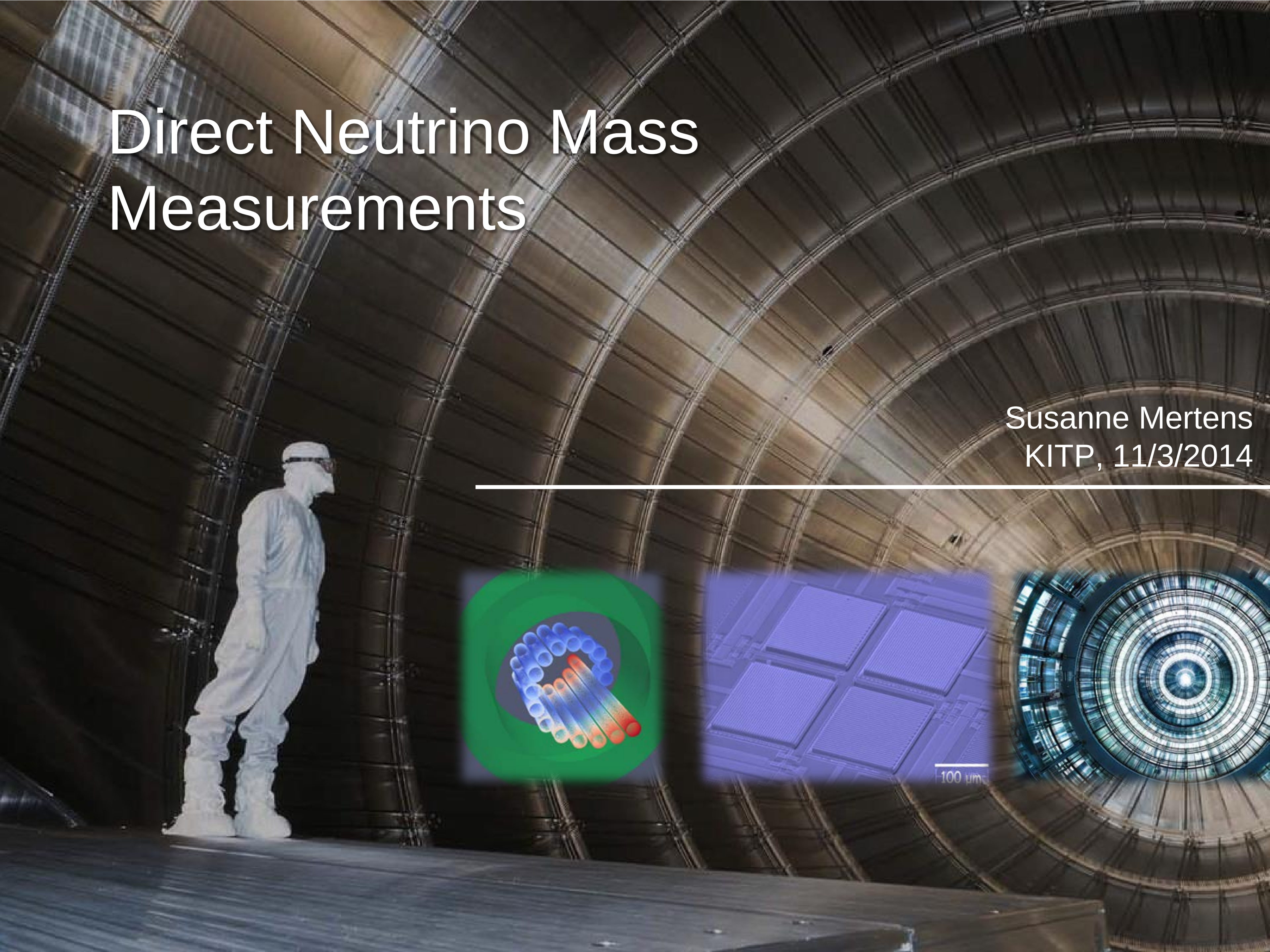
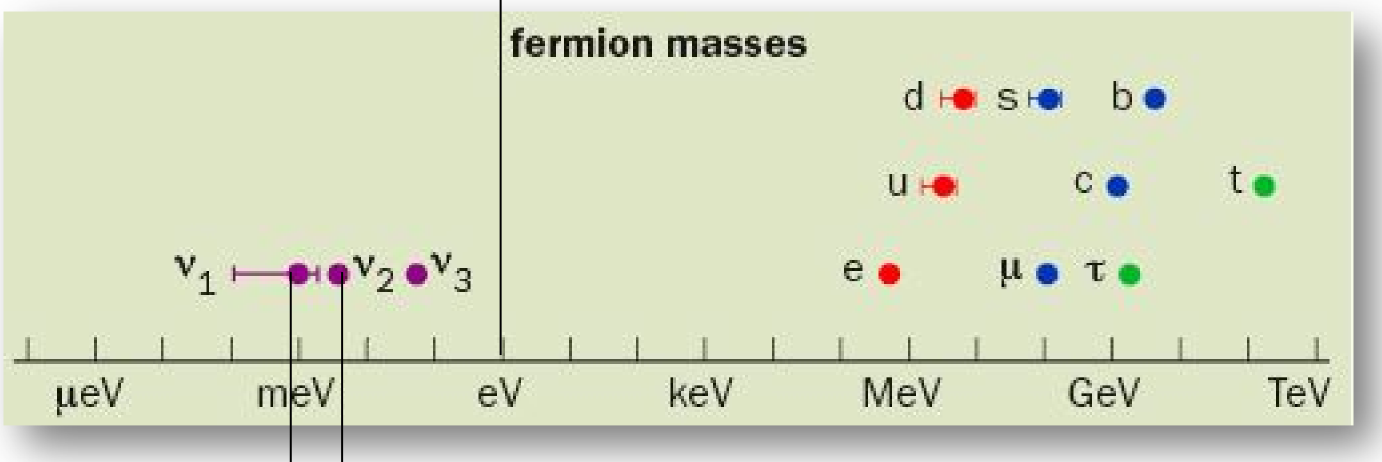
Direct Neutrino Mass Measurements

Susanne Mertens
KITP, 11/3/2014



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

$$m_\nu = \sum_i m_i$$

Search for 0νßß

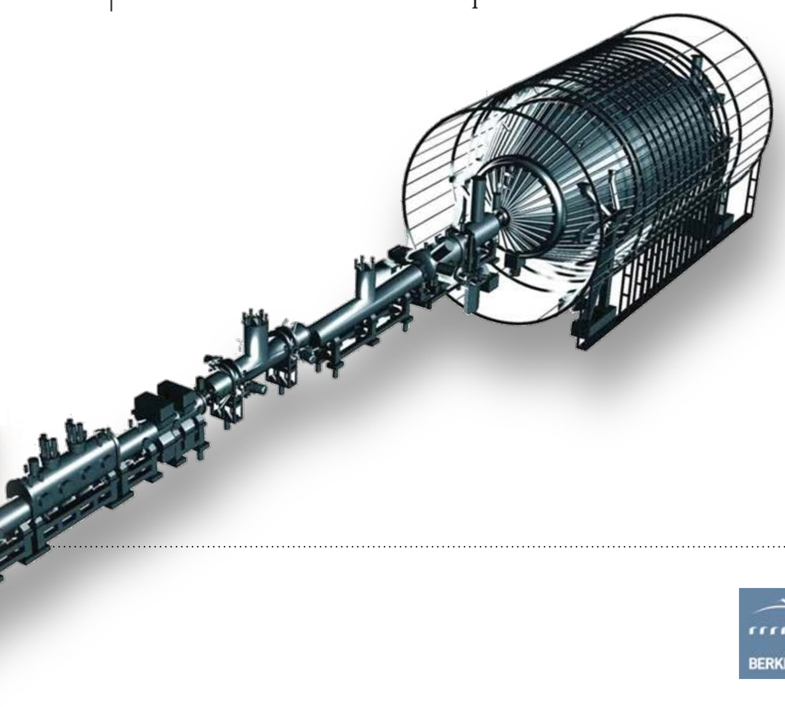
model-dependent
potential: $m_{ßß}$ = 20-50 meV
e.g. MAJORANA

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

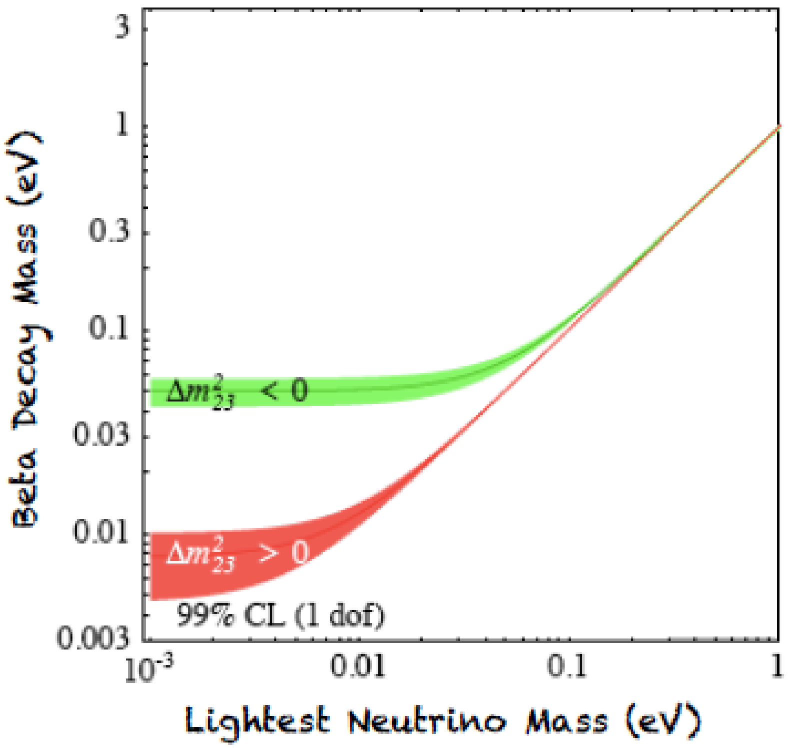
Kinematics of ß-decay

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

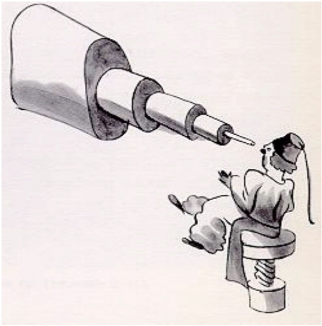
$$m_{\nu_{\mathrm{e}}}^2 = \sum_{\mathrm{i}} |U_{\mathrm{ei}}|^2 \cdot m_{\nu_{\mathrm{i}}}^2$$



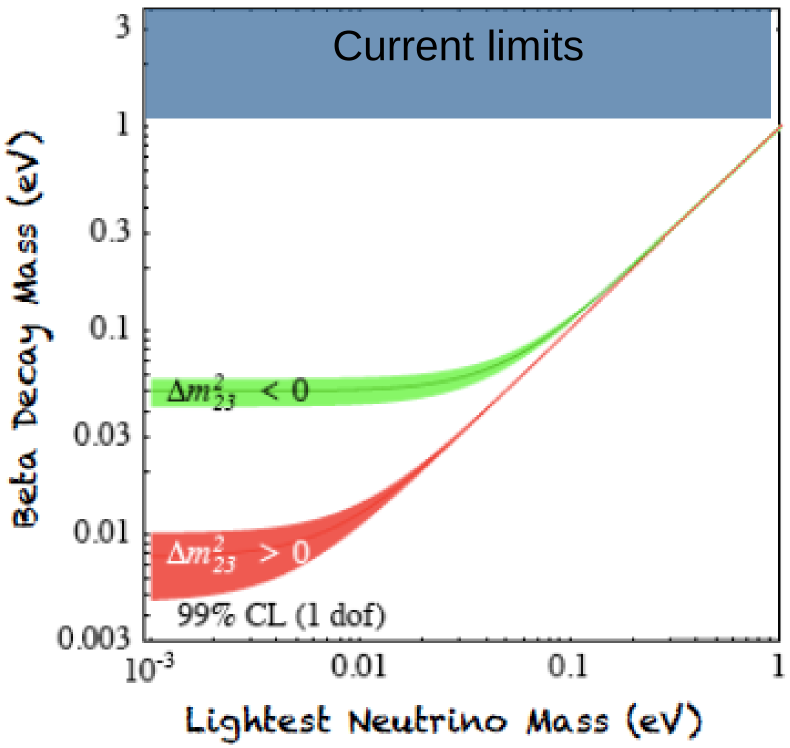
Neutrino mass



Knowledge of neutrino mass has an impact on both particle physics and cosmology

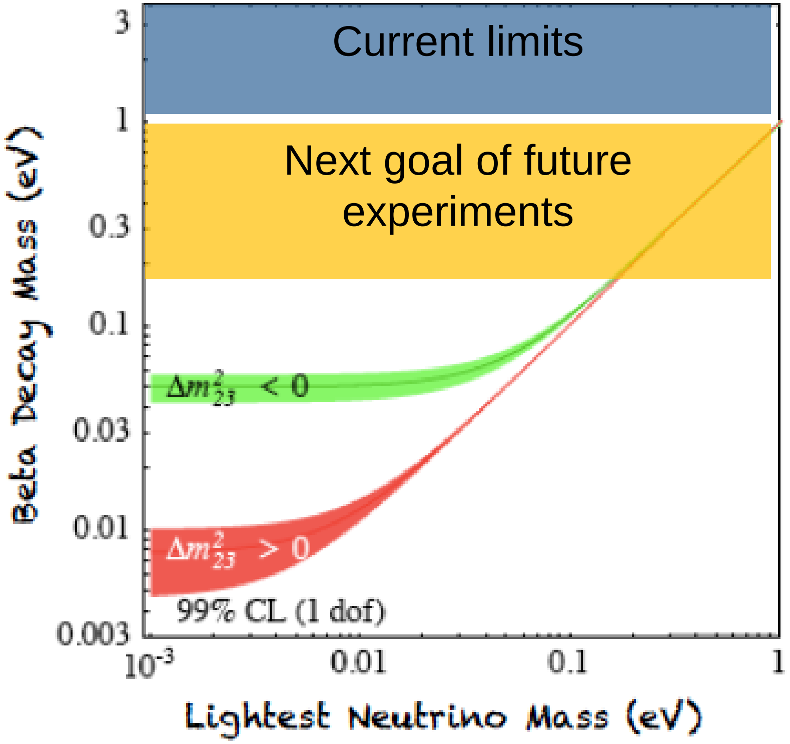


Neutrino mass



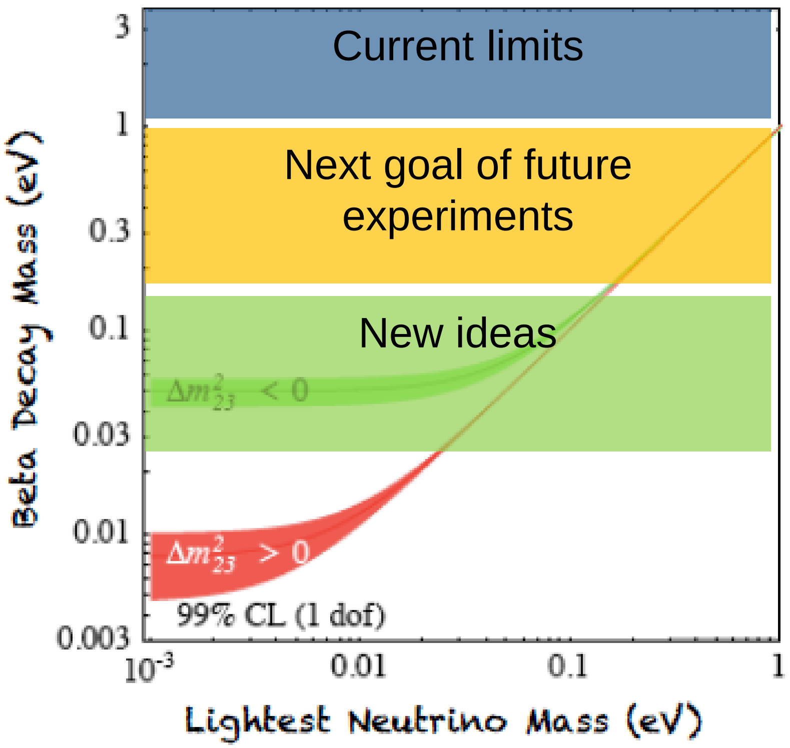
- Neutrinos excluded as Dark Matter

Neutrino mass



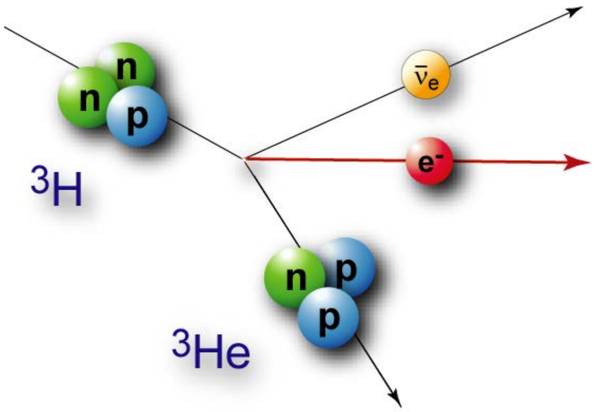
- Neutrinos excluded as Dark Matter
- Distinquish between hirarchical and degenerate scenario, impact on structure formation

Neutrino mass

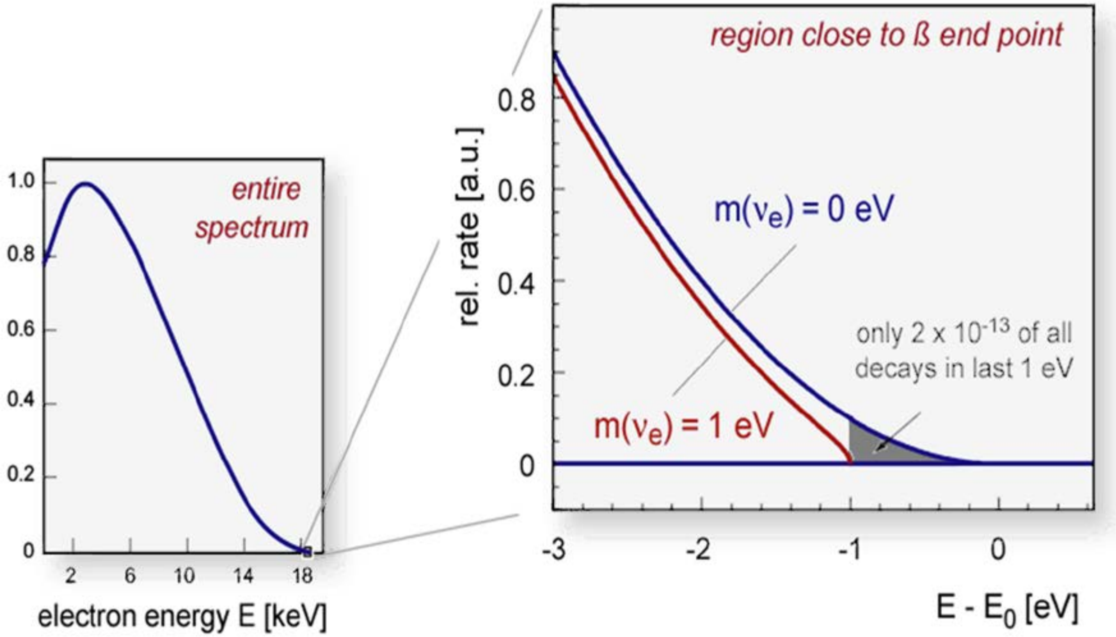


- Neutrinos excluded as Dark Matter
- Distinquish between hirarchical and degenerate scenario, impact on structure formation
- Resolve neutrino mass hierarchy

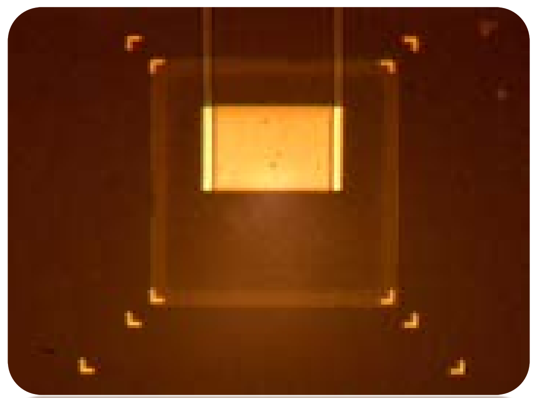
General Idea

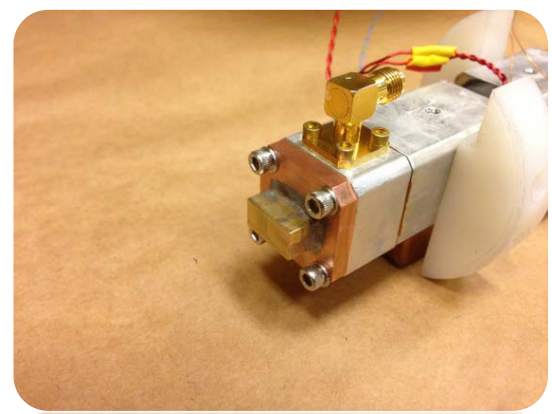


- A kinematic determination of the neutrino mass
- No model dependence on cosmology or nature of mass



3 Experimental Efforts

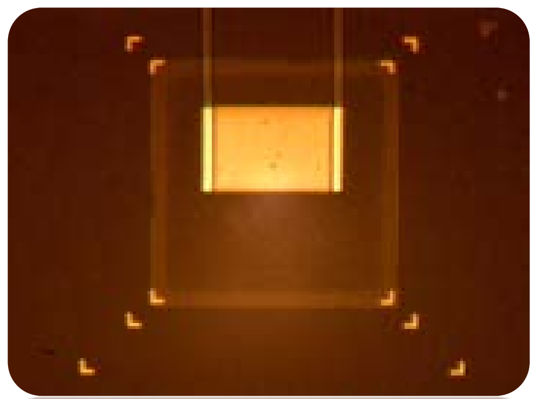


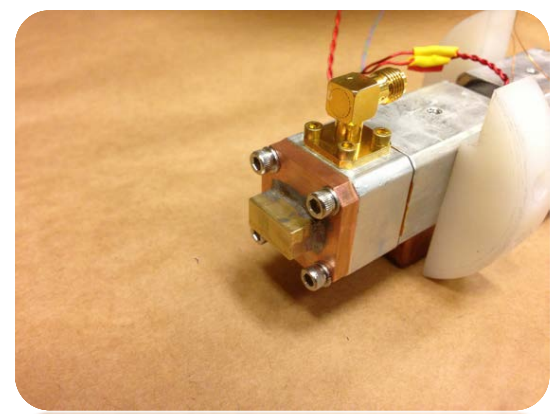


Drexlin, V. Hannen, S. M., C. Weinheimer, Adv. High Energy Physics 2013, Article ID 293986, (2013)

