Heavy Element Nucleosynthesis

Part I: The Basics

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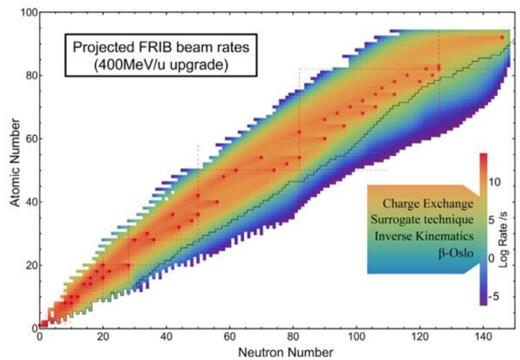
Ohio University

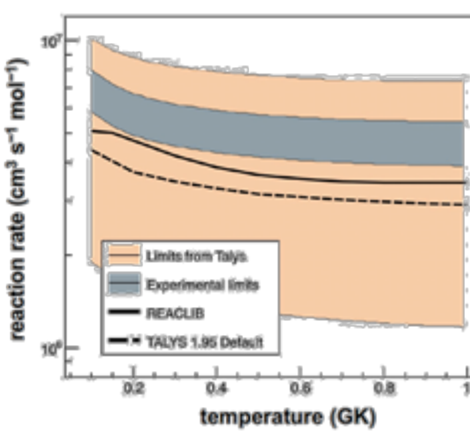
Open Questions and Research Tools in Nuclear Astrophysics

IReNA IANNA CeNAM OHIO UNIVERSITY FRIB Lawrence Livermore National Laboratory

What's the Plan?



A.C. Larsen *et al.* PPNP **107** 69 (2019)



A. Spyrou *et al.*, PRL **132**, 202701 (2024)

Overview of Heavy Element Nucleosynthesis and Introduction of Nuclear Data

Nuclear Data Uncertainties and Experiments

Deep Dive into Indirect Neutron Capture and Wrap-up

Big Questions in Nuclear Science

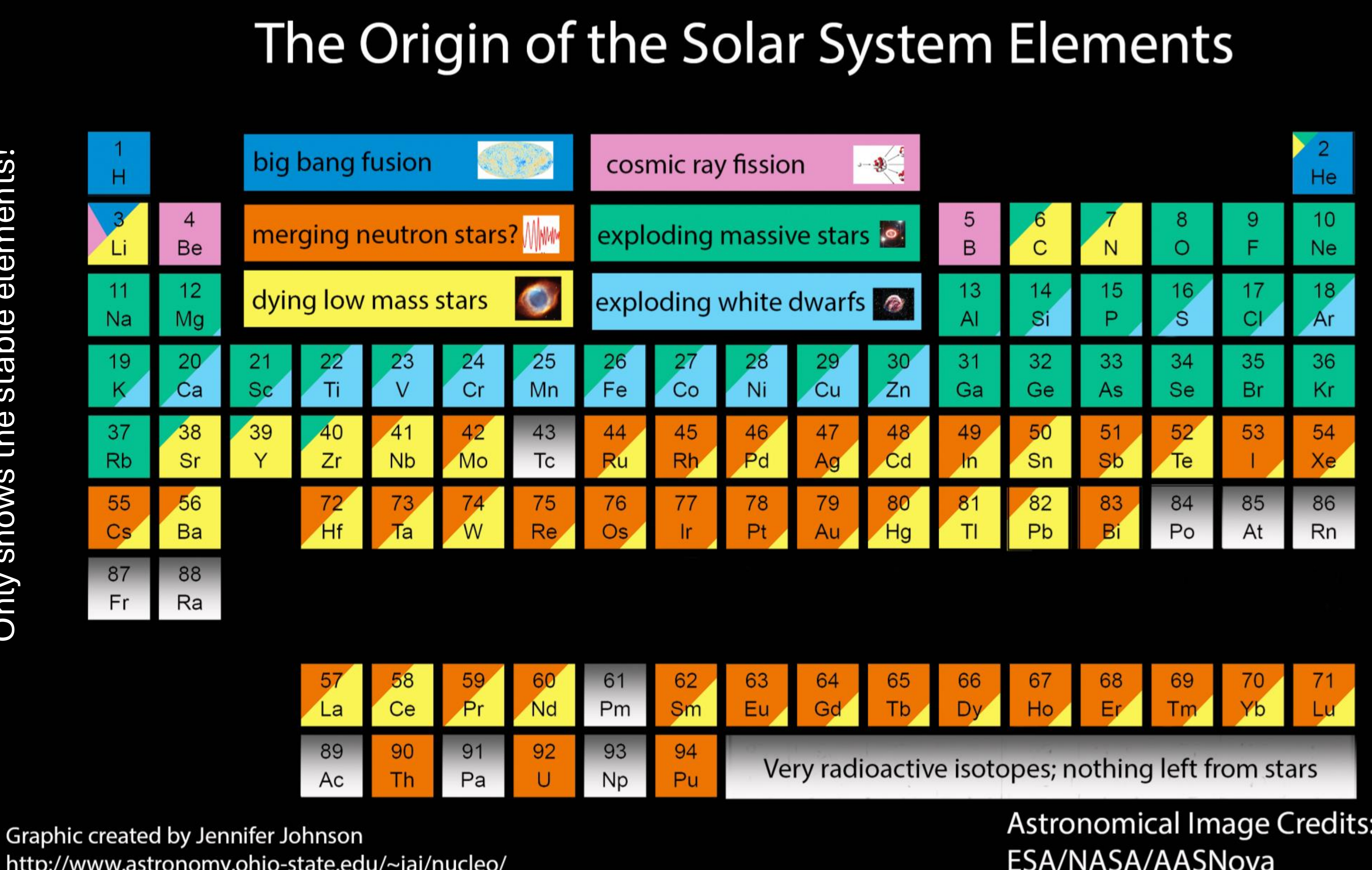
The 2023 Long Range Plan for Nuclear Science had 4 main questions:

- How do quarks and gluons make up protons, neutrons, and, ultimately, atomic nuclei?
- How do the rich patterns observed in the structure and reactions of nuclei emerge from the interactions between neutrons and protons?
- **What are the nuclear processes that drive the birth, life, and death of stars?**
- How do we use atomic nuclei to uncover physics beyond the Standard Model?

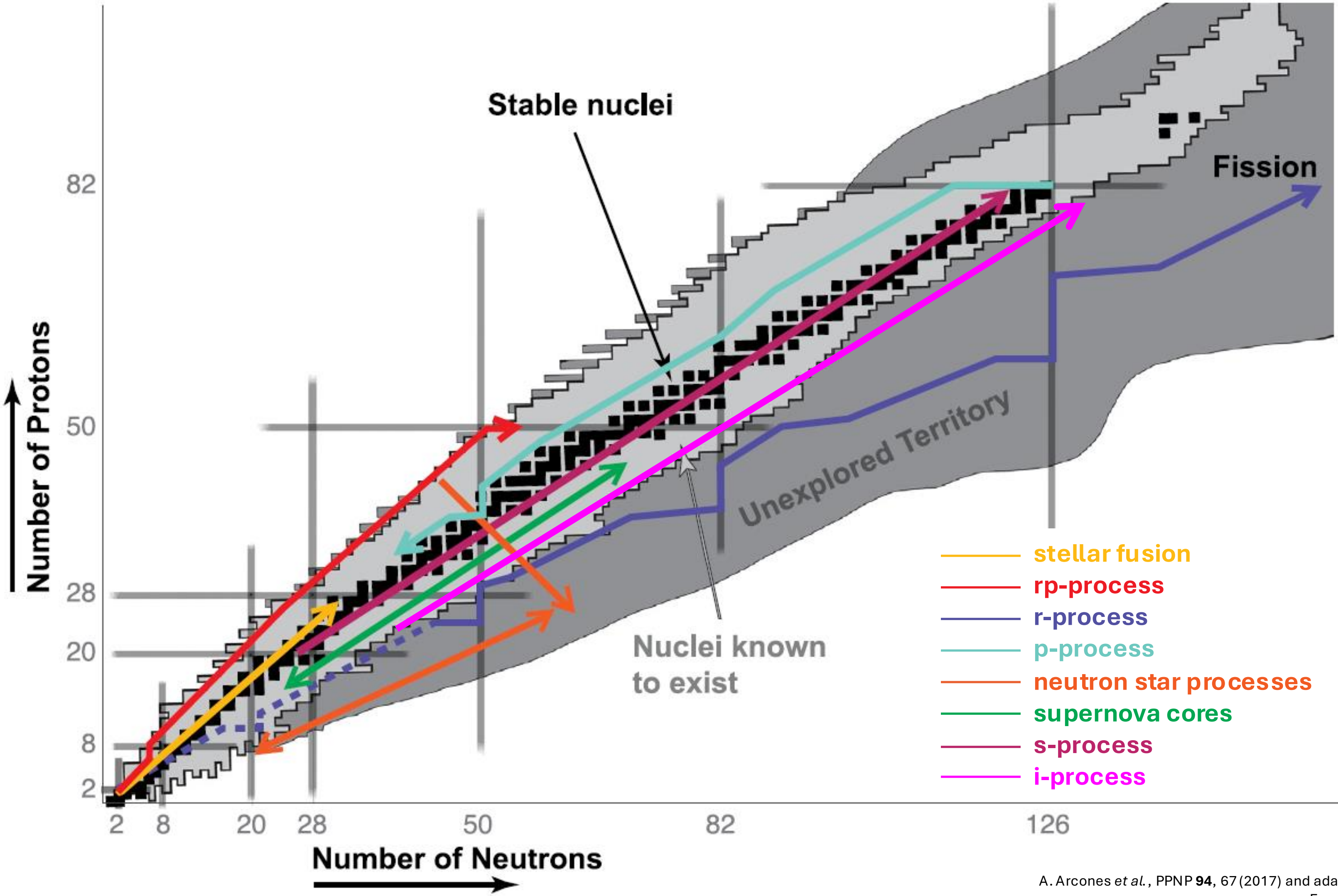
nuclearsciencefuture.org

A great place to start...

Only shows the stable elements!

