Origin of the Heavy Elements

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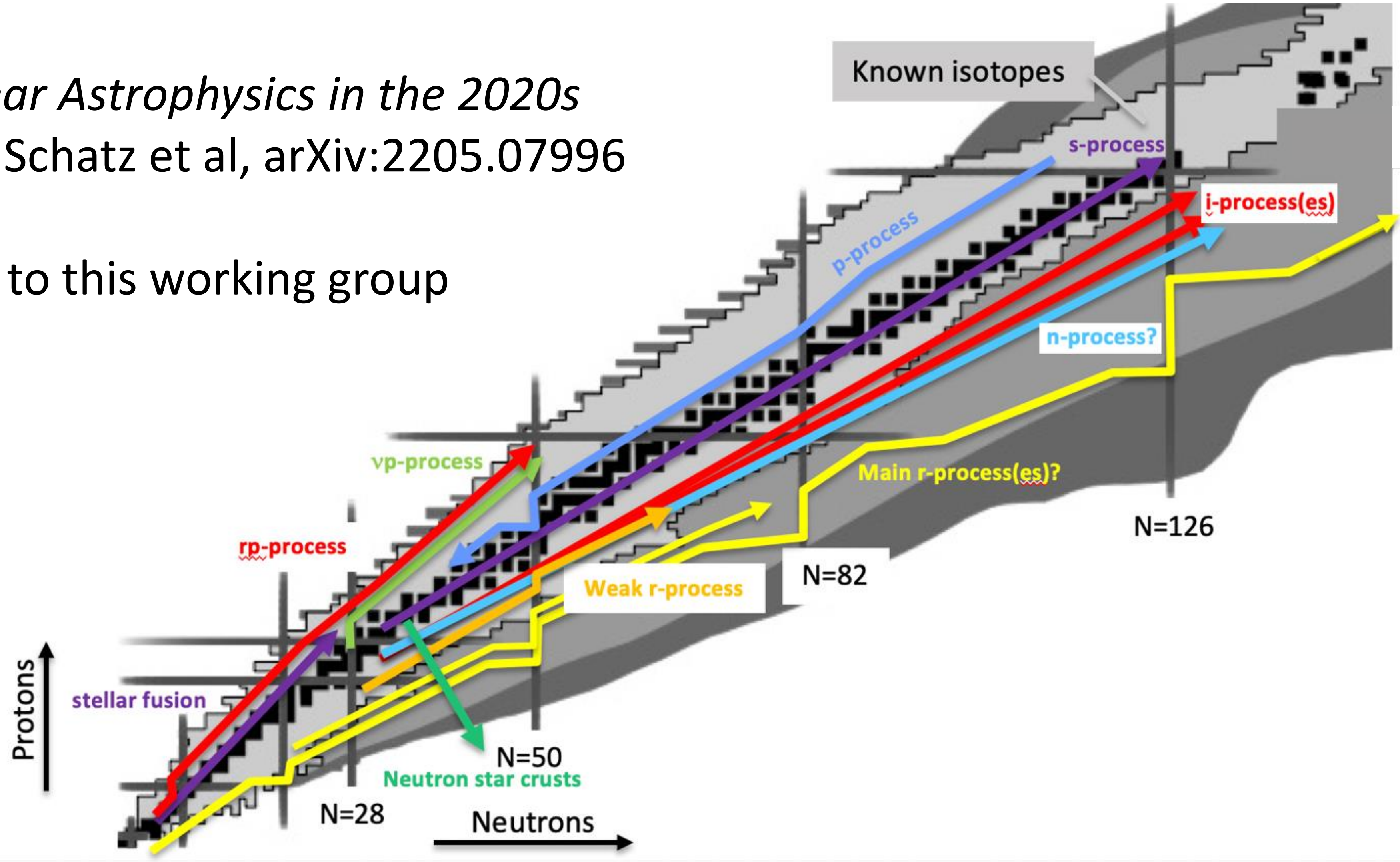
Central Michigan University

2022 NSAC Long Range Plan Townhall Meeting

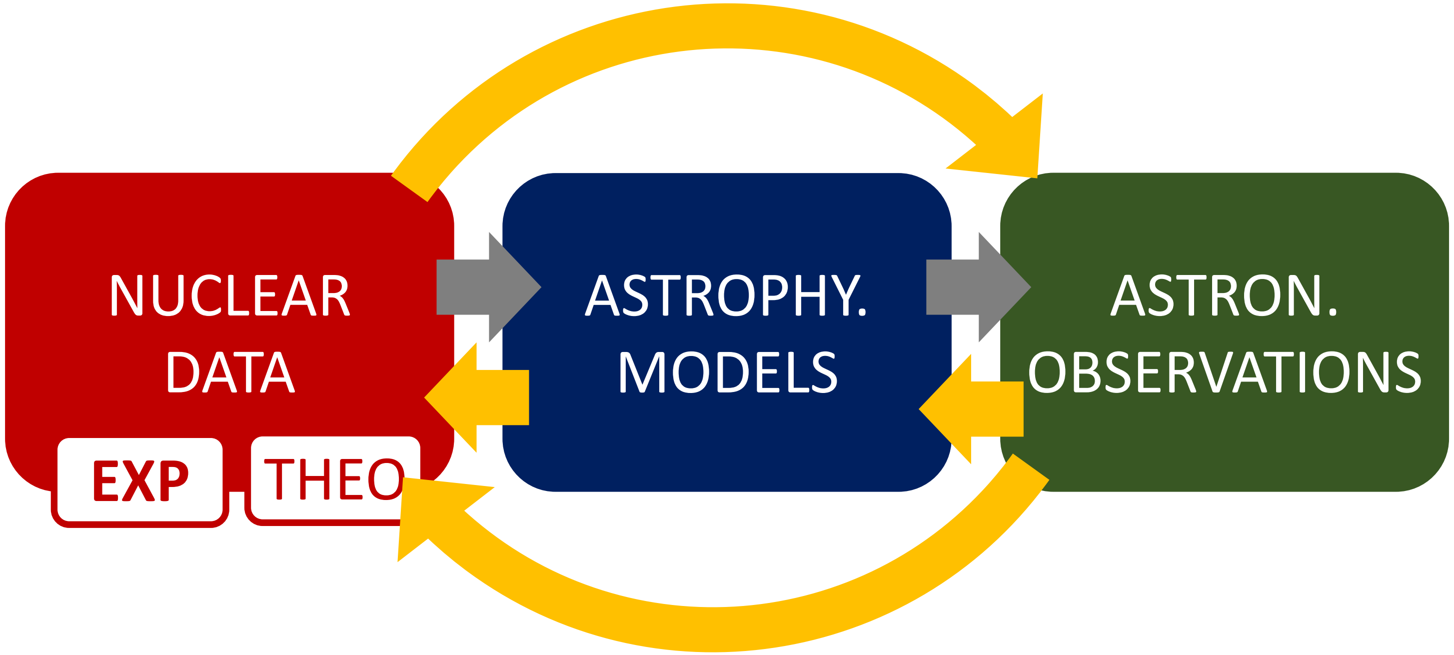
How are heavy elements created by processes acting far from β-stability in explosive astrophysical environments?

Horizons: Nuclear Astrophysics in the 2020s and beyond, H. Schatz et al, arXiv:2205.07996

+ contributions to this working group



Nucleosynthesis is an intrinsically interdisciplinary field where a collaborative approach is essential



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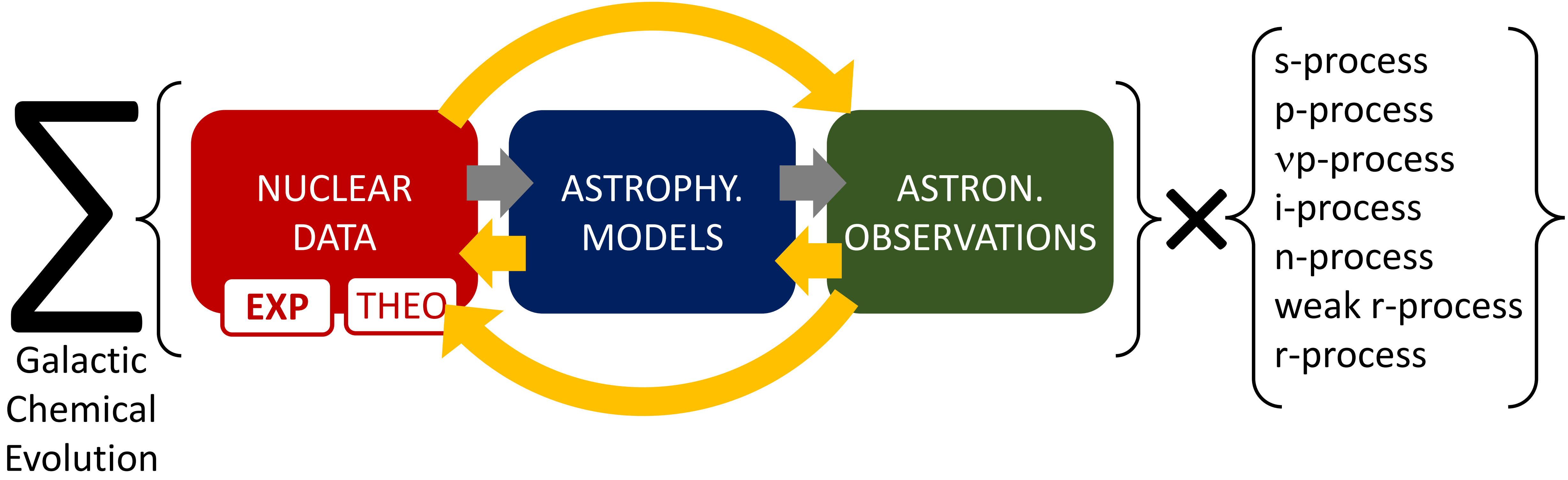


Open questions about the origin of the heavy elements

- **What are the astrophysical sources, and how heavy-element nucleosynthesis contributes to the chemical evolution of the Galaxy?**
- What are the properties of unstable isotopes and their reactions relevant to nucleosynthesis and how to access them experimentally?
- How do we improve the accuracy of nucleosynthesis yields and evaluate their uncertainty given experimental and computational developments?
- How do we disentangle the contribution of different processes to the synthesis of medium-mass elements (germanium to cadmium)?
- How are heaviest elements beyond Pb and Bi produced, what role does fission have in the process, and what are their observational signatures?

