Measuring the neutrino masses: KATRIN, ^{163}Ho, Project 8

CCAPP seminar
Ben Monreal

There are three different neutrinos:

- ν_1, ν_2, ν_3 are ordinary massive particles
- ν_e, ν_μ, ν_τ are our favorite superpositions

neutrino source uses some particular charged lepton

$$\begin{matrix} W^+ + e^- \\ W^+ + \mu^- \\ W^+ + \tau^- \end{matrix} = \left\{ \begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix} \right\} \left\{ \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \right\} \quad \begin{matrix} \text{light } \nu \\ \text{medium } \nu \\ \text{heavy } \nu \end{matrix}$$

Quantum phases obey Schrodinger's equation during flight

$$\left\{ \begin{matrix} U_{e1}\nu_1 \, e^{im1t} \\ U_{e2}\nu_2 \, e^{im2t} \\ U_{e3}\nu_3 \, e^{im3t} \end{matrix} \right\} \left\{ \begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix} \right\} = \begin{matrix} W^+ + e^- \\ W^+ + \mu^- \\ W^+ + \tau^- \end{matrix}$$

neutrino detector uses some particular charged lepton

Neutrino oscillations

- Phase relationships define "flavor"
- Phase evolution = flavor oscillation

detection:
projection onto a flavor eigenstate

$n\, \nu \rightarrow p^+ e^-$

propagation:

$e^{iE1t}\, 0.3\, |m_1\rangle + e^{iE2t}\, 0.3\, |m_2\rangle + e^{iE3t}\, 0.3i\, |m_3\rangle =$

neither a mass nor a flavor eigenstate

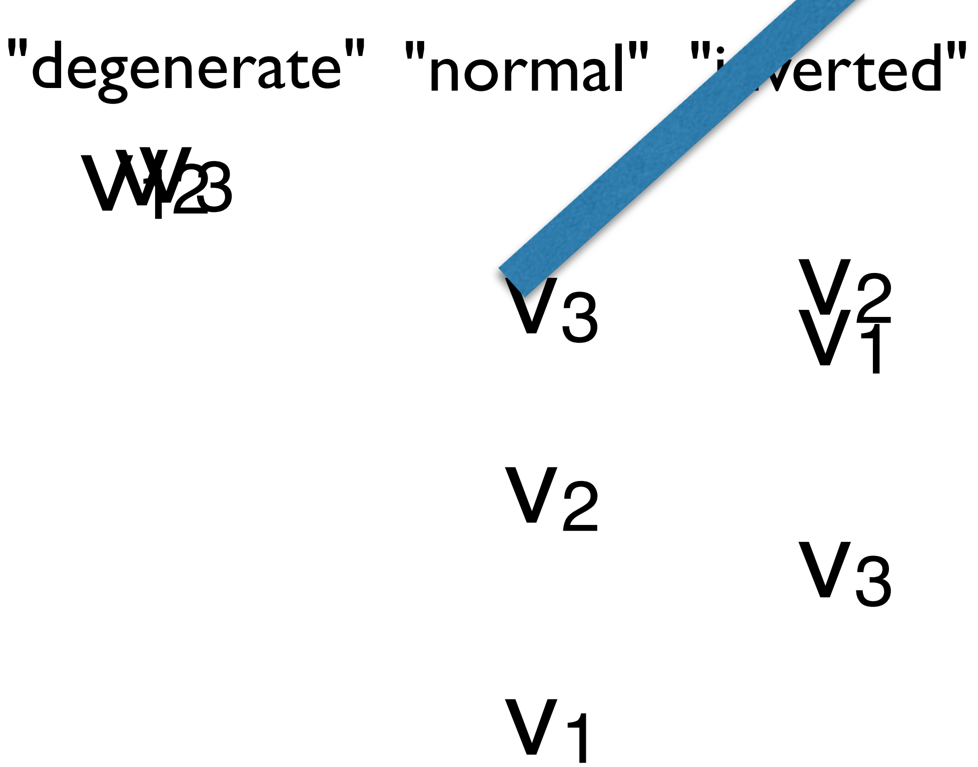
$\pi^+ \rightarrow \mu^+ \nu$

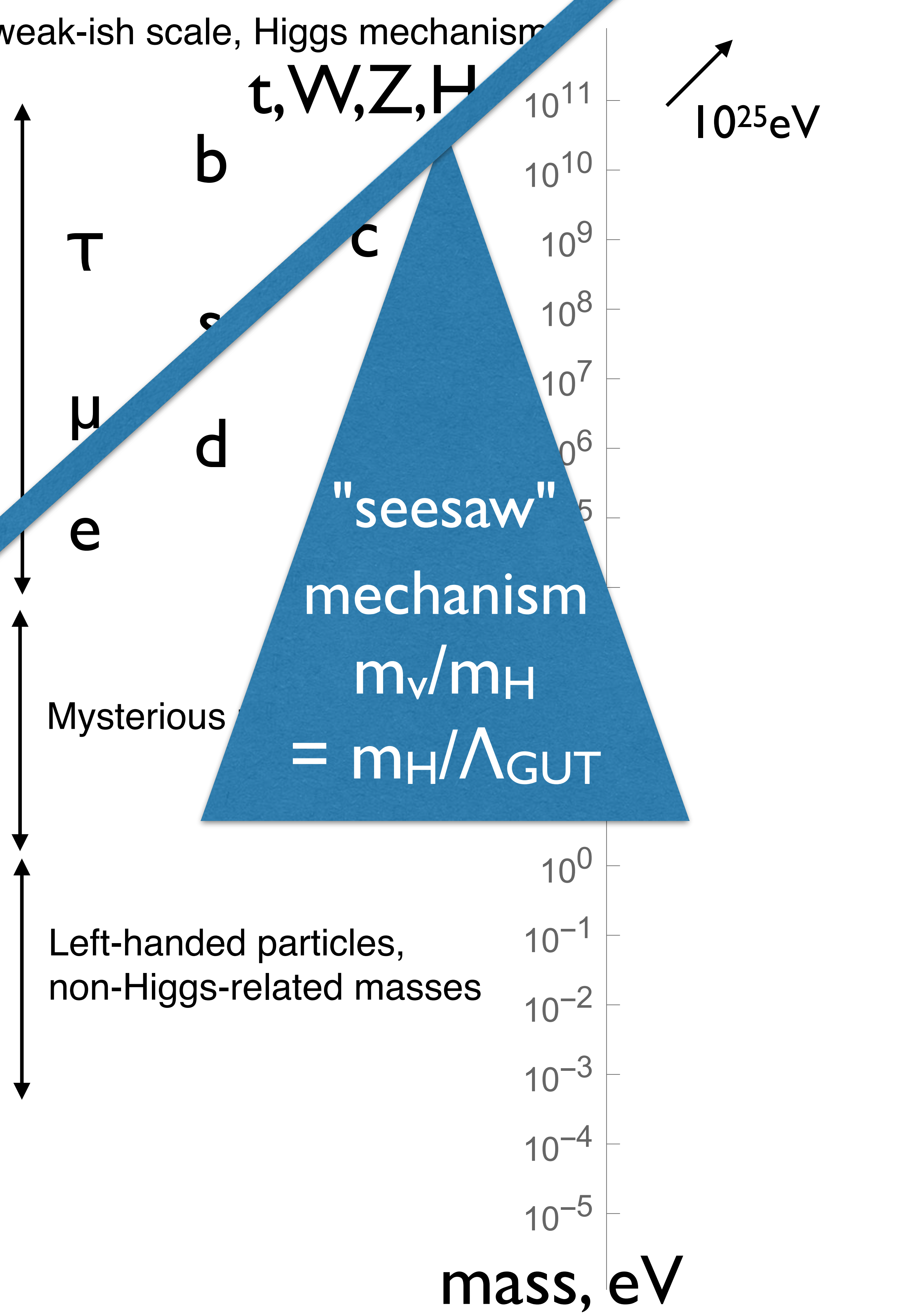
"muon neutrino" = flavor eigenstate

$= 0.3\, |m_1\rangle + 0.3\, |m_2\rangle + 0.3i\, |m_3\rangle$

not a mass eigenstate

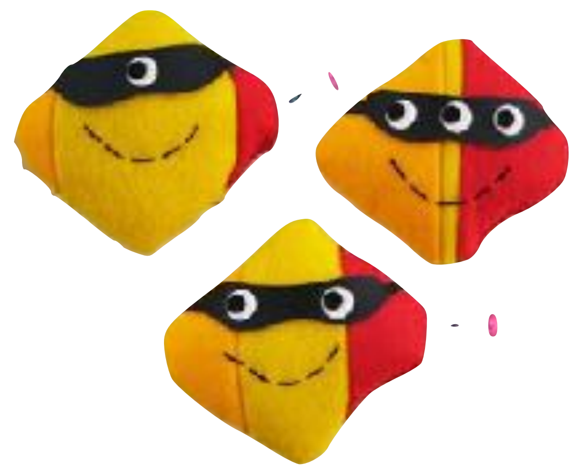
	Create	Detect	Useful for
Sun	e	e disappear	Proves $m_2 > m_1$
Reactor	$\bar{e}$	e disappear	θ_{12}, θ_{13} $m_1^2 - m_2^2$
Accelerator	$\mu,\bar{\mu}$	μ disappear e,τ appear	Many things
Atmosphere	$\mu,\bar{\mu}$	μ disappear e appear	θ_{23} $m_2^2 - m_3^2$





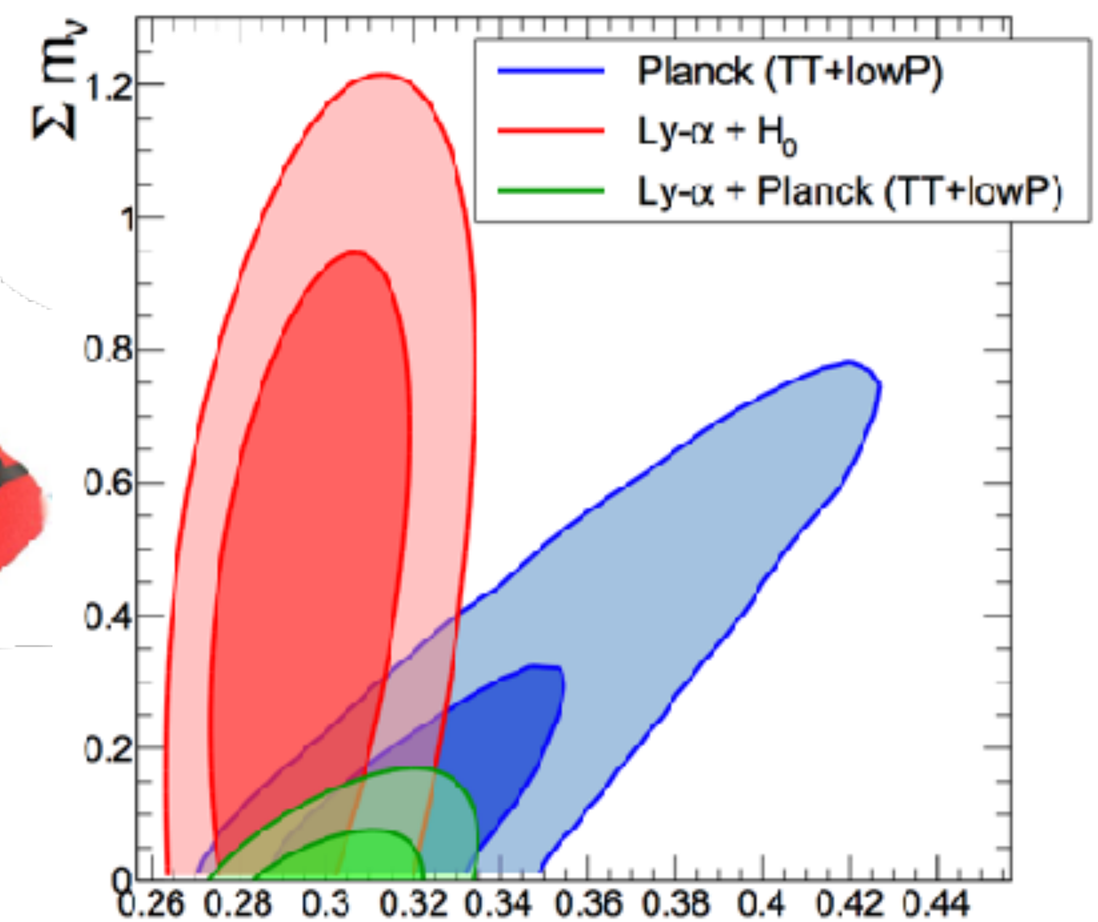
Cosmological mass

ν1, ν2, ν3
have different masses



← kinematics/relativity only cares about these

$$\sum_{i=1,2,3} m_i$$



Nathalie Palanque-Delabrouille 1506.05976

outgoing state is:

$$|\nu_l\rangle = U_{l1}\,|\nu_3\rangle + U_{l2}\,|\nu_2\rangle + U_{l3}\,|\nu_1\rangle$$

a different superposition depending on the charged lepton

Beta decay emits ν1 (~70%) or ν2 (~30%) or ν3 (~2%).

Studying neutrinos without detecting them

$^{14}_{6}C \rightarrow {}^{14}_{8}N \quad e^-$

Spin = 0 Spin = 1 Spin = 1/2

$^{214}_{83}Bi \rightarrow {}^{214}_{84}Po^+ \; e^-$

E = ? E = ? Ee = anywhere between 0 and 3.2 MeV

In Fig. 1, the end of the distribution curve for $\mu=0$ and for large and small values of μ is sketched. The greatest similarity to the empirical curves is given by the theoretical curve for $\mu=0$.

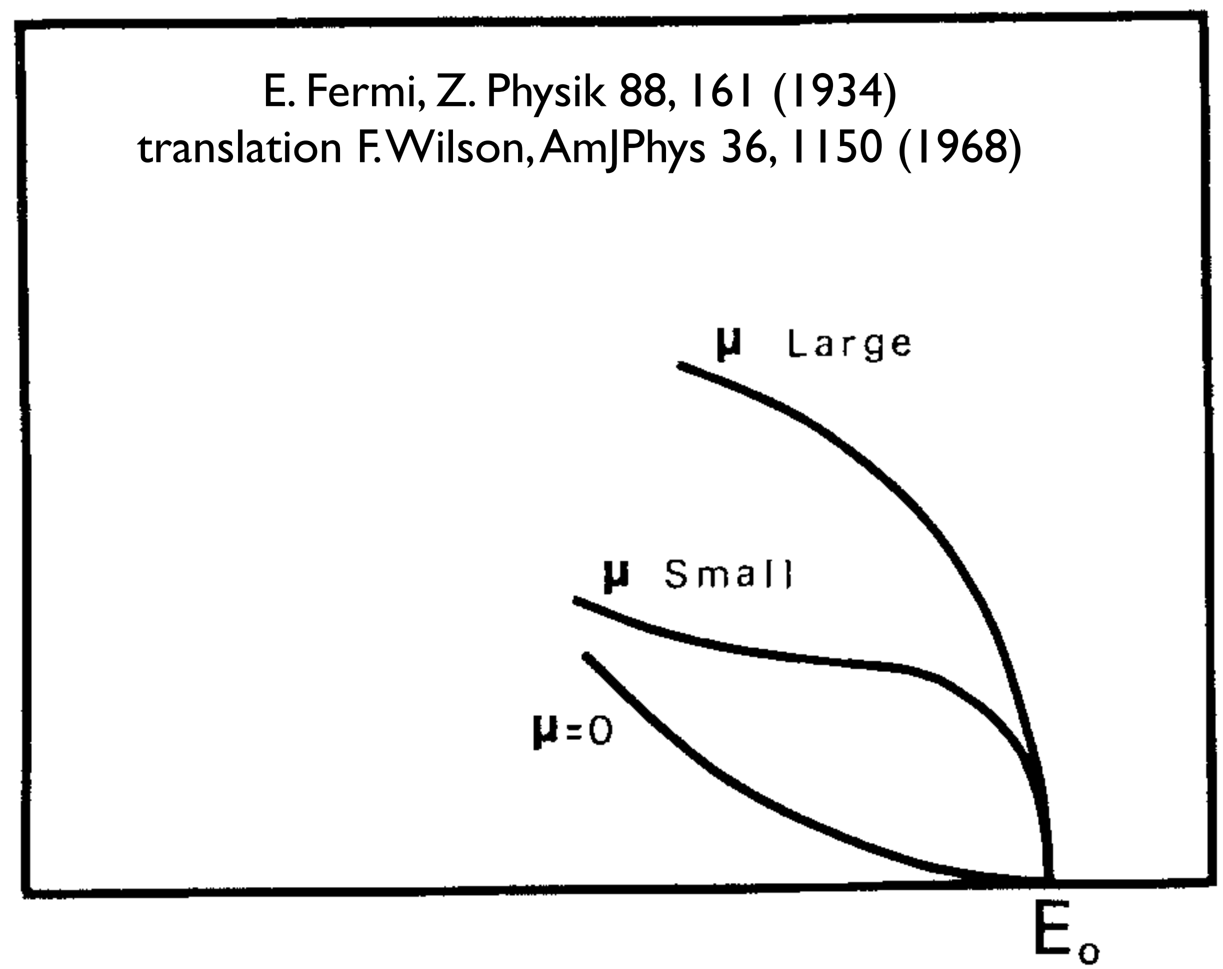


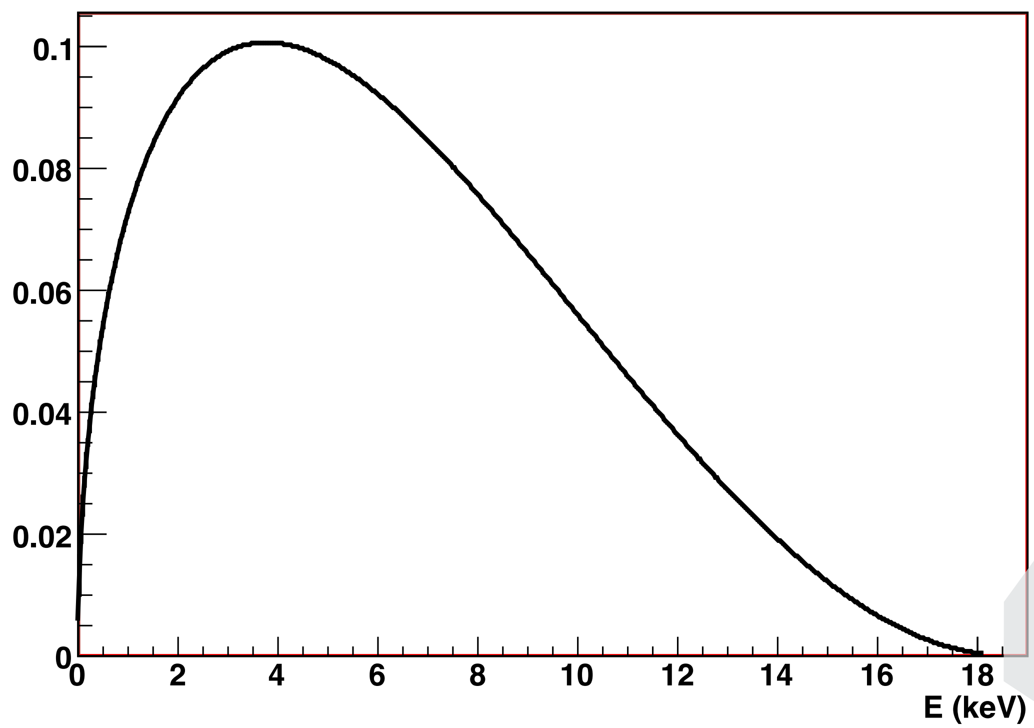
FIG. 1. The end of the distribution curve for $\mu=0$ and for large and small values of μ.

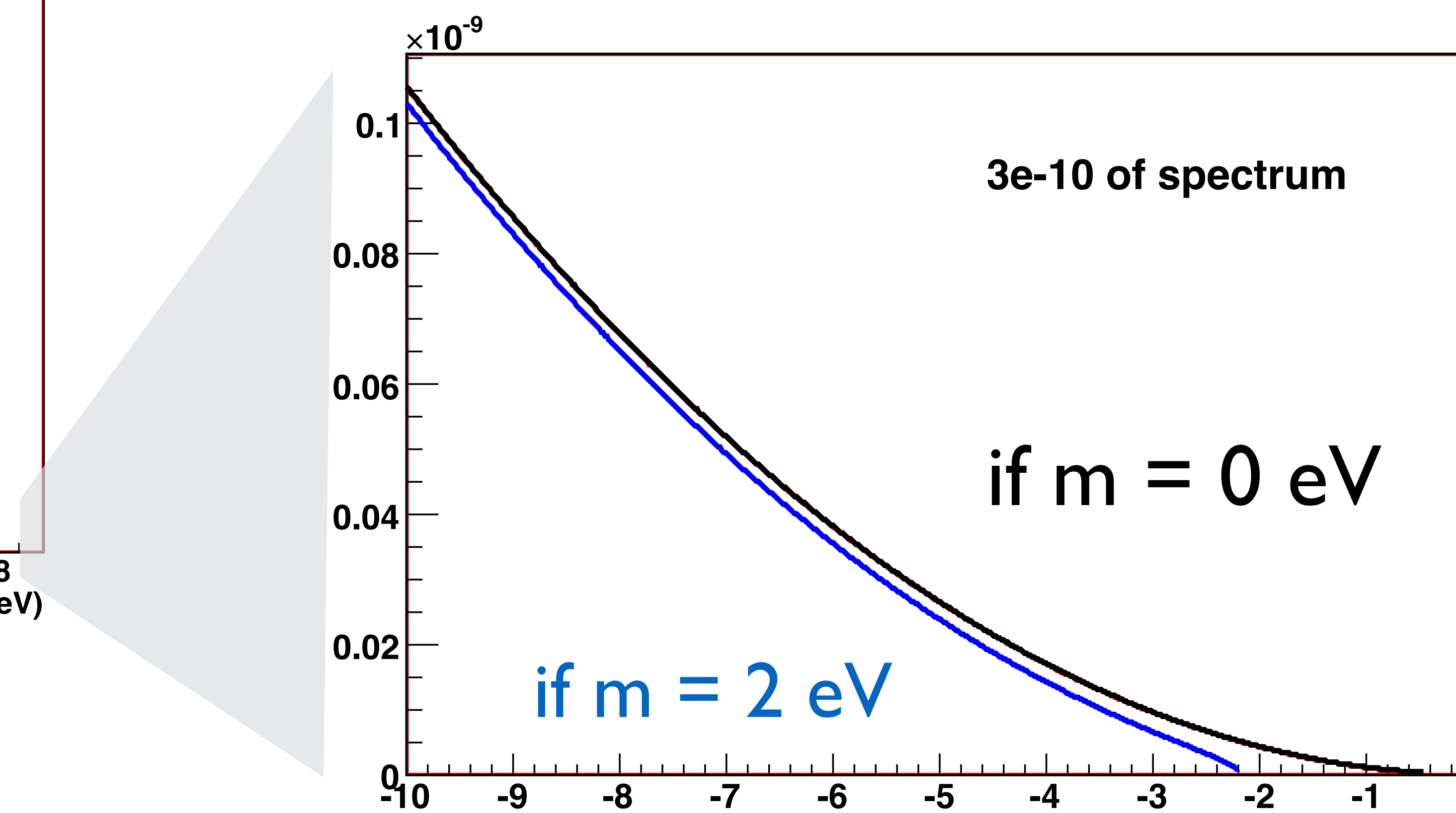
Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron.[10] In the

Direct = kinematic neutrino mass measurement

Measure kinematics
of a three-body decay with a
neutrino nearly at rest

- Tiny phase space = rare
- need good energy resolution
- same energy scale as atomic/ molecular effects

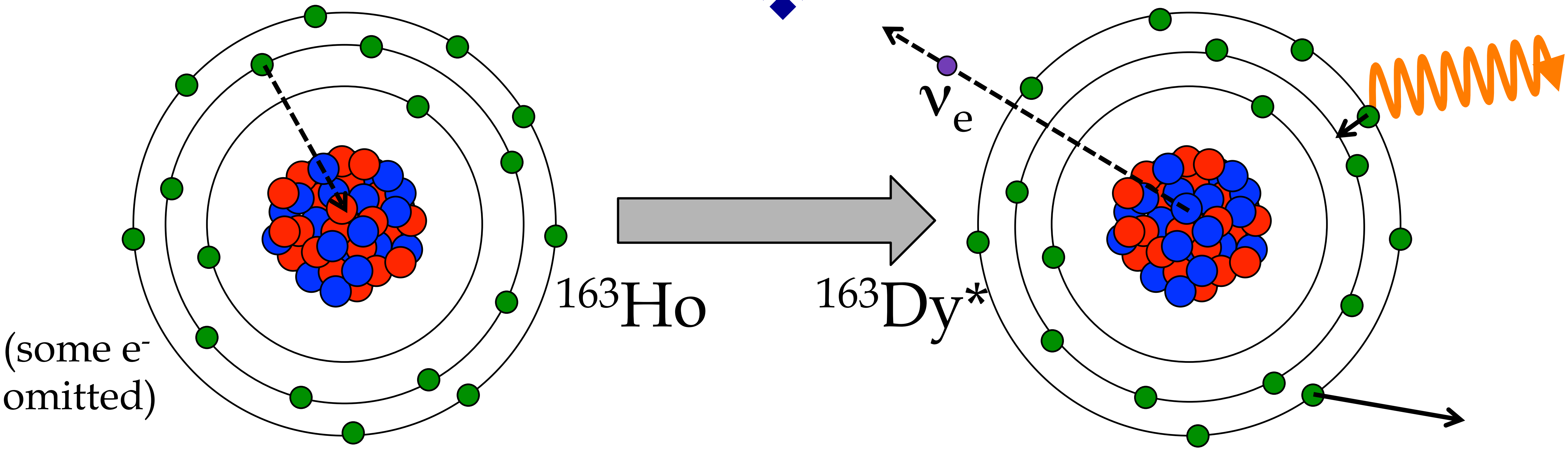




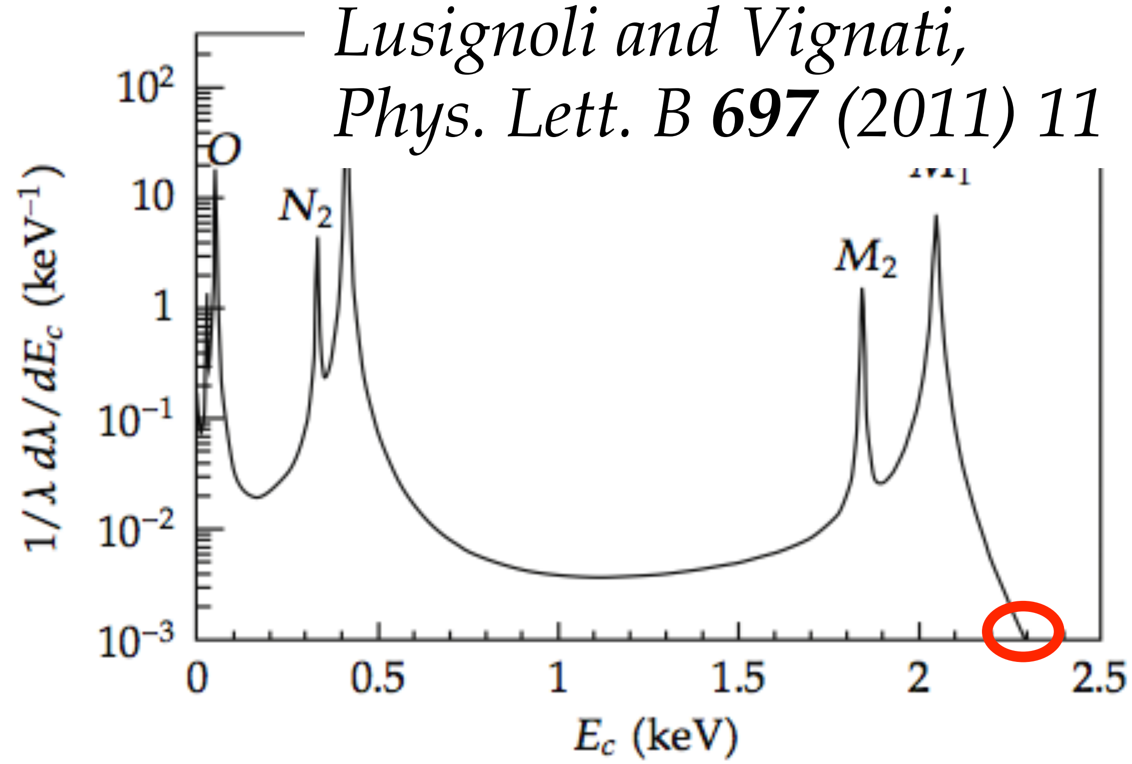
$$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \overline{\nu}_e$$

