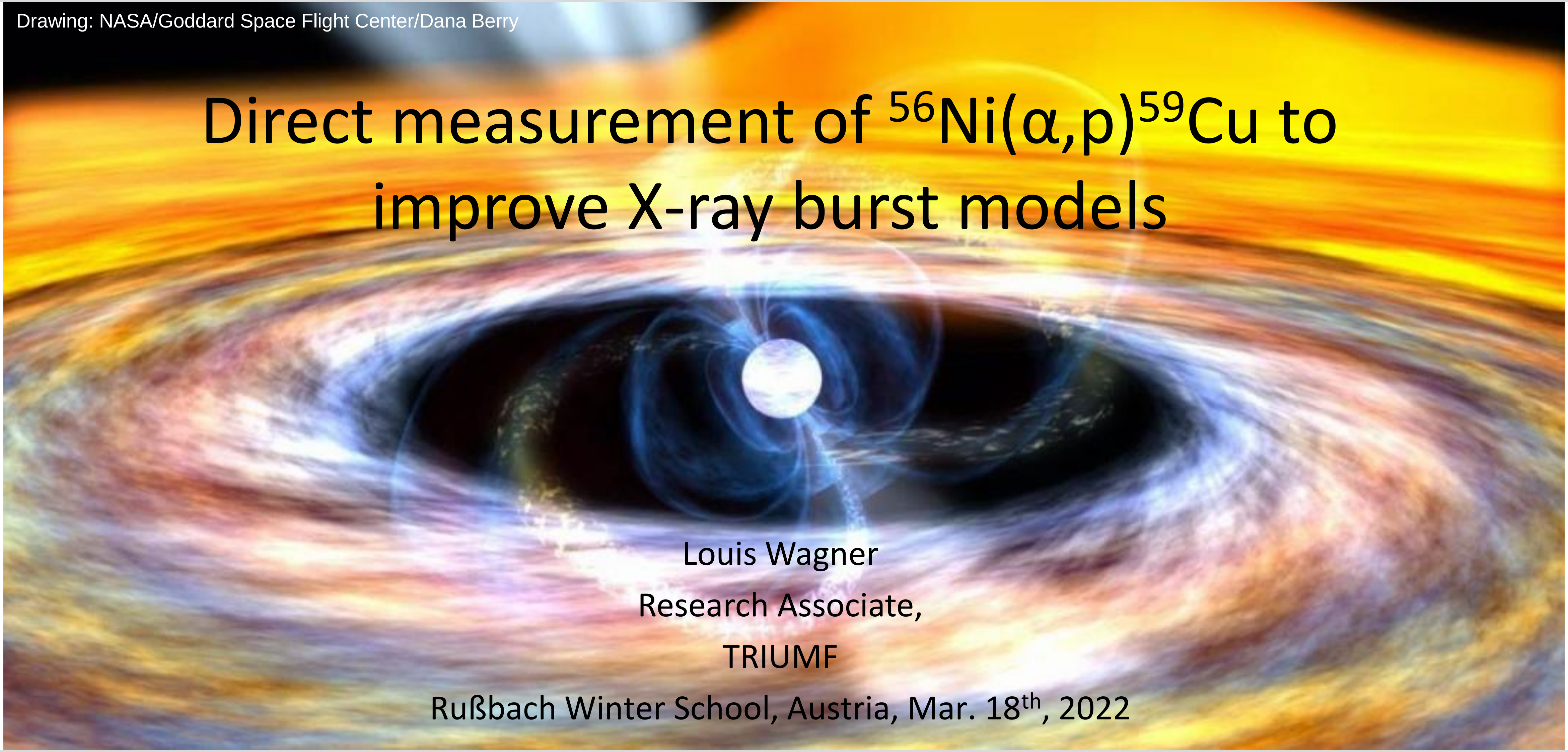


Drawing: NASA/Goddard Space Flight Center/Dana Berry

Direct measurement of $^{56}Ni(\alpha,p)^{59}Cu$ to improve X-ray burst models

Louis Wagner

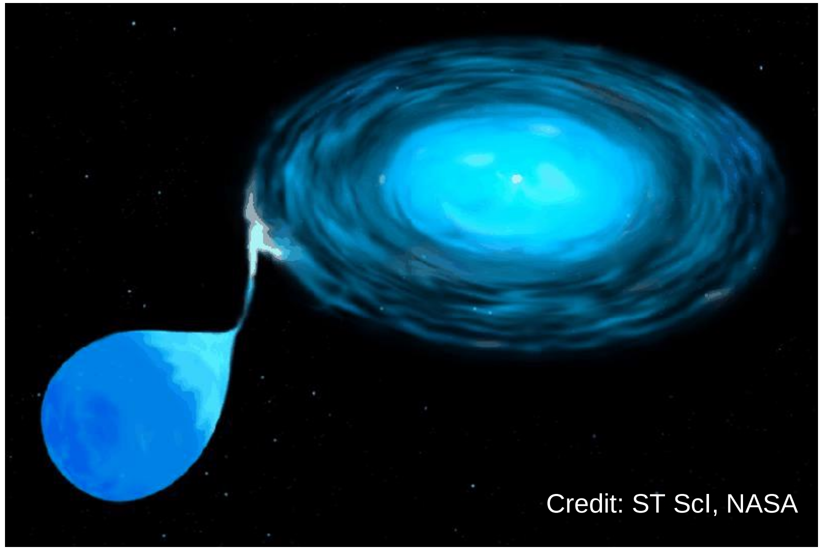
Research Associate,

TRIUMF

Rußbach Winter School, Austria, Mar. 18th, 2022

Accreting neutron stars

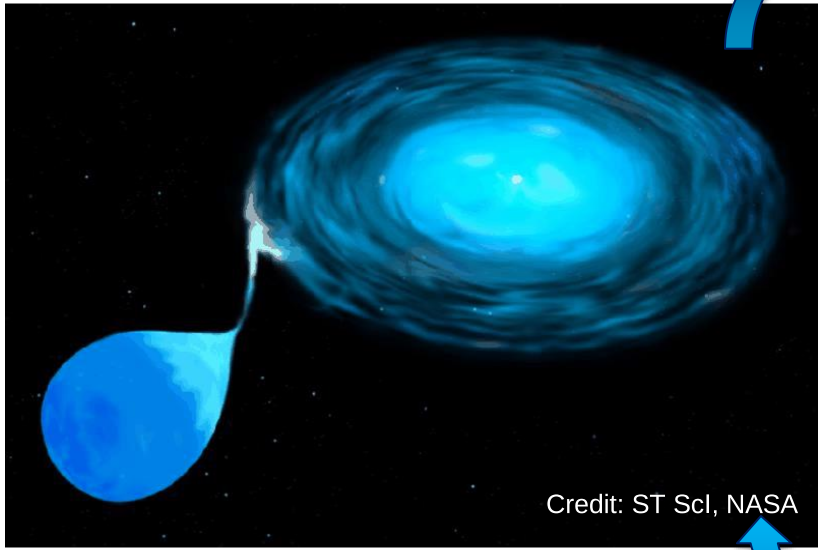
- X-ray burster are binary systems consisting of neutron star (NS) + main sequence star (MS)
- Material from MS is accreted on the NS when it exceeds the Roche lobe and “falls” on the NS
- Similar process happens for recurring novae or millisecond pulsars
- Captured Hydrogen is fused to Helium on NS surface by hot CNO cycle once density and temperature conditions are created by gravitational compression within a few hours

