Neutron-Star Mergers and New Opportunities in Rare Isotope Research

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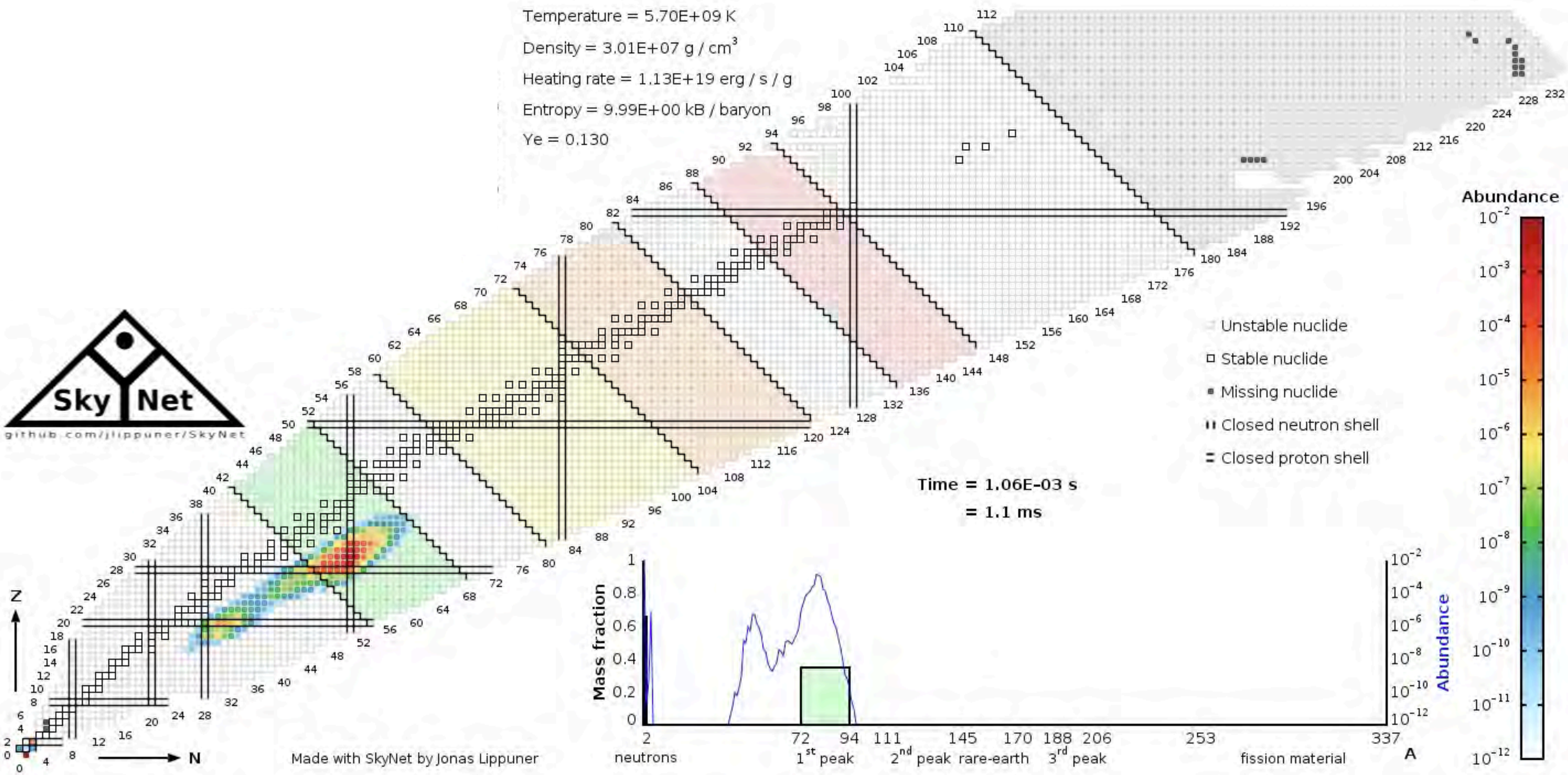
NSCL

Research supported by NSF

r-process in neutron-star mergers



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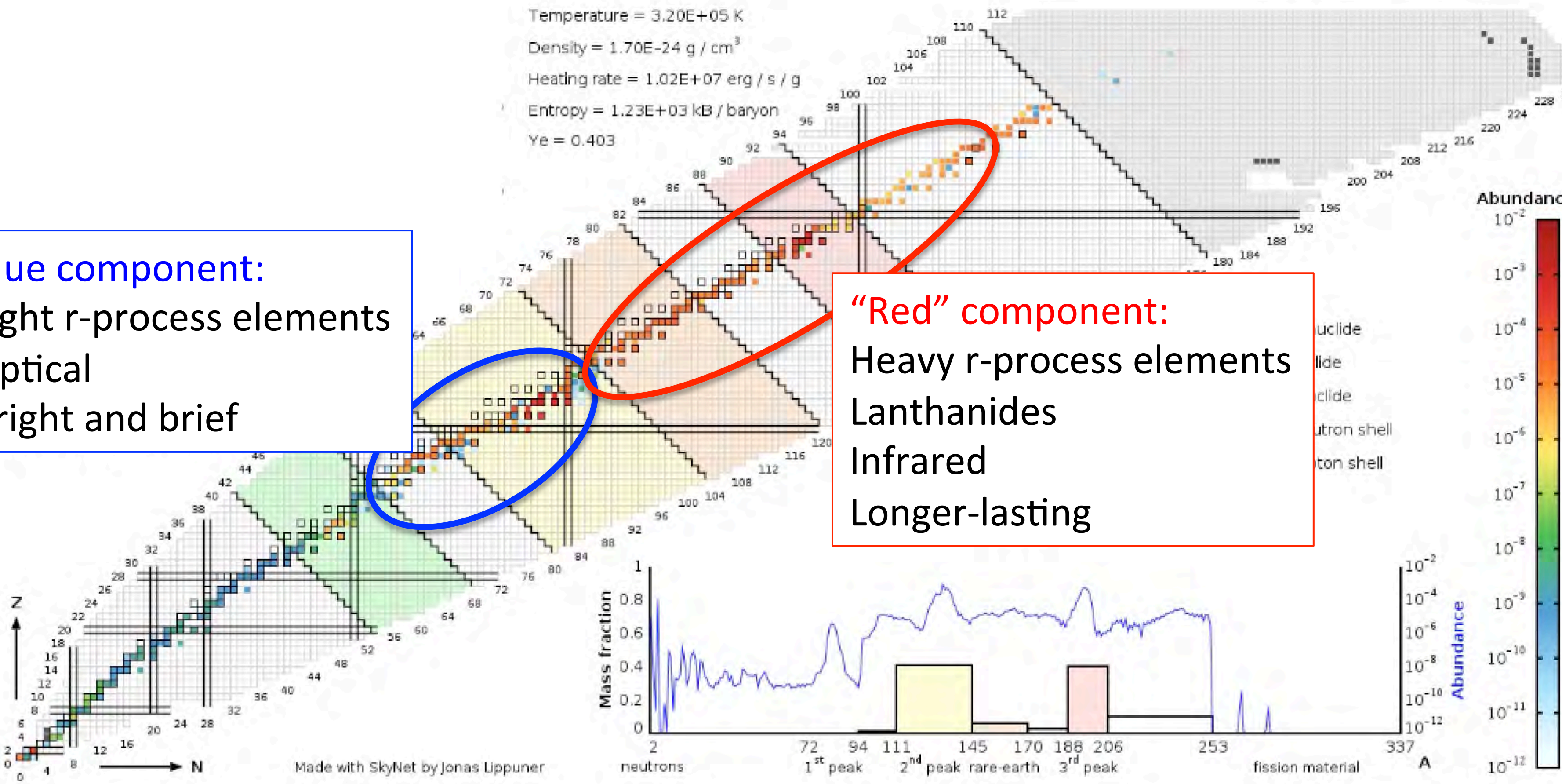
r-process in neutron-star mergers



