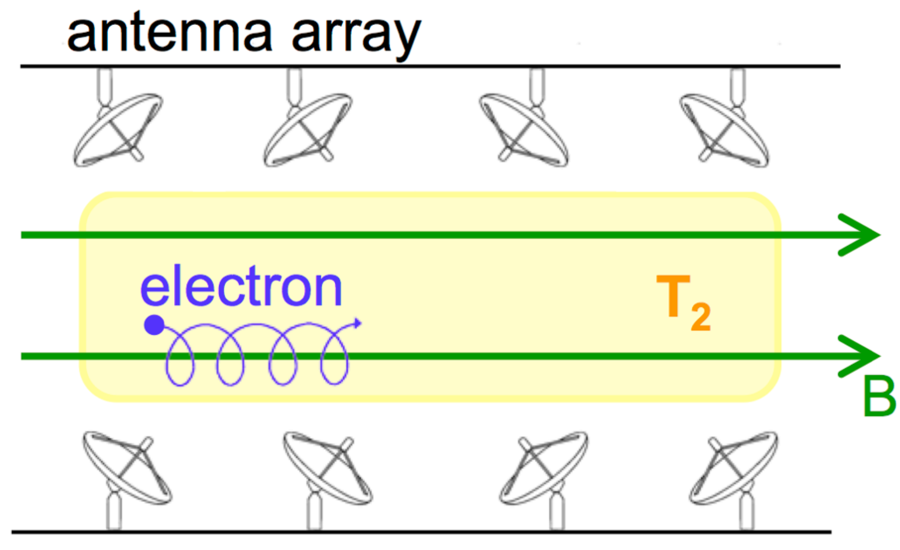
Drexlin, V. Hannen, S. M., C. Weinheimer, Adv. High Energy Physics 2013, Article ID 293986, (2013)

PROJECT 8

UW/Seattle, MIT,
UC/Santa Barbara
Yale, Pacific NW,
Livermore, NRAO,
KIT

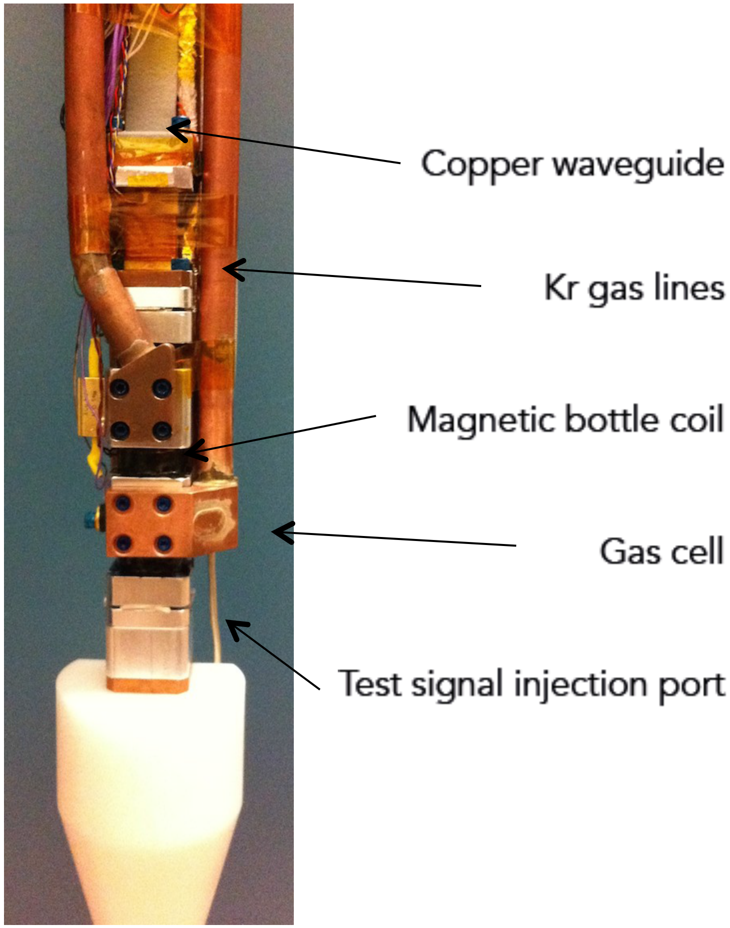
- Use cyclotron frequency to extract electron energy
- Non-destructive measurement of electron energy

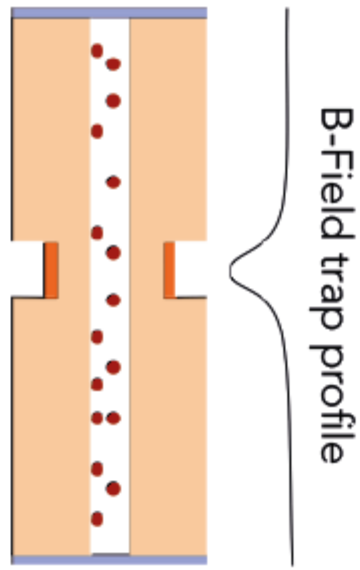
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



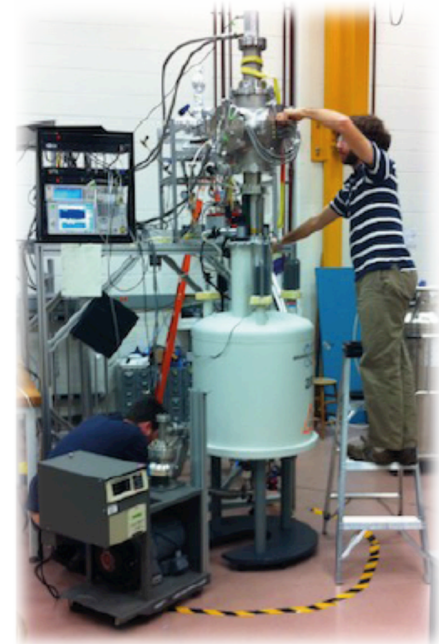
B. Monreal and Joe Formaggio, Phys. Rev D80:051301

