Frequency-based decay electron spectroscopy to probe the neutrino mass scale and chirality-flipping interactions

Martin Fertl

Physics of Fundamental Symmetries and Interactions 2016

UNIVERSITY *of* WASHINGTON

Outline

- Neutrino mass
- The tritium endpoint measurement scheme
- Project 8: A frequency based neutrino mass measurement
- ^{6}He decay: CRES using highly relativistic electrons!?
- Summary

Non-zero, but small neutrino masses

From oscillation experiments:

normal hierarchy inverted hierarchy

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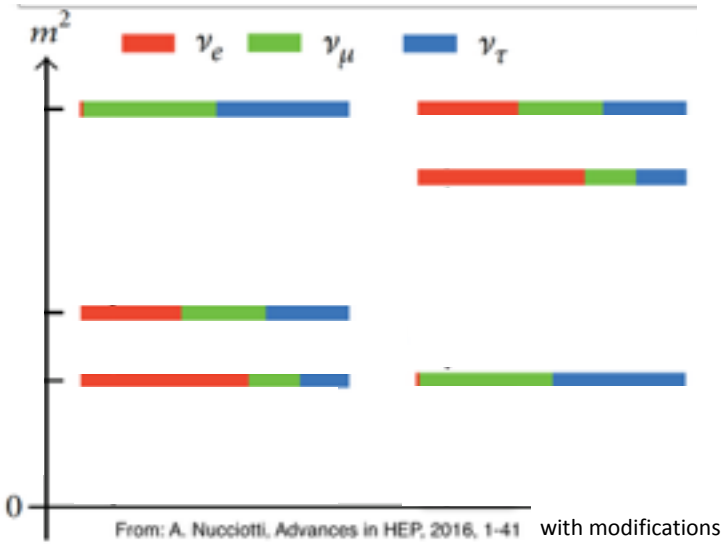

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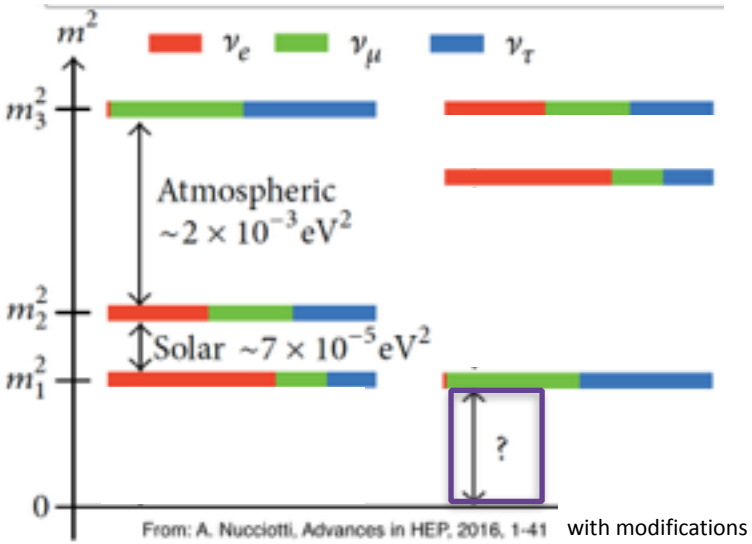

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LARGE mixing angles

TINY mass differences

NH or IH? ⟶ G. Brunetti, Tue 4:20 pm

No absolute mass scale sensitivity!

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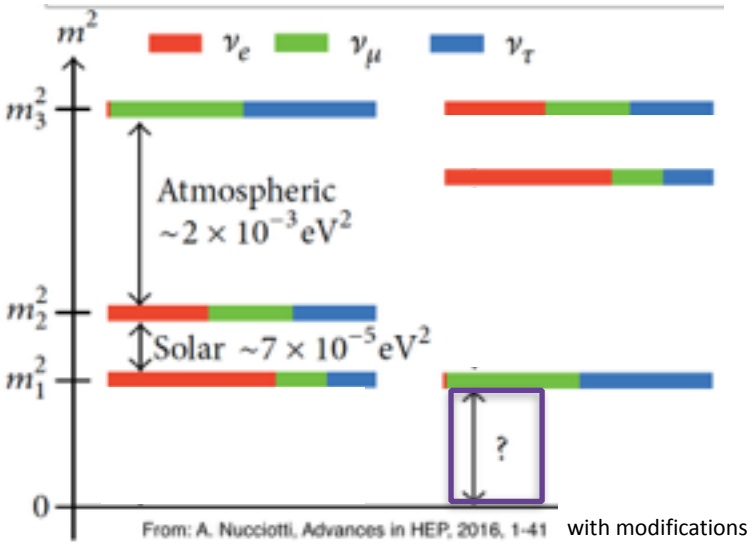

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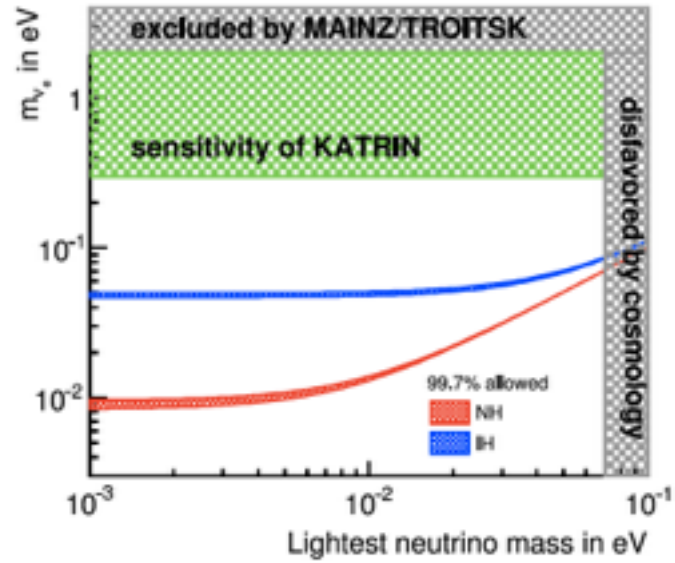

Qian and Vogel, Progress in Particle And Nuclear Physics 83 (2015), 1-30

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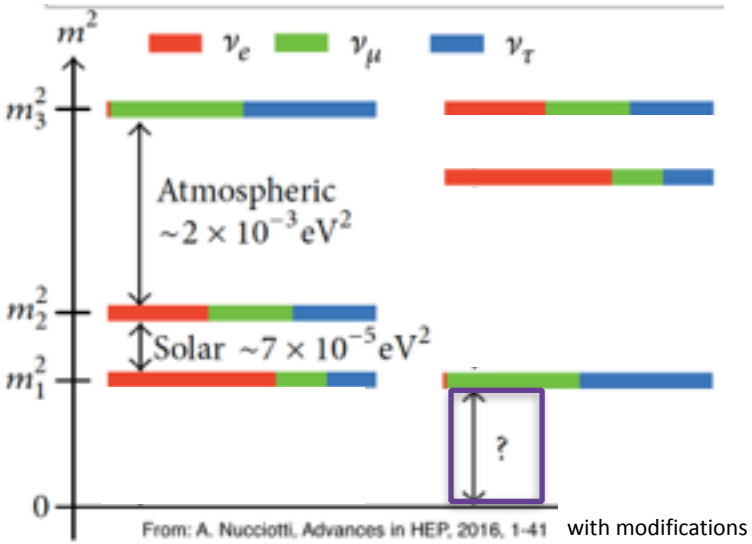

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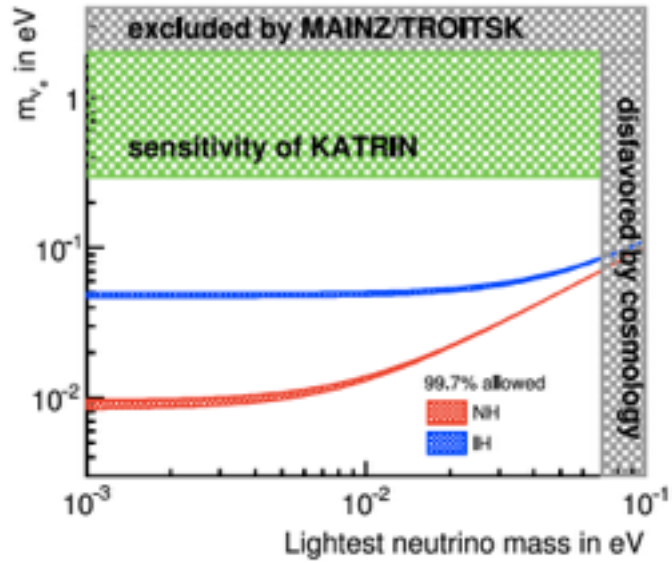

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KATRIN exp. probes degenerate mass region!

Now disfavored by cosmology.

Direct limits $m(\nu_e) < 2\,\mathrm{eV}/c^2$

Goal: Probe the complete IH allowed region!

The β^--spectrum of tritium decay

PHYSIQUE NUCLÉAIRE. — *Possibilité d'émission de particules neutres de masse intrinsèque nulle dans les radioactivités β.* Note de M. FRANCIS PERRIN, présentée par M. Jean Perrin.

SÉANCE DU 18 DÉCEMBRE 1933.

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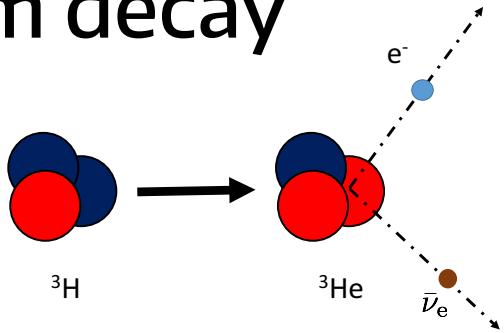

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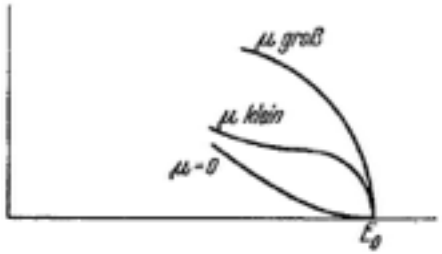

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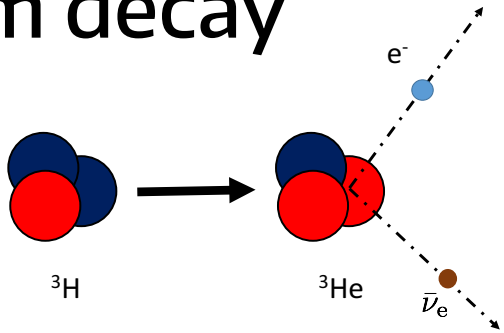

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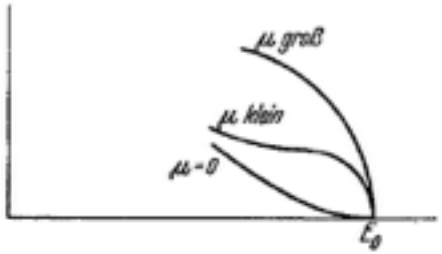

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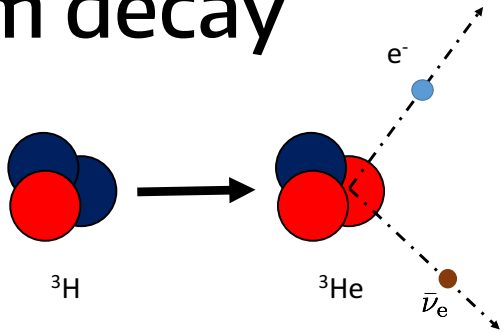

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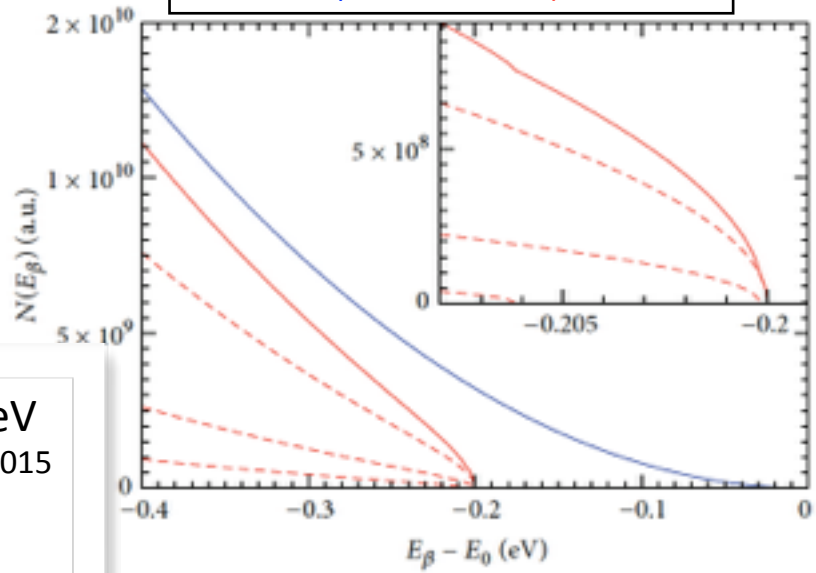
For T: m_β=0.0 eV m_β=0.2 eV



Nucciotti, Advances in High Energy Physics, Vol. 2016, 9153024

Q (T_A) = 18.59201(7) keV

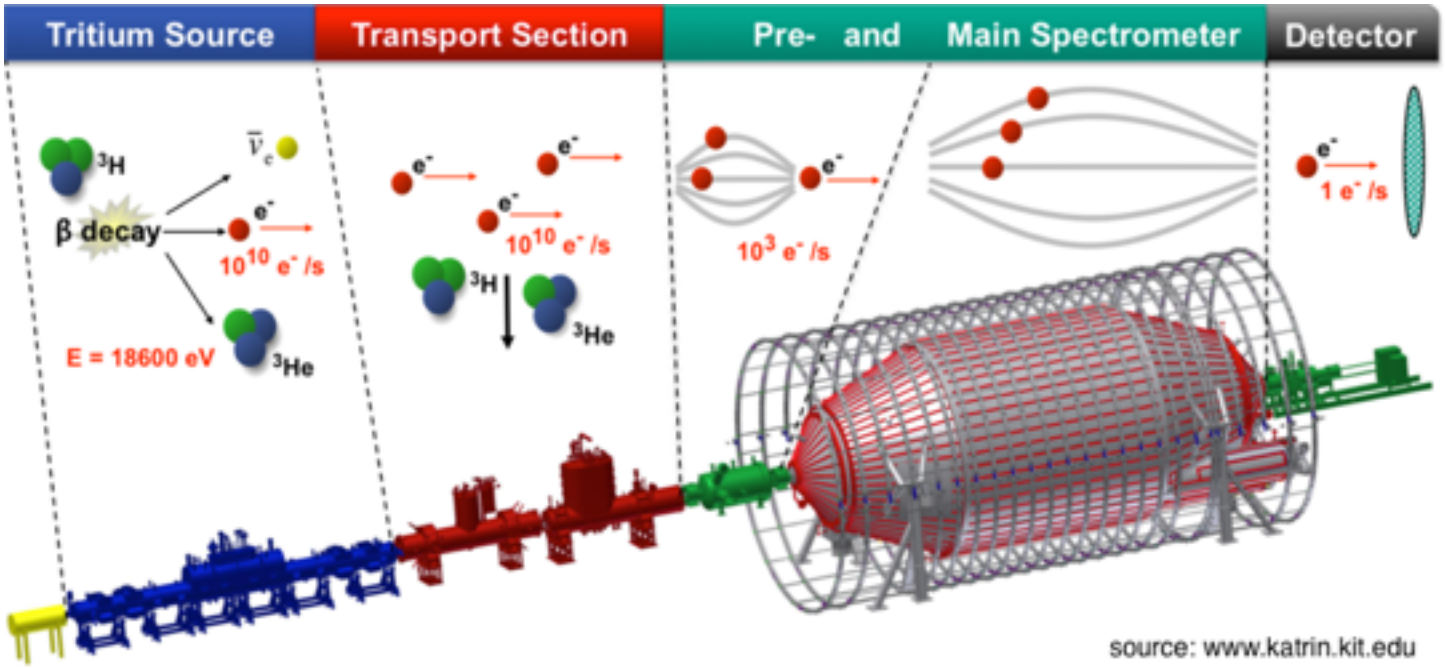
Myers et al, PRL 114, 013033, 2015

$T_{1/2}$ = 12.32 y

BR (1eV) = 2 x 10^{-13}

The current state of the art: MAC-E Filter

KATRIN: The largest MAC-E filter ever built pushes all boundaries to the extremes!



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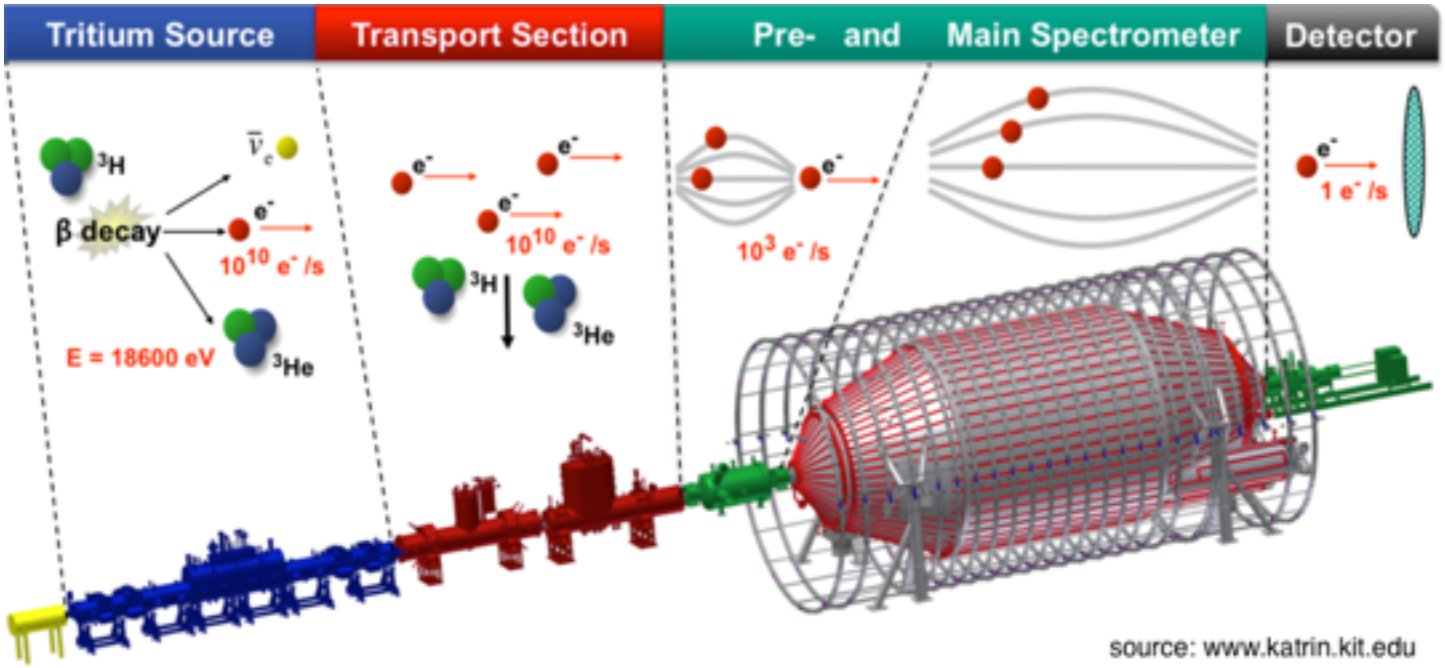

source: www.katrin.kit.edu

Highest statistics

Window less gaseous T_2 source (10^{11} Bq)

Column density limited

Tritium handling

T_2 suppression by more than 10^{14} !

Main spectrometer

Largest UHV tank ever built (1500 m^3, 10^{-11} mbar)!

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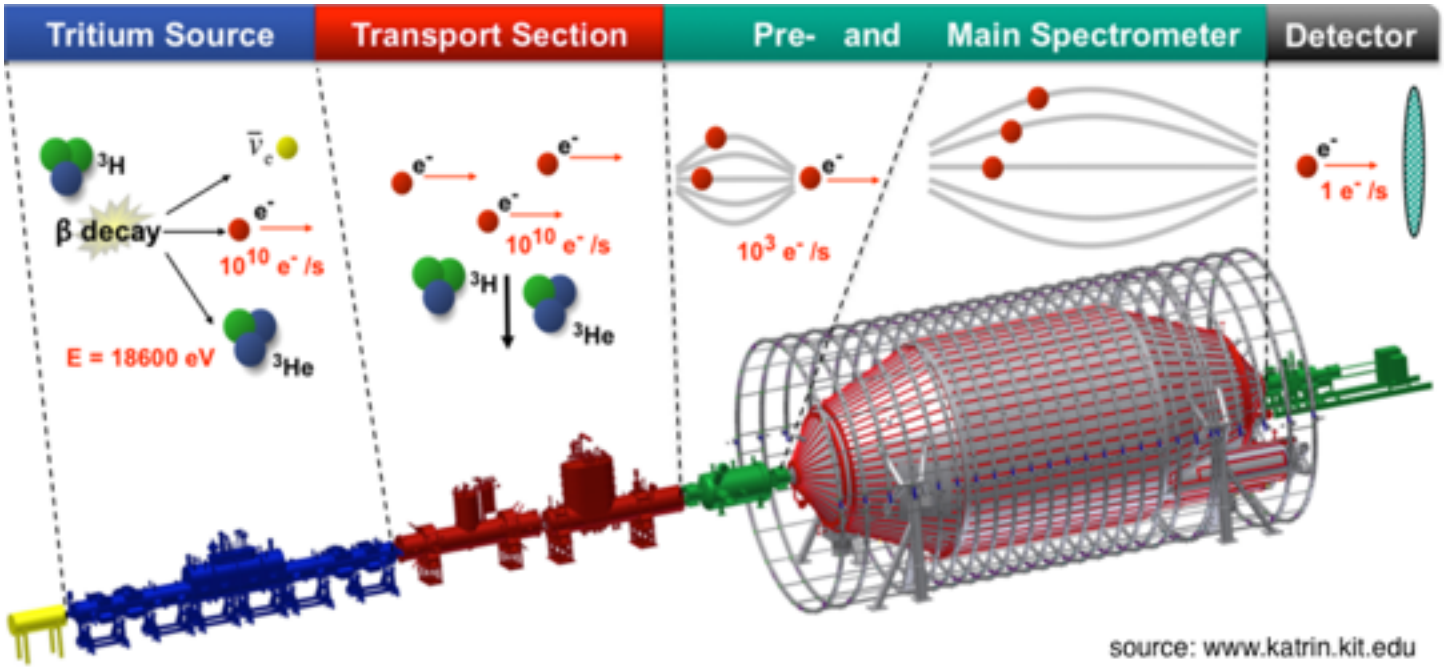

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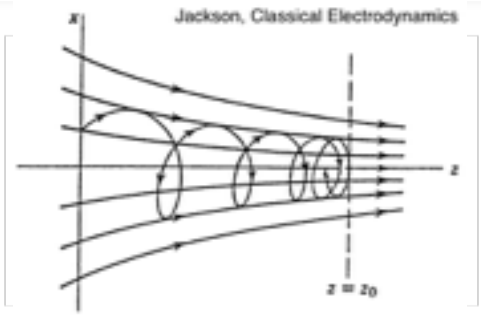

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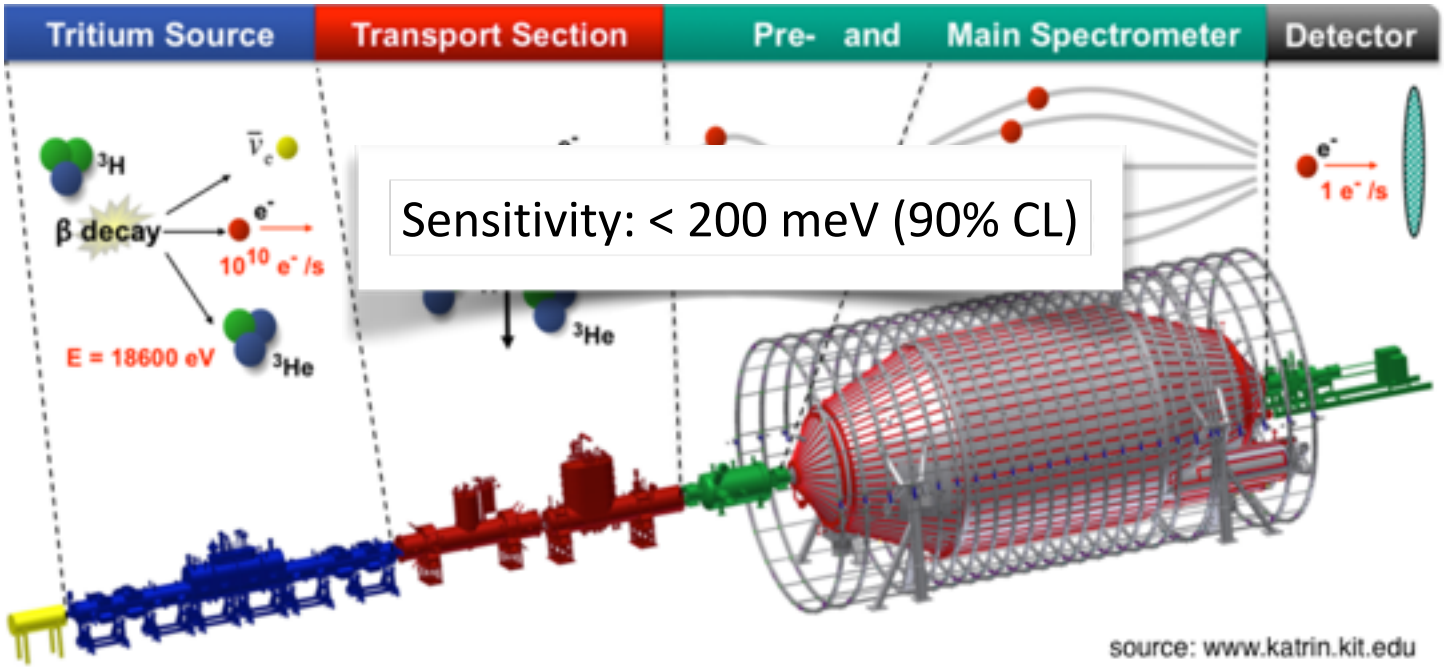

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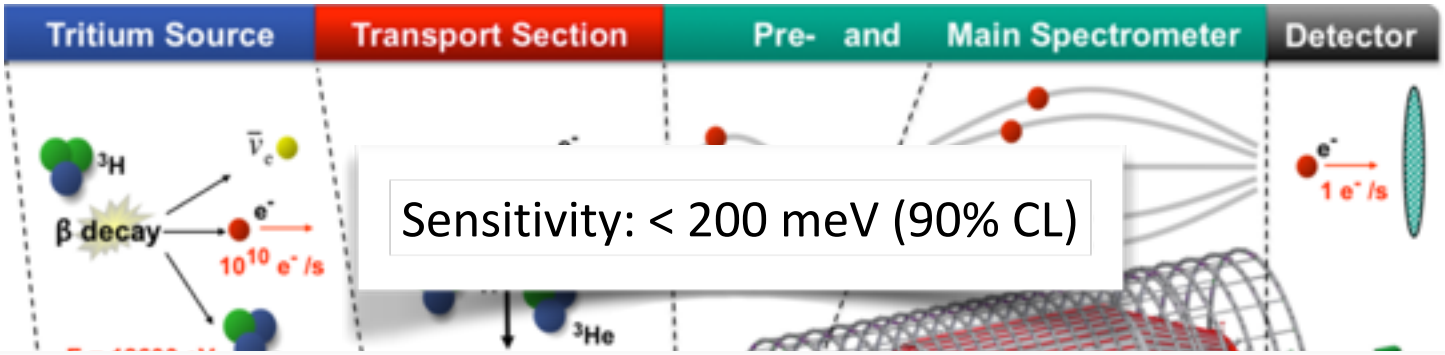

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First light on 10/14/2016! Tritium operation starts in 2017!

