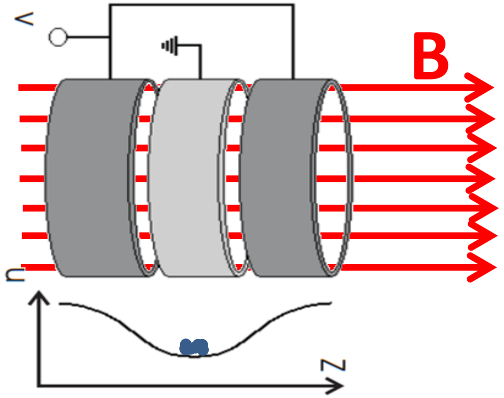
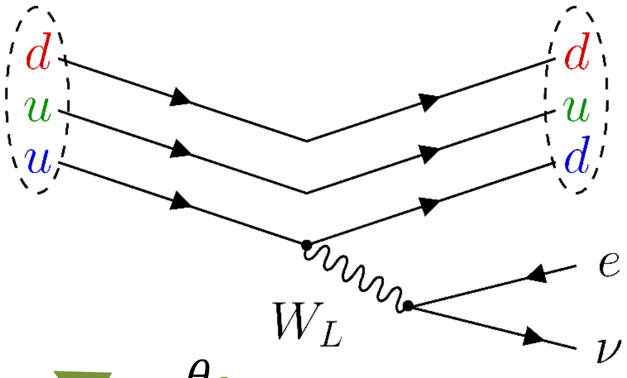
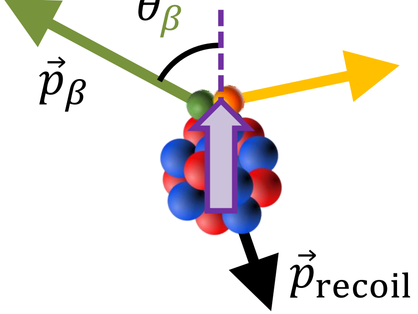
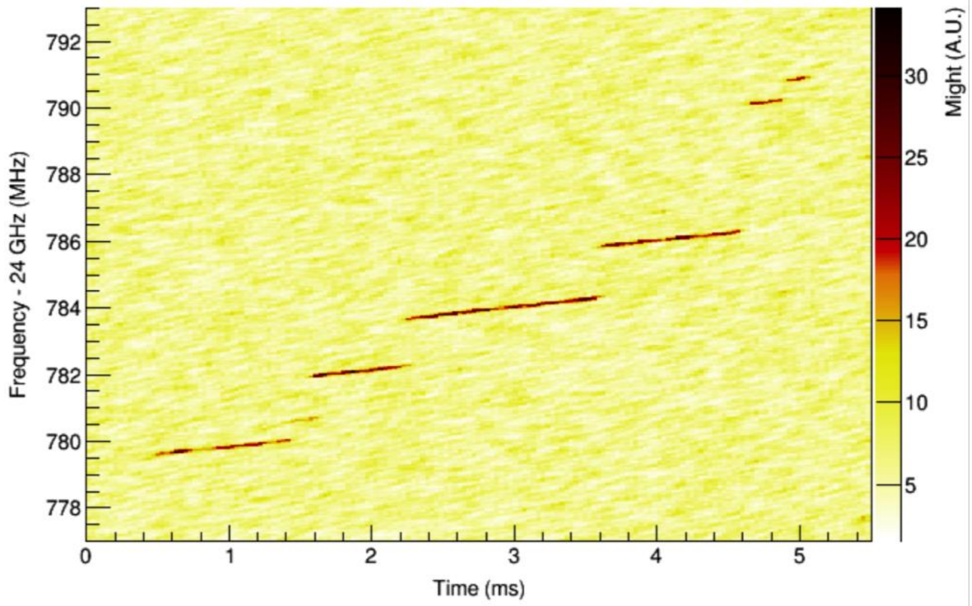
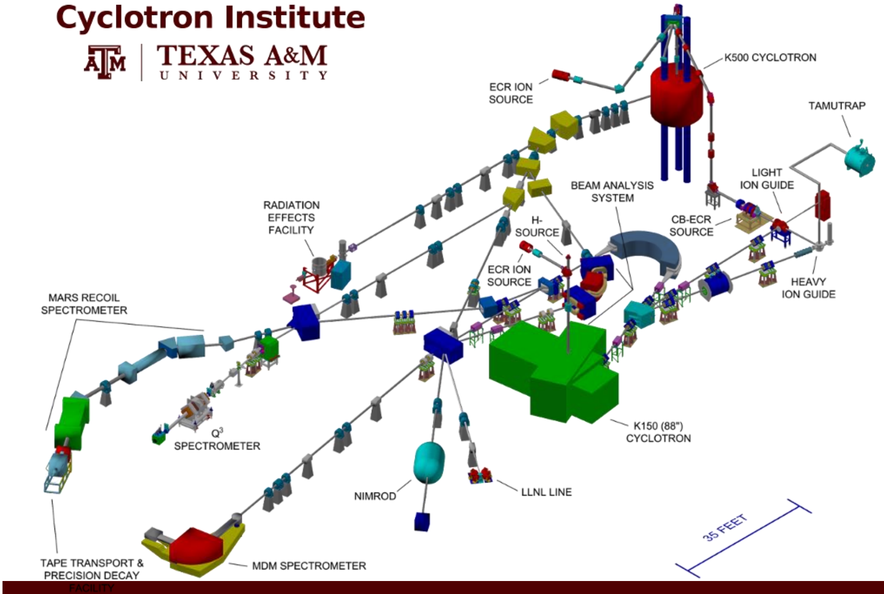
Searching for BSM physics via the precision frontier: β decay experiments using atom and ion traps

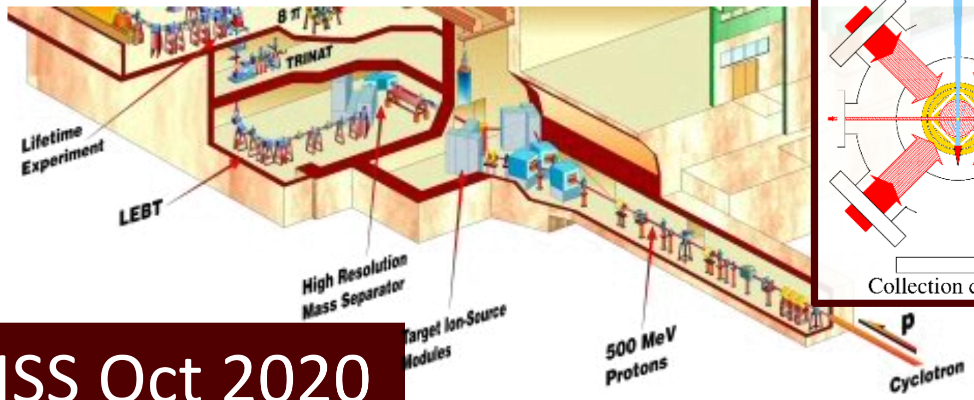


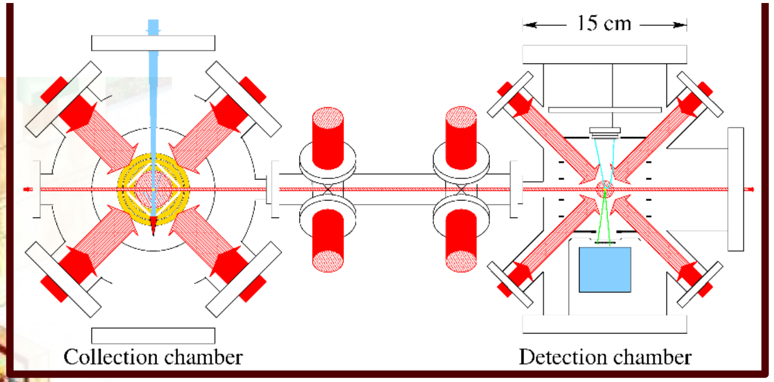












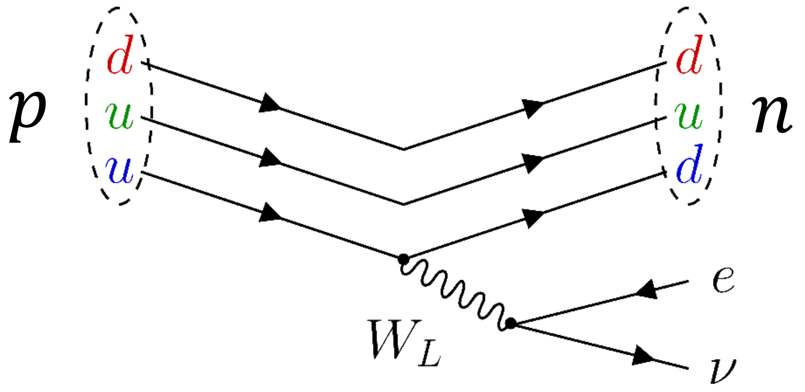
Dan Melconian – NSCL/FRIB VNSS Oct 2020

Outline

- **Introduction**
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- **^{37}K at TRIUMF**
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β
- **TAMUTRAP**
  - $T = 2$ decays to test the SM
  - Source production and commissioning mass measurements
- **^{6}He b_{Fierz} at UW**
  - Cyclotron radiation emission spectroscopy
  - Plans to implement an ion trap to remove wall collisions

The standard model and beyond

- This is the standard model:



pure $V - A$ interaction

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

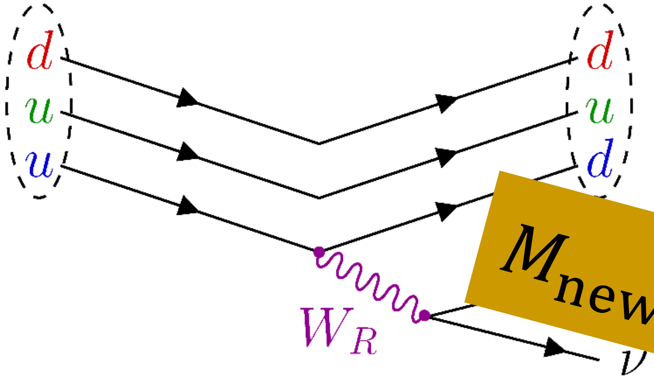
$$C_V = C_V' = 1$$

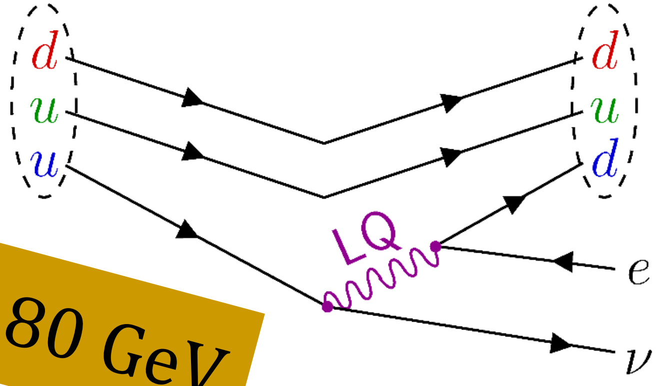
$$C_A = C_A' \approx 1.27$$

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

- These are not:

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





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

$C_i \neq C_i'$

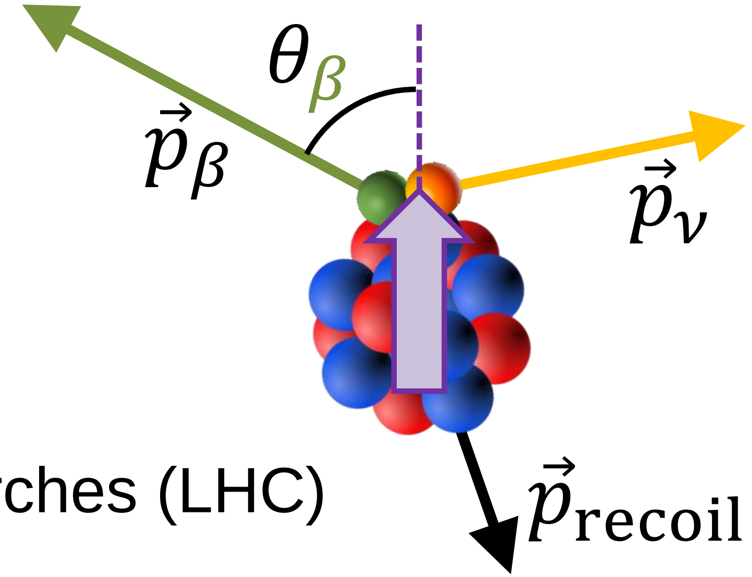
$C_S, C_T \neq 0$

- 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

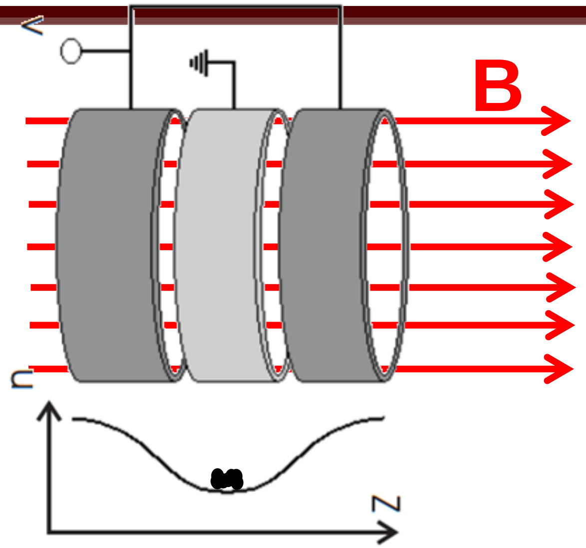
- Global gameplan:
  - Measure the β-decay parameters
  - Compare to SM predictions
  - Look for deviations ⇔ new physics
  - Precision of $\leq 0.1\%$ needed to complement other searches (LHC)



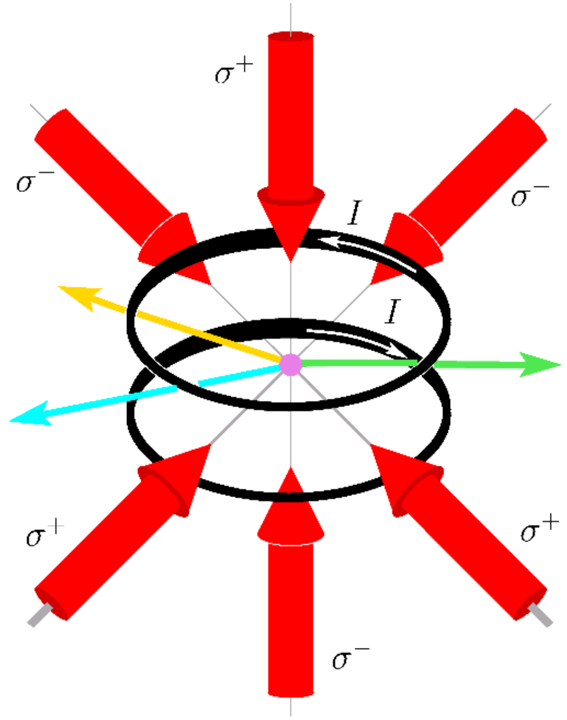
Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić and Severijns, Prog. Part. Nucl Phys **104**, 165 (2019)

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 1%; poised to reach 0.1% precision
  - 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)



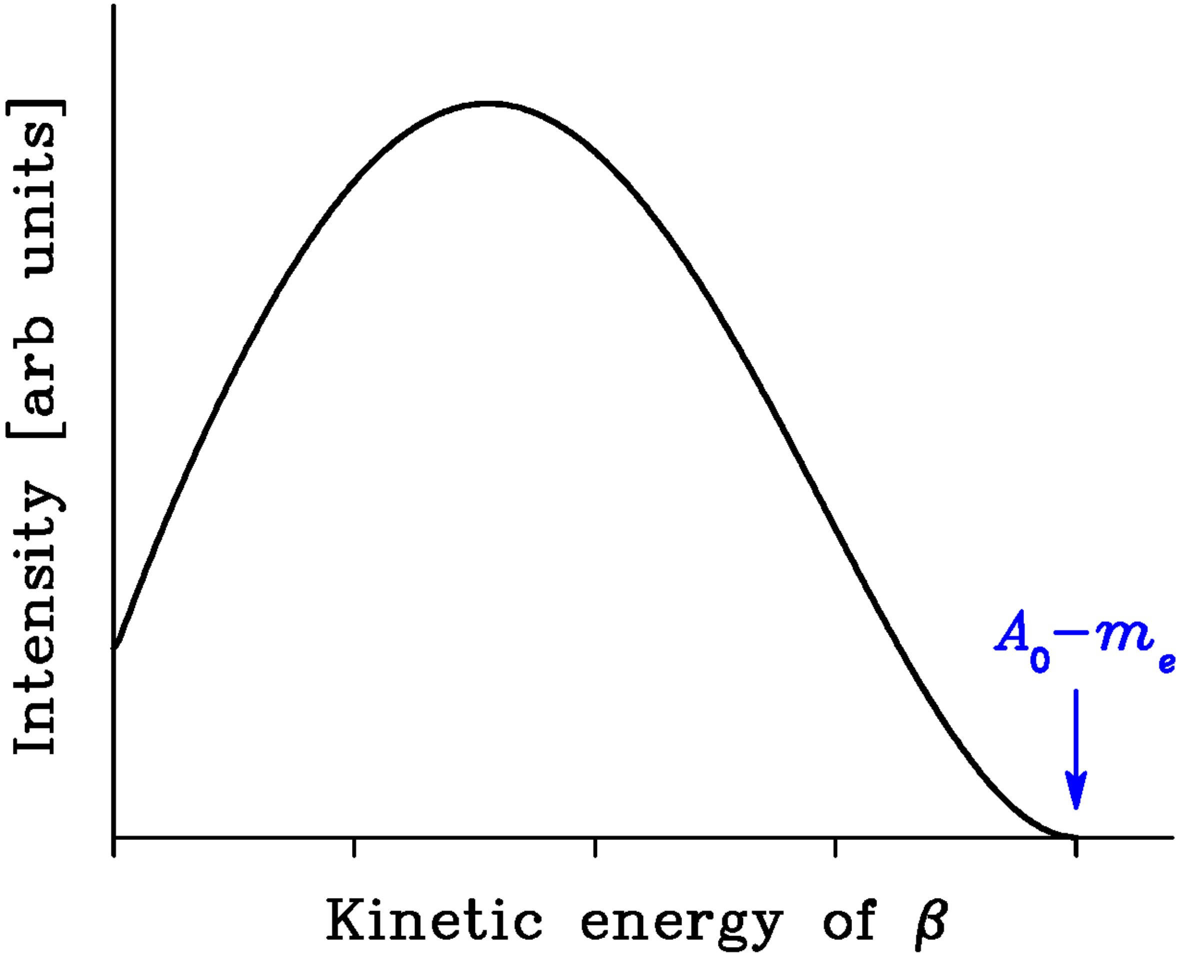
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - TRINAT @ TRIUMF (K isotopes)
  - ^{6}He @ UW
  - NeAT @ SARAF (Ne isotopes)



How does β decay test the SM?

- Begin by looking at the basic decay rate

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

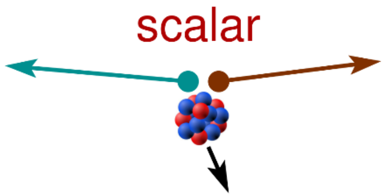


β decay and fundamental physics

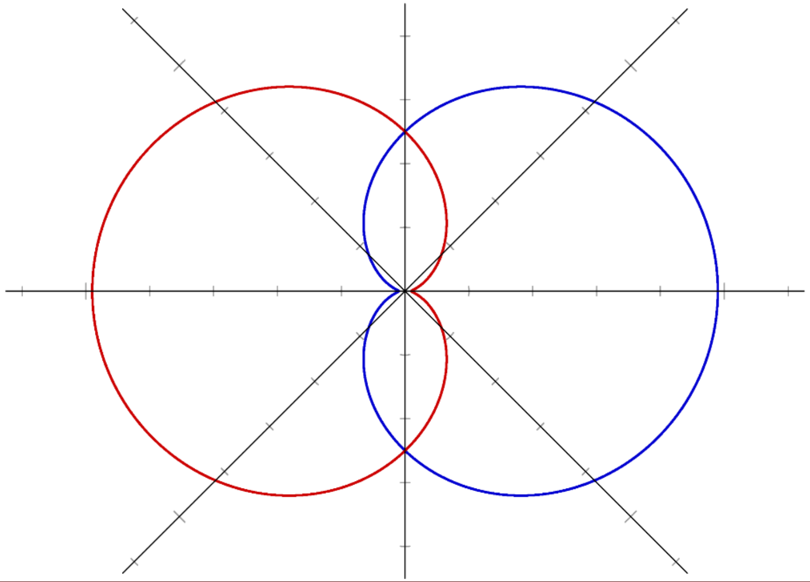
- Expand to the often-quoted angular distribution of the decay
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

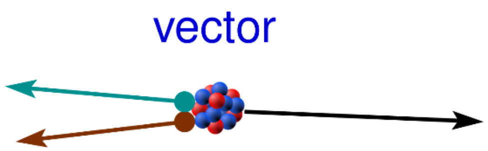
$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}} \xi \left(1 + \overbrace{\boldsymbol{a_{\beta\nu}} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{\boldsymbol{b}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

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



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





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

β decay and fundamental physics

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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

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

basic decay rate | $\beta-\nu$ correlation | Fierz term

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E \ldots)^2 \left(\ldots \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}} + b\frac{\Gamma m_e}{E_e} \right)$$

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

… in the couplings…not

… s linear:

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

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)

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

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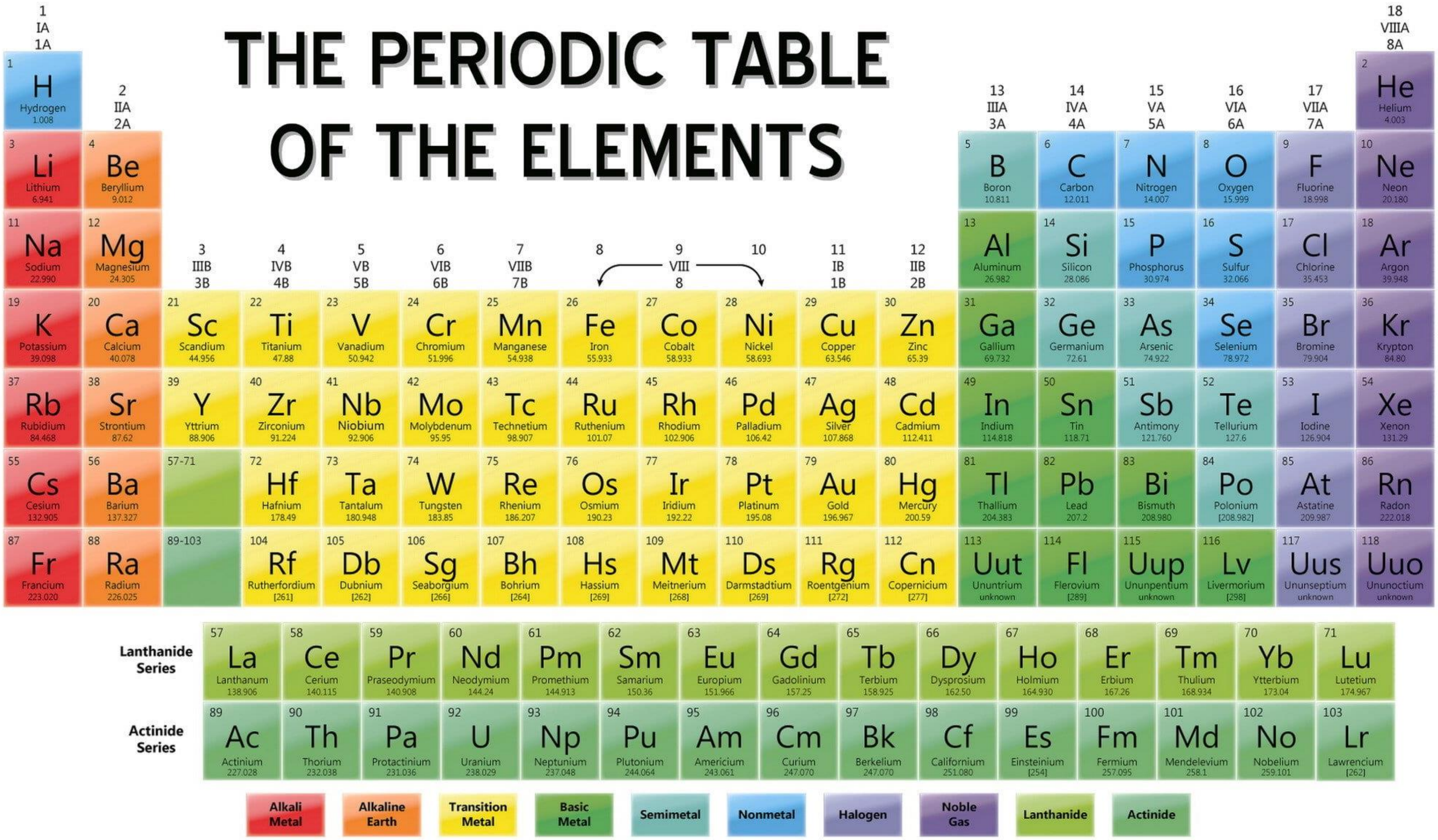
Difficulty with MOTs: not all atoms can be trapped



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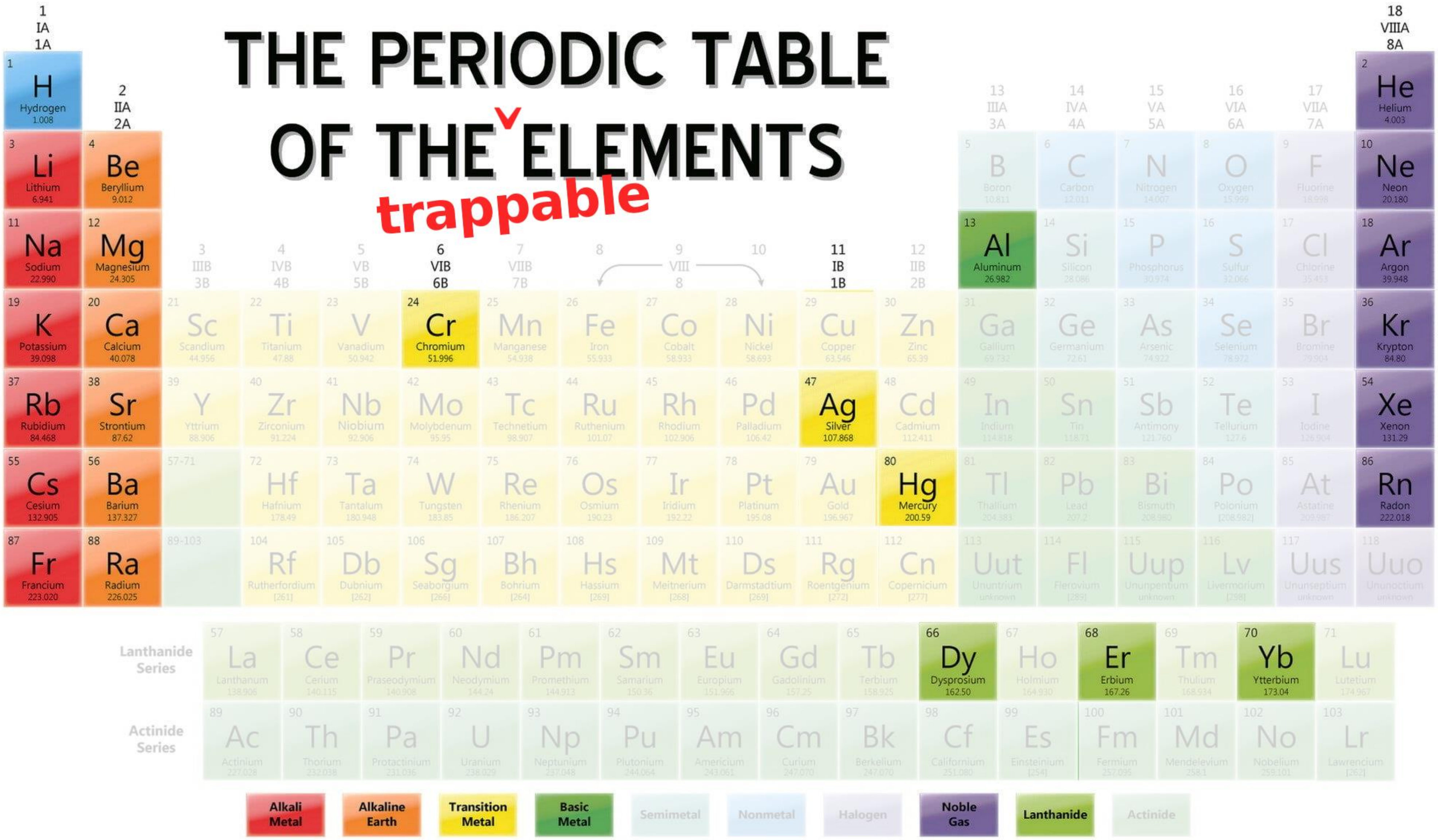