Project 8 Setup

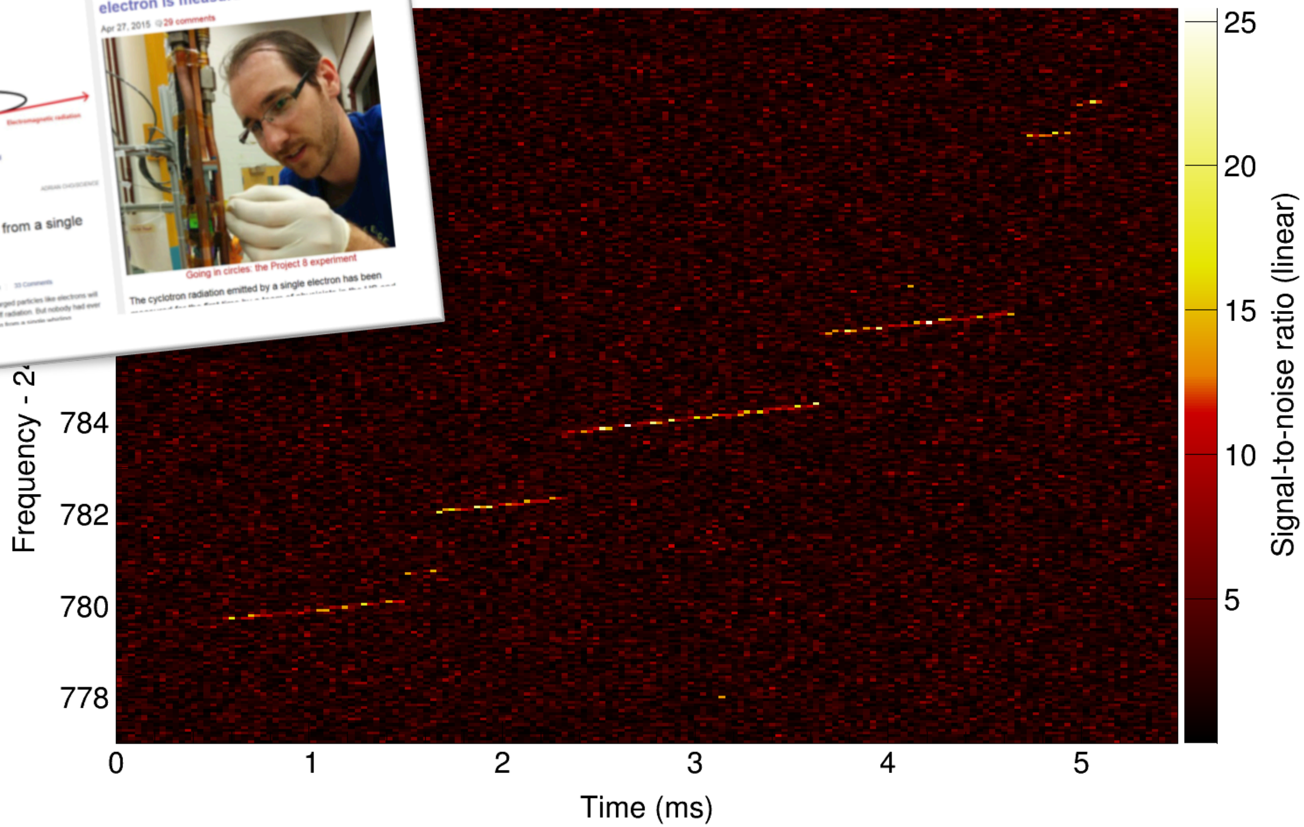




Waveguide
Cut-away



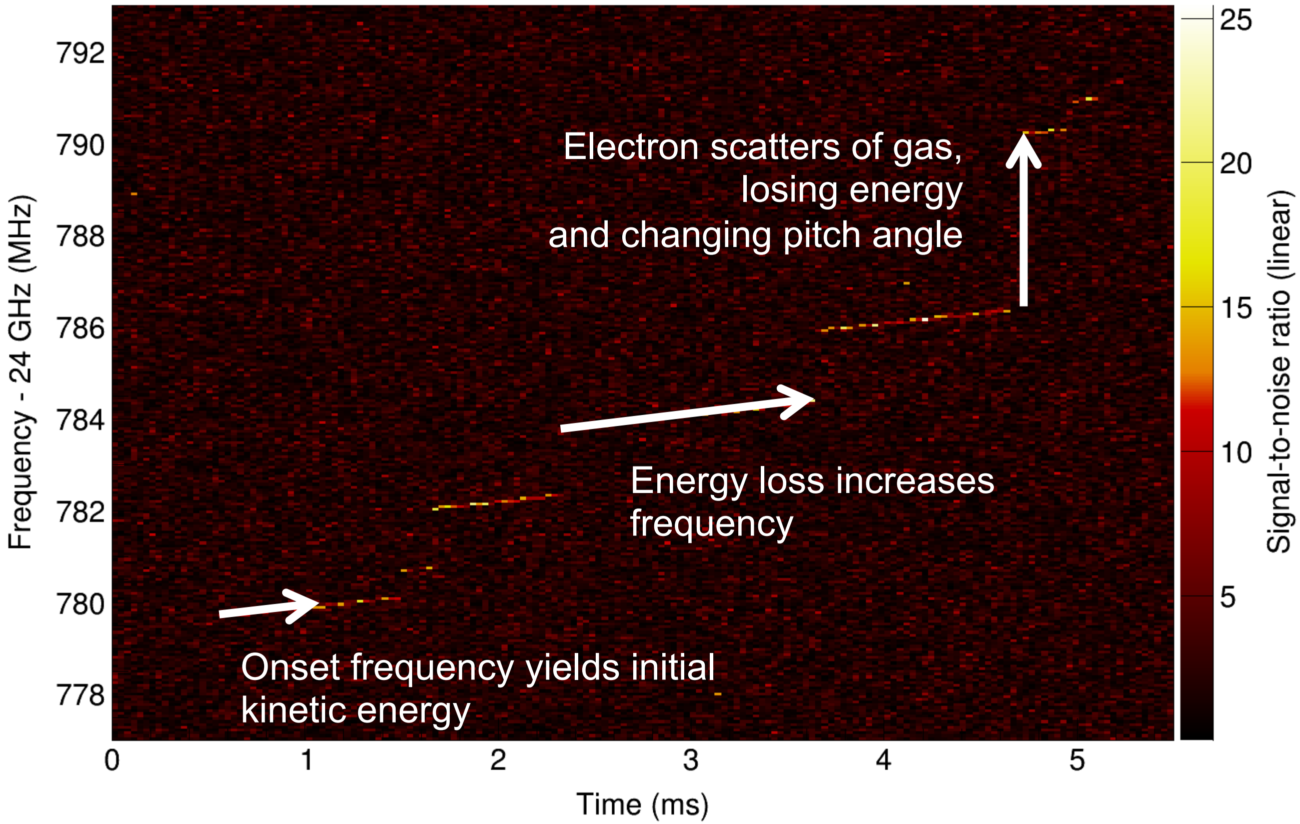
First electron detection



D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation,
Phys. Rev. Lett. 114, 162501 (2015)