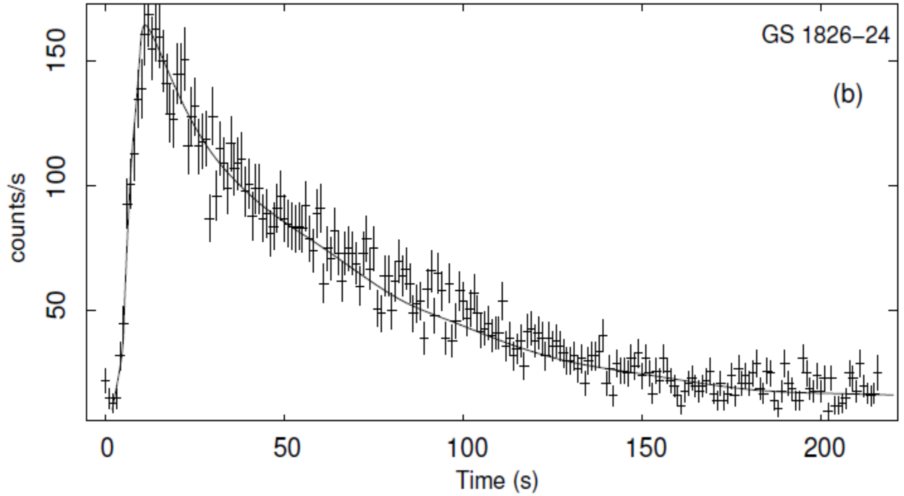


- Increasing temperature triggers thermonuclear runaway
- If accretion is transient neutron transfer reactions in crust and surface radiation can cool the NS and X-ray binary enters a quiescent phase

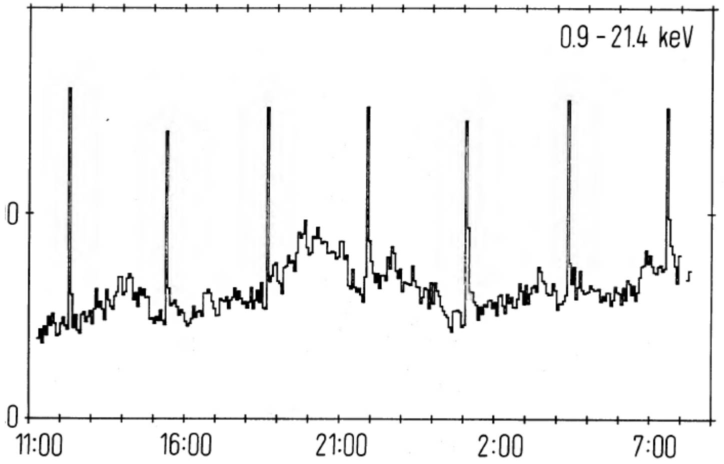
Type I X-ray burst

- Recurring bursts on accreting NS have distinct light curve patterns
- Type I X-ray bursts are short pulses with rise times of 1-10 s
- 10-100 times brighter luminosity (10^{39-40} ergs)
- They yield indirect information about NS radius and mass by model comparisons
- > 60 X-ray binaries observed in our galaxy with large database of burst properties





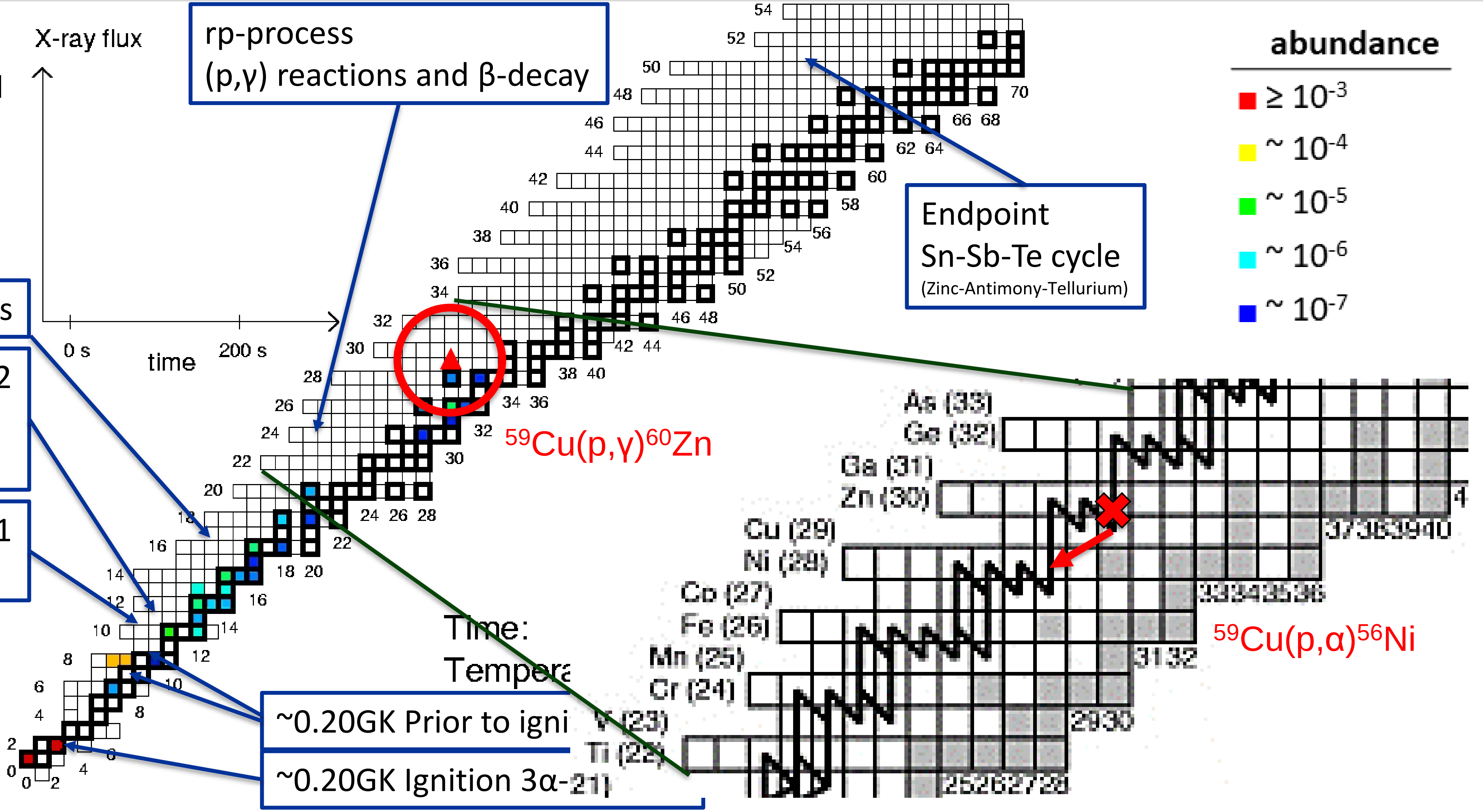
Type I X-ray burst GS 1826-24 by Swift/XRT from
A. Parikh *et al*., Prog. in Part.& Nucl. Phys. 69, 225 (2013)



