19TH EXOTIC BEAM SUMMER SCHOOL (EBSS2022)

Nuclear Astrophysics Experiment II

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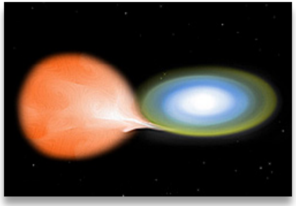
Argonne National Laboratory

June 9-10, 2022

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

EXAMPLES OF REAL EXPERIMENTS WITH RADIOACTIVE BEAMS

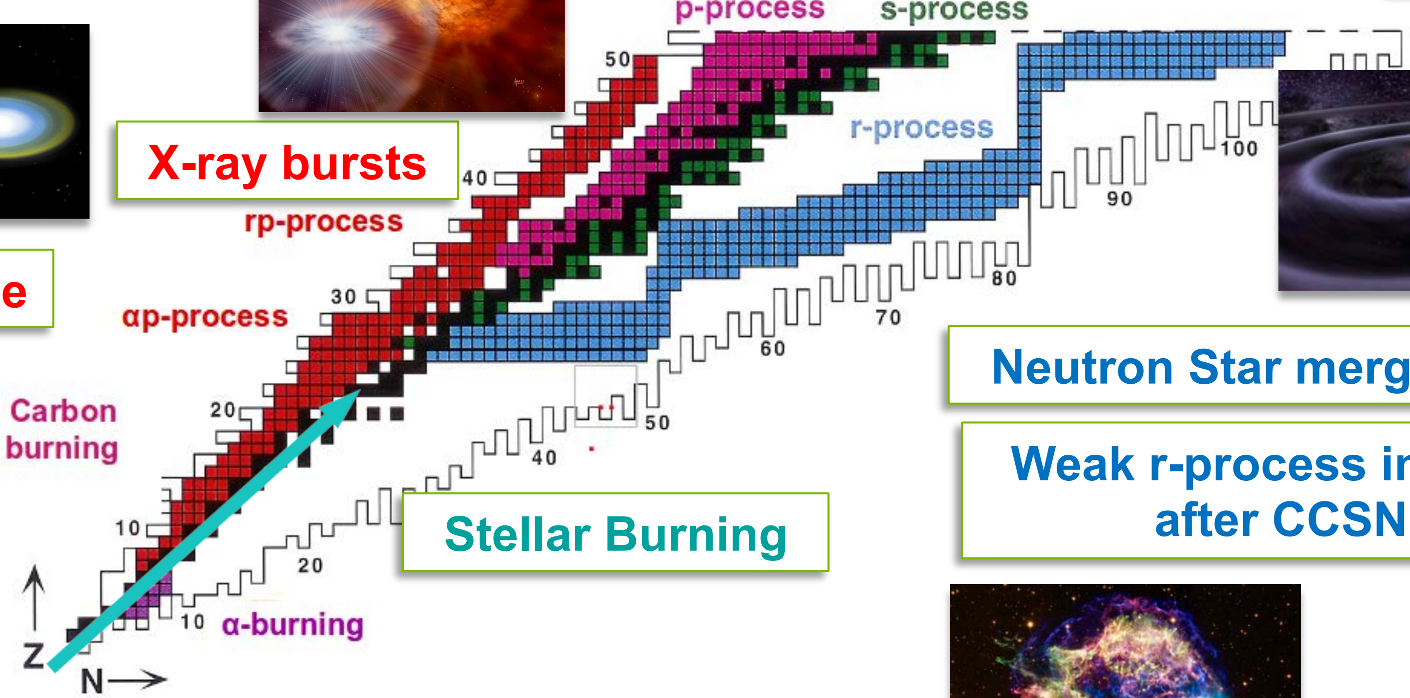
Nucleosynthesis Processes

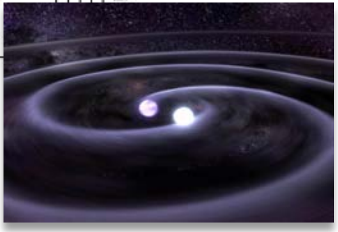


Red Giant Stars

X-ray bursts

Novae

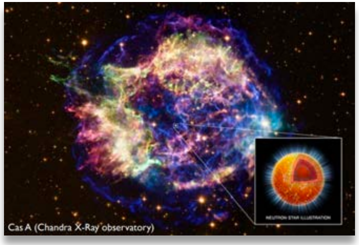




Neutron Star mergers

Weak r-process in NDW after CCSN

Stellar Burning



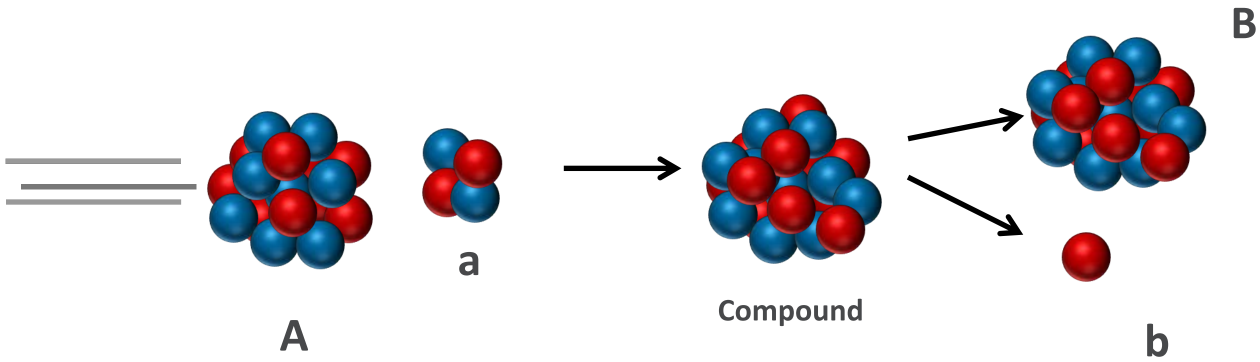
Modified image from:

M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, **51** (2001)

Experiments with radioactive beams

Things to consider

- Low intensities
- Inverse kinematics (beam mass > target mass)



Experiments with radioactive beams

Things to consider for detection of reaction products

- Efficient detectors are needed

- Reaction products go forward in the laboratory system (narrow cone)

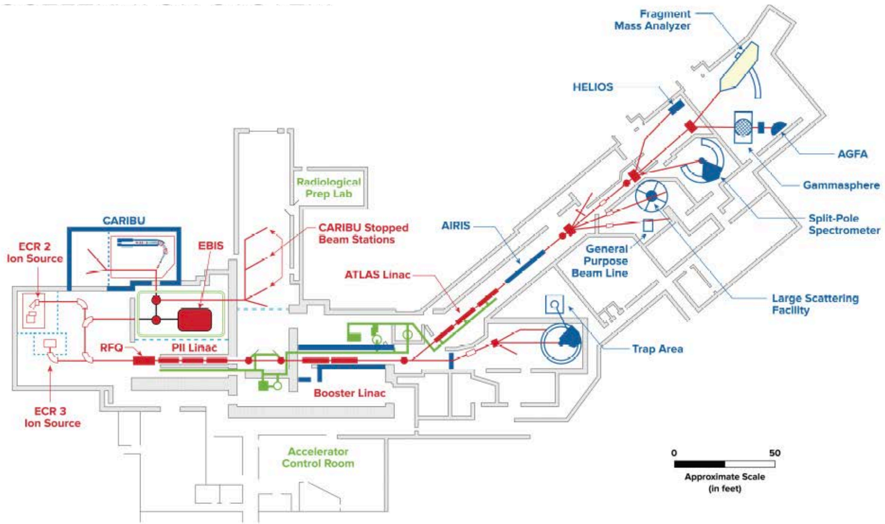
  – Angular distributions of reaction products is more difficult

  – Larger percentages of the reaction products detected in spectrometers

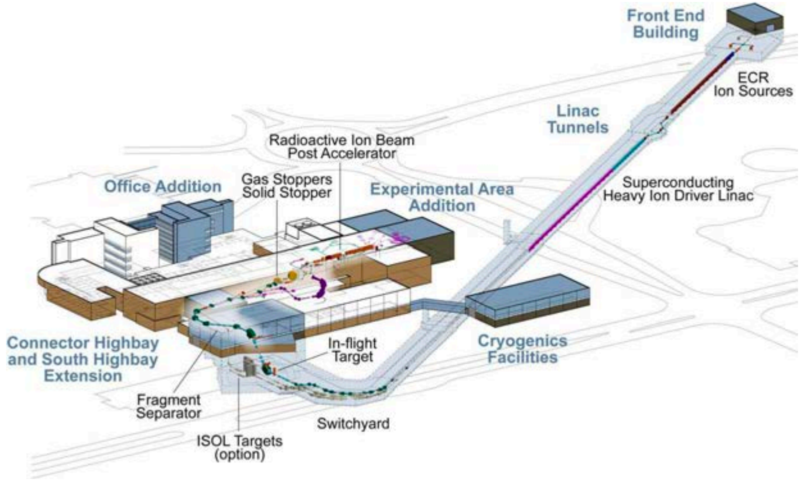
Opportunities at Several Facilities (US examples)

