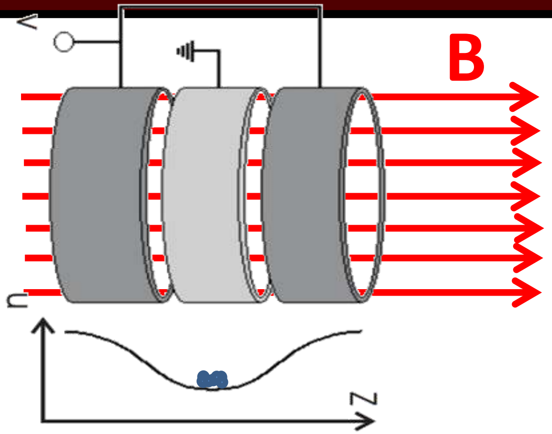
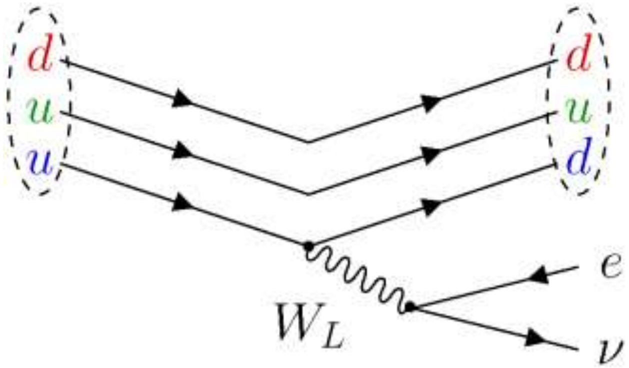
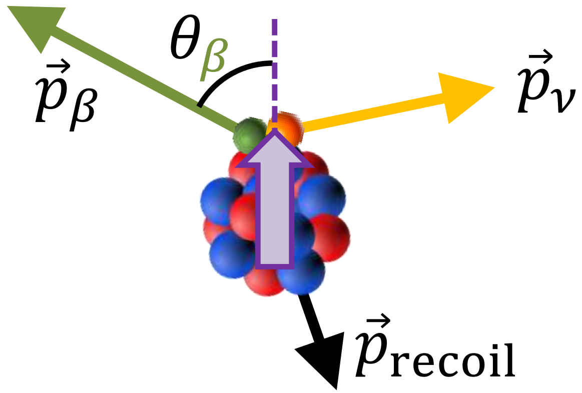
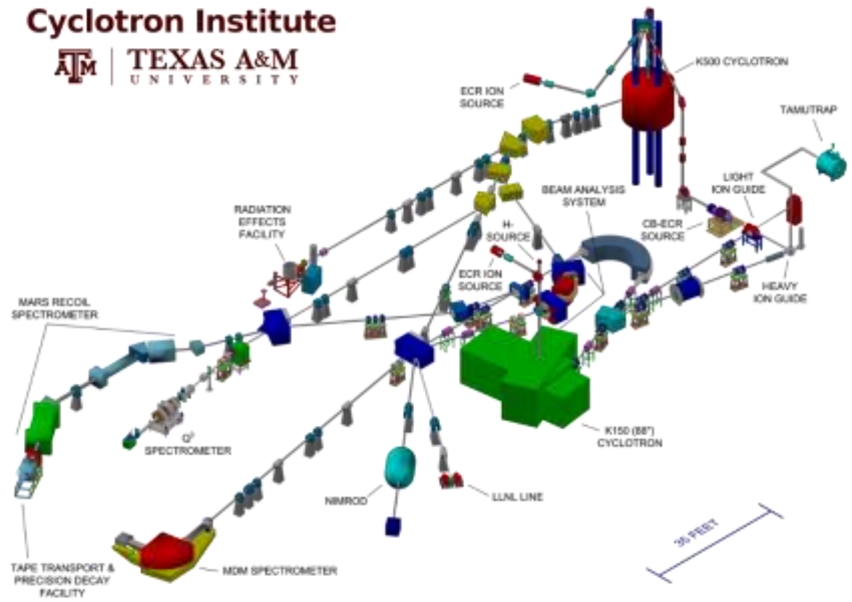
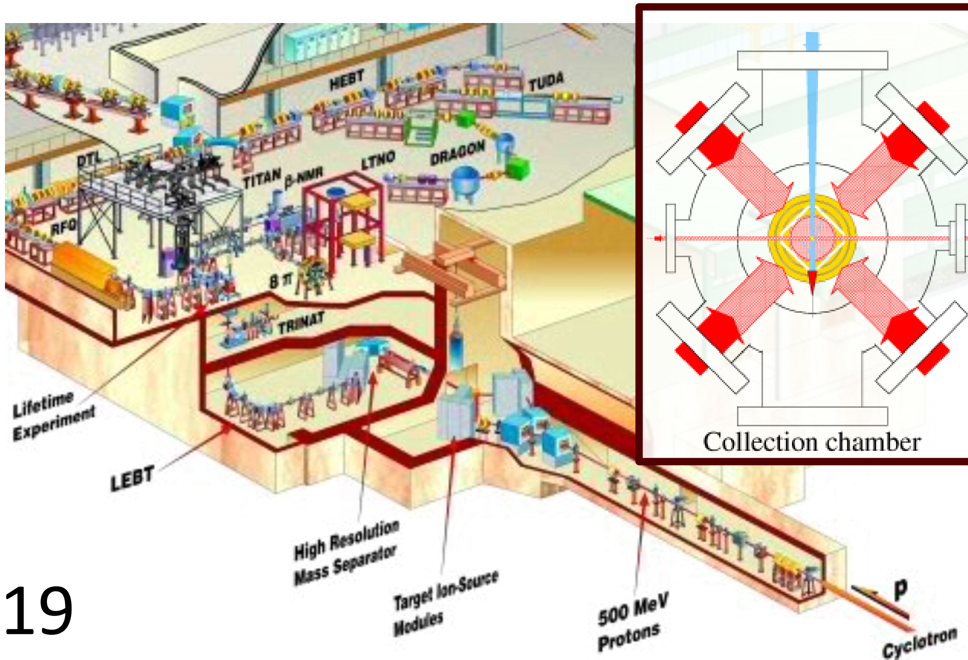
Fundamental Symmetry Tests using Atoms and Ions

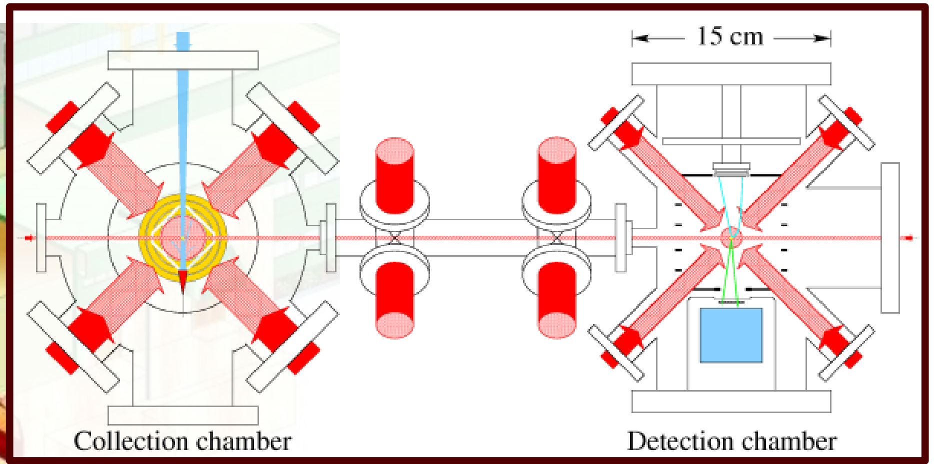












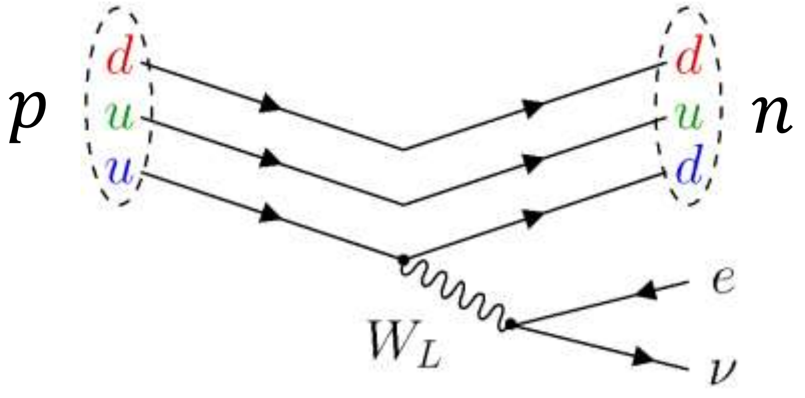
Dan Melconian – ANL, Feb 2019

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

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

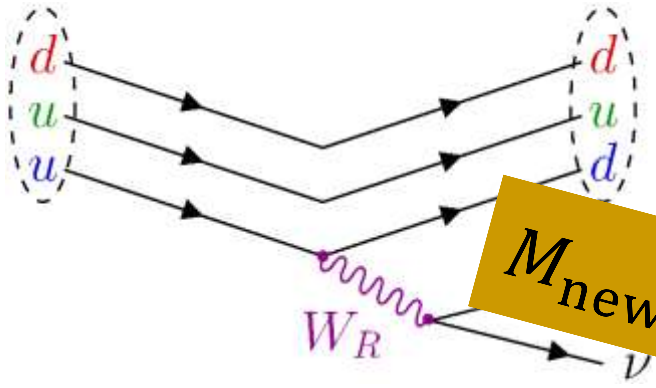
$$C_V = C_V' = 1$$

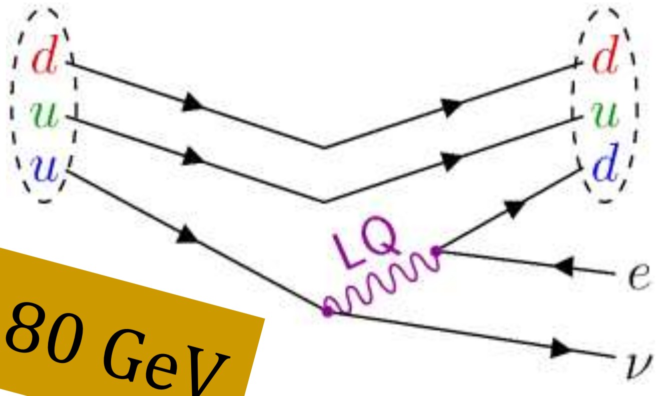
$$C_A = C_A' \approx 1.27$$

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

- These are not:

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





$M_{new} \gg 80$ GeV

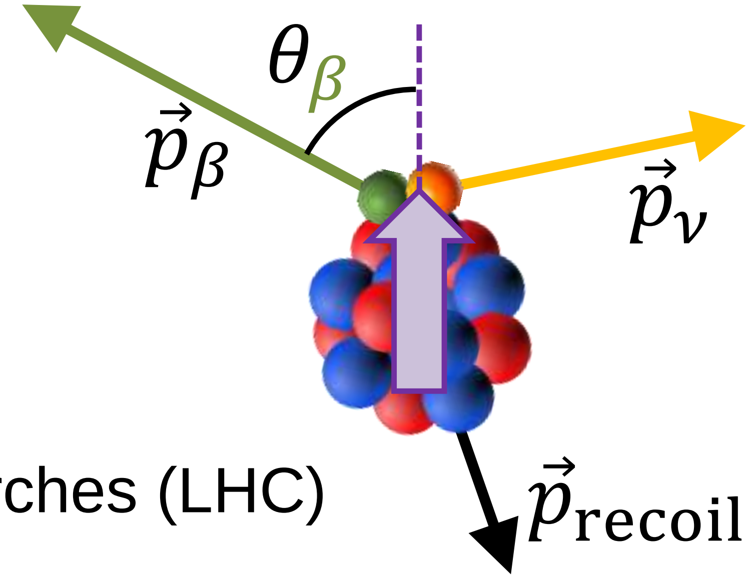
$C_i \neq C_i'$

$C_S, C_T \neq 0$

- 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

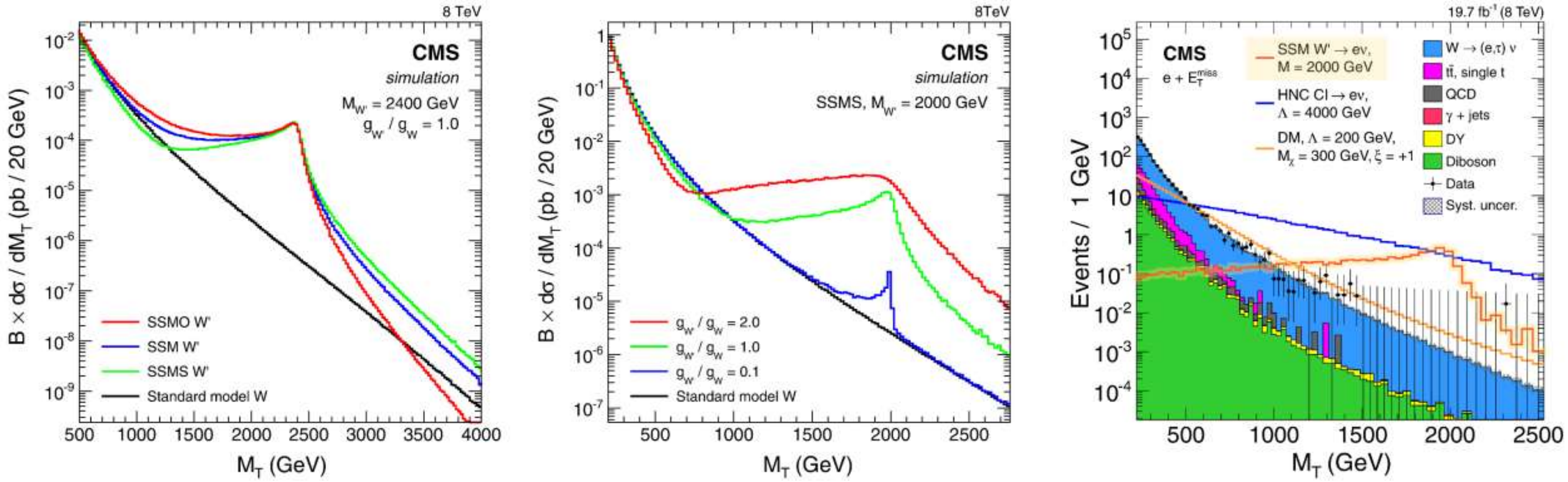


- Global gameplan:
  - Measure the β-decay parameters
  - Compare to SM predictions
  - Look for deviations ⇔ new physics
  - Precision of $\leq 0.1\%$ needed to complement other searches (LHC)

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)

The energy frontier

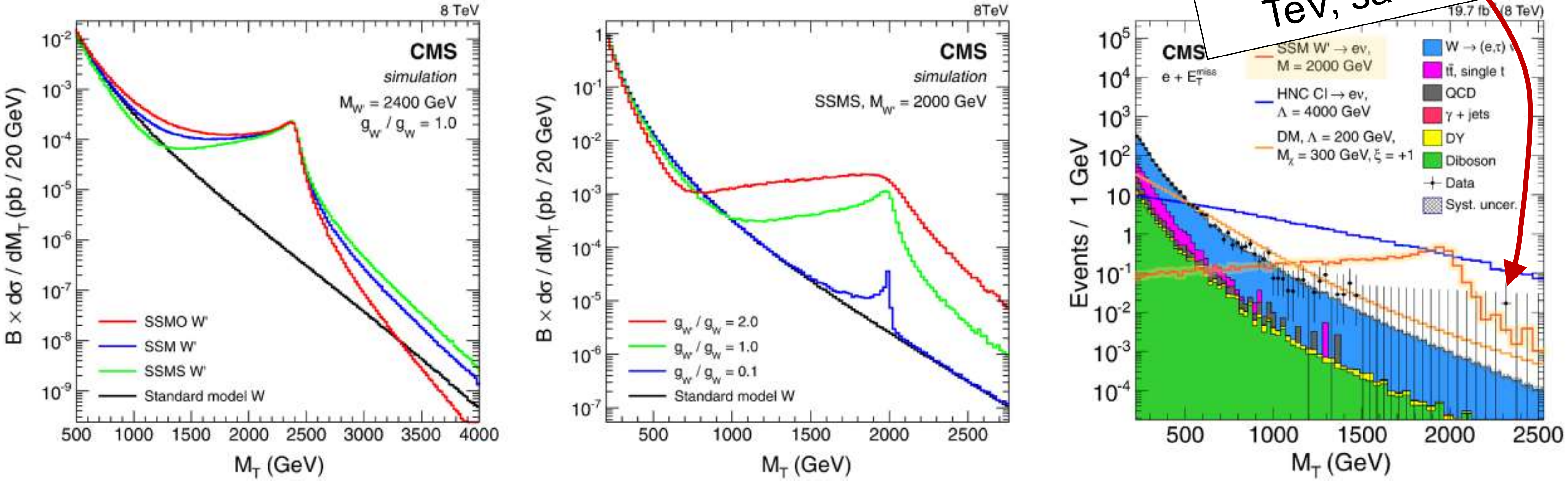
- CMS collaboration, Phys. Rev. D **91**, 092005 (2015)
  - Look for direct production ⇒ excess of events in the missing transverse energy
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$



The energy frontier

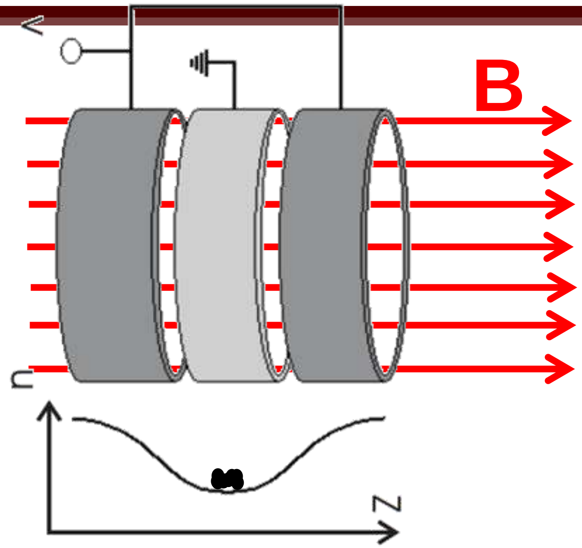
- CMS collaboration, Phys. Rev. D **91**, 092005 (2015)
  - Look for direct production ⇒ excess of events in the missing transverse energy
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$
  - No excess observed ⇝ place limits
    (see Gonzalez-Alonzo, Prog. Part. Nucl Phys **104** for EFT interpretation)

Expected 2.0±0.3 events above 1.5 TeV, saw one

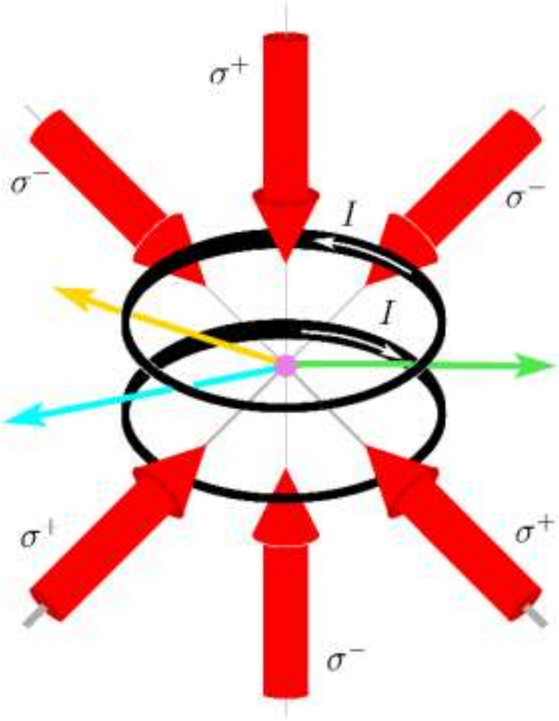


0.1% is a tall order…how to reach that precision?

- Ion traps
  - Can trap any ion; well-known for mass measurements (**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)



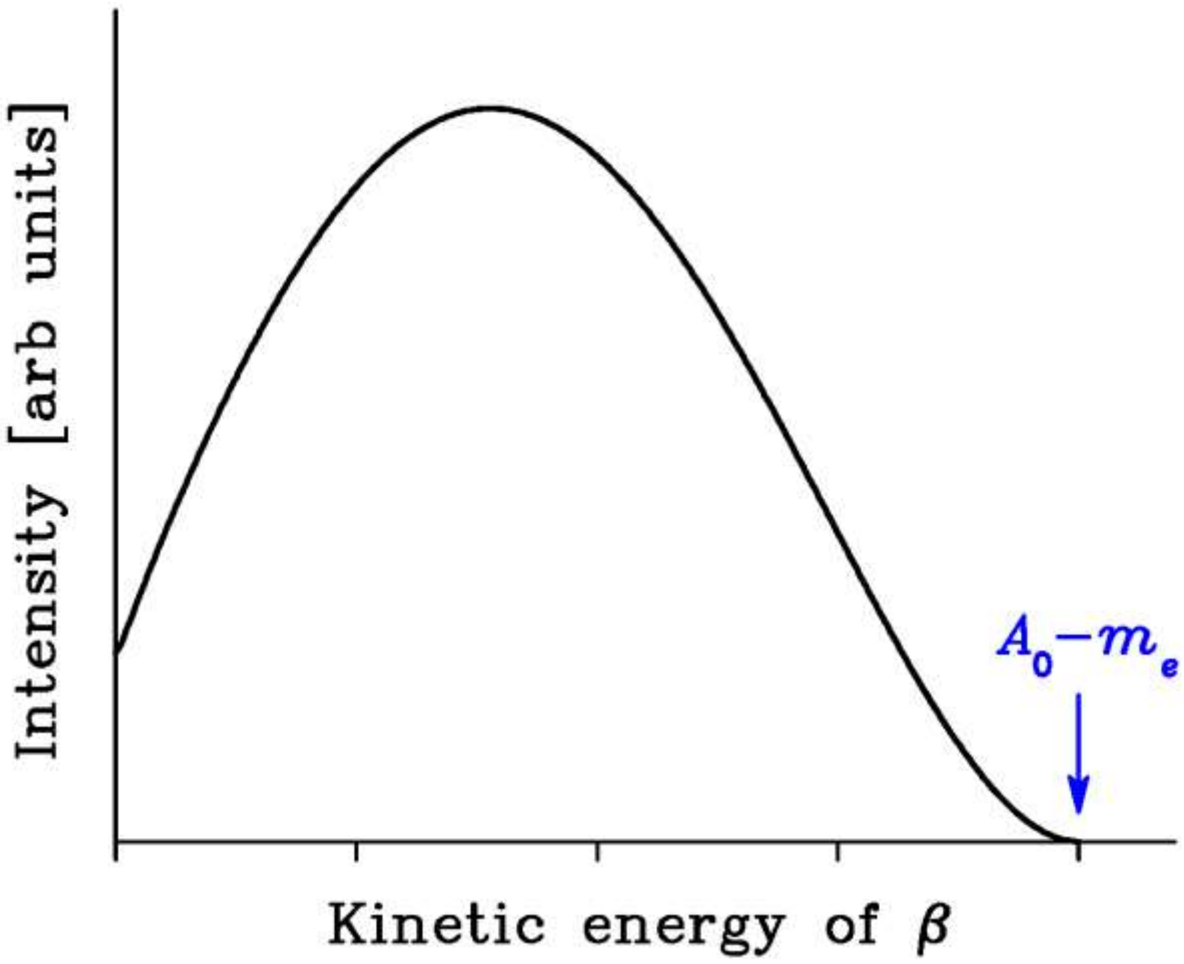
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - TRINAT @ TRIUMF (K isotopes)
  - **UW/ANL** (you know…! [^{6}He])
  - NeAT @ SARAF (Ne isotopes)



How does β decay test the SM?

- Begin by looking at the basic decay rate

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

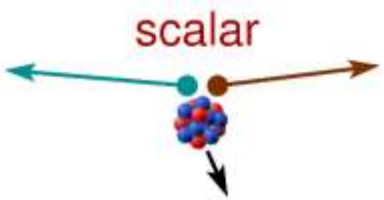


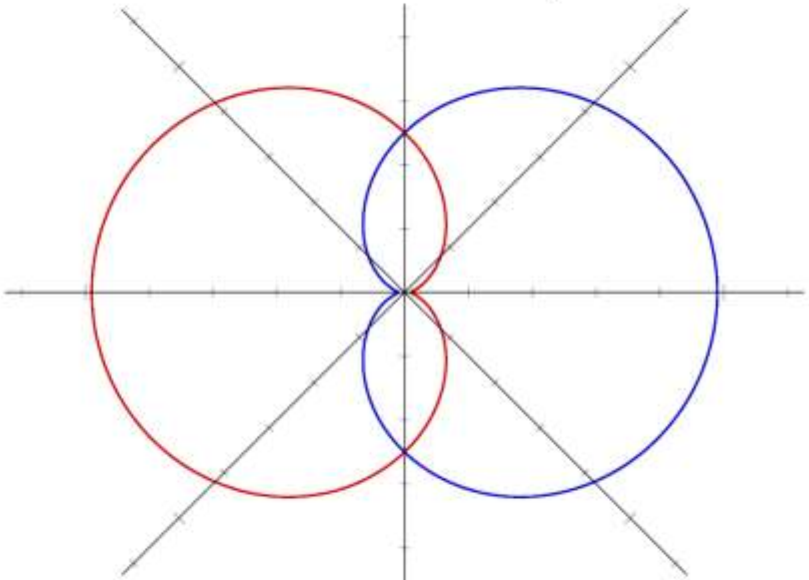
β decay and fundamental physics

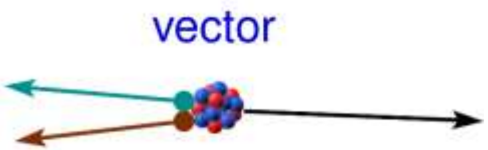
- Expand to the often-quoted angular distribution of the decay (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

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

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







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

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

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

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

… in the couplings…not … 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 $\Leftarrow$

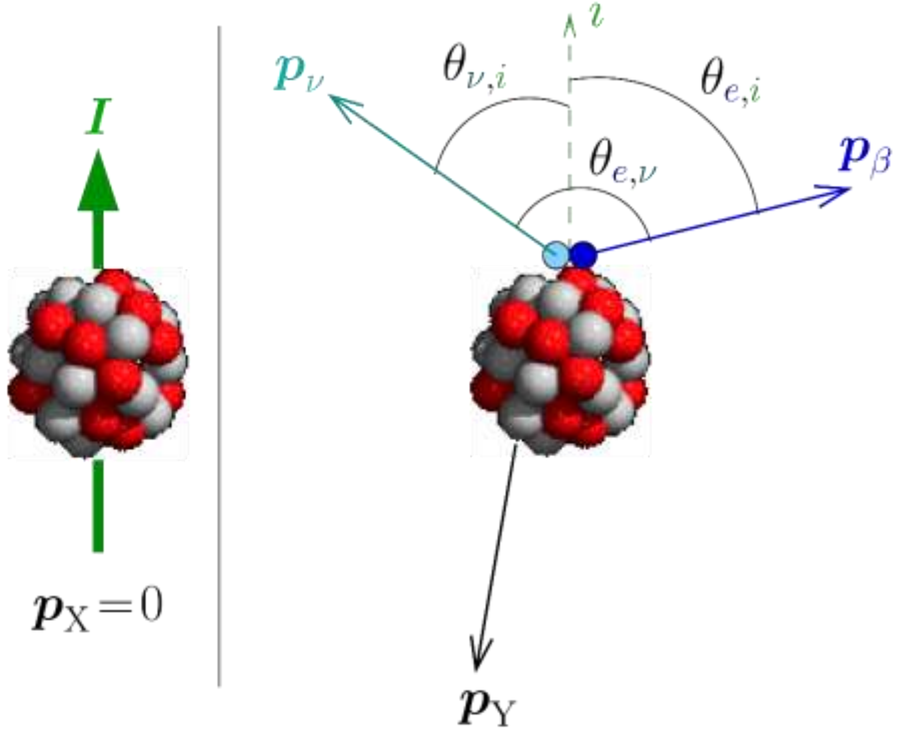
Goal must be $< 0.1\%$ precision to complement other searches (LHC)

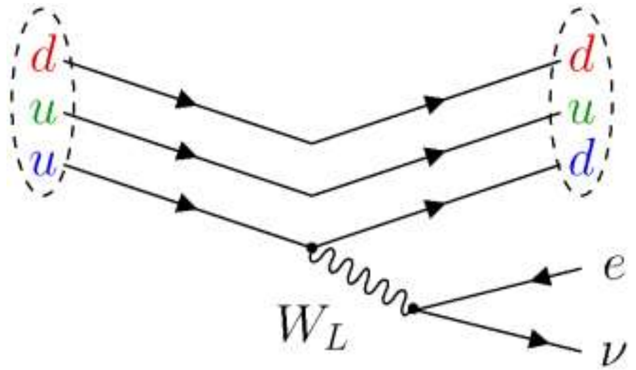
(see González-Alonso and Naviliat-Čunčić, PRC **94**, 0.35503 (2016))

How to achieve our goal?

