Nuclear Astrophysics
r-process nucleosynthesis
Constraining reaction rates

Artemis Spyrou

Michigan State University

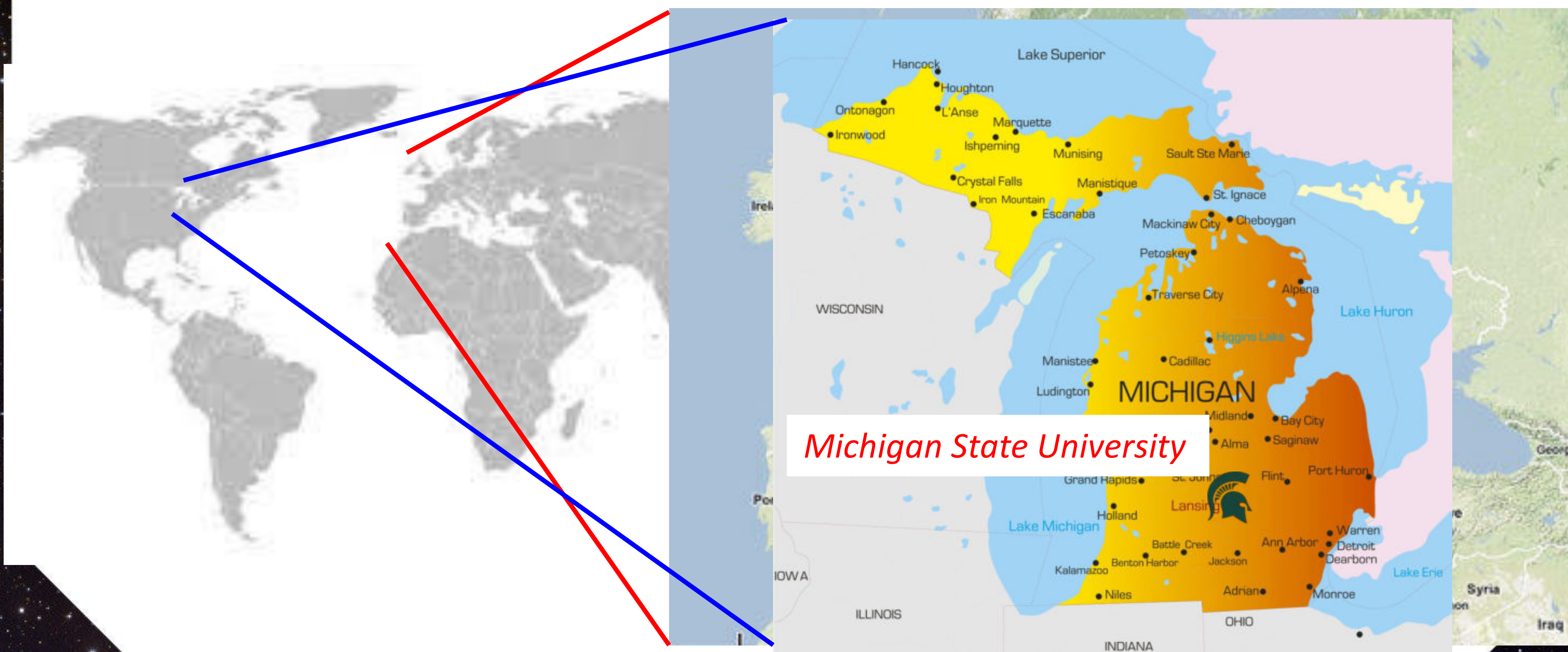
spyrou@frib.msu.edu

@ArtemisSpyrou

artemisspyrou.com

Nice to meet you !

- From Cyprus
- Undergraduate studies: Physics - Thessaloniki, Greece
- Graduate School: Nuclear Physics – Athens, Greece
- Postdoc: Michigan State University
- Assistant Professor, Associate Professor, Associate Director for Education, Professor, Faculty Outreach Advisor



Nice to meet you !

In school: Competitive swimming

Grad school: snowboarding

Miki

Katerina

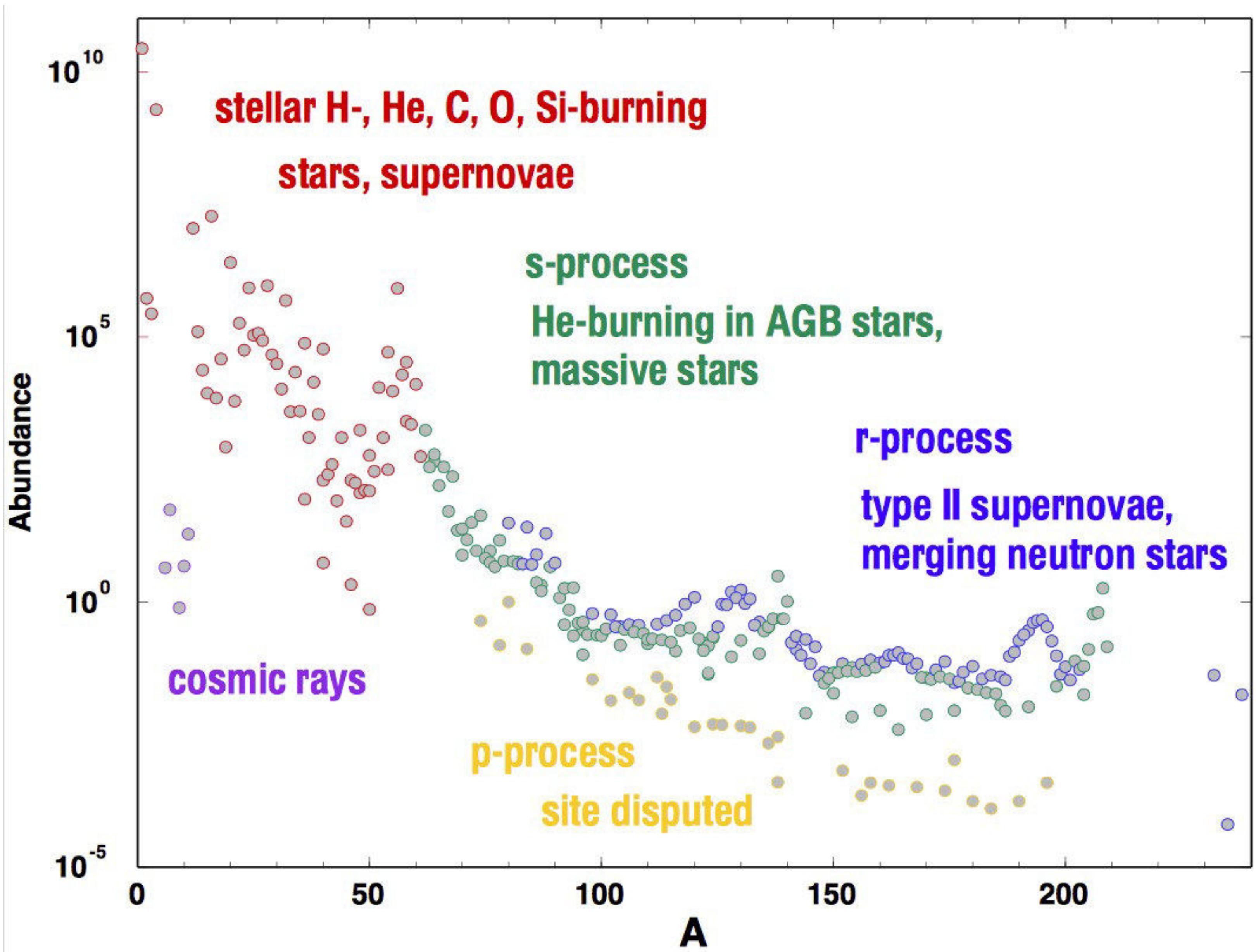
Fivo

Running

Piano

Baking

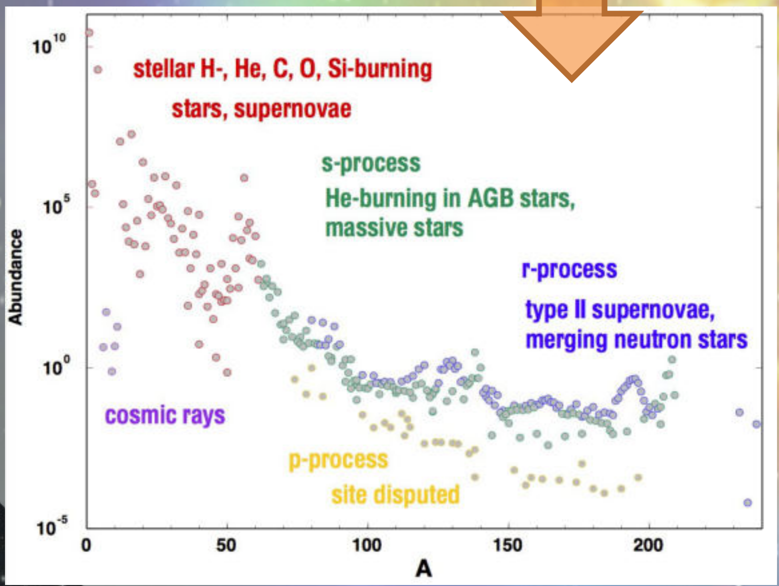
Abundances



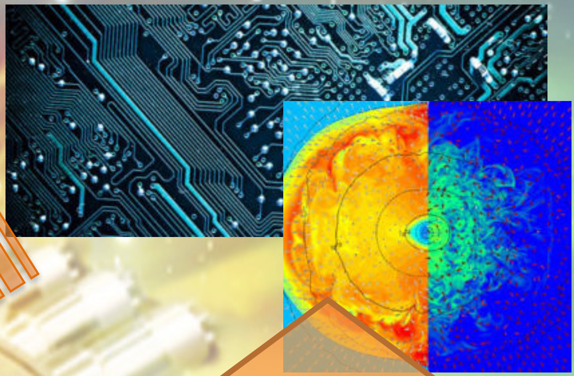
From M. Wiescher, JINA web

Nuclear Astrophysics

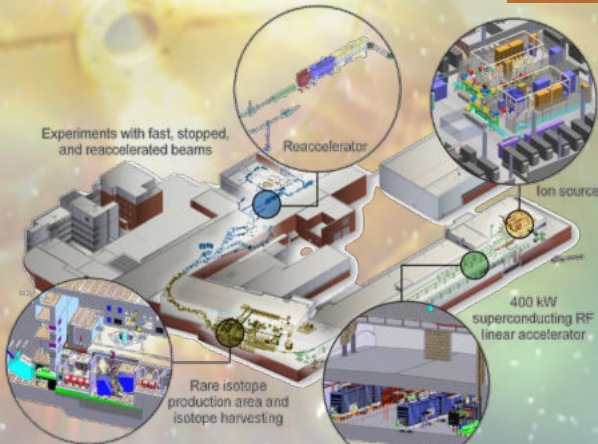
Observations



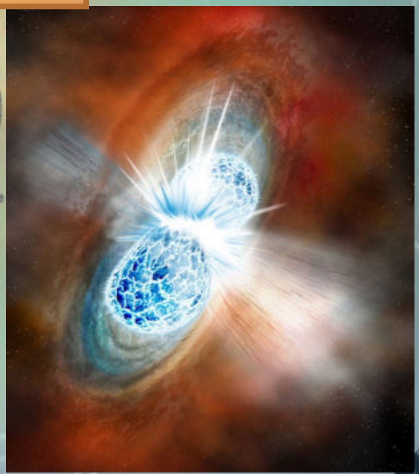
Models



Input



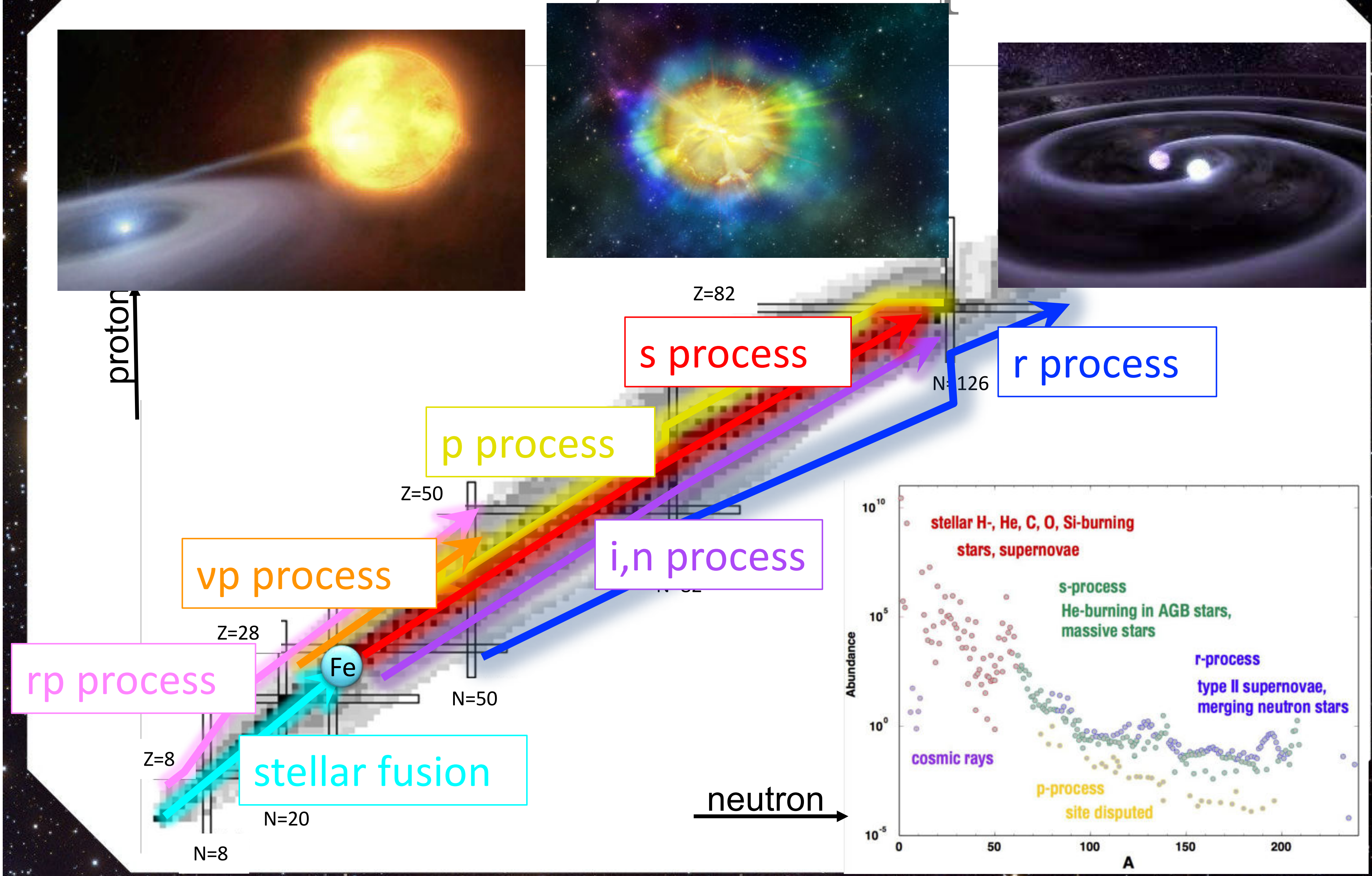
Nuclear



Astro

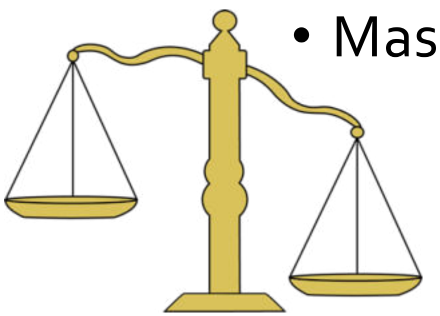
Figure Credit: Erin O'Donnel, NSCL

Nucleosynthesis paths

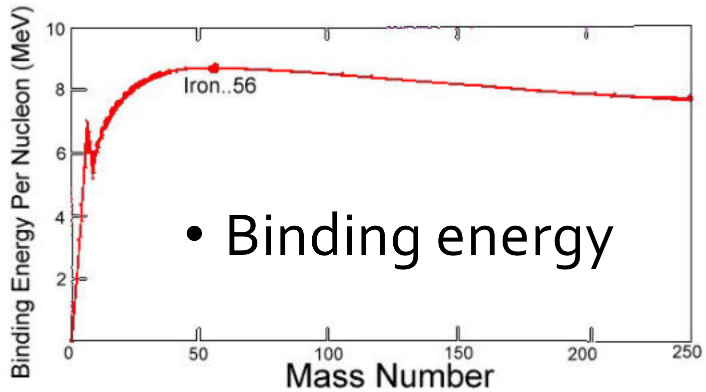


Nuclear input: What do we need?