Advanced astrophysical models show that nature provides a range of environments able to host a variety of nucleosynthesis processes

p-process

νp-process

weak r-process

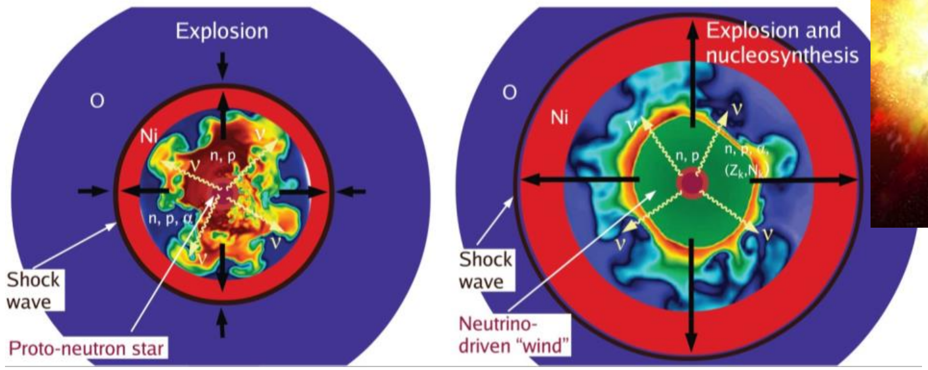
i-process

r-process

weak r-process

r-process

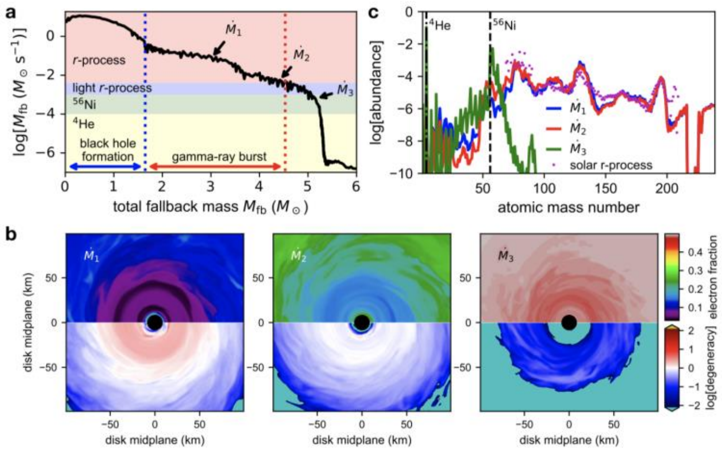
Core-collapse supernova



Janka++ 2012

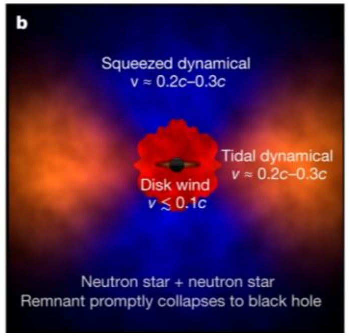
Rapidly-accreting white dwarfs

Collapsars



Siegel++ 2019

NS merger

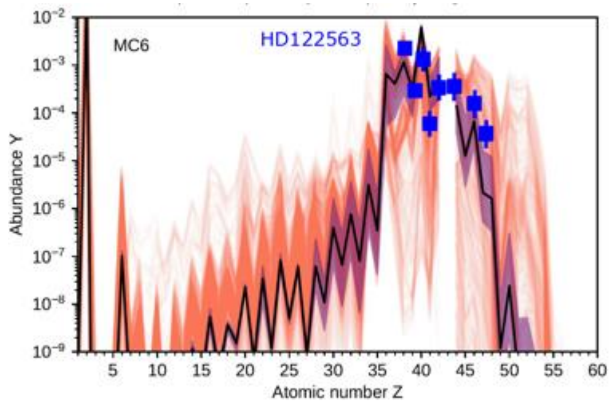


Kasen++ 2017

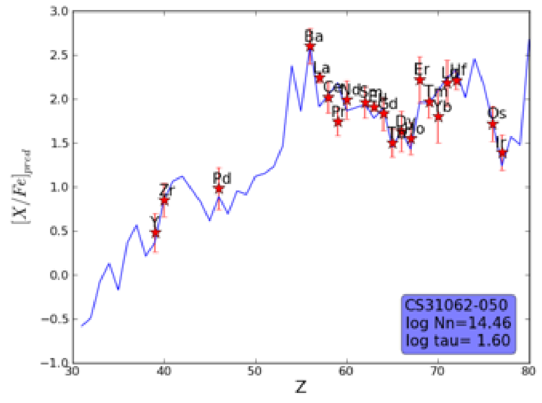
NEUTRON RICHNESS

High-resolution stellar spectroscopy provides further evidence that the light r-process elements are produced by more than one process

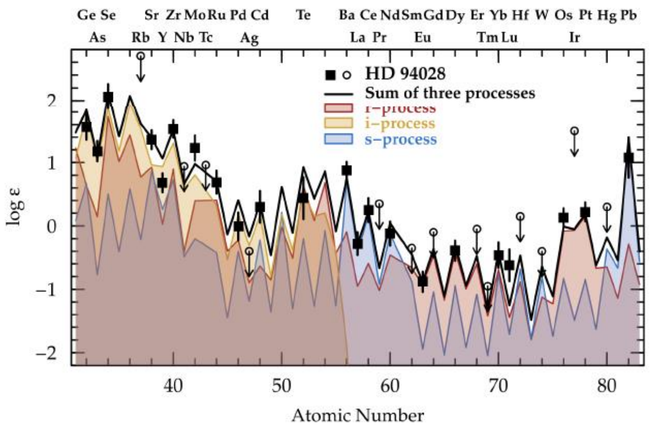
weak r-process

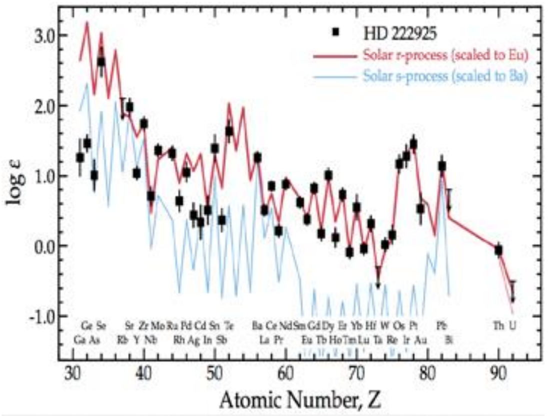


i-process



strong r-process + something else





+ Large-scale surveys dramatically increased the sample of observed r-process enriched stars – e.g. Hansen et al ApJ 858 (2018)

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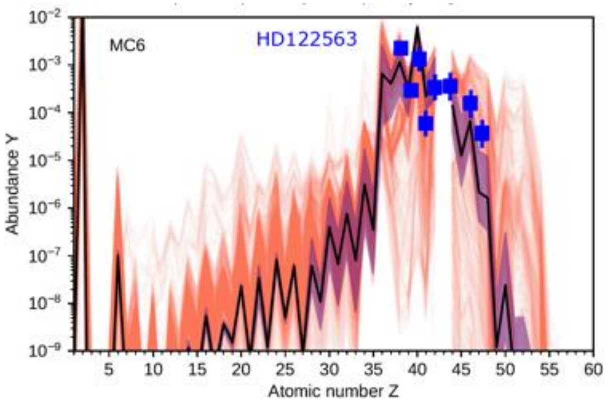

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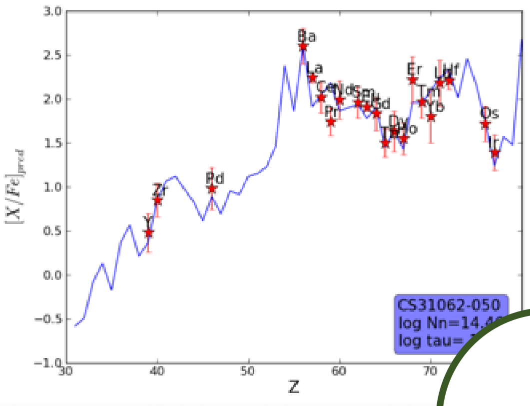

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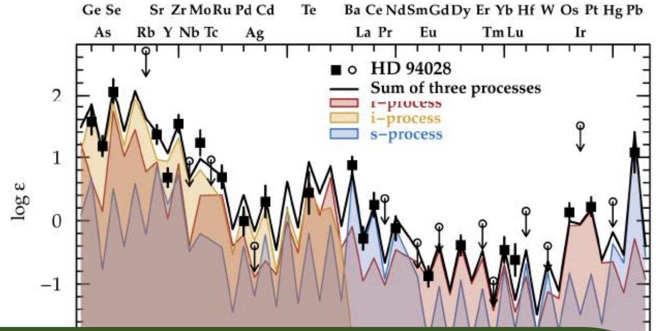

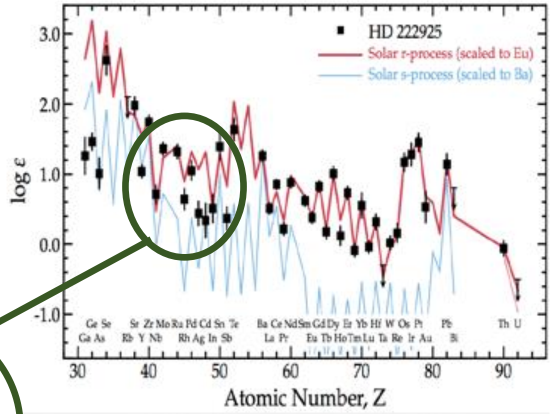

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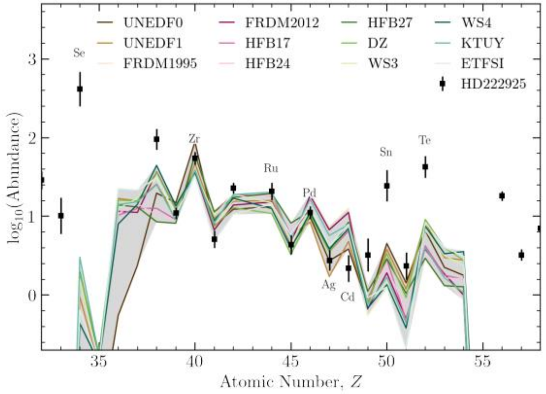
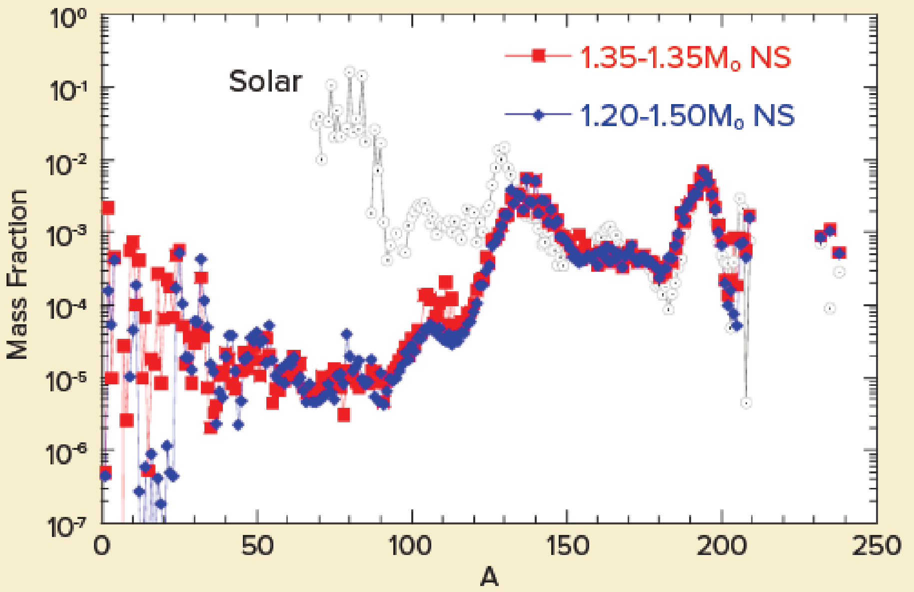


