Nuclear Astrophysics at FRIB

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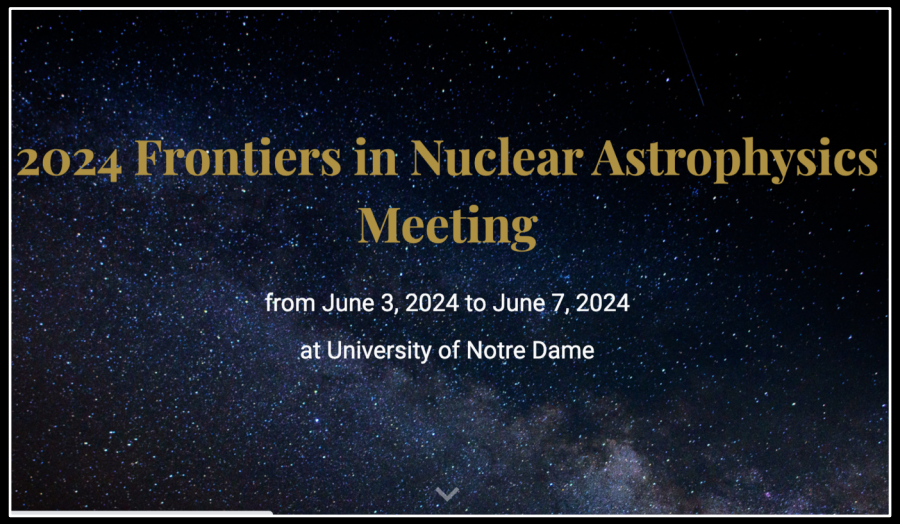
Michigan State University

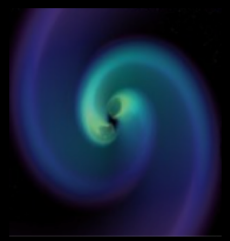
National Science Foundation
U.S. DEPARTMENT OF ENERGY | Office of Science

JINA and CeNAM

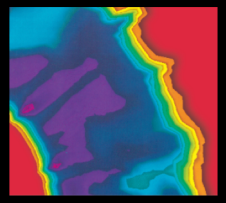
Center for Nuclear Astrophysics across Messengers

- Succeeds JINA as a center for nuclear astrophysics
- Fosters interdisciplinary connections in the multi-messenger era of nuclear astrophysics
  - Currently support for synergistic activities, data effort (with MSU support; postdoc?)





Fall 2023:
Workshop "Nuclear astrophysics in the era of gravitational wave astronomy at CSU Fullerton (Lead: J. Read)



Fall 2023:
Workshop "Grand Challenges in Nucleosynthesis" at INT (Lead: C. Fryer)

International Research Network for Nuclear Astrophysics (IReNA)

CaNPAN **Canadian Nuclear Physics for Astrophysics Network**
10 Groups from 6 institutions

New

Joint Institute for Nuclear Astrophysics
(Phasing out)

Being replaced by

Center for Nuclear Astrophysics across Messengers
(Proposal for funding pending)
57 Institutions, 82 Senior Participants

Ibero American Network for Nuclear Astrophysics
27 Scientists from 6 accelerator laboratories in 6 countries.

New

BRIDGCE UK
70 members from 19 institutions

EU COST Action
Nuclear Astrophysics Network
Headquartered at Keele University UK
30 European Countries

Extreme Matter Institute
Headquartered at GSI
Darmstadt, Germany
13 Institutions, 400 scientists

