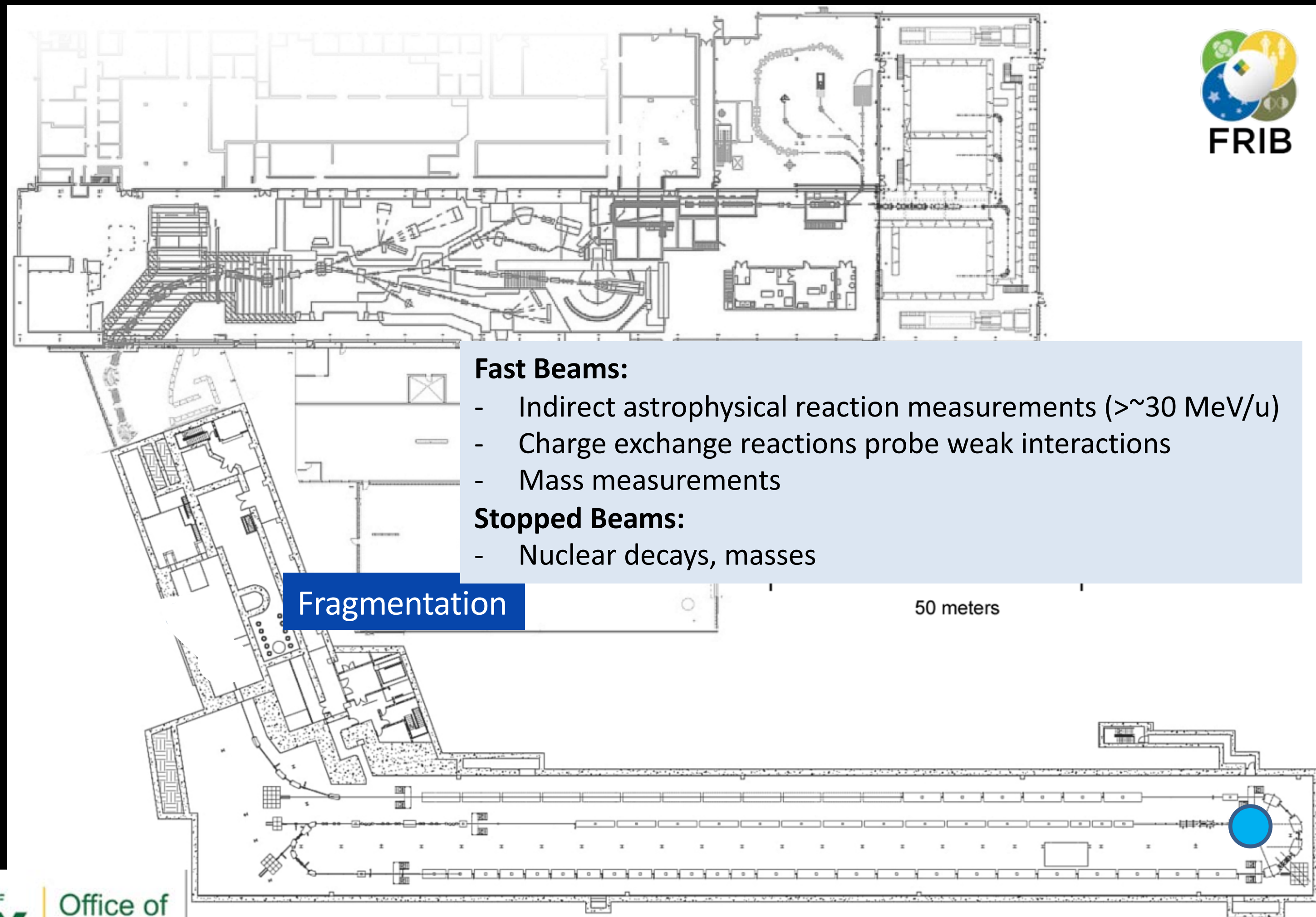
The r-Process and (Some) Other Nuclear Astrophysics at FRIB

Hendrik Schatz
Department of Physics and Astronomy
Facility for Rare Isotope Beams
Center for Nuclear Astrophysics Across Messengers (CeNAM)
Michigan State University

1. r-process
2. Accreting neutron stars
3. Supernovae (short)

National Science Foundation
U.S. DEPARTMENT OF ENERGY | Office of Science

FRIB Offers Broad Opportunities for Nuclear Astrophysics Measurements



Fast Beams:
- Indirect astrophysical reaction measurements (>~30 MeV/u)
- Charge exchange reactions probe weak interactions
- Mass measurements

Stopped Beams:
- Nuclear decays, masses

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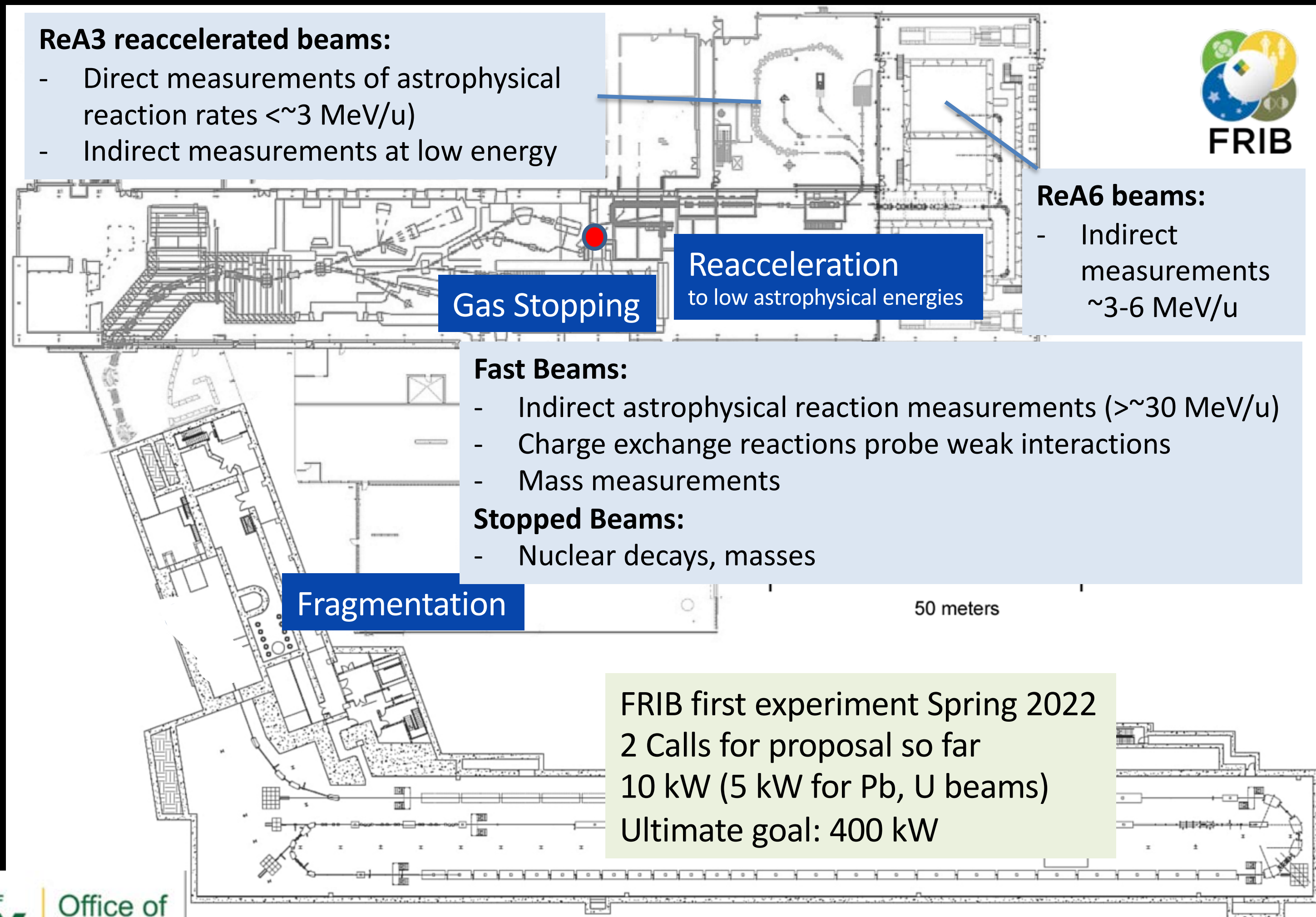
FRIB Offers Broad Opportunities for Nuclear Astrophysics Measurements



