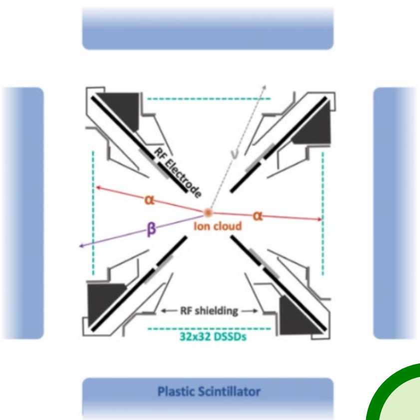
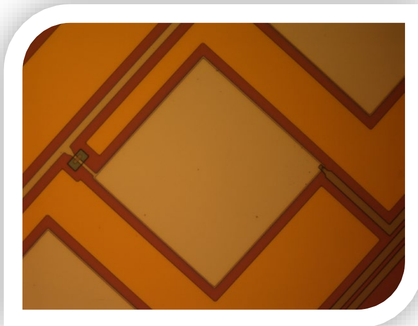
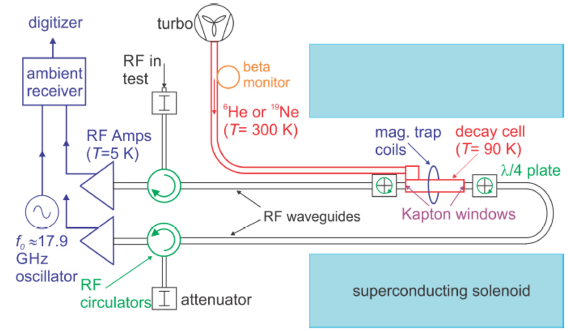
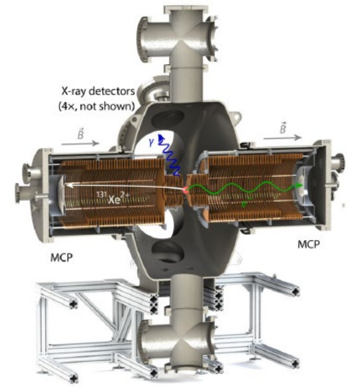
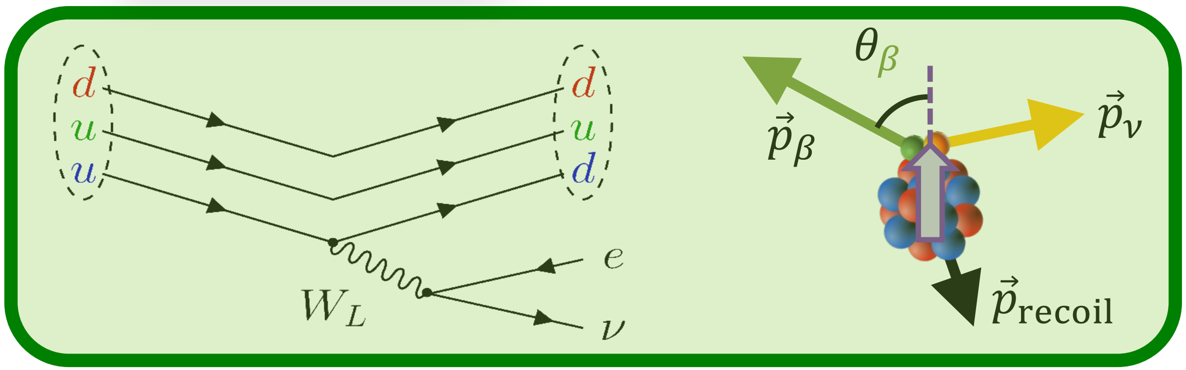
Technical developments for fundamental symmetry measurements

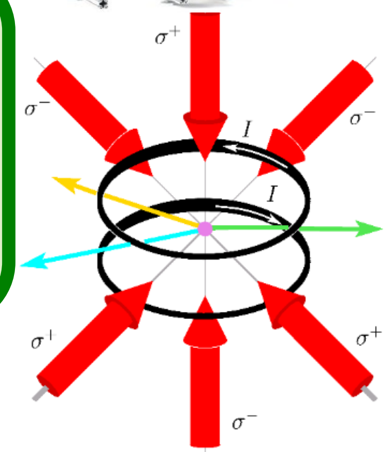


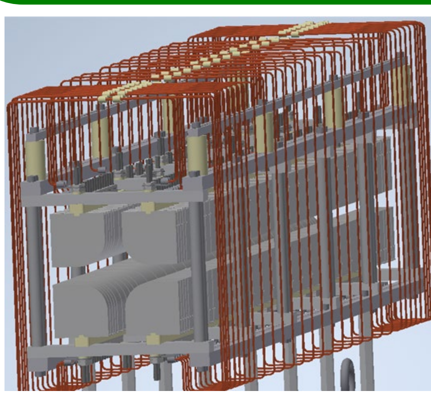


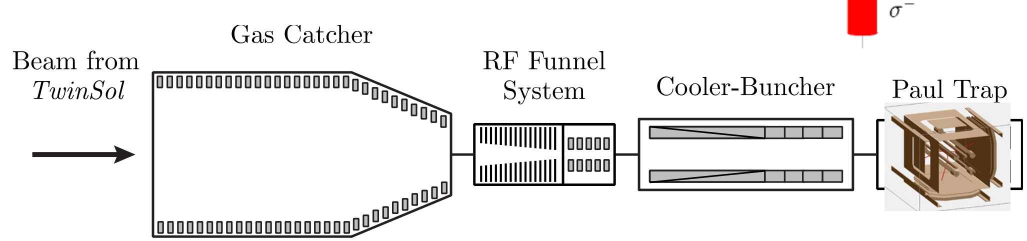












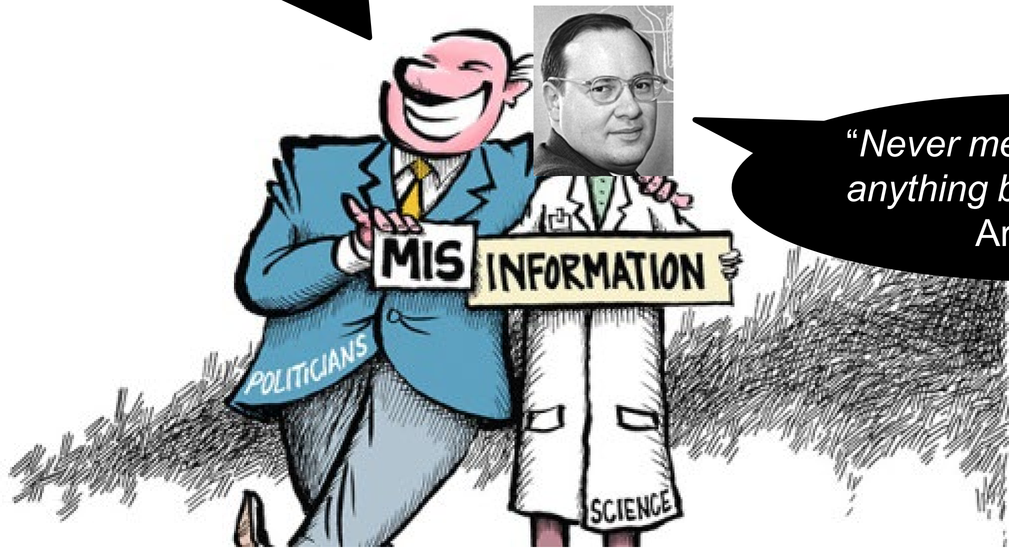
Dan Melconian

Outline

- Cyclotron Radiation Emission Spectroscopy
  - Project 8
  - He6-CRES collaboration; + Penning trap
- Ion traps
  - Mass measurements
  - Correlation measurements at ANL, ND and TAMU
- Atom traps
  - (un)polarized angular distributions with TRINAT
  - Sterile neutrinos with HUNTER
- Quantum sensors
  - EC using the BeEST
- No time for EDMs, neutrons, T-violating searches, …

Cyclotron Radiation Emission

"*It's the economy, stupid!*"
James Carville



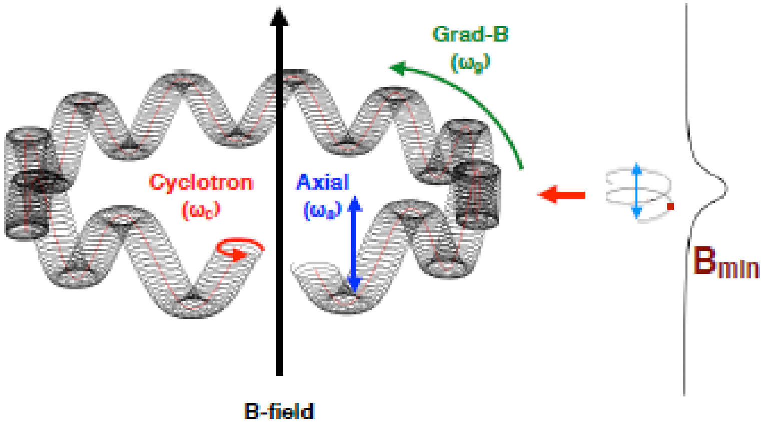
"*Never measure anything but frequency*."
Arthur Schawlow