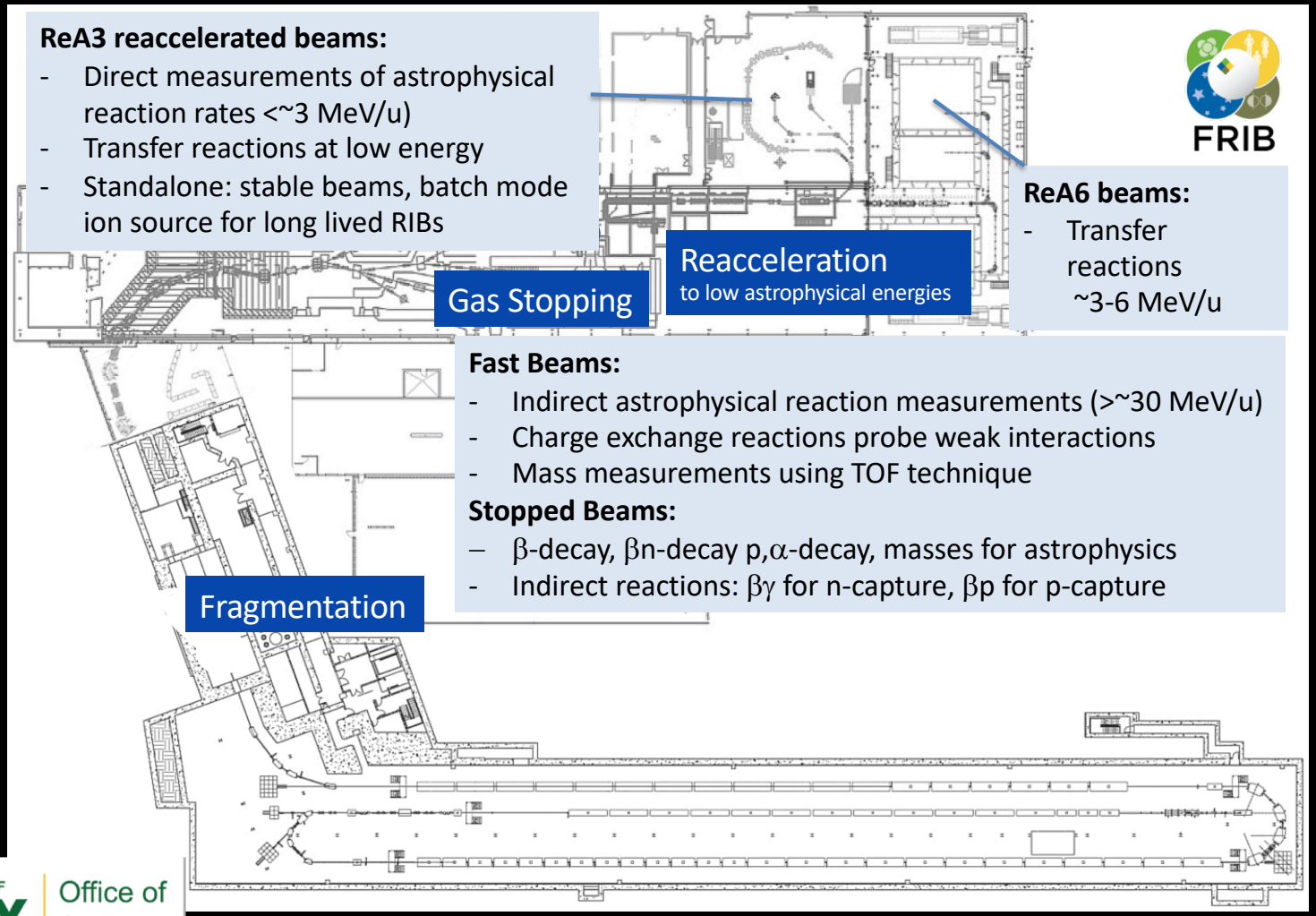
Computational Network
PI: Edinburgh UK, Victoria Canada, Budapest Hungary, York, UK, Keele, UK
24 Institutions, 64 scientists

Japanese Forum for Nuclear Astrophysics
16 Institutions
119 Scientists

Supports:
- **Joint workshops**
- **Schools**
- **Visits**
- **Online Seminar**

More at irenaweb.org
Join (first join a network)

FRIB Offers Broad Opportunities for Nuclear Astrophysics Measurements



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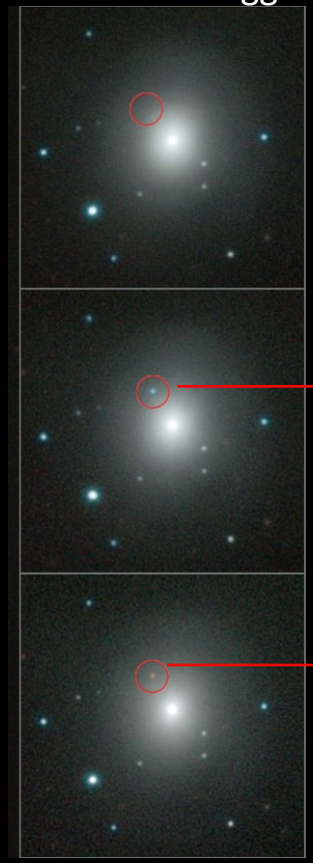
R-Process Nucleosynthesis in Neutron Star Mergers

GW170817 Trigger

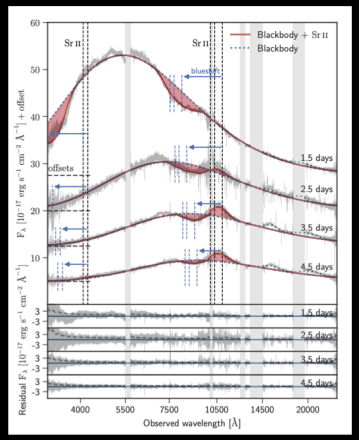


Blue

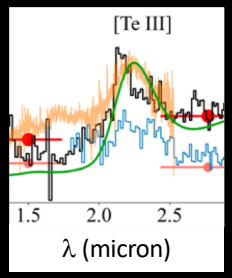
Red
→ Atomic opacity
→ Nuclear composition (Lanthanides?)

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

Line features

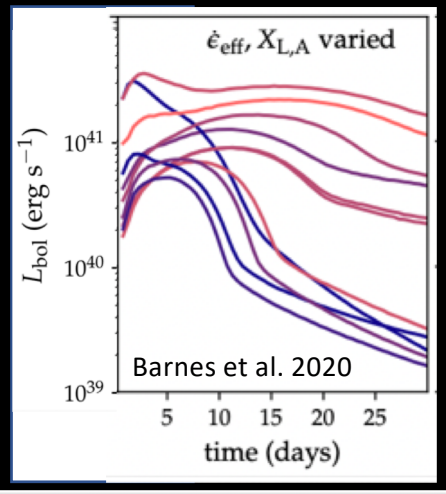


Sr feature: Watson et al. 2019
Or He? (Perego et al. 2022)



