Explosive Hydrogen Burning

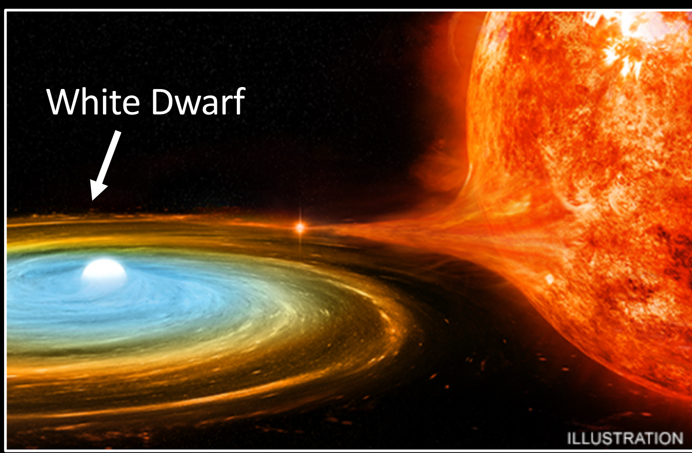
Hendrik Schatz
Department of Physics and Astronomy
Facility for Rare Isotope Beams
Center for Nuclear Astrophysics Across Messengers (CeNAM)
Michigan State University

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

Hot Explosive Hydrogen Burning

Hydrogen burns easily → need to inject hydrogen into hot and dense environment

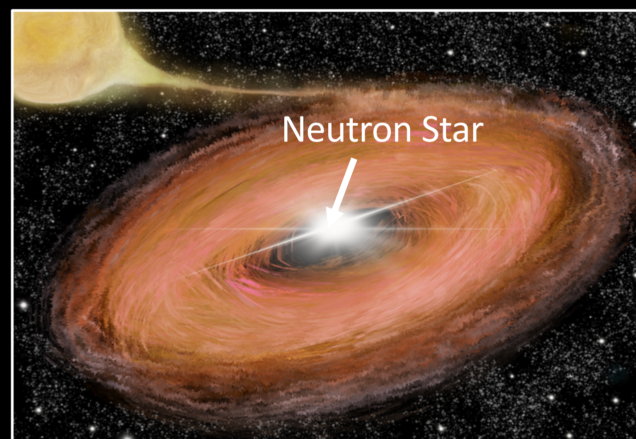
Nova Explosion



This Talk

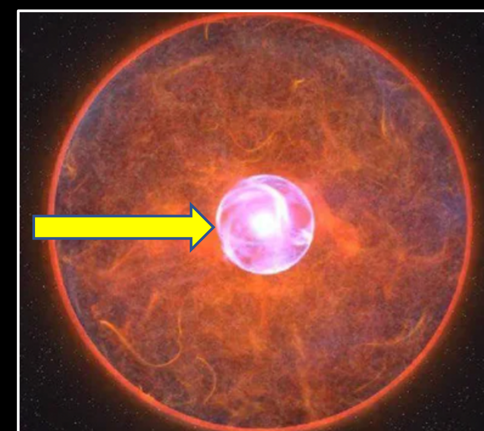
→ Talk by Thanassis Psaltis

X-ray Burst



This Talk

Neutron Star Inspiral
Thorne-Zytkow Object



→ Talk by Alexander Hall-Smith
→ Poster by Sophie Abrahams

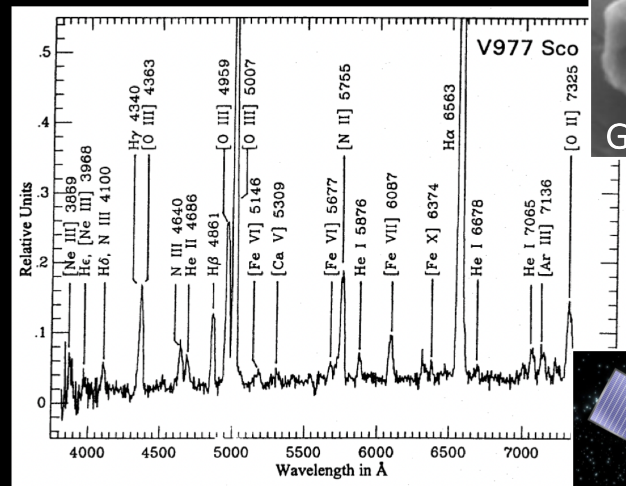

Credit: Bob King

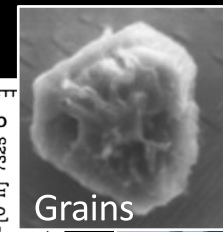
V5668_Sagittarii 2015
About 30-50/yr in the Galaxy)

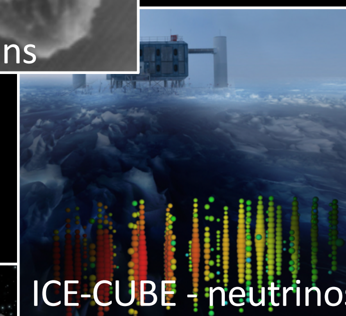
Credit: Bob King

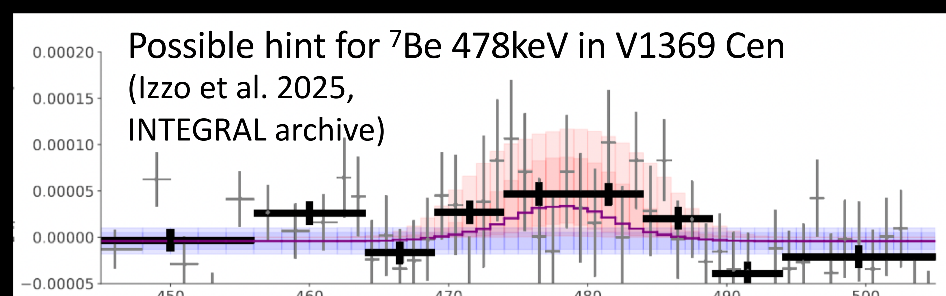
Novae Open Questions

- **What nuclei do novae make?**
  - Endpoint of nucleosynthesis?
    - Observed elements up to Ar, Ca?
  - Nucleosynthesis contribution?
    - Li, ^{13}C, ^{15}N, ^{17}O, F?, P?
    - ^{26}Al observed via γ-rays: up to 75% (2D GCE Vasini et al. 2025)
- **How is white dwarf material mixed into the ejecta?**
  - Lots of multi-D efforts → impacts explosion
- **Novae as multi-messenger sources?**
  - Are there pre-solar grains from Novae? (use isotope anomalies to identify)
  - Can we detect nuclear γ-rays from ^{7}Be, ^{18}F, ^{22}Na? (so far only upper limits – hint of ^{7}Be?)
  - What do GeV gamma-ray detections tell us?
  - Can we detect high energy neutrinos?
- **What is the ultimate fate of the system?**