Burst pattern of 4U/MXB 1820-30 from
F. Haberl *et al*., Astrophys. J. 314, 266 (1987)

X-Ray Burst Calculation

- Type I X-ray burst
- 1-D single-zone model
- Complete nuclear reaction network

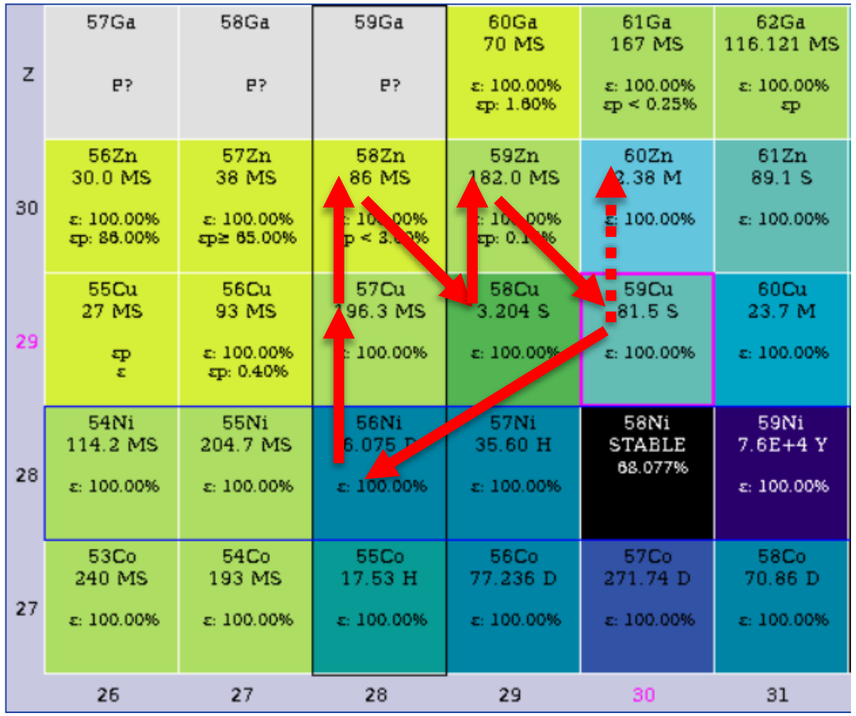


Movie provided by JINA-CEE

The Impact of $^{59}Cu(p,\alpha)^{56}Ni$

- NiCu cycle plays important role in burst models
- Consistently all sensitivity studies show that $^{59}Cu(p,\alpha)^{56}Ni$ has strong impact on X-ray bursts light curves

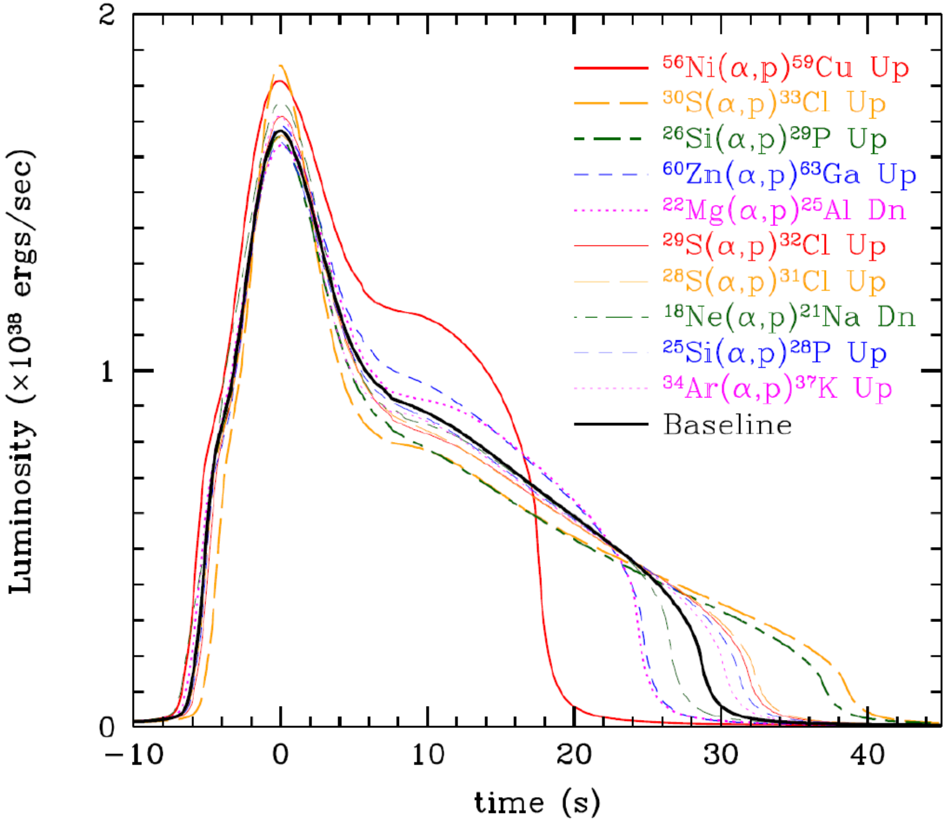
Z



N

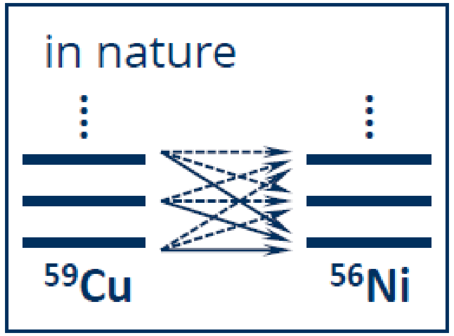
Mass Nr. A	Ash mass fraction change factor
12	83
28	76
30	750
31	214
33	15
34	57
75	10
78	11
82	10

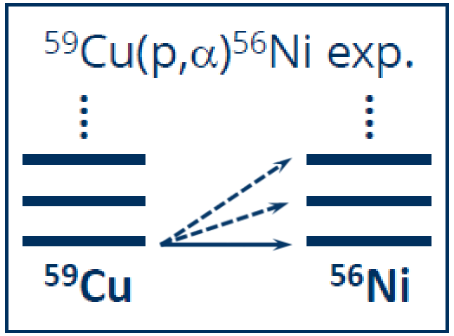
Ash sensitivity study showing ashes strongly impacted by changing $^{59}Cu(p,\alpha)^{56}Ni$ rate up and down by factor 100. Private communication with Adam Jacobs (MSU)

