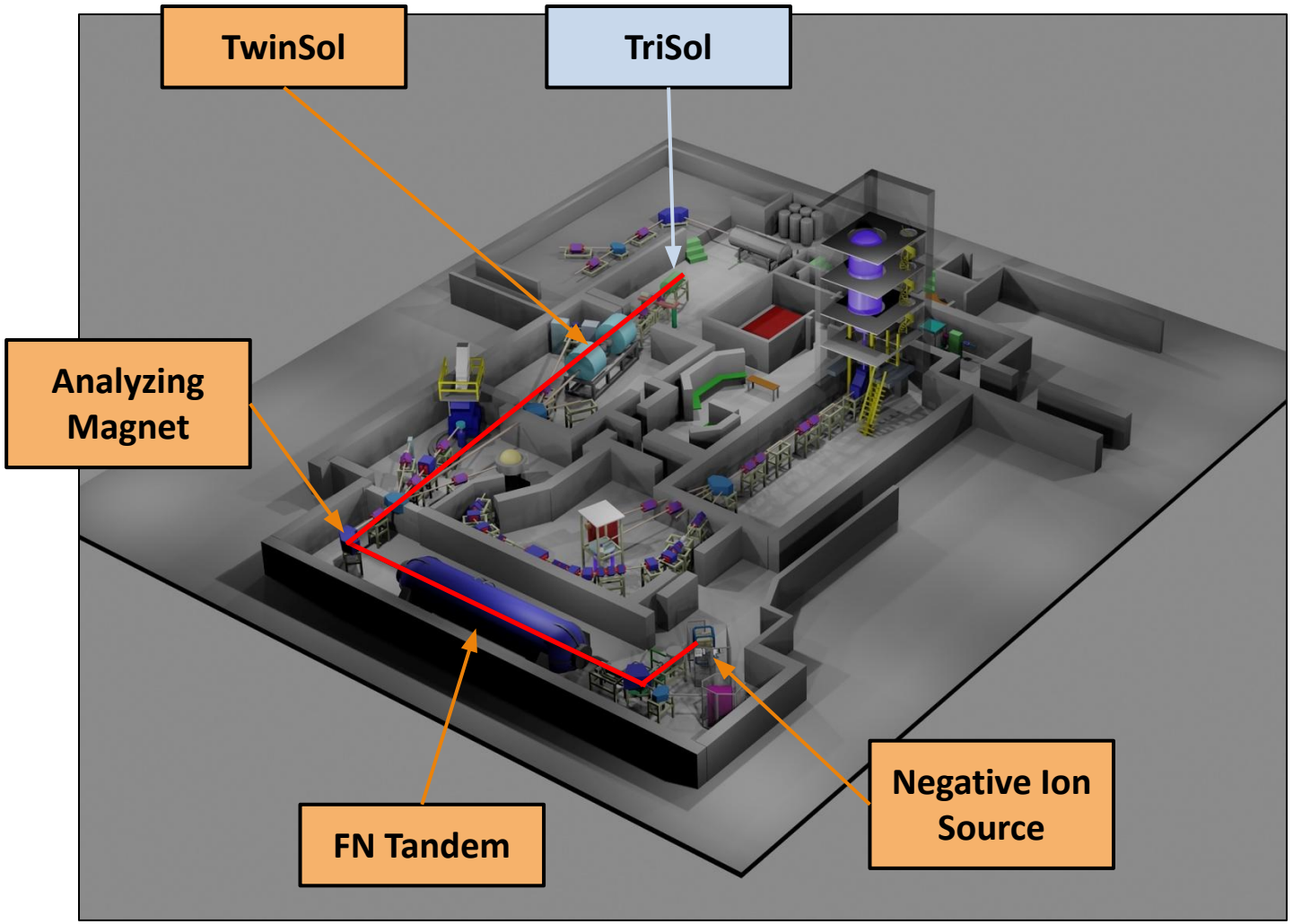
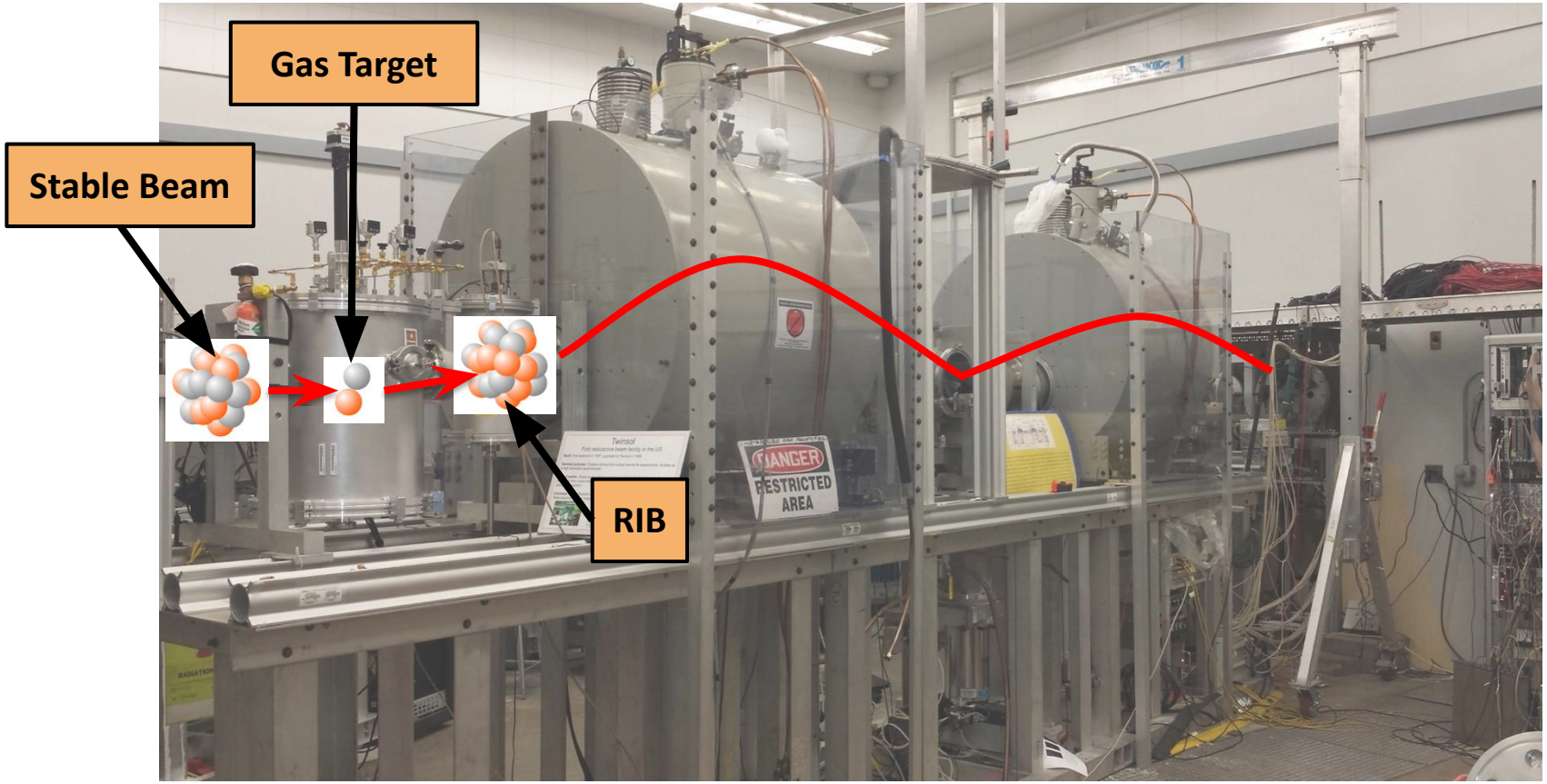
Radioactive ion beams at the Nuclear Science Laboratory

Sam Porter
University of Notre Dame

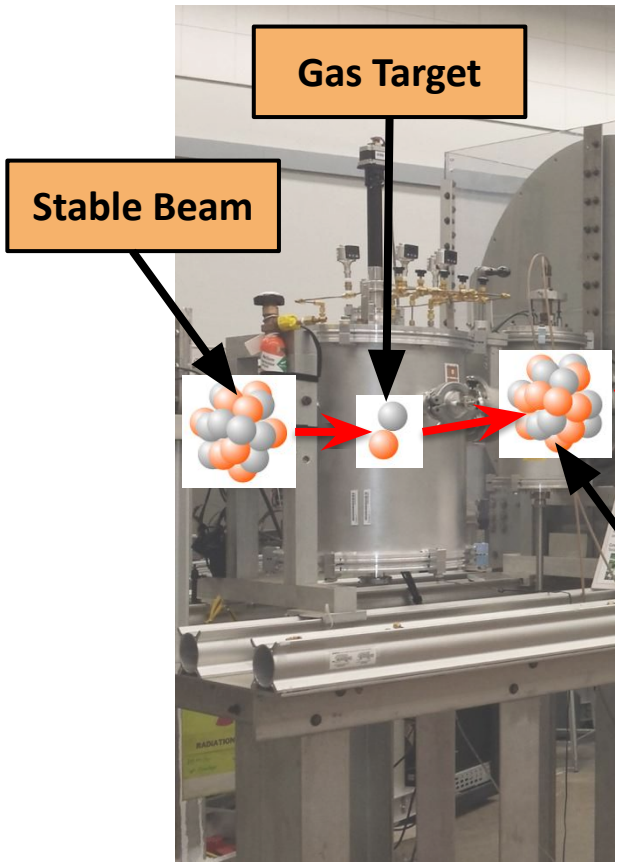
Nuclear Science Laboratory

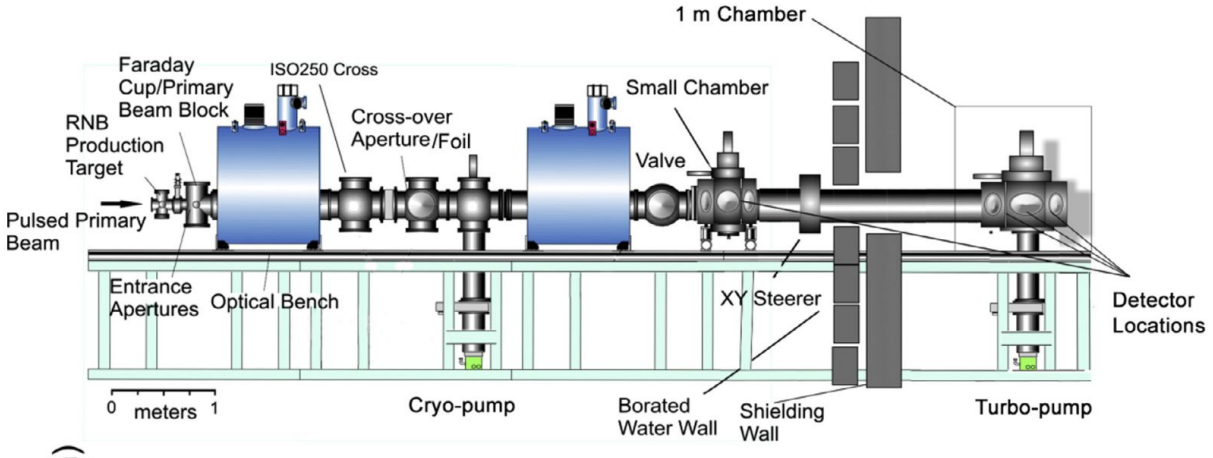


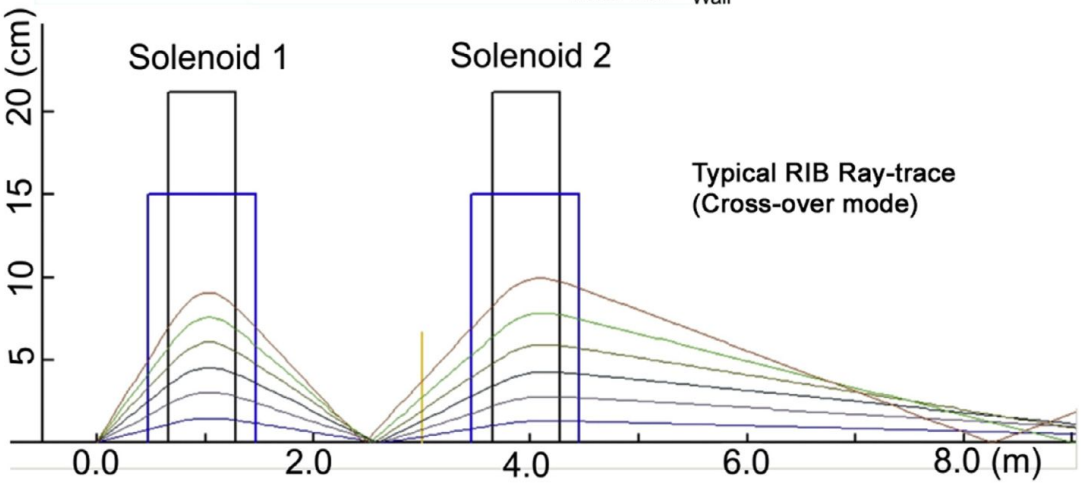
TwinSol @ NSL



TwinSol @ NSL

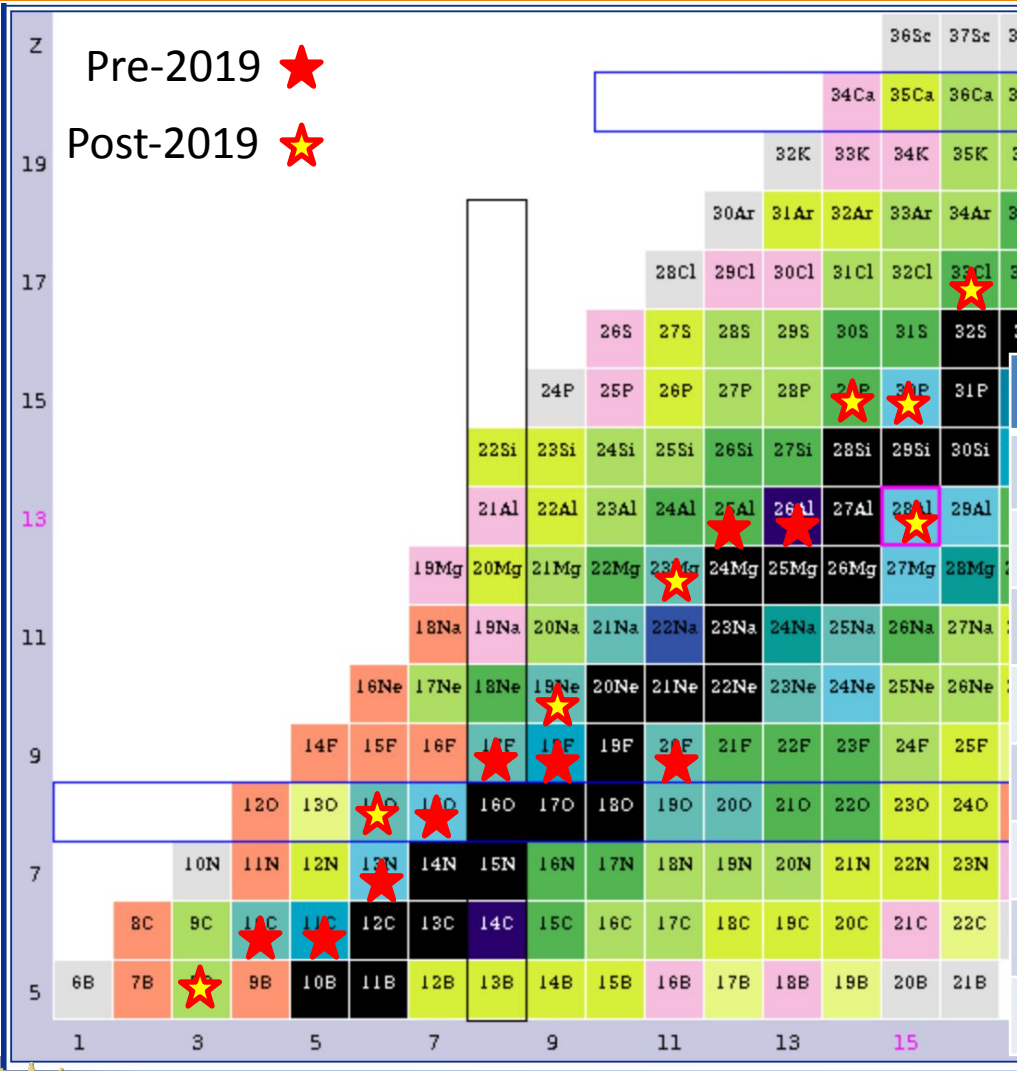






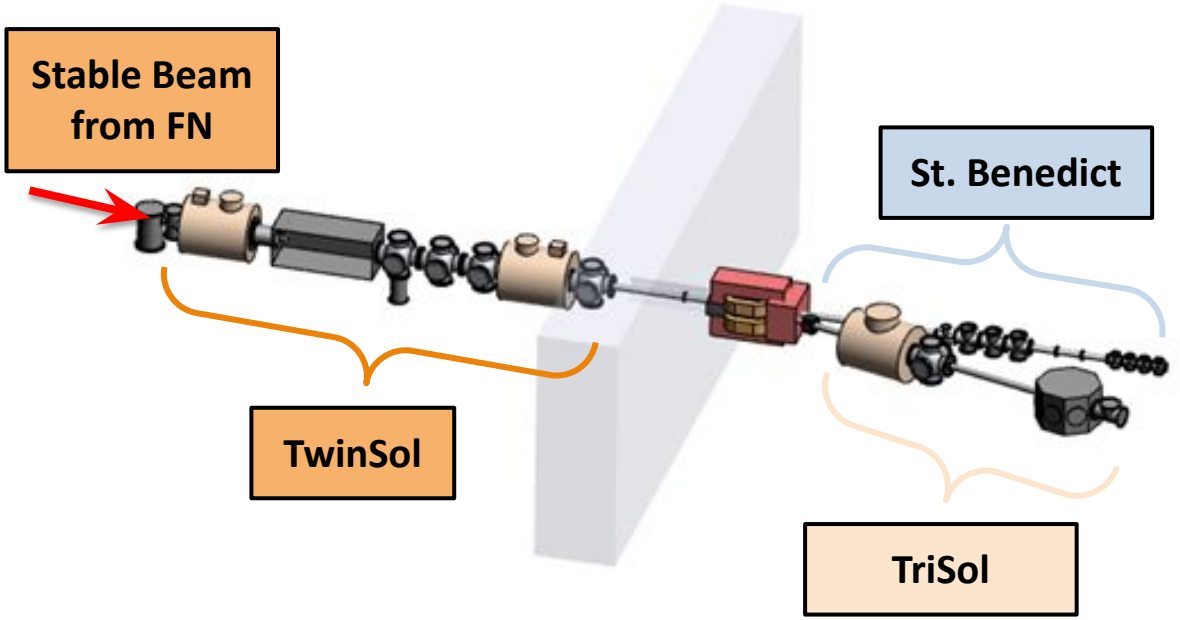
F.D. Becchetti *et. al.,* NIMB **376** 397-401(2016)

