Exploding stars and the synthesis of heavy elements

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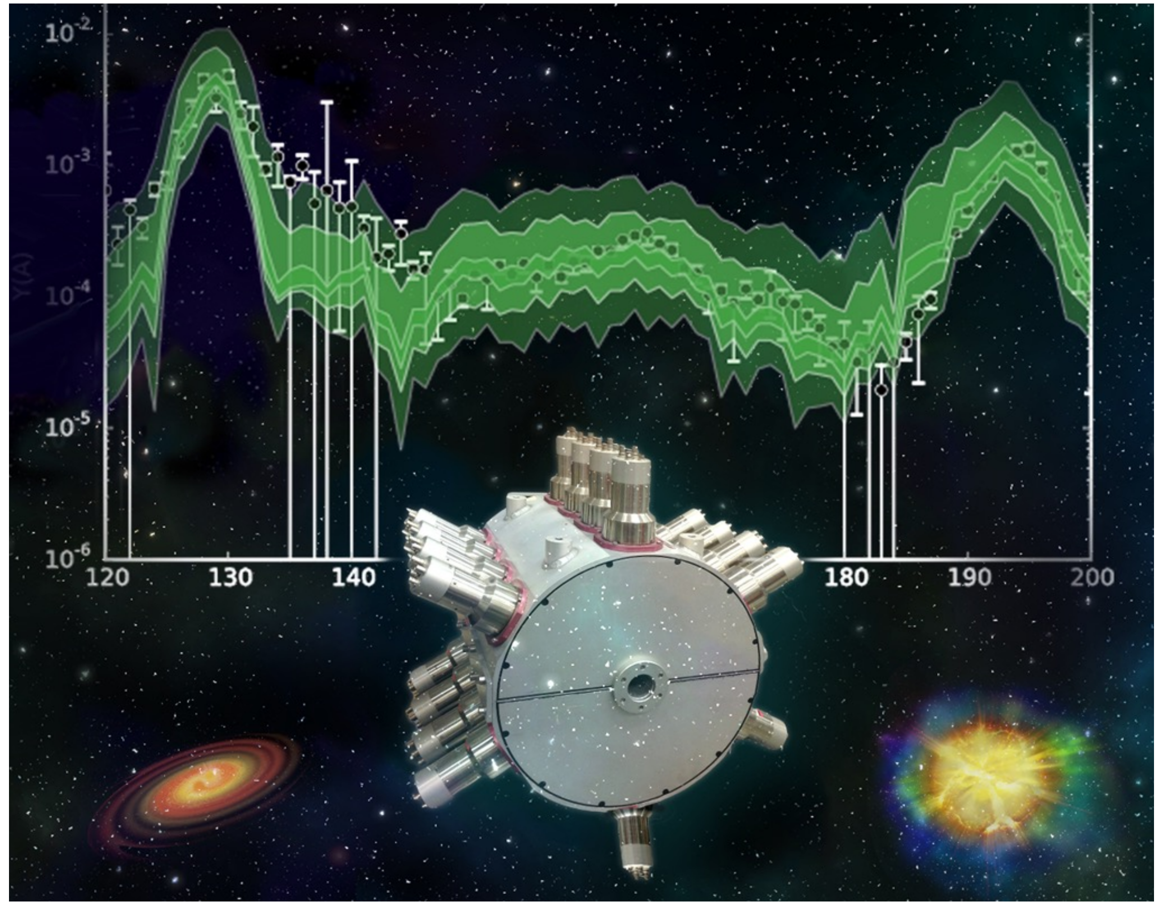
JINA-CEE
NSF Physics Frontiers Center

National Science Foundation
Michigan State University

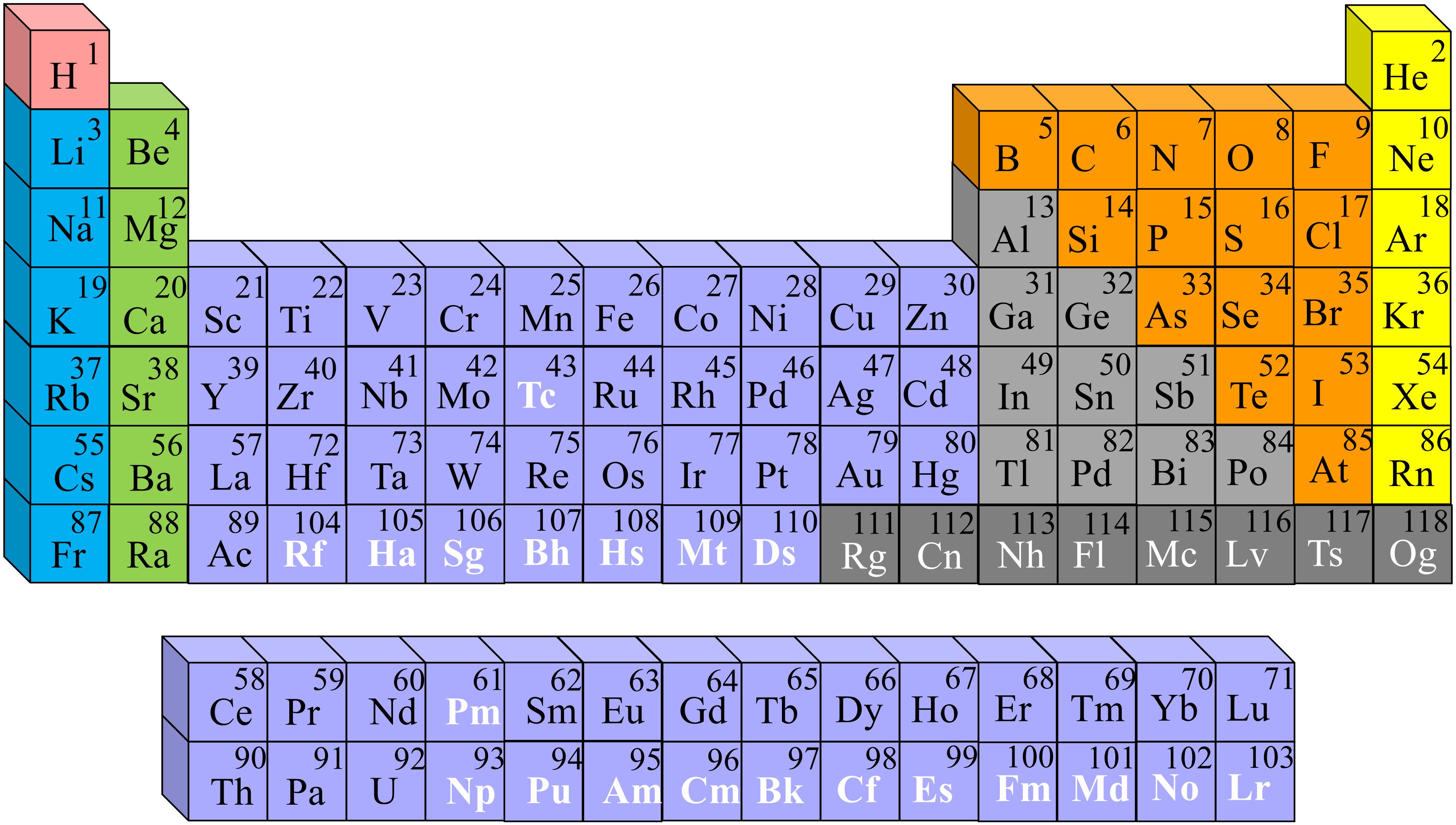
Overview

- Nuclear Astrophysics
- Heavy Element Synthesis
- R-process
- Nuclear Physics Input
- Current Experiments
- New Opportunities
- Future - FRIB

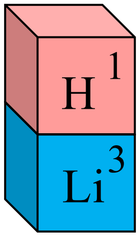


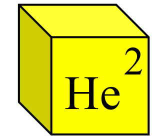
Credit: Erin O'Donnel, MSU

Elements in nature

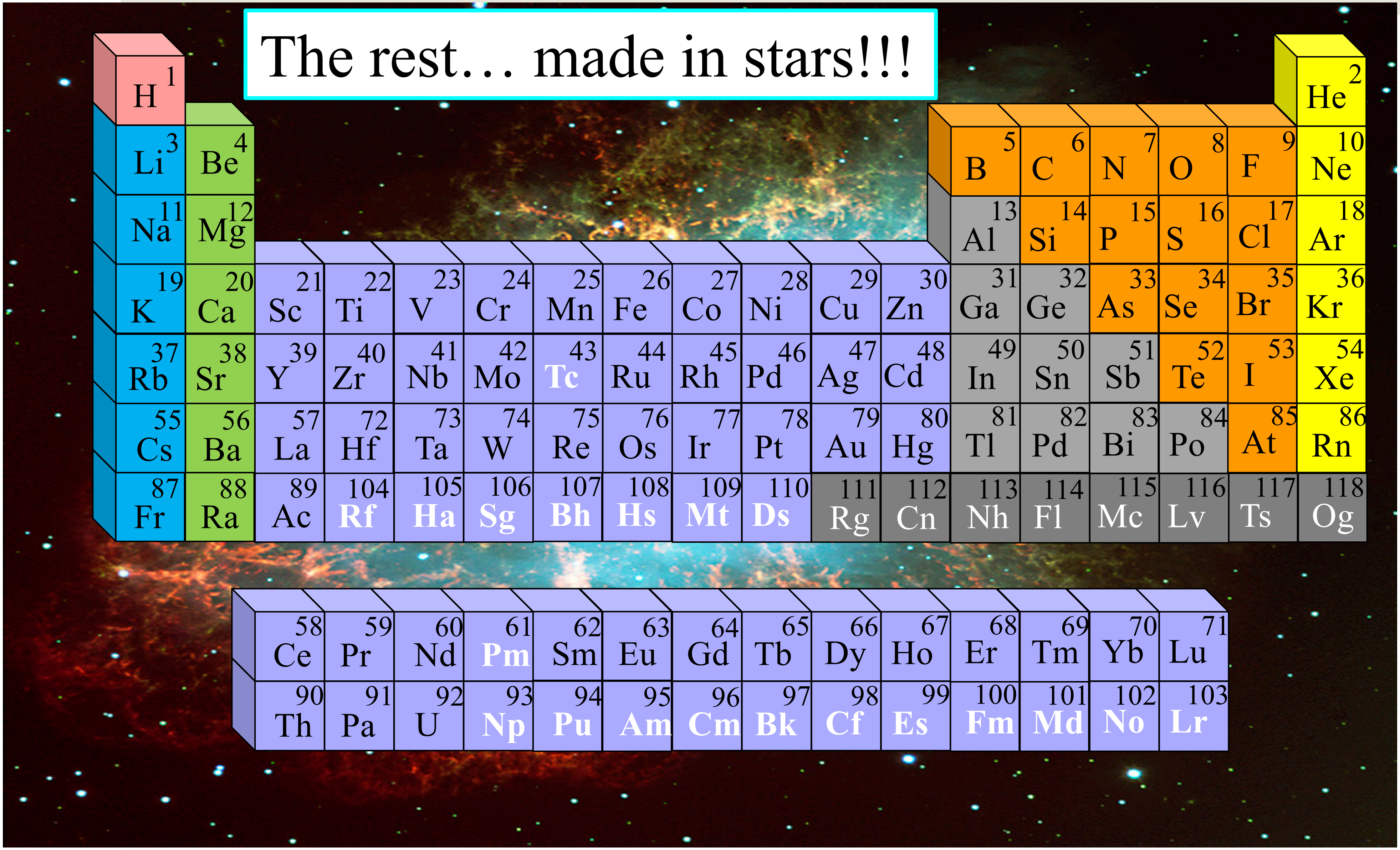


Elements in nature

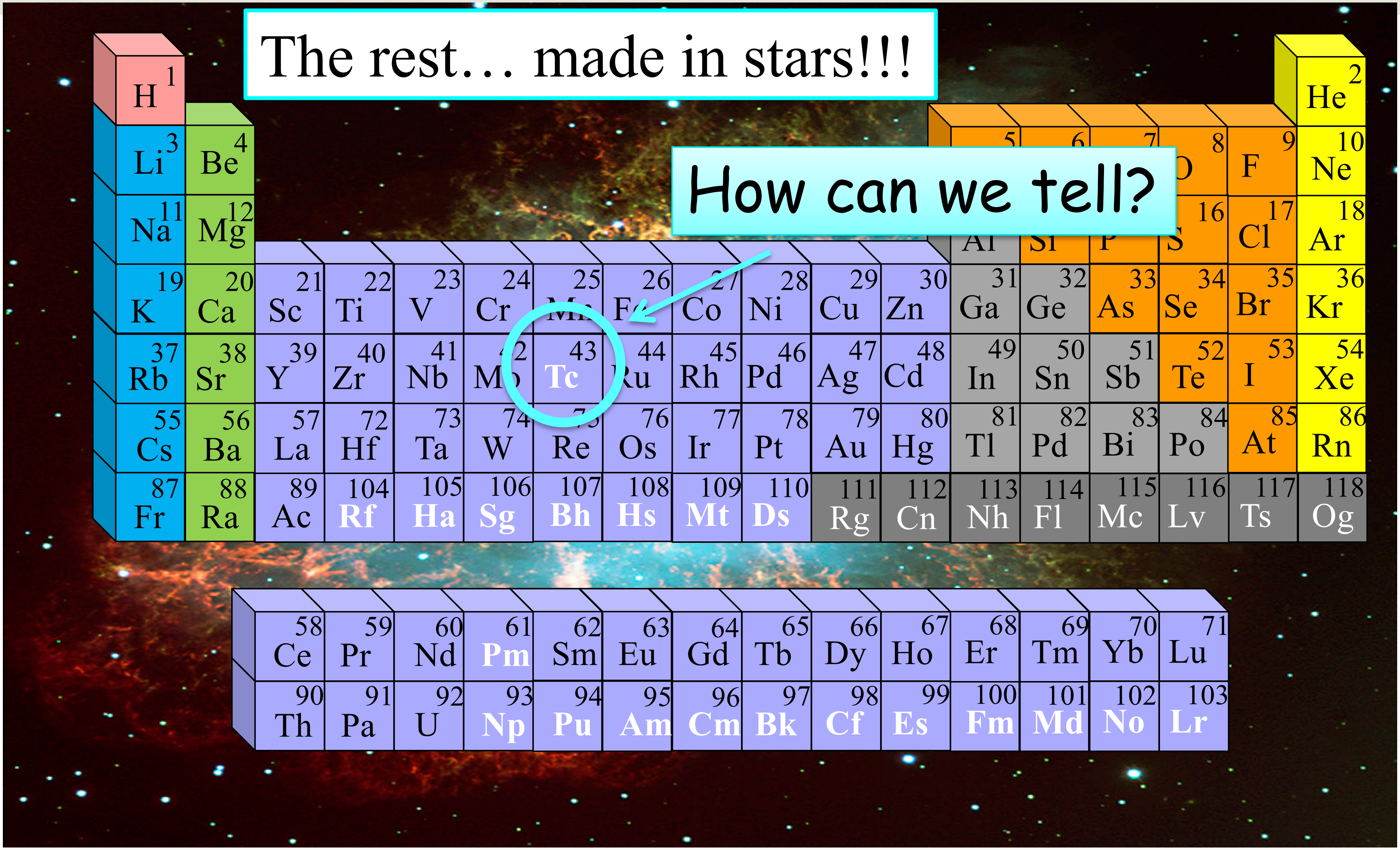




Elements in nature

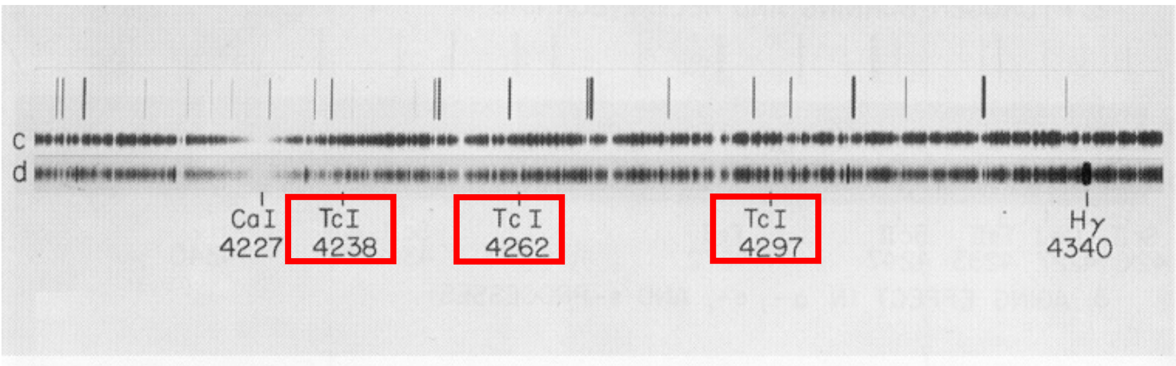


Elements in nature



How Can We Tell?