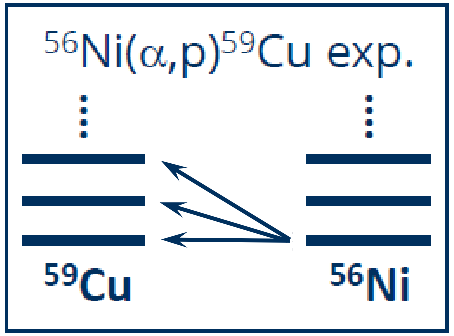


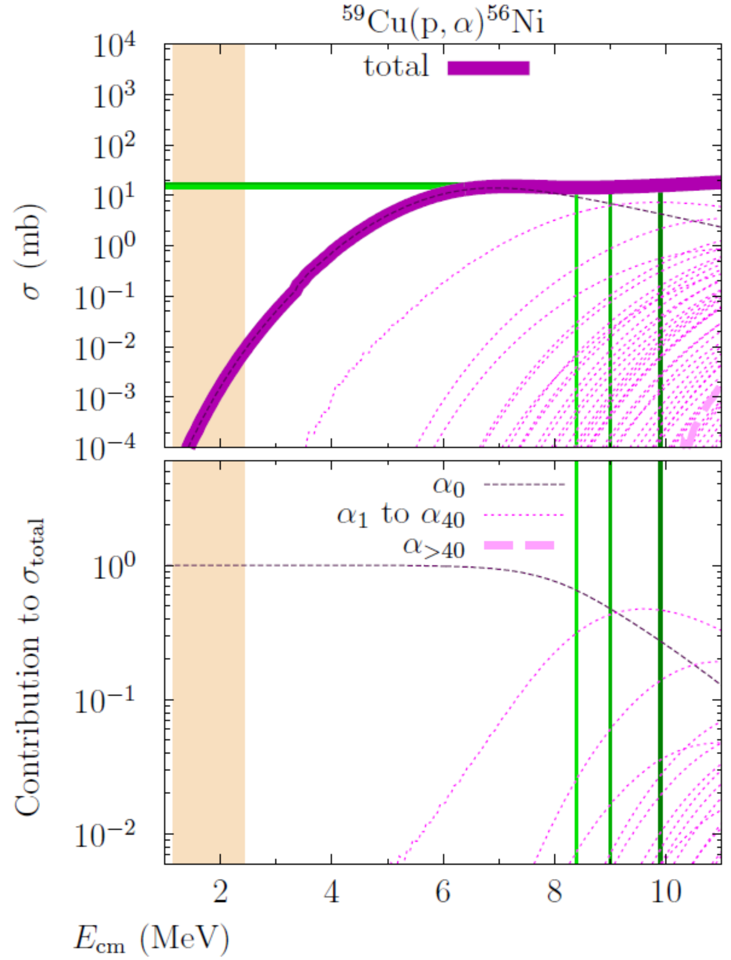
Model calculations with increased (Up) and decreased (Dn) specific rates by a factor of 100 adopted from R. H. Cyburt et al., Astrophys. J. 830, 55 (2016).

The reverse reaction $^{56}Ni(\alpha,p)^{59}Cu$









Forward and reverse cross sections are directly related via detailed balance

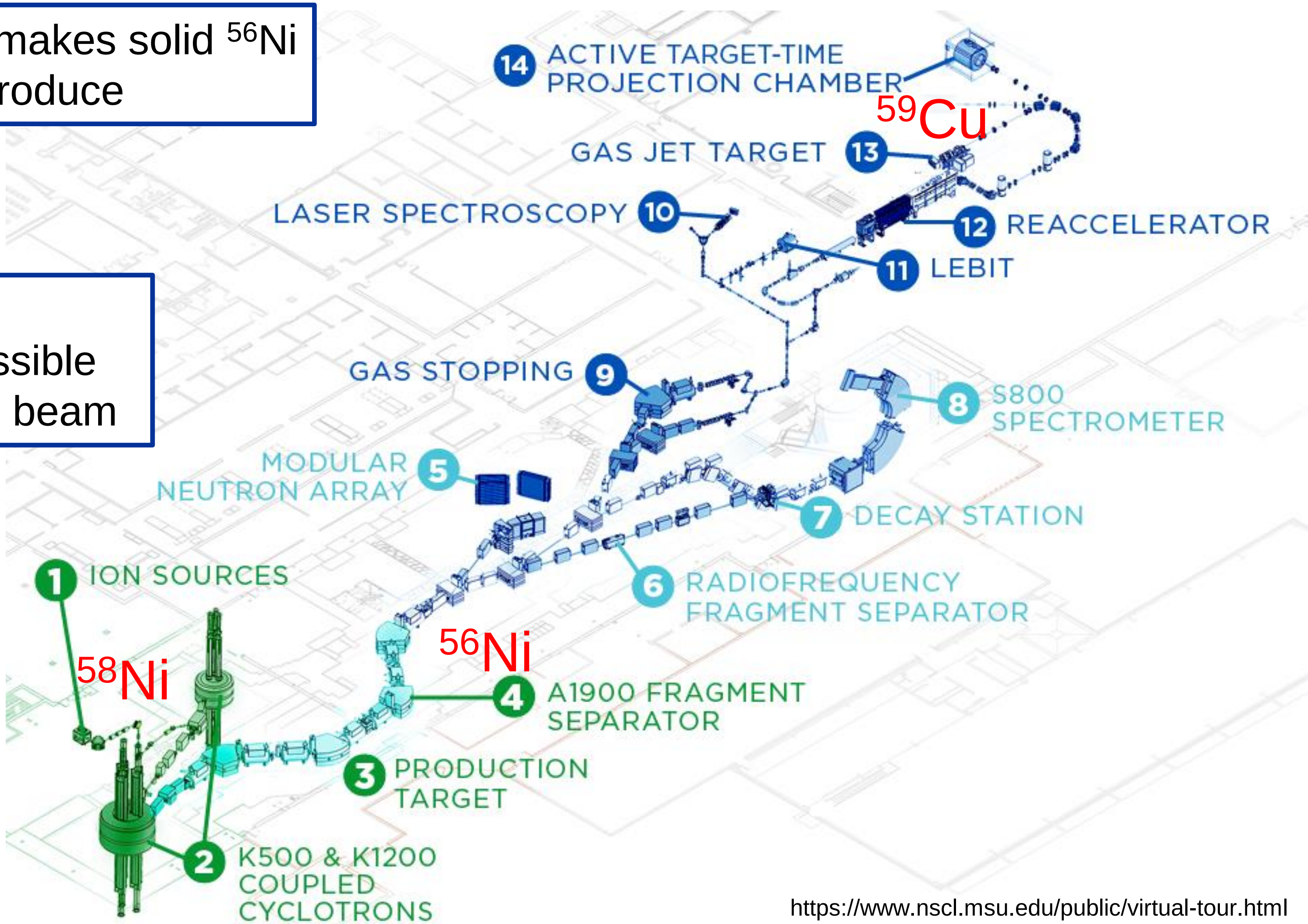
Reaccelerated ^{56}Ni beam at NSCL

Short ^{56}Ni half live makes solid ^{56}Ni targets difficult to produce

Inverse reaction ^{4}He(^{56}Ni,^{59}Cu)p possible with radioactive ion beam

He gas target:

- high density
- compact
- windowless
- pure

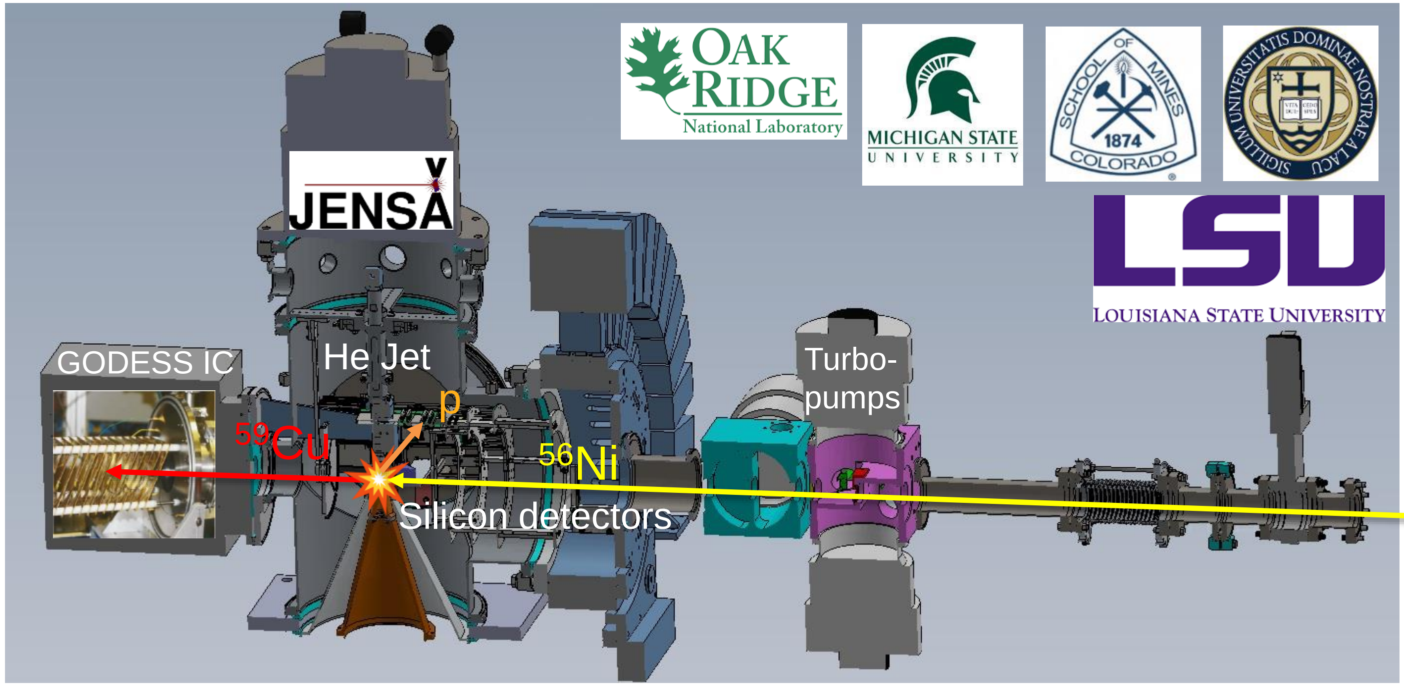


https://www.nscl.msu.edu/public/virtual-tour.html

JENSA Setup

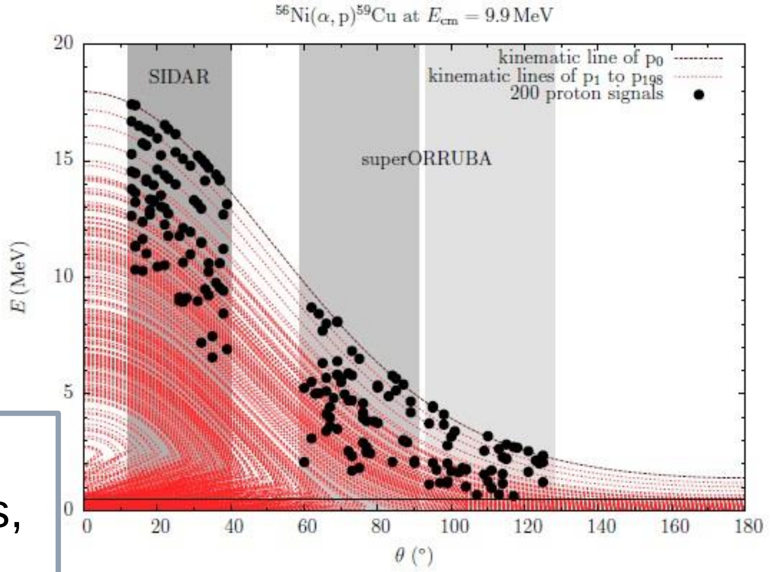
Jet Experiments in Nuclear Structure and Astrophysics

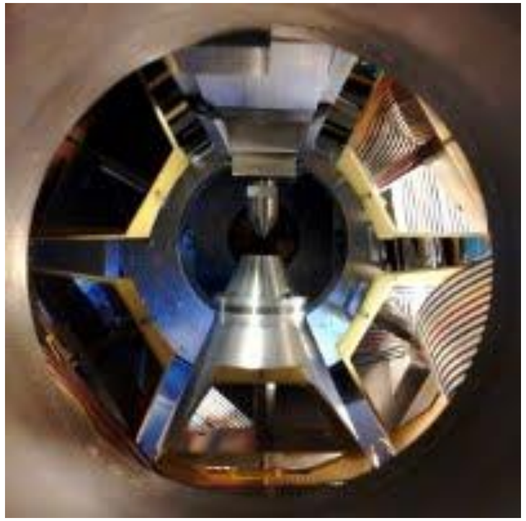
- He jet target: 4mm thick with density of $4\text{-}9 \cdot 10^{18}$ atm/cm^2
- α and p measured by superORRUBA Si detector array >1100 channels
- ^{56}Ni and ^{59}Cu particles counted by GODDESS ionization chamber
- Average beam current 3000 pps
- Additional stable beam time: ^{58}Ni(α,p)^{61}Cu and ^{56}Fe(α,p)^{59}Co