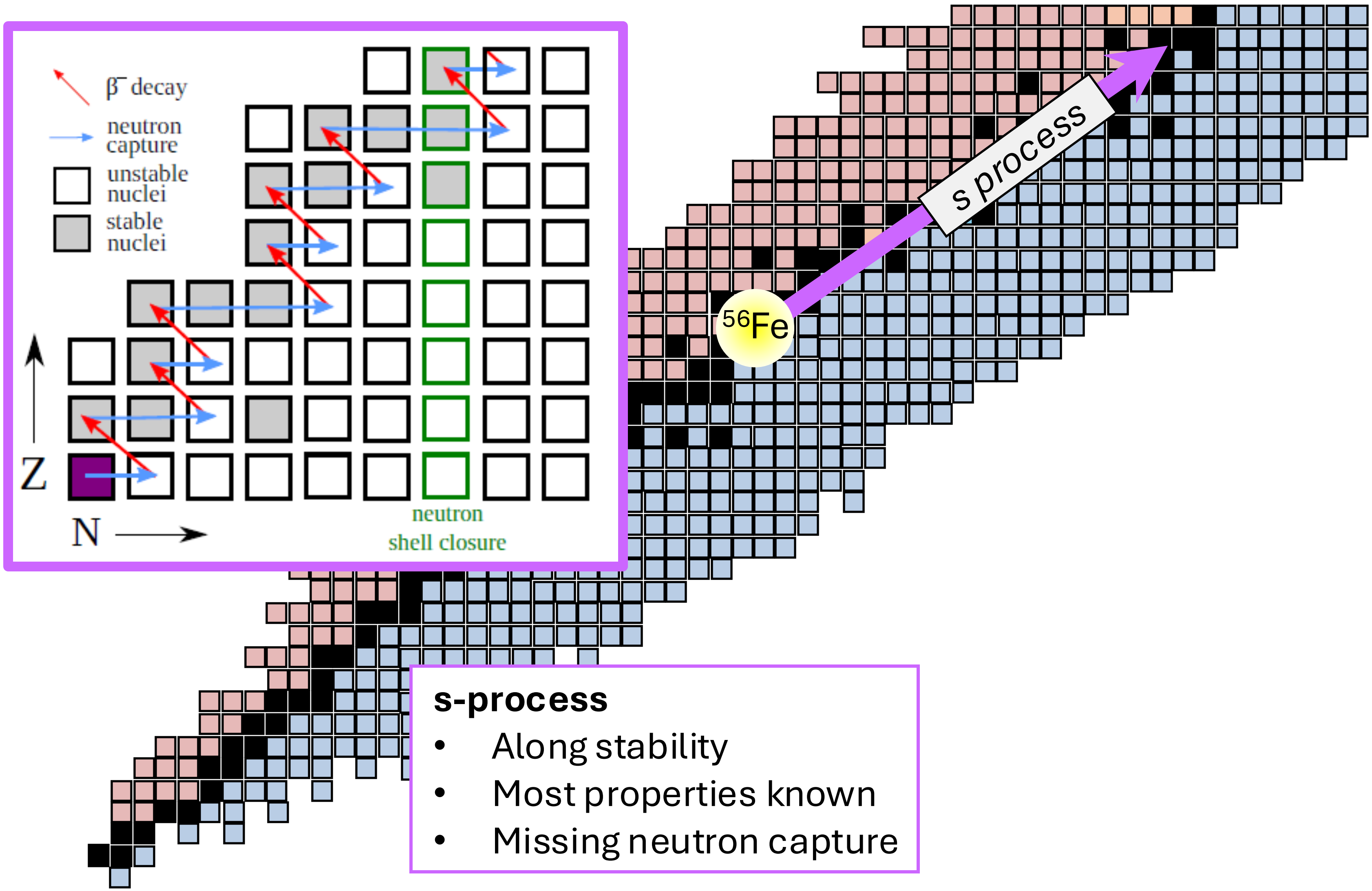


Overview of Nucleosynthesis Processes



A. Arcones *et al.*, PPNP **94**, 67 (2017) and adapted from Frank Timmes

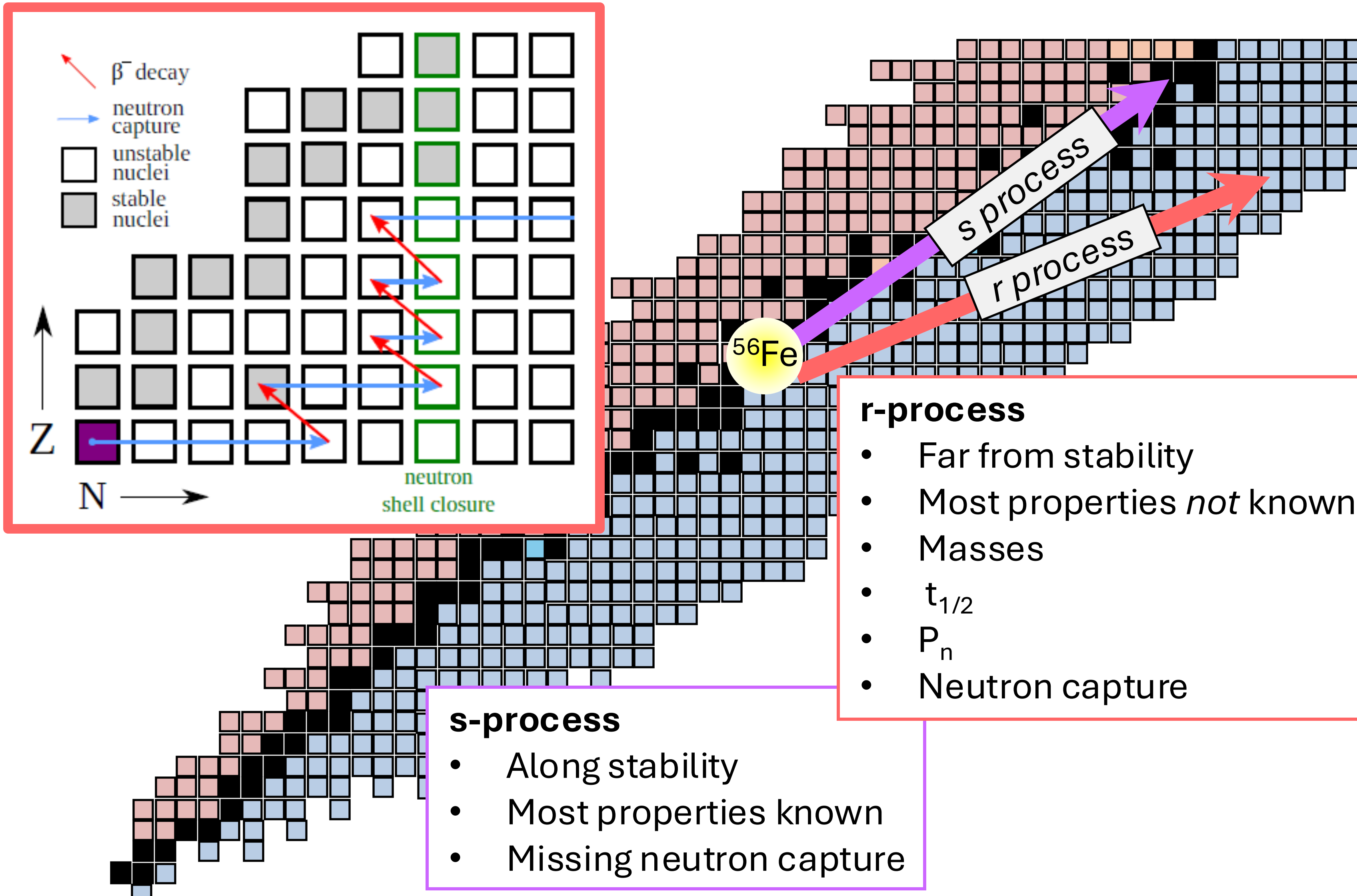
Nucleosynthesis Pathways



s-process

- Along stability
- Most properties known
- Missing neutron capture

Nucleosynthesis Pathways



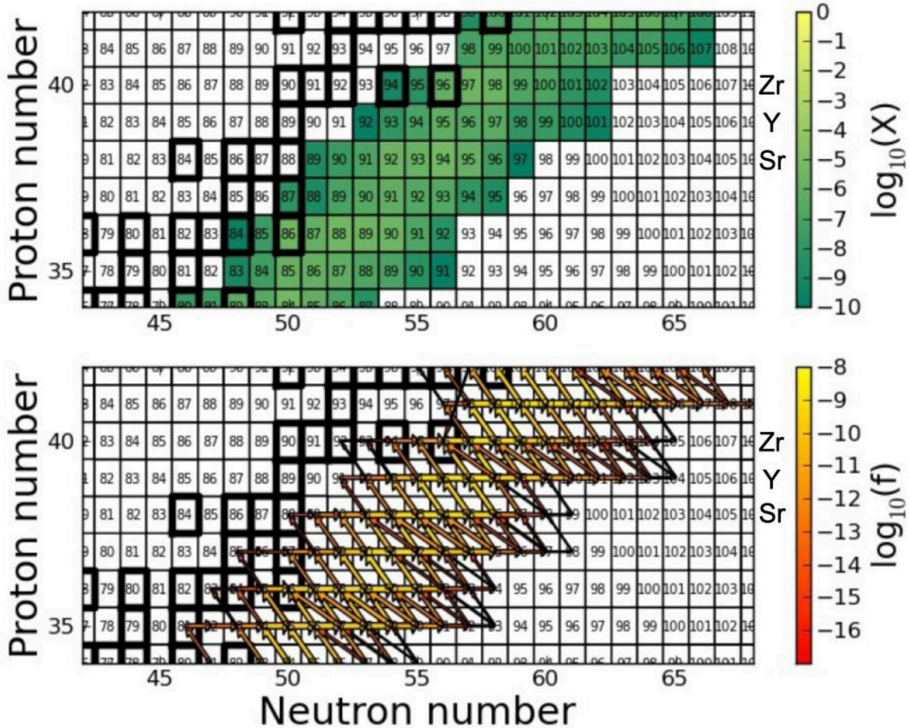
r-process

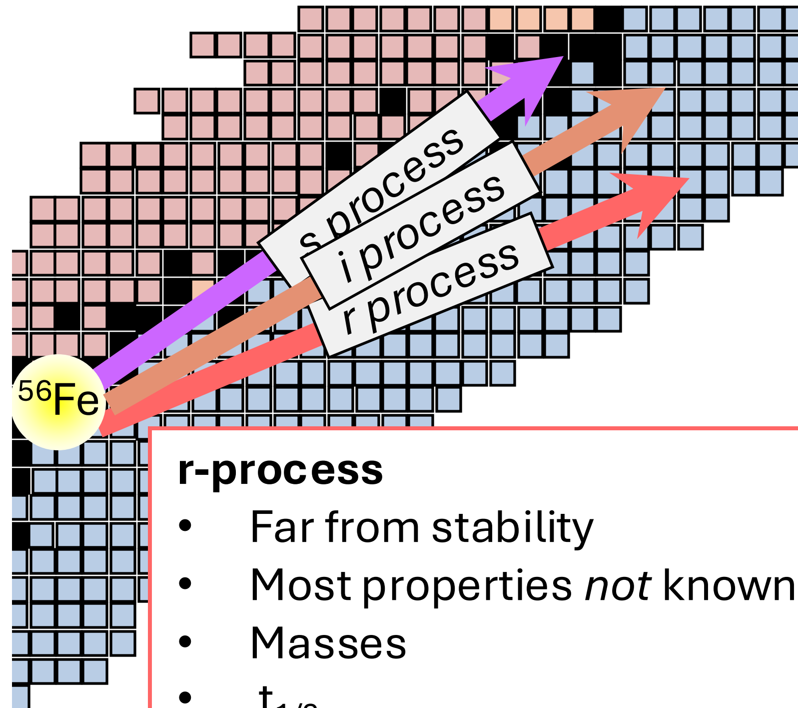
- Far from stability
- Most properties *not* known
- Masses
- $t_{1/2}$
- P_n
- Neutron capture

s-process

- Along stability
- Most properties known
- Missing neutron capture

Nucleosynthesis Pathways





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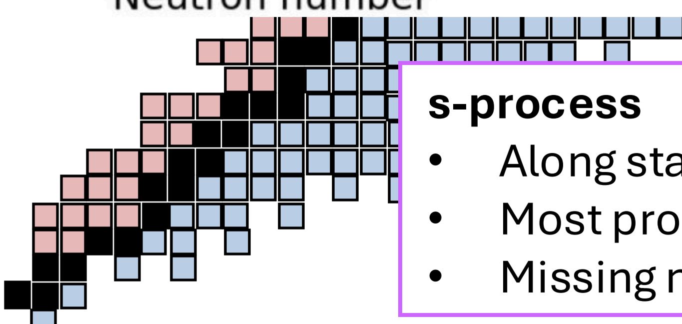


s-process

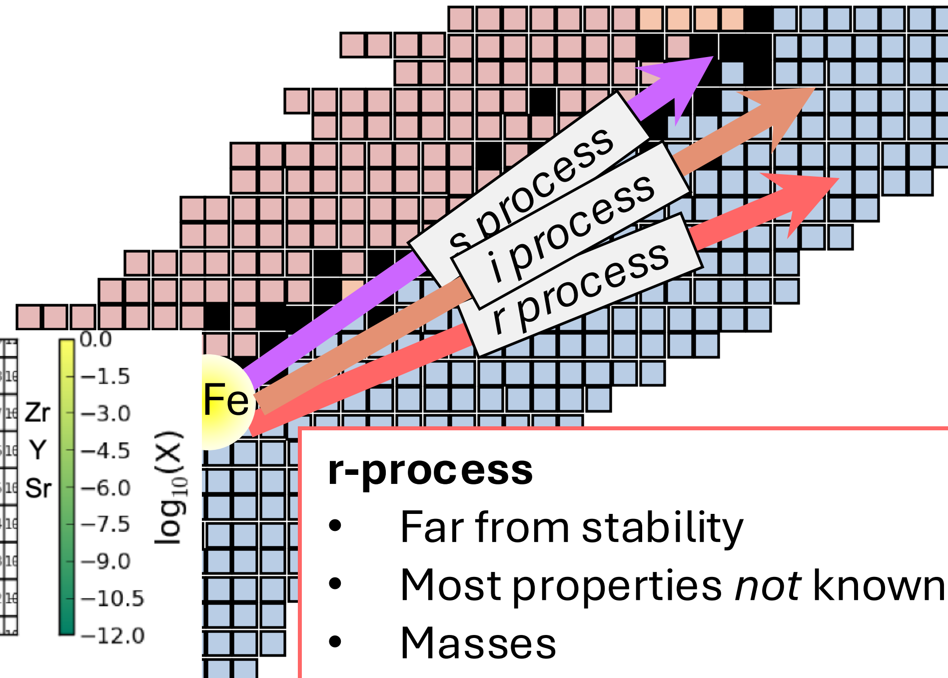
- Along stability
- Most properties known
- Missing neutron capture

i-process

- Between s and r
- Mass, $t_{1/2}$ known
- Missing neutron capture

Nucleosynthesis Pathways

n-process
- Between i and r
- Mass, $t_{1/2}$ mostly known
- Missing neutron capture



r-process
- Far from stability
- Most properties *not* known
- Masses
- $t_{1/2}$
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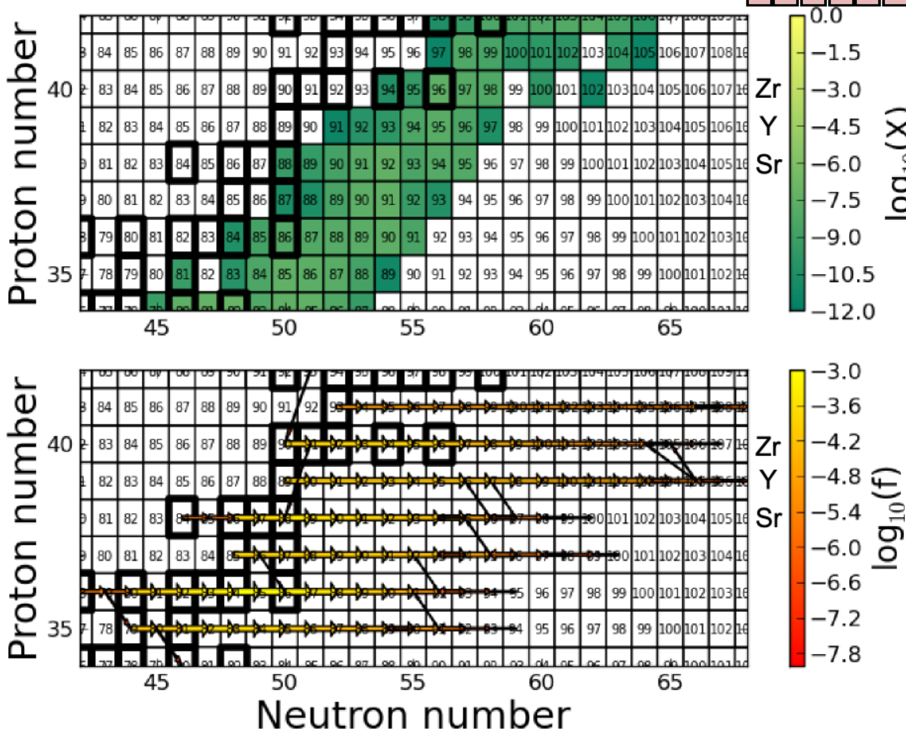
- Neutron capture



