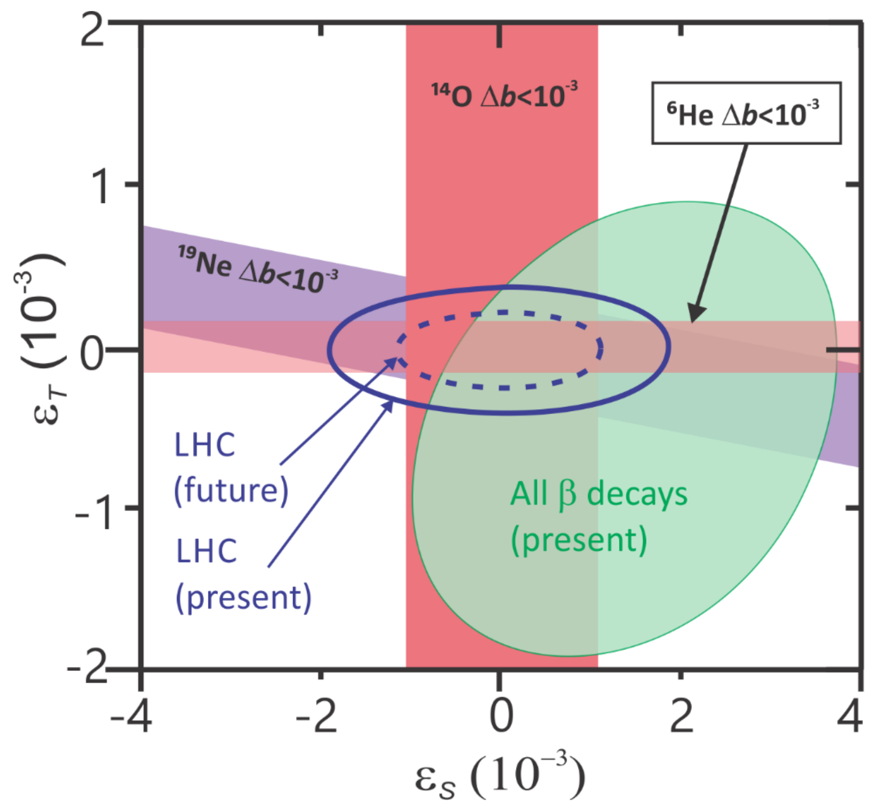
Microwaves for nuclear spectroscopy
Motivation



Search for chirality flipping currents beyond the LHC?

Challenging goal:
Measure beta spectra with accuracies 10^{-3} or better

Microwaves for nuclear spectroscopy
Traditional techniques

Beta spectroscopy, developed over many decades

- Calorimetry (Silicon semiconductors, Scintillators)
- Magnetic spectroscopy

Uncertainties typically at 1%
Maybe can improve to 0.1%, but beyond?
Any other possibilities?

Microwaves for nuclear spectroscopy

Basic idea of Cyclotron Radiation Emission Spectroscopy (CRES)

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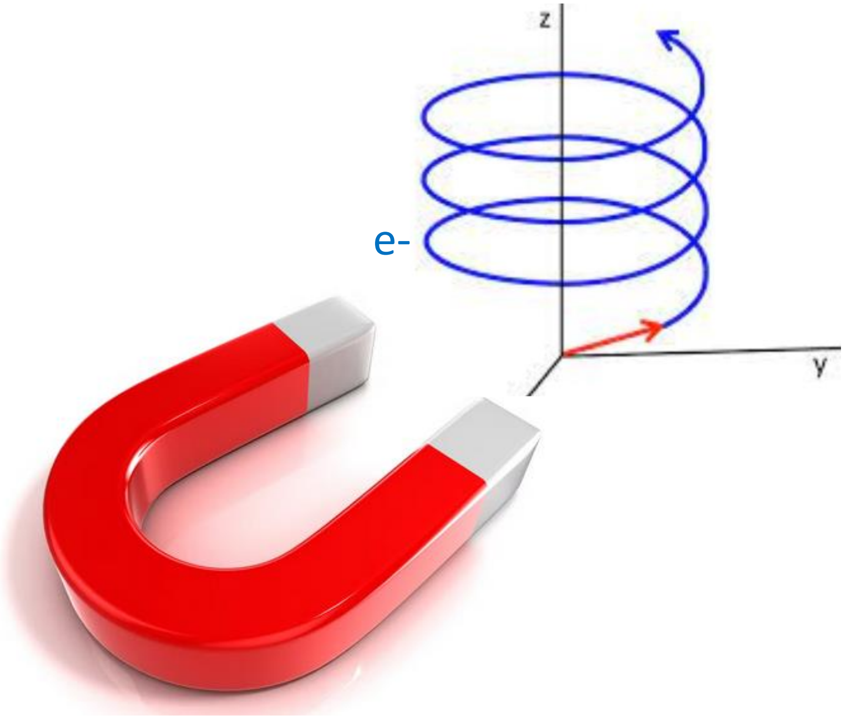
β undergoes cyclotron motion in B field.
radiation frequency → beta energy

$$\omega_{radiation} = \omega_{cyclotron} = \frac{qB}{E}$$

e- energy

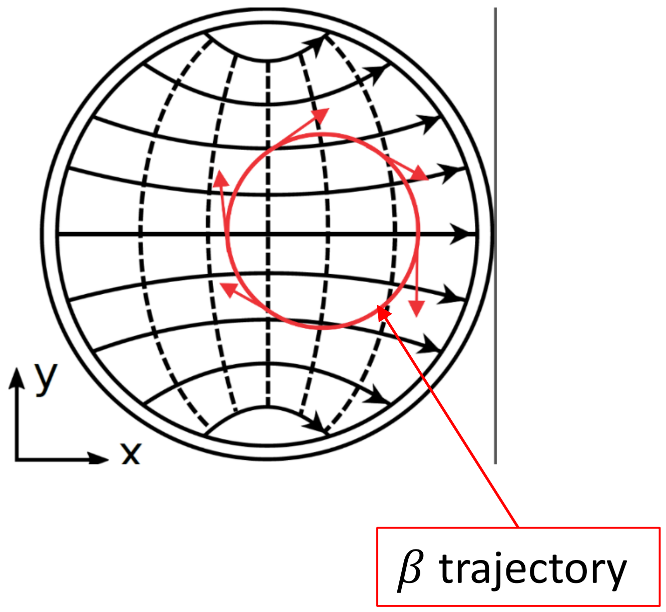


Microwaves for nuclear spectroscopy

Difficulty: power≈femtoWatt

Power ≈ femtoWatt
To detect small signals →
use waveguides

Example: TE_{11}-mode $\vec{E}$ lines



Radiation amplitude proportional to

$$\int d^3x\ \vec{E}_{11} \cdot \vec{J}$$

$$\omega_{radiation} = \omega_{cyclotron} = \frac{qB}{E}$$

Microwaves for nuclear spectroscopy

Proposal and 1st implementation: Project 8 collaboration

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Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

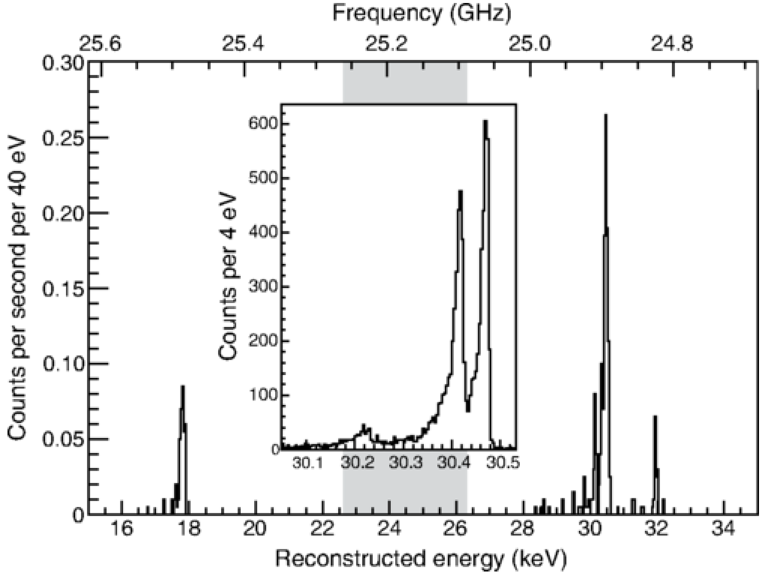
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

(Project 8 Collaboration)

Aimed at m_ν from ^{3}H
$Kmax$ ≈18 keV.

Project 8 collaboration
$\Delta K/K$ ≈10^{-3} resolution for ^{83}Kr conversion electrons of 18-32 keV.



He6-CRES – Collaboration

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W. Byron[1], W. DeGraw[1], M. Fertl[2], A. Garcia[1], B. Graner[1], H. Harrington[1], L. Hayen[3], X. Huyan[4] , D. McClain[5], D. Melconian[5], P. Mueller[6], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[7], D. Stancil[3], D. Storm[1], H.E. Swanson[1], R.J. Taylor[3], B.A. Vandeevender[4], F. Wietfeldt[7], A. Young[3]

6He-CRES

External collaborators' commitments

Mainz: general advice
(0.1 senior faculty.)

NCSU: RF calculations, magnetic trap, electric sweeper, analysis strategy
(0.1x2 senior faculty, 0.1 senior pdra, 0.5 student.)

ANL: develop ion source + advice with ion trap + advice with magnet
(0.1x2 senior faculty.)

Texas A&M: develop ion trap, help with beta monitors
(0.1 senior faculty, 0.2 senior pdra, 0.5 student.)

PNNL: help with RF, production of 83Kr, help with analysis
(0.1x2 senior staff, 0.1 posdoc.)

Tulane: participation in experiment, help with simulations, and some hardware
(0.1 senior faculty.)

He6-CRES – Collaboration

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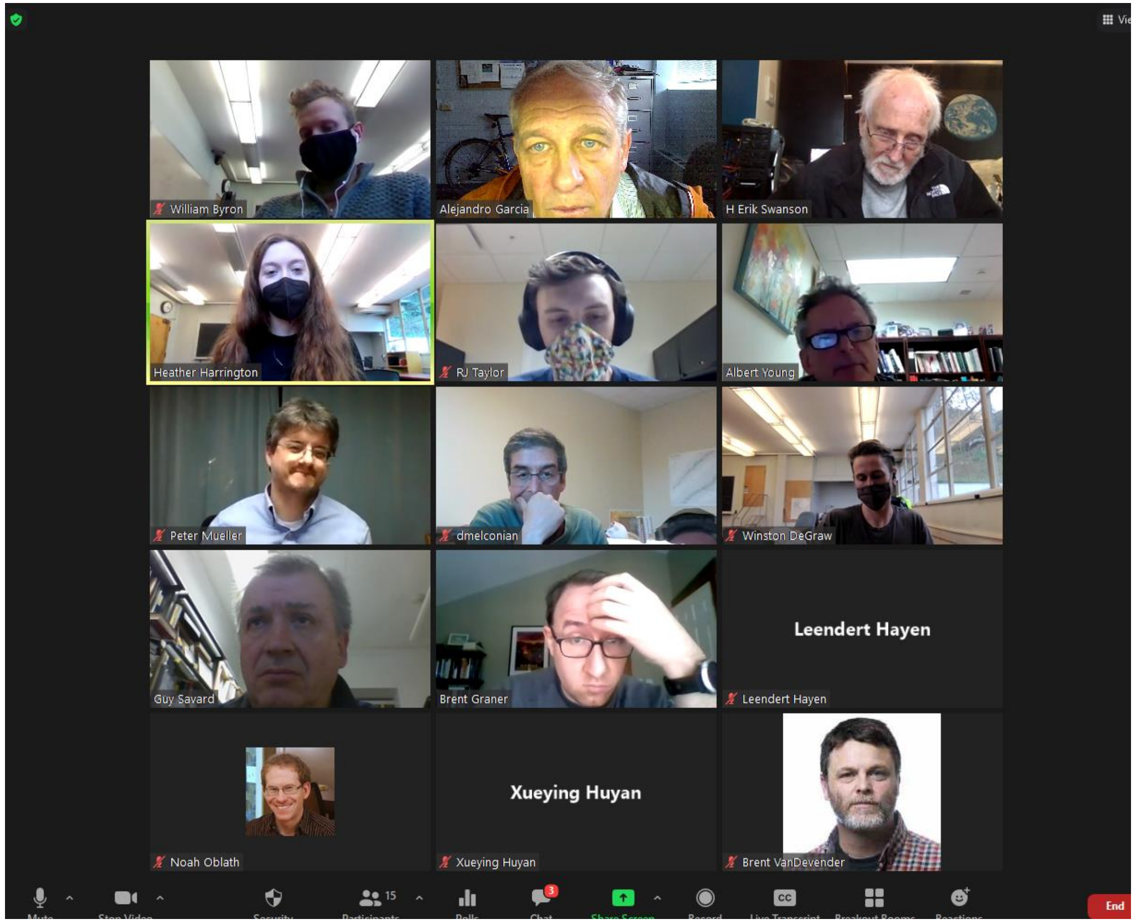

