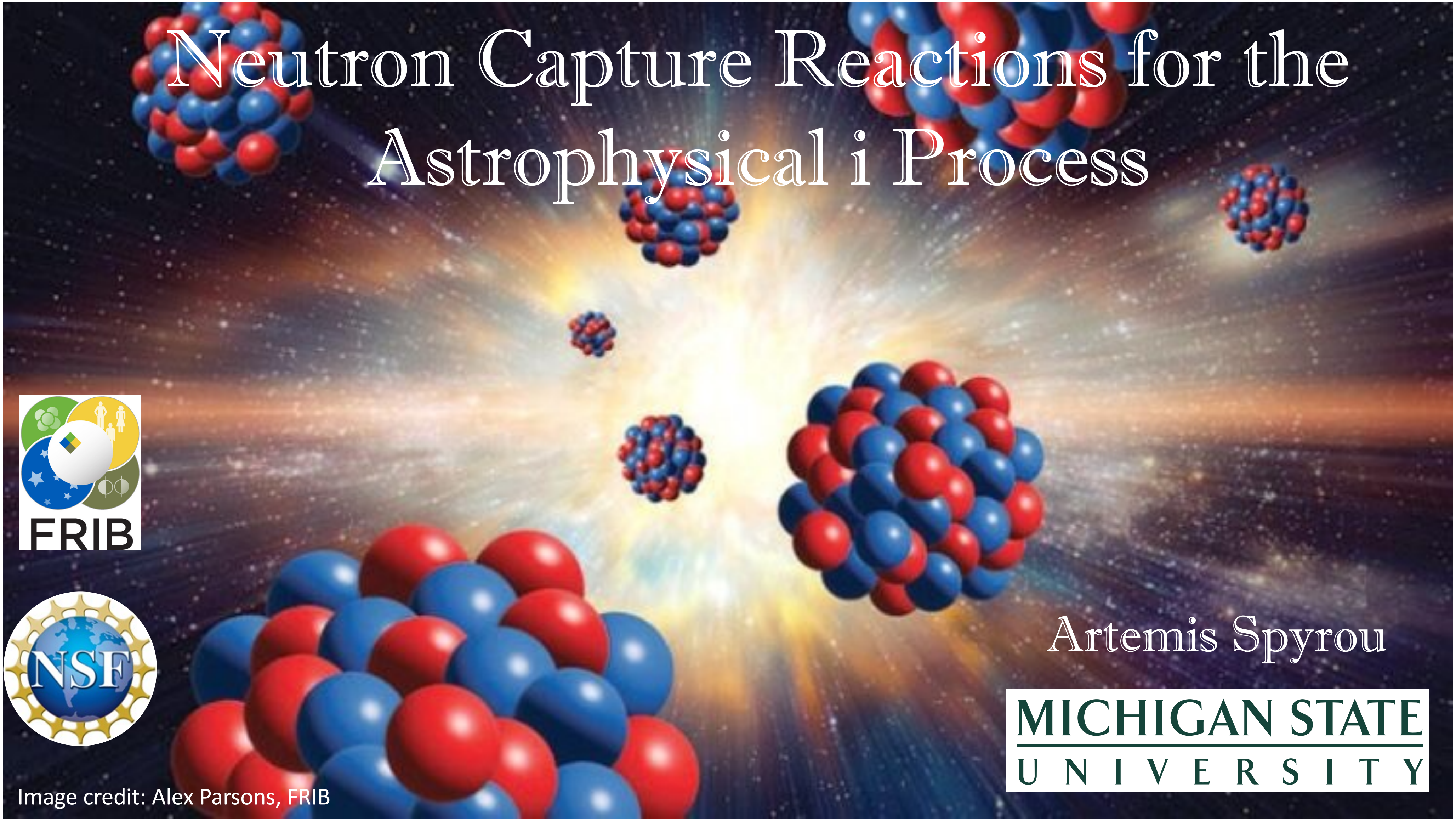
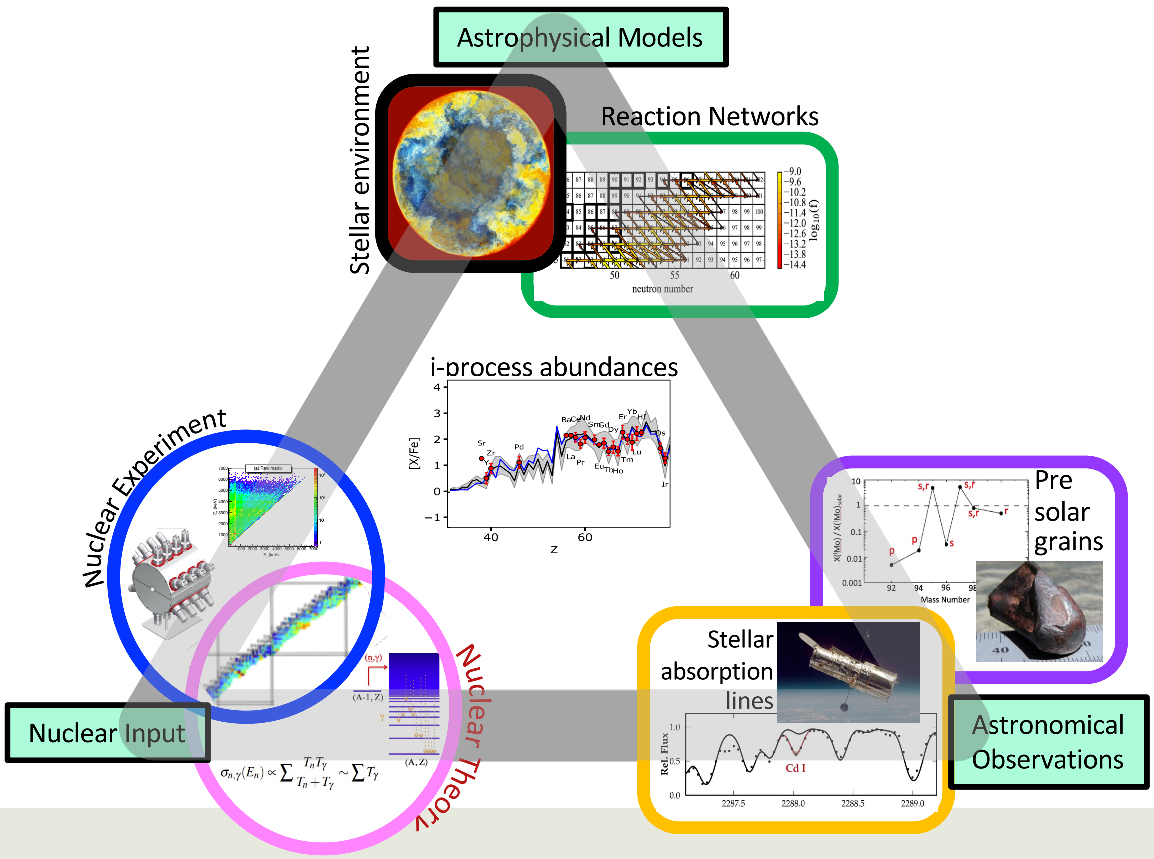
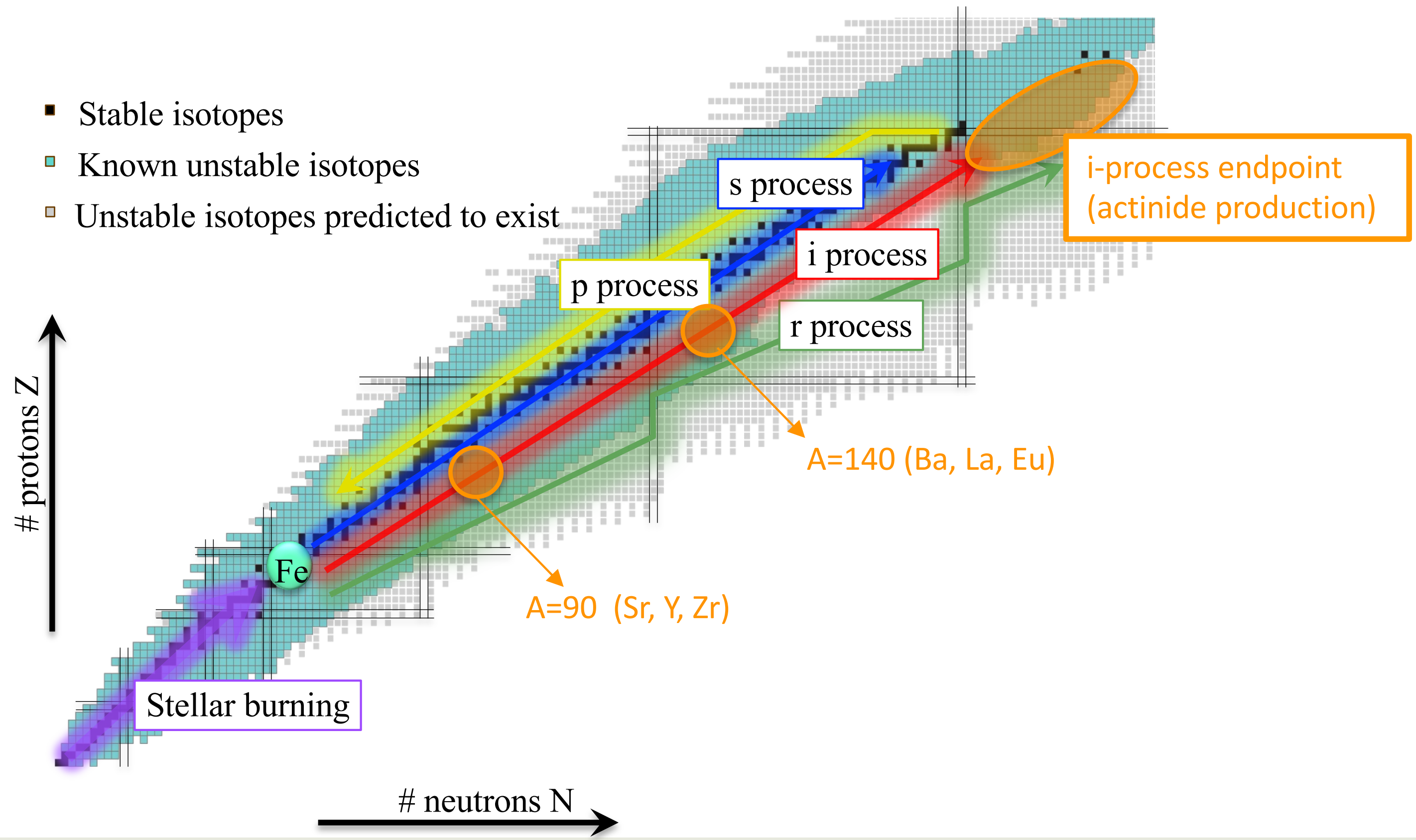