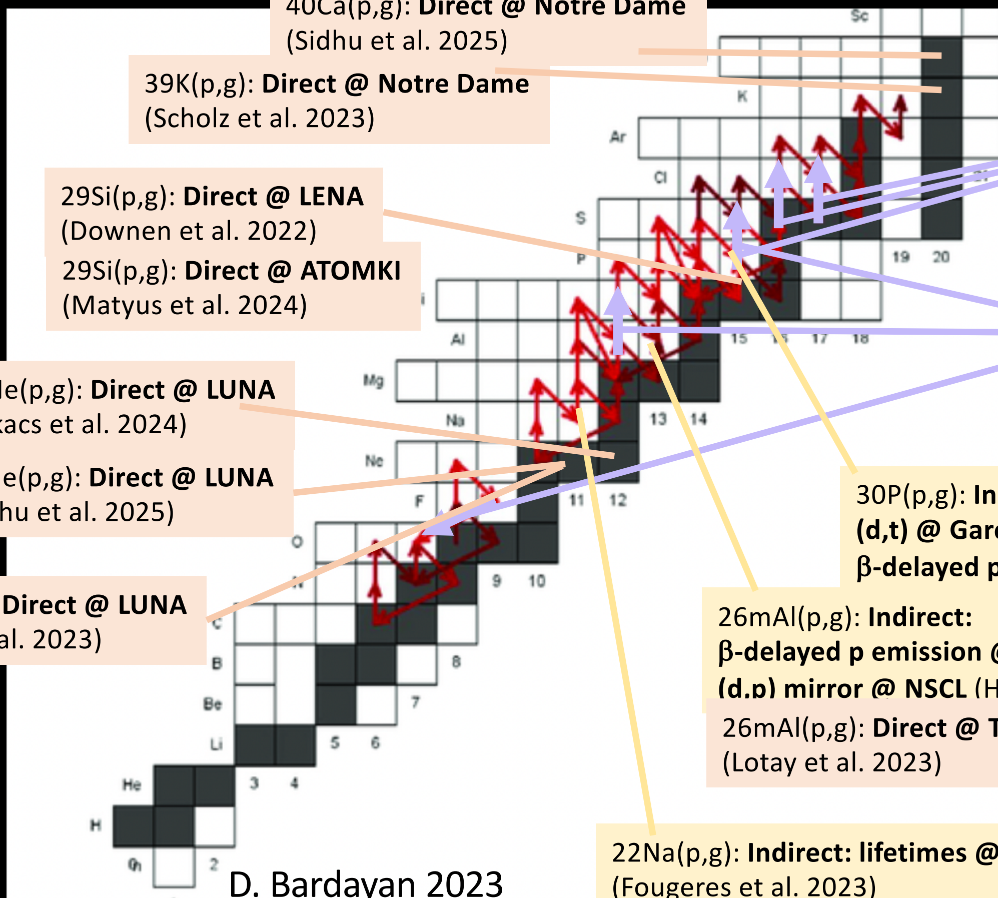








Nuclear Physics in Nova Explosions



D. Bardayan 2023

40Ca(p,g): **Direct @ Notre Dame**
(Sidhu et al. 2025)

39K(p,g): **Direct @ Notre Dame**
(Scholz et al. 2023)

29Si(p,g): **Direct @ LENA**
(Downen et al. 2022)

29Si(p,g): **Direct @ ATOMKI**
(Matyus et al. 2024)

22Ne(p,g): **Direct @ LUNA**
(Takacs et al. 2024)

21Ne(p,g): **Direct @ LUNA**
(Sidhu et al. 2025)

20Ne(p,g): **Direct @ LUNA**
(Masha et al. 2023)

Rate uncertainties affecting 28Si/29Si and 32S/33S ratios needed to ID nova grains (Ward et al. 2025)

Remaining main nuclear uncertainties (Jose 2024) (unstable!)

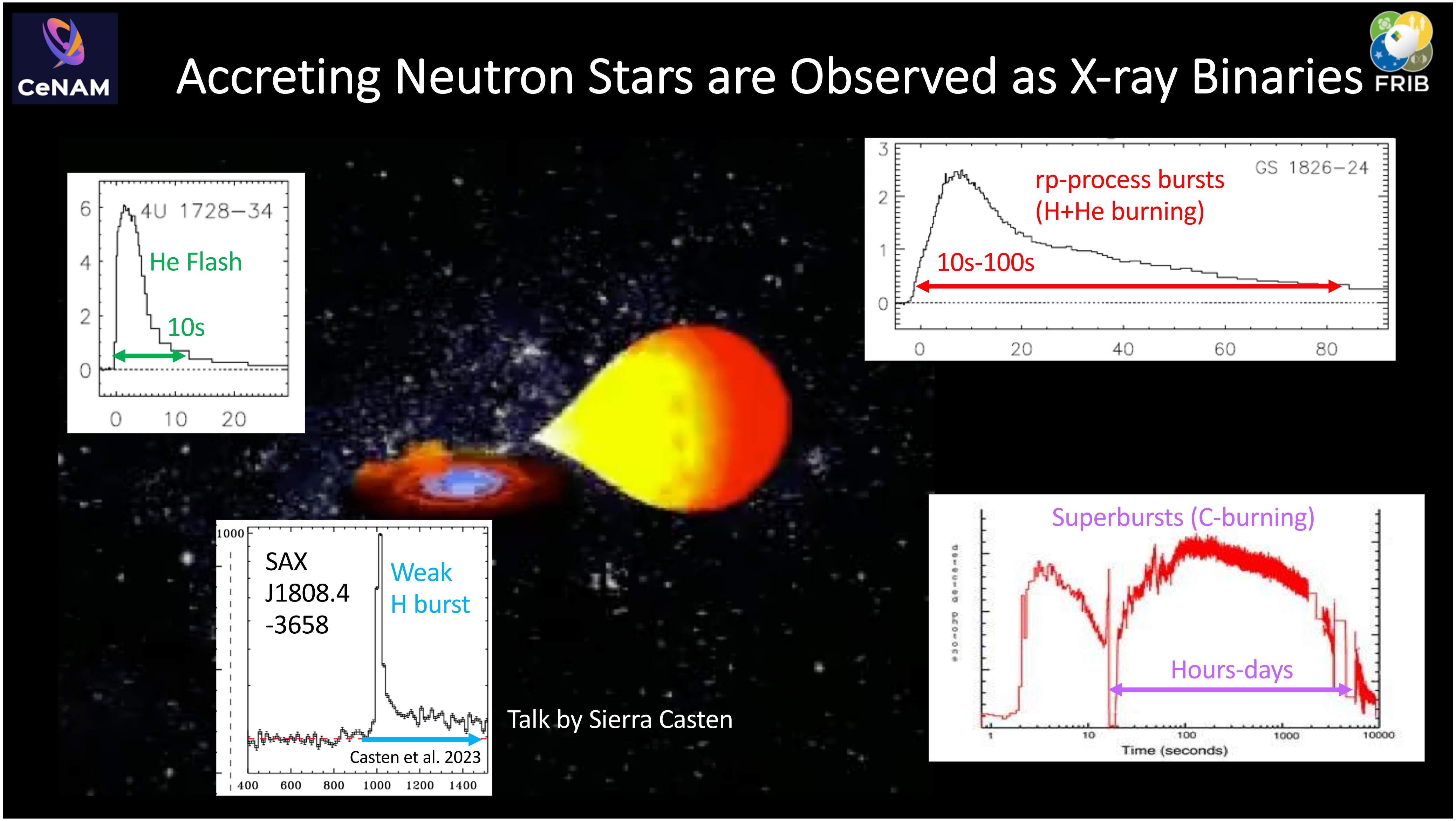
30P(p,g): **Indirect:**
(d,t) @ Garching (Kamil et al. 2023)
β-delayed p emission @ NSCL (Budner et al. 2023)