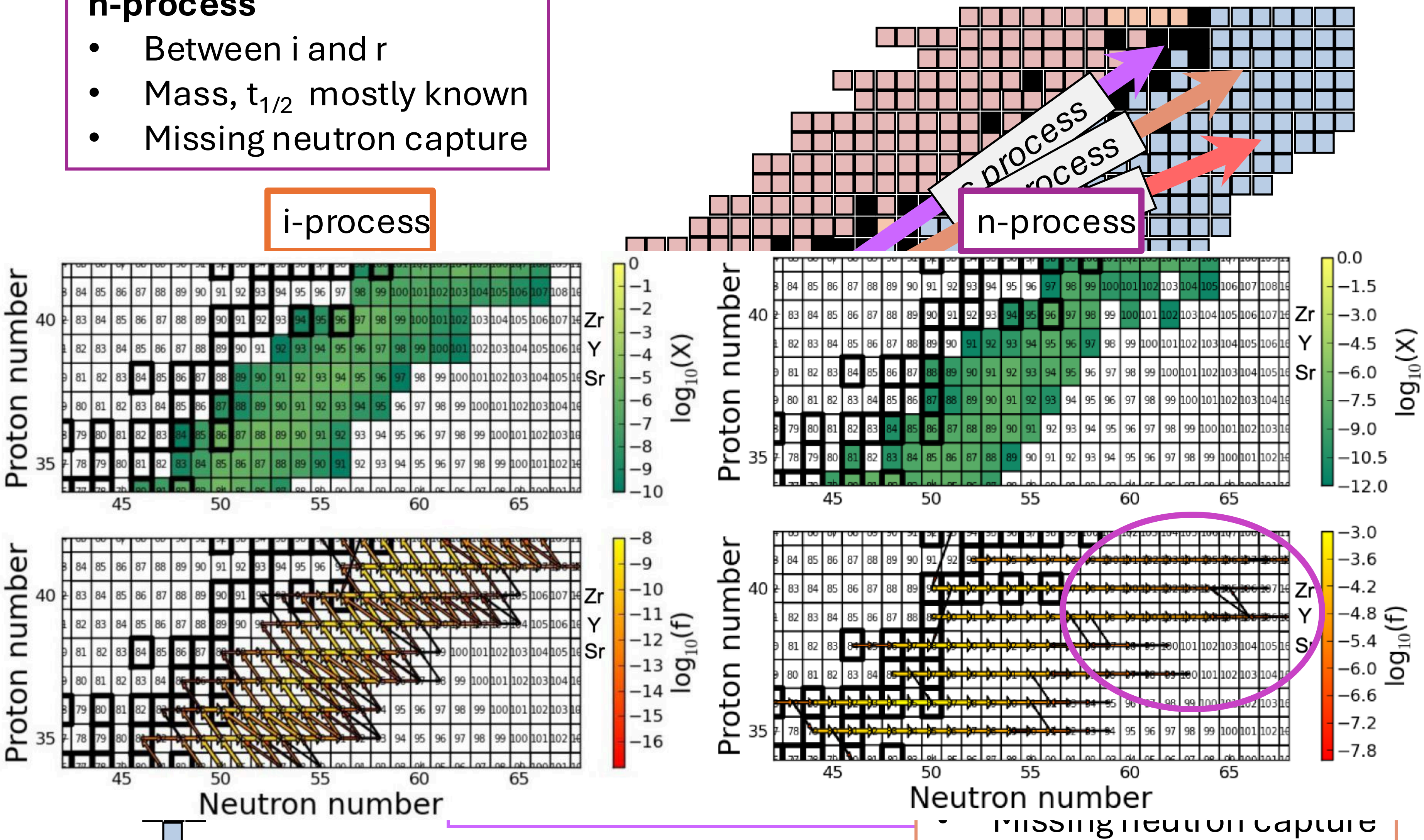
s known
n capture

i-process
- Between s and r
- Mass, $t_{1/2}$ known
- Missing neutron capture

Nucleosynthesis Pathways

n-process

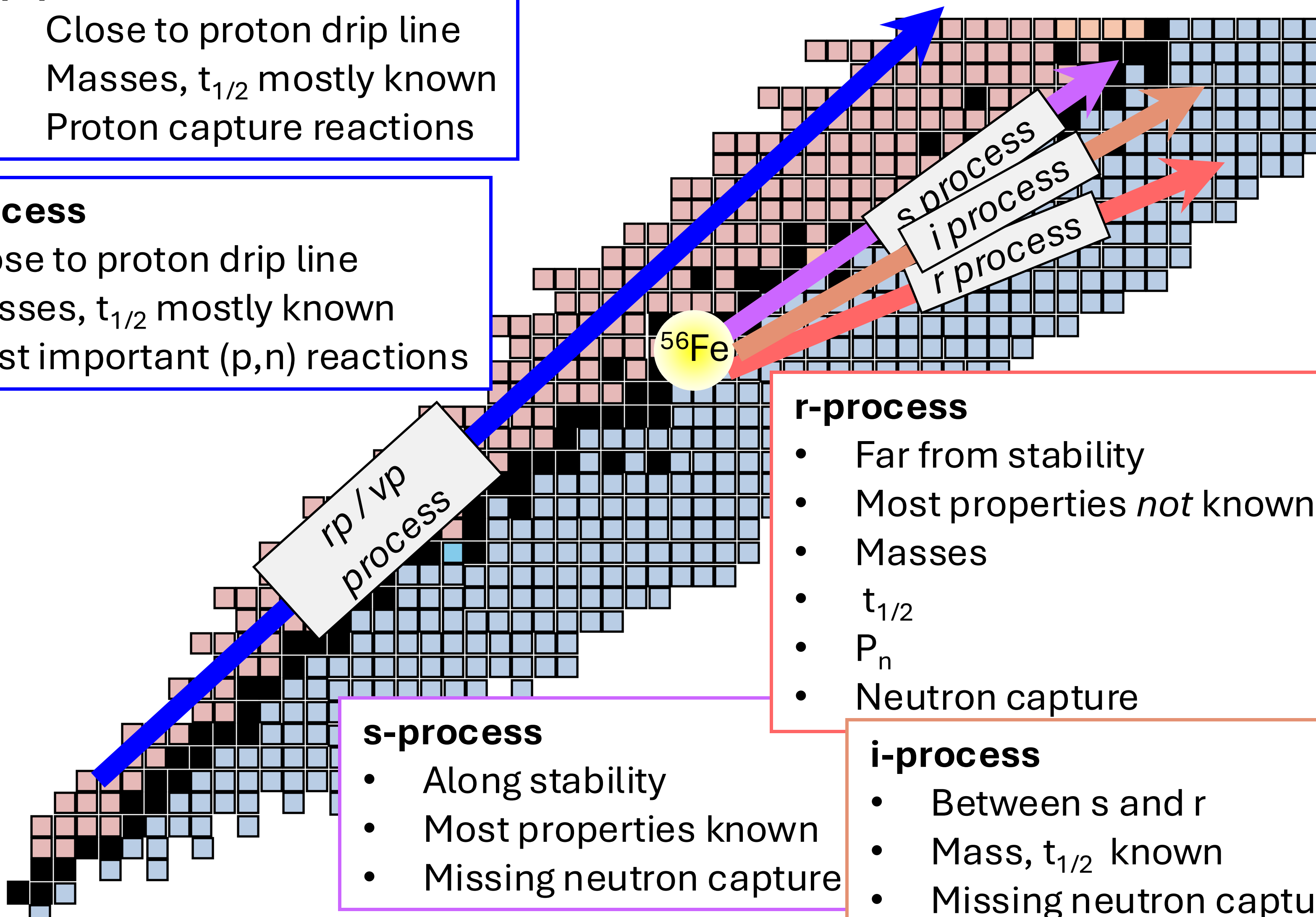
- Between i and r
- Mass, $t_{1/2}$ mostly known
- Missing neutron capture



Nucleosynthesis Pathways

rp-process
- Close to proton drip line
- Masses, $t_{1/2}$ mostly known
- Proton capture reactions

νp-process
- Close to proton drip line
- Masses, $t_{1/2}$ mostly known
- Most important (p,n) reactions

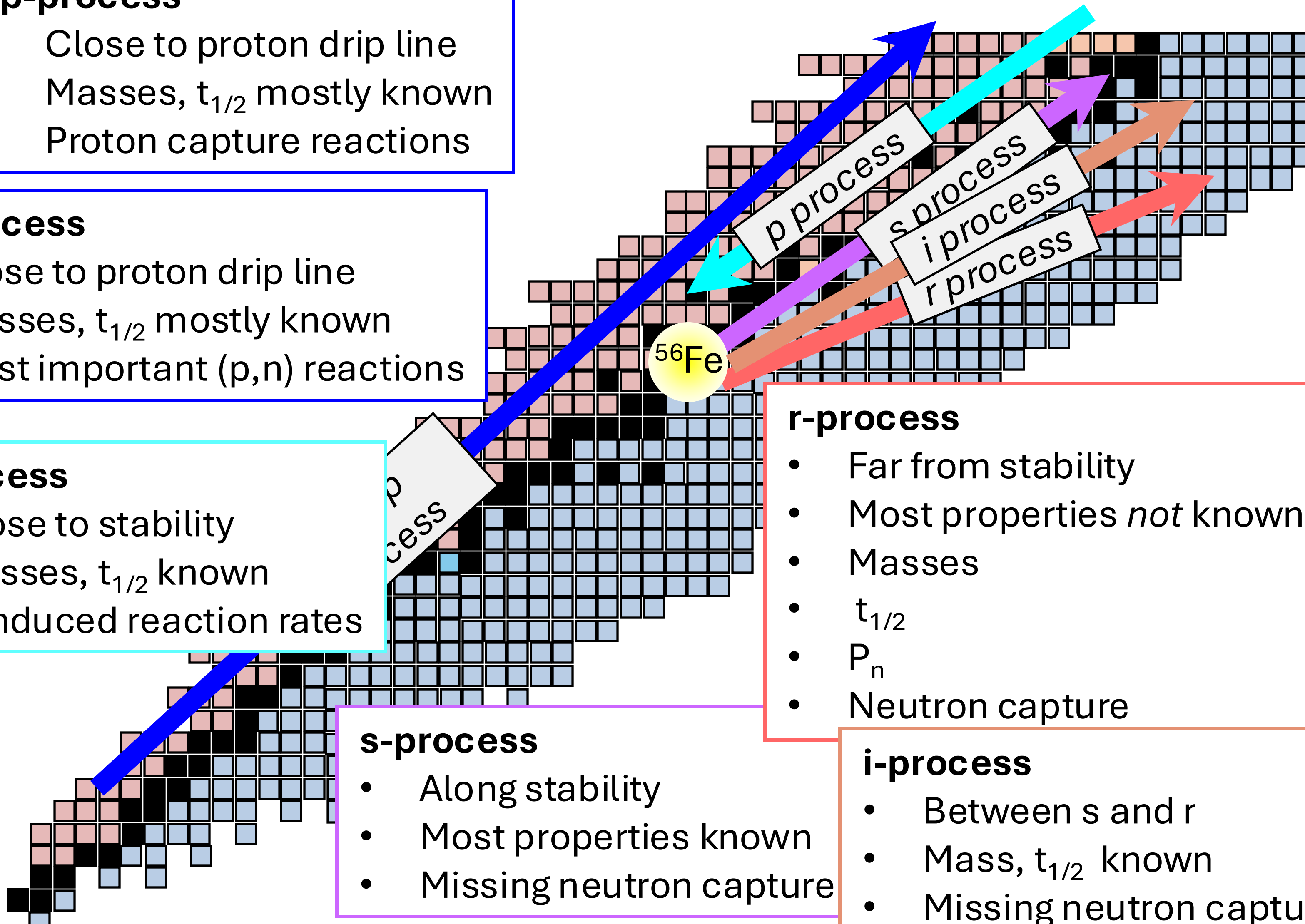


r-process
- Far from stability
- Most properties *not* known
- Masses
- $t_{1/2}$
- P_n
- Neutron capture

s-process
- Along stability
- Most properties known
- Missing neutron capture

i-process
- Between s and r
- Mass, $t_{1/2}$ known
- Missing neutron capture

Nucleosynthesis Pathways



rp-process
- Close to proton drip line
- Masses, $t_{1/2}$ mostly known
- Proton capture reactions

νp-process
- Close to proton drip line
- Masses, $t_{1/2}$ mostly known
- Most important (p,n) reactions