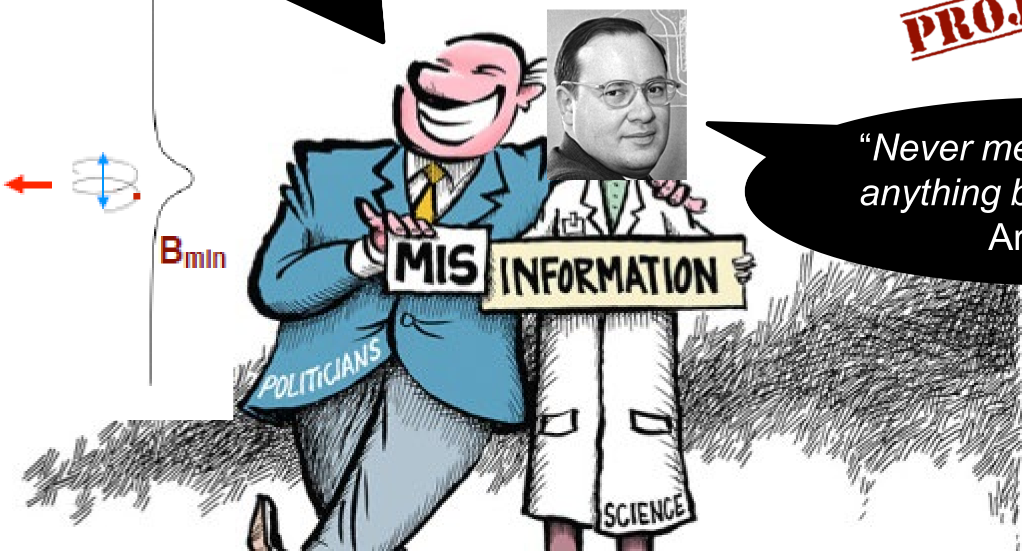
Cyclotron Radiation Emission

Formaggio and Monreal, Phys. Rev. D **80**, 051301(R), 2009

"It's the economy, stupid!"
James Carville

PROJECT 8





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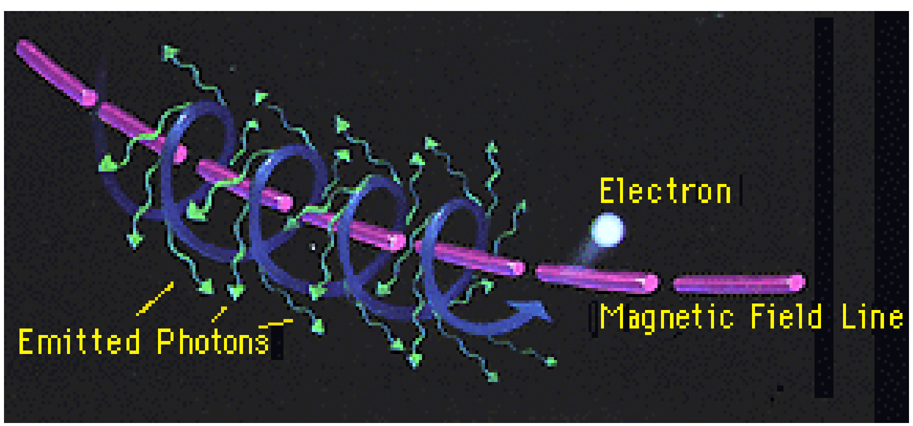
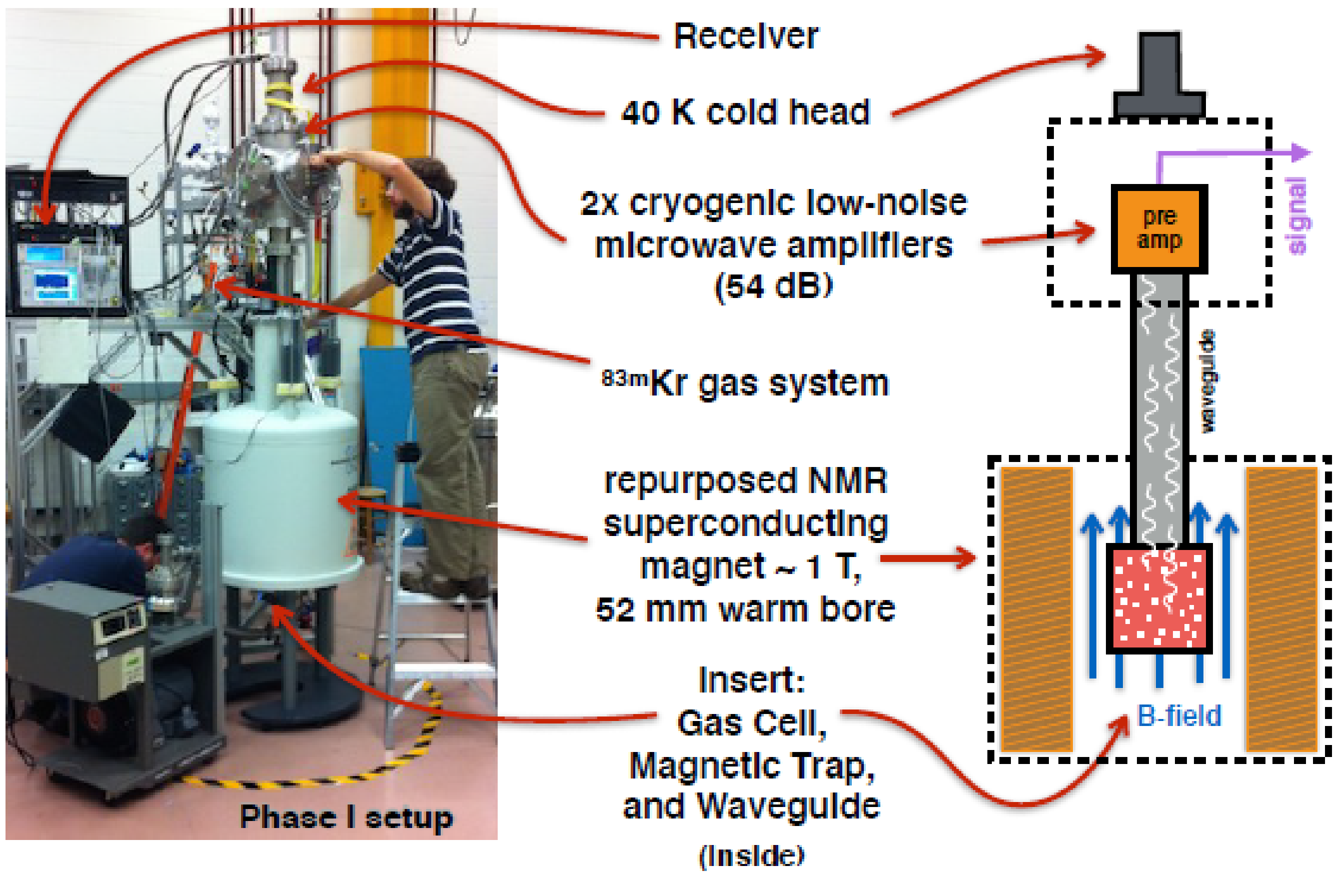


$$f_c = \frac{1}{2\pi}\frac{eB}{m_e + K}$$

Get kinetic energy from frequency!

CRES to measure tritium end-point

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



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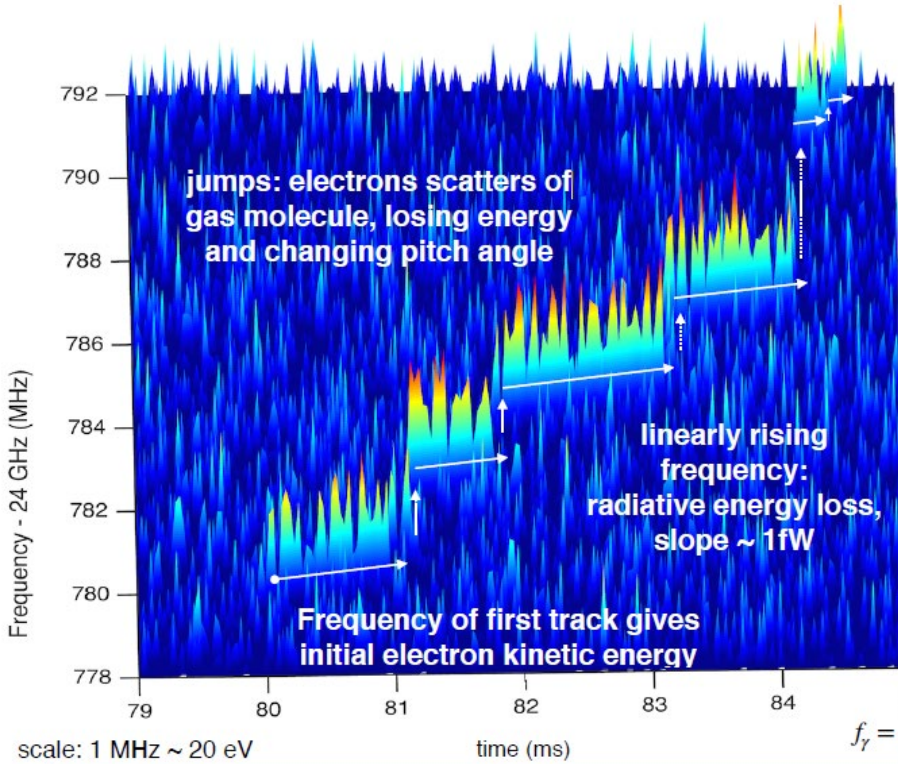
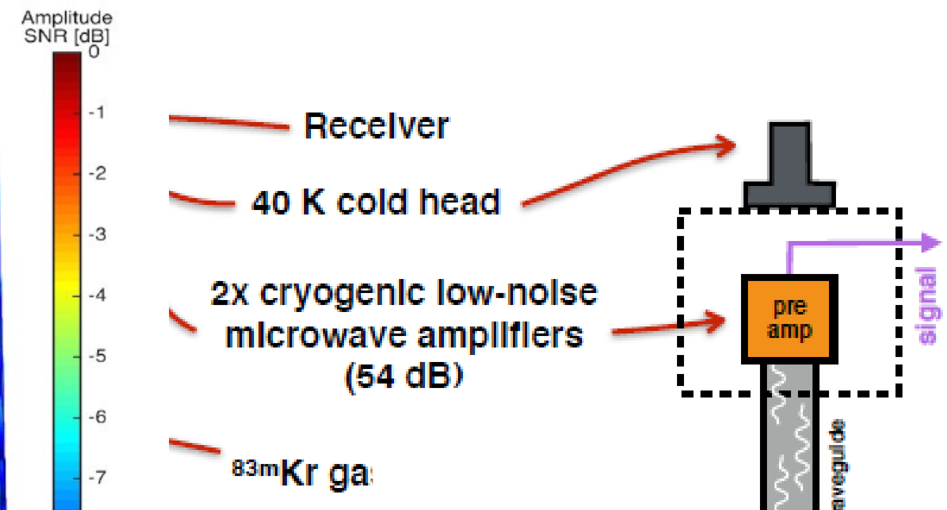


de Viveiros - Penn State



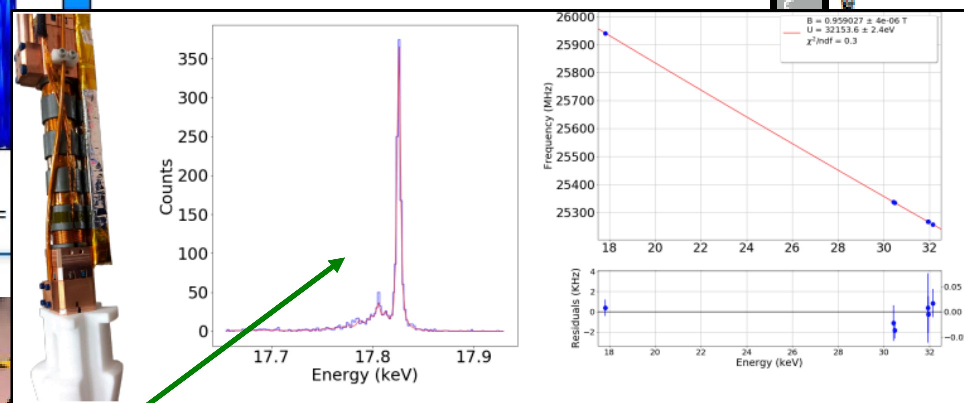


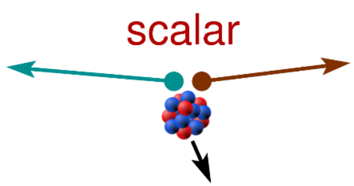
Figure 8: Left: The Phase II CRES cylindrical waveguide insert. Middle: Measured ^{83m}Kr K-Shell CE fitted with model including shake-up, shake-off, and electron collisions with hydrogen molecules and krypton atoms. Right: Measured frequency versus energy of the K, L and M-shell ^{83m}Kr CEs.

Phase II: instrumental resolution = 1.73 *eV* FWHM!

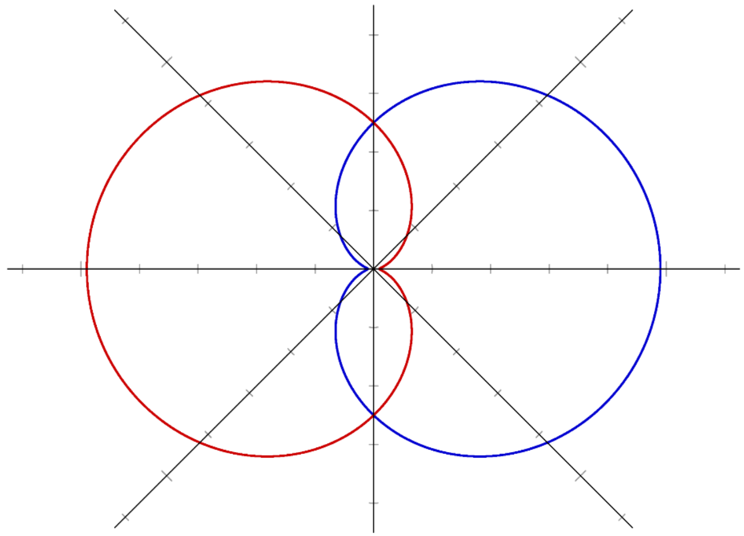
β-decay correlations

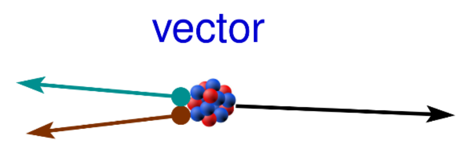
- Quick reminder:

$$dW = dW_0\left[1 + a\frac{\vec{p}_\beta\cdot\vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle\vec{I}\rangle}{I}\cdot\left(A_\beta\frac{\vec{p}_\beta}{E_\beta} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta\times\vec{p}_\nu}{E_\beta E_\nu}\right) + \cdots\right]$$



$$a_{\beta\nu} = \frac{-|C_S|^2 - |C_S'|^2}{|C_S|^2 + |C_S'|^2}$$





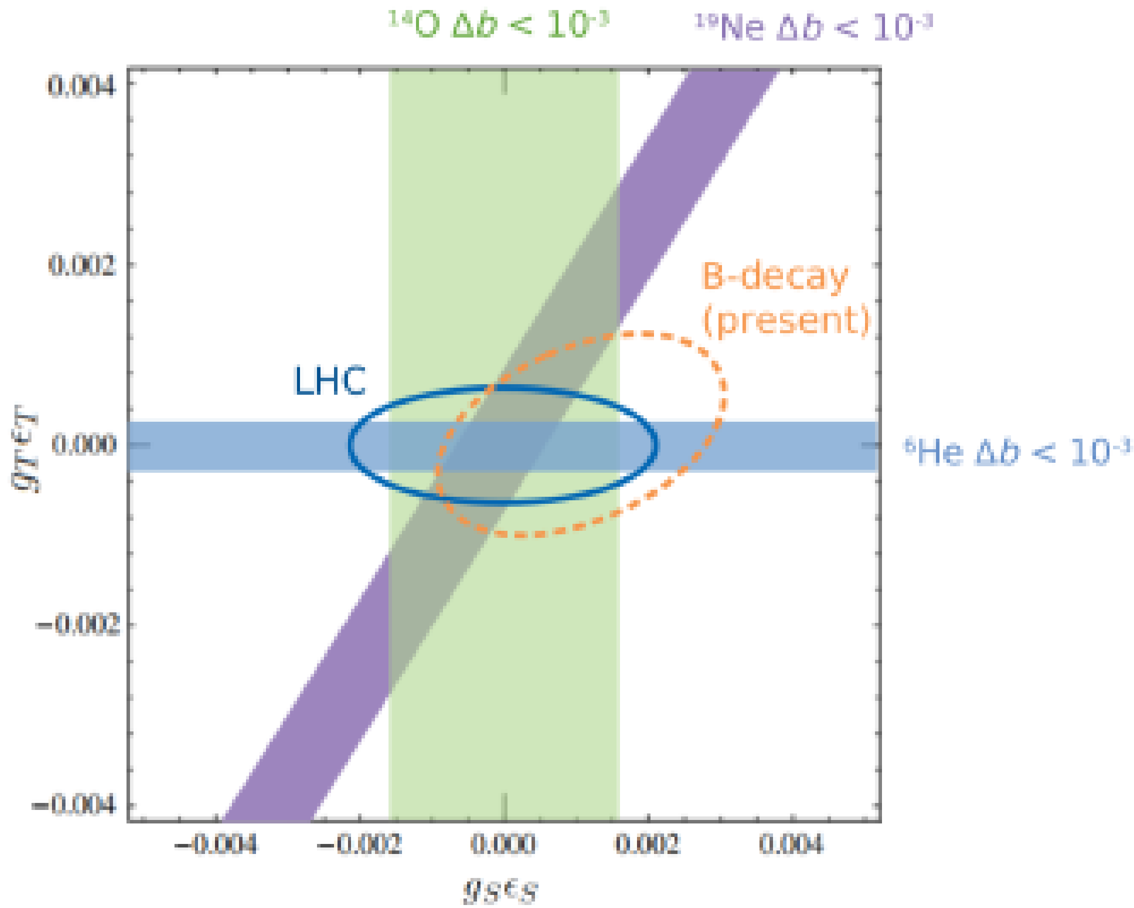
$$a_{\beta\nu} = \frac{|C_V|^2 + |C_V'|^2}{|C_V|^2 + |C_V'|^2}$$

$$a_{\beta\nu} = \frac{|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2} = 1??$$

$$b = \frac{-2\Re e(C_S^* C_V + C_S'^* C_V')}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2} = 0??$$