RIB Production @ *TwinSol*

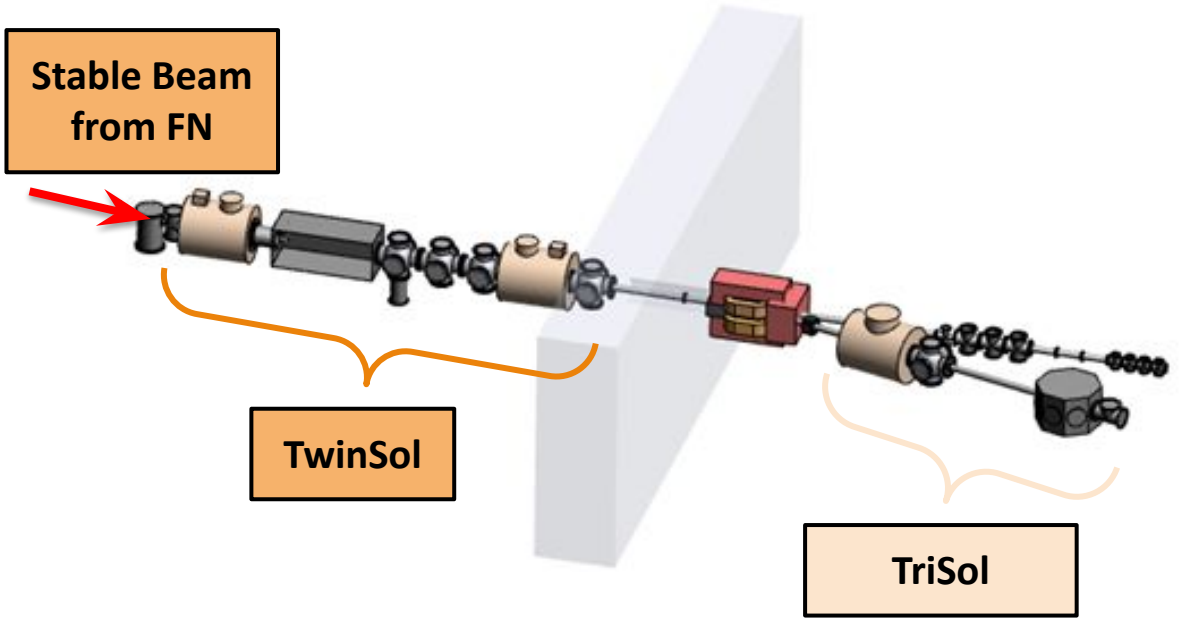


Isotope	Reaction	Rate (pps/μA)
^{11}C	^{10}B(d,n)	2.4x10^{5}
^{13}N	^{12}C(d,n)	8.1x10^{5}
^{15}O	^{14}N(d,n)	5.0x10^{6}
^{17}F	^{16}O(d,n)	1.5x10^{6}
^{25}Al	^{24}Mg(d,n)	3.0x10^{5}
^{29}P	^{28}Si(d,n)	2.0x10^{5}
^{33}Cl	^{33}S(d,n)	9x10^{3}
^{41}Sc	^{40}Ca(d,n)	4x10^{3}

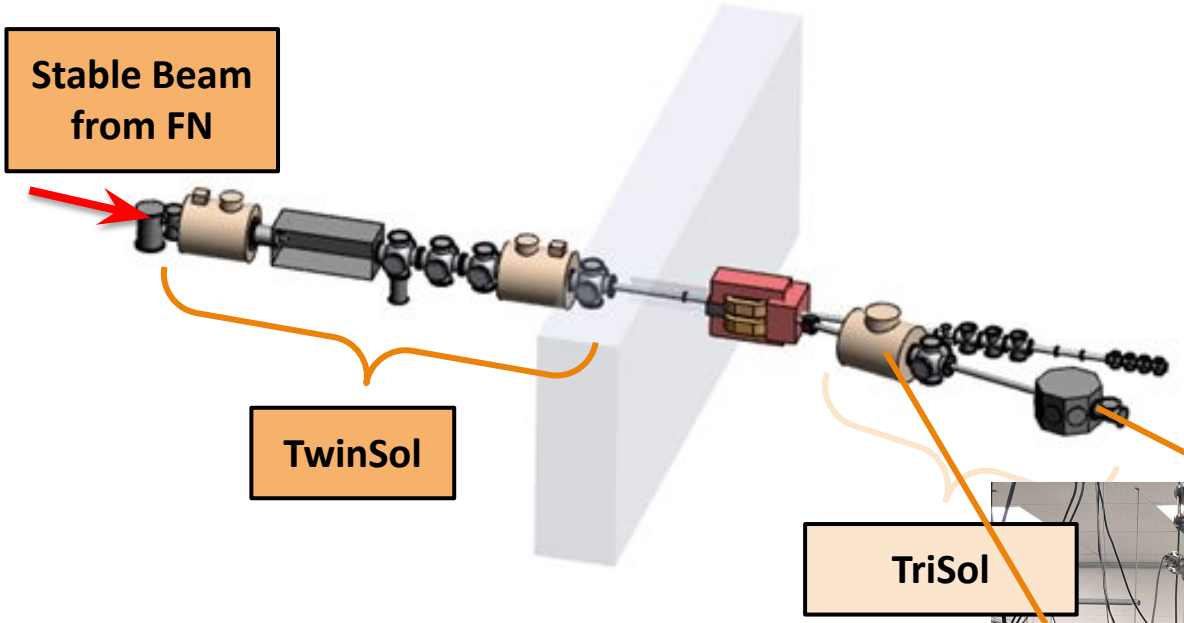
RIB Production Facilities @ NSL

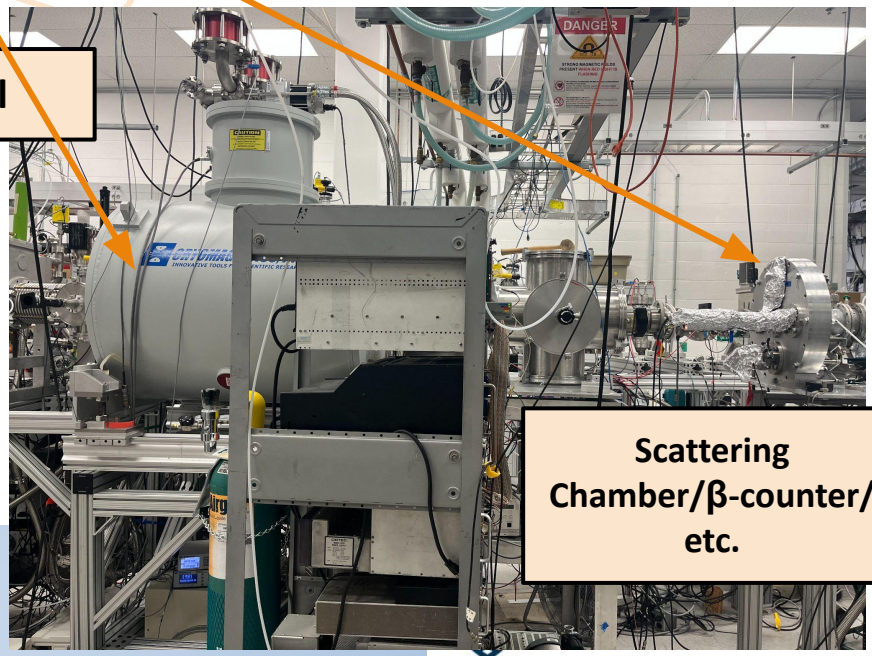


RIB Production Facilities @ NSL

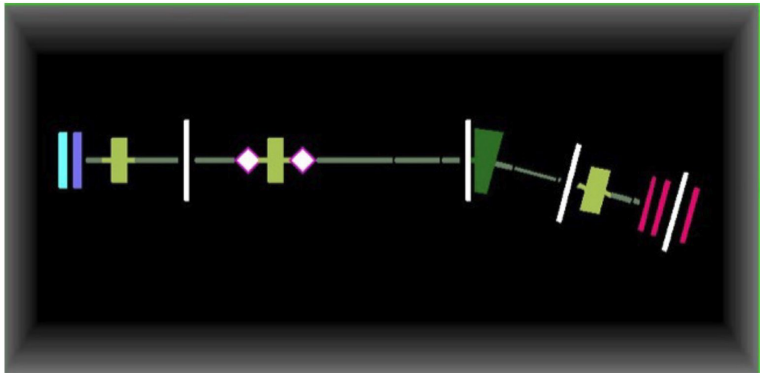


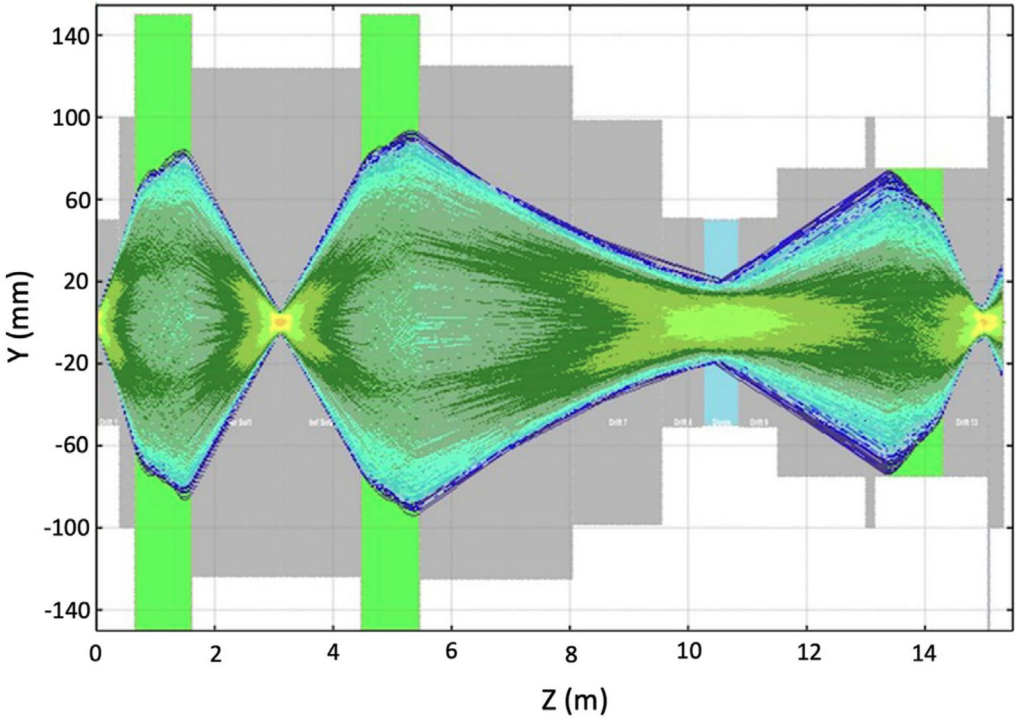
TriSol


Stable Beam from FN
TwinSol
TriSol


DANGER
Scattering Chamber/β-counter/ etc.

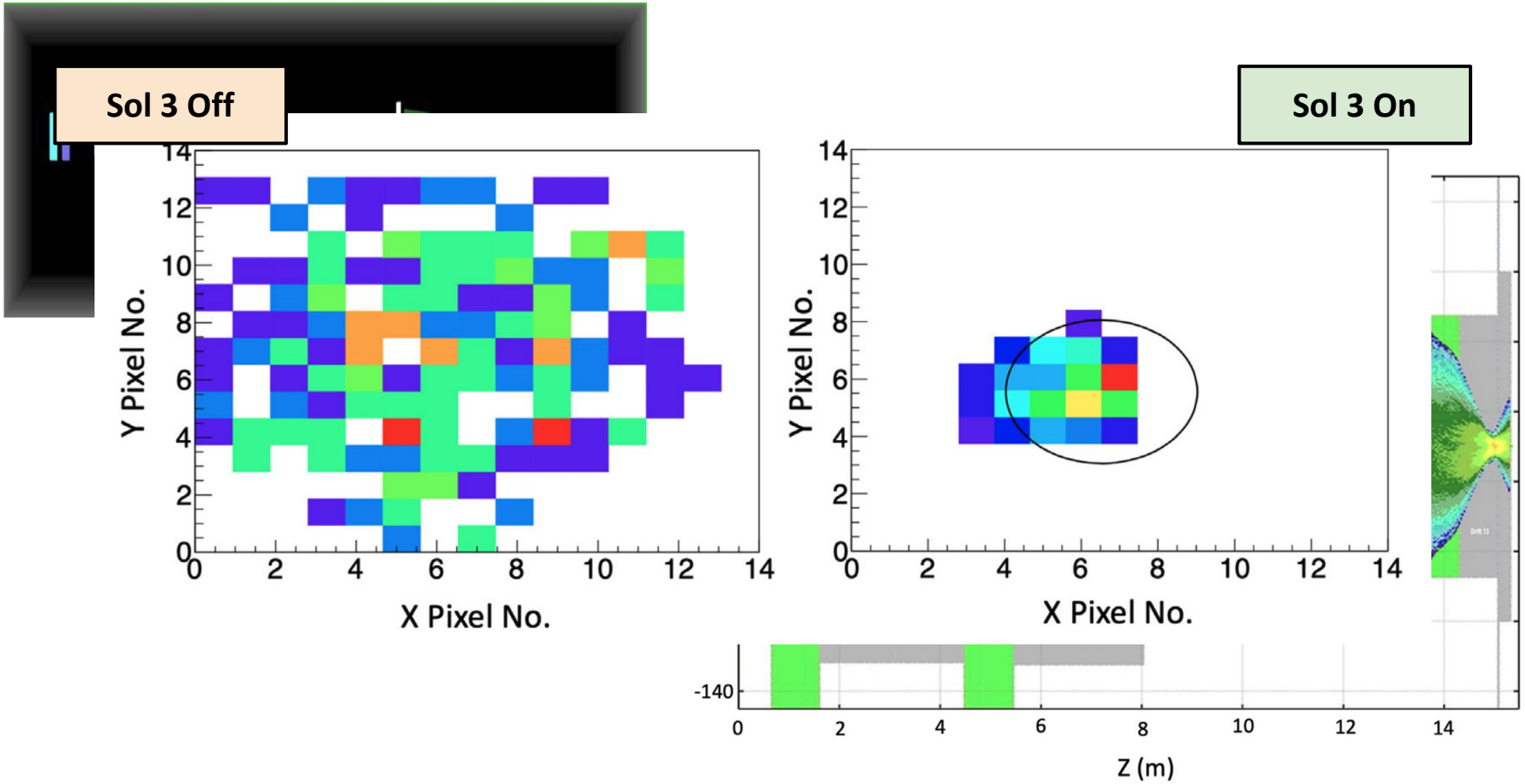
TriSol Simulations





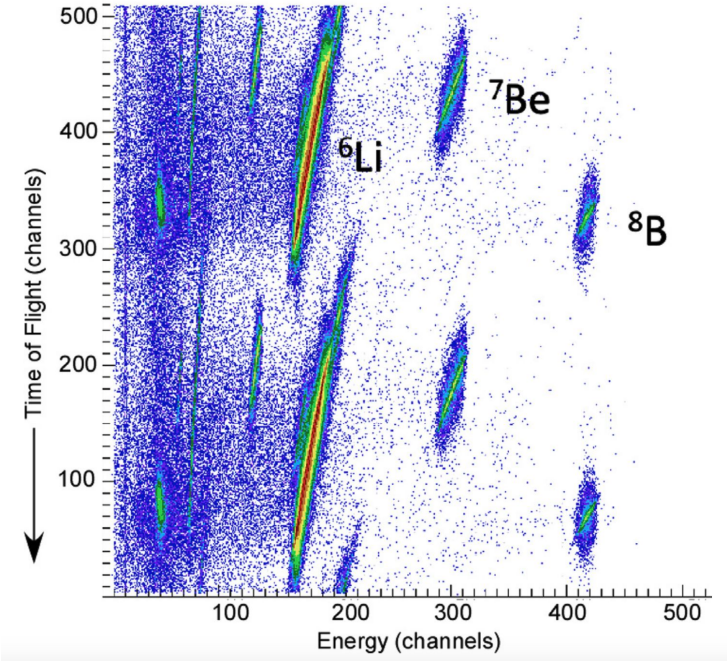
P.D O'Malley *et. al.,* NIMA **1047** 167784 (2023)

TriSol Simulations + Commissioning

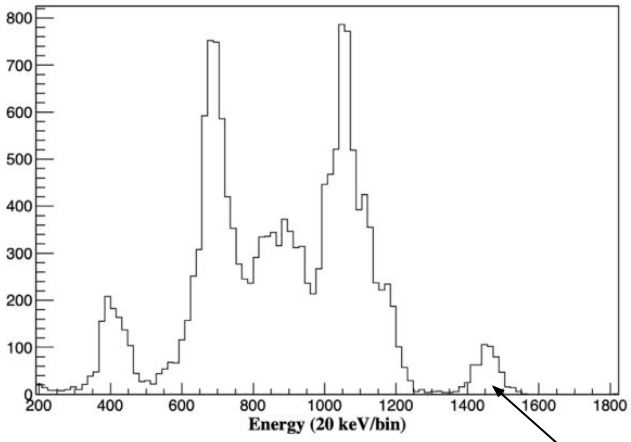


P.D O'Malley *et. al.*, NIMA **1047** 167784 (2023)

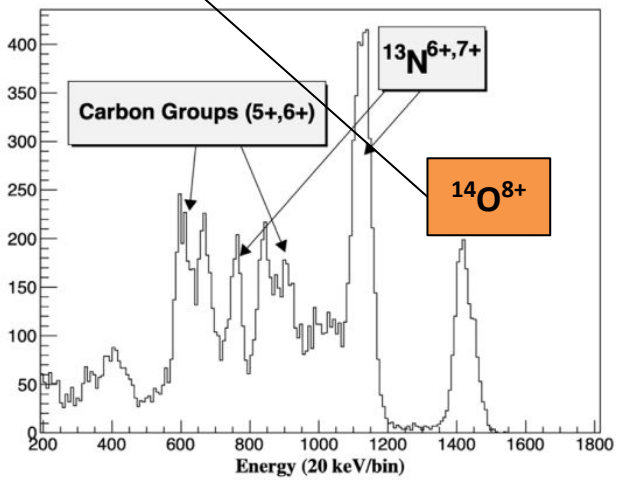
TriSol Simulations + Commissioning



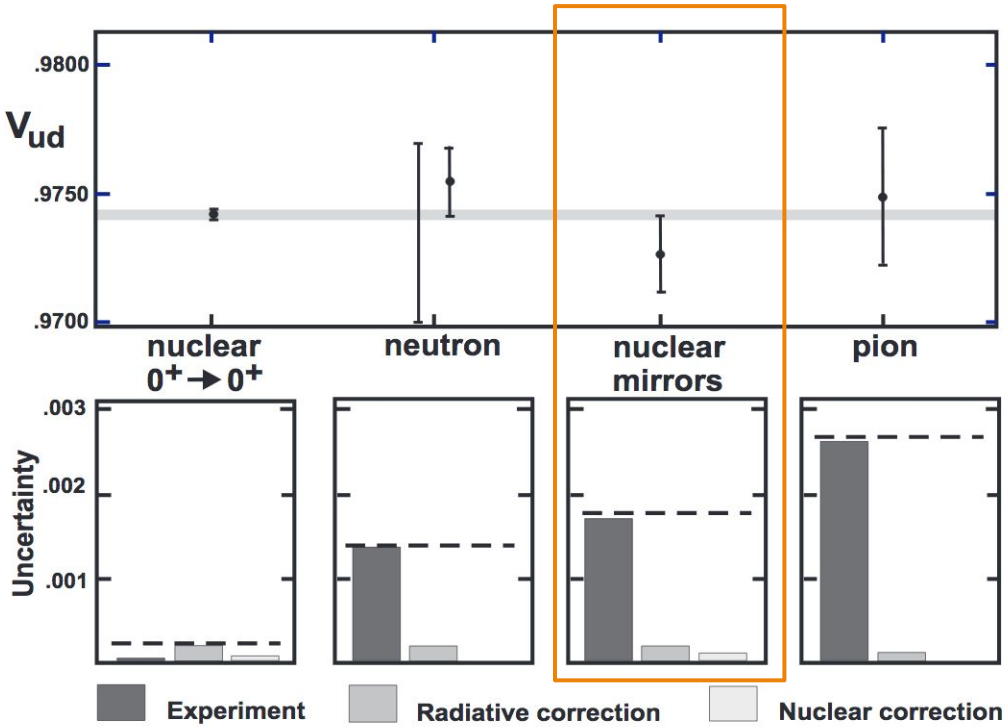
Improved ToF



Increased IOI-to-Contaminant Ratio by Factor 4



V_{ud} from superallowed mirror decays



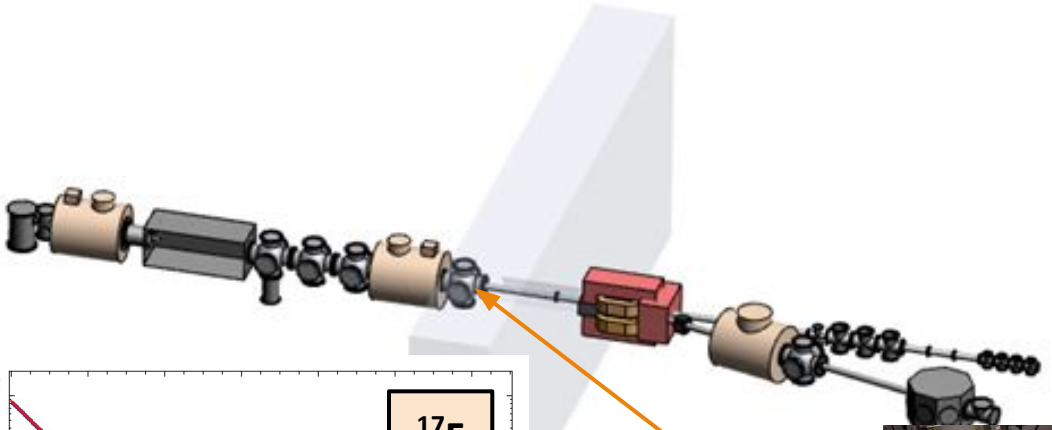
J.C. Hardy and I.S. Towner, arVix:1087.01146 [nucl-ex] (2018)