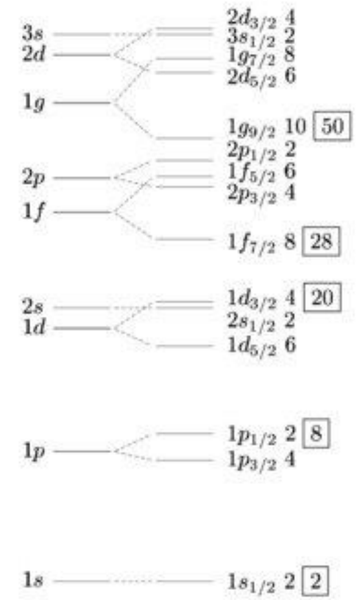
- Basic nuclear properties



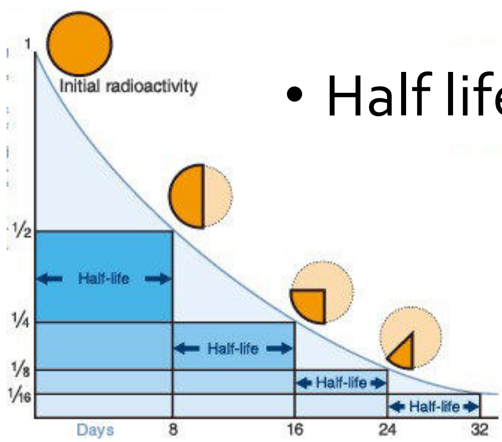
- Mass



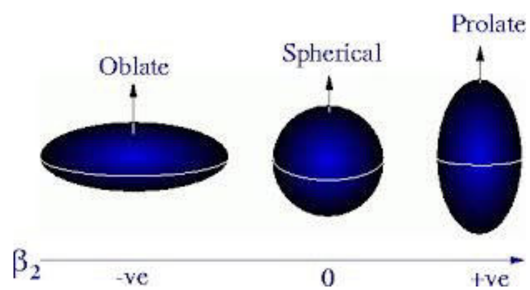
- Binding energy



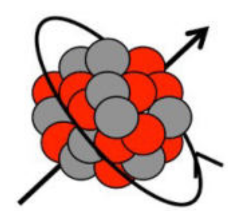
- Level structure



- Half life



- Nuclear radius/shape

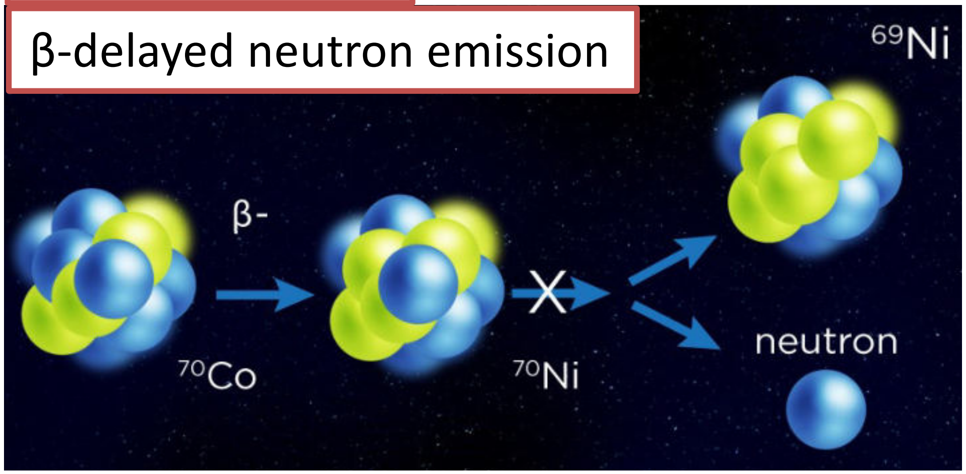


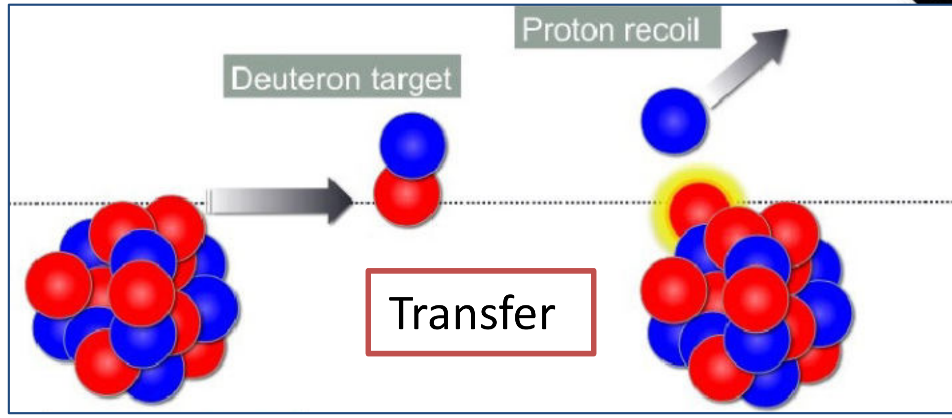
- Angular Momentum

Nuclear input: What do we need?