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New techniques and isotopes beyond KATRIN

MAC-E resolution scales with $B_{min} \propto$ area

Irreducible final state distribution in $^3HeT^+$

Electron transport: source ≠detector

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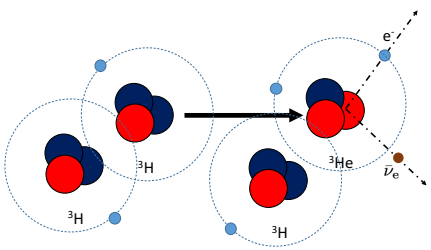
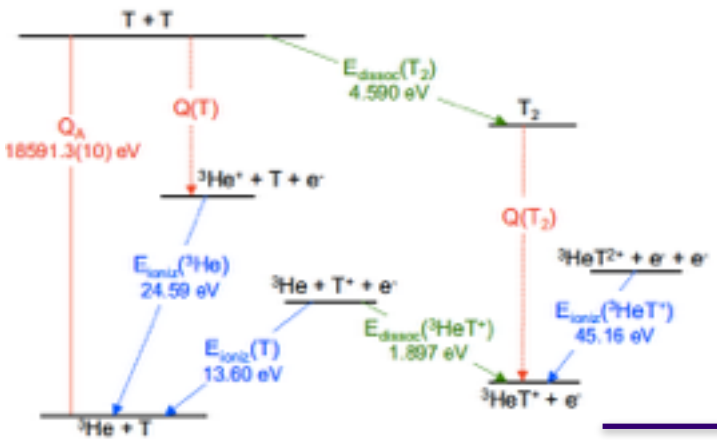
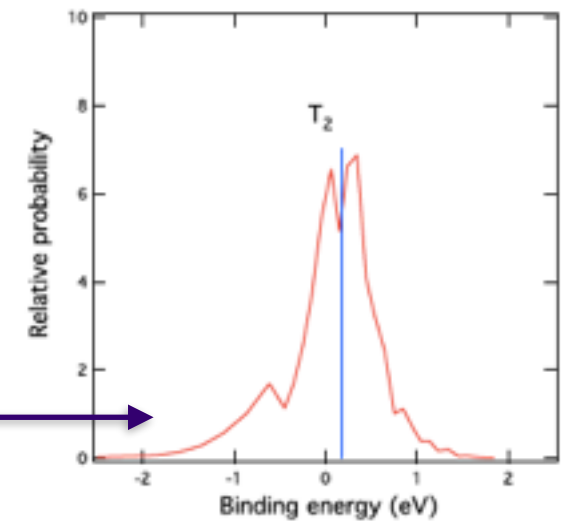




Bodine et al, PRC 91, 035505 (2015)



New techniques and isotopes beyond KATRIN

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ECHo HOLMES

NuMECS

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K. Blaum, Tue 11:00 AM
A. Rischka and R. Schüssler, Tue 5:40 PM

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NuMECS

Tritium

Project 8: Cyclotron radiation emission spectroscopy with (atomic) tritium

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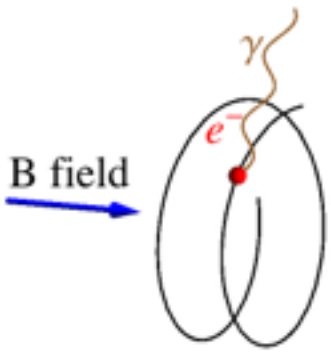
PROJECT 8

"Never measure anything but frequency"
A. Schawlow

Cyclotron radiation emission spectroscopy



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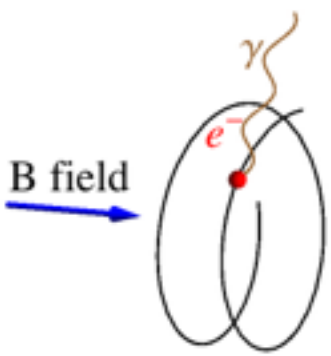

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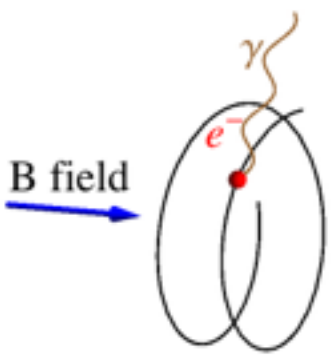

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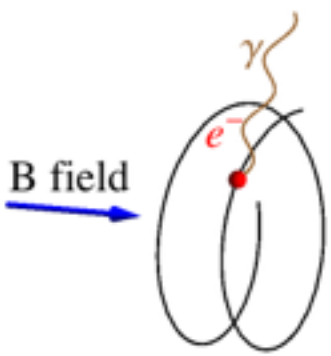

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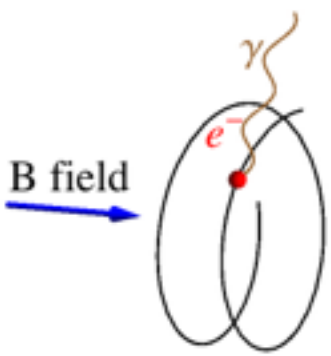

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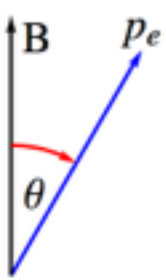

$$P\left(E_{kin}, m, \theta\right) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m^4 c^5} B^2 \left(E_{kin}^2 + 2\,E_{kin}\,m\,c^2\right)\sin^2\theta$$

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

Small but readily detectable with state of the art detectors

Frequency and energy resolution of CRES

Energy vs. frequency resolution:

$$\frac{\Delta E_{\mathrm{kin}}}{E_{\mathrm{kin}}} = \left(1 + \frac{m_{\mathrm{e}}c^2}{E_{\mathrm{kin}}}\right)\frac{\Delta\nu_{\mathrm{c}}}{\nu_{\mathrm{c}}}$$

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$$\nu_{\mathrm{c}} \approx 27\,\mathrm{GHz} \rightarrow \Delta \nu_{\mathrm{c}} \approx 11\,\mathrm{kHz}$$

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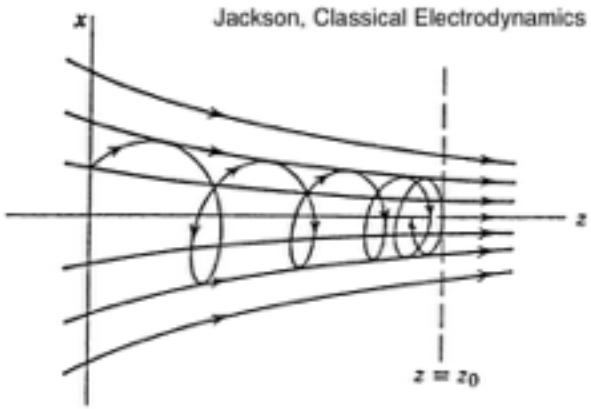
$\beta t_{\mathrm{obs}} \cos\theta \approx 20\,\mathrm{m}$ for a 18.6 keV electron and 89° pitch angle

Frequency and energy resolution of CRES



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$$\Delta \nu_{\mathrm{c}} \times t_{\mathrm{obs}} \geq \frac{1}{2\pi} \rightarrow t_{\mathrm{obs}} \geq 14\,\mu\mathrm{s}$$

$$\beta t_{\mathrm{obs}} \cos\theta \approx 20\,\mathrm{m}$$

for a 18.6 keV electron and 89° pitch angle

Frequency and energy resolution of CRES

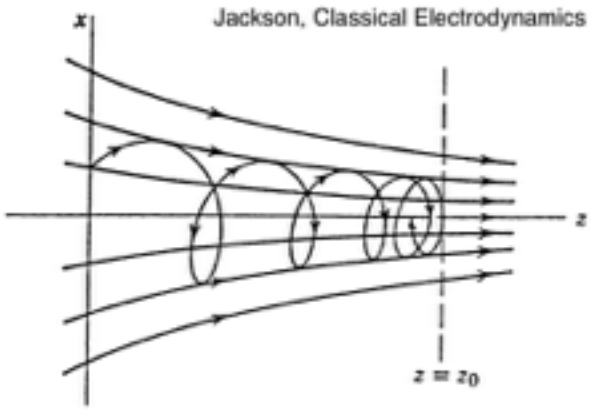
Energy vs. frequency resolution:

$$\frac{\Delta E_{\mathrm{kin}}}{E_{\mathrm{kin}}} = \boxed{\left(1 + \frac{m_{\mathrm{e}}c^2}{E_{\mathrm{kin}}}\right)} \frac{\Delta \nu_{\mathrm{c}}}{\nu_{\mathrm{c}}}$$

≈ 28 for e⁻ at T_2 endpoint 18.6 keV

$$\Delta E_{\mathrm{kin}} \approx 0.2\,\mathrm{eV} \rightarrow \frac{\Delta \nu_{\mathrm{c}}}{\nu_{\mathrm{c}}} \approx 4 \times 10^{-7}$$

$$\nu_{\mathrm{c}} \approx 27\,\mathrm{GHz} \rightarrow \Delta \nu_{\mathrm{c}} \approx 11\,\mathrm{kHz}$$



P8 typical: $\sin\theta_{\mathrm{min}} = \sqrt{\frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}} \rightarrow 85°$

Frequency resolution vs. observation time:

$$\Delta \nu_{\mathrm{c}} \times t_{\mathrm{obs}} \geq \frac{1}{2\pi} \rightarrow t_{\mathrm{obs}} \geq 14\,\mu\mathrm{s}$$

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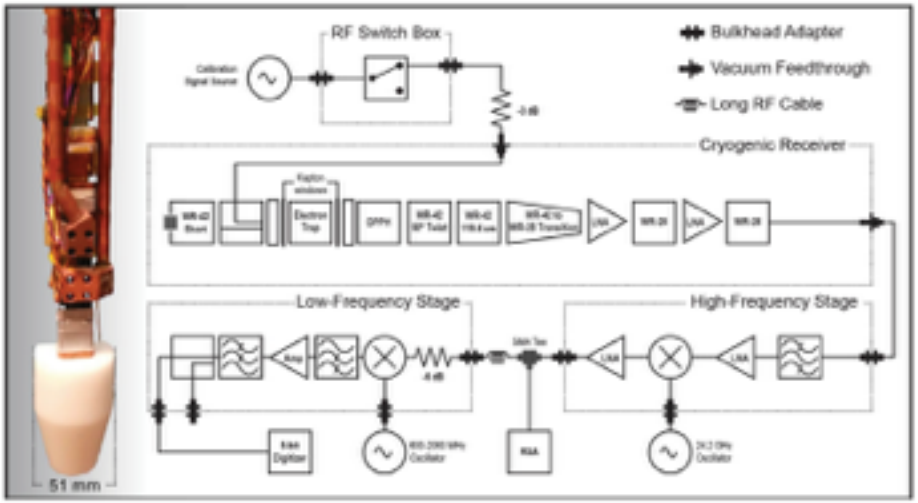
for a 18.6 keV electron and 89° pitch angle

harmonic trap

bath tub trap

Phase I setup and results



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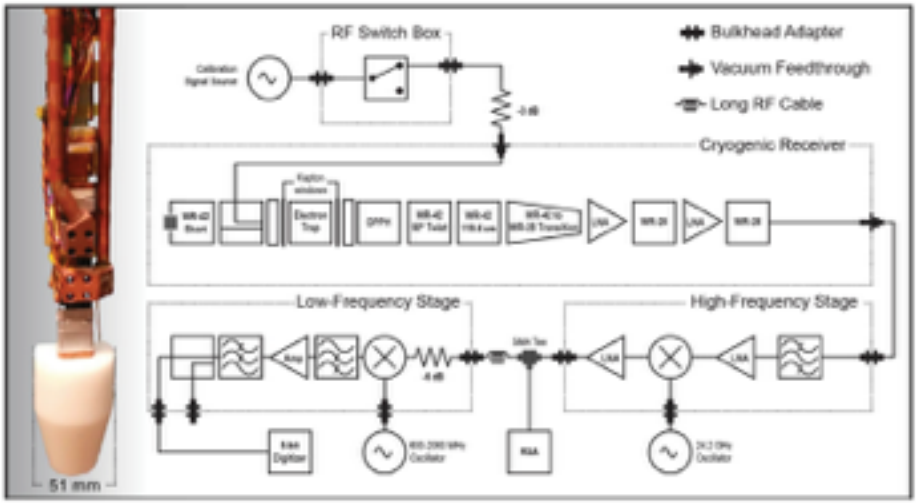
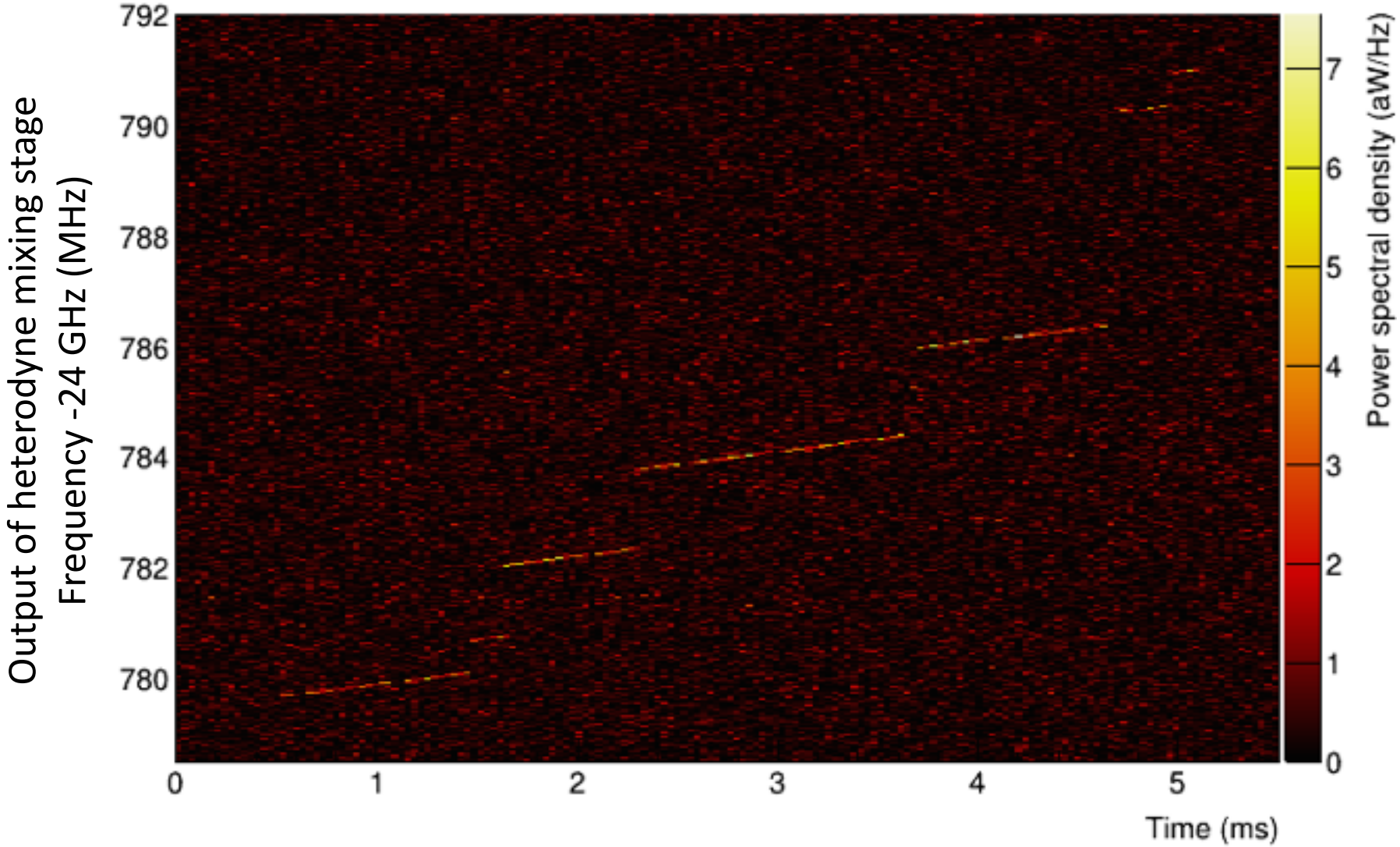


- Cryogenic waveguide cell and amplifiers
- RT heterodyne double mixing stage

Phase I setup and results



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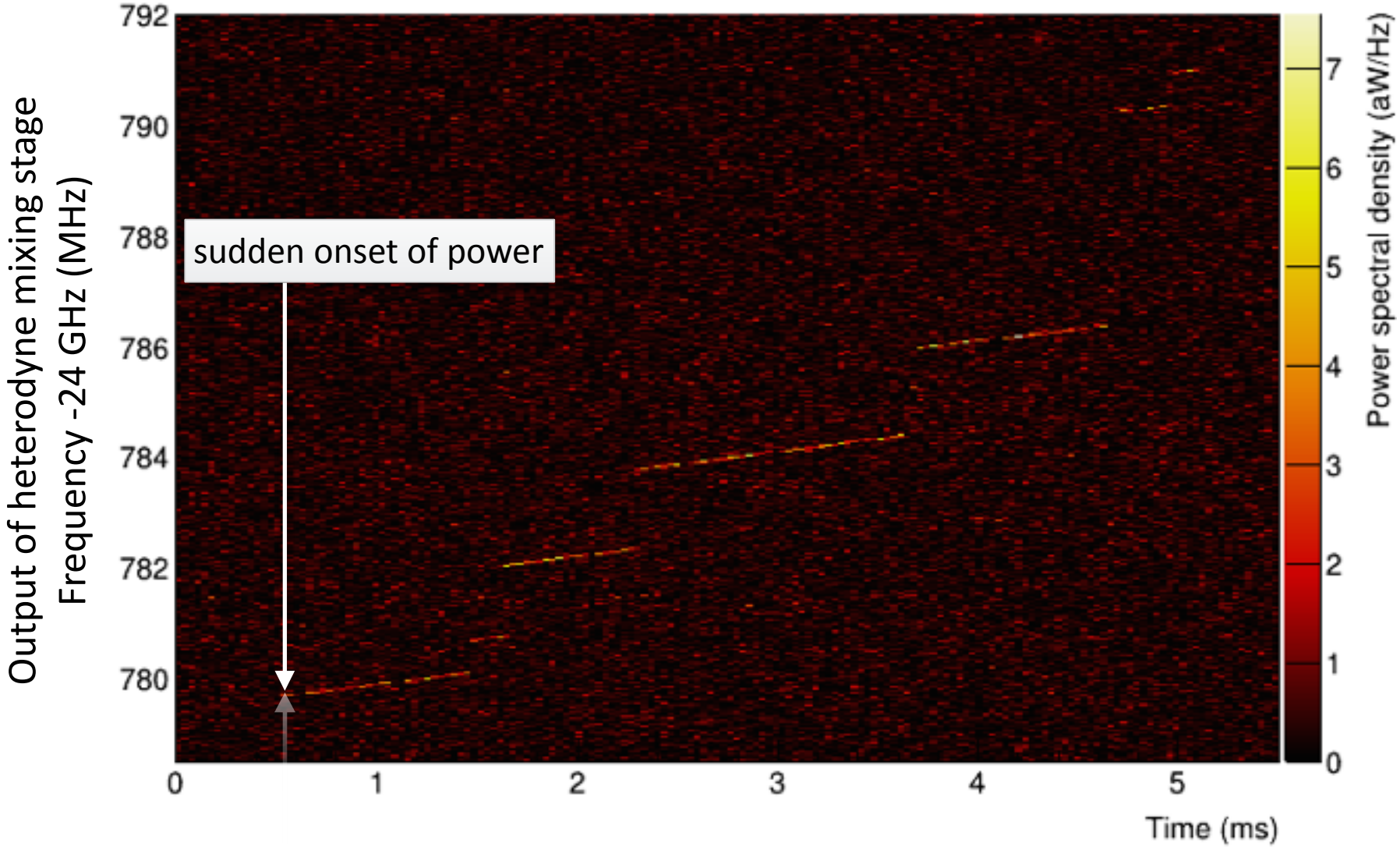

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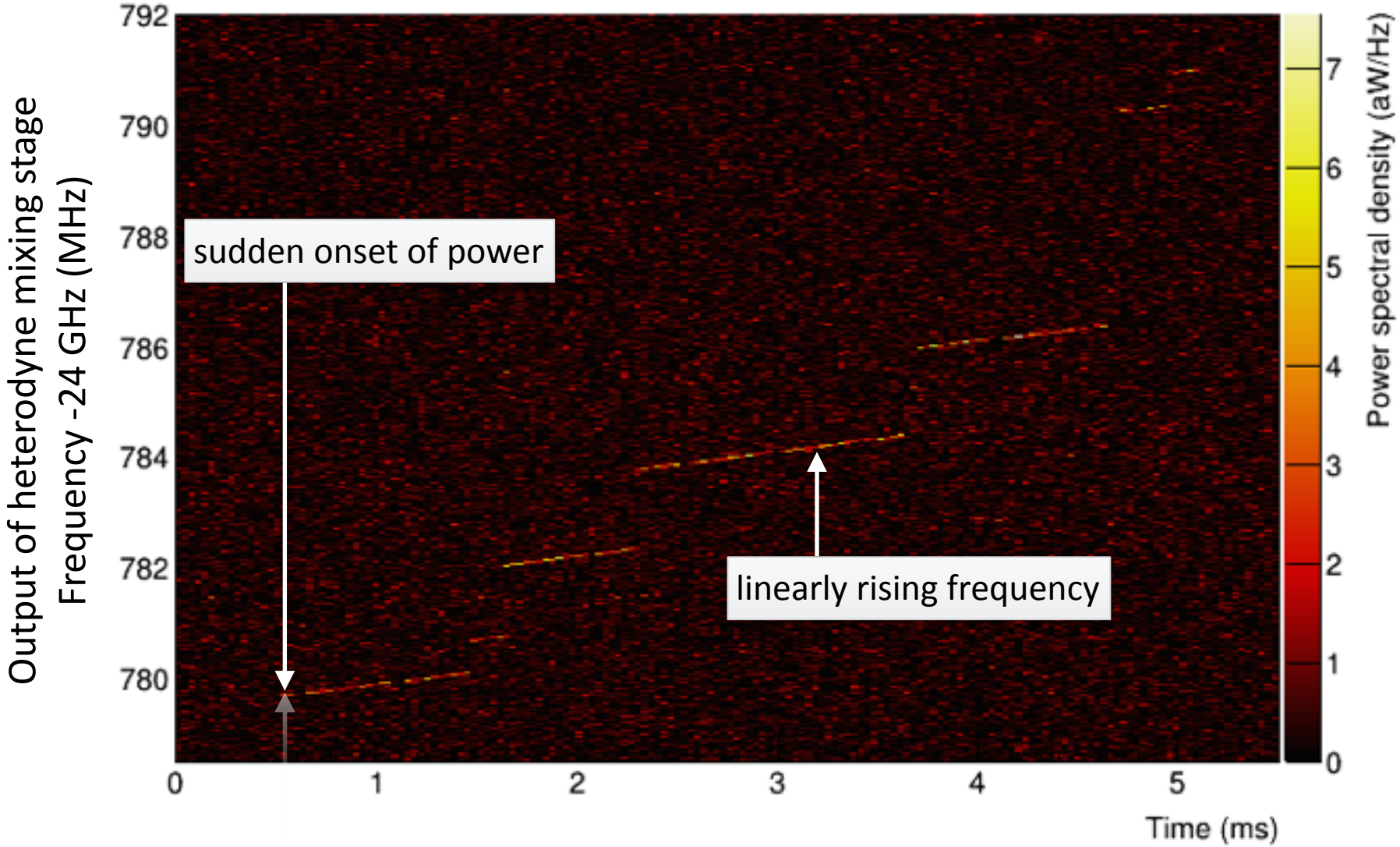