Neutron Capture Reactions for the Astrophysical i Process
Artemis Spyrou
MICHIGAN STATE UNIVERSITY
FRIB
NSF
Image credit: Alex Parsons, FRIB

The astrophysical i process

Nature Reviews (under review)
M. Wiedeking
S. Goriely
M. Guttormsen
F. Herwig
A.C. Larsen
S. Liddick
D. Muecher
A. Richard
S. Siem
A. Spyrou

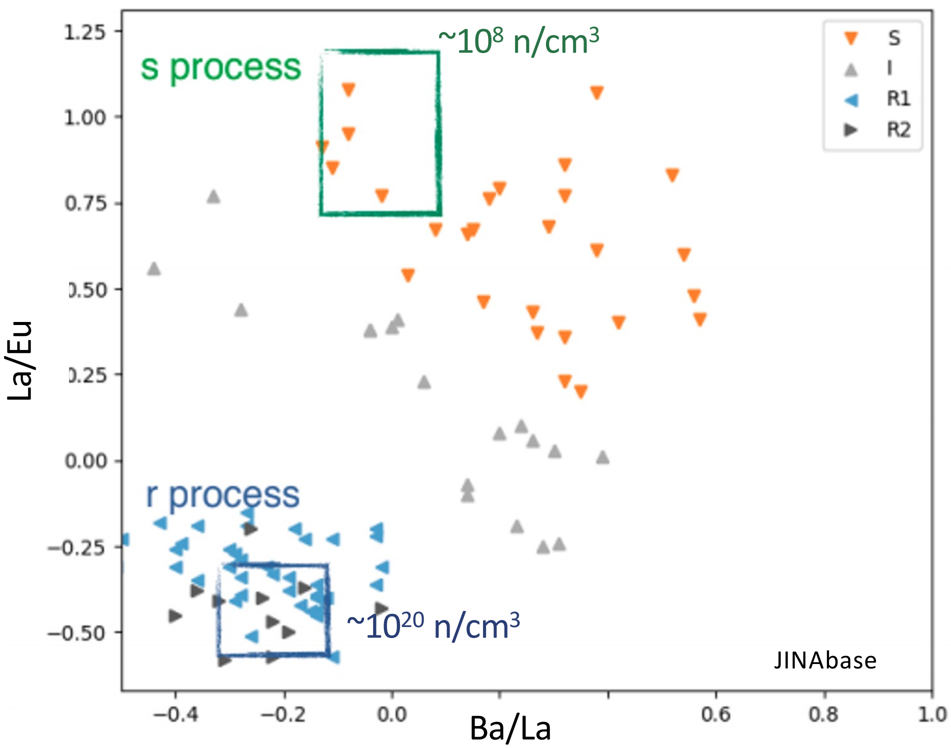


The astrophysical i process



i process calculations signatures

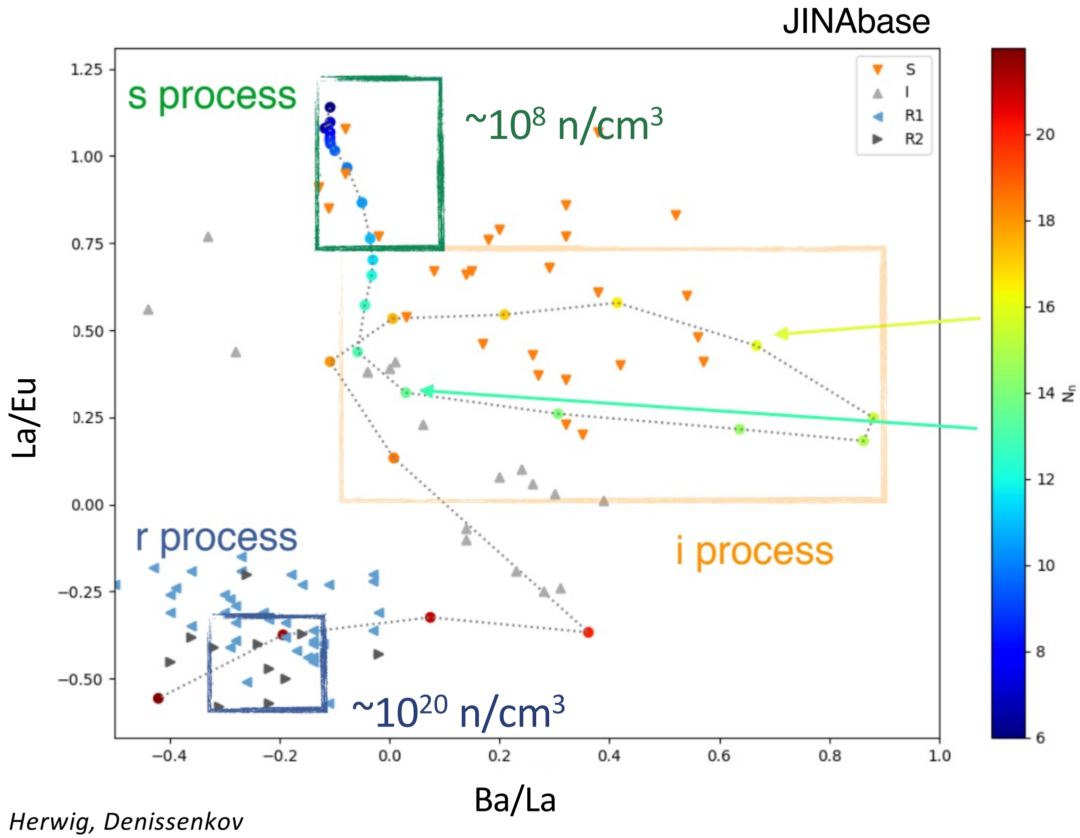
JINAbase



Herwig, Denissenkov

- Ba/La vs La/Eu sensitive to astrophysical conditions
- s and r process stars exhibit different abundance ratios
- Simple one zone model changing the neutron density
- Group of stars not explained by s or r neutron densities

Simple i process calculations



Herwig, Denissenkov

- Ba/La vs La/Eu sensitive to astrophysical conditions
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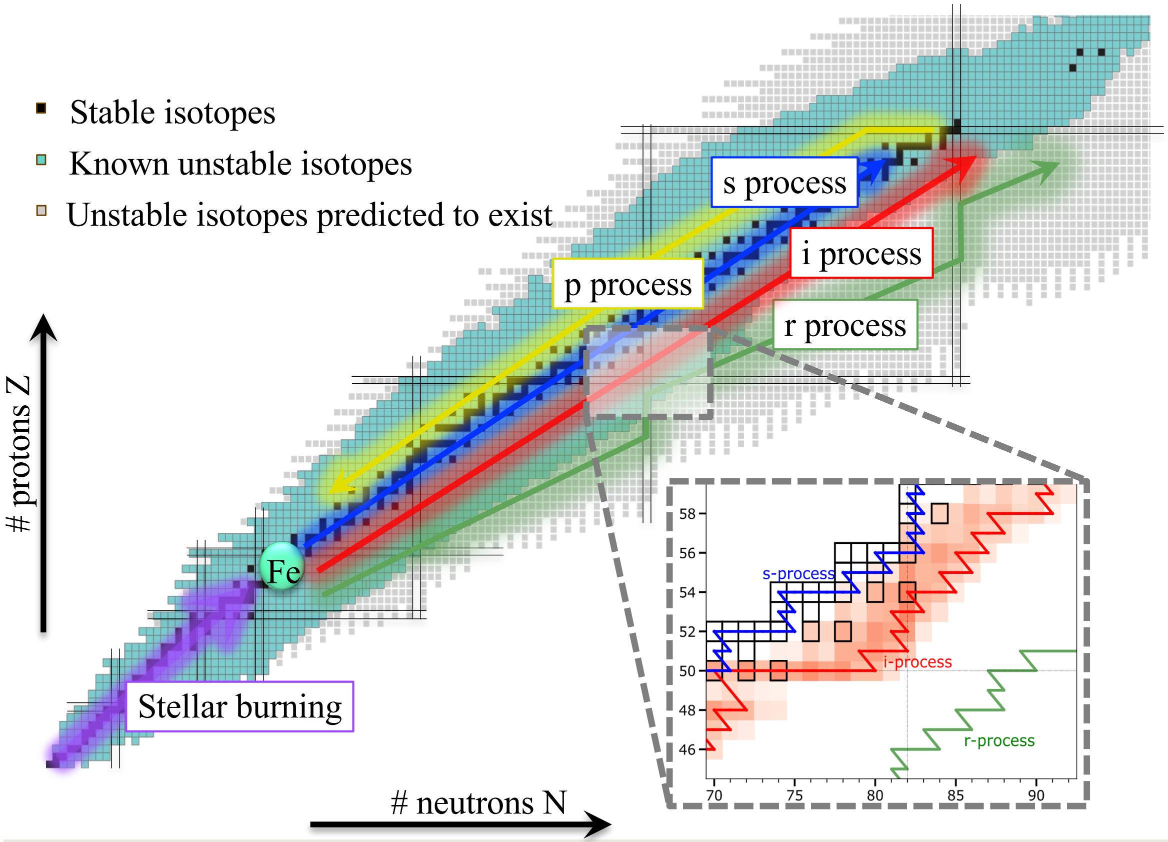
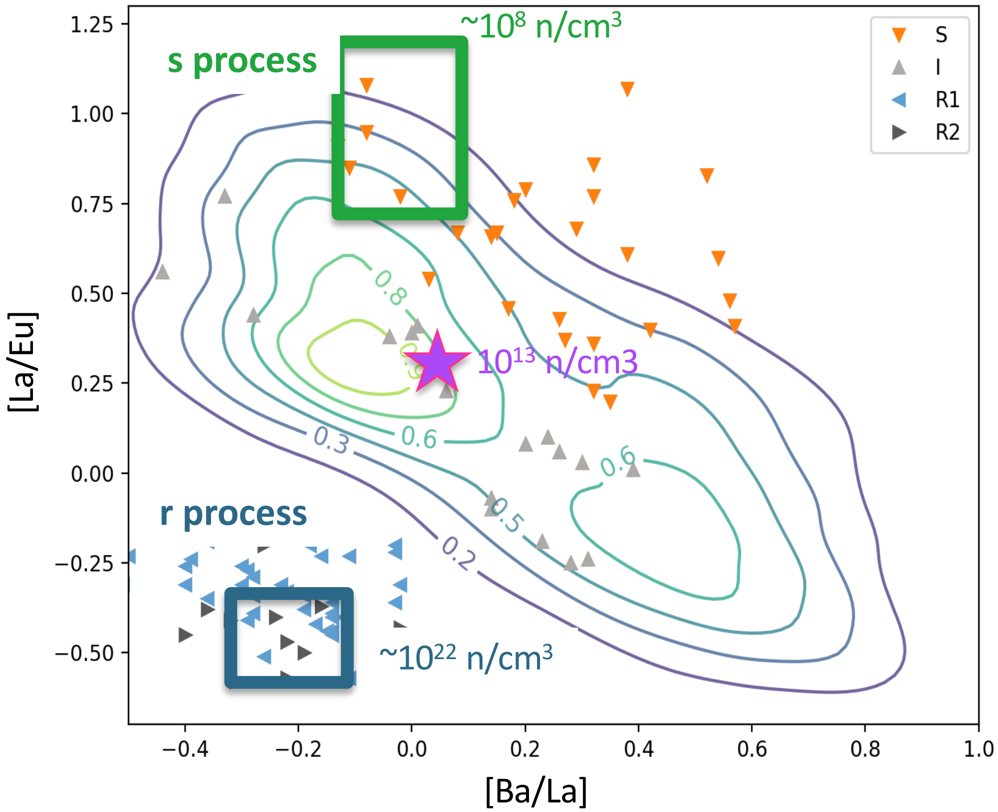
i-process nucleosynthesis



