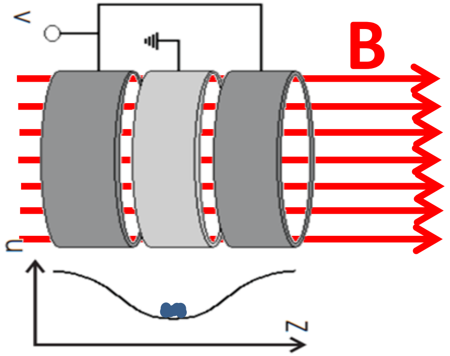
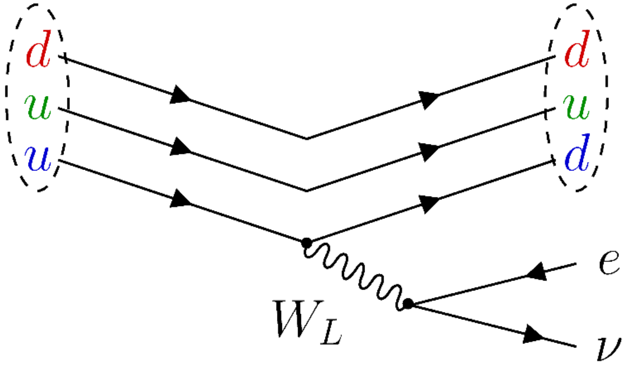
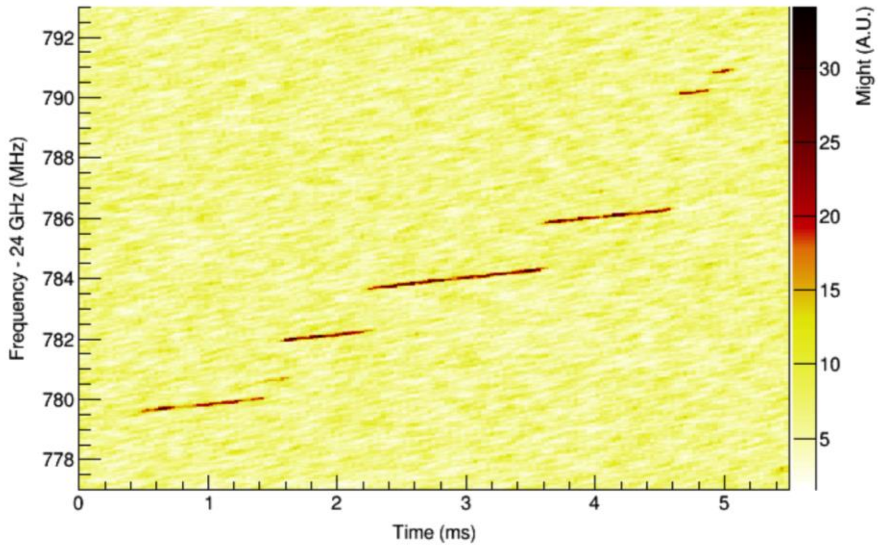
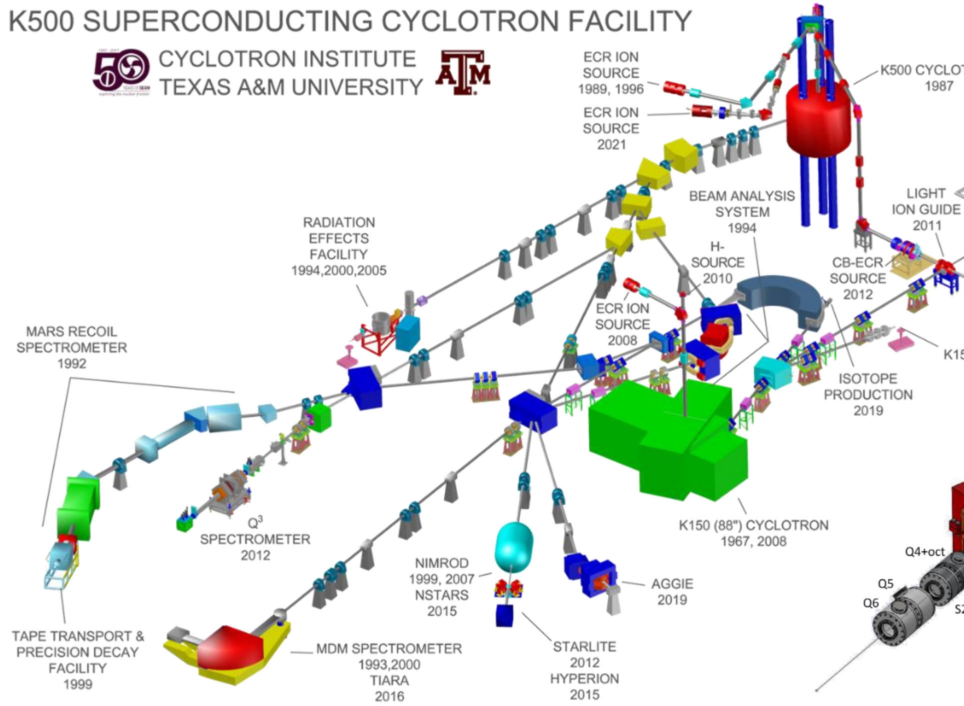
β decay as a probe of new physics: an overview of the fundamental symmetries research at the CI

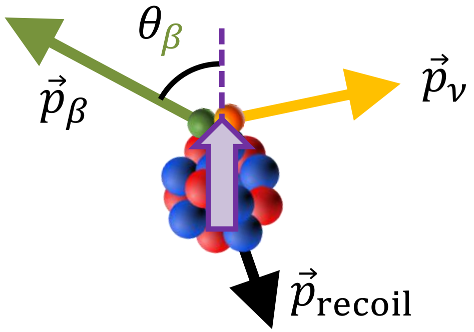
Dan Melconian

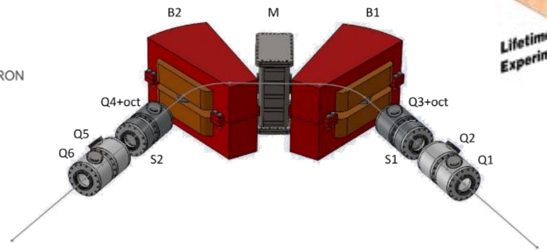


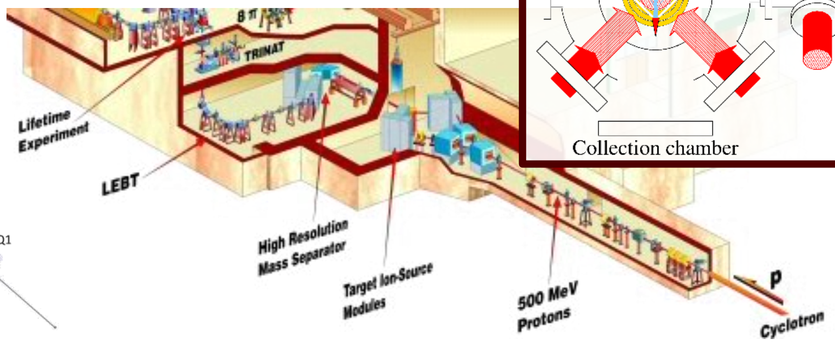


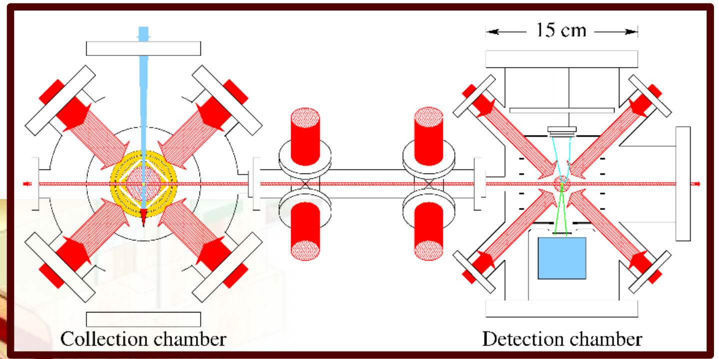






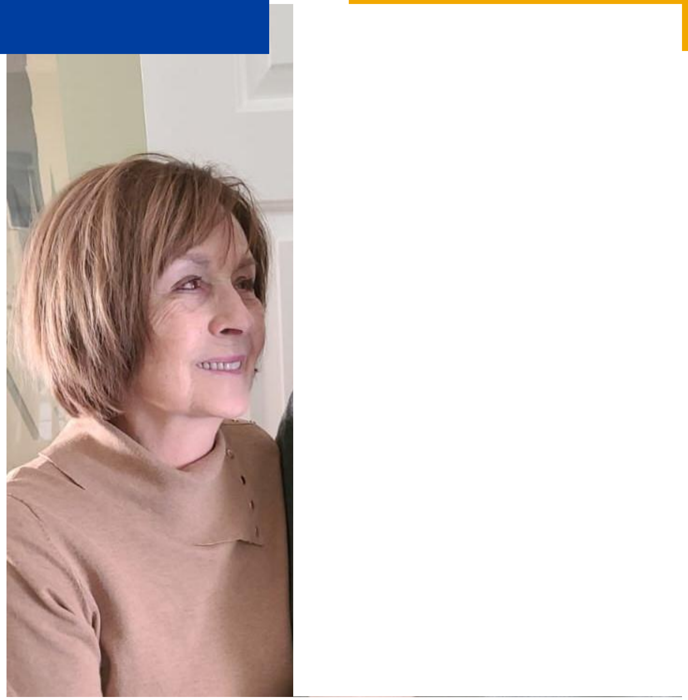






About me

- First and foremost: I'm half Croatian, half Armenian…



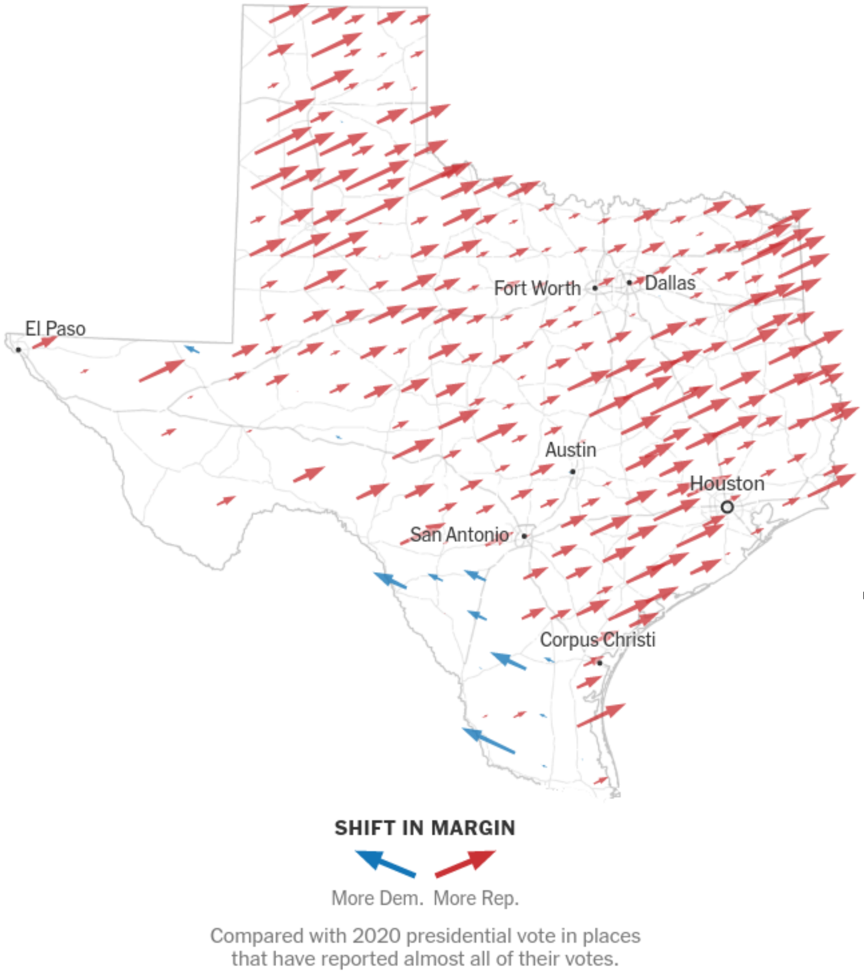
to any Brasilians: *mwhahahahaha*!!

Did you know: "ian" [or "yan"] means "son of"? So Melcon Melconian is like Donald McDonald. Until my grandfather changed our name, we were Agopian

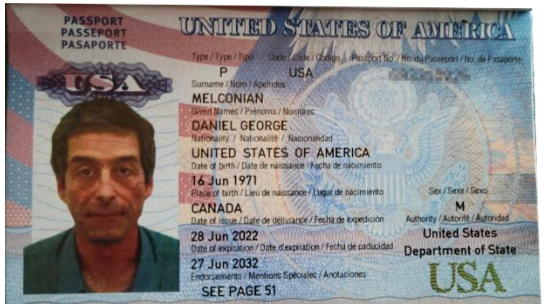
About me

- First and foremost: I'm half Croatian, half Armenian… and

100% CANADIAN!!



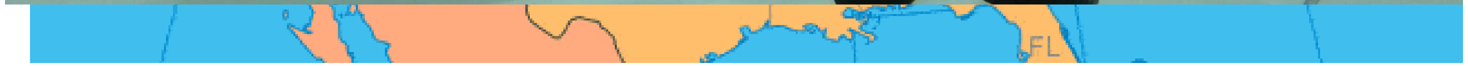
I recently became a dual citizen…



…but my vote was wasted in Texas

About me

- First and foremo
  Croatian, half Ar
  100% CANADIA
- I was born *south*
  Windsor, Ontario
- And like a good (
  started to play ho
- Moved to St. Catharines in grade 7; got sick of the Falls
- Saw my uncles *get paid* to live in Spain and England…that looked like the life for me!



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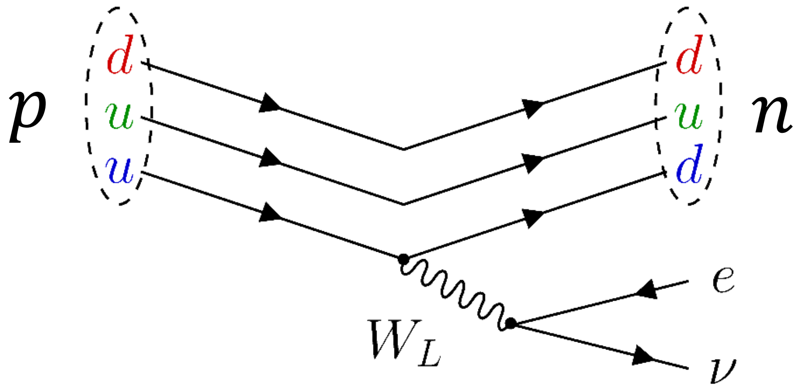
Outline

- **Introduction/motivation**
  - Testing the standard model via the precision frontier using nuclear β decay
- **He-LIG + LSTAR**
  - RIB production and purification of proton-rich nuclei
- **TAMUTRAP and WISArD**
  - $T = 2$ decays to test the SM via kinematic shift of β-delayed protons
- **Other CI efforts**
  - Lifetimes and branching ratios for improving V_{ud}; fission-fragment γ yields
- **^{6}He-CRES**
  - Cyclotron radiation emission spectroscopy on ^{6}He, ^{19}Ne and ^{14}O at CENPA
- **TRINAT**
  - Asymmetry measurements of highly-polarized, laser-cooled atoms
- **Outlook for the next 3 years**

The standard model and beyond

- This is the standard model:



pure $V - A$ interaction

$$H_\beta = \bar{p}\gamma_\mu n(C_V \bar{e}\gamma^\mu \nu + C_V' \bar{e}\gamma^\mu \gamma_5 \nu) - \bar{p}\gamma_\mu\gamma_5 n(C_A \bar{e}\gamma^\mu \gamma_5 \nu + C_A' \bar{e}\gamma^\mu \nu)$$

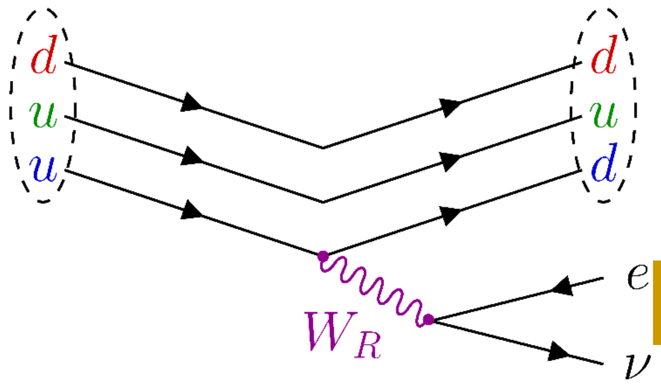
$$C_V = C_V' = 1$$

$$C_A = C_A' \approx 1.27$$

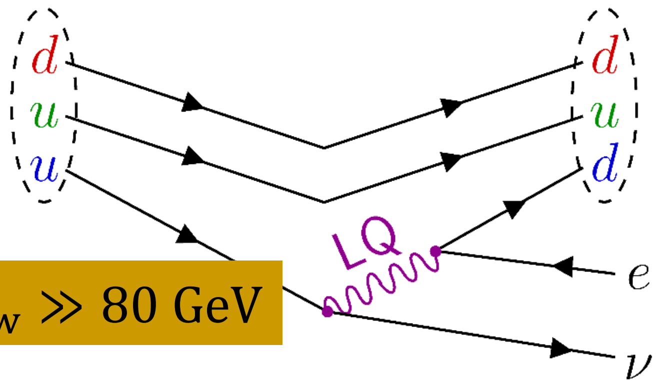
$$M_W = 80.385\ \mathrm{GeV}$$

- These are not:

Right-handed bosons, or scalar/tensor leptoquarks, or SUSY, or…



$M_{\mathrm{new}} \gg 80\ \mathrm{GeV}$



$C_i \neq C_i'$

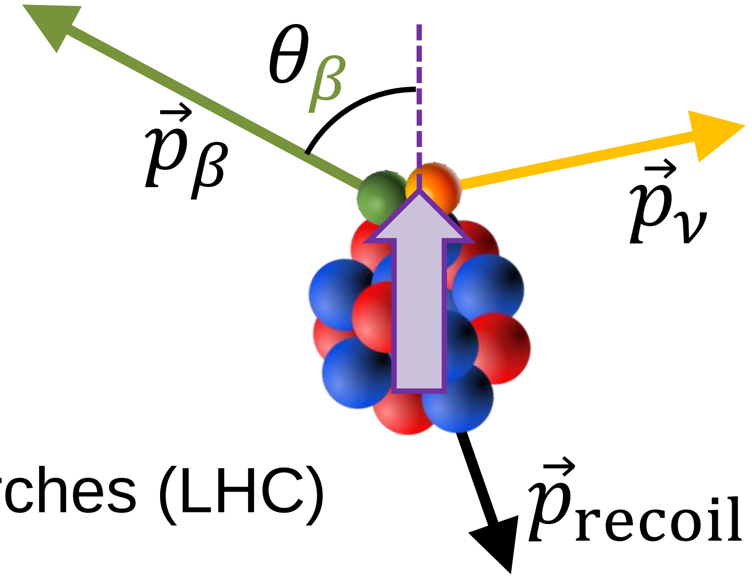
$C_S, C_T \neq 0$

- Profumo, Ramsey-Musolf, Tulin, Phys. Rev. D **75**, 075017 (2007)
- Vos, Wilschut, Timmermans, Rev. Mod. Phys. **87**, 1483 (2015)
- Bhattacharya *et al*., Phys. Rev. D **94**, 054508 (2016)

The precision frontier

- Goal:
  - To complement high-energy experiments by pushing the precision frontier
  - Angular correlations in β decay: values sensitive to new physics

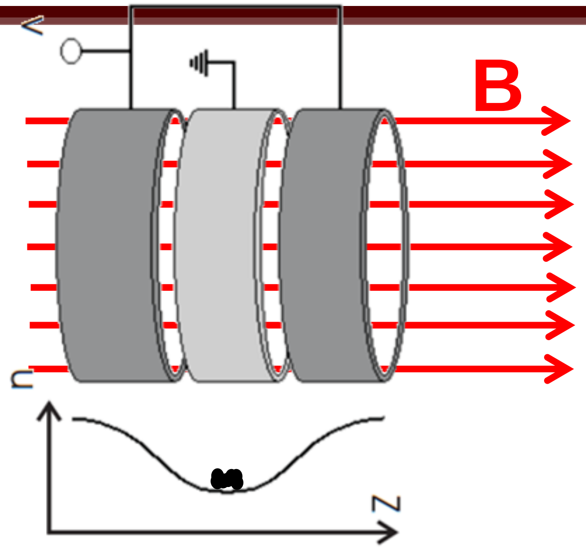
- Global gameplan:
  - Measure the β-decay parameters
  - Compare to SM predictions
  - Look for deviations ⇔ new physics
  - Precision of $\leq \mathbf{0.1\%}$ needed to complement other searches (LHC)



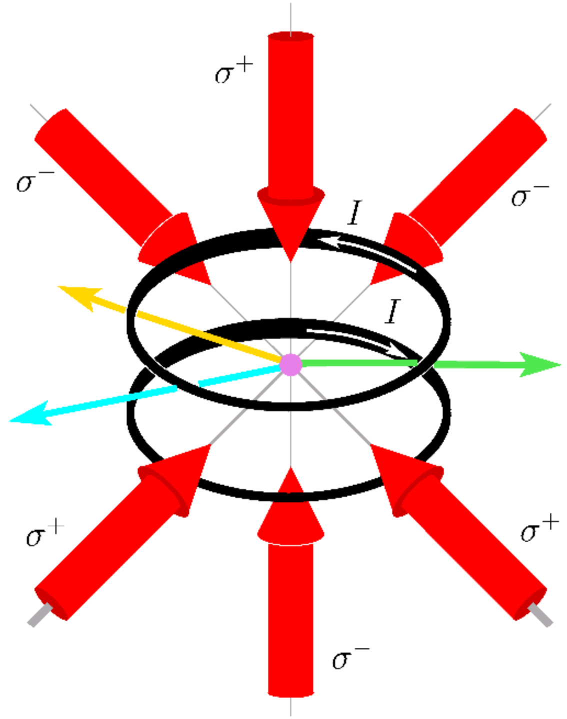
Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić and Severijns, Prog. Part. Nucl Phys **104**, 165 (2019)

0.1% is a tall order…how to reach that precision?

- Ion traps
  - Can trap any ion; well-known for mass measurements (CPT, ISOLTRAP, JYFLTRAP, LEBIT, TITAN,…)
  - Beta-Decay Paul Trap @ ANL
    - β-ν correlation of ^{8}Li to 0.7%; poised to reach 0.1% precision (expt)
  - No other correlation experiments completed yet, but a number planned:
    - TAMUTRAP @ Texas A&M (^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar; ^{36}Ca, ^{40}Ti)
    - LPCTrap @ GANIL (^{6}He)
    - EIBT @ Weizmann Institute → SARAF (^{6}He to start)
    - NSLTrap @ Notre Dame (^{11}C, ^{13}N, ^{15}O, ^{17}F)



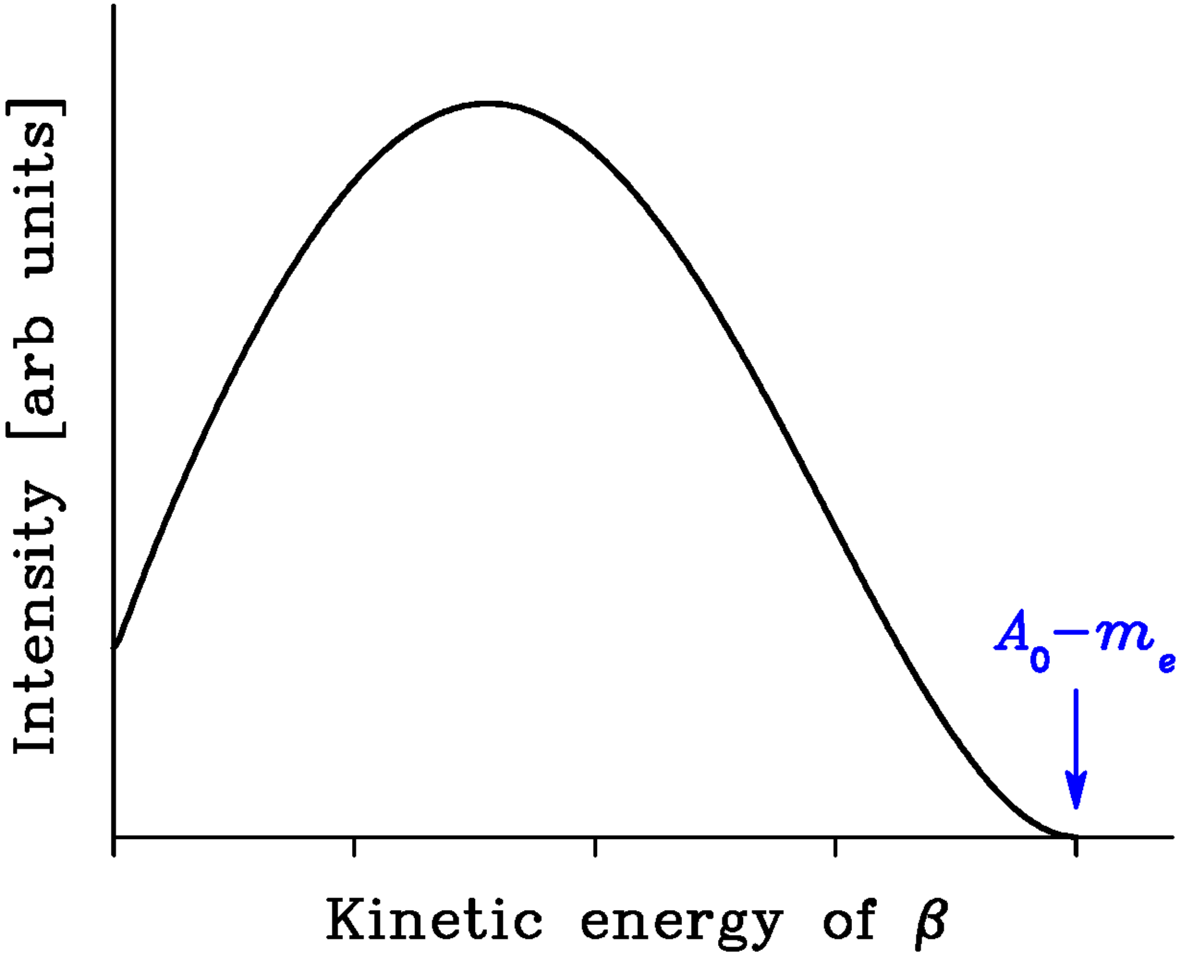
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - TRINAT @ TRIUMF (K isotopes)
  - ^{6}He @ UW
  - NeAT @ SARAF (Ne isotopes)



How does β decay test the SM?

- Begin by looking at the basic decay rate

$$\frac{dW}{dE_e} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}}$$

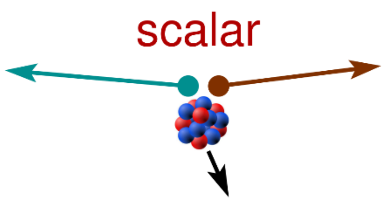


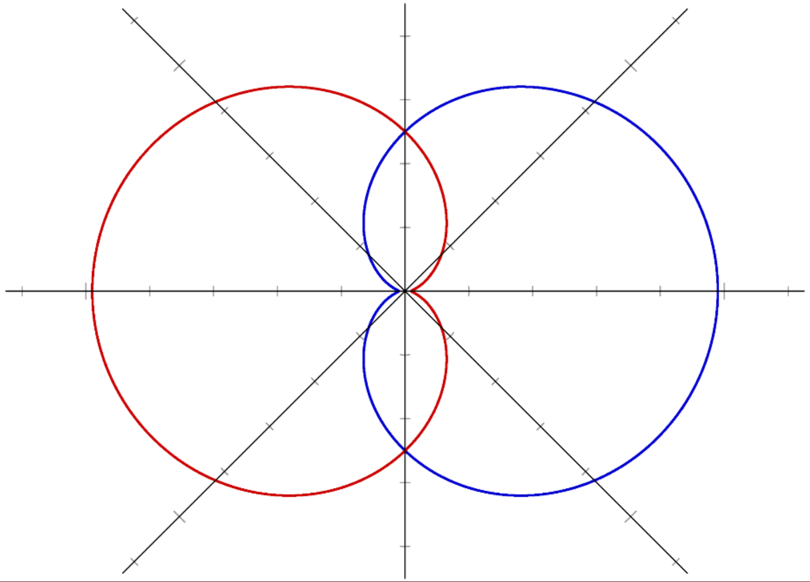
β decay and fundamental physics

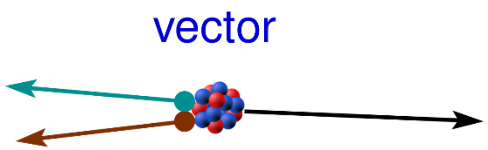
- Expand to the often-quoted angular distribution of the decay (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}} \xi \left(1 + \overbrace{\boldsymbol{a_{\beta\nu}} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{\boldsymbol{b} \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} \right)$$

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







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

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

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The β-ν correlation parameter is quadratic in the couplings…not as sensitive as the Fierz parameter, which is linear:

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

(see González-Alonso, Naviliat-Čunčić and Severijns, Prog. Part. Nucl Phys **104**, 165 (2019))

β decay and fundamental physics

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$$\ldots + \underbrace{D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}} \Big]$$

$$\underbrace{\ldots \Big[\frac{\ldots p_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e \cdot \hat{i})(\vec{p}_\nu \cdot \hat{i}))}{E_e E_\nu} \Big] \Big[\frac{I(I+1) - 3\langle M_I^2 \rangle}{I(2I-1)} \Big]}_{\text{alignment term}} + \ldots \Bigg)$$

Point is β decay depends on the current mediating the weak interaction

$\Rightarrow$ sensitive to new physics $\Leftarrow$

Goal must be $< 0.1\%$ precision to complement other searches (LHC)

There's a whole alphabet of terms…!