ReA3 reaccelerated beams:
- Direct measurements of astrophysical reaction rates <~3 MeV/u)
- Indirect measurements at low energy

ReA6 beams:
- Indirect measurements ~3-6 MeV/u

Fast Beams:
- Indirect astrophysical reaction measurements (>~30 MeV/u)
- Charge exchange reactions probe weak interactions
- Mass measurements

Stopped Beams:
- Nuclear decays, masses

FRIB first experiment Spring 2022
2 Calls for proposal so far
10 kW (5 kW for Pb, U beams)
Ultimate goal: 400 kW

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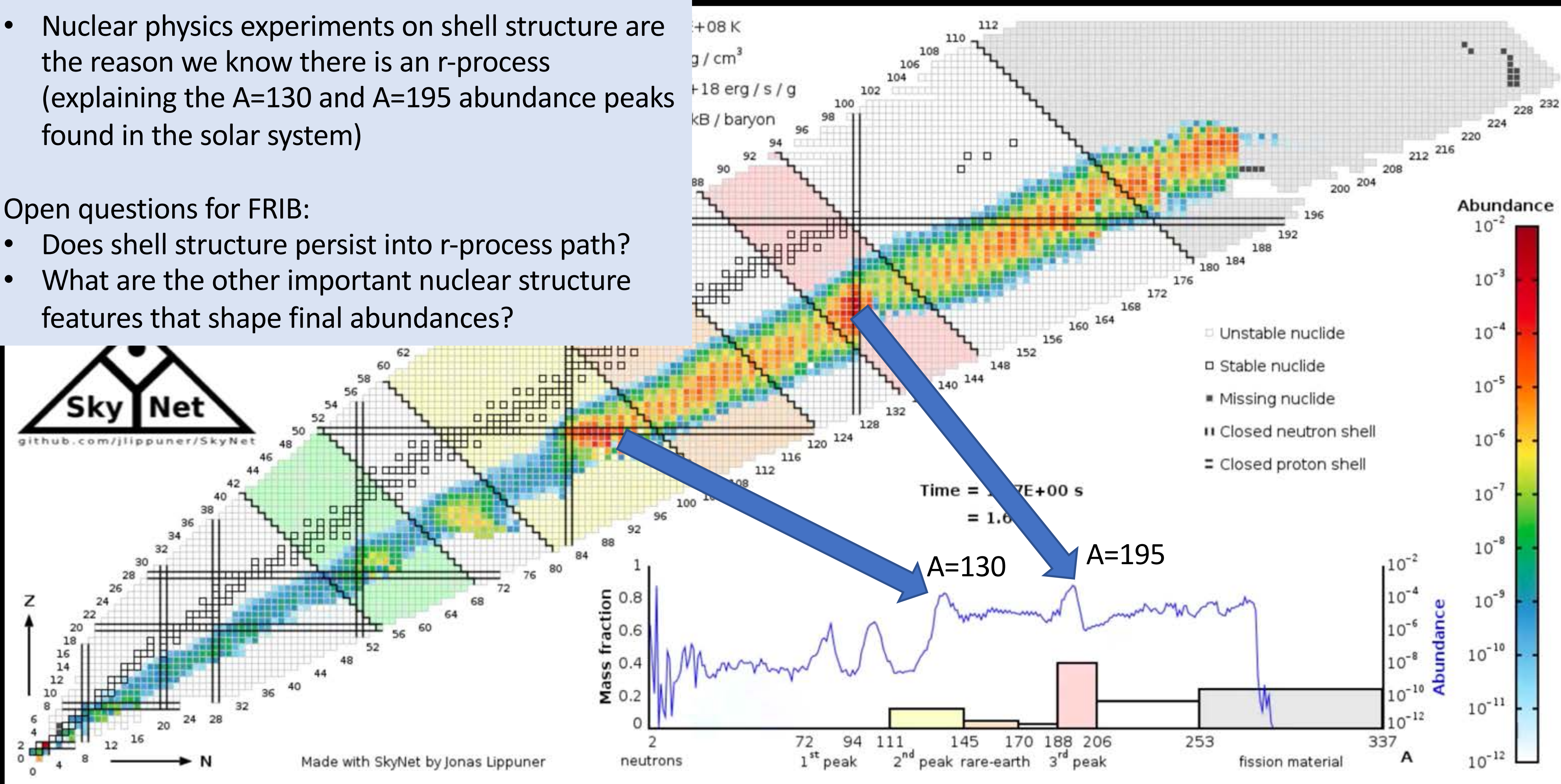
R-Process Involves Extremely Unstable Nuclei

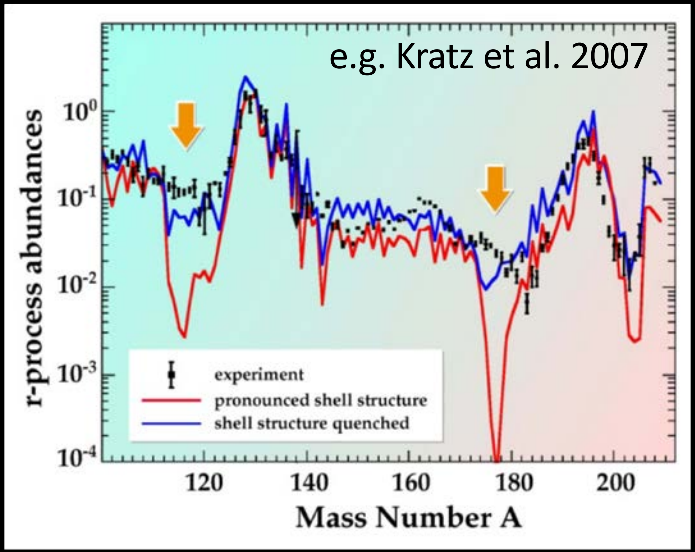
- Nuclear physics experiments on shell structure are the reason we know there is an r-process (explaining the A=130 and A=195 abundance peaks found in the solar system)

Open questions for FRIB:
- Does shell structure persist into r-process path?
- What are the other important nuclear structure features that shape final abundances?

