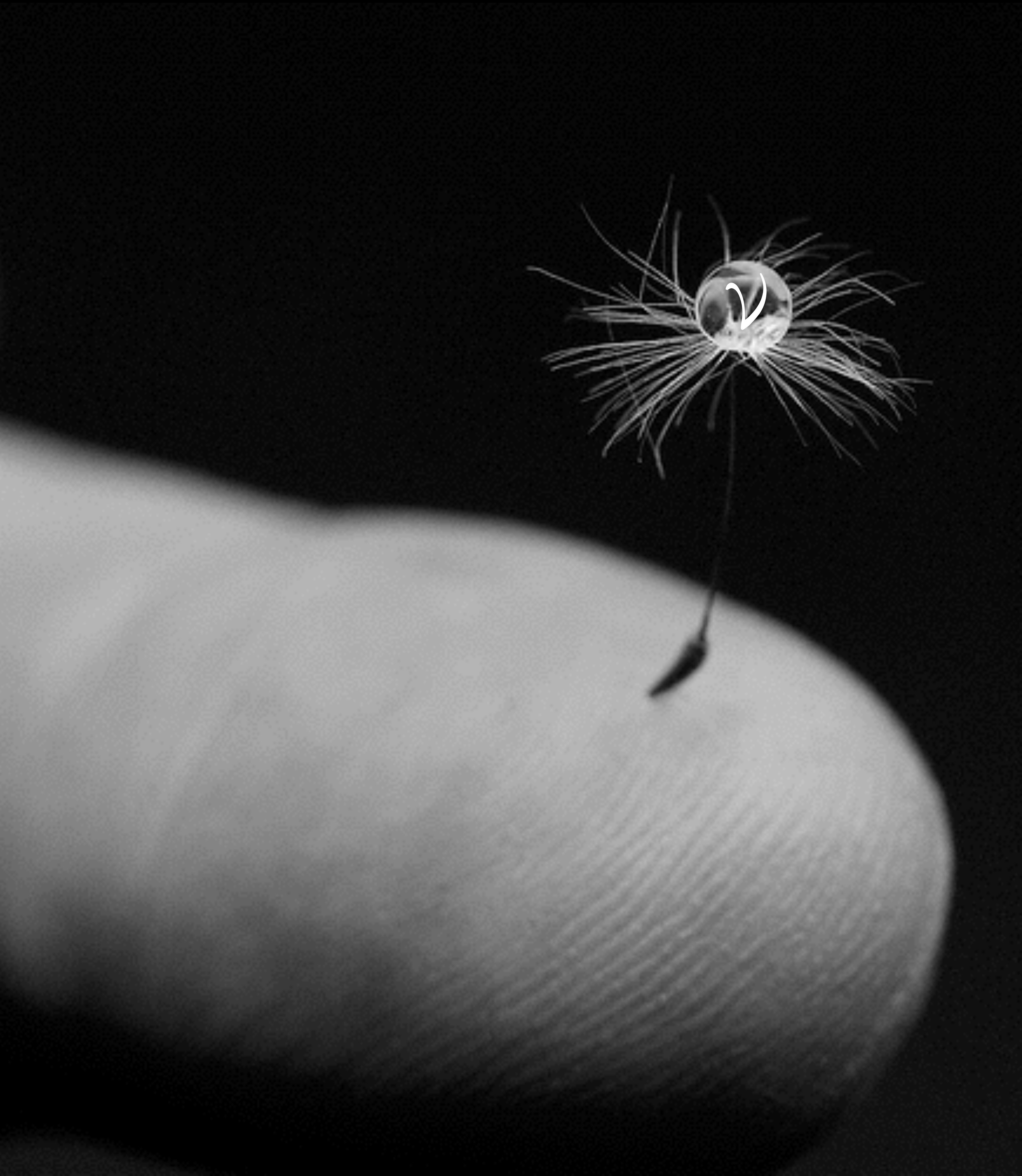
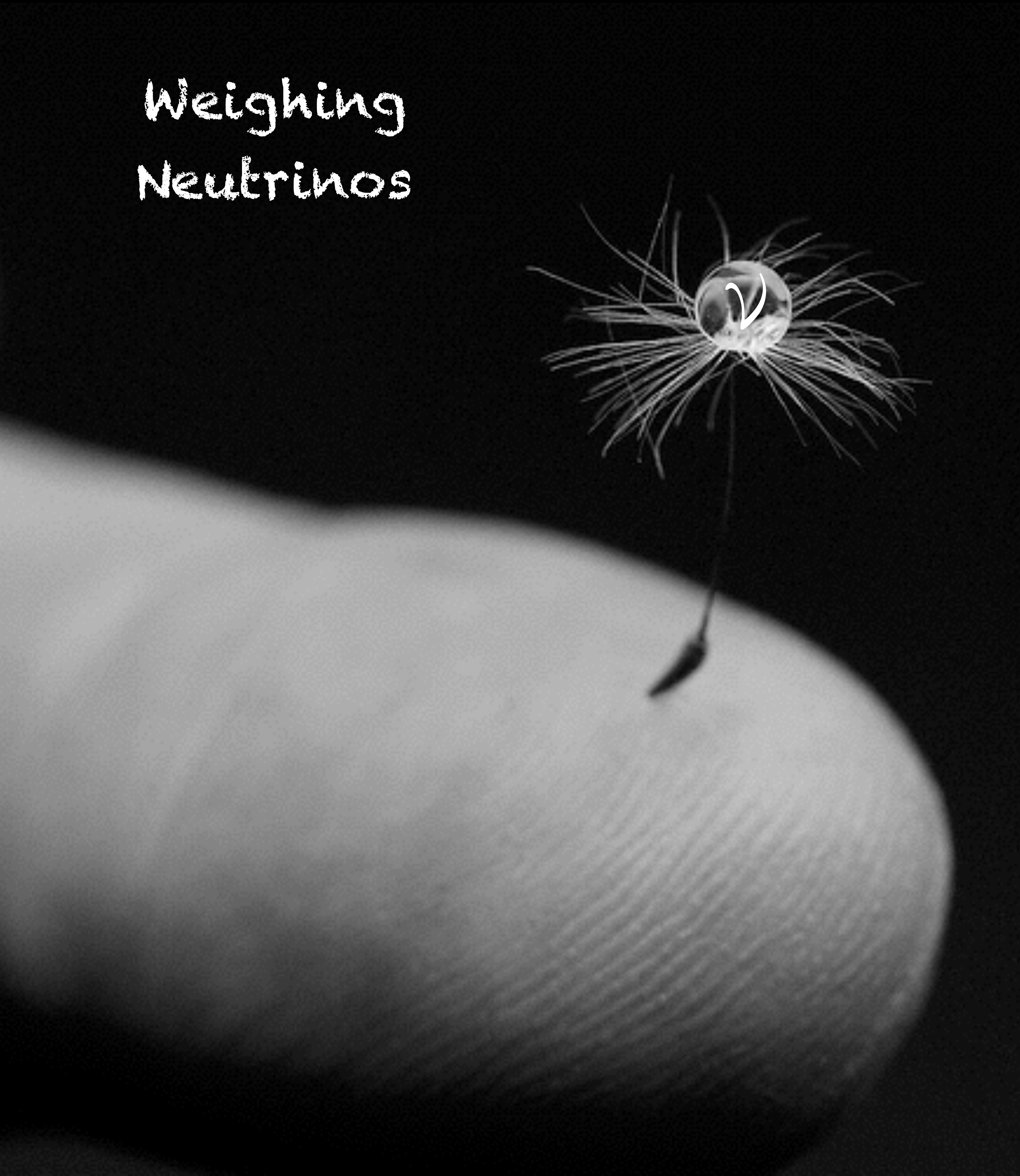


Weighing Neutrinos



WIN 2017

June 19th 2017

Joseph A. Formaggio
MIT

Discovery!

After decades of searching, Atlas and CMS groups report discovery of the Higgs, completing the architecture of the Standard Model.


NEW YORK, THURSDAY, JULY 5, 2012 $2.50

Physicists Find Elusive Particle Seen as Key to Universe

POOL PHOTO BY DENIS BALIBOUSE

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

Date Night at the Zoo, if Rare Species Play Along

By LESLIE KAUFMAN

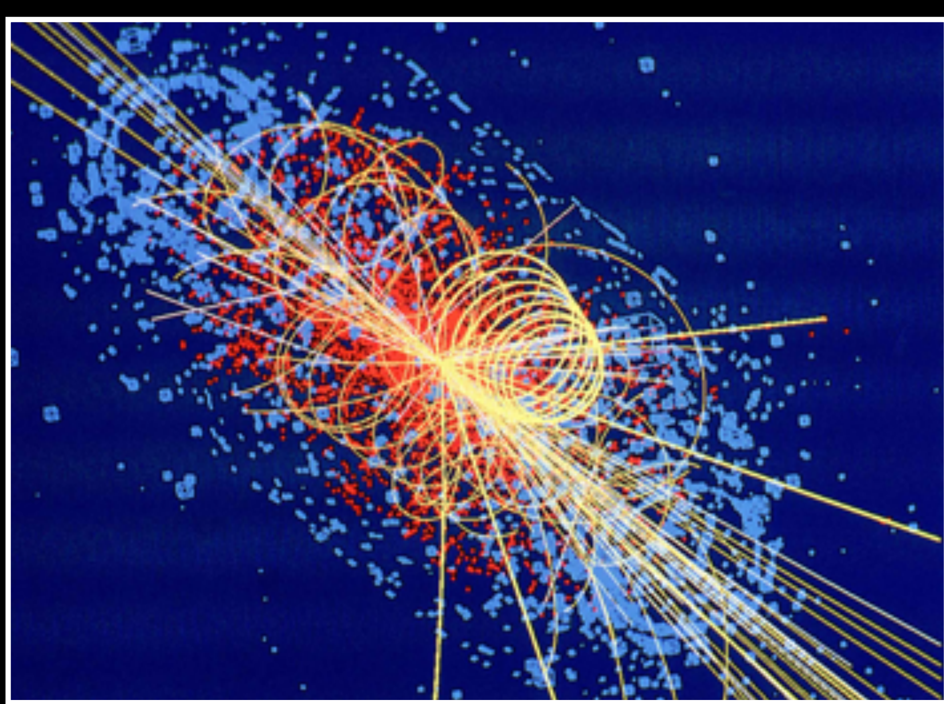
FRONT ROYAL, Va. — After cautiously sniffing the grass,

THE ANIMAL LIFEBOAT
Barriers to Breeding

thing but.

Eighty-three percent of those species in North American zoos are not meeting the targets set for maintaining their genetic di-

'I Think We Have It' Is Cheer of Day at Home of Search



Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

A R T I C L E   I N F O

Article history:
Received 31 July 2012
Received in revised form 9 August 2012
Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
CMS
Physics
Higgs

A B S T R A C T

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Almost immediately, we know *a lot* about this new particle...

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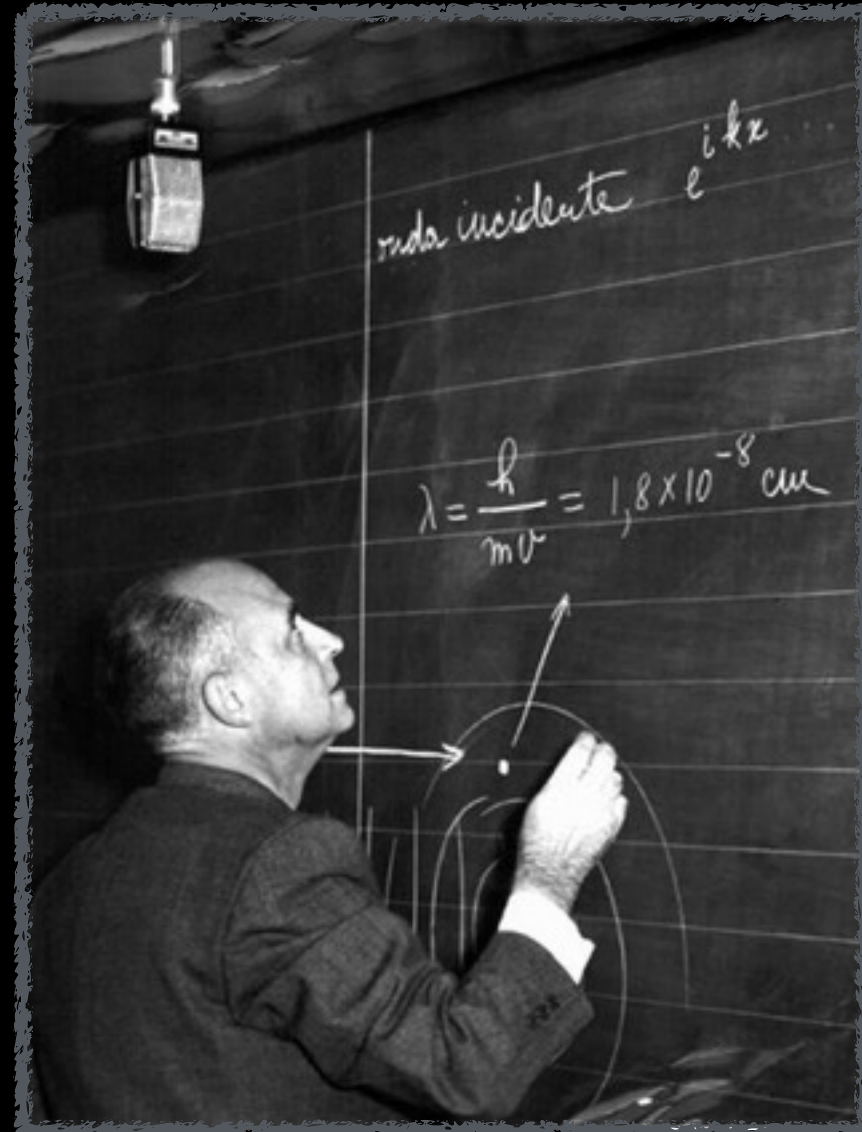
nt in the two decay modes with the
of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV.
with spin different from one.

... including its mass.

Wolfgang Pauli
1930
(proposal)

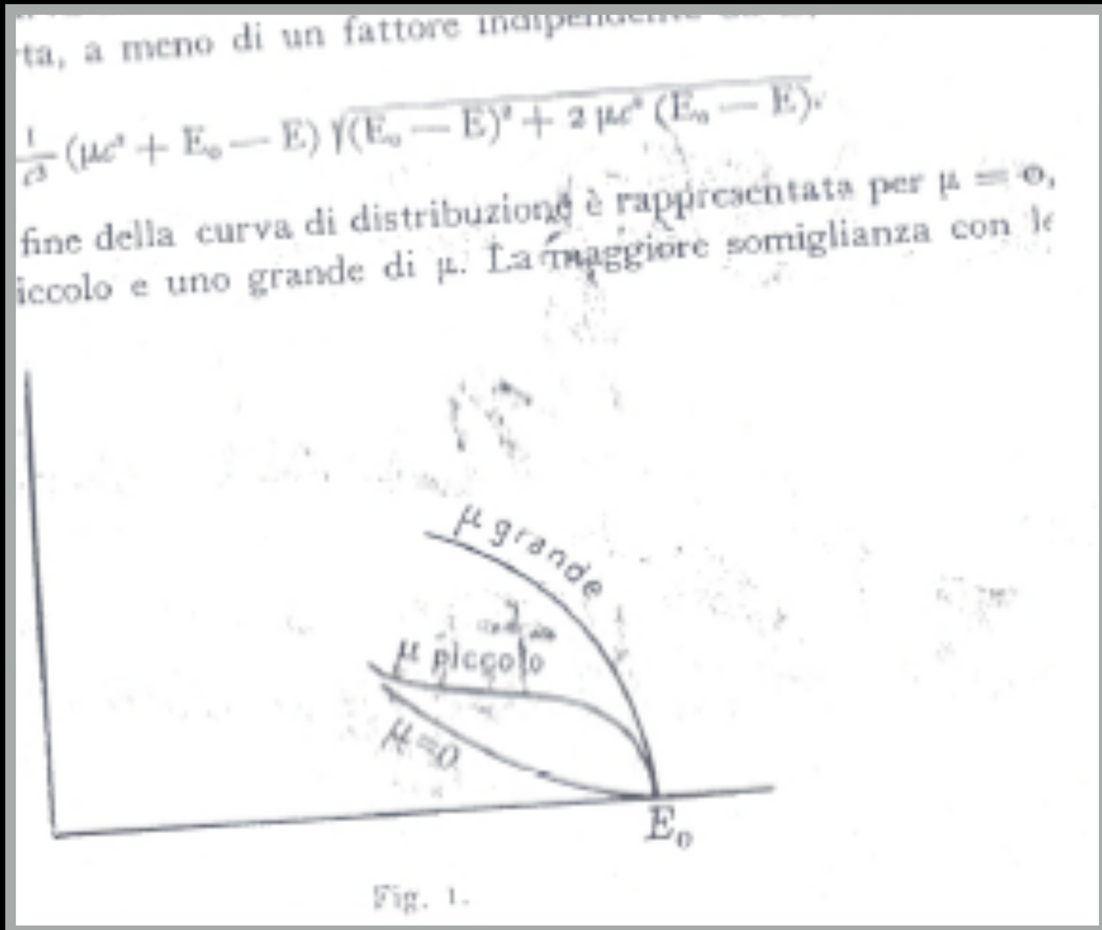


Enrico Fermi
1934
(theory)

Reines & Cowan
1956
(discovery)

26 years

One would imagine as similar pattern would unfold for all particle discoveries.


ta, a meno di un fattore indipendente ...

$$\frac{1}{c^5}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

fine della curva di distribuzione è rappresentata per $\mu = 0$,
iccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

After all this time, are we fundamentally still stuck in this paradigm where neutrino masses remain unknown?

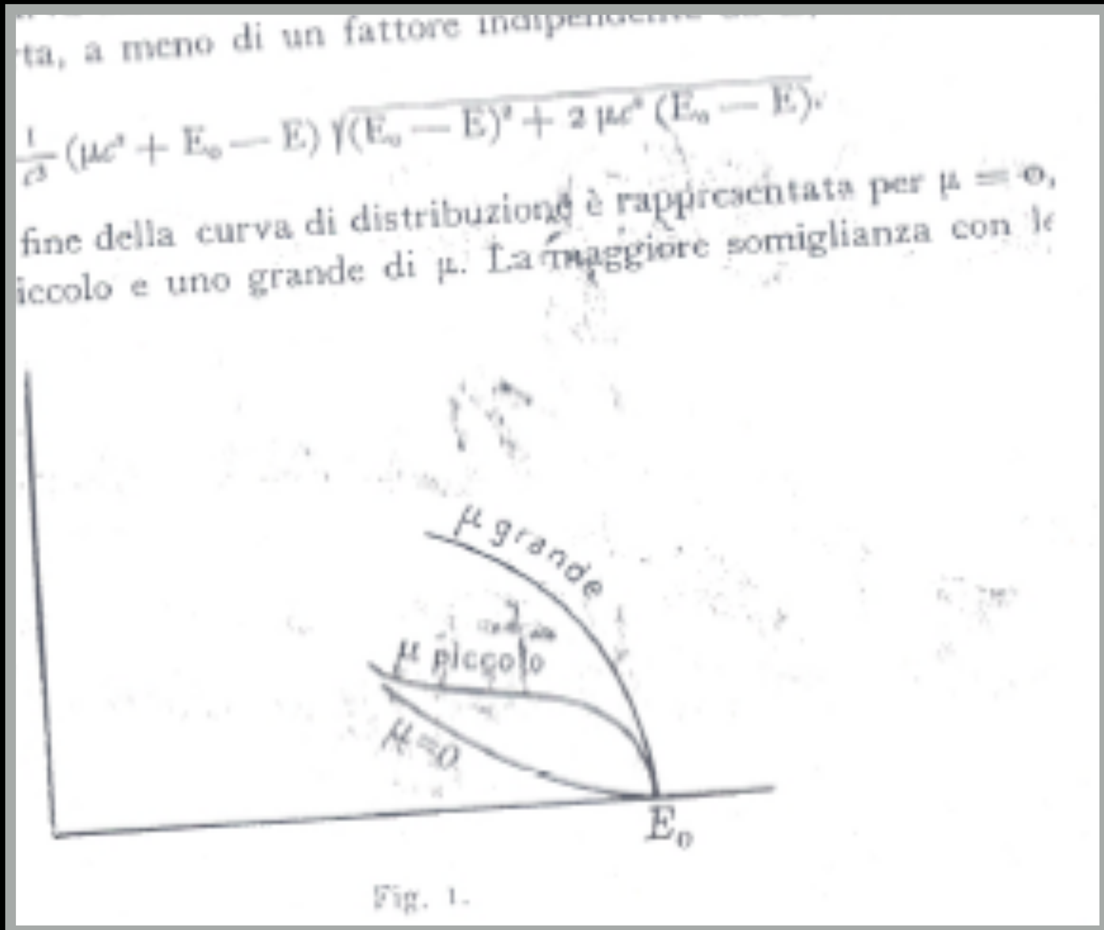

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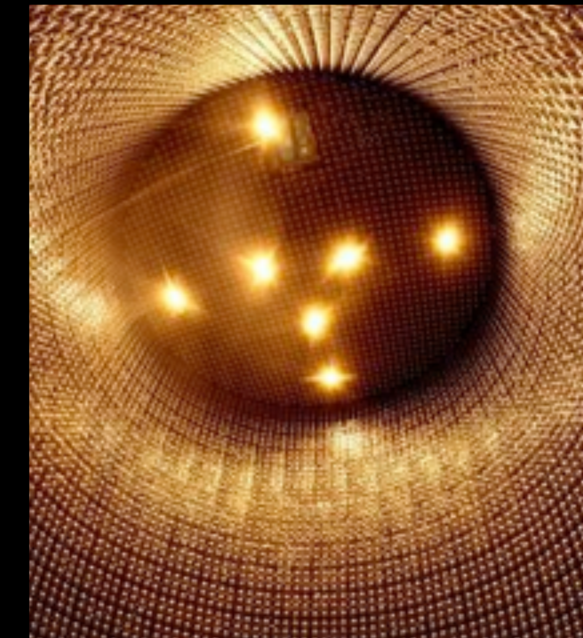
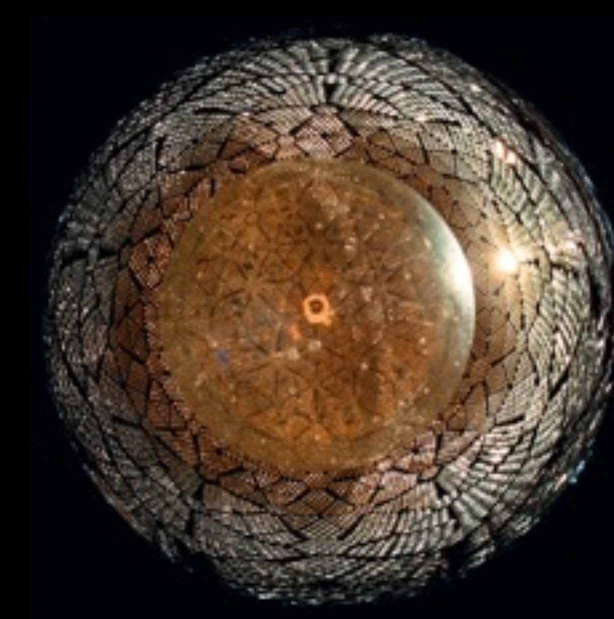
Fig. 1.