(see González-Alonso and Naviliat-Čunčić, PRC **94**, 0.35503 (2016))

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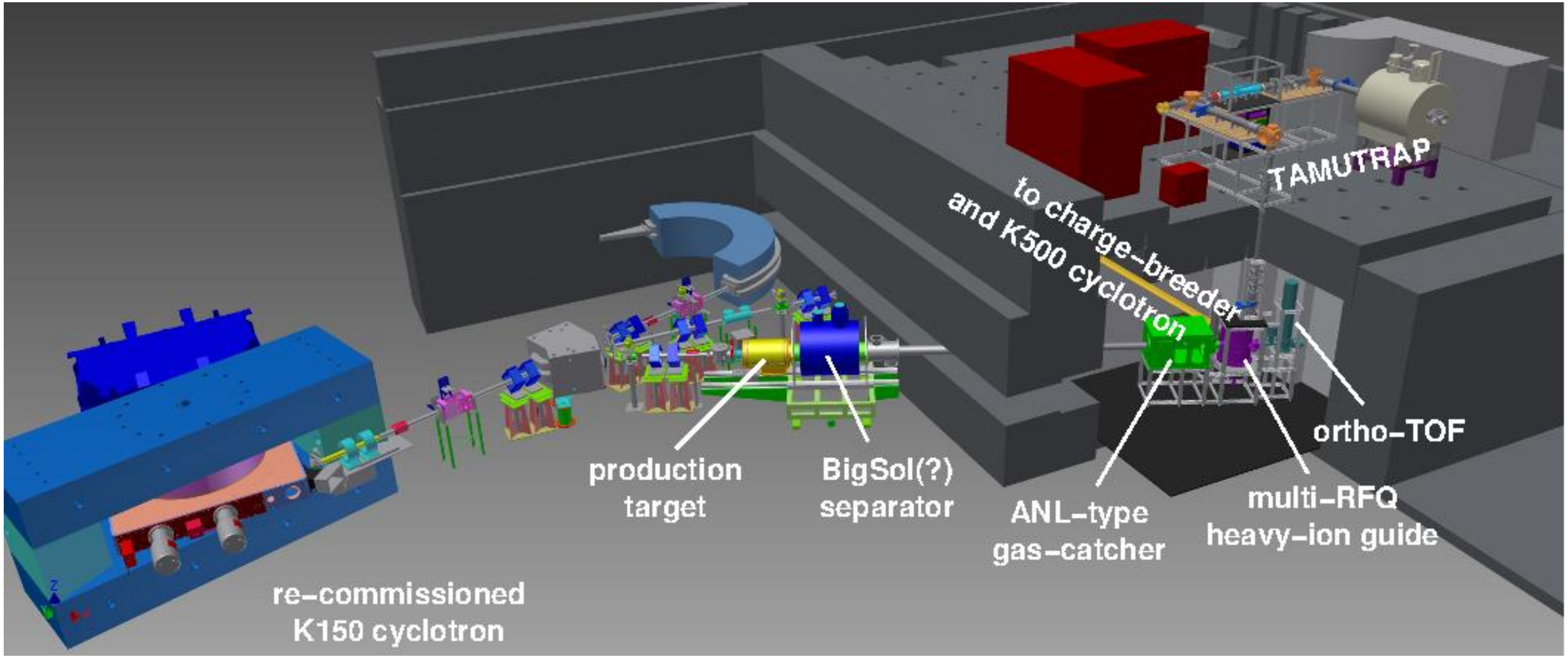
  - Asymmetry measurements of highly-polarized, laser-cooled atoms
- Outlook for the next 3 years

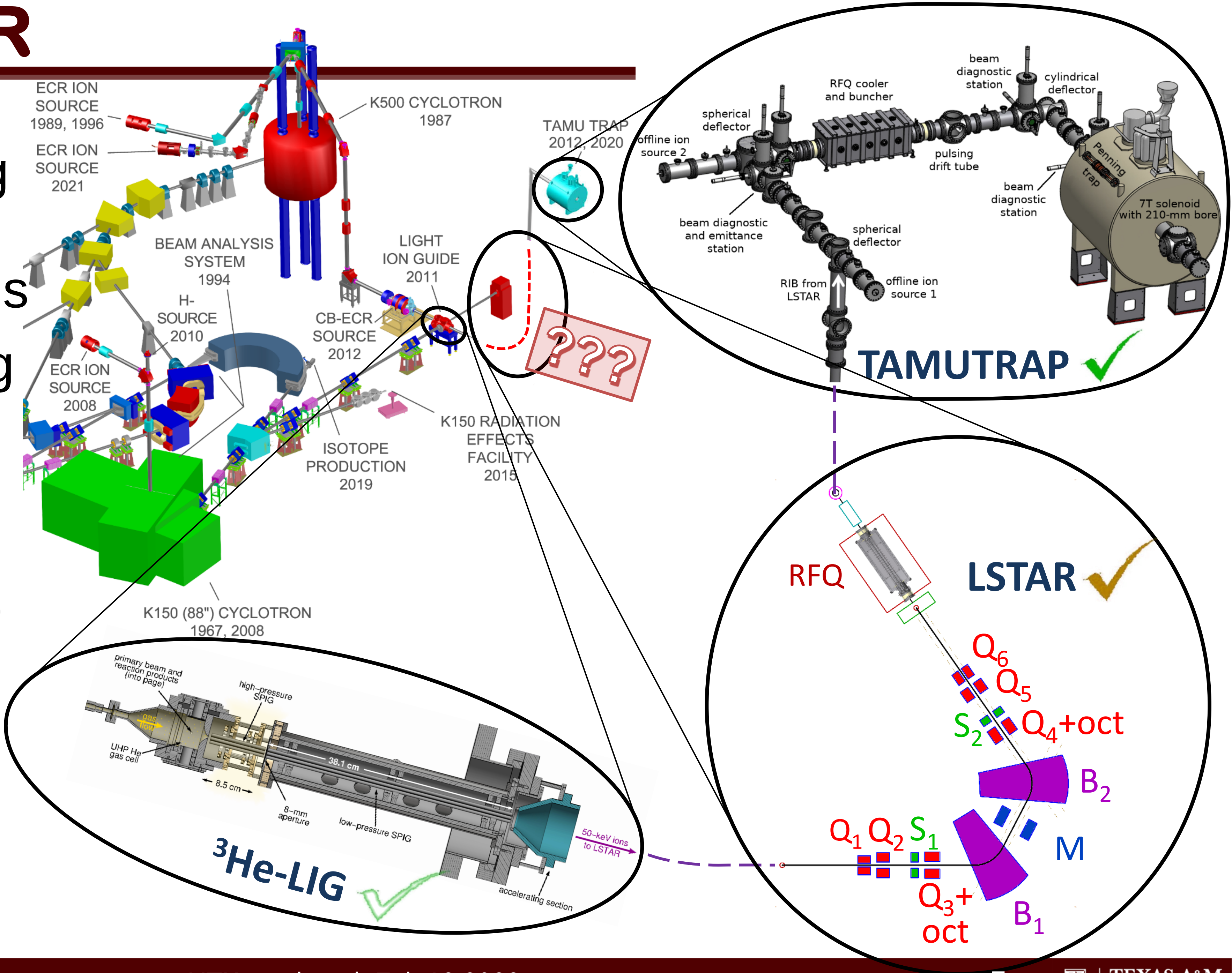
Original plan for TAMUTRAP: BigSol + gas catcher

- Heavy beam on light target, cleaned up by BigSol before being collected in an ANL-type gas catcher
- Abandoned in 2018 due to delays, BigSol issues, the K150 working better with low-mass beams, …



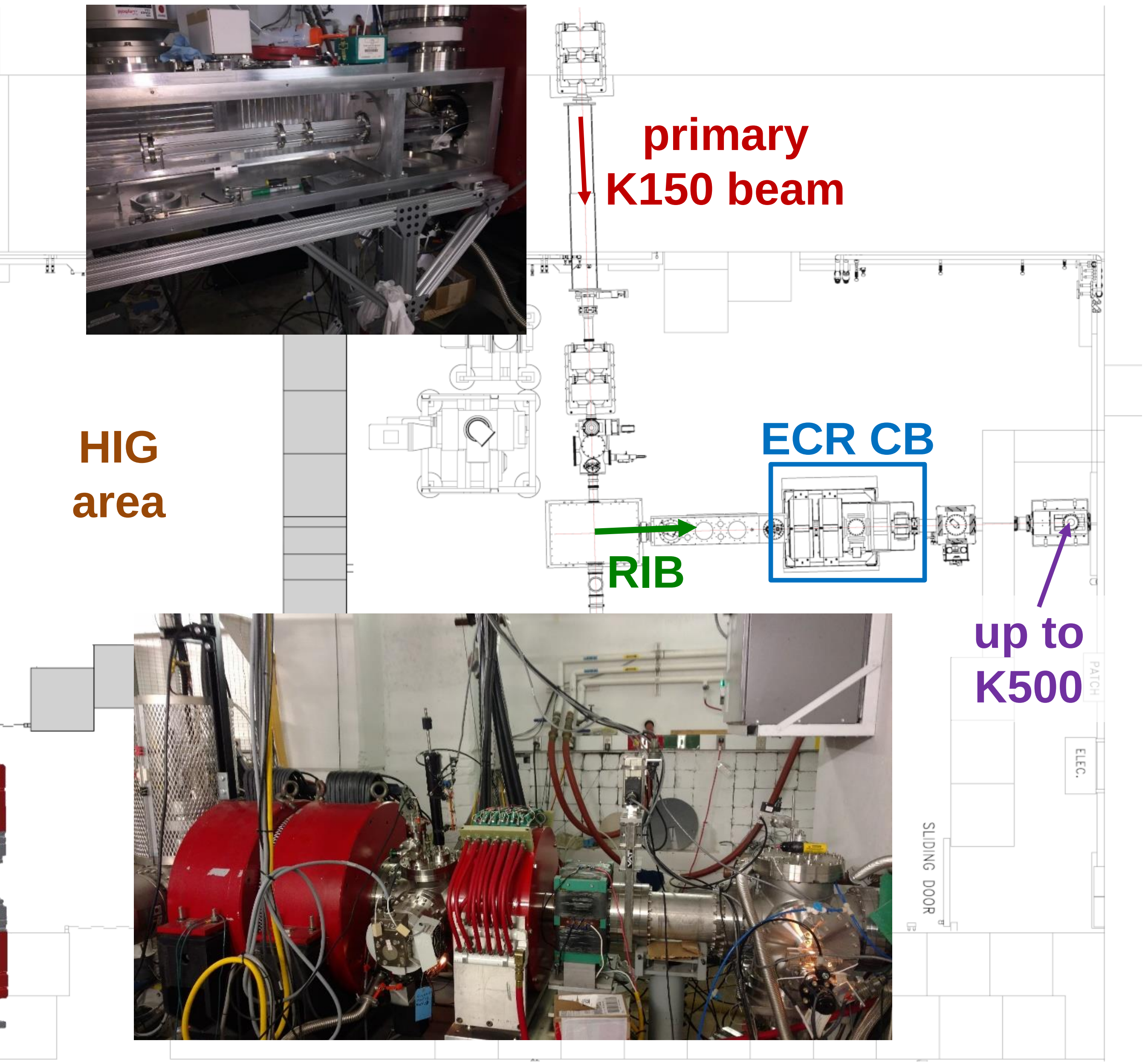
He-LIG + LSTAR

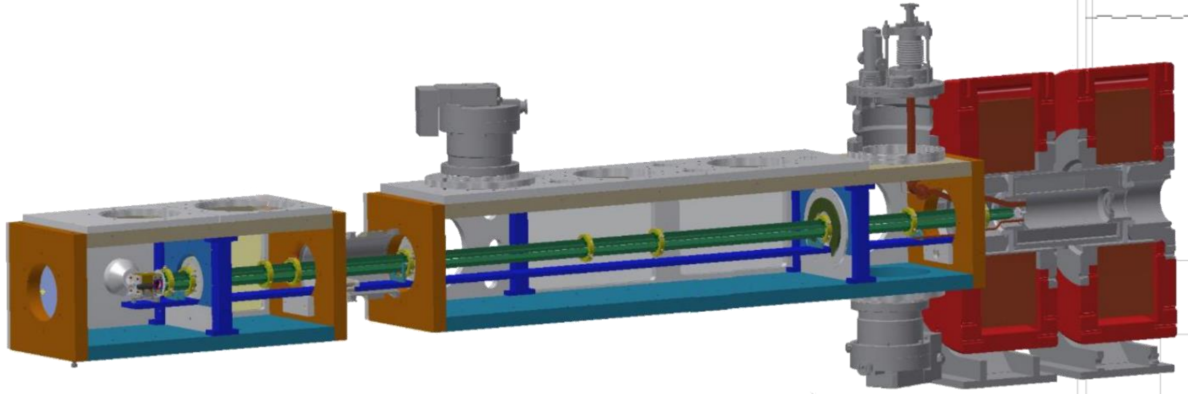
- 2018: pursue light-ion guide technique using ^{3}He to drive fusion-evapouration reactions
- Complements existing *p*-LIG system
  - RIB extracted in opposite direction
  - Need to share Cave 5
- Highly-efficient separator required so the RFQ cooler/ buncher doesn't get overloaded



RIB production: *p*-LIG and soon He-LIG

- Cave 5 at the Cyclotron Institute:
  - Shielding blocks separating (old) HIG area from *p*-LIG
  - Gabi Tabacaru leading *p*-LIG effort, which extracts beam to the right





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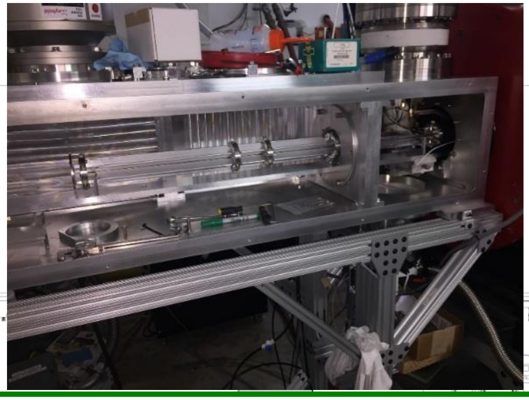
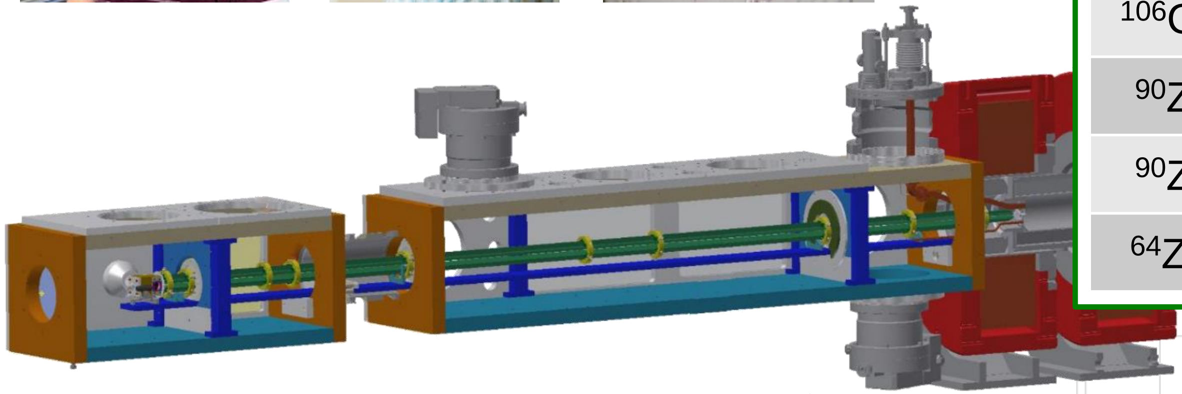
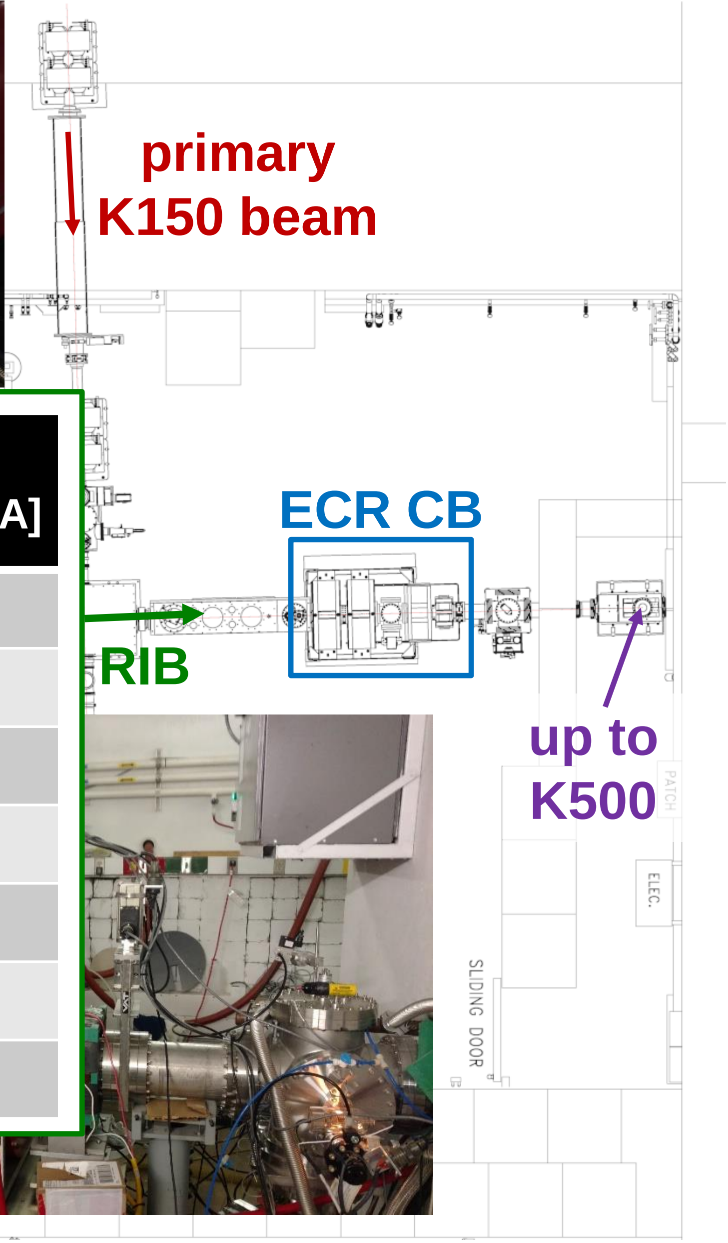
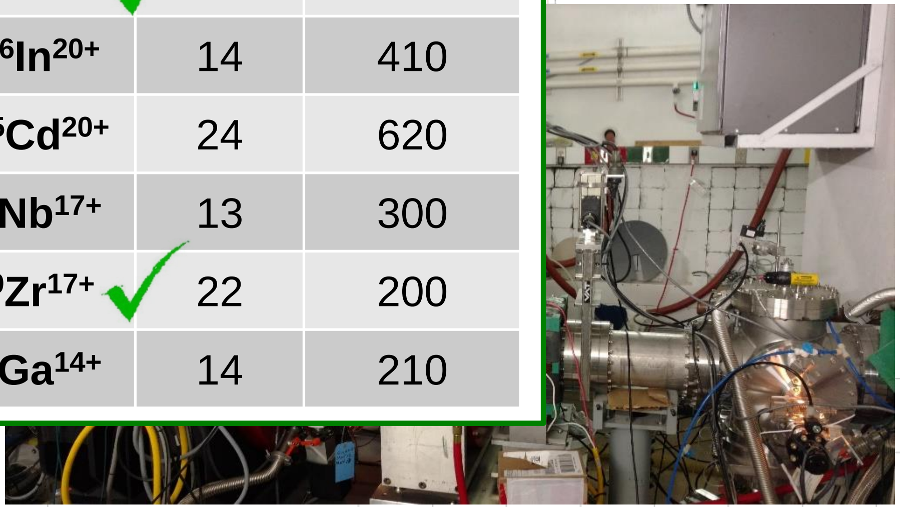




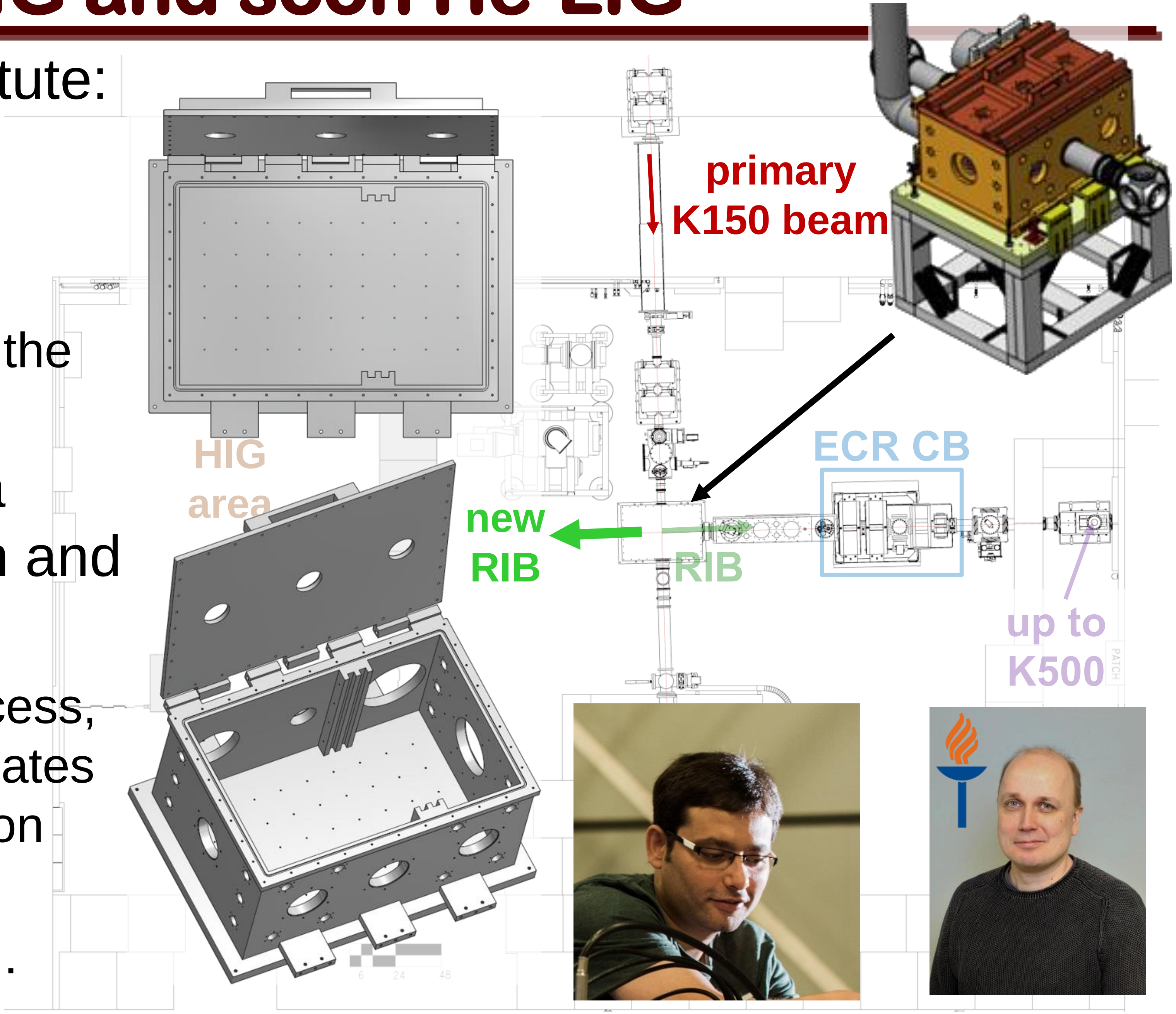




Target	RIB product	Beam energy [MeV]	Yield [ions/μA]
^{114}Cd	^{114}In^{19+}	10	685
^{114}Cd	^{112}In^{21+} ✓	28	975
^{106}Cd	^{106}In^{20+}	14	410
^{106}Cd	^{105}Cd^{20+}	24	620
^{90}Zr	^{90}Nb^{17+}	13	300
^{90}Zr	^{89}Zr^{17+} ✓	22	200
^{64}Zn	^{64}Ga^{14+}	14	210

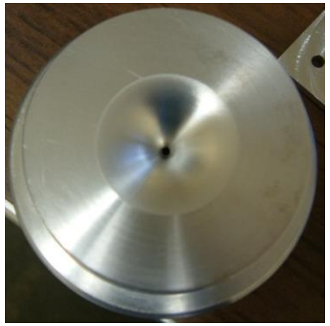
RIB production: *p*-LIG and soon He-LIG

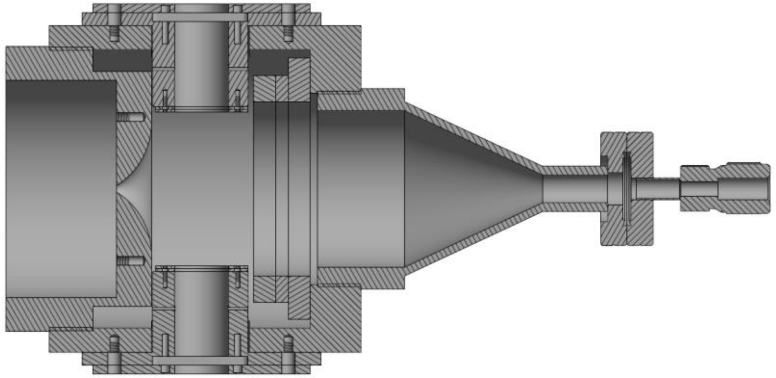
- Cave 5 at the Cyclotron Institute:
  - Shielding blocks separating (old) HIG area from *p*-LIG
  - Gabi Tabacaru leading *p*-LIG effort, which extracts beam to the right
- Praveen Shidling designed a new chamber for both proton and ^{3}He LIG production
  - Inspired by IGISOL. Easy access, alignment precise, accommodates *p* and ^{3}He gas cells & extraction optics
  - NorCal delayed >1 year now…

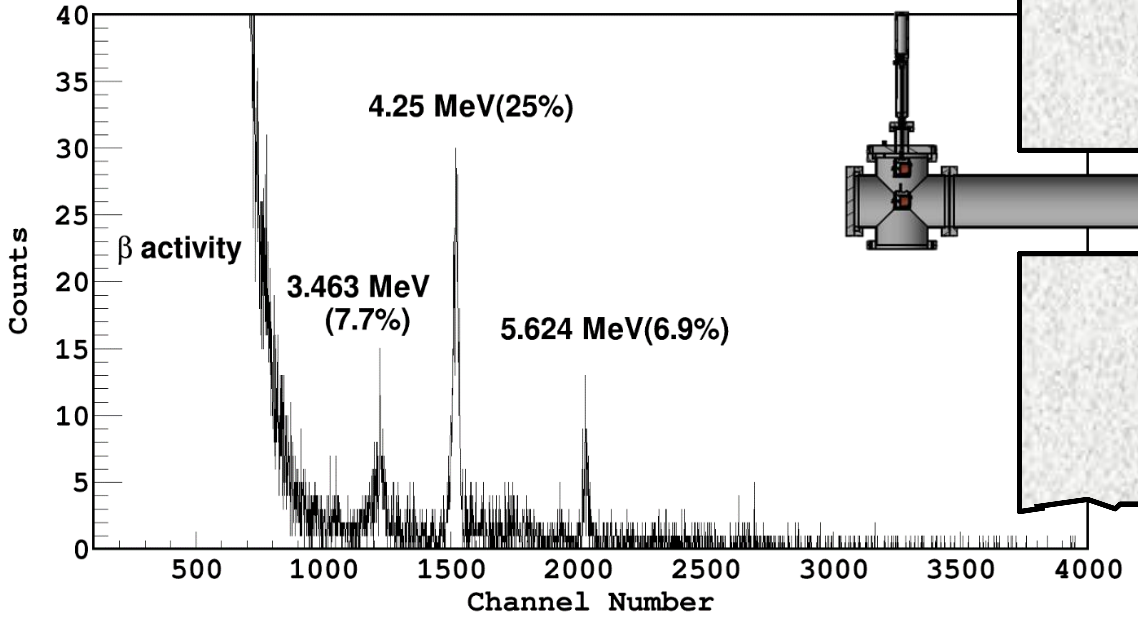


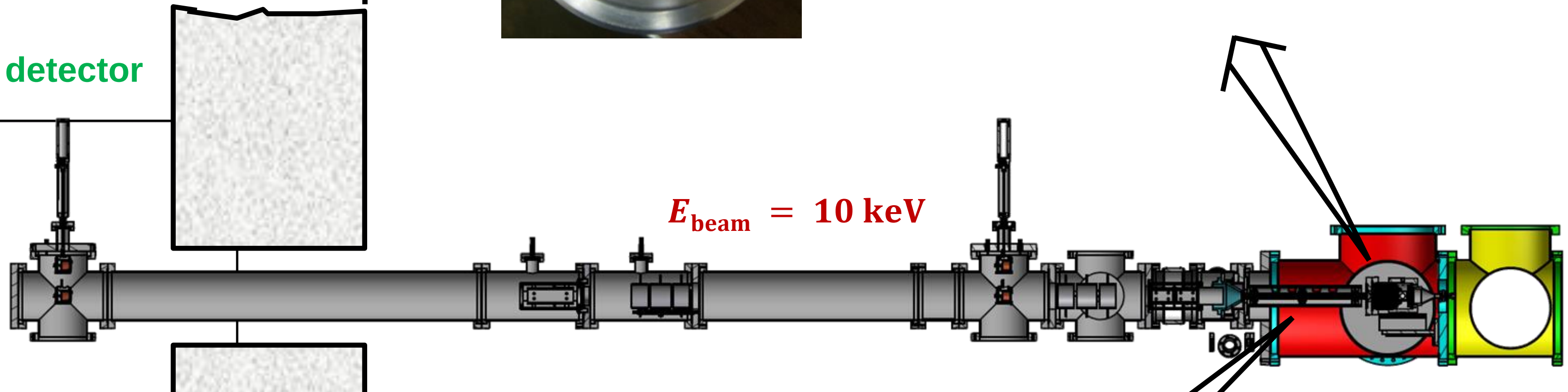
He-LIG: Expanding the CI's RIB capabilities

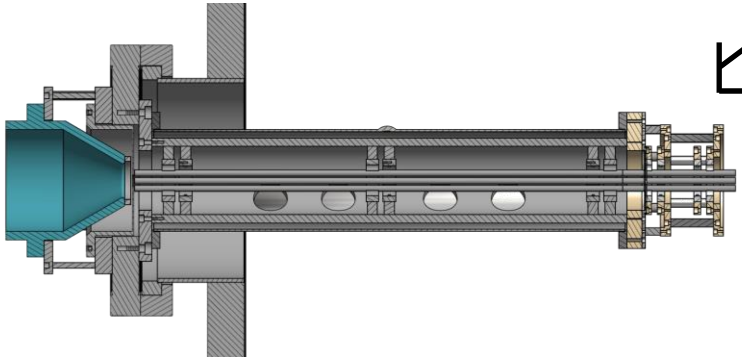
- Typical gas cell, we didn't reinvent the wheel
- Tested production of ^{25}Si in Feb, Aug & Dec 2019, and Mar 2020
  - ~0.1% efficiency; rf didn't seem to help
  - 1% is in sight!







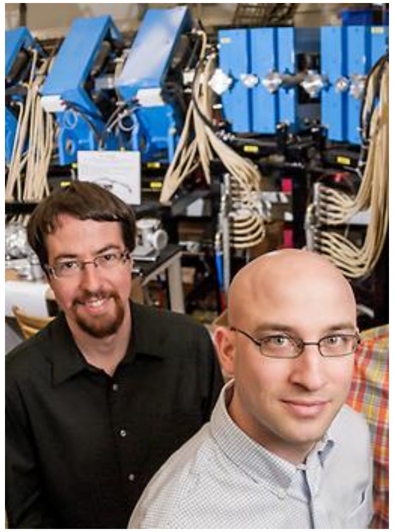


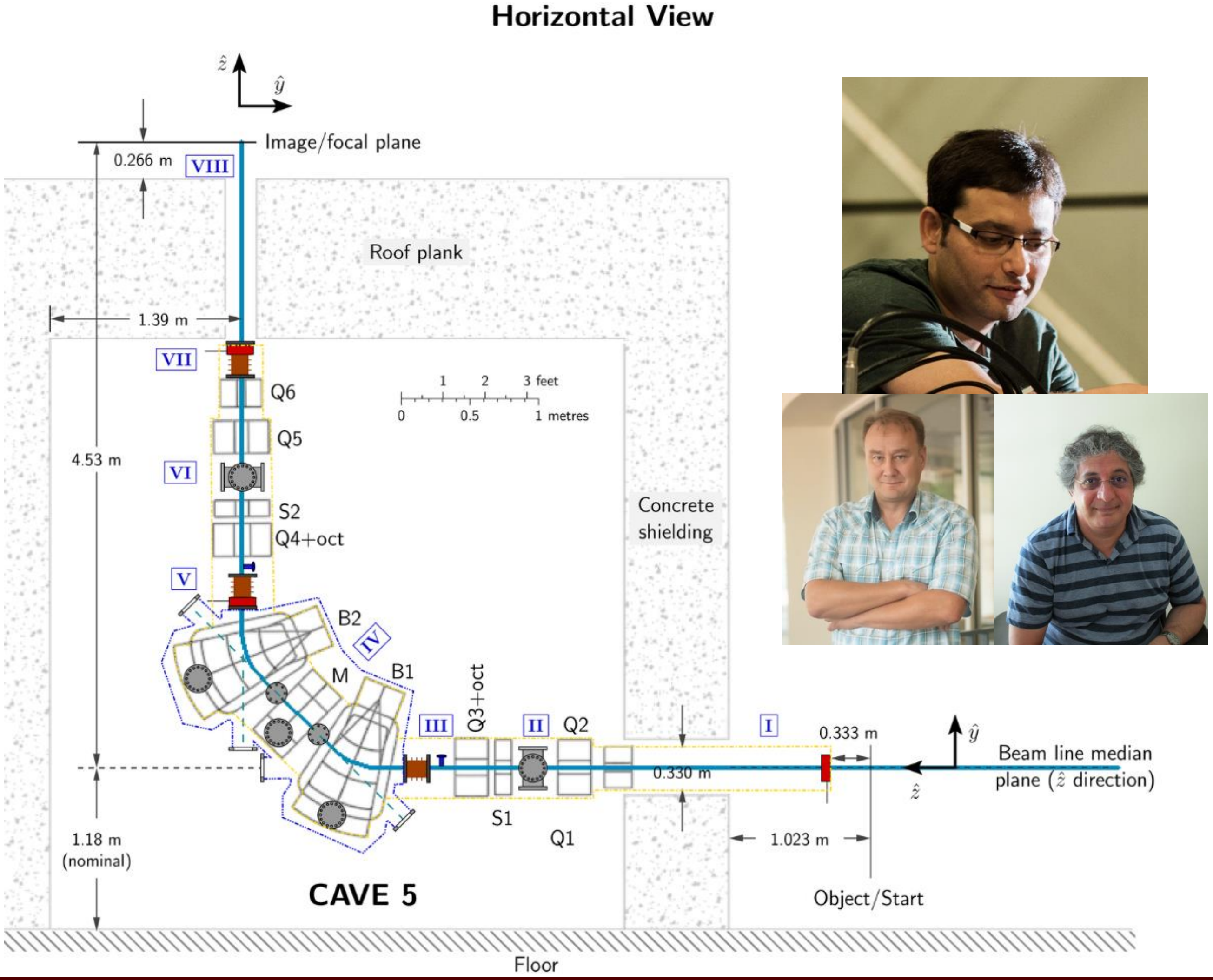


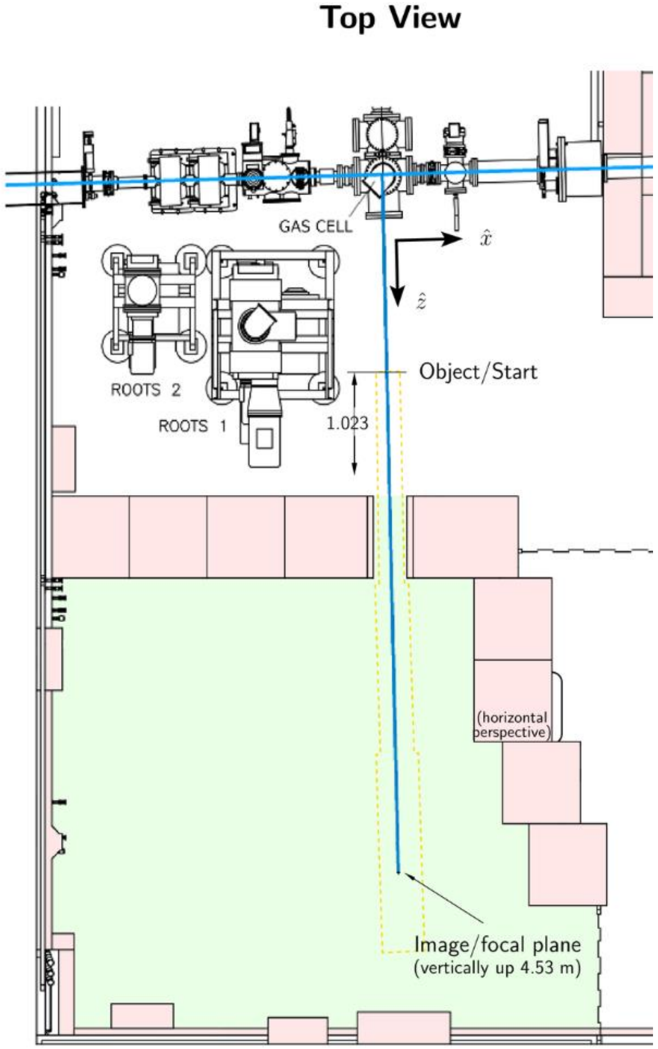
- Rebuild cell and amend SPIG design for transport to LSTAR

LSTAR: purify and transport up to TAMUTRAP

- In collaboration with Notre Dame (Berg, Couder, Brodeur), design based on $2 \times 60°$ separator at CARIBU. Ready to submit bids last year…







