Overview on Reactions on Unstable Nuclei for Astrophysics at FRIB

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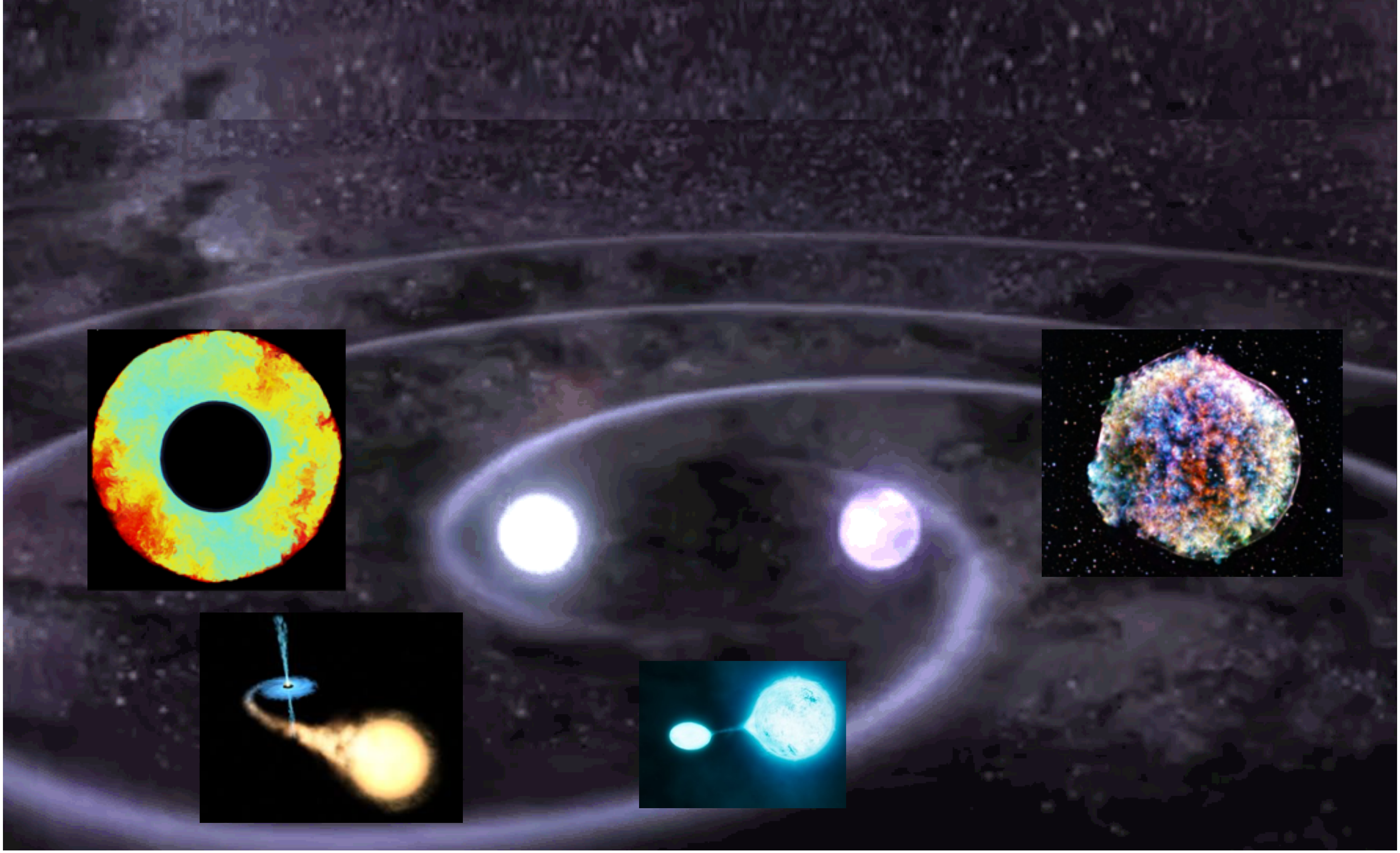
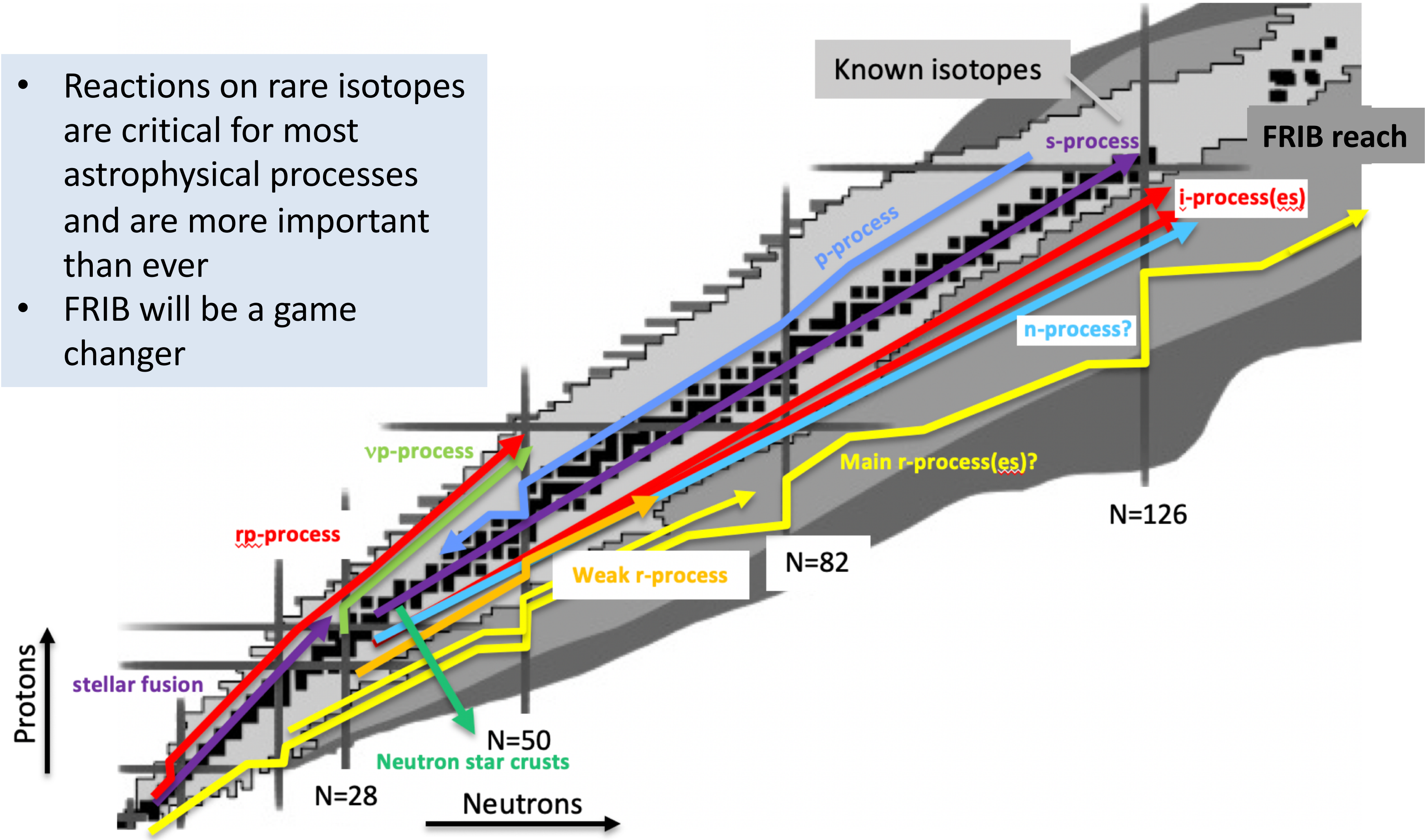
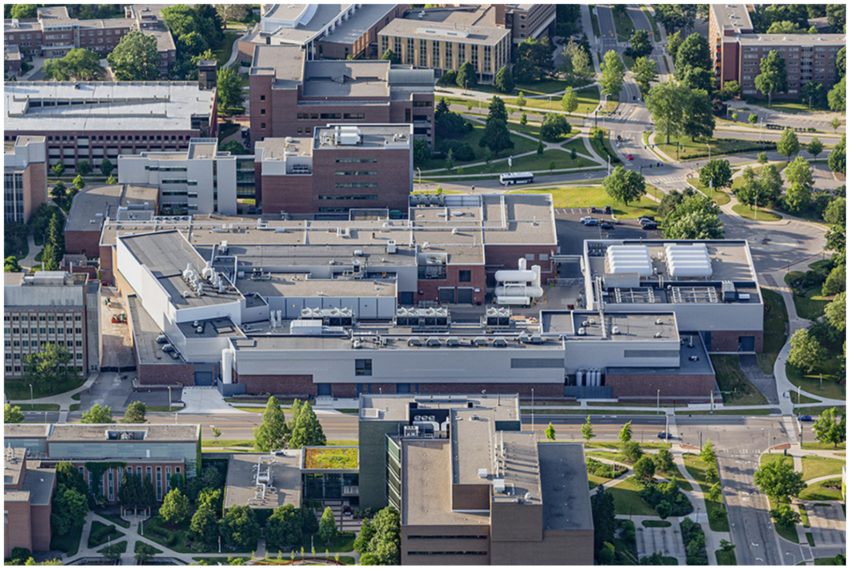