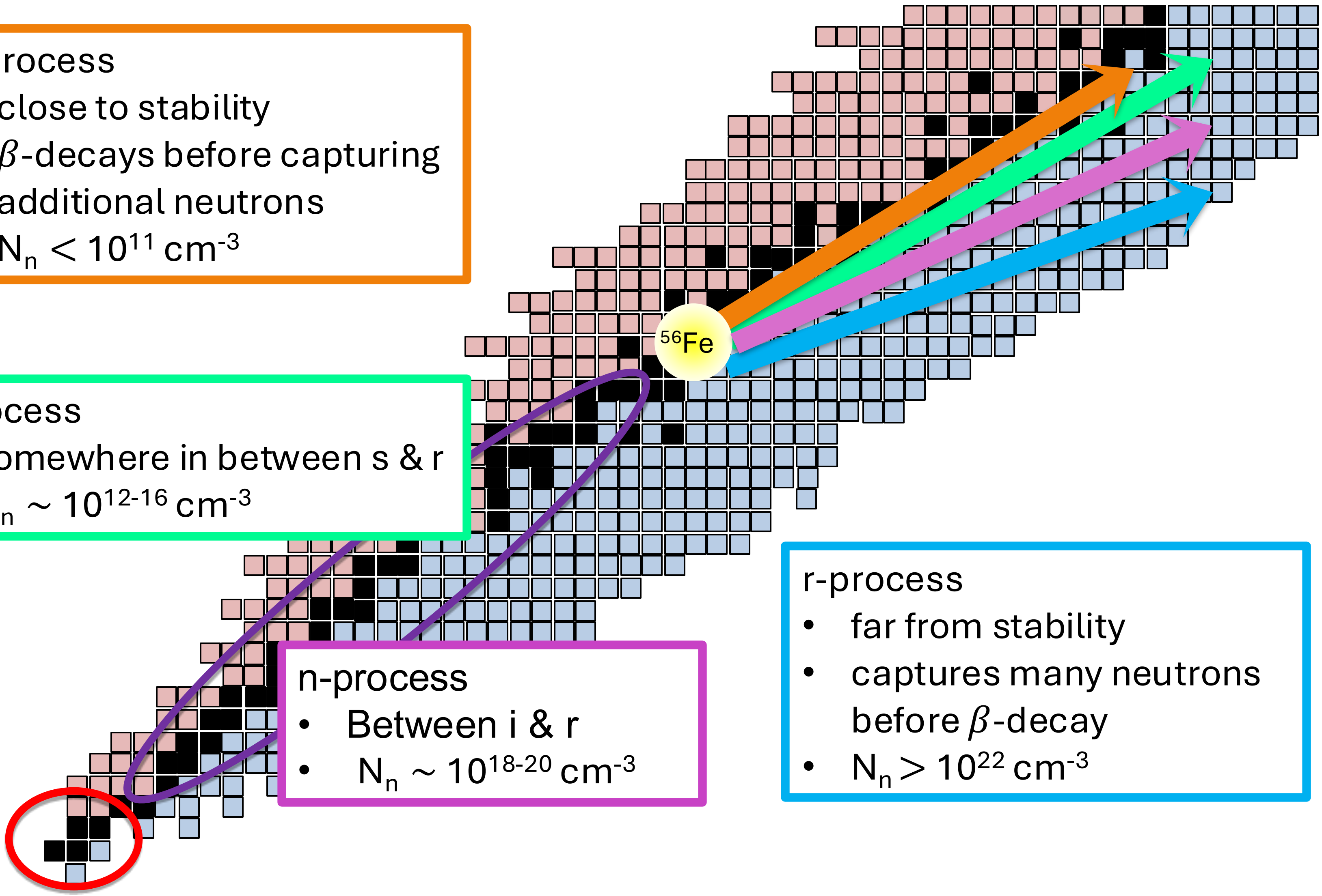
p-process
- Close to stability
- Masses, $t_{1/2}$ known
- γ-induced reaction rates

r-process
- Far from stability
- Most properties *not* known
- Masses
- $t_{1/2}$
- P_n
- Neutron capture

s-process
- Along stability
- Most properties known
- Missing neutron capture

i-process
- Between s and r
- Mass, $t_{1/2}$ known
- Missing neutron capture

Neutron-Capture Processes Summary



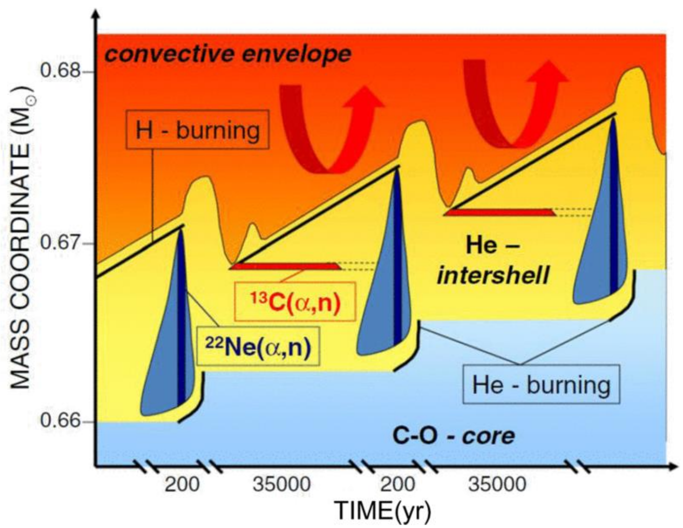
s-process
- close to stability
- β-decays before capturing additional neutrons
- $N_n < 10^{11}$ cm^{-3}

i-process
- somewhere in between s & r
- $N_n \sim 10^{12\text{-}16}$ cm^{-3}

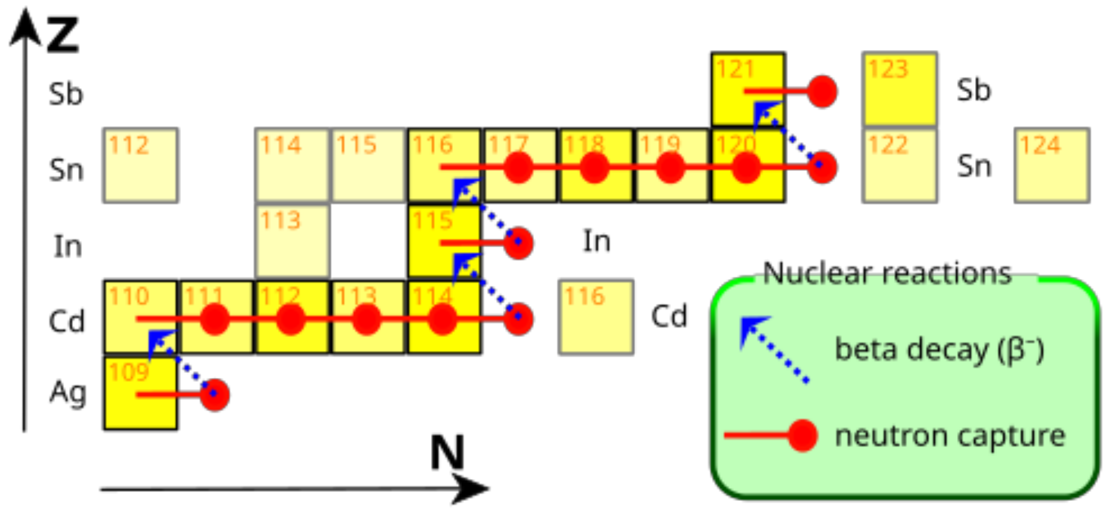
n-process
- Between i & r
- $N_n \sim 10^{18\text{-}20}$ cm^{-3}

r-process
- far from stability
- captures many neutrons before β-decay
- $N_n > 10^{22}$ cm^{-3}

Astrophysical *s*-Process



Wallner (2016)



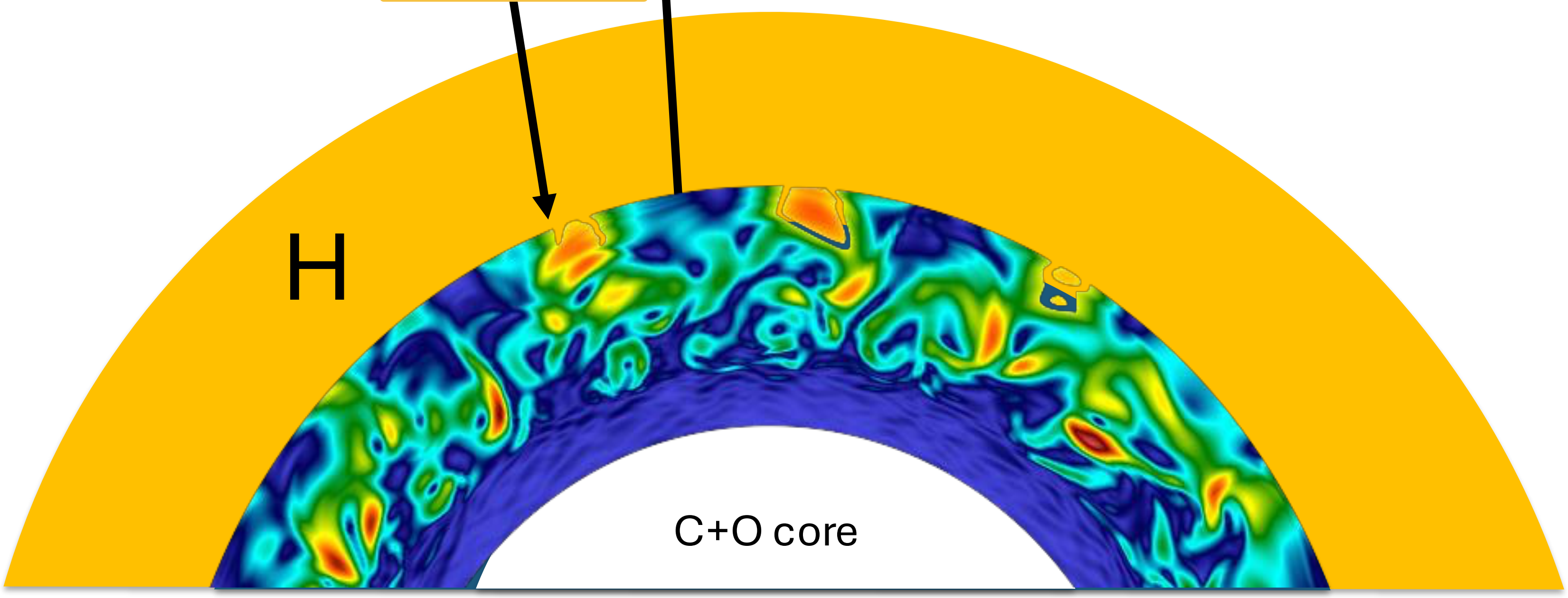
Wikipedia

- He burning layers of low mass AGB stars
- *Main s*-process component driven by $^{13}C(\alpha,n)^{16}O$ reaction neutron source
- *Weak s*-process in massive stars driven by $^{22}Ne(\alpha,n)^{25}Mg$ neutron source

*Phil will say more

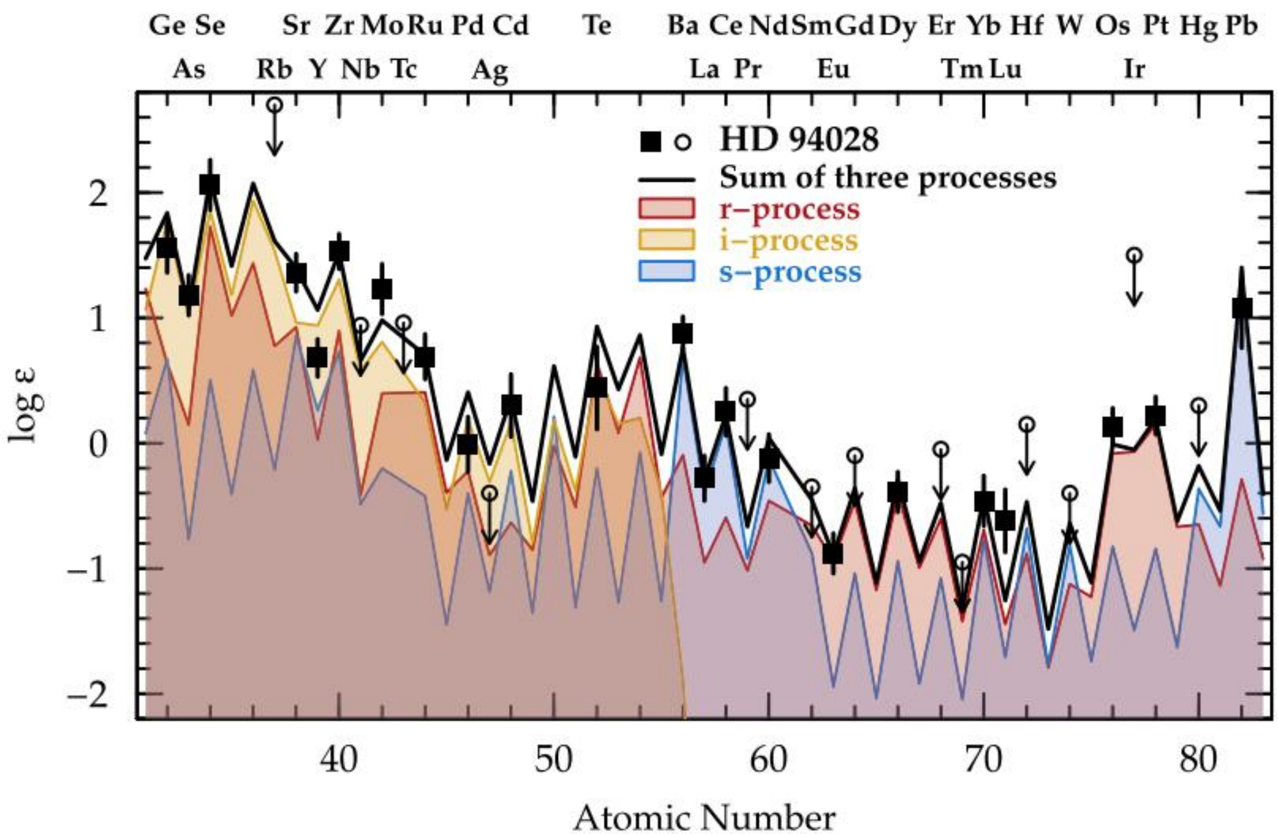
Astrophysical Site(s) of the *i*-Process

- Neutron density: $10^{12\text{-}16}$ cm^{-3}, intermediate between s process and r process
  - 2-8 mass units from stability where (n,γ) rates are unknown
- Proposed in the 1970s and revived recently to explain observations of "strange" abundance distributions (post-AGB, CEMP stars, and RAWDs)
- Requires mixing between H and He layers of the star
- Neutrons production: $^{13}C(\alpha,n)^{16}O$ reaction, like s-process
- ^{13}C replenished via $^{12}C(p,\gamma)^{13}N$, then $^{13}N(e^{+})^{13}C$, $T_{1/2}(^{13}N)$ ~ 10 minutes

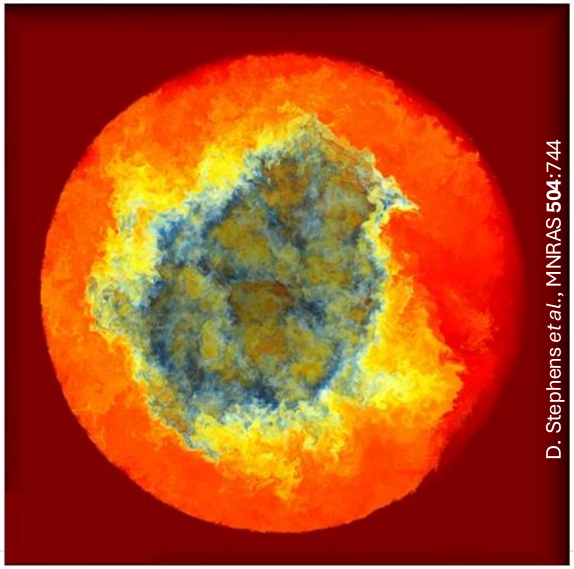


Modified from A. Spyrou
Denissenkov, P., *et al.*, J. Phys. G: Nucl. Part. Phys. **45** 055203 (2018)

