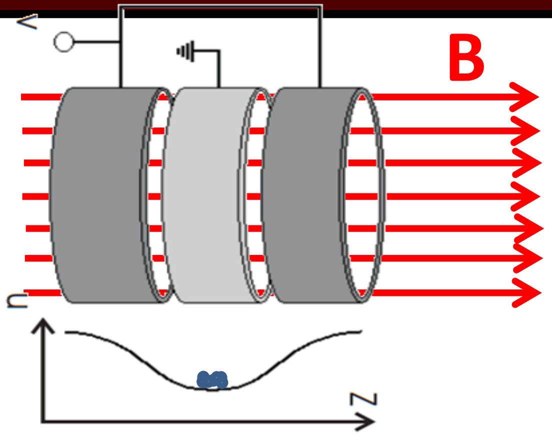
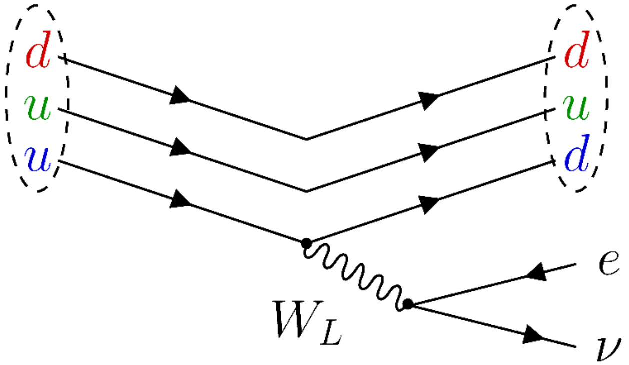
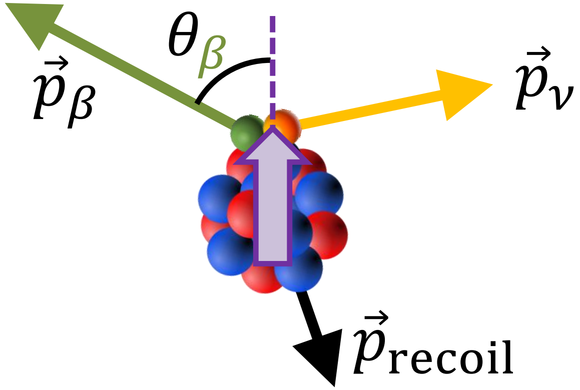
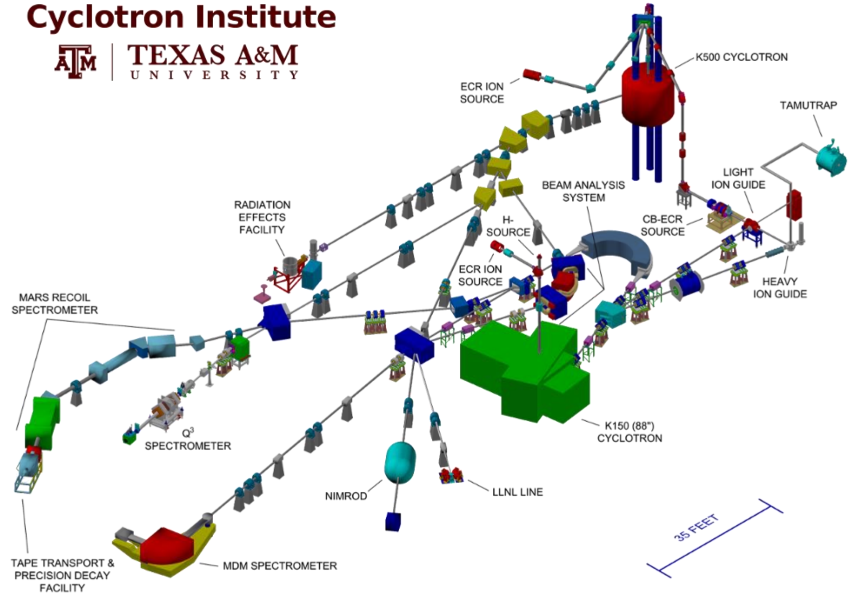
Trapped Atoms and Ions for Tests of the Charged Electroweak Interaction

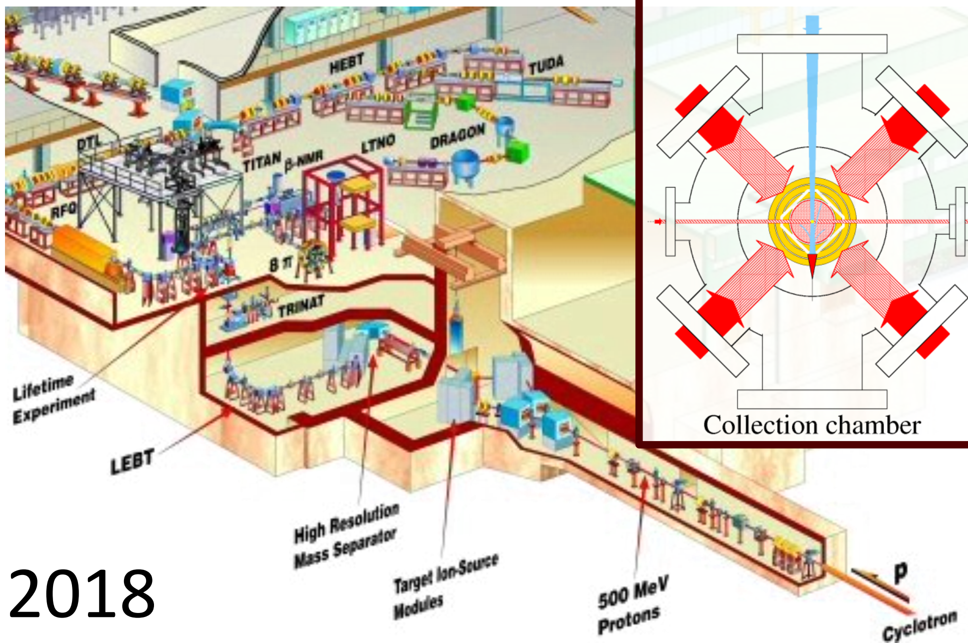


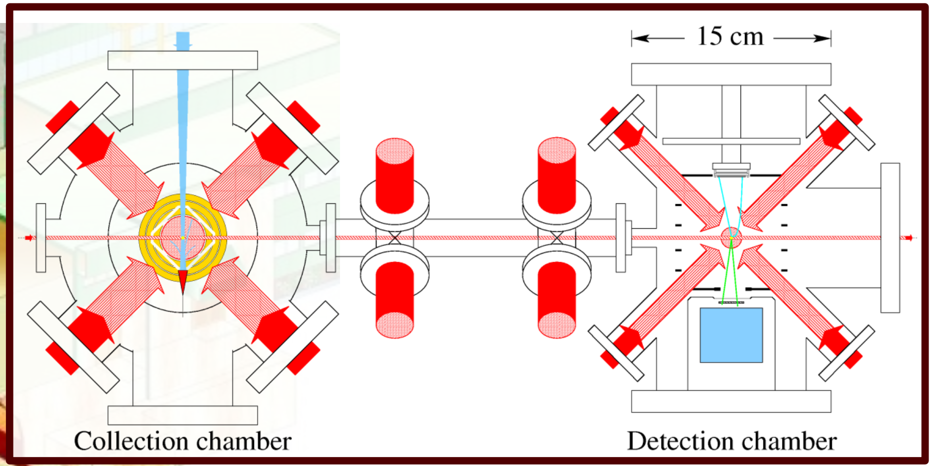




Cyclotron Institute
TEXAS A&M UNIVERSITY







Dan Melconian – CENPA, July 2018

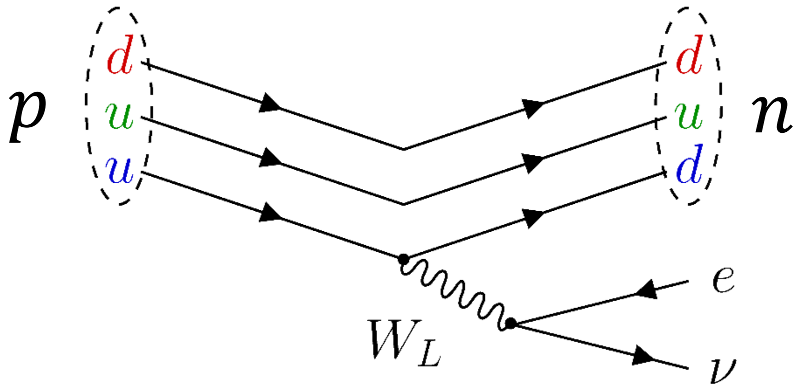
Outline

- Introduction
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- TAMUTRAP
  - $T = 2$ decays to test the SM
  - Current status
- ^{37}K at TRIUMF
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β

The standard model and beyond

- This is the standard model:

pure $V - A$ interaction

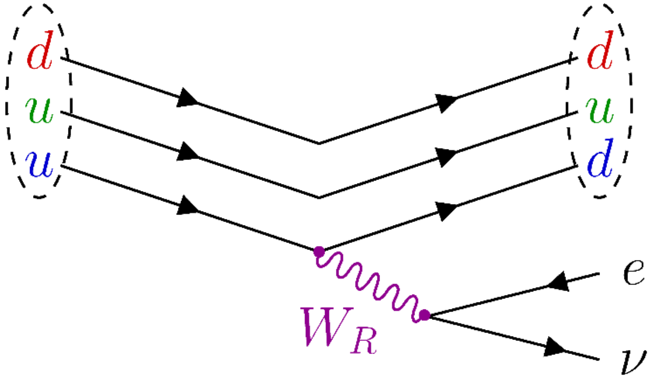


$$H_\beta = \bar{p}\gamma_\mu n(C_V \bar{e}\gamma^\mu \nu + C_V' \bar{e}\gamma^\mu \gamma_5 \nu) - \bar{p}\gamma_\mu\gamma_5 n(C_A \bar{e}\gamma^\mu\gamma_5 \nu + C_A' \bar{e}\gamma^\mu \nu)$$

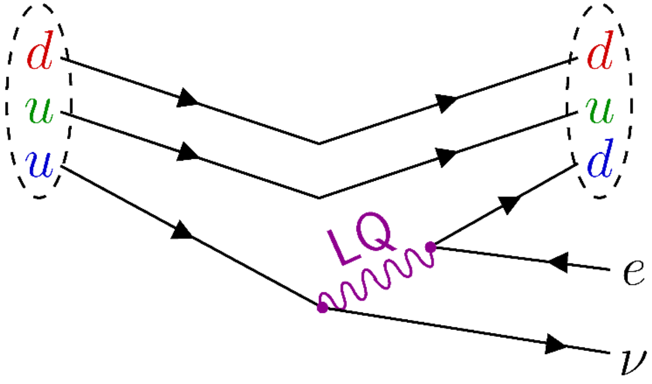
$$C_V = C_V' = 1$$
$$C_A = C_A' \approx 1.27$$

- These are not:

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



$$C_i \neq C_i'$$



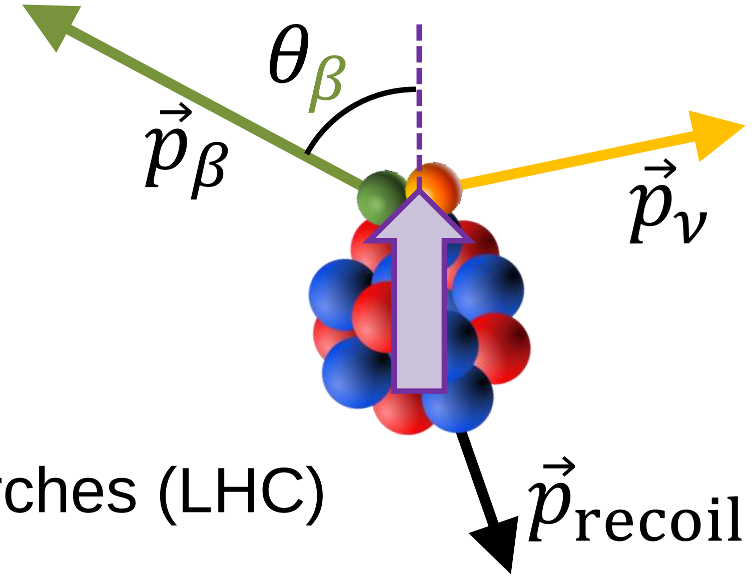
$$C_S, C_T \neq 0$$

- 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)

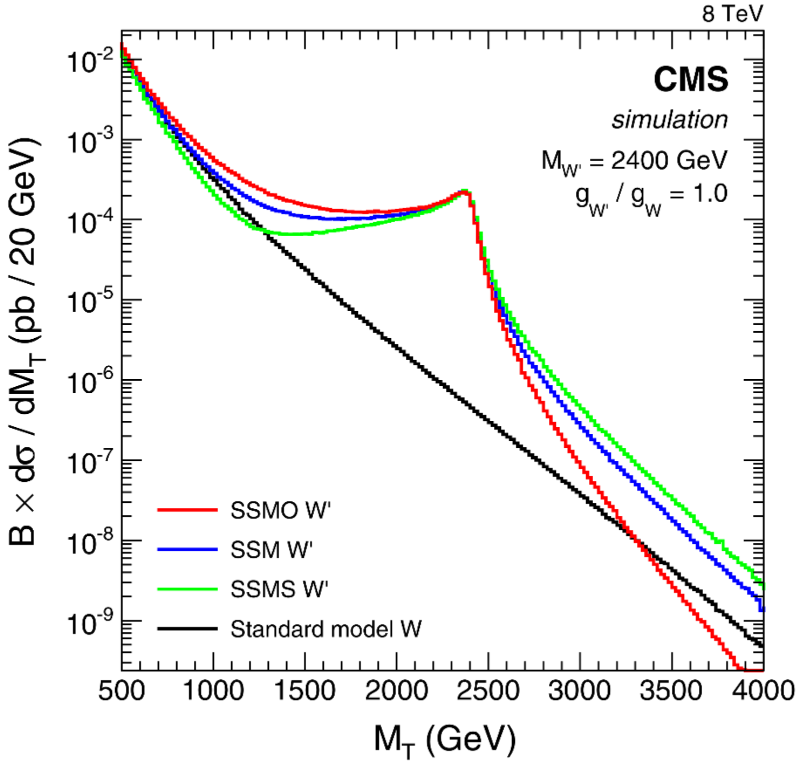


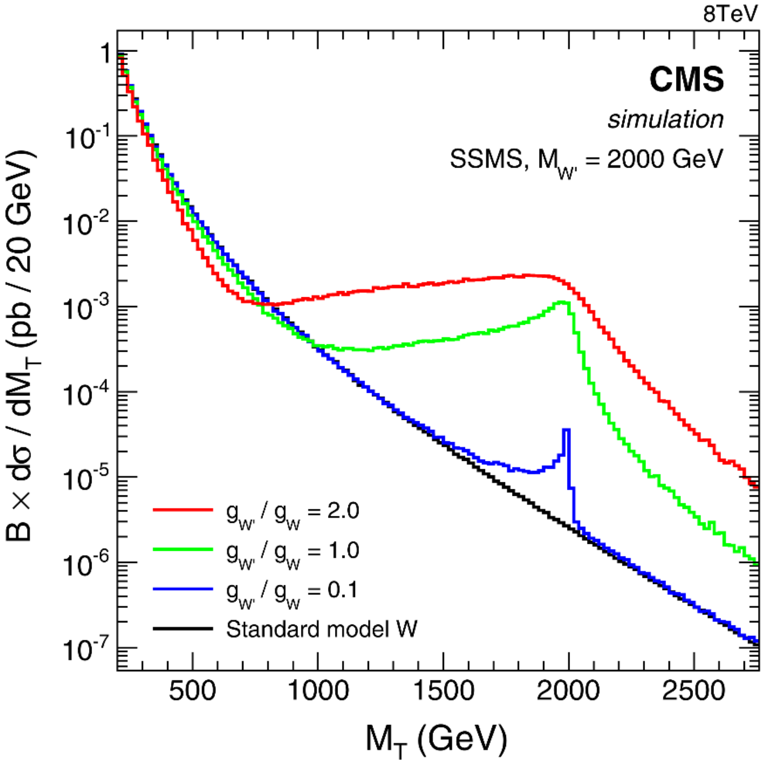
Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić and Severijns, arXiv:1803.08732

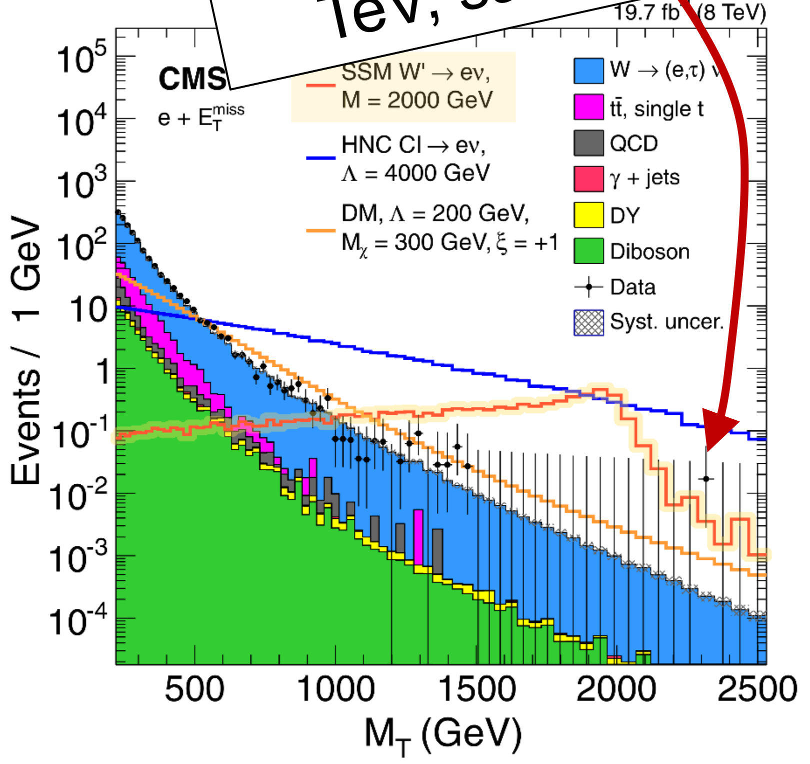
The energy frontier

- CMS collaboration, Phys. Rev. D **91**, 092005 (2015)
  - Look for direct production ⇒ excess of events in the missing transverse energy
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$
  - No excess observed ⇝ place limits
    (see Gonzalez-Alonzo, arXiv:1803.08732 for EFT interpretation)

Expected 2.0±0.3 events above 1.5 TeV, saw one

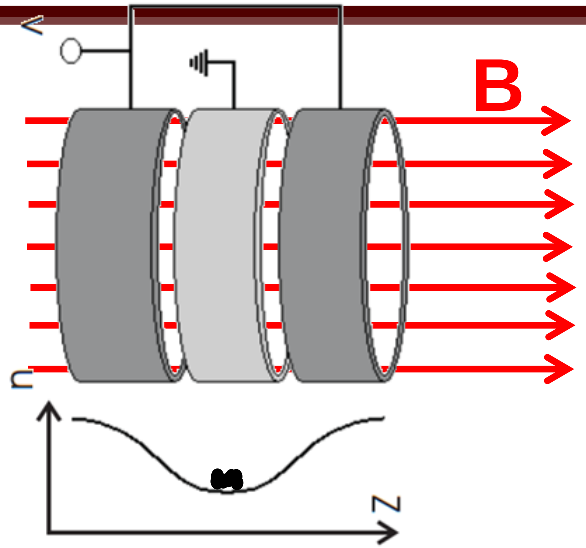




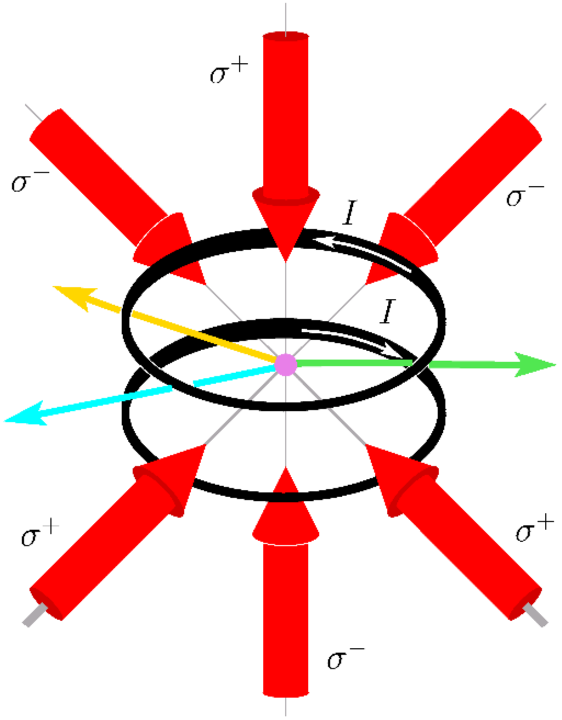


0.1% is a tall order…how to reach that precision?

- Ion traps
  - Can trap any ion; well-known for mass measurements (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 (^{32}Ar; ^{20}Mg, ^{24}Si, ^{28}S, ^{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)



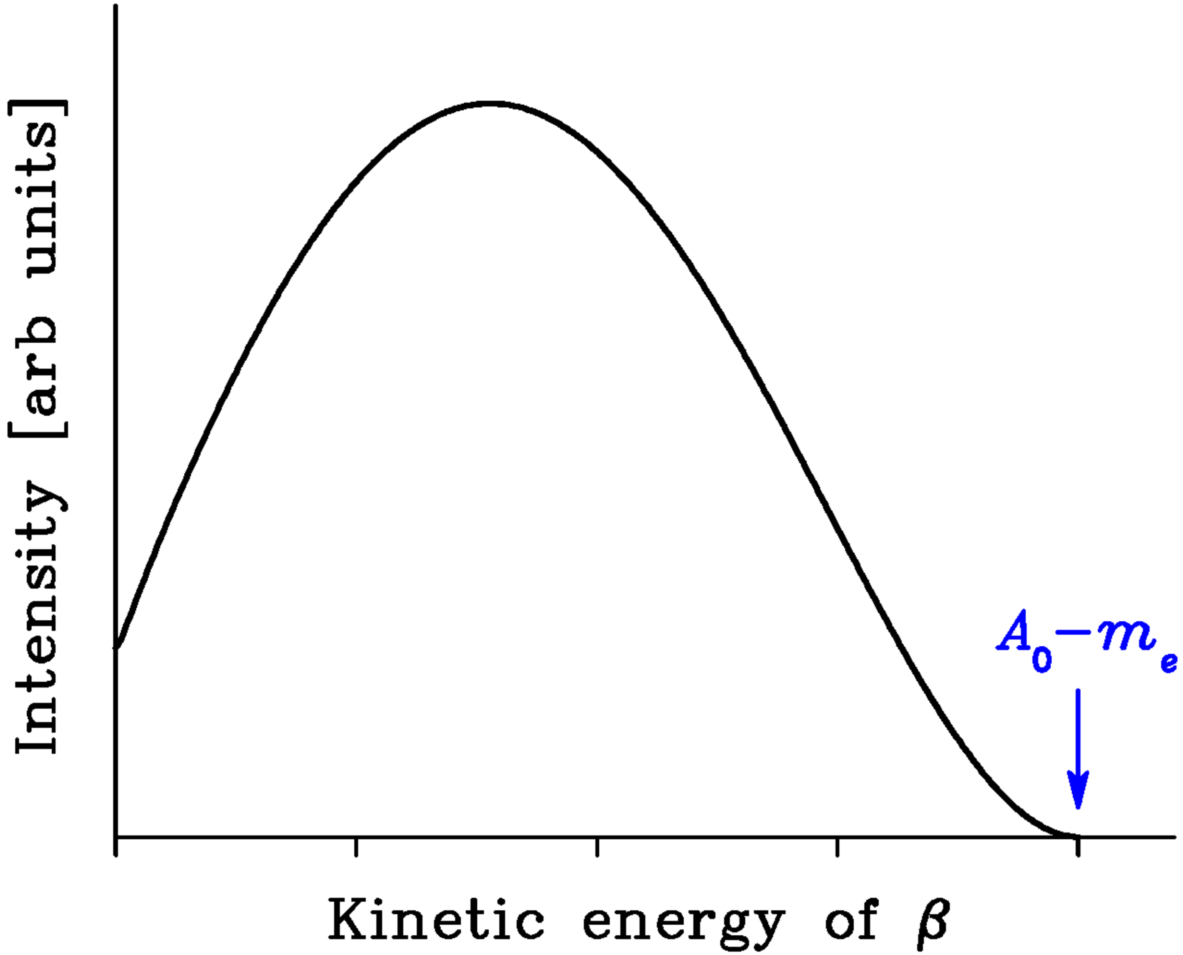
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - TRINAT @ TRIUMF (K isotopes)
  - UW/ANL (you know…!)
  - NeAT @ SARAF (Ne isotopes)



How does β decay test the SM?

- Begin by looking at the basic decay rate

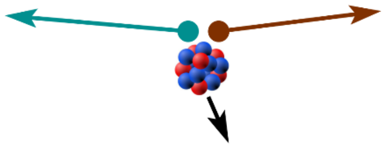
$$\frac{dW}{dE_e} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}}$$



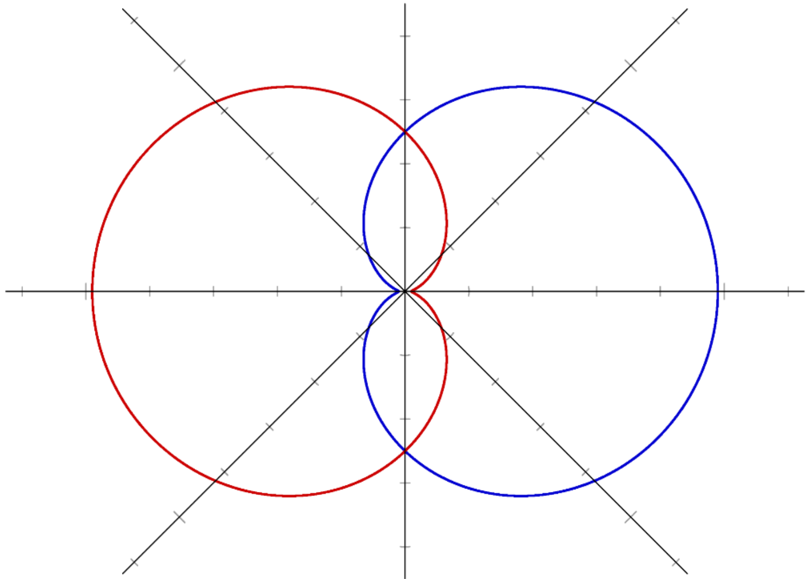
- Expand to the often-quoted angular distribution of the decay (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

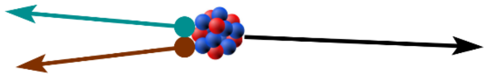
$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}} \xi \left(1 + \overbrace{\boldsymbol{a_{\beta\nu}} \frac{\vec{p_e} \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{\boldsymbol{b}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

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



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





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

a … in the couplings…not … s linear:

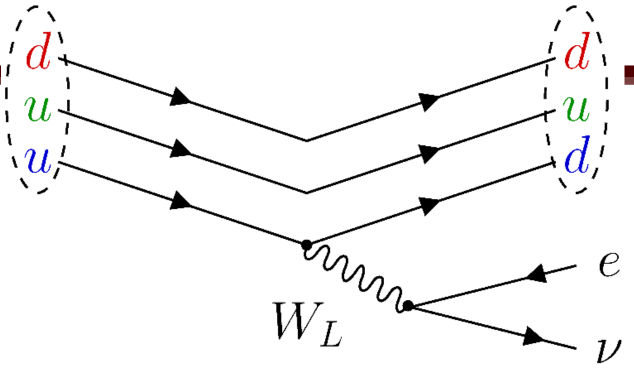
$$b = \frac{-2\Re e(C_S^* C_V + C_S'^* C_V')}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2} = 0??$$

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

How to achieve our goal?

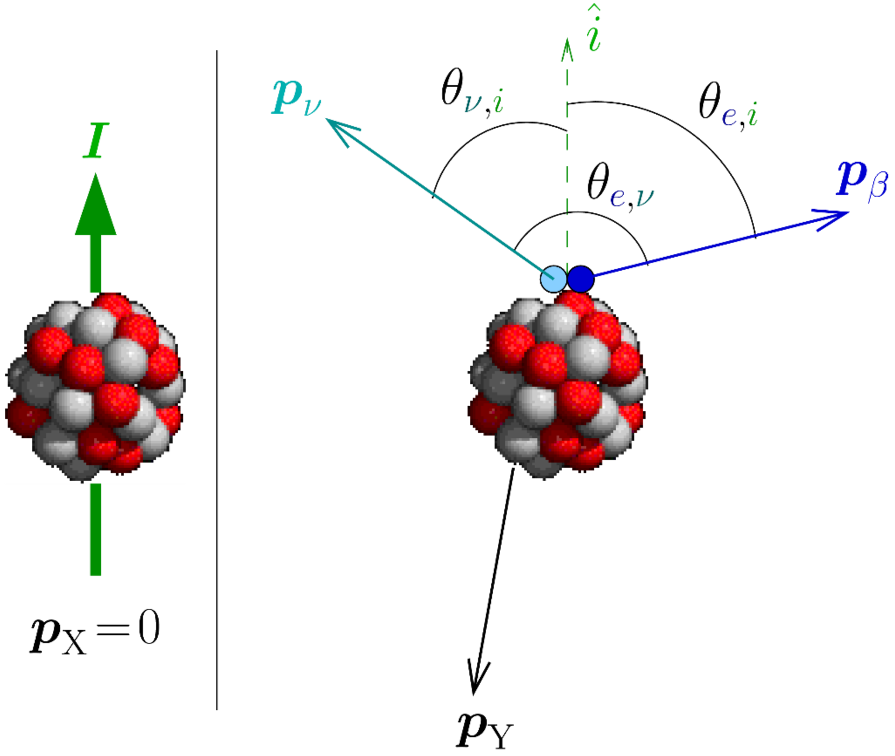


- Perform a β decay experiment on short-lived isotopes

- Make a precision measurement of the angular correlation parameters

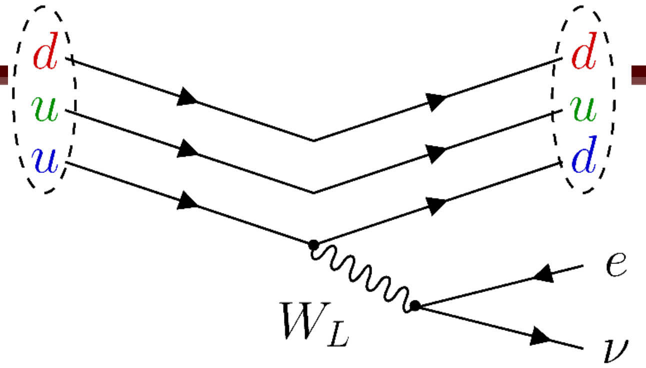
$$^{Z}_{A}X \longrightarrow {}^{Z\mp1}_{A}Y + e^{\pm} + \nu_e$$

- Compare the SM predictions to observations



- Look for deviations as an indication of new physics

How to achieve our goal?