Better nuclear data is needed for an astrophysical interpretation of the abundances - Holmbeck++ 2022

Sidebar 4.3: Advanced LIGO and Nuclear Physics

The detection of gravitational radiation from the violent merging of neutron stars in binary systems could have profound implications for nuclear astrophysics. We expect such mergers to be rare events in a galaxy like ours, perhaps happening once per 10 thousand to 1 million years. Fortuitously, the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) will very soon be able to detect gravitational waves from these events out to a distance of 200 megaparsecs, a volume encompassing some millions of galaxies. In fact, the first observable from this observatory will be the *rate* of neutron star mergers, a key parameter in differentiating between sites proposed for the origin of the heaviest nuclei, like uranium. We have known for more than 50 years that roughly half the nuclei with mass numbers greater than 100 originate in the r-process. It is a vexing problem that we know the r-process happens, but we do not know *where* it happens. Proposed production sites have centered on astrophysical environments either having abundant free neutrons or where neutrino or nuclear reactions can *mine* neutrons from lighter nuclei. Core collapse supernovae, which happen about once per century in our galaxy, and the much less frequent neutron star mergers are the leading candidate sites. Whatever site or sites contribute, 10 thousand solar masses of r-process nuclei must be synthesized in our galaxy in 10 billion years. That datum, combined with an Advanced LIGO-inferred observed merger rate, could tell us whether mergers are a significant r-process source. If the r-process nuclei originate in neutron star mergers, the observed local rate of these events, combined with abundance observations at high redshift from the next generation of ground-based telescopes, may suggest a higher rate of compact object mergers in the past.

The gravitational waves that Advanced LIGO will observe come from violent motions of matter at nuclear density. As a result, the details of the observed neutron star in-spiral gravitational-wave signal may provide insights into the nature and behavior of ultradense neutron matter and the general conditions in the merger environment. In both mergers and core collapse supernovae, weak interactions, neutrino flavor physics, and neutrino-nucleus processes are key ingredients in understanding r-process nucleosynthesis. Knowing more about the merger environment can help guide this research.



Page 60 of the 2015 Long Range Plan

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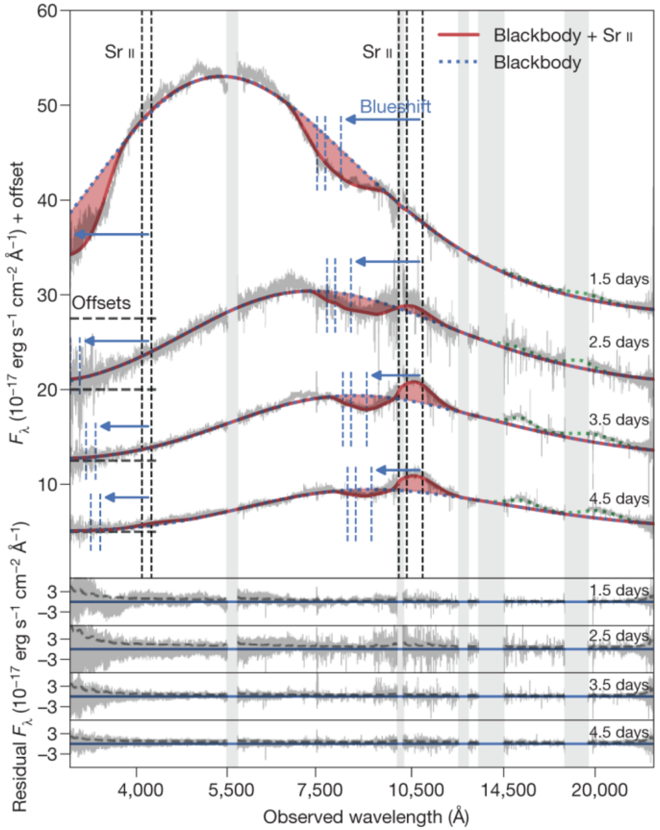
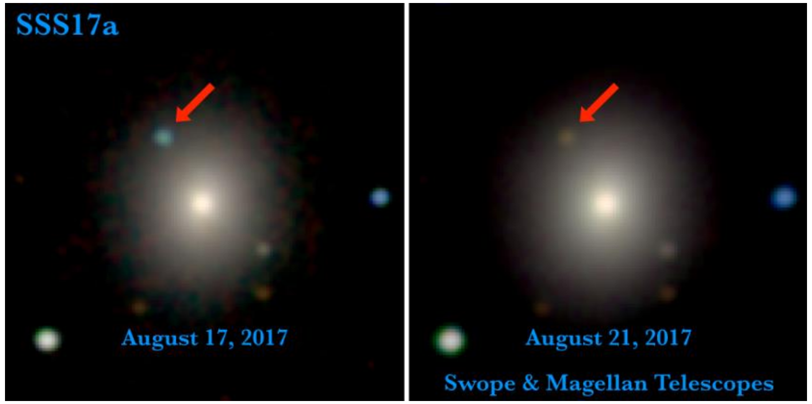
GW170817: Multimessenger observation of an r-process event

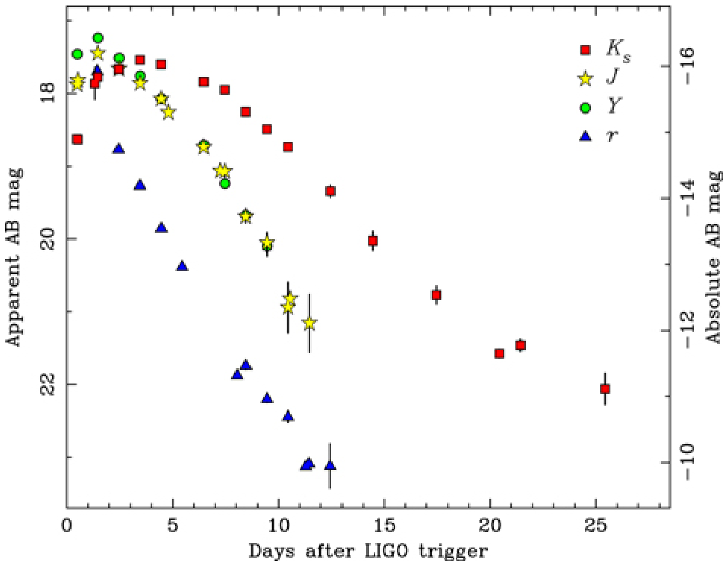
Sr absorption lines in GW170817 kilonova



D. Watson et al, Nature 574, 497 (2019)

Synthesis of Lanthanides and different components in the NS merger ejecta deduced from time evolution of the kilonova light curve



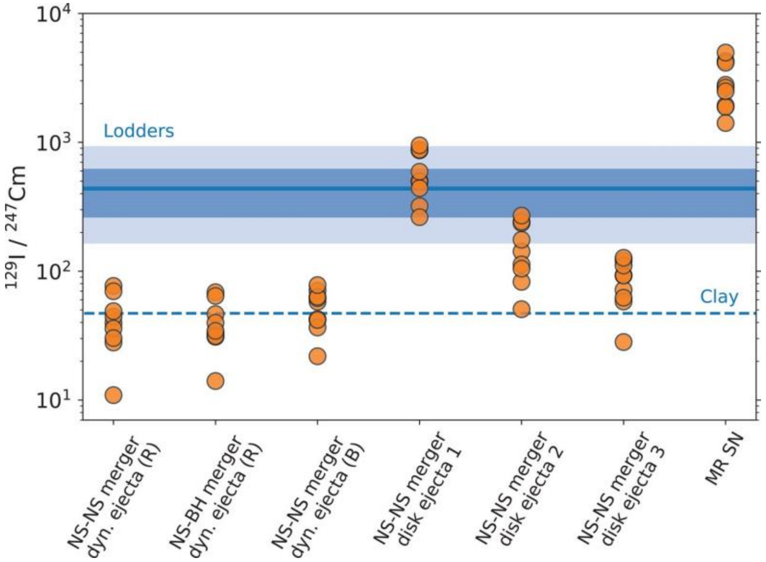


Tanvir et al, ApJ 848, L27 (2017)

We need to reduce the nuclear physics uncertainty in kilonova models for quantities such as decay heat – e.g. Barnes++ ApJ 918 (2021)

