Accreting Neutron Star Physics at FRIB

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Accreting Neutron Stars are Observed as X-ray Binaries

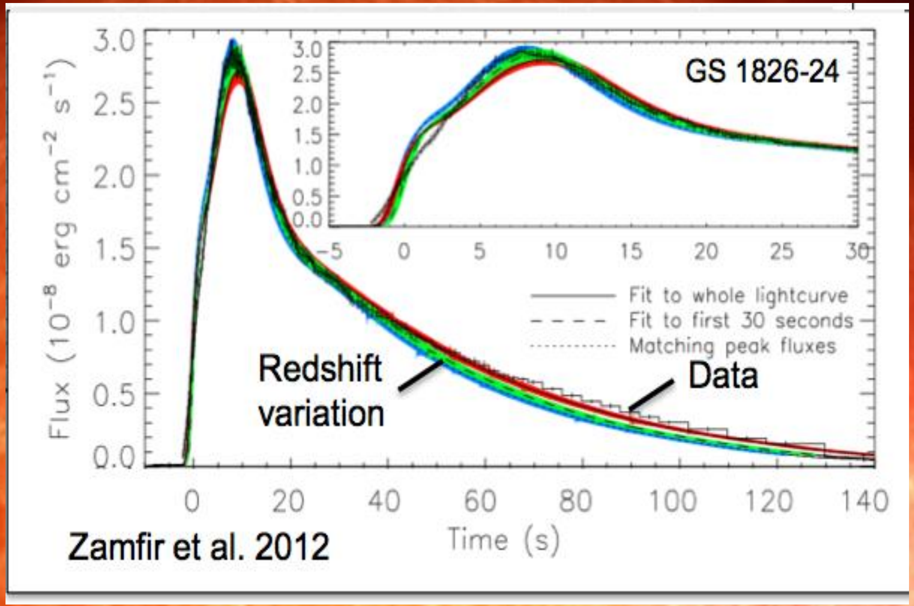
Bright persistent X-ray source powered by gravitational energy.

Brief X-ray bursts powered by nuclear reactions on top of persistent flux

- Durations: 10-100~s
- Recurrence time: hours-days

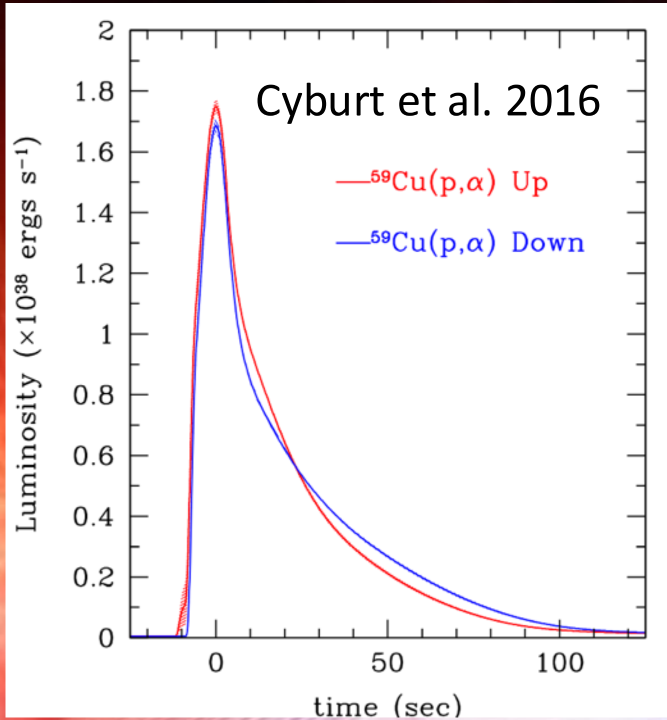
→ A more gentle probe compared neutron star mergers
→ >100 in the Galaxy, bright and easy to observe

X-ray Burst Observables Probe Neutron Star Properties



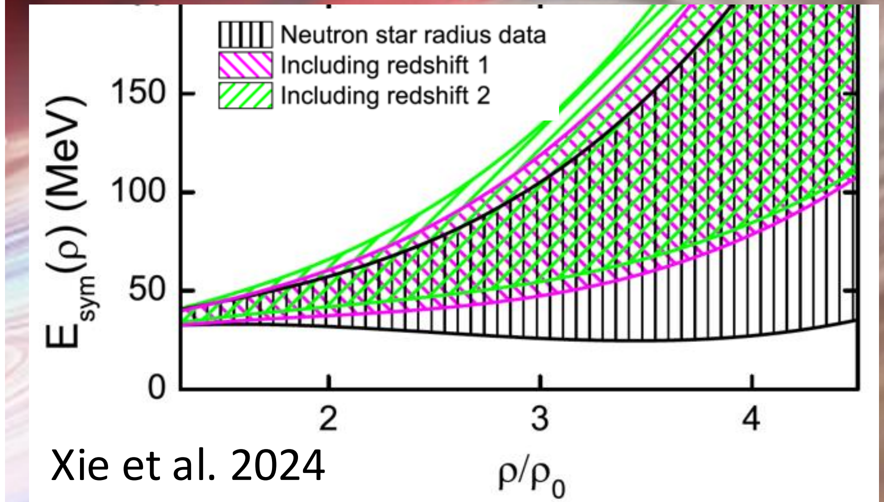
→ Extract surface redshift to constrain compactness (mass, radius)

→ Burst properties probes surface heat



→ But - Need nuclear physics to extract information from light curve

Example for EOS constraints with current nuclear physics (updated masses – Zhou et al. 2023)

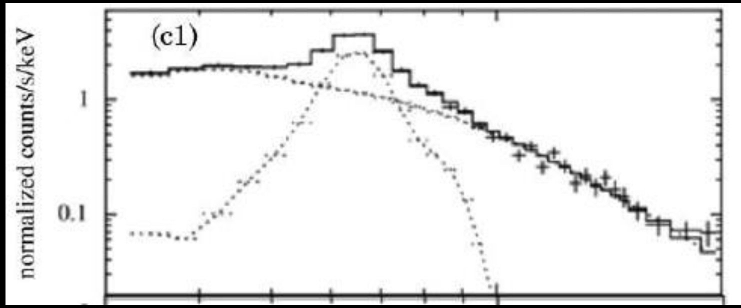


→ Redshifts from bursts do provide complementary EOS constraints

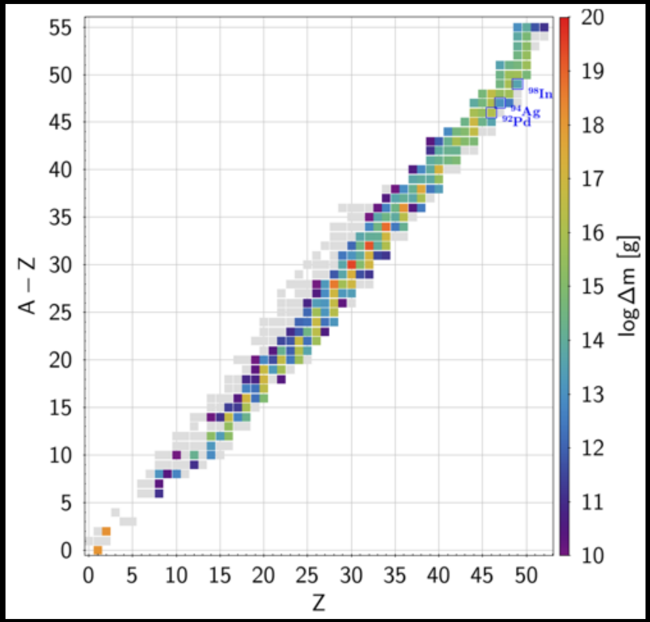
Open Questions Related to Bursts: What Isotopes are Created and What Observables are Affected?

- Do bursts eject material?
- Observable features in spectra?
- Contribution to nucleosynthesis (A=92-98 p-nuclei)?