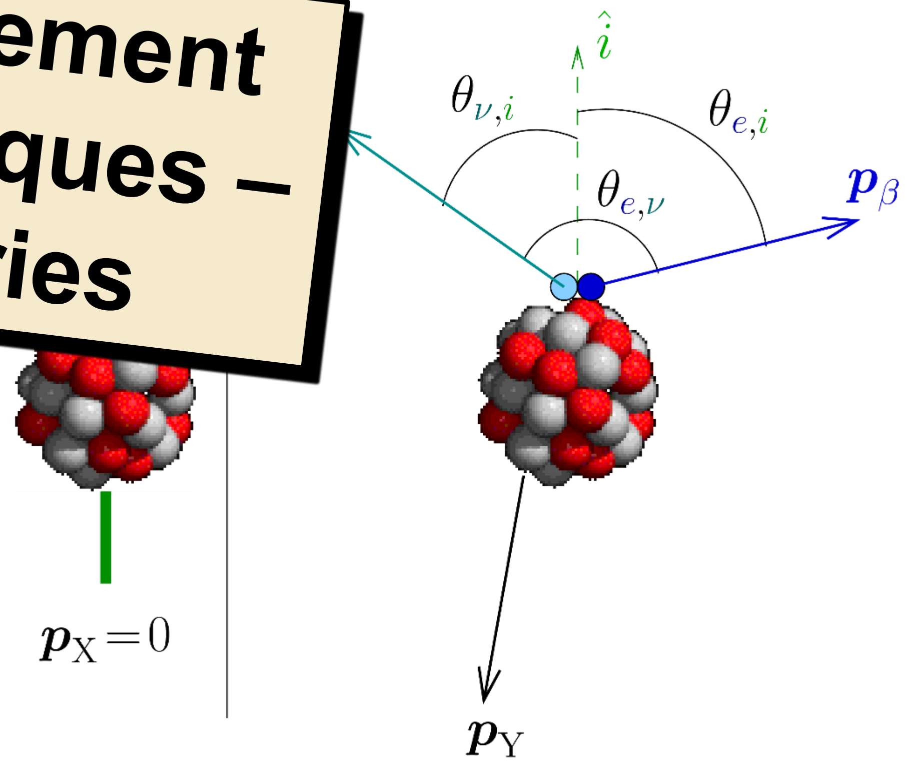


- Perform a β decay experiment on short-lived isotopes

- Make a … of the angular …

Perform a nuclear measurement – often using atomic techniques – to test high-energy theories

$$^{Z}_{A}X \longrightarrow {}^{Z\mp1}_{A}Y + e^{\pm} + \nu_e$$



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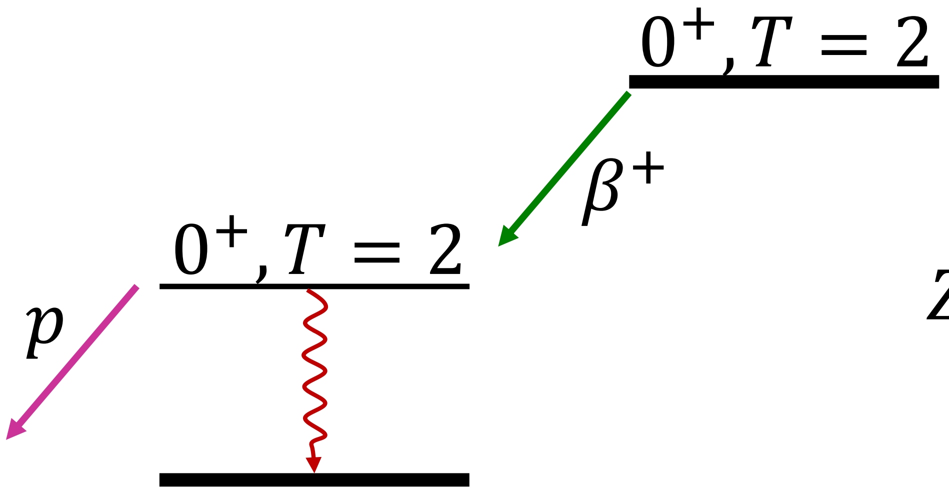
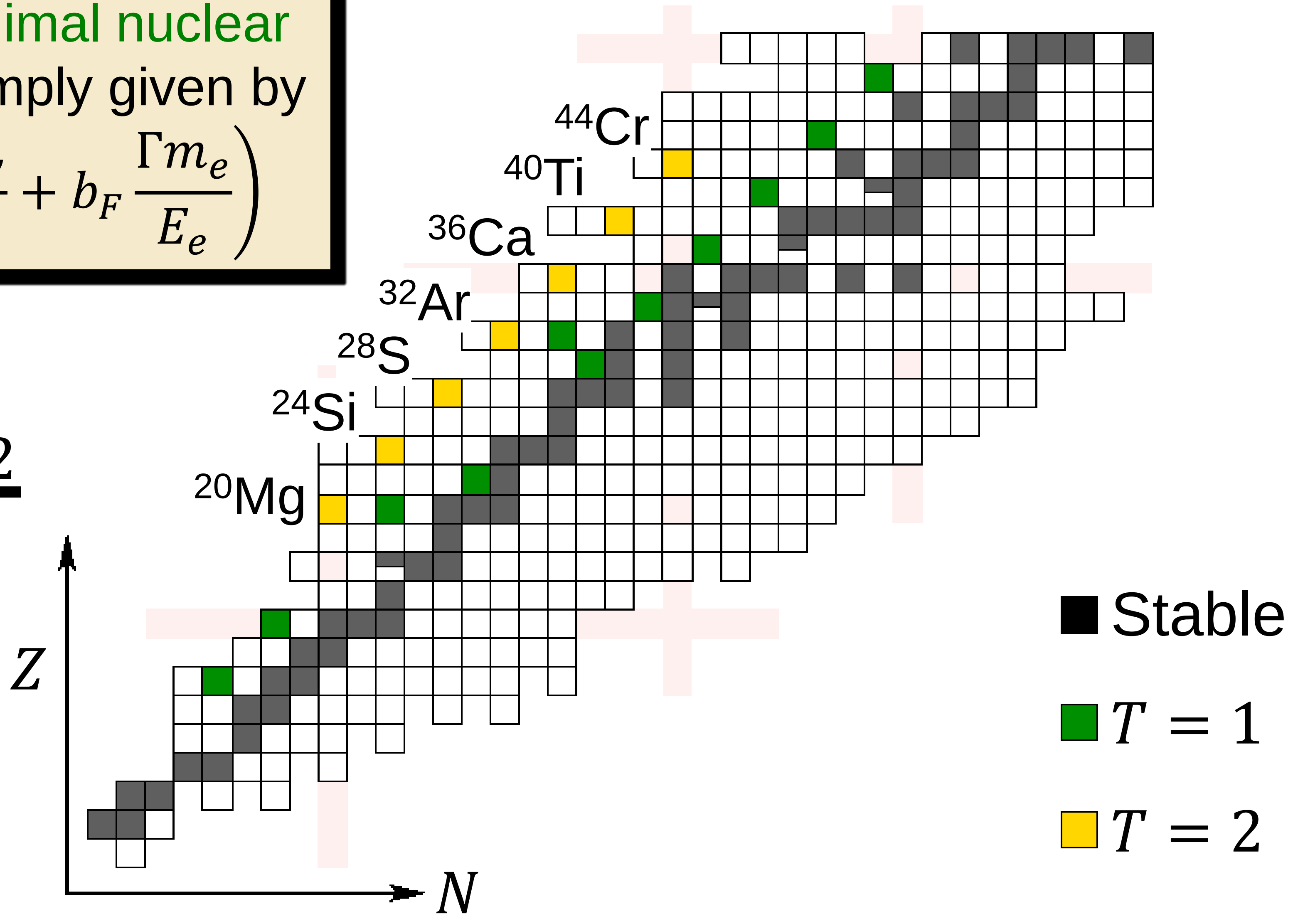
  - Recent measurement of A_β

$T = 2$ Superallowed decays

Recall: pure Fermi decay ⇔ minimal nuclear structure effects; decay rate is simply given by

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





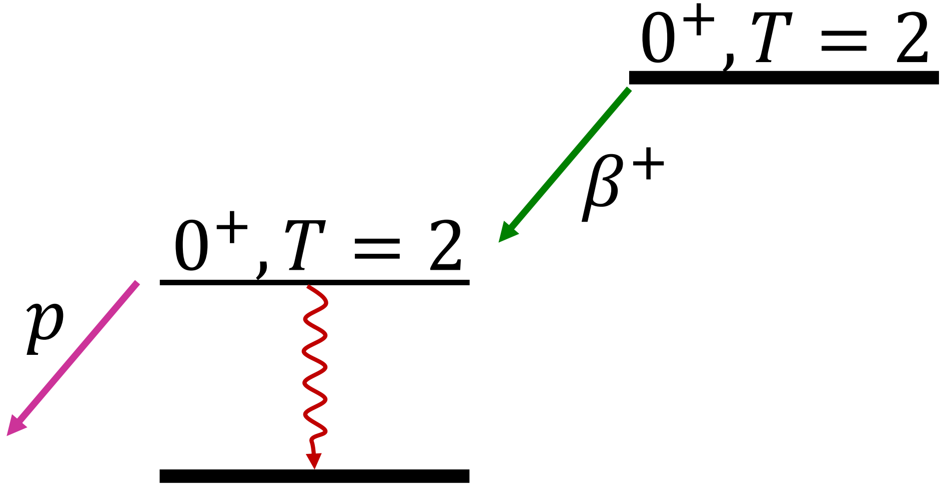
β-ν correlation – A good idea…going back 20 yrs

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

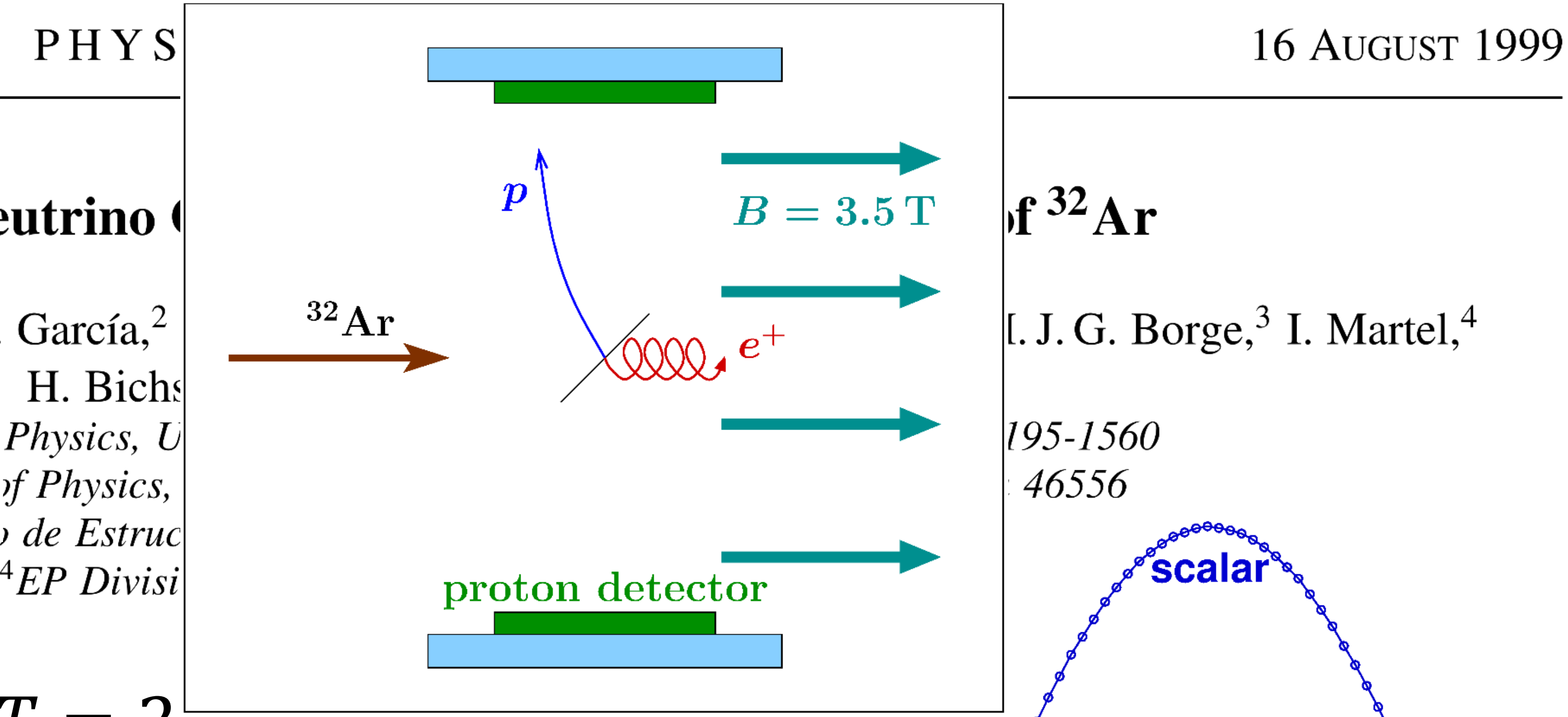
Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

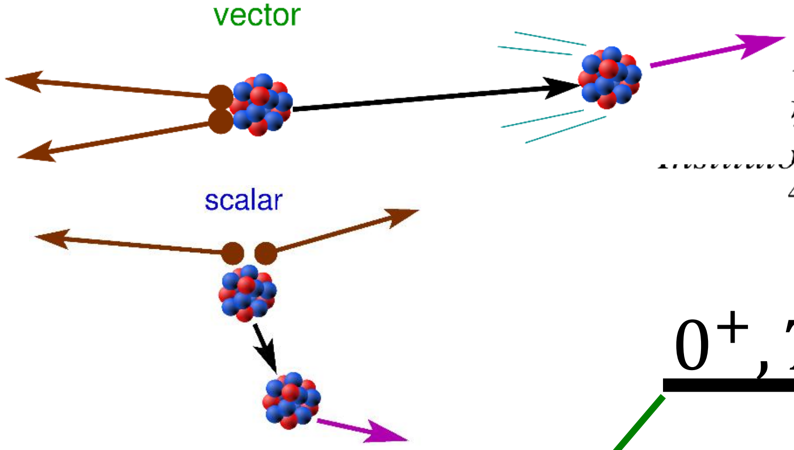
E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4] H. Bichsel,[1] and the ISOLDE Collaboration[4]
[1]*Department of Physics, University of Washington, Seattle, Washington 98195-1560*
[2]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[3]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[4]*EP Division, CERN, Geneva, Switzerland CH-1211*
(Received 24 February 1999)

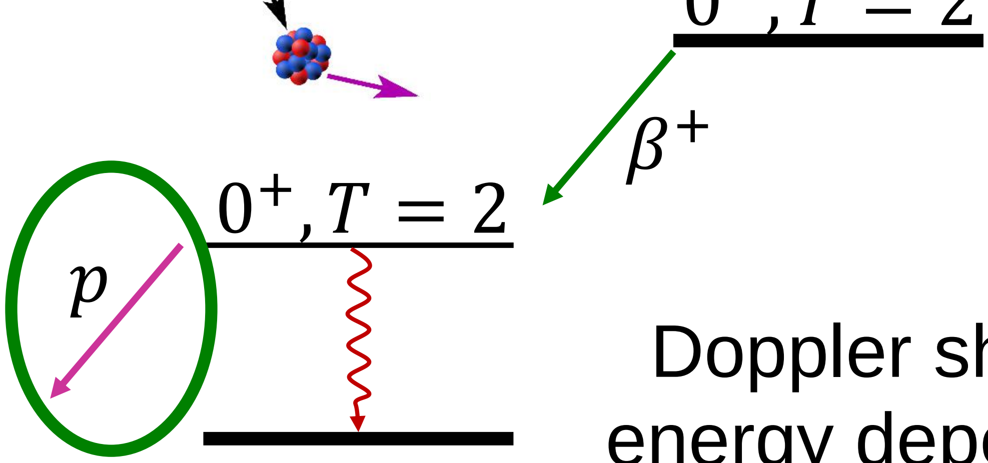
n the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar was measured at ISOLDE by
ı the shape of the narrow proton group following the superallowed
ıe standard model prediction. For vanishing Fierz interference we
which yields improved constraints on scalar weak interactions.

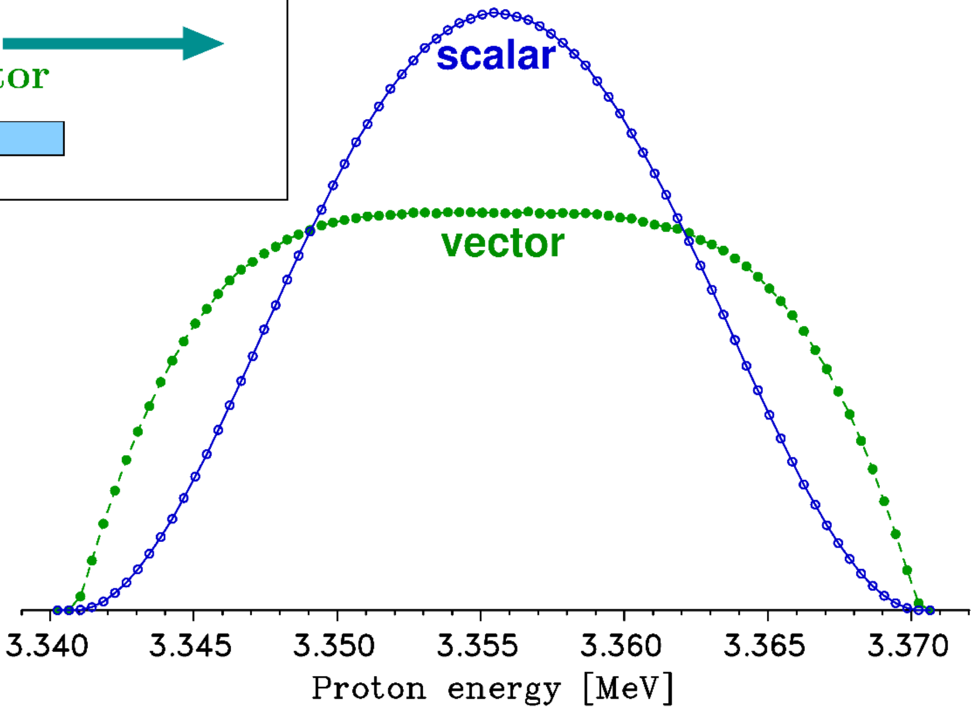


β-ν correlation – A good idea…going back 20 yrs







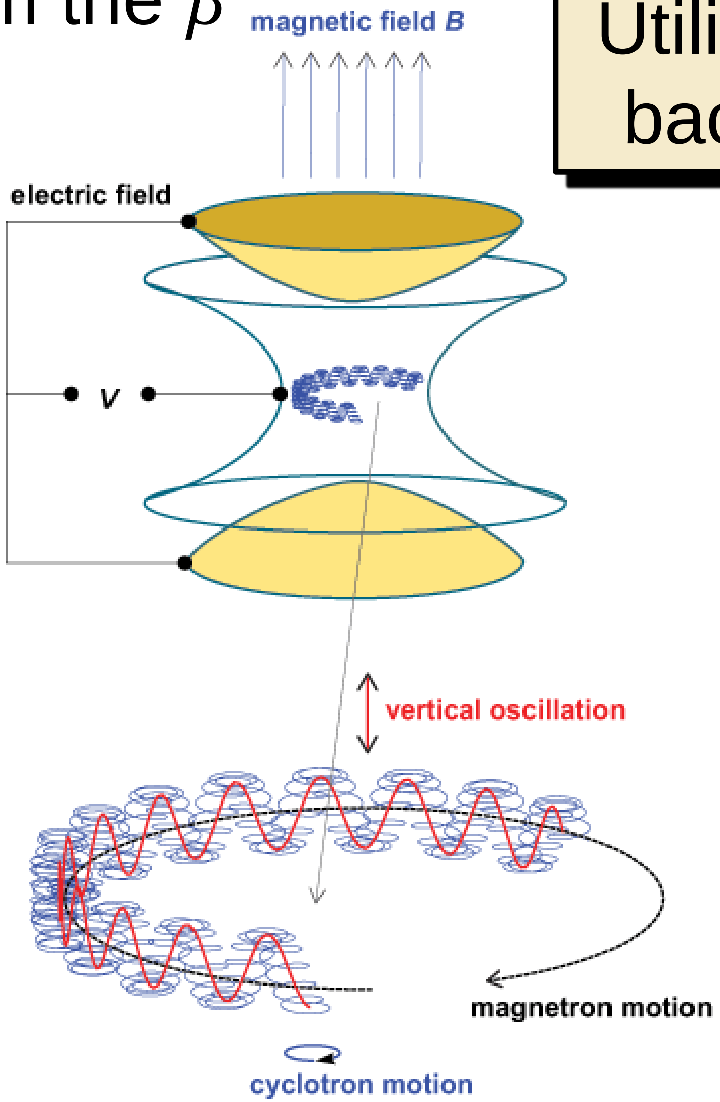


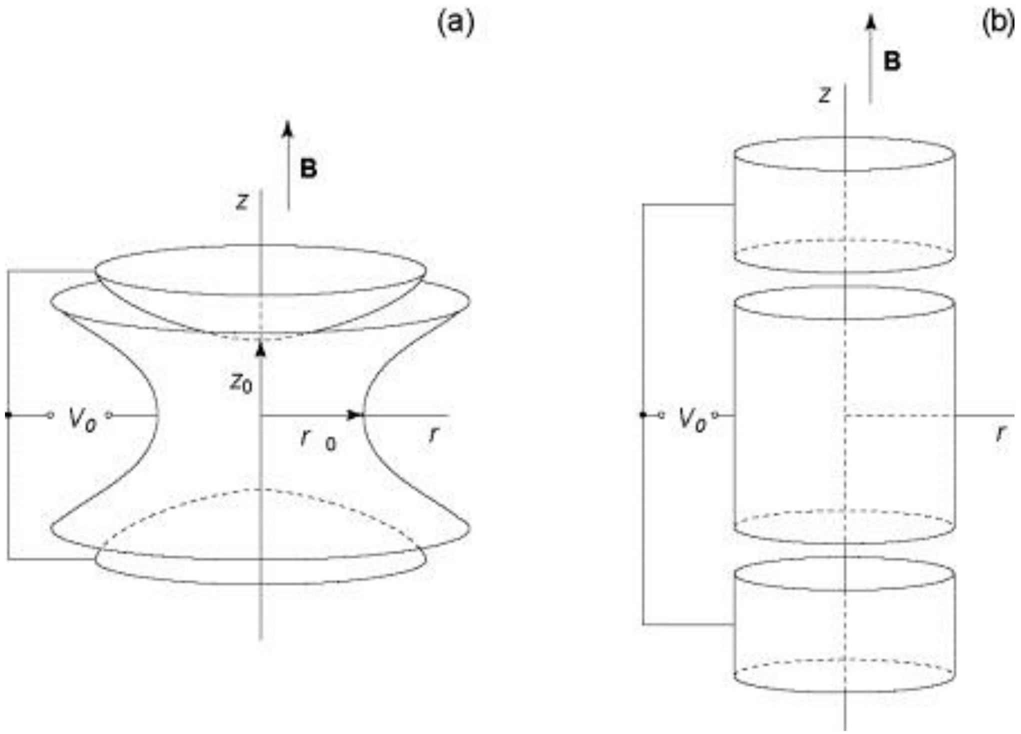
Doppler shape of proton energy depends on $\vec{p}_\beta \cdot \vec{p}_\nu$!

But why throw away useful information?