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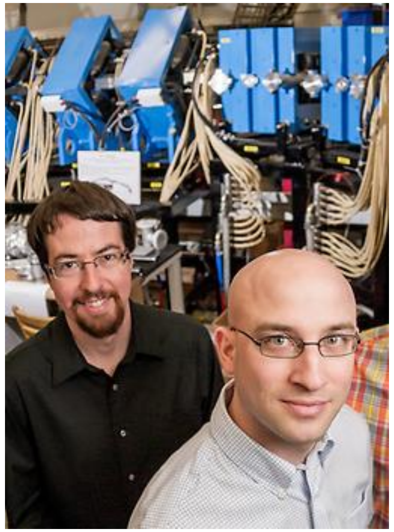
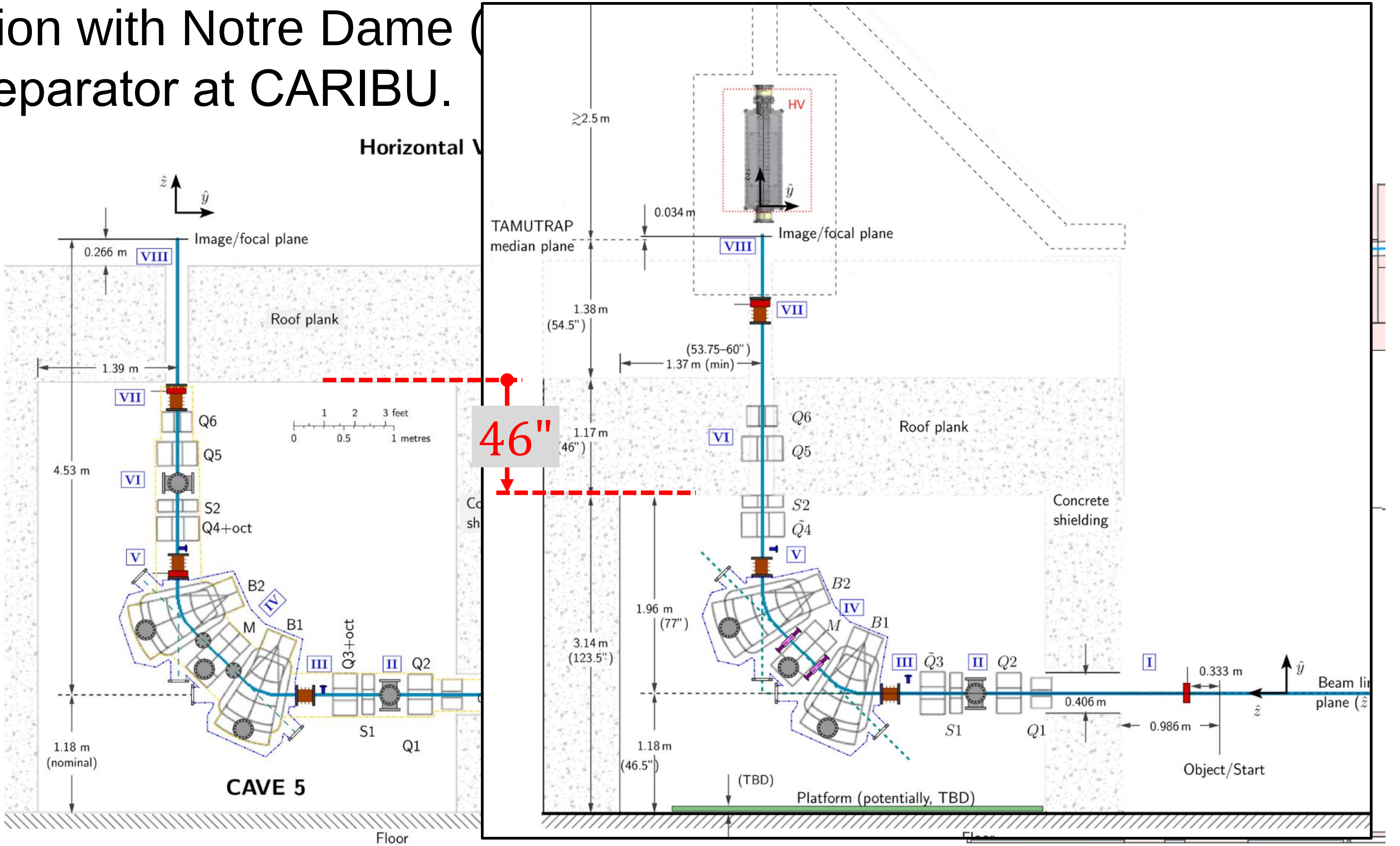
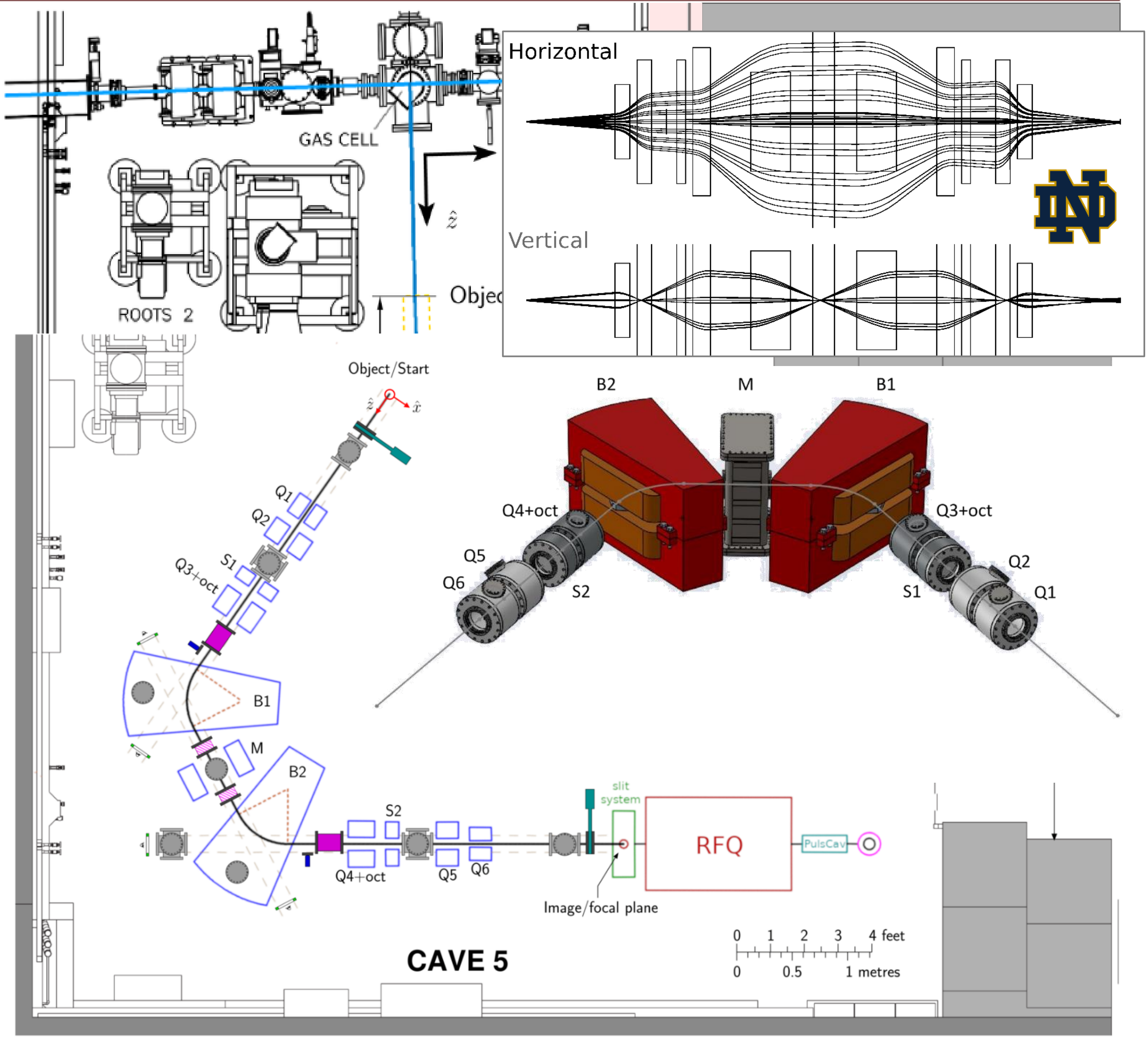




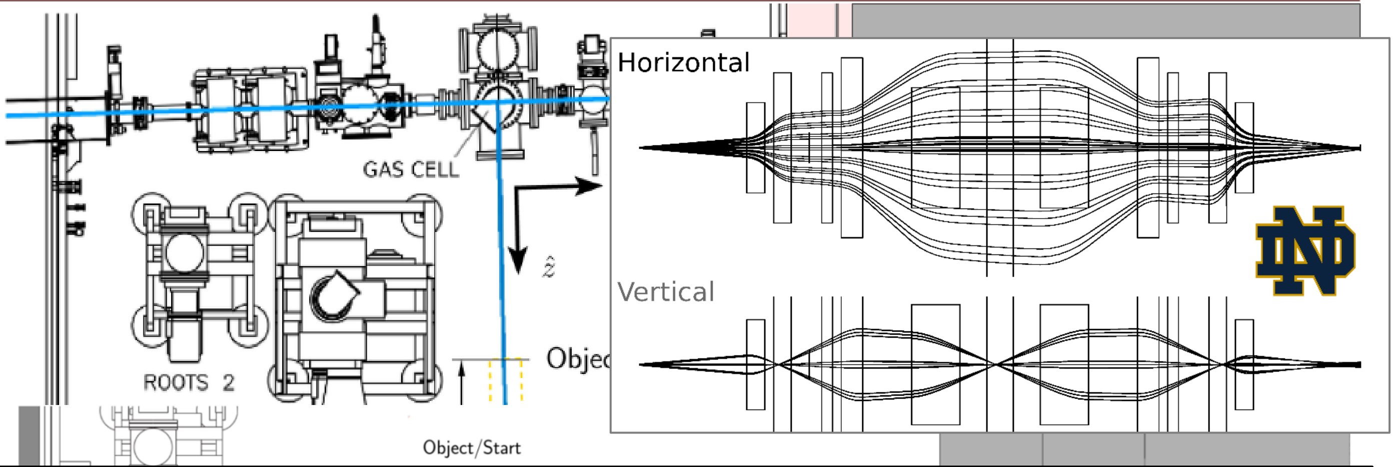
After a few dark days, a bright light turned on

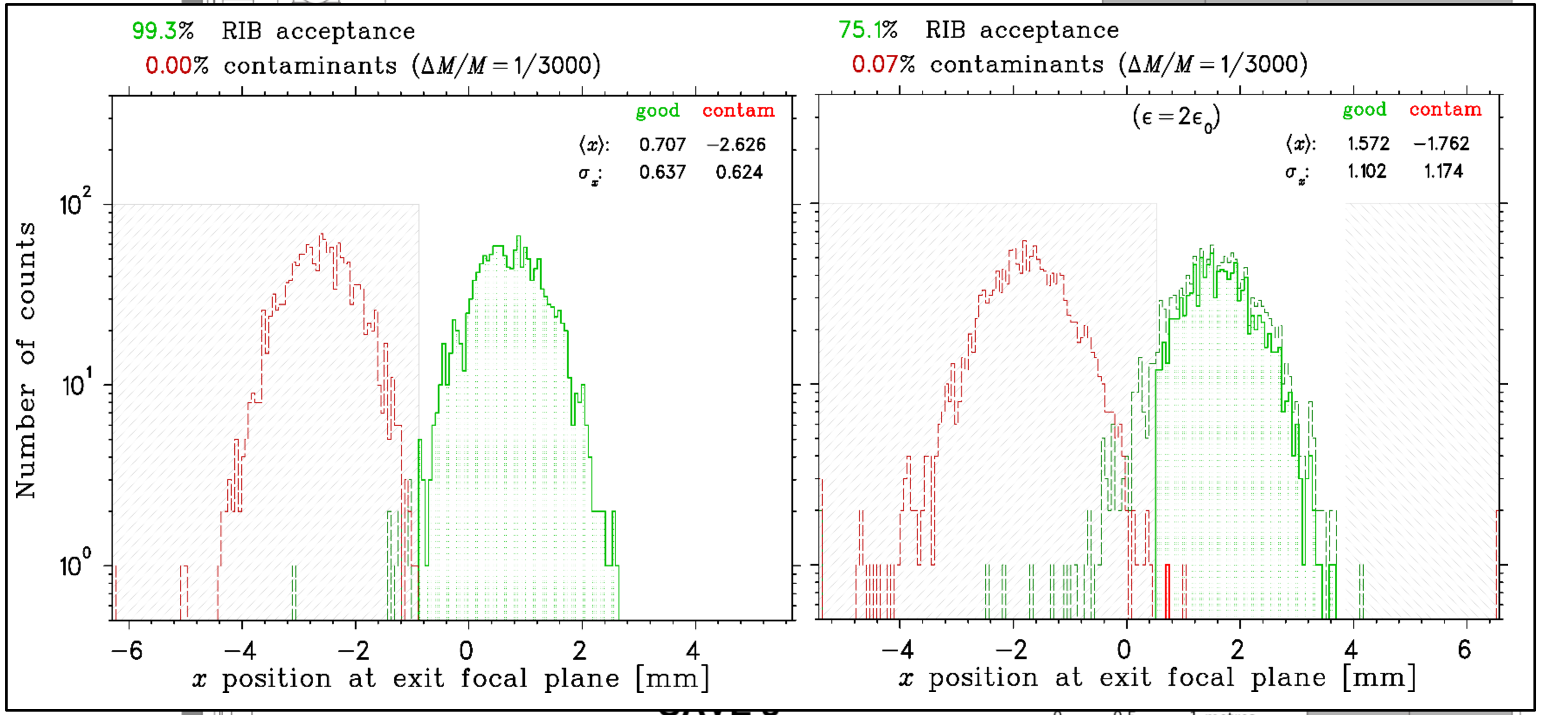
- We *can* remove the shielding blocks ⇒ a *lot* more real estate
- New design is **significantly** better
  - $2 \times 62.5°$ – nearly 40% more than original $2 \times 45°$
  - Entirely horizontal – better alignment, easier
  - Has enough room we can place the RFQ in Cave 5!
    - Significantly higher efficiency versus transporting 65-keV RIB
    - Hole in roof plank significantly smaller
    - Both HV platforms now in Cave 5



After a few dark days, a bright light turned on

- We *can* remove the shielding blocks ⇒ a *lot* more real estate
- New design is **significantly** better
- Detailed MC studies using SimION-calculated rays
  - nominally >95% acceptance with zero contaminants
  - >75% acceptance, even if systematics are under-estimated (*e.g.* 2 × SimION emittance, 50% more energy spread, ±0.5-mm and ±20-mdeg misaligns, ...)

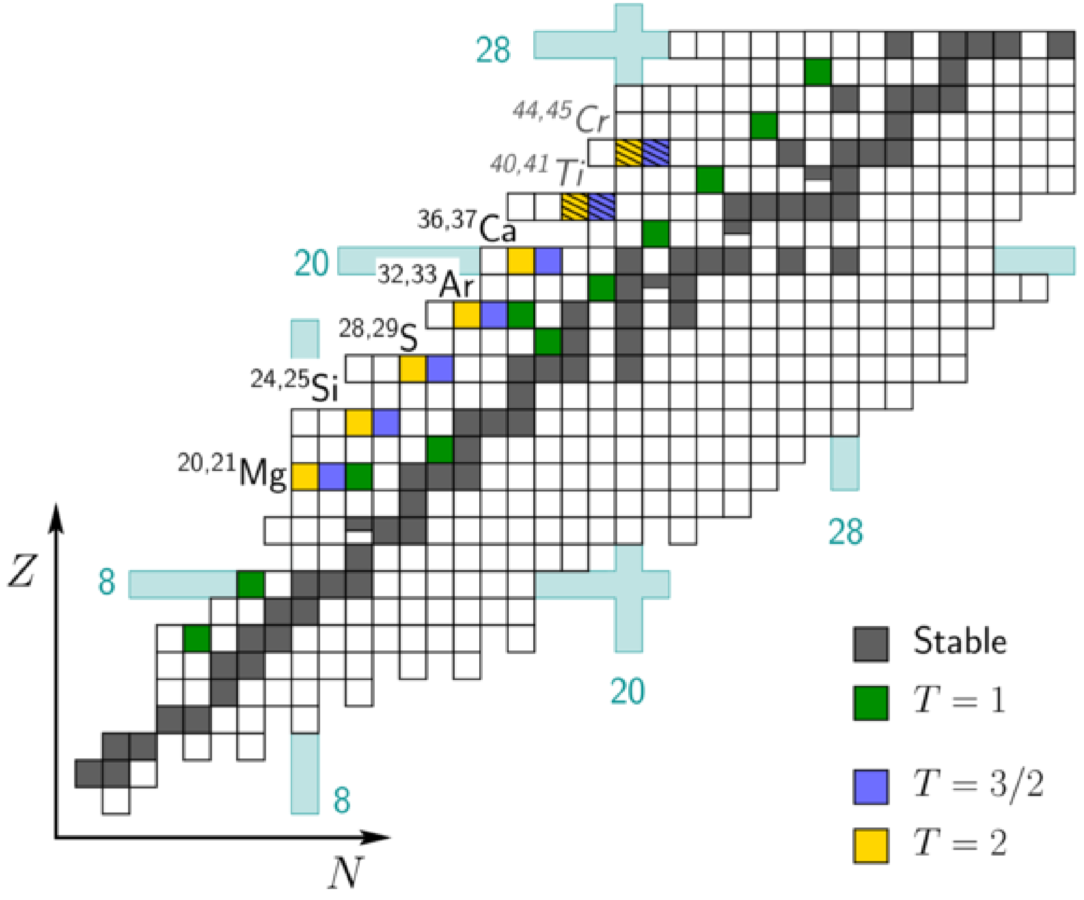




RIBs desired for TAMUTRAP

- 1st beams to come from He-LIG/LSTAR:

Target	Product	Production rate	Estimated rate in trap
^{20}Ne	^{20}Mg ^{21}Mg	4×10^3 3×10^5	8 – 23 550 – 1600
^{24}Mg	^{24}Si ^{25}Si	3×10^3 2×10^5	6 – 17 290 – 860
^{28}Si	^{28}S ^{29}S	3×10^3 8×10^4	5 – 16 175 – 520
^{32}S	^{32}Ar ^{33}Ar	0.9×10^3 0.9×10^5	1 – 5 160 – 460
^{36}Ar	^{36}Ca ^{37}Ca	0.2×10^3 0.2×10^5	0.4 – 1 40 – 115



- Future: general decay station; charge-breed with EBIT and inject in K500

Rough timeline

- He-LIG
  - Rebuild gas cell; redesign SPIG transport; test production (2023)
  - Develop pepper-pot emittance station, characterize beam out of SPIGs (2024)
- LSTAR
  - Submit bids soon
  - 2024 shutdown start to prepare the area for the separator? (remove shielding blocks, power, water, …)
  - Hoping delivery will be in 2–3 years, but this is completely unknown

- He-LIG + LSTAR
  - RIB to TAMUTRAP and first measurements ~1 year after LSTAR installed
  - Develop visions for expansion in future (dedicated decay station; charge-breeder and injection in K500)

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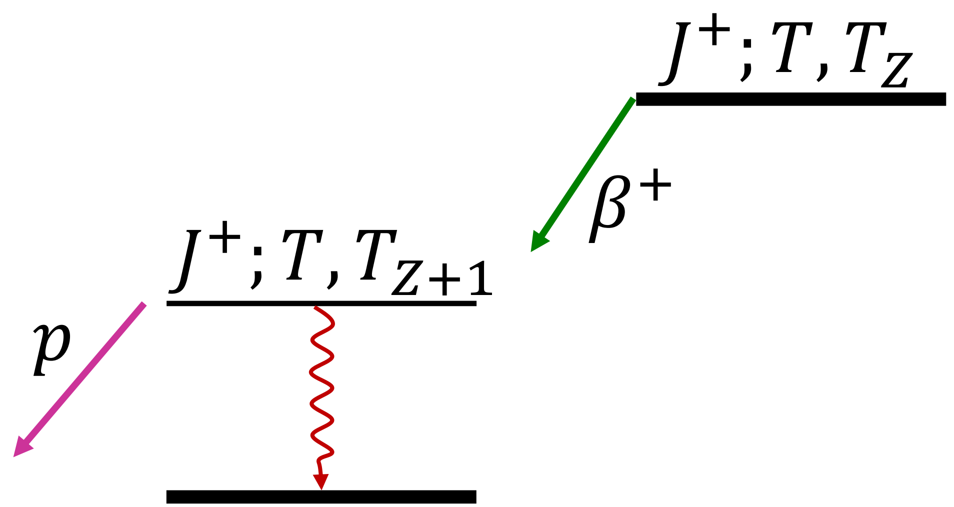
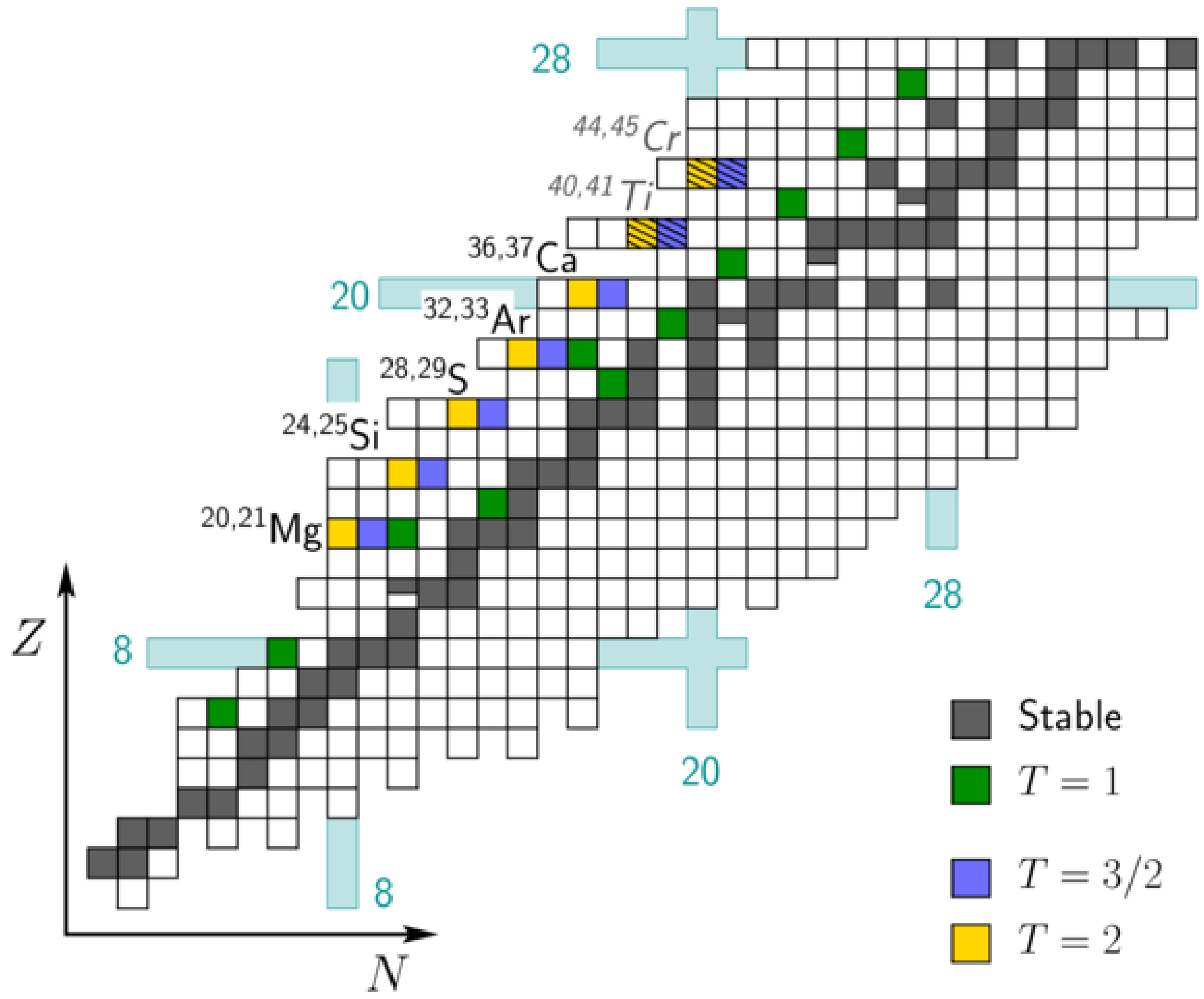
$T = 2, 3/2$ pure Fermi and Gamow-Teller decays

Odd cases: $J^{\pi} = \frac{5}{2}^{+}, T = \frac{3}{2}$

Even cases: $J^{\pi} = 0^{+}, T = 2$

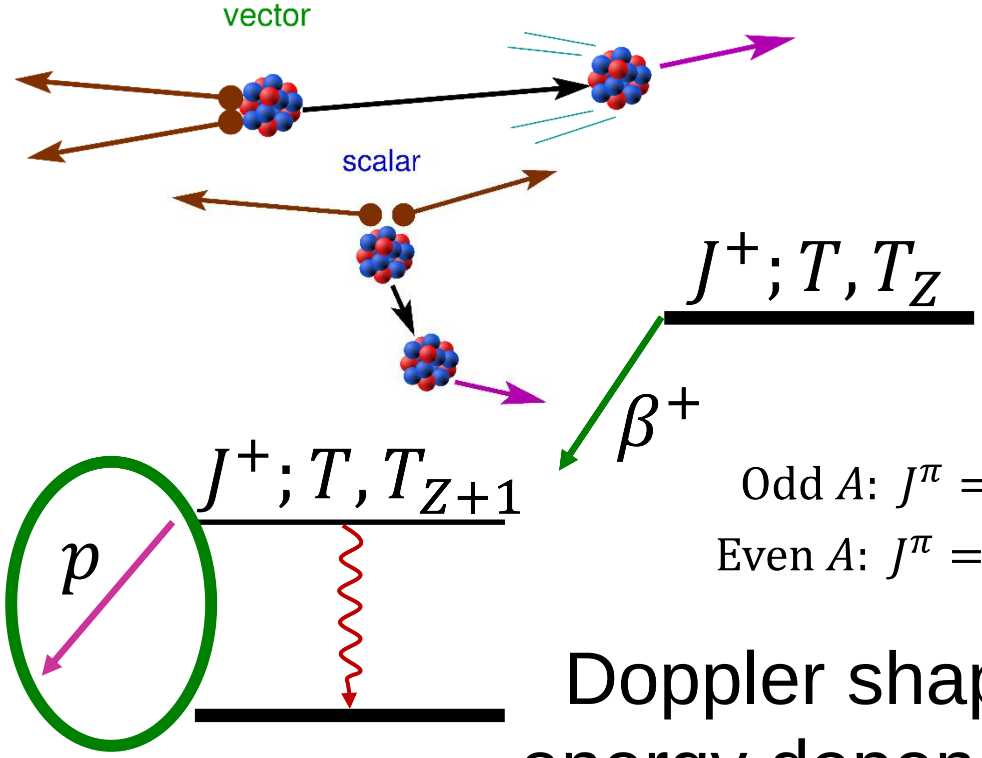




$T = 2, 3/2$ pure Fermi and Gamow-Teller decays

Pure Fermi decay ⇒ minimal nuclear structure effects; decay rate is simply given by

$$p_e E_e (A_0 - E_e)^2 \xi \left(1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e}\right)$$



Odd A: $J^\pi = \frac{5}{2}^+, T = \frac{3}{2}$

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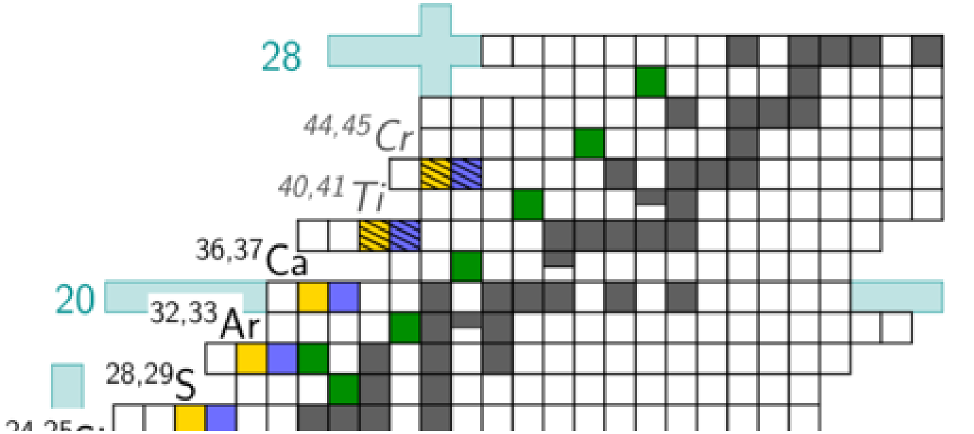
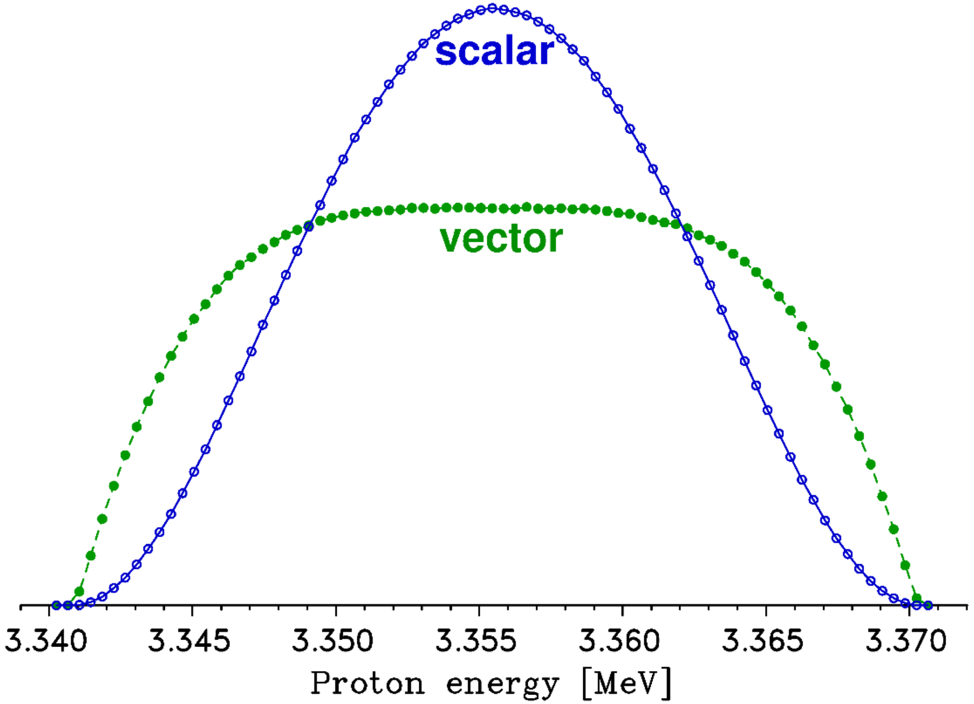
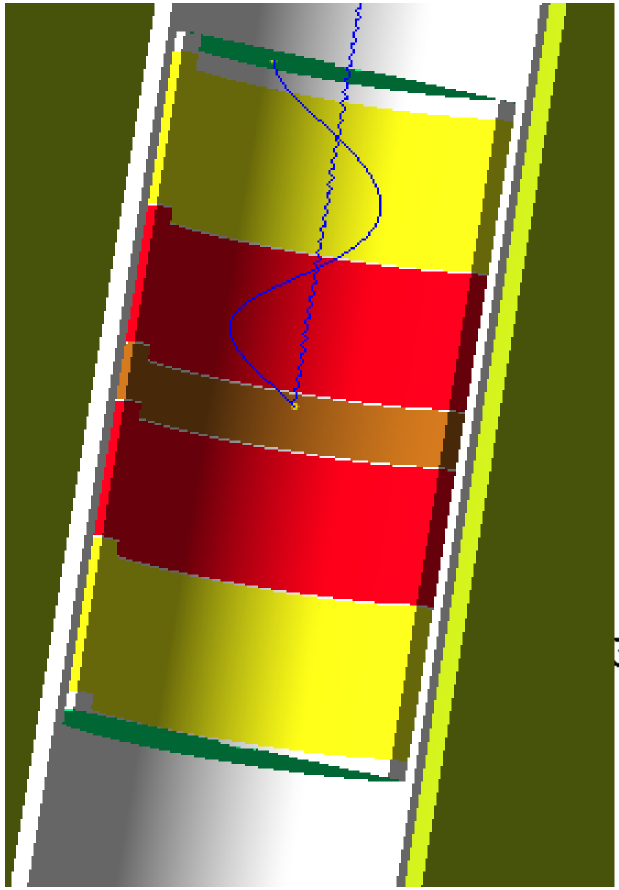
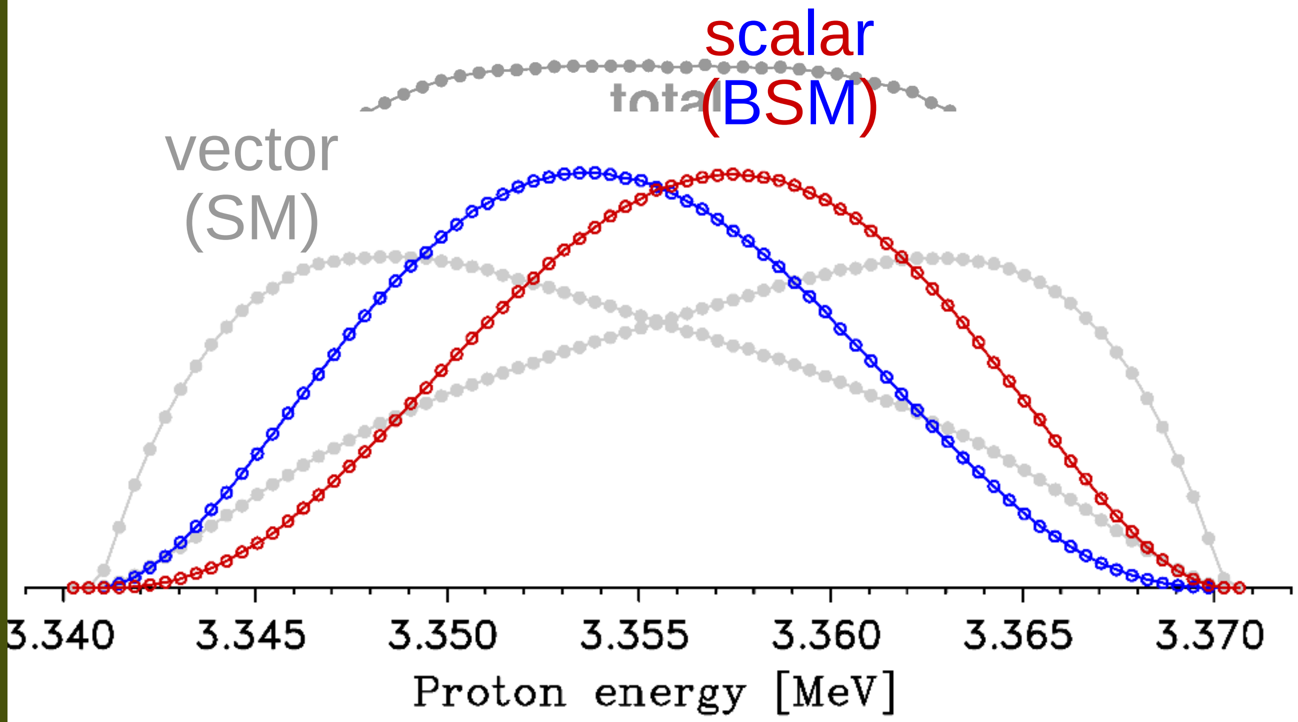


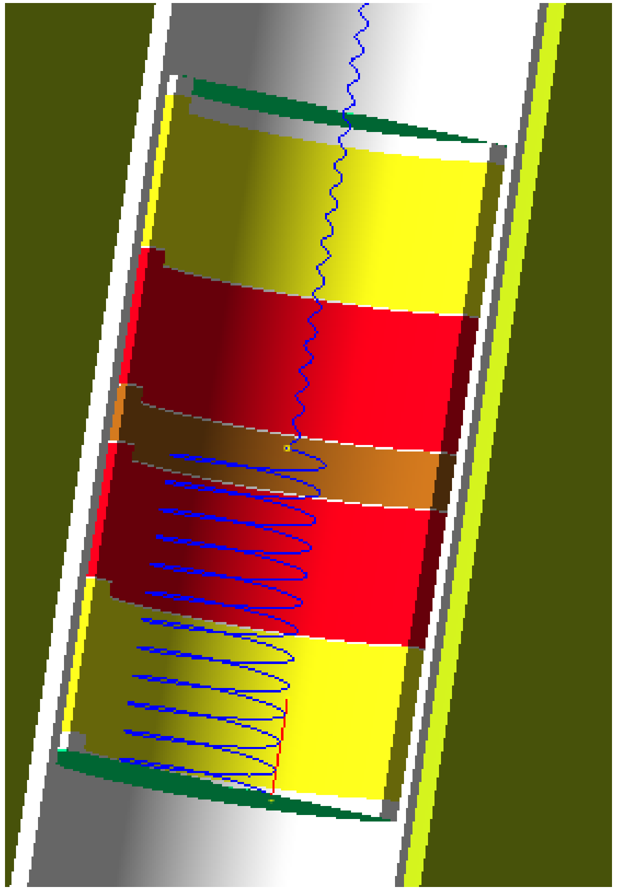


Doppler shape of proton energy depends on $\vec{p}_\beta \cdot \vec{p}_\nu$!