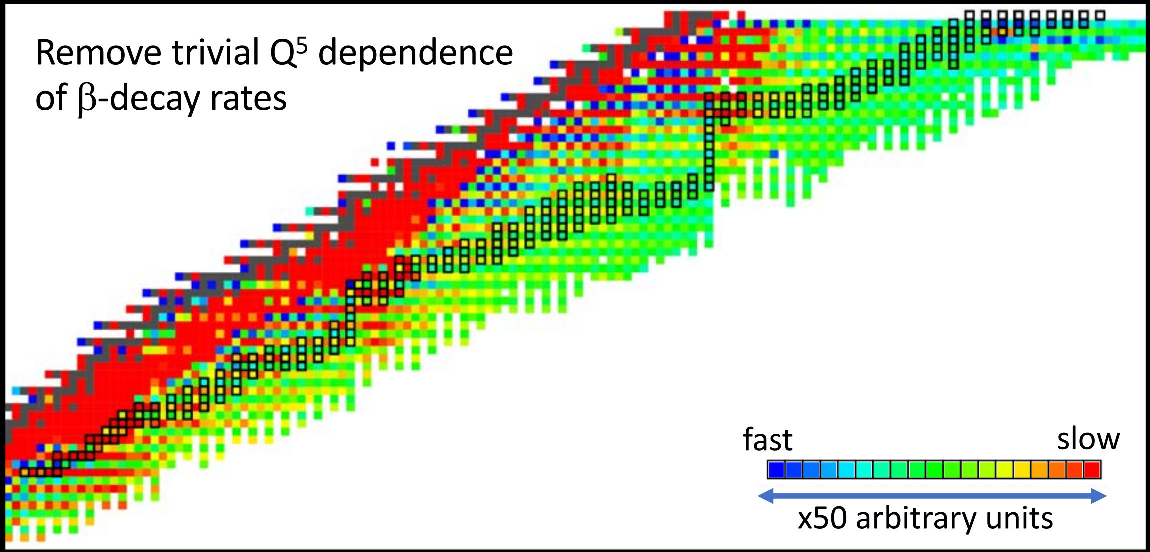


Nuclear Physics is the DNA of the Cosmos[1]

Shell gap sizes affect the composition of the universe



Example for the nuclear structure patterns underlying β-decay half-lives→ this is what needs to be understood



→ Understanding the origin of the elements means understanding nuclear structure far from stability and how it links to the composition of the cosmos

→ This needs to be mapped out experimentally

[1] Stan Woosley

Experiments are Needed to Interpret Kilonova Observations

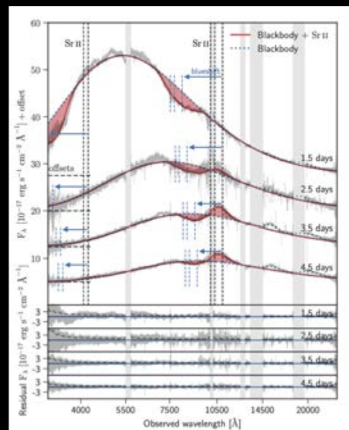
GW170817 Trigger

Blue

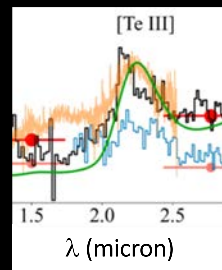
Red
→ Atomic opacity
→ Nuclear composition

ESO/N.R. Tanvir, A.J. Levan
and the VIN-ROUGE collaboration

Line features

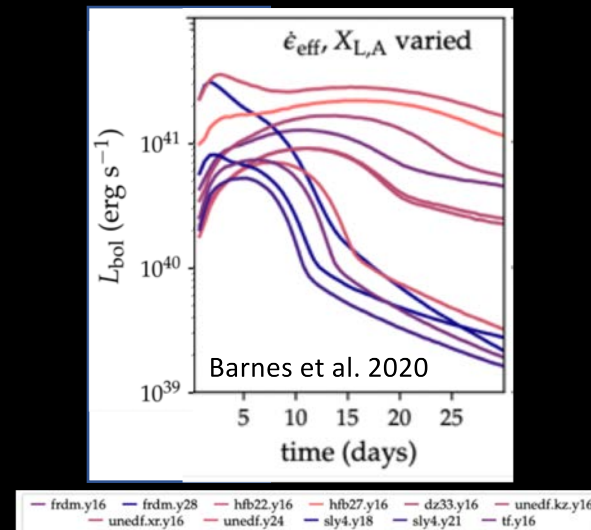


Sr feature: Watson et al. 2019
Or He? (Perego et al. 2022)



Levan et. al.
JWST detection of Te

Light curves depend on nuclear physics



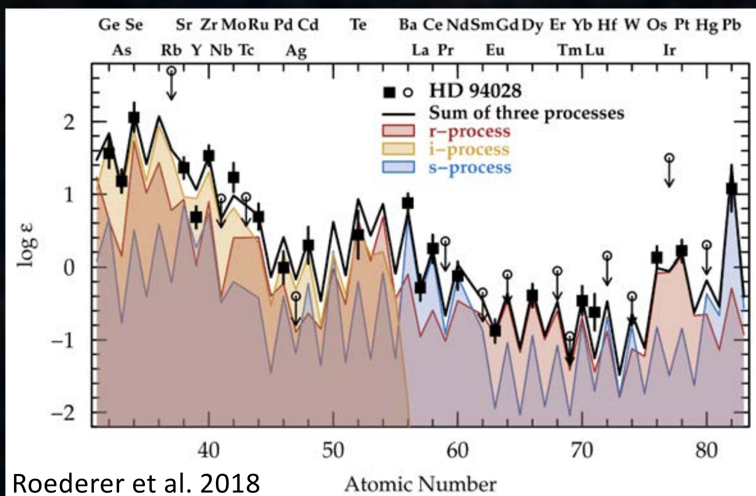
Key question:
What elements and isotopes are made in neutron star mergers?
→ Need nuclear physics to “fit” astrophysical parameters to observations
→ With astrophysical conditions constrained, need nuclear physics to “Interpolate” sparse observations and obtain the complete abundance pattern

R-Process Experiments are Needed to Interpret r-Process Signatures in Metal poor stars

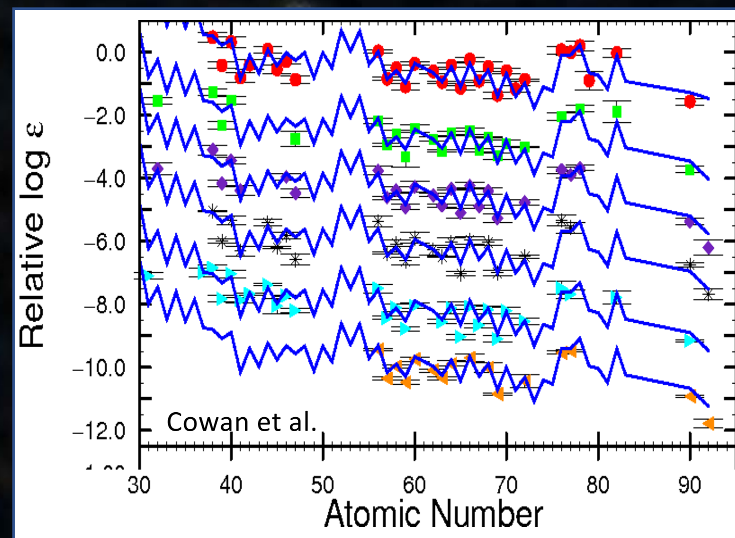
FRIB

CeNAM

Multi-event patterns



Strongly enhanced r-process stars



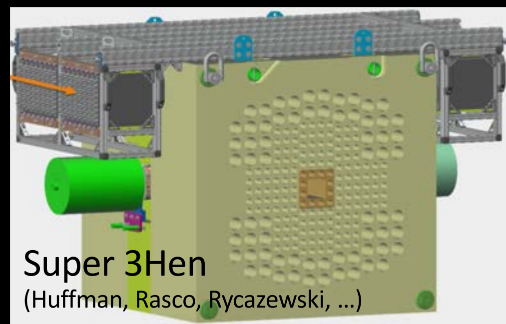
Nuclear physics needed to predict contribution patterns from each process
→ can then disentangle individual components

- Need nuclear physics to fit models to observations to constrain astrophysical parameters
- May also have to disentangle multiple components (NS mergers, MHD supernovae, Collapsars – e.g. Yamazaki et al. 2023)
- Once that fits, need nuclear physics to determine isotopic abundance contributions