26mAl(p,g): **Indirect:**
β-delayed p emission @ Texas A&M (Stefanescu et al. 2024)
(d,p) mirror @ NSCL (Hallam et al. 2021)

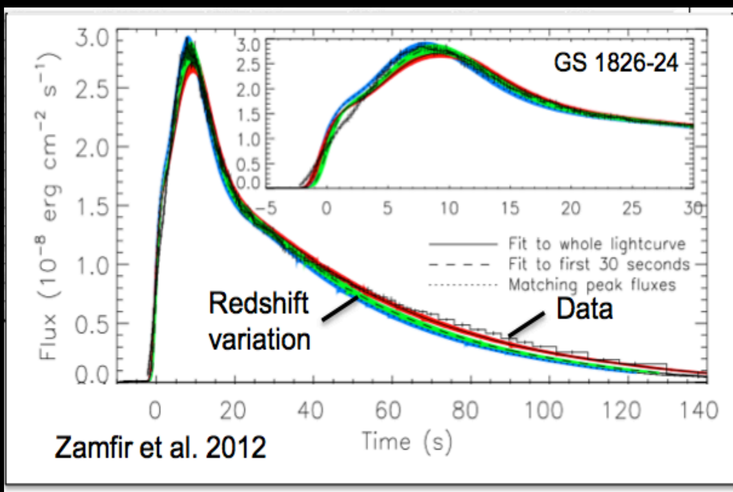
26mAl(p,g): **Direct @ TRIUMF**
(Lotay et al. 2023)

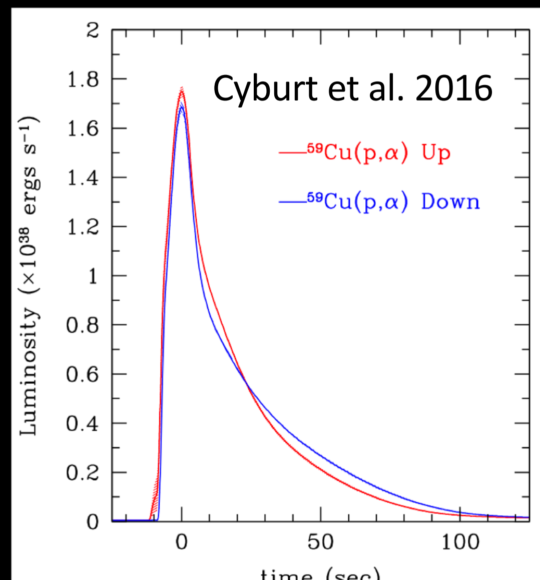
22Na(p,g): **Indirect: lifetimes @ GANIL**
(Fougeres et al. 2023)

Accreting Neutron Stars are Observed as X-ray Binaries

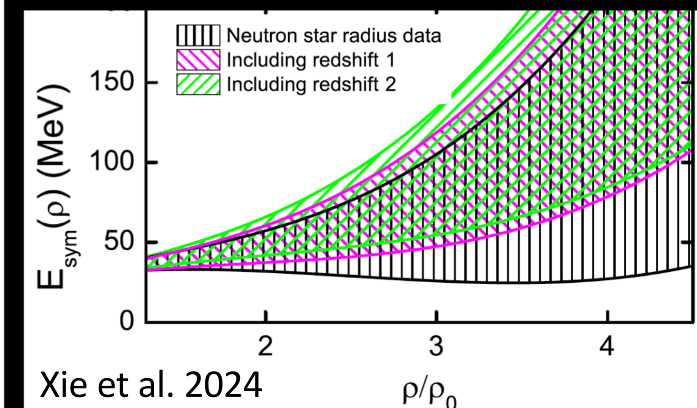


Open Question: Neutron Star Properties from Light Curve?





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



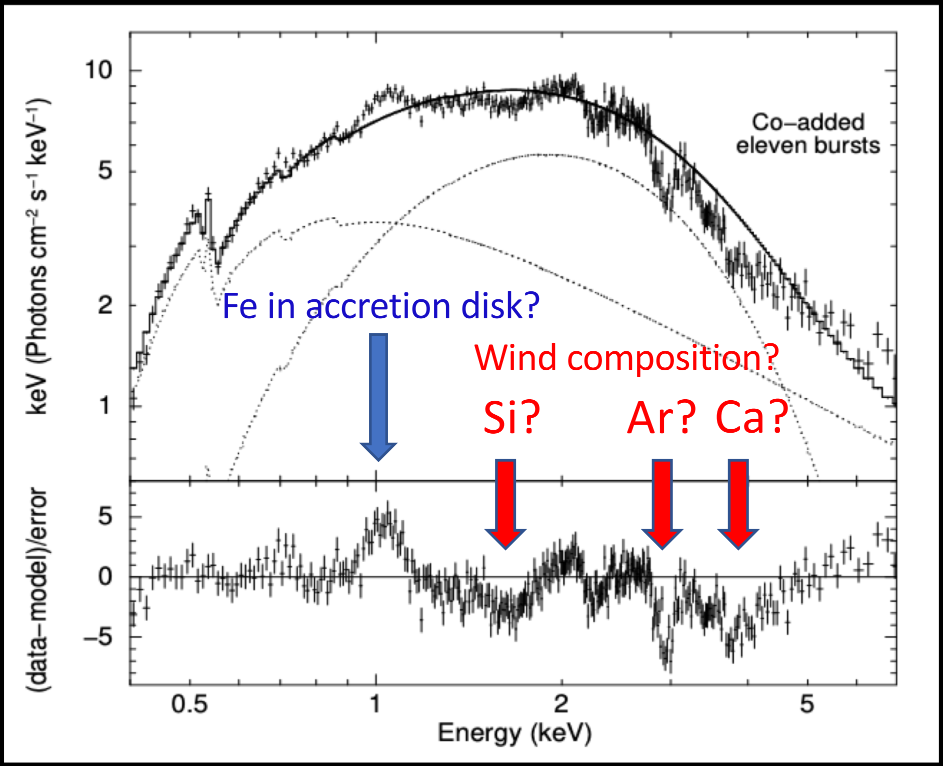
→ Extract surface redshift (REF)
to constrain compactness (mass, radius)
→ Burst frequency probes surface heat
and NS interior (REF)

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

→ Redshifts from bursts do provide
Complementary EOS constrtaints

Open Questions: Is Material Ejected?