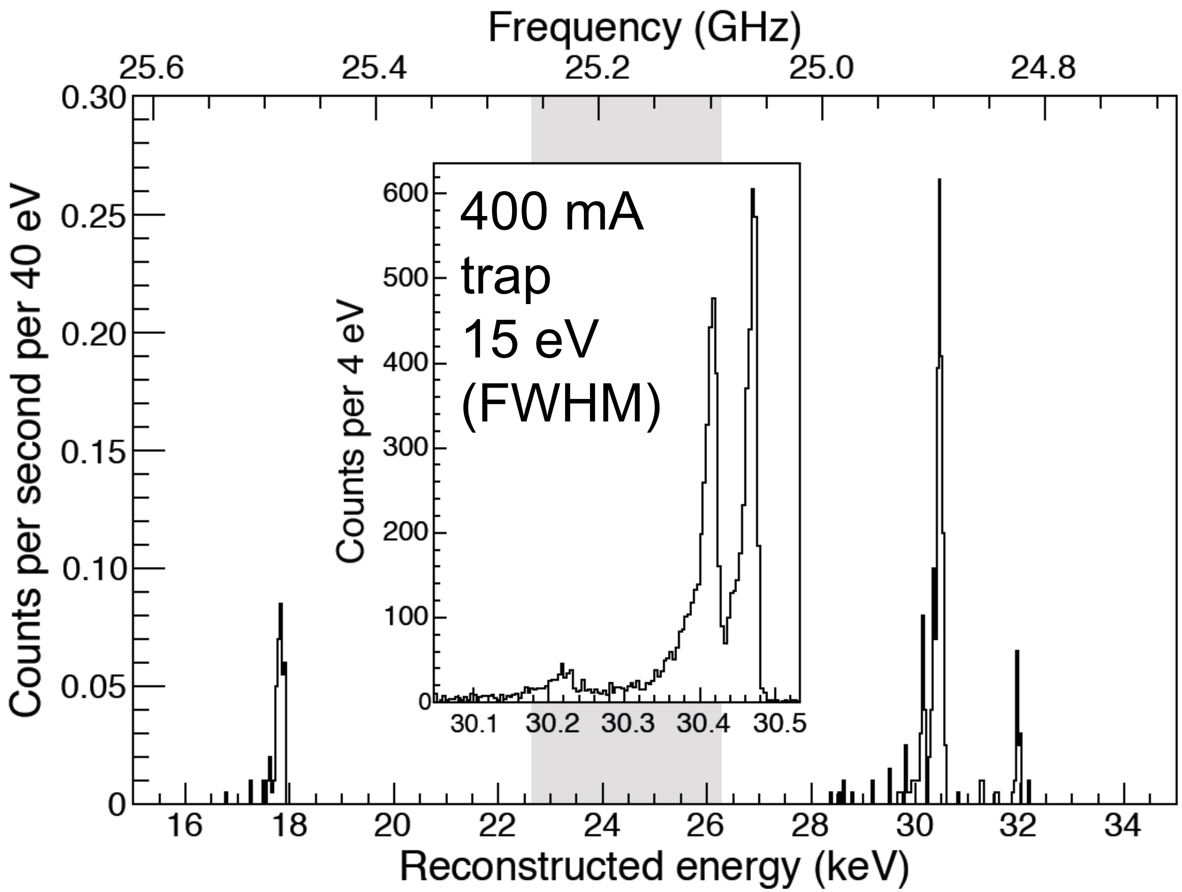
BERKELEY LAB

First electron detection



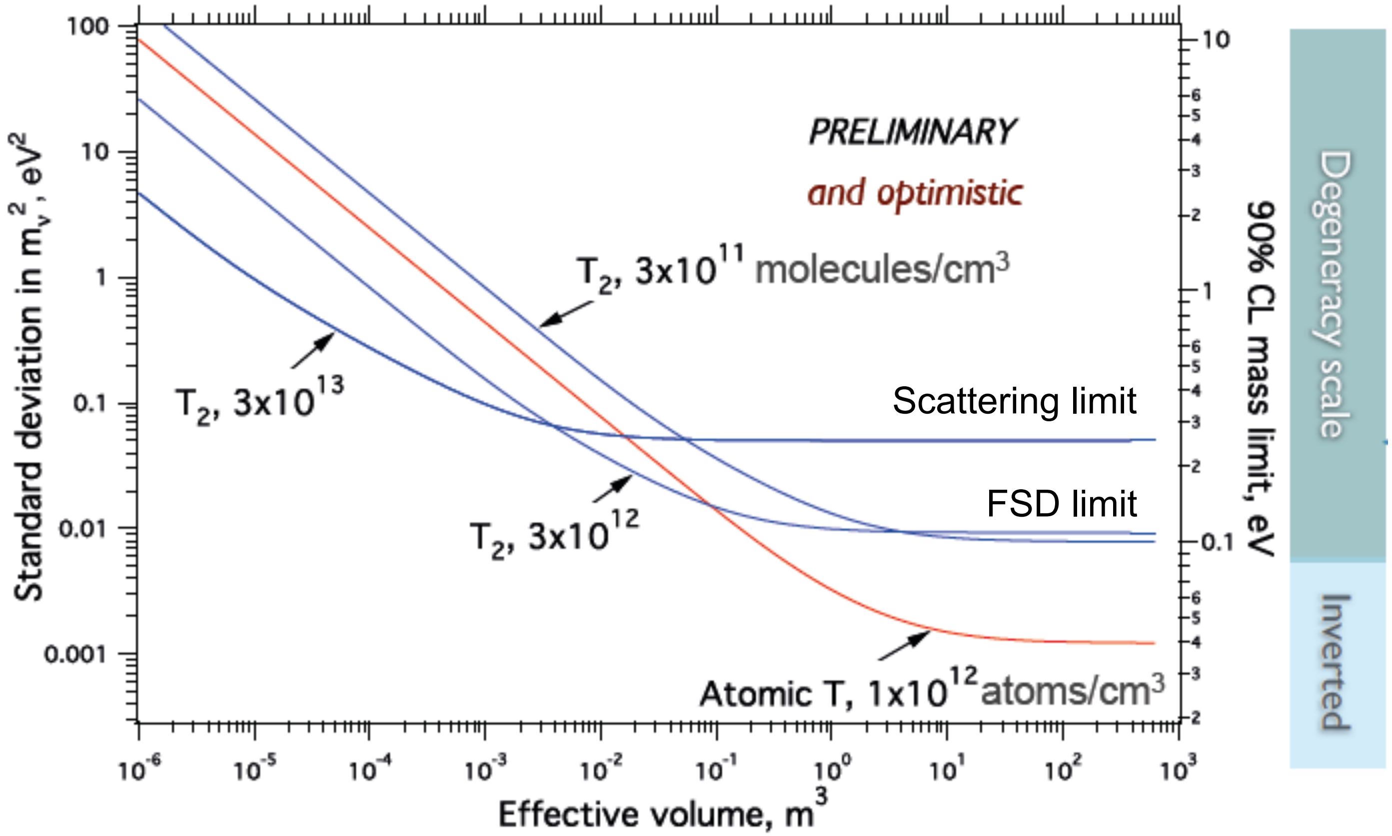
D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation,
Phys. Rev. Lett. 114, 162501 (2015)

First electron detection



D.M. Asner et al., Single electron detection and spectroscopy via relativistic cyclotron radiation, Phys. Rev. Lett. 114, 162501 (2015)

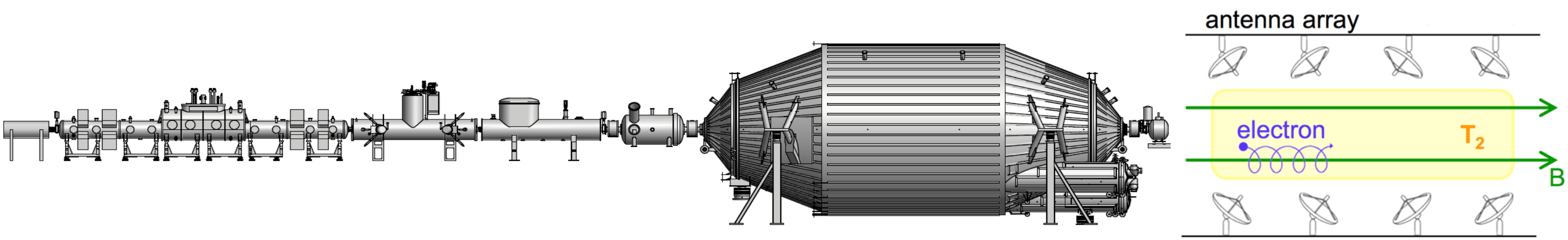
Future Perspectives…



Joining efforts …

KATRIN selects the electrons….