$$^{163}Ho \rightarrow 163Dy^{+} + \overline{\nu}_e + \gamma$$

Direct m_ν from Electron Capture

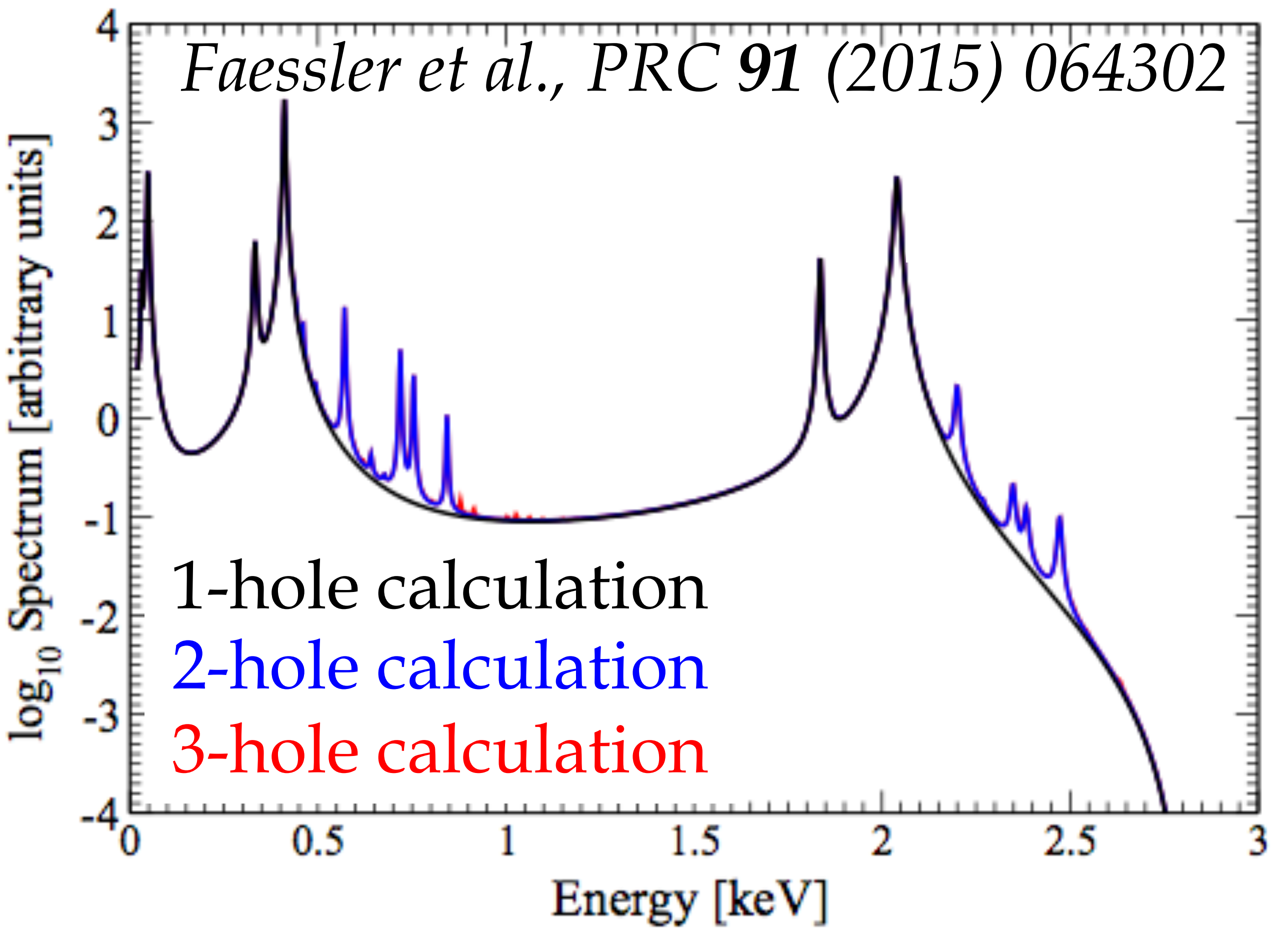


- Capture de-excitation energy in $^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^* + \nu_e$



^{163}Ho: Shakeup

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



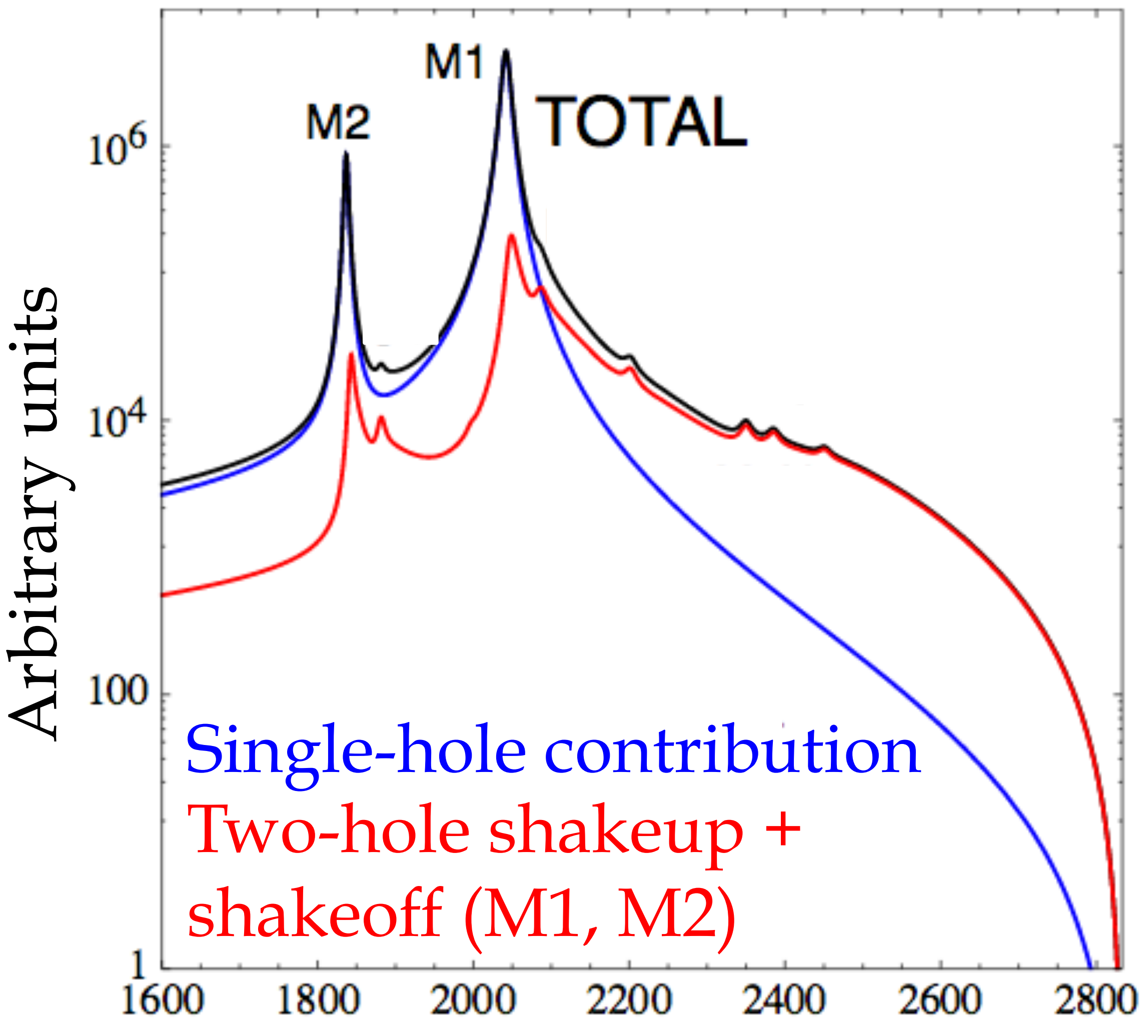
- New resonance(s)
- Structure near endpoint complicates m_ν^2 extraction

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

- Looks like a few % effect, separated from endpoint

^{163}Ho: Shakeoff

- Electrons can also be excited to the continuum
  - 3-body process, $^{163}\mathrm{Ho} \longrightarrow {}^{163}\mathrm{Dy}[H,H'] + e^- + \nu_e$

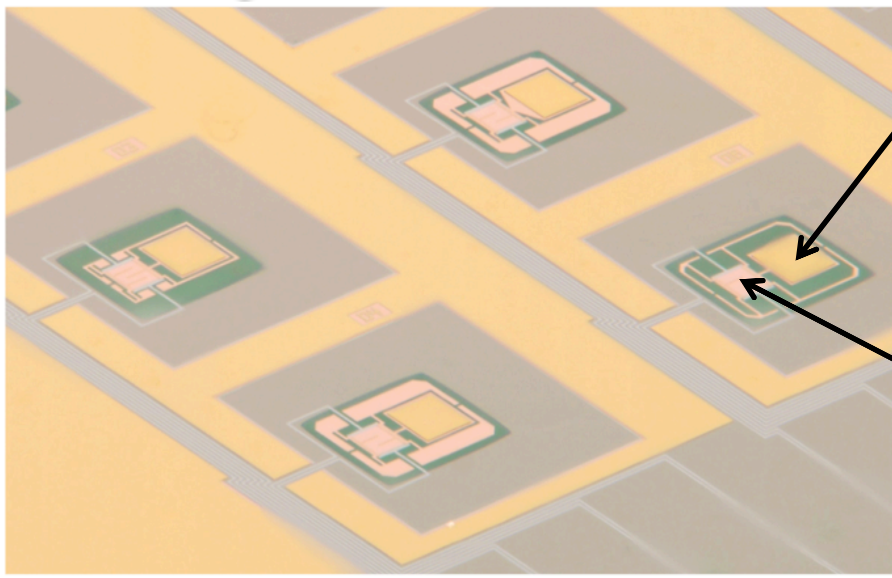


De Rújula and Lusignoli, JHEP ***2016*** *15, 2016*

- Recent preliminary calculations near endpoint
  - Enhanced statistics (40x near endpoint)
  - Relative pileup contribution reduced
  - More complex analysis?
- Ongoing theory work

Direct m_ν from Electron Capture

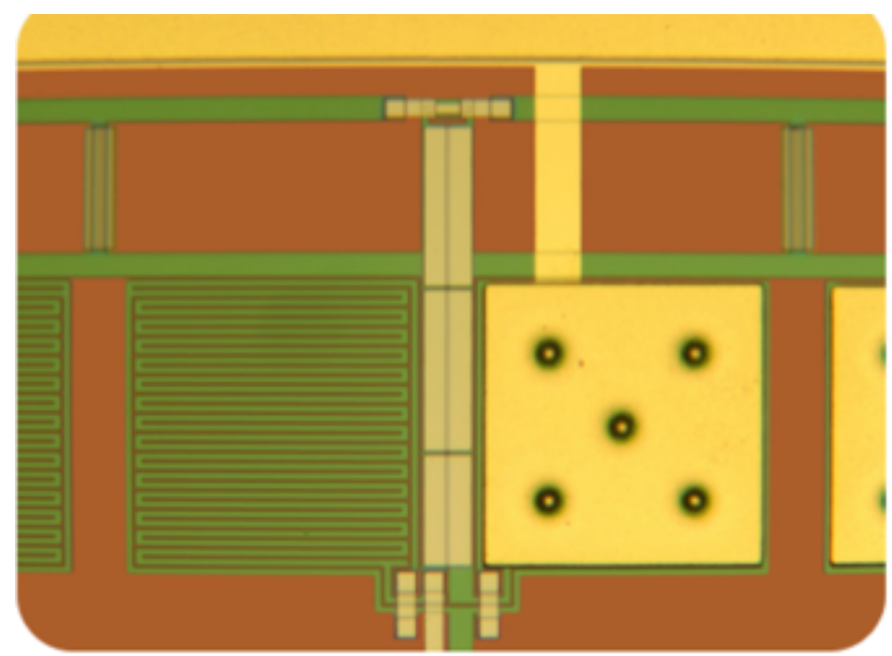
HOLMES



Au absorber with ^{163}Ho filling

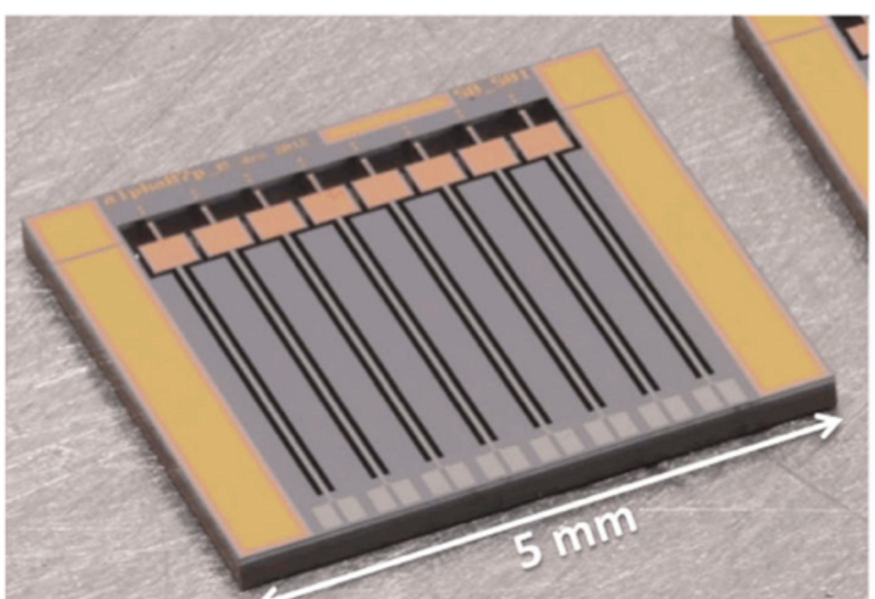
Mo-Cu transition edge sensor

ECHo

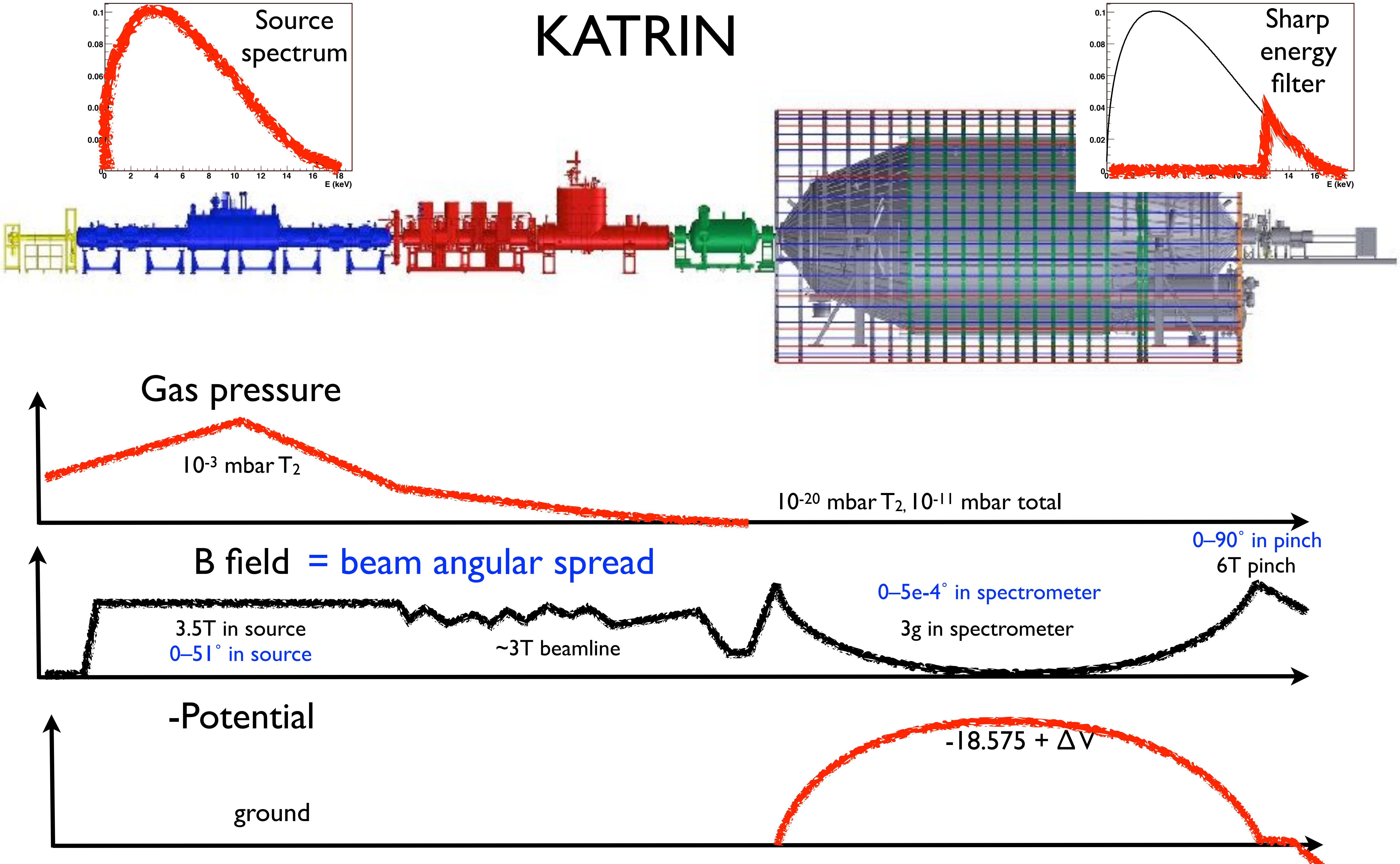


MMC

NuMECS



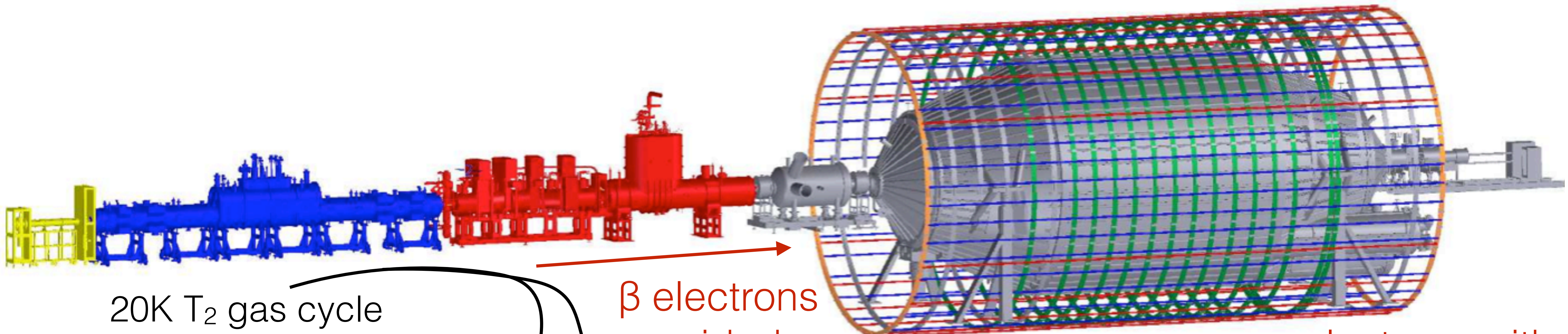
KATRIN



WGTS
Windowless Gaseous Tritium Source

"MAC-E filter"
Magnetic Adiabatic Collimation + Electrostatic filter

KATRIN

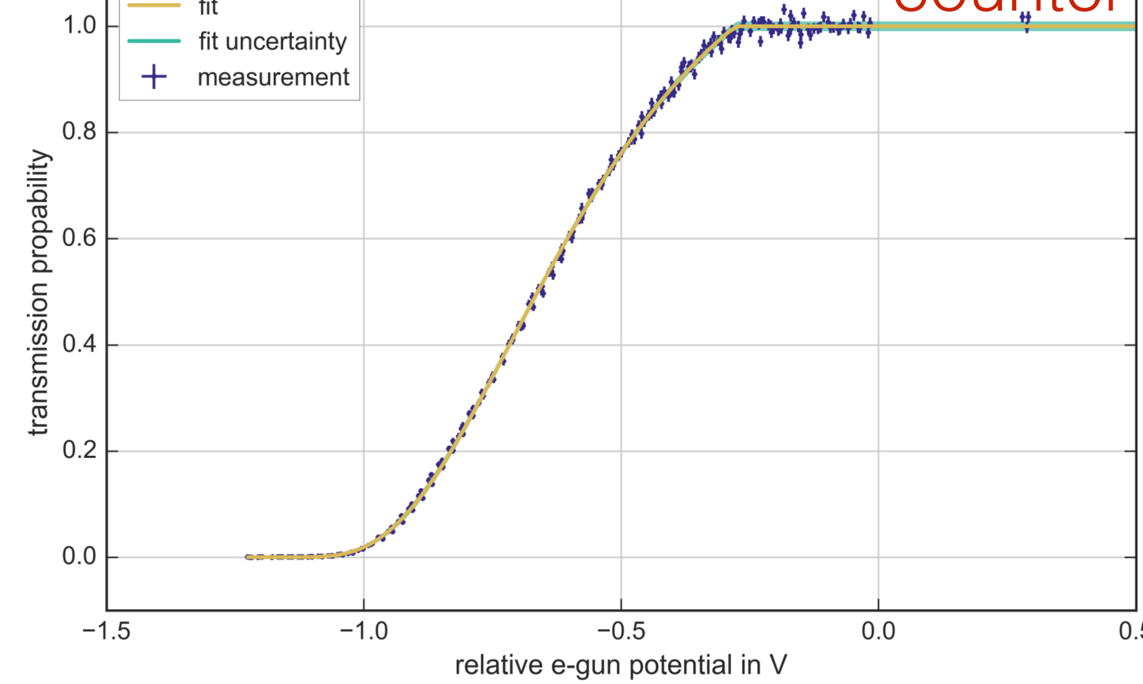


20K T_2 gas cycle
some decays in
3.5 T magnet

β electrons
guided
magnetically

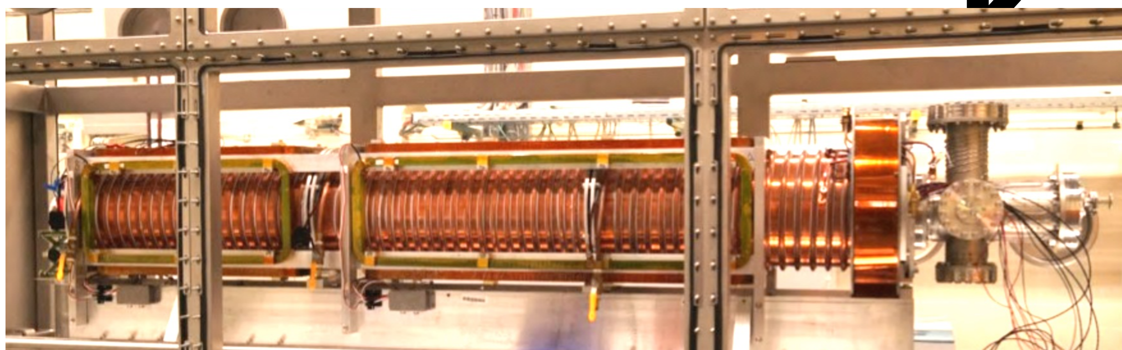
electric potential
reflects electrons
with E < qV

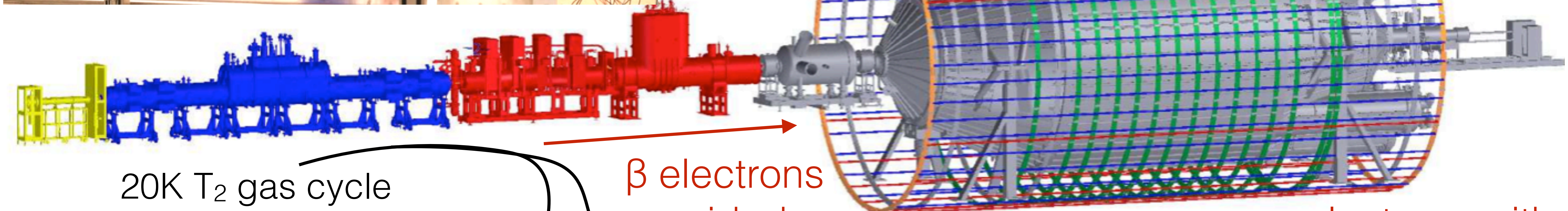
electrons with
E > qV pass
and arrive at
counter



Sharp highpass filter
width = 0.9 eV
very well known shape

KATRIN





20K T_2 gas cycle
some decays in
3.5 T magnet

β electrons
guided
magnetically

electric potential
reflects electrons
with $E < qV$

electrons with
$E > qV$ pass
and arrive at
counter

Beamline
closed now

e- transmission
this month!