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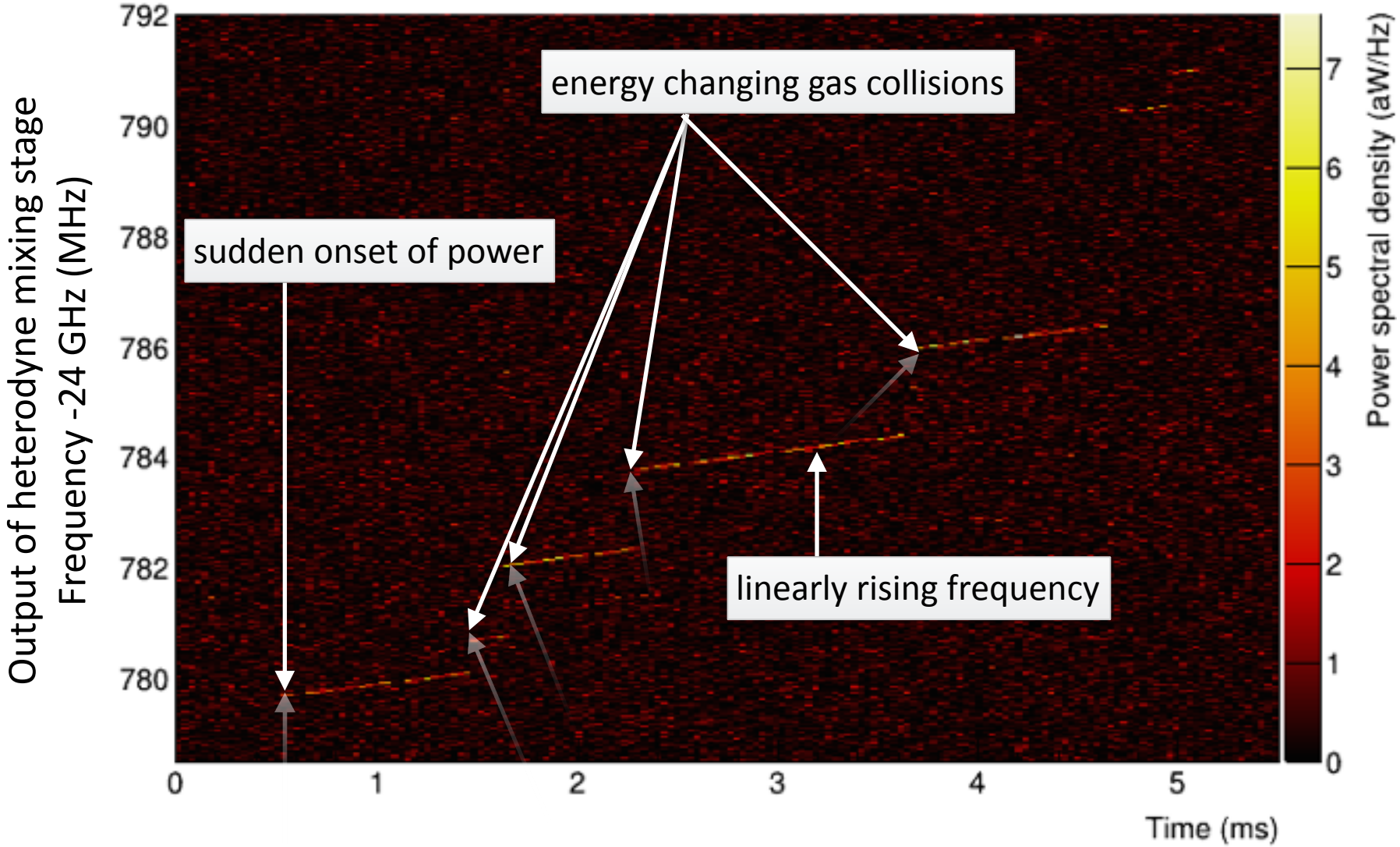

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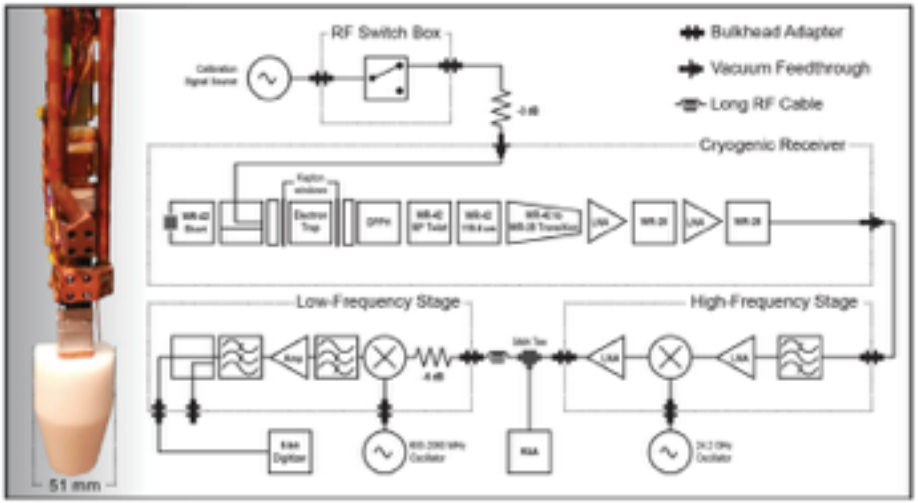
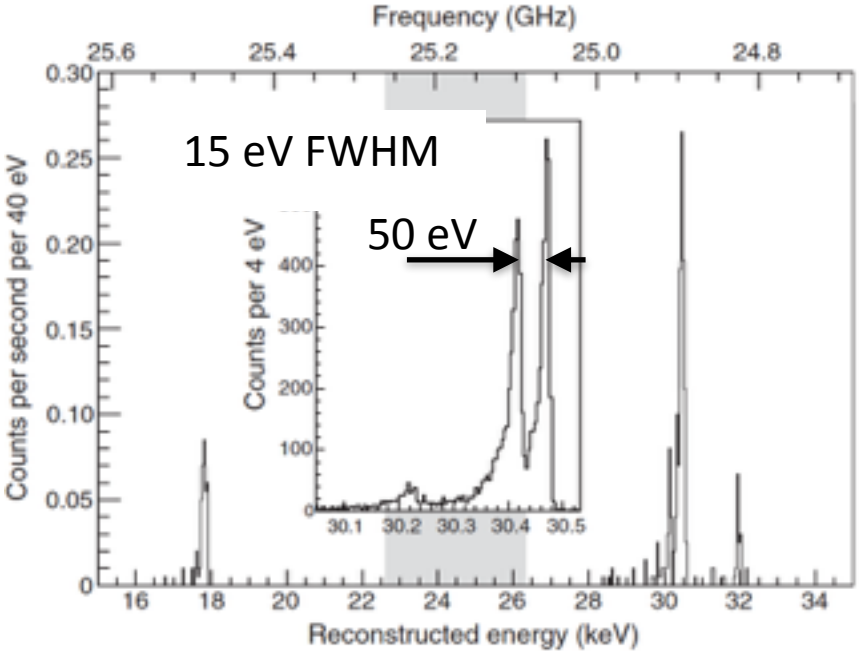
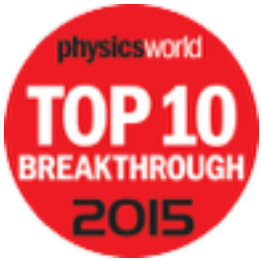




Asner et al., Physical Review Letters, 114, 162501 (2015)

- Cryogenic waveguide cell and amplifiers
- RT heterodyne double mixing stage
- Initial resolution: 15 eV in harmonic trap



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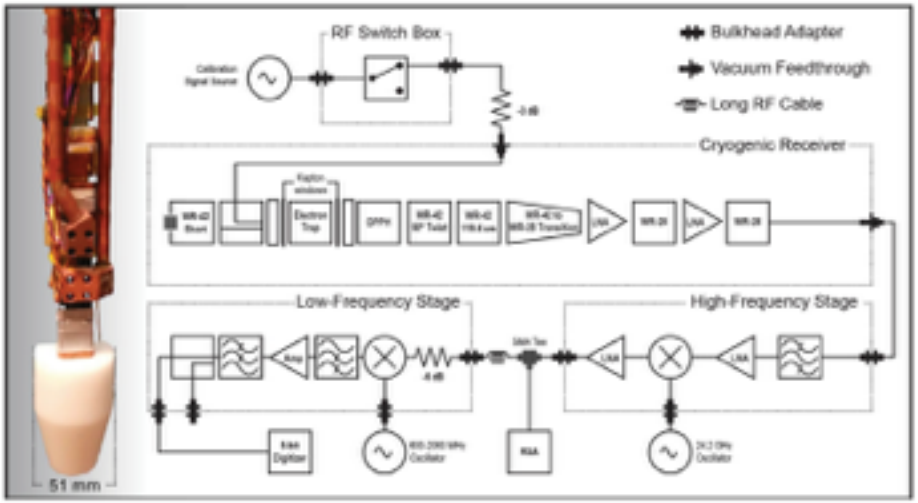

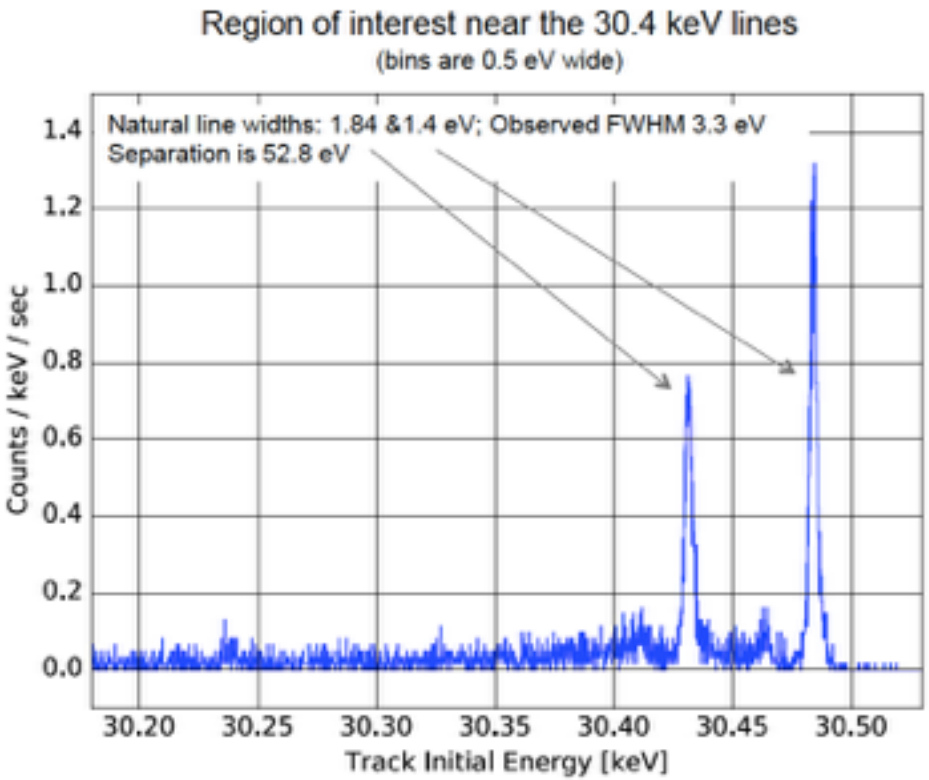

- Cryogenic waveguide cell and amplifiers
- RT heterodyne double mixing stage
- Initial resolution: 15 eV in harmonic trap
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physicsworld TOP 10 BREAKTHROUGH 2015

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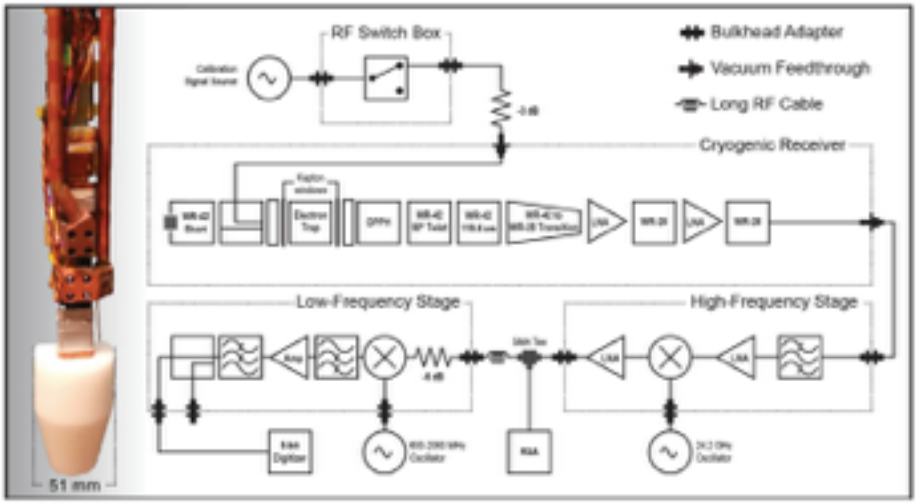

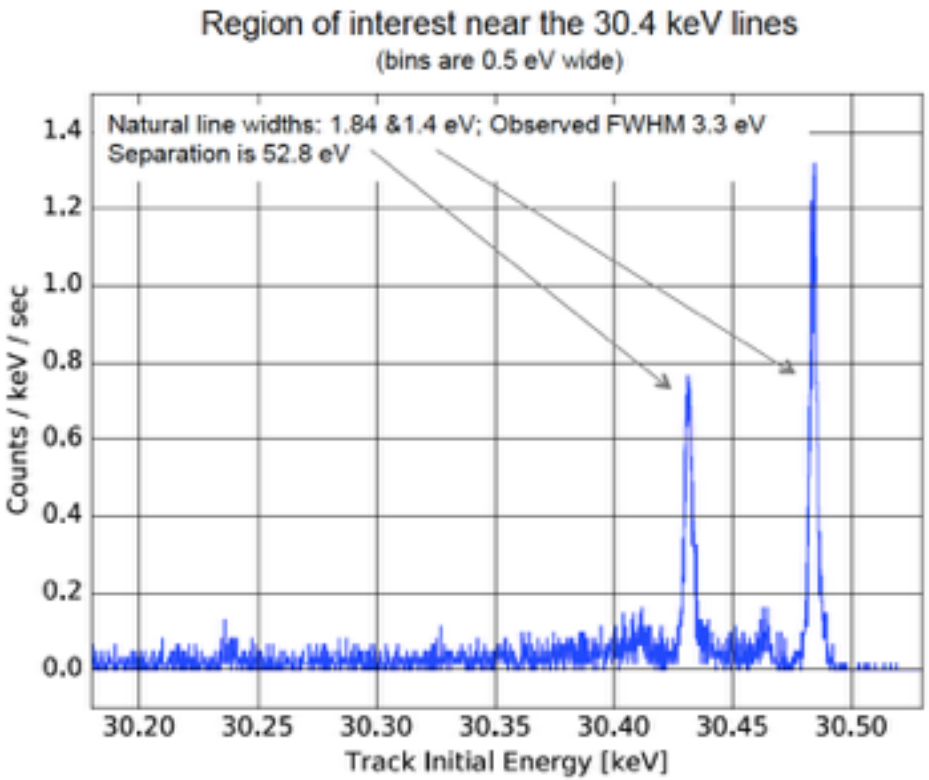

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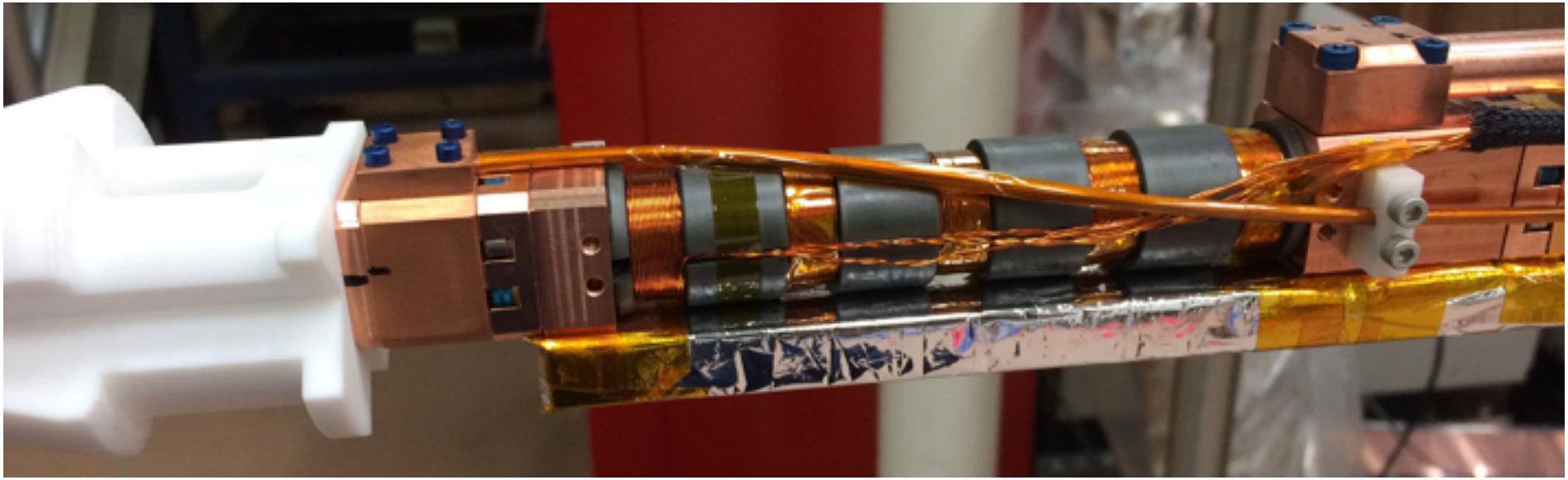
- Initial resolution: 15 eV in harmonic trap
- Bathtub trap: 3.3 eV resolution
- With power cut under investigation:
  2.2 eV FWHM

physicsworld TOP 10 BREAKTHROUGH 2015

The Project 8 Phase II waveguide cell



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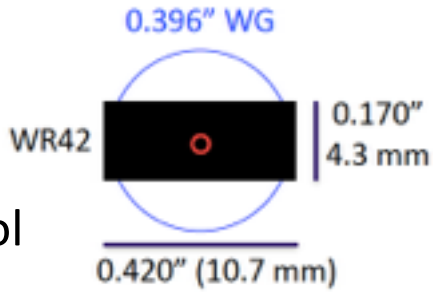
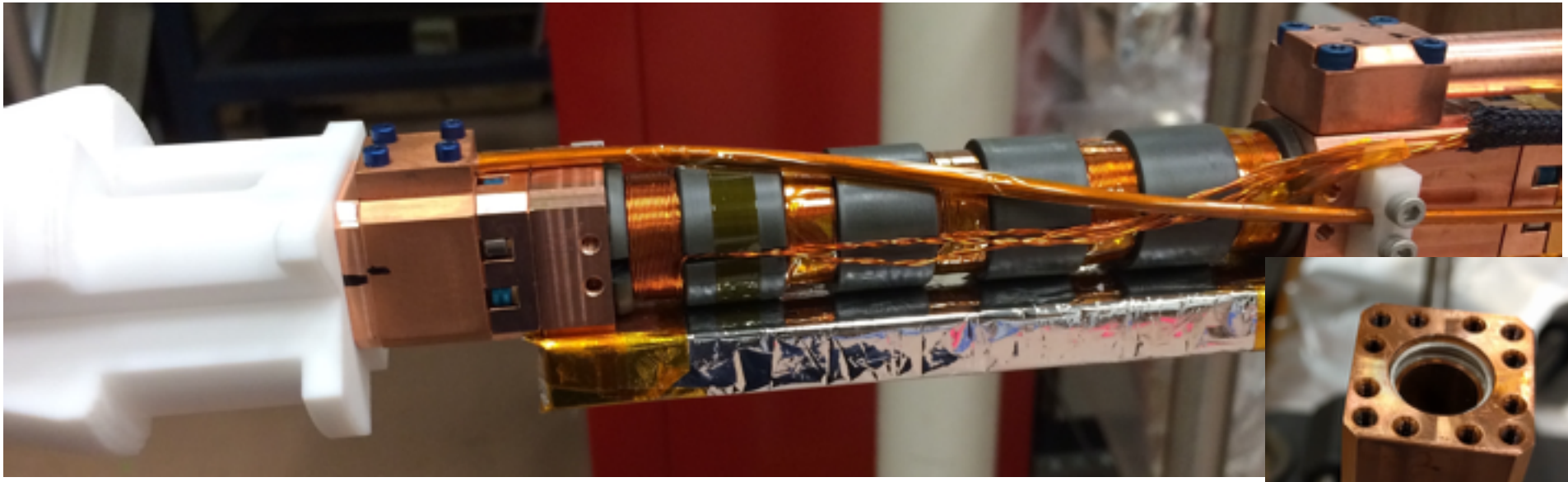
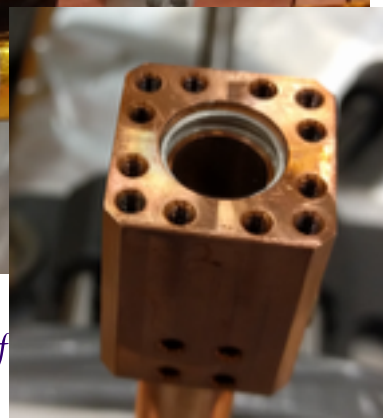
- Circulator and cryo termination → 3dB more signal, better control of the microwave background







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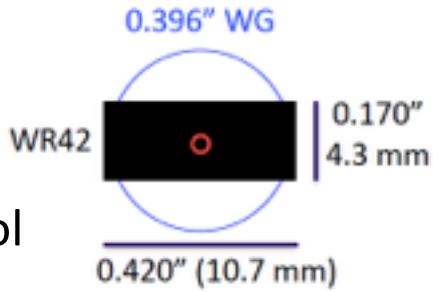

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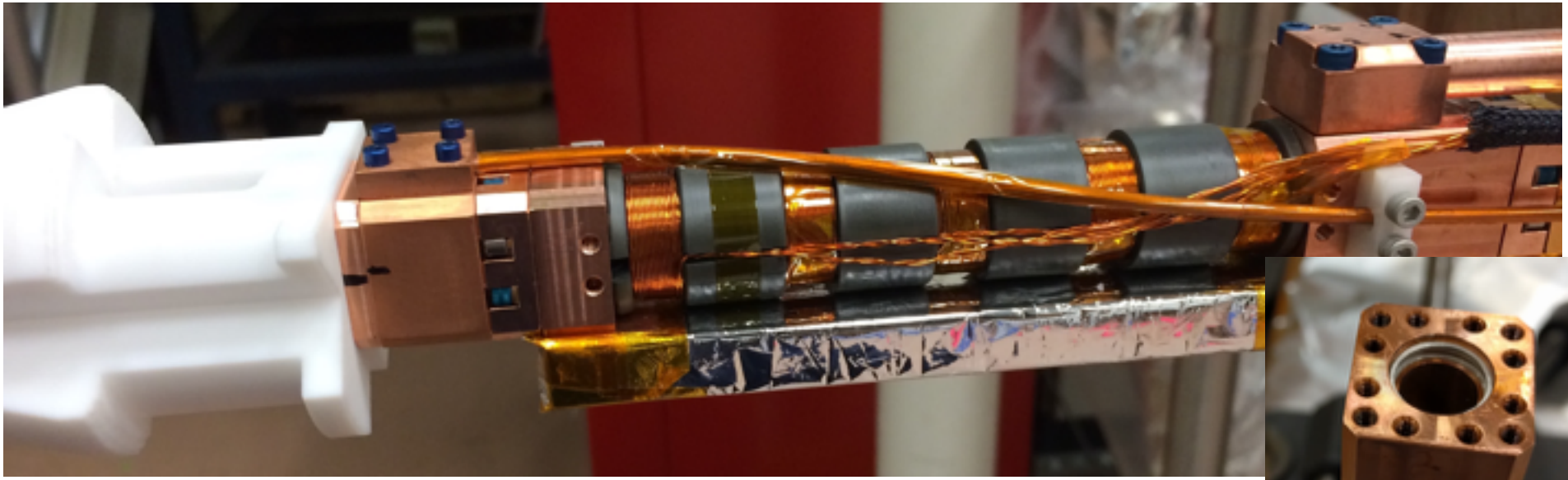