Much of r-Process Nuclear Physics Within Reach at FRIB

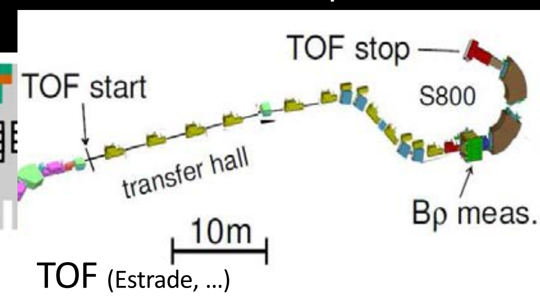
β-decay Half-lives, levels

Decay branchings for n-emission

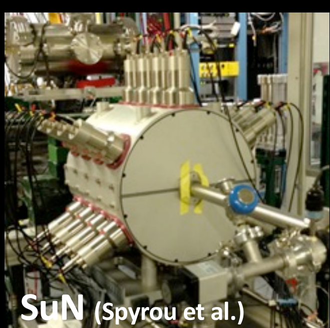


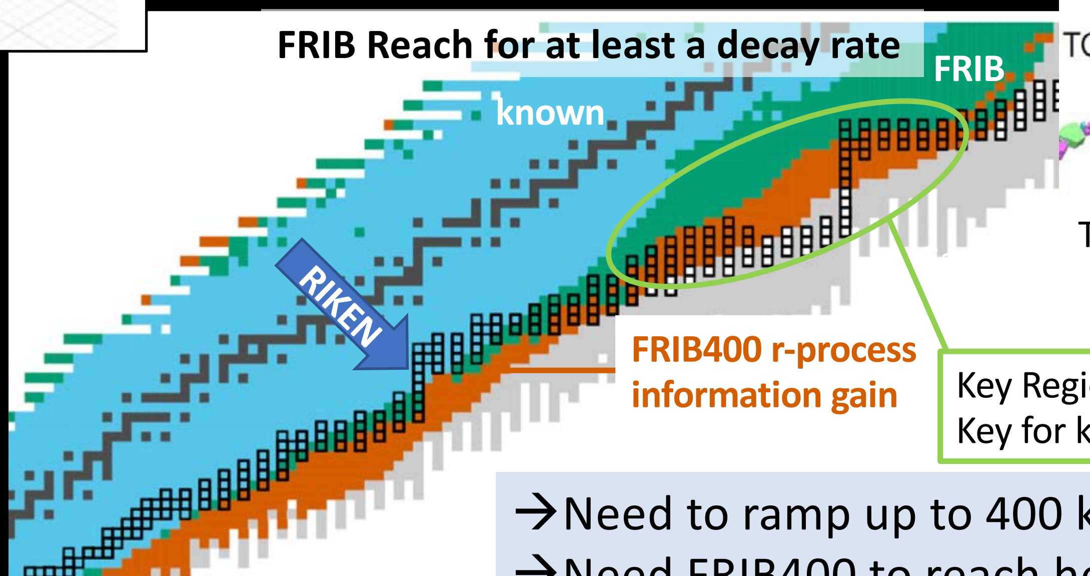
Masses ~10^{-8} precision

Masses ~10^{-6} precision



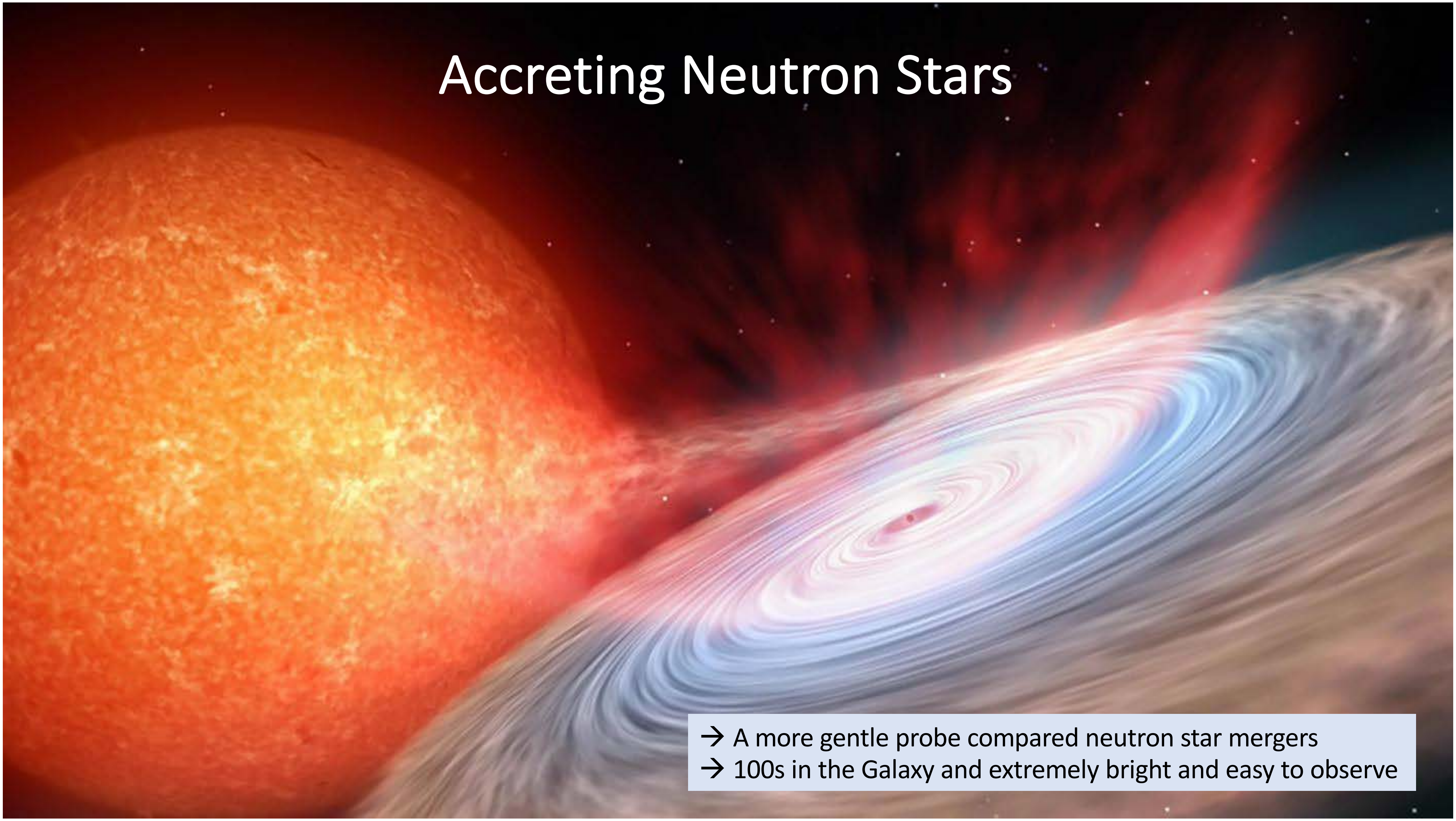
n-capture rates (indirect)
β-Oslo method