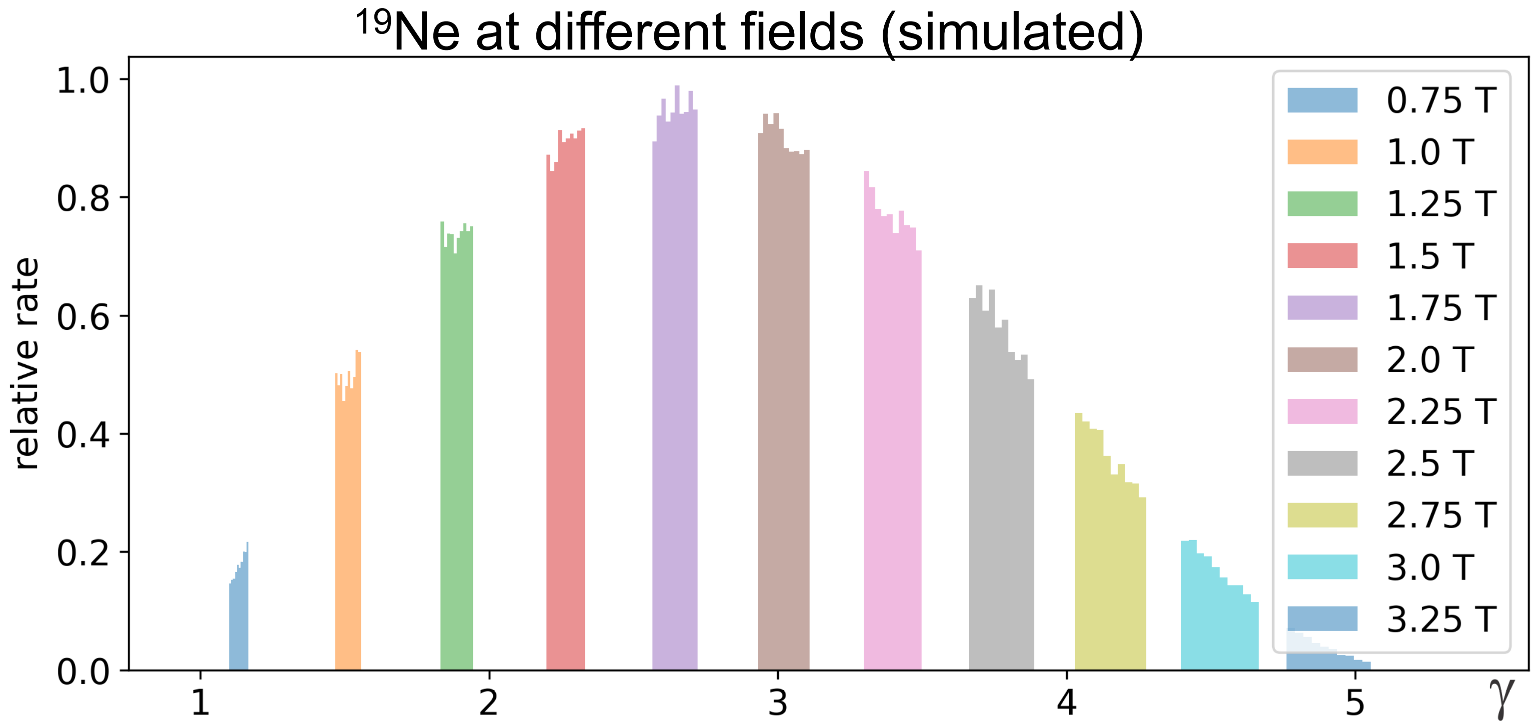
He6-CRES: MeV-scale β spectra

- He6-CRES collaboration based at UW to adapt CRES technique to measure b_{Fierz}
  - ^{6}He (GT), ^{19}Ne (F/GT) and ^{14}O (F); $\beta^{\pm}$ opposite sign in b_{Fierz}

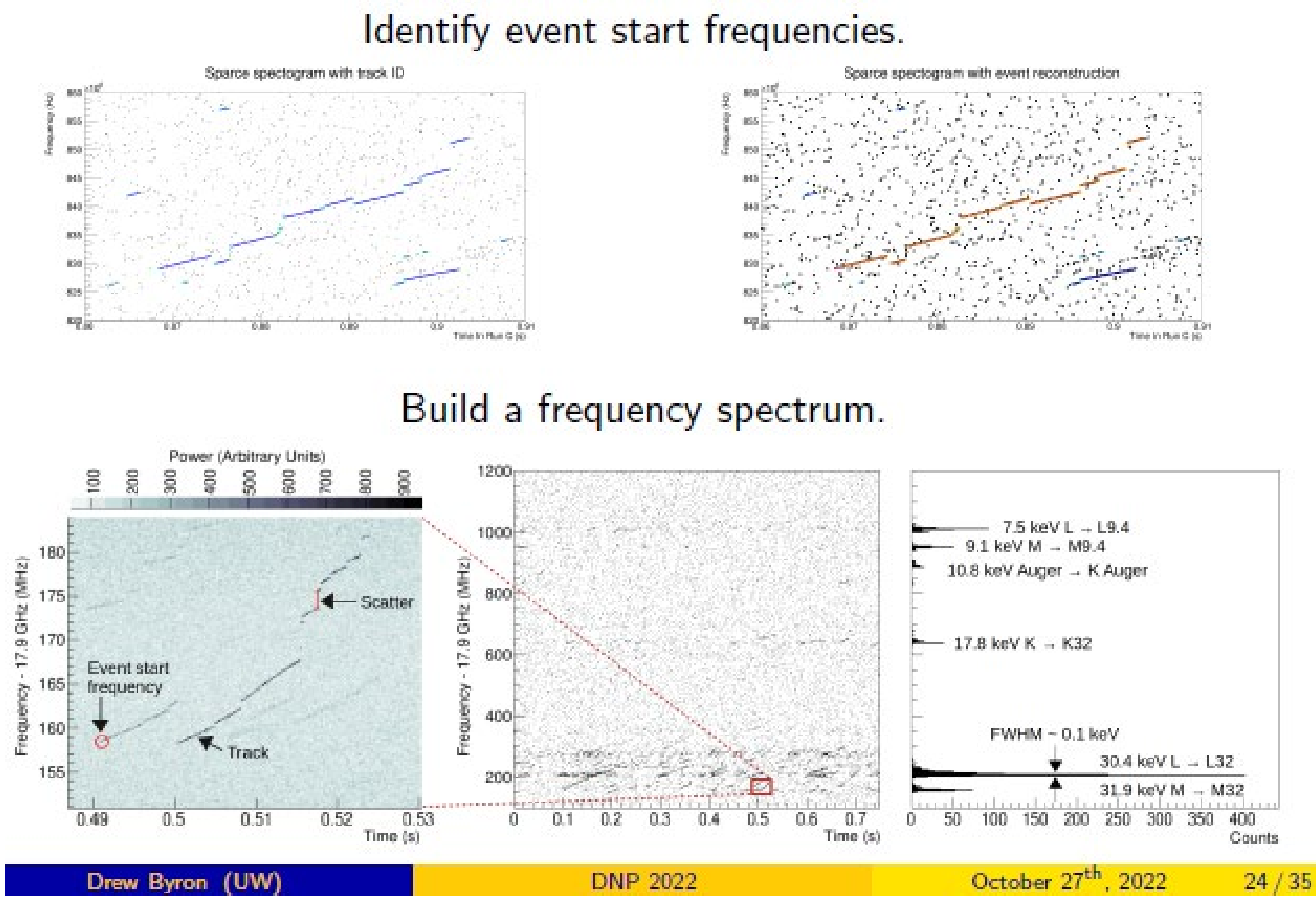


He6-CRES: MeV-scale β spectra

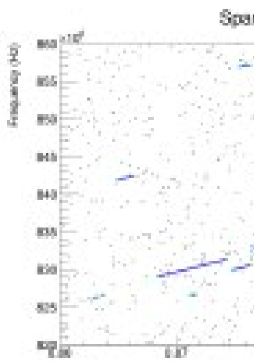
- He6-CRES collaboration based at UW to adapt CRES technique to measure b_{Fierz}
  - ^{6}He (GT), ^{19}Ne (F/GT) and ^{14}O (F); $\beta^{\pm}$ opposite sign in b_{Fierz}
  - Much larger bandwidth needed compared to Project 8
  - Other modes, harmonics, wall effects