Levan et. al.
JWST detection of Te

Light curves depend on nuclear physics

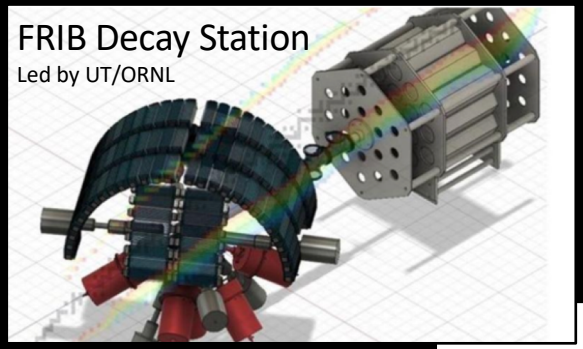


frdm.y16 frdm.y28 hfb22.y16 hfb27.y16 dz33.y16 unedf.kz.y16
unedf.xr.y16 unedf.y24 sly4.y18 sly4.y21 tf.y16

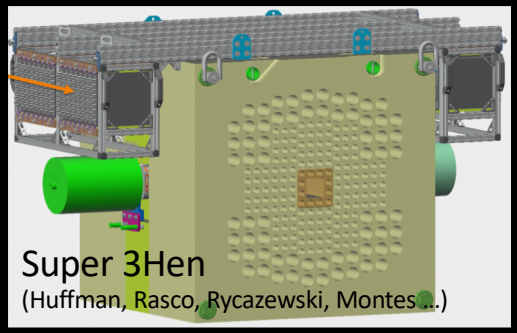
Key question:
What elements and isotopes are made in neutron star mergers?
→ Need nuclear physics to identify (and sometimes tune) astrophysical models that are consistent with observations
→ With astrophysical conditions constrained, need nuclear physics to "Interpolate" sparse observations and obtain the complete abundance pattern (elements and isotopes)

