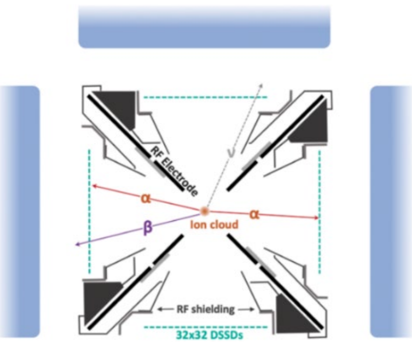
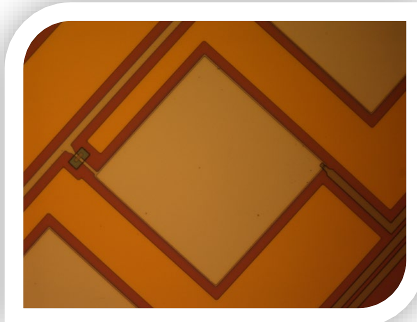
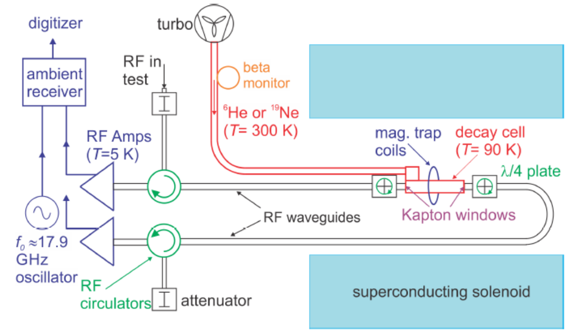
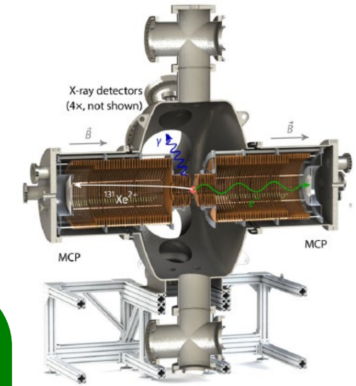
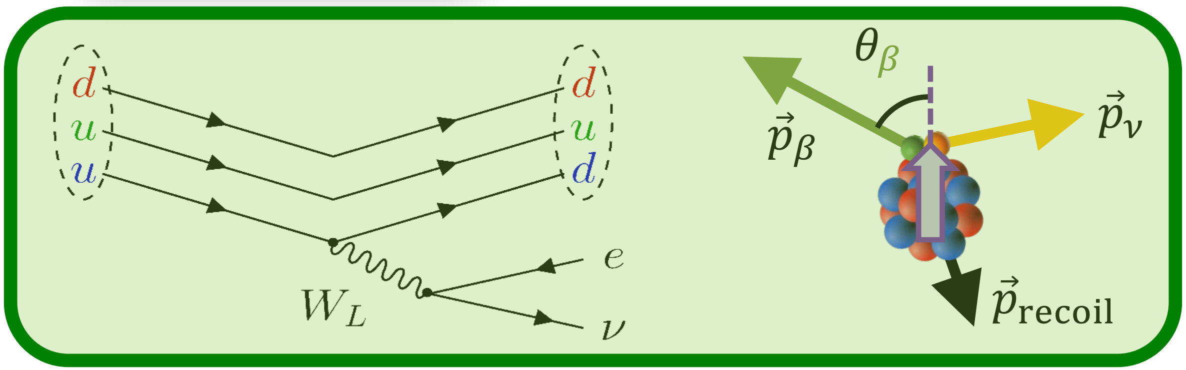
# Precision $\beta$ decay: nuclei

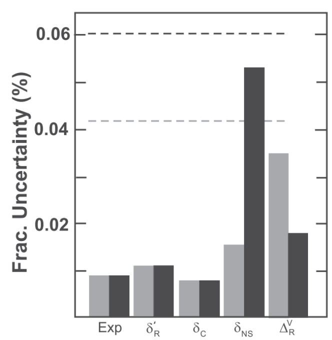


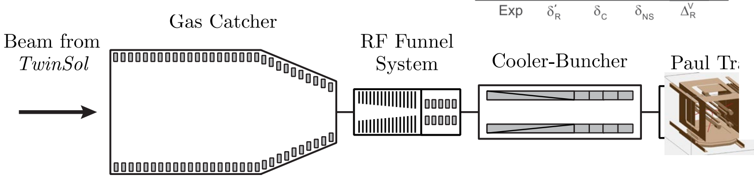



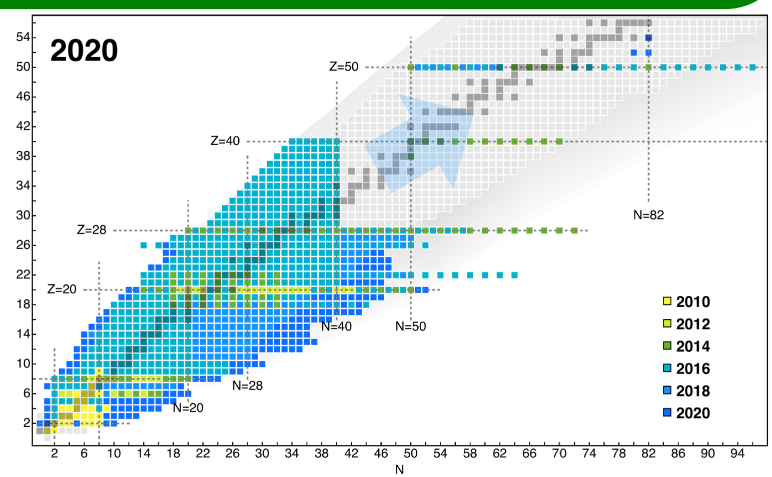


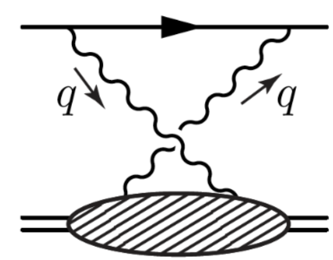



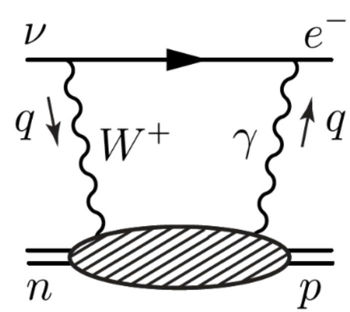




Dan Melconian

# Outline

## Nuclear $\beta$ decay as a probe for physics beyond the standard model (white paper)


M. Brodeur,[1] N. Buzinsky,[2] M.A. Caprio,[1] J.A. Clark,[3] P.J. Fasano,[1] J.A. Formaggio,[4] A.T. Gallant,[5] A. Garcia,[2] S. Gandolfi,[6] S. Gardner,[7] A. Glick-Magid,[2] L. Hayen,[8,9] H. Hergert,[10,11] J. D. Holt,[12,13] M. Horoi,[14] M.Y. Huang,[15] K.D. Launey,[16] K.G. Leach,[17,18] B. Longfellow,[5] A.E. McCoy,[18,19] D. Melconian,[20,21] P. Mohanmurthy,[4] D.C. Moore,[22] P. Mueller,[3] E. Mereghetti,[23] P. Navratil,[24] S. Pastore,[19,25] M. Piarulli,[19,25] D. Puentes,[26,18] B.C. Rasco,[27] M. Redshaw,[14] G.S. Sargsyan,[5] G. Savard,[3,28] N.D. Scielzo,[5] C.-Y. Seng,[2,18] A. Shindler,[10,11] S.R. Stroberg,[1] J. Surbrook,[26,18] A. Walker-Loud,[29] C. Wrede,[26,18] A. R. Young,[30,31] and V. Zelevinsky[26,18]

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# Outline

- CKM matrix unitarity tests
  - Theory has made huge progress
  - New experiments targeting low-Z cases, mirror transitions
- Searches for scalar and tensor currents
  - Spectrum-shape for Fierz
  - Ion and atom traps
- $\beta$ decays for neutrino physics
  - Ultra-low *Q*-values for direct $m_\nu$ measurements
  - Sterile neutrinos via EC
  - Reactor antineutrino anomaly

# In case I run out of time (which I will…)

- Start with the White Paper recommendations:
  - Experimental + theoretical alliance for Vud and CKM unitarity
  - Investing in small- and mid-scale projects
  - Establishing support for nuclear theory
  - Developing cutting-edge techniques
  - Promote diverse and inclusive environment, and better support students

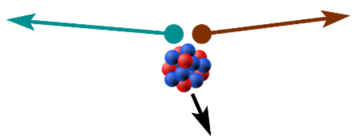
- Thanks for input (apologies to all)
  - Maxime Brodeur, Drew Byron, Jason Clark, Leendert Hayen, Kyle Leach, Charlie Rasco, Matt Redshaw, Nick Scielzo, Chien Yeah Seng, Louis Varrian, and everyone on the nuclear $\beta$ decay White Paper

# $\beta$-decay correlations and $ft$ values

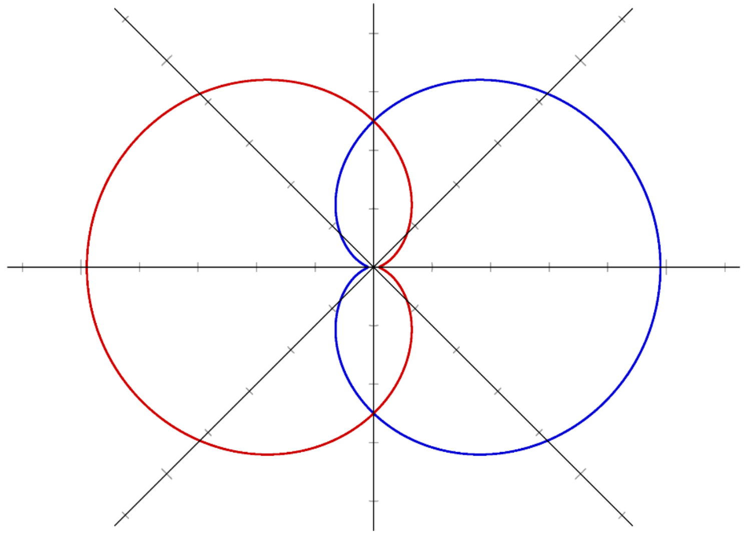
- Quick reminder:

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

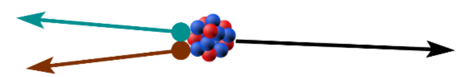
scalar



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



vector



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

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

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

# $\beta$-decay correlations and $ft$ values

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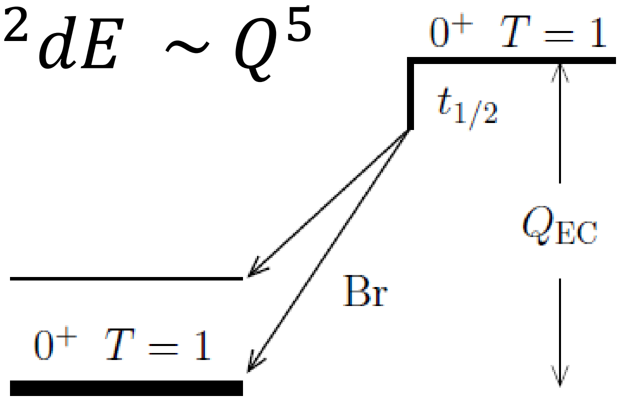
- Comparative half-life:

$$f = \int F(Z',E)C(E)pE(E-E_0)^2 dE \sim Q^5$$

and

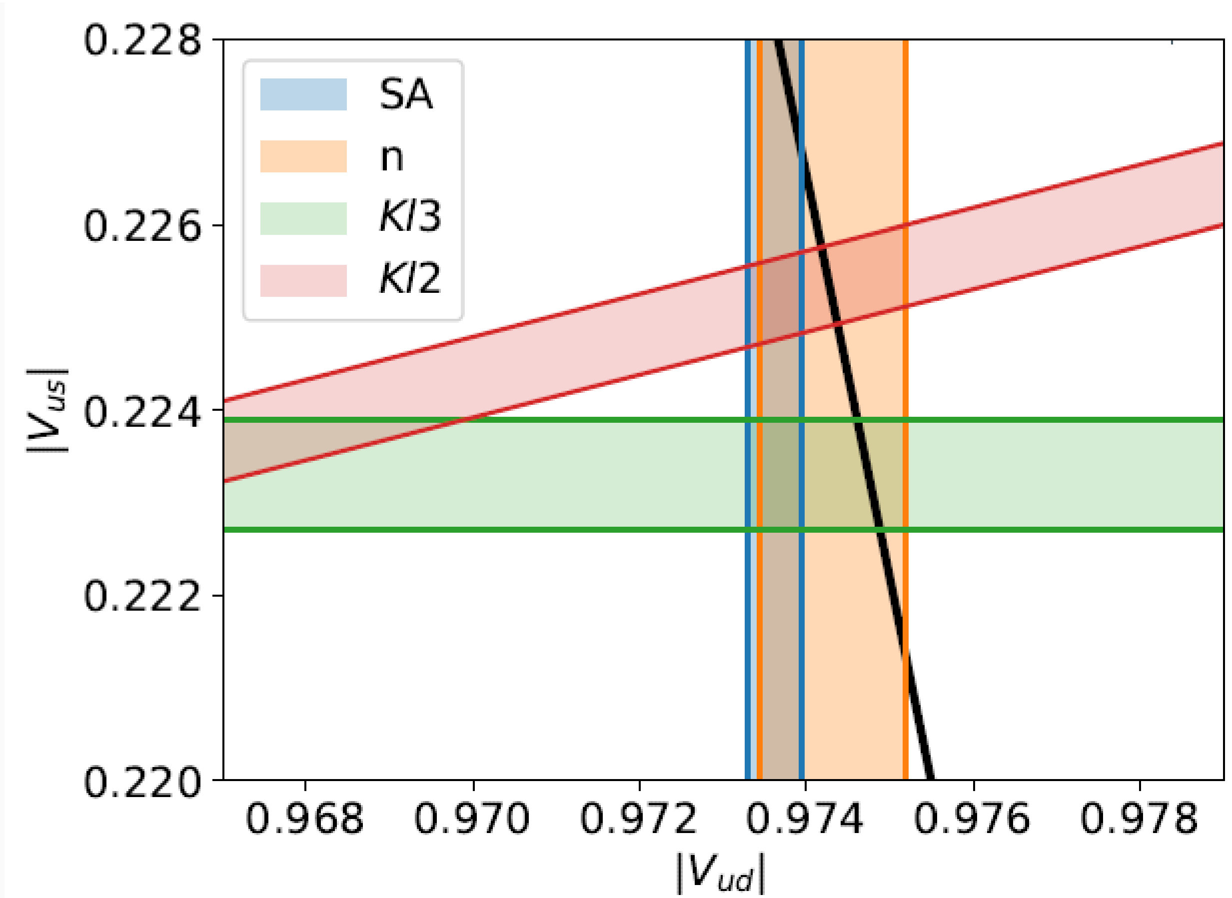
$$t = \frac{t_{1/2}}{\mathrm{Br}}(1+P_{\mathrm{EC}})$$




$$Ft \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K/G_F^2}{|V_{ud}|^2 M_F^2(1+\Delta_R^V)}$$

# CKM Unitarity

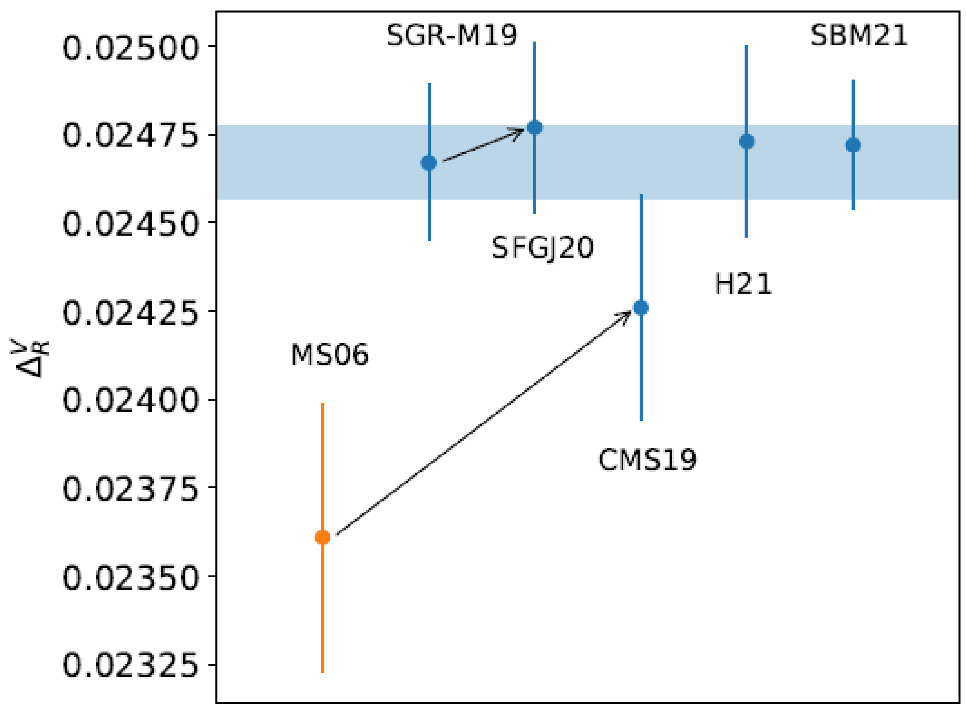
- There are currently indications of non-unitarity at a few $\sigma$ level

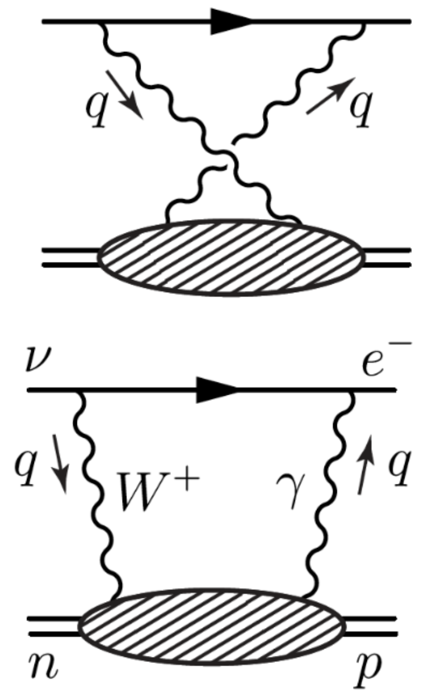



$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9982(6)$$

# Recent development: theory

- Hint of new physics due largely to new calculations of $\Delta_R^V$

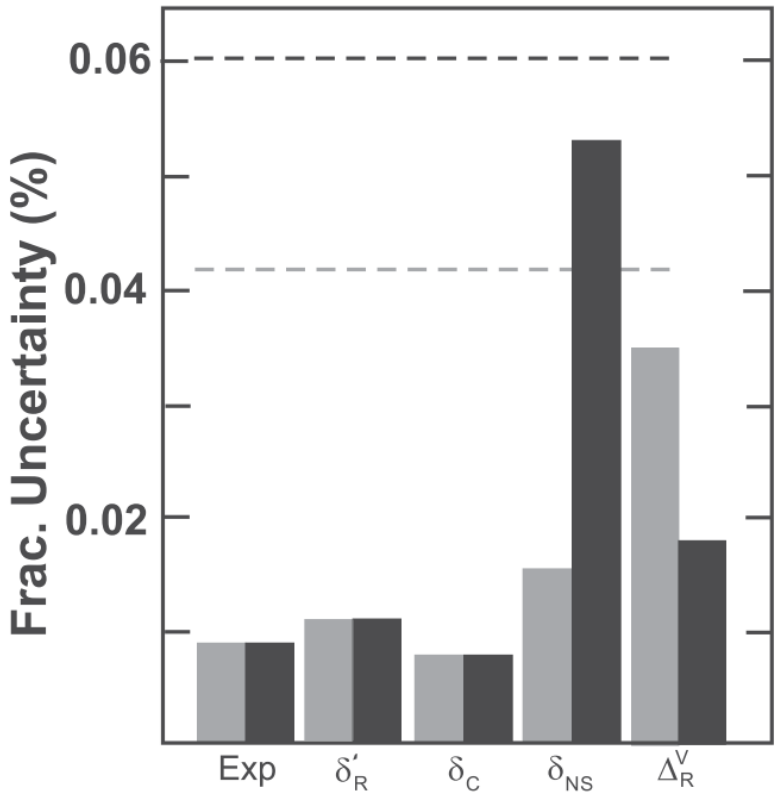



Smaller uncertainty *and* a shift

# Recent development: theory

- Hint of new physics due largely to new calculations of $\Delta_R^V$
- New effects to $\delta_{\rm NS}$ from quasi-elastic contributions and nuclear polarization effects (1812.03352, 1812.04229): $\delta_{\rm NS}(E)$
  - Now the (by far) dominant theoretical uncertainty
  - Rigorous theory framework based on dispersion relation to compute the NS effects (2211.10214)
  - New collaborations are formed to compute $\delta_{\rm NS}$ with ab-initio methods for light nuclei

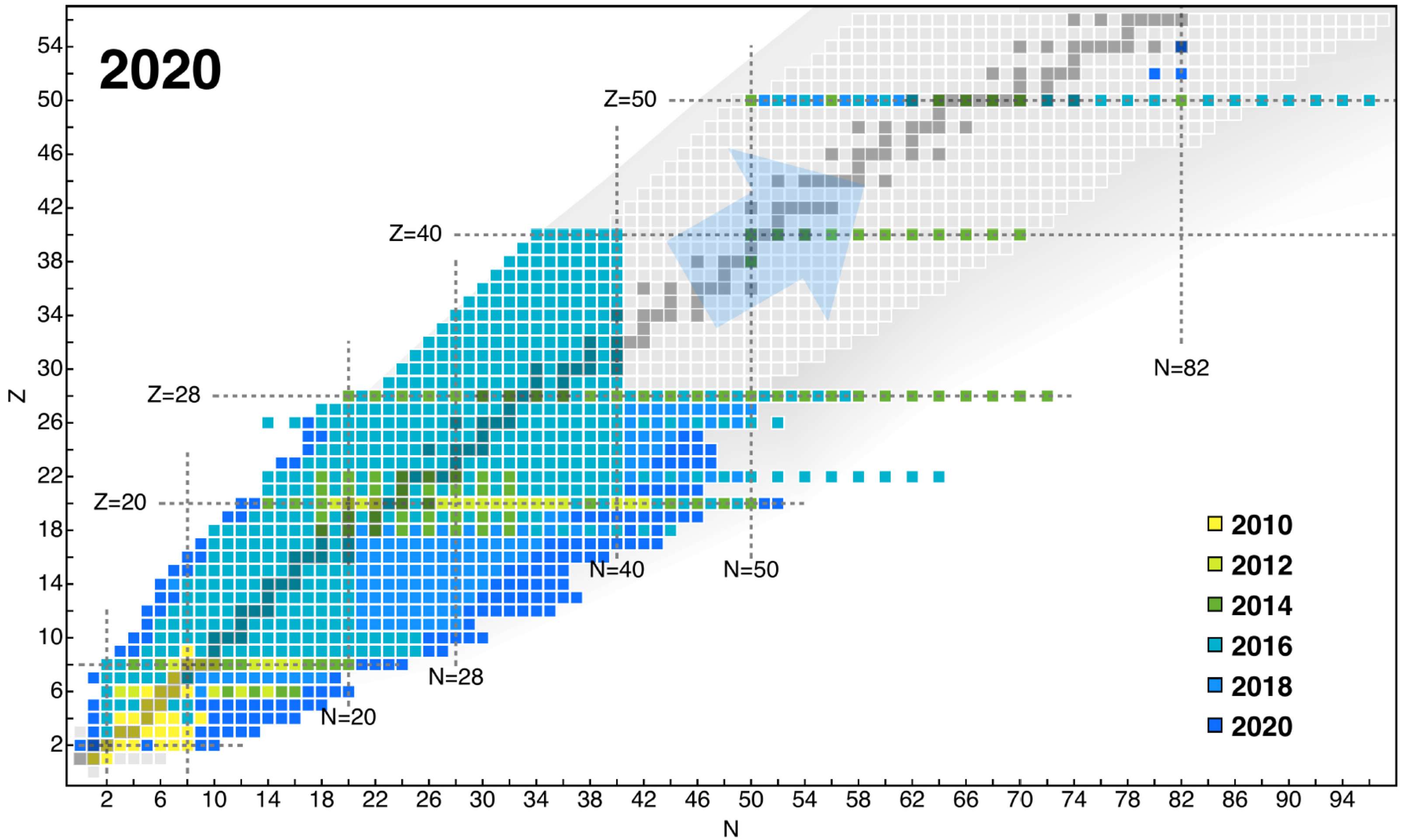


# Recent development: theory

- Hint of new physics due largely to new calculations of $\Delta_R^V$
- New effects to $\delta_{\text{NS}}$ from quasi-elastic contributions and nuclear polarization effects (1812.03352, 1812.04229): $\delta_{\text{NS}}(E)$
  - Now the (by far) dominant uncertainty comes the SM theory input
- New connections are found between experimental measurements of charge radii and the isospin breaking correction ($\delta_C$) (2208.03037) and recoil corrections in $\beta$ decay (C.Y.Seng, 2212.XXXXX, will post soon)

# Ab initio nuclear theory

- ***Amazing*** progress in just 10 years!!