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He6-CRES – Technique Basics

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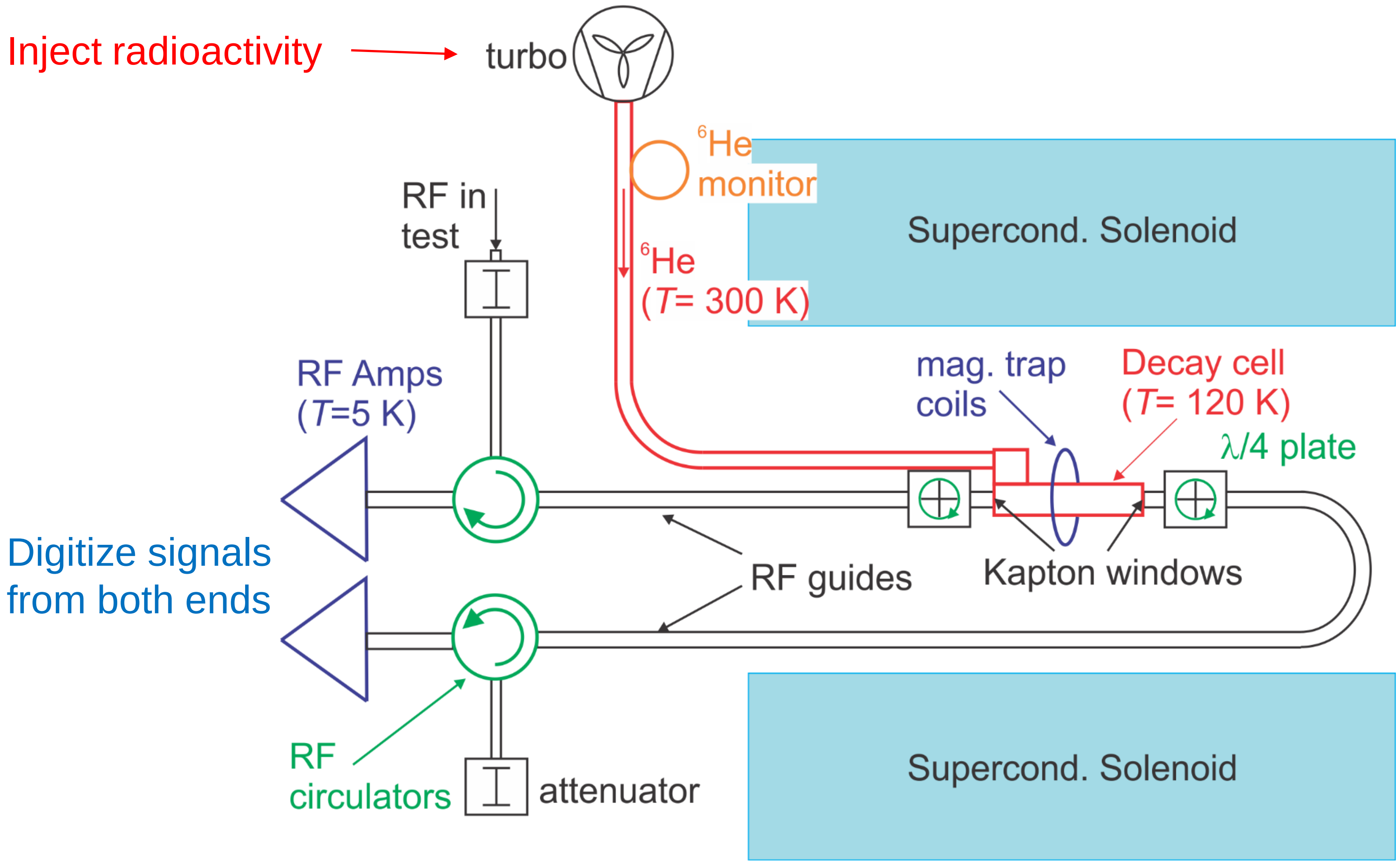
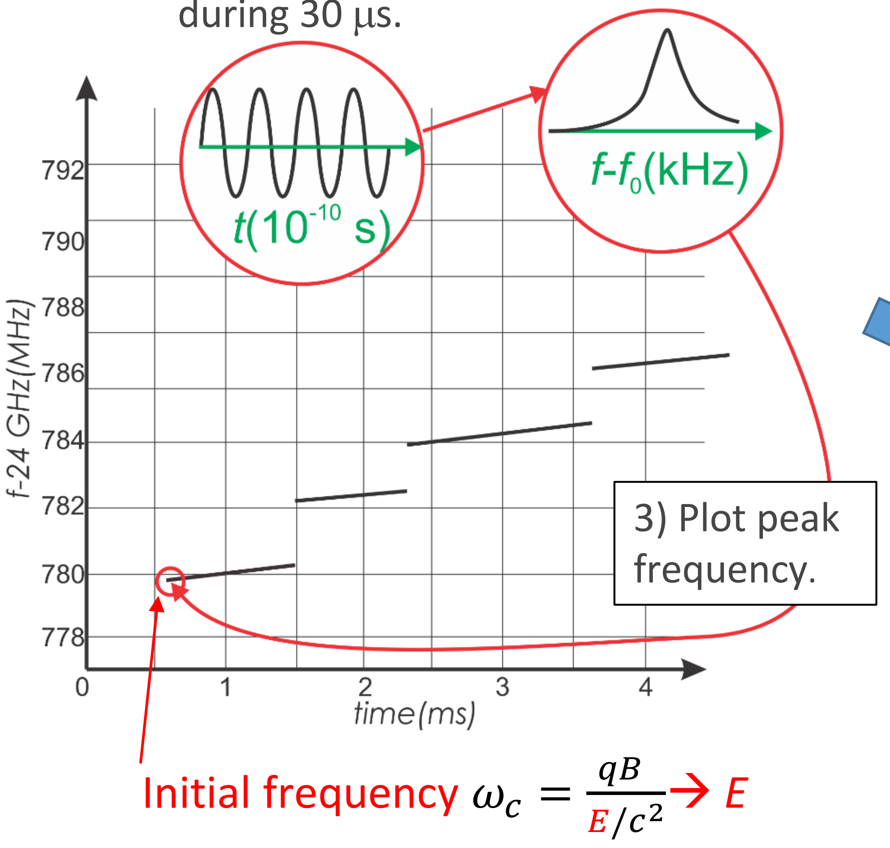


The e- cyclotron motion excites RF waves with

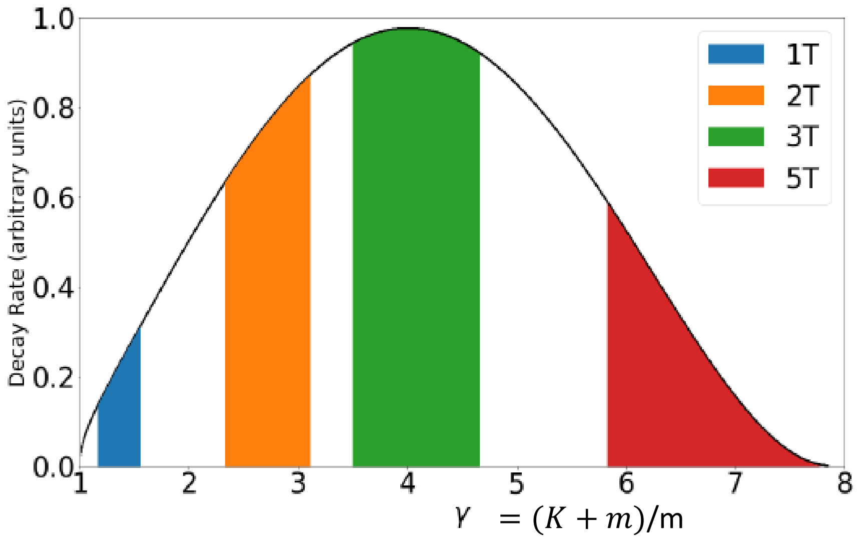
$$\omega_c = \frac{qB}{E/c^2} \rightarrow E$$

He6-CRES – Technique Basics

- **Measures beta energy at creation, before complicated energy-loss mechanisms.**
- No background from room photon or e scattering.
- 6He/19Ne in gaseous form works well with the technique.
- Counts needed not a big demand on running time.
- High resolution: allows debugging of systematic uncertainties.



Frequency band: 18-24 GHz



He6-CRES – Technique Basics

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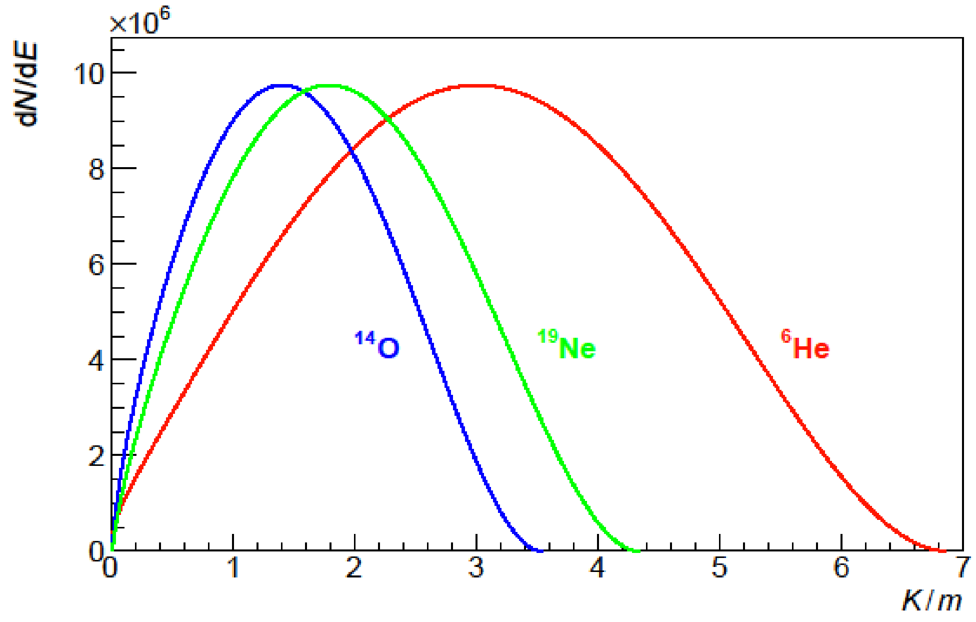
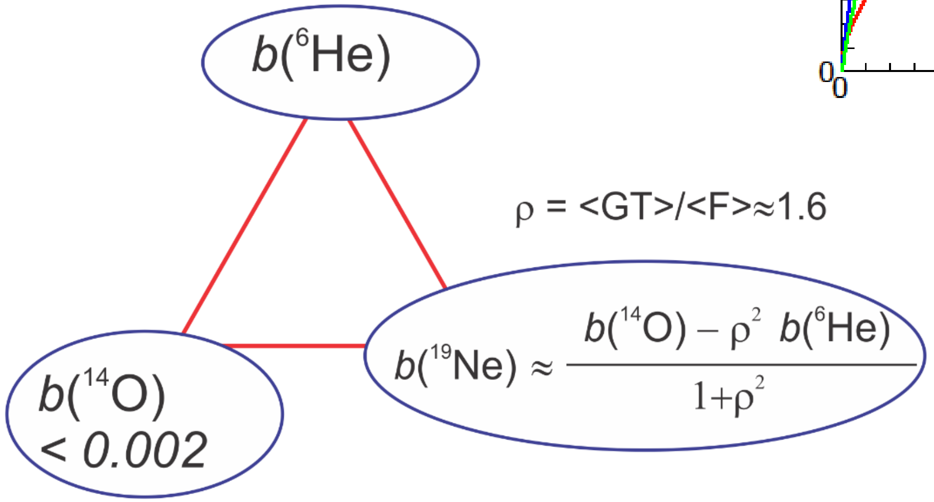
^{6}He-CRES: how to confirm a real signal?
Check on signature by measuring ^{14}O and ^{19}Ne:



Both ^{14}O and ^{19}Ne can be produced in similar quantities as ^{6}He at CENPA.

^{19}Ne source already working.

^{14}O as CO (T_{freeze} = 68 K)
Previous work at Louvain and TRIUMF.