Exotic beams for Nuclear astrophysics

RAISOR at ATLAS

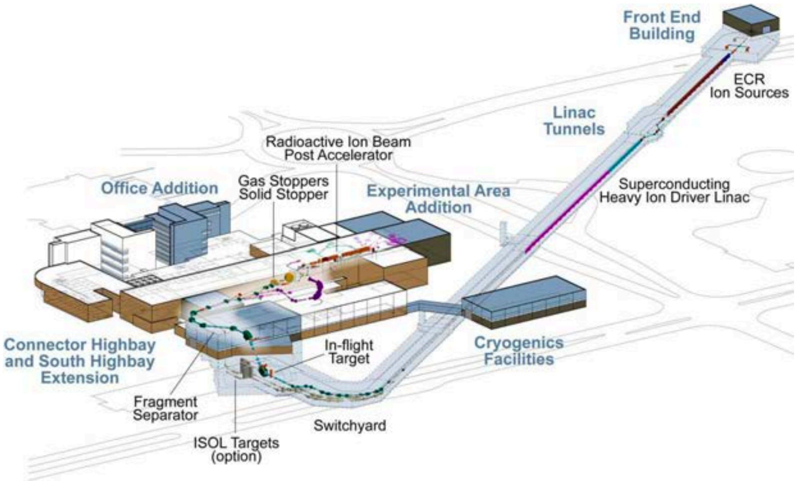


FRIB



Facility For Rare Beam Isotope Beams

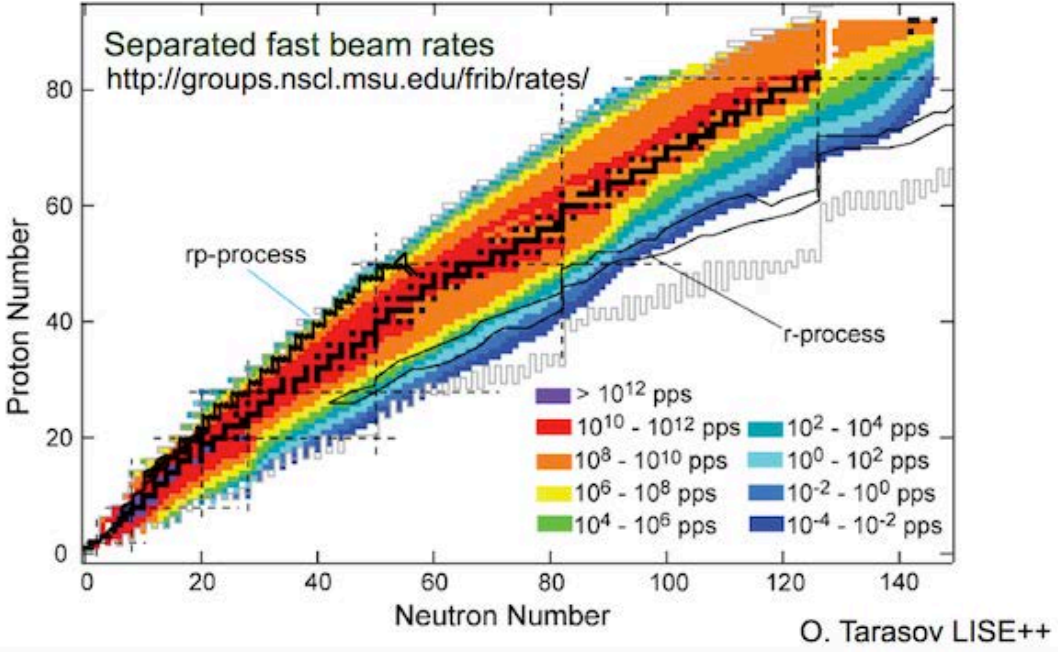
Ribbon cutting ceremony on May 2nd. First experiment on May 9th. Exciting!!



U.S. Secretary of Energy Jennifer M. Granholm (center right) and MSU President Samuel L. Stanley Jr., M.D. (center left) cut the ribbon

Facility For Rare Beam Isotope Beams

FRIB is funded by the DOE-SC, MSU and the State of Michigan.

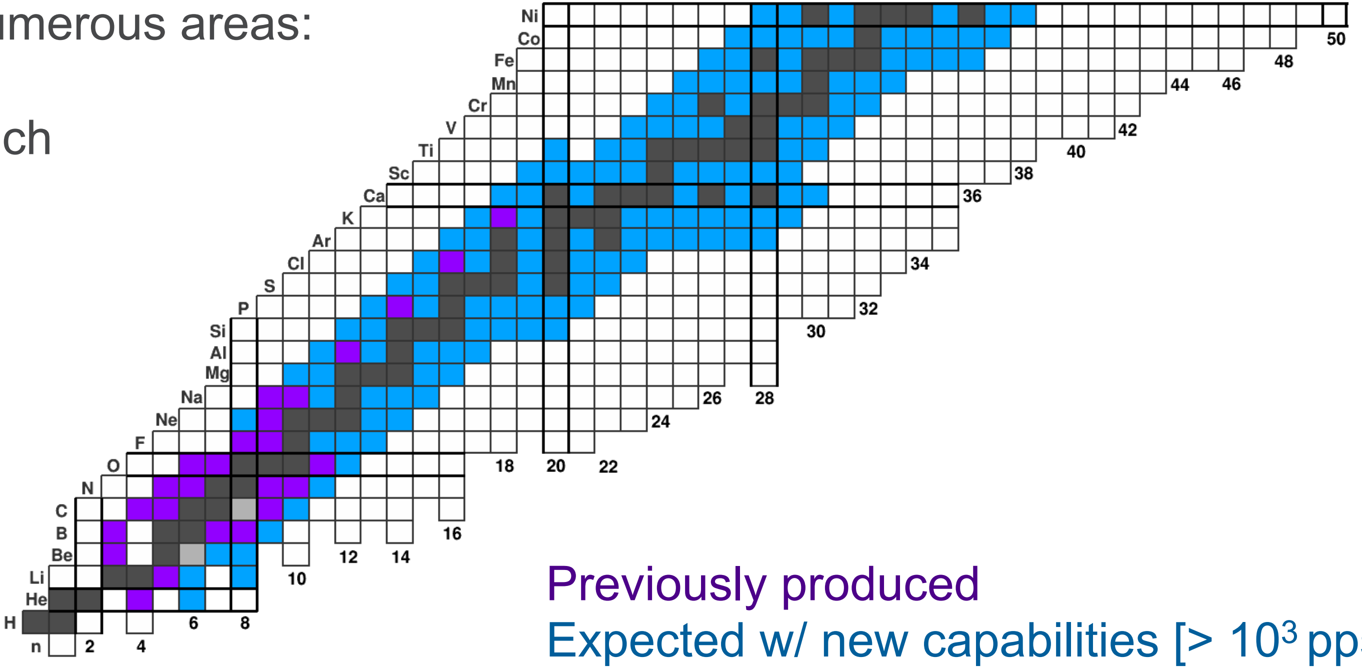


RAdioactive Ion Separator (RAISOR)

Upgrade of the In-Flight capabilities at ATLAS (2018)

Improvement in numerous areas:

- Intensity
- Selectivity & Reach
- Accessibility



Previously produced

Expected w/ new capabilities [> 10^3 pps]

Slide courtesy of C. Hoffman

Nucleosynthesis In Type I X-ray Bursts

- Most common thermonuclear explosions in the Galaxy.
- Explosive hydrogen-helium burning arising from thermonuclear ignition in the envelope of a neutron star in close binary systems.

Neutron Star:

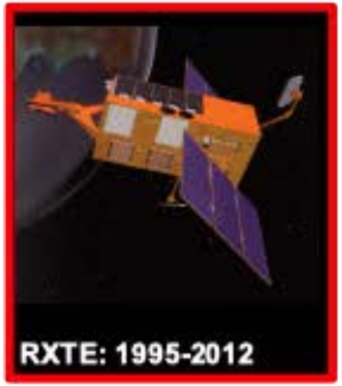
- Mass ≈ 1.4 $M_\odot$
- Radius ≈ 10-15 km
- Density ≈ 10^{14} g/cm^3
- Gravity ≈ 10^{14} cm/s^2

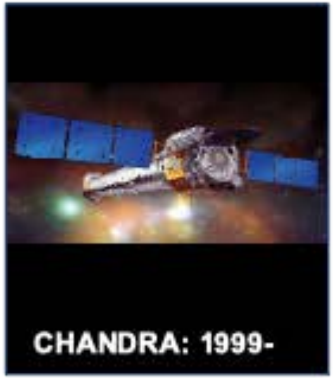
Companion Star:

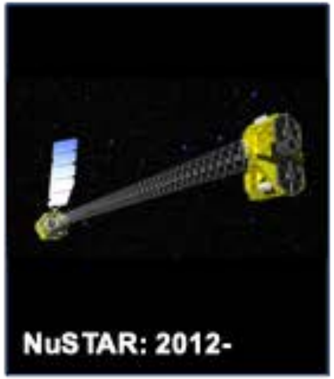
- Main sequence star (≤1.5 $M_\odot$)
- Typically composition similar to the sun.
- Predominantly H and He

