Laboratory Nuclear Astrophysics

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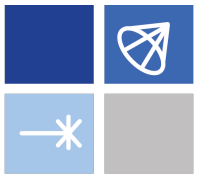
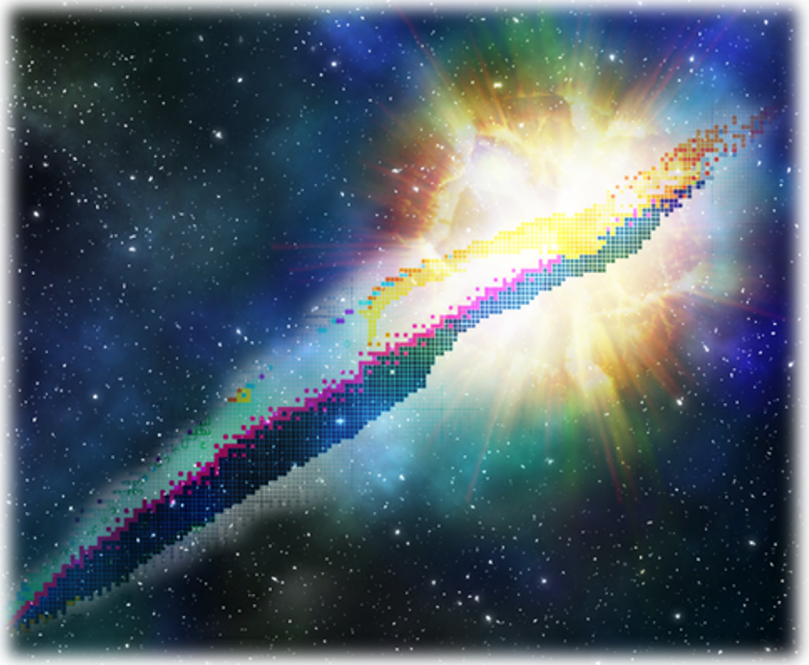
MICHIGAN STATE UNIVERSITY



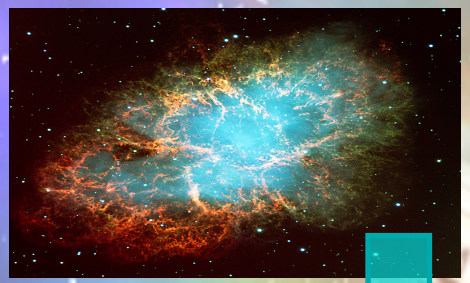
Overview

- **Nuclear needs for understanding astrophysical events**
  - Focus on radioactive beam needs relevant for TRIUMF and other radioactive-beam facilities
- **Facilities**
  - Producing radioactive beams for astrophysics
  - Energy regimes
    - » High energy
    - » Low energy
    - » "stopped" beams
- **Equipment**
  - Unique capabilities at TRIUMF and elsewhere
  - Examples of science results

