Measuring the $^{15}O(\alpha,\gamma)^{19}Ne$ Reaction in Type I X-ray Bursts using ^{20}Mg β-decay

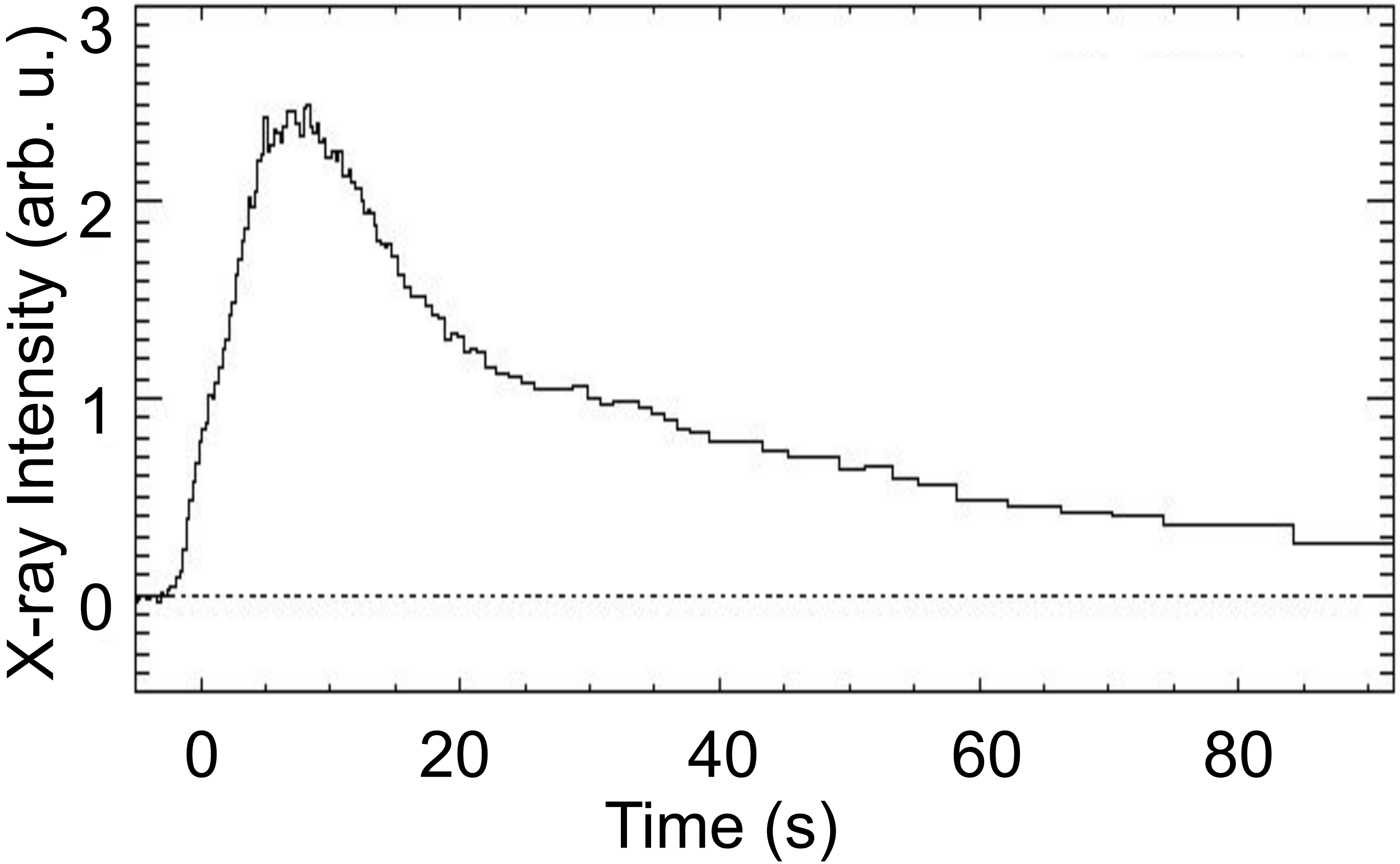
Nuclei in the Cosmos (NIC XVII)
Daejeon, Korea 2023

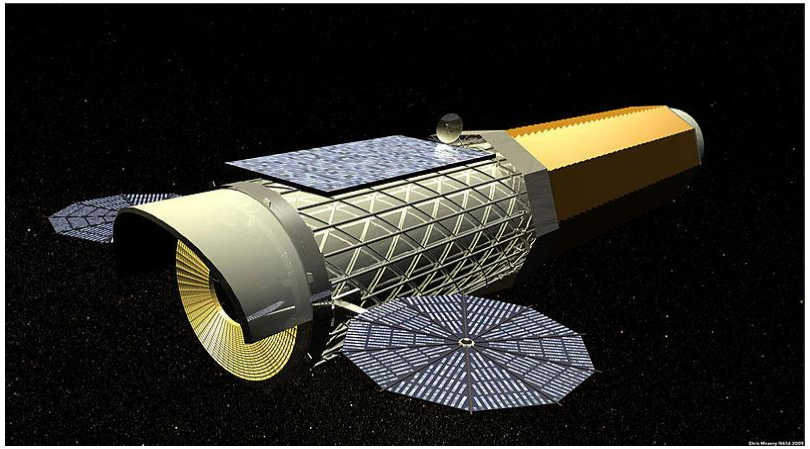
Tyler Wheeler for the FRIB E21072 Collaboration

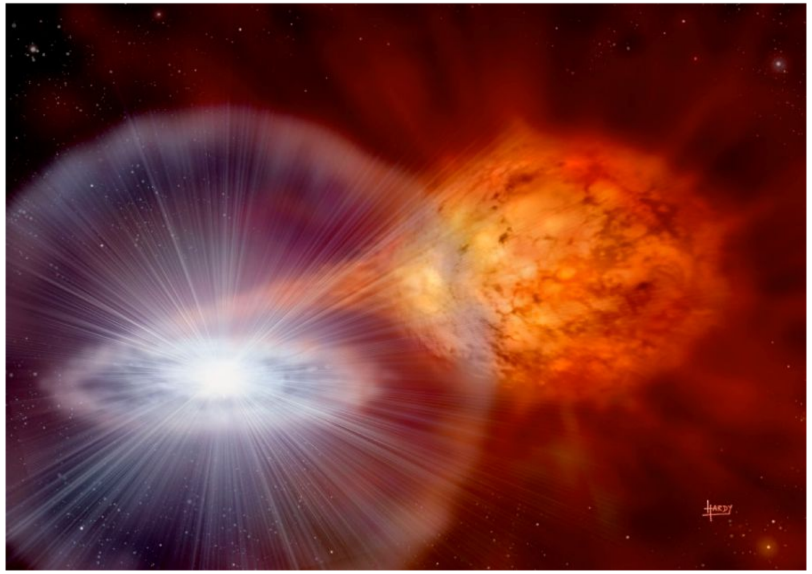
Outline

- **Summary of Experiment**
  - Astrophysical Motivation
  - Underlying Nuclear Physics
  - Experimentally Constraining the $^{15}O(\alpha,\gamma)^{19}Ne$ Reaction using ^{20}Mg Decay
- **GADGET II FRIB Experiment 21072**
  - Construction of Full GADGET II Detection System
  - Experimental Data
- **Ongoing Data Analysis**
  - Search Region on Range vs Energy Plots
  - CNN Development for Rare Event Search in Data
  - Candidate Events
- **Future Outlook**
- **Summary**