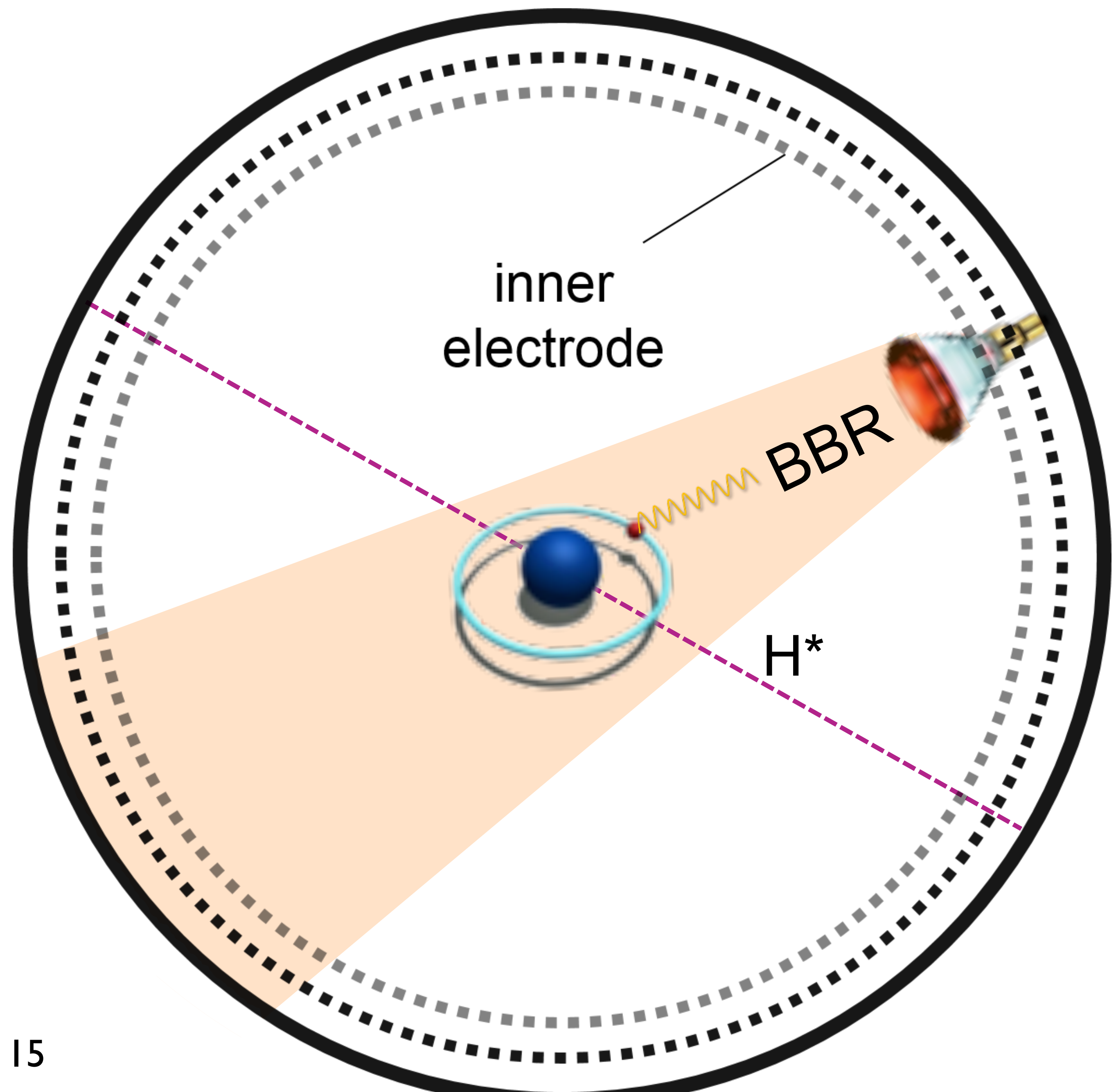
KATRIN status

- Krypton running now
- Current expectations:
  - Background rates *worse* than design report
  - ~~0.20~~ 0.23 eV sensitivity
  - Systematics control *better* than design report
- Tritium in early 2018

Example of unexpected background:

a) Radioactivity sputters H* from wall

b) H* thermally ionizes in flight



BM & Formaggio, PhysRevD 2009

The Project 8 concept

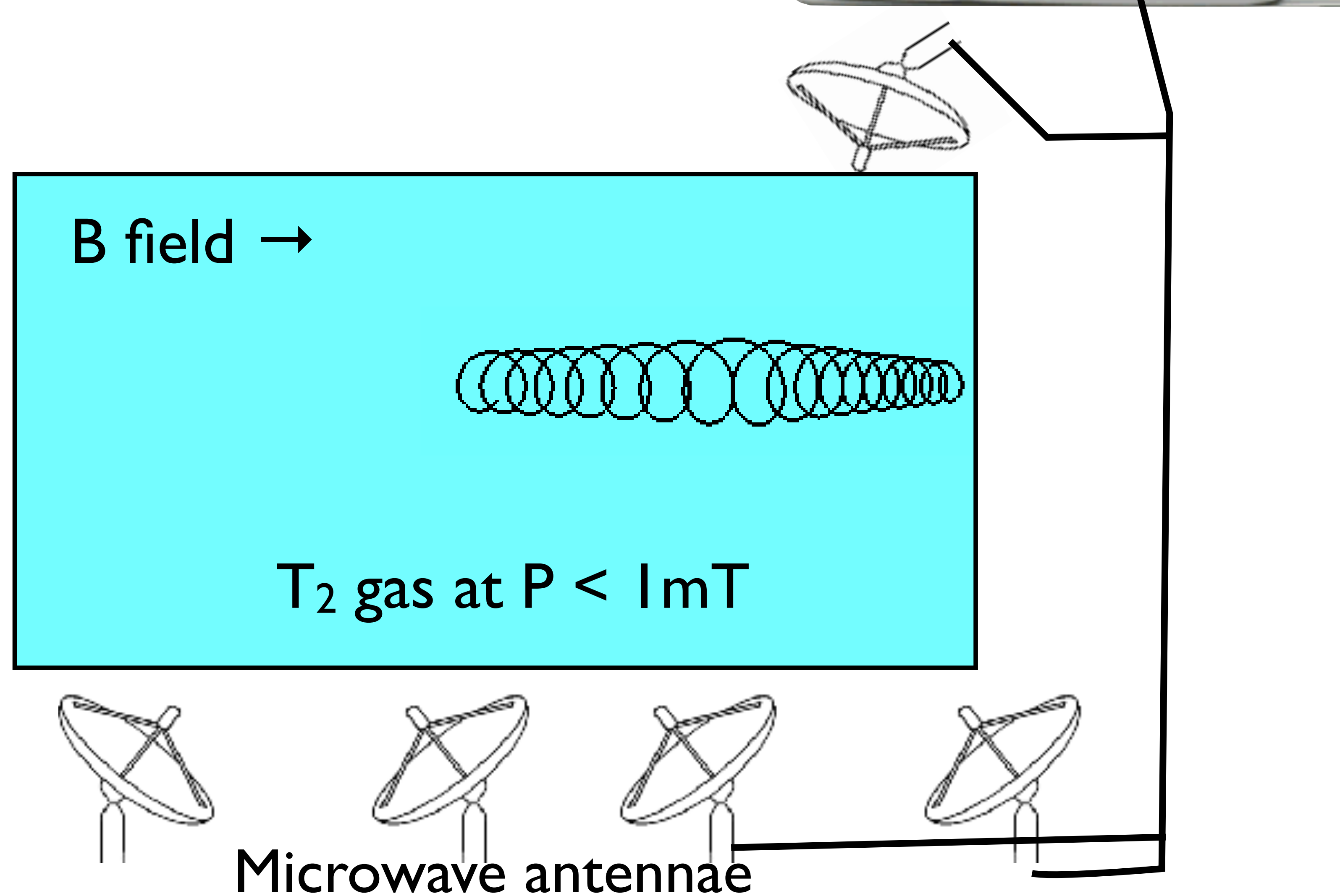
Cyclotron radiation

- emitted by mildly relativistic electrons
- Coherent, narrowband
- 10^{-15} W per electron

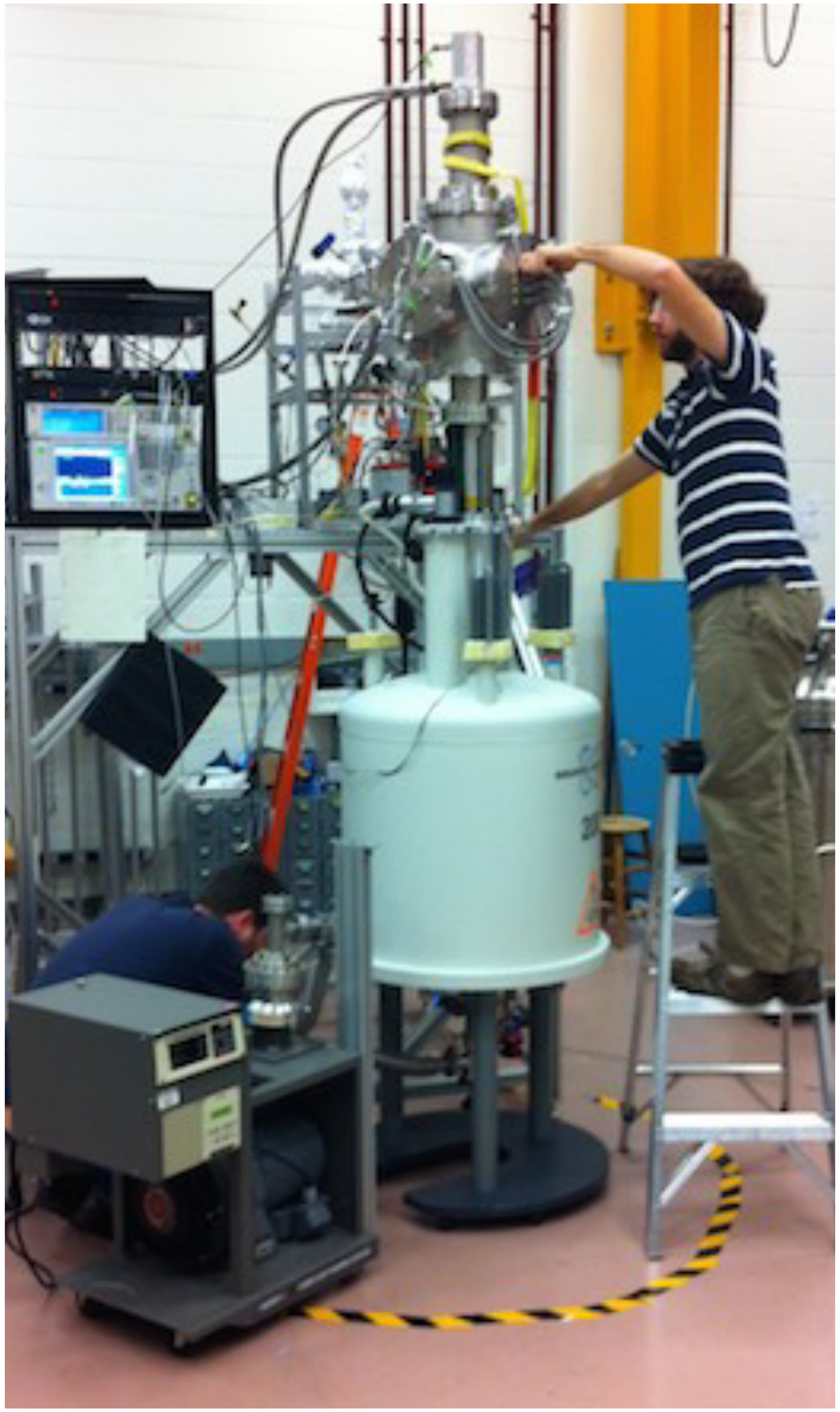
$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi(m_e + K/c^2)}$$

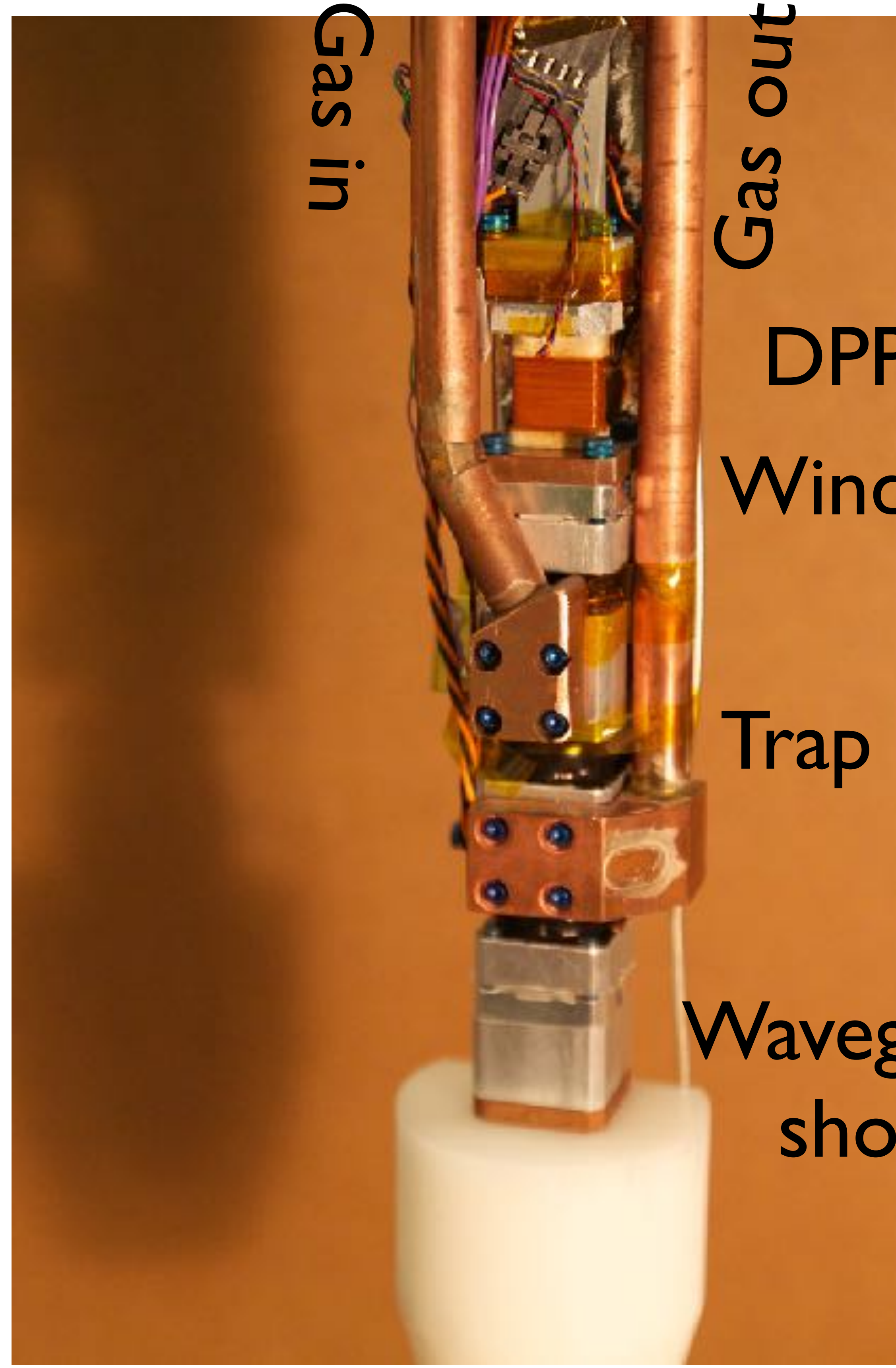
$$P_{\mathrm{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

- Electron energy contributes to velocity v, power P, frequency ω
  - *Can we detect this radiation, measure v, P, ω, and determine* E ± 1 eV?