Spectral features:
Many tentative observations in literature



Herrera et al. 2023:
~3% ejected: ^{60}Ni,^{64}Zn,^{68}Ge

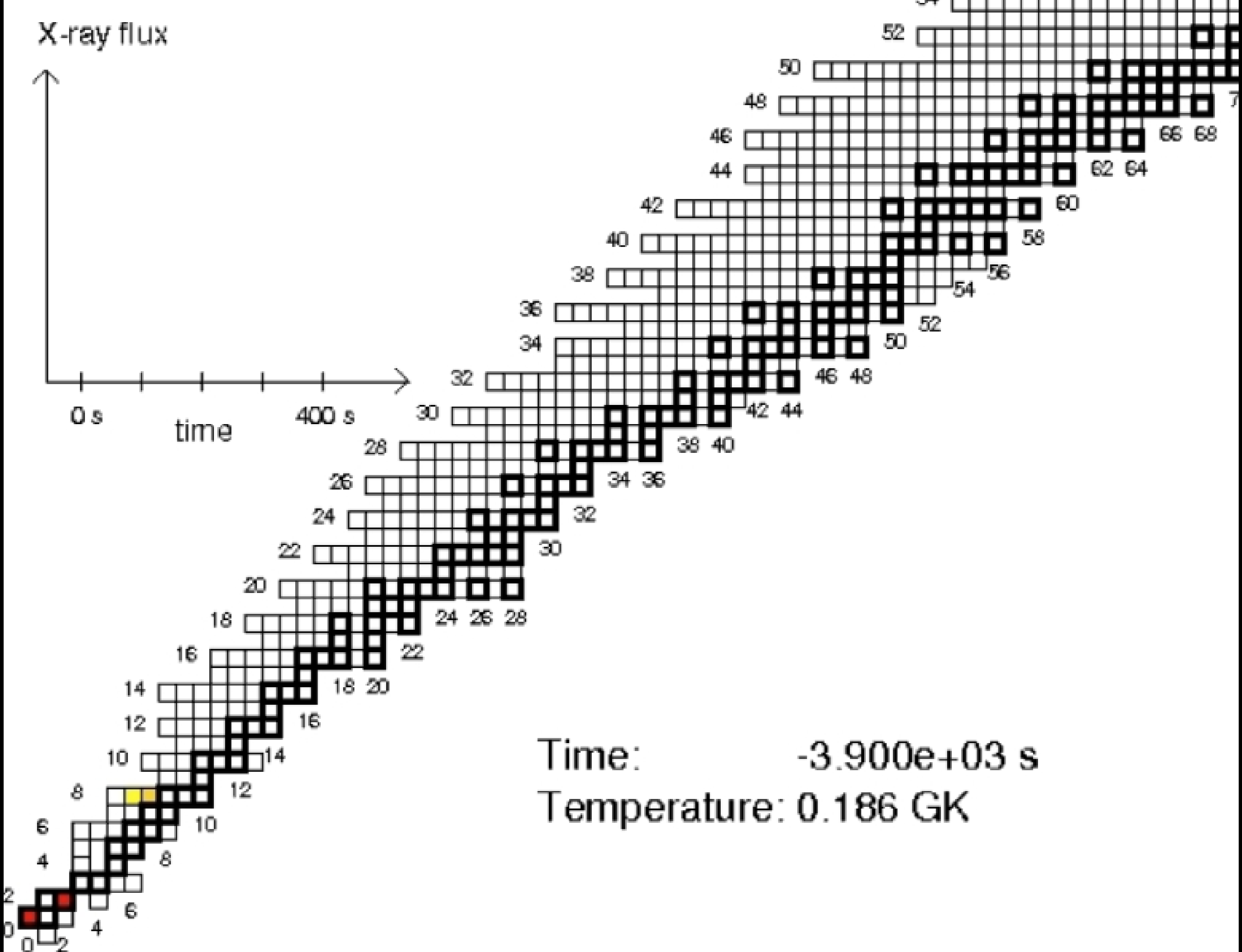


Also Weinberg et al. 2002:
~few % ^{28}Si, ^{60}Zn, ^{62}Zn

→ Not enough systems to explain p-process?

Recent example: (Wataru et al. 2021)
- "Unusual Emission Structure" 40h after superburst
- Possibly mix of Fe, Cr, Co ejected in wind and falling back
- Also get red shift → NS compactness

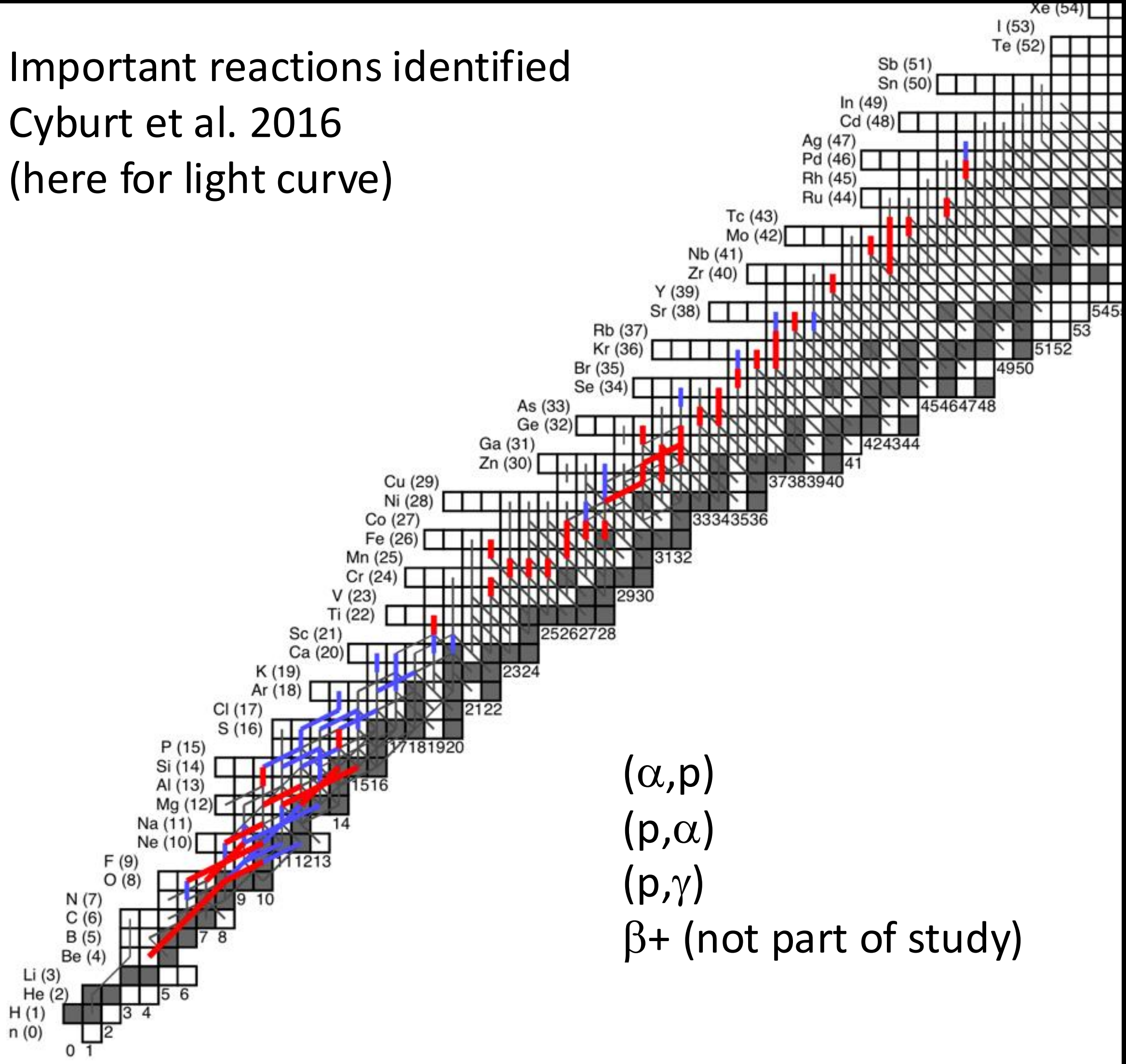
Also: Not ejected material→ Sets Composition of Neutron Star Crust



Based on model
By A. Heger

X-ray Burst Reactions

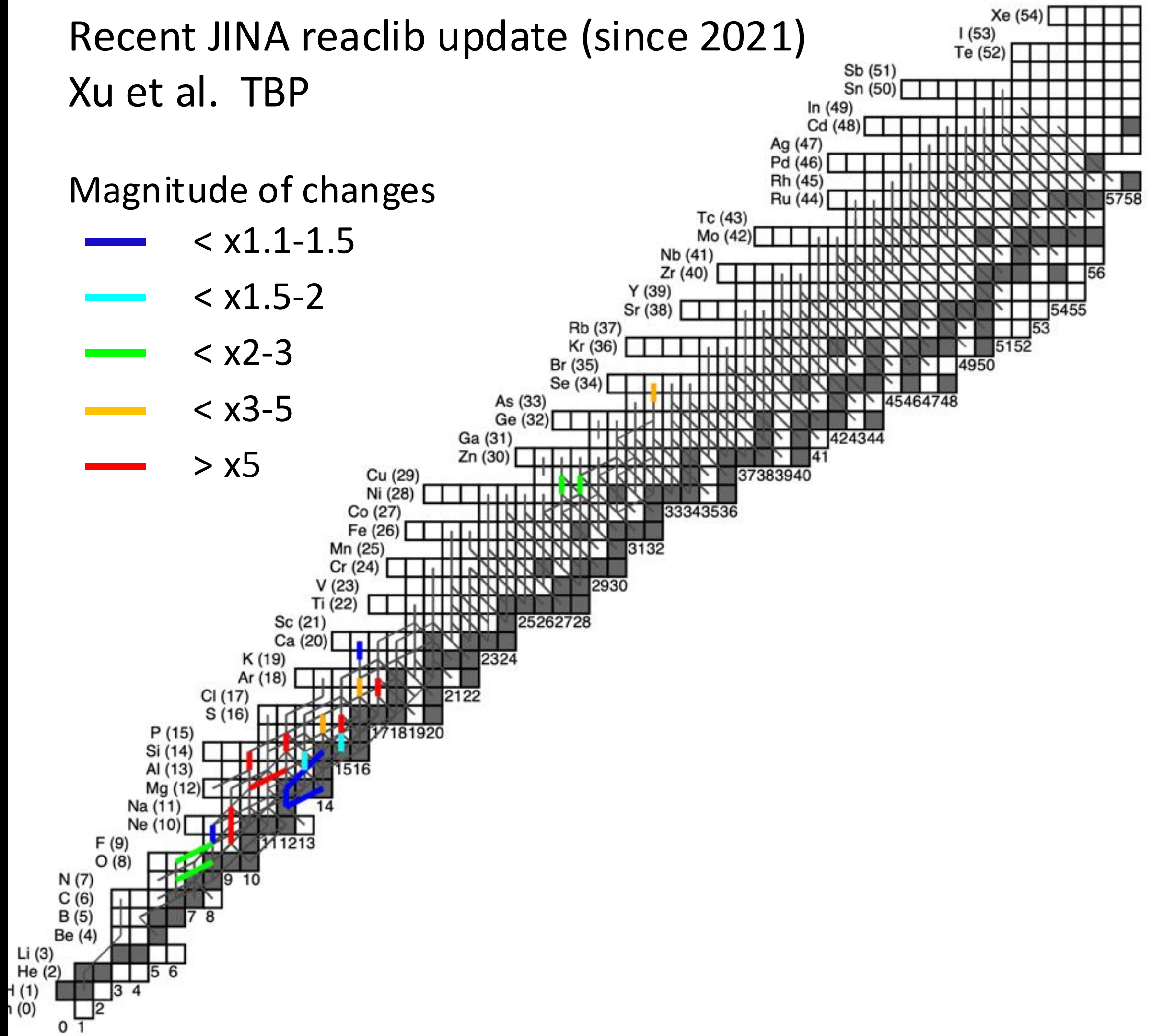
Important reactions identified
Cyburt et al. 2016
(here for light curve)