He6-CRES – Experimental Setup

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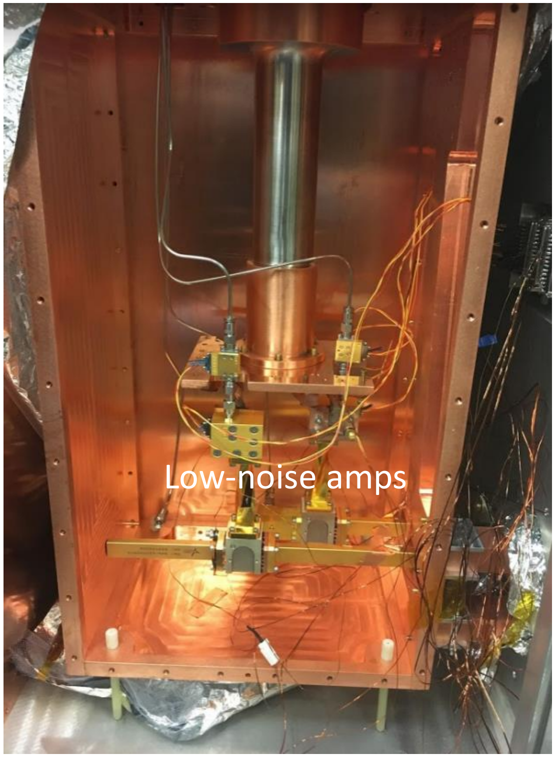
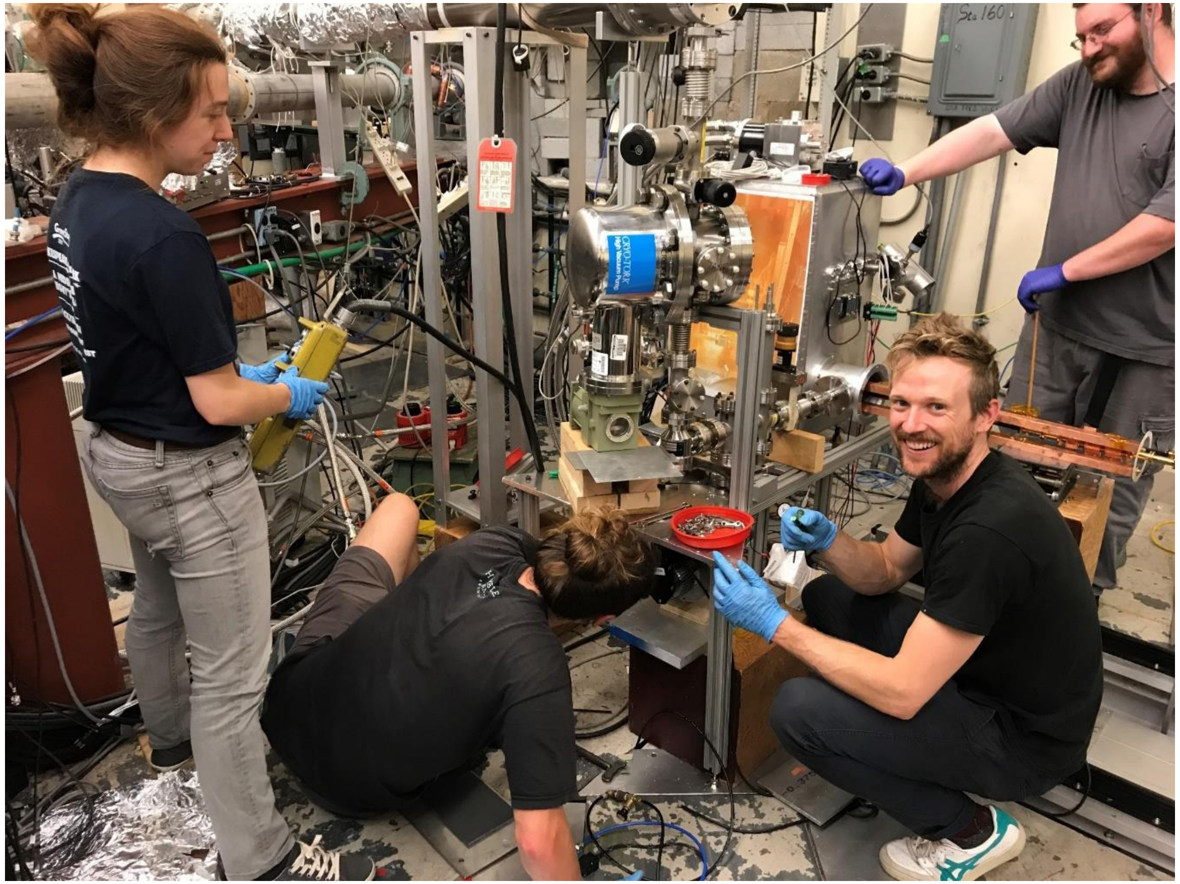
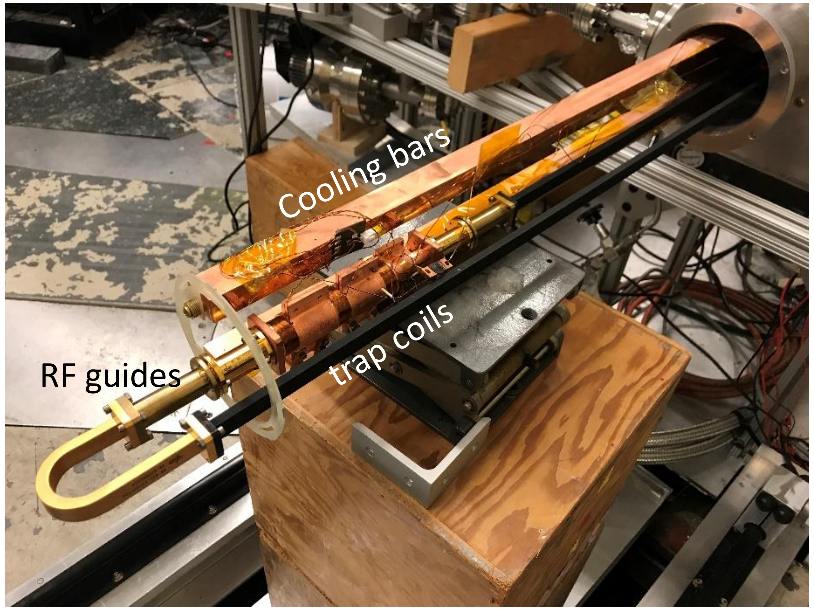
Cryo-box insides



Assembly



Decay cell



He6-CRES – FN Tandem at Seattle

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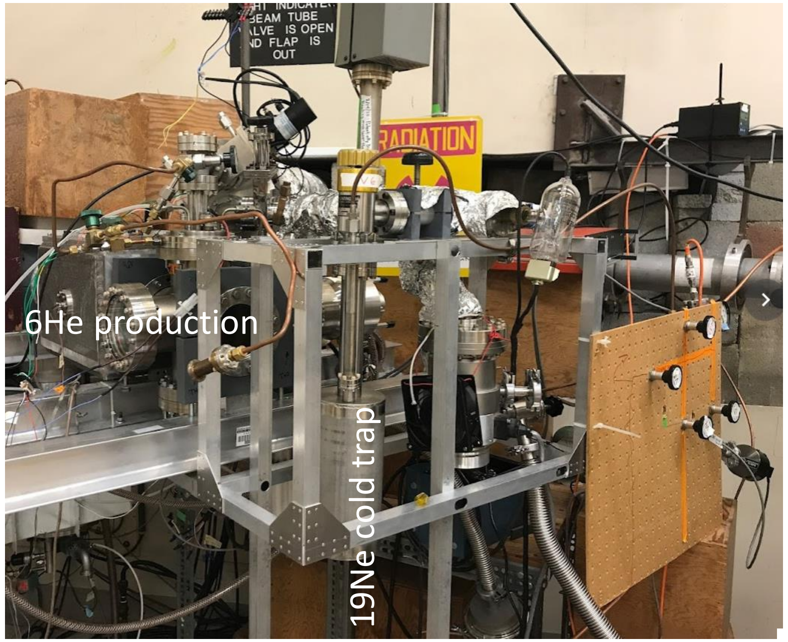
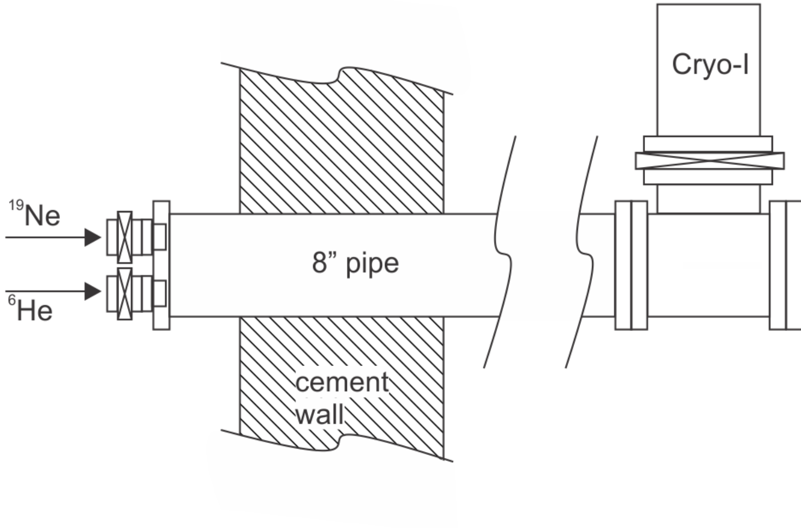
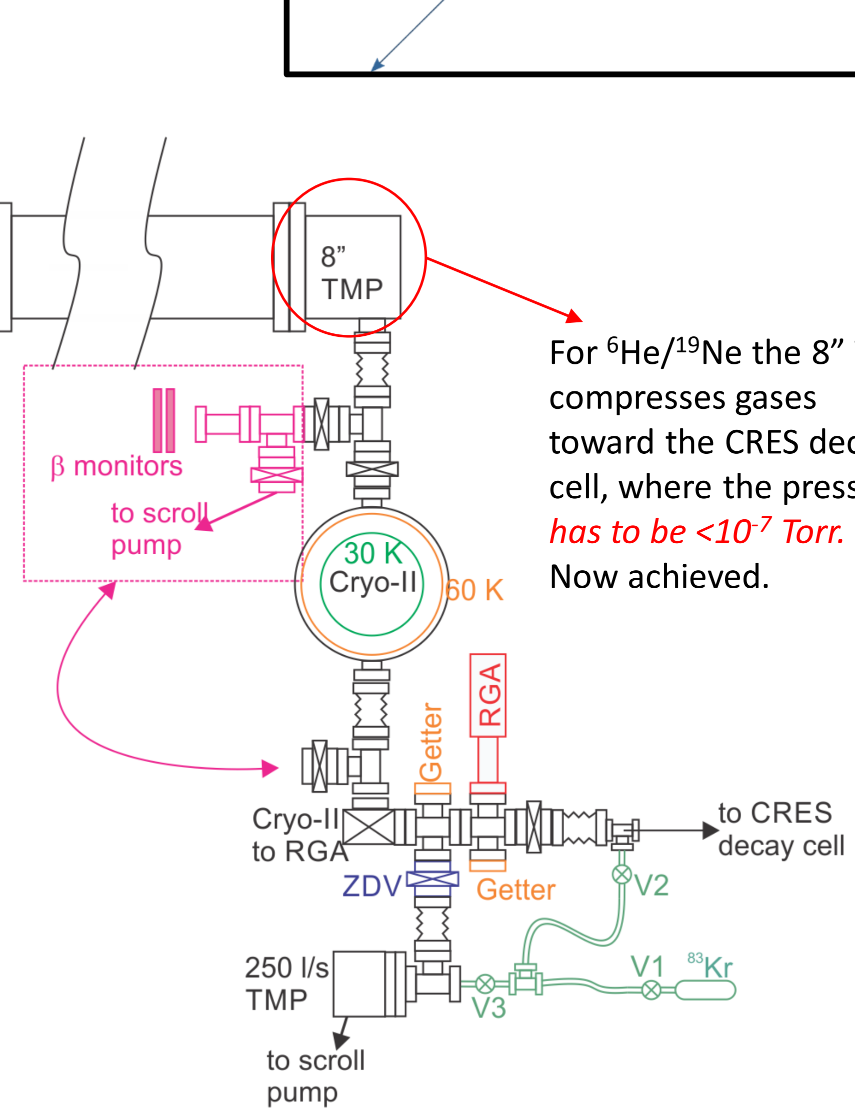
Presently:
^{6}He via ^{7}Li(d,^{3}He) $t_{1/2} \approx 0.8$ s
^{19}Ne via ^{19}F(p,n) $t_{1/2} \approx 17$ s

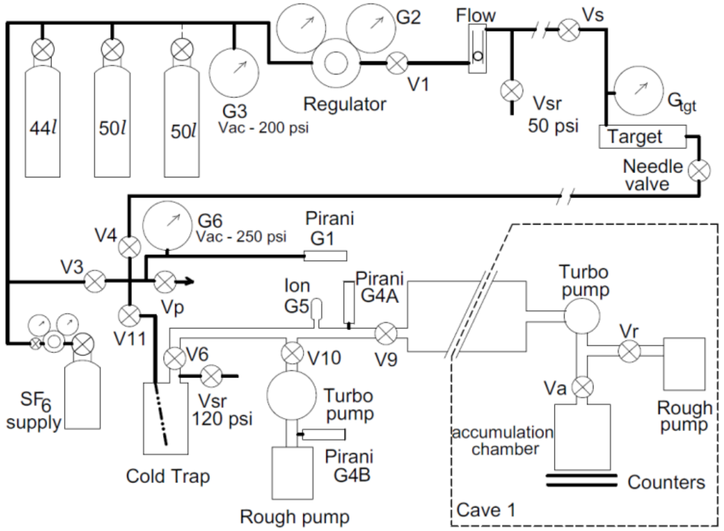
He6-CRES – Radioactivity Transport

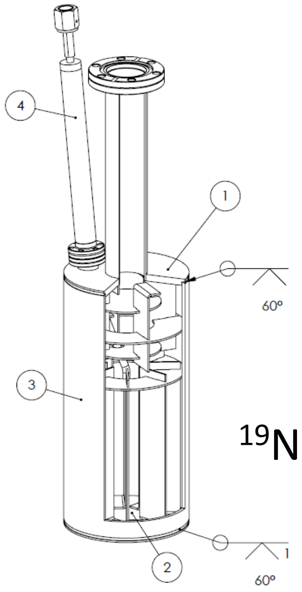


For ^{6}He/^{19}Ne the 8” TMP compresses gases toward the CRES decay cell, where the pressure *has to be <10^{-7} Torr.* Now achieved.