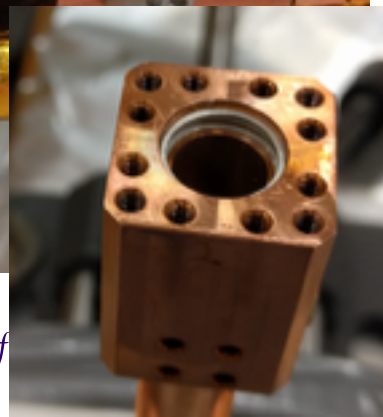

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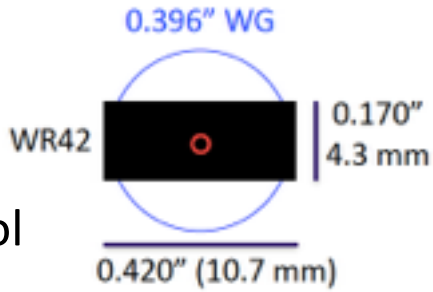

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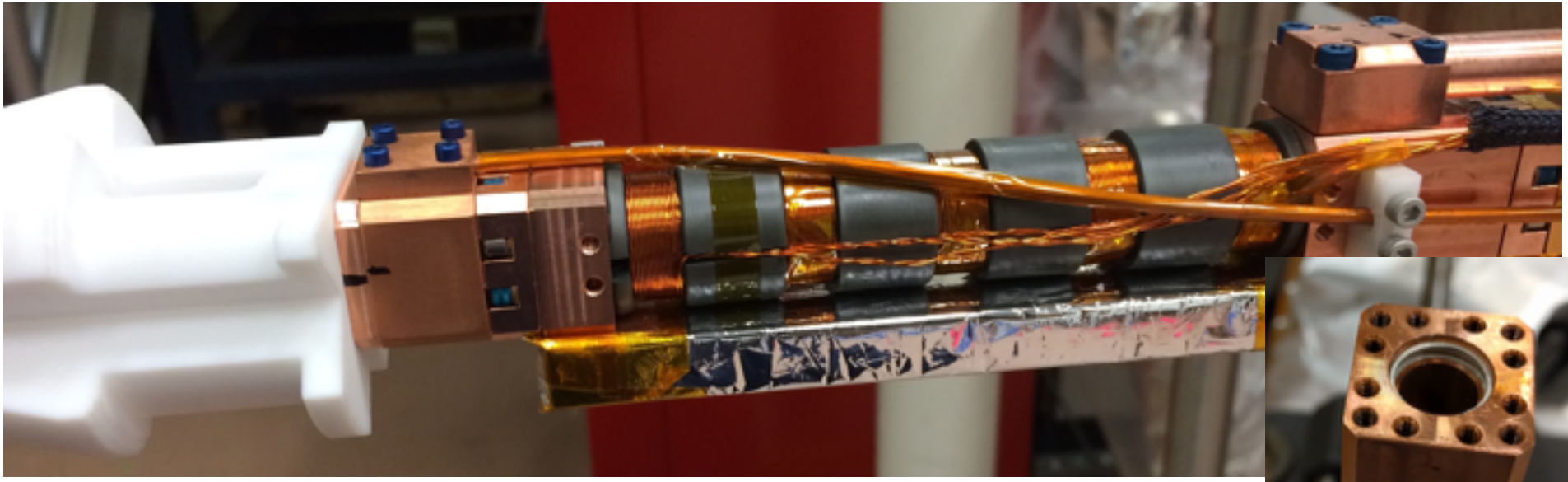
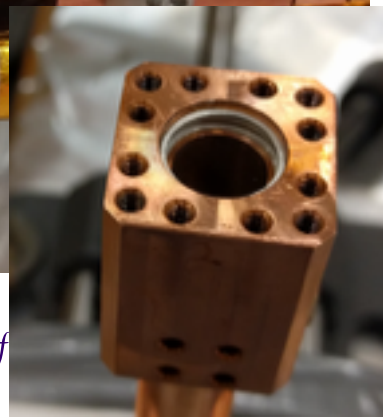
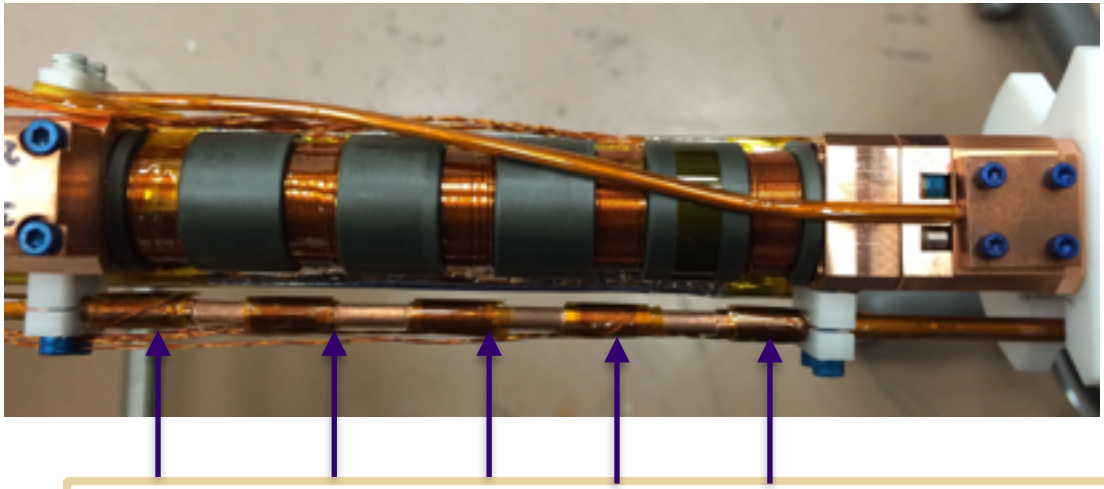
- 5 off-axis ESR magnetometers → B field stability measurements



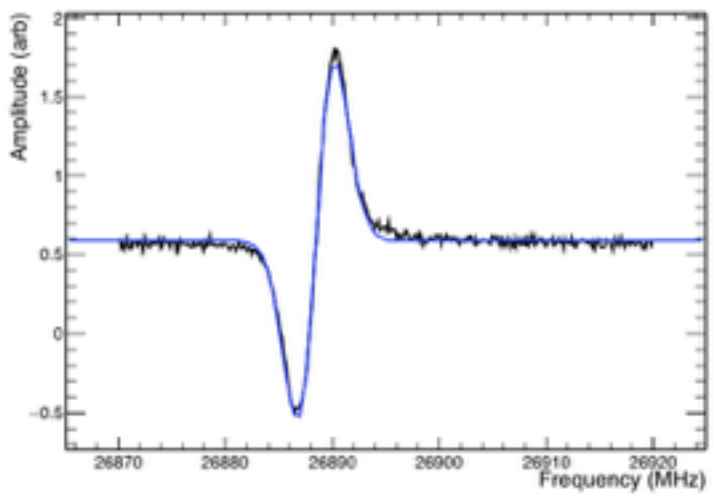


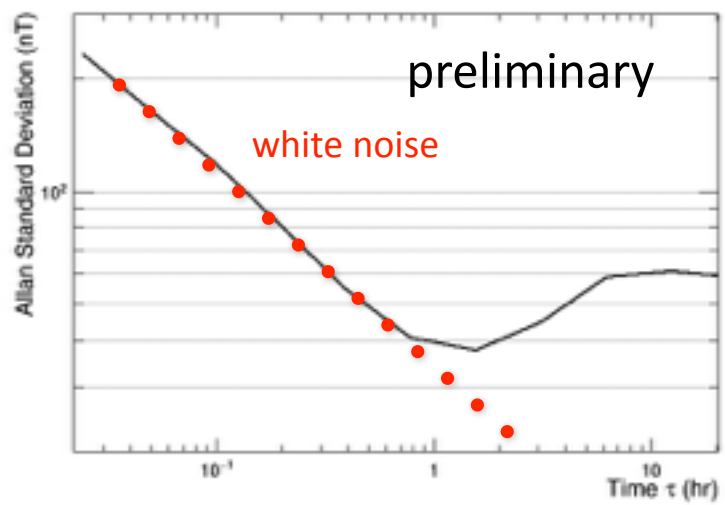
ESR magnetometer



- New diagnostics tool for Project 8
- Rel. B precision 0.3 ppm measured
- Rel. B stability 40 ppb/hr measured
- B field drift has negligible influence on Phase II energy resolution

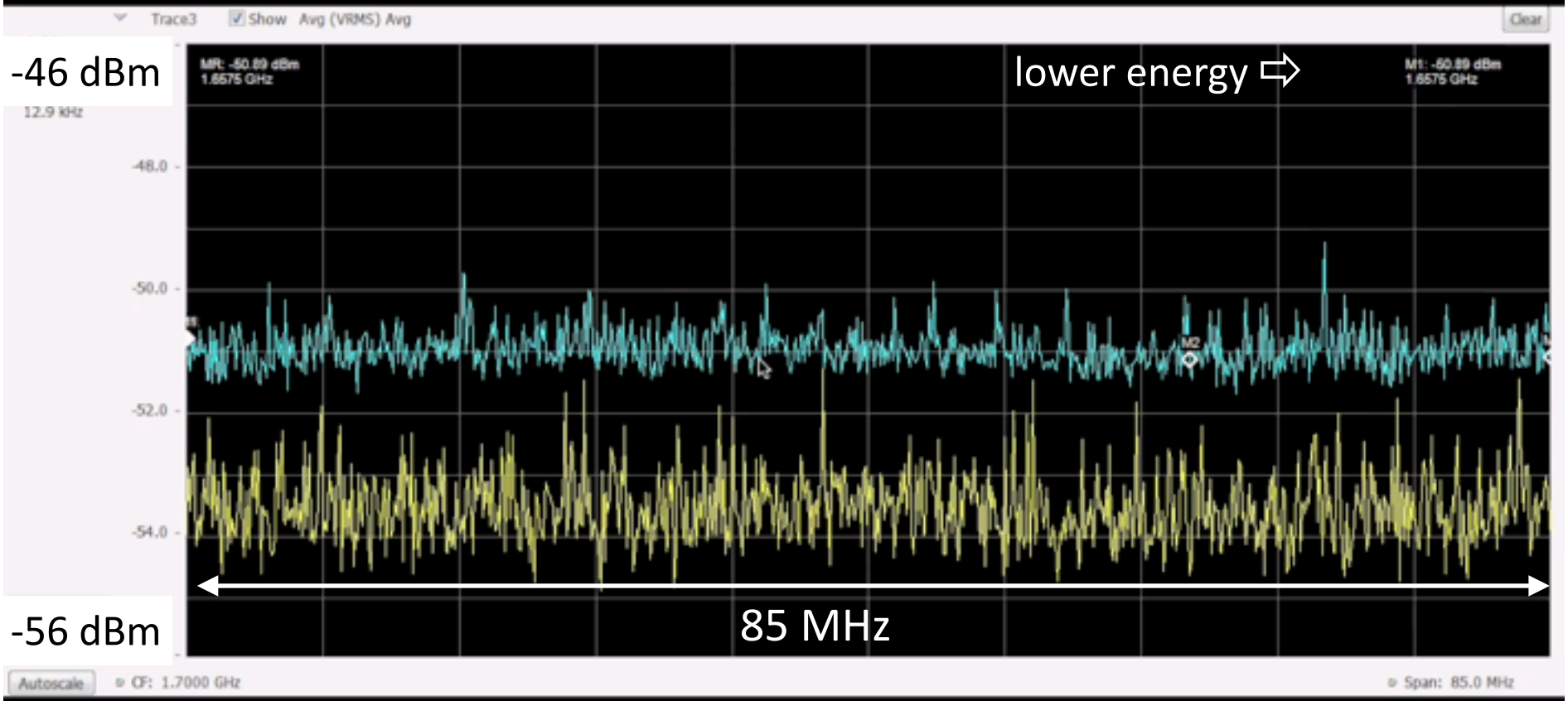
5 sample ESR magnetometer with BDPA (thanks to P. Hautle)





^{83m}Kr conversion electrons in Phase II

17.6 keV electrons, realtime x20



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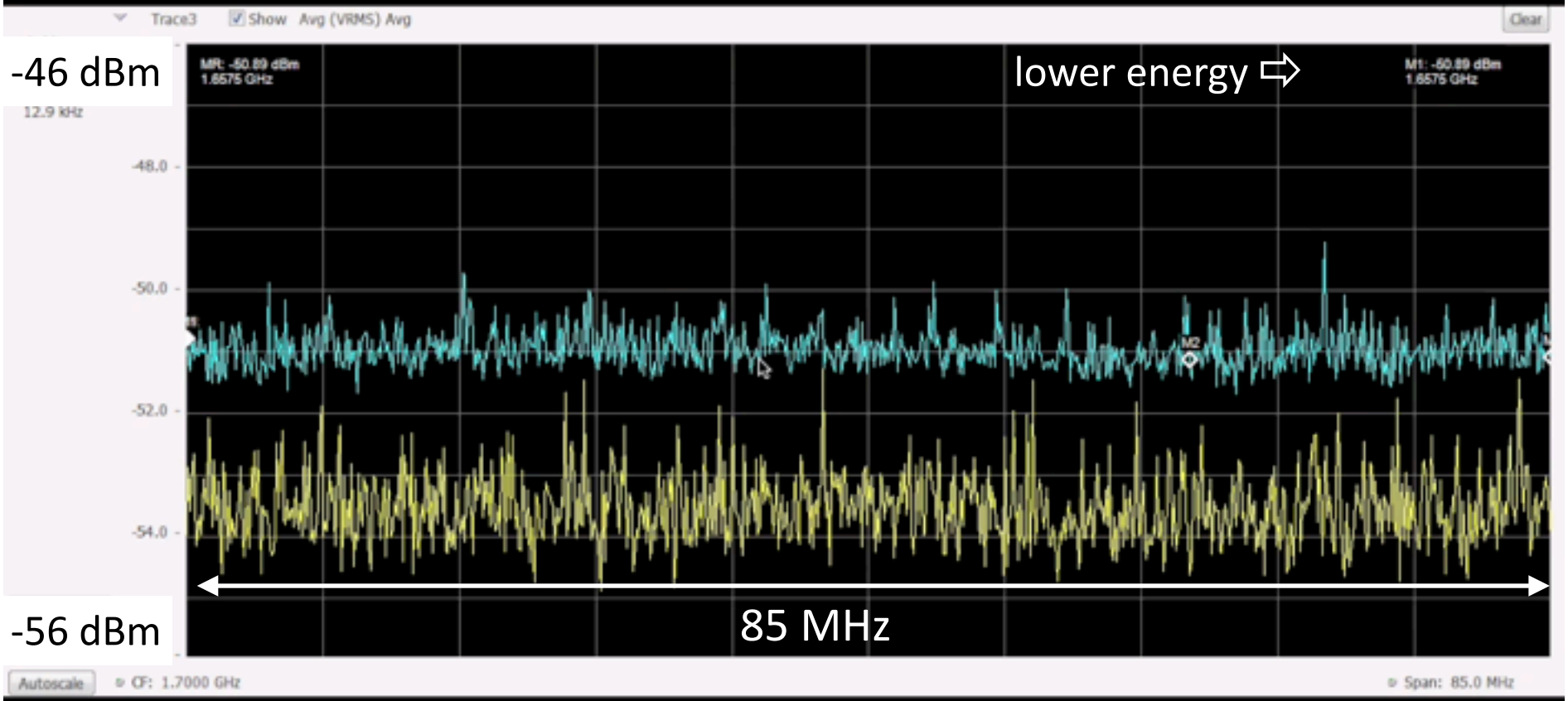
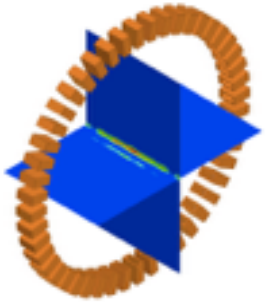


Project 8 Phase III+IV: Free space radiation

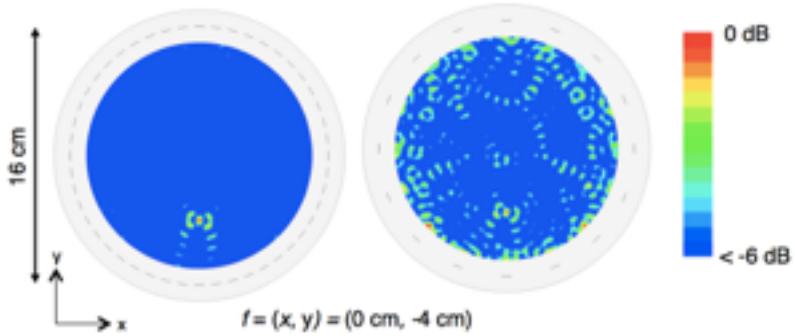
Phase III (2016-2020)

- 10 cm^3 eff. T_2 source volume (1 yr)
- Sensitivity goal: 2 eV (90% CL)
- Study of phased antenna array
- Commissioning MRI magnet

48 elements



16 elements



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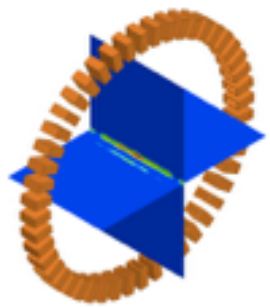

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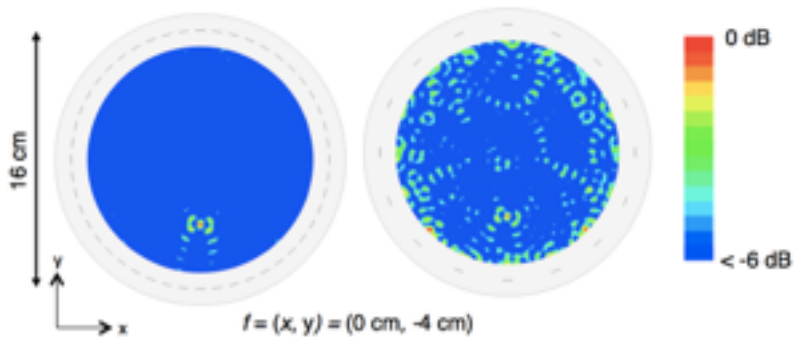
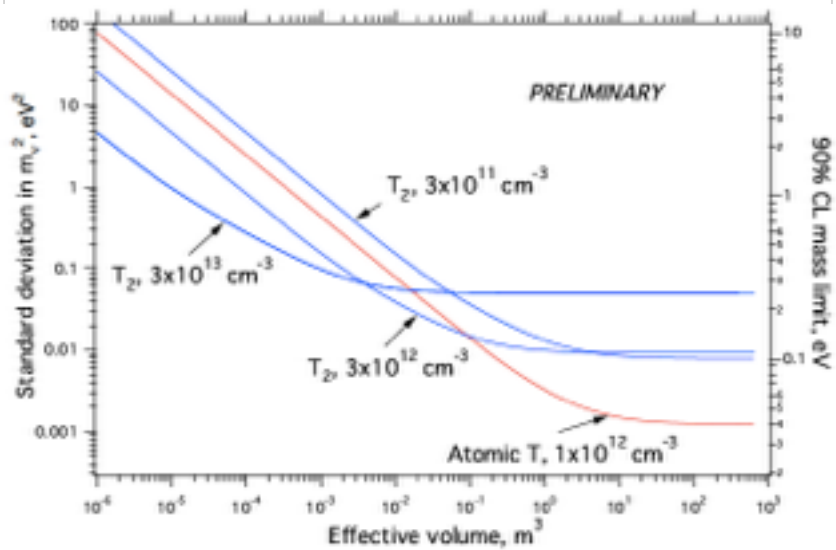


Phase IV (2017-2022+)

- Large-scale experiment
- Atomic tritium source
- IH, sub-eV sensitivity
- Trapped atomic tritium



^{6}He: High energy CRES for chirality flipping interactions

Goal: Measure Fierz interference term "b" in ^{6}He decay to better than 10^{-3}!

$$dw = dw_0 \left(1 + a \frac{\vec{p_e}}{E_e} \cdot \frac{\vec{p_\nu}}{E_\nu} + b_{\mathrm{Fierz}} \frac{m_e}{E_e}\right) \qquad a \approx -\frac{1}{3} \frac{2\left|C_A\right|^2 - \left|C_T\right|^2 + \left|C'_T\right|^2}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C'_T\right|^2} \qquad b \approx \frac{\Re\left(2C_A\left(C_T + C'_T\right)\right)}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C'_T\right|^2}$$

"Fierz" measurements: X. Huyan, J. Wexler, E. Scott

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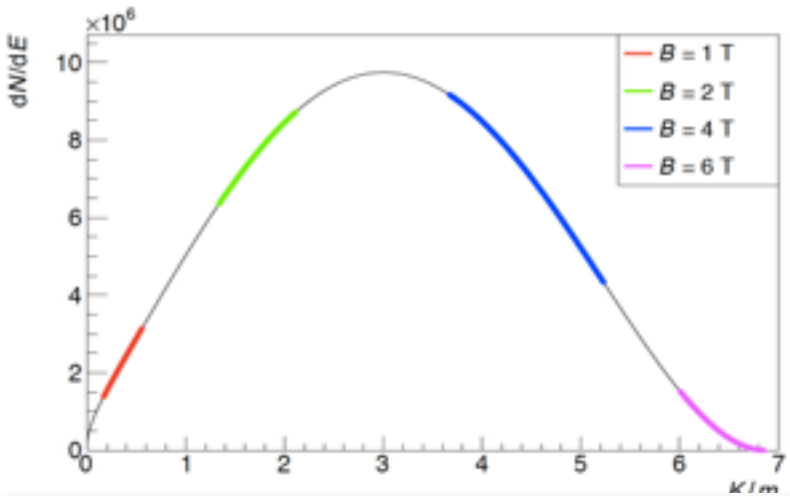
Fixed frequency range 18-24 GHZ ⟶ Scan B field to scan e$^-$ energy



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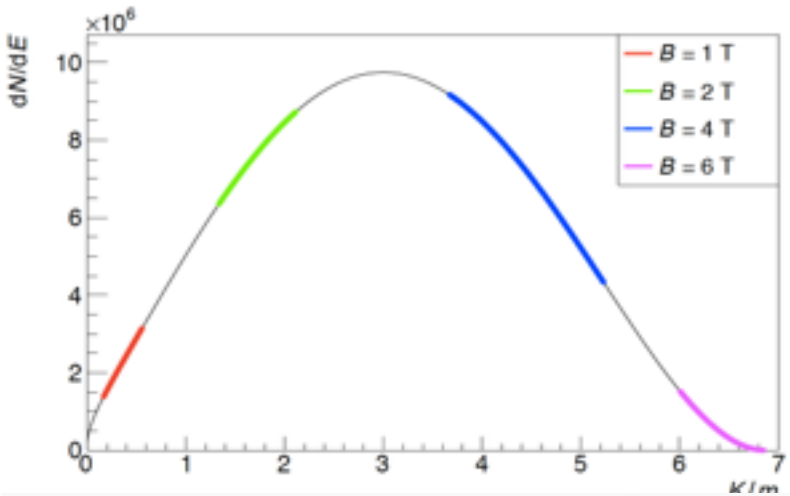

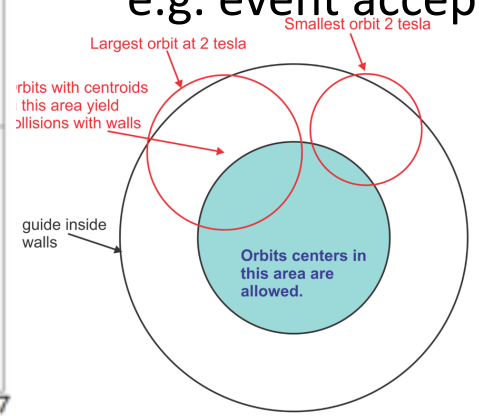

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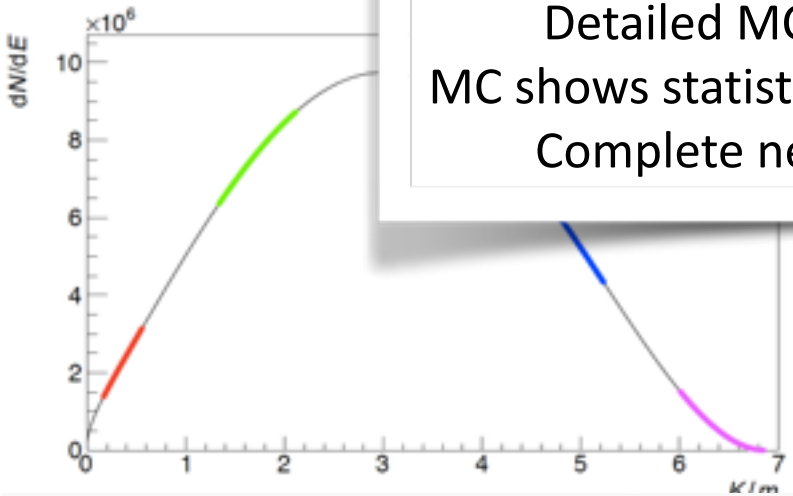
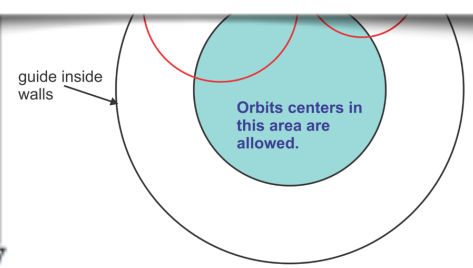
Fixed frequer

Expand CRES to high energy range.
Detailed MC studies are ongoing for ^{6}He.
MC shows statistics for $\sigma(b)<10^{-3}$ in 1 day @ CENPA.
Complete new class of systematic effects!