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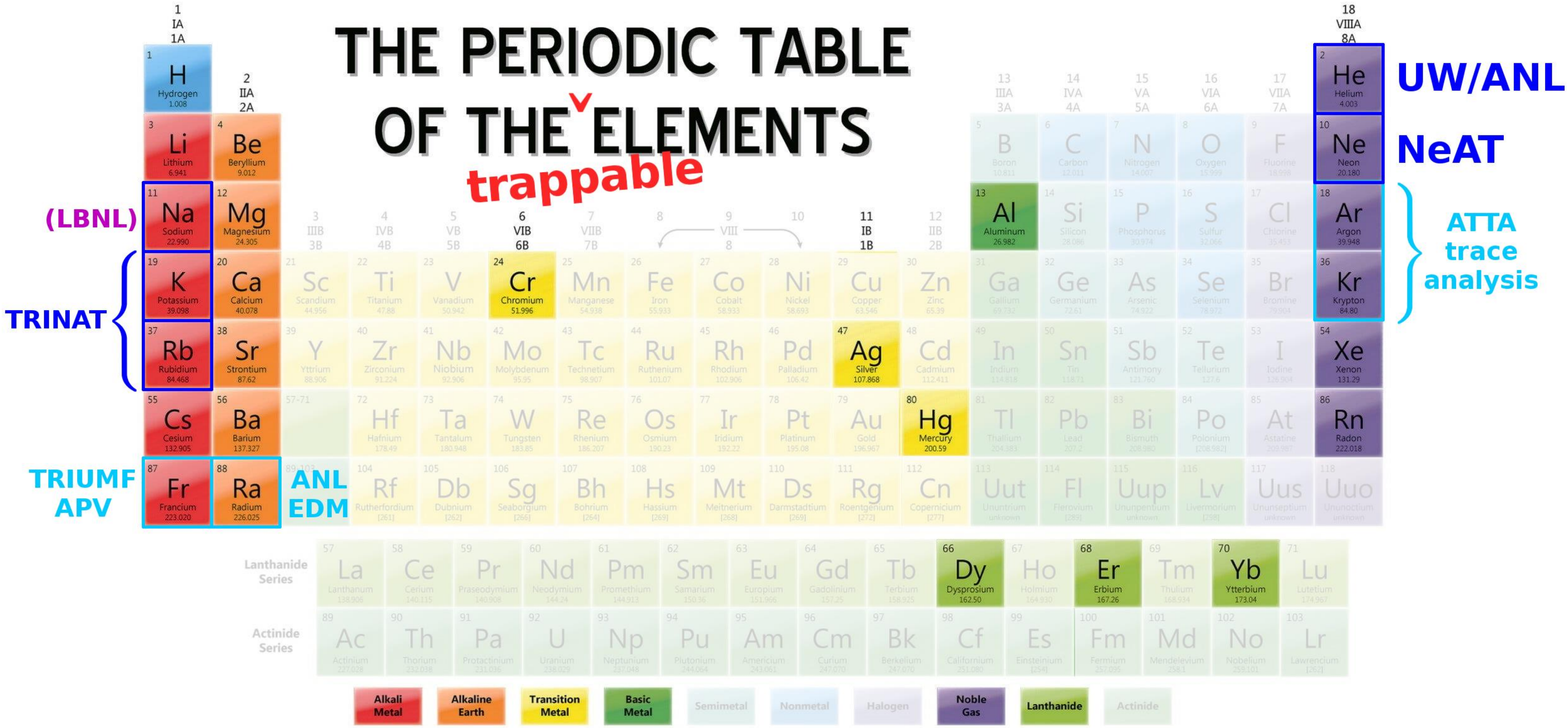
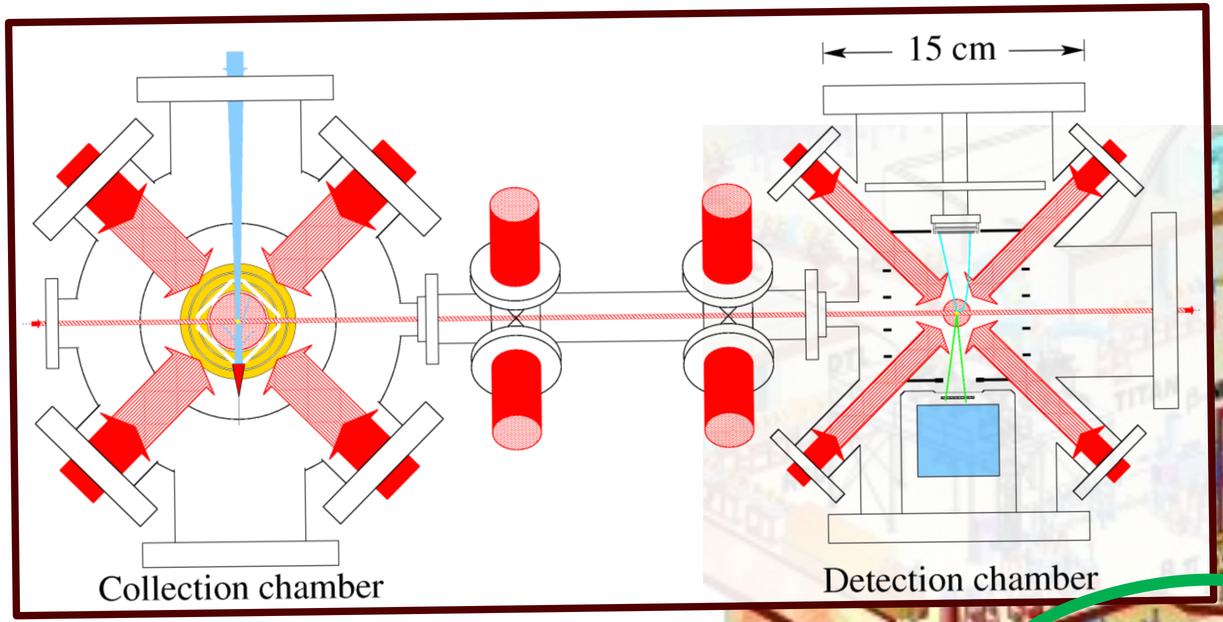
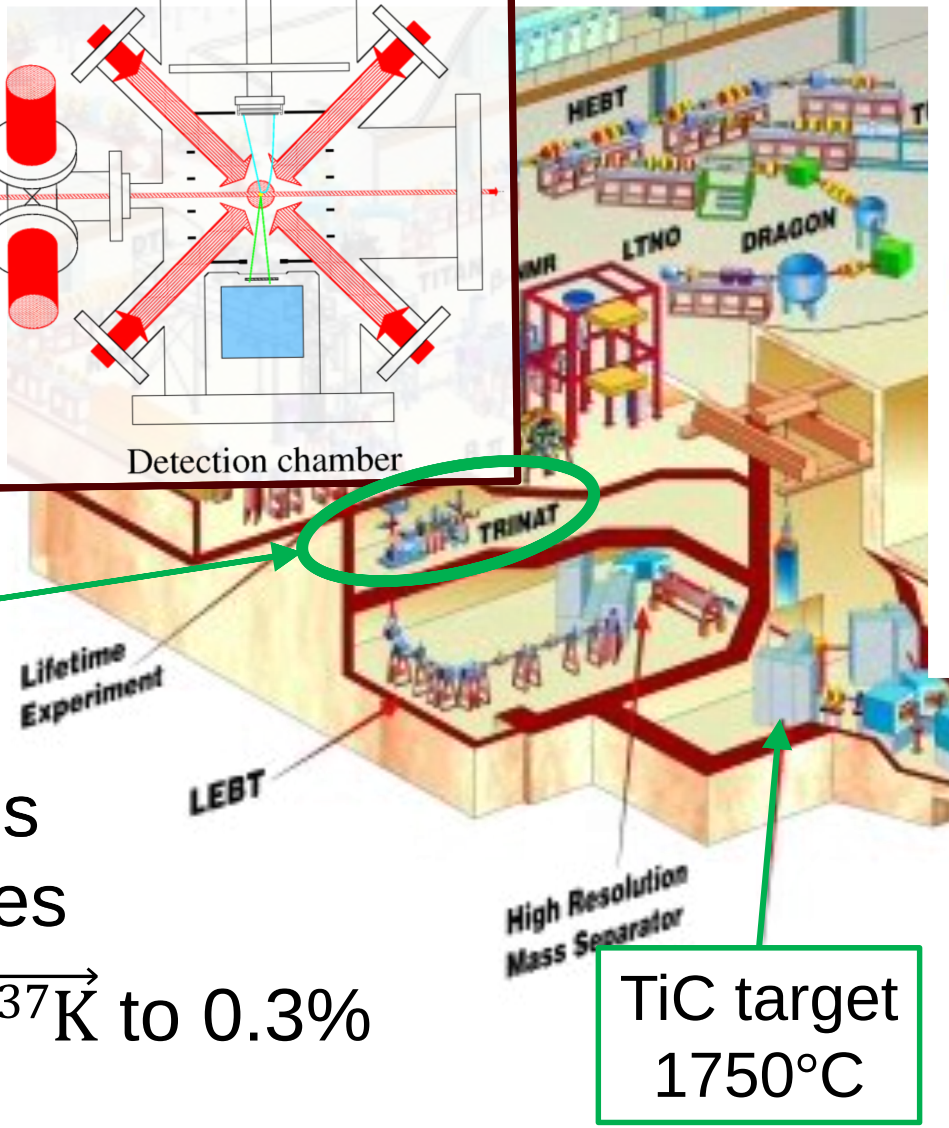
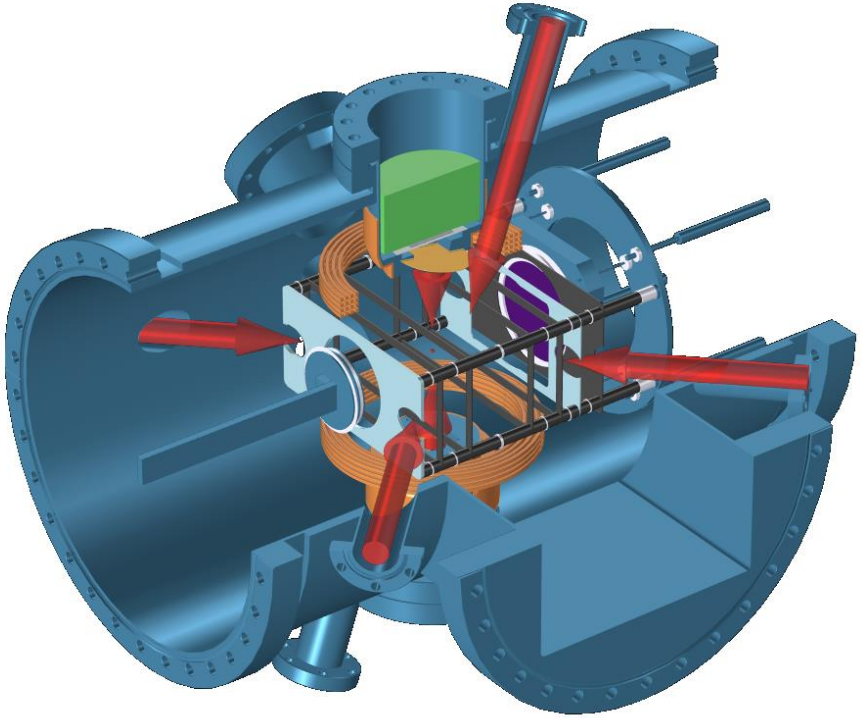


The TRIUMF Neutral Atom Trap







up to 8×10^{7} ^{37}K/s

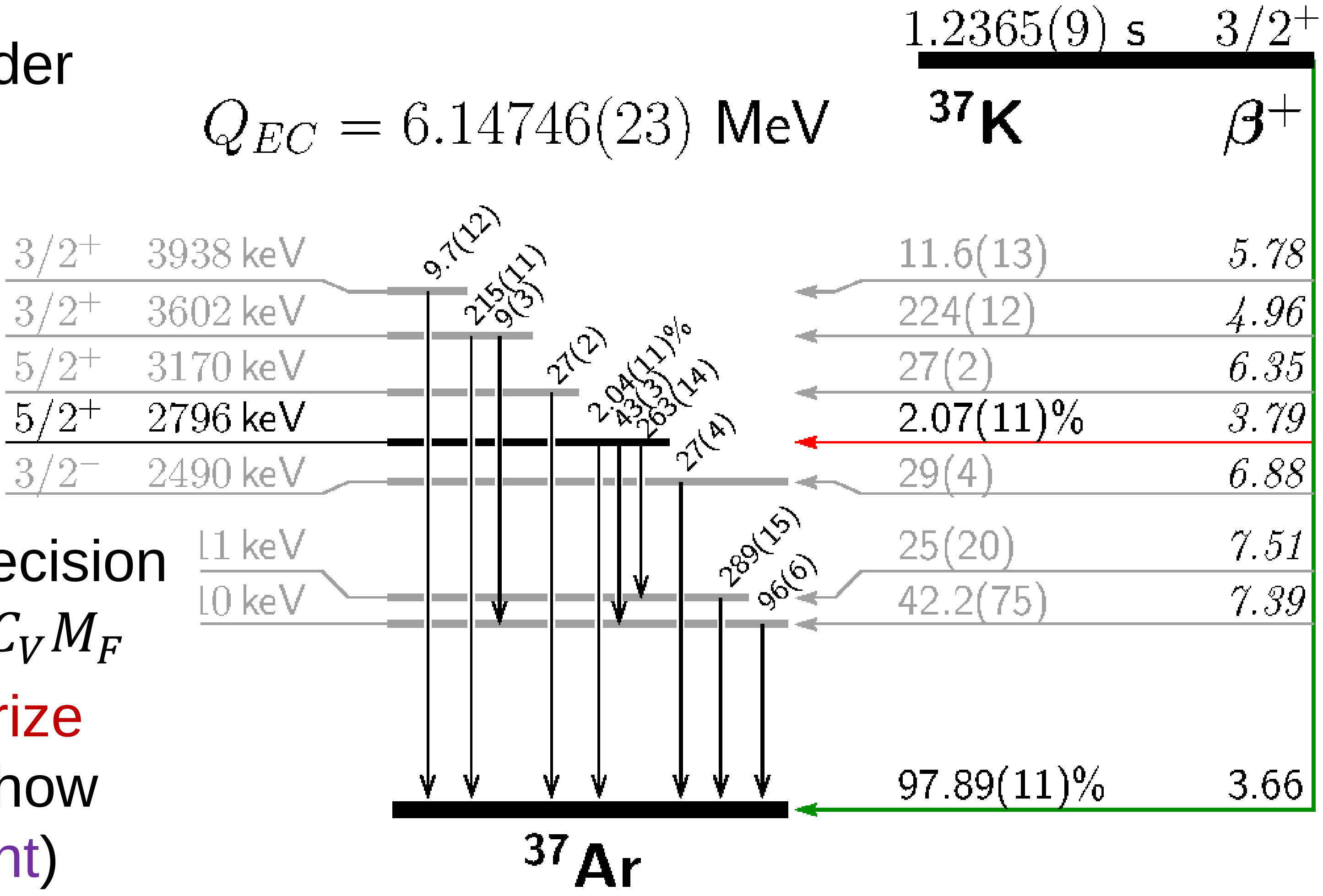
TiC target 1750°C

70 µA protons

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

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)

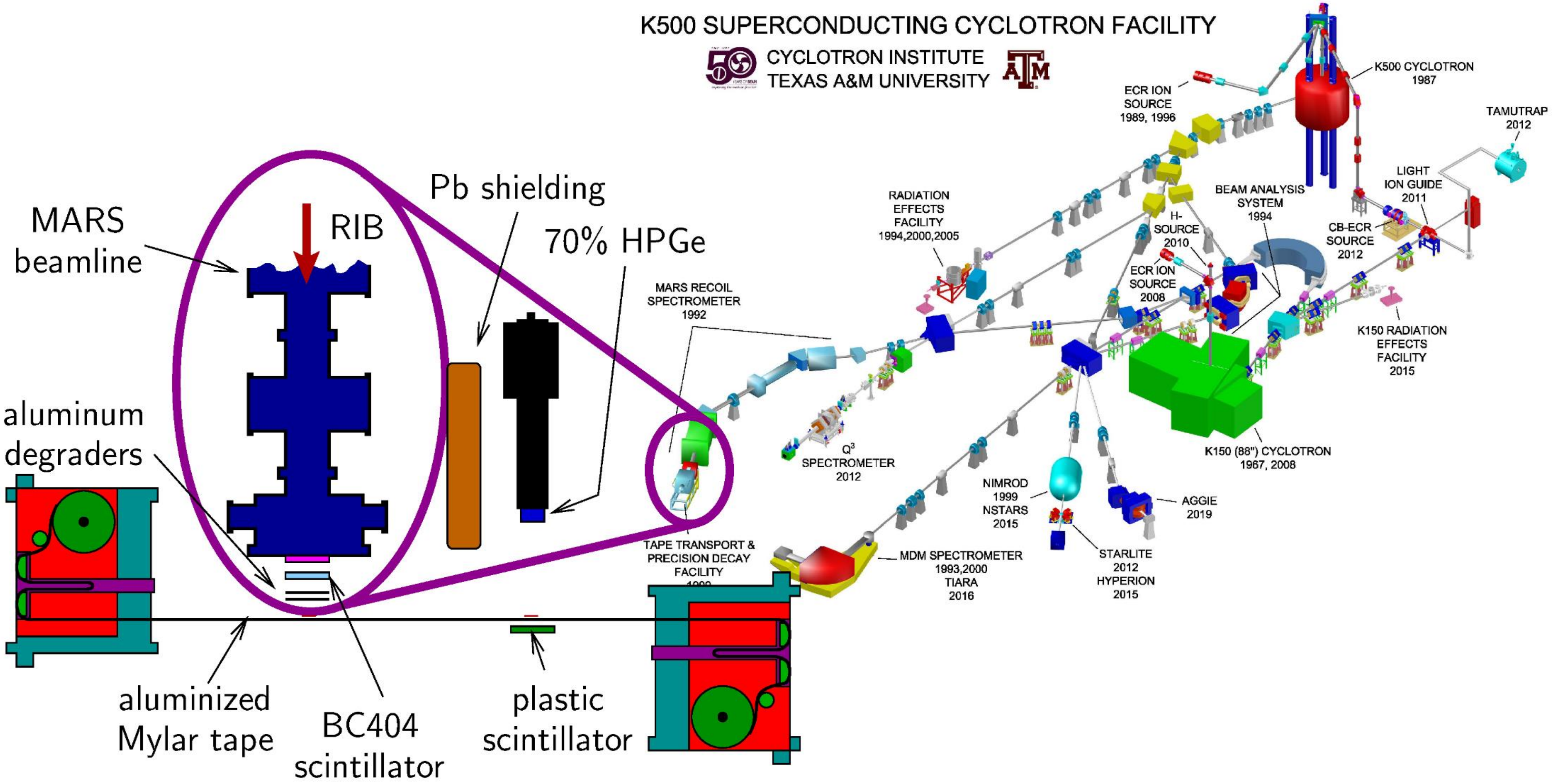
$$dW = dW_0\left[1 + a\frac{\vec{p}_\beta\cdot\vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle\vec{I}\rangle}{I}\cdot\left(A_\beta\frac{\vec{p}_\beta}{E_\beta} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta\times\vec{p}_\nu}{E_\beta E_\nu}\right) + \text{alignment term}\right]$$

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

- Looking forward, we don't want the ft value to limit a SM test



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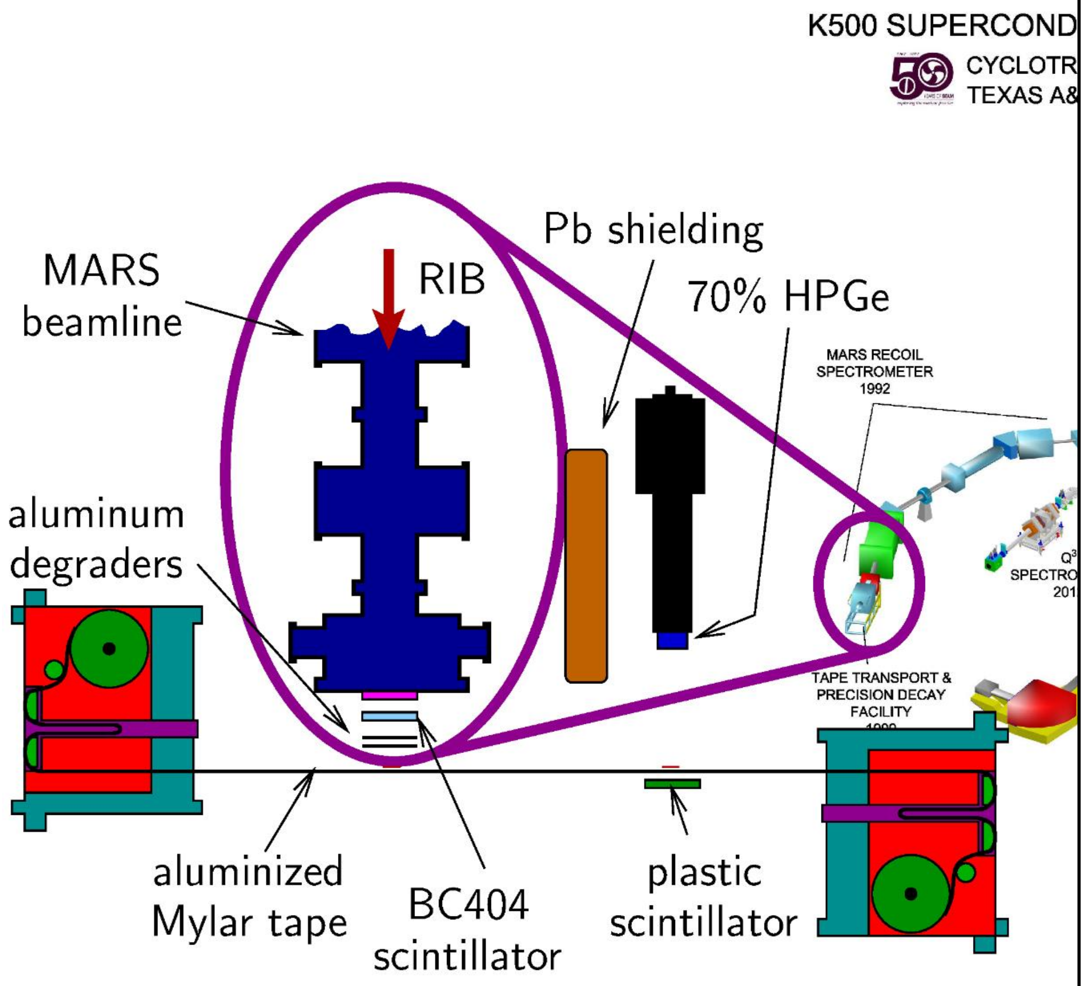
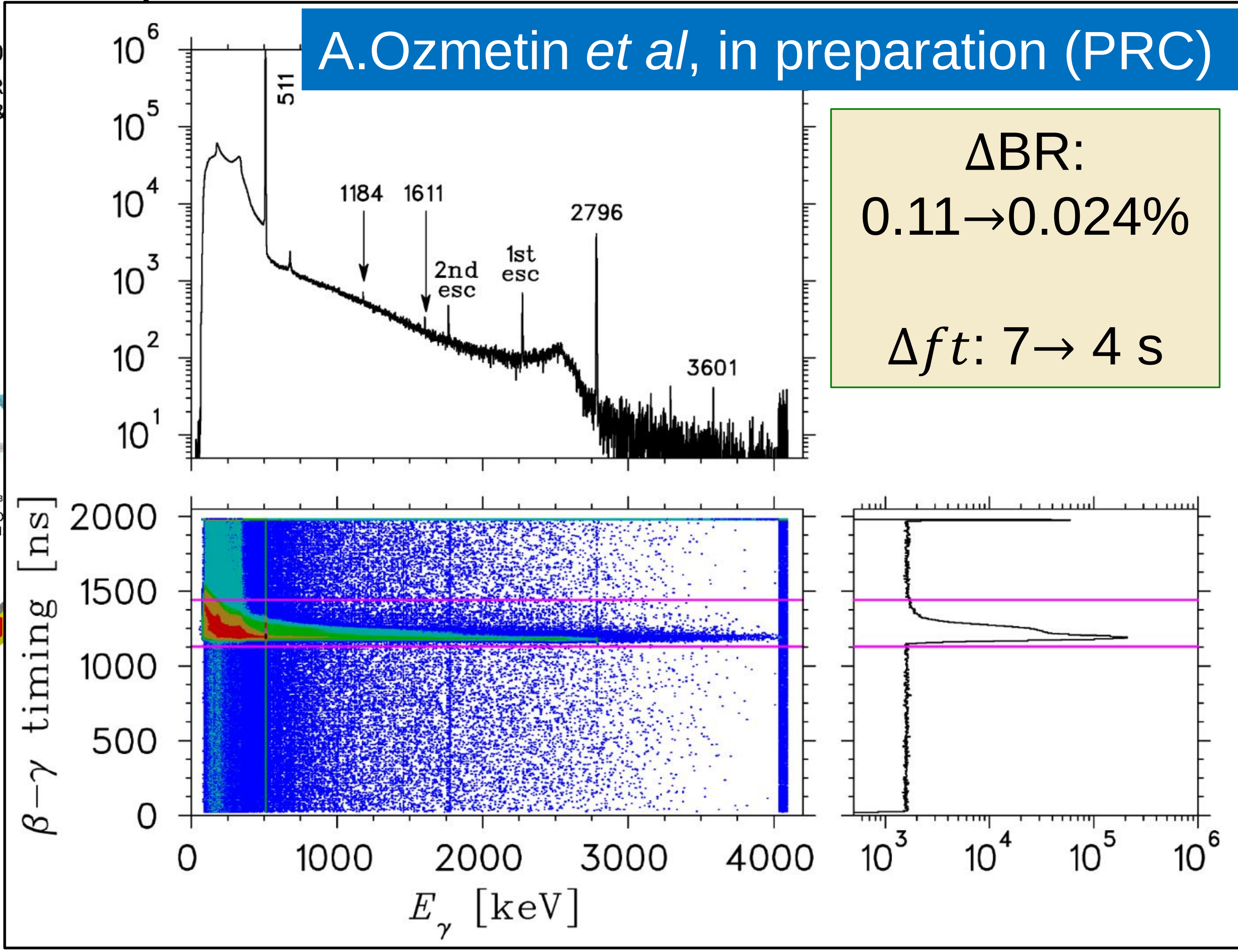




A.Ozmetin *et al*, in preparation (PRC)

ΔBR:
0.11→0.024%

Δft: 7→ 4 s

he Ft is measured well enough

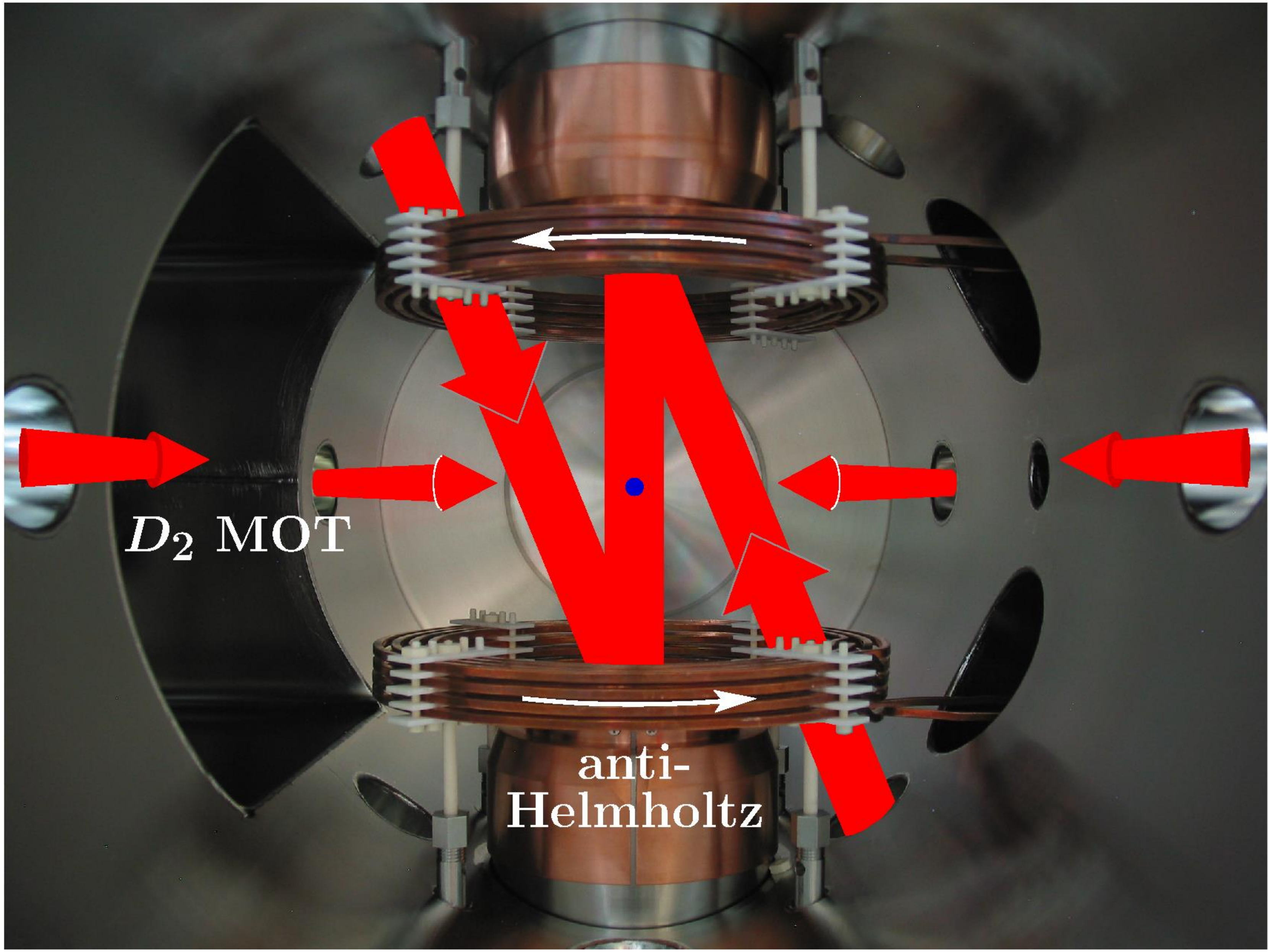
$$dW = dW_0 \left[1 + a \frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b \frac{\Gamma m_e}{E_\beta} + \frac{\langle \vec{I} \rangle}{I} \cdot \left(A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right) + \begin{matrix}\text{alignment}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

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 ⇜

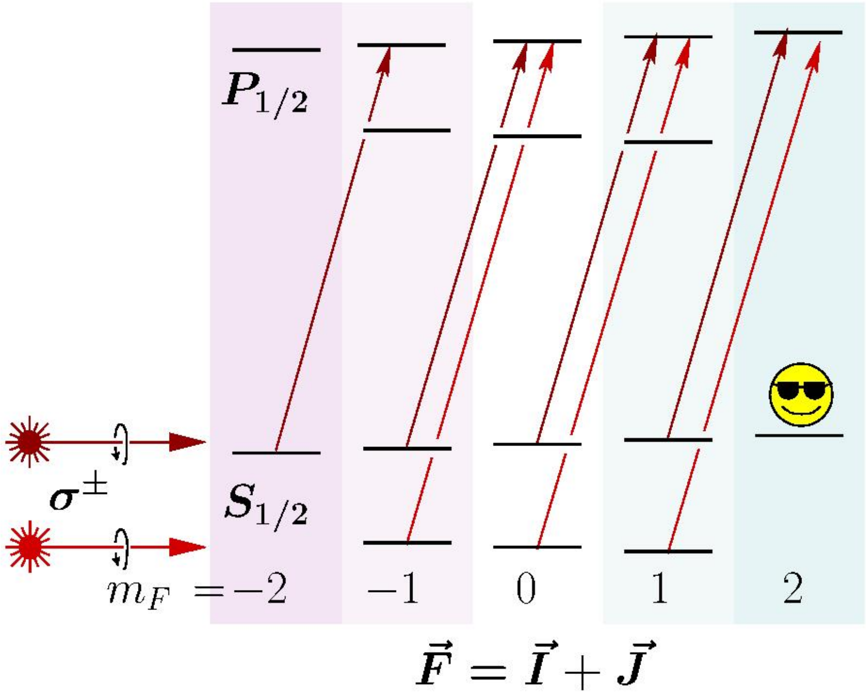
Outline of TRINAT's β asym & polarization measurements