^{19}Ne gas system





^{19}Ne cold trap

Garcia- University of Washington

He6-CRES – First ^{83}Kr Conv. e's detection

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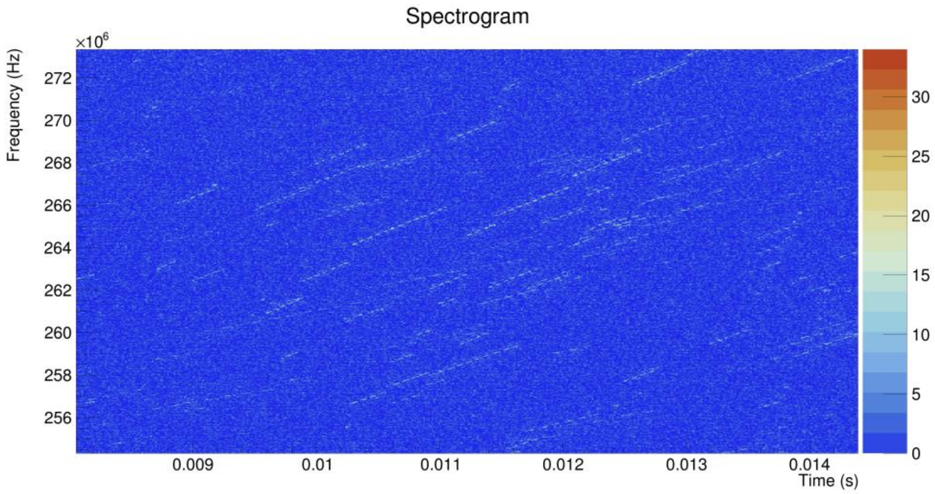
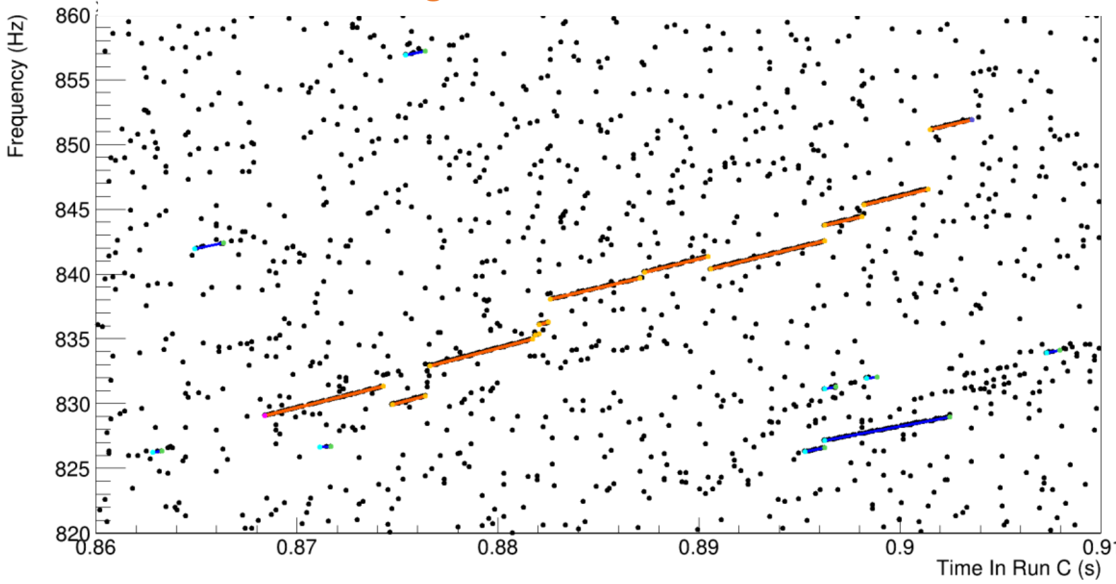
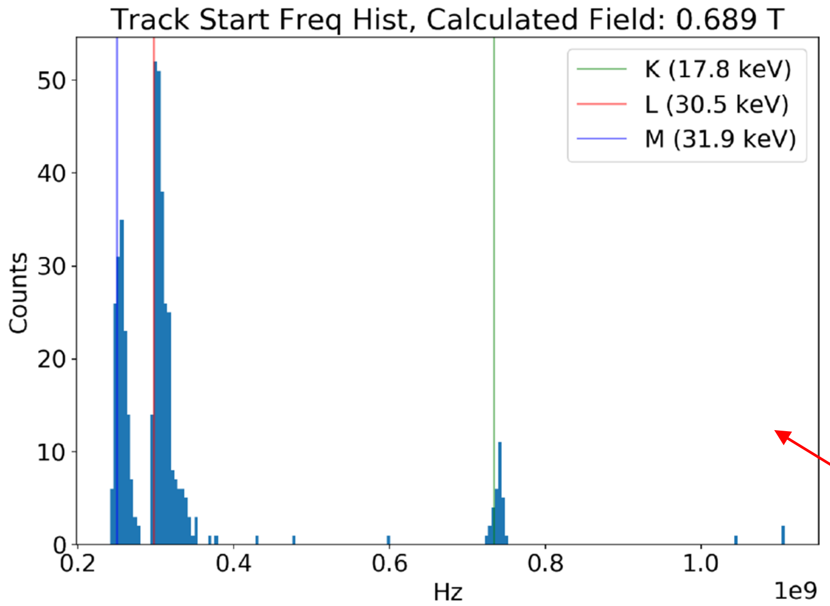


Events from ^{83}Kr:
All RF working well!

Identification software working
Blue: tracks; Orange: tracks into events.



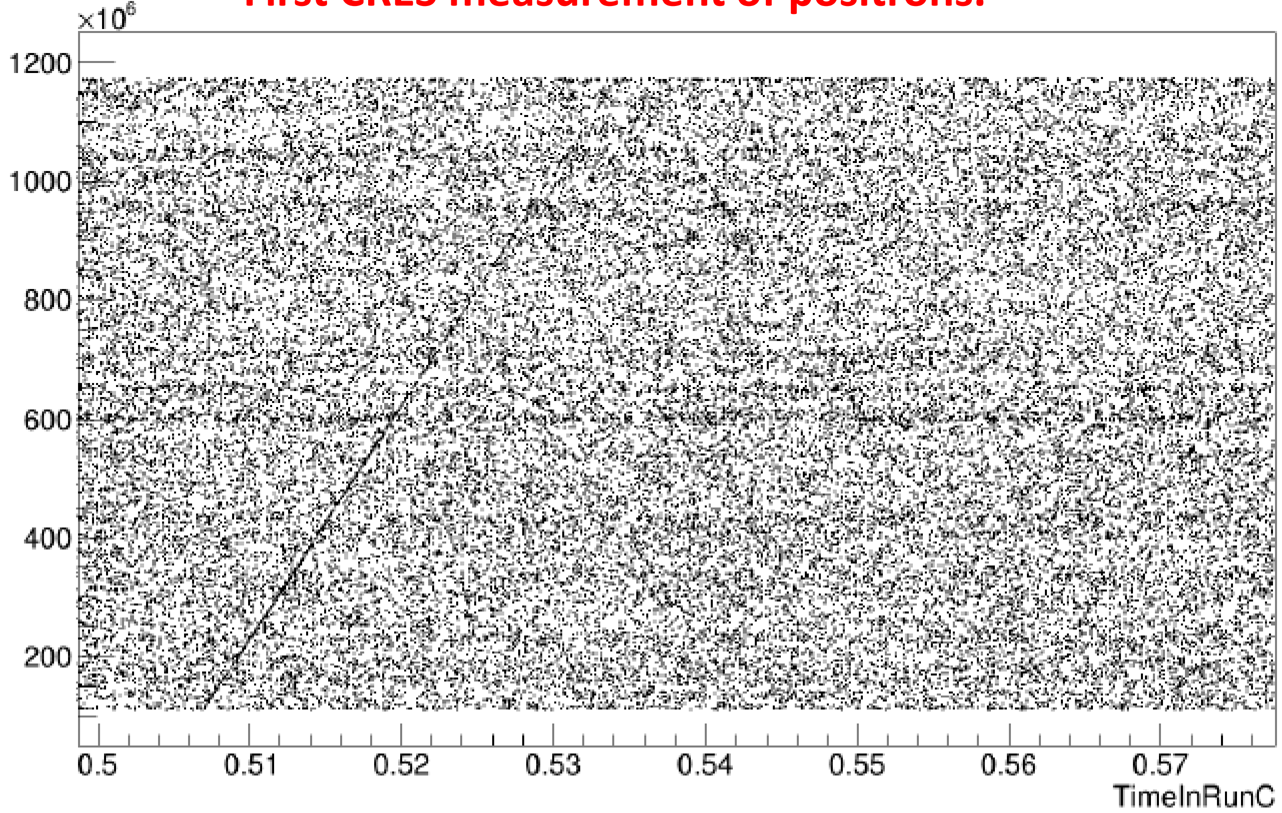


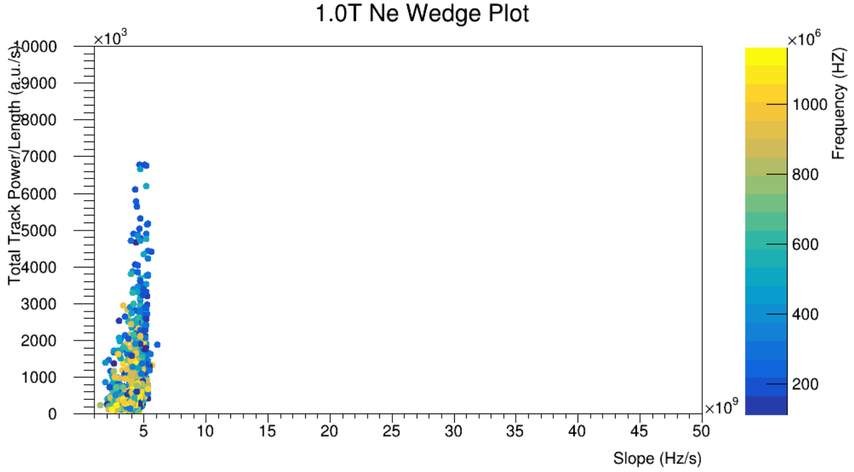
Bandwidth: 1.2 GHz
First time CRES measurement with this bandwidth.
Happy with the achievement!

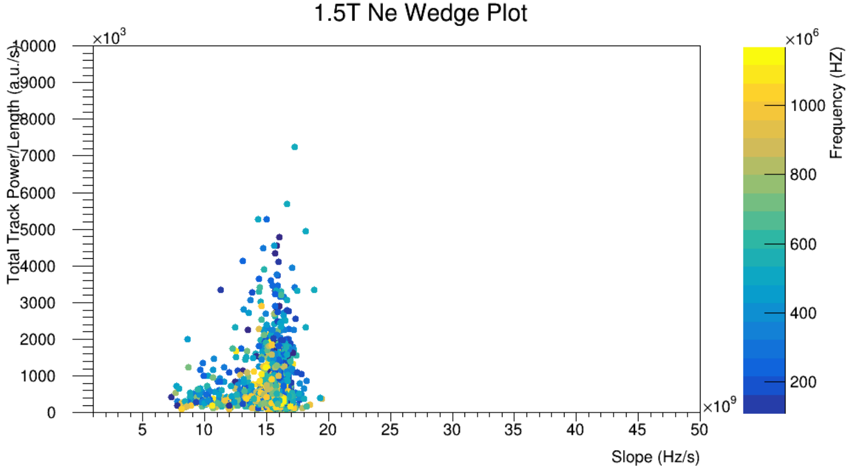
He6-CRES – ^{19}Ne

Events from ^{19}Ne:

- **First CRES measurements at $E > 30$ keV;**
- **First CRES measurement of positrons.**







He6-CRES – Next 3 years goals

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[1]*University of Washington,*
[2]Johannes Gutenberg University Mainz,
[3]*North Carolina State University,*
[4]*Pacific Northwest National Laboratory*
[5]*Texas A&M University,*
[6]*Argonne National Lab,*
[7]Tulane University

He6-CRES phases

Phase I: proof of principle
- Observe ^{83}Kr lines
- Understand RF issues and spectra
- Study power distribution
- Detect of cycl. radiation from ^{6}He and ^{19}Ne

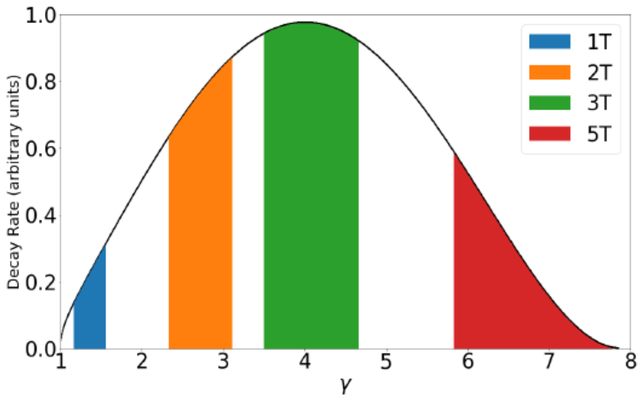
Phase II: first measurement ($b < 10^{-3}$)
- ^{6}He and ^{19}Ne measurements.
- Develop ^{14}O source.

Phase III: ultimate measurement ($b < 10^{-4}$)
- ^{14}O measurements.
- ion-trap for no limitation from geometric effect.