(α,p)
(p,α)
(p,γ)
β+ (not part of study)

Recent JINA reaclib update (since 2021)
Xu et al. TBP

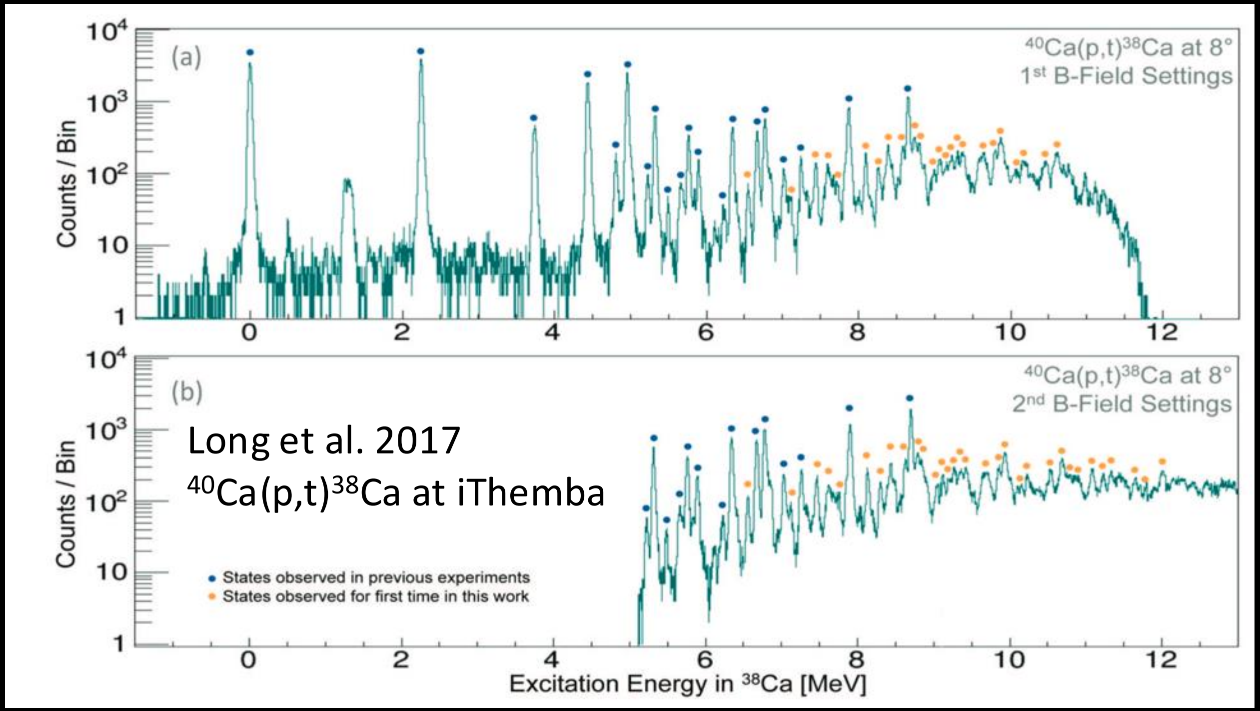
Magnitude of changes
- < x1.1-1.5
- < x1.5-2
- < x2-3
- < x3-5
- > x5



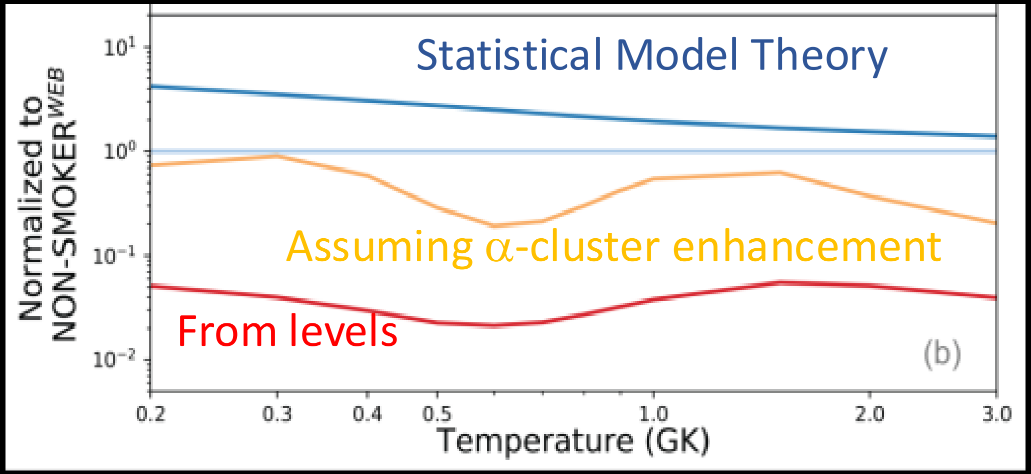
Questions About (α,p) Reactions

Levels in ^{38}Ca needed for ^{34}Ar(α,p)

^{34}Ar + α → ^{38}Ca → ^{37}K + p



Calculate ^{34}Ar(α,p) rate based on resonance levels



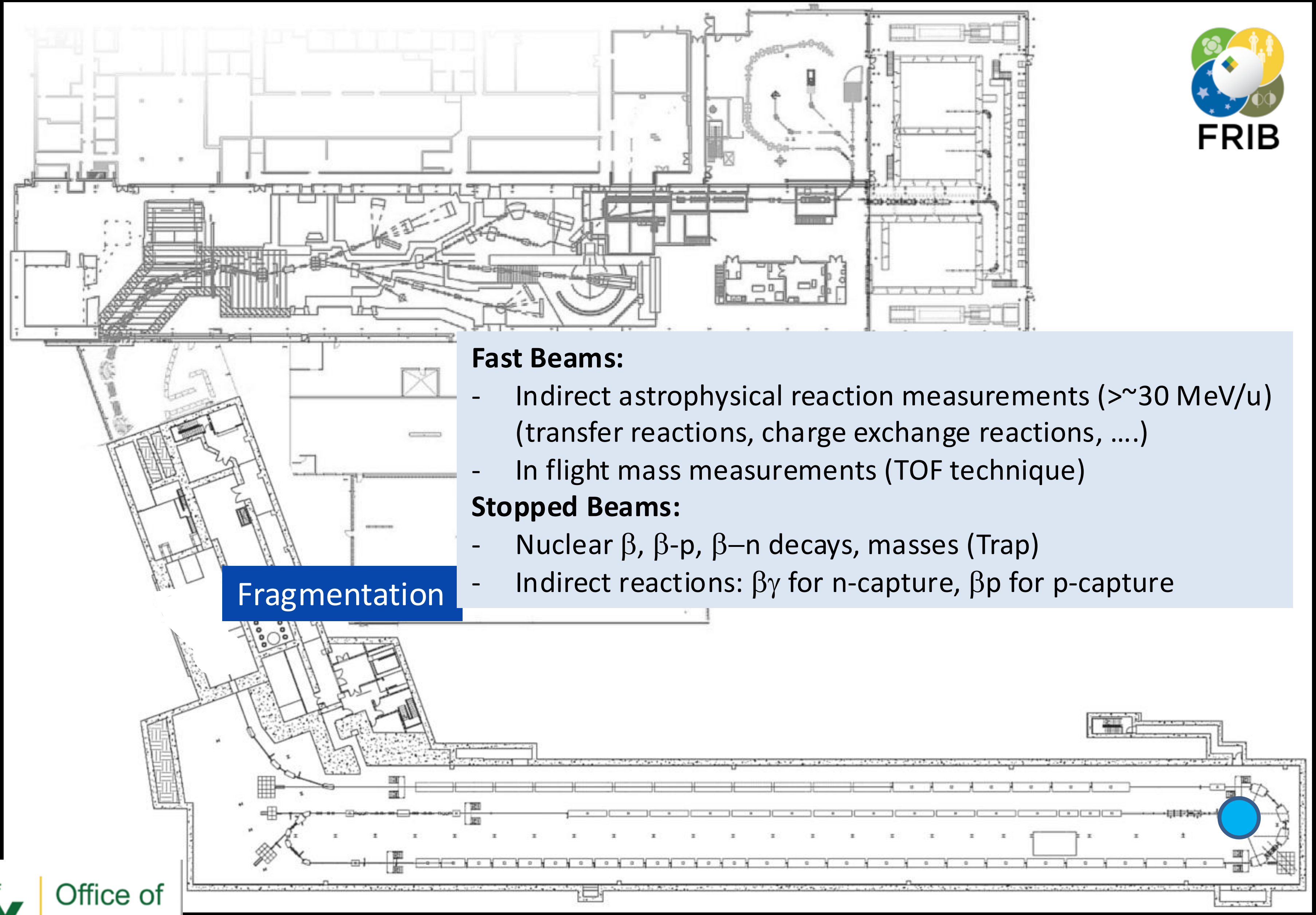
→ Possible orders of magnitude issues with Statistical model predictions

FRIB Radioactive Beam Facility at MSU

FRIB Status:

- First experiment May 2022 at 1 kW 200 MeV/u beam energy
- Since then two PACs, routine operation
- Power ramp up to 20 kW now
- 400 kW over next years
- 400 MeV/u upgrade planned

FRIB Provides Fast, Stopped, and Reaccelerated Beams



Fast Beams:

- Indirect astrophysical reaction measurements (>~30 MeV/u) (transfer reactions, charge exchange reactions, ….)
- In flight mass measurements (TOF technique)