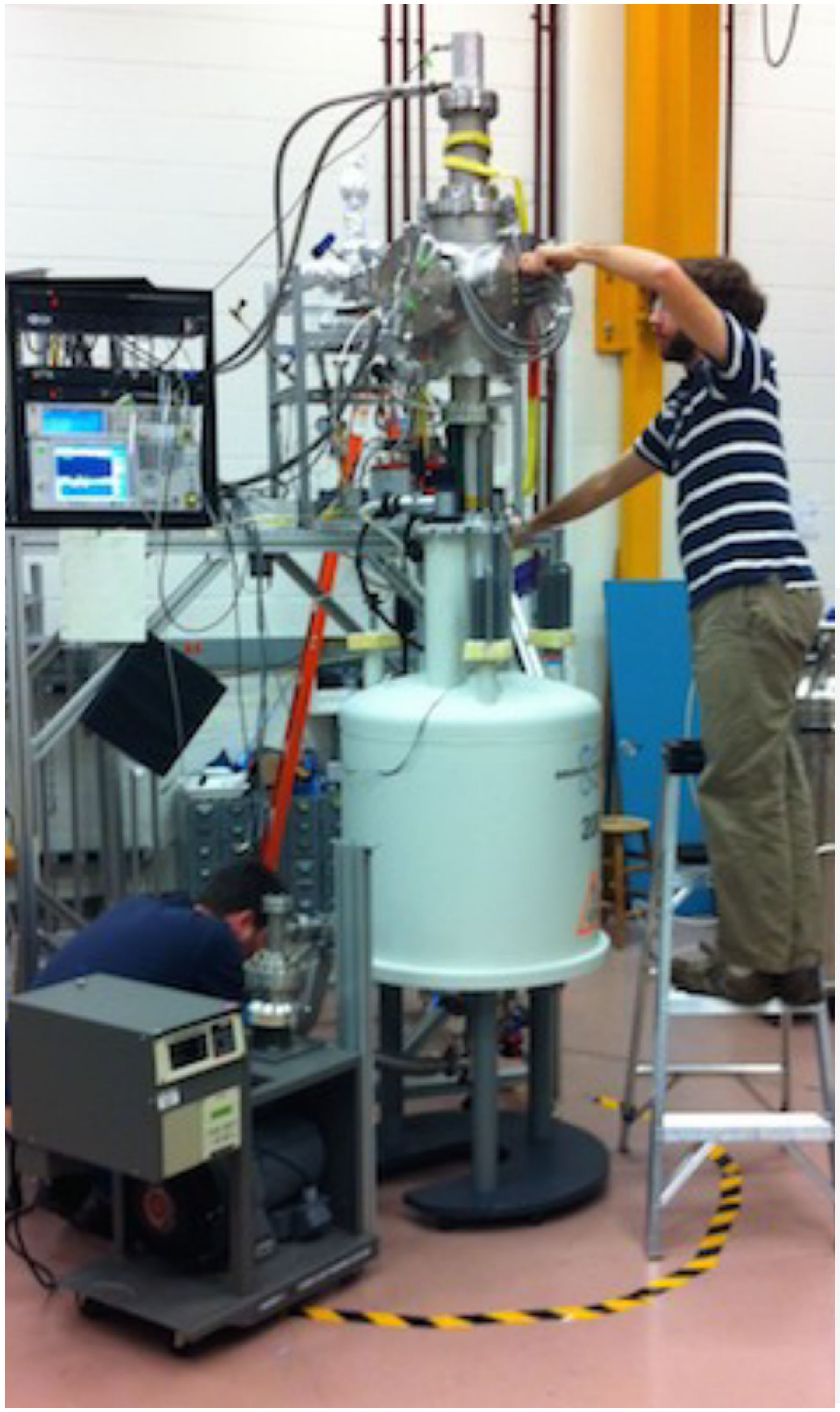


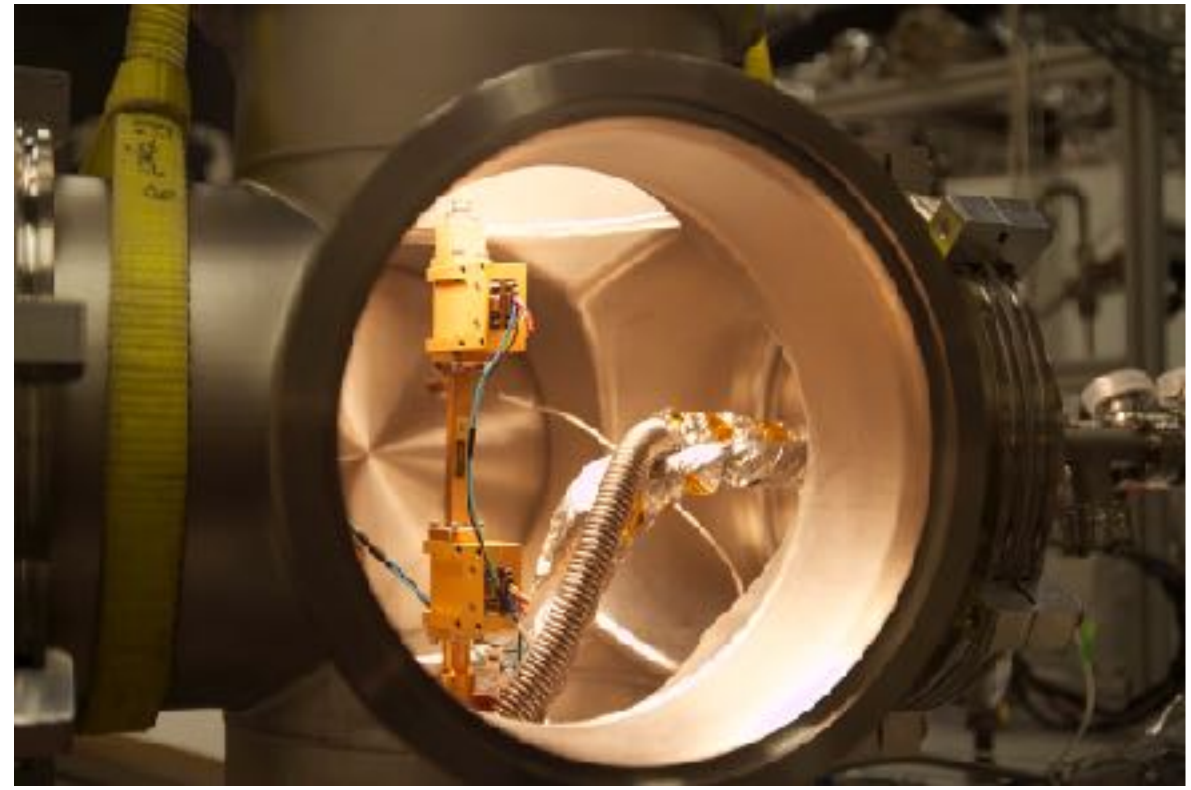
RF chain and reciever

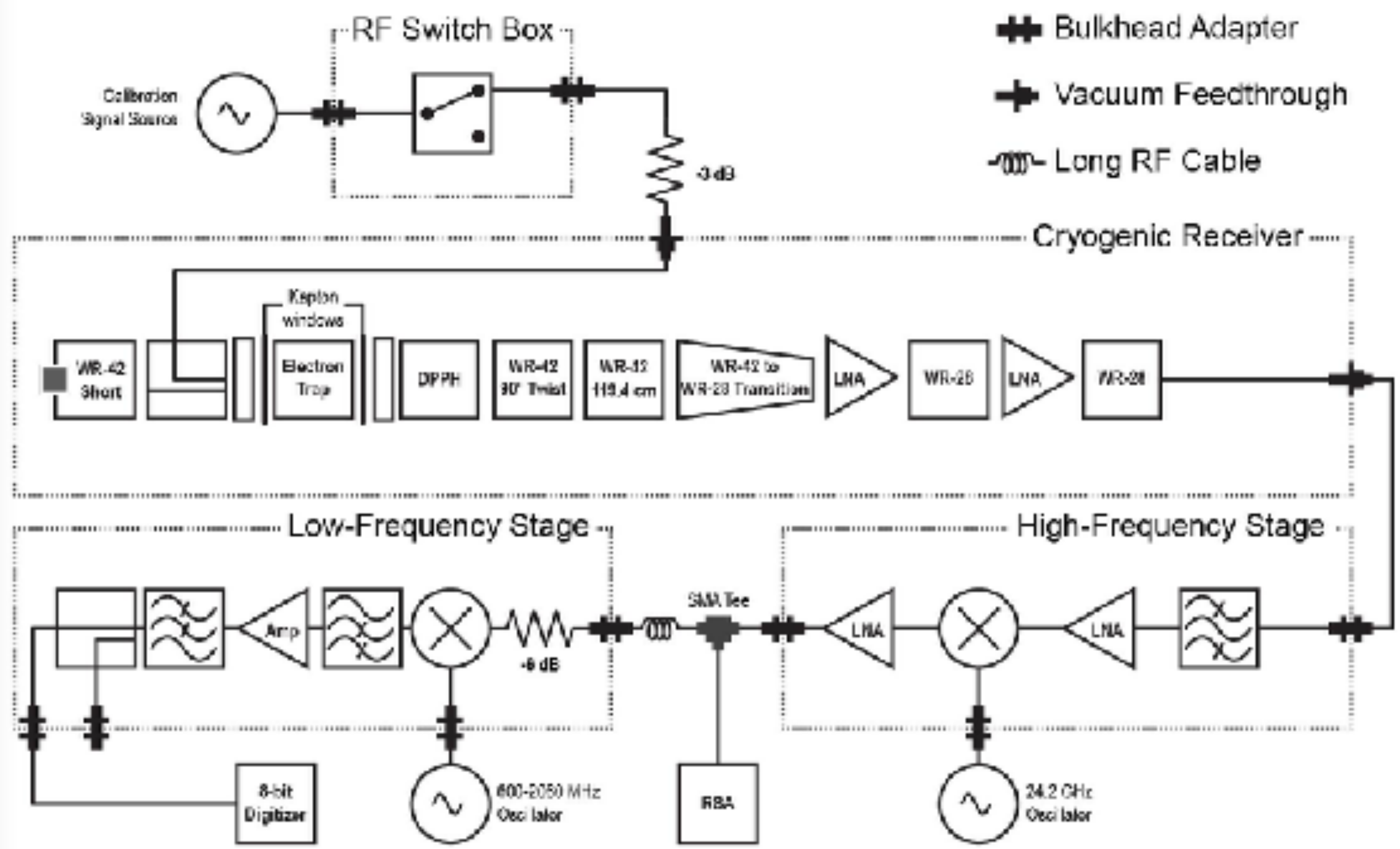




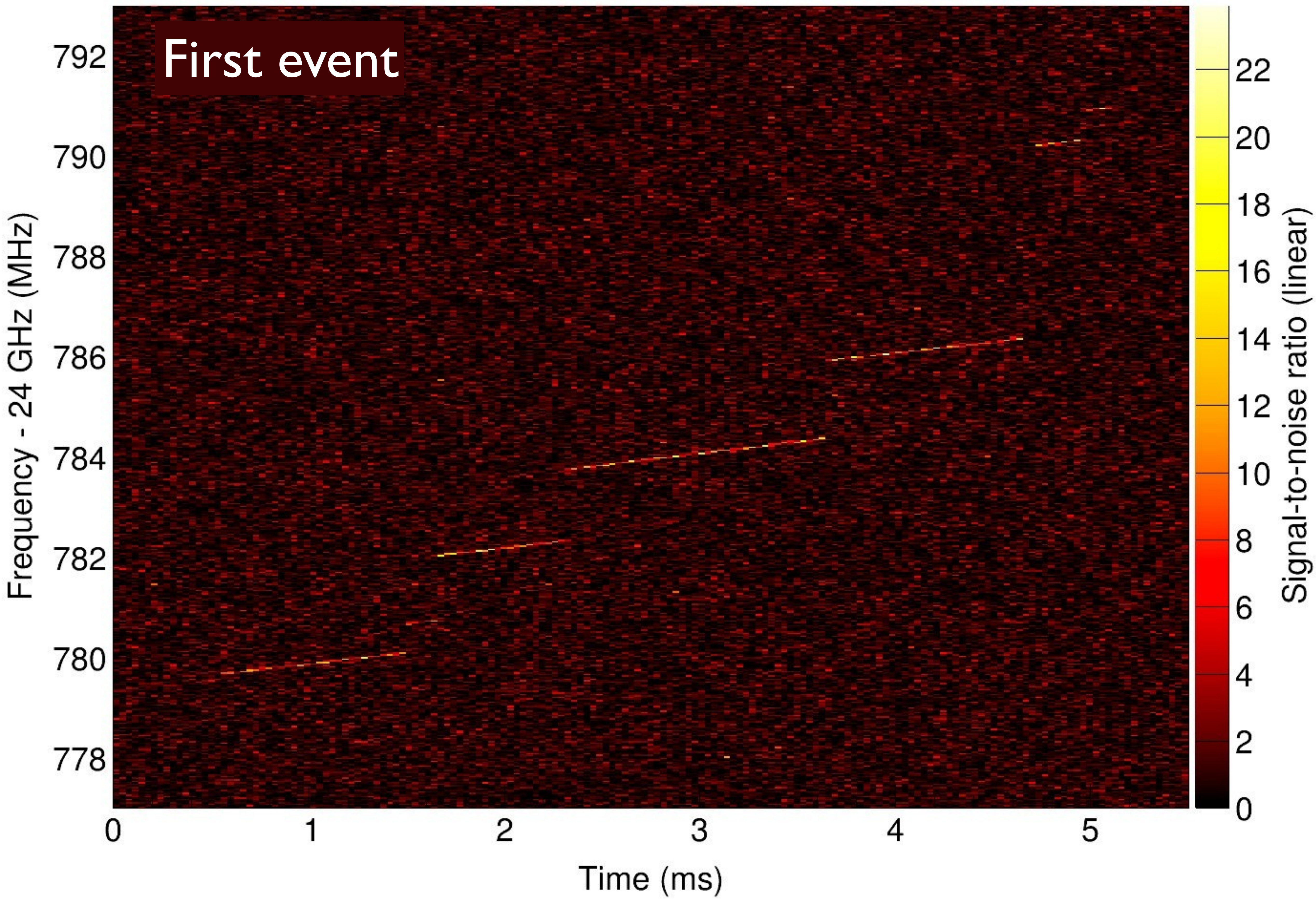
RF chain and reciever



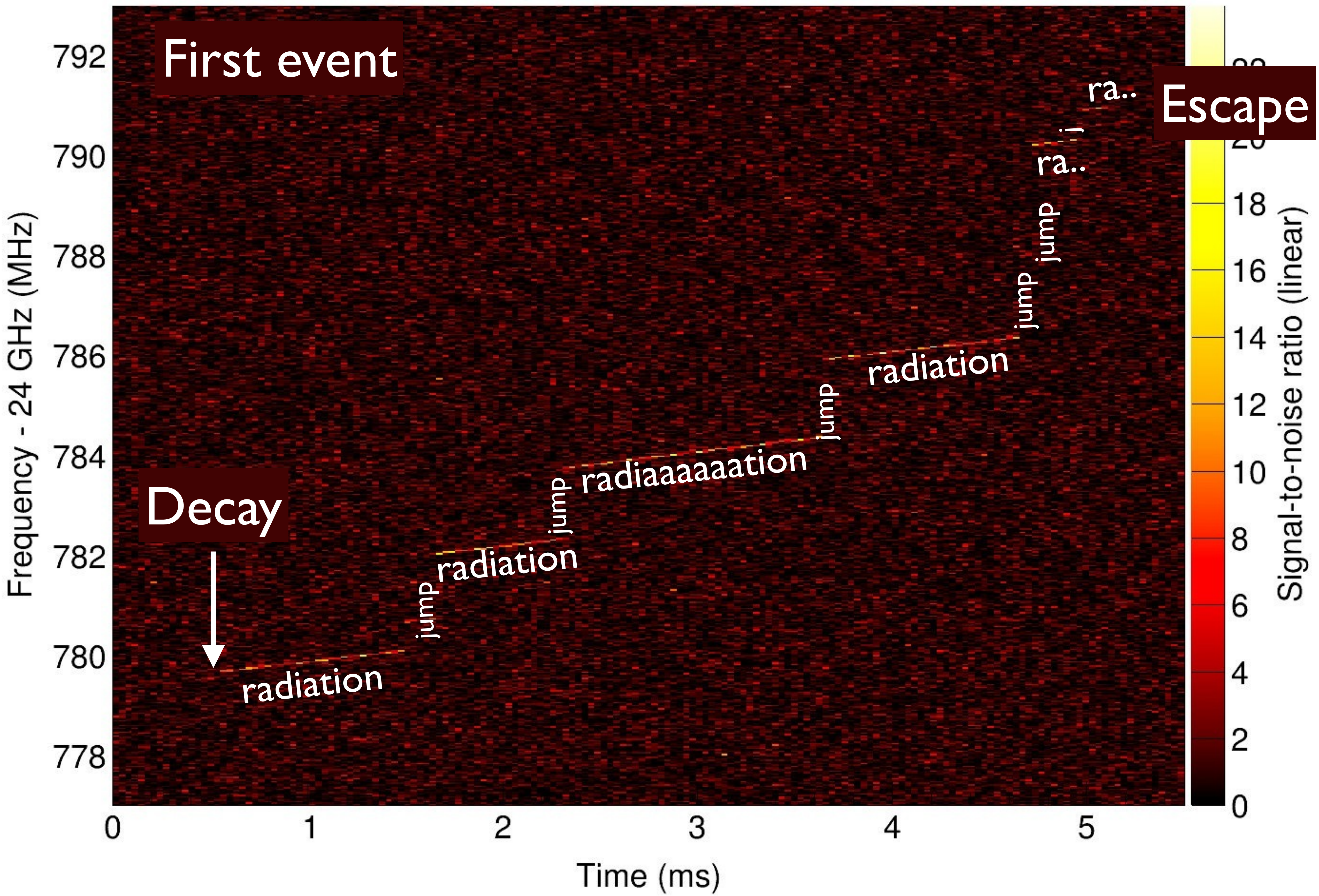




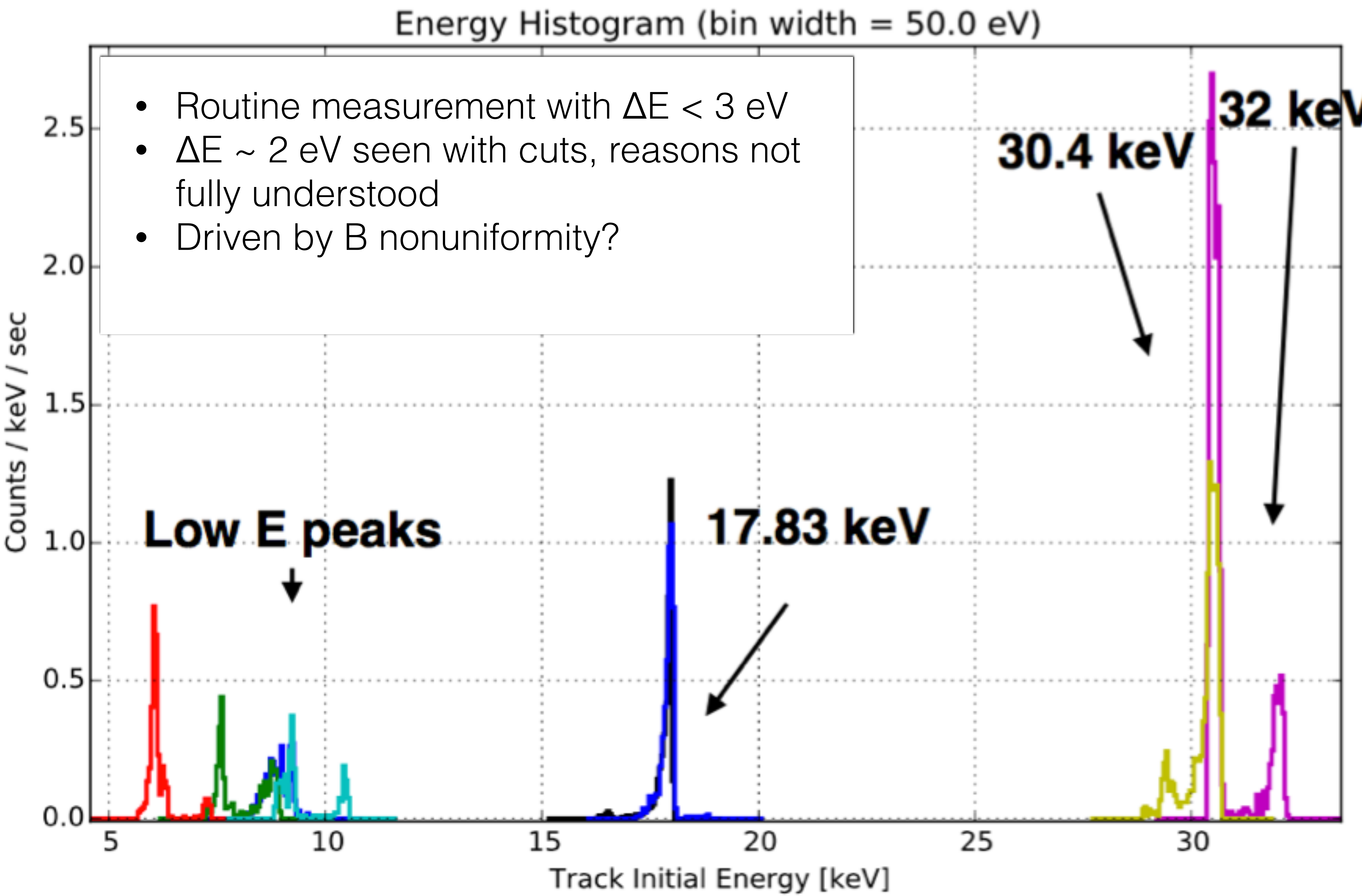
D. M. Asner et al. Phys. Rev. Lett. 114, 162501 (2015)



D. M. Asner et al. Phys. Rev. Lett. 114, 162501 (2015)

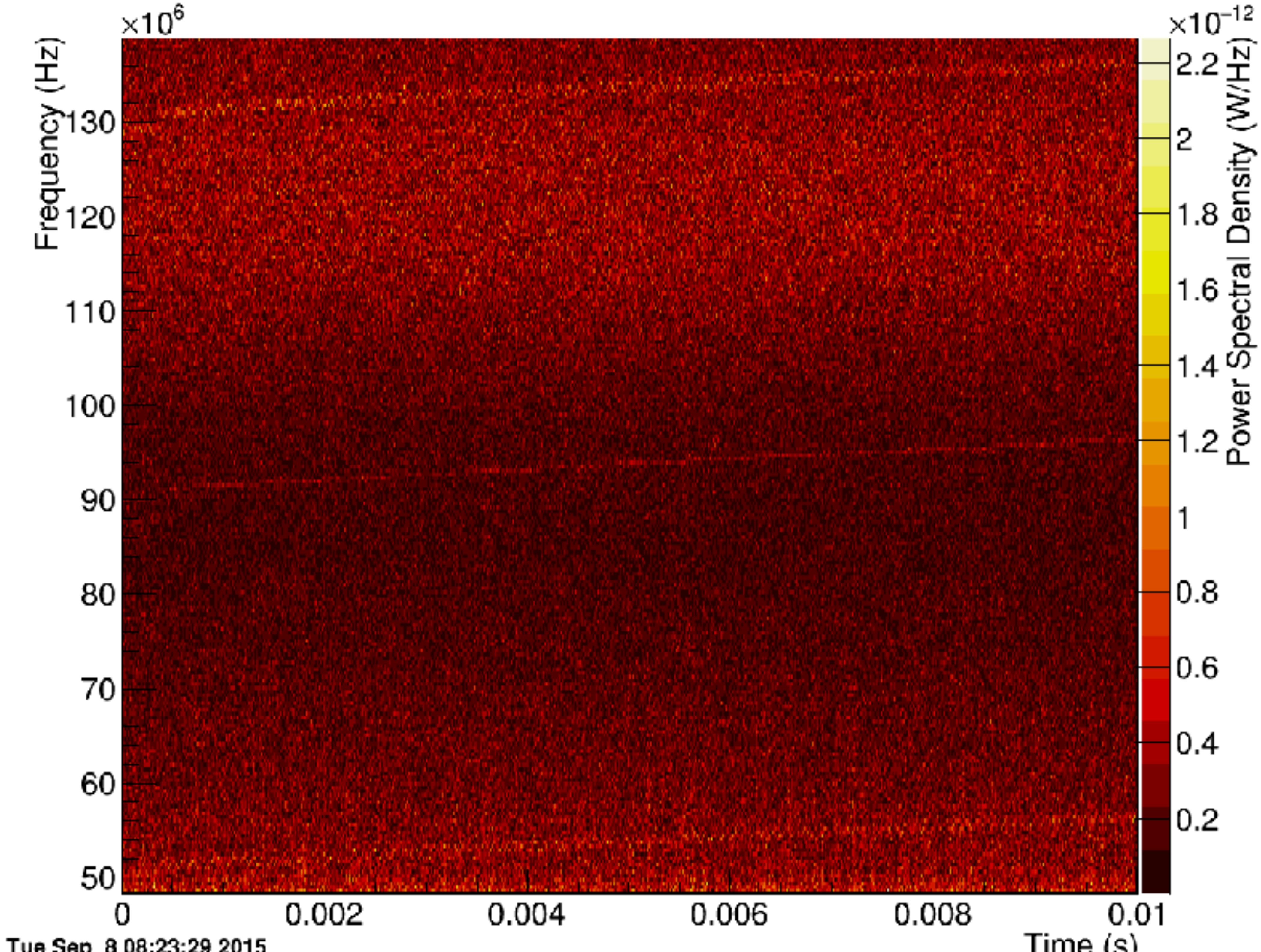


- Routine measurement with ΔE < 3 eV
- ΔE ~ 2 eV seen with cuts, reasons not fully understood
- Driven by B nonuniformity?