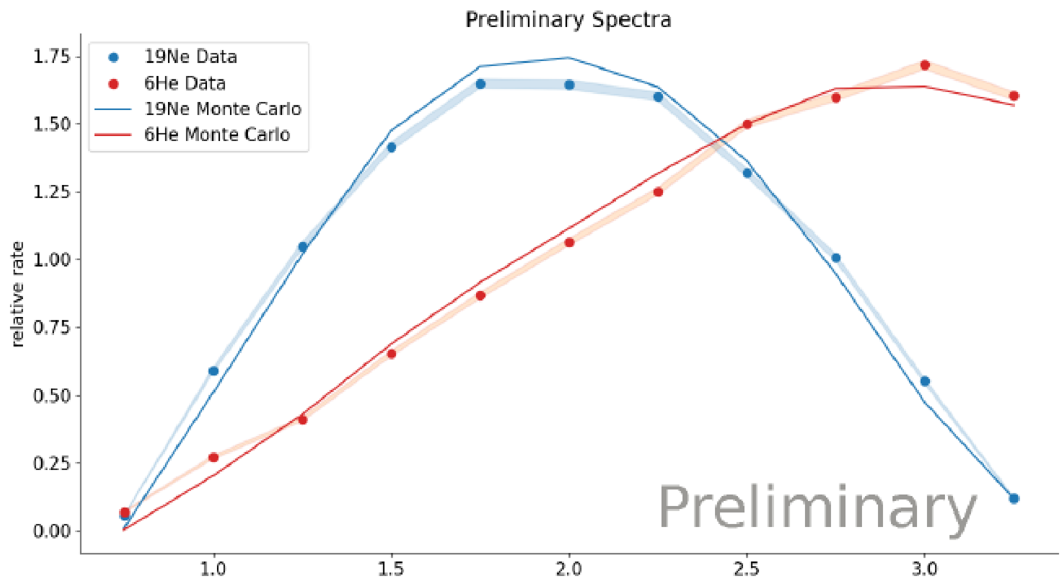


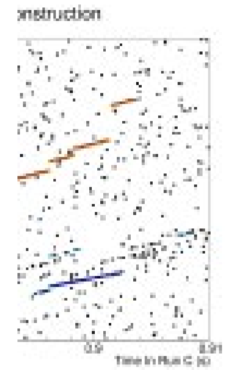
First CRES signals seen

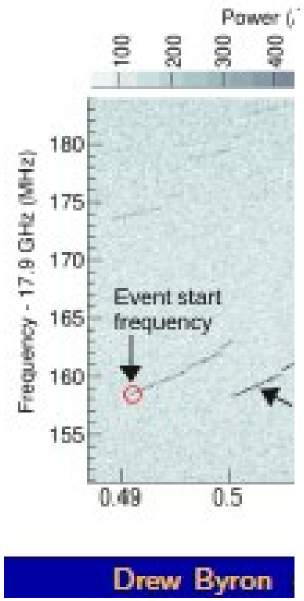


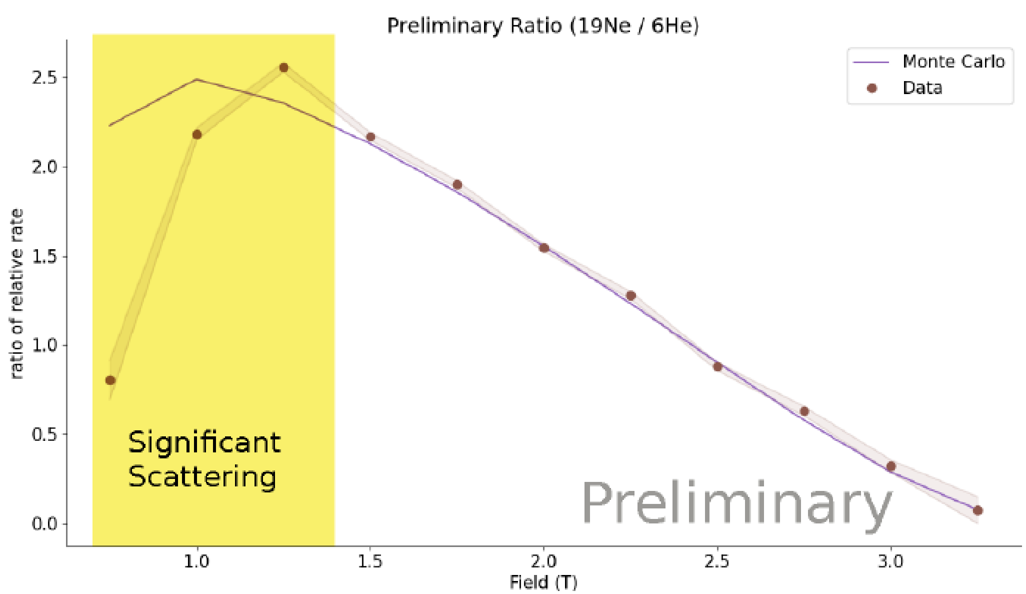
First CRES signals seen

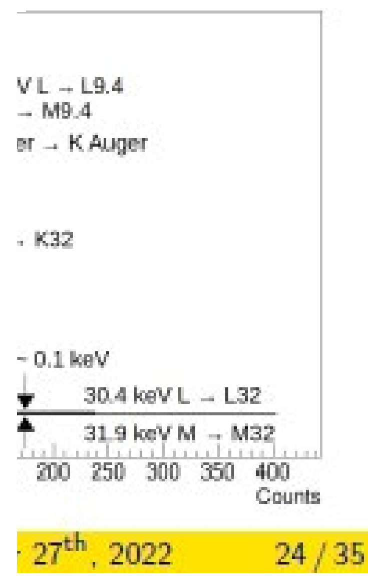






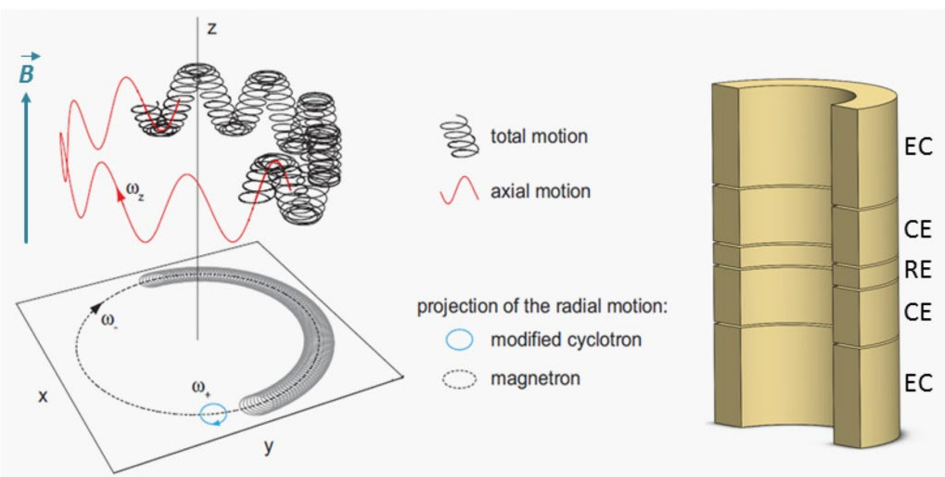


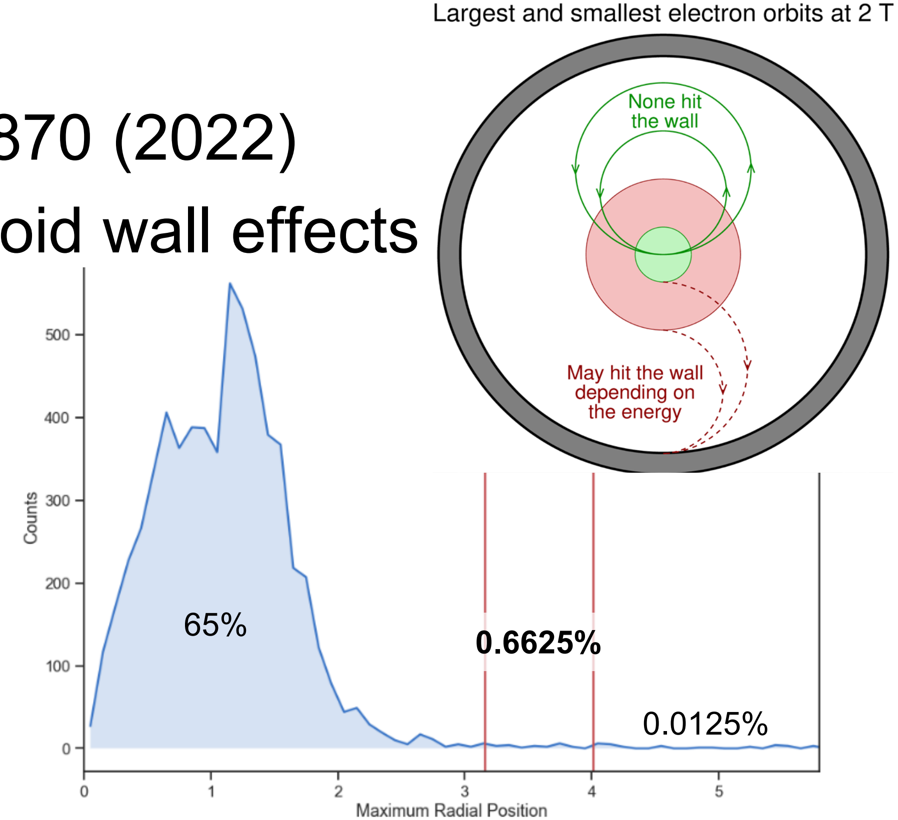




What is the future of CRES?

- Project 8 making great progress. Scale-up challenging
- He6-CRES measured signals from ^{6}He and ^{19}Ne β decay for the first time
  - W. Byron *et al*., arxiv:2209.02870 (2022)
  - Decay cell → Penning trap, avoid wall effects





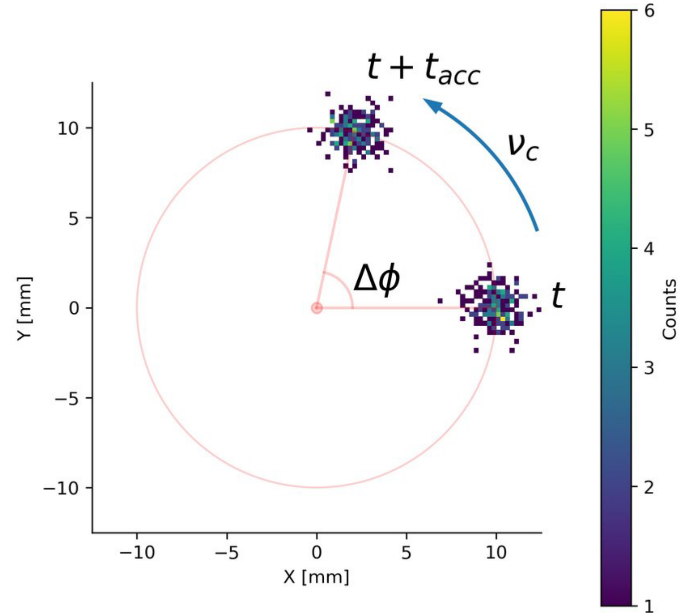
- Requiring waveguides is restrictive, but CRES offers a unique way to precisely measure electron energies

Paul and Penning traps

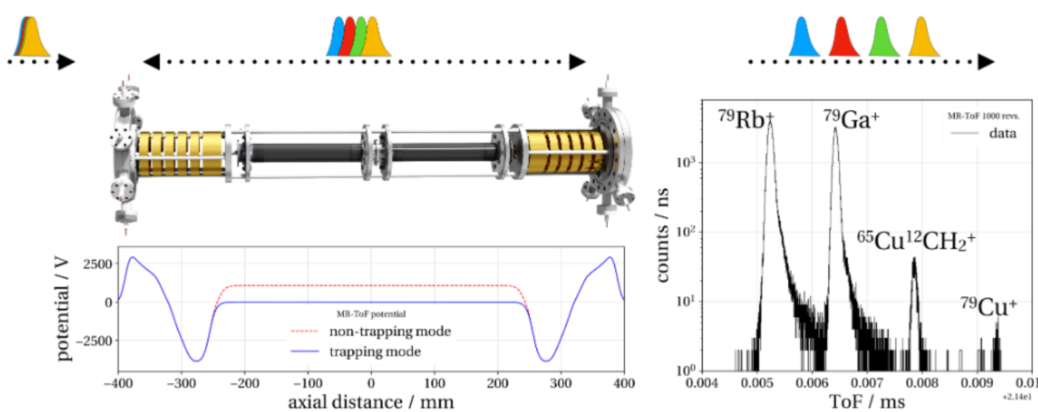
- Ion traps are now a standard technology in NP, but:
  - Technological developments → improved mass precision
  - Expanding range of applications
    - β-α-α correlations @ ANL (beta decay Paul trap)
    - β-ν correlation studies @ Notre Dame (St. Benedict) and @ TAMU (TAMUTRAP)
    - Coupling to the CRES technique (He6 collaboration)
- Lots of activity in the field of quantum computing (says someone very far removed from that area!)
  - Like us, qubits want fine control and long stability times

Mass measurements with Penning traps

- TOF-ICR the workhorse for many years
- Phase-image ion-cyclotron-resonance (PI-ICR) improves precision
  - LEBIT, CPT (TITAN, JYFLTRAP, …)



- MR-TOF has really exploded in recent years; every major lab has one now



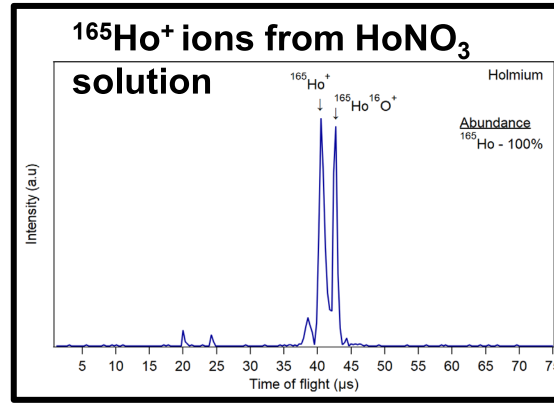
Q-values for ν mass and EC studies

CHIP-TRAP : Central Michigan University High Precision Penning Trap

Goals: Ultra-high-precision (10^{-10} – 10^{-11} relative mass uncertainty)
β-decay Q value measurements for neutrino physics

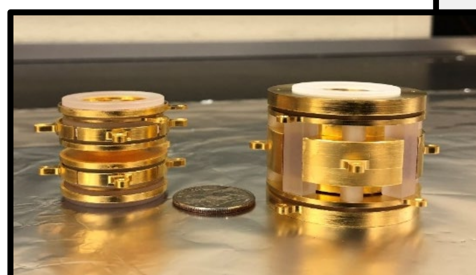
Measurement Goals: ^{163}Ho EC Q value to ~1 eV
^{7}Be EC Q value to ~1 eV
Ultra-low β-decay Q values e.g. ^{188}W

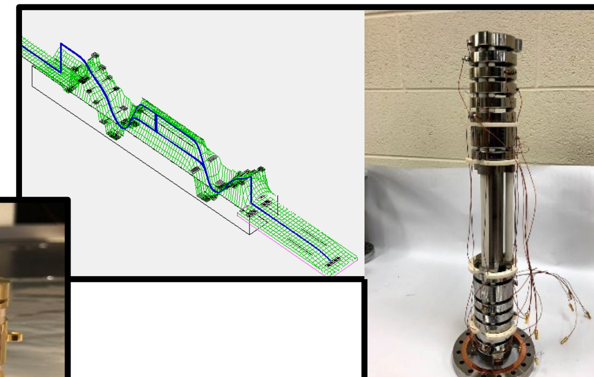
Highlights: Laser ablation ion source
MR-TOF-MS for beam purification
Double-Penning trap for simultaneous mass comparisons
Cryogenic operation and detection electronics