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

- Perform a β decay experiment on short-lived isotopes
- Make a precision measurement of the angular correlation parameters
- Compare the SM predictions to observations
- Look for deviations as an indication of new physics





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- Perform a β decay experiment on short-lived isotopes
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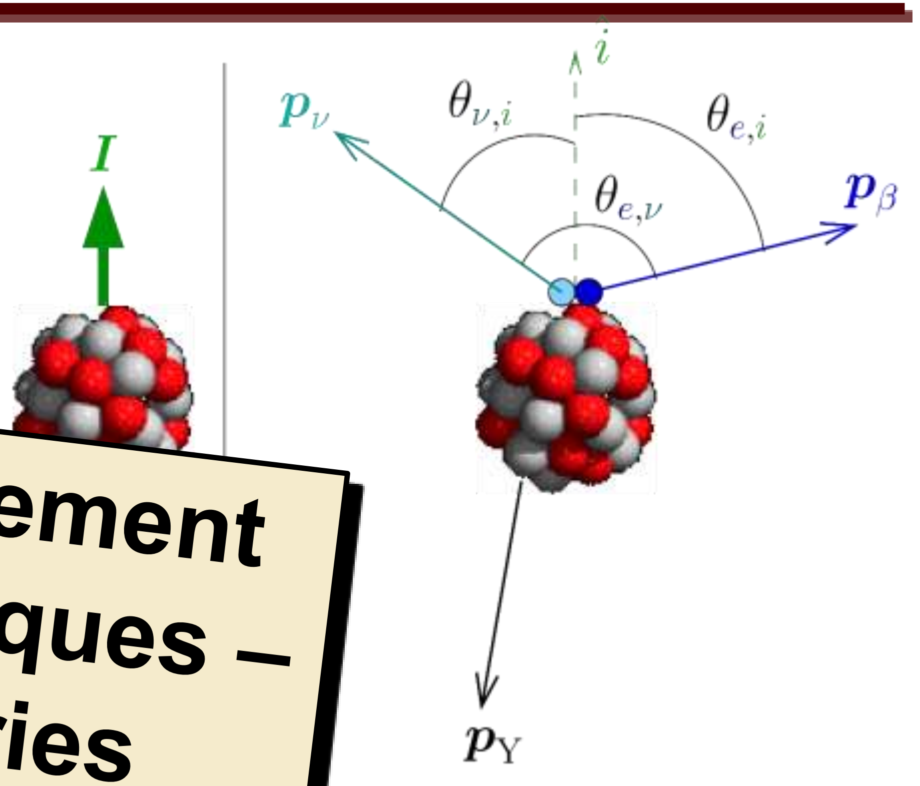
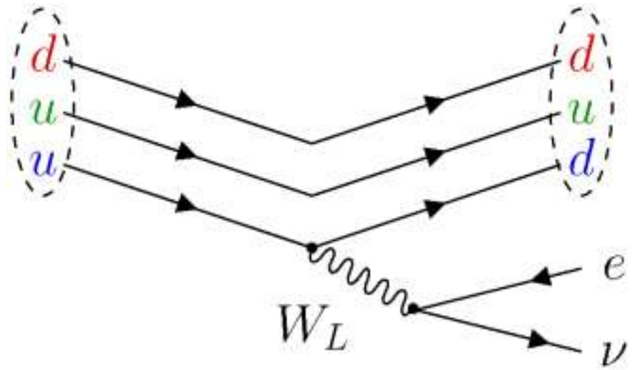
Perform a nuclear measurement – often using atomic techniques – to test high-energy theories





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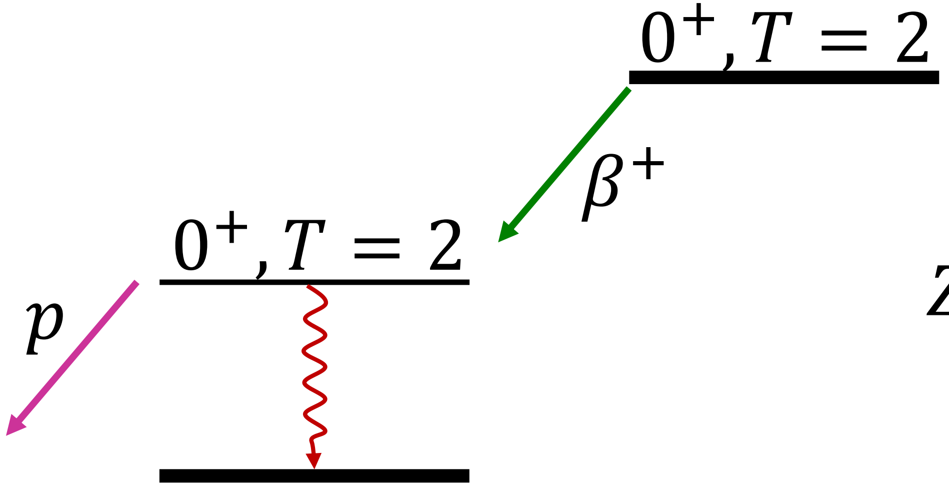
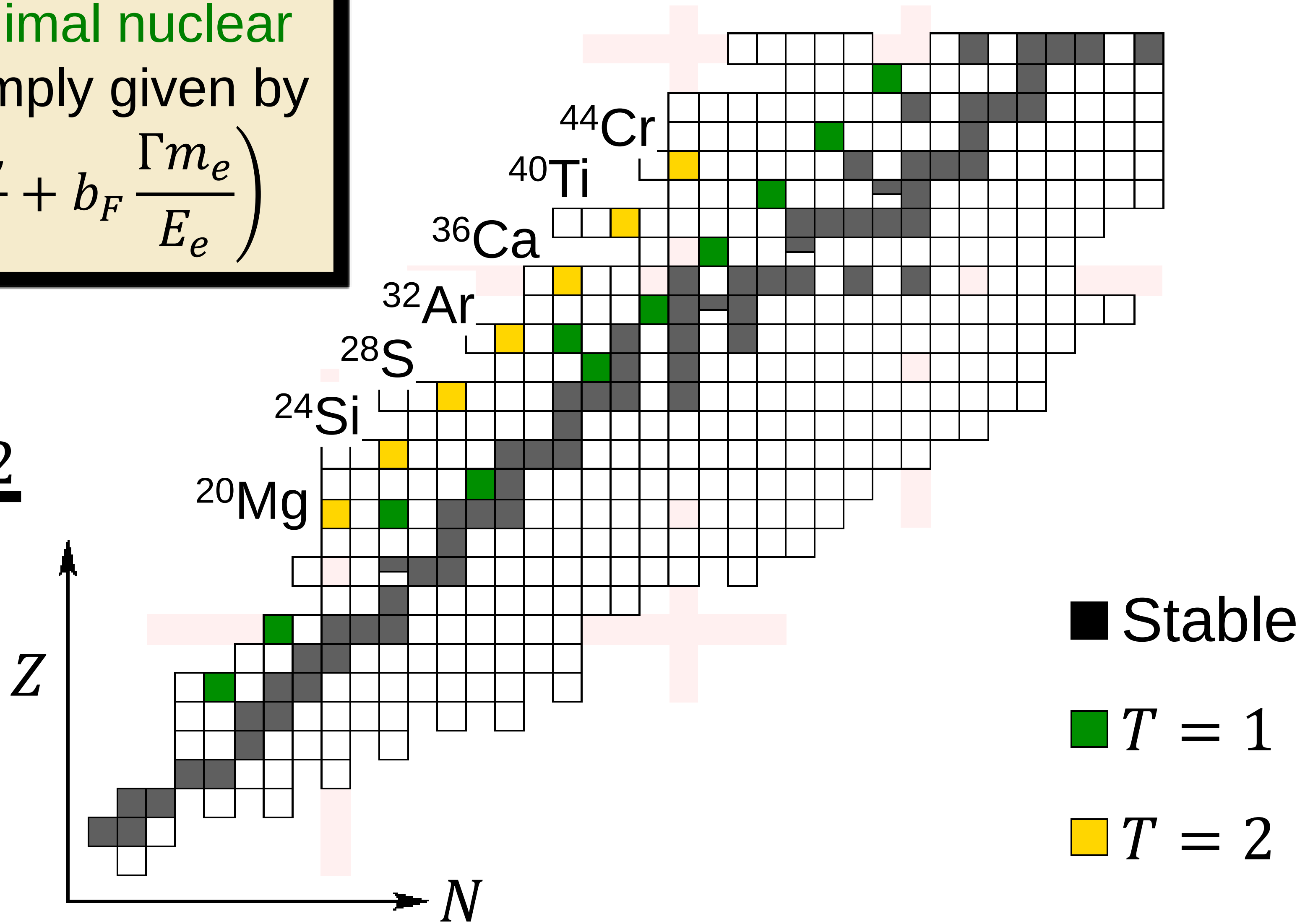
$T = 2$ Superallowed decays

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)

The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.

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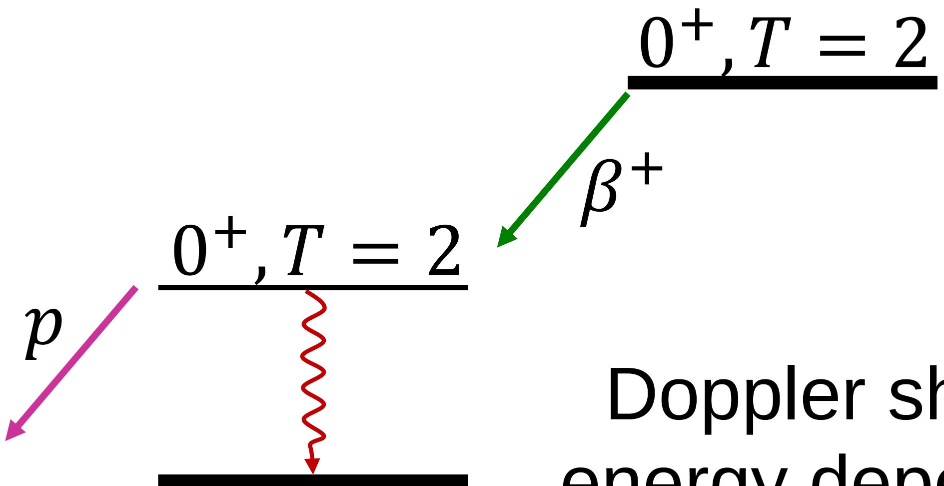

Doppler shape of proton energy depends on $\vec{p}_\beta \cdot \vec{p}_\nu$!

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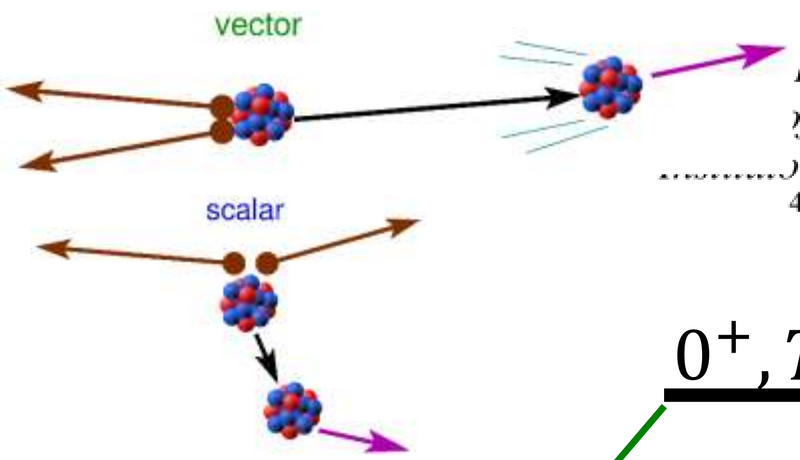

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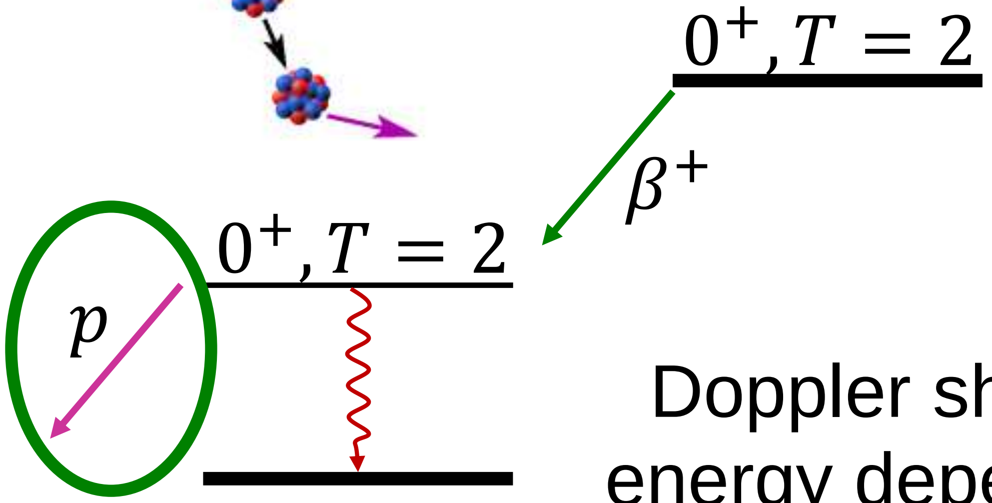

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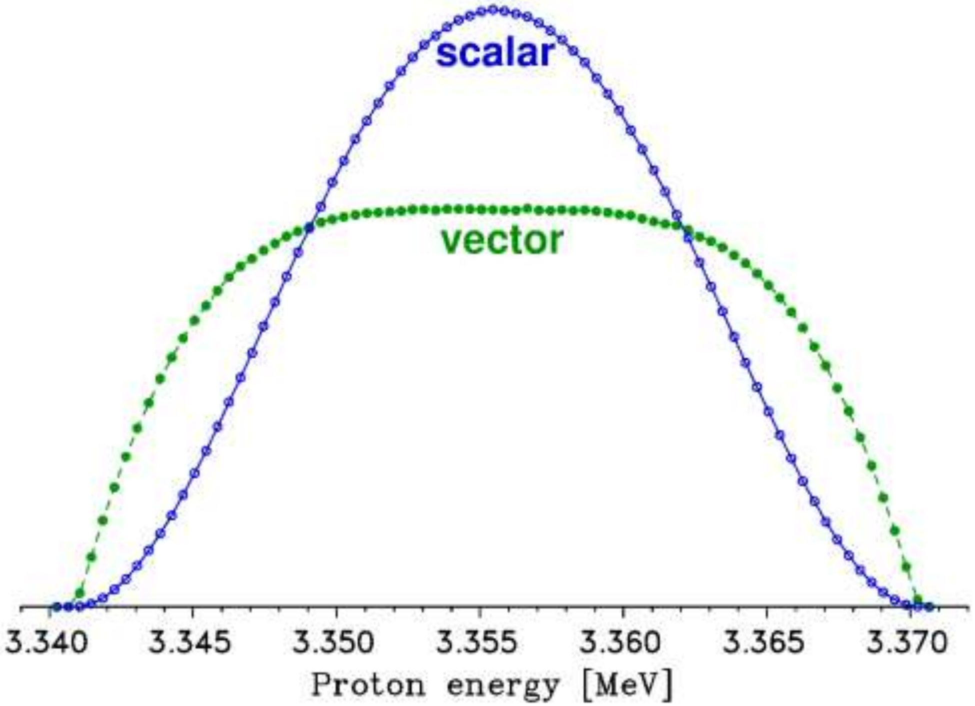

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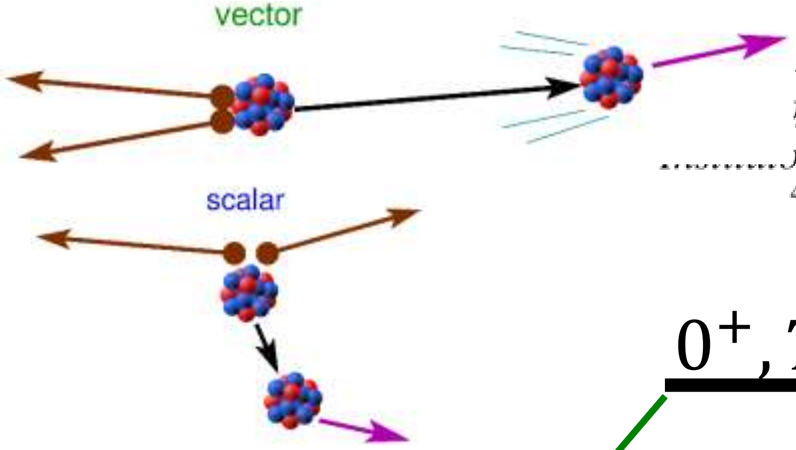

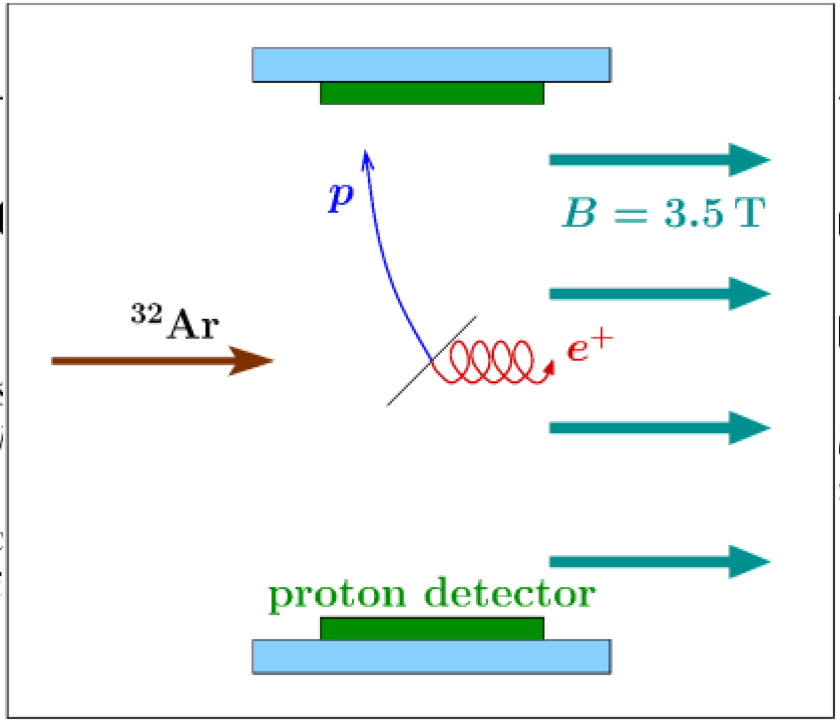

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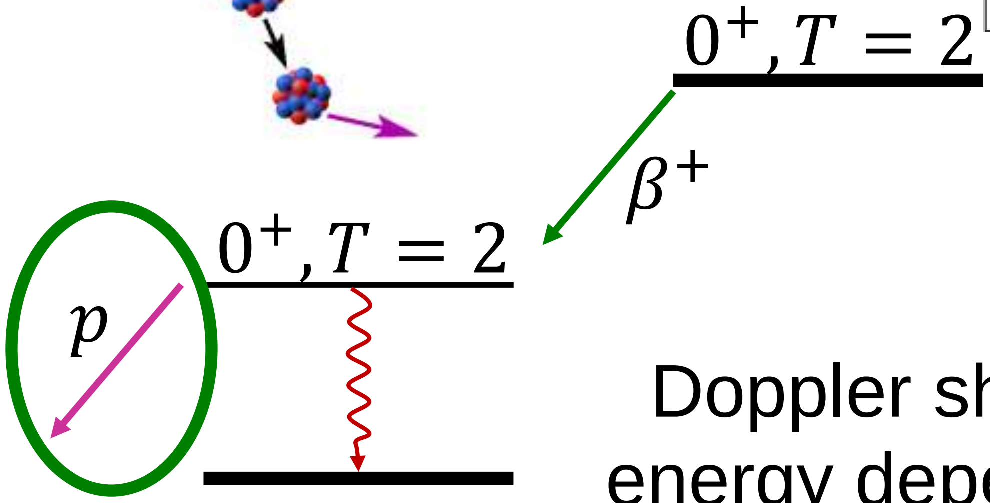

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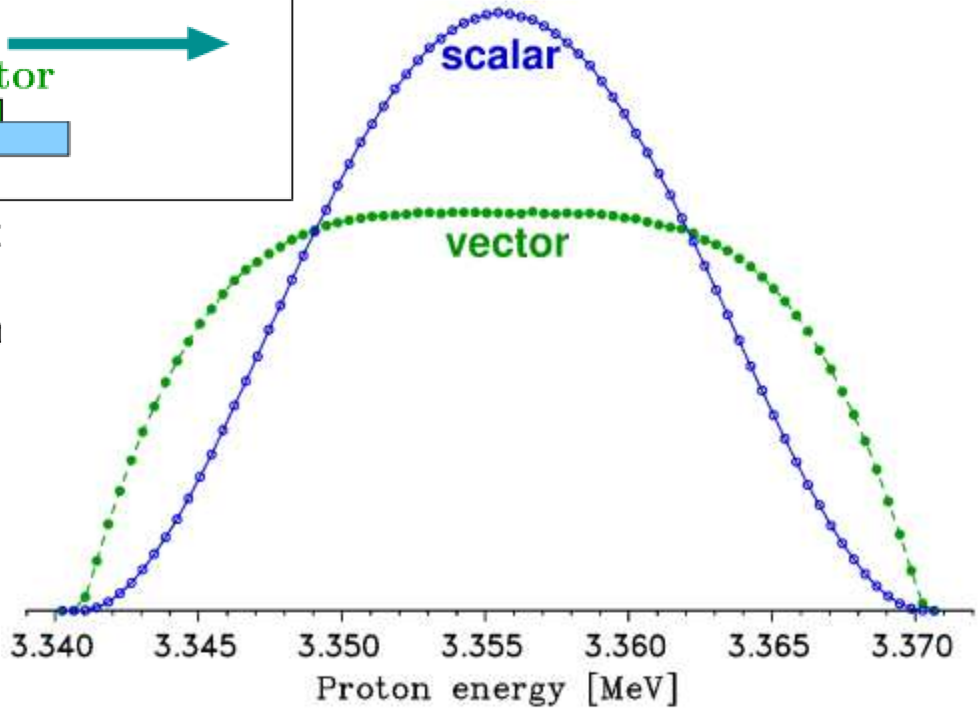
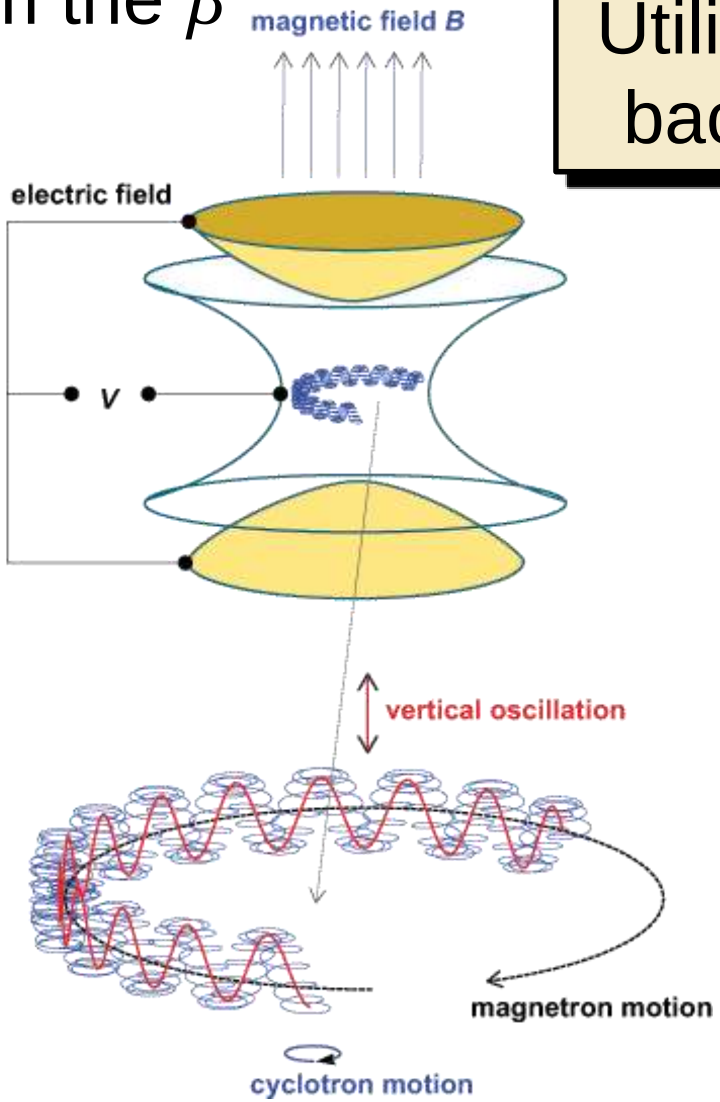
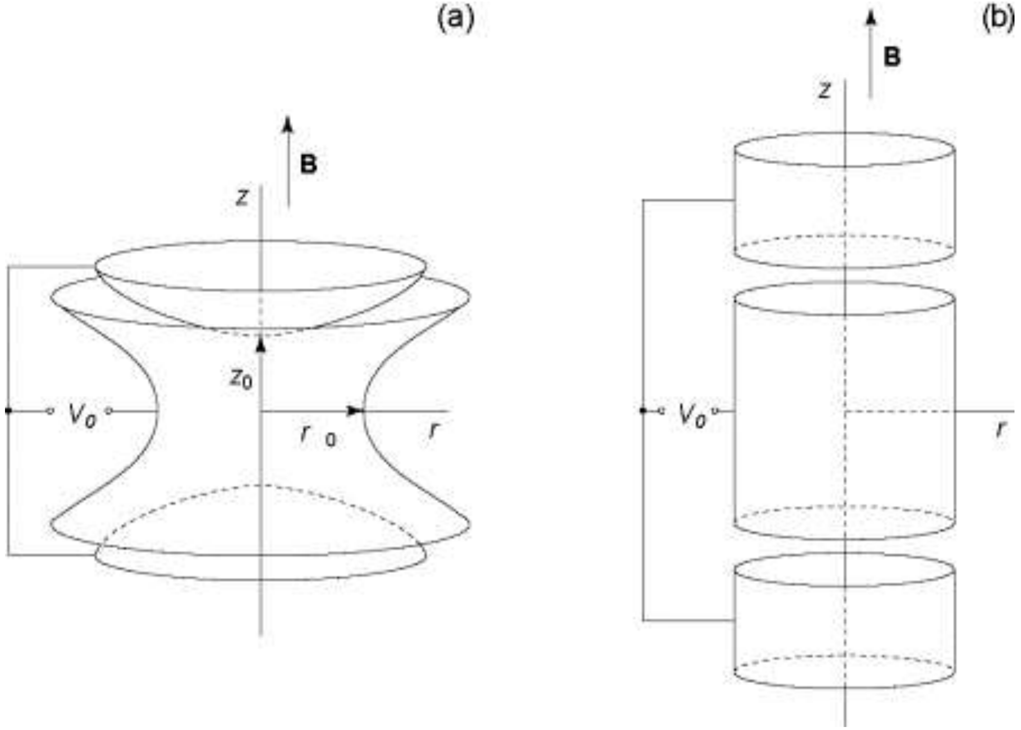


But why throw away useful information?

- 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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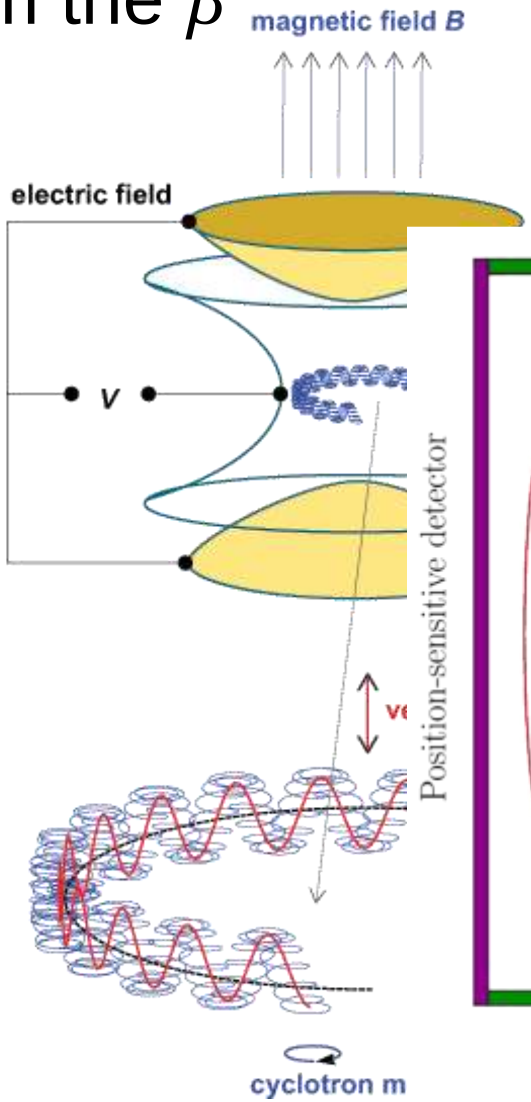
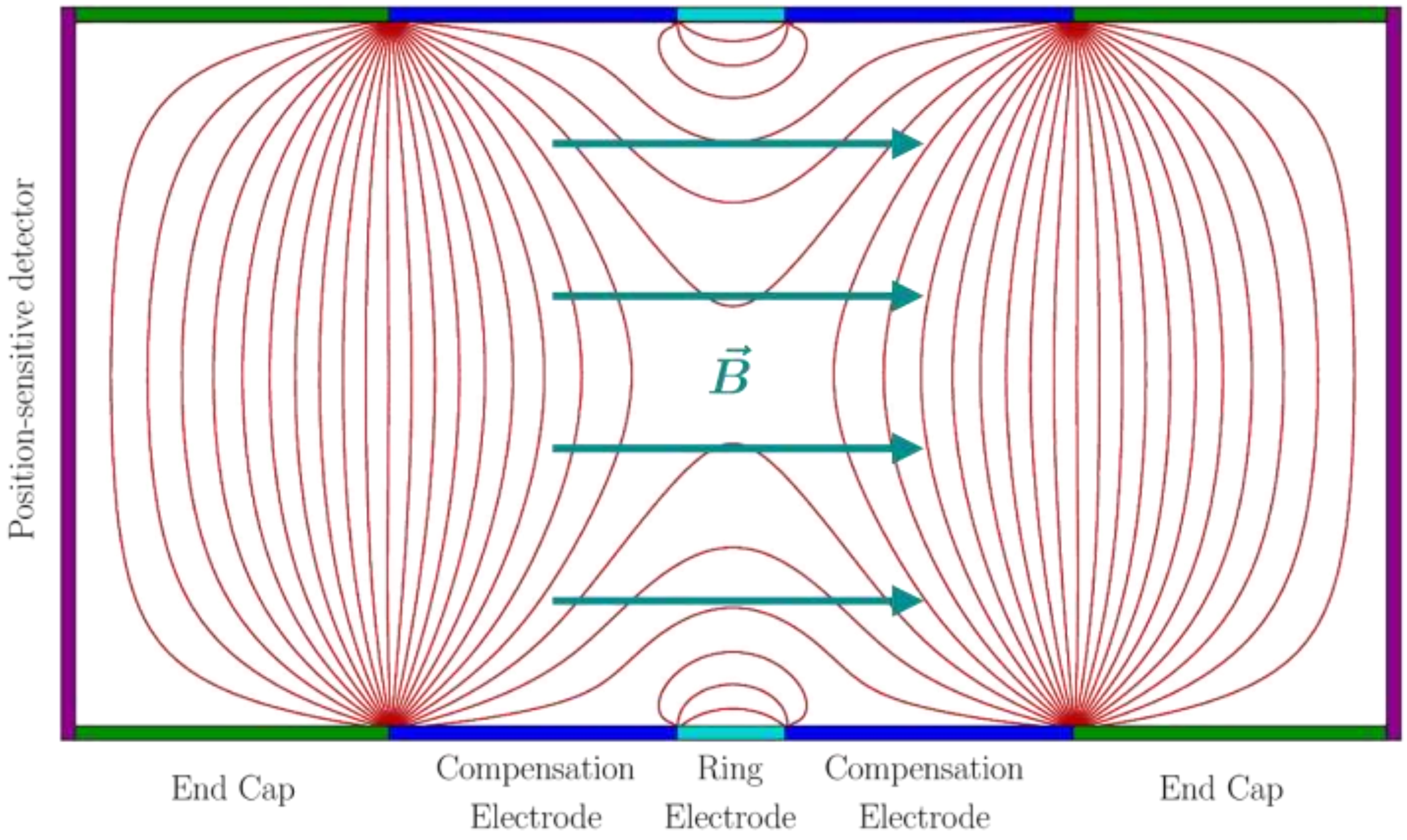
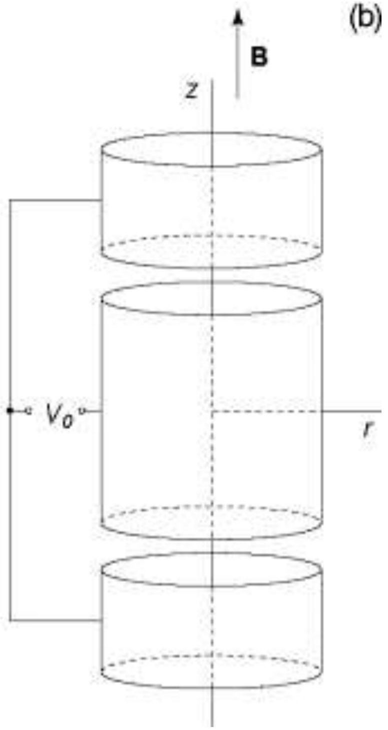
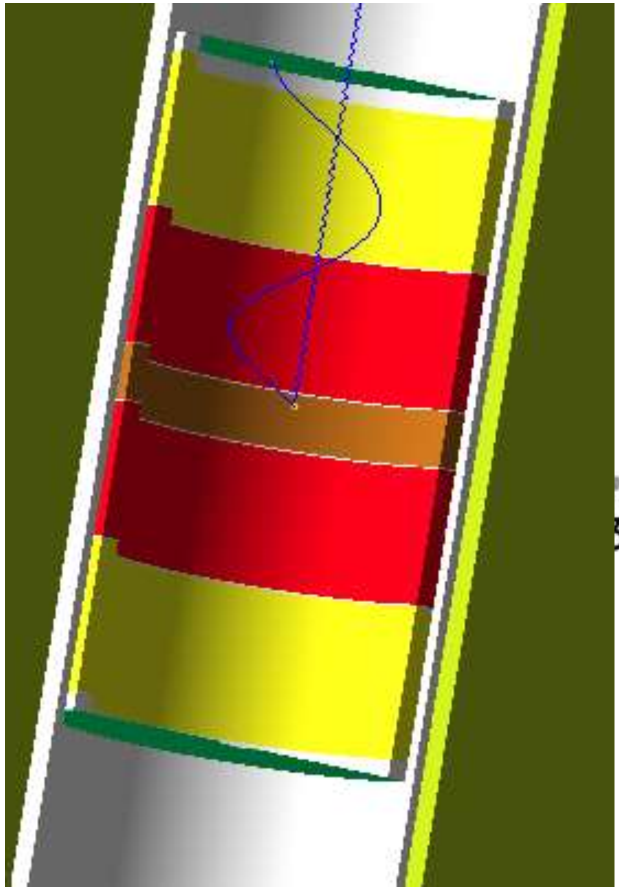
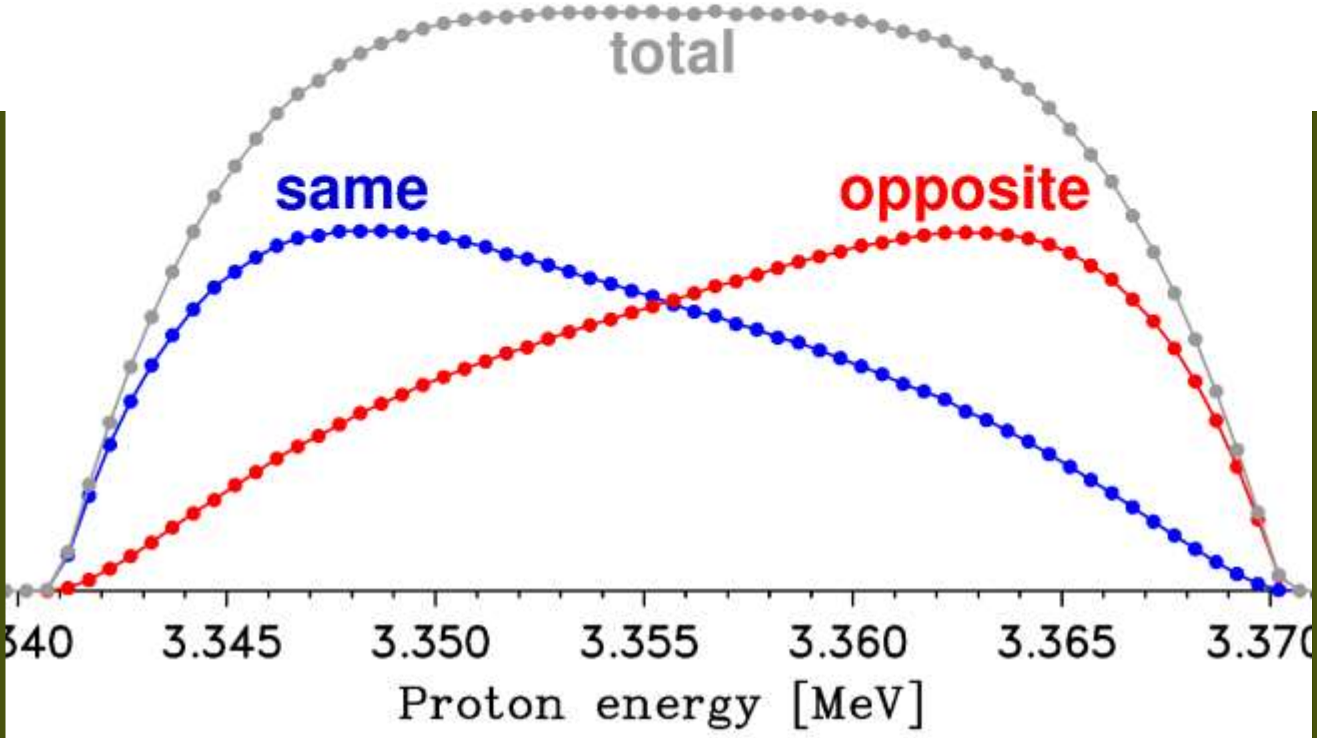