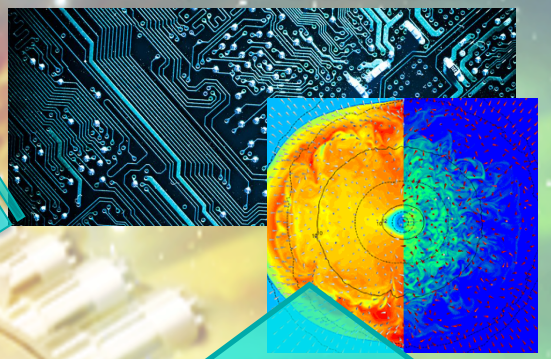


Nuclear Astrophysics

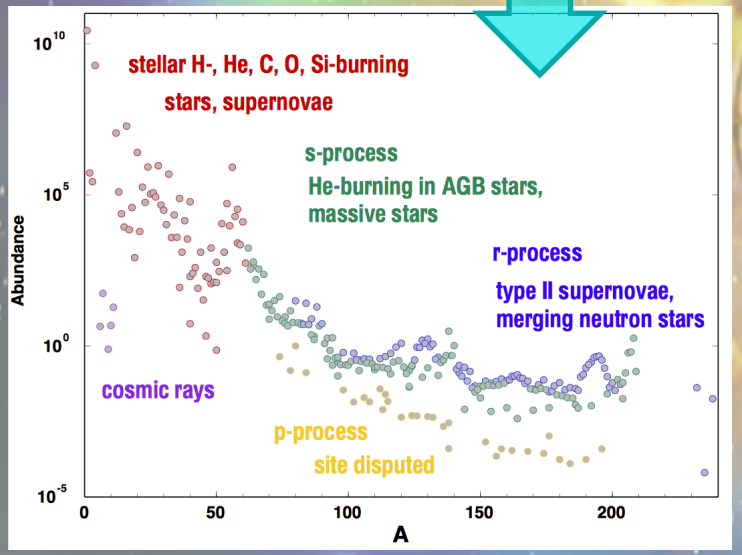
Observations

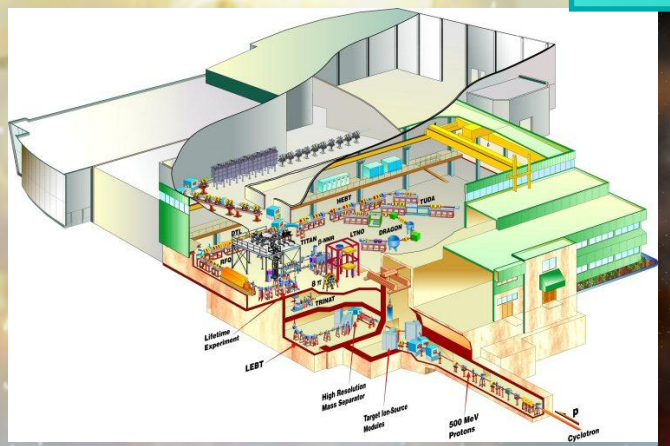


Models

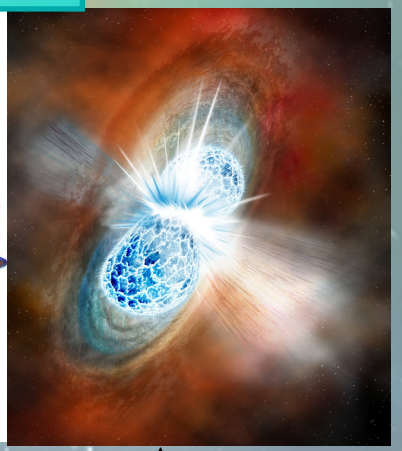


Input





Nuclear

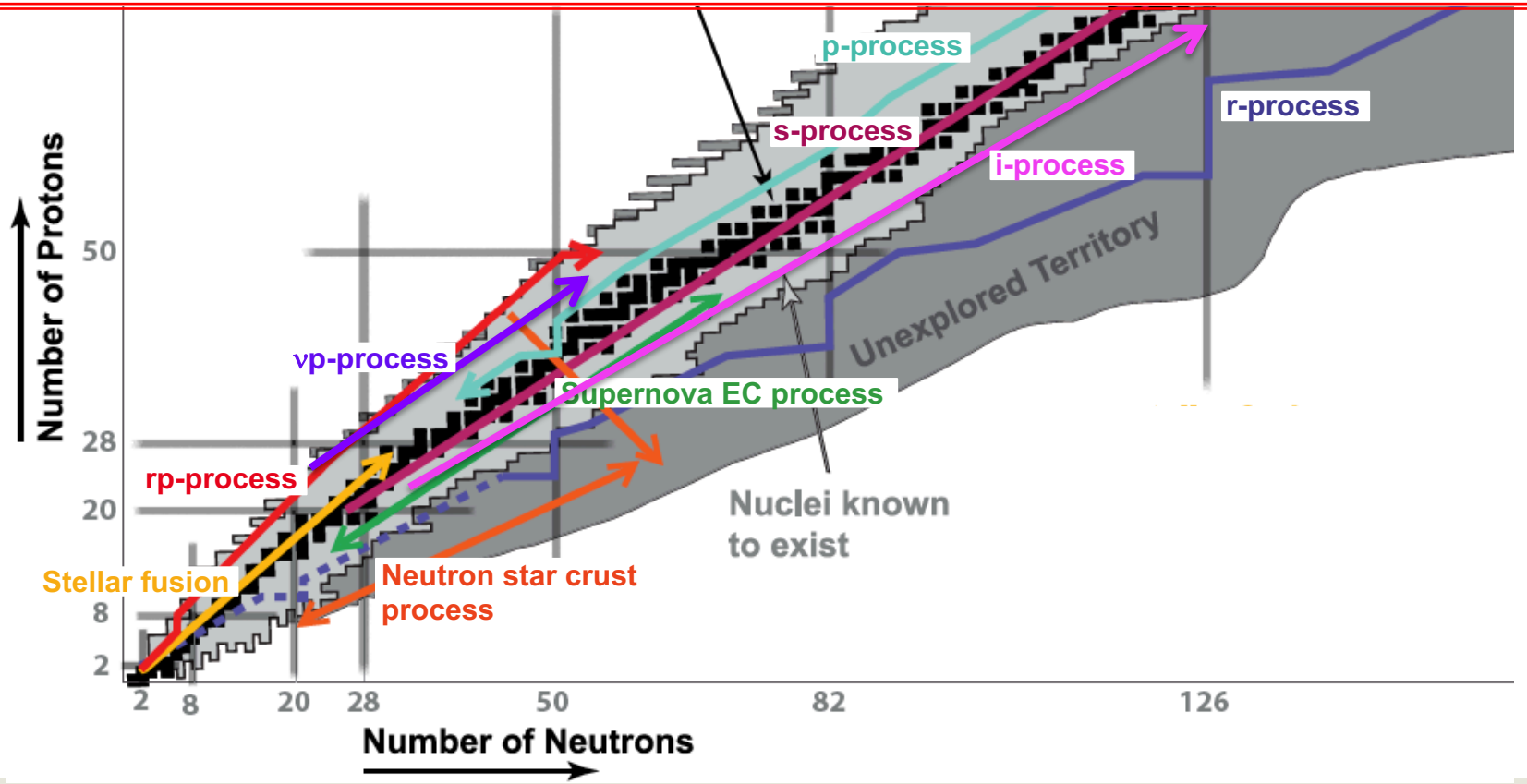


Astro

Figure Credit: Erin O'Donnel, NSCL

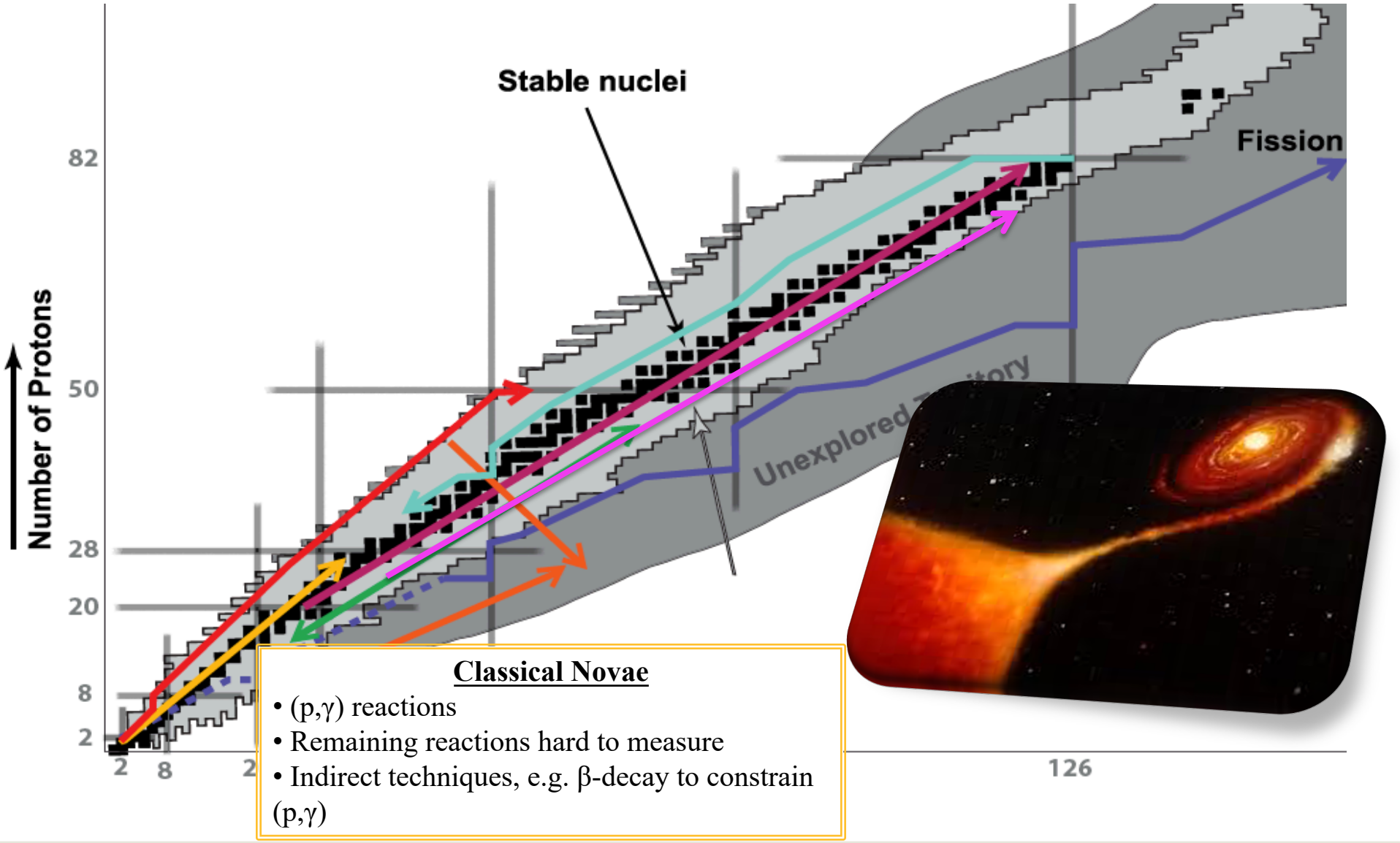
Nuclear Astrophysics

- Most astrophysical processes extend into radioactive nuclei
- Nuclear properties needed: mass, β-decay half-life, β-delayed neutron emission
- Nuclear reaction rates
- Current facilities (e.g. TRIUMF, NSCL, RIKEN, GSI, …)
- Future facilities (e.g. FRIB, ARIEL, FAIR) will provide access to these nuclei



Adapted from Frank Timmes / Hendrik Schatz

Nuclear Properties needs



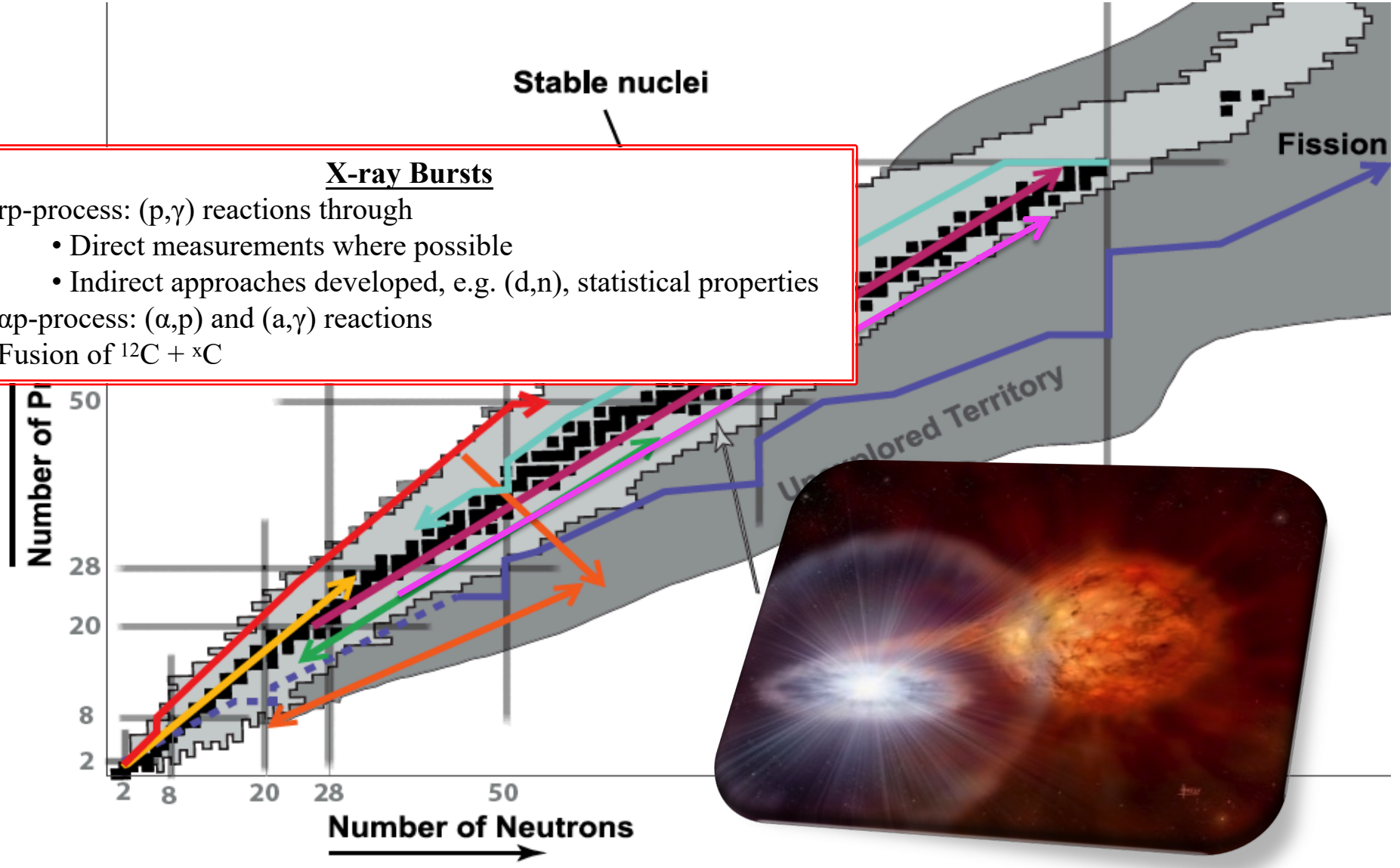
Classical Novae

- (p,γ) reactions
- Remaining reactions hard to measure
- Indirect techniques, e.g. β-decay to constrain (p,γ)

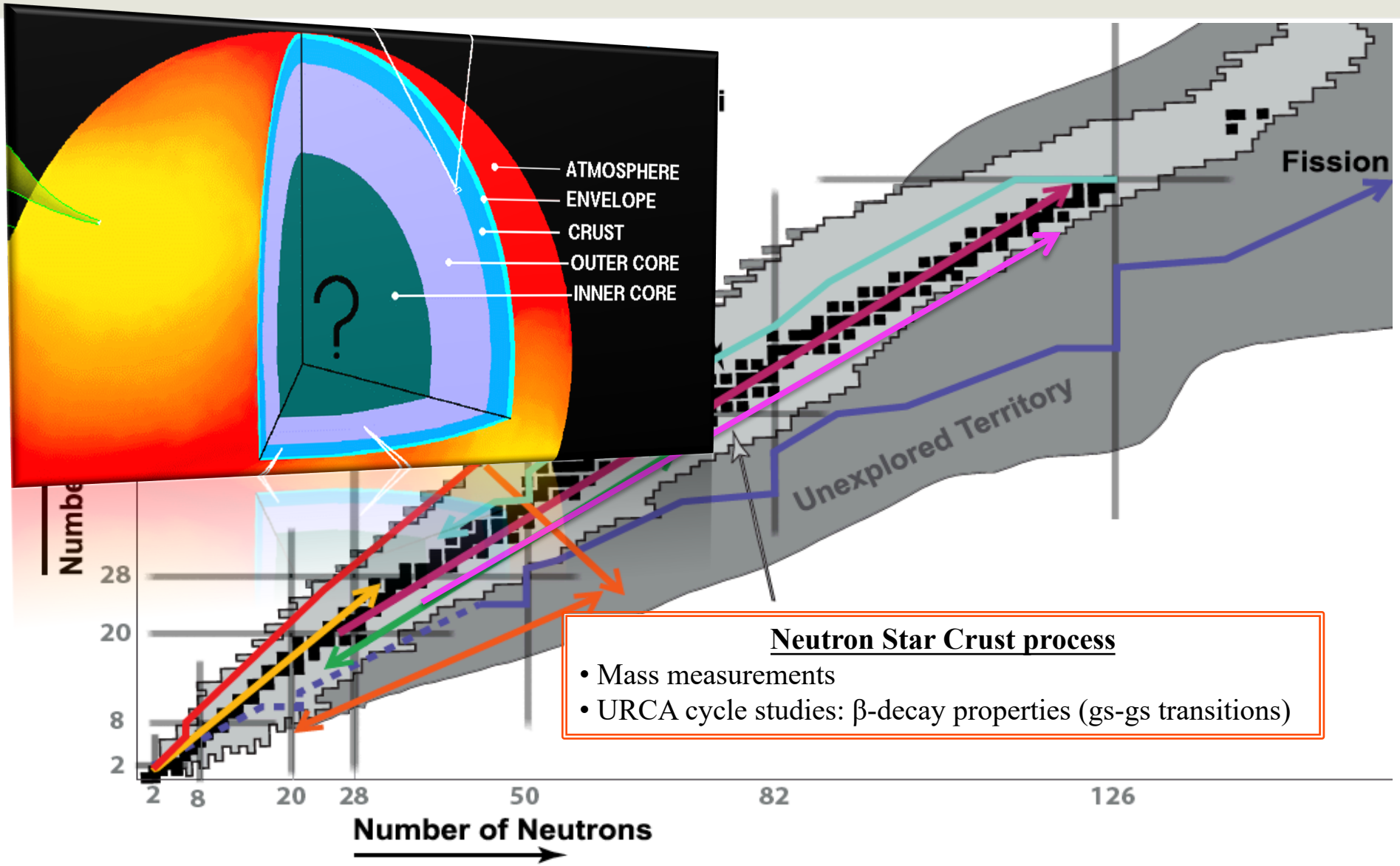
Nuclear Properties needs

X-ray Bursts

- rp-process: (p,γ) reactions through
  - Direct measurements where possible
  - Indirect approaches developed, e.g. (d,n), statistical properties
- αp-process: (α,p) and (a,γ) reactions
- Fusion of $^{12}C + {}^{x}C$