H. Hergert, Frontiers in Physics (2020)

# Experimental efforts

- Being low-$Z$, $^{10}$C and $^{14}$O are the most interesting (scalar currents); Ronald will talk about this later

**SALER: Superconducting Array for Low-Energy Radiation**

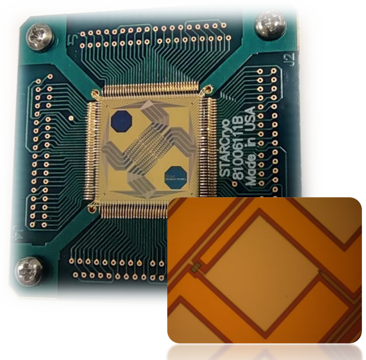
*Direct implantation and measurement of eV-scale radiation from short-lived ($T_{1/2}$ > 1 ms) rare isotopes for BSM physics searches (CKM unitarity, exotic weak currents, etc.)*

SALER

FRIB

GORDON AND BETTY MOORE FOUNDATION

U.S. DEPARTMENT OF ENERGY | Office of Science

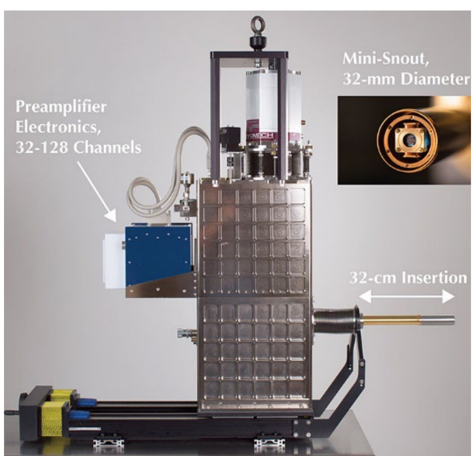


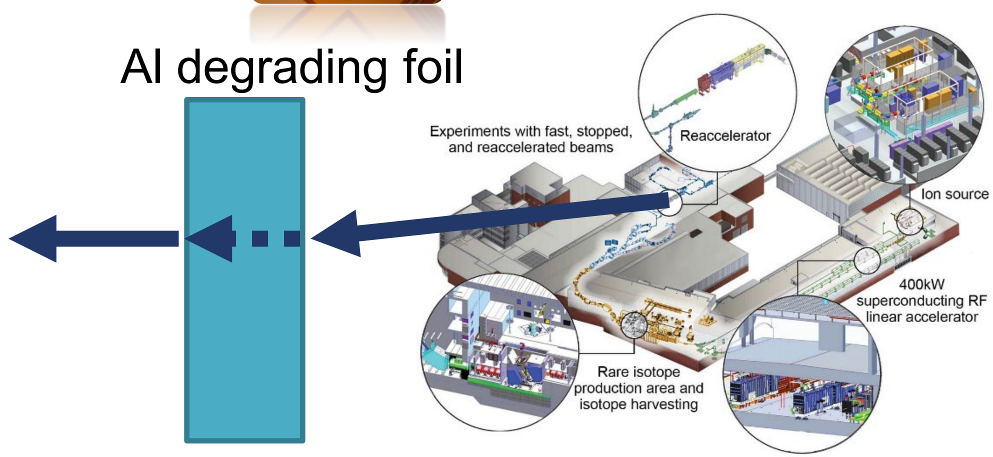
COLORADO SCHOOL OF MINES — EARTH • ENERGY • ENVIRONMENT

STAR CRYOELECTRONICS

NC STATE UNIVERSITY

***eV-scale nuclear recoil spectroscopy for BSM physics studies***



# Experimental efforts

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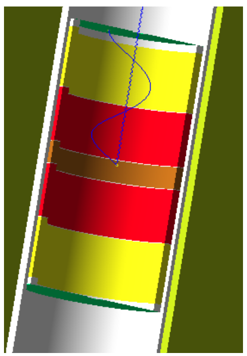
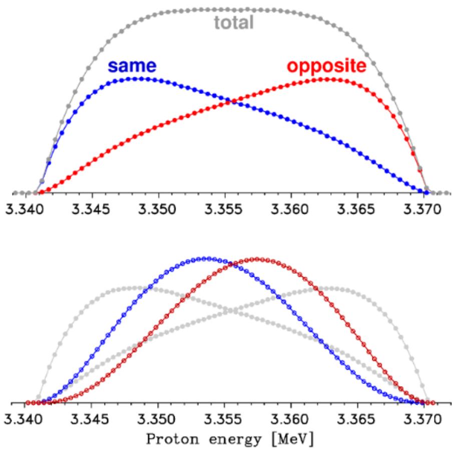
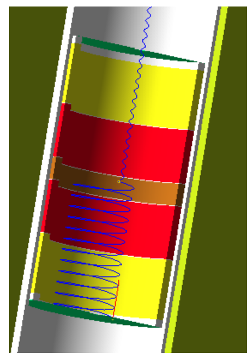
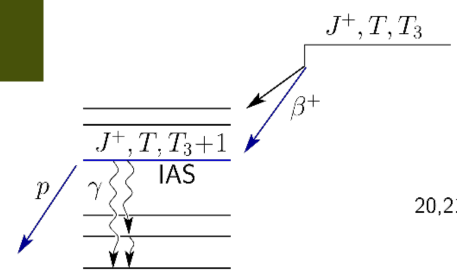
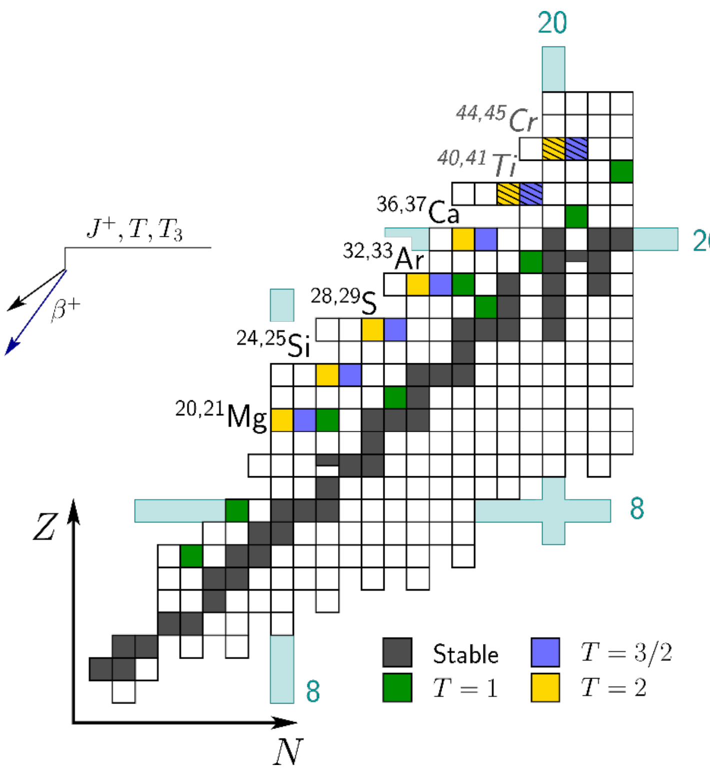
- Proton-rich cases to be studied with TAMUTRAP via the kinematic shift of $\beta$-delayed proton decays