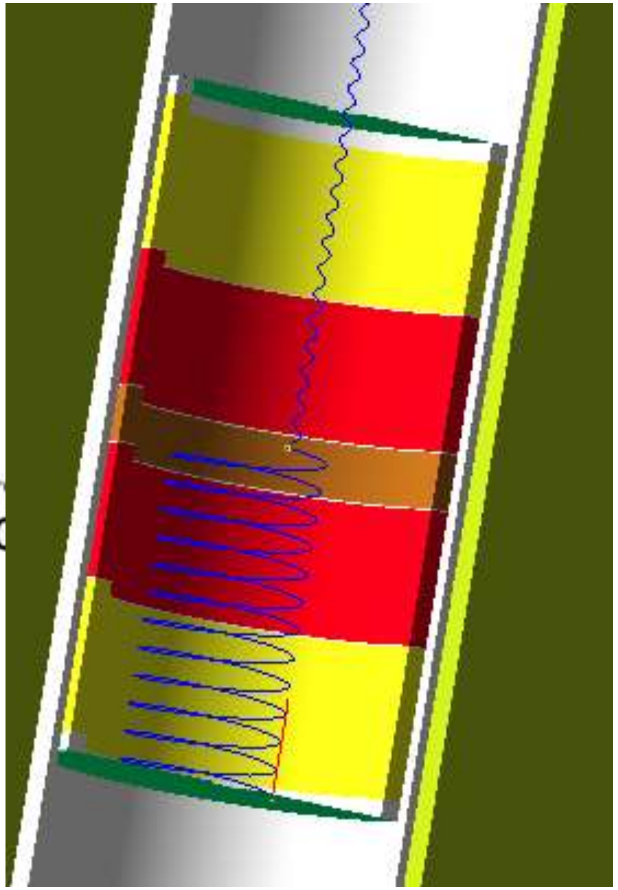


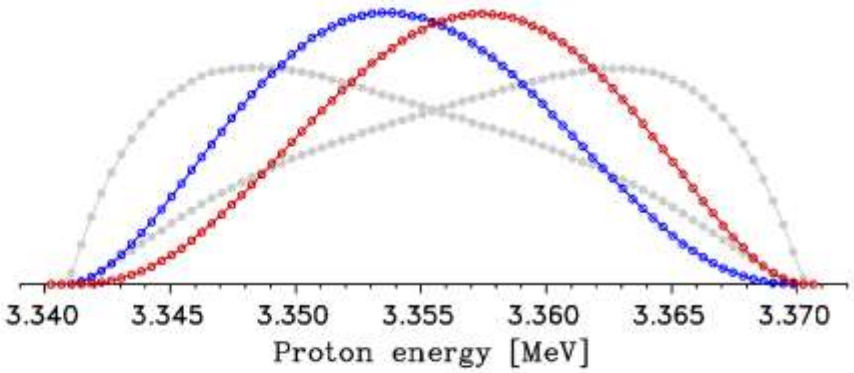


Measure means instead of 2^{nd} moments







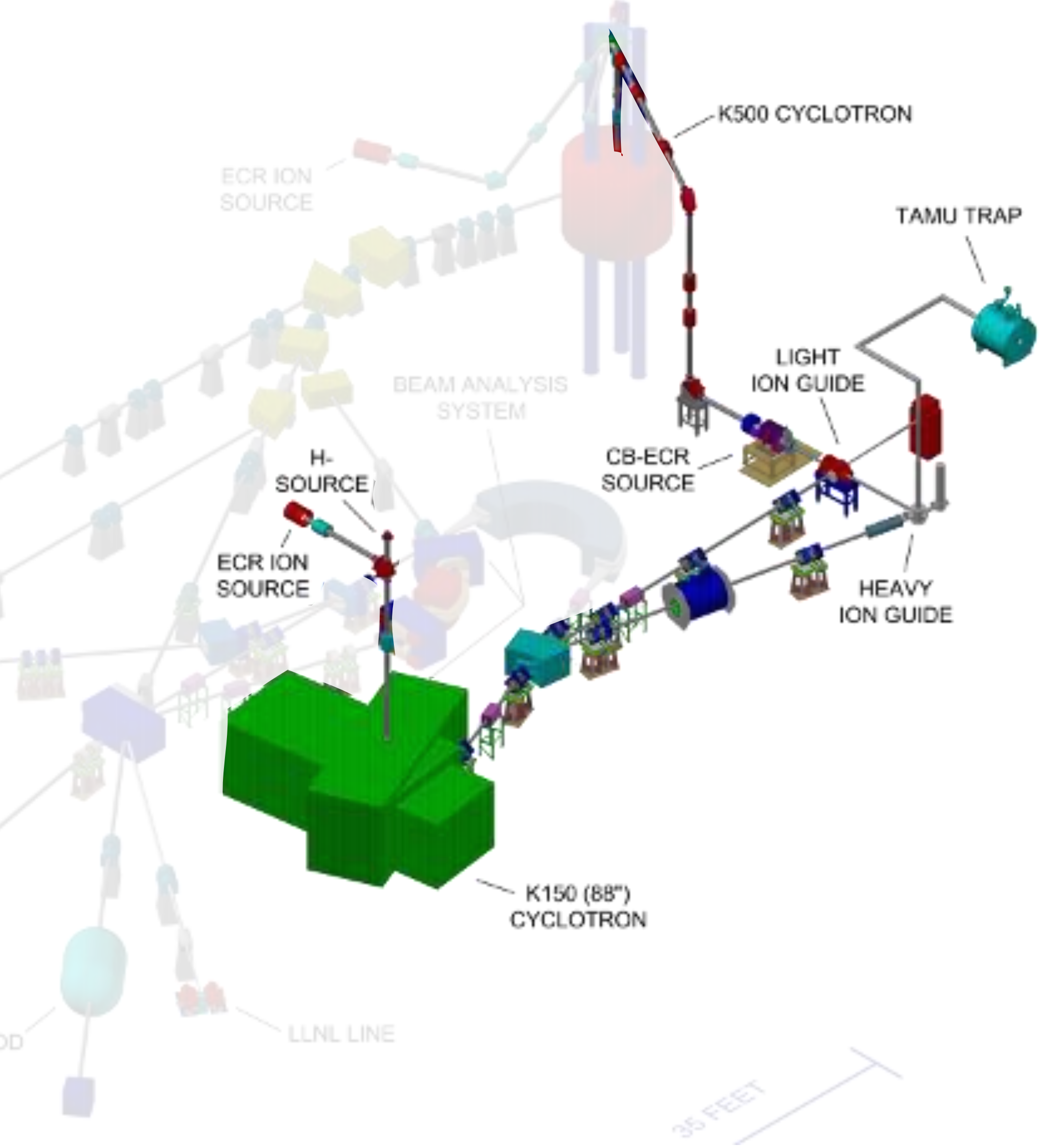


The T-REX Upgrade Project

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

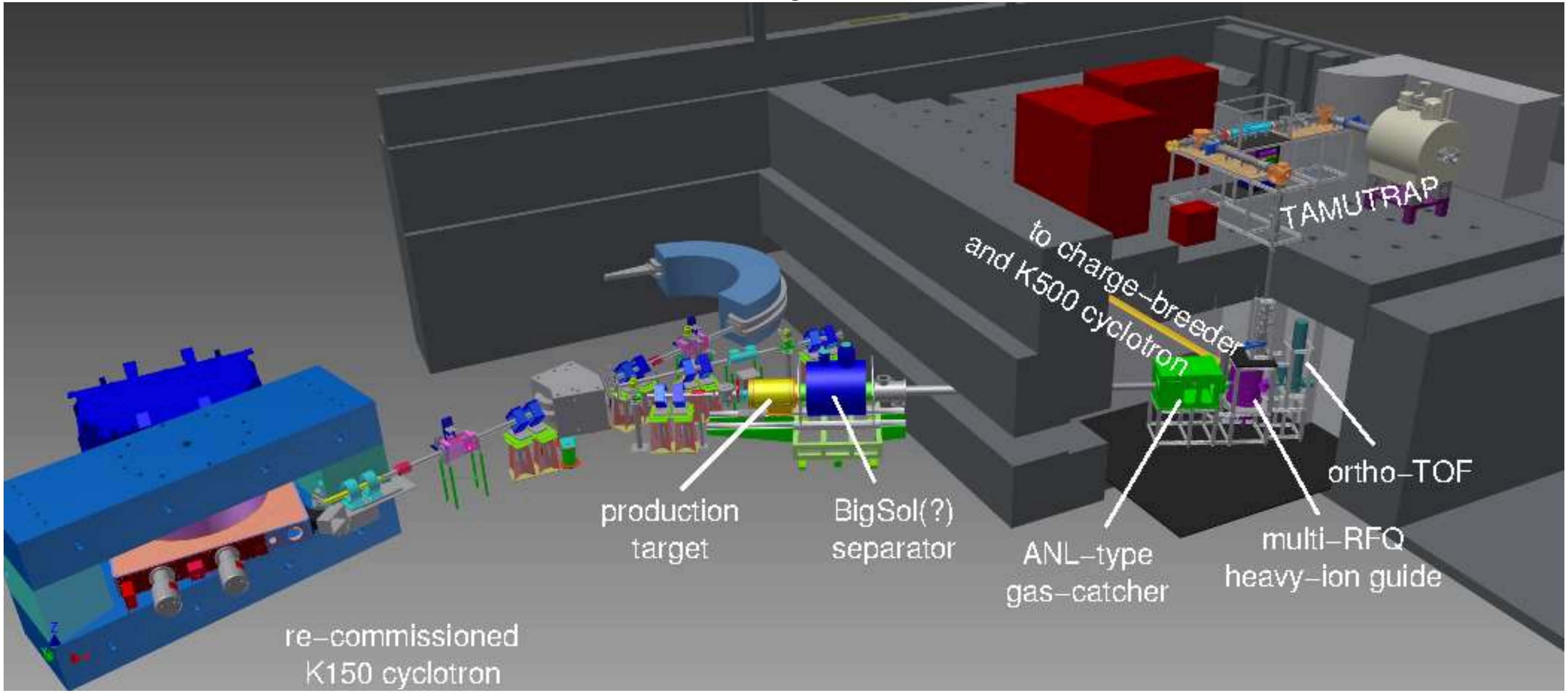
- Light Ion Guide – used for production of neutron deficient RIBs via $A(p,xn)B$ reactions

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



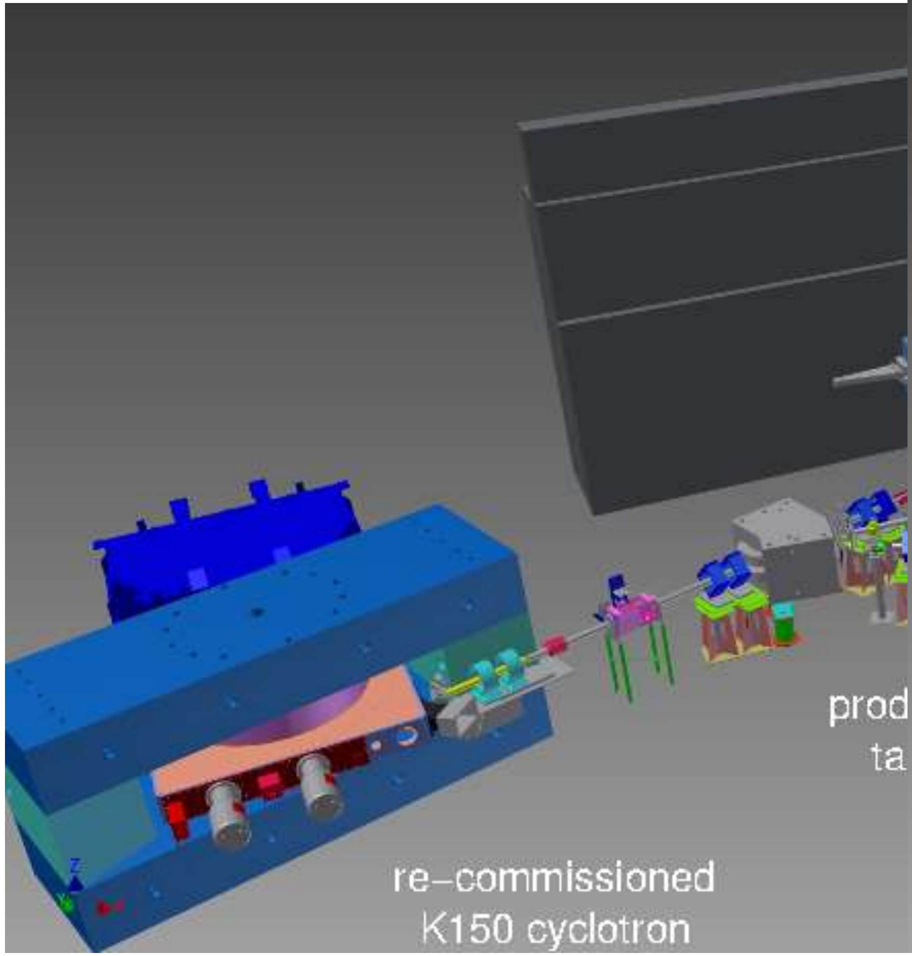
The Heavy Ion Guide

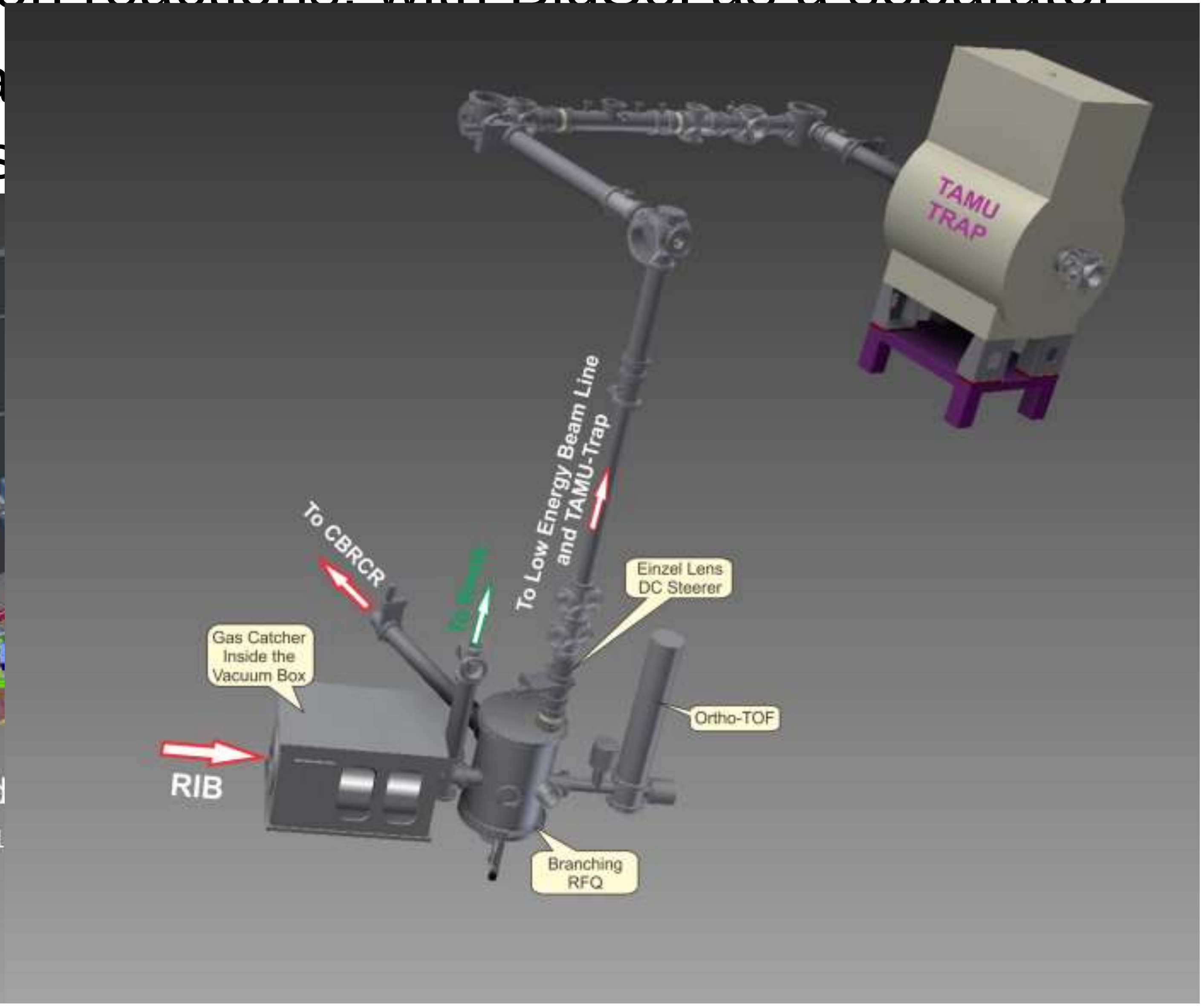
- Deep-inelastic and fragmentation reactions, with BigSol as a separator
- Stopped in an ANL-type gas-catcher; able to transport to CB-ECR or TAMUTRAP with a multi-RFQ switchyard



The Heavy Ion Guide

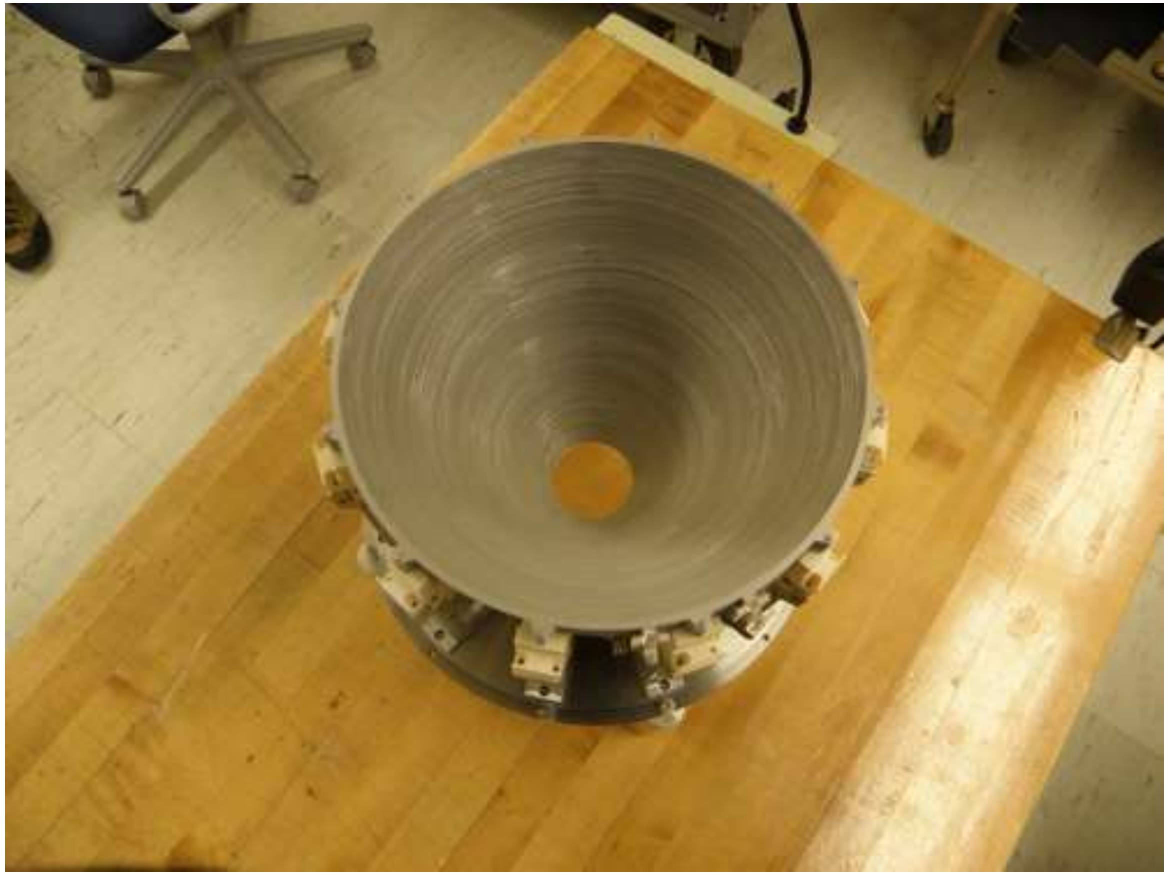
- Deep-inelastic and fragmentation reactions, with BigSol as a separator
- Stopped in an ANL-type gas-ca
TAMUTRAP with a multi-RFQ s





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



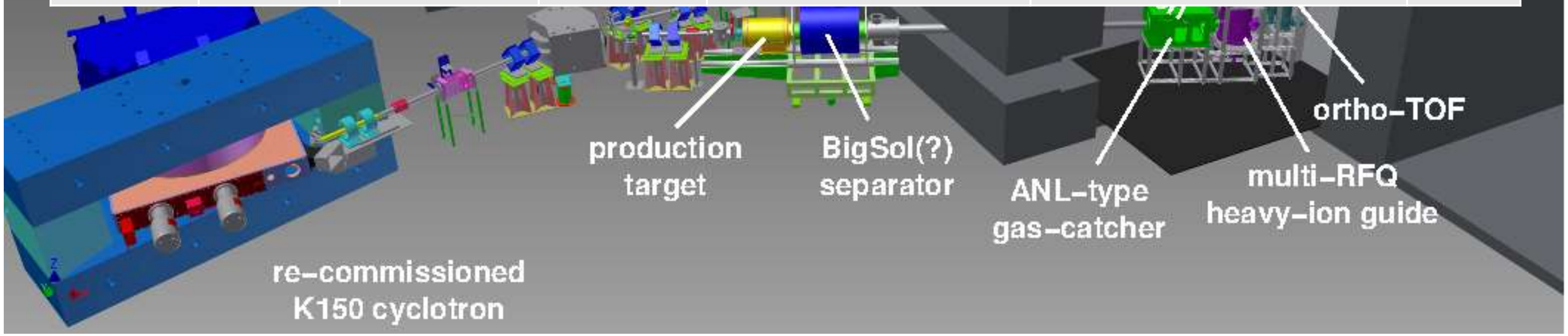
Transporting the stopped RIBs

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

The original plan for TAMUTRAP

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

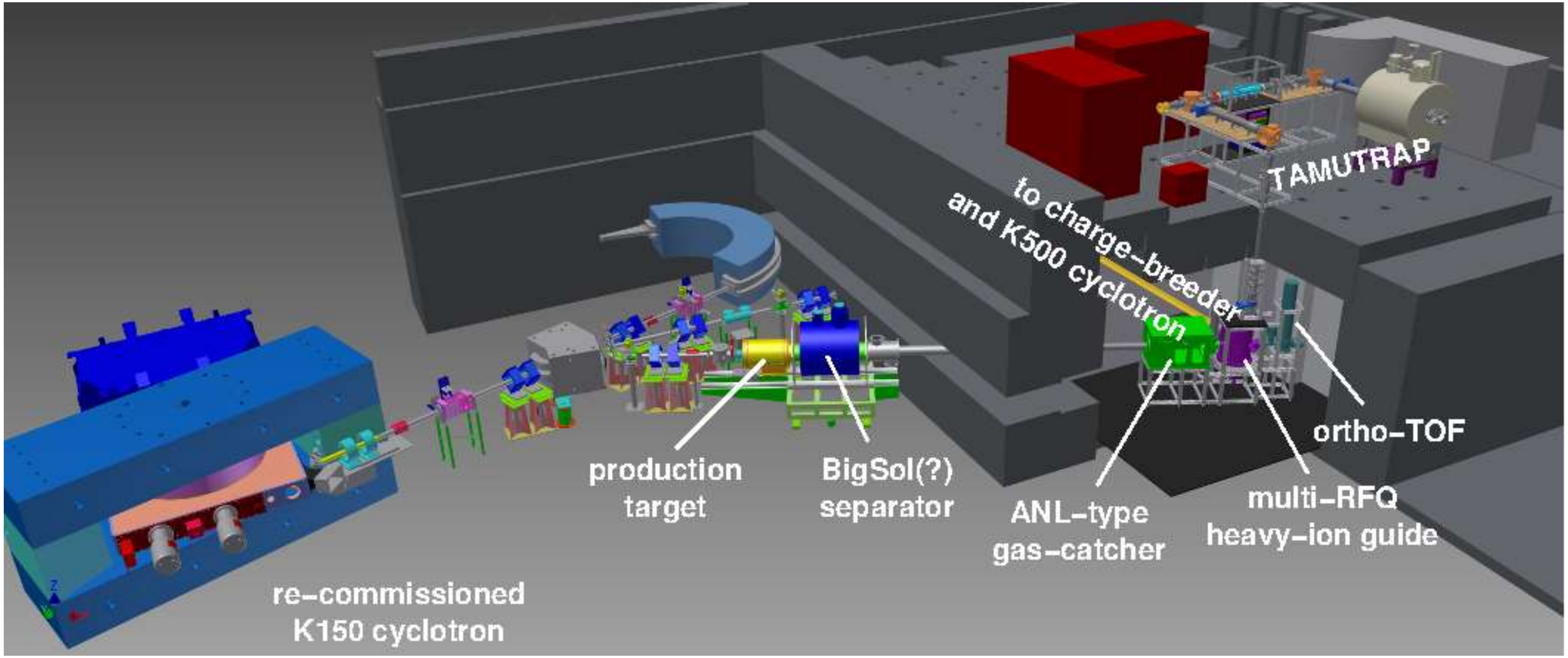
RIB	$t_{1/2}$ [ms]	Projectile	Energy [MeV/u]	Target thickness [mg/cm²]	Expected rate @ target chamber [pps]
^{20}Mg	90	^{20}Ne	23-30	22.5 (66)	$68\ (400) \times 10^4$
^{24}Si	140	^{24}Mg	22-30	22.5 (70)	$26\ (160) \times 10^4$
^{28}S	125	^{28}Si	22-30	22.5 (60)	$7\ (40) \times 10^4$
^{32}Ar	98	^{32}S	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)	$4\ (8) \times 10^4$



