The $^{15}O(\alpha,\gamma)^{19}Ne$ Reaction in Type I X-ray Bursts

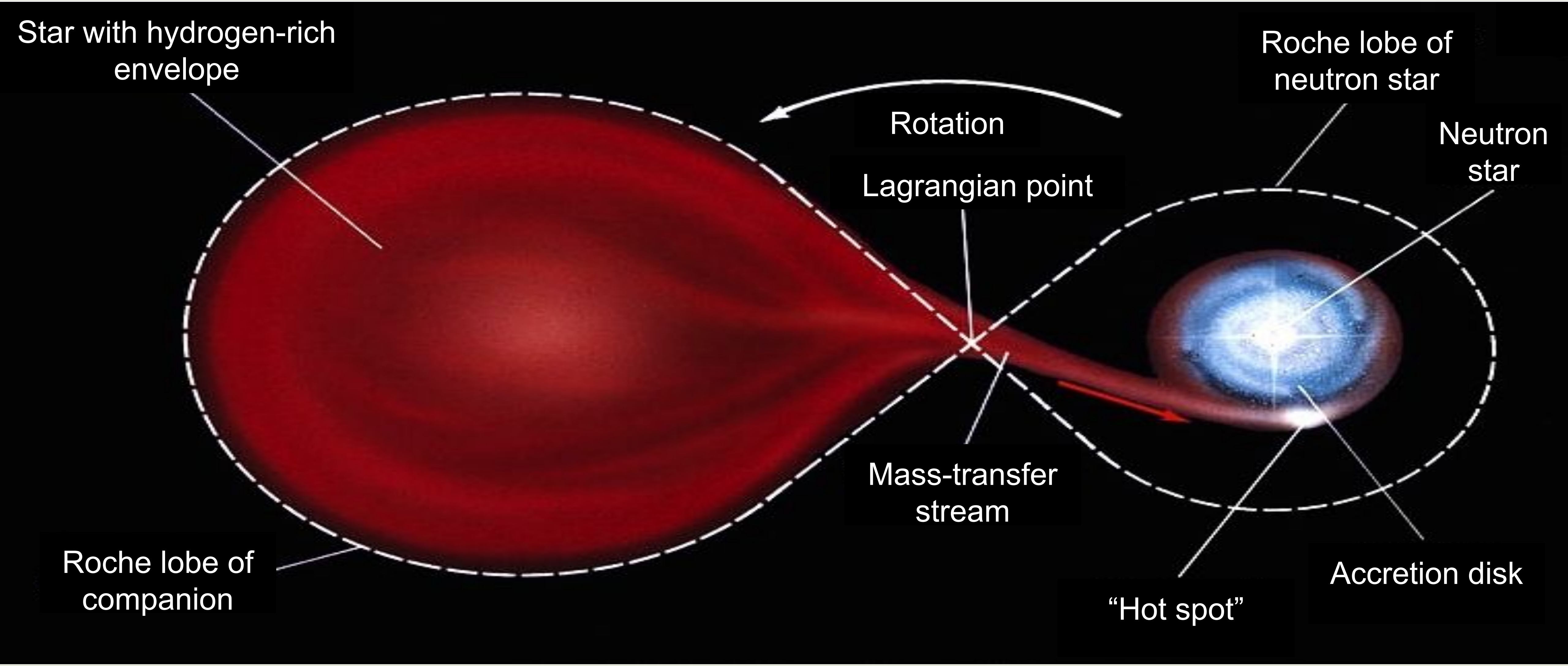
17th Rußbach School on Nuclear Astrophysics

Tyler Wheeler

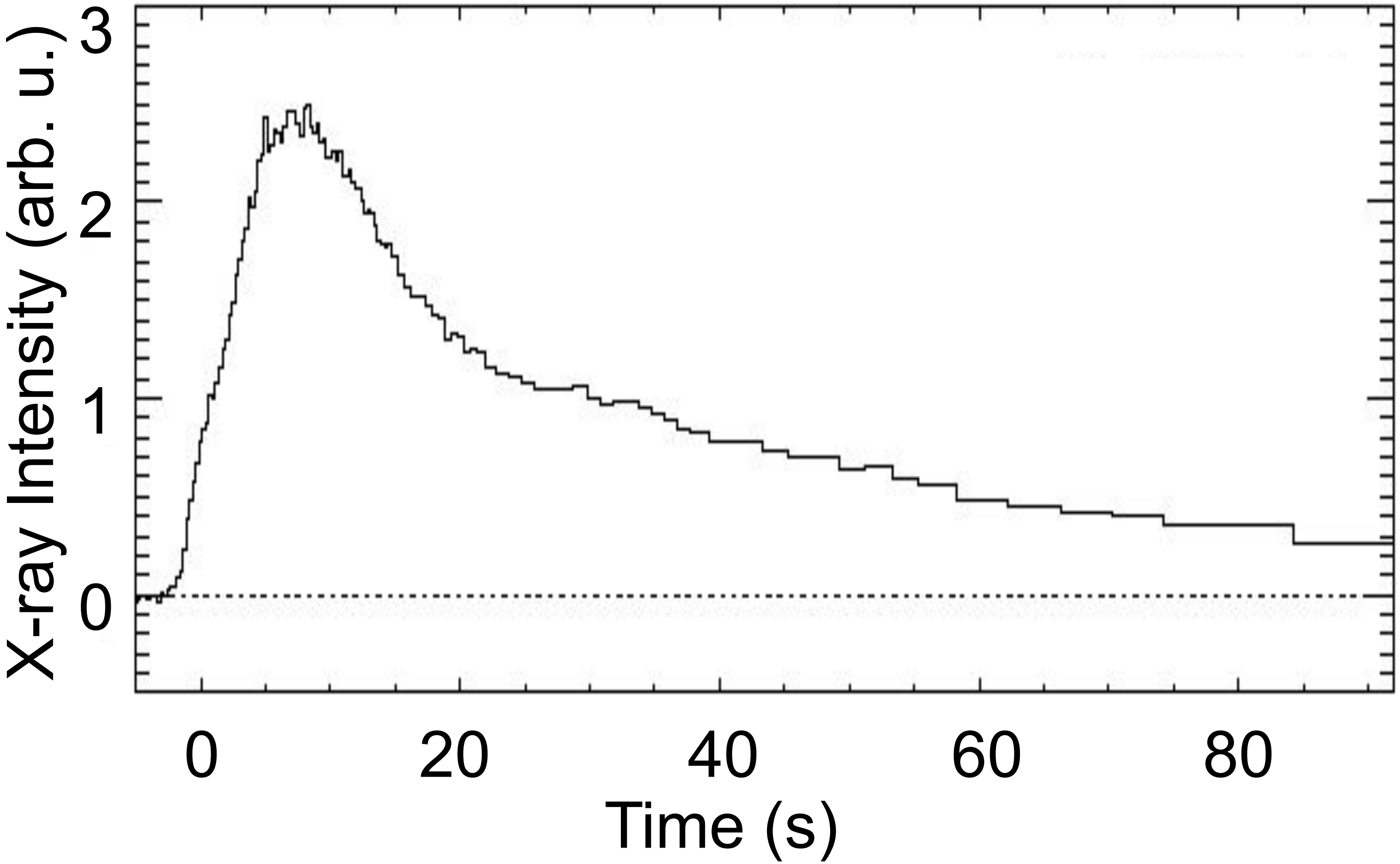
Outline

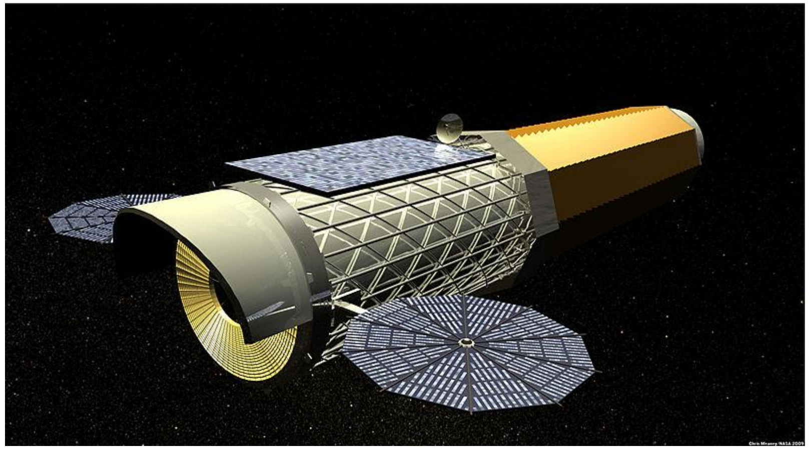
- **Astrophysical Motivation**
  - Roche Lobe overflow
  - Type I X-ray bursts from neutron stars
- **Underlying Nuclear Physics**
  - HCNO breakout
  - $^{15}O(\alpha, \gamma)^{19}Ne$ Bottleneck
  - Feeding of the 4.03 MeV resonance via the $^{20}Mg(\beta p\alpha)^{15}O$ decay sequence
- **Measuring the Reaction**
  - FRIB
  - Time Projection Chambers
  - GADGET II
- **Data Analysis**
  - Simulating events of interest and background
  - Image analysis with convolutional neural network
- **Summary**