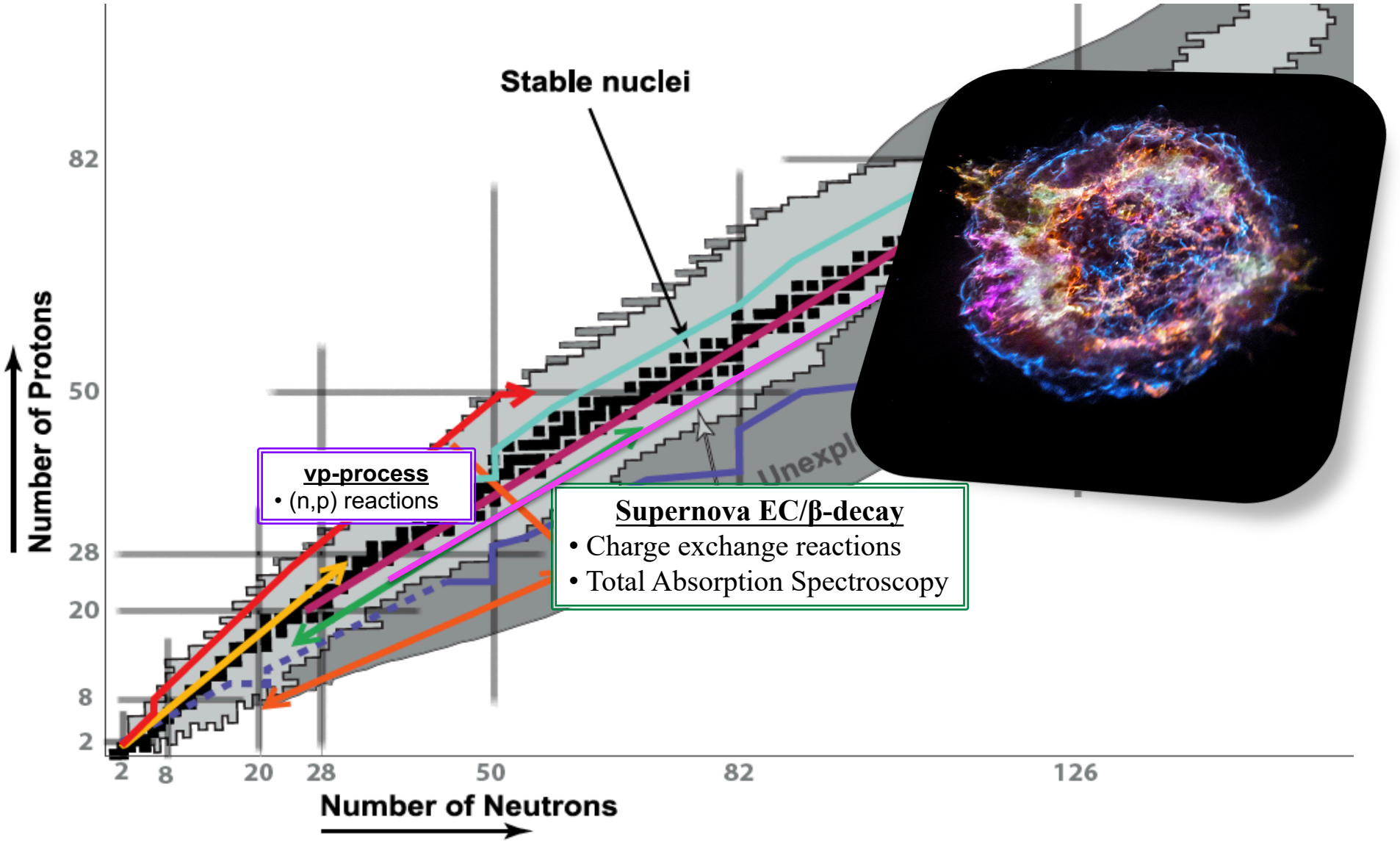
Nuclear Properties needs



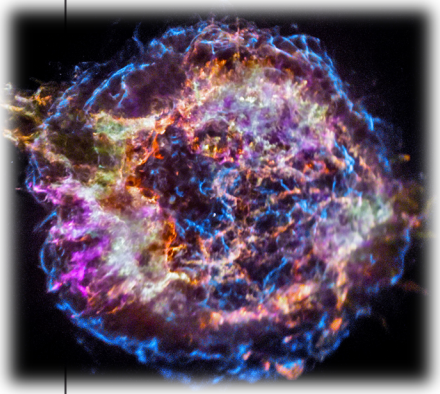
Neutron Star Crust process

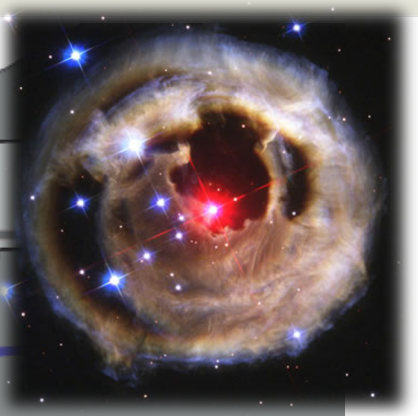
- Mass measurements
- URCA cycle studies: β-decay properties (gs-gs transitions)

Nuclear Properties needs



Nuclear Properties needs





Stable nuclei

p-process
• (p,γ) and (α,γ) reactions

s-process
• (n,γ) reactions

i-process
• (n,γ) reactions

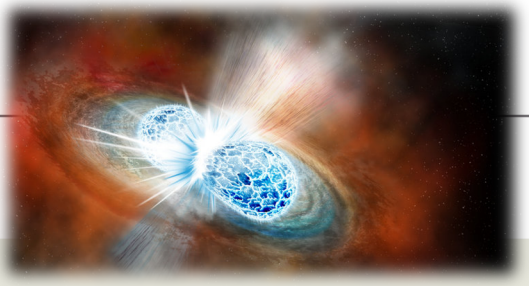
r-process
• Masses
• (n,γ) reactions – indirect approaches
• β-decay half-lives
•β-delayed neutron emission
• (α,n) reactions
• fission properties