… and Project 8 measures their energy

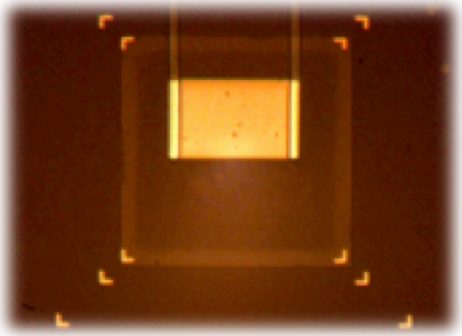


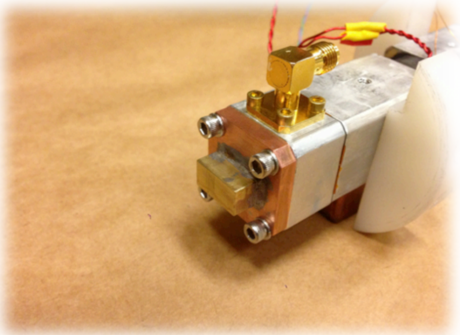
1) Trigger the electron → close the trap

2) Measure the energy

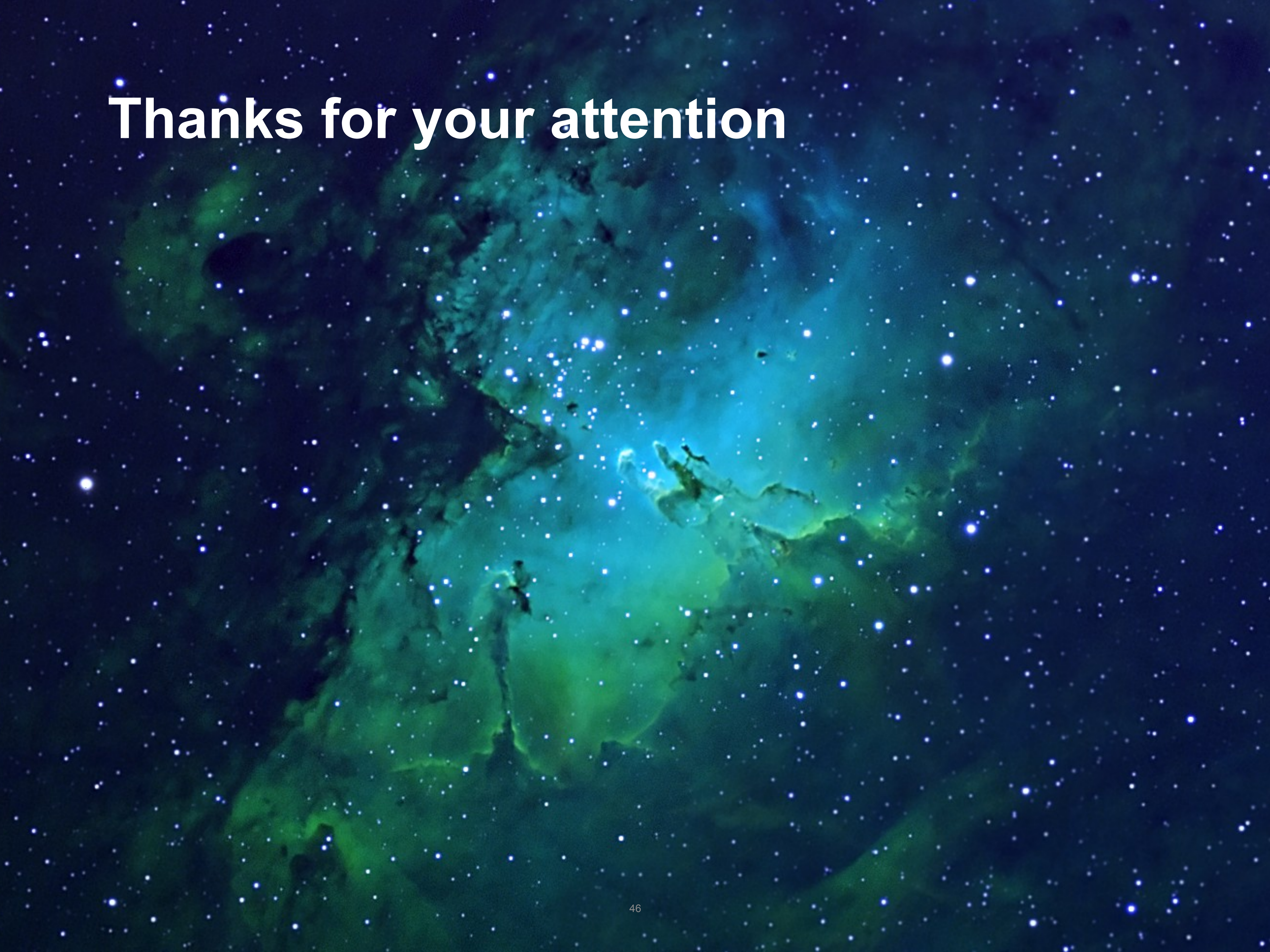
Summary

- In 2016 KATRIN will start tritium measurements. KATRIN will probe the entire degeneracy scale. Interesting potential to search for sterile neutrinos
- Cryogenic techniques are advancing to achieve the sub-eV sensitivity
- Project 8 proved a completely new concept via frequency measurement. Very promising to reach sub-eV sensitivity