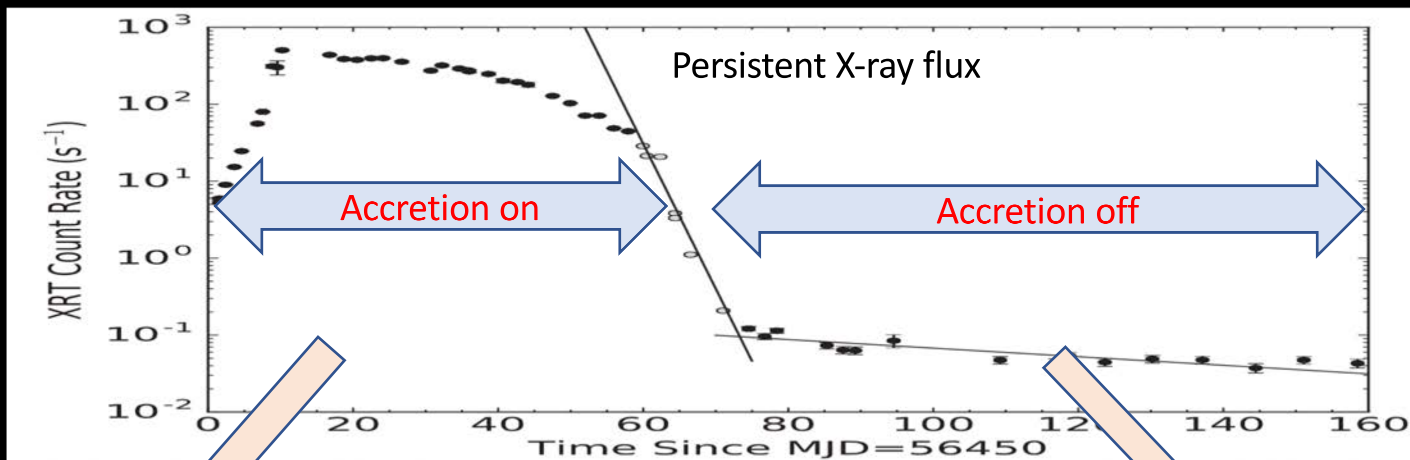


Key Region: Gateway to heavier nuclei
Key for kilonovae

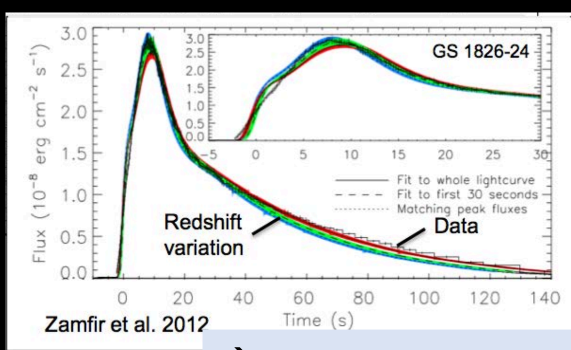
→Need to ramp up to 400 kW
→Need FRIB400 to reach heavy r-process region


Accreting Neutron Stars
→ A more gentle probe compared neutron star mergers
→ 100s in the Galaxy and extremely bright and easy to observe

Quasi Persistent Transients Probe Neutron Star Physics



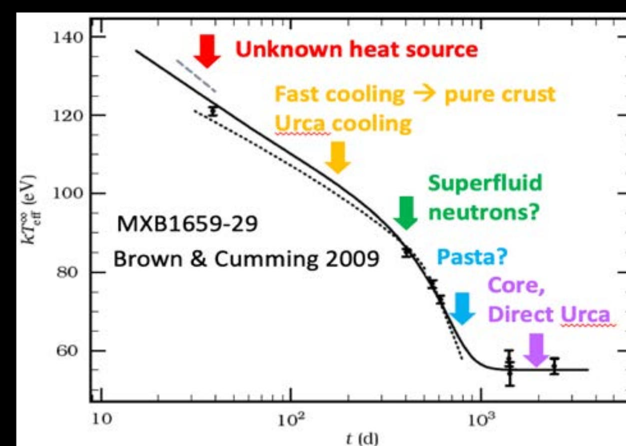
X-ray bursts – on top of persistent flux



→ NS compactness, EOS

Both observables are powered by rare isotope physics

Crust cooling



X-ray Bursts Powered by the rp-Process

Notre Dame /ORNL/ LSU/MSU led

Recoil Separator
→ Direct reaction measurements

ORNL/CSM/MSU led

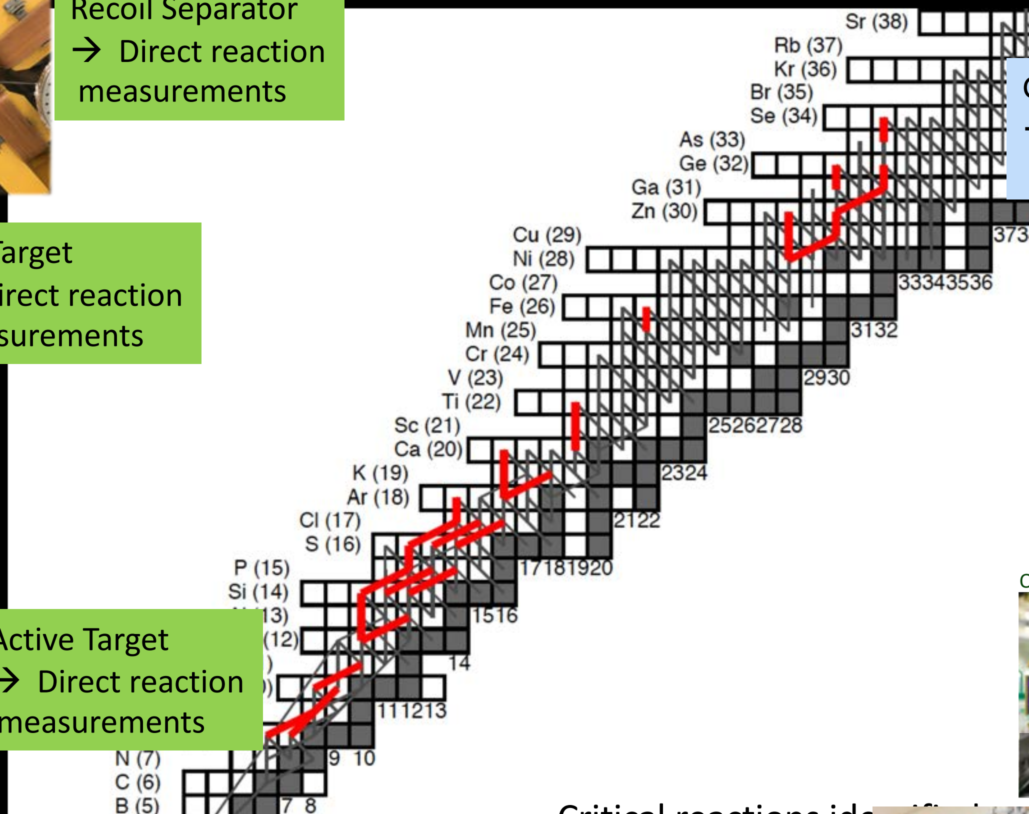
Gas Target
→ Direct reaction measurements

ANL/MSU led

Active Target
→ Direct reaction measurements

MSU led (Wrede)

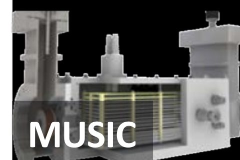
Decay particle spectroscopy for indirect reaction studies



Critical reactions ide
(here for light curve
Cyburt et al. 2016

Ge γ-detector Array
→ Indirect reaction measurements

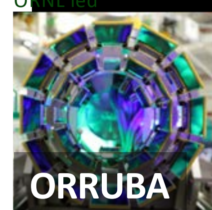
LBNL/ANL/FSU/MSU/ORNL led



ANL led

MUSIC
→ Direct reaction measurements

ORNL led



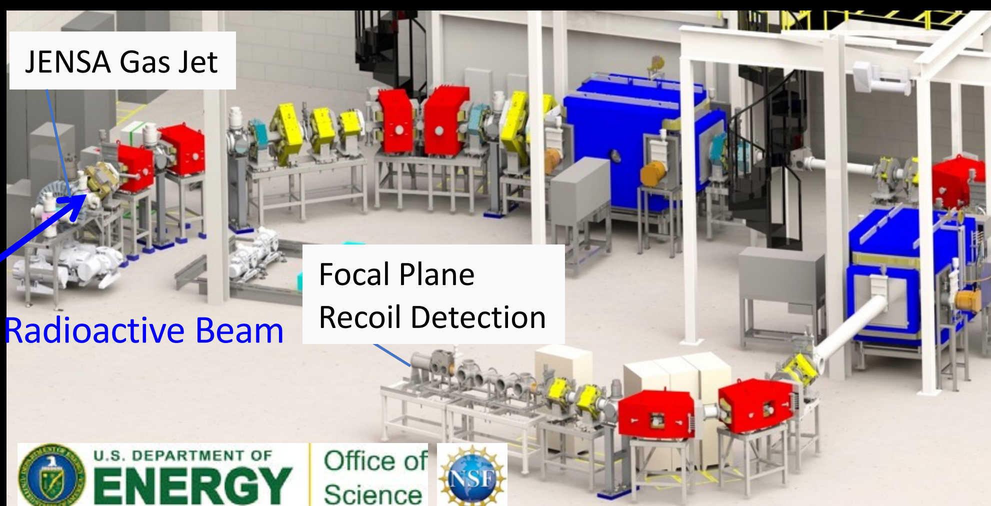
Si-Detector Array
→ Direct/Indirect reaction measurements