Number of Protons

50
28
20
8
2

2 8 20 28 50 126

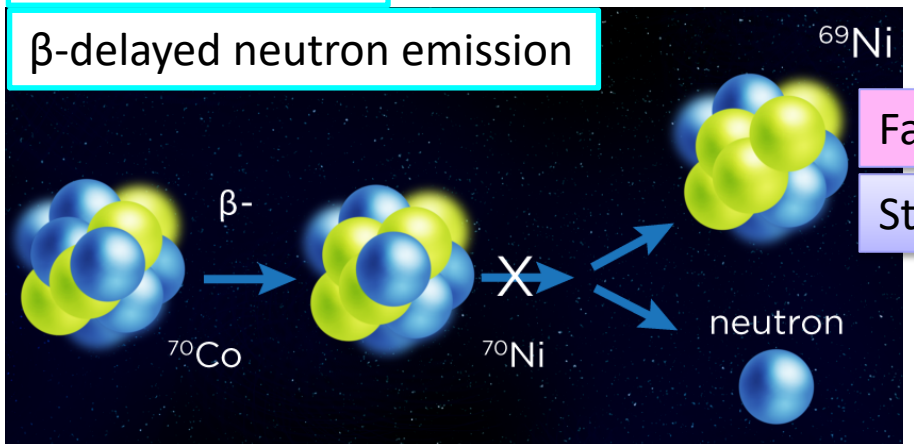
Number of Neutrons



Nuclear Data Needs

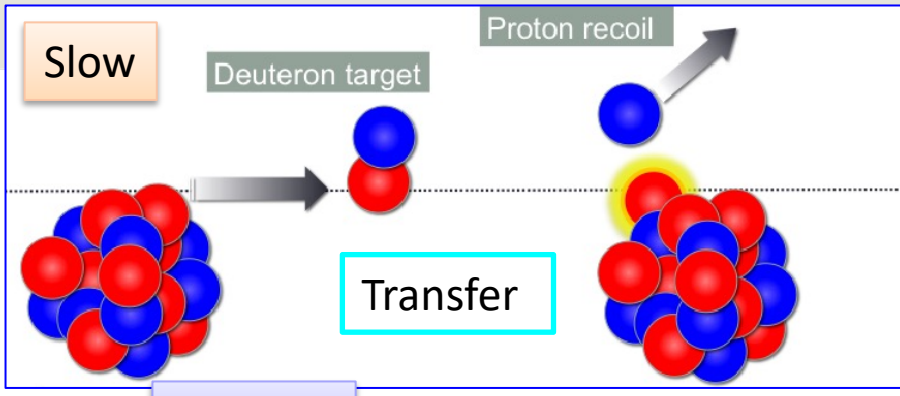
β-decay half-lives

β-delayed neutron emission



Fast

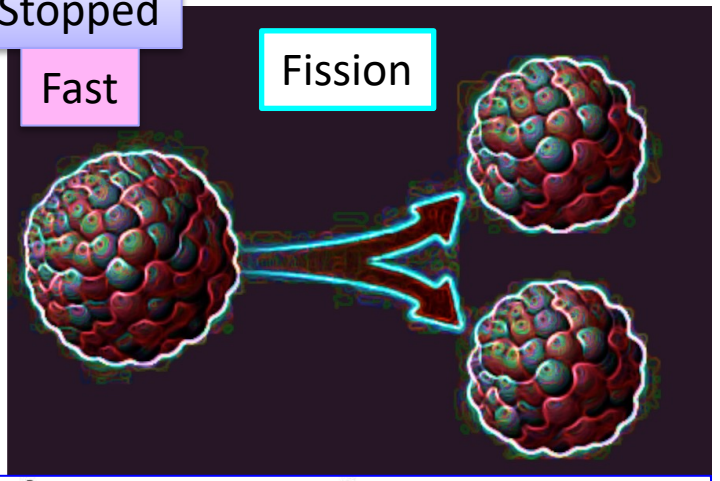
Stopped



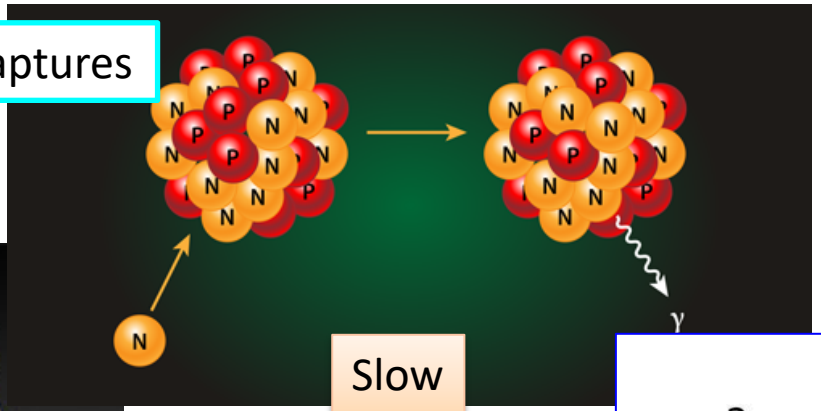
Stopped

Fast

Fission



Neutron/proton Captures

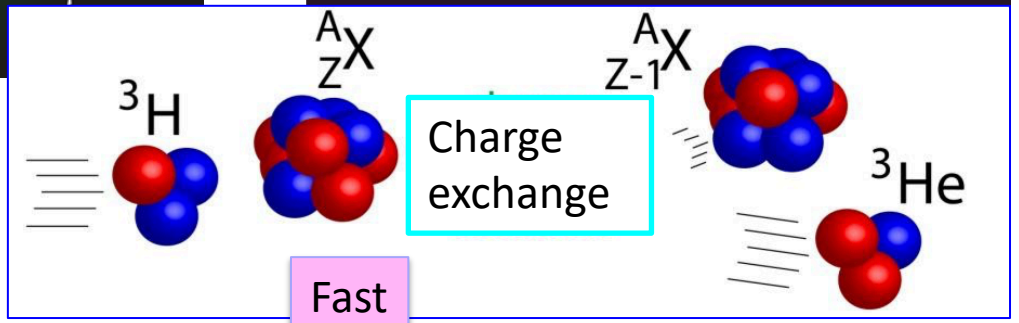


Slow

Masses

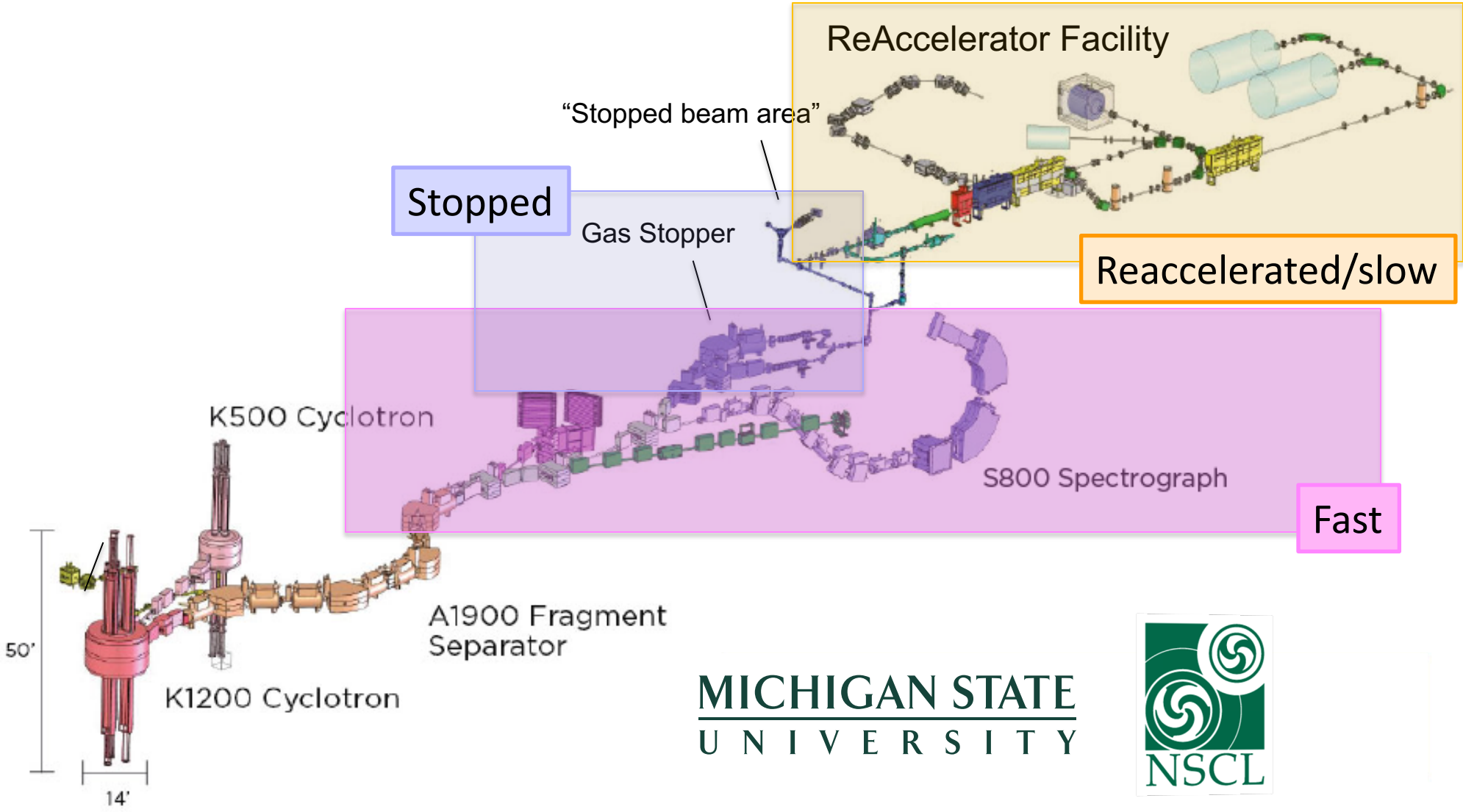
Fast

Stopped



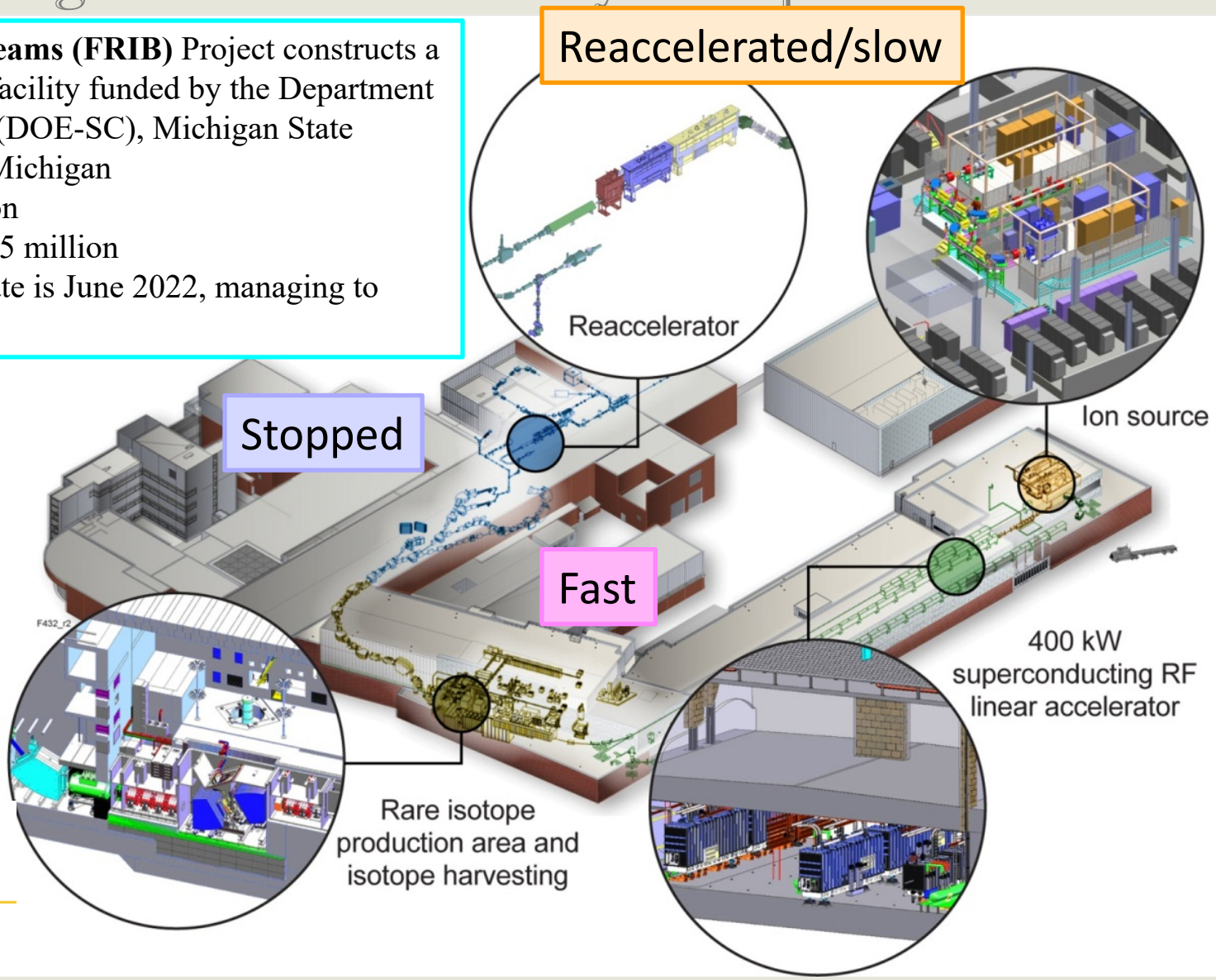
Fast

National Superconducting Cyclotron Lab



Facility for Rare Isotope Beams, FRIB
Michigan State University Campus

- **Facility for Rare Isotope Beams (FRIB)** Project constructs a $730 million scientific user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
  - DOE-SC $635.5 million
  - State of Michigan $94.5 million
- Planned FRIB completion date is June 2022, managing to early completion in 2021