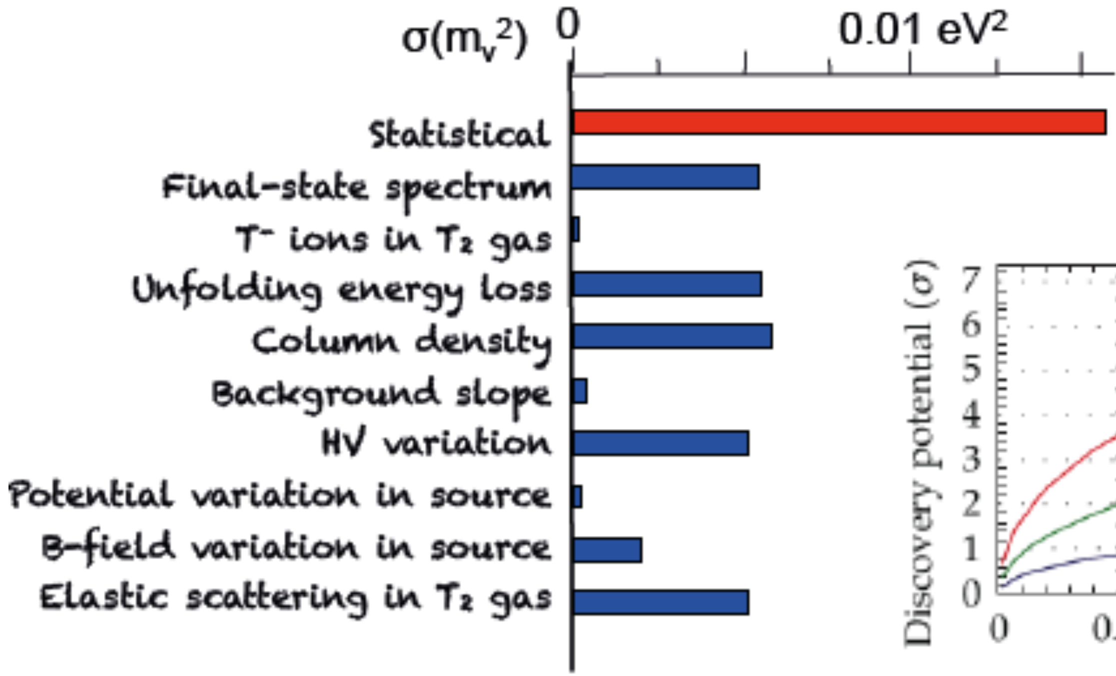


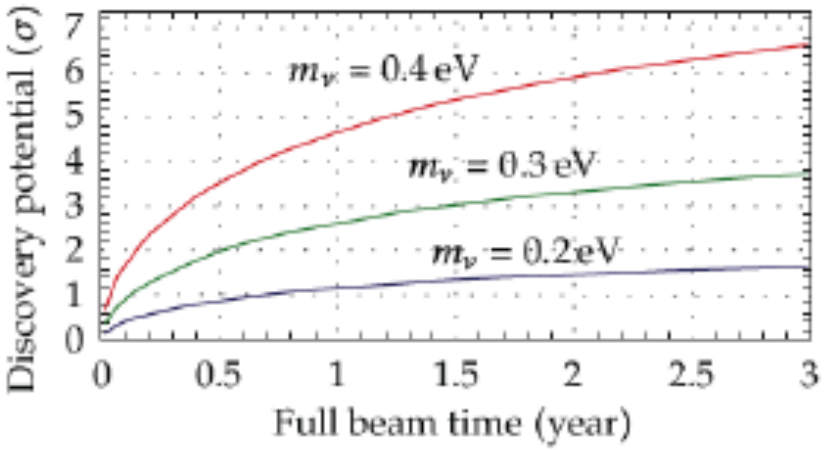
Thanks for your attention



KATRIN Backup slides

Systematics



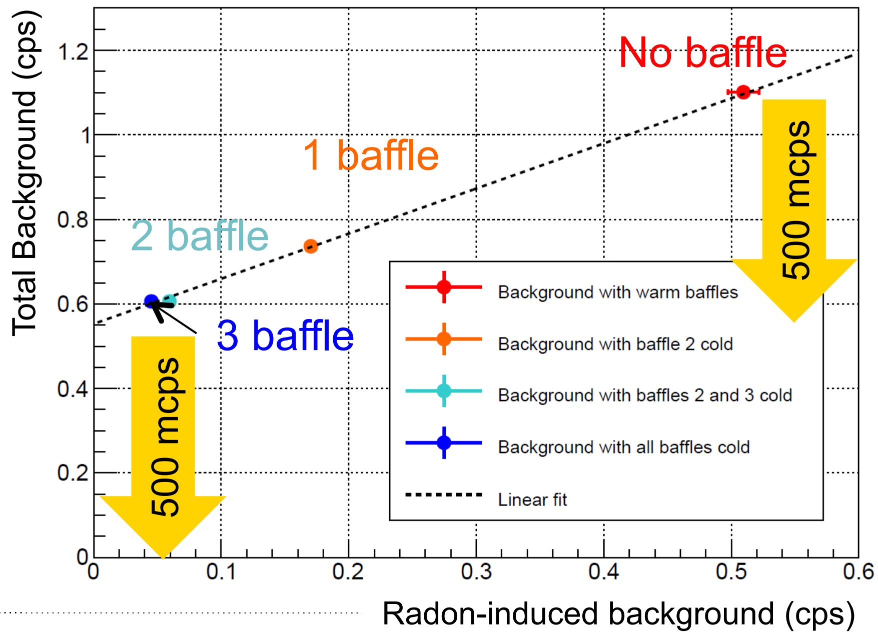


Susanne Mertens

KATRIN Spectrometer Status

2015: 2nd measurement phase completed

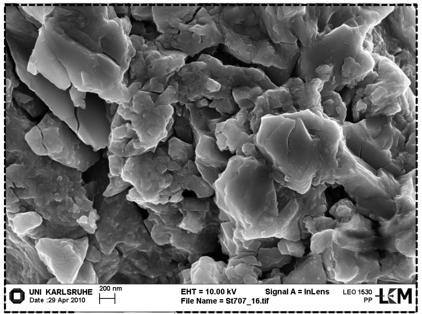
- Spectrometer works as MAC-E Filter
- Liquid nitrogen cooled baffles eliminate Radon-induced background with an efficiency of ε = (97± 2)%
- Remaining background is under investigation at the moment