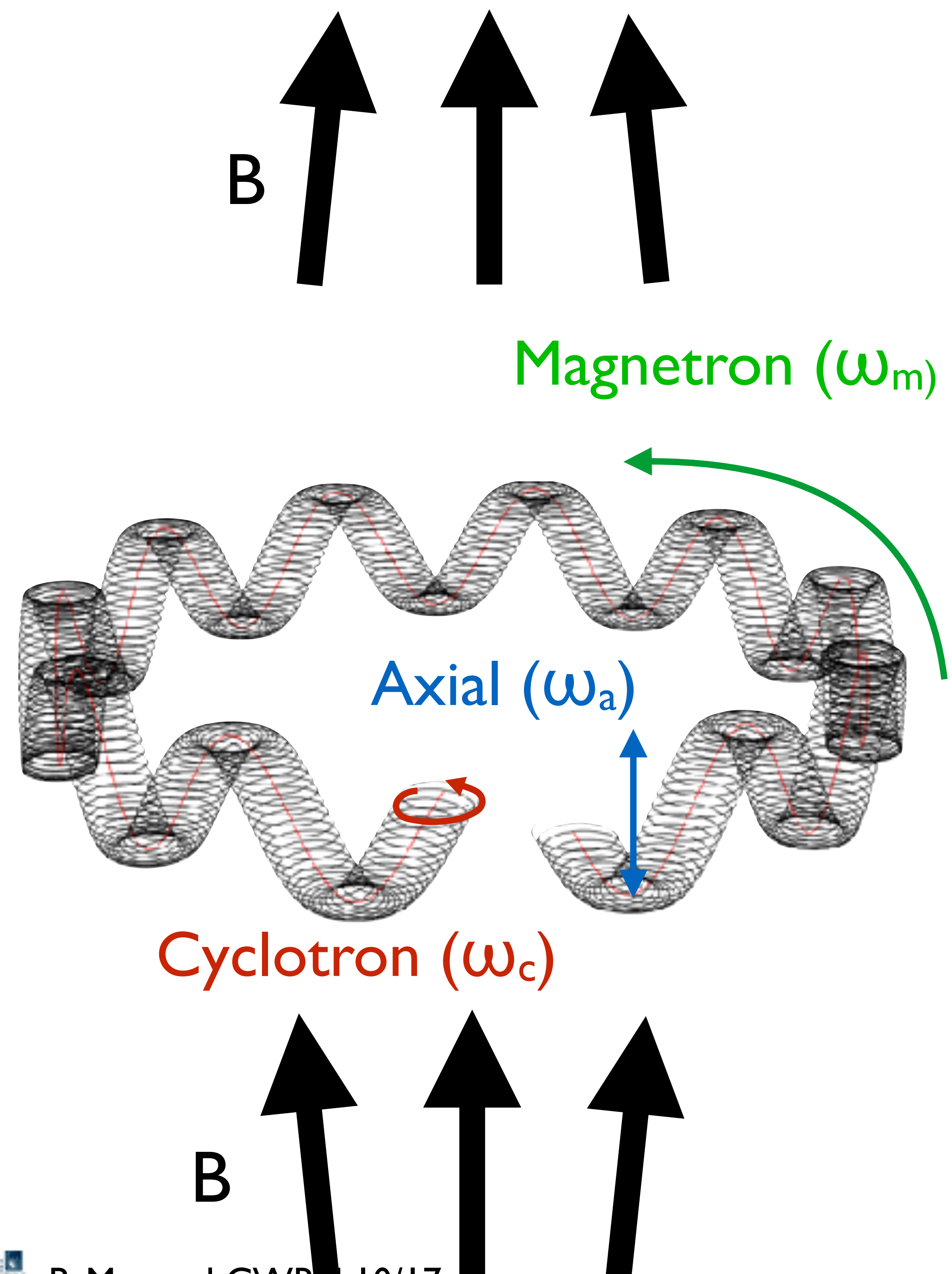


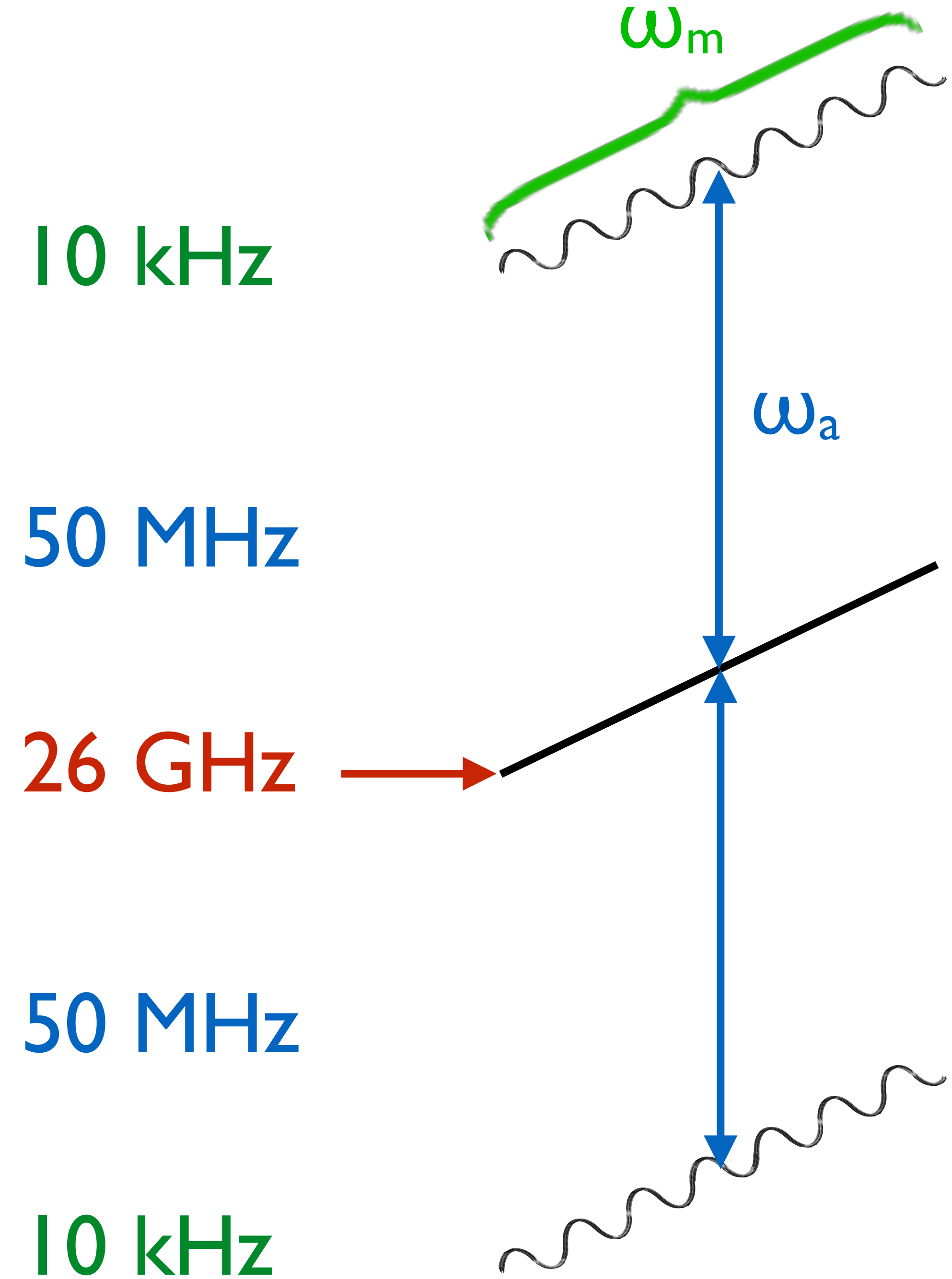
Run 2: knocking down the noise

Cold head rebuild
Tighten screws (!)
new DAQ

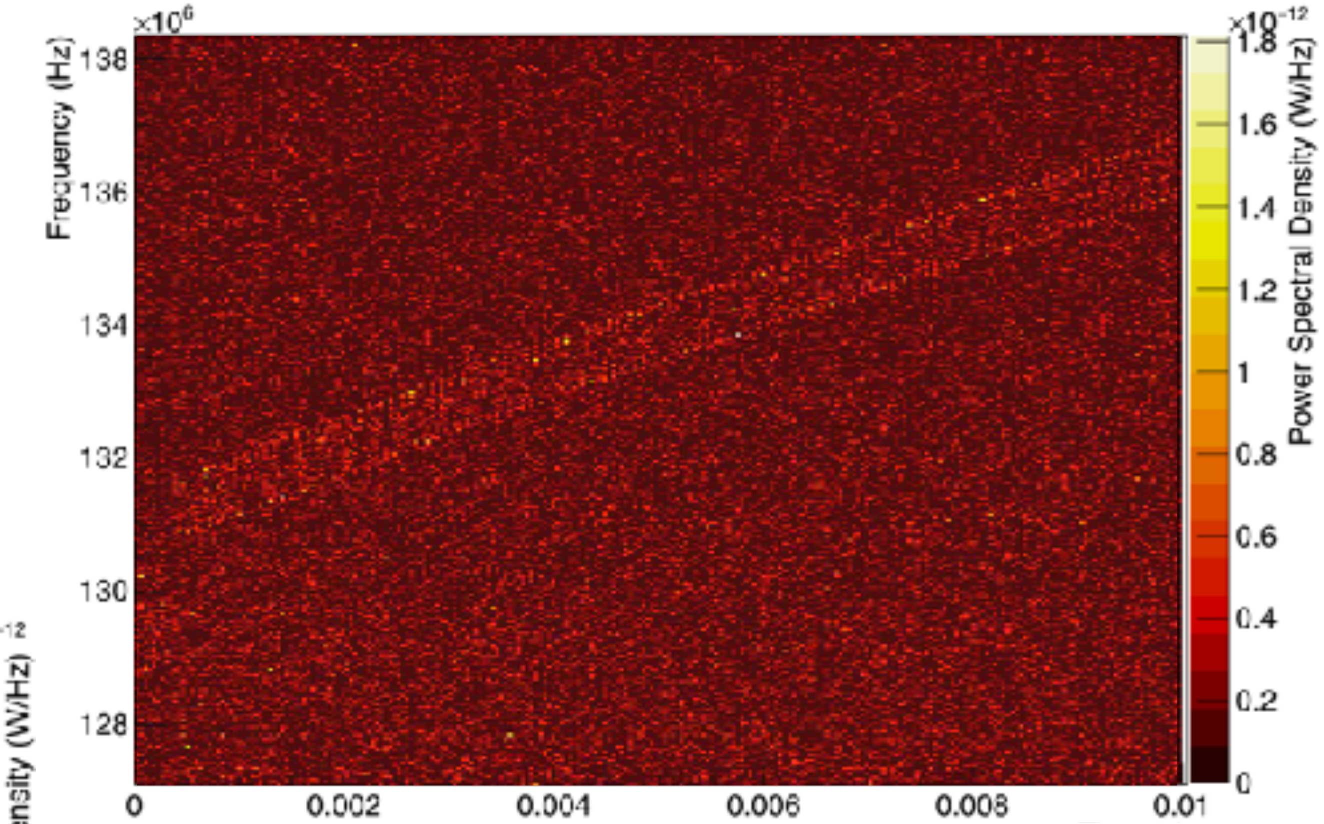


Doppler shifts and nonuniformities

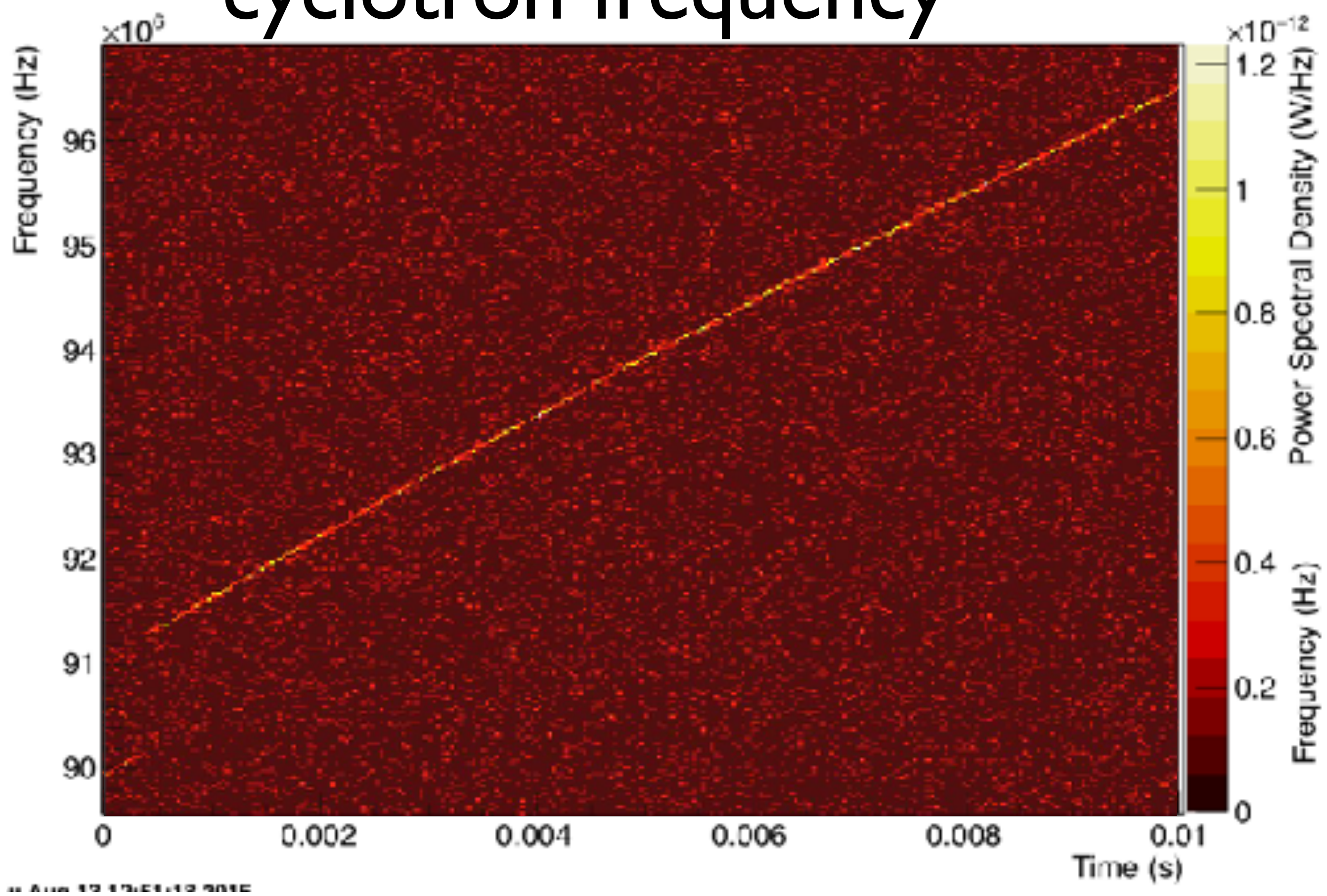




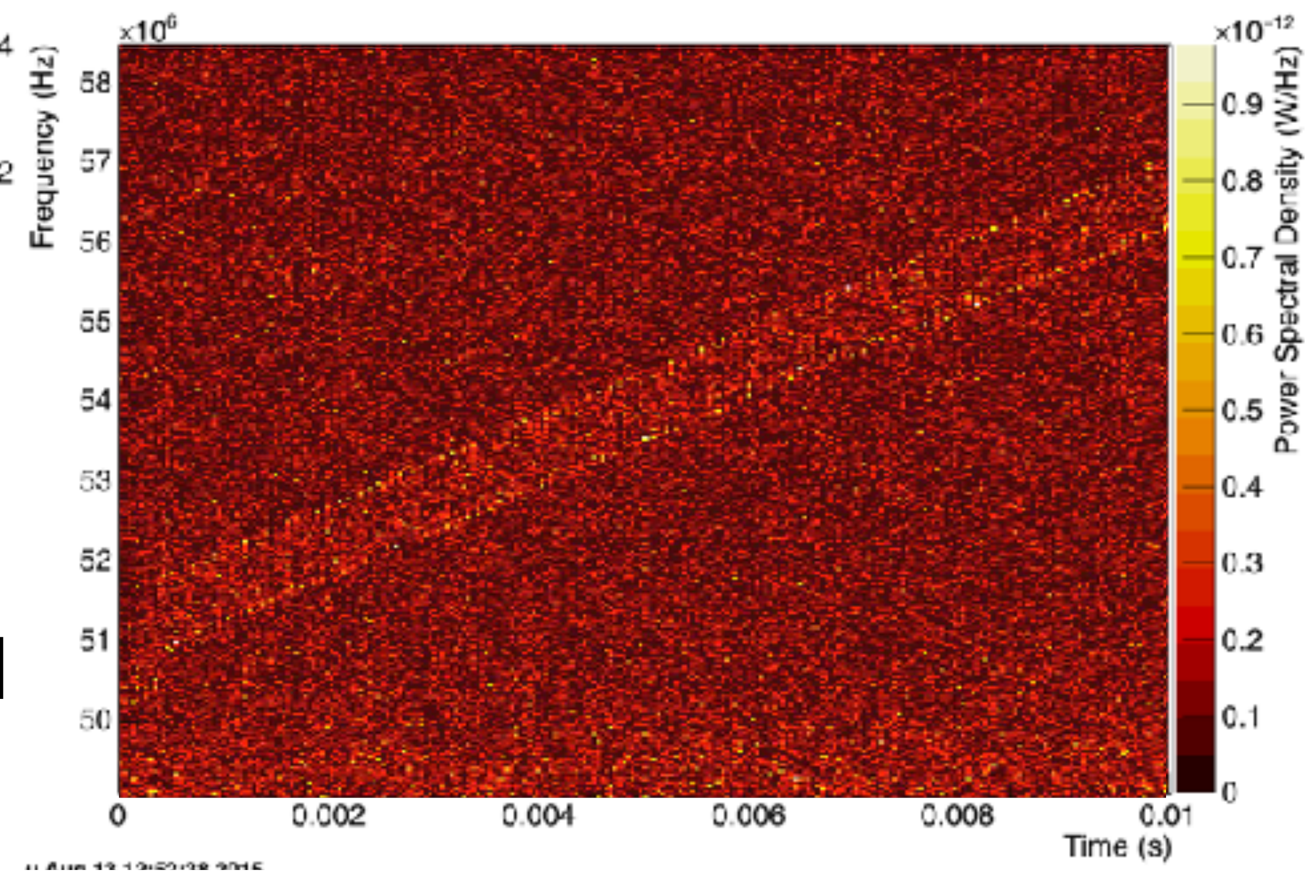
upper sideband



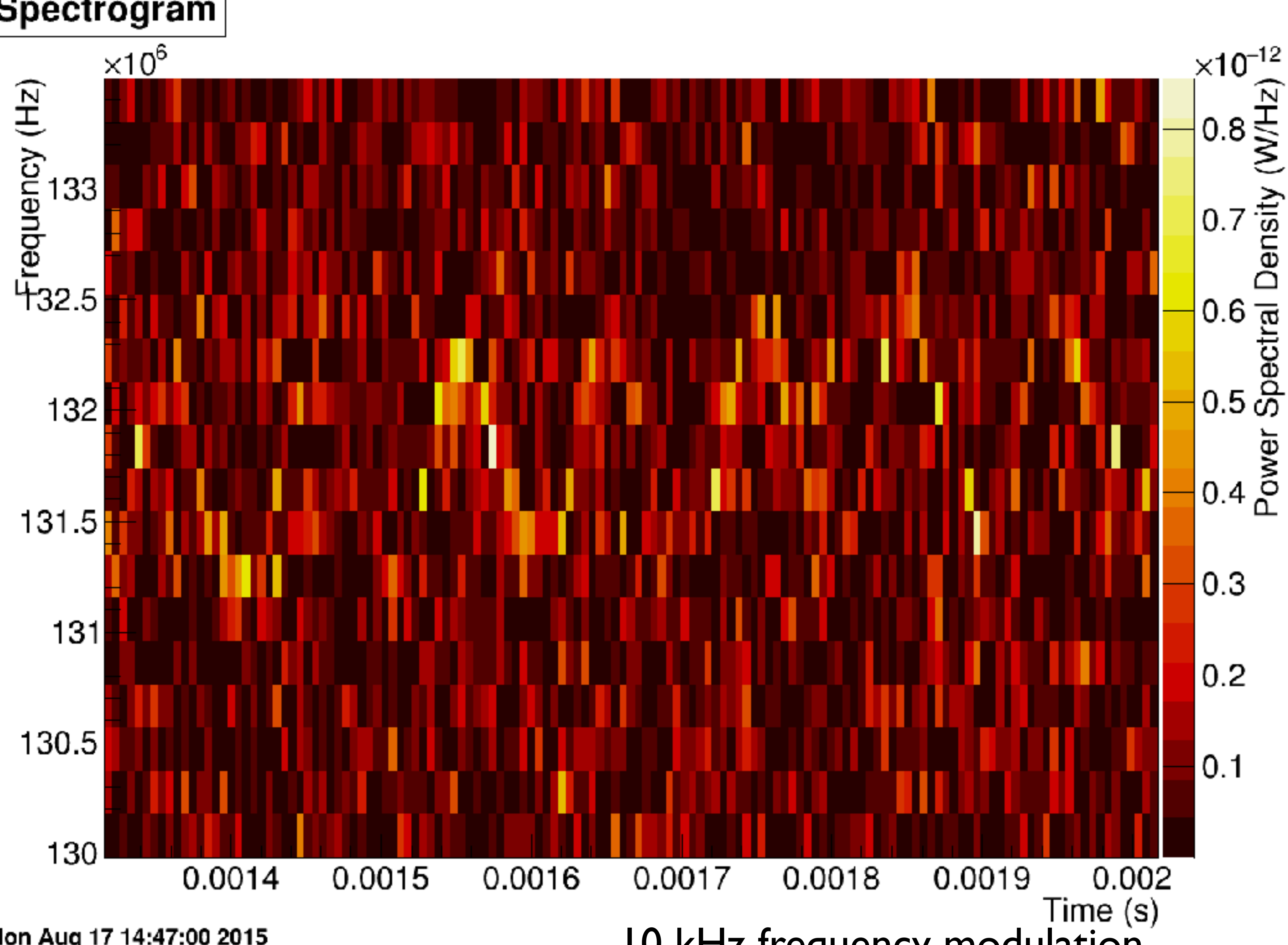
cyclotron frequency



± 40 MHz

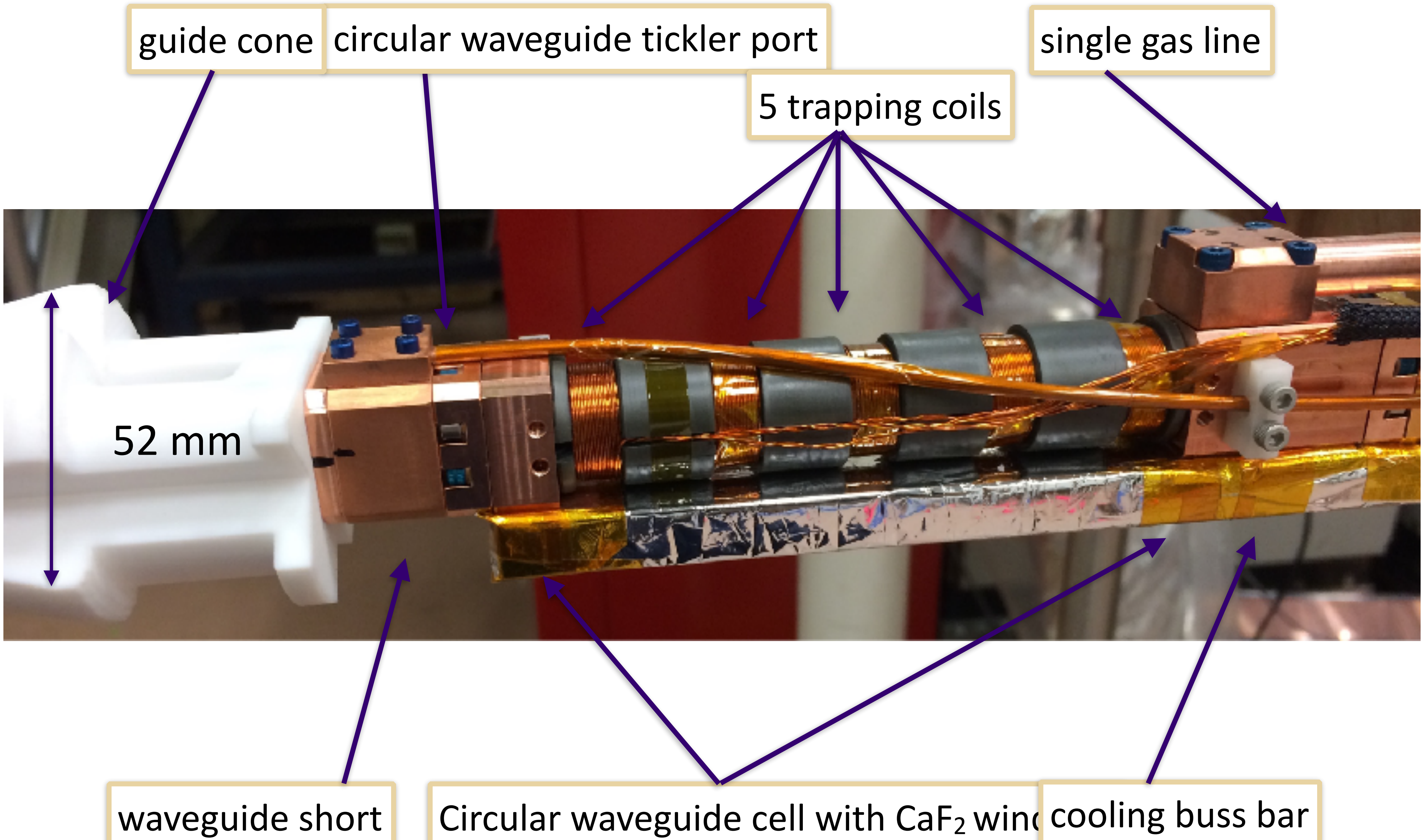


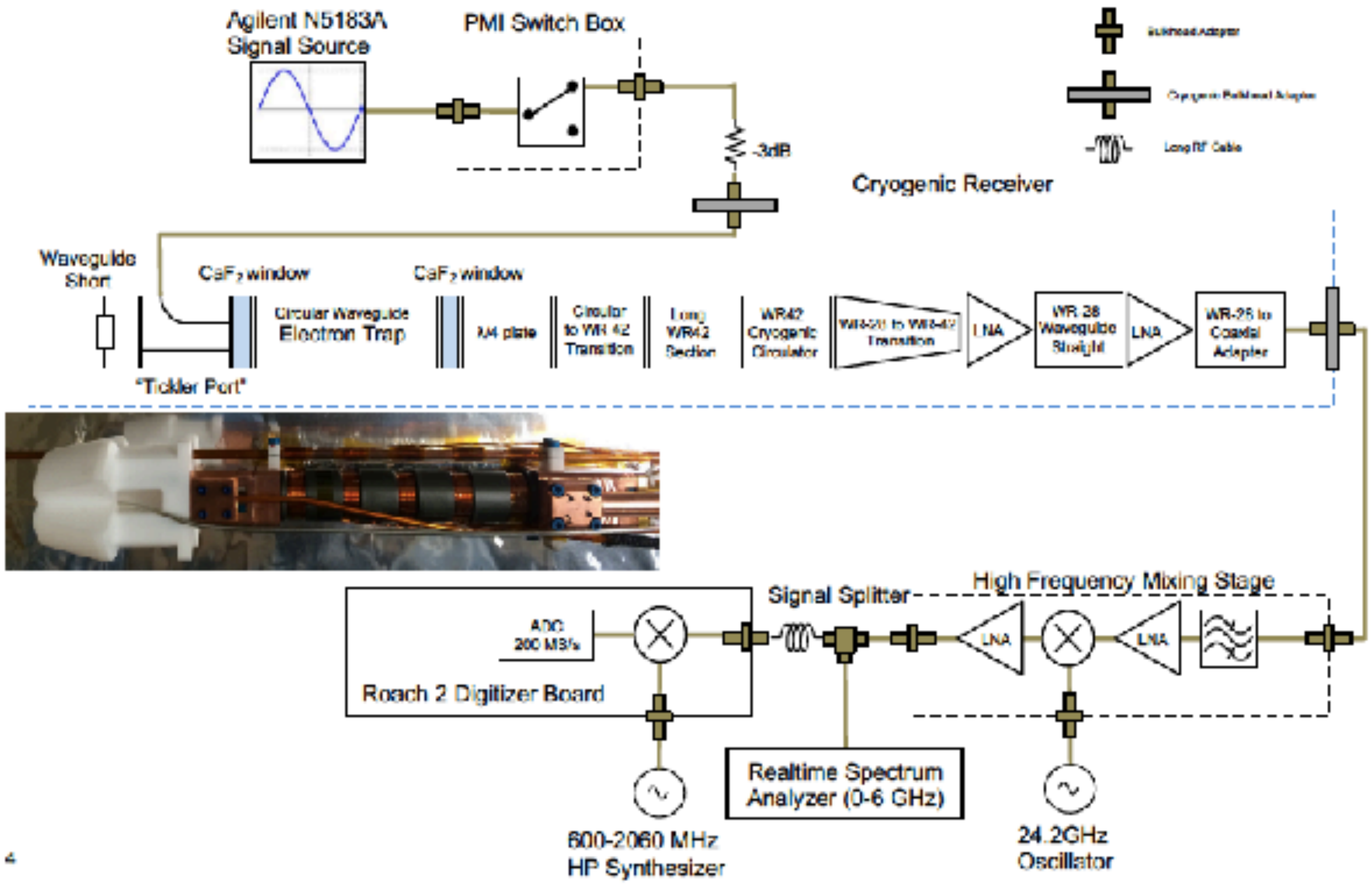
lower sideband

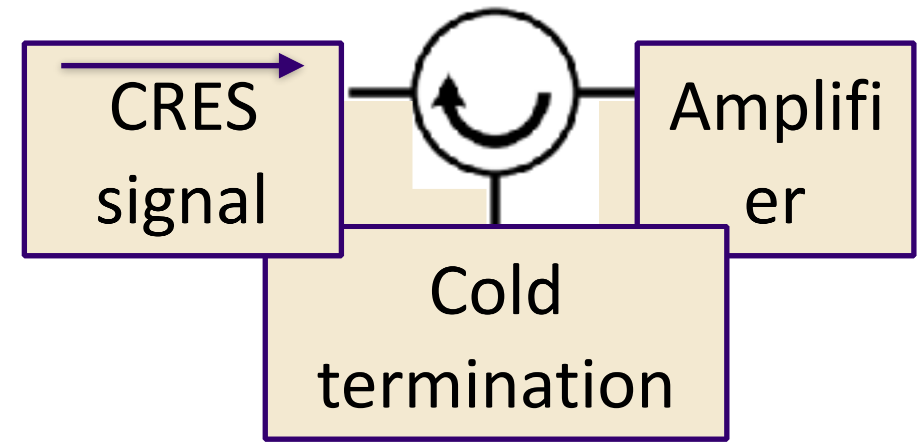


10 kHz frequency modulation

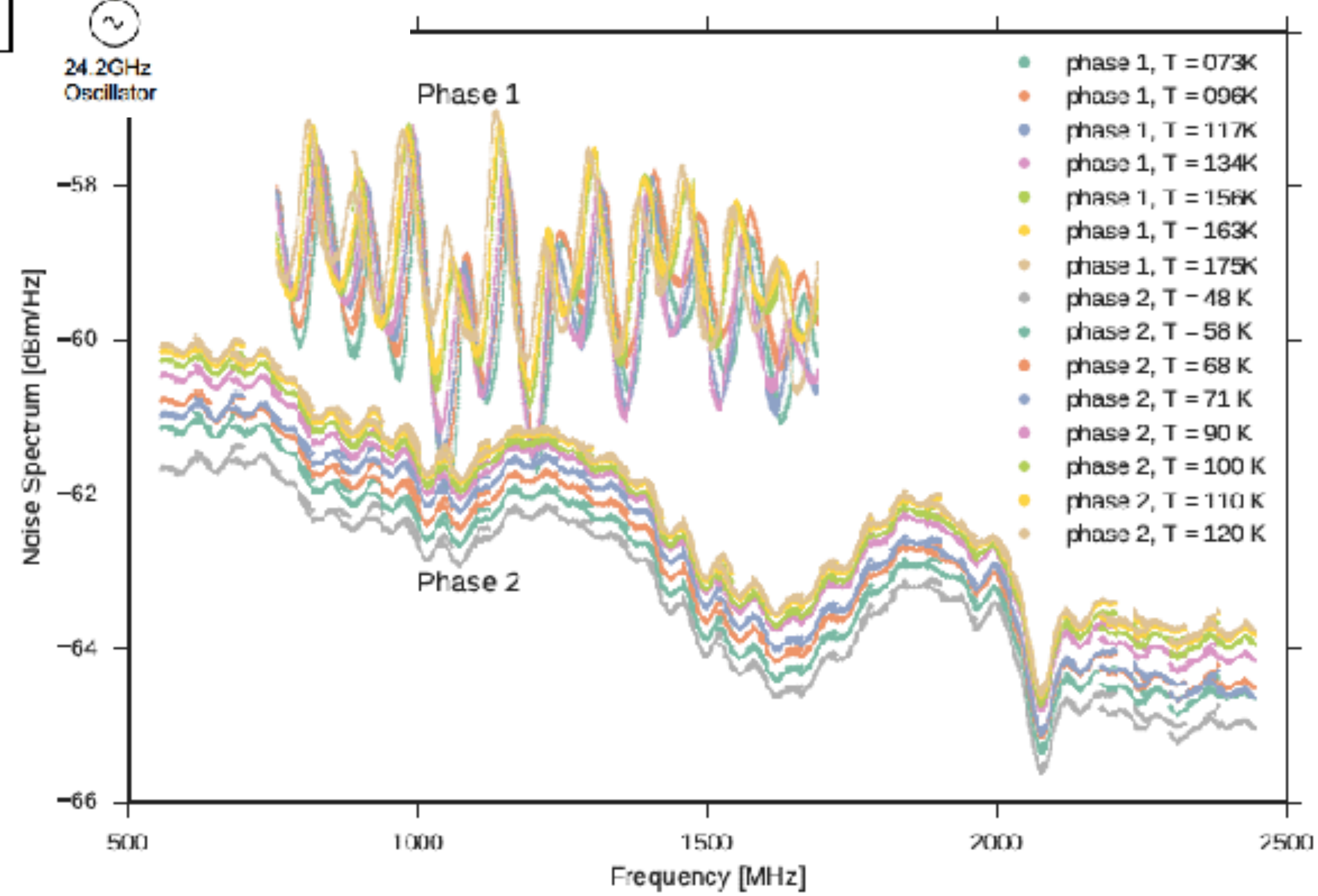
The Phase IIa CRES cell before installation

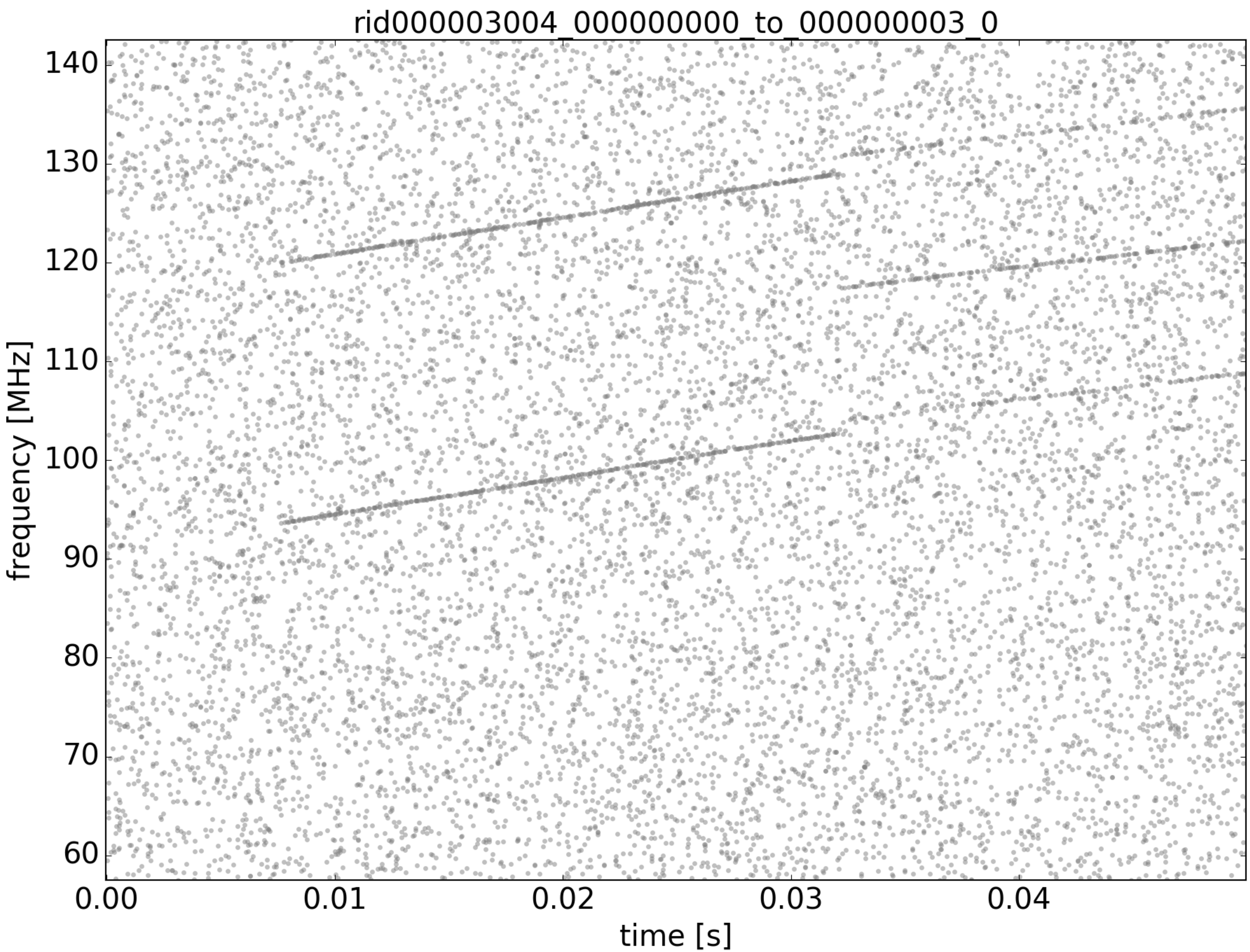




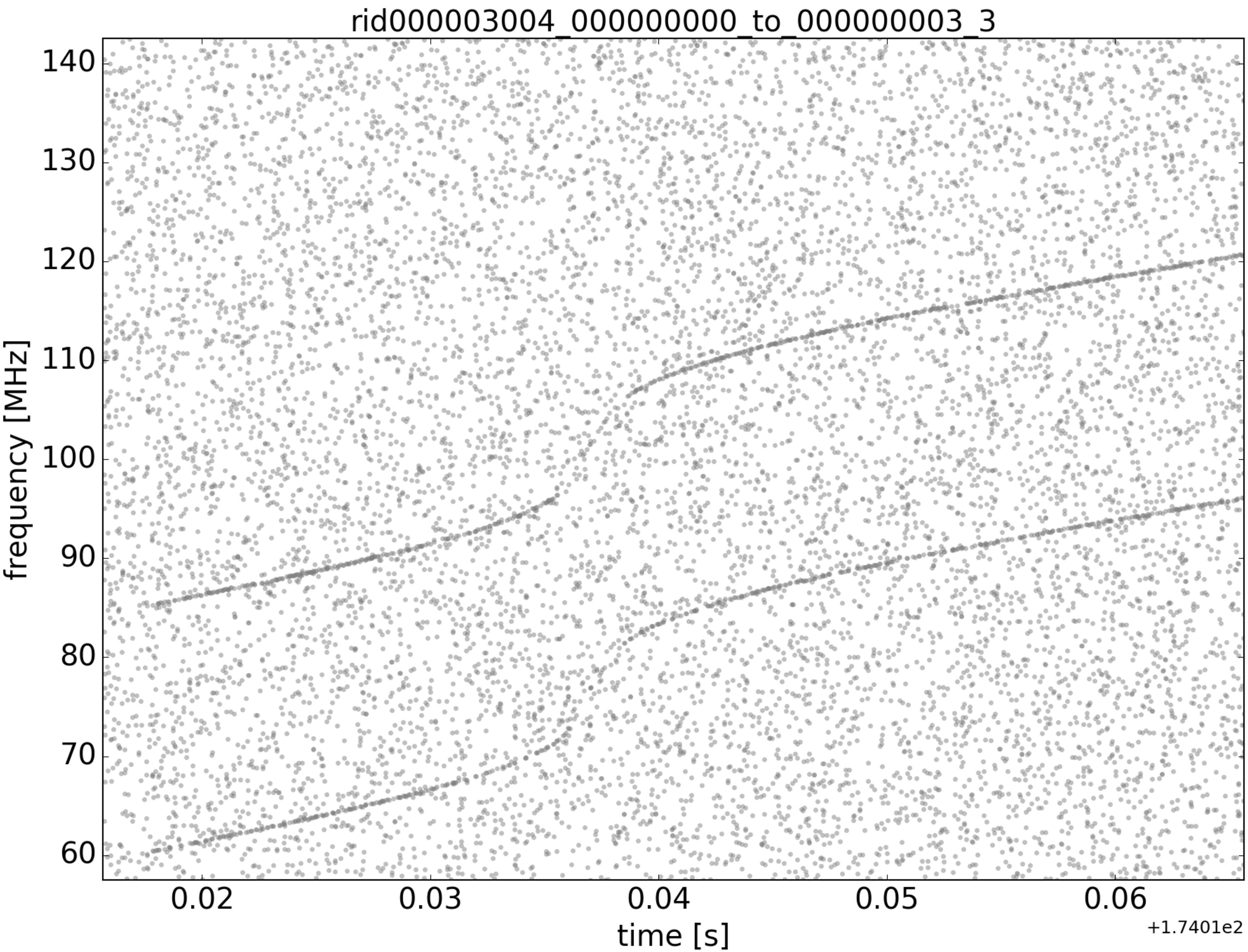


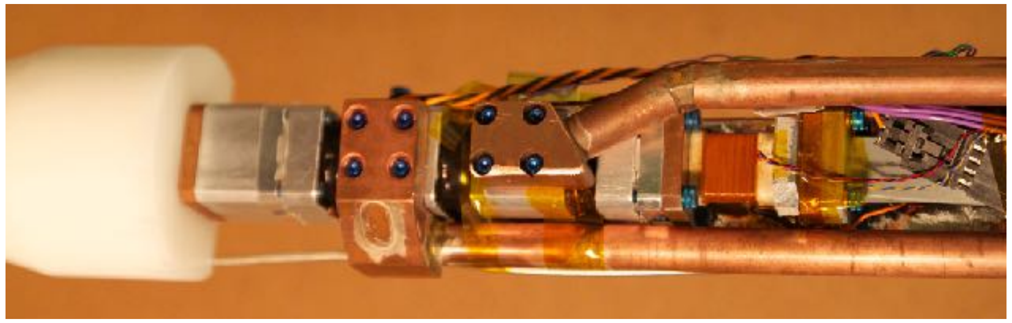
Many small improvements have knocked down the thermal noise

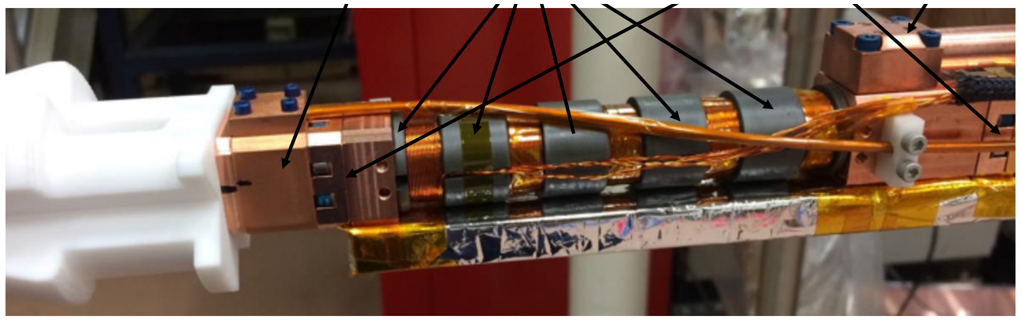




rid000003004_000000000_to_000000003_0
frequency [MHz]
140
130
120
110
100
90
80
70
60
0.00
0.01
0.02
0.03
0.04
time [s]


rid000003004_000000000_to_000000003_3
frequency [MHz]
140
130
120
110
100
90
80
70
60
0.02
0.03
0.04
0.05
0.06
time [s]
+1.7401e2





Phase I
- Demonstrate single-electron detection
- CRES spectrum of 83mKr
- 2010 – 2016
- ^{83m}Kr source
- Waveguide

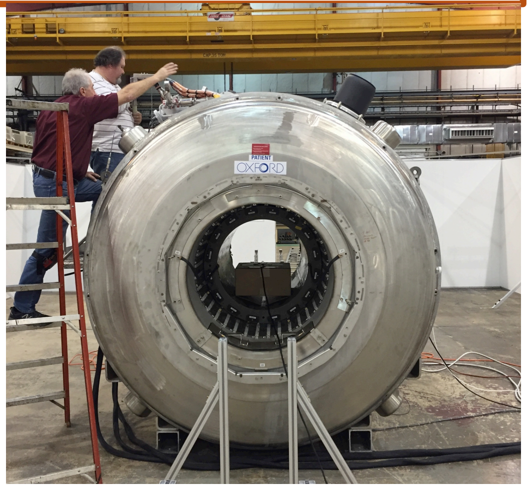
done!