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

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

- GW170817 observations distinguish between heavy (red) and light (blue) components, but cannot get individual element contributions.
- Nuclear physics data needed to figure out the different contributions

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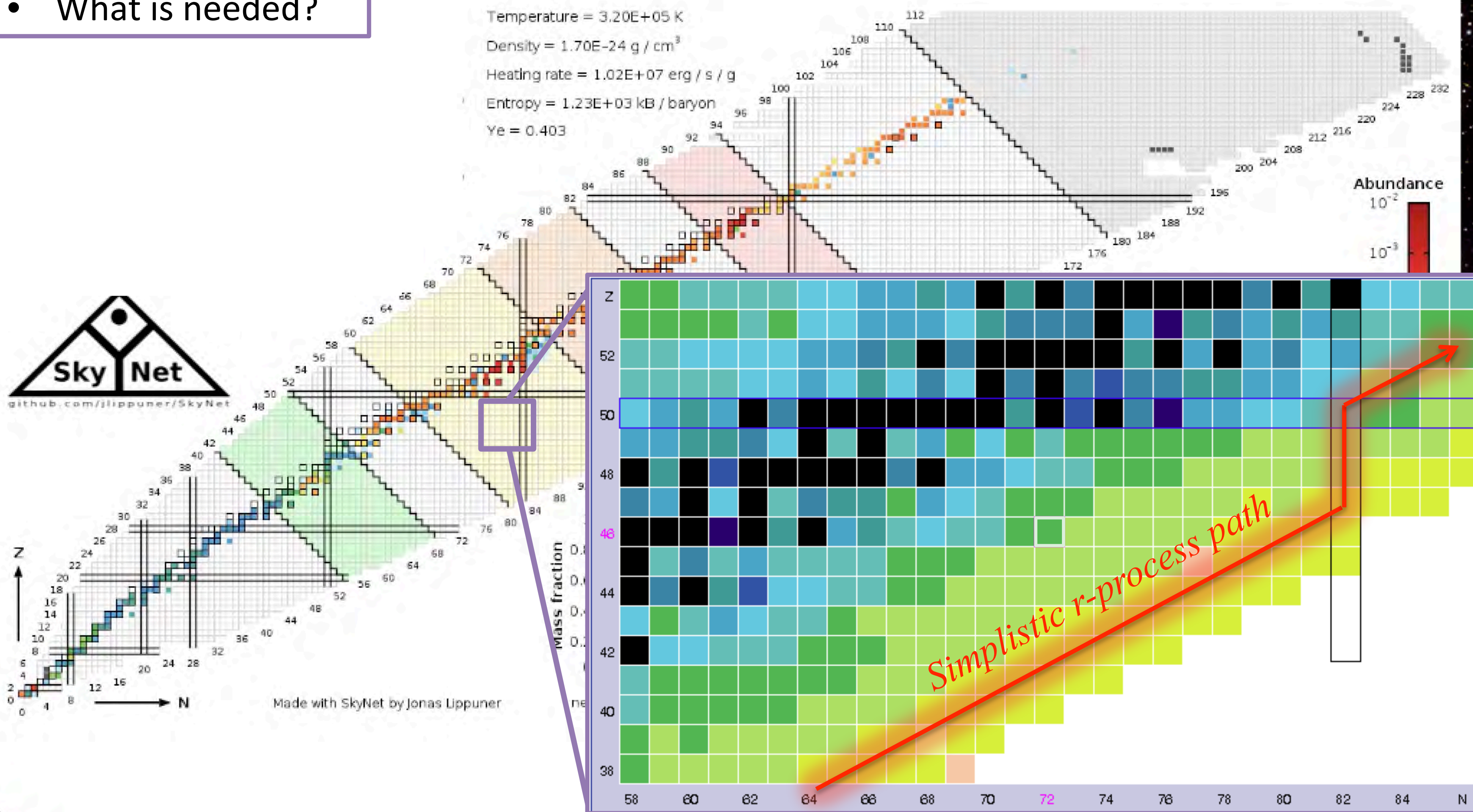
r-process in neutron-star mergers

- What is needed?