Takaaki Kajita
(Super-Kamiokande)

So far, we now know that both "grande" and "zero" are ruled out.

But the nature and even scale of neutrino masses remains an open question?

Arthur B. McDonald
(Sudbury Neutrino Observatory)

Neutrinos are odd little birds...

To date, they remain the only particles whose essential Standard Model properties are still in question...

Do neutrinos violate CP?

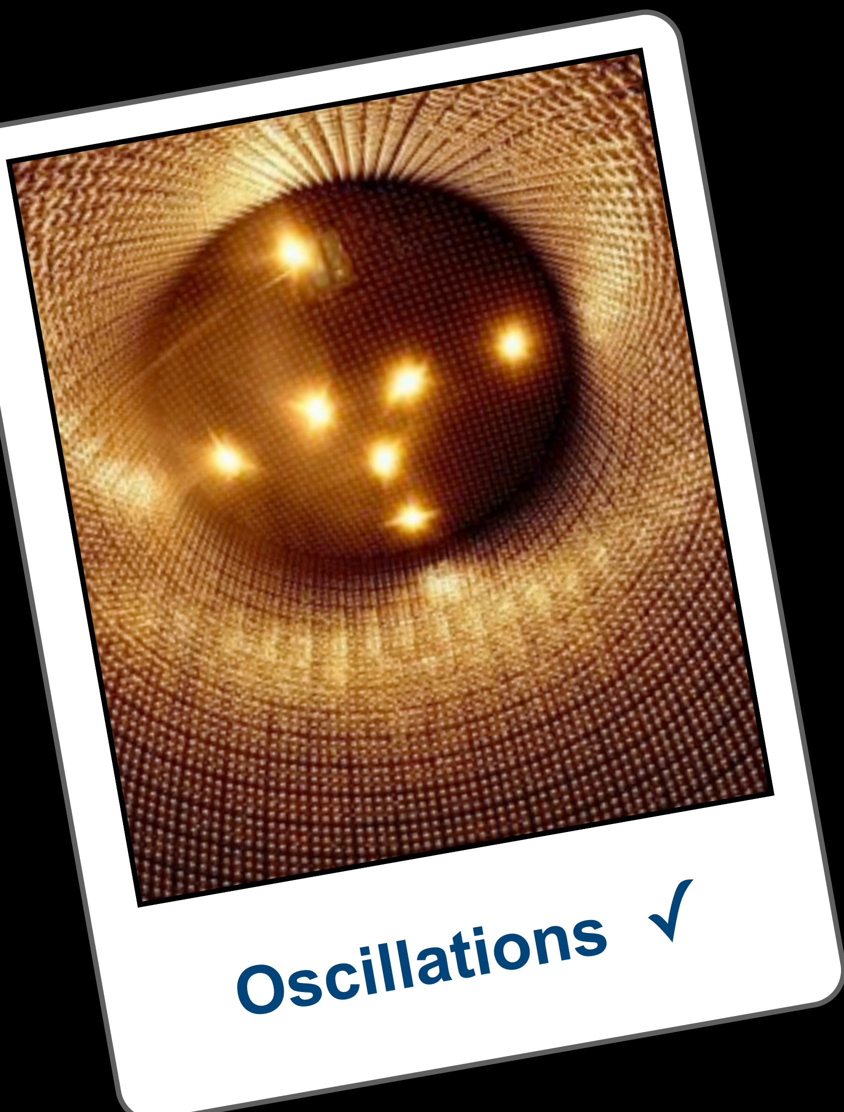
Are they their own anti-particle?

Inverted or Normal ordering?

What is their mass scale?

With oscillations established, the scale of neutrino masses can be probed with several techniques.

Beta-decay (electron capture) measurements are the hardest to advance, but offer kinematic only constraints.



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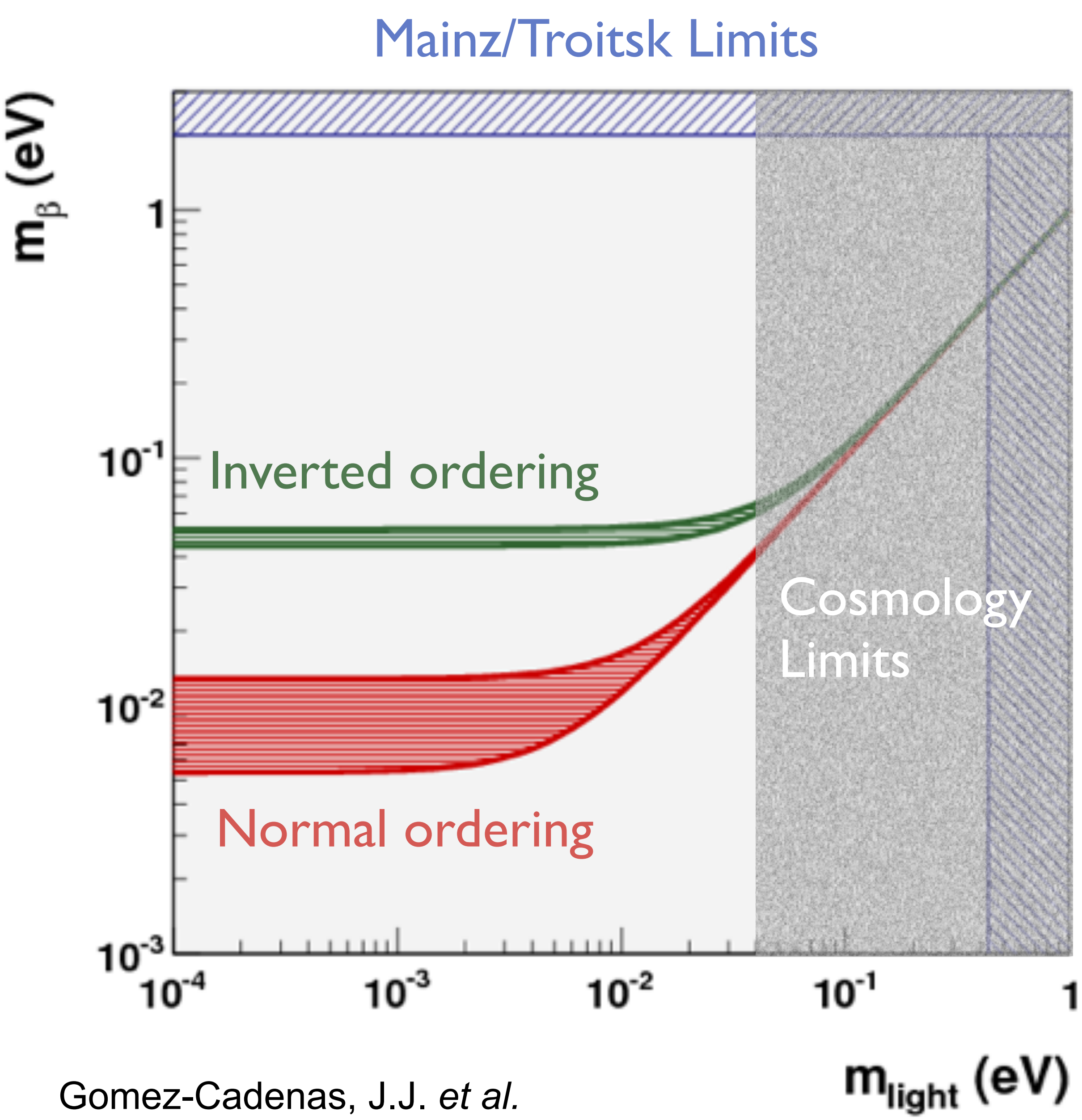
Landscape Outlook



Gomez-Cadenas, J.J. *et al.*
Riv.Nuovo Cim. 35 (2012) 29

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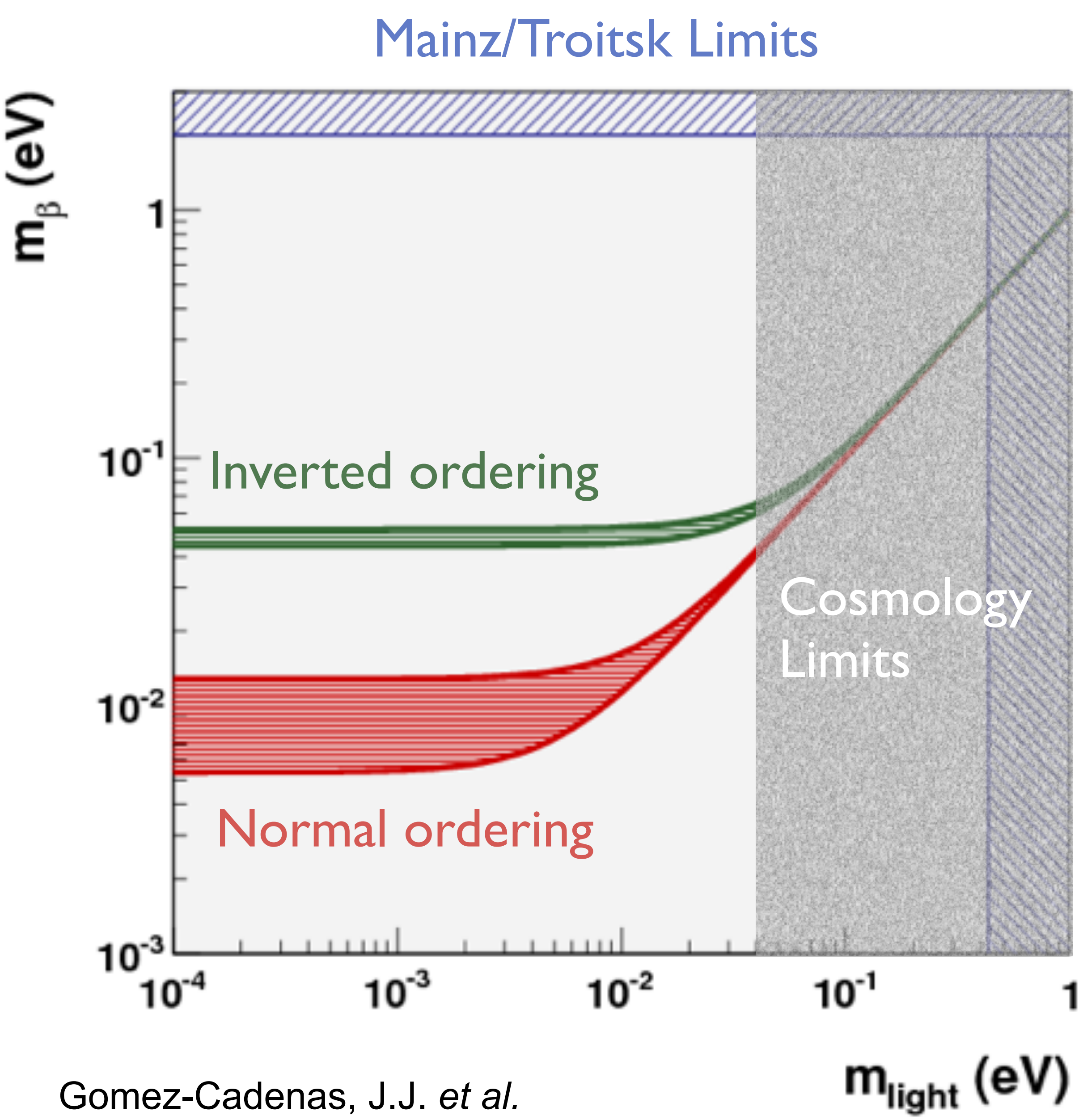


Gomez-Cadenas, J.J. *et al.*
Riv.Nuovo Cim. 35 (2012) 29

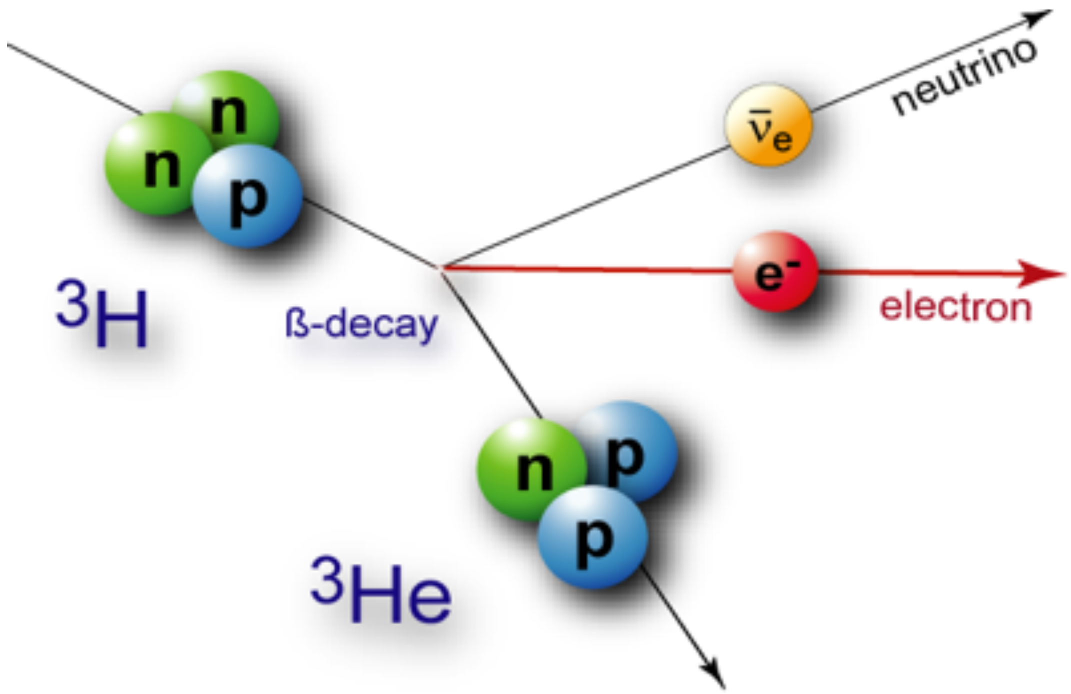
With oscillations established, the scale of neutrino masses can be probed with several techniques.

CMB Only:
$\sum m_\nu$ < 140-590 meV

CMB + LSS:
$\sum m_\nu$ < 120 meV

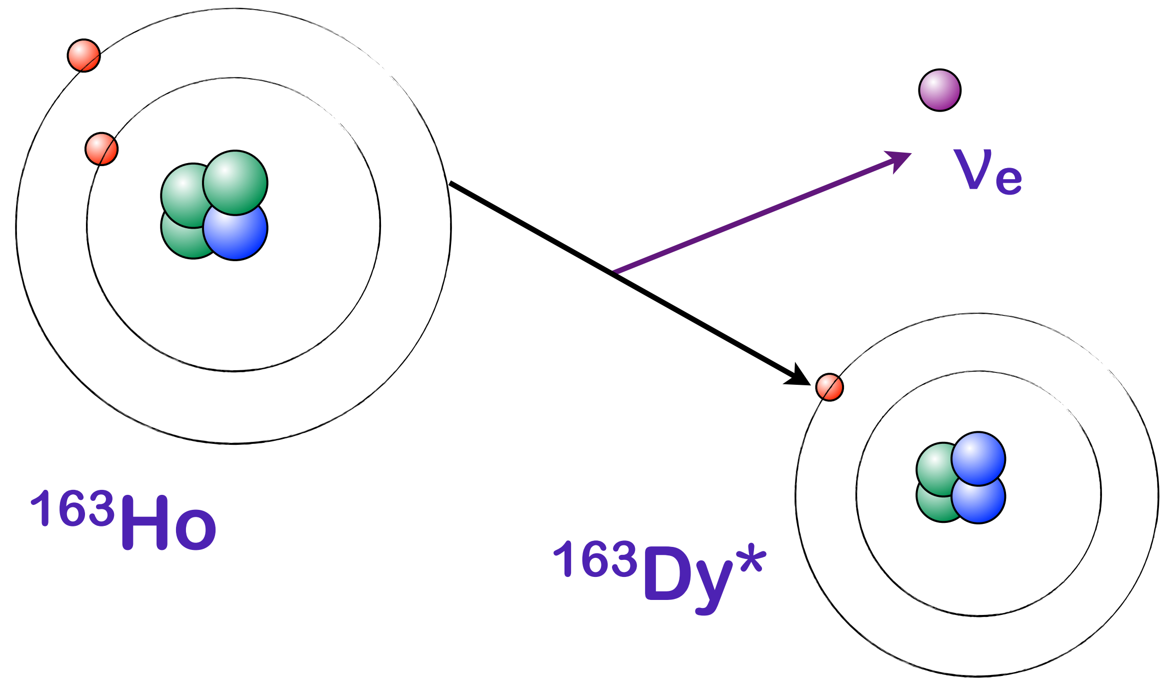
Future:
$\sum m_\nu$ < 40-60 meV

Tritium beta decay



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

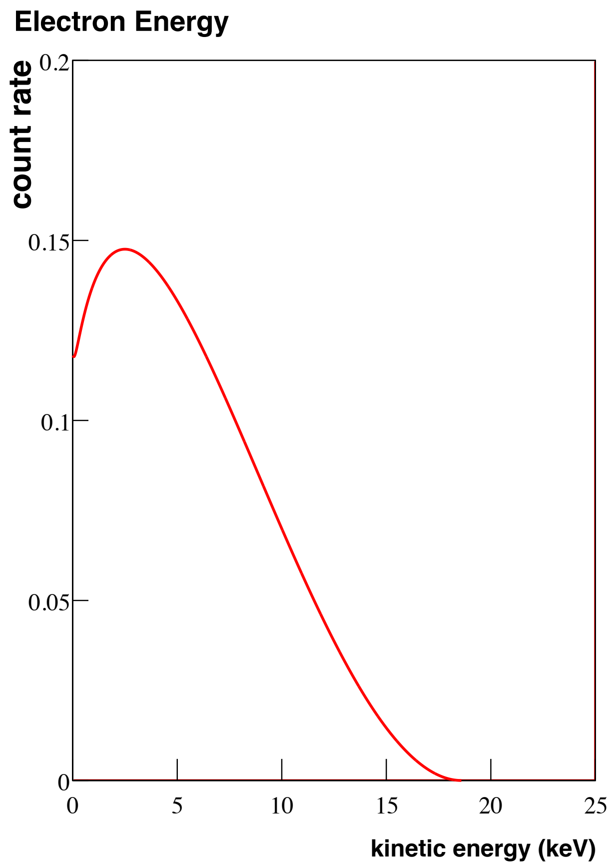
Holmium electron capture



$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

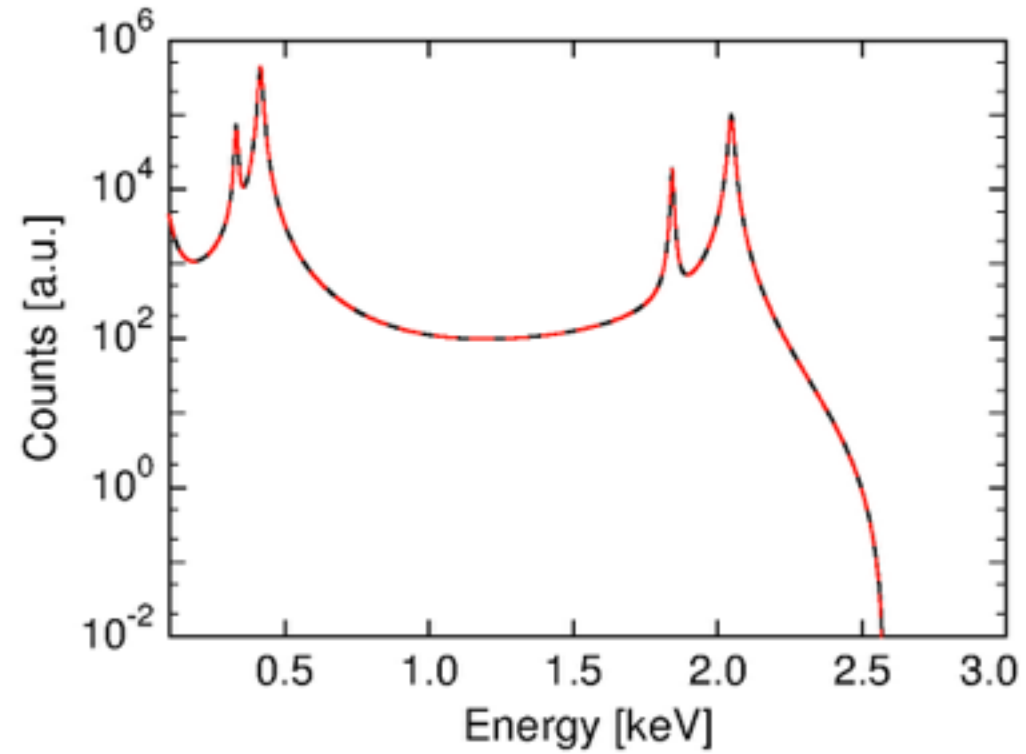
Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.