Much of r-Process Nuclear Physics Within Reach at FRIB

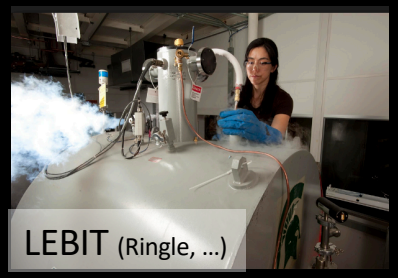
β-decay Half-lives, levels



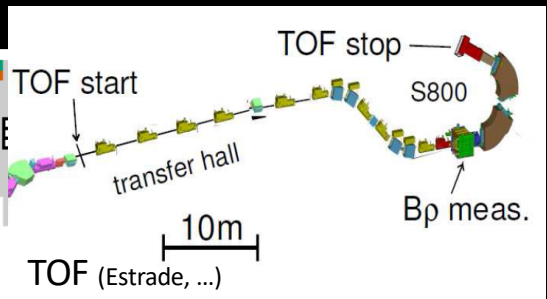
Decay branchings for n-emission



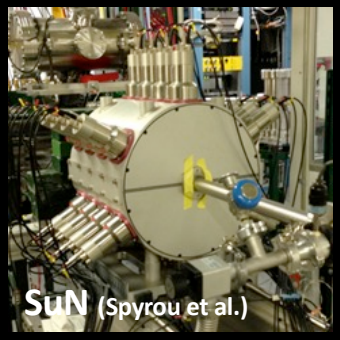
Masses ~10^{-8} precision

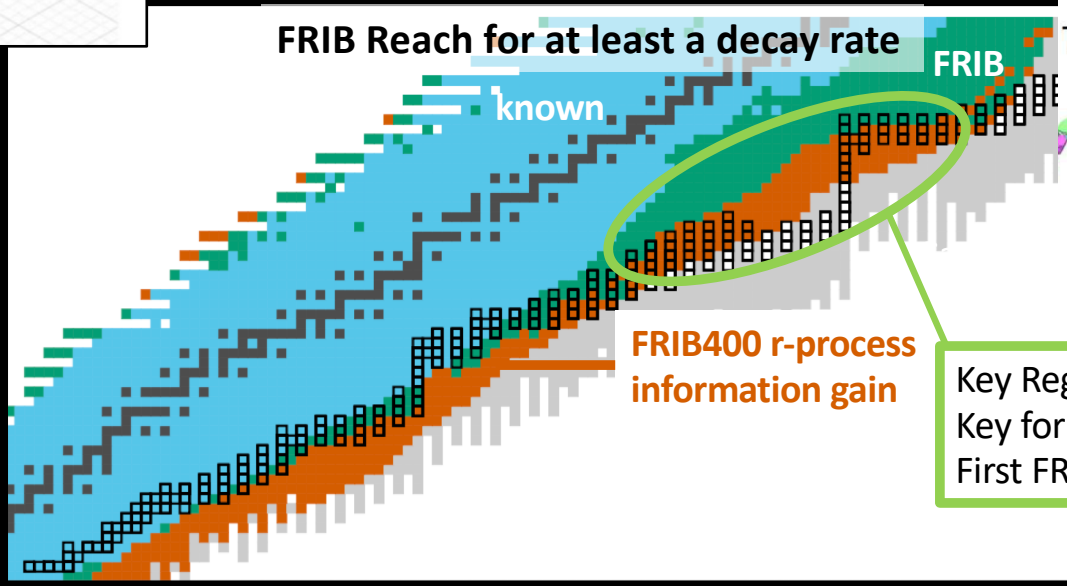


Masses ~10^{-6} precision



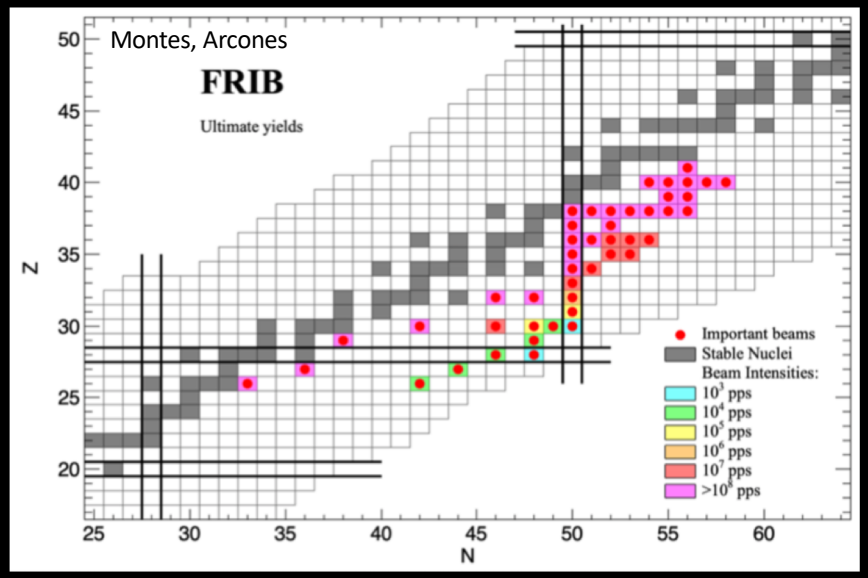
n-capture rates (indirect)
β-Oslo method



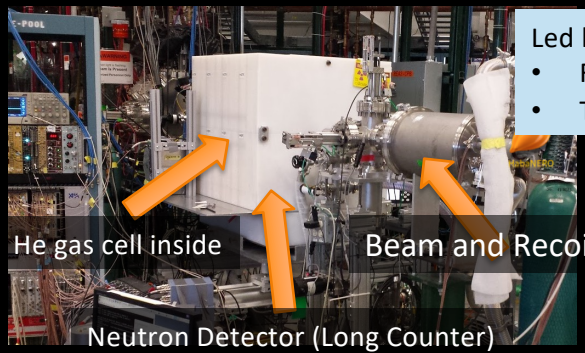


Key Region: Gateway to heavier nuclei
Key for kilonovae
First FRIB experiment approved

(α,n) Reactions for Supernova Weak r-process

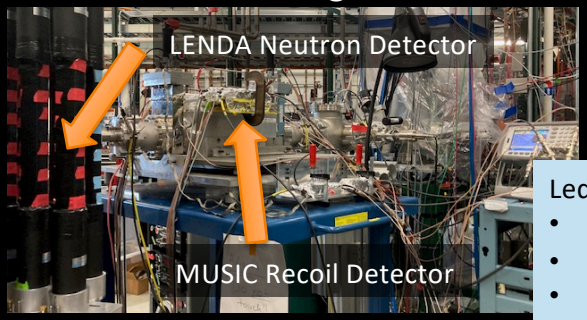


HABANERO Neutron Detector

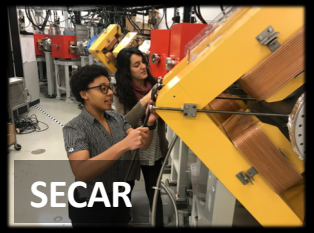


Led by:
- F. Montes (MSU)
- T. Ahn (IBS, Korea)