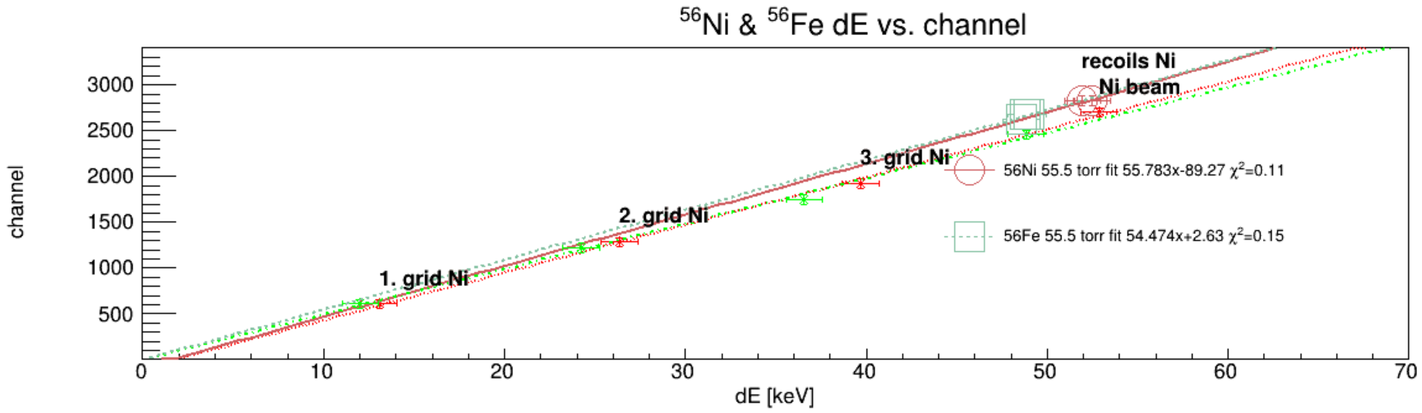
Based on idea of Kelly Chipps, ORNL and Uwe Greife, Colorado School of Mines

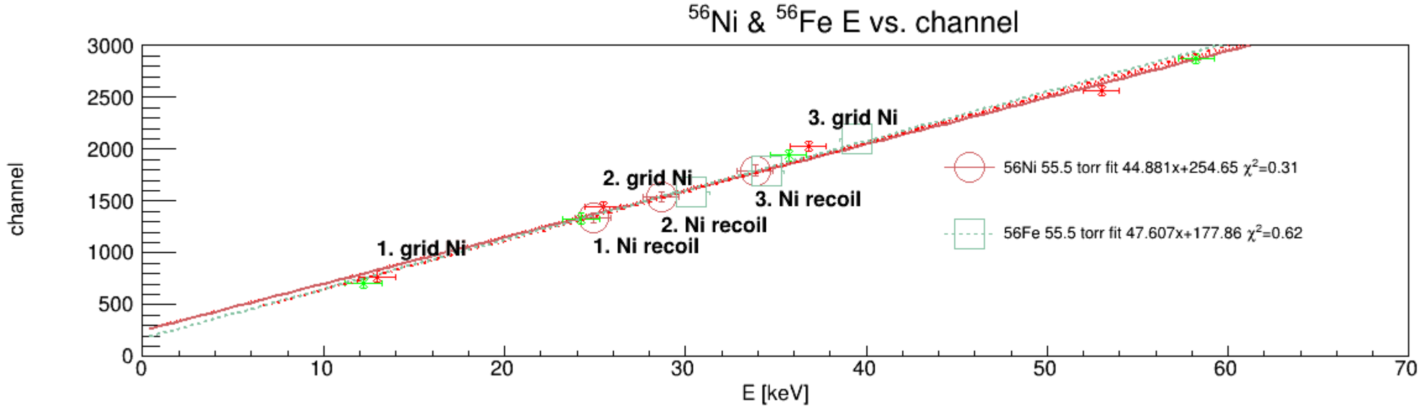
^{56}Ni beam



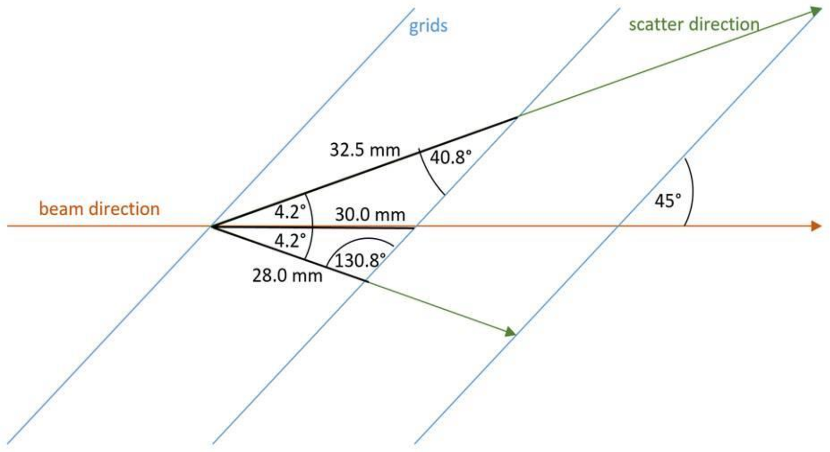


1. IC energy calibration





Fit results for 132MeV beam and 55.5 Torr IC pressure



- Calibration based on energy loss calculations with ICE
- Includes geometry from CAD drawings of GODDESS IC
- IC pressure varied by ±10%
- Beam energy varied by ±6MeV
- -> selected p and E where fits for beam and recoils match the closest