- Intermediate between s and r processes
- Involves nuclei up to ~10 steps from stability
- Nuclear properties studied experimentally (masses, T1/2, β-decays)
- Missing ingredient: neutron-capture reactions
- Sensitivity studies show the impact of uncertain neutron-captures (Denissenkov 2018, Martinet 2024)

Sensitivity to neutron-capture rates

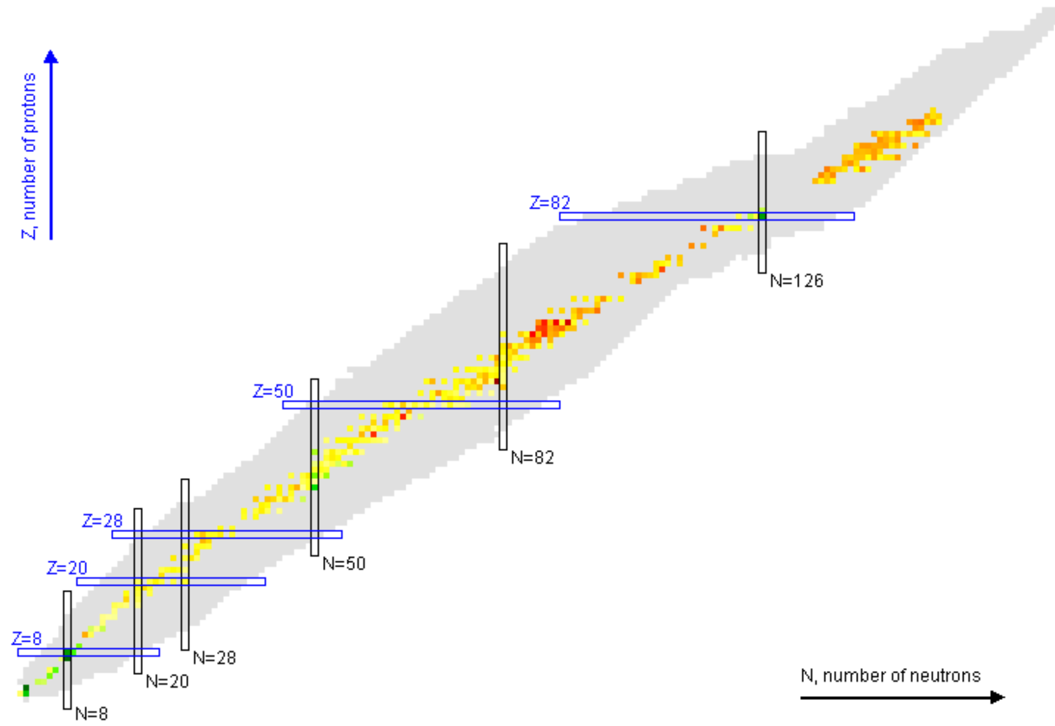


Element	Reaction	$r_P(f_i, X_k/X_{k,0})$
Ba	^{134}I	+0.3689
	^{137}Cs	-0.6842
La	^{139}Cs	-0.2558
	^{139}Ba	-0.8651
Eu	^{151}Nd	-0.5975
	^{151}Pm	-0.4975

Denissenkov, et al, MNRAS (2019)

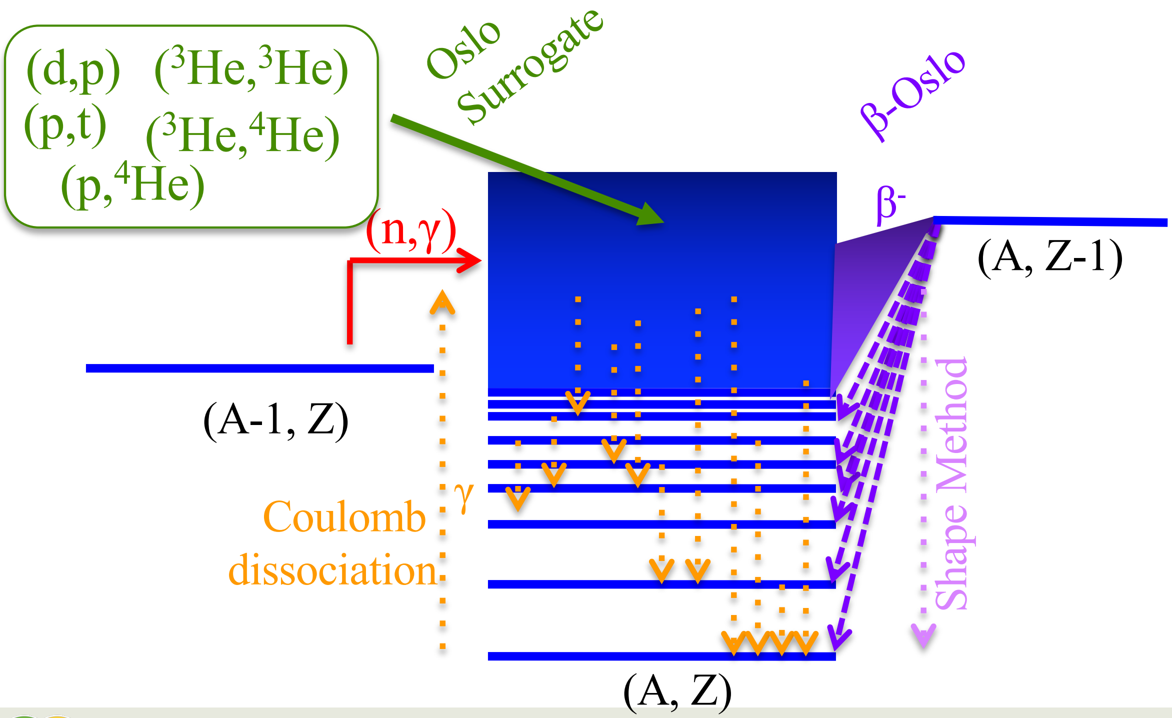
The issue with neutron capture reactions

- Measuring Neutron Capture reactions on short-lived nuclei is challenging
- Cannot make a neutron target
- Cannot make a target out of a short-lived isotope
- Need indirect techniques



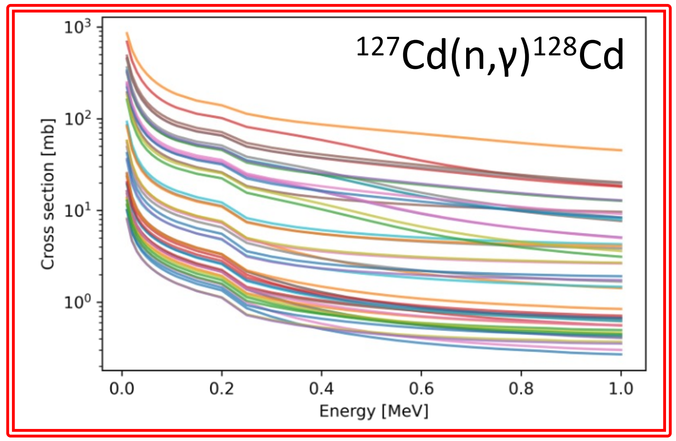
Neutron Captures

- Direct measurement of (n,γ) reactions on short-lived isotopes: challenging
- Indirect techniques to provide constraints



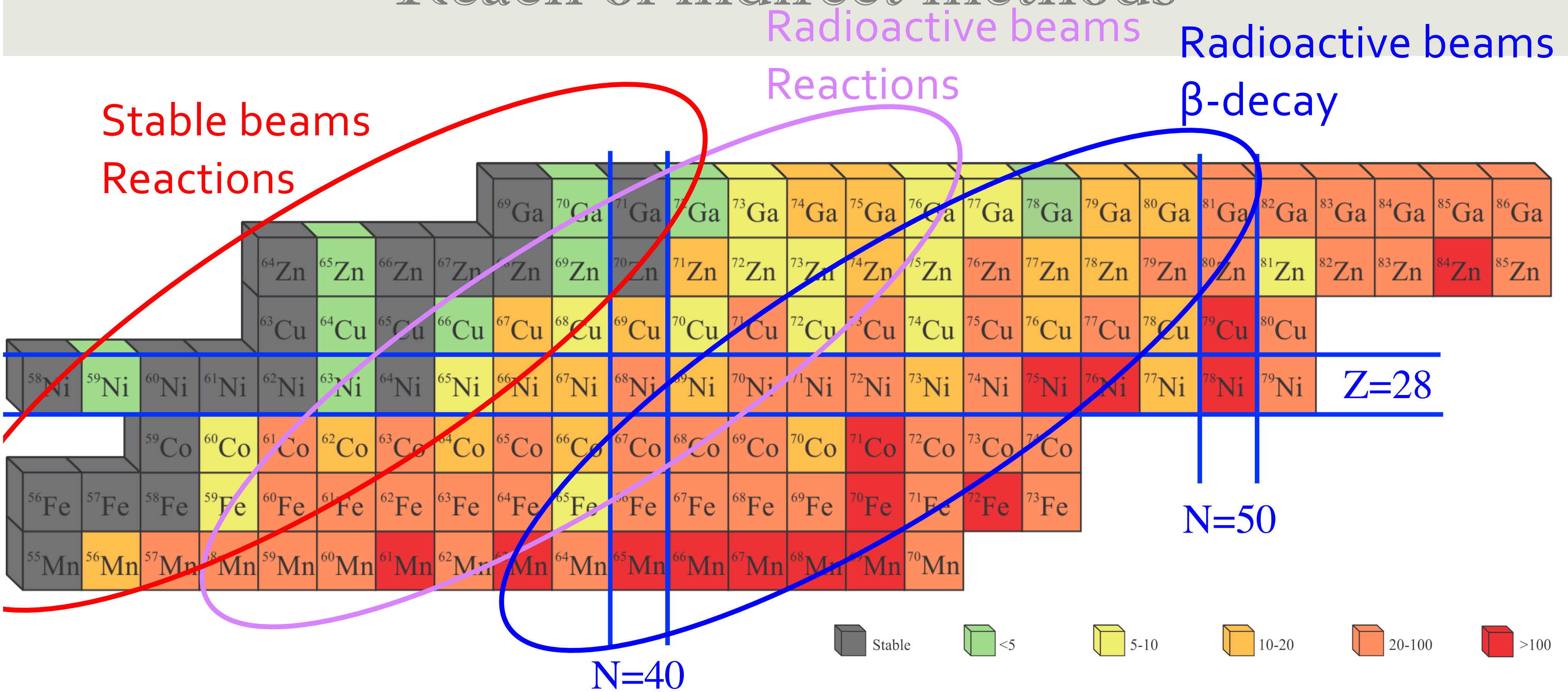
Hauser – Feshbach (Statistical Model)