Spectral features in 4U 1820–30 with NICER



Jaisawal et al. 2025

Theory:

- Energy arguments Enuc/E_grav=~2.5%
- Burst+Wind model
  Herrera, Sala, Jose 2023: 2.6%

→ Contribution to the origin of the light p-nuclei?

Need nuclear physics to guide observations

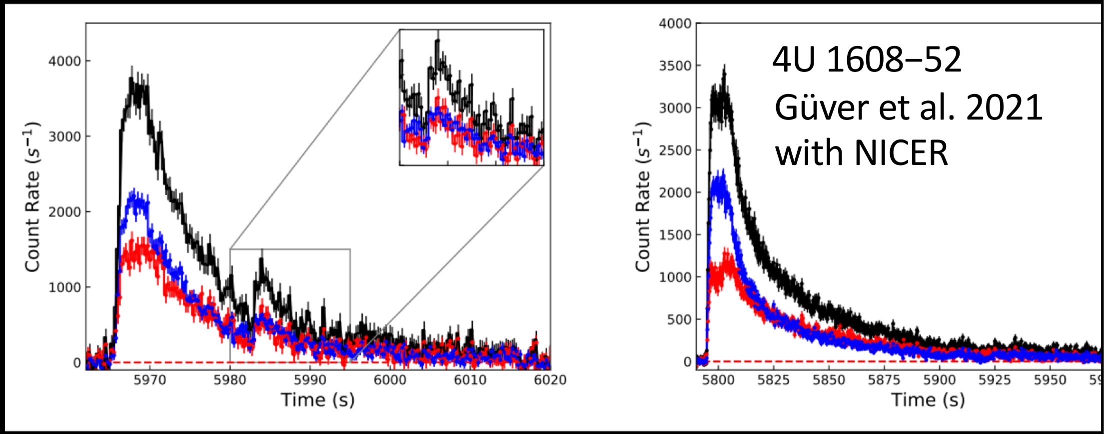
Open Question: Multi-D Effects?

Reduced burst activity at high accretion rates
→ Multi-D?

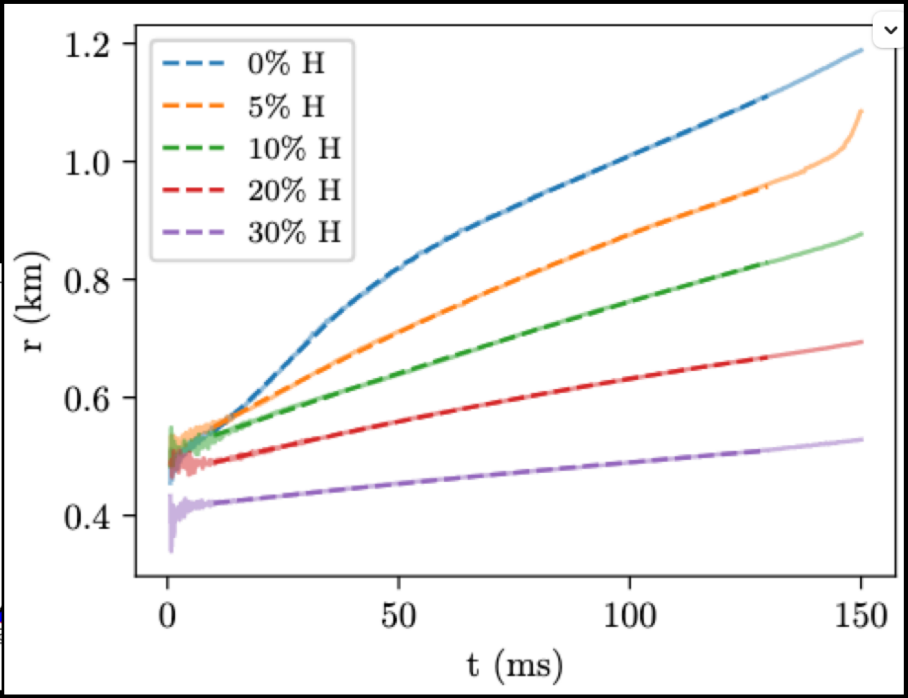
✓ Solved: See poster by Yuri Cavecchi

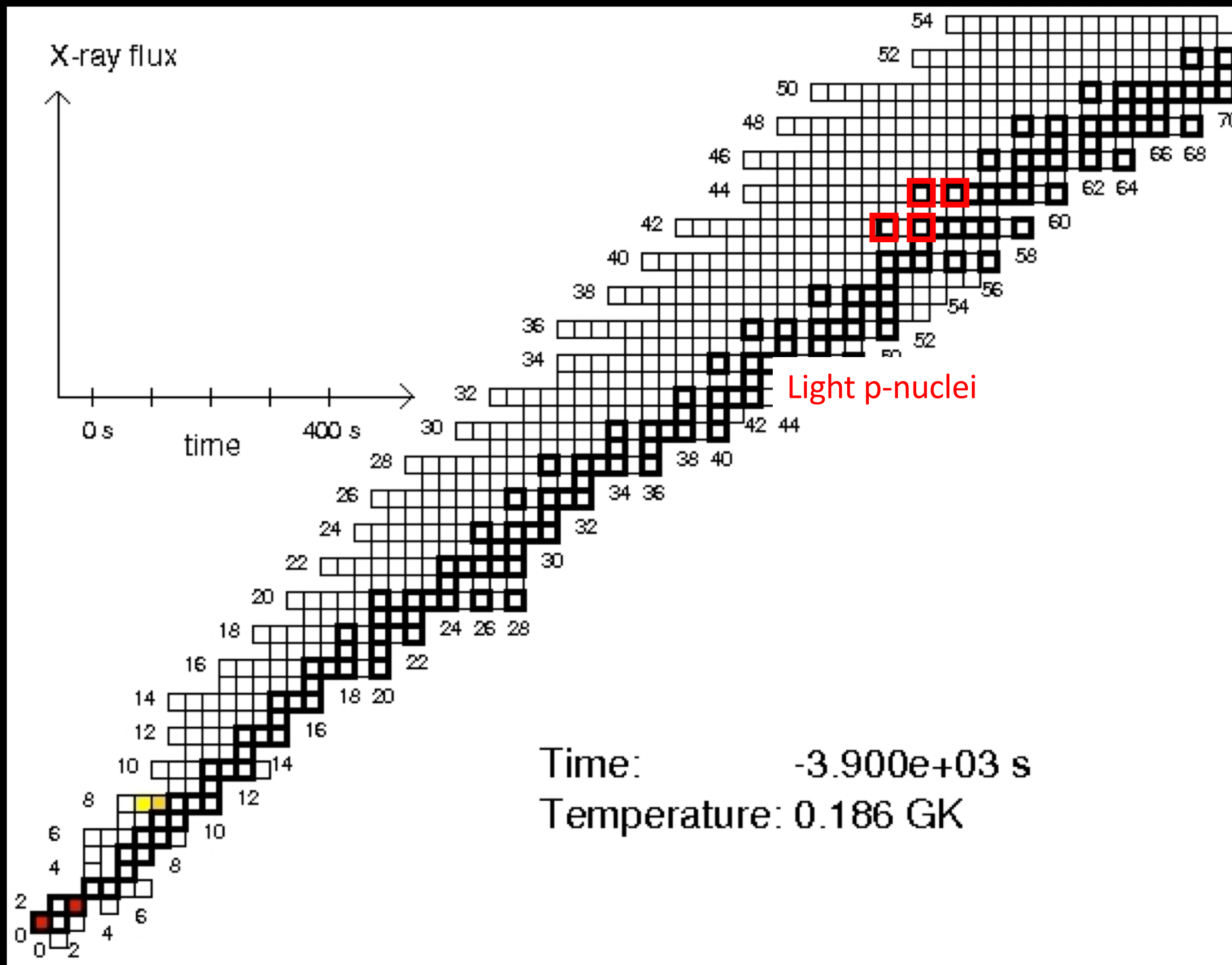
Quasi-Periodic Oscillations of X-ray flux
→ Multi-D? R-Modes?