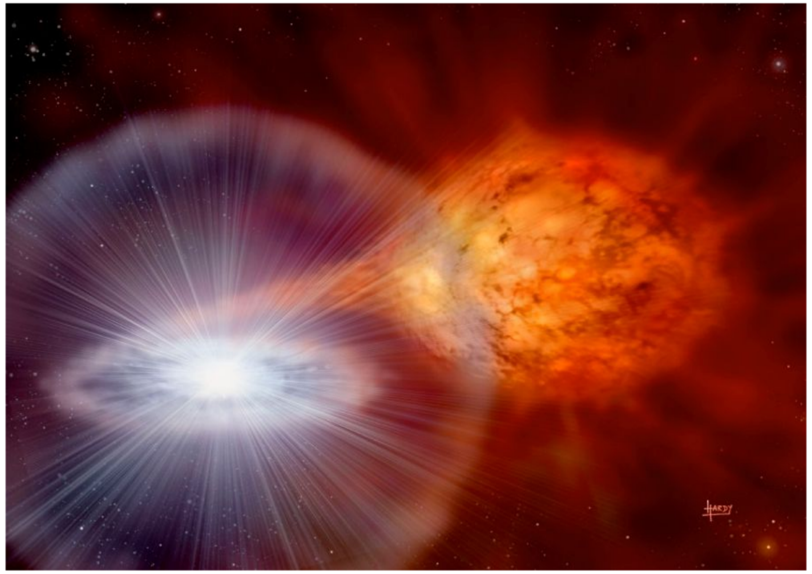
Roche Lobe Overflow



Type I X-ray Bursts







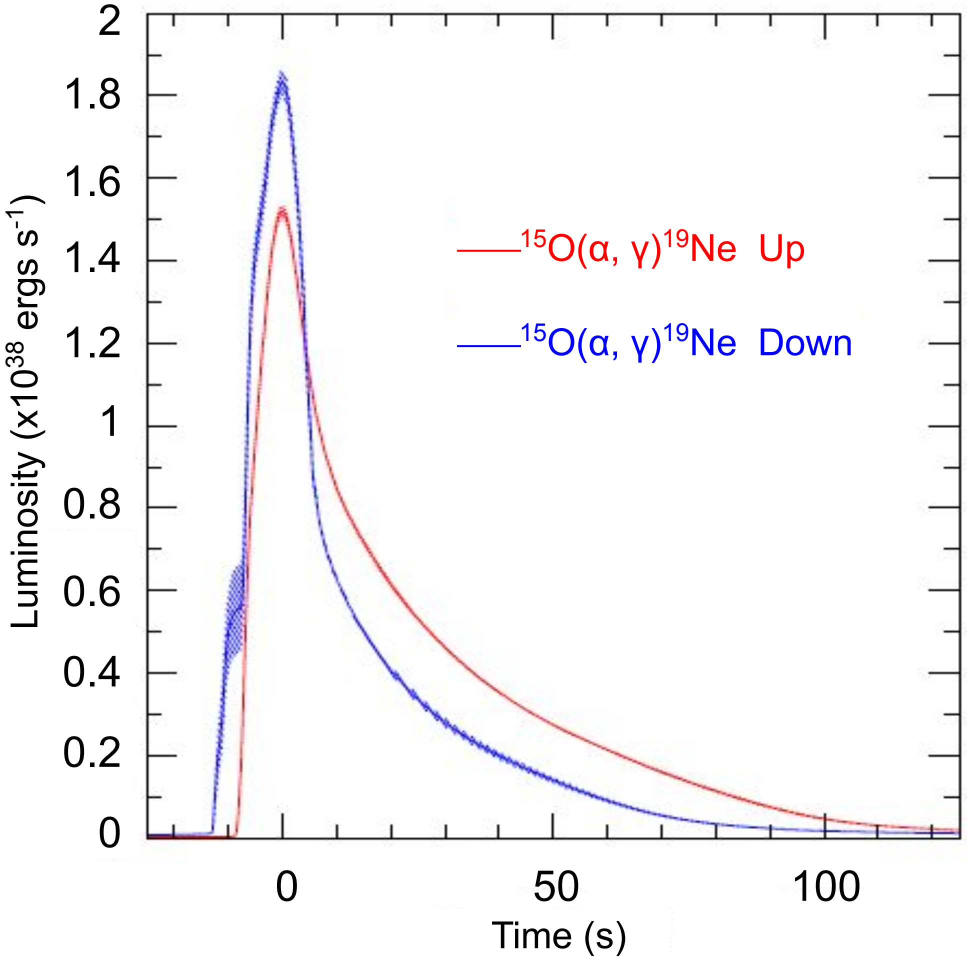
Credit: David A. Hardy, www.astroart.org
RXTE; Galloway et al., Astrophs. J. 179, 360 (2008)

Bottleneck in Type I X-ray Bursts

Reactions that Impact the Burst Light Curve
in the Multi-zone X-ray Burst Model

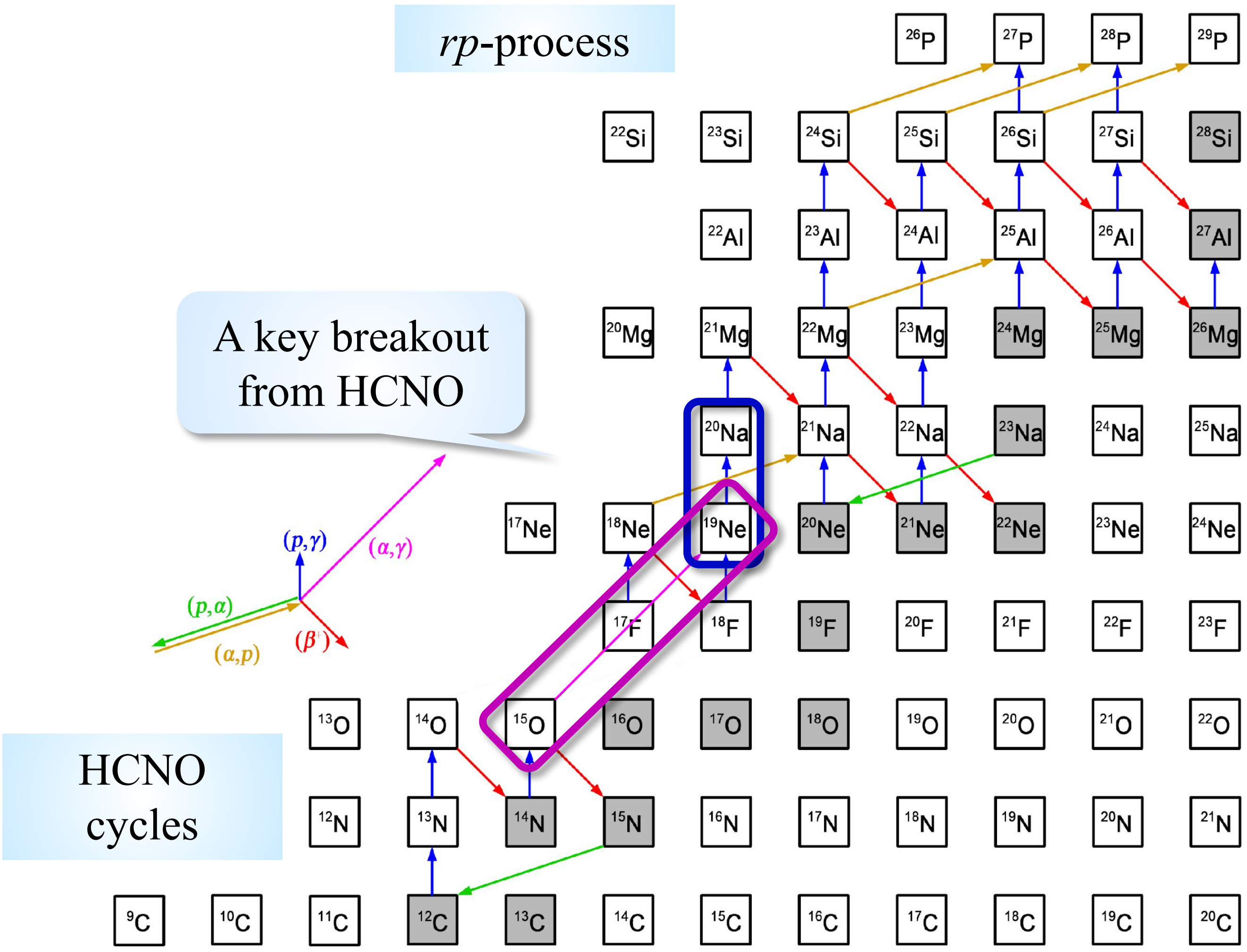
Rank	Reaction
1	$^{15}O(\alpha, \gamma)^{19}Ne$
2	$^{56}Ni(\alpha, p)^{59}Cu$
3	$^{59}Cu(p, \gamma)^{60}Zn$
4	$^{61}Ga(p, \gamma)^{62}Ge$
5	$^{22}Mg(\alpha, p)^{25}Al$
6	$^{14}O(\alpha, p)^{17}F$
7	$^{23}Al(p, \gamma)^{24}Si$
8	$^{18}Ne(\alpha, p)^{21}Na$
9	$^{63}Ga(p, \gamma)^{64}Ge$
10	$^{19}F(p, \alpha)^{16}O$
11	$^{12}C(\alpha, \gamma)^{16}O$
12	$^{26}Si(\alpha, p)^{29}P$
13	$^{17}F(\alpha, p)^{20}Ne$
14	$^{24}Mg(\alpha, \gamma)^{28}Si$
15	$^{57}Cu(p, \gamma)^{58}Zn$
16	$^{60}Zn(\alpha, p)^{63}Ga$
17	$^{17}F(p, \gamma)^{18}Ne$
18	$^{40}Sc(p, \gamma)^{41}Ti$
19	$^{48}Cr(p, \gamma)^{49}Mn$