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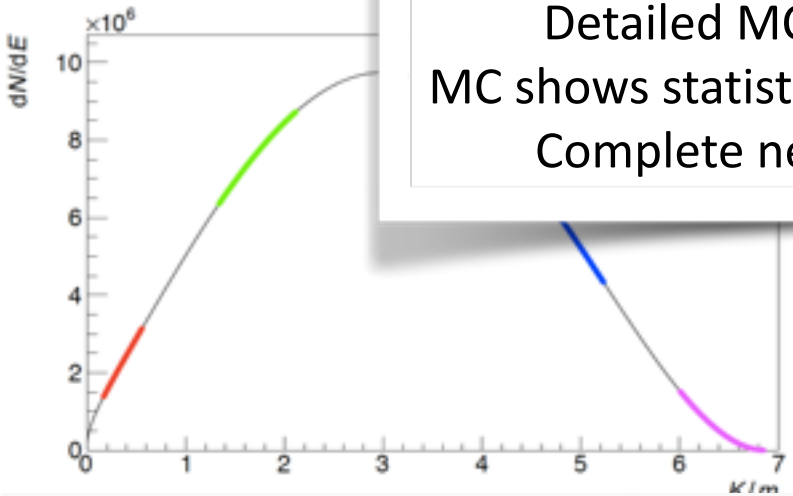

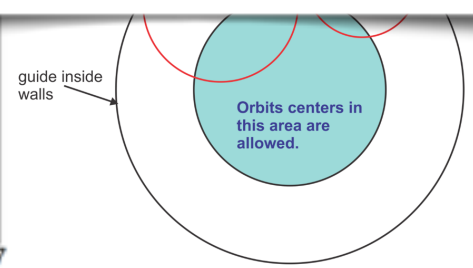

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The Project 8 collaboration

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Massachusetts Institute of Technology, Cambridge, MA
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University of California, Santa Barbara, CA
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Yale University , New Haven , CT
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Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Böser, Ch. Claessens,
Universität Mainz, Mainz, Germany
S. Doeleman, J. Weintroub, A. Young
Harvard-Smithsonian Center for Astrophysics,
K.Kazkaz, Lawrence Livermore National Laboratory

The Project 8 collaboration is supported by:

- U.S. Department of Energy, Office of Science, Office of Nuclear Physics
- National Science Foundation
- Institutional Computing at Pacific Northwest National Laboratory
- University of Washington Royalty Research Foundation
- Massachusetts Institute of Technology Wade Fellowship
- Laboratory Directed Research and Development Program Pacific Northwest National Laboratory

The collaborations

Project 8

CRES on ^{6}He collaboration forming

Postdocs

Summary and Outlook

Project 8

- Phase I: 1st observation of cyclotron radiation from a single electron
- Phase I: Successfully measured ^{83m}Kr spectrum using CRES
- Phase II: Taking commissioning data with ^{83m}Kr to prepare for molecular tritium gas
- Phase III and IV: planning and design ongoing in parallel

CRES on ^{6}He: Fierz interference term “b” beyond 10^{-3} seems promising

Thank you!

CENPA is hiring post docs

https://www.npl.washington.edu/cenpa-jobs

Post Doc positions open for

^{6}He CRES spectroscopy
0νββ decay with Majorana
RF axion search with ADMX

The University of Washington Center for Experimental Nuclear Physics and Astrophysics (CENPA) has immediate openings for postdoctoral appointments for work on one or more of the following experiments: the Axion Dark-Matter eXperiment (ADMX), which is a RF-cavity search for axion dark matter in our galactic halo; a ^{6}He beta decay experiment that is searching for non-standard-model currents in weak decays; and the Majorana Demonstrator, which is testing the Majorana nature of the neutrino.

Back up slides

The PMNS matrix elements

Oscillation experiments depend on PNMS matrix and mass differences:

"solar" mixing angle

"atmospheric" mixing angle

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

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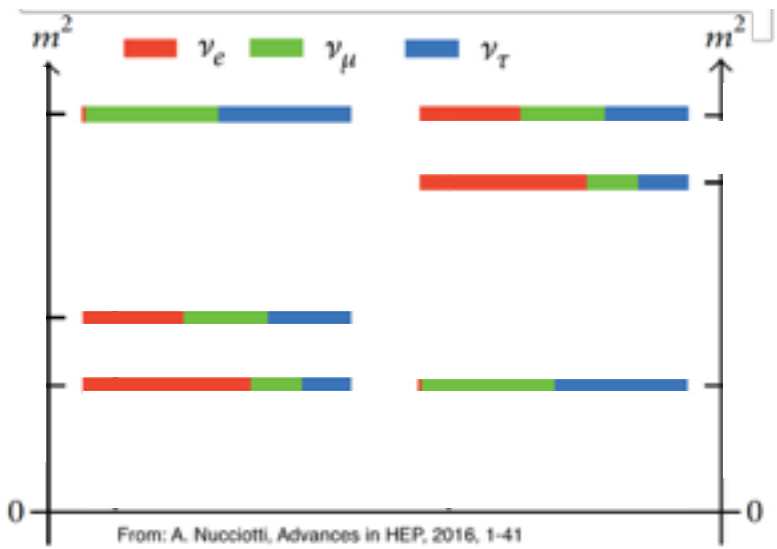
LARGE mixing angles

$$\theta_{23} \approx 45^\circ, \theta_{13} \approx 9^\circ, \theta_{12} \approx 34^\circ$$



From: A. Nucciotti, Advances in HEP, 2016, 1-41

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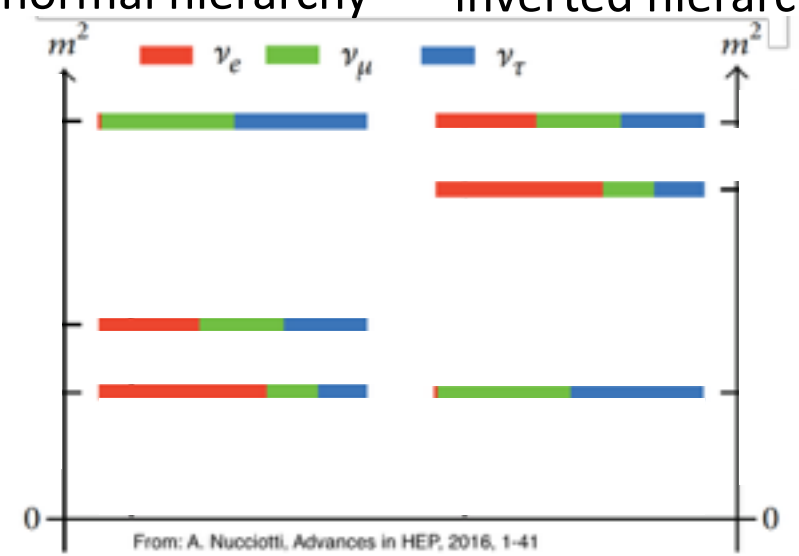
normal hierarchy

inverted hierarchy



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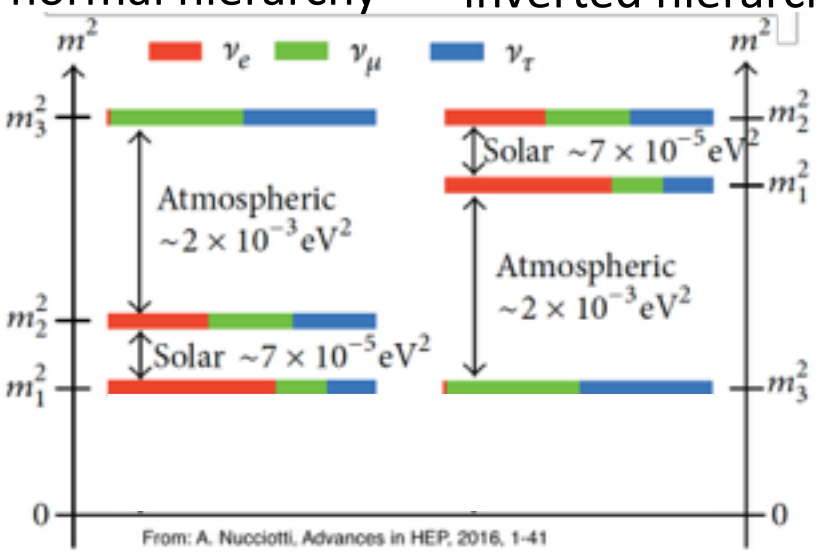

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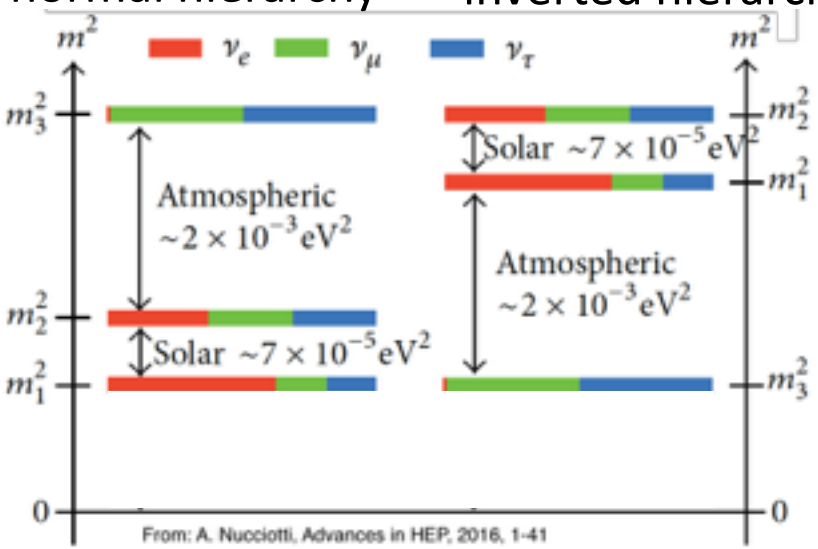

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No sensitivity to absolute mass scale

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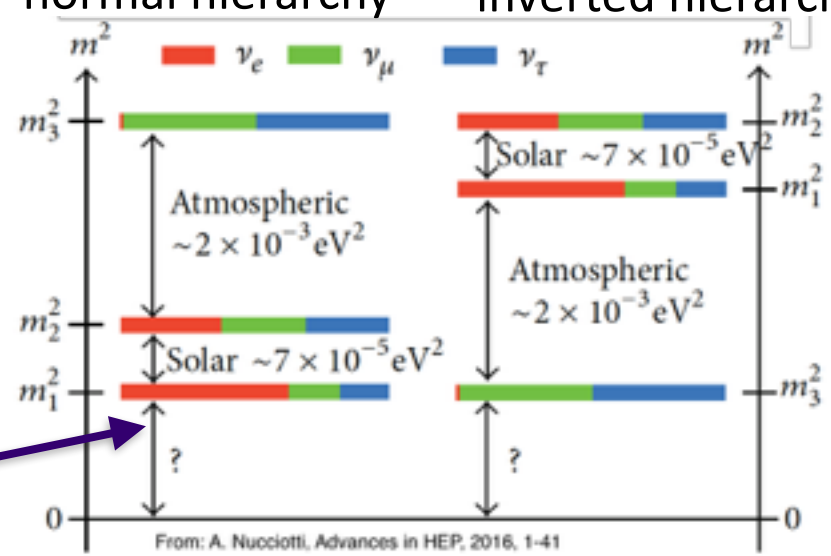

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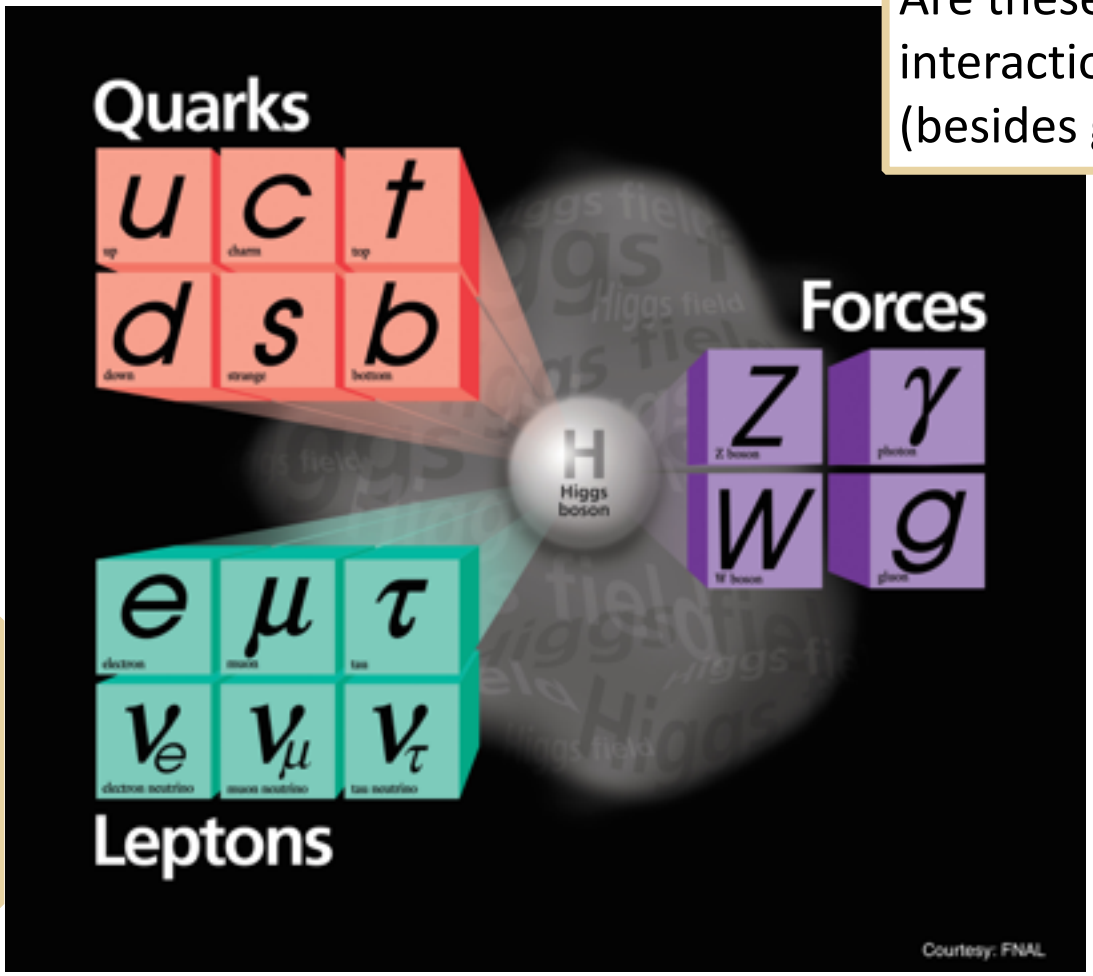
The Standard Model of Particle Physics in one picture

Are these the only interactions in nature (besides gravity)?



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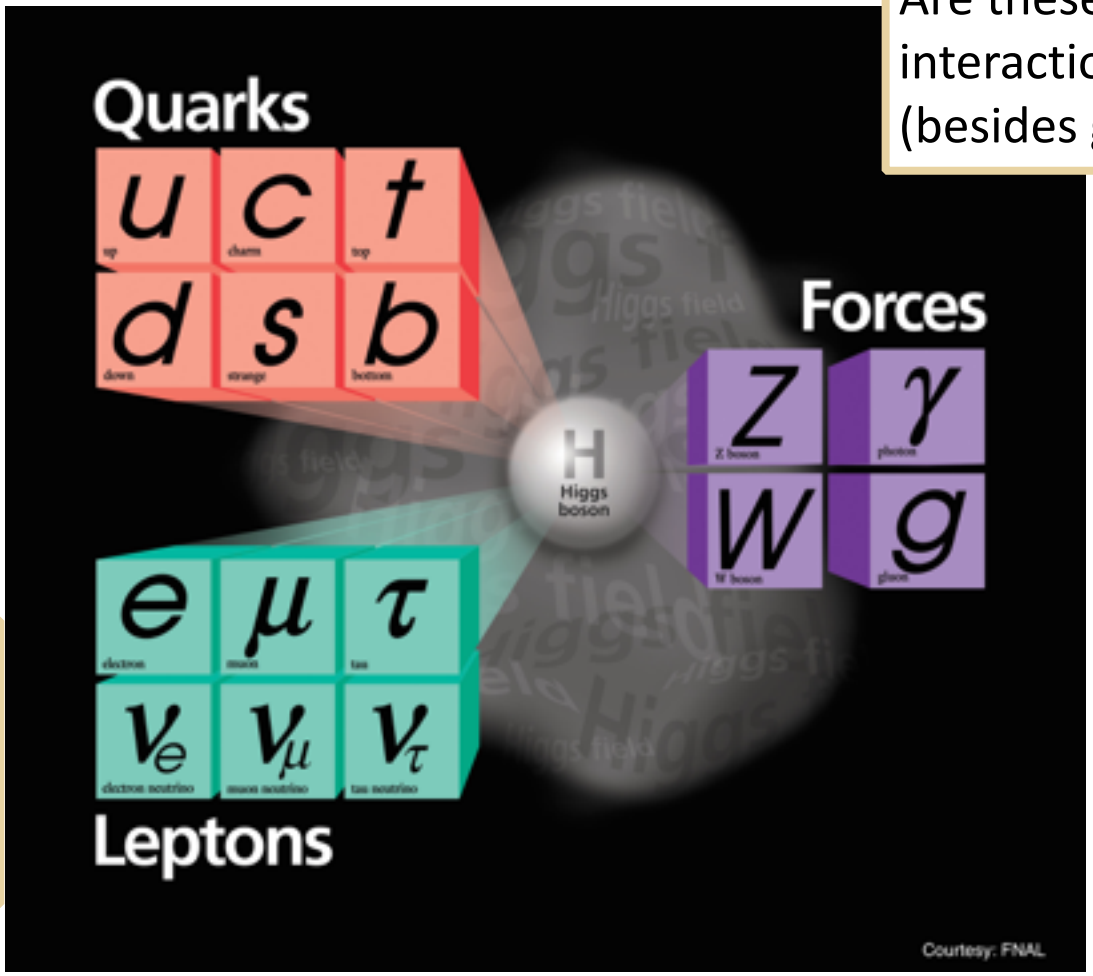

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Beta decay electron spectrum

With neutrino mixing and nuclear recoil for T_{nuc}:

$$\frac{dN}{dE_{\mathrm{e}}} = \frac{G_{\mathrm{F}}^2 m_{\mathrm{e}}^5 \cos^2\theta_{\mathrm{C}}}{2\pi^3\hbar^7} \left|M_{\mathrm{nuc}}\right|^2 F\left(Z, E_{\mathrm{e}}\right) p_{\mathrm{e}} E_{\mathrm{e}} \sum_i \left|U_{\mathrm{ei}}\right|^2 \left(E_{\mathrm{max}} - E_{\mathrm{e}}\right)$$
$$\times \sqrt{\left(E_{\mathrm{max}} - E_{\mathrm{e}}\right)^2 - m_{\nu\mathrm{i}}^2} \cdot \Theta\left(E_{\mathrm{max}} - E_{\mathrm{e}} - m_{\nu\mathrm{i}}\right)$$

For unresolved neutrino mass splitting:

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Spectrum of certain nuclei can be used to search for chirality flipping interactions

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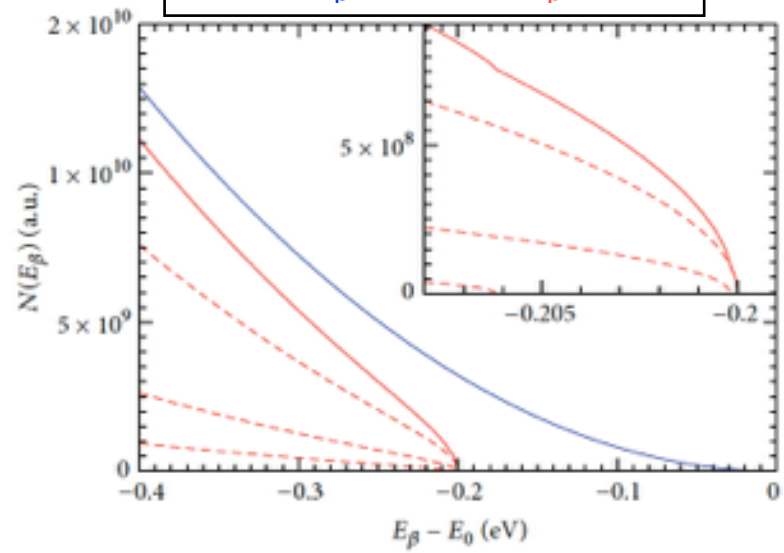

Nucciotti, Advances in High Energy Physics, Vol. 2016, 9153024

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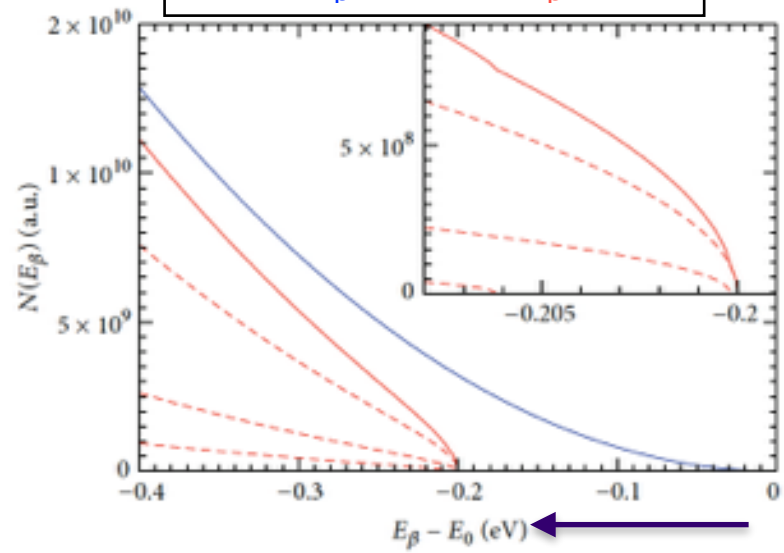

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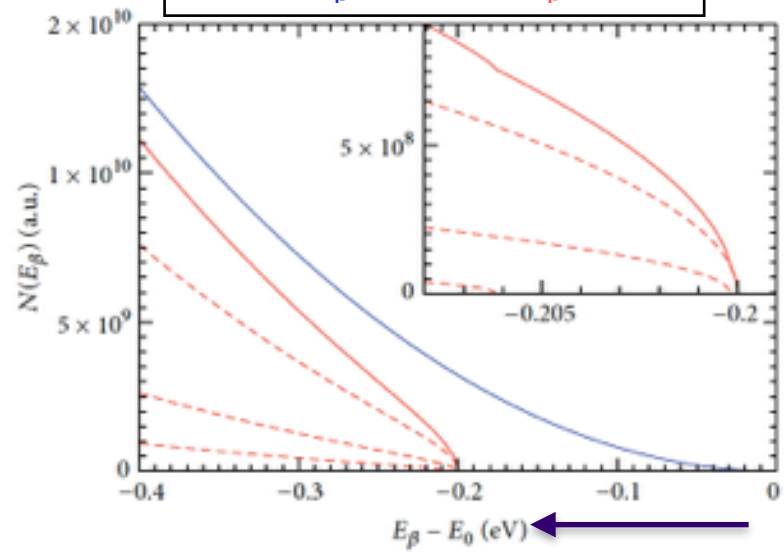

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Tritium
Q (T_A) = 18.59201(7) keV
Super allowed transition
$T_{1/2}$ = 12.32 y
BR (1eV) = 2 x 10^{-13}

Myers et al, PRL 114, 013033, 2015

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Anti-electron neutrino mass limits from tritium beta decay experiments

T_2 β^- decay kinematics
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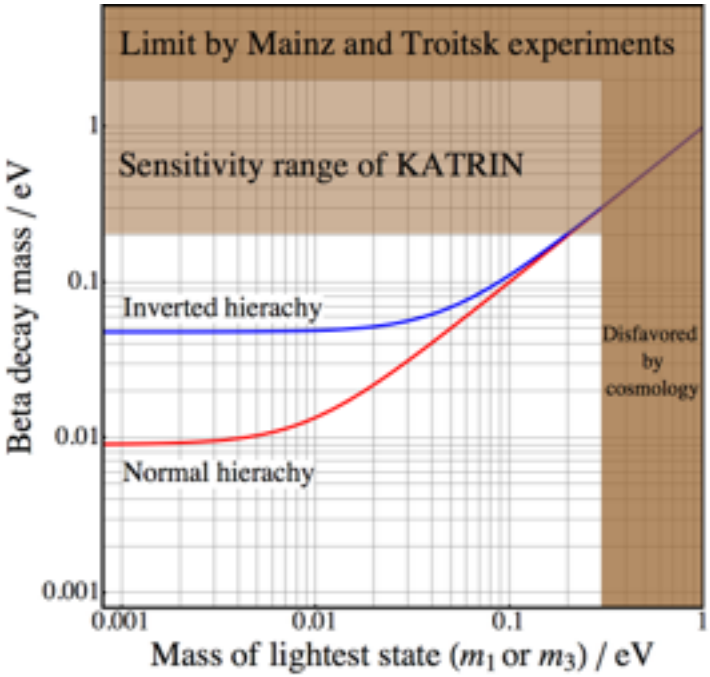