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	$^{56}Ni(\alpha, p)^{59}Cu$
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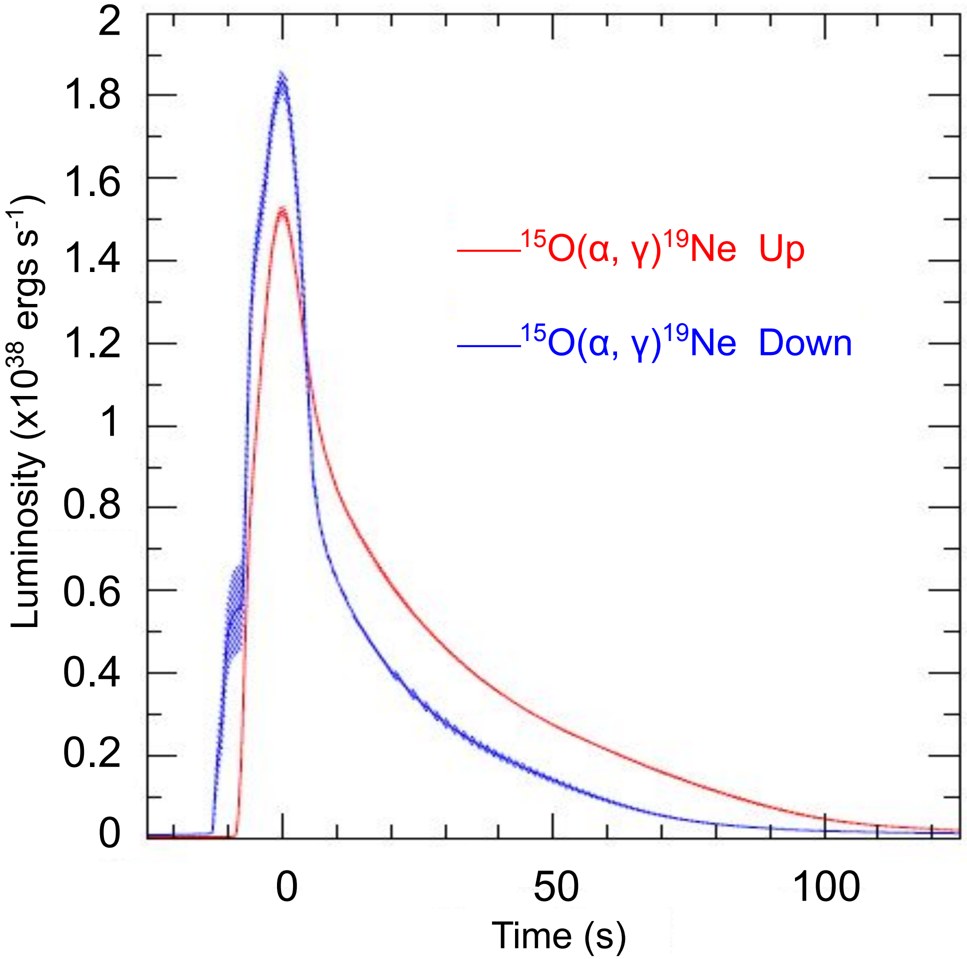
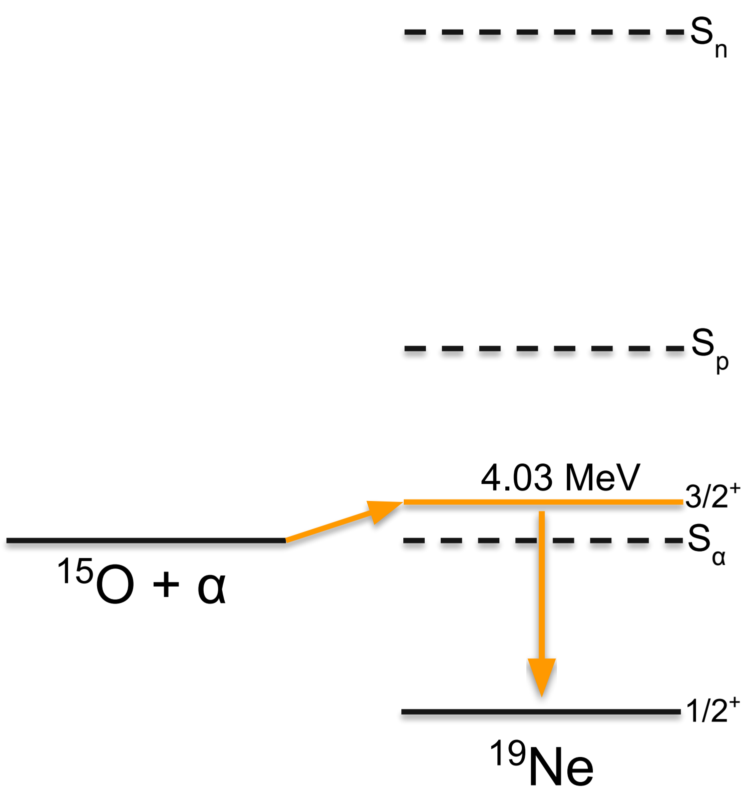
19	$^{48}Cr(p, \gamma)^{49}Mn$

Simulated Light Curve



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:

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

$$\omega\gamma \propto \frac{\Gamma_\alpha}{\Gamma}\frac{1}{\tau}$$ [1], [2], [3]

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

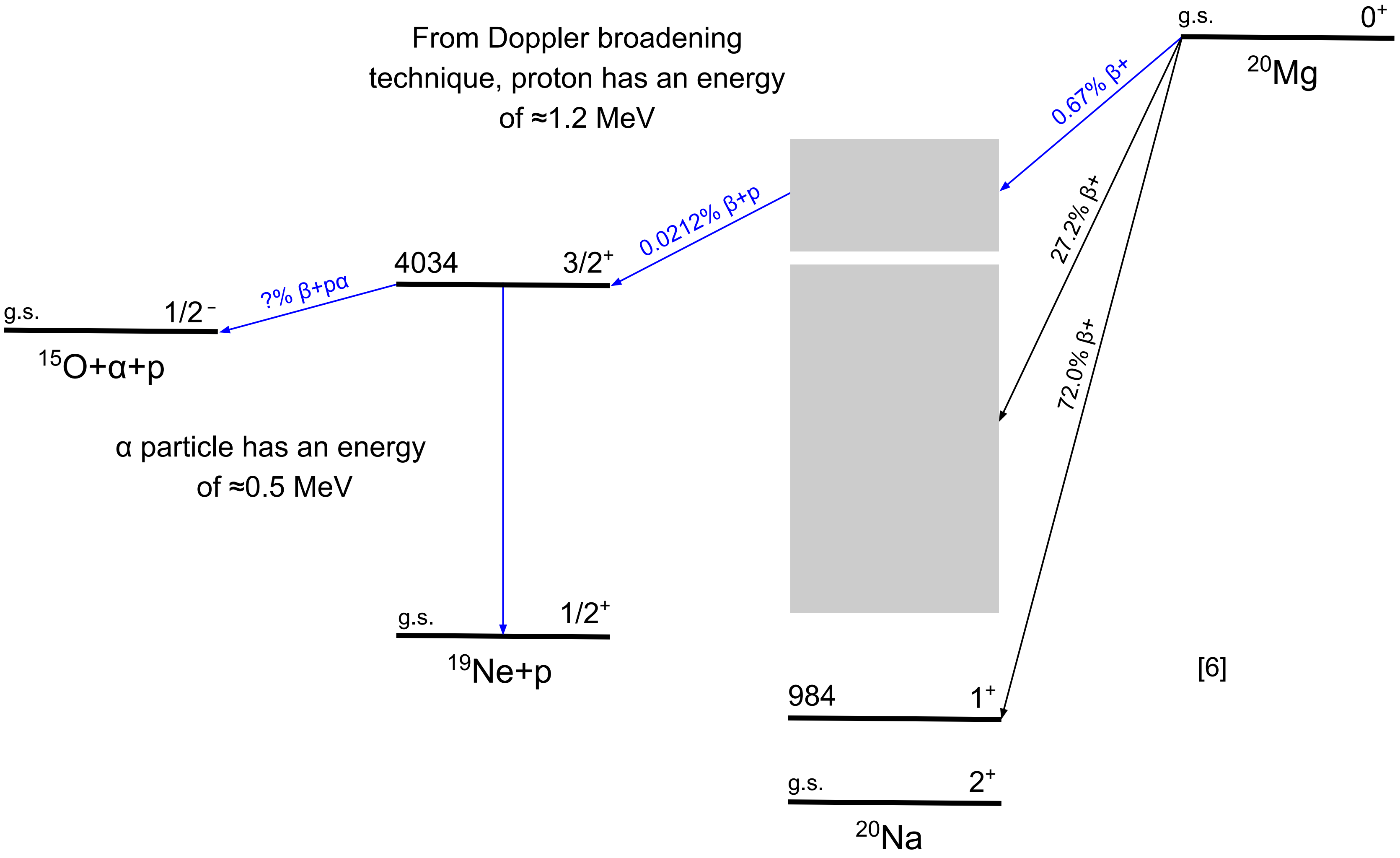
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