Kinematic determination of neutrino mass (dispersion relation).

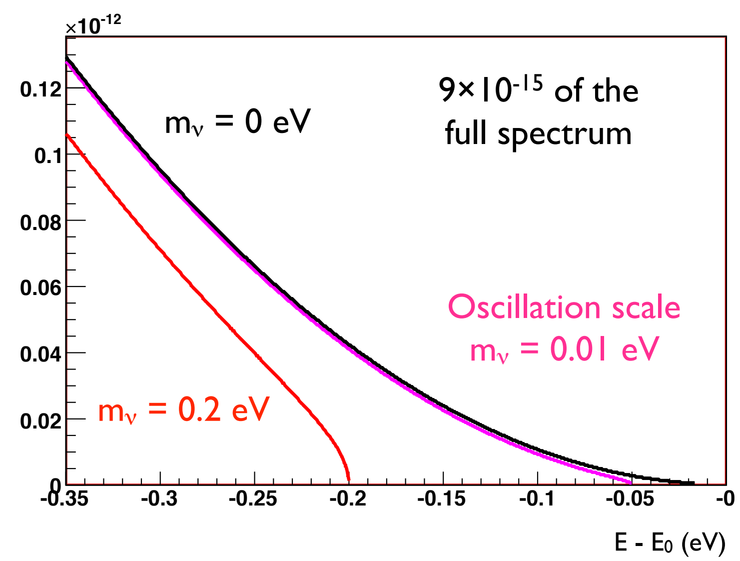


$$\dot{N} \propto p_\nu E_\nu$$

In both cases, differential spectrum depends on the neutrino momentum.



Endpoint of the Tritium β-decay Spectrum



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

Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.

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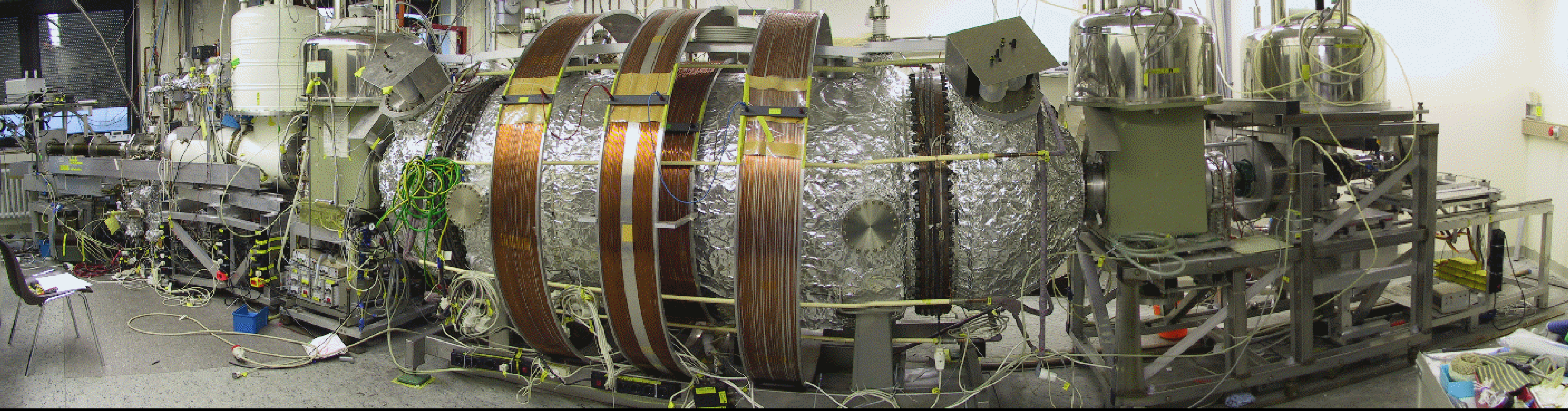
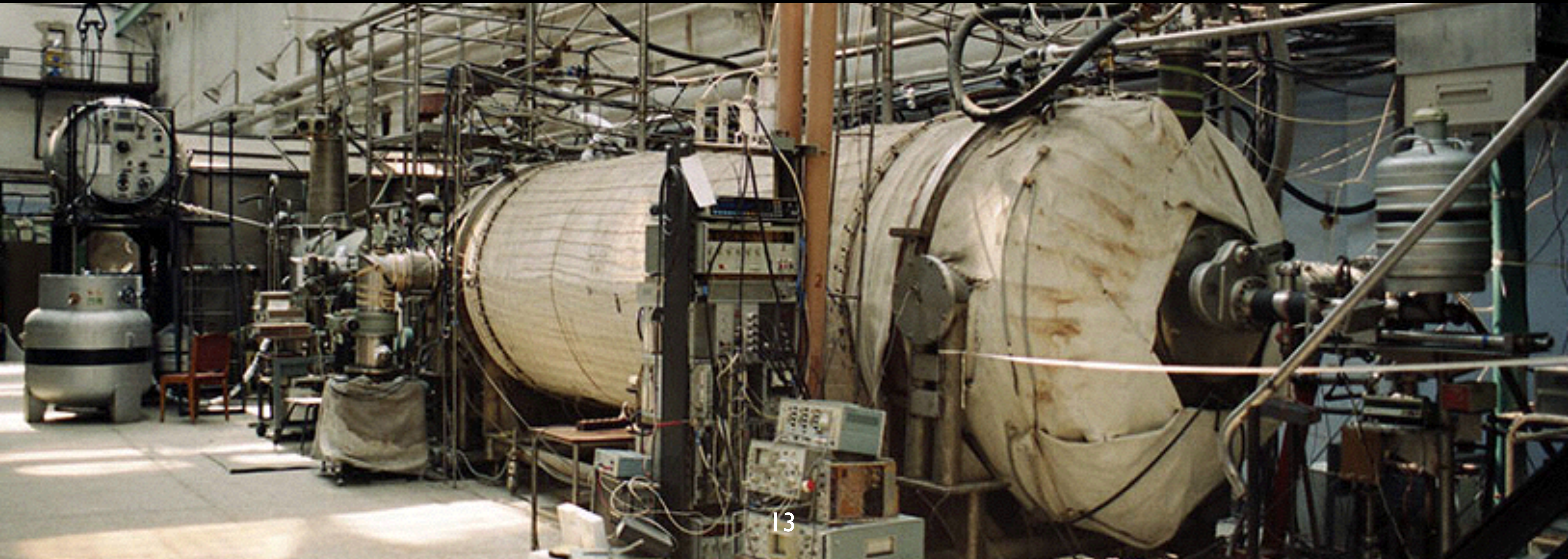


Predecessors: Mainz & Troitsk (Limit m_β < 2 eV 90% C.L.)



Modern-day Techniques

MAC-E Technique (KATRIN)

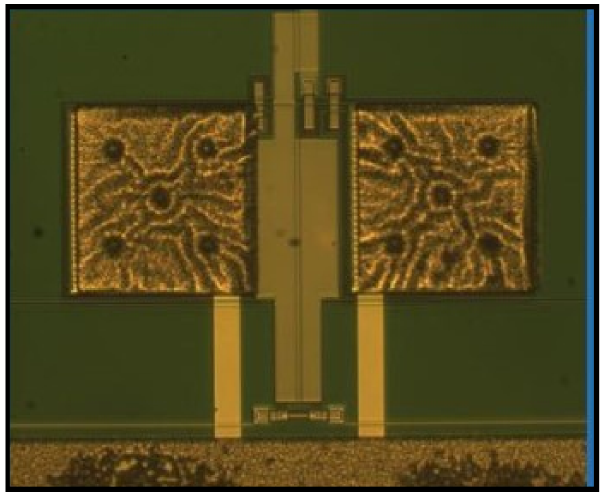
Magnetic Adiabatic Collimation with Electrostatic Filtering

Commissioning

Calorimetry (HOLMES, ECHO & NUMECS)

Bolometric measurement of ^{163}Ho

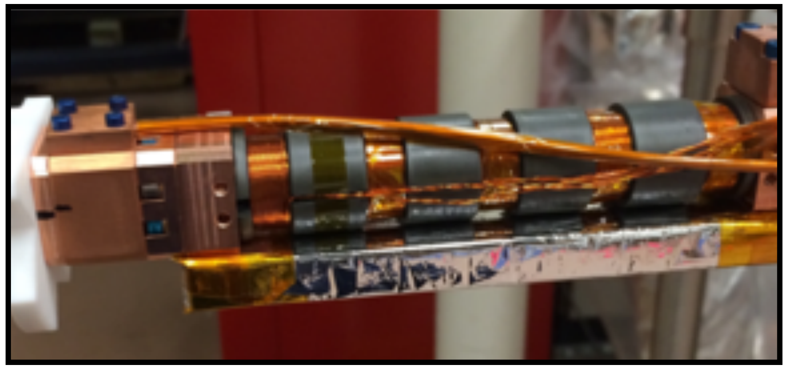
Arrays in development



Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

Commencing first tritium measurements



MAC-E Filter Technique

(KATRIN)

KATRIN

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

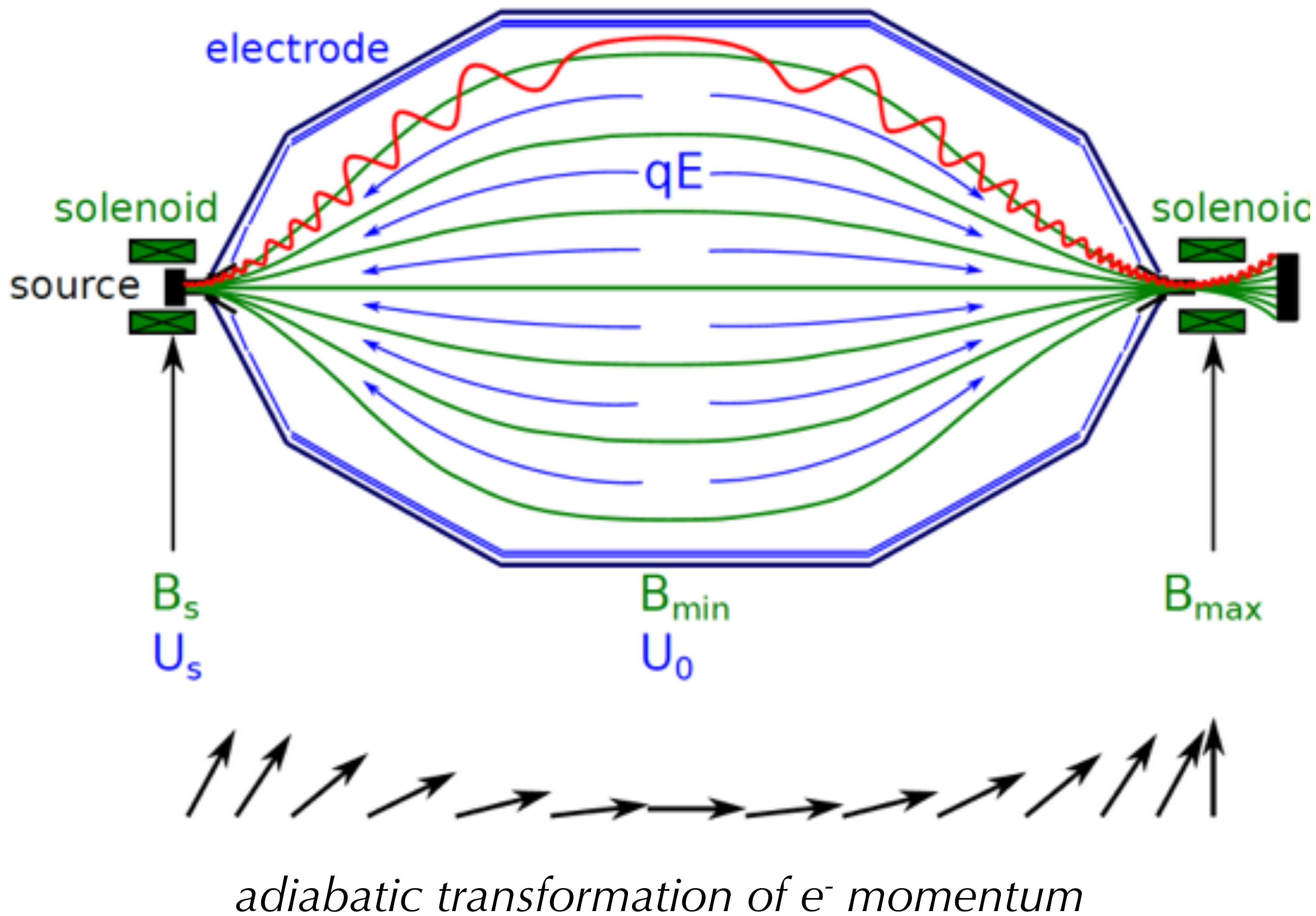
MAC-E Filter Technique

(KATRIN)

KATRIN

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Spectroscopic: MAC-E Filter



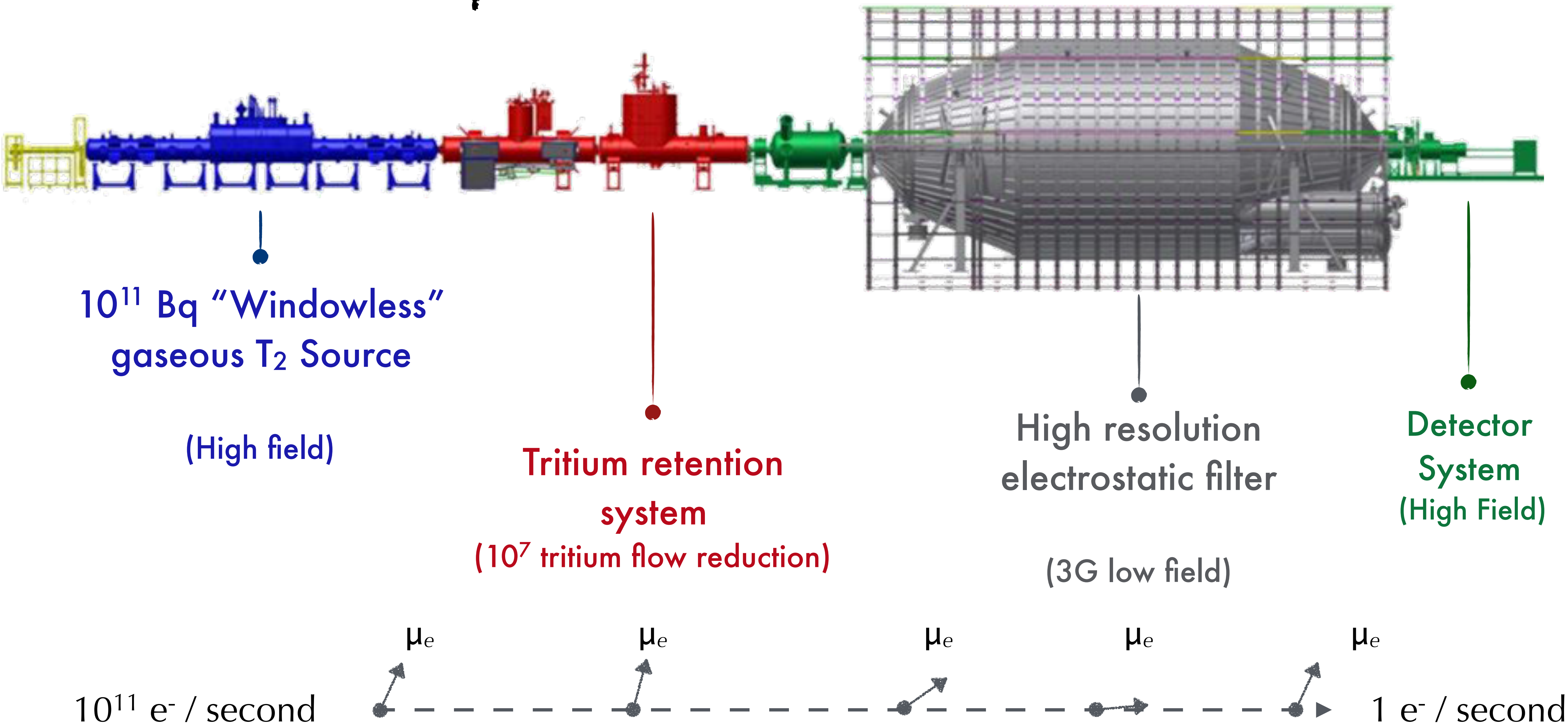
Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

($\Delta E/E = B_{min}/B_{max} = 0.93$ eV)

The KATRIN Setup



Adiabatic transport ensures high retention of phase space for decay

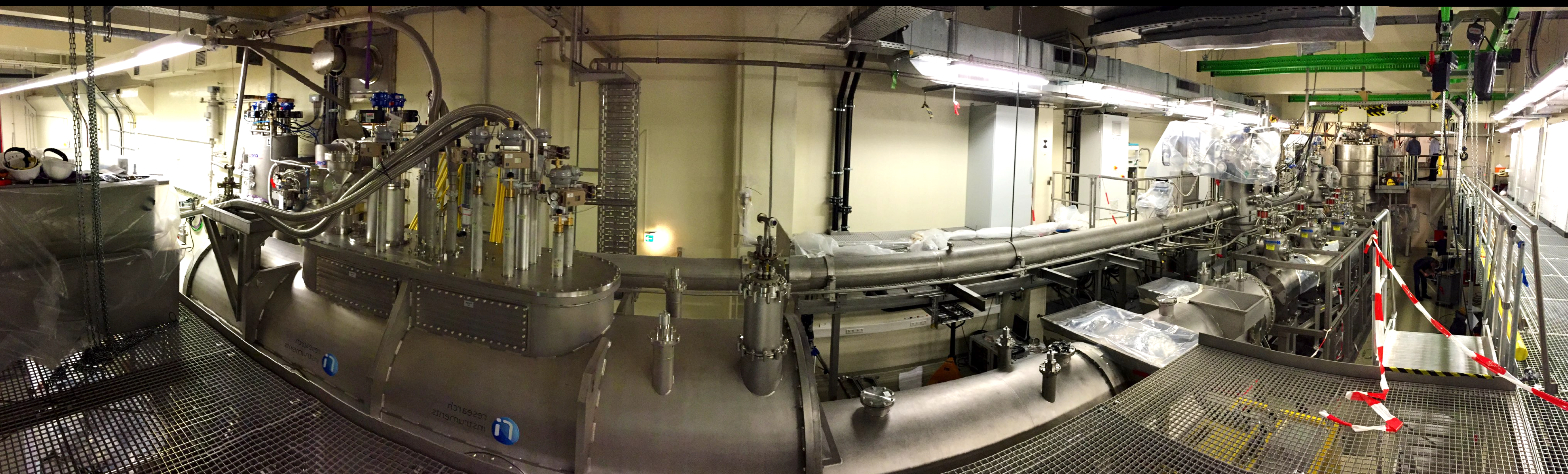
$$\frac{\Delta E}{E} = \frac{B_{\rm min}}{B_{\rm max}} \rightarrow 0.93 \text{ eV}$$