Light from a red giant (s-process):



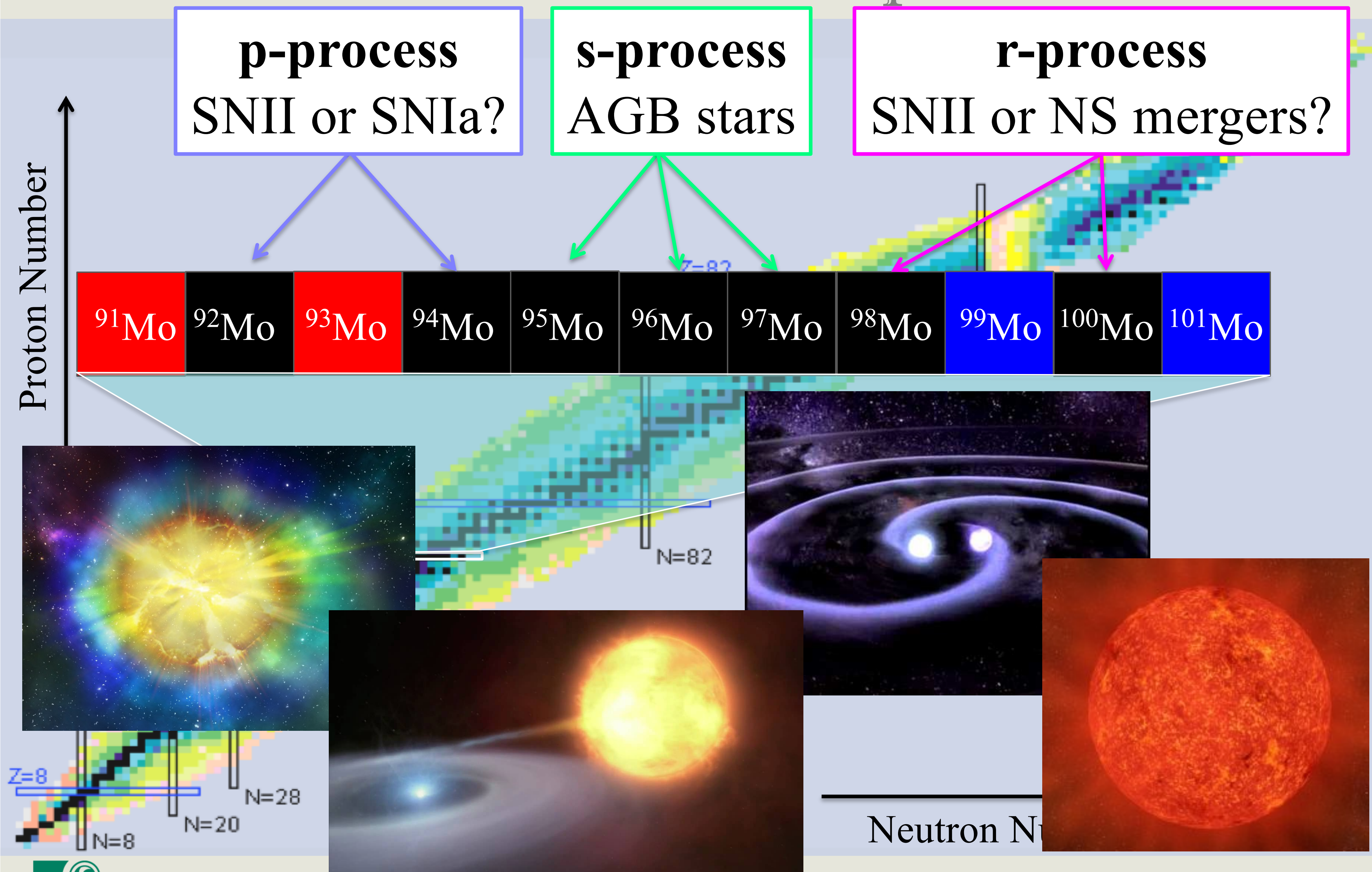
Star contains Technetium (Tc) !!!
(heavy element Z=43, $T_{1/2}$ = 4 Million years
Merrill 1952)

Paul Merrill,
Mount Wilson Observatory

NATIONAL ACADEMY OF SCIENCES
Abstracts of Papers Presented at the Annual Meeting
April 28–30, 1952, Washington, D. C.

Merril 1952: “It is surprising to find an unstable element in the stars”
…“(1) A stable isotope (of technetium) actually exists although not yet found on Earth; or (2) S-type stars somehow produce technetium as they go along; or (3) S-type stars represent a comparatively transient phase of stellar existence”

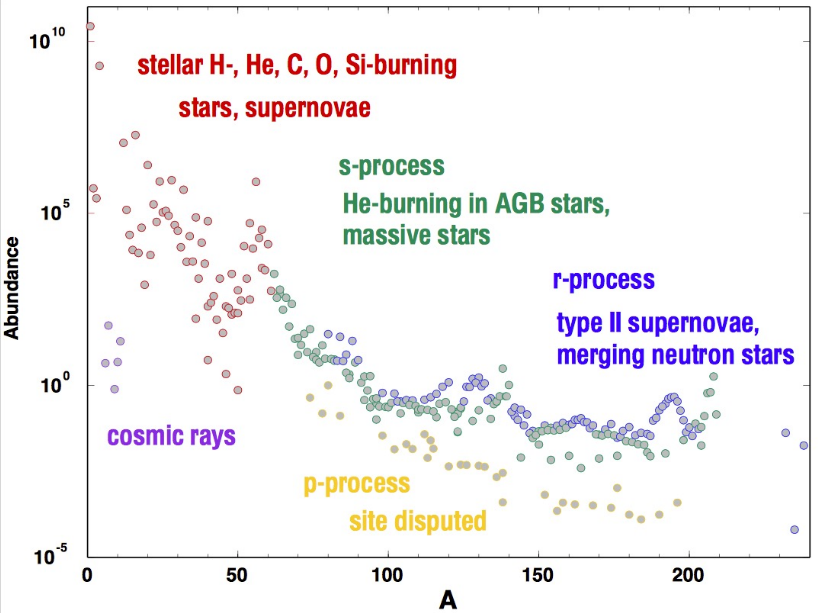
Nuclear Landscape



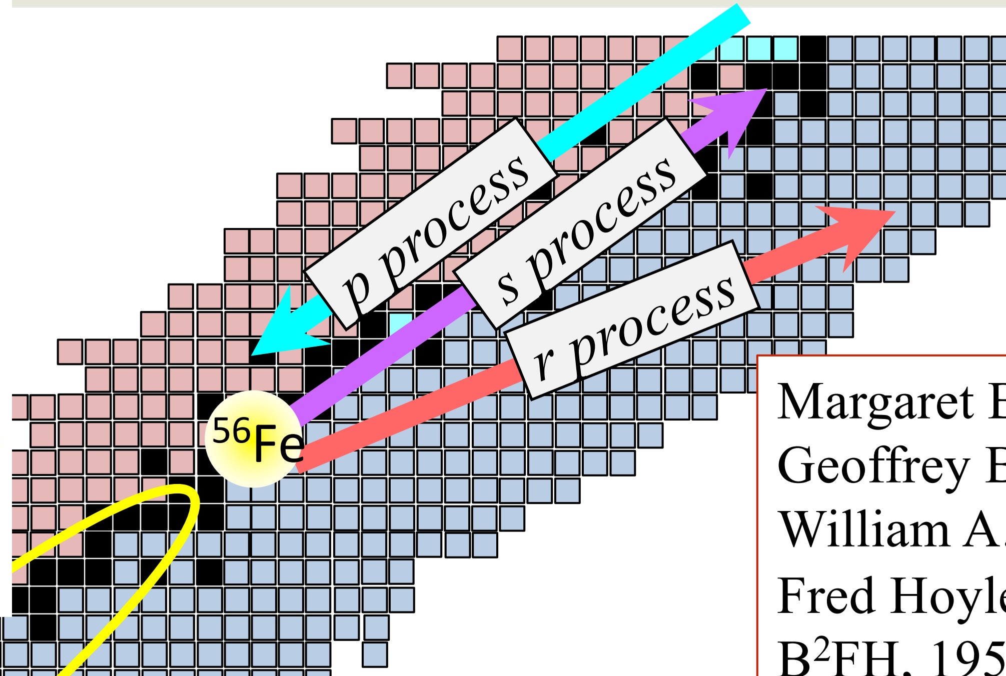
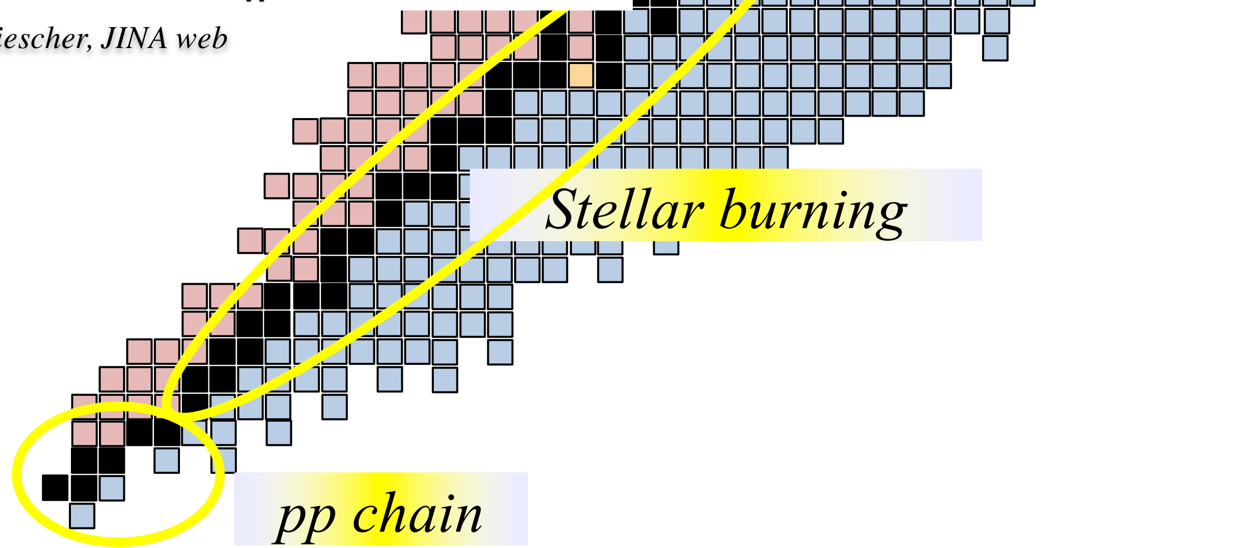
Credit: Erin O'Donnell, MSU