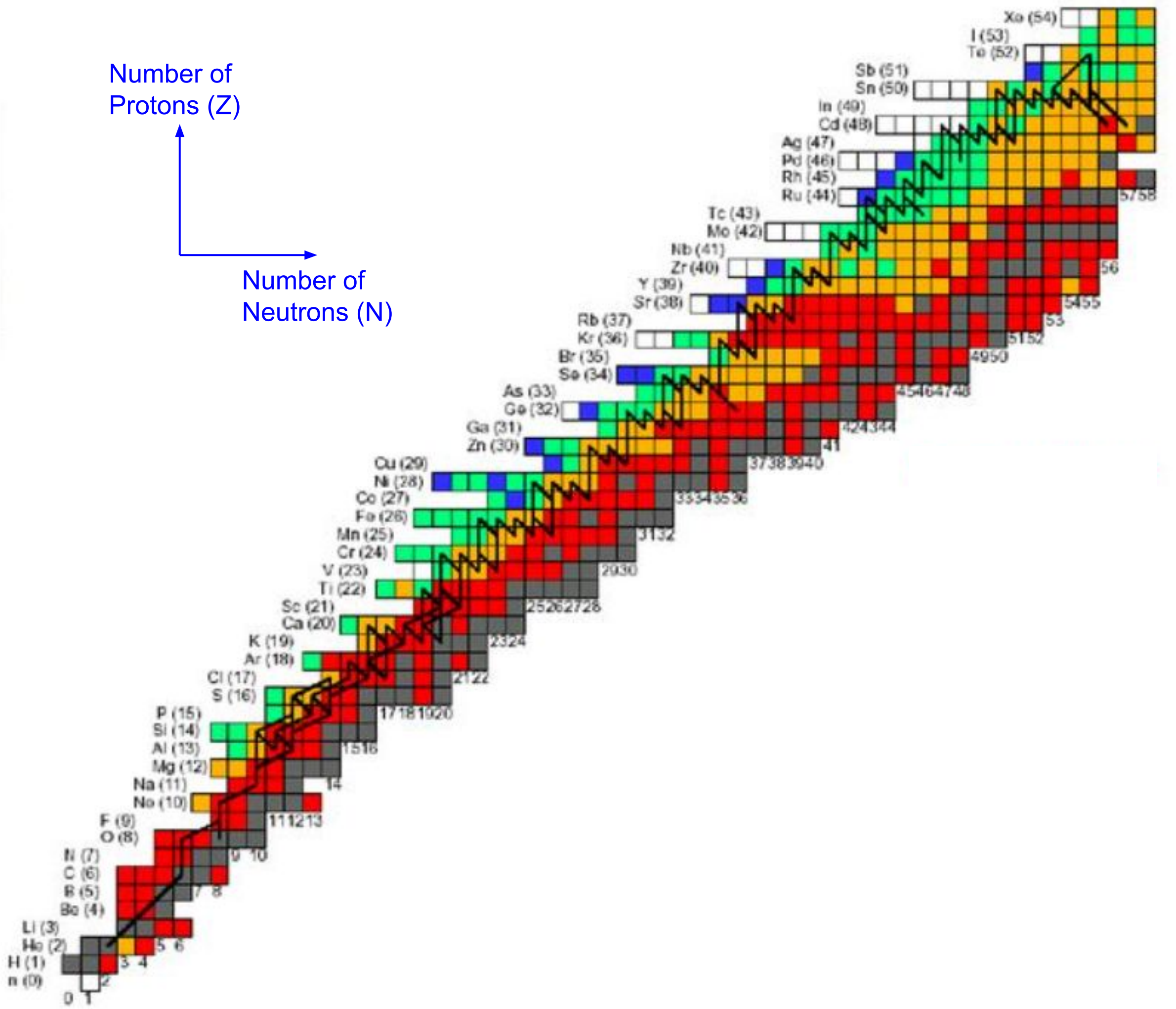
Simulated Light Curve



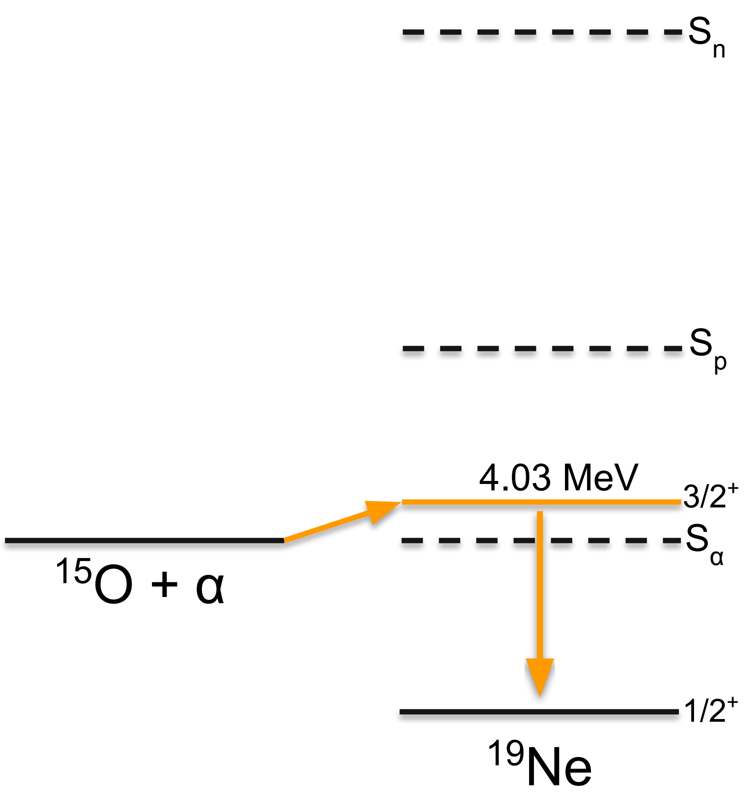
Adapted from: R. Cyburt, *et al.*, APJ 930, 2 (2016)

Breaking out of the Hot-CNO cycles





The $^{15}O(\alpha, \gamma)^{19}Ne$ reaction proceeds by resonant capture



Reaction rate:

$$\langle\sigma v\rangle = [(2\pi)/(kT\mu)]^{3/2}\hbar^2 e^{-E_r/kT}\omega\gamma$$

Resonance Strength:

$$\omega\gamma = \frac{2J+1}{(2J_\alpha+1)(2J_{15O}+1)} \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma}$$

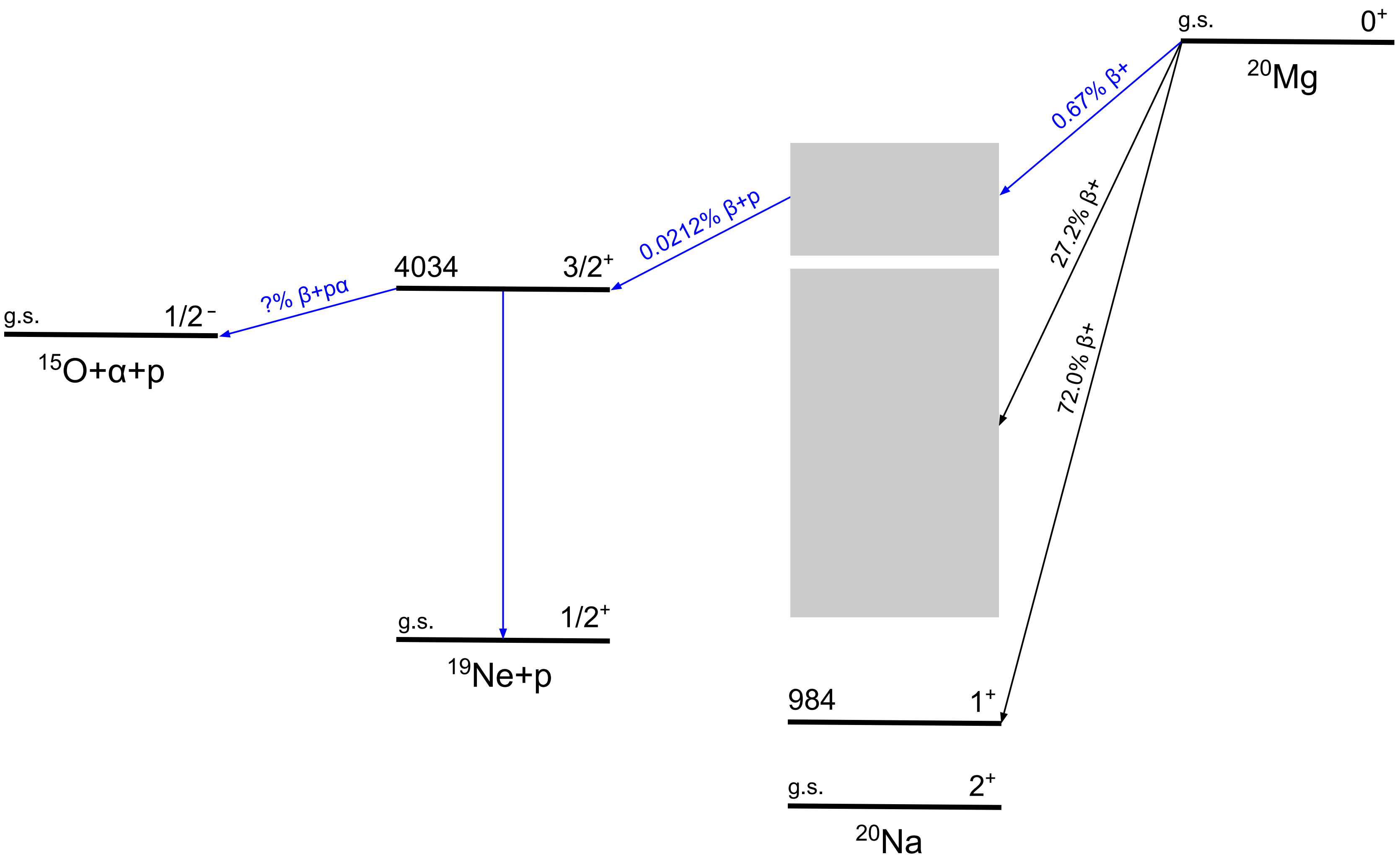
$$\omega\gamma \propto \frac{\Gamma_\alpha}{\Gamma} \frac{1}{\tau}$$

Only need to measure the alpha particle branching ratio to determine the reaction rate.

B. Davids, R. H. Cyburt, J. José, and S. Mythili, Astrophys. J. **735**,40 (2011)

Feeding the 4.03 MeV state via ^{20}Mg(βp) decay

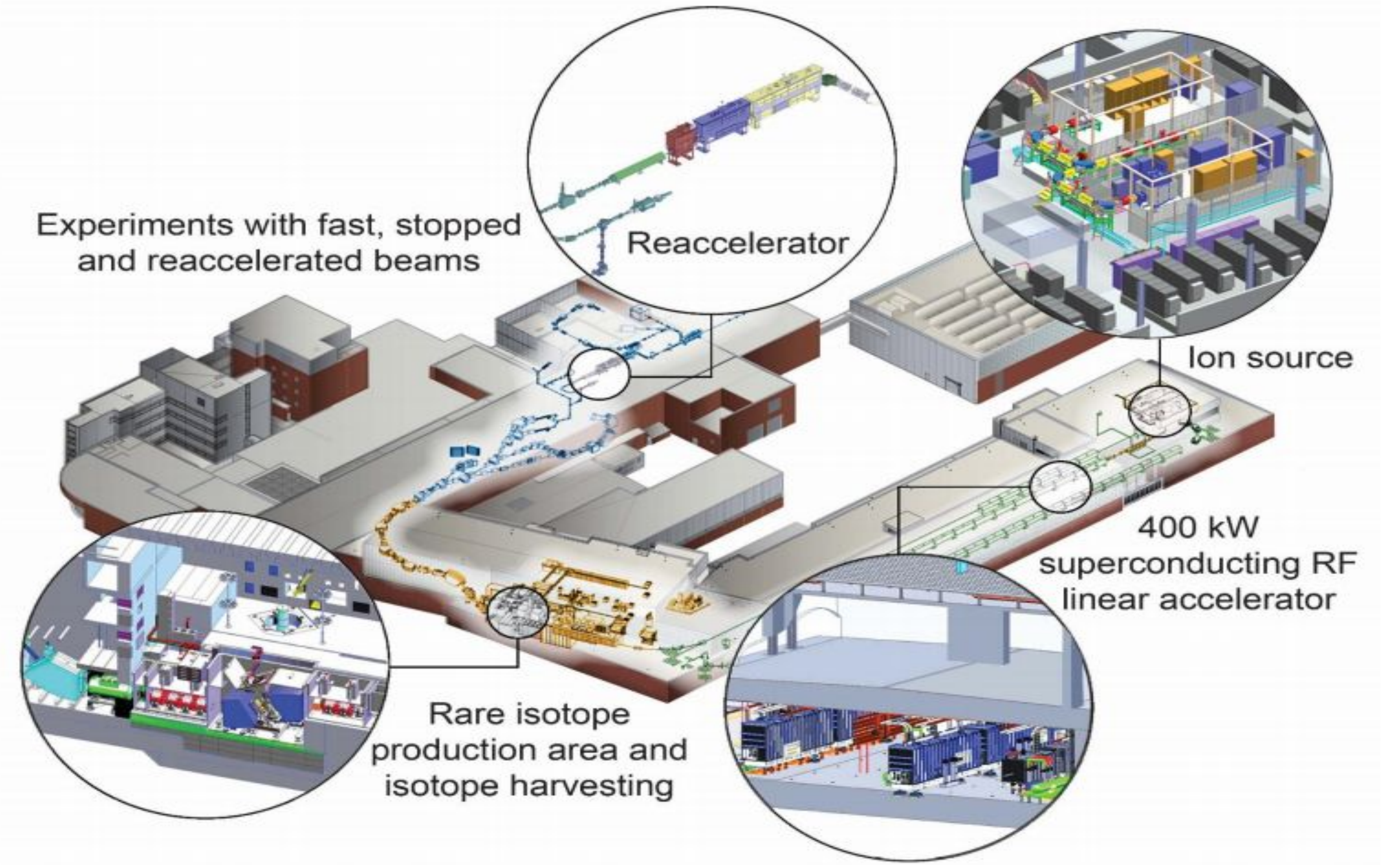
- We will utilize the decay sequence ^{20}Mg(βp) to populate the 4.03 MeV state in ^{19}Ne
- α particle has an energy of ≈0.5 MeV
- From doppler broadening technique, proton has an energy of ≈1.2 MeV.