Issues with original plan

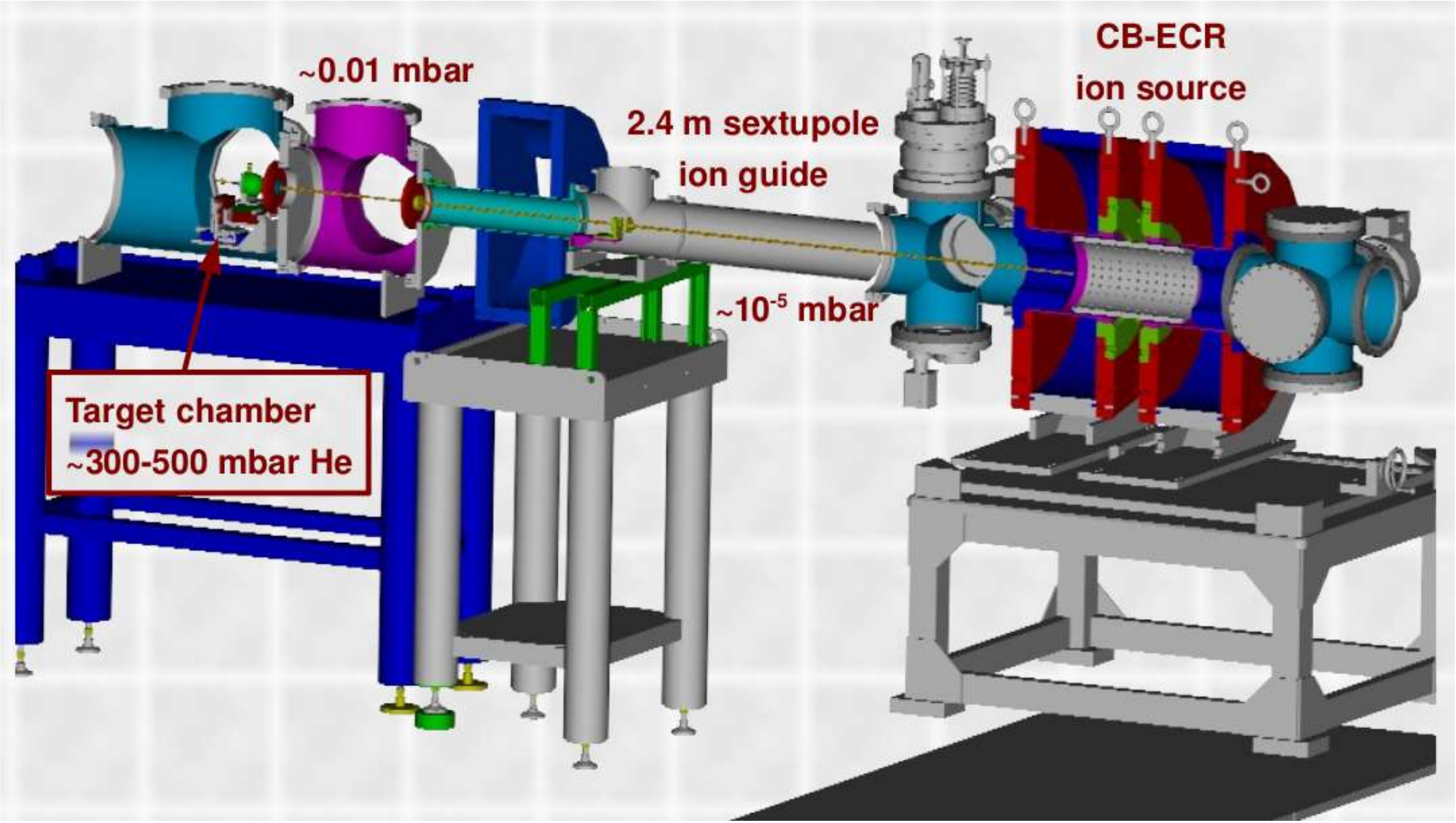
- Ion source not performing to specs
- K150 not able to go to full energy/intensity
- No separator, no one working on it

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



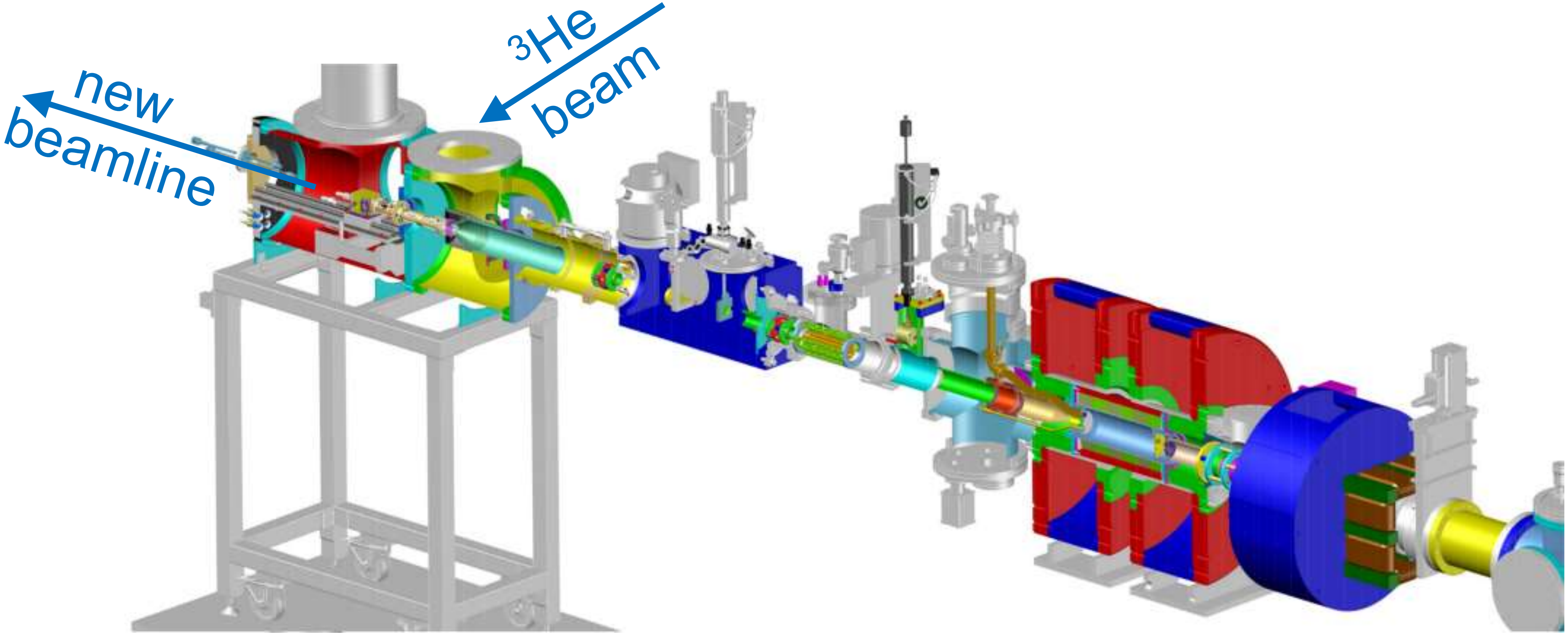
The Light Ion Guide is farther along

- Concept: like Jyvaskyla, light ions on heavy target



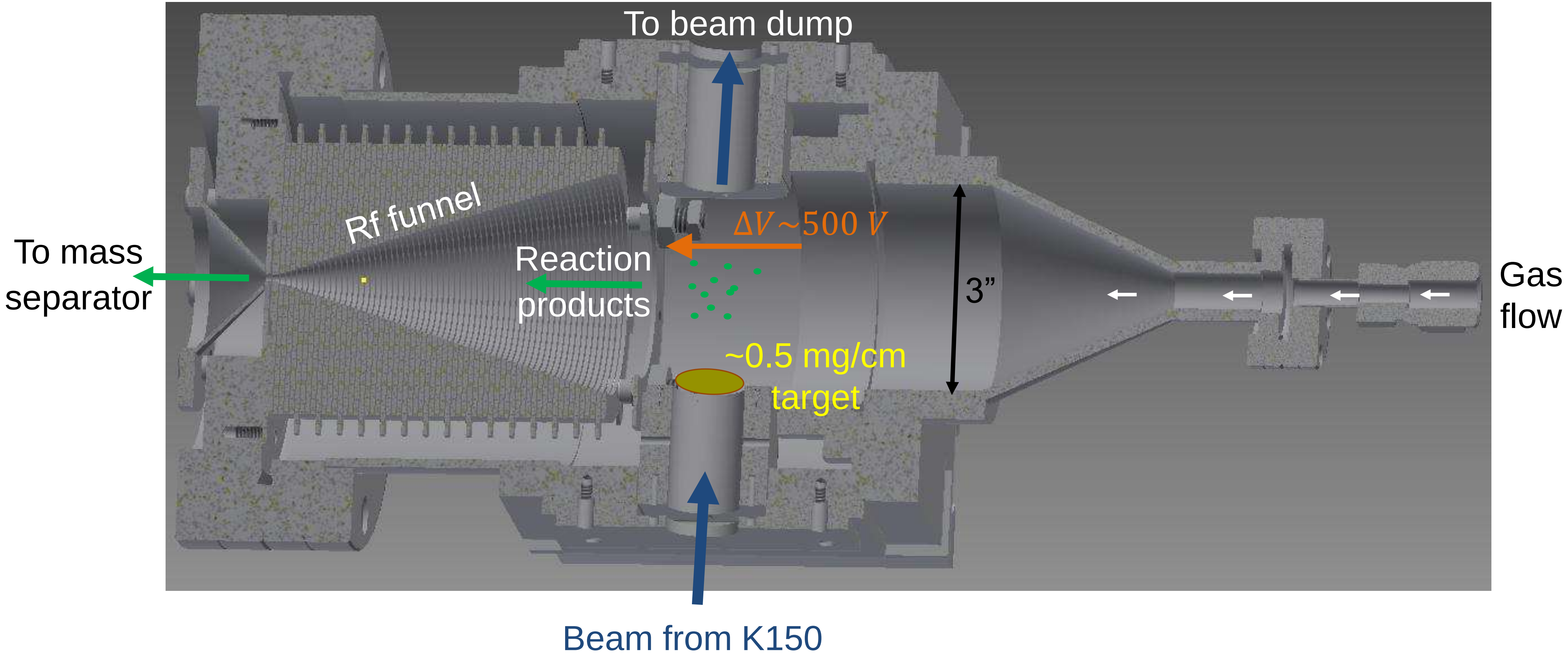
Latest plan: try using the LIG for TAMUTRAP

- Use (^{3}He,3n) reaction; e.g., expect 5,000 ^{24}Si/sec using a ^{24}Mg target
- Same reaction cross-sections, lighter is better for the K150
- New gas cell. Mass separation? Incompatible with HIG…



New gas cell – to be tested this spring

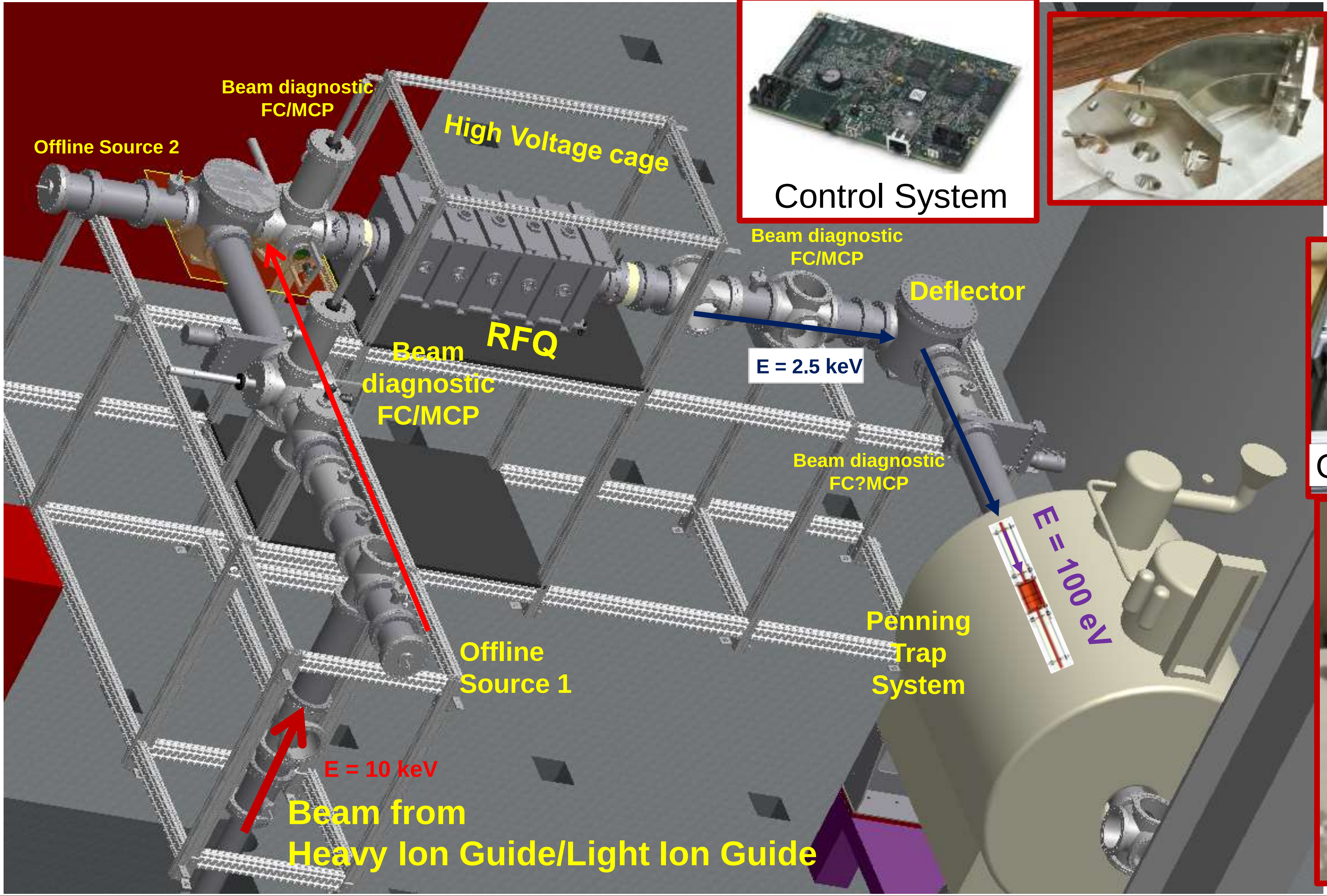
- Efficiency is absolutely critical – need ~20% overall efficiency
  - Gas cell → separator → cooler/bunch → Penning trap



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


Einzel Lens

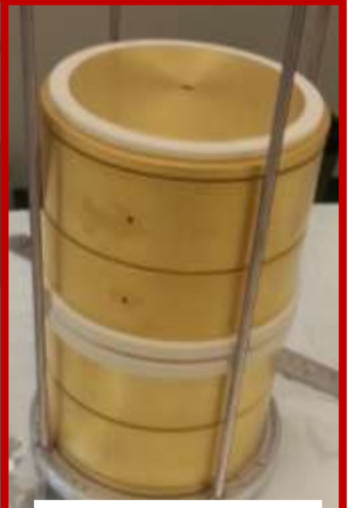

Steerer



Control System

Deflectors

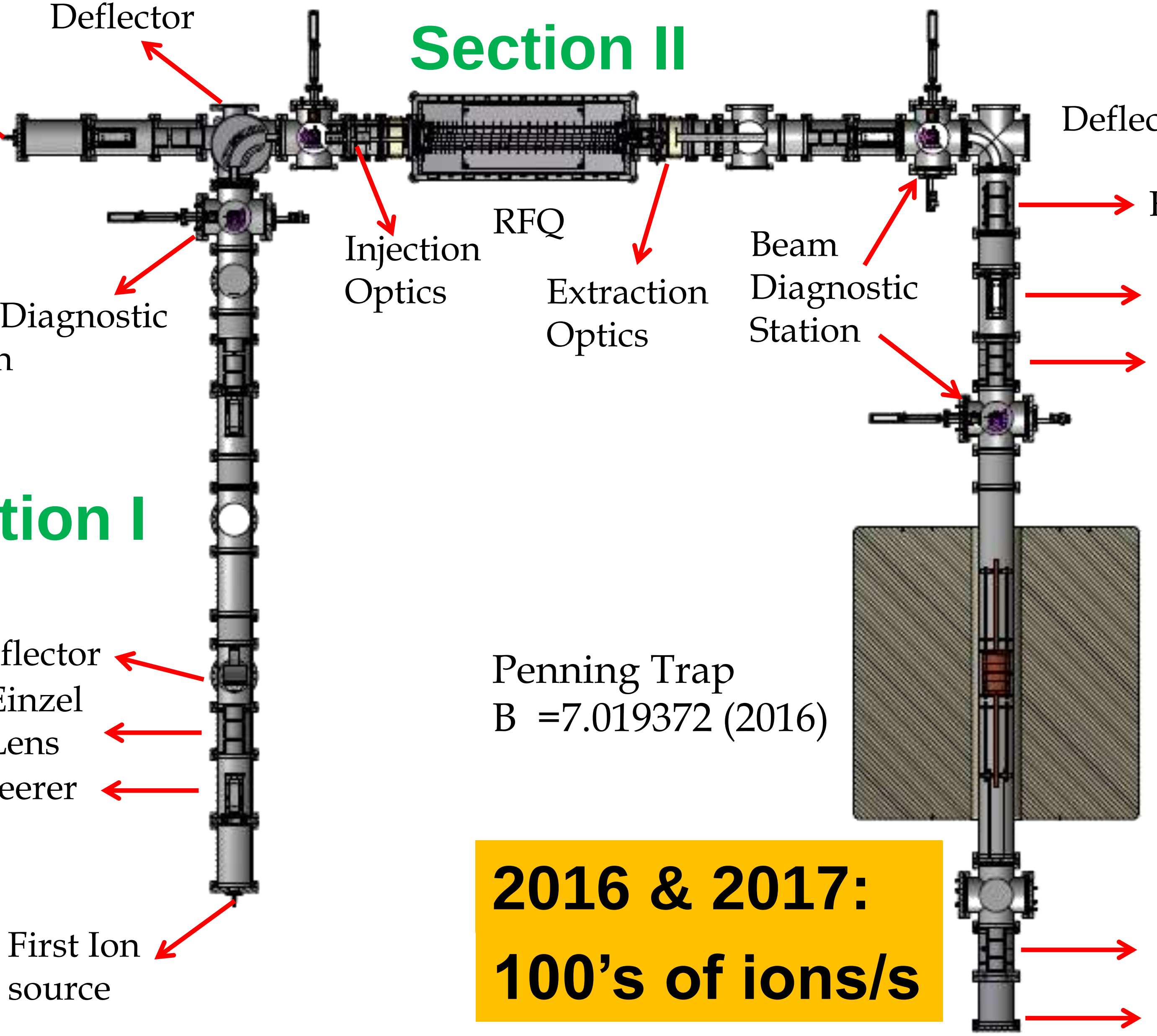

Offline Source


Penning trap

Optimizing the TAMUTRAP beamlines

2016: 120 pA

2017: <1 pA

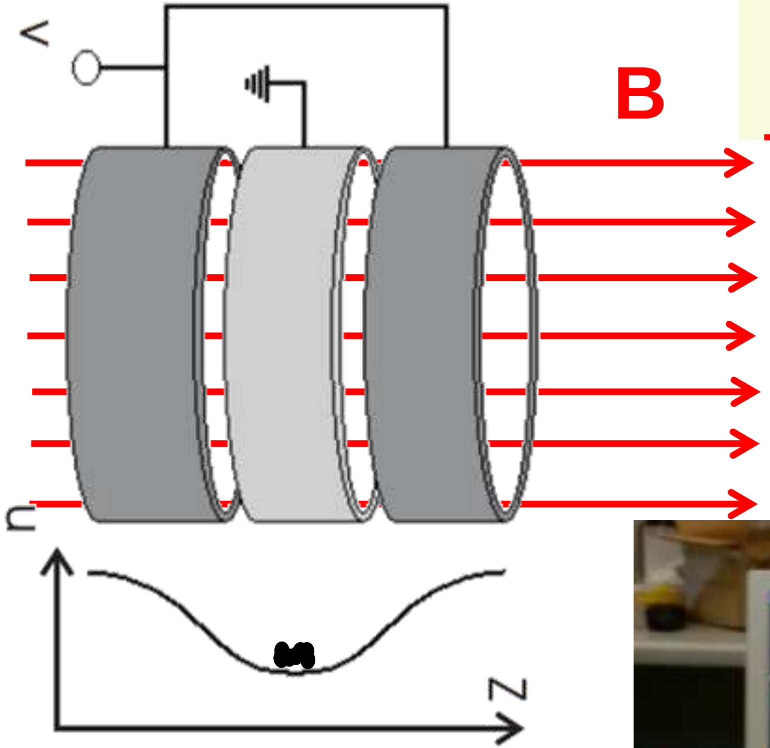


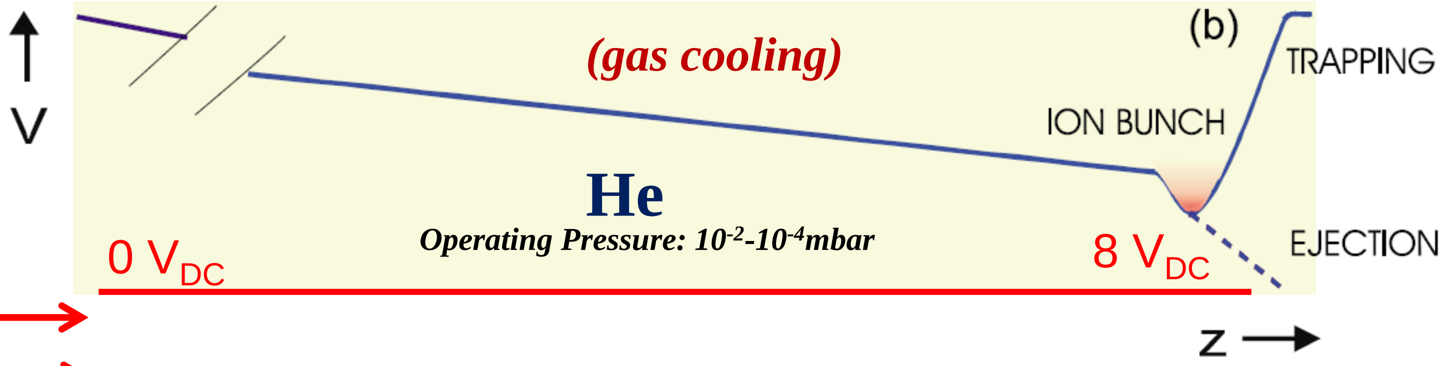
2016 & 2017:

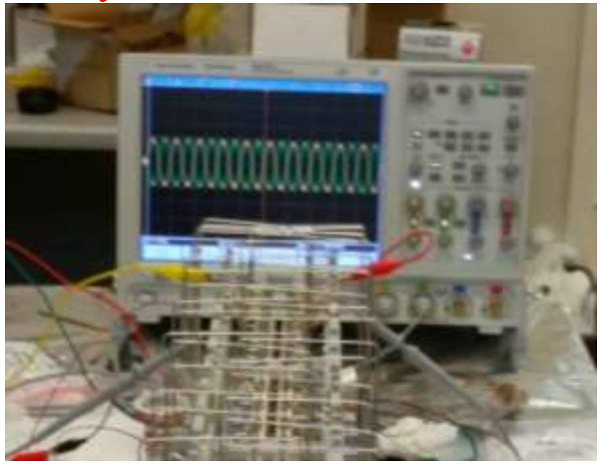
100’s of ions/s

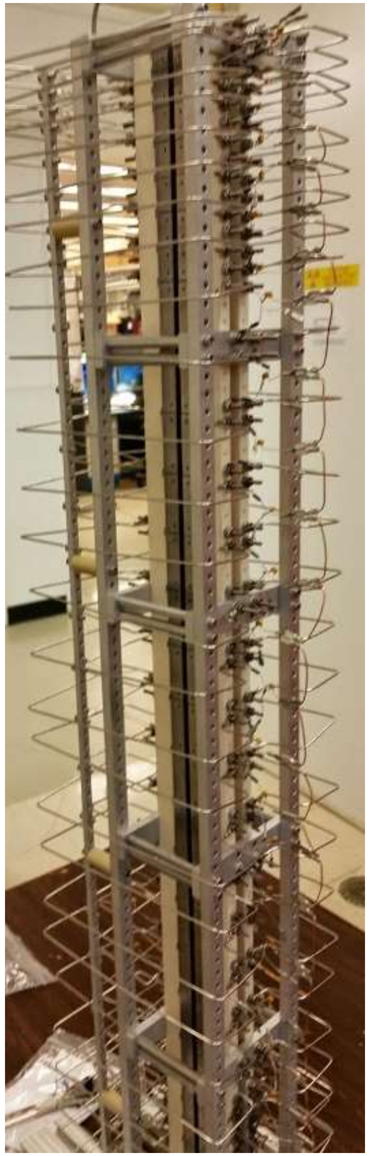
The RFQ cooler/buncher (v2)

- Need bunched beams to load the trap





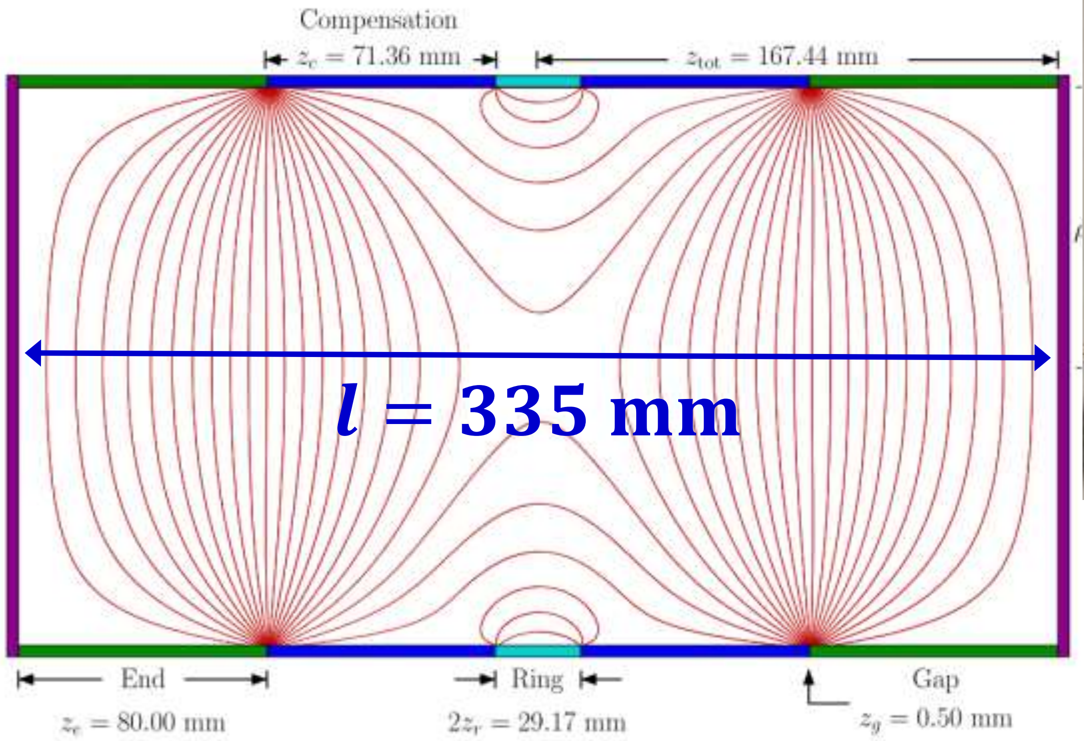


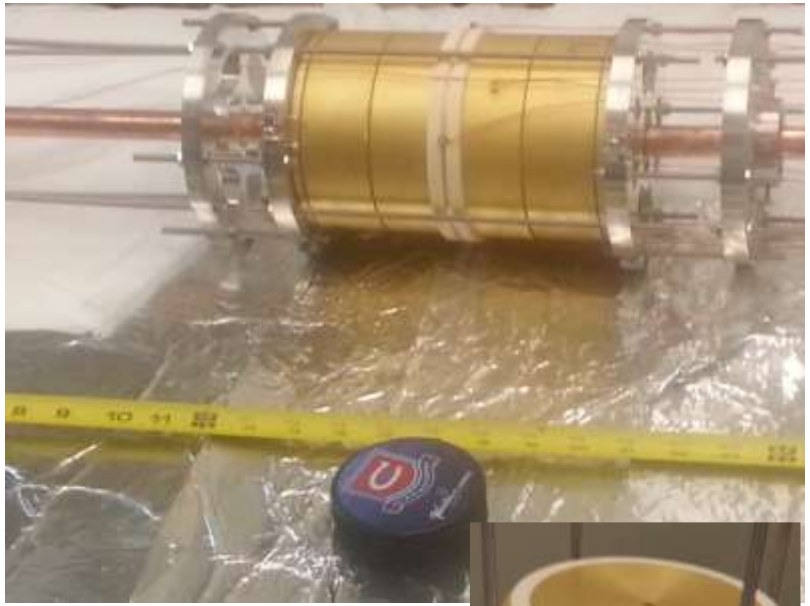


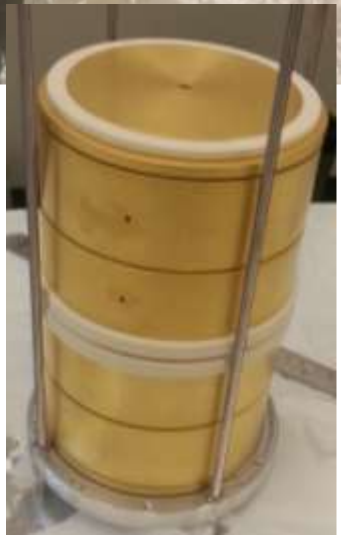
M. Mehlmann (Ph.D. Thesis)

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 $r = 90\ \mathrm{mm}$
  - Needed a new design to make it fit in the 7T magnet