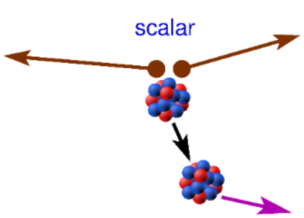


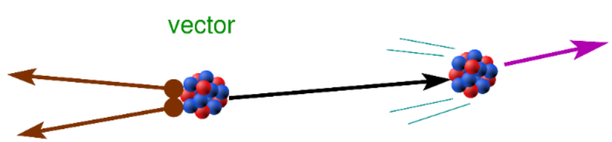




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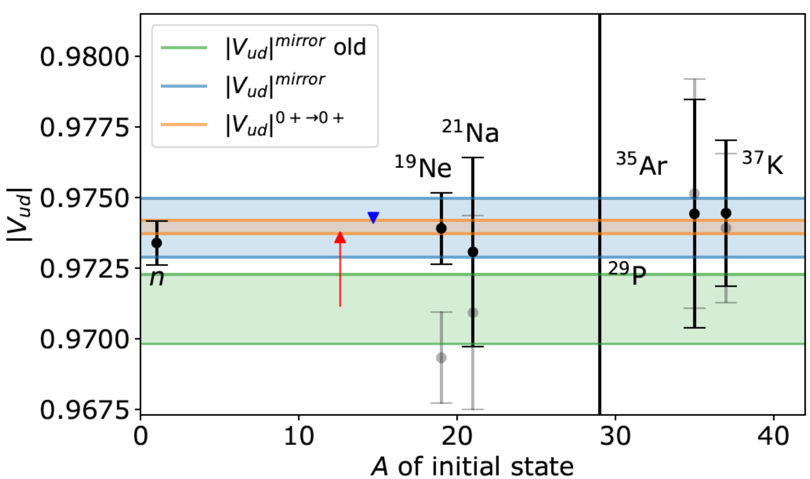
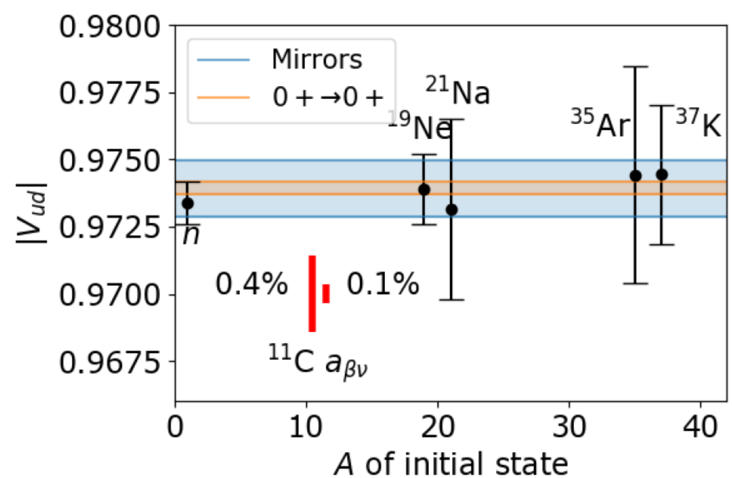
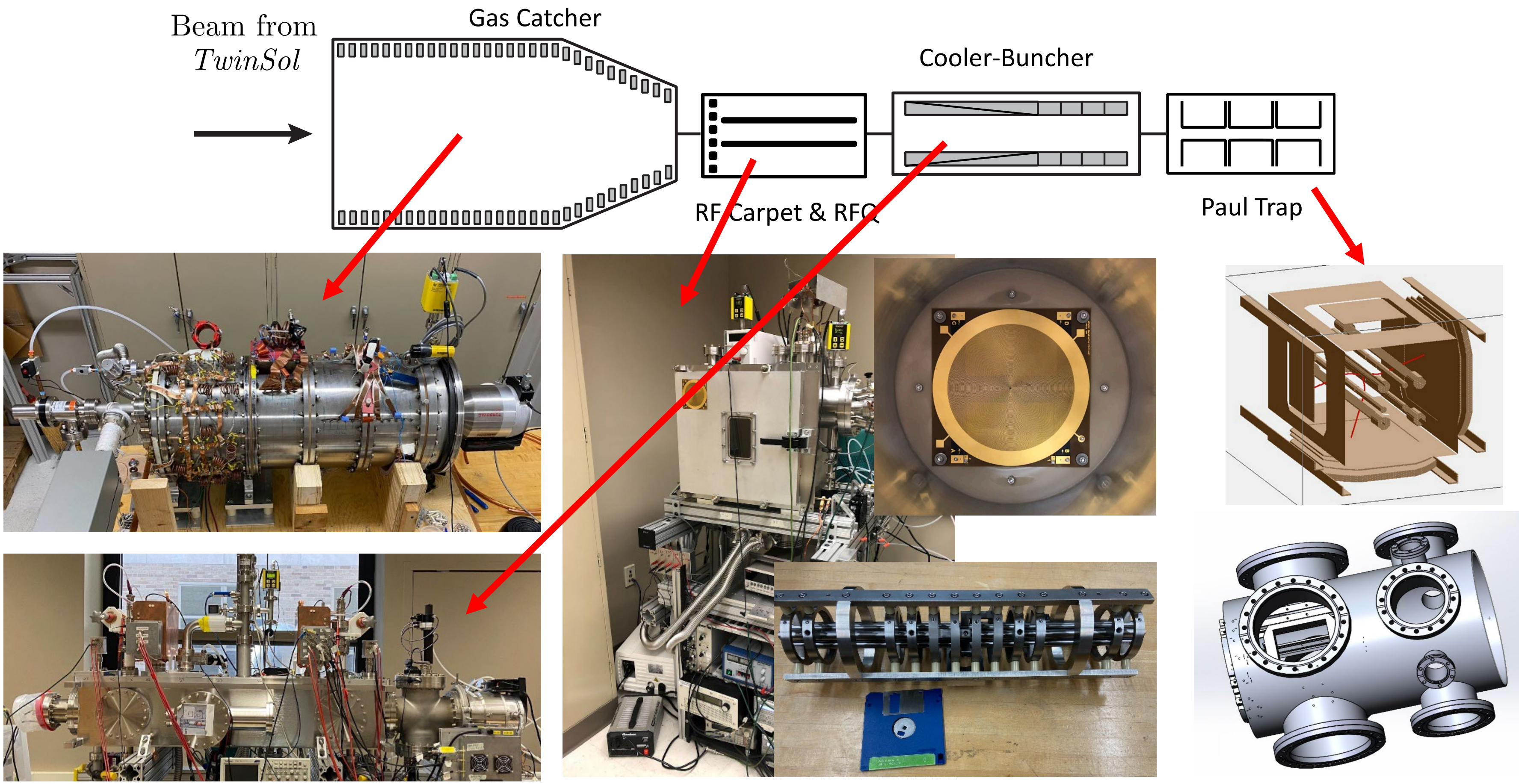
- Proton-rich cases to be studied with TAMUTRAP via the kinematic shift of $\beta$-delayed proton decays
- Mirror nuclei continue to be improved as an alternate to $0^+ \rightarrow 0^+$ (and of course the neutron, next talk)
  - Lifetimes, $\beta$-$\nu$ correlations with St. Bendict @ Notre Dame



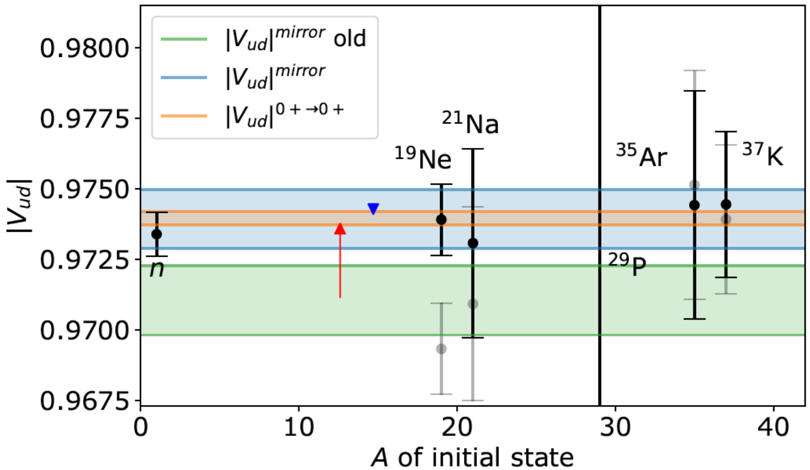
# Superallowed Transisiton Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict)

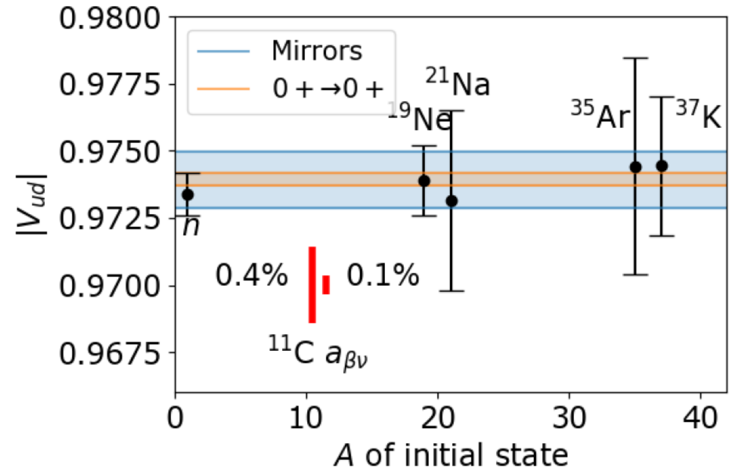



- Gas catcher from ANL: RF/DC & vacuum tested; transport tests underway
- RF carpet tested; ion guide assembled and RF circuit being tested
- Cooler/buncher commissioned
- Paul trap has been simulated and manufactured

# Experimental efforts

- Being low-Z, $^{10}$C and $^{14}$O are the most interesting (scalar currents)
- Proton-rich cases to be studied with TAMUTRAP via the kinematic shift of $\beta$-delayed proton decays
- Mirror nuclei continue to be improved as an alternate to $0^+ \rightarrow 0^+$ (and of course the neutron, next talk)
  - Lifetimes, $\beta$-$\nu$ correlations with St. Bendict @ Notre Dame
  - Lifetimes, branching ratios (fast-tape + HPGe), $\beta$-$\nu$ correlations (TAMUTRAP) at the Cyclotron Institute



# Outline

- CKM matrix unitarity tests
  - Theory has made huge progress
  - New experiments targeting low-Z cases, mirror transitions
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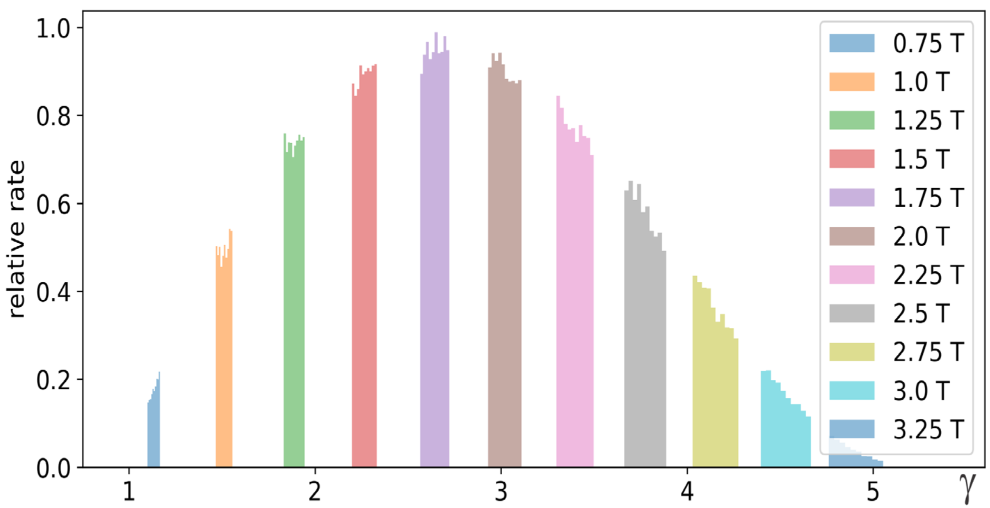
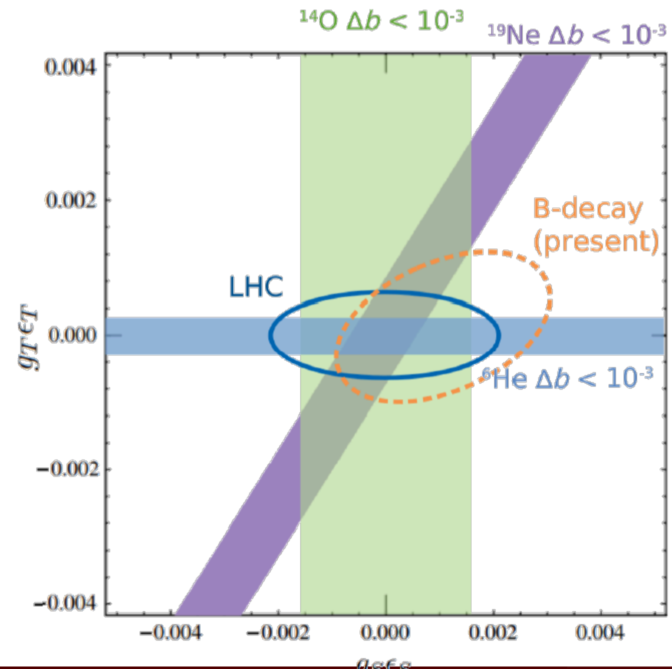
  - Spectrum-shape for Fierz
  - Ion and atom traps
- $\beta$ decays for neutrino physics
  - Ultra-low Q-values for direct $m_\nu$ measurements
  - Sterile neutrinos via EC
  - Reactor antineutrino anomaly