Credit: NASA Goddard

Nucleosynthesis paths



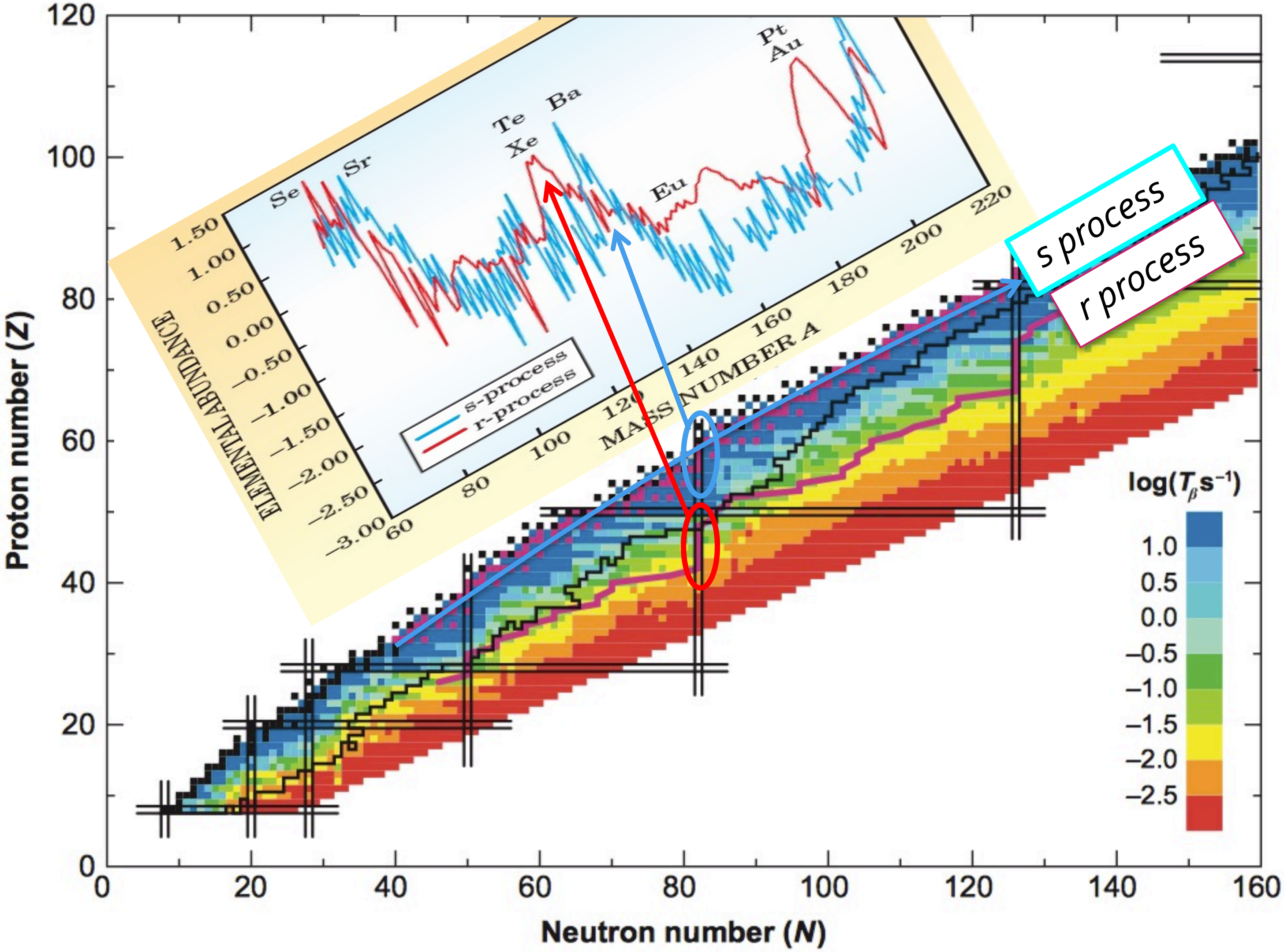
From M. Wiescher, JINA web

Margaret Burbidge
Geoffrey Burbidge
William A. Fowler
Fred Hoyle
B^2FH, 1957

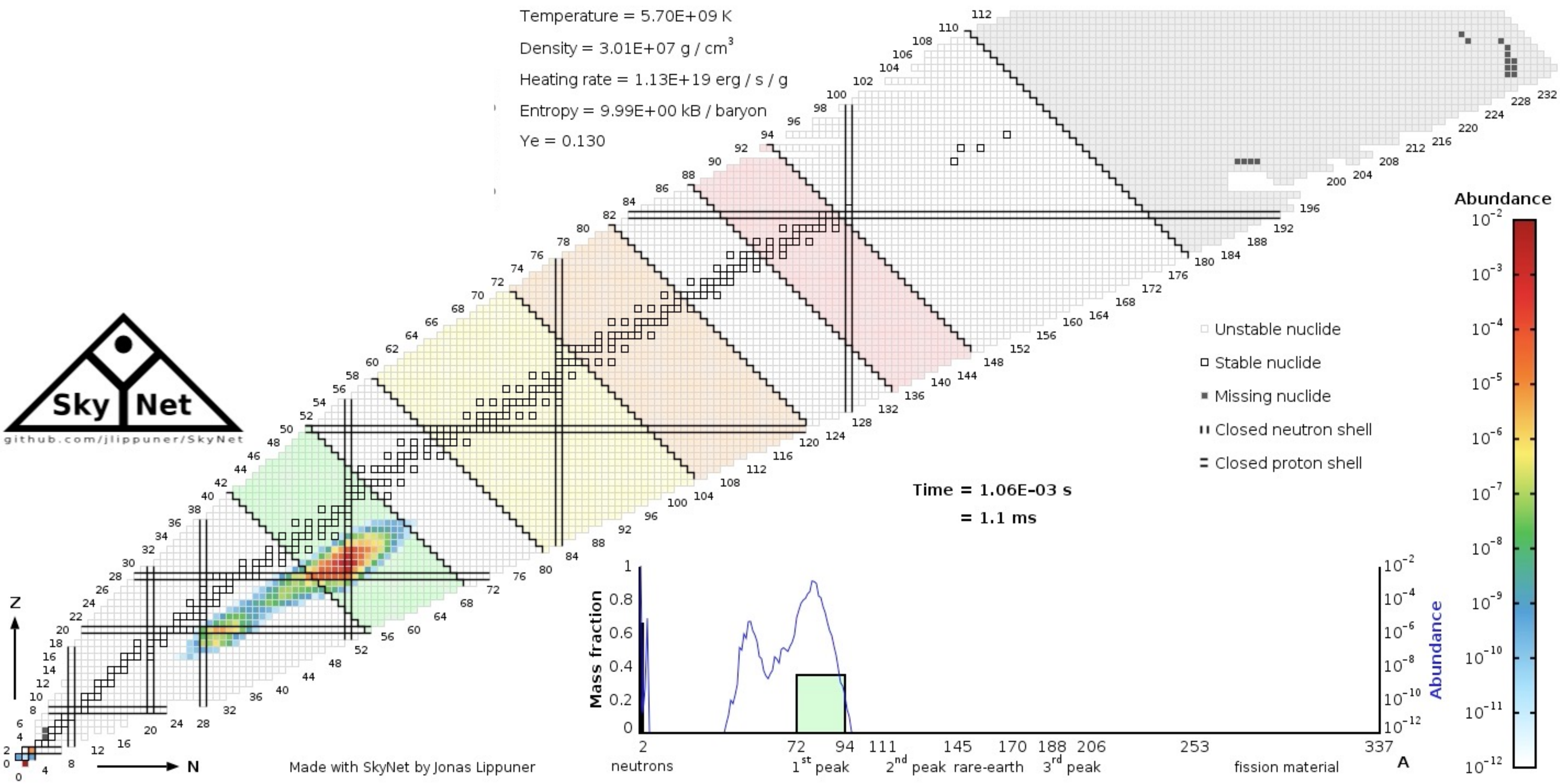
From St. John's College, University of Cambridge

s/r-process paths and abundances

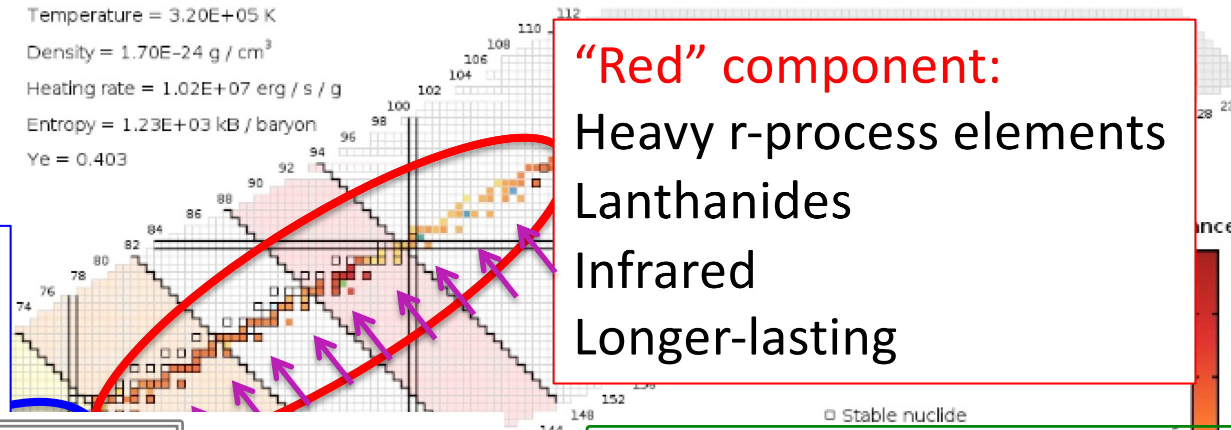


Sneden, C., Cowan, J. J., & Gallino, R., *Ann. Rev. Ast. Ap.* **46** (2008) 241.

R-Process Simulation



Kilonova in GW170817 Neutron Star Merger

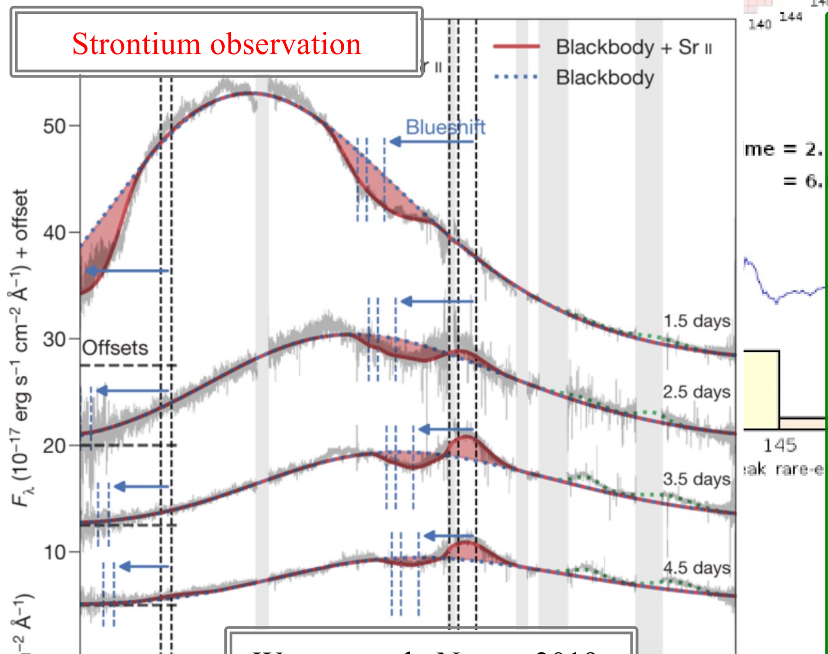


"Red" component:
Heavy r-process elements
Lanthanides
Infrared
Longer-lasting

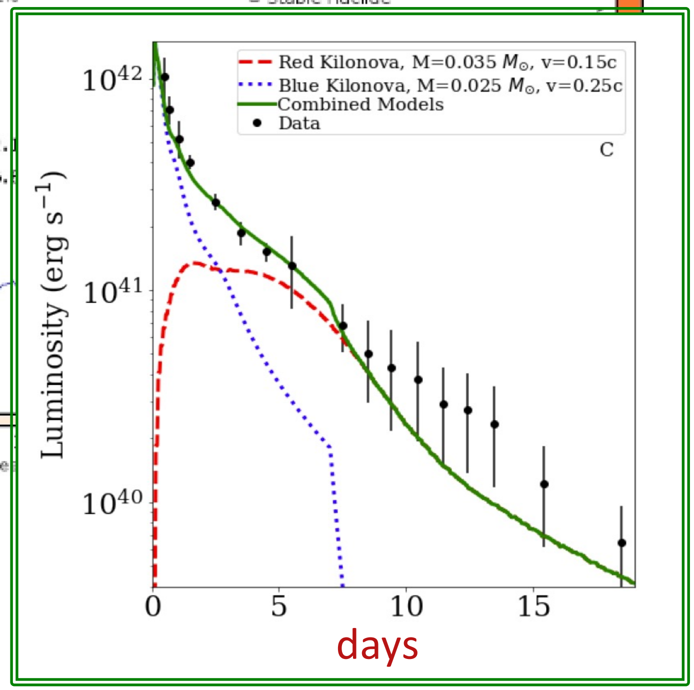
Blue component:
Light r-process elements
Optical
Bright and brief

Credit: NASA Goddard

Strontium observation



Watson et al., Nature 2019



Kasen et al., Nature 2017

Kilpatrick, et al, Science 2017

More observations

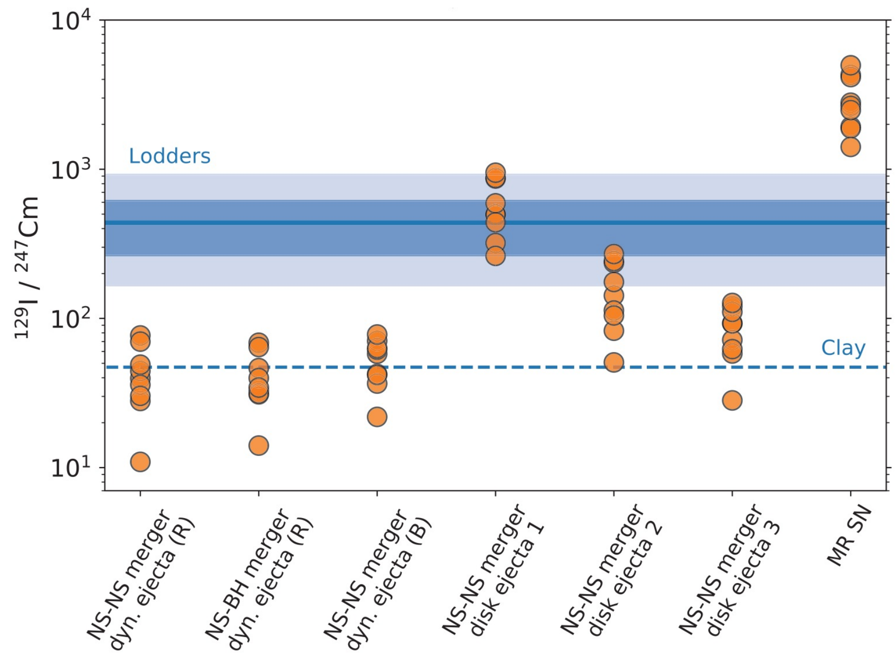
Science 26 Feb 2021:
Vol. 371, Issue 6532, pp. 945-948
DOI: 10.1126/science.aba1111

NUCLEAR ASTROPHYSICS

^{129}I and ^{247}Cm in meteorites constrain the last astrophysical source of solar r-process elements

Benoit Côté[1,2,3]*, Marius Eichler[4], Andrés Yagüe López[1], Nicole Vassh[5], Matthew R. Mumpower[6,7], Blanka Világos[1,2], Benjámin Soós[1,2], Almudena Arcones[4,8], Trevor M. Sprouse[5,6], Rebecca Surman[5], Marco Pignatari[9,1], Mária K. Pető[1], Benjamin Wehmeyer[1,10], Thomas Rauscher[10,11], Maria Lugaro[1,2,12]