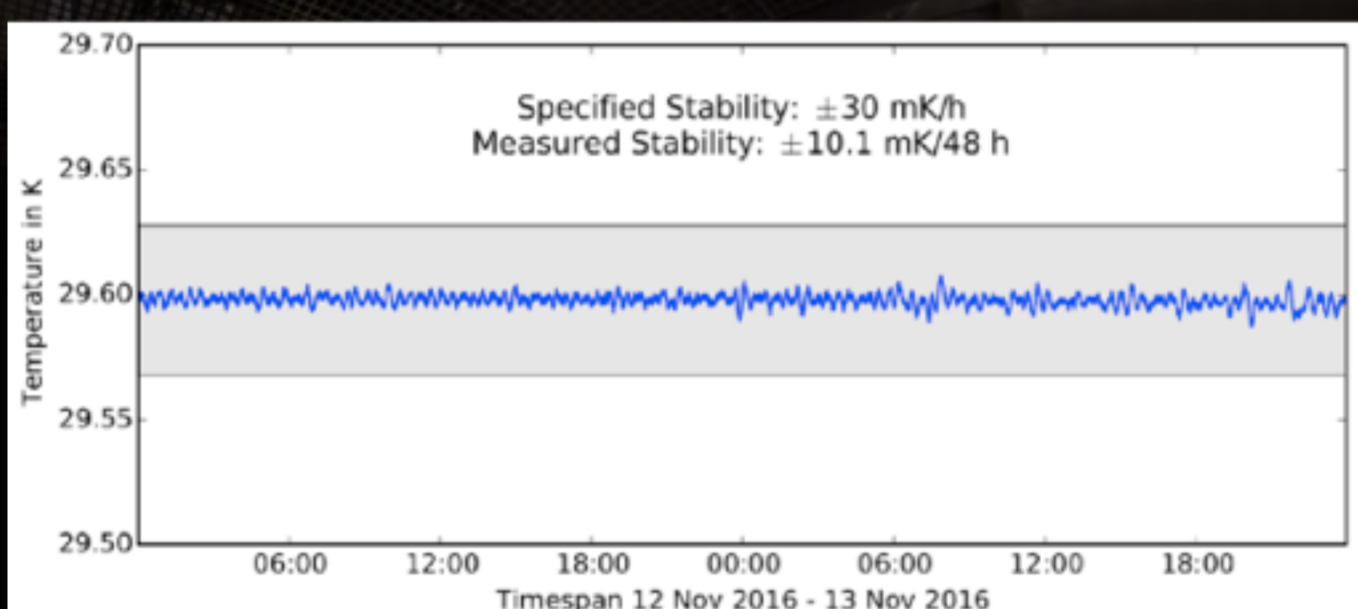
Energy resolution scales as the ratio of minimum / maximum fields

Sep. 2015

Windowless Gaseous Tritium Source (WGTS) arrives on site.

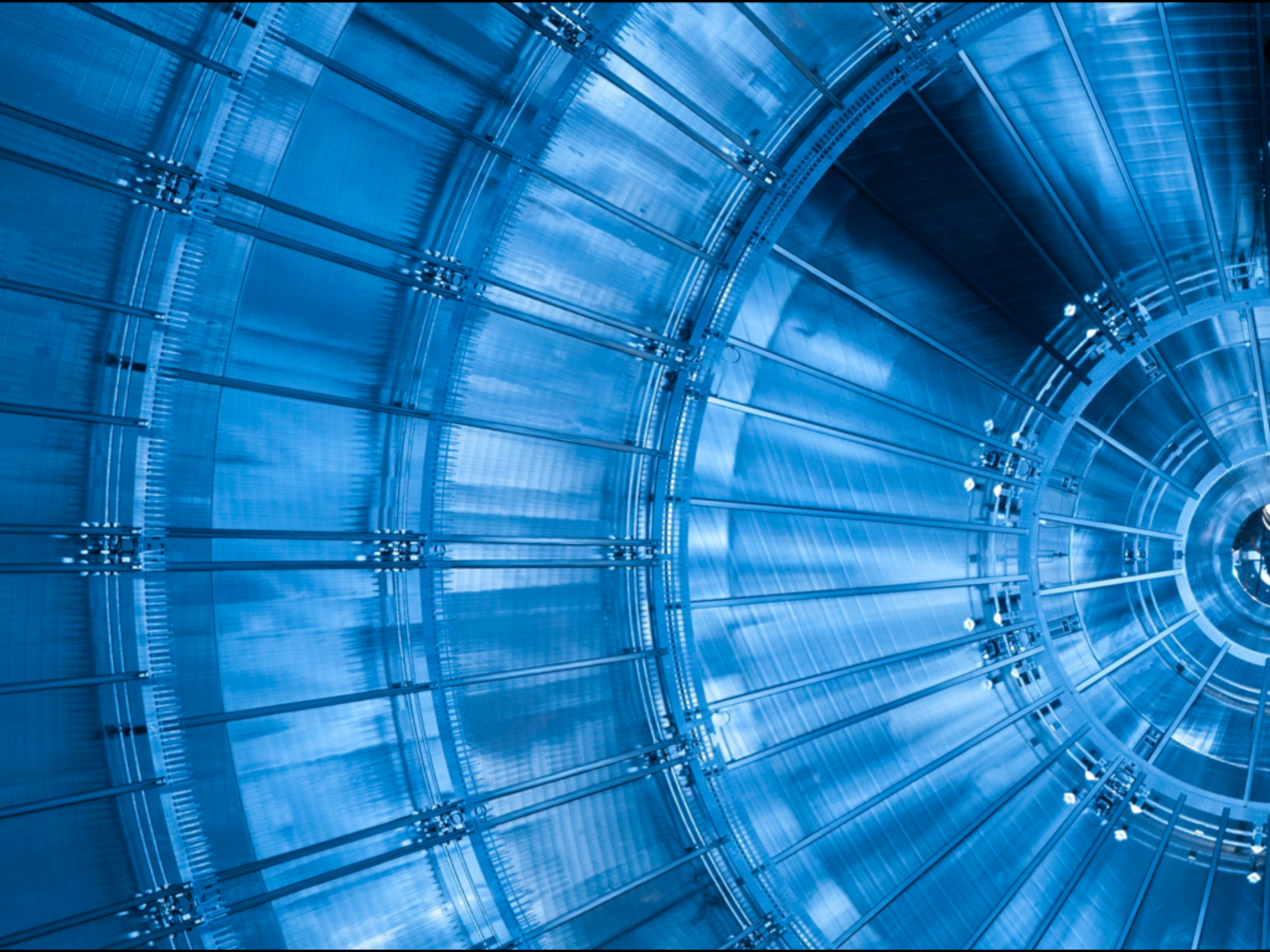
Windowless Gaseous Tritium Source (WGTS) now fully installed and being commissioned.

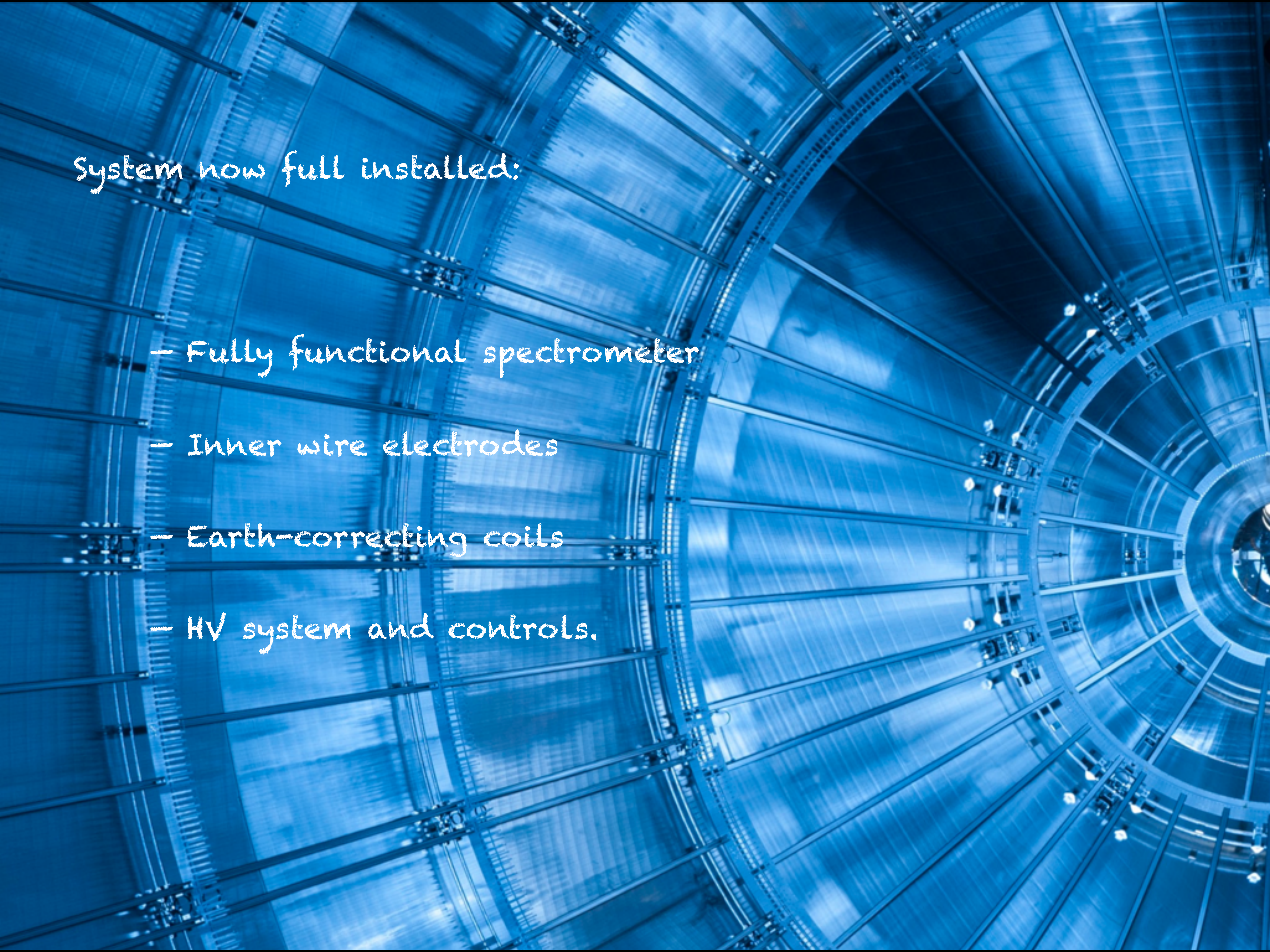




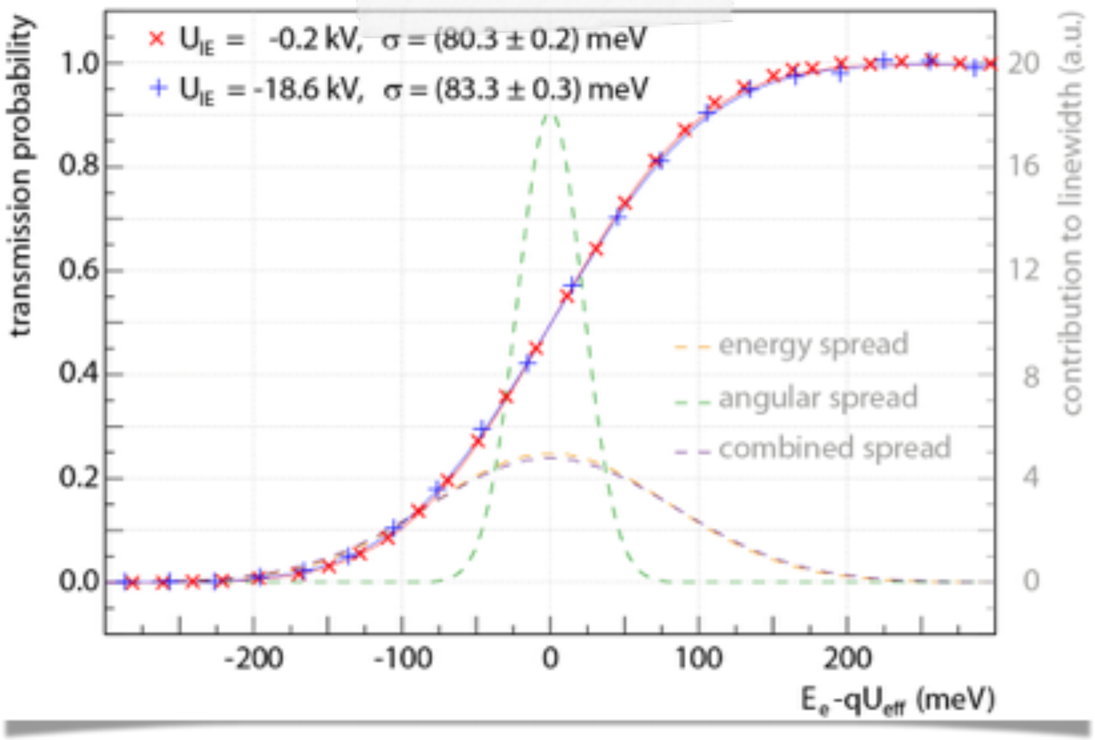
Temperature stability specification of 30 mK/hour well exceeded.

Main analyzing spectrometer arrives on KIT site

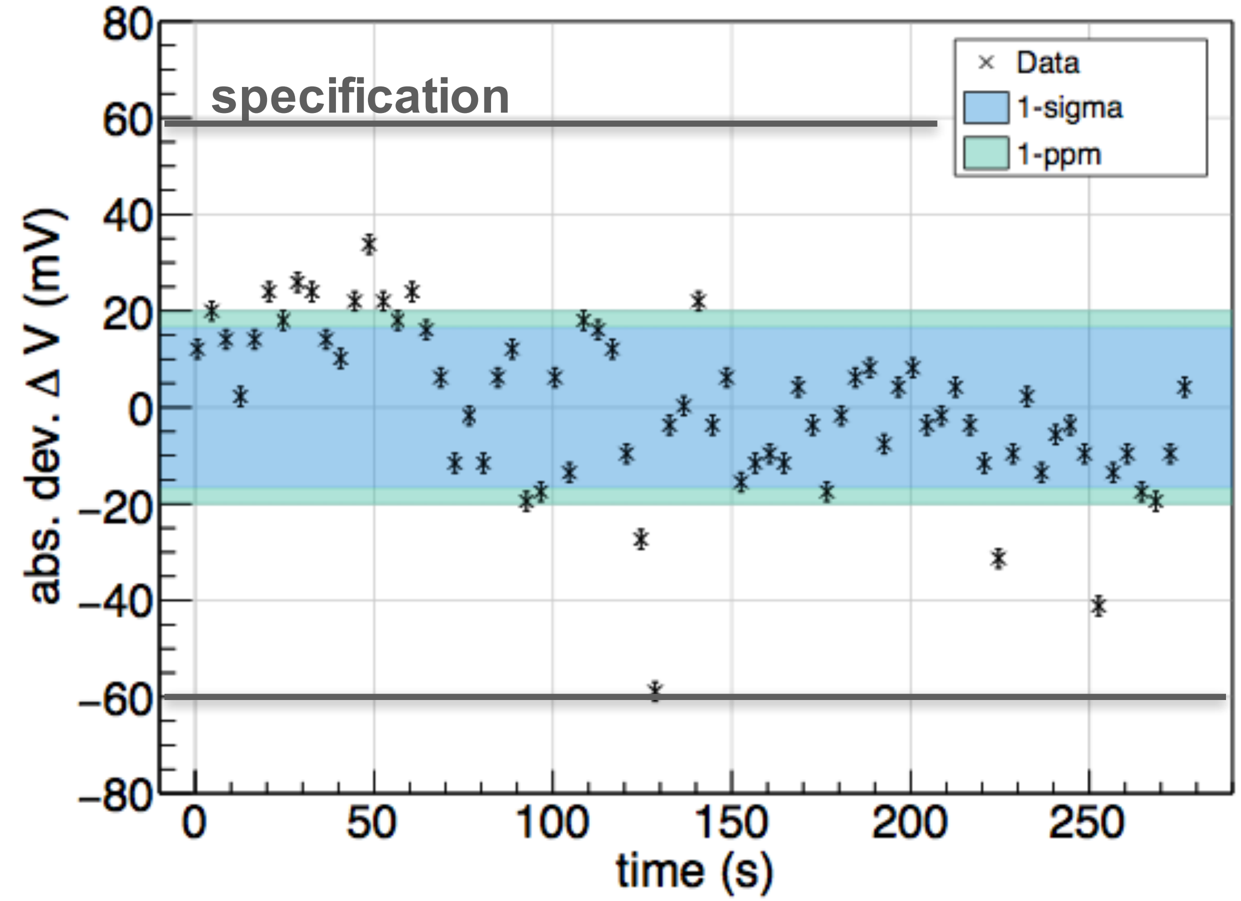



System now full installed:
– Fully functional spectrometer
– Inner wire electrodes
– Earth-correcting coils
– HV system and controls.

Transmission Function



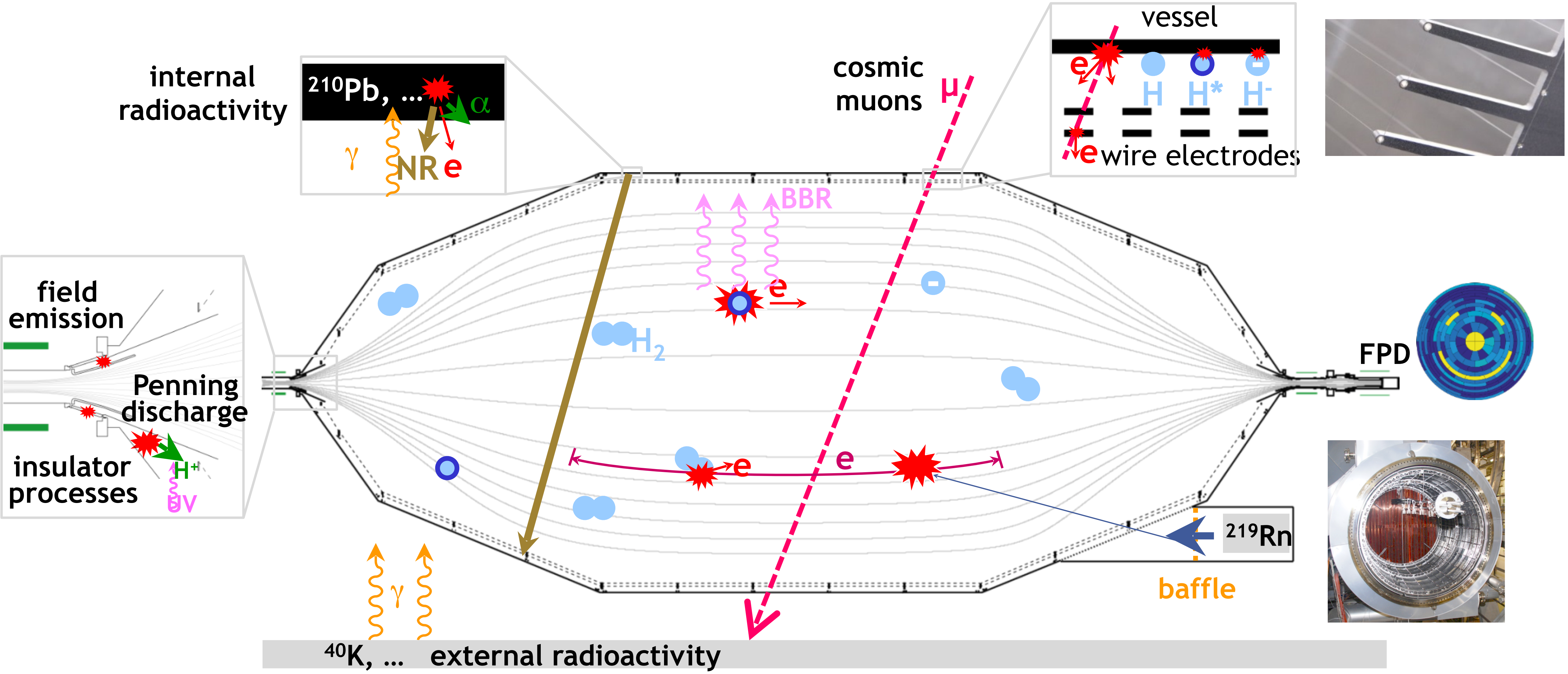
At -18.6 keV, better than
50 meV resolution at single angle
emittance
Sharpest transmission function
for a MAC-E filter



Specification of voltage stability
and performance exceeds
specifications by ~ factor of 3.