FRIB

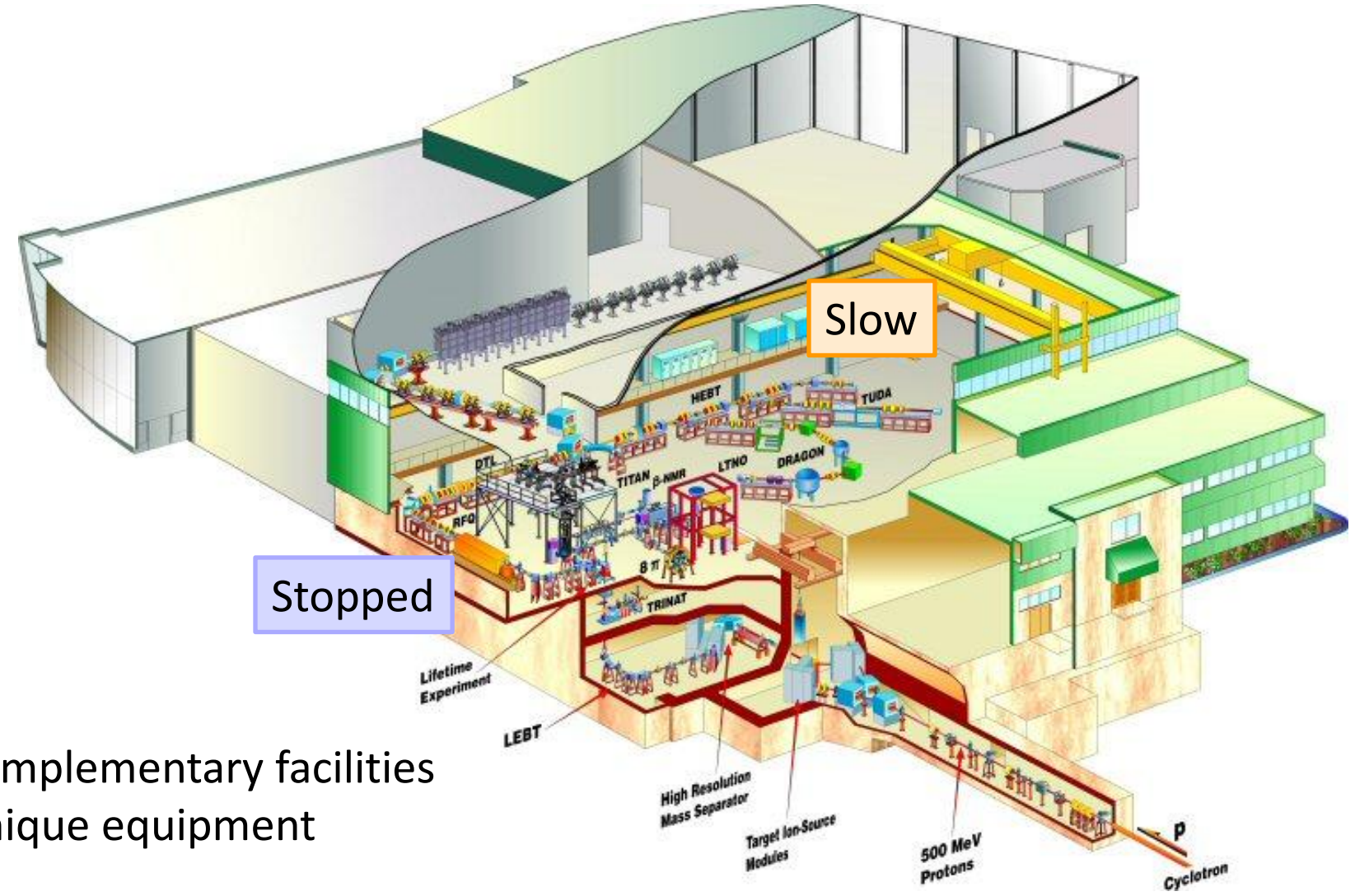
U.S. DEPARTMENT OF ENERGY

Office of Science

National Science Foundation
Michigan State University

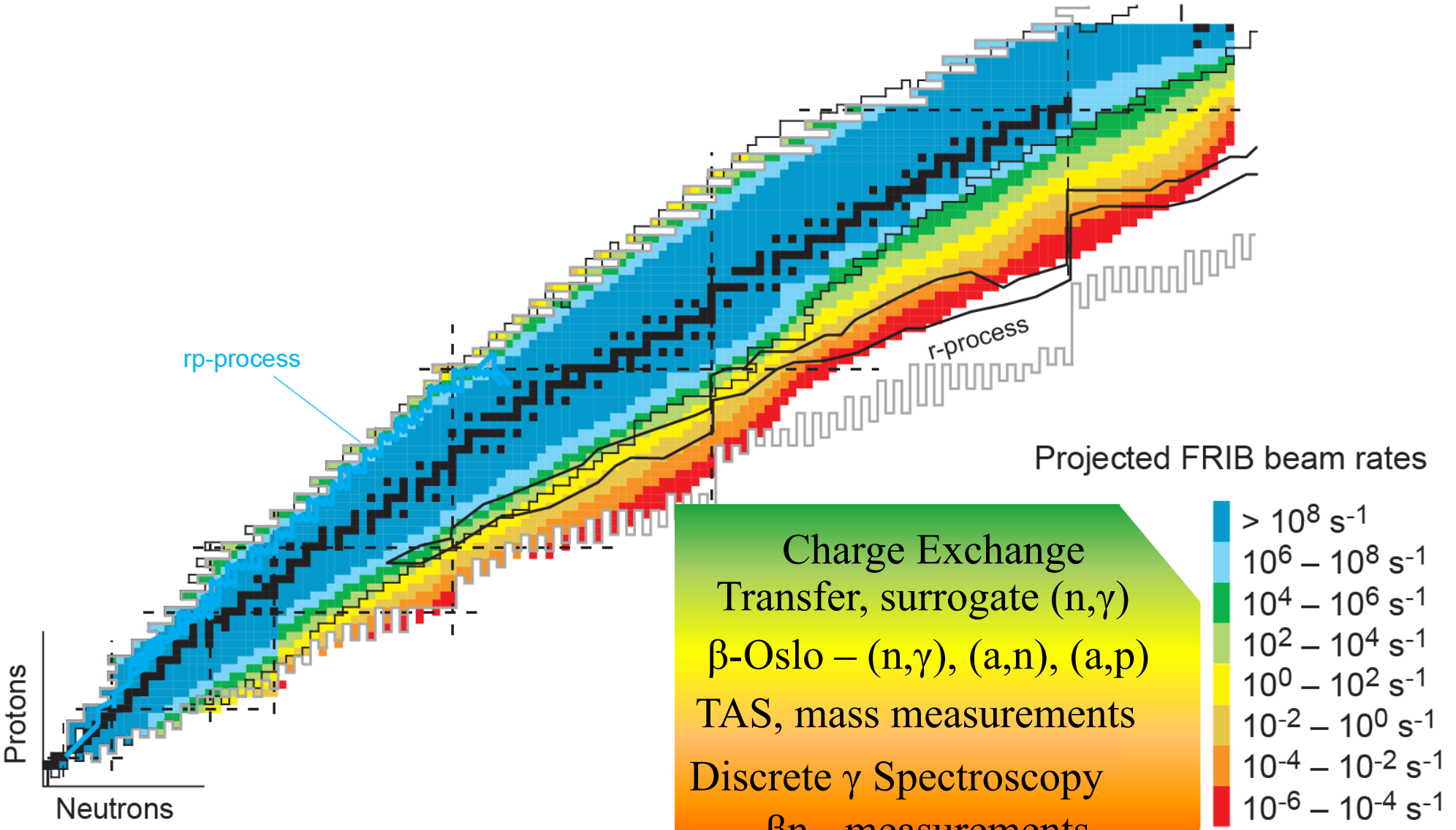
NSCL

TRIUMF



- Complementary facilities
- Unique equipment

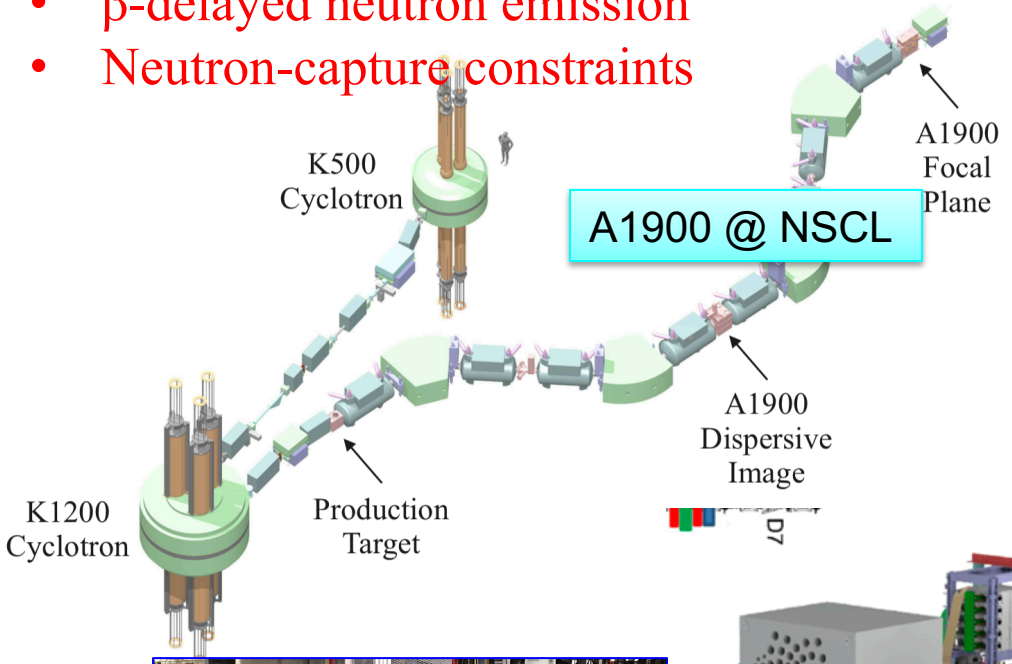
FRIB Rates

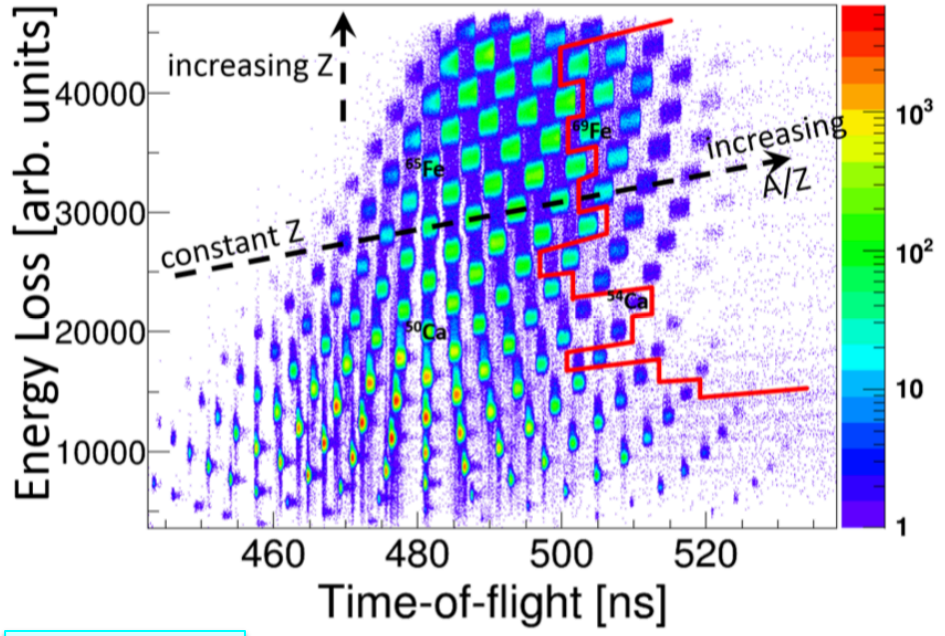

rp-process
r-process
Protons
Neutrons
Projected FRIB beam rates
> 10^8 s^-1
10^6 – 10^8 s^-1
10^4 – 10^6 s^-1
10^2 – 10^4 s^-1
10^0 – 10^2 s^-1
10^-2 – 10^0 s^-1
10^-4 – 10^-2 s^-1
10^-6 – 10^-4 s^-1
Charge Exchange
Transfer, surrogate (n,γ)
β-Oslo – (n,γ), (a,n), (a,p)
TAS, mass measurements
Discrete γ Spectroscopy