Multi-peaked bursts
→ Multi-D? (Bhattacharyya et al. 2006)
→ Nuclear waiting points (e.g. Fisker et al. 2004, Lampe et al. 2016, Liyu et al. 2024 With MESA)?



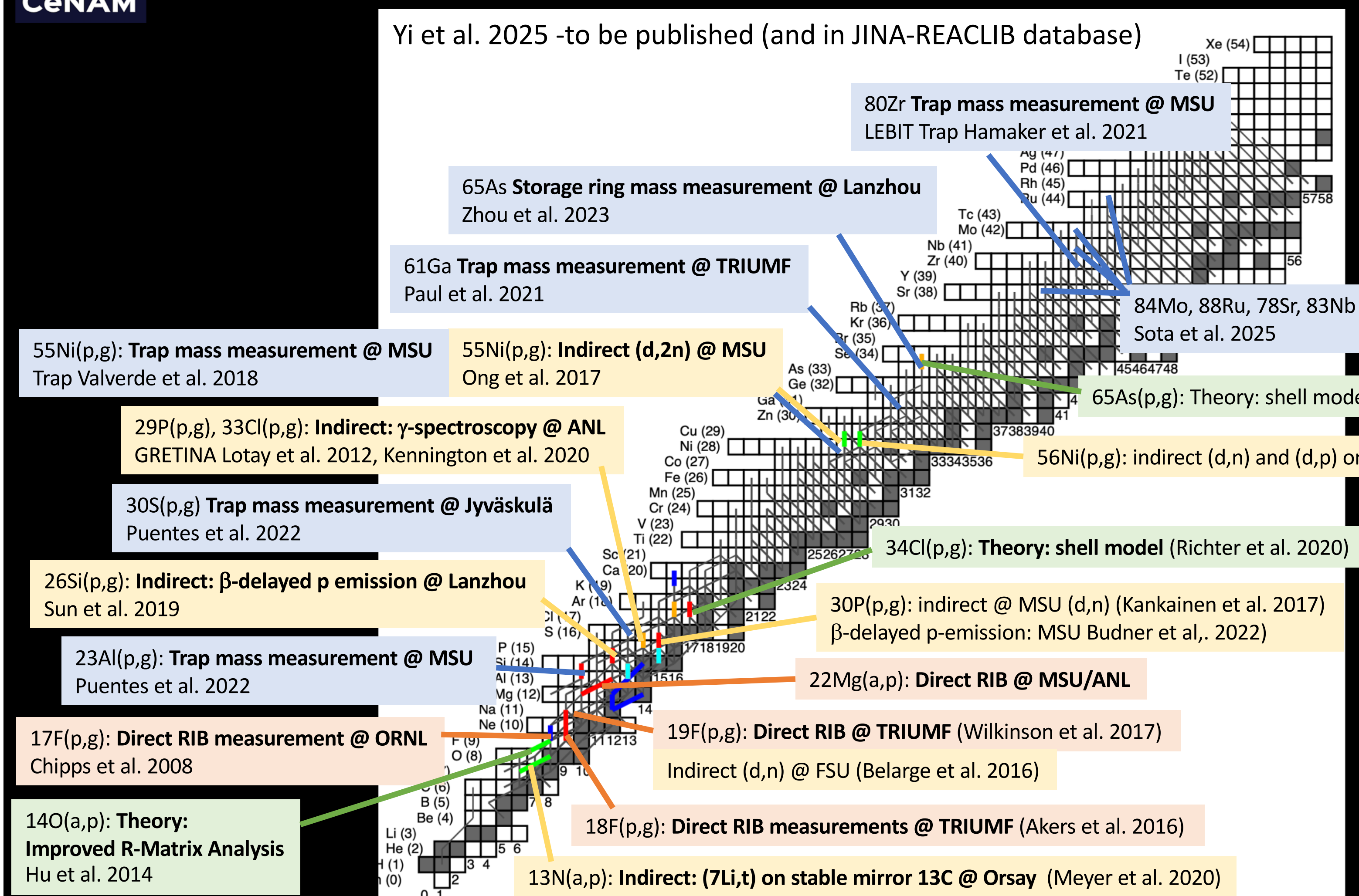
2D modeling of flame spreading
(Johnson & Zingale 2025)





Based on model
By A. Heger
Mixed H/He

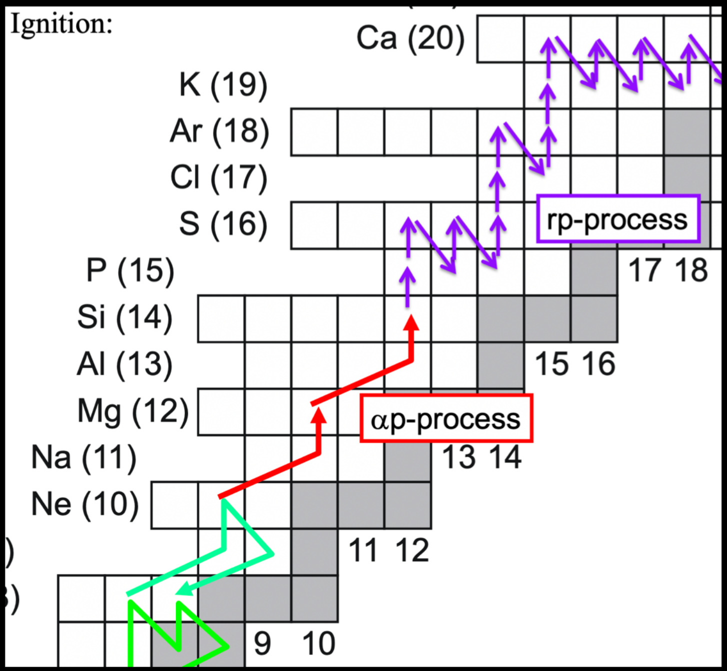
Recent X-ray Burst Nuclear Physics Updates