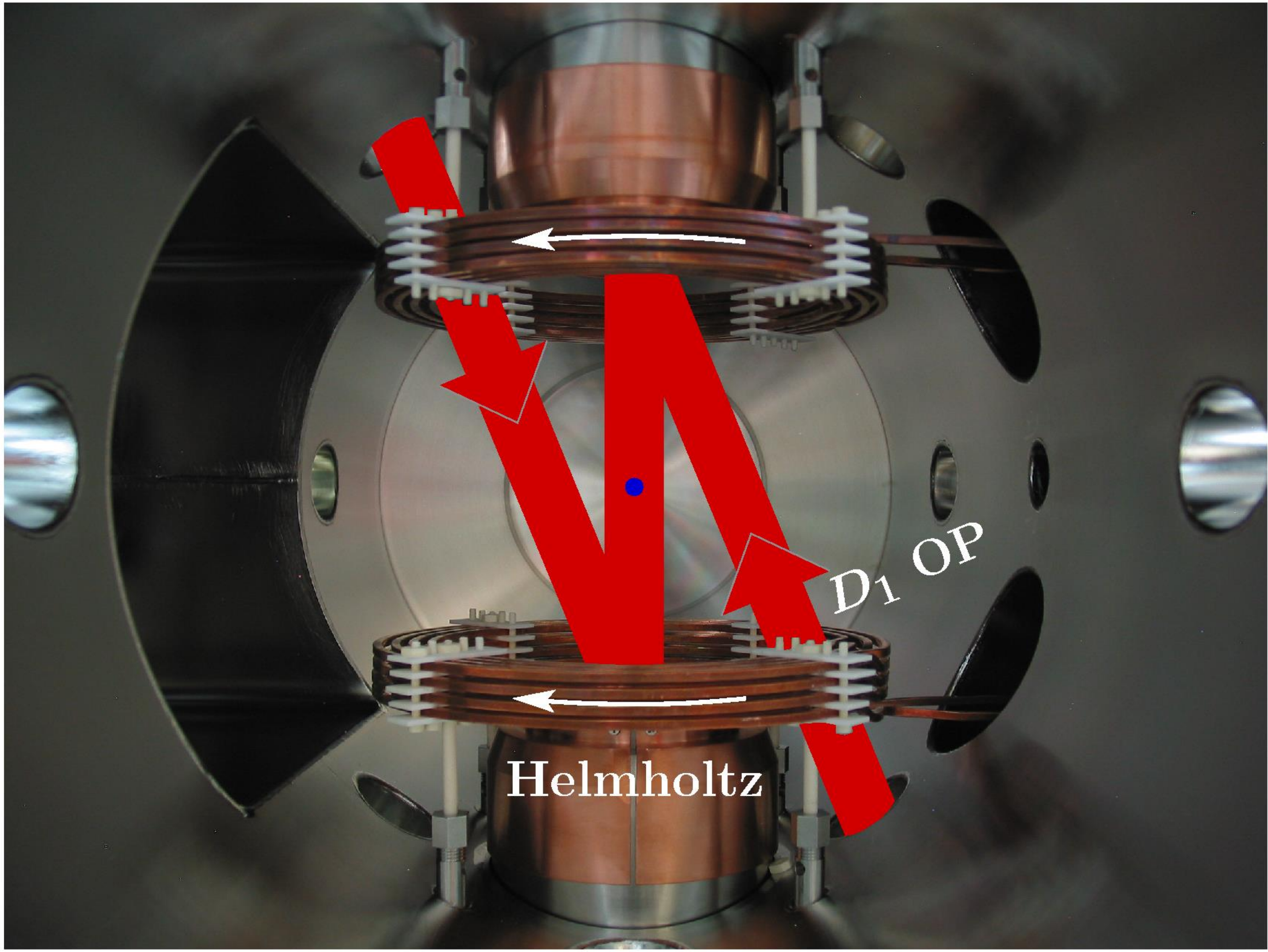
- MOTs provide a source that is:
  - Cold ($\sim 1\ \mathrm{mK}$)
  - Localized ($\sim 1\ \mathrm{mm}^3$)
  - In an open, backing-free geometry
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\rm rec}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event



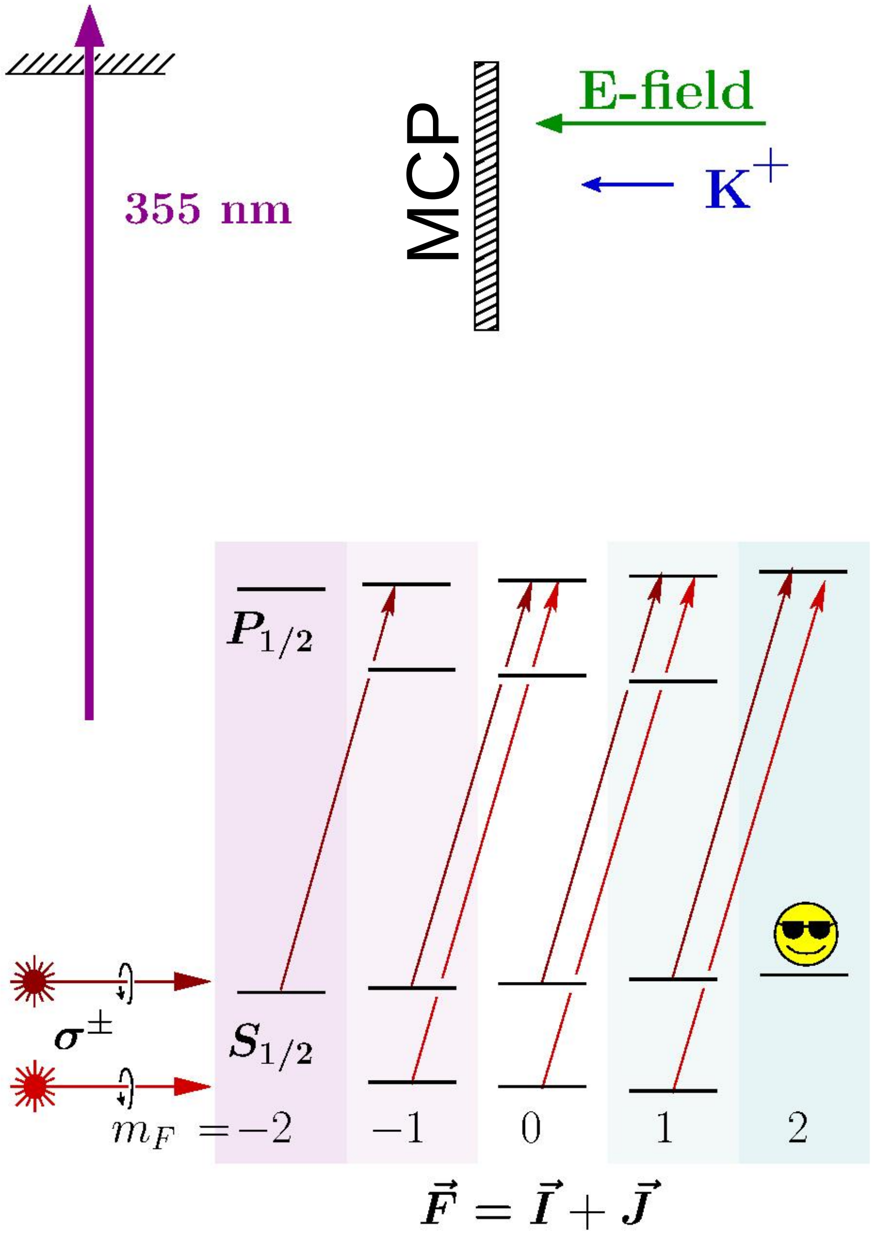
Outline of TRINAT's β asym & polarization measurements

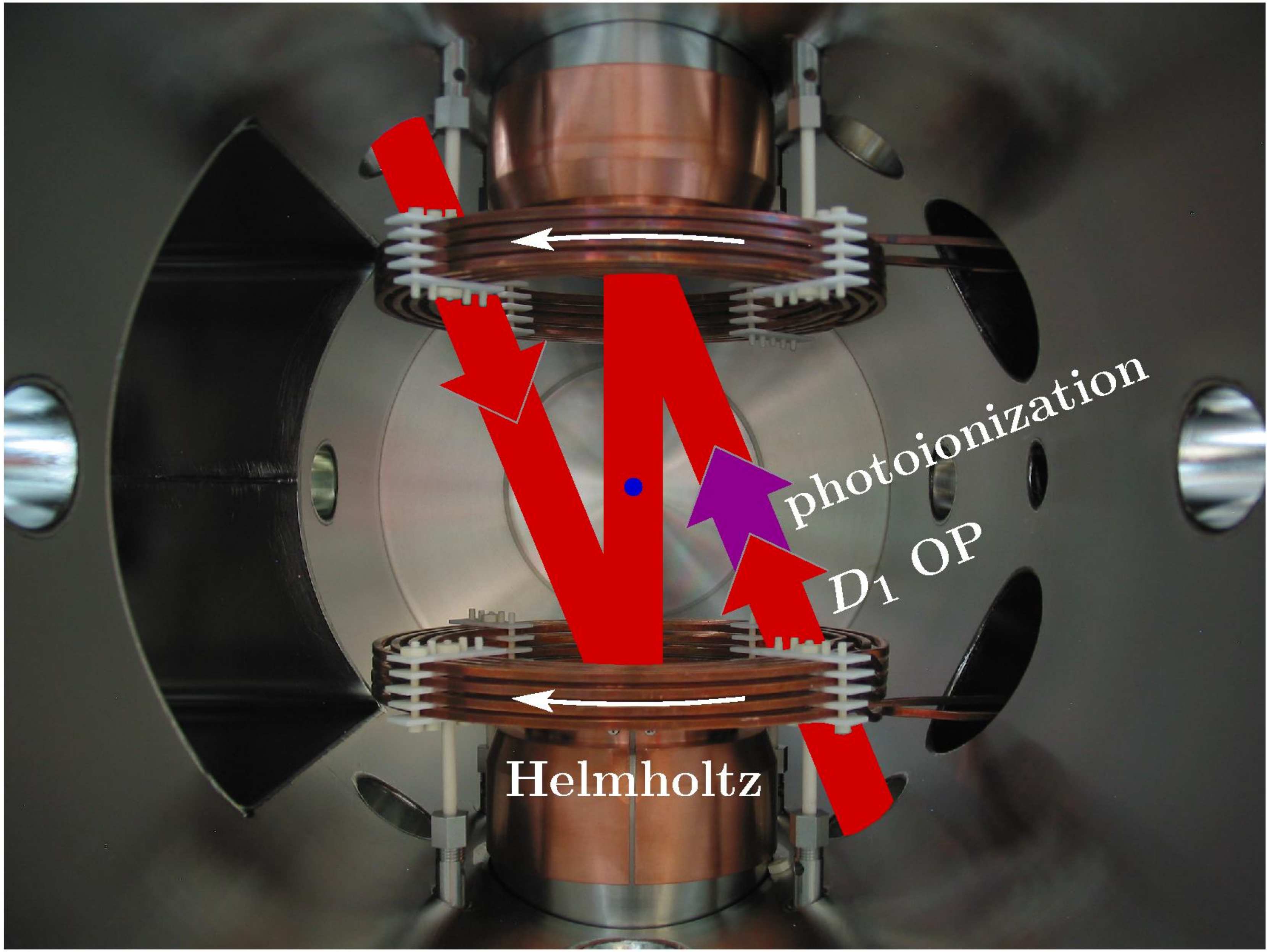
- Optical pumping:
  - Polarized light transfers angular momentum to the atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand





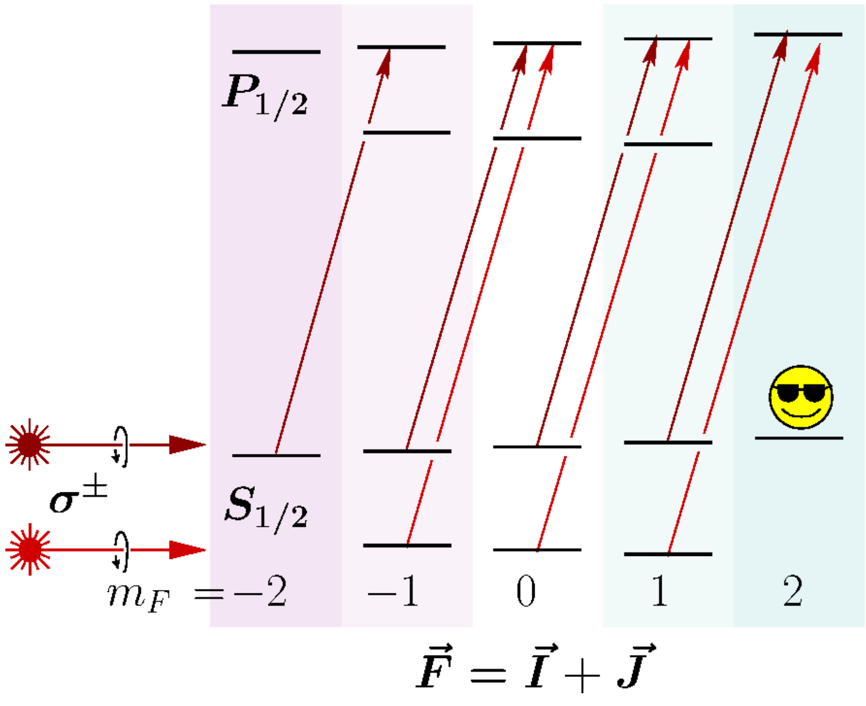
Outline of TRINAT's β asym & polarization

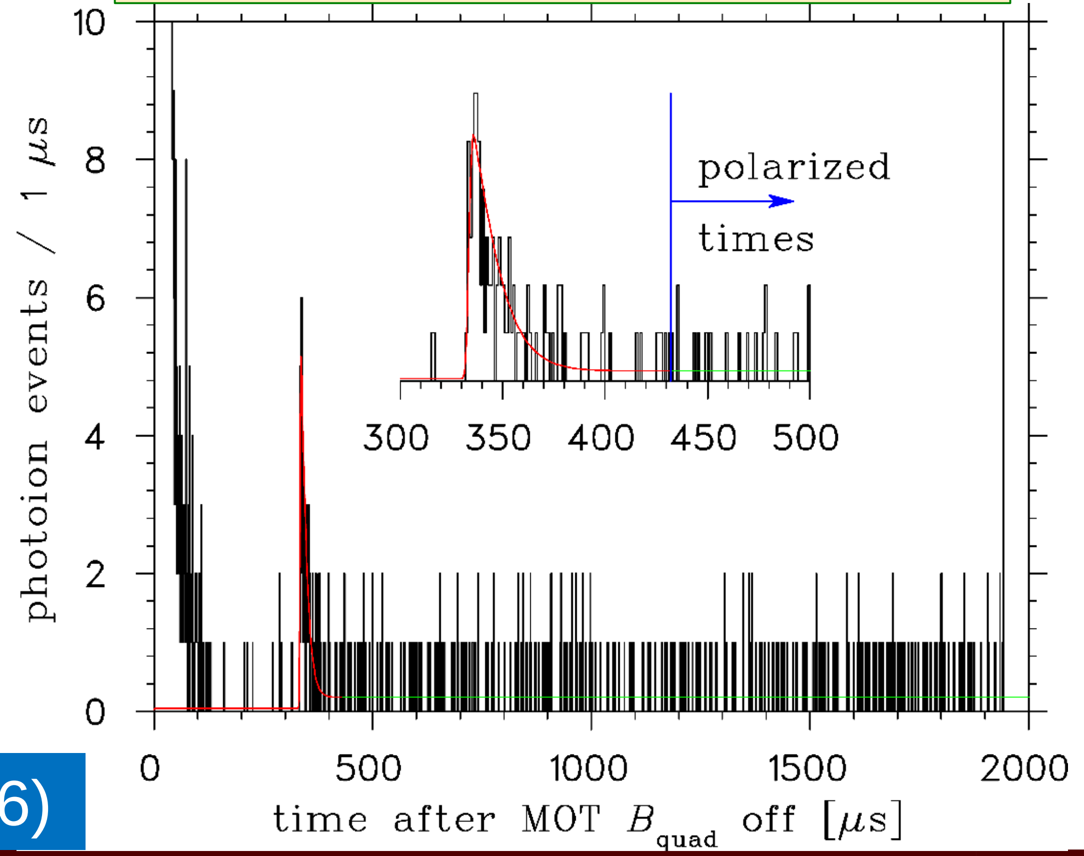




Optical pumping is fast and *efficient*!

- 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: $\langle |P_{\mathrm{nucl}}| \rangle = 0.9913(9)$





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

The β asymmetry measurement

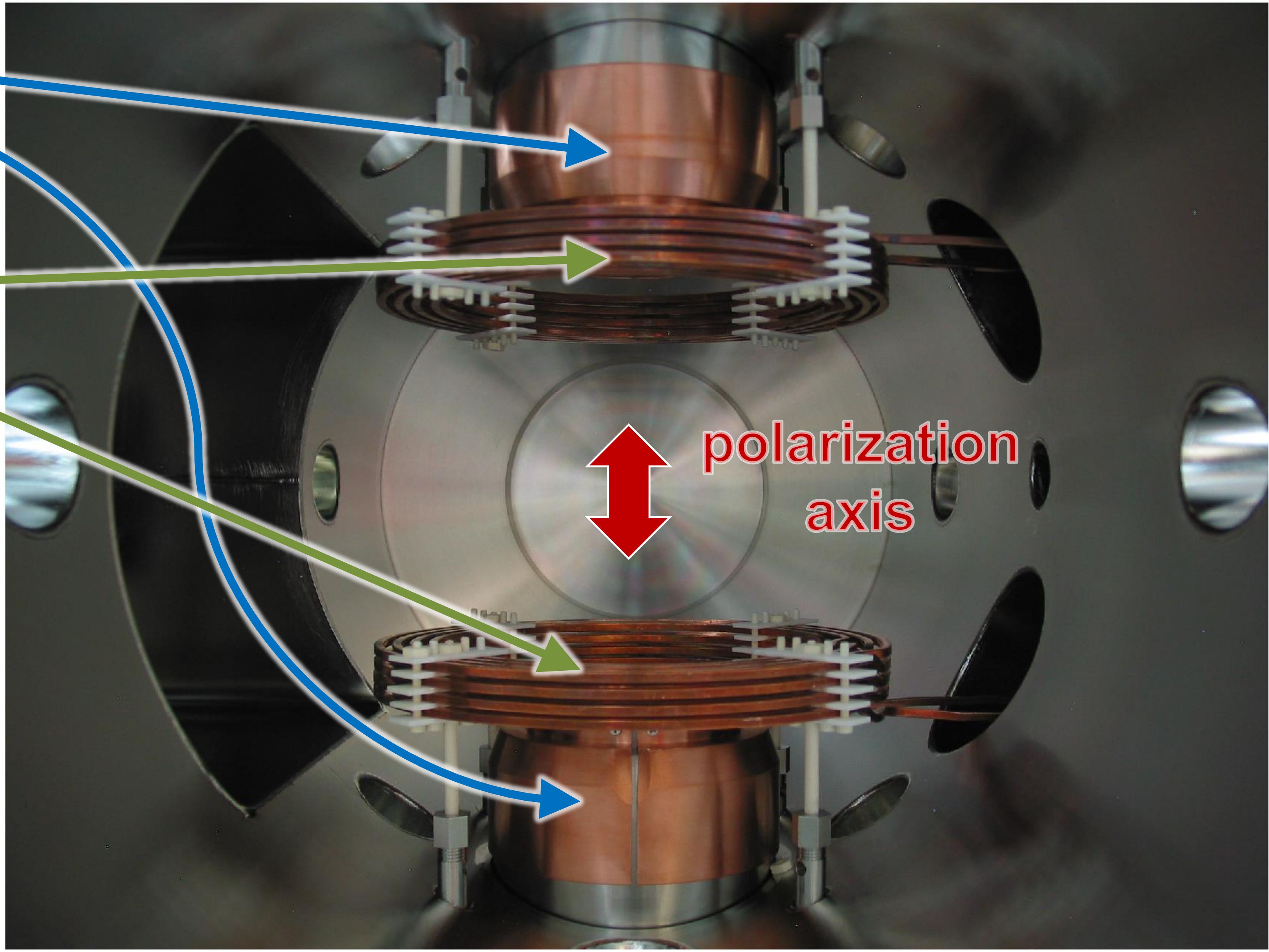
E_β detectors:
Plastic scintillator

ΔE_β detectors:
Double-sided Si-strip

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

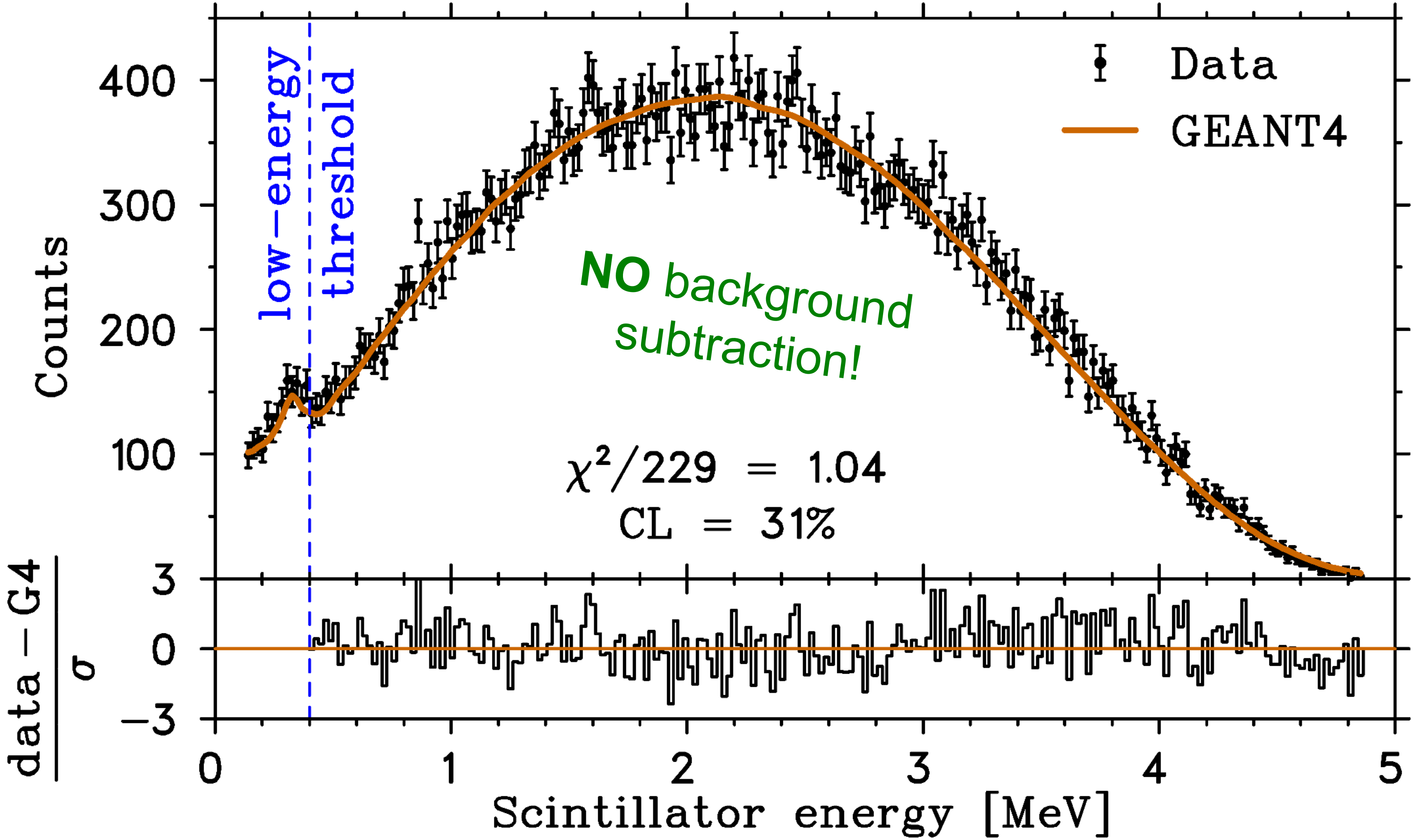
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