$l/r = 3.72$

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

Mass measurement of ^{23}Na

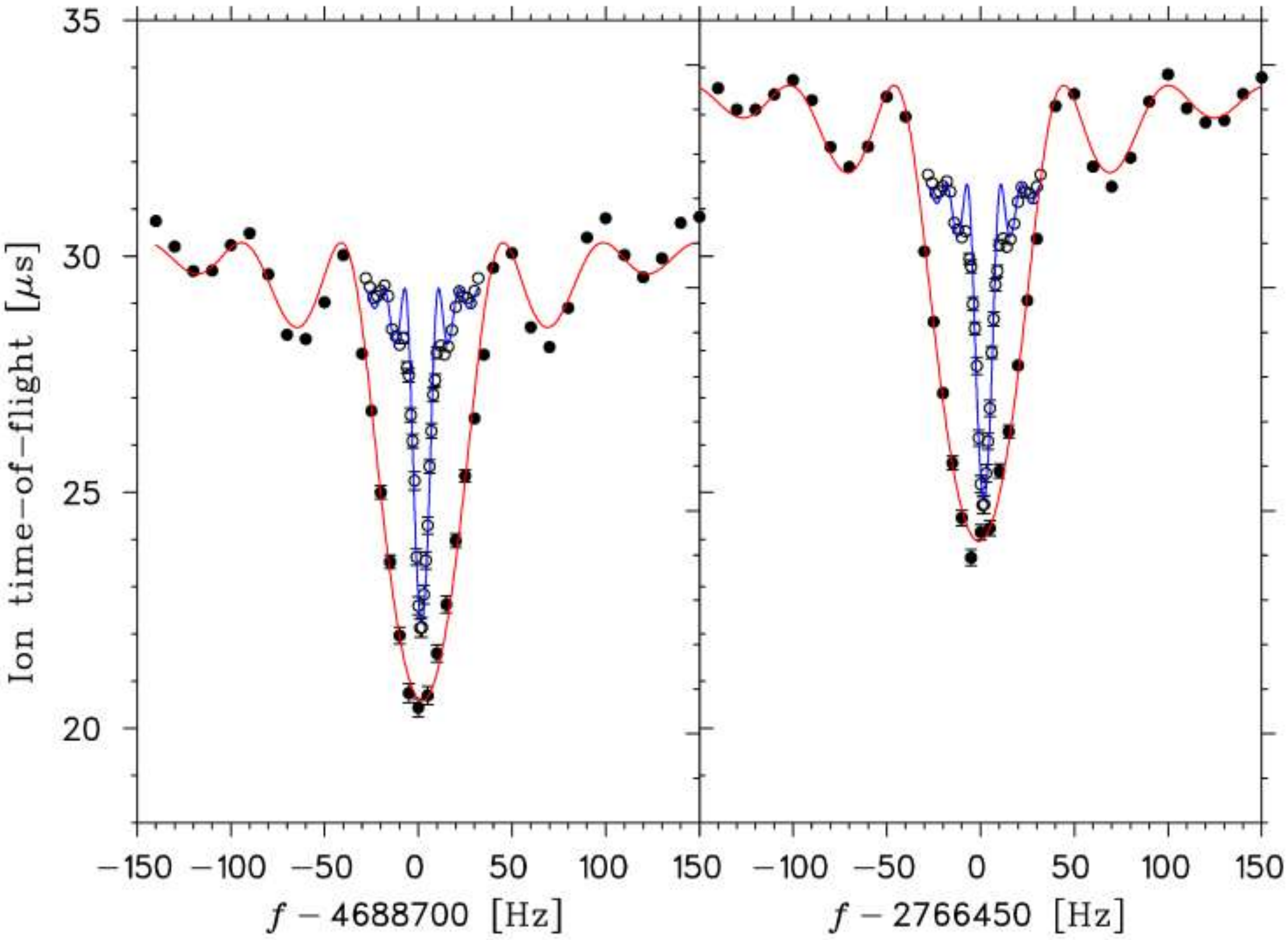
- Find resonant frequencies for ^{23}Na and ^{39}K
- Use AME value for ^{39}K, and calculate $M(^{23}\mathrm{Na})$
- 20 ms excitation (solid points, red curve)

  $\Rightarrow M_{\mathrm{diff}} = \text{calc} - \mathrm{AME}$
  $= 2.8 \pm 2.5\ \mathrm{keV}$

  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

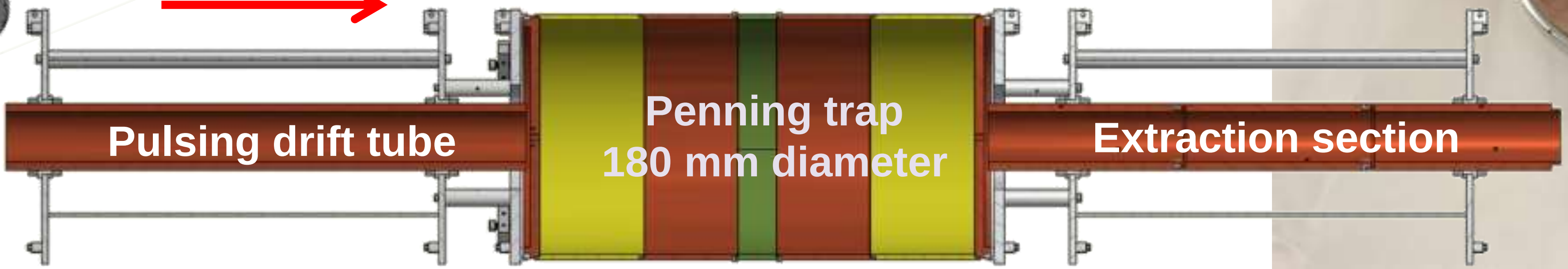


About to install the full Penning trap

- 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

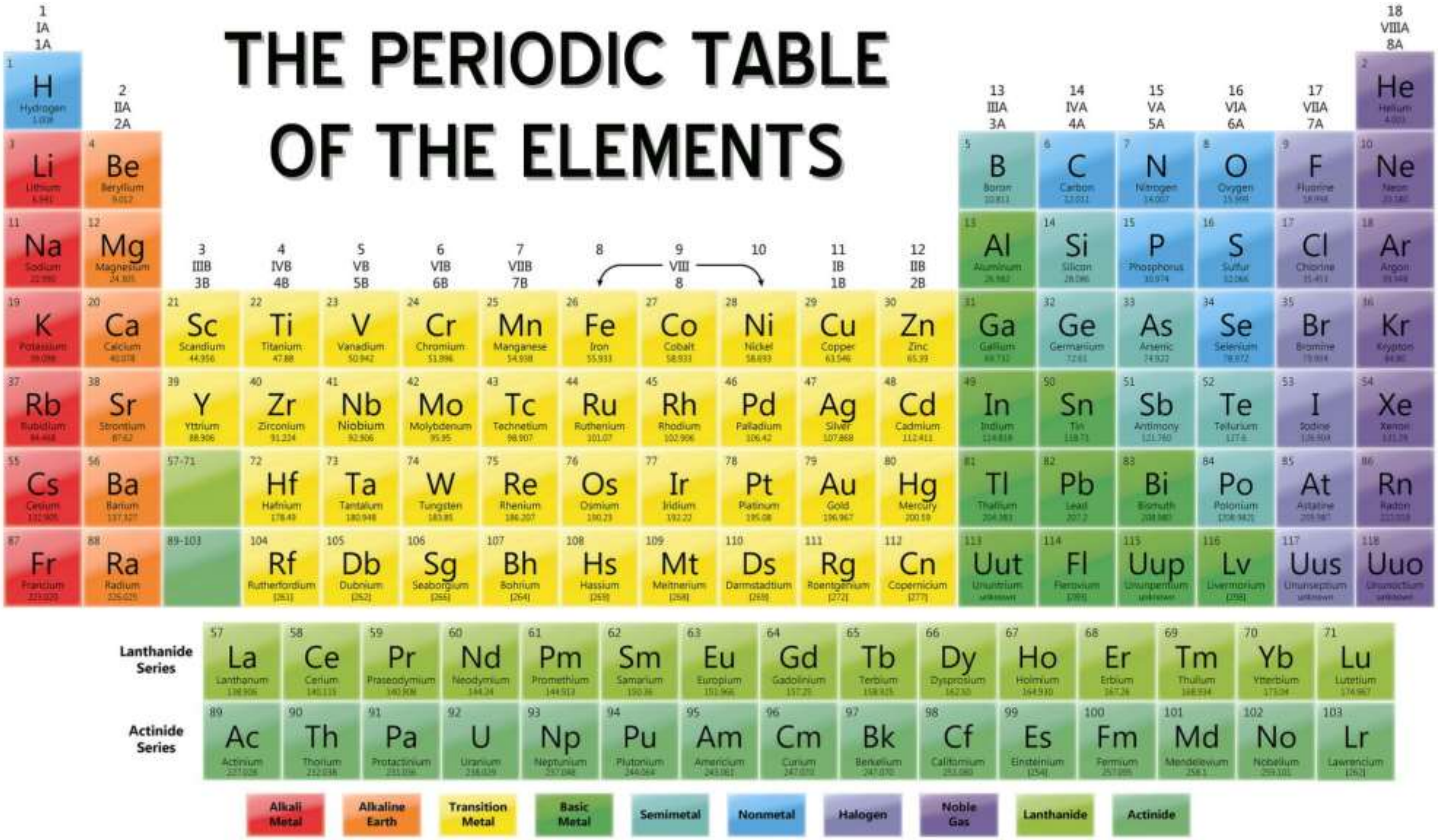
Beam energy 140 eV



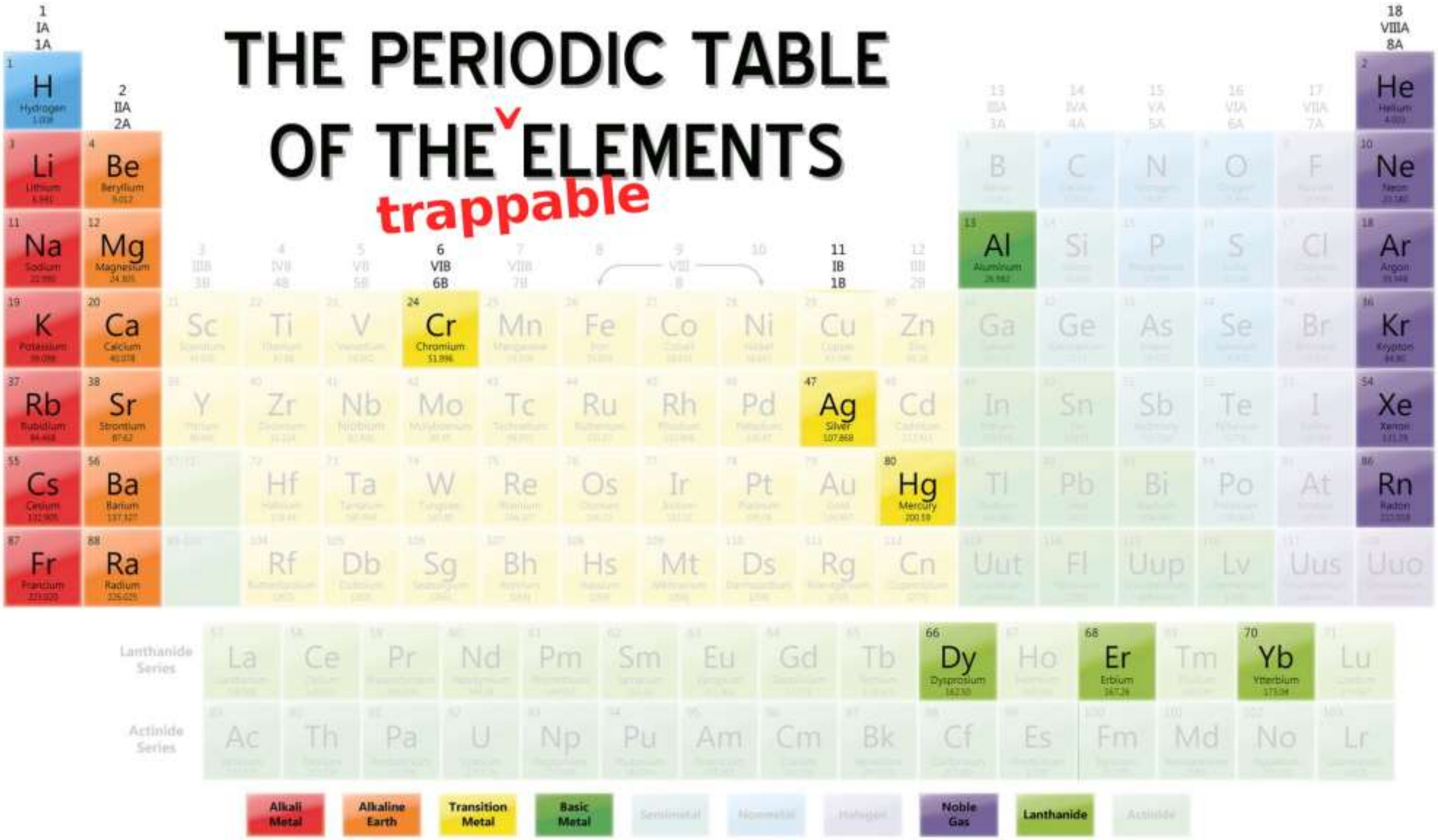
Outline

- 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

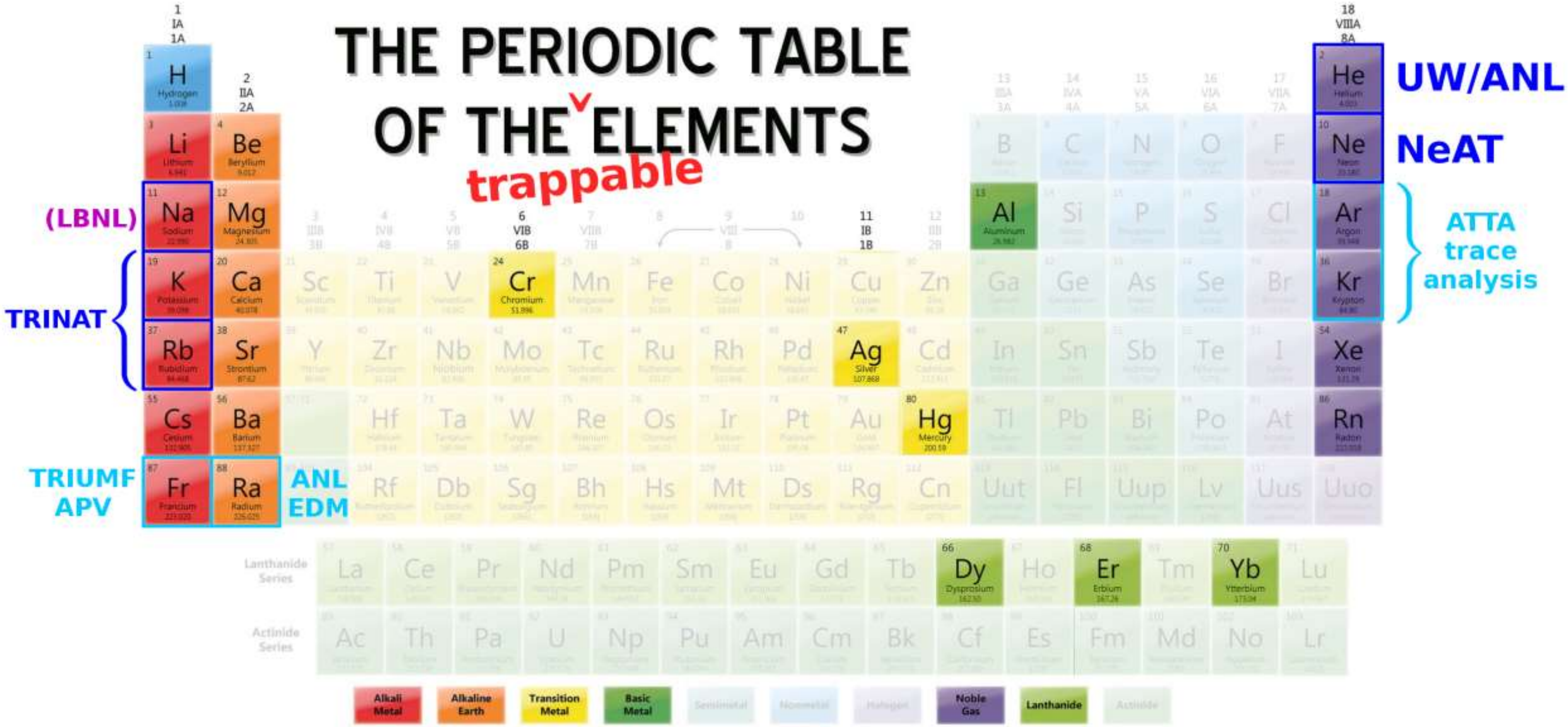
Difficulty with MOTs: not all atoms can be trapped



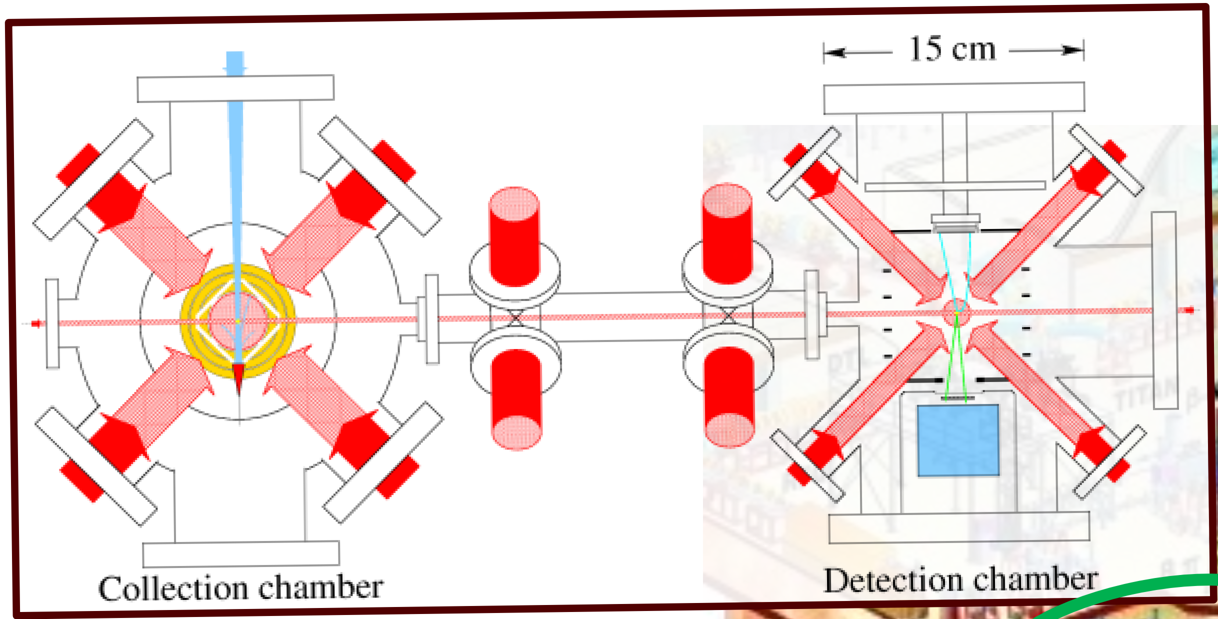
Difficulty with MOTs: not all atoms can be trapped

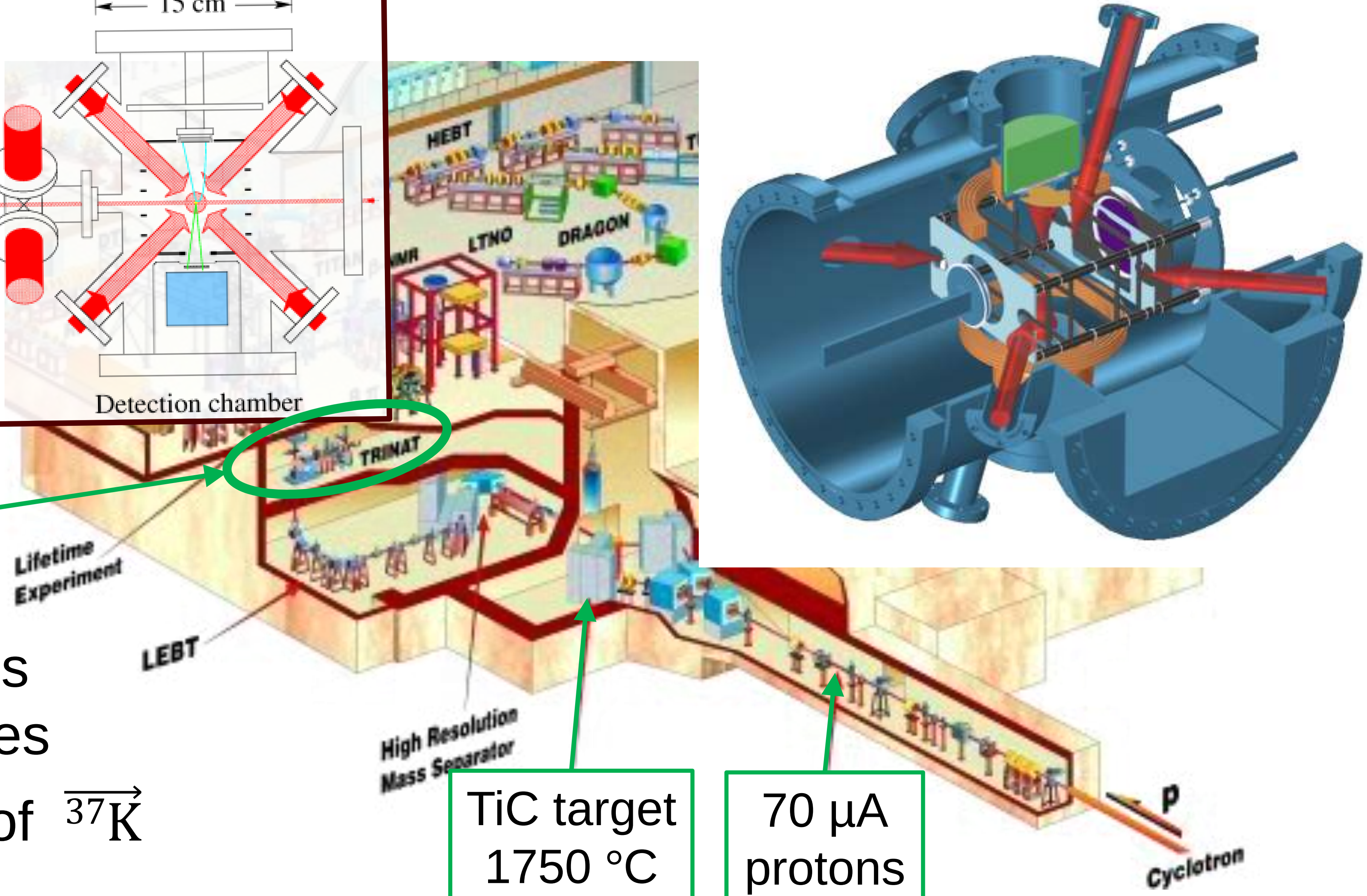


Difficulty with MOTs: not all atoms can be trapped



The TRIUMF Neutral Atom Trap





up to 8×10^7 ^{37}K/s

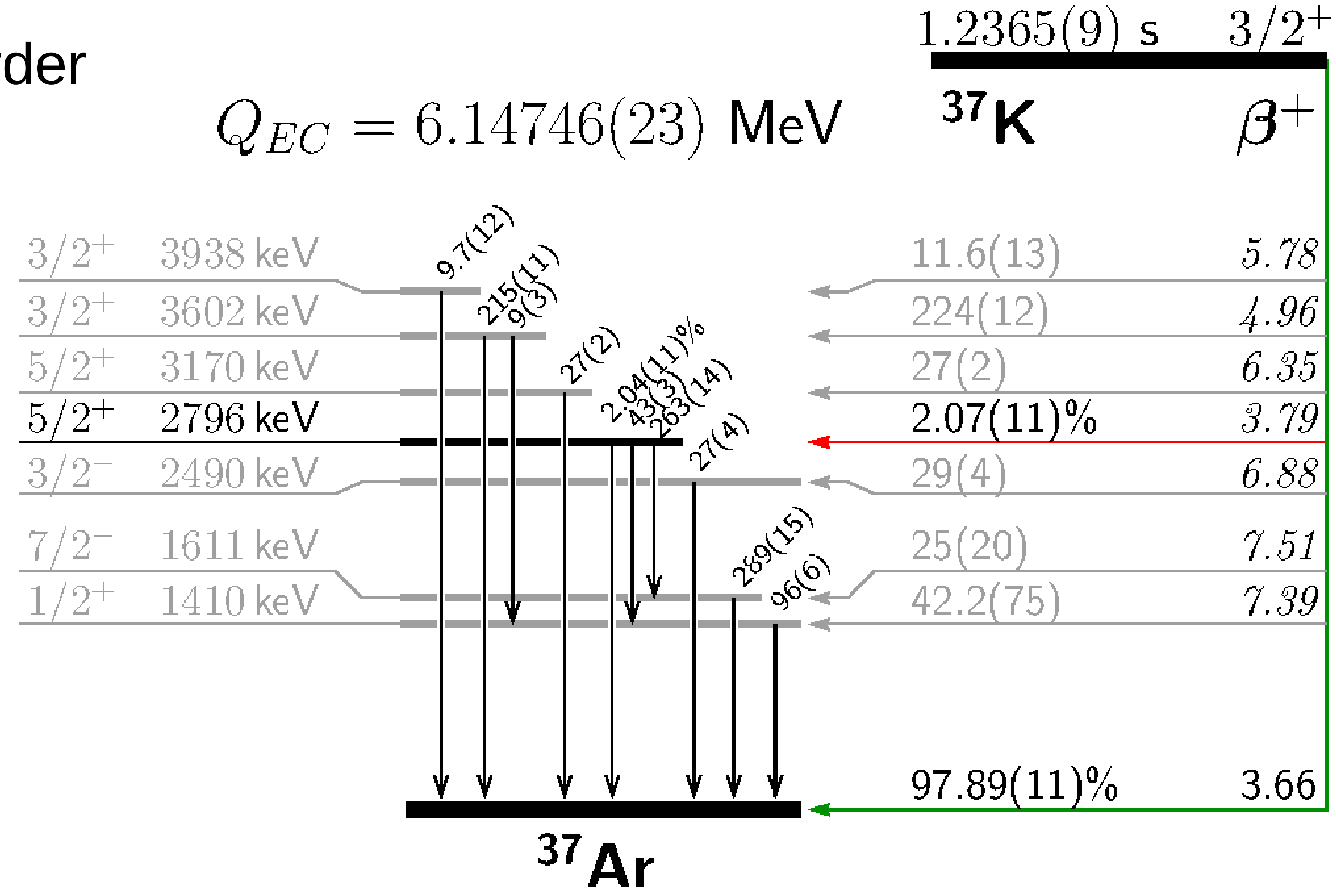
TiC target 1750 °C

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.



Isobaric analogue decay of ^{37}K

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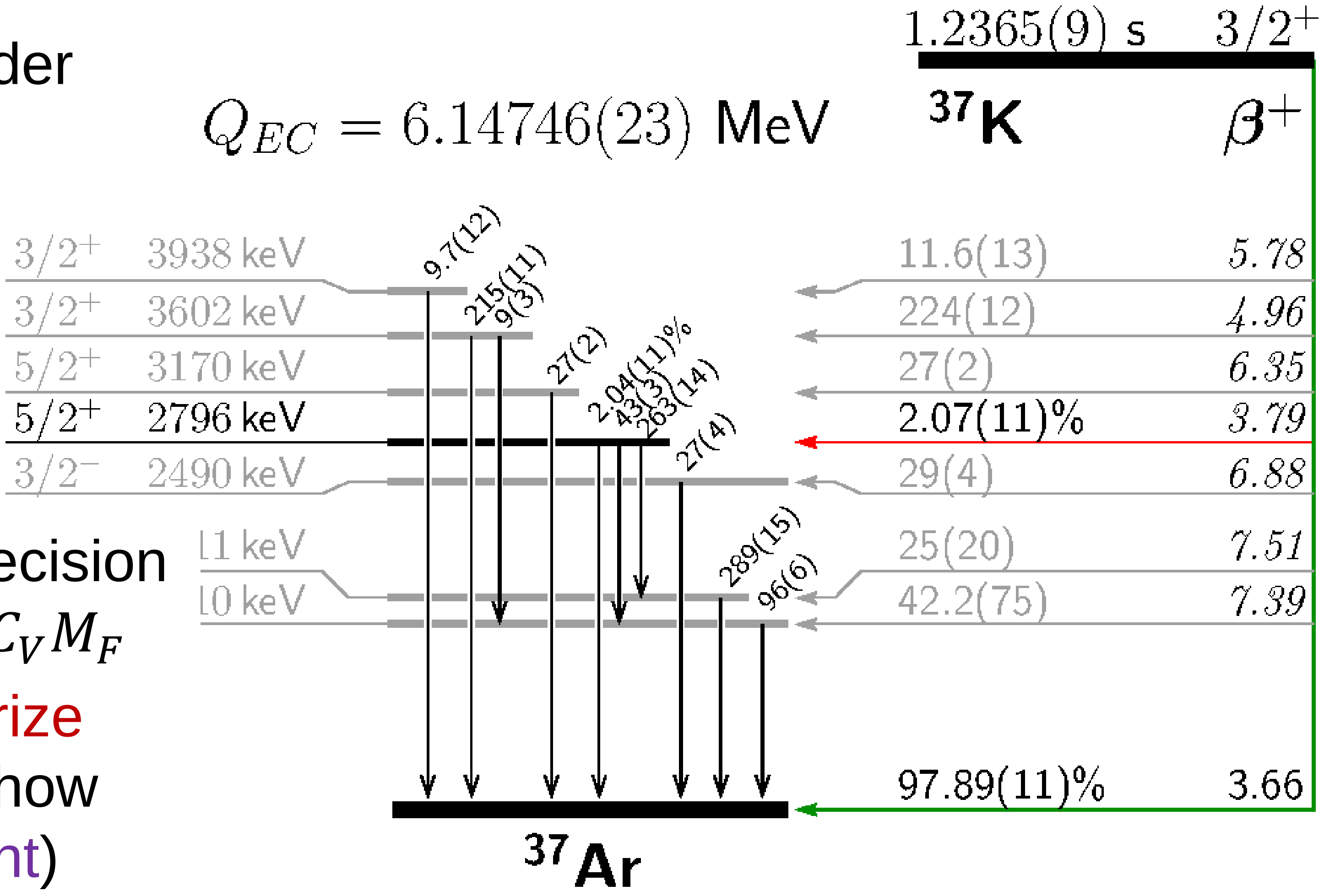
  - Alkali atom ⇒ “easy” to trap with a MOT and polarize with optical pumping
  - Isobaric analogue decay
    ⇒ theoretically clean; recoil-order corrections under control
  - Lifetime, *Q*-value and branches (*i.e.* the Ft value) well known
  - Strong branch to the g.s.
- But there are challenges…
  - 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)