Phase II
- Kurie plot and systematics studies
- m_ν < 10-100 eV
- 2015 – 2017
- T_2 source
- Waveguide

imminent

Phase III
- High-rate sensitivity
- m_ν < 2 eV
- 2016 – 2020
- T_2 source
- Phased antenna array

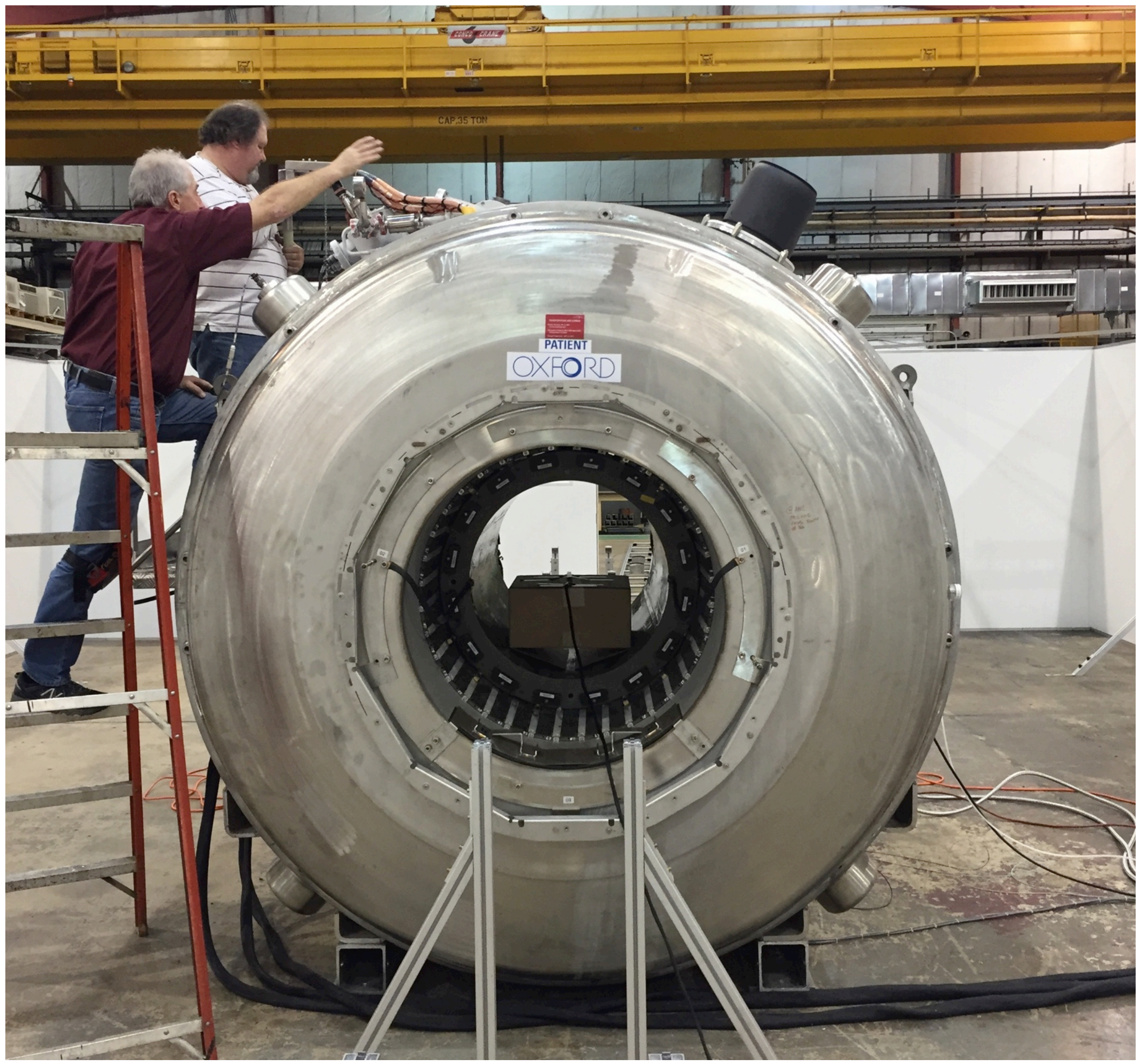
design



Phase IV
- Atomic tritium source
- m_ν < 40 meV
- 2017 –
- T source
- ?

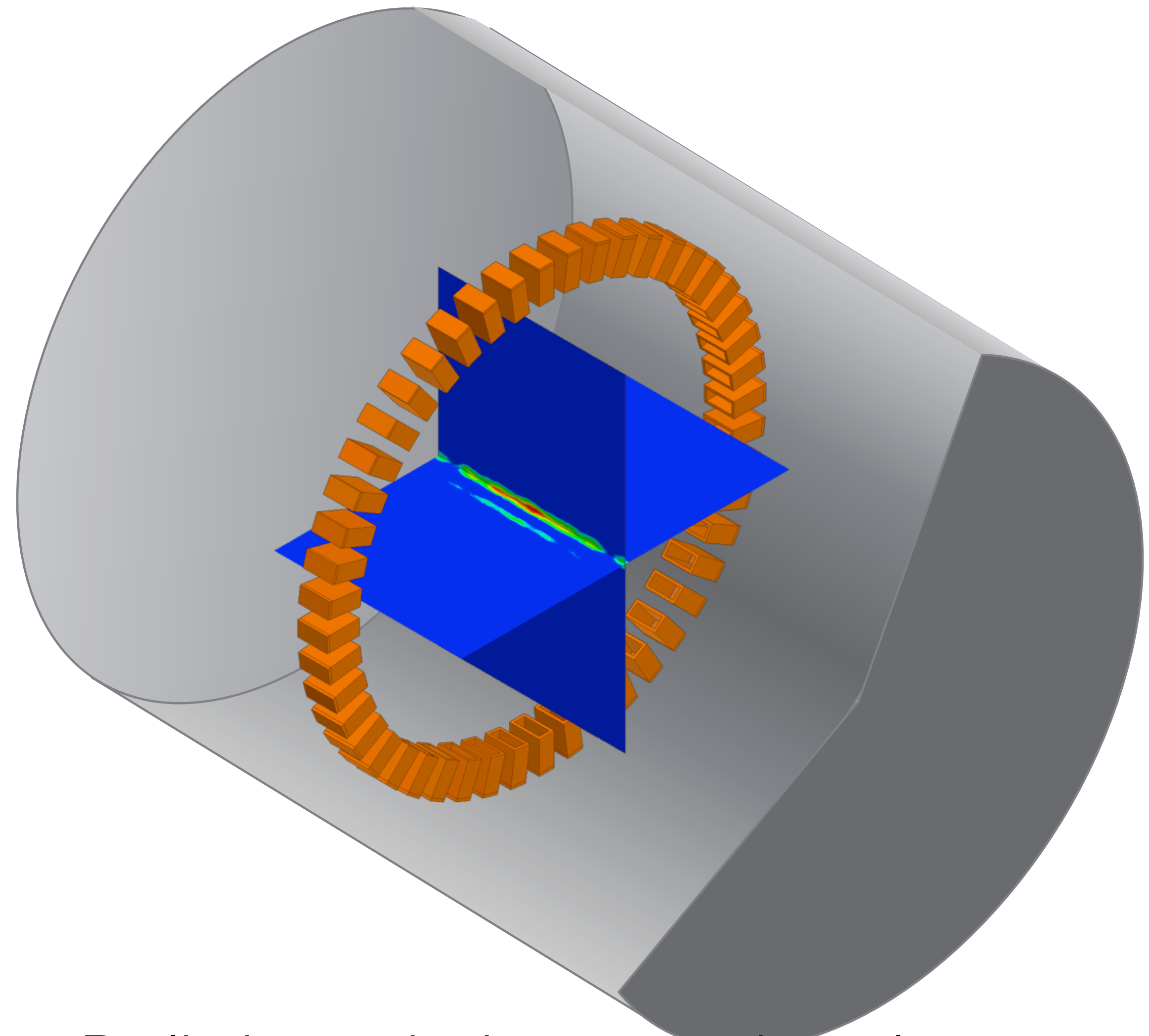
concept studies

Phase III: multi-antenna



- Surplus MRI magnet
- 10^{-6} uniformity in central 50cm

"Antenna barrel": must choose a focus if you want to coherently add signals

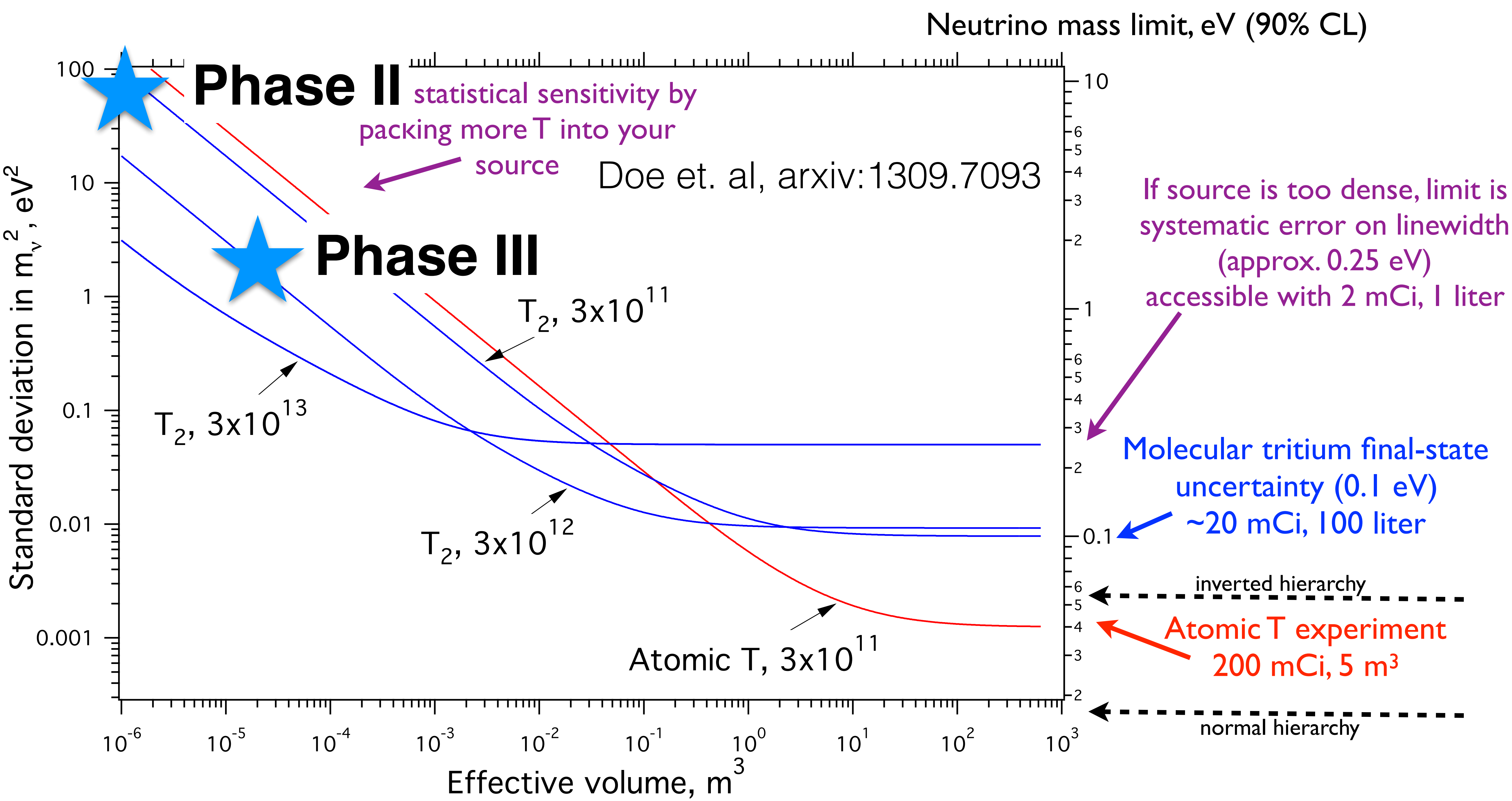


Preliminary design: 10cm barrel, 30 antennas, >10 dB SNR.

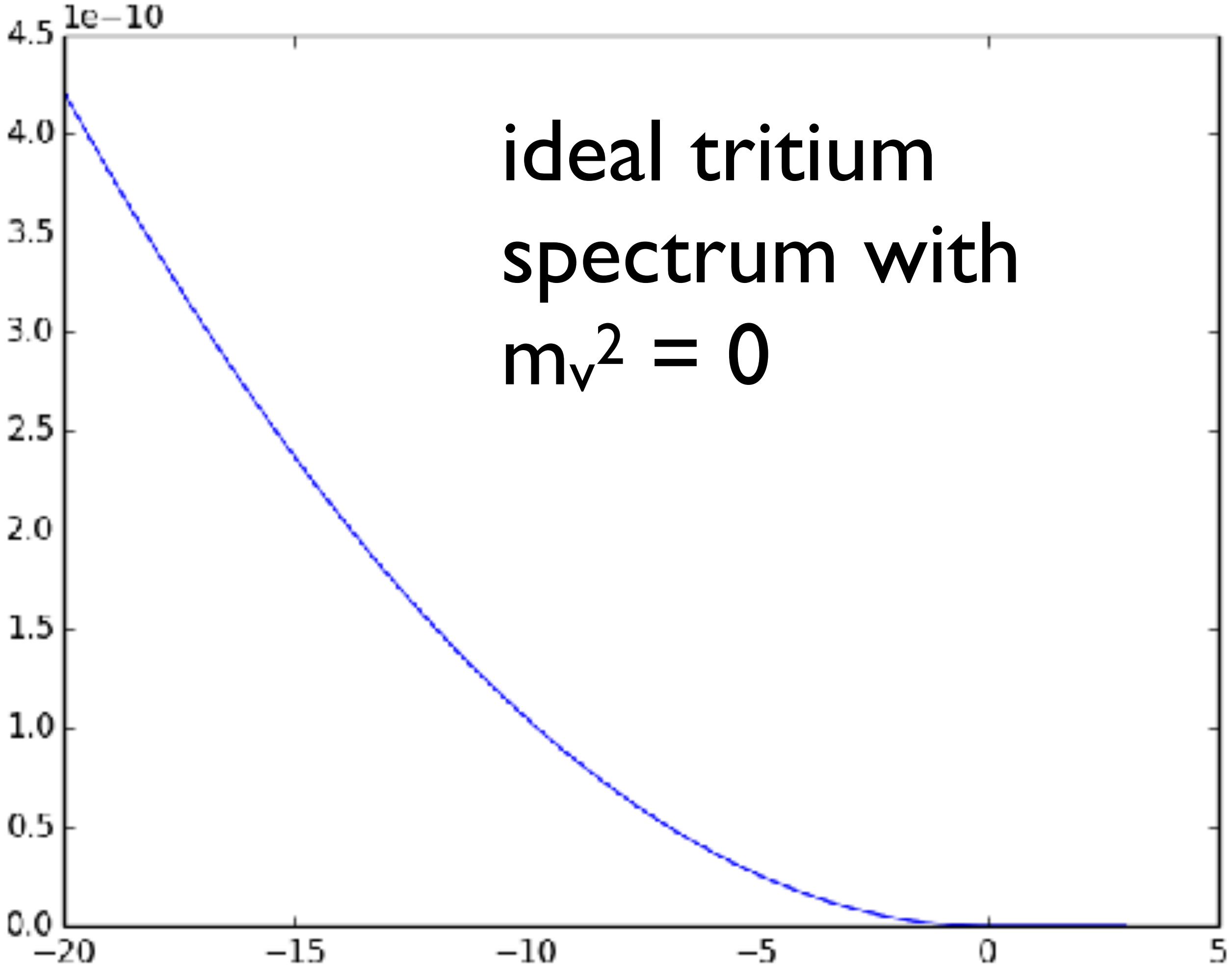
ROACH2 + GPU farm for synthetic focus = radio astronomy tech

Project 8 sensitivity estimates:

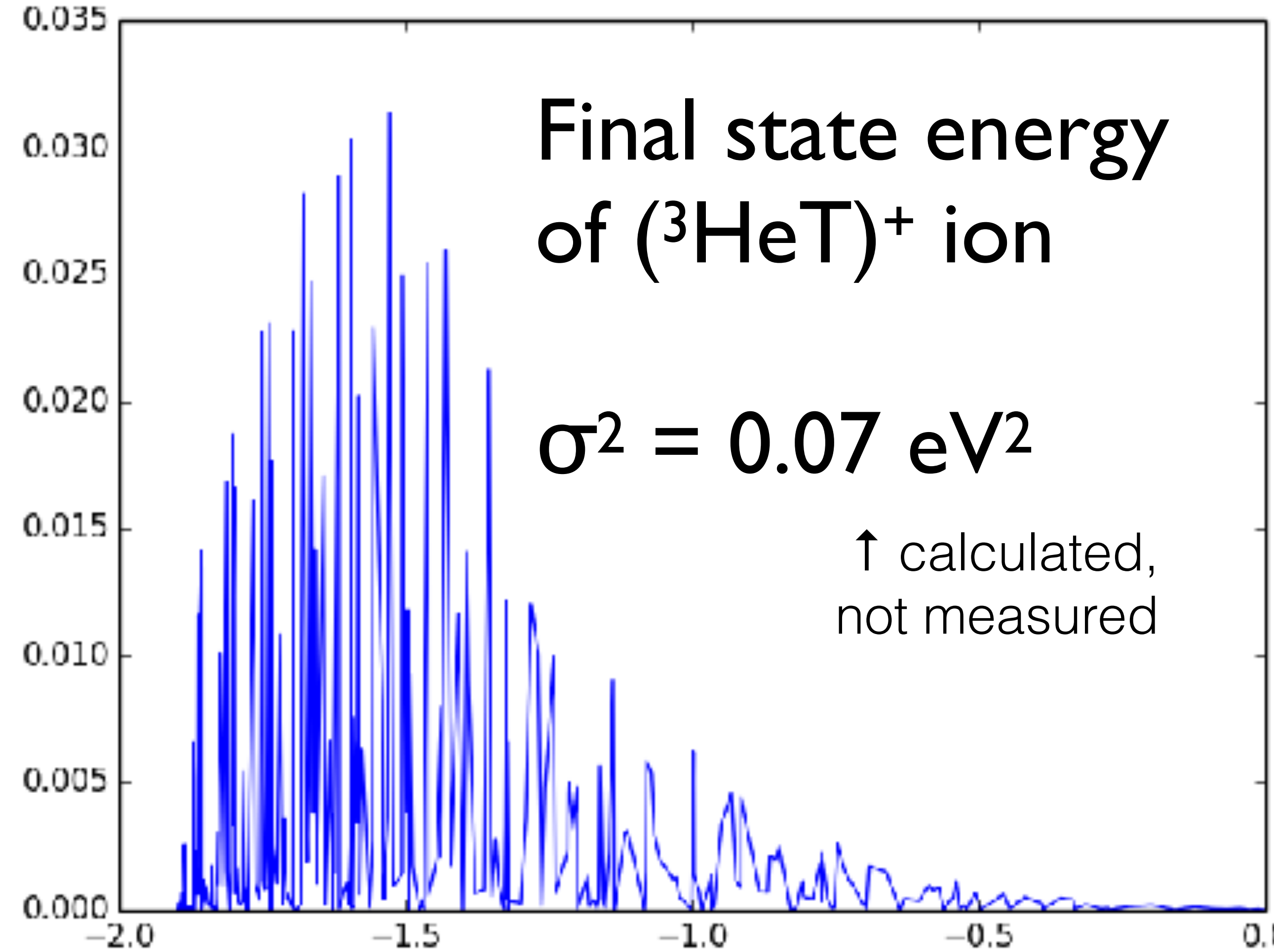
Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μHz/eV, livetime 1y, angular acceptance 1 ster, pressure broadening known to 1%, field broadening < 10^{-7}



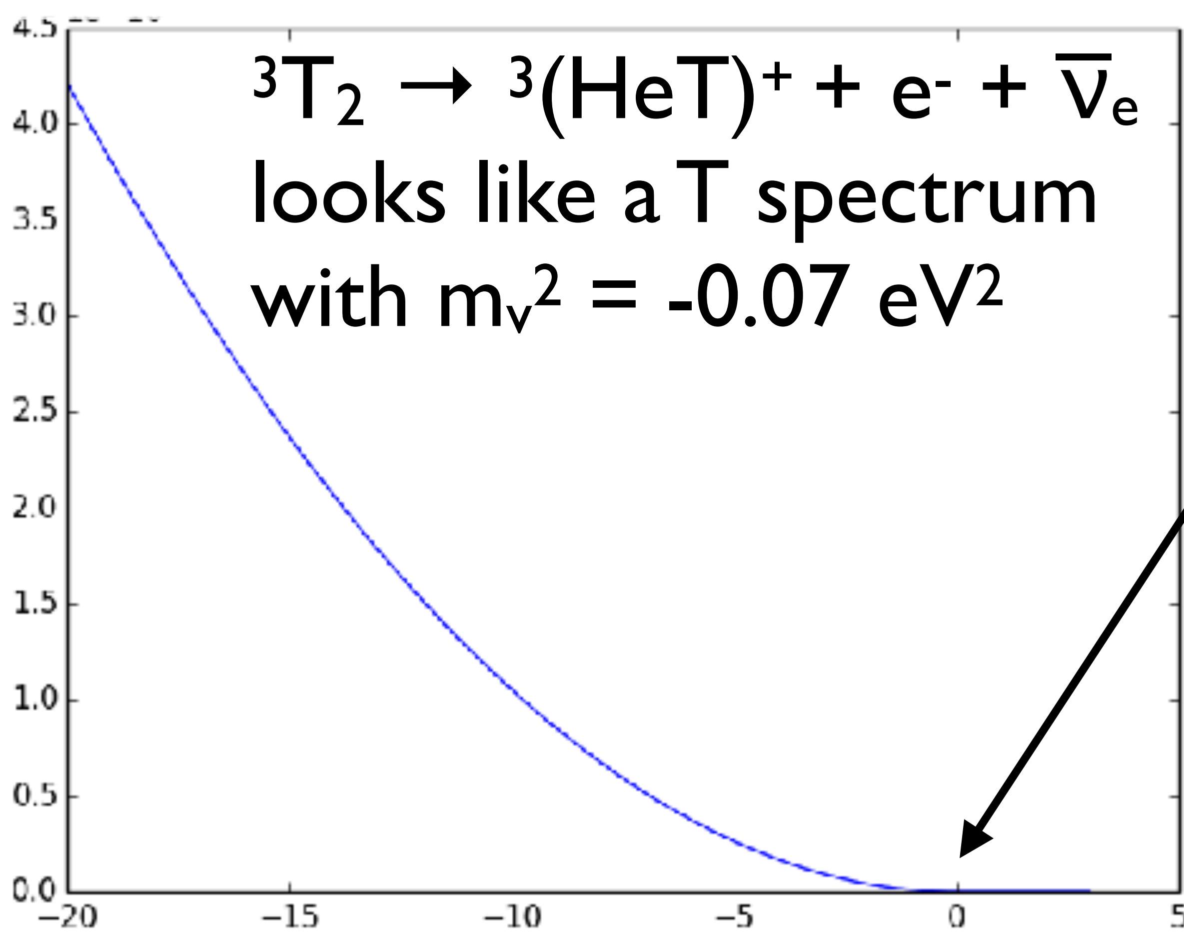
ideal tritium spectrum with $m_\nu^2 = 0$



Final state energy of $(^3HeT)^+$ ion

$\sigma^2 = 0.07\ eV^2$

↑ calculated, not measured



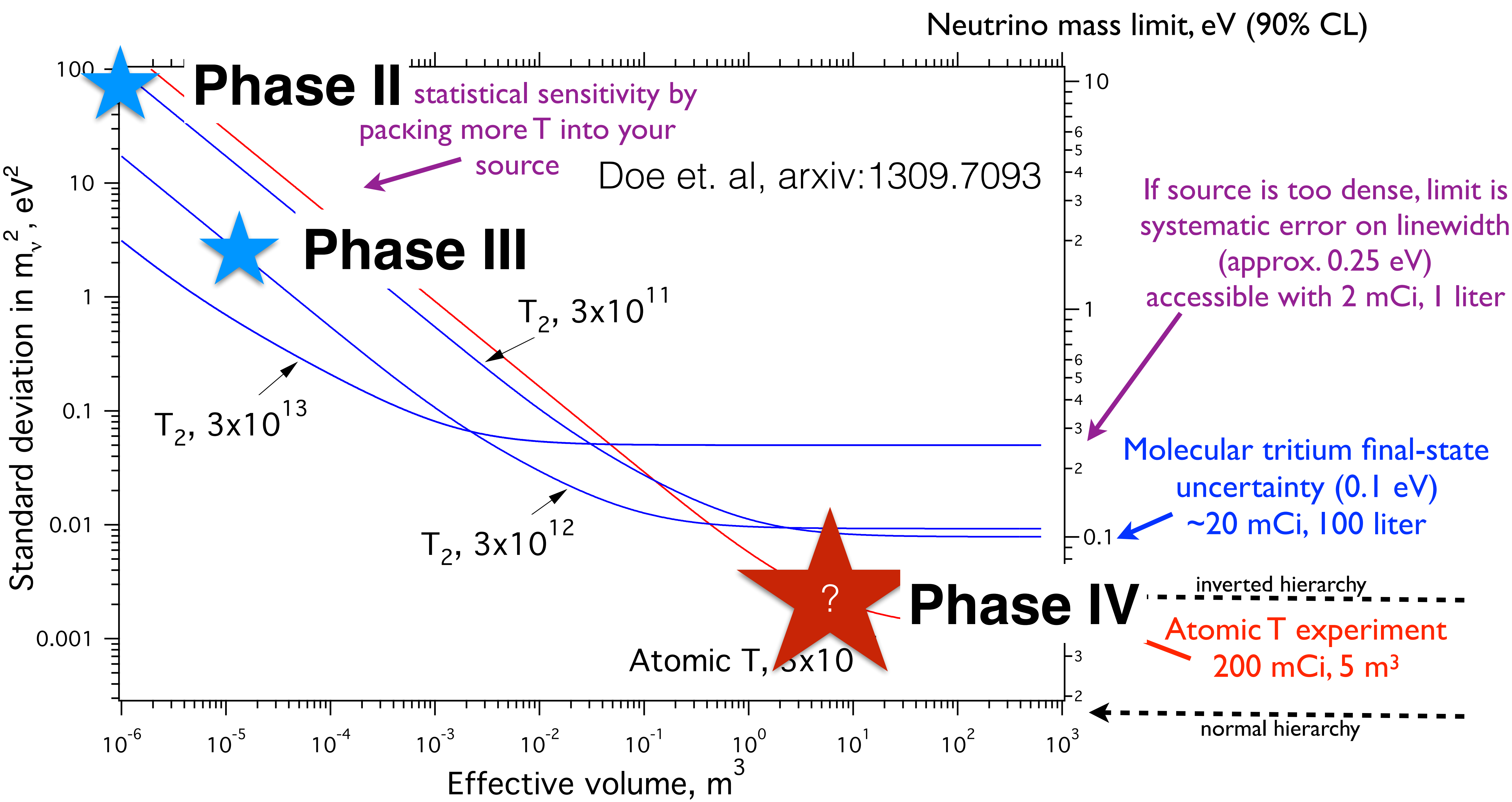
$^3T_2 \rightarrow {}^3(HeT)^+ + e^- + \overline{\nu}_e$ looks like a T spectrum with $m_\nu^2 = -0.07\ eV^2$

different here, but usually not resolvable

- T_2 molecular physics is both blurring and adding systematics
- Worth moving to T_1 source if at all possible