MICHIGAN STATE UNIVERSITY

[1] W. P. Tan *et al., PRC* 72, 041302 (2005)
[2] R. Kanungo *et al., PRC* 74, 045803 (2006)
[3] S. Mythili *et al., PRC* 77, 035803 (2008)

Feeding the 4.03 MeV state via $^{20}Mg(\beta p)$ decay

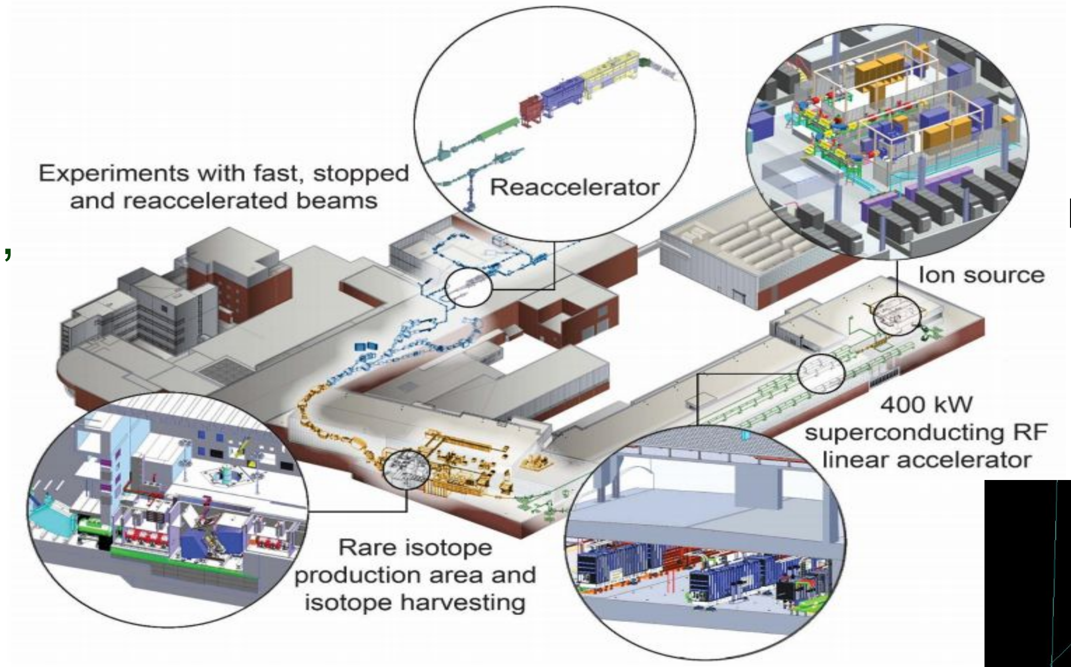
- Transfer reactions have been used to populate the 4.03 MeV state:
  $p(^{21}Ne, t)^{19}Ne^*$ [1]
  $^{3}He(^{20}Ne, \alpha)^{19}Ne^*$ [2]
  $^{19}F(^{3}He, t)^{19}Ne^*$ [3]
- Transfer reaction methods have produced a strong upper limit on the branching ratio ($\sim 10^{-4}$) [4]
- Our method utilized the decay sequence $^{20}Mg(\beta p)$ to populate the 4.03 MeV state in ^{19}Ne [5], [6]



[1] B. Davids *et al., PRC* 67, 062808 (2003)
[2] K. E. Rehm *et al., PRC* 67, 065809 (2003)
[3] W. P Tan *et al., PRL 98, 242503* (2007)
[4] B. Davids *et al., ApJ* 735 40 (2011)
[5] B. E. Glassman *et al., PRC* 99, 065801(R) (2019)
[6] C. Wrede *et al., PRC* 96, 032801(R) (2017)

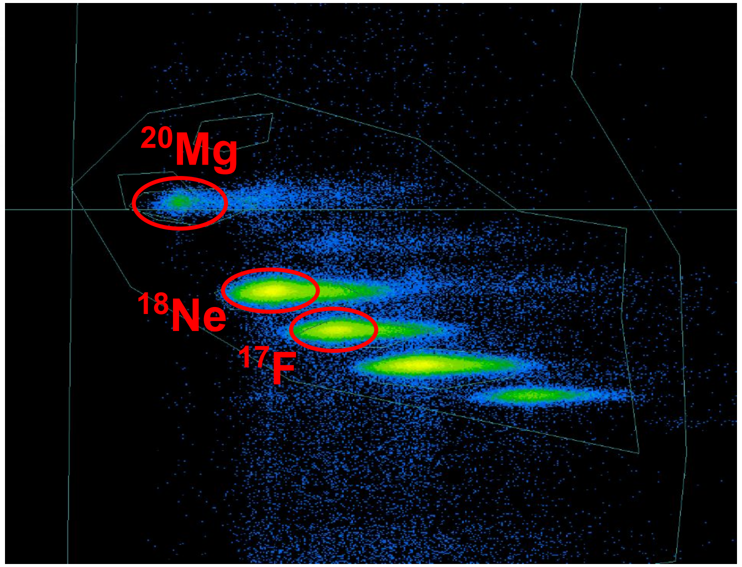
E21072 at the Facility for Rare Isotope Beams (FRIB)

- Ran experiment 21072 in November of 2022 (spokesperson is Chris Wrede, MSU/FRIB[1])
- 4th experiment to run at FRIB
- ^{36}Ar primary beam that impinged on a ^{12}C target to create a fast beam of ^{20}Mg
- ~1800 ^{20}Mg beam particles per second



[2]

Energy Loss (dE) vs Time of Flight (ToF)