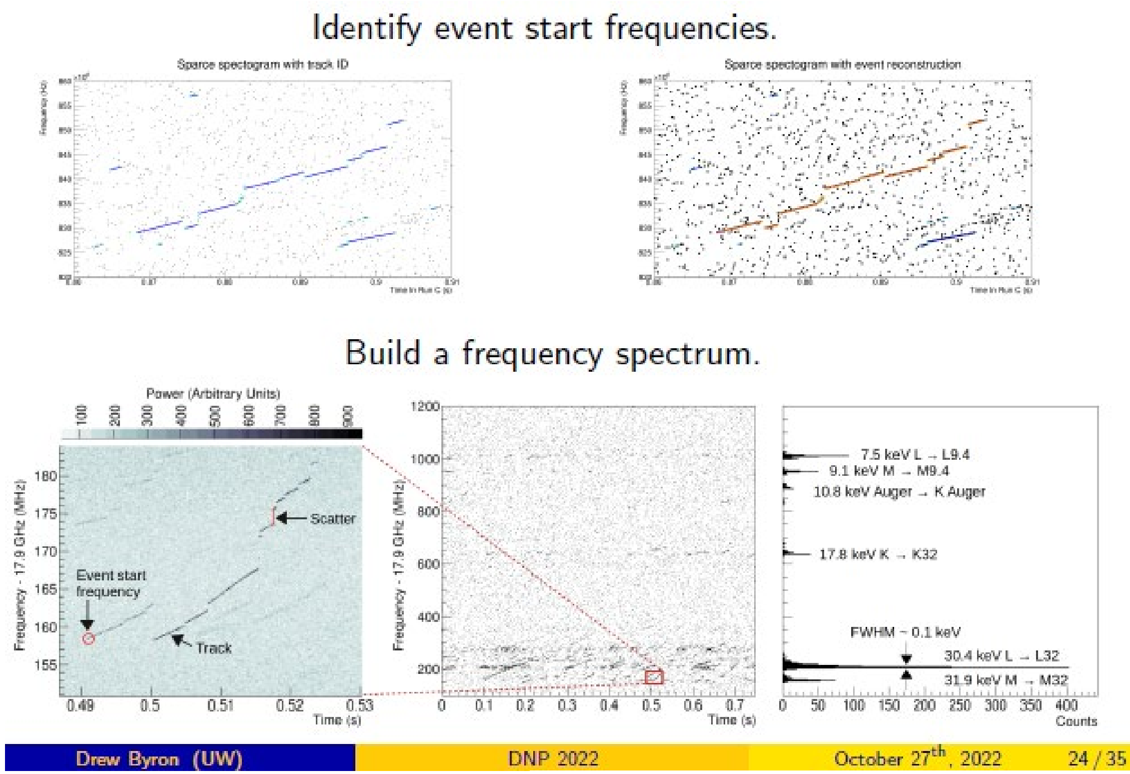
# Searches for Scalar/Tensor currents

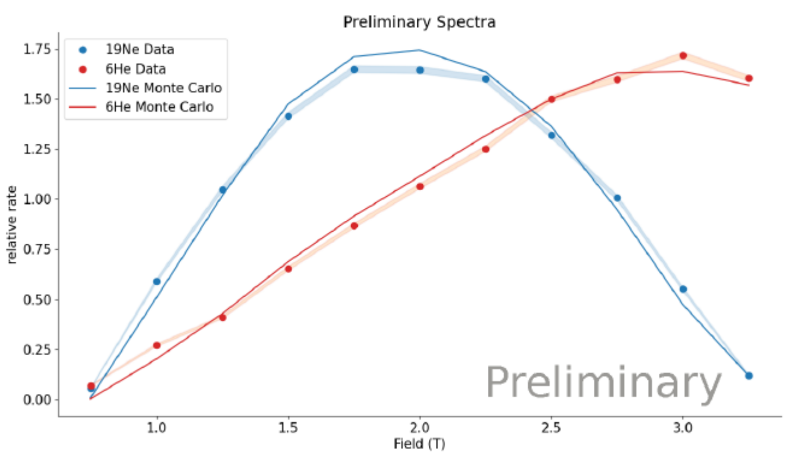
- Most sensitive probe is $b_{\text{Fierz}}$ – linear in exotic couplings
- Cyclotron radiation emission spectroscopy (He6-CRES)
  - $^{6}$He (GT), $^{19}$Ne (F/GT) and $^{14}$O (F); $\beta^{\pm}$ opposite sign in $b_{\text{Fierz}}$
  - Much larger bandwidth needed compared to Project 8
  - Other challenges: other modes, harmonics, wall effects

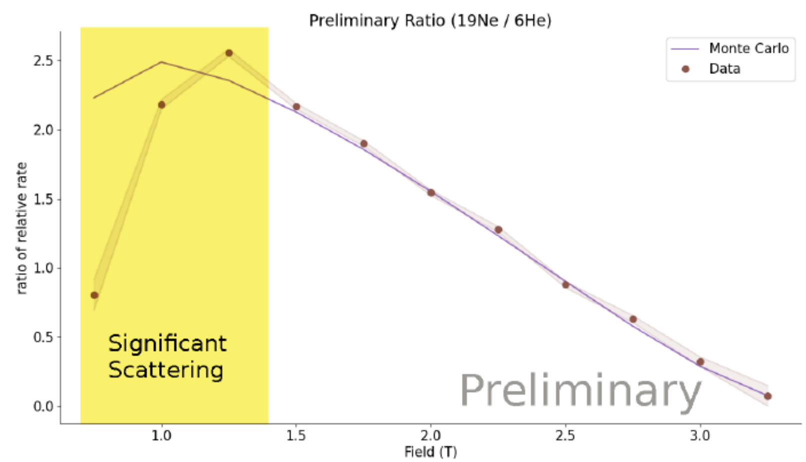


# First CRES signals seen

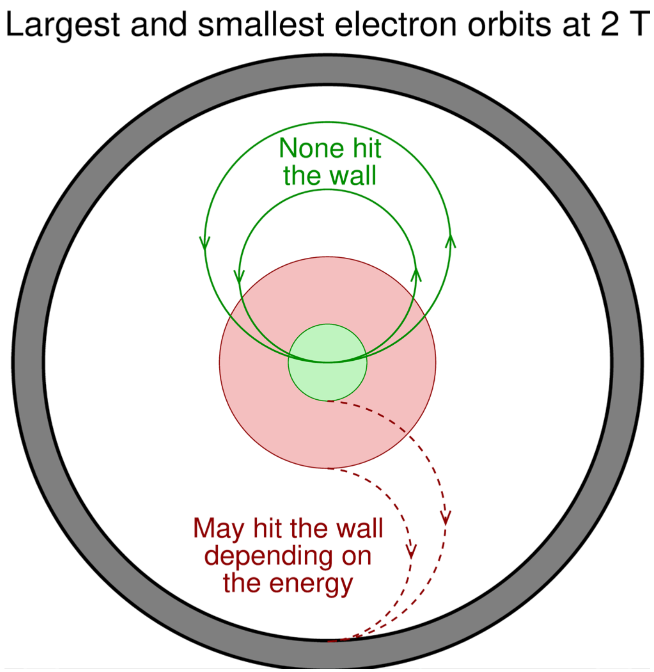


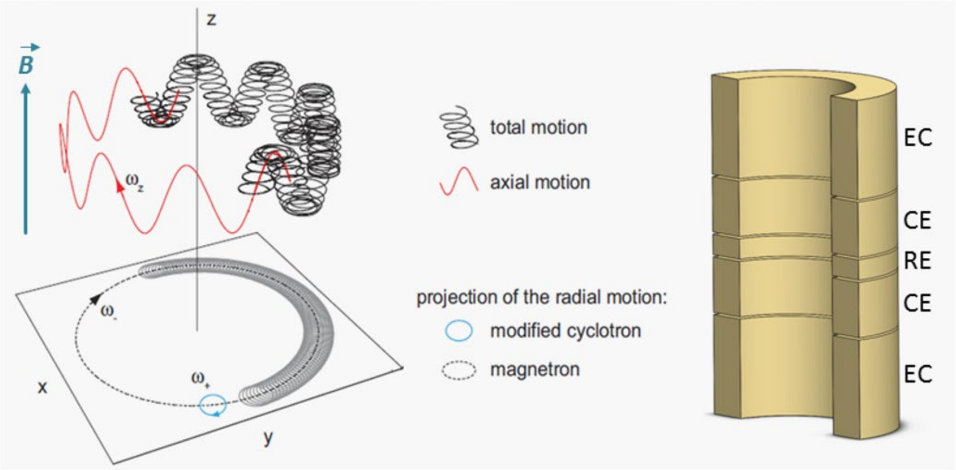



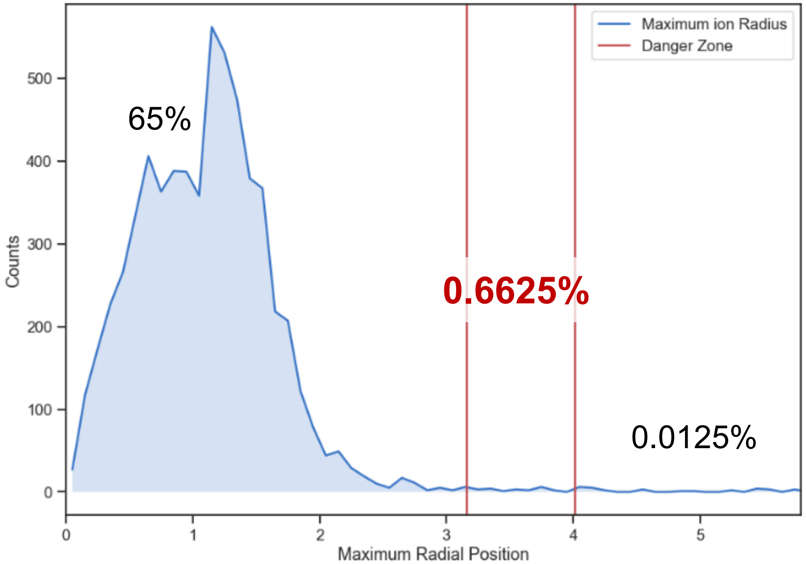
# Ion trap + CRES

- Wall effects expected to be a limiting systematic




- Simulations indicate the rf signal not degraded, and rates *should* be high enough



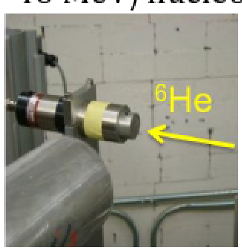
# Searches for Scalar/Tensor currents

- Most sensitive probe is $b_{\text{Fierz}}$ – linear in exotic couplings
- Cyclotron radiation emission spectroscopy (CRES)
- Implantation at FRIB (Naviliat-Cuncic); next $^{26m}$Al

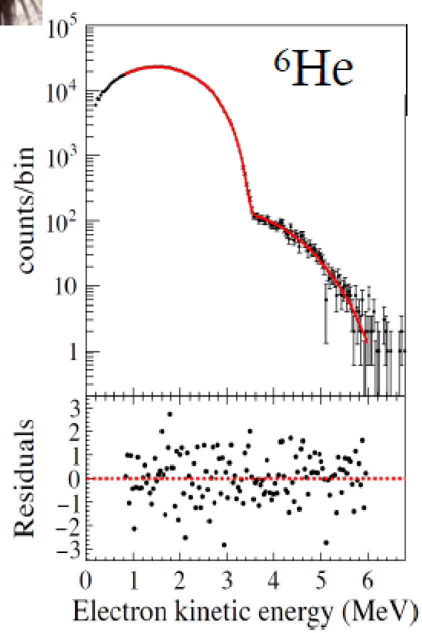
Fragmentation reactions enable choosing the most suitable candidates.