Abundances in the *i*-Process



I. Roederer *et al.*, ApJ **821**:37 (2016)

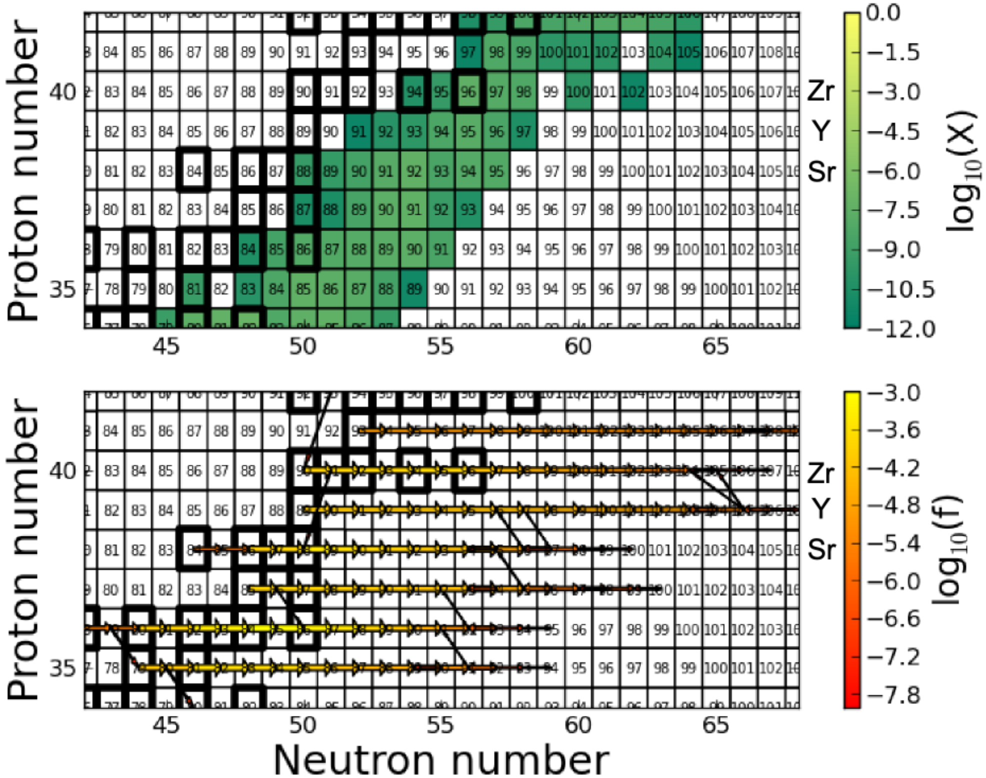


D. Stephens *et al.*, MNRAS **504**:744

Combinations of s-process and r-process do not account for observed abundances in the Ge-La region (s + r ≠ i)

Proposed Astrophysical Site of the *n*-Process

- First proposed in 1976 by Blake & Schramm
  - Neutron-capture rates in competition with β-decay rates
- Explosive He-burning in core-collapse supernovae (CCSN)
- Neutron densities: 10^{18} /cm^3 < N_n < 10^{20} /cm^3
- Neutron capture triggered by $^{22}Ne(\alpha,n)^{25}Mg$ reaction due to high temperature in CCSN in massive AGB stars and super-AGB stars
  - ^{22}Ne comes from CNO abundances in SN
  - Neutron burst strongly affects isotopic abundances
- No sensitivity study so far, but likely (n,γ) rates play an important role
- Strong evidence from grain data



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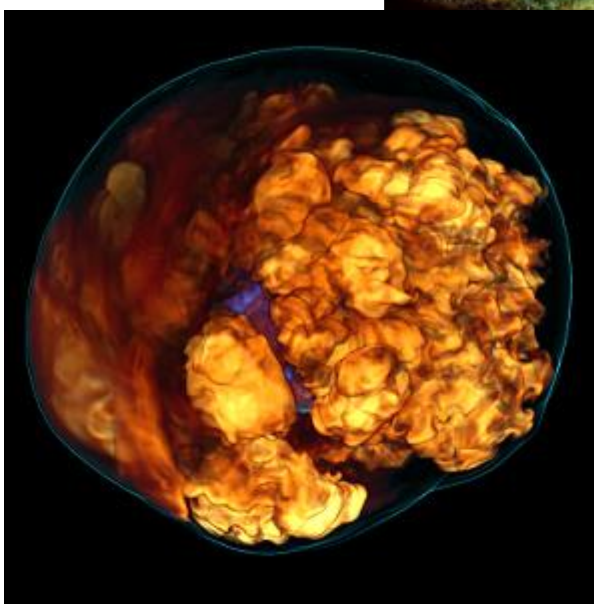
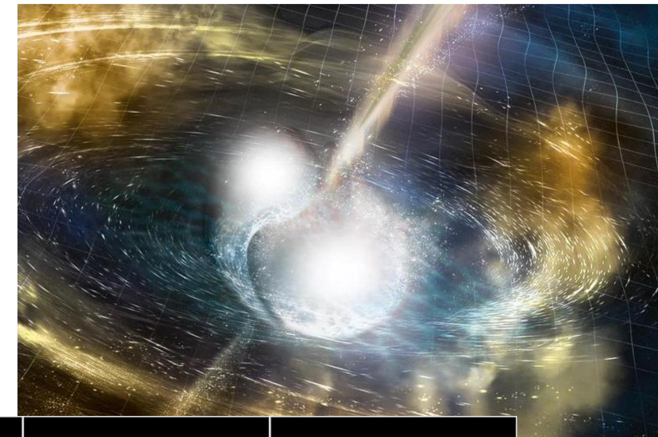
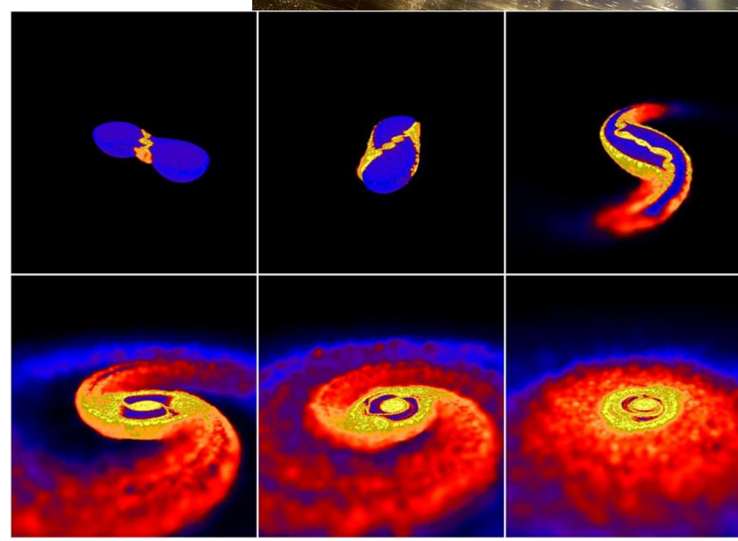
Astrophysical Site(s) of the *r*-process

Core Collapse Supernovae



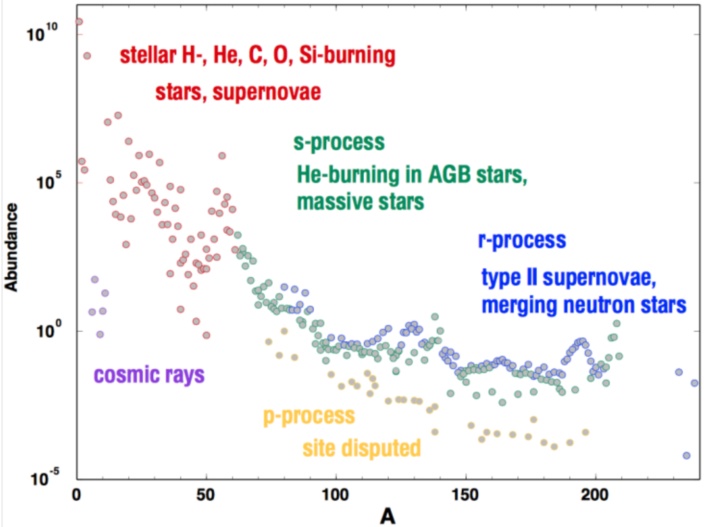
Neutron star mergers (confirmed)

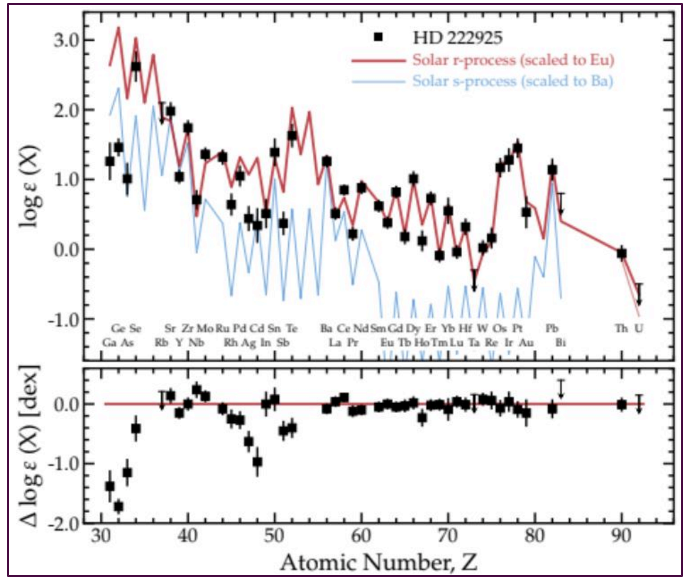




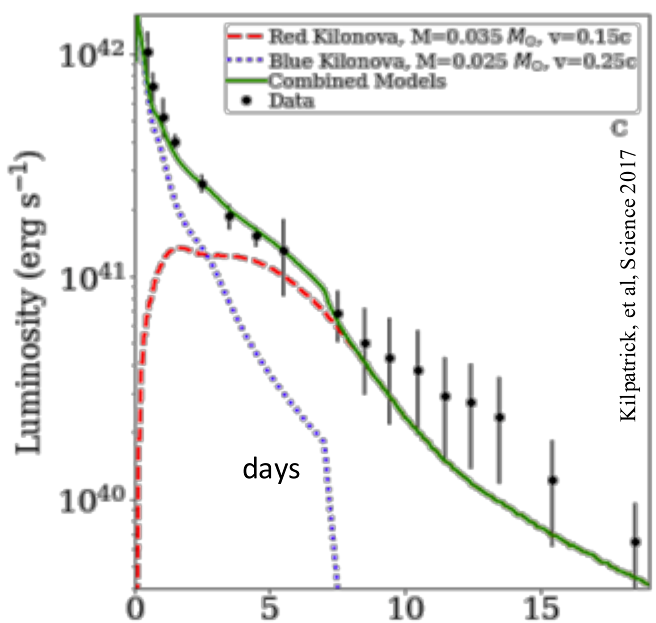
CCSNe: Crab nebula: NASA, ESA, J. Hester and A. Loll (Arizona State University)
E. O'Connor/K-C. Pan/YT
NSM: NSF LIGO Sonoma State University / A. Simonnet
Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