Type I X-ray Bursts Observations

Observations by X-ray telescopes







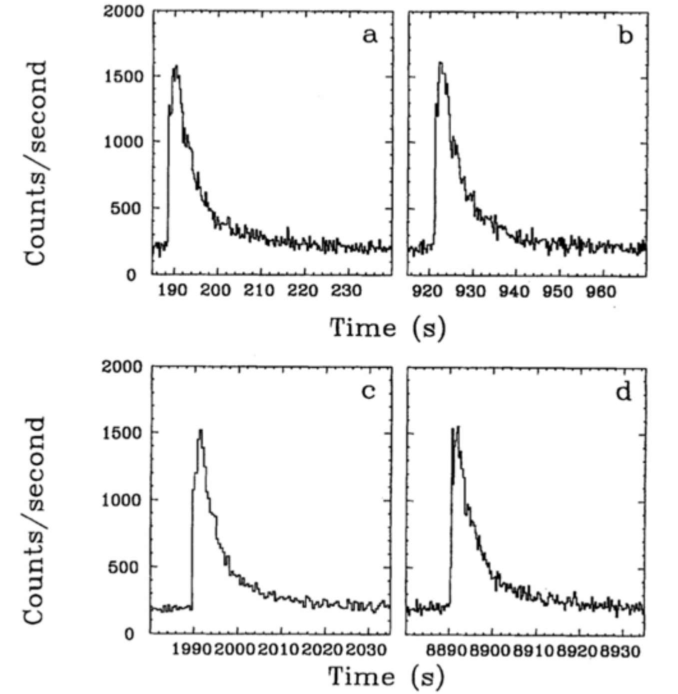
Type I X-ray Bursts Observables

Light curves properties

- Peak luminosity ~10^{38} erg s-1
- Burst duration 10-100 s
- Fast rise time ~ 0.5-10 s
- Decay time ~ 10-100 s
- No cataclysmic event recurrence rate: hours to days

Accumulation of accreted matter for hours - Unstable nuclear burning for seconds

Four of seven burst observed with EXOSAT in Aug 19 1985 during 20 hr observation



W.H.G Lawin et al. 1993

Nucleosynthesis In Type I X-ray Bursts

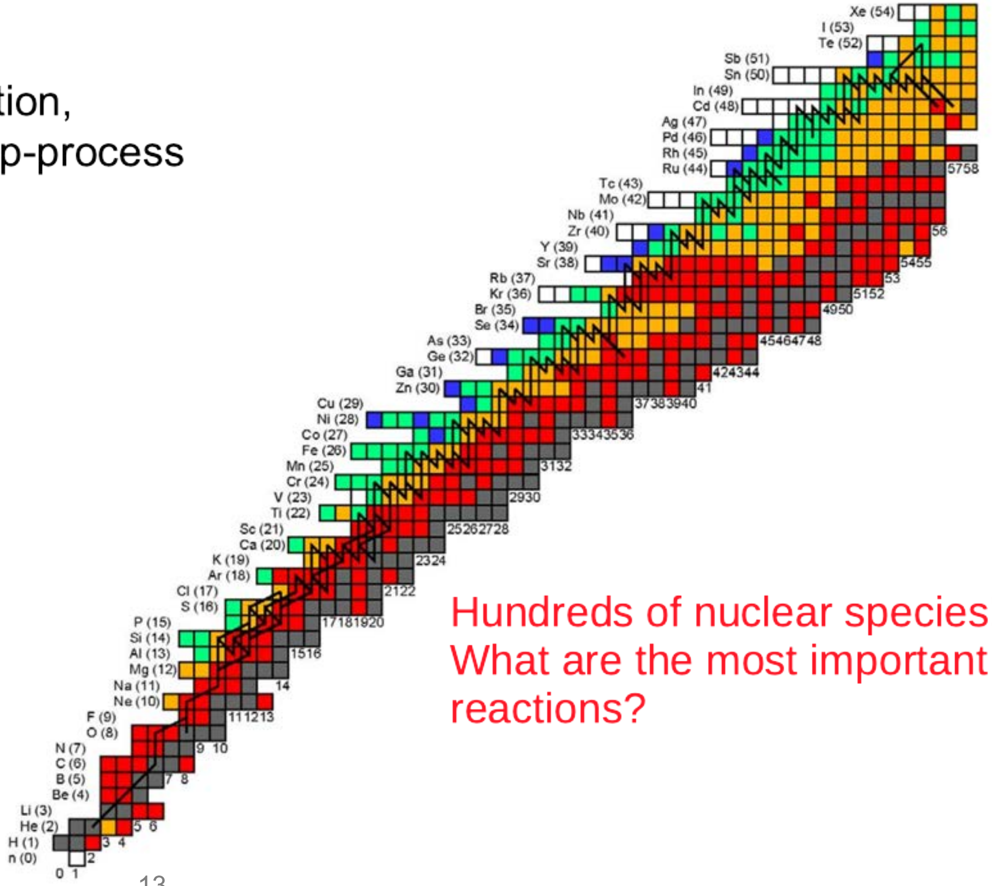
The burst is powered by the 3α reaction,
followed by the αp-process and the rp-process

- αp process

  (α,p) and (p,γ) reactions

- rp (rapid proton capture) process

  (p,γ) reactions and β decays

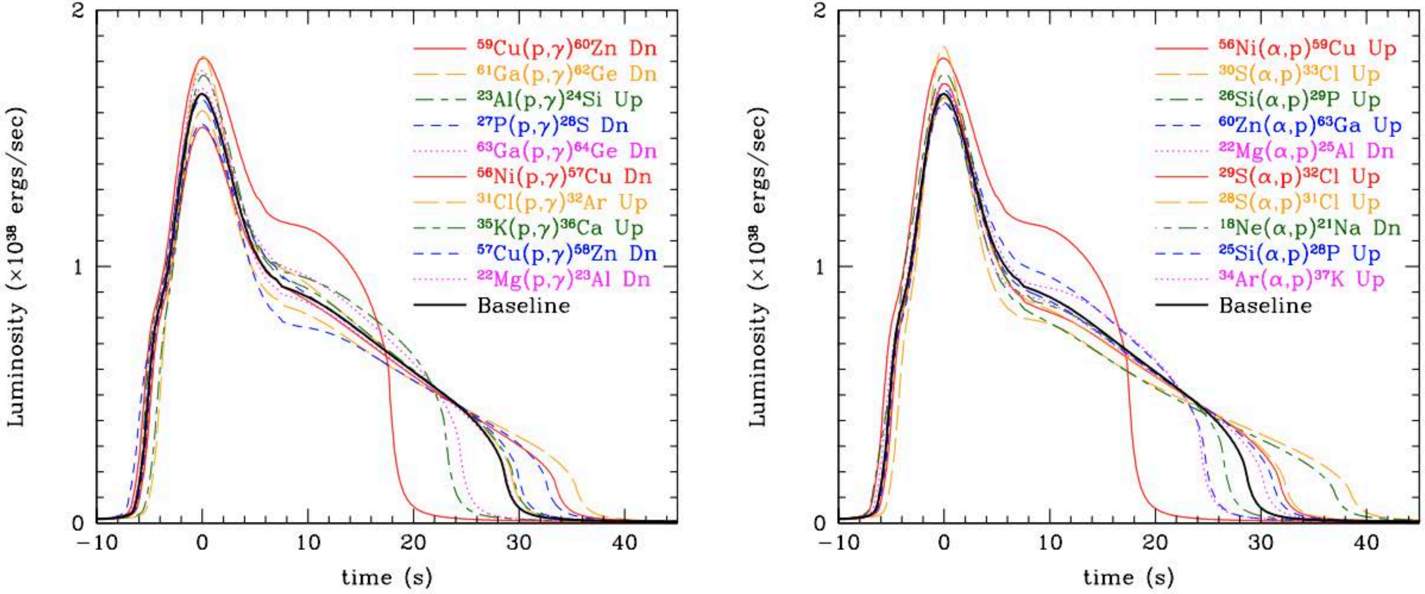


Hundreds of nuclear species!
What are the most important reactions?

α-Induced Reactions In X-ray Bursts

Sensitivity Studies

- Dependence on uncertainties in (p,γ), (α,γ), and (α,p) nuclear reaction rates using fully self-consistent burst models



R.H. Cyburt et al., ApJ 830, 55 (2016)

Experimental Equipment

Some examples

(p,γ) reactions:

SECAR – Separator for Capture Reactions

(α,p) reactions:

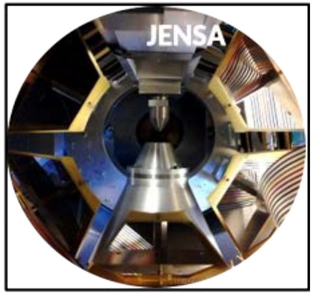
JENSA – The Jet Experiment in Nuclear Structure and Astrophysics

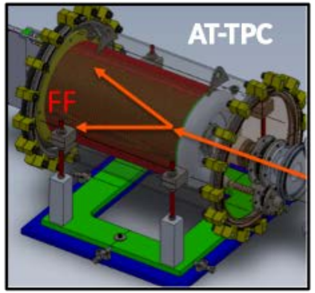
Active targets

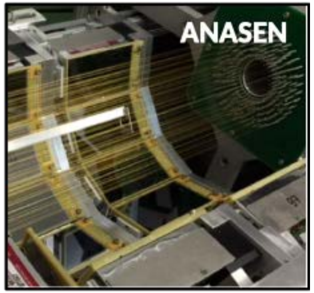
AT-TPC – The active Target Time Projection Chamber

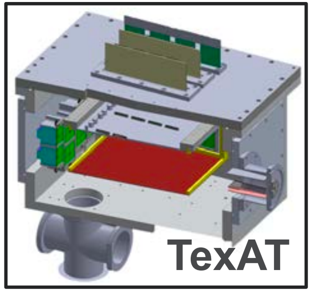
ANASEN- Array for Nuclear Astrophysics and Structure with Exotic Nuclei