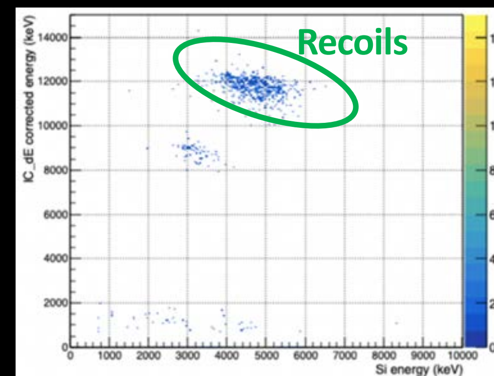
Neutron Detector
→ (d,n) Indirect reaction measurements

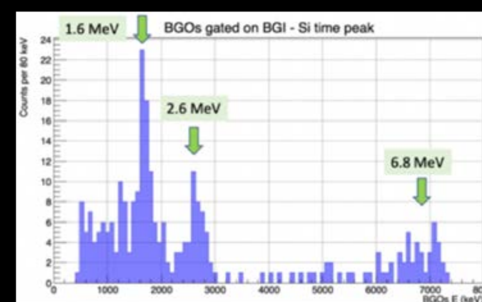
MSU led (Zegers)

SECAR Recoil Separator Enables Direct p-Capture Rate Measurements at FRIB

Lead
G. Berg, M. Couder, Notre Dame
(Design based on St. George)
F. Montes, H. Schatz, MSU
J. Blackmon, LSU
K. Chipps, M. Smith, ORNL
U. Greife, CSM



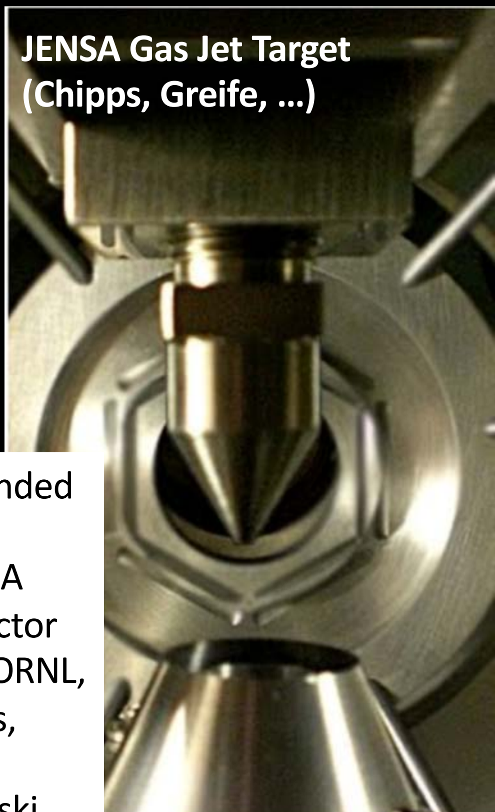




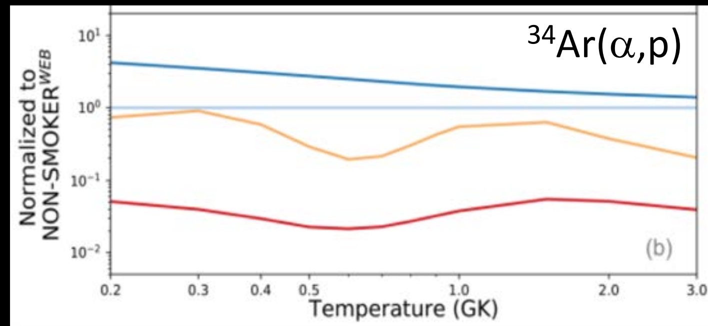
First recoil detection from $^{16}O(\alpha,\gamma)^{20}Ne$ concludes construction
→ Scientific commissioning ongoing

(α,p) Reaction Rate Measurements with JENSA and ORRUBA Using Low Energy Reaccelerated Radioactive Beams at NSCL

Open questions concerning these types of rates (Long et al. 2017)



Surrounded with ORRUBA Si detector array (ORNL, Rutgers, Pain, Ciezewski, …)