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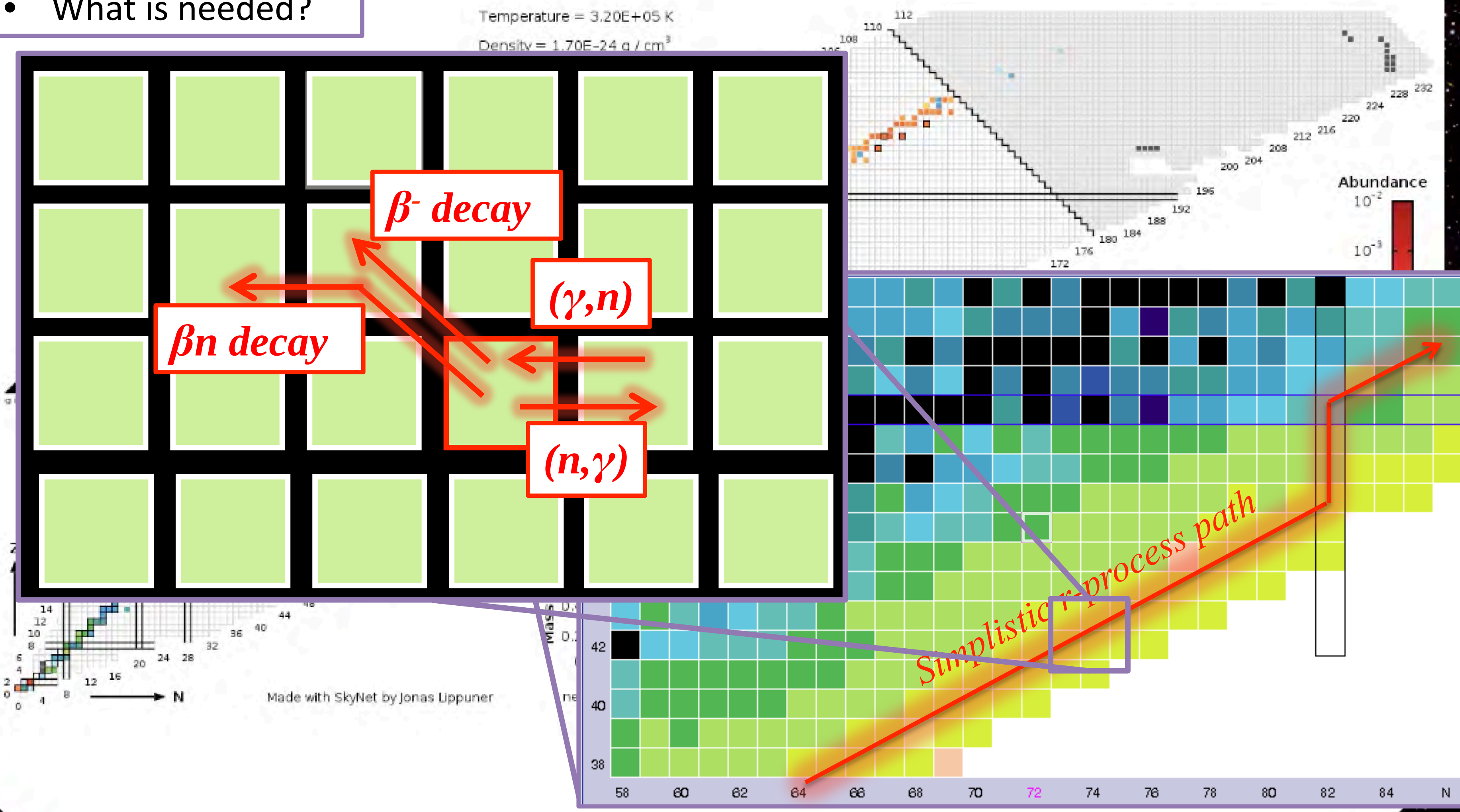
r-process in neutron-star mergers

- What is needed?



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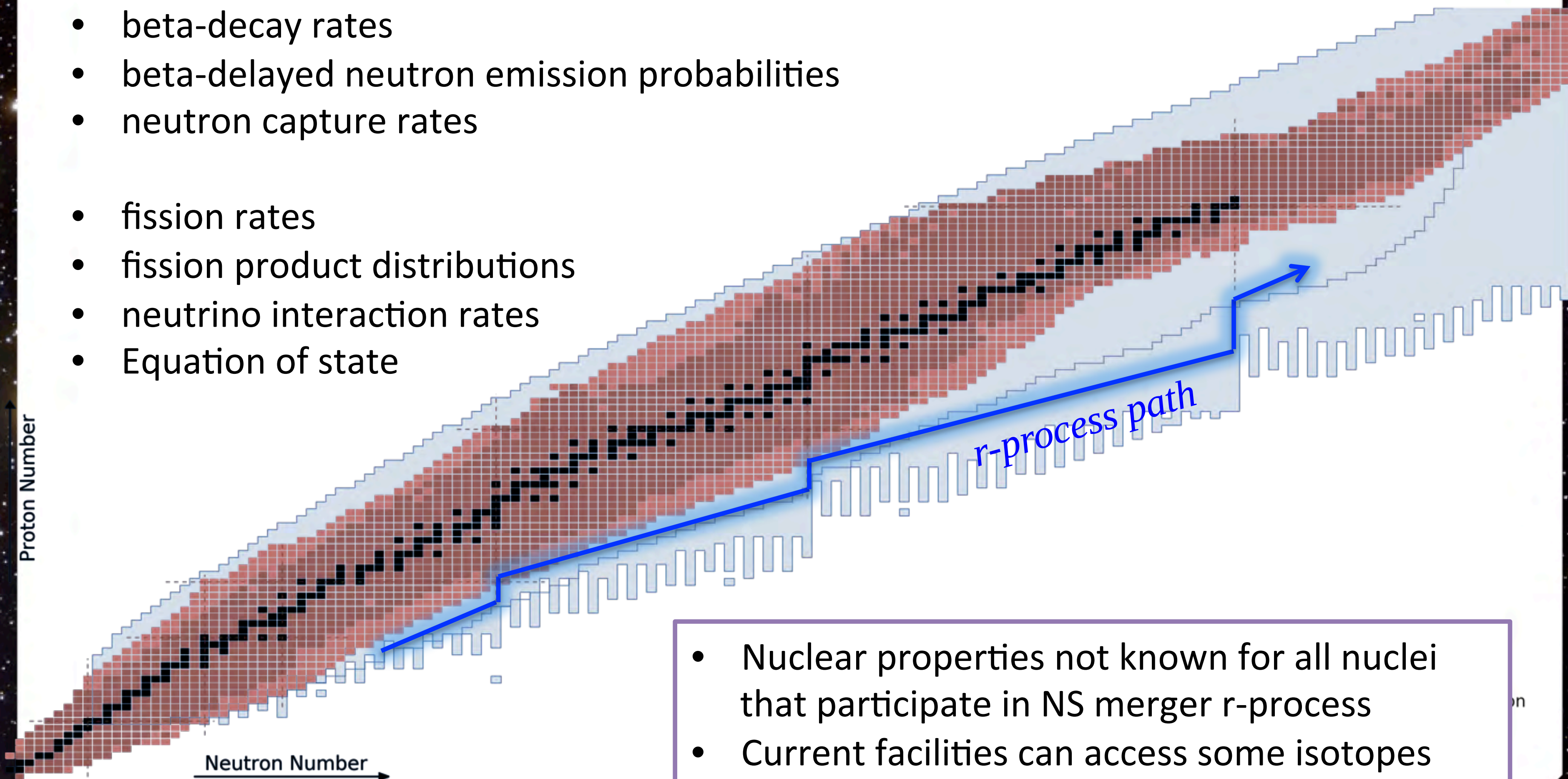
Nuclear Input for r-process