Measure means instead of 2^{nd} moments



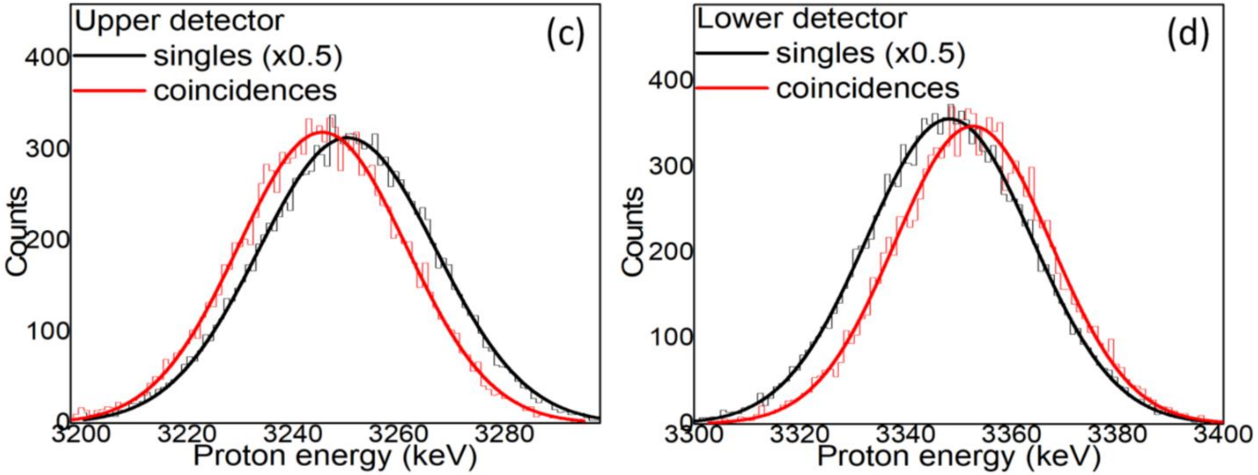


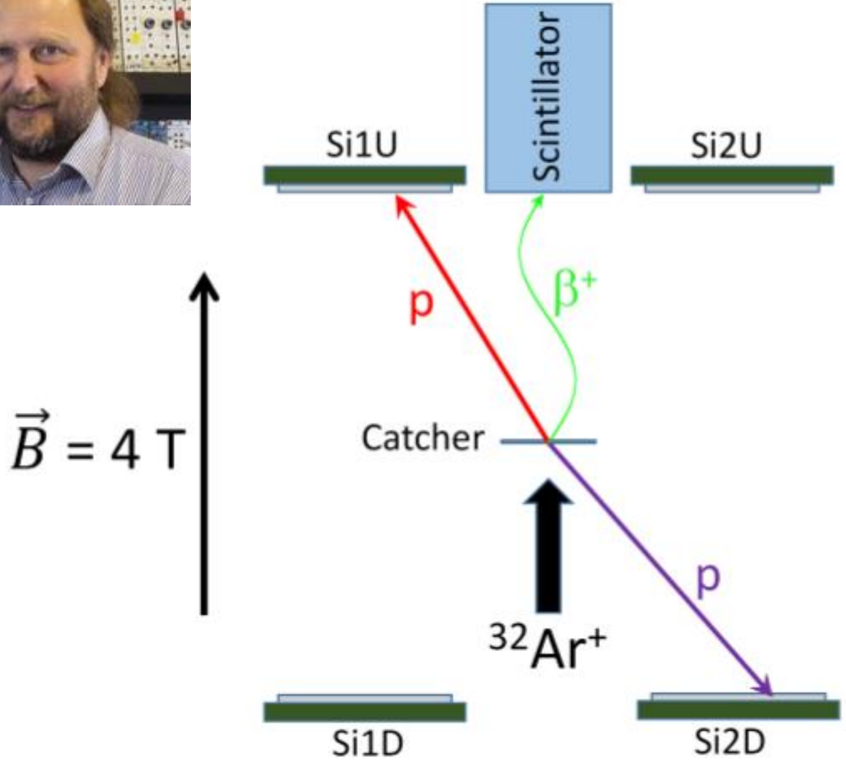


WISArD: same idea, but simpler (faster)

- After hosting three interns from ENISCAEN, the Weak Interaction Studies of ^{32}Ar Decay (WISArD) was formed

- Quick test run using the WITCH magnet, clearly see kinematic shift





$$\Rightarrow \ \tilde{a}_{\beta\nu} = 1.007(32)(25)$$ (4% precision)

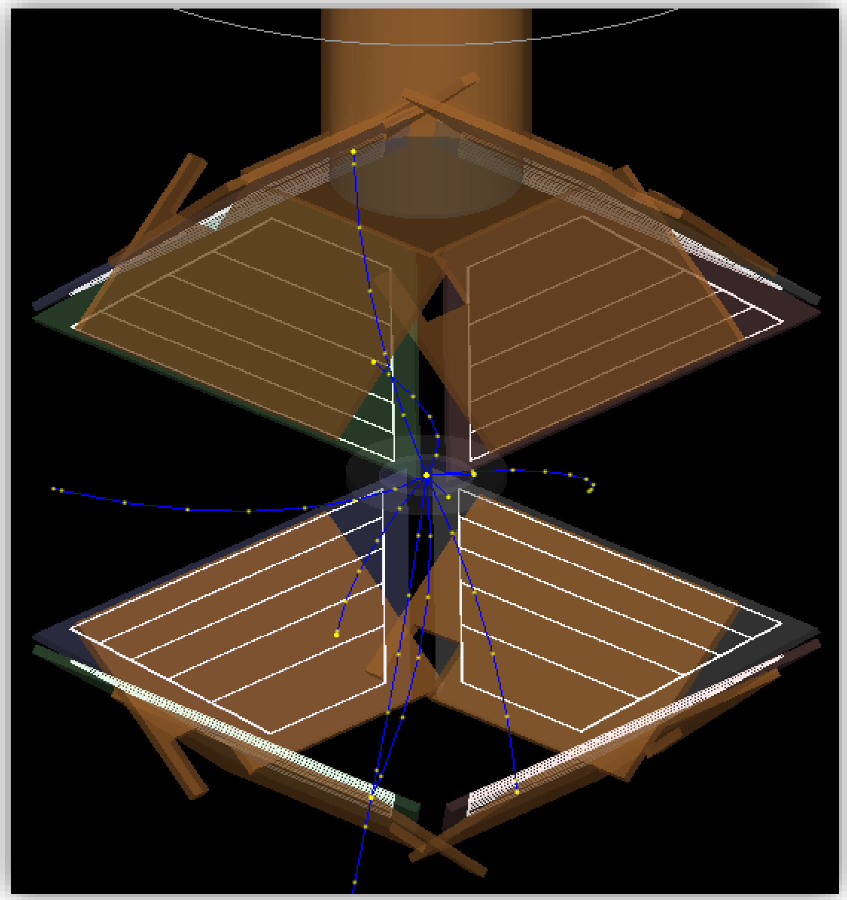
WISArD collab, PRC **101**, 055501 (2020)

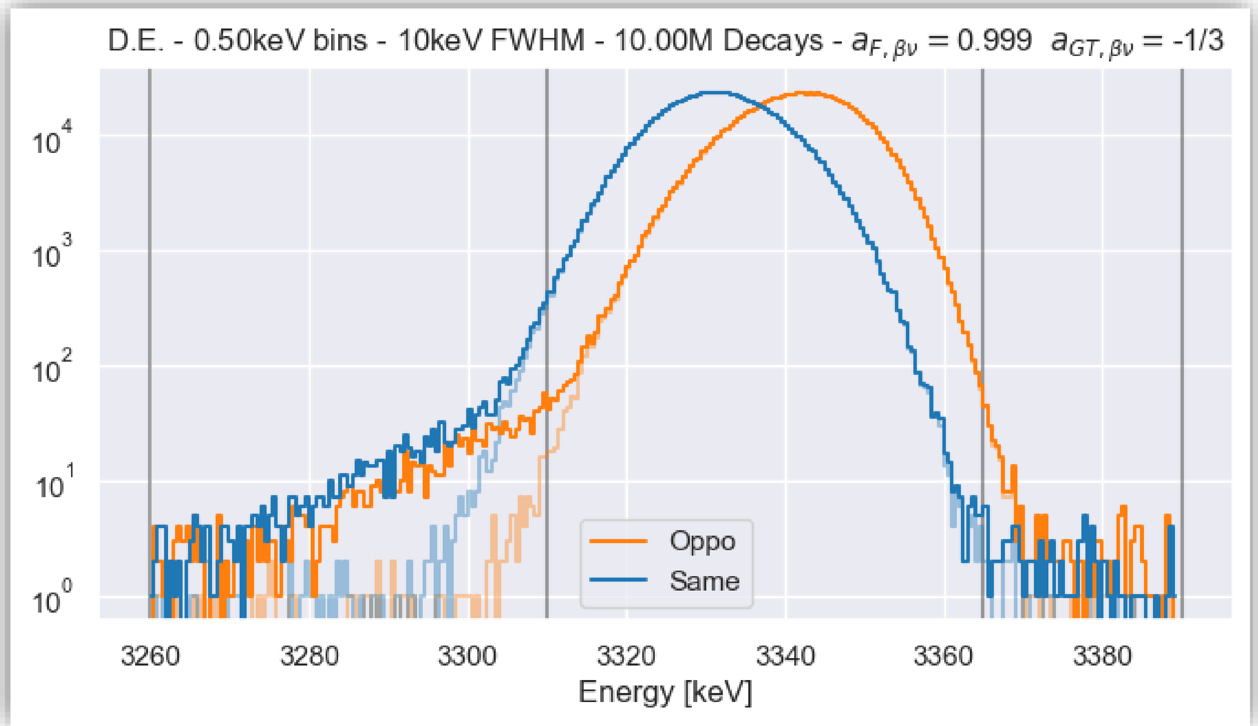
- Joined complementary effort, PhD thesis for Morgan Nasser

Simpler, but still not easy!

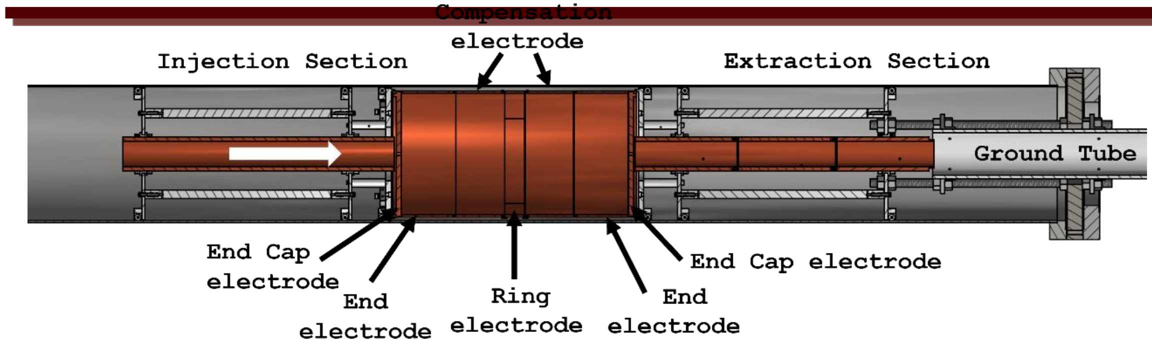
- Upgraded Si detectors, thinner catcher foil, …
- TAMU: PENELOPE vs G4; R-matrix and interferences
- Beamtime approved for this summer

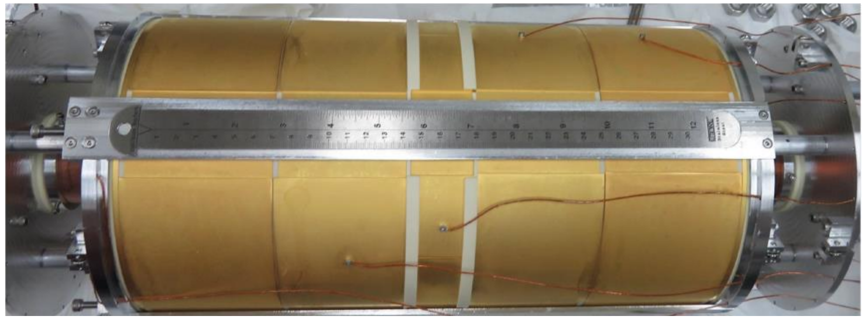
→ PhD data for Morgan Nasser





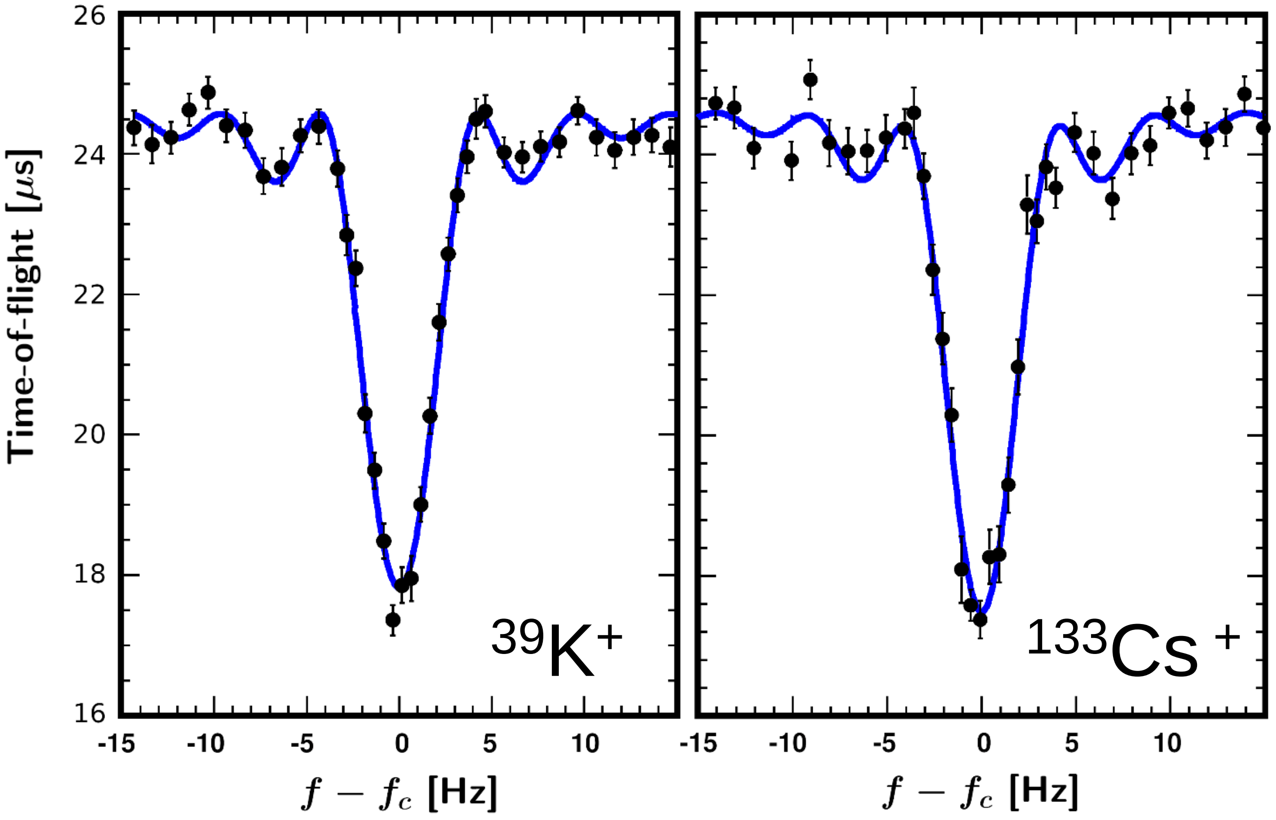
Mass measurement of stable ions





- Find resonant frequencies for ^{23}Na, ^{85,87}Rb, ^{133}Cs and ^{39}K (ref). Precisions obtained (2020):
  - ^{23}Na: 400 ppb
  - ^{85}Rb: 500 ppb
  - ^{87}Rb: 500 ppb
  - ^{133}Cs: 800 ppb

TOF ICR, 200 ms excitation time



All agree with AME

P.Shidling *et al*., Hyperfine Interact. **240**, 40 (2019)
P.Shidling *et al*., Int. J. Mass Spectr. **468**, 116636 (2021)

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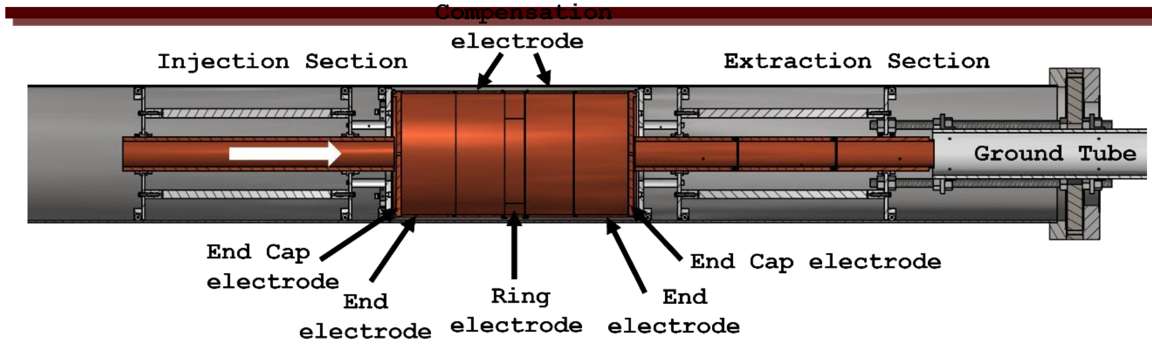

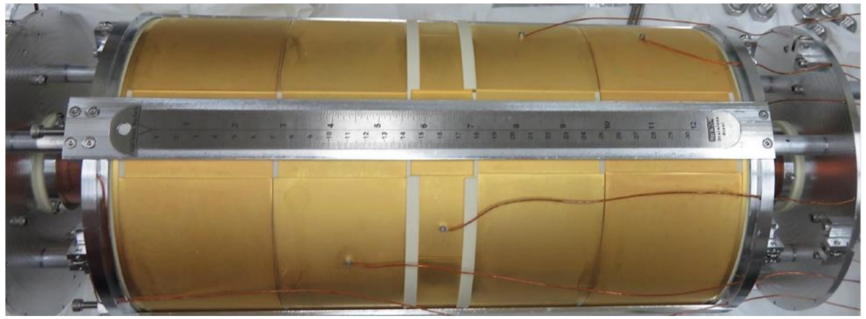

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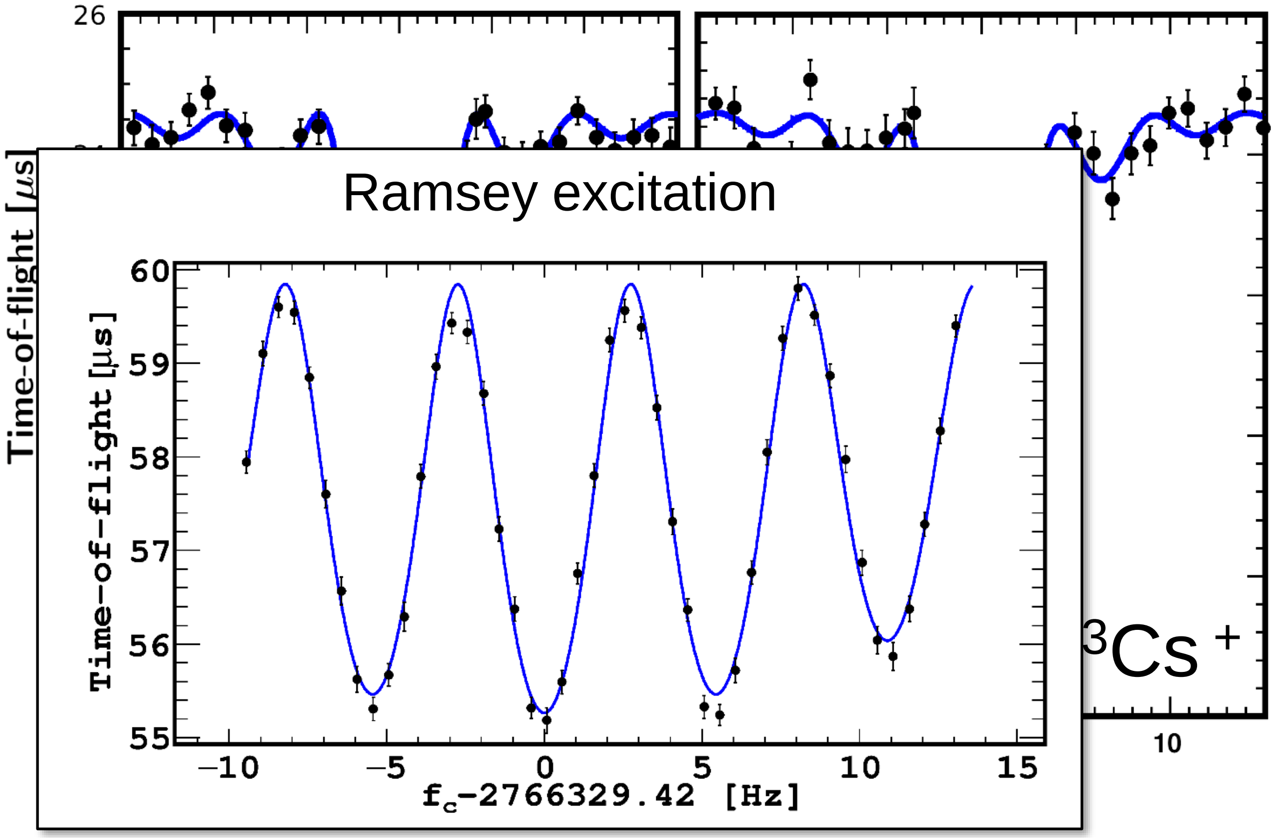

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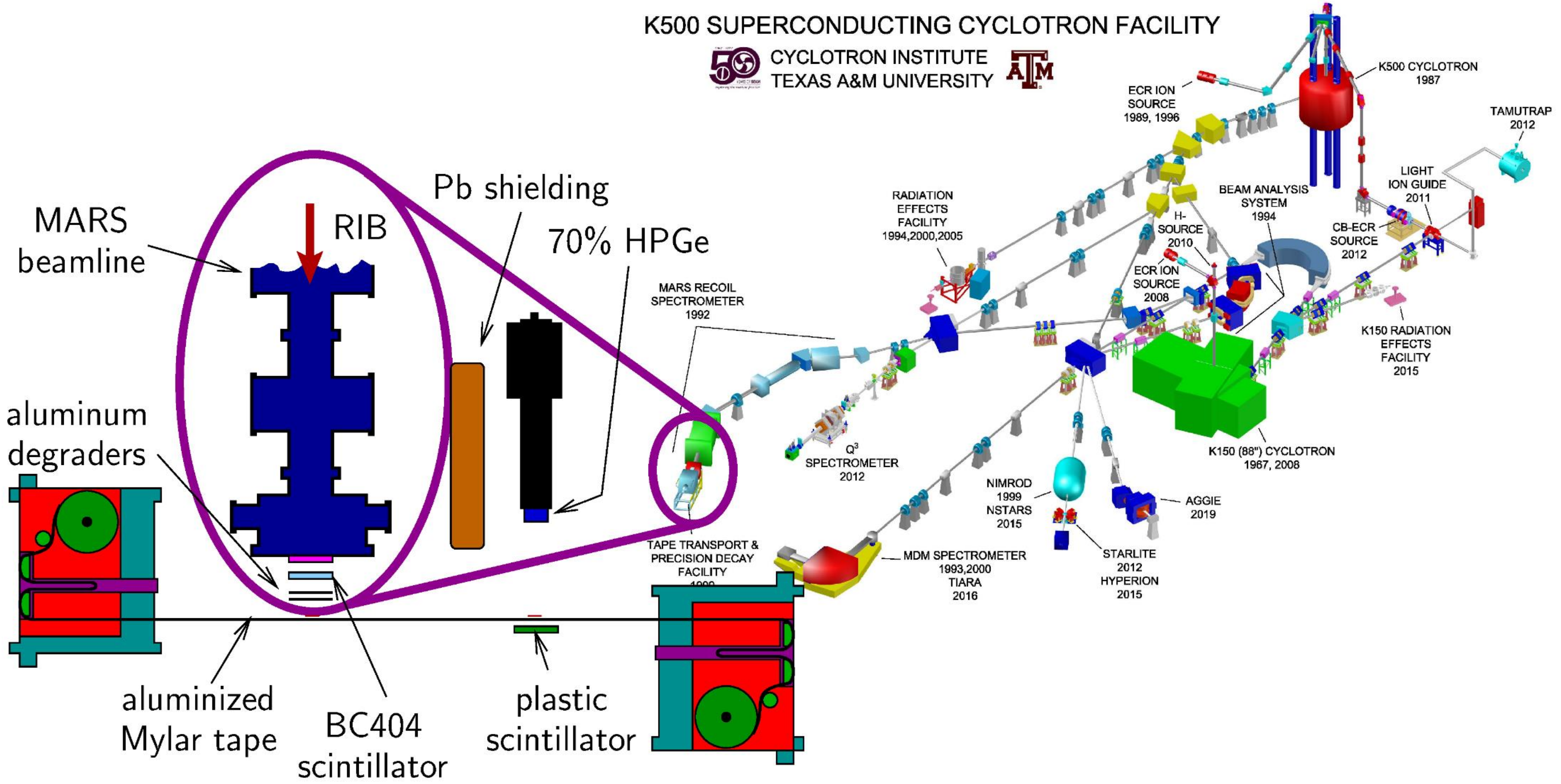
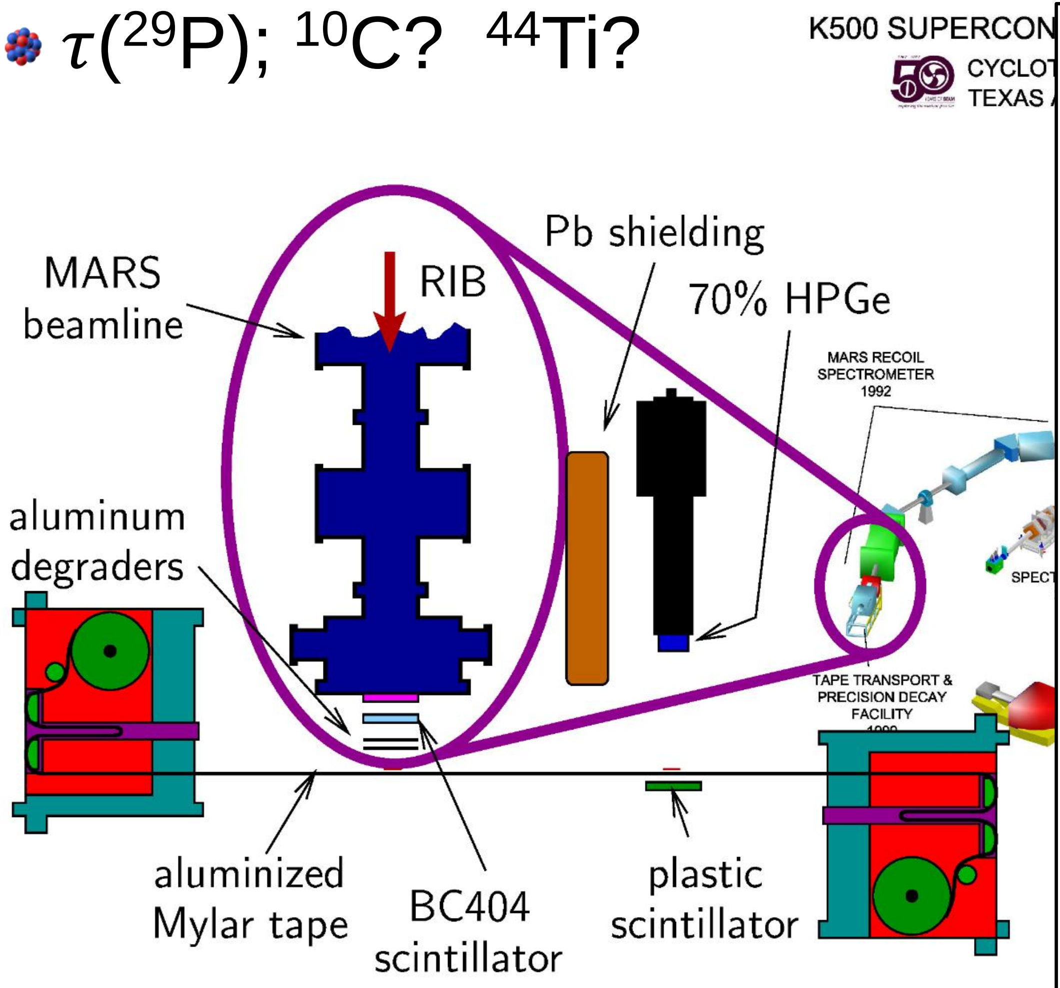
Improving the ft value at the Cyclotron Institute

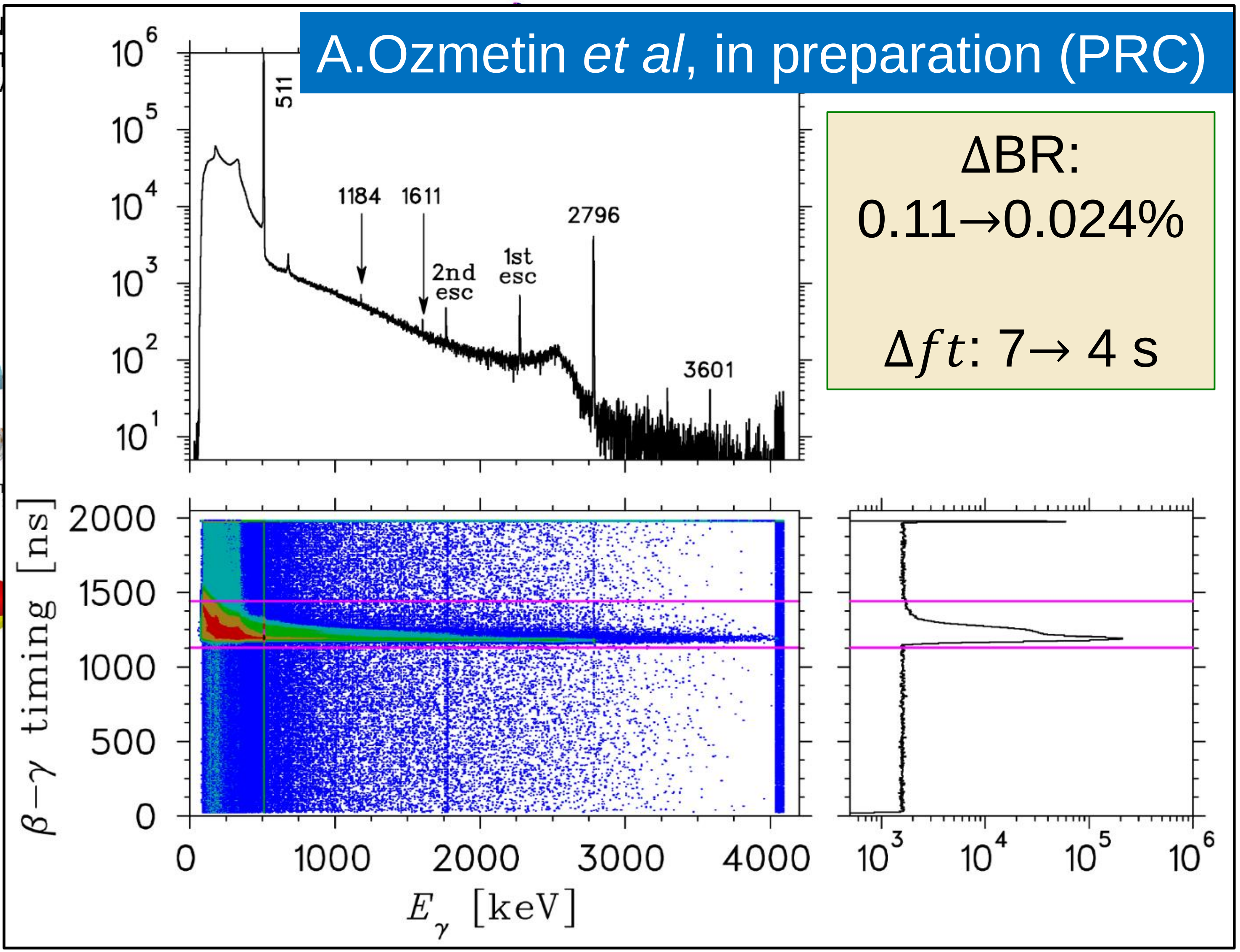
- Fast-tape transport system and Hardy's HPGe detector still being used!