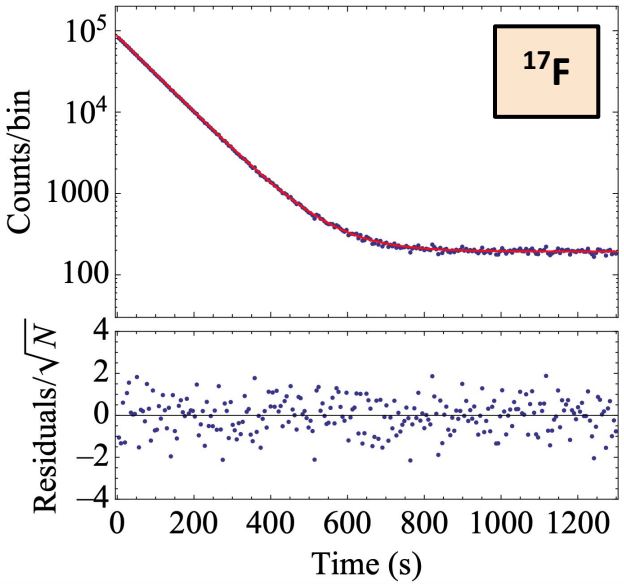
- Only **5 nuclei**

- ❑ Half-life
- ❑ Branching Ratios
- ❑ Q-values
- ❑ Fermi-to-Gamow Teller Mixing Ratio (**ρ**)

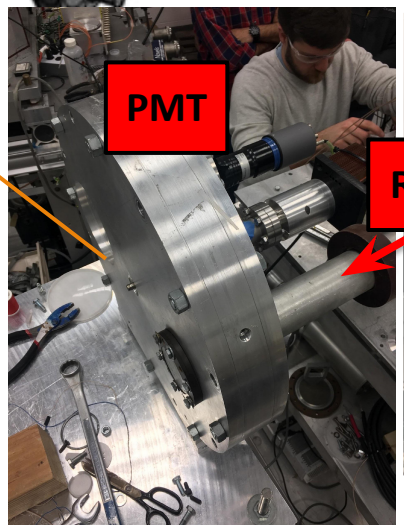
$$ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R)(1+\frac{f_A}{f_V}\rho)}$$

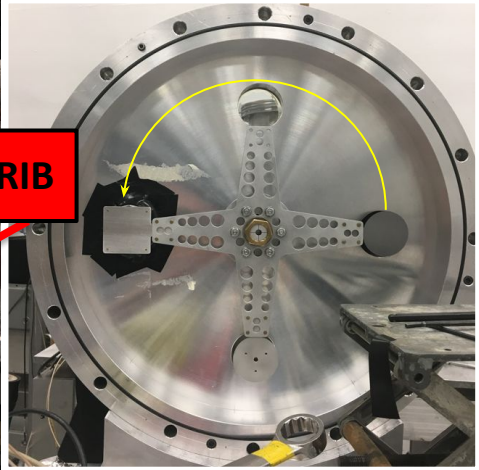
Half-Life Measurements



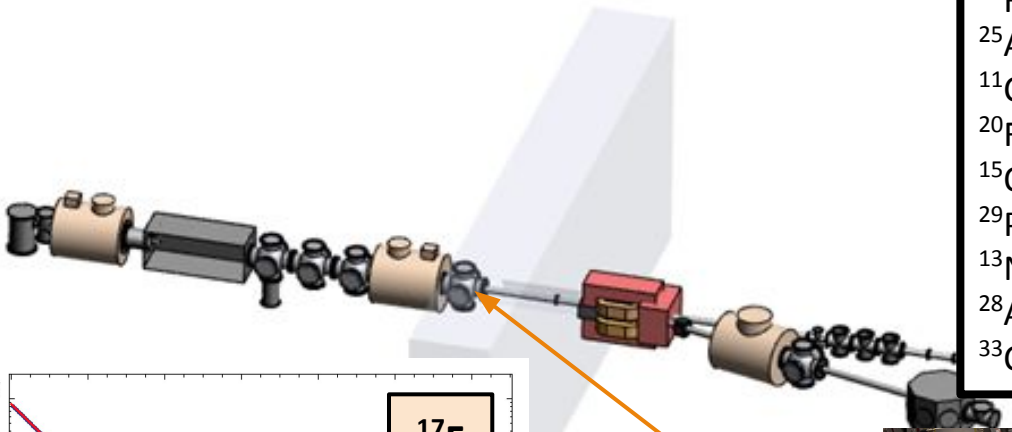


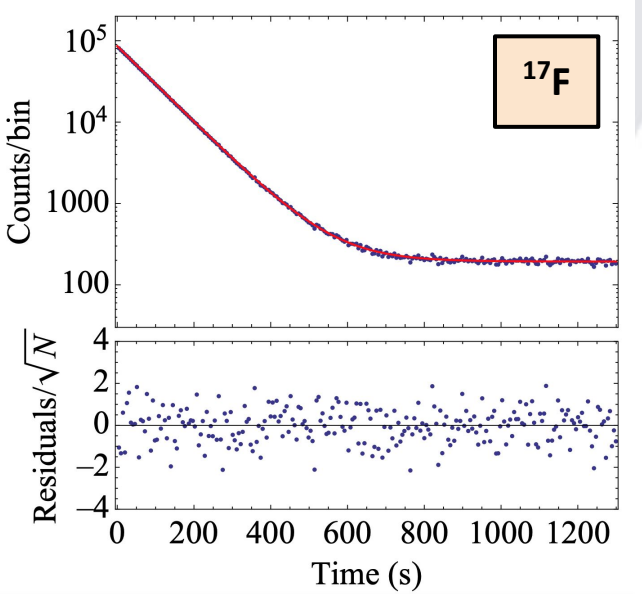
M. Brodeur *et. al.*, PRC **93** 025503 (2016)





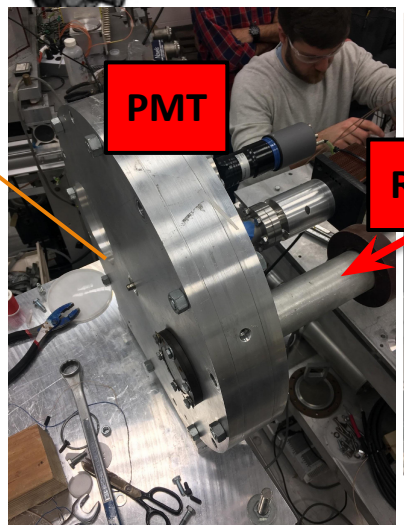
Half-Life Measurements

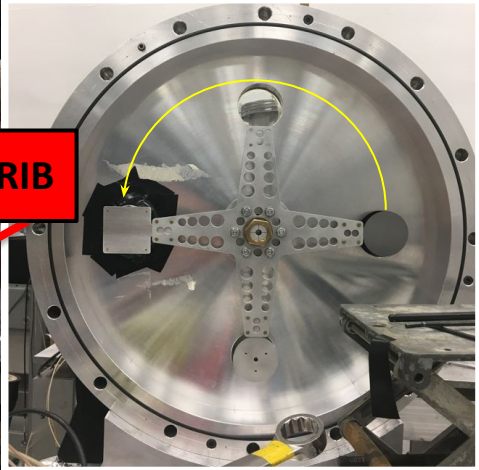




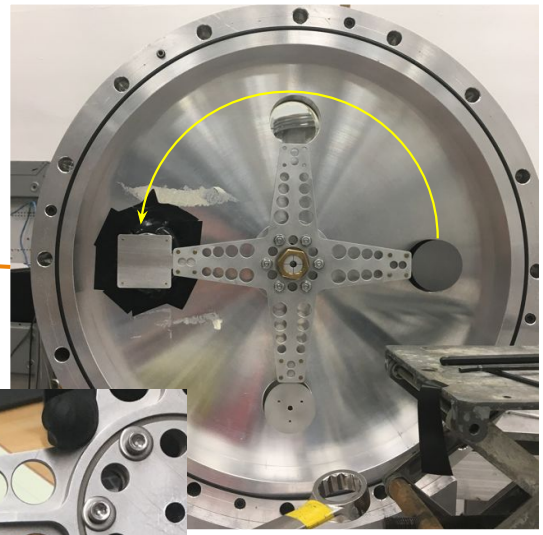
M. Brodeur *et. al.*, PRC **93** 025503 (2016)

^{17}F: M. Brodeur *et al.* PRC **93** 025503 (2016).
^{25}Al: J. Long *et al.* PRC **96**, 015502 (2017) .
^{11}C: A. A. Valverde *et al.* PRC **97**, 035503 (2018).
^{20}F: D.P. Burdette *et al.* PRC **99**, 015501 (2019).
^{15}O: D.P. Burdette *et al.* PRC **101** 055504 (2020).
^{29}P: J. Long *et al.* PRC **101**, 015501 (2020).
^{13}N: J. Long *et. al.* PRC **106**, 045501 (2022).
^{28}Al: B. Liu *et al.* PRC **112,** 045504 (2025).
^{33}Cl: R. Zite *et al.* under analysis.



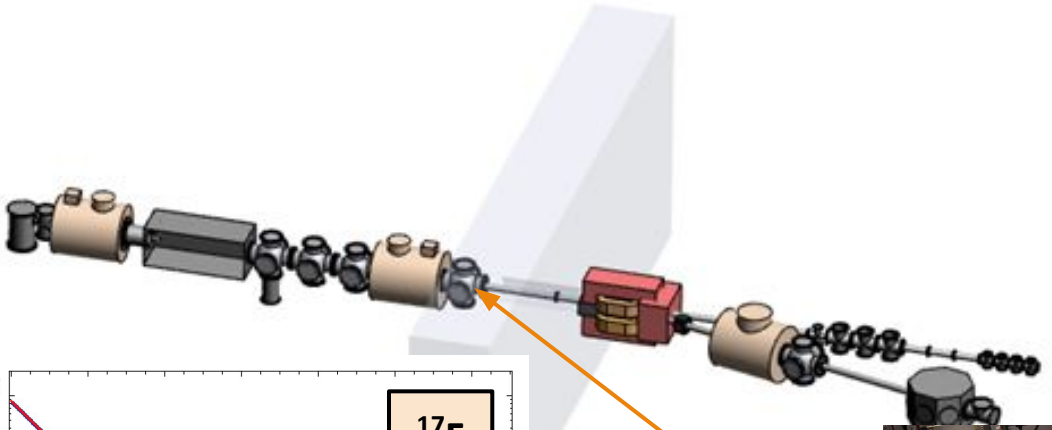


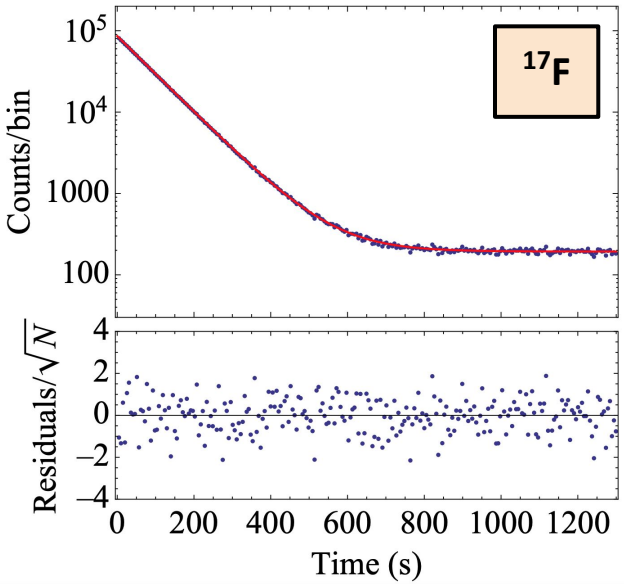
Measurement Procedure



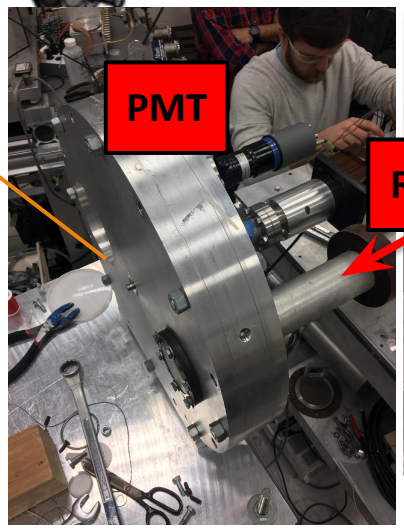
1) Implant ion beam on a Ta foil for ~3 $t_{1/2}$.
2) Deflect beam entering tandem.
3) Rotate foil in front of 1 mm plastic scintillator coupled to a PMT.
4) Count for ~25 $t_{1/2}$.
5) Rotate back to implant position, turn on the beam and repeat.

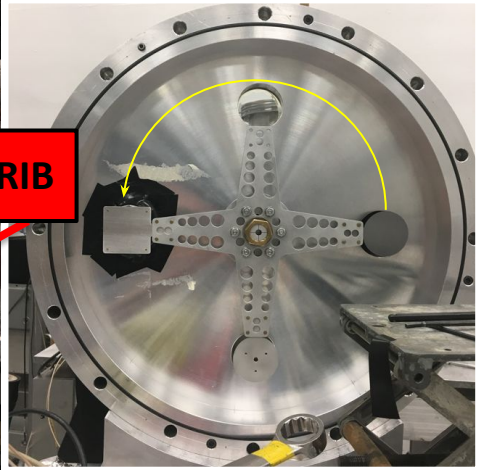
Half-Life Measurements



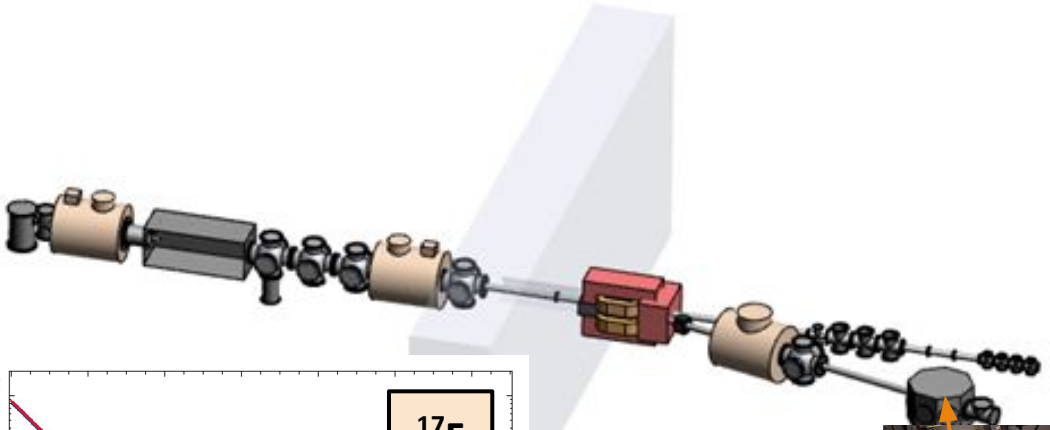


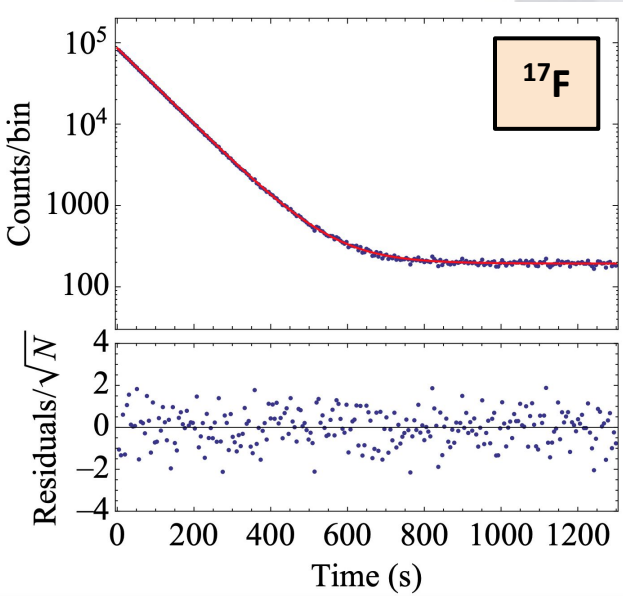
M. Brodeur *et. al.*, PRC **93** 025503 (2016)





Half-Life Measurements with TriSol





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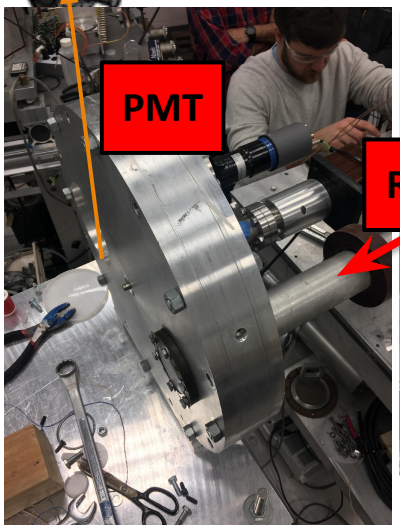
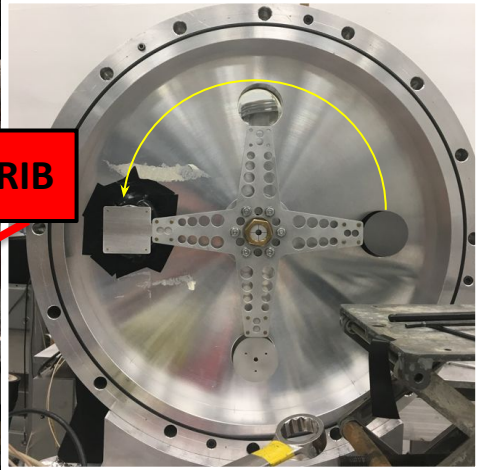
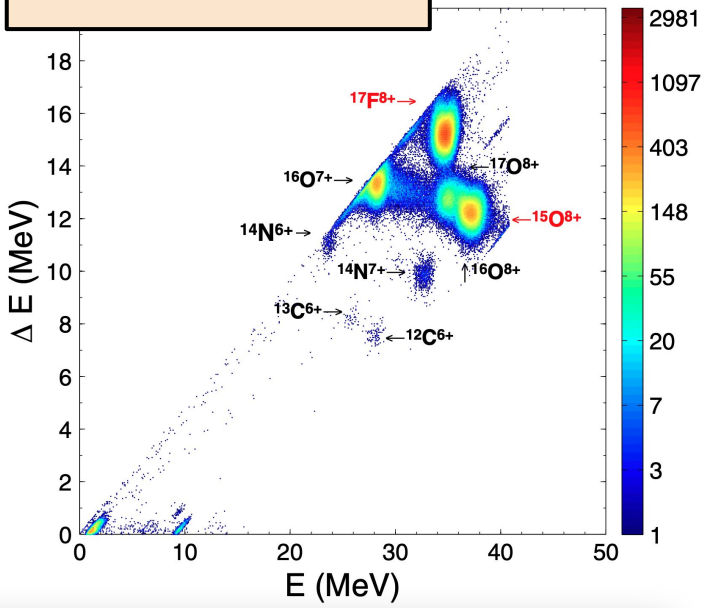