A New Picture of Nucleosynthesis: Many More Nuclear Pathways in the Cosmos

- Reactions on rare isotopes are critical for most astrophysical processes and are more important than ever
- FRIB will be a game changer

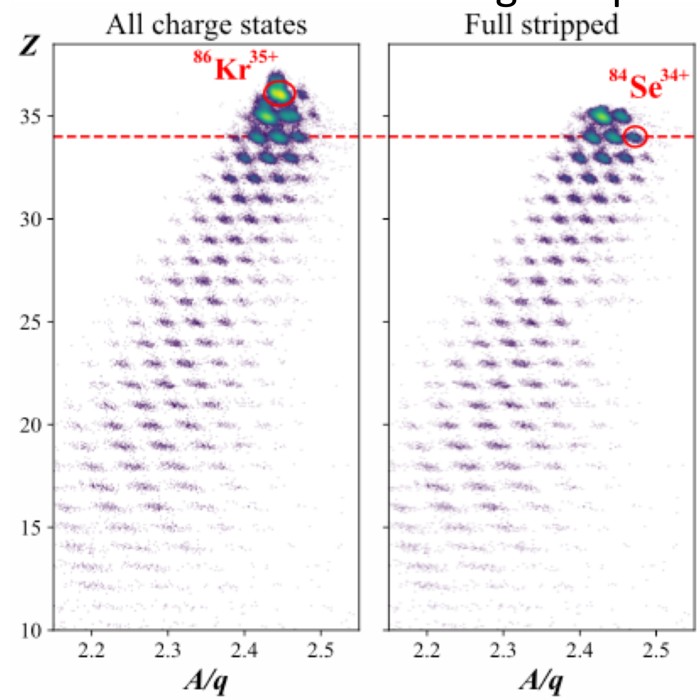


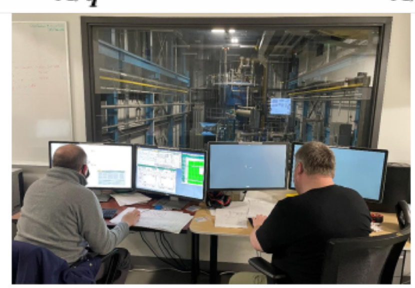
FRIB Provides New Opportunities for Nuclear Astrophysics