C. Wrede and B. E. Glassman et al., PRC **96**, 032801(R) (2017)
B. E. Glassman et al., PRC **99**, 065801(R) (2019)

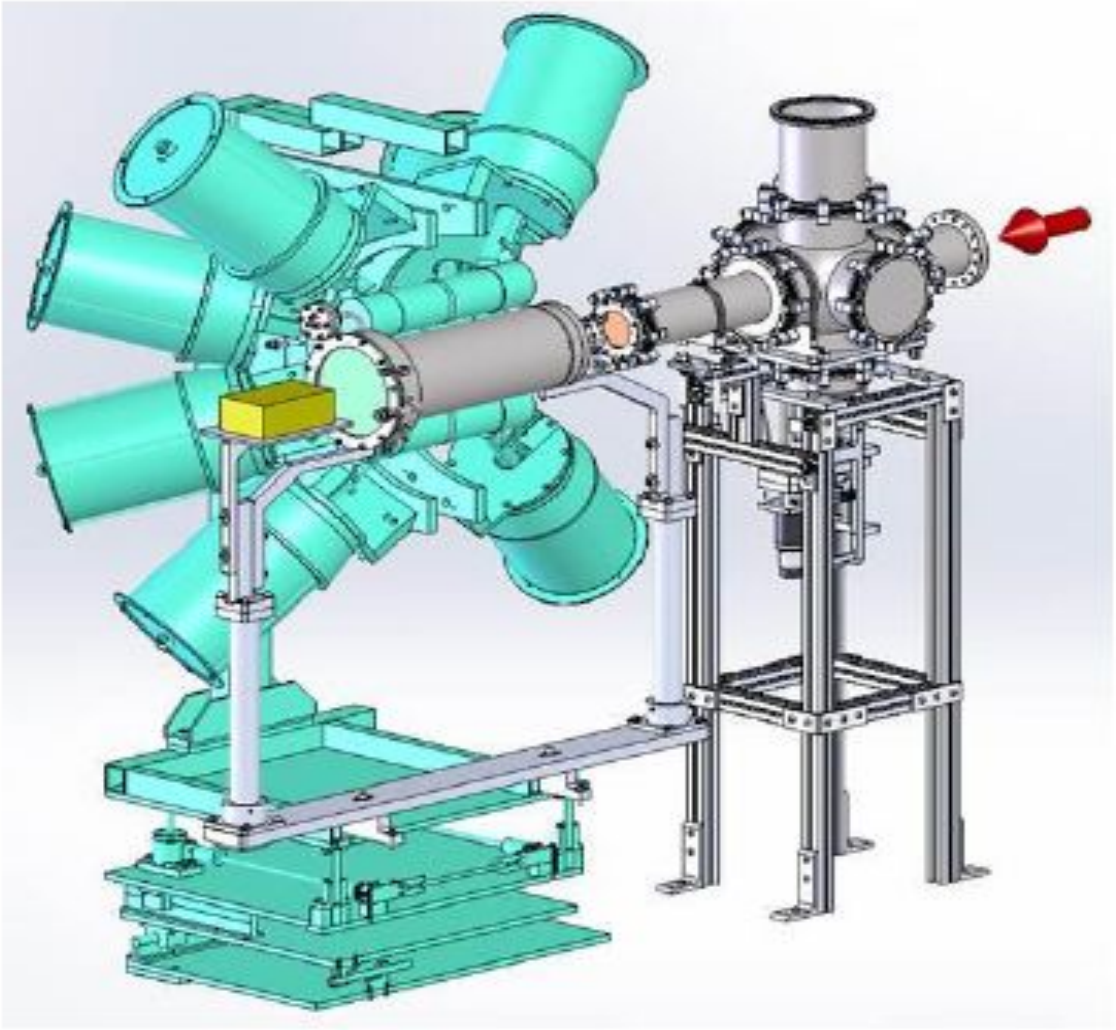
Facility for Rare Isotope Beams (FRIB)

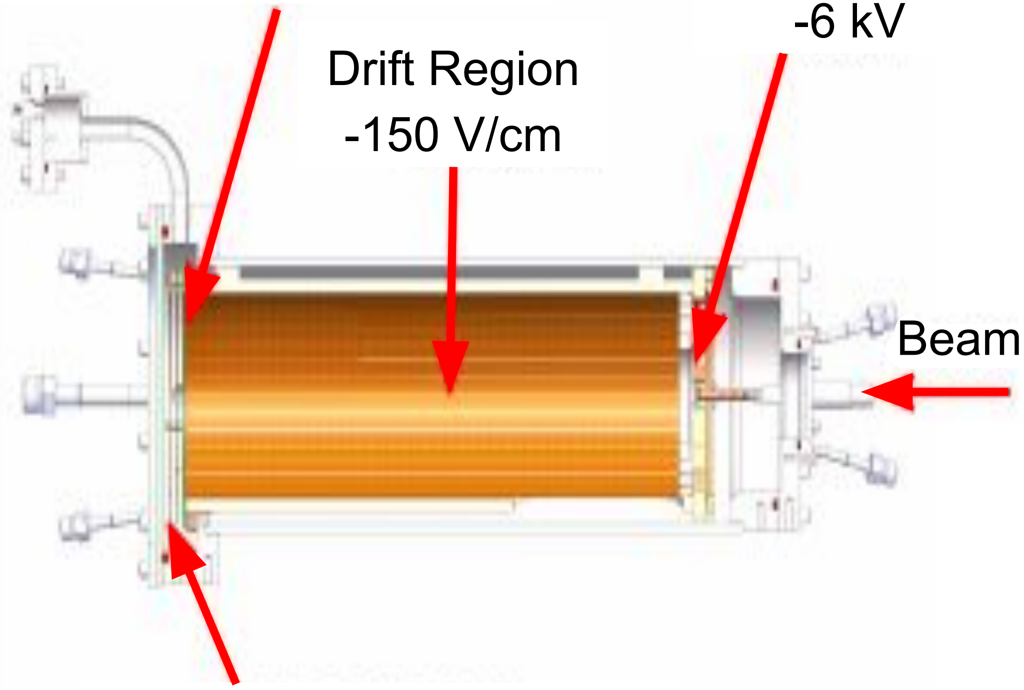
- Operational in March of 2022
- PAC approved FRIB Experiment, valid to February 2024
- ^{36}Ar primary beam that will impinge on a ^{12}C target to create a fast beam of ^{20}Mg
- Beam rate of 4.75e+5 pps



Motobayashi, Tohru. (2014). 10.1051/epjconf/20146601013.

Gaseous Detector w/ Germanium Tagging (GADGET I)

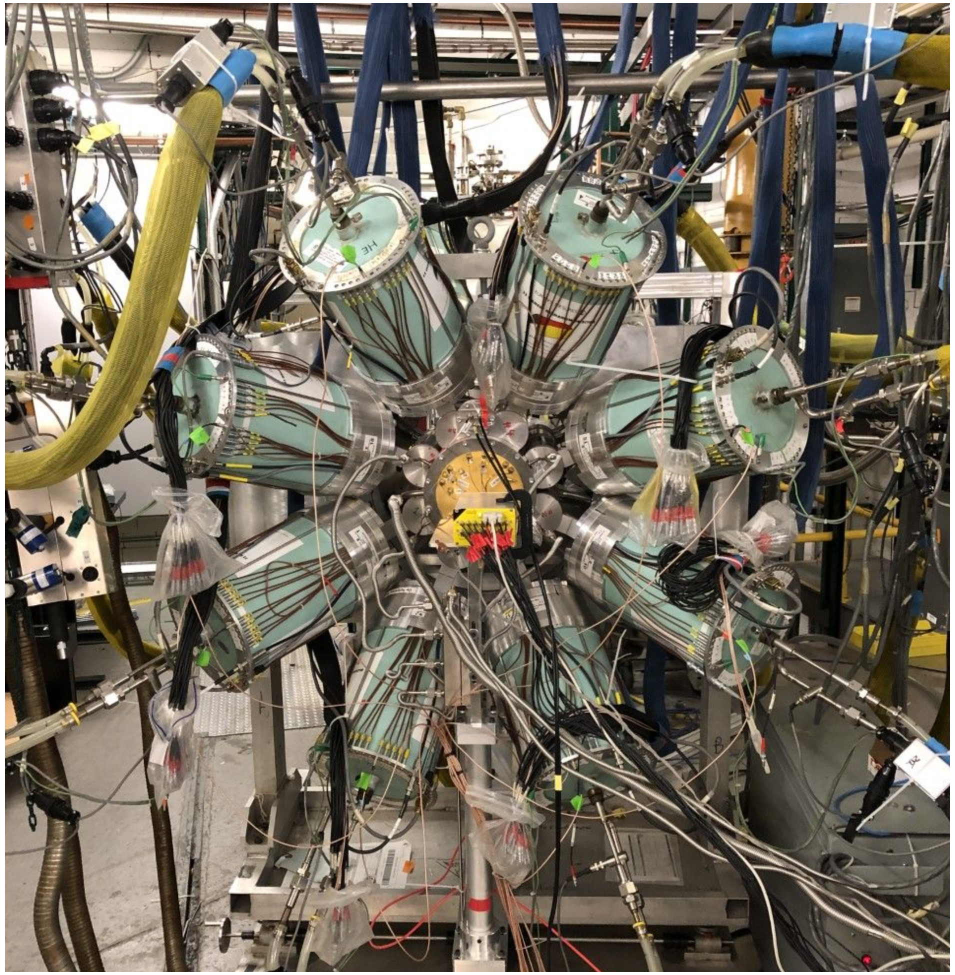




M. Friedman et al,. Nucl. Instrum. Methods Phys. Res., Sect. A, 940, 93 (2019)

GADGET I Science Results

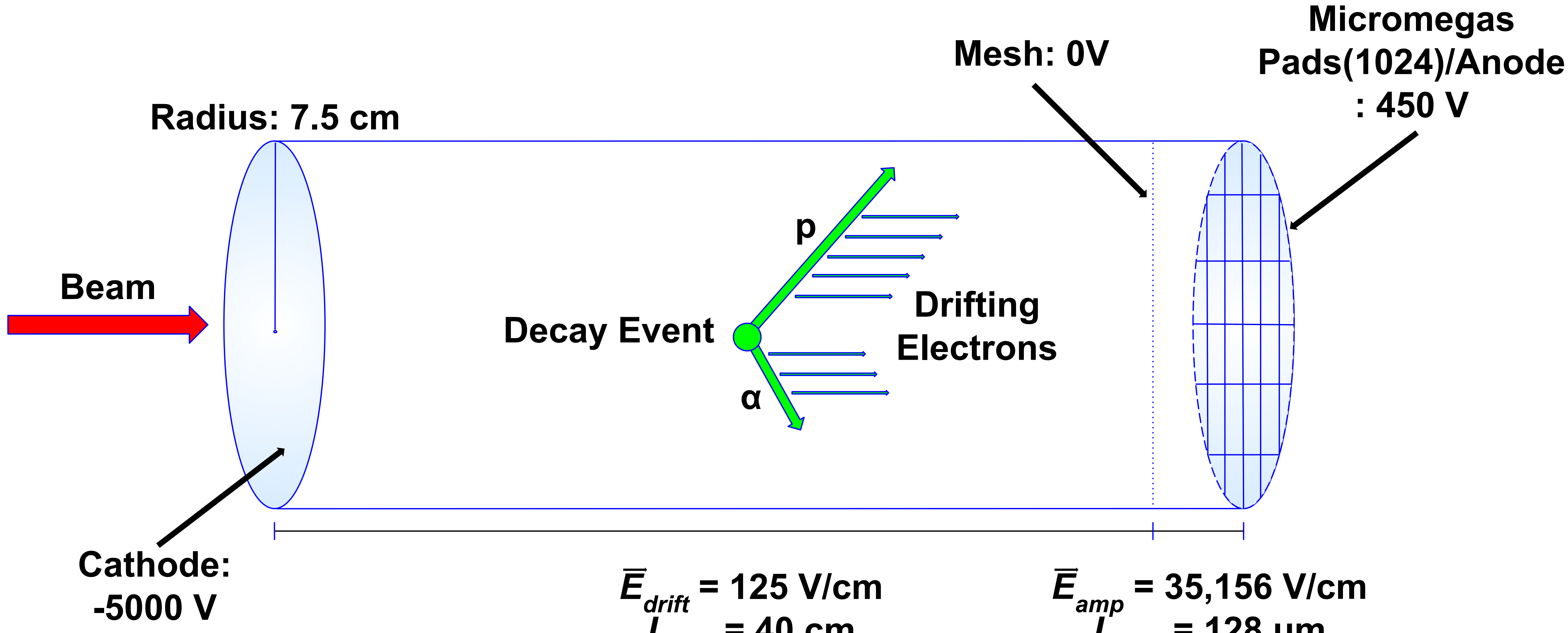
Experimental Setup



Selected Research

- Tamas Budner et al.
  - Constraining $^{30}P(p, \gamma)^{31}S$ for nova nucleosynthesis by measuring low-energy 31Cl β-delayed proton decays
- Moshe Friedman et al.
  - Low-energy ^{23}Al β-delayed proton decay and ^{22}Na destruction in novae
- Jason Surbrook et al.
  - A search for novel beta-minus delayed proton decay in ^{11}Be