- We can gain sensitivity and reduce backgrounds by using information from the β

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





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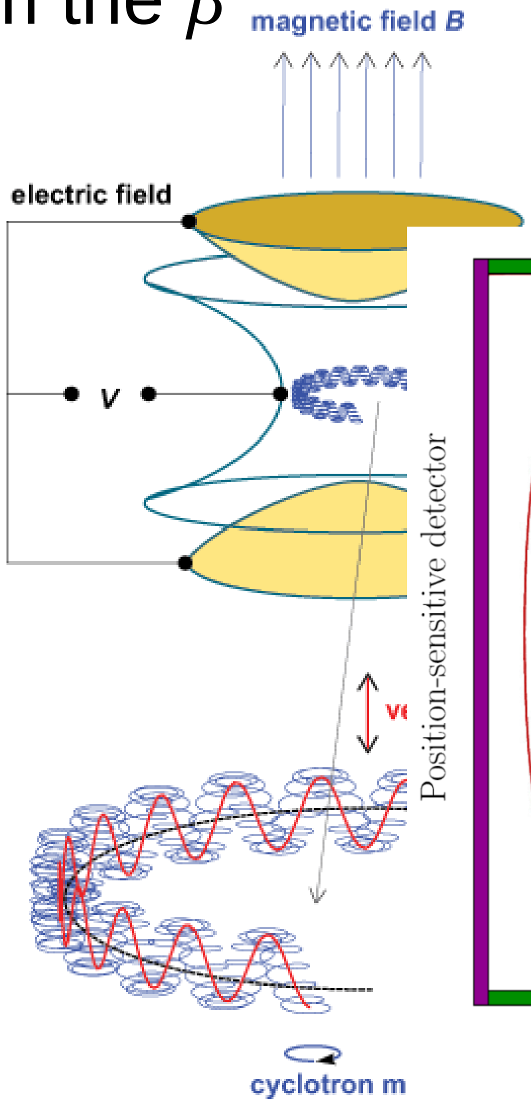
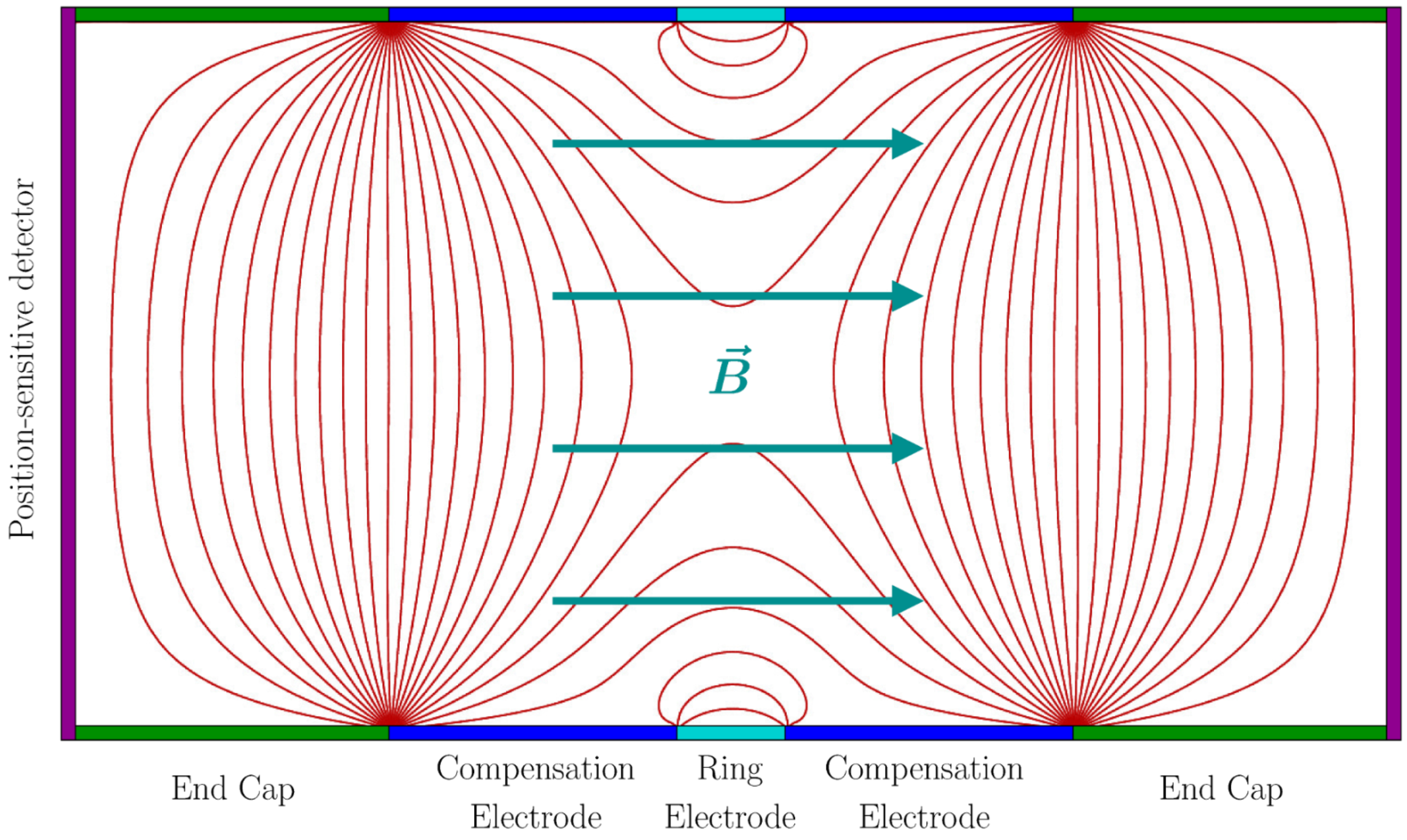
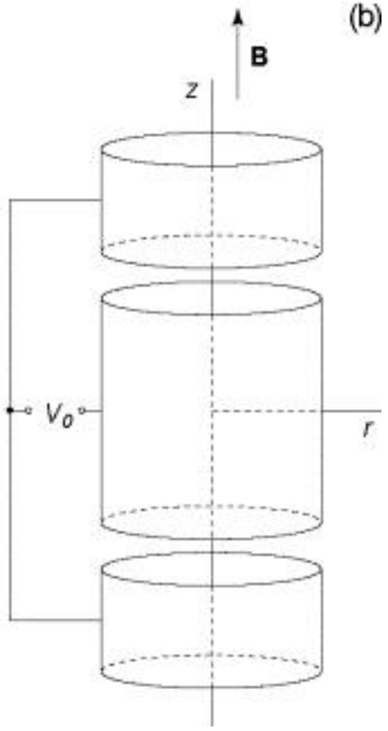
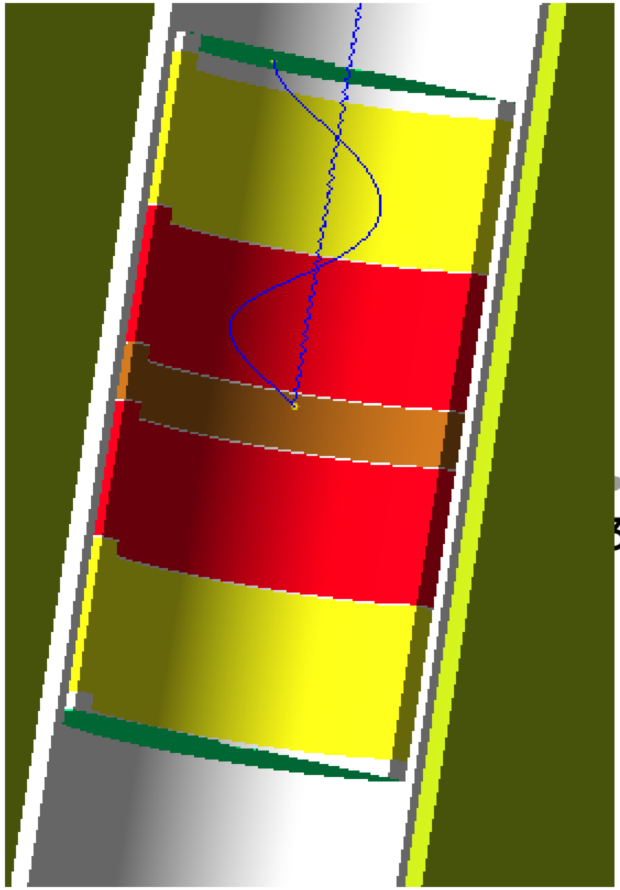
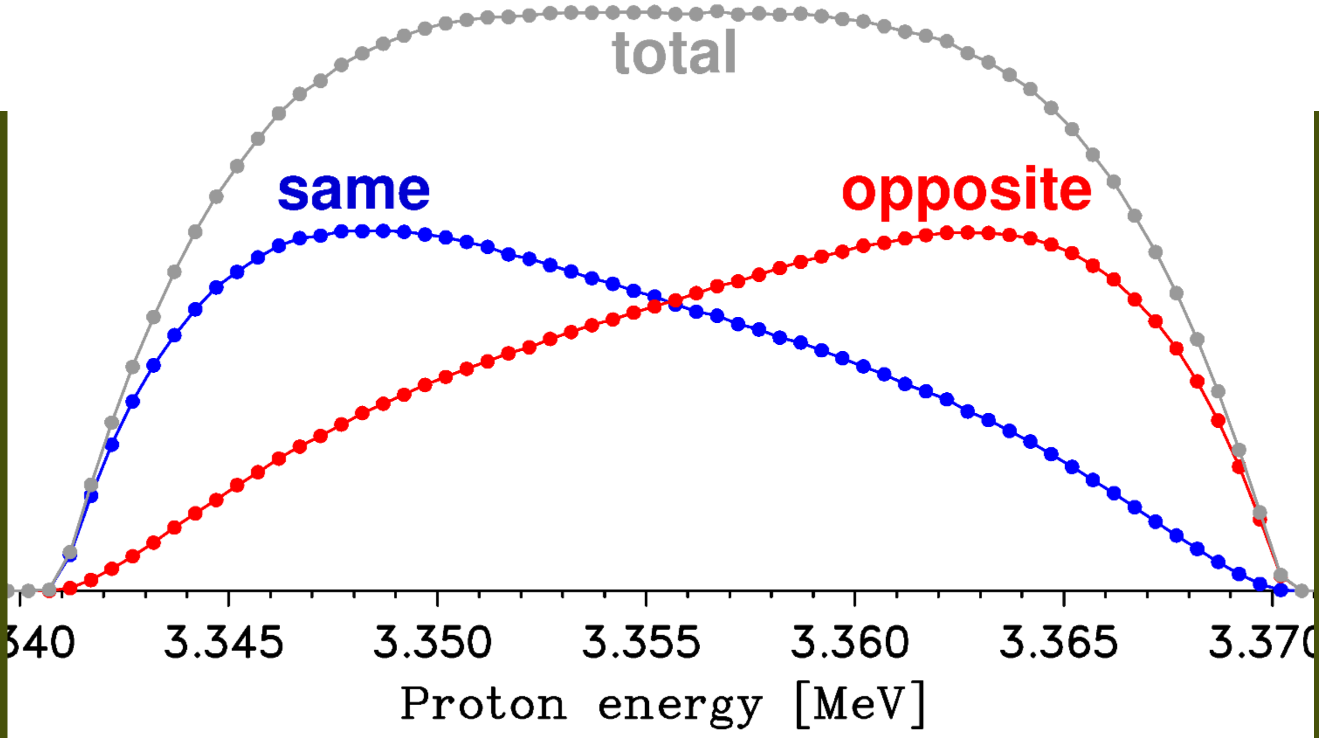


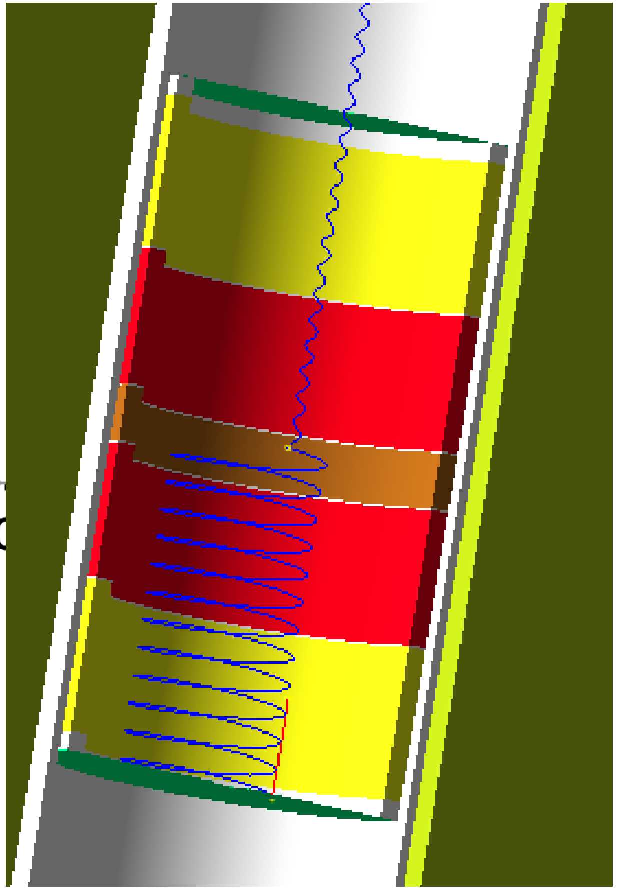


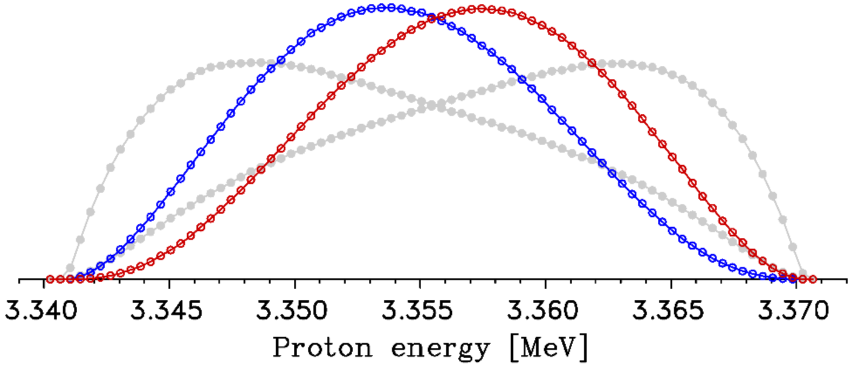


Measure means instead of 2nd moments







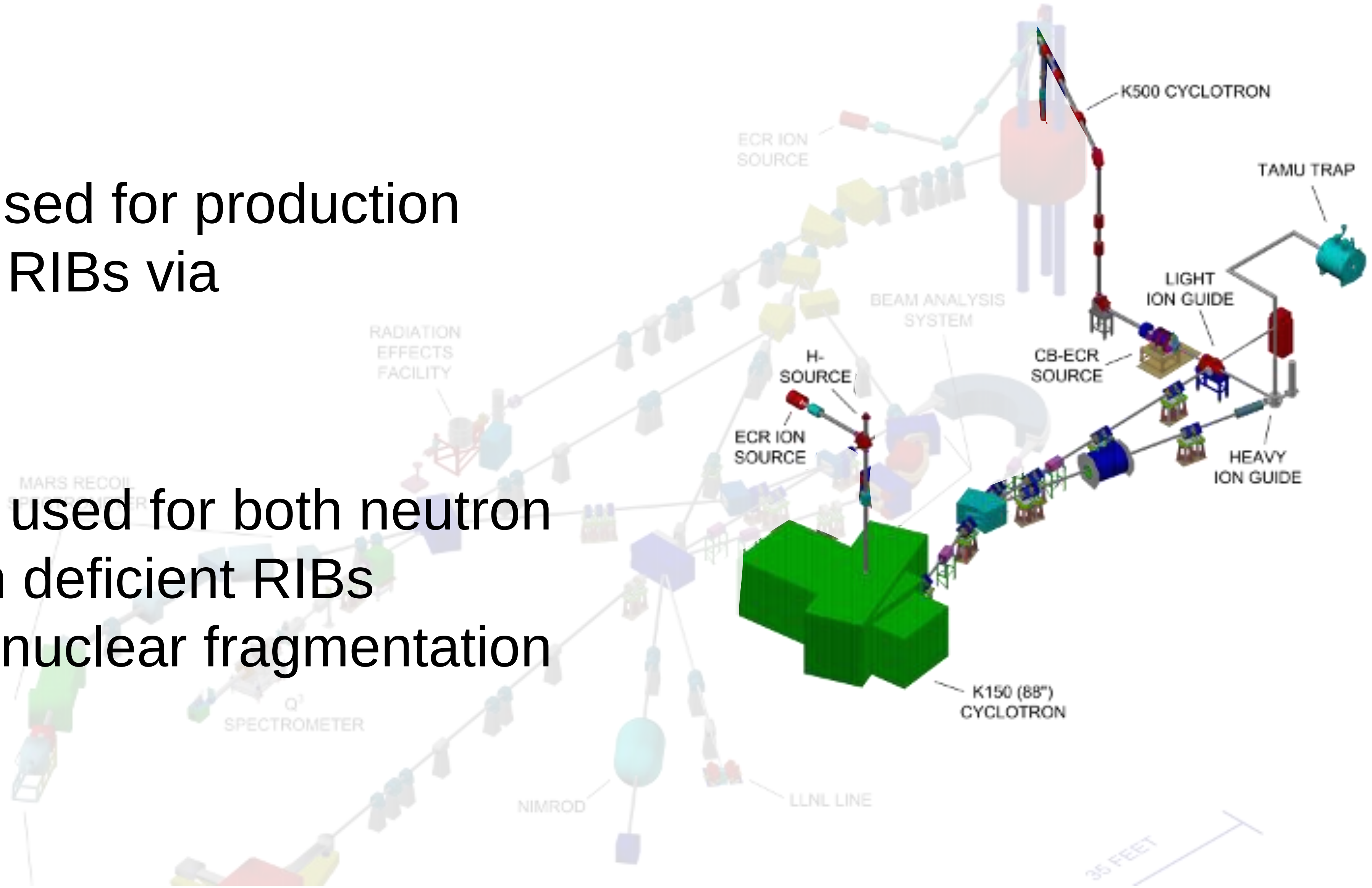


The T-REX Upgrade Project

- Re-commission the K150 for high intensity beams and/or to re-accelerate RIBs in the K500

- Light Ion Guide – used for production of neutron deficient RIBs via $A(p,xn)B$ reactions

- Heavy Ion Guide – used for both neutron deficient and proton deficient RIBs (deep inelastic and nuclear fragmentation reactions)



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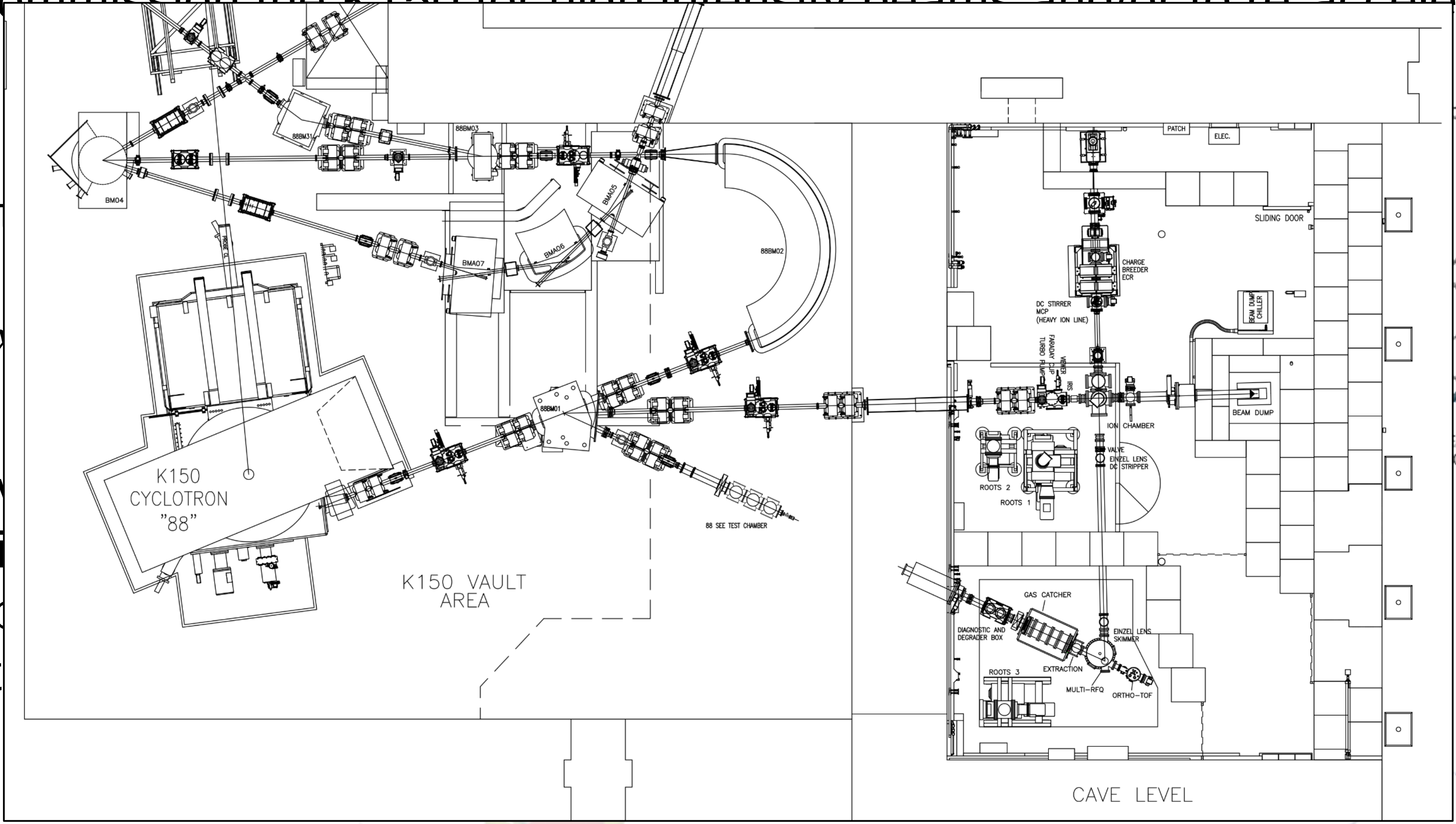
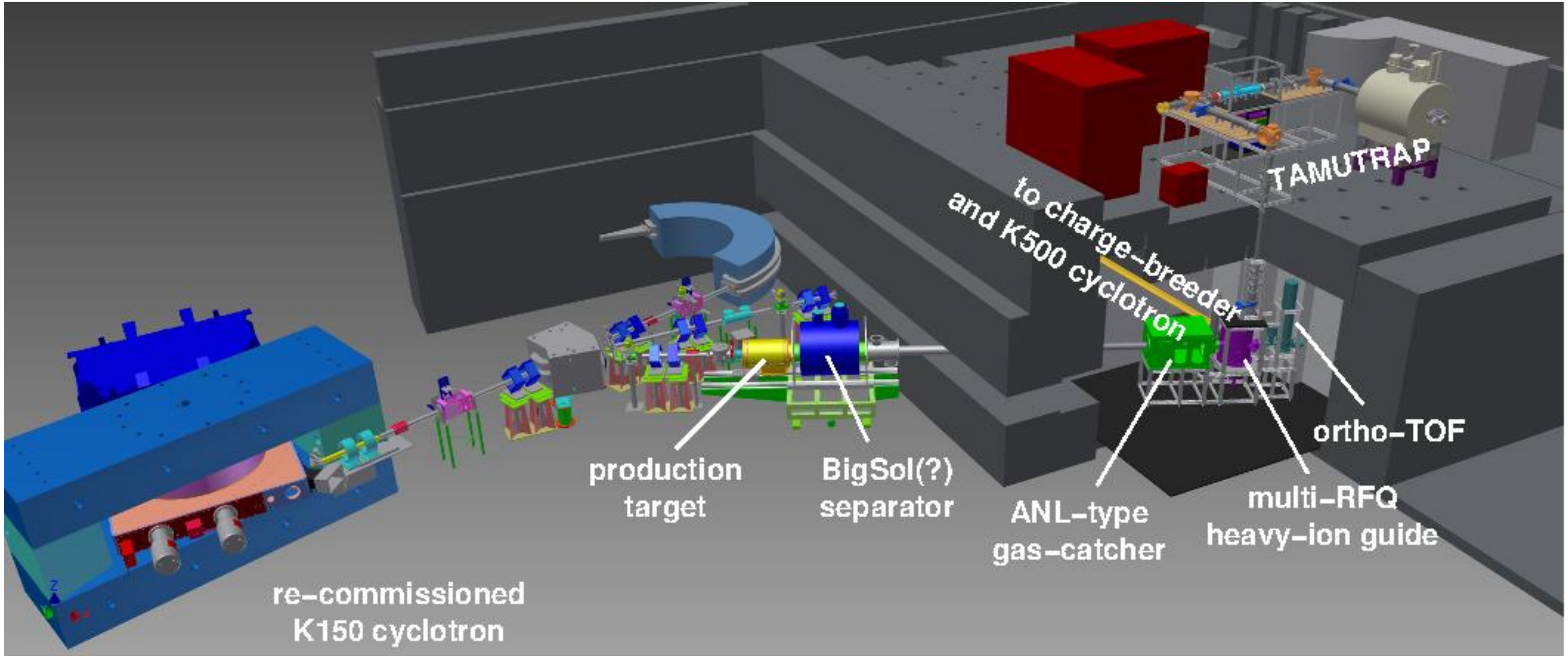


The original plan

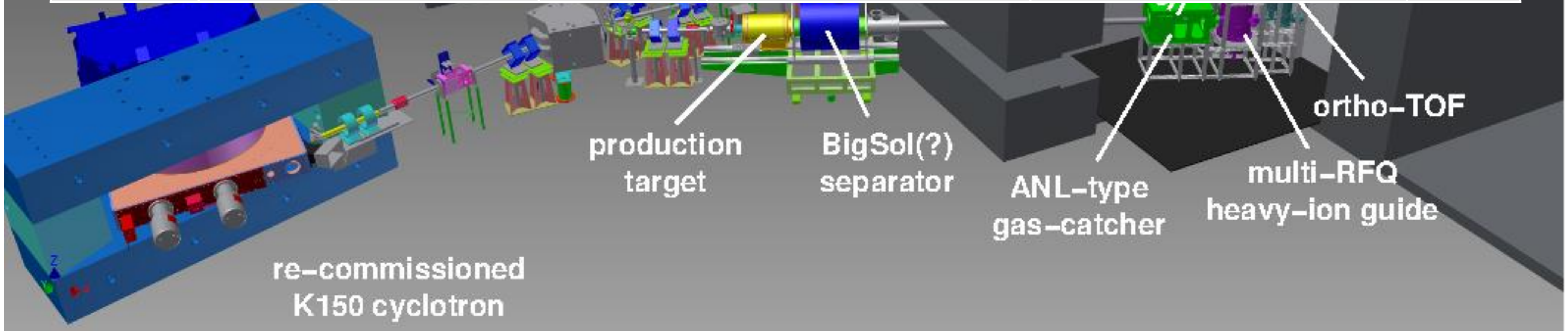
- Use the heavy ion guide to produce the proton-rich nuclei



The original plan

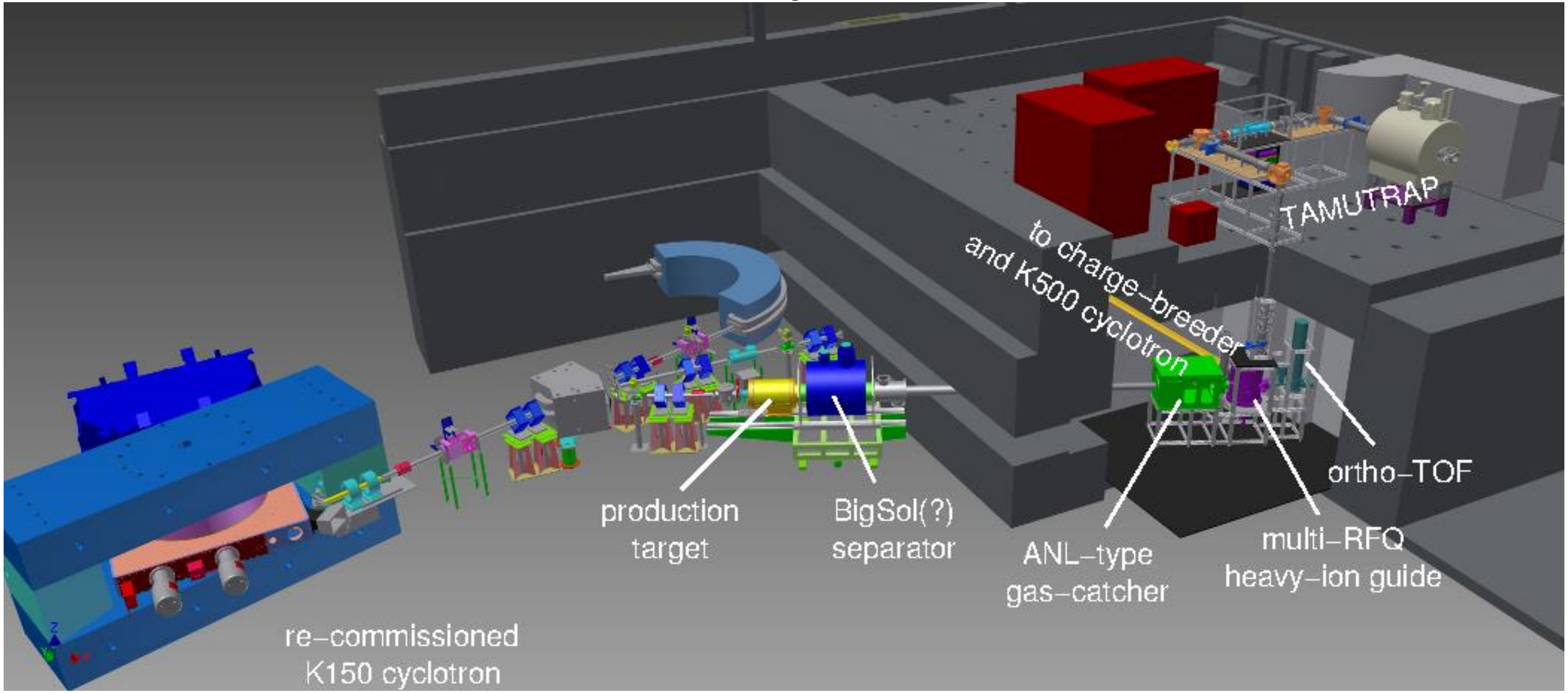
- Use the heavy ion guide to produce the proton-rich nuclei
  - ^{3}He target, 10% overall efficiency, assuming K150 specs from White Paper

RIB	$t_{1/2}$ [ms]	Projectile	Energy [MeV/u]	Target thickness [mg/cm^2]	Expected rate @ target chamber [pps]
^{20}Mg	90	^{20}Ne	23-30	22.5 (66)	$68\ (400) \times 10^4$
^{24}Si	140	^{24}Mg	22-30	22.5 (70)	$26\ (160) \times 10^4$
^{28}S	125	^{28}Si	22-30	22.5 (60)	$7\ (40) \times 10^4$
^{32}Ar	98	^{32}S	20-24	22.5 (42)	$5\ (17) \times 10^4$
^{36}Ca	102	^{36}Ar	23-30	22.5 (28)	$12\ (31) \times 10^4$
^{40}Ti	53	^{40}Ca	23-30	22.5 (26)	$4\ (8) \times 10^4$



The Heavy Ion Guide

- Deep-inelastic and fragmentation reactions, with BigSol as a separator
- Stopped in an ANL-type gas-catcher; able to transport to CB-ECR or TAMUTRAP with a multi-RFQ switchyard