Resolution function of MAC-E Filter shown to perform better than specifications.

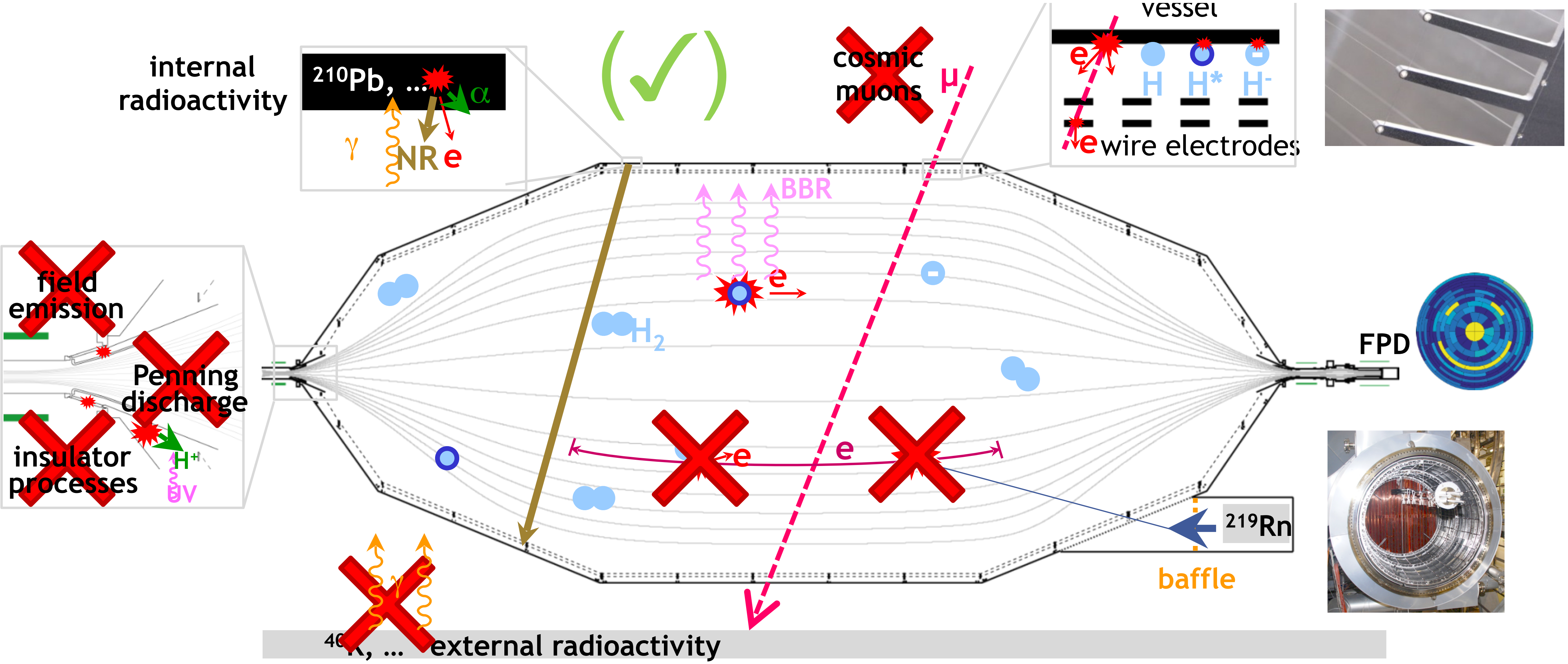
Background Rates



Various processes can contribute to the spectrometer background.

Various spectrometer backgrounds were investigated in detail during two measurement phases (SDS1 & SDS2).

Background Rates



Background rate about 50 times larger then design value (10 mcps), presumably due to ionization of Rydberg atoms by black body radiation.

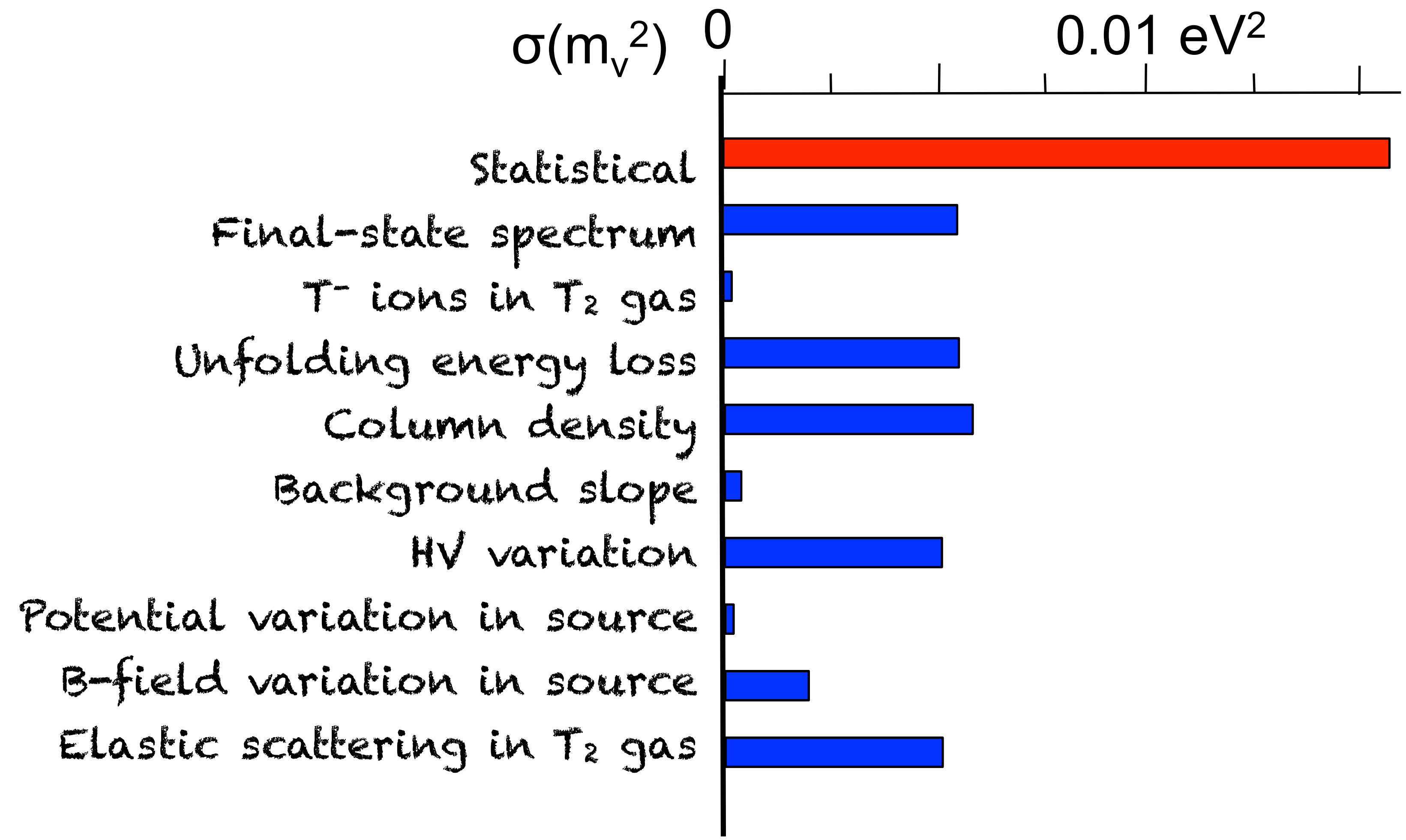
Rydberg atoms created in the decay of ^{210}Pb and accompanying processes, enter the spectrometer volume where they are ionized by thermal radiation, thus creating low-energy electrons.

First Light!

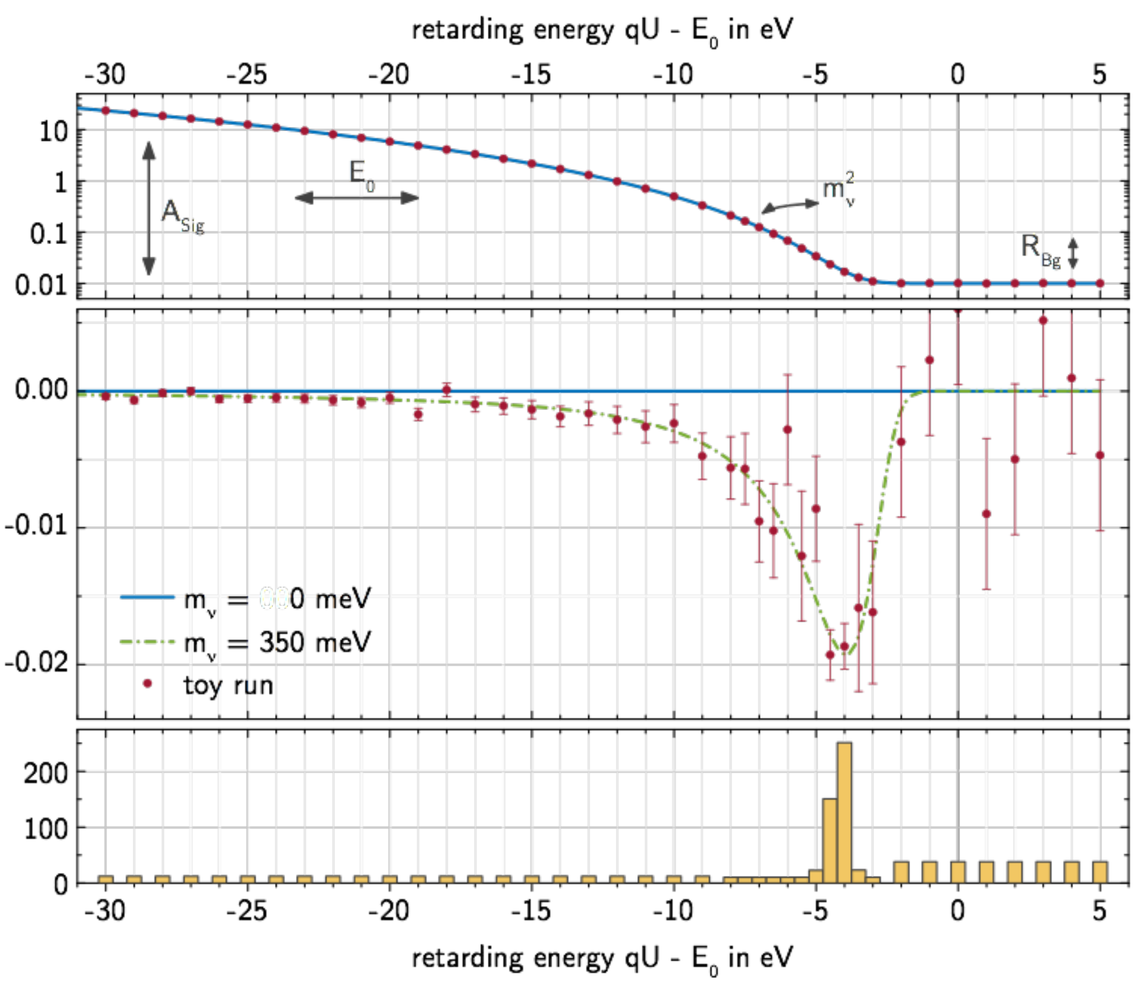
Electrons sent from one end of the KATRIN experiment to the other (calibration source to detector).

Major milestone in preparation for tritium data taking in 2017.

Projected Sensitivity



Simulated 5-sigma signal



Neutrino Mass Goals

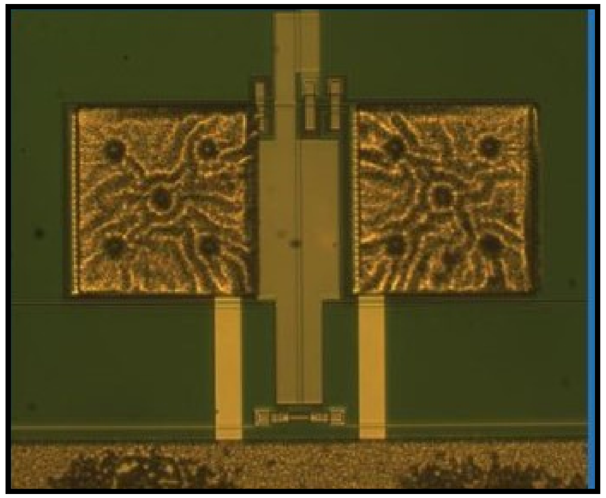
Discovery: 350 meV (at 5σ)

Sensitivity: 200 meV (at 90% C.L.)

First gaseous Kr injection to begin this summer!

Calorimetry

(ECHO, HOLMES & NuMECS)

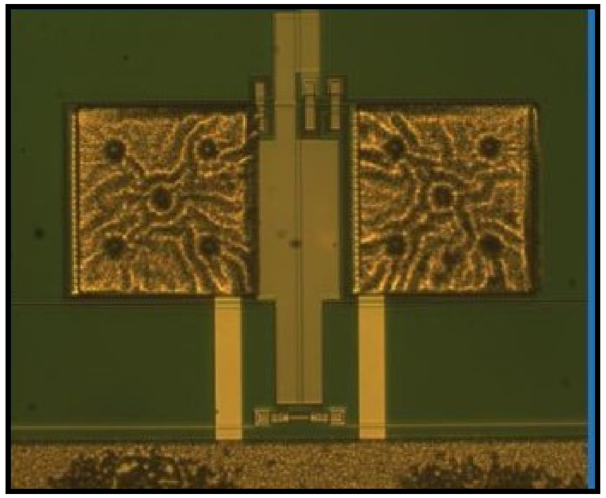


Calorimetric Approach

$$^{163}\mathrm{Ho} + e^- \rightarrow \; ^{163}\mathrm{Dy}^* + \nu_e$$

Calorimetry

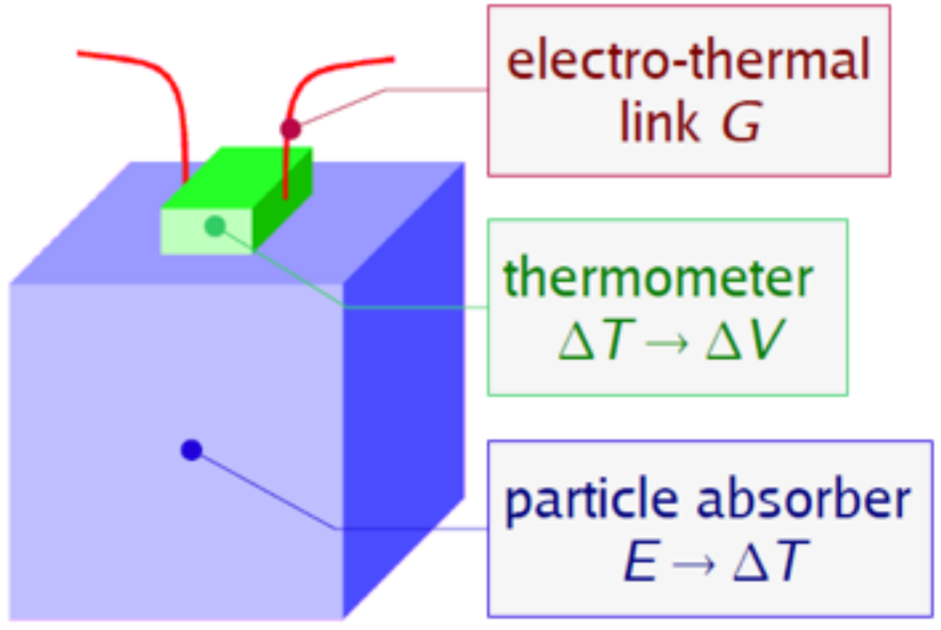
(ECHO, HOLMES & NuMECS)



Calorimetric Approach

$$^{163}\mathrm{Ho} + e^{-} \rightarrow \ ^{163}\mathrm{Dy}^{*} + \nu_e$$

Cryogenic Bolometers

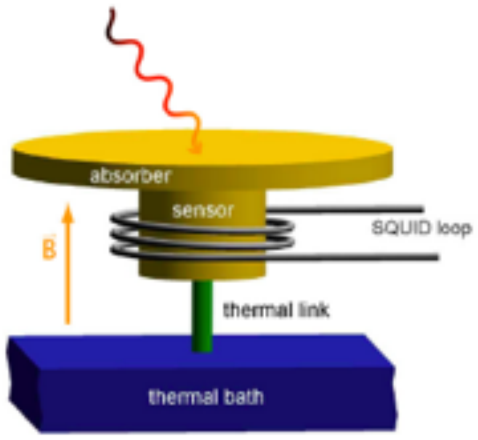


Temperature rise in cryogenic bolometers proportional to energy deposition & capacitance.

Since capacitance drops as T^3 in insulators/superconductors, one can achieve high energy resolution.

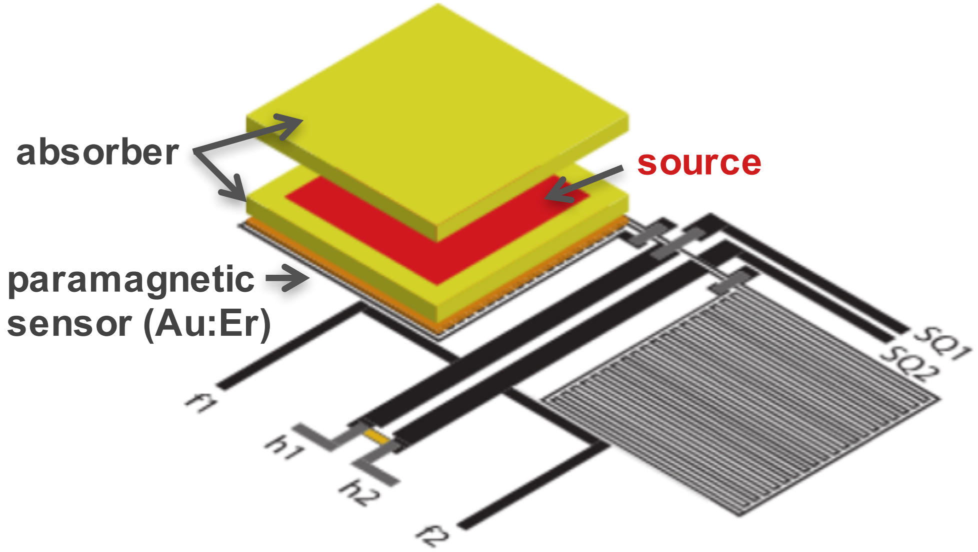
ALL energy is absorbed. No issues with backscattering, final states, etc.