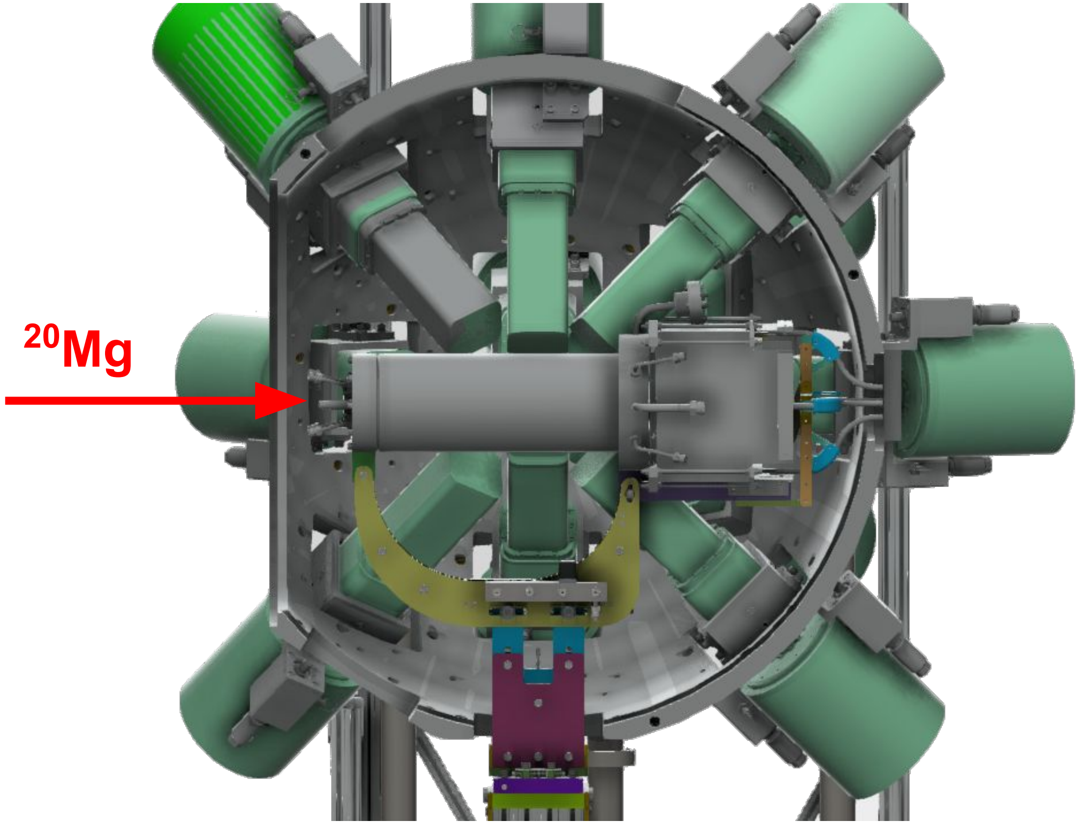


[1] Wrede, C. (2015). *Proceedings of XIII Nuclei in the Cosmos — PoS(NIC XIII)*
[2] Wrede, C. (2015). The facility for Rare isotope beams. EPJ Web of Conferences, 93, 07001.

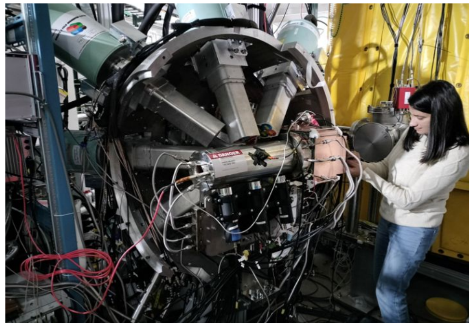
The GADGET II Detection System

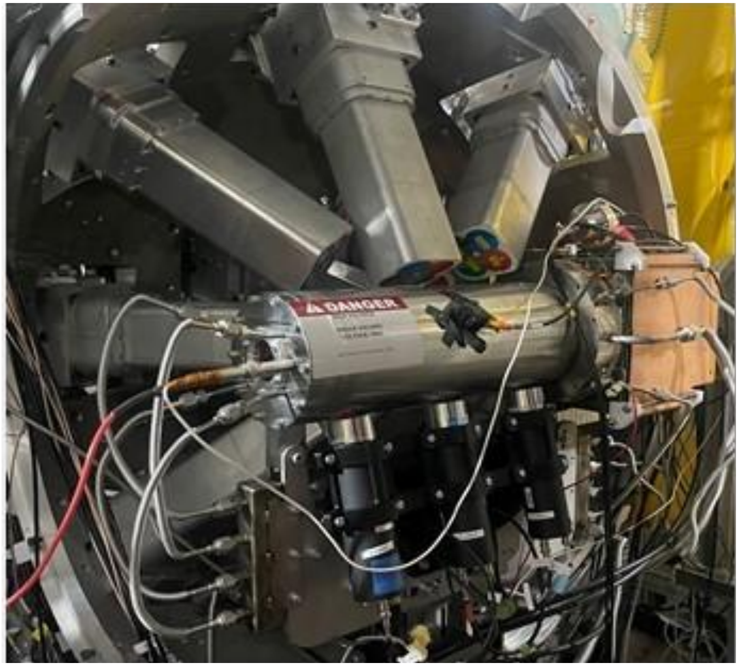
GADGET II Detection System Design

TPC surrounded by the DEcay Germanium Array initiator (DEGAi)
DEGAi is part of the FRIB Decay Station initiator (FDSi)



Final Experimental Setup (Nov. 2022)