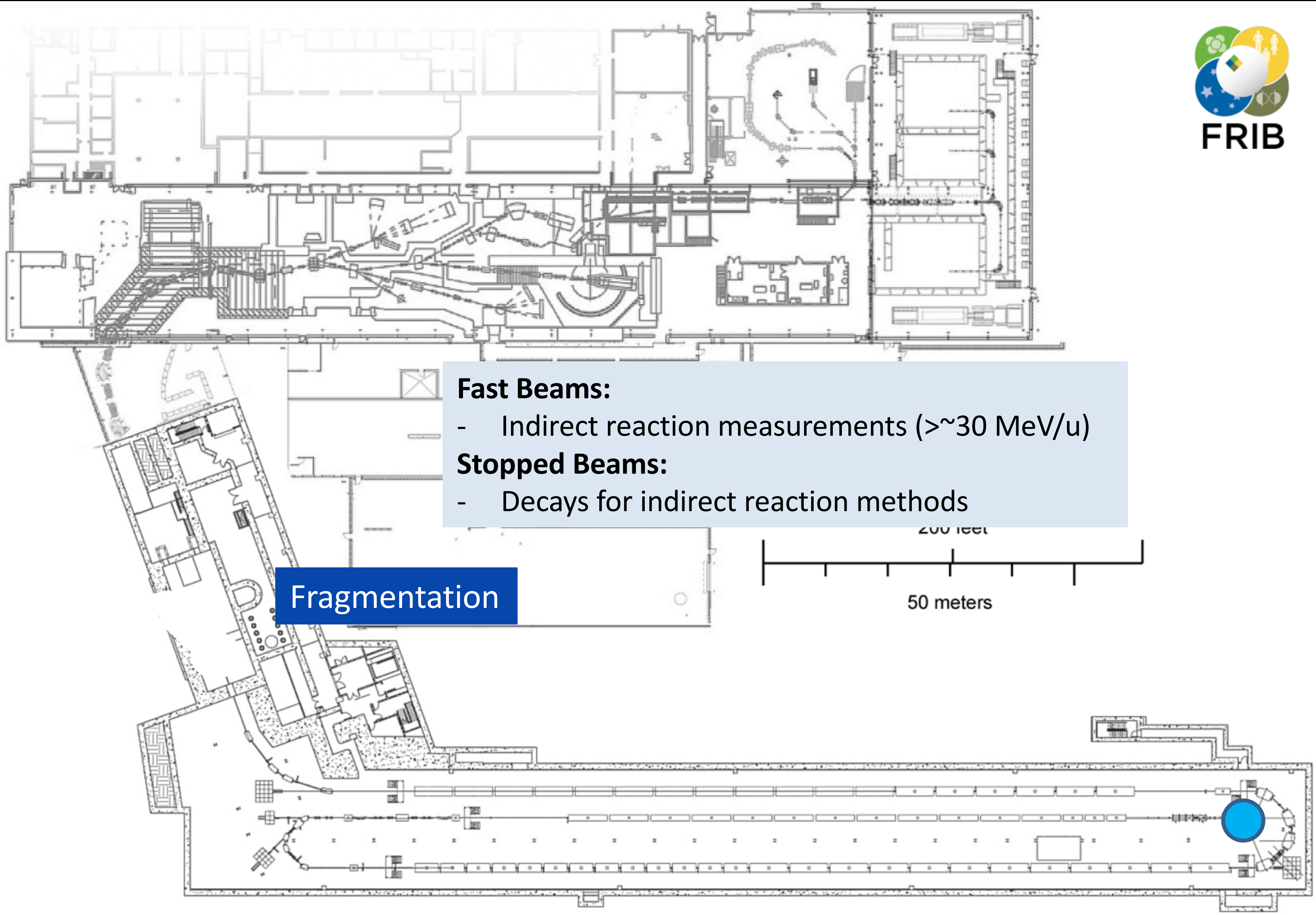
- FRIB has completed all milestones and is on track for delivering first beams to experiments in Spring
- Unique opportunities for Nuclear Astrophysics

Final beam commissioning completed:





FRIB Provides Fast, Stopped, and Reaccelerated Beams



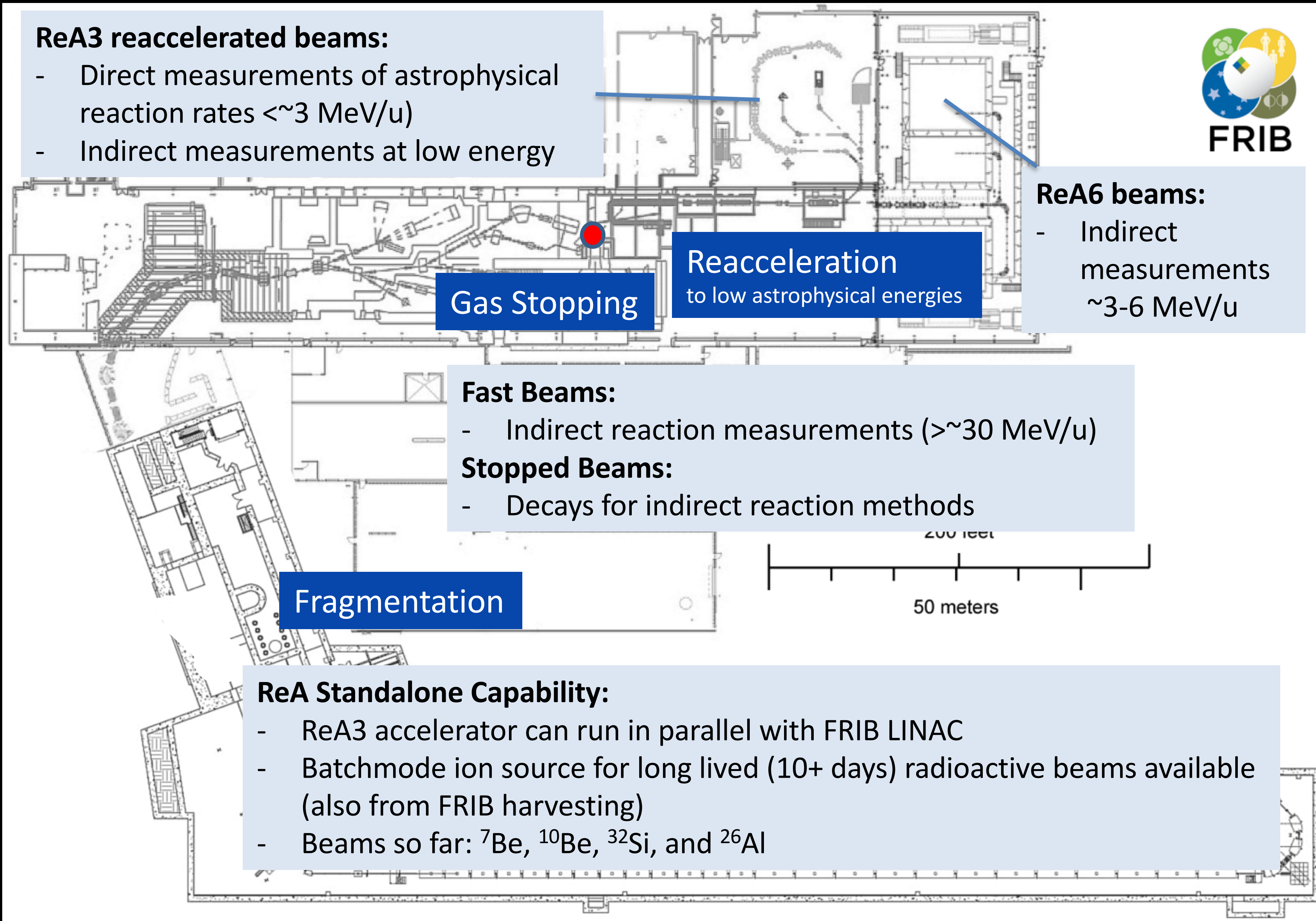
Fast Beams:
- Indirect reaction measurements (>~30 MeV/u)