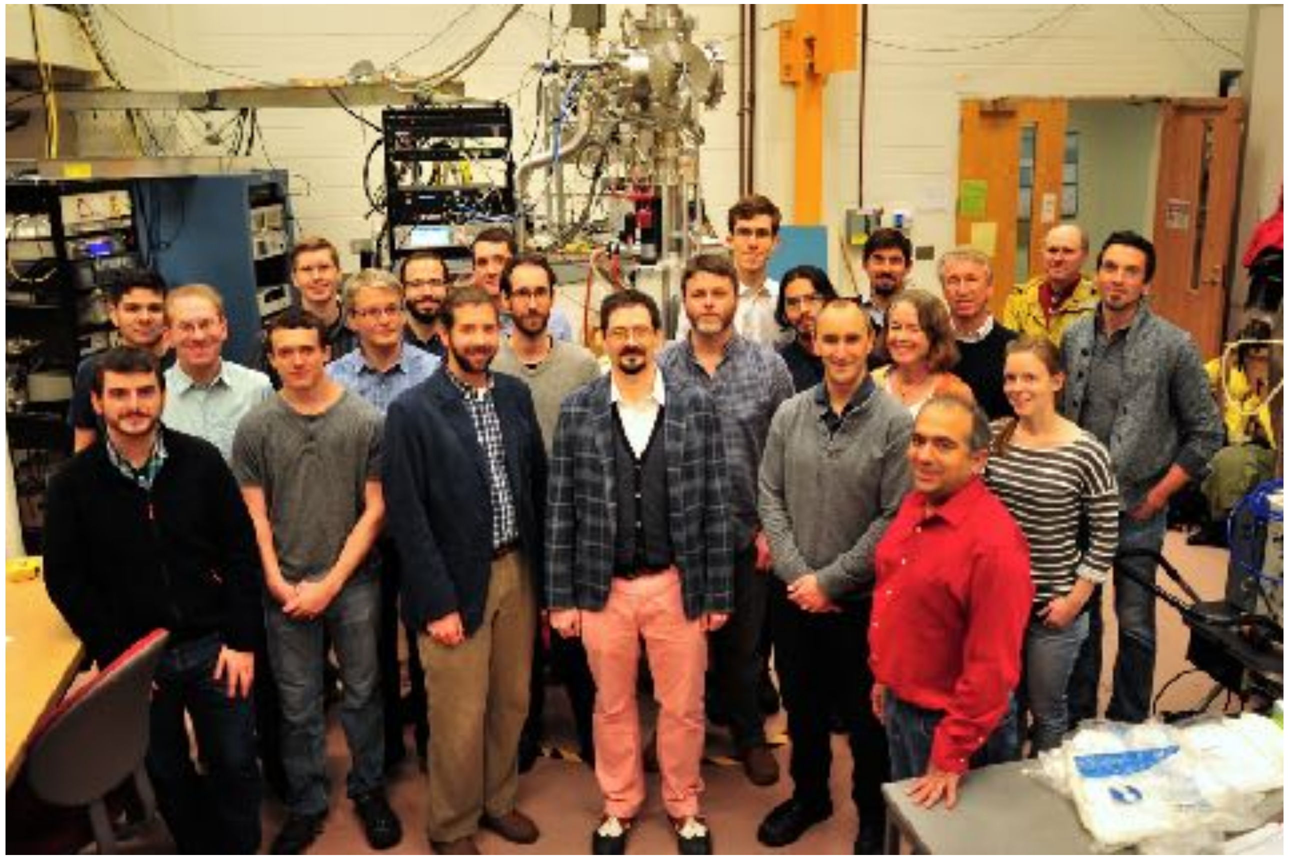
Project 8 sensitivity estimates:

Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μHz/eV, livetime 1y, angular acceptance 1 ster, pressure broadening known to 1%, field broadening < 10^{-7}

Benjamin Monreal, Yu-Hao Sun, Laura Gladstone
Case Western Reserve University
Sebastian Böser, Christine Claessens, Alec Lindman
Johannes Gutenberg Universität, Mainz
Thomas Thümmler, Marcel Walter
Karlsruhe Institute of Technology
Kareem Kazkaz
Lawrence Livermore National Laboratory
Nicholas Buzinsky, Joseph Formaggio, Joseph Johnston, Valerian Sibille, Evan Zayas
Massachusetts Institute of Techno
Erin Finn, Mathieu Guigue, Mark Jones, Benja Oblath,
Jonathan Tedeschi, Brent VanDevender
Pacific Northwest National Laboratory
Luiz de Viveiros, Timothy Wendler
Pennsylvania State University
Shep Doeleman, Jonathan Weintroub, Andre Young
Smithsonian Astrophysical Observatory
Ali Ashtari Esfahani, Raphael Cervantes, Peter Doe, Martin Fertl, Eric Machado,
Walter Pettus, Hamish Robertson, Leslie Rosenberg, Gray Rybka
University of Washington
Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum
Yale University

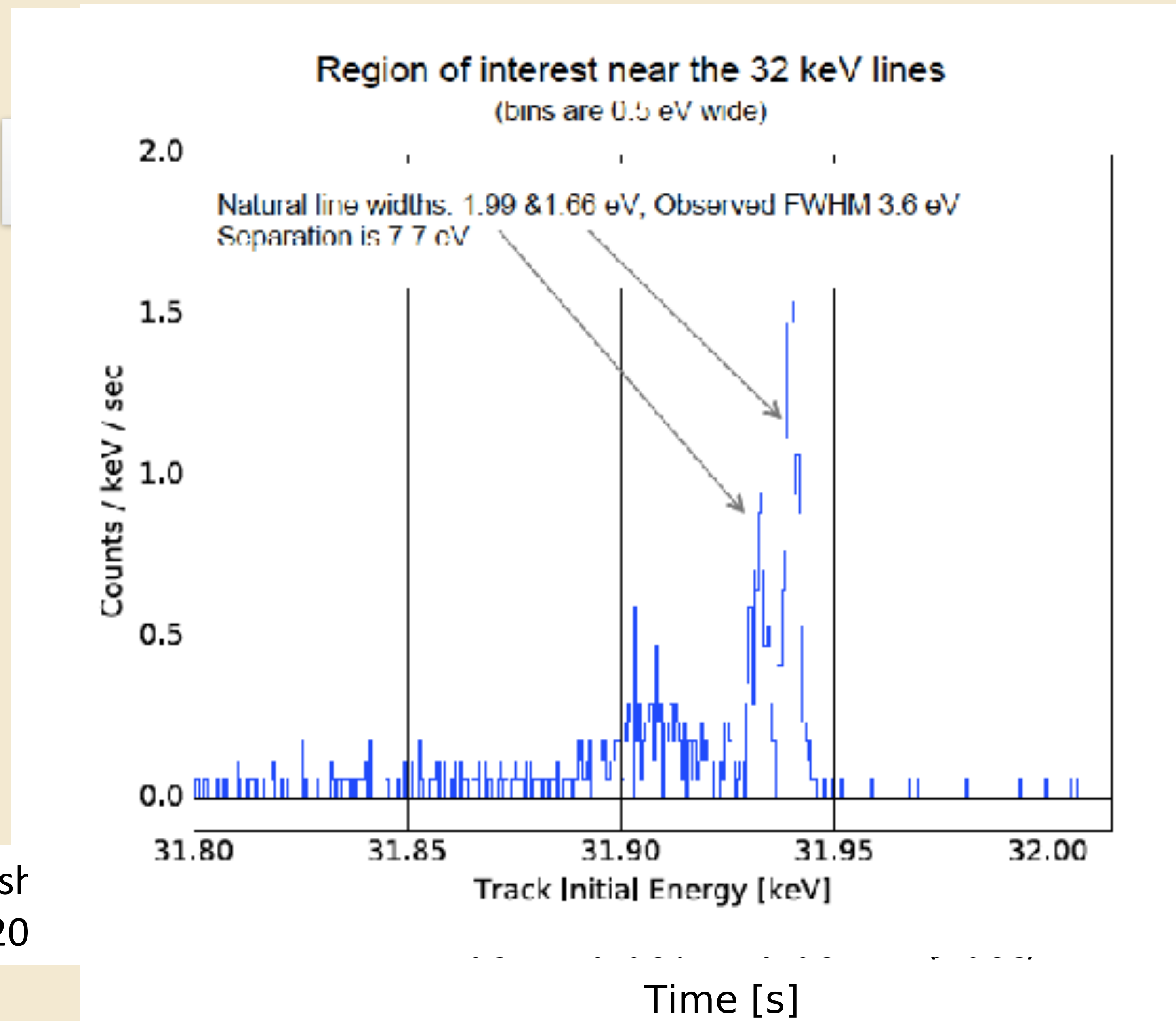


The first light in the detector from a single electron

Digitize output of a super-heterodyne mixing stage

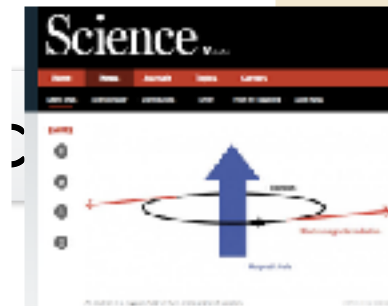
Fourier transform short time slices

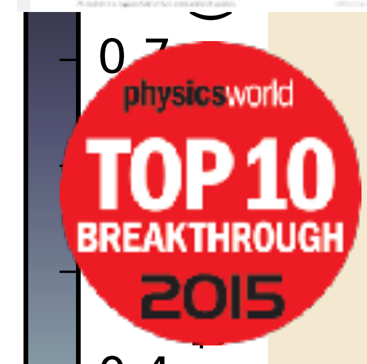
Plot power vs. frequency as function of time



Ash
(20

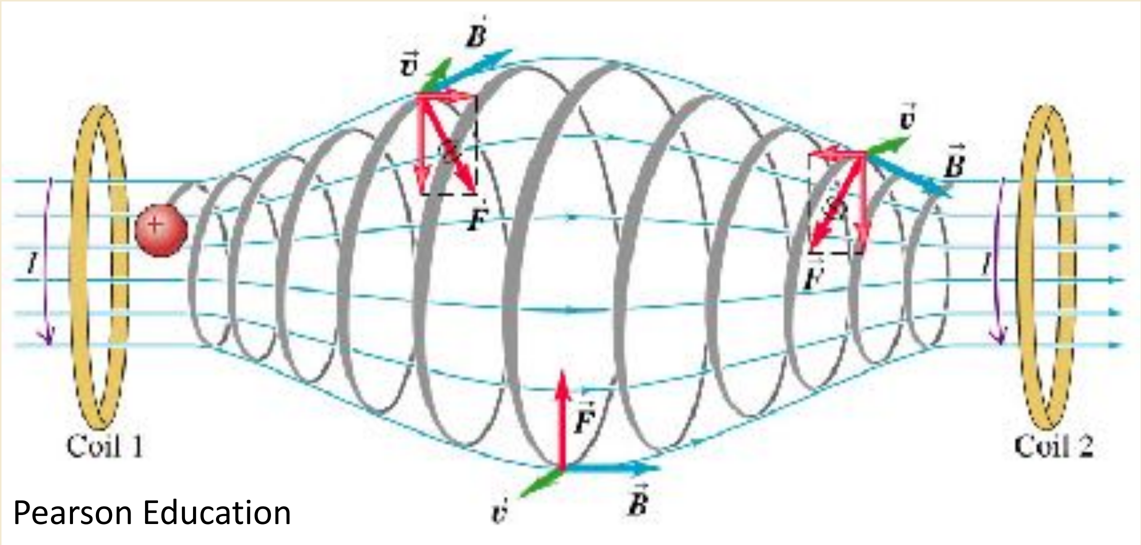
Time [s]



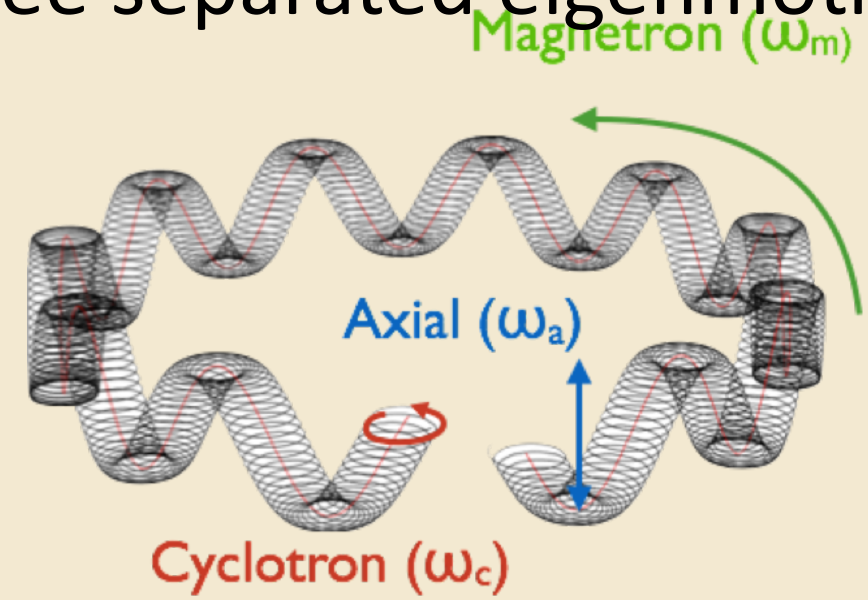


Rich frequency spectrum of raw CRES signal

e^- confinement in magnetic bottle:
→ Non-trivial e^- motion



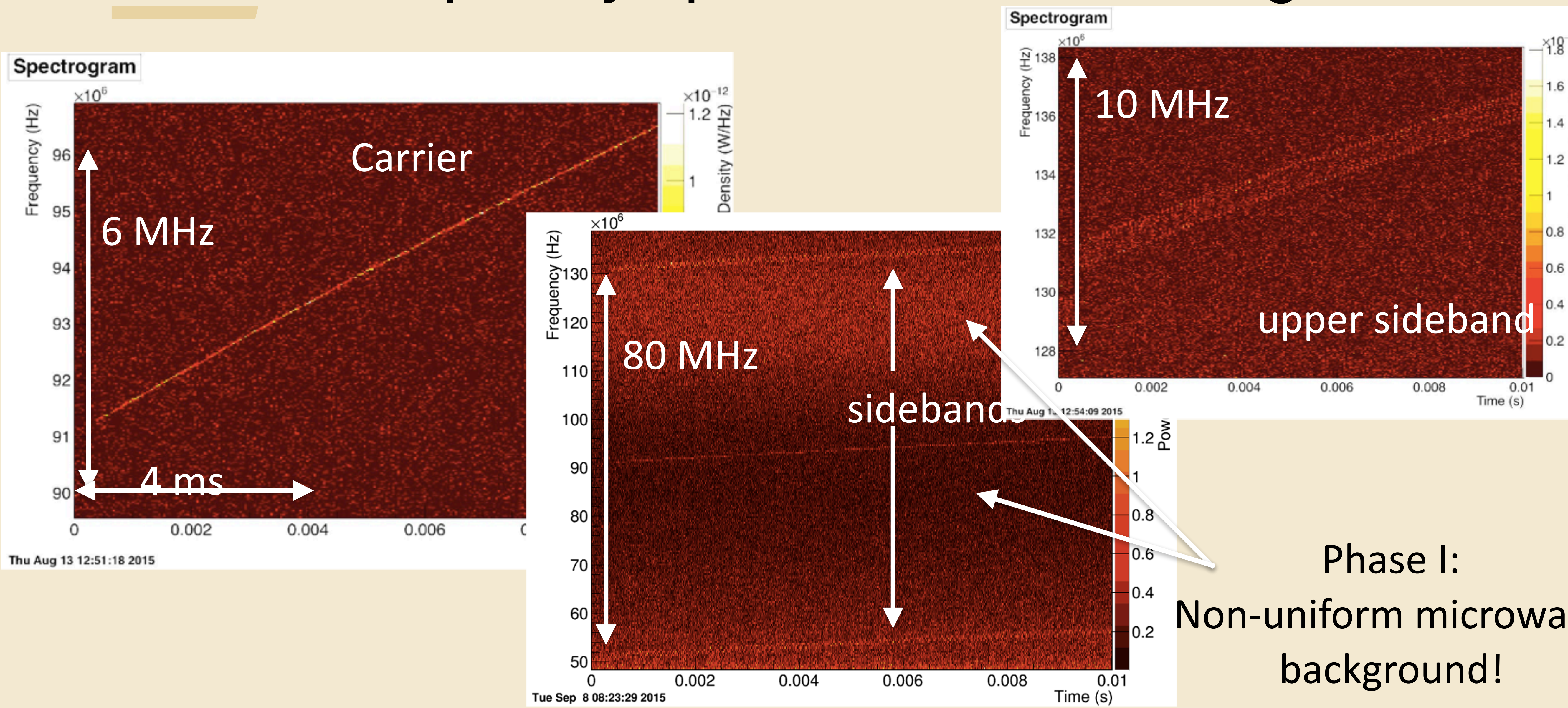
Similarity to Penning trap with three separated eigenmotions



http://wswww.physik.uni-mainz.de/werth/g_fak/

Signal model predicts frequency side bands due to B-modulation and Doppler-effect!

Rich frequency spectrum of CRES signals



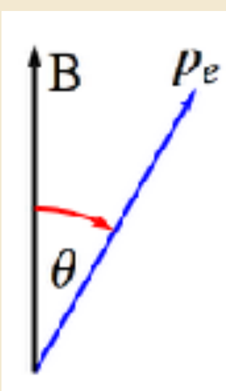
Phase I:
Non-uniform microwave background!

Pitch angle correction

In a harmonic magnetic trap (B ~ z²) the measured microwave frequency depends on the electron pitch angle:

magnetic field at trap bottom

pitch angle ≅ 90°



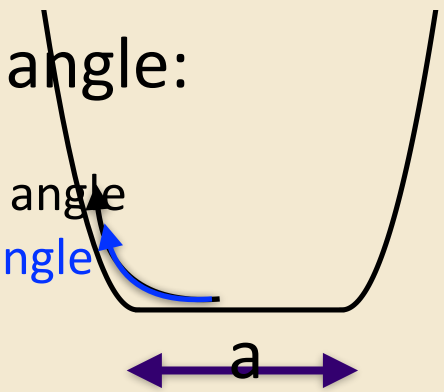
$$\omega_\gamma = \frac{eB}{m+E_{\mathrm{kin}}}\left(1+\frac{\cot^2\theta}{2}\right)$$

measured microwave frequency

kinetic energy

More details: see talk C. Claessens

Approximate model of the bathtub trap



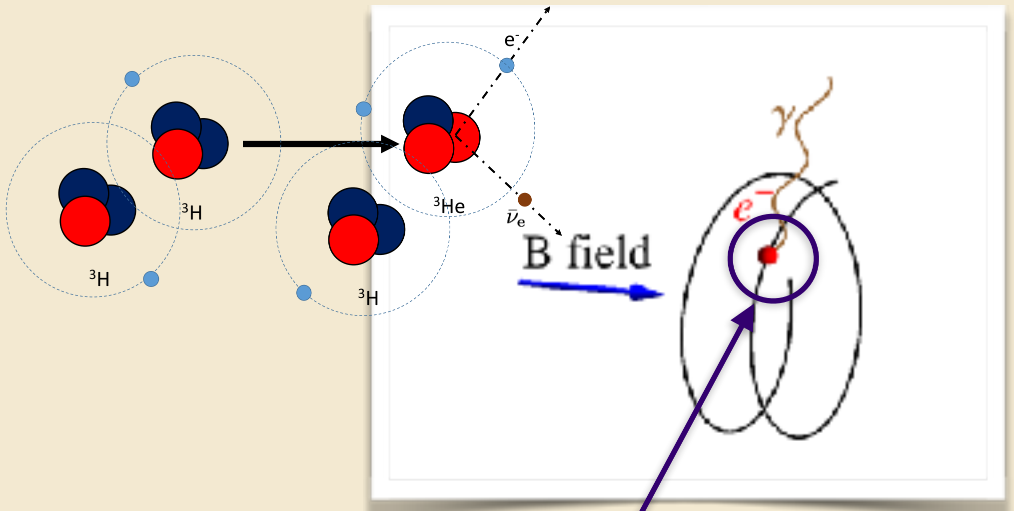
harmonic trap wa

flat bottom of bathtub trap

Approximate expression for axial freque

$$\omega_{\mathrm{a}} \propto v\left(\frac{a}{\sin\theta}+\frac{4\sin\theta}{m\cos^2\theta}\right)^{-1}$$

Project 8 Phase II: A combined T_2 and ^{83m}Kr source



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

Source of T_2 decay electrons:
- Safe handling of T_2 gas
- Temperature range: ≅ 80-300 K
- Fine T_2 pressure regulation
- 10^{-9}-10^{-5} torr operation pressure
- Gas composition measurements

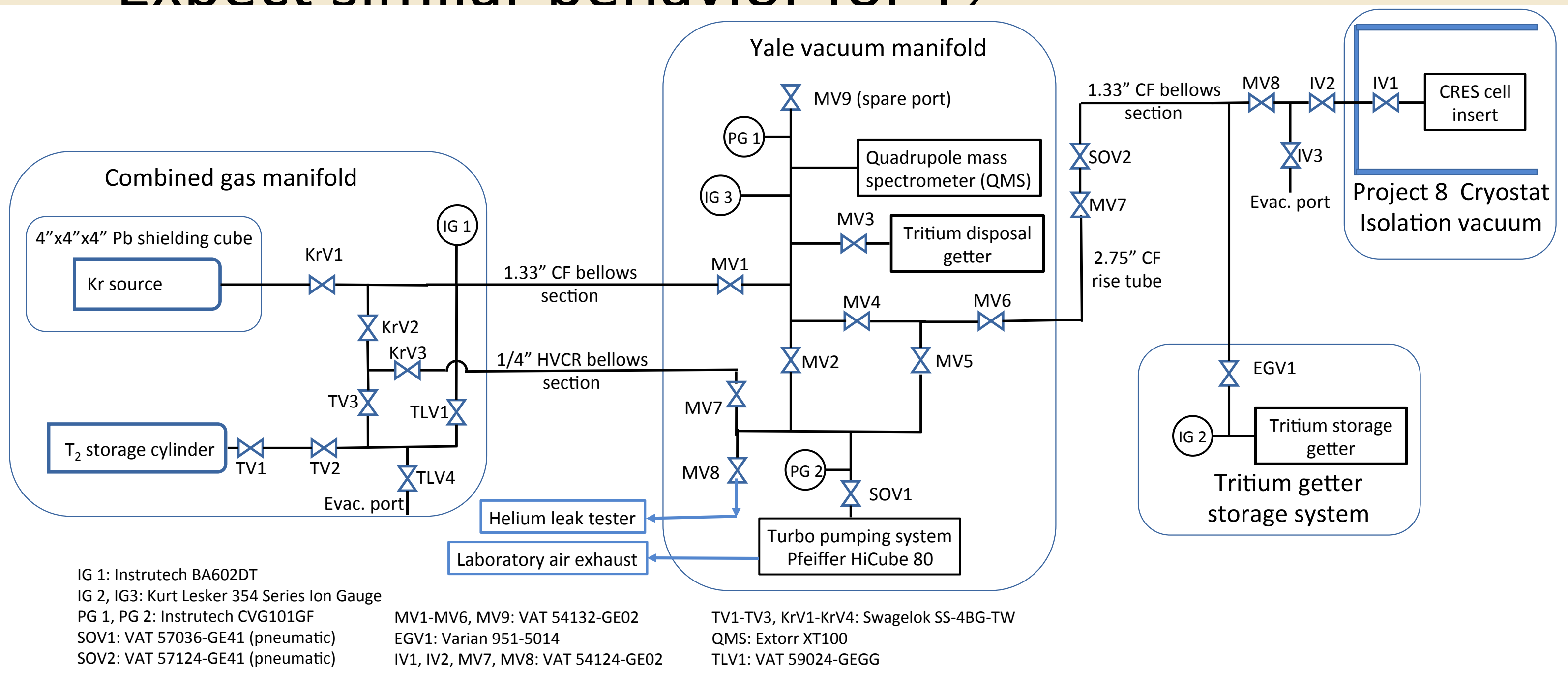
Source of ^{83m}Kr conversion electrons:
- ^{83m}Kr CE energies well known
- Matching CE energy range 9 - 32 keV
- B field long term stability
- ^{83m}Kr goes where T_2 goes (co-magnetom

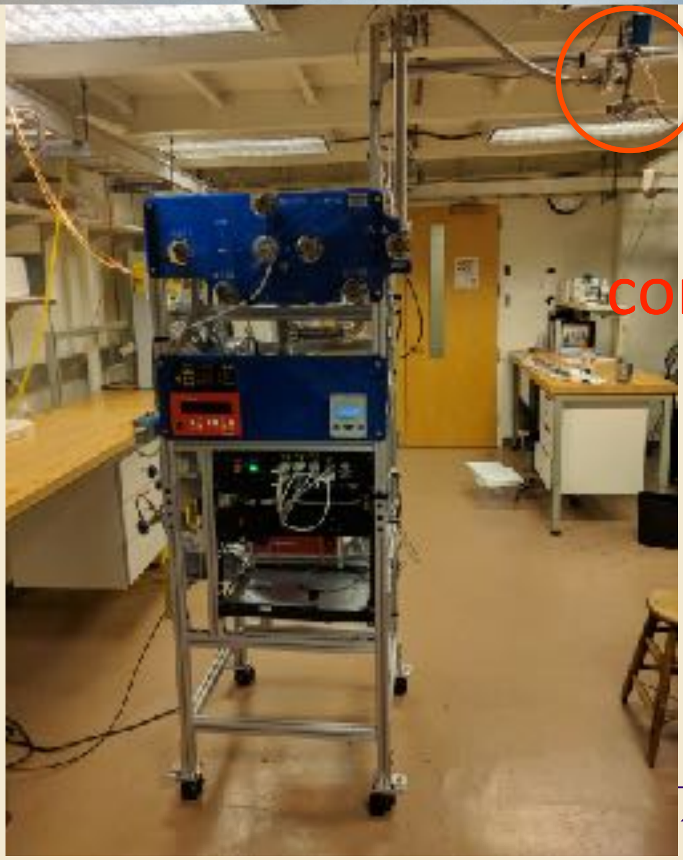
Tritium storage in metal getter

Successfully tested the loading and release of D_2 from a SAES St172 getter sample (togeth

- Continuous pumping of H_2, CO, CO_2, H_2O, CH_4
- Simple pressure regulation
- Expect similar behavior for T_2