Challenge: Understanding αp-process

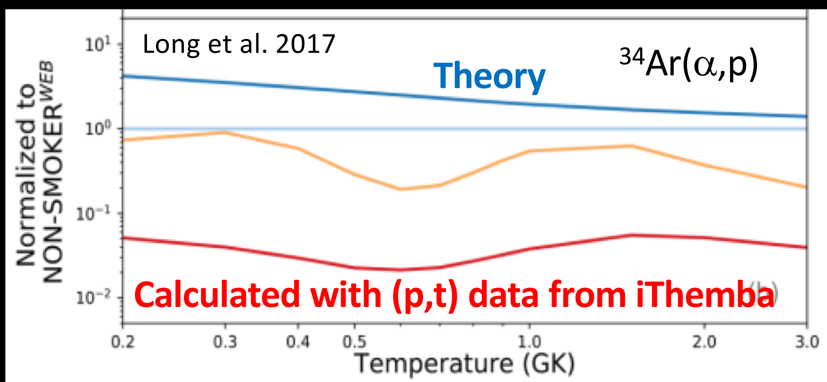
αp-process plays important role

- Fast energy production component
- Defines H/seed ratio and endpoint of rp-process – affects burst tail



Indirect and Direct Measurements of ^{34}Ar(α,p)

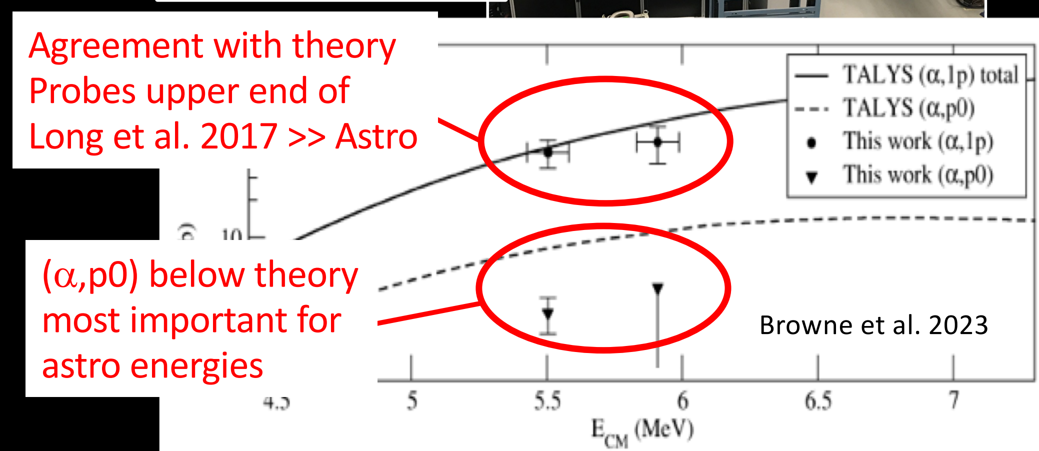
Indirect: identify resonance states in ^{34}Ar(a,p) via ^{40}Ca(p,t) at iThemba



(α,p) rates may be overestimated by x10-100

→ Confirmed by Lauer et al. 2025 populating resonances with ^{37}K(p,p) using ANASEN at NSCL/FRIB

^{34}Ar(α,p) direct measurement at NSCL/FRIB JENSA Gas Target + ORRUBA Si array

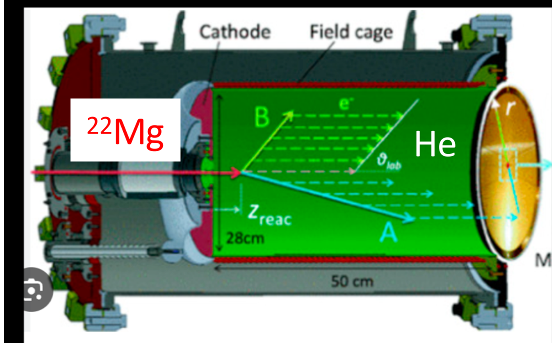


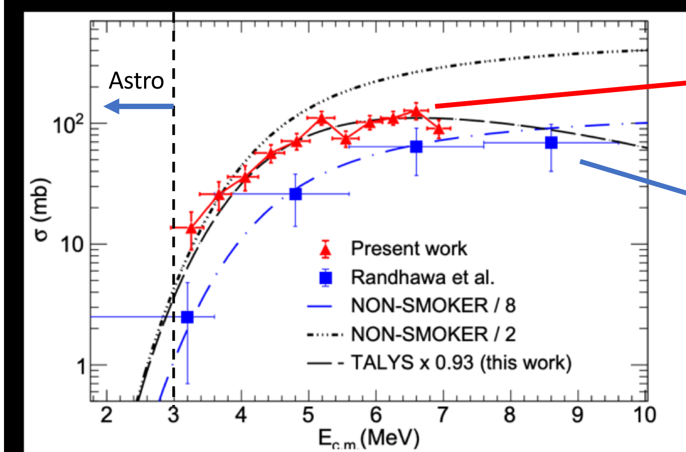
Direct Measurements of ^{22}Mg(α,p)

CeNAM

FRIB

^{22}Mg(α,p) with active target TPC

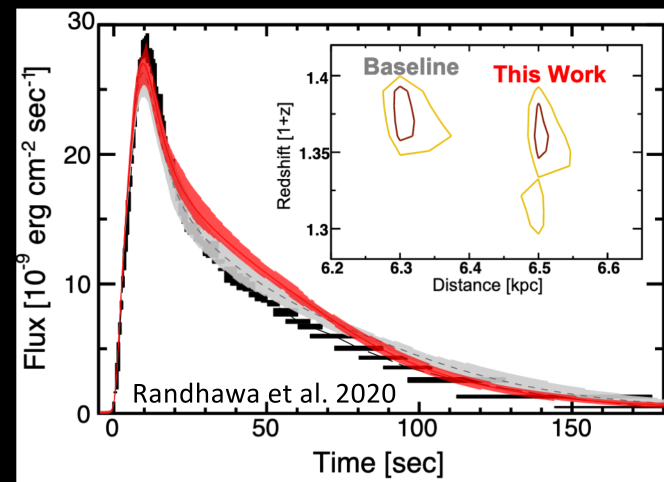




New measurement with MUSIC active target at ANL (Jayatissa et al. 2022)
→ Agrees with Theory