- Nuclear Level Density (NLD)
- γ-ray strength function (γSF)
- Optical model potential



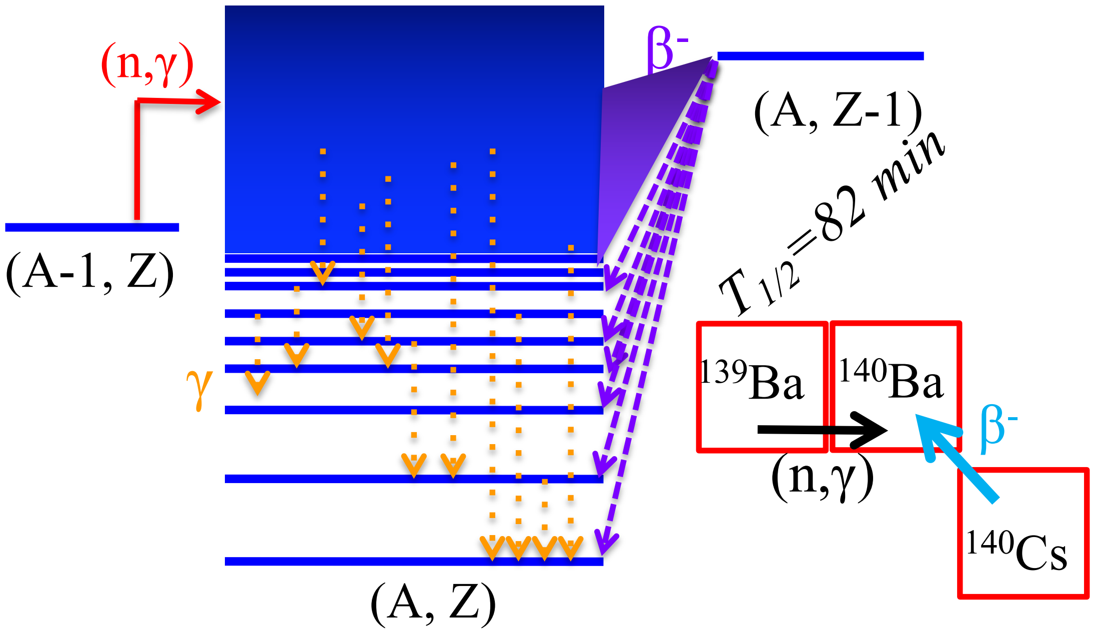
Larsen et al, PPNP 107 (2019) 69
Escher et al, PRL 121 (2018) 052501
Spyrou, Liddick, et. al., PRL 2014
Wiedeking et al PRC 2021
Muecher, Spyrou et al, PRCL 2023

Reach of indirect methods



Liddick, Spyrou et. al., PRL 2016

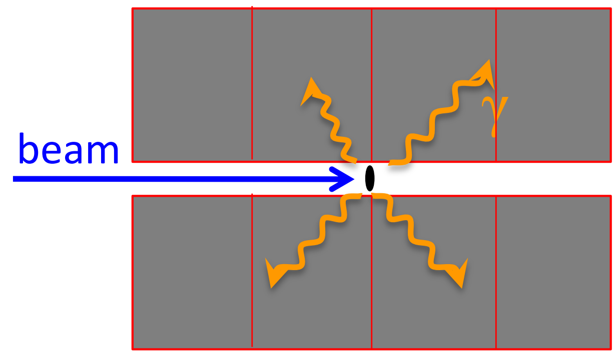
β-Oslo method



- Disadvantage: limited by Q-value, S_n, nuclear structure
- Advantage of β-decay: feasible with low beam intensities

•Need:

- ✓ Radioactive Beam
- ✓ Segmented γ-ray calorimeter:

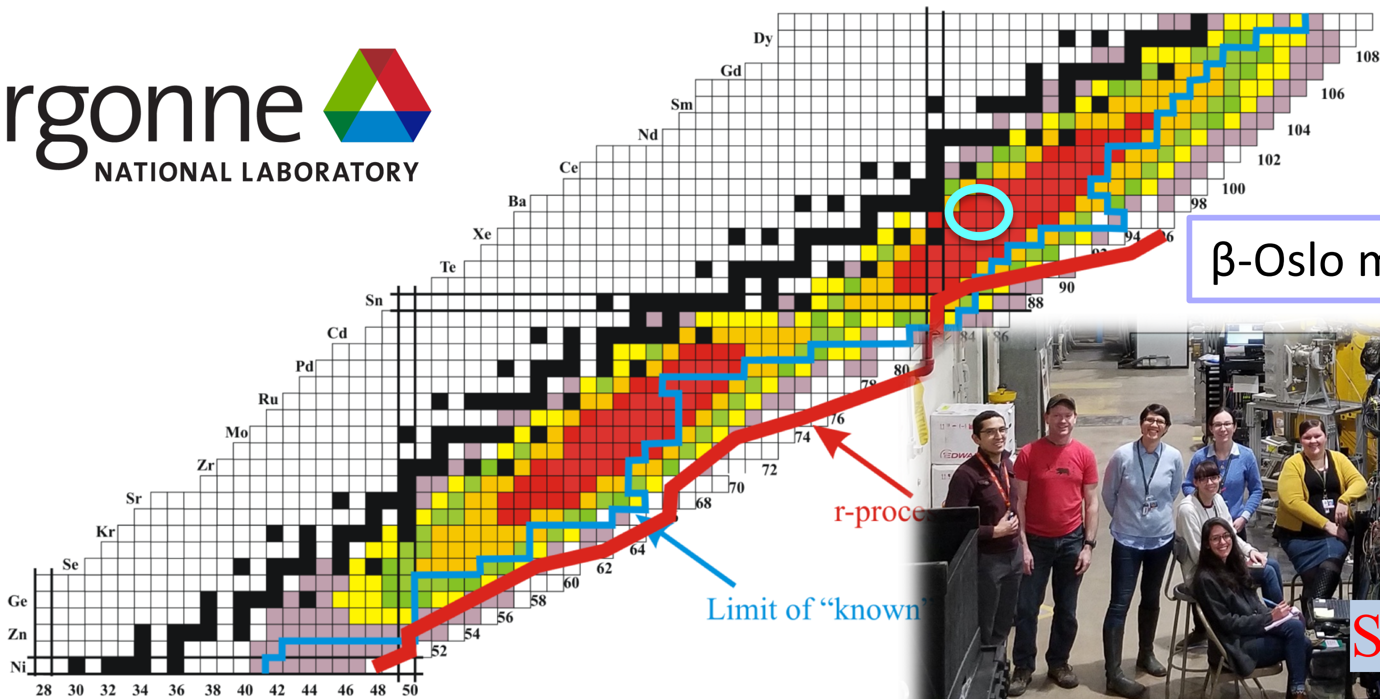


$$E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots$$

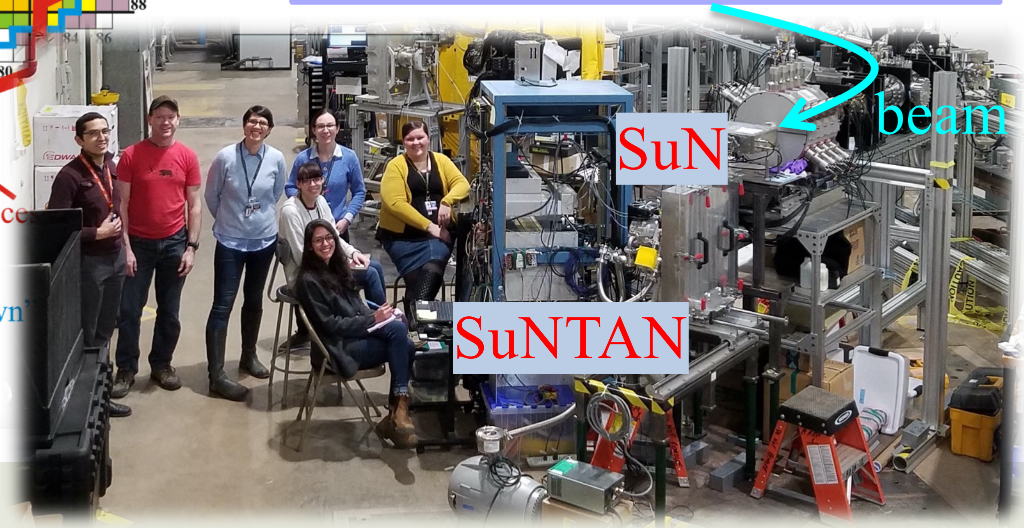
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