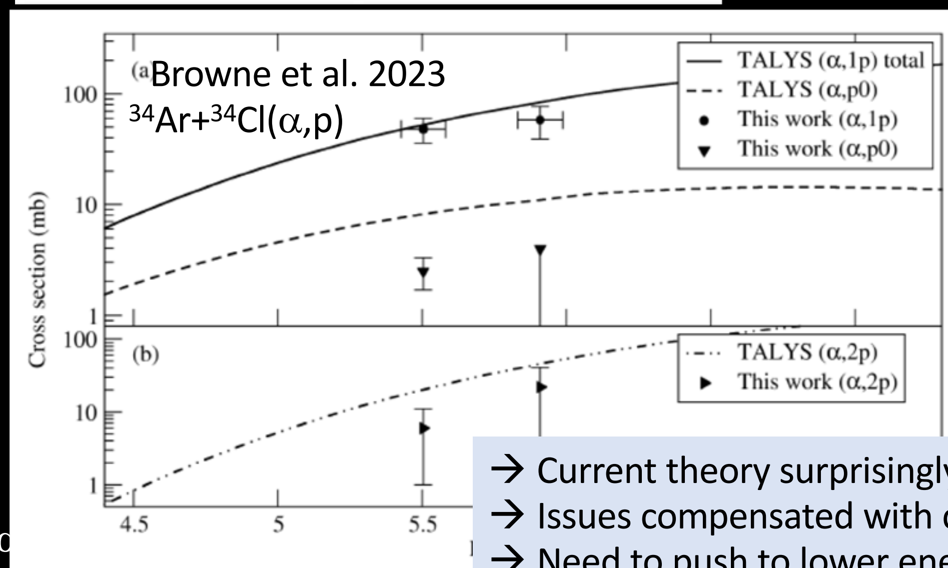
Theory

Clustering enhancement

Estimate from ^{40}Ca(p,t) levels

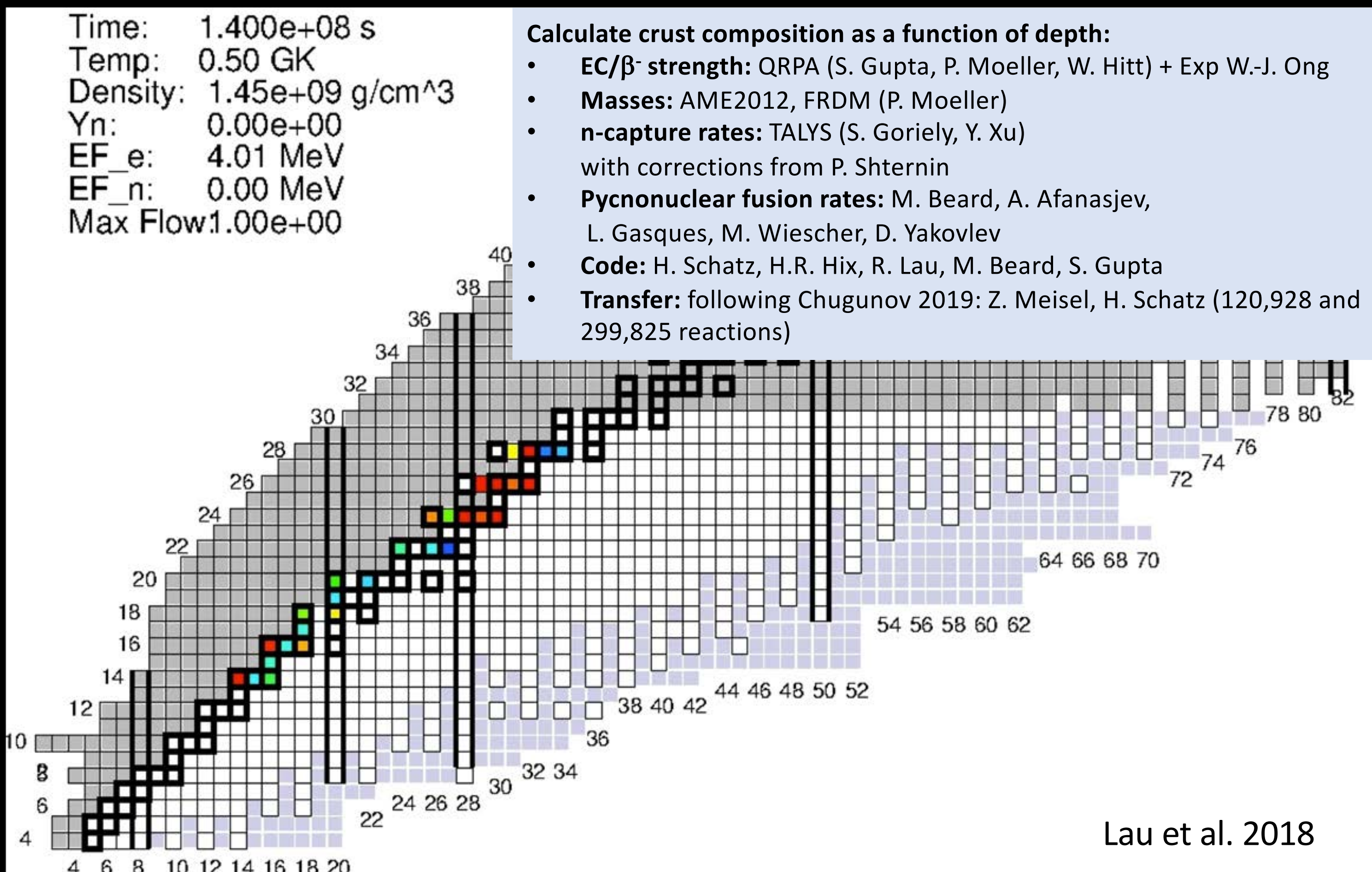
Long et al. @ indirect ^{40}Ca(p,t)

^{34}Ar(α



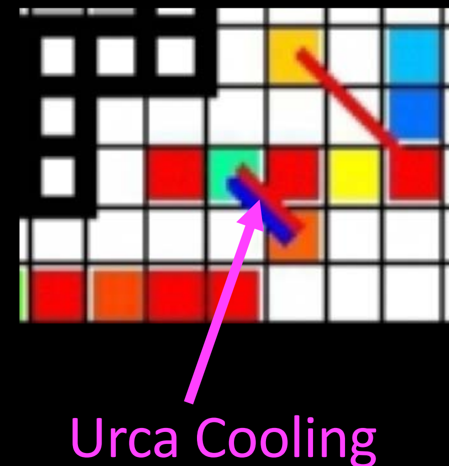
→ Current theory surprisingly good
→ Issues compensated with cluster effects?
→ Need to push to lower energies

Reactions Heating (and Cooling !) the Crust During Accretion Identified



Calculate crust composition as a function of depth:

- **EC/β⁻ strength:** QRPA (S. Gupta, P. Moeller, W. Hitt) + Exp W.-J. Ong
- **Masses:** AME2012, FRDM (P. Moeller)
- **n-capture rates:** TALYS (S. Goriely, Y. Xu) with corrections from P. Shternin
- **Pycnonuclear fusion rates:** M. Beard, A. Afanasjev, L. Gasques, M. Wiescher, D. Yakovlev
- **Code:** H. Schatz, H.R. Hix, R. Lau, M. Beard, S. Gupta
- **Transfer:** following Chugunov 2019: Z. Meisel, H. Schatz (120,928 and 299,825 reactions)



For gs-gs electron capture inverse β-decay is not completely Pauli blocked
→ EC and β-decay Rapidly alternate
(Schatz et al. 2014)

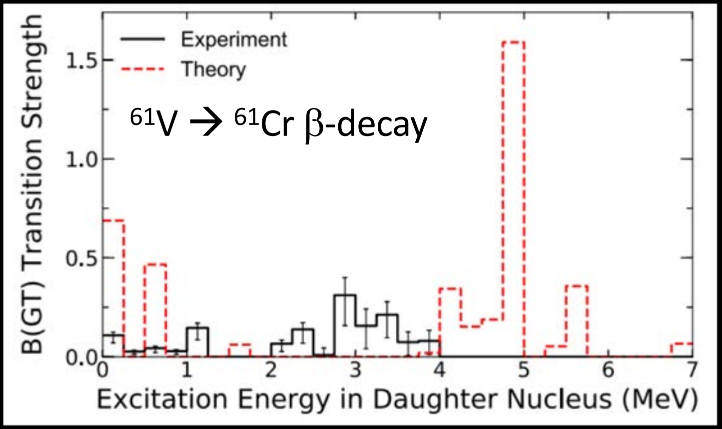
Urca Cooling from A=61 Nuclei Weaker than Expected

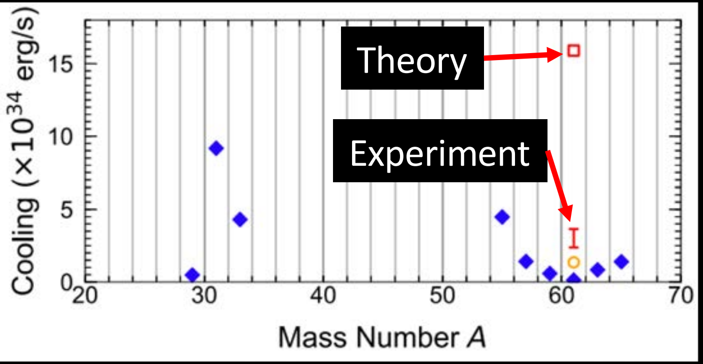
Measure all γ-branches with SuN Total Absorption Spectrometer