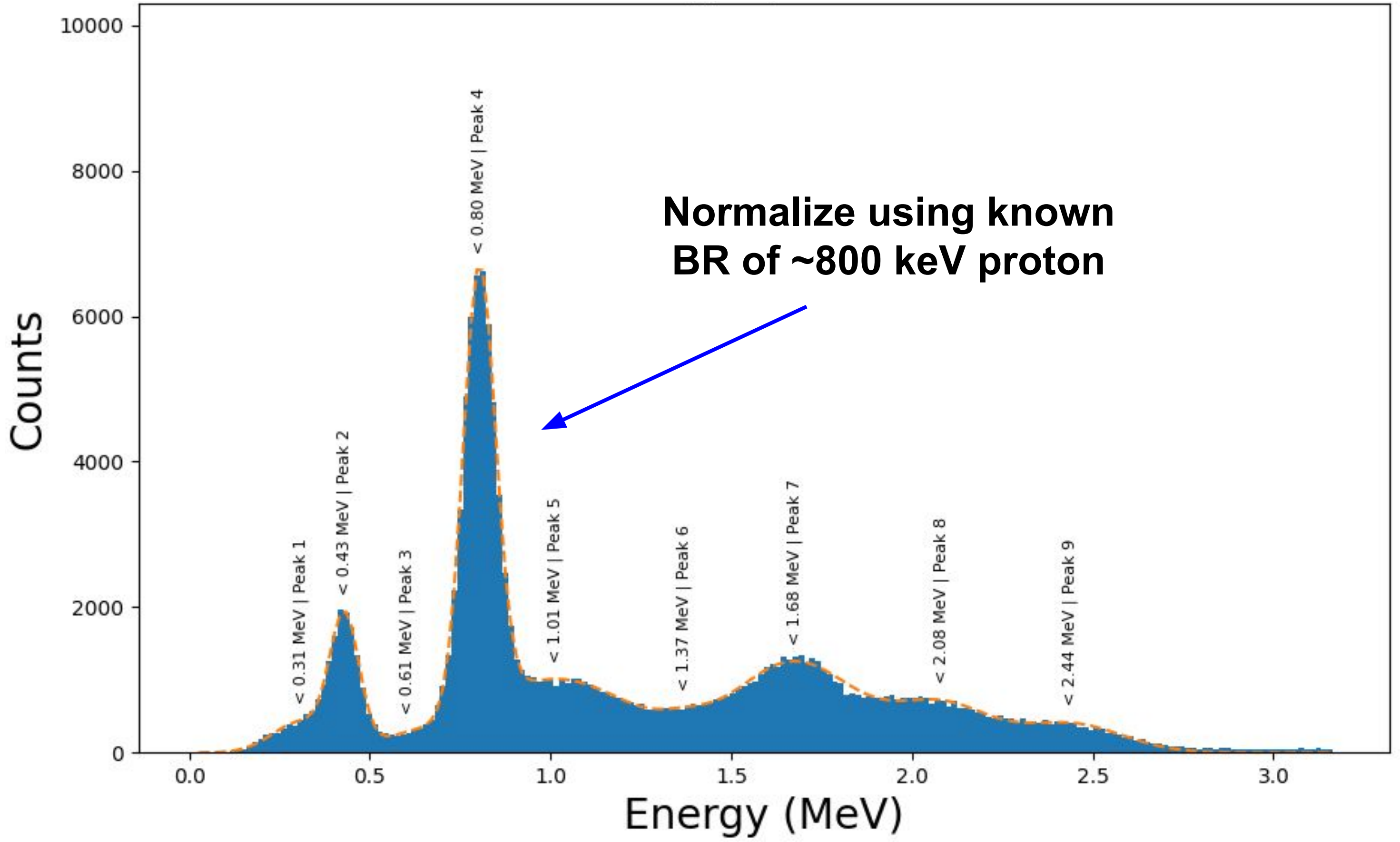


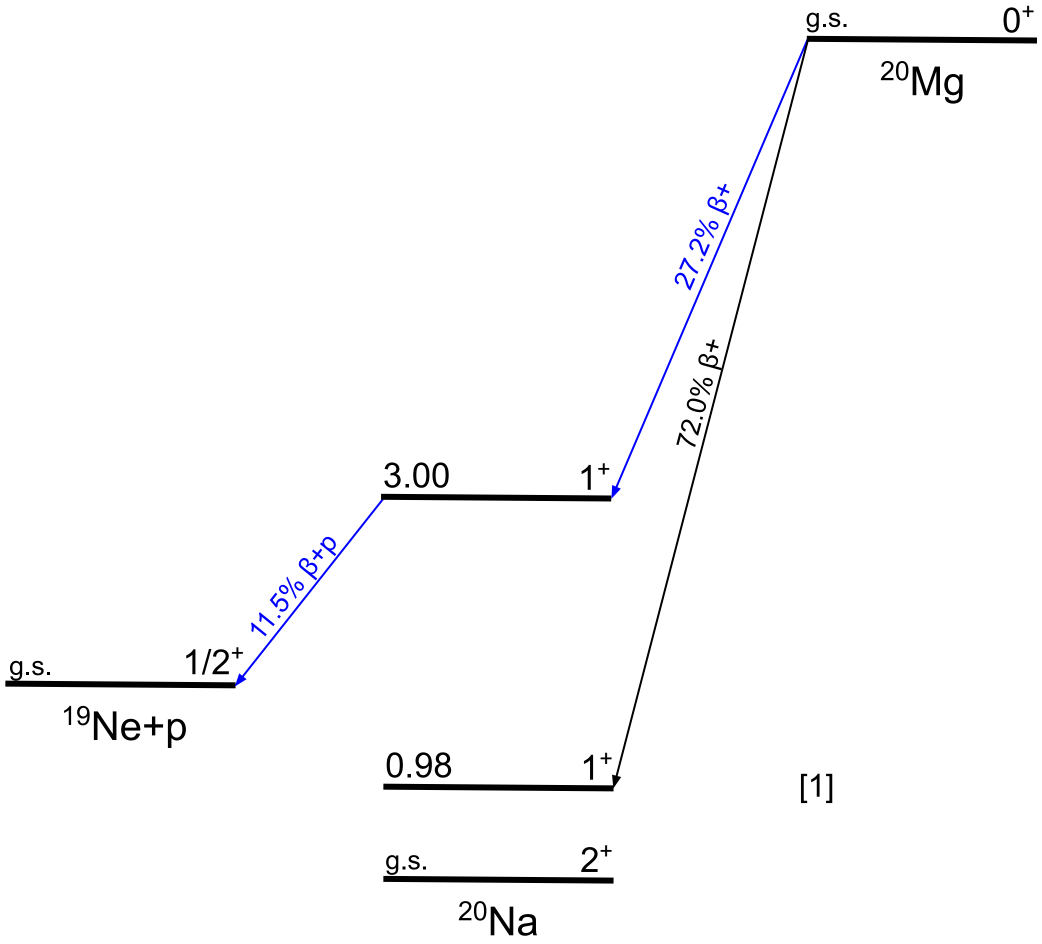


Ruchi Mahajan,
MSU/FRIB
(Postdoc)

[1] M. Friedman *et al., NIM* 940 93-102 (2019)
[2] R. Mahajan *et al., Time Projection Chamber for GADGET II,* In Preparation (2023)

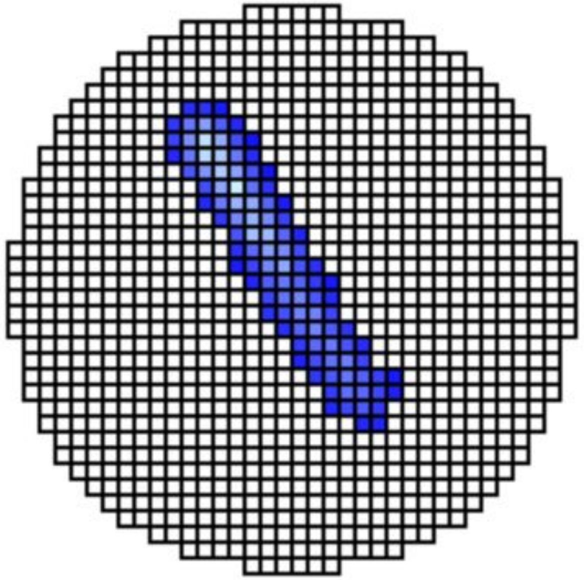
TPC Raw Energy Spectrum
1 hr Run from Experiment 21072

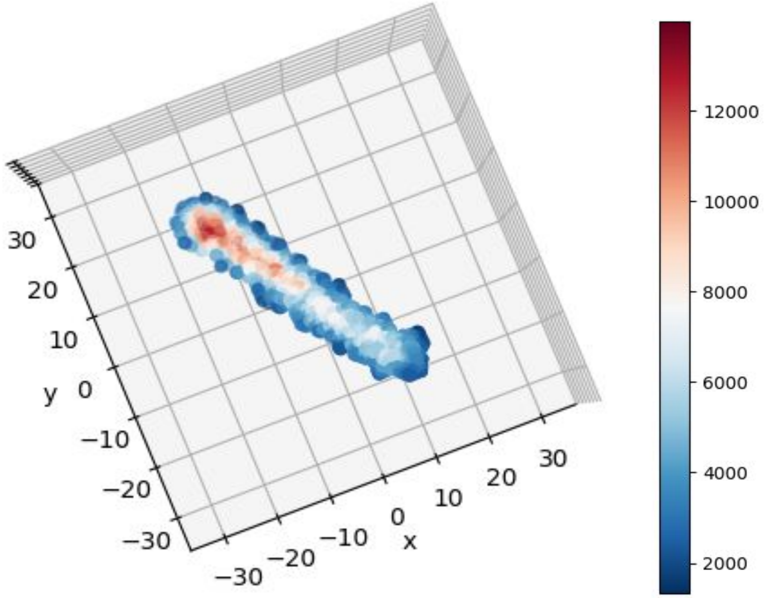




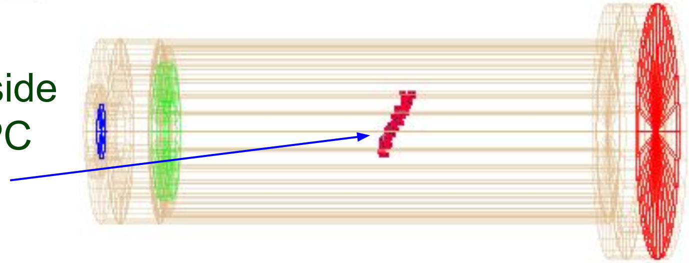
Range vs Energy Search Region
1 hr Run from Experiment 21072