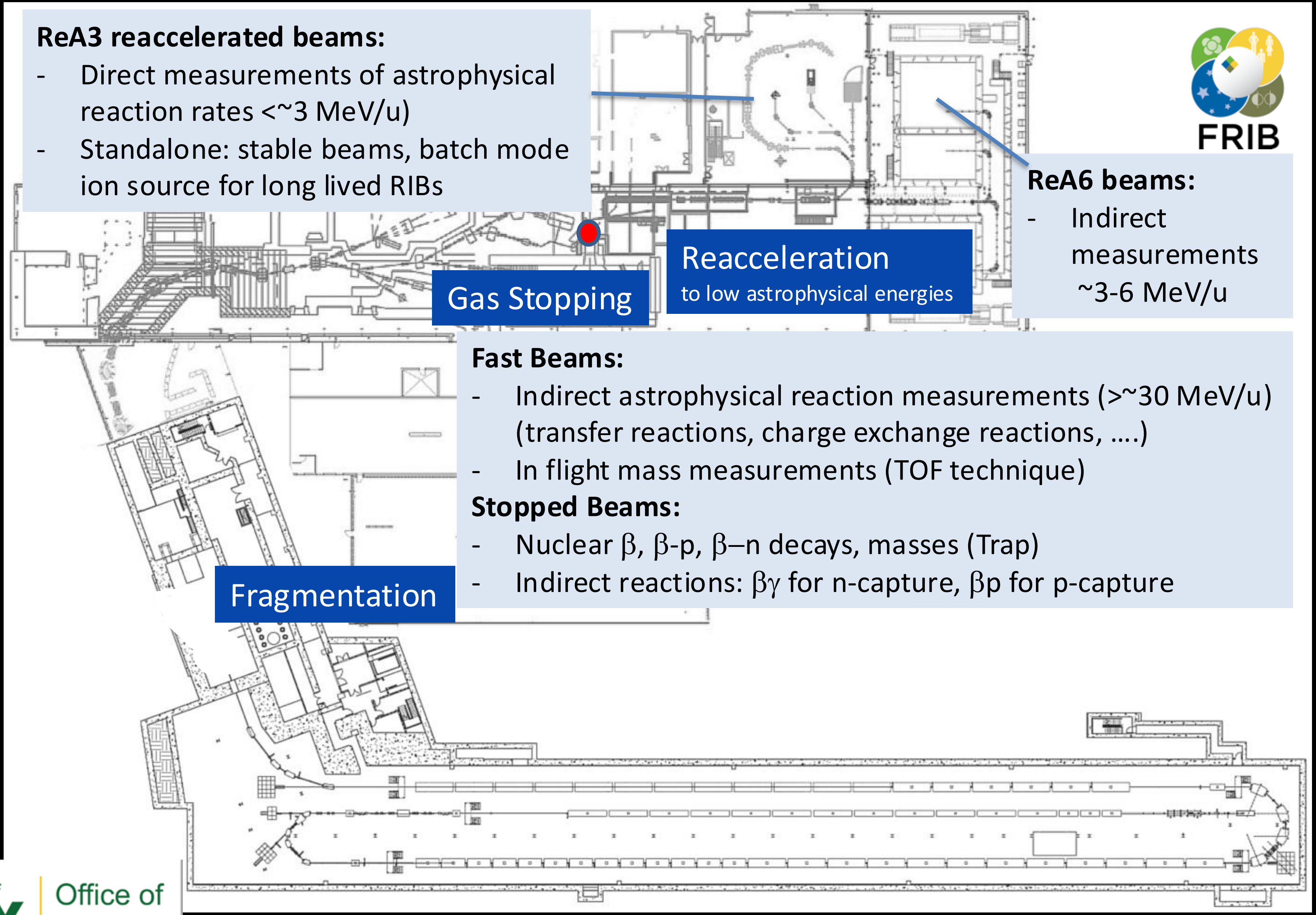
Stopped Beams:

- Nuclear β, β-p, β–n decays, masses (Trap)
- Indirect reactions: βγ for n-capture, βp for p-capture

FRIB Provides Fast, Stopped, and Reaccelerated Beams

ReA3 reaccelerated beams:

- Direct measurements of astrophysical reaction rates <~3 MeV/u)
- Standalone: stable beams, batch mode ion source for long lived RIBs



ReA6 beams:

- Indirect measurements ~3-6 MeV/u

Fast Beams:

- Indirect astrophysical reaction measurements (>~30 MeV/u) (transfer reactions, charge exchange reactions, ….)
- In flight mass measurements (TOF technique)

Stopped Beams:

- Nuclear β, β-p, β–n decays, masses (Trap)
- Indirect reactions: βγ for n-capture, βp for p-capture

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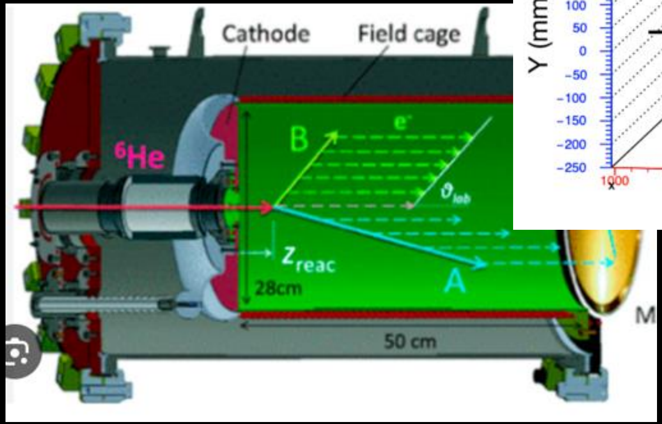
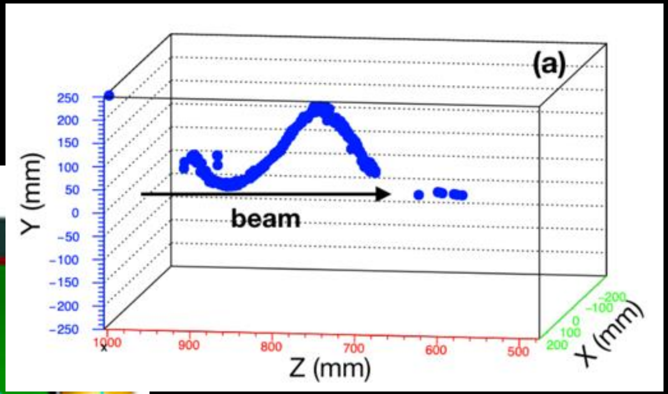
Direct Measurements of (α,p) Reactions at FRIB

$^{22}Mg(\alpha,p)$

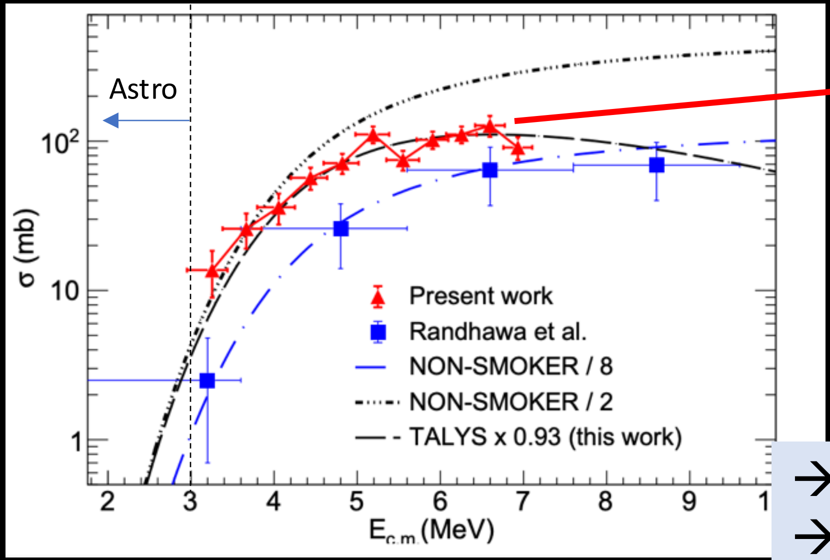
Active target TPC





Randhawa et al. 2020

→ x8 lower than theory



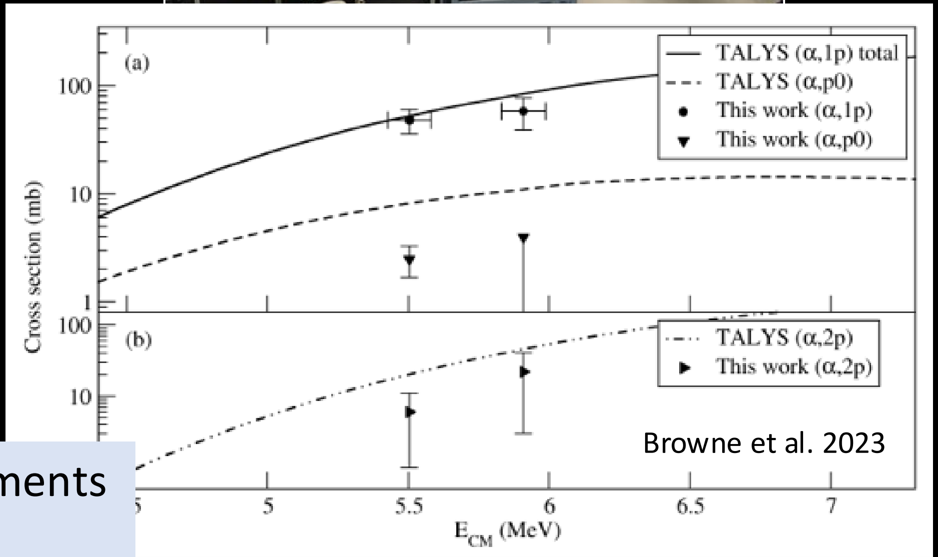
Remeasured
at ANL
with MUSIC
Active target
(Jayatissa et al. 2022)
→ Agrees with Theory