β-decay half-lives

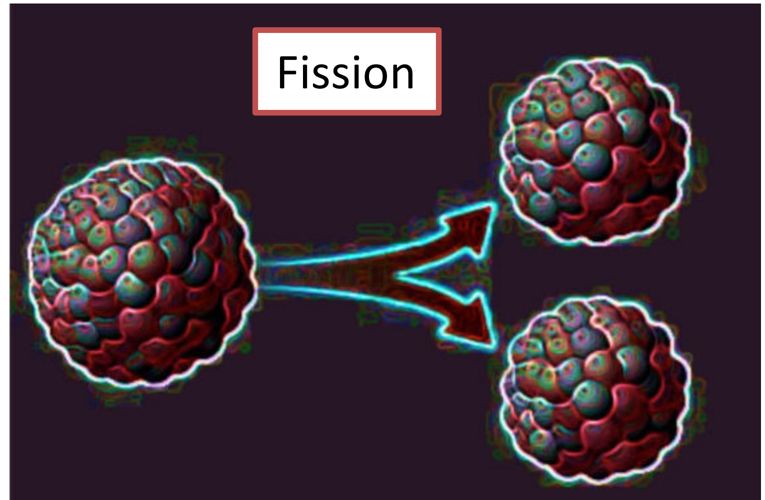
β-delayed neutron emission



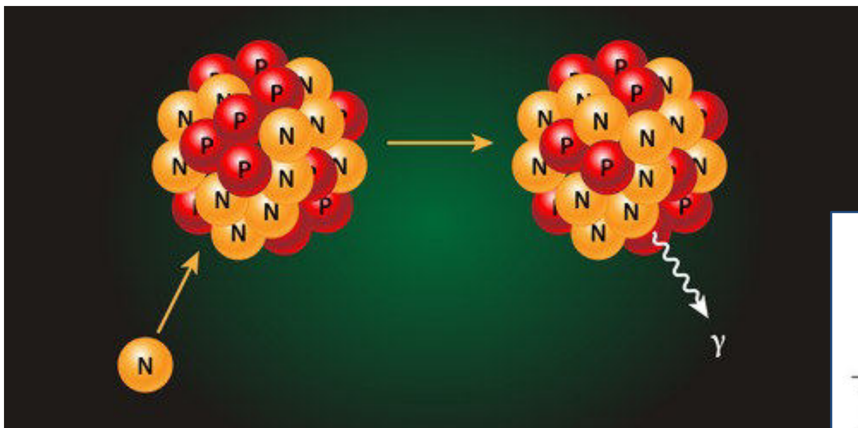


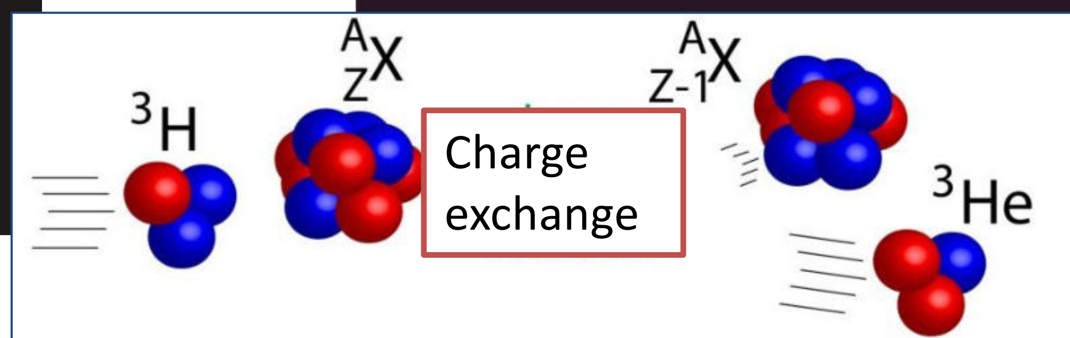
Transfer

Fission



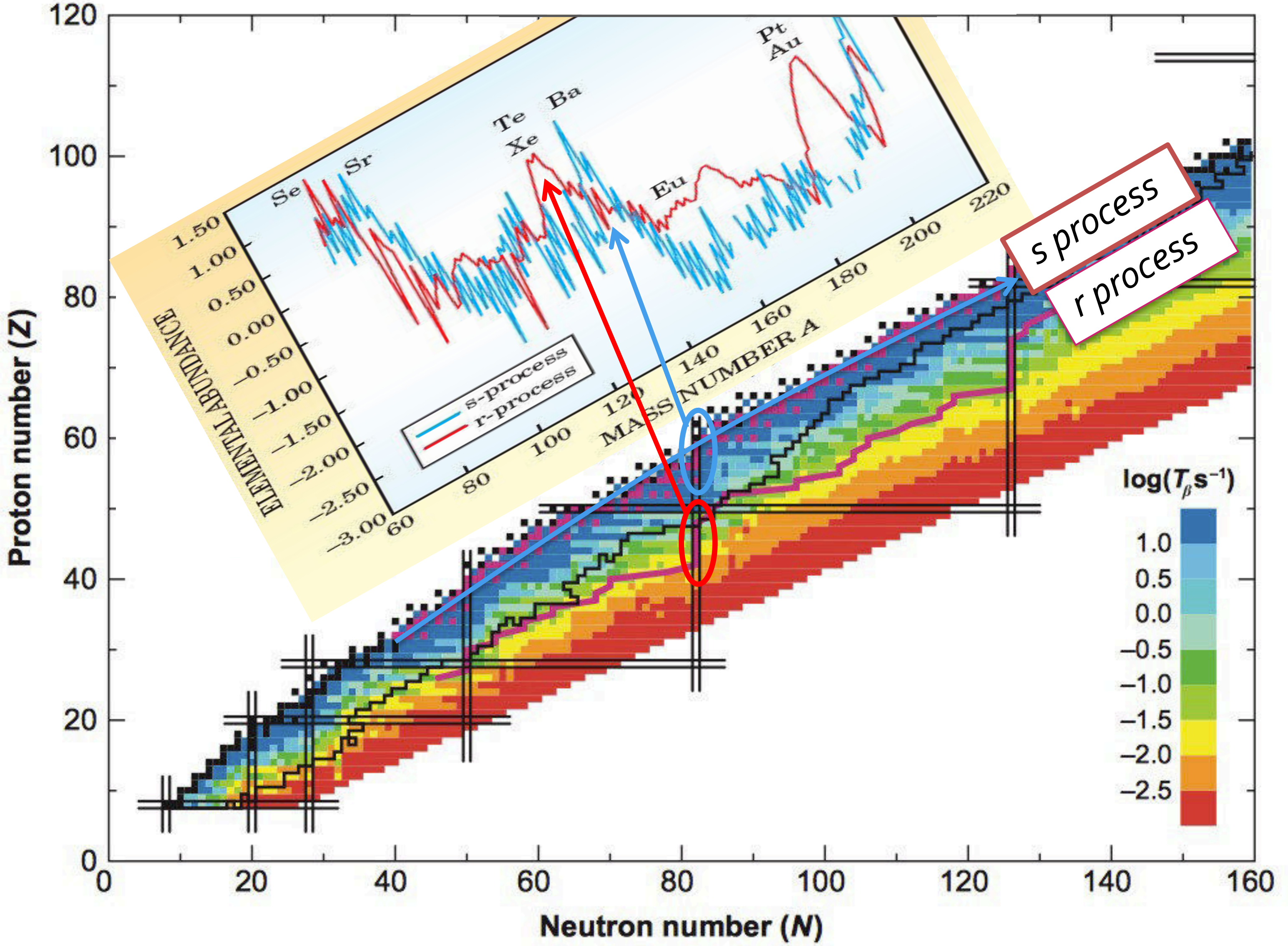
Neutron/proton Captures





Charge exchange

From nuclei to stars

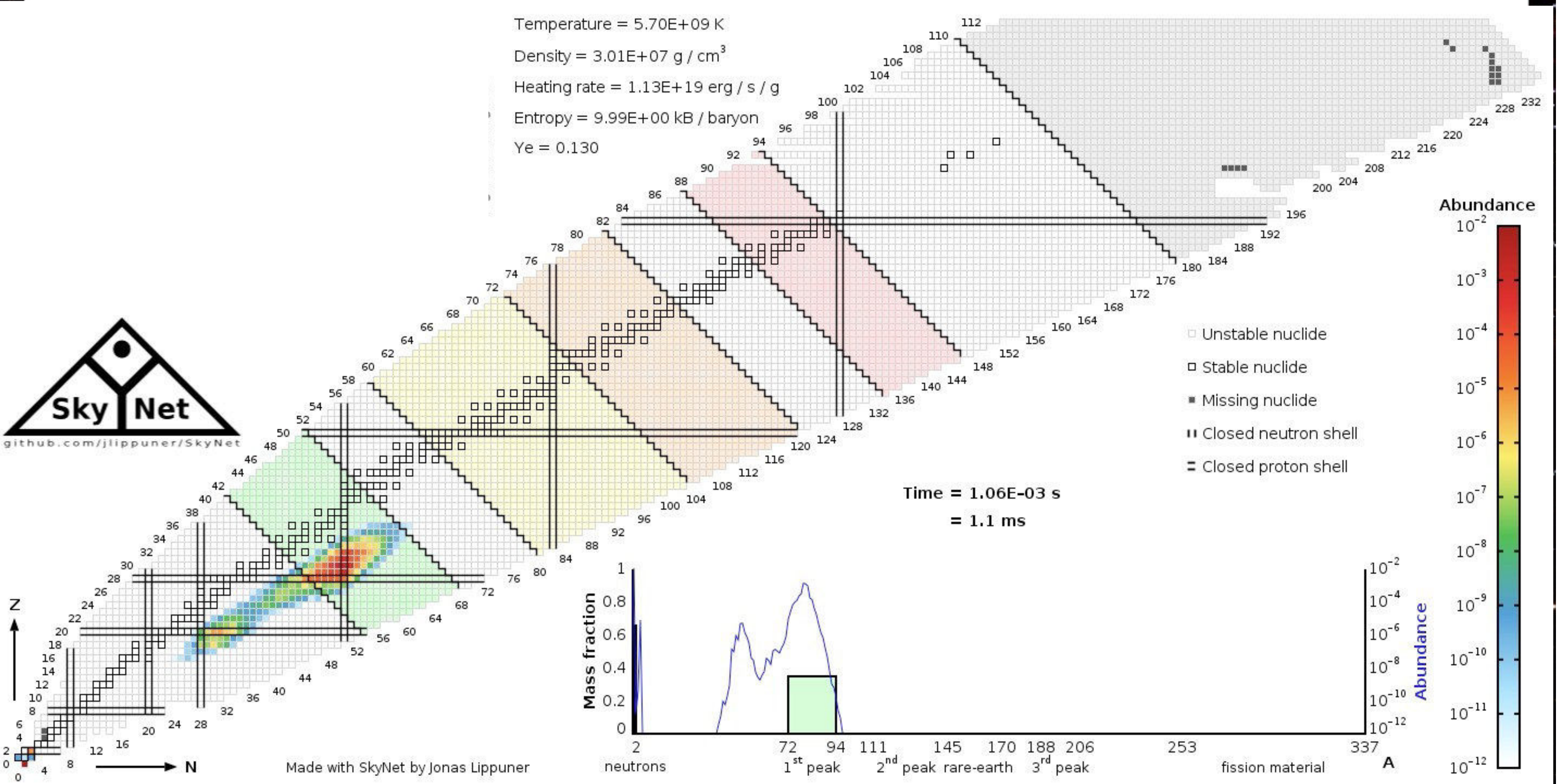


Sneden, C., Cowan, J. J., & Gallino, R., *Ann. Rev. Ast. Ap.* **46** (2008) 241.

r-process

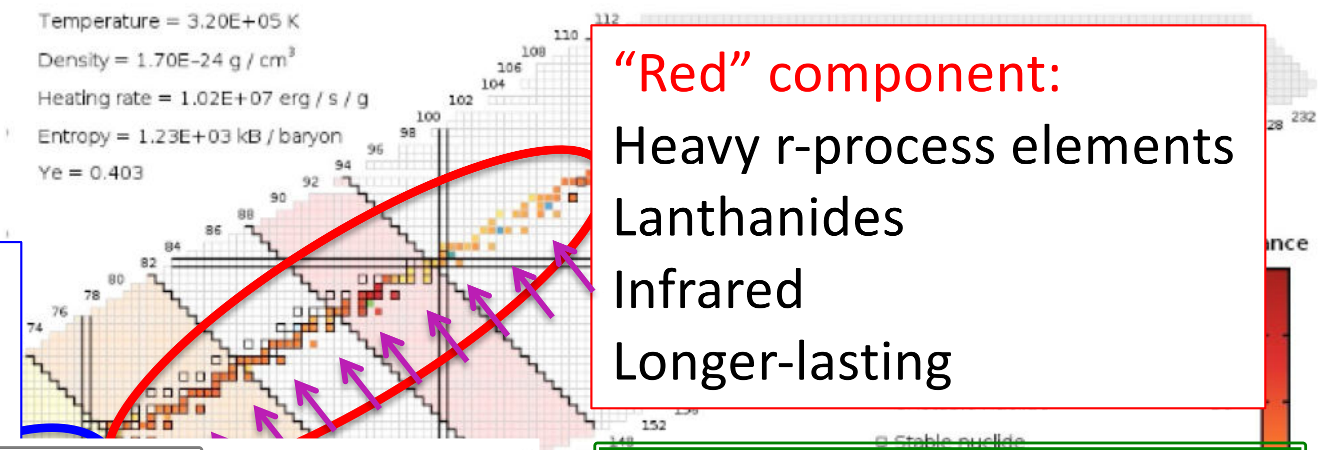
Main focus on capture reactions

r-process simulations



Made with SkyNet by Jonas Lippuner

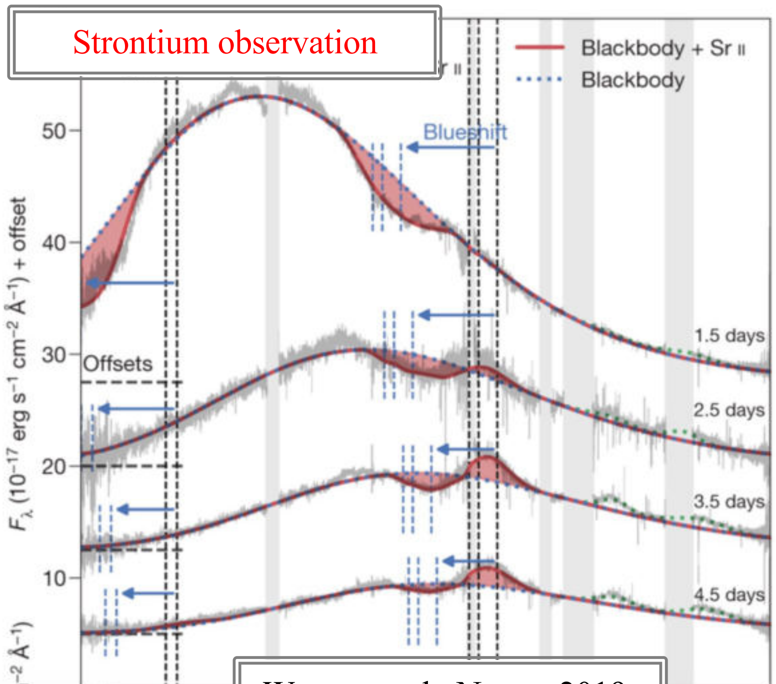
Kilonova in GW170817 Neutron Star Merger



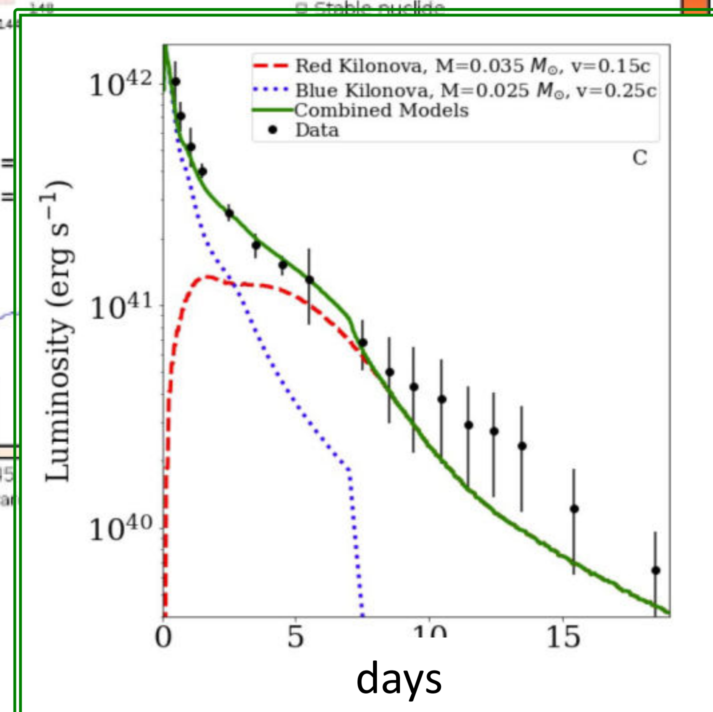
"Red" component:
Heavy r-process elements
Lanthanides
Infrared
Longer-lasting

Blue component:
Light r-process elements
Optical
Bright and brief

Credit: NASA Goddard



Watson et al., Nature 2019

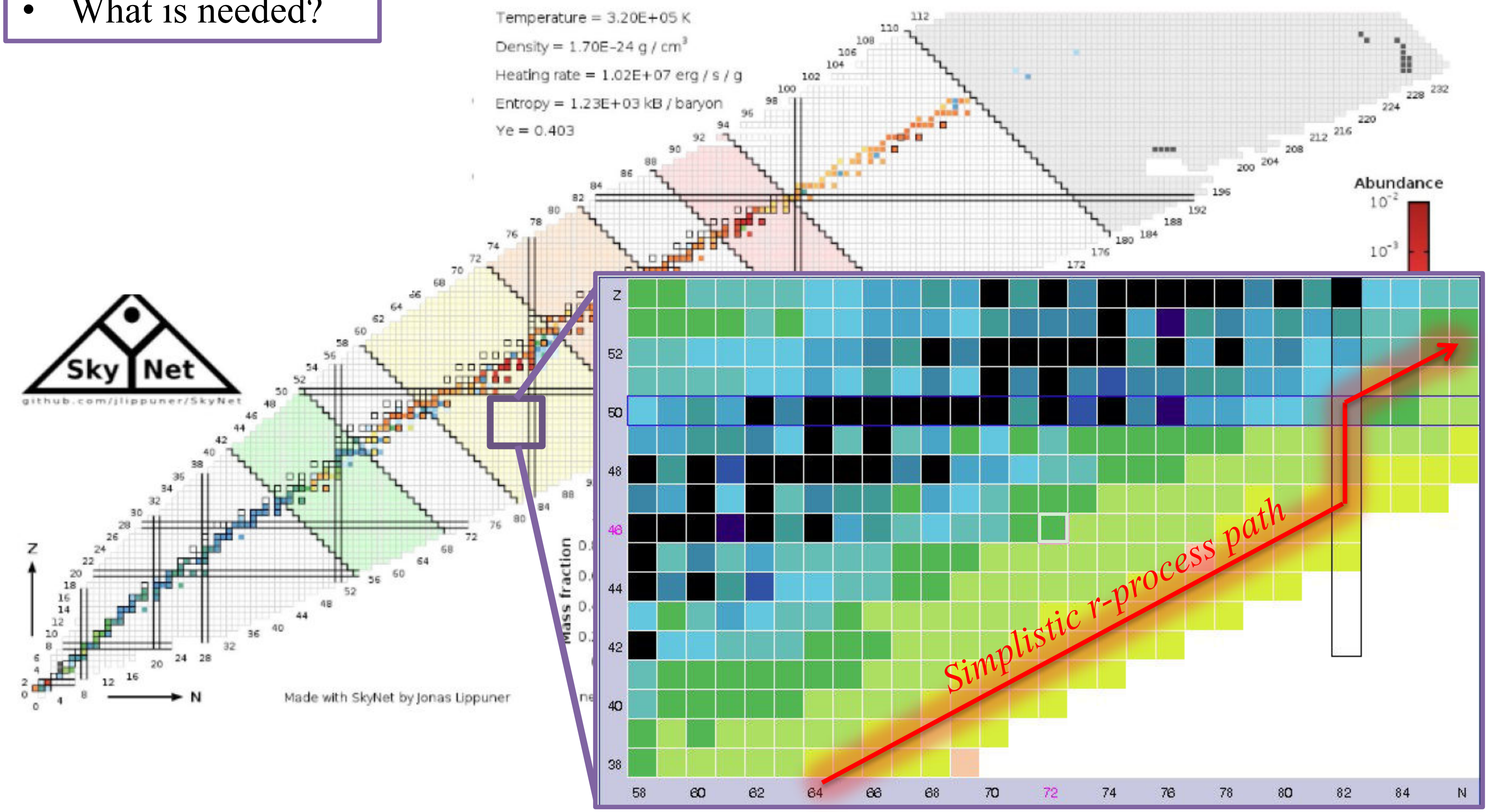


Kasen et al., Nature 2017

Kilpatrick, et al, Science 2017

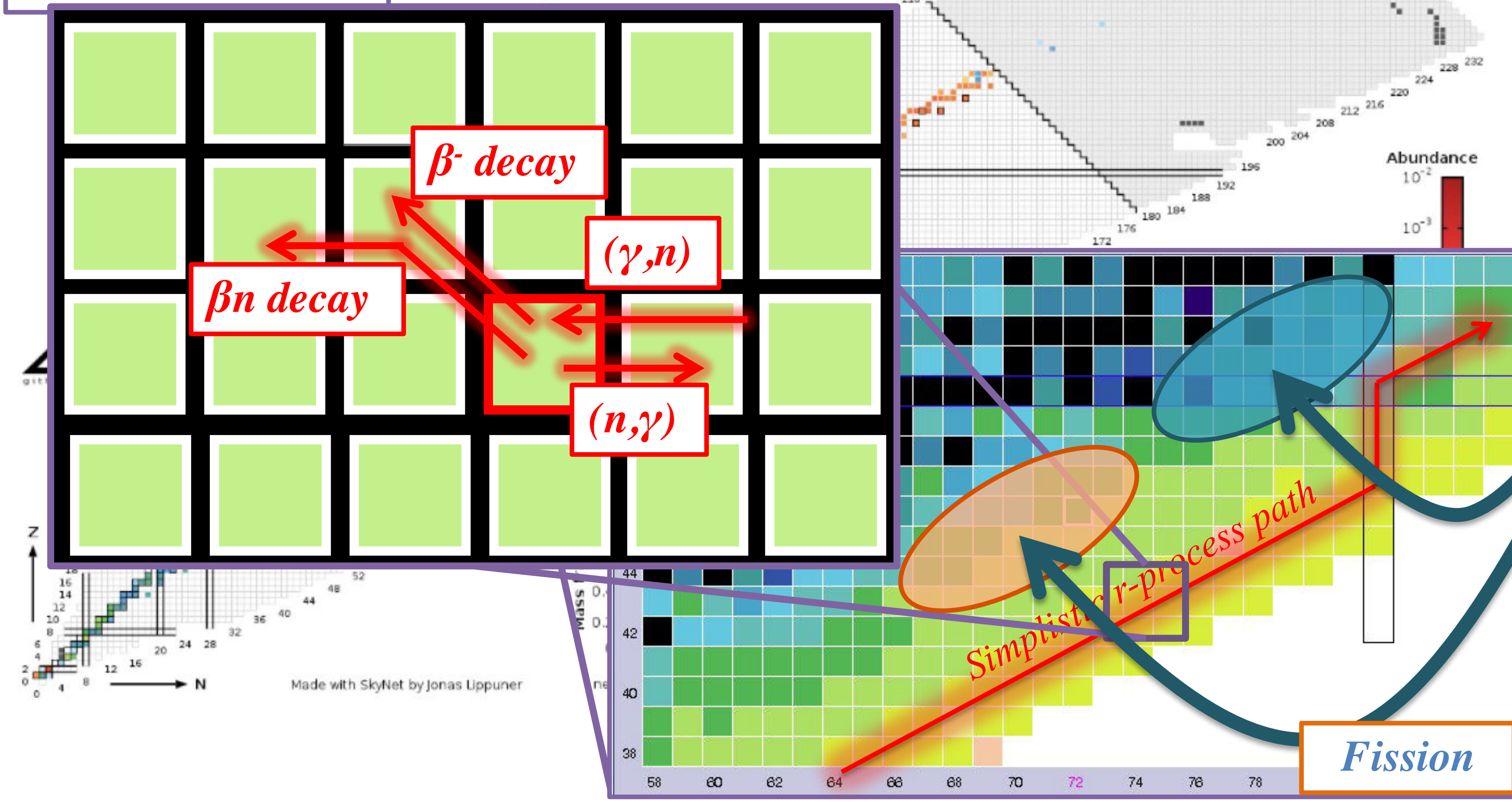
r-process: nuclear input

- What is needed?