Improving the ft value at the Cyclotron Institute

- Fast-tape transport system and Hardy's HPGe detector still being used!
- $\tau(^{29}P)$; ^{10}C? ^{44}Ti?



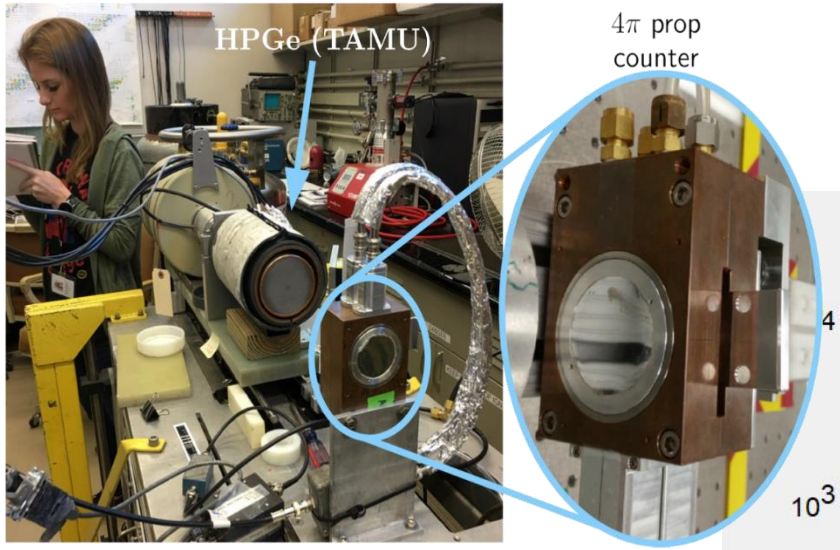


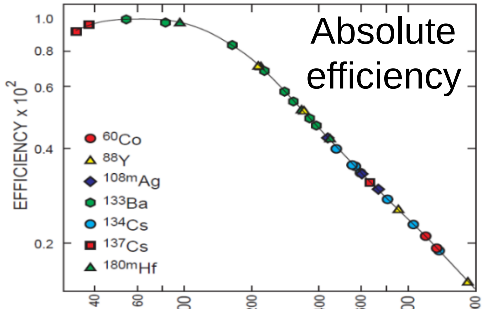
ΔBR: 0.11→0.024%

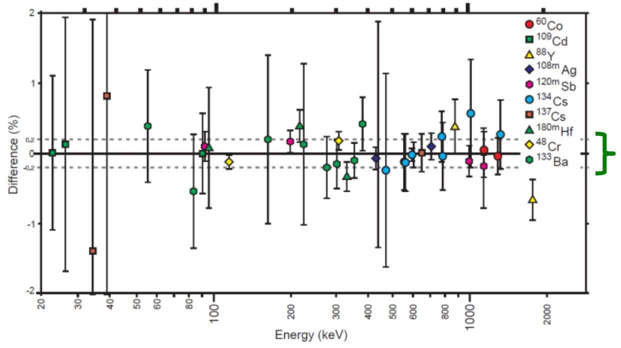
Δft: 7→ 4 s

γ-ray yields of fission fragments

R.G.Helmer, INEEL Gamma-Ray Spectrum Catalogue
Ge and Si Detector Spectra. (4th ed., 1999)

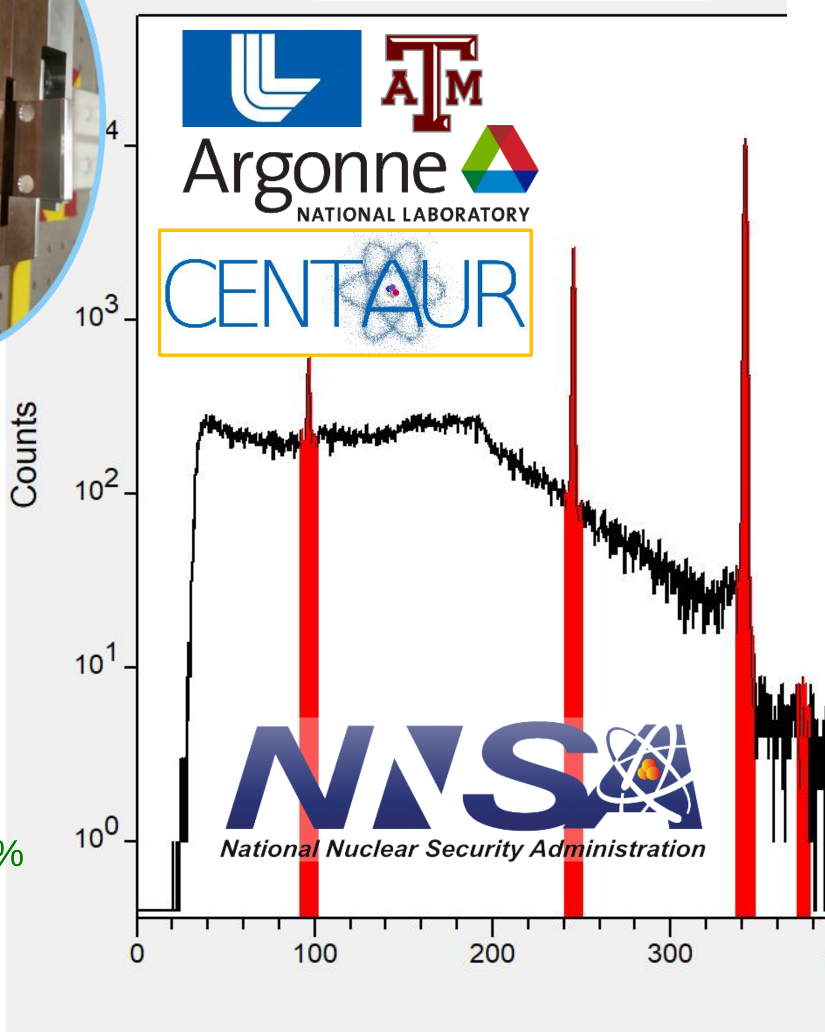


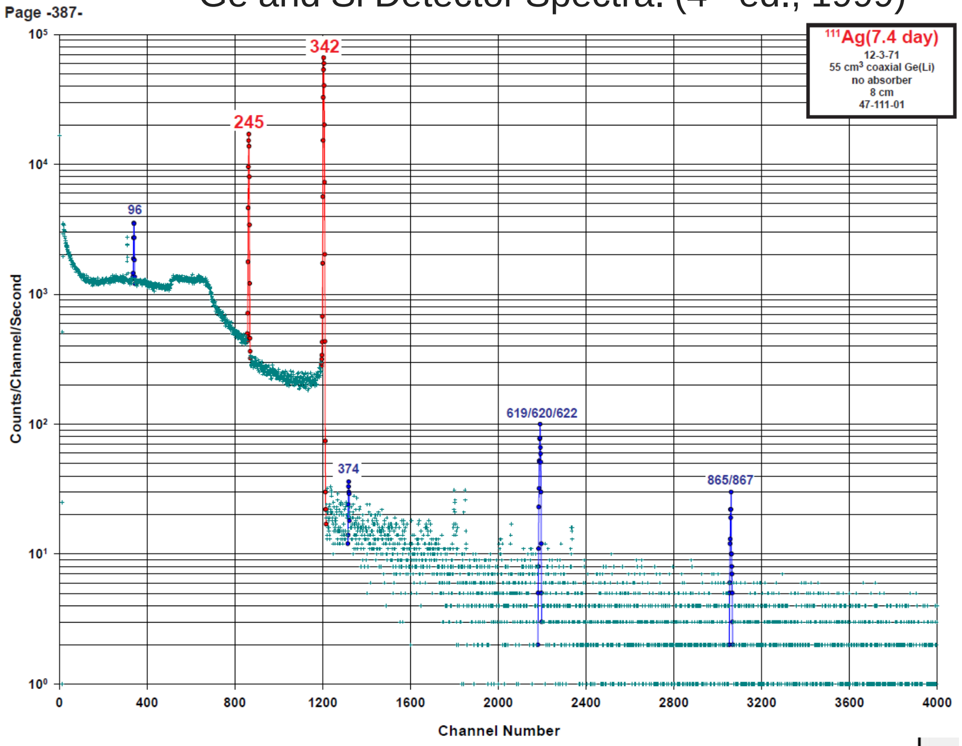




} ±0.2%

Best available before the 2022 CI measurement





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^{6}He, ^{19}Ne (^{14}O) at UW – CRES technique

- Cyclotron Radiation Emission Spectroscopy (CRES) represents a quantum leap in charged-particle spectroscopy
- Innovation: cover wide band of energies for MeV-scale βs (^{6}He, ^{19}Ne, ^{14}O)

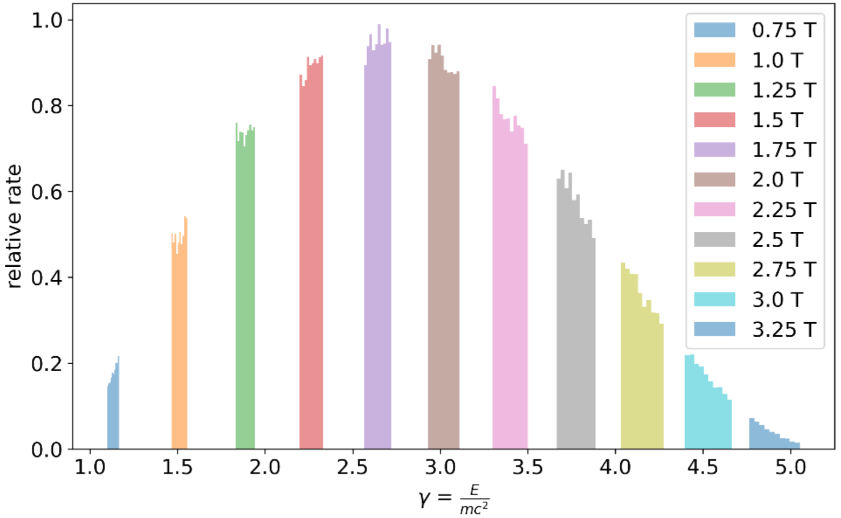
Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

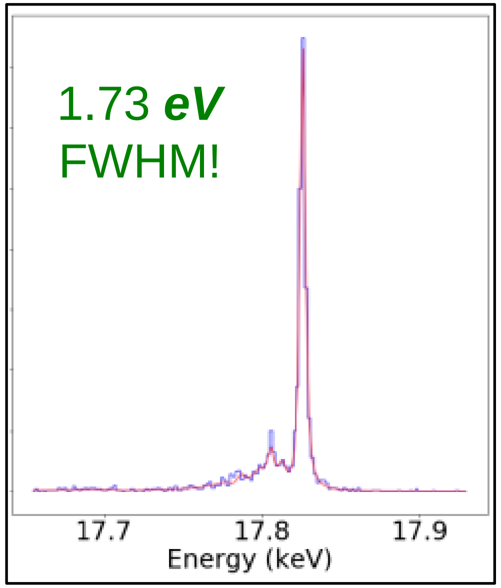
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

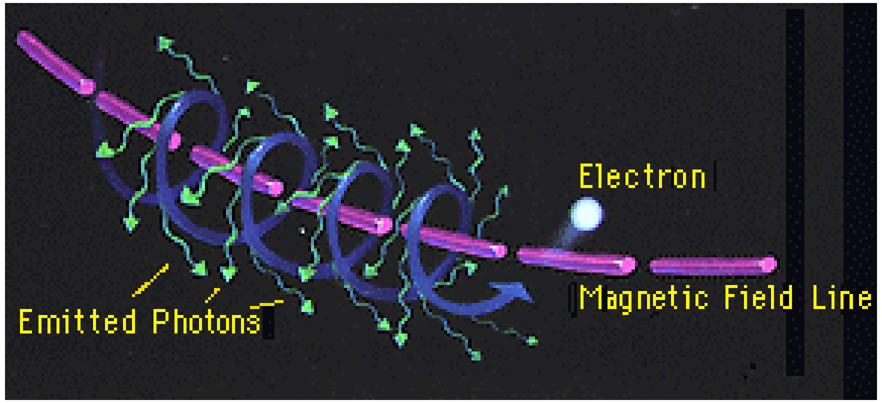
D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. 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)

6He-CRES







^{6}He, ^{19}Ne (^{14}O) at UW – CRES technique

- Cyclotron Radiation Emission Spectroscopy (CRES) represents a quantum leap in charged-particle spectroscopy
- Innovation: cover wide band of energies for MeV-scale βs (^{6}He, ^{19}Ne, ^{14}O)
- Goal: $\Delta b \leq 10^{-3}$, ***better*** than the LHC can limit scalar/tensor interactions

^{6}He-CRES

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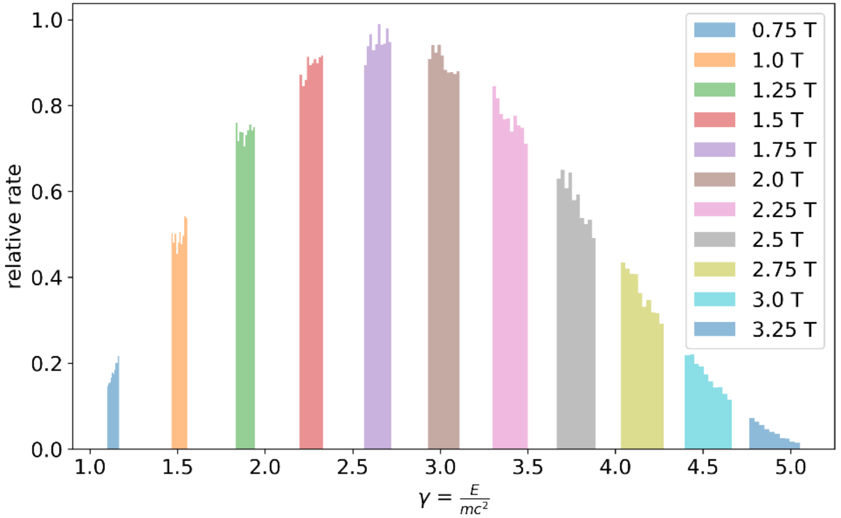
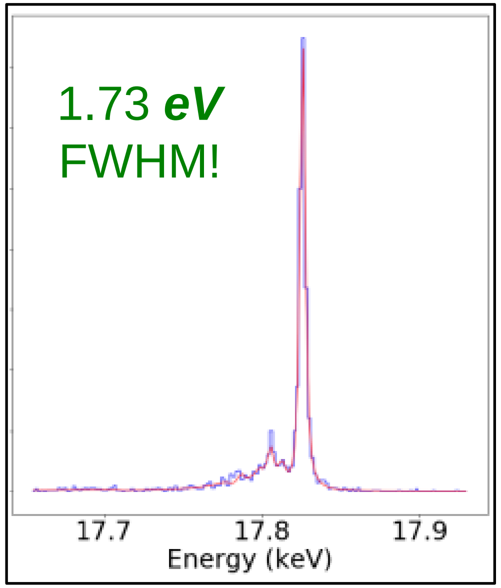
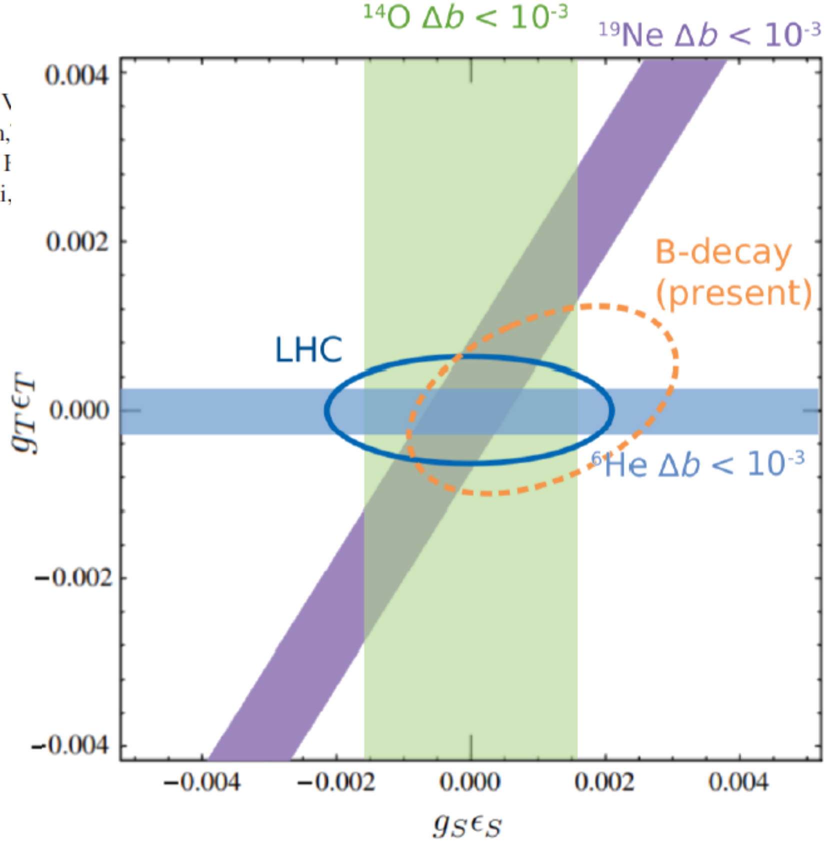
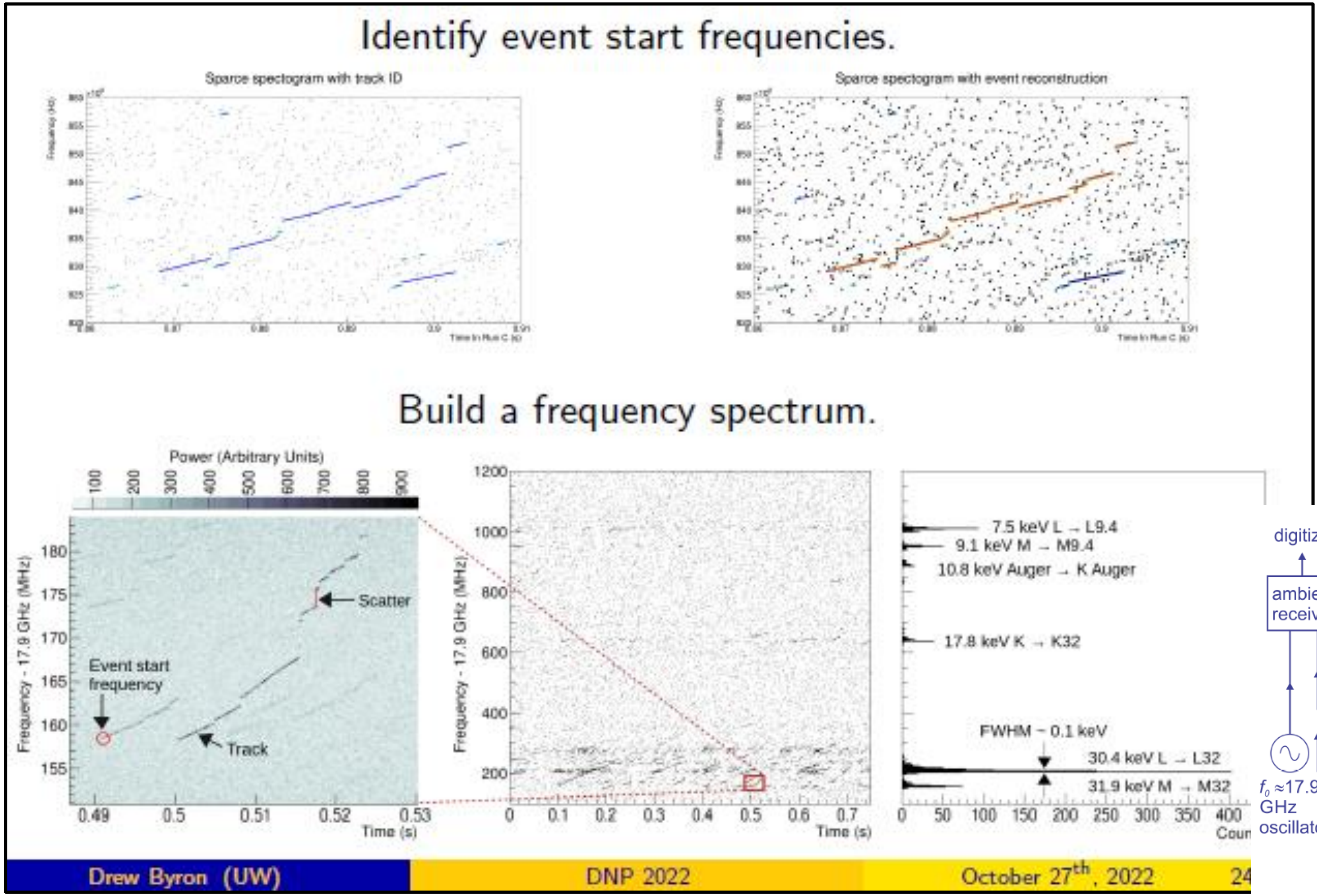


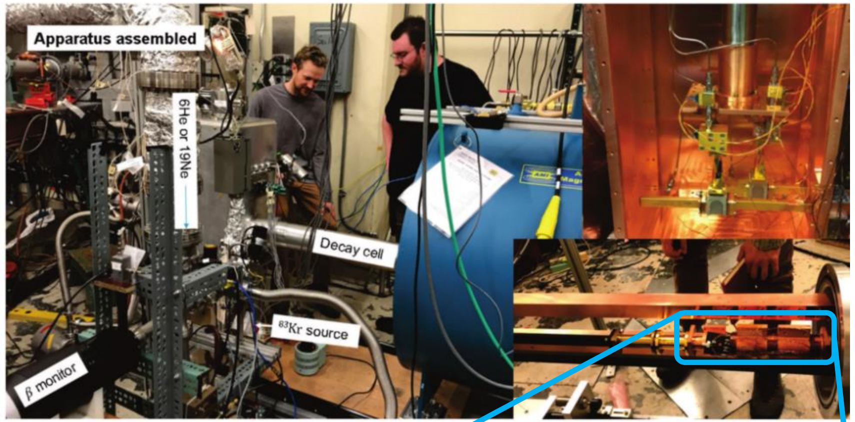


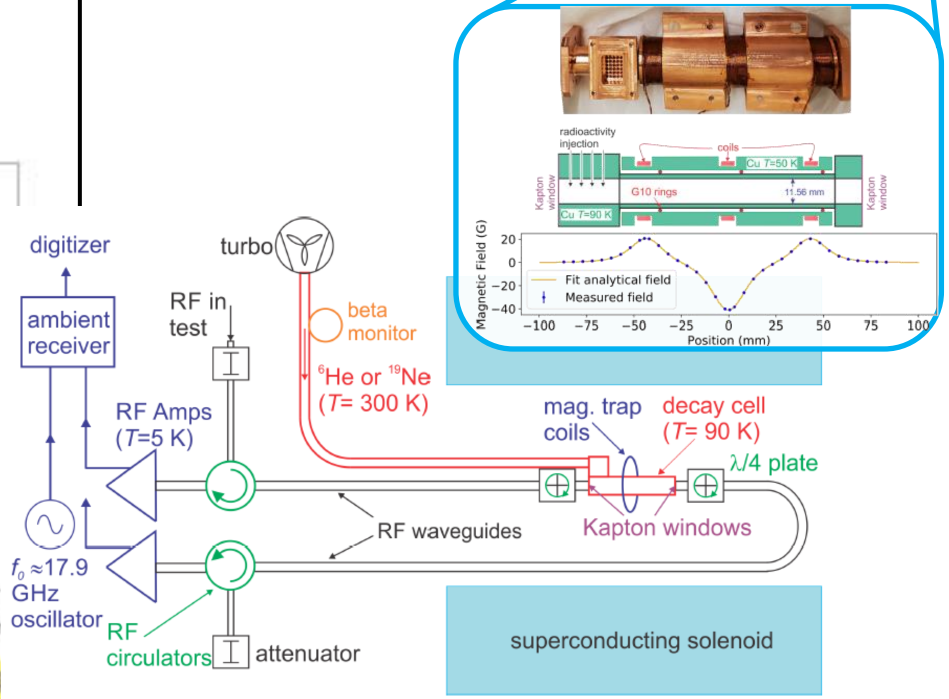


^{6}He at UW – CRES technique

- First CRES signals from nuclear β decay observed!







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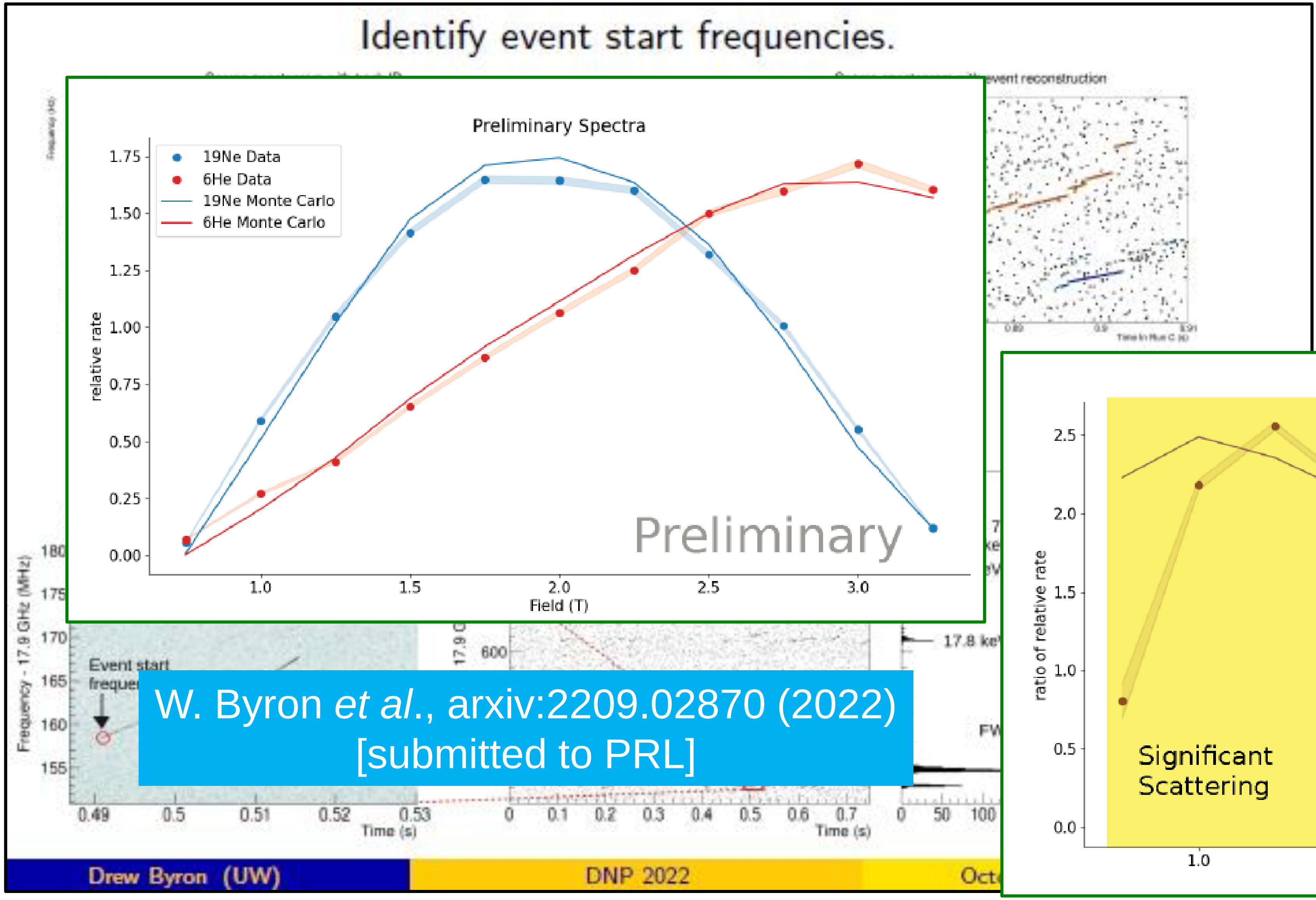
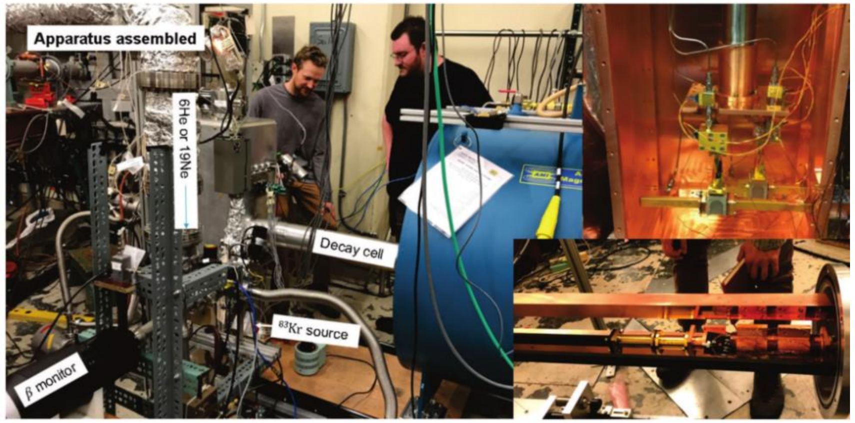
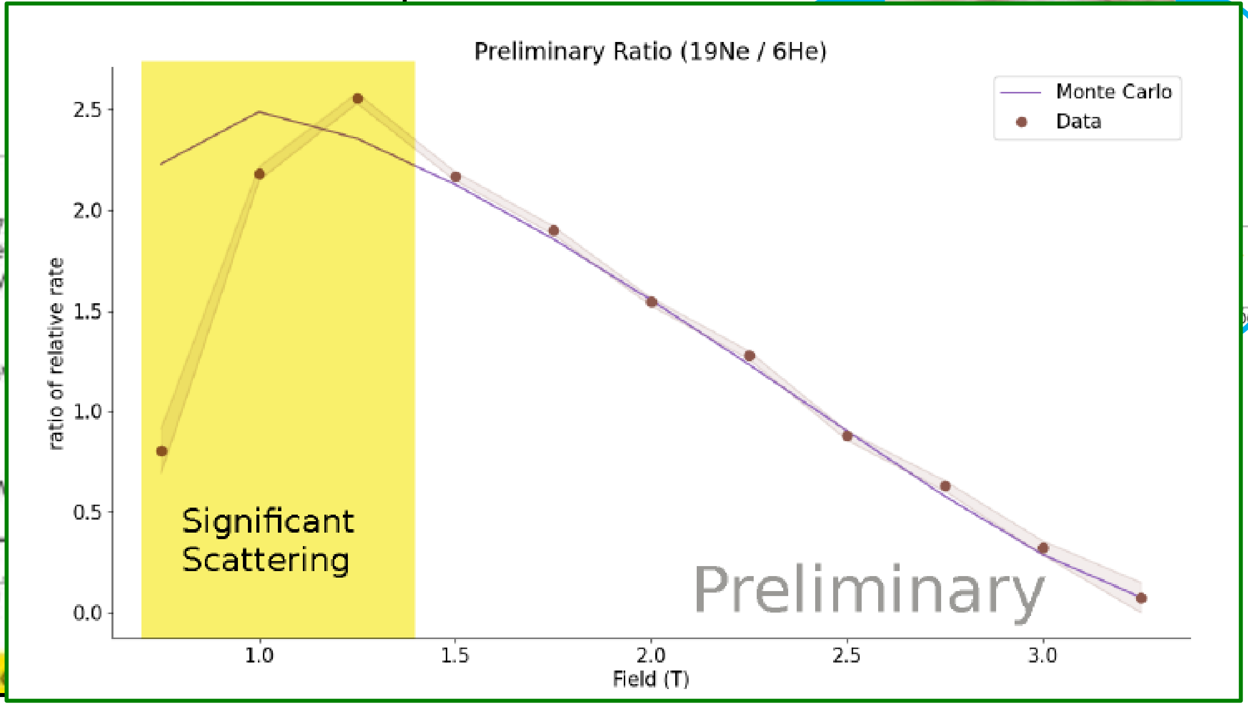


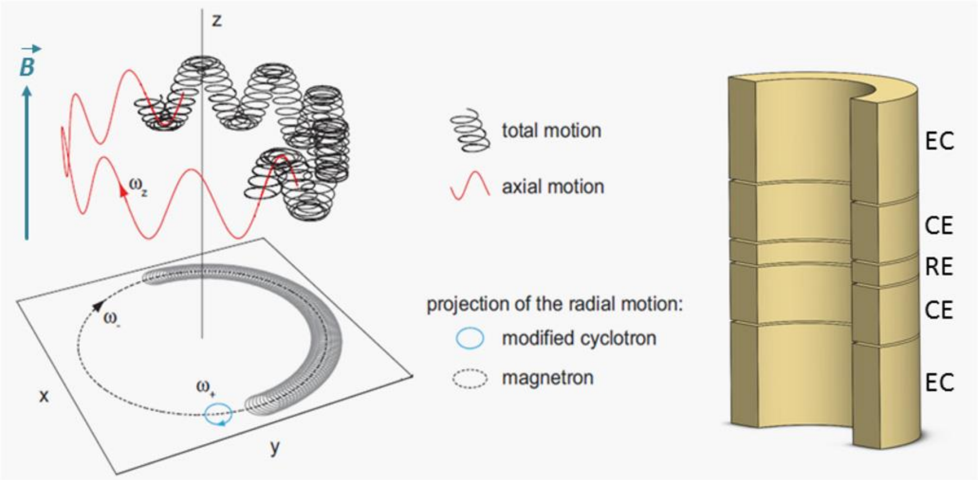
W. Byron *et al.*, arxiv:2209.02870 (2022) [submitted to PRL]



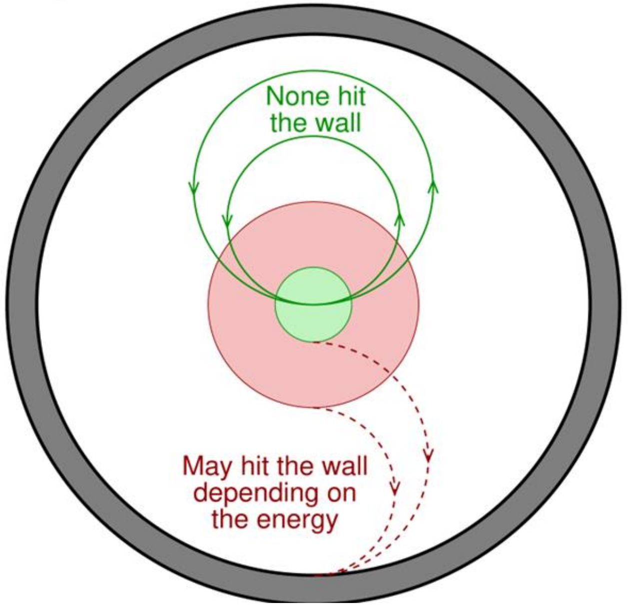


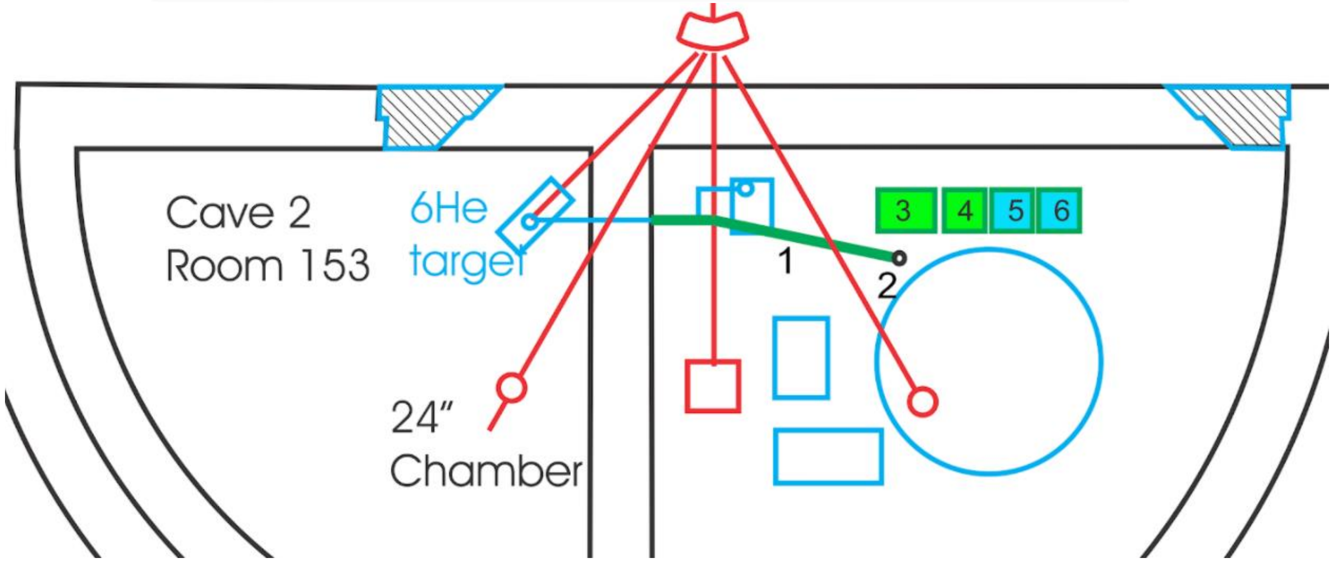
Upgrade of CRES: radial confinement using a trap

- Expected limiting factor: wall effects
- Solution: Decay cell → Penning trap!