Precision measurement traps

Purification trap





- Made ^{165}Ho$^+$ ions; MR-TOF and Penning traps being commissioned

Correlations – Pioneering work paying off

- Beta-decay Paul Trap @ ANL
  - ^{8}Li ang distr: $g_1 + g_2 \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e} + g_{12}\left(\left[\hat{p}_\alpha \cdot \frac{\vec{p}_e}{E_e}\right][\hat{p}_\alpha \cdot \hat{p}_\nu] - \frac{1}{3}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e}\right)$
  - β-α-α coincidence M.T. Burkey *et al.*, PRL **128**, 202502 (2022)

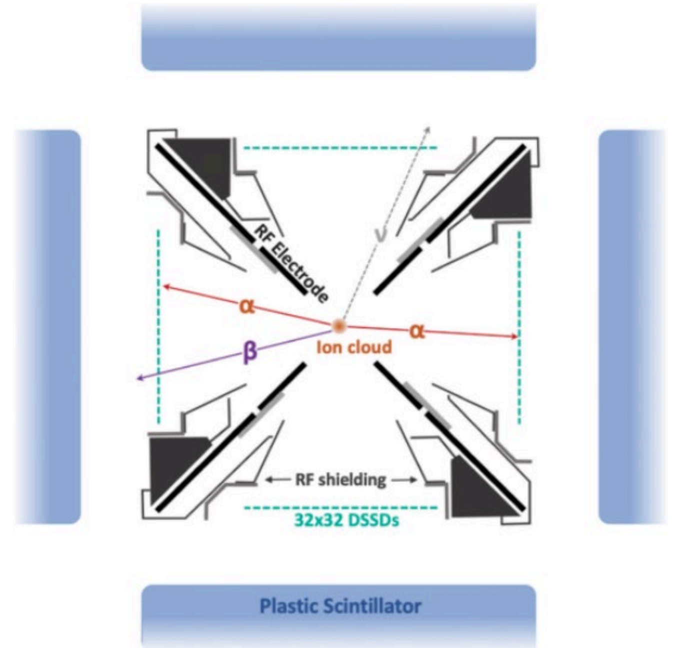
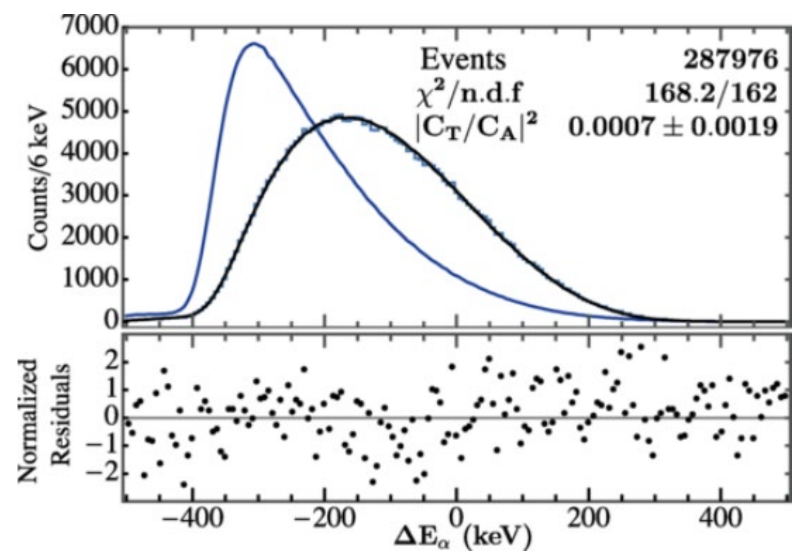


TABLE I. Summary of dominant systematic corrections and uncertainties, listed at 1σ.

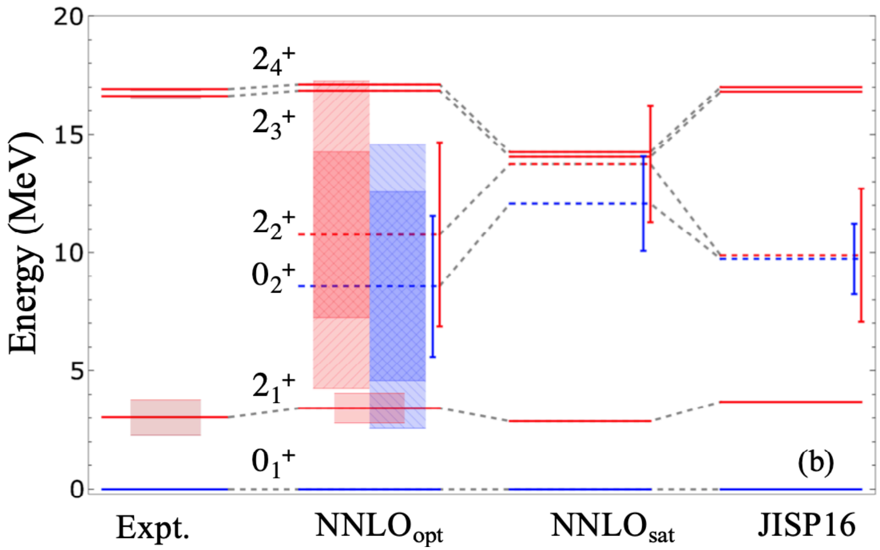
Source		Correction	Uncertainty
Theory	Intruder state (added linearly)	+0.0005	0.0005
	Recoil and radiative terms		0.0015
Experiment	α-energy calibration		0.0007
	Detector line shape		0.0009
	Data cuts		0.0009
	β scattering		0.0010
Total		+0.0005	0.0028



Theory improvements

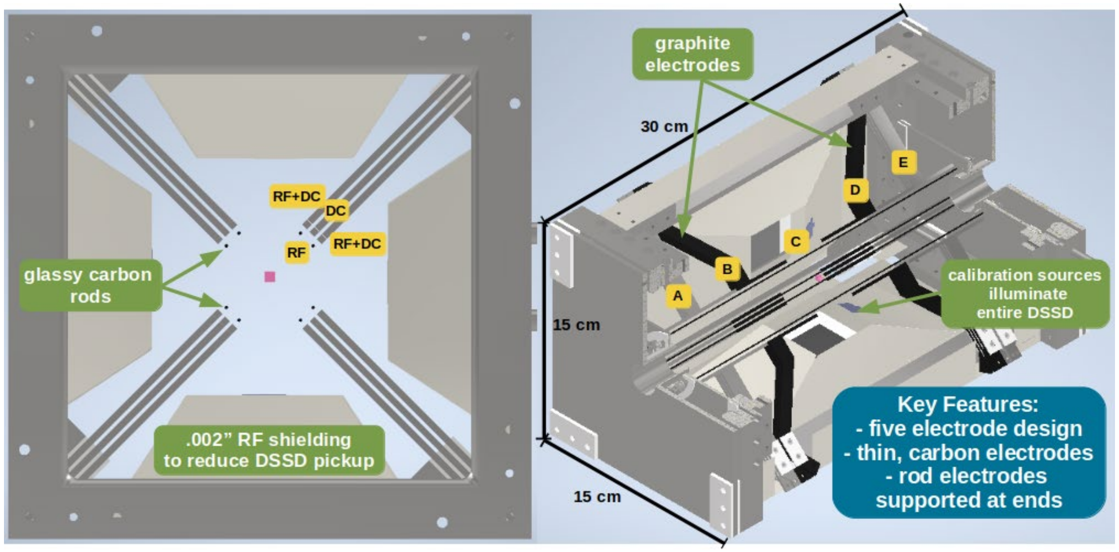
- G.H. Sargsyan, K.D. Launey, et al., PRL 128 202503 (2022).
- Theory improvements to radiative and recoil order corrections – reduce theory uncertainties by factor of 2!
- Possible intruder state in ^{8}Be?

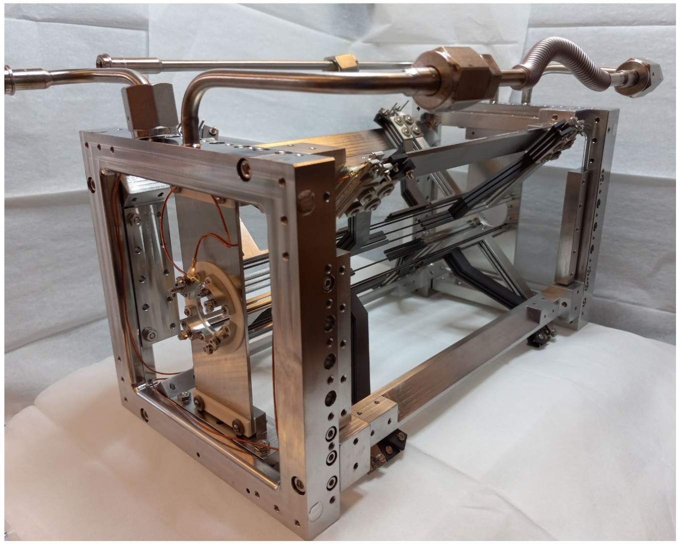
	j_2/A^2c_0	j_3/A^2c_0	d/Ac_0	b/Ac_0
2_1^+	-956 ± 37	-1547 ± 42	10.0 ± 1.0	6.0 ± 0.4
2_2^+ (new)	-10 ± 10	-80 ± 30	-0.5 ± 0.5	3.7 ± 0.4
2_3^+ (doublet 1)	12 ± 5	-60 ± 15	0.3 ± 0.2	3.8 ± 0.2
2_4^+ (doublet 2)	11 ± 3	-65 ± 11	0.2 ± 0.2	3.8 ± 0.2



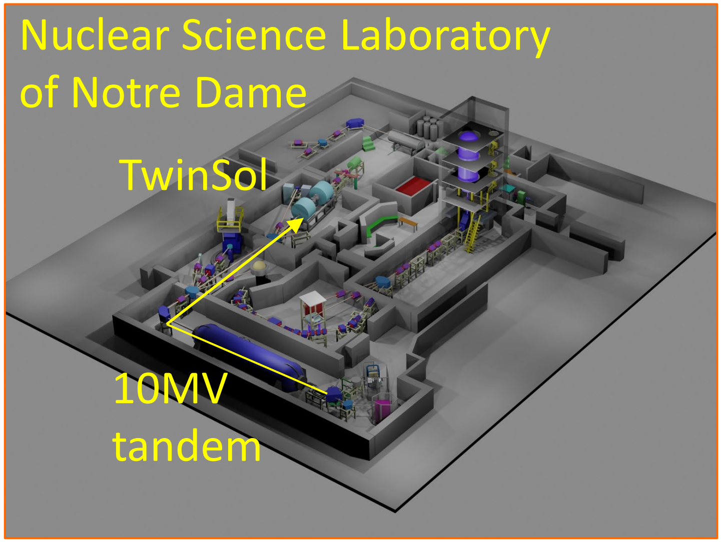
Next step: Beta-decay Paul Trap Mk. IV.

- Recently commissioned with ATLAS
  - Designed and built by Louis Varriano (graduate student, University of Chicago).
  - Commissioned with ATLAS beam during May-June 2022; collected 2.7 million events (~30% increase in statistics).
  - Design and commissioning paper in progress.
  - Reduces beta scattering by factor of 4, a key source of systematic uncertainty.
    - Aim to improve uncertainty by factor of 2 from recently published result.