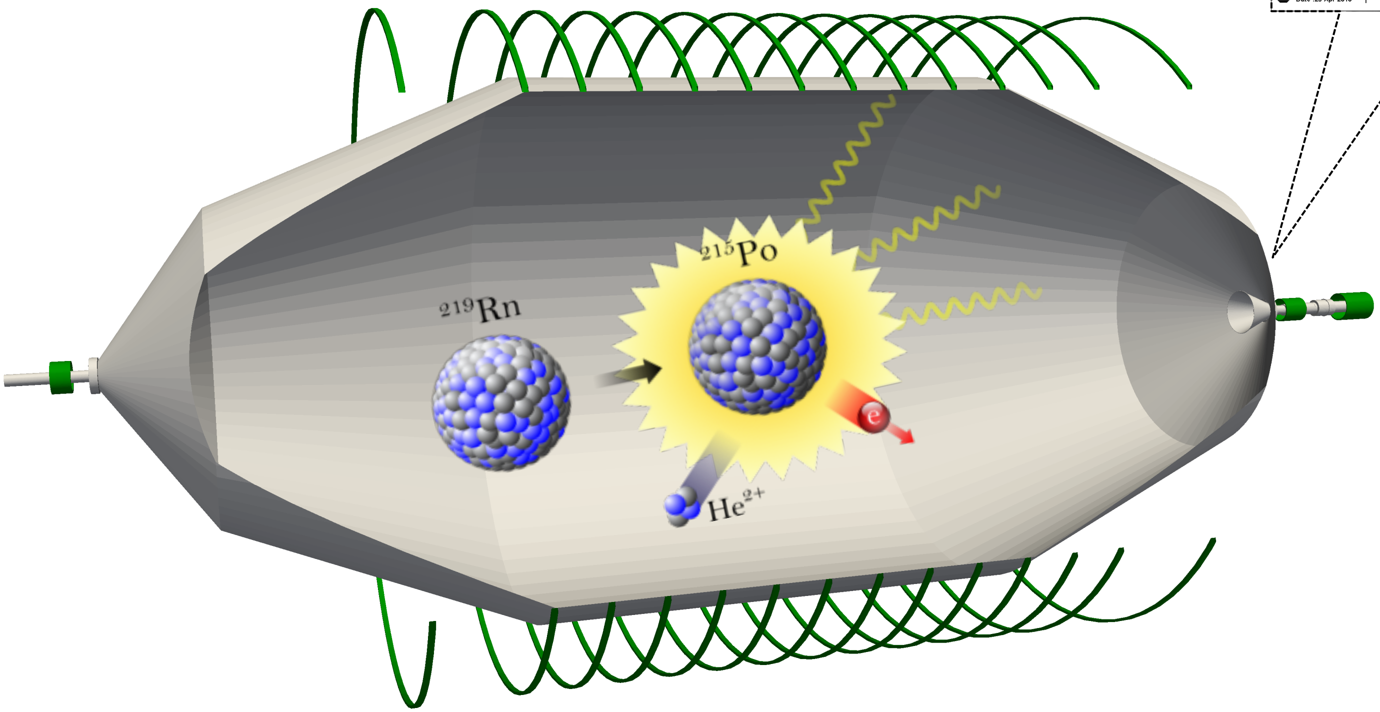


Radon-induced Background

$t_{1/2}(^{219}Rn) = 3.96$ s
$t_{1/2}(^{220}Rn) = 55.6$ s

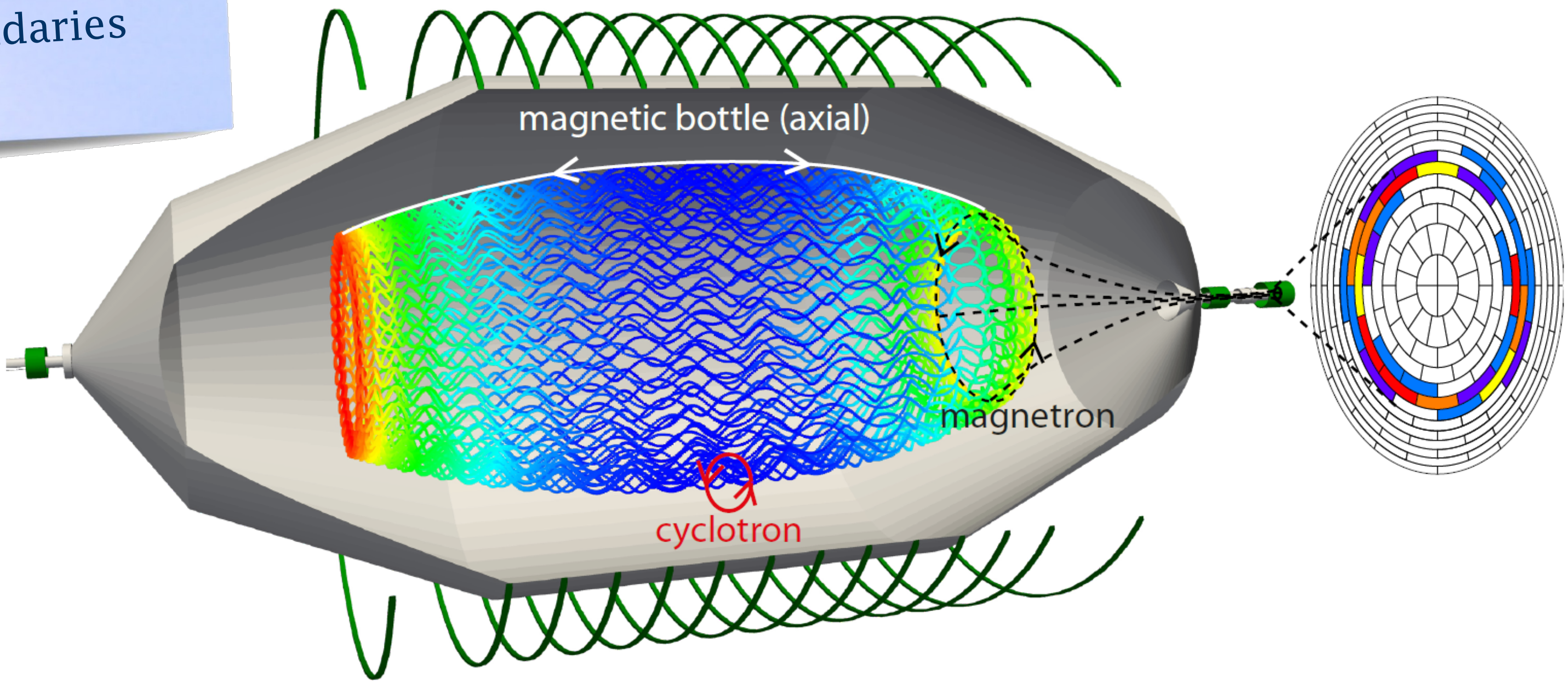
Getter pump





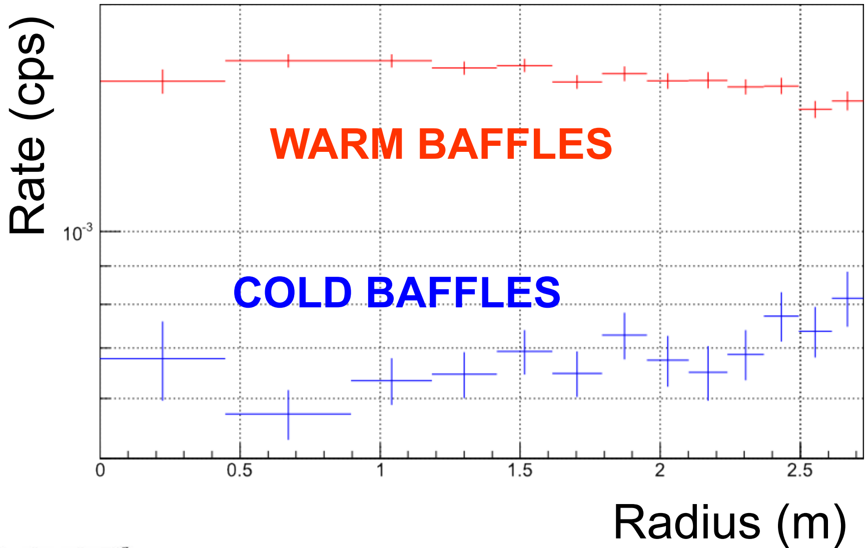
Radon-induced Background