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

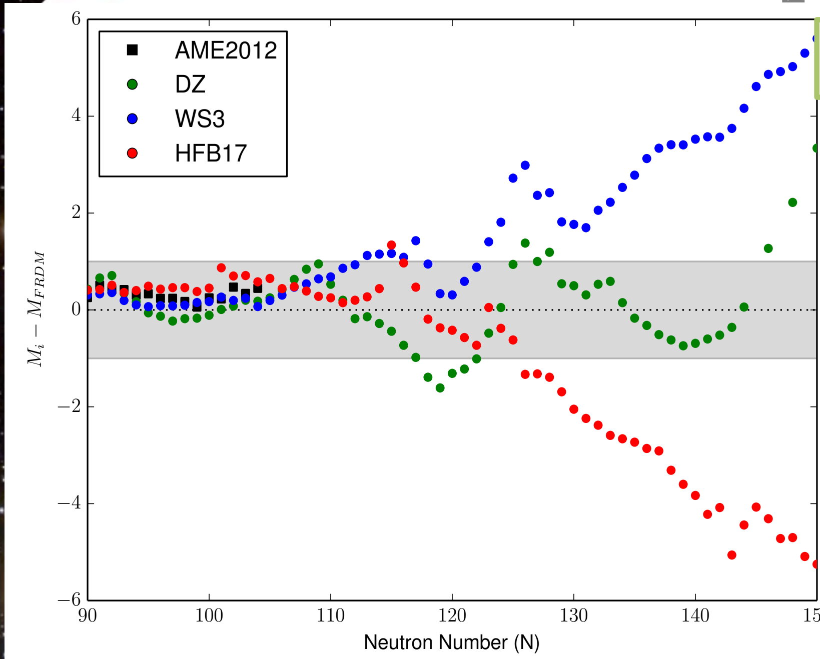
- fission rates
- fission product distributions
- neutrino interaction rates
- Equation of state



- Nuclear properties not known for all nuclei that participate in NS merger r-process
- Current facilities can access some isotopes
- Next generation facilities will give access to the majority of r-process nuclei

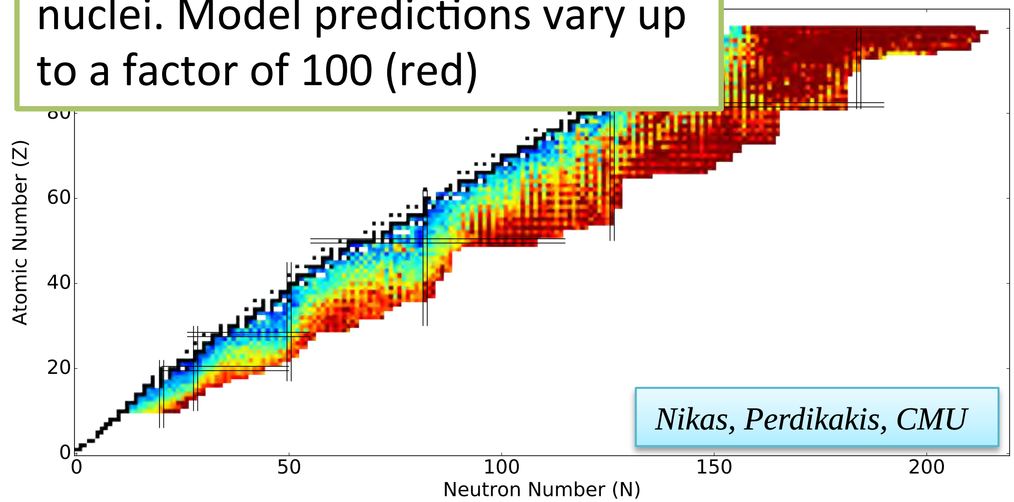
figure by M. Mumpower

How well can we predict nuclear properties?