MUSIC Active Target Detector

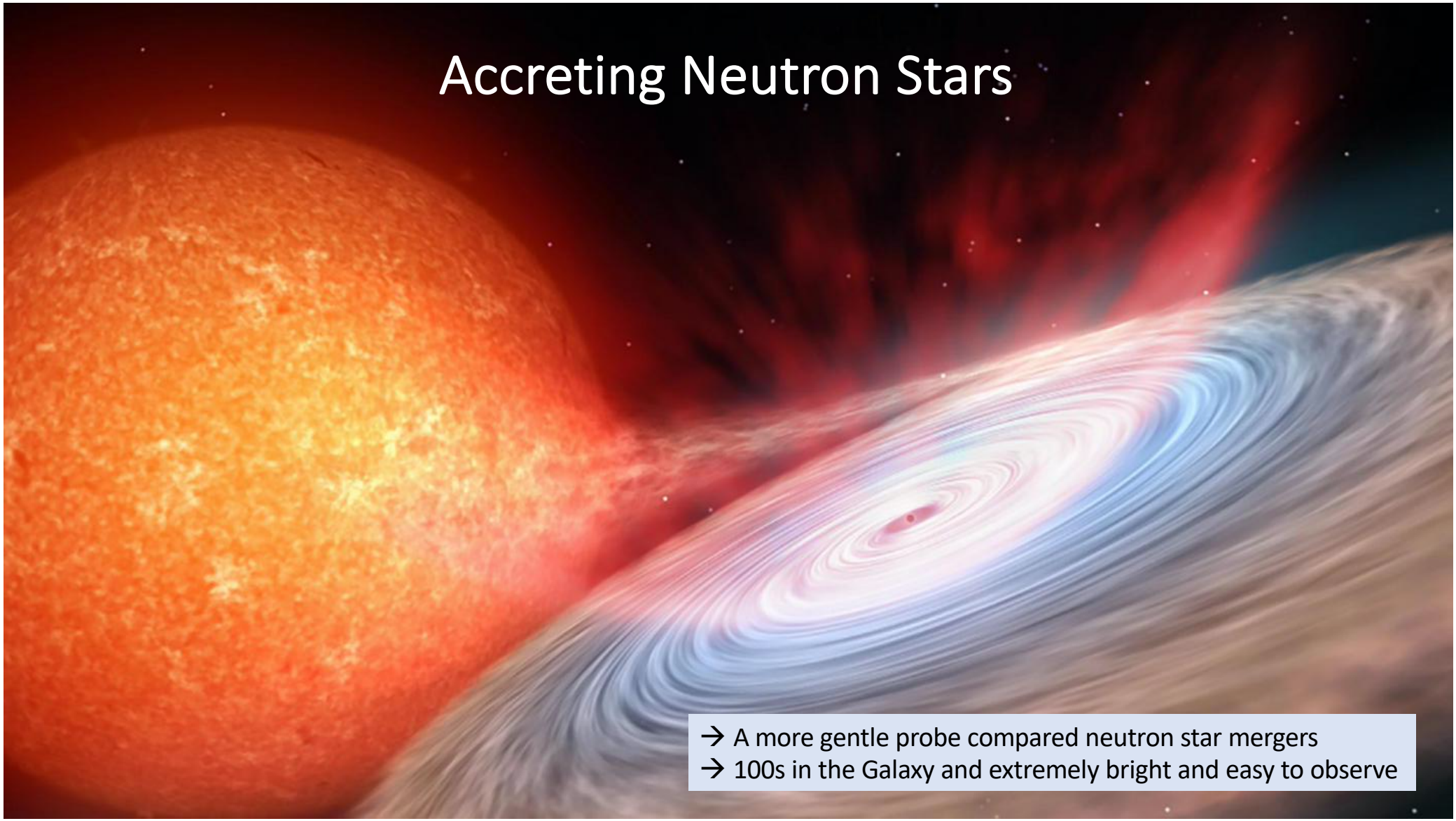


Led by:
- M. Avila (ANL)
- J. Pereira (MSU)
- F. Montes (MSU)



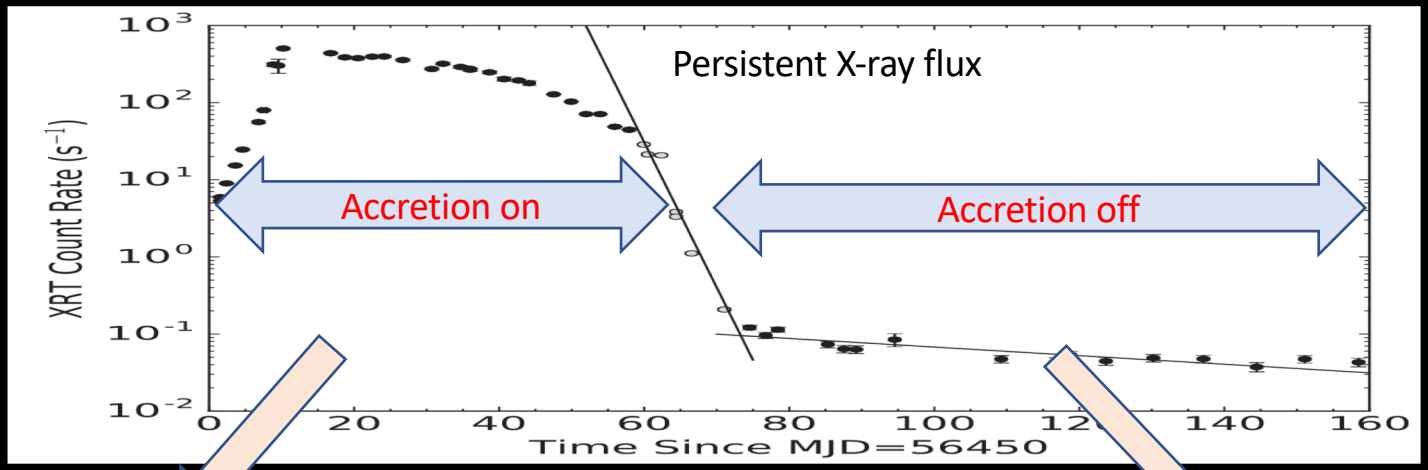
SECAR Program (see Montes)

Accreting Neutron Stars

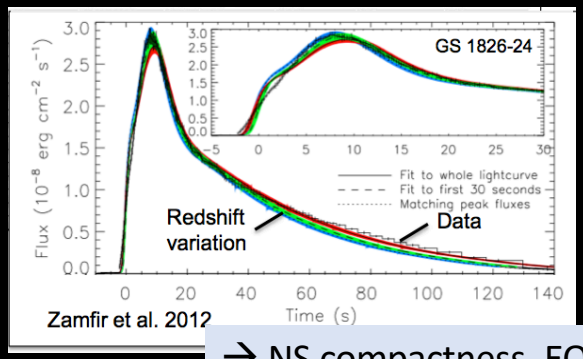


→ A more gentle probe compared neutron star mergers
→ 100s in the Galaxy and extremely bright and easy to observe

Quasi Persistent Transients Probe Neutron Star Physics



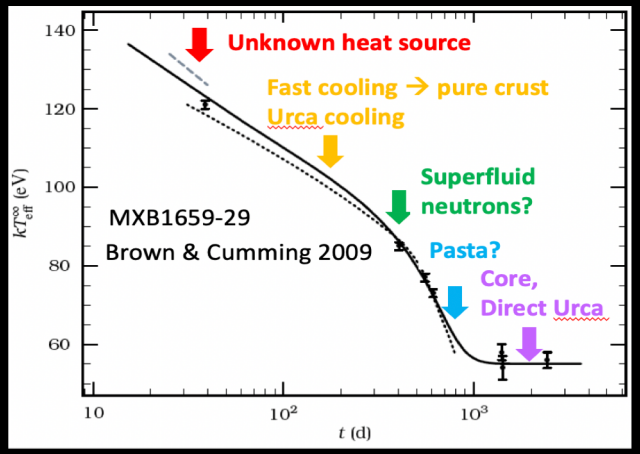
X-ray bursts – on top of persistent flux