GADGET II: Time Projection Chamber (TPC)

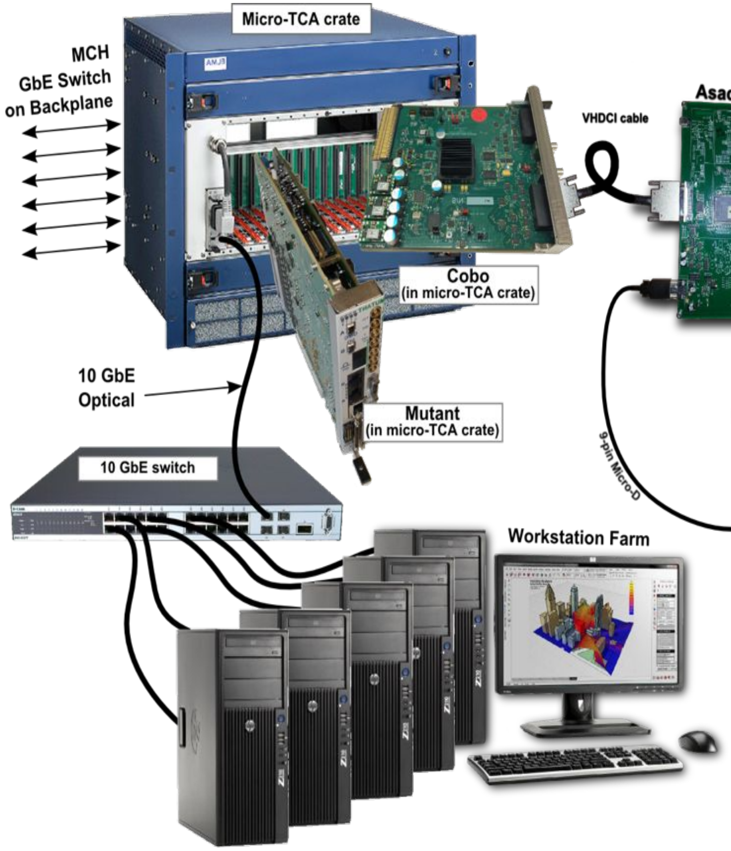


$\vec{E}_{drift}$ = 125 V/cm
L_{drift} = 40 cm

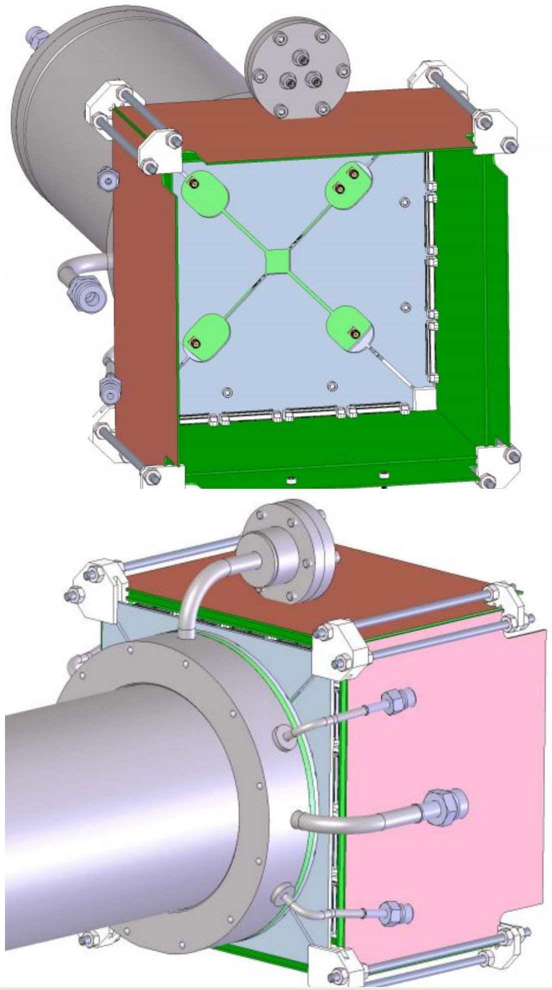
$\vec{E}_{amp}$ = 35,156 V/cm
L_{amp} = 128 μm

GADGET II: Final Setup

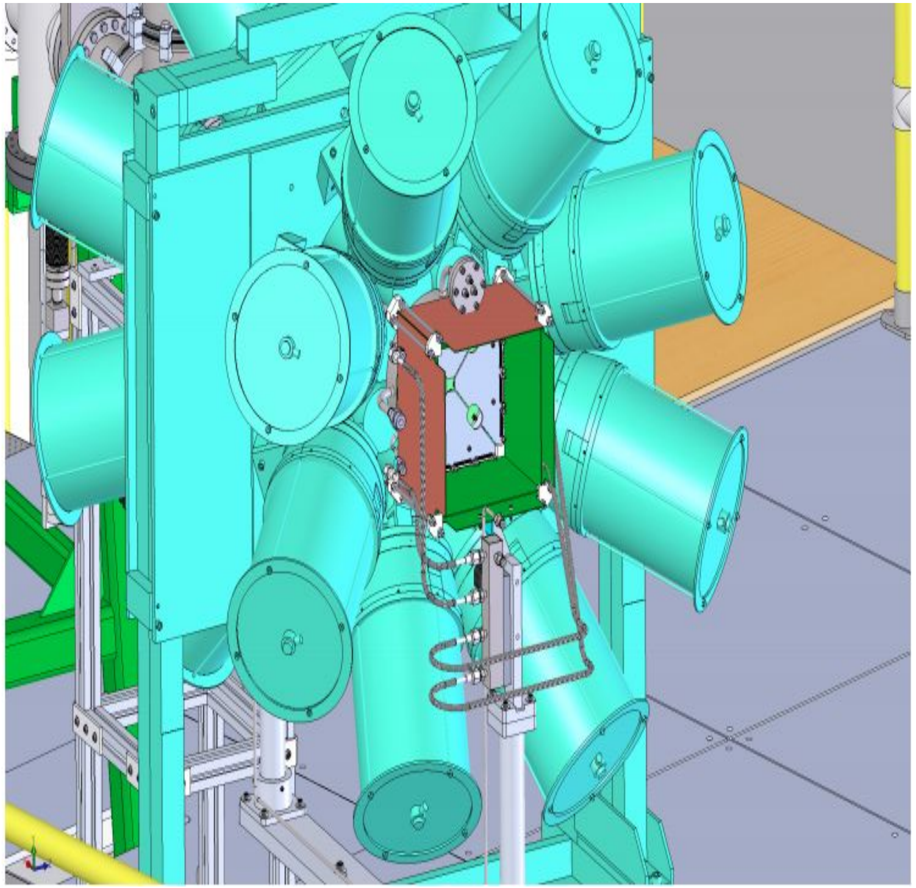
GET DAQ System



TPC & AsAd Box



GADGET II Detection System



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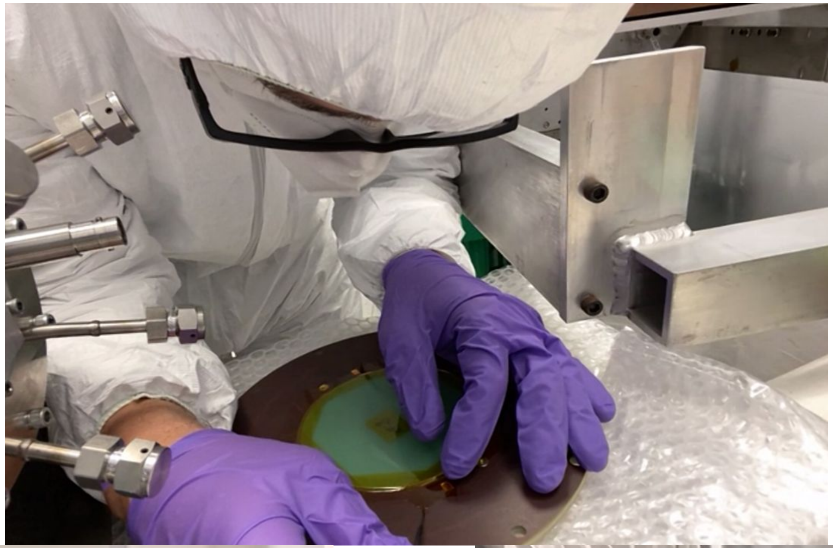
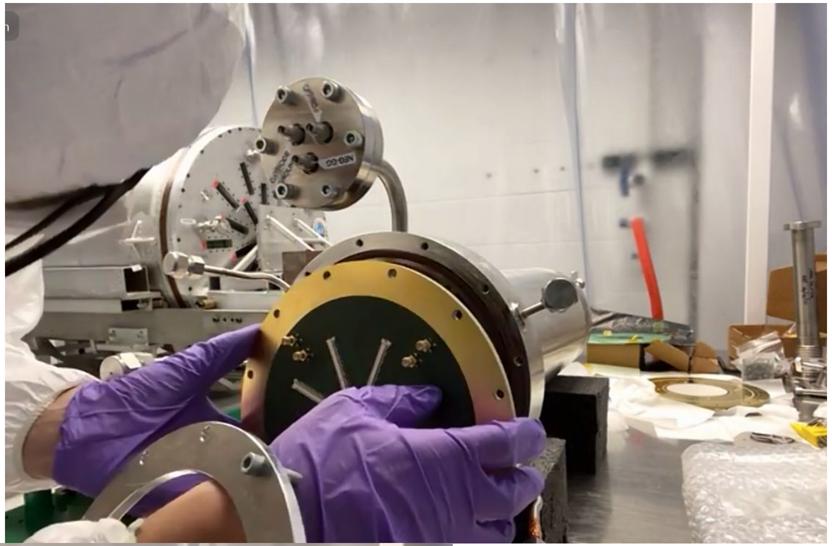
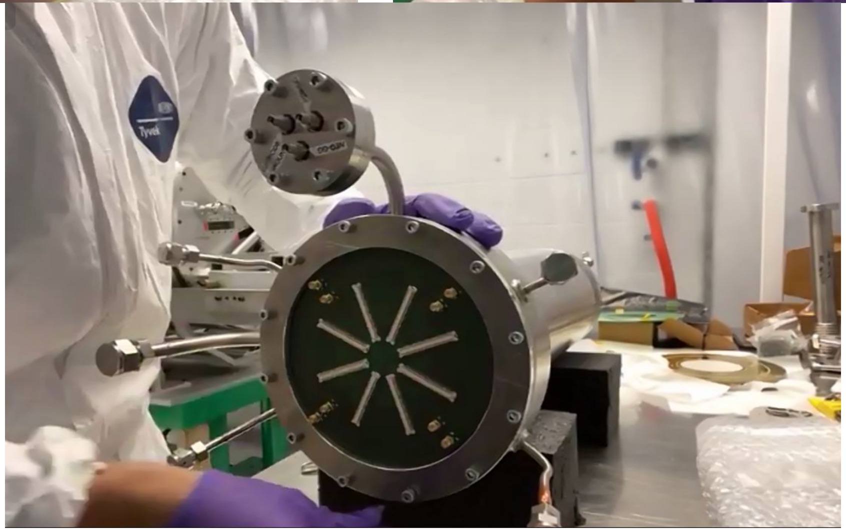
Left Figure Credit: Shelbi Anvar, *Internal Communication*