MUSIC – The Multi Sampling Ionization Chamber





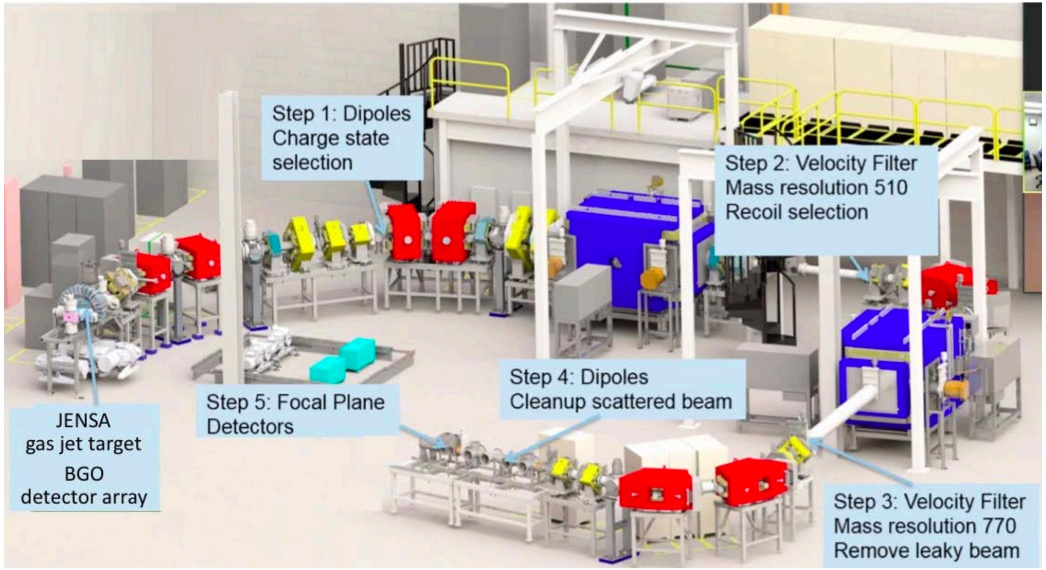




SECAR

The SEparator for CApture Reactions

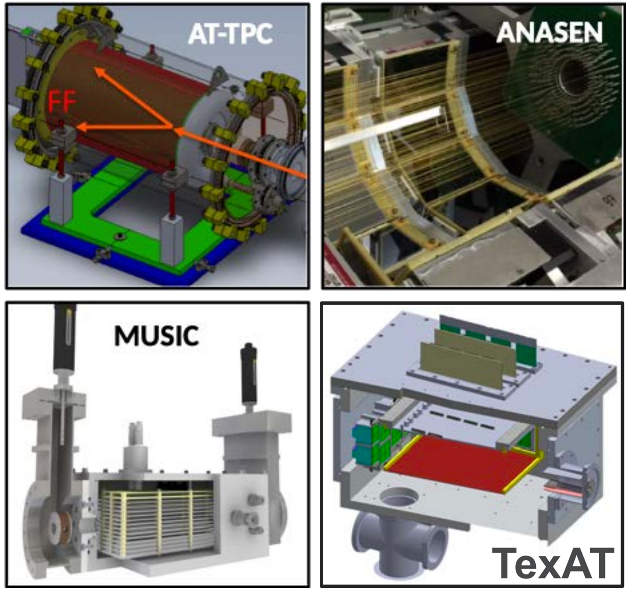
- SECAR will be used to advance our understanding of stellar explosions including novae, X-ray bursts, and supernovae, as well as other exotic astrophysical sites
- Designed with the required sensitivity to study (p,γ) and (α,γ) reactions



Active targets
Advantages

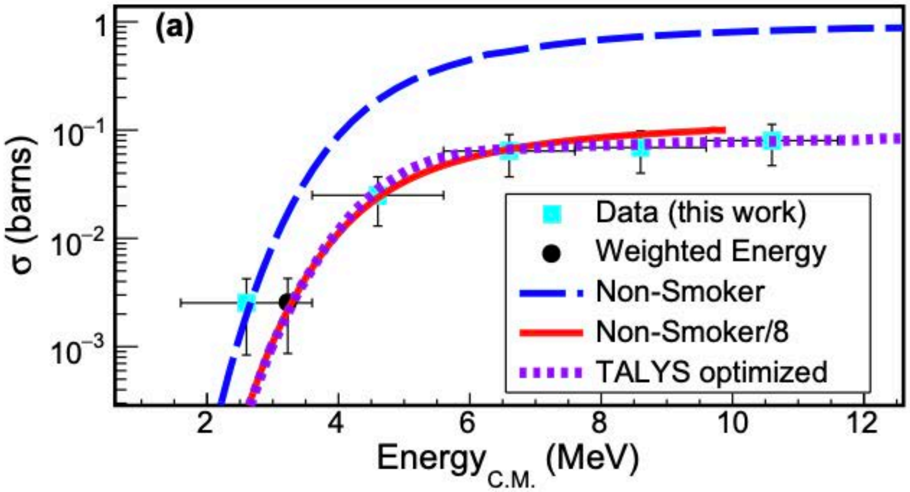
Active targets are versatile detectors that take full advantage of radioactive beams

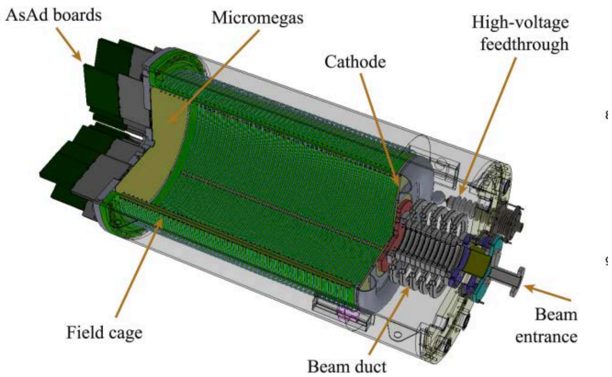
- Measure a large range of excitation functions using single beam energies
- High efficiency
- Possible measurements:
  - $^{18}Ne(\alpha,p)^{21}Na$ → ANASEN
  - $^{22}Mg(\alpha,p)^{25}Al$ → AT-TPC & MUSIC
  - $^{26}Si(\alpha,p)^{29}P$
  - $^{30}S(\alpha,p)^{33}Cl$
  - $^{34}Ar(\alpha,p)^{37}K$



AT-TPC: Direct measurement of the ^{22}Mg(α,p) reaction

First direct measurement



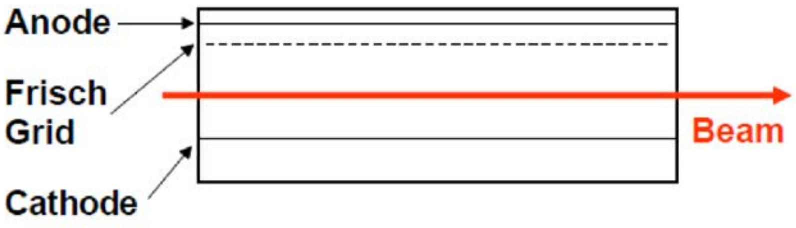


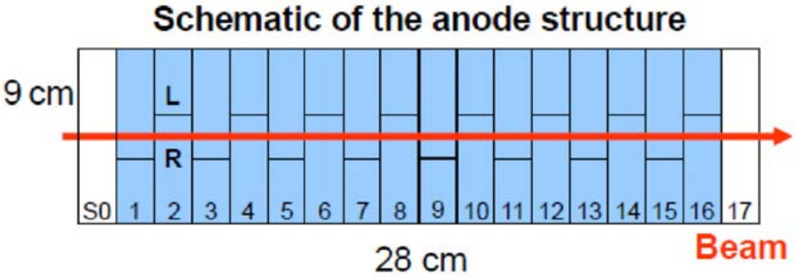
J. S. Randhawa et al., Phys. Rev. Lett. 125, 202701 (2020)

This reaction has also been recently measured with the MUSIC detector

Measurements with MUSIC

MUlti-Sampling Ionization Chamber





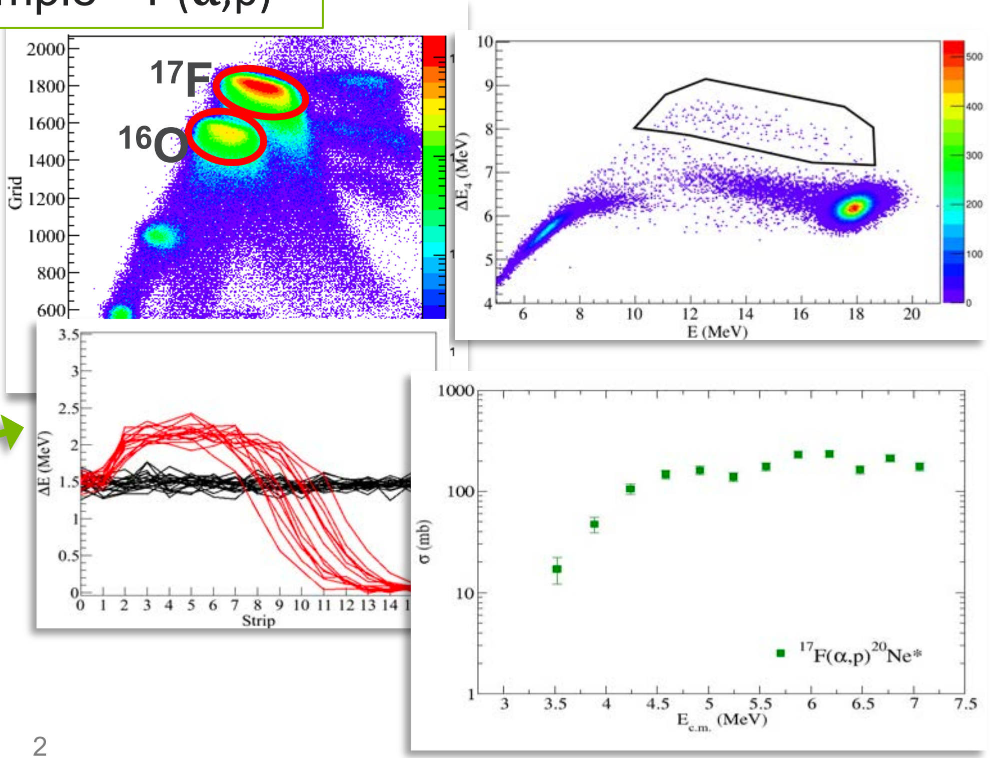
- Close to 100% efficiency
- Measure a large range of excitation functions of angle and energy integrated cross sections using single beam energy
- Self normalizing: No additional monitors for absolute normalization
- 34 channels