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



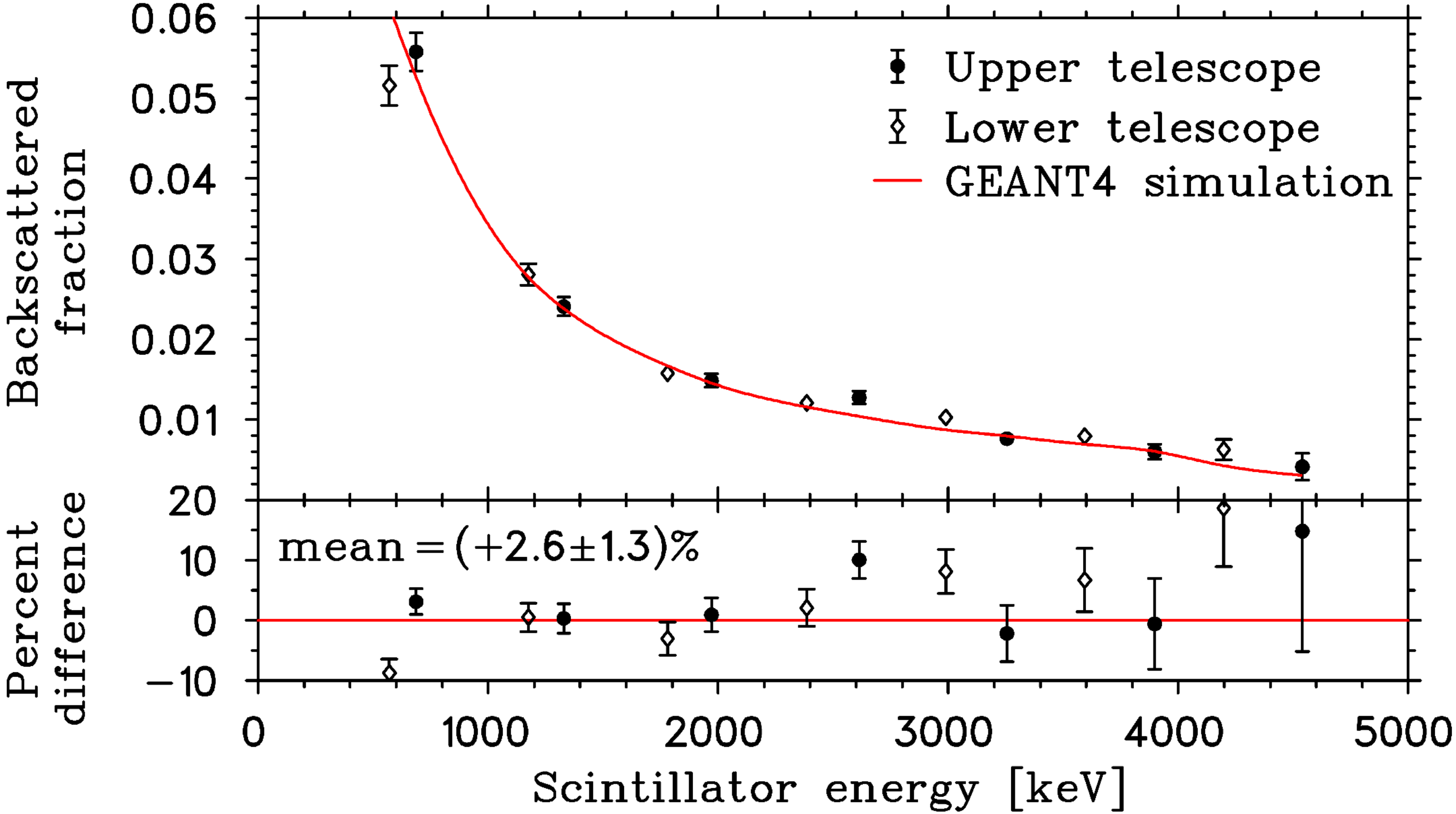
^{37}K β asymmetry measurement

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



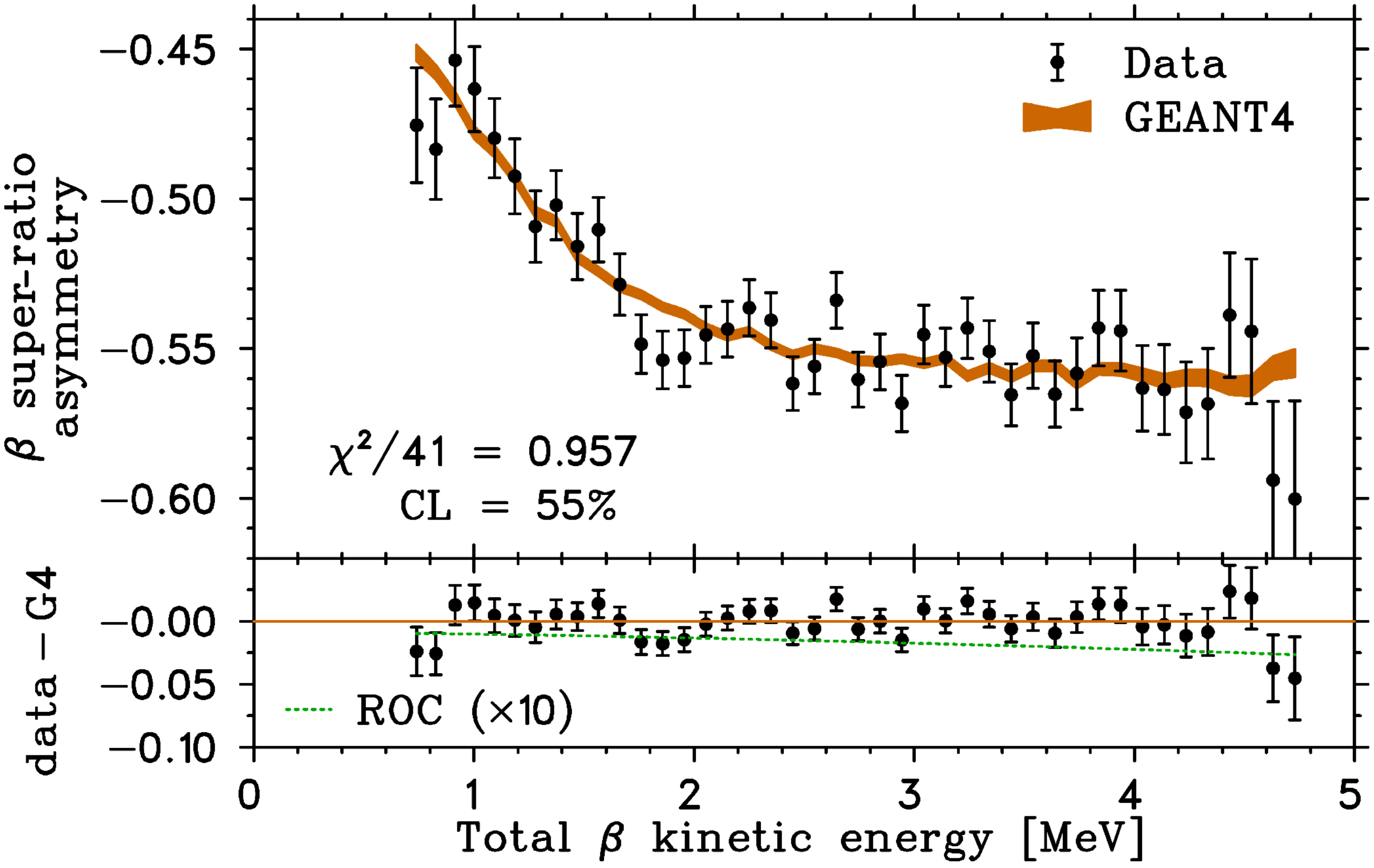
^{37}K β asymmetry measurement

- 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

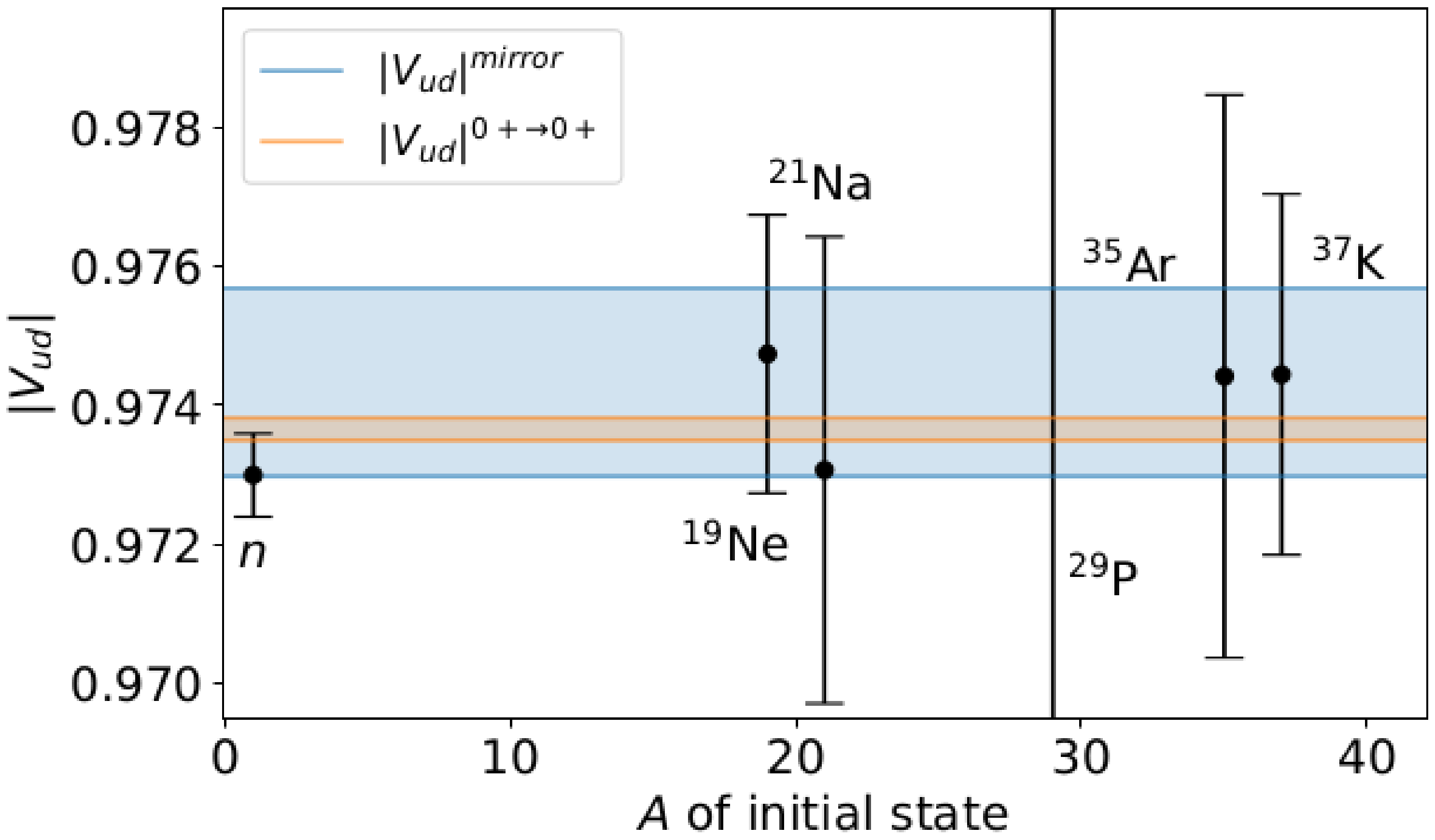
Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	1.0014	**8** $\times 10^{-4}$
β scattering	1.0230	**7** $\times 10^{-4}$
Trap position		4×10^{-4}
Trap movement		5×10^{-4}
ΔE position cut		4×10^{-4}
Shake-off e^- TOF region		3×10^{-4}
TOTAL SYSTEMATICS		**13** $\times 10^{-4}$
STATISTICS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

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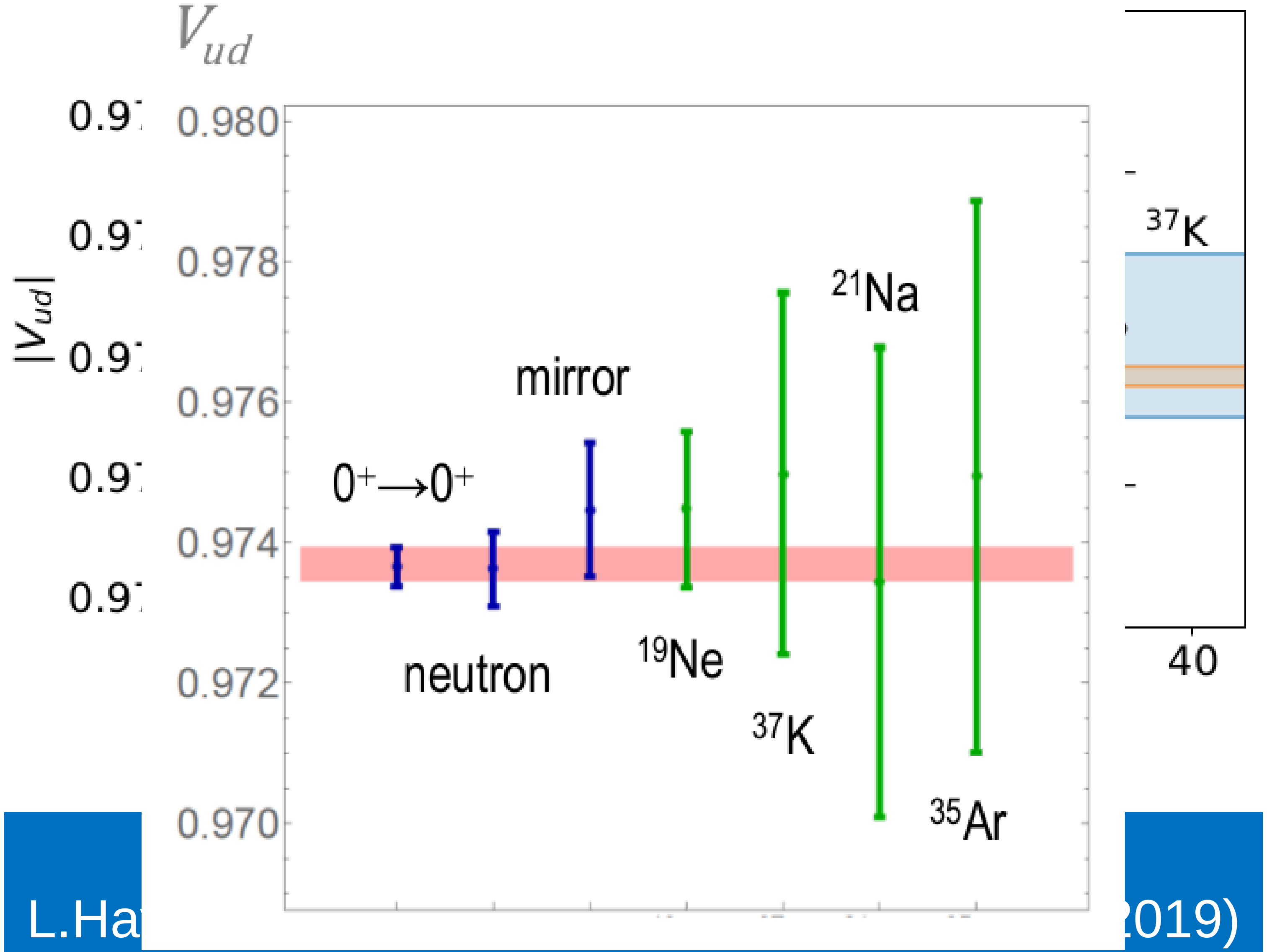
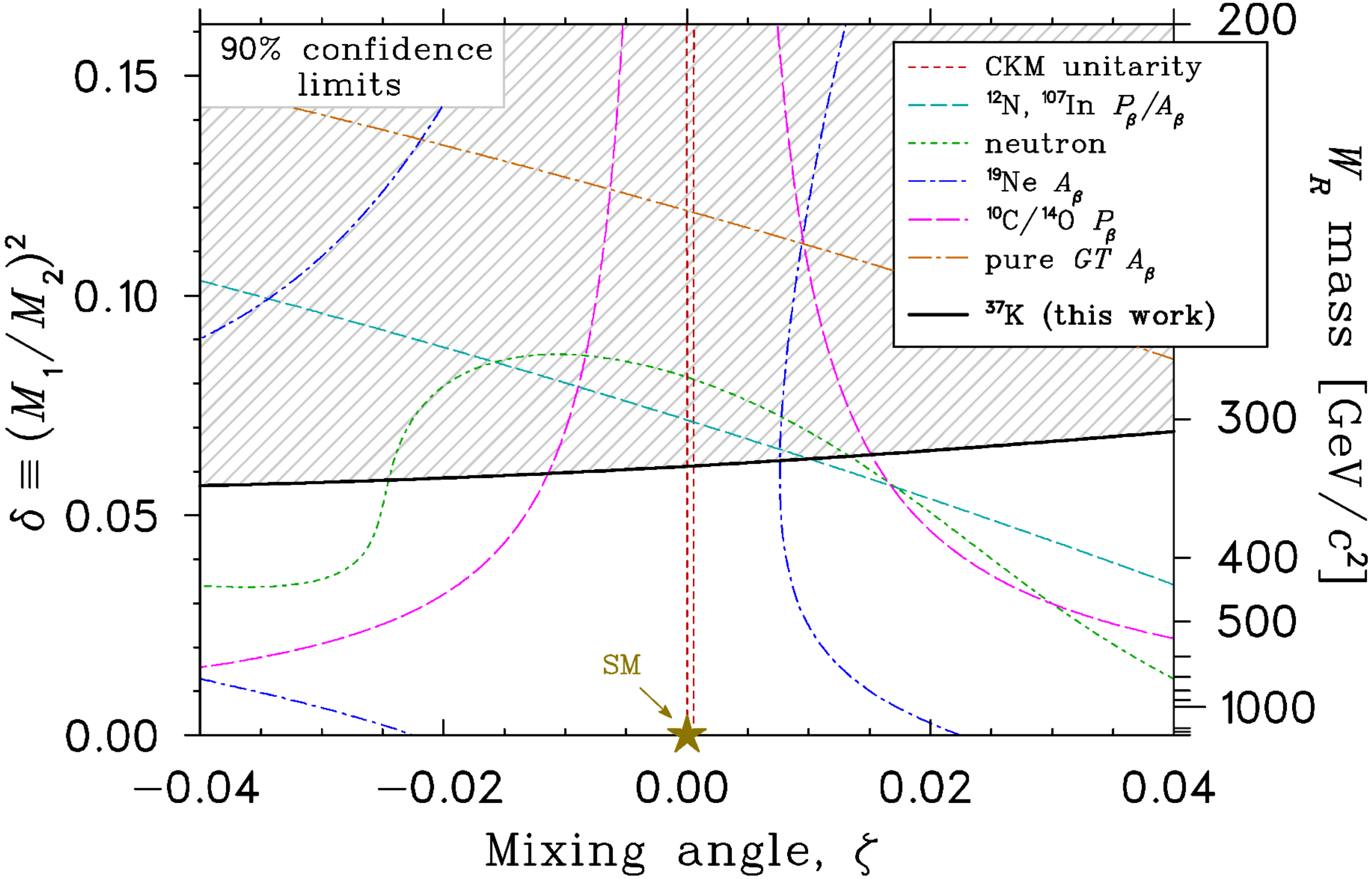


L.Ha… 019)

Falkowski *et al.*, arXiv:2010.13797 (today!)

Interpretation and future prospects

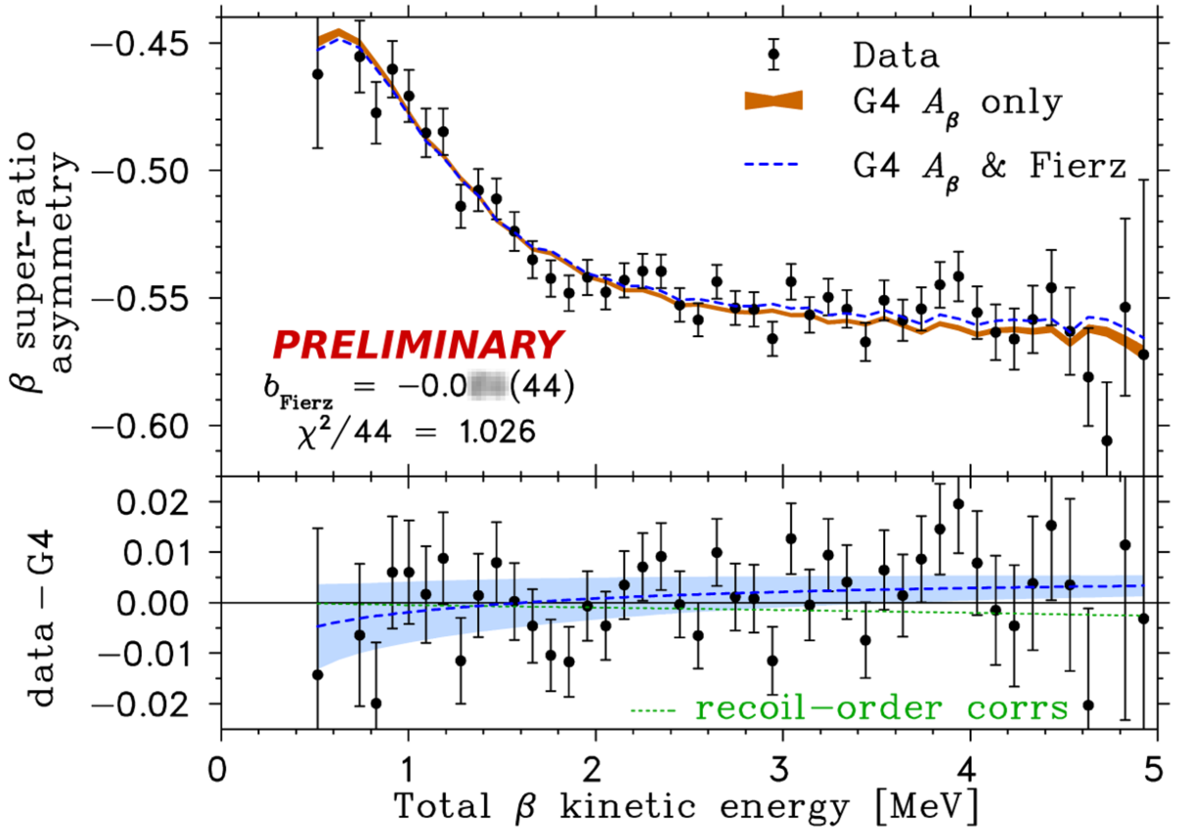
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents

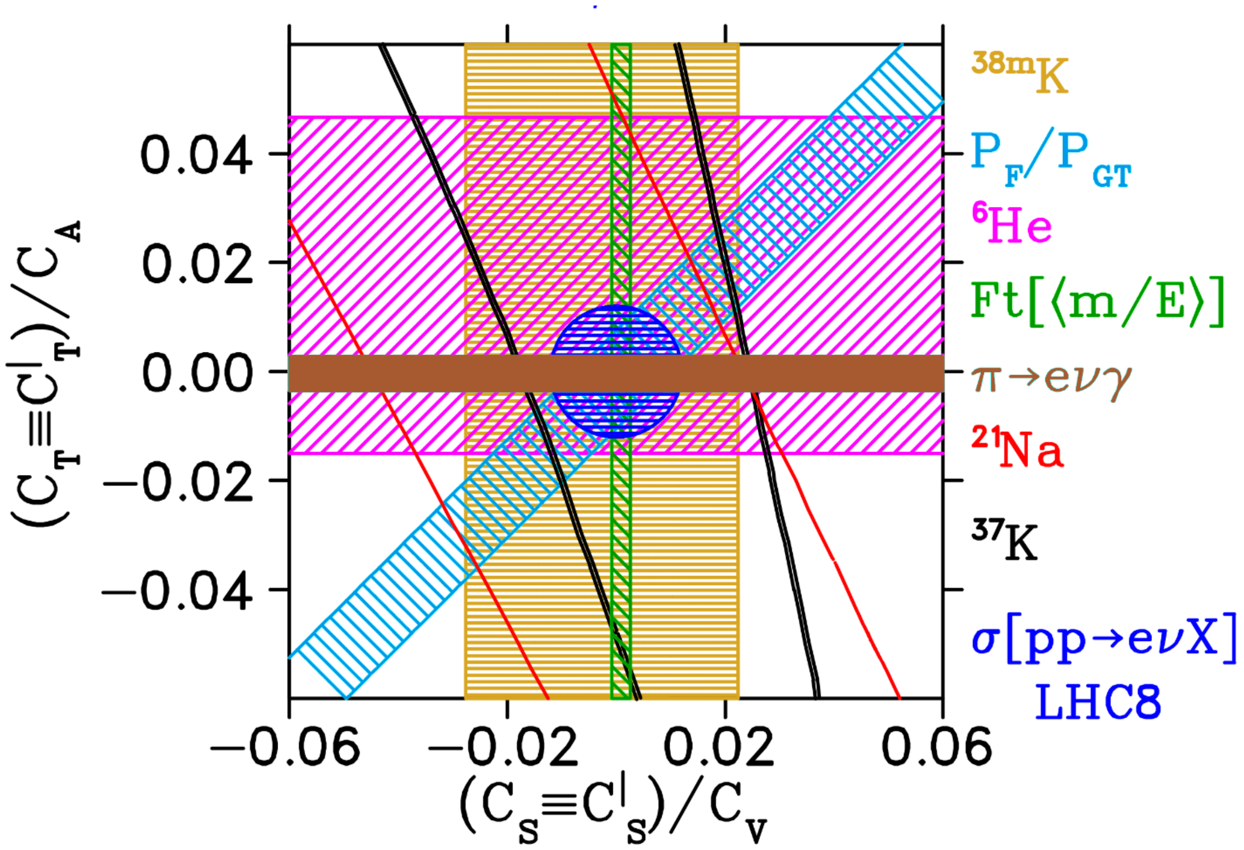


B.Fenker *et al*, PRL **120**, 062502 (2018)

Future plans

- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2[nd] class currents
- Improve A_β measurement by $3-5\times$





PRELIMINARY

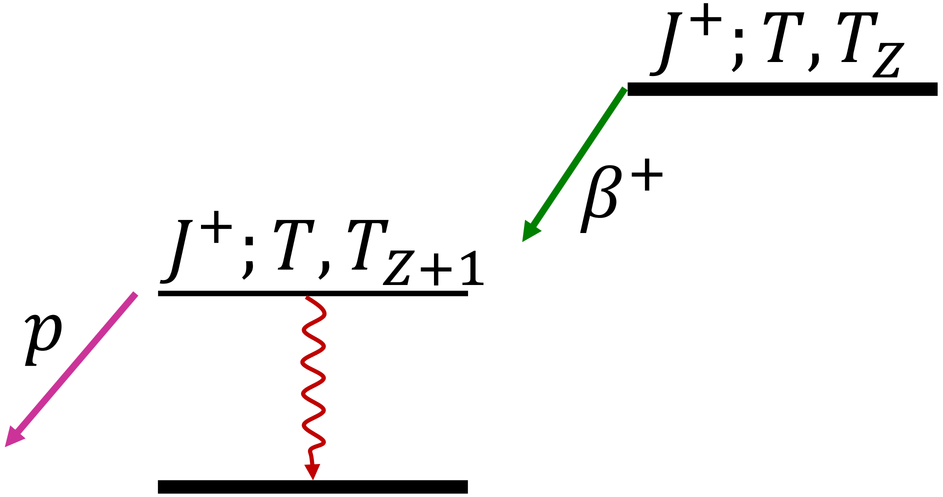
Outline

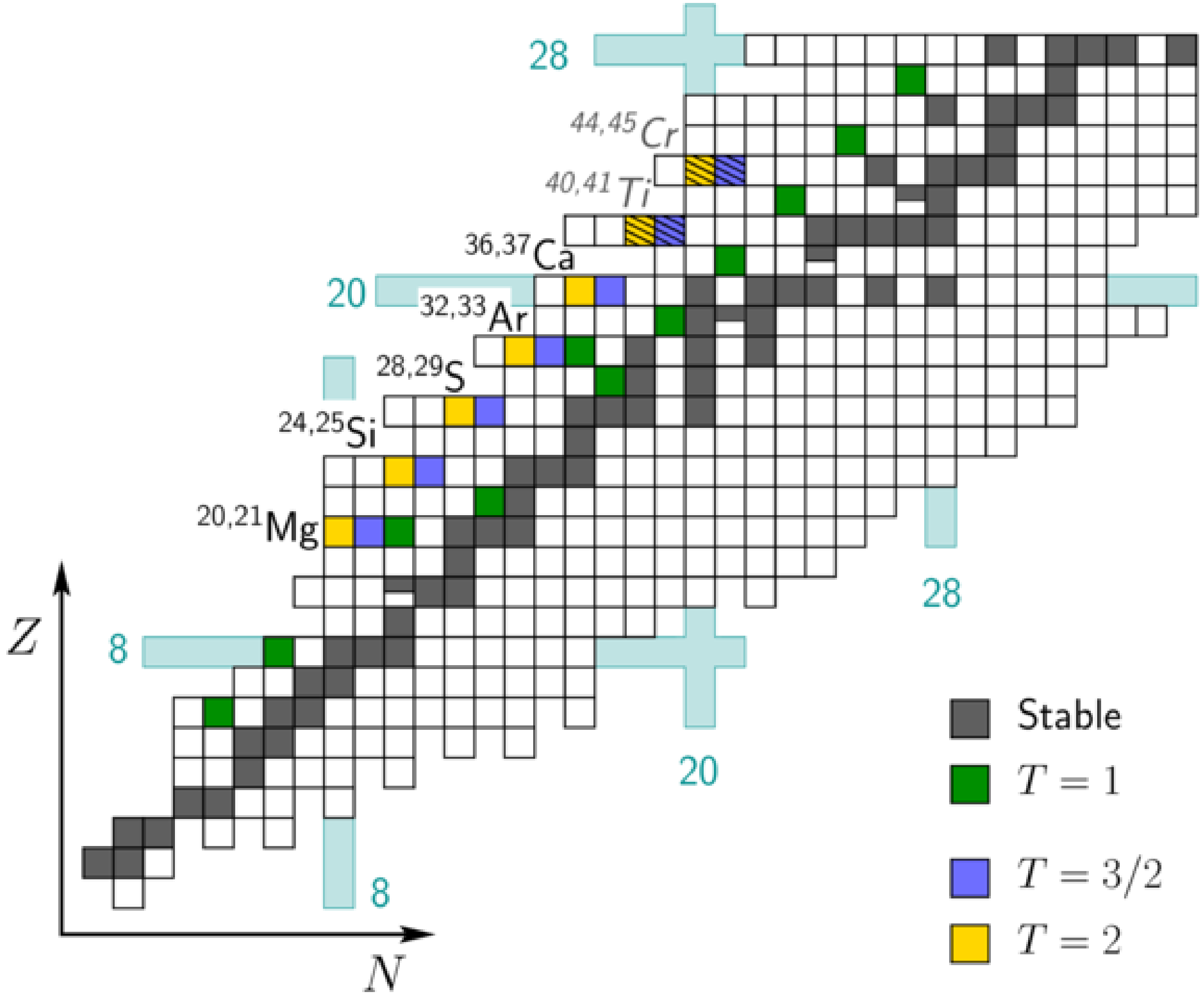
- **Introduction**
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- **^{37}K at TRIUMF**
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β
- **TAMUTRAP**
  - $T = 2$ decays to test the SM
  - Source production and commissioning mass measurements
- **^{6}He b_{Fierz} at UW**
  - Cyclotron radiation emission spectroscopy
  - Plans to implement an ion trap to remove wall collisions

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

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

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

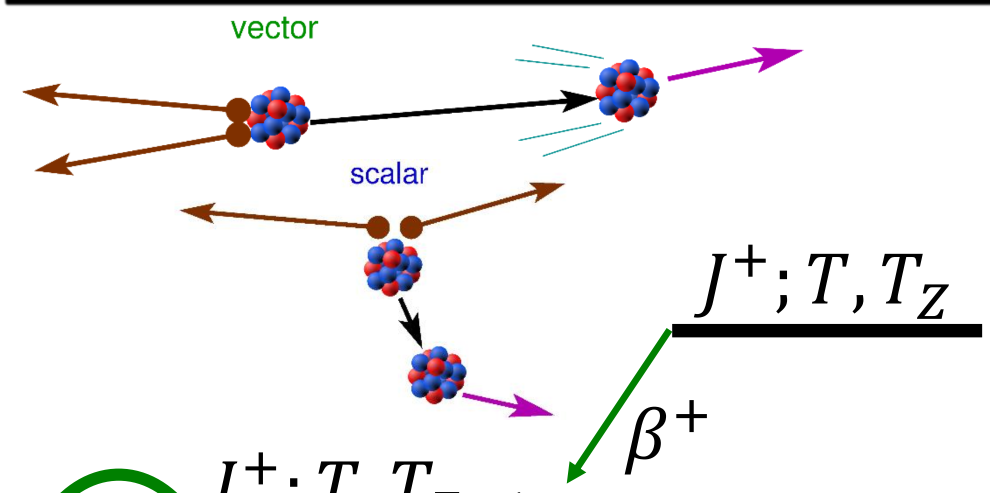


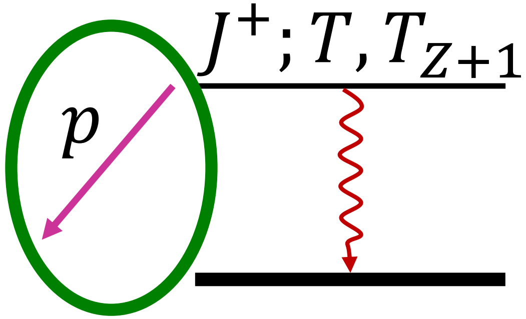


$T = 2, 3/2$ pure Fermi and Gamow-Teller decays

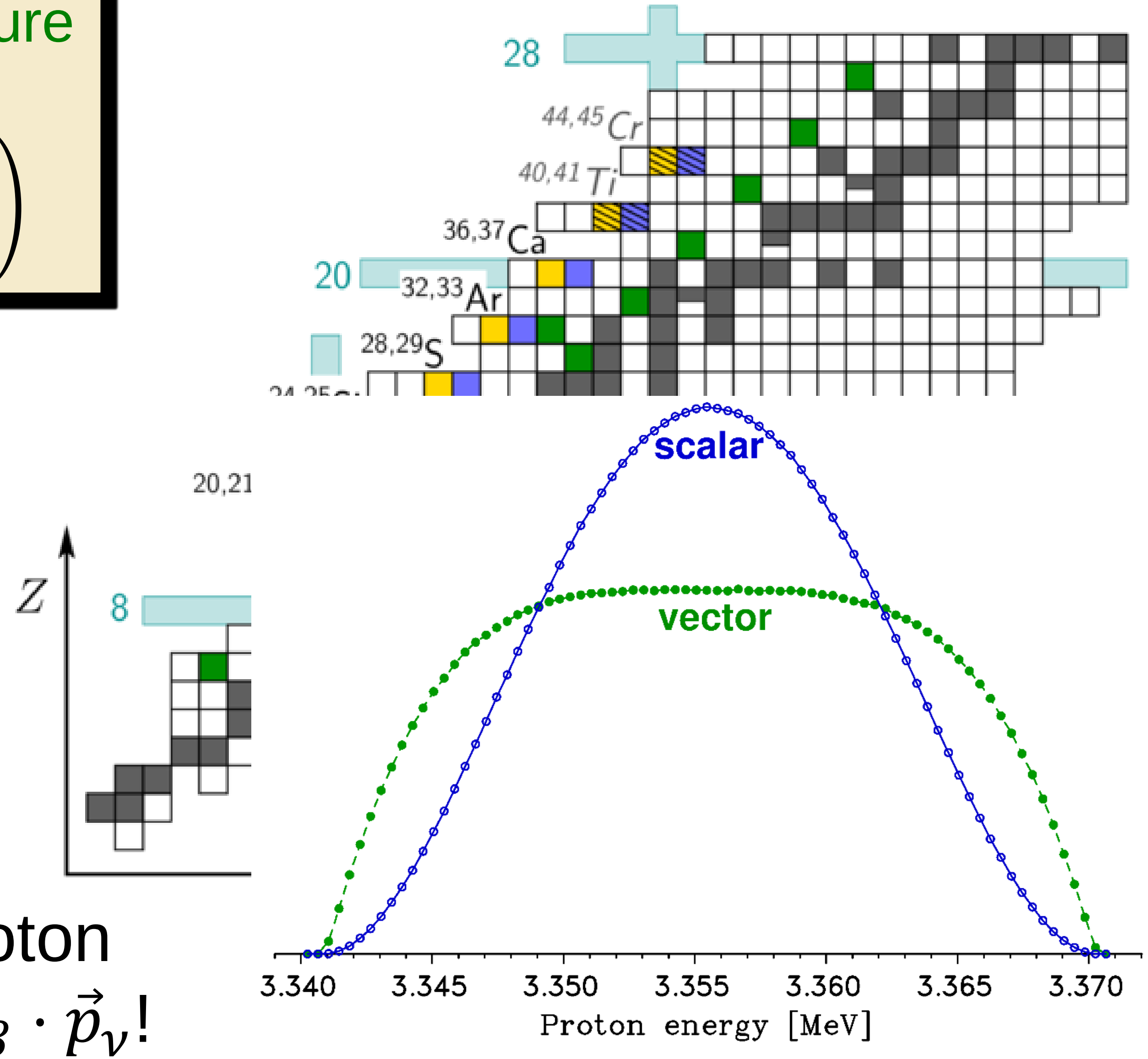
Pure Fermi decay ⇒ minimal nuclear structure effects; decay rate is simply given by