3 Experimental Efforts

Spectroscopy
(KATRIN)

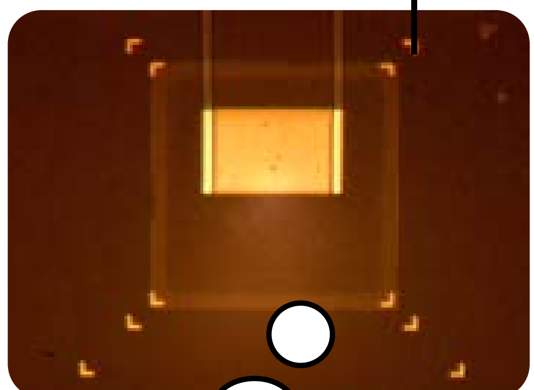


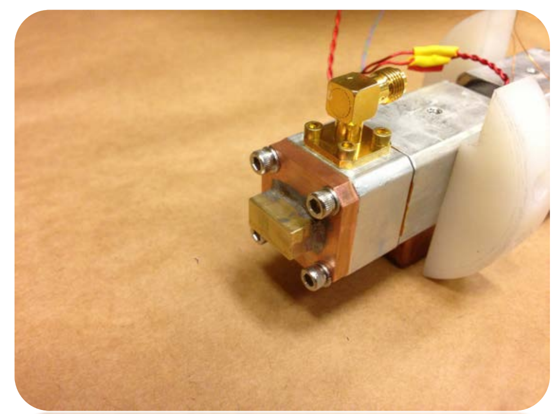


3 Experimental Efforts

Spectroscopy
(KATRIN)

Calorimetry
(HOLMES, ECHO
&NUMECS)





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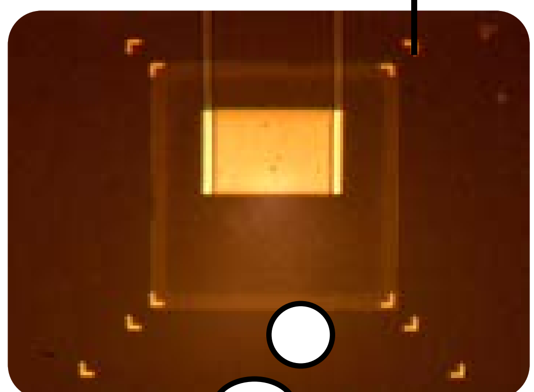
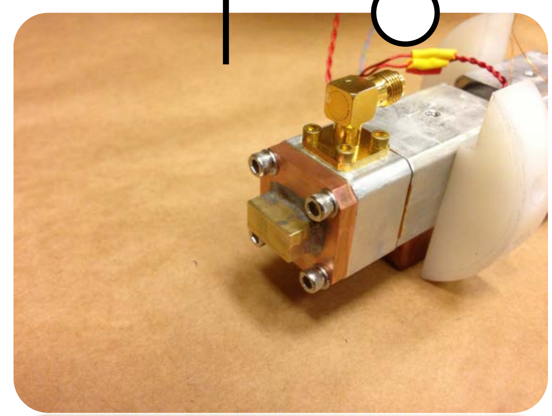


Frequency
(Project 8)



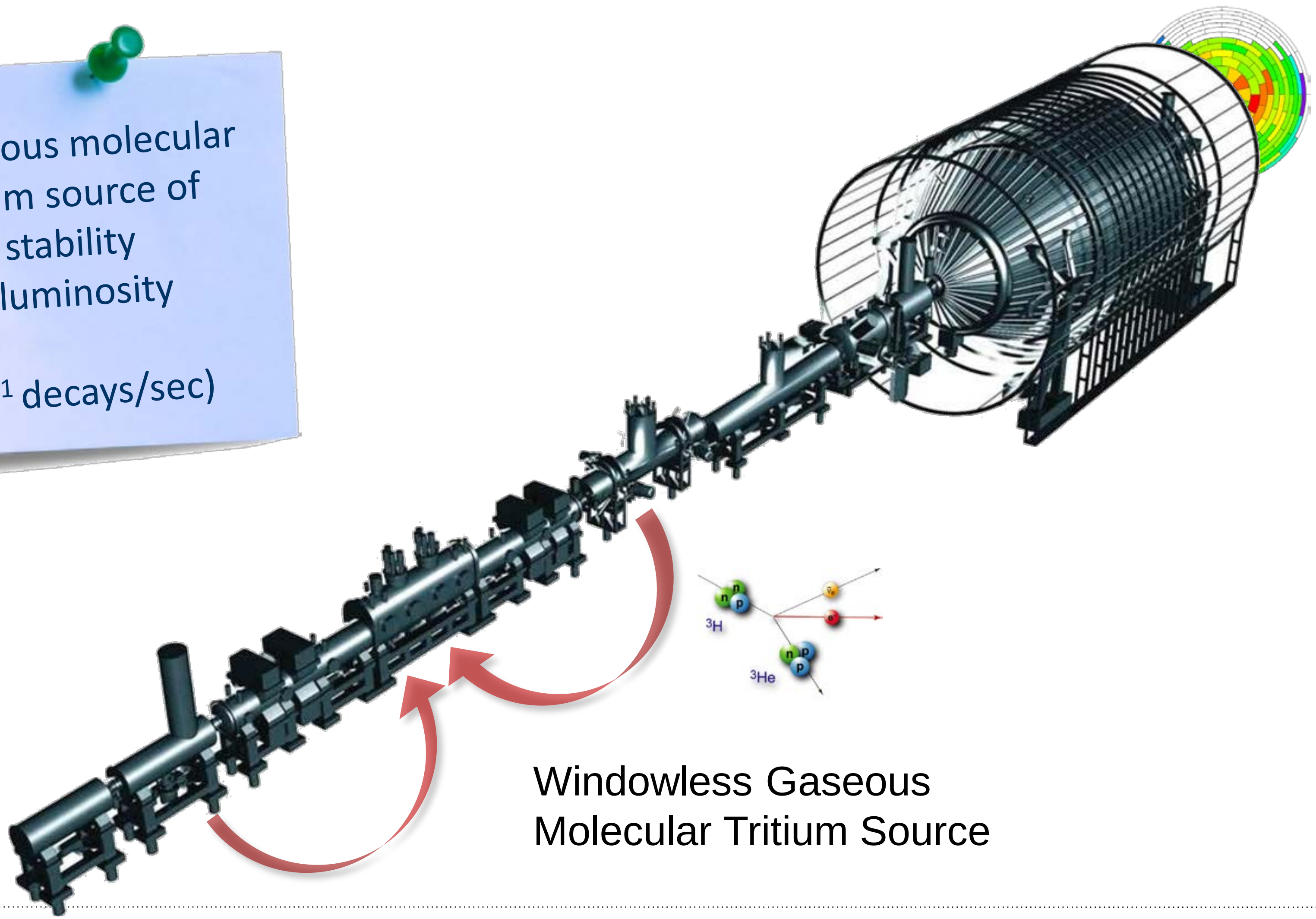
Karlsruhe Tritium Neutrino Experiment

- 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

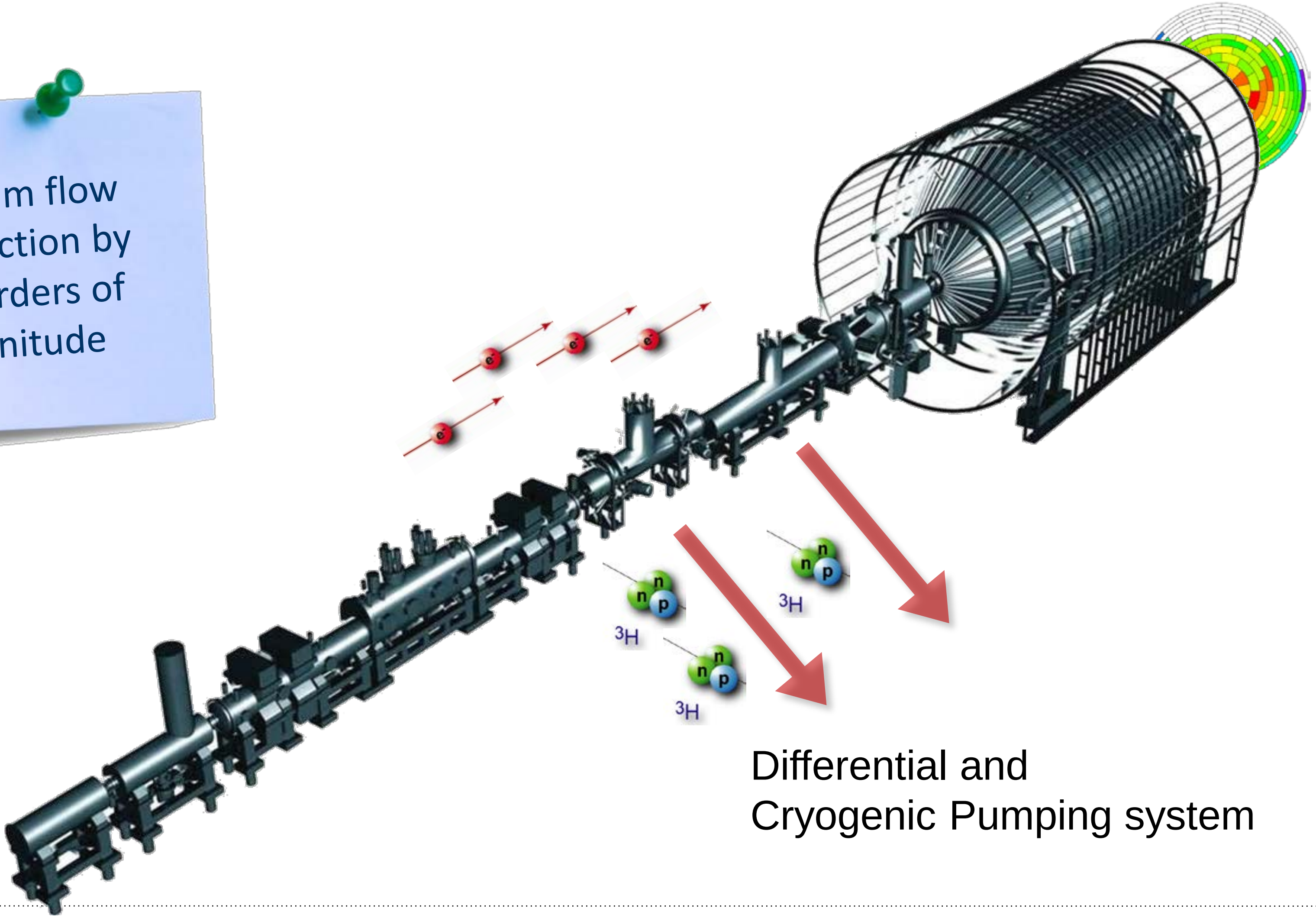
(10^{11} decays/sec)



Windowless Gaseous Molecular Tritium Source

KATRIN Overview

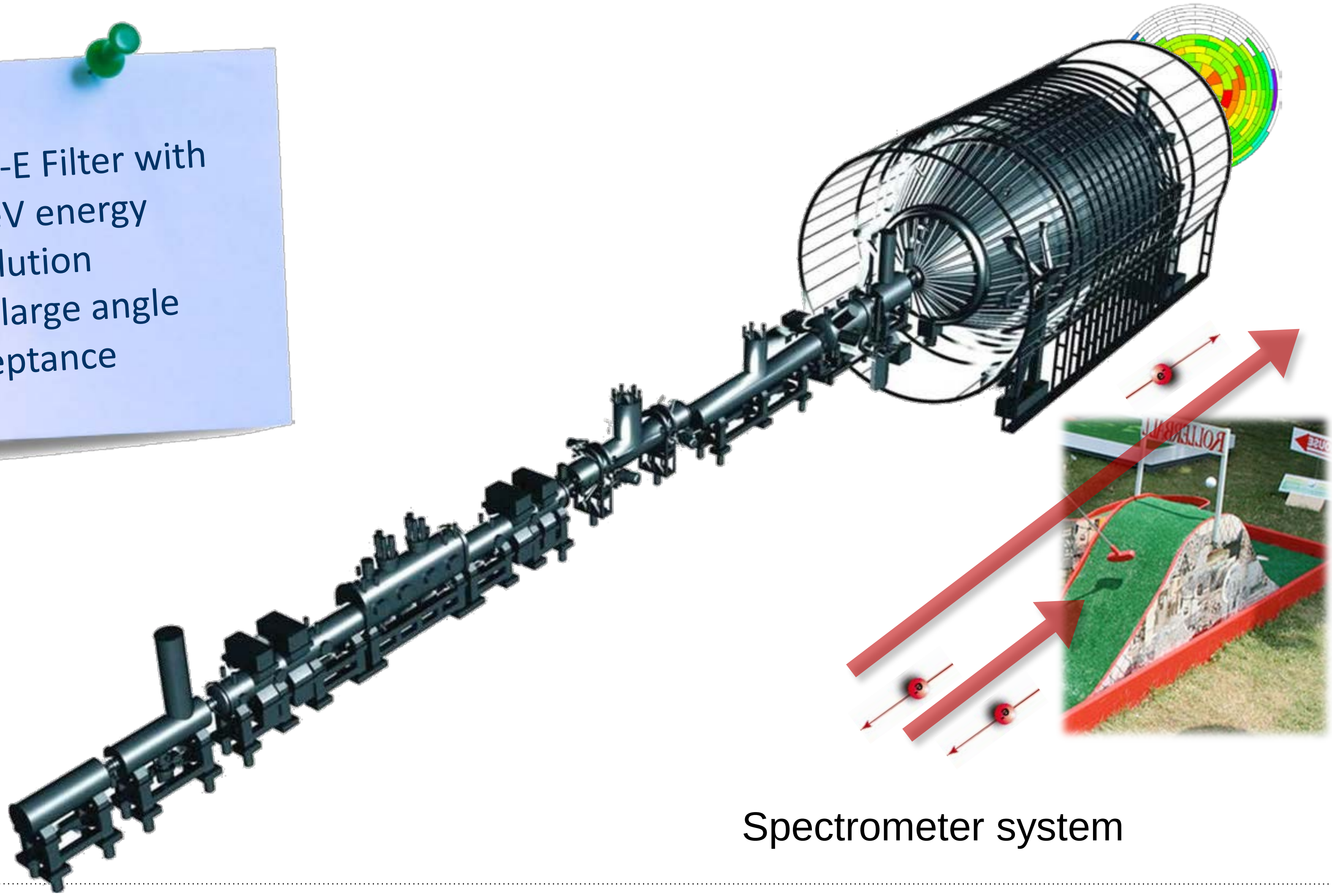
Tritium flow reduction by 14 orders of magnitude



Differential and
Cryogenic Pumping system

KATRIN Overview

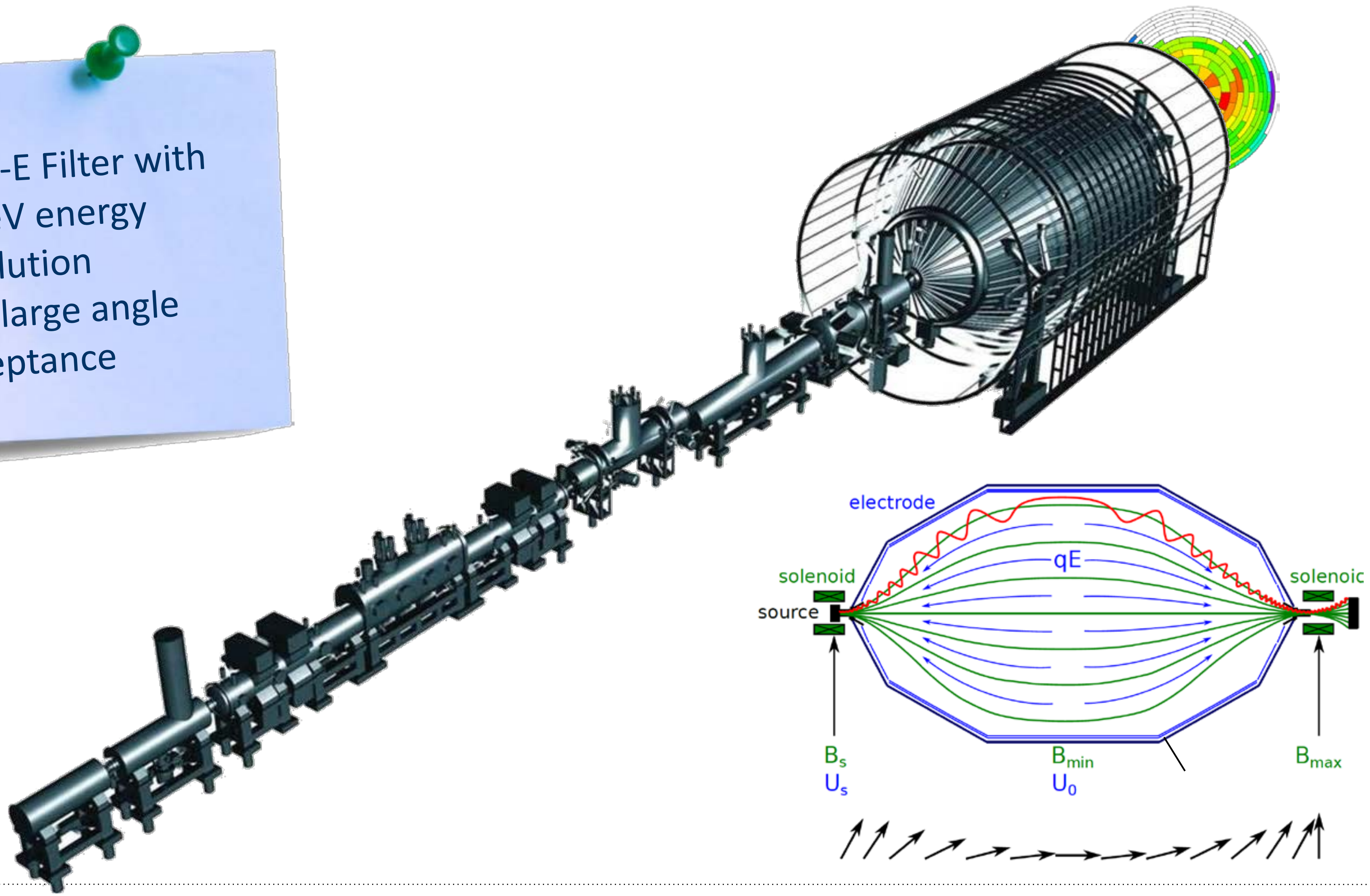
MAC-E Filter with
< 1 eV energy
resolution
and large angle
acceptance