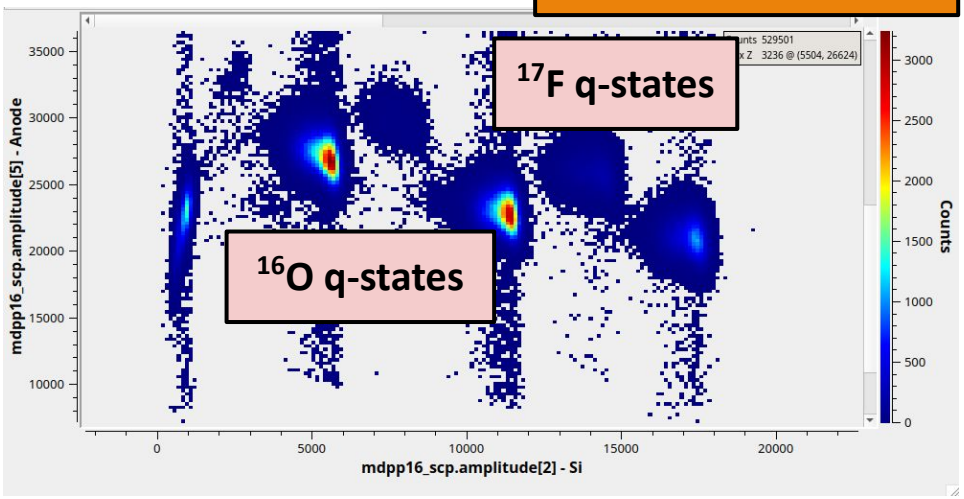


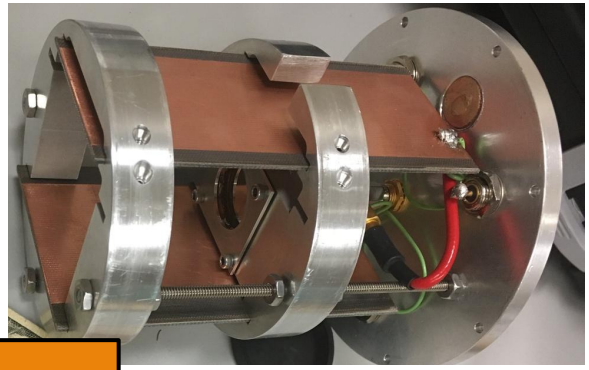
Half-Life Measurements with TriSol

^{17}F in 2016 -- TwinSol



^{17}F in 2025 -- TriSol

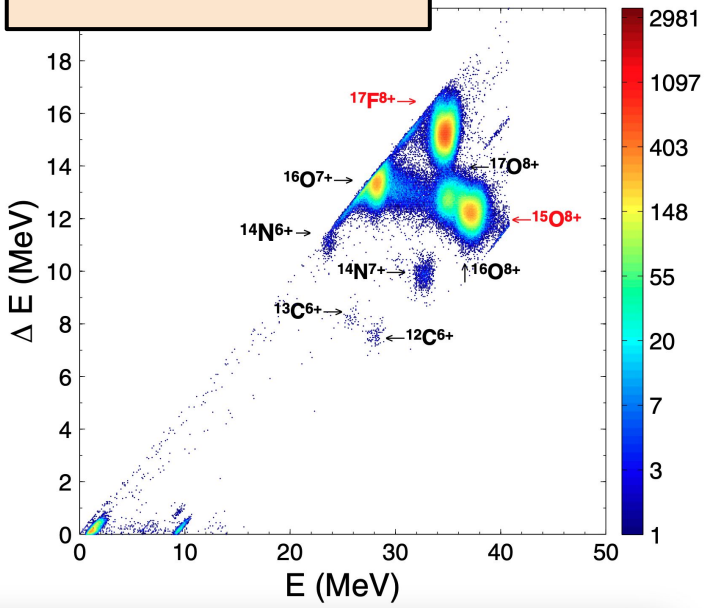




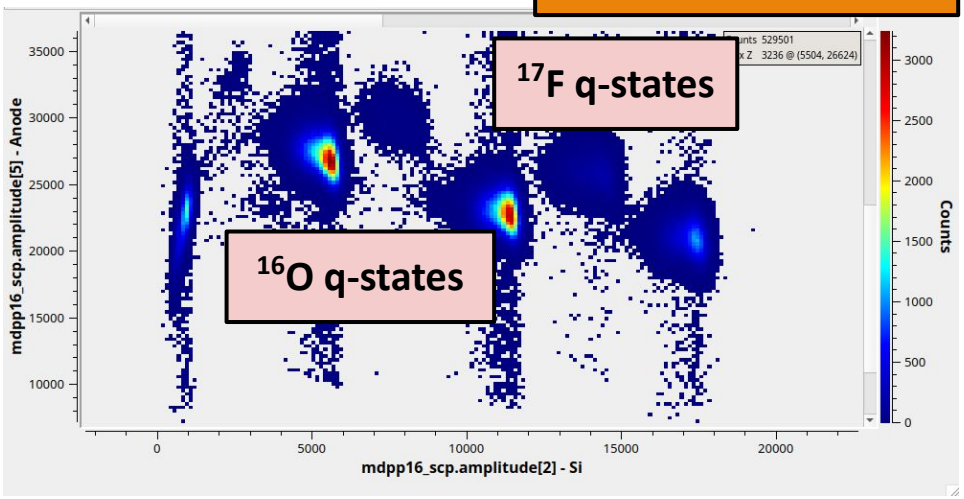
ACKBAR

Half-Life Measurements with TriSol

^{17}F in 2016 -- TwinSol

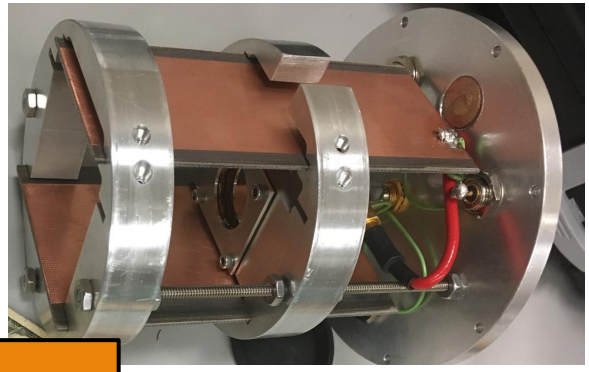


^{17}F in 2025 -- TriSol

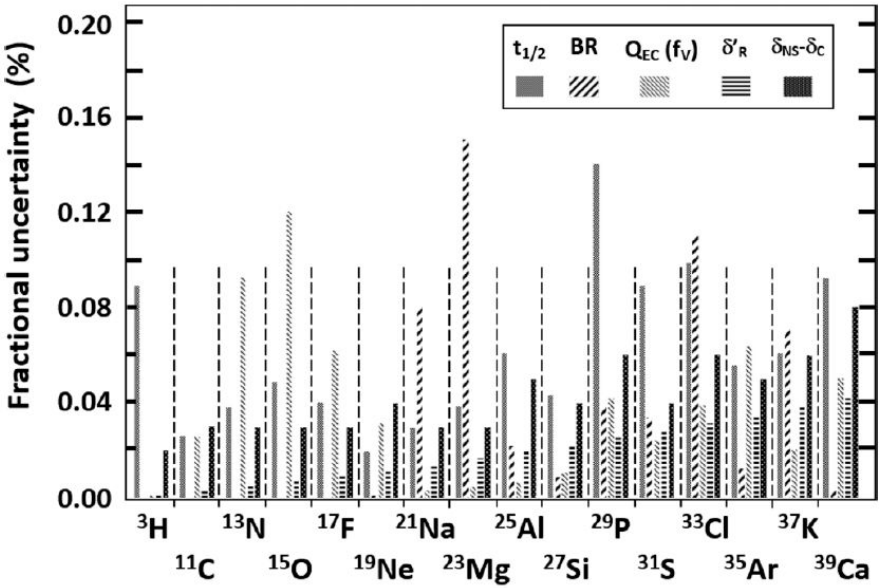


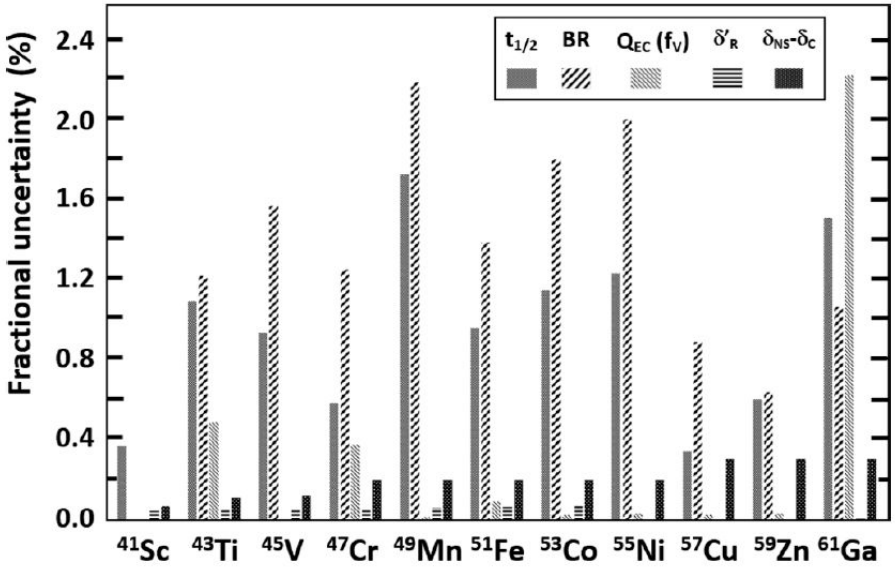
Improved Radioactive IOI-to-Contaminant Ratio

ACKBAR



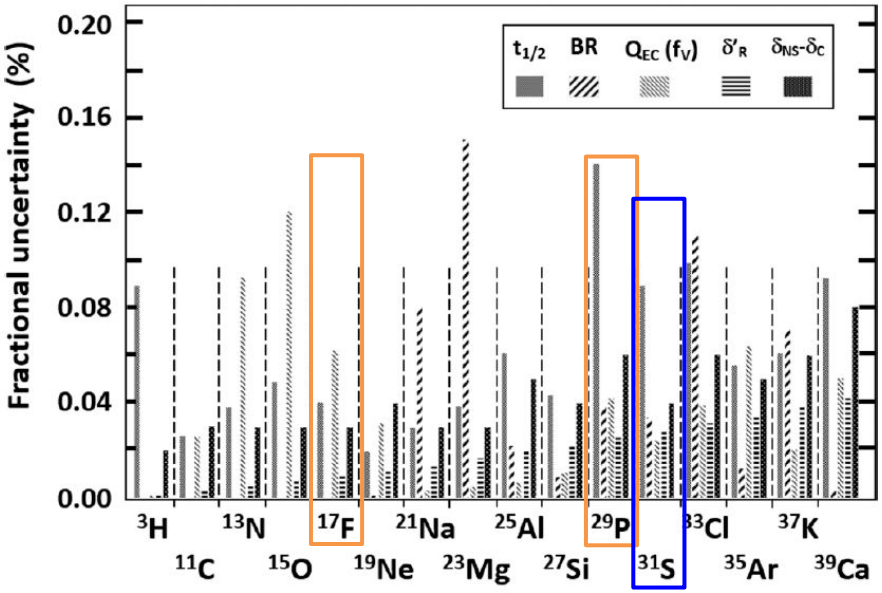
Half-Life Measurements with TriSol

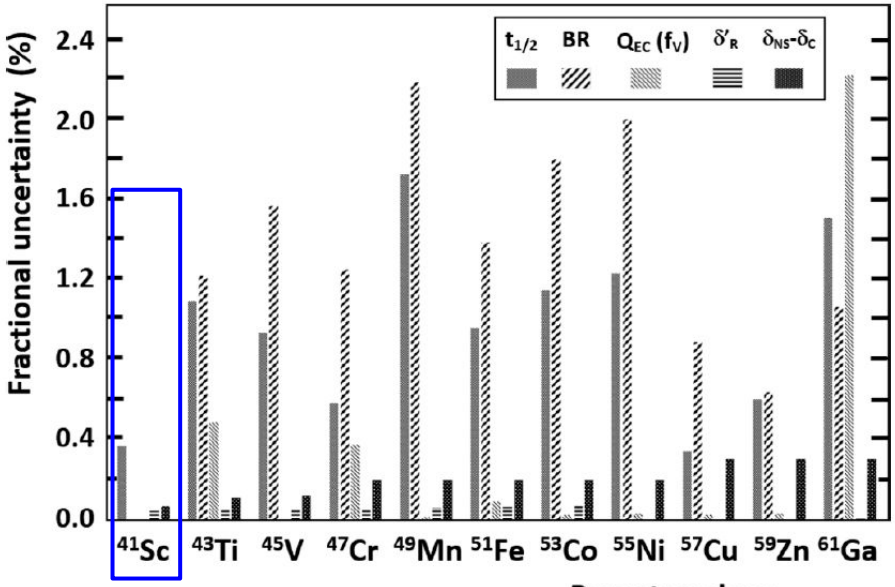




N. Severijns *et. al.,* PRC **107** 015502 (2023)

Half-Life Measurements with TriSol





N. Severijns *et. al.*, PRC **107** 015502 (2023)

Improving Previous Measurements

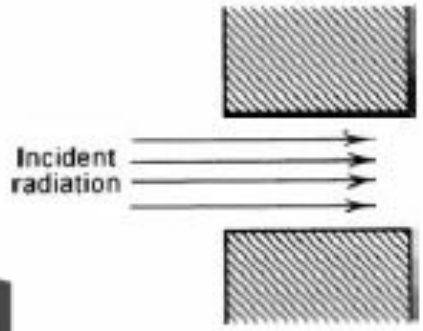
Accessing New Measurements

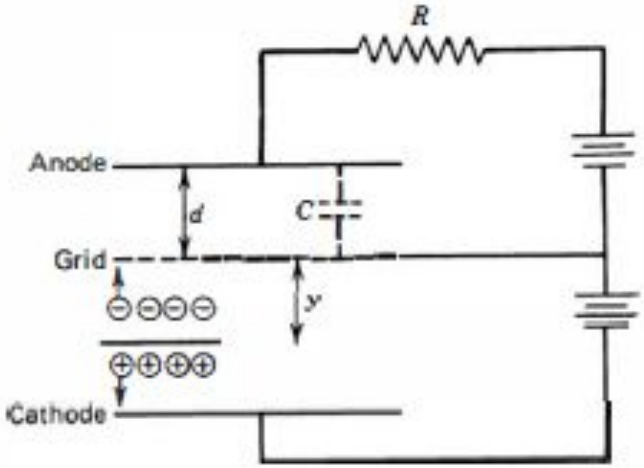
Active Target High Efficiency Detector for Nuclear Astrophysics

S N A P

Will von Seeger

- ATHENA
- Based on Multi-Sampling Ionization Chamber at Argonne National Labs
- Designed to measure total cross sections for helium-induced reactions important to astrophysics





Knoll, *Radiation Detection and Measurement*

$$V_{max} = \frac{Ne}{C} = \frac{eE_d}{WC} \qquad E_d \propto Z^2$$

W: Energy to create an e^-/ion pair

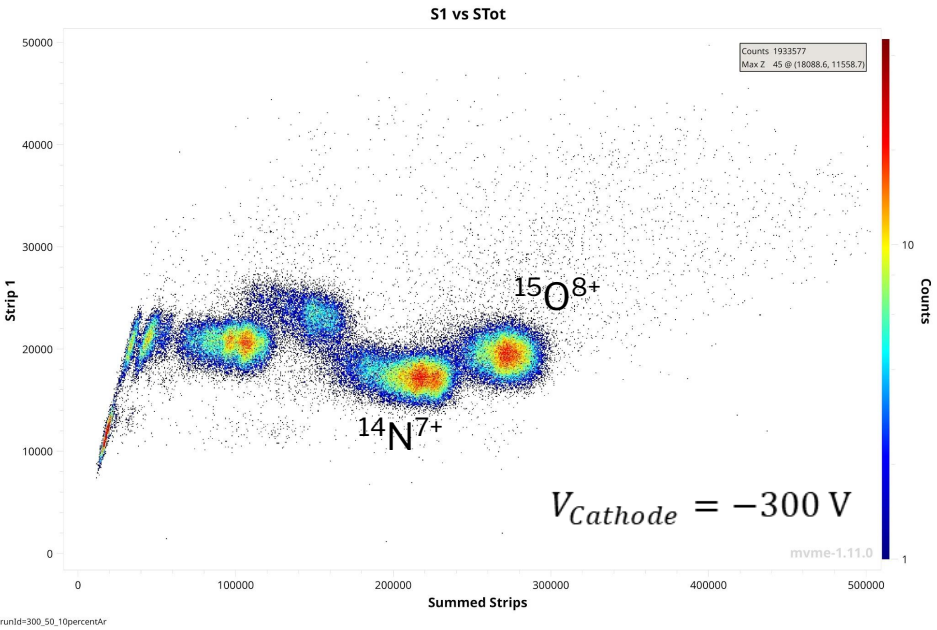
UNIVERSITY OF NOTRE DAME

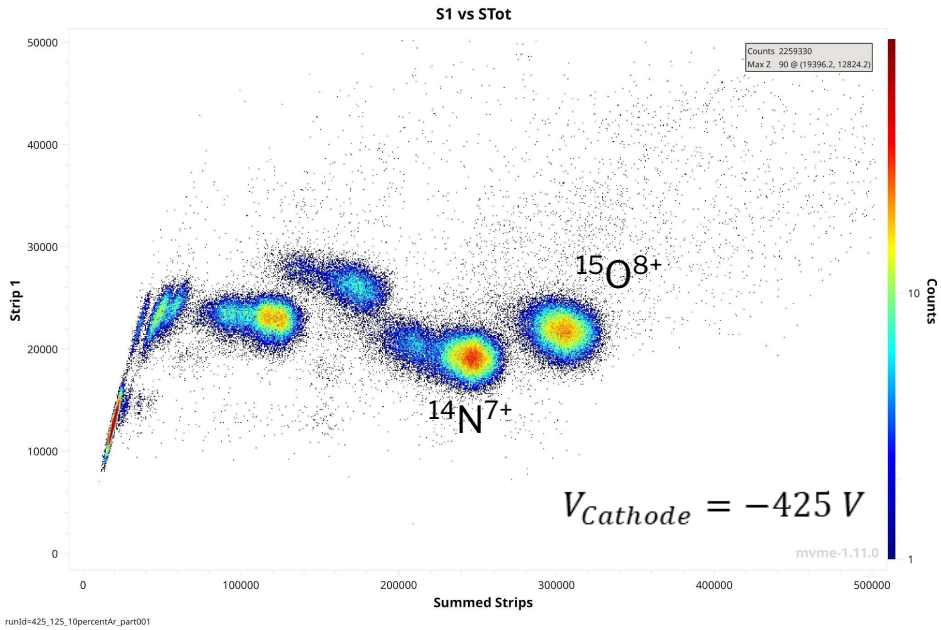
Recent ATHENA Improvements

High dead time in DAQ → Implement digitizers in DAQ

Helium low W-value → Dope helium with a good counting gas (CF_4)

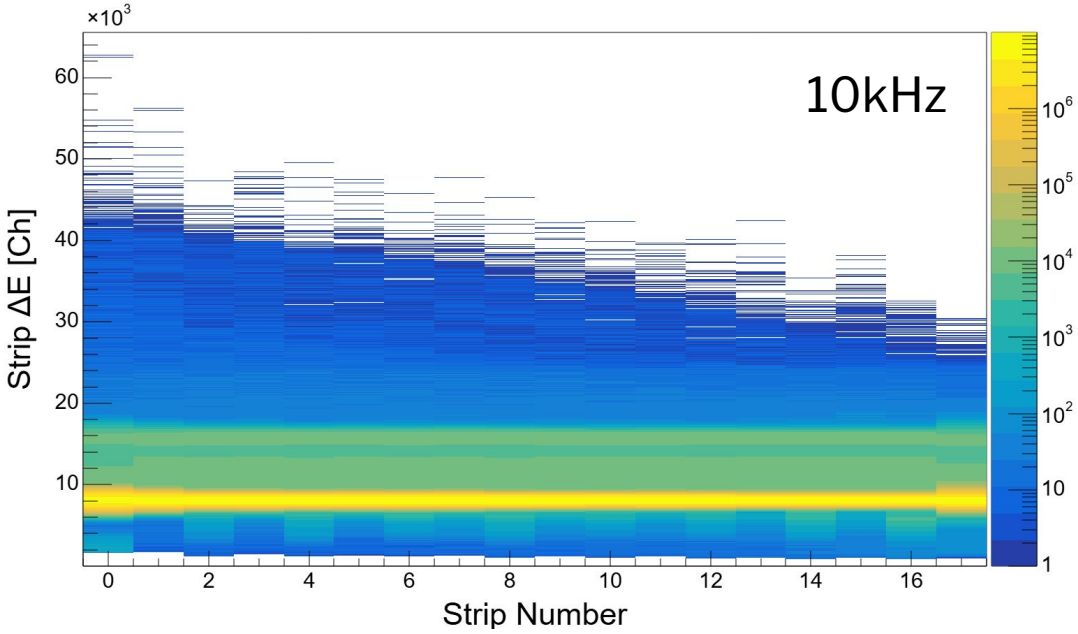
Helium low e^- drift speeds → Make cathode sheath for higher cathode voltages