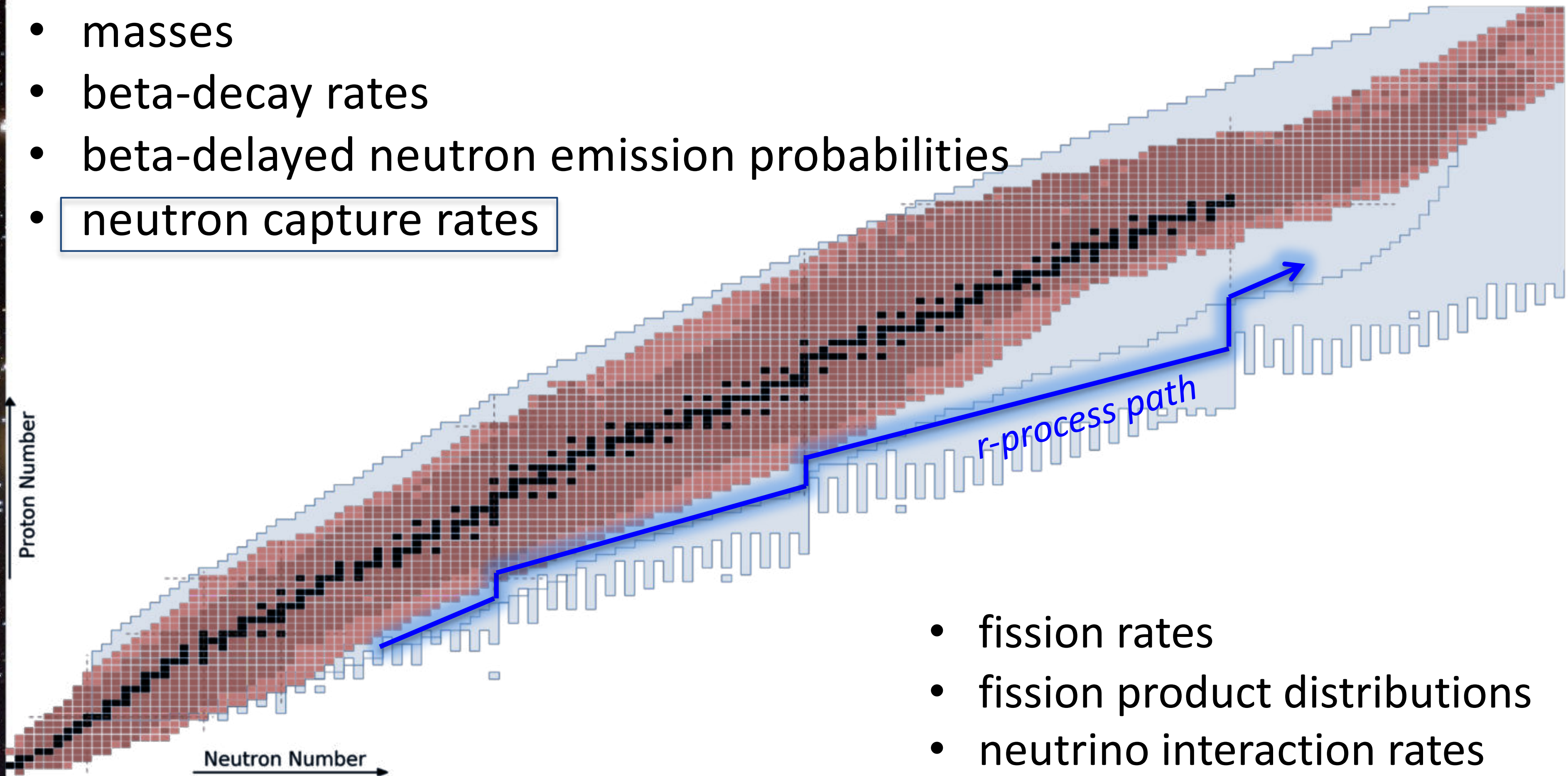
r-process: nuclear input

- What is needed?



What's known?

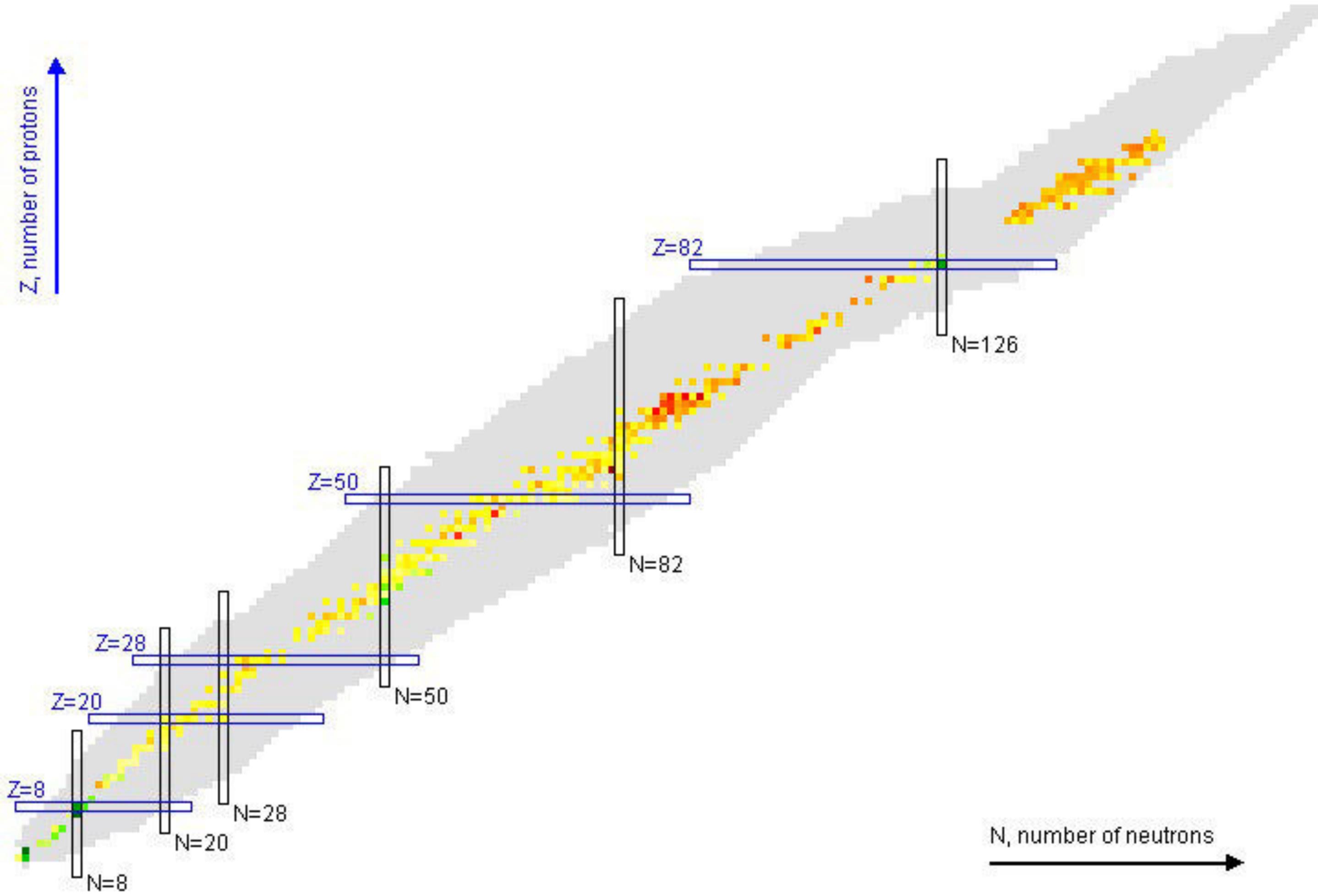
- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates



- fission rates
- fission product distributions
- neutrino interaction rates
- Equation of state

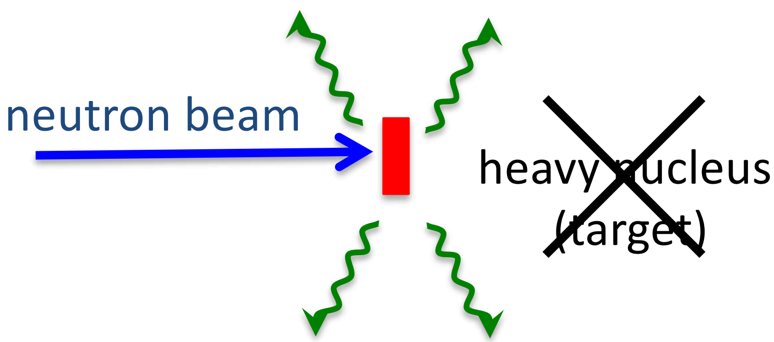
figure by M. Mumpower

Current (n,γ) measurements



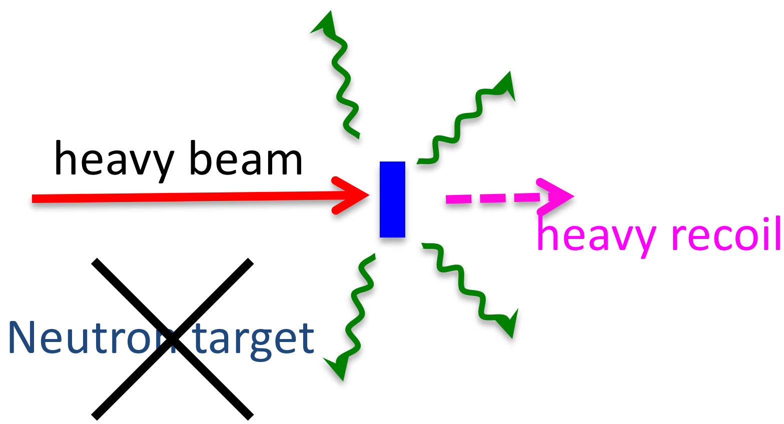
The trouble with neutron capture

- Regular kinematics

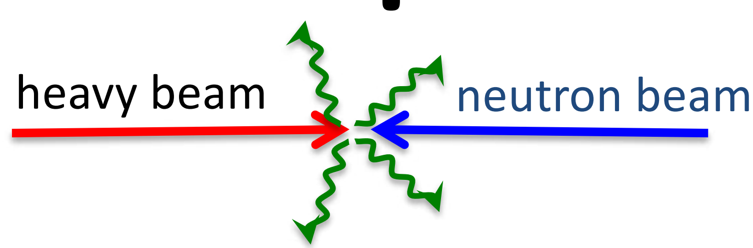


- Measuring Neutron Capture reactions on short-lived nuclei is at best challenging
- **Need indirect techniques**
- Surrogate technique (d,p)-(n,γ)
- Measure NLD, γSF
- Can also be applied to (p,γ) – why?

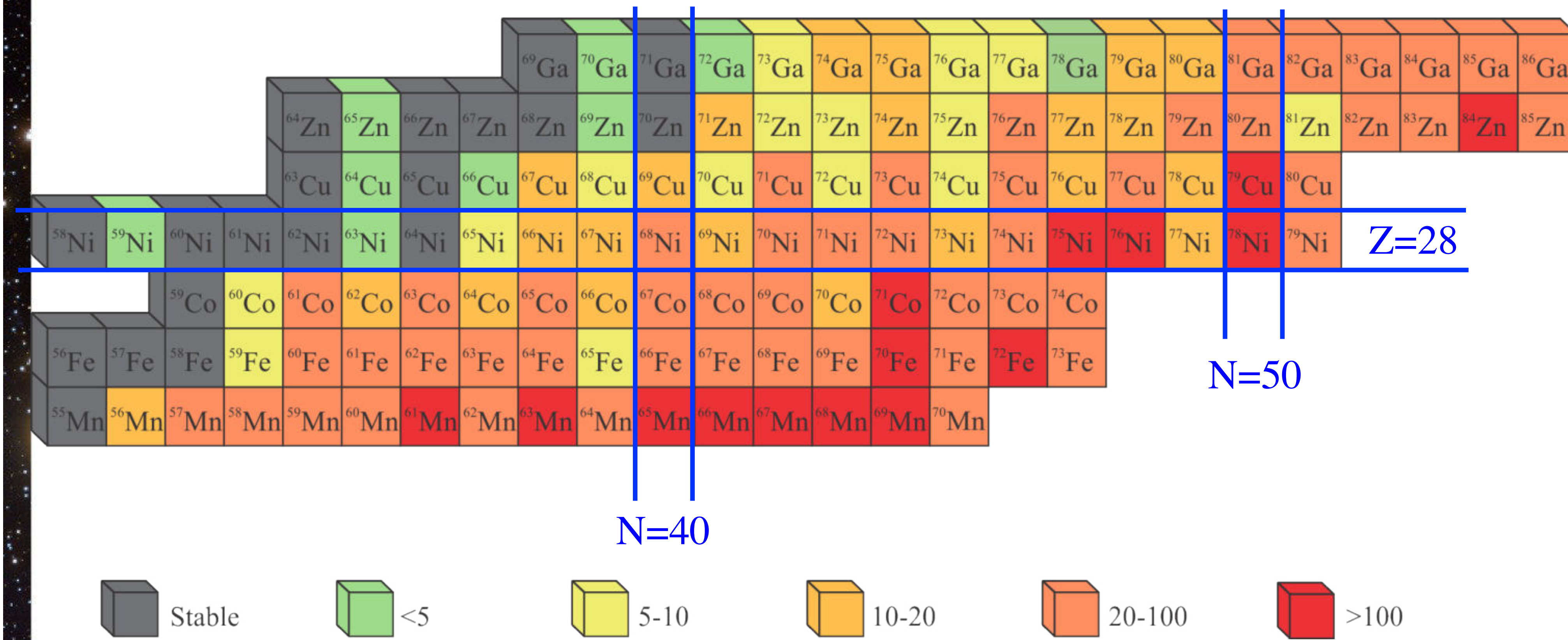
- Inverse kinematics



- Colliding beams ?