$^{34}Ar(\alpha,p)$

JENSA Gas Target + ORRUBA Si array

~10^{19} cm^{-2}

Windowless
He Jet



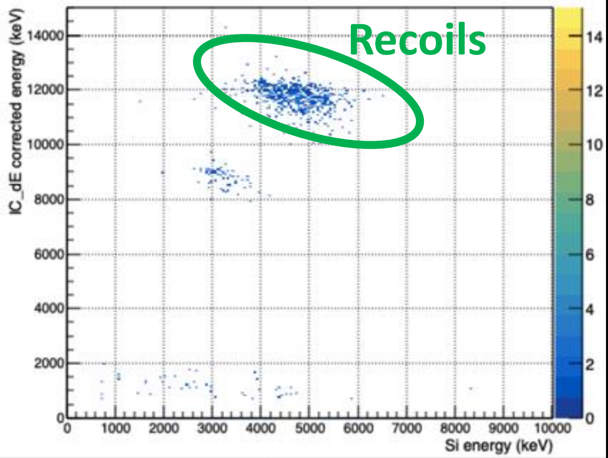
Browne et al. 2023

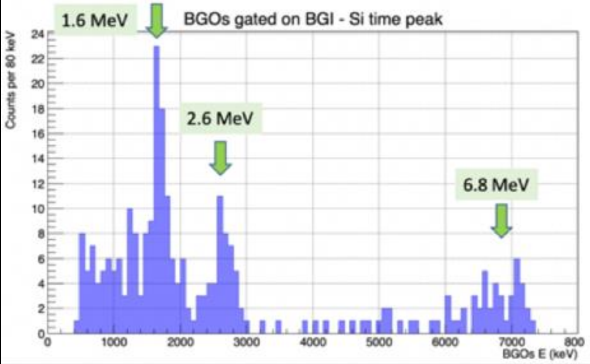
→ Need to address discrepant measurements

→ Need to push to lower energy

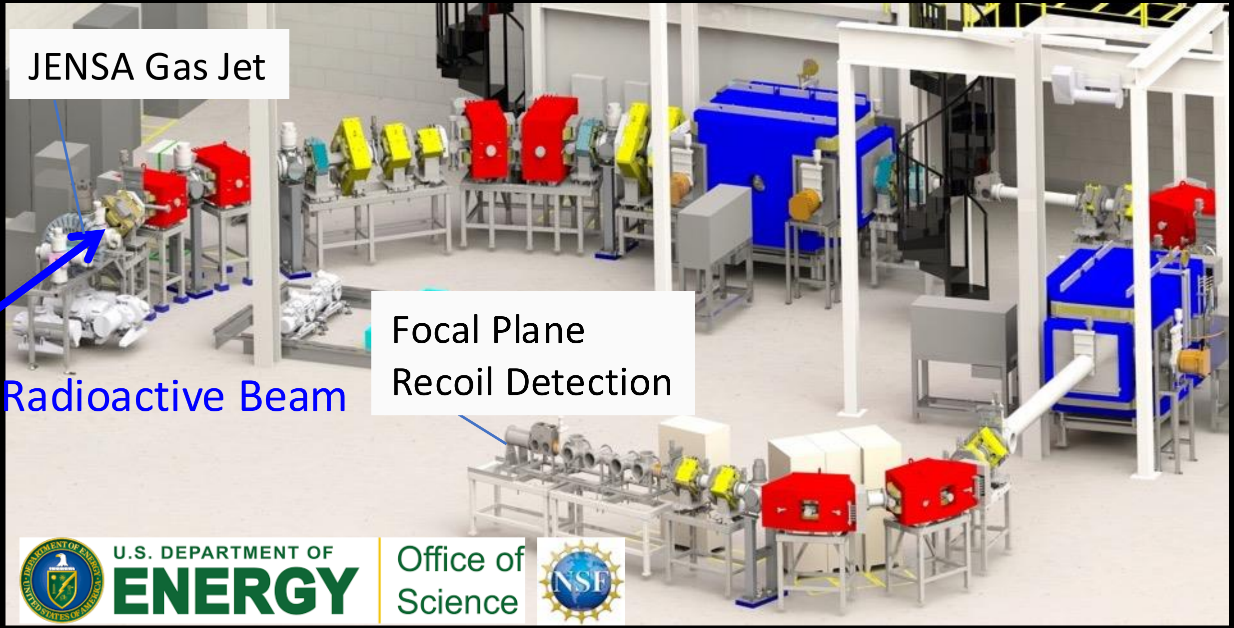
Direct Measurements of (α,γ) and (p,γ) reactions with the new SECAR Recoil Separator at FRIB

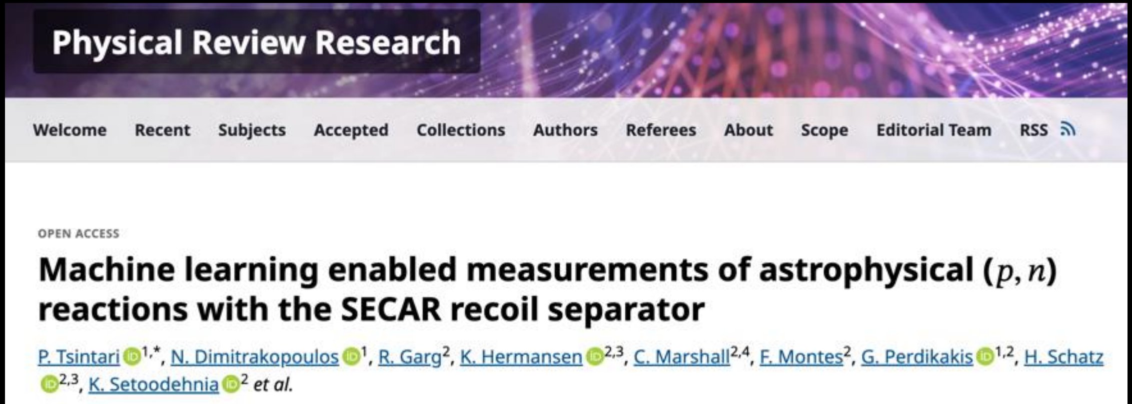
Lead
G. Berg, M. Couder, Notre Dame
(Design based on St. George)
F. Montes, H. Schatz, MSU
J. Blackmon, LSU
K. Chipps, M. Smith, ORNL
U. Greife, CSM





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

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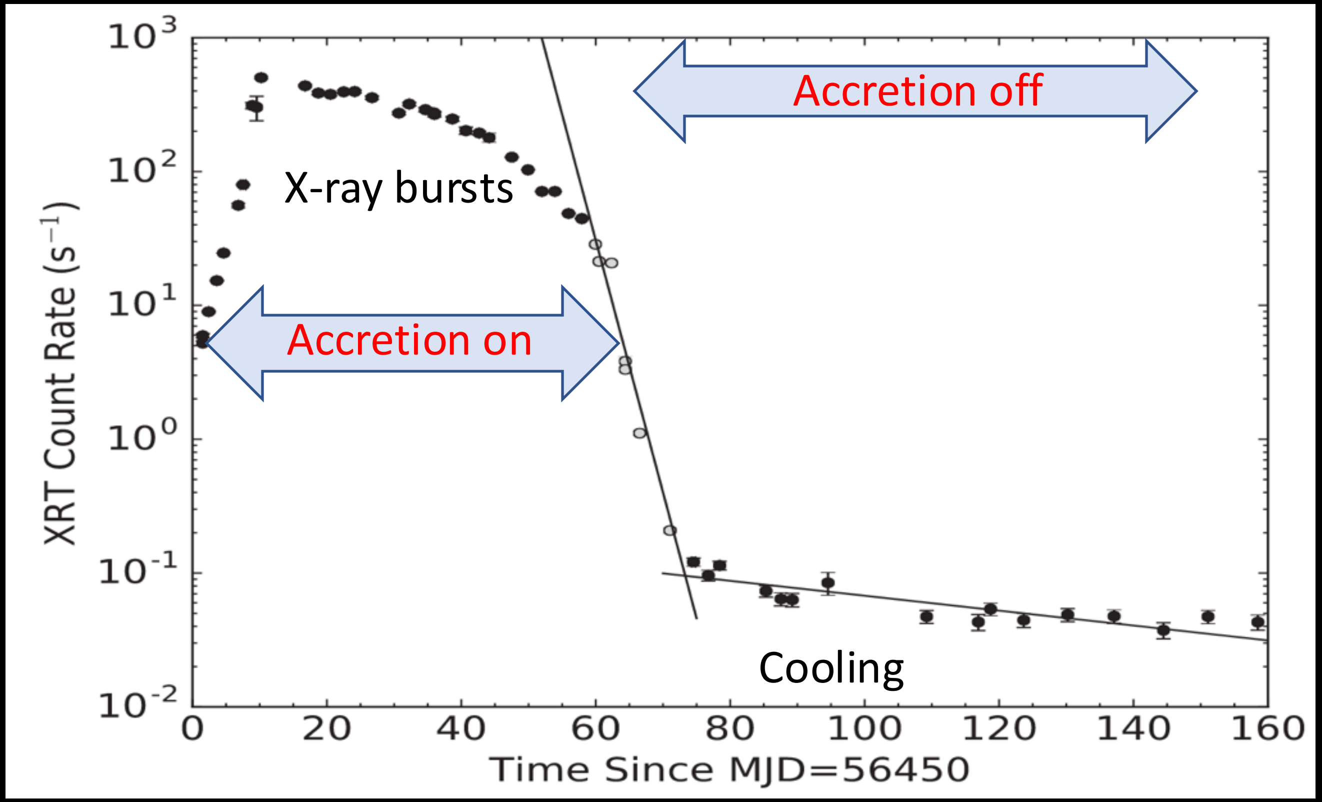
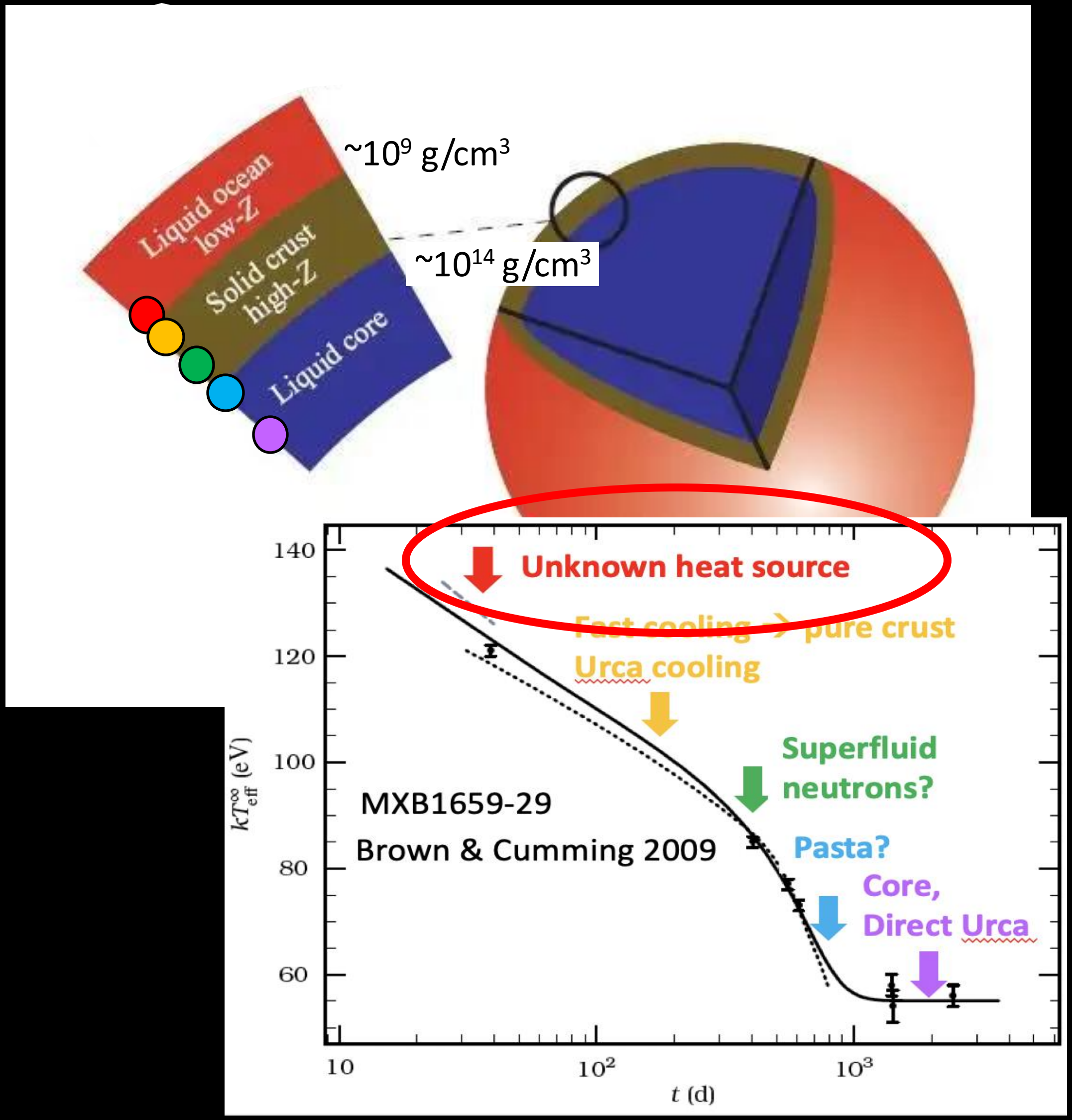
Machine learning enabled measurements of astrophysical (p, n) reactions with the SECAR recoil separator