Spectrometer system

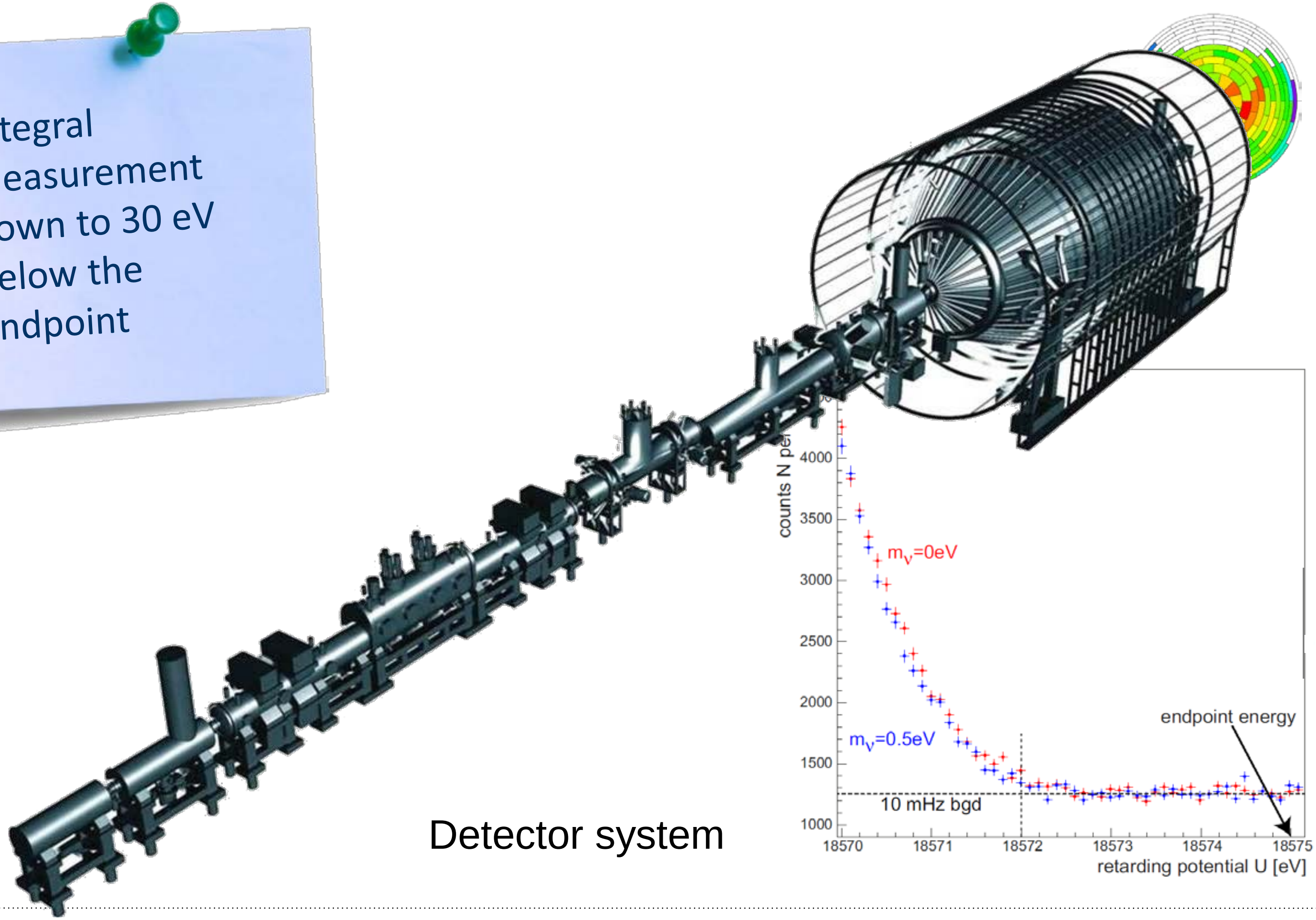
KATRIN Overview

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



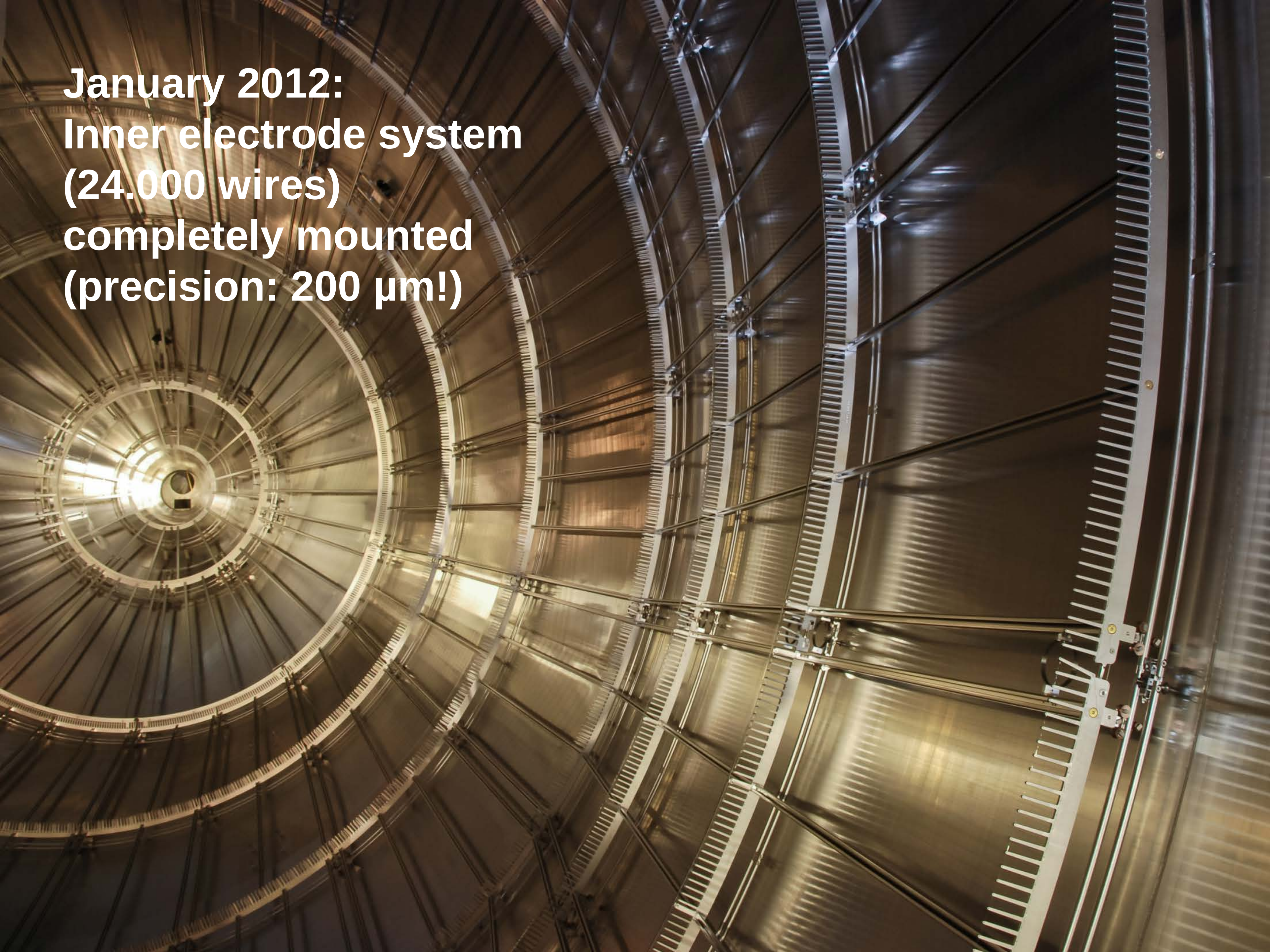
KATRIN Overview

Integral measurement down to 30 eV below the endpoint




2006: Arrival of
Main Spectrometer
in Karlsruhe


2011: fully
commissioned Aircoil
system

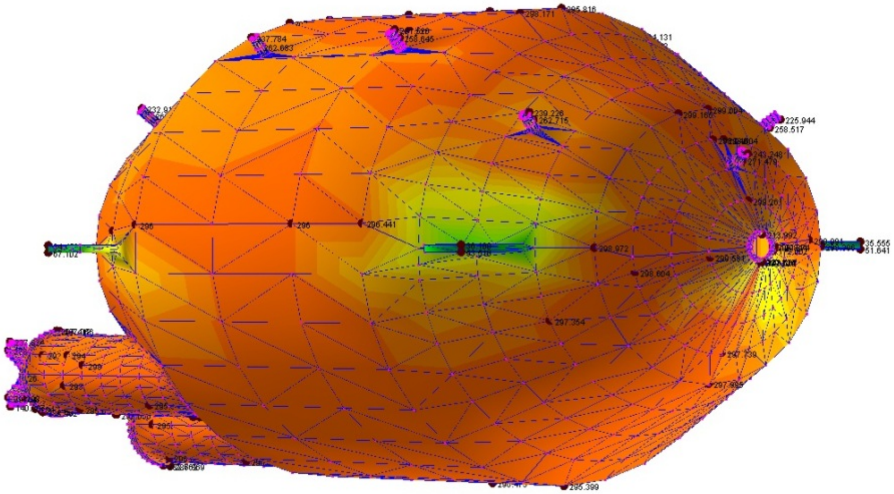

January 2012:
Inner electrode system
(24.000 wires)
completely mounted
(precision: 200 µm!)

May 8, 2012 14:11
spectrometer pump
ports are closed

Commissioning of main spectrometer

- Successful bake-out of spectrometer vessel at 300° C
- Inner electrode system: no broken wire
- NEG pump activated: pressure at 5×10^{-11} mbar

- “First light” last summer



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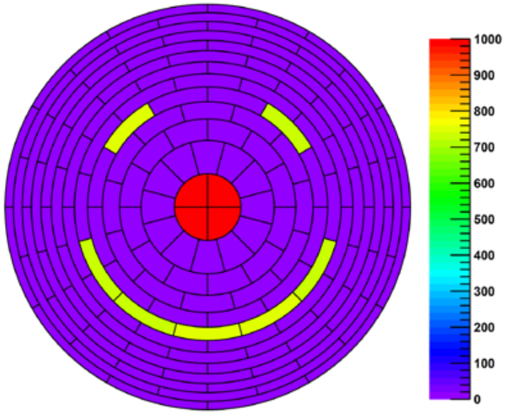
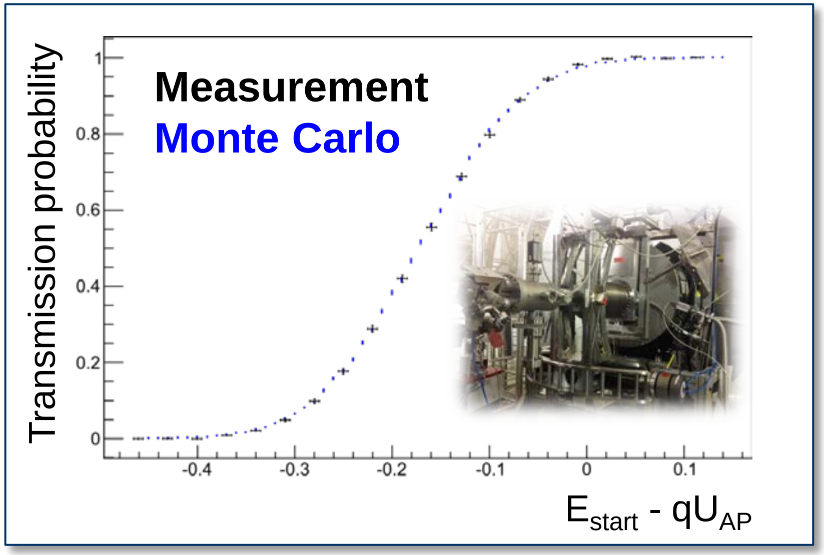


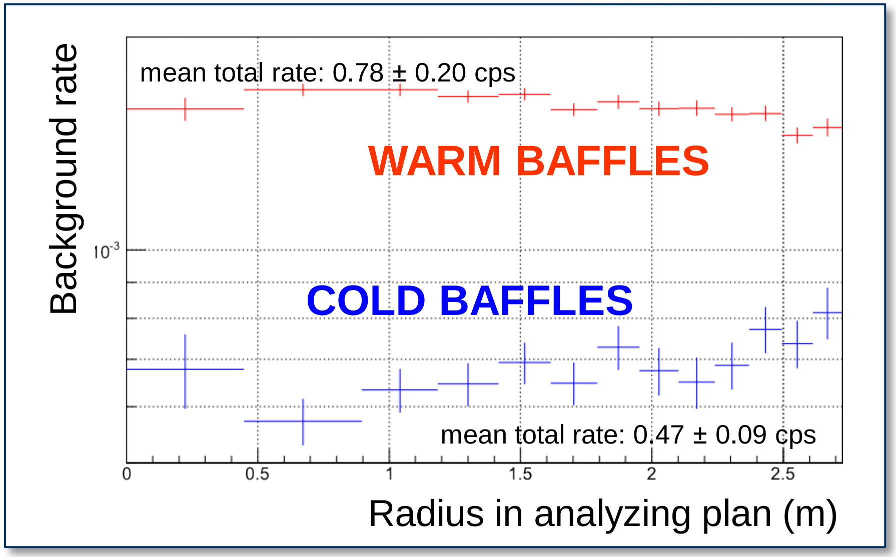
Commissioning of main spectrometer

Transmission Properties



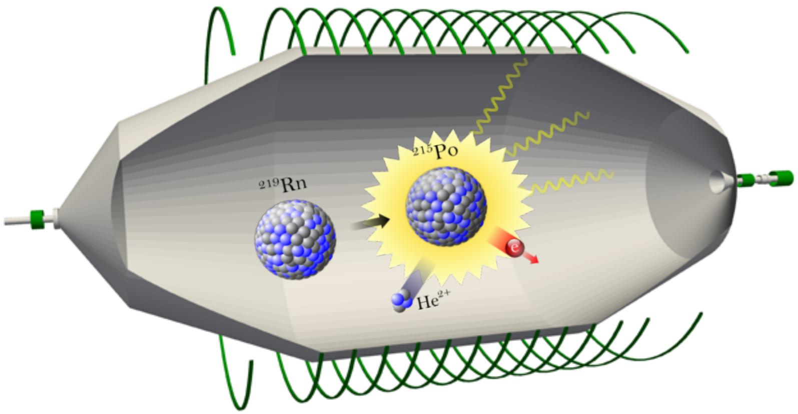
Spectrometer transmits electrons as expected !

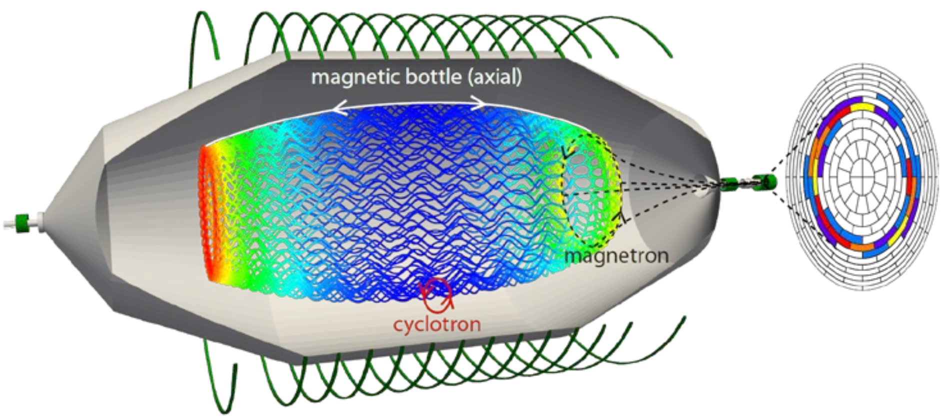
Background Rates



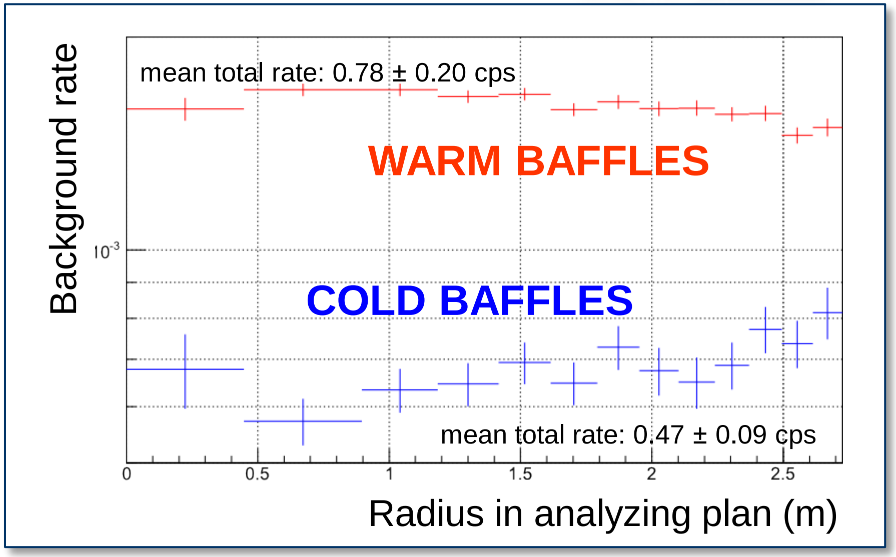
Background rate of order Hz (10 mHz desired).
Greater reduction of backgrounds to come

Commissioning of main spectrometer



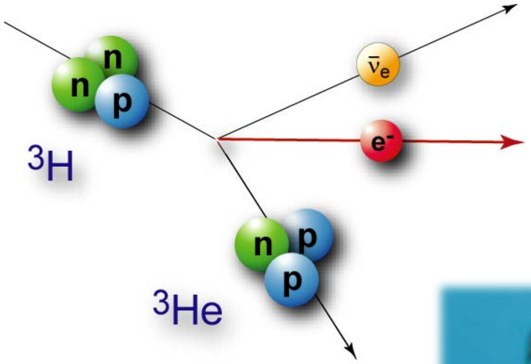


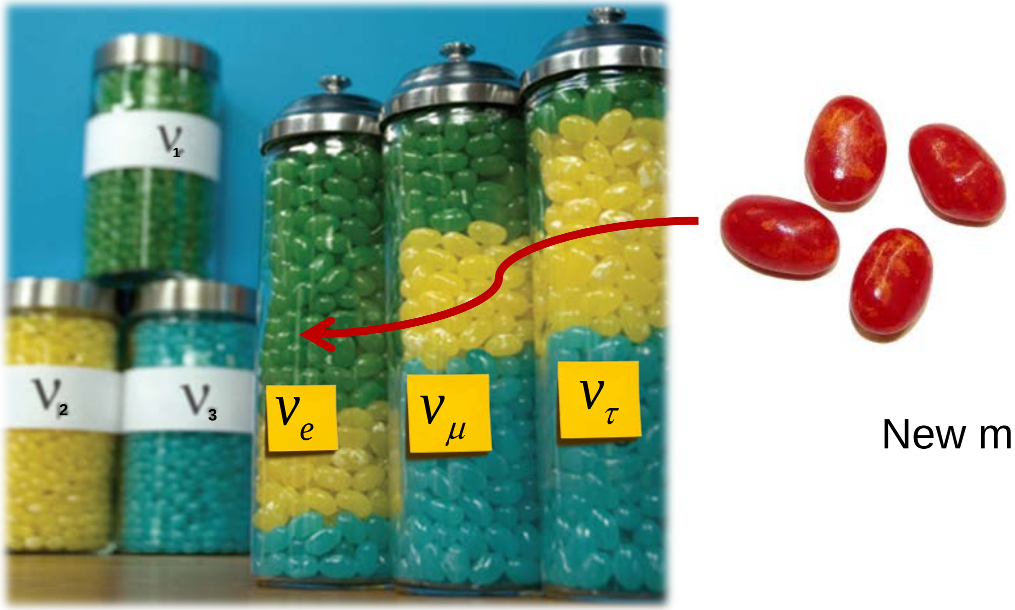
Background Rates



Background rate of order Hz (10 mHz desired).
Greater reduction of backgrounds to come