βn - measurements
Half-life, ToF mass

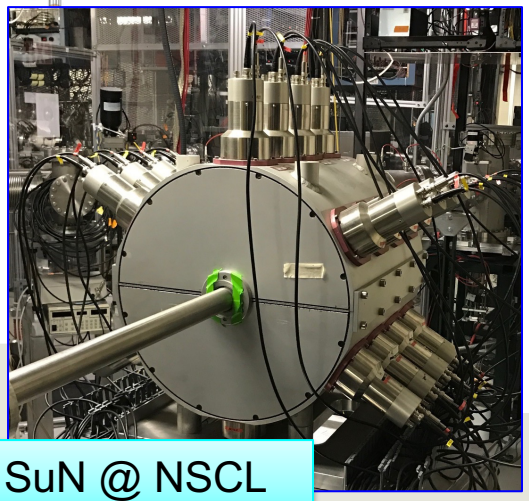
Fast Beams

(NSCL/FRIB, RIKEN, FAIR)

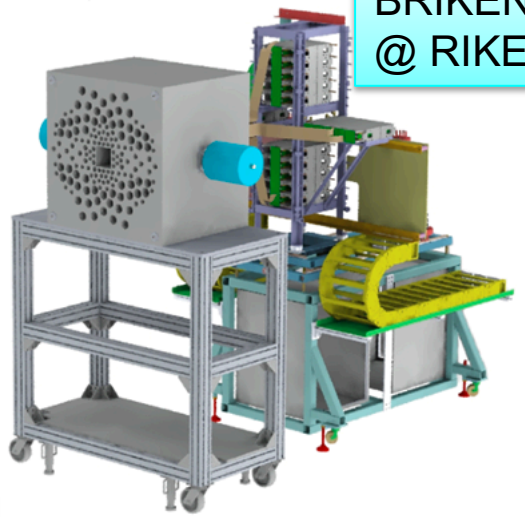
- Mass measurements (ToF)
- Half-lives
- β-delayed neutron emission
- Neutron-capture constraints



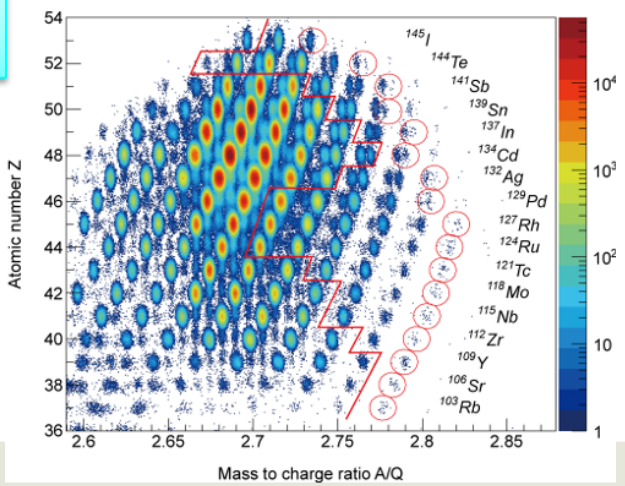




SuN @ NSCL



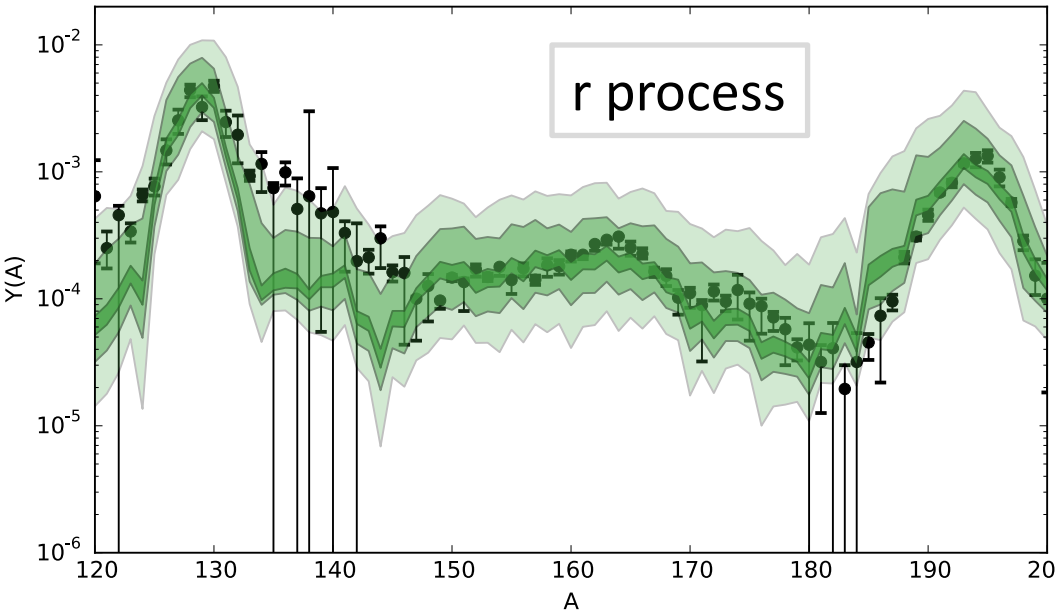
BRIKEN
@ RIKEN



Fast Beams (examples)
(NSCL/FRIB, RIKEN, FAIR)

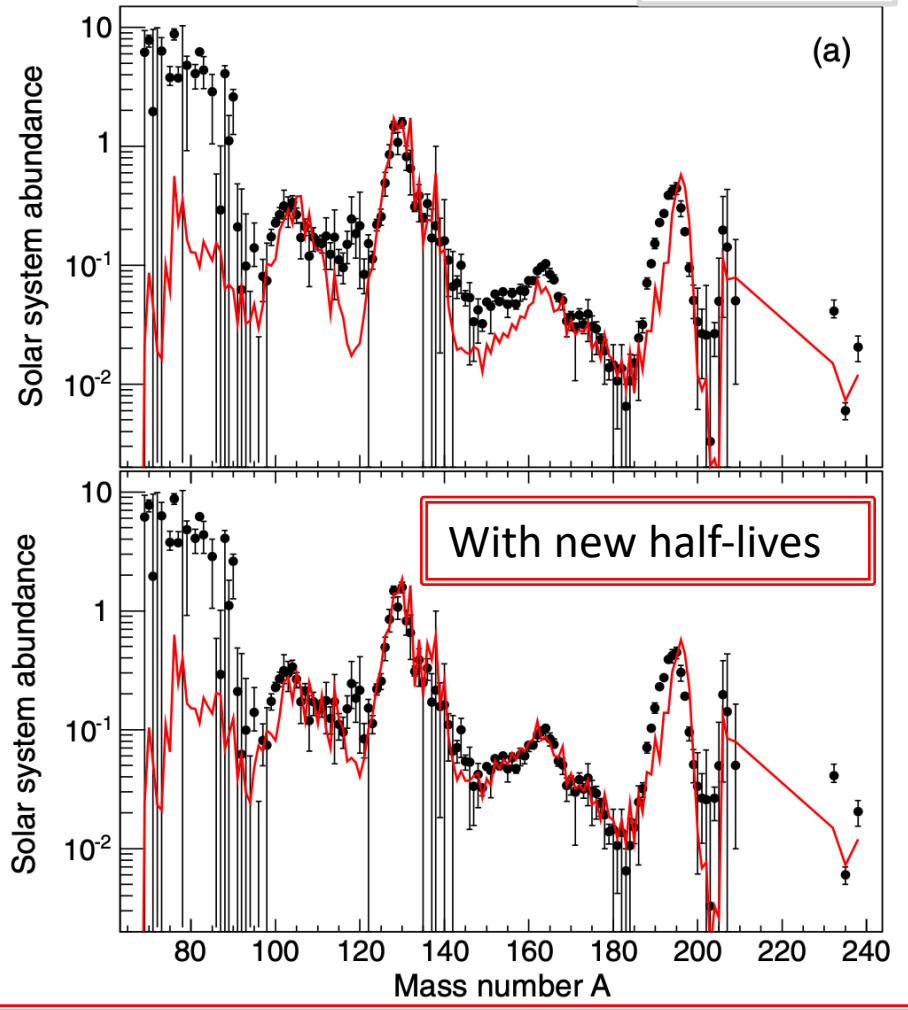
r process

Indirect neutron-capture constraints: β-Oslo method factor of 2-3 (MSU-Oslo)



Monte-Carlo variations of (n,γ) rates within a factor
100 – 10 – 2
light – darker – dark bands