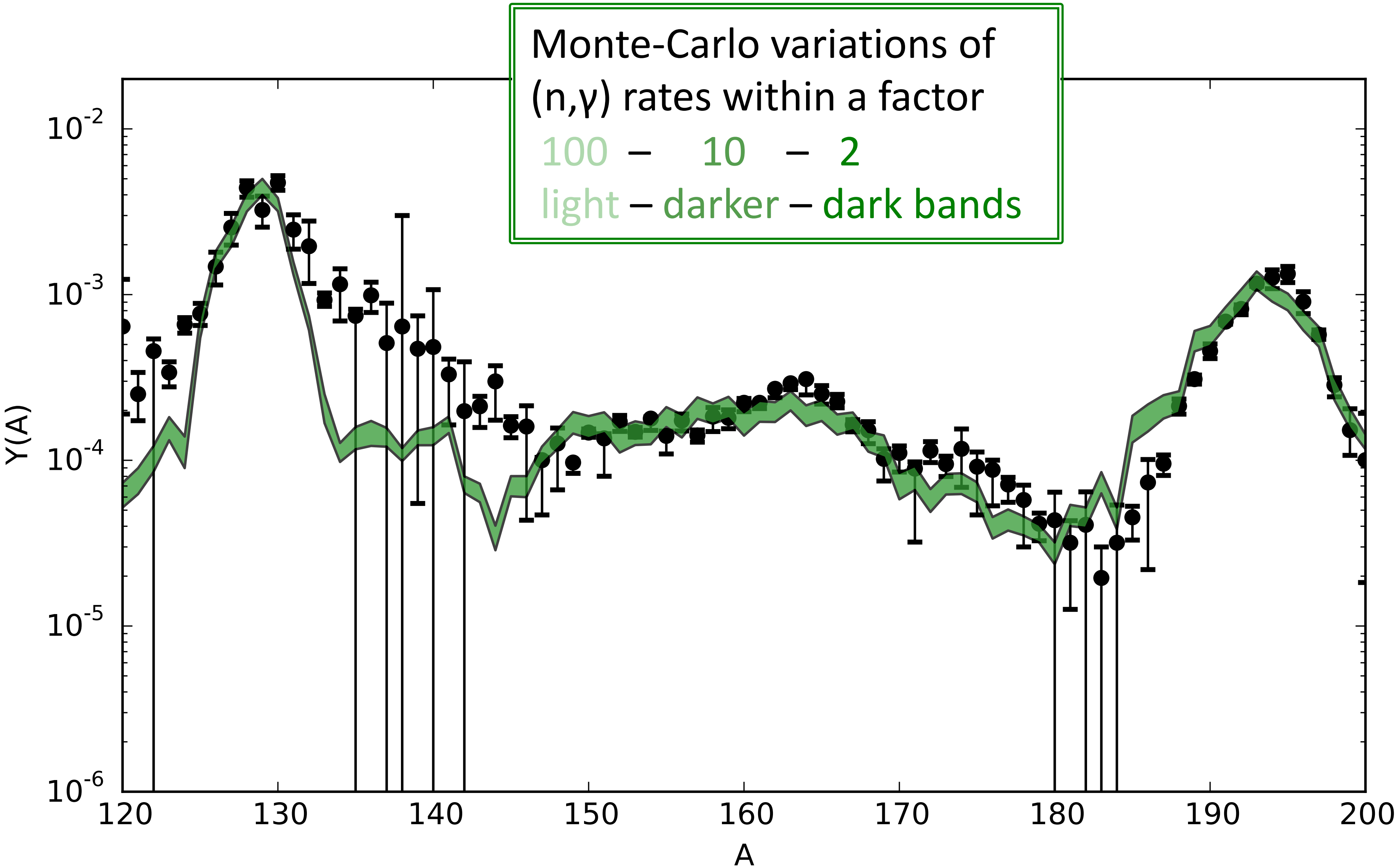


Neutron capture reactions



- Variation of theoretical predictions using TALYS code, changing model parameters
- Predictions diverge moving away from stability

R-process sensitivity to neutron captures

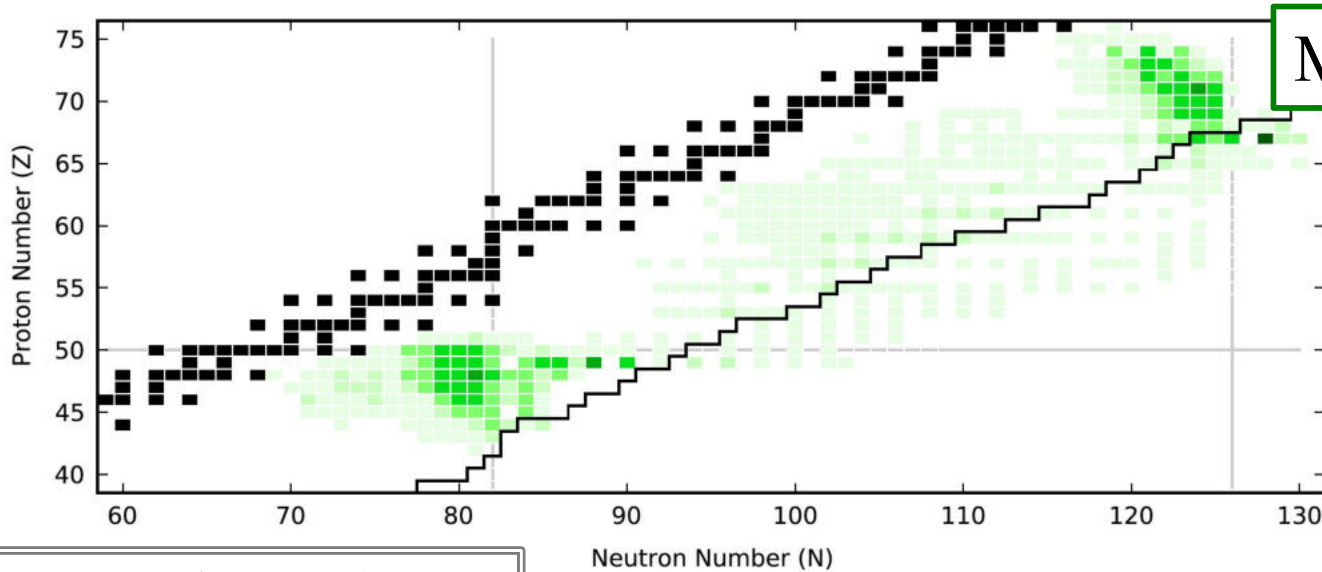


Liddick, Spyrou, et al., PRL 2016

R-process sensitivity to neutron captures

Main r-process

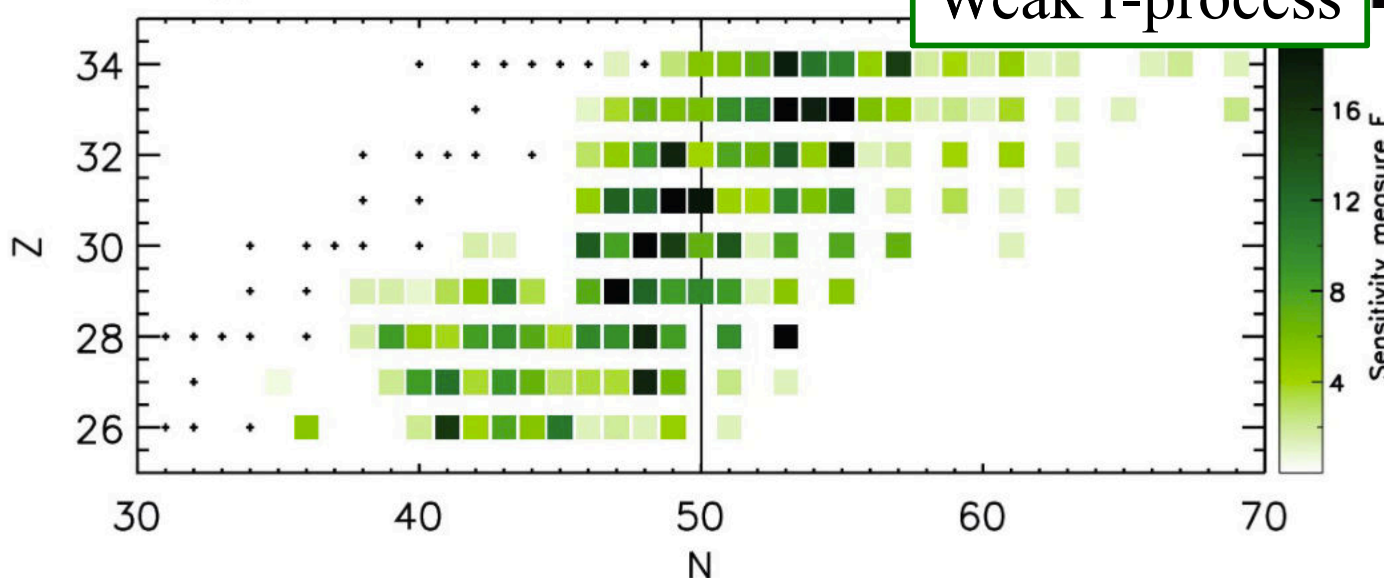
Neutron-star merger



Mumpower et. al., PPNP 86 (2016) 86

Supernova

Weak r-process



Surman, et al., , AIP Advances 4, 041008 (2014)

Indirect techniques for neutron capture reactions for the r process

Review article:
Larsen, Spyrou, Liddick, Guttormsen
Progress in Particle and Nuclear Physics 107 (2019) 69–108

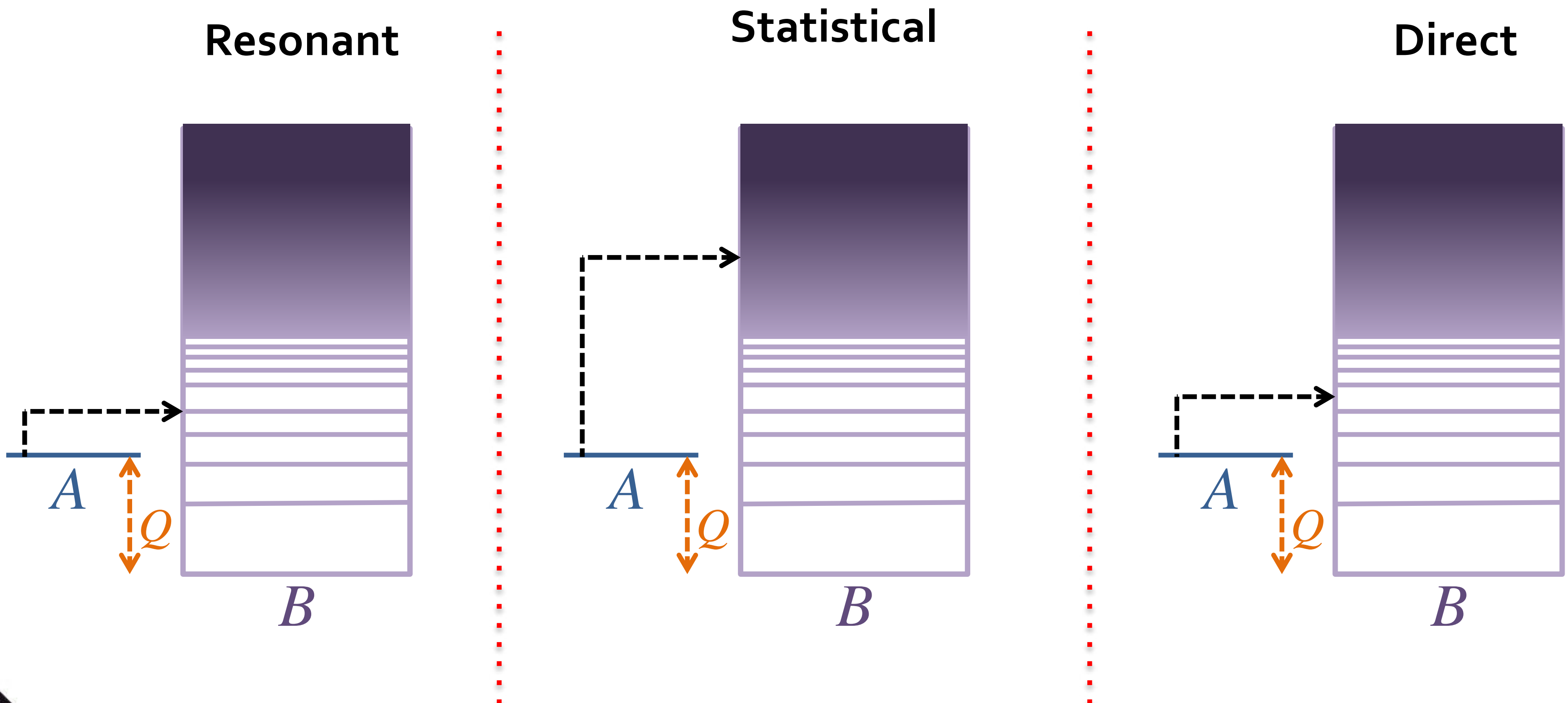
Nuclear input: What do we need?