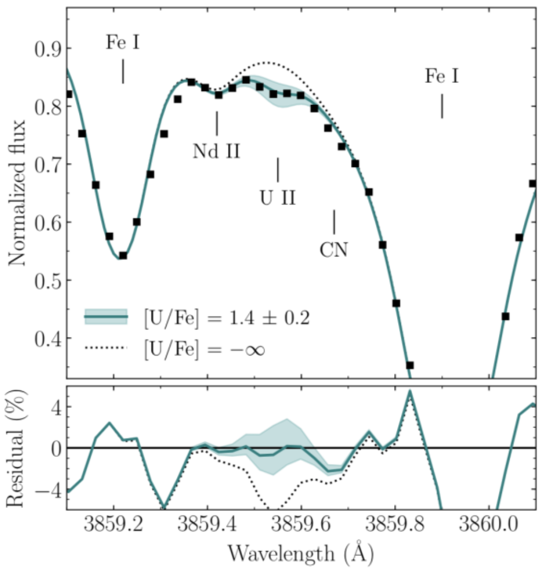
Other notable results

chemical evolution models

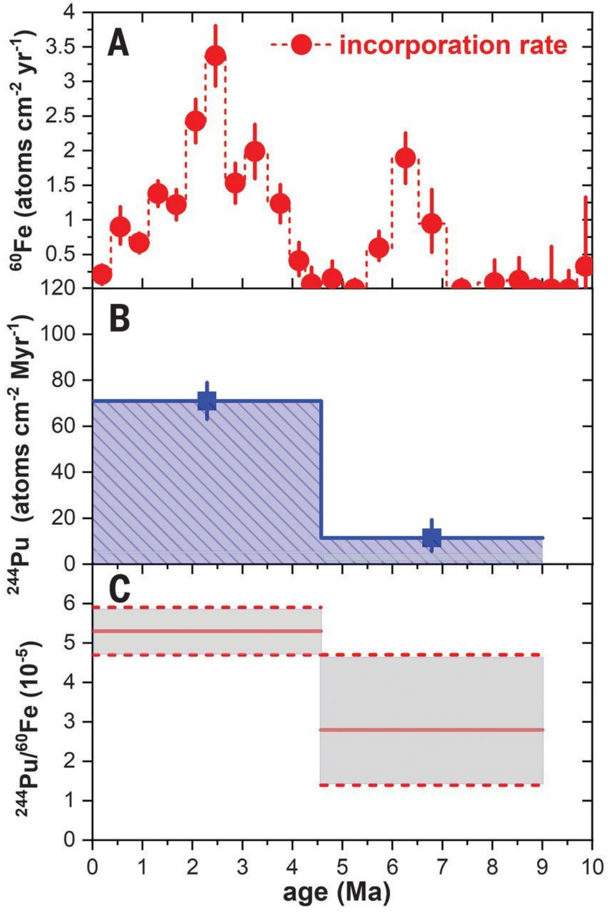


B. Cote et al, Science 371 945-948 (2021)

observation of long-lived actinides

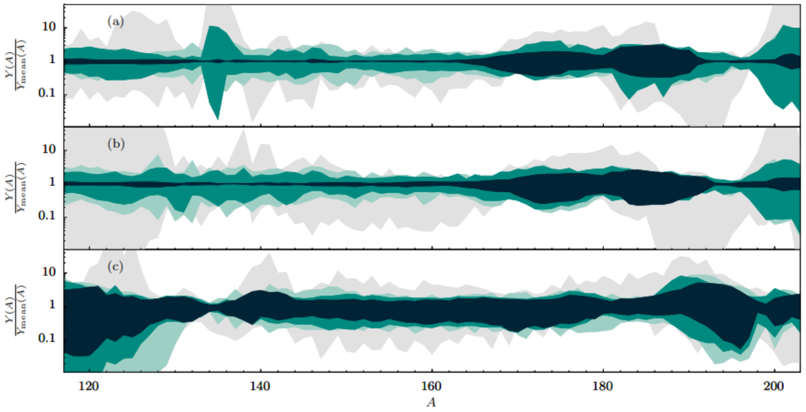


E. Holmbeck et al, ApJ 859, L24 (2018)



Wallner et al, Science 372, 6543 (2021)

propagation of nuclear data uncertainties

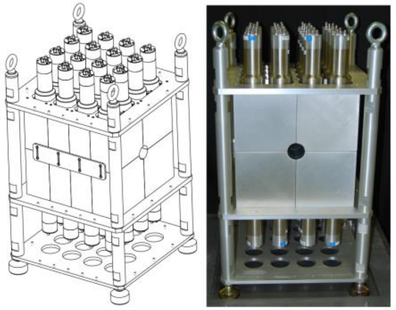


Sprouse et al, Phys. Rev. C 101, 055803 (2020)

Over the past decade we developed a plethora of new experimental tools to measure nuclear properties relevant to nucleosyntesis

measurement devices

HECTOR (TAS detector)

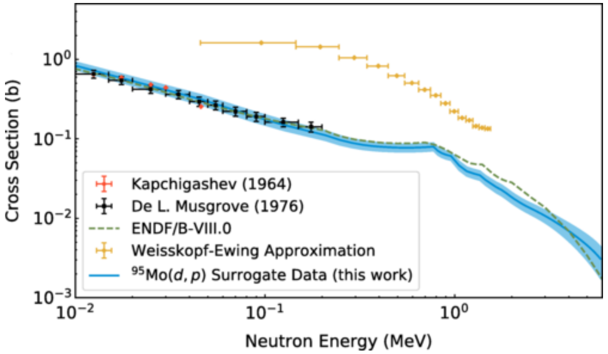


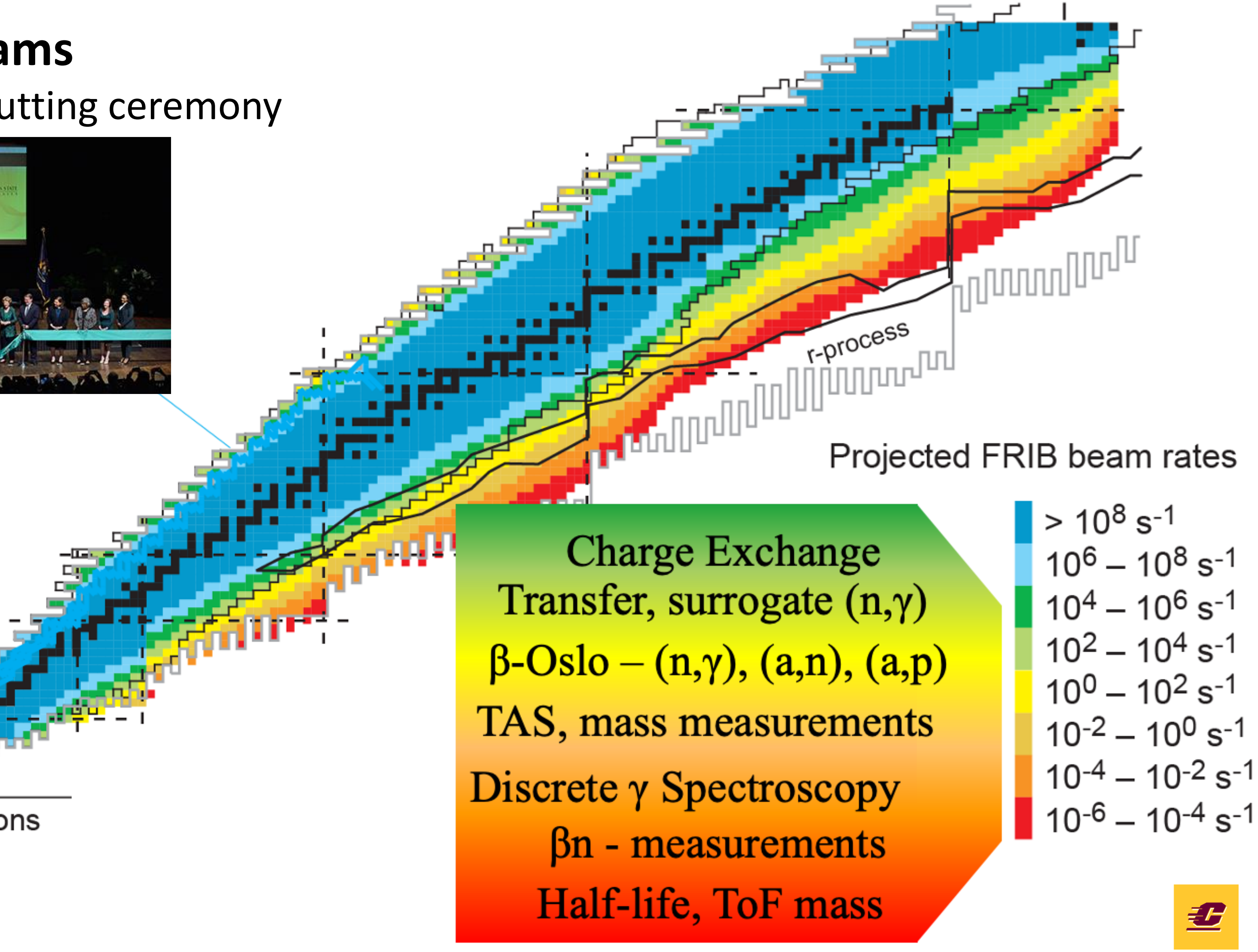
isotope beams

FRIB ribbon-cutting ceremony

experimental techniques

surrogate reactions method





just a few of many examples …

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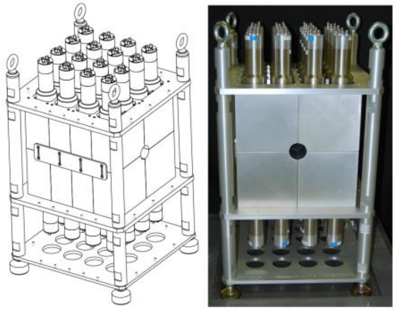