Stopped Beams:
- Decays for indirect reaction methods

FRIB Provides Fast, Stopped, and Reaccelerated Beams

ReA3 reaccelerated beams:
- Direct measurements of astrophysical reaction rates <~3 MeV/u)
- Indirect measurements at low energy

ReA6 beams:
- Indirect measurements ~3-6 MeV/u

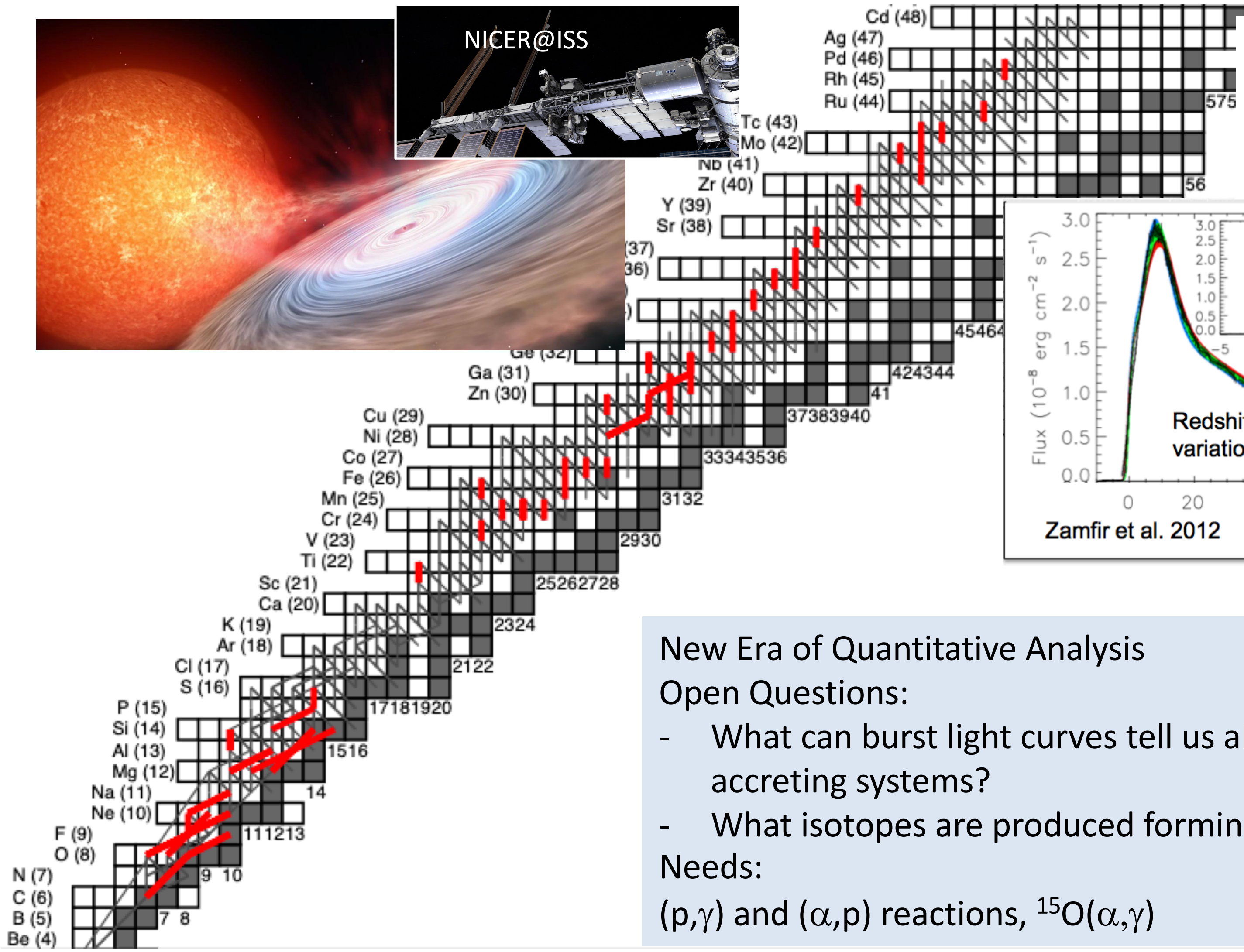


Fast Beams:
- Indirect reaction measurements (>~30 MeV/u)

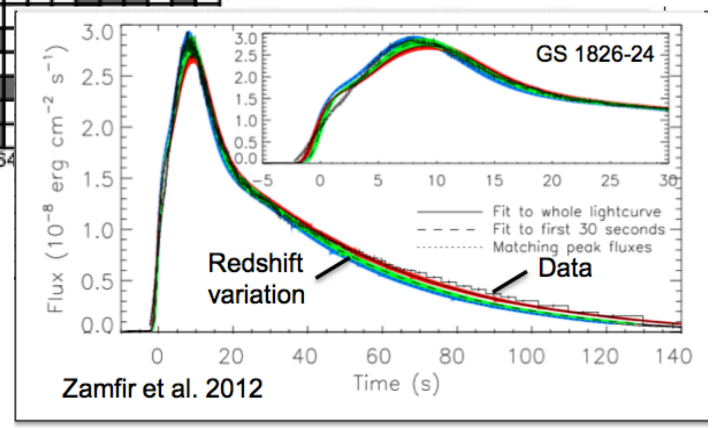
Stopped Beams:
- Decays for indirect reaction methods