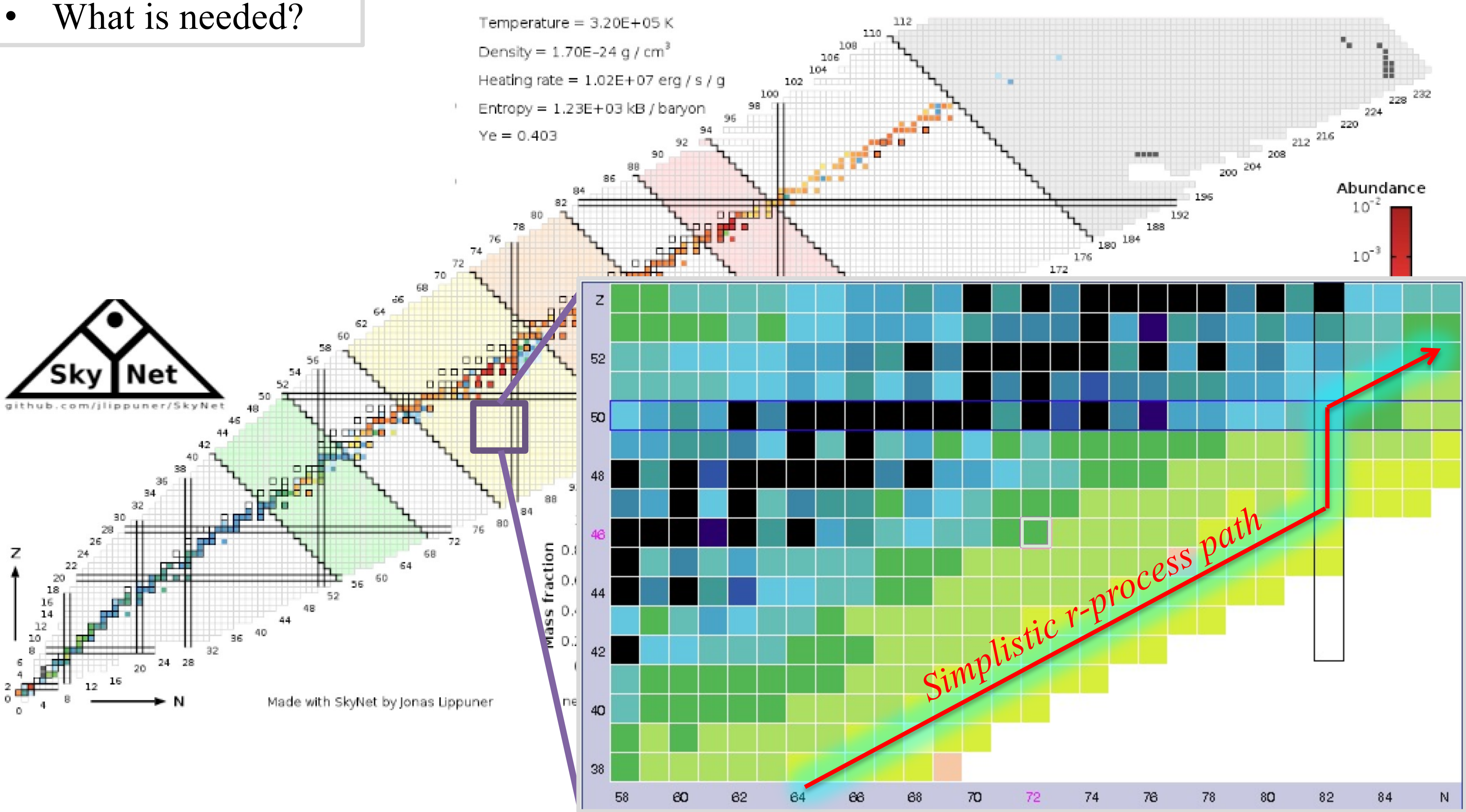
The composition of the early Solar System can be inferred from meteorites. Many elements heavier than iron were formed by the rapid neutron capture process (r-process), but the astr where this occurred remain poorly understood. We demonstrate that the near-id (≈15.6 million years) of the radioactive r-process nuclei iodine-129 and curium-24 irrespective of the time between production and incorporation into the Solar Sys last r-process source by comparing the measured meteoritic ratio ^{129}I/^{247}Cm = 4 nucleosynthesis calculations based on neutron star merger and magneto-rotatio simulations. Moderately neutron-rich conditions, often found in merger disk ejecta consistent with the meteoritic value. Uncertain nuclear physics data limit our co conclusion.



Uncertain nuclear physics data limit our confidence in this conclusion

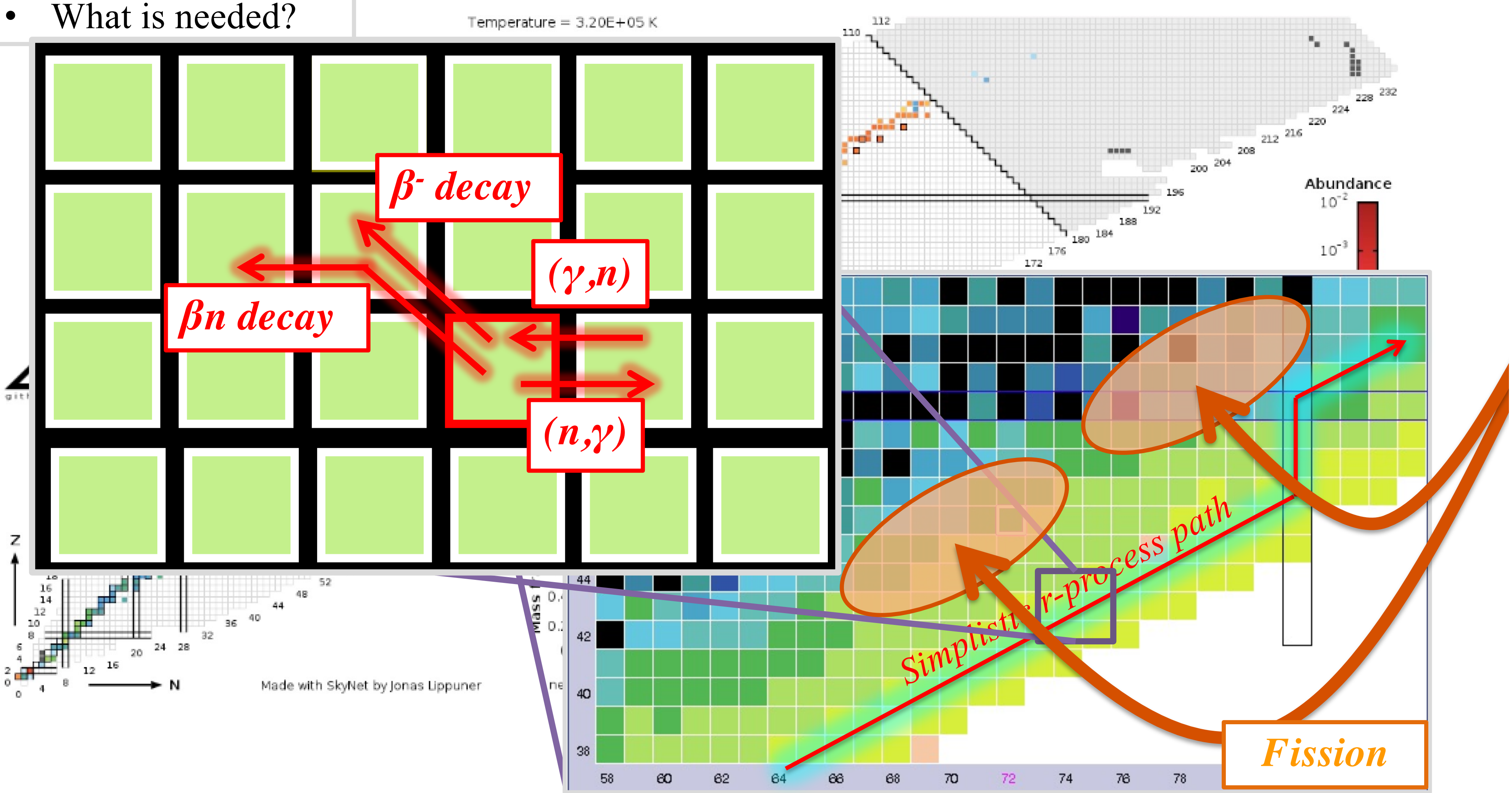
r-process in neutron-star mergers

- What is needed?



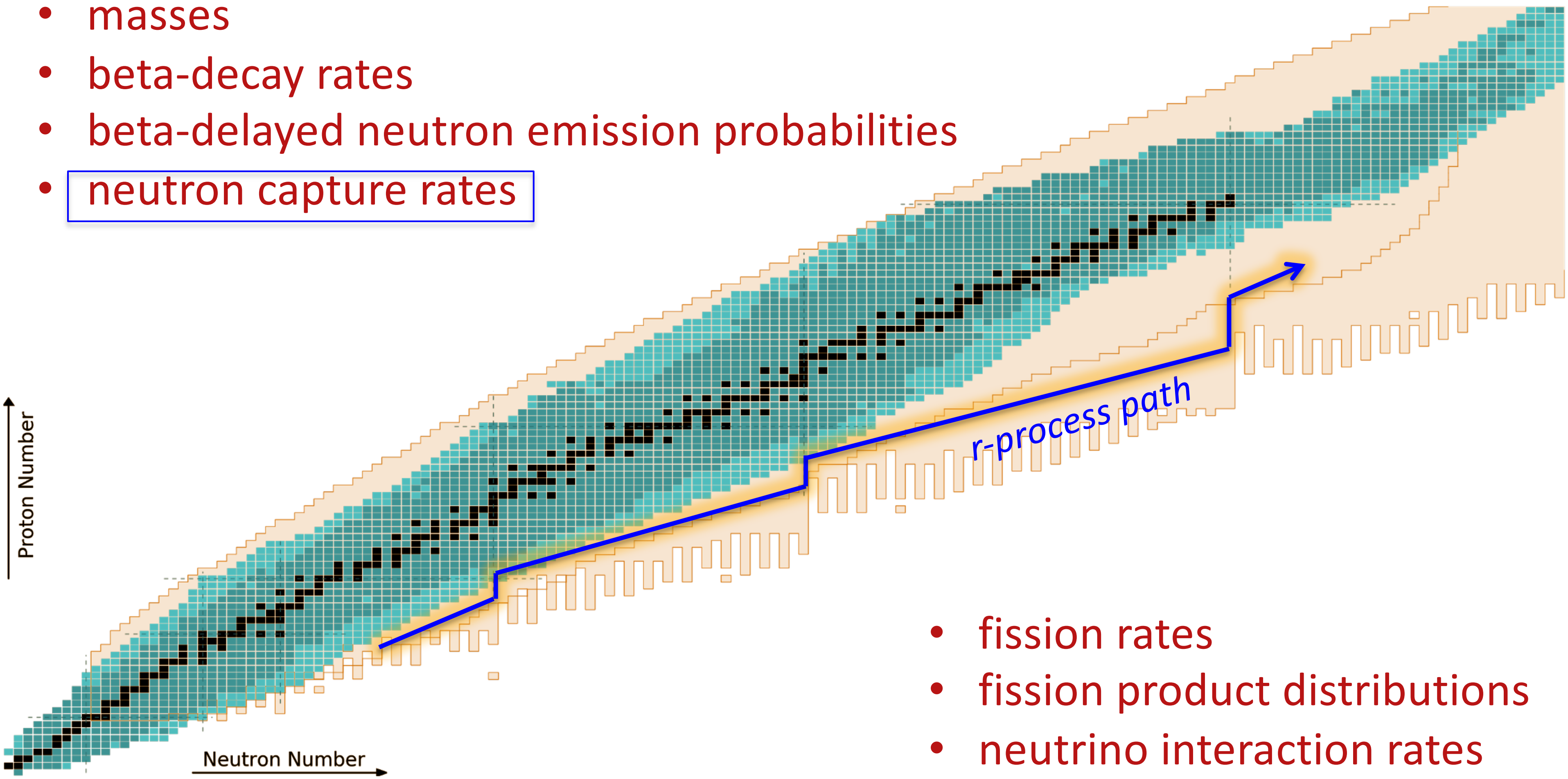
r-process in neutron-star mergers

- What is needed?



What's known?

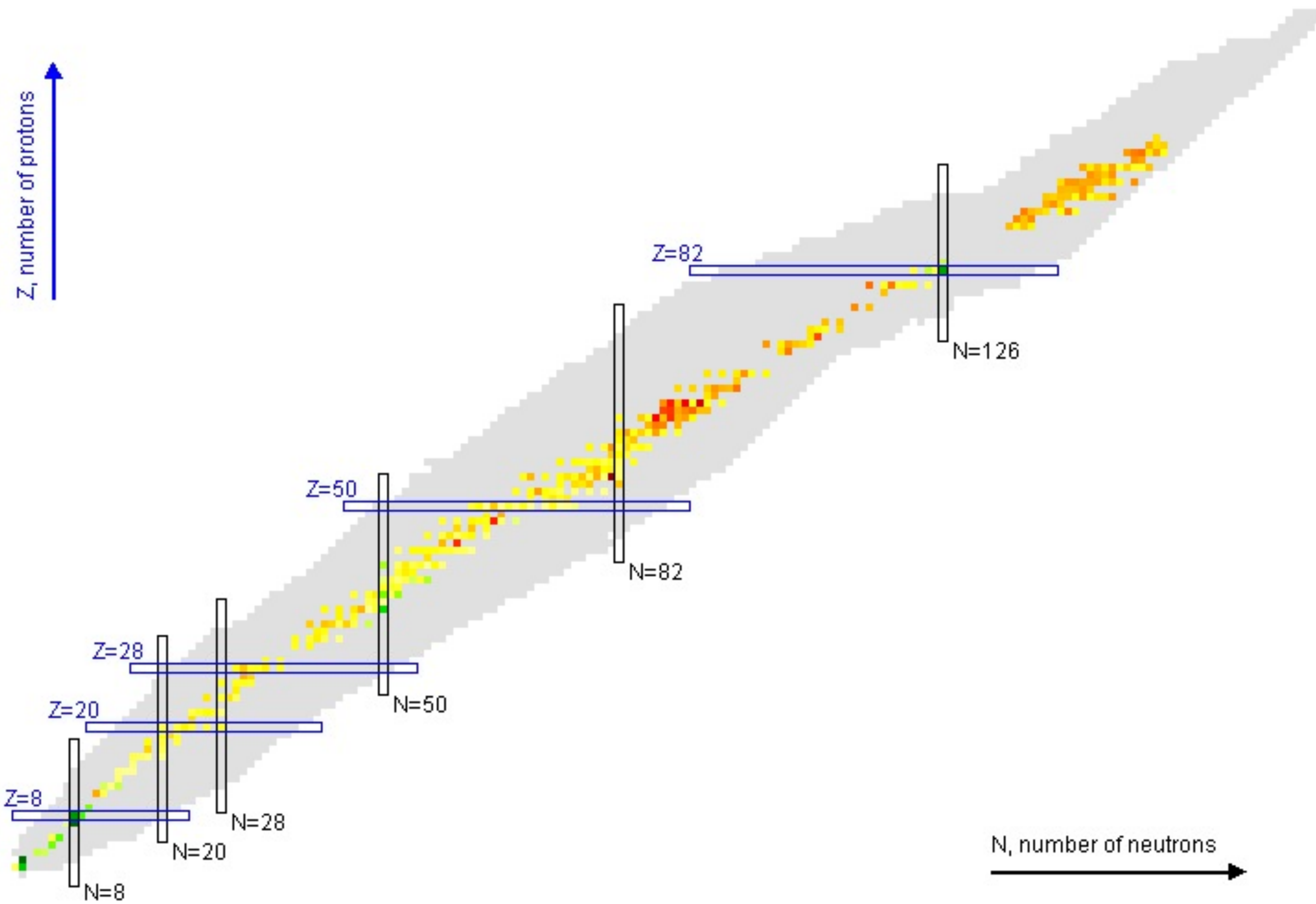
- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates



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

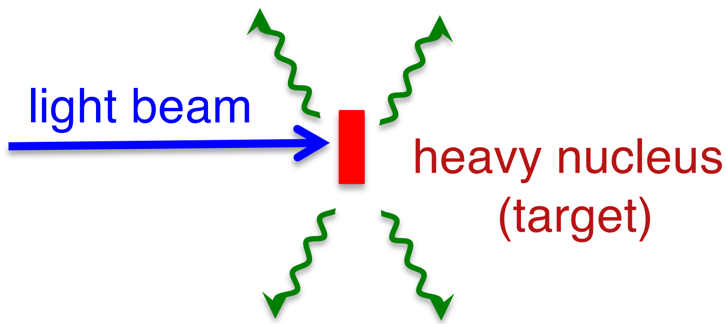
figure by M. Mumpower

Current (n,γ) measurements

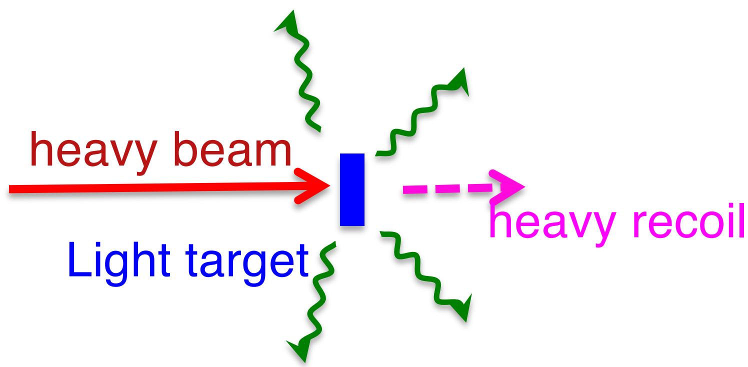


The trouble with Neutron Capture Reactions

- Regular kinematics

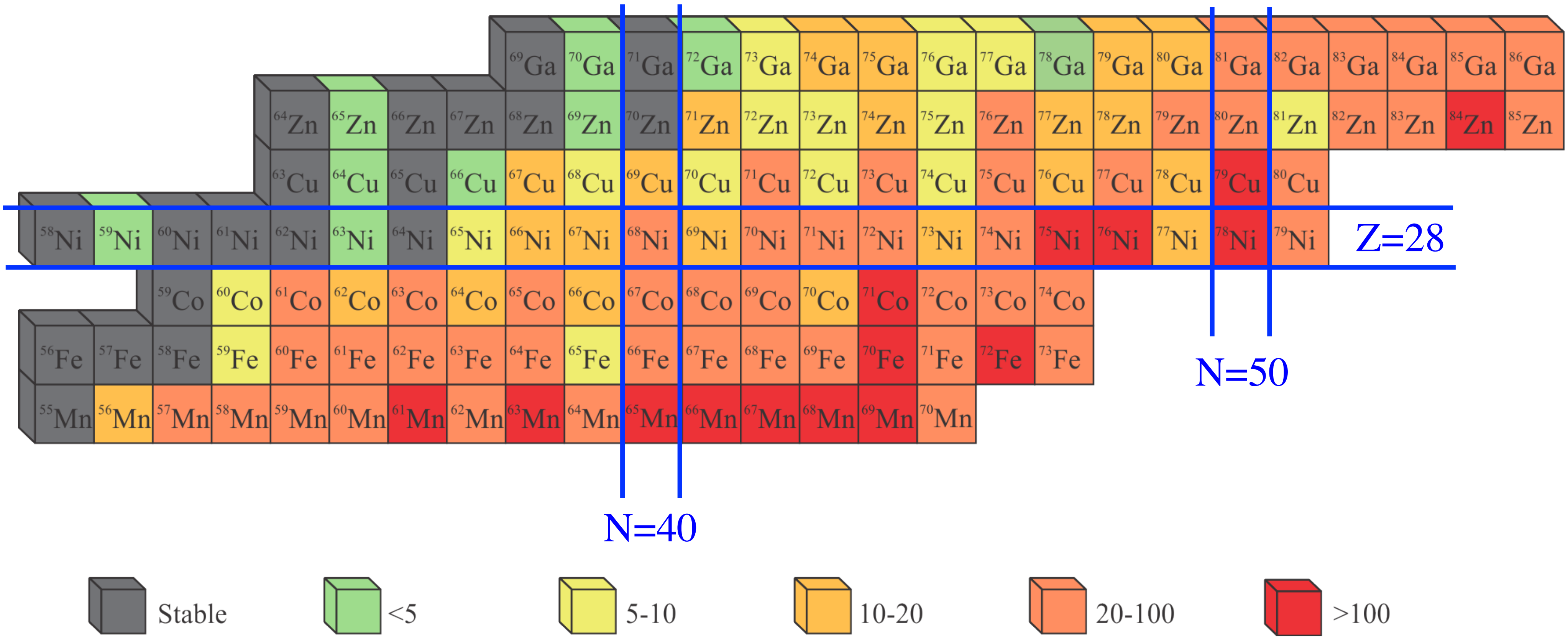


- Inverse kinematics



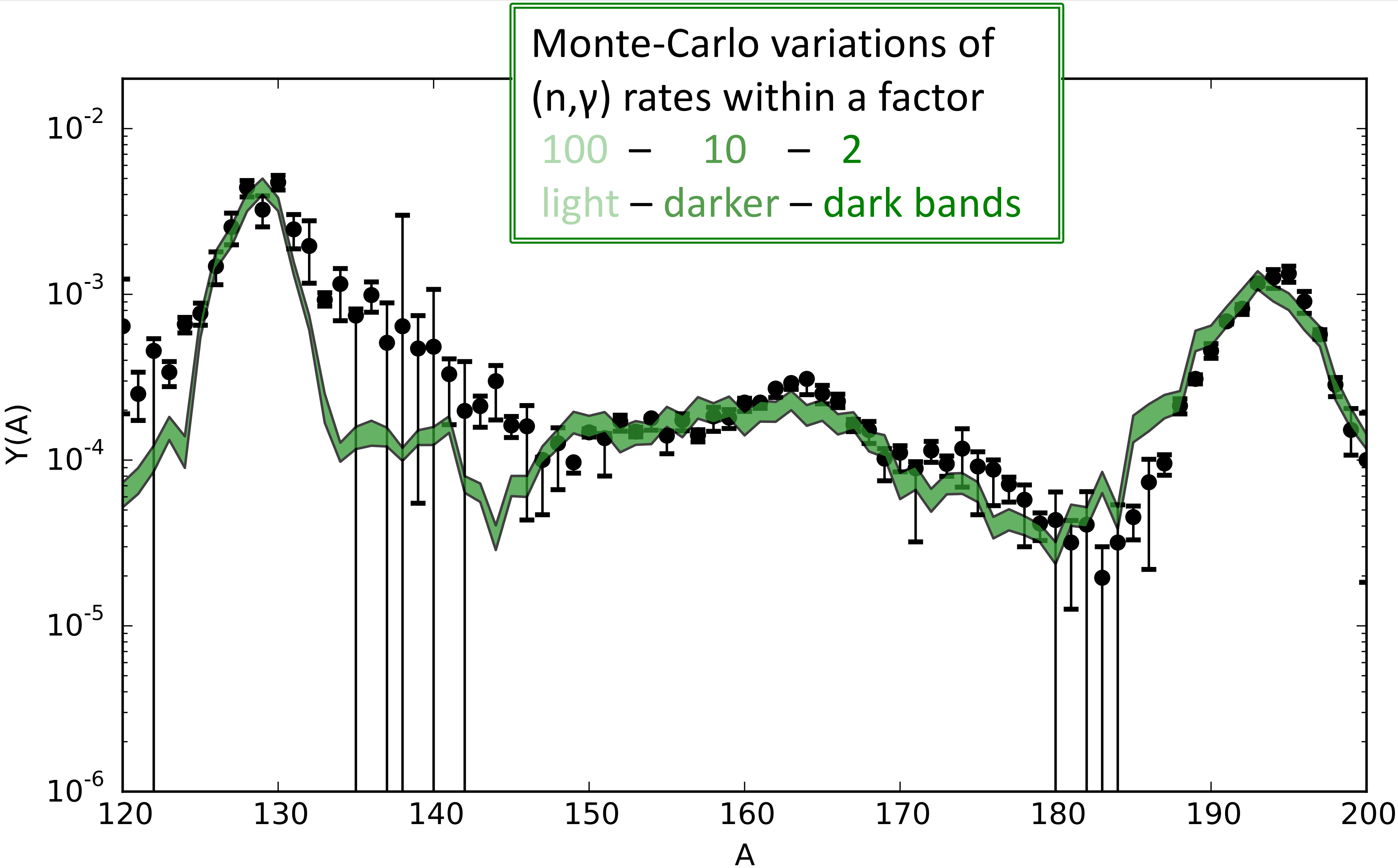
- Measuring Neutron Capture reactions on short-lived nuclei is challenging
- Cannot make a neutron target
- Cannot make a target out of a short-lived isotope
- Need indirect techniques

Neutron capture reactions



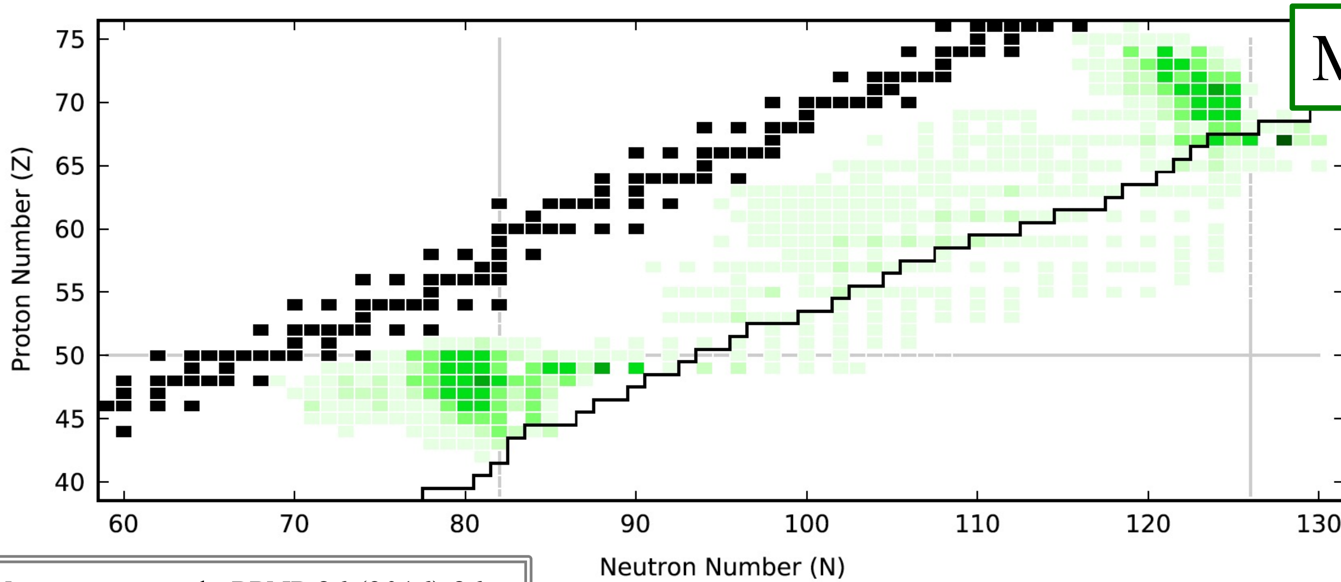
- Variation of theoretical predictions using TALYS code, changing model parameters
- Predictions diverge moving away from stability

R-process sensitivity to neutron captures



Liddick, Spyrou, et al., PRL 2016

R-process sensitivity to neutron captures



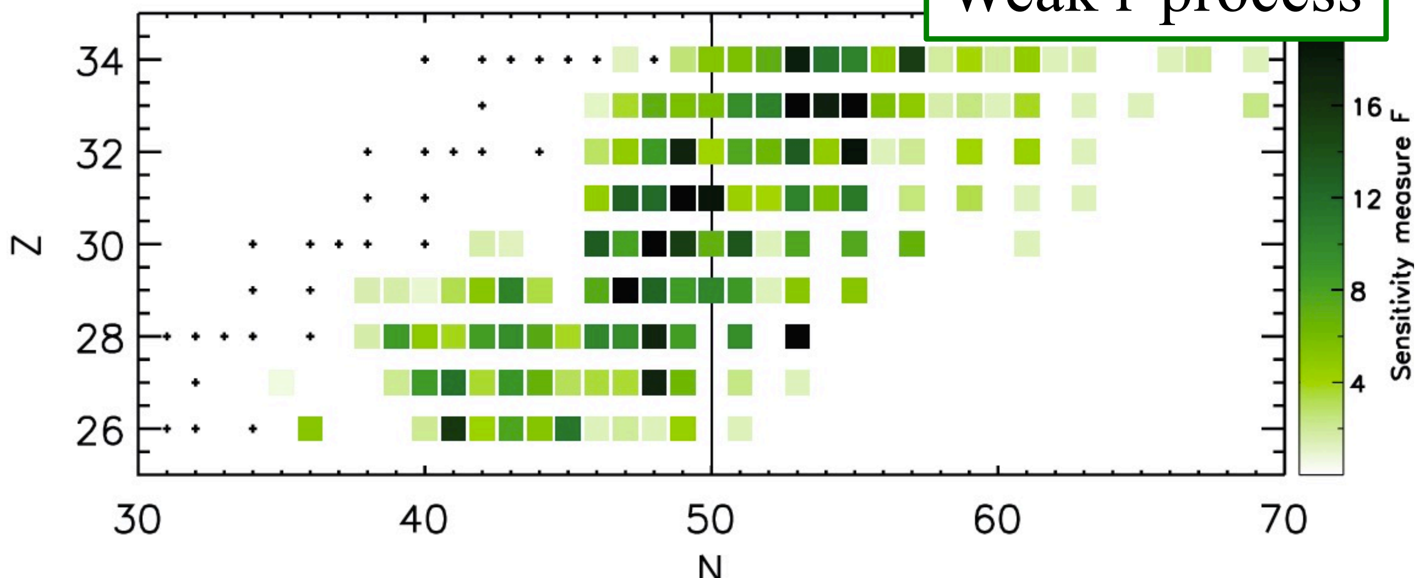
Main r-process

Neutron-star merger

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

Supernova

Weak r-process

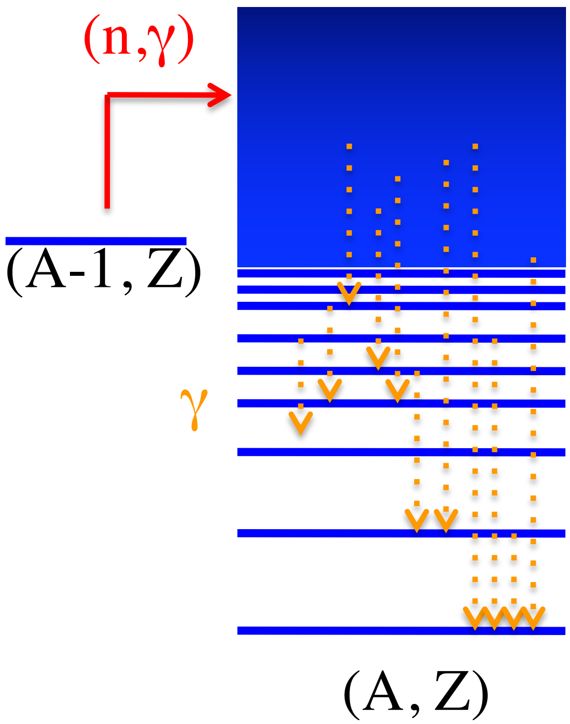


Surman, et al., , AIP Advances 4, 041008 (2014)