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





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



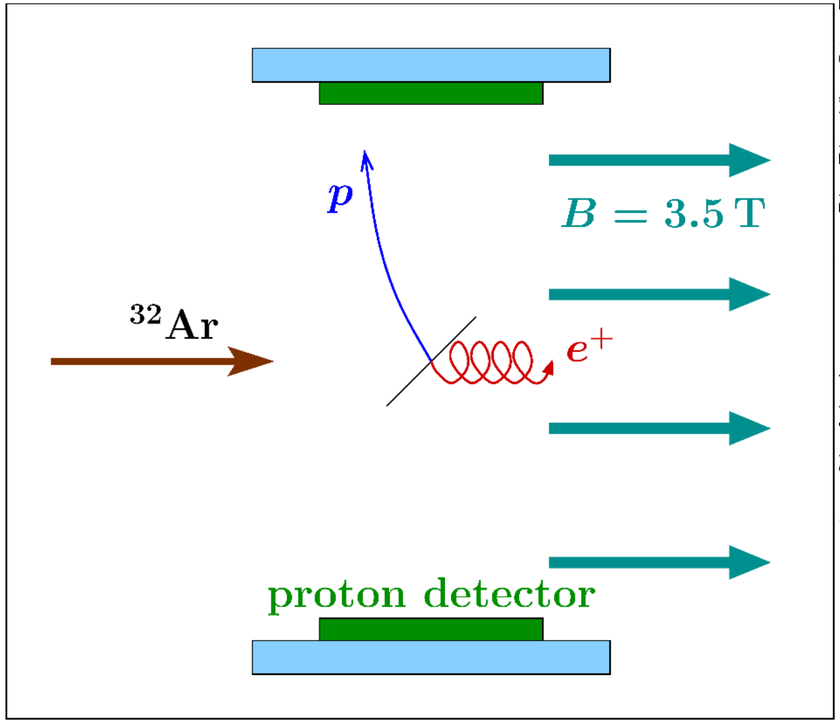
β-ν correlation – A good idea…going back 20 yrs

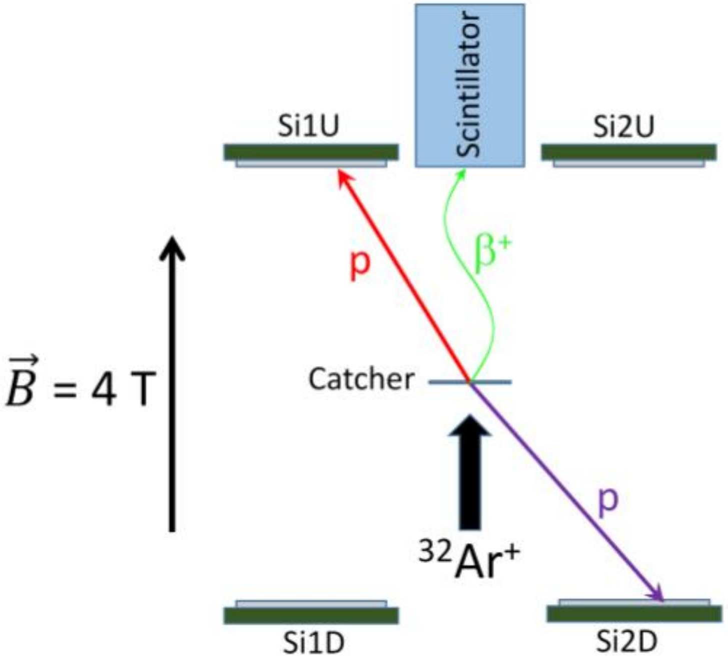
VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4]
ichsel,[1] and the ISOLDE Collab
s, University of Washington, Seattle
ics, University of Notre Dame, Notr
structura de la Materia, CSIC, E-28
ivision, CERN, Geneva, Switzerland
(Received 24 February 1999)

tion in the $0^+ \rightarrow 0^+$ β decay of
coil on the shape of the narrow proto
with the standard model prediction.
0039, which yields improved constr

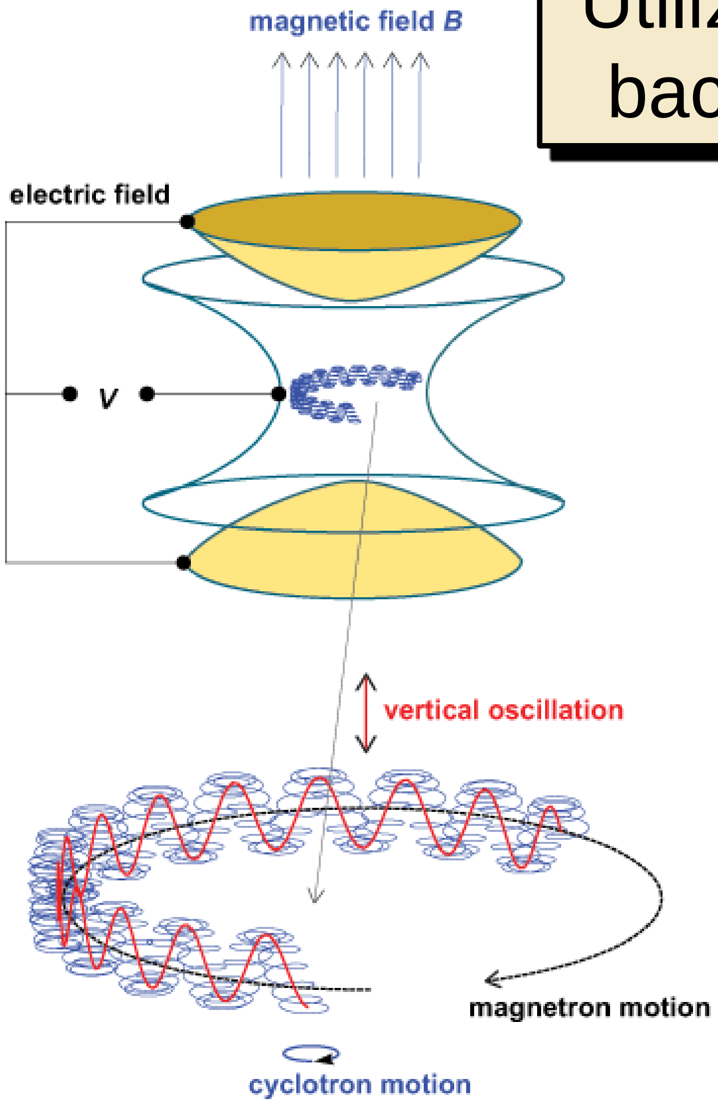


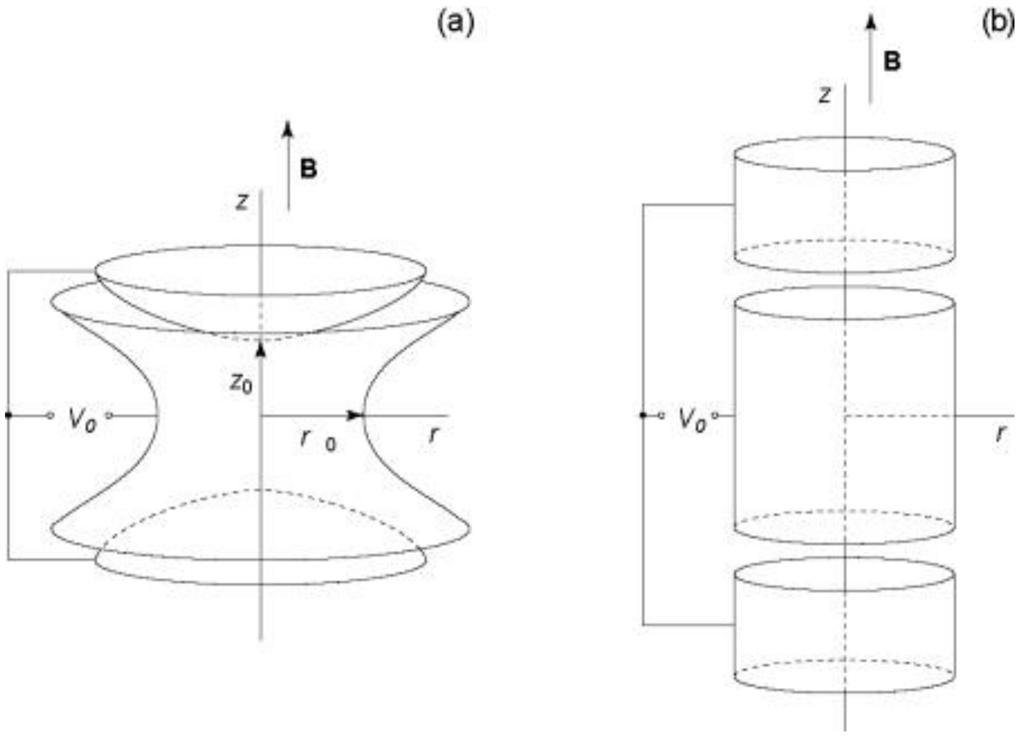


WISArD collab, PRC **101**, 055501 (2020)

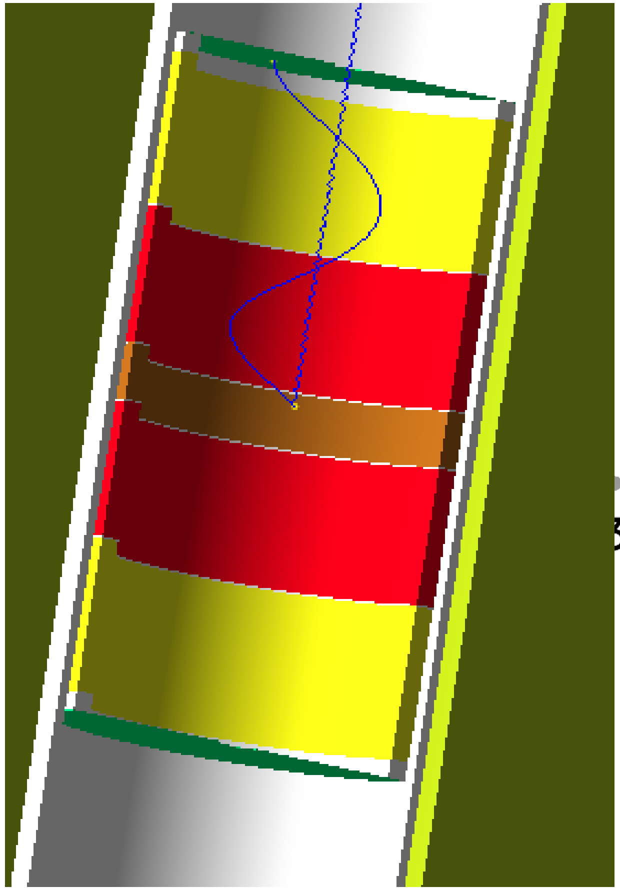
Scattering and energy loss in the foil…

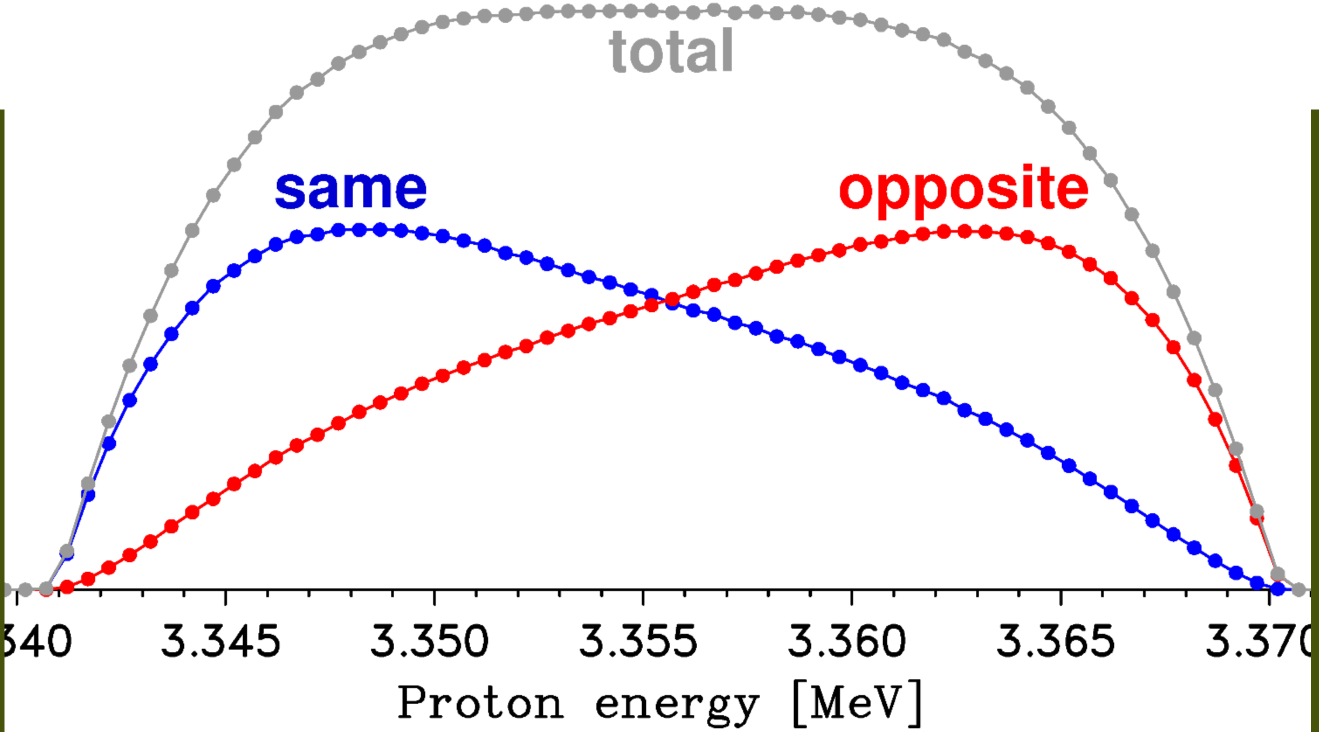
Utilize the technology of Penning traps to provide a backing-free source of localized radioactive ions!!

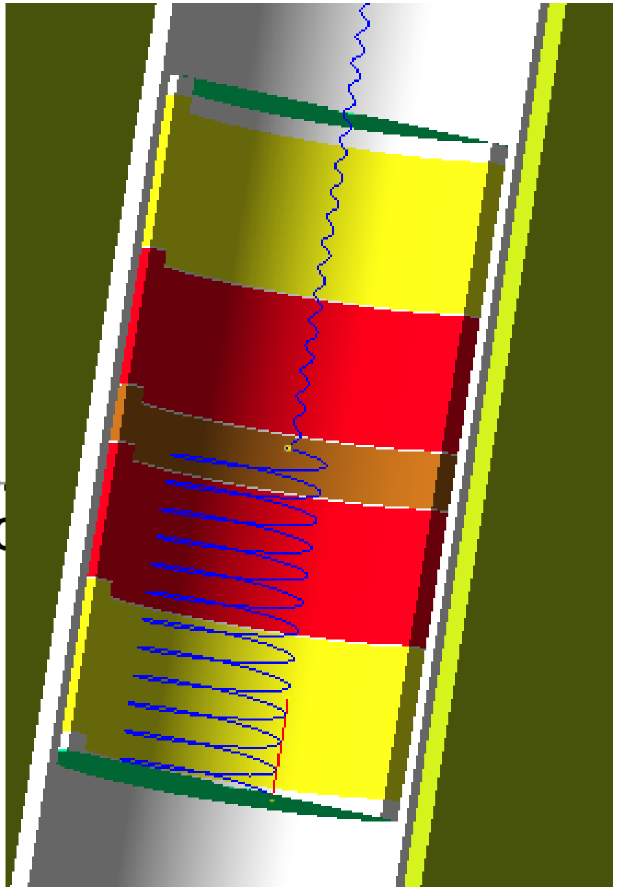


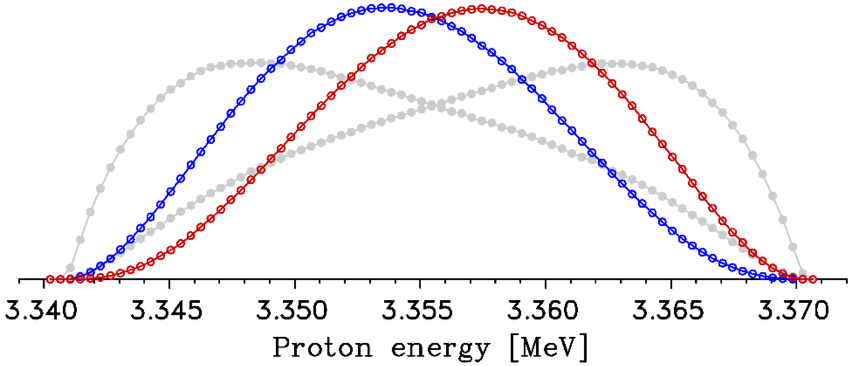


Measure means instead of 2^{nd} moments

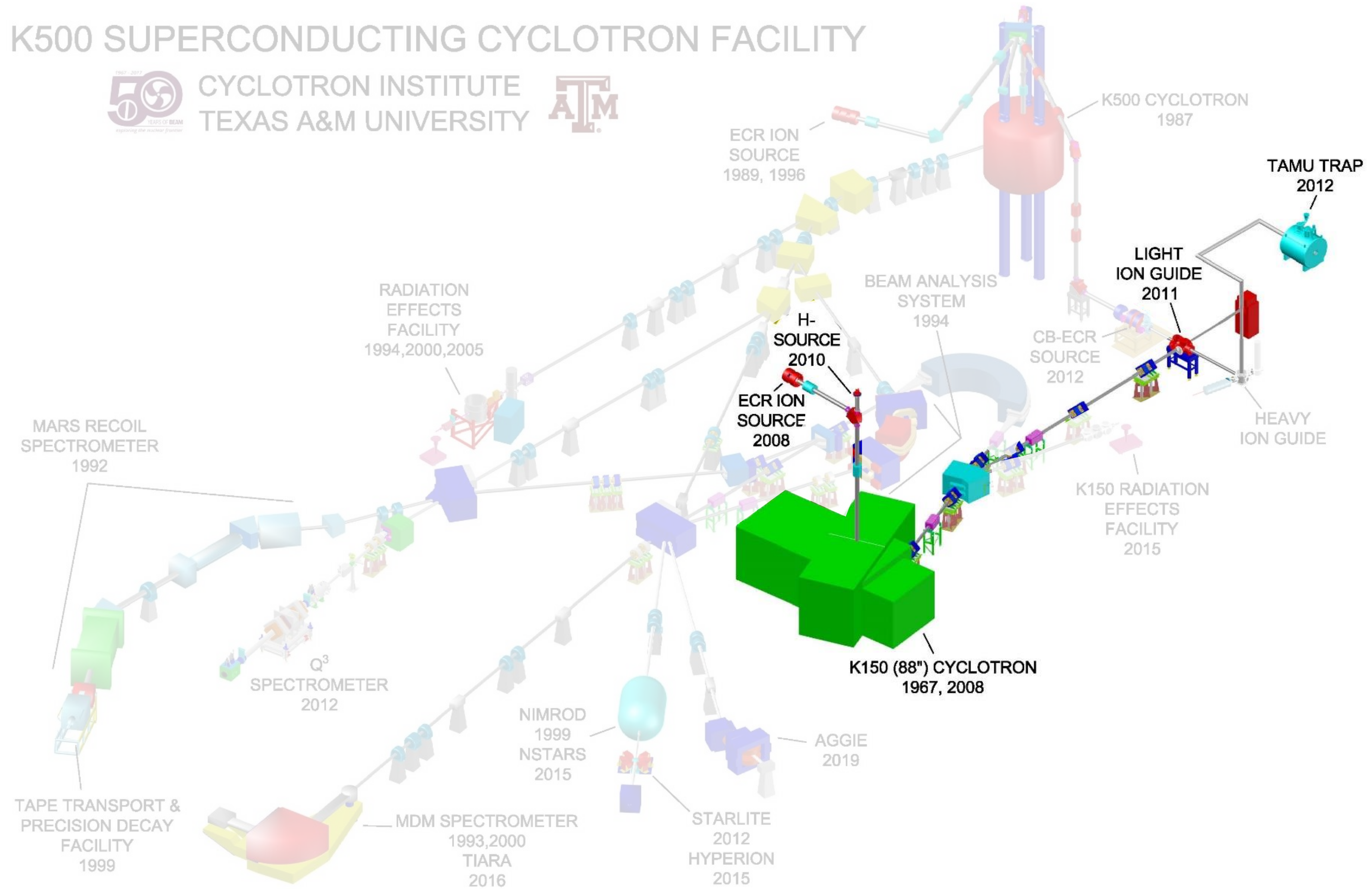








An IGISOL system at the Cyclotron Institute



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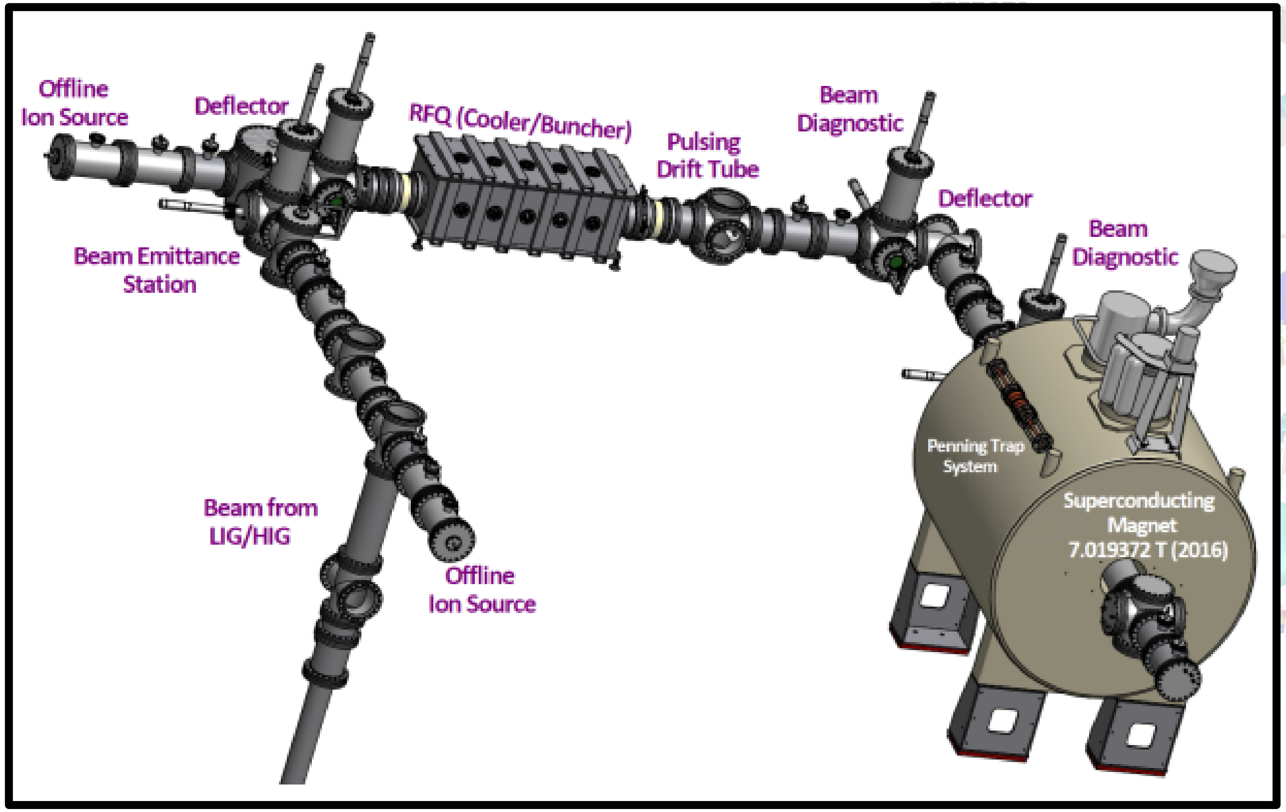
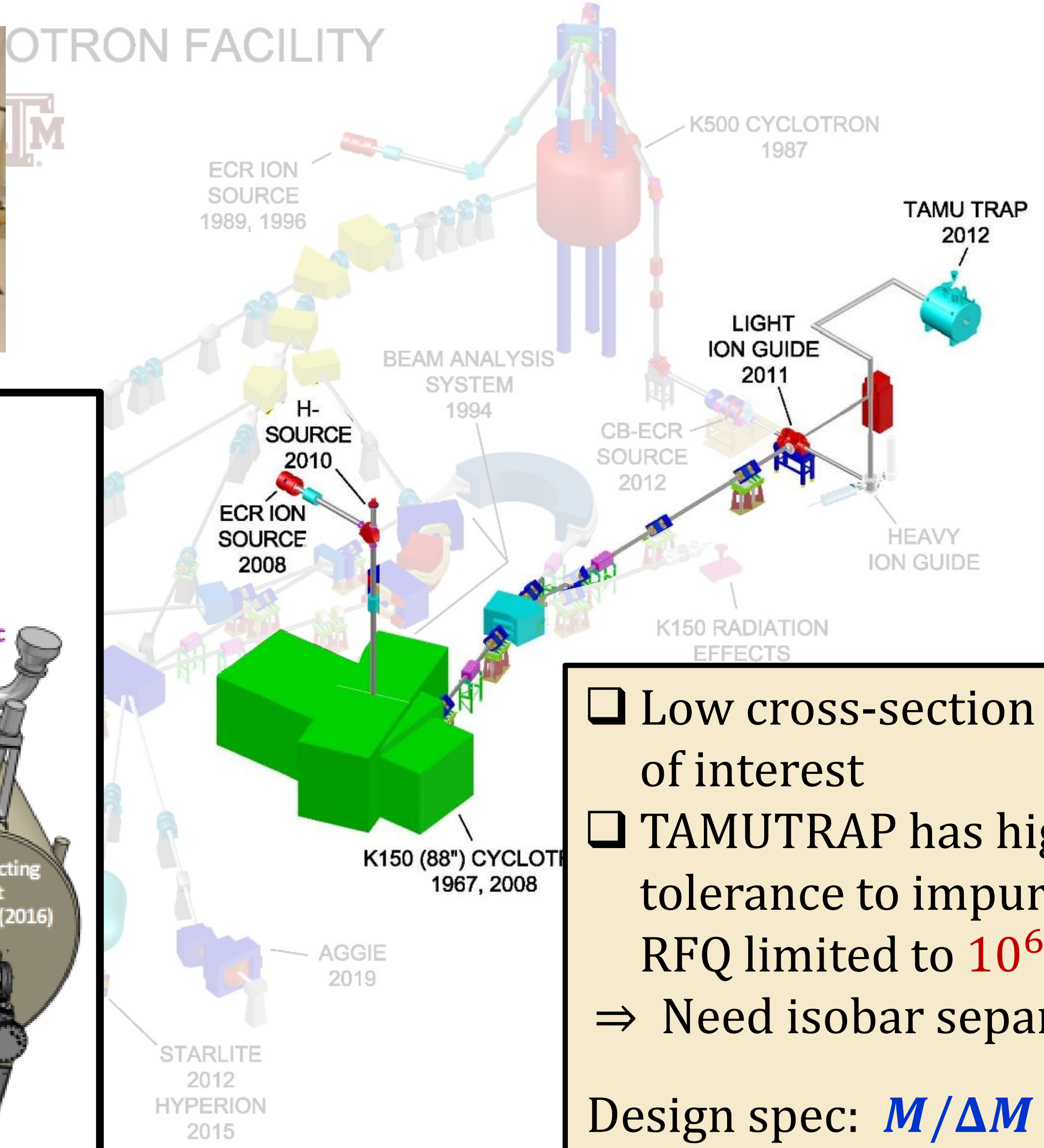




- ❑ Low cross-section for ions of interest
- ❑ TAMUTRAP has high tolerance to impurities, but RFQ limited to 10^6 ions/sec