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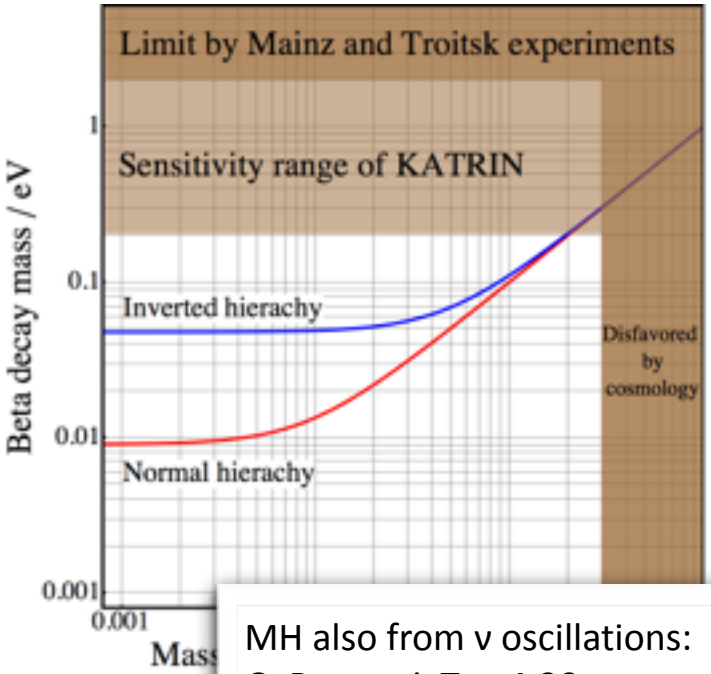

MH also from ν oscillations:
G. Brunetti, Tue 4:20 pm

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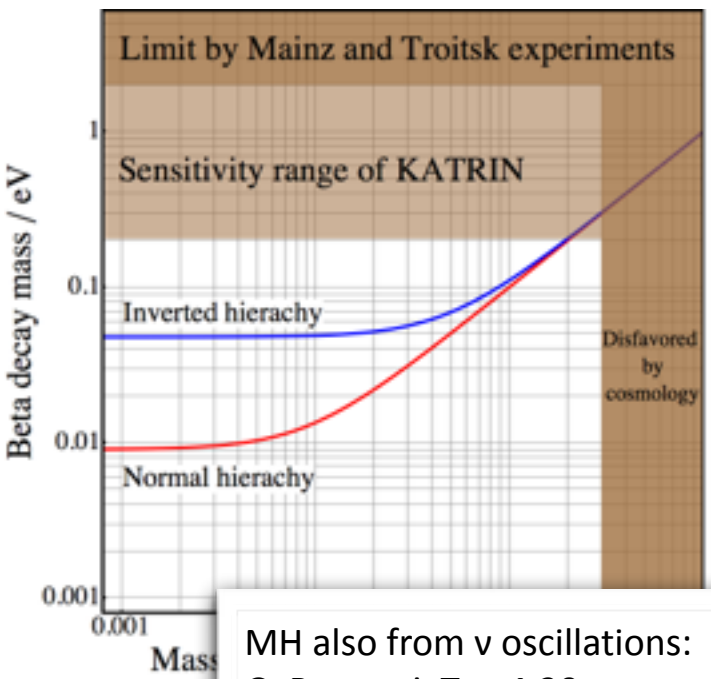

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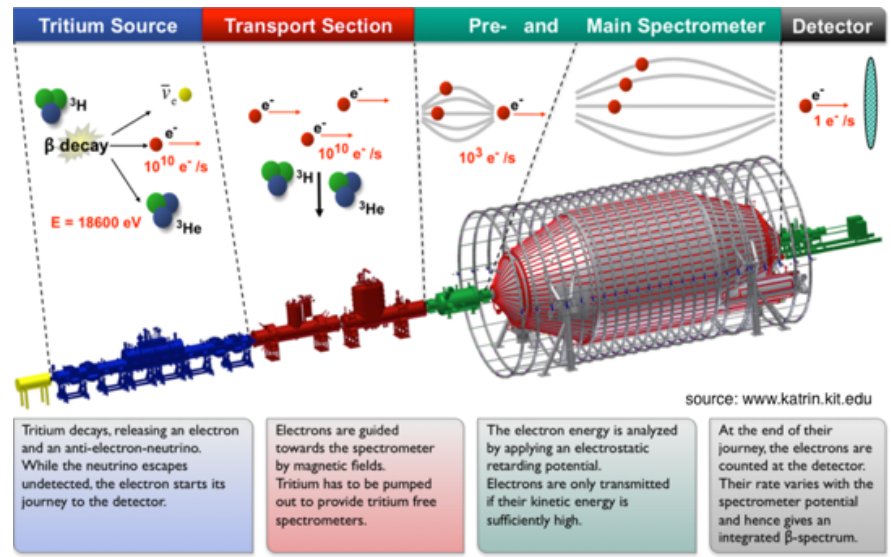

- Window less gaseous T_2 source (10^{11} Bq)
- MAC-E filter technique scales like area
- Column density limited, T_2 final states
- Sensitivity: < 200 meV (90% CL)

First light in October 2016!

Highest precision measurements …

… often follow A. Schawlow's advice:

"Never measure anything but frequency"

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Hydrogen 1S-2S	Electron g-factor	Electron mass in u
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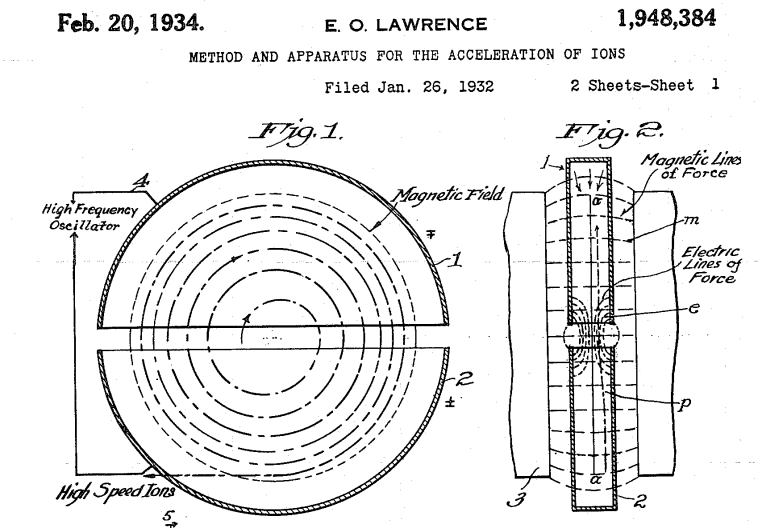
New frequency based measurements also for:

Anti-electron neutrino mass

New chirality flipping interactions?

The cyclotron frequency in a nutshell



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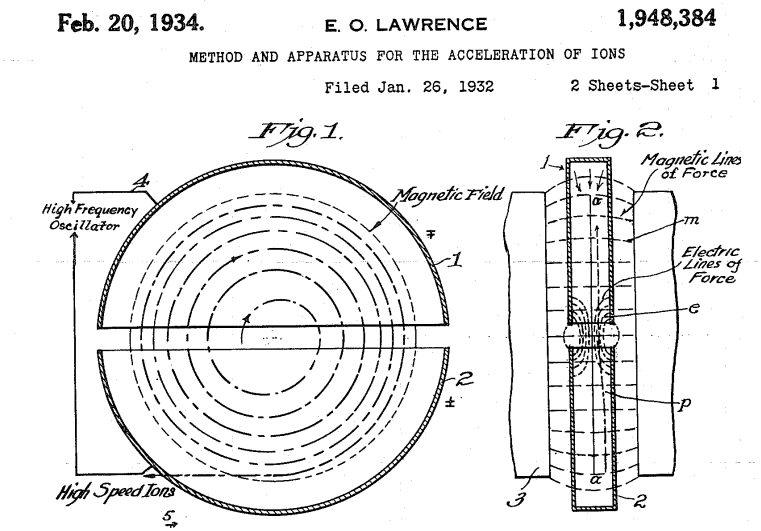

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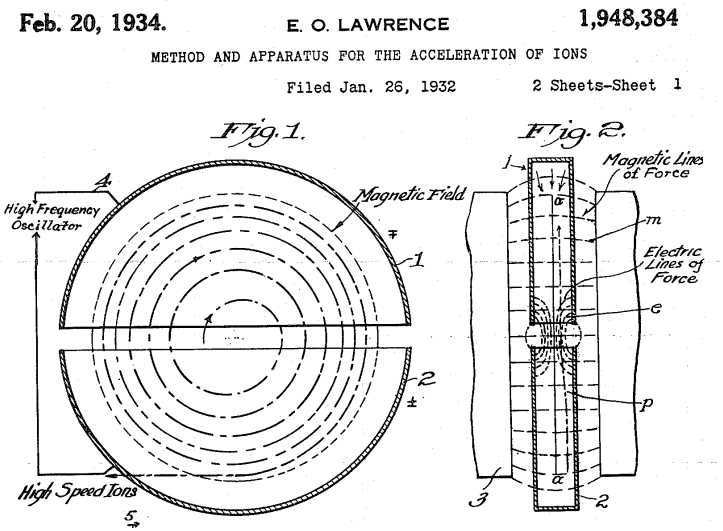

Cyclotron motion:

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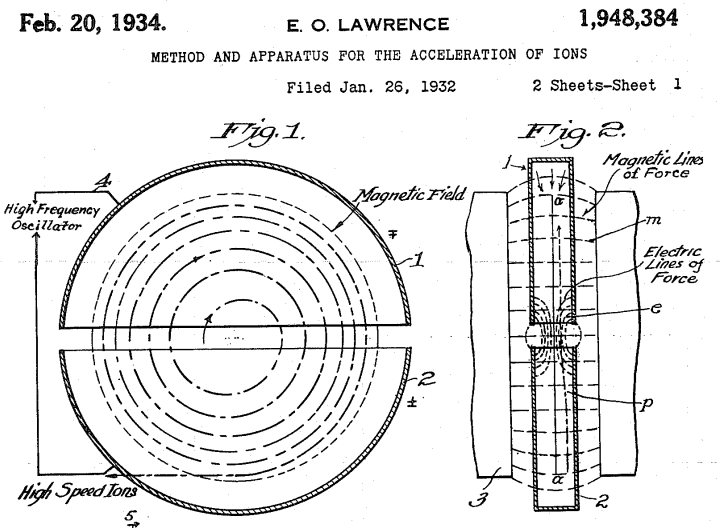

Cyclotron motion:

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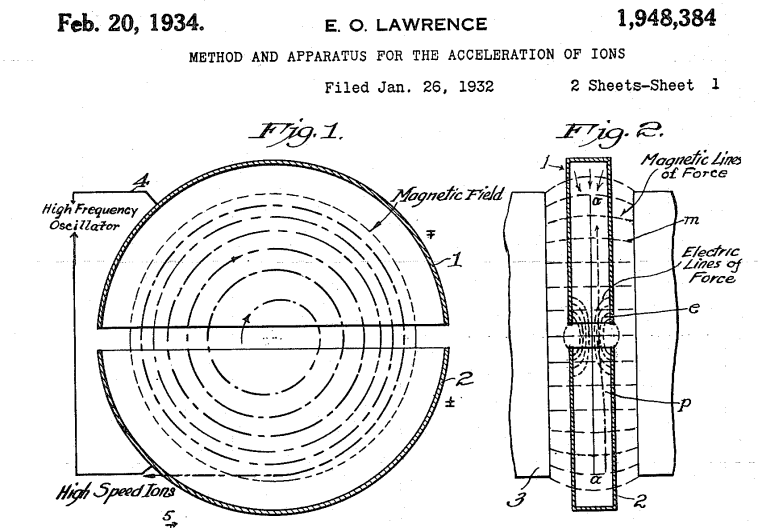

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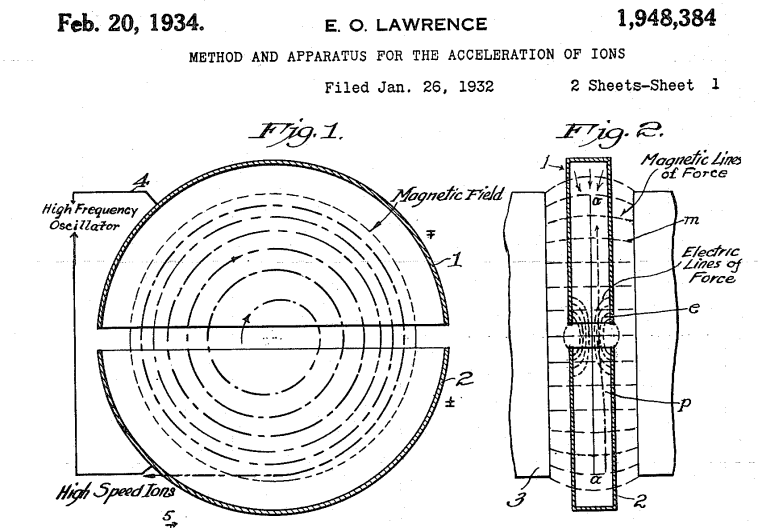

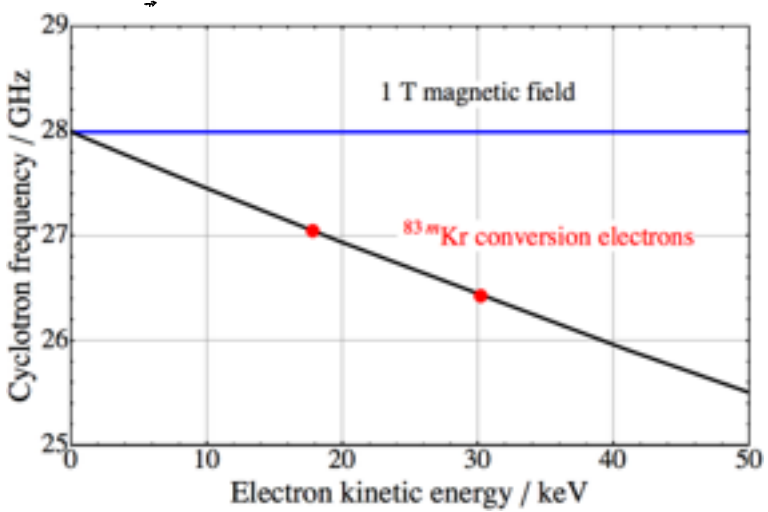

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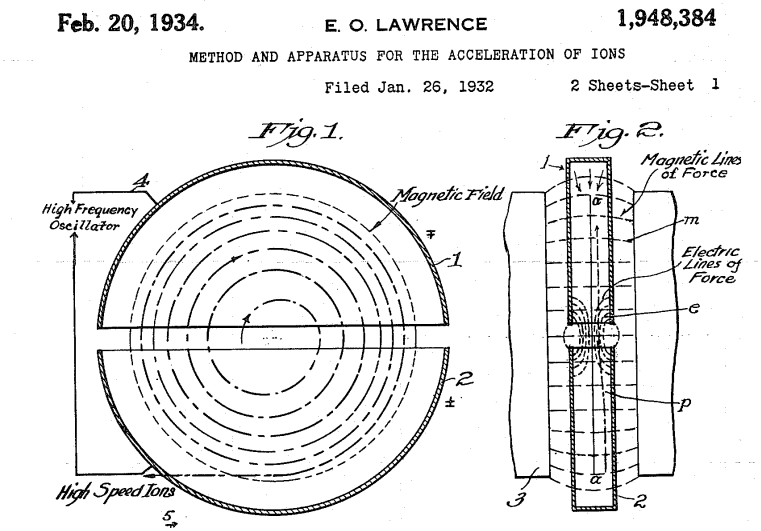

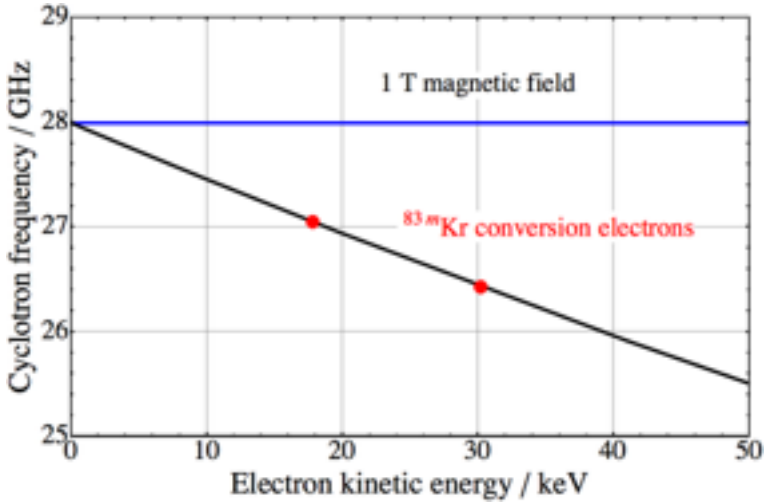

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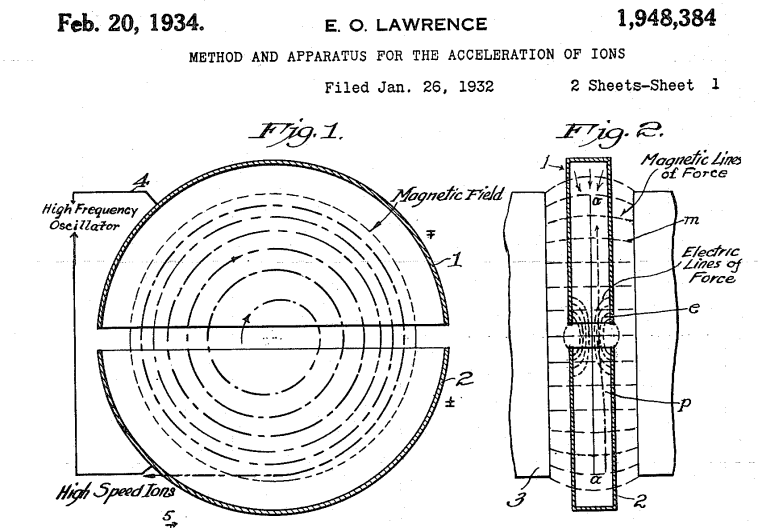
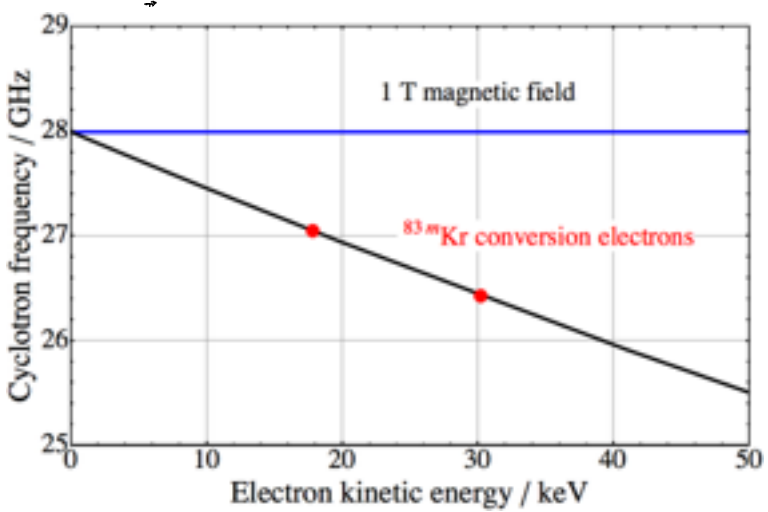
Limits the cyclotron as accelerator

The cyclotron frequency in a nutshell


Feb. 20, 1934. E. O. LAWRENCE 1,948,384

METHOD AND APPARATUS FOR THE ACCELERATION OF IONS

Filed Jan. 26, 1932 2 Sheets-Sheet 1



Cyclotron motion:

- Only charged particles
- In non relativistic limit a ratio of precisely measured constants

$$f_{\mathrm{c},0} = \frac{1}{2\pi}\frac{eB}{m_{\mathrm{e}}}$$

- Energy dependent (Lorentz factor)

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

Limits the cyclotron as accelerator

Measurement of kinetic energy!

Axial motion: side band generation

Harmonic magnetic bottle introduces a degeneracy between kinetic energy and pitch angle!

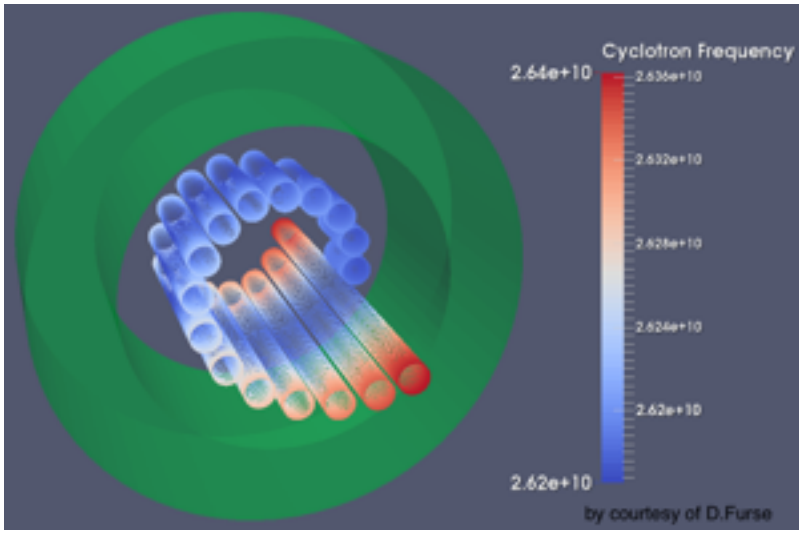
$$f_{\mathrm{c}} = \frac{eB}{m + E_{\mathrm{kin}}/c^2}\left(1 + \frac{\cot^2\theta}{2}\right)$$

Axial motion: side band generation

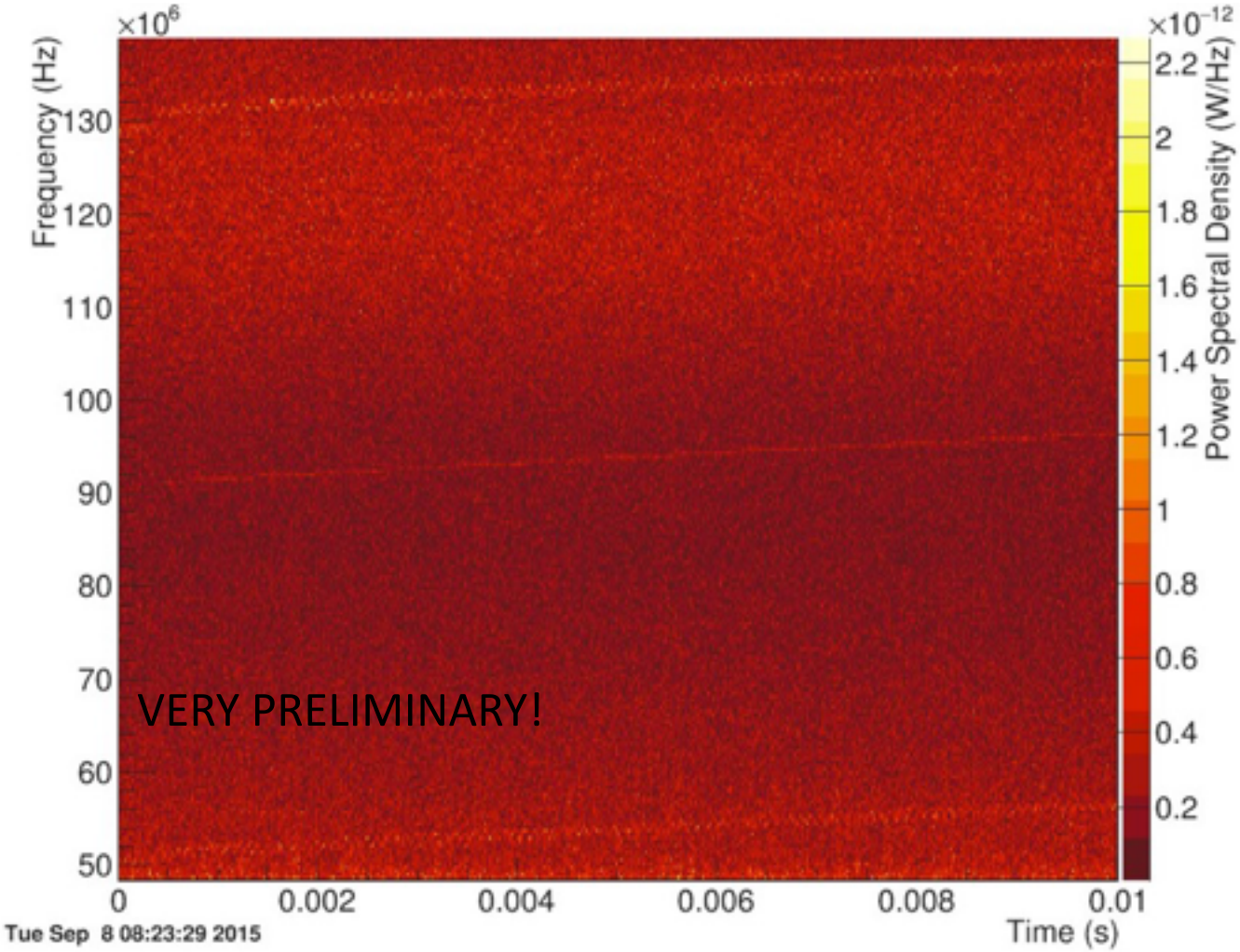
Harmonic magnetic bottle introduces a degeneracy between kinetic energy and pitch angle!