Randhawa et al. 2020
→ x8 lower than theory

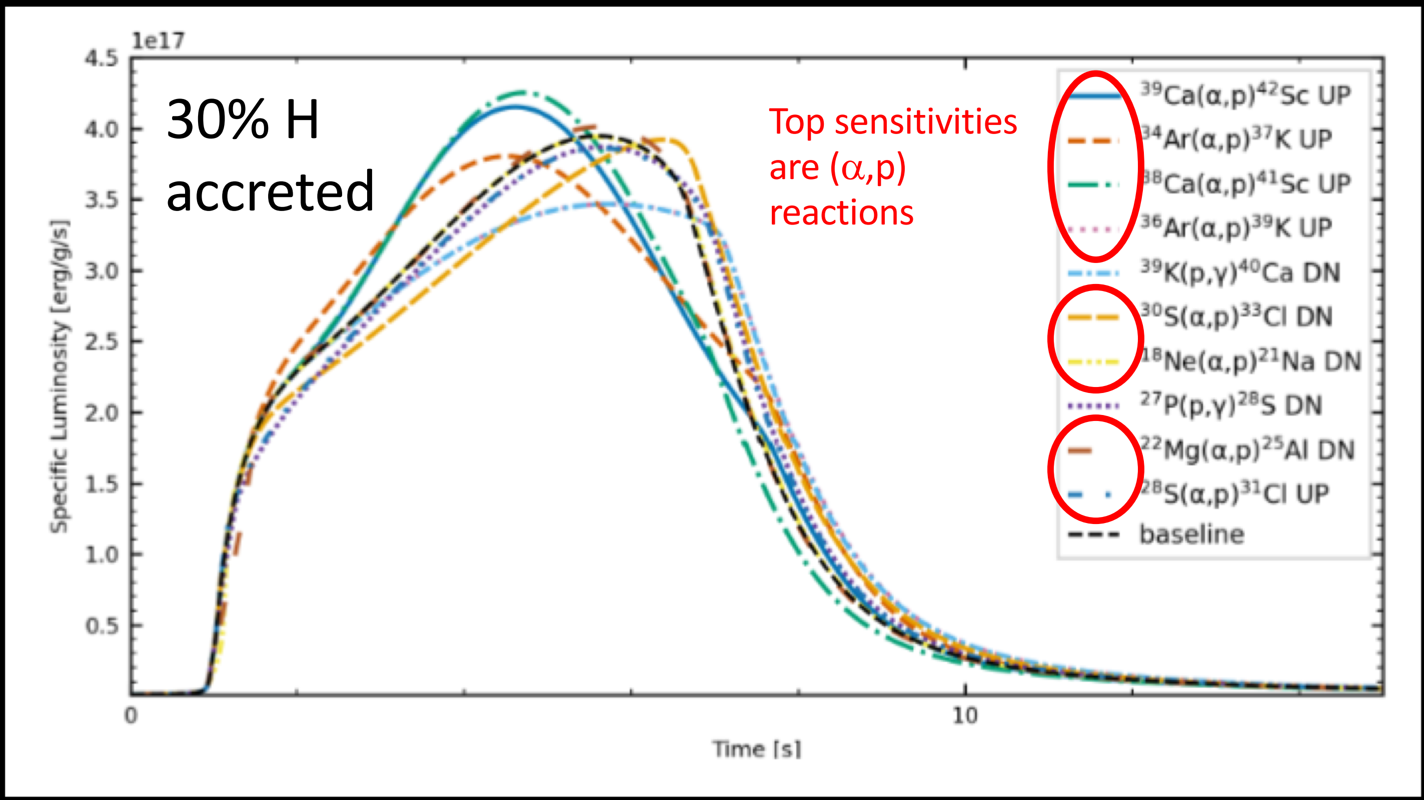
Impact on observations



→ Significant changes in light curve
→ Hu et al. 2021 find better fit to data

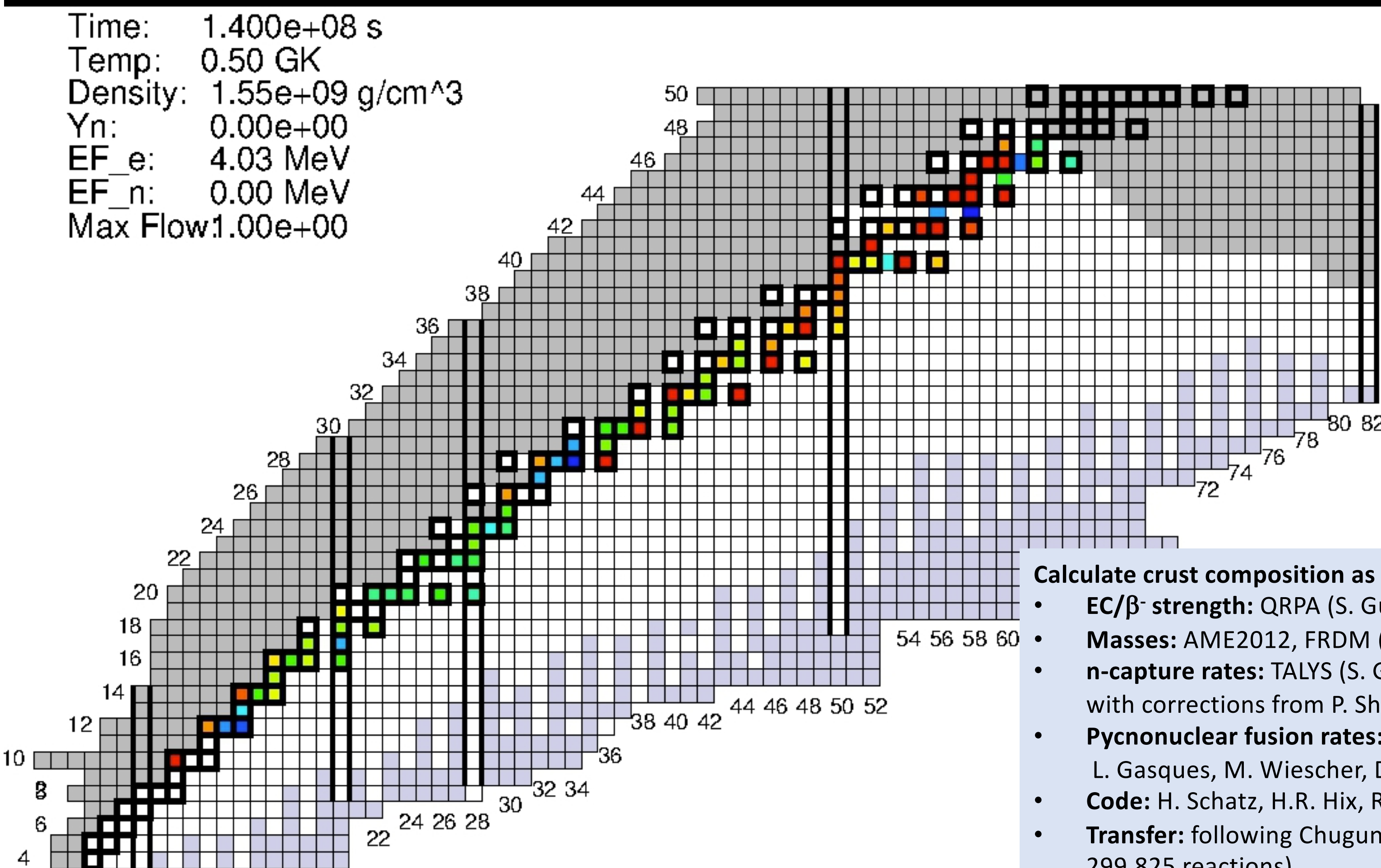
→ Need to address discrepant measurements
→ Need to push to lower energy