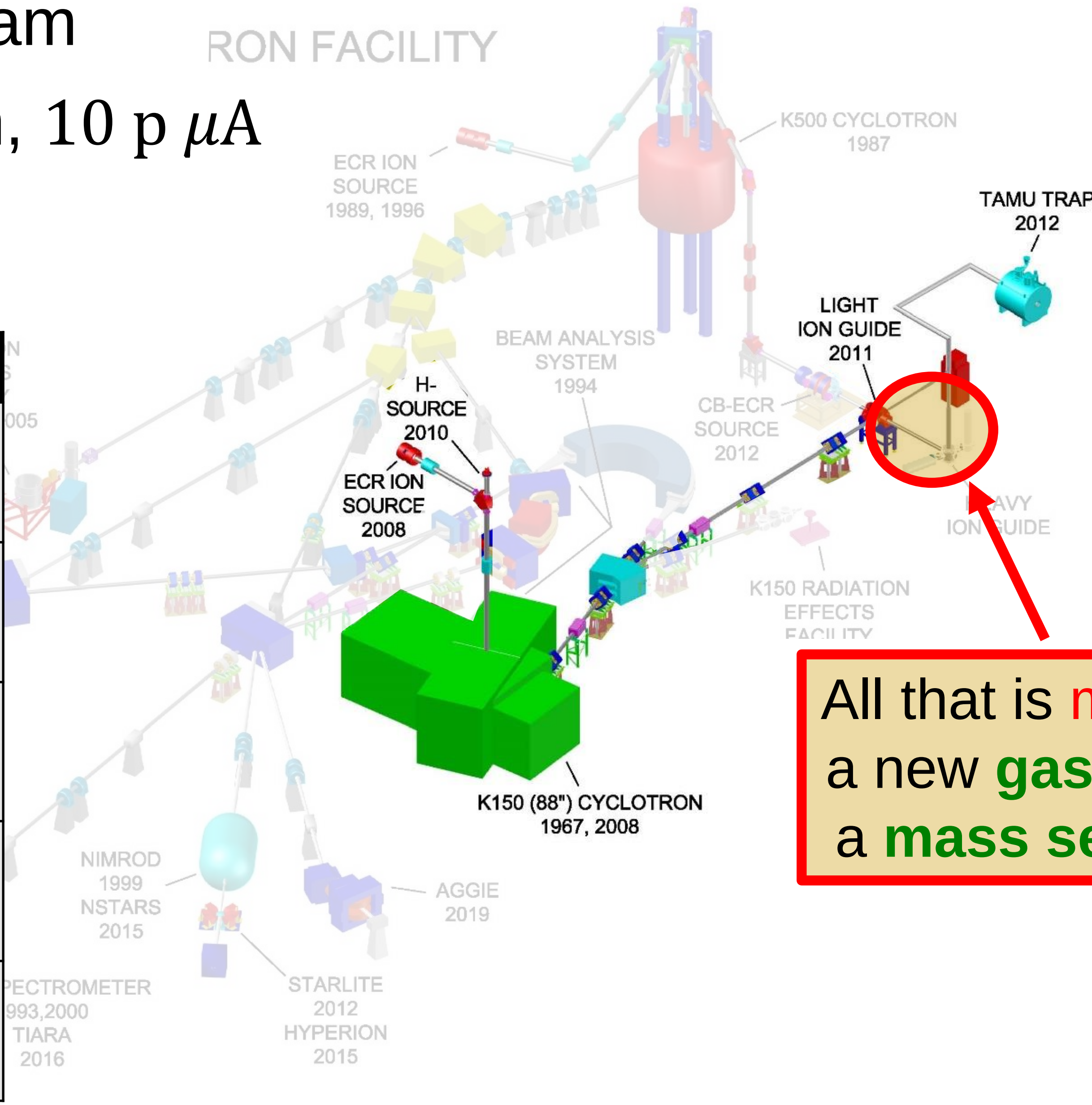
$\Rightarrow$ Need isobar separation $\Leftarrow$

Design spec: $M/\Delta M > 2,000$

An IGISOL system at the Cyclotron Institute

- 10-25 MeV/u ^{3}He primary beam
- Fusion-evapouration reaction, 10 p μA

Target	Product	Production rate
^{20}Ne	^{20}Mg	4×10^3
	^{21}Mg	3×10^5
^{24}Mg	^{24}Si	3×10^3
	^{25}Si	2×10^5
^{28}Si	^{28}S	3×10^3
	^{29}S	8×10^4
^{32}S	^{32}Ar	0.9×10^3
	^{33}Ar	0.9×10^5
^{36}Ar	^{36}Ca	0.2×10^3
	^{37}Ca	0.2×10^5



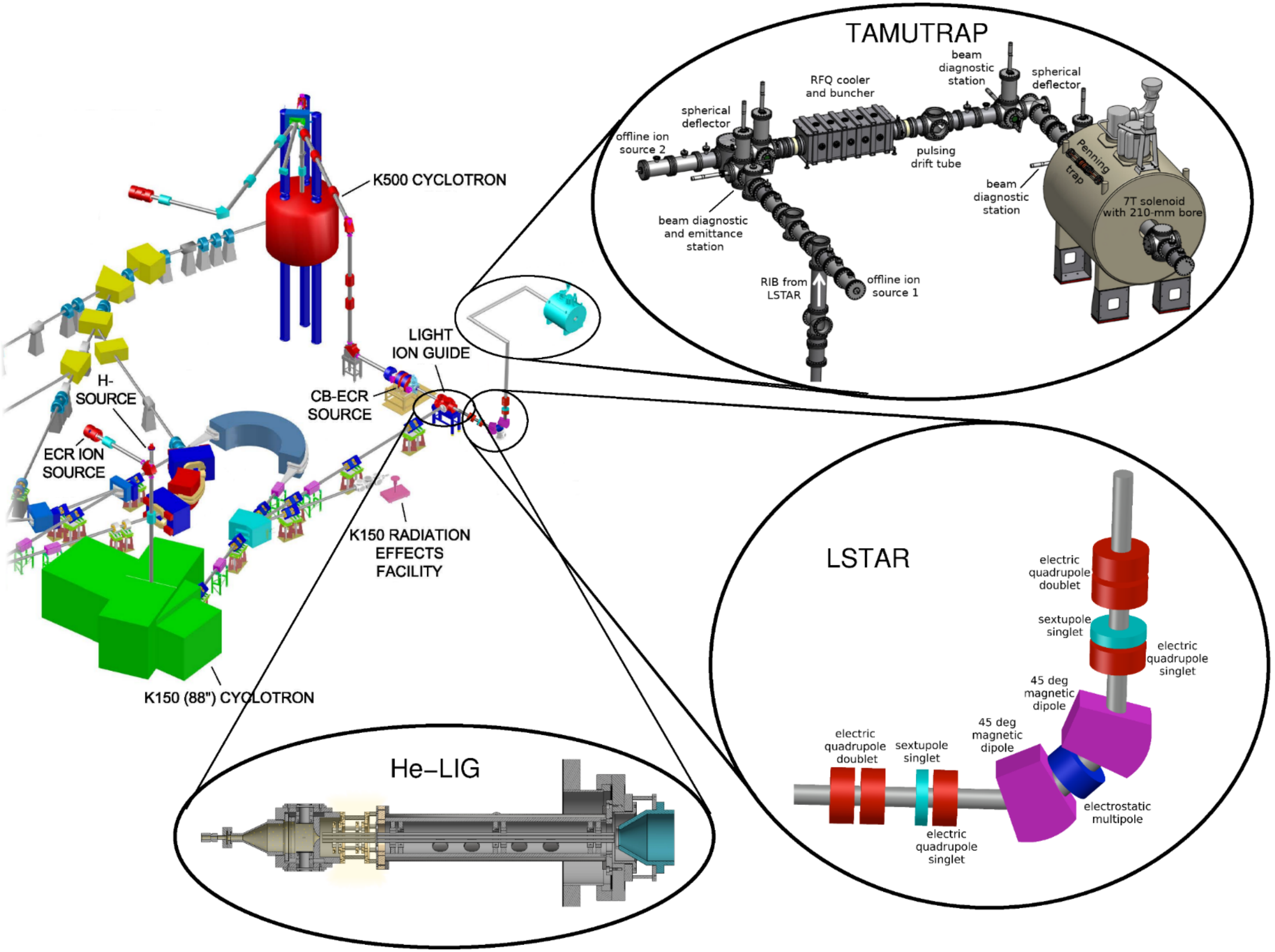
All that is missing is a new **gas cell** and a **mass separator**

Developing the RIBs for TAMUTRAP

- Efficiency is absolutely critical
  - IGISOL at Jyvaskyla quotes 5% efficiency for gas cell
  - Gas cell [5%] → separator [85%] → cooler/buncher [20%] → Penning trap
  - Estimate for rates of proton-rich nuclei in the trap:

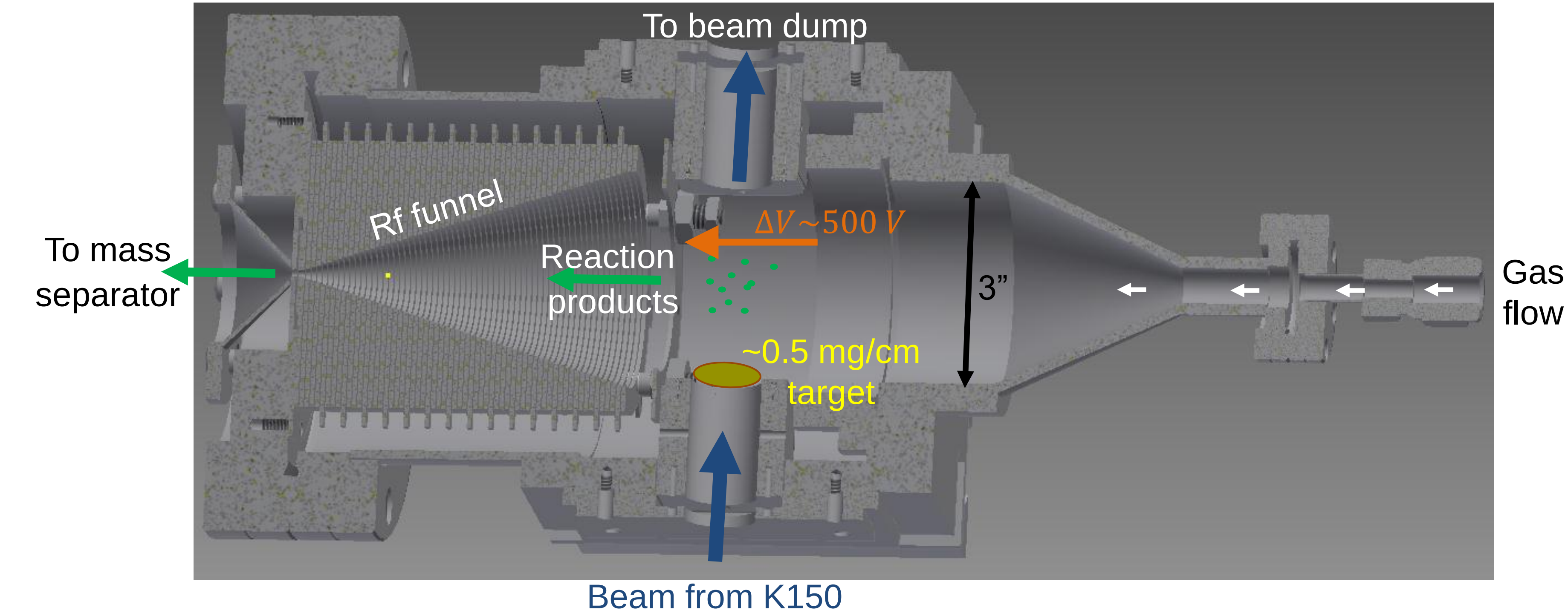
^{21}Mg	2650
^{25}Si	1425
^{29}S	850
^{33}Ar	760
^{37}Ca	190

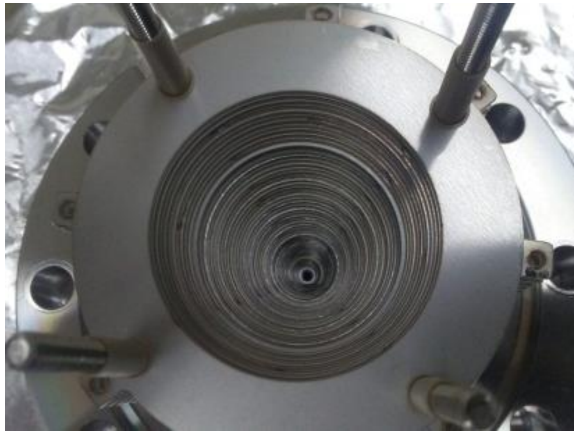
^{20}Mg	40
^{24}Si	30
^{28}S	25
^{32}Ar	10
^{36}Ca	2

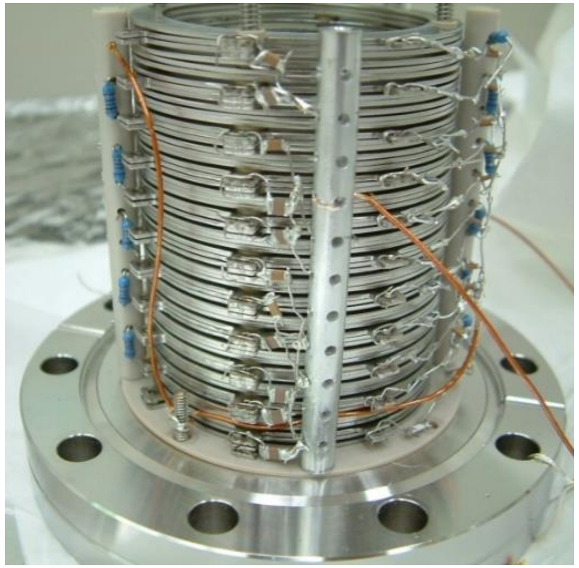


We have been developing a new gas cells

- We have tried testing a gas cell with rf
  - May enhance ion transport, reduce interactions with cell walls
  - Plasma effects always cast doubt on viability…



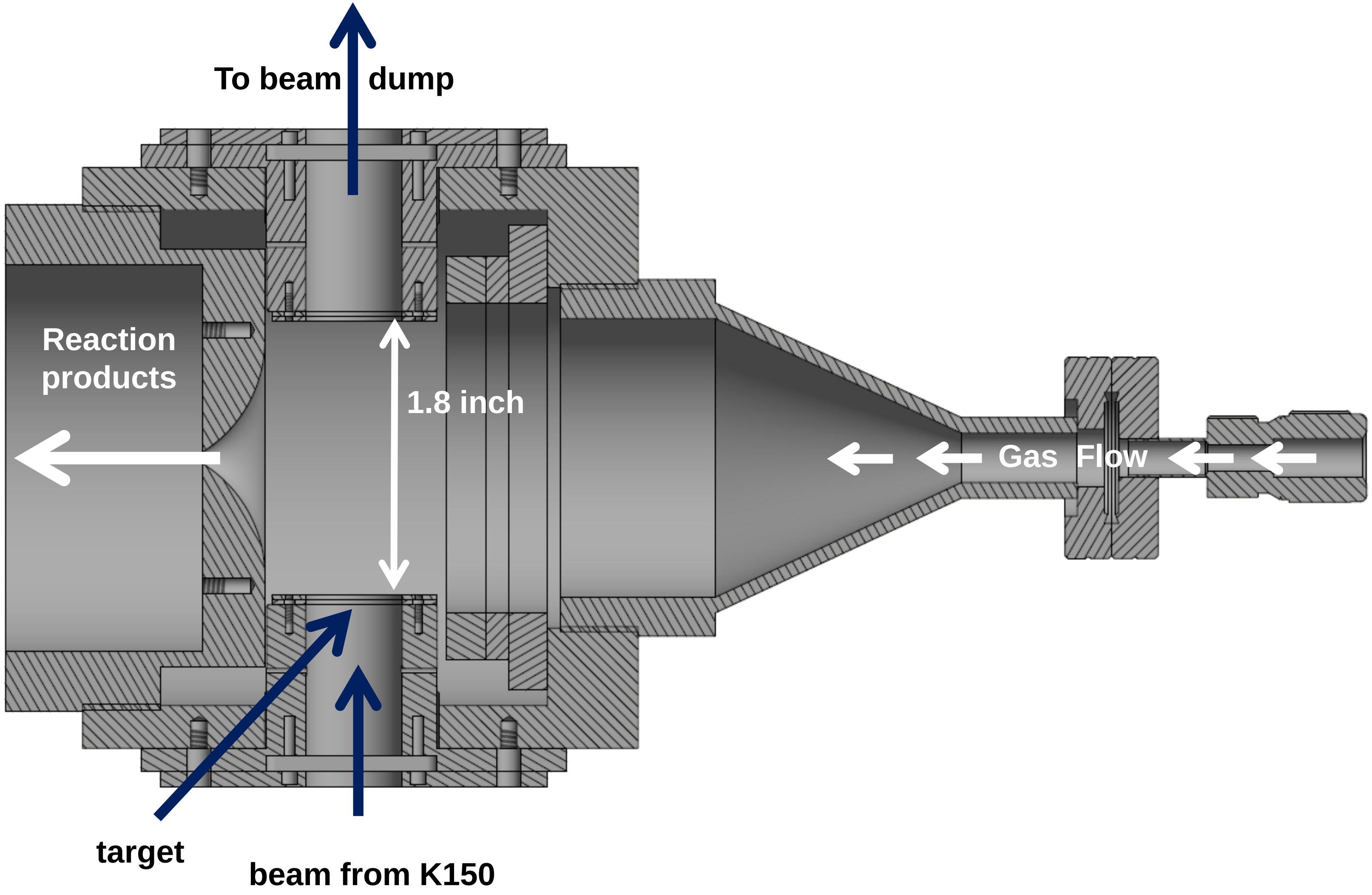


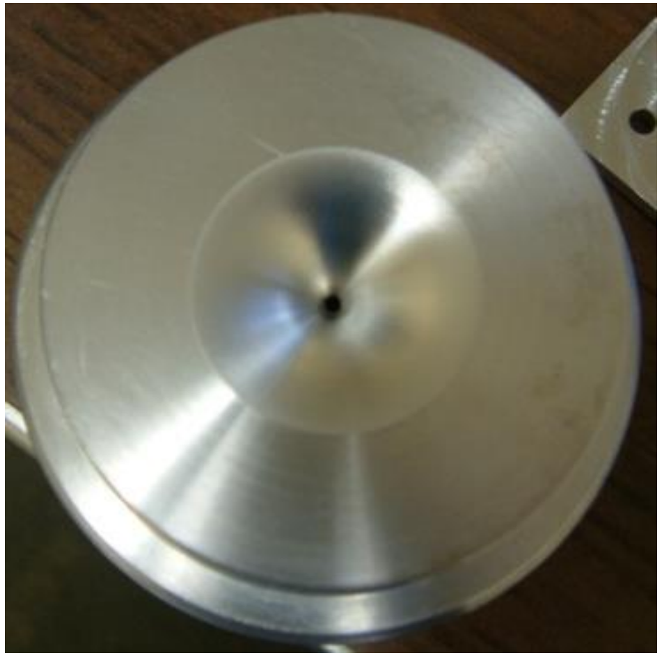


  - Results to date have been inconclusive (bad vacuum, connection issues, …); shelving this for now

We have been developing a new gas cell

- Also testing a typical (gas-only cell)
  - Simpler than with rf; shorter length





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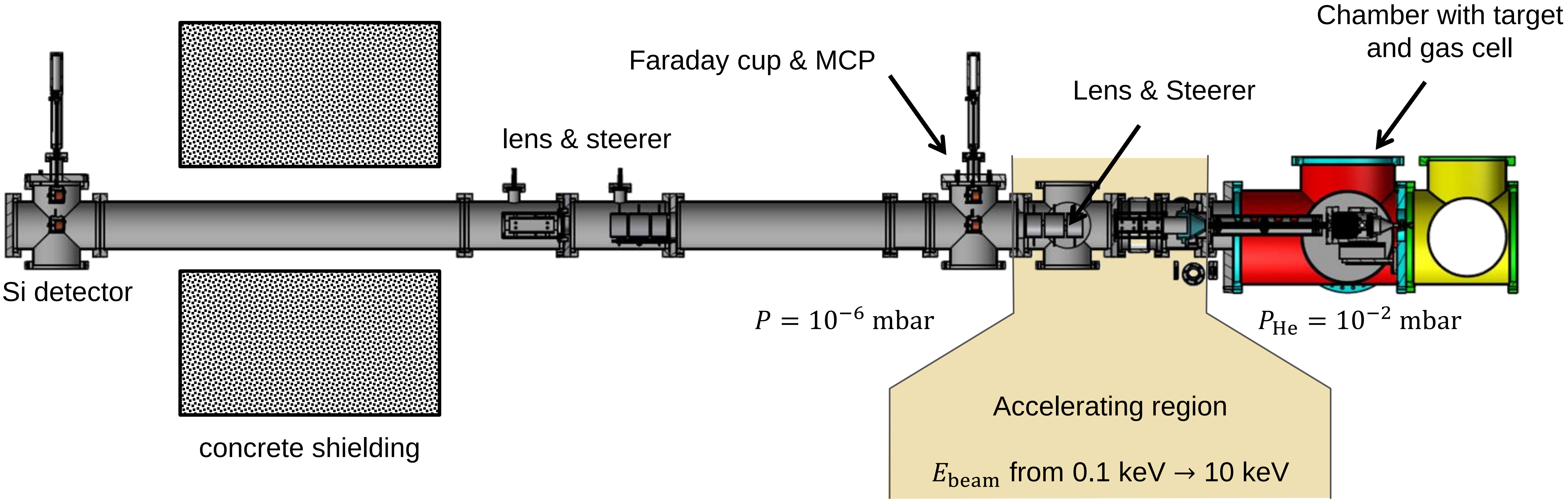
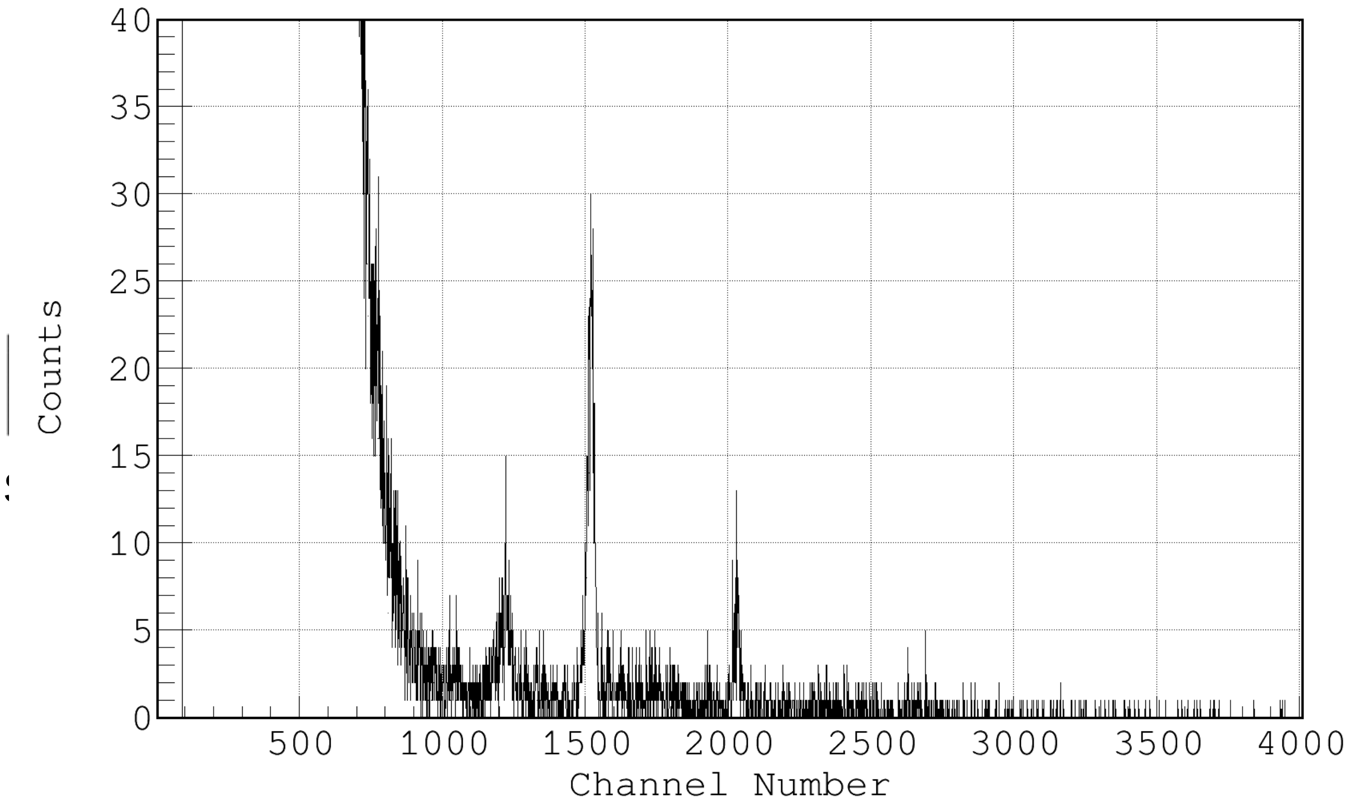


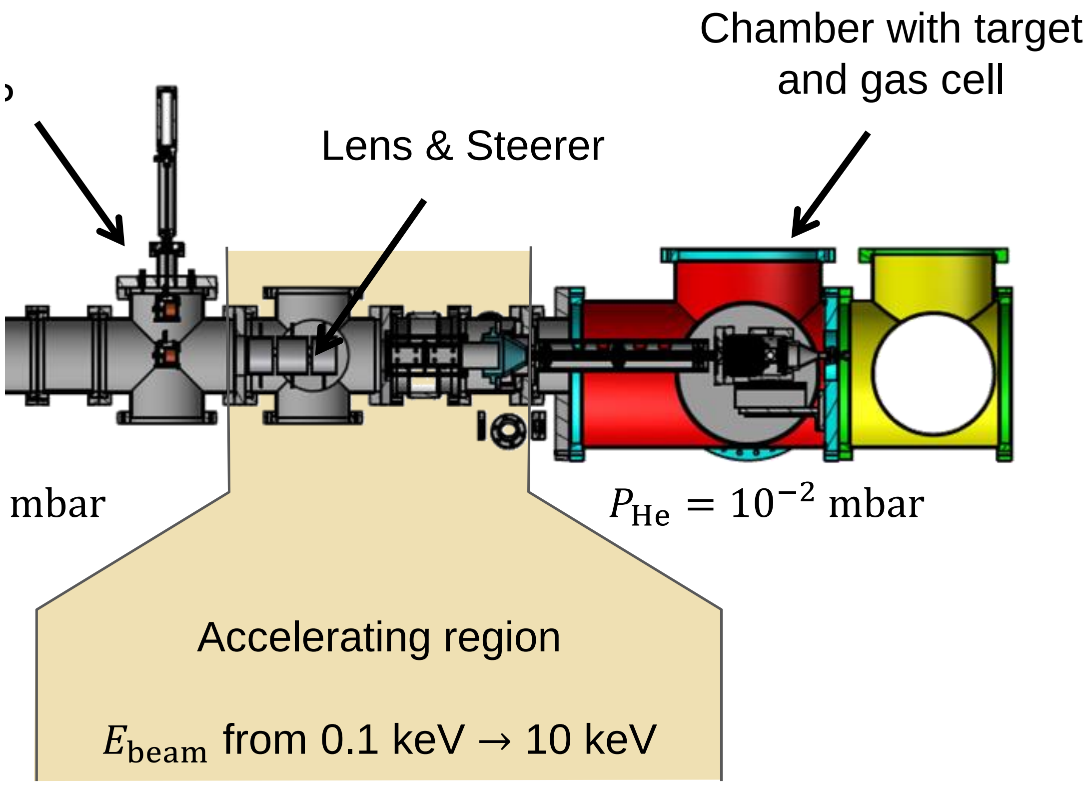
We have been developing a new gas cell

- Also testing a typical (gas-only cell)
  - Simpler than with rf; shorter length

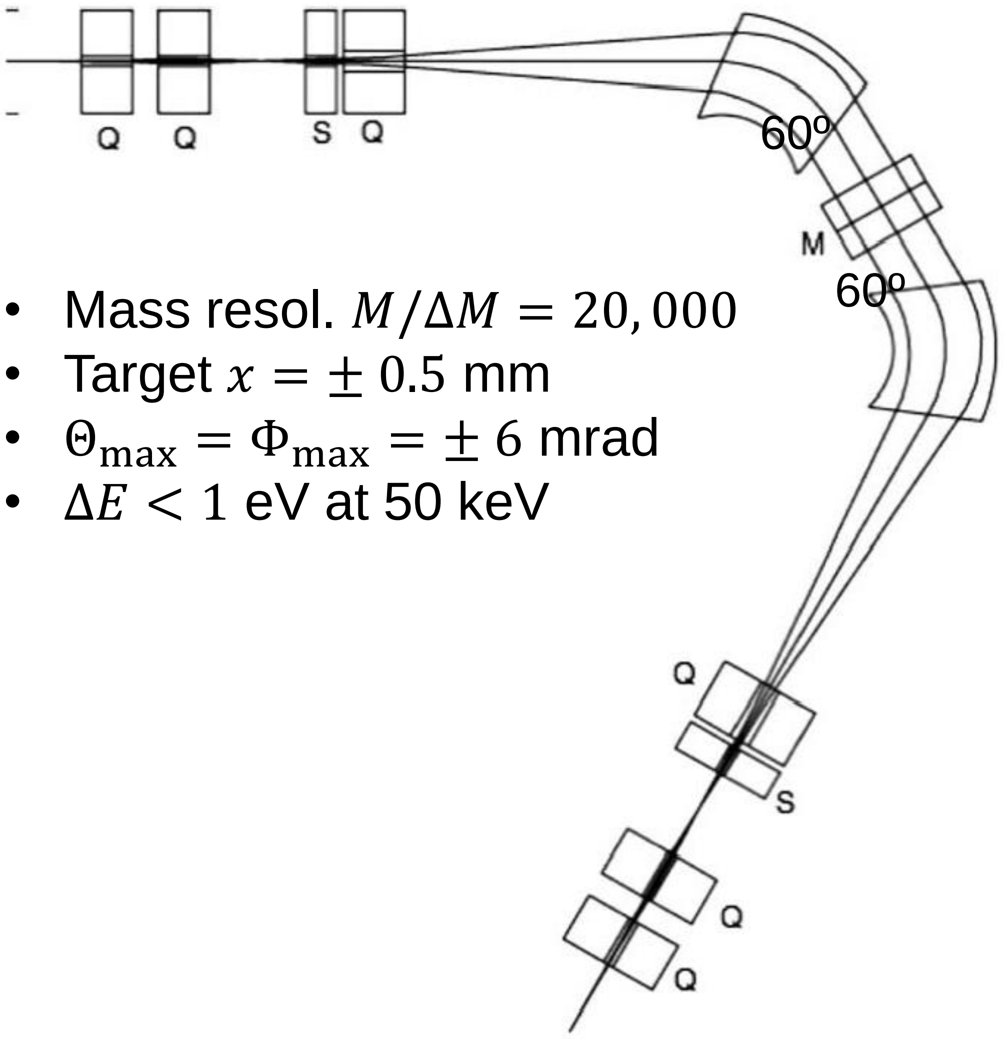
Efficiency of ^{25}Si production *already* **0.13(2)%**!!