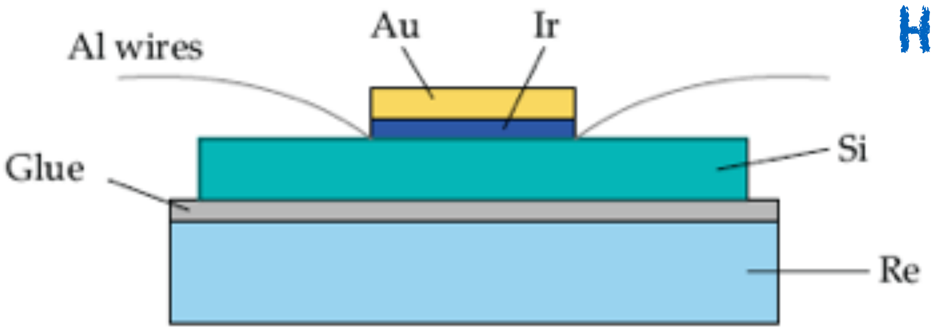
Same Isotope, Different Technologies



ECHO Experiment

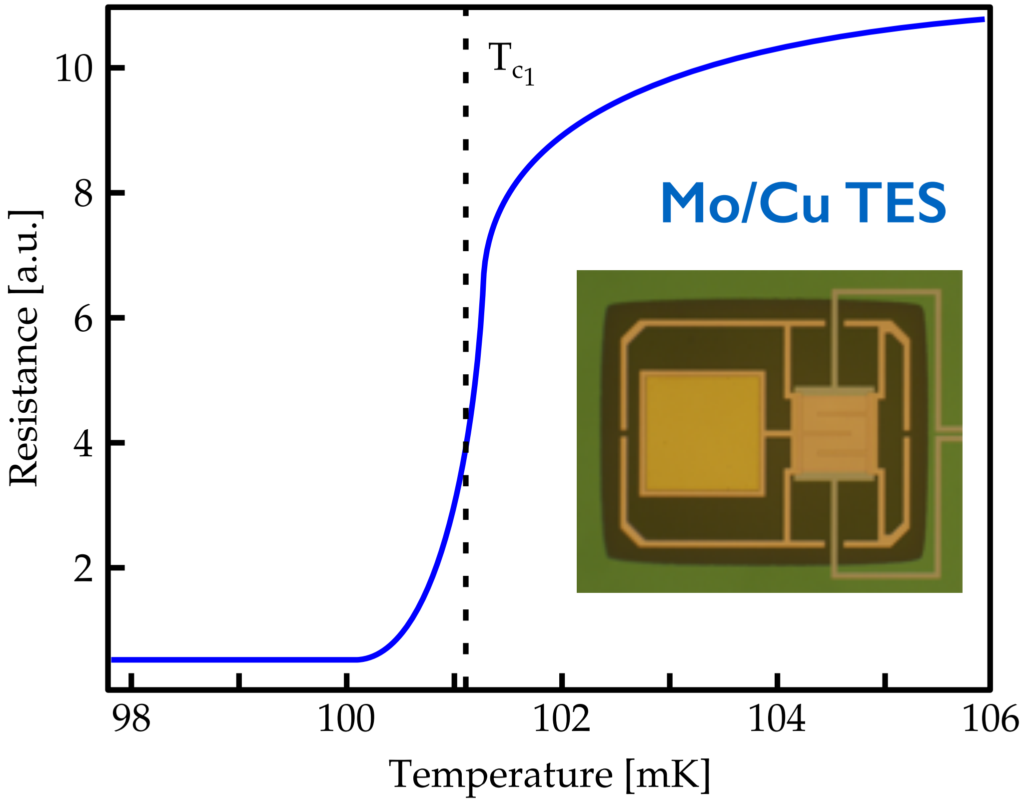
Metallic Magnetic Calorimeters





HOLMES, NuMECS

Transition Edge Sensors

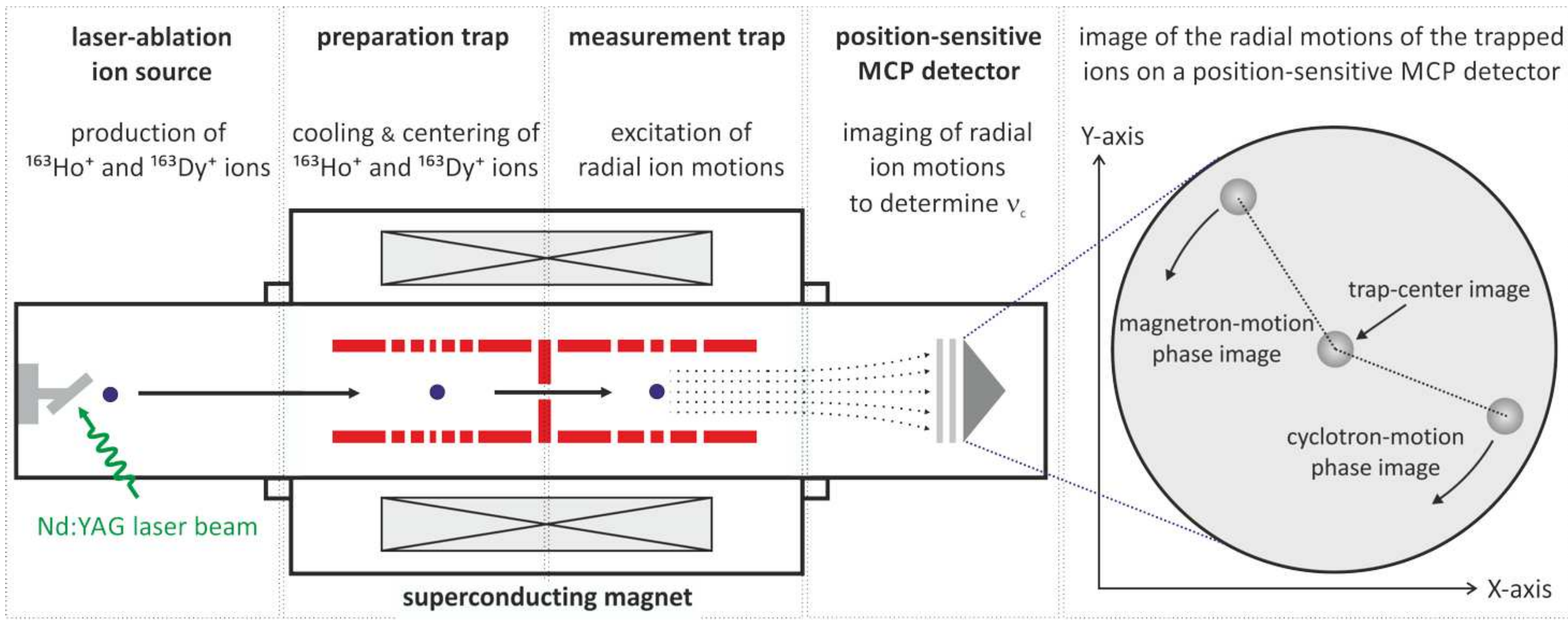


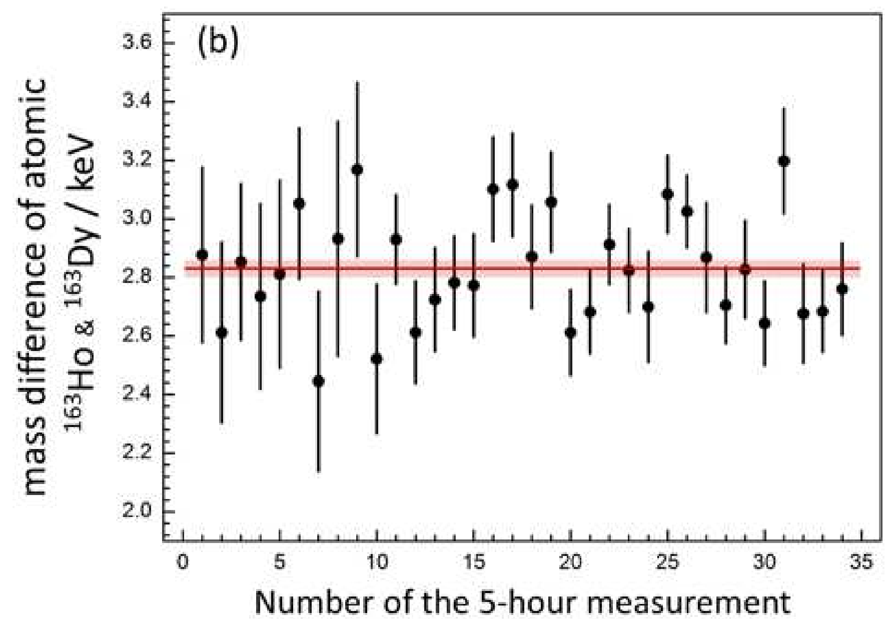
All experiments must meet the same challenges:

- Good energy resolution
- Fast timing (to minimize pileup)
- Multiplexing
- Understanding of endpoint
- Clean source extraction of ^{163}Ho
- Low background levels.

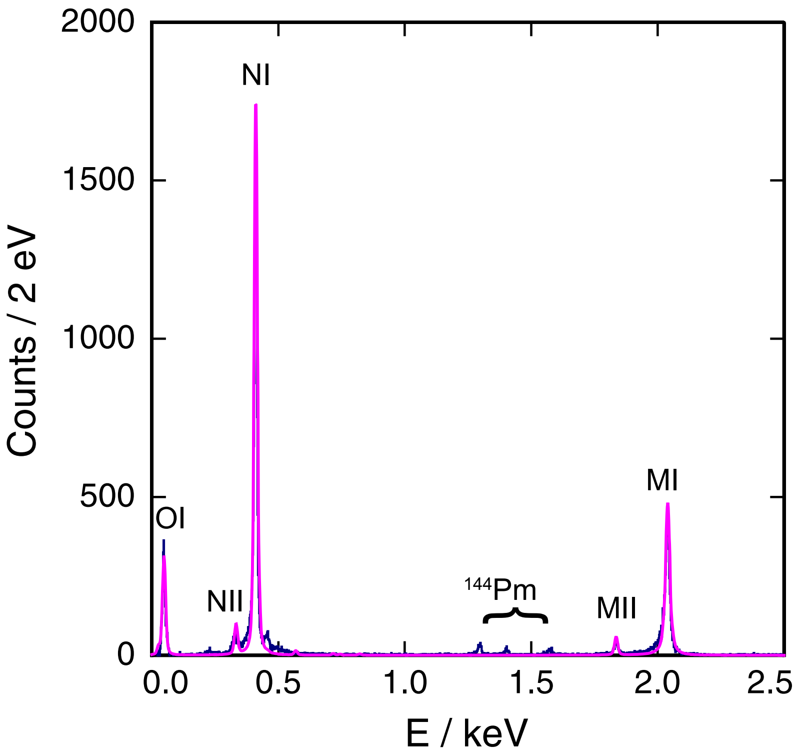
Removing Obstacles

SHIPTRAP Q_{meas}
2833 ± 30 ± 15 eV



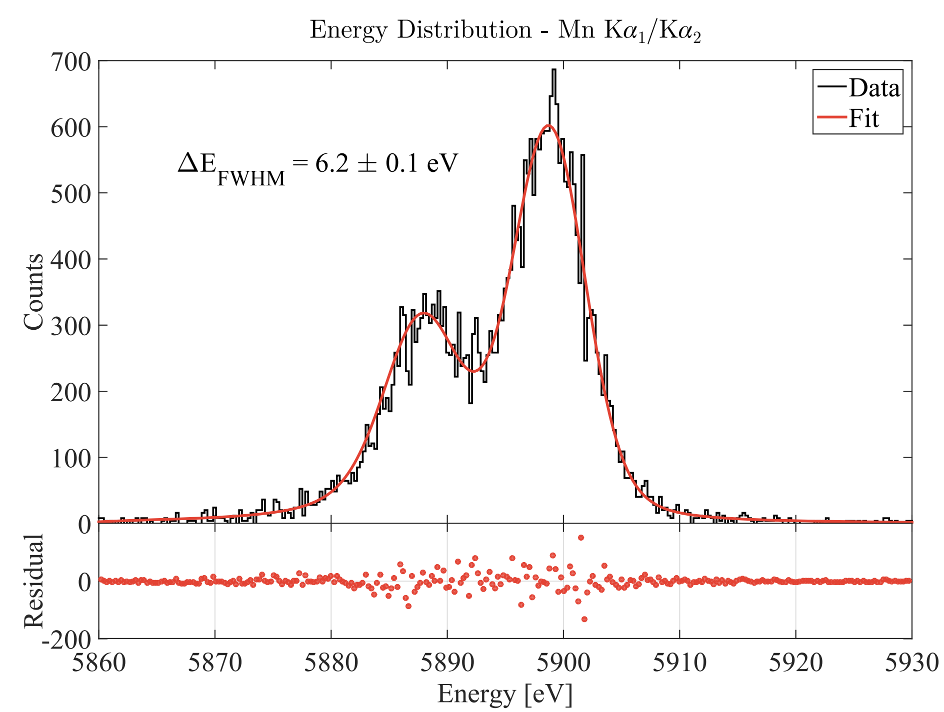


Q-value measurement of Ho/Dy system



ΔE = 2.3 eV (FWHM)
τ = 130 ns
achieved by ECHO

ΔE = 6.1 eV (FWHM on ^{55}Fe)
τ_{rise} = 10 us
achieved by HOLMES

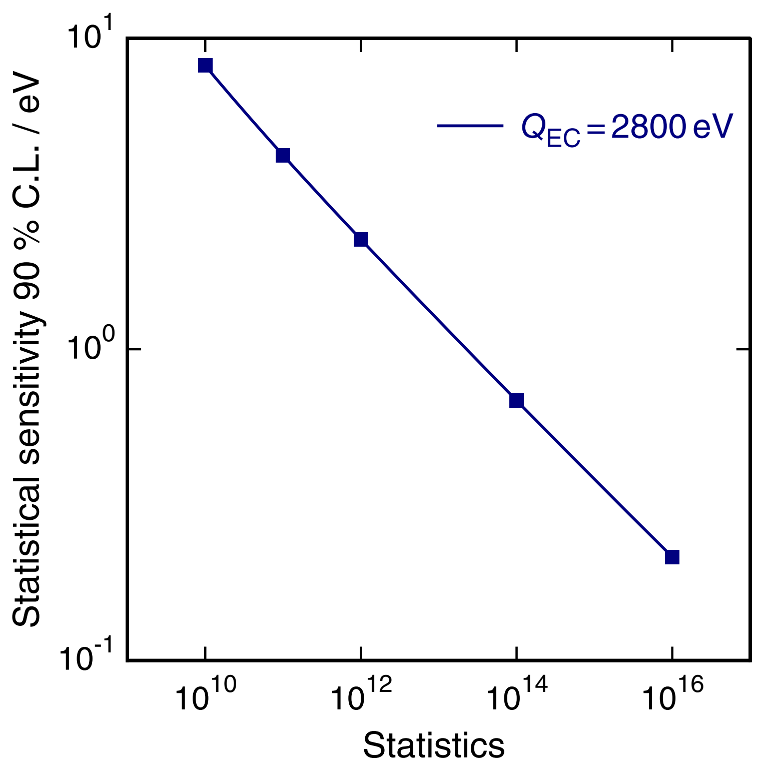


Energy resolution & timing measurements.

Moving Forward

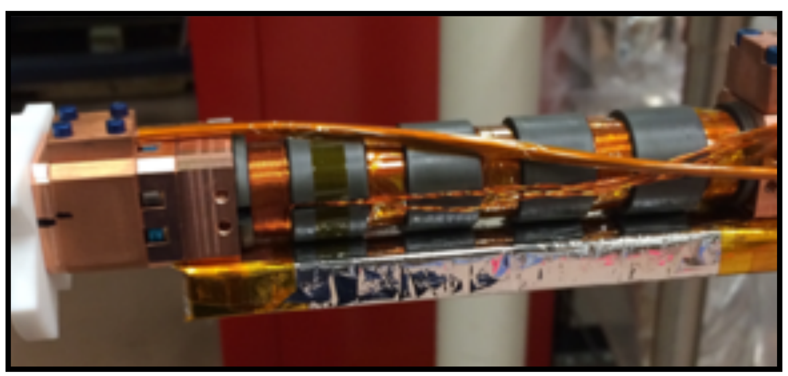
	ECHO	HOLMES	NuMECS
Detector	MMC	TES	TES
ΔE (FWHM)	2.3 eV	6.1 eV	7.5 eV
t_{rise}	0.13 us	10 us	
Multiplexing	RF	RF	RF
^{163}Ho production	^{162}Eu(n,γ)	^{162}Eu(n,γ)	^{nat}Dy(p,xn)

- All experiments moving toward enough activity / detectors to have 10^{10} decay statistics: eV scale!
- Pave the road for ~1000 pixel detectors (10^{16} decay statistics) needed for sub-eV scale reach.



Frequency

(Project 8)



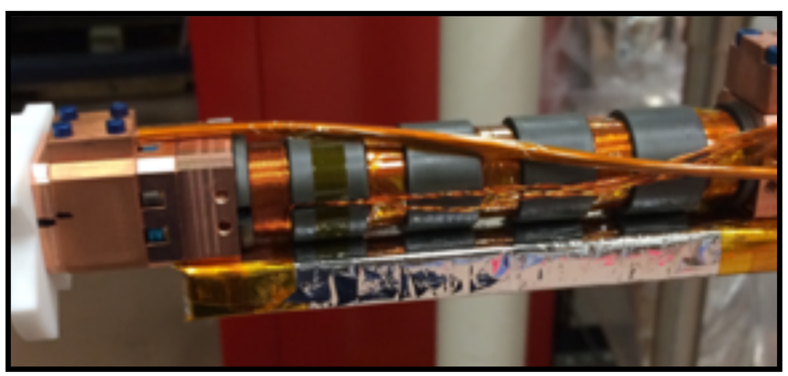
PROJECT 8

Frequency Approach

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

Frequency

(Project 8)

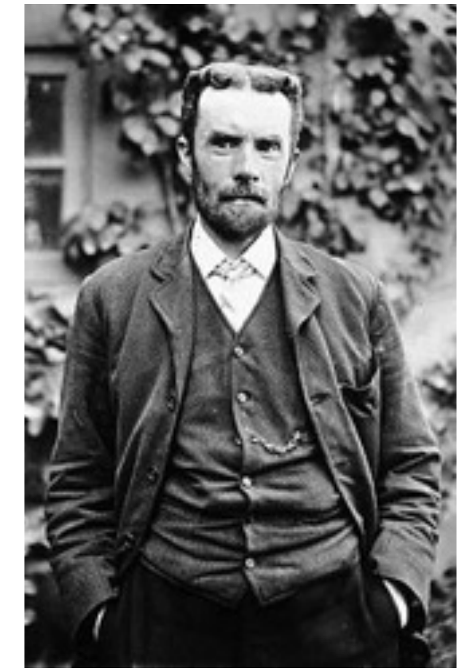


PROJECT 8

Frequency Approach

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

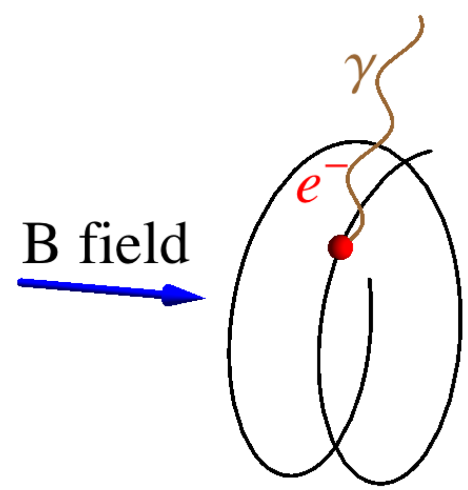
"Never measure anything but frequency."