- <u>Nuclear reactions/Astrophysical reaction rates</u>

Incoming channel

$$a + A \rightarrow B^* \rightarrow B + \gamma$$

Radiative capture reactions



Calculate: Cross Section

Hauser-Feshbach theory

$$\sigma_{\alpha\beta} = \pi\lambda_a \frac{1}{(2i_a+1)(2J_a+1)} \sum_{J,\pi} (2J_C^{\pi}+1) \frac{T_a^{J^\pi} T_\beta^{J^\pi}}{\sum_e T_e^{J^\pi}}$$

Transmission coefficients

γ rays → γSF: γ ray strength function

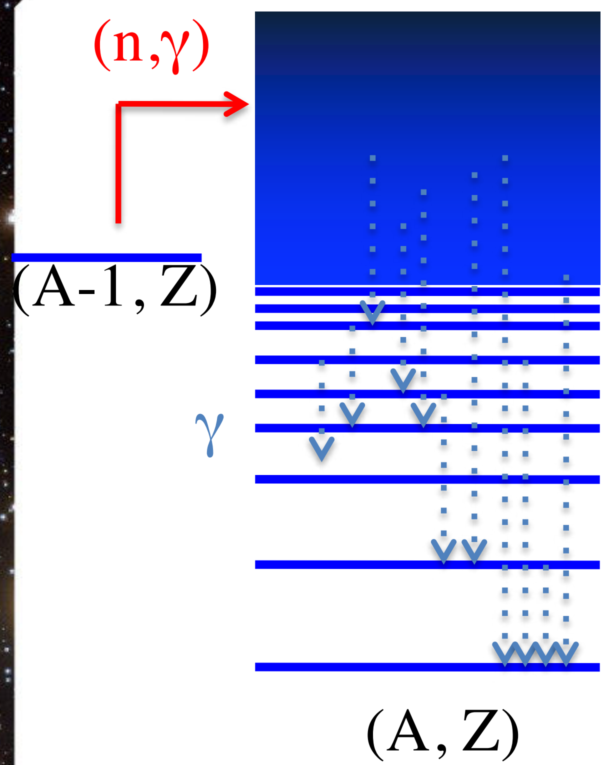
particles → OMP: Optical model potential

continuum:

$$T_\beta^{J^\pi}(E) = \sum_{i=1}^{w} T_\beta^{J^\pi}(E) + \int_{E_w}^{U} T_\beta^{J^\pi}(E)\,\rho(E,J)\,dE$$

→ NLD: Nuclear level densities

Calculate (n,γ) Cross Section



Hauser – Feshbach

- Nuclear Level Density

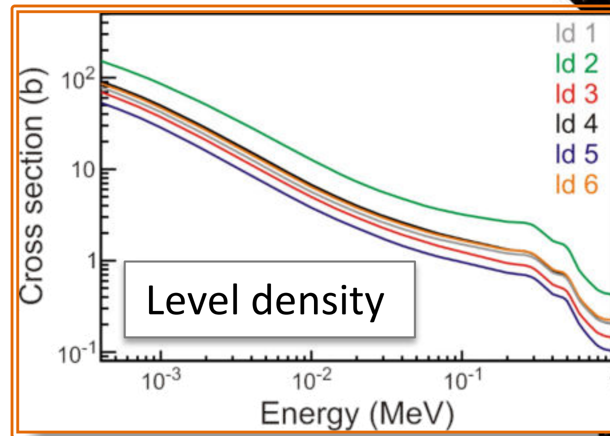
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

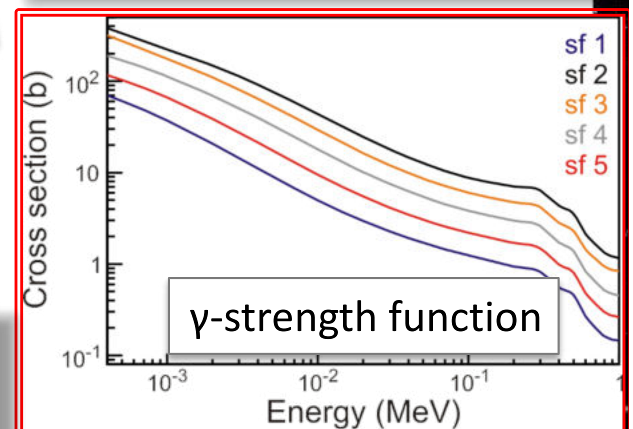
- γ-ray strength function

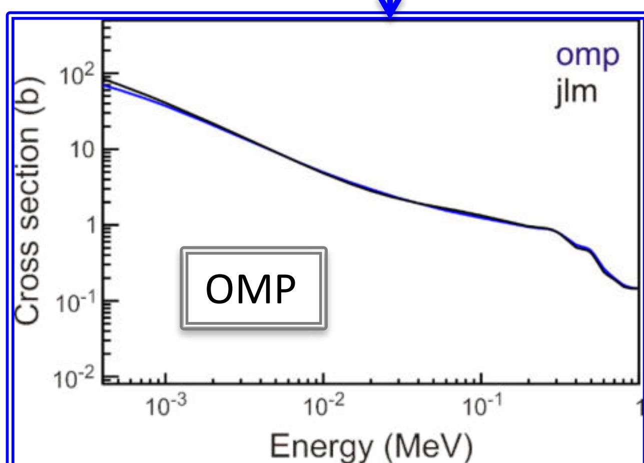
Generalized Lorentzian, Brink-Axel, various tables

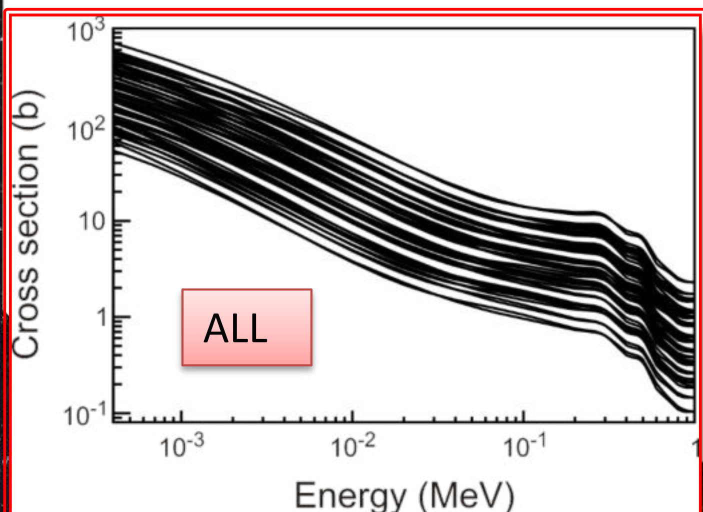
- Optical model potential

Phenomenological, Semi-microscopic









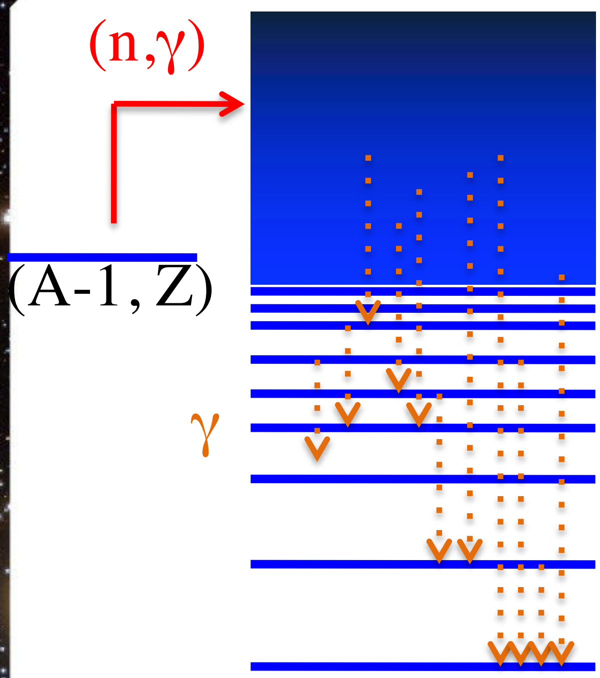
$^{95}Sr(n,\gamma)^{96}Sr$

TALYS

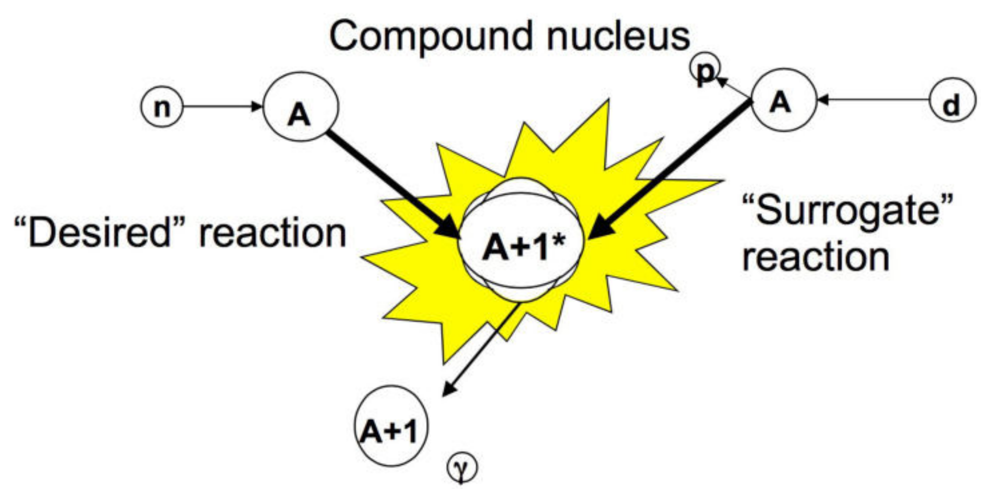
Indirect Measurements

- Transfer reactions (d,n) and (d,p) for (p,γ) and (n,γ) reactions respectively
- β-decay feeding levels of interest and extracting branchings
- Various reaction studies to extract spins of levels
- Trojan Horse method for low-energy reaction rates
- Surrogate Method for (n,γ) reactions
- Oslo/β-Oslo for (n,γ) reaction studies
- Various reactions for extracting nuclear level density or γ-ray strength function
- Coulomb dissociation for γ-ray strength

Surrogate technique



- Formation of compound nucleus (CN) independent of its decay
- Form same CN as (n,γ) via (d,p)
- Study its decay
- Inform the models
- Applicable in regular and inverse kinematics
- Applicable a few steps from stability

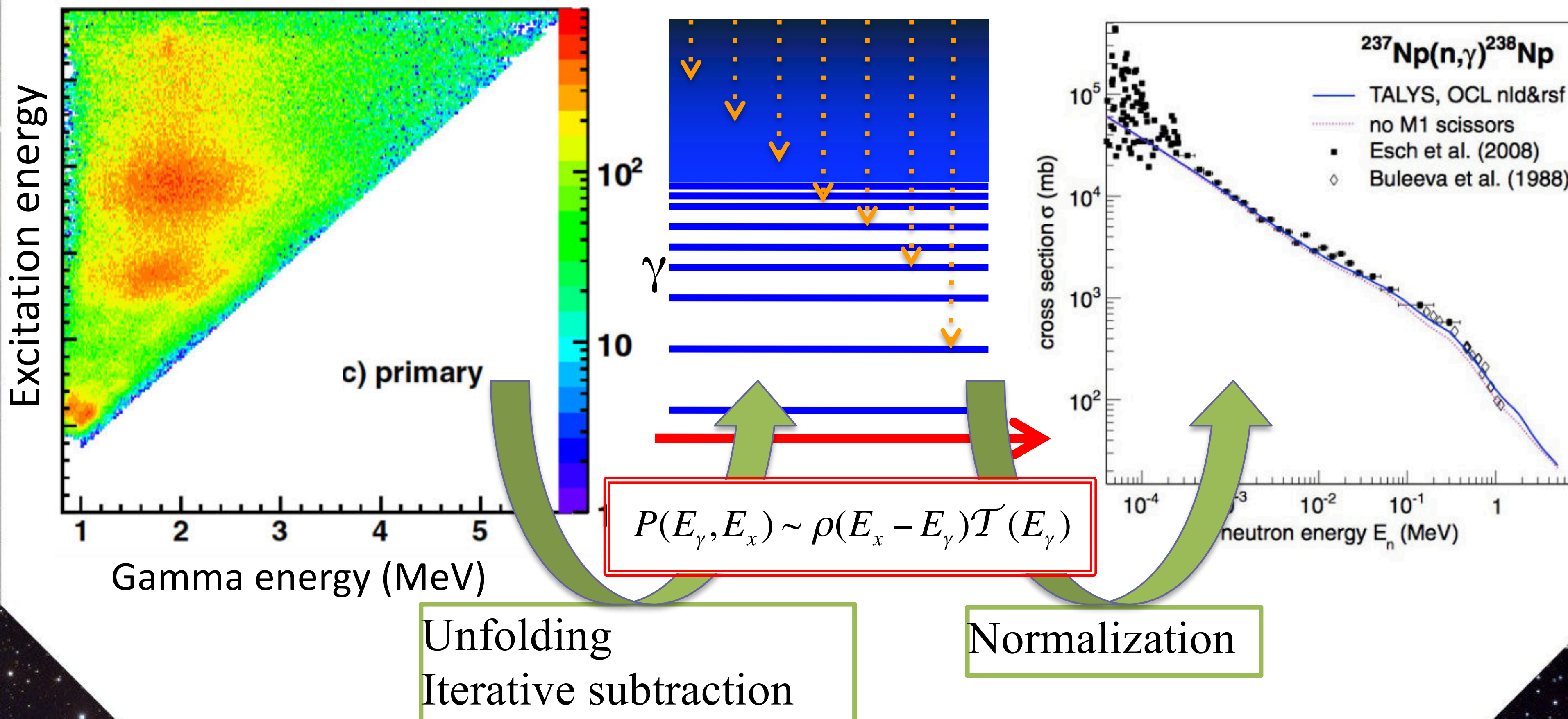


Validation: $^{95}Mo(n,\gamma)^{96}Mo$
Significant progress during the last couple of years

Ratkiewicz, Cizewski, et al PRL 122 (2019) 052502
Escher et al, PRL 121 (2018) 052501

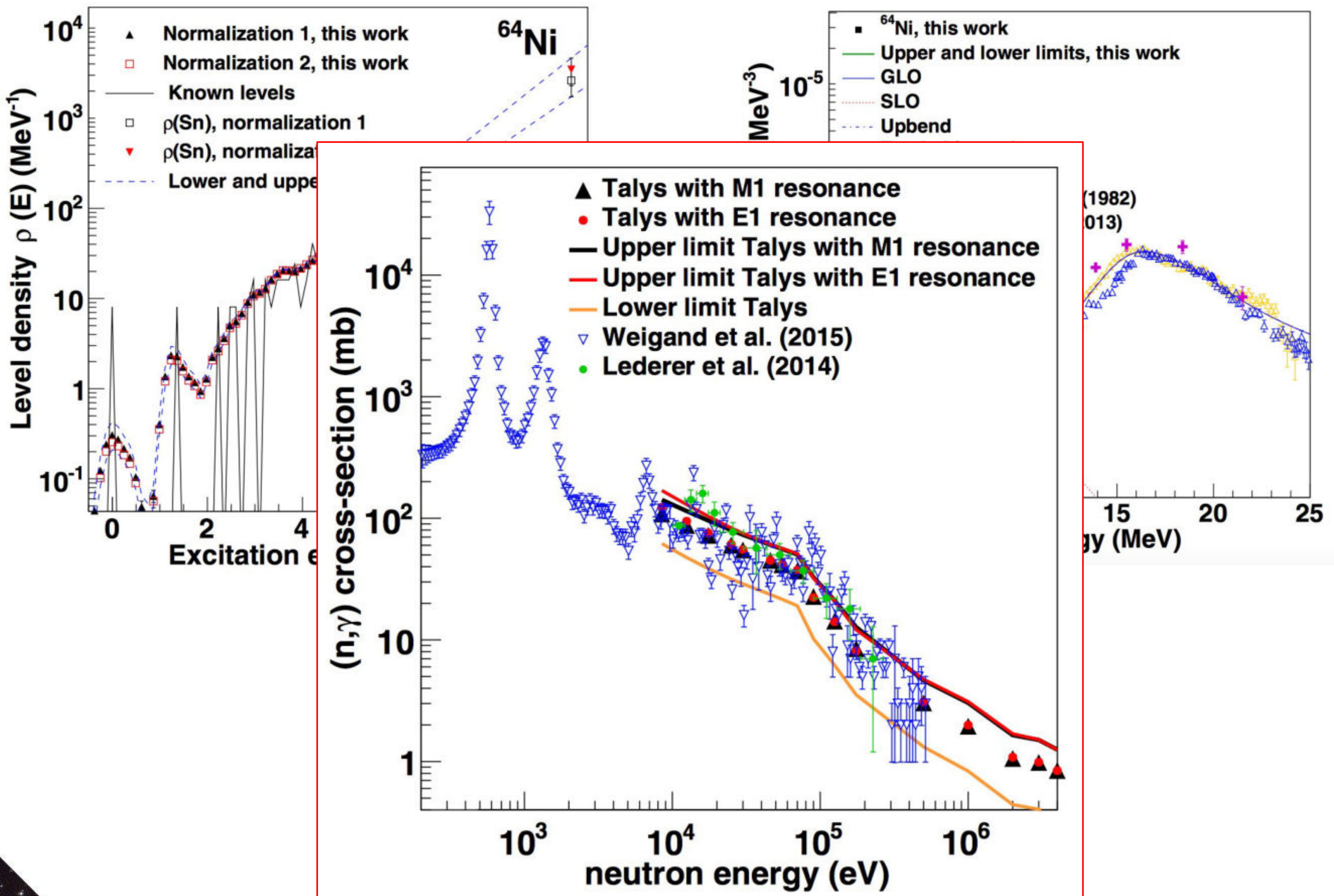
Traditional Oslo method

- Use reaction to populate the compound nucleus of interest
- Measure <u>excitation energy</u> and <u>γ-ray energy</u>
- Extract **level density** and **γ-ray strength function** (external normalizations)
- Calculate "semi-experimental" (n,γ) cross section
- Excellent agreement with measured (n,γ) reaction cross sections