1–2% no problem; 5% is achievable



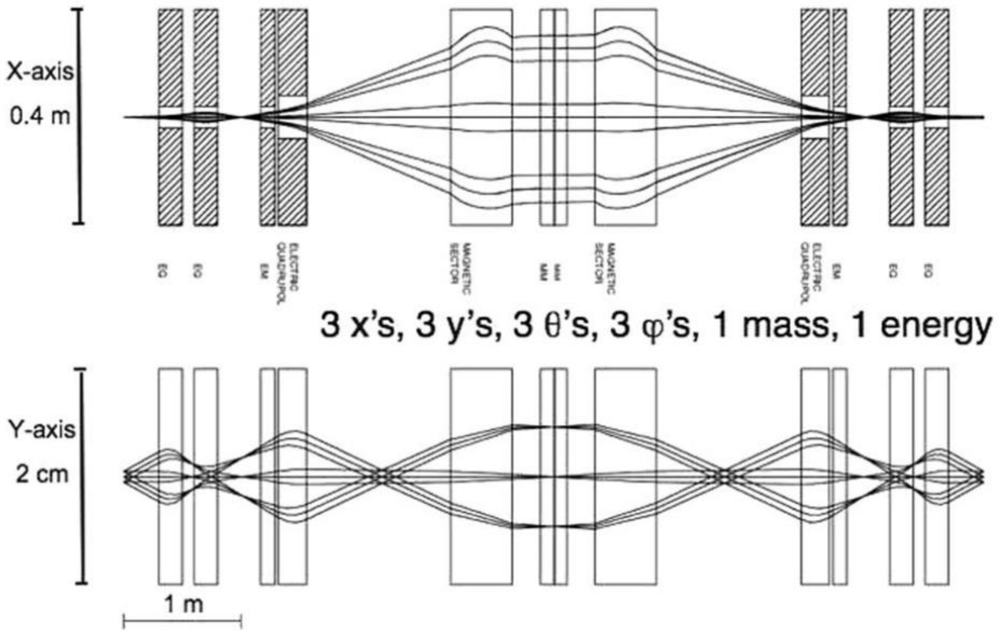


Concept for mass separator – CARIBU @ ANL



- Mass resol. $M/\Delta M = 20,000$
- Target $x = \pm\, 0.5$ mm
- $\Theta_{\max} = \Phi_{\max} = \pm\, 6$ mrad
- $\Delta E < 1$ eV at 50 keV

Fig. 1. Layout of the isobar separator, showing the two 60° bending magnets with $\rho = 0.5$ m, two quadrupole (Q) doublets, two quadrupole singlets, two sextupole (S) singlets and an electrostatic multipole (M).

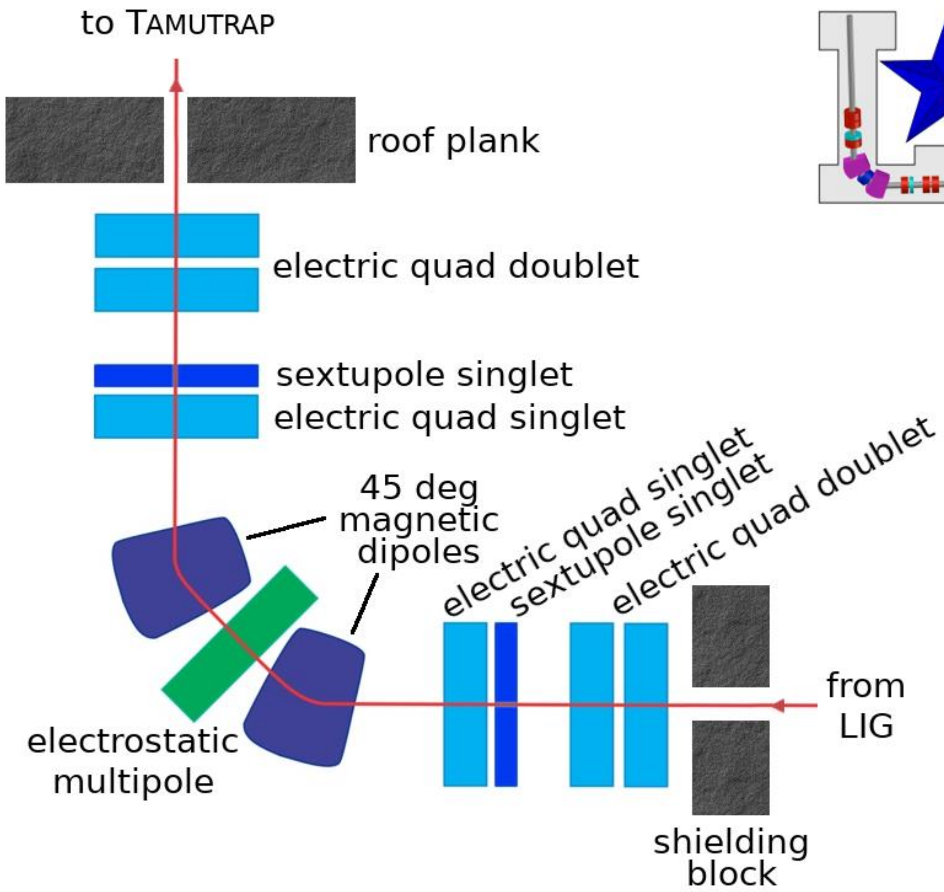


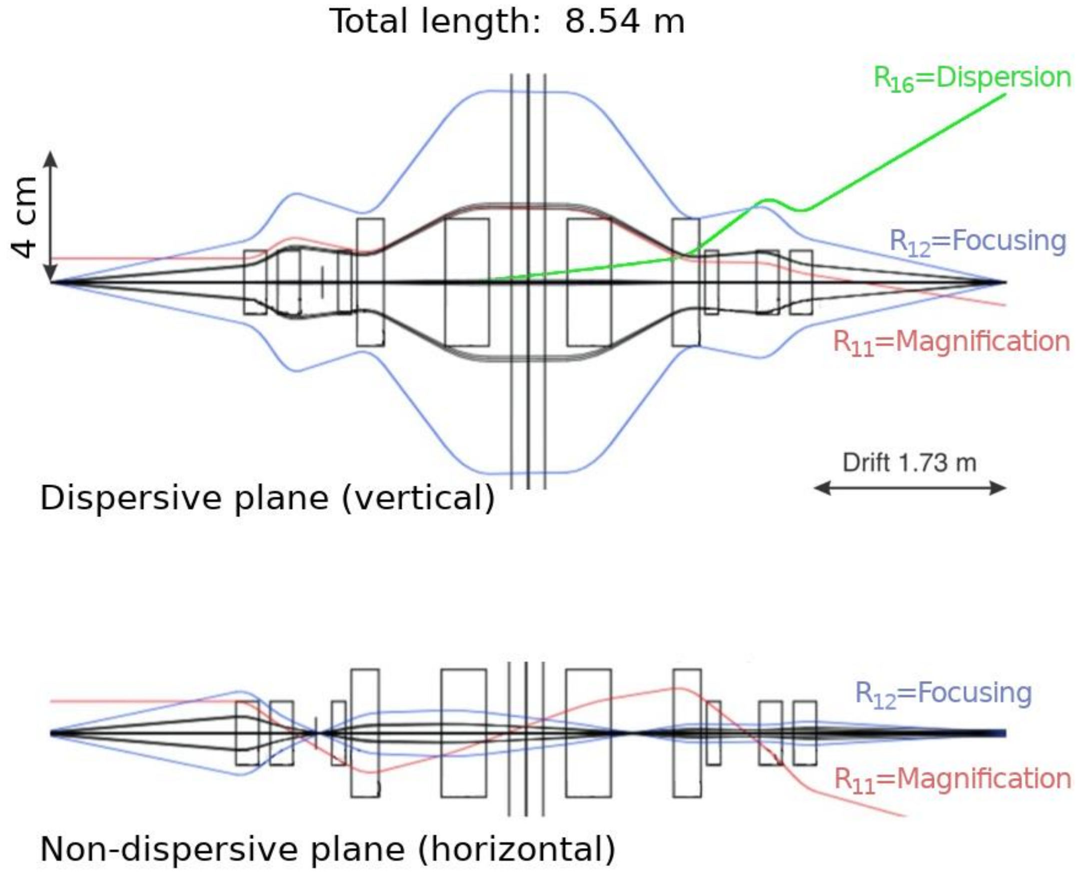
ptics of the isobar separator in the x- (dispersive) and y- (non-dispersive) planes. Note the different scales in the two planes.

Davids and Peterson, NIMB **266**, 4449 (2008)

But 120° doesn't fit our existing equipment…

- To bend up, need $45° + 45°$ instead
- Collaborate with G. Berg, M. Couder and M. Brodeur (ND) to build the Light-ion guide Separator for TAMU's K150 RIBs





LSTAR performance specs and status

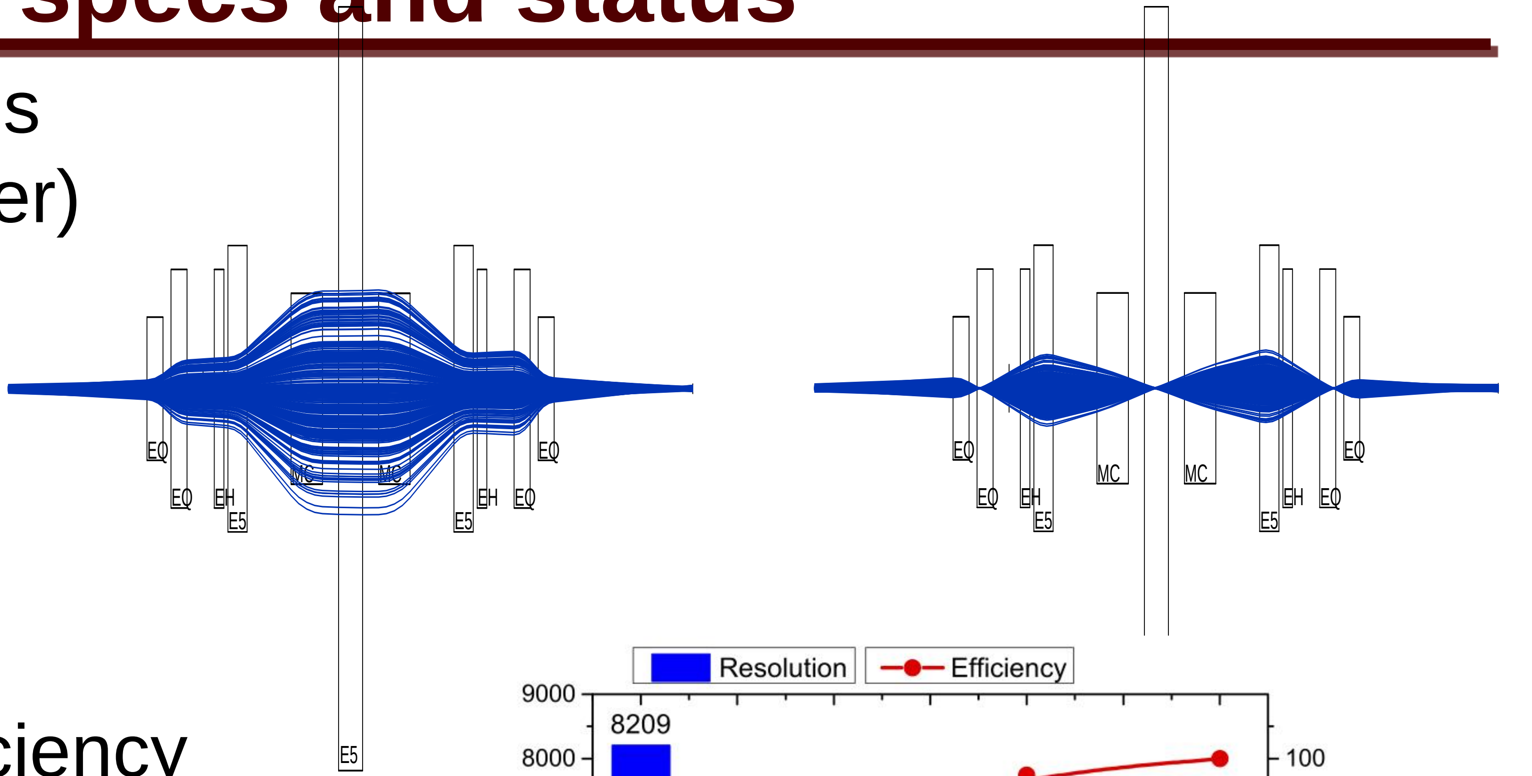
- With higher-order abberations corrected (G. Berg, M. Couder)

  Cuts: $\theta_x, \theta_y = \pm 2$ mrad

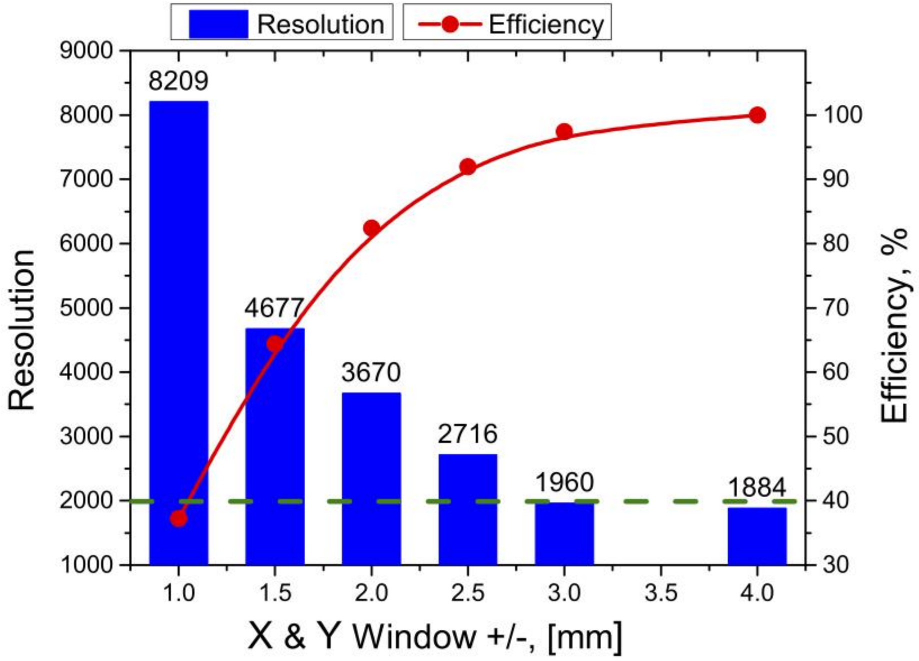
  $x, y = \pm 2$ mm

  Resolution: $\frac{M}{\Delta M} = 4400$

  Efficiency: 81%



- Using COSY to optimize efficiency versus resolution

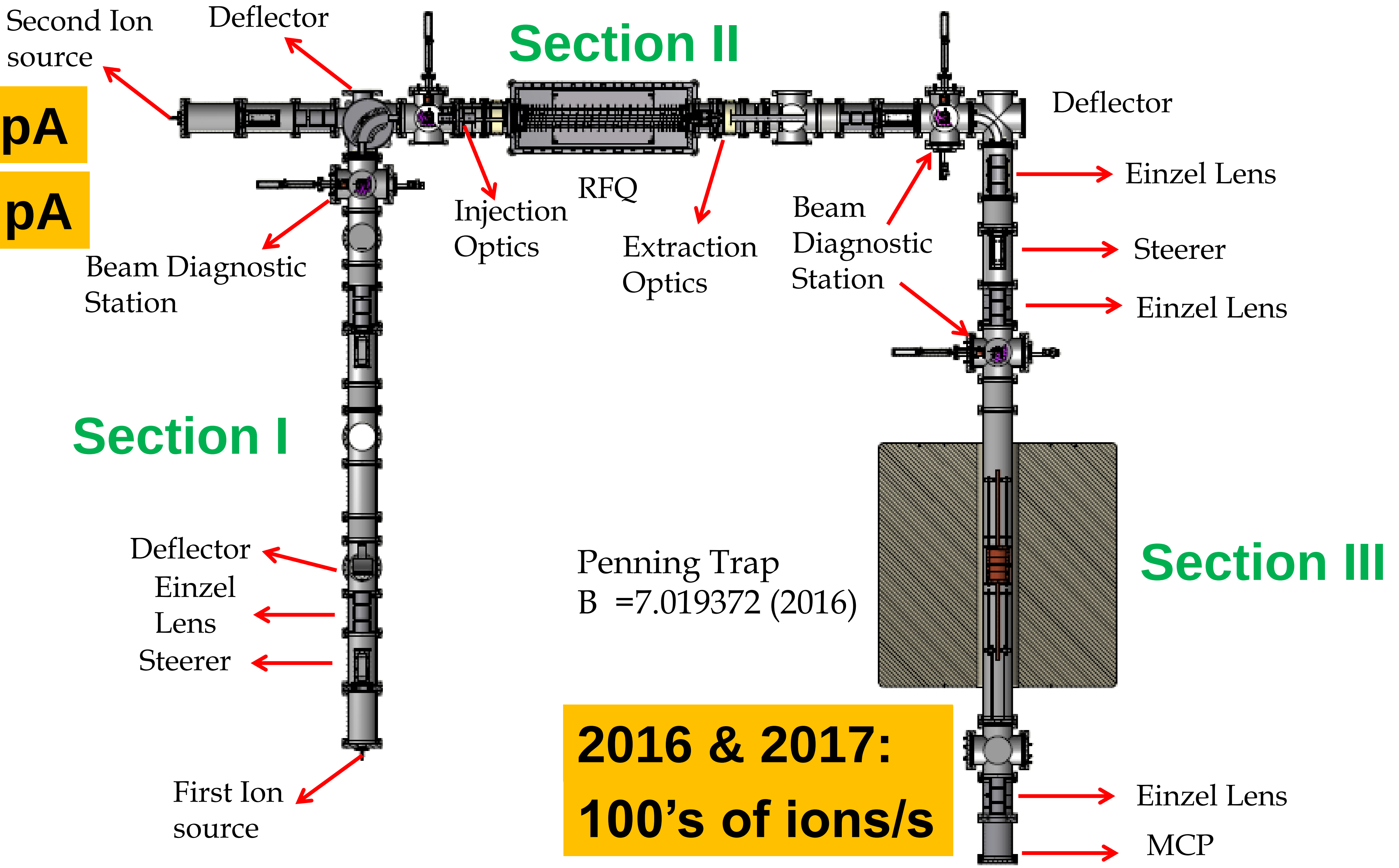


- $0.75M proposal submitted to DOE
  - Start construction Spring 2021

The TAMUTRAP facility at the Cyclotron Institute

2016: 120 pA

2017: <1 pA

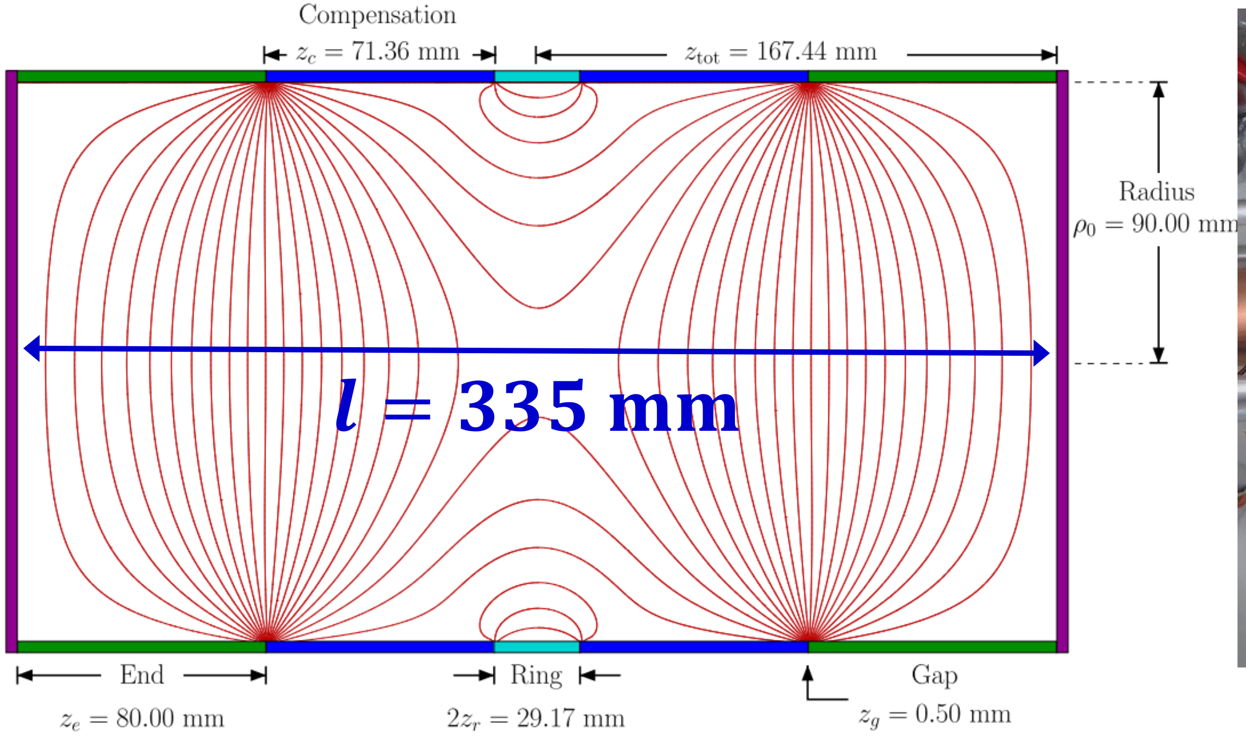


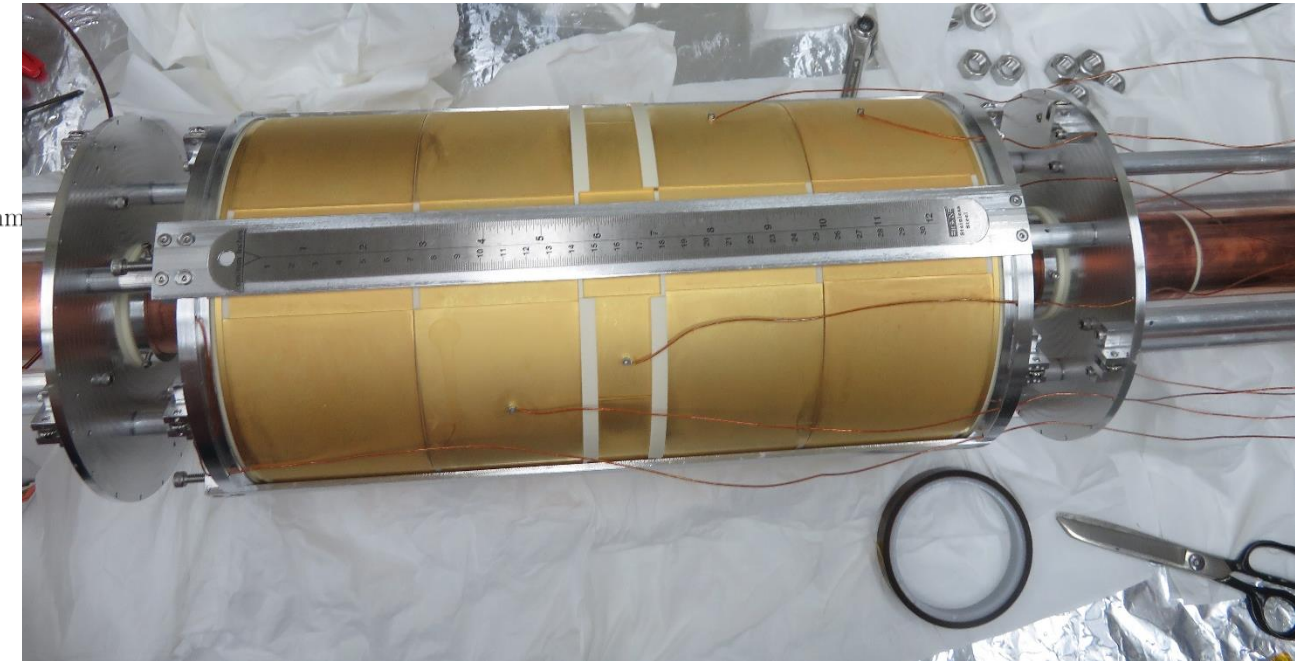
2016 & 2017:

100's of ions/s

World's largest Penning trap commissioned

- Most cylindrical Penning traps have a length-to-radius ratio of $l/r = 11.75$
- To confine the protons from $T = 2$ decays, need $r = 90$ mm
  - Needed a new design to make it fit in the 7T magnet





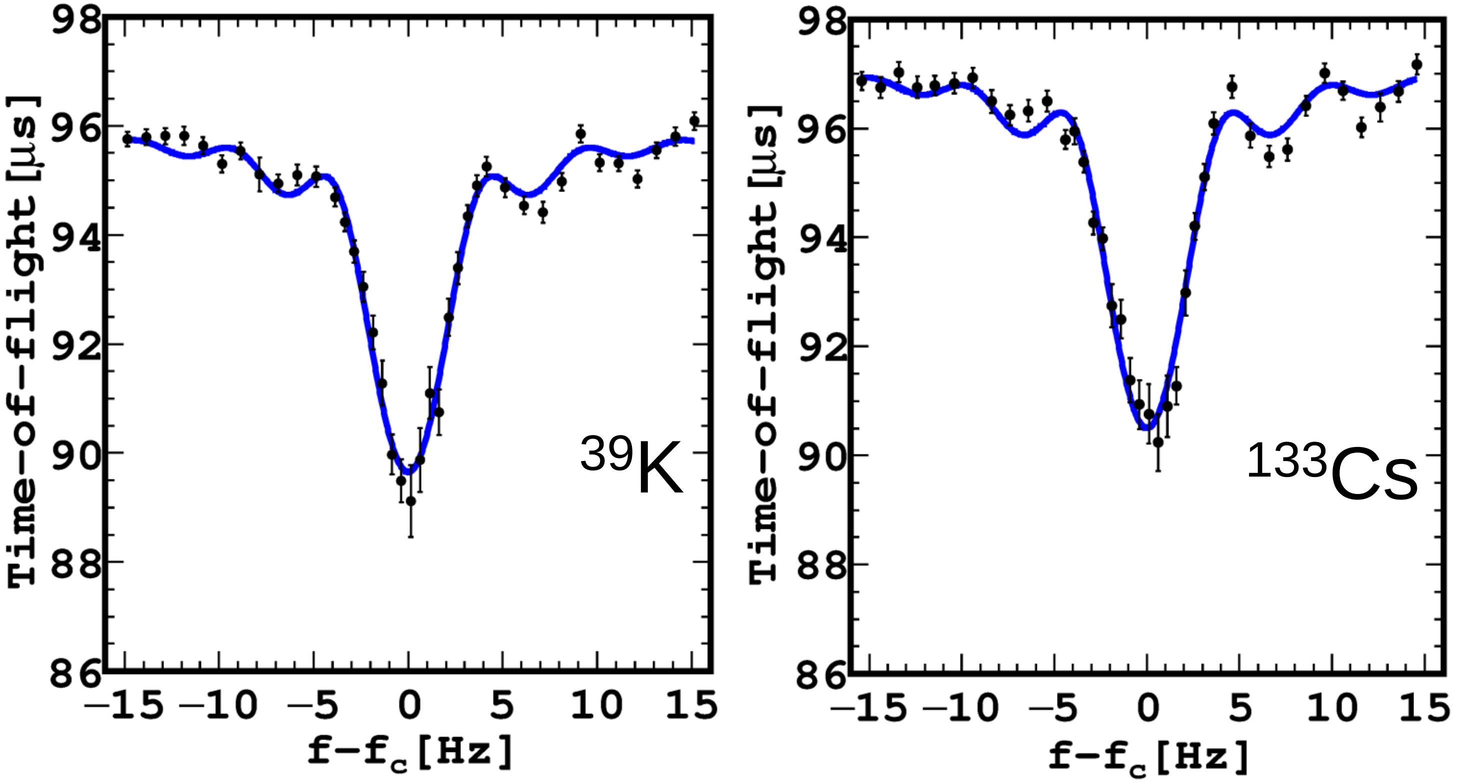
$$l/r = 3.72$$

M.Mehlman *et al*., NIMA **712**, 9 (2013)
P.Shidling *et al*., Hyperfine Interact **240**, 40 (2019)

Mass measurement of stable ions

- Find resonant frequencies for ^{23}Na, ^{85,87}Rb, ^{133}Cs and ^{39}K
- Use AME value for ^{39}K, and calculate other masses
- Good agreement with AME values (within uncertainties)
- Precision
  - ^{23}Na: 240 ppb
  - ^{85}Rb: 5 ppb
  - ^{87}Rb: 6 ppb
  - ^{133}Cs: 7 ppb

200 ms excitation time



P.Shidling *et al*., in preparation (Phys Rev Accel & Beams)

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  - Cyclotron radiation emission spectroscopy
  - Plans to implement an ion trap to remove wall collisions

^{6}He at UW

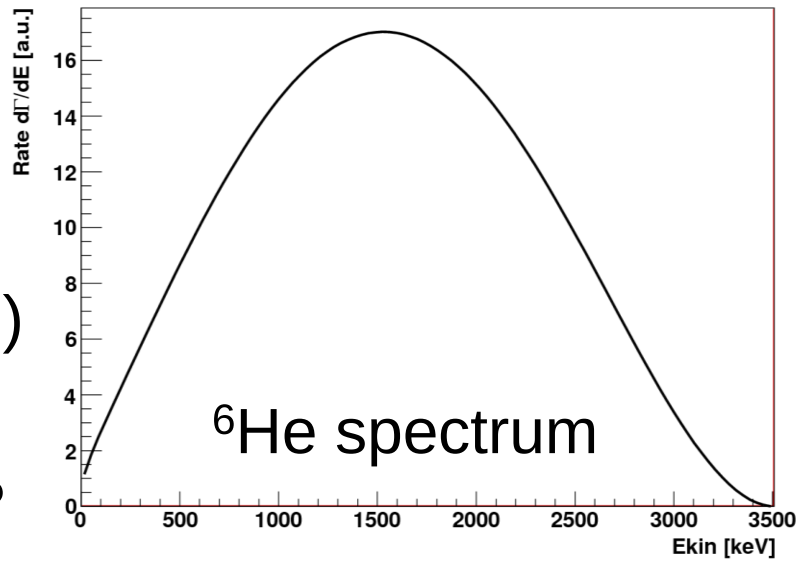
- Most sensitive probe is the Fierz interference:
  - Decay rate is: $dw = dw_0 \left[1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{\Gamma m_e}{E_e}\right]$
- ^{6}He is a great case!
  - Large endpoint (3.5 MeV)
  - Nuclear structure under control
  - Simple decay
  - Sensitive to tensor interactions
- Status:
  - Lifetime (PRC **86**, 035506)
  - Charge state fractions
  - $a_{\beta\nu}$: stats for 0.2%; systs?