A. L. Schawlow

O. Heaviside

Use frequency measurement of cyclotron radiation from single electrons:

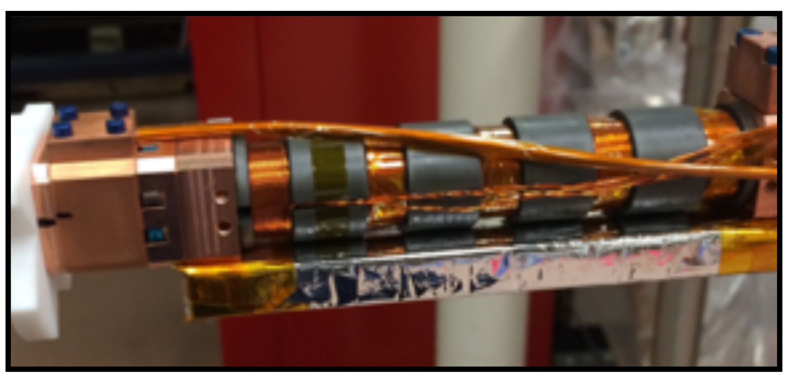


- Source transparent to microwave radiation
- No e- transport from source to detector
- Highly precise frequency measurement

B. Monreal and JAF, Phys. Rev D80:051301

Frequency

(Project 8)



PROJECT 8

Frequency Approach

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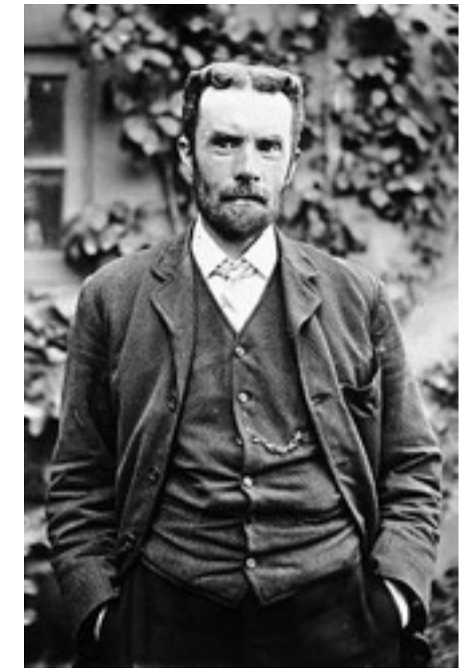


O. Heaviside

Use frequency measurement of cyclotron radiation from single electrons:

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$

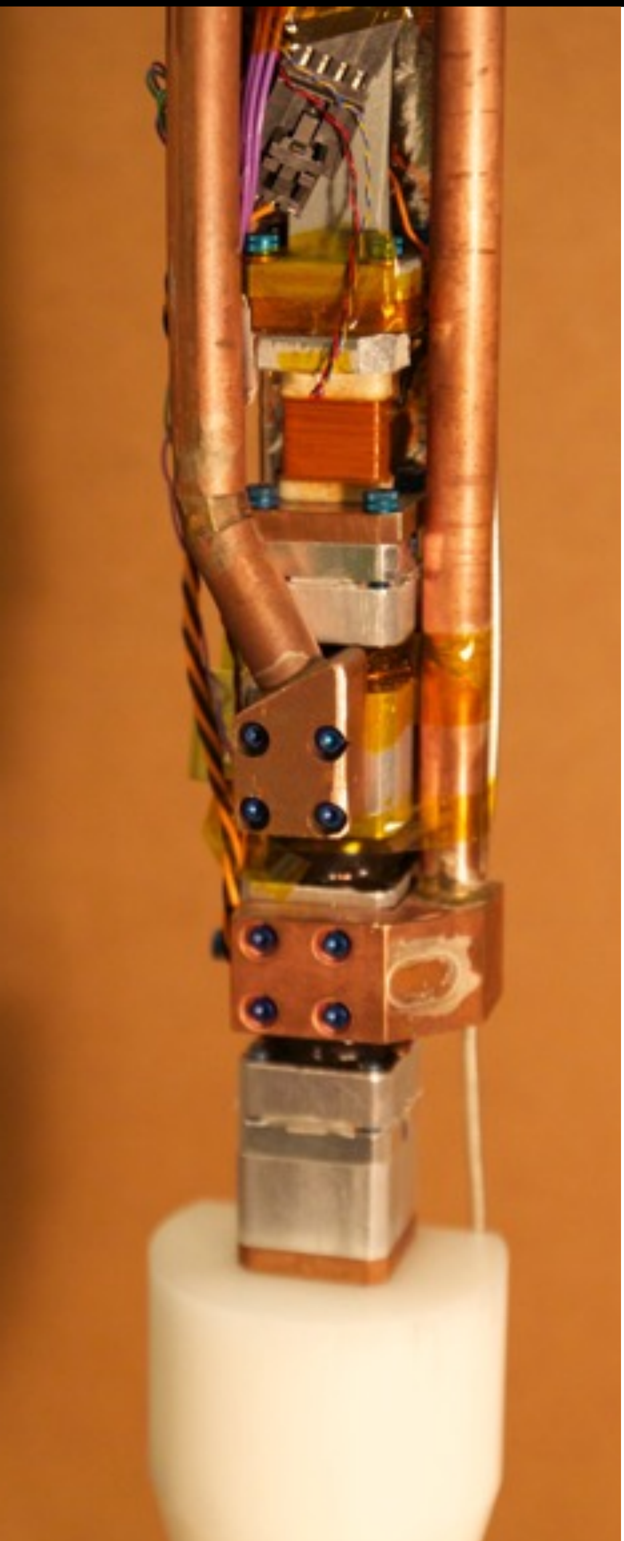
- Highly precise frequency measurement (~26 GHz).
- Small, but detectable power emitted.

$$P\,(17.8\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}) = 1\,\mathrm{fW}$$
$$P\,(30.2\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}) = 1.7\,\mathrm{fW}$$

B. Monreal and JAF, Phys. Rev D80:051301

Phase I Demonstration: ^{83m}Kr

- Waveguide insert with small magnetic trapping coil.
- Use ^{83m}Kr gas as calibration source; mono-energetic lines at 17 keV and 30 keV.



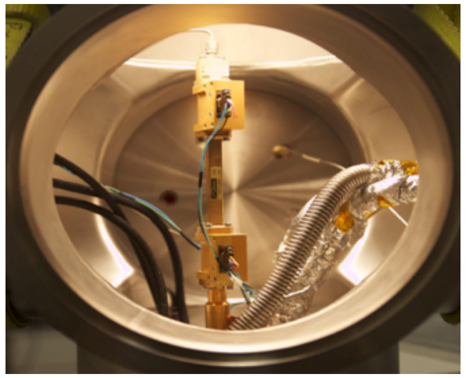
Copper waveguide

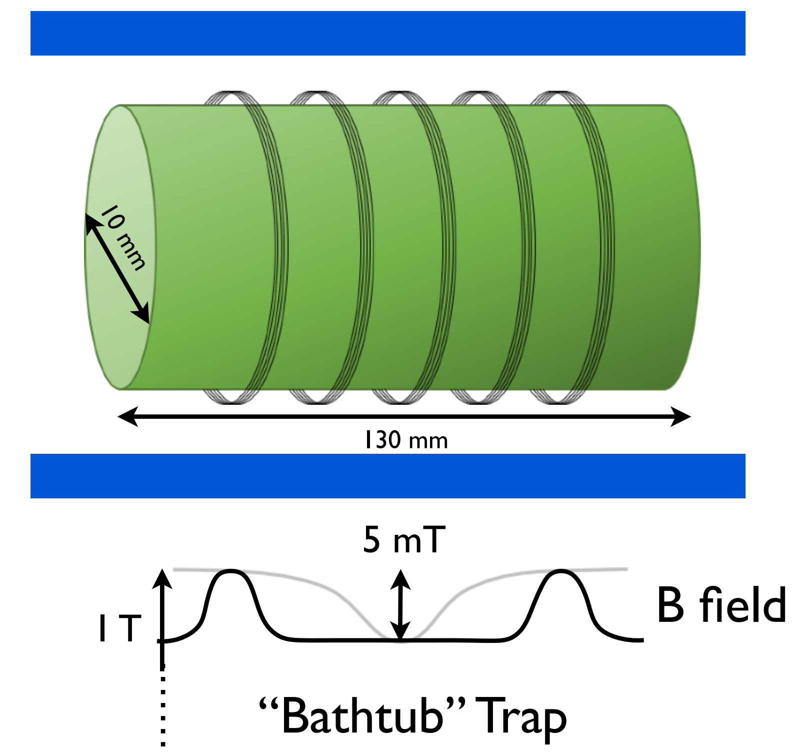
Kr gas lines

Magnetic bottle coil

Gas cell

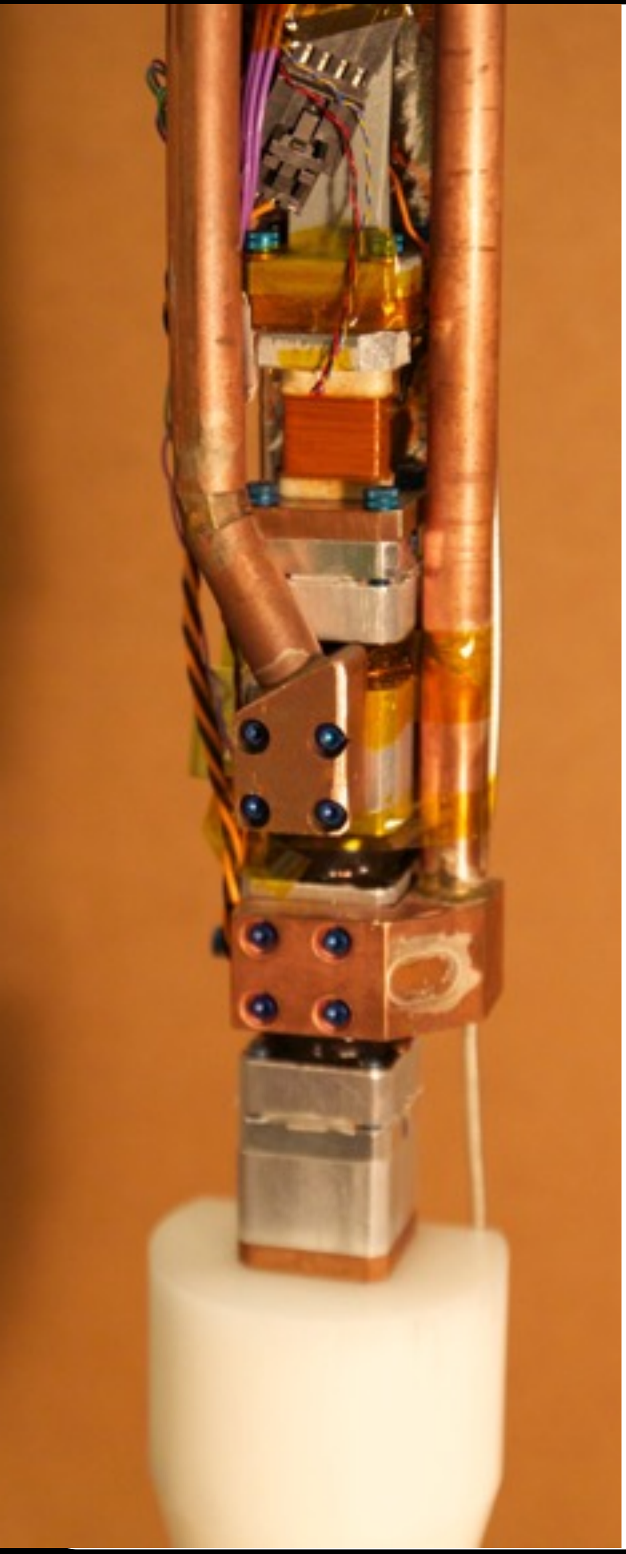
Test signal injection port





Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

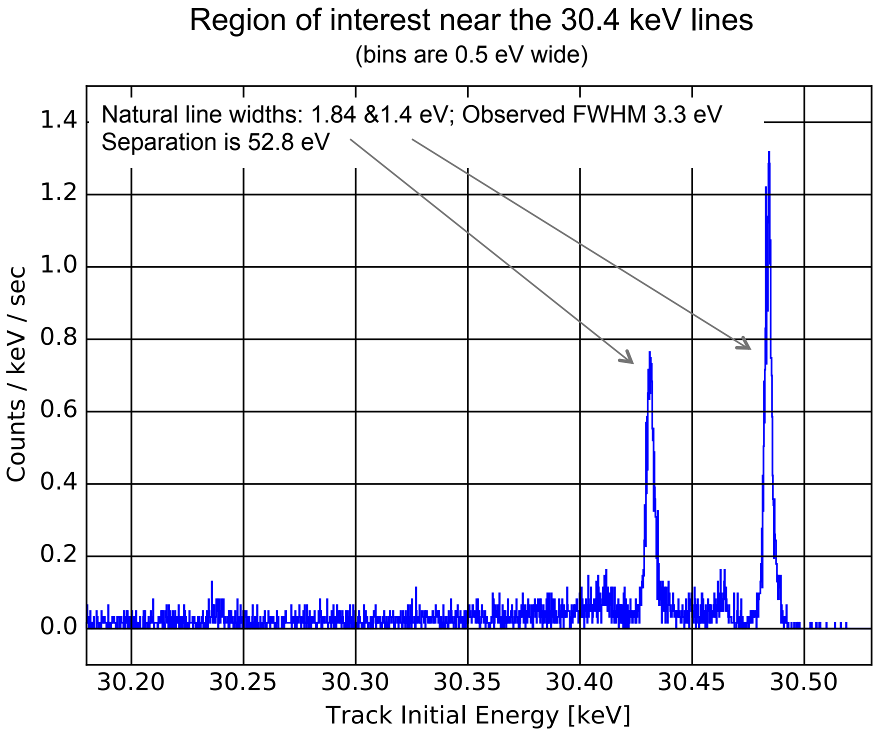
Magnetic bottle allows for trapping of electron within cell for measurement.

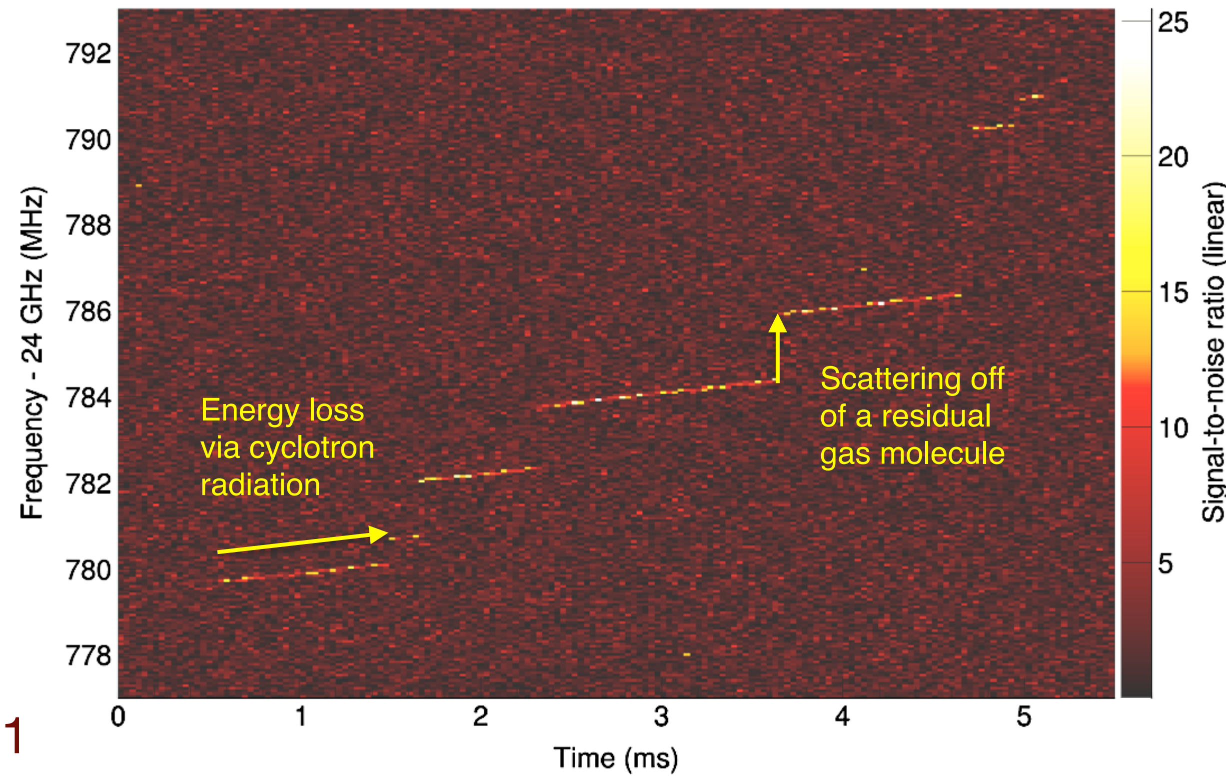


Phase I

Demonstration: ^{83m}Kr

- CRES technique demonstrated through imaging 90 17 and 30 keV Kr lines.
- Energy resolution of 3.3 eV (FWHM) achieved.
- Additional features (sidebands) also measured.





Phys. Rev. Lett. 114 (2015) 16, 162501

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

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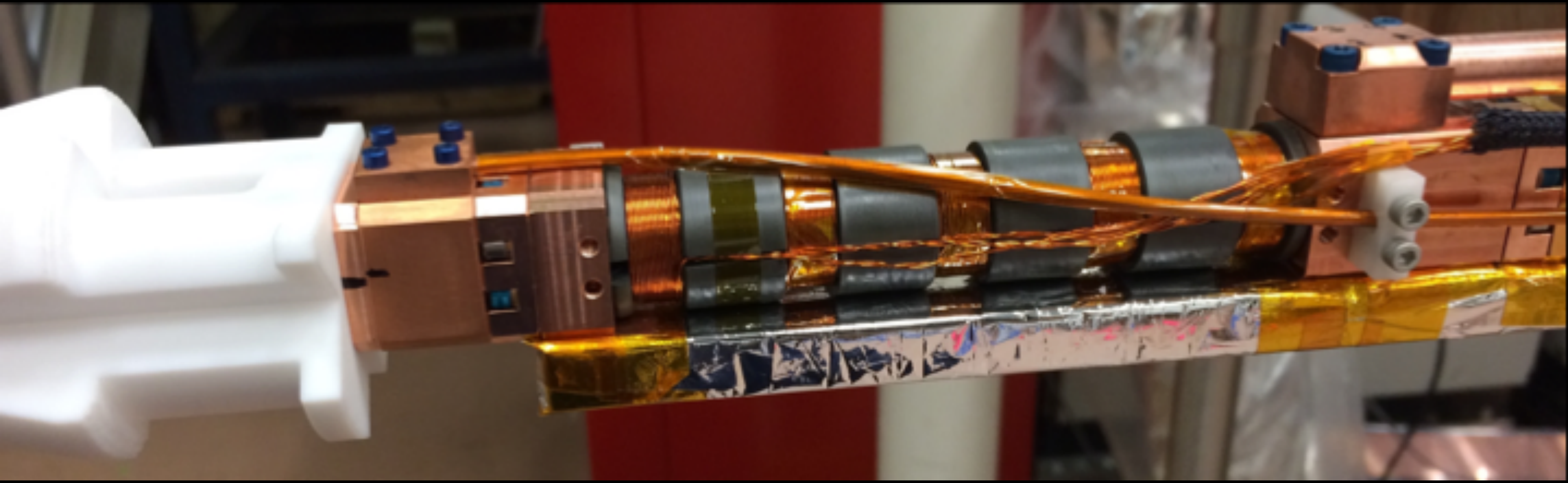
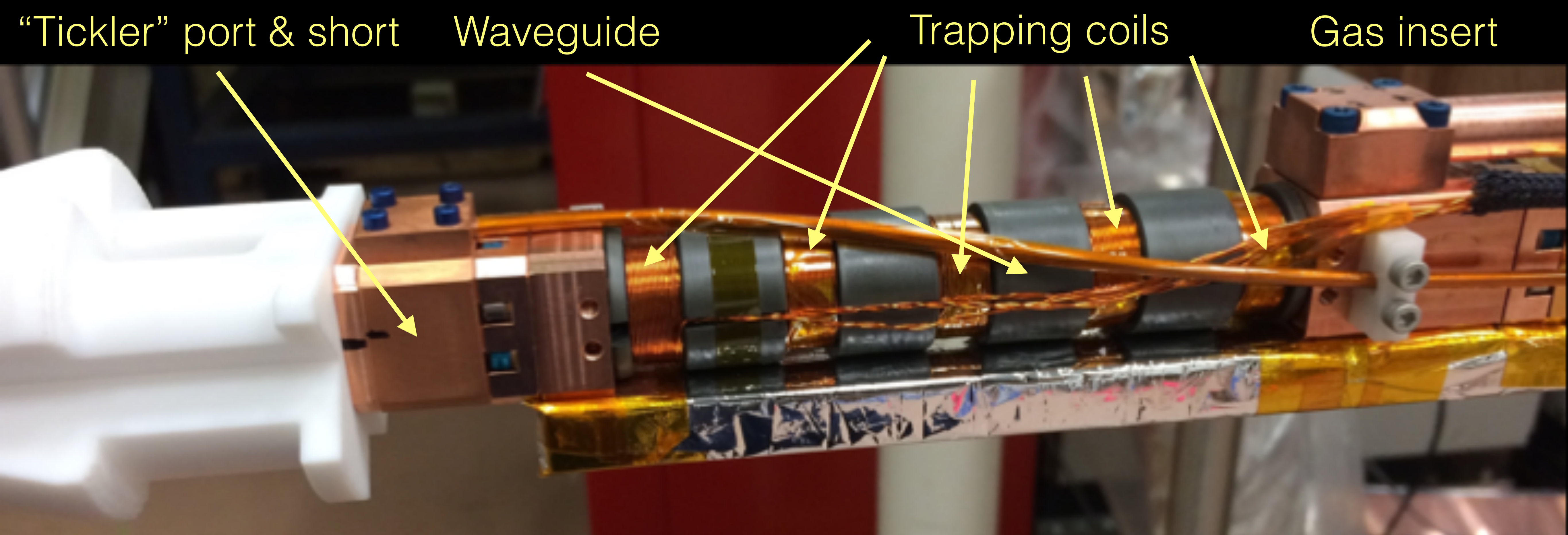
Phase II: Tritium & Kr Cell



- Next stage will incorporate tritium with Kr as co-magnetometer.
- New 5-coil circular waveguide constructed, already in operation.
- Inject tritium through getter heating. Initial tests with deuterium show good control of pressures.
- Aiming to inject first tritium this summer!