Rate capability: About 1x10^5 pps (^{4}He)
Counting gases: He, He-Kr, CH_4, Ne, Ar
Typical Pressures: 100-760 Torr

X-ray bursts research with MUSIC

α-induced reactions play an important role for reproducing light curves from type I X-ray bursts.

Example $^{17}F(\alpha,p)$



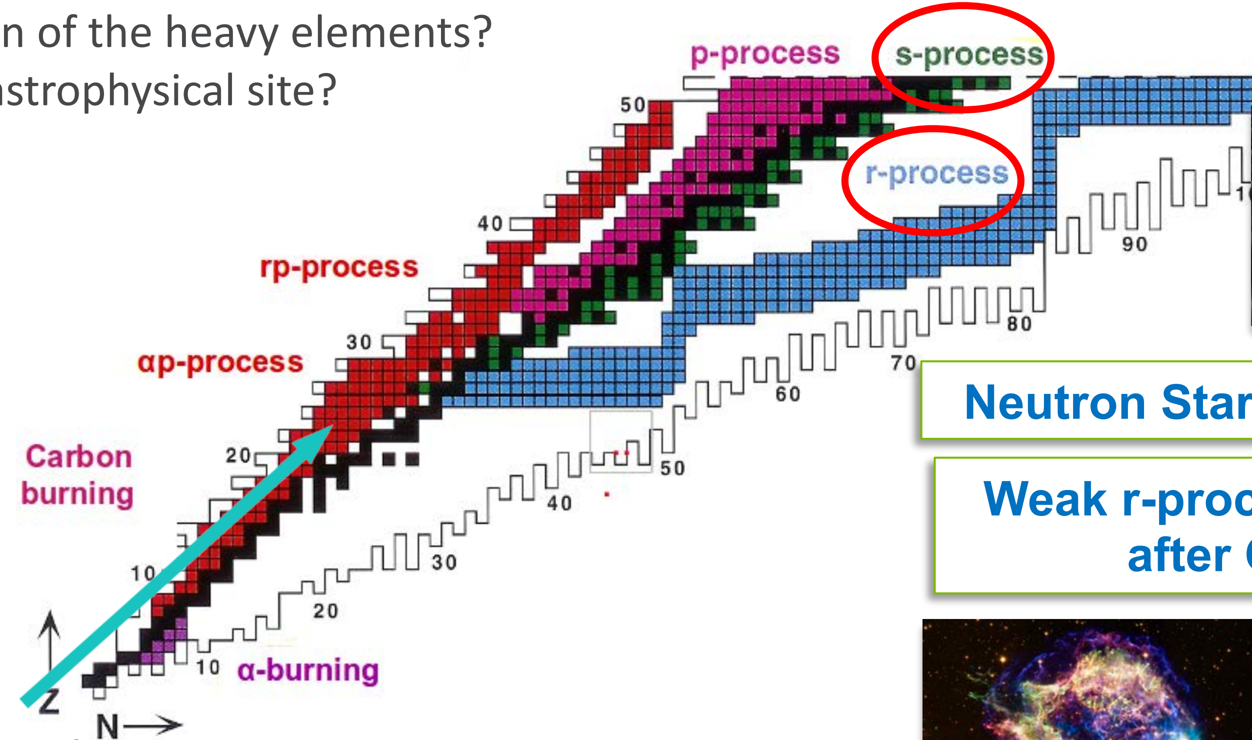
(α,p) reactions for X-ray bursts

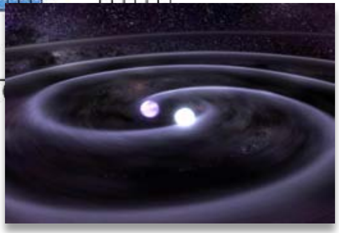
Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha,p)^{17}F$	D	5.8	1
7	$^{25}Al(p,\gamma)^{26}Si$	D	4.6	1
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p,\alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha,\gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha,p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha,p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha,\gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p,\gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha,p)^{63}Ga$	U	1.1	2
17	$^{17}F(p,\gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p,\gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p,\gamma)^{49}Mn$	D	1.2	2

R.H. Cyburt et al., ApJ 830, 55 (2016)

Production of the heavy elements

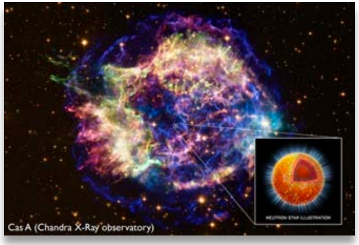
- What processes are responsible for the creation of the heavy elements?
- What astrophysical site?





Neutron Star mergers

Weak r-process in NDW after CCSN



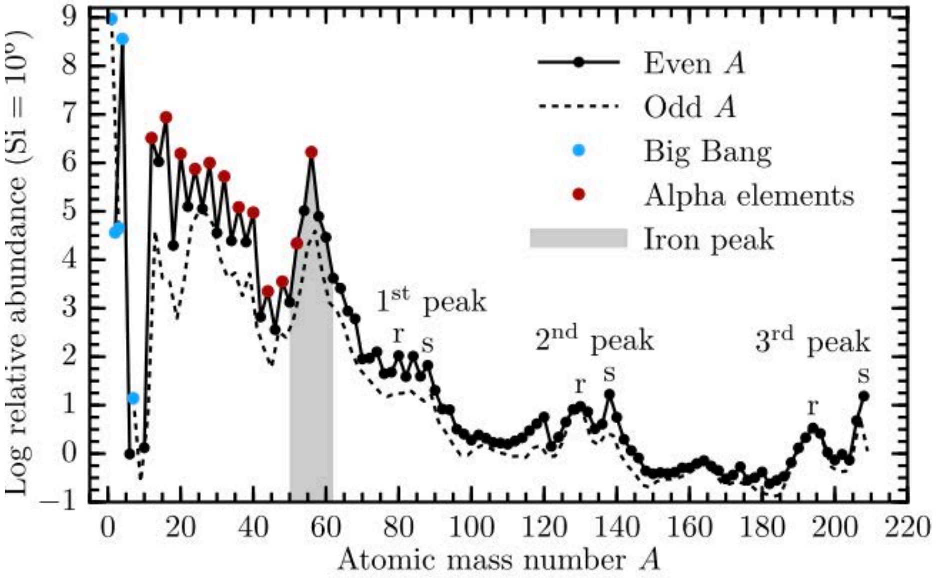
Modified image from:

M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, **51** (2001)

Production of the heavy elements

What are the processes responsible for their production?

Nucleosynthesis beyond iron occurs primarily in stellar environments with free-neutron densities



s-process (slow neutron capture)

- density ~10^9 neutrons/cm3
- capture neutrons slower than β-decay
- path close to stability
- Well understood

r-process (rapid neutron capture)

- density ~10^{23} neutrons/cm3
- capture neutrons more rapidly than β-decay
- path to the more neutron-rich
- Many open questions

r-process

What is the site that produces them in the r-process?

- On 17 August 2017, gravitational waves (GW170817) and electromagnetic radiation from radio to γ-rays associated with the merger of two neutron stars were detected.