CARIBU @ ANL

^{252}Cf spontaneous fission yield from 1 Ci source

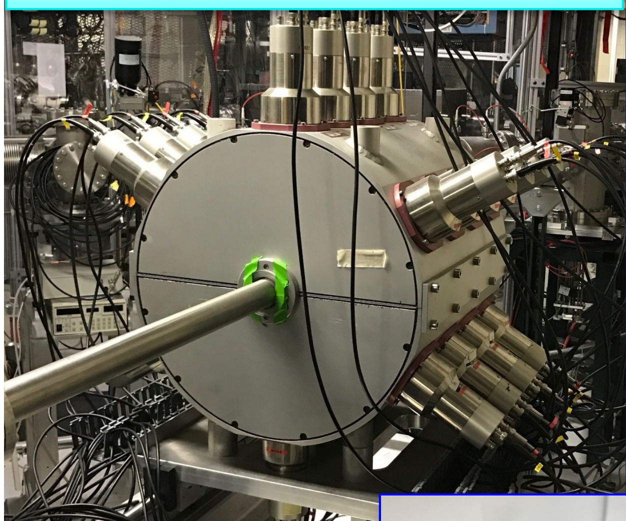


β-Oslo method with SuN at ANL

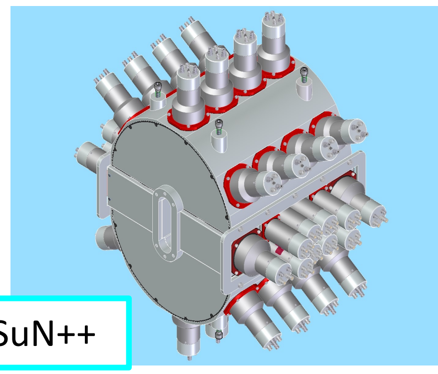


β-Oslo method

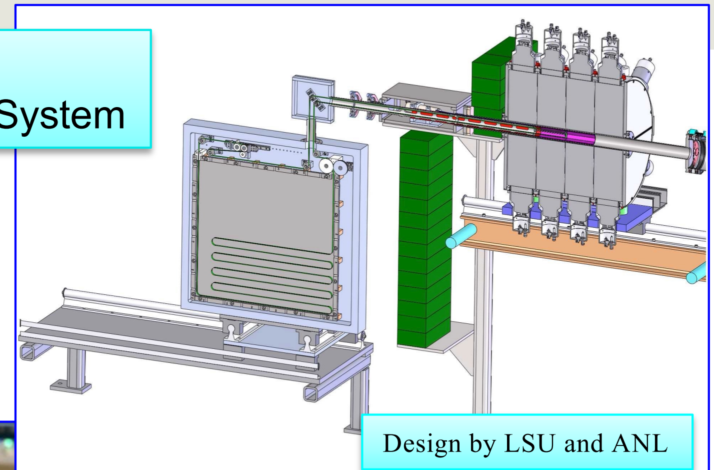
SuN
γ-Total Absorption Spectrometer



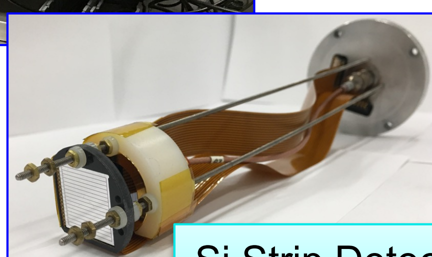
SuN++



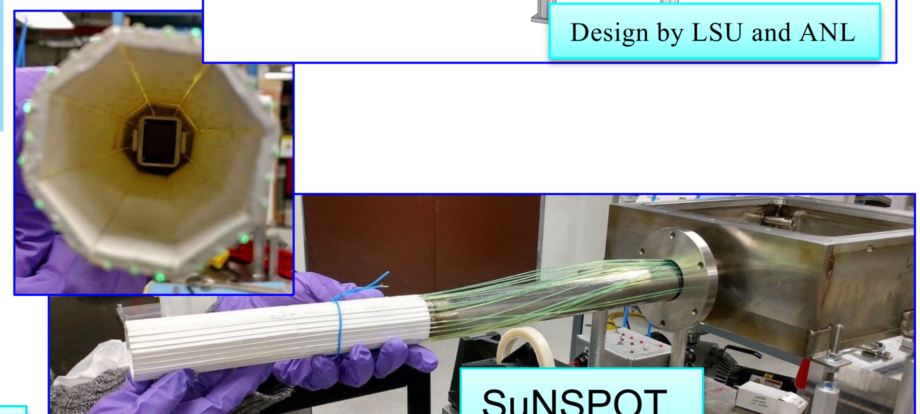
SuNTAN
Tape Transport System



Design by LSU and ANL



Si Strip Detector
Implantation-decay correlation

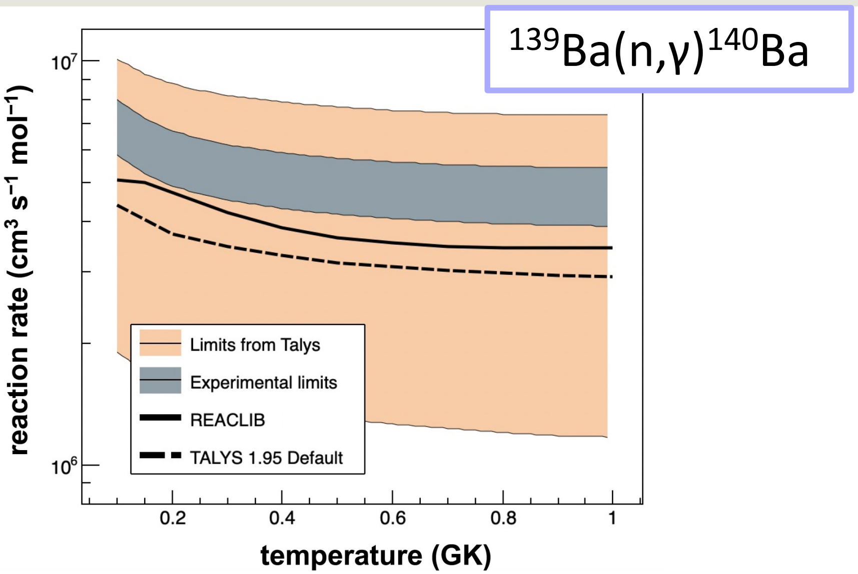


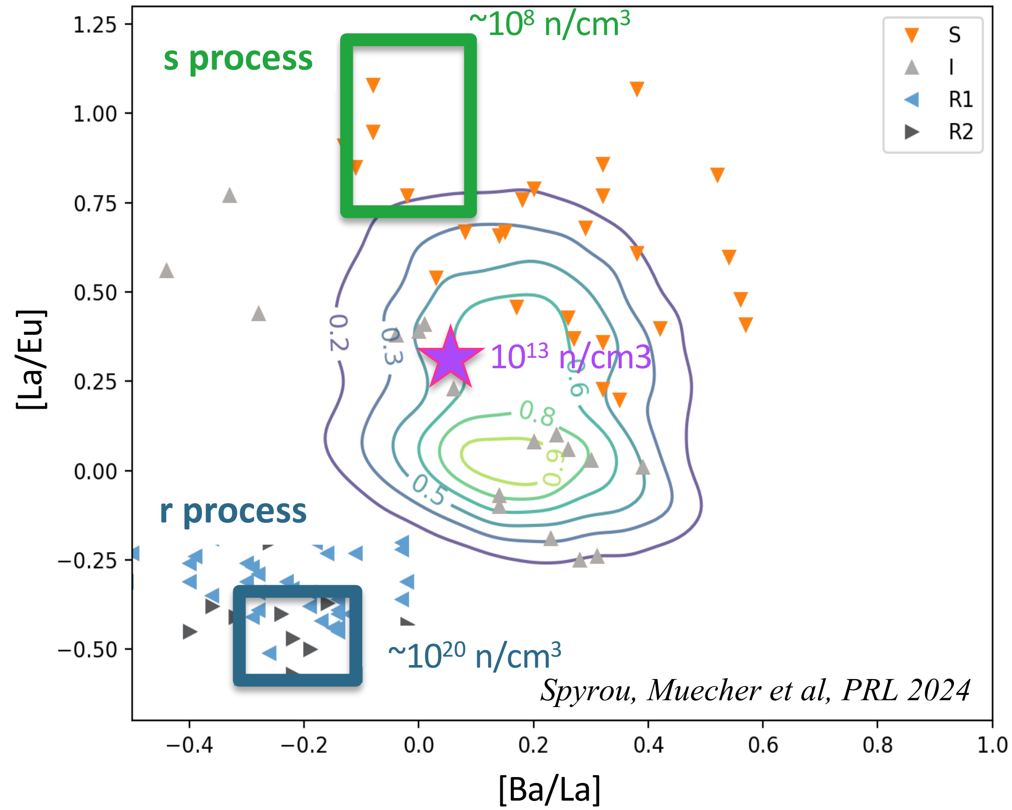
SuNSPOT
β-detection

Hope College

A. Simon, S.J. Quinn, A.S., et al., Nucl. Instr. Meth A 703, 16 (2013)

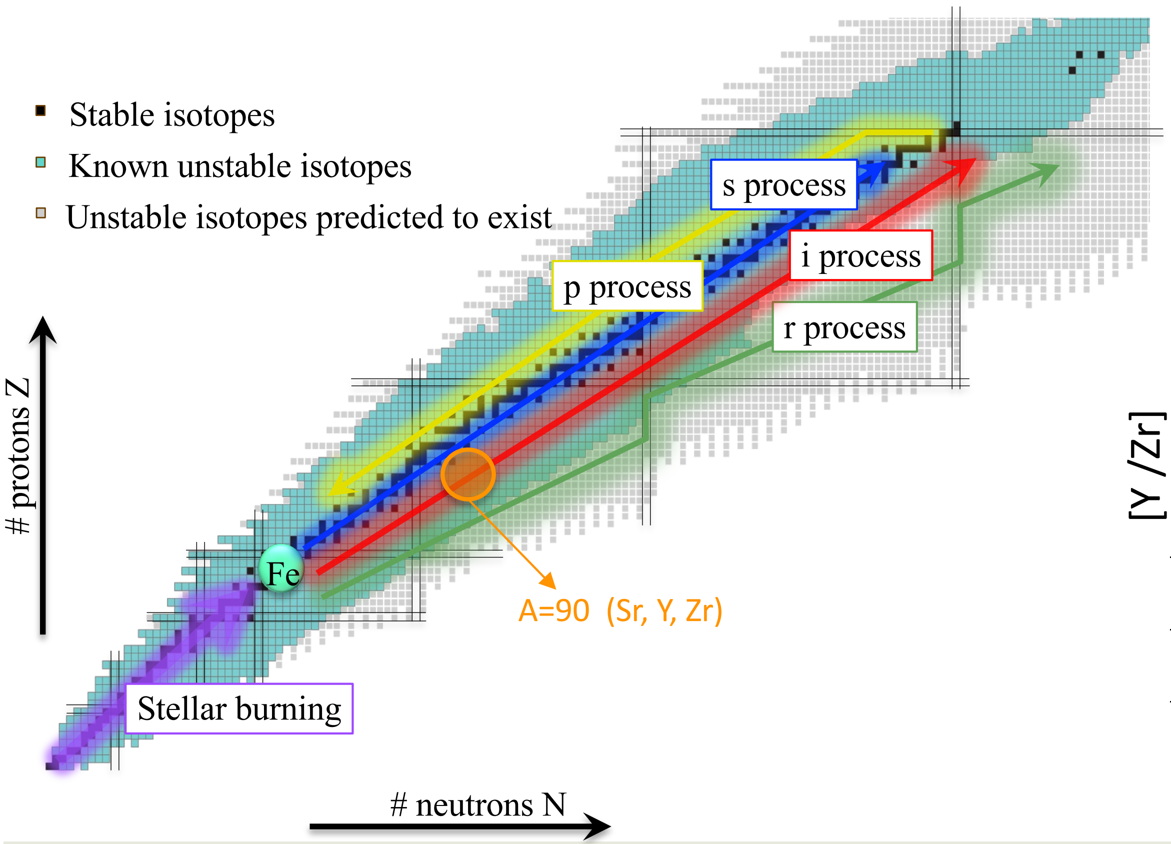
Sensitivity to neutron-capture rates

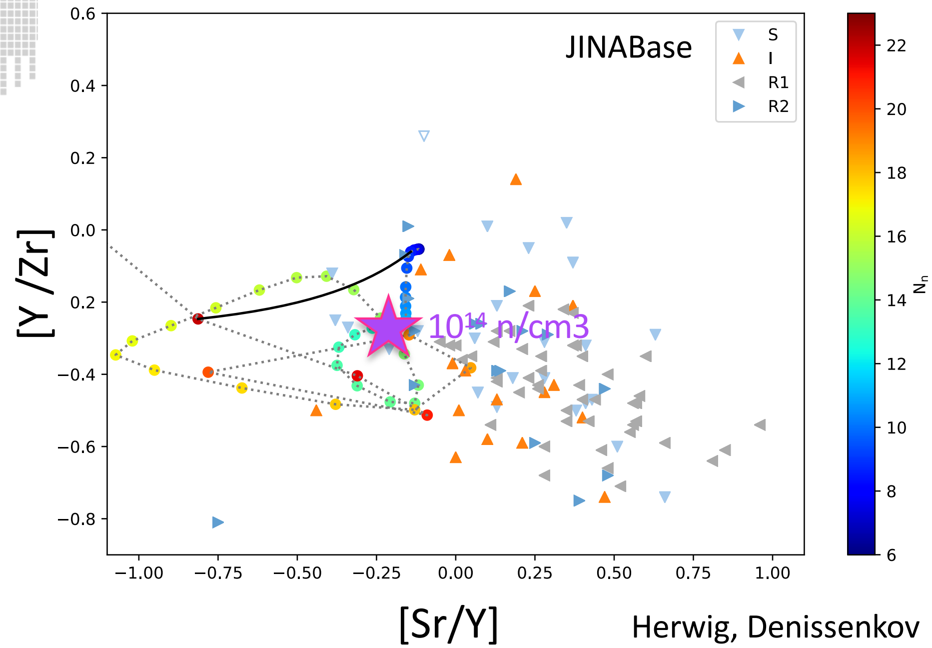




- Verified that within the specific model, 10^{13}n/cm^3 is a viable neutron density to reproduce observations
- Can be used to identify conditions that could reproduce specific stars
- New: $^{151}Nb(n,\gamma)^{152}Nb$ to constrain Eu