Largest and smallest electron orbits at 2 T





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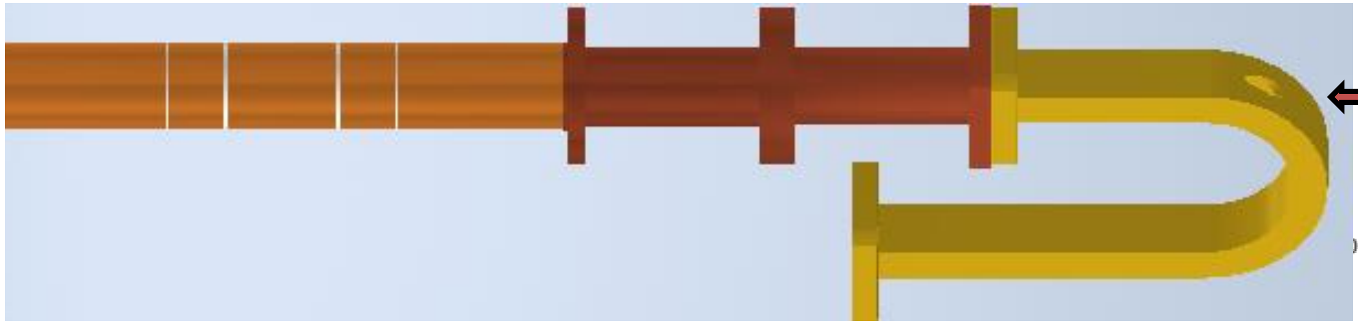

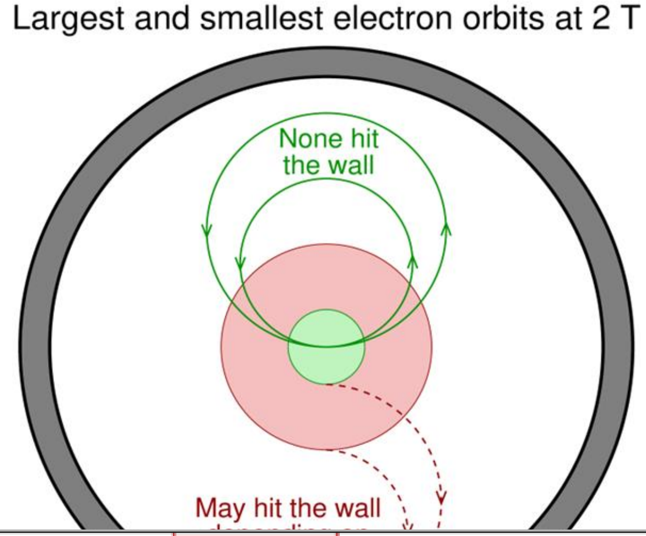

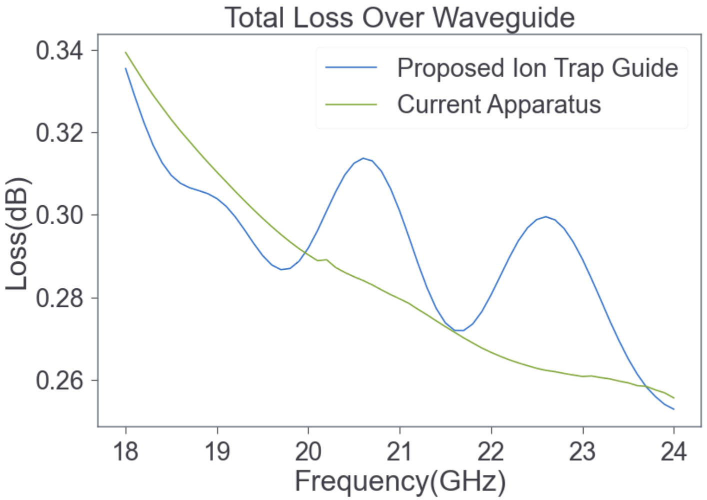

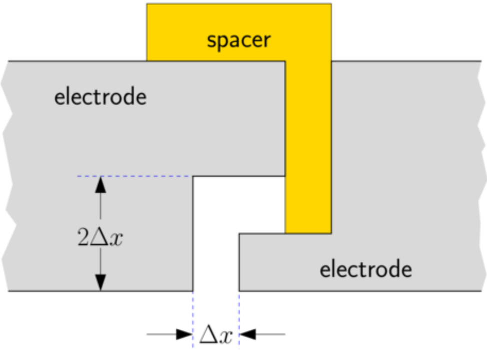

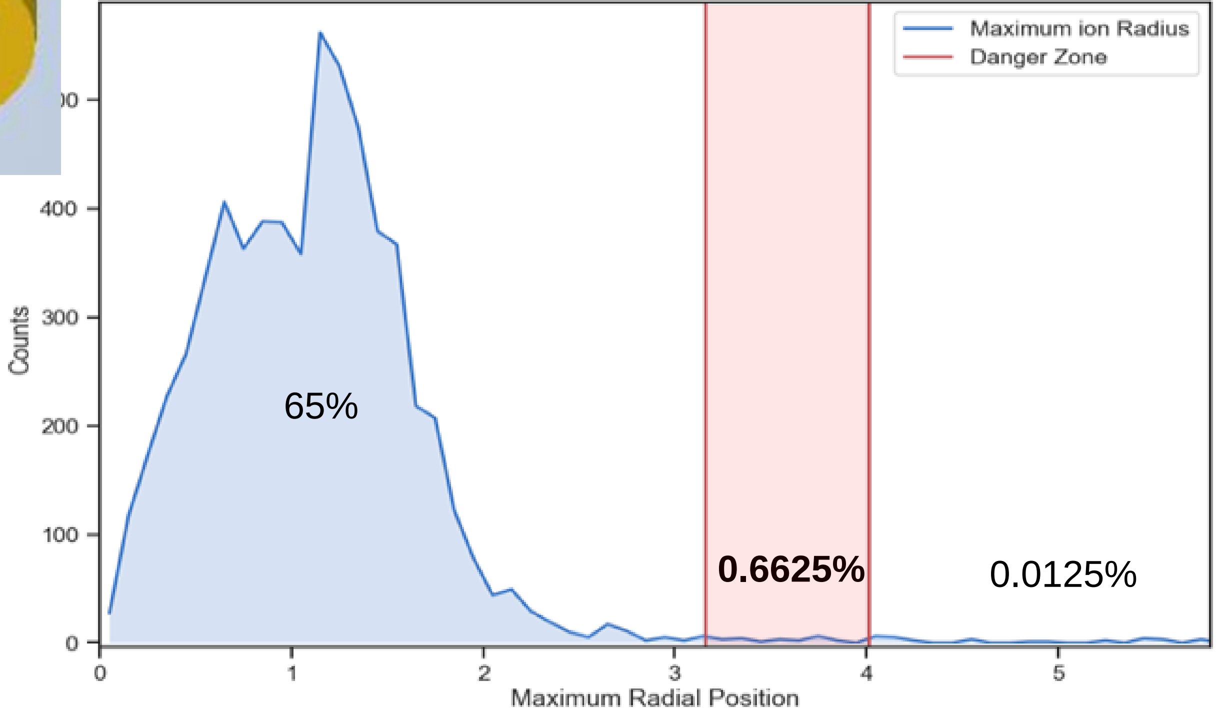

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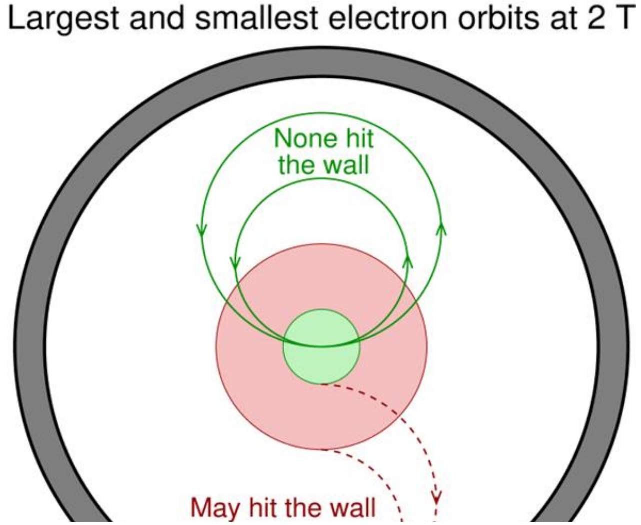
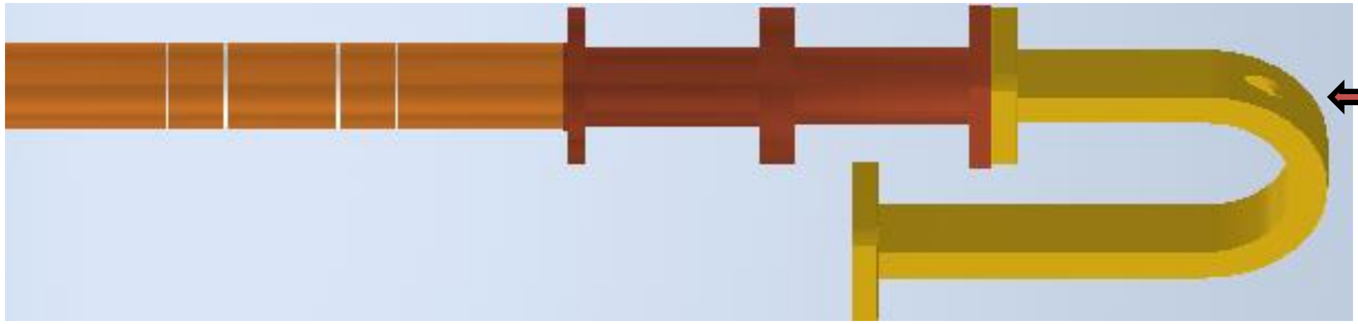
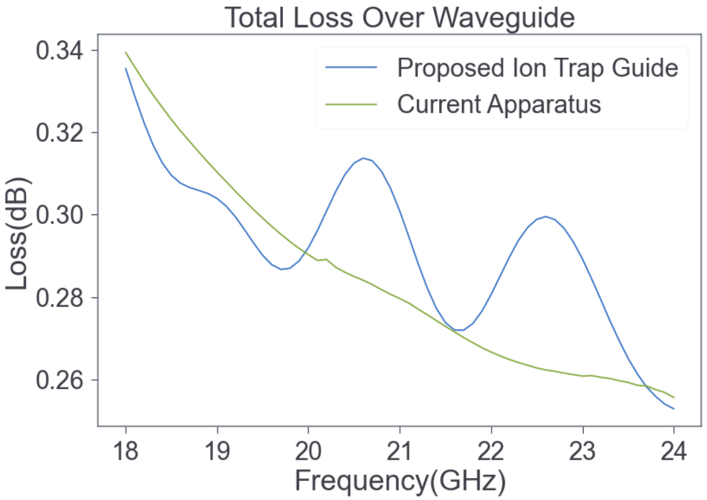
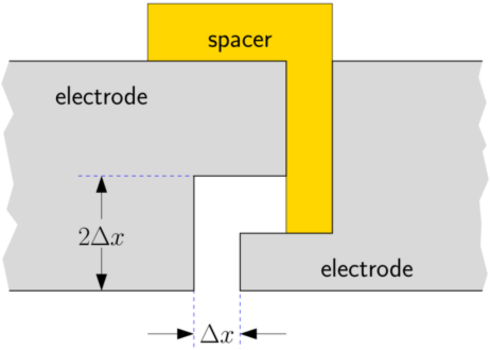
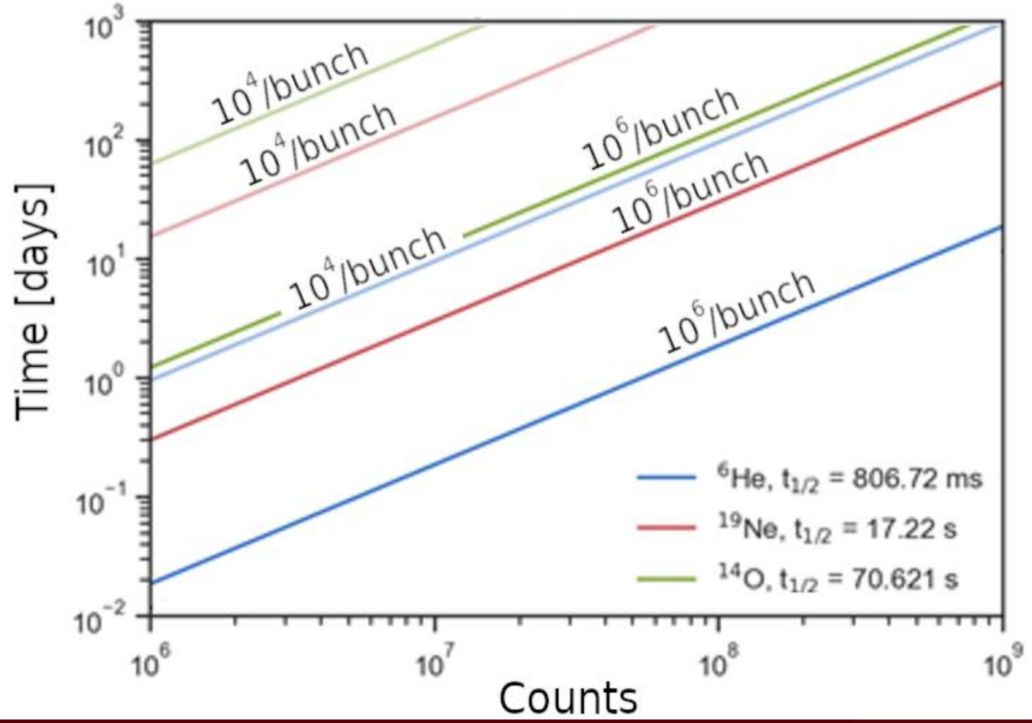










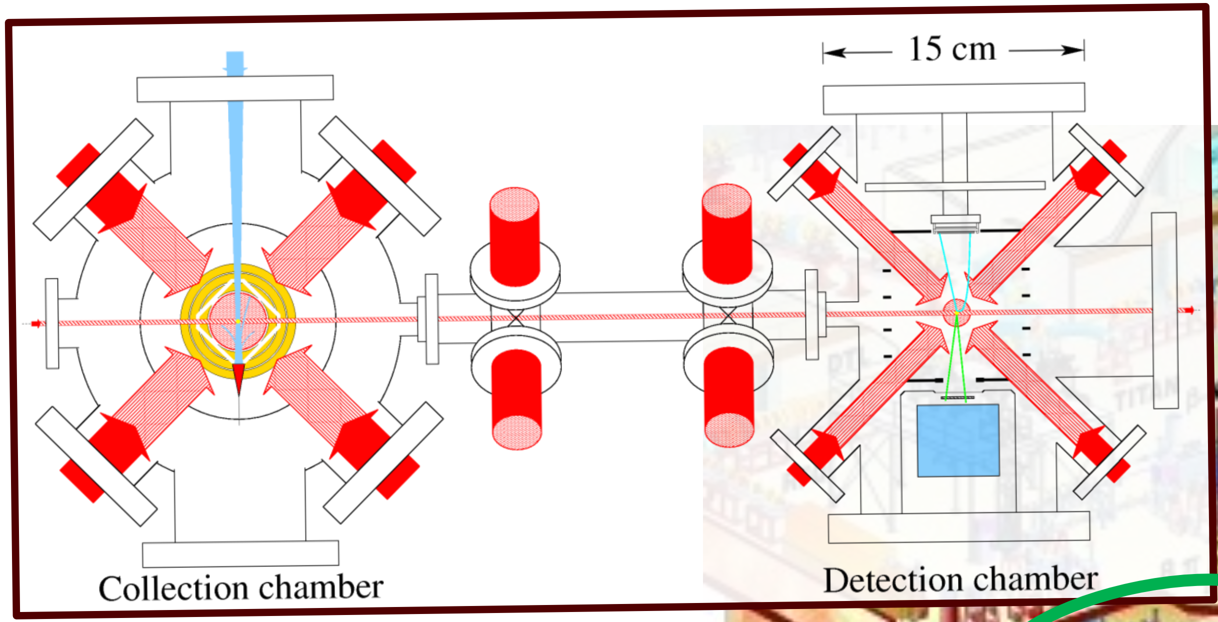
Upgrade of CRES: radial confinement using a trap

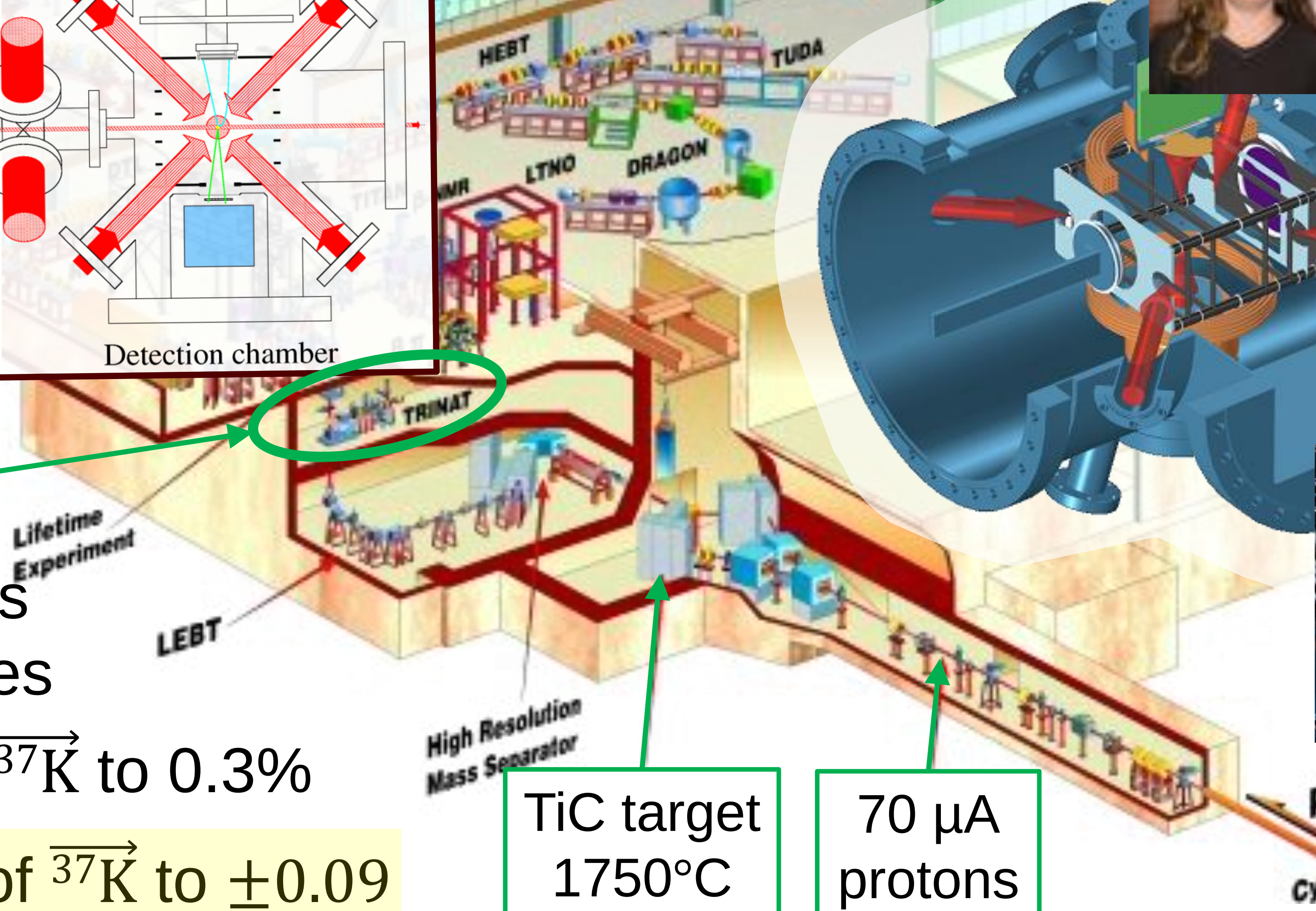
- Expected limiting factor: wall effects
- Solution: Decay cell → Penning trap!
  - It should work…*if* we can get 10^6 ions/s through the RFQ
- Bids for RFQ almost ready to go out
  - Borrow from TAMUTRAP (chamber, gas-handling, power supplies, pumps) for tests with Li^+ in H_2 buffer gas, Fall 2023
- Penning trap is designed; save (relatively simple) construction once high-capacity RFQ is demonstrated
- Working with G. Savard and P. Mueller (ANL), plan to submit a proposal for upgrade this fall
  - Ionizer, Wien filter, RFQ, Penning trap and associated beamlines/power supplies

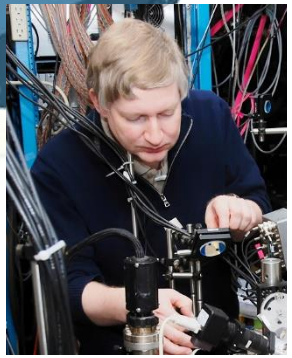
Outline

- **Introduction/motivation**
  - Testing the standard model via the precision frontier using nuclear β decay
- **He-LIG + LSTAR**
  - RIB production and purification of proton-rich nuclei
- **TAMUTRAP and WISArD**
  - $T = 2$ decays to test the SM via kinematic shift of β-delayed protons
- **Other CI efforts**
  - Lifetimes and branching ratios for improving V_{ud}; fission-fragment γ yields
- **^{6}He-CRES**
  - Cyclotron radiation emission spectroscopy on ^{6}He, ^{19}Ne and ^{14}O at CENPA
- **TRINAT**
  - Asymmetry measurements of highly-polarized, laser-cooled atoms
- **Outlook for the next 3 years**

The TRIUMF Neutral Atom Trap







up to 8×10^7 ^{37}K/s

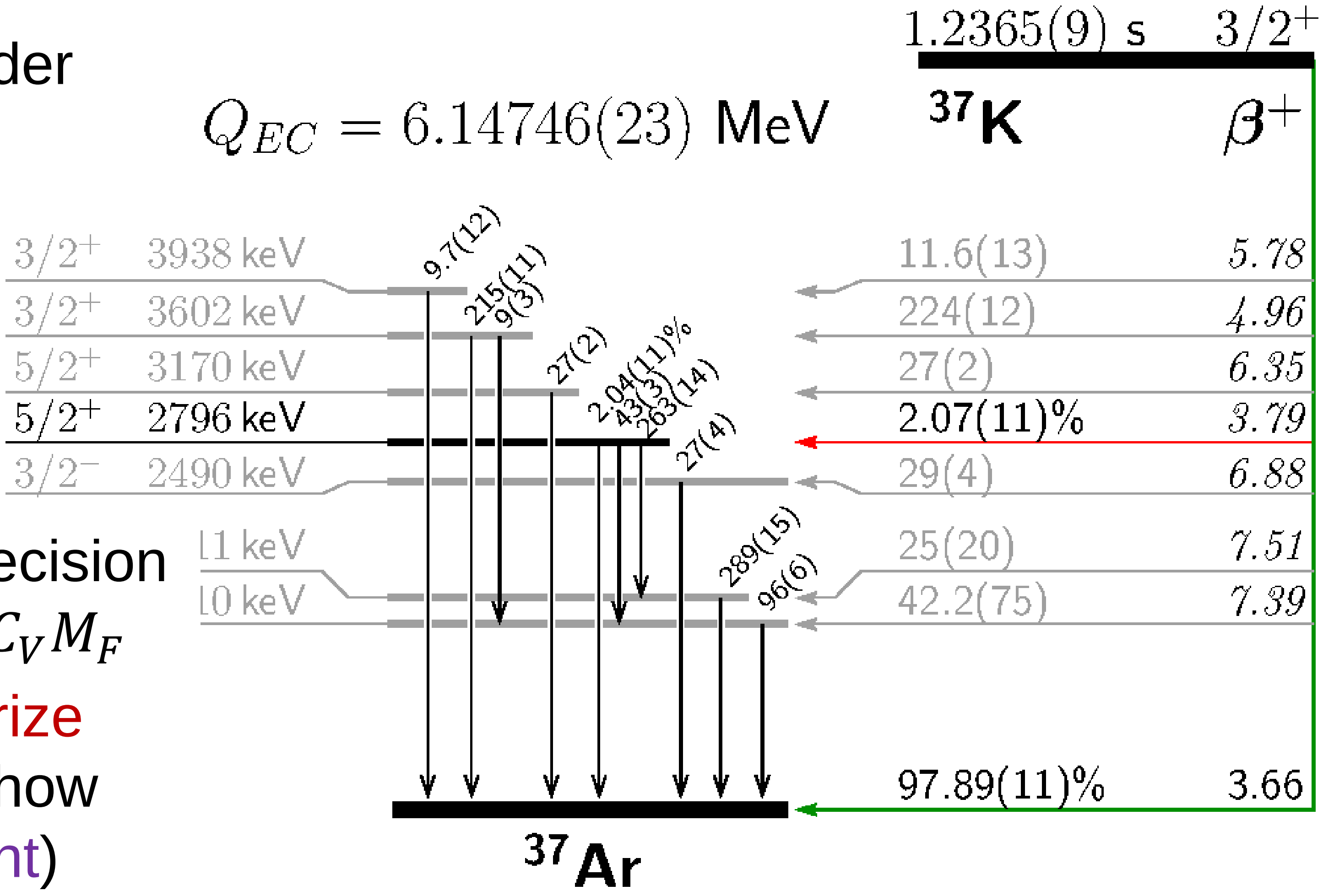
TiC target 1750°C

70 µA protons

- Angular correlations of K and Rb isotopes
- 2018 result: A_β of $\overrightarrow{^{37}\mathrm{K}}$ to 0.3%
- 2023 result: b_{Fierz} of $\overrightarrow{^{37}\mathrm{K}}$ to ± 0.09

Isobaric analogue decay of ^{37}K

- Beautiful nucleus to test the standard model:
  - Alkali atom ⇒ "easy" to trap with a MOT and polarize with optical pumping
  - Isobaric analogue decay
    ⇒ theoretically clean; recoil-order corrections under control
  - Lifetime, *Q*-value and branches (*i.e.* the $\mathcal{F}t$ value) well known
  - Strong branch to the g.s.
- But there are challenges…
  - Can't calculate $C_A M_{GT}$ to high precision
    ⇒ need to measure $\rho \equiv C_A M_{GT}/C_V M_F$
  - Nuclear spin 3/2 ⇒ need to polarize the atoms, and especially know how polarized they are (also alignment)



The Ft is measured well enough (for now)

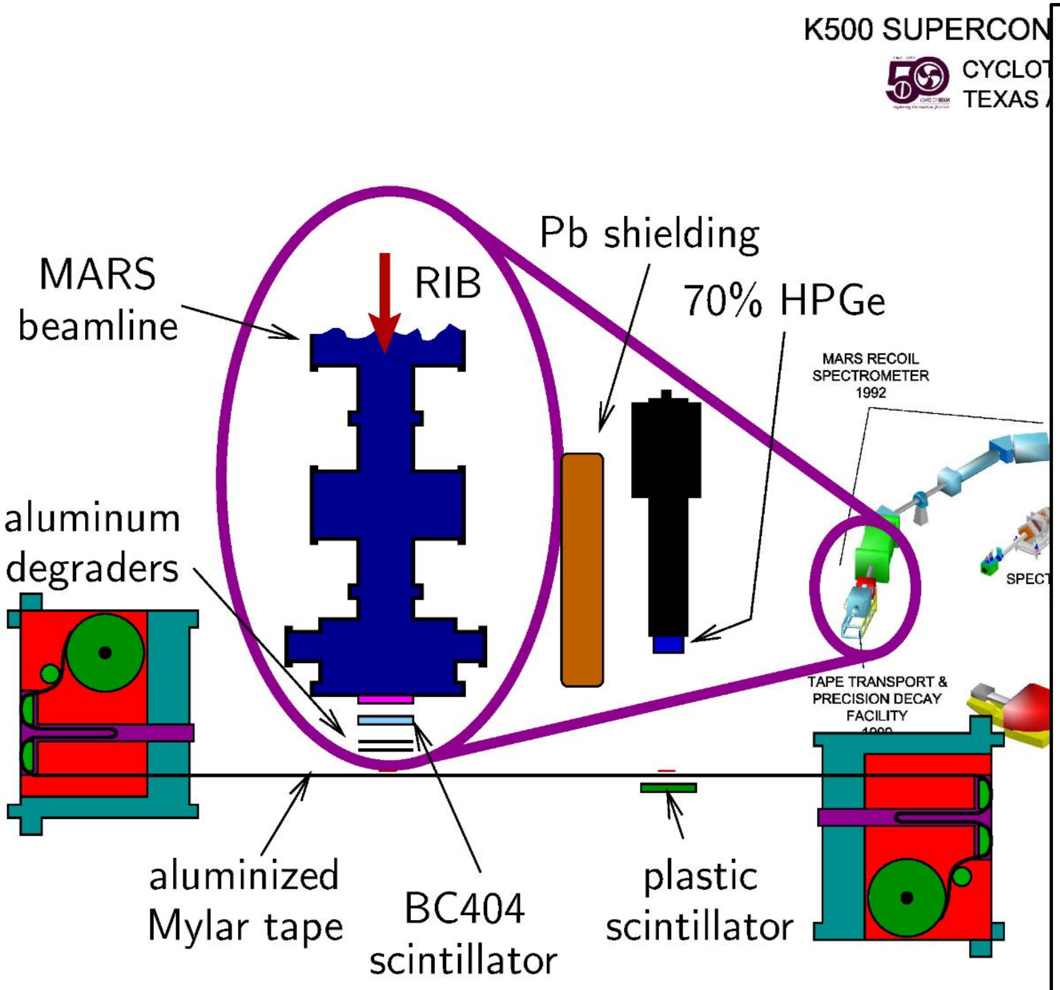
$$dW = dW_0 \left[1 + a \frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b \frac{\Gamma m_e}{E_\beta} + \frac{\langle \vec{I} \rangle}{I} \cdot \left(A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right) + \text{alignment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

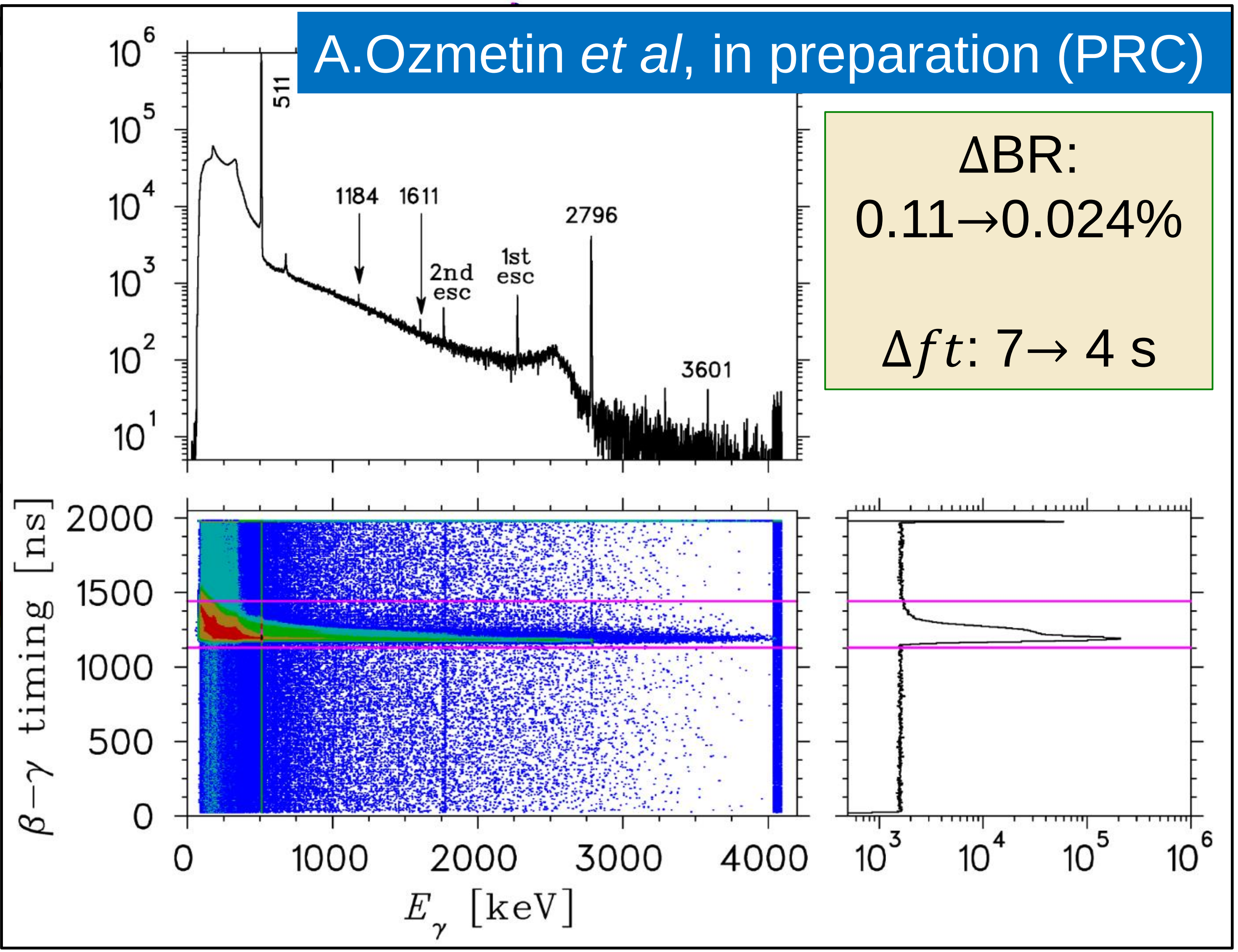
Correlation	SM expectation
$\beta - \nu$ correlation	$a_{\beta\nu} = 0.6648(18)$
Fierz interference	$b = 0$ (sensitive to scalars & tensors)
β asymmetry	$A_\beta = -0.5706(7)$
ν asymmetry	$B_\nu = -0.7702(18)$
Time-violating correlation	$D = 0$ (sensitive to imaginary couplings)

SM predictions currently limited by the >20-yr-old 97.89(11)% ground state branching ratio

Improving the ft value at the Cyclotron Institute

- Fast-tape transport system and Hardy's HPGe detector still being used!