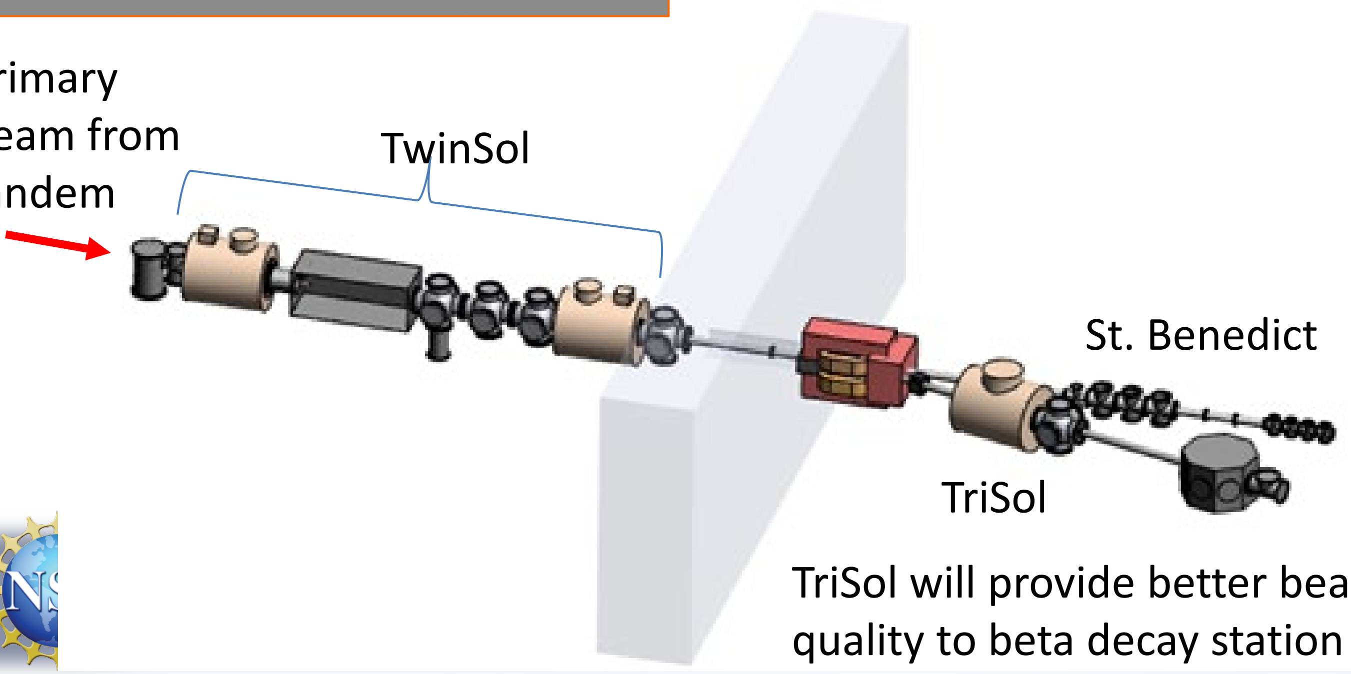


St. Benedict and TriSol upgrade

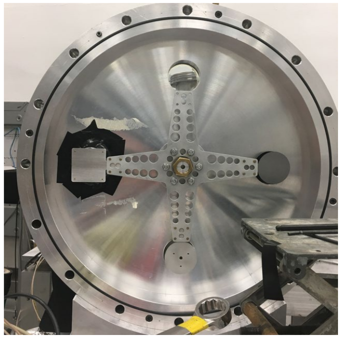


FS program at Notre Dame centered on superallowed mixed transitions.

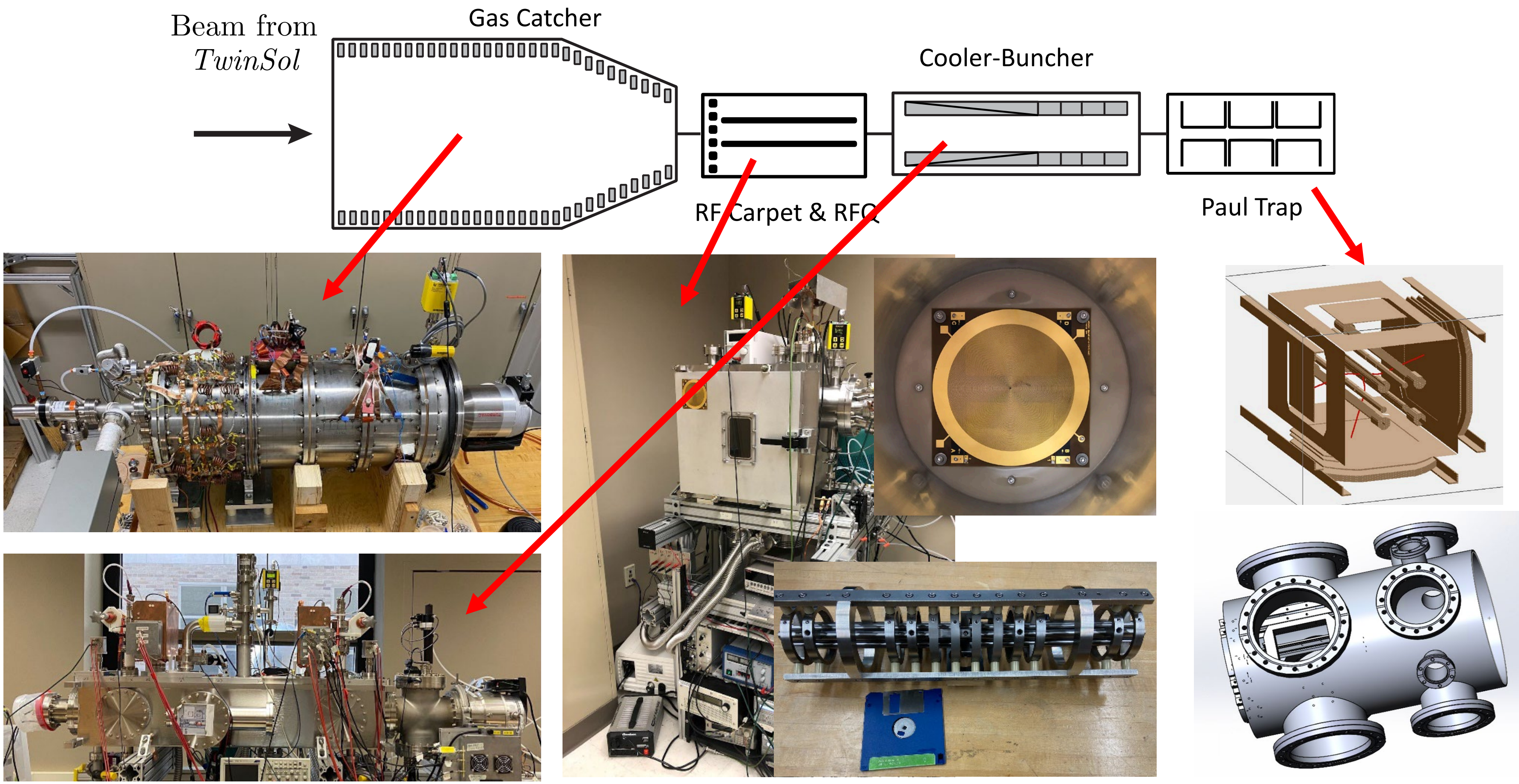
- Precision half-life measurements
- Beta-neutrino angular correlation measurements using St. Benedict
  - Improve accuracy of Vud
  - Search for scalar/tensor currents
  - BSM tensor coupling to RH neutrinos



TriSol will provide better beam quality to beta decay station

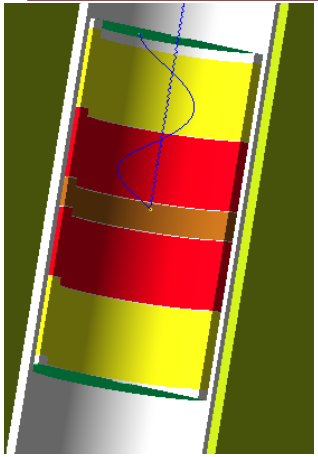


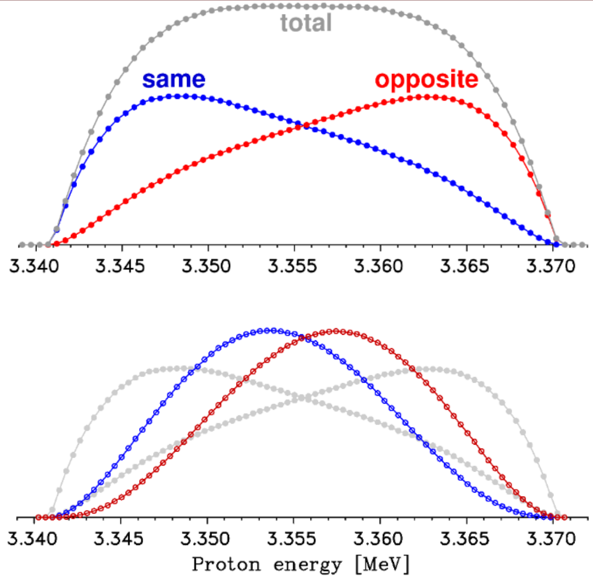
Superallowed Transisiton Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict)

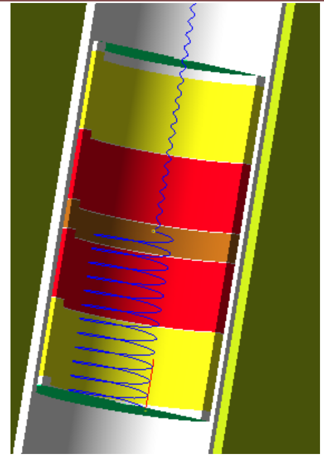


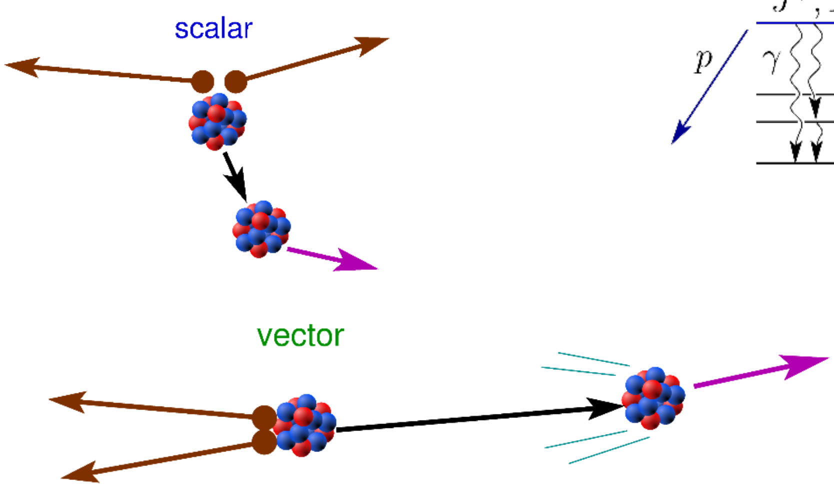
- Gas catcher from ANL: RF/DC & vacuum tested; transport tests underway
- RF carpet tested; ion guide assembled and RF circuit being tested
- Cooler/buncher commissioned
- Paul trap has been simulated and manufactured