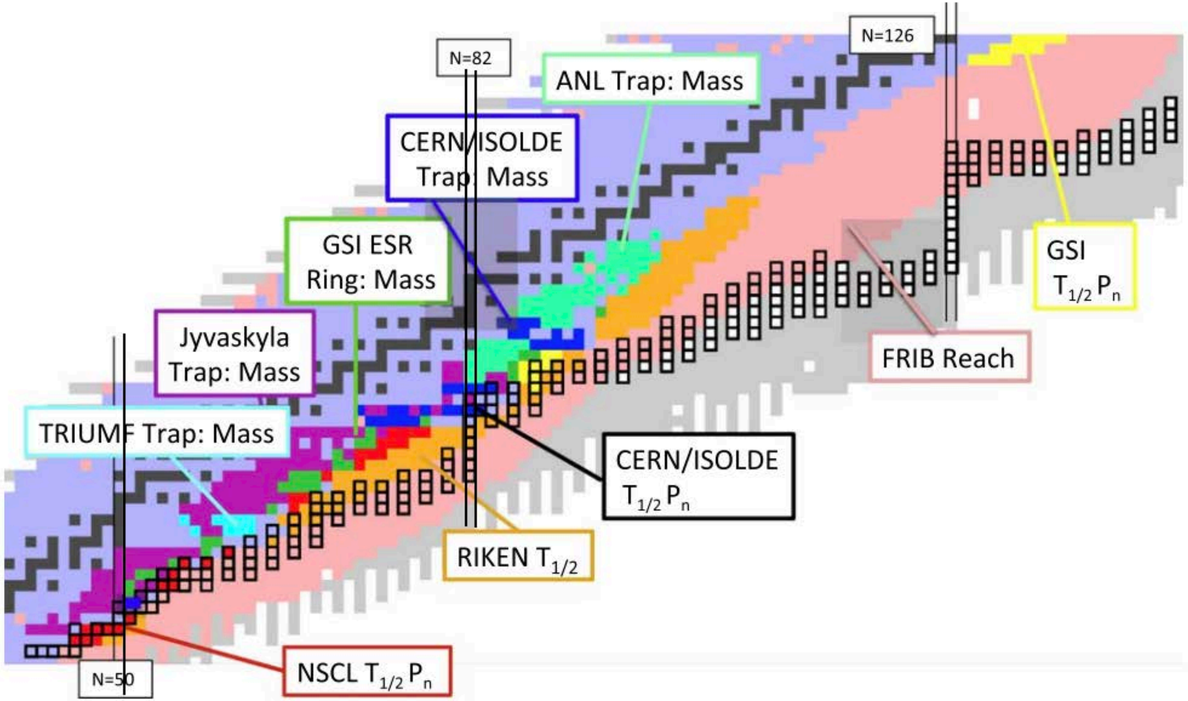
- Evidence suggest that these mergers are a the dominating site of r-process nucleosynthesis

- Nuclear physics needed to infer the physical conditions in neutron star mergers that lead to the observed r-process features

r-process

What is needed?

- β-decay rates
- Masses
- Neutron capture rates
- β-delayed neutron emission branchings

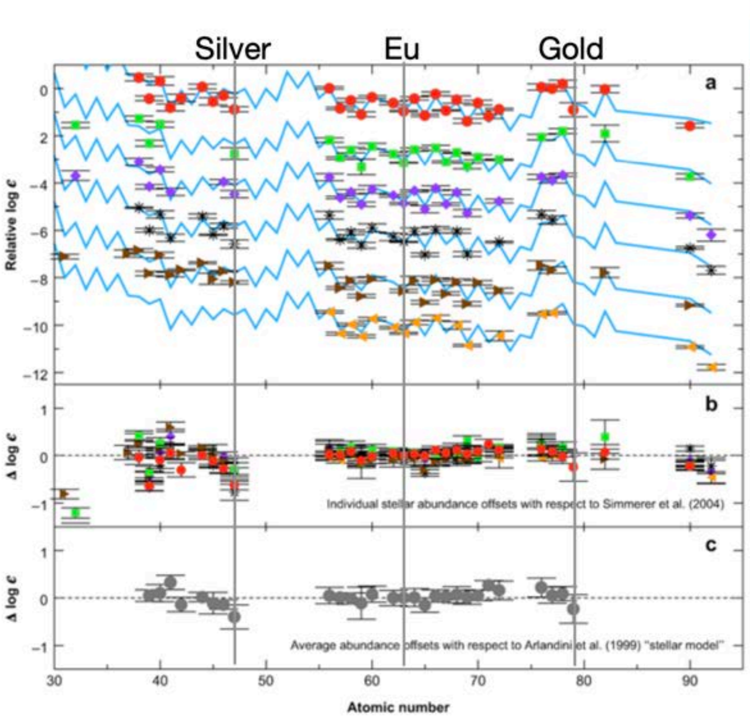


C J Horowitz et al., J. Phys. G: Nucl. Part. Phys. 46 (2019) 083001

Recent r-process motivated experiments measuring masses or β-decay halflives $T_{1/2}$ at various radioactive beam facilities

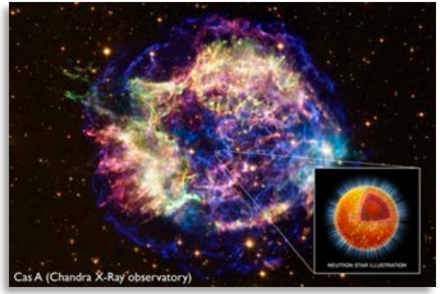
r-process

Is Neutron Star Merger the only site?



- Ultra metal poor stars show robust abundance pattern for second and third r-process peak
- First peak show star-to-star scatter
- lighter elements in the r-process (weak r-process) are probably produced in a different site

Weak r-process



- It has been proposed that core-collapse supernovae and their neutrino-driven winds are possible production sites for the lighter elements in the r-process (30<Z<45).

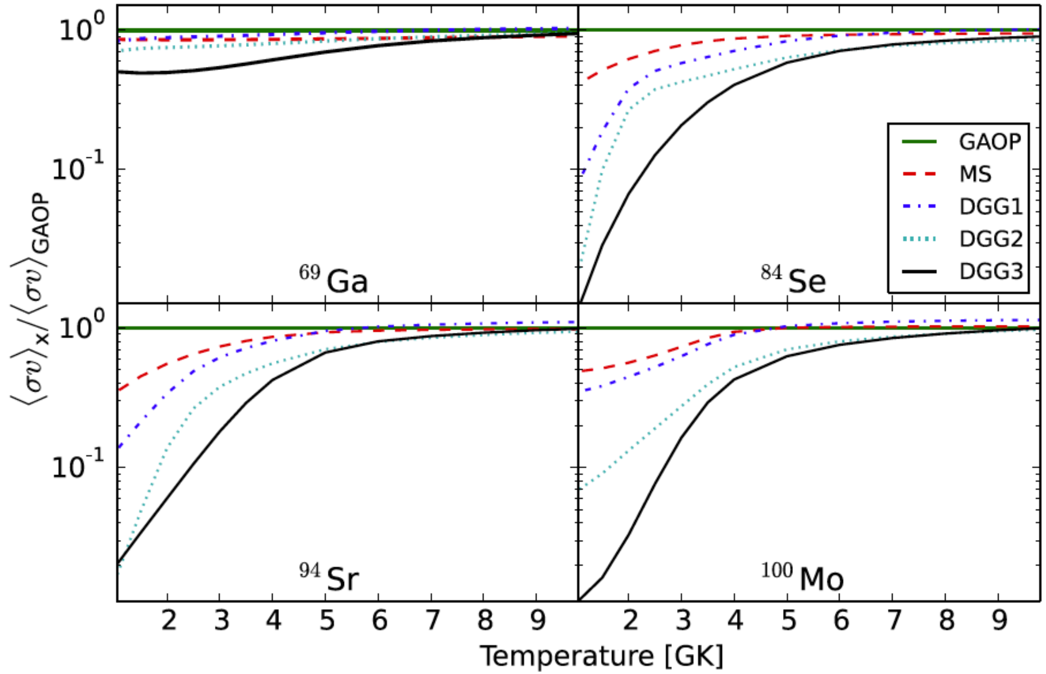
- (α, n) rate uncertainties are crucial to predict abundances.

- *“These reactions are critical to redistribute the matter and allow it to move from light to heavy elements after nuclear statistical equilibrium freezes out.”*

J. Bliss et al., Journal of Physics G: Nuclear and Particle Physics **44**, 054003 (2017)

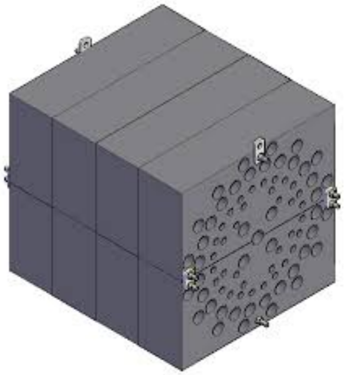
(α,n) reactions in the weak r-process

Uncertainties in Hauser-Feshbach calculations

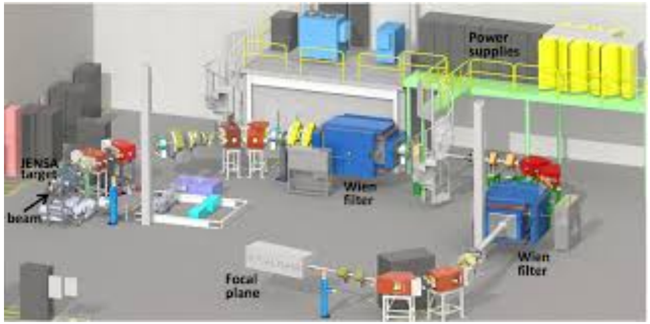


J. Bliss et al., Journal of Physics G: Nuclear and Particle Physics **44**, 054003 (2017)

Most recent experimental efforts (some examples)