X. Huyan, PhD
thesis 2019

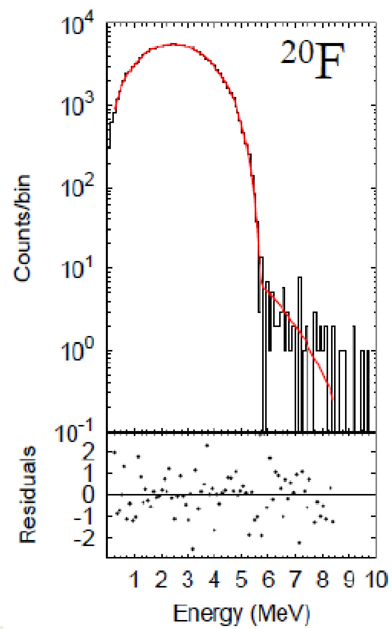
46 MeV/nucleon



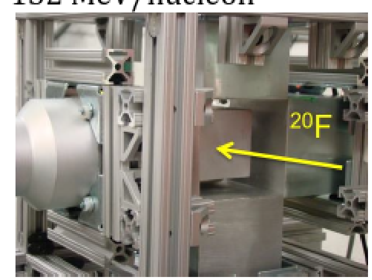

Analysis near completion. Expected $\Delta b_{GT}$~0.01




M. Hughes, PhD
thesis 2019



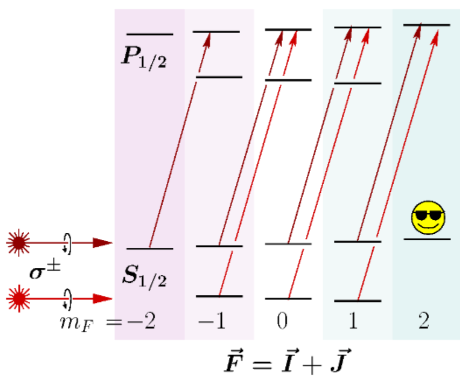

132 MeV/nucleon




Analysis completed: reached $\Delta b_{GT}$~0.02 including systematics

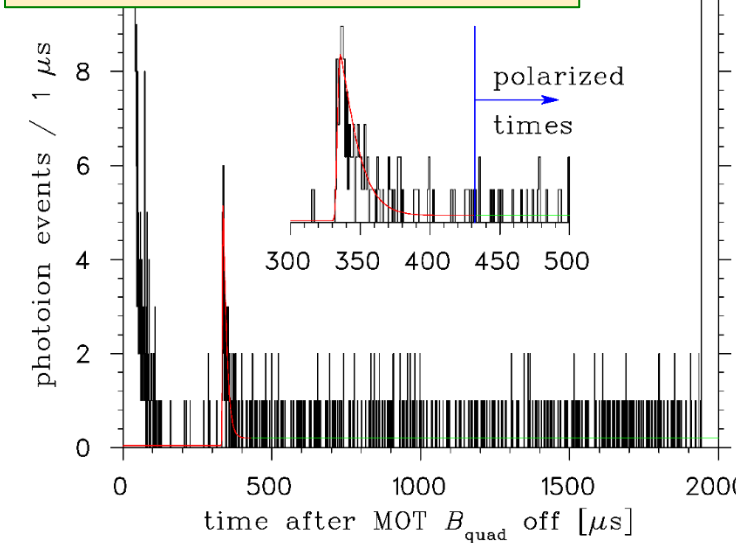
# Atom and ion traps for BSM searches

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

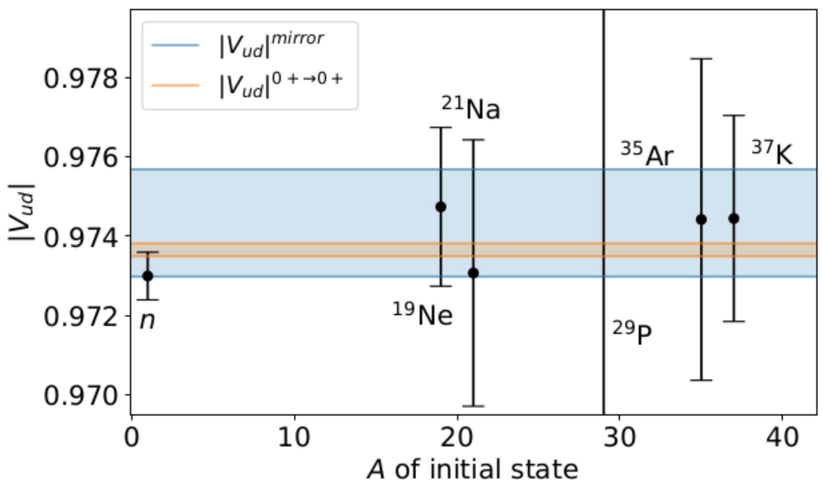



B.Fenker *et al*, New J. Phys. **18** (2016)

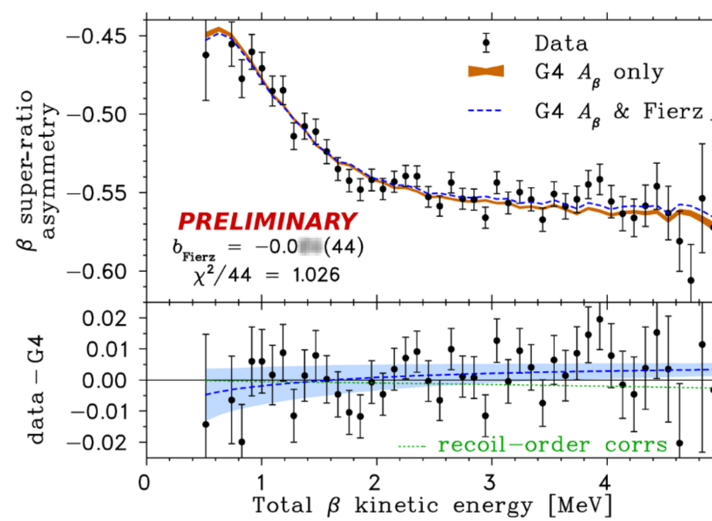
$\langle|P_{\mathbf{nucl}}|\rangle = \mathbf{0.9913(9)}$




  - Physics result: $A_\beta$ to 0.3%




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



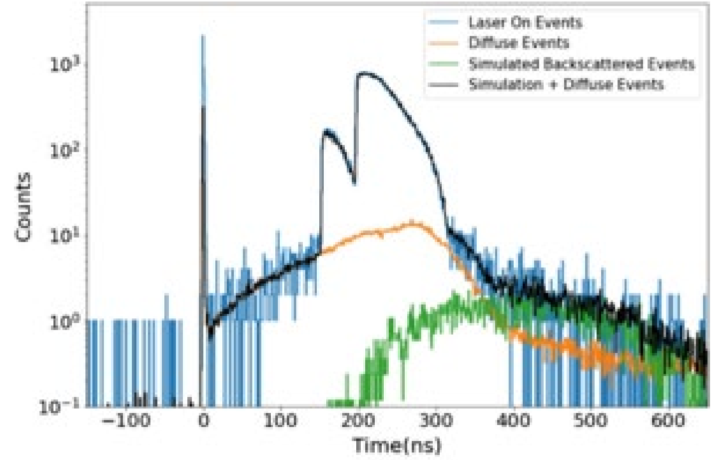
# Atom and ion traps for BSM searches

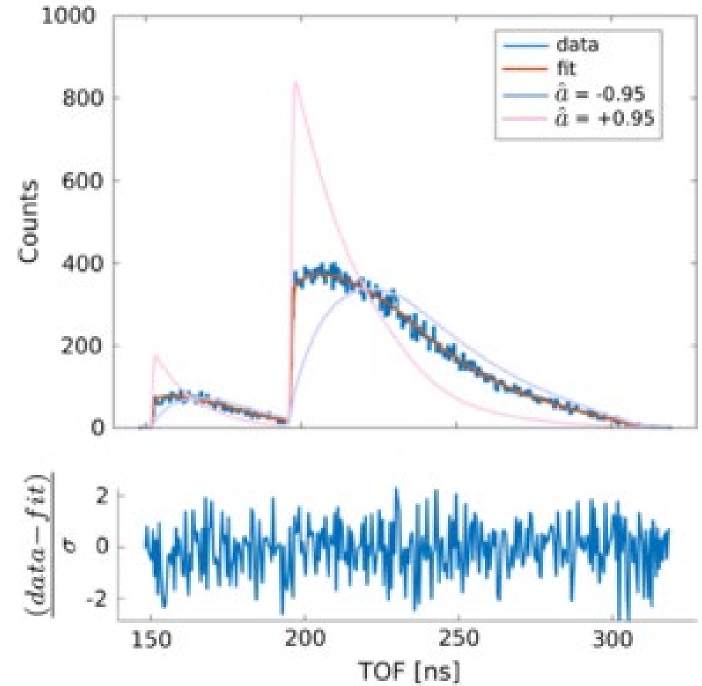
- TRINAT has developed some pretty cool techniques
  - High nuclear polarization
  - Physics result: $A_\beta$ to 0.3%
  - $< 0.1\%$ within reach!
- $^6$He at CENPA in collaboration with ANL
  - Recently published result:

$$\tilde{a} = -0.3268(46)(41)$$

$$\Leftrightarrow\ 0.007 \leq |C_T/C_A| \leq 0.111 \text{ (90\% CL)}$$

Muller *et al.*, PRL **129**, 182502 (2022)



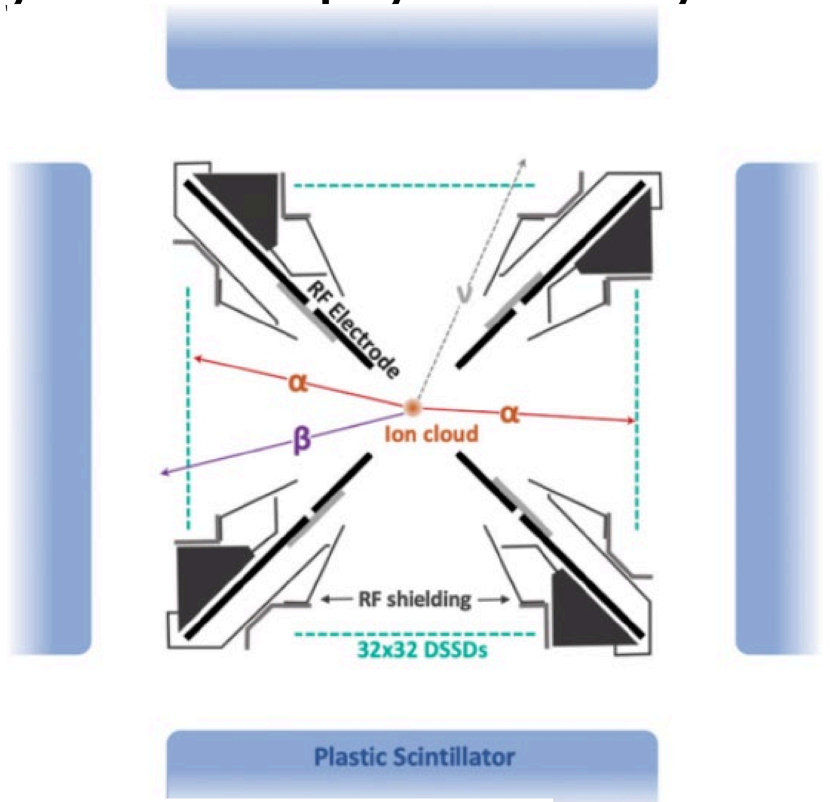



# Atom and ion traps for BSM searches

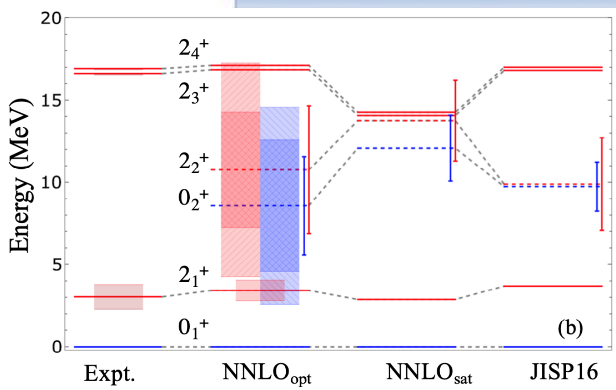
- We heard about the beta-decay Paul trap yesterday
  - $\beta$-$\alpha$-$\alpha$ coincidence M.T. Burkey *et al.*, PRL **128**, 202502 (2022)

TABLE I. Summary of dominant systematic corrections and uncertainties, listed at $1\sigma$.