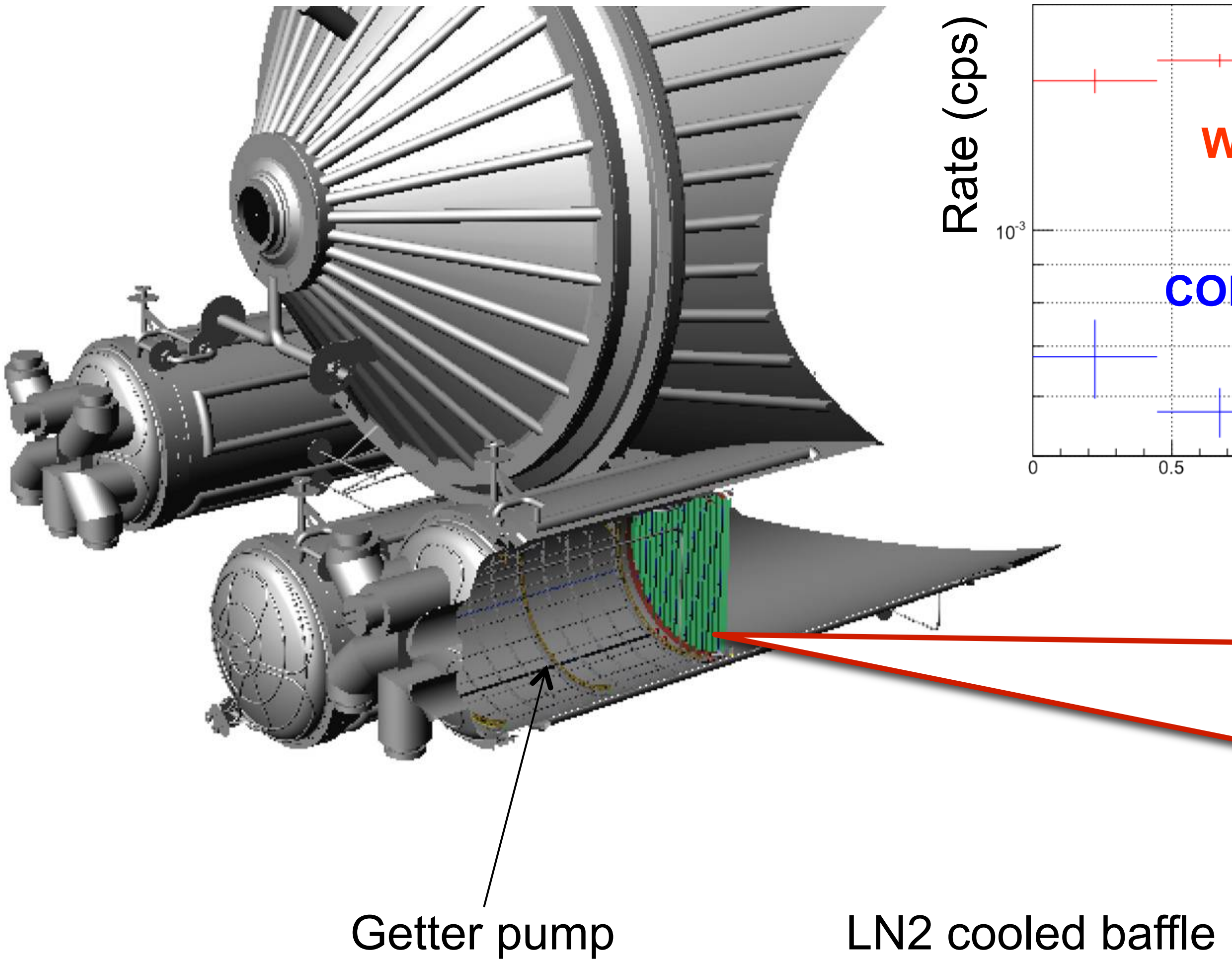
Single Radon decay produces hundreds of secondaries



N. Wandkowsky et al., New J. Phys. 15 (2013) 083040
N. Wandkowsky et al., J. Phys. G 40 (2013) 8
S. M. et al., Astropart. Phys. 41 (2013) 52