$$f_c = \frac{eB}{m + E_{\mathrm{kin}}/c^2}\left(1 + \frac{\cot^2\theta}{2}\right)$$

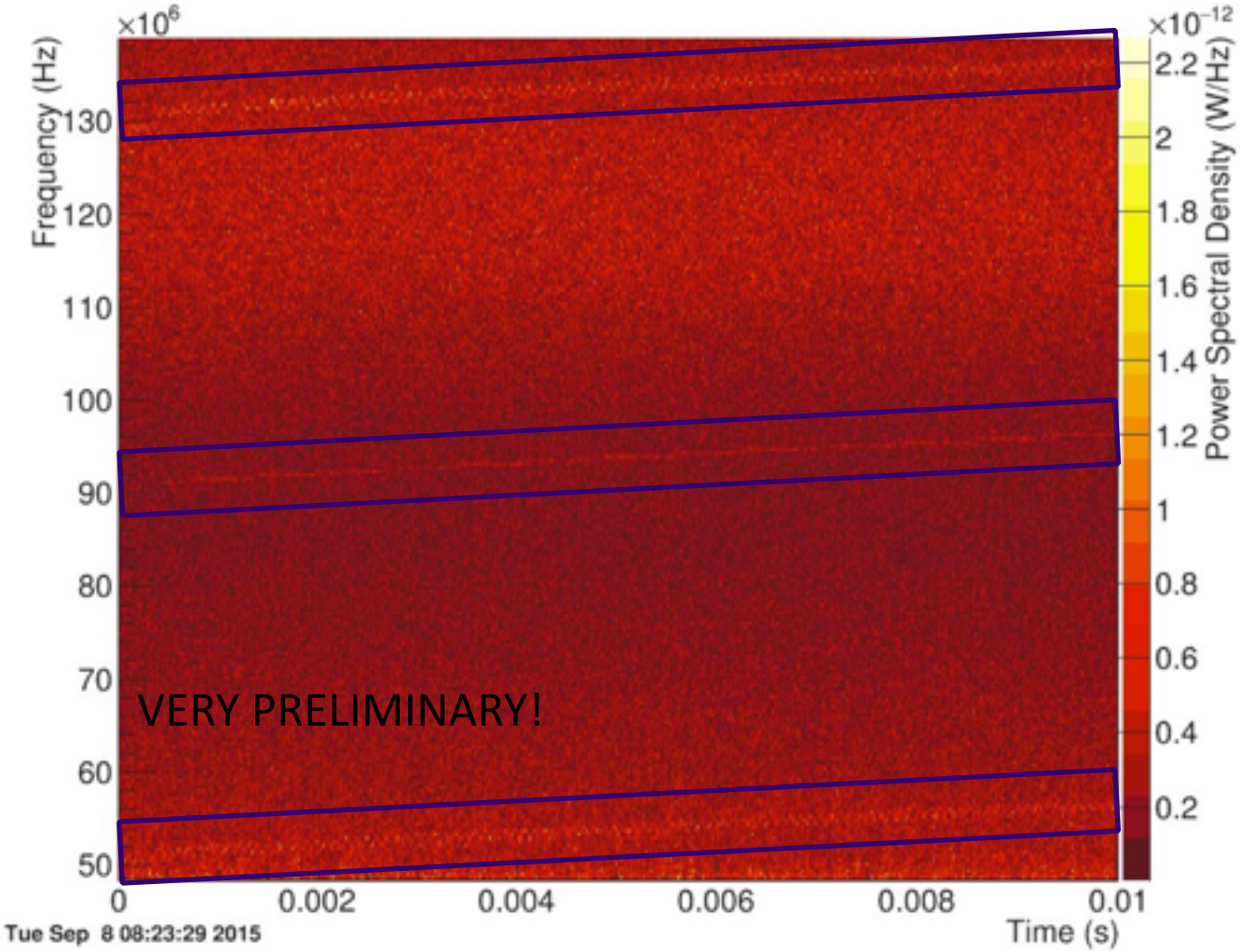
Axial electron motion ⟶ Modulation of cyclotron frequency ⟶ Side band generation



Axial motion: side band generation

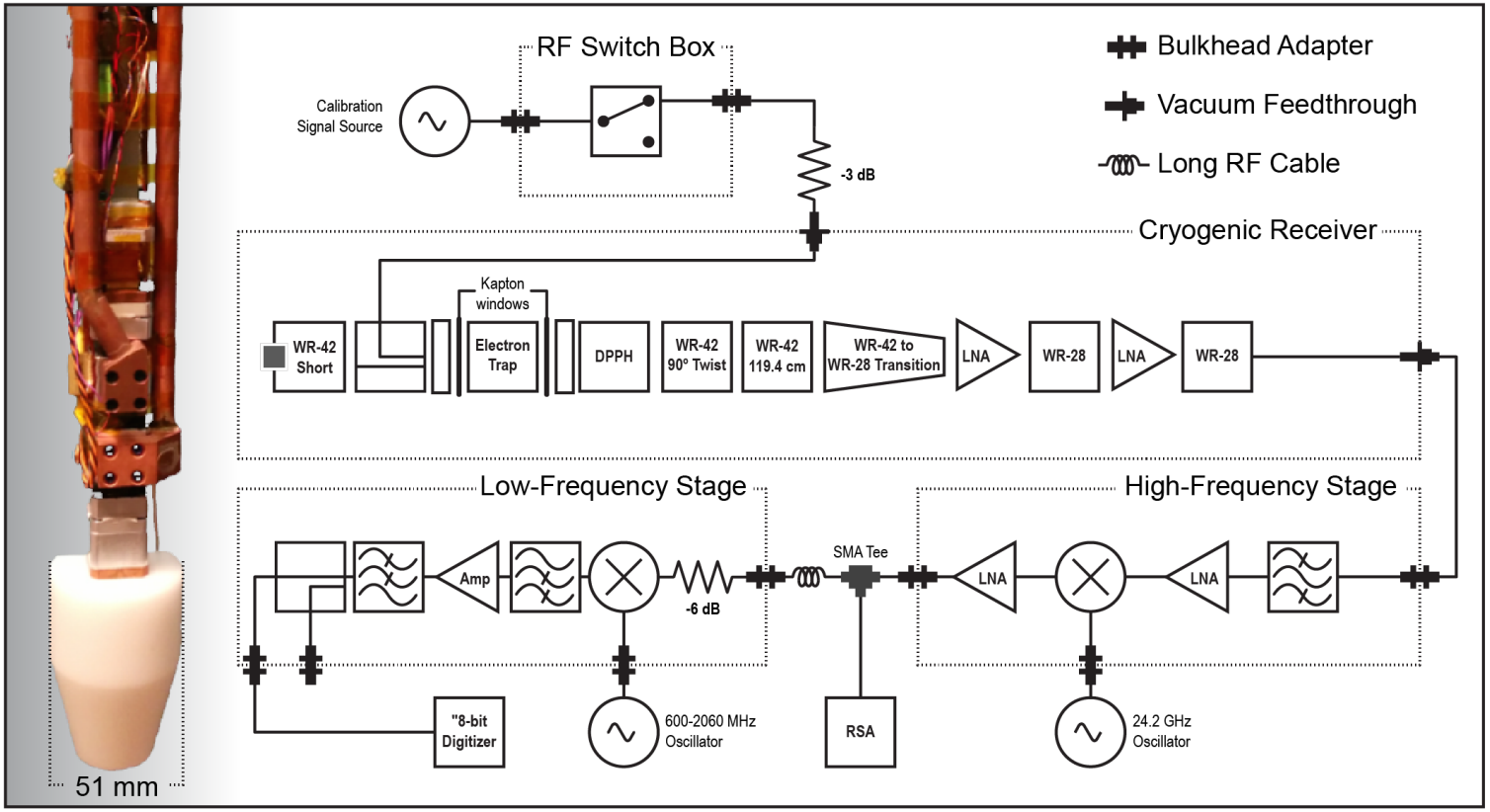


Axial motion: side band generation

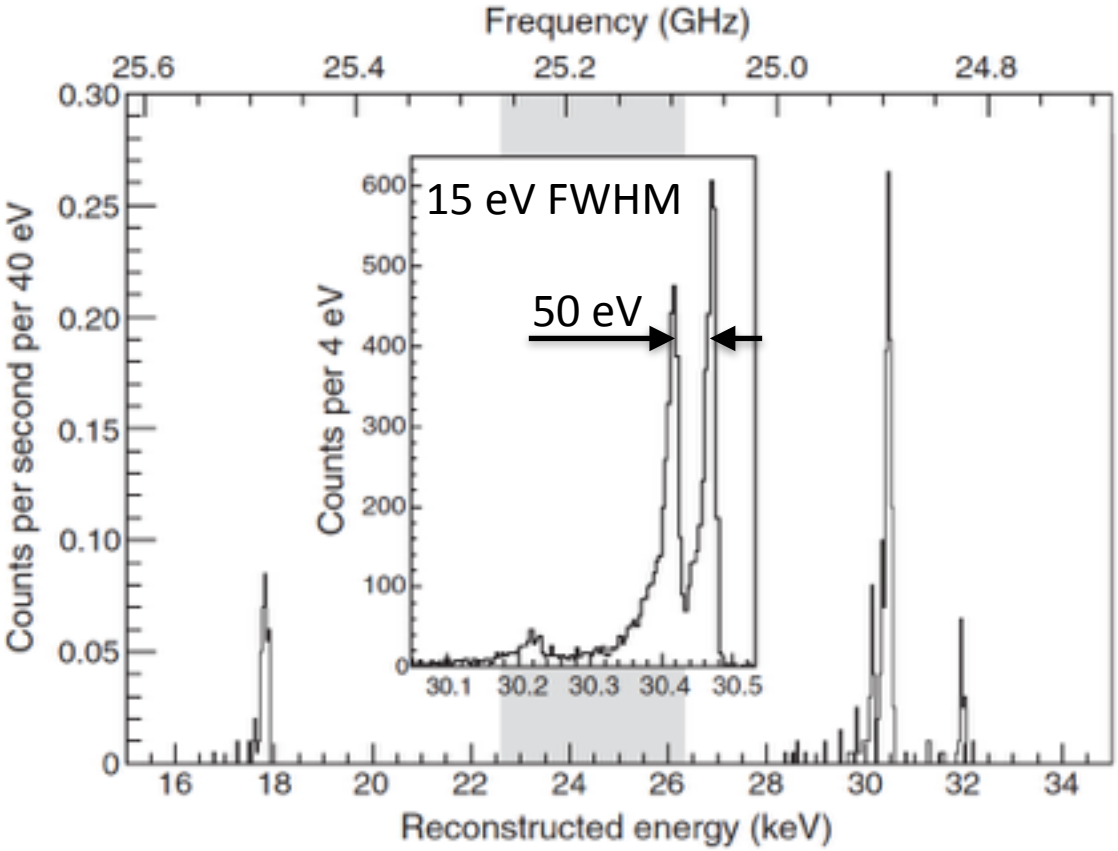


The microwave detector

- Cryogenic preamplifiers (50K physical temp.)
- Double stage frequency mixing (24.2 GHz, 0.6 GHz to 1.2 GHz)

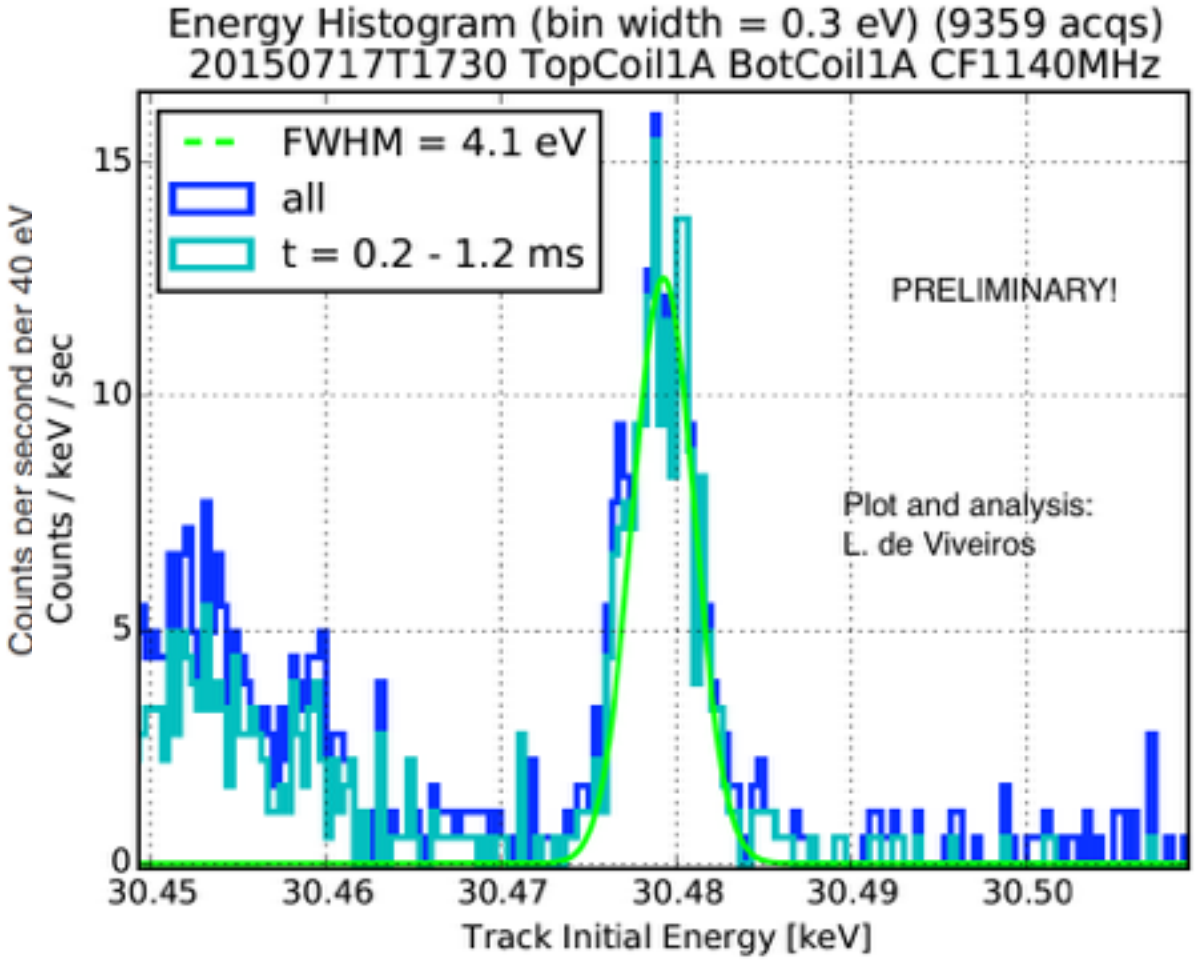


A cyclotron radiation emission spectrum of ^{83m}Kr conversion electrons

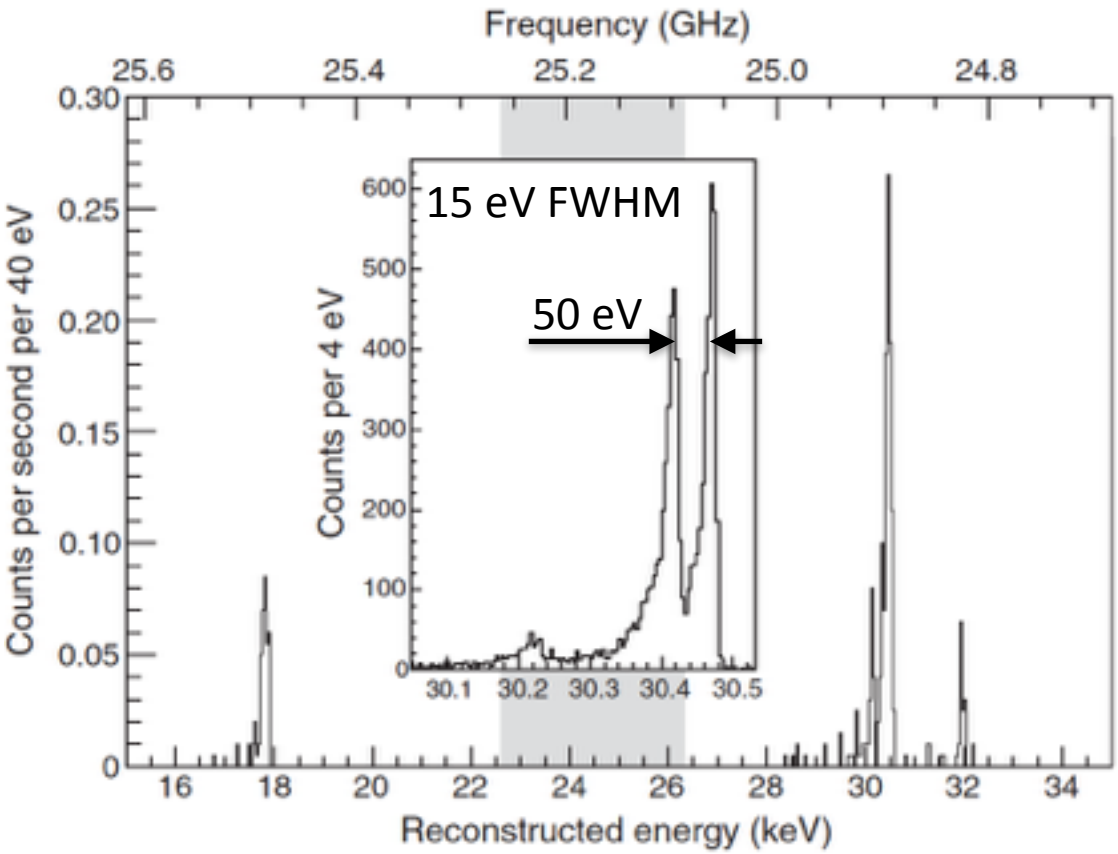


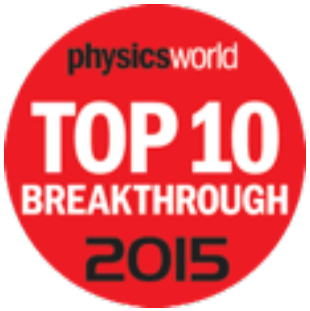
Asner et al., Physical Review Letters, 114, 162501 (2015)

A cyclotron radiation emission spectrum of ^{83m}Kr conversion electrons



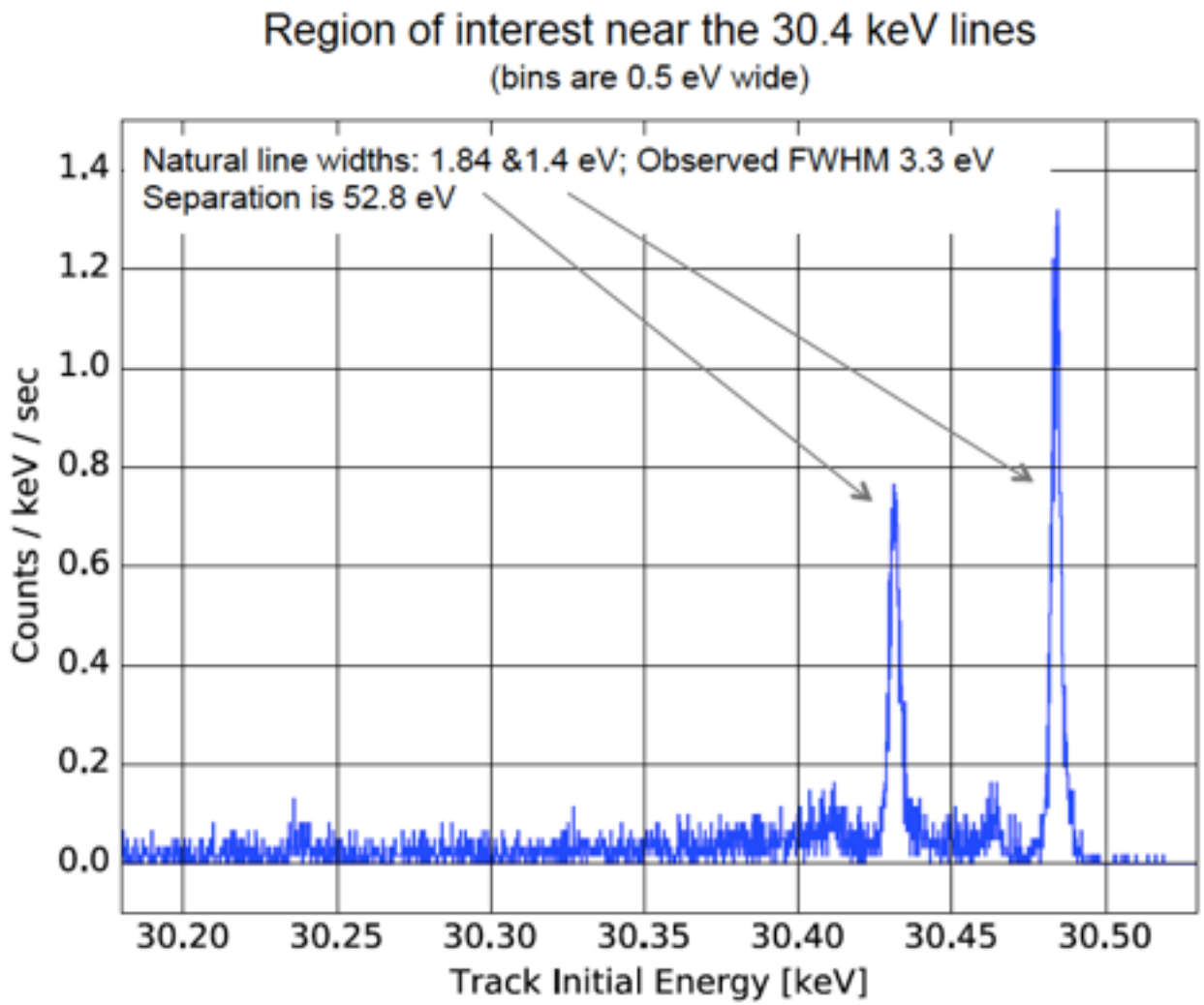
CRES spectrum of ^{83m}Kr conversion electrons

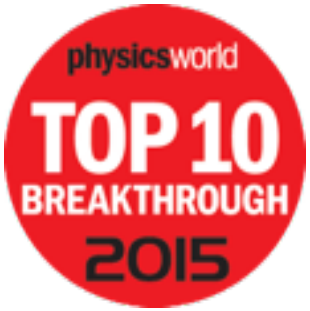




Asner et al., Physical Review Letters, 114, 162501 (2015)

CRES spectrum of ^{83m}Kr conversion electrons





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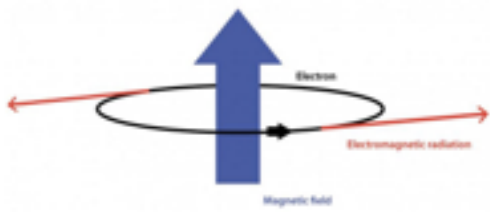

An electron in a magnetic field will turn circles and emit radiation.

Viewpoint

Cyclotron Radiation from One Electron

Patrick Huber
Center for Neutrino Physics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

Published April 20, 2015

An electron's energy can be determined with high accuracy by detecting the radiation it emits when moving in a magnetic field.

physicsworld TOP 10 BREAKTHROUGH 2015

In: symmetry, May 2015

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Nuclear Physics (NP)

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November 2015

Project 8 Detects Individual Electrons by their Cyclotron Radiation

New electron spectroscopy technique may lead to an improved neutrino mass determination.

Новости

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29.04.15 | Физика, *Игорь Иванов* | Комментарии (17)

QUICK STUDY

Ben Monreal is an assistant professor of physics at the University of California, Santa Barbara.

Single-electron cyclotron radiation

Benjamin Monreal

Experiments that track the radiation emitted by a lone electron orbiting a magnetic field may, in time, reveal the effects of neutrino mass.