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




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



# Atom and ion traps for BSM searches

- We heard about the beta-decay Paul trap yesterday
  - $\beta$-$\alpha$-$\alpha$ coincidence M.T. Burkey *et al.*, PRL **128**, 202502 (2022)

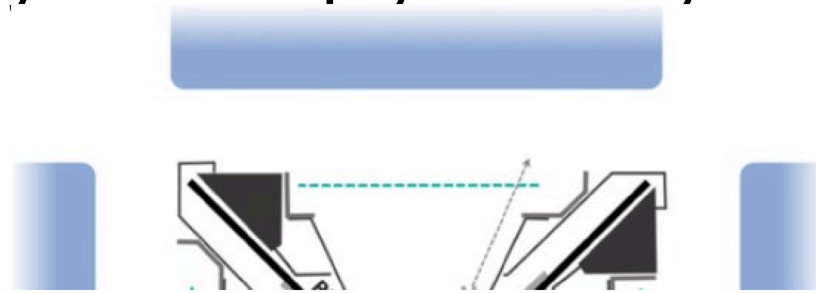
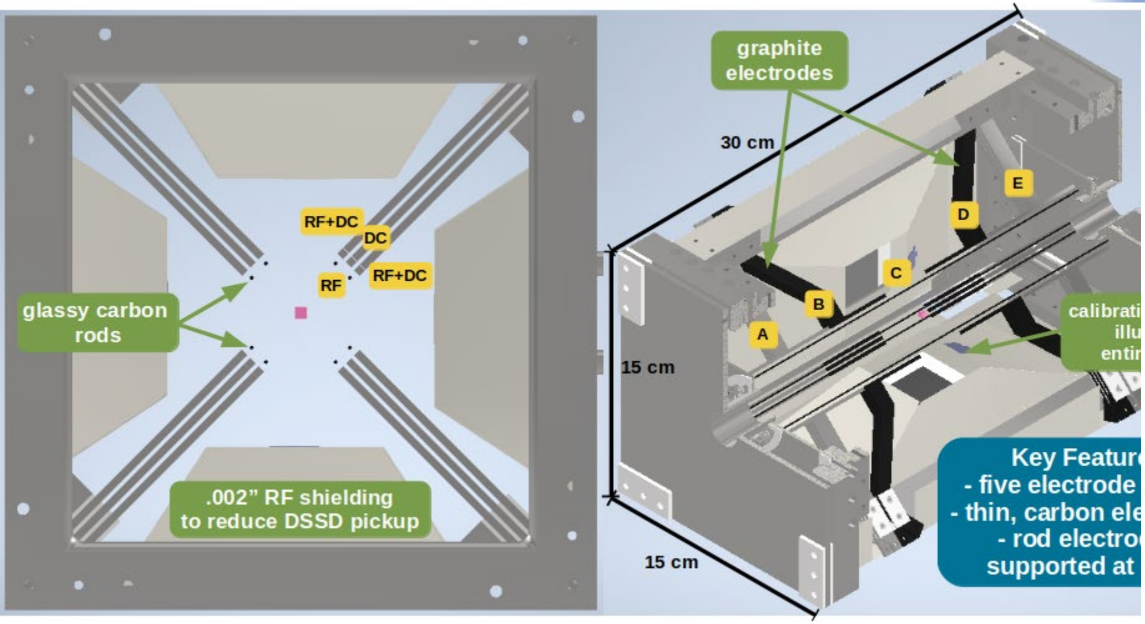
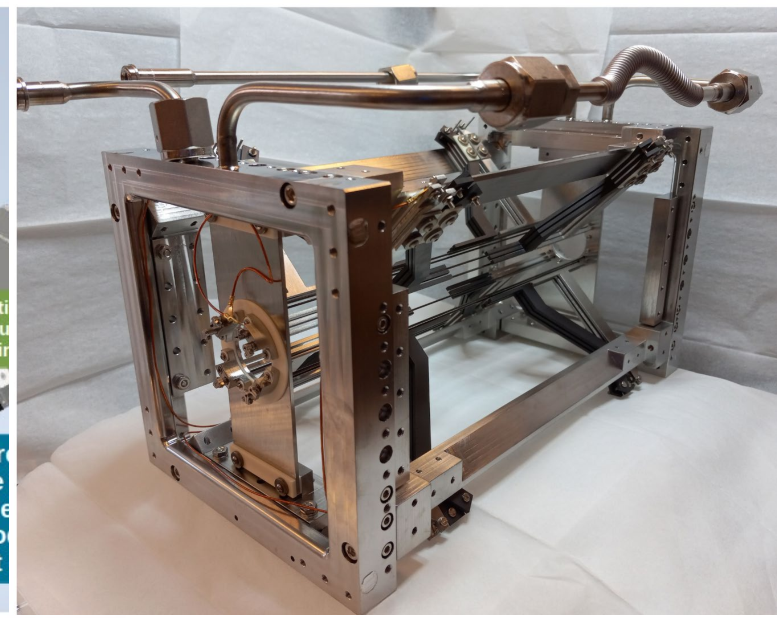


TABLE I. Summary of dominant systematic corrections and uncertainties, listed at $1\sigma$.

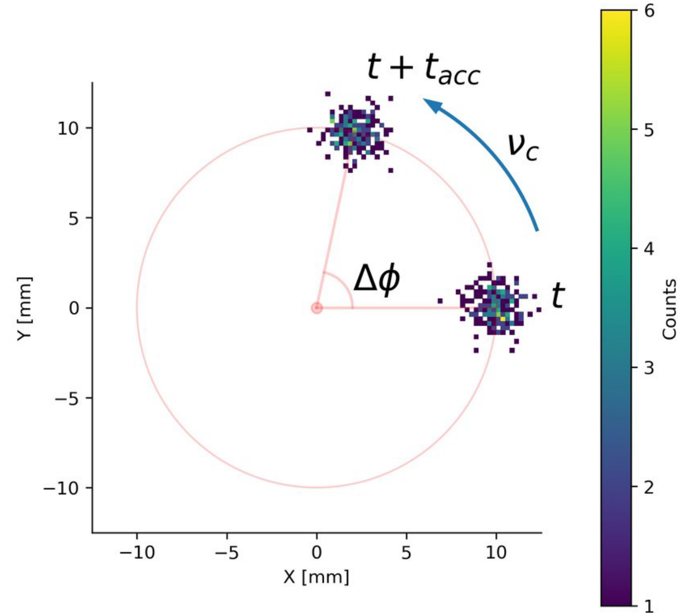


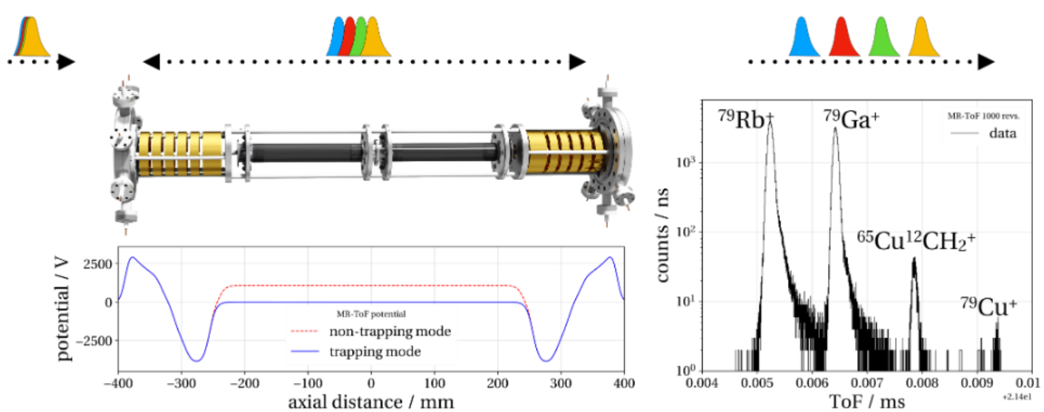
  - Upgrade will reduce $\beta$ scattering by $4\times$. Goal is to improve uncertainty by factor of 2 from recently published result.

# 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



# Outline

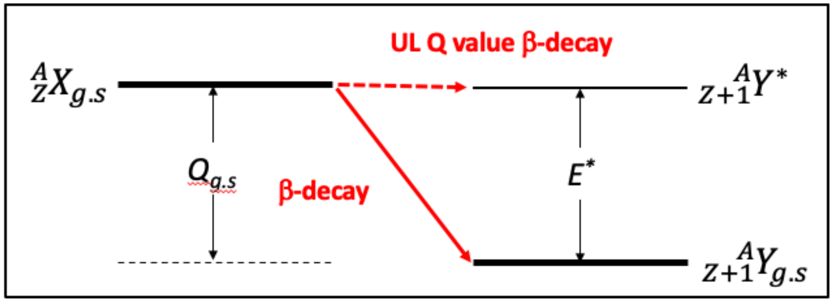
- CKM matrix unitarity tests
  - Theory has made huge progress
  - New experiments targeting low-Z cases, mirror transitions
- Searches for scalar and tensor currents
  - Spectrum-shape for Fierz
  - Ion and atom traps
- $\beta$ decays for neutrino physics
  - Ultra-low $Q$-values for direct $m_\nu$ measurements
  - Sterile neutrinos via EC
  - Reactor antineutrino anomaly

# Ultra-low Q value measurements with CHIP-TRAP

**Penning traps**: Independent $\beta$-decay Q value from mass ratio of parent and daughter nuclides

$$Q_{g.s.} = (M_P - M_D)c^2 = (M_P - m_e)(1-R)c^2 \qquad R = M_D^+/M_P^+$$

## Ultra-low Q value $\beta$-decay: $Q_{UL} = Q_{g.s.} - E^* < 1$ keV




More precise Q values needed to identify candidates

**Some promising potential candidates**

| Isotope | Decay | Forbiddenness | Half-life | $Q_{ES}$ (keV) |
|---|---|---|---|---|
| $^{136}$Cs | $\beta^-$ | Allowed | 13 dy | 3.7(19) |
| $^{188}$W | $\beta^-$ | Allowed | 70 dy | -4.6(32) |
| $^{155}$Eu | $\beta^-$ | 1st Forbidden | 5 yr | 0.3(16) |
| $^{156}$Eu | $\beta^-$ | 1st Forbidden | 15 dy | 1.0(37) |
| $^{56}$Co | EC | Allowed | 78 dy | 4.76(55) |
| $^{97}$Tc | EC | Allowed | 4.2 Myr | -0.1(42) |
| $^{175}$Hf | EC | Allowed | 70 dy | 1.0(26) |
| $^{81}$Kr | EC | 1st Forbidden | 229 kyr | 3.2(15) |
| $^{146}$Pm | EC | 1st Forbidden | 6 yr | -0.3(45) |
| $^{157}$Tb | EC | 1st Forbidden | 71 yr | -2.3(14) |
| $^{173}$Lu | EC | 1st Forbidden | 1.5 yr | 1.0(18) |
| $^{183}$Re | EC | 1st Forbidden | 70 dy | 2.5(81) |
| $^{195}$Au | EC | 1st Forbidden | 186 dy | 1.9(12) |
| $^{148}$Eu | $\beta^+$ | Allowed | 55 dy | -15(10) |
| $^{105}$Ag | $\beta^+$ | 1st Forbidden | 41 dy | 5.7(47) |
| $^{144}$Pm | $\beta^+$ | 1st Forbidden | 1 yr | -4.8(32) |
| $^{146}$Pm | $\beta^+$ | 1st Forbidden | 6 yr | -4.3(45) |

2201.08790v2

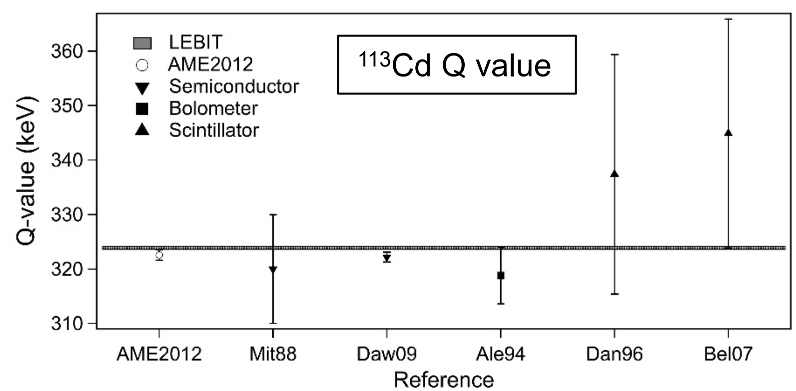
## Q values for forbidden $\beta$-decays

High-precision $\beta$-spectra provide:

- Possibility to extract $g_A$ via spectral shape method.
- Data for radionuclide metrology (applications in nuclear medicine and nuclear power).
- Improved knowledge of rare decays – potential backgrounds in $0\nu\beta\beta$ and dark matter detectors.
- Improved data for testing theoretical calculations.

Penning trap Q values provide:

- Direct test of systematics via comparison of Q value and end point energy.
- Precise Q value for phase space factor calculations.