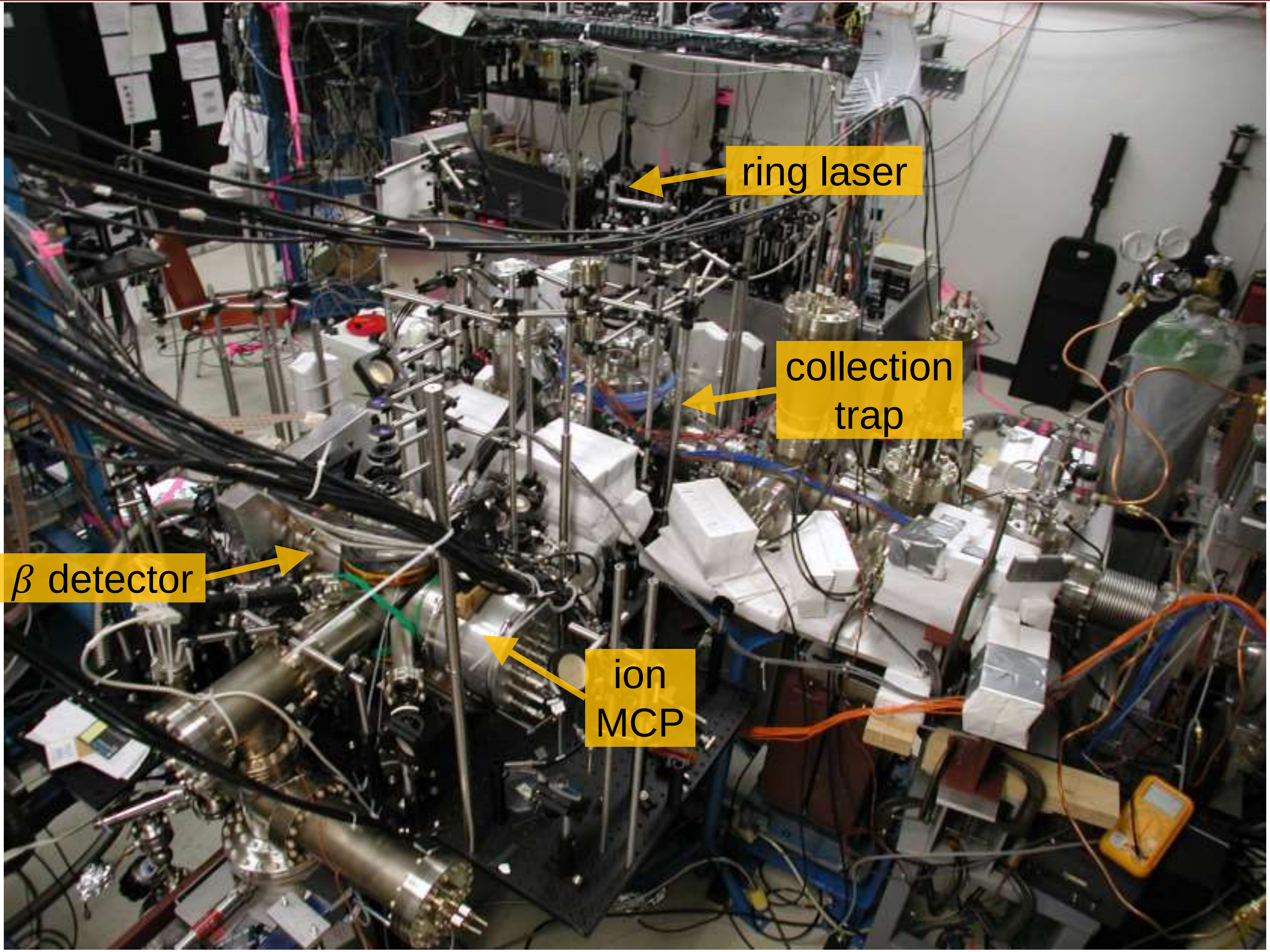
The Ft is measured well enough (for now)

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

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)

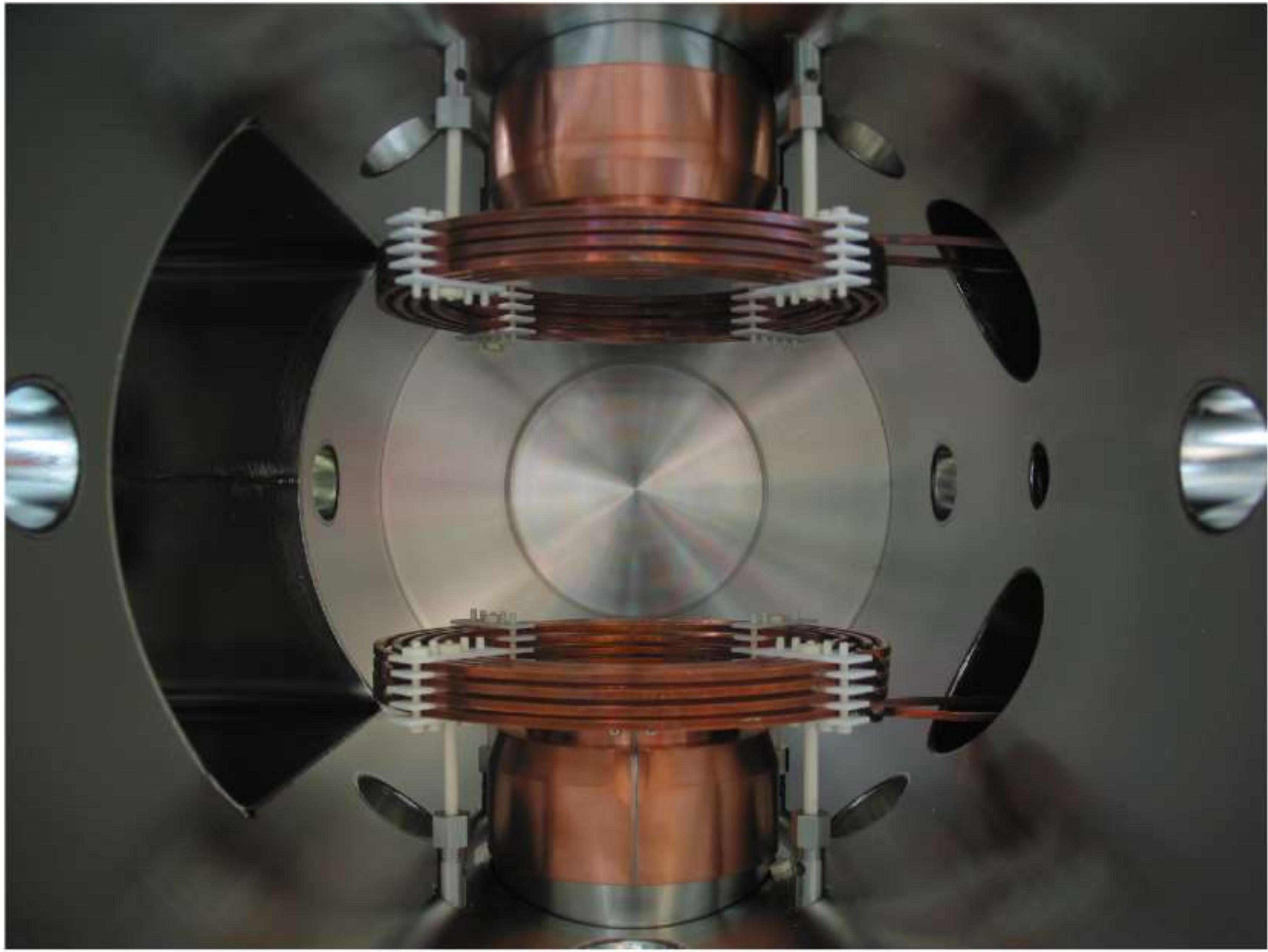
The TRINAT lab (an older picture)



RIB from ISAC

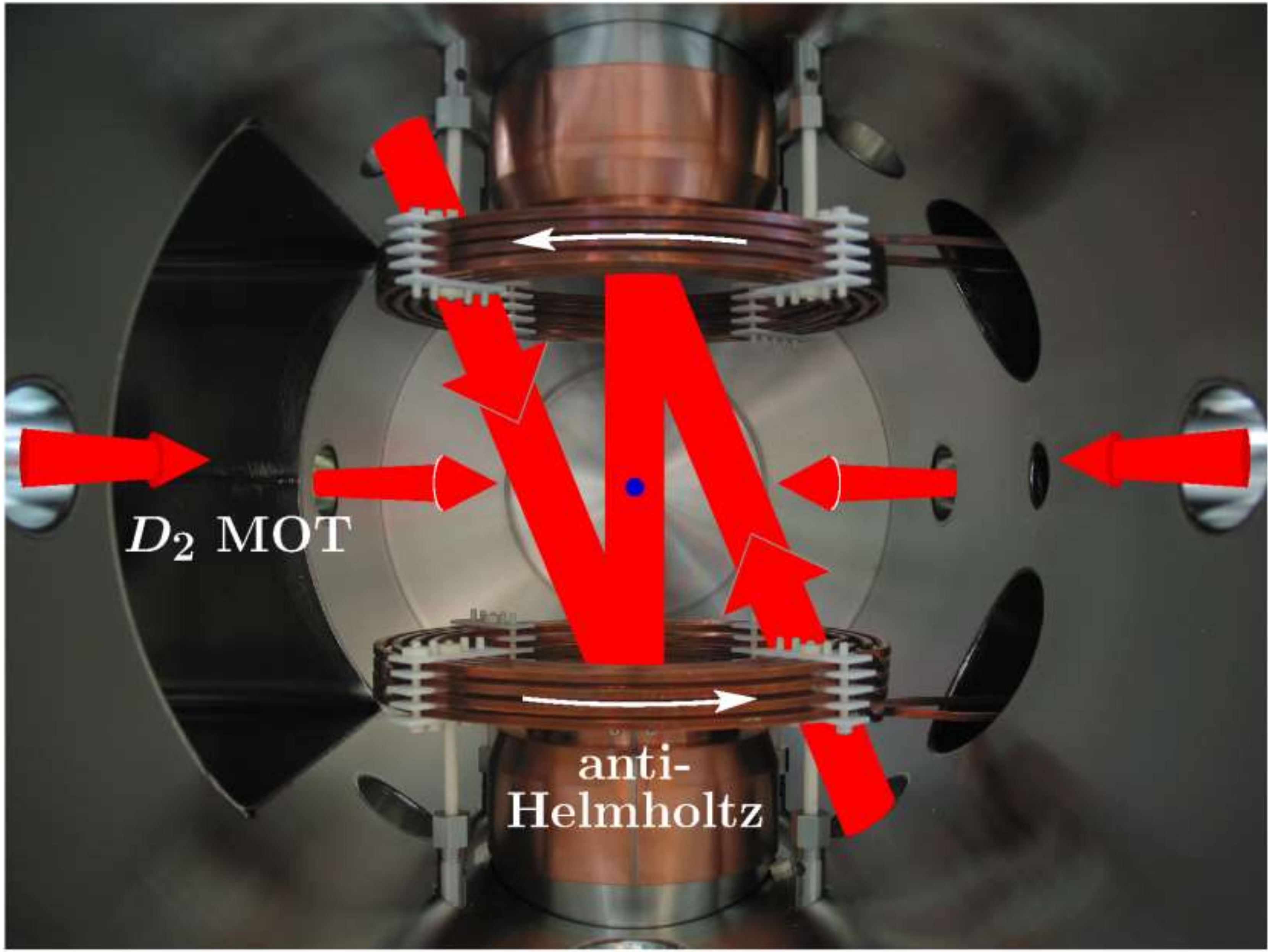
Outline of β asym & polarization measurements

- 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)



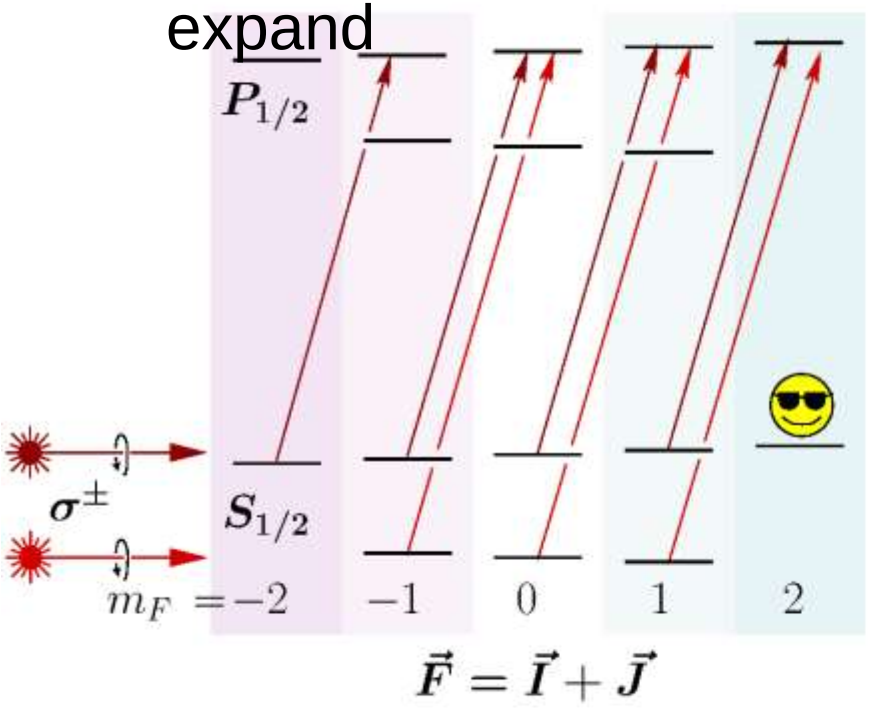
Outline of β asym & polarization measurements

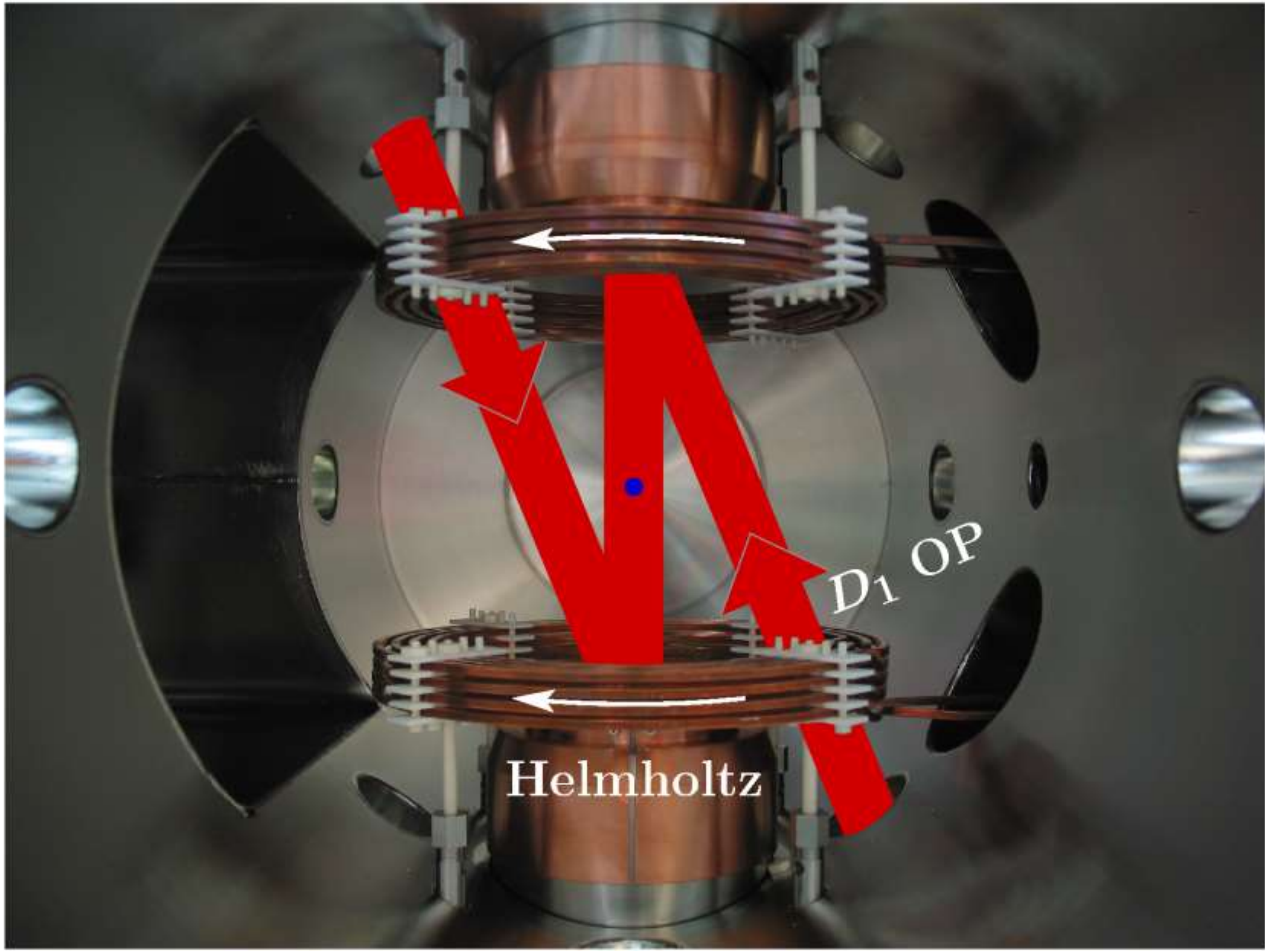
- MOTs provide a source that is:
  - Cold ($\sim 1\ \mathrm{mK}$)
  - Localized ($\sim 1\ \mathrm{mm}^3$)
  - In an open, backing-free geometry
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\mathrm{rec}}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event



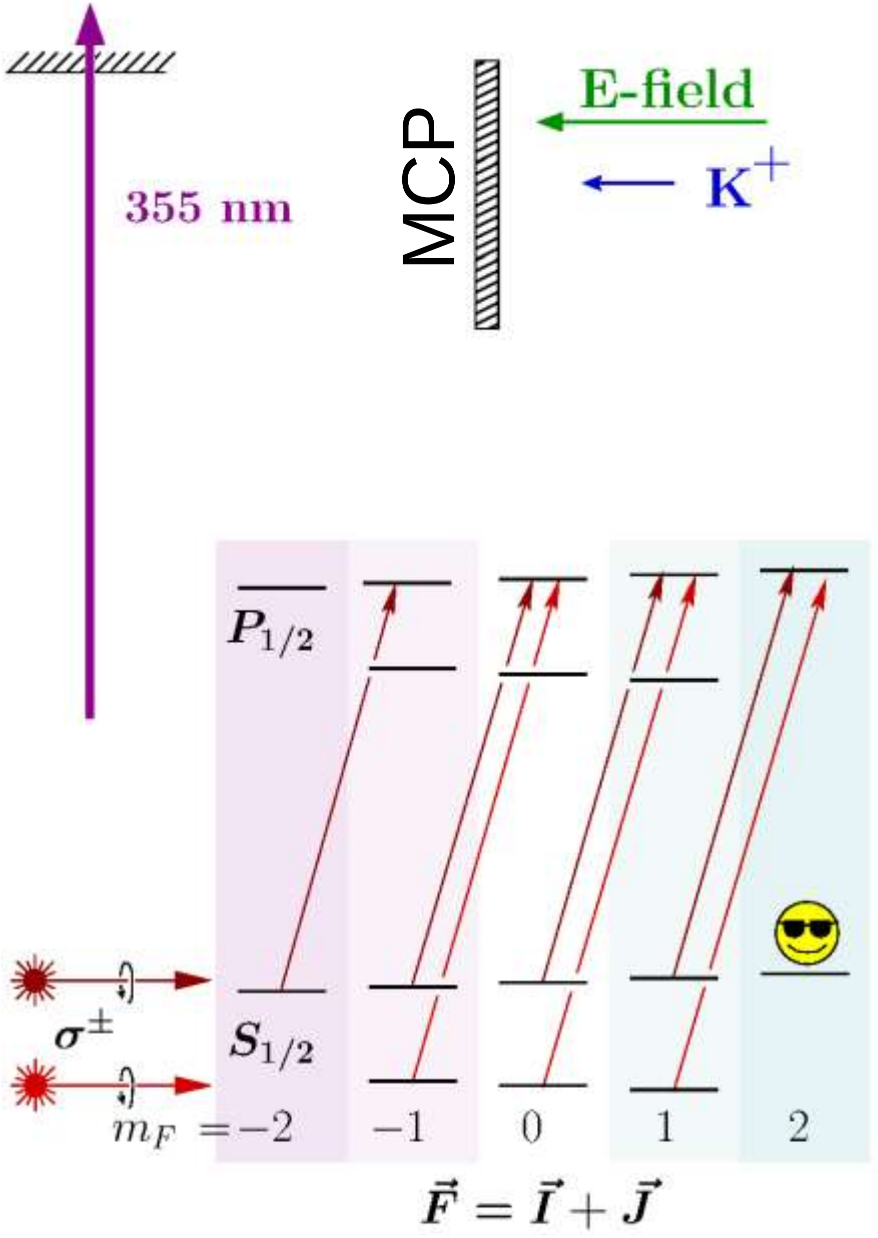
Outline of β asym & polarization measurements

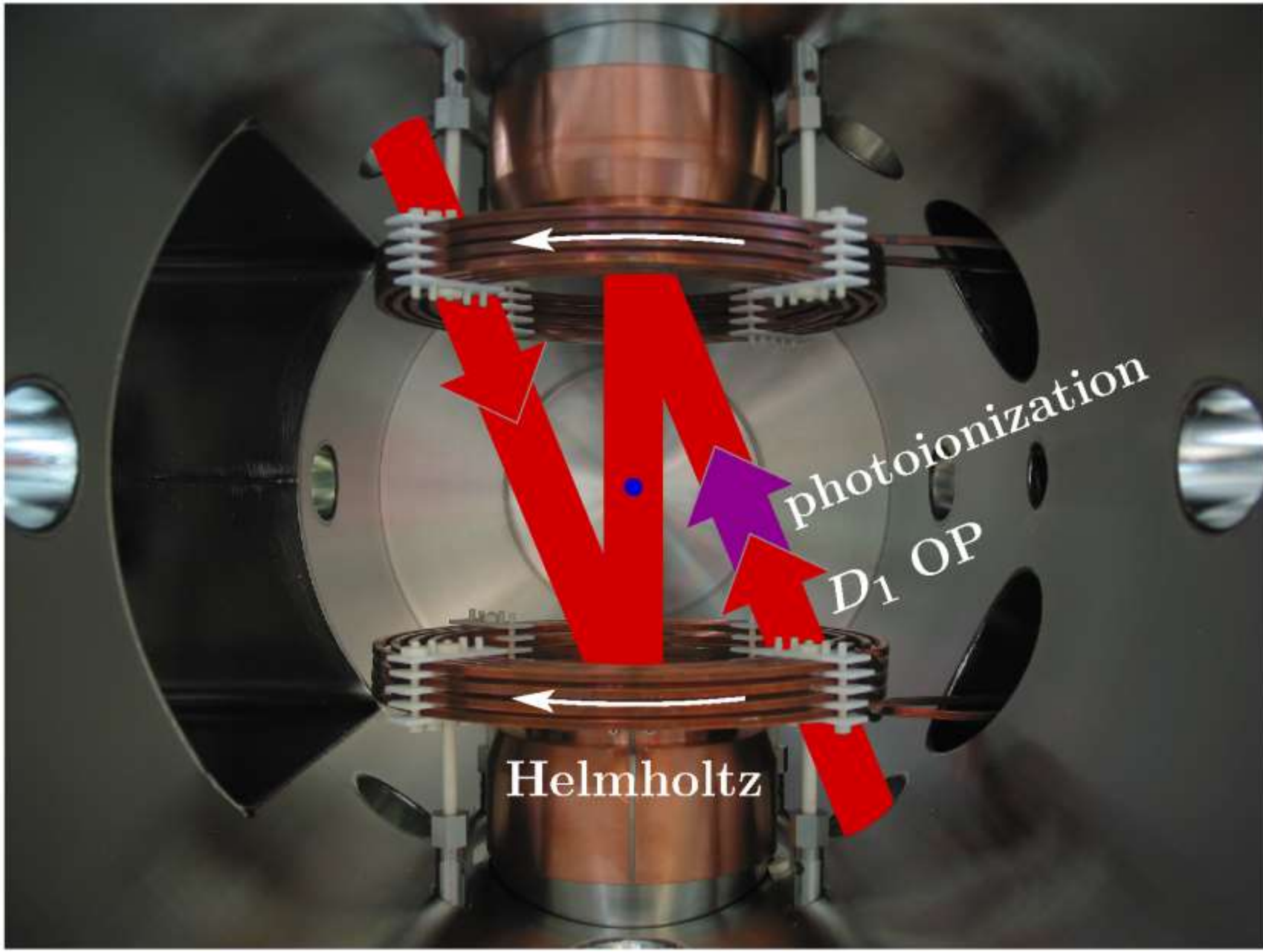
- Optical pumping:
  - Polarized light transfers ang momentum to atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand





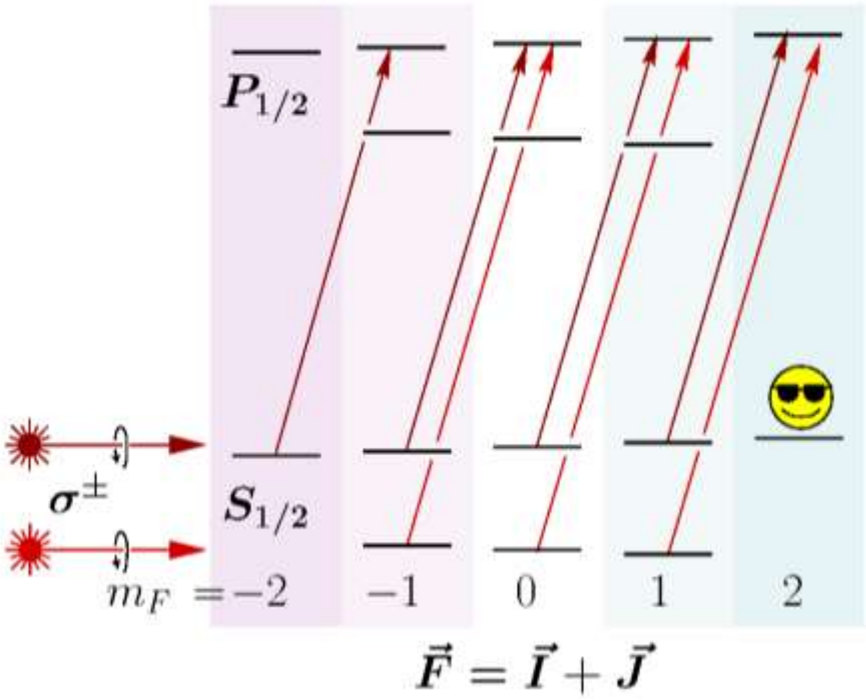
Outline of β asym & polarization measurements

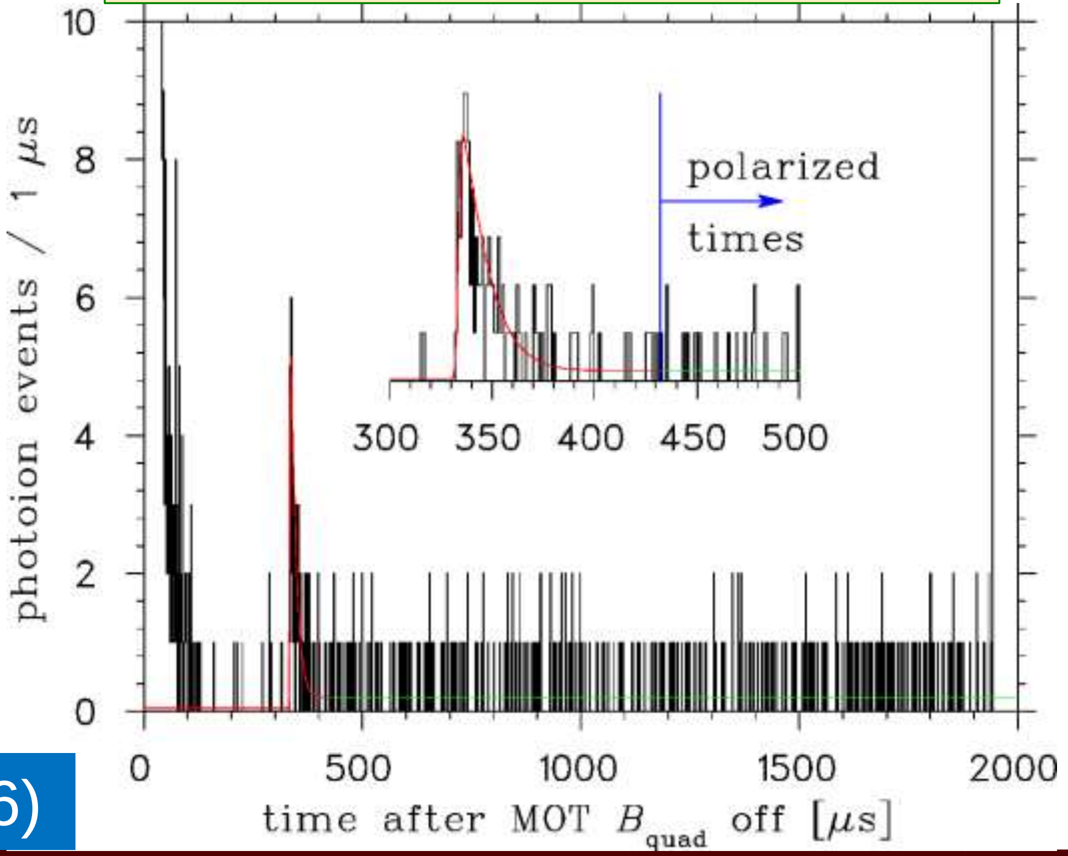




Optical pumping is fast and *efficient*!