→ NS compactness, EOS

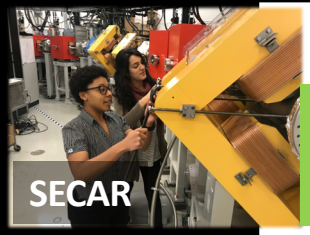
Both observables are powered by rare isotope physics

Crust cooling



p,α induced reactions on n-deficient nuclei for X-ray bursts, novae, supernovae (νp- and p-process)

FRIB

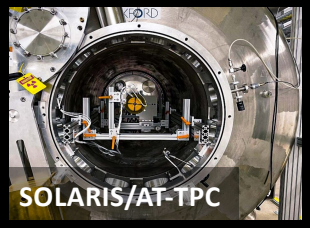


Recoil Separator
→ Direct reaction measurements

Notre Dame /ORNL/ LSU/MSU led

Gas Target
→ Direct reaction measurements
(α,p) (p,α)

ORNL/CSM led

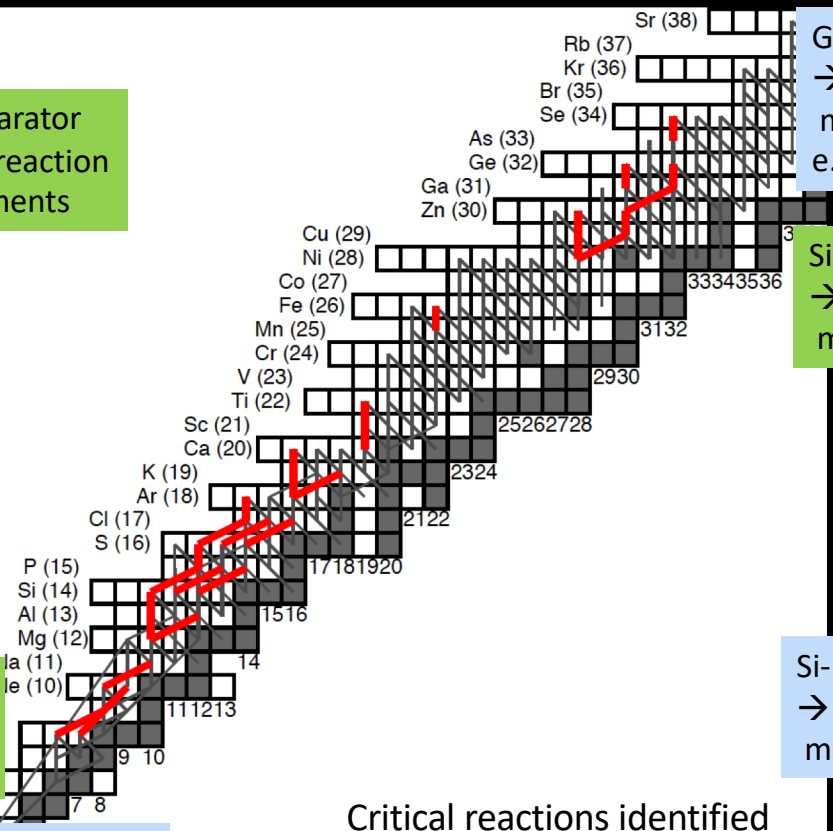


Active Target
→ Direct reaction measurements

ANL/MSU led

Decay particle spectroscopy for indirect reaction studies

MSU led (Wrede)



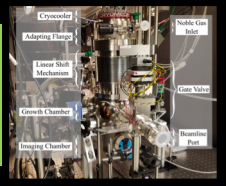
Critical reactions identified (here for light curve)
Cyburt et al. 2016

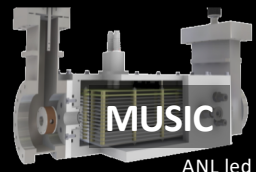
Ge γ-detector Array
→ Indirect reaction measurements
e.g. d,n and others

LBNL/ANL/FSU/MSU/ORNL led

Single Atom Microscope
→ Direct reaction measurements

MSU led (Singh)





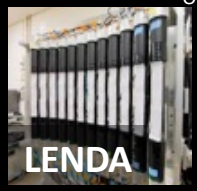
MUSIC
→ Direct reaction measurements

ANL led

Si-Detector Array
→ Direct/Indirect reaction measurements

ORNL Rutgers

Neutron Detector
→ (d,n) Indirect reaction measurements

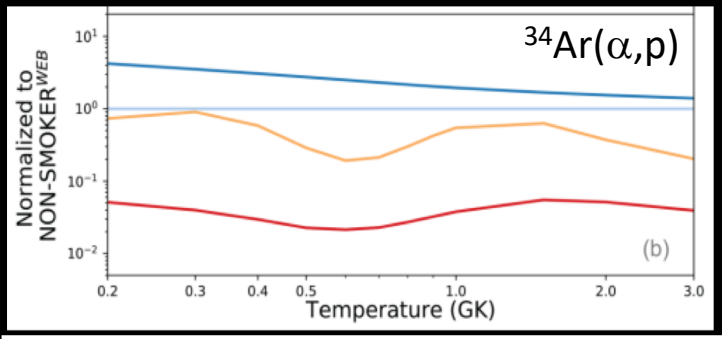


MSU led (Zegers)