Experimental Data: Typical Proton Track
Energy = 1.67 MeV | Length = 55 mm

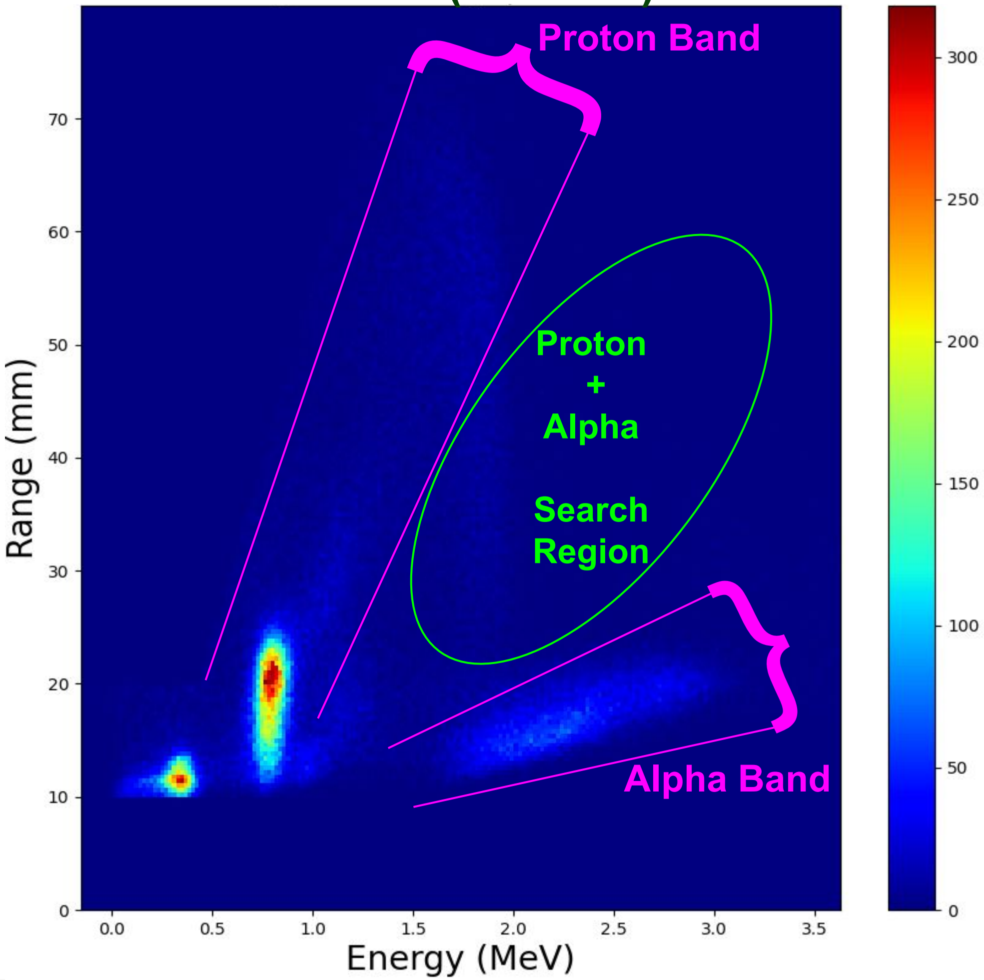




Proton event inside GADGET II TPC geometry



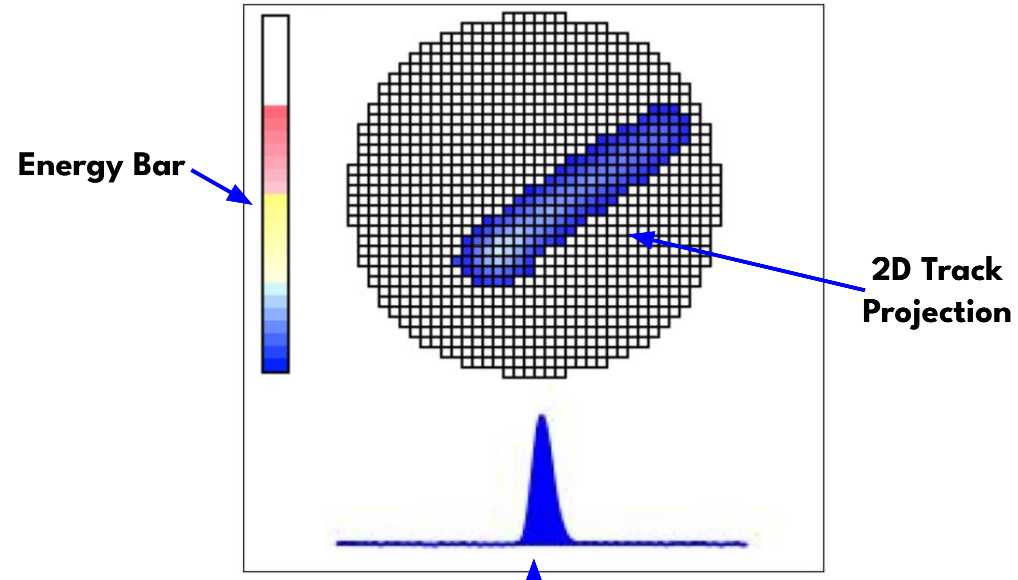
Range vs Energy Plot for Experiment 21072 (1 hr run)



Early Data Fusion w/ Convolutional Neural Net (CNN)