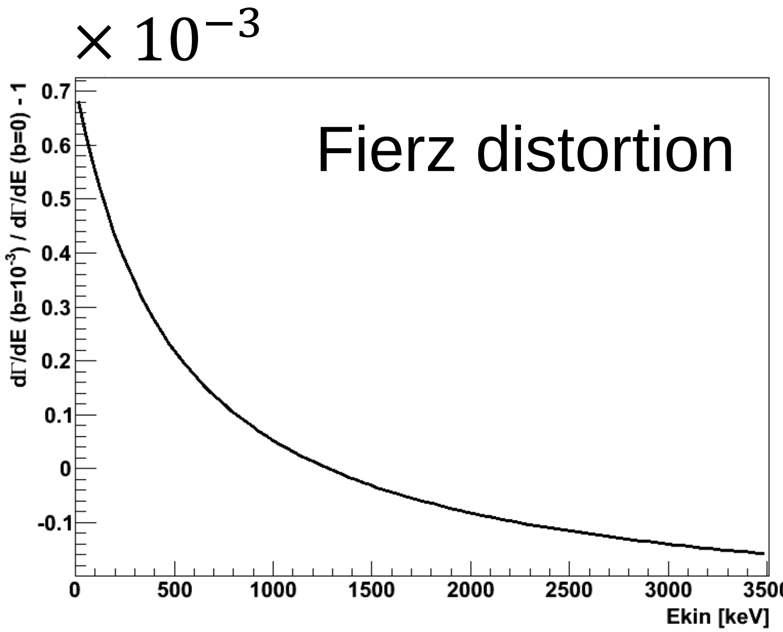
$$a_{\beta\nu} \approx -\frac{1}{3}\left(1 - \frac{C_T^2 + C'^2_T}{2C_A^2}\right)$$

$\beta - \nu$ correlation

$$b \approx \pm \frac{(C_T + C_T')}{C_A}$$

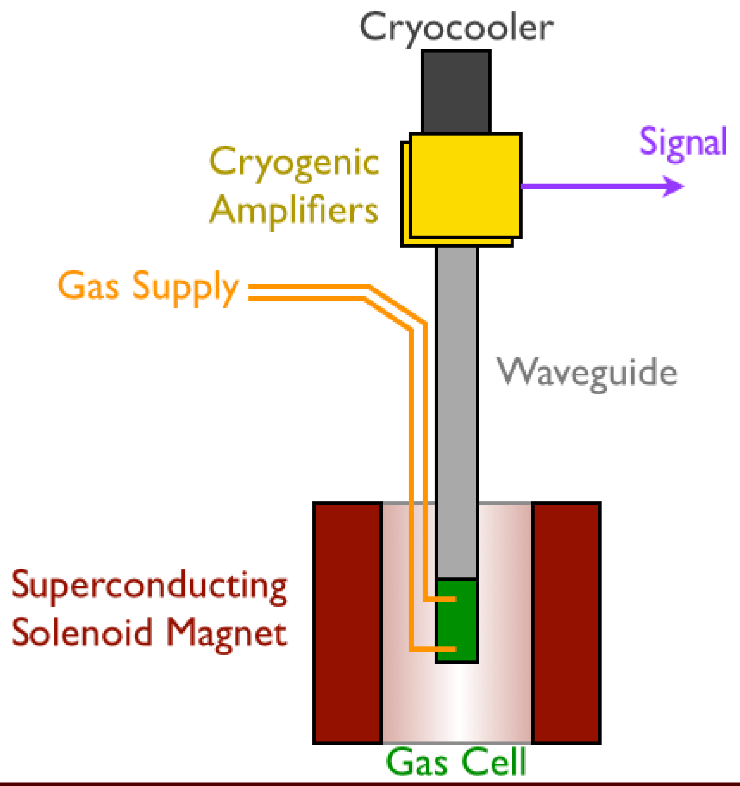
Fierz interference





^{6}He at UW – CRES technique

- New idea: use the Cyclotron Radiation Emission Spectroscopy (CRES) technique
  - Project 8 collaboration gets $\frac{FWHM}{E} \approx 10^{-3}$ resolution for conversion electrons of 18 – 32 keV

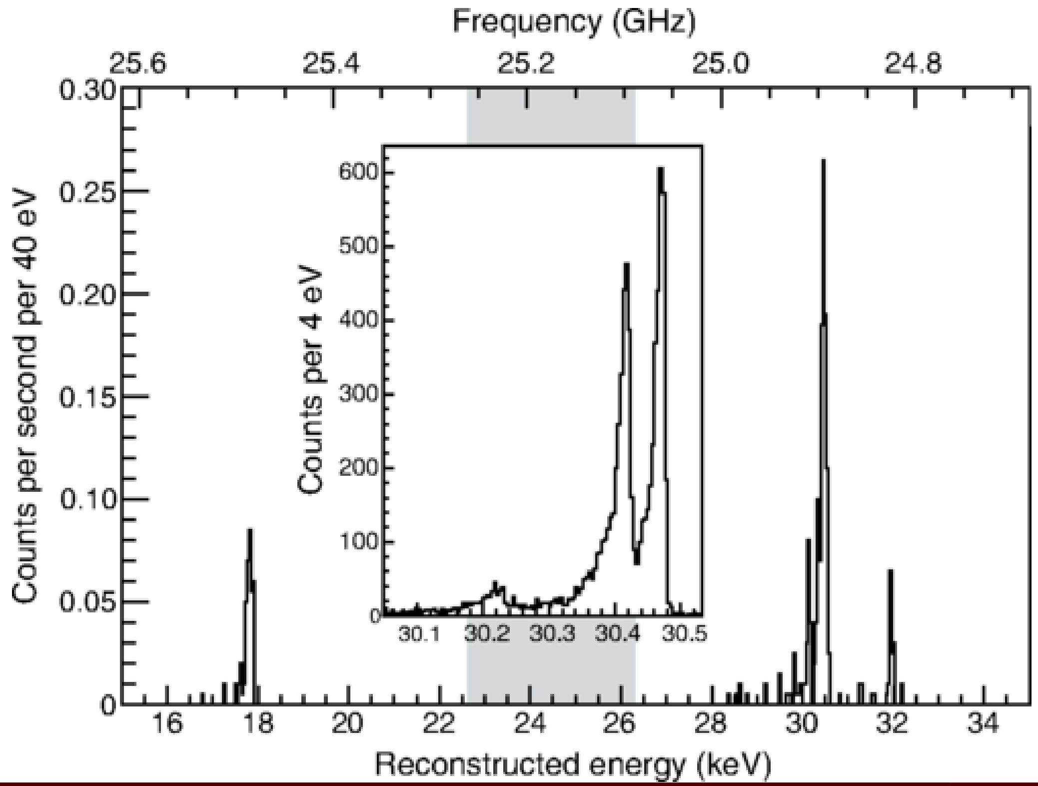


Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

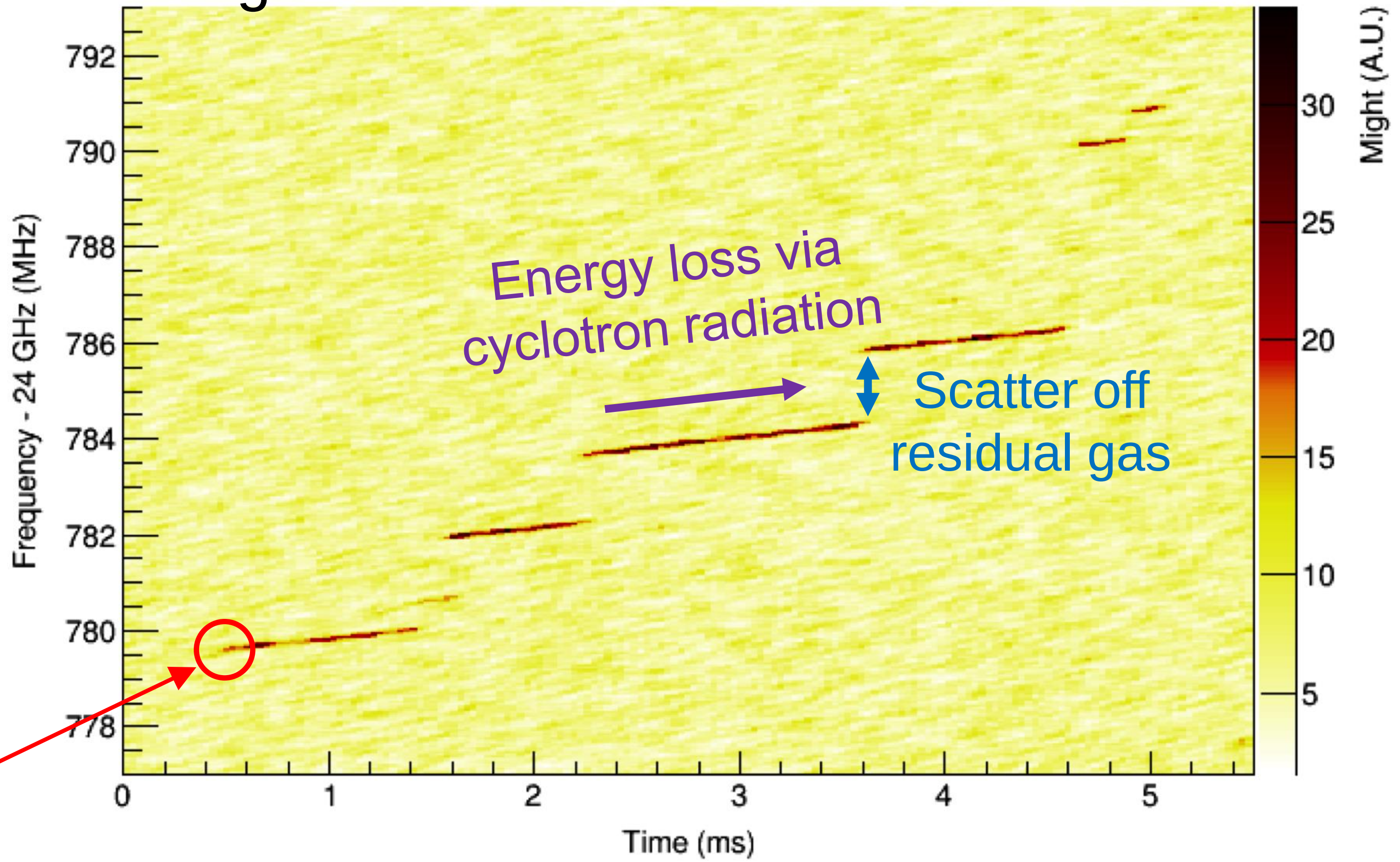
D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R.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



^{6}He at UW – CRES technique

- Why CRES for ^{6}He?
  - Measures β energy at creation, before complicated energy-loss mechanisms
  - High resolution allows debugging of systematic uncertainties
  - No background from photon or e scattering
  - ^{6}He in gaseous form works well with the technique
  - ^{6}He ion trap allows sensitivity higher than any other proposed
  - Counts needed not a big demand on running time

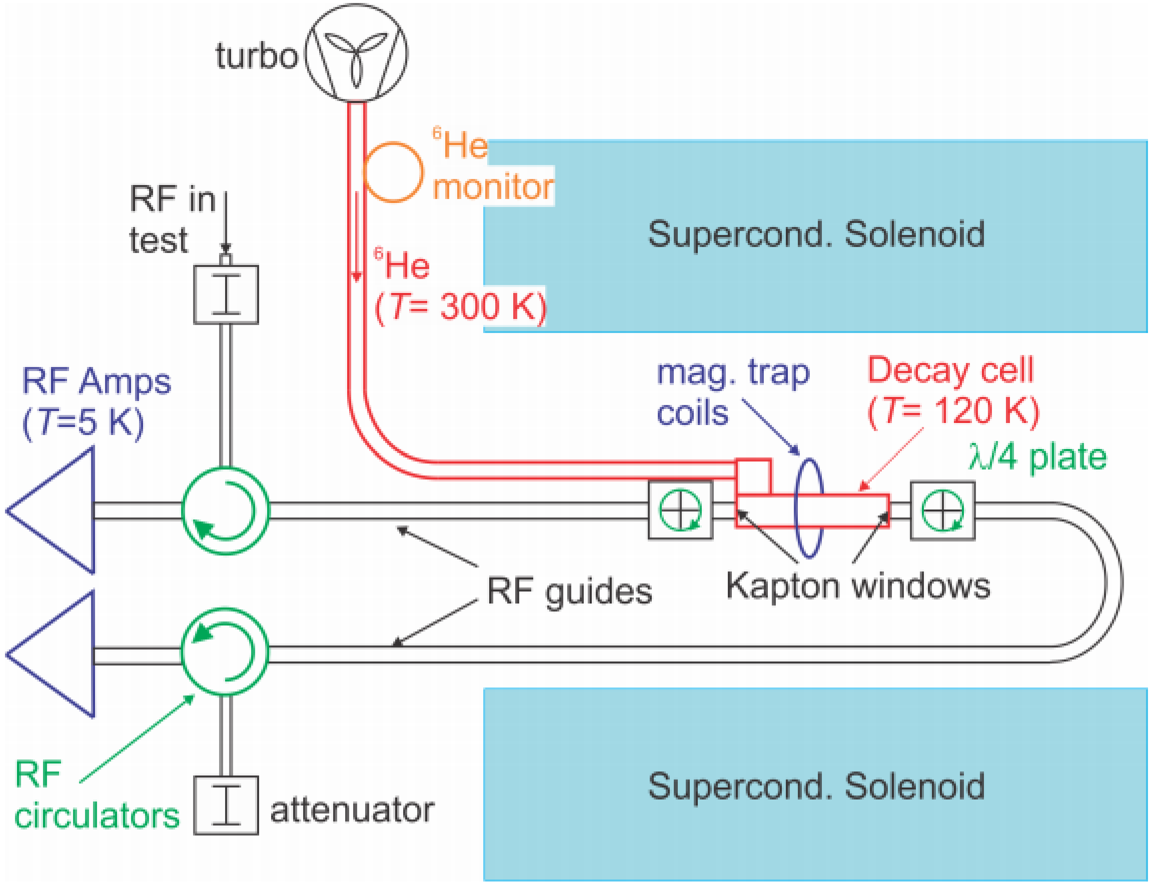


$$2\pi f = \frac{qB}{m + E_{\text{kin}}}$$

Initial frequency → E

^{6}He little-*b* collaboration

- Phase I: proof of principle (next 3 yrs)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution



Emerging ^{6}He little-*b* collaboration

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  - 2 GHz bandwidth
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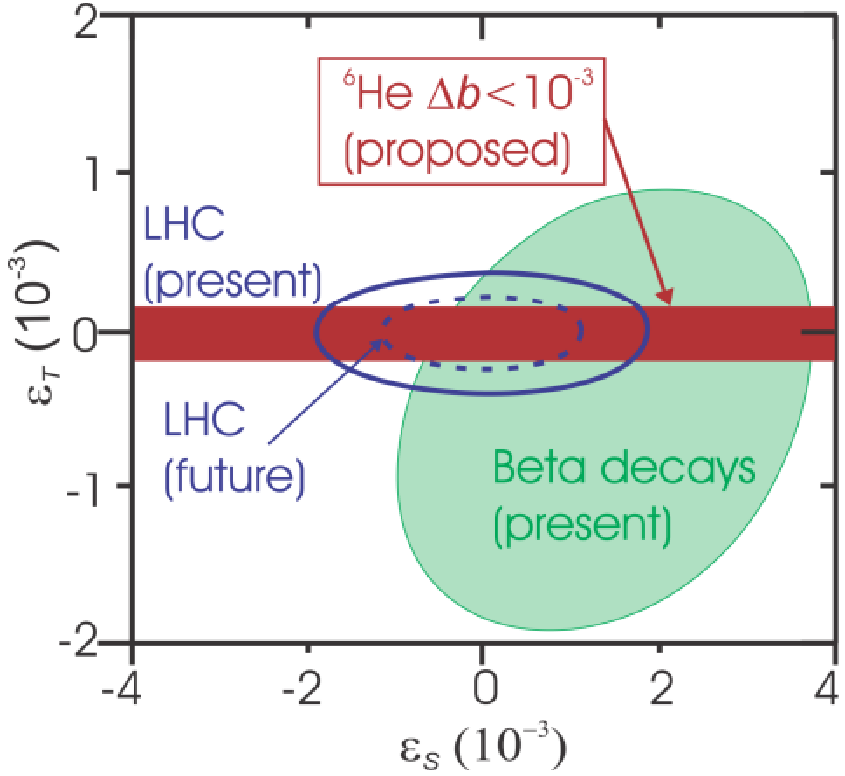
Effect	Δb No trap	Δb Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}

- Phase II: first measurement ($b < 10^{-3}$)
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements



Emerging ^{6}He little-*b* collaboration

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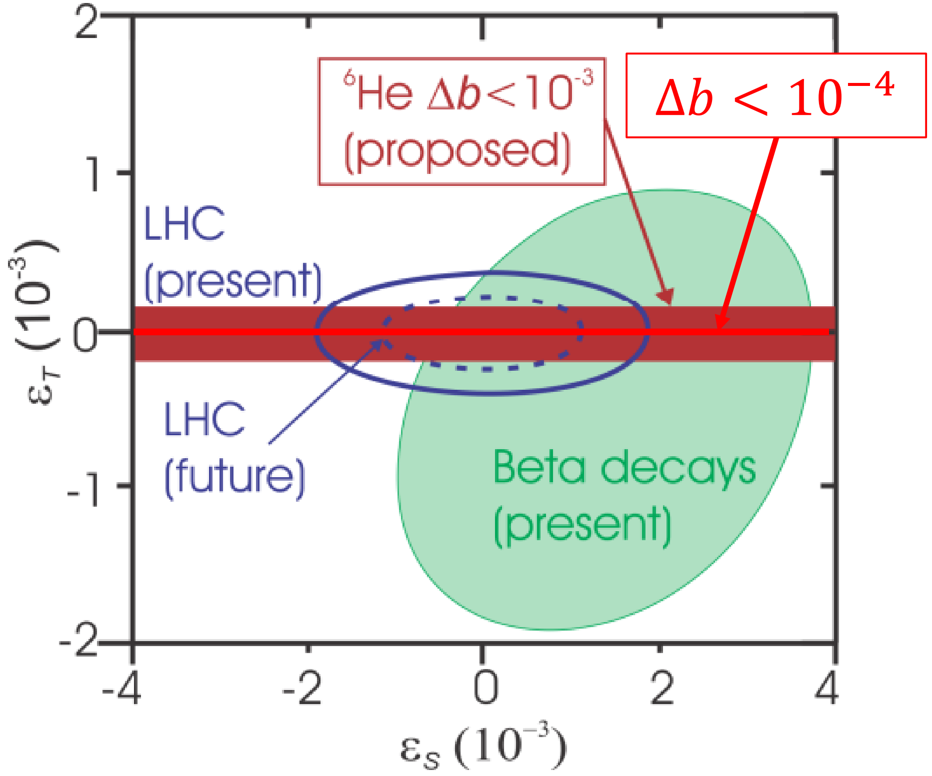
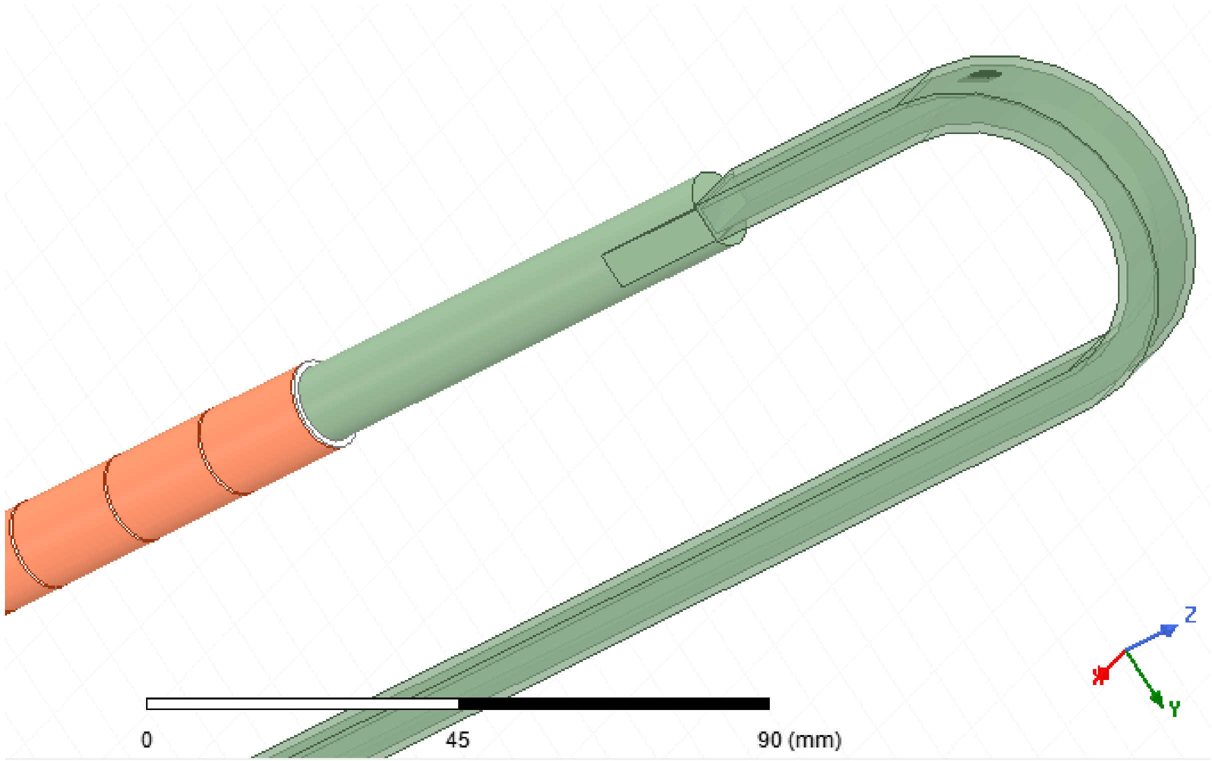
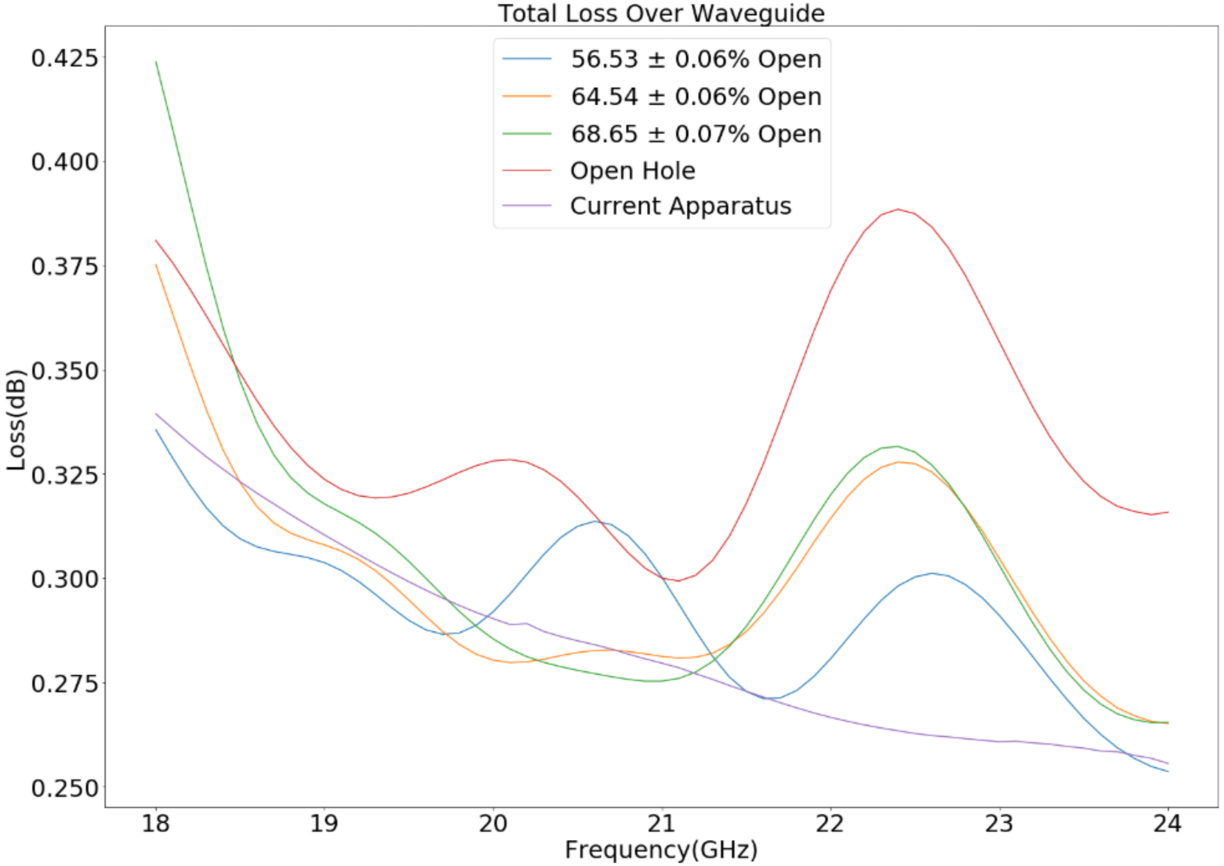


- Phase III: ultimate measurement ($b < 10^{-4}$)
  - Ion trap for no limitation from geometric effect

TAMU's contribution is starting

- To bring ions into the trap, need a hole in the waveguide
  - HFSS ⇒ signal degradation is <0.5 dB (no problem)





- Start designing RFQ cooler/buncher and Penning trap

Final thoughts, collaborators and thanks

- Ion and atom traps are helping pave the way for the precision frontier
- TRINAT: recent A_β result demonstrates ability; future is bright!
- TAMUTRAP: commissioned, just need radioactive ions…LSTAR starting
- ^{6}He b_{Fierz} with CRES: Phase 3 will crush the LHC!

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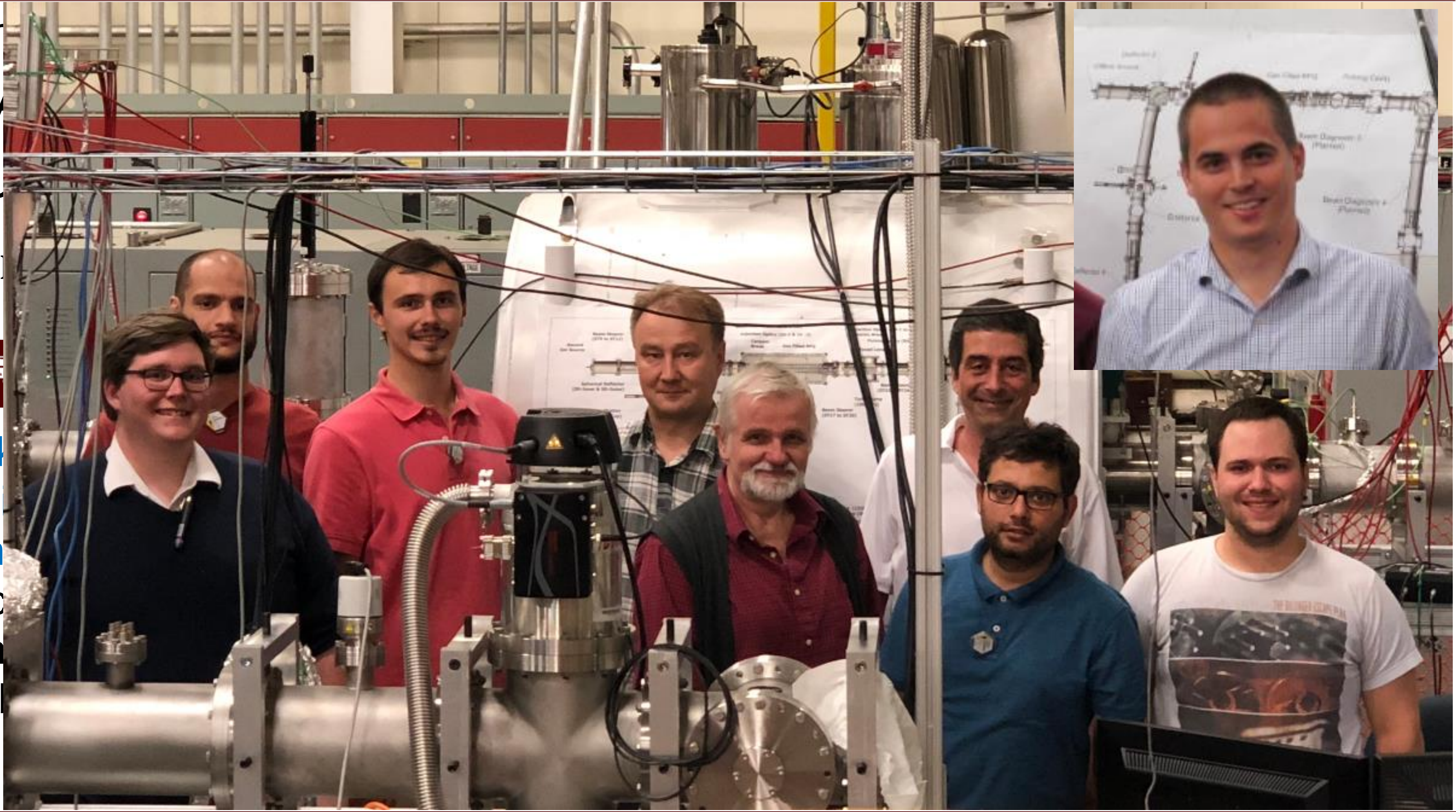
Final thoughts, collaborators and thanks

- Ion ar
- TRIN
- TAMU
- ^{6}He b



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Thanks, and FYI we're hiring

TENURE-TRACK POSITION

PHYSICS & ASTRONOMY
TEXAS A&M UNIVERSITY

EXPERIMENTAL NUCLEAR PHYSICS
TEXAS A&M UNIVERSITY

The Physics and Astronomy Department at Texas A&M University seeks applications for a tenure-track assistant professor position in experimental nuclear physics under the auspices of the Nuclear Solutions Institute. This institute combines basic and applied nuclear science with nuclear security technology and policy; it already encompasses a broad spectrum of faculty members drawn from across the university. A selected candidate must hold an earned Ph.D. in physics or a related area. The appointment is expected to begin on or before September 1, 2021.

The successful candidate for this position will assume a tenure-track position in the Department of Physics and Astronomy with a joint appointment in the Cyclotron Institute and the Nuclear Solutions Institute. More senior candidates may be considered at the associate professor or professor level. He/she is expected to assume full teaching responsibilities at the graduate and undergraduate levels and is also expected to conduct a vigorous research program based at the Cyclotron Institute and employing the facilities there, which include two cyclotrons – a newly refurbished K150 and a superconducting K500 – together with a wide variety of modern experimental equipment. An upgrade project, nearing completion, will utilize the two accelerators to make radioactive beams available to all target locations.