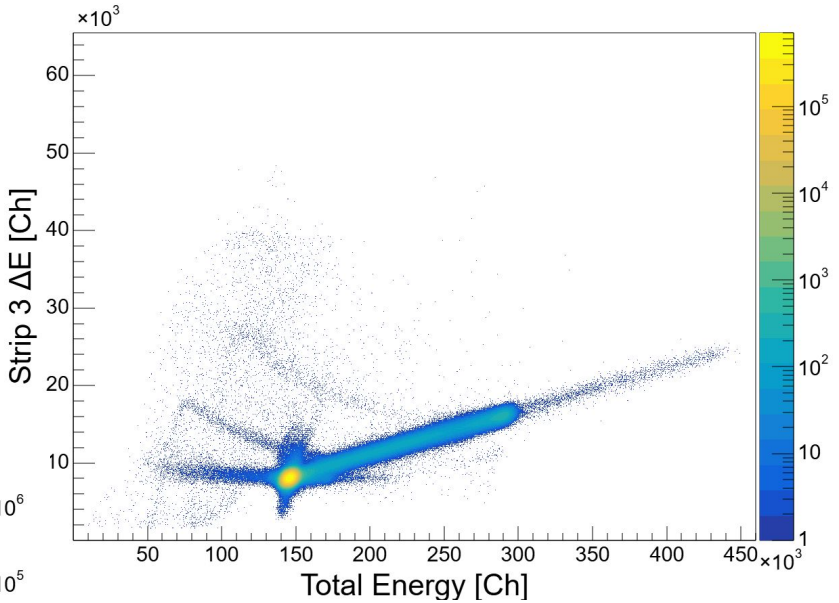




ATHENA at High Rate

- Recommissioned with $^{12}C+^{12}C$ fusion
- 41 MeV ^{12}C beam
- 150 Torr methane
- Ran at rates from 4kHz-150kHz
- Online spectra indicated that <150kHz





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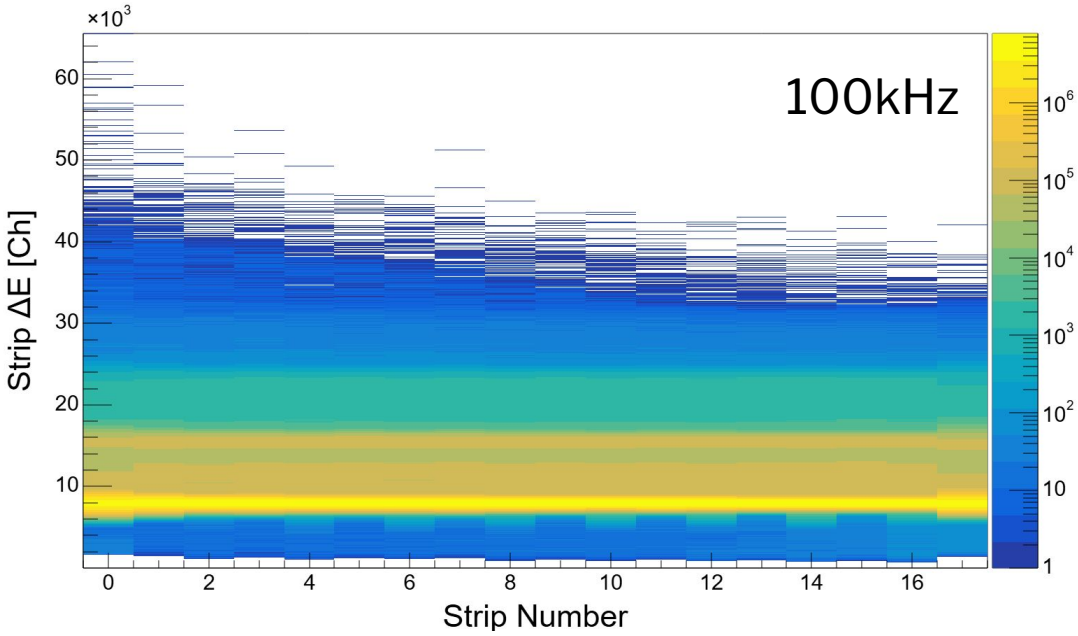
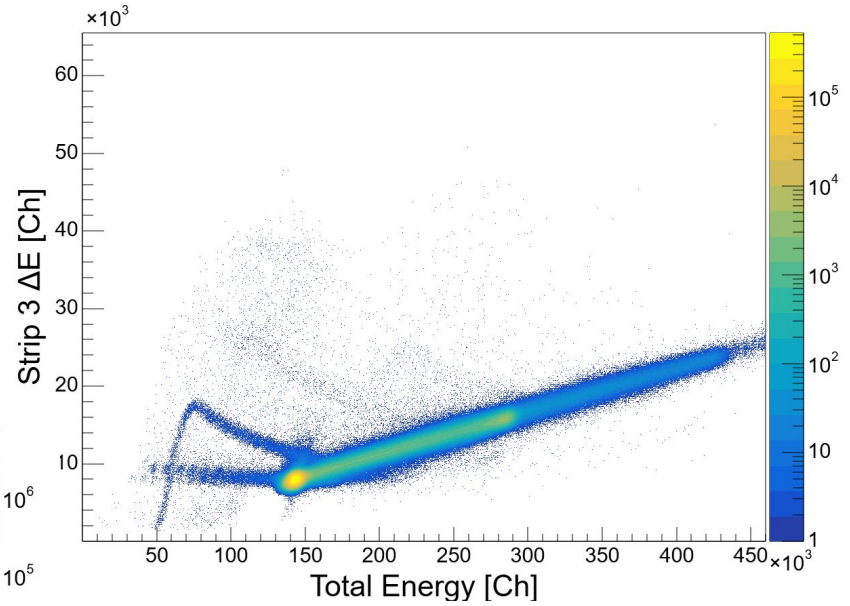
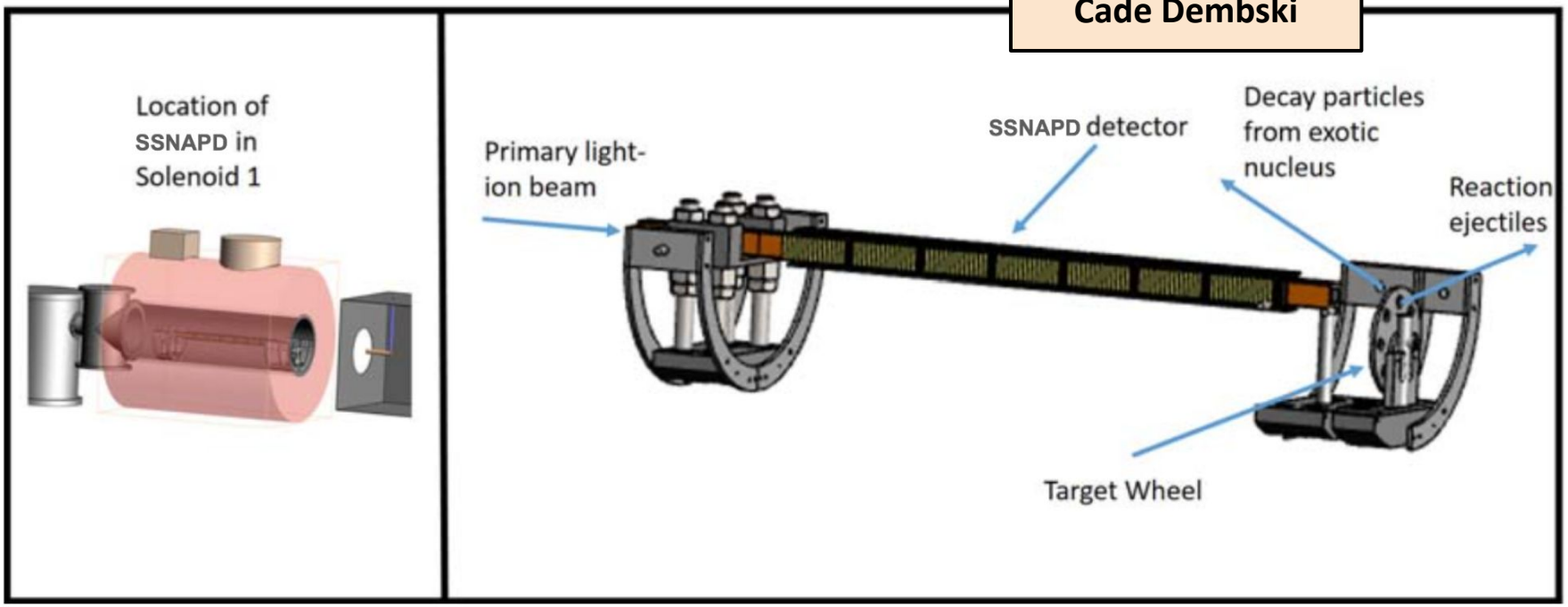
- Online spectra indicated that <150kHz





*S*olenoid *S*pectrometer for *N*uclear *A*stro*P*hysics and *D*ecays (*SSNAPD*)

Cade Dembski

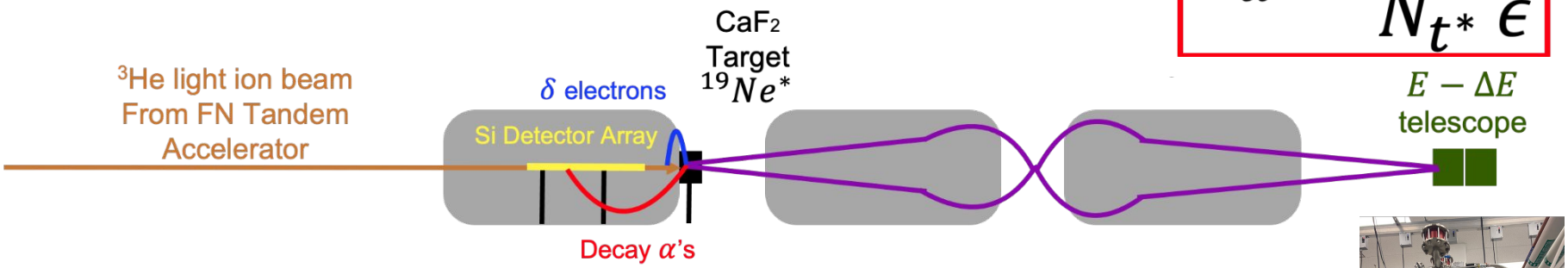


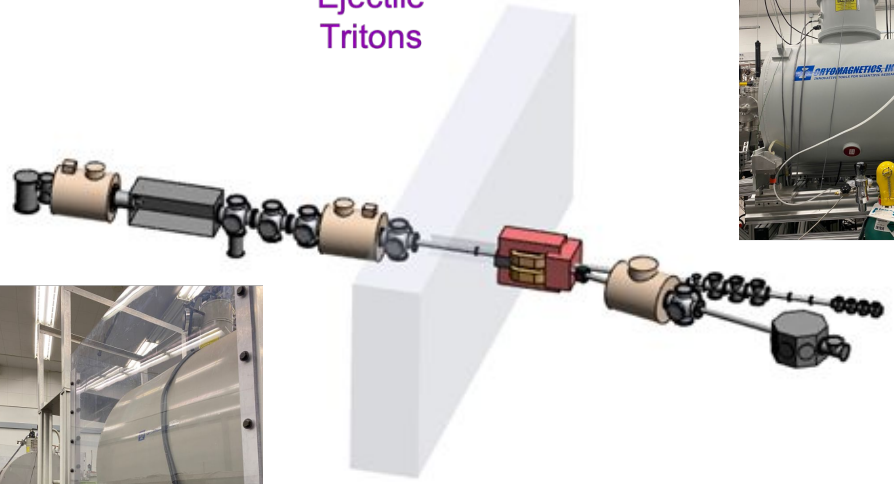
- Modification of the solenoidal spectrometer design used frequently in nuclear structure research (e.g. HeLiOS, SOLARIS, ISS)
- High geometric efficiency and robust particle ID capabilities are ideal for studying charged particle decays to constrain astrophysical reaction rates
- Recent upgrade to TriSol radioactive beam facility enables sensitive measurements of low proton- and α-branching ratios

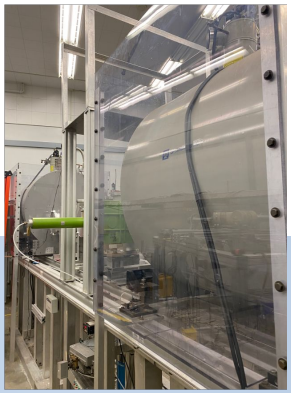
SSNAPD @ TriSol

Example: $^{19}Ne * \alpha$-branching for $^{15}O(\alpha,\gamma)^{19}Ne$ via $^{19}F(^{3}He,t)^{19}Ne$

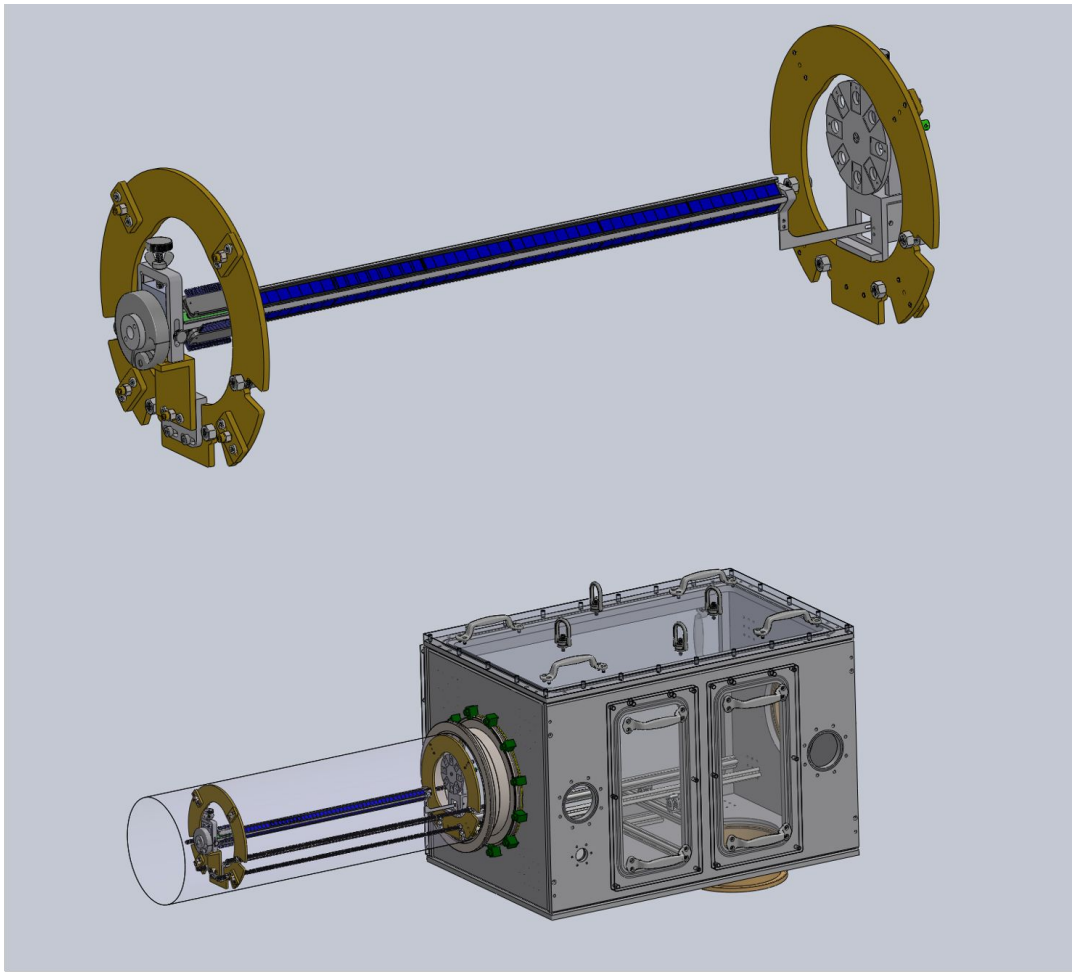
$$B_\alpha = \frac{N_\alpha}{N_{t^*}} \frac{1}{\epsilon}$$





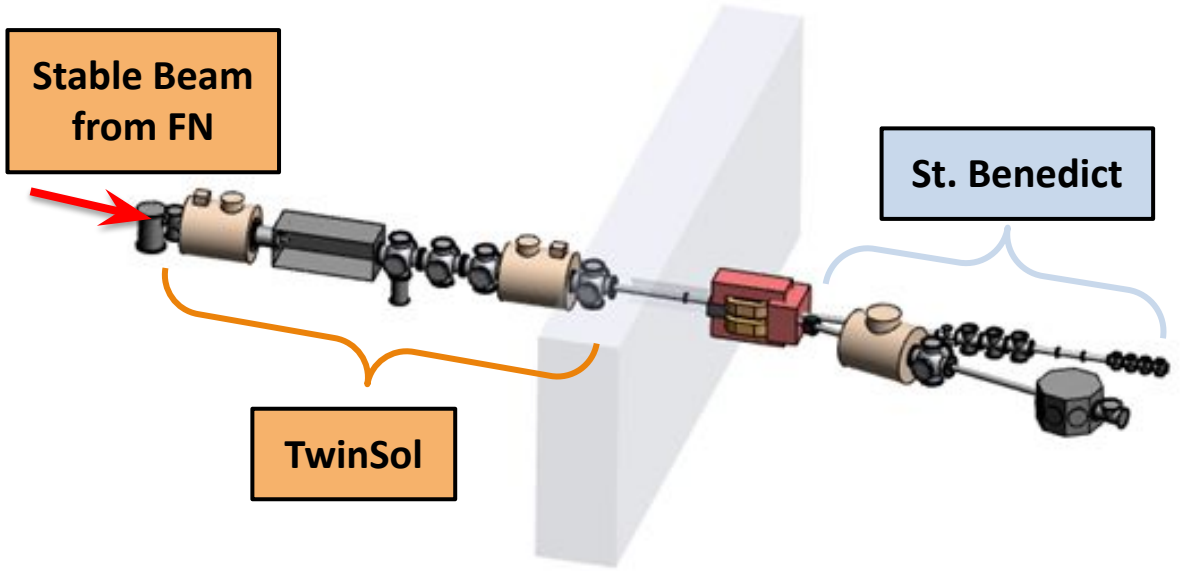


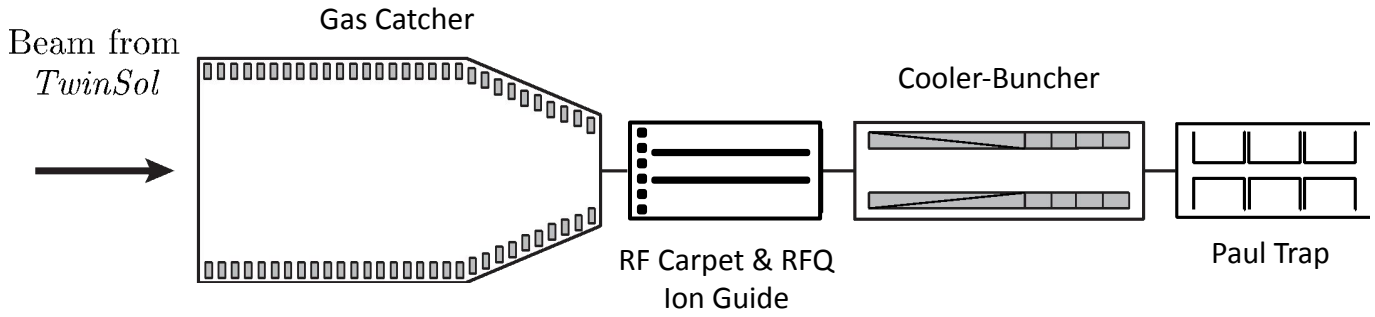
SSNAPD Designs



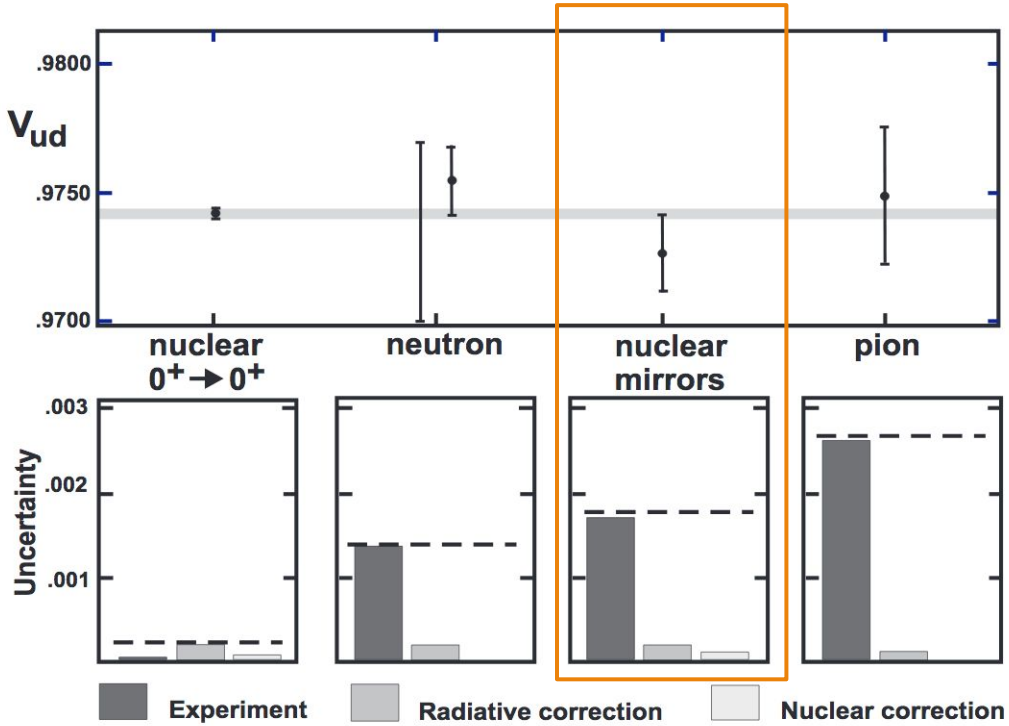
- Mounting frame and target wheel designed w/ ND Engineering and Design Core
- Assembly chamber for array built and leak tested
- More to come soon…