(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)

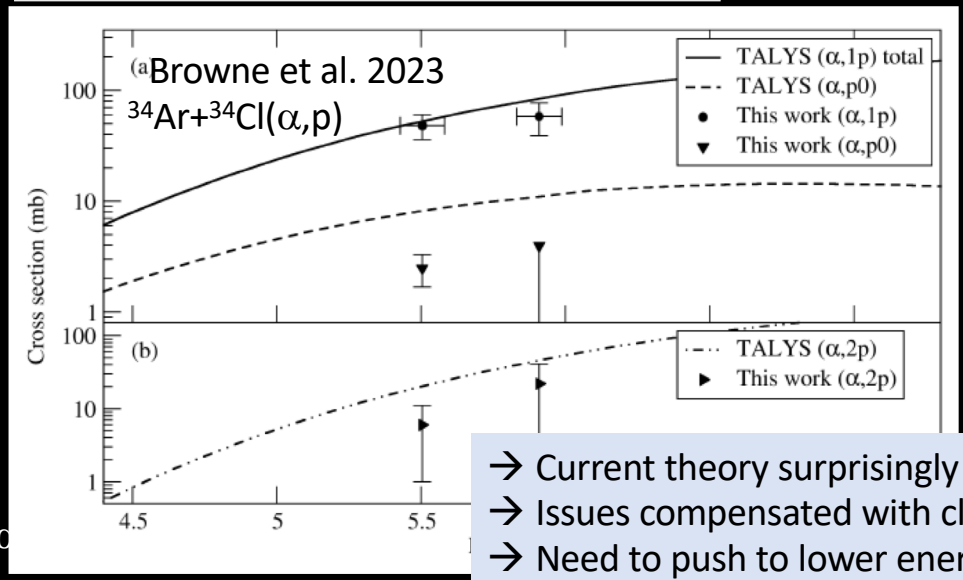
Surrounded with ORRUBA Si detector array (ORNL, Rutgers, Pain, Ciezewski, …)



Theory

Clustering enhancement

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

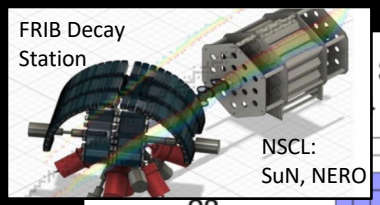


→ Current theory surprisingly good
→ Issues compensated with cluster effects?
→ Need to push to lower energies

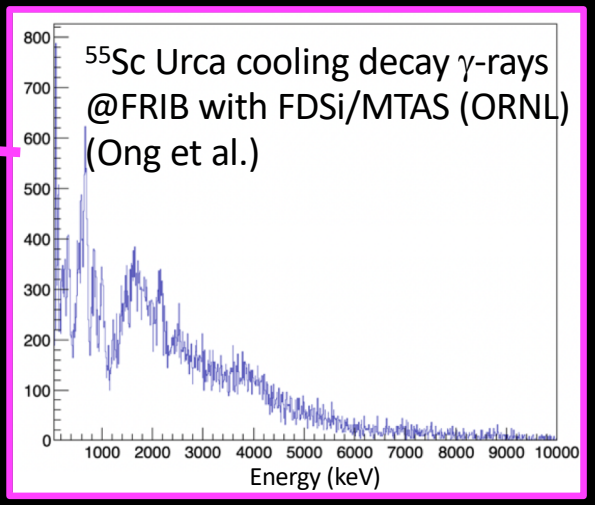
^{34}Ar(α

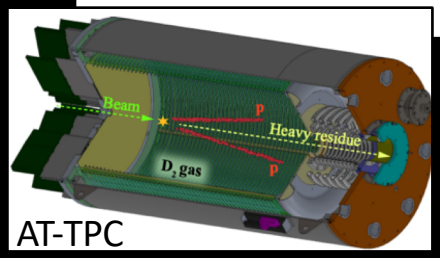
Long et al. @ indirect ^{40}Ca(p,t)

All Rare Isotopes in Neutron Star Crusts Within Reach at FRIB



FRIB Opportunity:
gs-gs β-transition strength from β–γ and β-n spectroscopy for crust Urca cooling



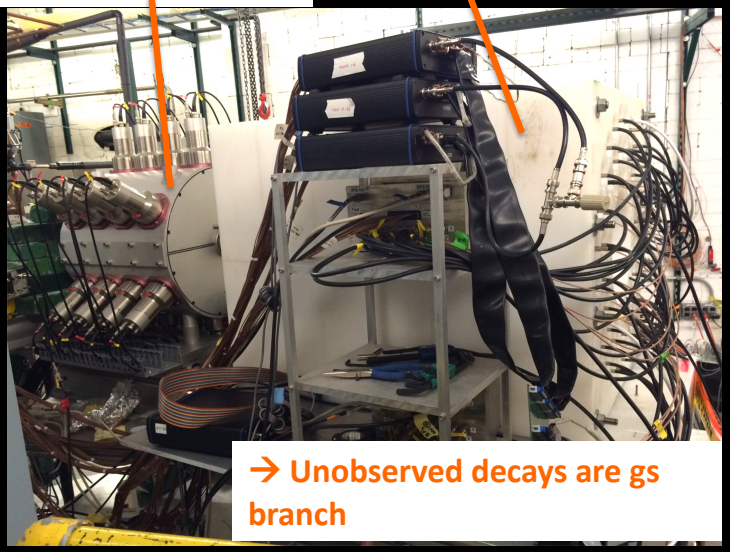


FRIB Opportunity:
d,^{2}He charge exchange on key unstable nuclei to probe electron capture rates (also for supernova neutrino signals) – Giraud et al. 2013