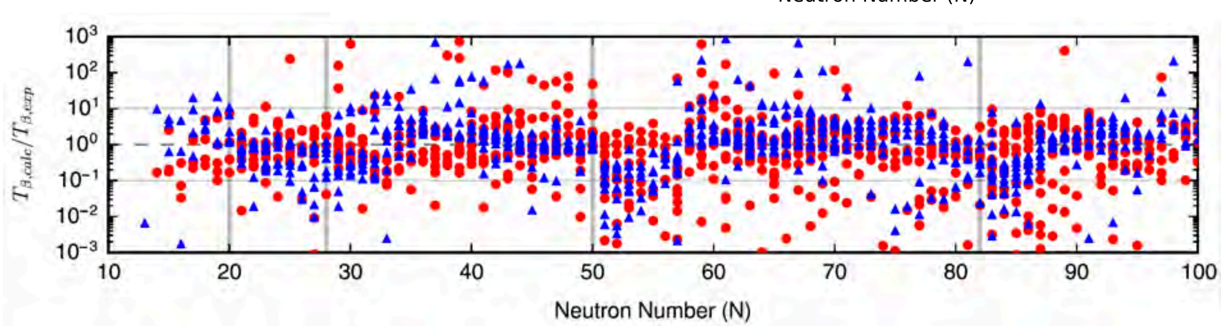


Mass models diverge when no data is available

Neutron-captures are completely unconstrained for r-process nuclei. Model predictions vary up to a factor of 100 (red)



Half-life calculations can be more than a factor of 10 different than experiment

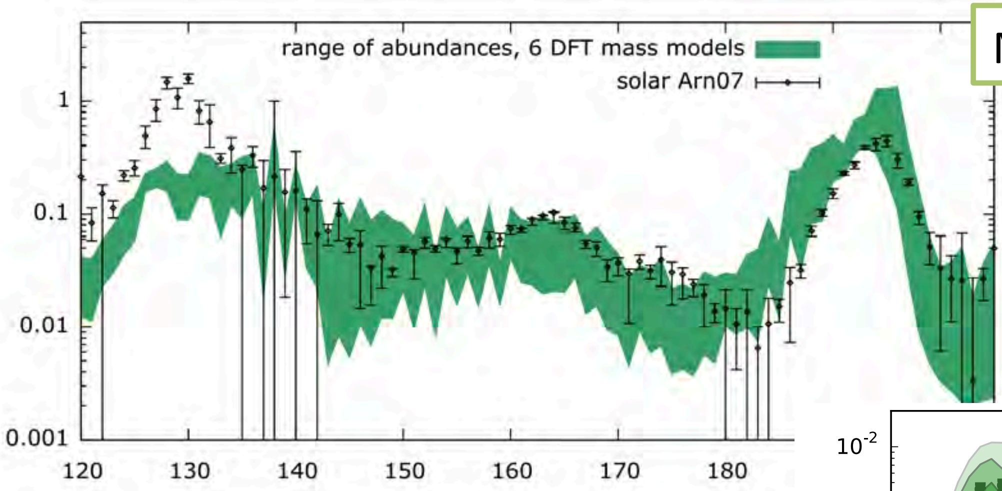


M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126

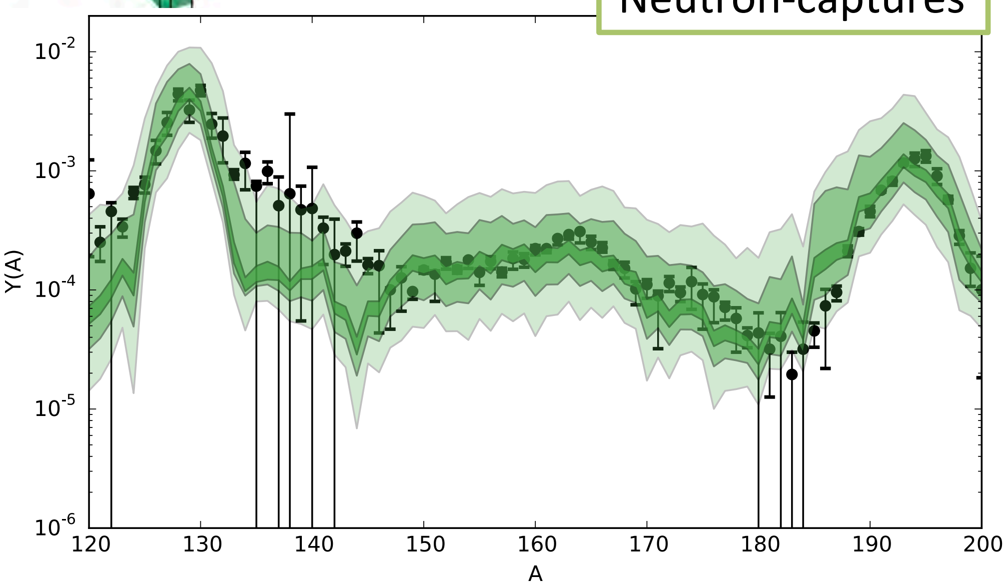
Impact of nuclear uncertainties

With GW170817 discovery, nuclear physicists can focus on NS merger scenario instead of running a range of speculative sites.