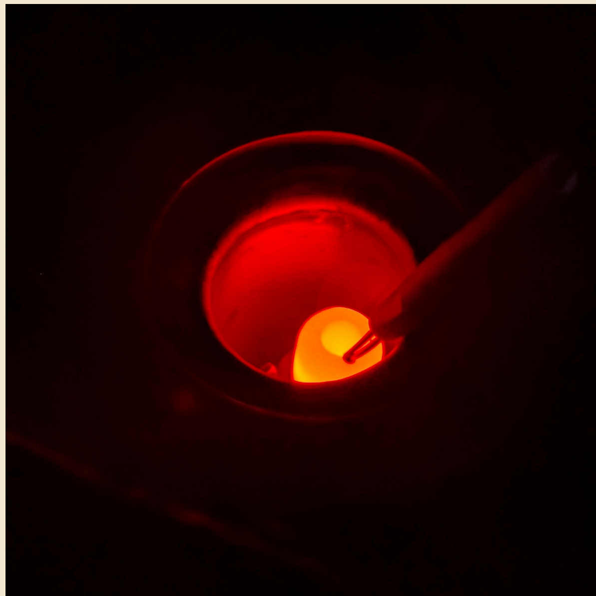
Compact T_2 reservoir built and com

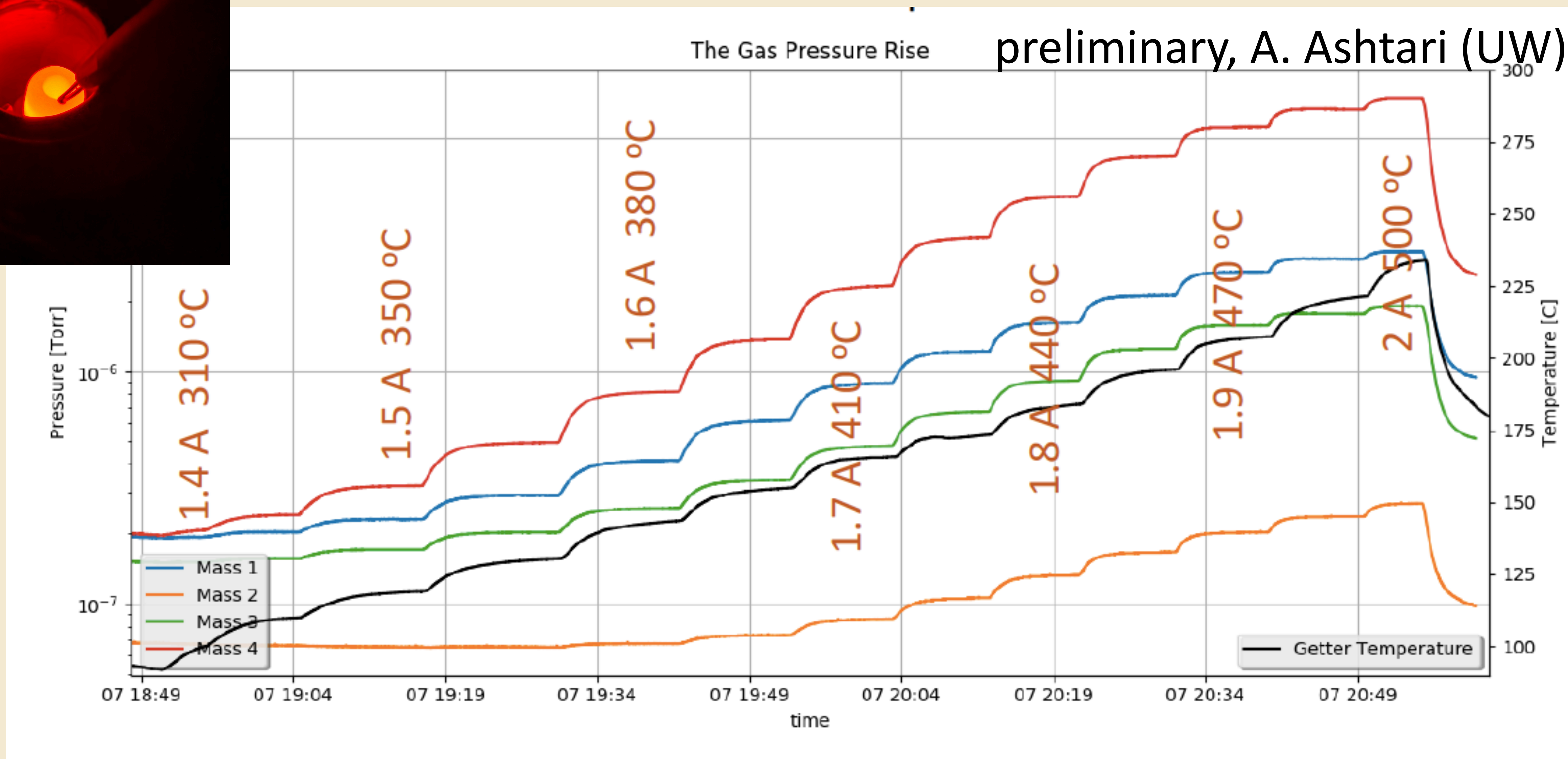




Getter compartment

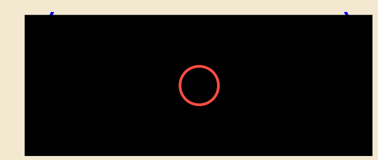
Tritium storage in metal getter





Project 8 Phase II: T_2 compatible CRES cell

Phase I: WR42WG



0.170” (4.3 mm)

0.420” (10.7 mm)

Technical challenges for a T_2 compatible CRES cell

1. Transport circularly polarized radiation.
2. Larger volume!
3. Low-loss microwave guide!
4. No ferromagnetic construction material.
5. Hermetic confinement of T_2 gas
6. Low loss microwave transparent windows
7. Cryogenic operation
8. Matched thermal expansion coefficients

Oxygen-free high-conductivity copper

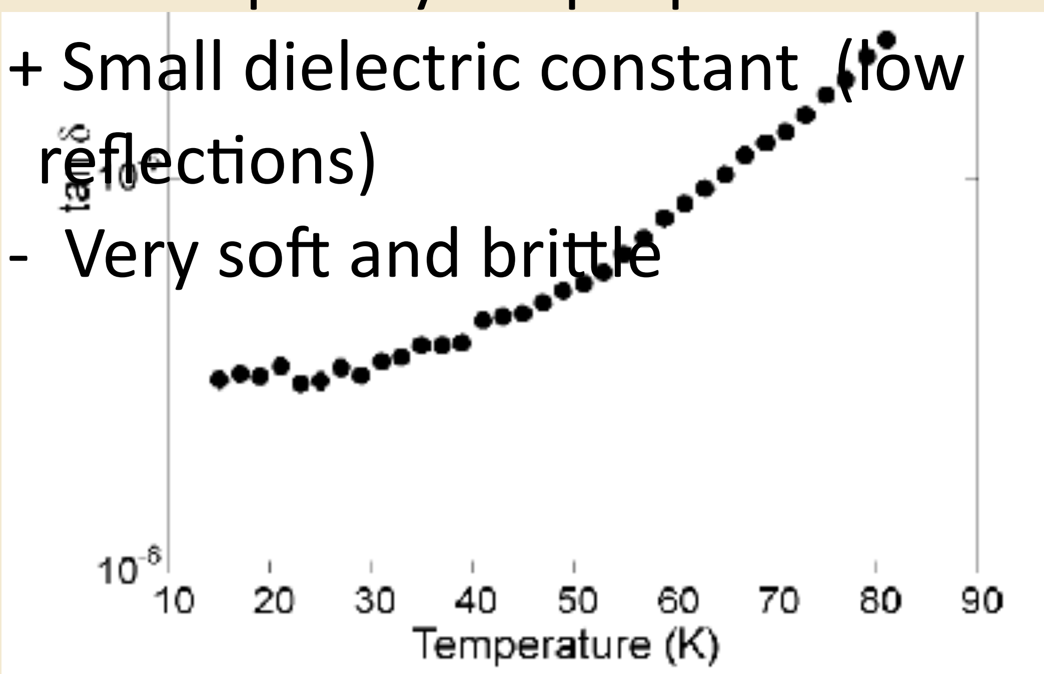
No organic (kapton) window material

Calcium difluoride windows, indium s

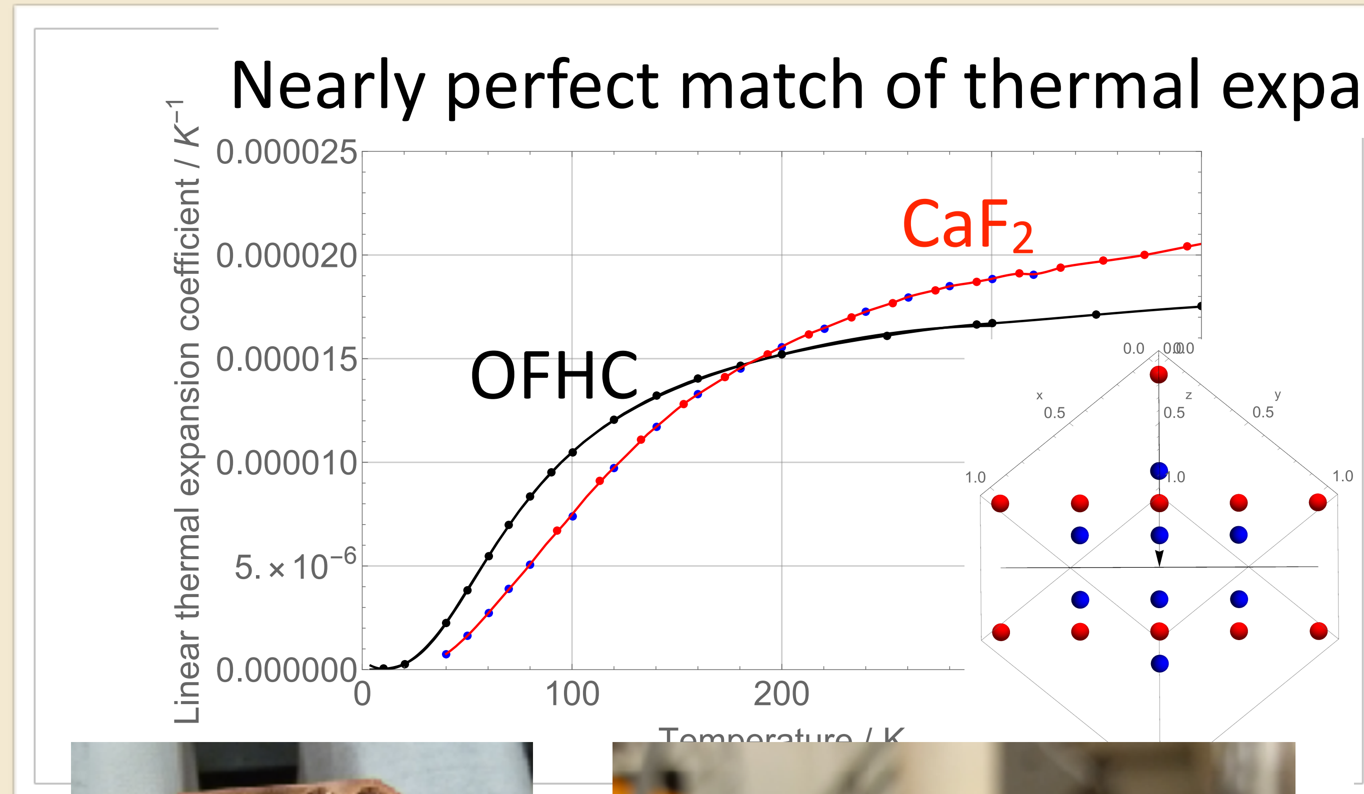
CaF_2 windows are ideal but very brittle!

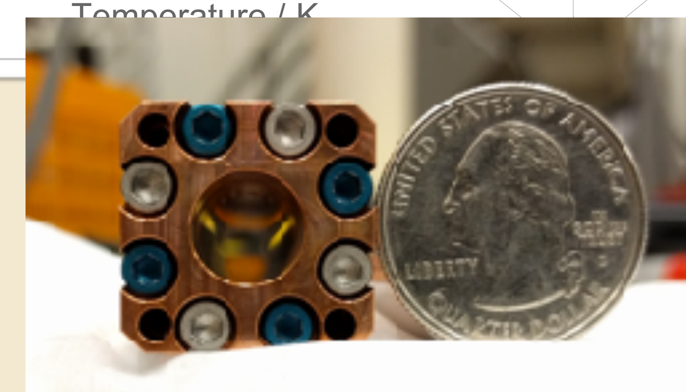
CaF_2 window material:

+ Low loss tangent (low absorption loss)
+ Isotropic crystal properties
+ Small dielectric constant (low reflections)
- Very soft and brittle

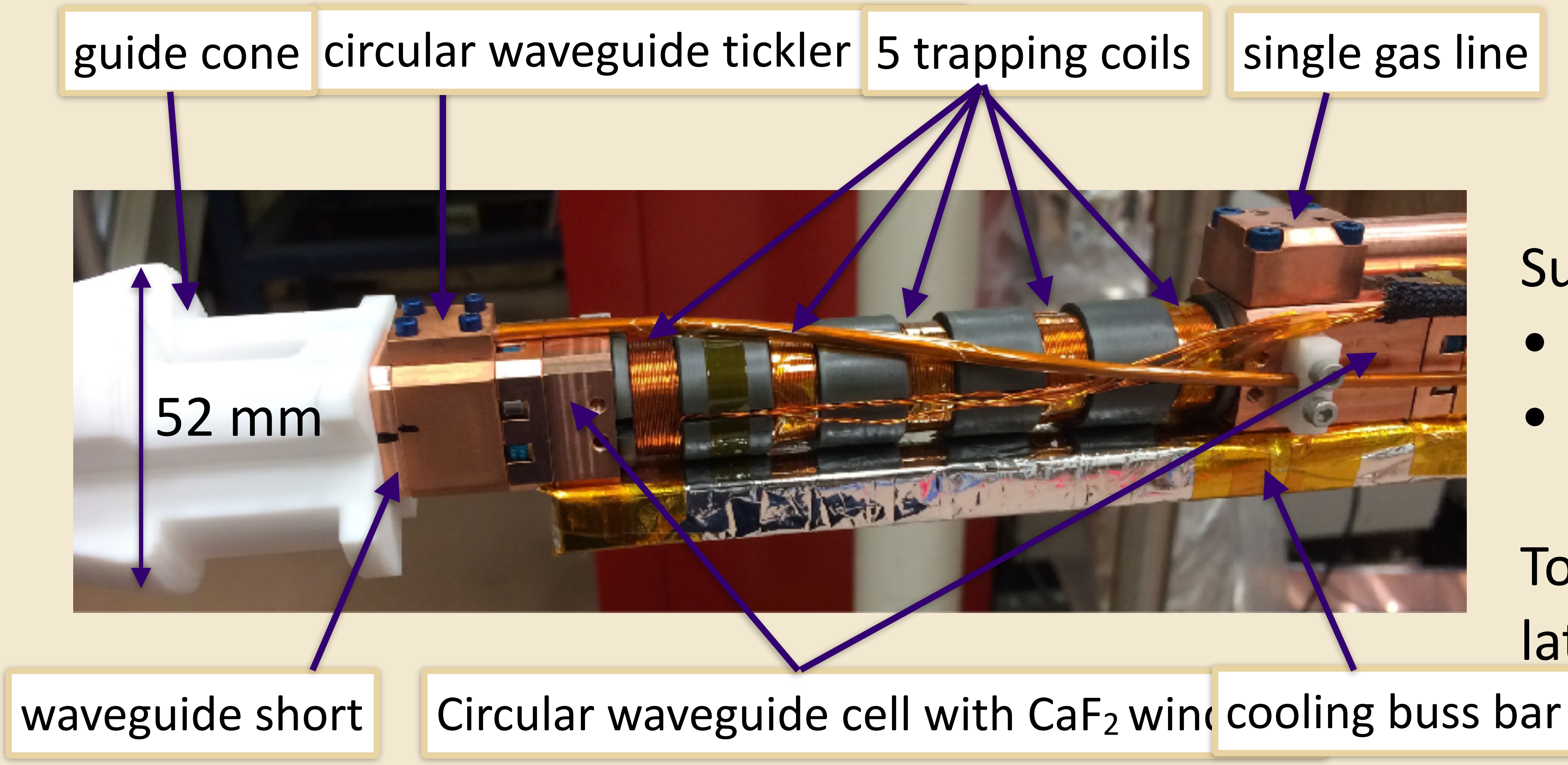


M. Jacob et al., J. of the Europ. Ceramic Society 23 (200…





The Phase IIa CRES cell before installation



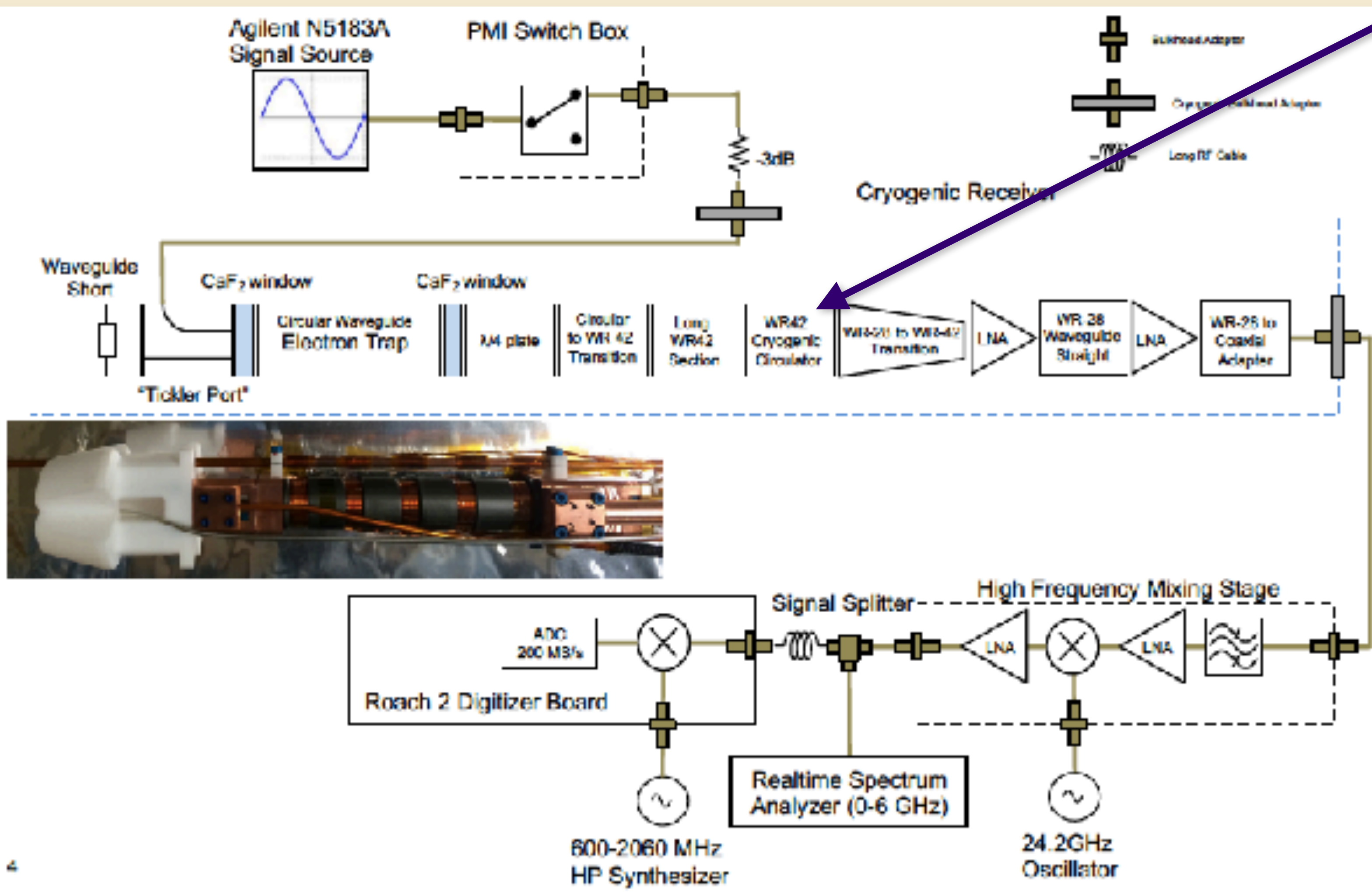
Successful CRES cell opera

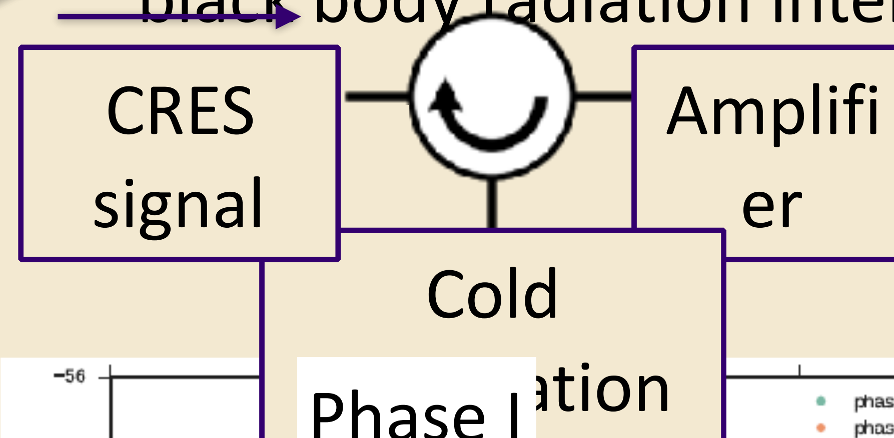
- Commissioning with ^{83m}
- 50-300 K cell temperatu

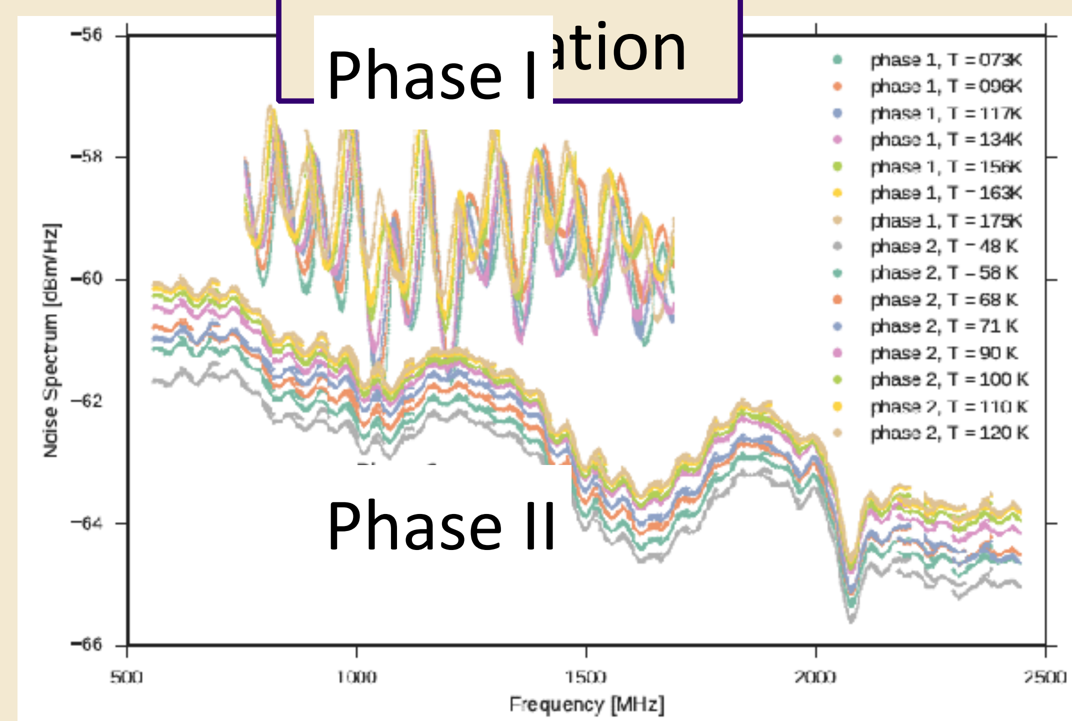
To be used with T_2 gas afte late fall 2017!

Upgraded microwave infrastructure

Crvogenic circu ... sses
black body radiation interferenc

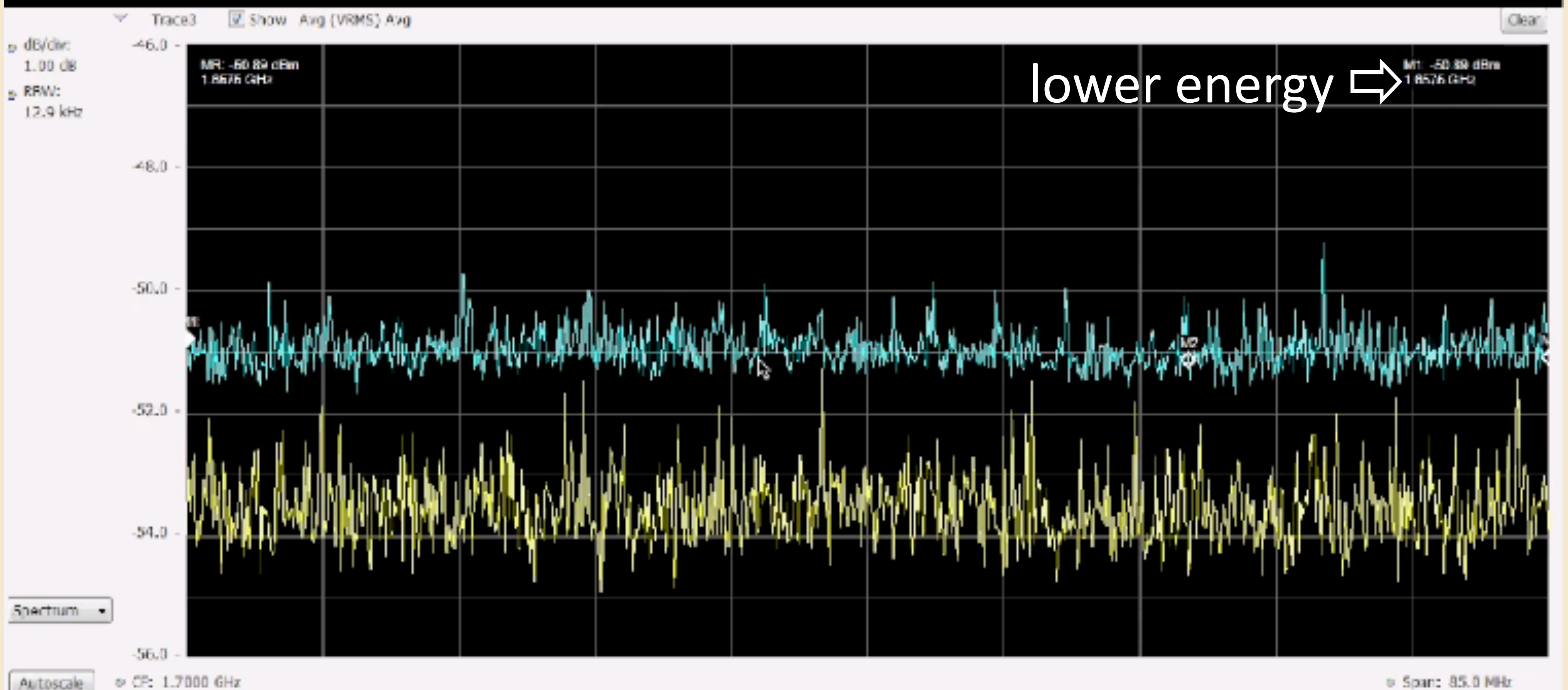






Typical CRES signals live

17.8 keV electrons, realtime x20



ongoing commissioning with ^{83m}Kr

DAQ Phase II upgrade and the path towards Phase III

Multichannel, scalable DAQ system update for Phase II based on ROACH:

- **R**econfigurable **O**pen **A**rchitectur
  Computing **H**ardware
- Widely used in radioastronomy
- Based on Xilinx Virtex 5 FPGA
- Project 8 is curr commission
  3 channel versi

see C. Claessens
(Thursday)

Increase T_2 gas volume for Phase III:
larger magnetic field volume,
free space antenna array

see S. Boeser's talk (Thursday)

Summary

Project 8:

- Phase I: 1st direct observation of cyclotron radiation from a single electron
- Phase I: Successfully measured ^{83m}Kr spectrum using CRES
- Phase II: Operation of a T_2 compatible CRES cell initially with ^{83m}Kr
  - Combined T_2 and ^{83m}Kr gas system built and operation approved
  - First T_2 CRES measurement later this fall
- Phase III+IV: R&D program concurrent with Phase II