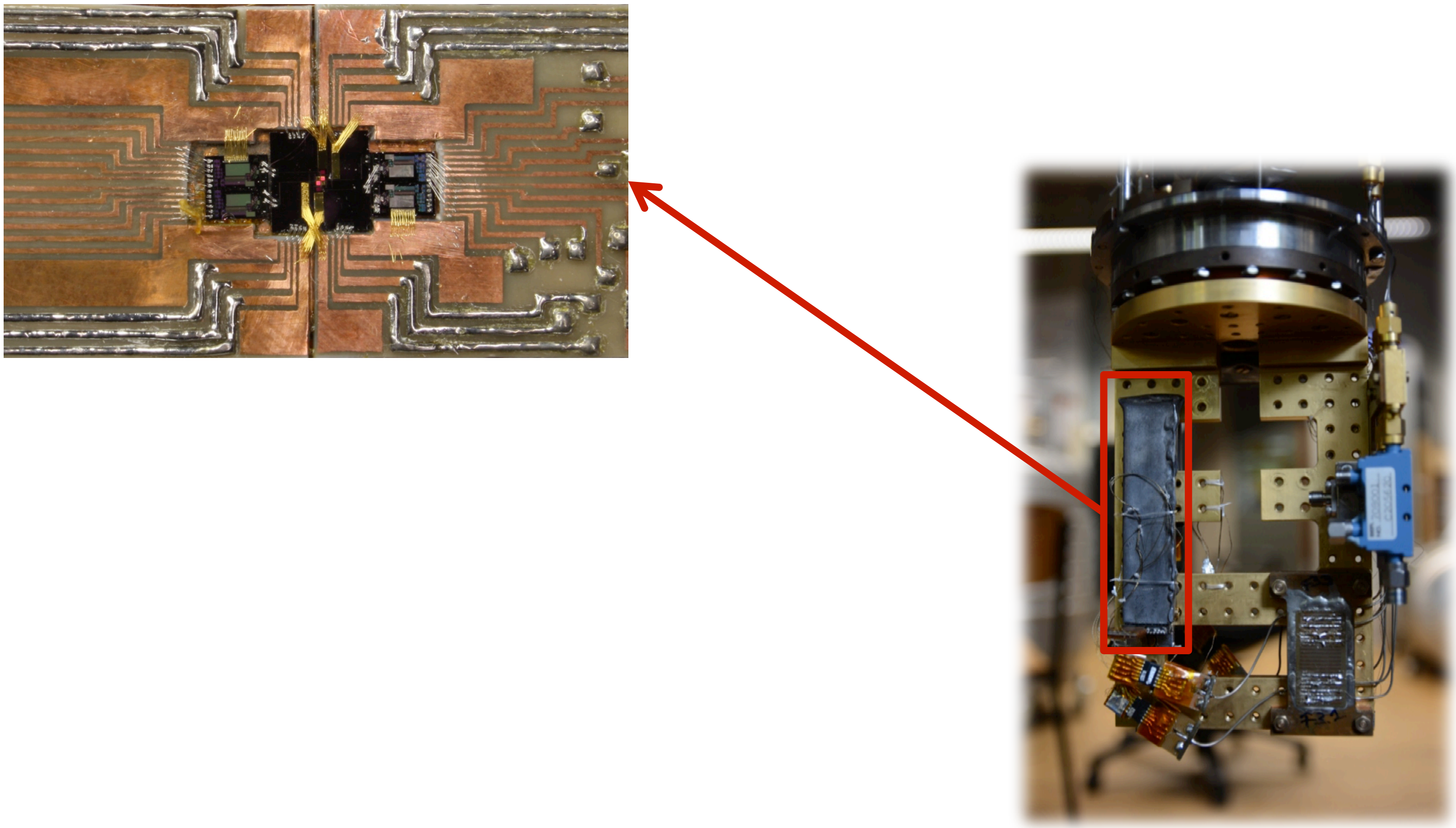
Passive Reduction Technique



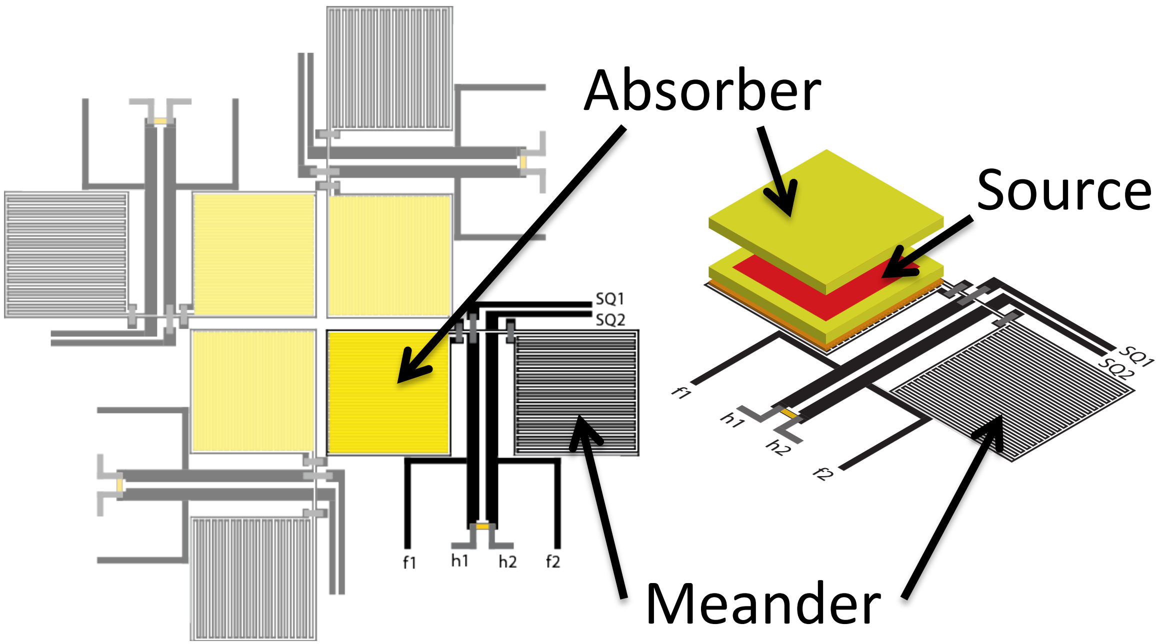


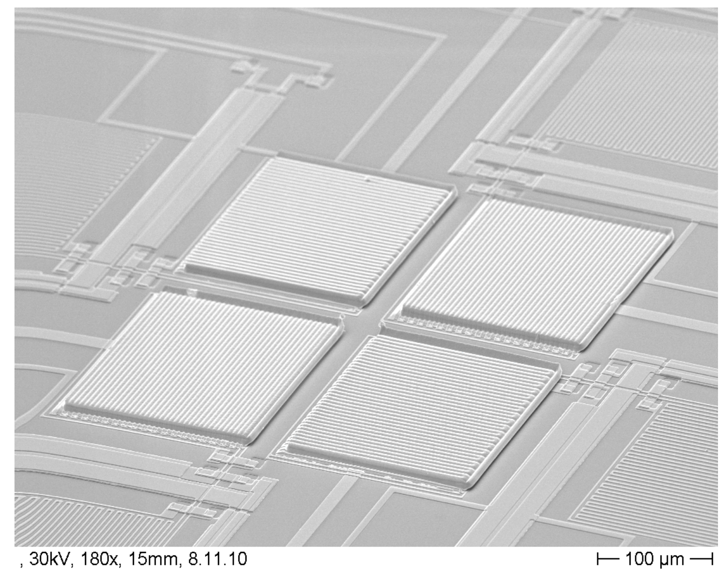
Holmium backup slides

ECHo: First Setup



ECHo: First Setup

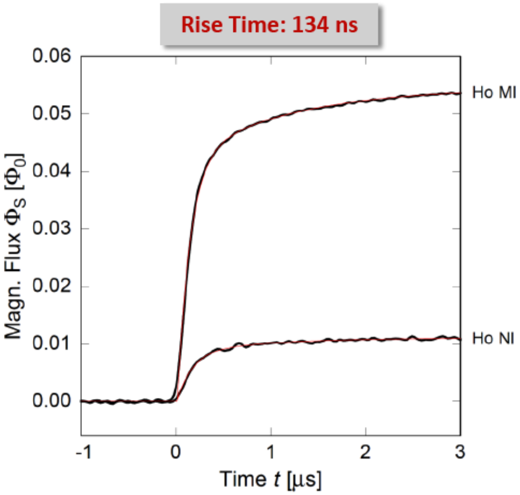


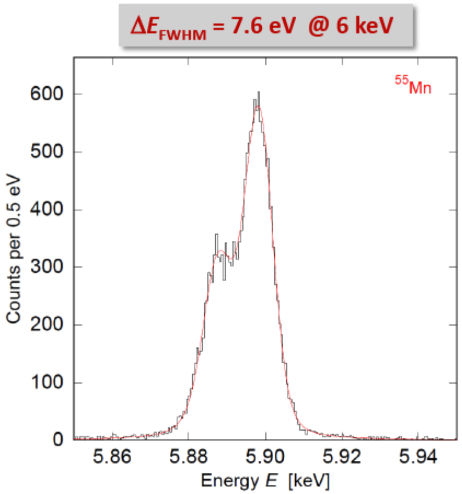


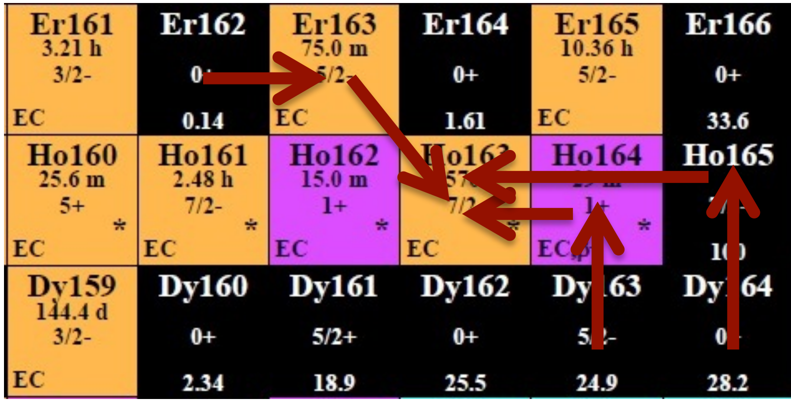
ECHo: Some details

100 pixel with 10 - 100 Bq per pixes

Neutron activation of erbium 162, purification and mass separation, implantation







Project 8 backup slides

Future Perspectives…