Astrophysical *r* process - observables

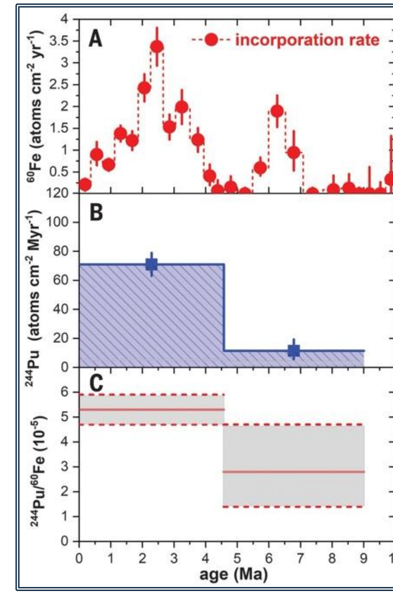




Roederer, ApJS 2022



Kilpatrick, et al, Science 2017

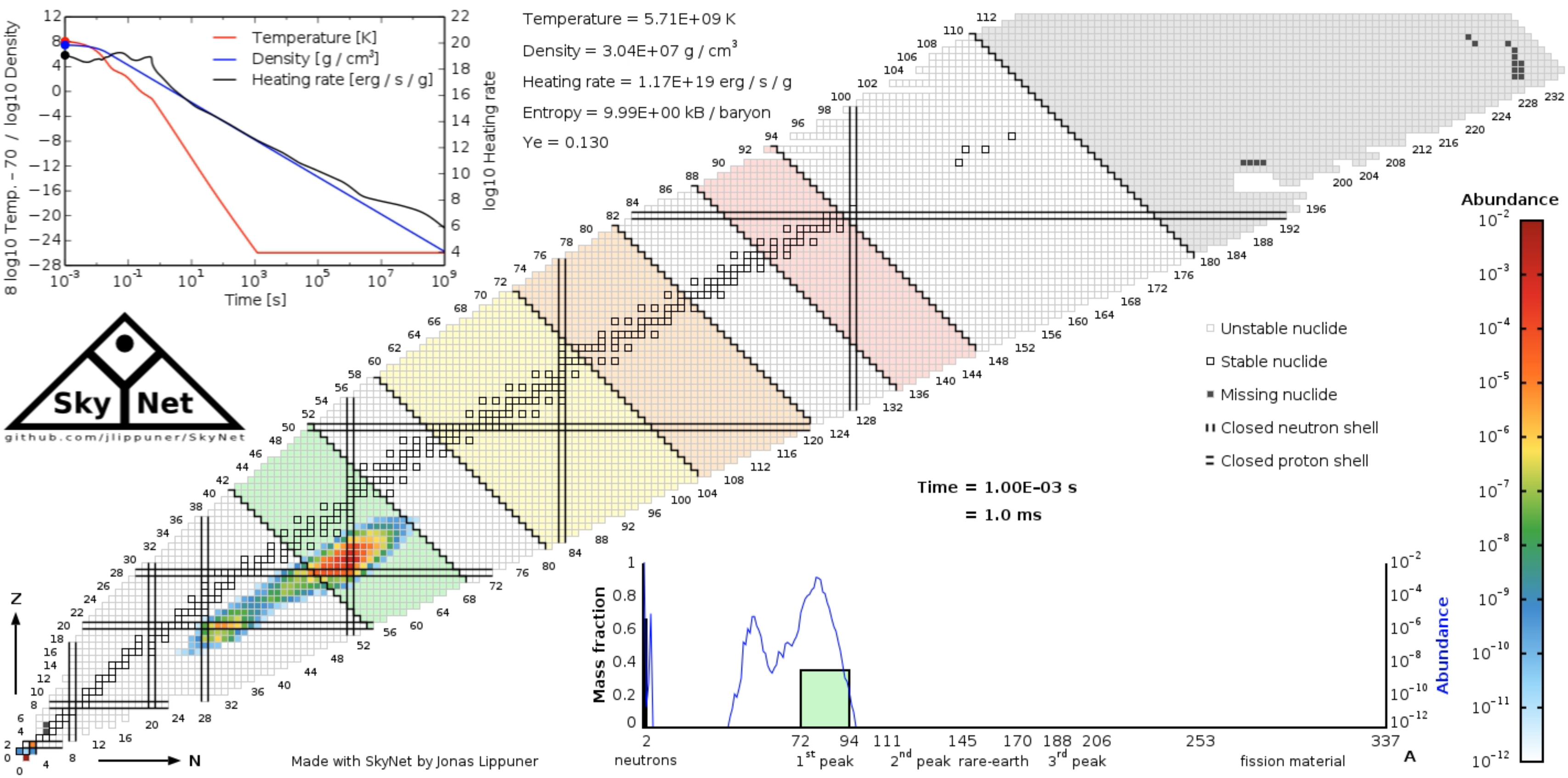


Wallner et al, Science 2021

- Solar system abundances
- Metal-poor star observations
- Kilonova signal from neutron-star merger
- Signals from deep-sea archives

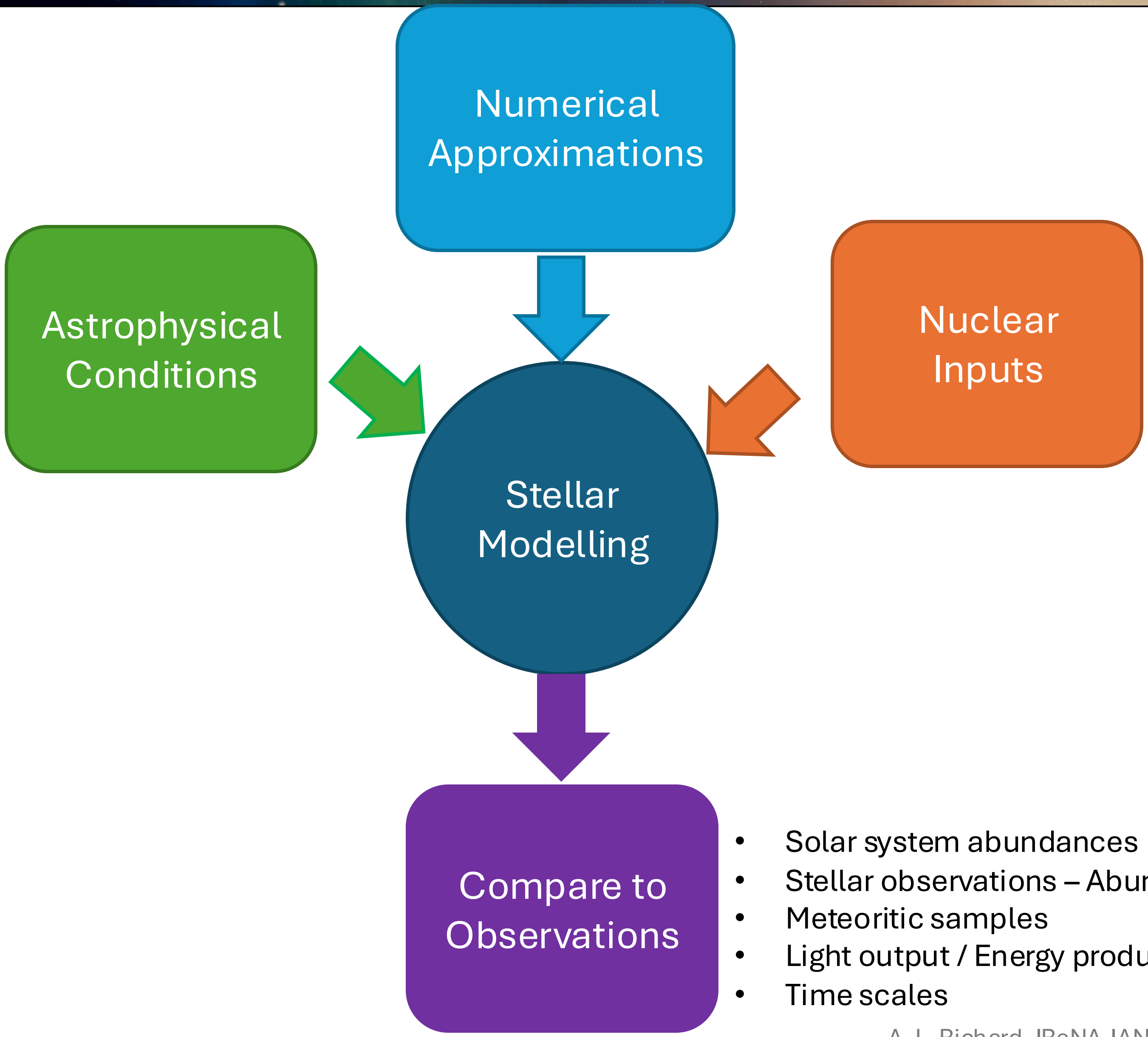
A. Spyrou

r-process simulations



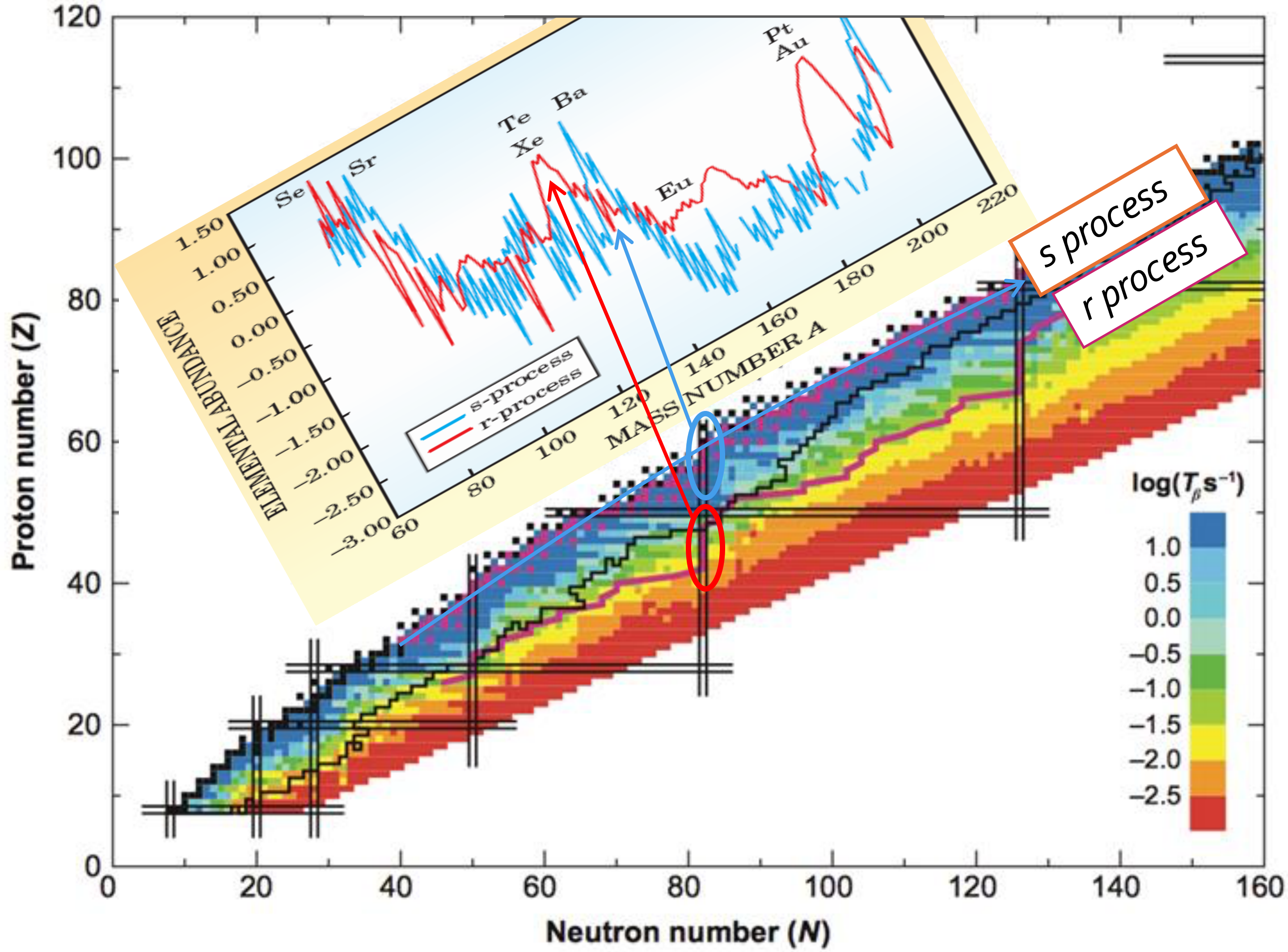
SkyNet

How does Nuclear Astrophysics Work?



- Solar system abundances
- Stellar observations – Abundances
- Meteoritic samples
- Light output / Energy production
- Time scales

Nucleosynthesis Goals

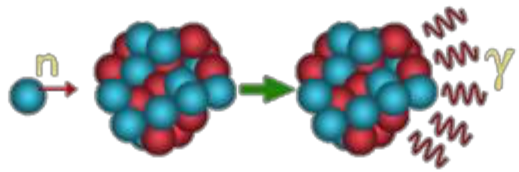


Sneden, C., Cowan, J. J., & Gallino, R., *Ann. Rev. Ast. Ap.* **46** (2008) 241.