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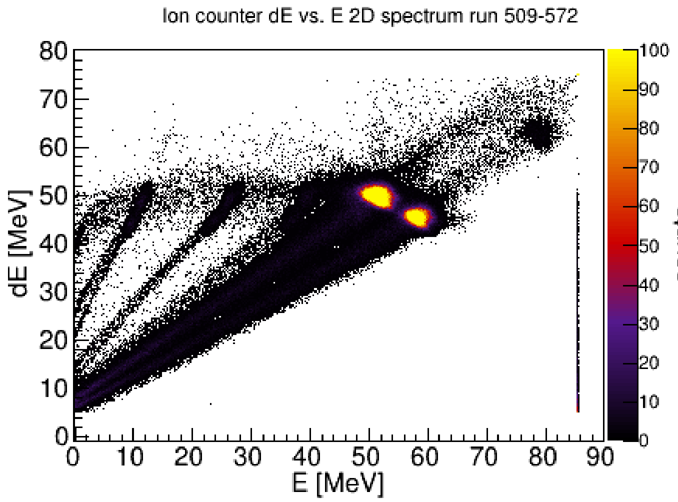
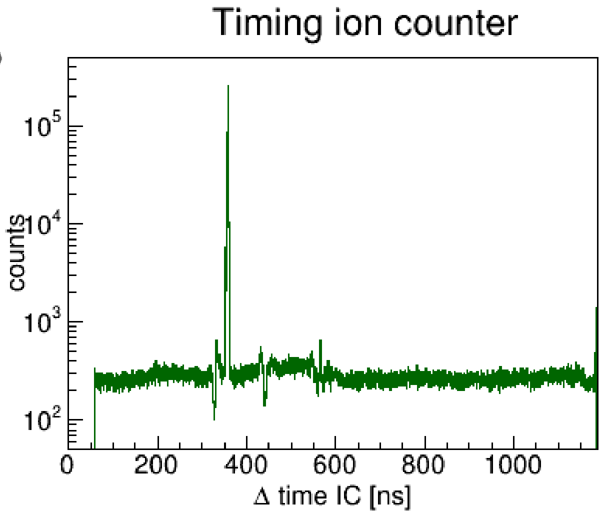
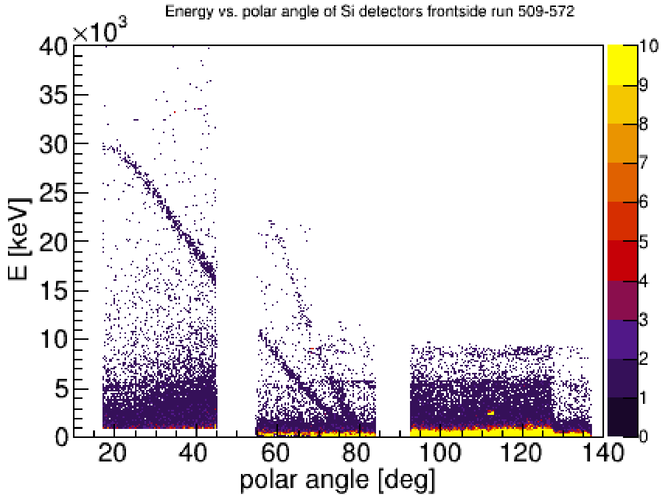
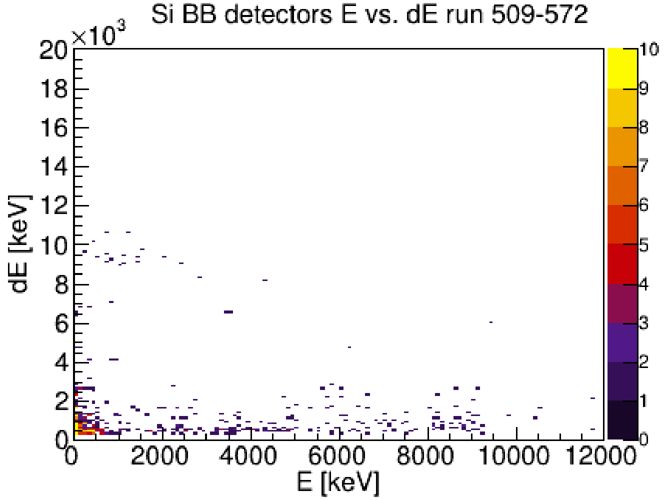
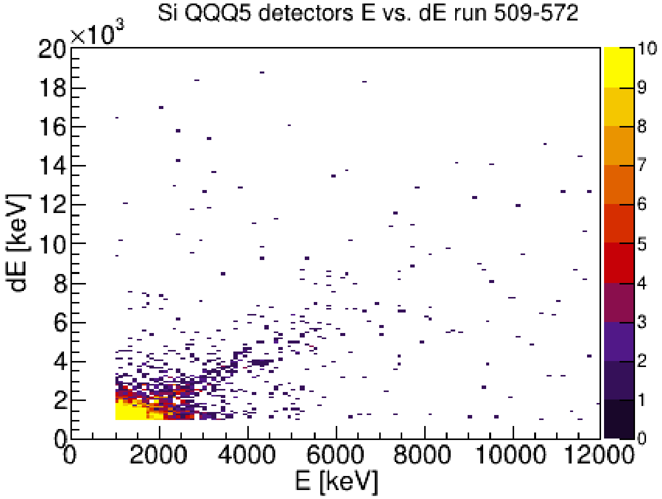
3. Gates for proton search… A.) no gates