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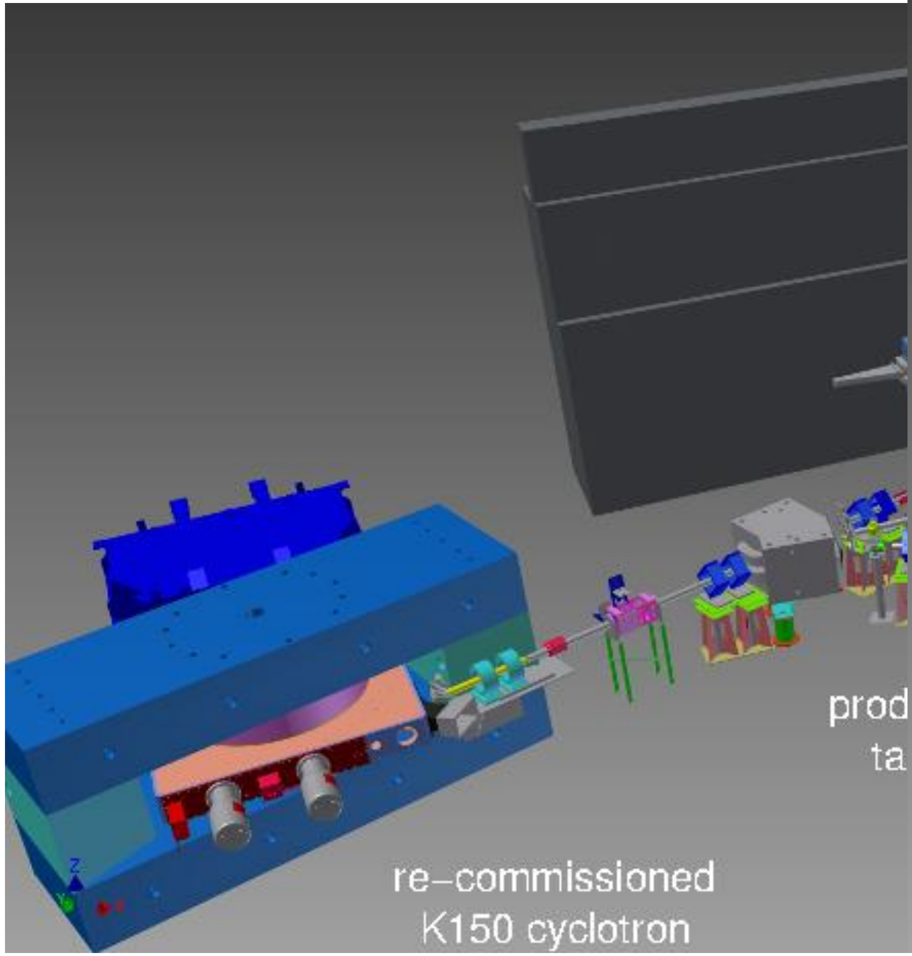
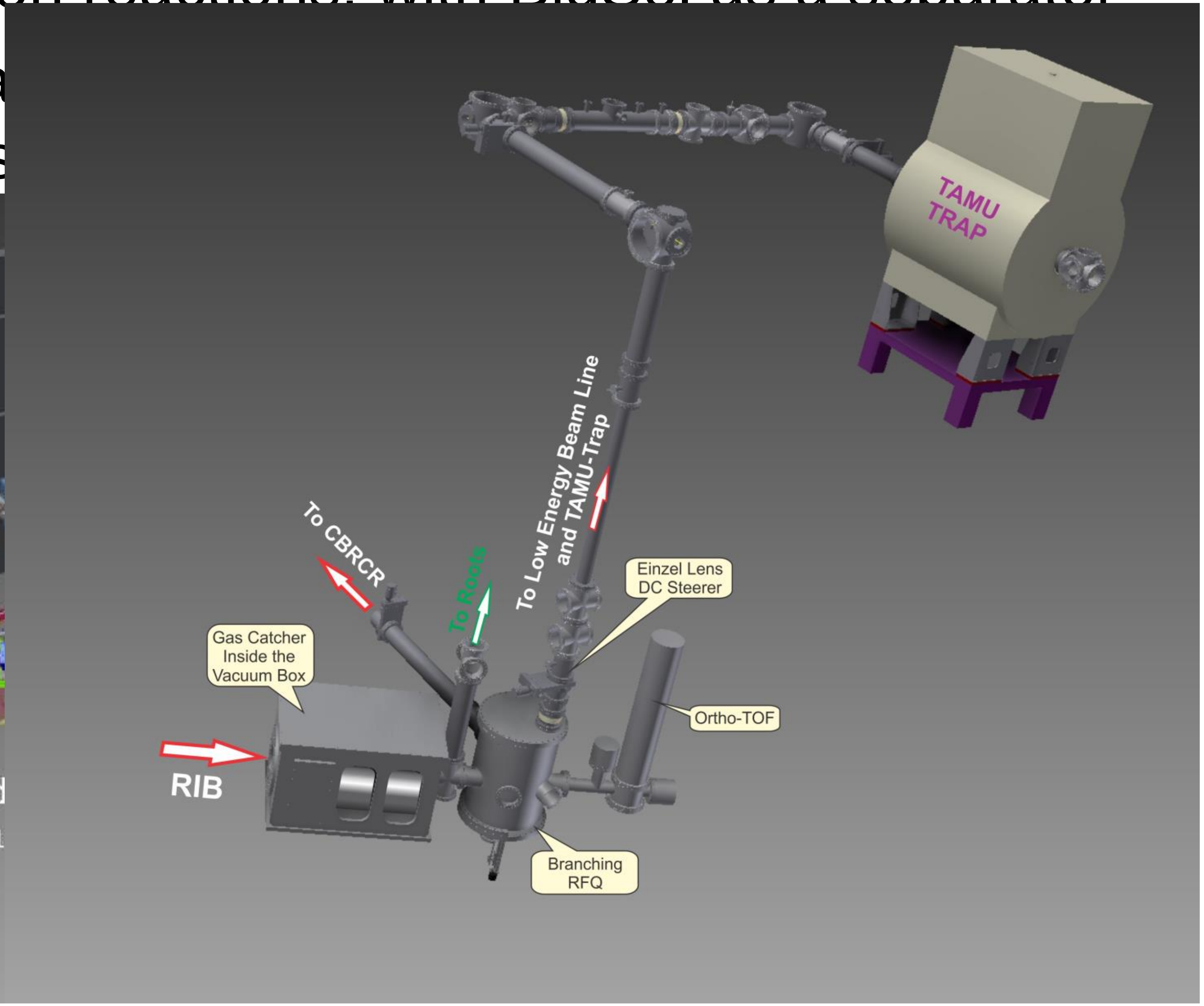
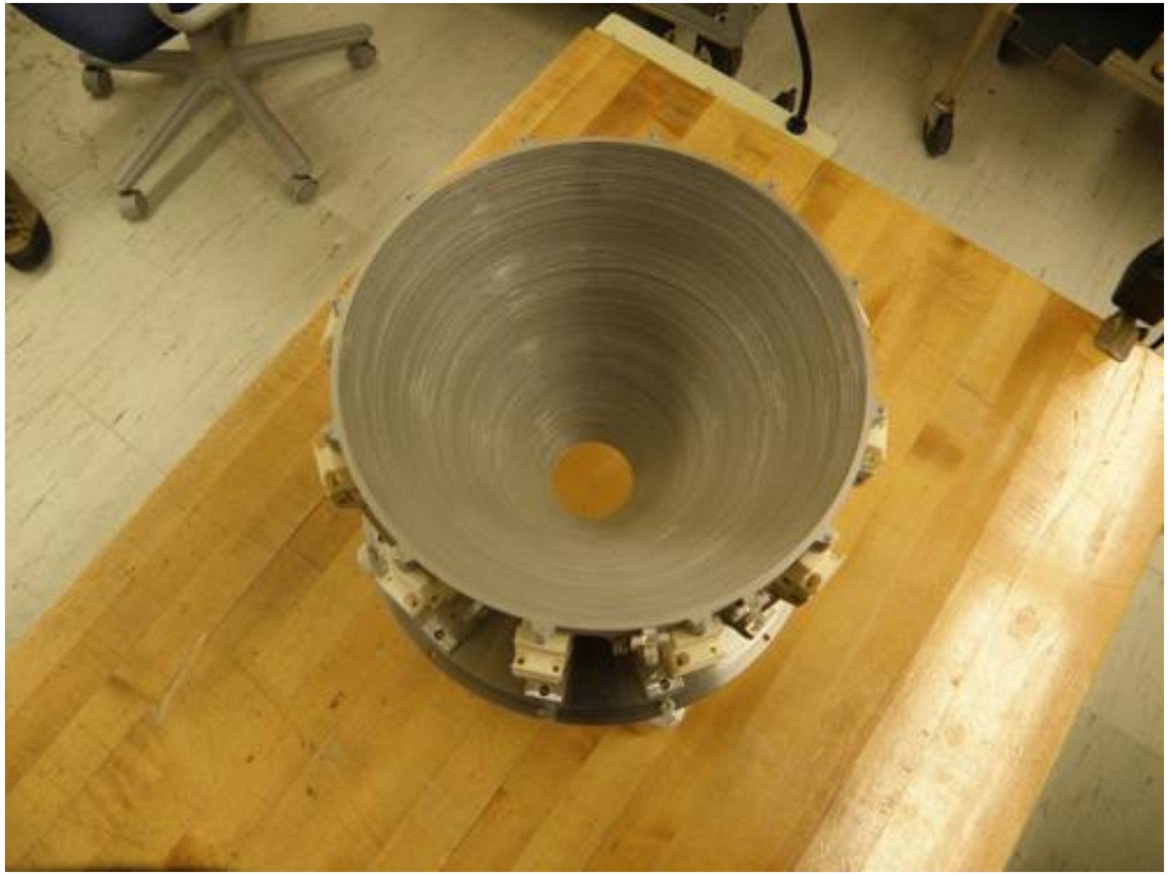




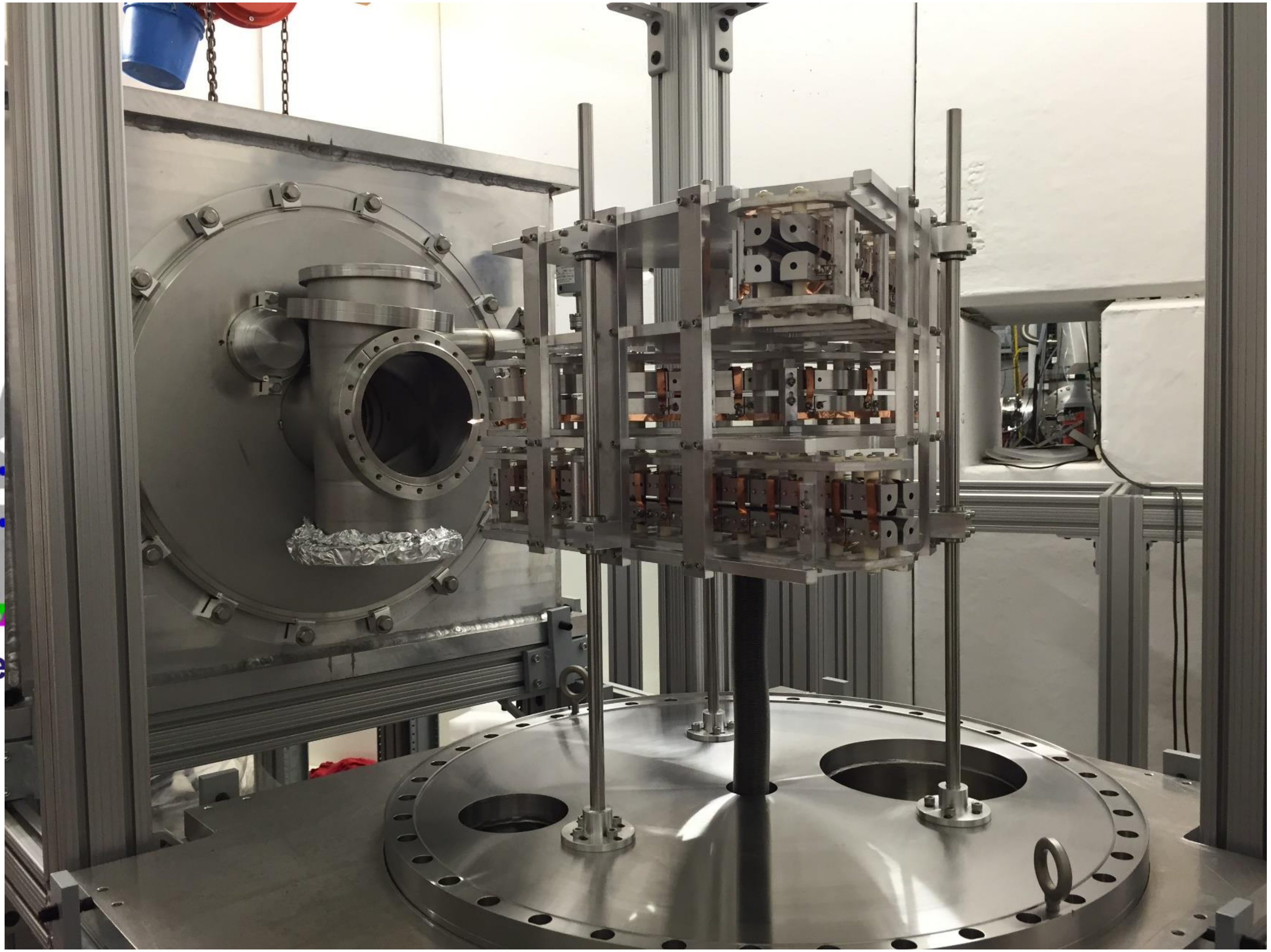
The Heavy Ion Guide gas catcher

- Designed and built in close collaboration with G. Savard (ANL)
- In a vacuum box to avoid condensation from cooling lines



Transporting the stopped RIBs

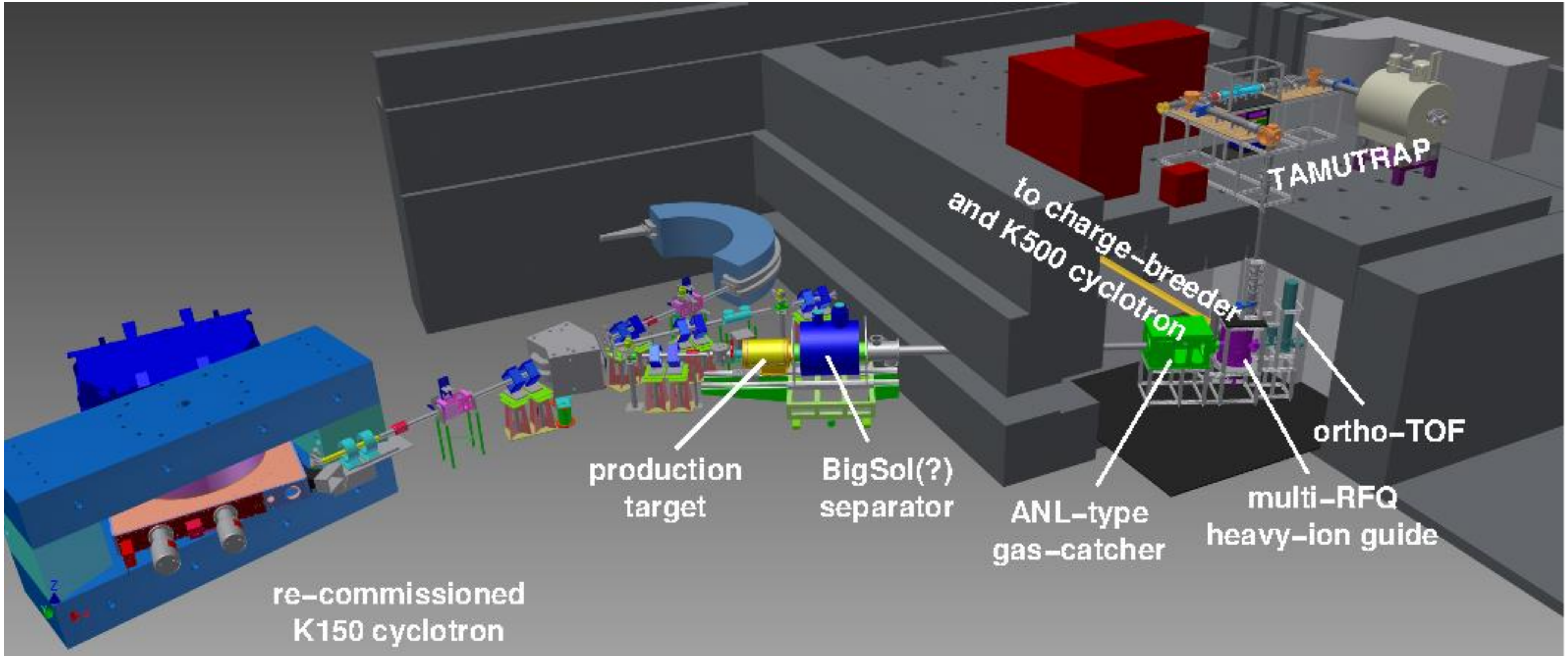
- Gas flow and rf funnel guide RIB through multi-RFQ system



Issues with original plan

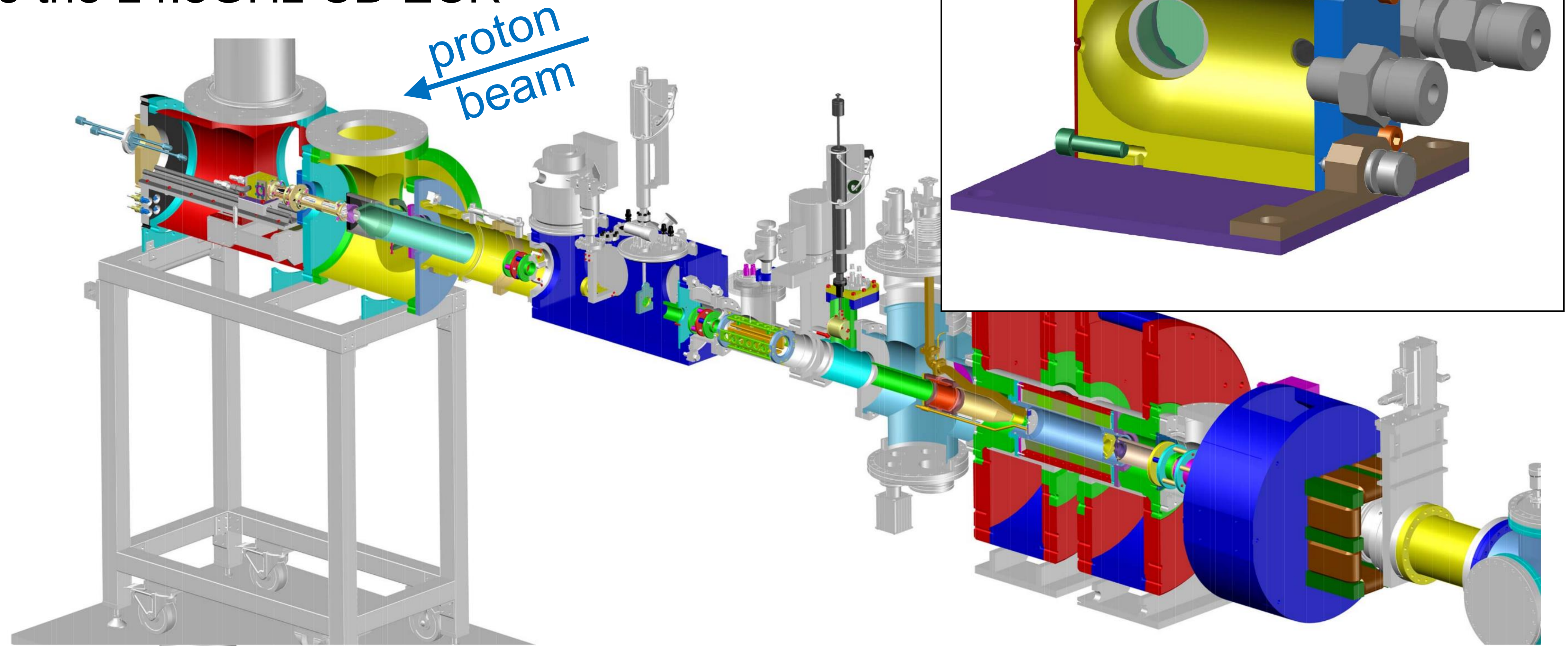
- Ion source not performing to specs
- K150 not able to go to full energy
- No separator, no one working on it

"*You can expect one ion every 9 or 10 seconds*"



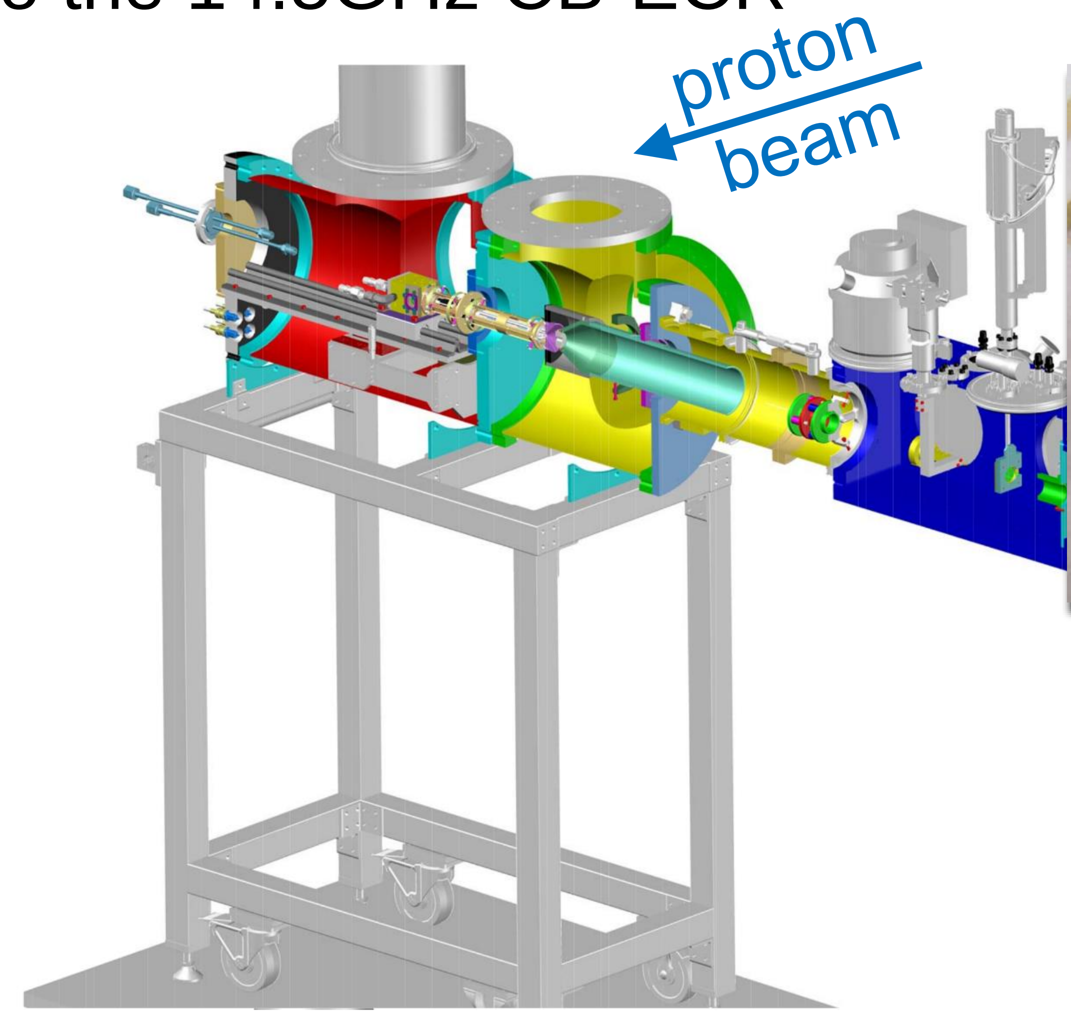
The Light Ion Guide (farther along)

- 130 mbar He gas, RIB extracted with differential pumping system and transported to the 14.5GHz CB-ECR

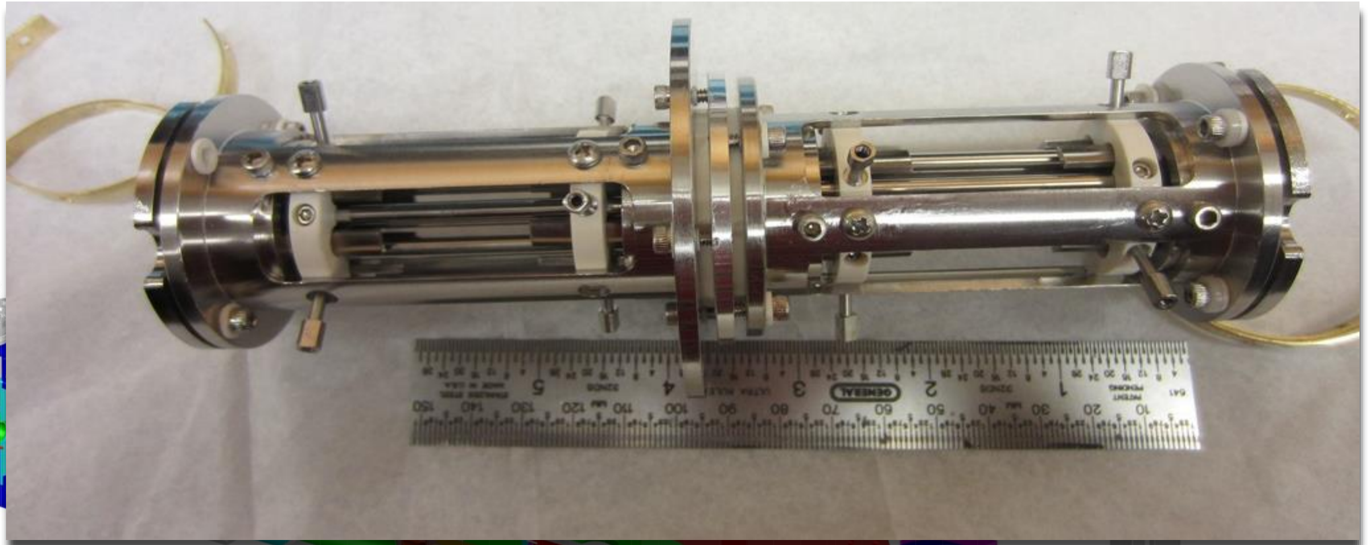


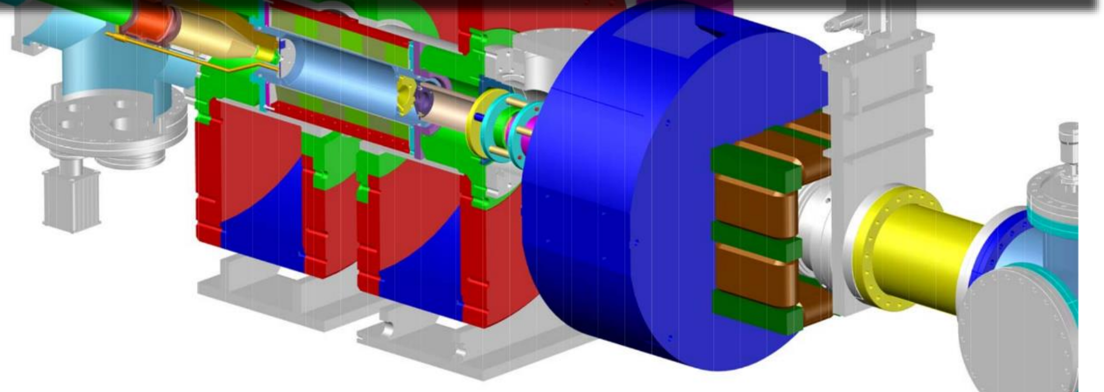
The Light Ion Guide

- 130 mbar He gas, RIB extracted with differential pumping system and transported to the 14.5GHz CB-ECR



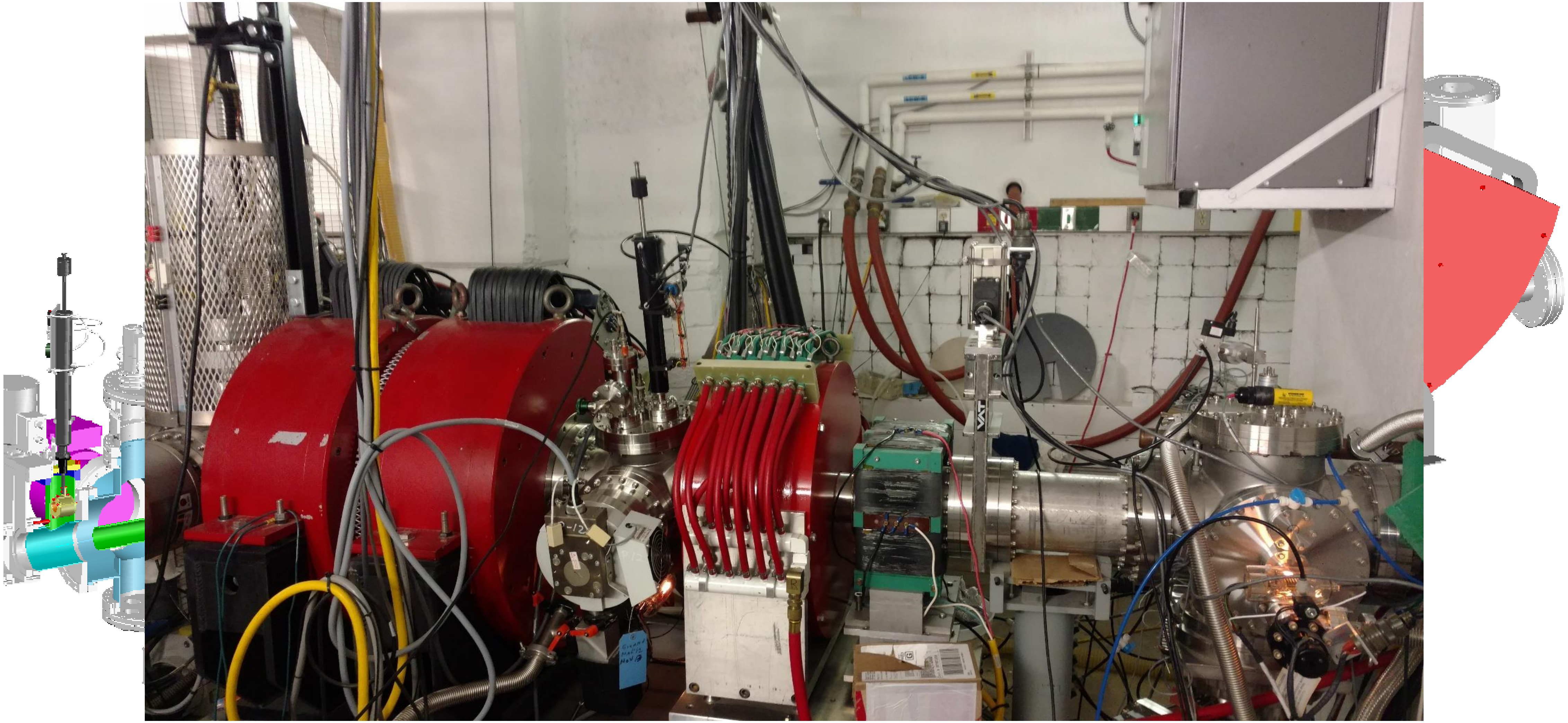
RF-only sextupole





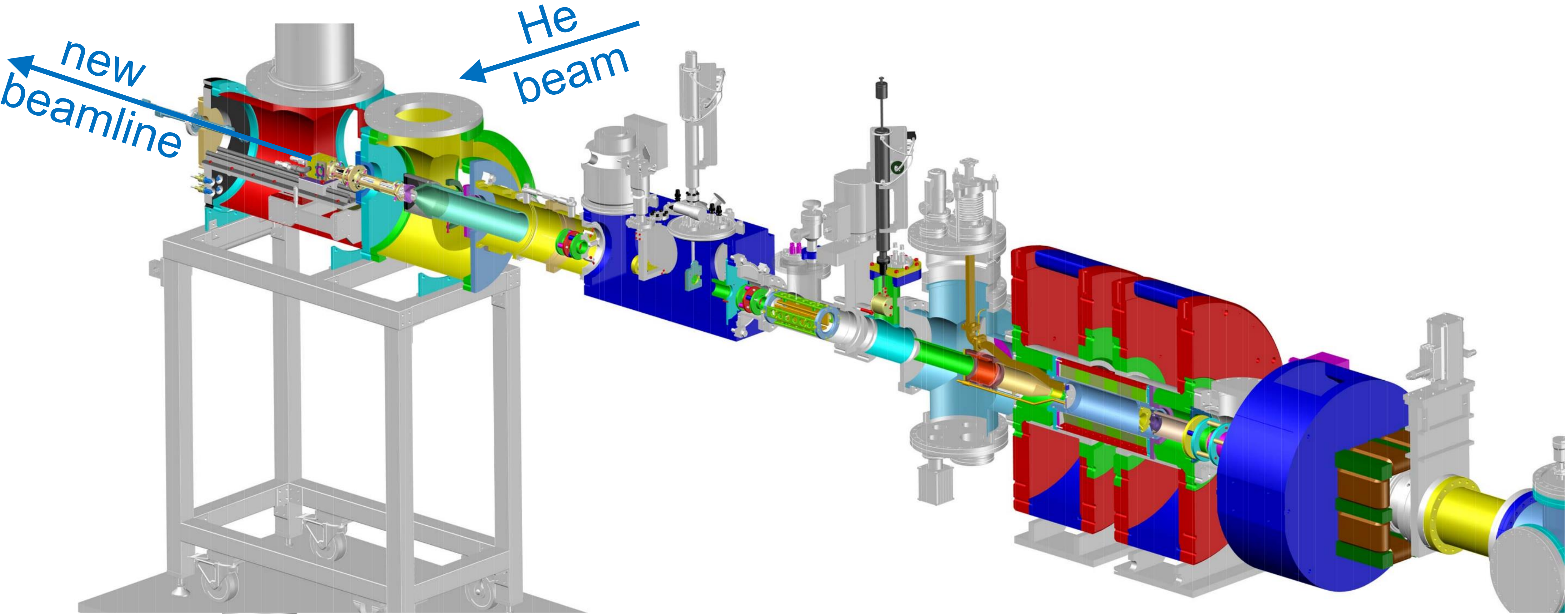
The Light Ion Guide

- 90° analyzing magnet to transport highly charged (e.g. 12^+ or higher ^{64}Ga) for injection into the K500