Measure all n-branches with NERO

→ Unobserved decays are gs branch

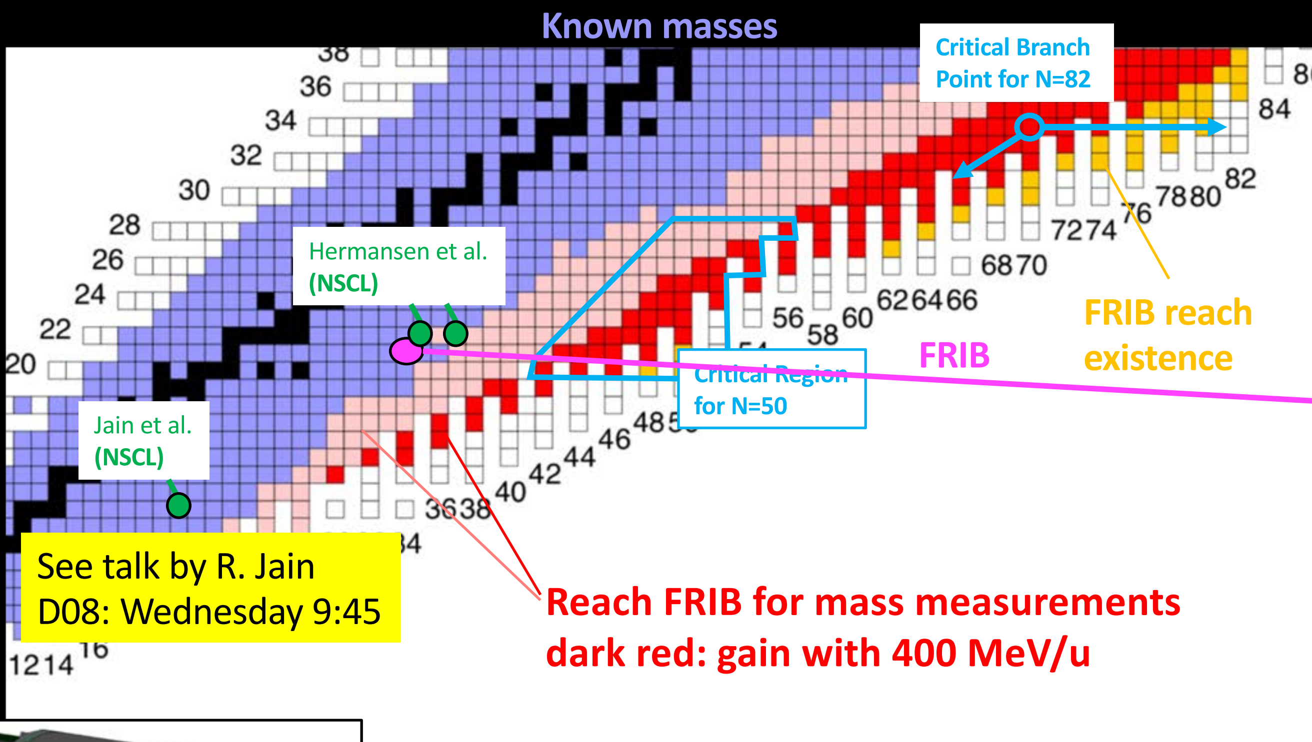
Ong et al. 2020



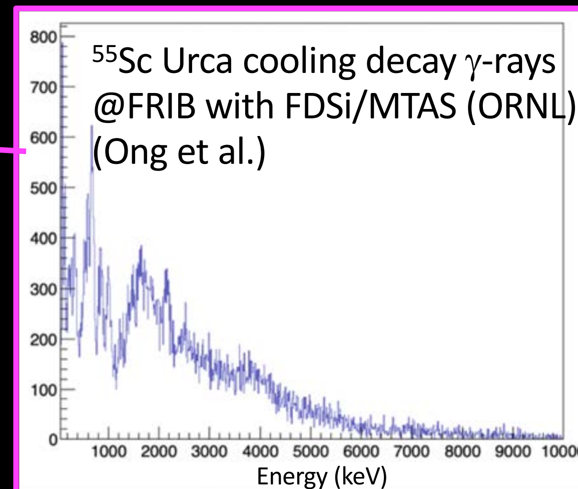


Of decay chain in neutron star

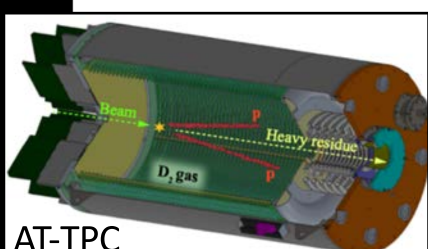
All Rare Isotopes in Neutron Star Crusts Within Reach at FRIB



FRIB400 can reach all nuclei involved in heating or cooling of accreted neutron star crusts



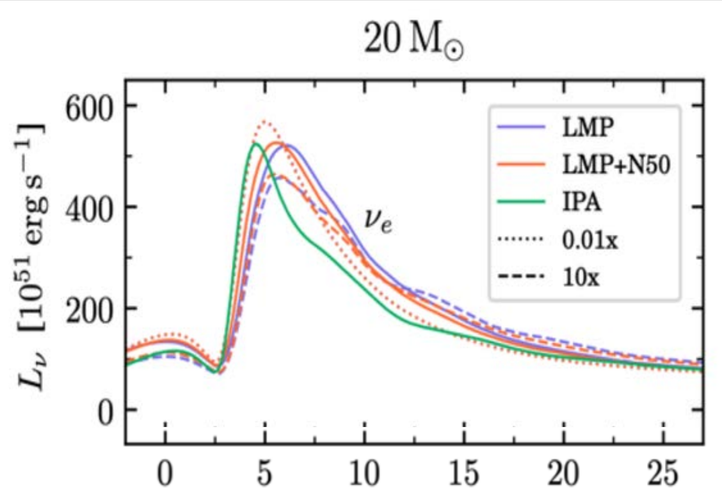
→ Can determine gs-gs transition strength and cooling rate



FRIB Opportunity:
d,^{2}He charge exchange on key unstable nuclei to probe electron capture rates (also for supernova neutrino signals) – Giraud et al. 2013

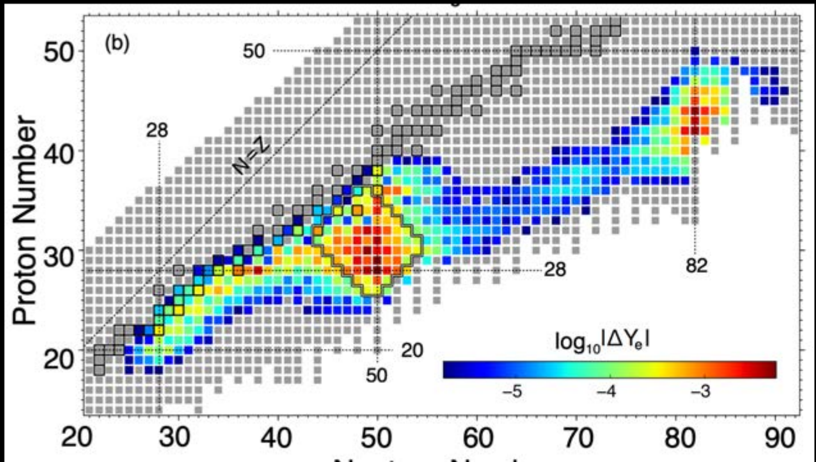
Supernova Neutrino Signals Depend on Rare Isotope Physics

Neutrino signal depends on rare isotope electron capture rates:



Johnston et al. 2022

EC on neutron rich nuclei is important
(similar nuclei than what is needed for neutron star crusts)



Sullivan et al. 2016

→ Also impacts explodability, remnant properties, …..
→ Need experimental data on weak interactions on neutron rich nuclei beyond b-decay
→ Charge exchange reactions at FRIB with the AT-TPC open up that opportunity

Summary

- Nuclear physics is essential to understand origin of the elements and neutron stars
  - Fundamental nuclear physics questions about rare isotopes and their reactions are linked to astronomical observables
  - FRIB offers an opportunity to address many of these questions
  - **If you want to know more: Workshop on Origin of the Heavy Elements tomorrow 9 – 15:30**
- Extraordinary opportunity for nuclear astrophysics with start of FRIB coinciding with major advances in multi-messenger astronomy and 3D computational modeling
- Also essential:
  - Stable beam experiments (above and below ground)
  - Nuclear theory for what cannot be measured experimentally
- Theorist, Computational modelers, Experimentalists, and Observers need to work together – centers and networks are critical
  - JINA and now Center for Nuclear Astrophysics Across Messengers (CeNAM)
  - International Research Network for Nuclear Astrophysics (IReNA) irenweb.org
  - N3AS, NP3M, NUCLEI, ….