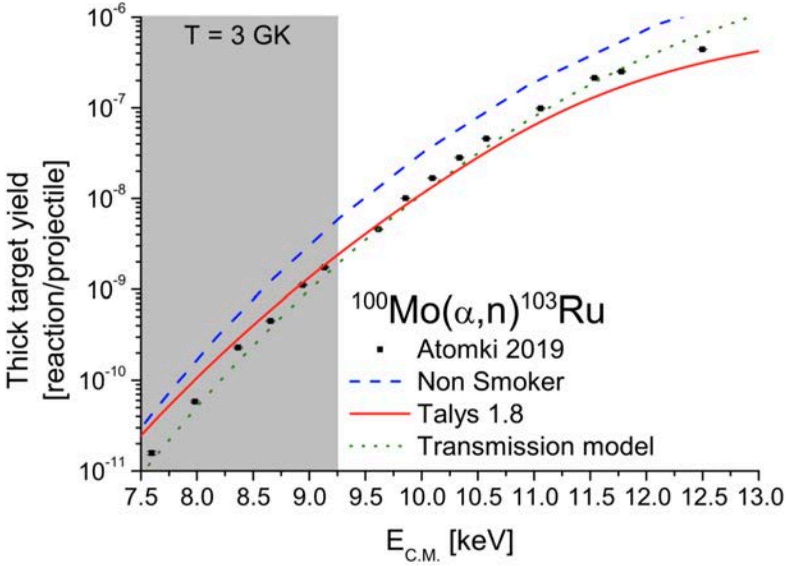


- Measurements at NSCL using the HabaNERO detector (S. Ahn et al.)
- Future measurements at Ohio University HeBGB (K. Brandenburg et al.)
- Measurements at NSCL using the SECAR+LENDA (Z. Meisel & F. Montes et al.)
- Activation method at ATOMKI



Experimental efforts (some examples)

- Activation method at ATOMKI (Hungary)



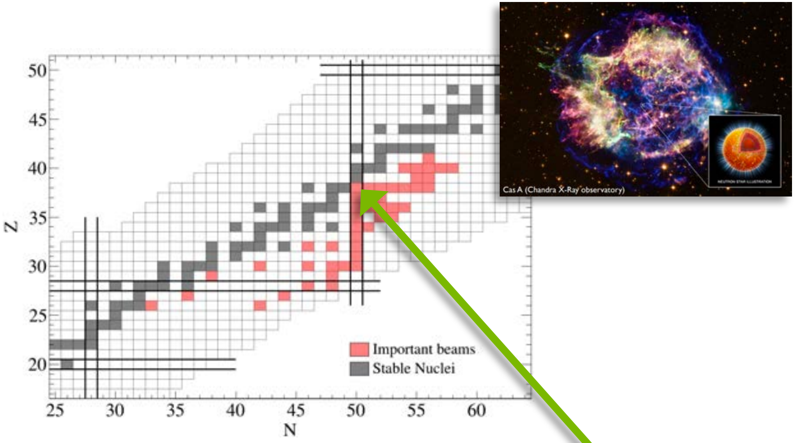
- Thick Mo targets were irradiated with α-beam

- The determination of the number of ^{103}Ru products was based on measuring the yield of emitted γ-rays

T.N. Szegedi *et al* 2020 *J. Phys.: Conf. Ser.* **1668** 012041

Weak r-process studies with MUSIC

(α,n) reactions in neutrino-driven winds after CCSN

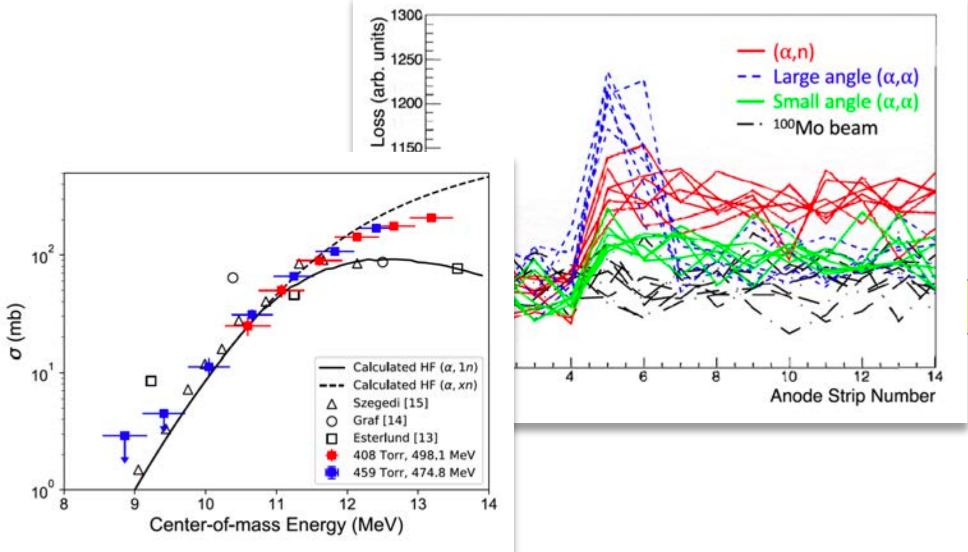


- (α, n) reaction affecting the nucleosynthesis of lighter heavy nuclei in r-process (weak r-process) were identified.

J. Bliss et al., Phys Rev C 101, 055807 (2020)

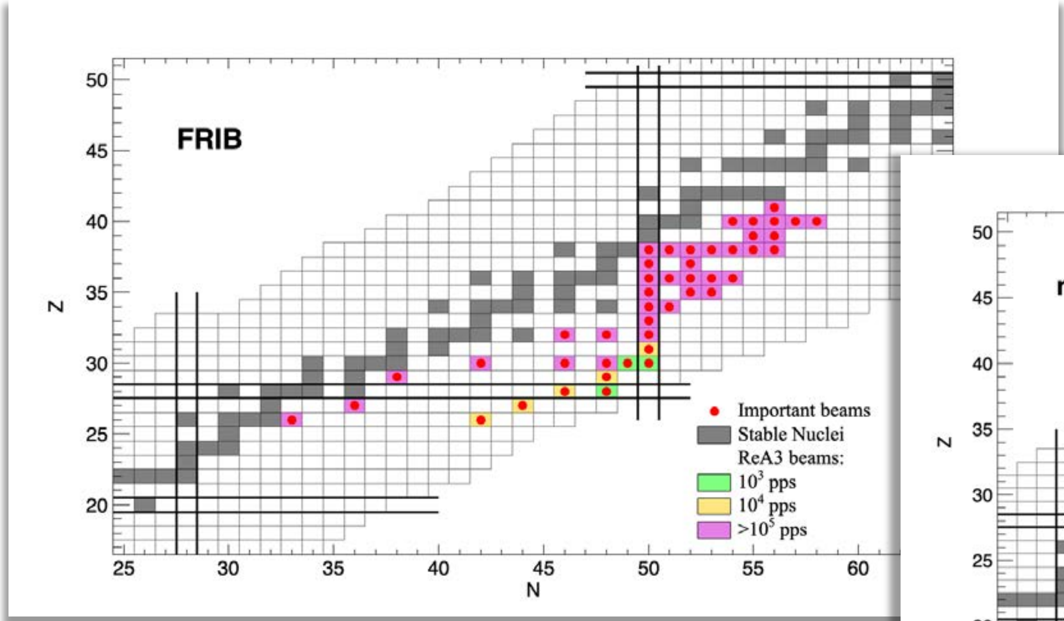
- Measurement of the ^{100}Mo(α,n) reaction

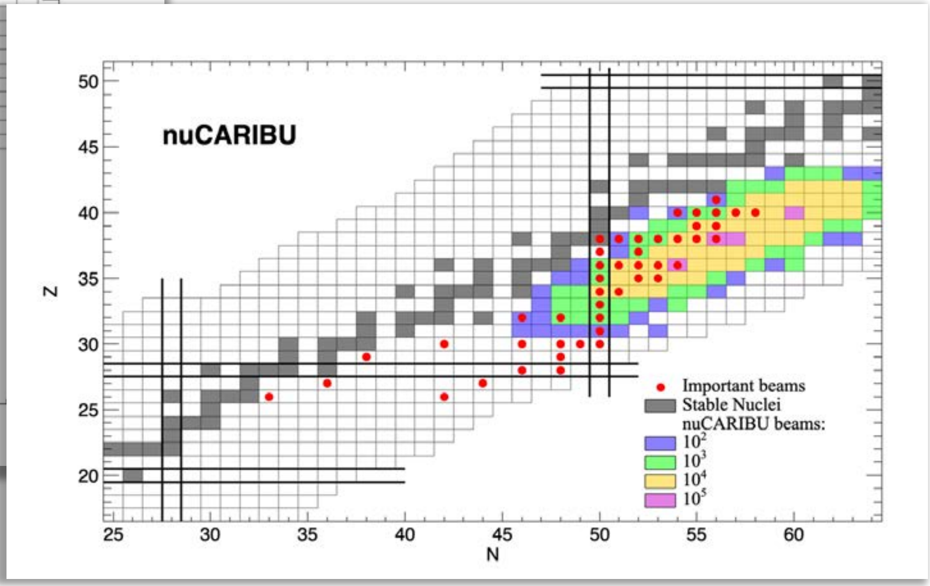
W.J. Ong et al., PRC 105, 055803 (2022)



- Recent measurement of the ^{88}Sr(α,n) reaction!