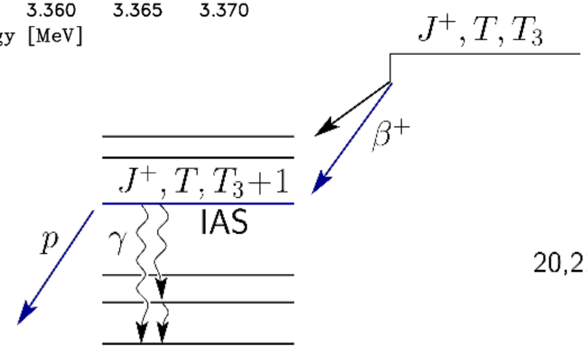
TAMUTRAP at the Cyclotron Institute

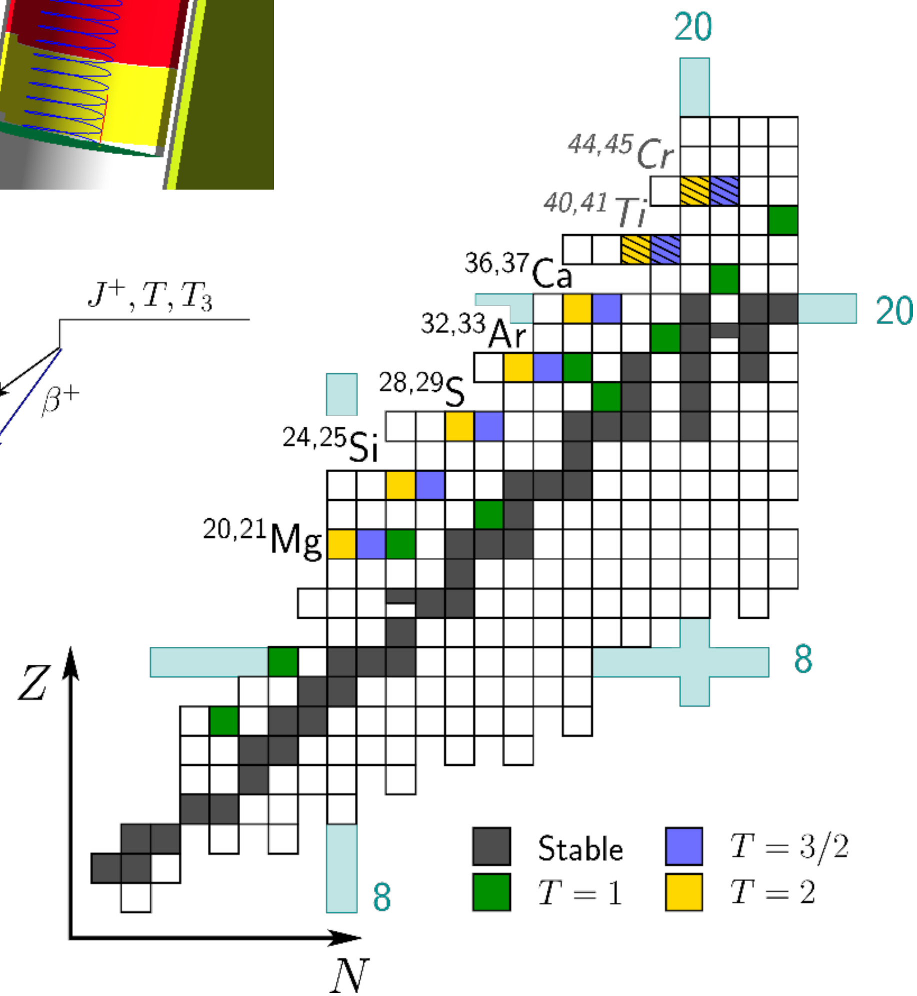






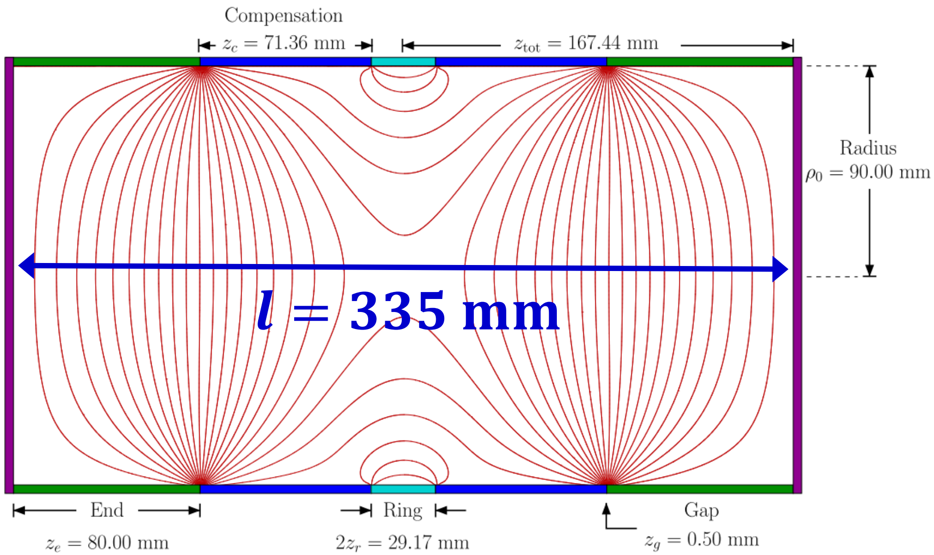


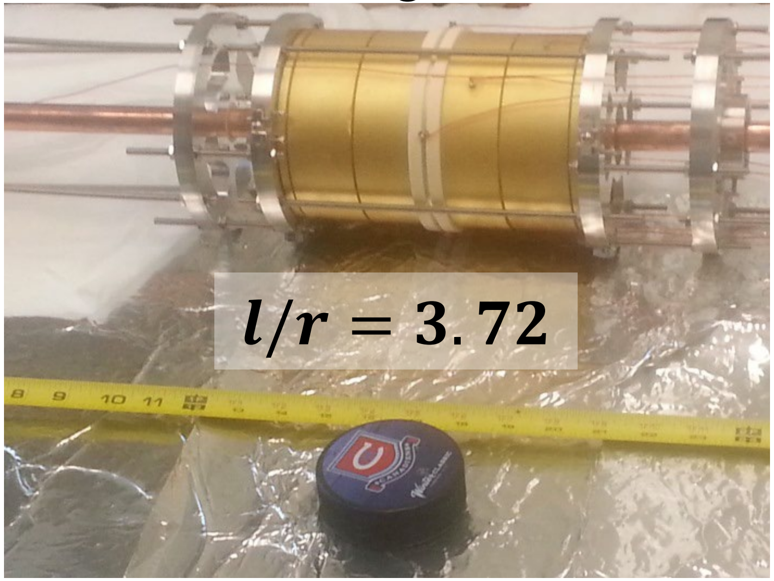


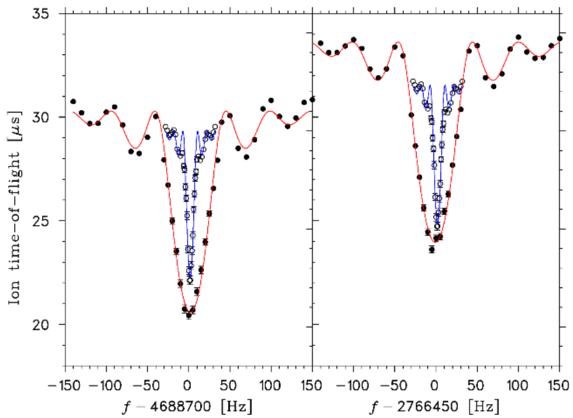


World's largest Penning trap commissioned

- Typical cylindrical traps have $l/r = 11.75$; to confine the protons from $T = 2$ decays, we need $r = 90\ \mathrm{mm}$
  - Needed a new design to make it fit in the 7T magnet





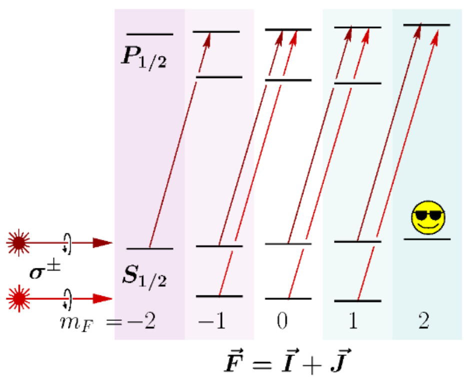


M.Mehlman *et al.*, NIMA **712** (2013)
P.Shidling *et al.*, Int J Mass Spectr **468** (2021)

Stable masses via TOF-ICR agree to few ppb ⇒ it works!

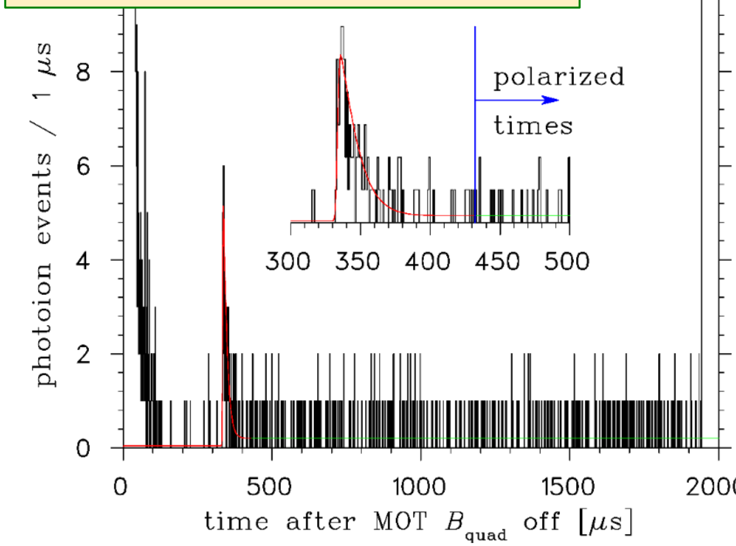
Atom traps

- TRINAT has developed some pretty cool techniques
  - High nuclear polarization

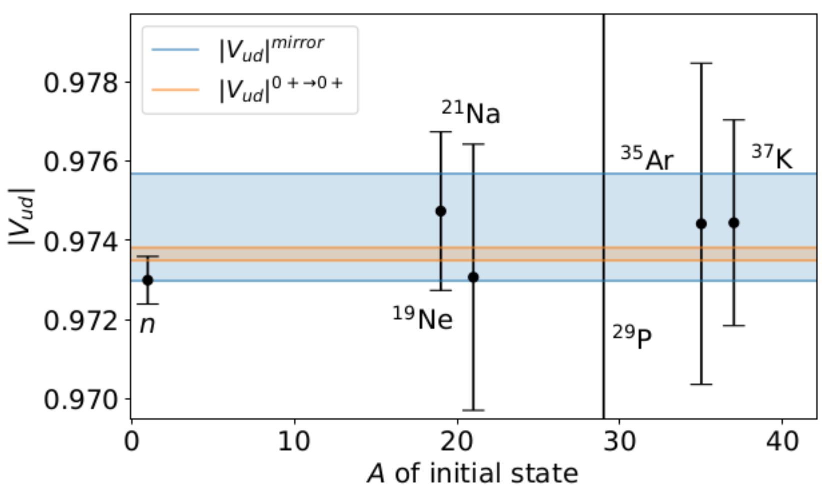


B.Fenker *et al*, New J. Phys. **18** (2016)

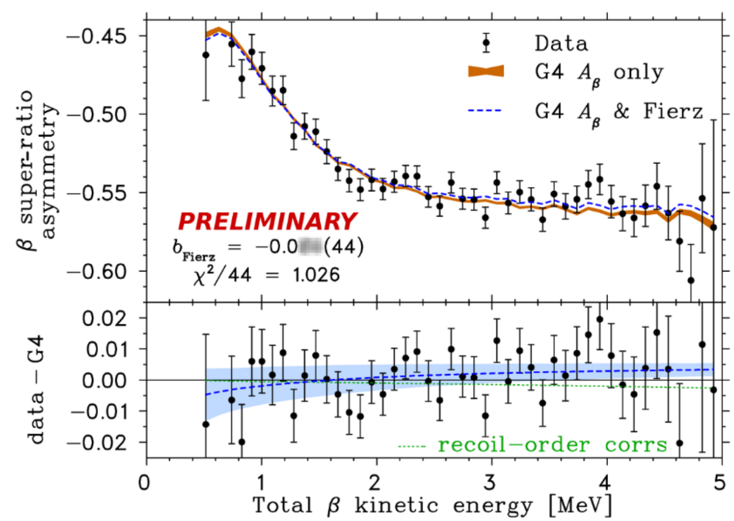
$\langle |P_{\text{nucl}}| \rangle = 0.9913(9)$



  - Physics result: A_β to 0.3%

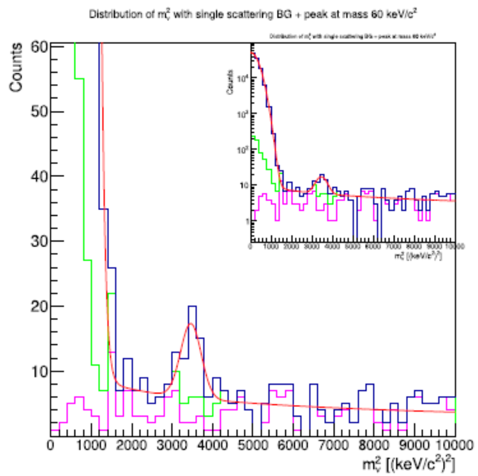


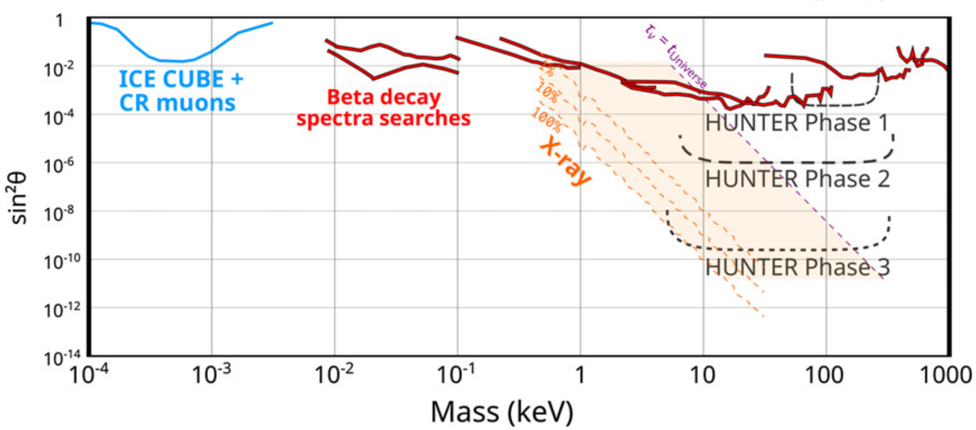
B.Fenker *et al*, PRL **120** (2018)