Liddick, Spyrou, et. al. PRL 2016



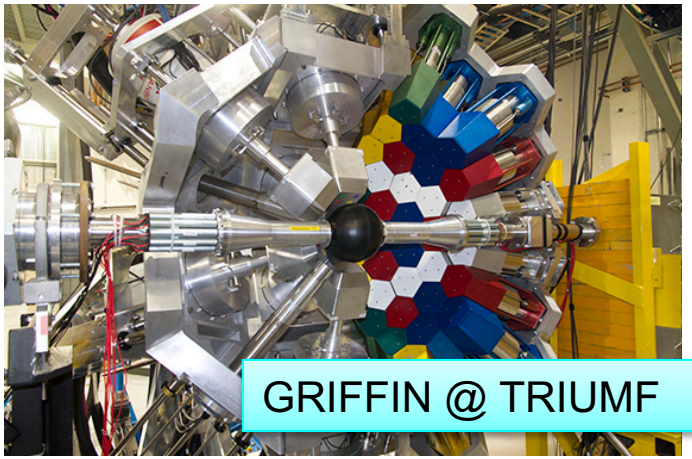
Half-life measurements @RIKEN provide better constraints for abundance calculations

Lorusso, et. al. PRL 2015

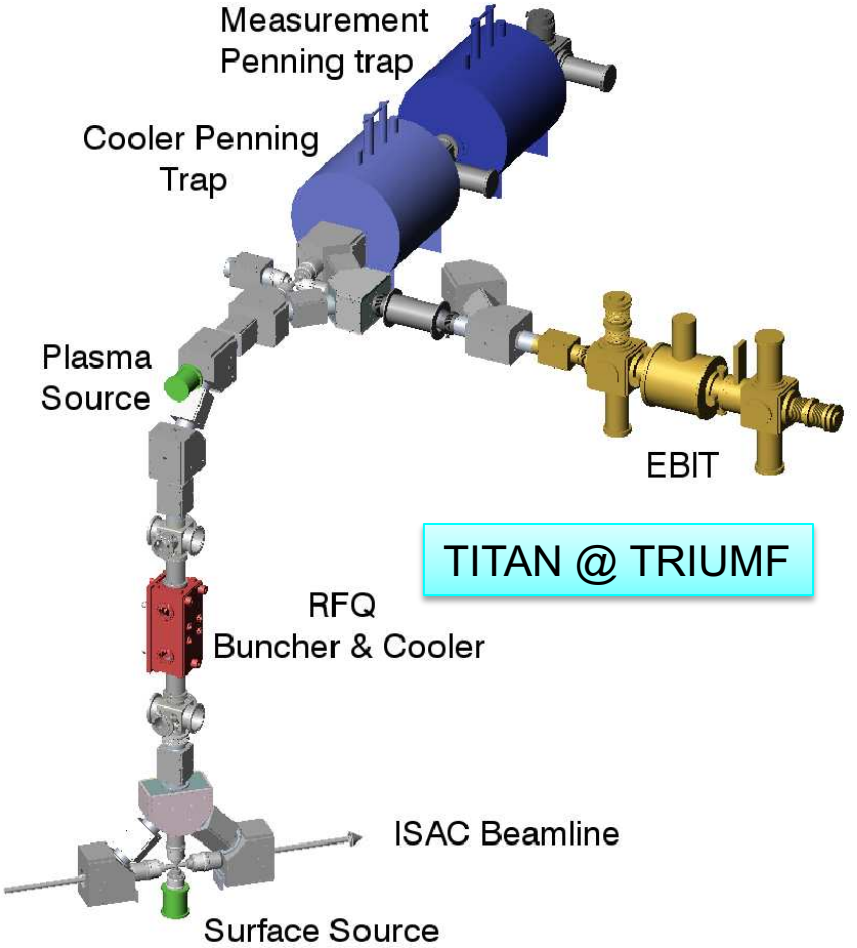
Stopped Beams

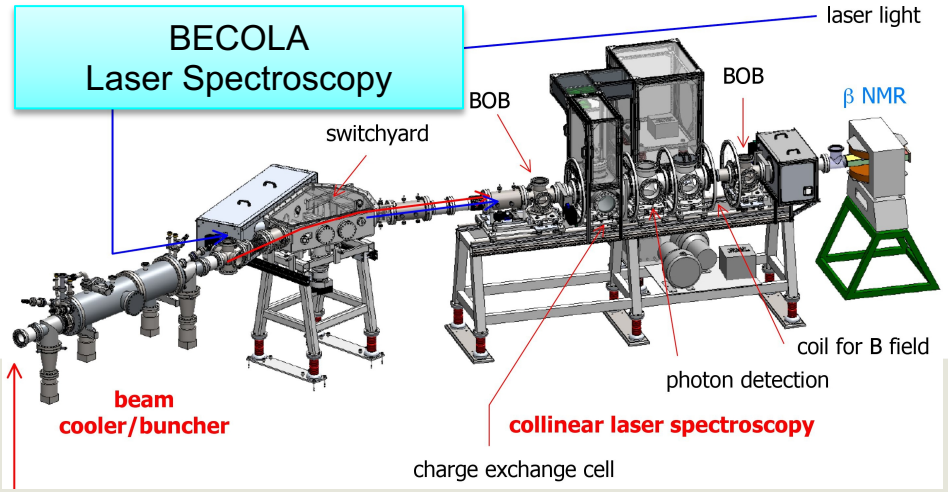
NSCL/FRIB, RIKEN, FAIR, TRIUMF, Argonne, …

- Mass measurements with traps
- Decay spectroscopy
- β-delayed neutron emission
- Laser Spectroscopy



GRIFFIN @ TRIUMF

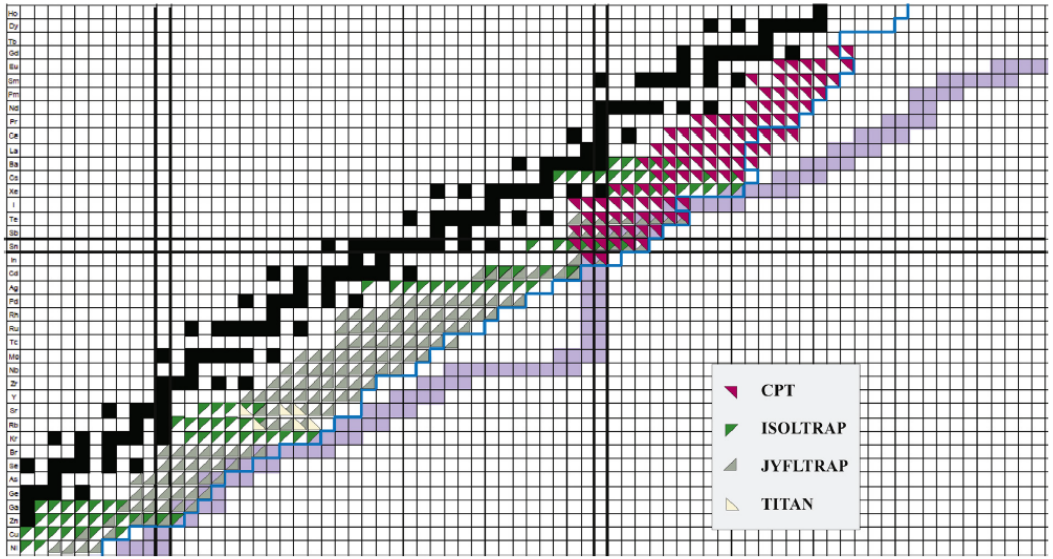




Stopped Beams (examples)

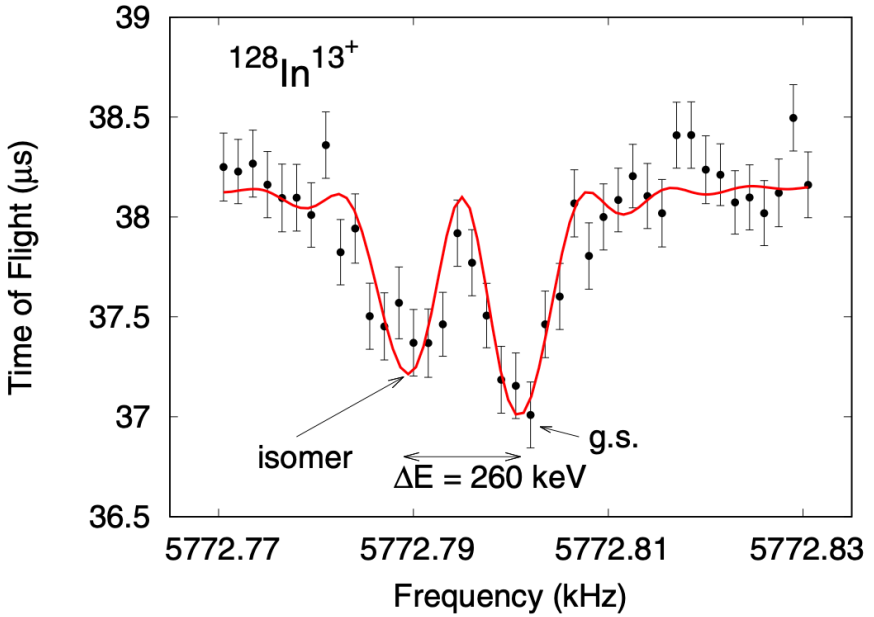
NSCL/FRIB, RIKEN, FAIR, TRIUMF, Argonne, …

Mass measurements at Argonne National Lab @CARIBU facility



J. A. Clark and G. Savard, Int. J. Mass Spectrom. 2013

Isomer measurements at TITAN (TRIUMF)