Future facilities

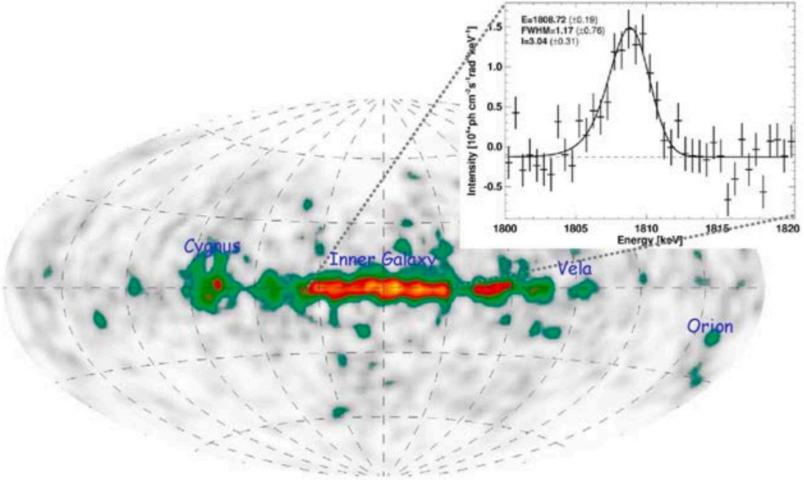




All of the beams relevant for the weak r-process will be available in the near future!

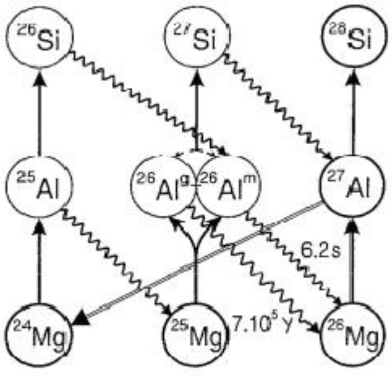
^{26}Al production

^{26}Al$^{g.s}$ (5^{+}, $T_{1/2}$=7.4x10^{5} y) is observed I the Galaxy via the 1.8-MeV γ-ray line, provides evidence of ongoing nucleosynthesis in stars

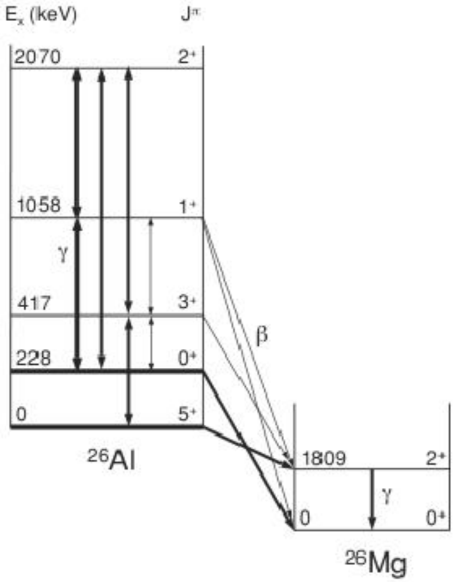


Credits: MPE Garching/Roland Diehl

^{26}Al production



C. Iliadis et al AJSS2002



- Need to understand all of the reaction that produce and destroy ^{26}Al
- Things get more complicated due to isomer
- ^{26}Al in the Galaxy is mainly destroyed via ^{26}Al(p,g)^{27}Si reactions.

The $^{26}Al^{m}(p,\gamma)^{27}Si$ reaction

How can we constrain this reaction?

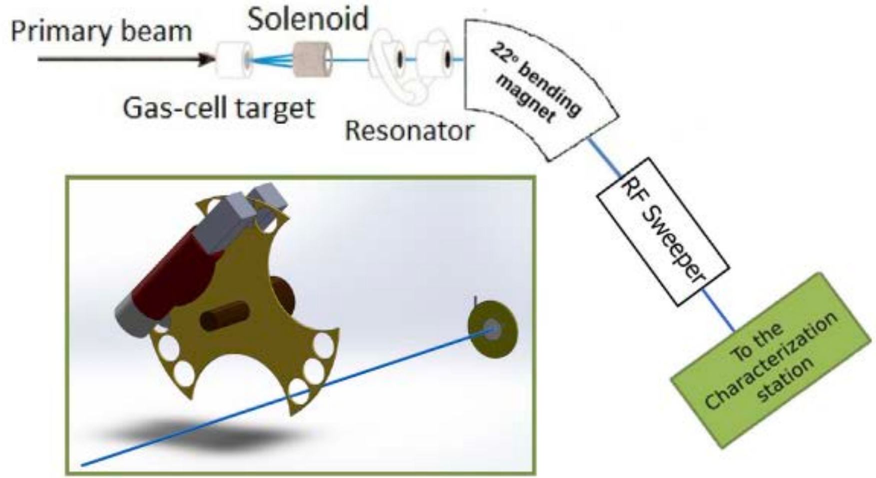
What about the $^{26}Al^{m}(d,p)^{27}Al$ reaction? (Neutron transfer reaction)

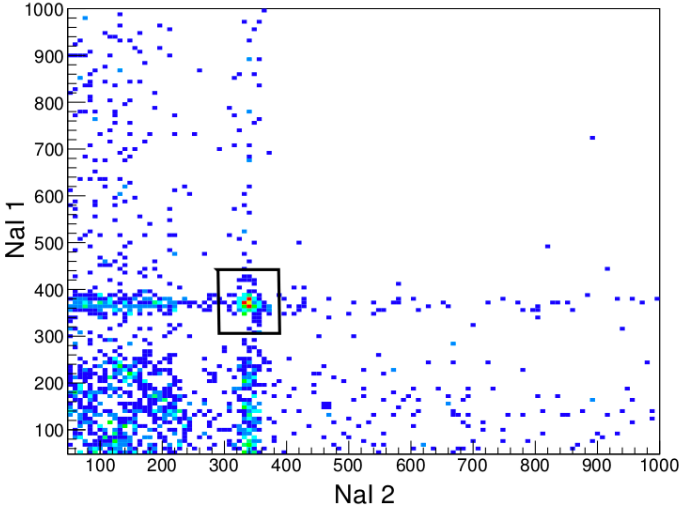
Things to consider:

- Spectroscopic information of states in ^{27}Al populated can be extracted.
- Symmetry considerations between members of the A = 27 mirror system (^{27}Al, ^{27}Si) can be used to constrain the $^{26}Al^{m}(p,\gamma)^{27}Si$ reaction rate in relevant astrophysical scenarios.
- Can we produce an isomeric beam?

^{26}Al beam production at ATLAS

B. W. Asher et al., Nucl. Instrum. Meth. Phys. Res. Sect. A 899, 6 (2018)

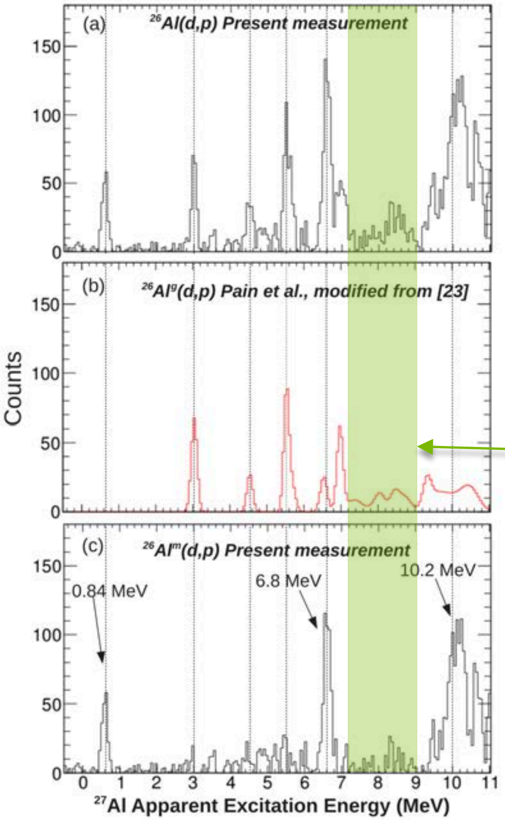




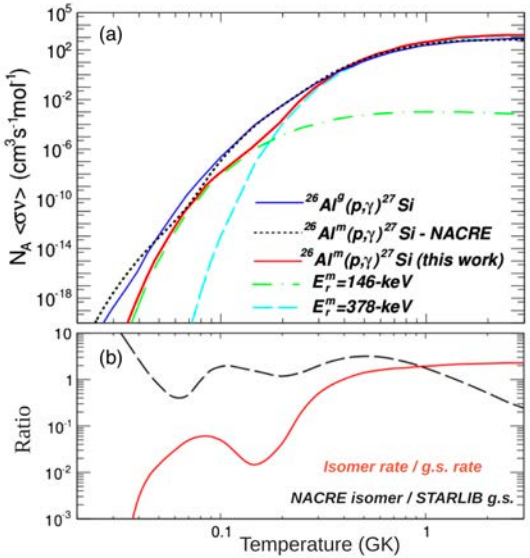
- Developed and characterized a ^{26}Al^{m} beam at ATLAS via in-flight technique using the ^{26}Mg(p,n) reaction.
- Choosing the production energy we can manipulate the isomer content
- A 120 MeV ^{26}Al beam (70% isomer,) with I~ $2.5\text{x}10^{5}$ pps

^{26}Al results

- Some resonances in 27Al only populated by the isomer.
- Experimental rate of this reaction measured for the first time!



Energy region of interest



S. Almaraz-Calderon et al., Phys. Rev. Lett. 119, 072701(2017)

SUMMARY

- Nuclear physics is key to understand stellar processes
- Several experimental techniques can be used to constrain reaction rates relevant for different astrophysical scenarios
- Both direct and indirect techniques can be used to constrain reaction rates
- Exciting opportunities in the near future at FRIB!

QUESTIONS?