Masses



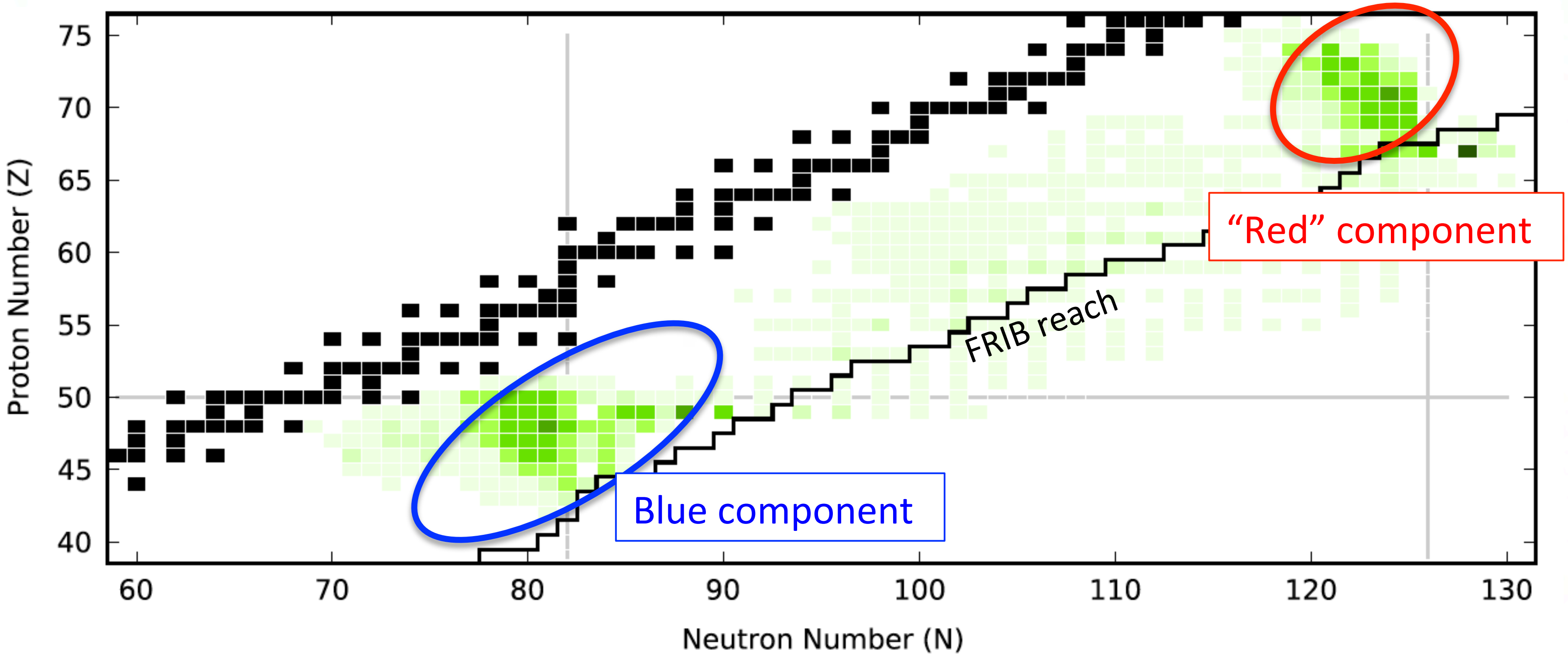
Neutron-captures



Varying nuclear properties within their uncertainties has a large impact on the r-process abundance calculations

Liddick, AS, et al., PRL 2016, Surman et al ,2016

Which nuclei are the most important?



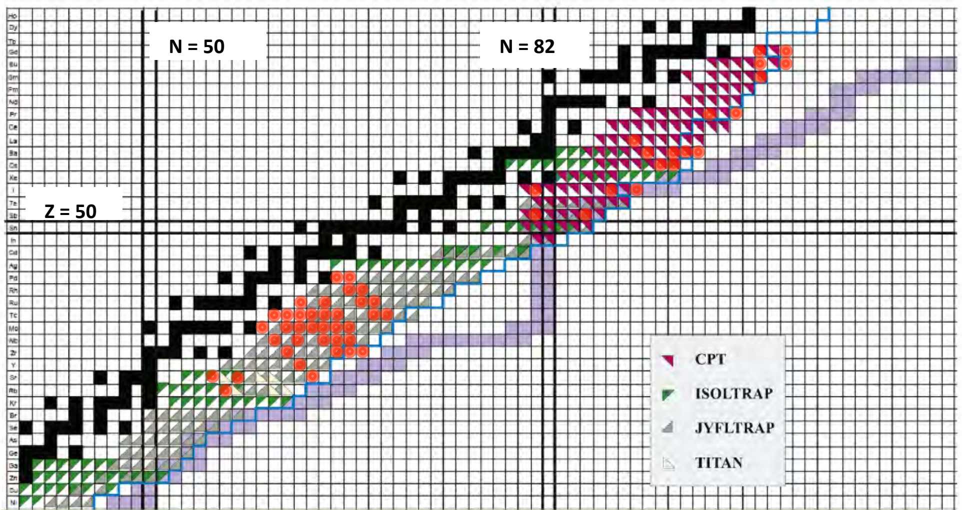
Important nuclei for both components identified and within reach of FRIB

M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126

Experiments – current efforts

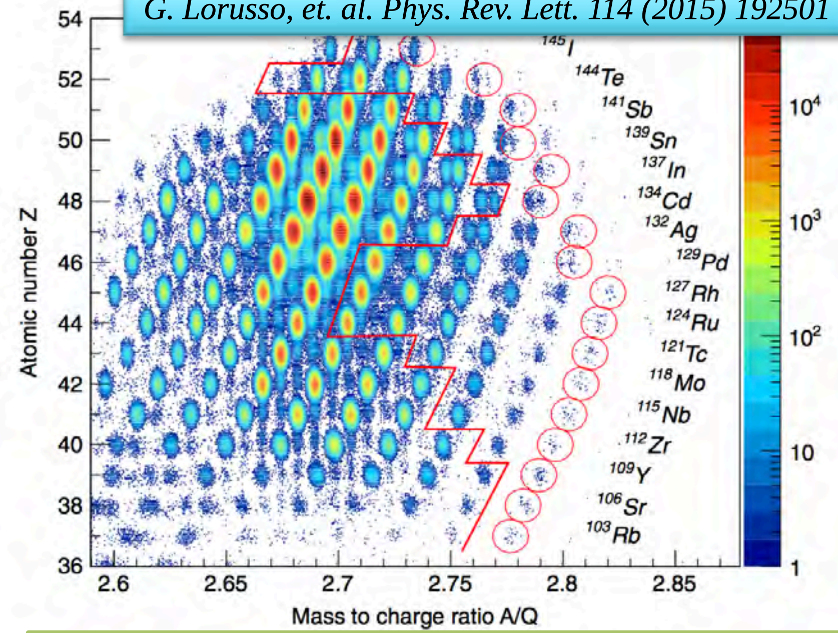
Radioactive beam facilities around the world are measuring important nuclear properties for the r-process