A.Ozmetin *et al*, in preparation (PRC)

ΔBR: 0.11→0.024%

Δft: 7→ 4 s

he Ft is measured well enough

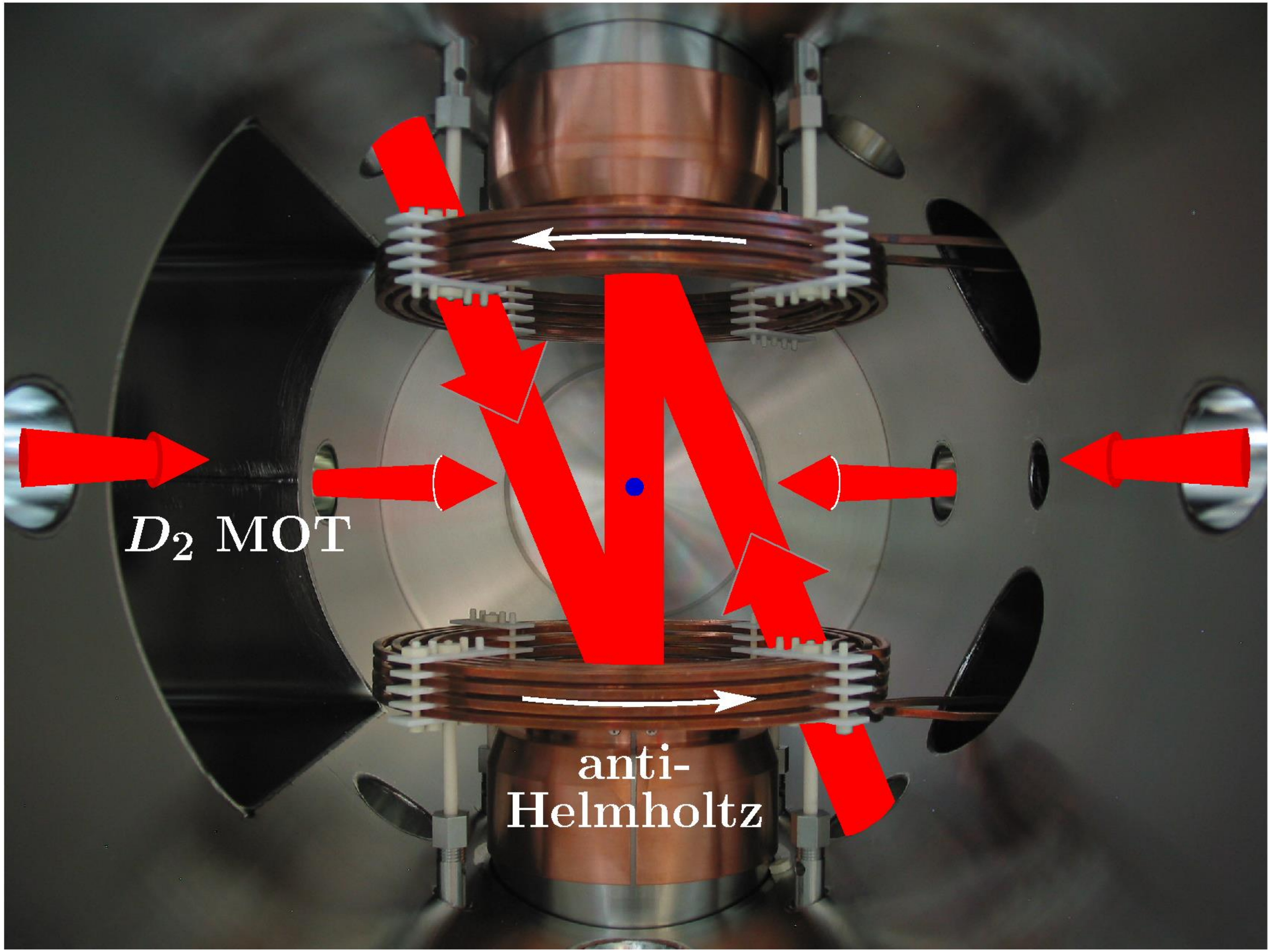
$$dW = dW_0 \left[1 + a\frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle \vec{I} \rangle}{I} \cdot \left(A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right) + \begin{matrix}\text{alignment}\\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

Correlation	SM expectation
$\beta - \nu$ correlation	$a_{\beta\nu} = 0.6648(\mathbf{18}) \rightarrow 0.6668(\mathbf{11})$
Fierz interference	$b = 0$ (sensitive to scalars & tensors)
β asymmetry	$A_\beta = -0.5706(\mathbf{7}) \rightarrow -0.5708(\mathbf{4})$
ν asymmetry	$B_\nu = -0.7702(\mathbf{18}) \rightarrow -0.7707(\mathbf{11})$
Time-violating correlation	$D = 0$ (sensitive to imaginary couplings)

⇝ A precision measurement of A_β will not be limited by uncertainties in the SM predictions ⇜

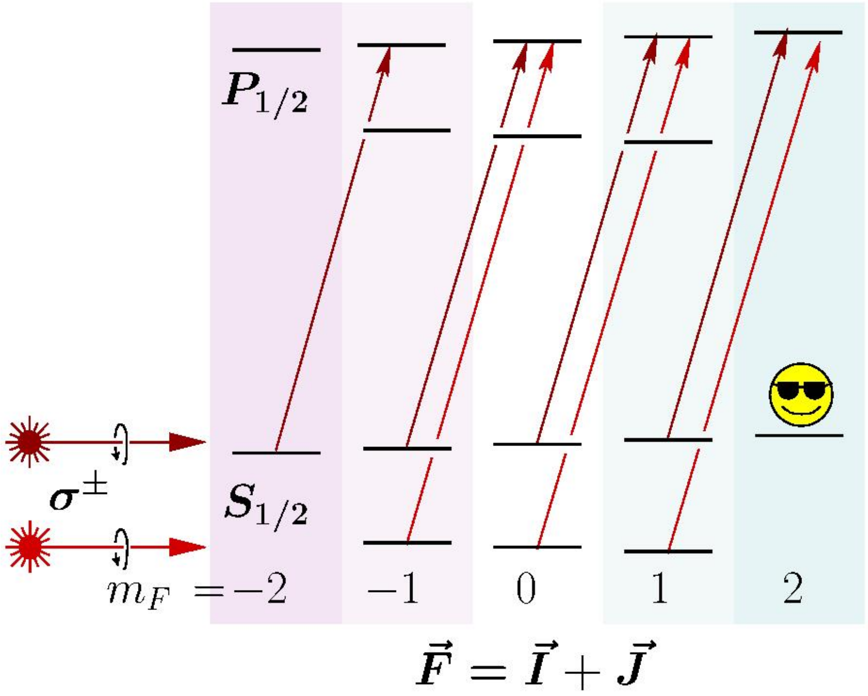
Outline of TRINAT's β asym & polarization measurements

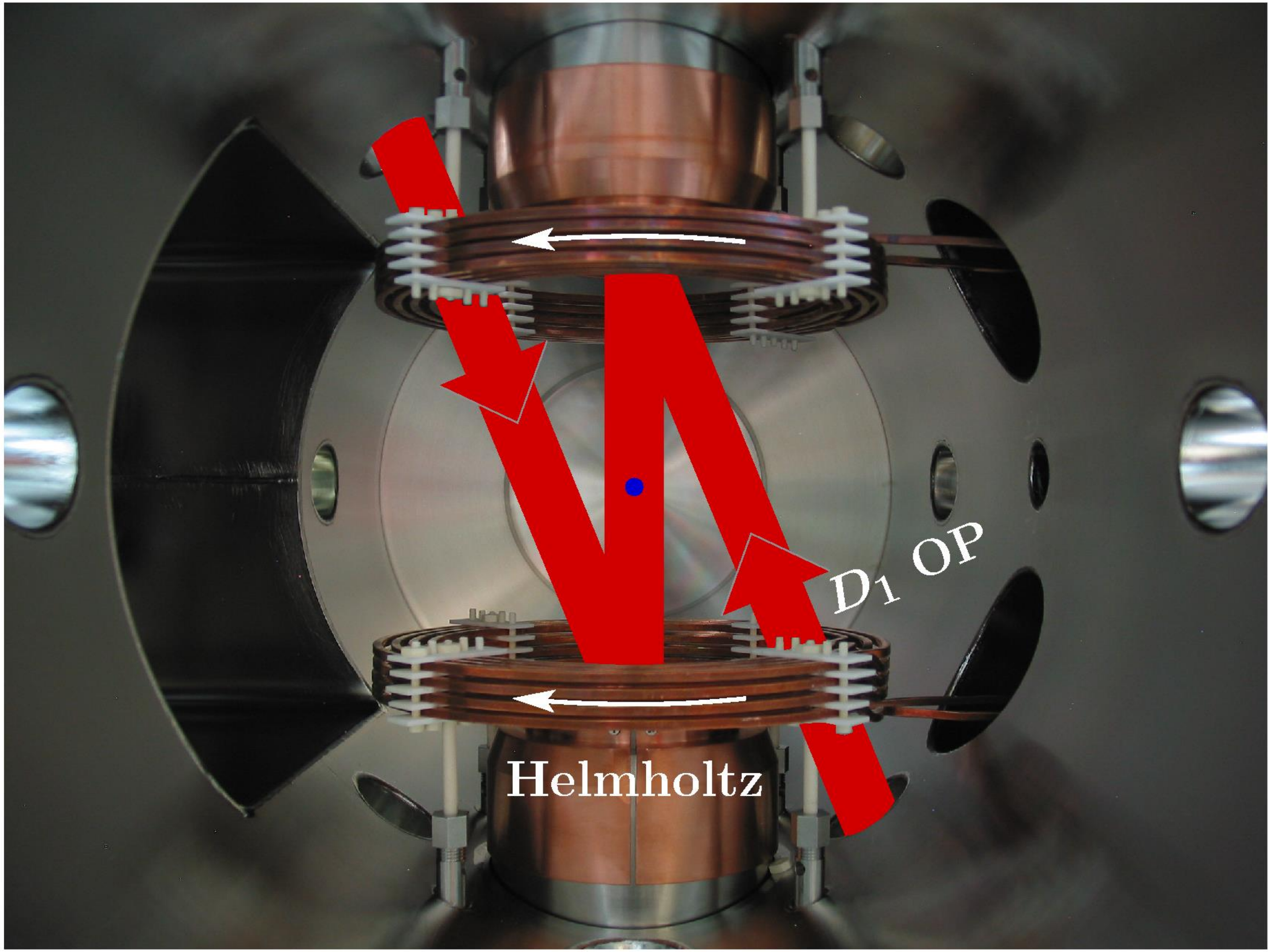
- MOTs provide a source that is:
  - Cold (~ 1 mK)
  - Localized ($\sim 1\ \text{mm}^3$)
  - In an open, backing-free geometry
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\text{rec}}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event



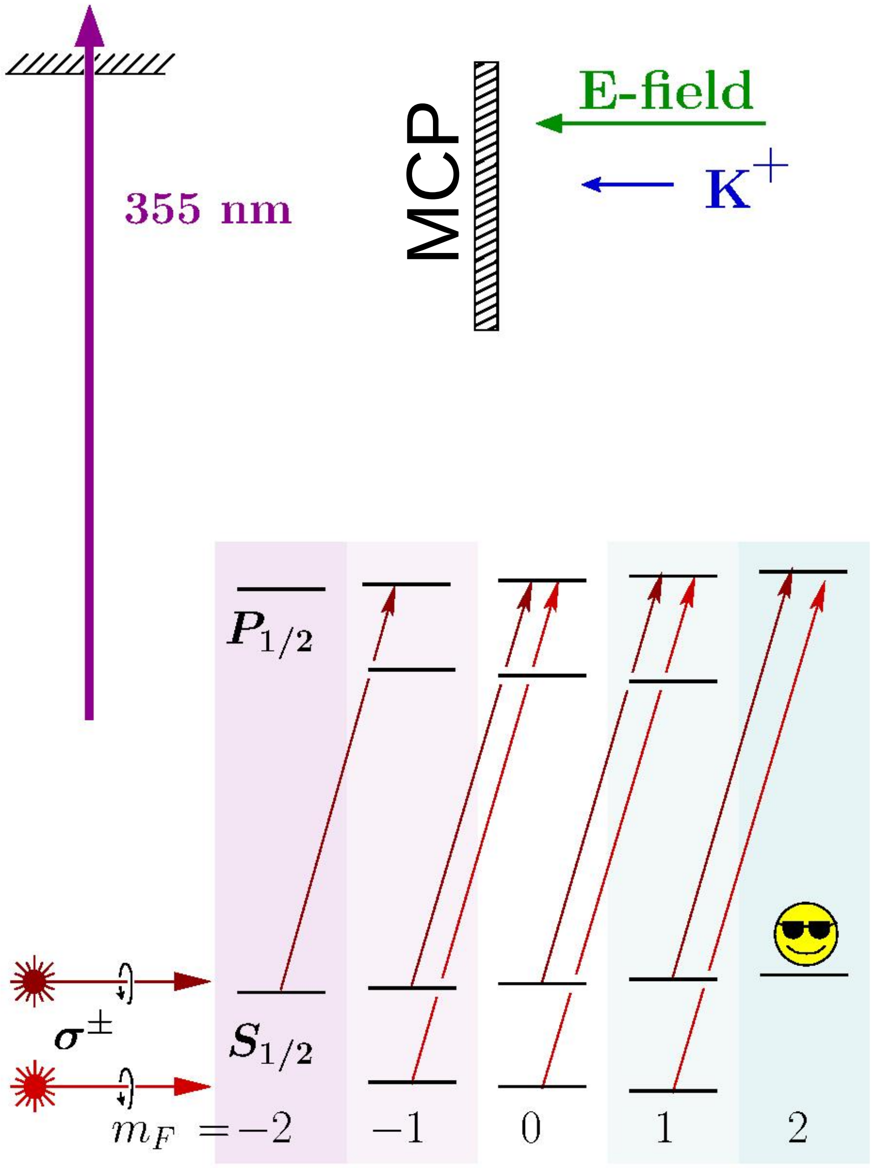
Outline of TRINAT's β asym & polarization measurements

- Optical pumping:
  - Polarized light transfers angular momentum to the atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand

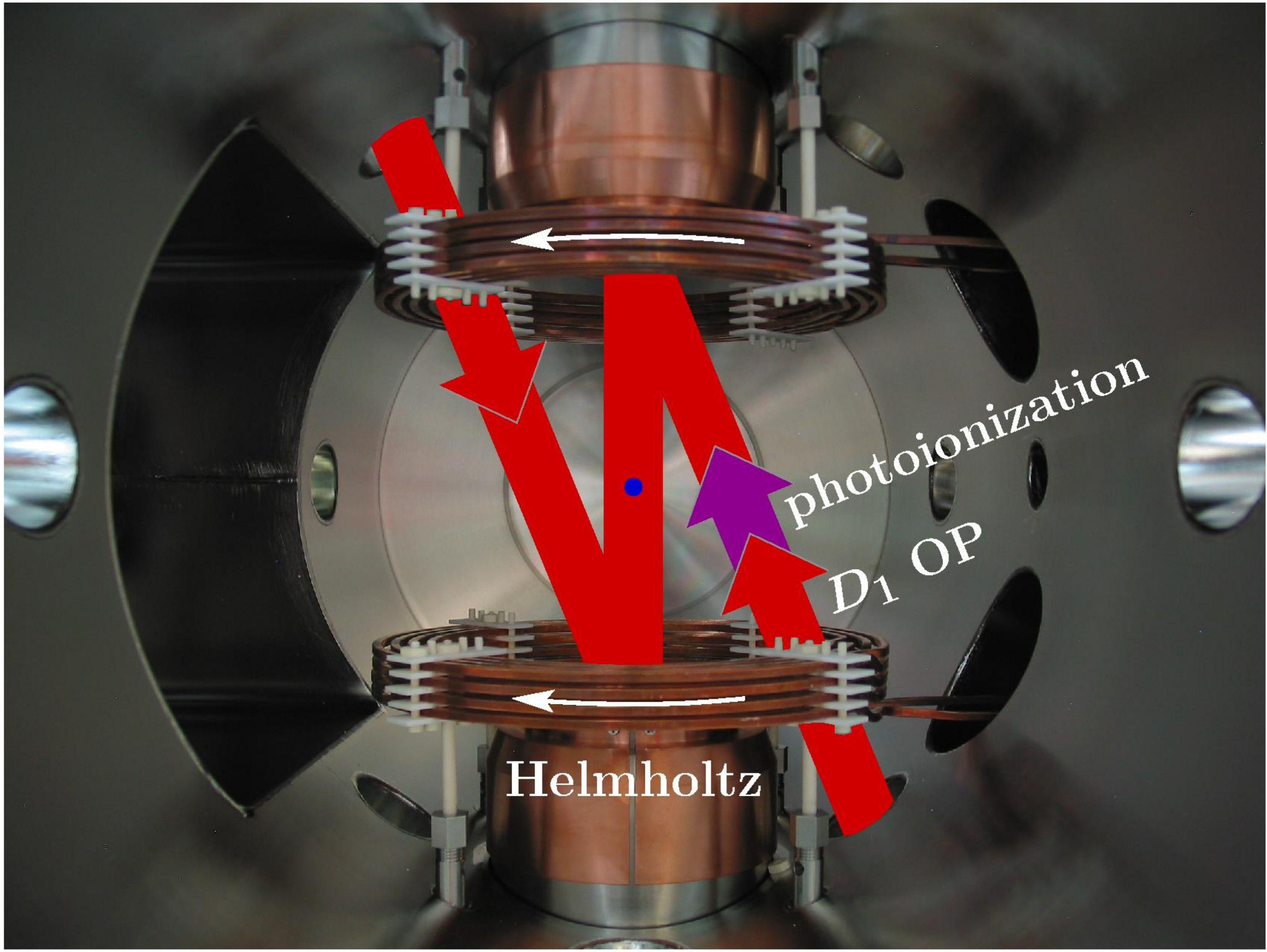




Outline of TRINAT's β asym & polarization

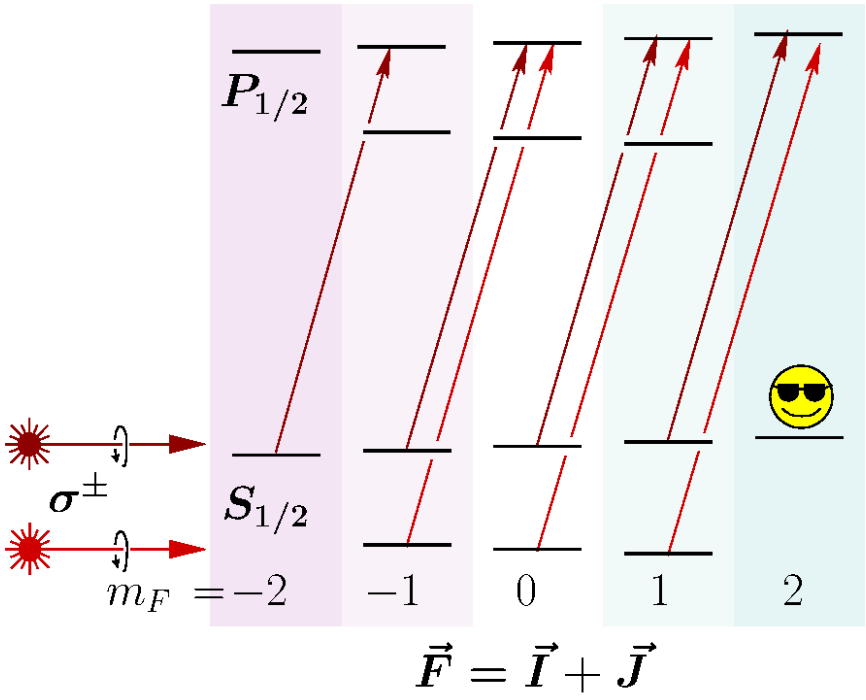


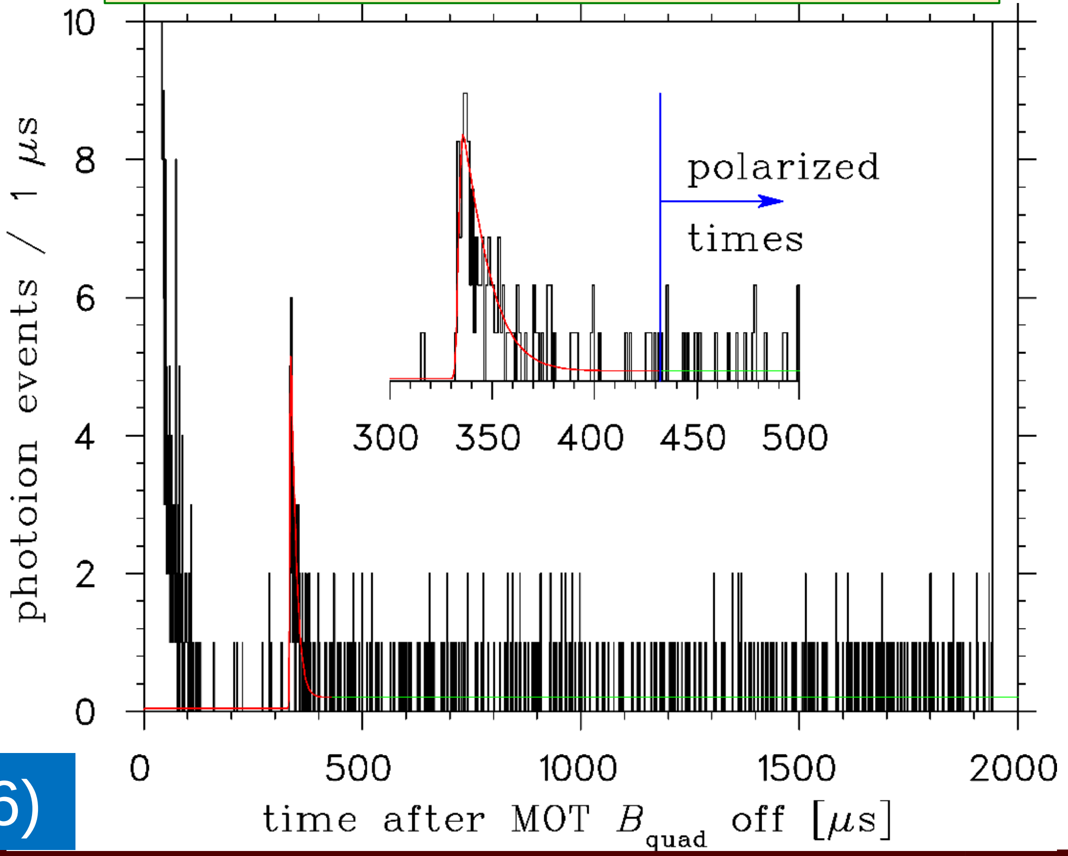
$\vec{F} = \vec{I} + \vec{J}$



Optical pumping is fast and *efficient*!

- No time to go into details, but basically
  - Measure the rate of photons (⇔ fluorescence) as a function of time
  - Model sublevel populations using the optical Bloch equations
  - Determine the average nuclear polarization: $\langle|P_{\mathbf{nucl}}|\rangle = 0.9913(9)$





B.Fenker *et al*, New J. Phys. **18**, 073028 (2016)

The β asymmetry measurement

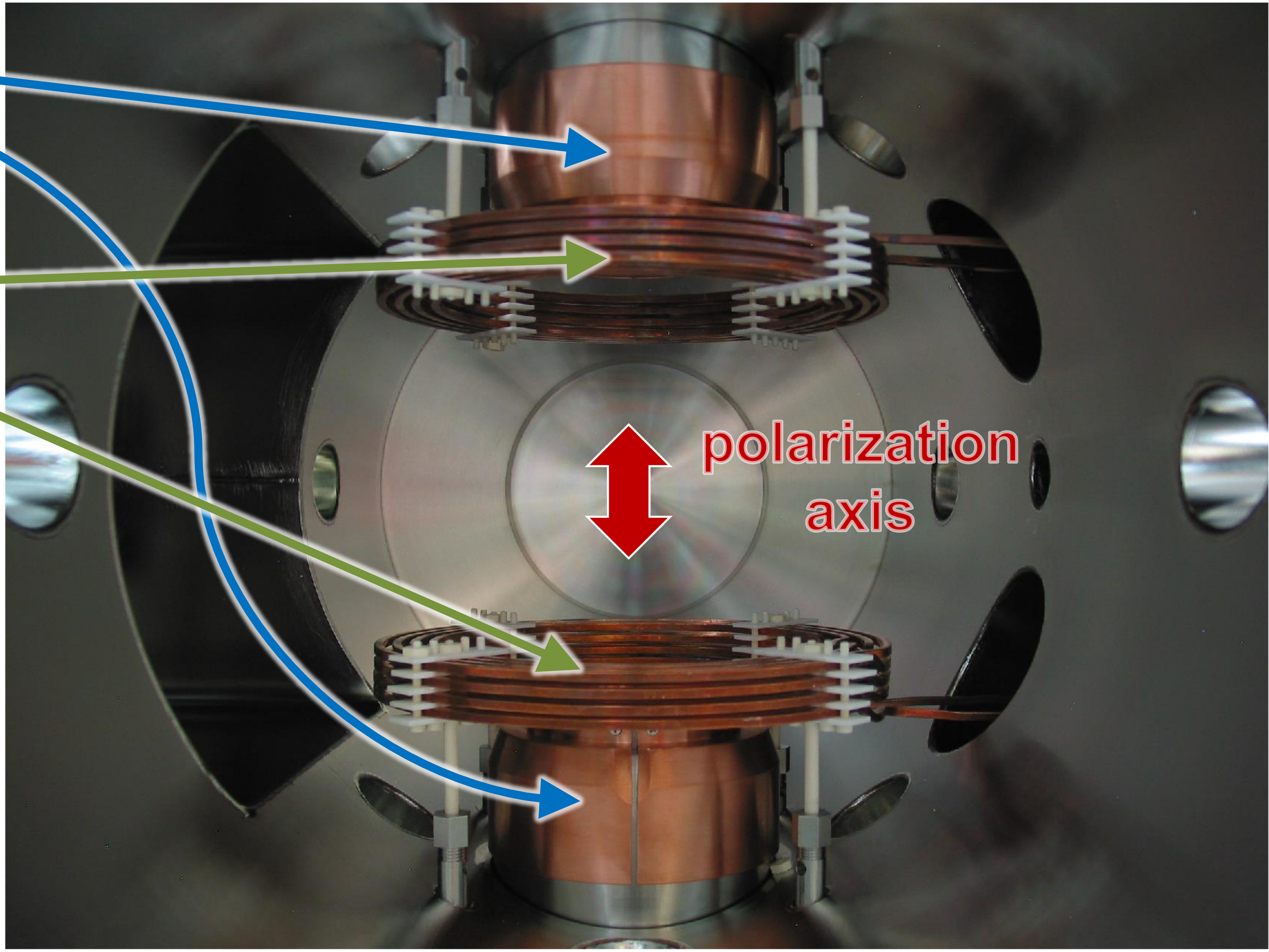
E_β detectors:
Plastic scintillator

ΔE_β detectors:
Double-sided Si-strip

Use **all** information via the super-ratio:

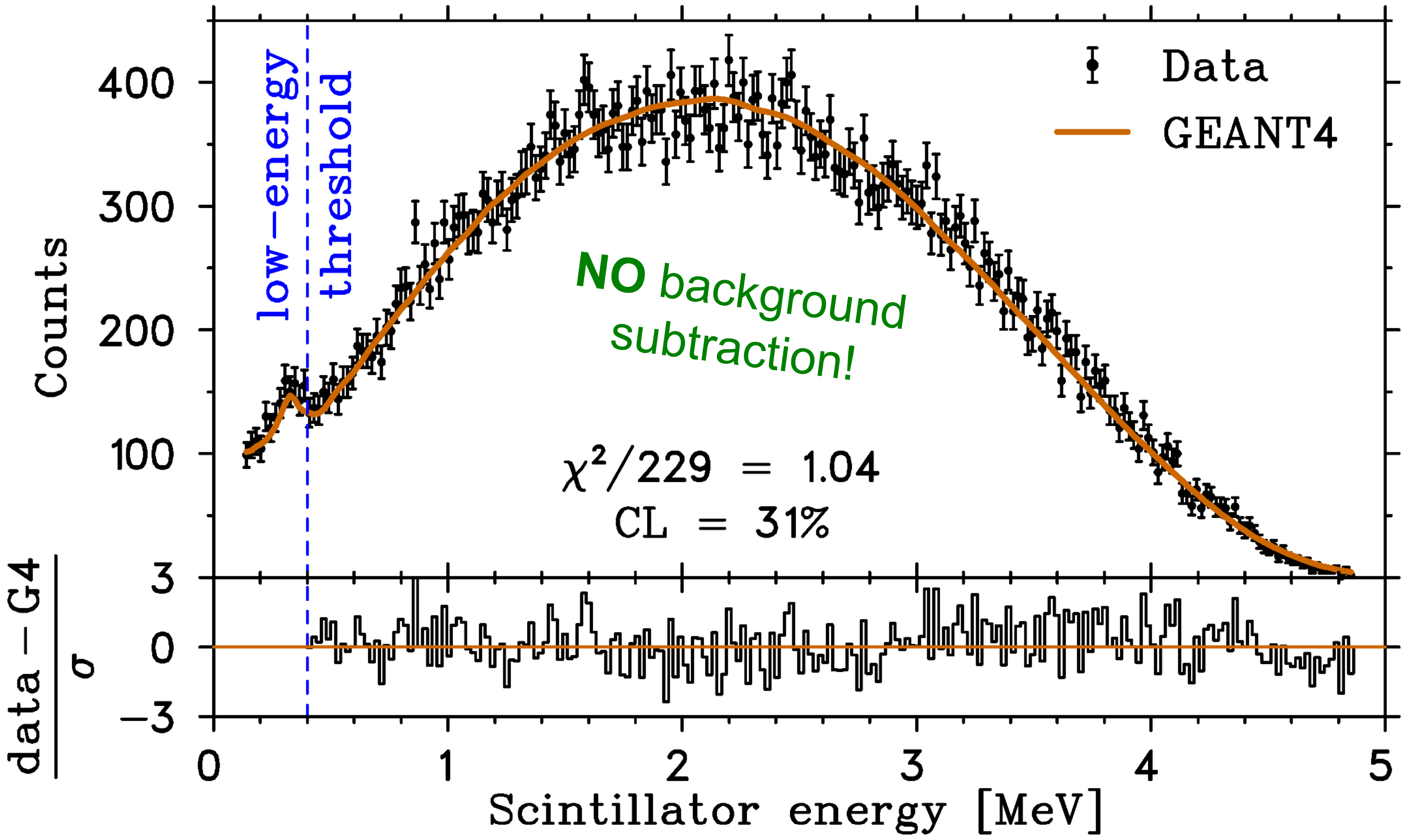
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

with $S(E_e) = \sqrt{\frac{r_1^{\uparrow}(E_e)\, r_2^{\downarrow}(E_e)}{r_1^{\downarrow}(E_e)\, r_2^{\uparrow}(E_e)}}$