RIB Production Facilities @ NSL





V_{ud} from superallowed mirror decays



J.C. Hardy and I.S. Towner, arVix:1087.01146 [nucl-ex] (2018)

- Only **5 nuclei**

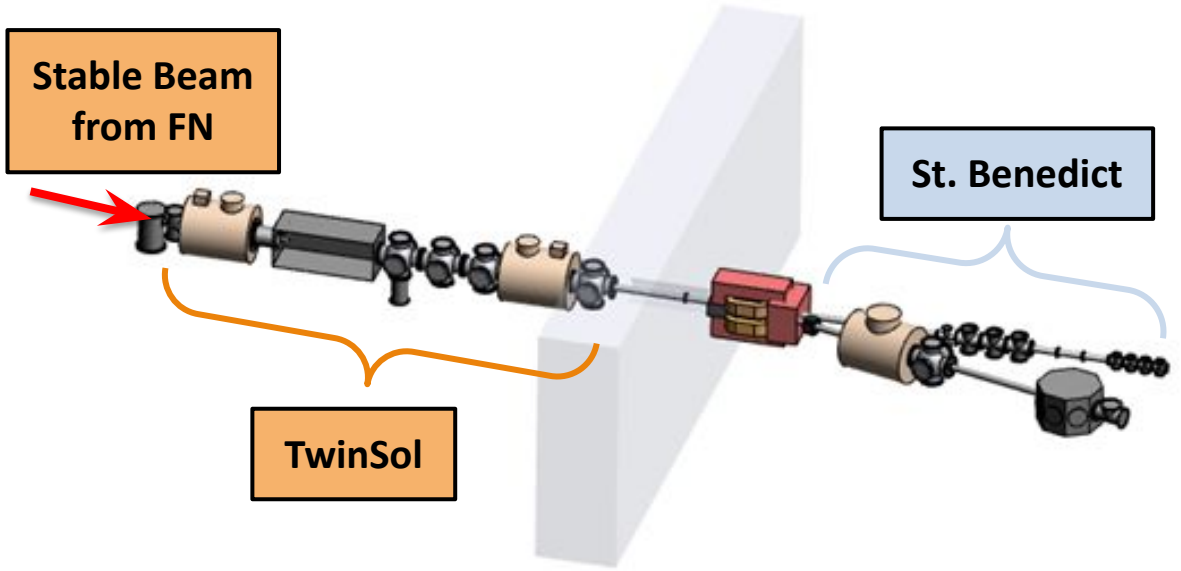
- ❑ Half-life
- ❑ Branching Ratios
- ❑ Q-values
- ❑ Fermi-to-Gamow Teller Mixing Ratio (**ρ**)

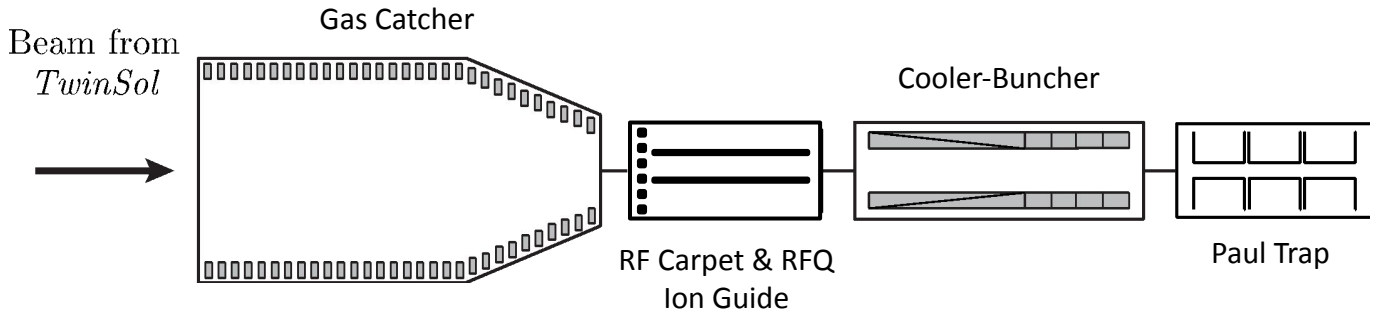
$$ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R)(1+\frac{f_A}{f_V}\rho)}$$

ρ

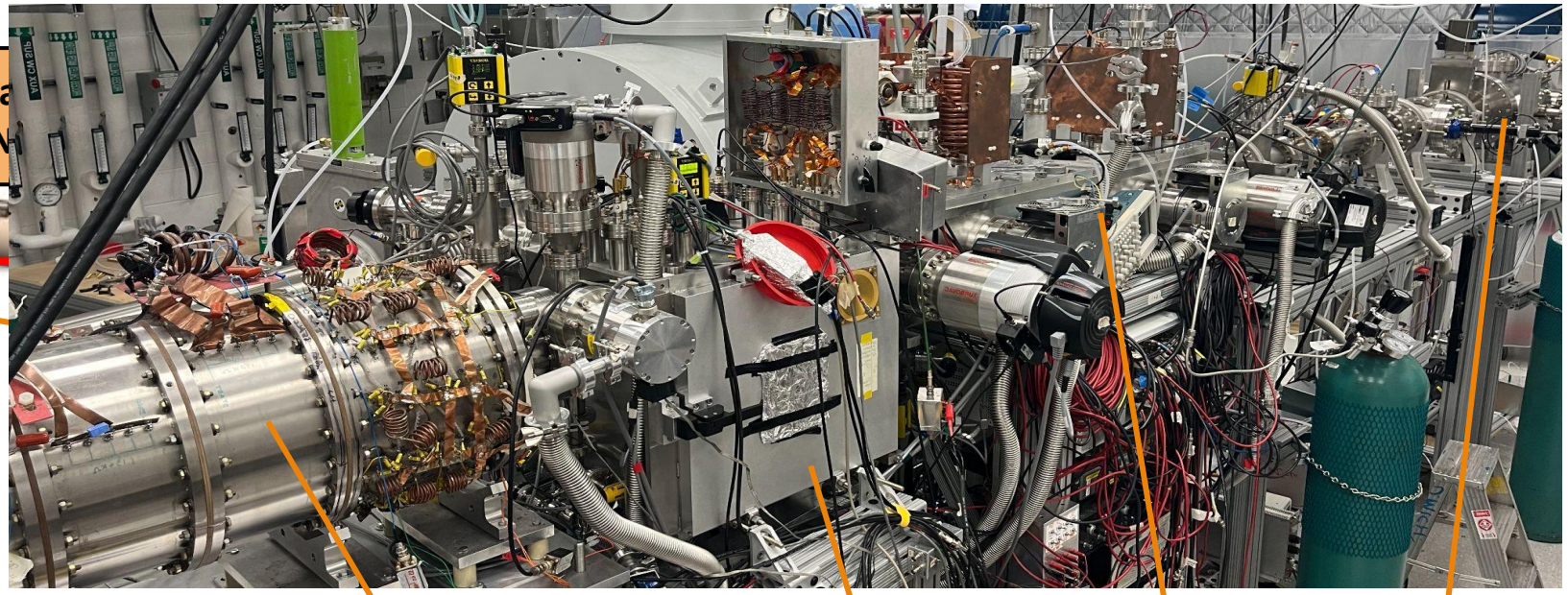
- β asymmetry parameter $\mathbf{A_\beta}$
- ν asymmetry parameter $\mathbf{B_\nu}$
- β-ν angular correlation $\mathbf{a_{\beta\nu}}$

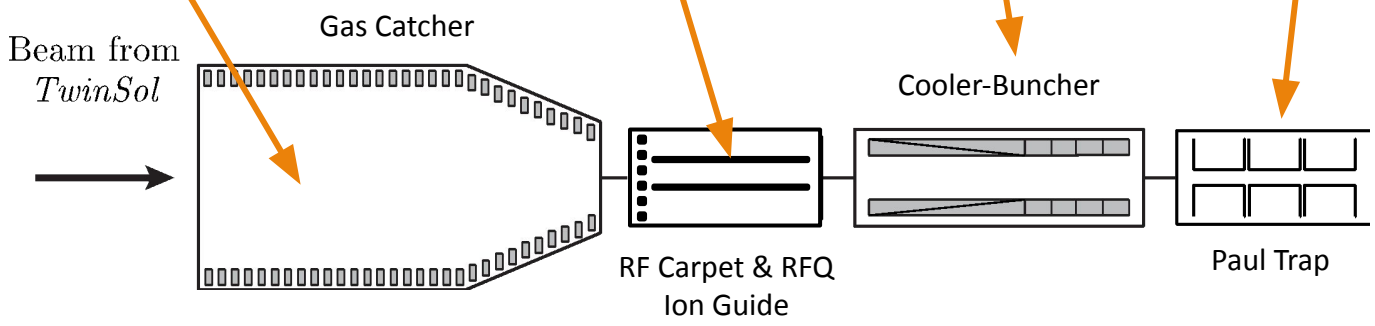
RIB Production Facilities @ NSL



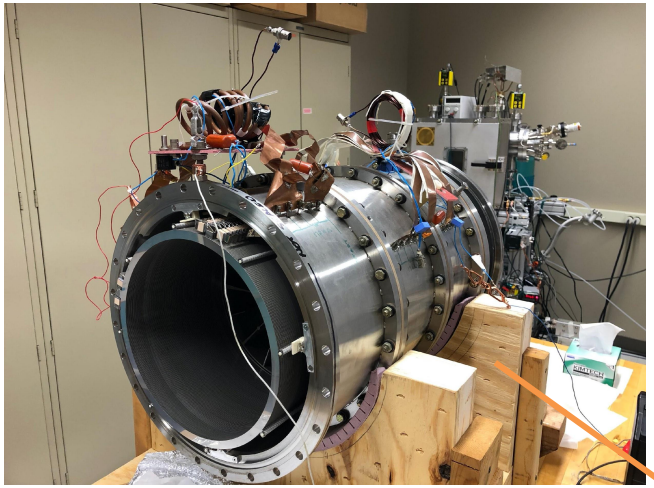


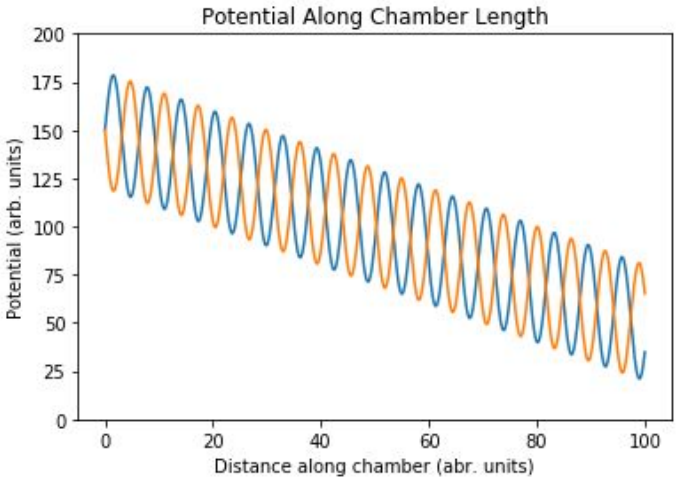
Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap

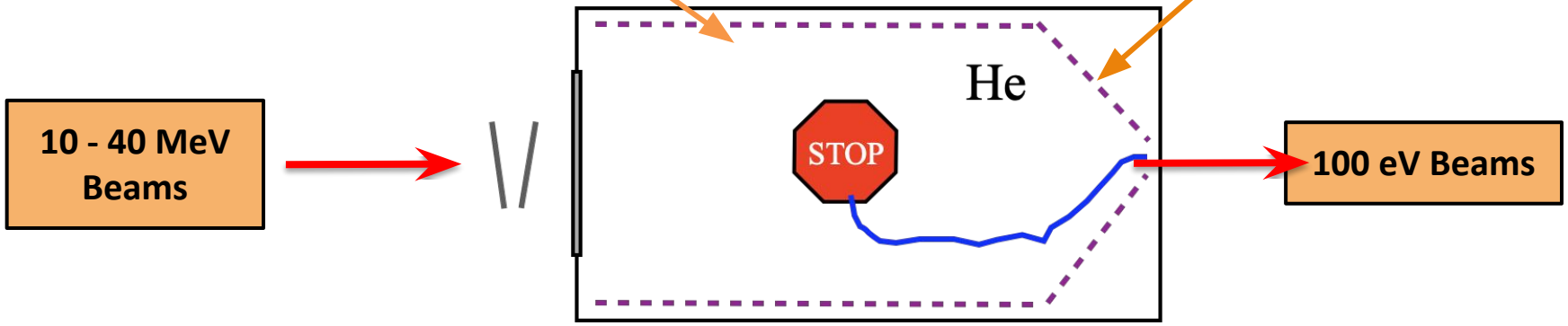




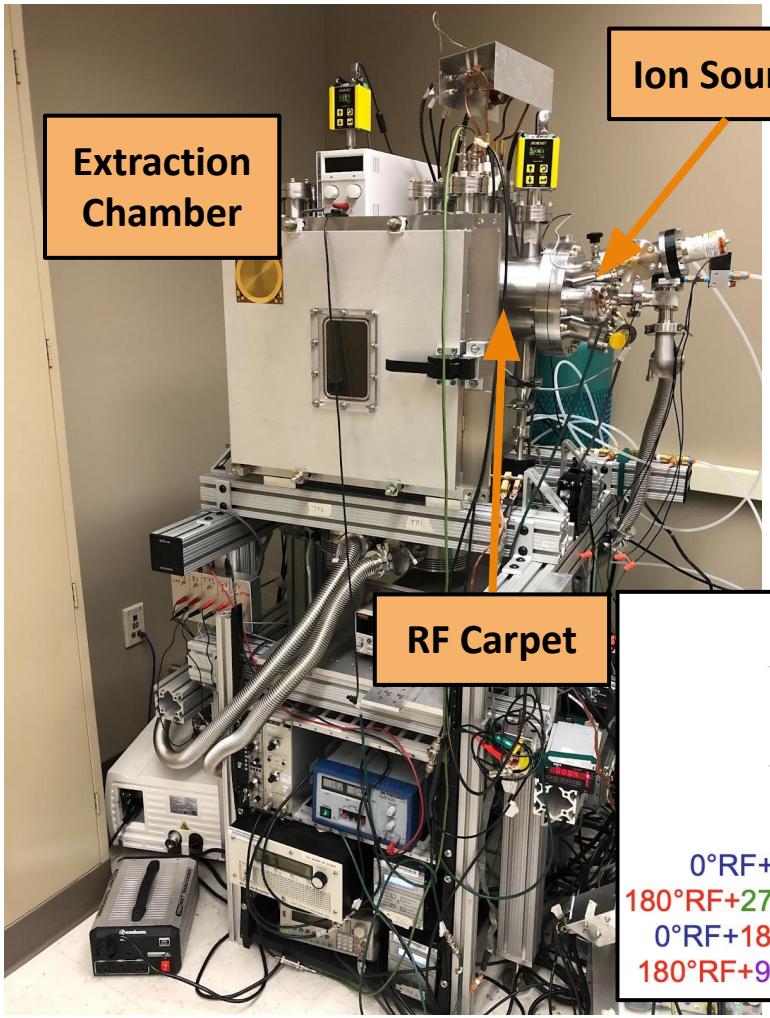
Gas Catcher

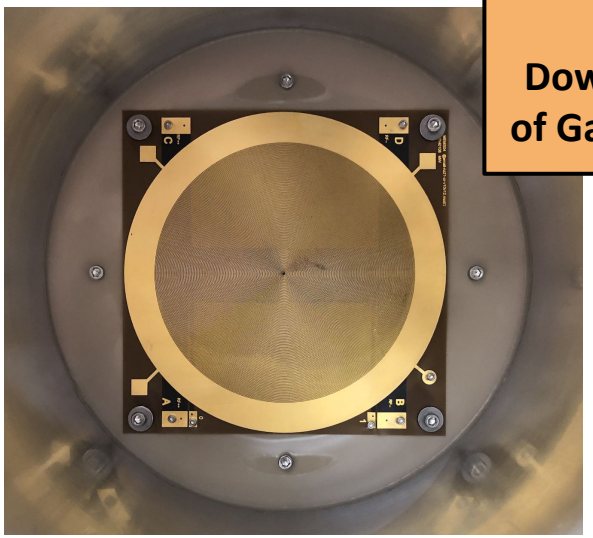


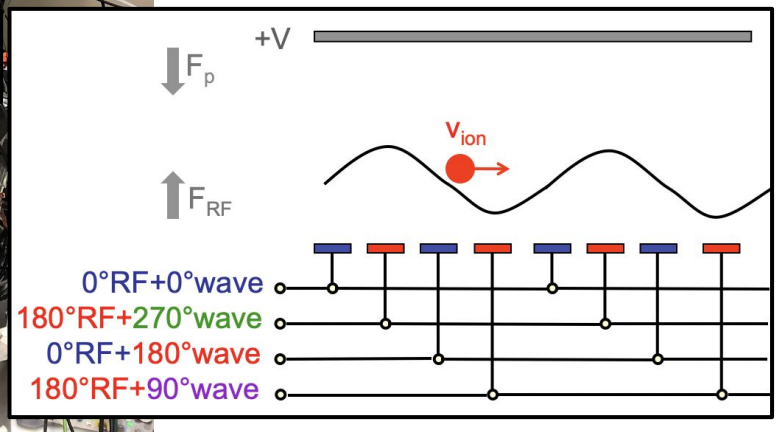

Potential Along Chamber Length
Potential (arb. units)
200
175
150
125
100
75
50
25
0
0
20
40
60
80
100
Distance along chamber (abr. units)