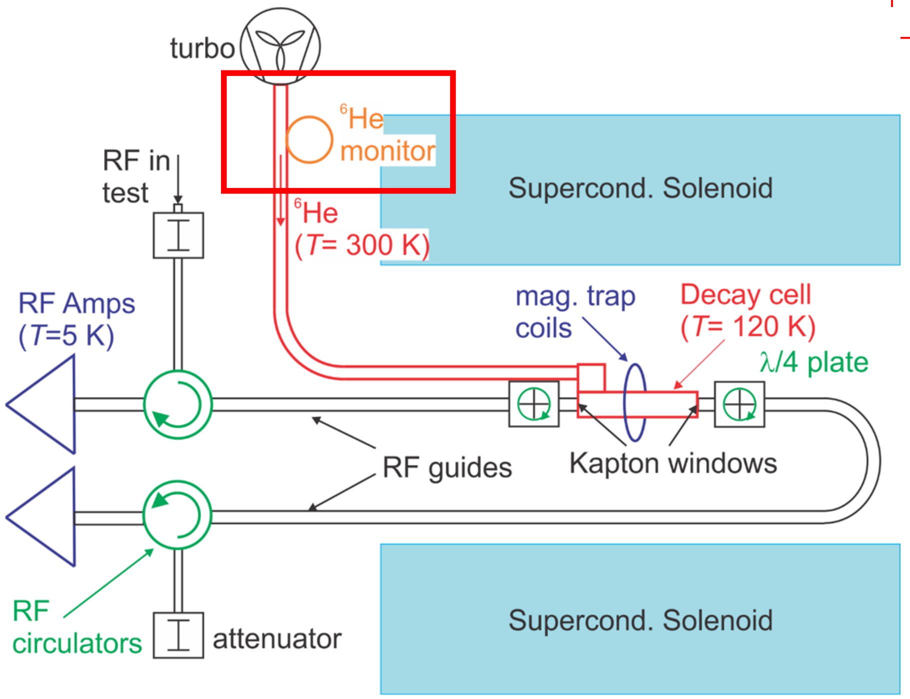
Next 3 years:
- Finish Phase I
- Get started Phase II ($b \approx 10^{-2}$ first goal)
- Prepare proposal Phase III

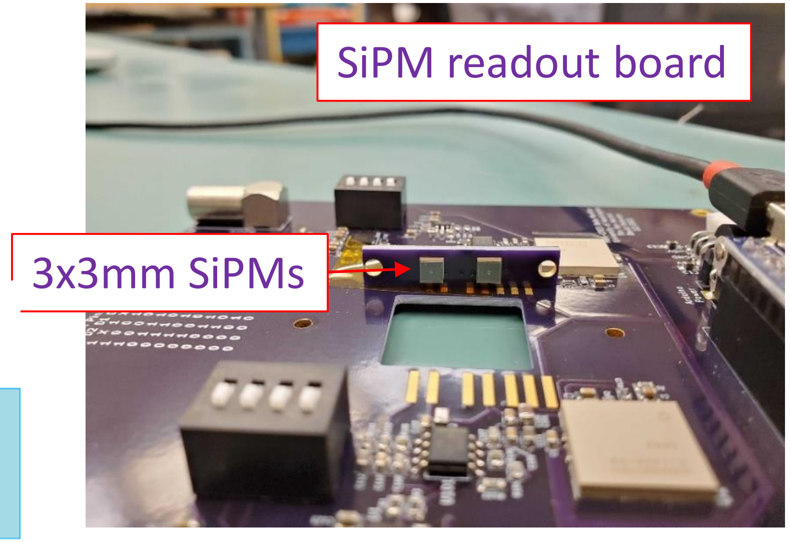
He6-CRES – Beta Monitor

To connect spectra at different B fields, use Beta Monitor



SiPM readout for scintillators
Insensitive to B field.





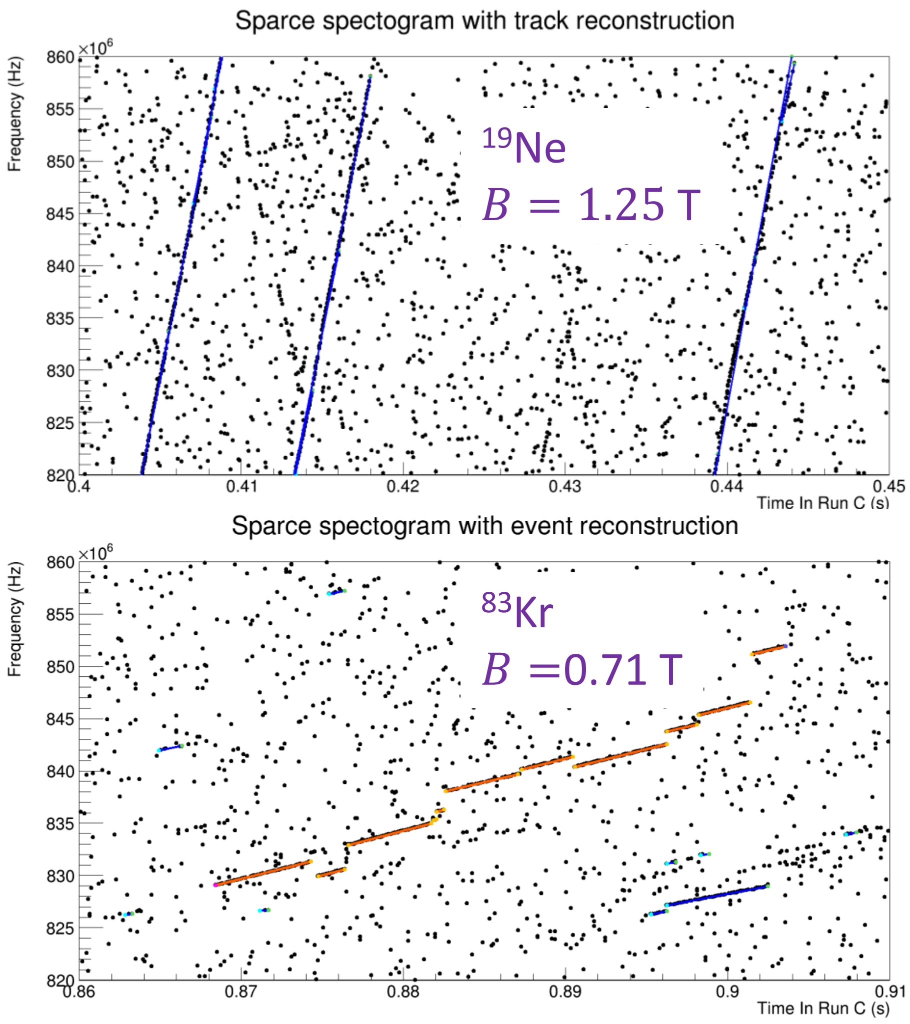
SiPM board, based on MuSun design

He6-CRES: Waterfall plot slopes

Need careful studies of systematic effects.

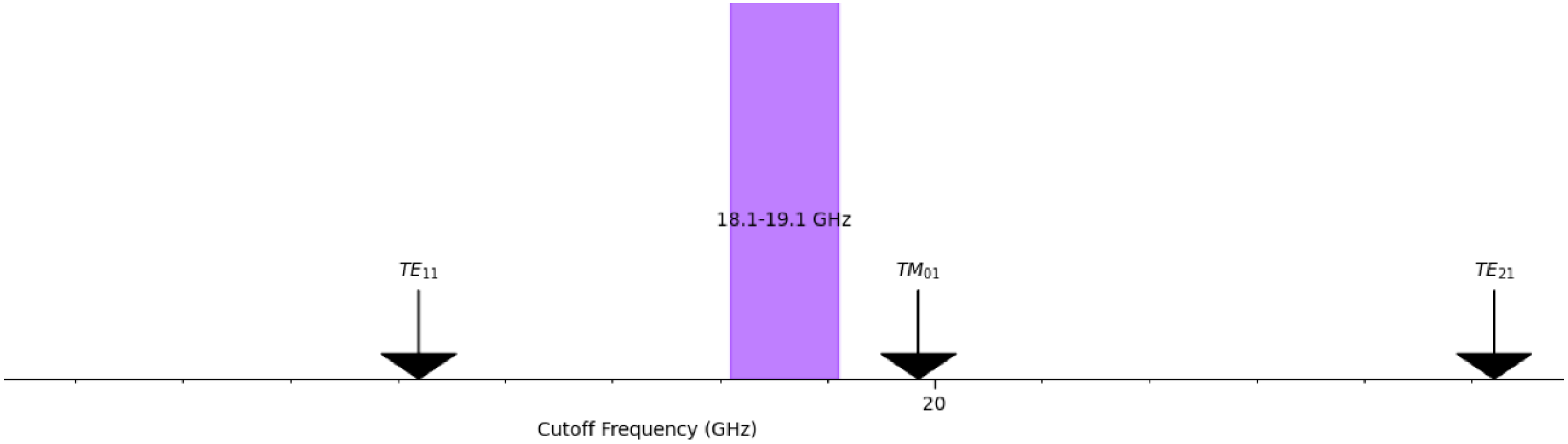
Example: compare ^{19}Ne to ^{83}Kr.

Finite freq./time resolution and large difference in df/dt
→ variation of response versus beta energy.



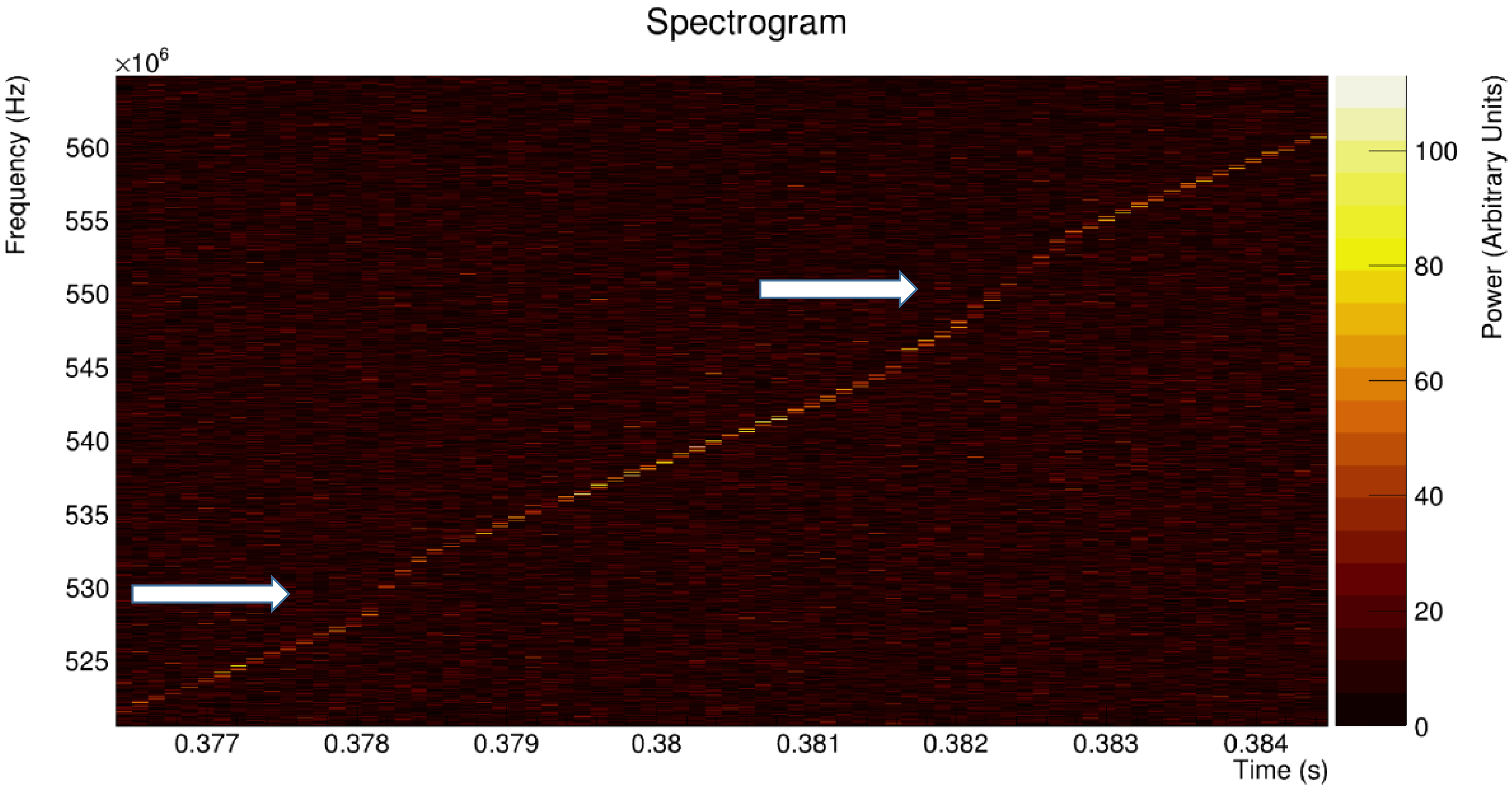
He6-CRES: Waterfall plot slopes
Something unexpected

We designed our experiment to look in the frequency range where betas would only be radiating into lowest TE_{11} propagating mode.