P. Tsintari[1,*], N. Dimitrakopoulos[1], R. Garg[2], K. Hermansen[2,3], C. Marshall[2,4], F. Montes[2], G. Perdikakis[1,2], H. Schatz[2,3], K. Setoodehnia[2] et al.

Demonstrated (p,n) capability with $^{58}Fe(p,n)$

Accreting Neutron Stars as Quasi Persistent Transients Probe Neutron Star Physics



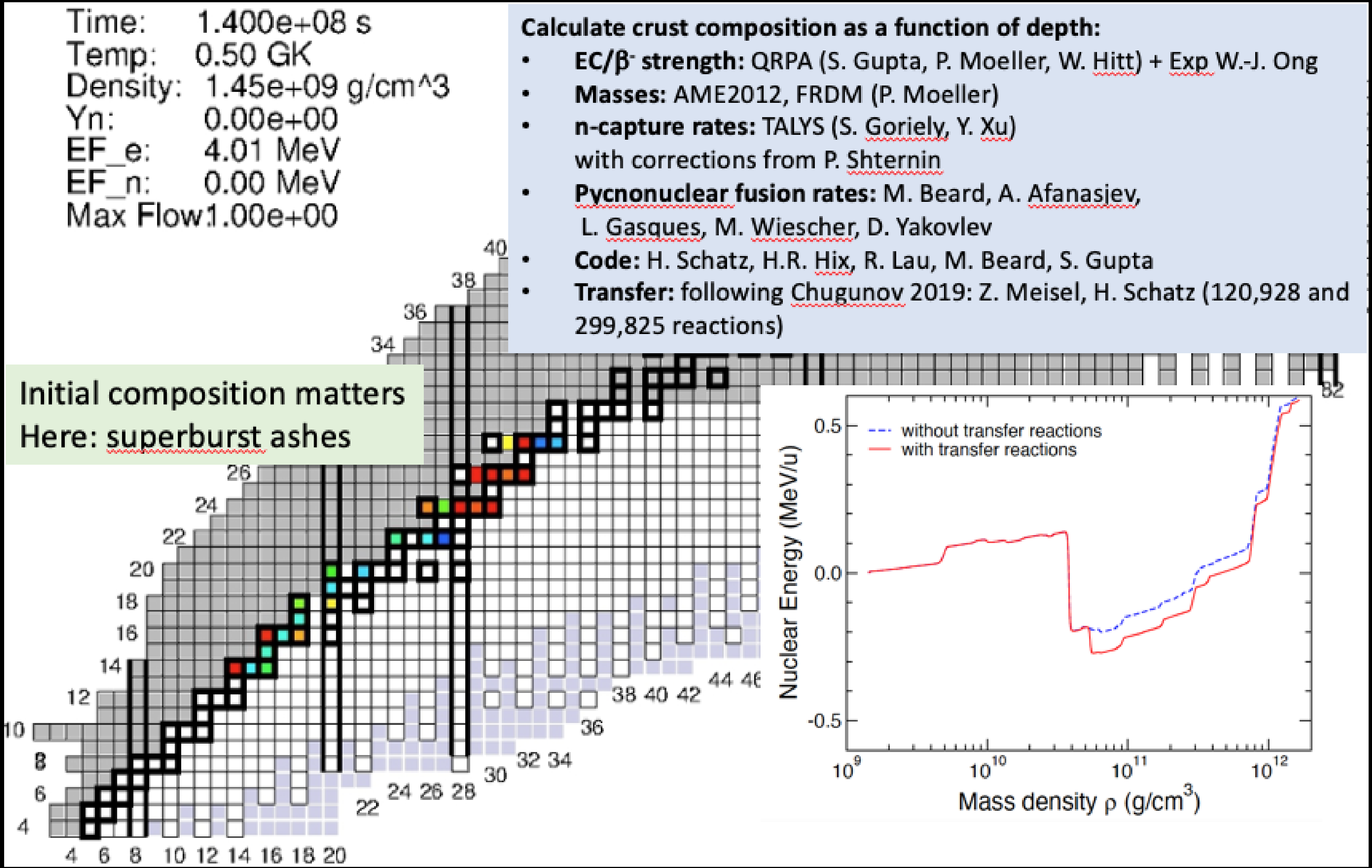


→ Nuclear reactions during accretion heat the crust
→ Cooling curves probe dense matter physics at increasing depth as time goes on

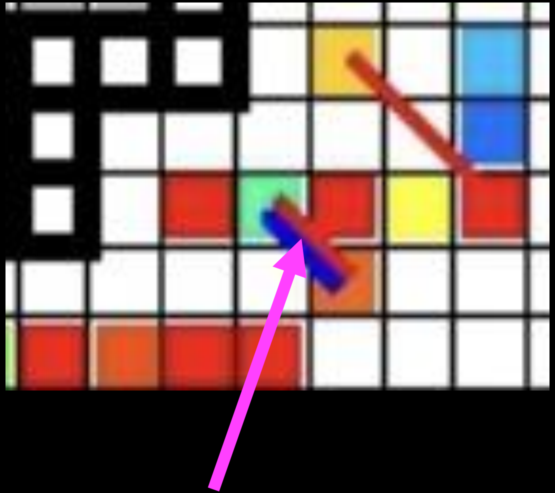
Reactions Heating the Crust During Accretion Identified

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)