In: Physics Today 69(1), 70 (2016)

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Física de Materiais - UFU
June 23, 2015

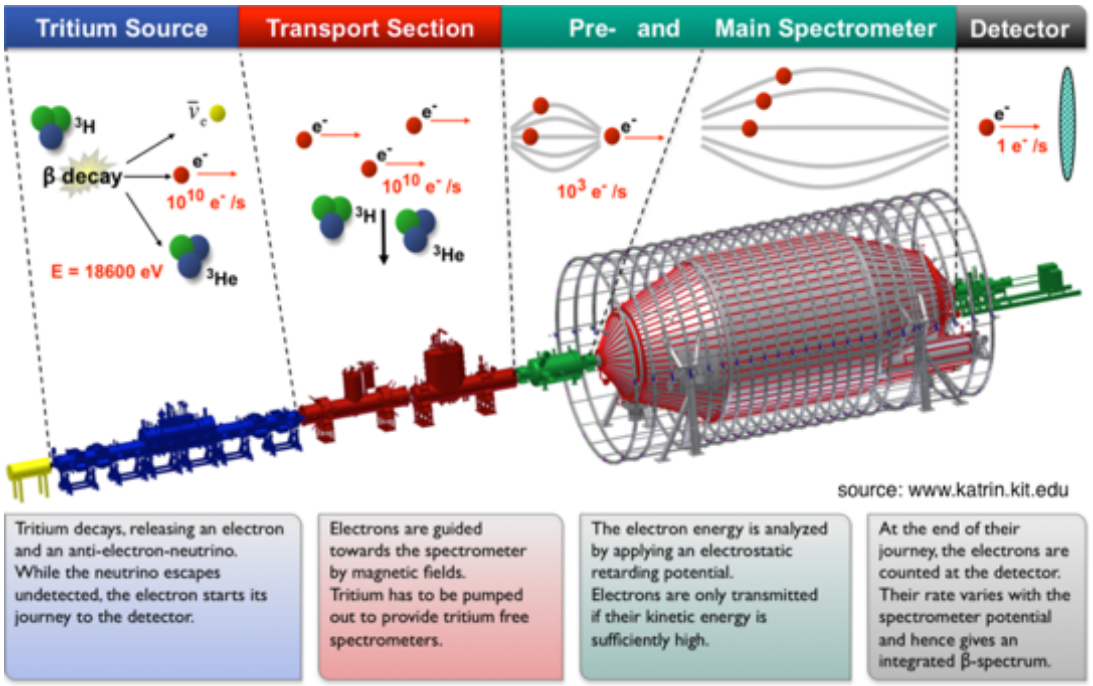
Journal Club 😊

O Journal Club da próxima sexta-feira, 26 de Junho, às 11:30 no Anfiteatro do Bloco 1X, será apresentado pelo Prof. Ricardo Kagimura. Segue a referência:

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation
D. M. Asner et al.
Phys. Rev. Lett. 114, 162501 (2015)

Electrostatic spectrometer with magnetic adiabatic conversion (MAC-E) technique

70 m long, 10 m diameter vacuum tank



- Window less gaseous tritium source (10^{10} Bq)
- Molecular T_2
- Anticipated mass sensitivity: < 200 meV (90% CL)
- Resolution scales like the area of the analyzing plane

First light in October 2016, tritium operation starting in early 2017!

Electrostatic spectrometer with magnetic adiabatic conversion (MAC-E) technique

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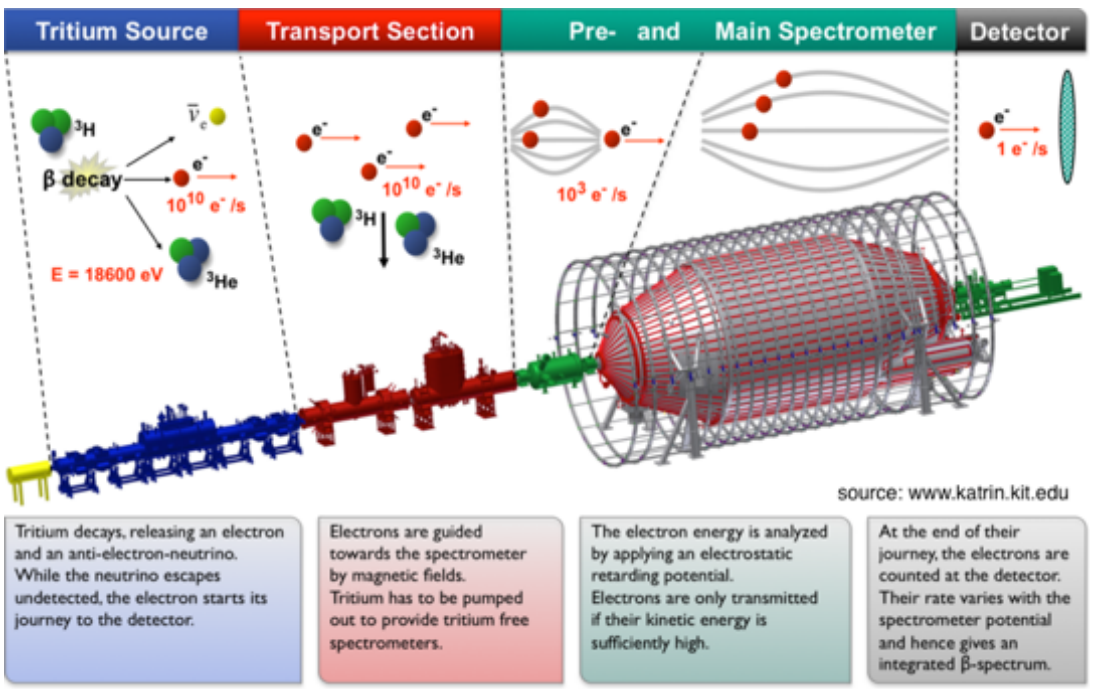


- Window less gaseous tritium source (10^{10} Bq)
- Molecular T_2
- Anticipated mass sensitivity: < 200 meV (90% CL)
- Resolution scales like the area of the analyzing plane

New technique needed for independent confirmation or to scale beyond MAC-E sensitivity

First light in October 2016, tritium operation starting in early 2017!

KATRIN: MAC-E-TOF

Neutrino mass sensitivity by MAC-E-Filter based time-of-flight spectroscopy with the example of KATRIN

Nicholas Steinbrink[1,3], Volker Hannen[1], Eric L Martin[2], R G Hamish Robertson[2], Michael Zacher[1] and Christian Weinheimer[1]

New Journal of Physics **15** (2013) 113020 (29pp)
Received 6 August 2013

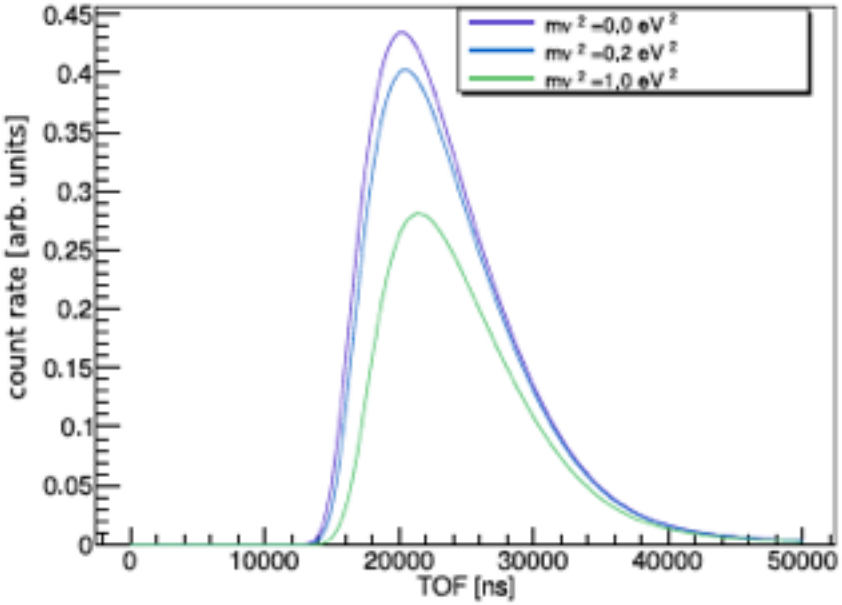


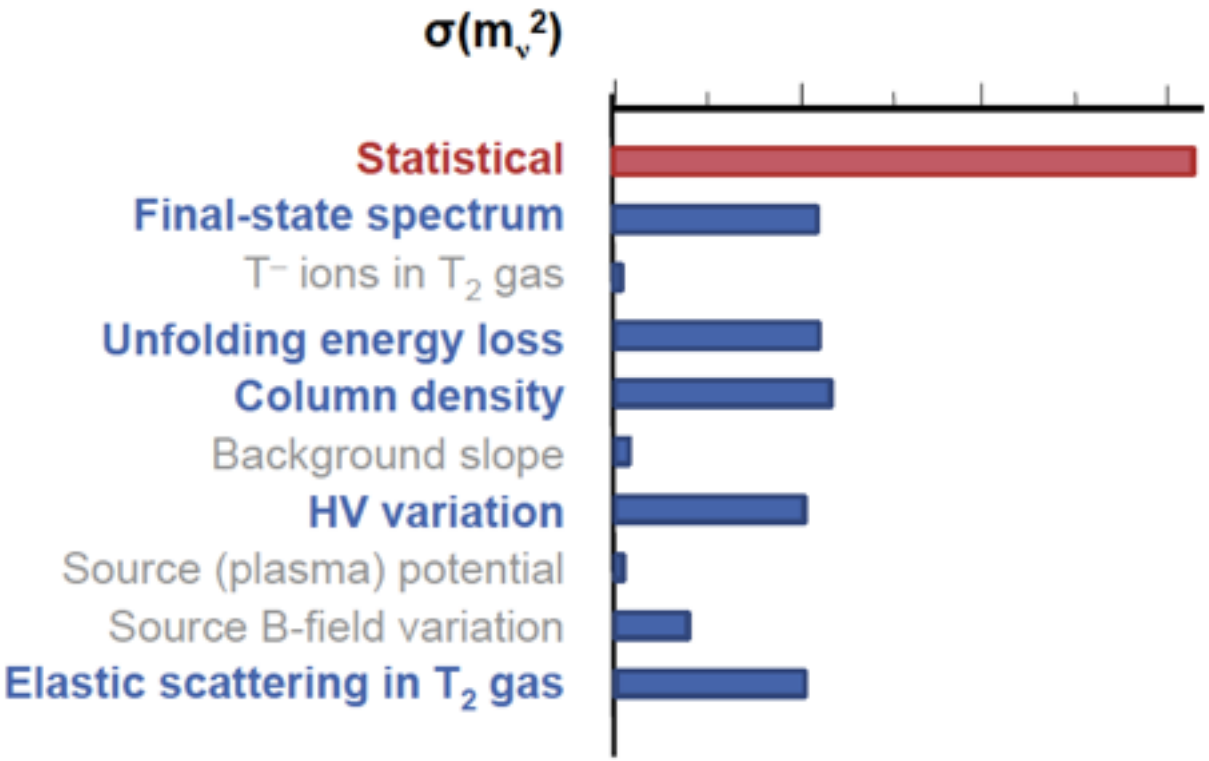
Figure 6. Effects on the TOF spectrum for different neutrino masses at a high retarding potential (18 570 eV) with endpoint $E_0 = 18\,574.0$ eV. The scaling of the y-axis is arbitrary.

But requires individual electron tagging!

as a function of the measurement interval below the endpoint E_0 (difference between lowest retarding potential and the endpoint E_0 using $E_0 = 18.575$ keV). Compared with the reference value of KATRIN, $\sigma_{\rm stat}(m_{\nu_e}^2) = 0.018\,{\rm eV}^2/c^4$ (see figure 13 curve (b) for measurement interval

of 30 eV), a statistical improvement of up to a factor 5 is possible in the optimal case (figure 13 (1)), equivalent to a factor of more than 2 in statistical sensitivity of m_{ν_e}. It can be shown (compare the difference in figure 13 between curves (b) and (c) w.r.t. point (2)) that this improvement factor is essentially not caused by neglecting the background but by intrinsic advantages of the method itself. A total improvement factor needs to take the systematics

The sensitivity reach of KATRIN

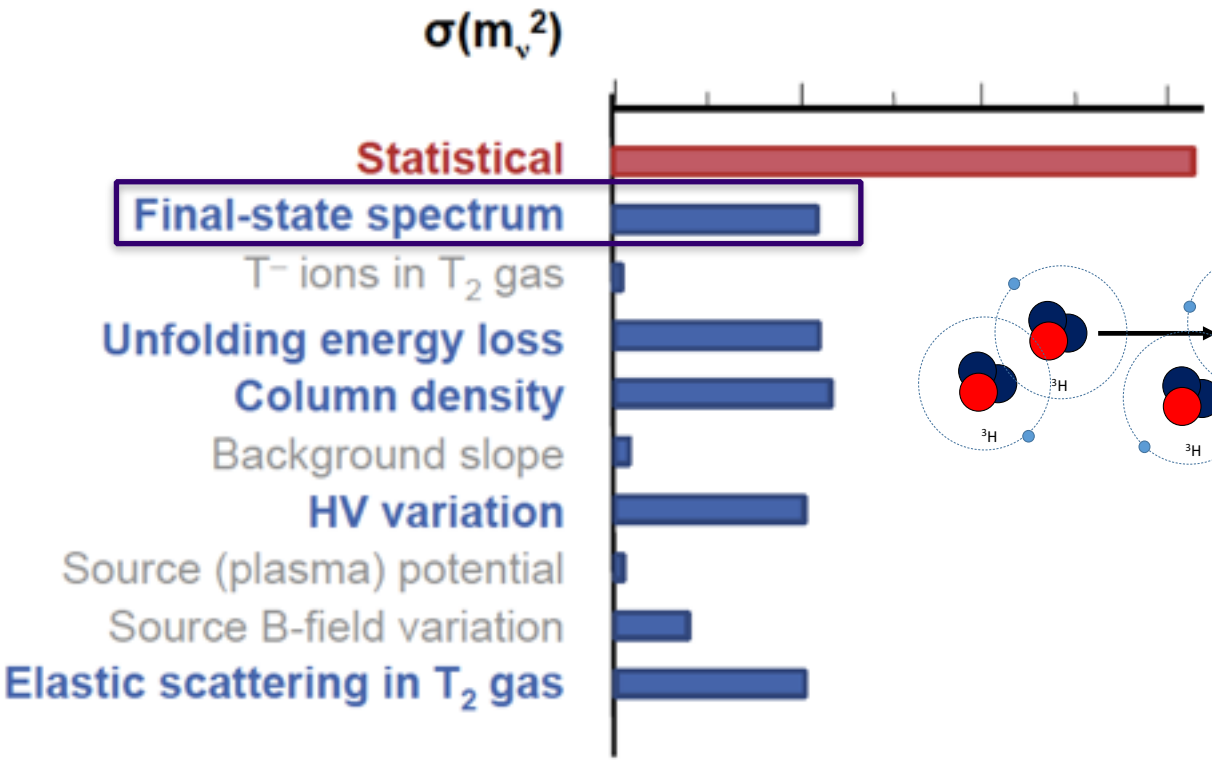


$\sigma(m_\nu^2)_{stat} = 0.018\ eV^2$

$\sigma(m_\nu^2)_{syst} = 0.017\ eV^2$

Kathrin Valerius, HEPHY Colloquium, Vienna, Jan 2016

The sensitivity reach of KATRIN



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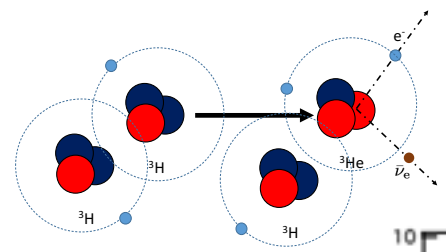
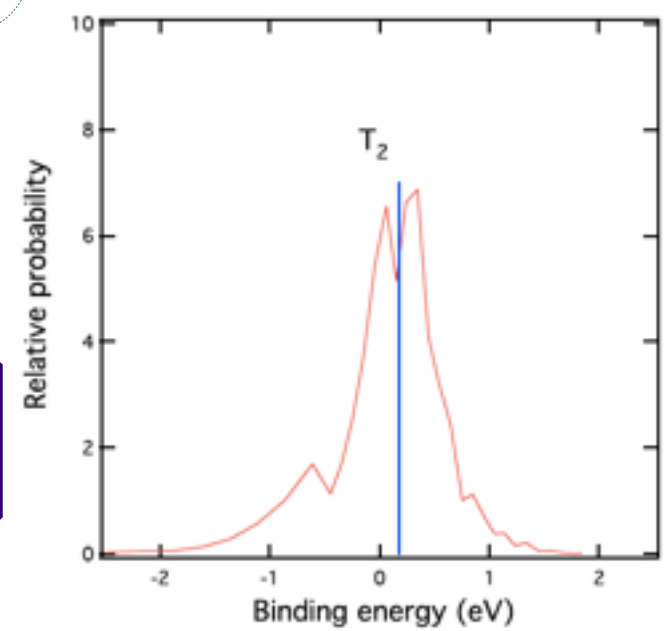
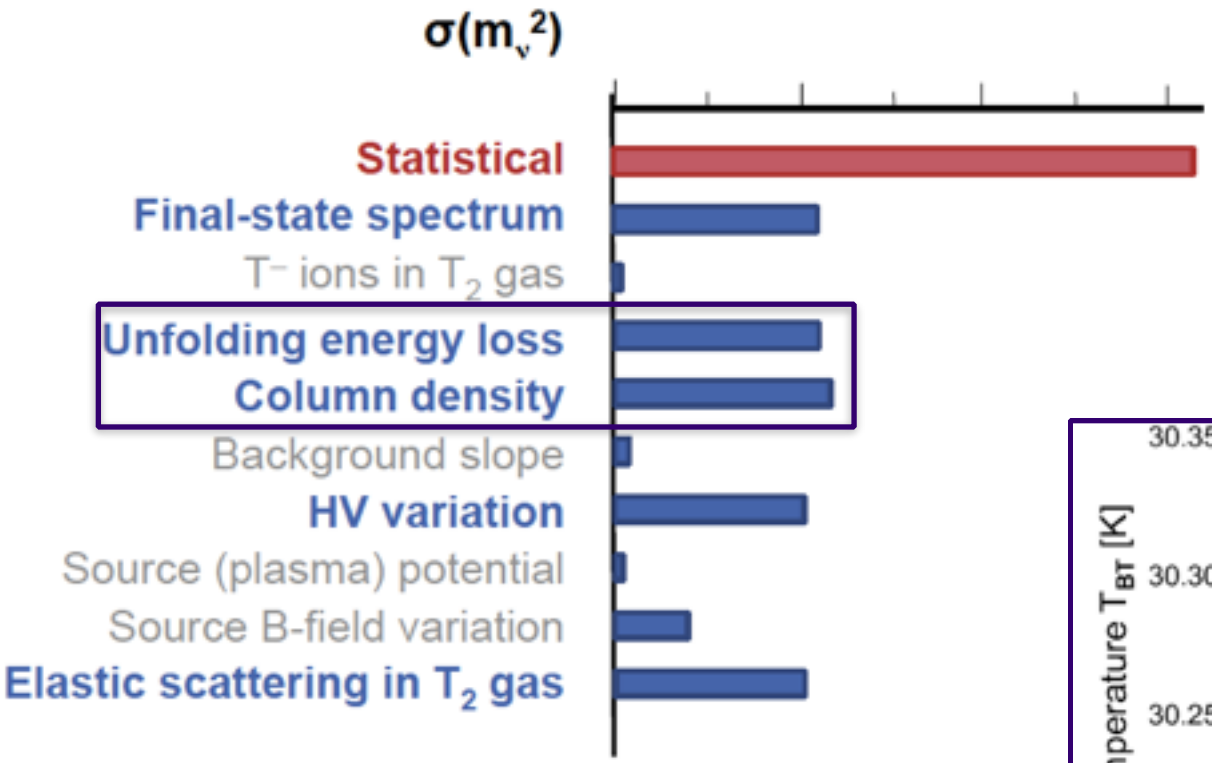




Any T_2 experiment suffers from irreducible excitation of ro-vibrational initial and final states

Kathrin Valerius, HEPHY Colloquium, Vienna, Jan 2016

The sensitivity reach of KATRIN



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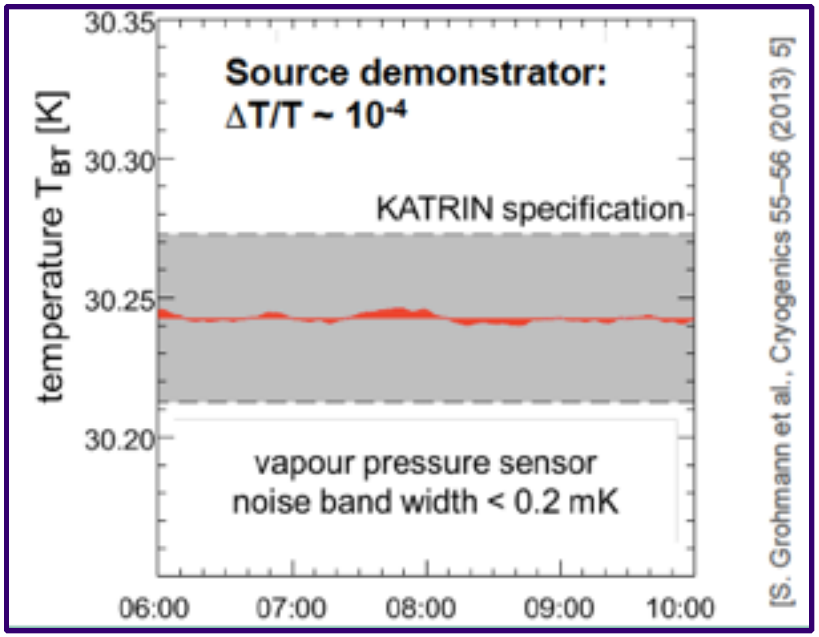

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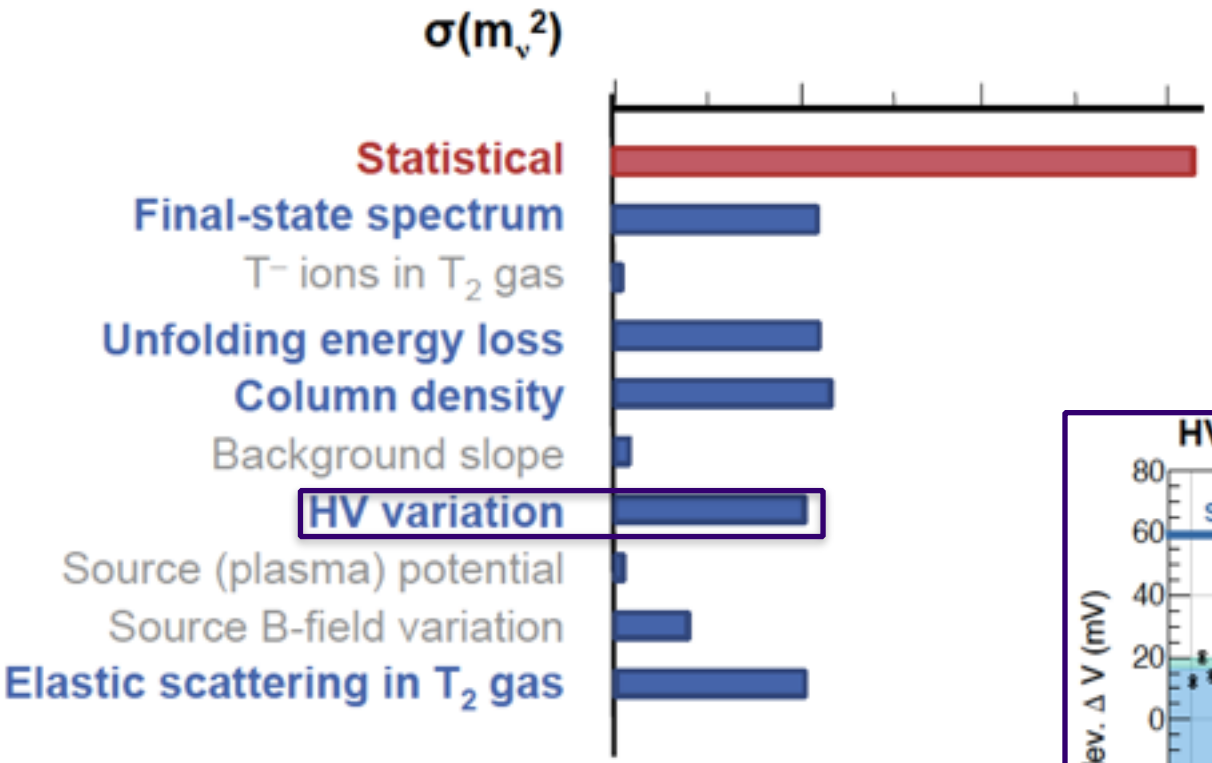
The sensitivity reach of KATRIN



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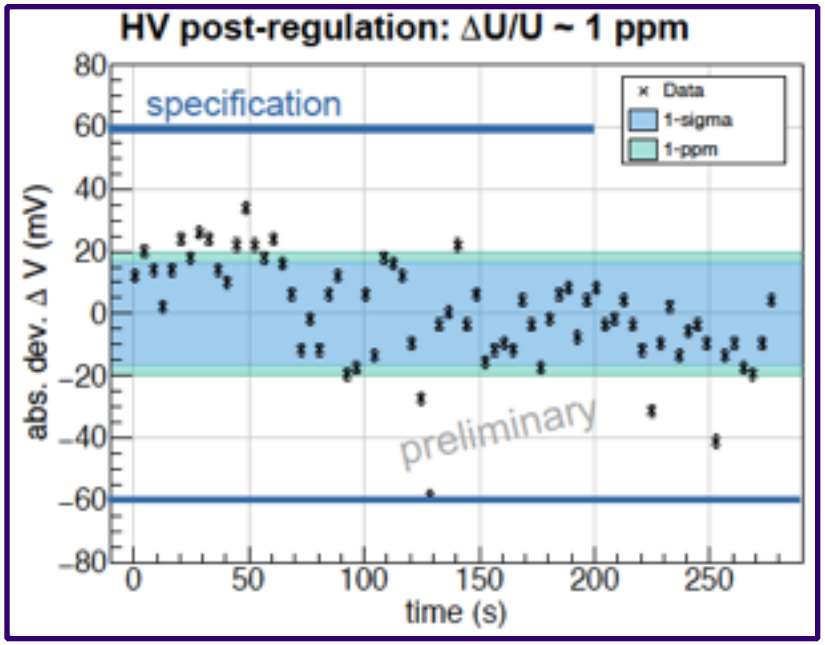

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