i process around A=90

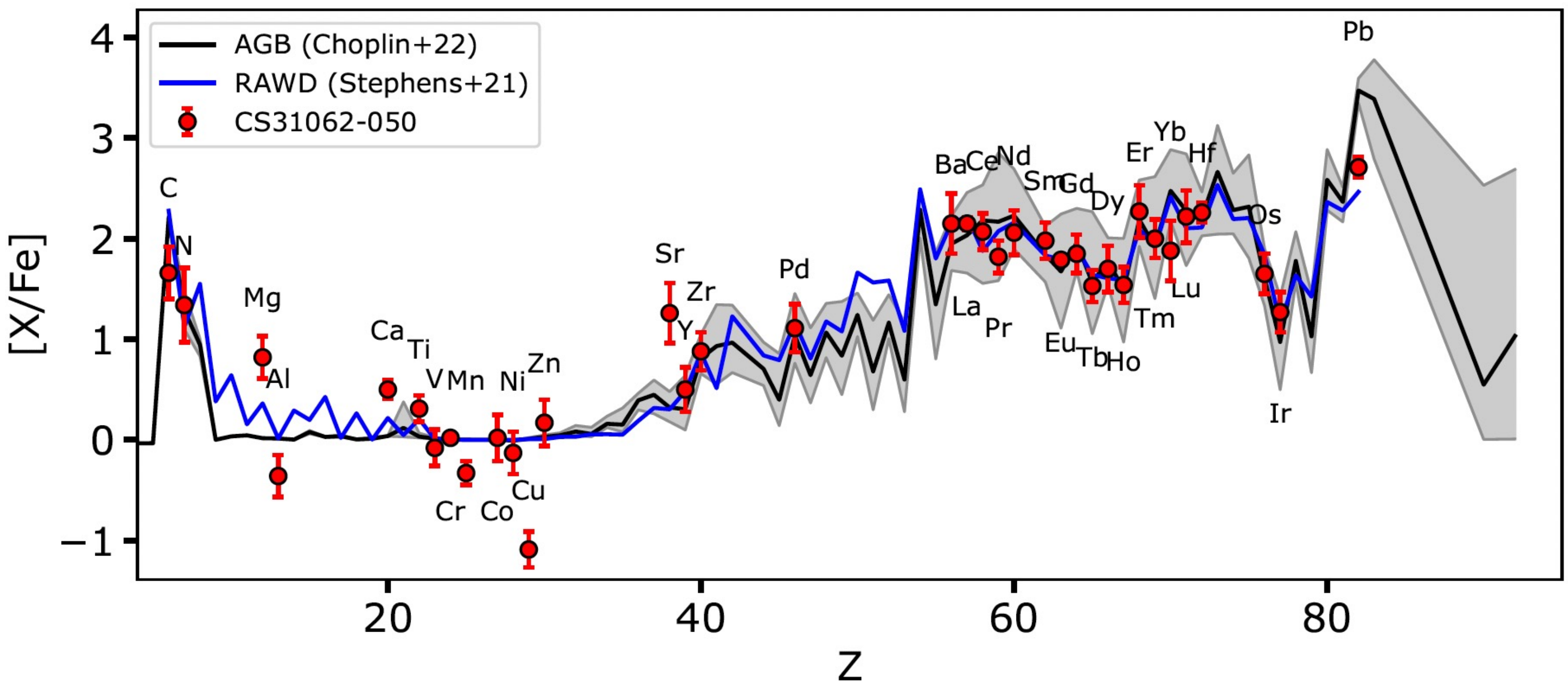




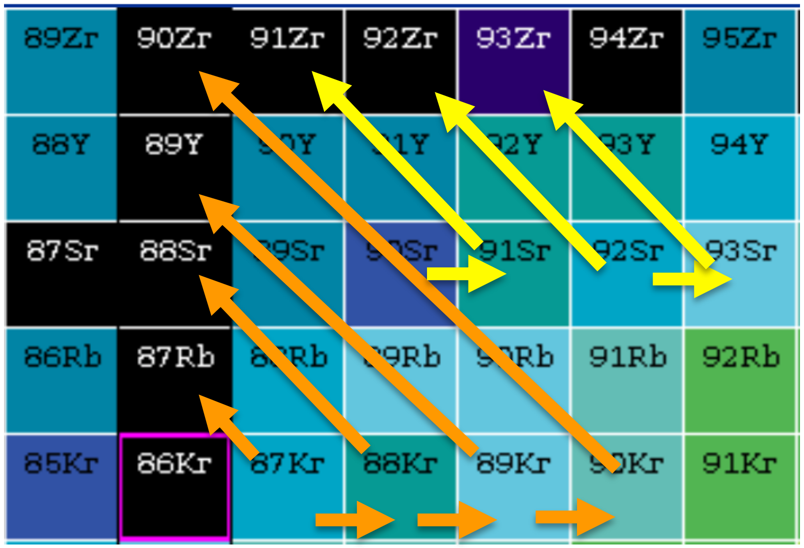
Herwig, Denissenkov

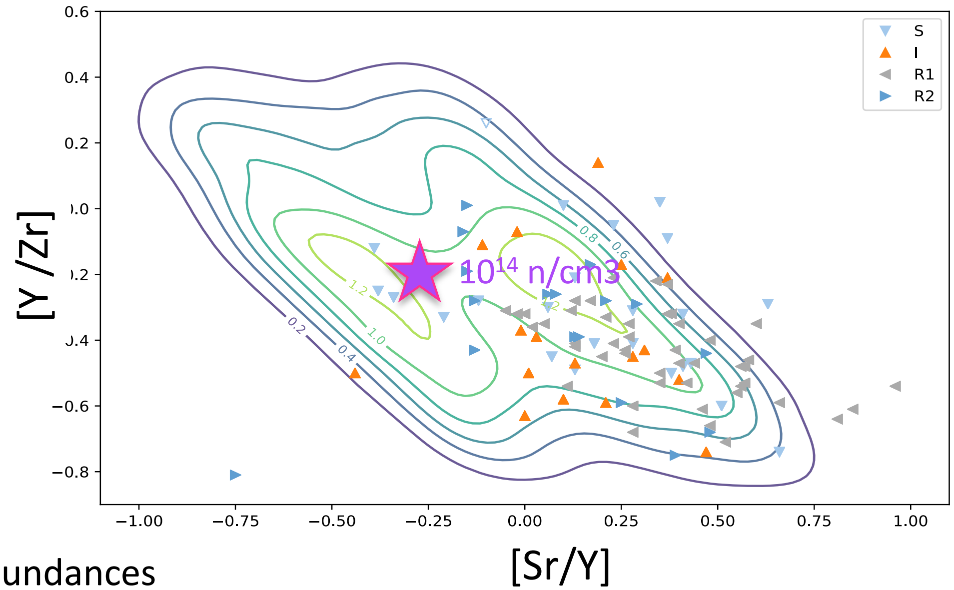
The Sr puzzle: i-process models

*Wiedeking et al, **Nature Reviews** (under review)*



i process around A=90

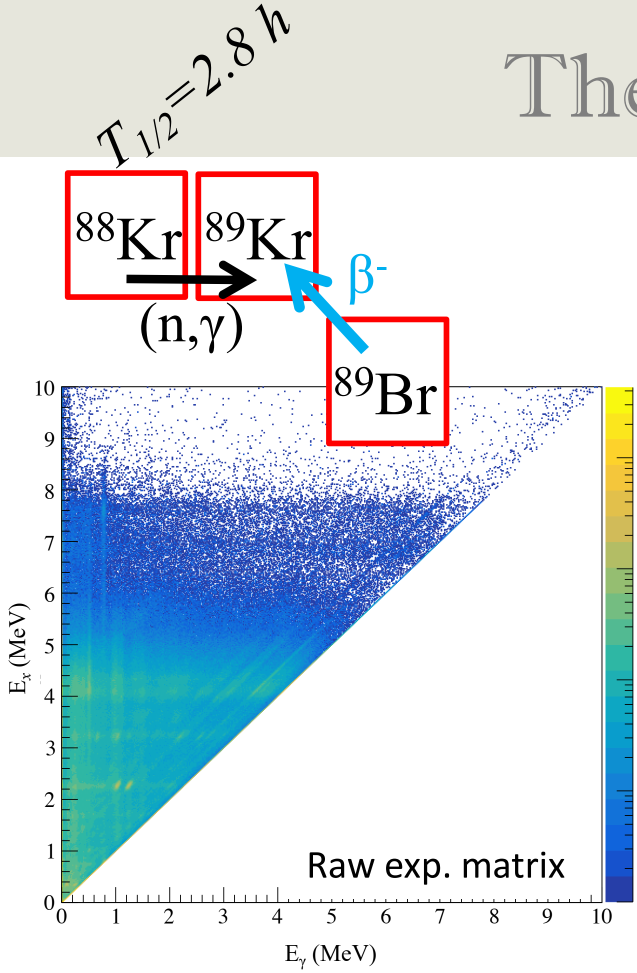




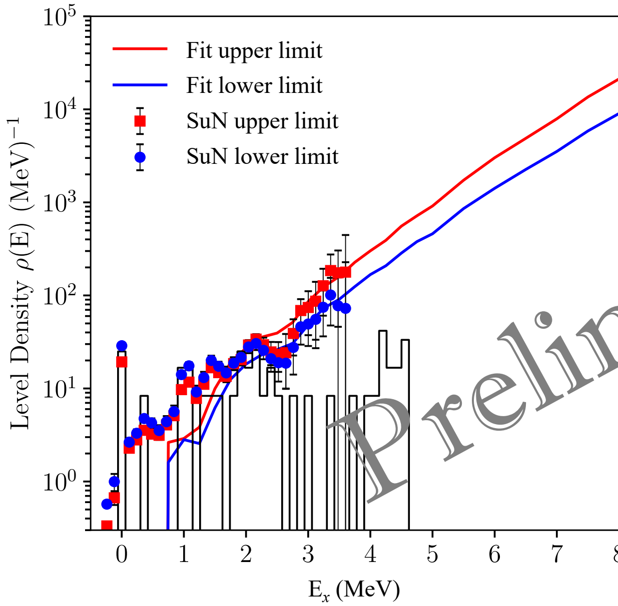
- $^{88}Kr(n,\gamma)^{89}Kr$ – has the largest impact on the Sr and Y abundances
- $^{87}Kr(n,\gamma)^{88}Kr$ also identified affecting Rb (Muecher et al. PRCLett2023, Uthayakumaar et al., in prep.)