ReA Standalone Capability:
- ReA3 accelerator can run in parallel with FRIB LINAC
- Batchmode ion source for long lived (10+ days) radioactive beams available (also from FRIB harvesting)
- Beams so far: ^{7}Be, ^{10}Be, ^{32}Si, and ^{26}Al

Need Accurate Nuclear Physics for X-ray Burst Models



Important Rates for Light Curve:
Cyburt et al. ApJ 830 (2016) 55
Important Masses:
Schatz & ApJ 844 (2017) 193



New Era of Quantitative Analysis

Open Questions:

- What can burst light curves tell us about neutron stars in accreting systems?
- What isotopes are produced forming the neutron star crust

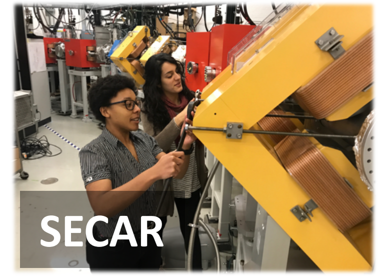
Needs:

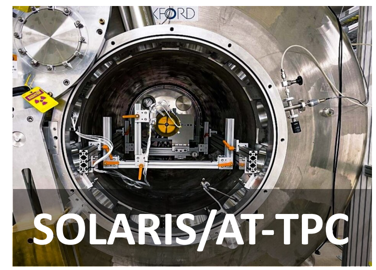
(p,γ) and (α,p) reactions, $^{15}O(\alpha,\gamma)$

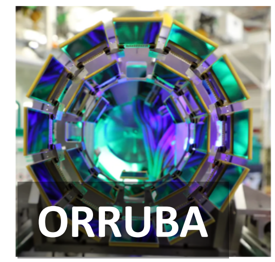
FRIB Will Address X-ray Burst Reactions

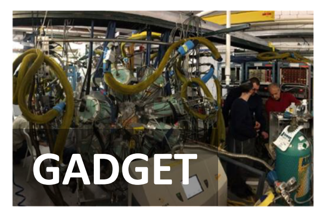
(also needed for Novae, p-process, explosive Si burning in supernovae…)

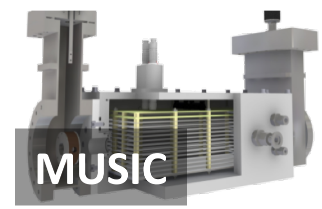
- **Typical $T_{1/2}$: seconds - minutes**
- **Direct reaction rate measurements with reaccelerated beams:**
  - (α,p): JENSA Gas Target, AT-TPC Active Target, MUSIC
  - (p,γ): SECAR Recoil Separator
- **Indirect reaction measurements are also essential**
  - Some important resonances are too weak to be measured directly
  - Pave the way for direct measurements (some resonance properties need to be known)
  - Studies of narrow resonances (low level density):
    - (d,nγ), (^{3}He,d) p-transfer with fast beams (S800 spectrometer, GRETINA γ-array, LENDA n-detector) and with reaccelerated beams (ORRUBA Si-array, SECAR, SOLARIS spectrometer) – can use ANC method (also THM)
    - (d,p) n-transfer on mirror for N=Z nuclei (ORRUBA)
    - β-decay, β-p decay (GADGET gas detector) to study resonance decay branches
  - Studies to improve Hauser-Feshbach calculations (high level density)
    - Level densities and strength functions