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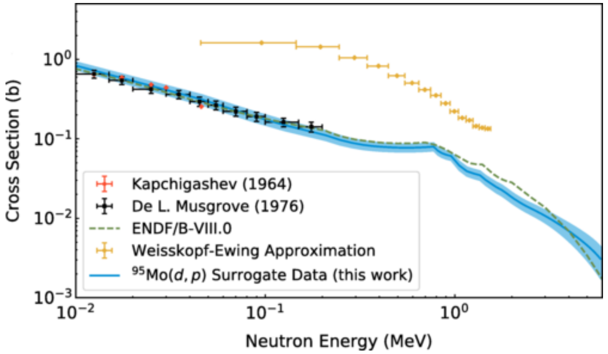
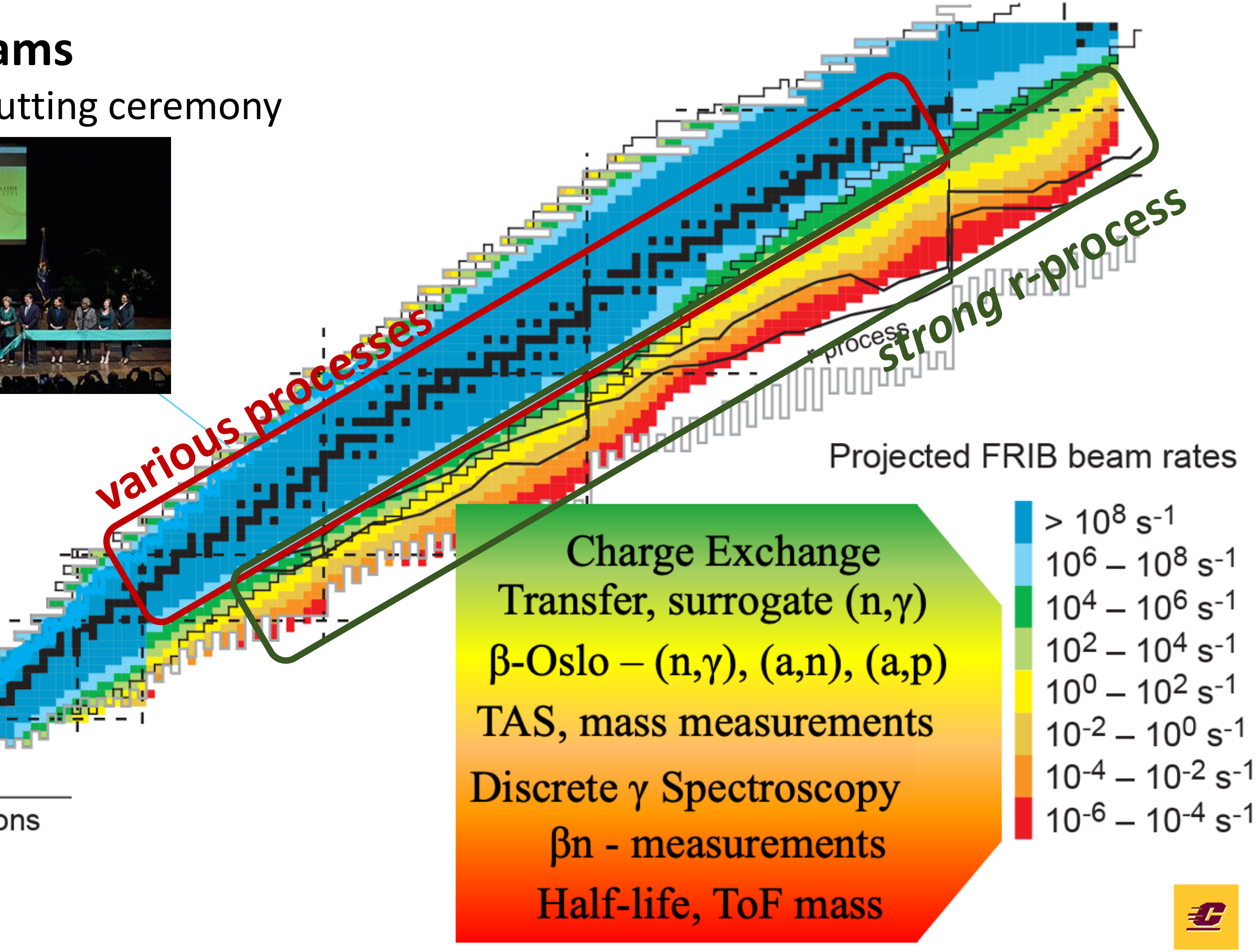


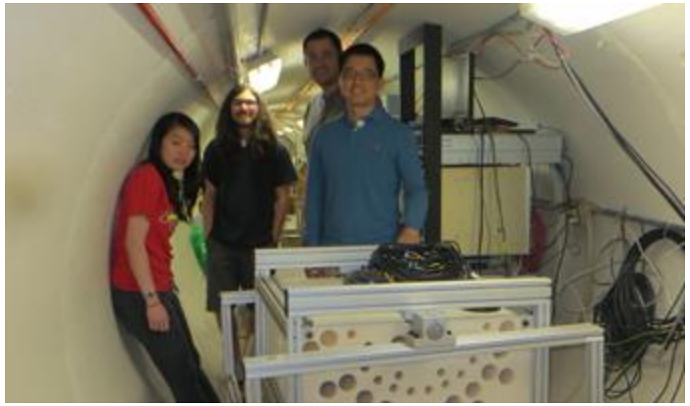


just a few of many examples …

There are clear opportunities to constrain experimentally all (α,n) reactions relevant to *weak* r-process models in the next decade

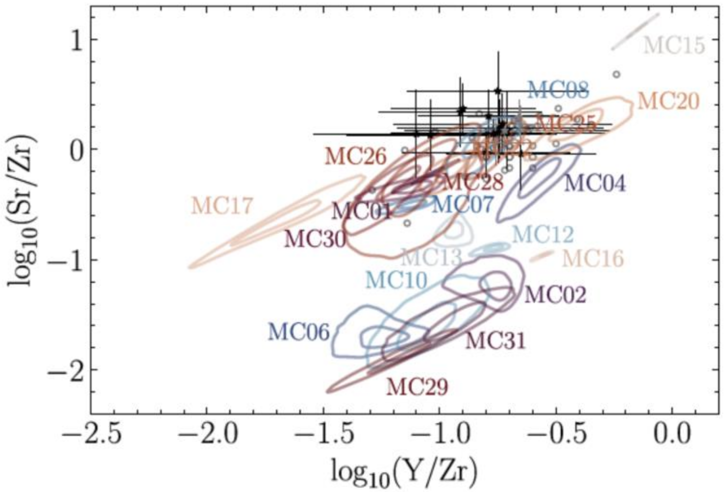
experimental tools:

HabaNERO comissioning at Edwards Lab



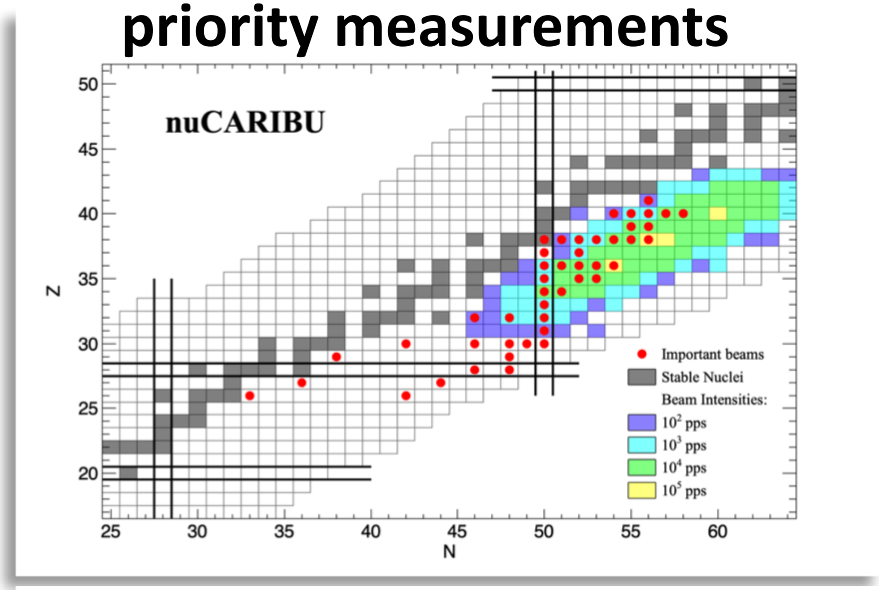
astrophysical significance:

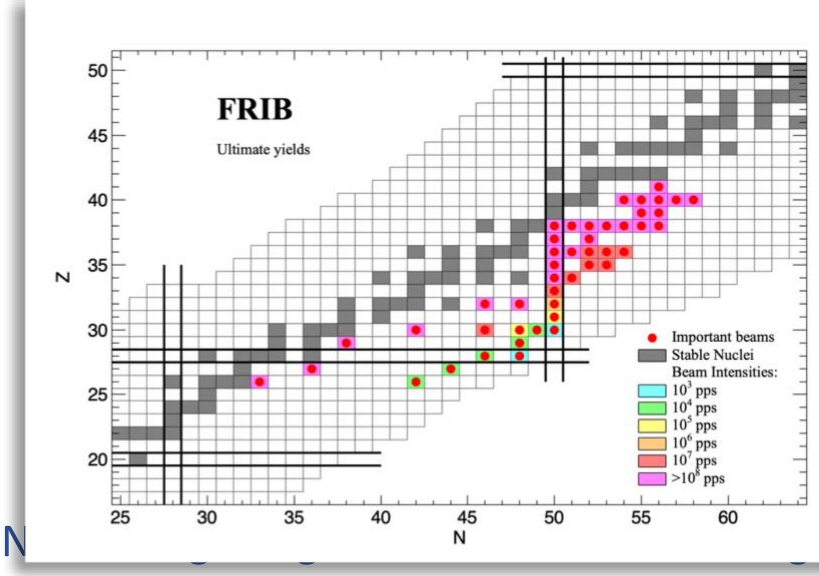
impact in weak r-process yields



Bliss , Arcones, Montes, Pereira PRC (2020)
Psaltis et al. APJ (2022)