Slide prepared by Heather Harrington

He6-CRES: Waterfall plot slopes
Something unexpected



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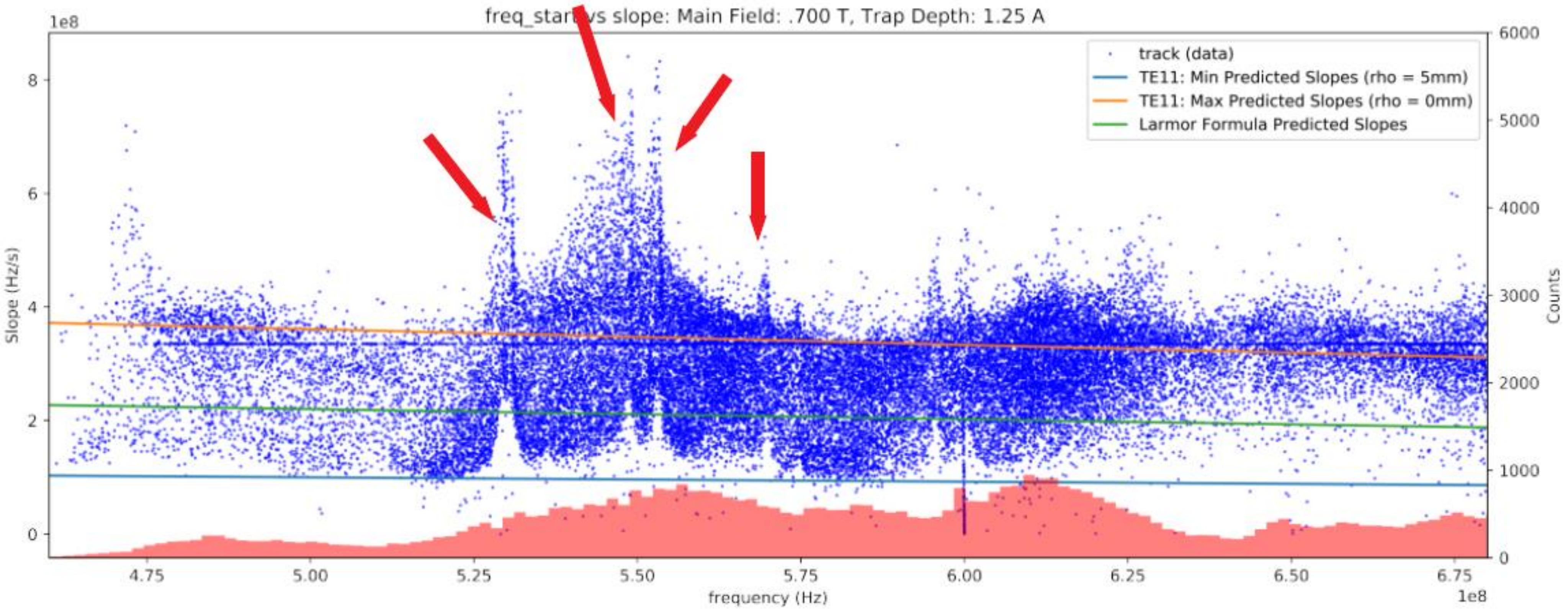
He6-CRES: Waterfall plot slopes
Slopes show resonance-like structures



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He6-CRES: Waterfall plot slopes

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PHYSICAL REVIEW LETTERS

Inhibited Spontaneous Emission

Daniel Kleppner

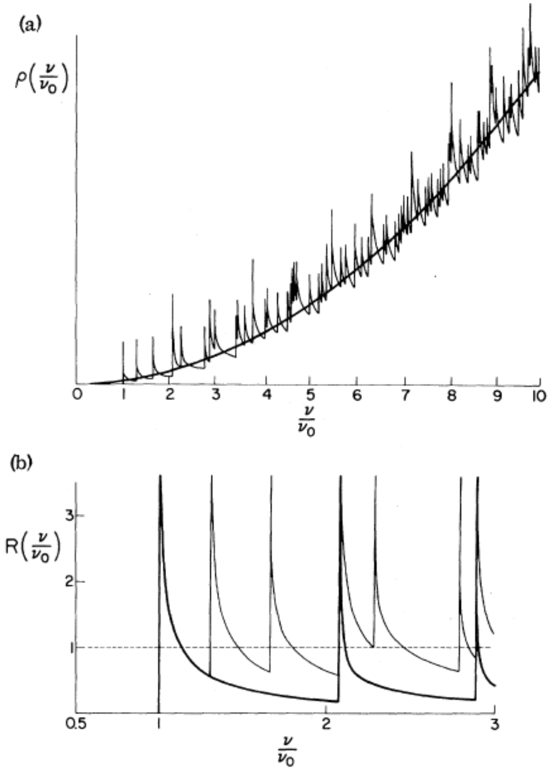


FIG. 1. (a) Mode density in a perfectly conducting cylindrical waveguide. Frequency is in units of the lowest cutoff frequency of the waveguide, $\nu_0 = 0.29c/a$, where a is the radius. For clarity, the singularities have been truncated. The smooth curve represents the mode density in free space. (b) Ratio of waveguide mode density to free-space mode density. The heavy

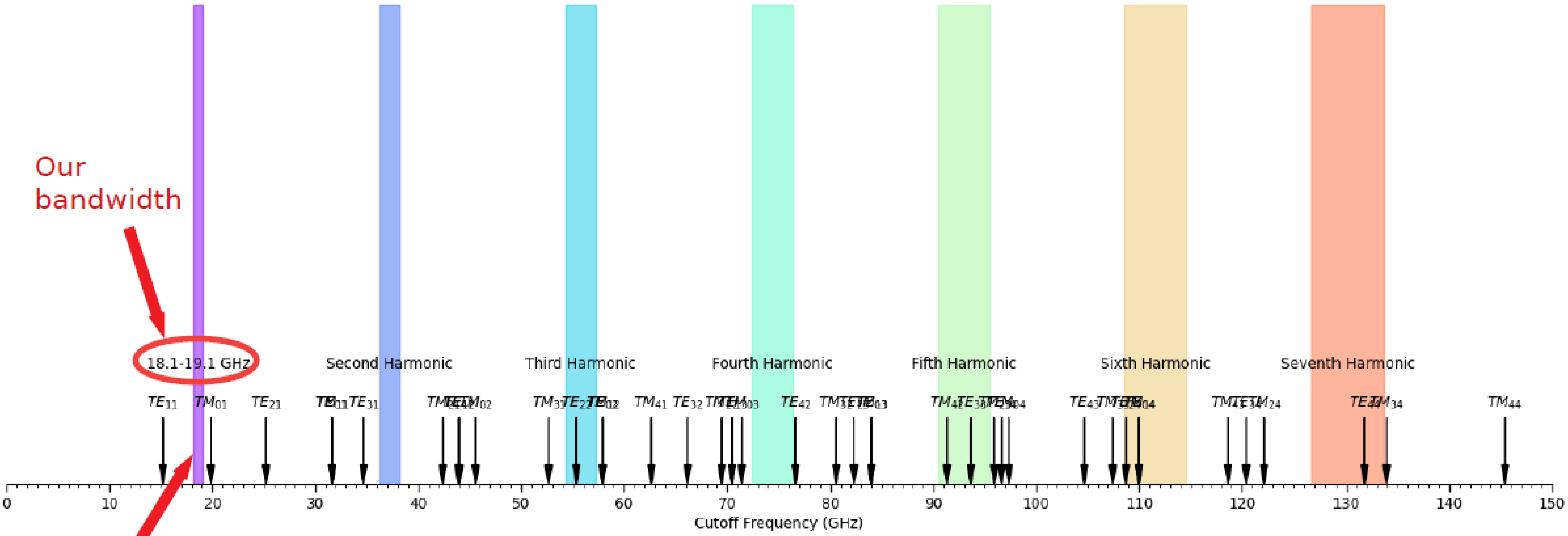
We now understand that the $\boldsymbol{E}_{nm}.\boldsymbol{J}$ coupling has higher harmonics that need to be considered.

Kleppner had actually anticipated such behavior: PRL **47**, 233 (1981)

At cutoff, the guides behave like cavities, which show up as resonances in the waterfall plot slopes.

He6-CRES: Waterfall plot slopes

Our bandwidth



Fundamental is the cyclotron frequency

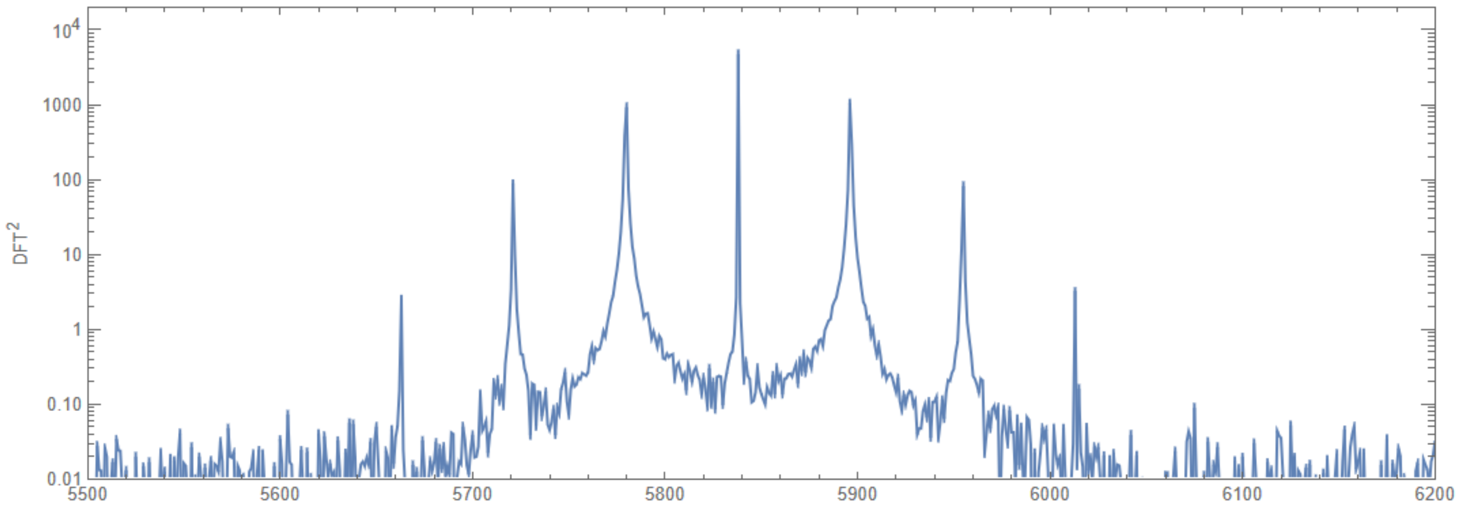
$$\omega_c = \frac{eB}{m\gamma} = \frac{eB}{m(1+K/mc^2)}$$

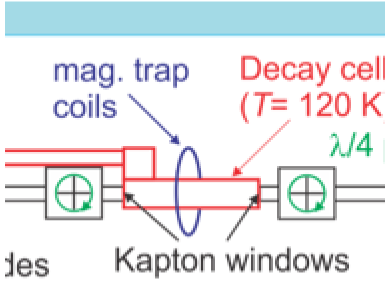
Slide prepared by Heather Harrington

He6-CRES: Doppler effect

As betas move axially in the magnetic trap, the signals show up with Doppler shifts.
The axial frequency is approx. cyclotron freq./500

Consequence: side bands → power in main band weaker → worse SNR





Decay cell

Slide prepared by Drew Byron

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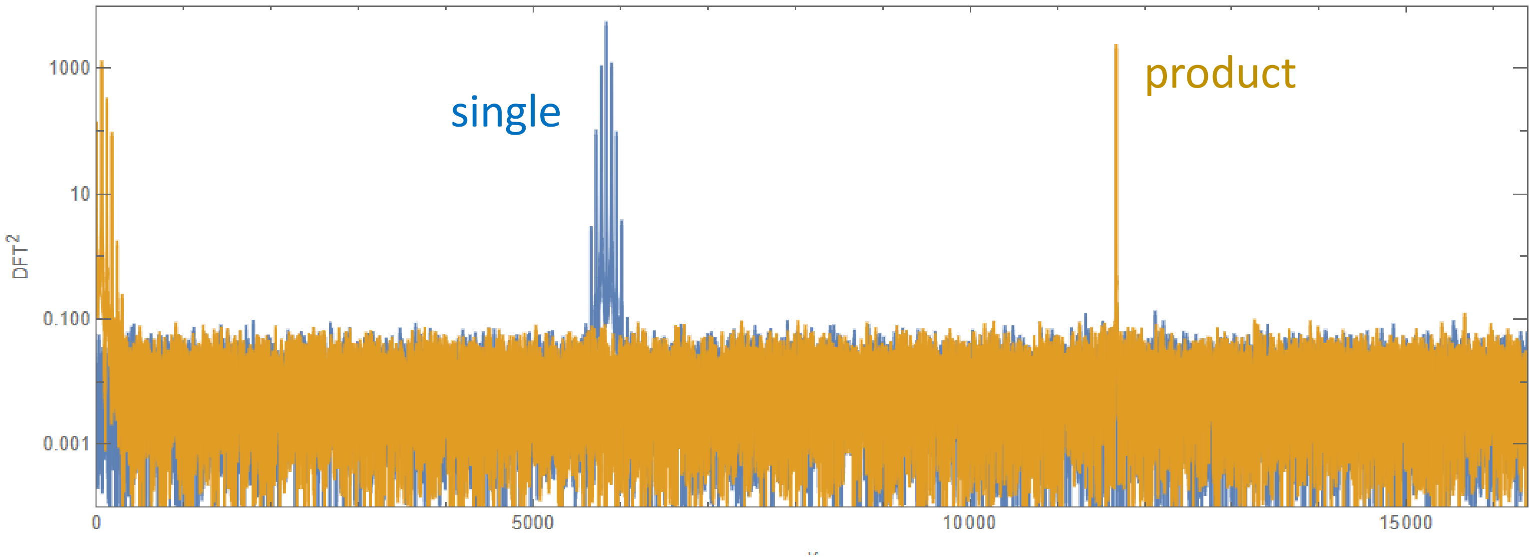
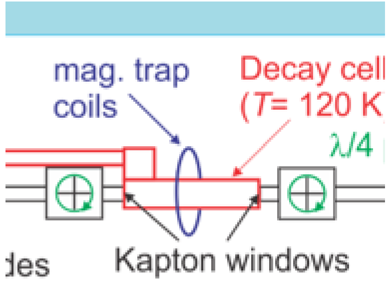
Up until recently our plan was to do product of the signals from two ends