2016

National Science Foundation
Michigan State University
NSCL

Neutron Capture – Uncertainties



Hauser – Feshbach (Statistical Model)

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

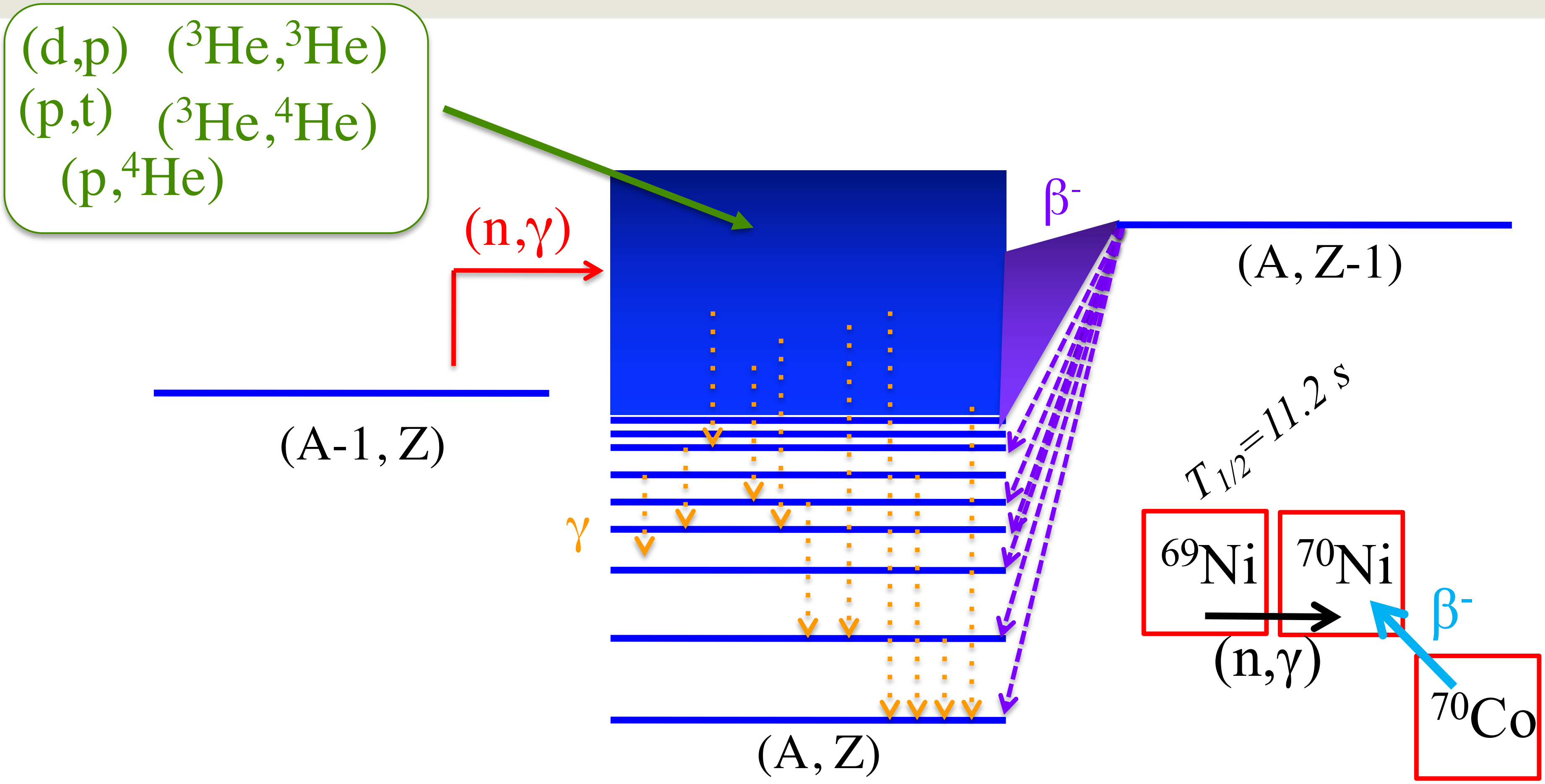
} Dominate uncertainties

- Optical model potential → Large uncertainties further from stability

β-Oslo collaboration:
- Liddick, Spyrou (MSU)
- Larsen, Guttormsen (Oslo)

β-Oslo method:
- Combine traditional **Oslo Method** with **Total Absorption Spectroscopy**
- Use β-decay to populate the compound nucleus of interest
- Advantage: study nuclei far from stability

Neutron Capture – Indirect studies



- Populate the compound nucleus via β-decay
- Study nuclei far from stability
- Feasible with low beam intensities

•Need:

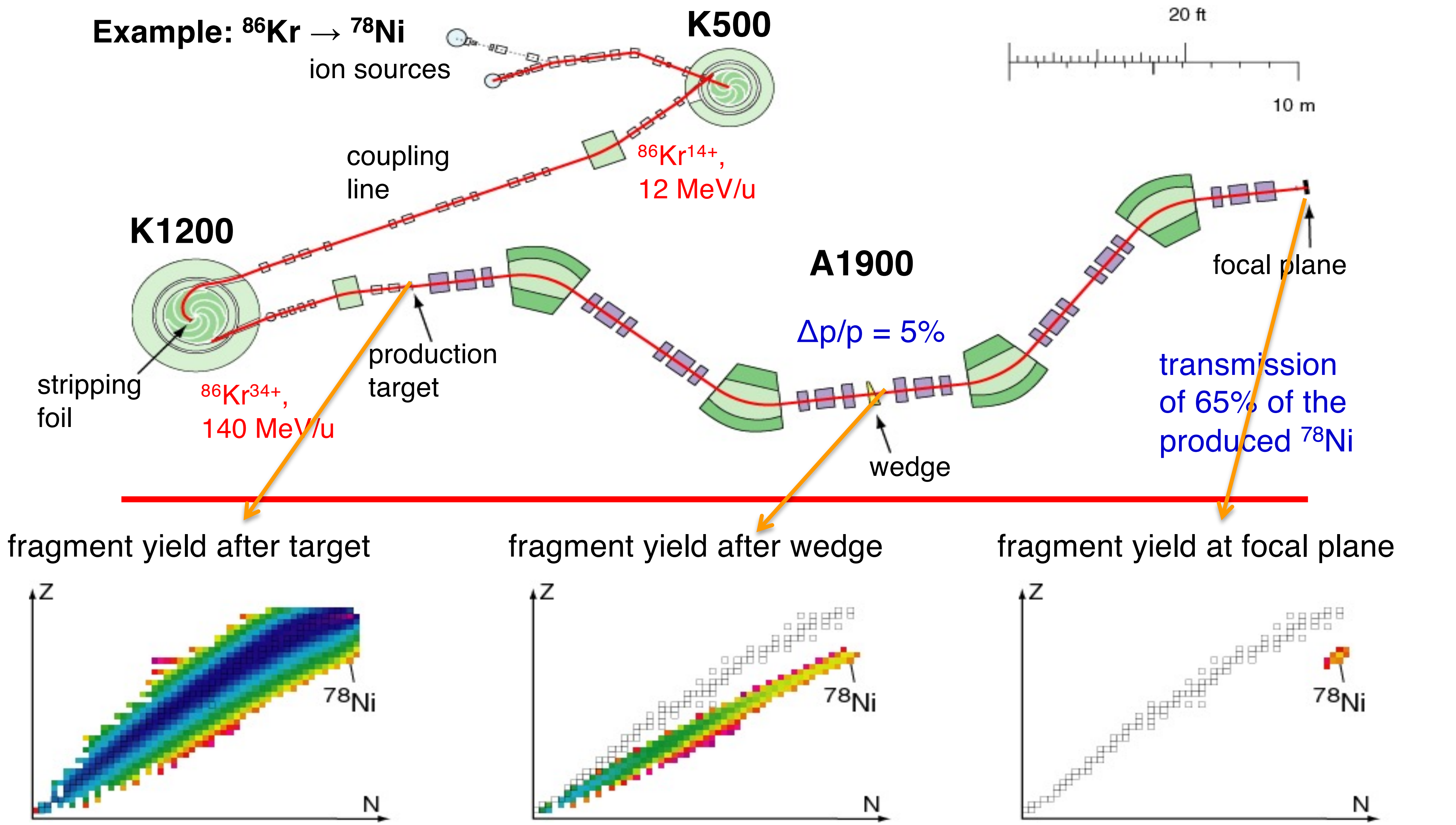
✓ Radioactive Beam

✓ Segmented γ-ray calorimeter

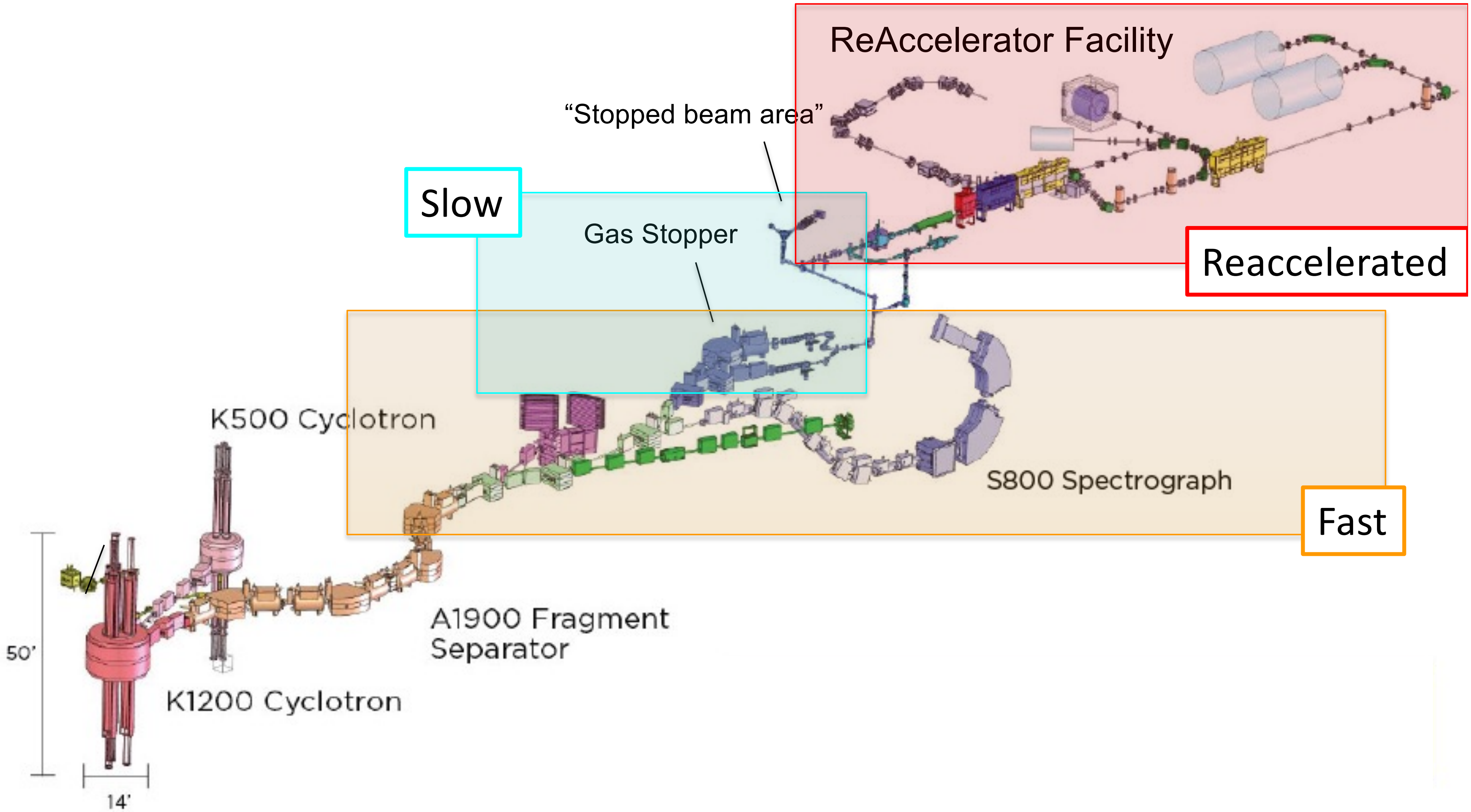
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