Latest plan: try using the LIG for TAMUTRAP

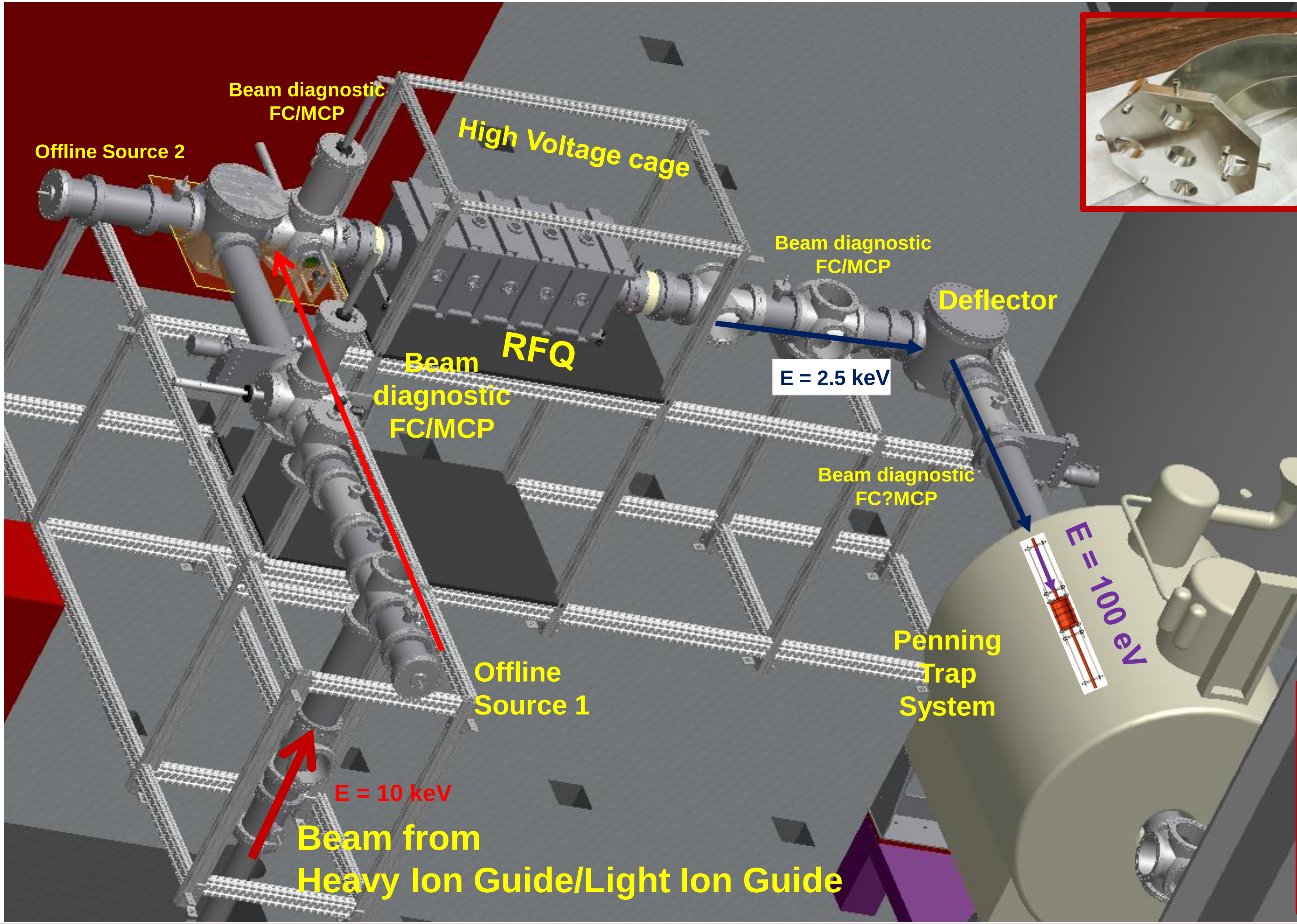
- Same reaction cross-sections, lighter is better for the K150
- New gas cell. Mass separation? (In)compatible with HIG?

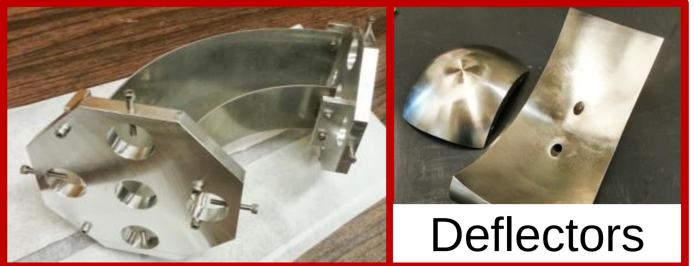


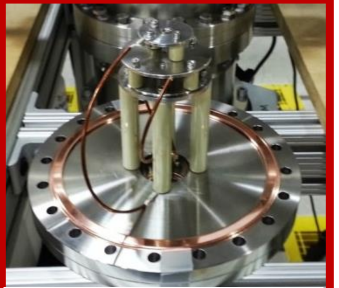
In the meantime, we haven’t been picking our noses…


Einzel Lens


Steerer




Deflectors

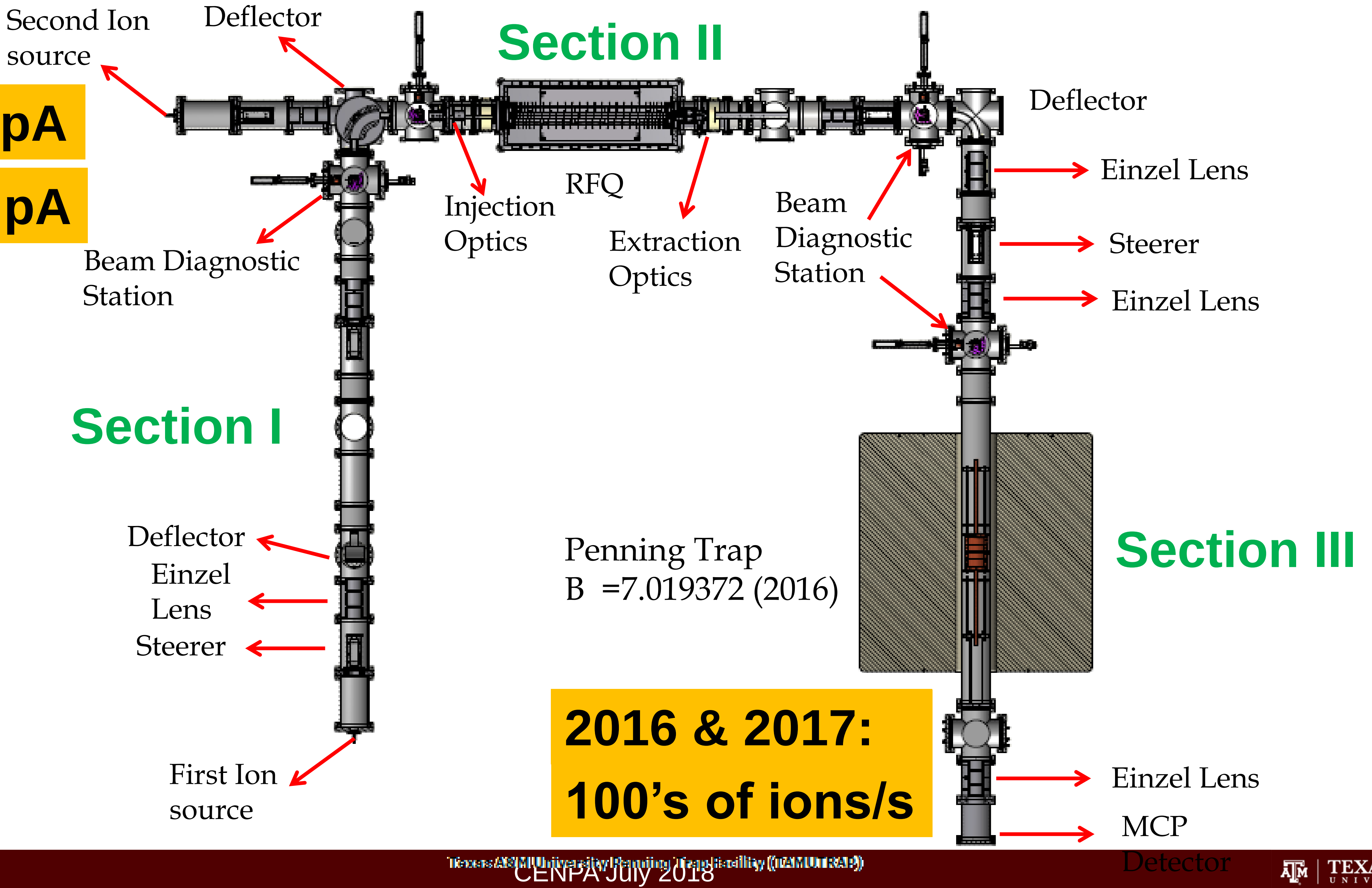

Offline Source


Control System

Optimizing the TAMUTRAP beamlines

2016: 120 pA

2017: <1 pA

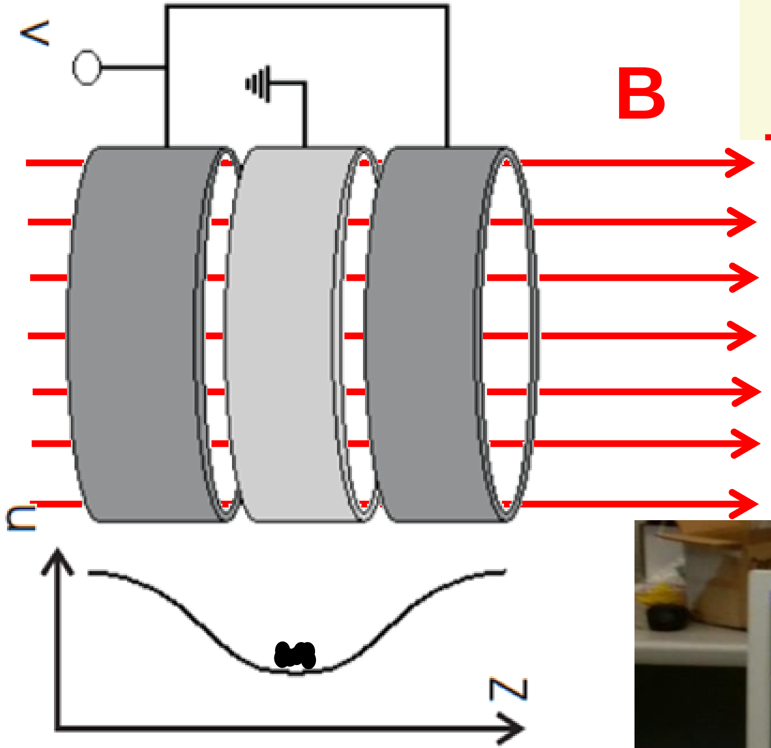


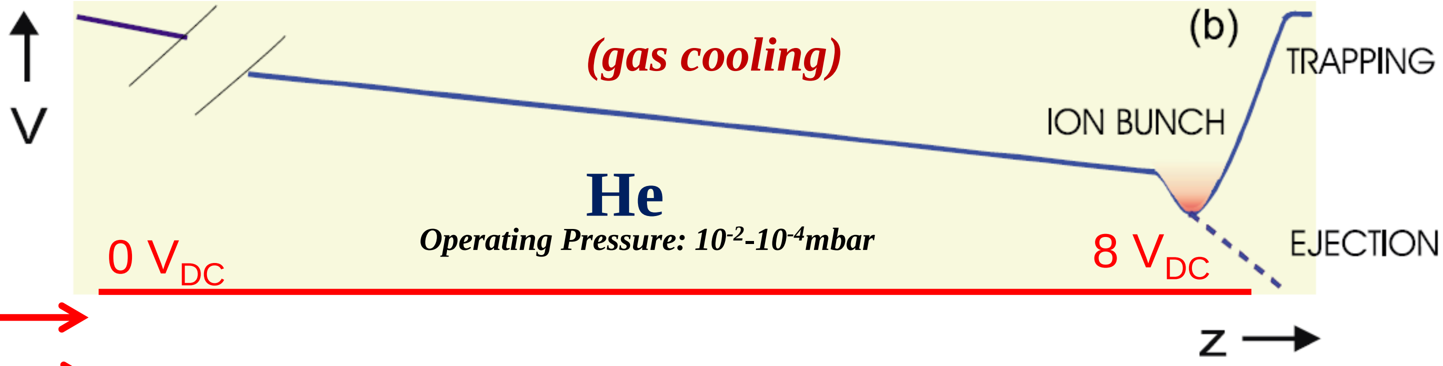
2016 & 2017:

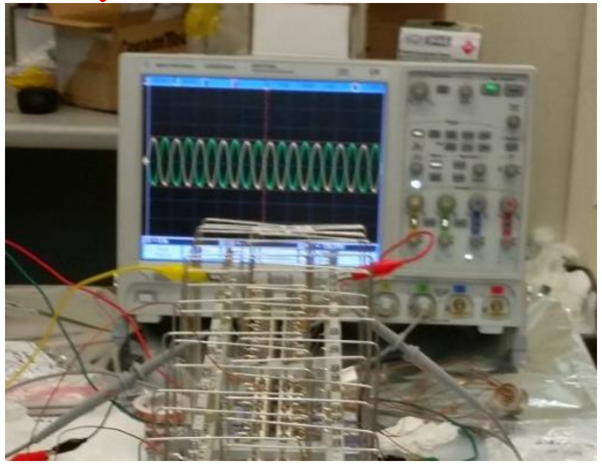
100's of ions/s

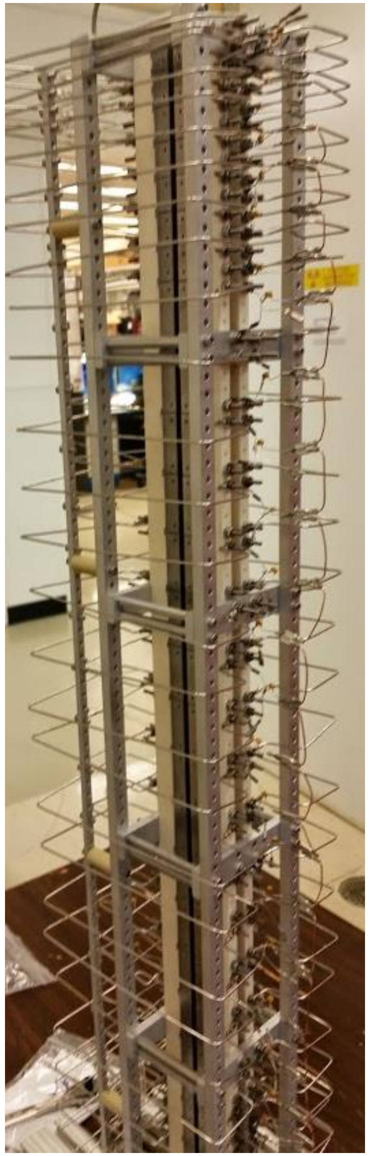
The RFQ cooler/buncher (v2)

- Need bunched beams to load the trap





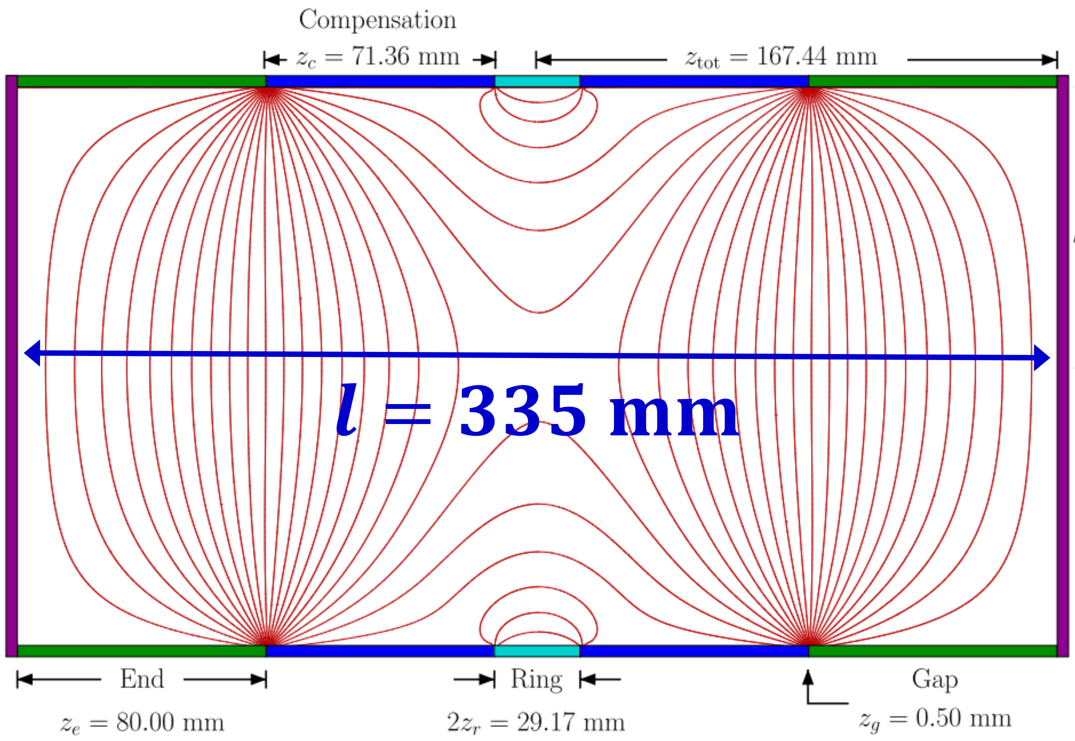


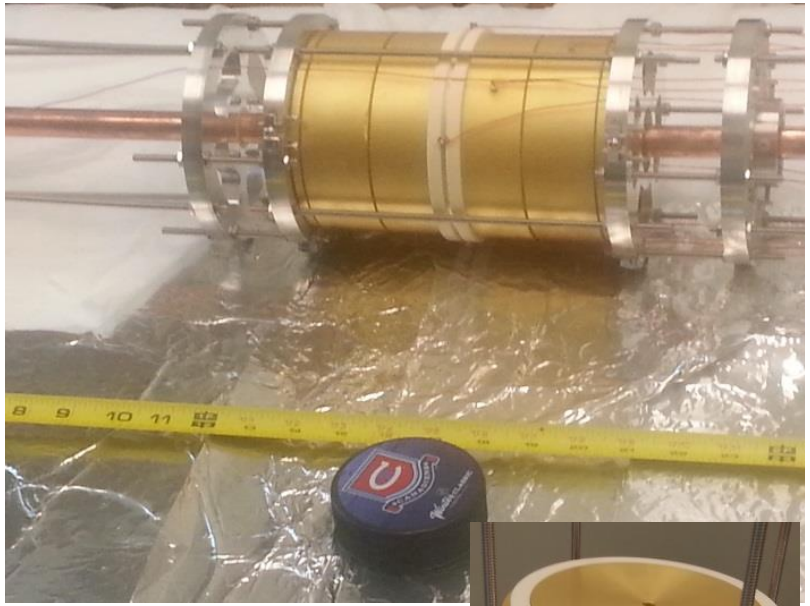


M. Mehlmann (Ph.D. Thesis)

Prototype 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



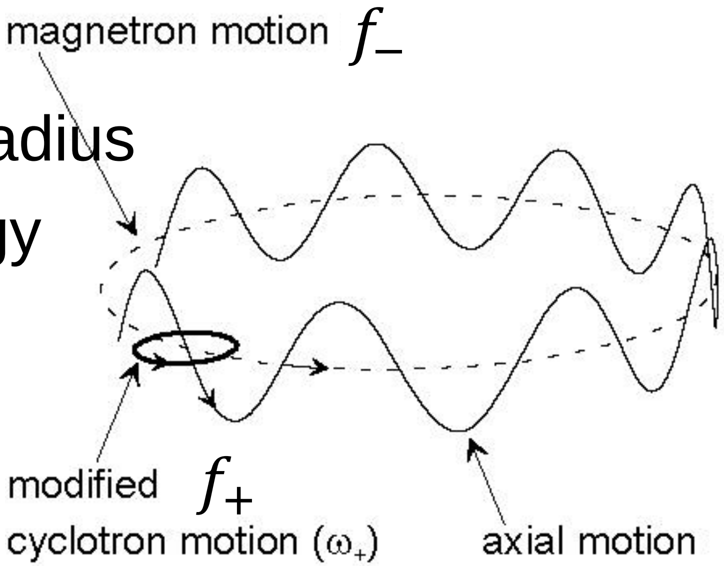


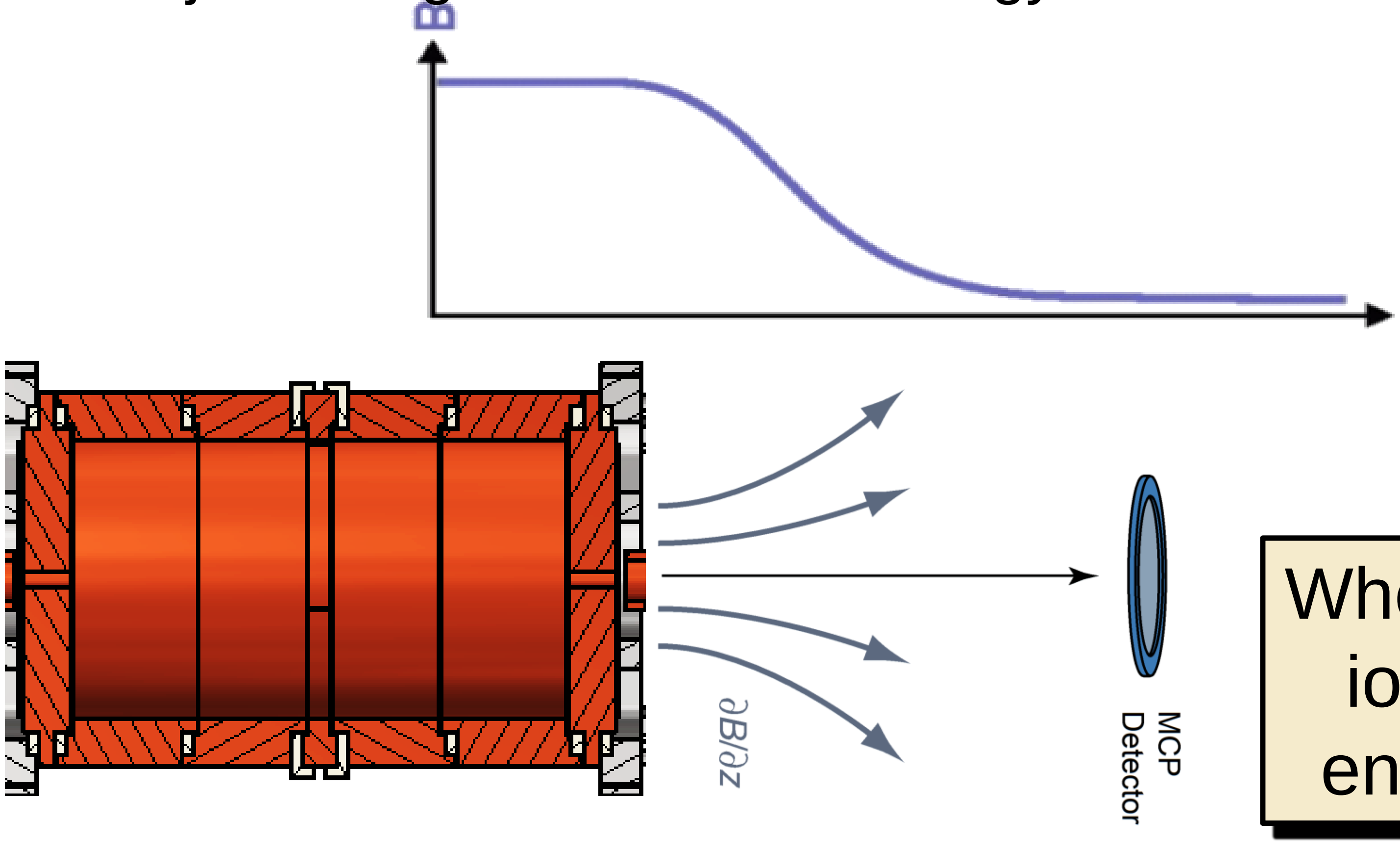
$l/r = 3.72$

M. Mehlman *et al.*
NIMA **712** (2013) 9

As we wait for RIB, learn to measure masses

- Time-of-flight cyclotron resonance technique
  - Dipole radial excitation at f_- ⇒ increase magnetron radius
  - Quadrupole excitation near f_c ⇒ increase radial energy
  - Eject along field ⇒ radial energy converted to axial





$$f_- + f_+ = f_c \text{ where } f_c = \frac{1}{2} \cdot \frac{q}{m} \cdot B$$

When rf frequency is in resonance, ions will end up with more axial energy and hence a shorter TOF

Mass measurement of ^{23}Na

- Find resonant frequencies for ^{23}Na and ^{39}K
- Use AME value for ^{39}K, and calculate $M(^{23}\mathrm{Na})$
- 20 ms excitation (solid points, red curve)

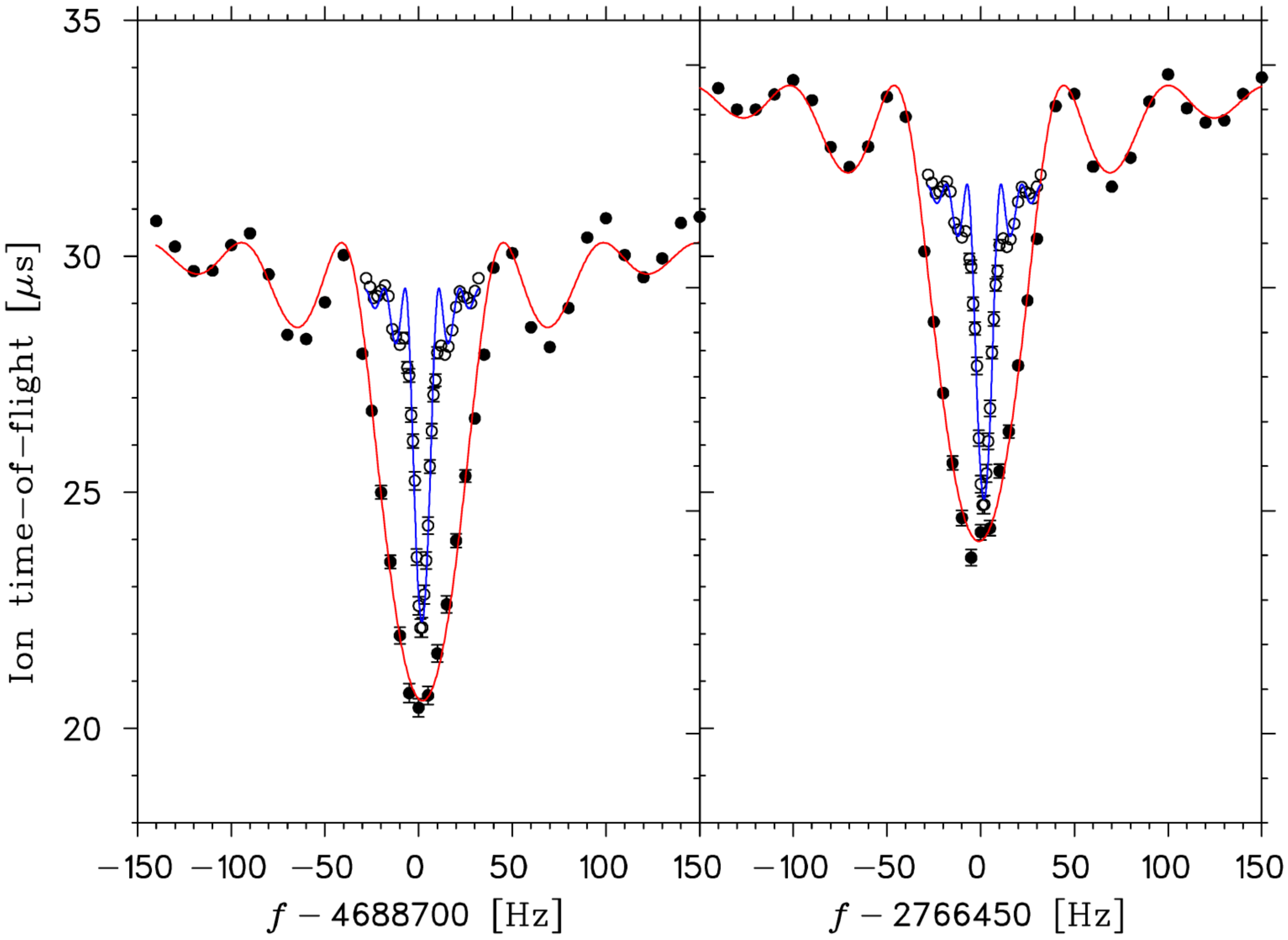
  $\Rightarrow M_{\mathrm{diff}} = \text{calc} - \mathrm{AME}$