- 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

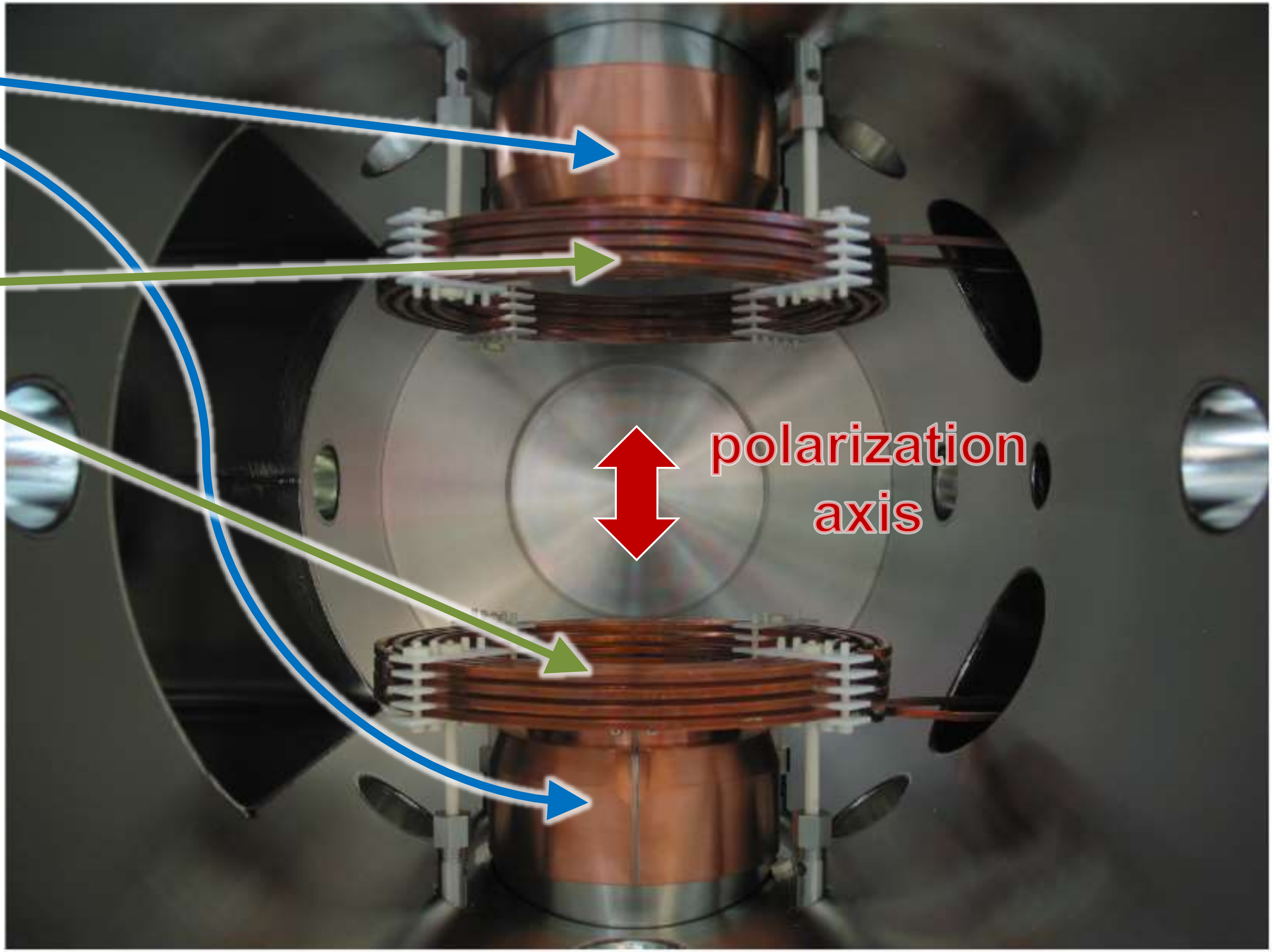
E_β **detectors**:
Plastic scintillator

ΔE_β **detectors**:
Double-sided Si-strip

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

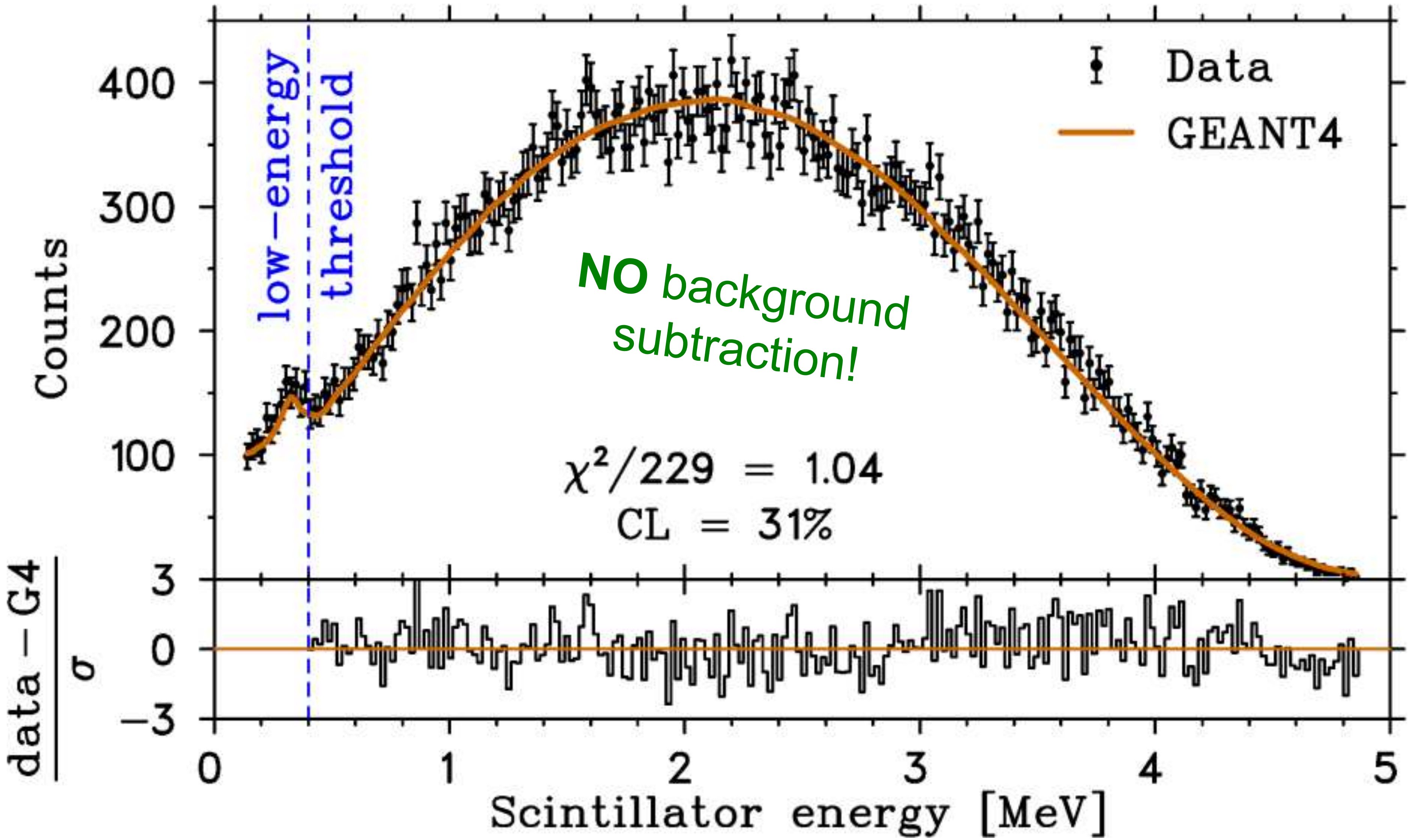
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

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



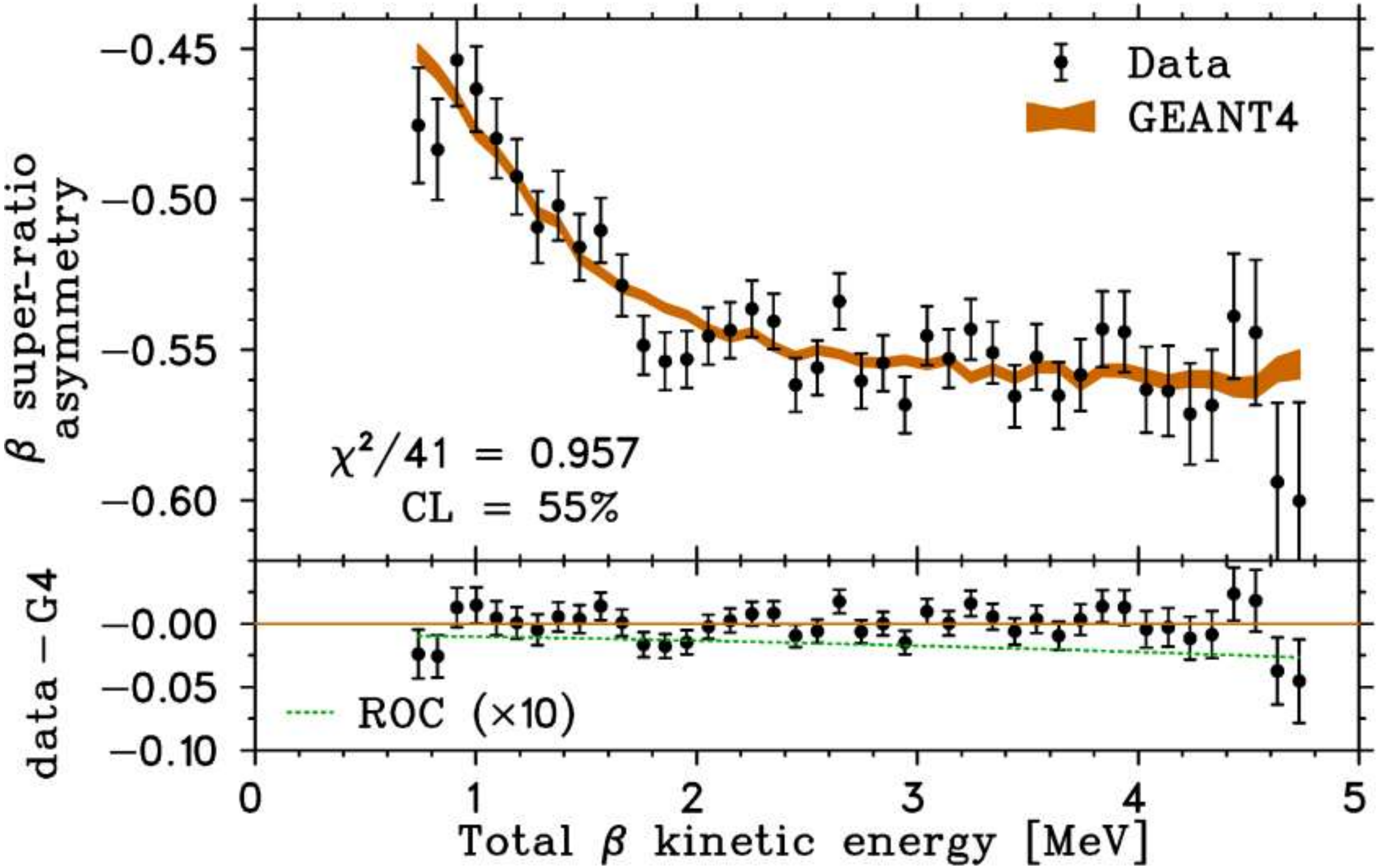
^{37}K β asymmetry measurement

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



^{37}K β asymmetry measurement

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

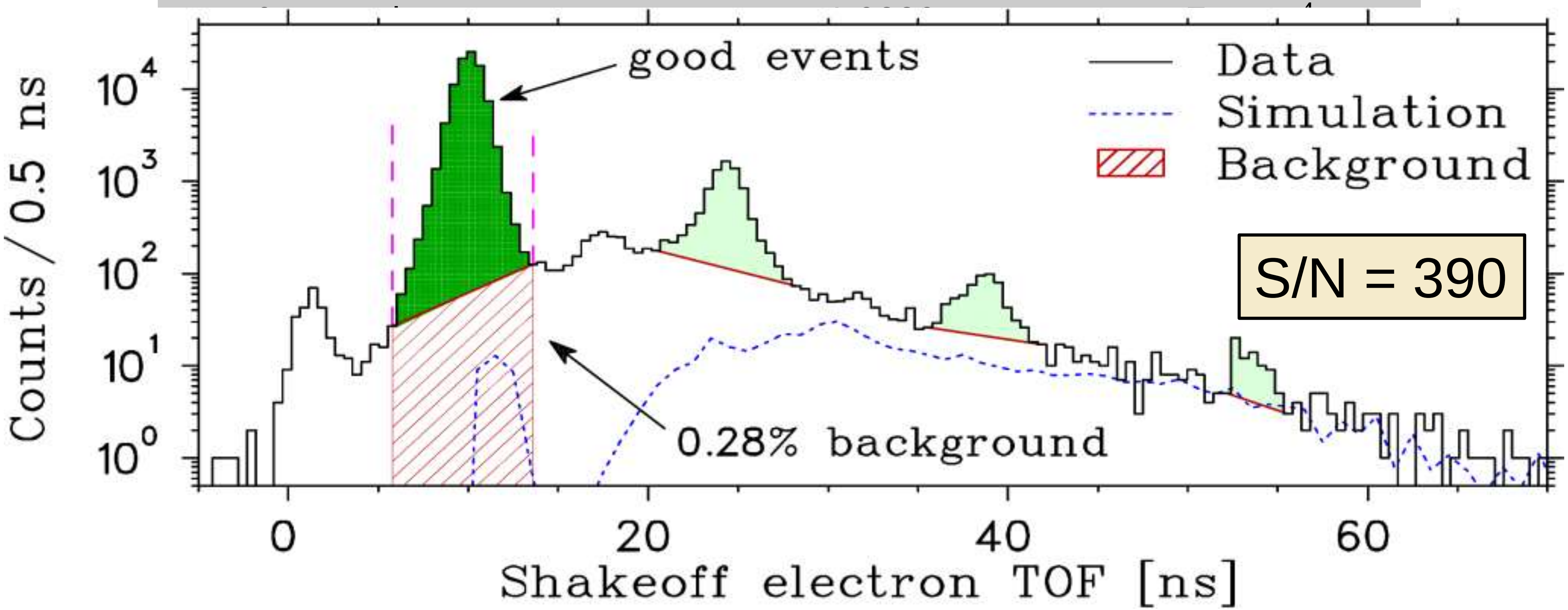


(Dominant) Error budget

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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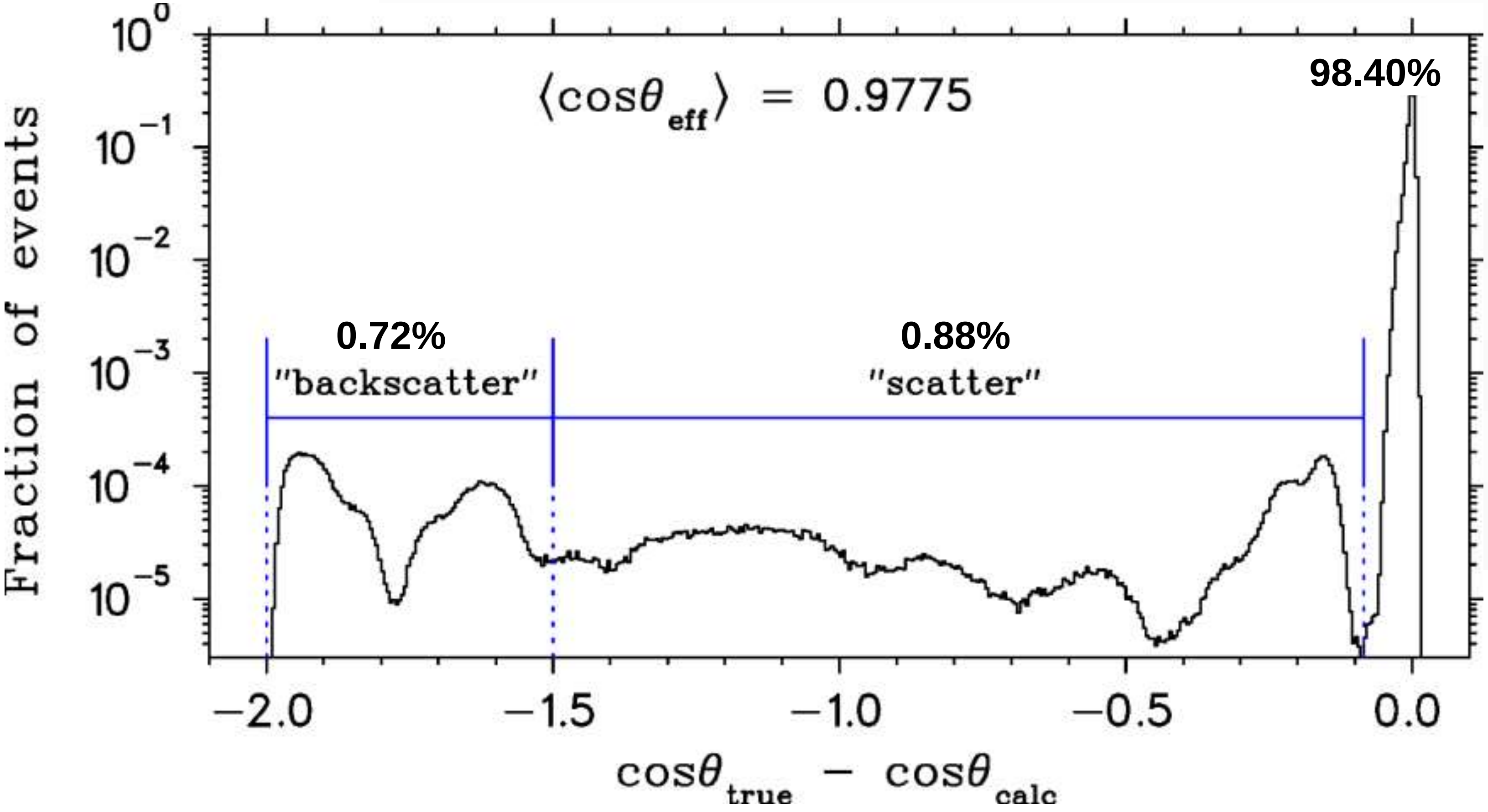
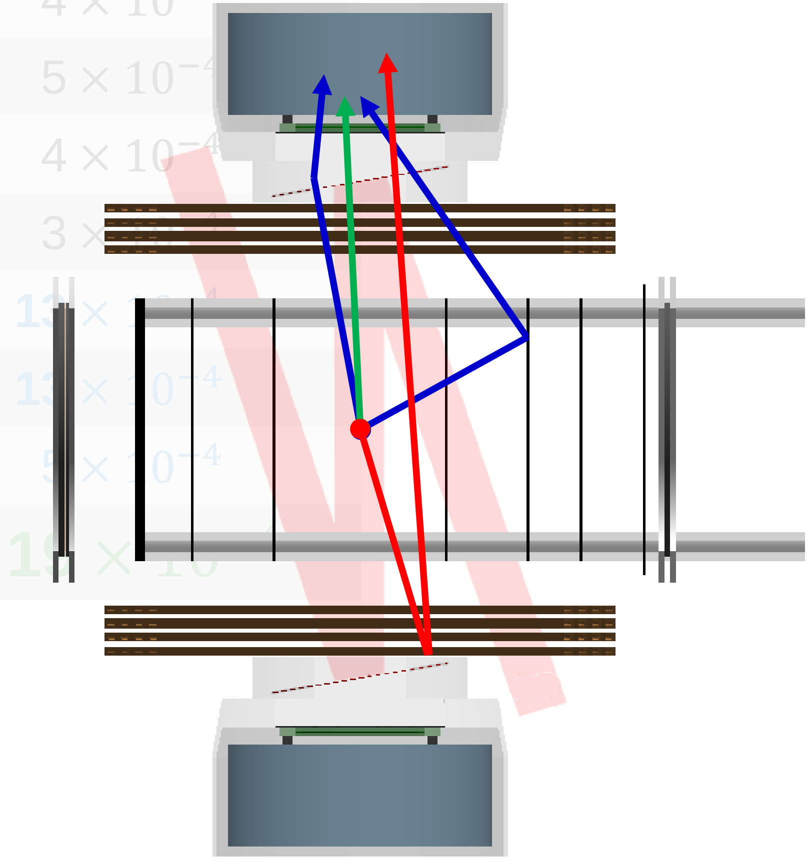
Systematics		
Background	1.0014	8×10^{-4}
β scattering	**1.0230**	**7×10^{-4}**

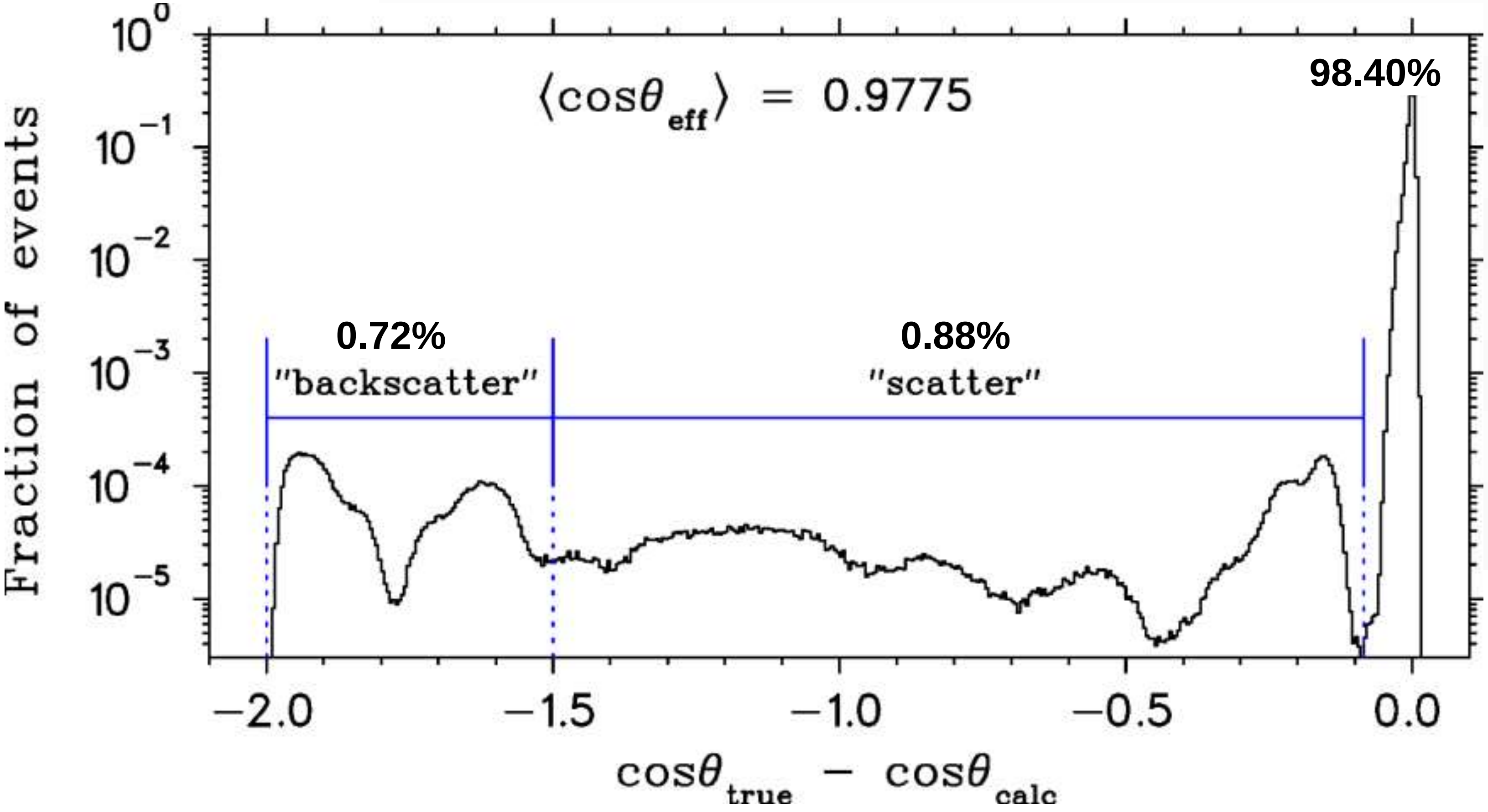


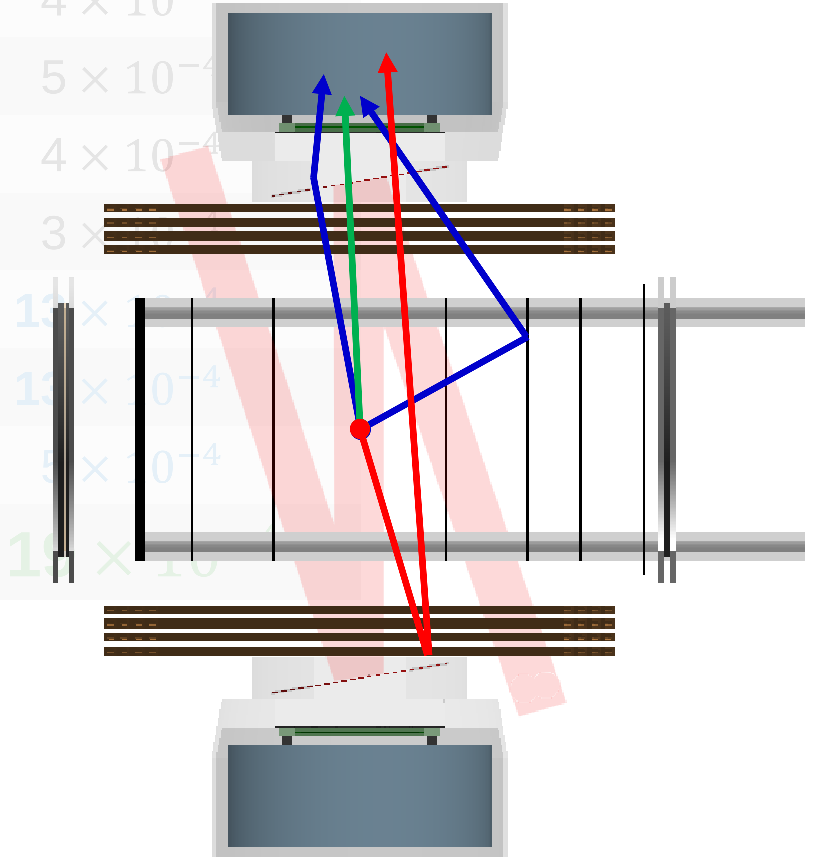


(Dominant) Error budget and A_β result

How well can we trust GEANT4 to simulated β scattering?

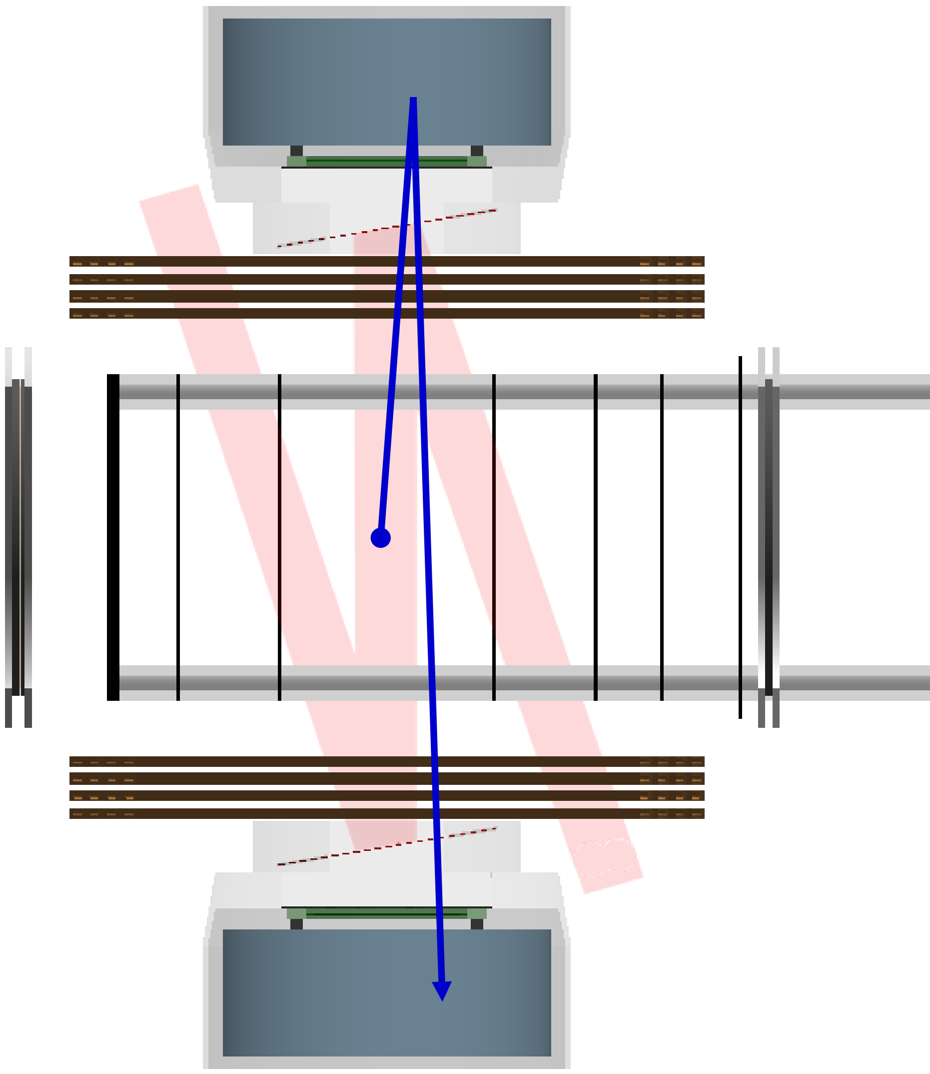
	Correction	Uncertainty, ΔA_β
	1.0014	8×10^{-4}
β scattering	**1.0230**	**7×10^{-4}**





Measurement of β scattering

- Our geometry allows us to measure backscattering of βs and compare to GEANT4 simulations
- Obvious, very clean check: both telescopes register a β event
- Due to small solid angle to go from one to the other ($\sim 0.25\%$), not enough statistics with current data set ($\sim 10^{-4}$ of non-scattered)