GADGET II: TPC Construction







NSCL FRIB
U.S. Department of Energy Office of Science
National Science Foundation
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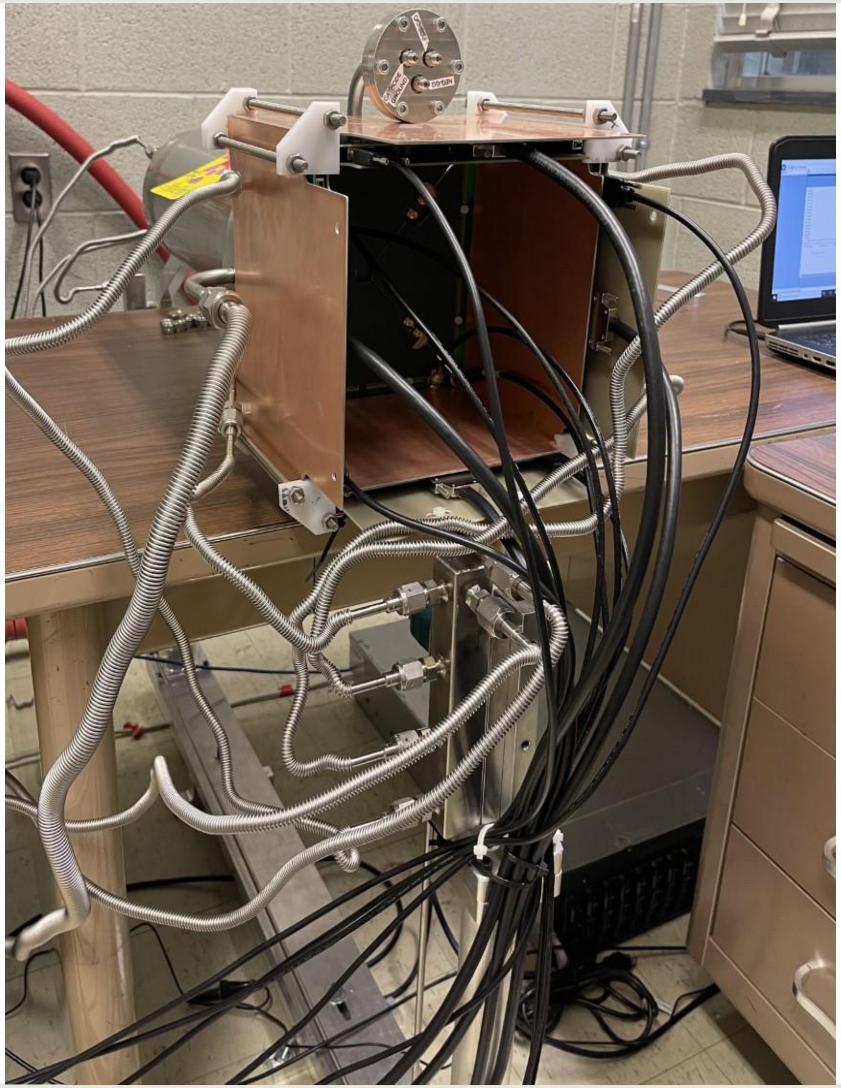
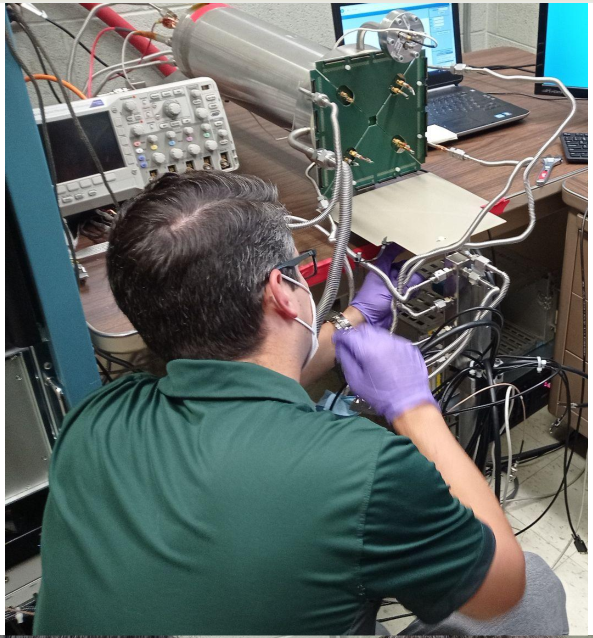
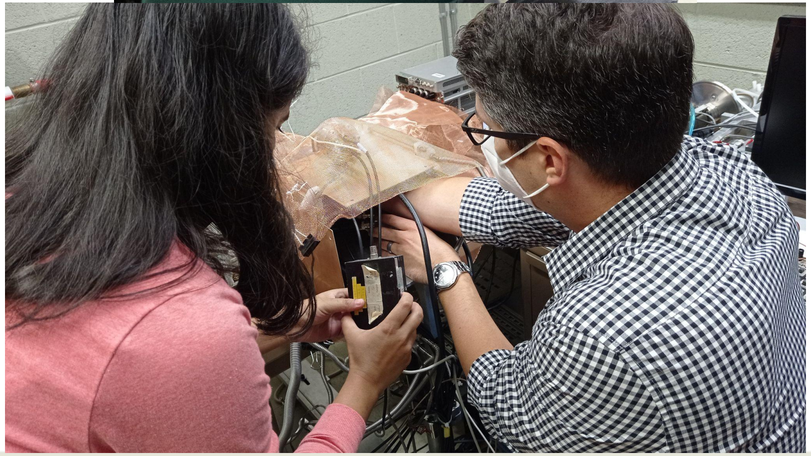
GADGET II: AsAd Box Construction







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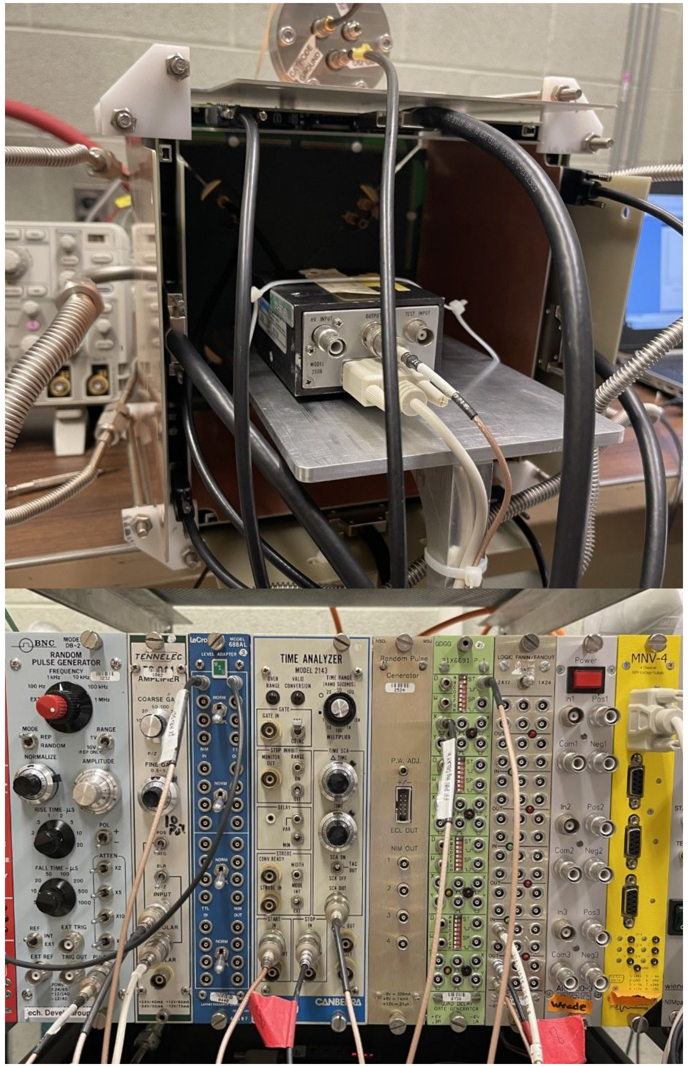
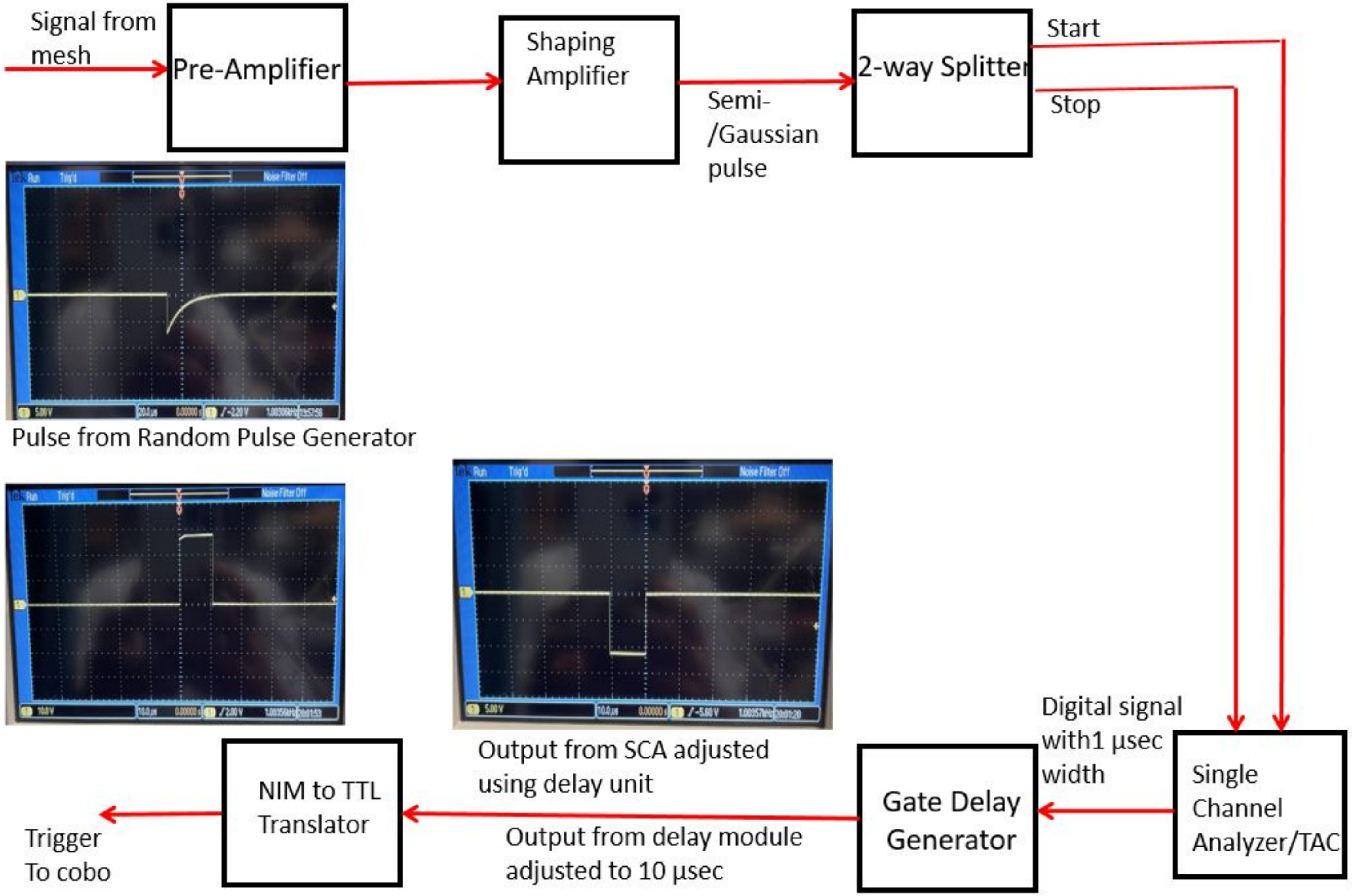
Triggering on the Mesh