Nuclear Data Inputs

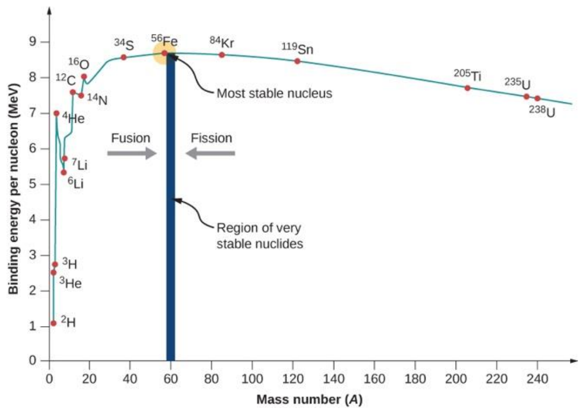
Nuclear Data Inputs

Neutron-Capture Rates

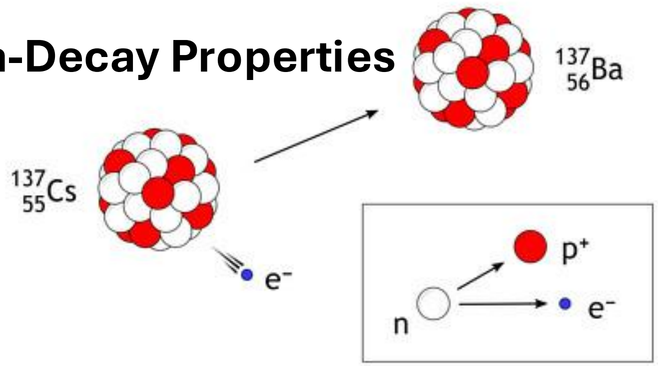


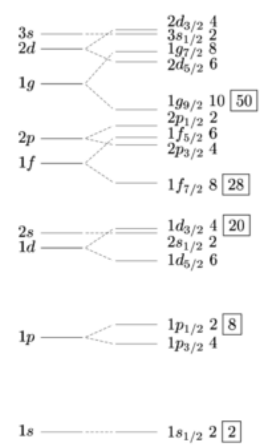
Mass

Binding Energy

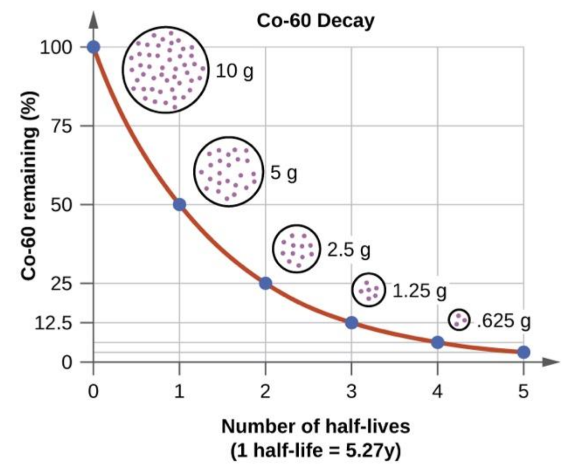


Beta-Decay Properties

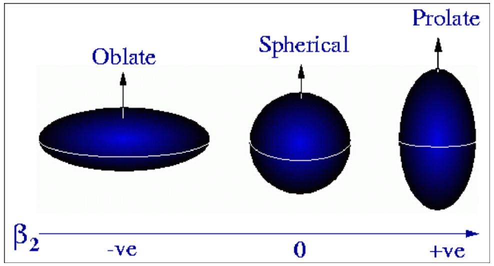




Level structure

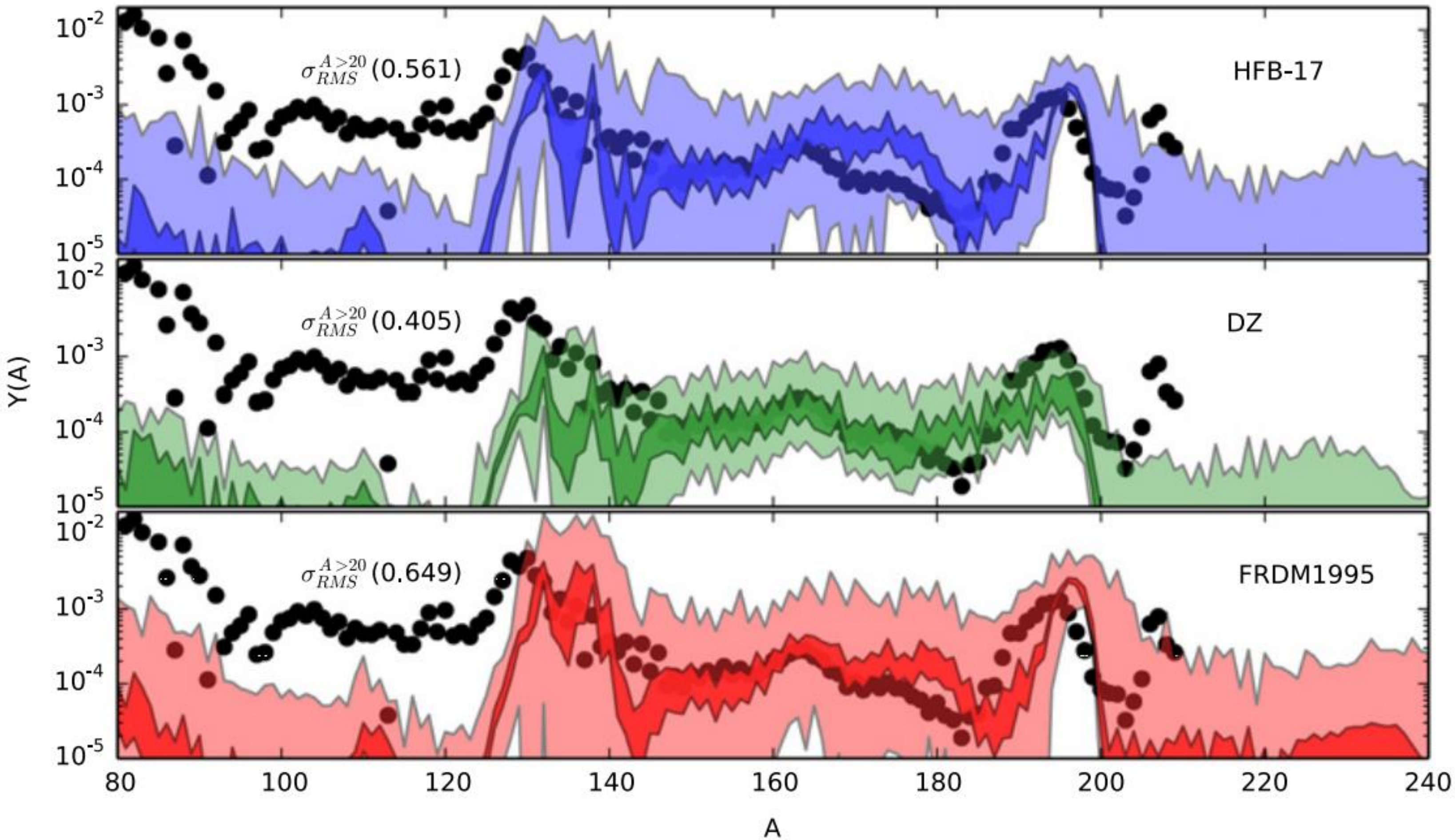


Half-life



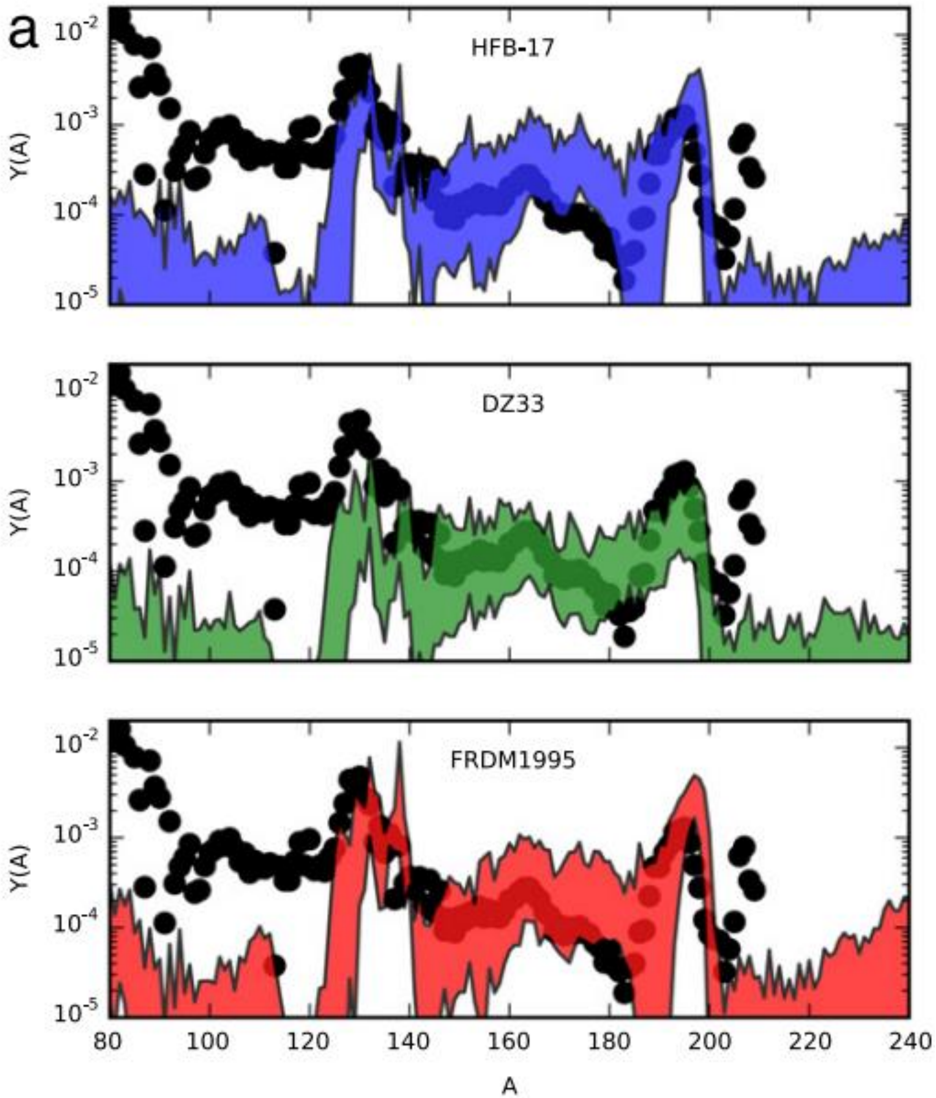
Nuclear Shapes

Sensitivity to Mass Uncertainties



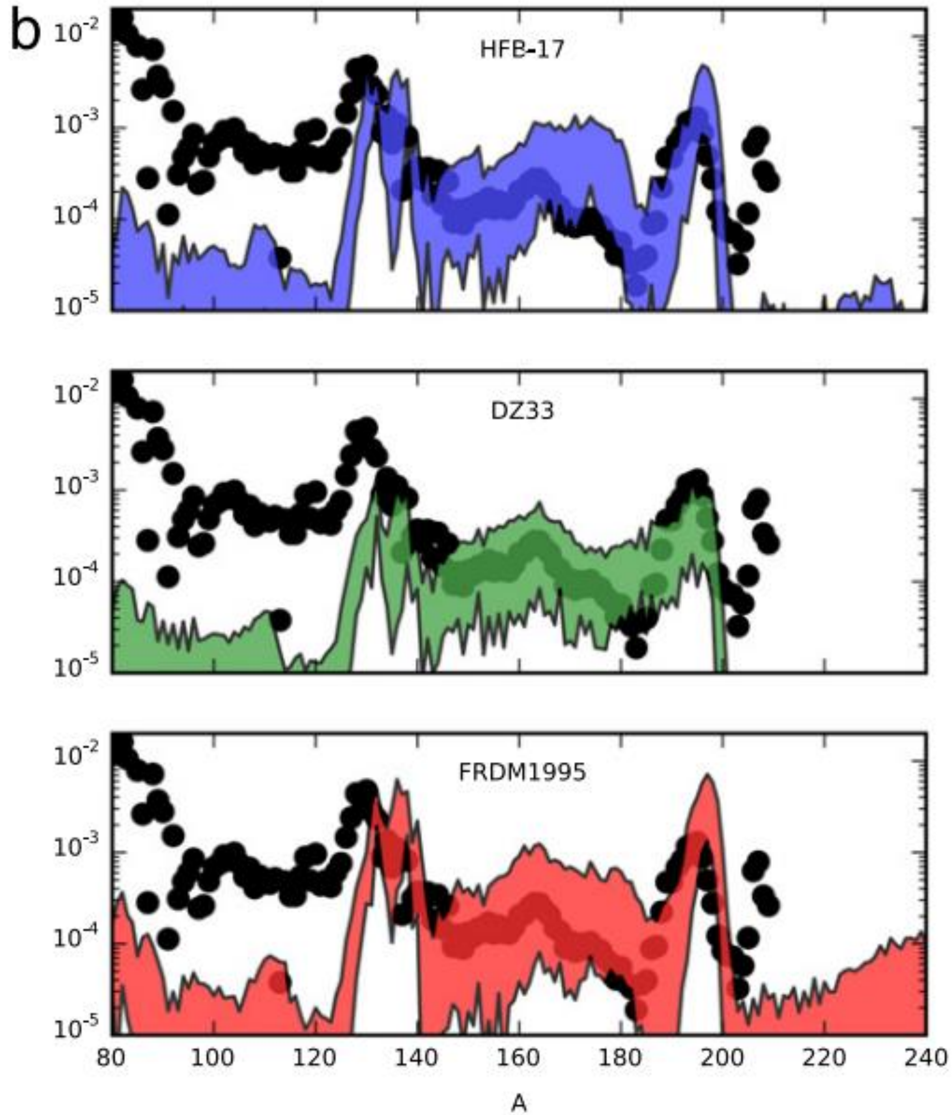
Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

Sensitivity to Half-Life Uncertainties



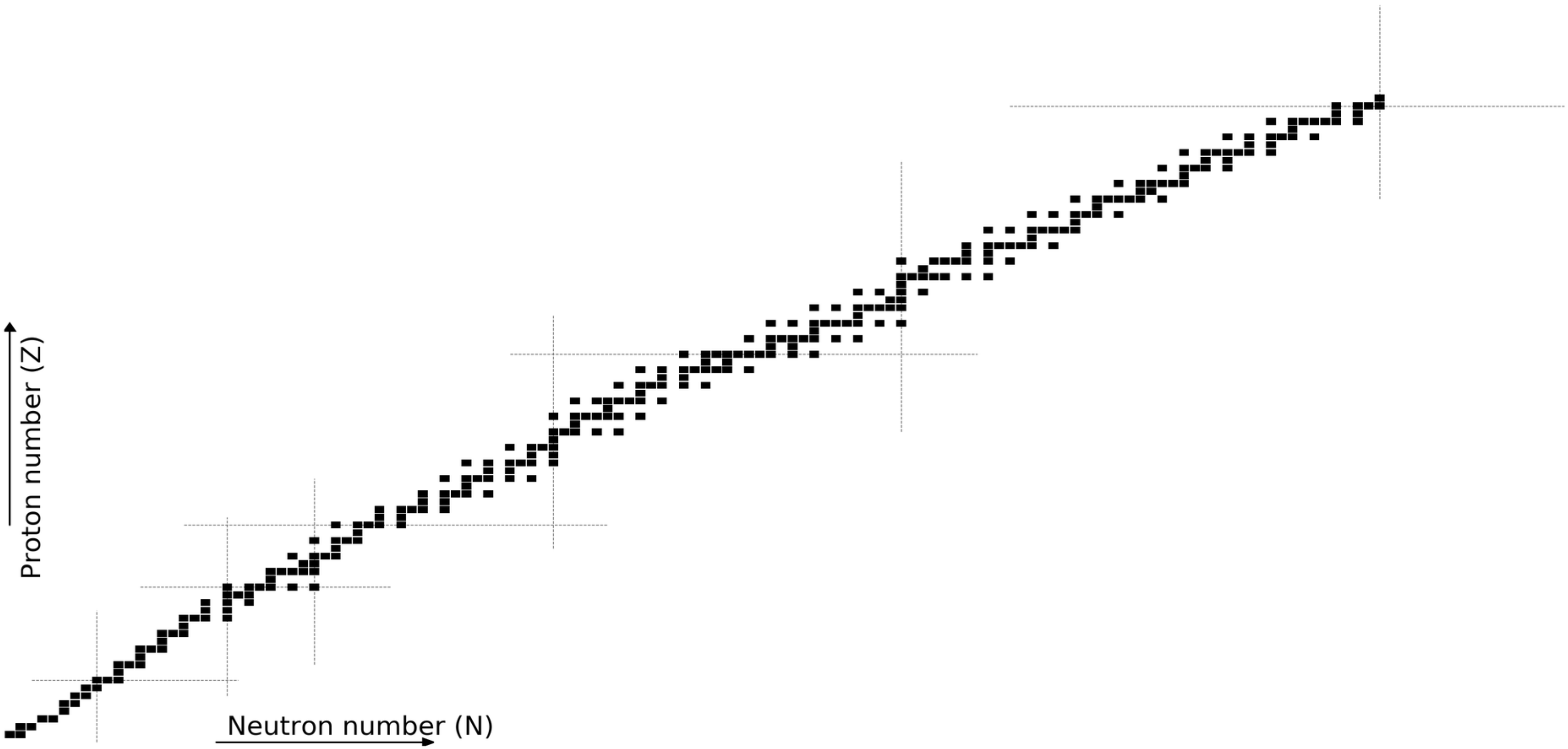
Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