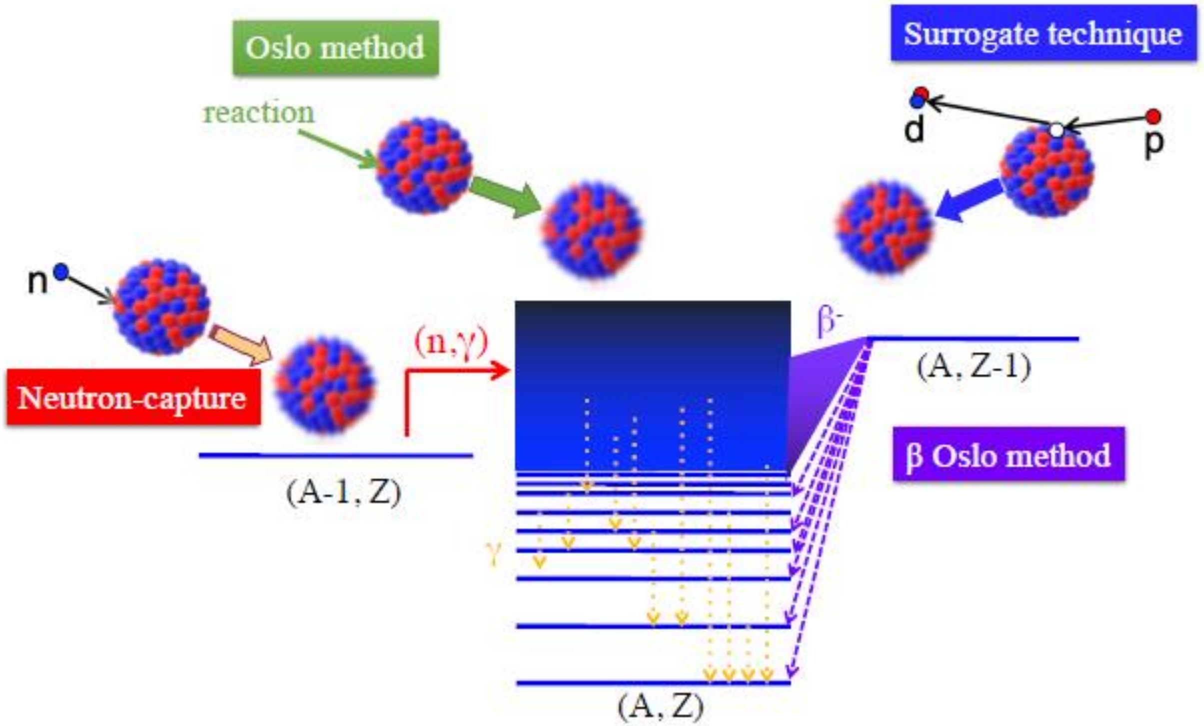
priority measurements





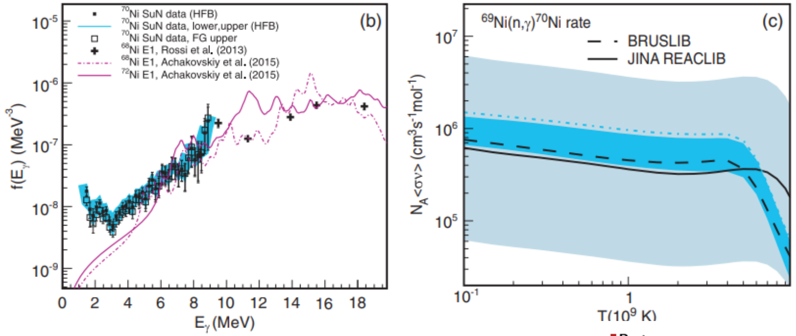
- Complementary techniques: MUSIC, HabaNERO, SECAR, EMMA
- First experiments completed and several proposals accepted
- Relevant measurements possible within 10 years

Constraining neutron capture reactions for nucleosynthesis will require indirect techniques and collaboration with reaction theory

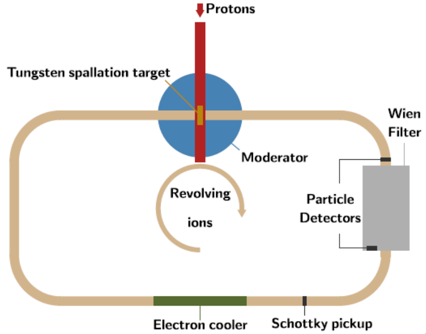


Direct measurements with unstable isotopes are very challenging

β-Oslo measurement for ^{69}Ni(n,γ); Lidick+ 2016



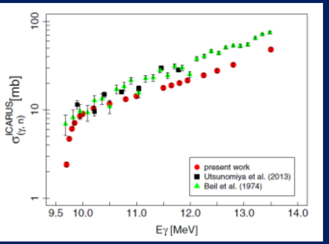
(n,γ) with unstable beams at LANSCE?



see talks: Ratkiewicz, Richard, Mosby …

Fission: theory connection also essential

p-process, νp-process: also direct and indirect measurements, and theory to constrain rates



^{94}Mo(γ,n) at HIgS

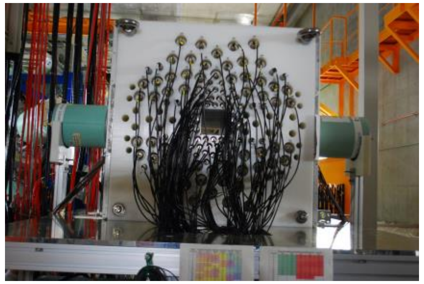
BRIKEN: a campaign of β-decay measurements reaching the r-process path

P_n-values measured with a high efficiency neutron detector at RIBF – large fraction of ^{3}He counters provided by ORNL will be part of FDS at FRIB

facilities

intense beams at RIBF

instrumentation



BRIKEN detector

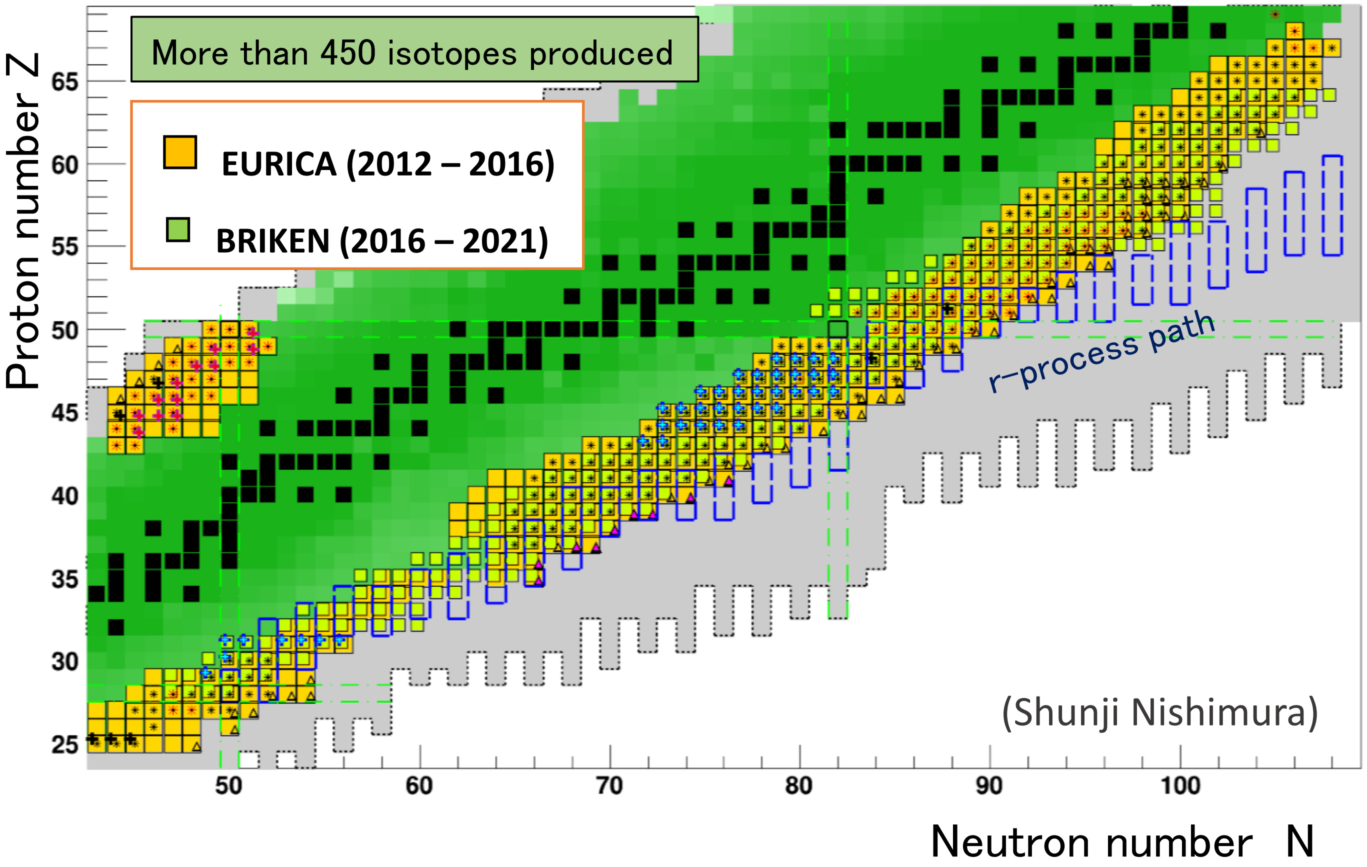
users

15 grad students + 7 postdocs
+ 15 *core* scientists

\+

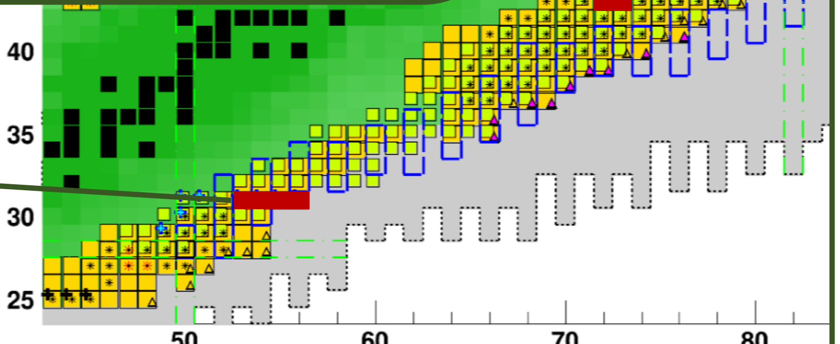
operations

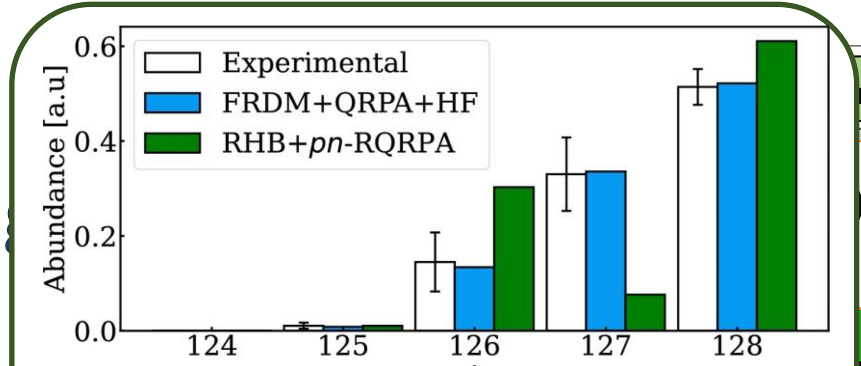
beamtime!