Babcock, et al., PRC 2018

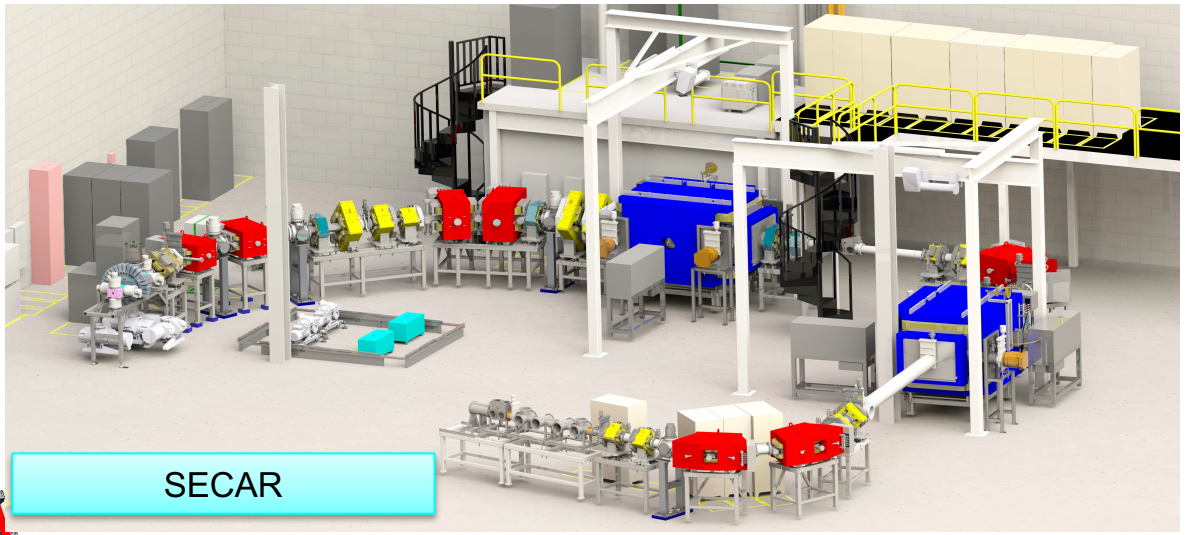
"Slow" Beams

NSCL/FRIB, FAIR, TRIUMF, Argonne, …

Fragmentation facilities have to slow down and re-accelerate the beam

From NSCL gas stopping

^{238}U 0.3 – 3 MeV/u
^{48}Ca 0.3 – 6 MeV/u

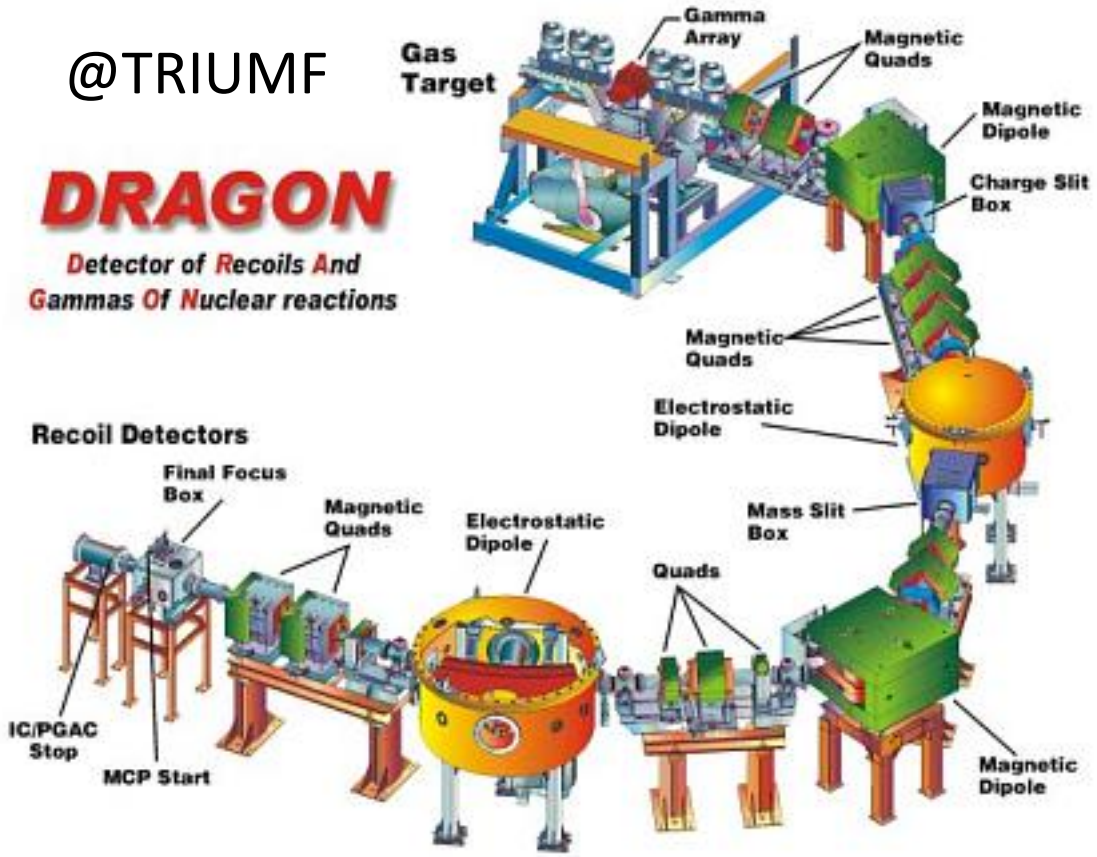


ReA facility at NSCL/FRIB

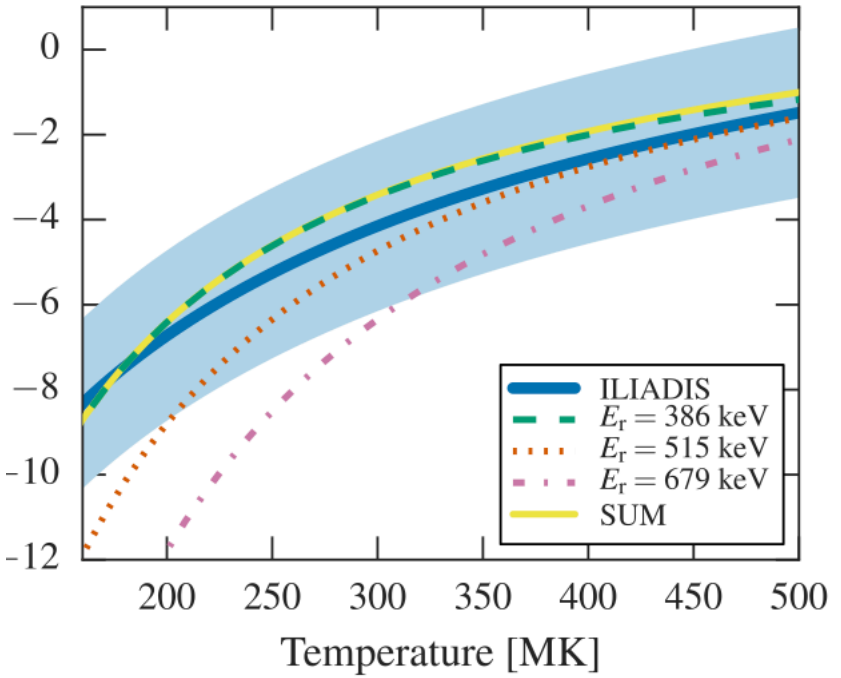
"Slow" Beams (example)

NSCL/FRIB, FAIR, TRIUMF, Argonne, …

@TRIUMF



- Direct measurement of $^{38}K(p,\gamma)^{39}Ca$
- Better understanding of Oxygen-Neon novae

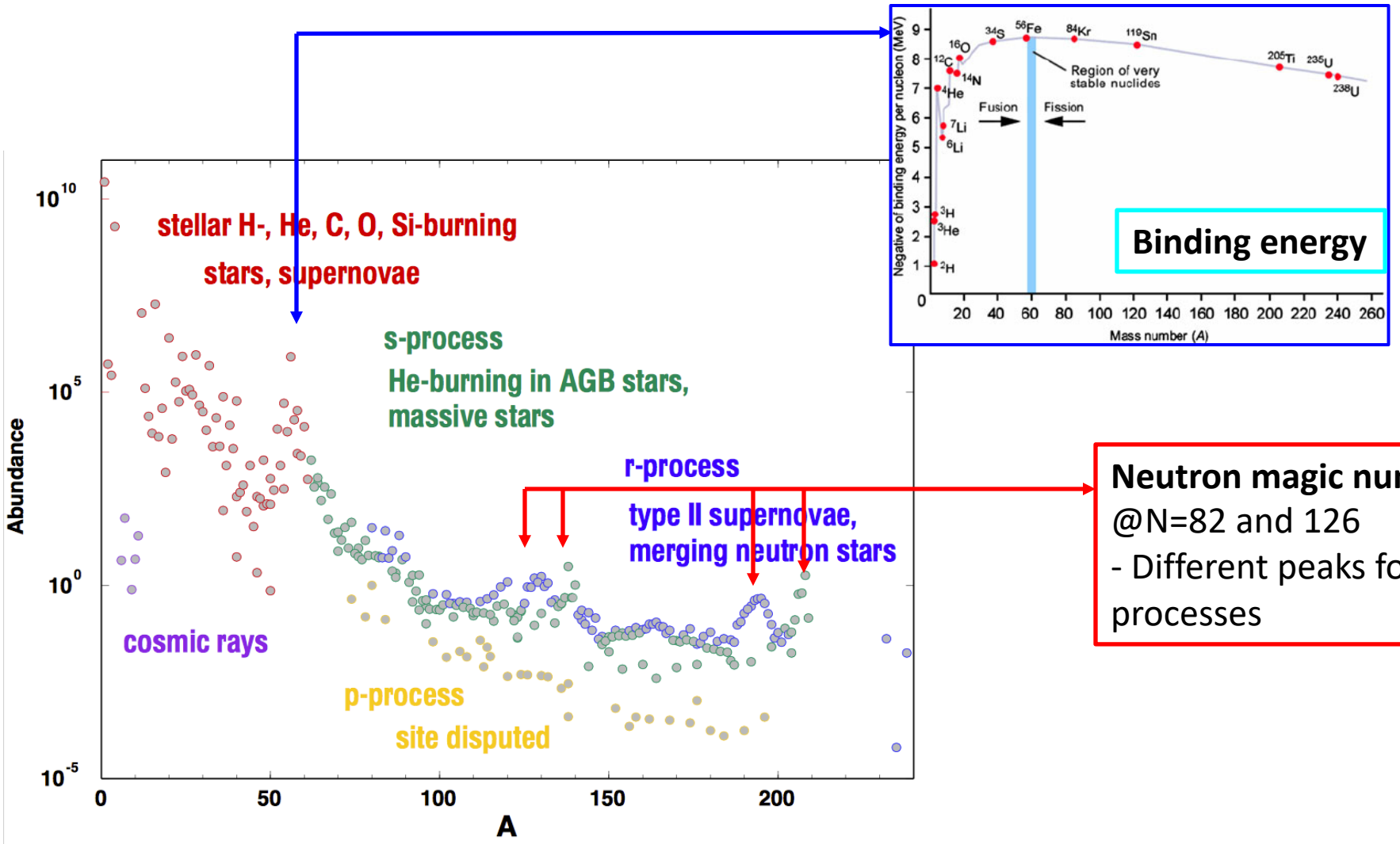


Lotay, Christian, et al., PRL 2016

Summary

- Nuclear input is critical for better understanding astrophysical processes.
- Complementary facilities, devices and techniques to address the large variety of data needs.
- Nuclear Astrophysics Community has developed and optimized detectors suitable to address big open questions in the field
- Next generation facilities will provide access to critical nuclei

Connections to nuclear physics



Neutron magic numbers
@N=82 and 126
- Different peaks for **s** and **r** processes