Sensitivity to Neutron-Capture Uncertainties



Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

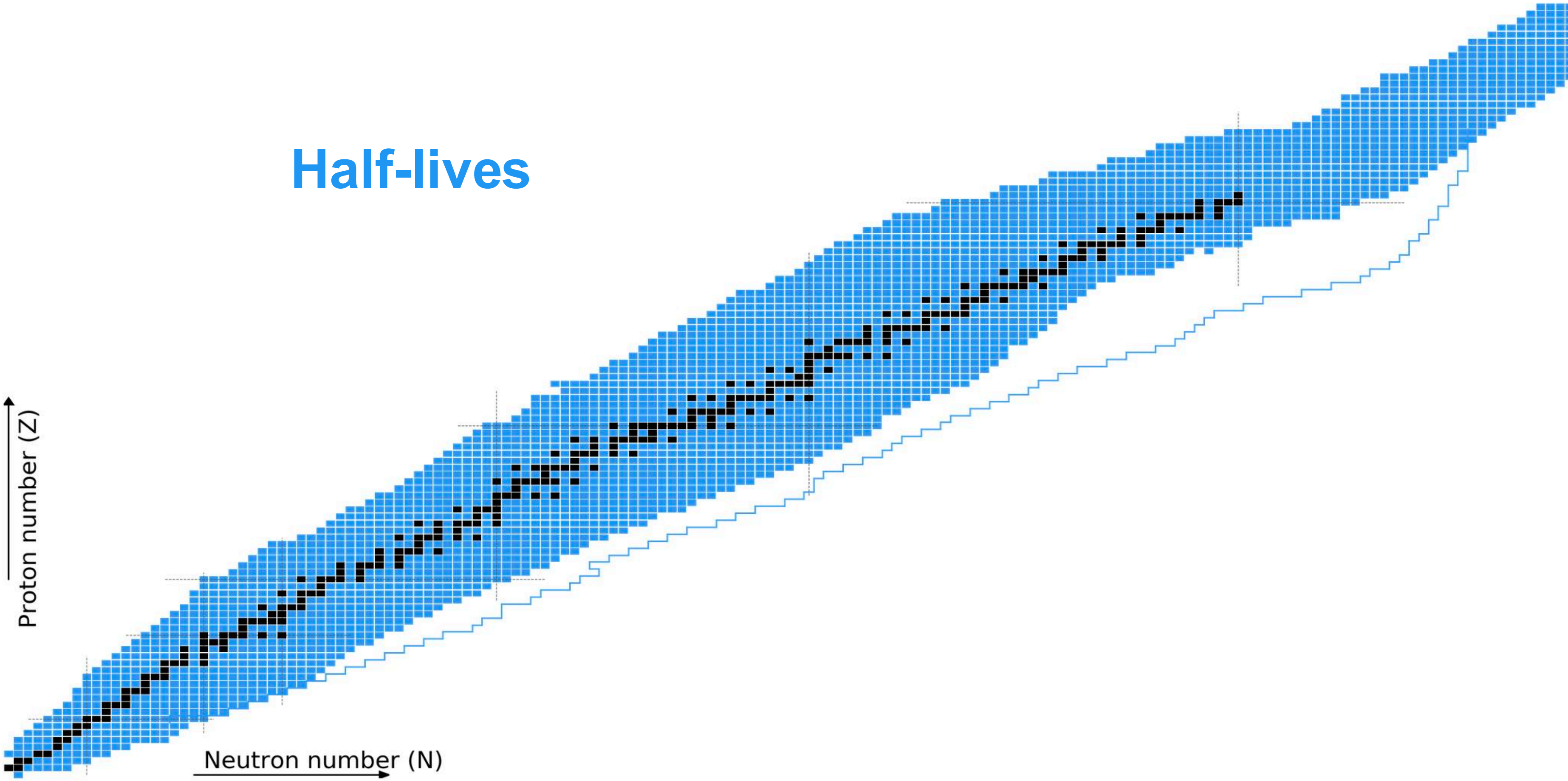
What do we know?



Modified from M. Mumpower

Nuclear Data Needs for SINR

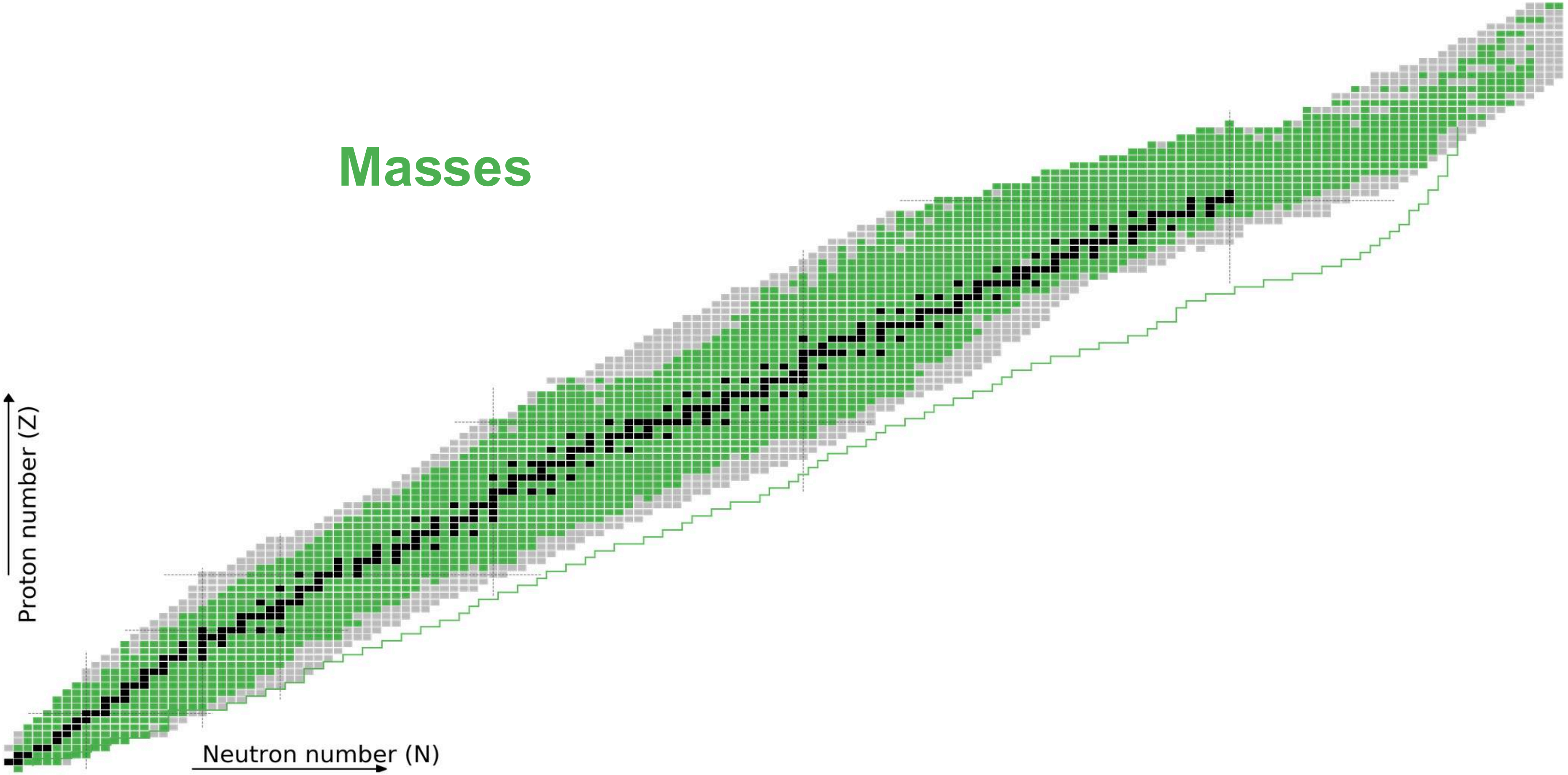
What do we know?



Modified from M. Mumpower

Nuclear Data Needs for SINR

What do we know?



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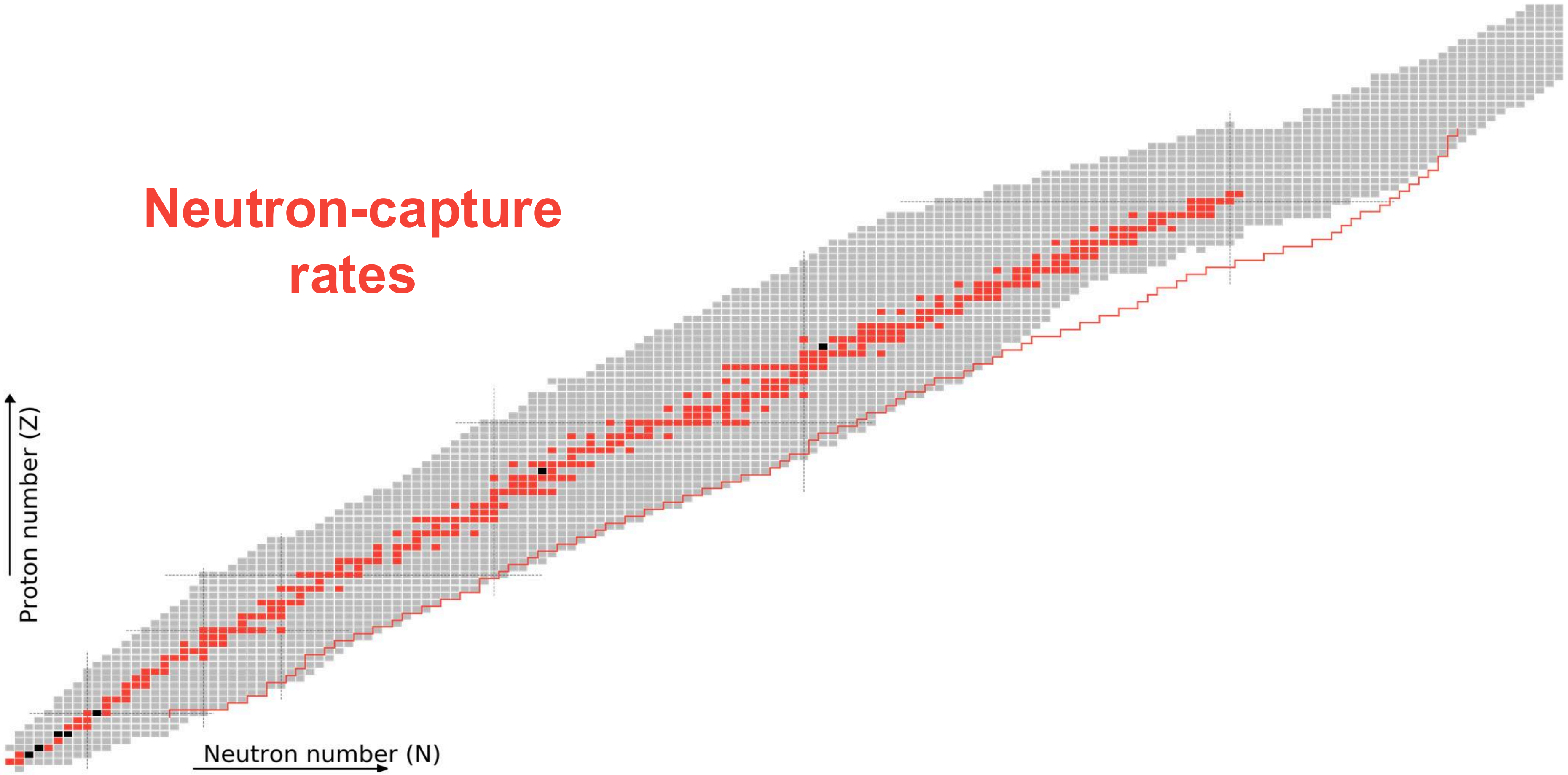
Nuclear Data Needs for SINR

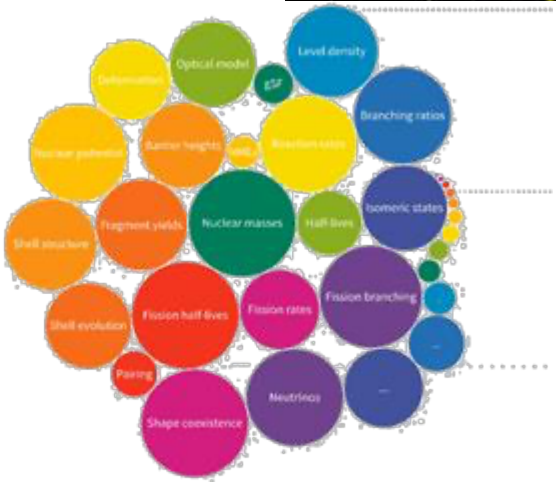
What do we know?



Modified from M. Mumpower

Summary

- Neutron-capture nucleosynthesis is responsible for synthesizing more than half of the elements in the universe
- The *s*, *i*, *n*, and *r* processes span the neutron-rich side of the chart
- Astrophysical sites are “better” understood but there are still large uncertainties on the astrophysics and nuclear inputs.



Tomorrow we will talk about nuclear data measurements for the s, i, and r processes!