  $= 2.8 \pm 2.5\ \mathrm{keV}$

  a 0.13 ppm measurement
- 100 ms (open points, blue)

  $\Rightarrow M_{\mathrm{diff}} = -0.3 \pm 1.3\ \mathrm{keV}$

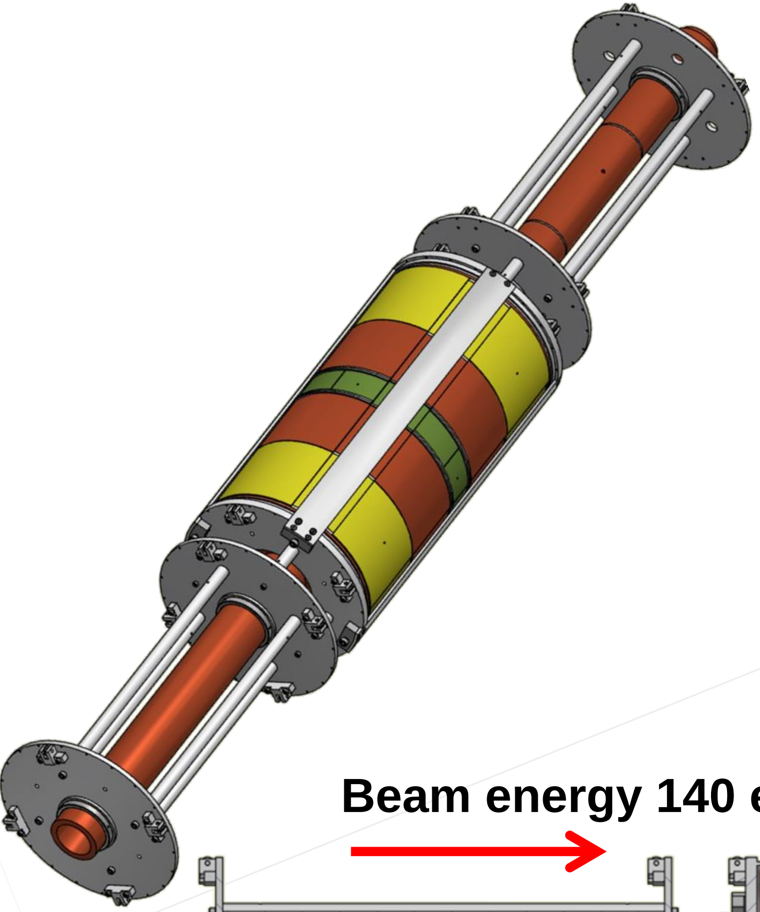
  a 0.06 ppm measurement

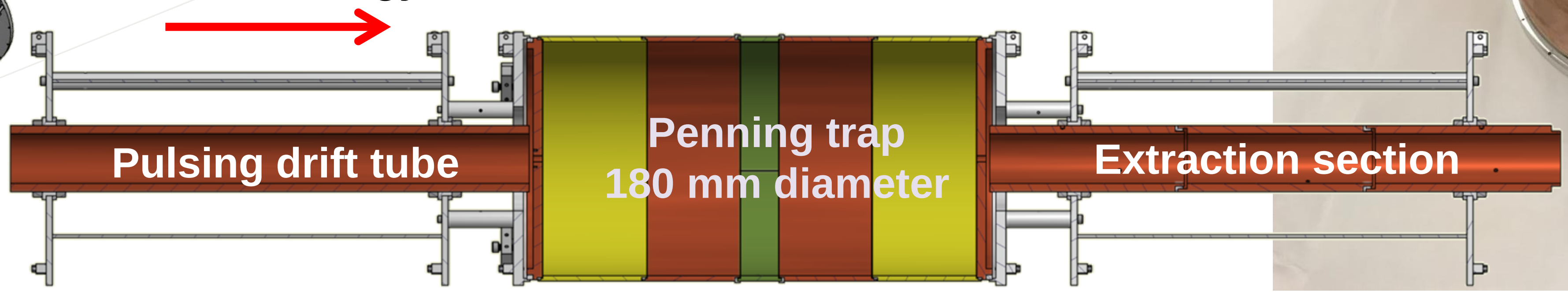


About to install the full Penning trap

- 180 mm in diameter

Nuclide	Larmour radius (mm)
^{20}Mg	42.7
^{24}Si	40.8
^{28}S	39.7
^{32}Ar	37.8
^{36}Ca	33.0
^{40}Ti	39.9
^{48}Fe	22.9

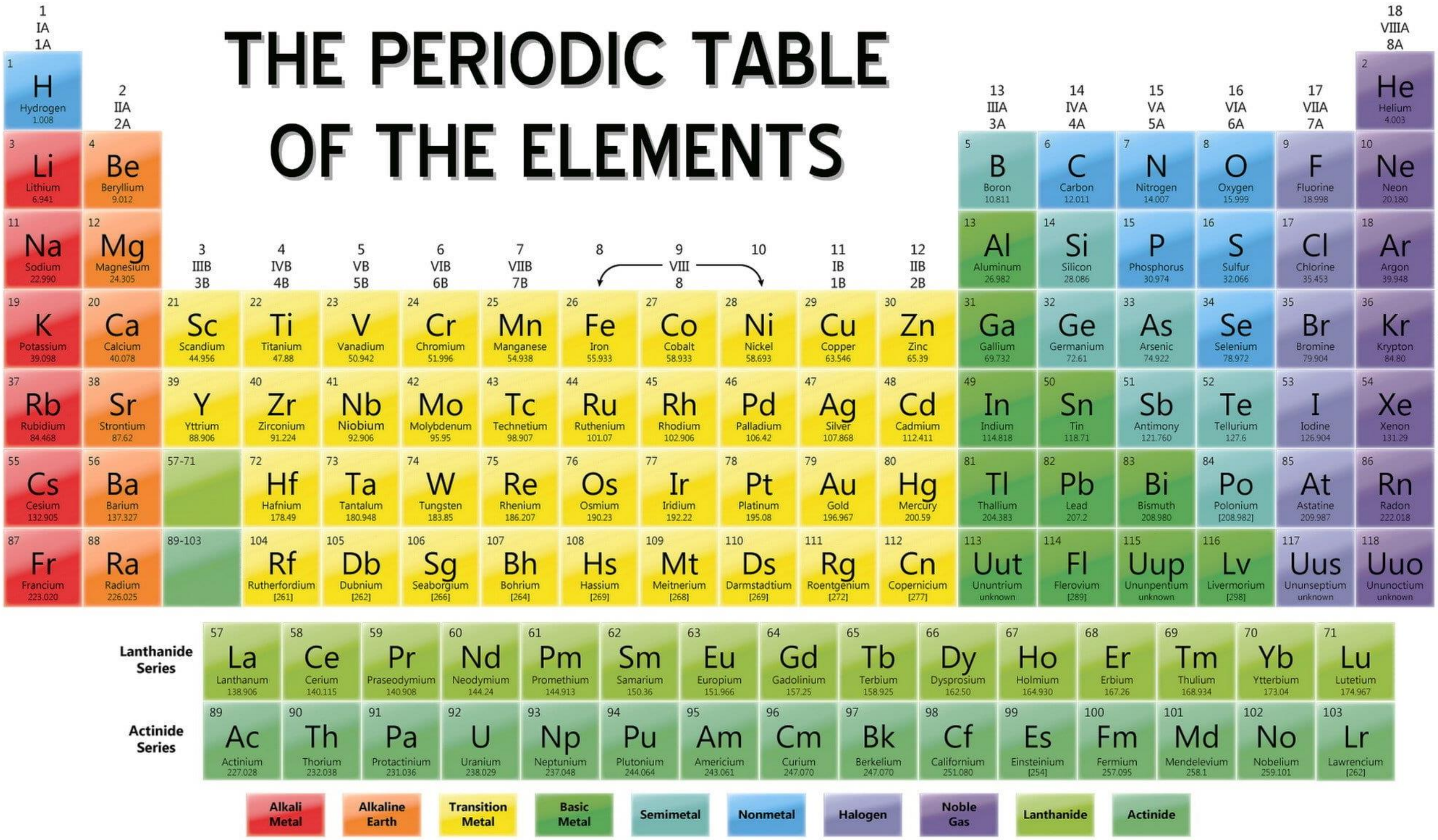




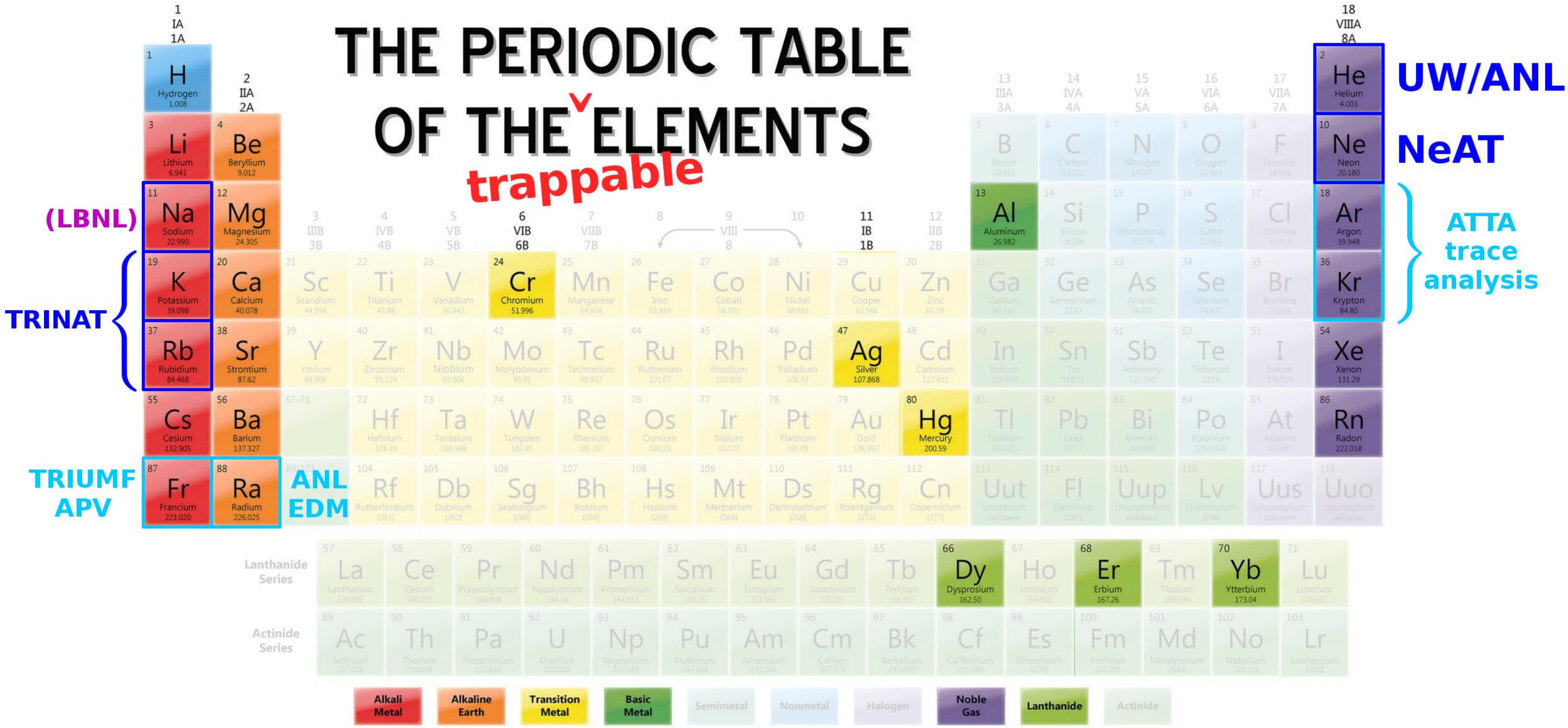
Outline

- Introduction
  - Testing the standard model via the precision frontier
  - Angular correlations of β decay
- TAMUTRAP
  - $T = 2$ decays to test the SM
  - Current status
- ^{37}K at TRIUMF
  - The TRINAT facility
  - Polarizing the cloud
  - Recent measurement of A_β

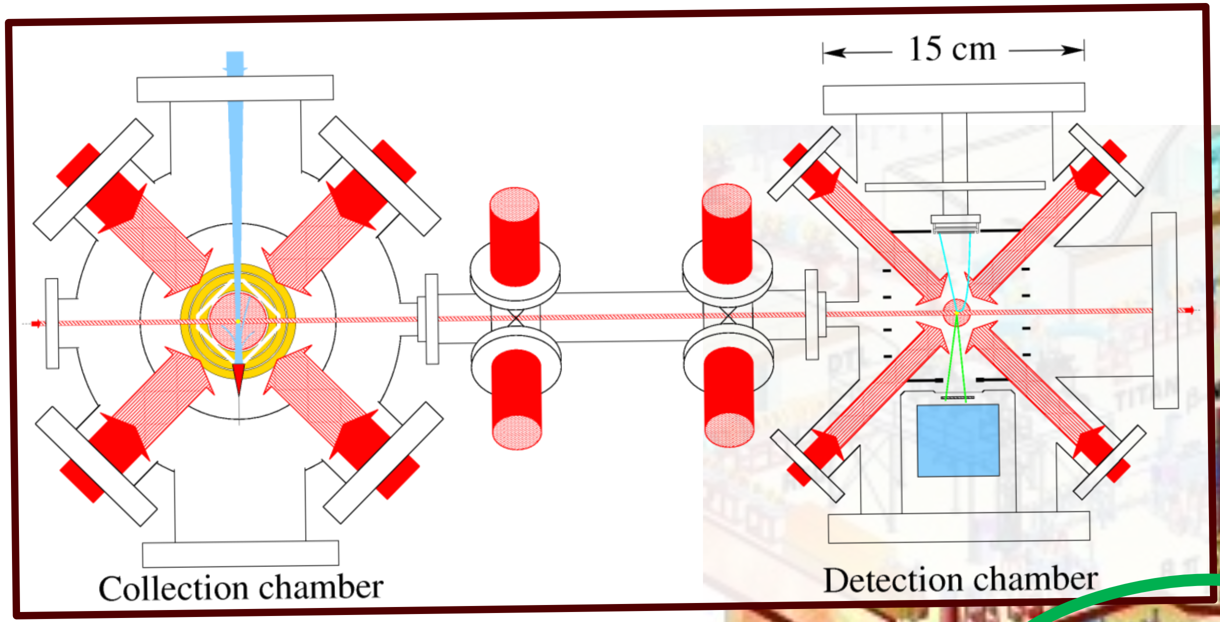
Difficulty with MOTs: not all atoms can be trapped

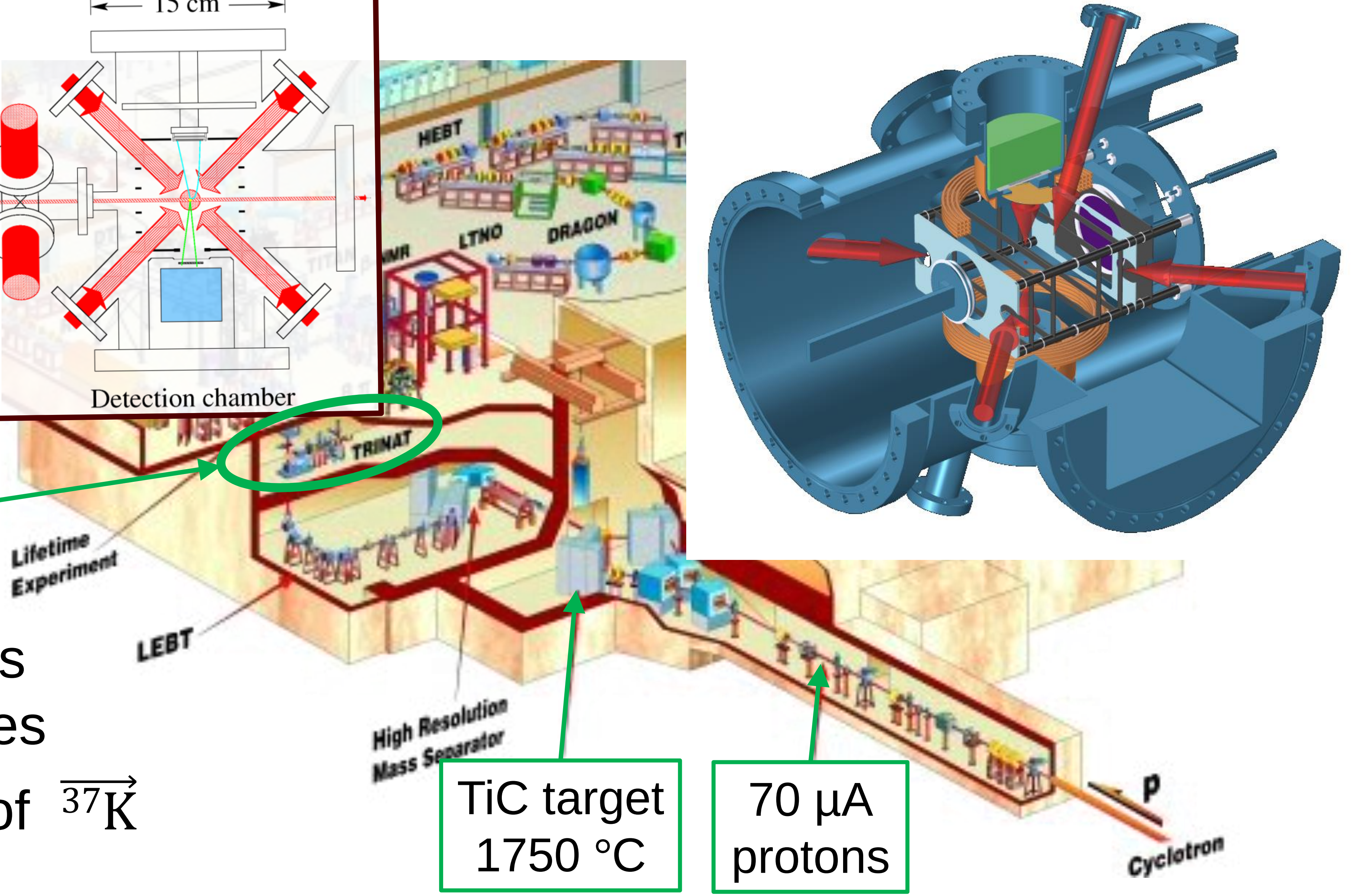


Difficulty with MOTs: not all atoms can be trapped



The TRIUMF Neutral Atom Trap





up to 8×10^7 ^{37}K/s

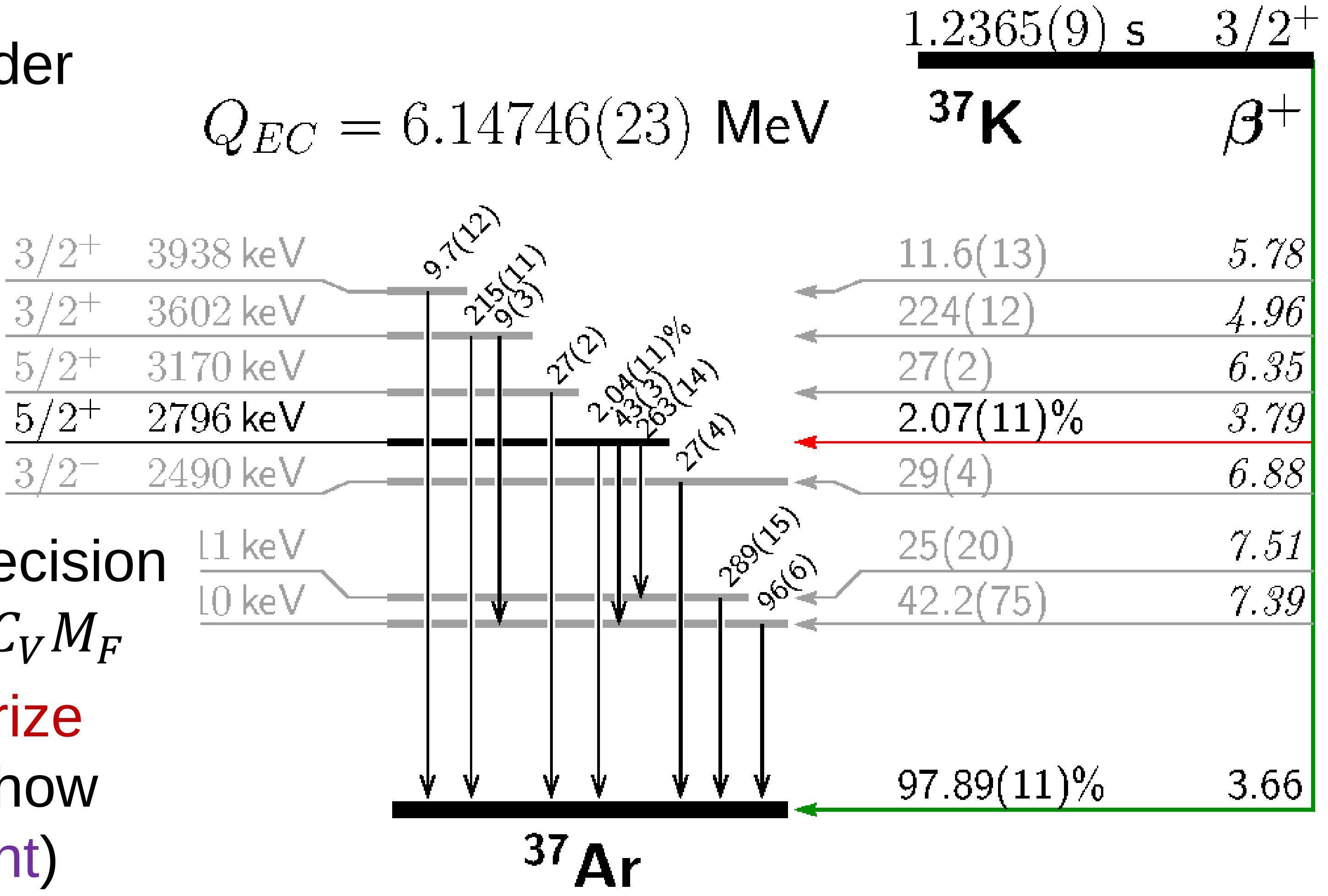
TiC target 1750 °C

70 µA protons

- Angular correlations of K and Rb isotopes
- Recent result: A_β of $\overrightarrow{^{37}\mathrm{K}}$

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)



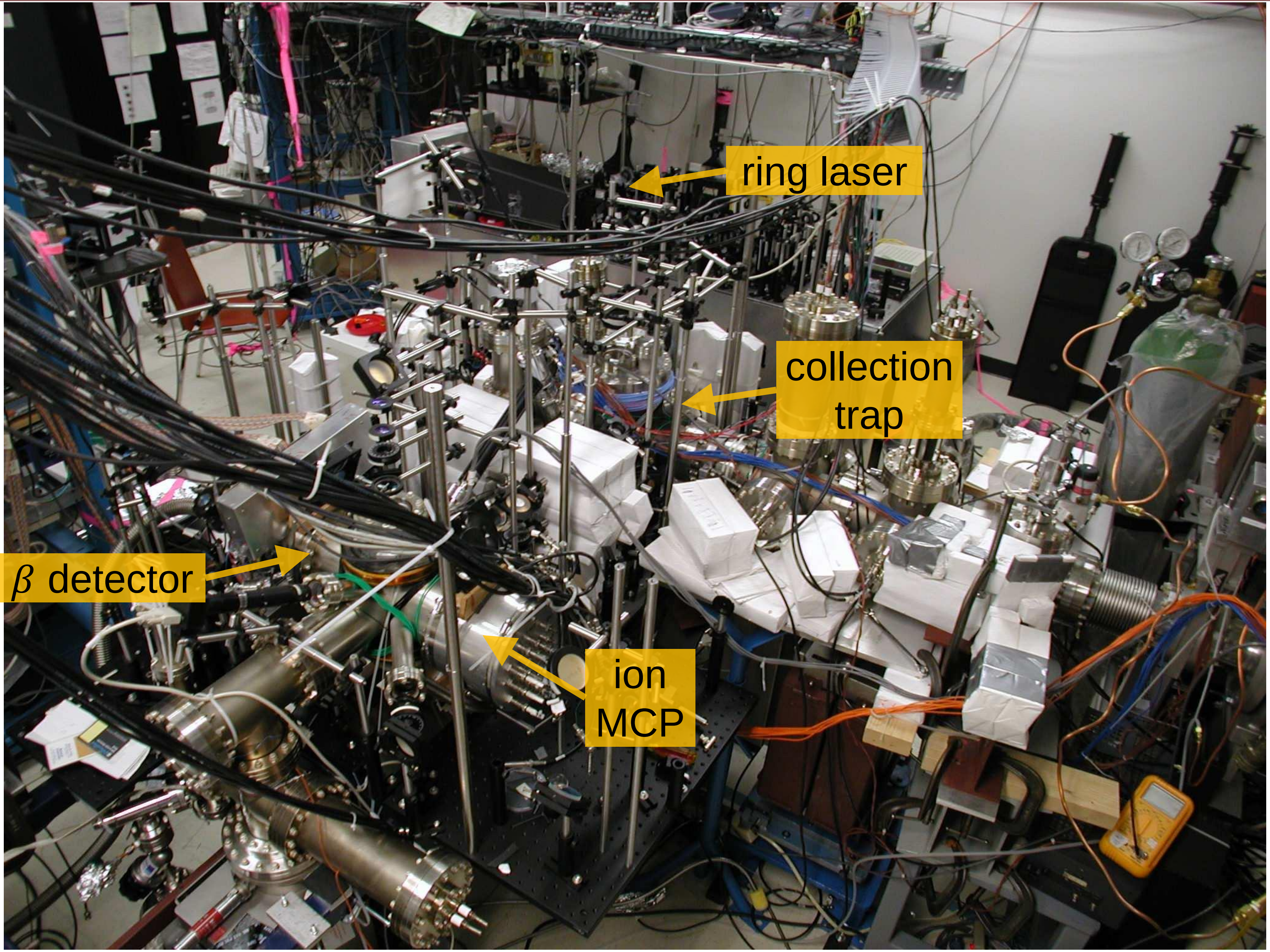
The Ft is measured well enough (for now)

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

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

⇝ Data is in hand for improved branching ratio (currently limits predictions)

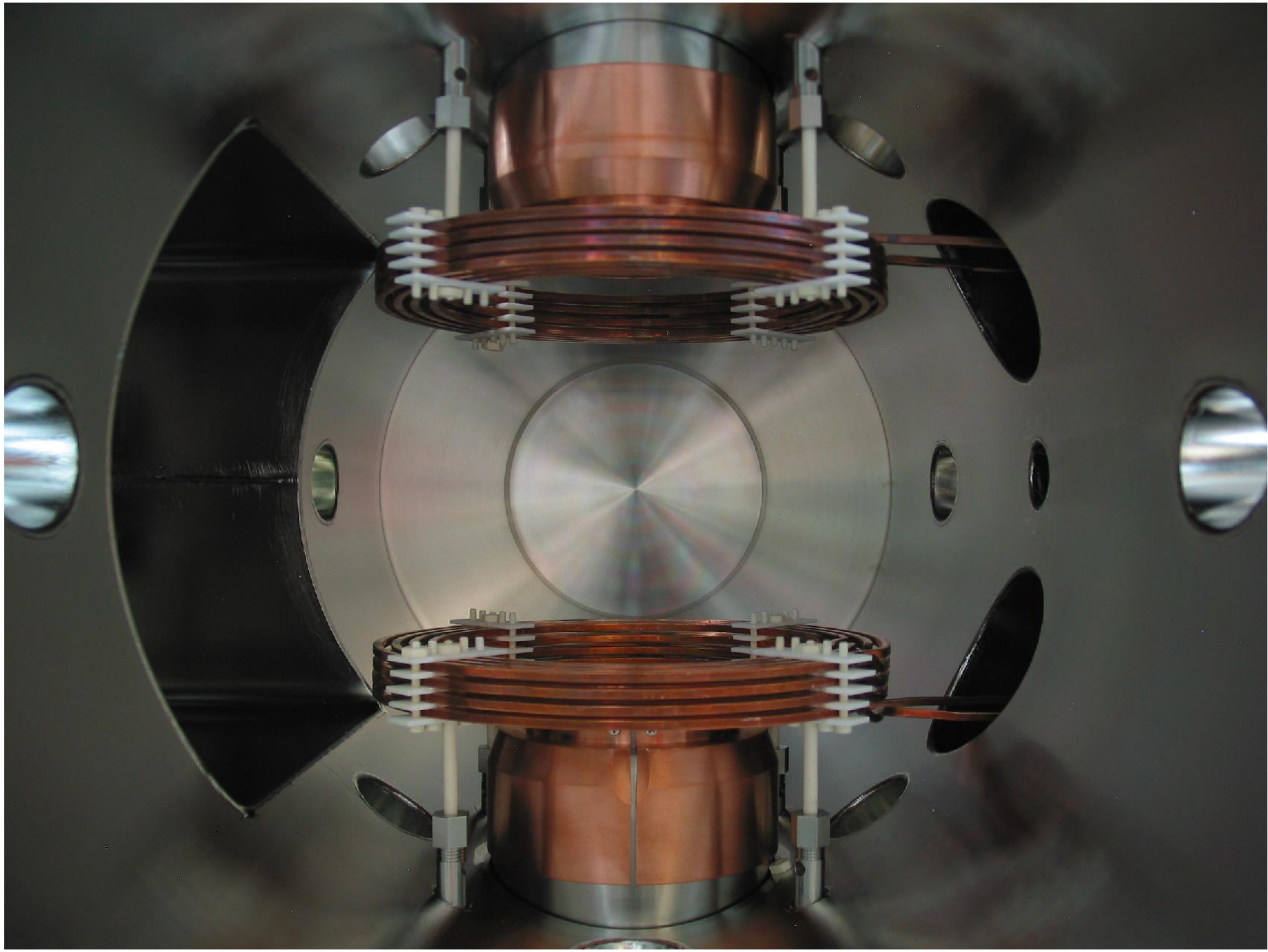
The TRINAT lab (an older picture)