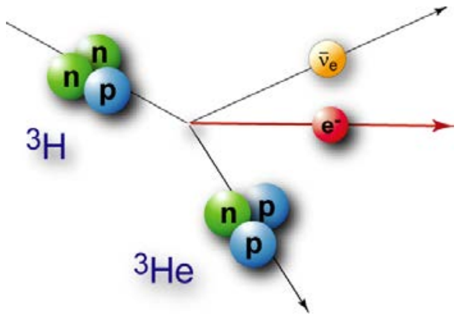
KATRIN and sterile neutrinos

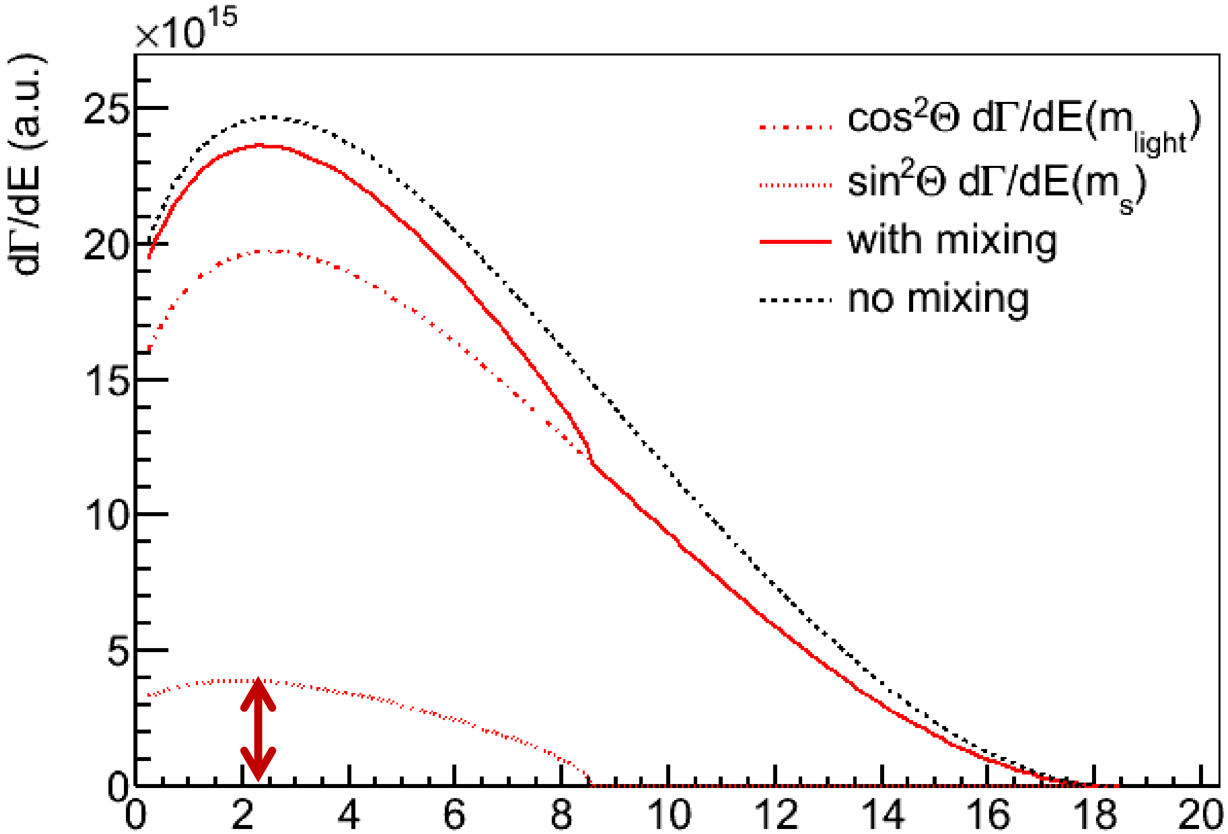




New mass eigenstate

KATRIN and sterile neutrinos

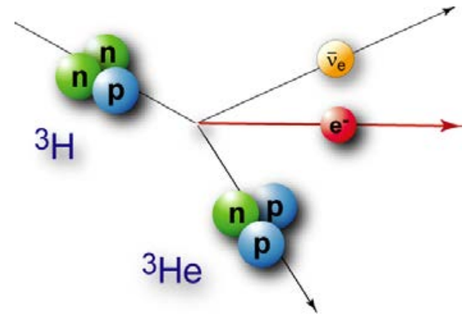


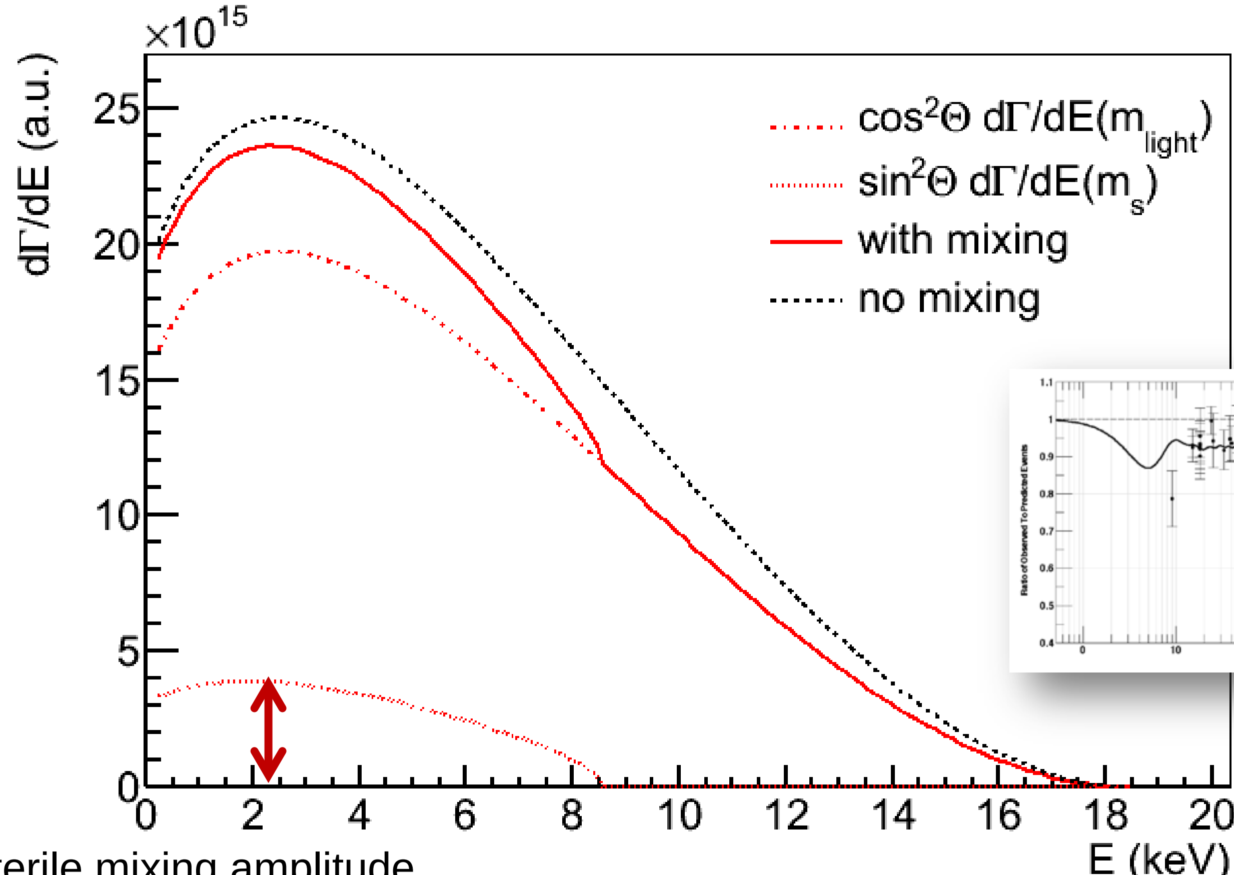


Active-to-sterile mixing amplitude

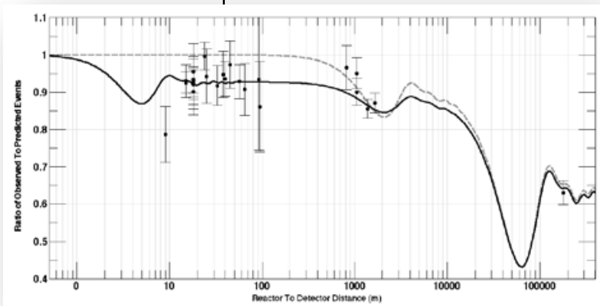
Mass of the sterile neutrino

KATRIN and sterile neutrinos





eV-sterile neutrinos



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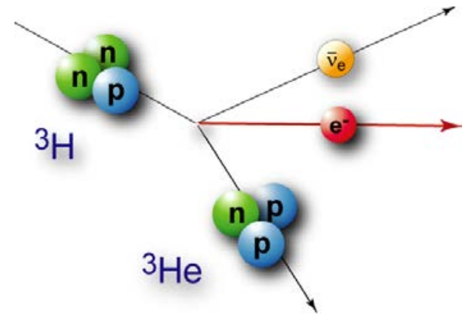
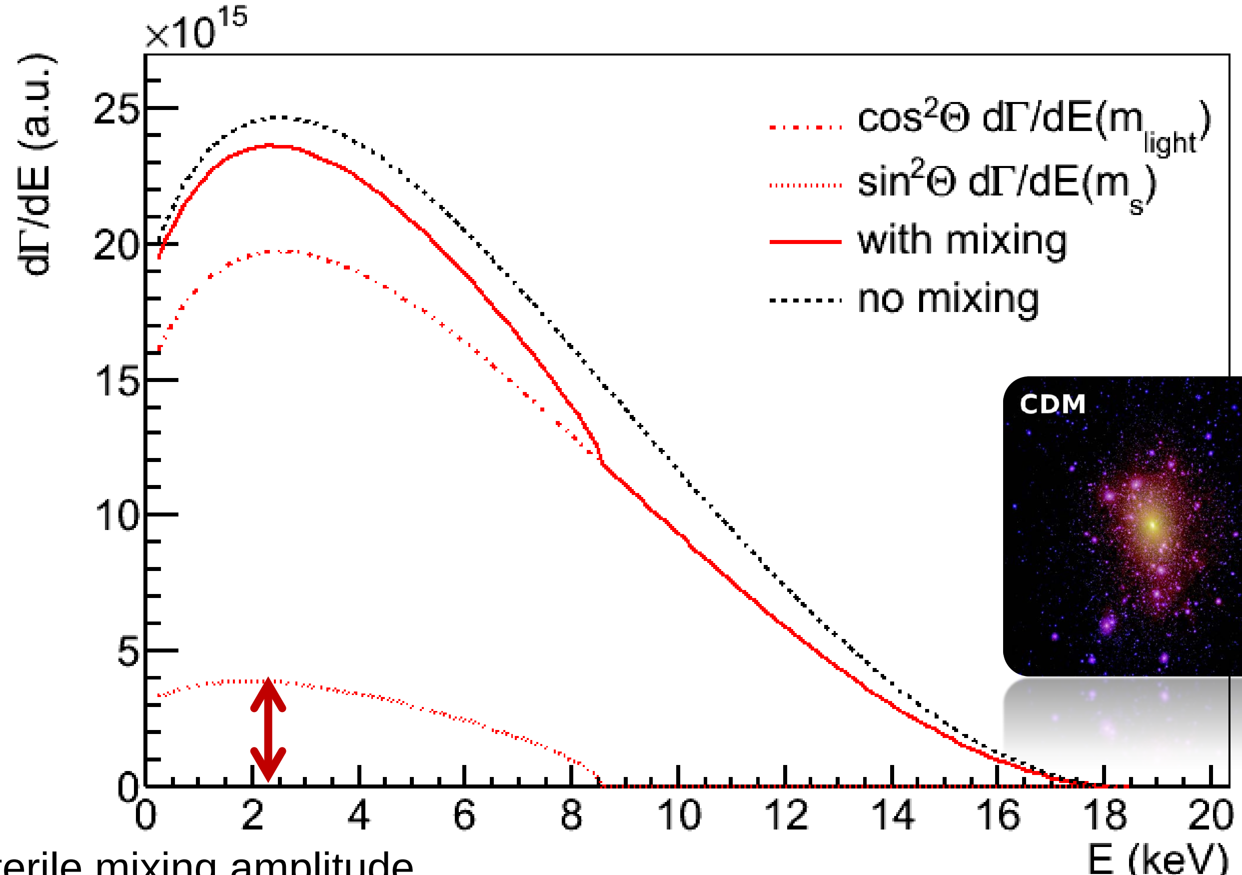
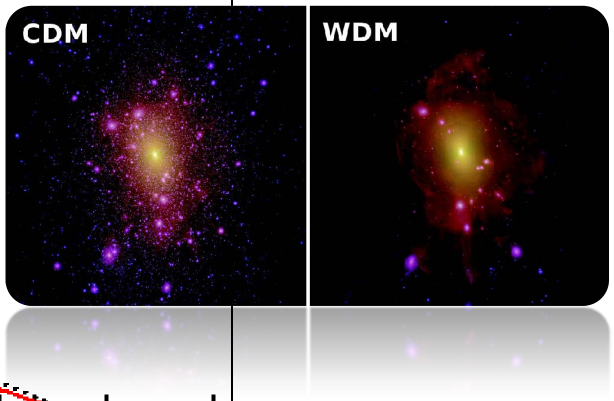
KATRIN and sterile neutrinos





keV-sterile neutrinos



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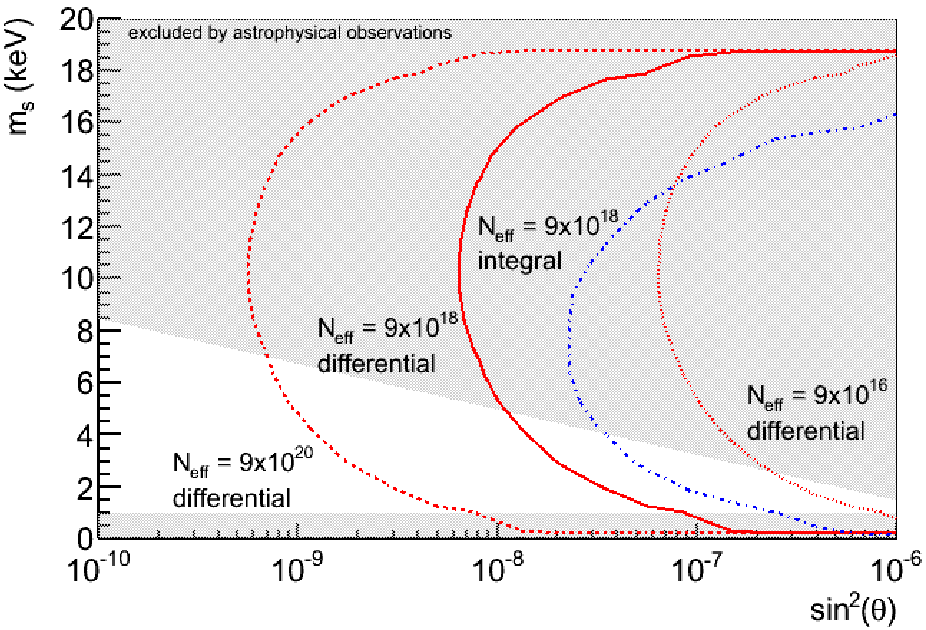
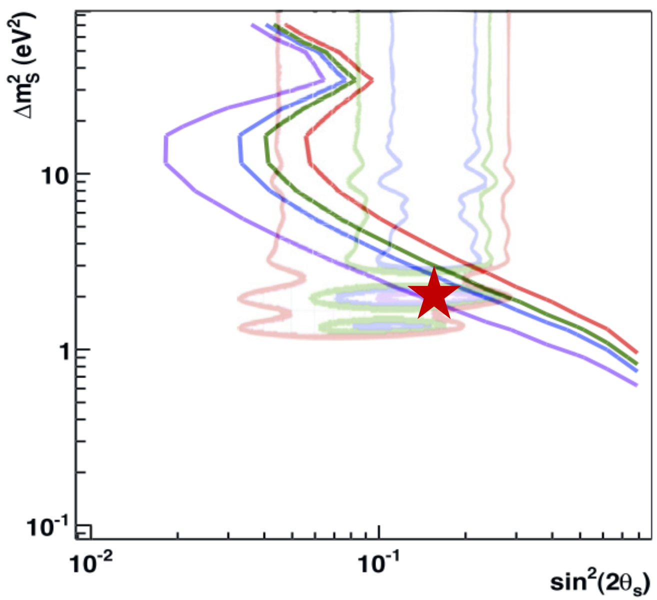
KATRIN and sterile neutrinos





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

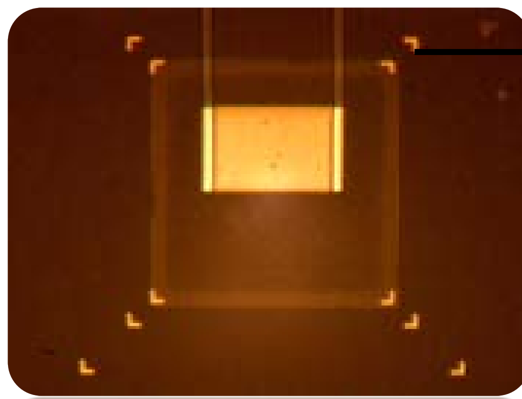
KATRIN **as is** probes the favored parameter space for light sterile neutrinos

S. M. et al, arXiv:1410.7684, (2014)
S. M. et al, arXiv:1409.0920, (2014)

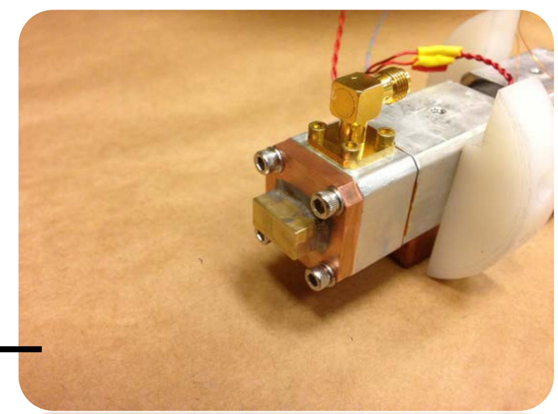
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Esmaili, O.L.G. Peres, Phys. Rev. D 85, 117301
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011

3 Experimental Efforts

Spectroscopy
(KATRIN)



Calorimetry
(HOLMES, ECHO
&NUMECS)



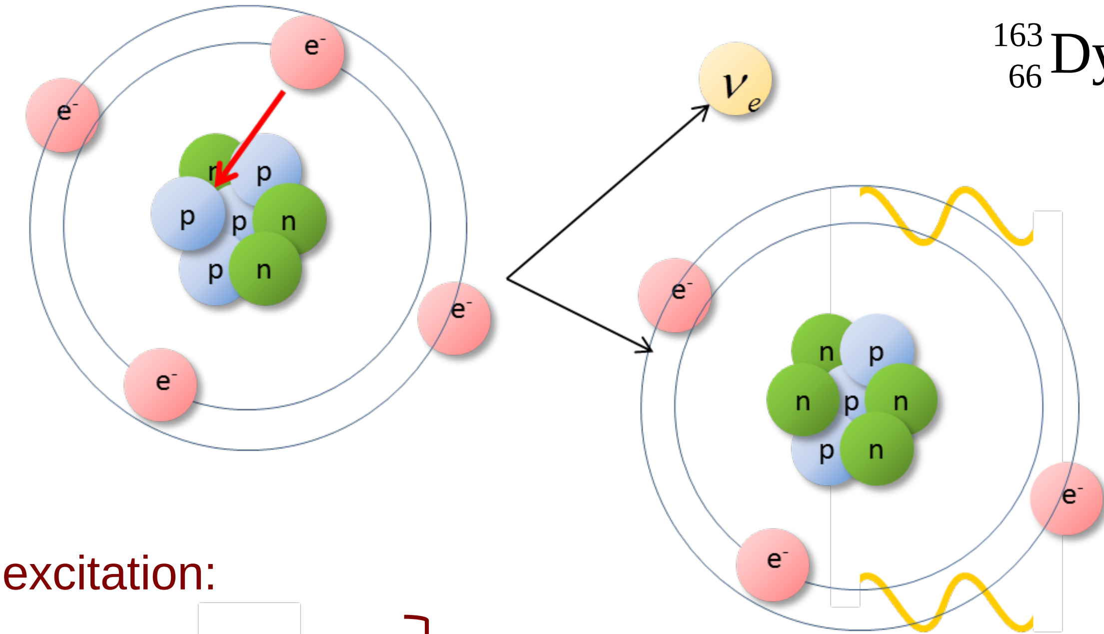
Frequency
(Project 8)

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

Electron Capture on Holmium

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

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

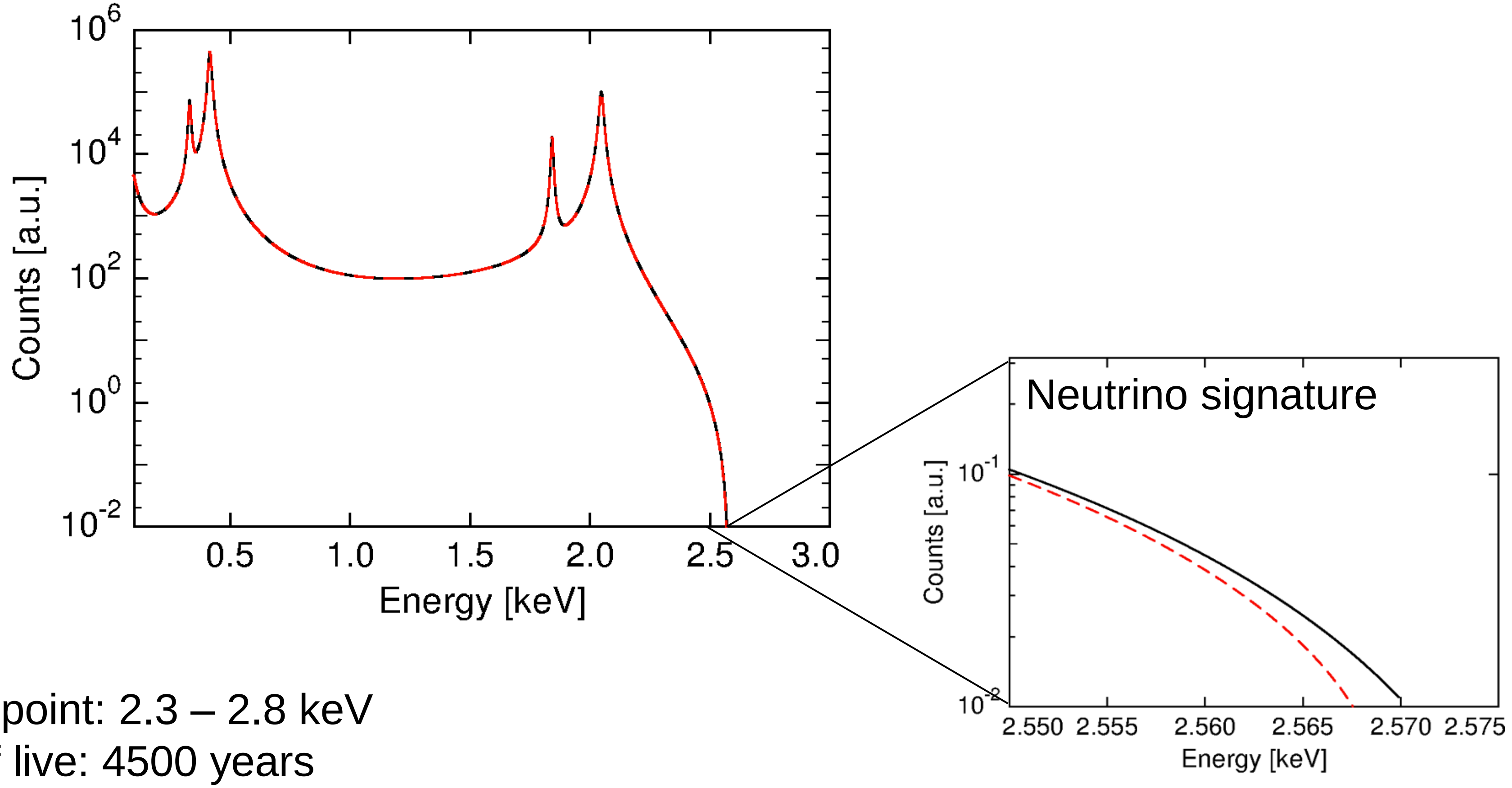


Atomic de-excitation:

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

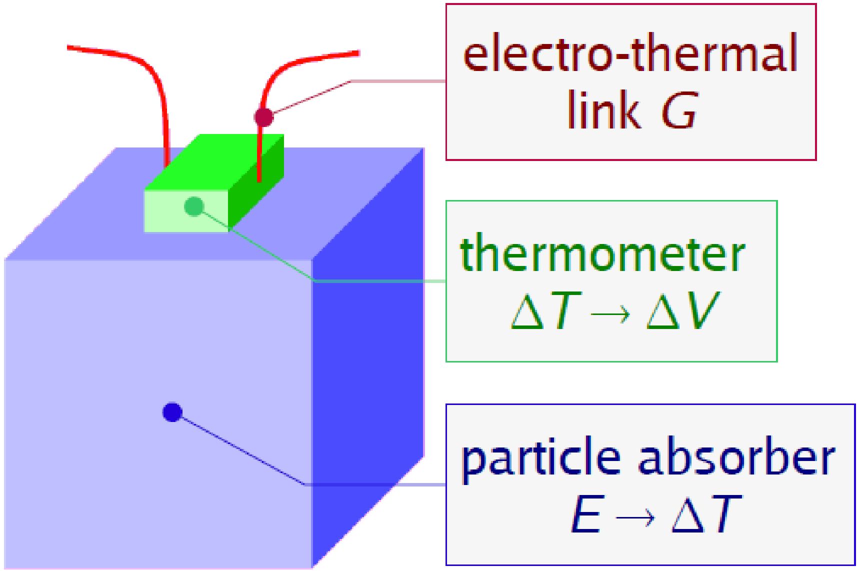
} Calorimetric measurement

Electron Capture on Holmium



- Endpoint: 2.3 – 2.8 keV
- Half live: 4500 years

Calorimetric measurement



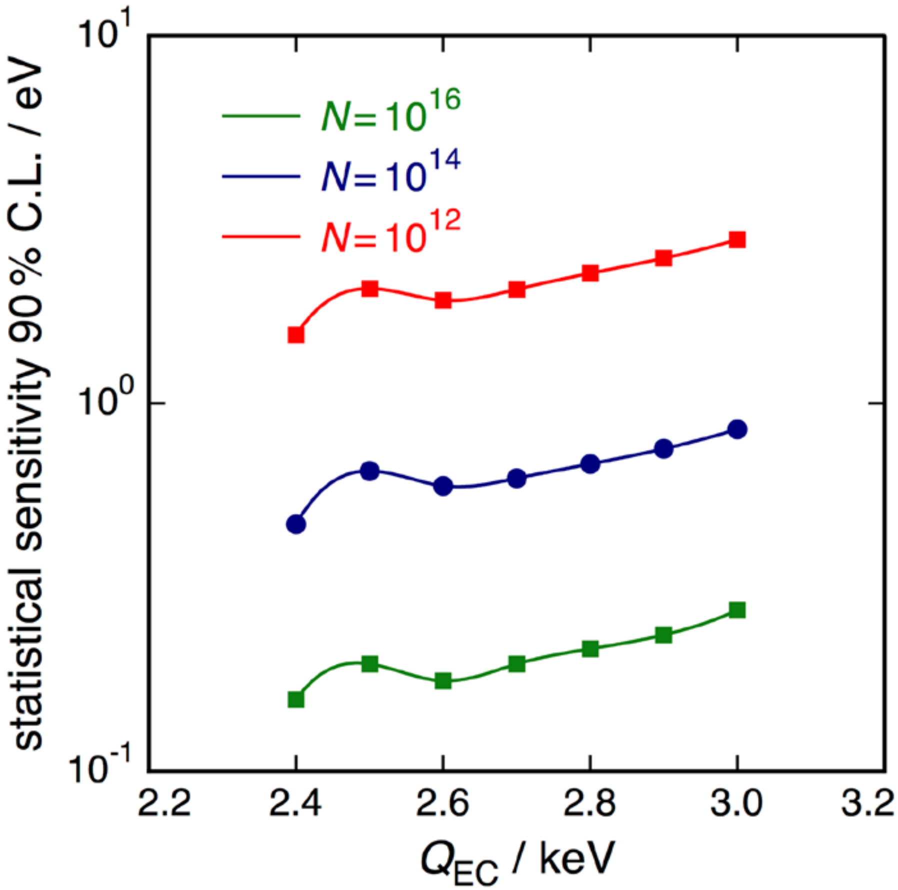
Advantages:

- Source = detector
- All energy is detected
- No molecular final states
- Self-calibrating

Challenges:

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

Calorimetric measurement



Advantages:

- Source = d...
- N...
-
-

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

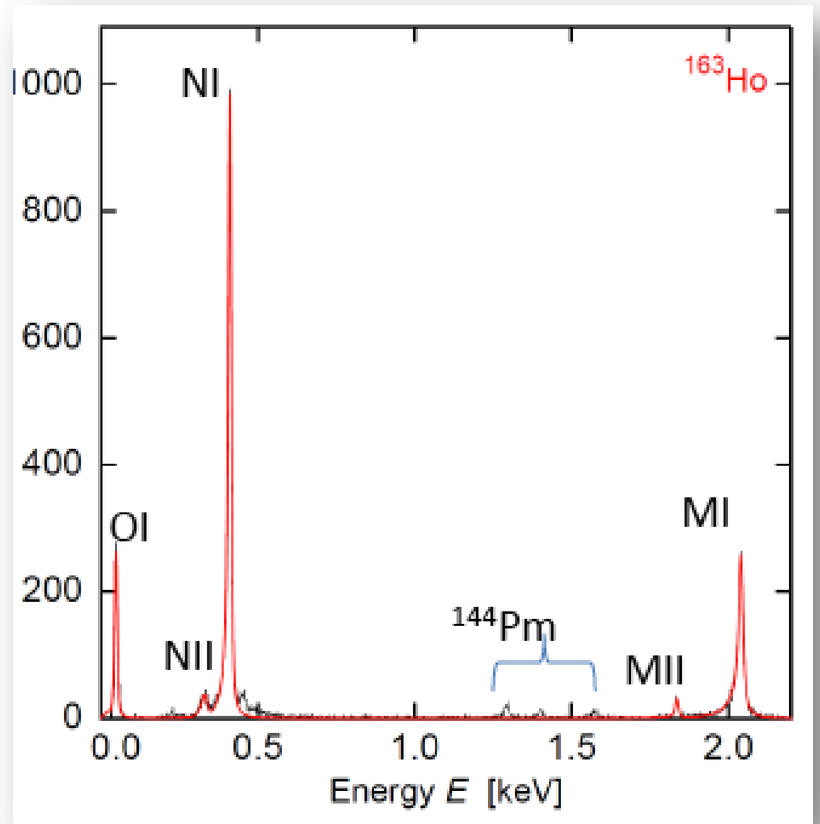
Challenges:

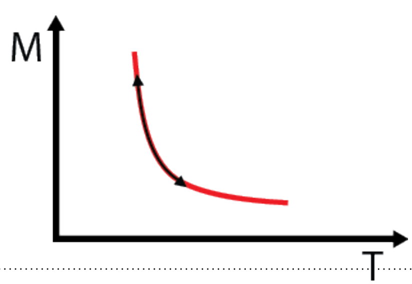
- ΔE_{FWHM} < 10
- $\tau_{risetime}$ < 1 μs to avoid background due to pile-up
- Sufficient isotope production

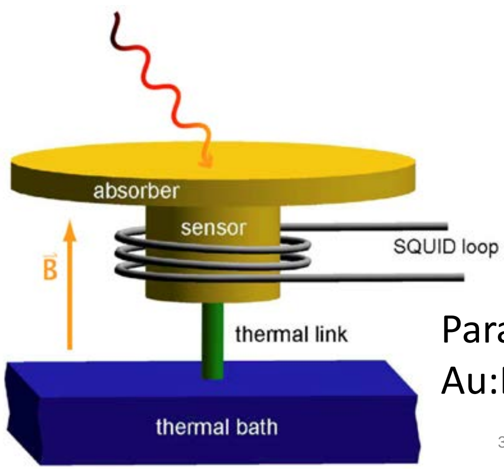
The ECHo Experiment

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)
- Fast rise times (τ = 130 ns), good energy resolutions (7.6 eV @ 6keV), and linearity demonstrated
- Microwave Multiplexing techniques (RF-SQUID)







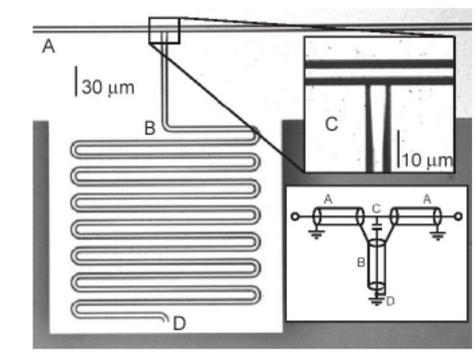
Paramagnetic sensor
Au:Er @ 30 mK

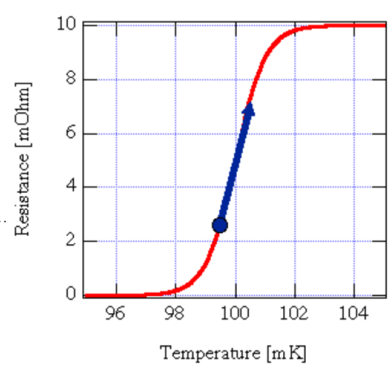
A. Fleischmann et al., *AIP Conf. Proc.* 1185, 571, (2009)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
P. C.-O. Ranitzsch et al., JLTP 167, 1004 (2012)
S. Kempf et al, JLTP *10.1007/s10909-013-1041-0*

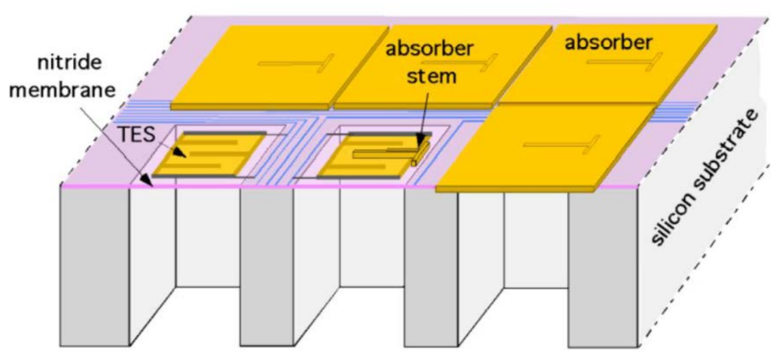
The HOLMES Experiment

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





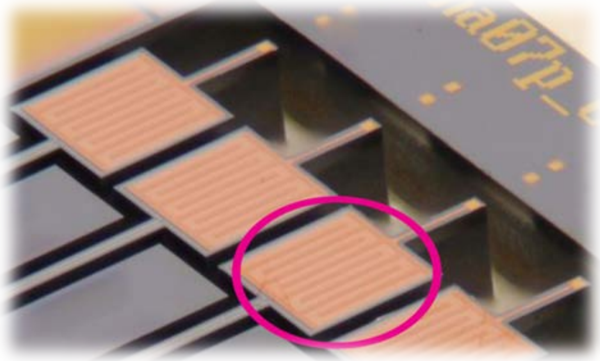


M. Ribeiro Gomes et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

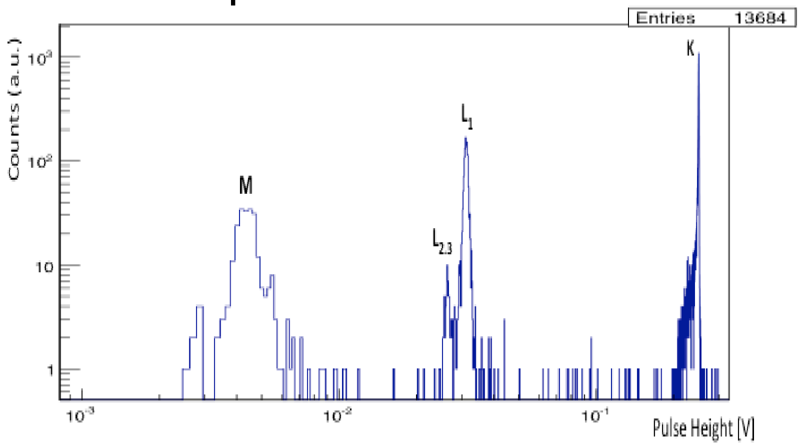
Los Alamos,
NIST,
U Madison
and others

The NuMecs Experiment

- Transition-Edge Sensors (TES)
- Good energy resolution (6 eV @ 6 keV with 55Fe surrogate).
- Concentration on high purity ^{163}Ho production – proton activation of dysprosium
- Show scalability through a demonstrator experiment with 4 x 1024 TES array of Ho-implanted detectors with RF-SQUID multiplexing



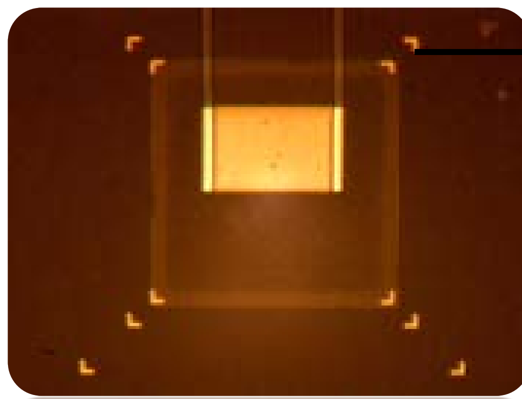
55Fe spectrum



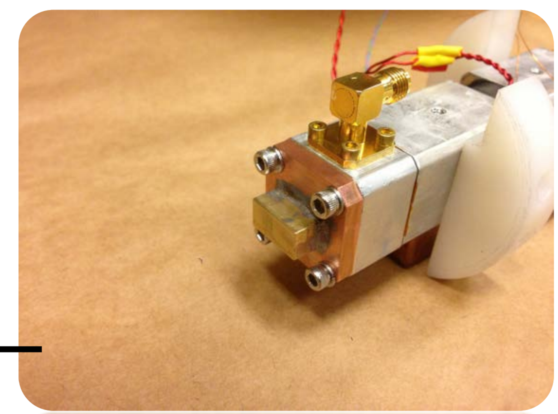
J.W. Engle et al. NIM B 311 (2013) 131–138
http://fsnutown.phy.ornl.gov/fsnufiles/positionpapers/FSNu_Project8.pdf

3 Experimental Efforts

Spectroscopy
(KATRIN)



Calorimetry
(HOLMES, ECHO
&NUMECS)



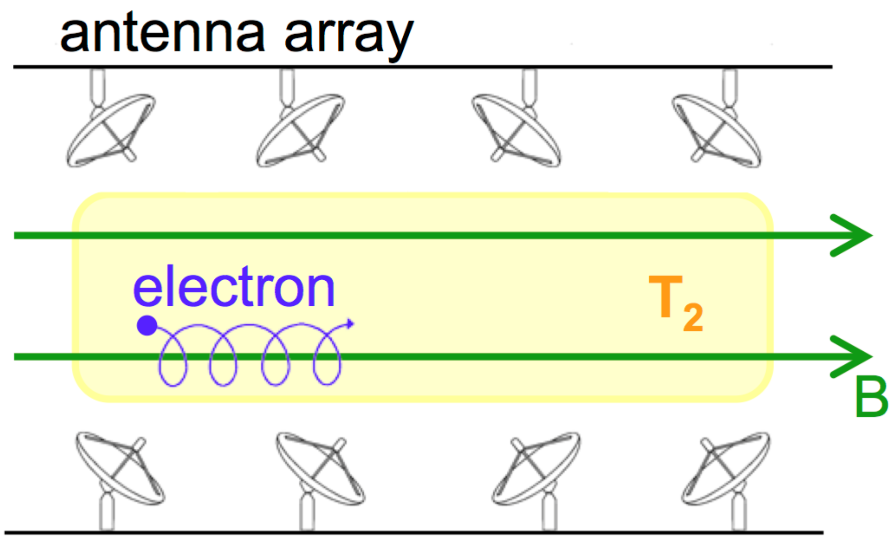
Frequency
(Project 8)

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

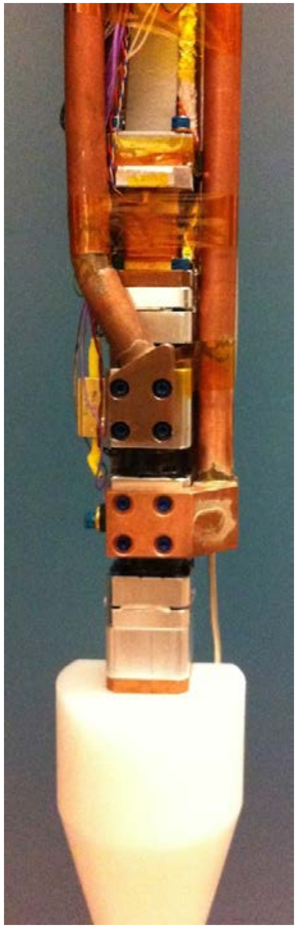
- Use cyclotron frequency to extract electron energy
- Non-destructive measurement of electron energy

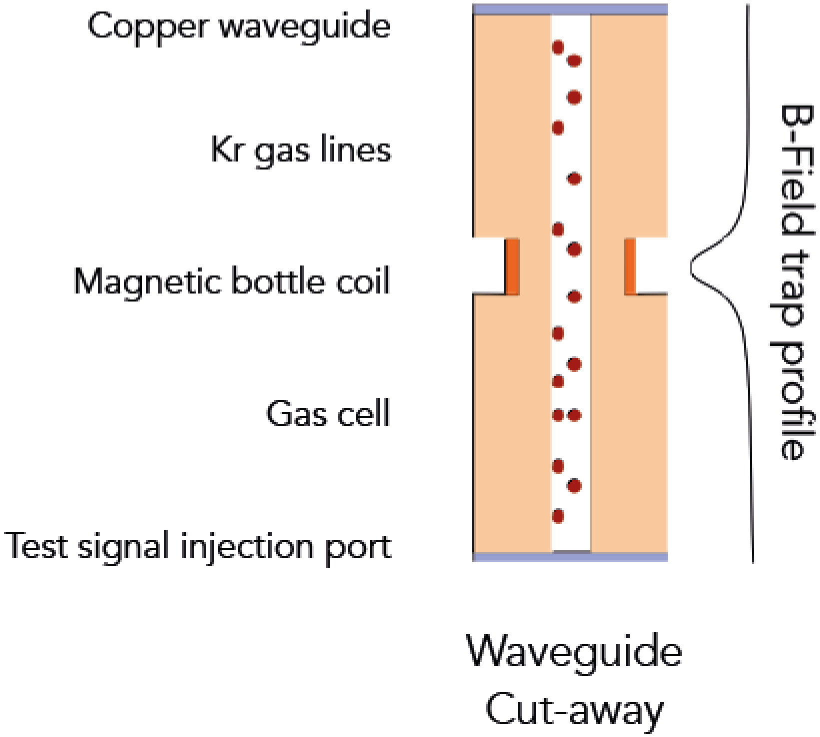


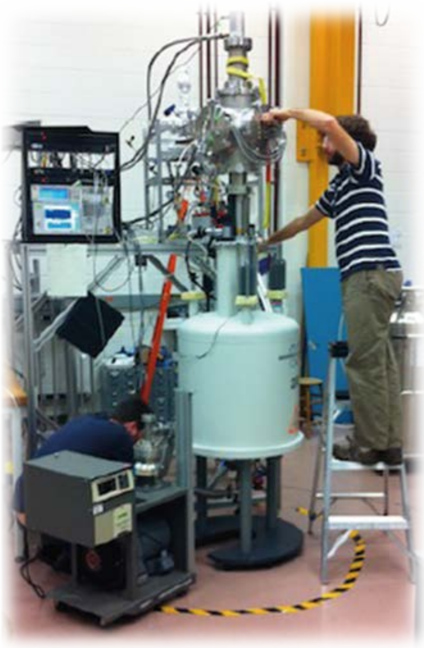
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