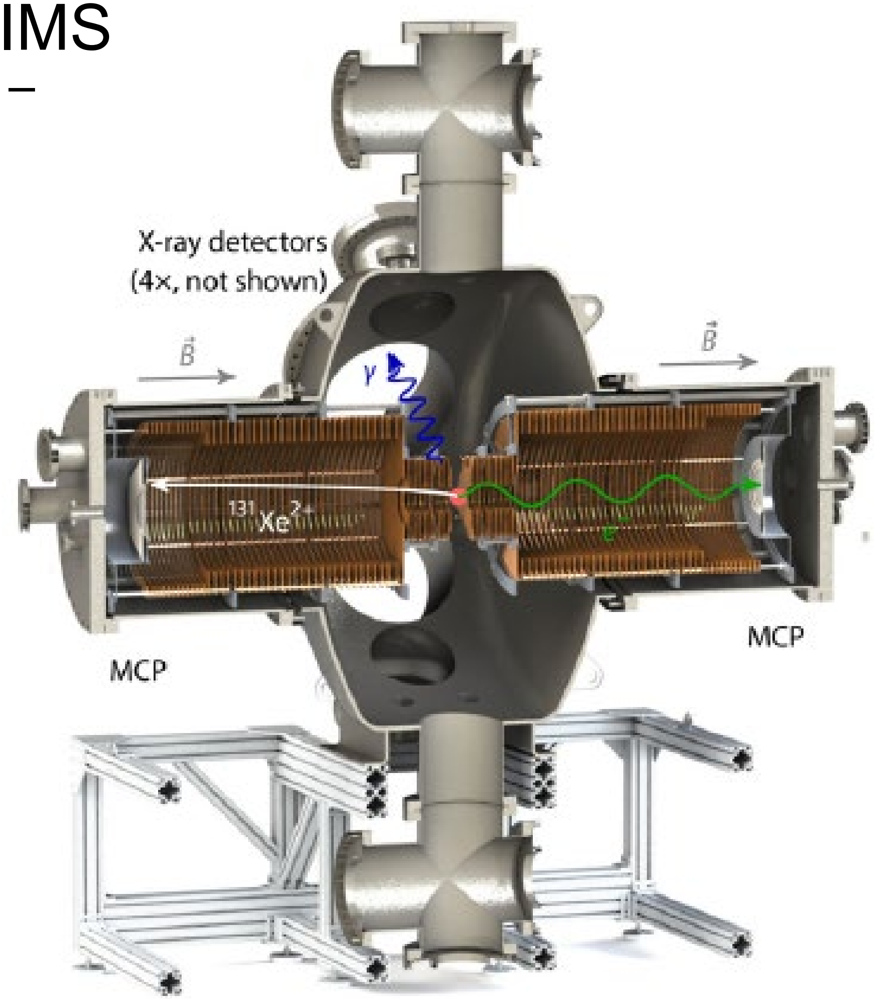


Sterile ν search with HUNTER

- ^{131}Cs in a MOT, reconstruct momenta to search for mixing to a sterile ν (5–100 keV)
  - Recoil-momentum with MOTRIMS technique; X-rays and Auger e^-

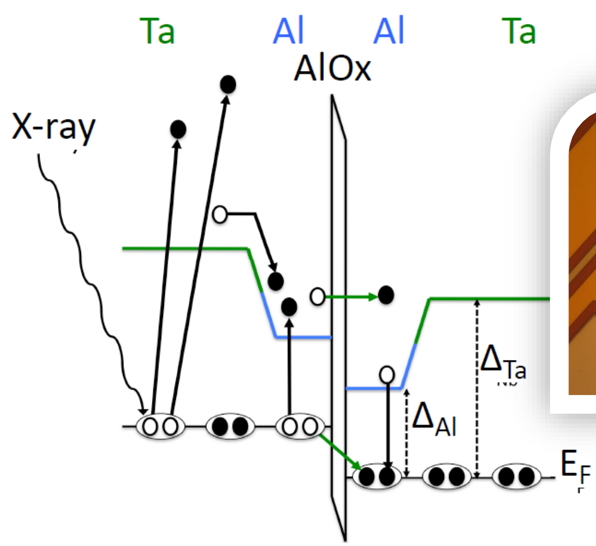


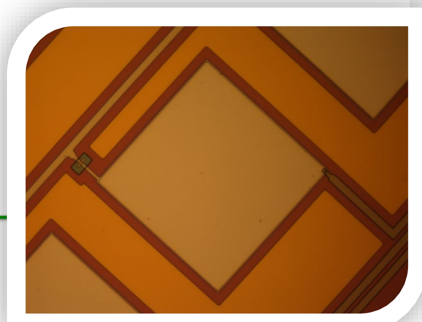


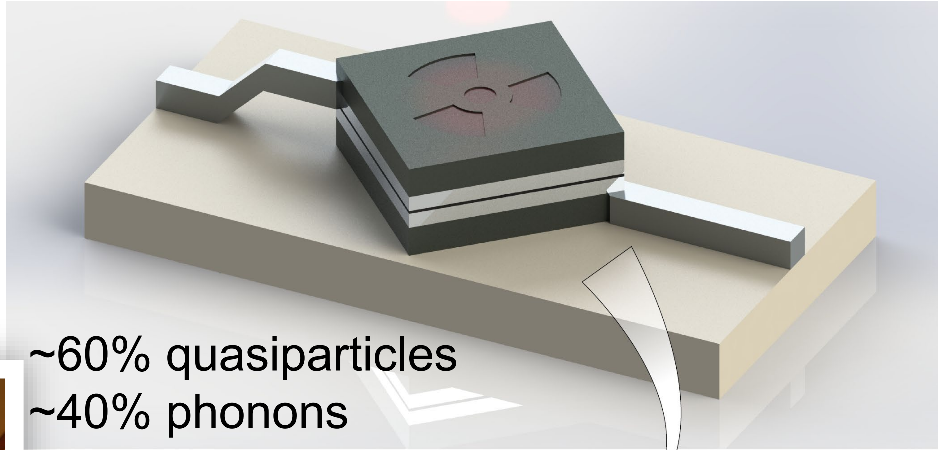


Superconducting Tunnel Junctions (STJs)

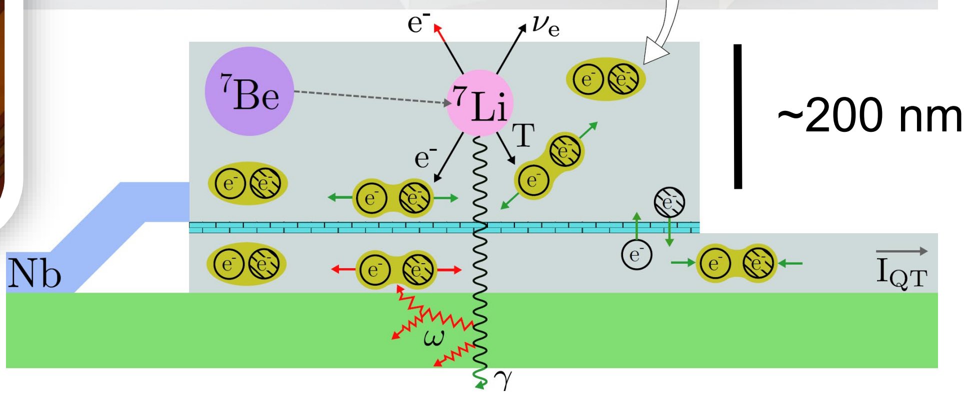
- *Cryogenic-charge* superconducting sensor
- Superconducting energy gap Δ is of order ~meV
  - High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, allowing for faster count rates than most superconducting sensors
  - "High" Rate (10^4 s^{-1} per pixel)



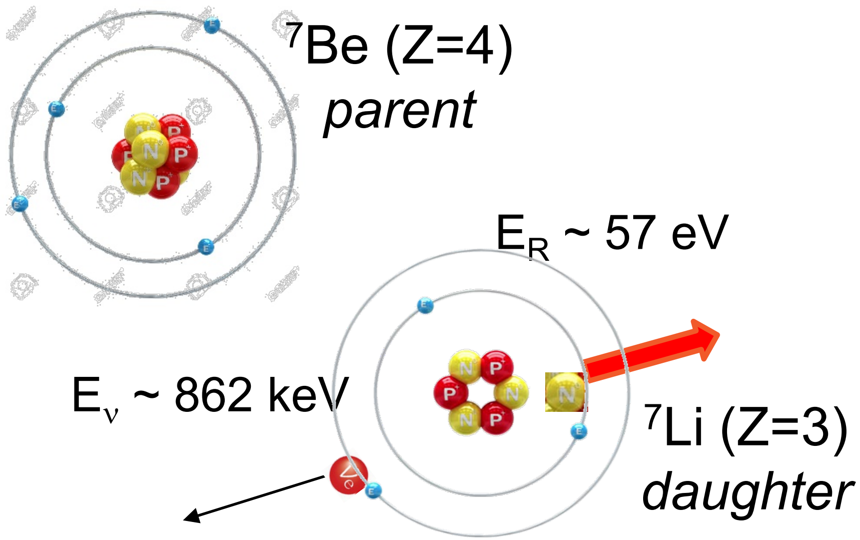


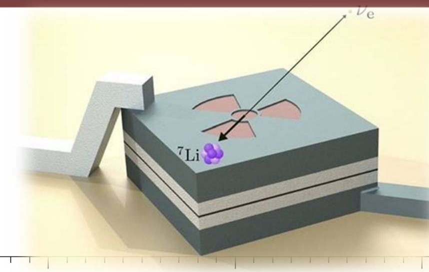


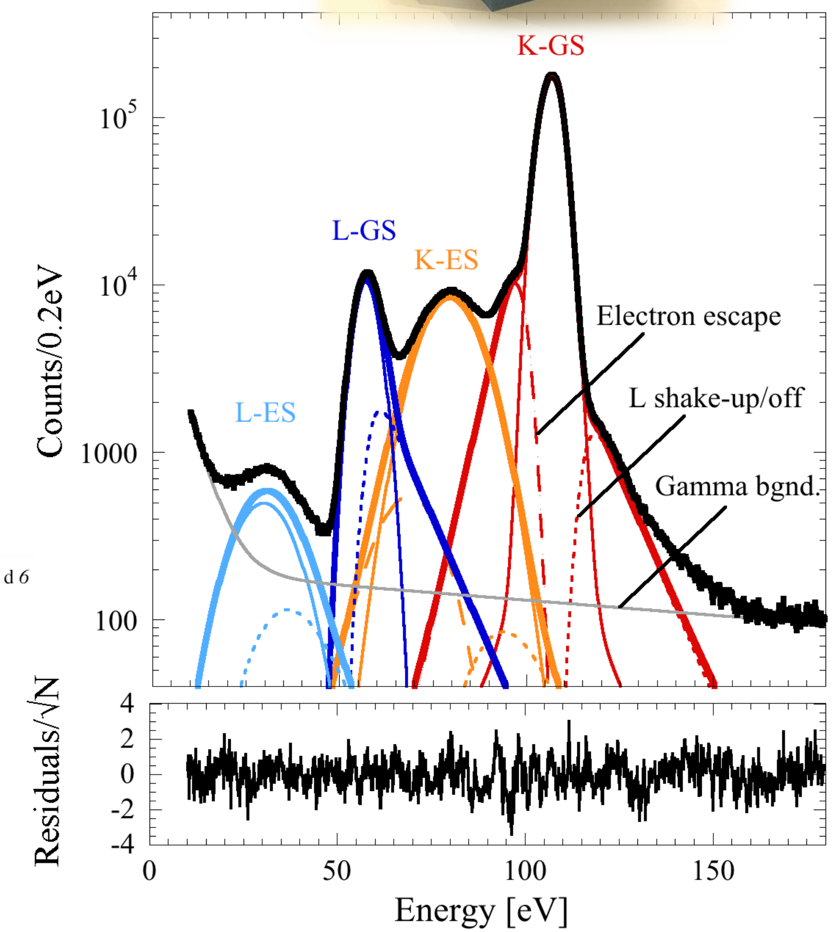
~60% quasiparticles
~40% phonons



First Nuclear Recoil Experiments with STJs – ^{7}Be Decay

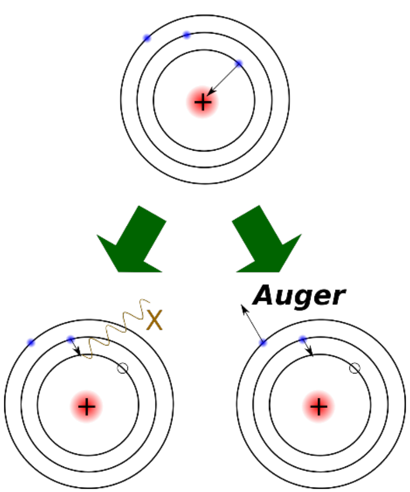




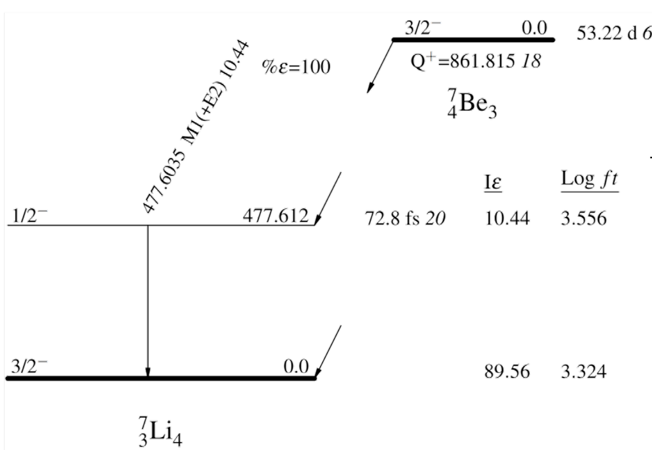


S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

Atomic Effects



Nuclear Effects



Conclusions/Thanks

- Fundamental symmetries requires high precision $\Leftrightarrow$ we develop some really cool techniques to accomplish this
- We all know each other, but meetings like this are a great idea – I hope it breeds new ideas/collaborations!
- Sorry if I didn't show your work, sorry if I asked for slides too late…
- Thanks to Kyle (!), Maxime Brodeur, Drew Byron, Matt Redshaw, Nick Scielzo, Louis Varriano (Jason), …, Google…
- And of course, the DOE!

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