Initial composition matters
Here: superburst ashes



Urca Cooling

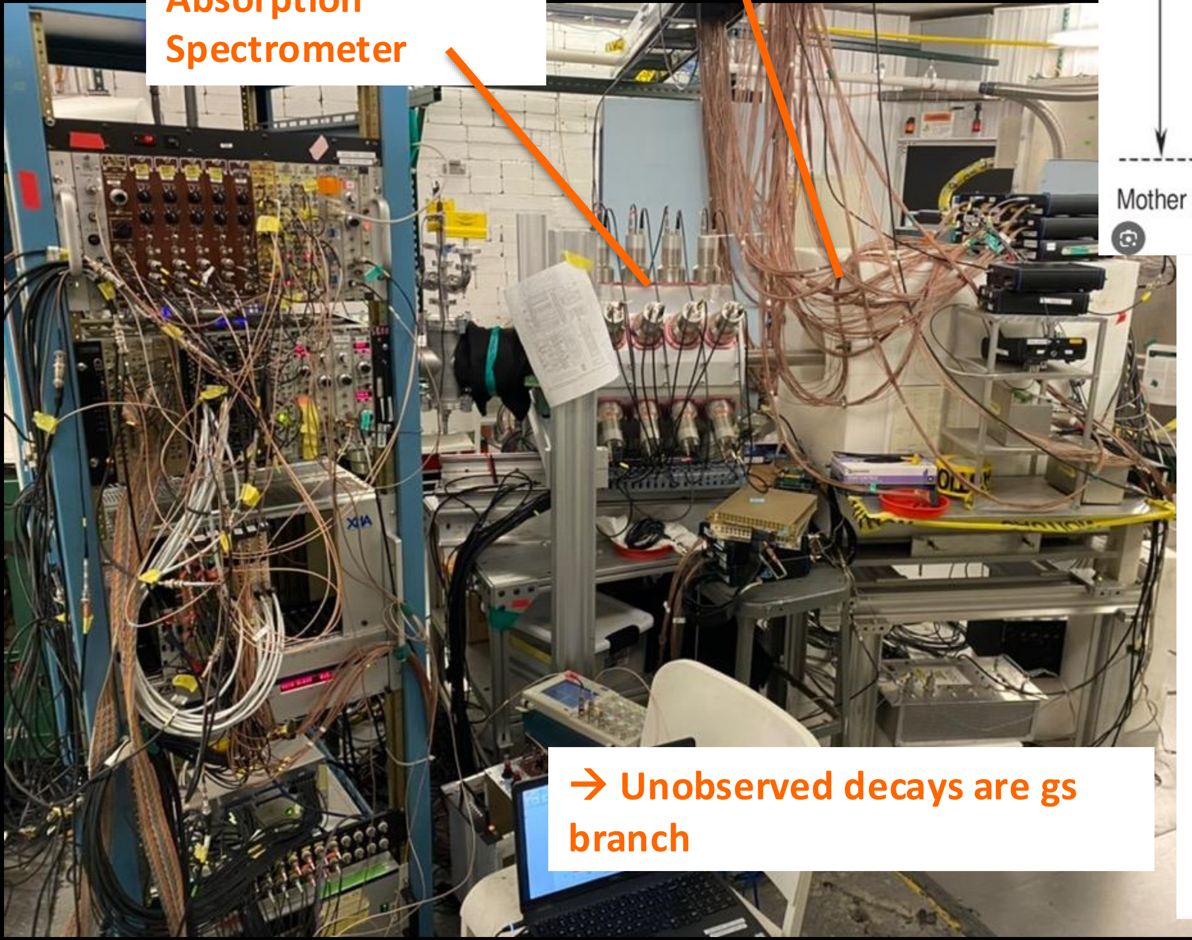
During EC transition gs-gs β-decay is not completely Pauli blocked as emitted electrons can have very high energy
→ EC and β-decay Rapidly alternate

Probe Urca Cooling Rates Via β-delayed Total Absorption Gamma Spectroscopy → Get Strength of gs-gs β-decay transitions

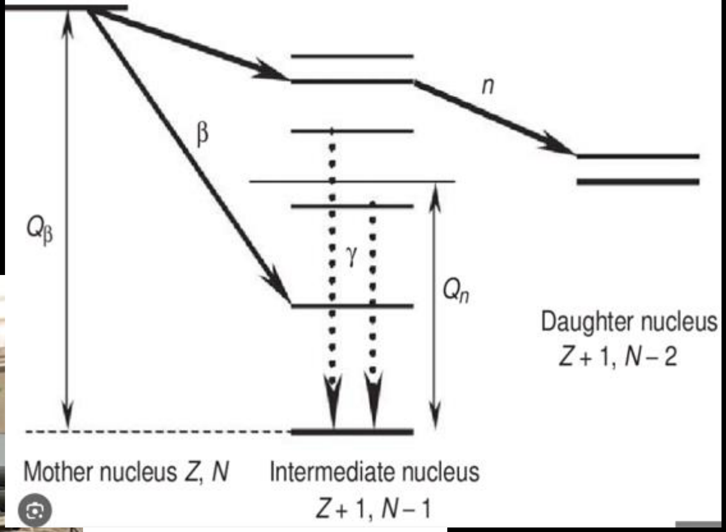
Setup at NSCL@MSU

Measure all γ-branches with SuN Total Absorption Spectrometer

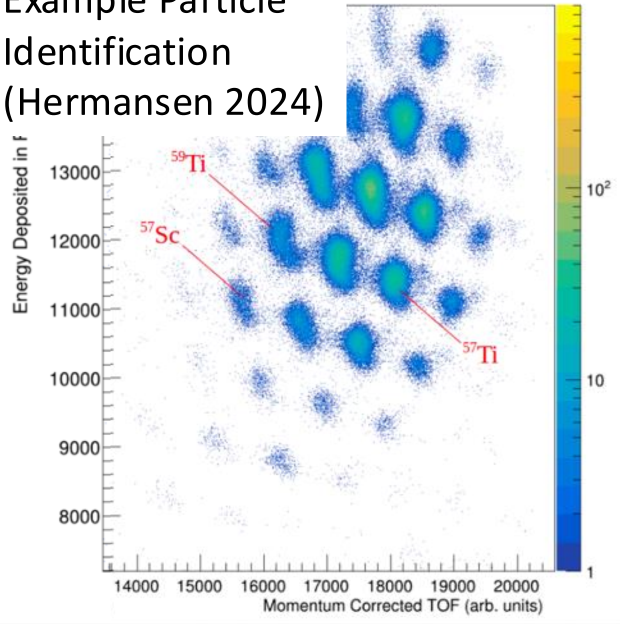
Measure all n-branches with NERO



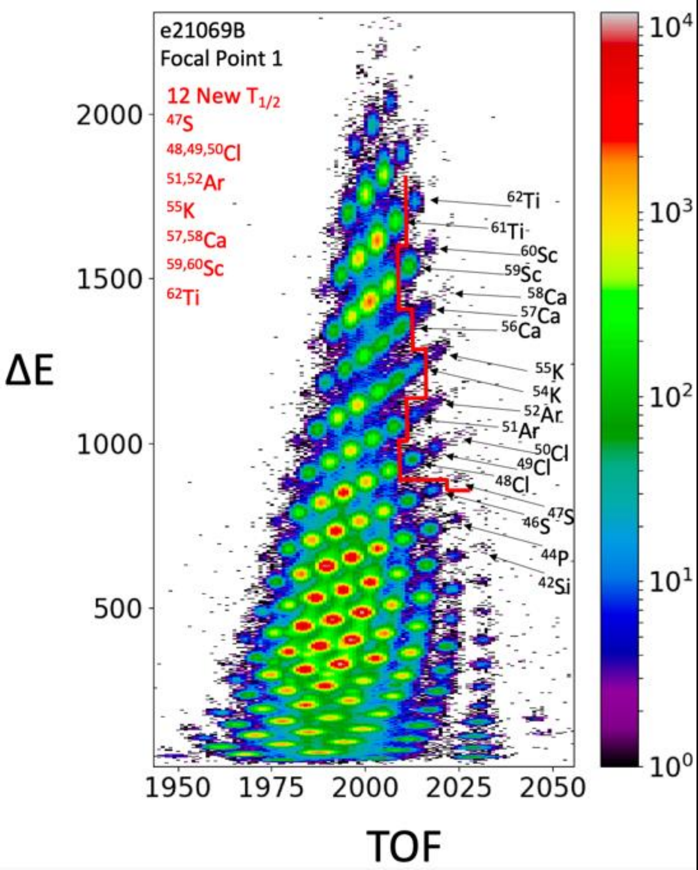
→ Unobserved decays are gs branch



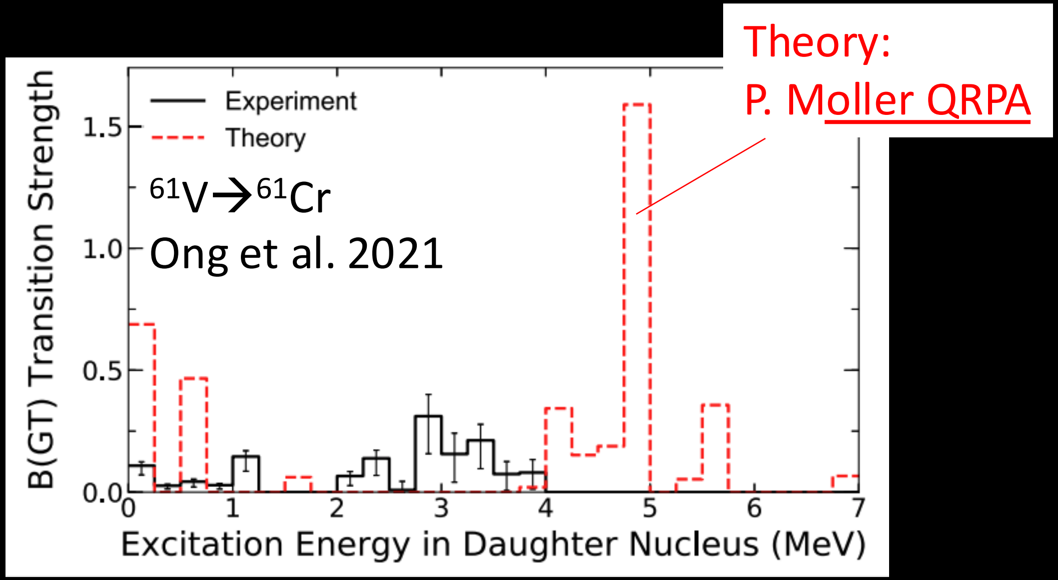
Example Particle Identification (Hermansen 2024)