Michigan State University
National Superconducting Cyclotron Laboratory

Coupled Cyclotron Facility

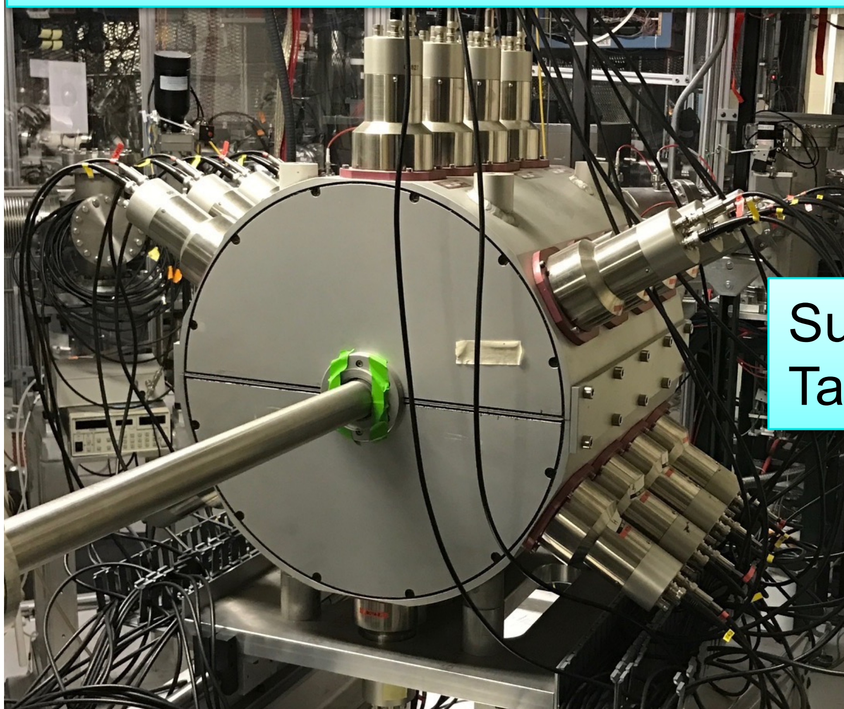


National Superconducting Cyclotron Lab

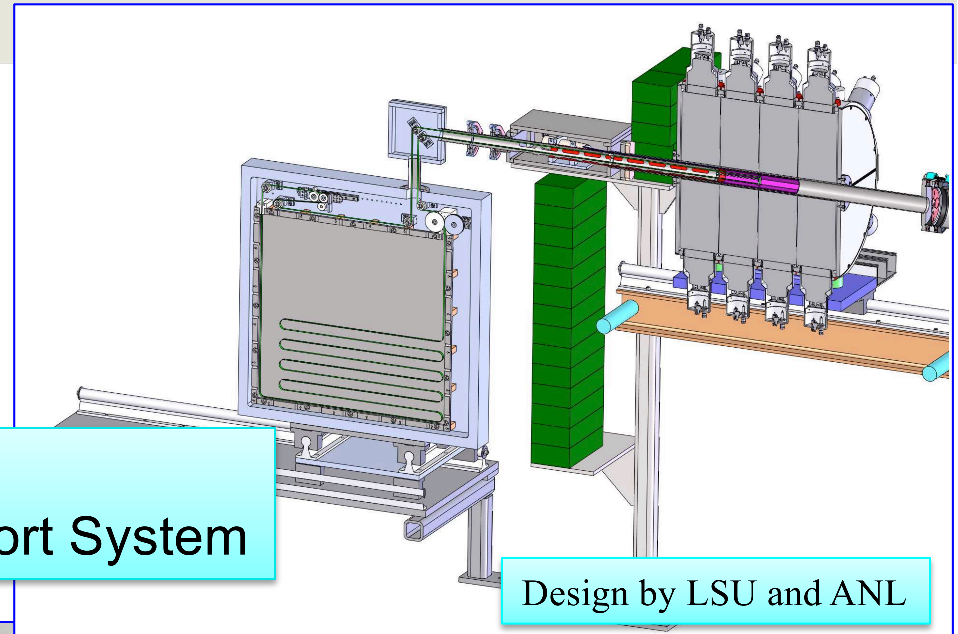


Summing NaI – SuN and friends

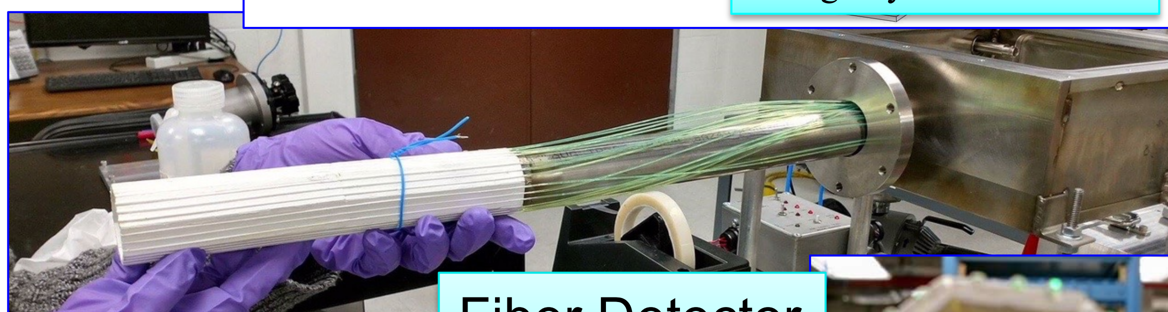
SuN
γ-Total Absorption Spectrometer



SuNTAN
Tape Transport System

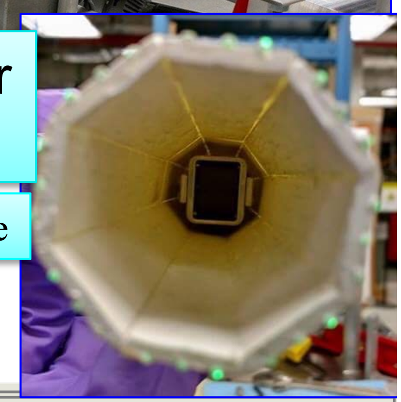


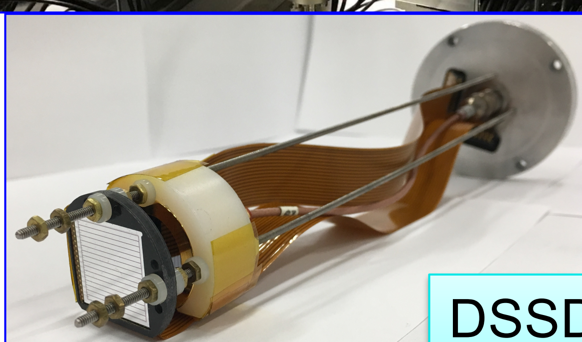
Design by LSU and ANL



Fiber Detector
β-detection

Hope College

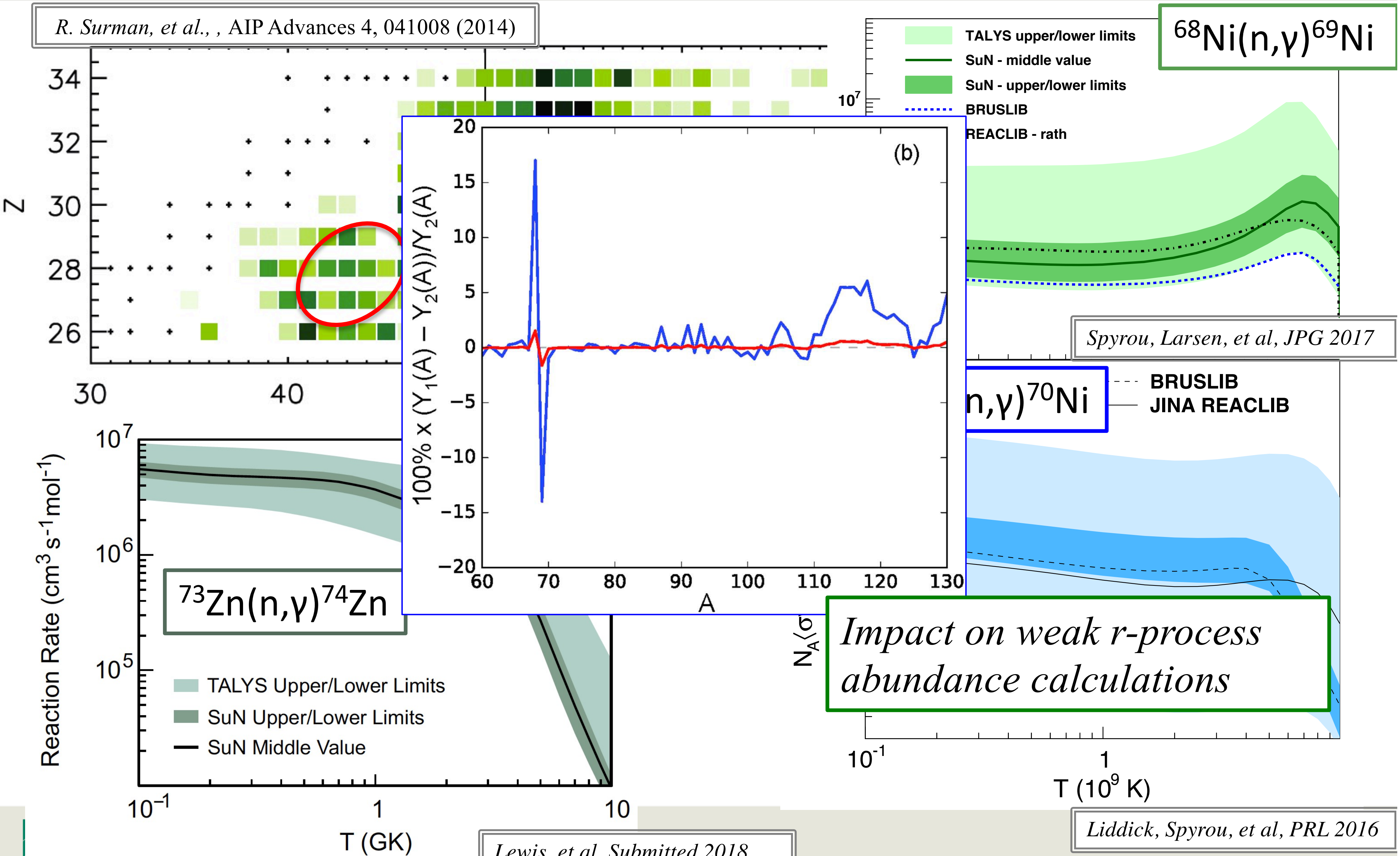




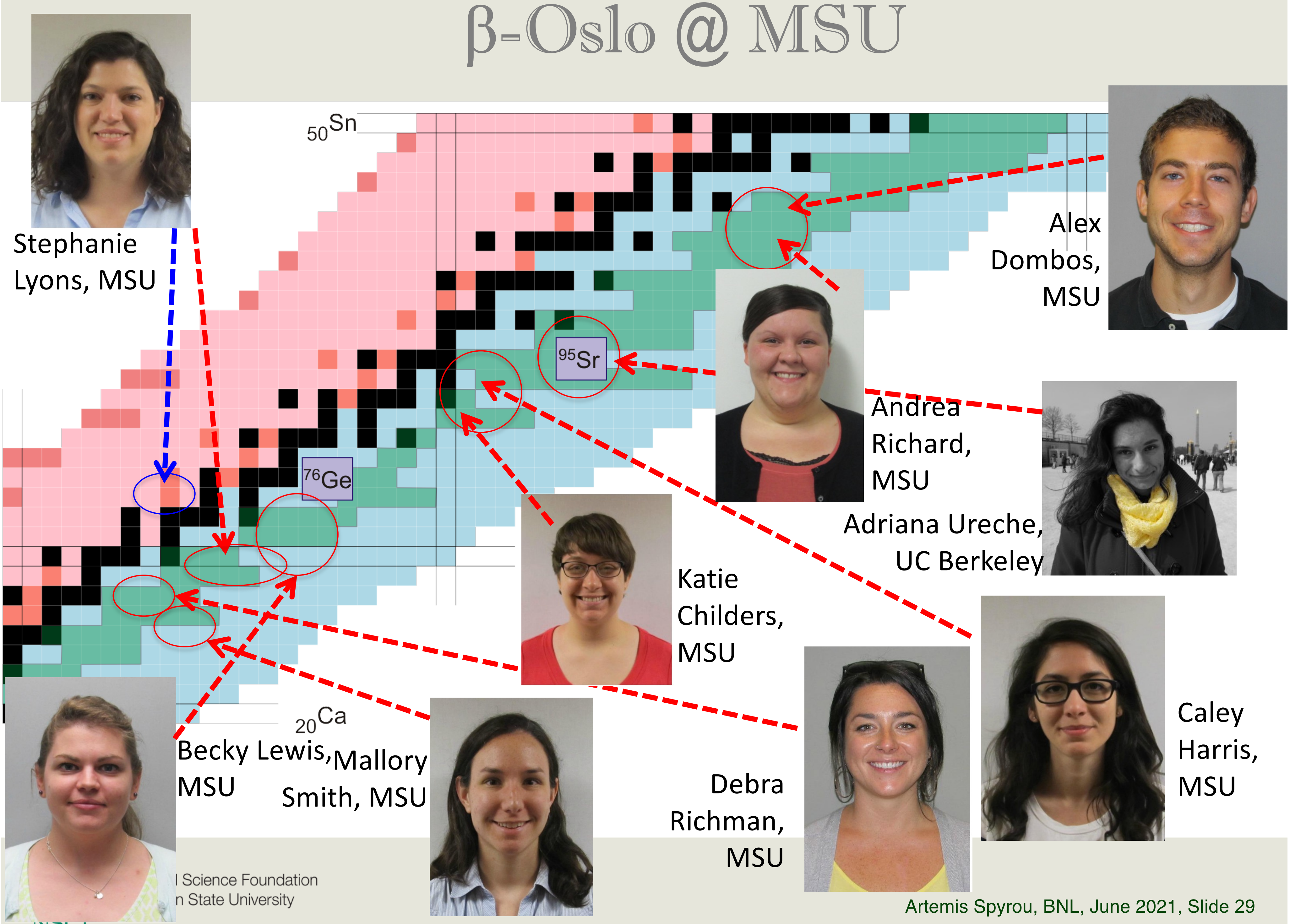
DSSD
Implantation-decay correlation

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

Weak r-process measurements

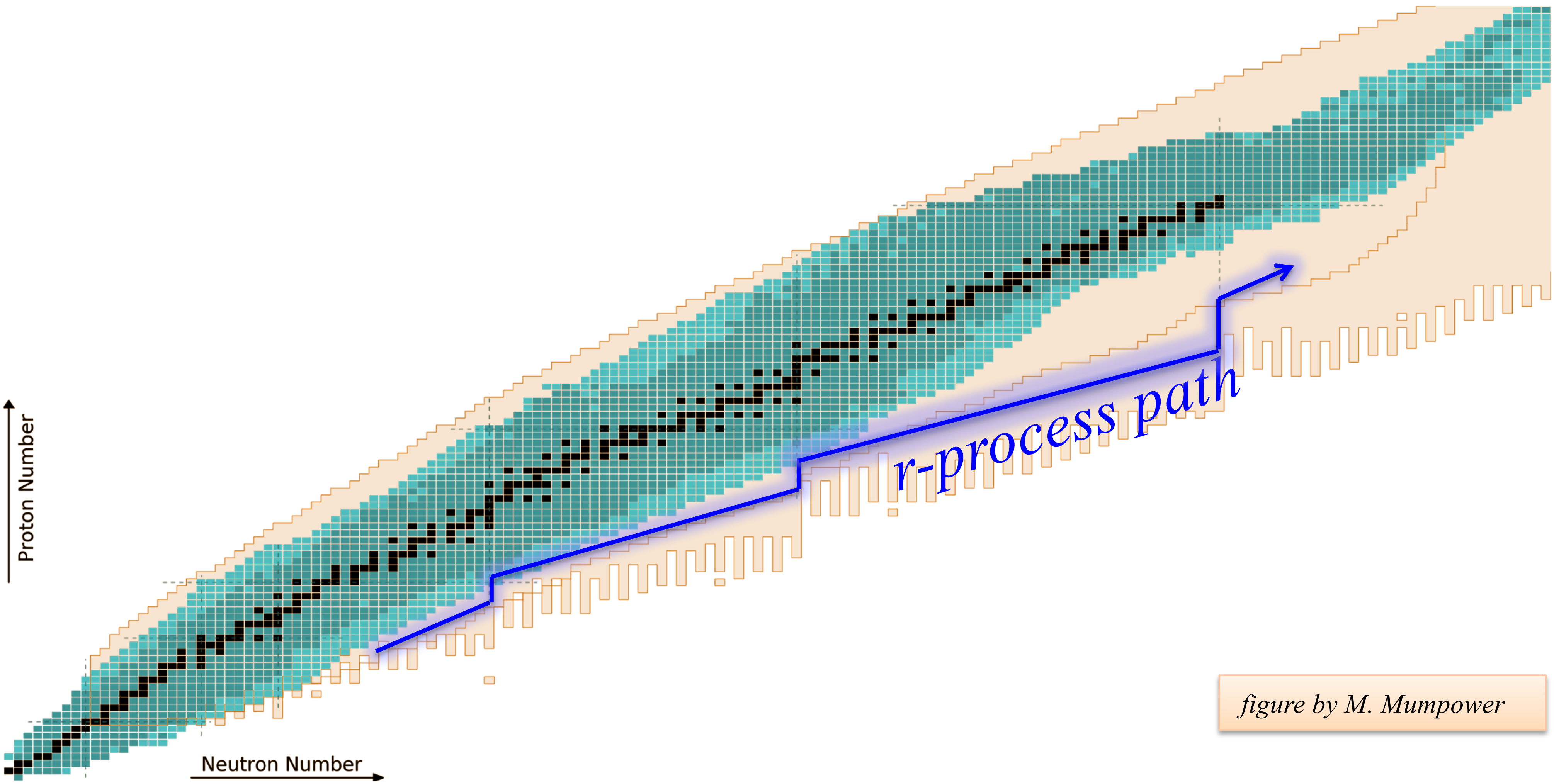


β-Oslo @ MSU



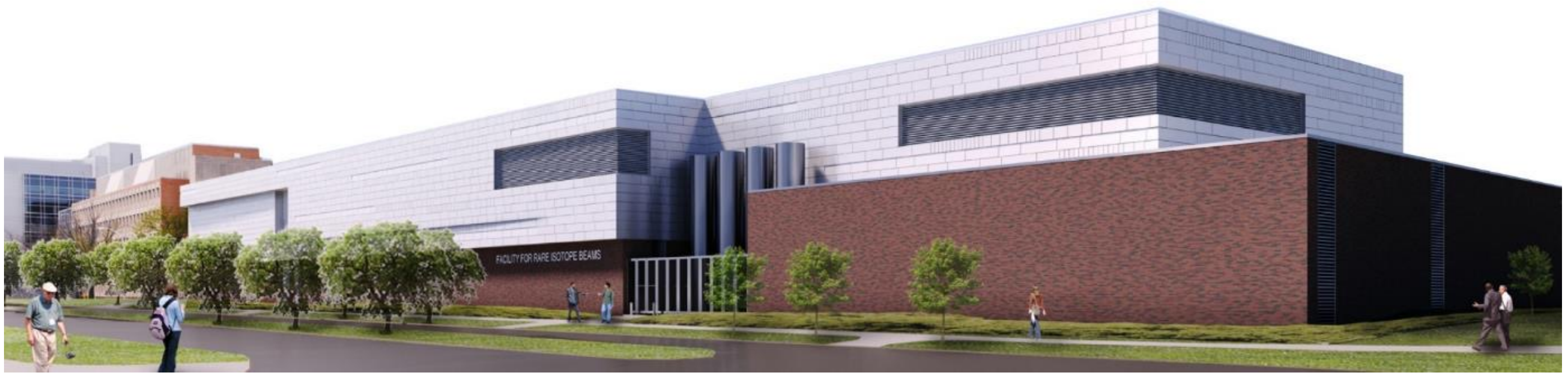
$_{50}$Sn
$_{20}$Ca
^{76}Ge
^{95}Sr
Stephanie Lyons, MSU
Alex Dombos, MSU
Andrea Richard, MSU
Adriana Ureche, UC Berkeley
Katie Childers, MSU
Caley Harris, MSU
Becky Lewis, MSU
Mallory Smith, MSU
Debra Richman, MSU

Current Reach



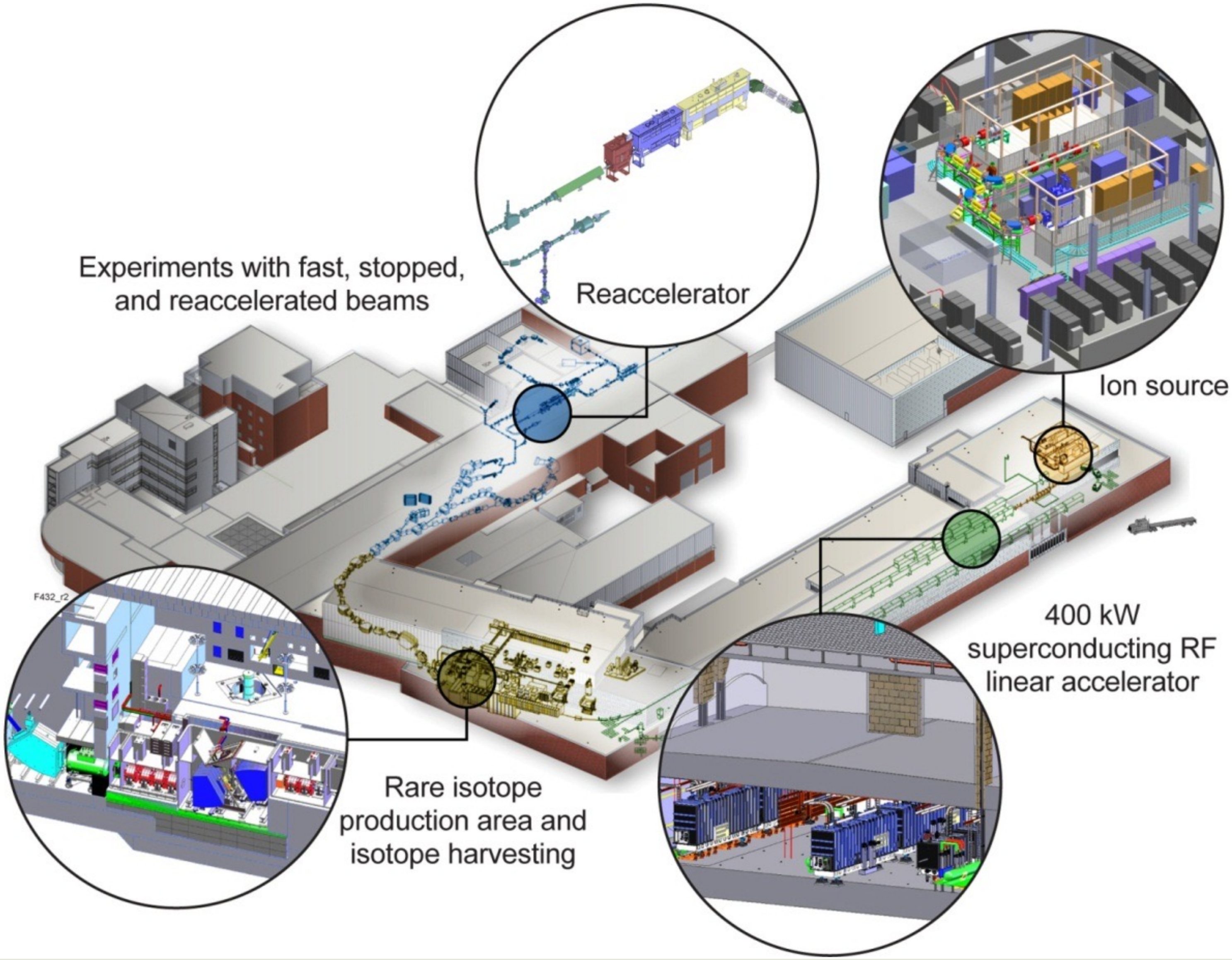
Facility for Rare Isotope Beams