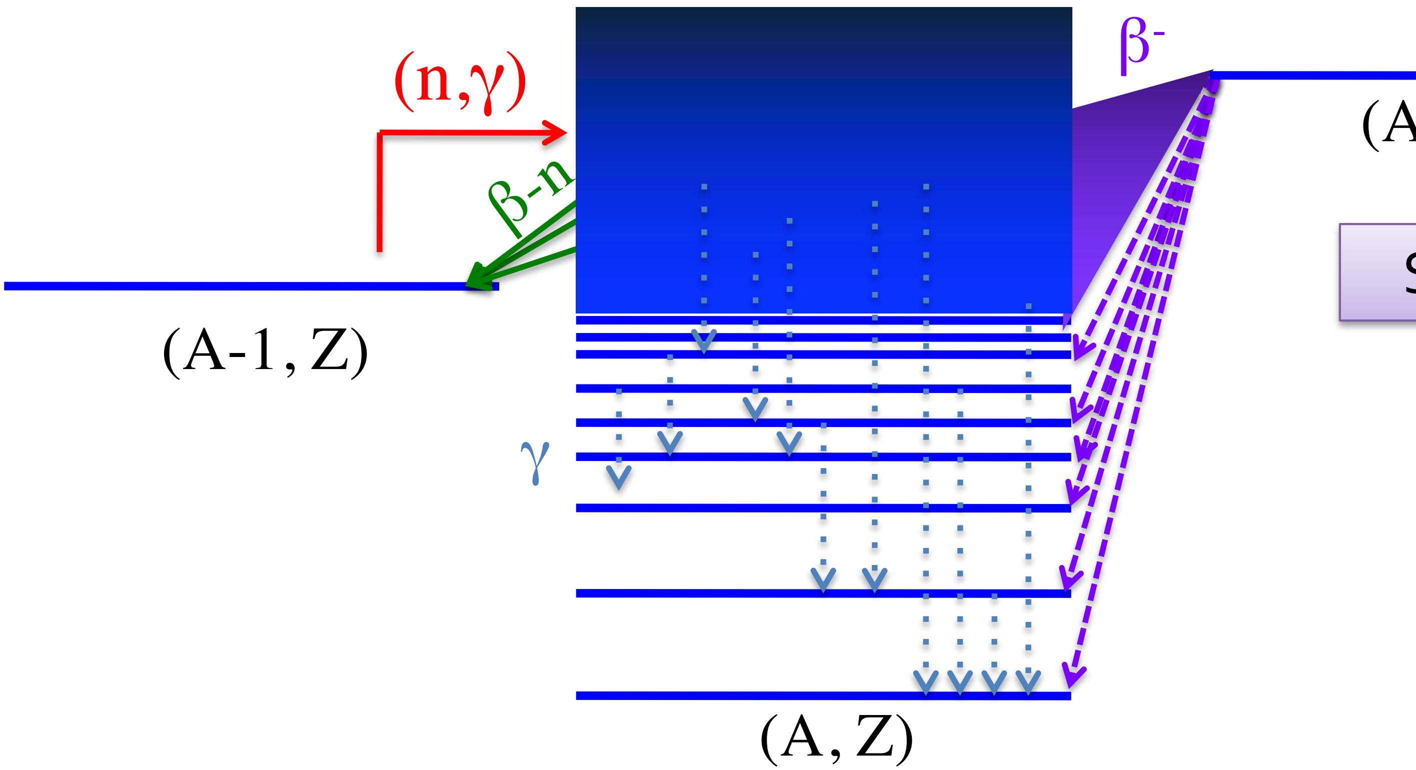
T.G. Tornyi, M. Guttormsen, et al., PRC2014

Example Oslo method

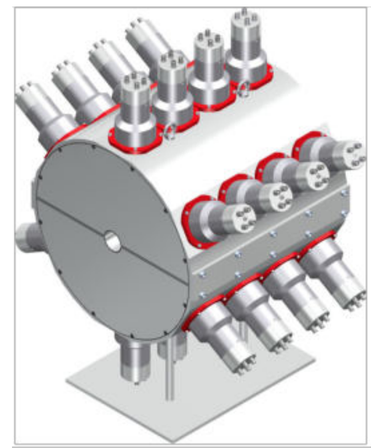


L. Crespo-Campo, et. al. PRC 94 (2016) 044321

β-Oslo



SuN @ MSU

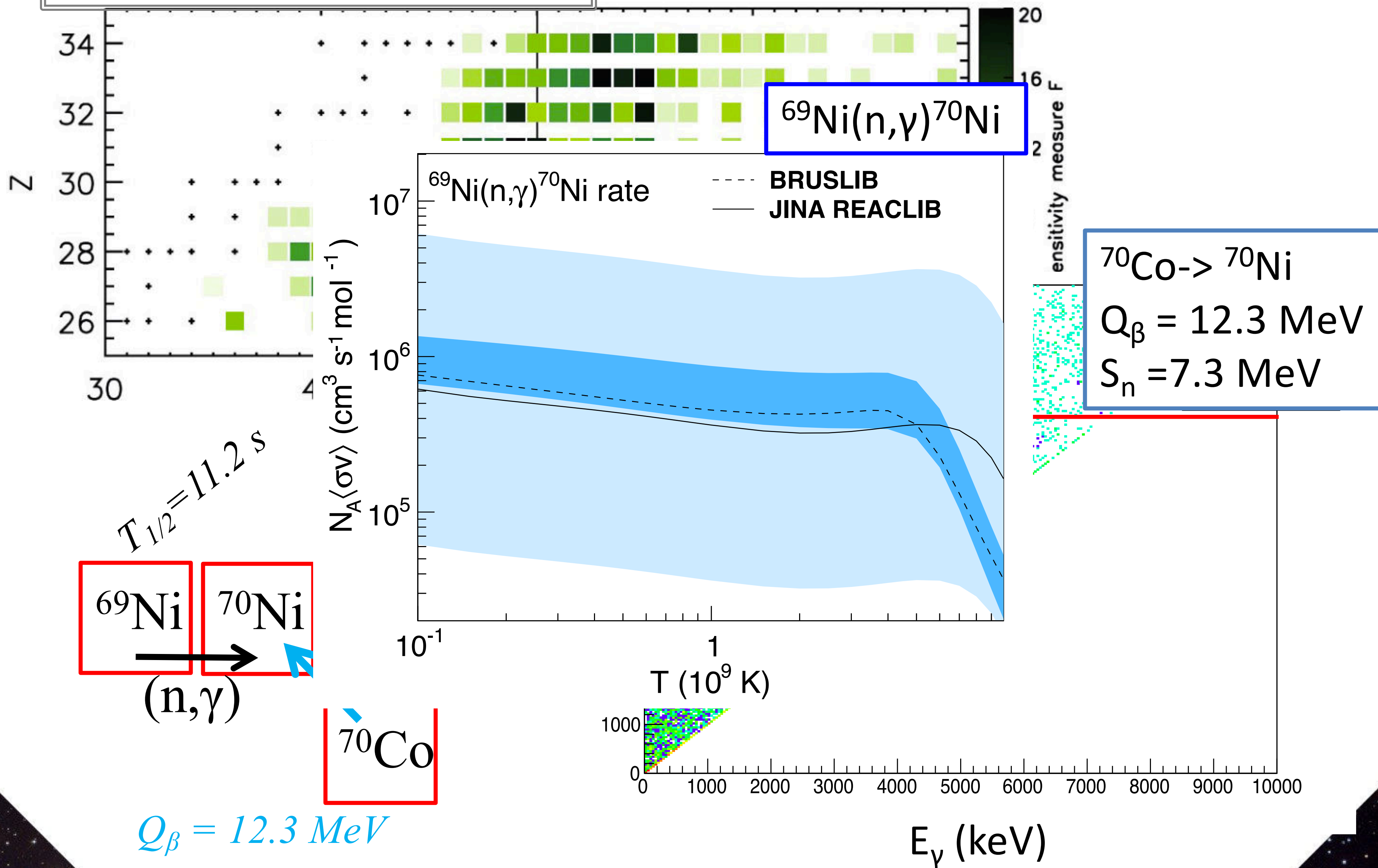


- Populate the compound nucleus via β-decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions with beam intensity down to 1 pps.

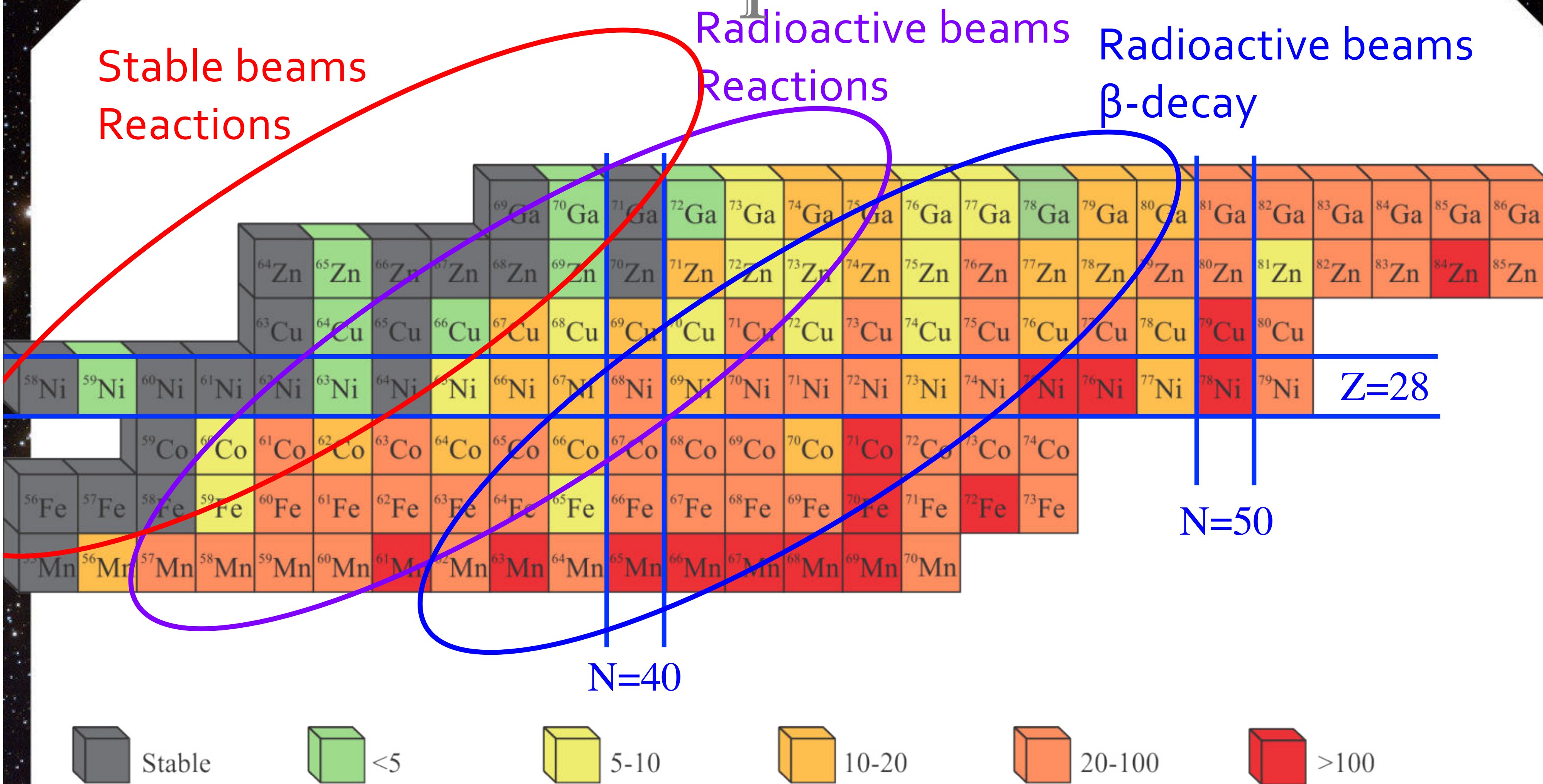
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

Example β-Oslo

R. Surman, et al., , AIP Advances 4, 041008 (2014)



Neutron-Capture variation

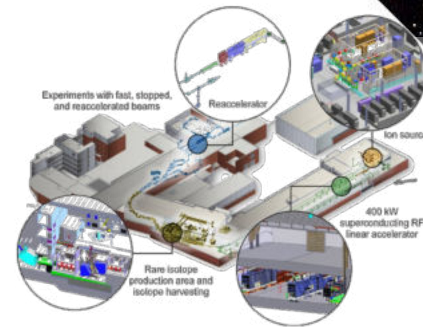


- Variation of theoretical predictions using TALYS, changing NLD and γSF
- Predictions diverge moving away from stability

Radioactive Beams

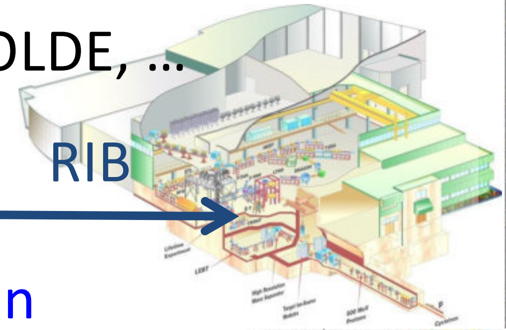
- **Fragmentation**: NSCL/FRIB, GSI/FAIR, RIKEN, HIRFL …

Fast Stable beam → Target (Fragmentation) → Separation → RIB



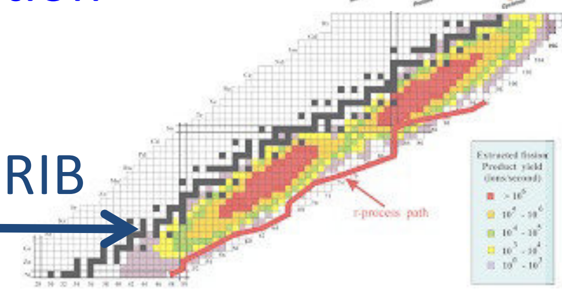
- **Isotope Separation On-Line (ISOL)**: TRIUMF, SPIRAL, ISOLDE, …