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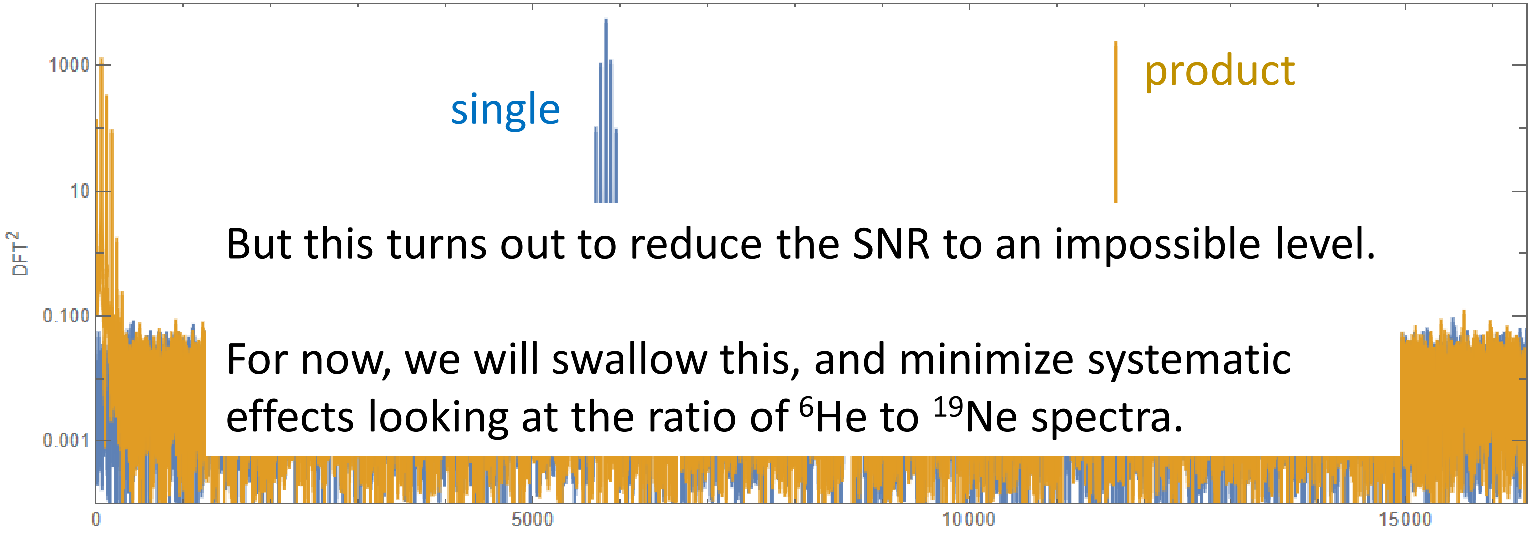
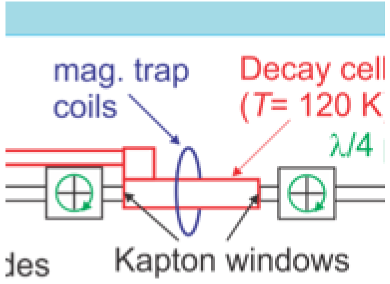


But this turns out to reduce the SNR to an impossible level.

For now, we will swallow this, and minimize systematic effects looking at the ratio of ^{6}He to ^{19}Ne spectra.

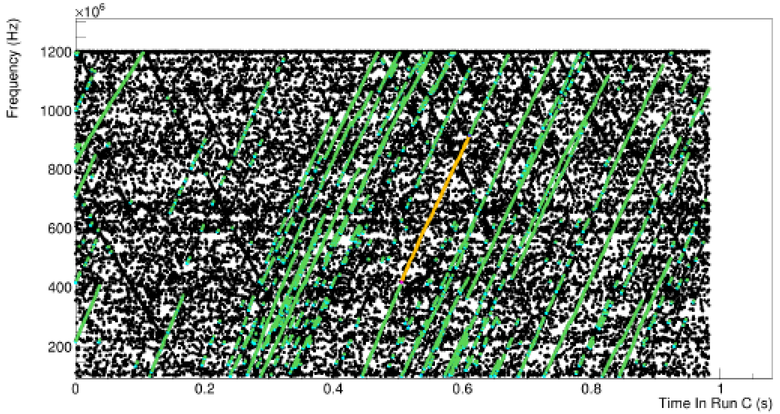


Decay cell

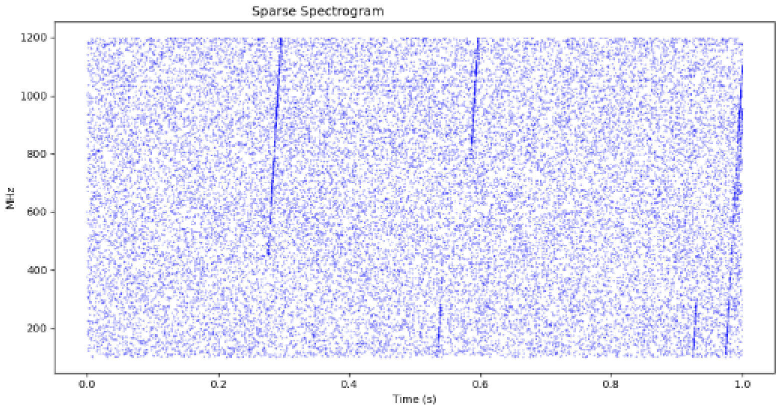
Slide prepared by Drew Byron

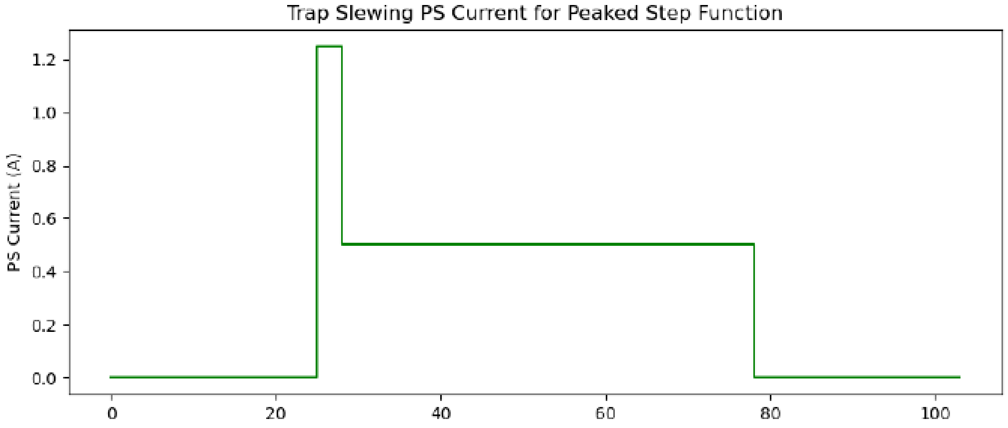
He6-CRES: trap emptying

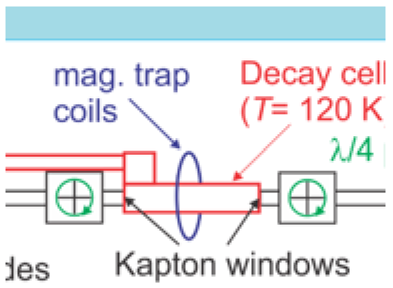
Without trap slewing:



With trap slewing:







Decay cell

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He6-CRES: trap emptying & identifying events

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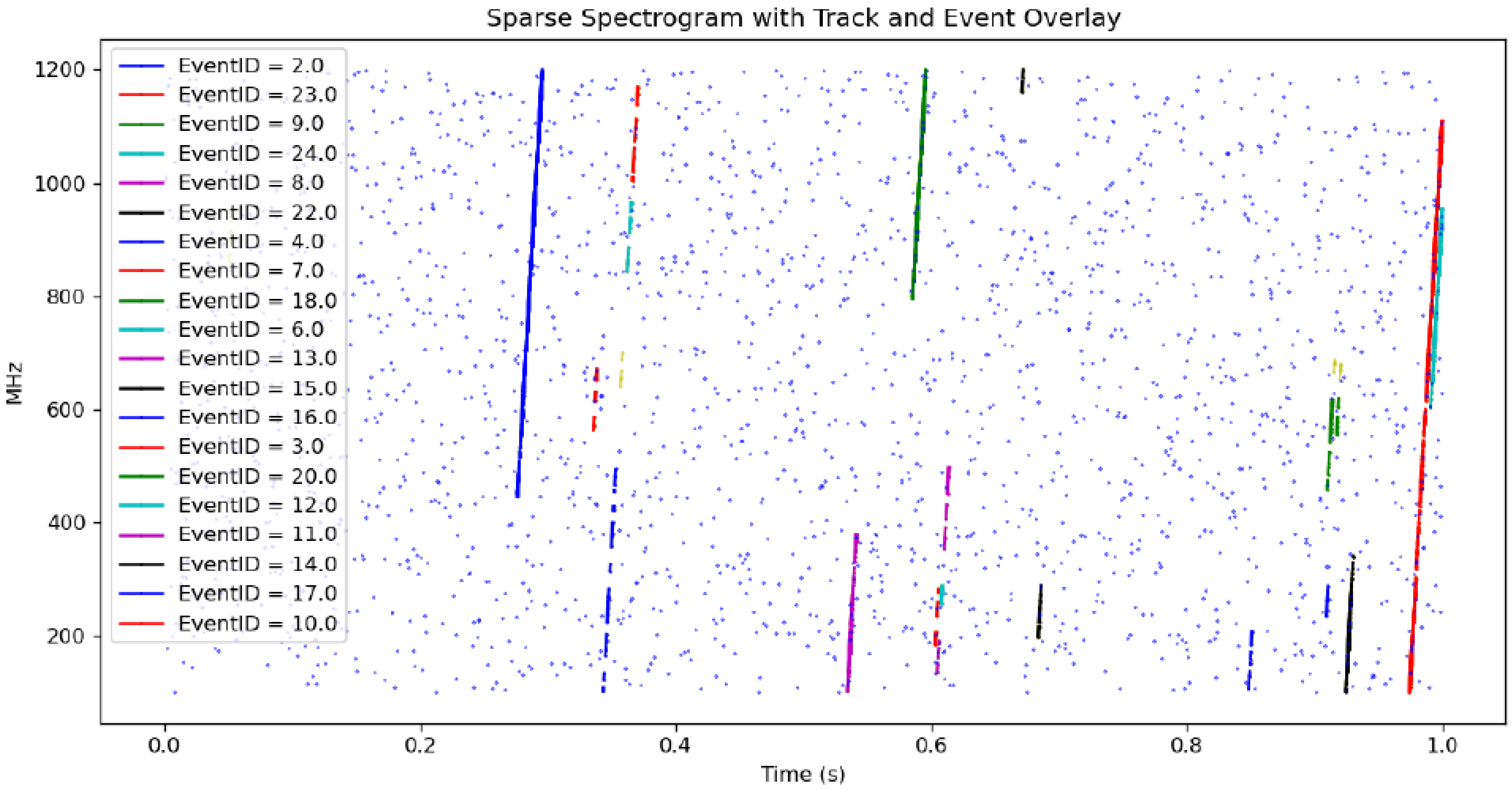

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He6-CRES: trap emptying & identifying events