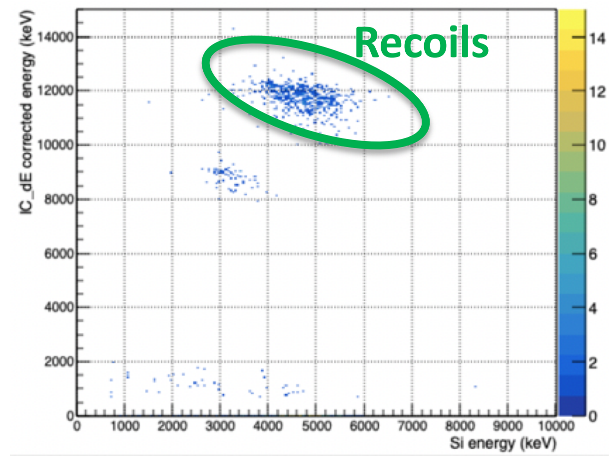


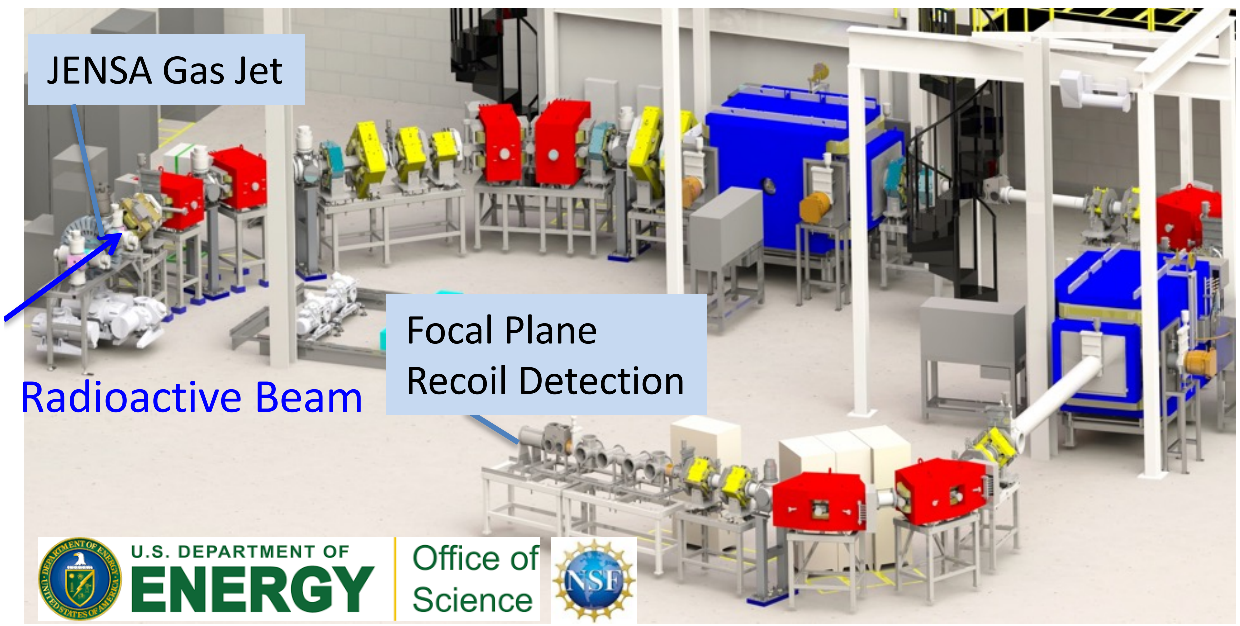


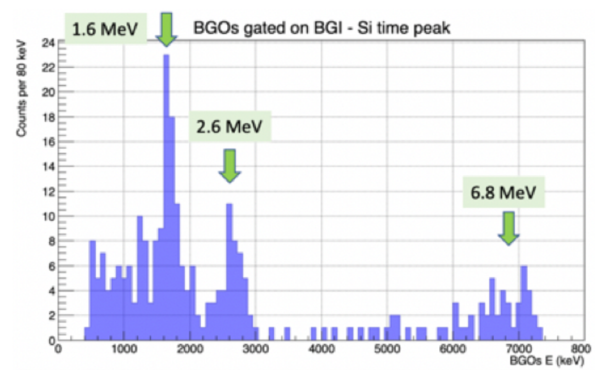


SECAR Recoil Separator Enables Direct Measurements of p,γ and α,γ-Astrophysical Reactions at FRIB

Notre Dame – MSU – LSU – Colorado School of Mines – ORNL – CMU- Ohio U collaboration







First recoil detection from $^{16}O(\alpha,\gamma)^{20}Ne$ concludes construction

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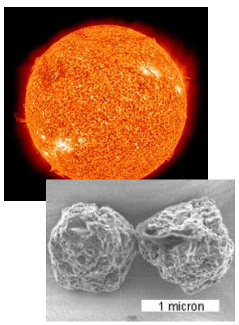
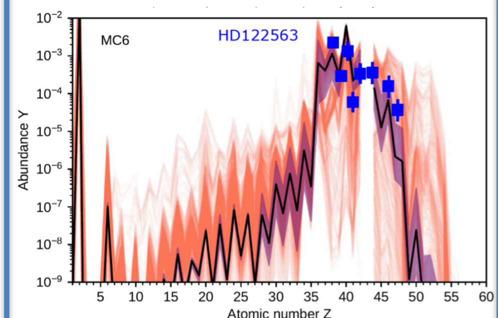
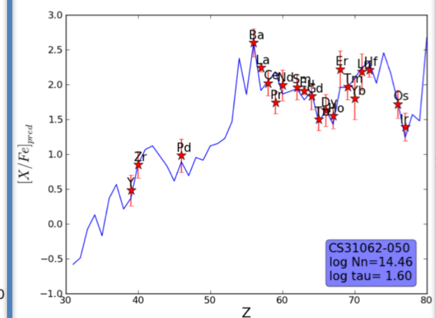
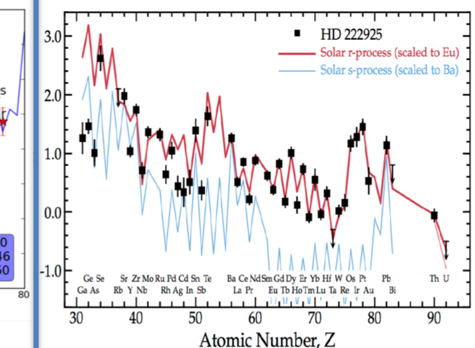
FRIB Will Address Reactions for Heavy Element Nucleosynthesis

Open Questions:

- What are the relative contributions of these processes to the origin of the elements?
- What do the abundance patterns tell us about the physics of astrophysical environments?

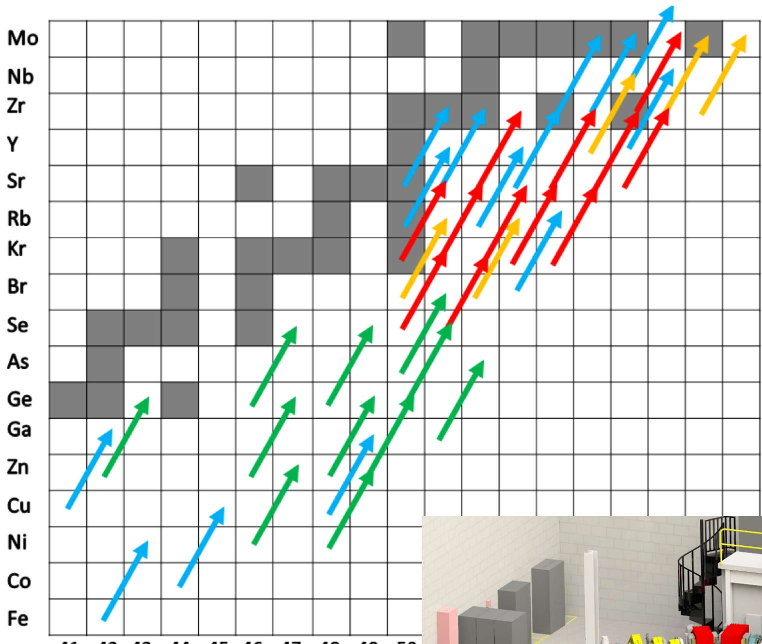
	s-processes	Weak r-process	i,n-processes	r-processes
				
Seed Production	-	(α,n) reactions Stable & n-rich A = 68 - 98	-	ααn - reaction
Neutron Production	(α,n) reactions ^{13}C,^{22}Ne, …	ν-reactions, EOS	(α,n) reactions ^{22}Ne, …	ν-reactions, EOS
n-capture	(n,γ) stable and $T_{1/2}$ days-years	Very few (n,γ)	(n,γ) on $T_{1/2}$ 2 min – 30 yr	(n,γ) on $T_{1/2}$ 10 ms – 2 min