= DATA

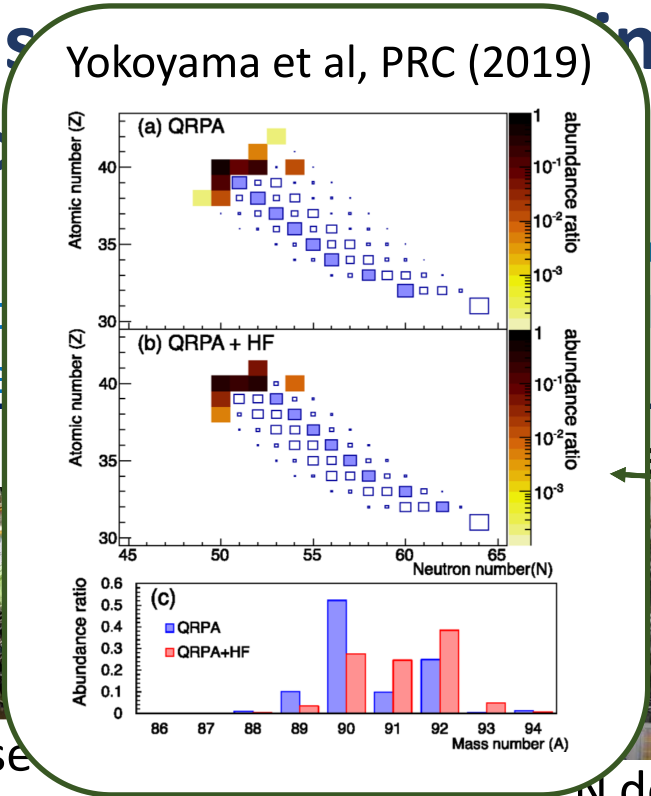
BRIKEN: a campaign of meas... proc...

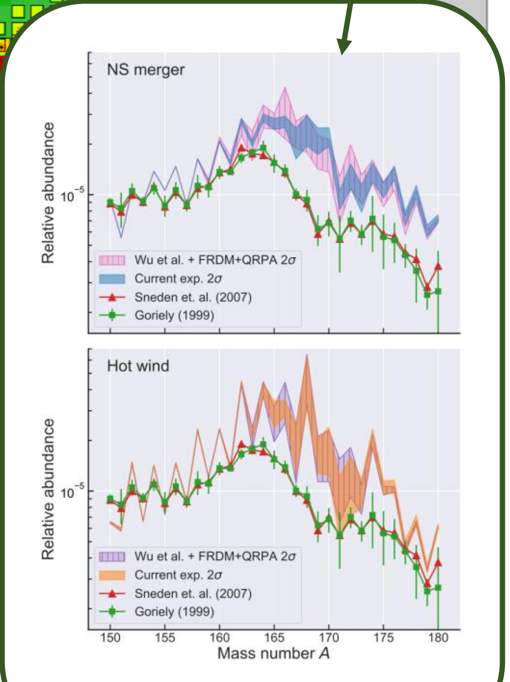




Hall et al, PLB (2021)
Phong et al, PRL (2022)

P_n-valu... e
detecto... e counters
provide... at FRIB





Kiss et al, ApJ (2022)

facil... ...**entation**

intense ...

BRIKEN detector

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= DATA

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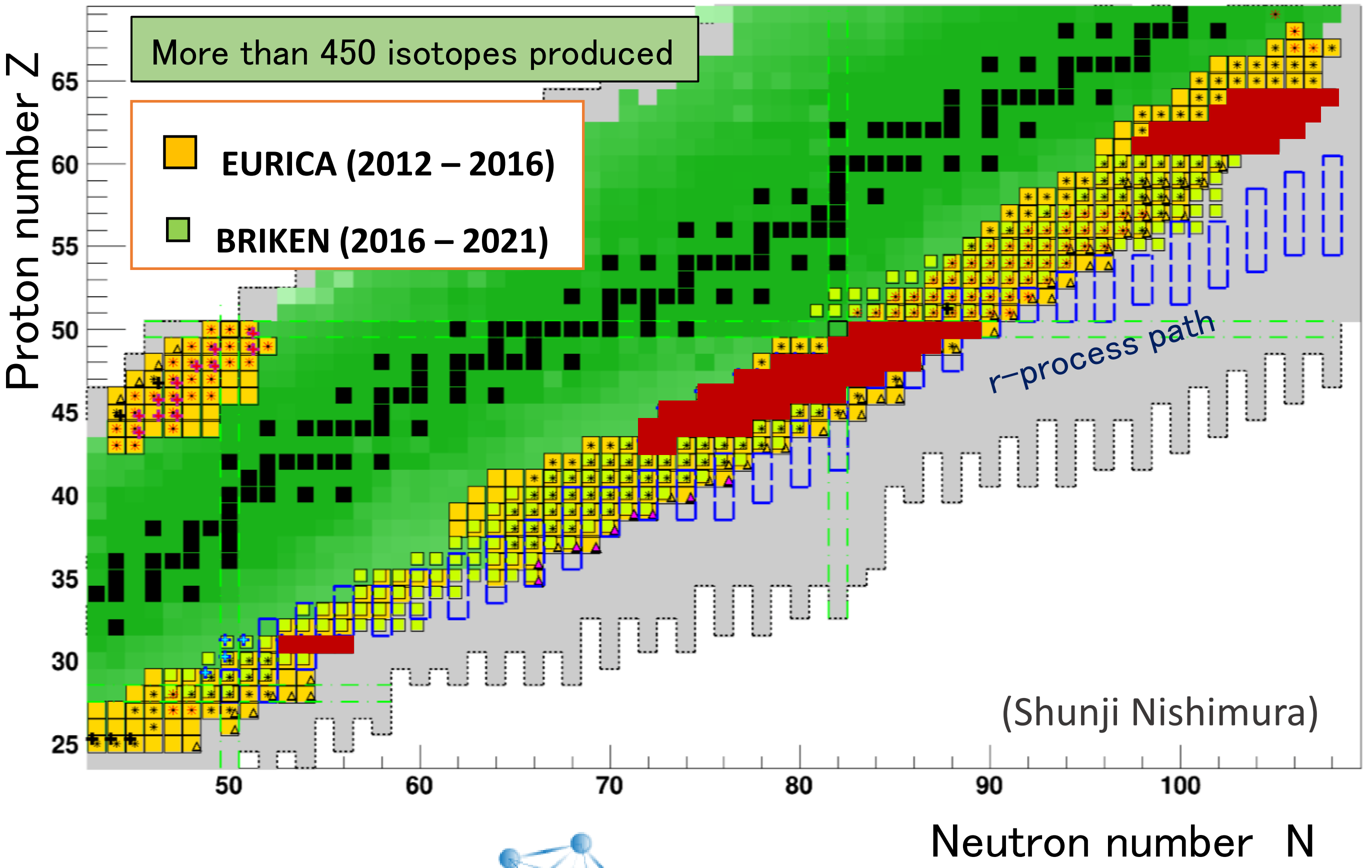

facilities

intense beams at RIBF

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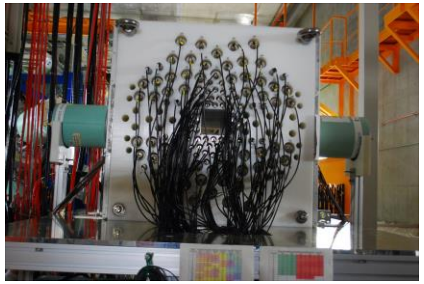
instrumentation



BRIKEN detector

operations

beamtime!

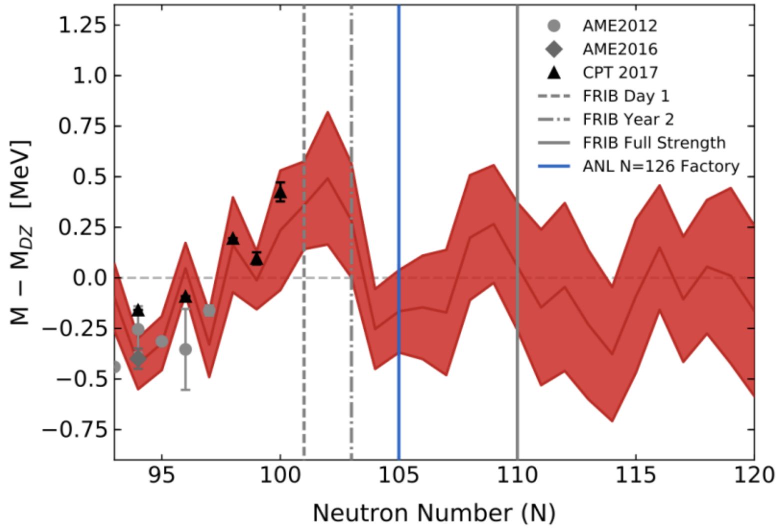
= DATA (speed up)

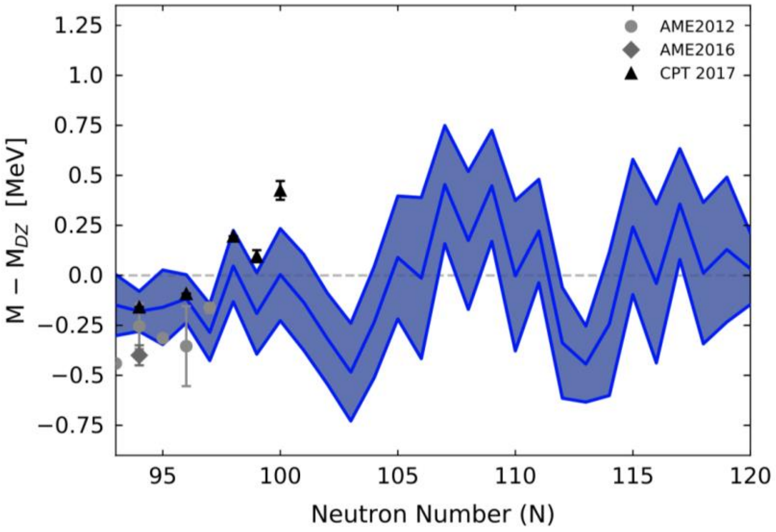
IReNA

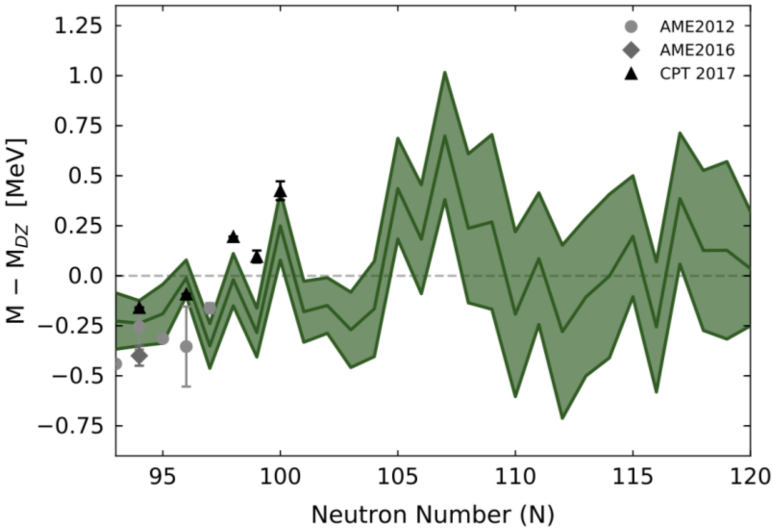
\+ CENTERS = SCIENCE

Reverse engineering the r-process and mass measurements with CPT: an example of an interdisciplinary experimental campaign guided by a specific nucleosynthesis question