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

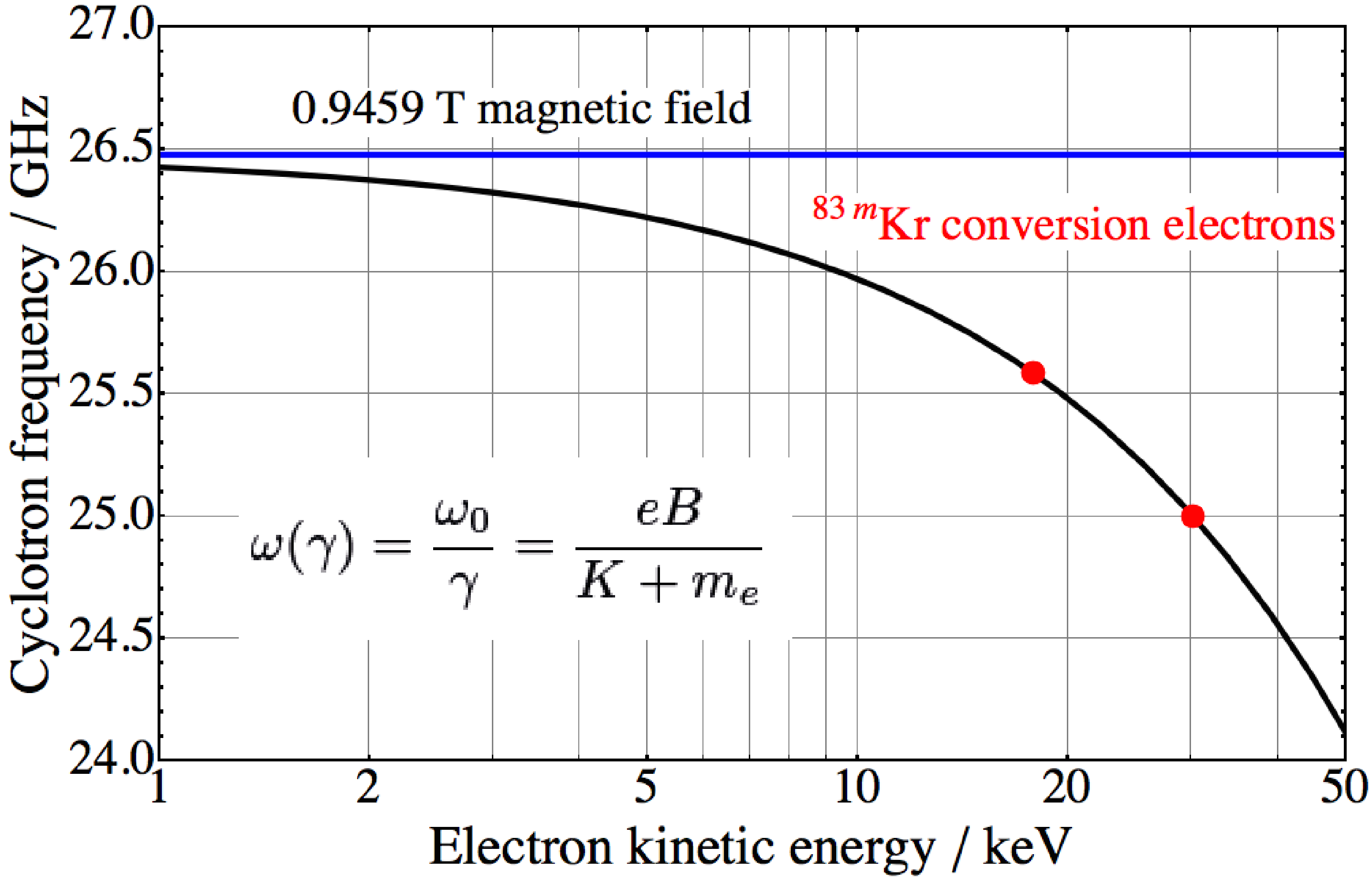
Project 8 Setup



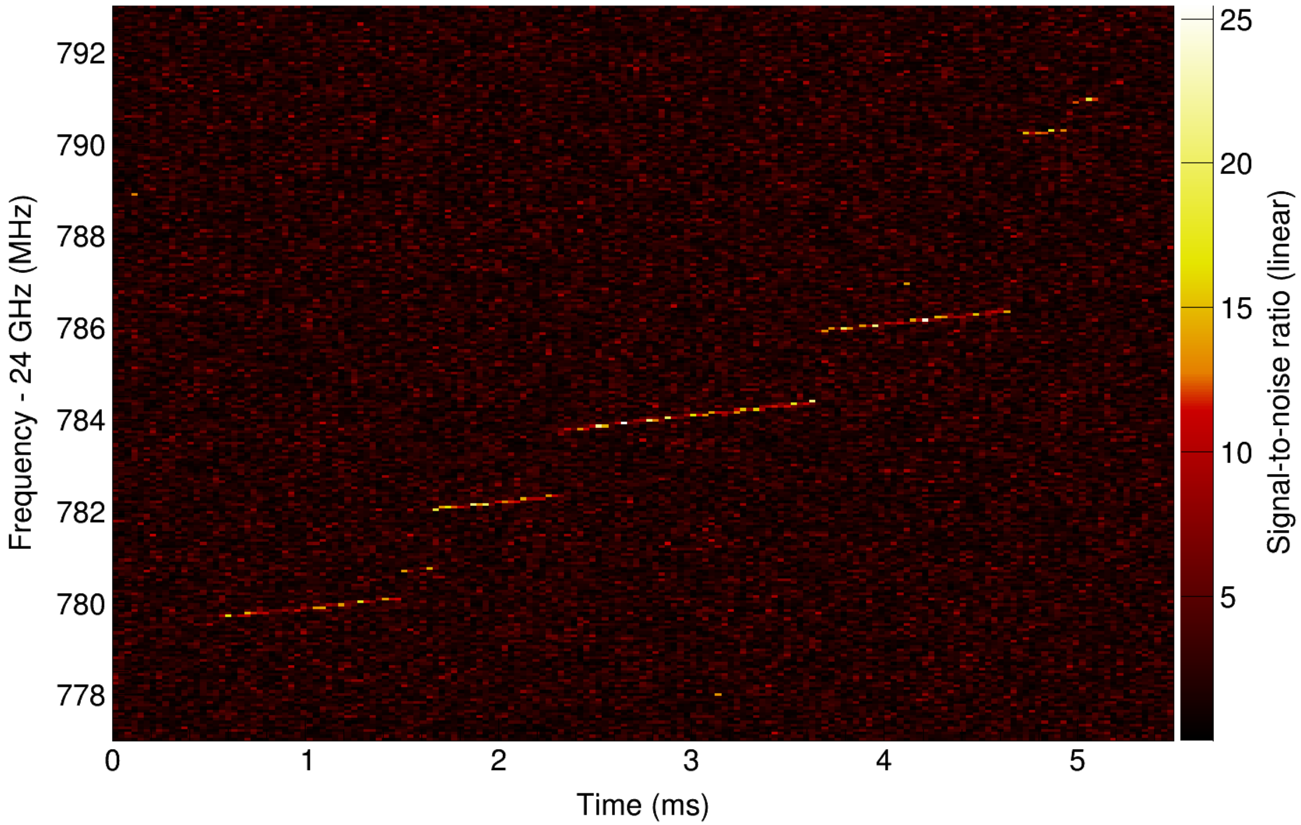




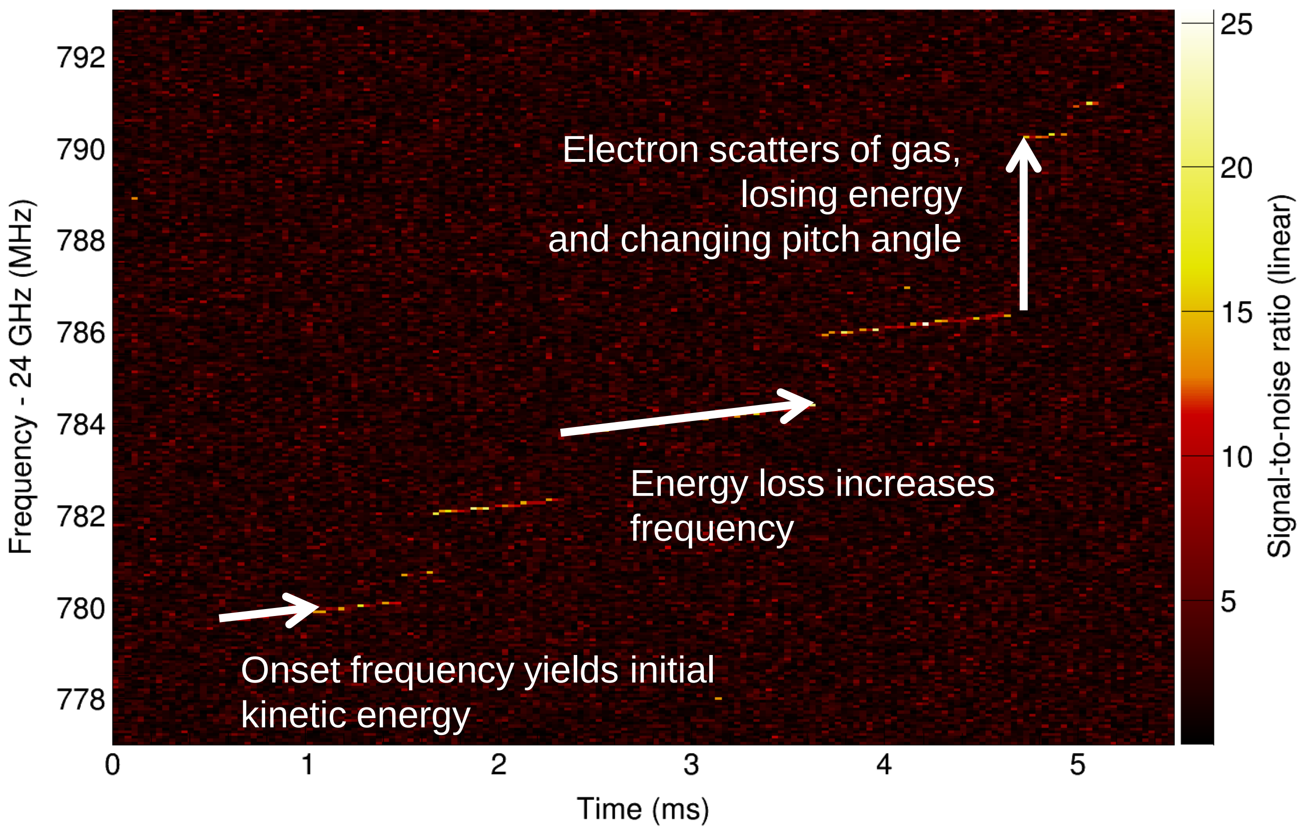
Test measurement with Krypton



First electron detection

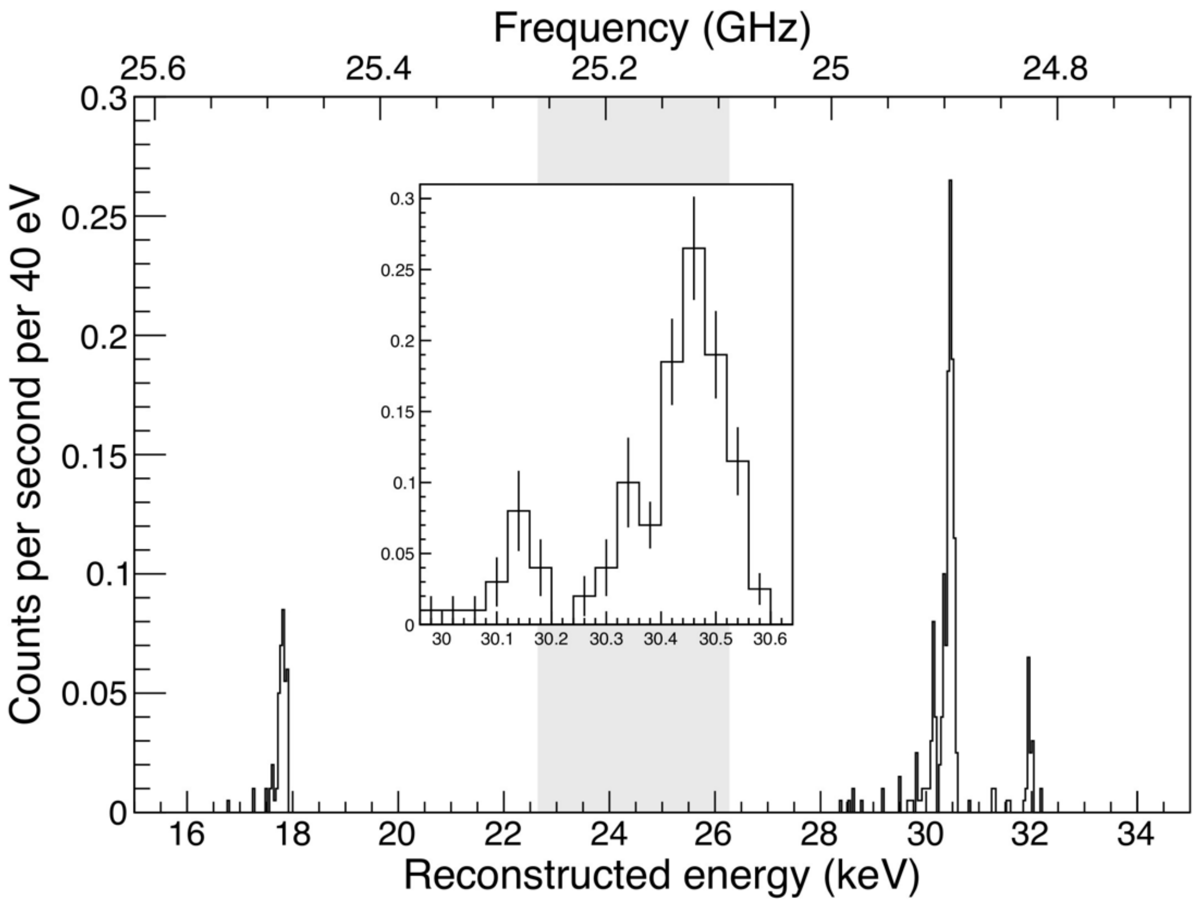


First electron detection



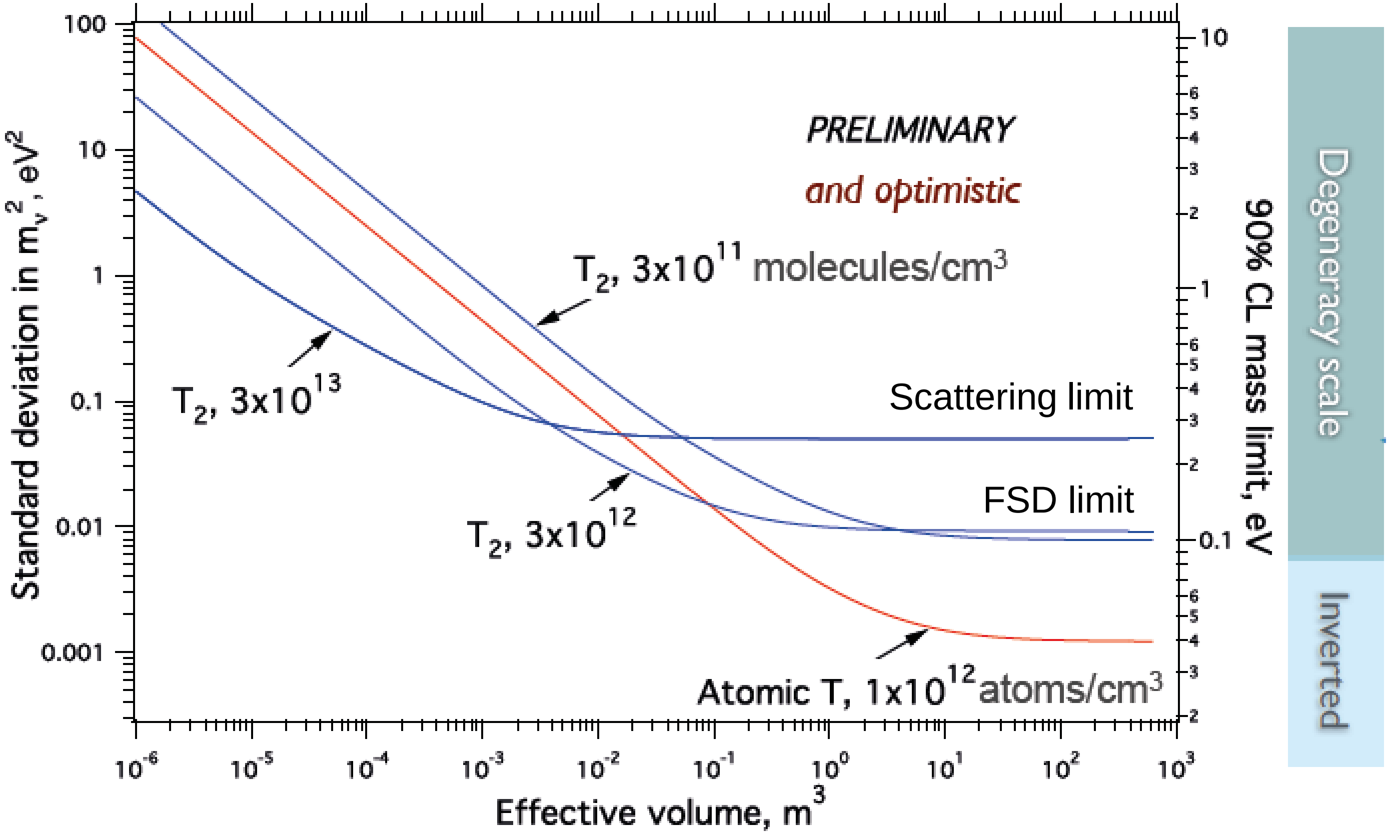
First electron detection

FWHM ~ 140 eV



http://lanl.arxiv.org/abs/1408.5362

Future perspective of Project 8

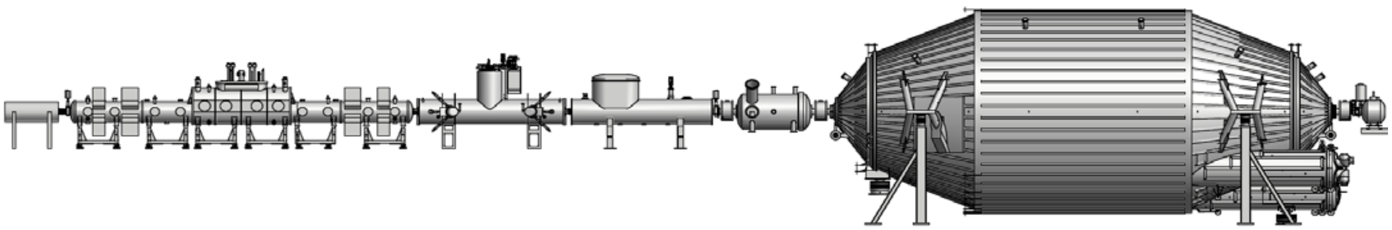


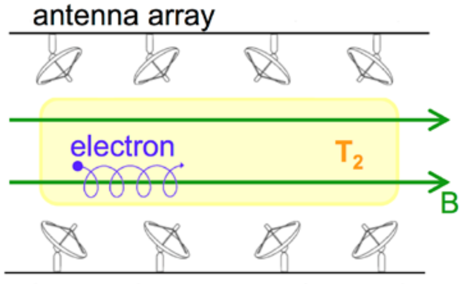
http://fsnutown.phy.ornl.gov/fsnufiles/positionpapers/FSNu_Project8.pdf

Joining efforts …

KATRIN selects the electrons….

… and Project 8 measures their energy



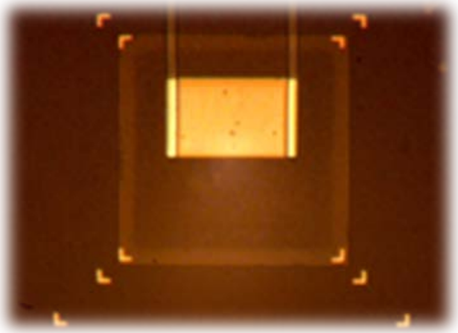


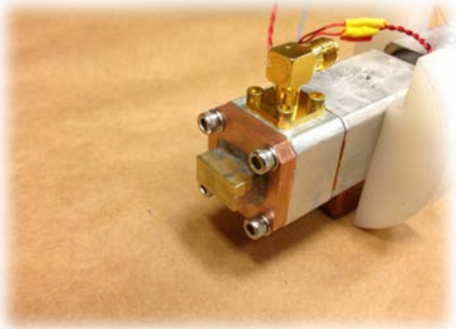
1) Trigger the electron → close the trap

2) Measure the energy

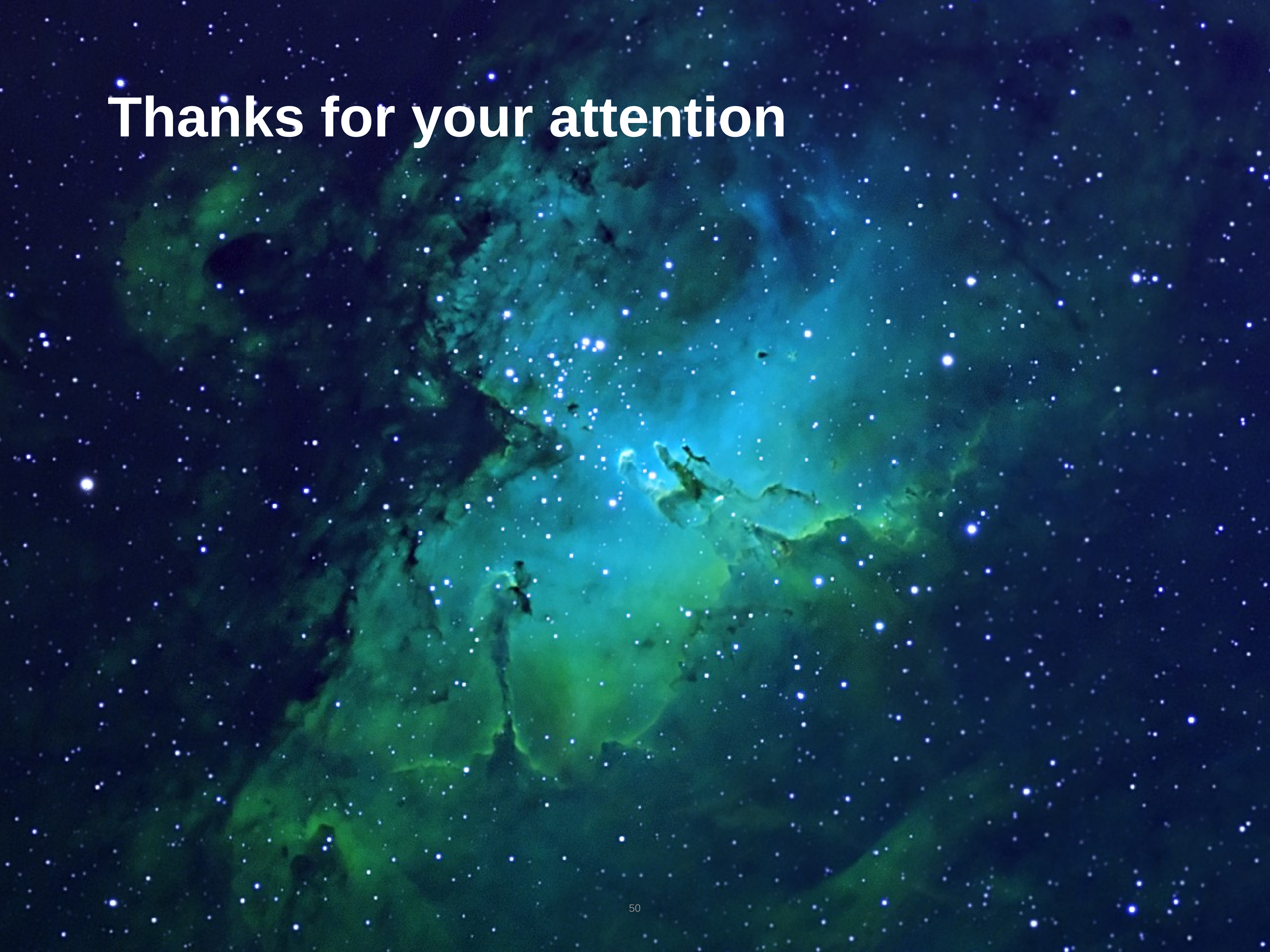
Summary

- In 2016 KATRIN will start neutrino mass measurements and will probe the entire degeneracy scale
- 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