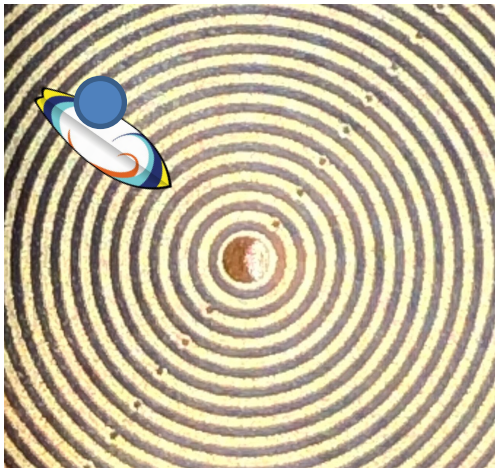

10 - 40 MeV Beams
He
STOP
100 eV Beams

RF Carpet

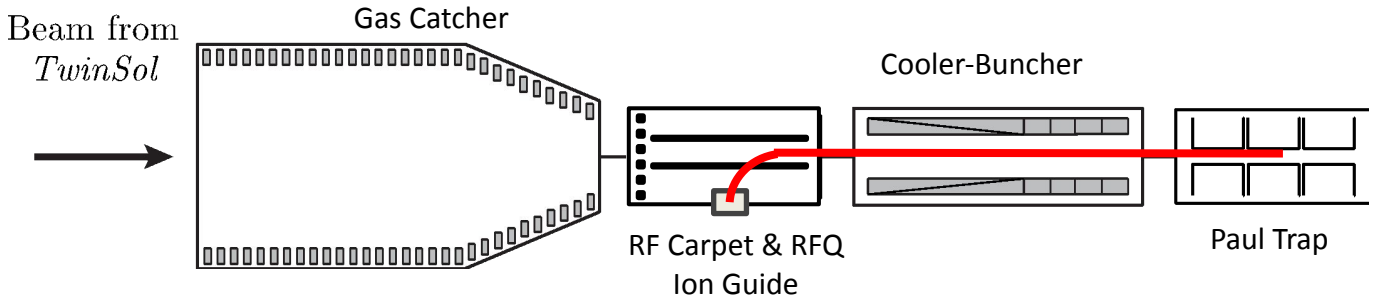

Extraction Chamber
Ion Source
RF Carpet

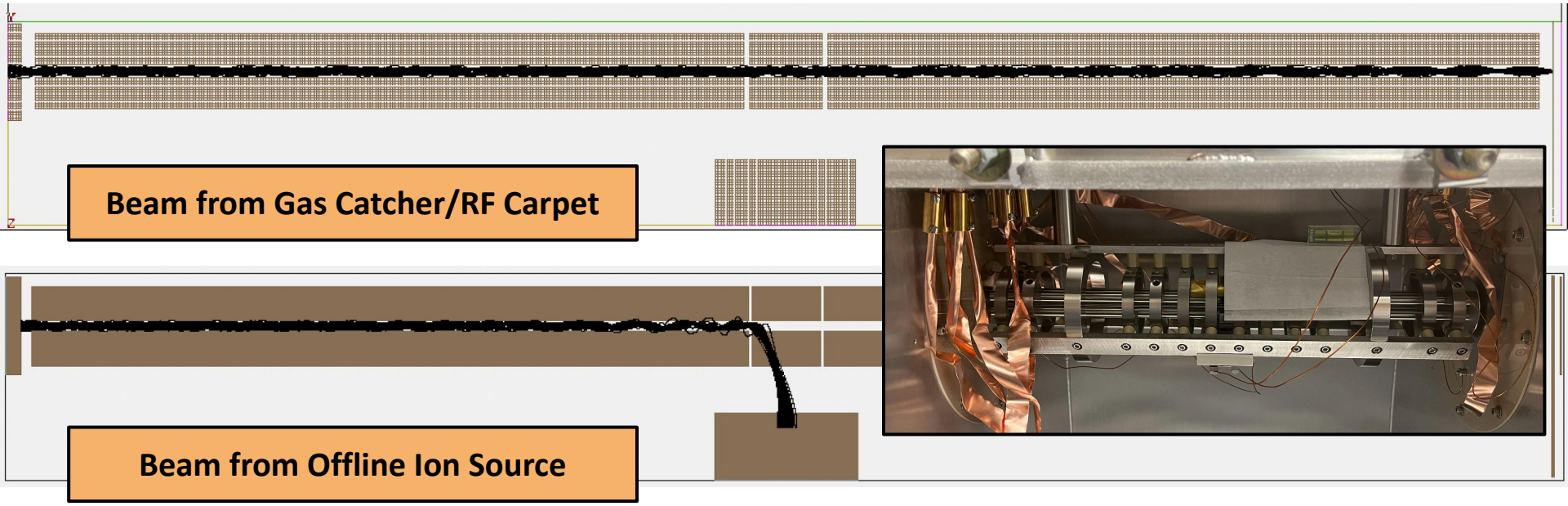

View Downstream of Gas Catcher


+V
F_p
V_{ion}
F_{RF}
0°RF+0°wave
180°RF+270°wave
0°RF+180°wave
180°RF+90°wave

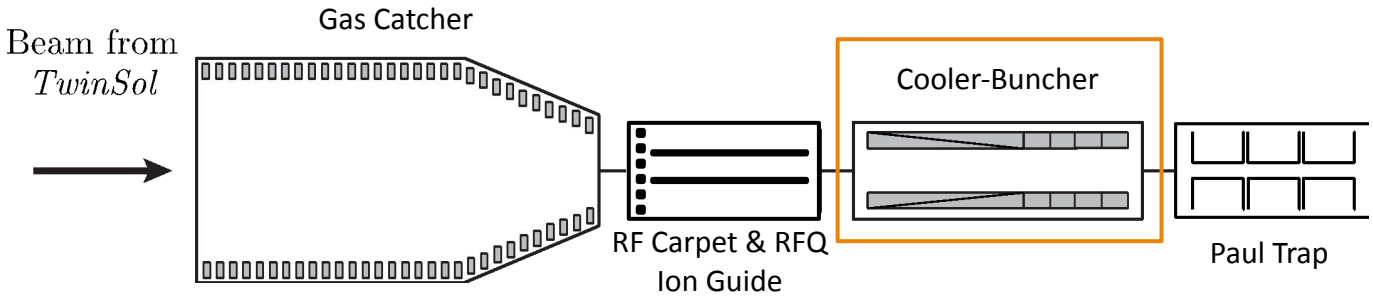


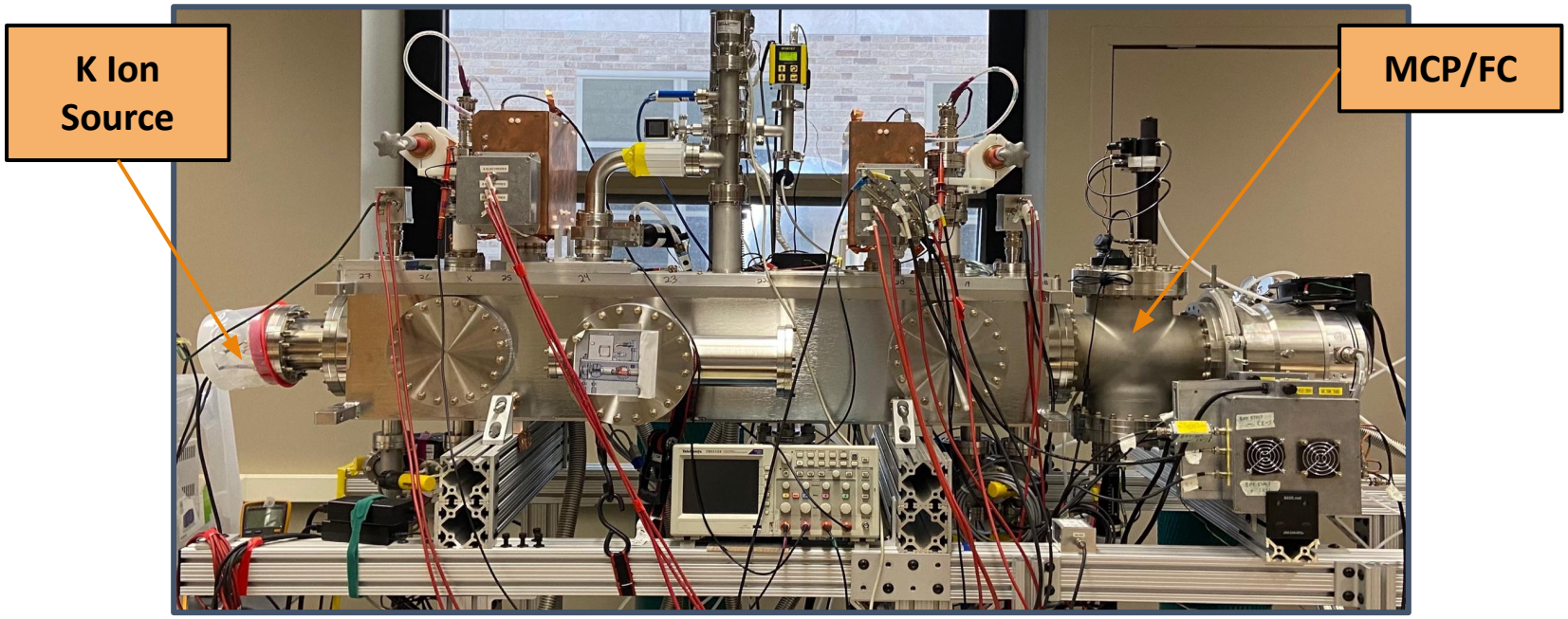
RFQ Ion Guide (+ Offline Ion Source)