J. A. Clark and G. Savard, Int. J. Mass Spectrom. ***349-350****, 81 (2013).*



Mass measurements at Argonne National Lab

G. Lorusso, et. al. Phys. Rev. Lett. 114 (2015) 192501



Half-life measurements at RIKEN, Japan

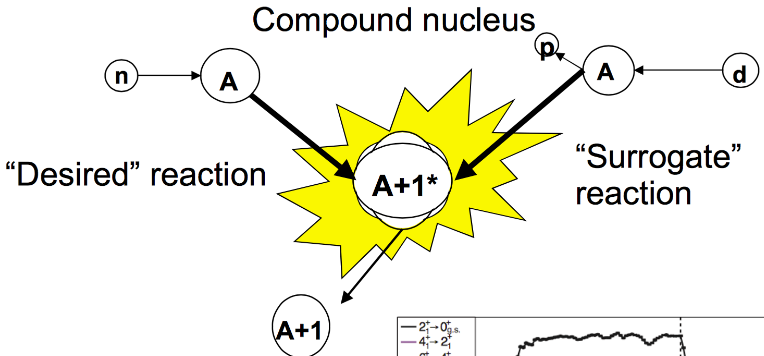
- Masses and half-lives can be measured directly, provided the radioactive beam of interest is available
- Neutron captures extremely challenging to measure on radioactive nuclei

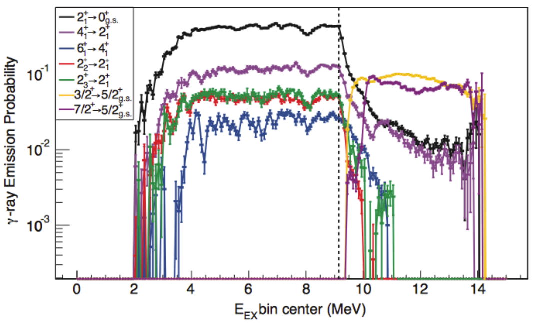
Neutron Captures

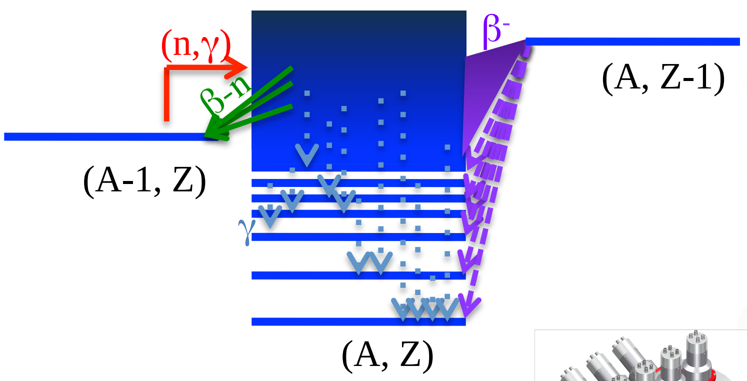
- Direct measurement of (n,γ) reactions on short-lived isotopes: challenging
- Indirect techniques developed
- (d,p) reactions as surrogate for (n,γ)
- Measuring nuclear structure properties like nuclear level densities and γ strength to constrain (n,γ) far from stability (β-Oslo)
- Ready to be applied with FRIB beams

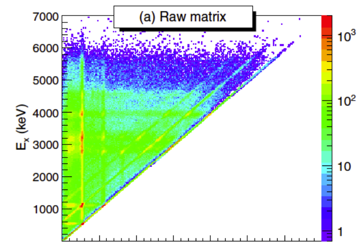
A. Ratkiewicz, J. Cizewski, et. al. EPJ WoConf. 2015