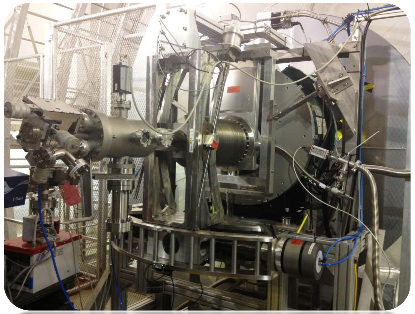


Thanks for your attention

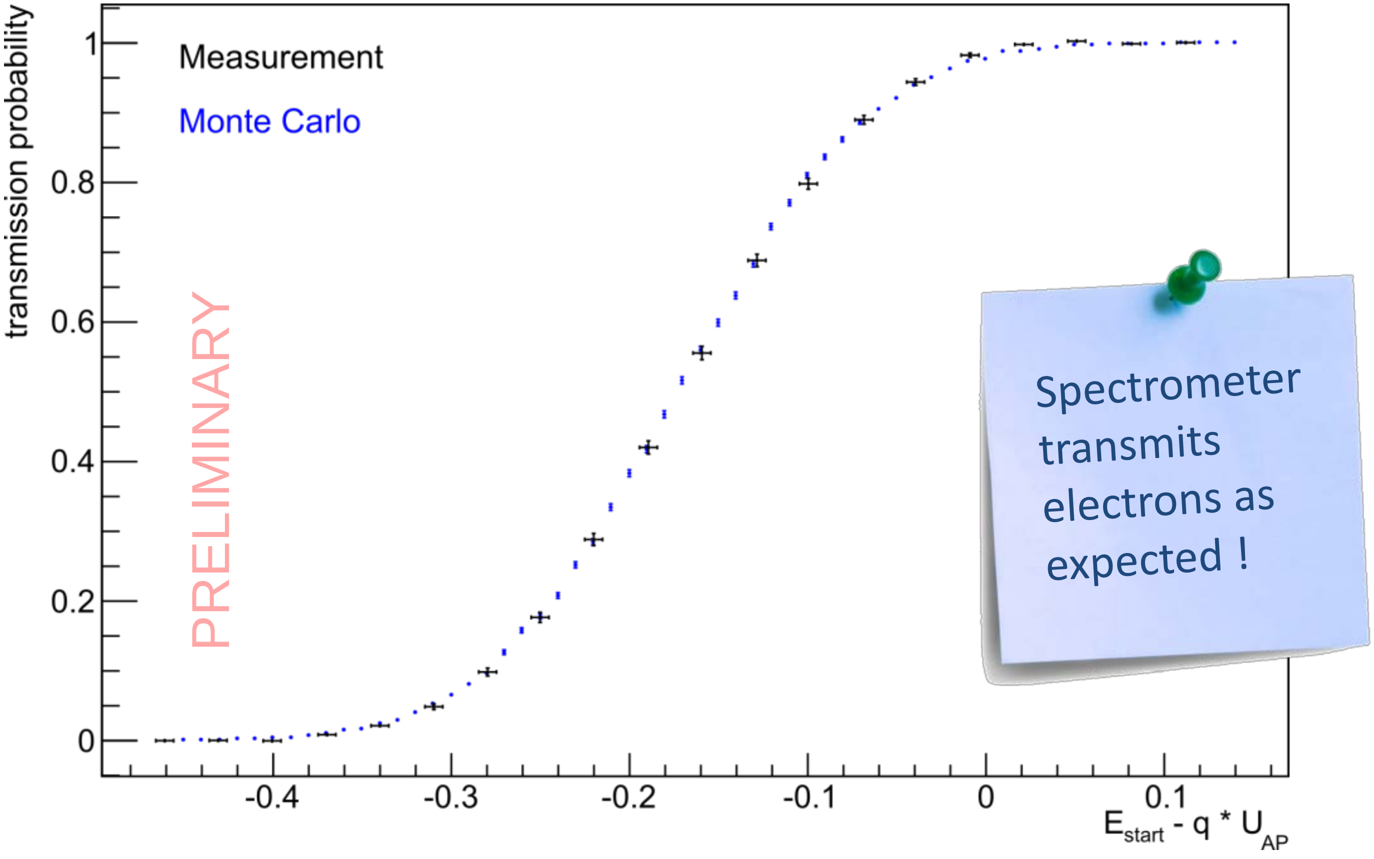


KATRIN Backup slides

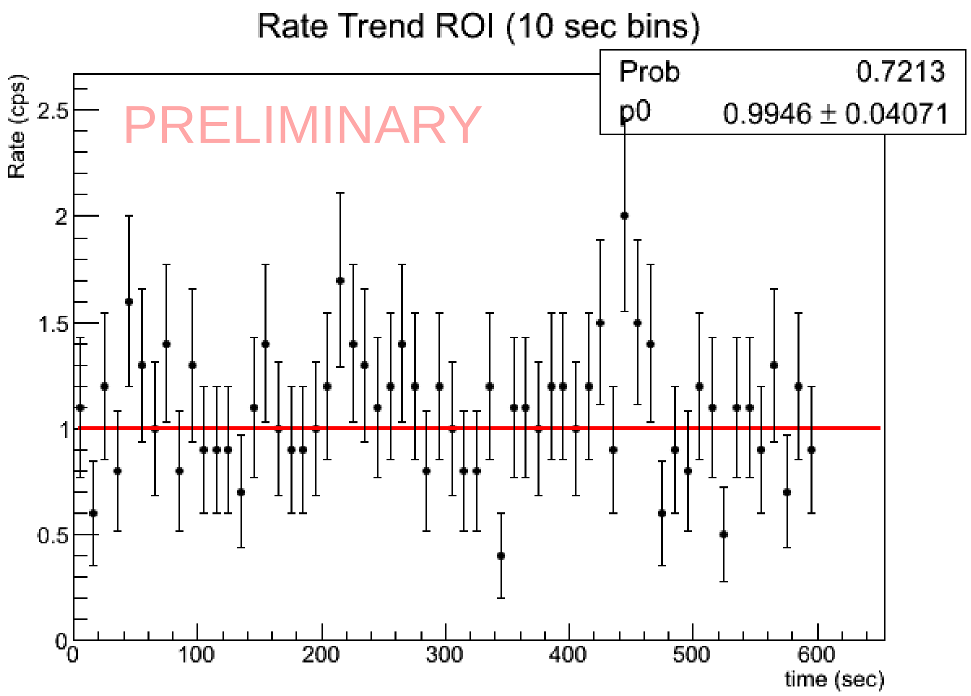
First Transmission Measurement



angular selective egun



First Background Measurement



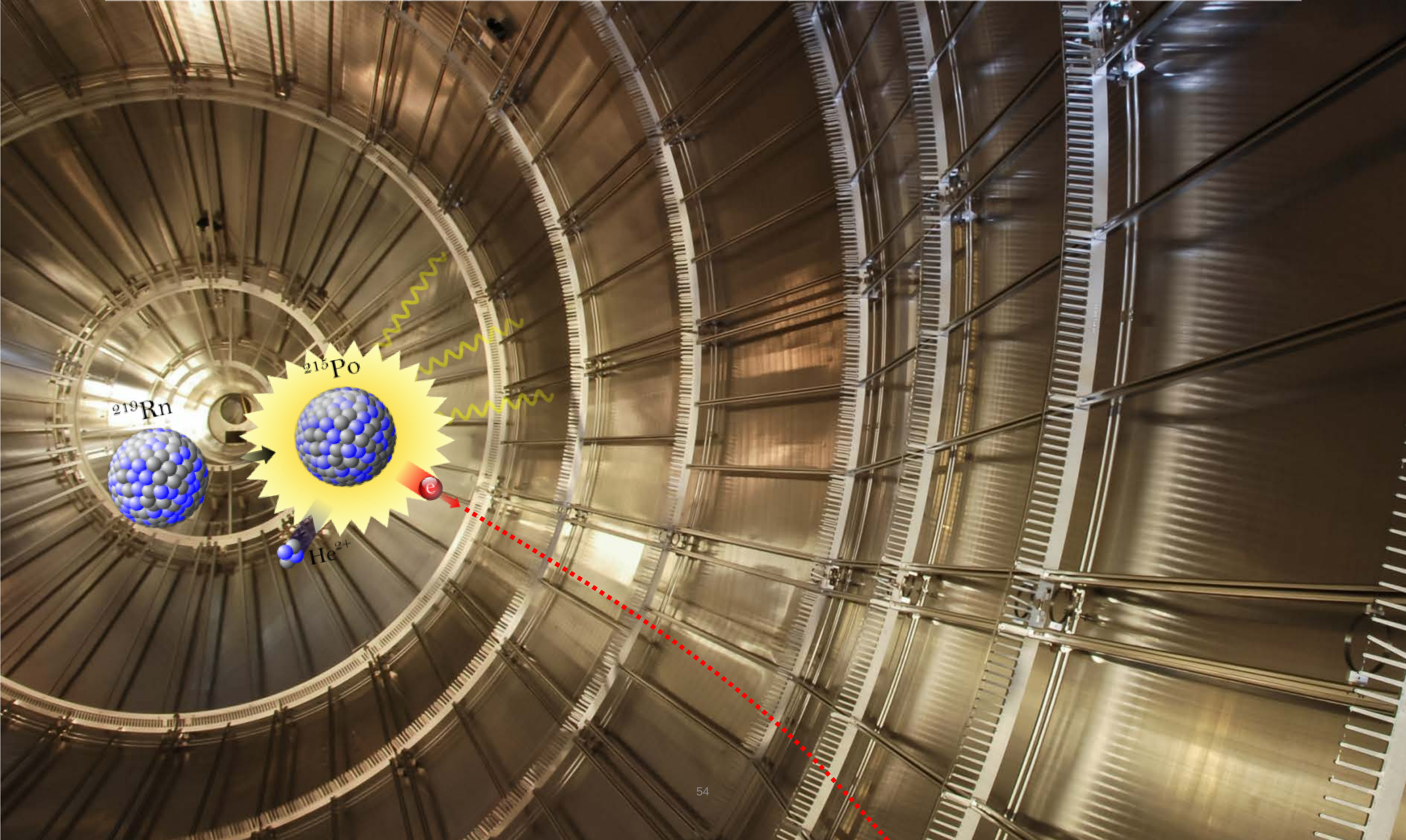
Desired background rate: 10 mcps

Initial measured rate: 1 cps

No Penning discharge !!!

Magnetic shielding works !

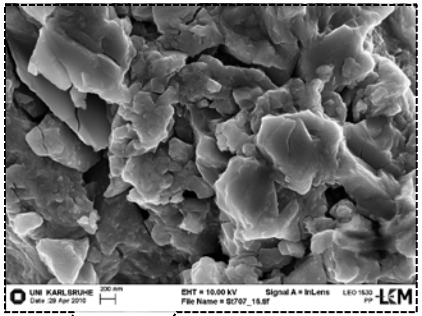
Radon-induced Background

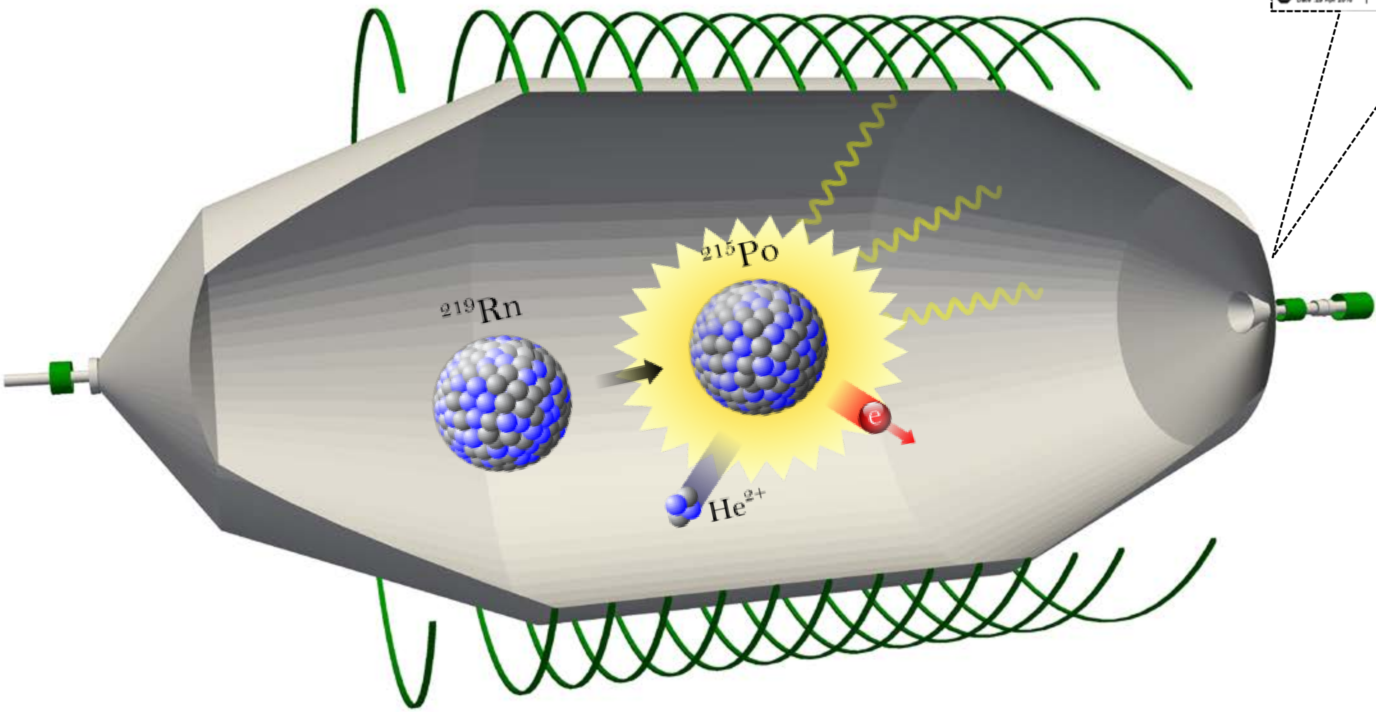


Radon-induced Background

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

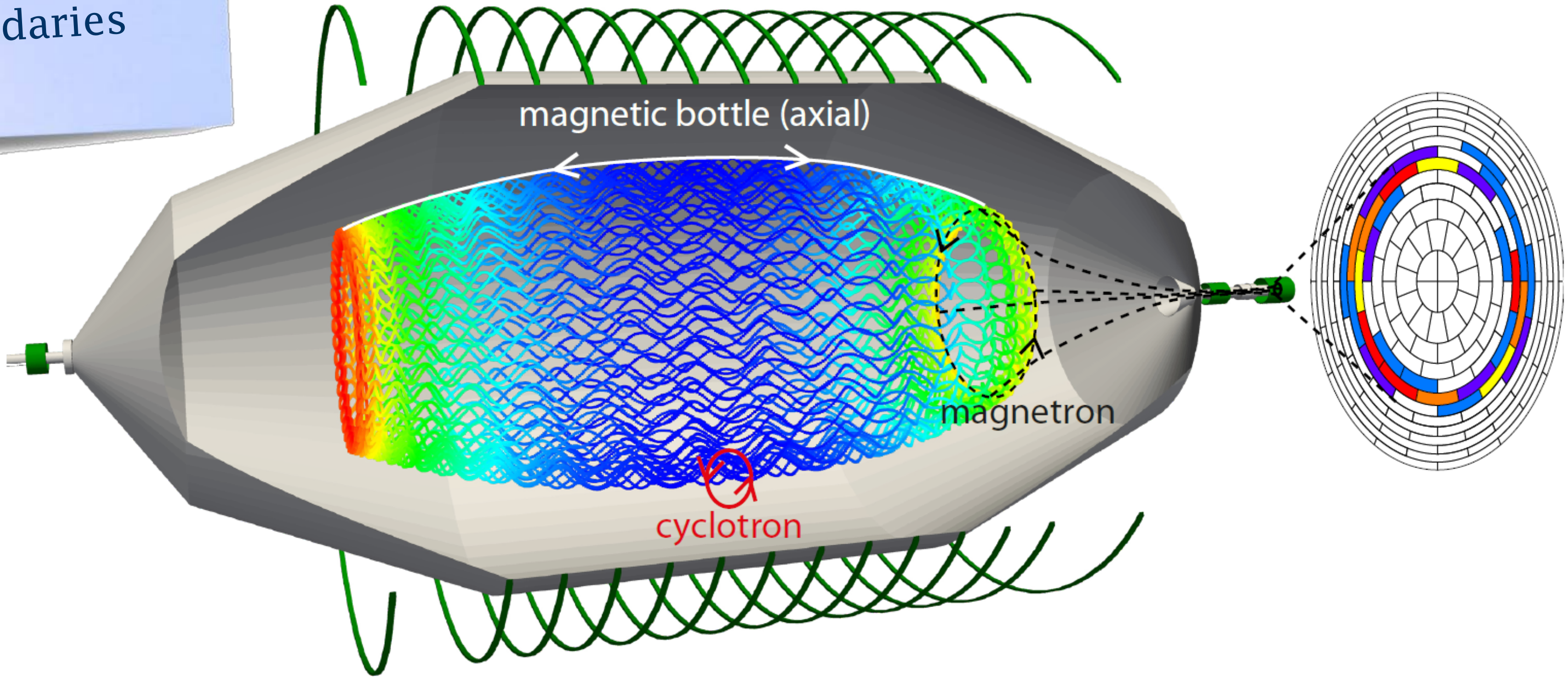
Getter pump





Radon-induced Background

Single Radon decay produces hundreds of secondaries

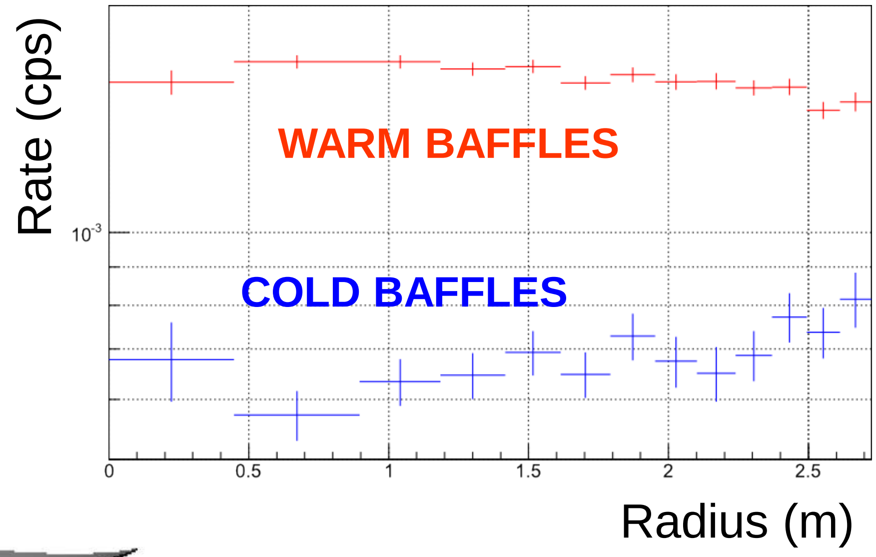


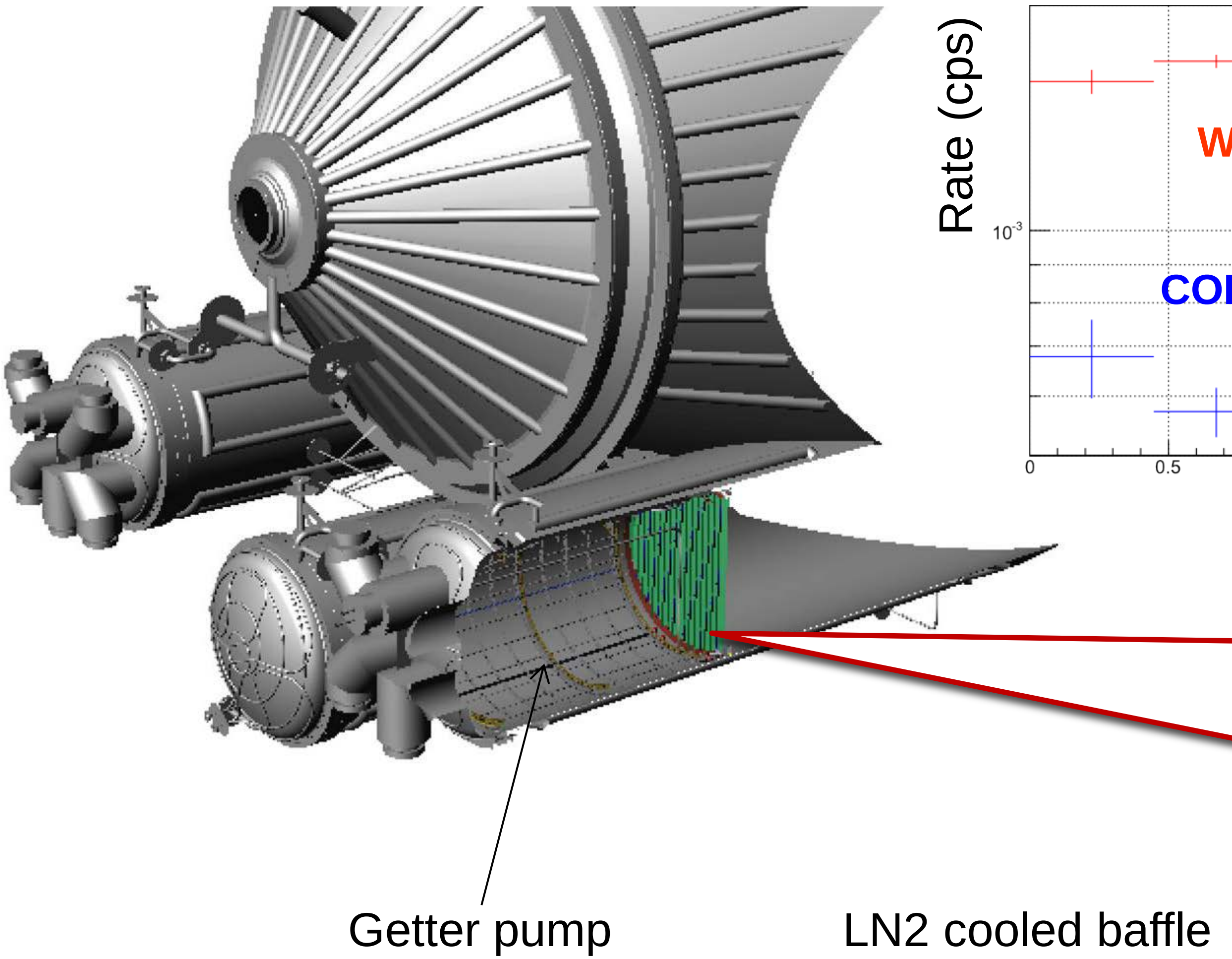
N. Wandkowsky et al., New J. Phys. 15 (2013) 083040