- $^{90,92}Sr(n,\gamma)^{91,93}Sr$ affecting Zr (Sweet et al PRC2024, Greaves et al, PRC submitted)

The ^{88}Kr(n,γ)^{89}Kr reaction

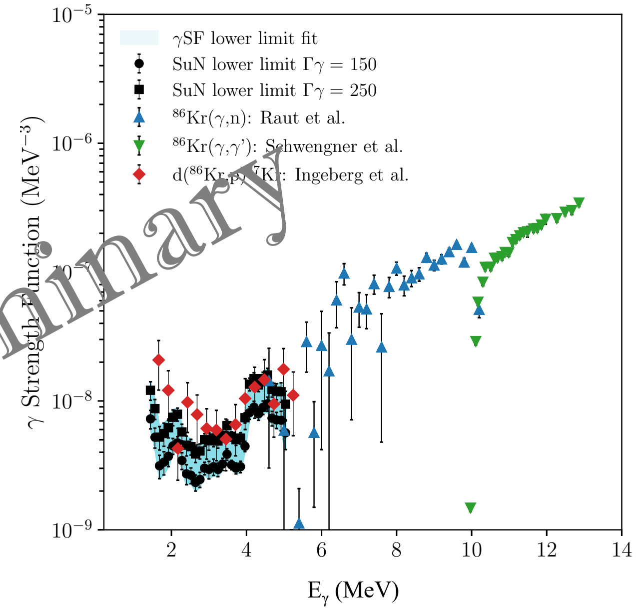
Caley Harris
MSU



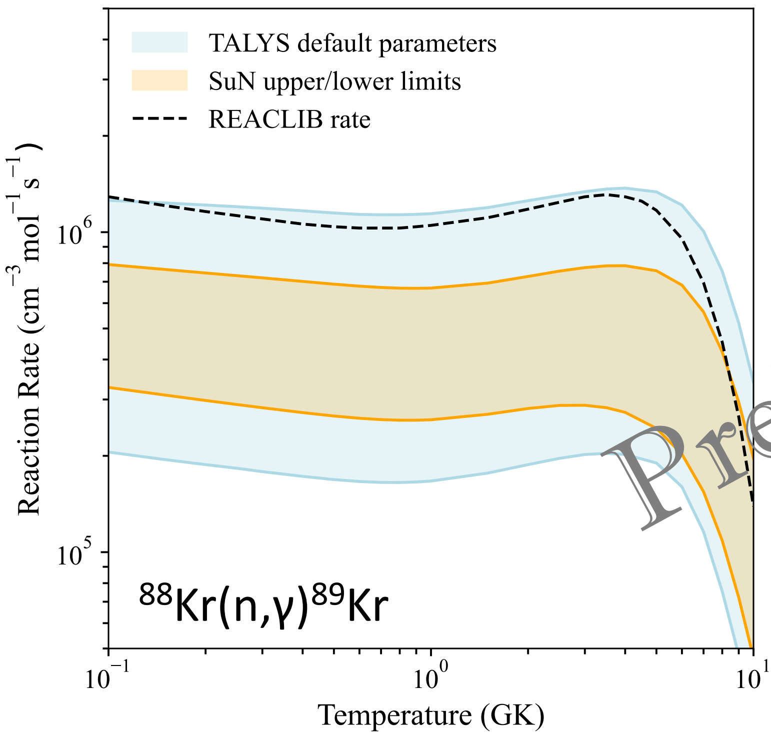
^{89}Kr Nuclear Level Density

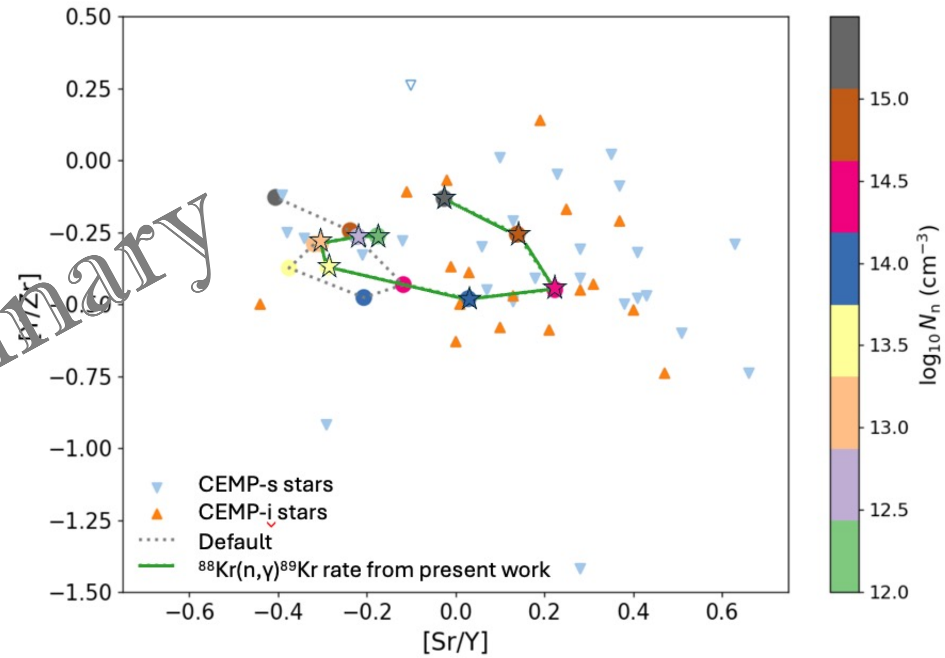


^{89}Kr γ-ray Strength Function



Results and impact of $^{88}Kr(n,\gamma)^{89}Kr$ reaction



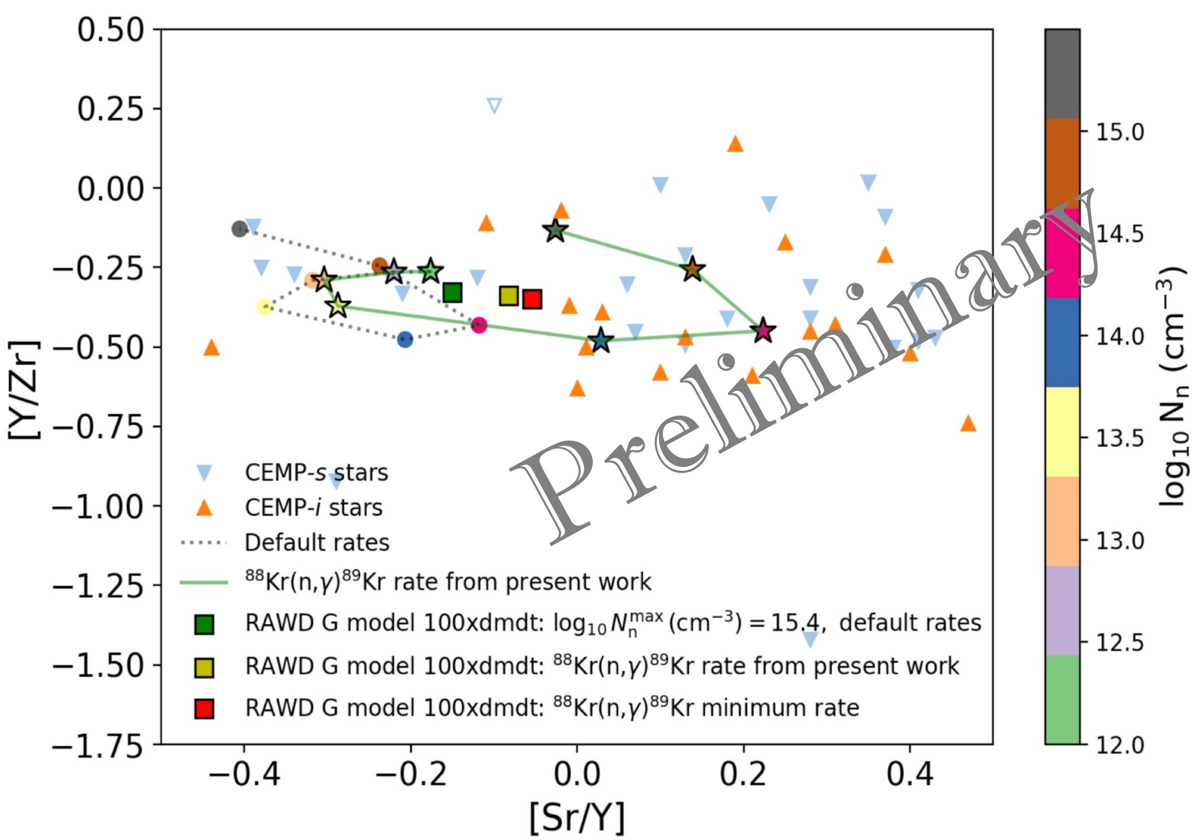


Preliminary

- **$^{88}Kr(n,\gamma)^{89}Kr$** reaction rate lower than default
- Higher production of Sr in i-process models
- Remaining uncertainties due to $^{89}Rb(n,\gamma)^{90}Rb$ and other reactions.