Stable beam → Target → Extraction → Separation → Reacceleration → RIB



- **Fission source**: CARIBU/ANL

Fission source → Extraction → Separation → Acceleration → RIB



- **Low energy reactions**: ANL, FSU, Texas A&M, Notre Dame, …

Low energy Stable beam → Target (Reaction) → Separation? → RIB

Current and Future Reach

Facility for Rare Isotope Beams

- Coming online soon at Michigan State University
- $700M project
- Rare Isotopes via Fragmentation
- Access to isotopes never produced before

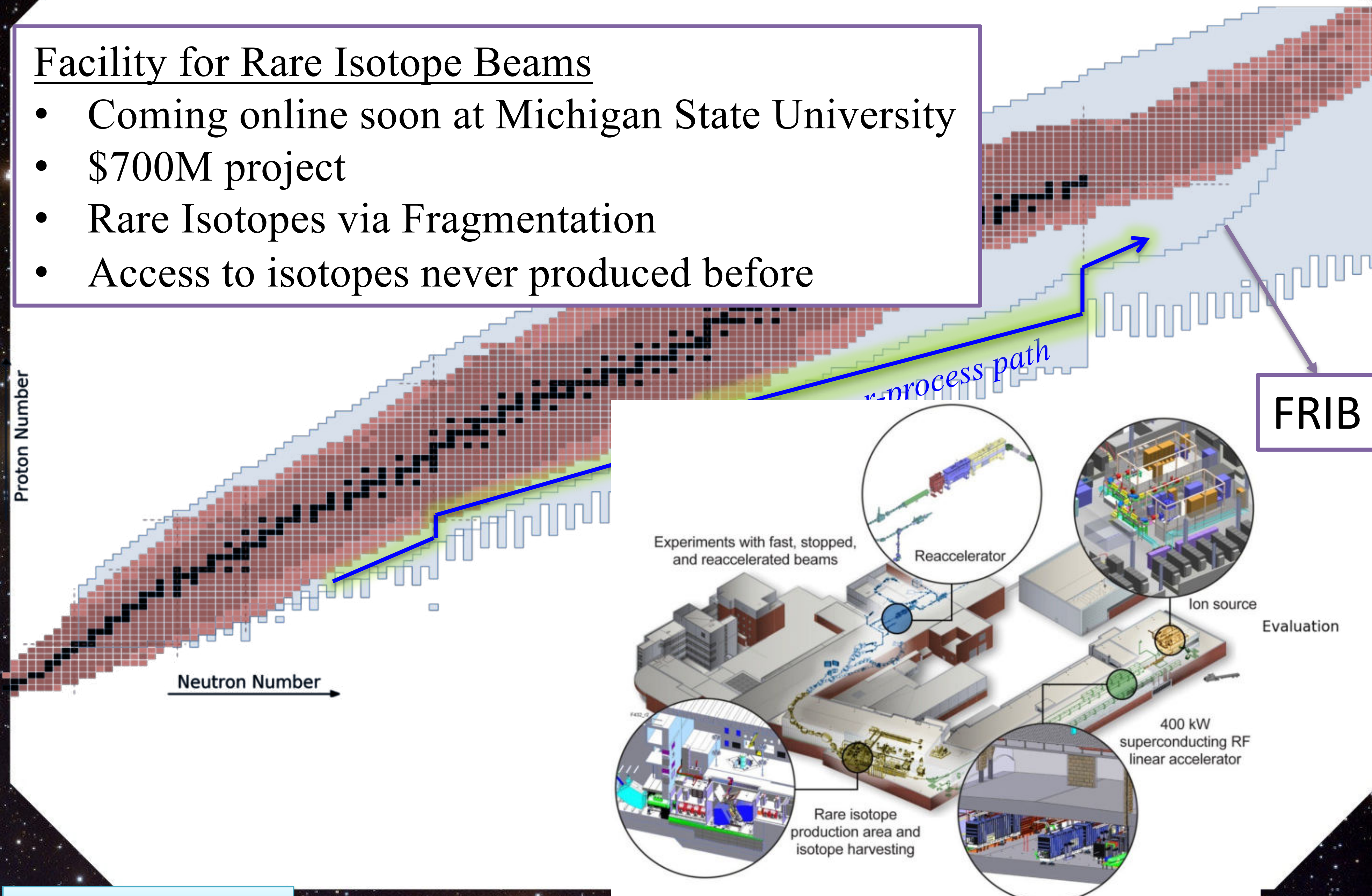
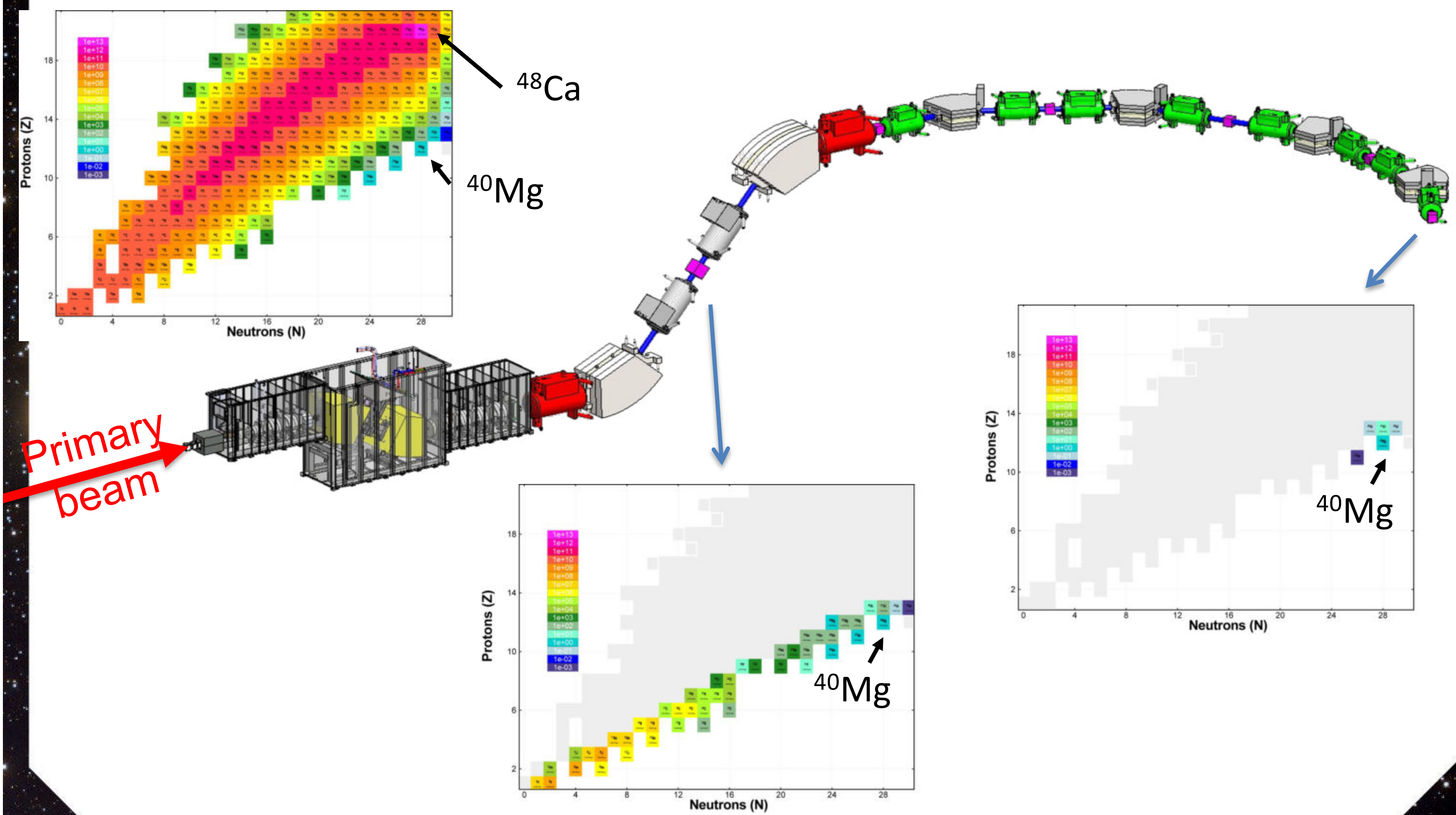


figure by M. Mumpower

FRIB

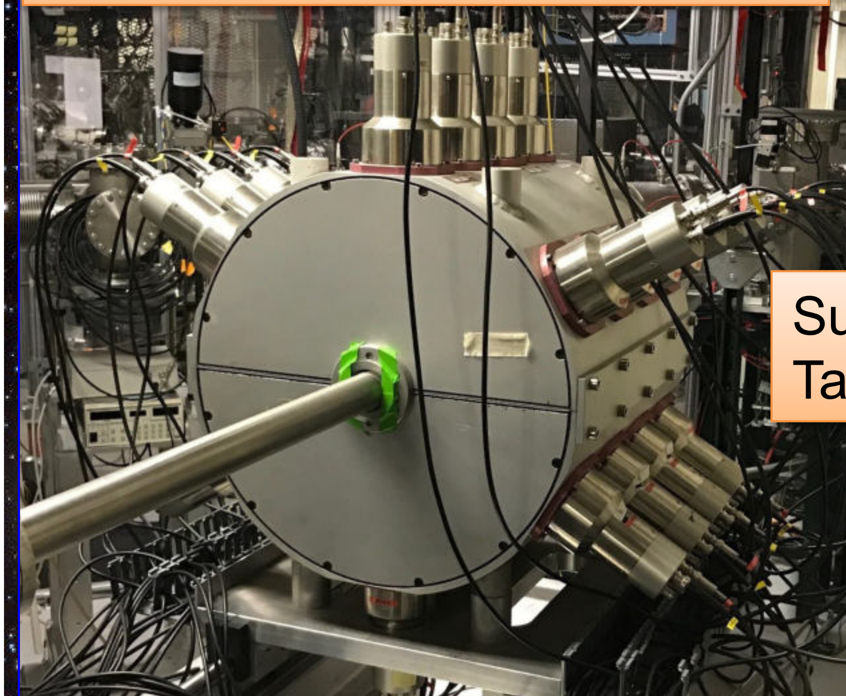
https://www.youtube.com/watch?v=EPG919lJK8s&t=53s

Separator: a powerful filter

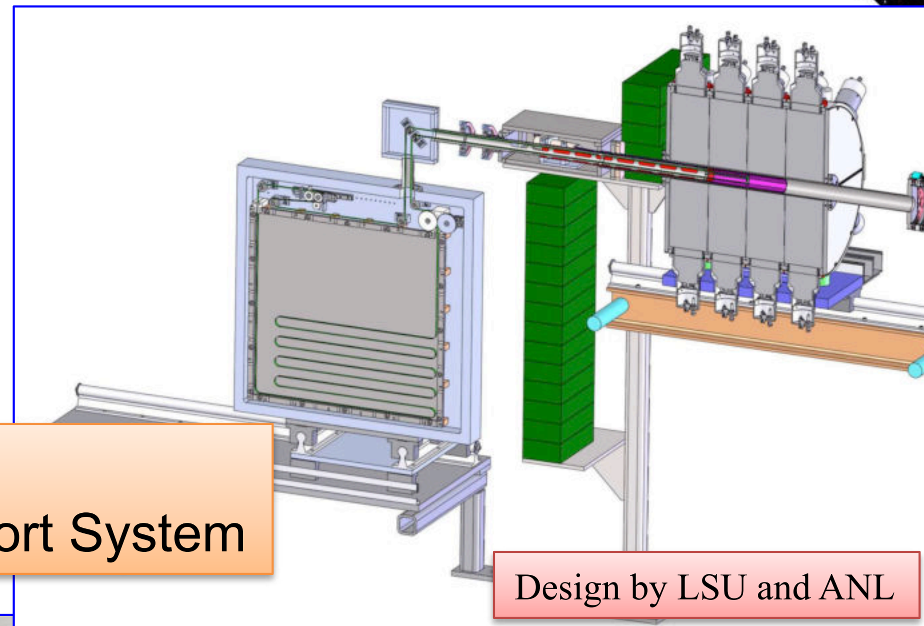


Summing NaI – SuN and friends

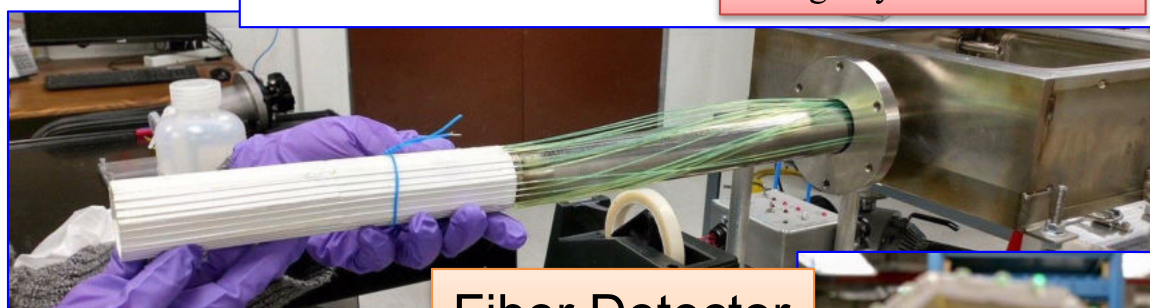
SuN
γ-Total Absorption Spectrometer

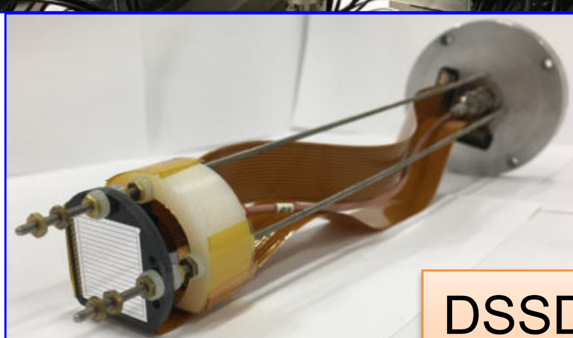


SuNTAN
Tape Transport System



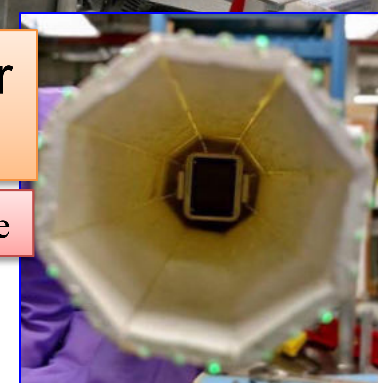
Design by LSU and ANL





Fiber Detector
β-detection

Hope College



DSSD
Implantation-decay correlation

A. Simon, S.J. Quinn, A.S., et al., Nucl. Instr. Meth A 703

Summary - Conclusions

- Nuclear structure and reactions are important input in astrophysical calculations
- Techniques to solve the problem of unconstrained neutron-capture reactions far from stability
- FRIB will bring new capabilities and access to a lot more exotic nuclei