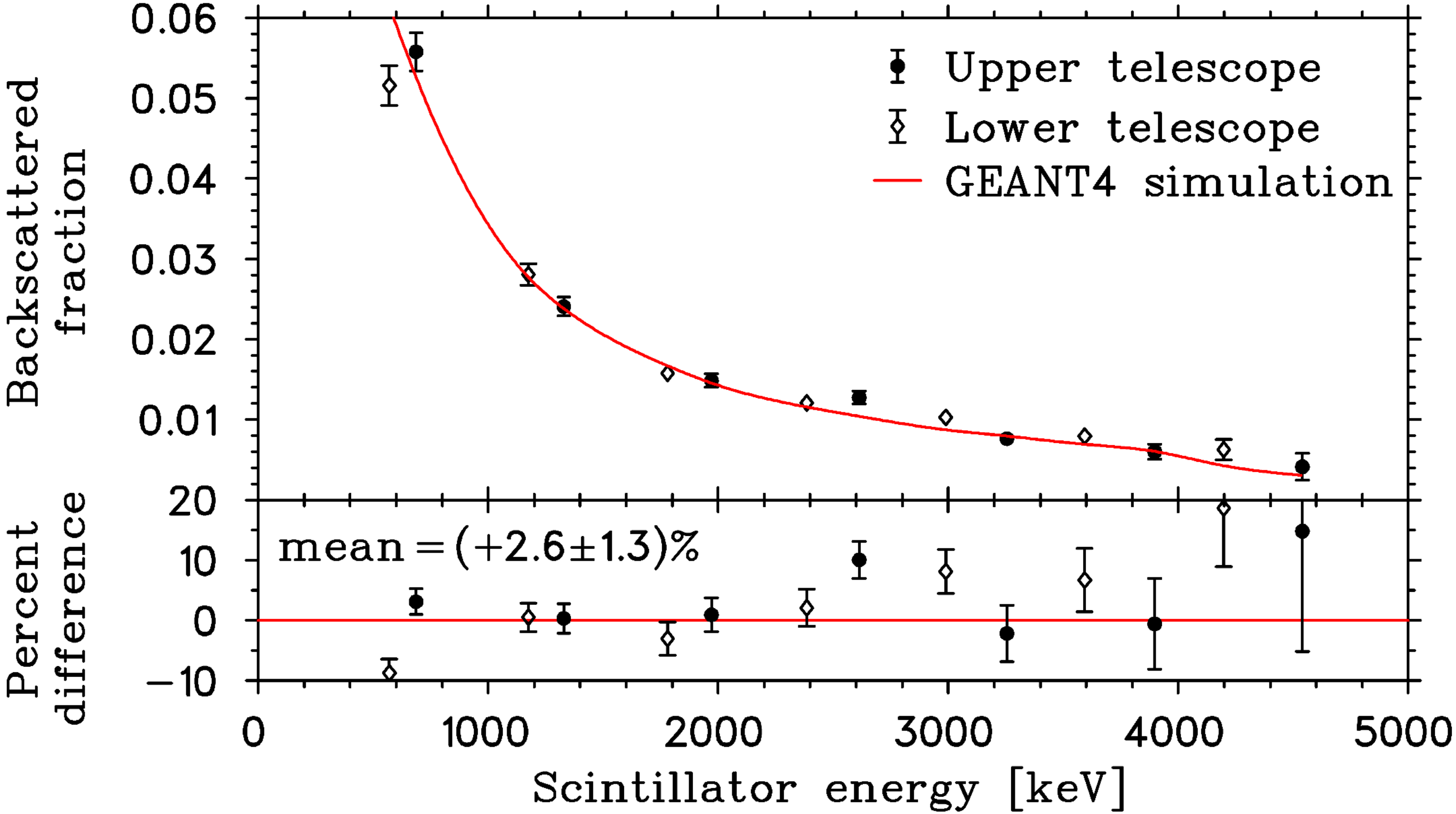
^{37}K β asymmetry measurement

- Energy spectrum – ***great agreement*** with GEANT4 simulations:



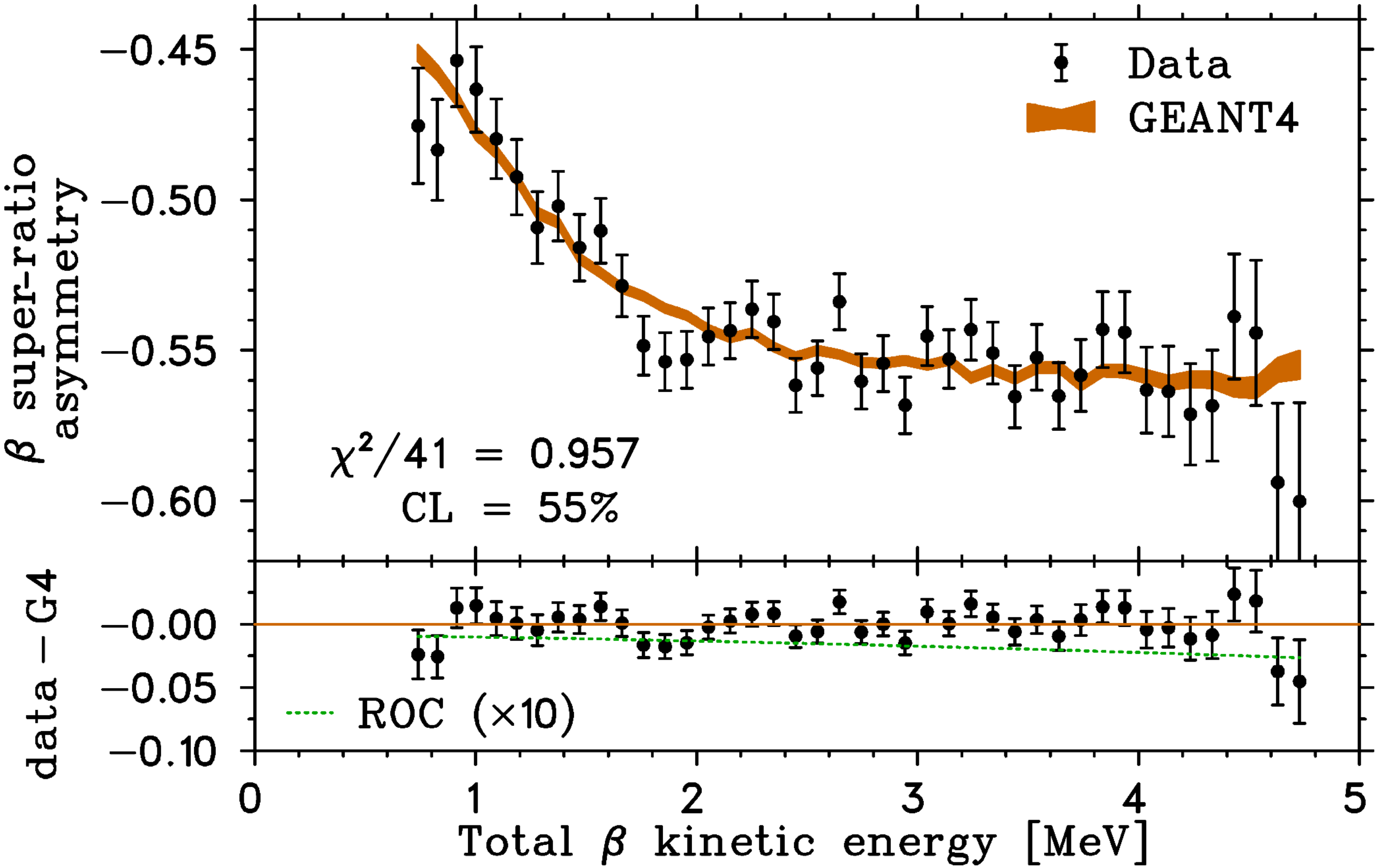
^{37}K β asymmetry measurement

- Energy spectrum – ***great agreement*** with GEANT4 simulations:
  - Backscattering too!



^{37}K β asymmetry measurement

- Asymmetry as a function of β energy after unblinding (again, **no** background subtraction!):



(Dominant) Error budget and A_β result

Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	1.0014	**8**$\times 10^{-4}$
β scattering	1.0230	**7**$\times 10^{-4}$
Trap position		4×10^{-4}
Trap movement		5×10^{-4}
ΔE position cut		4×10^{-4}
Shake-off e^- TOF region		3×10^{-4}
TOTAL SYSTEMATICS		**13**$\times 10^{-4}$
STATISTICS		**13**$\times 10^{-4}$
POLARIZATION		5×10^{-4}
TOTAL UNCERTAINTY		**19**$\times 10^{-4}$

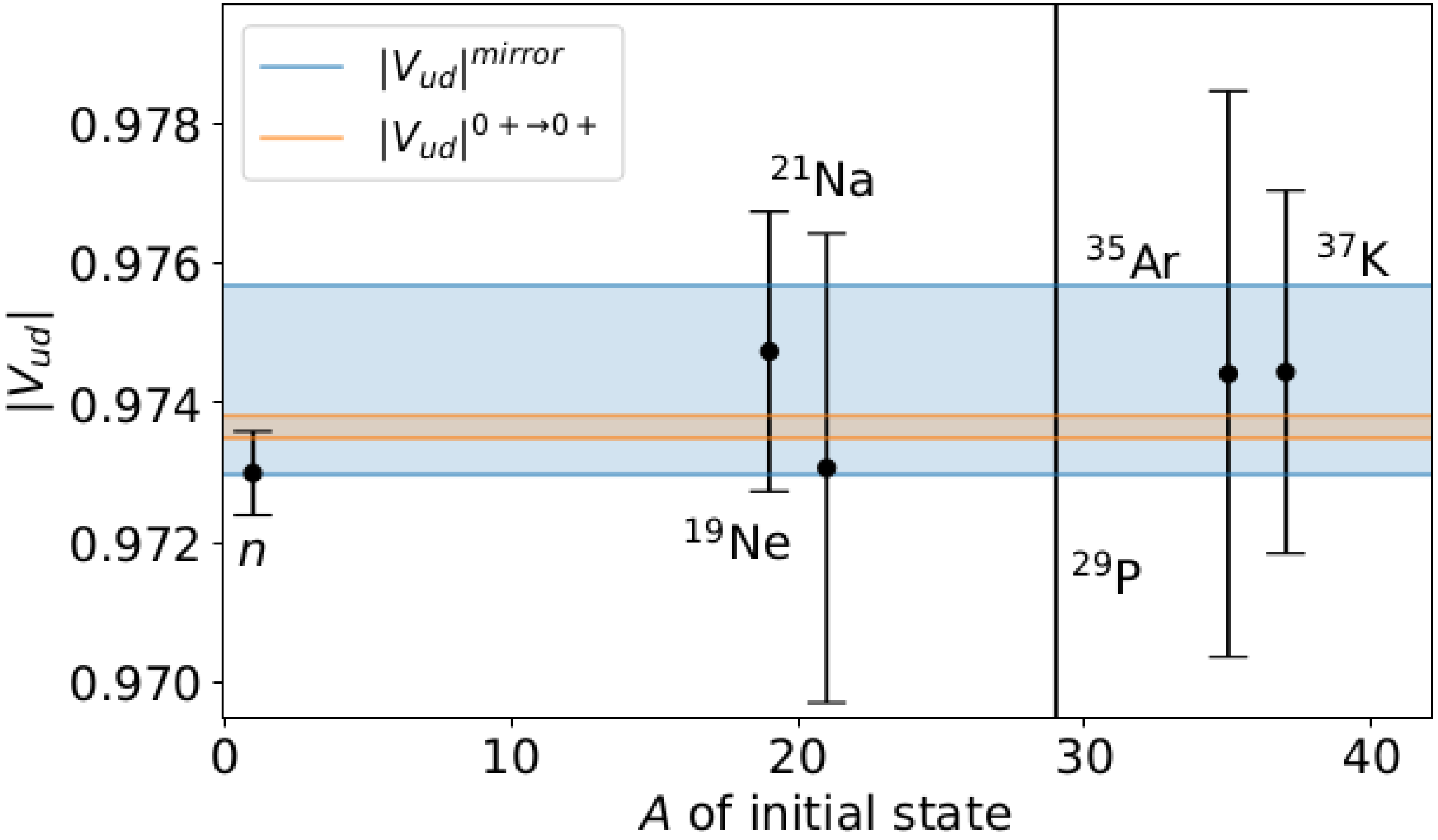
$$A_\beta^{\mathbf{meas}} = -0.5707(19) \quad cf \quad A_\beta^{SM} = -0.5706(7)$$

(includes recoil-order corrections, $\Delta A_\beta \approx -0.0028 \frac{E_\beta}{E_0}$)

B.Fenker *et al*, PRL **120**, 062502 (2018)

Interpretation and future prospects

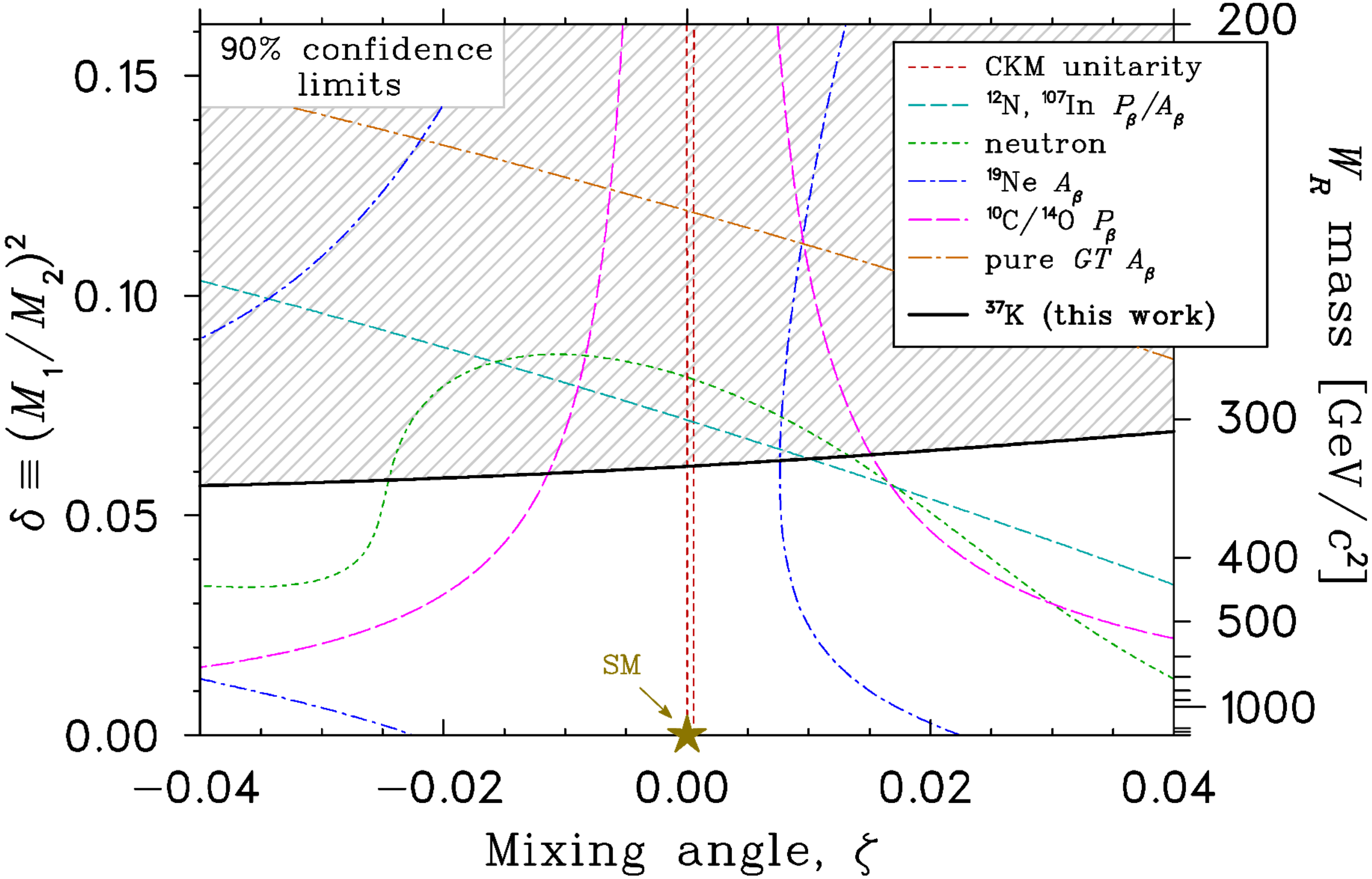
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays



B.Fenker *et al.*, PRL **120**, 062502 (2018)
L.Hayen and N.Severijns, arXiv:1906.09870 (2019)

Interpretation and future prospects

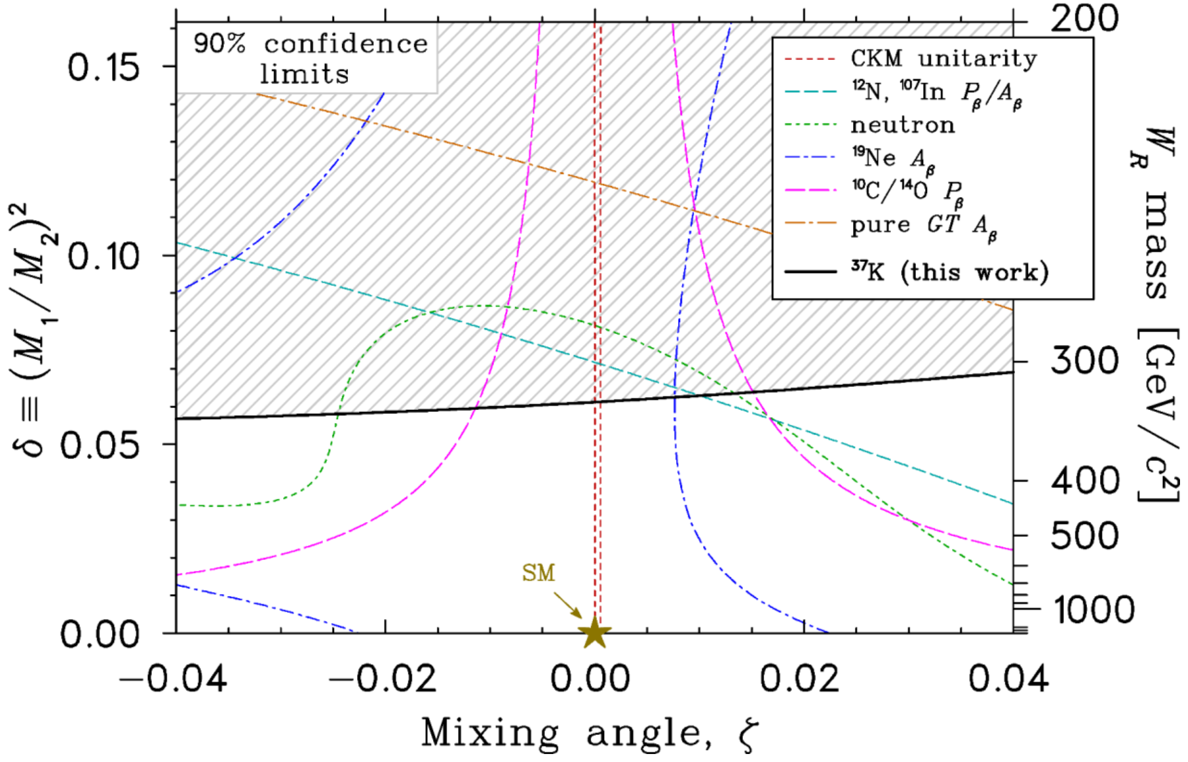
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents



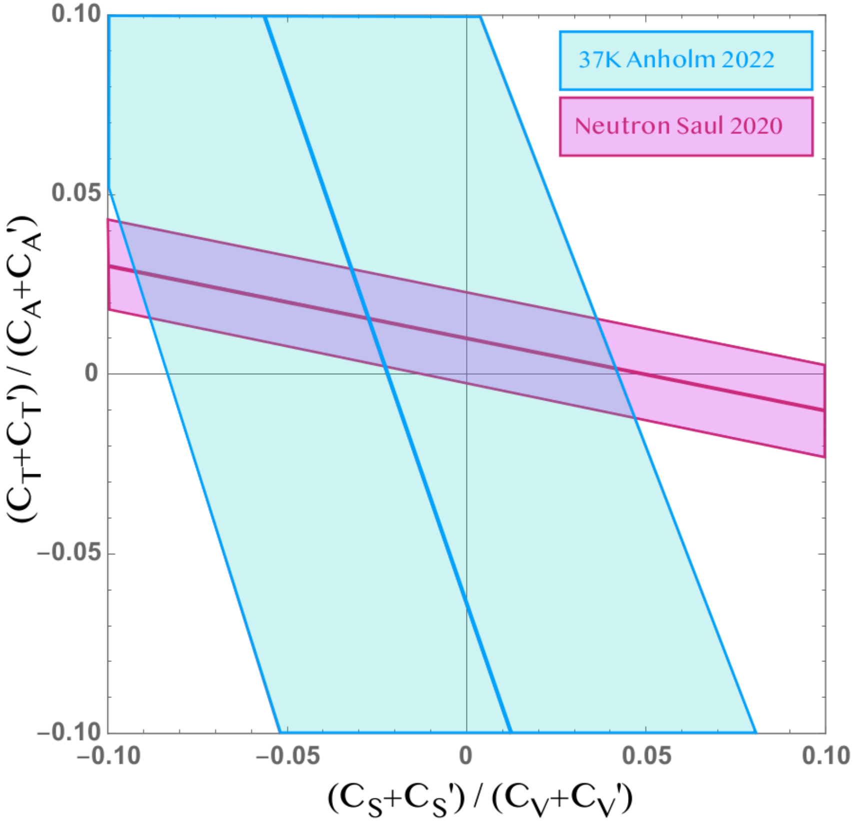
B.Fenker *et al*, PRL **120**, 062502 (2018)

S1188 – Summary of polarized ^{37}K experiment

- 0.3% measurement of A_β and <0.1% nuclear polarization
- Completed analysis as a function of E_β ⇒ Fierz

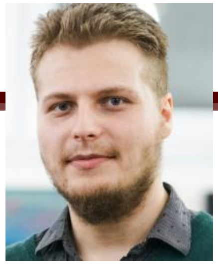


B.Fenker *et al*, New J. Phys. **18**, 073028 (2016)
B.Fenker *et al*, PRL **120**, 062502 (2018)
B.Fenker, PhD thesis (2018)



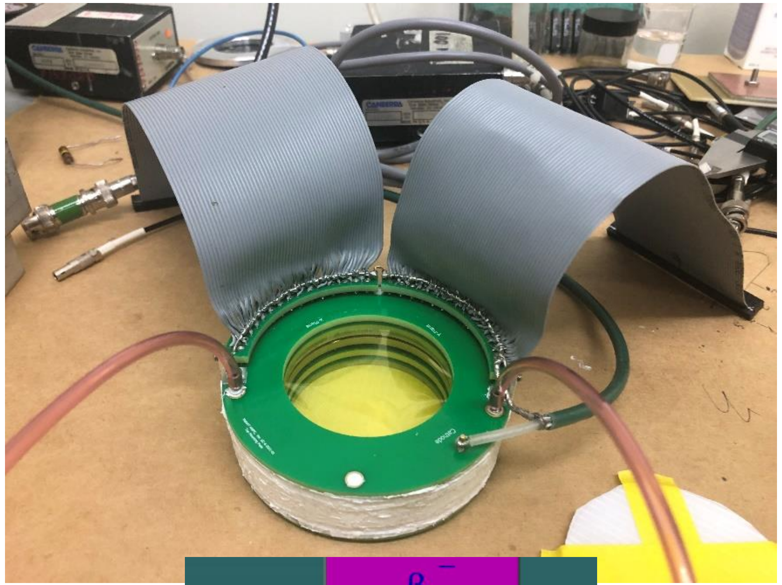
M. Anholm, PhD thesis (2022)
⋮

TRINAT plans

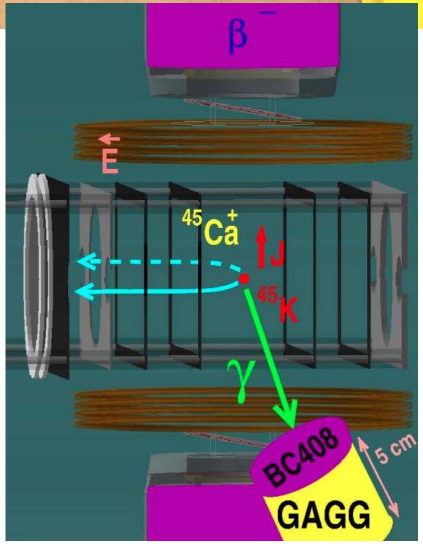


- U. Manitoba student analysis of b_{Fierz} has defended
  - Write a paper or two

- Next TAMU Ph.D. student: upgraded experiment
  - A&M: DSSD → MWPC and PMT → SiPM
  - TRINAT: pellicle mirrors, lasers, diagnostics, …
    ⇒ expect great improvements over Ben's 0.3%



- Once student identified and up to speed, request beamtime for a $< 0.1\%$ measurement of A_β
- Peripherally help with other TRINAT efforts:
  - E_ν spectrum in $0^- \to 0^+$ decay of ^{92}Rb
  - Time-violating search in ^{45,47}K with new GAGG detectors
  - Recoil-singles asymmetry $A_{\text{recoil}} \propto A_\beta + B_\nu$



Timelines for various projects

Year I

- He-LIG/LSTAR
  - Re-build He-LIG gas cell, transport SPIGs; test emittance with new chamber
  - Submit bid, begin preparing Cave 5; develop laser-alignment system
- TAMUTRAP/WISArD
  - Test emittance throughout beamlines; Ramsey excitations (?)
  - Take PhD data for Morgan
- ^{6}He-CRES
  - Build and test high-throughput RFQ
  - Submit proposal for trap upgrade with ANL
- TRINAT
  - Complete MWPC's and install in time for Aug beamtime. If major issues, consider commercial
  - Attract a GS for thesis on ^{37}K A_β to <0.1%
- Other
  - Publish ^{29}P lifetime and ^{37}K BR
  - Organize a workshop on VudU
  - Talk with Ronald Garcia-Ruiz about molecular EDMs @ FRIB

Year II

- He-LIG/LSTAR
  - Implement any lessons learned in Year I
  - Continue preparing Cave 5 (HV platform, shield walls, hole in roof plank, …)
- TAMUTRAP/WISArD
  - Plan the detection system to replace endcap electrodes; G4 simulations
  - Complete analysis of WISArD run; M. Nasser PhD
- ^{6}He-CRES
  - Continue to test and optimize H_2-filled RFQ
  - Build Penning trap
- TRINAT
  - Test new detectors, prepare for $^{37}\vec{K}$ beamtime
  - Develop G4 simulations
- Other
  - Continue developing VudU
  - ^{10}C? ^{44}Ti?
  - Molecular EDM?

Year III

- He-LIG/LSTAR†
  - Ensure He-LIG is commissioned, and Cave 5 is prepared for installation of LSTAR
  - Begin aligning LSTAR?
- TAMUTRAP/WISArD†
  - Re-configure high bay and prepare to move the RFQ to Cave 5
  - Start upgrading detector/DAQ system
- ^{6}He-CRES
  - In concert with ANL, upgrade CRES to utilize ion trapping
- TRINAT
  - Fix/upgrade β detectors (if necessary)
  - If a PhD student is found, take ^{37}K data for a <0.1% measurement of A_β
- Other
  - Continue with VudU
  - ^{10}C? ^{44}Ti?
  - Molecular EDM?

†These plans are very contingent on the delivery time for LSTAR from the commercial vendor

People who have helped make things happen

TEXAS A&M UNIVERSITY

TBD ($\times n$)
D. McClain
M. Nasser
V. Iacob
J. Klimo
D. Melconian

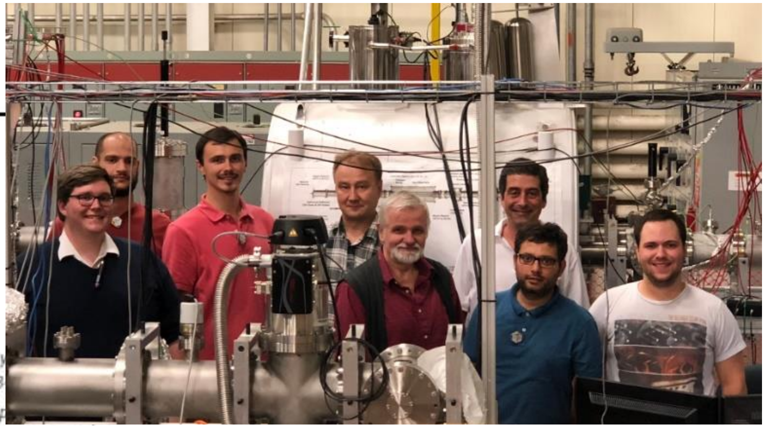
UNIVERSITY OF NOTRE DAME

G. Berg
M. Brodeur
M. Couder

Argonne NATIONAL LABORATORY
Lawrence Livermore National Laboratory
TRIUMF
KU LEUVEN
ENSICAEN ÉCOLE NATIONALE SUPÉRIEURE D'INGÉNIEURS DE CAEN & CENTRE DE RECHERCHE
CENBG
Pacific Northwest NATIONAL LABORATORY
JG|U
CENPA
lpc caen

U.S. DEPARTMENT OF ENERGY | Office of Science

Alumni



Research scientists

Praveen Shidling	Mar 2010 – Dec 2021
Grigor Chubaryan	Jan 2020 – May 2022

Post-doctoral researchers

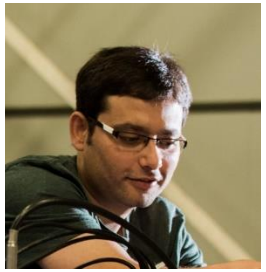
Veli Kolhinen	Jun 2017 – Dec 2020

Ph.D. Graduates

Benjamin Fenker	May 2013 – Dec 2016	*"Precise measurement of the β-asymmetry in the decay*
Michael Mehlman	May 2012 – May 2015	*"Development of the TAMUTRAP facility for precision β*
Richard Behling	Sep 2008 – Feb 2015	*"Measurement of the standard model beta asymmetry p*

M. S. Graduates

Morgan Nasser	Sep 2017 – Jul 2020	*"Commissioning the Texas A&M University Penning Trap via Offline Mass Measurements"*
Naomi Schroeder	May 2017 – Apr 2020	*"Viability of ft Measurements with TAMUTRAP"*
Asim Ozmetin	Sep 2017 – Apr 2020	*"Improving the ft value of ^{37}K via a precision measurement of the branching ratios"*
Yakup Boran	Jan 2012 – Jul 2013	*"Design and commissioning of an off-line ion source for TAMUTRAP"*
Benjamin Fenker	Jan 2011 – Apr 2013	*"Measurement of asymmetry parameters in ^{37}K: Optical*
Michael Mehlman	Jan 2010 – Apr 2012	*"Design of an open-geometry Penning trap"*



PHYS 491 Senior Research Students

Ryan Mueller	Jan – May 2012	*"LabView control of the gas-handling system for an RFQ cooler*
Michael Northup	Jan – May 2012	*"Rate equation model of the optical pumping of alkali atoms"*

M.Parnell

B.Diaz

Non-thesis Undergraduates

Matias Chavez	Summer 2019
Adam Argersinger	Summer 2016
Jaime Cardona	Summer 2016
Austin Griesbach	Summer 2016
Chloe Dixon	Oct 2013 – May 2015
Levi Clark	Sep 2011 – Dec 2012

International undergraduates

Etienne Gilg (ENSICAEN, France)	Summer 2017	*"The first TOF-ICR measurement with TAI*
Francois Bidault (ENSICAEN, France)	Summer 2016	*"Commissioning a microchannel plate dete*
Maxime Soulard (ENSICAEN, France)	Summer 2015	*"Hardware optimization of an RFQ for TAI*

NSF Research Experience for Undergraduates Program

Olivia Bruce	Summer 2022	*"Measuring Ions per Bunch in TAMUTRAP's RFQ"*
Margaret McDonough	Summer 2019	*"Installing and commissioning of TAMUTRAP through mas*
Lupe Duran	Summer 2018	*"Na and beamline upgrades to the TAMUTRAP Facility"*
Cristhian Gonzalez	Summer 2018	*"Mass measurements using TAMUTRAP and upgrades to*
Carlos Marquez	Summer 2017	*"The first mass measurement (stable Na) using TAMUTRA*
Kassie Marble	Summer 2016	*"The cleaning, assembling, and testing of a unique open-e*
Louis Cooper	Summer 2014	*"Development of the DC electronics for the TAMUTRAP RI*
Robert McAfee	Summer 2014	*"Analysis of the cylindrical beam deflector for the TAMUTR*
Eames Bennett	Summer 2013	*"Transport efficiency of a cylindrical deflector for TAMUTR*
Natalie Foley	Summer 2012	*"Ion cooler for the TAMUTRAP facility"*
Erin France	Summer 2011	*"Optimization of a scintillator for the measurement of trapp*
Heather Stephens	Summer 2010	*"Production of short-lived ^{37}K"*
Russell TerBeek	Summer 2009	*"Design of a high-precision β telescope"*
Mark Hernberg	Summer 2008	*"New measurements of γ-ray branching ratios in the β^+ de*