Pavel Denissenkov

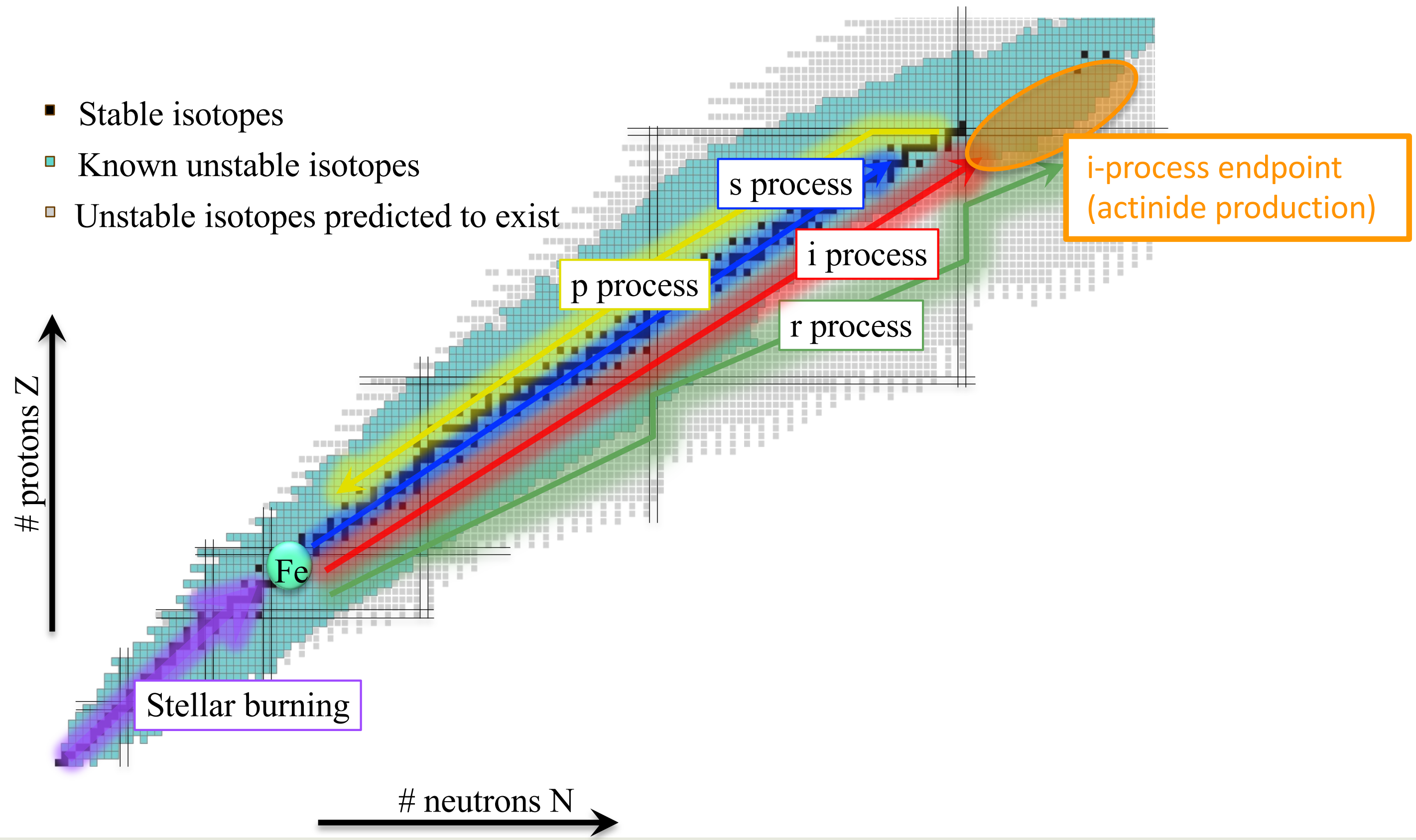
Results and impact of $^{88}Kr(n,\gamma)^{89}Kr$ reaction



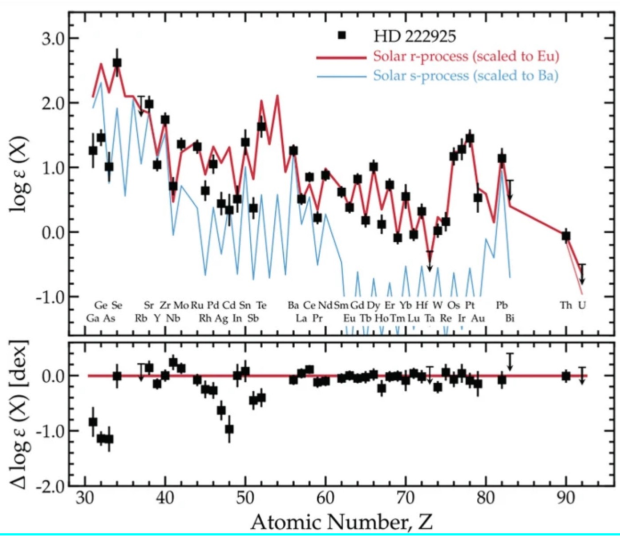
- Simple one-zone model can explain observations at high neutron densities
- More realistic multi-zone RAWWD calculations do not reproduce data.
- Investigate the issue further.

Pavel Denissenkov

The astrophysical i process



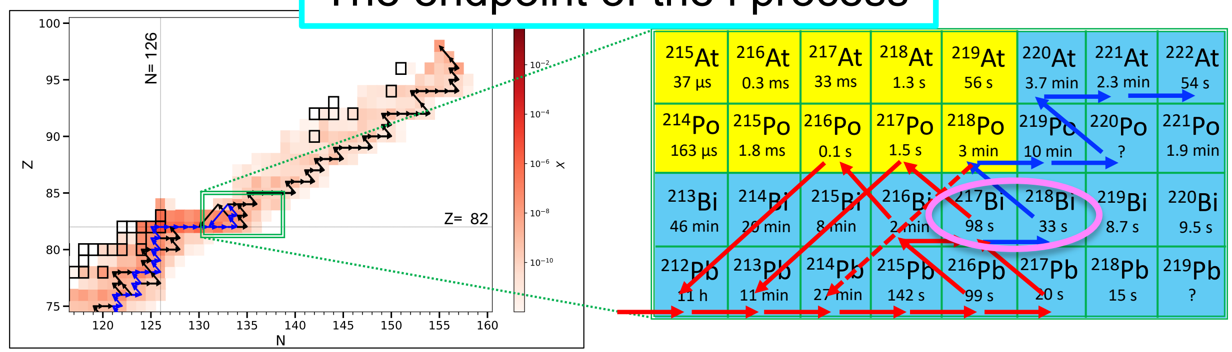
Actinide production

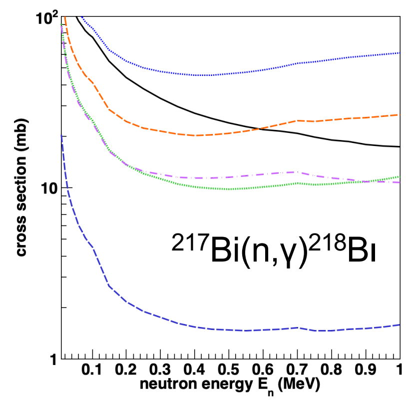


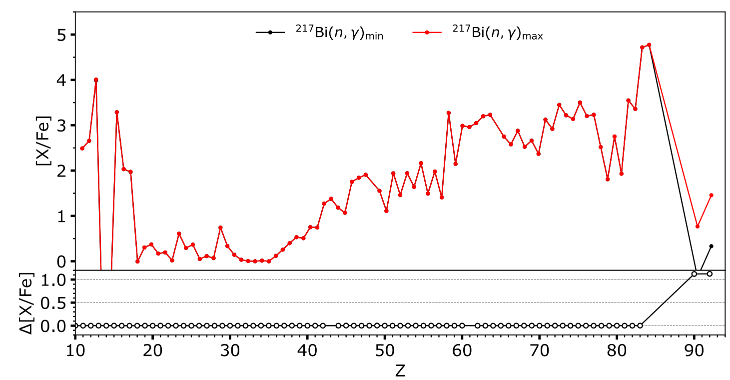
“Uranium comes exclusively from the r process”

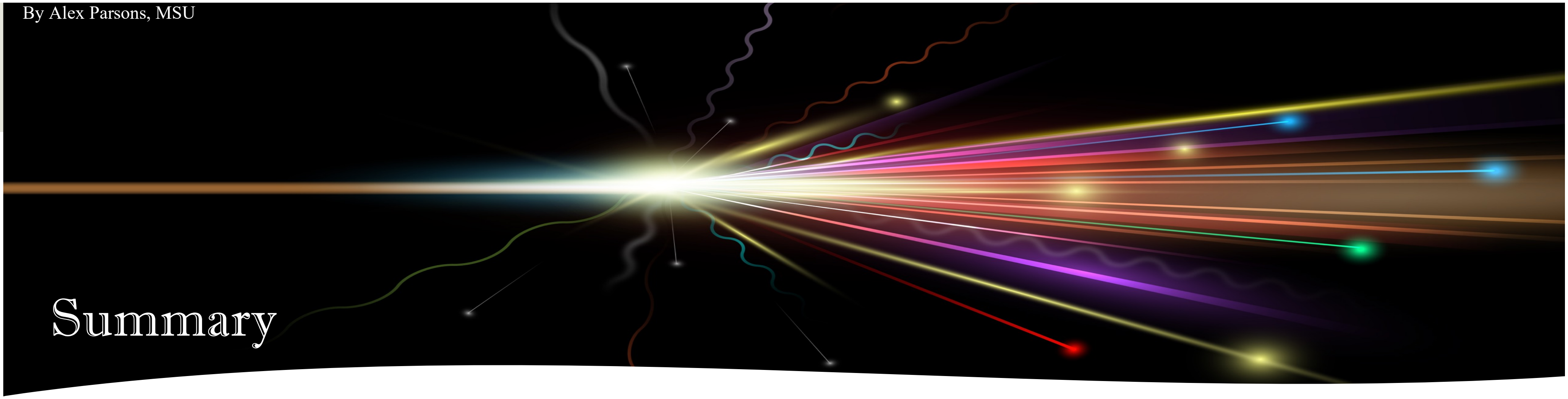
Is this statement accurate?

The endpoint of the i process









Summary

- Neutron-capture reactions important for ı-process calculations
- Direct measurements not currently possible. Have to rely on indirect techniques
- New results in the **mass 90 and 140 regions** help constrain i-process conditions
- Closer look into statistical properties (nuclear level density and gamma strength function)
- FRIB will bring new capabilities and access to a lot more exotic nuclei – **explore the endpoint of the i process**

Collaboration

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