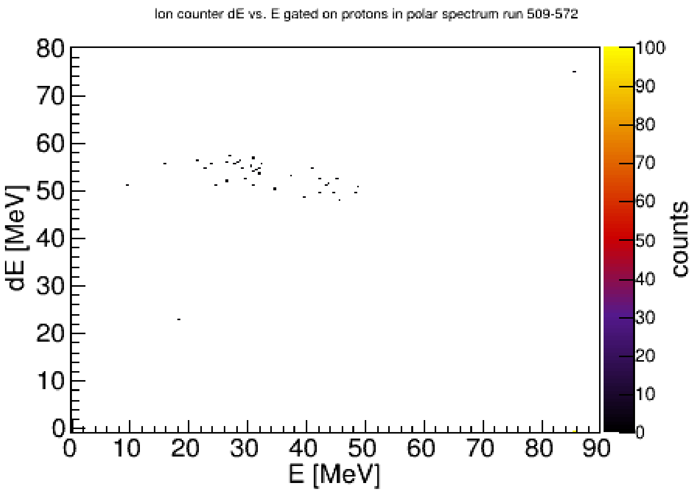


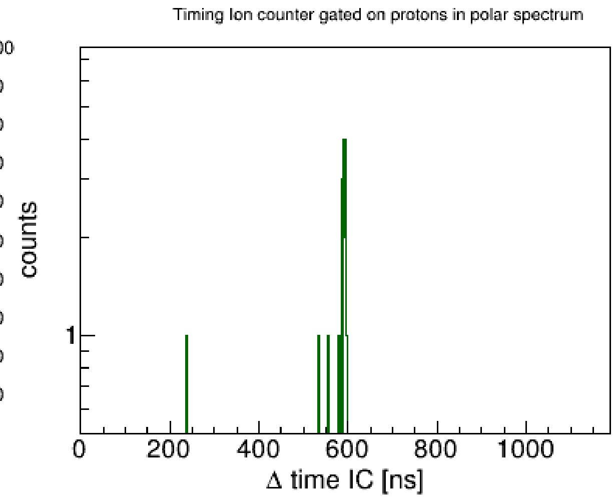


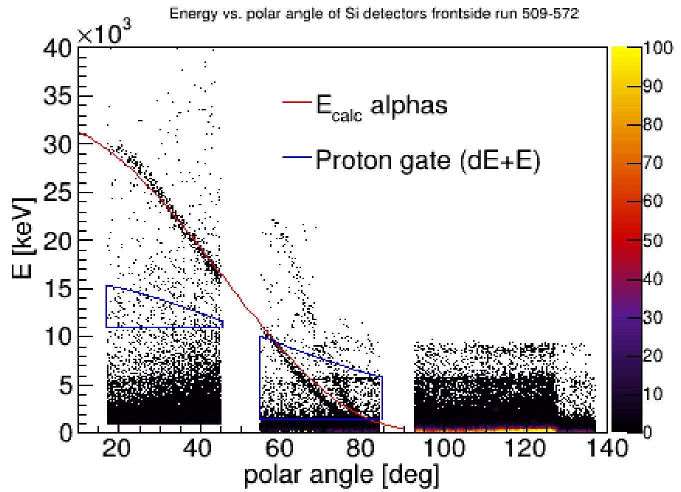


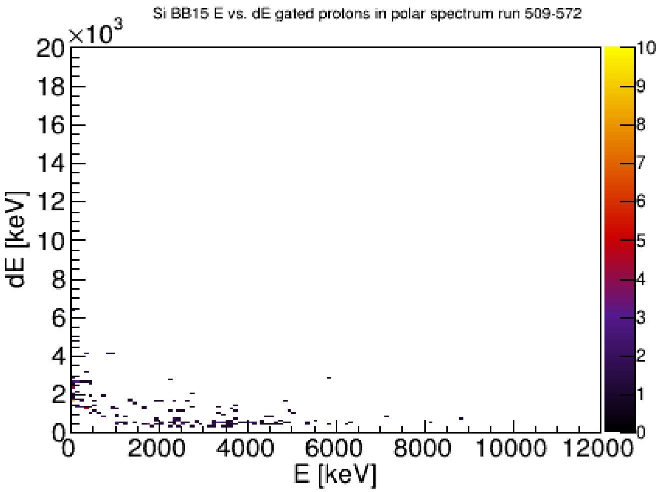


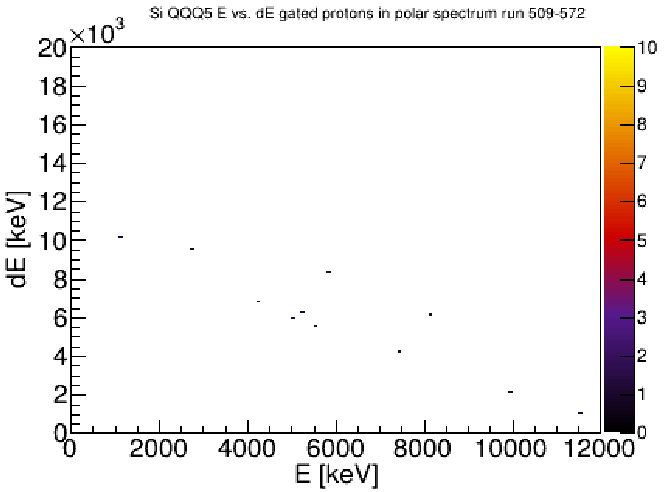
3. Gates for proton search… B.) gate p_{Esum} & p_θ







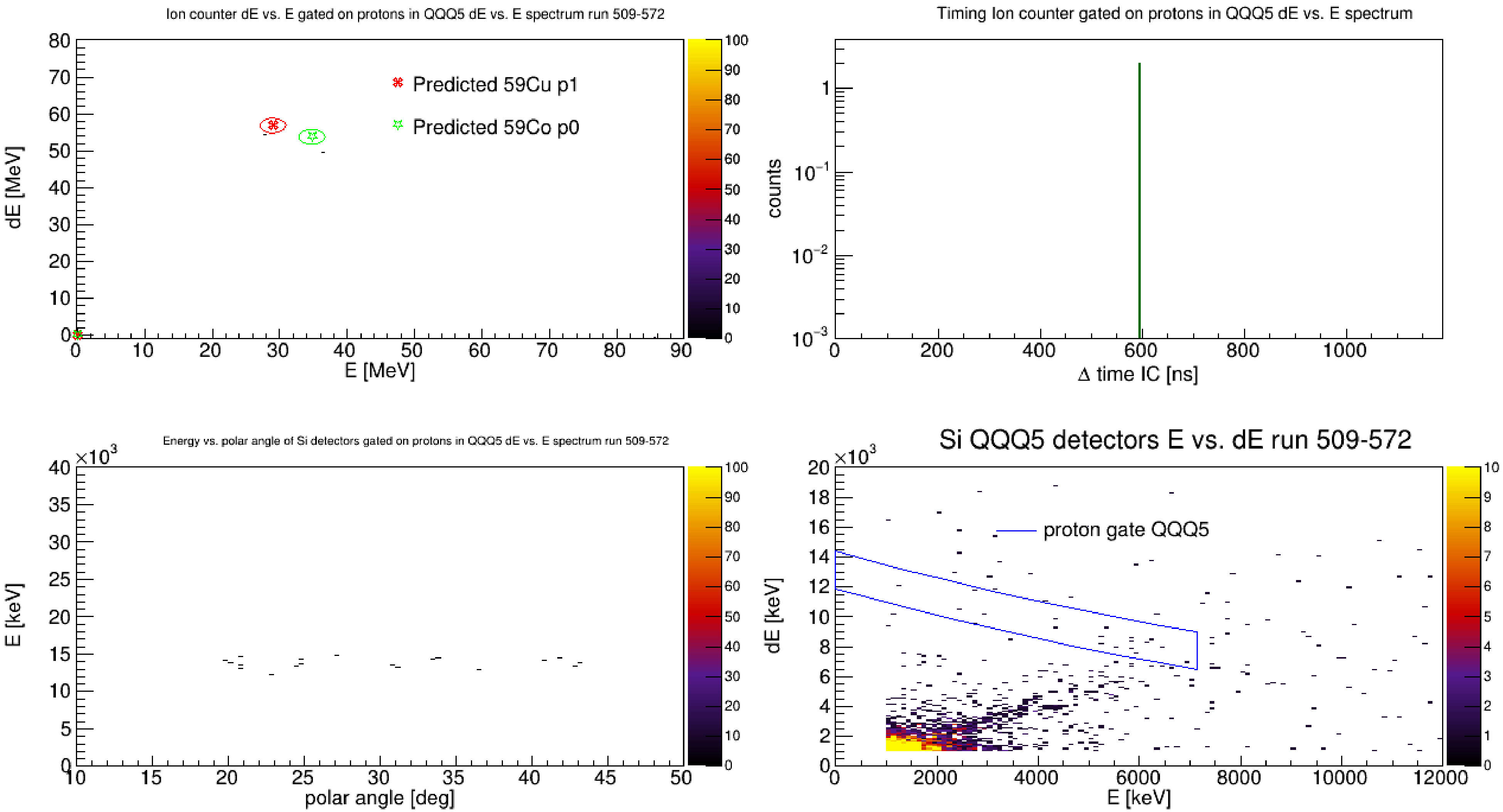




Gate defined by:

- max p_0 energy vs. angle
- min single QQQ5 E loss
- min BB10 dE noise threshold

3. Gates for proton search… D.) gate p_{dE} & p_E



Gate defined by expected p energy loss in Si from LISE++

Summary

- X-ray binaries are great to study neutron stars multidisciplinary
- Reaction rates sensitive to astrophysical observables of X-ray Bursts are measured to improve model accuracy & predictive power of these extreme astrophysical scenarios
- $^{56}Ni(\alpha,p)^{59}Cu$ experiment will provide constraints on NiCu cycle influence on rp-process
- FYI this reaction is assumed to be key for heavy element synthesis in the νp-process!

Thanks to the Collaborators of the JENSA and SECAR collaborations

S. Ayoub, D. Blankstein, S. Carmichael, L. Caves, K. Chae, K. A. Chipps, M. Couder, S. Ahn, D. W. Bardayan, J. C. Blackmon, J. Browne, A. Garrity U. Greife, K. Hermansen, R. Jain, Z. Meisel, F. Montes, P. D. OMalley, W-J. Ong, N. Rijal, S. D. Pain, H. Schatz, K. Schmidt, H. Sims, K. Smith, M. S. Smith, J. Shilun, P. J. Thompson, C. Ummel and many more...

The SECAR project is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-SC0014384 and by the National Science Foundation under grant No. PHY-1624942. Additional support for this work comes from National Science Foundation grants No. PHY-1430152 (Joint Institute for Nuclear Astrophysics and JINA-CEE) and PHY-1565546 (NSCL).