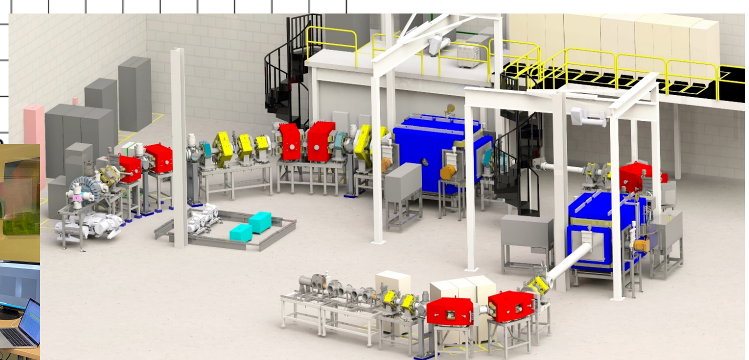
FRIB

Stable and neutron beam facilities

FRIB Will Directly Measure (α,n) Reaction Rates for the Weak r-Process

Important reactions affecting the final abundances
Have been identified (Pereira et al. 2020, Bliss et al. 2020)





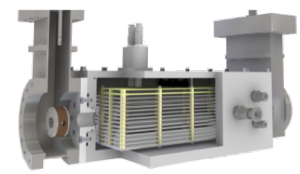
Marshall, Meisel, Montes, et al.

Direct measurement techniques for reaccelerated beams developed:

Neutron detection:

(Meisel, Montes, et al.)

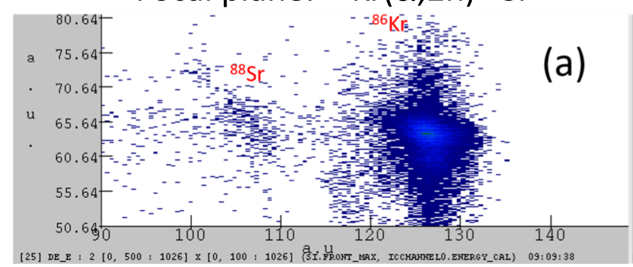
Recoil detection
MUSIC



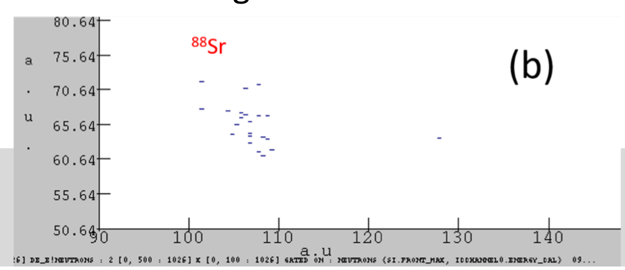
(Avila, Ong, et al.)

Recoil + Neutron detection: SECAR + LENDA

Focal plane: ^{86}Kr(α,2n)^{88}Sr

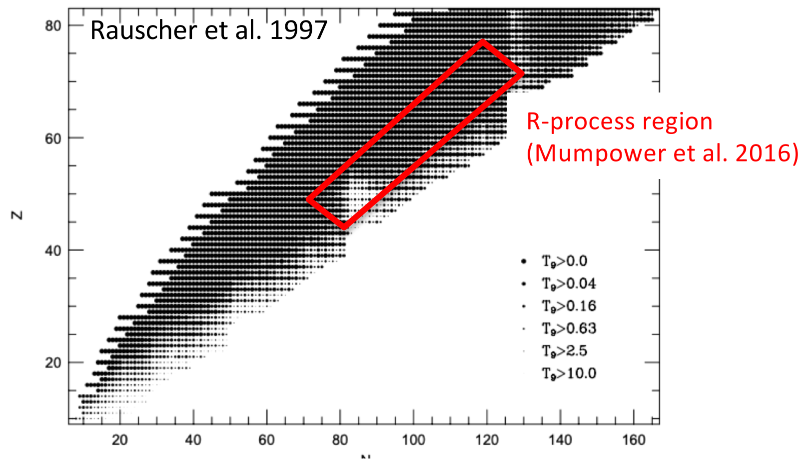


With target neutron coincidence

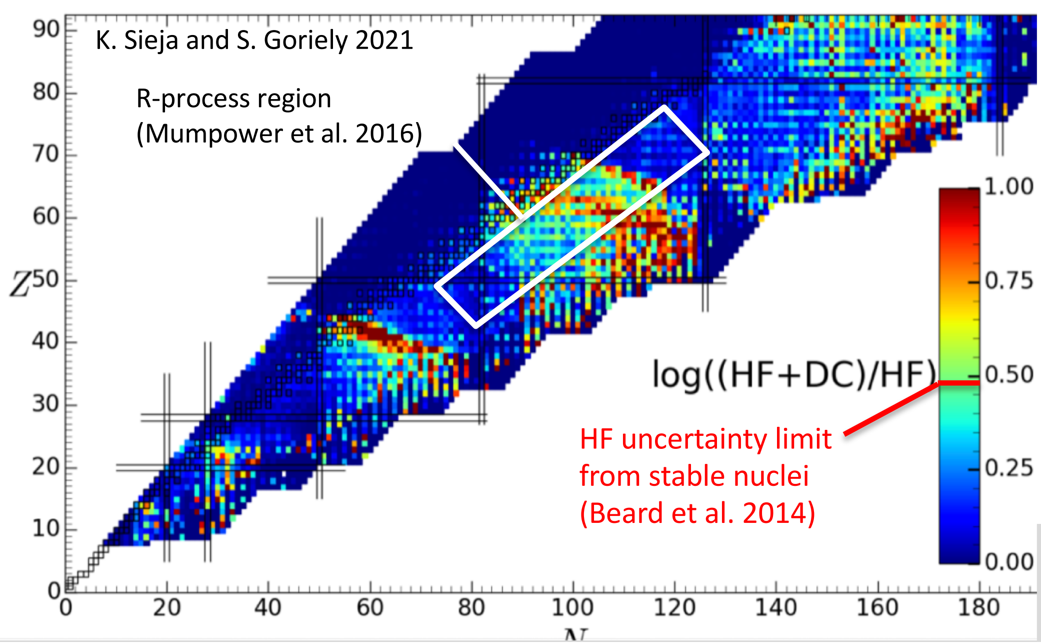


Constraining Neutron Capture Rates on Unstable Nuclei at FRIB

Statistical Model Applicability



Importance of Direct Capture vs Statistical Model



Direct measurements:

- Long lived samples:
    - FRIB Harvesting
    - Transport to external n-beam facility
    - Future n-beam at FRIB?
- Far future: storage ring and n-target **(see talk by Mosby)**