Measurement of β scattering

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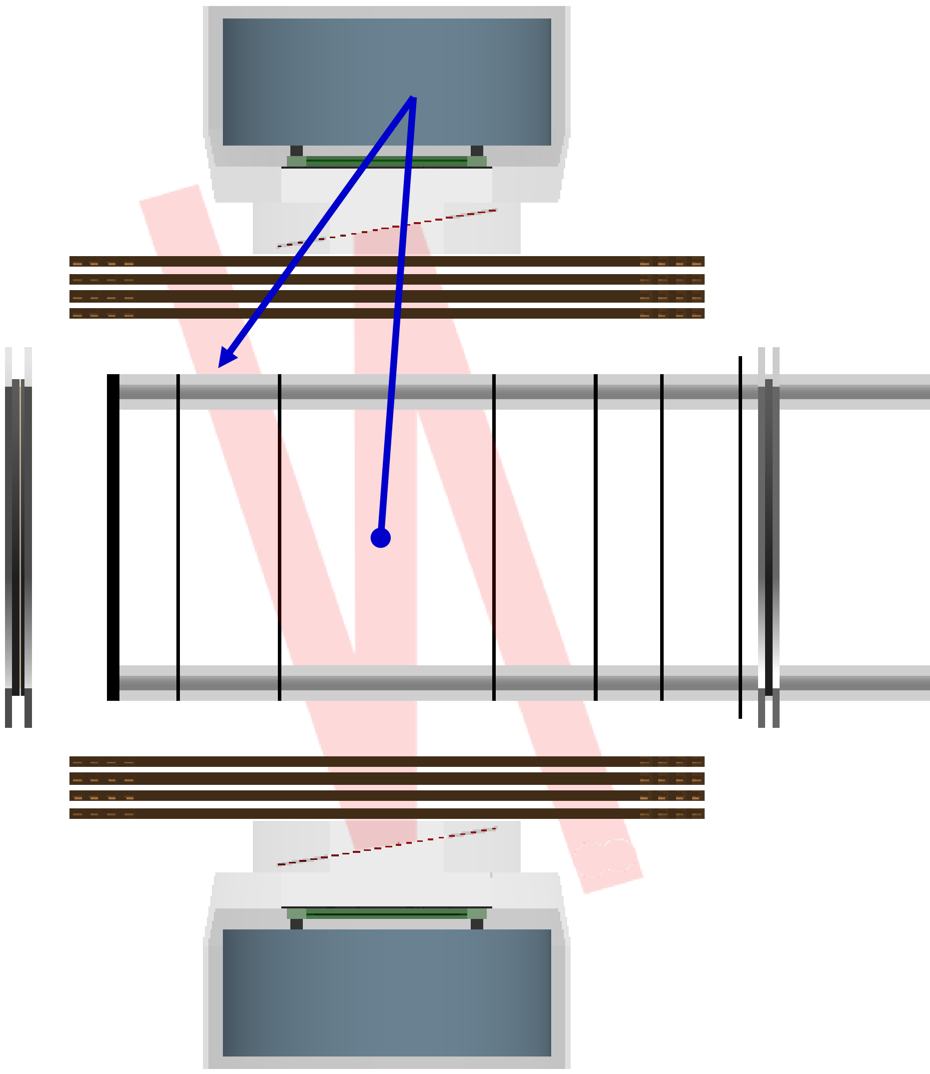
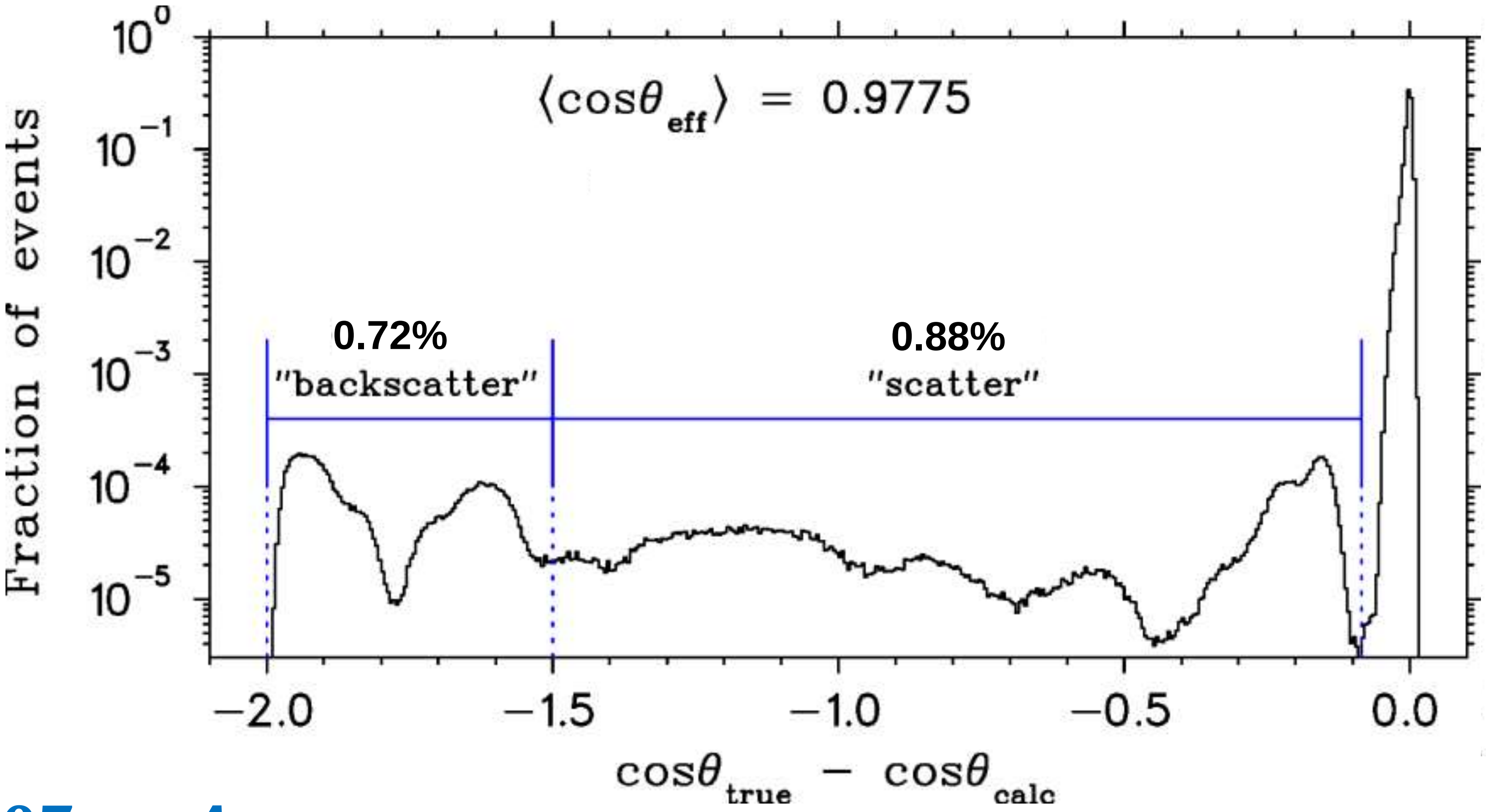
- Obvious, very clean check: both telescopes register a β event
- Due to small solid angle to go from one to the other ($\sim 0.25\%$), not enough statistics with current data set ($\sim 10^{-4}$ of non-scattered)
- Much more common: backscattered out of the scintillator
- Signature: two separate pixels in the double-sided Si-strip detector with energy deposited in the scintillator



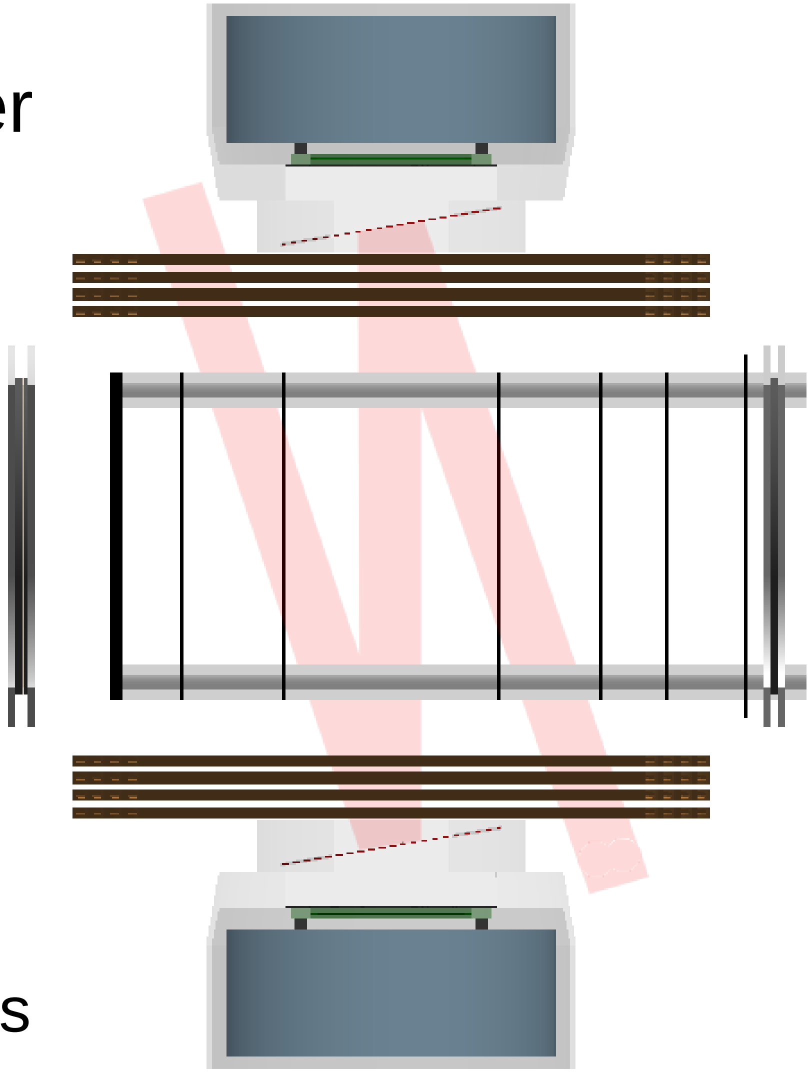
How does GEANT4 do?

- With non-standard options: **Surprisingly well**!!
- Take 2σ limit on observed deviation, or 5.1%, for “backscattered” events
- Assign 10% uncert to “scattered” events
- All together, a ± 0.0012 uncert on $\langle \cos\theta_{\text{eff}} \rangle$ and **± 0.0007 on A_β**



Looking forward: reducing β scattering systematic

- Goal: better benchmark our MC simulations
- ^{80,92}Rb production **>500x** higher than ^{37}K; recent run has many more β^- decays (data in hand, under analysis)
  - Much more precise scintillator backscatter benchmark
  - Rb data in hand which should have enough decays to see two-telescope backscatters
- If necessary, further tests can be made with minimal disruption to our system:
  - Replace upper telescope with other active detectors (thick Si, CsI, BGO, …)
  - Compare with/without inactive scattering volumes (W, Ta, stainless, …), normalizing to shake-off e^-/recoils



(Dominant) Error budget and A_β result

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}

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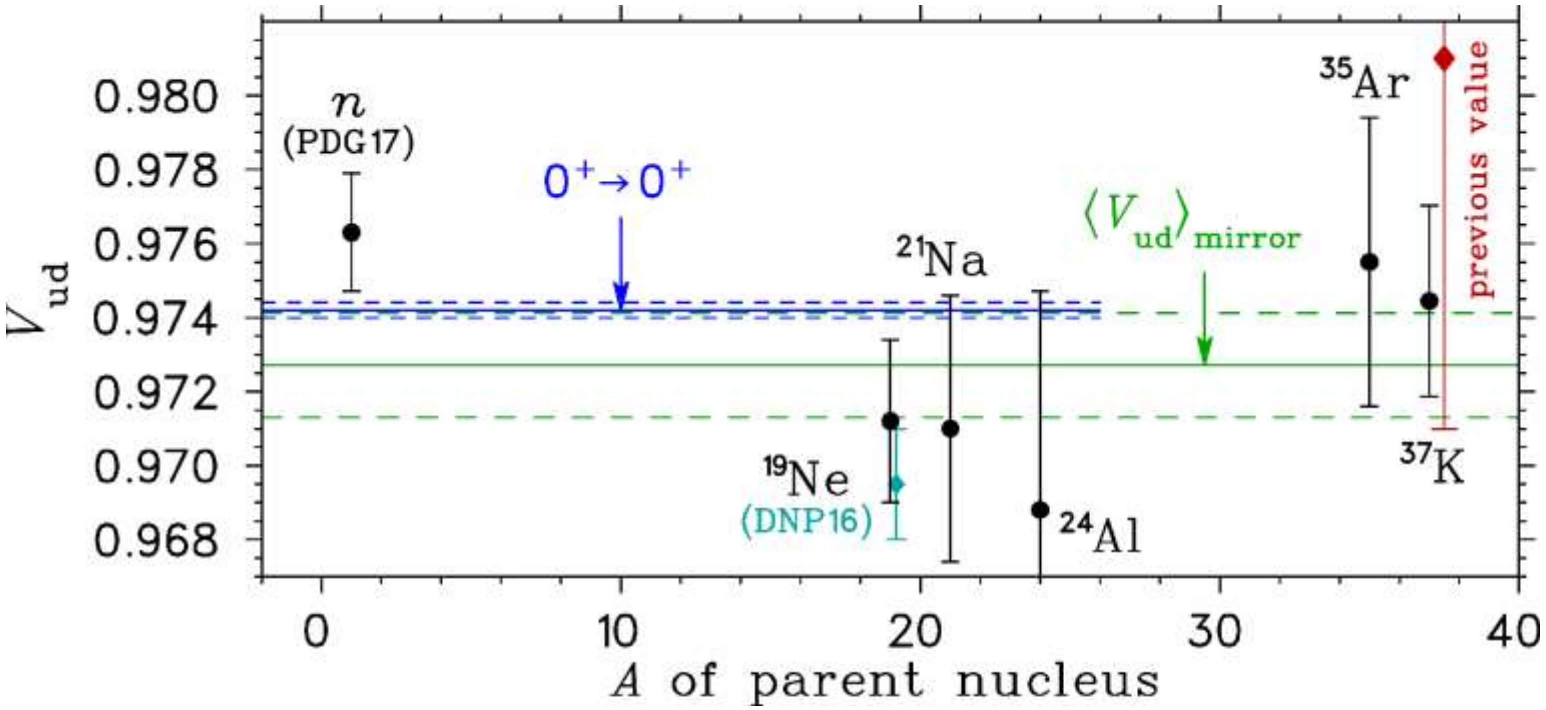
$A_\beta^{\mathrm{meas}} = -0.5707(19)$ *cf* $A_\beta^{\mathrm{SM}} = -0.5706(7)$ (includes recoil-order corrections, $\Delta A_\beta \approx -0.0028\frac{E_\beta}{E_0}$)

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

Interpretation and future prospects

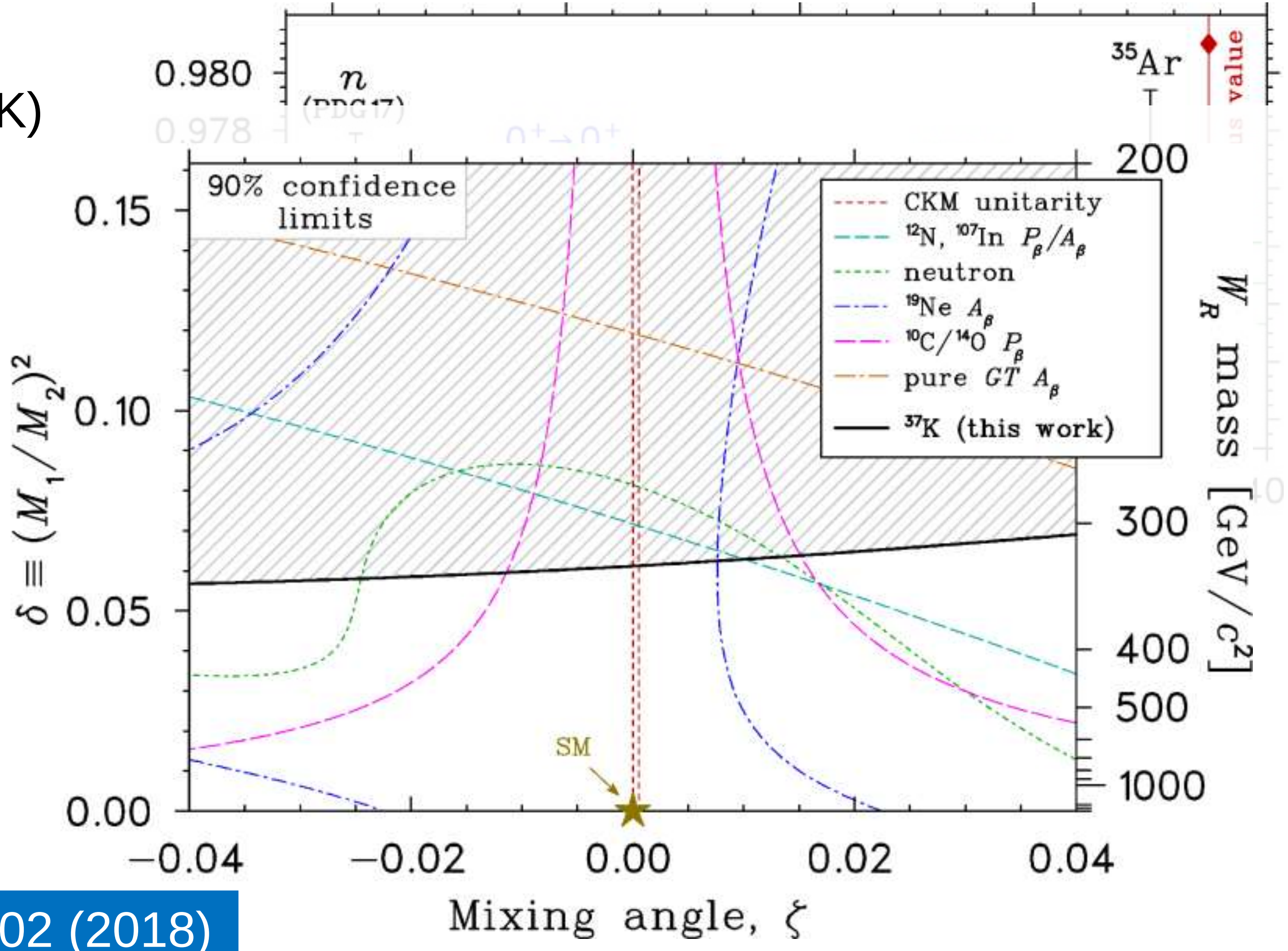
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays



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

Interpretation and future prospects

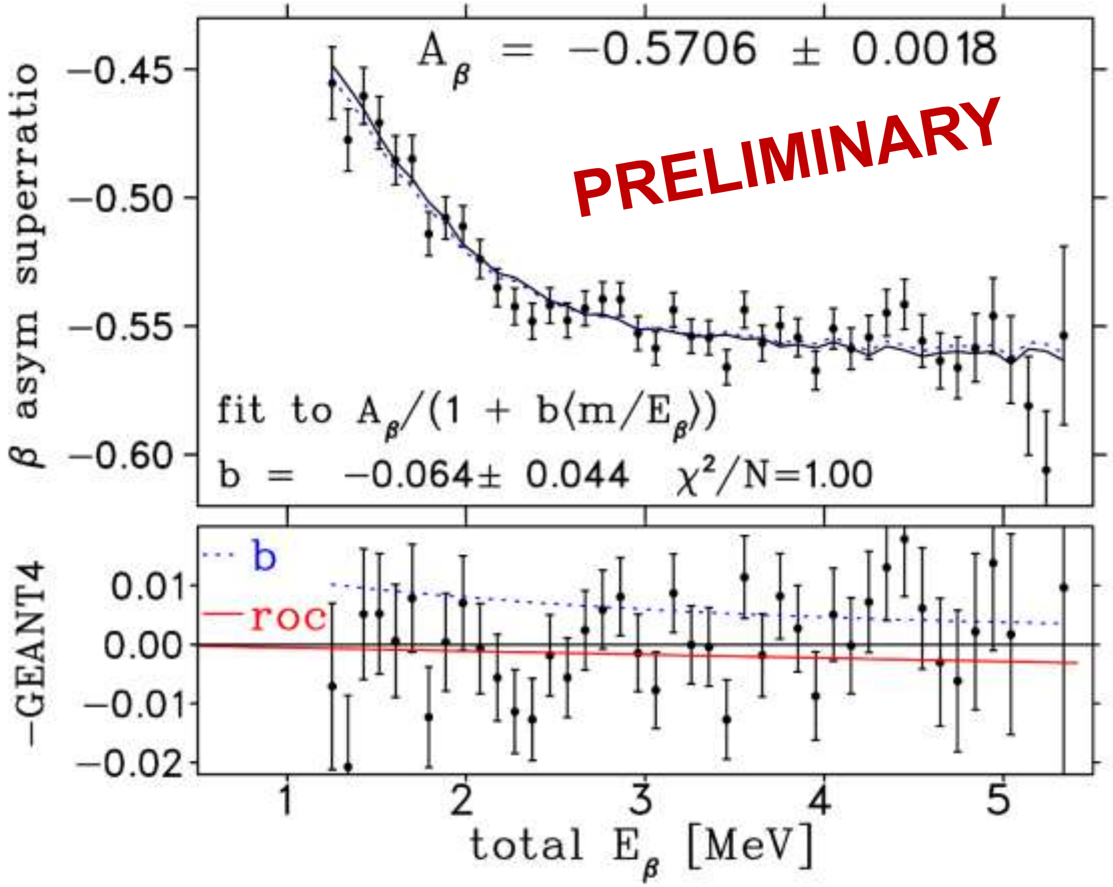
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents

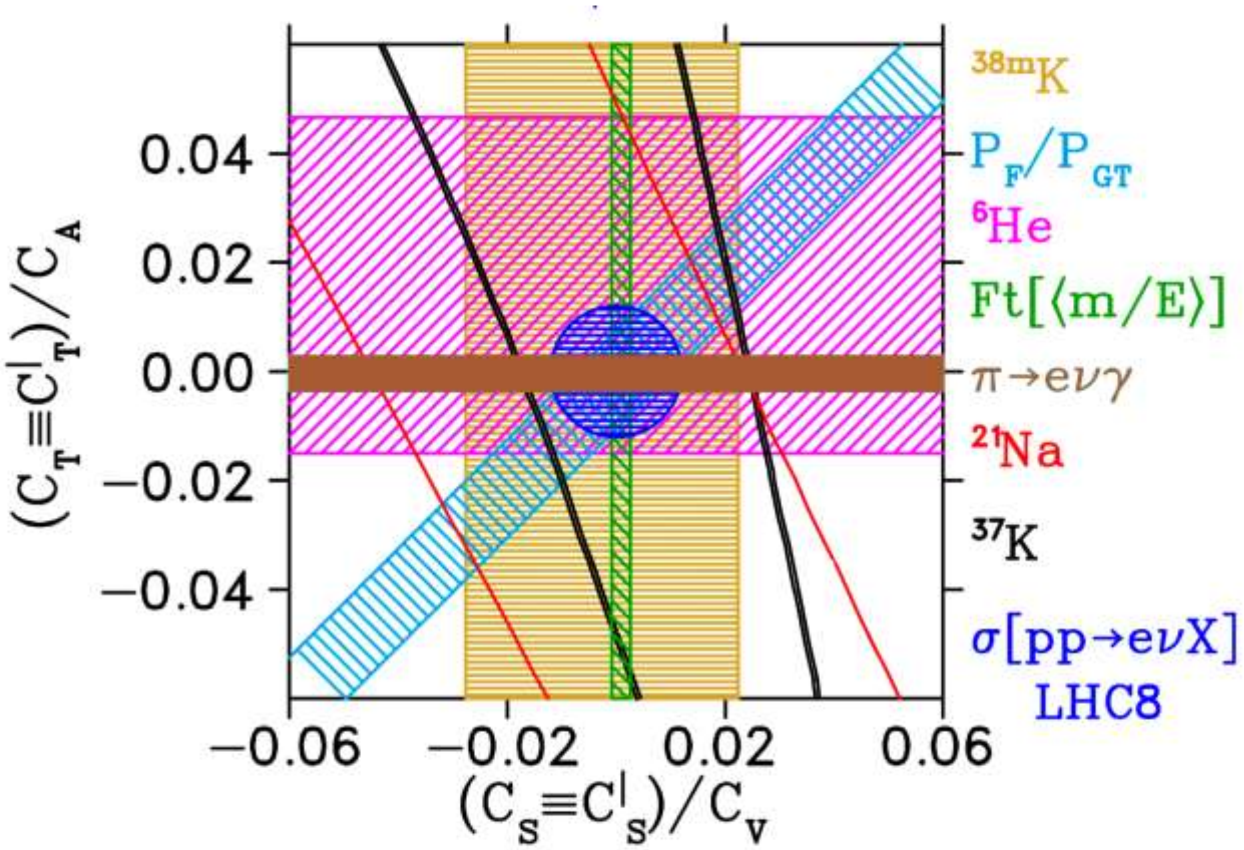


B.Fenker *et al*, PRL **120**, 062502 (2018)

Future plans

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

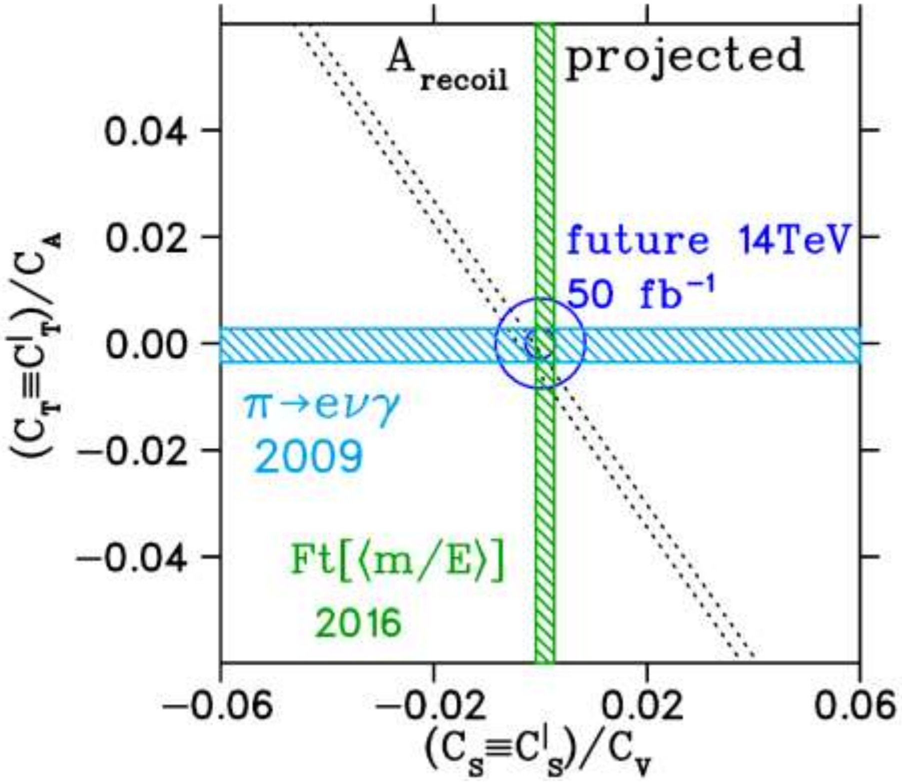




PRELIMINARY

Future plans

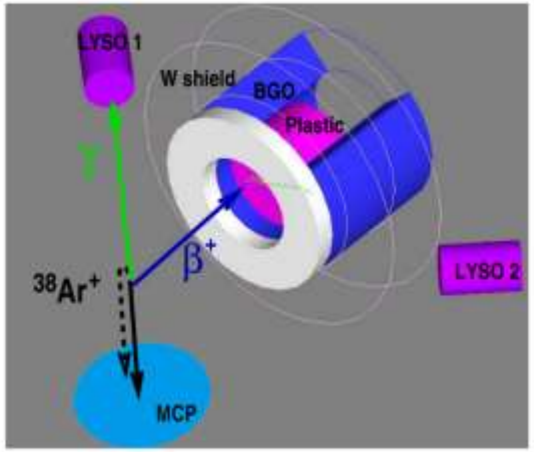
- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$
- Measure $A_{\text{recoil}} \propto A_\beta + B_\nu$
  - Technique demonstrated in ^{80}Rb (Pitcairn *et al*., PRC **79**, 015501 (2009))
  - High statistics measurement

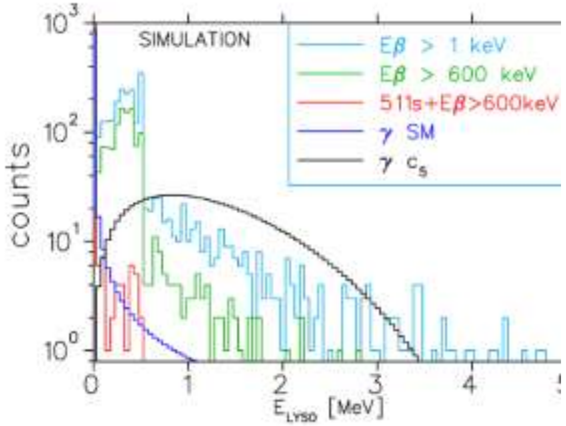


(assumes the LHC sees a 2σ signal)

Future plans

- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$
- Measure $A_{\rm recoil} \propto A_\beta + B_\nu$
  - Technique demonstrated in ^{80}Rb (Pitcairn *et al*., PRC (2009))
  - High statistics measurement
- Measure triple-vector $(\vec{p}_e \times \vec{k}_\gamma)\cdot\vec{p}_\nu$ (T-violating) correlation in ^{38m}K
  - Motivated by Gardner and He, PRD **87**, 116012 (2013)





- Effect 250x larger than for the neutron
- Fake final state effect small: 8×10^{-4}
- unique measurement in 1st generation
- $\sigma \sim 0.02$ in 1 week

Future plans

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  - Motivated by Gardner and He, PRD **87**, 116012 (2013)
- E_ν spectrum in $0^- \to 0^+$ decay of ^{92}Rb
  - Important for modeling nuclear reactors (sterile ν?) and non-proliferation

⋮

Final thoughts, collaborators and thanks

- Ion and atom traps are helping pave the way for the precision frontier
- TAMUTRAP: commissioned, just need radioactive ions…
- TRINAT: recent A_β result demonstrates ability; future is bright!

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- Ion ar
- TAMU
- TRINA

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S. Behl

M. Meh

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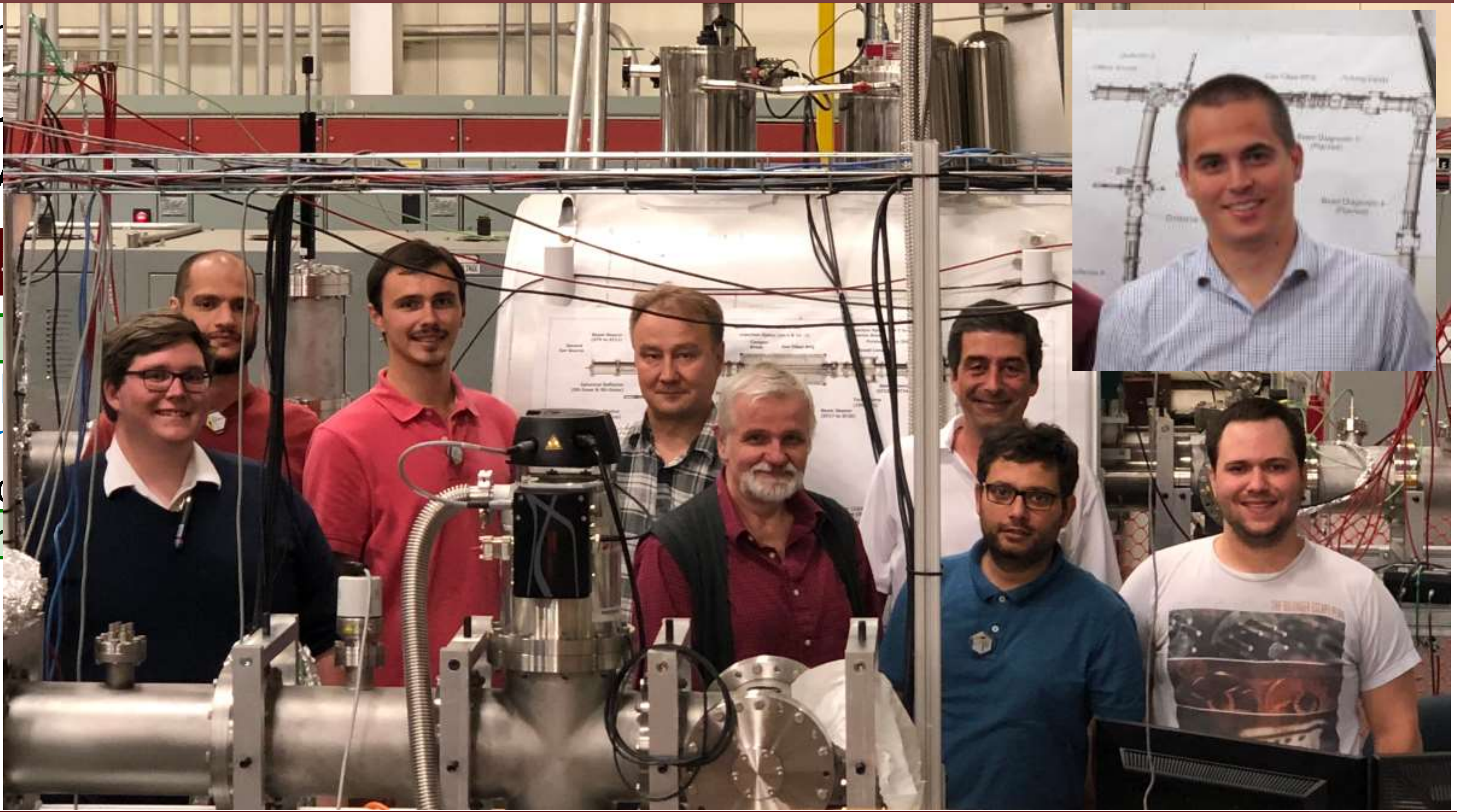
P.D. Sh



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