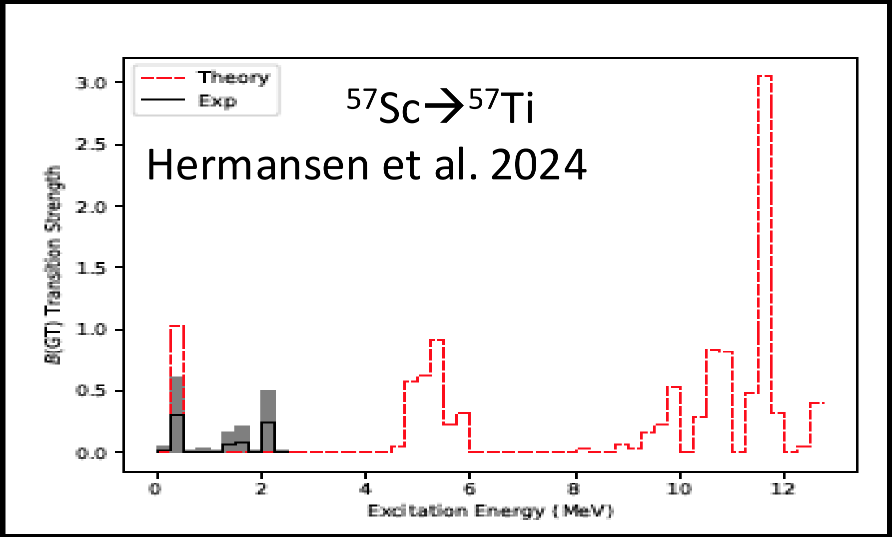


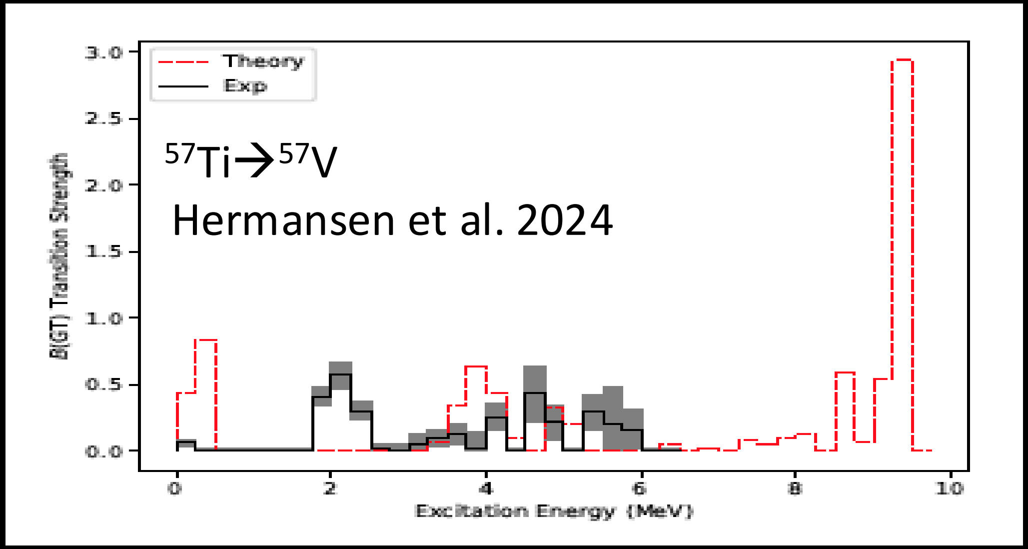
Recent FRIB experiment (Ong et al.)

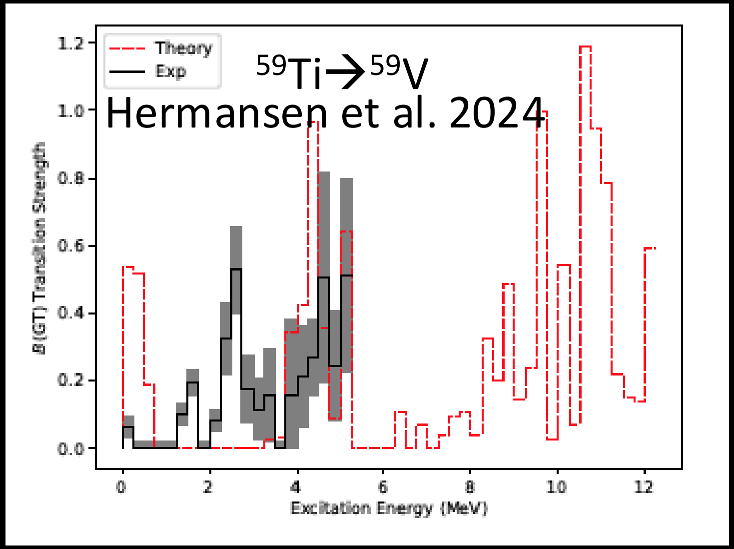


Recent Results







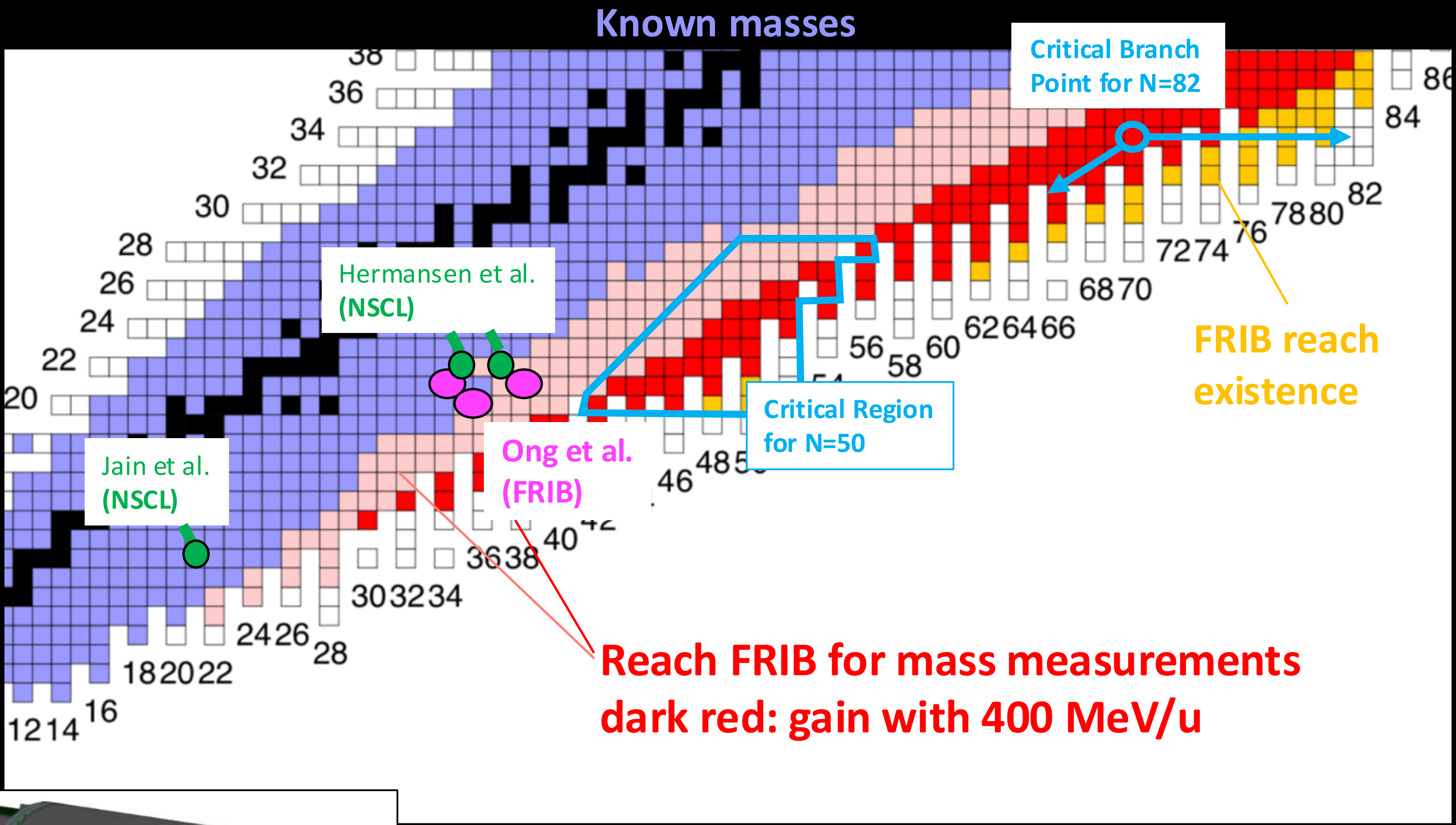


Trend:
Weaker population of ground state than expected
→ Weaker Urca cooling

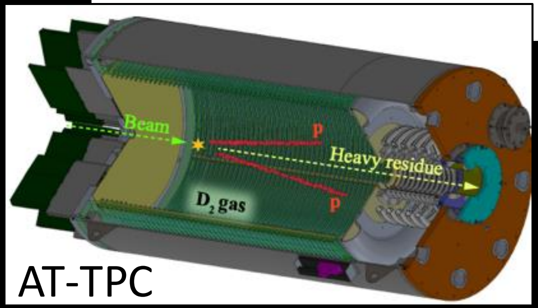
All Rare Isotopes in Neutron Star Crusts Within Reach at FRIB

CeNAM

FRIB



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



AT-TPC

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

International Research Network for Nuclear Astrophysics (IReNA) – Connects Astrophysics, Nuclear Physics, ….

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

BRIDGCE UK
70 members from 19 institutions

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

Joint Institute for Nuclear Astrophysics (JINA-CEE)

Becoming

Center for Nuclear Astrophysics across Messengers (CeNAM)
57 Institutions, 82 Senior Participants

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

UKAKUREN/JaFNA
Japanese Forum for Nuclear Astrophysics
16 Institutions
119 Scientists

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

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

ChETEC INFRA

Supports:
- Joint workshops
- Schools
- Visits/Exchanges
- Online Seminar
- Professional Development
- Young Researchers Organization
- Blog!

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Summary

- Major opportunities for neutron star surface and crust physics at rare isotope beam facilities
  - New Generation of Rare isotope facilities (RIKEN RIBF, FRIB – others under construction: FAIR in Germany, RAON in Korea, HIAF in China, ARIEL in Canada, nu-CARIBU at ANL, ….)
  - Complementary to FRIB program to probe nuclear EOS in heavy ion collisions
- Large amount of X-ray data available. Desired:
  - More spectroscopic data
  - Catch transients early (days) and add late long term data points – both are critical
  - New X-ray missions are important (XRISM)
- Together major opportunities to address long standing and new open questions
- Multi-disciplinary international collaborations essential and need to be stimulated by centers and networks
  - CeNAM
  - IReNA