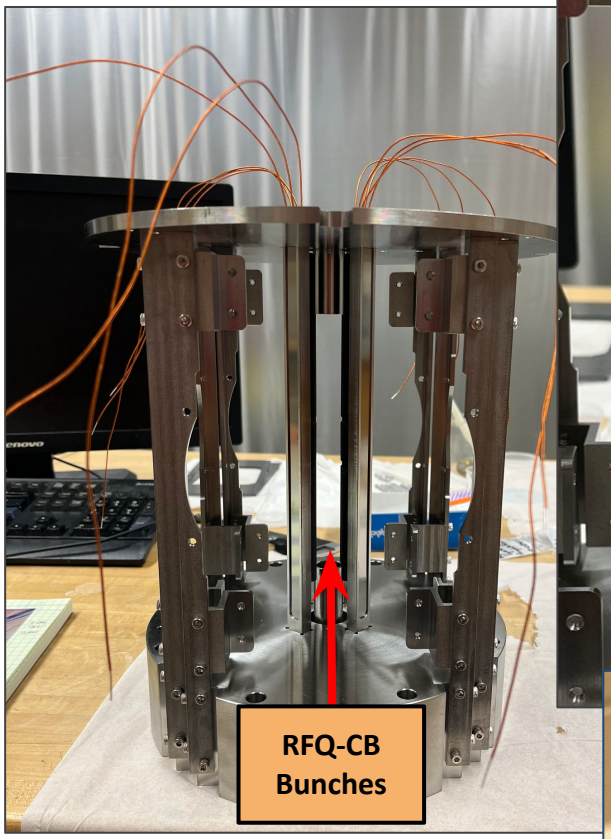


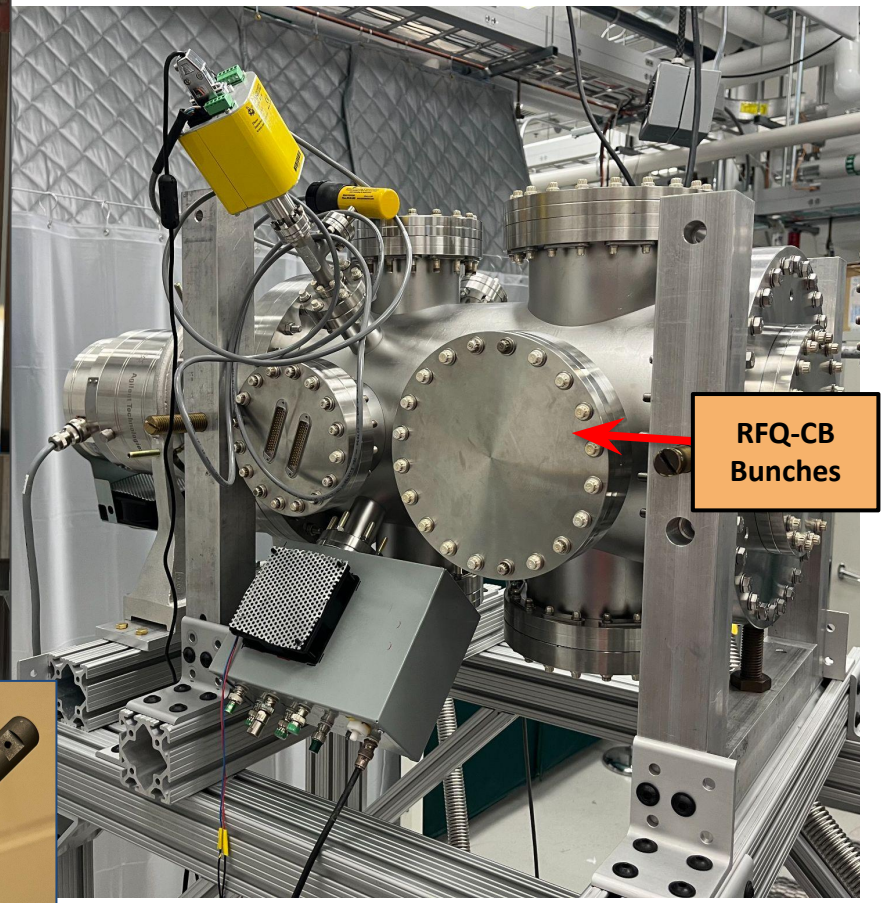
RFQ Cooler-Buncher



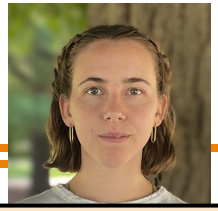


Paul Trap

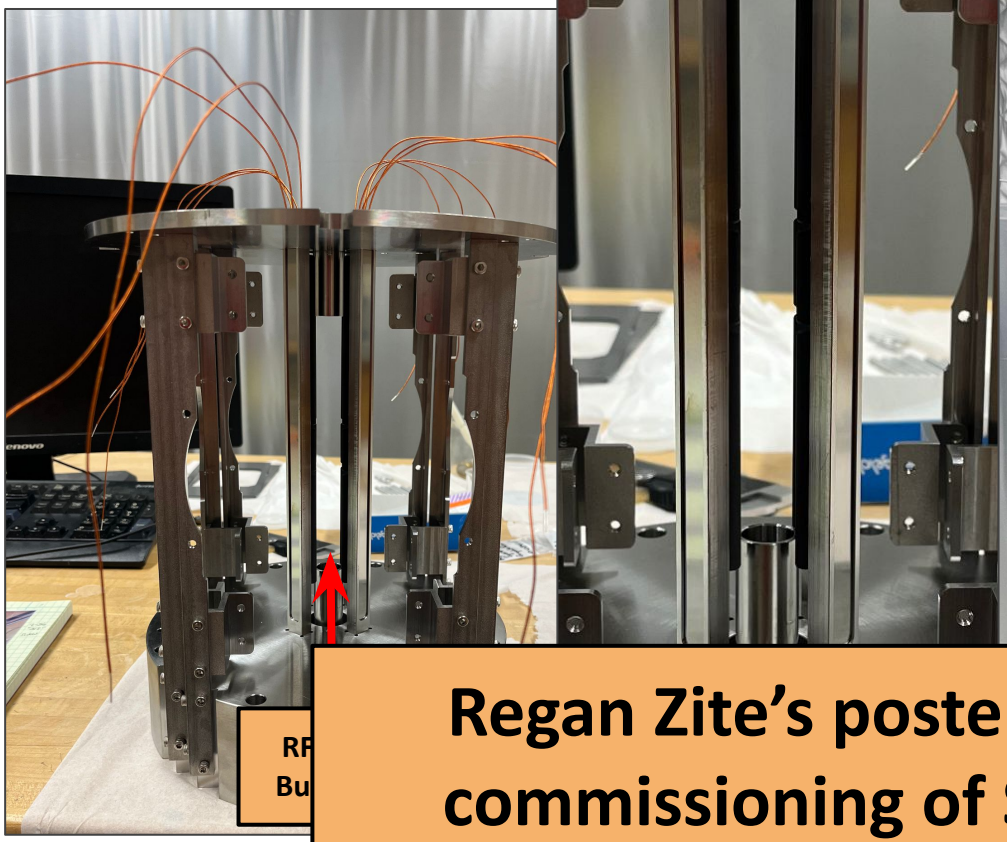


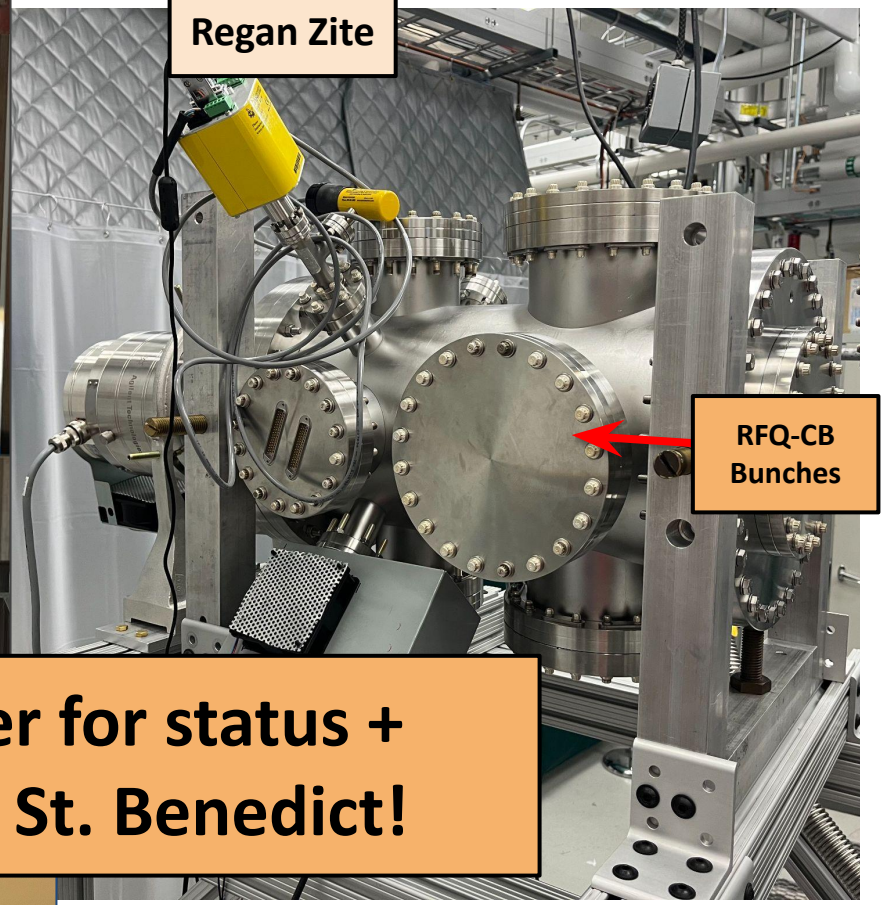


Paul Trap



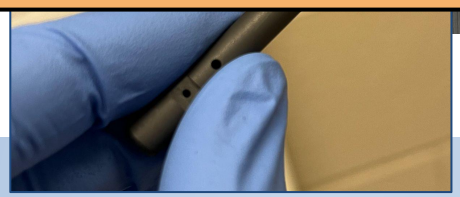
Regan Zite



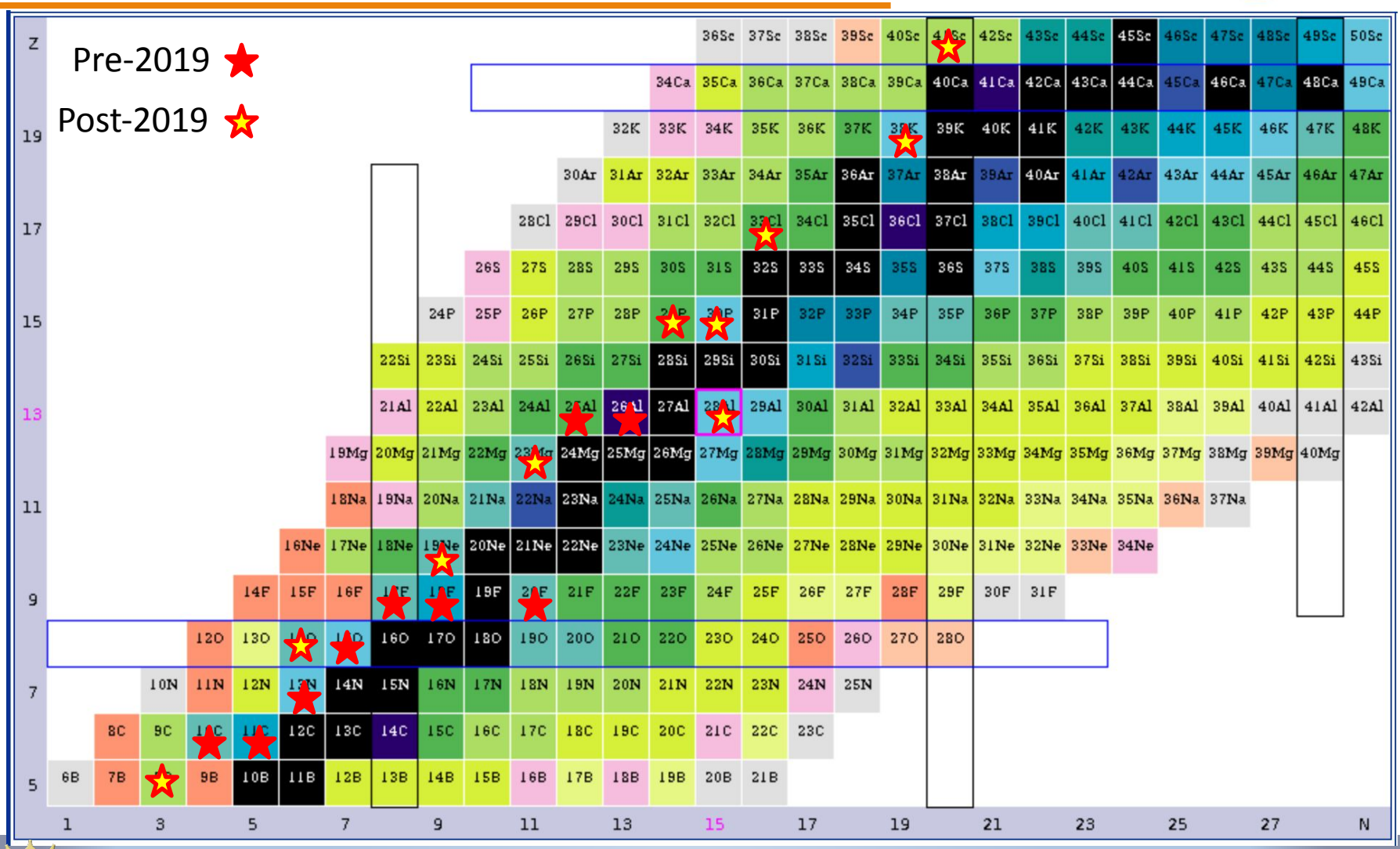


RFQ-CB Bunches

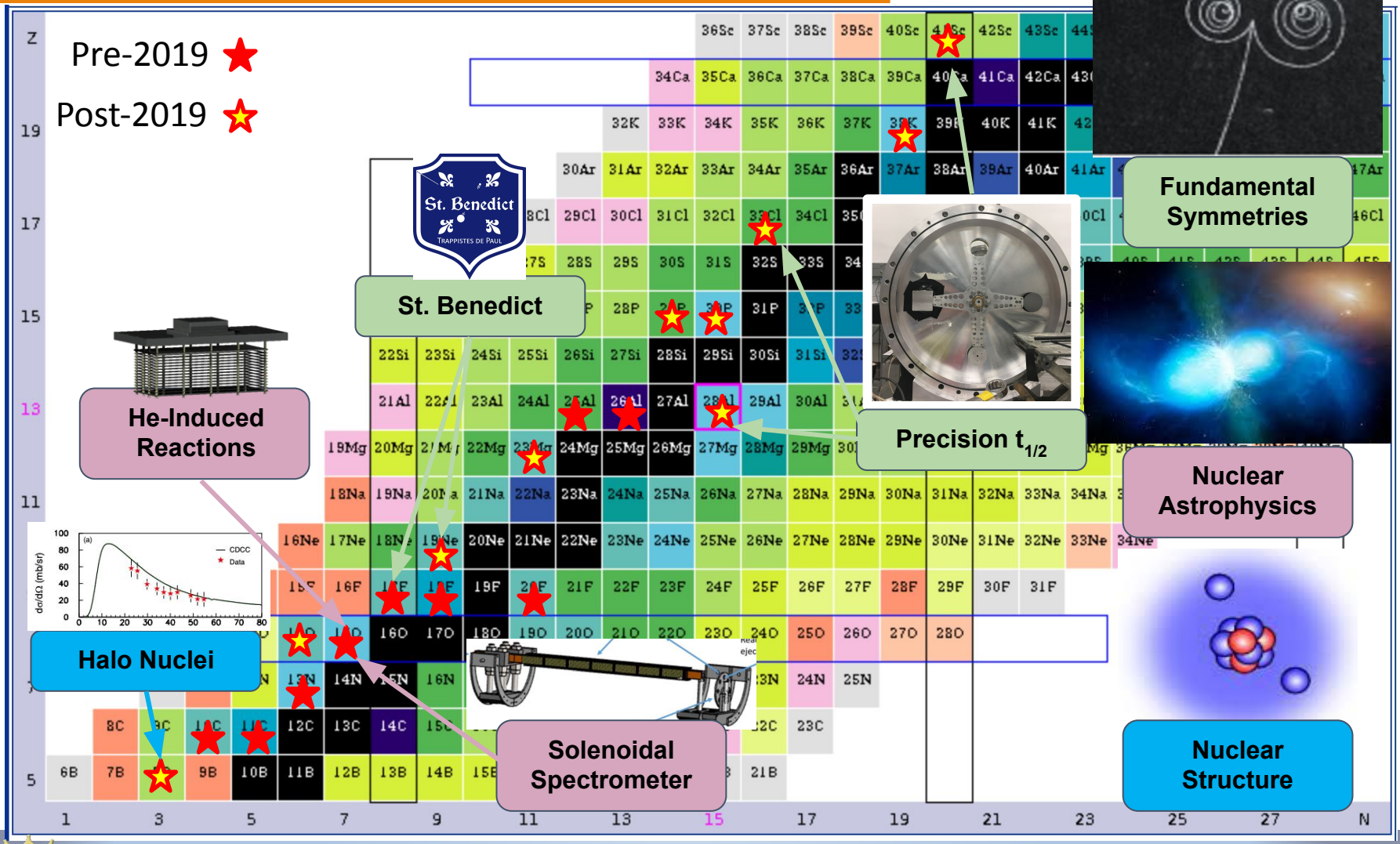
Regan Zite's poster for status + commissioning of St. Benedict!



RIBs @ NSL



RIBs @ NSL


Pre-2019
Post-2019
St. Benedict
TRAPPISTES DE PAUL
St. Benedict
He-Induced Reactions
Halo Nuclei
Solenoidal Spectrometer
Precision $t_{1/2}$
Fundamental Symmetries
Nuclear Astrophysics
Nuclear Structure
Z
N

Summary

- *TwinSol* has a long history of provide RIBs for a wide range of scientific applications, and will continue to provide such beams to the St. Benedict facility
- The advent of *TriSol* improves the quality and purity of RIB deliverable, enabling access to new experiments and radioactive isotopes
- These improvements unlock many new scientific opportunities in fundamental symmetries, with precision half-life measurements, nuclear astrophysics, with ATHENA and SSNAPD, and beyond

Acknowledgements

The TwinSol/TriSol Collaboration:

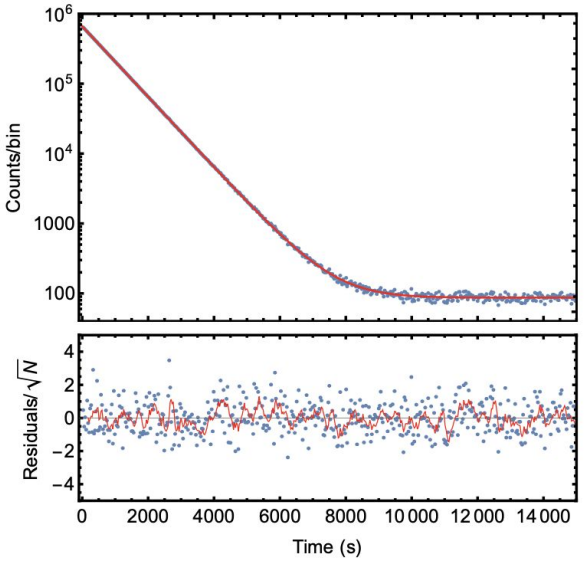
Dan Bardayan
Olivia Bruce
Max Brodeur
Scott Carmichael
Sydney Coil
Cade Dembski
Jim Kolata
Patrick O'Malley
Fabio Rivero
Adrian Valverde
Dan Schroeder
Will von Seeger
Regan Zite

Expanding mirror nuclei $a_{\beta\nu}$ measurements

Parent nucleus	ΔV_{ud}	a / $(\Delta V_{ud})^{\text{limit}}$	Factor $\Delta\mathcal{F}t$	
^{3}H	0.0011	0.0010	2.1	
^{11}C	0.0025	0.0016	4.0	←
^{13}N	0.0017	0.0017	1.0	←
^{15}O	0.0020	0.0016	2.4	←
^{17}F	0.0019	0.0013	3.1	←
^{19}Ne	0.0011	0.0010	1.5	
^{21}Na	0.0022	0.0017	2.7	
^{23}Mg	0.0025	0.0018	3.1	
^{25}Al	0.0019	0.0018	1.7	←
^{27}Si	0.0029	0.0018	4.1	
^{29}P	0.0026	0.0018	3.4	←
^{31}S	0.0038	0.0018	5.9	
^{33}Cl	0.0021	0.0018	2.0	←
^{35}Ar	0.0019	0.0018	1.1	
^{37}K	0.0034	0.0017	5.8	
^{39}Ca	0.0024	0.0016	3.5	
^{41}Sc	0.0029	0.0022	2.7	

N. Severjins and O. Naviliat-Cuncic, Phys. Scr. T**152**, 014018 (2013)

^{17}F: M. Brodeur *et al.* PRC **93** 025503 (2016).
^{25}Al: J. Long *et al.* PRC **96**, 015502 (2017) .
^{11}C: A. A. Valverde *et al.* PRC **97**, 035503 (2018).
^{20}F: D.P. Burdette *et al.* PRC **99**, 015501 (2019).
^{15}O: D.P. Burdette *et al.* PRC **101** 055504 (2020).
^{29}P: J. Long *et al.* PRC **101**, 015501 (2020).
^{13}N: J. Long Ph.D. Thesis (2020). Accepted at PRC.
^{28}Al: B. Liu *et al.* In preparation.
^{33}Cl: P.D. O'Malley *et al.* under analysis.



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^{41}Sc	0.0029	0.0022	2.7

N. Severjins and O. Naviliat-Cuncic, Phys. Scr. T**152**, 014018 (2013)

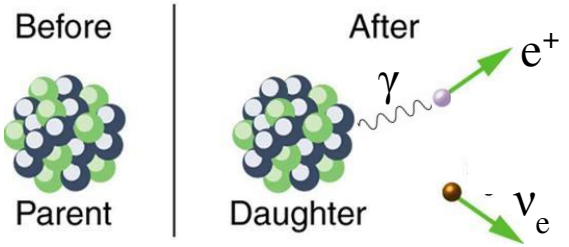
Nucleus	n	^{3}H	^{11}C	^{13}N	^{15}O	^{17}F	^{19}Ne
ρ	−2.20	−2.10	0.75	0.56	−0.63	−1.28	1.60
J	1/2	1/2	3/2	1/2	1/2	5/2	1/2
$\delta A_\beta/A_\beta$	4.0	5.1	0.04	0.04	0.7	−0.06	−12.6
$\delta a_{\beta\nu}/a_{\beta\nu}$	3.6	4.6	−1.2	−0.7	−0.9	−3.6	−13.1

Table I. Calculated sensitivities to $\delta\rho/\rho$ for the lowest mass mirrors, with approximate ρ values taken from [10] and the leading order expressions.

L. Hayen and A.R. Young, arVix:2009.11364 (2020)

- Will greatly improve on previous ^{17}F ϱ measurement based on a measurement of A_β (N. Severjins *et. al.*, PRL **63**, 1050 (1989)) due to improved sensitivity

Radiative Corrections



The emitted positron will interact with the nucleus.

Radiative corrections:

$$|M_{fi}|^2 = 2(1-\delta_c)(1+\delta_R)(1+\Delta_R^V)$$

Transition-dependent: δ_R ~1.4%

Long-distance, depend on e^+ energy.

$$\delta_R = \delta'_R + \delta_{NS}$$

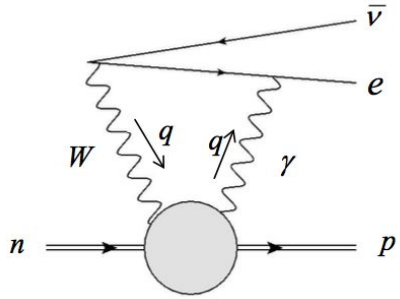
Nuclear structure independent

Nuclear structure dependent

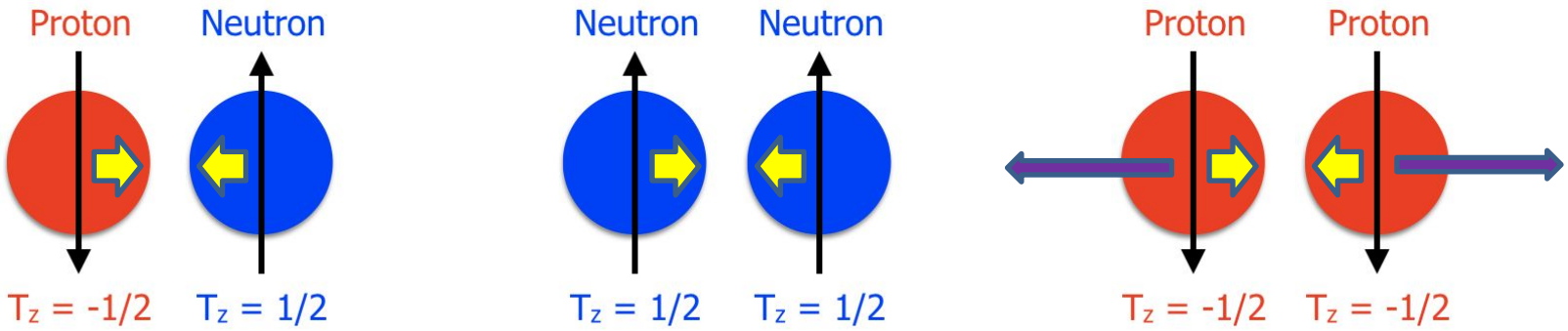
Transition-independent: Δ^V_R ~2.4%

Short-distance, no e^+ energy-dependence.

Includes W-γ box diagrams.



Isospin Symmetry Breaking Correction

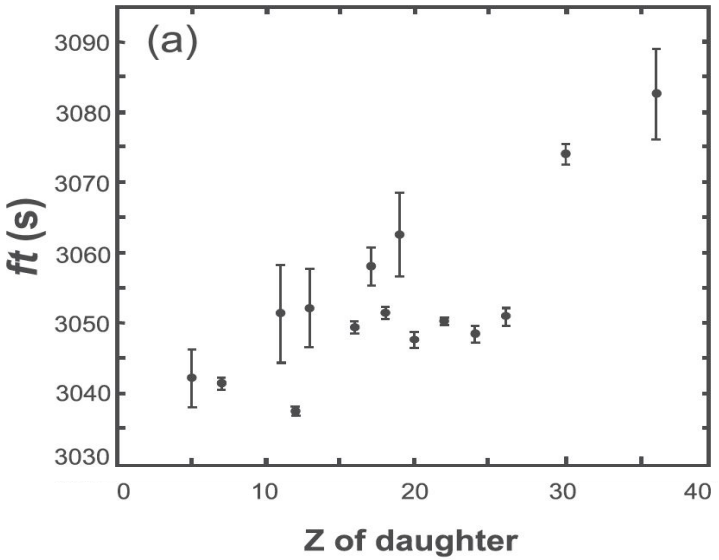


Isospin symmetry is broken in nuclei due to:

- Proton-neutron mass difference
- Coulomb interaction

Isospin Symmetry Breaking correction
δ_c: ~0.2 - 1.5%

$$|M_{fi}|^2 = 2(1 - \delta_c)$$

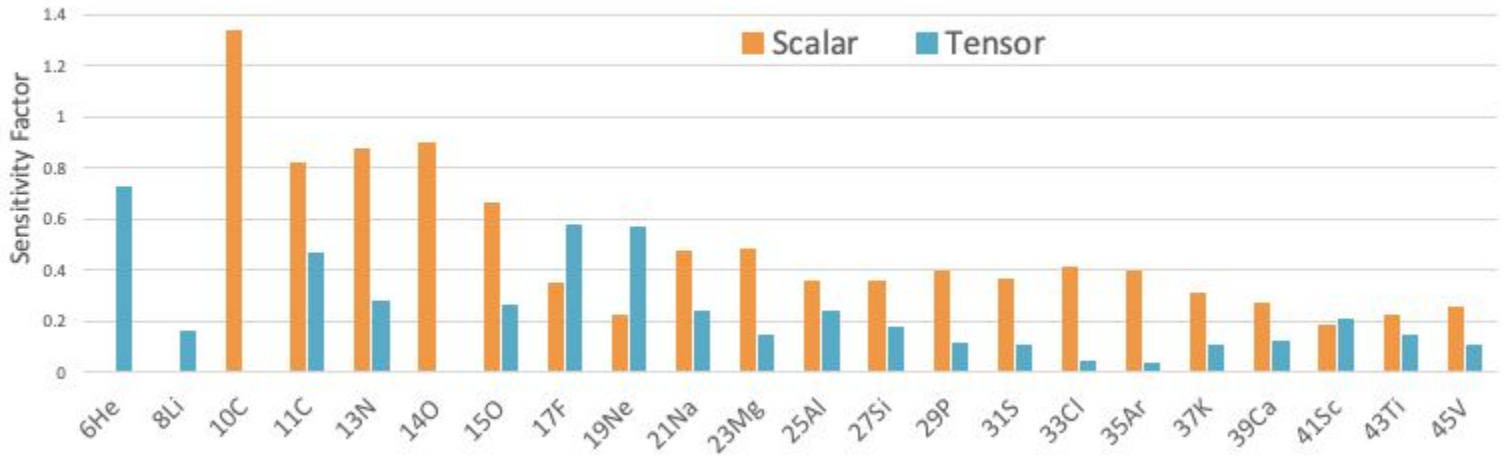


Probing exotic currents

$$b_{Fermi} \approx \pm 2\gamma \, Re\left(\frac{C_S + C'_S}{C_V + C'_V}\right)$$

$$b_{mirror} \approx \pm \frac{2\gamma}{1 + |\tilde{\rho}^2|} \, Re\left(\frac{C_S + C'_S}{C_V + C'_V} + |\tilde{\rho}^2| \frac{C_T + C'_T}{C_A + C'_A}\right)$$

$$ft = \frac{K}{\left|M'_{fi}\right|^2} \frac{1}{1 + \frac{\gamma}{W} b}$$



Back Up Slide - V_{us} and V_{ub}

V_{us}

Obtained through Kaon decay:

$$K \rightarrow \pi \ell \nu$$

(Constrained by theory)

$$\tau^- \rightarrow \pi^- \nu \text{ or } \tau^- \rightarrow K^- \nu$$

(Purely experimental)

Discrepancy between each method which could have effects on the unitarity sum.

V_{ub}

Obtained most accurately from:

$$B \rightarrow \pi \ell \nu$$

Uncertainty dominated by QCD calculations