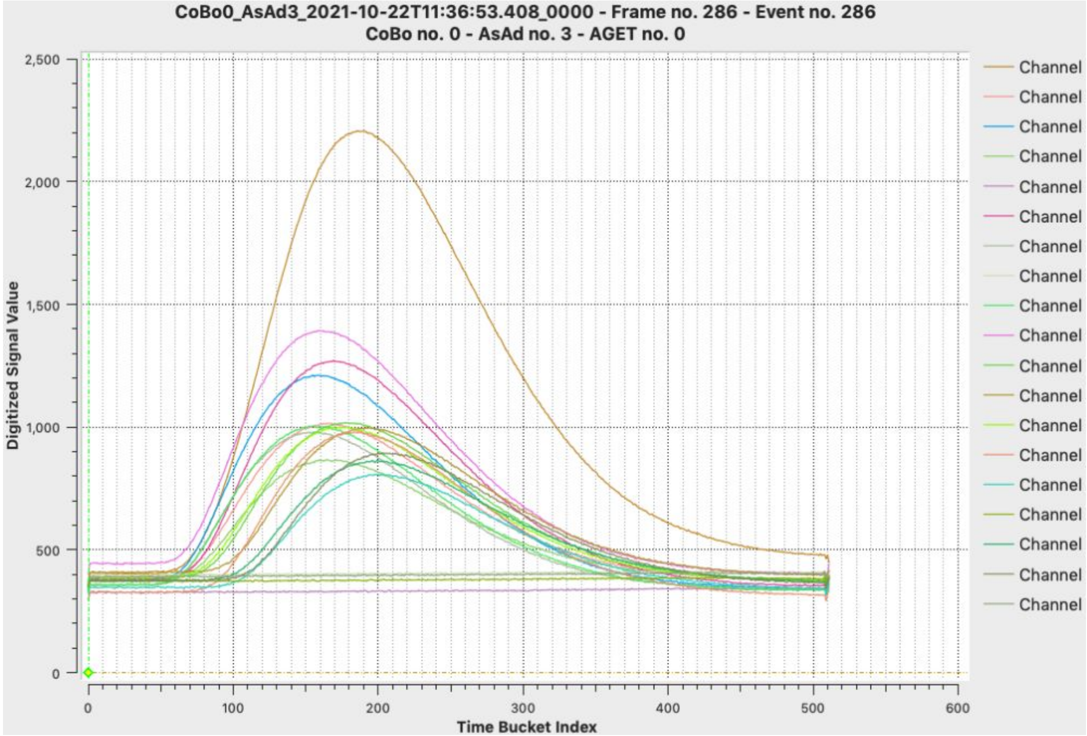




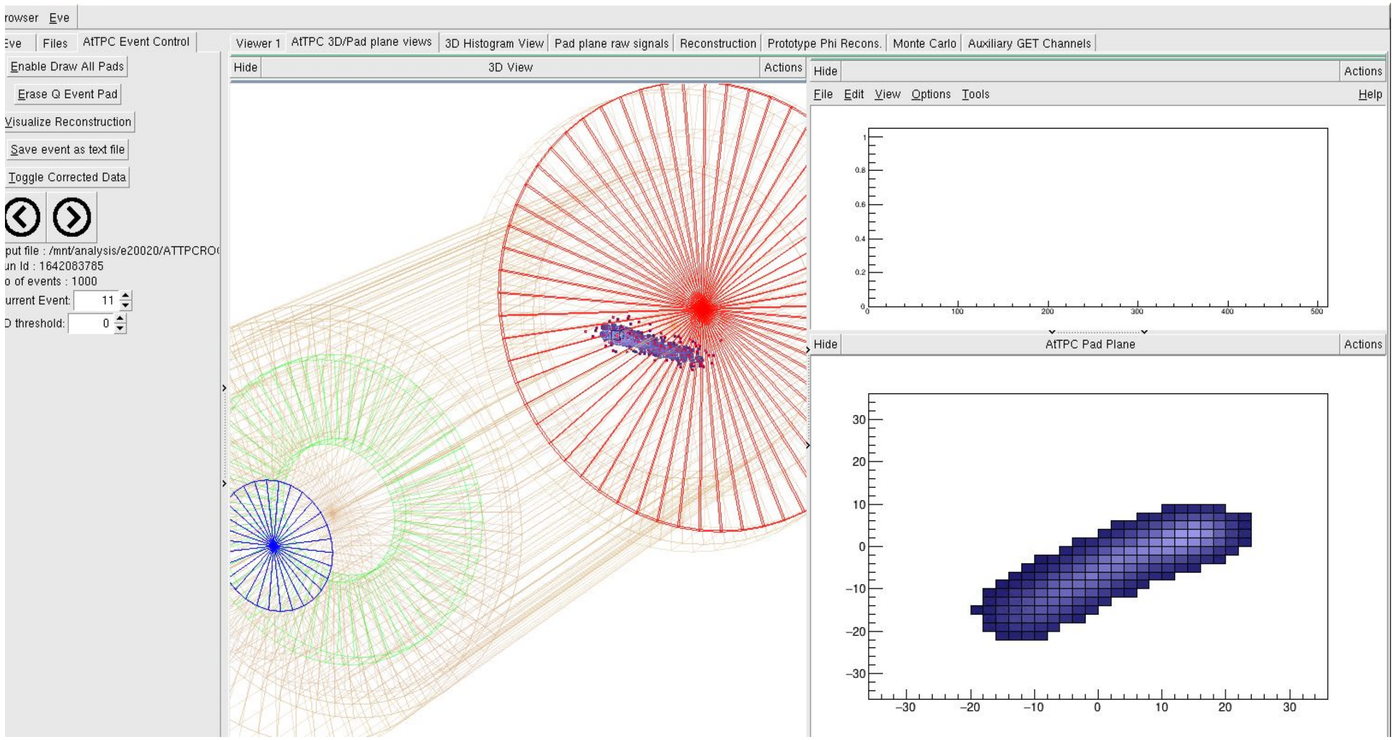
Right Figure Credit: R. Mahajan, internal communication