# BSM with Rare-Isotope Doped Superconductors

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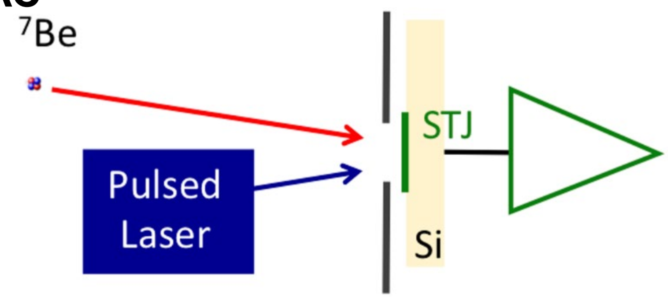
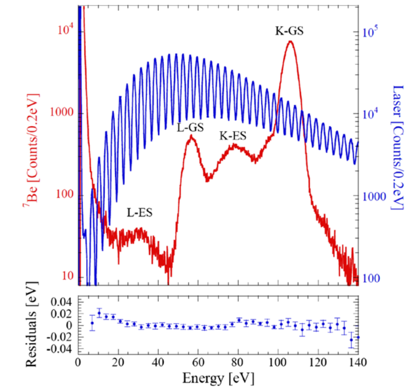
TRIUMF

THE BeEST

- Embedding radioactive atoms into superconducting tunnel junctions (STJs)
- Measure eV-scale decay recoils
- Search for keV – MeV sterile neutrinos

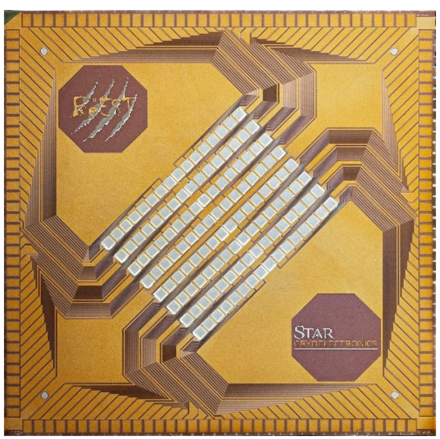
## $^{7}$Be implantation at TRIUMF-ISAC

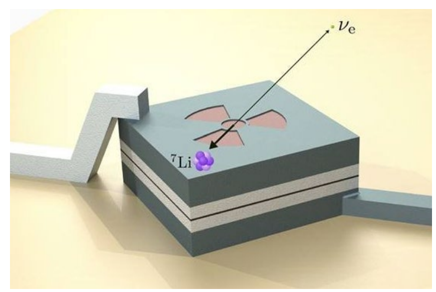



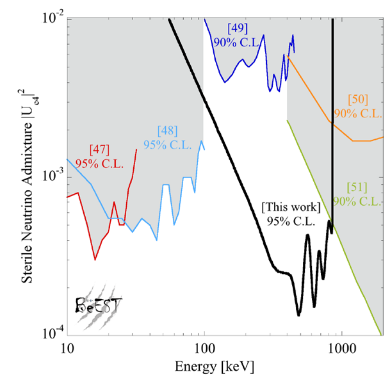




STAR CRYOELECTRONICS

## Ta, Al, and Nb-based STJ Sensors





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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States



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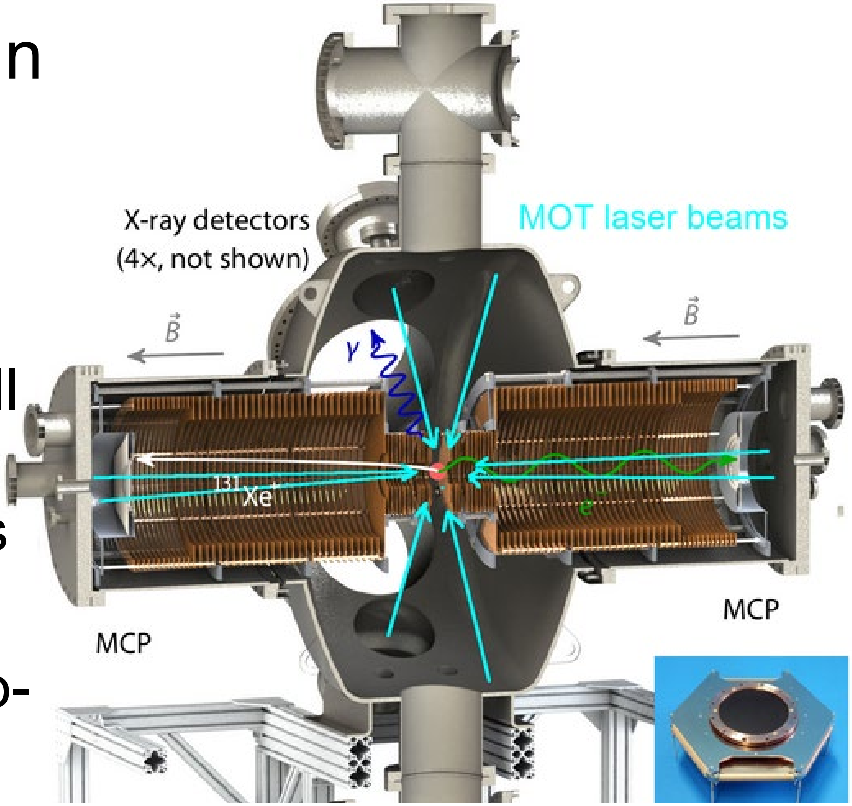
S. Fretwell *et al*., Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al*., J. Low Temp. Phys. **200**, 200 (2020)

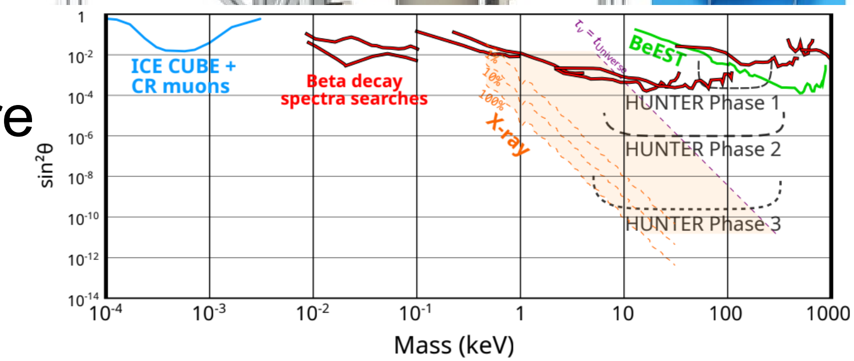
# HUNTER

(Ronald will talk about this later)

Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction

- Kinematic reconstruction of $m_\nu$ in individual EC decays of $^{131}$Cs atoms at rest
  - Kinematic reconstruction - not an oscillation experiment. Measure all decay product momenta & reconstruct missing neutrino mass event-by-event
  - $^{131}$Cs is at rest - held in a Magneto-Optical Trap and laser cooled to 20 μK
  - Reaction Ion Microscopes measure recoil nucleus and Auger electron directions & momenta with high efficiency & resolution 0.1-1%



# Measuring β Transitions in Complex β Decays

Currently only β energy spectra of ***very*** simple β decays are studied

We are developing the

***β*-Spectrum Module (βSM)**

**with ORNL's MTAS Detector**

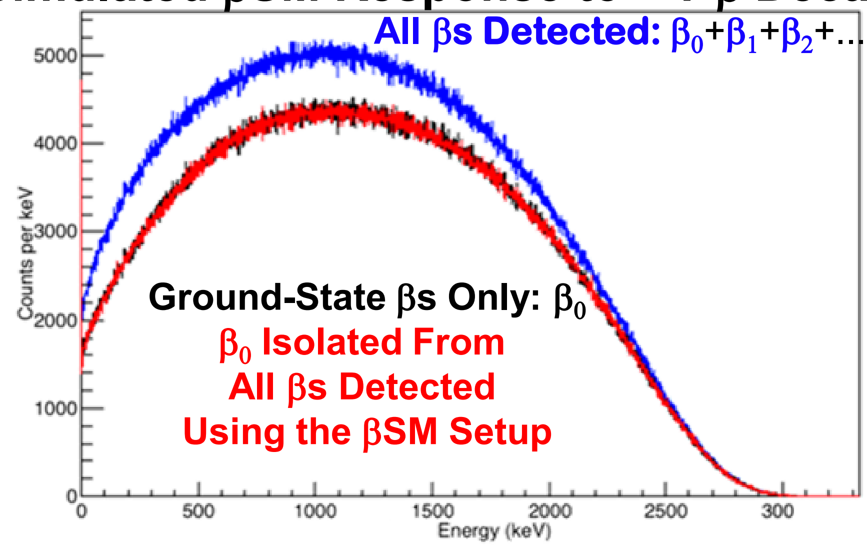
to measure entire β-energy spectra for each individual β-decay transition

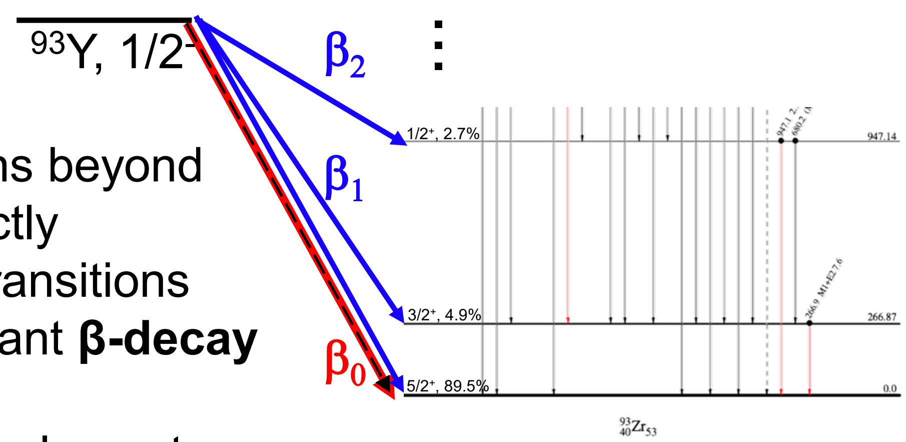
Isolate Individual β transitions with ~99% efficiency

Permits extraction of various allowed and 1st -forbidden β shapes all from the same parent

- Improve reactor antineutrino flux predictions beyond the 5% level down to the ~1% level by directly measuring β-shape factors of individual β transitions
- Expand by hundreds the number of important **β-decay shape factors** that can be studied
- Allows access to $g_V$ and $g_A$, nuclear matrix elements
- Can minimize systematics by measuring different β transitions from the same β-decaying parent

**Simulated βSM Response to $^{93}$Y β Decay**




**Work supported by Nuclear Data FOA-2440, Rasco *et al.*, 2022**

# Summary

- **Why are the next few years interesting:**
  - Increased precision of $V_{ud}$ could confirm CKM unitarity deficit
    - Precision of $V_{ud}$ from neutron decay is gradually catching up. Comparisons between $V_{ud}$ from different determinations could possibly unveil new anomalies.
    - It is possible for the first time to compute quantities such as $\delta_{\mathrm{NS}}$ and $\delta_C$ with rigorously-quantified theory uncertainties
  - Cutting-edge technologies opening up new opportunities for significant increase in precision for BSM searches and (sterile) neutrino searches (CRES, quantum sensors, traps, …)
- **What might get accomplished during this LRP:**
  - Formation of a topical group (e.g. VudU, "Vud unitarity" alliance) to facilitate collaborations
  - Compute $\delta_{\mathrm{NS}}$ with ab-initio methods for light and medium nuclei; improve $\delta_C$ and recoil-order corrections
  - Experimental programs maturing to reach 0.1% and beyond, and orders of magnitude on sterile neutrinos

**Poised for great results to come out of this LRP**

# In case I run out of time (I didn't?!?!)

- Start and end with the White Paper recommendations:
  - Experimental + theoretical alliance for Vud and CKM unitarity
  - Investing in small- and mid-scale projects
  - Establishing support for nuclear theory
  - Developing cutting-edge techniques
  - Promote diverse and inclusive environment, and better support students
- Thanks for input (apologies to all)
  - Maxime Brodeur, Drew Byron, Jason Clark, Leendert Hayen, Kyle Leach, Charlie Rasco, Matt Redshaw, Nick Scielzo, Chien Yeah Seng, Louis Varrian, and everyone on the nuclear $\beta$ decay White Paper
  - DOE and NSF for support

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