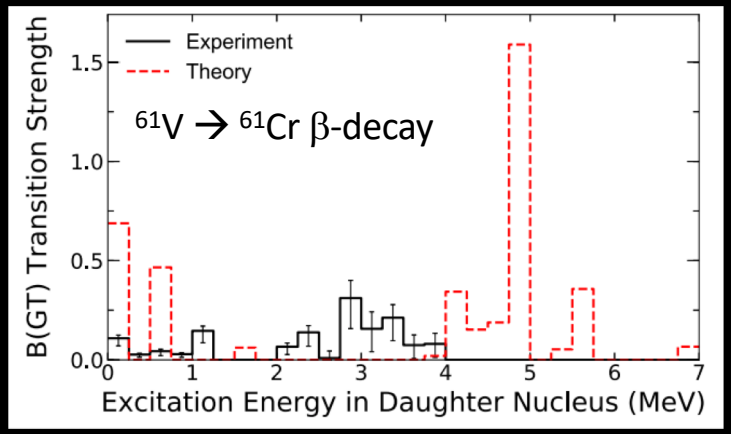
Urca Cooling from A=61 Nuclei Weaker than Expected

Measure all γ-branches with SuN Total Absorption Spectrometer

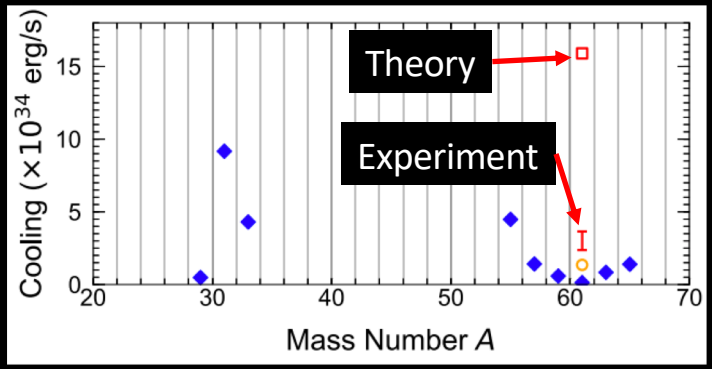
Measure all n-branches with NERO



→ Unobserved decays are gs branch



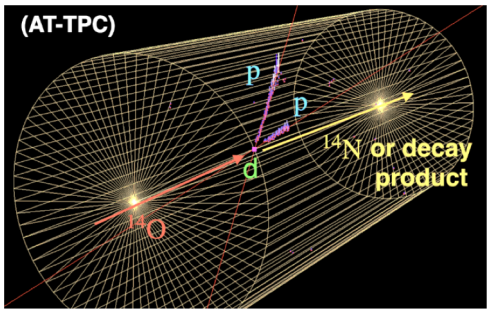
Ong et al. 2020



Of decay chain in neutron star

Opportunities for Studying the Isovector Response of Nuclei With Charge-Exchange Reactions – contact: Remco Zegers

- Experiments are focused on:
  - Reaction rates in astrophysical phenomena mediated by the weak nuclear force (electron-captures, neutrino-induced reactions, and β-decay)
  - The evolution of nuclear structure in nuclei with asymmetric proton-to-neutron ratios through studies of Gamow-Teller strengths
  - Novel probes for isolating the isovector response (e.g. giant resonances) in nuclei – equation of state of nuclei and nuclear matter



- Isovector response of unstable nuclei in the β^- (p,n) and β^+ (n,p) direction by performing (p,n) and (d,^{2}He) experiments in inverse kinematics.
  - (p,n) experiments in inverse kinematics at ~100 MeV/u performed with the S800 spectrometer and the Low-Energy Neutron Detector Array (LENDA)
  - (d,^{2}He) experiments in inverse kinematics at ~100 MeV/u performed with the S800 spectrometer and the Active-Target Time Projection Chamber (AT-TPC)
- Novel unstable reaction probes for isolating isovector responses in stable nuclei:
  - E.g., (^{10}Be,^{10}B[0$^+$]) and (^{10}C,^{10}B[0$^+$]) probes for isolating spin-non-transfer and spin-transfer isovector excitations (GRETINA+S800)
  - (t,^{3}He), (t,^{3}He+n/γ) probes for high-resolution transitions in the β^+ direction (S800+LENDA,GRETINA,SuN)
- Development of astrophysical weak-reaction rate library

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Summary and Outlook

- Extraordinary opportunity for nuclear astrophysics with start of FRIB coinciding with major advances in multi-messenger astronomy and 3D computational modeling
- Very broad experimental capabilities and associated nuclear astrophysics research programs at FRIB, many opportunities to collaborate
- Some possible areas of interest from my perspective:
  - SECAR – designed for direct measurements but other opportunities (Fernando's Talk)
  - Updated reaction rate data (within CeNAM/IReNA)
  - Beam stopping and extraction
  - …. all activities are open
- Opportunities from connections with astronomy, astrophysics, gravitational wave physics, cosmo-chemistry, ……
  - MSU Theorists: Nuclear theory group, astronomy group, …
  - CeNAM, IReNA - welcome to join and become active