Data Fused Images

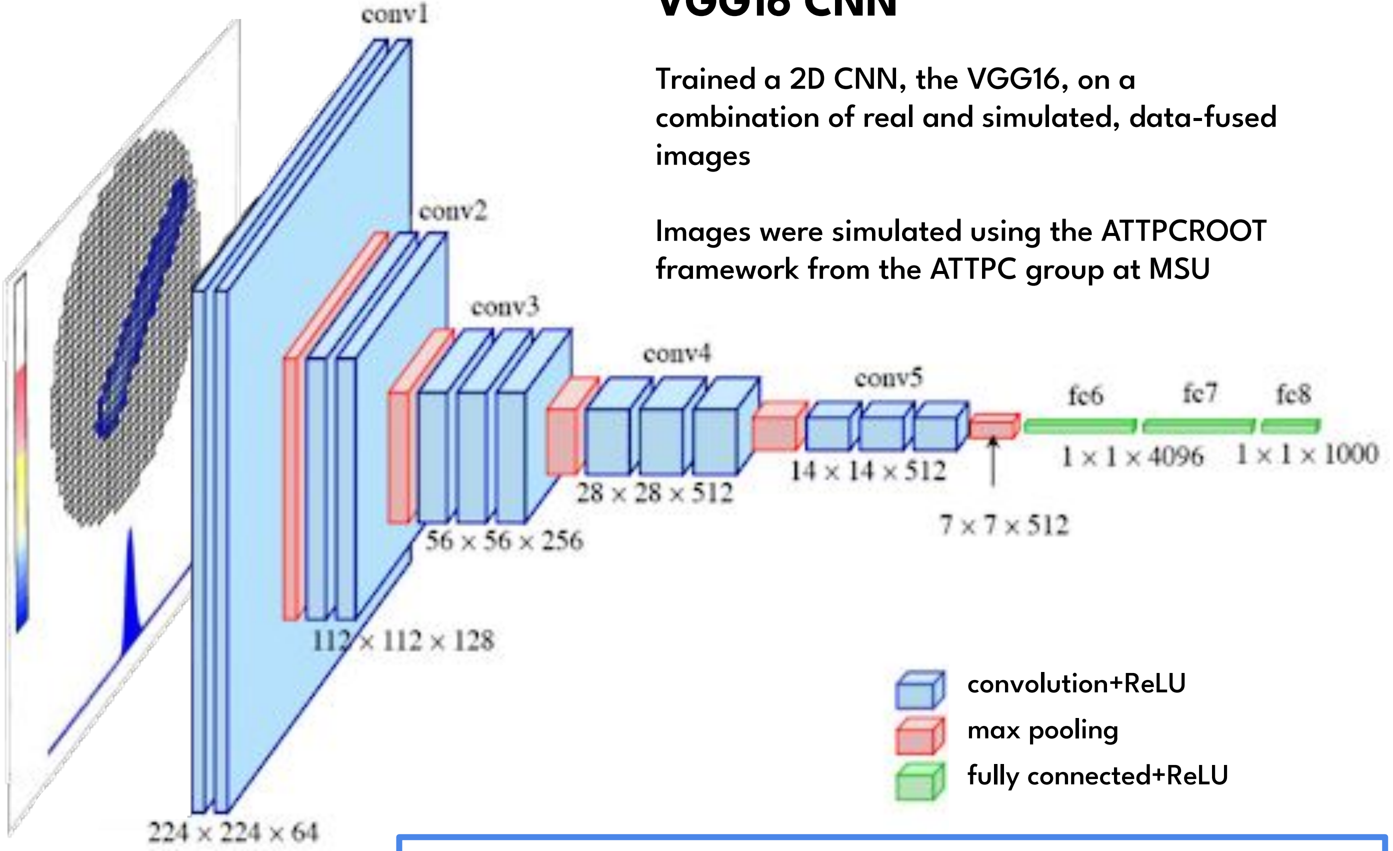
Used early data fusion to compress 3D images into 2D data-fused images with no loss of topology uniqueness



VGG16 CNN

Trained a 2D CNN, the VGG16, on a combination of real and simulated, data-fused images

Images were simulated using the ATTPCROOT framework from the ATTPC group at MSU



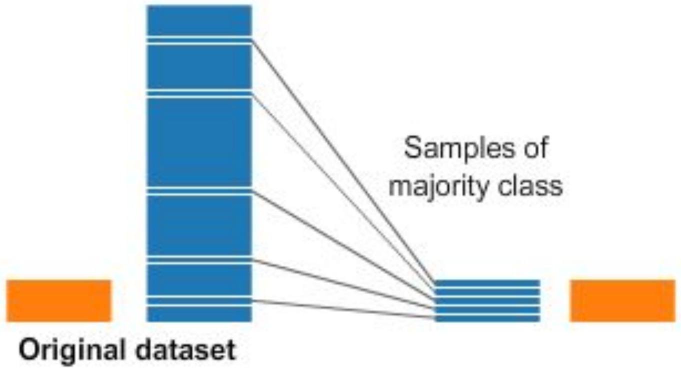
For simulated data we achieved a training and testing accuracy of 100%

Right: https://medium.com/mlearning-ai/an-overview-of-vgg16-and-nin-models-96e4bf398484

Combatting Imbalanced Data for Rare Event Search in TPC Data

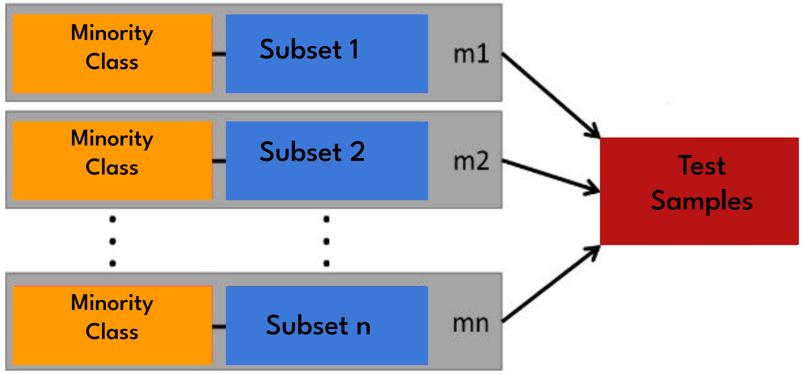
Undersampling/Oversampling

Undersampling the majority class and oversampling the minority class to create a balanced data set improves model performance



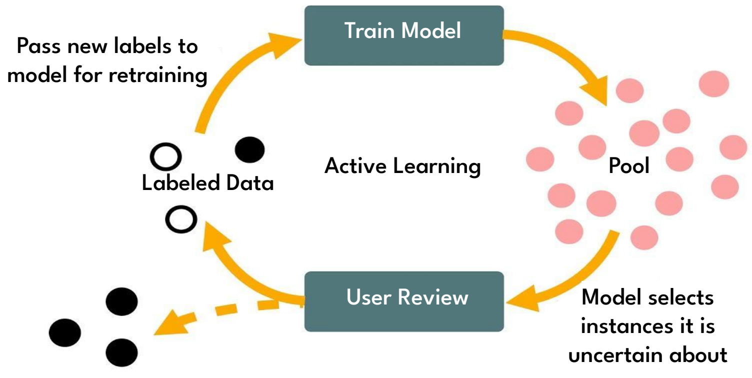
Ensemble Method w/ Majority Vote

Train multiple CNNs and use a majority voting approach to make final predictions from the ensemble



Active Learning

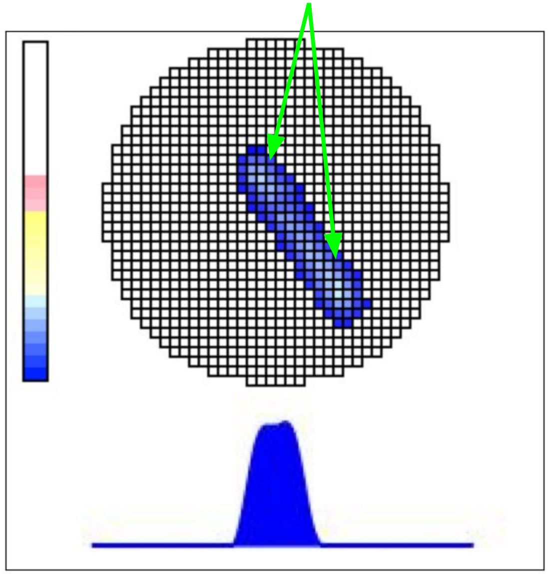
Deploy models on unlabeled data and have them query the user to obtain labels for the most informative examples



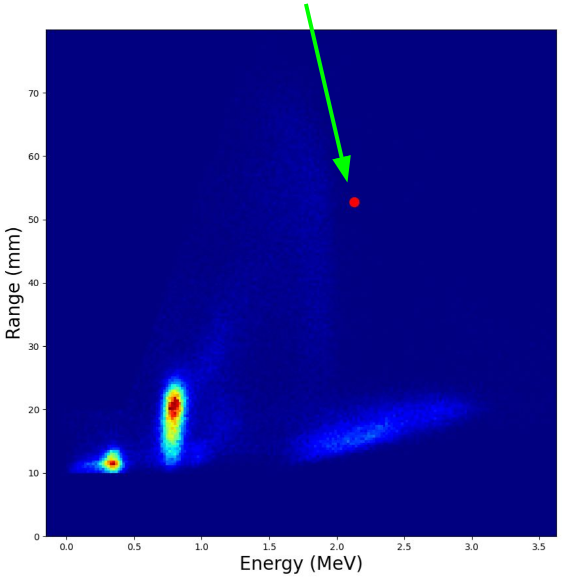
All of these methods combined to give us ~97% accuracy in identifying real two-particle events