RIB from ISAC

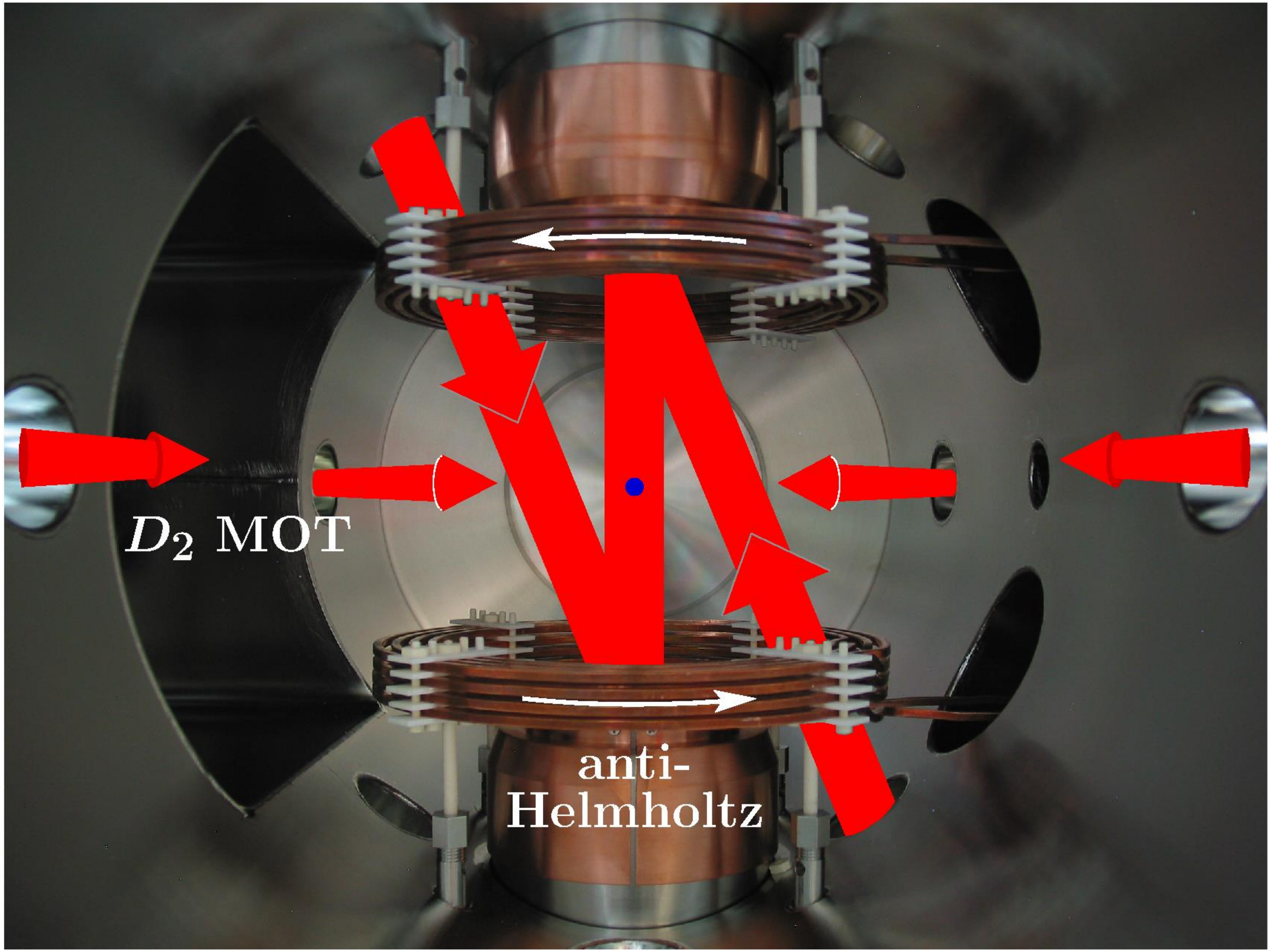
Outline of β asym & polarization measurements

- Not shown:
  - Recoil MCP detector into page
  - Shake-off e^- MCP out of page
  - Hoops for electric field to collect recoil and shake-off e^-
  - The β telescopes within the re-entrant flanges (top *and* bottom)



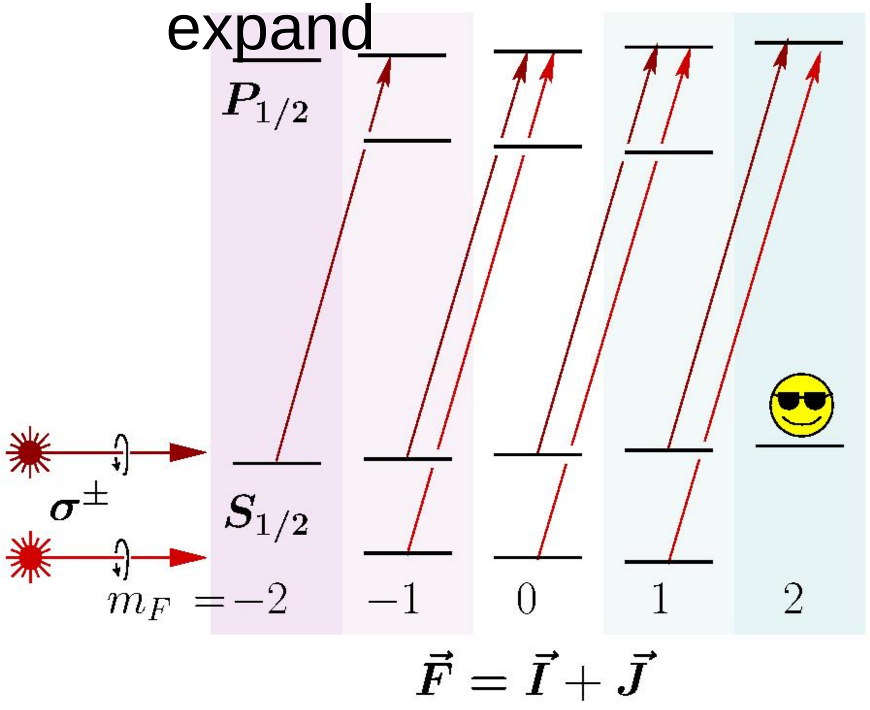
Outline of β asym & polarization measurements

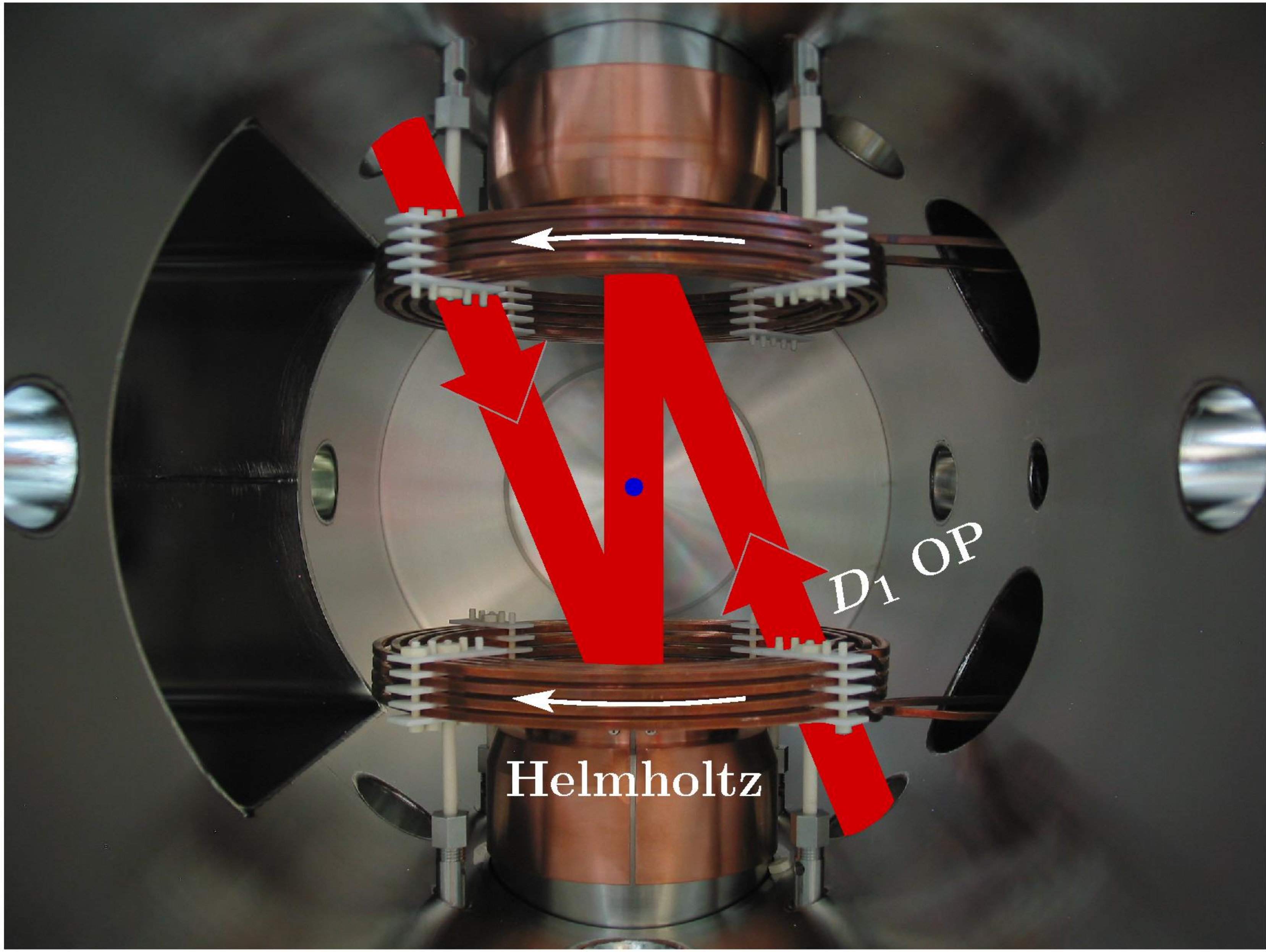
- MOTs provide a source that is:
  - Cold ($\sim 1\ \mathrm{mK}$)
  - Localized ($\sim 1\ \mathrm{mm}^3$)
  - In an open, backing-free geometry
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\mathrm{rec}}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event



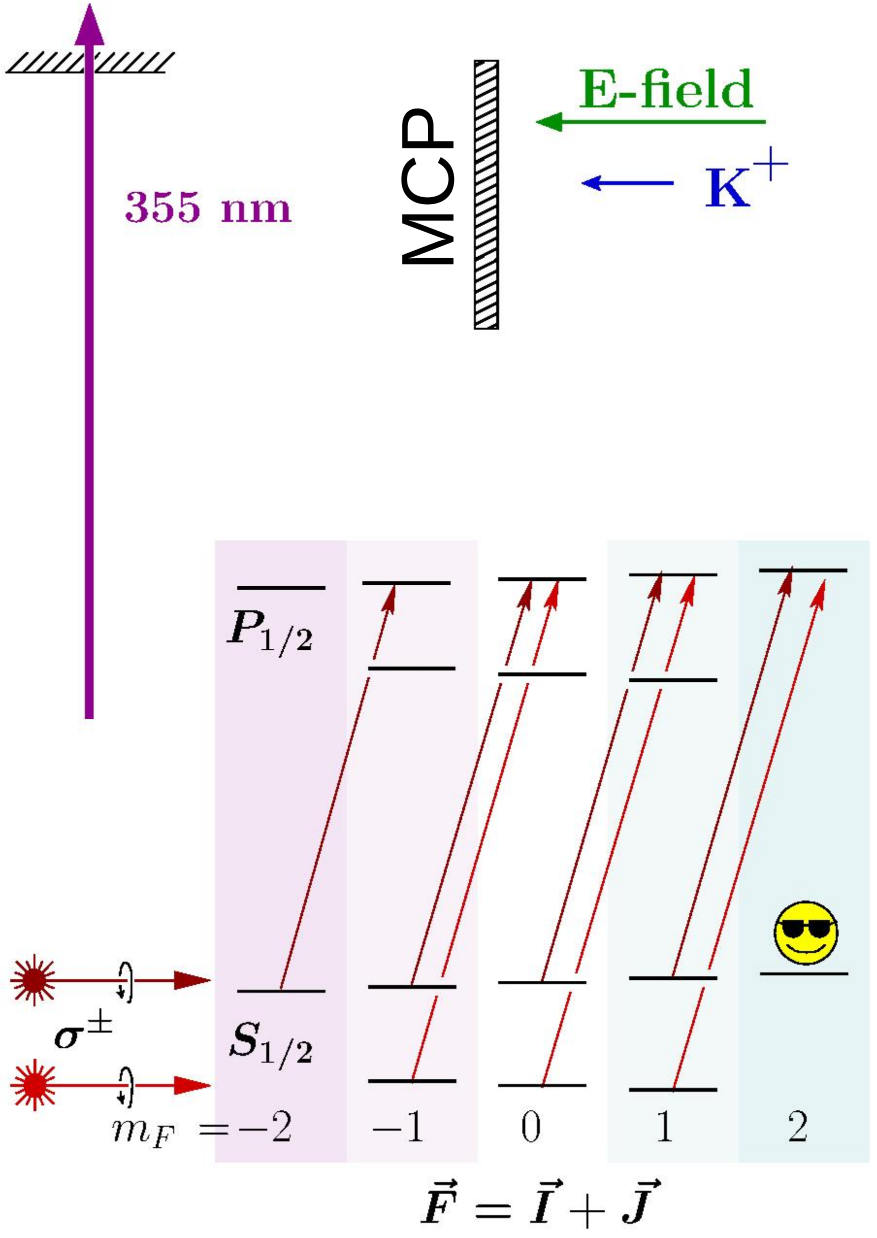
Outline of β asym & polarization measurements

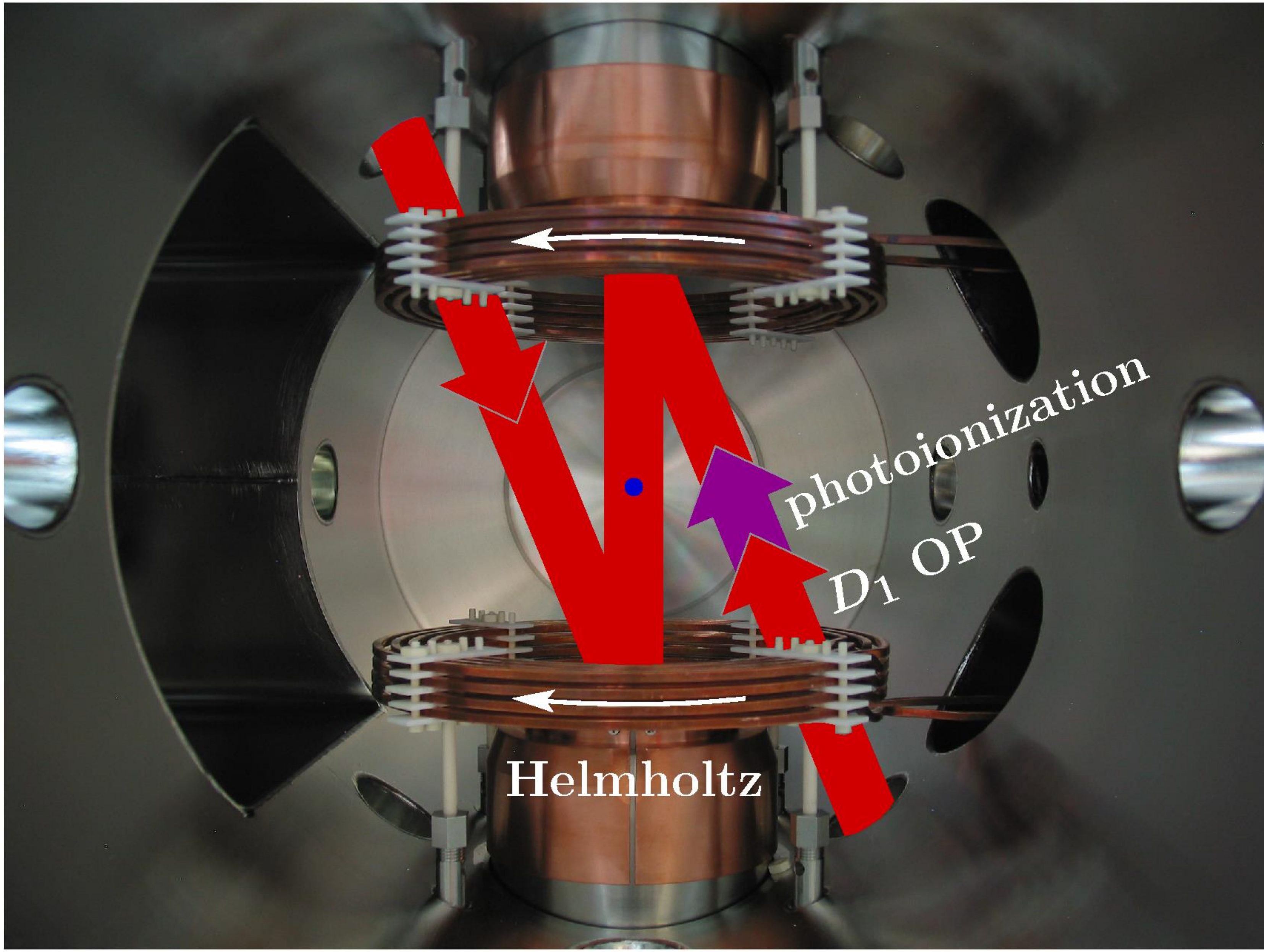
- Optical pumping:
  - Polarized light transfers ang momentum to atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand





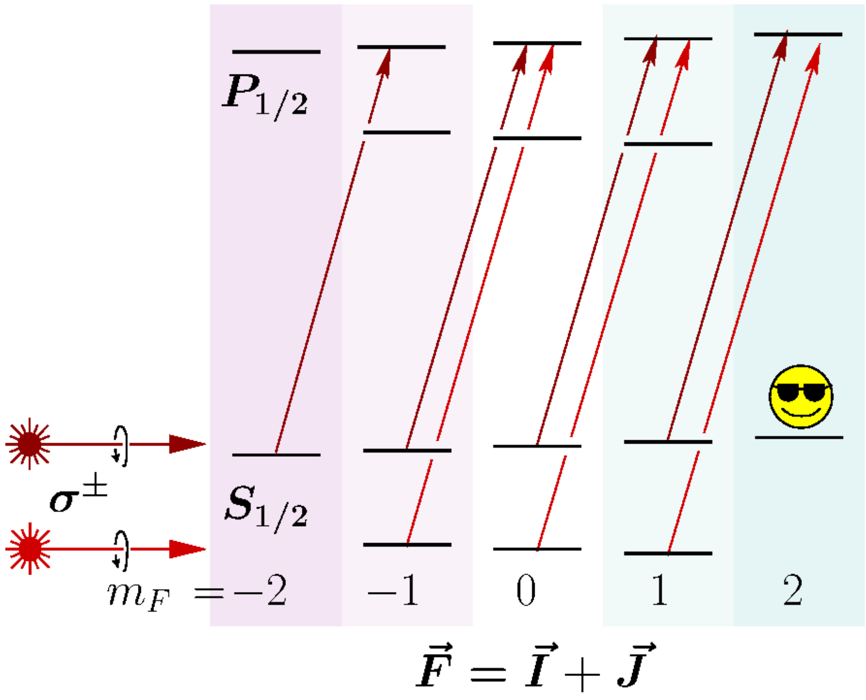
Outline of β asym & polarization measurements

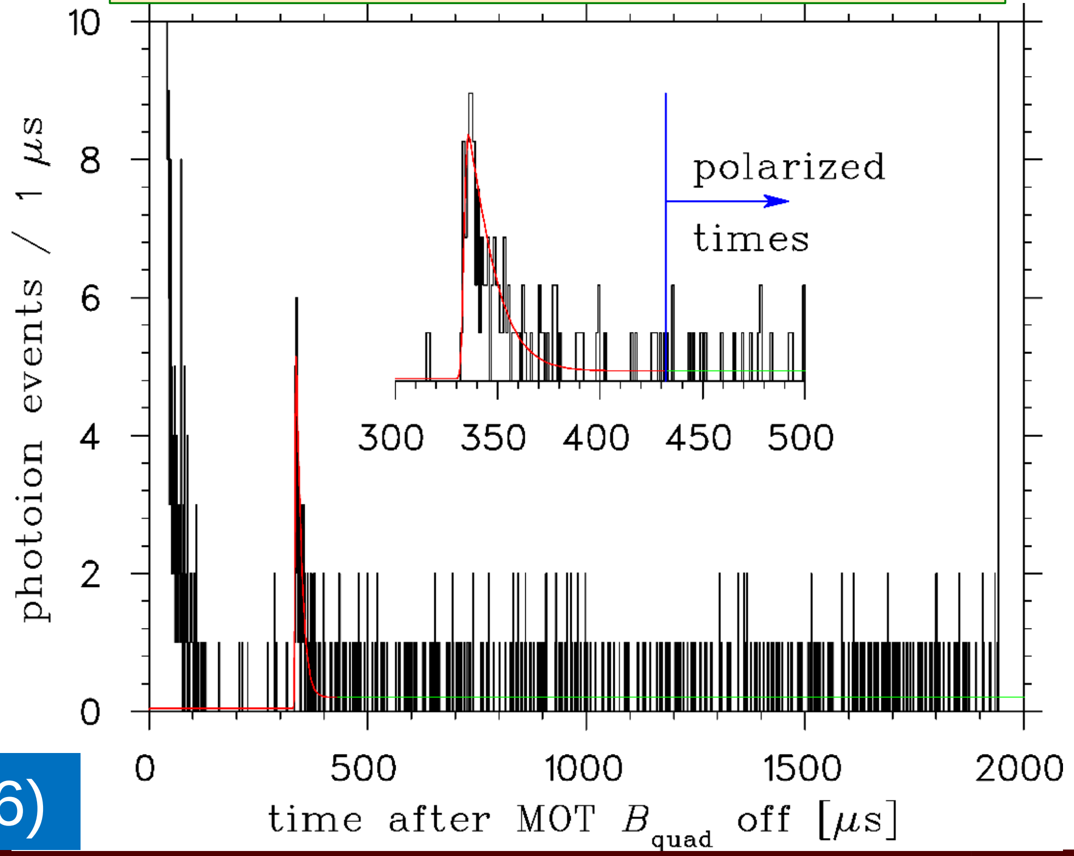




Optical pumping is fast and *efficient*!

- 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

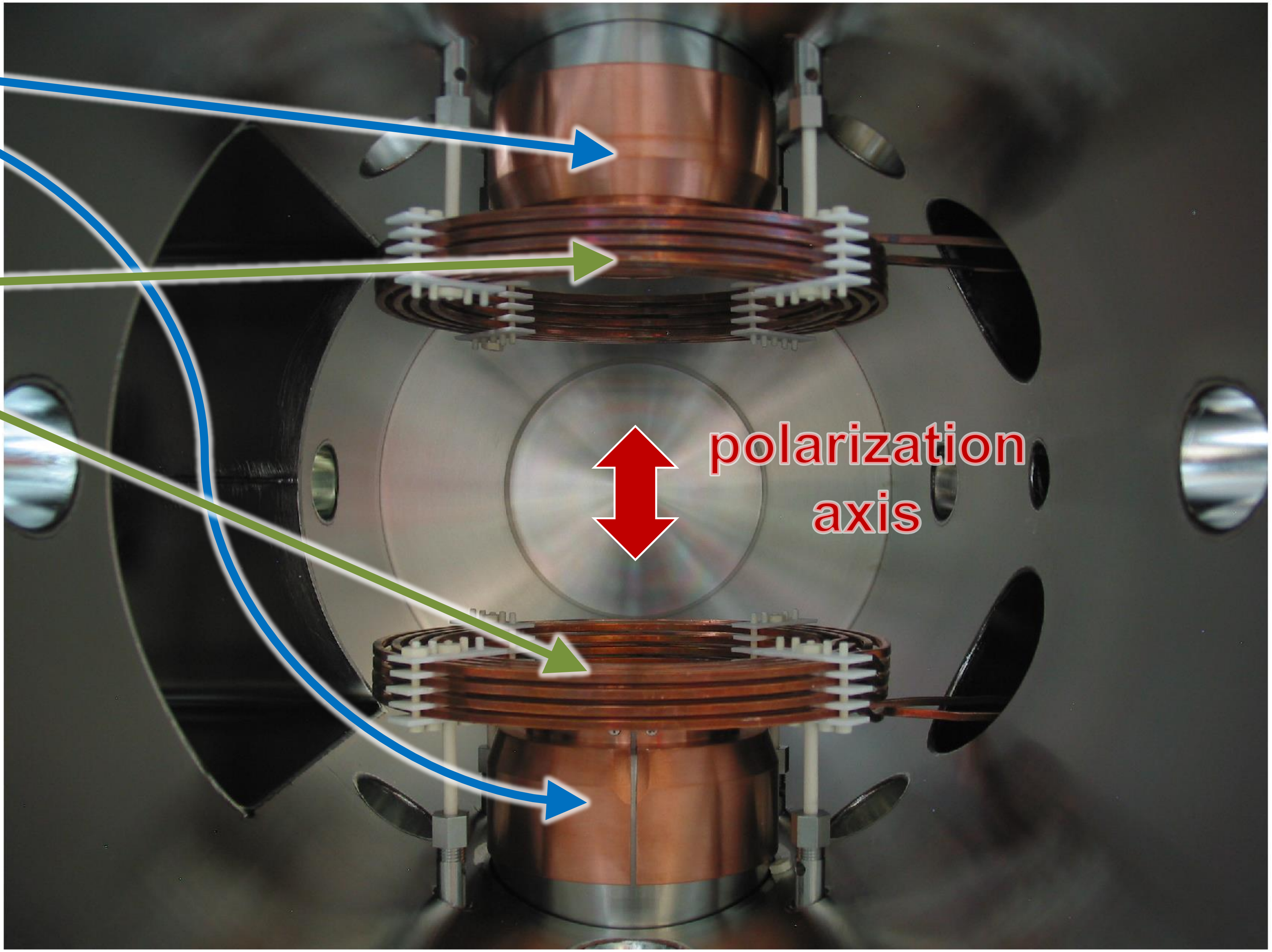
E_β detectors:
Plastic scintillator

ΔE_β detectors:
Double-sided Si-strip

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

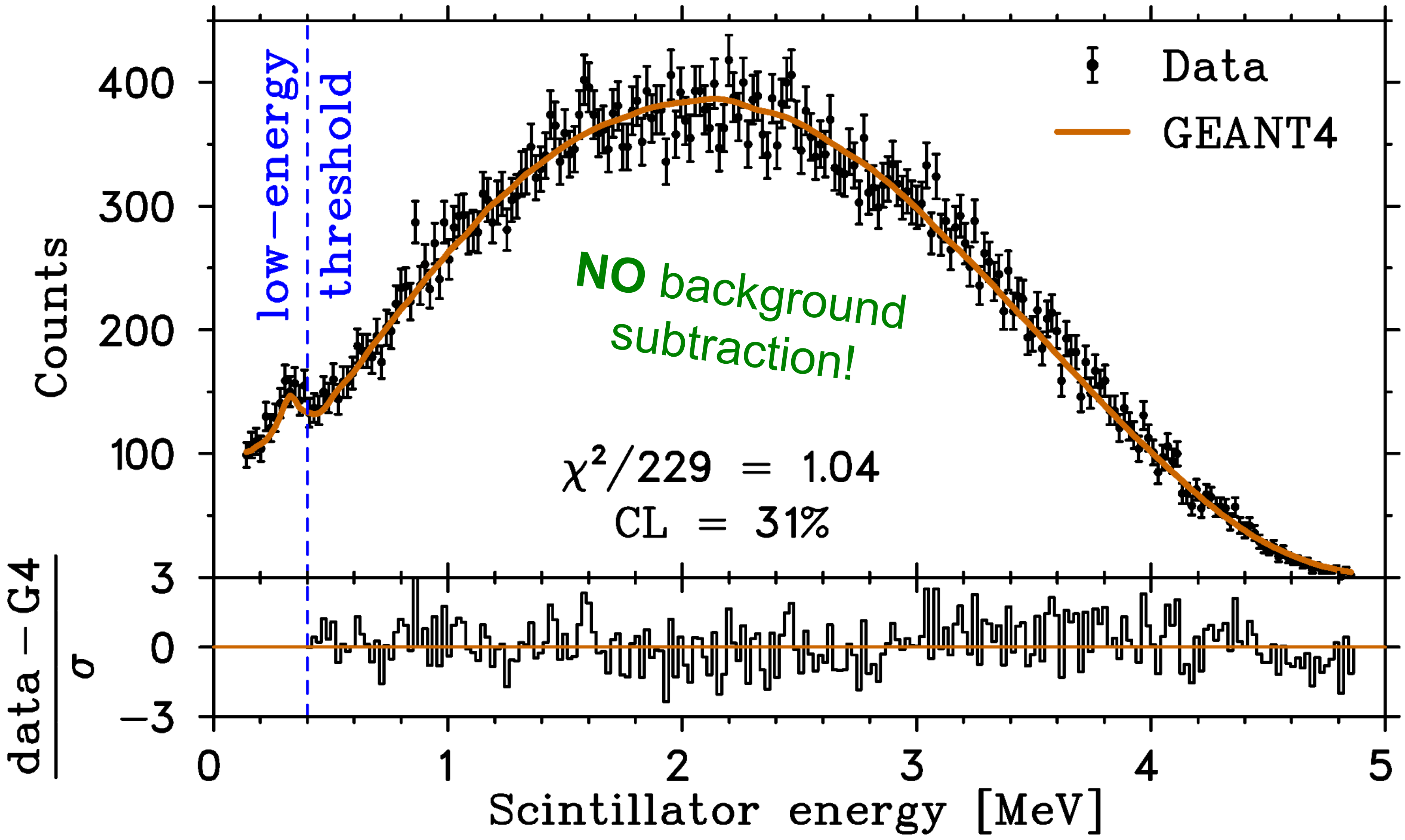
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