^{220}Rn Alpha Events in GADGET II

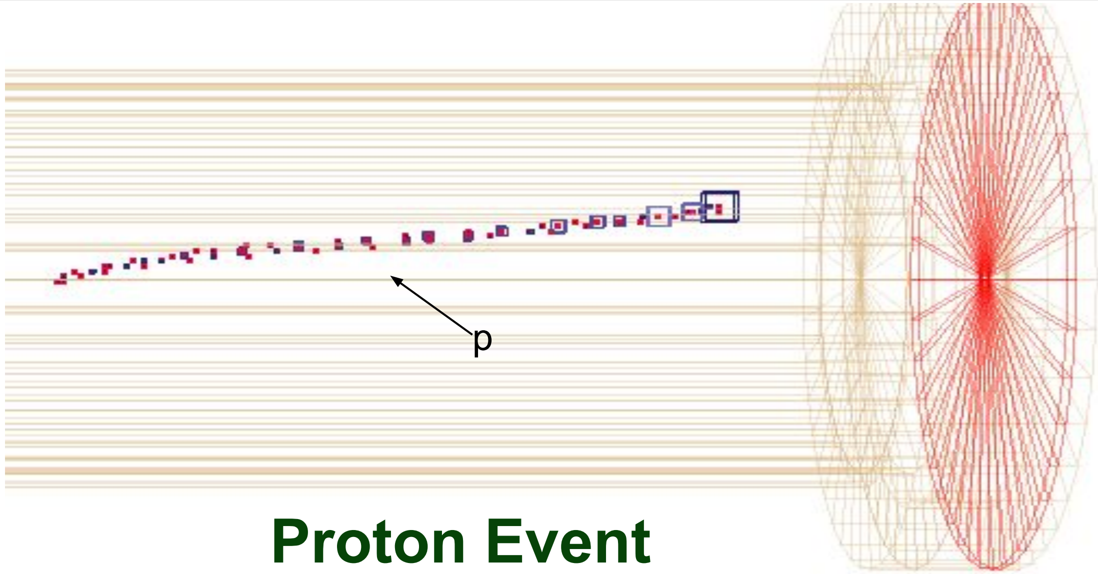
Traces From MM Pads



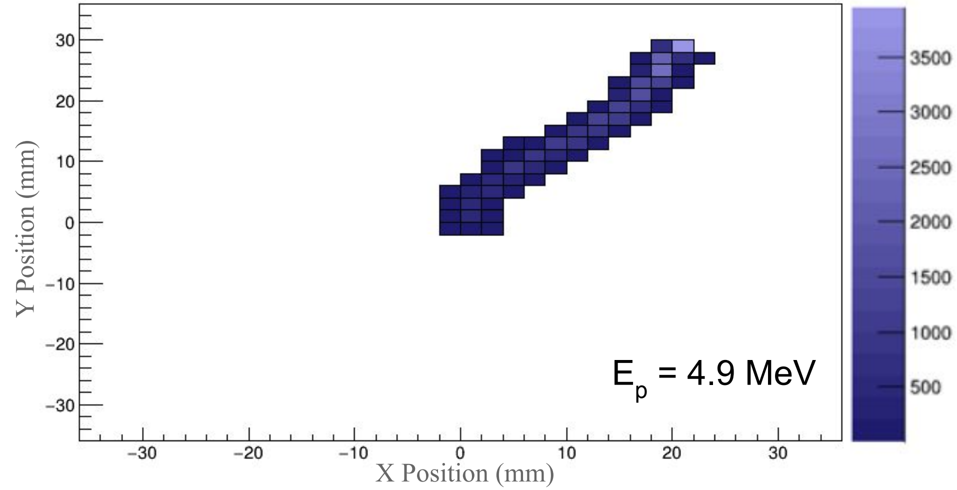
Reconstructed Track

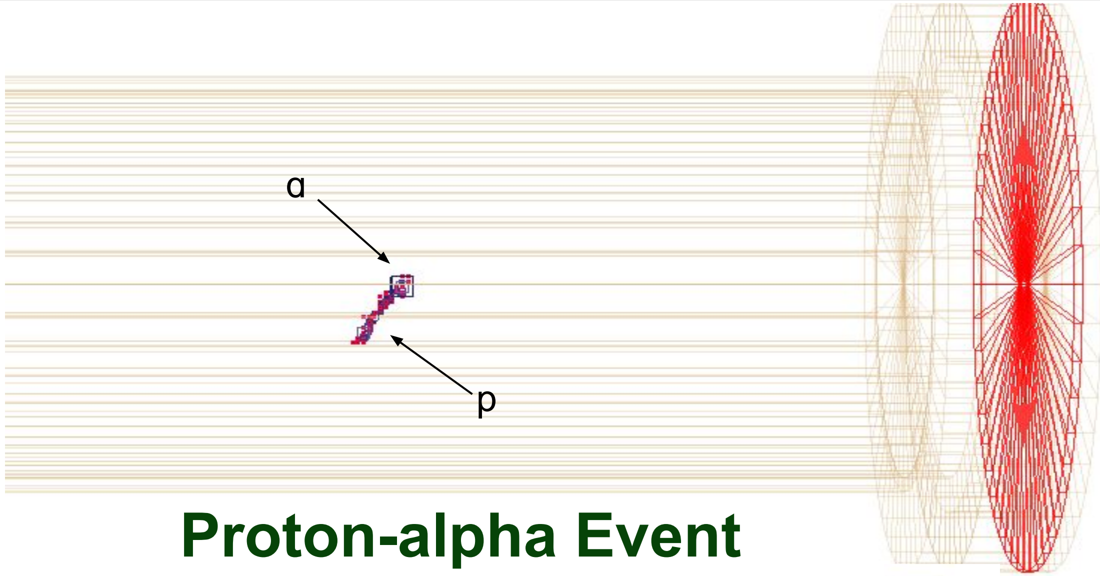


Simulating Decay Events in ATTPCROOTv2

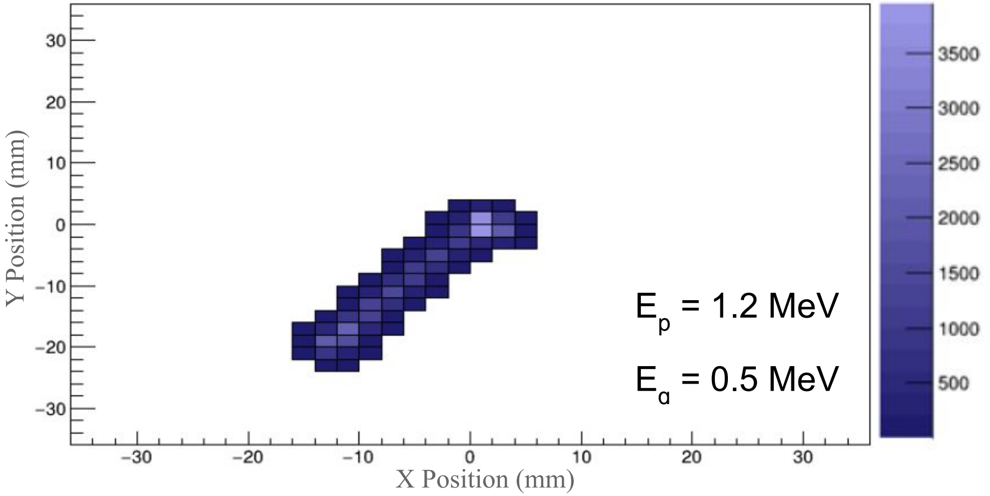


Proton Event





Proton-alpha Event



VGG16 Convolutional Neural Network (CNN)

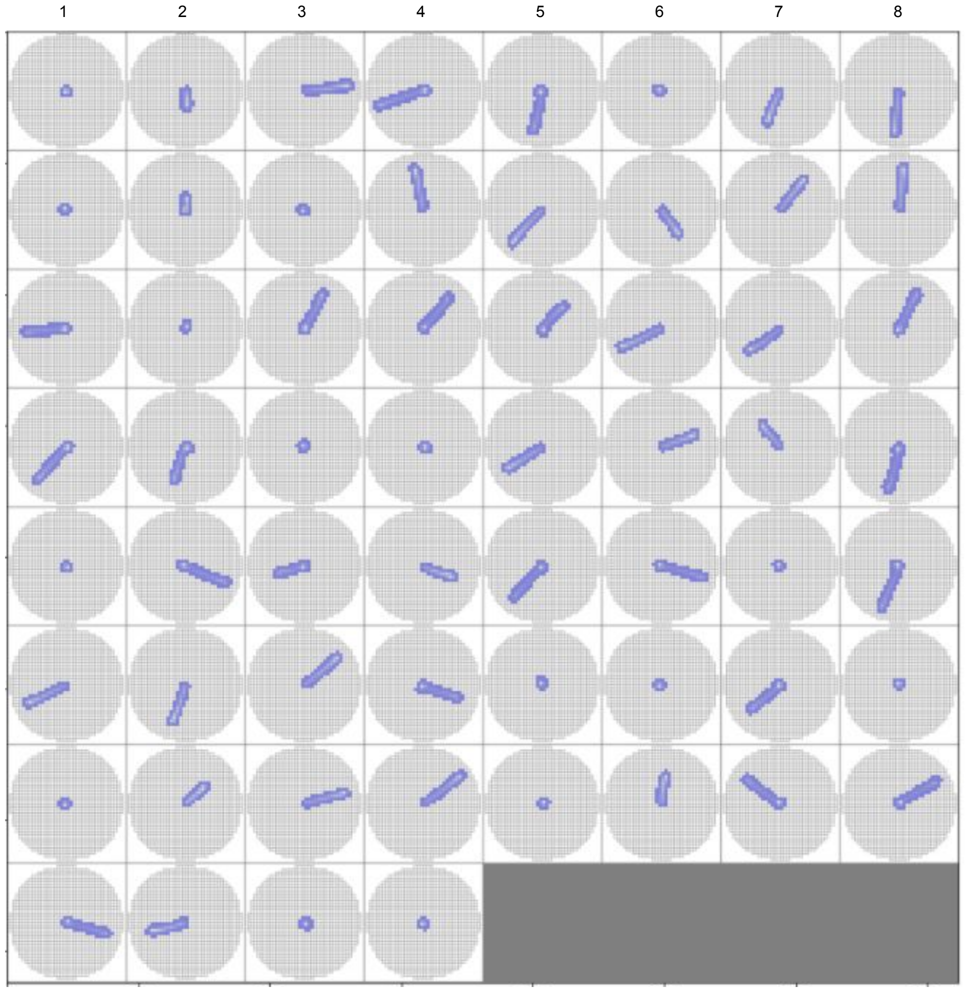


Image Num	Prediction	Label
1	Alpha	Alpha
2	Alpha-Proton	Alpha-Proton
3	Proton	Proton
4	Alpha-Proton	Alpha-Proton
5	Alpha-Proton	Alpha-Proton
6	Alpha	Alpha
7	Proton	Proton
8	Proton	Proton
9	Alpha	Alpha
10	Alpha-Proton	Alpha-Proton
11	Alpha	Alpha
12	Proton	Proton
13	Proton	Proton
14	Proton	Proton
15	Proton	Proton
16	Proton	Proton
17	Alpha-Proton	Alpha-Proton
18	Alpha	Proton
19	Alpha-Proton	Alpha-Proton
20	Alpha-Proton	Alpha-Proton
21	Alpha-Proton	Alpha-Proton
22	Proton	Proton
23	Proton	Proton
24	Alpha-Proton	Alpha-Proton
25	Alpha-Proton	Alpha-Proton
26	Alpha-Proton	Alpha-Proton
27	Alpha	Alpha
28	Alpha	Alpha
29	Proton	Proton
30	Proton	Proton
31	Proton	Proton
32	Alpha-Proton	Alpha-Proton
33	Alpha	Alpha
34	Alpha-Proton	Alpha-Proton
35	Alpha-Proton	Alpha-Proton
36	Proton	Proton
37	Alpha-Proton	Alpha-Proton
38	Alpha-Proton	Alpha-Proton
39	Alpha	Alpha
40	Alpha-Proton	Alpha-Proton
41	Proton	Proton
42	Proton	Proton
43	Proton	Proton
44	Alpha-Proton	Alpha-Proton
45	Alpha	Alpha
46	Alpha	Alpha
47	Alpha-Proton	Alpha-Proton
48	Alpha	Alpha
49	Alpha	Alpha
50	Proton	Proton
51	Proton	Proton
52	Proton	Proton
53	Alpha	Alpha
54	Proton	Proton
55	Alpha-Proton	Alpha-Proton
56	Alpha-Proton	Alpha-Proton
57	Alpha-Proton	Alpha-Proton
58	Proton	Proton
59	Alpha	Alpha
60	Alpha	Alpha

Learning Rate: 1e-4

Epocs: 50

Final Loss: 0.04570

Training Acc.: 99.58%

Testing Acc.: 98.33%

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Summary

- The $^{15}O(\alpha, \gamma)^{19}Ne$ reaction is the most important reaction rate uncertainty underlying X-ray bursts from neutron stars and the resulting nucleosynthesis
- The resonance strength and corresponding reaction rate can be determined by measuring the alpha particle branching ratio from the 4.03 MeV state in ^{19}Ne
- We can measure the alpha emission from this state by using the $^{20}Mg(\beta p\alpha)^{15}O$ decay sequence at FRIB with a fast beam of ^{20}Mg and the GADGET II TPC
- We will develop ML algorithms (CNNs) to identify the events of interest
- Once the reaction rate is calculated we will model X-ray burst light curves from neutron stars

Thank you to our GADGET II Collaborators!

Collaboration for FRIB experiment # 21072

A. Adams[1,2], *J.* Allmond[4], *H.* Alvarez Pol[5], *E.* Argo[1,2], *Y.* Ayyad[5], *D.* Bardayan[6], *D.* Bazin[1,2], *T.* Budner[1,2], *A.* Chen[7], *K.* Chipps[4], *B.* Davids[8], *J.* Dopfer[1,2], *M.* Friedman[9], *H.* Fynbo[10], *R.* Grzywacz[11], *J.* Jose[12], *J.* Liang[7], *R.* Mahajan[1], *S.* Pain[4], *D.* Pérez-Loureiro[13], *E.* Pollacco[14], *A.* Psaltis[15], *S.* Ravishankar[3], *A.* Rogers[16], *L.* Schaedig[1,2], *L. J.* Sun[1], *J.* Surbrook[1,2], *L.* Weghorn[1,2], and *C.* Wrede[1,2]

[1]Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA
[2]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[3]Department of Computational Mathematics, Science, and Engineering, Michigan State University, East Lansing, Michigan 48824, USA
[4]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA
[5]Instituto Galego de Física de Altas Enerxías (USC), Spain
[6]Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA
[7]McMaster University, Canada
[8]TRIUMF, Vancouver, British Colombia, Canada
[9]The RACAH institute of Physics, Hebrew University of Jerusalem, Israel
[10]Aarhus University, Aarhus C, Denmark
[11]University of Tennessee, Knoxville, USA
[12]Universitat Politècnica de Catalunya, Barcelona, Spain
[13]Canadian Nuclear Laboratories, Canada
[14]IRFU, CEA Saclay, GIF-sur-Yvette, France
[15]Technical University of Darmstadt, Germany
[16]University of Massachusetts Lowell, USA

The End

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Thank you!