N. Wandkowsky et al., J. Phys. G 40 (2013) 8

S. M. et al., Astropart. Phys. 41 (2013) 52

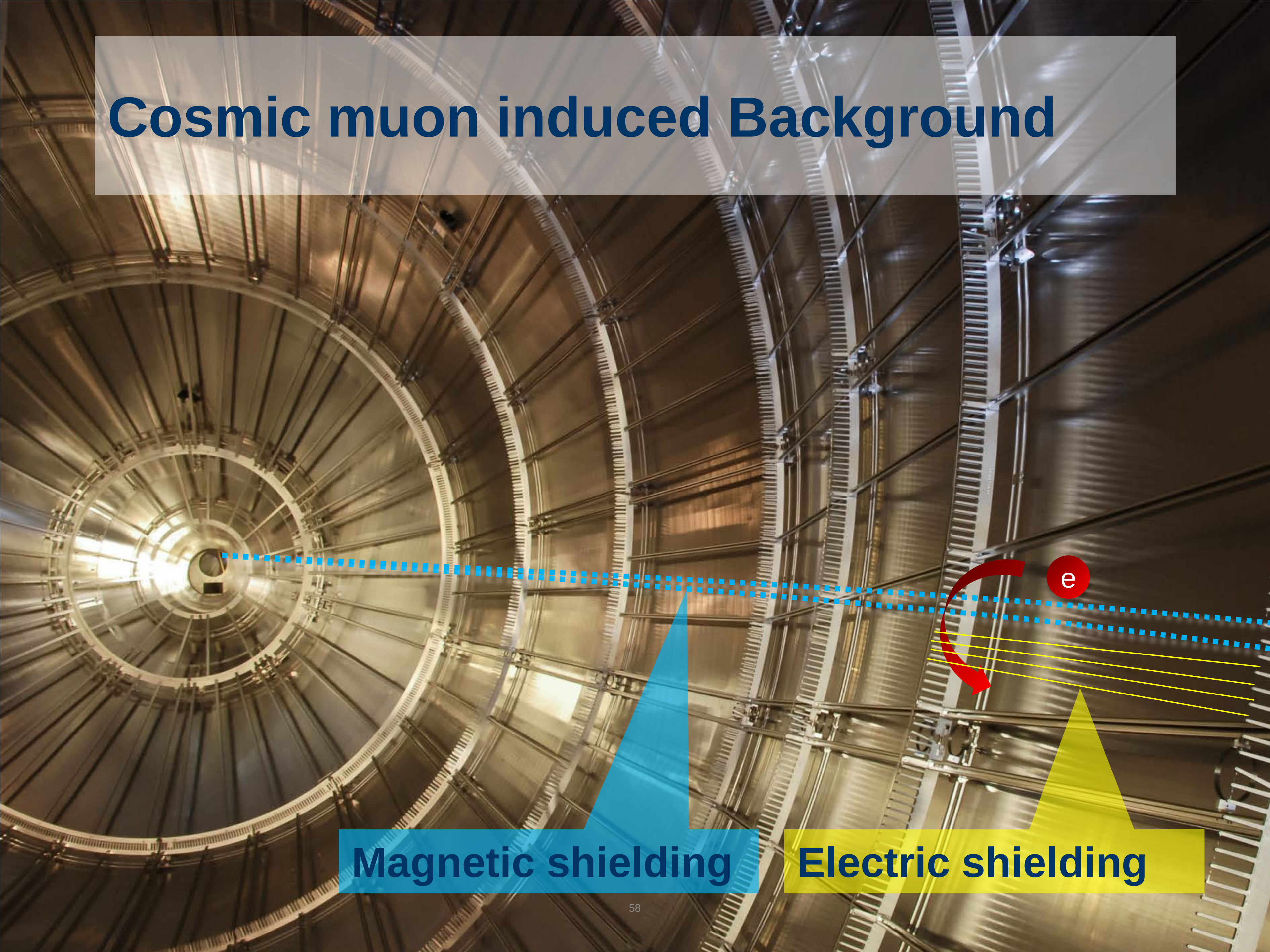
Passive Reduction Technique



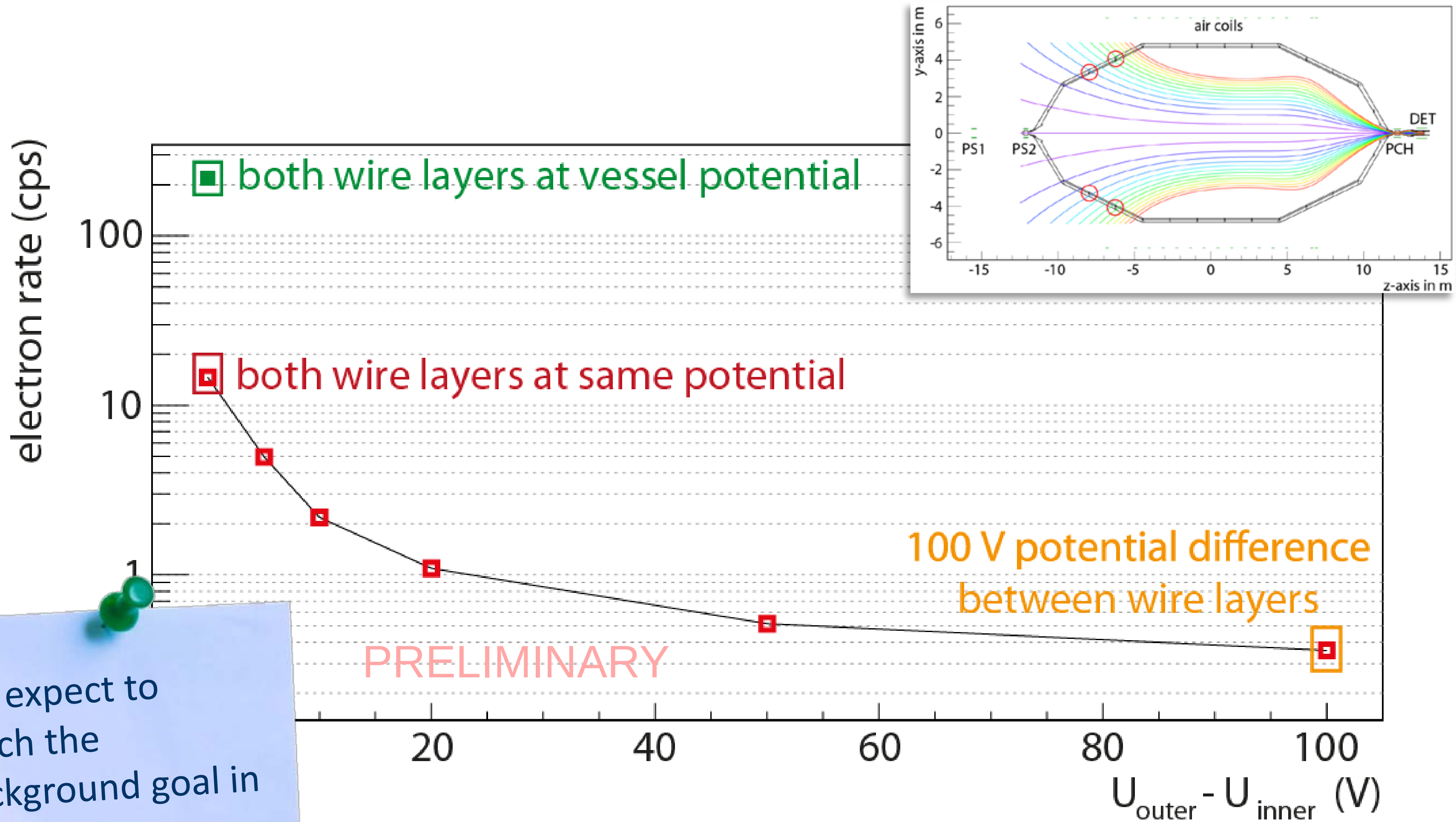


BERKELEY LAB

Cosmic muon induced Background



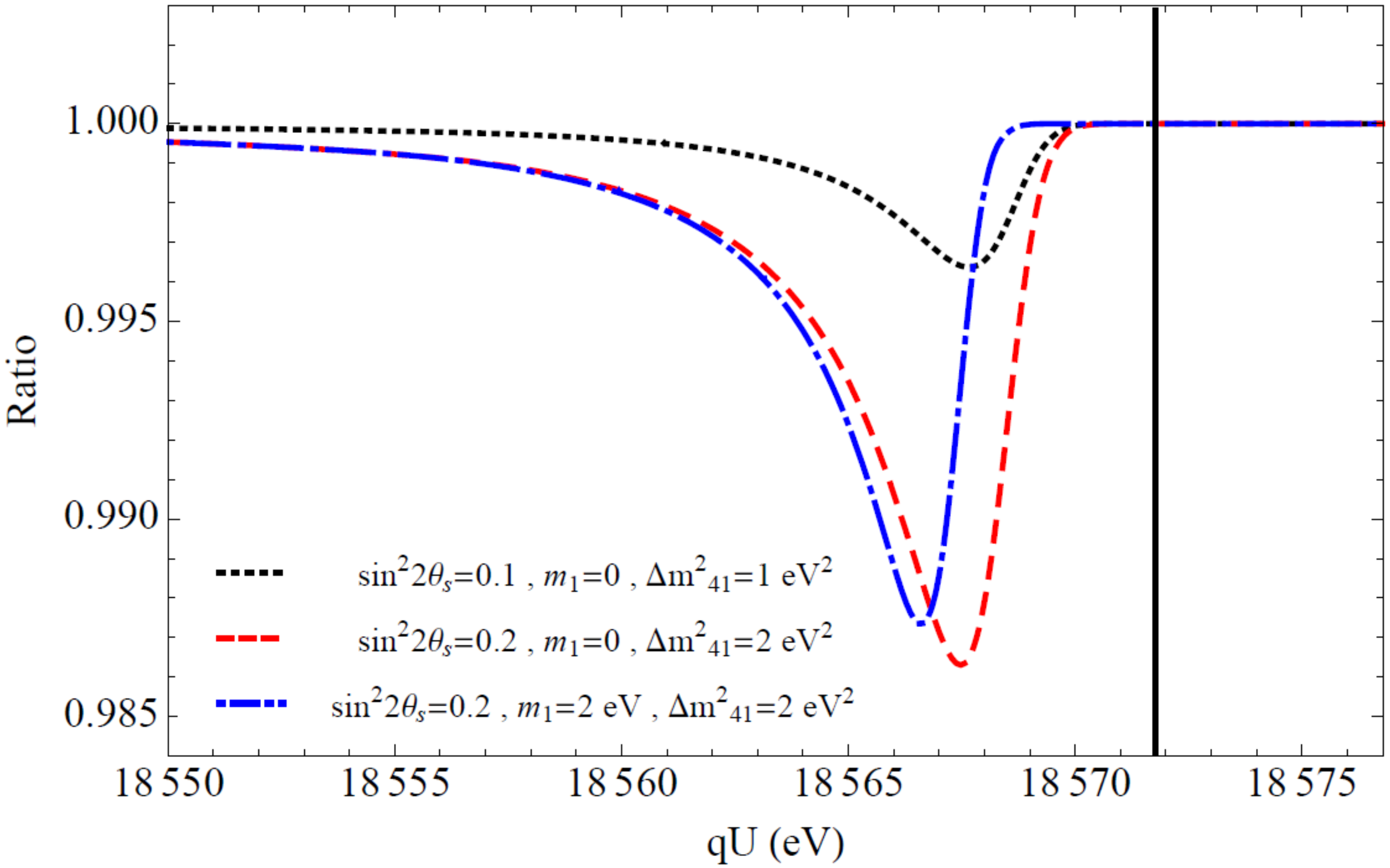
Effect of wire electrode



We expect to reach the background goal in the next measurement phase!

BERKELEY LAB

Signature of eV neutrinos

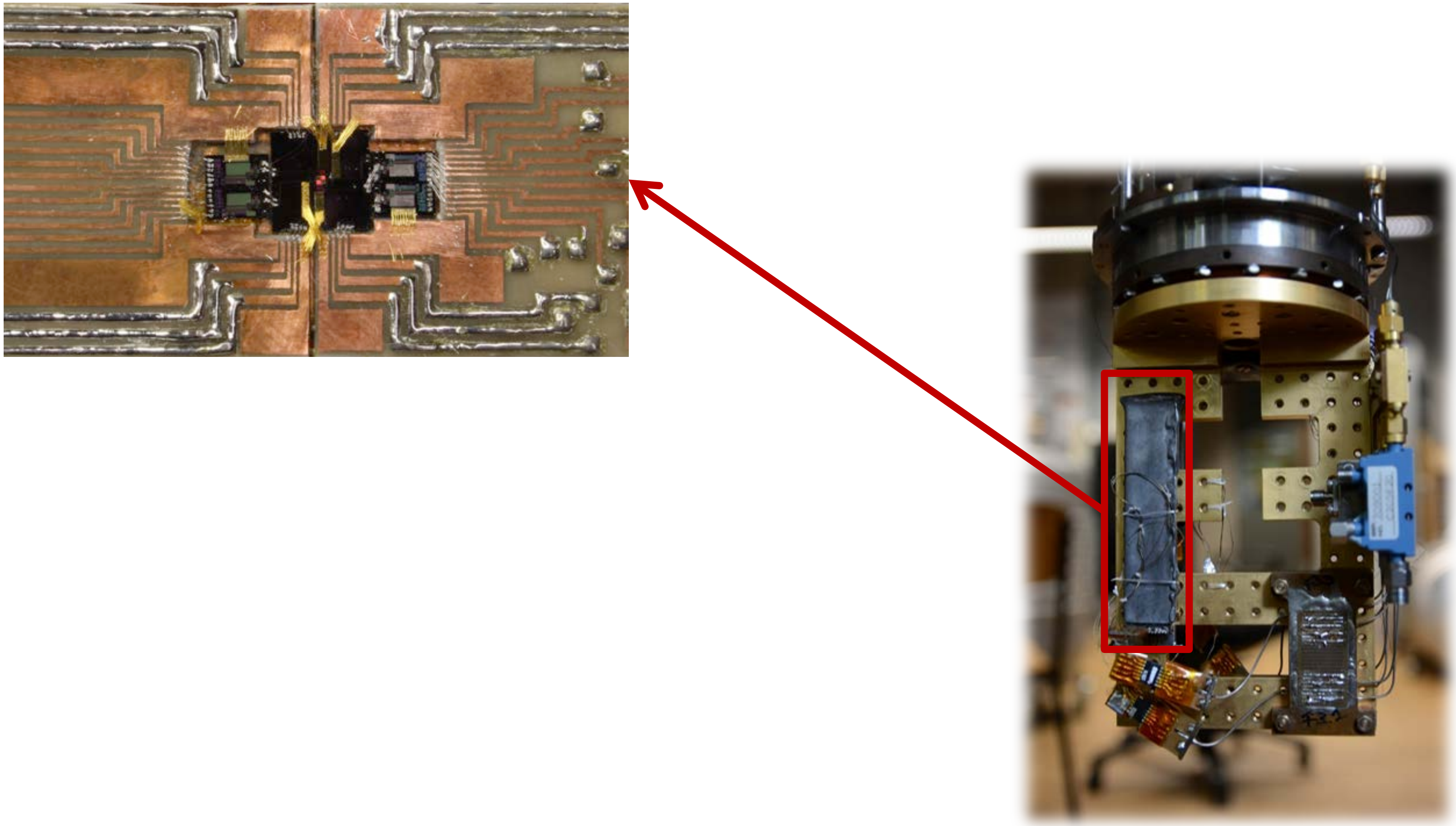


KATRIN - summary

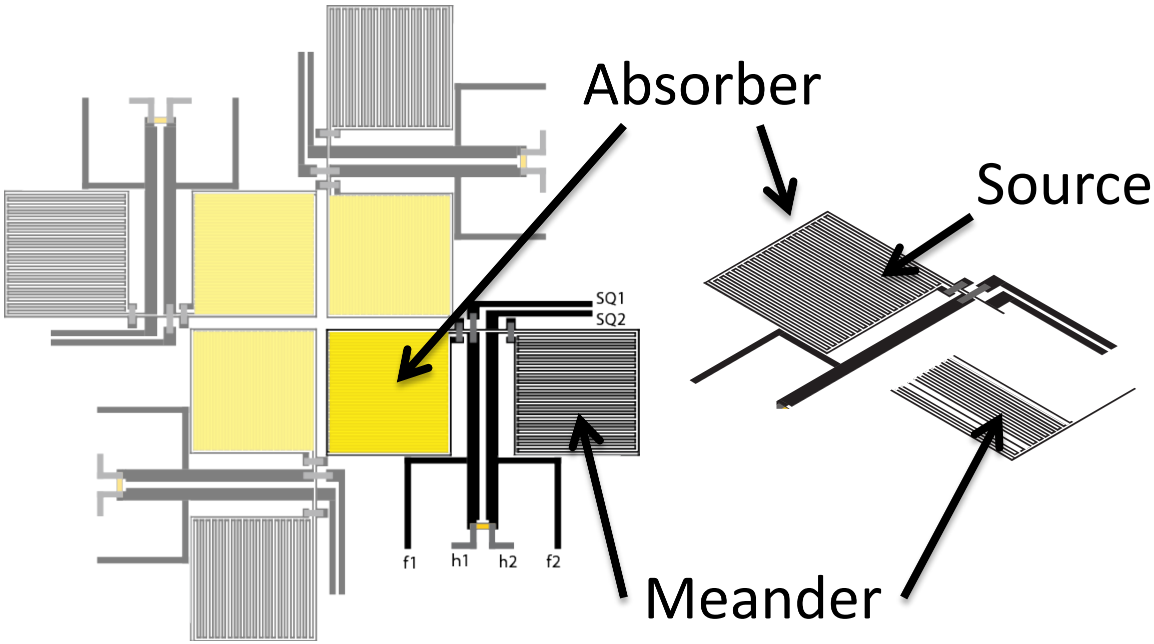
- KATRIN is designed to reach a sensitivity of 200 meV (90%CL) after 3 years of measurement time
- Successful commissioning of main spectrometer
- Next measurement phase began last week
- Start of Neutrino mass measurements 2016
- Promising potential to search for eV to keV sterile neutrinos in a model-independent way

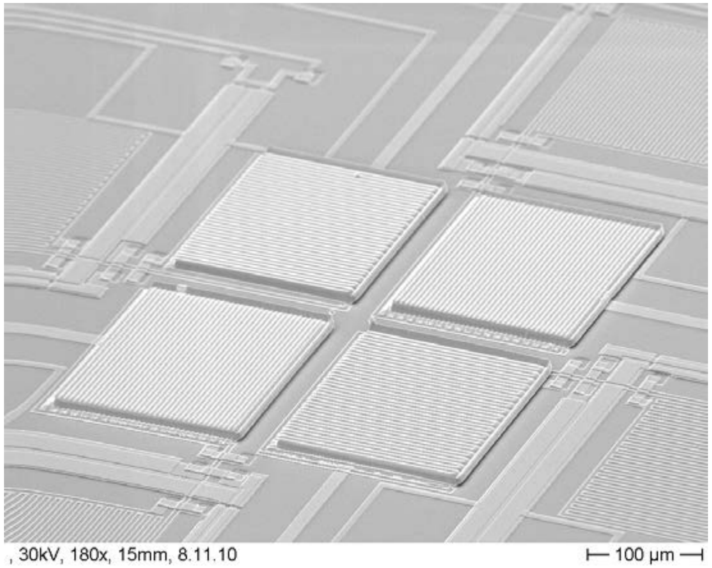
Holmium backup slides

ECHo: First Setup



ECHo: First Setup

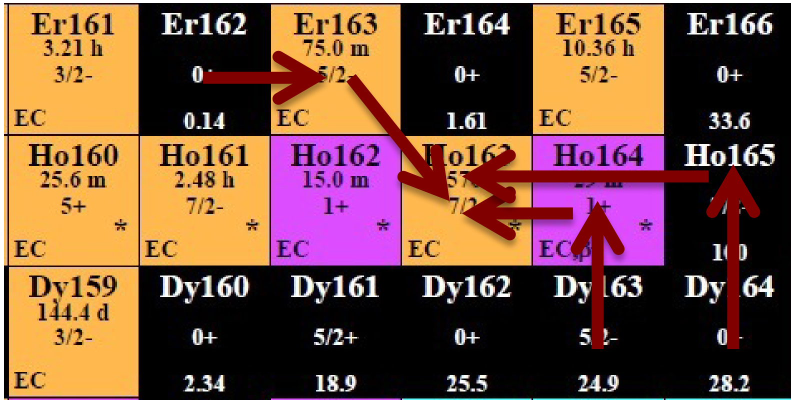


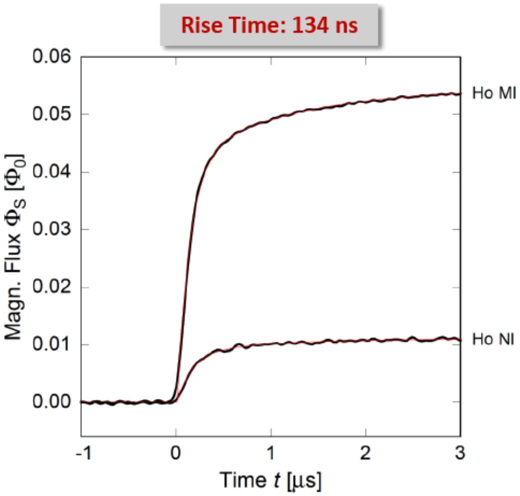


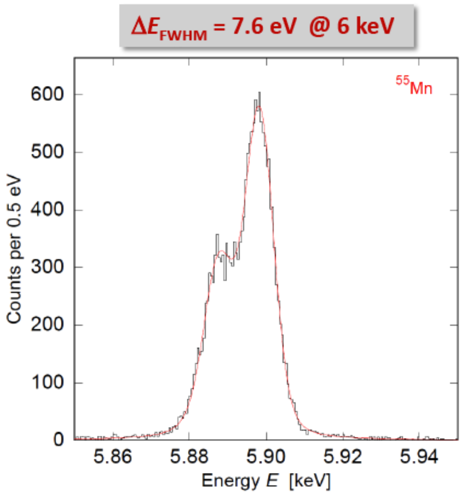
ECHo: Some details

100 pixel with 10 - 100 Bq per pixes

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

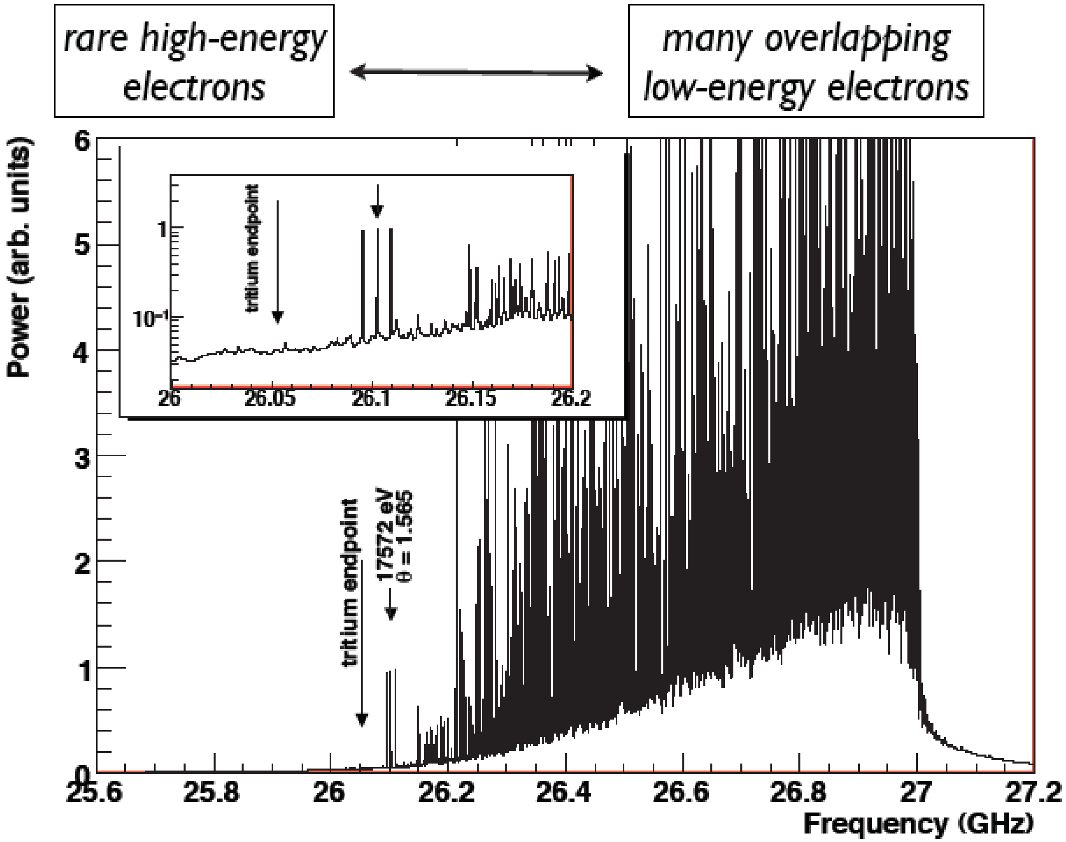






Project 8 backup slides

Simulated tritium frequency spectrum



100,000 tritium decays in 30μs

Future Perspectives…