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



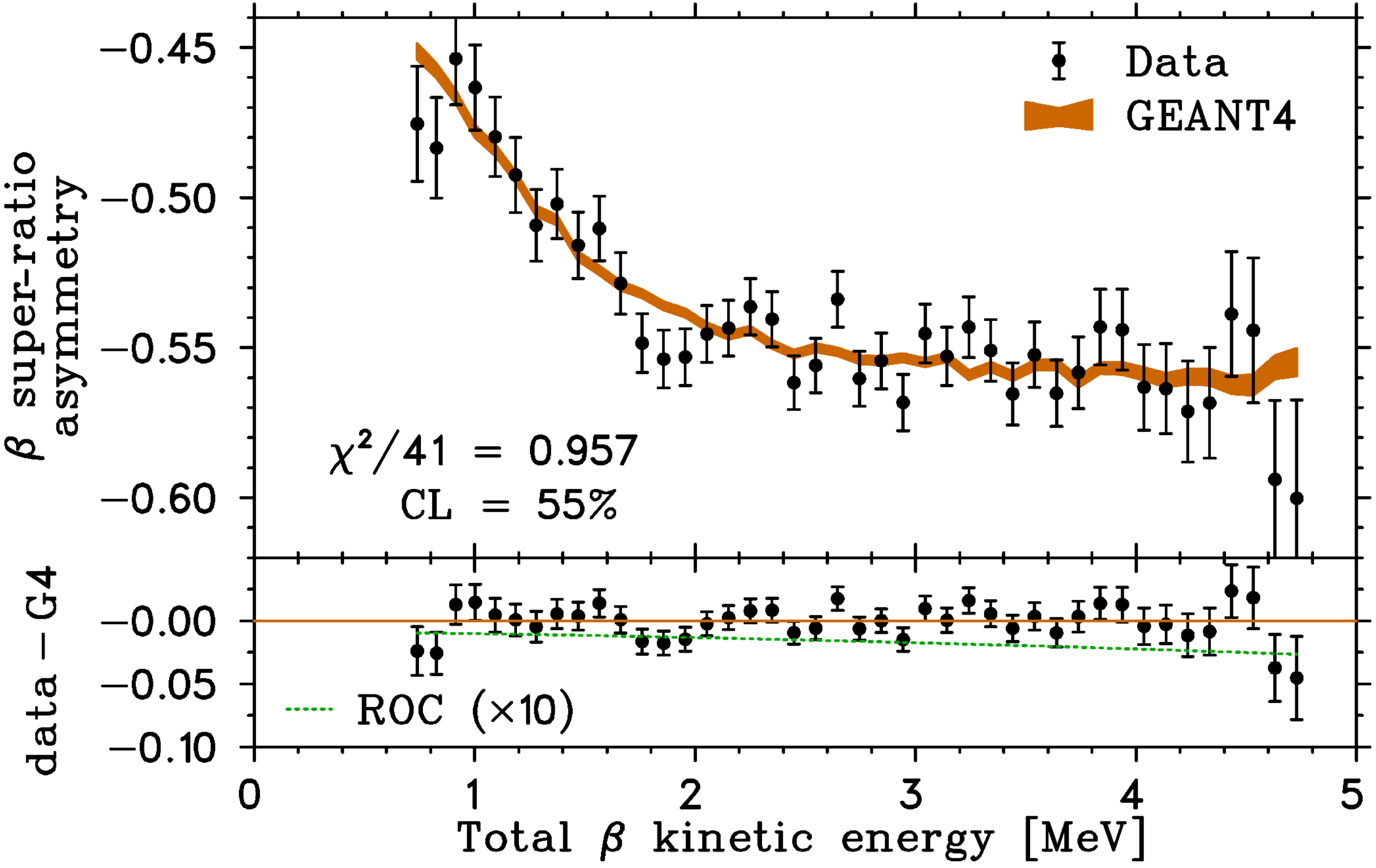
^{37}K β asymmetry measurement

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



^{37}K β asymmetry measurement

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

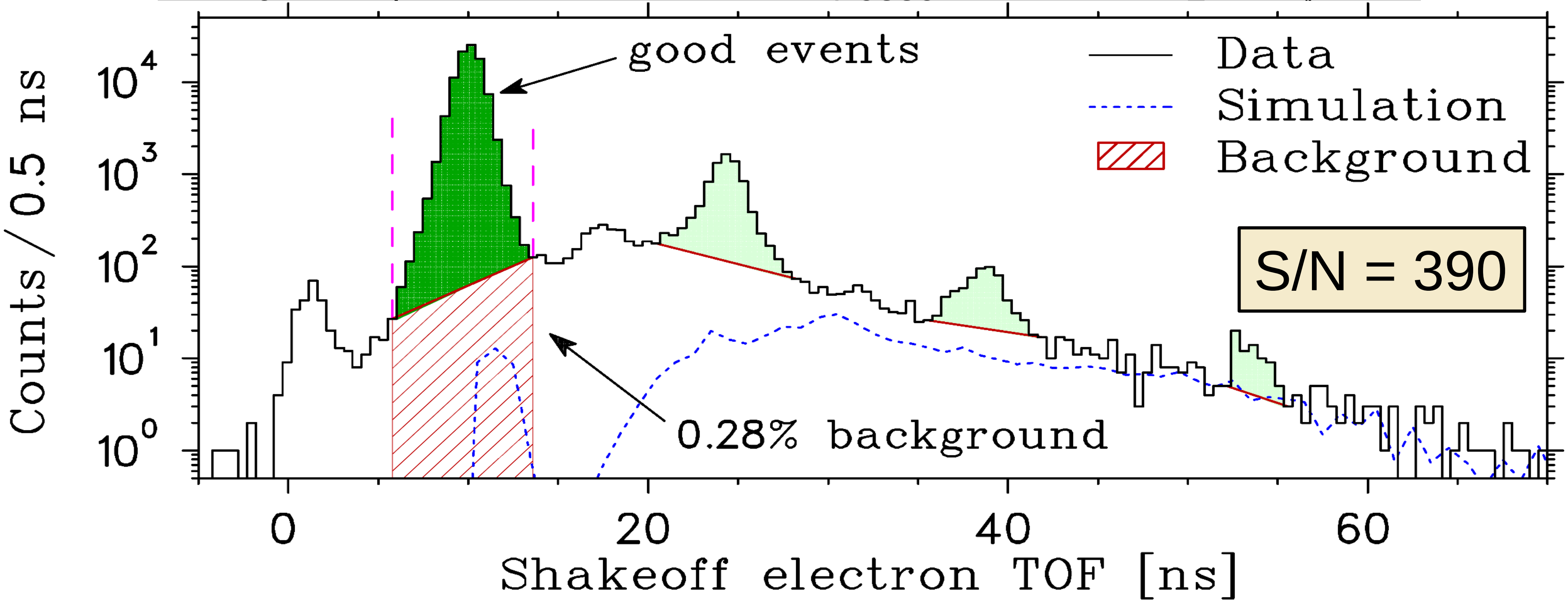


(Dominant) Error budget

Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	1.0014	8×10^{-4}
β scattering	1.0230	7×10^{-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		13×10^{-4}
STATISTICS		13×10^{-4}
POLARIZATION		5×10^{-4}
TOTAL UNCERTAINTY		19×10^{-4}

(Dominant) Error budget and A_β result

Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	**1.0014**	**8×10^{-4}**



(Dominant) Error budget and A_β result

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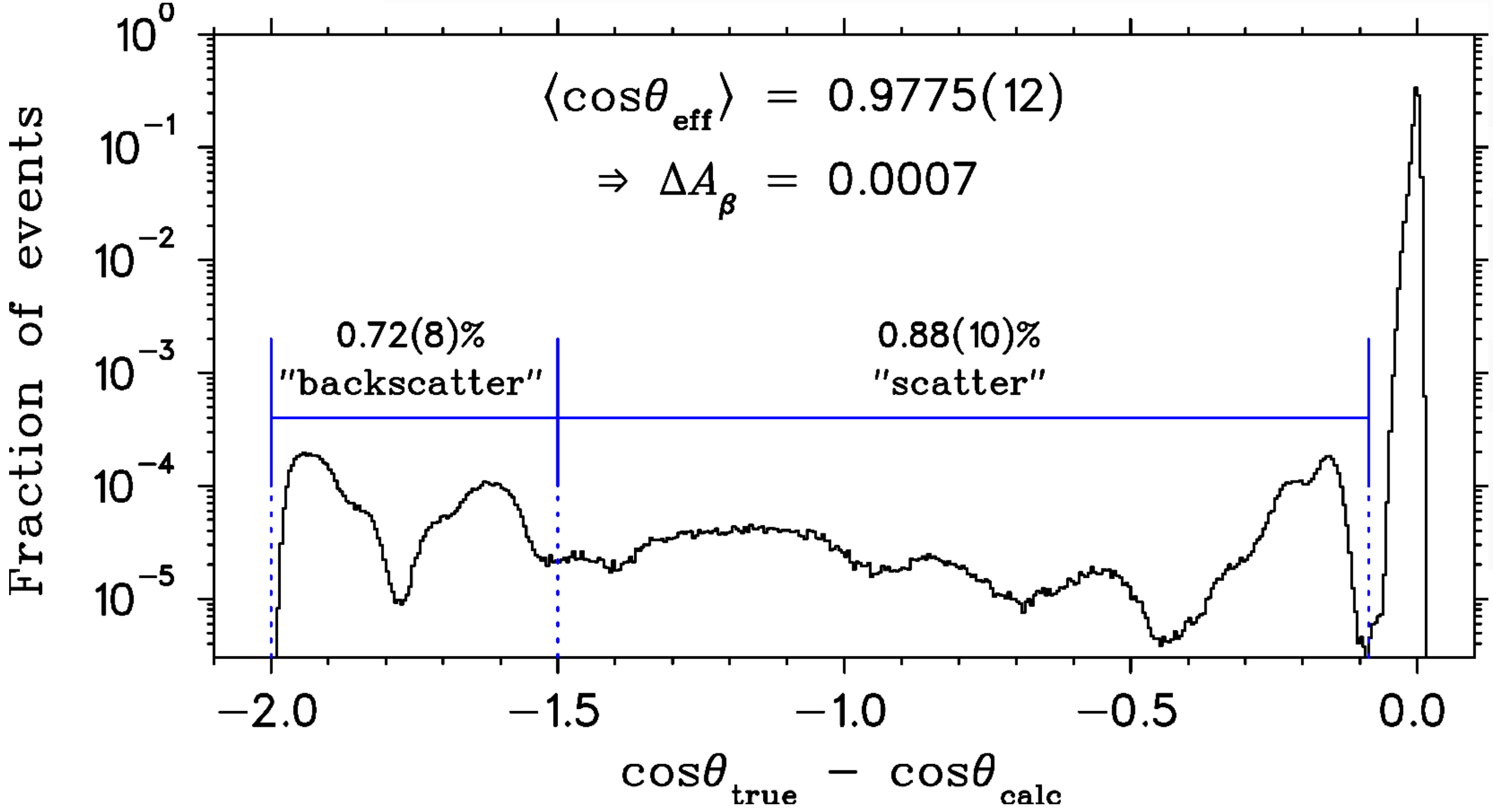

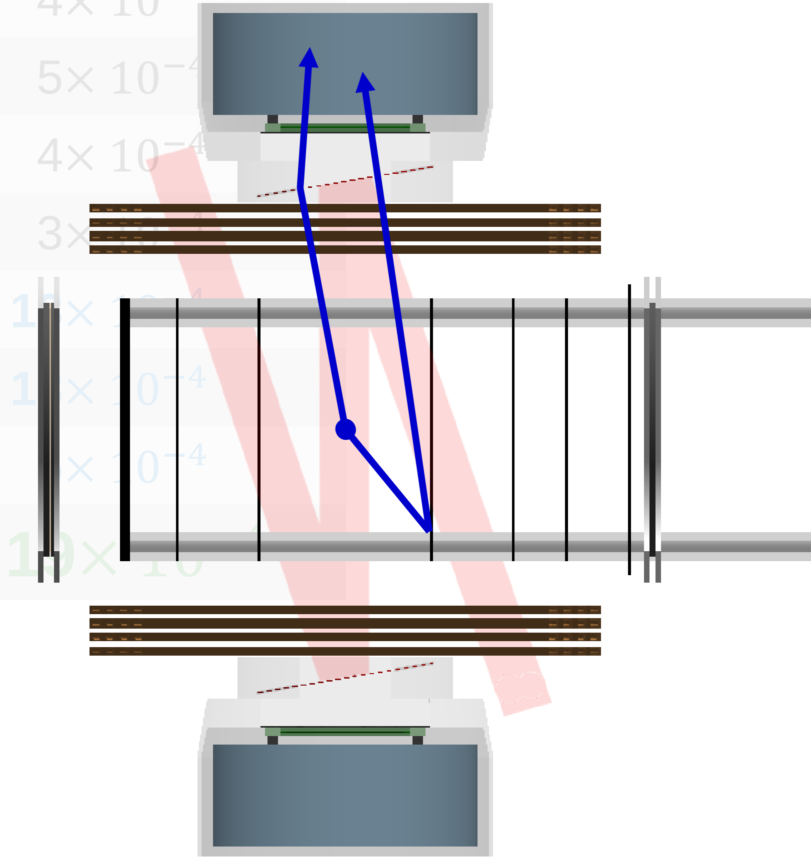

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(Dominant) Error budget and A_β result

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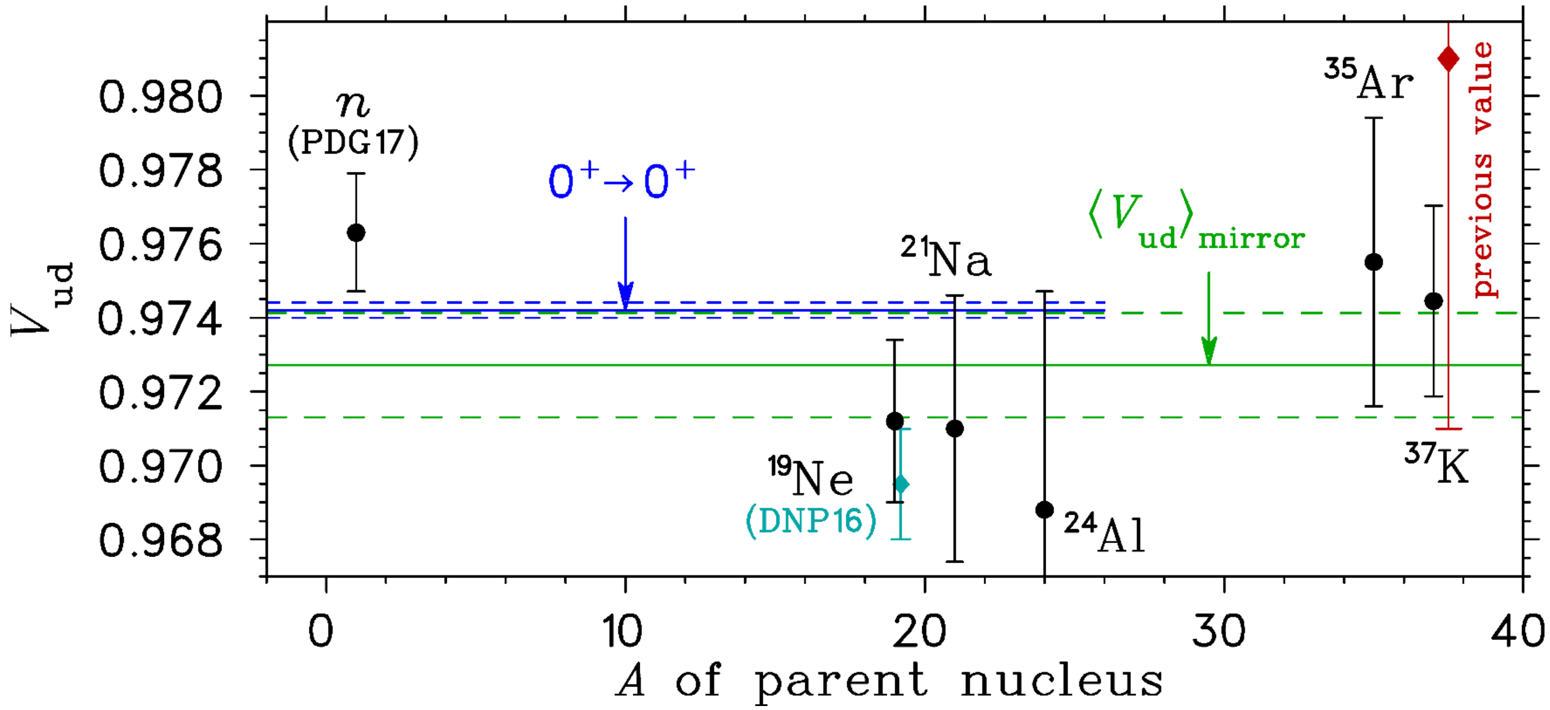
TOTAL SYSTEMATICS		13×10^{-4}
STATISTICS		13×10^{-4}
POLARIZATION		5×10^{-4}
TOTAL UNCERTAINTY		19×10^{-4}

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

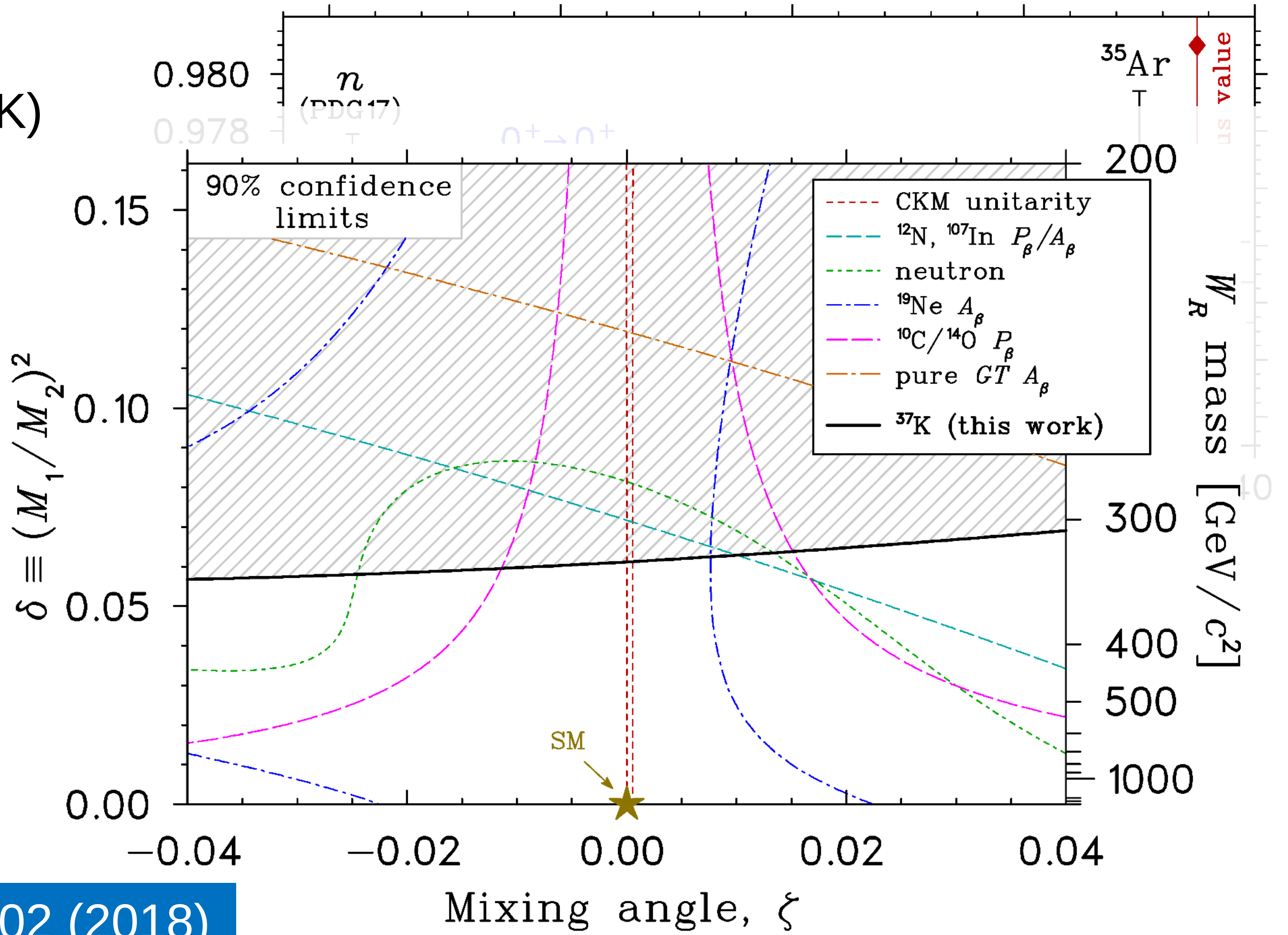
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays



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

Interpretation and future prospects

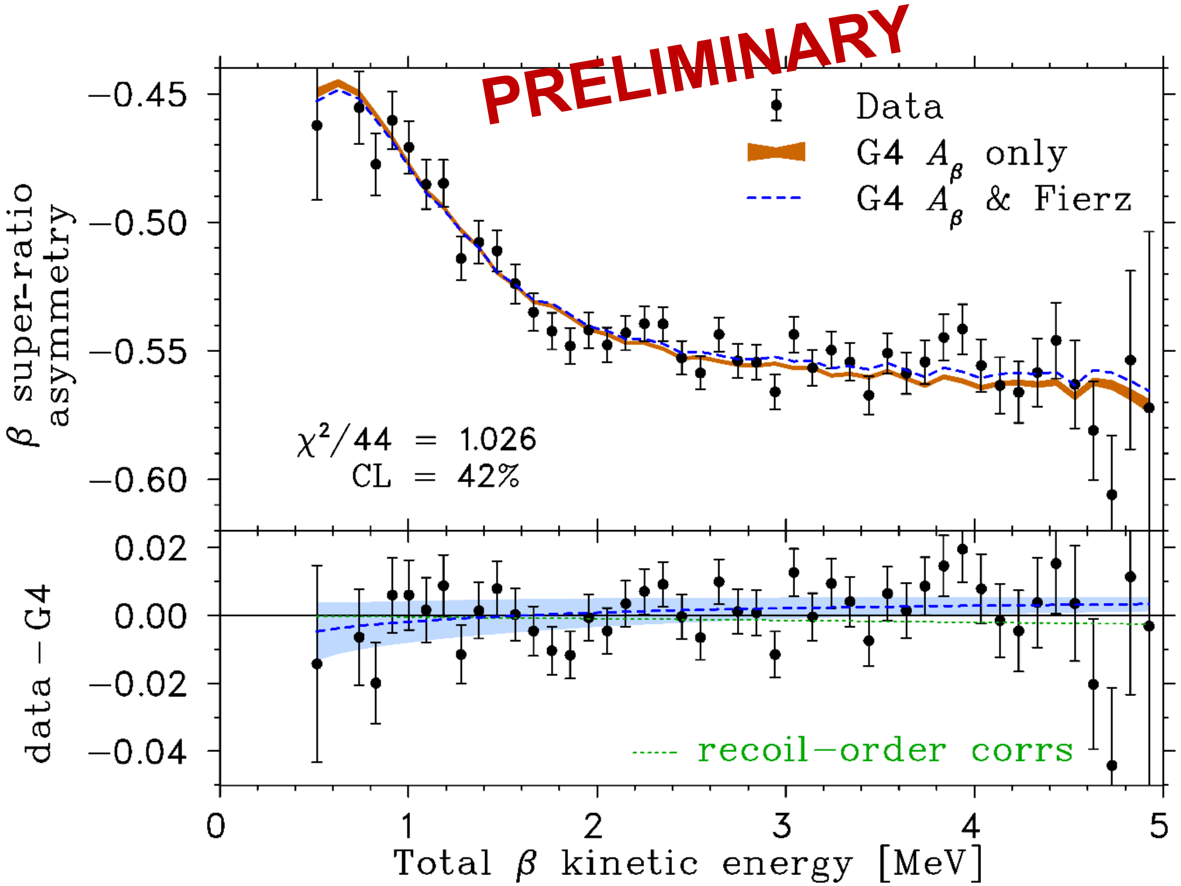
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents

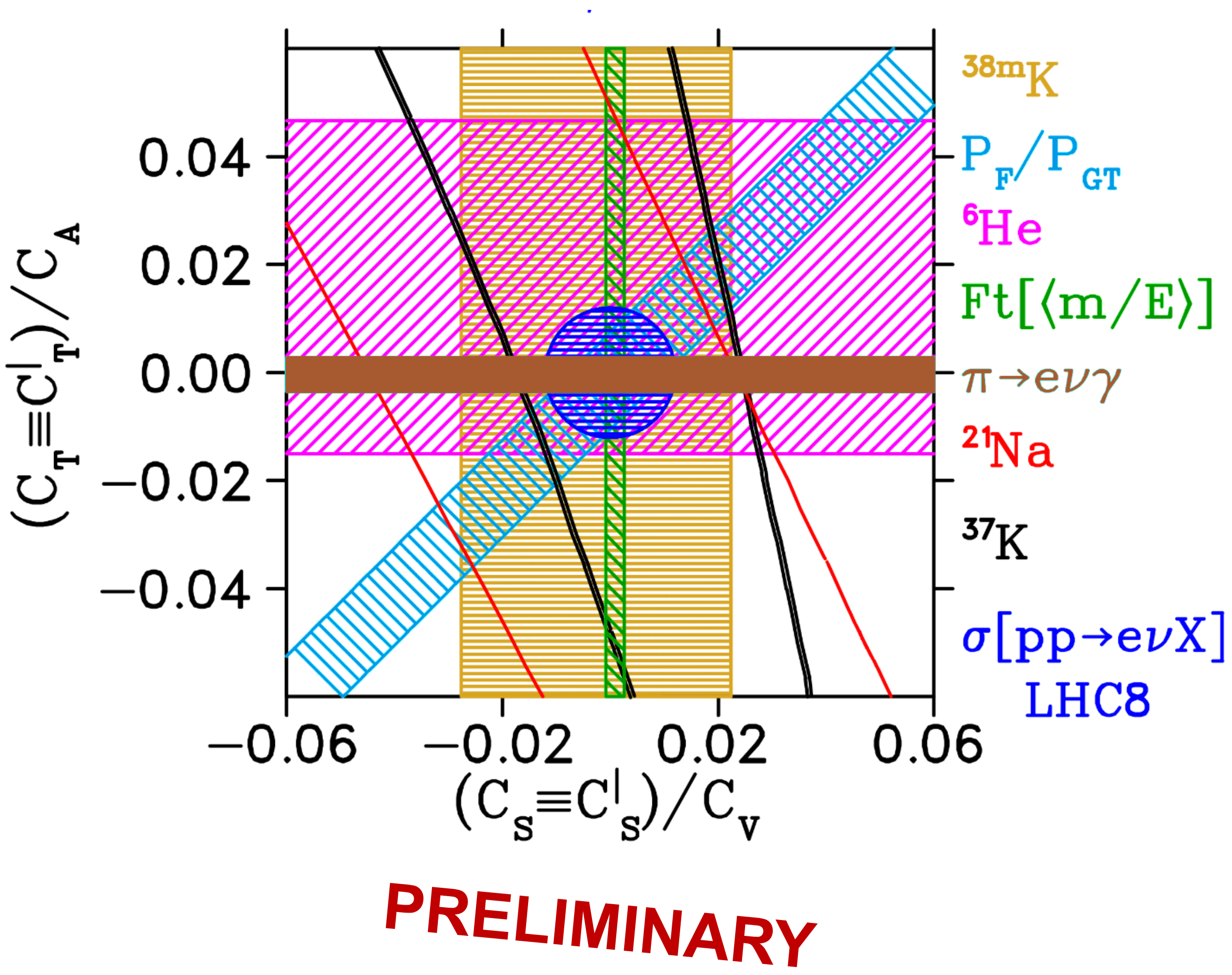


B.Fenker *et al*, PRL **120**, 062502 (2018)

Future plans

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





Collaborators and thanks

- Ion and atom traps are helping pave the way for the precision frontier
- TAMUTRAP: no radioactive ions yet, but facility is fully commissioned
- TRINAT: recent A_β result demonstrates ability; future is bright!

TEXAS A&M UNIVERSITY

B. Fenker
S. Behling
M. Mehlman
D. Melconian
P.D. Shidling

TRIUMF

J.A. Behr
I. Craiciu
A. Gorelov
S. Smale
C.L. Warner

University of Manitoba

M. Anholm
G. Gwinner

Tel Aviv University

D. Ashery
I. Cohen

UBC University of British Columbia

J. McNeil

Support provided by:

- The DOE and State of Texas
- NSERC, NRC through TRIUMF
- Israel Science Foundation