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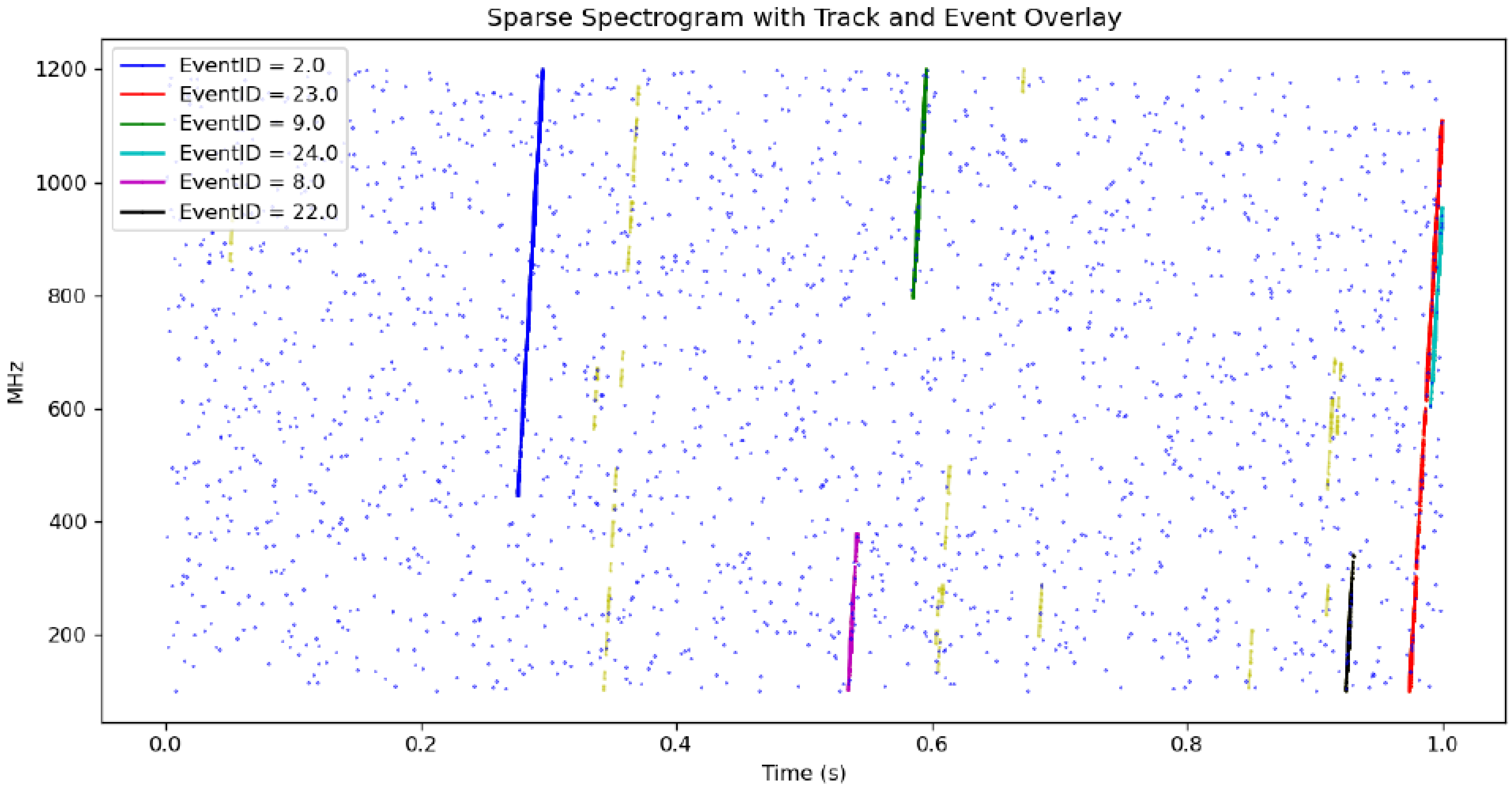

Slide prepared by Drew Byron

He6-CRES: trap emptying & identifying events

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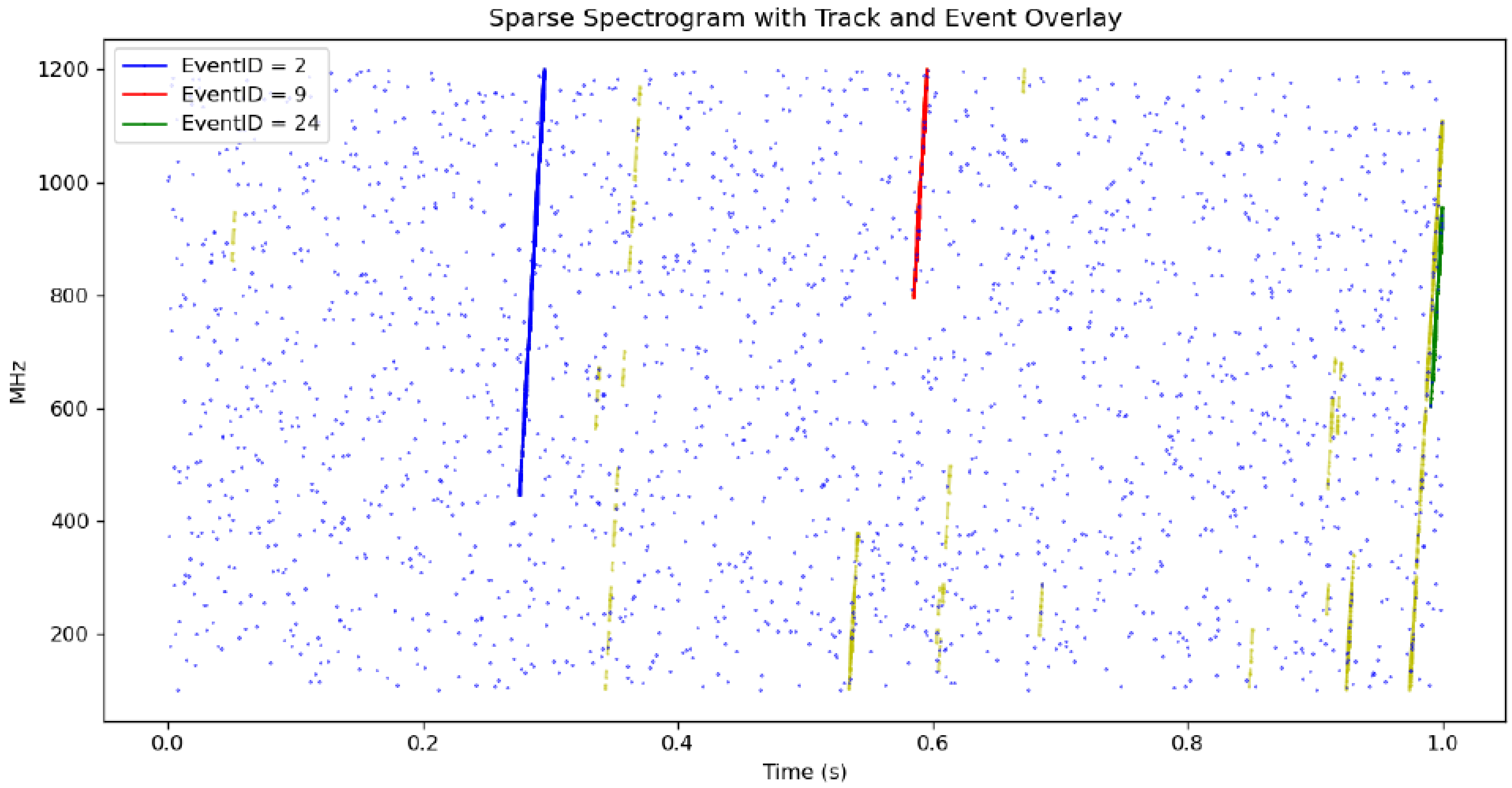
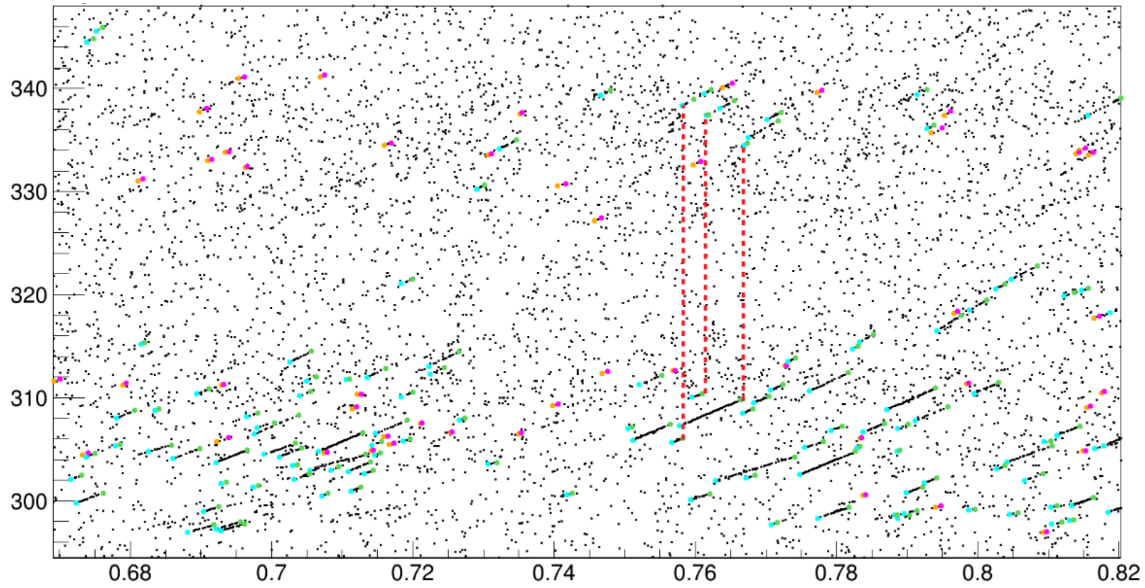
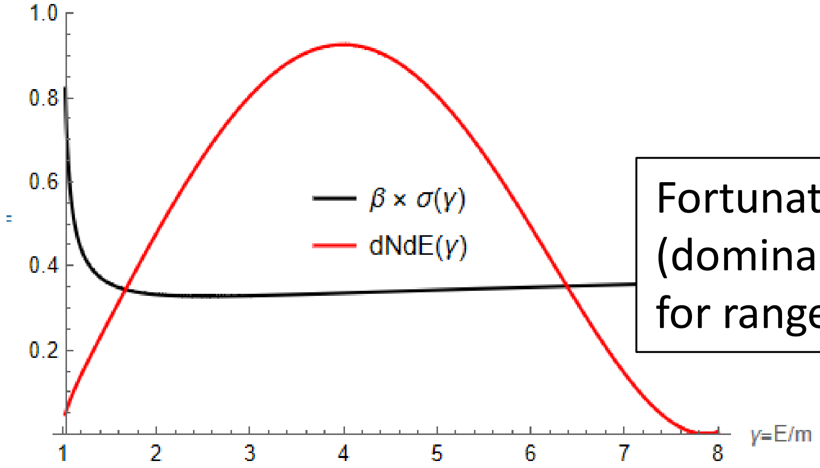


Slide prepared by Drew Byron

He6-CRES – Scattering with residual gas

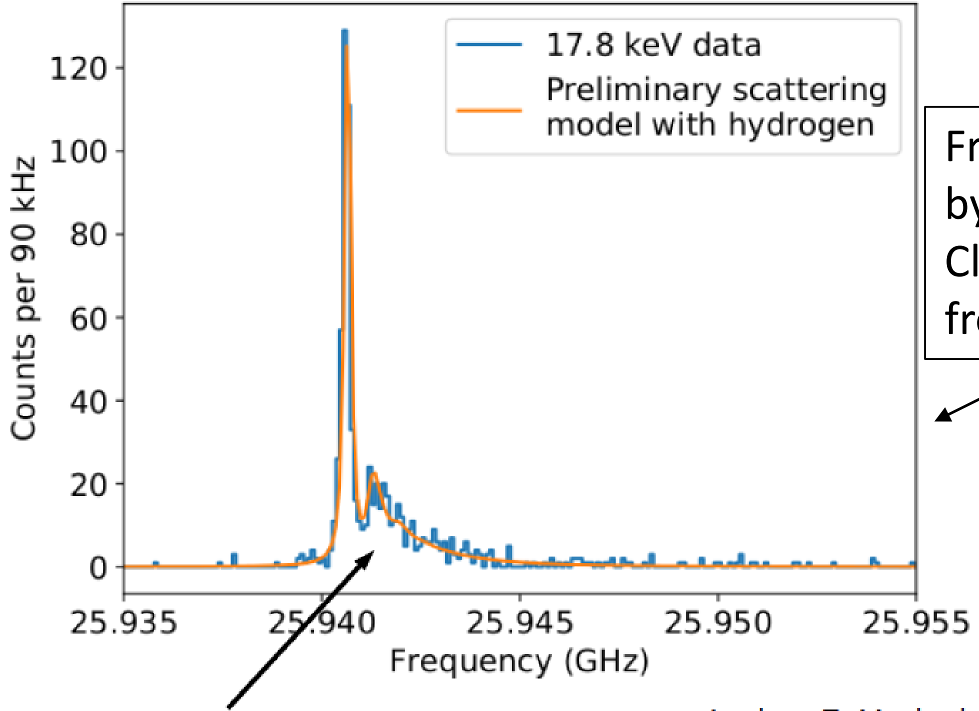
Scattering: leads to non-trivial response function





Fortunately σ on H (dominant) is rather flat for range of interest.

Miss-identification of scattering leads to asymmetrical line shapes, that could affect *b*



From talk by Christine Claessens from P8

Analyst: E. Machado

He6-CRES: Status & Summary

CRES: potentially powerful technique for beta spectroscopy

But small SNR → have to work to avoid systematic distortions.
DAQ: challenging, get about 1 Gbyte/s.

By now have observed CRES events from ^{83}Kr, ^{6}He and ^{19}Ne

Next: systematically take data from ^{6}He and ^{19}Ne and analyze ratio
(less sensitive to issues related to events with small SNR)