Predicted MCMC masses for Nd isotopes for hot outflow (red), cold outflow (blue) and green outflow (green) models

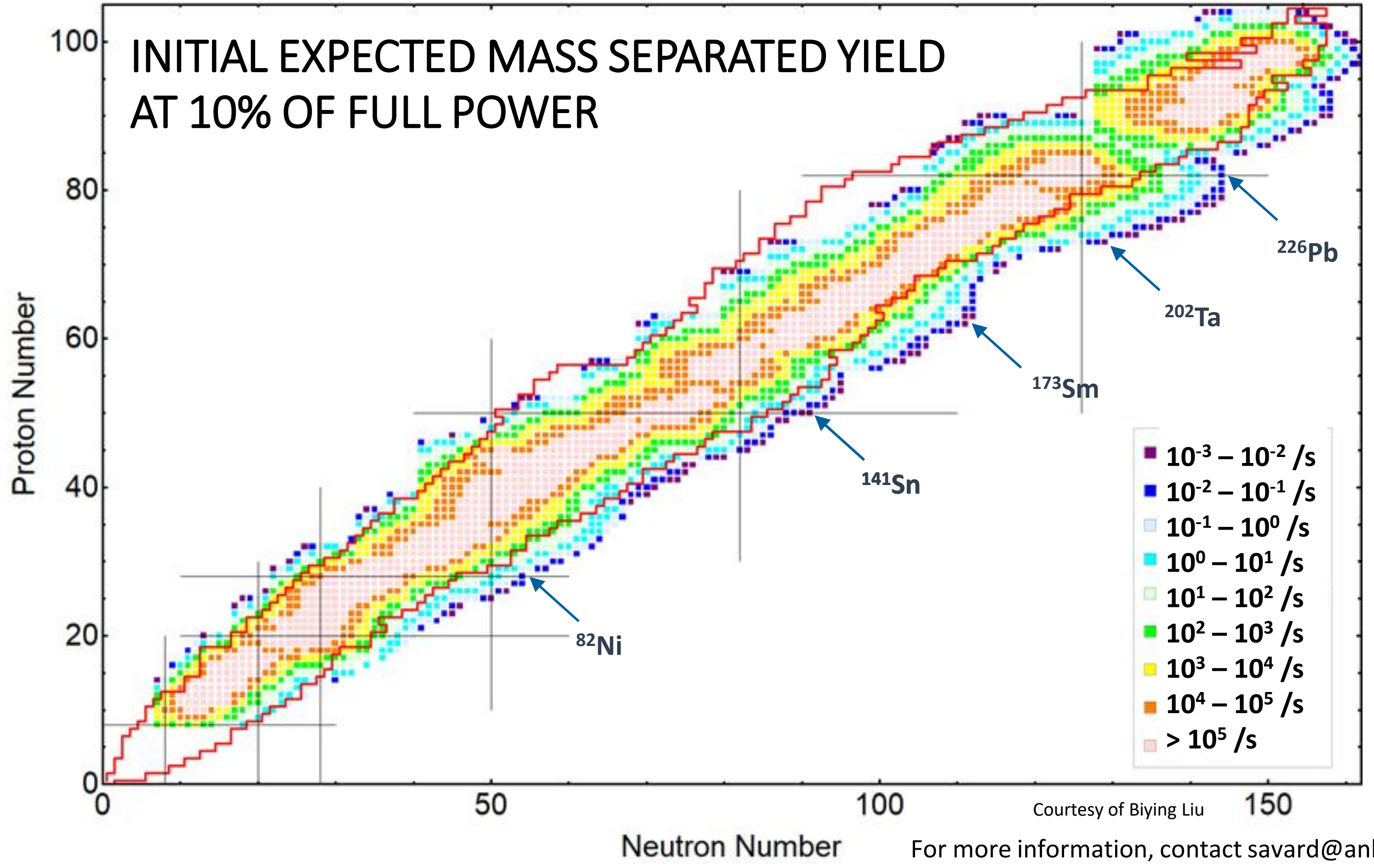






N. Vassh et al, ApJ 907, 98 (2021)
R. Orford et al, Phys. Rev. C 105, L052802 (2022)

N=126 Factory: isotope production by multi-nucleon transfer reactions to expand the program of r-process experiments at ANL



For more information, contact savard@anl.gov

International interest & competition on MNT beams:

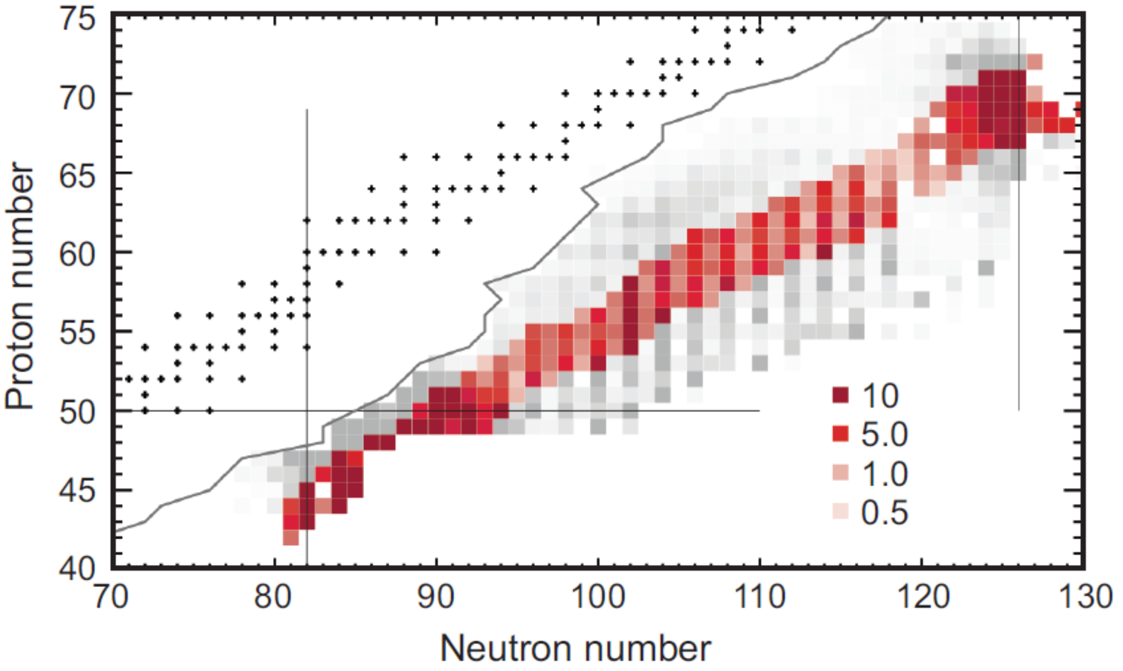
- **IGISOL at JYFL Accelerator Lab**
- **KISS project at RIBF**
- **SHIP at GSI/FAIR**

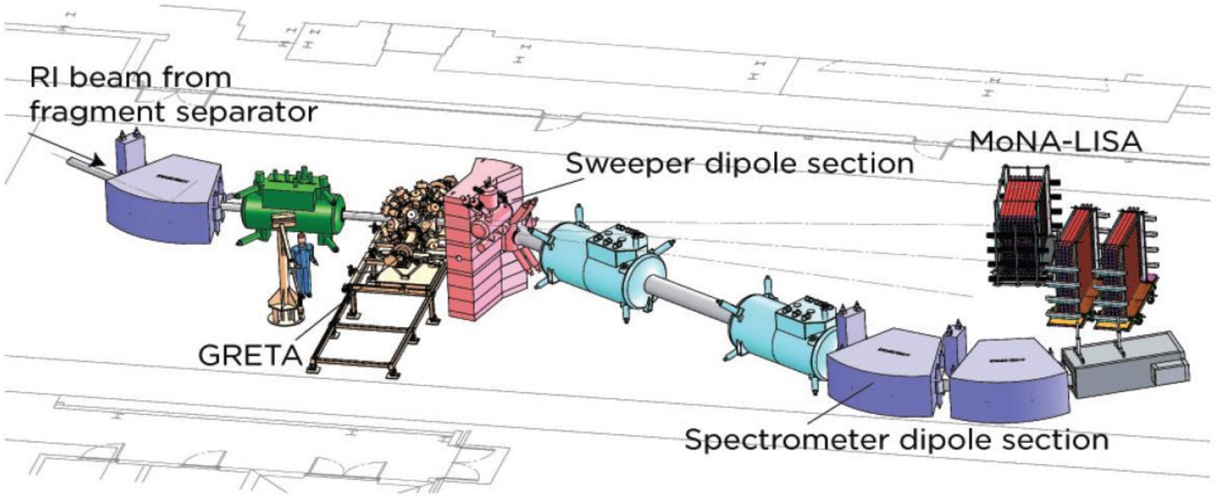
nuCARIBU additional beams for mass and decay experiments. Also mass measurements with LEBIT and TOF-Bρ at FRIB

Tools required to exploit full opportunities for r-process experiments at FRIB

- FRIB Decay Station
- High-Rigidity Spectrometer
- ISLA (e.g. νp-process reactions)
- FRIB 400 MeV/u upgrade

gain of intensities with FRIB 400 MeV/u upgrade





HRS: masses, fission, reactions

Horizons 2020 summary: what do we need?

necessary tools (open list!)		Intnl. competition/collaboration
FRIB nuCARIBU N=126 FRIB400 ReA beams	unstable isotope beams	RIBF ARIEL FAIR ISOL/IGISOL
MUSIC HabaNERO SECAR SOLARIS ISLA	charged particle reactions	EMMA CRYRING
GRETA reaction techniques & theory	nuclear structure and reactions	
HRS	reactions, masses, fission	SAMURAI
HECTOR HIγS	photodisintegration reactions	ATOMKI ESR
FDS	decay properties	DESPEC/RIBF
Penning traps TOF-Bρ	nuclear masses	Traps and MR-TOF Rare-RI Ring
LANSCE+harvesting LANSCE: target+ring	neutron capture rates	Ring at TRIUMF

Interdisciplinary nuclear astrophysics centers

Predictive nuclear theory
Computing resources
Nuclear data

Voice support for relevant astronomy and astrophysics needs: ASTRO2020 decadal surv.

Thank you