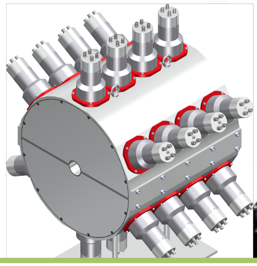
Spyrou, Liddick, et. al., PRL 2014











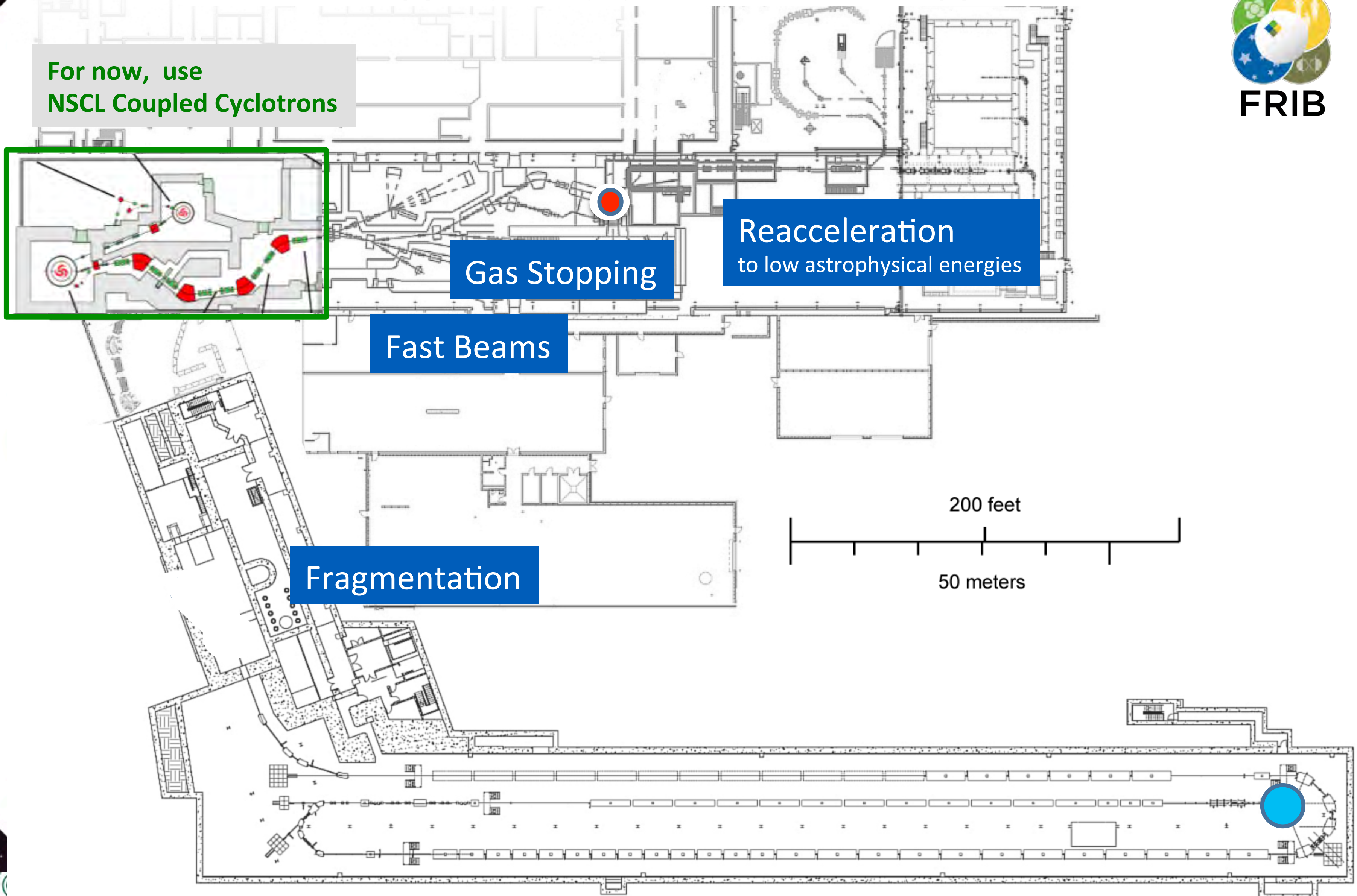
SuN @ NSCL

FRIB Project Summary

DOE Office of Science supports establishment of FRIB

- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion date is June 2022, managing to an early completion in fiscal year 2021
- FRIB will serve as a national user facility for world-class rare isotope research, (~1400 scientists currently engaged) and builds on more than 50 years of nuclear science expertise developed at MSU

How does FRIB work



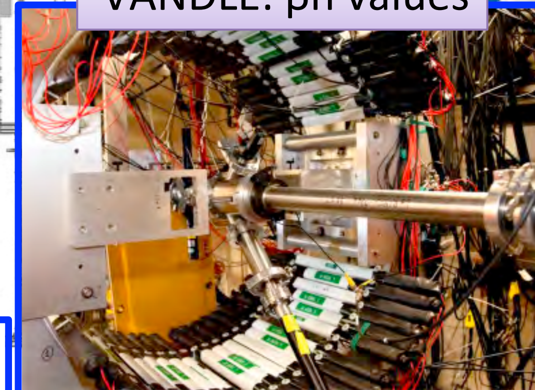
Courtesy, H. Schatz

Available Equipment for r-process experiments

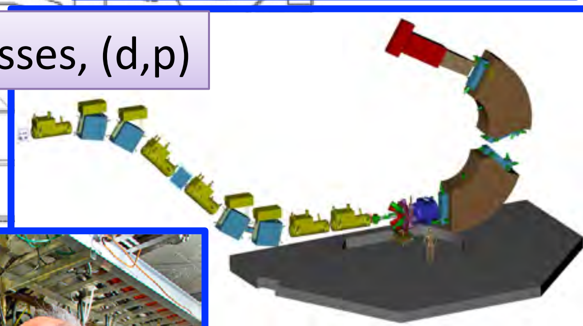
For now, use
NSCL Coupled Cyclotrons

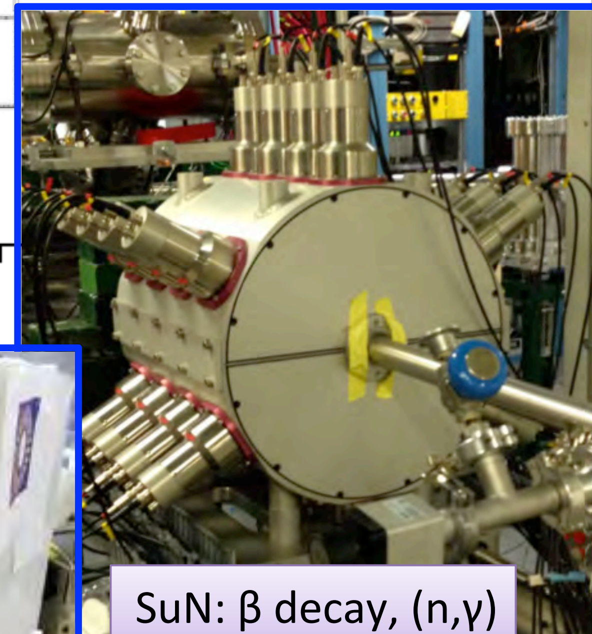
LEBIT: Masses

VANDLE: βn values



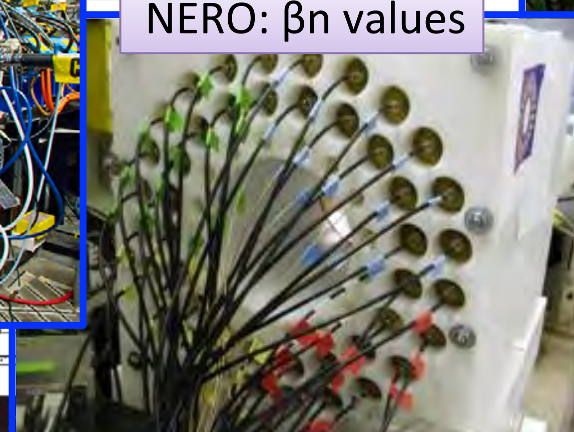
S800: masses, (d,p)





SuN: β decay, (n,γ)

GRETINA: (d,p) for (n,γ)



NERO: βn values

Conclusions

For questions:
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- GW170717 discovery creates opportunities for nuclear science
- Better understanding of the individual element contributions in NS mergers requires accurate nuclear input
- R-process measurements already at current facilities
- Important nuclei identified and within reach of FRIB
- Existing equipment and techniques ready for FRIB day-1 experiments
- New equipment under development to take full advantage of FRIB capabilities