Phase II: Tritium & Kr Cell



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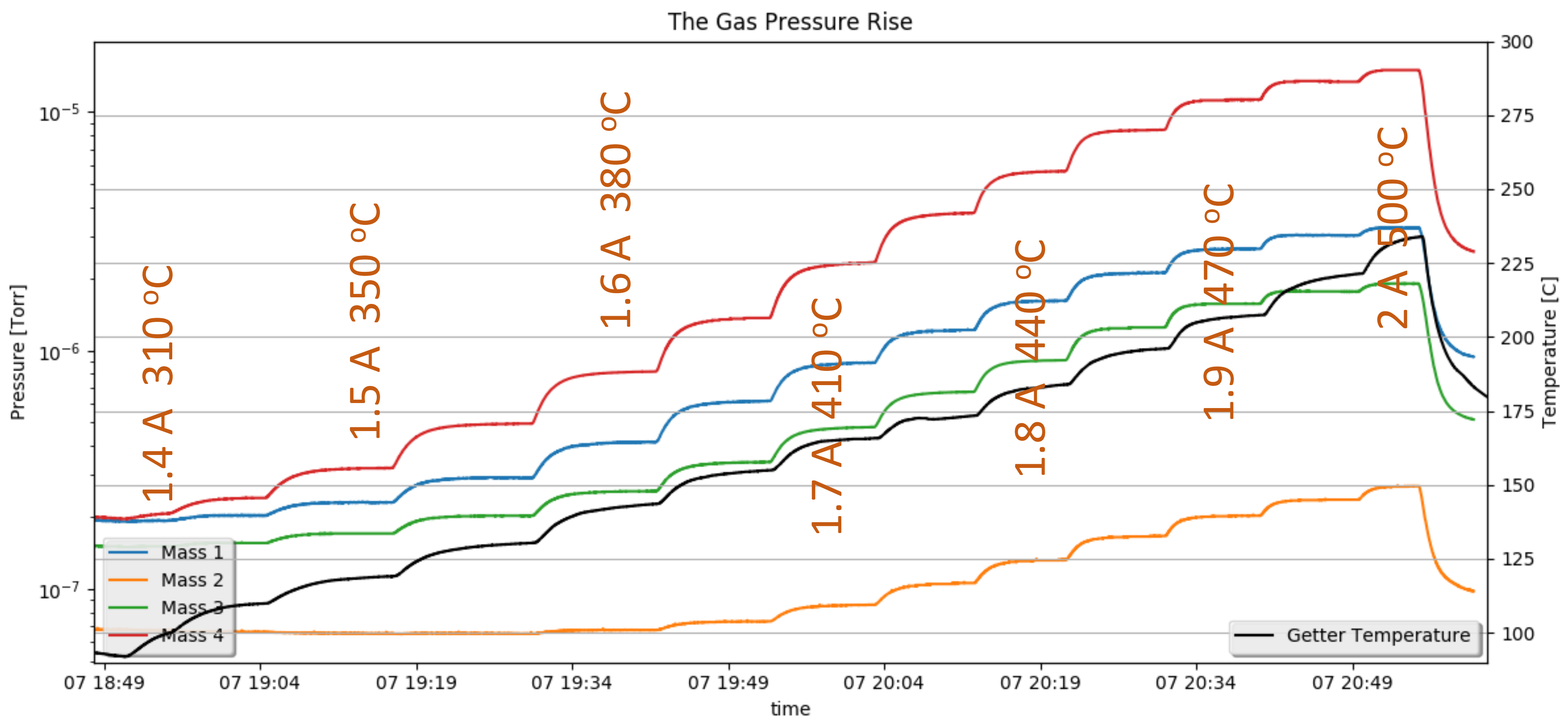

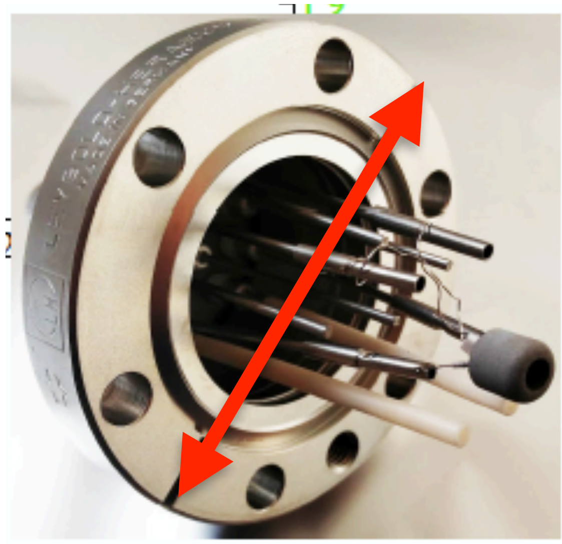

M. Walter, T. Thümmler

Pressure test with deuterium load.

- Next stage will incorporate tritium with Kr as co-magnetometer.
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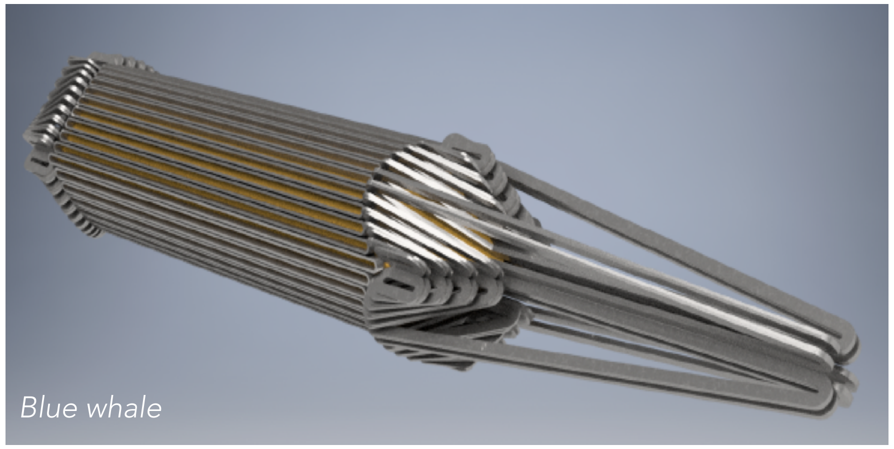
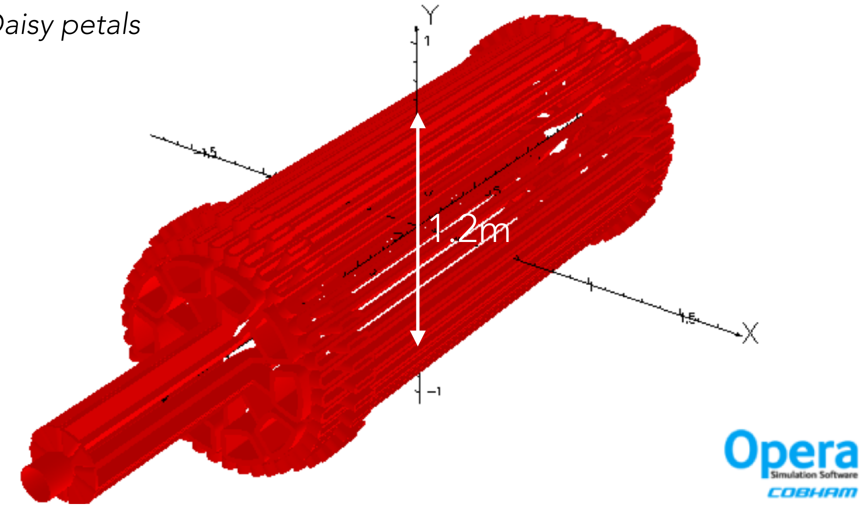
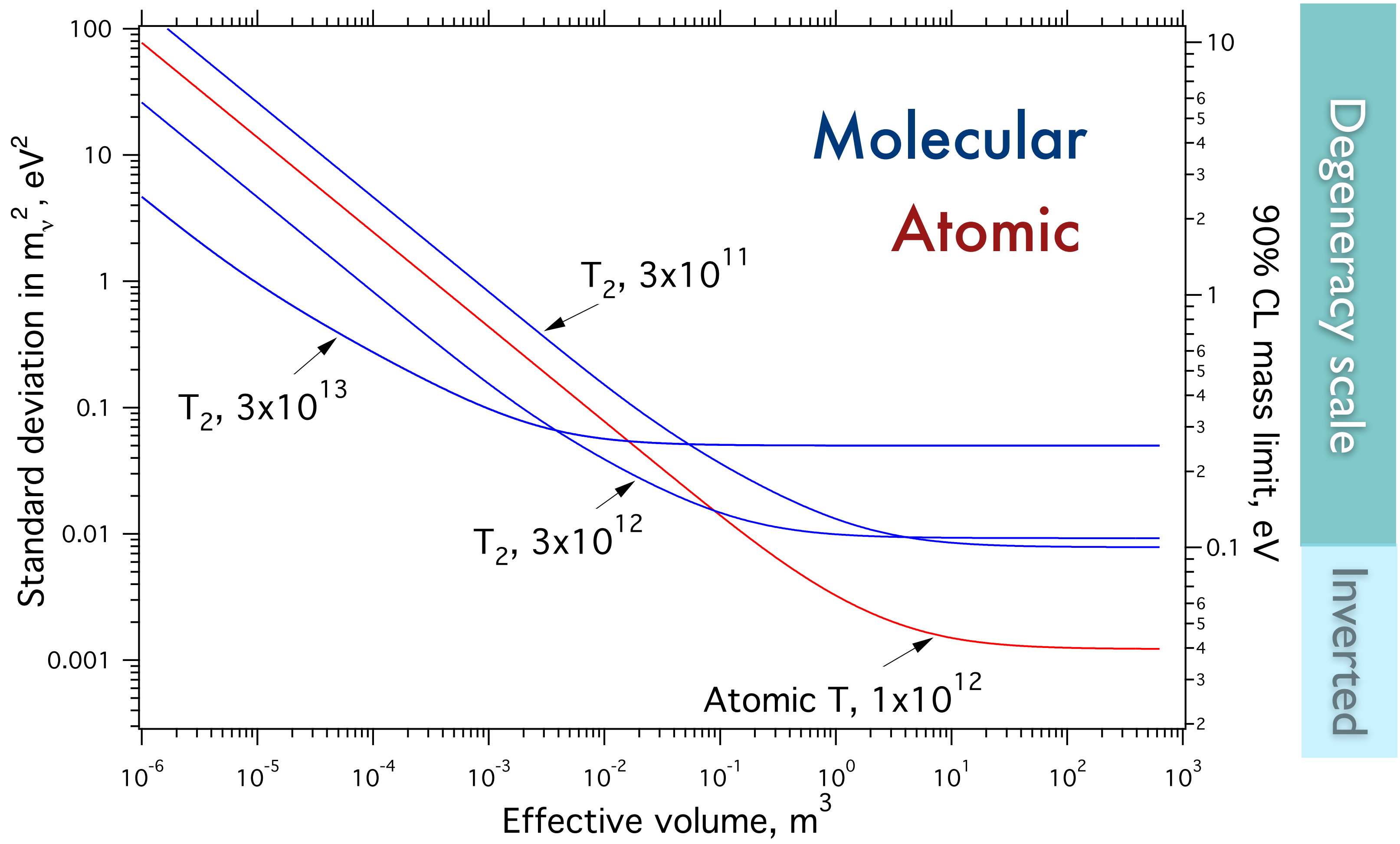
Looking forward

Phase IV: Atomic Tritium



Daisy petals



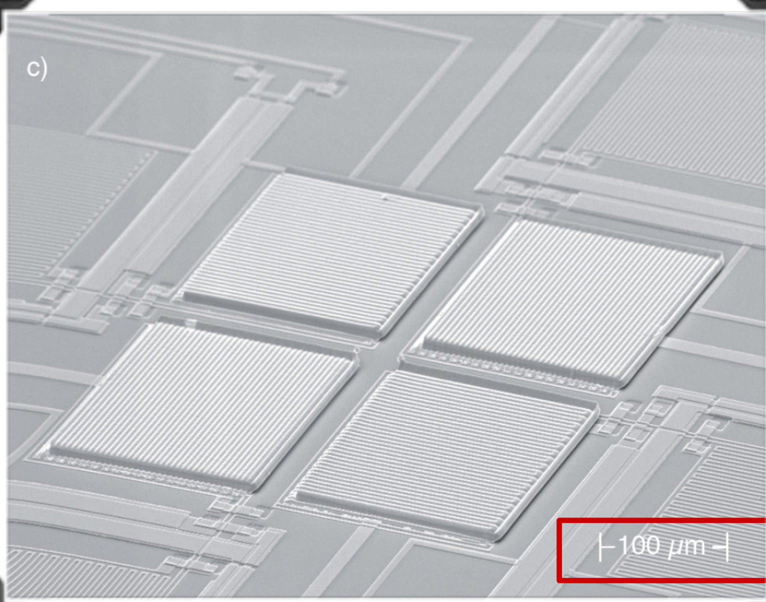


Preliminary designs for Ioffe trapping coils for tritium containment (under study).

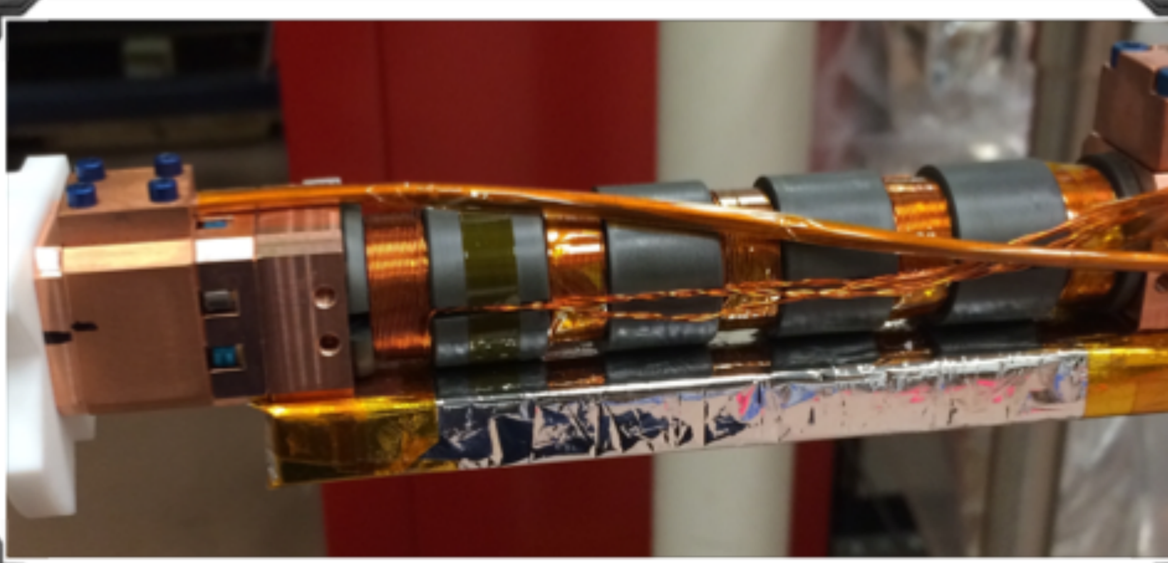
- While scalability is being tested, collaboration aims to switch from molecular tritium to atomic tritium.
- Take advantages of magnetic trapping to confine cold T and cleanly separate from T_2 contamination.

Fermi's original challenge seems to emerge on the horizon…

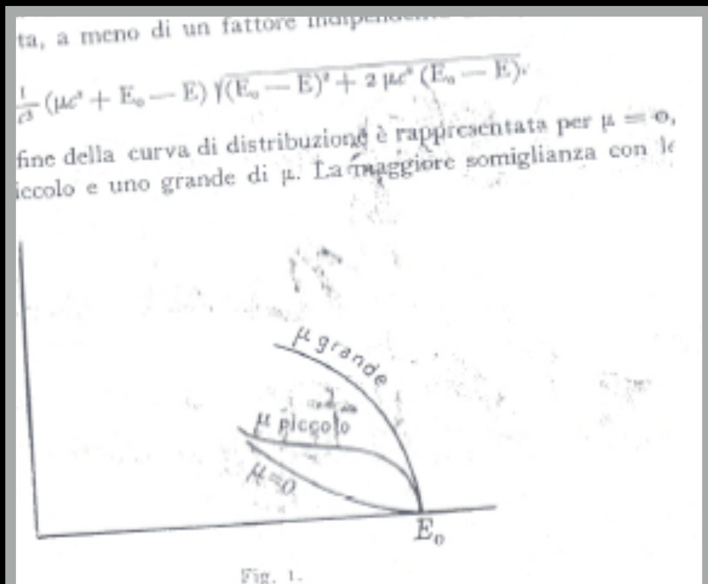
KATRIN is poised to commence tritium data taking. Improved limits (or discovery!) coming soon (first tritium 2018).

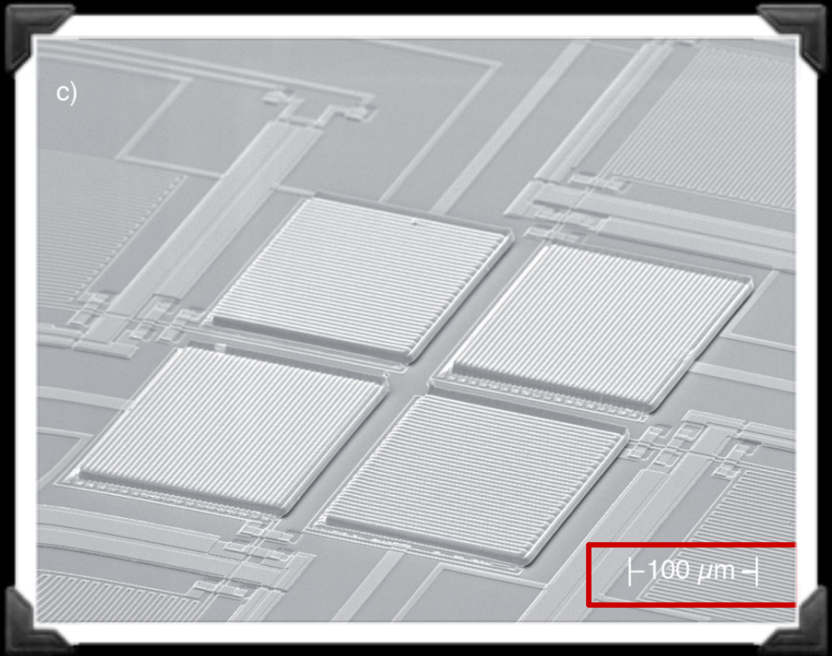


ECHO, HOLMES and NuMECS currently aim at the eV scale are being constructed, with sub-eV in their sights (eV scale next 3-5 yrs).

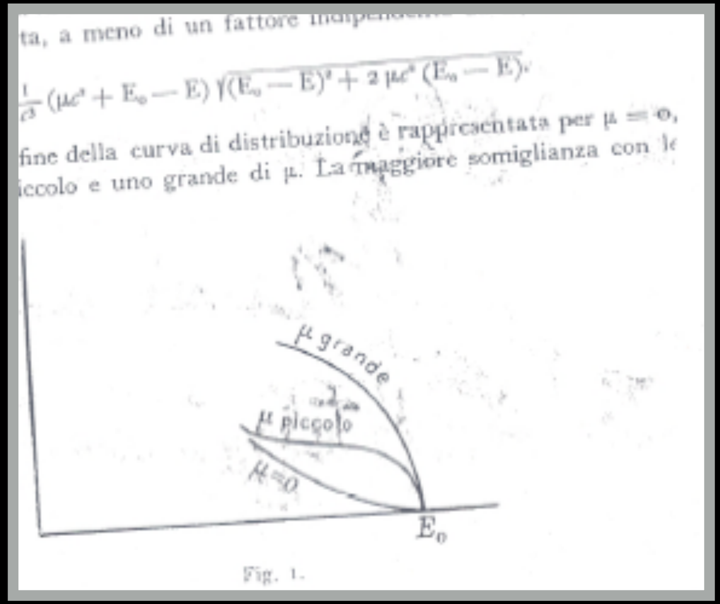


Project 8 advances forward, with cross-hairs focuses at the inverted scale (2 eV by 2020).





Thank you for your attention



Recent papers of interest related to this talk:

HOLMES: arXiv:1612.03947v3

SHIPTRAP: arXiv:1604.04210v1

ECHO: J Low Temp Phys (2016) 184:910-921

Project 8: J. Phys. G 101588 (2016).