- 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
- Upon FRIB completion, NSCL stops operation and FRIB Laboratory starts operation as a DOE-SC scientific user facility for world-class rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC



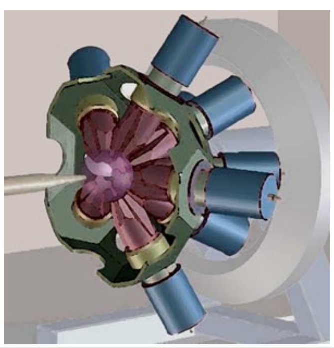
Facility for Rare Isotope Beams, FRIB

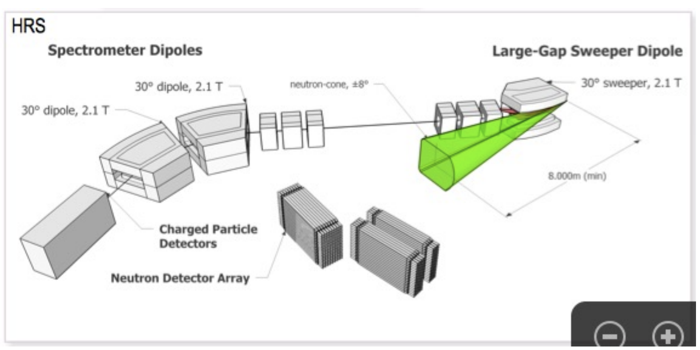
Michigan State University Campus

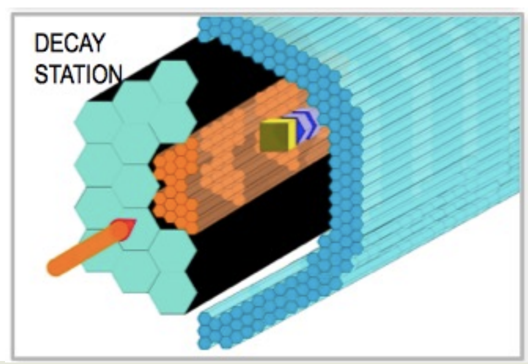


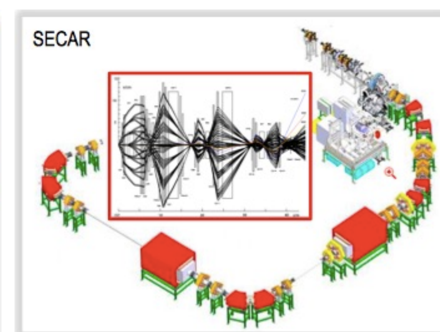
Summary - Conclusions

- Nuclear structure and reactions are important input in astrophysical calculations
- New 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









Collaboration

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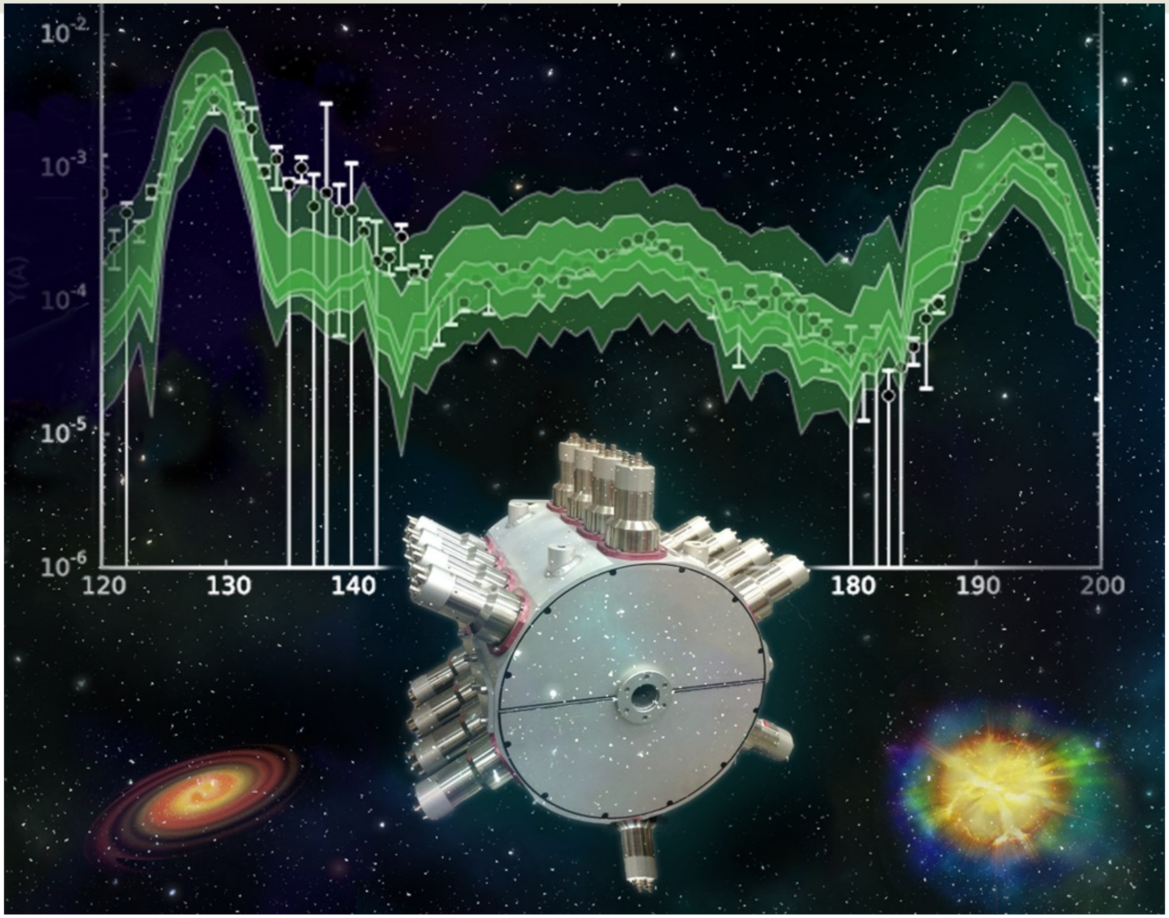
C.S. Sumithrarachchi
R.G.T. Zegers



A.C. Larsen
M. Guttormsen
T. Renstrøm
S. Siem
L. Crespo-Campo

Los Alamos NATIONAL LABORATORY EST. 1943

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S. Mosby

G. Perdikakis
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A. Simon

I. Dillman

TRIUMF

Lawrence Livermore National Laboratory

D. L. Bleuel

UNIVERSITY of GUELPH

D. Muecher