Indirect studies: if HF is Applicable

- Improve HF calculations: strength functions, level densities (β-Oslo – **see talk by Liddick**)

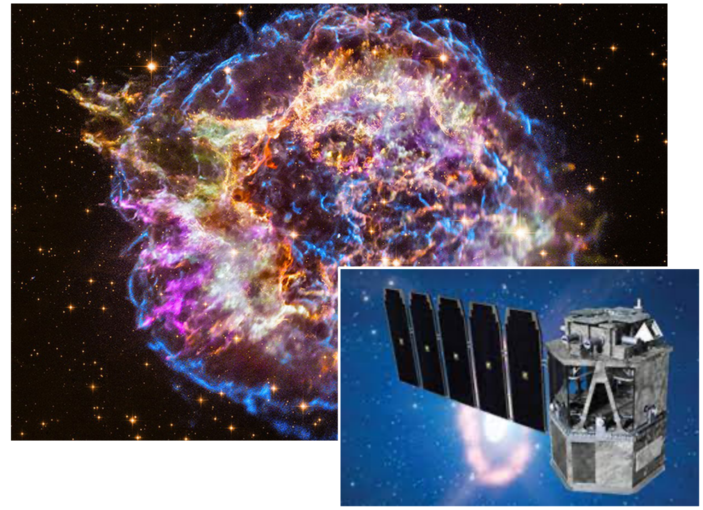
Indirect studies: If single resonances or direct capture dominate (talk by Escher)

- Surrogate method **(talk by Ratkiewicz)**
- d,pγ neutron transfer

FRIB Will Address Reactions in Explosive Stellar Burning

Open Questions:

- What are the abundances of long-lived γ-ray emitters in supernova ejecta?
- What would observations with γ-ray observatories (e.g. future COSI) tell us about supernova physics?



Reaction	Impact	Isotope Affected
$^{42}K(n,\gamma)^{43}K$	4.18	^{43}K
$^{44}Ti(\alpha,p)^{47}V$	2.61, 1.31, 1.12[a]	^{44}Ti, ^{48}V, ^{49}V
$^{43}K(p,n)^{43}Ca$	2.51	^{43}K
$^{59}Cu(p,\gamma)^{60}Zn$	2.16	^{59}Ni
$^{42}K(p,n)^{42}Ca$	2.13	^{43}K
$^{23}Na(\alpha,p)^{26}Mg$	2.12, 1.14, 1.13, 1.12[a]	^{43}K, ^{47}Sc ^{49}V, ^{55}Fe
$^{27}Al(\alpha,p)^{30}Si$	1.91, 1.58[a]	^{43}K, ^{47}Sc
$^{28}Al(p,\alpha)^{25}Mg$	1.89, 1.37[a]	^{43}K, ^{47}Sc

Reaction	Impact	Isotope Affected
$^{47}Sc(n,\gamma)^{48}Sc$	1.88	^{47}Sc
$^{47}Ti(n,p)^{47}Sc$	1.85	^{47}Sc
$^{48}Cr(\alpha,p)^{51}Mn$	1.84, 1.16[a]	^{48}V, ^{51}Cr
$^{51}Mn(p,\gamma)^{52}Fe$	1.76	^{51}Cr
$^{41}K(p,\alpha)^{38}Ar$	1.72	^{43}K
$^{43}K(n,\gamma)^{44}K$	1.65	^{43}K
$^{46}Sc(n,\gamma)^{47}Sc$	1.55	^{47}Sc
$^{46}Sc(p,n)^{46}Ti$	1.45	^{47}Sc
$^{53}Fe(n,p)^{53}Mn$	1.41	^{53}Mn
$^{49}Mn(p,\gamma)^{50}Fe$	1.34	^{49}V
$^{55}Co(p,\gamma)^{56}Ni$	1.32	^{55}Fe
$^{45}Ca(n,\gamma)^{46}Ca$	1.31	^{47}Sc
$^{32}S(n,\alpha)^{29}Si$	1.31, 1.29[a]	^{43}K, ^{47}Sc
$^{40}Ar(p,\gamma)^{41}K$	1.30	^{43}K

Key reactions for broad range of γ-ray emitters identified (Hermansen et al. 2020)

Broad range of reactions needed:

(p,γ), (p,n), (p,α), (α,p) – techniques discussed so far

(see talk by Perdikakis on p,n)

(n,γ), (n,p), (n,α) – techniques discussed so far

n-rich isotopes T_{12} 2 min – 160 d

p-rich isotopes T_{12} 0.3 s – 60 yr

→ Some long-lived enough suitable for harvesting/batchmode/sample production

Need Dedicated Data Efforts for Nuclear Astrophysics

- Dedicated efforts are needed to
  - Evaluate nuclear data for astrophysics
  - Transform nuclear data into data that can be used in astrophysics
    - USNDP data are key input
    - Combine experimental data, incl. resonance strengths, with theoretical data, compute astrophysical reaction rates, and correct for stellar environments **(comments by Sharon yesterday)**
  - Disseminate data so they can be easily accessed across field boundaries.
- Ongoing activities are very important but address only aspects and need to be greatly expanded
  - (JINA REACLIB, STARLIB, BRUSLIB, nu-Lib, nucastrodata.org, pynucastro, ….)
- A new development: URSA: Unified Reaction Structures for Astrophysics
  - Overcomes limitations from multiple formats and scattered data sources – unified format-independent data flow for all nuclear data needed for astrophysics
  - Initially developed at LANL: T. Sprouse, M. Mumpower, O. Korobkin, J. Lippuner, J. Miller
  - Continued development (B. Cote) in international framework within IReNA (NSF AccelNet Network of Networks connects international nuclear astrophysics networks) – continued support will be critical

Conclusions

- Unprecedented opportunities at FRIB to advance reaction measurements for nuclear astrophysics to address open questions related to the origin of the elements, accreting neutron stars and other extreme astrophysical environments
  - Fast beams
  - Stopped beams (decays)
  - Reaccelerated beams – ReA3 and ReA6
  - Standalone batchmode beams of long-lived species – ReA3 and ReA6
  - Harvesting
- Need close collaboration between experimentalists and reaction theorists
- Need close collaboration between nuclear scientists, computational astrophysicists, observers, cosmo-chemists, …..
- Need dedicated data effort for nuclear astrophysics