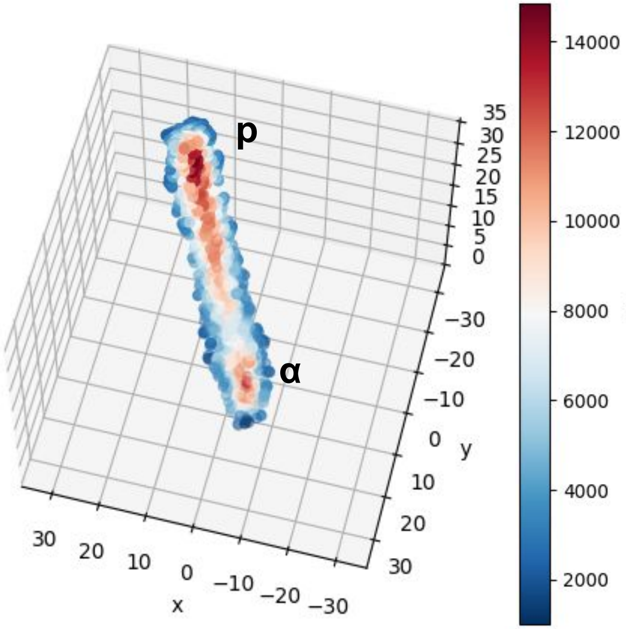
Ongoing Analysis of Experimental Data: Example of Candidate p-α Event

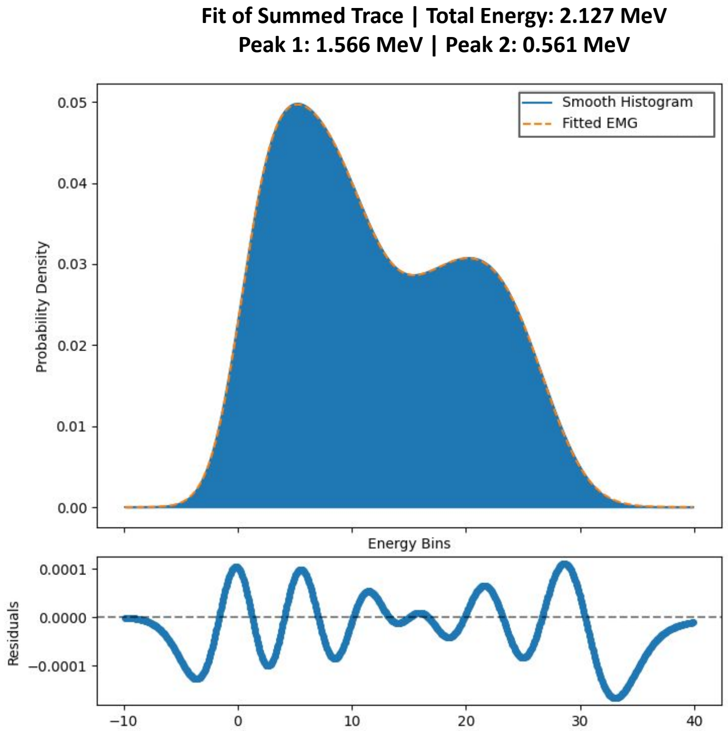
Double Bragg Peak



Event Lies in Region of Interest







Future Outlook: GADGET II FRIB Experiment E23035

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

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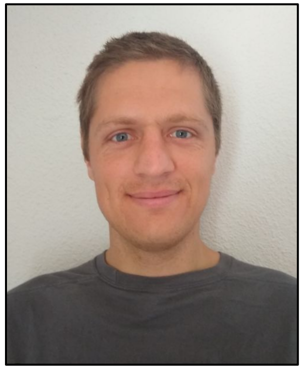
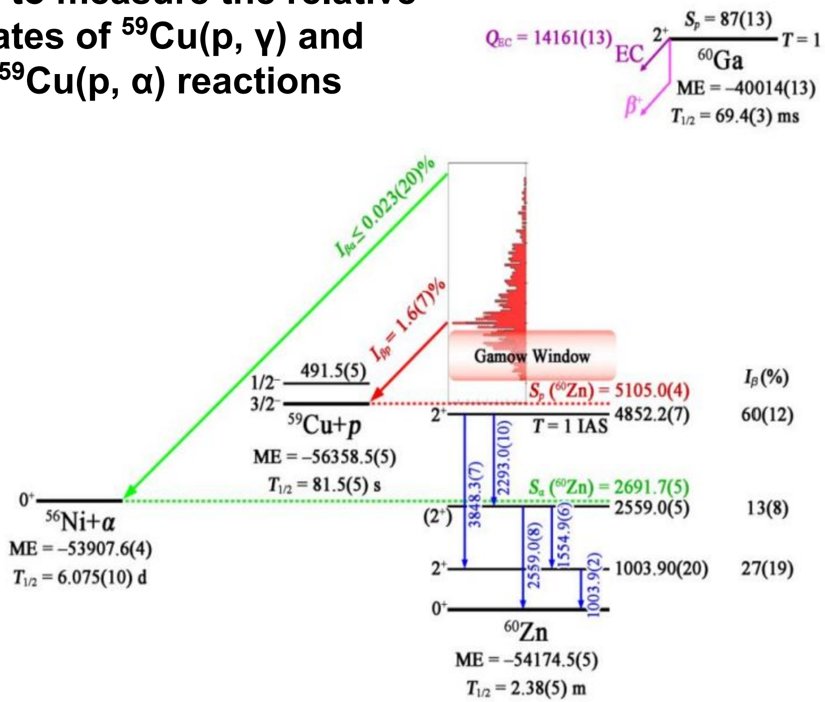
PAC 2 approved FRIB experiment to measure two critical reactions in Type I X-ray bursts

Chris Wrede, MSU/FRIB (Spokesperson)



Alexander Adams, MSU/FRIB (Thesis Experiment)

Will utilize the β-decay of ^{60}Ga to measure the relative rates of $^{59}Cu(p, \gamma)$ and $^{59}Cu(p, \alpha)$ reactions



A simplified decay scheme for ^{60}Ga.

Left: Adapted from: R. Cyburt, *et al.*, APJ 930, 2 (2016)
Righ: A. Adams, poster, *"Studying the NiCu Cycle with the GADGET 2 System"*

Summary

- The $^{15}O(\alpha, \gamma)^{19}Ne$ reaction is one of the most important reaction rate uncertainties underlying X-ray bursts from neutron stars
- The reaction rate can be determined by measuring the alpha particle branching ratio from the 4.03 MeV state in ^{19}Ne
- We are searching for the alpha emission from this state by using the ^{20}Mg decay sequence at FRIB with a fast beam of ^{20}Mg and the GADGET II TPC
- We will continue to analyze experimental data with the aid of ML algorithms (CNNs) to identify the rare events of interest
- Once the reaction rate is calculated we will model X-ray burst light curves from neutron stars and investigate the next-most-important reactions

Thank you to our GADGET II Collaborators!

Collaboration for FRIB experiment # 21072

Michigan State University
희귀핵 CENS
University of Notre Dame
The Hebrew University of Jerusalem
ibs 기초과학연구원 Institute for Basic Science
De la recherche à l'industrie cea
UMass Lowell
The University of Tennessee Knoxville
FRIB
Argonne National Laboratory
Aarhus University
Australian National University
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
Colorado School of Mines
USC Universidade de Santiago de Compostela
Shanghai Jiao Tong University
McMaster University

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Thank you!