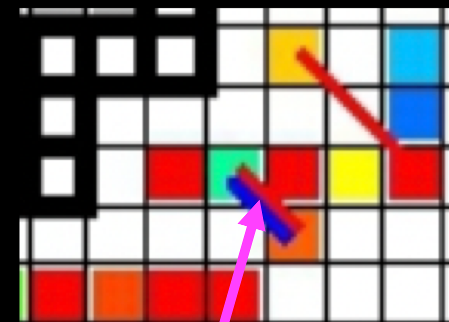
Enhanced Importance of (α,p) in He-rich Bursts



Sultana,
Estrade et al. TBP

Nuclei Stored in Neutron Stars do Interesting Things Too!





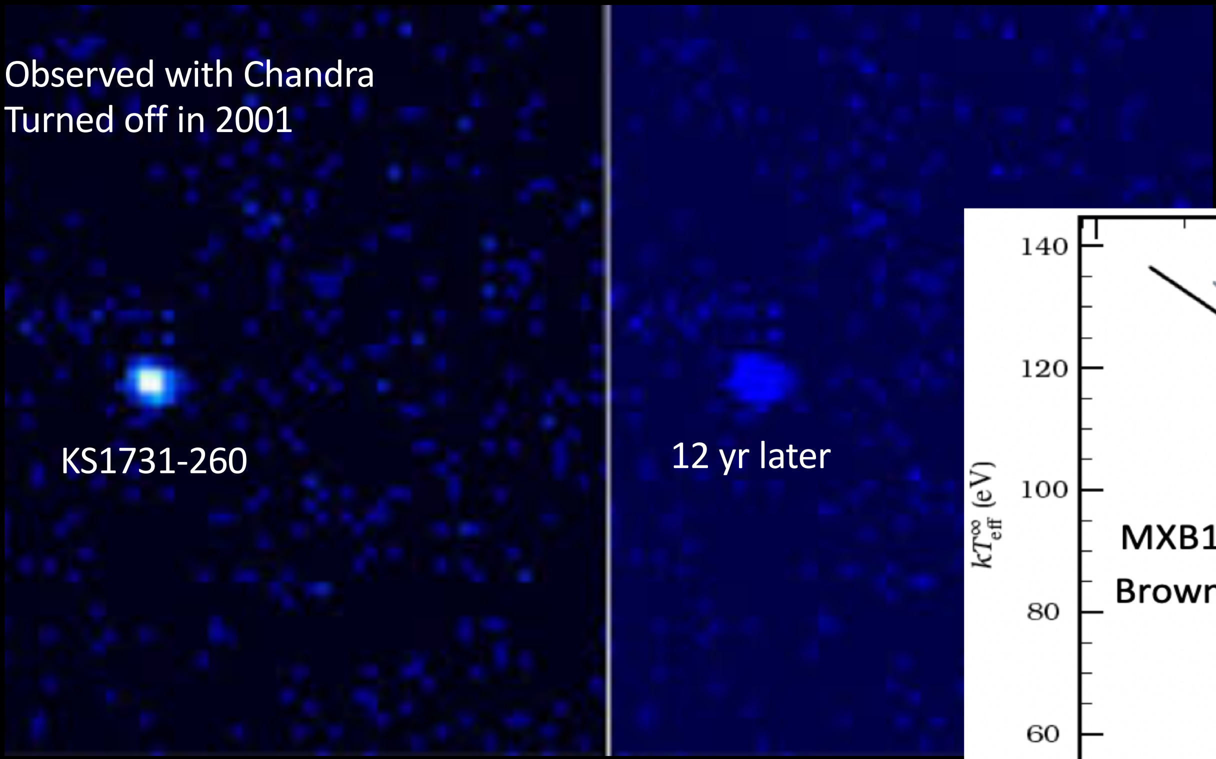
Urca Cooling

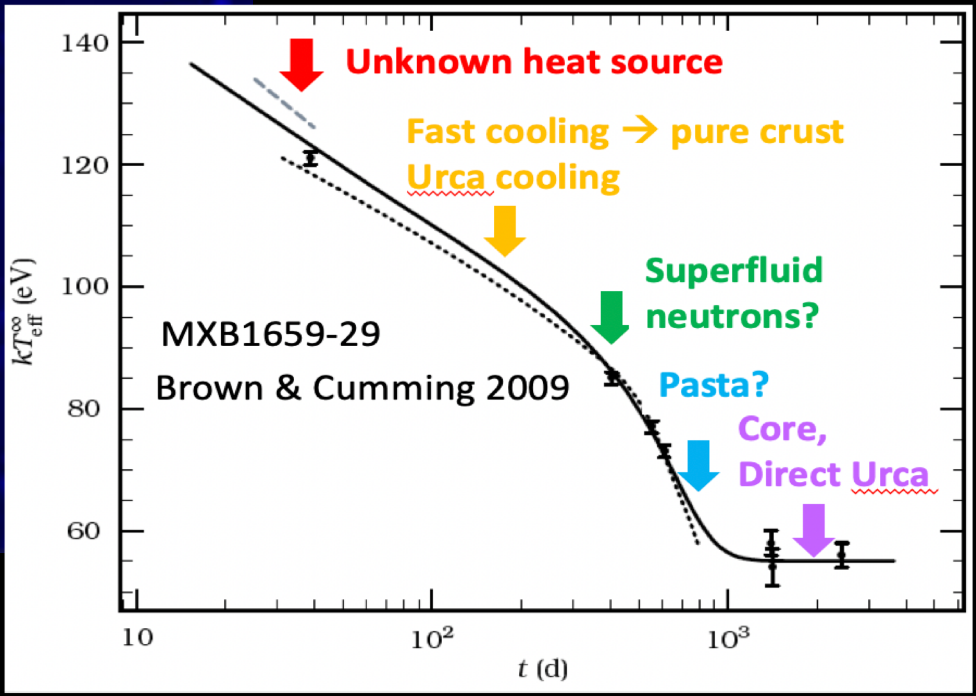
Strength depends on gs-gs transition strength of β-decay and electron capture

Calculate crust composition as a function of depth:

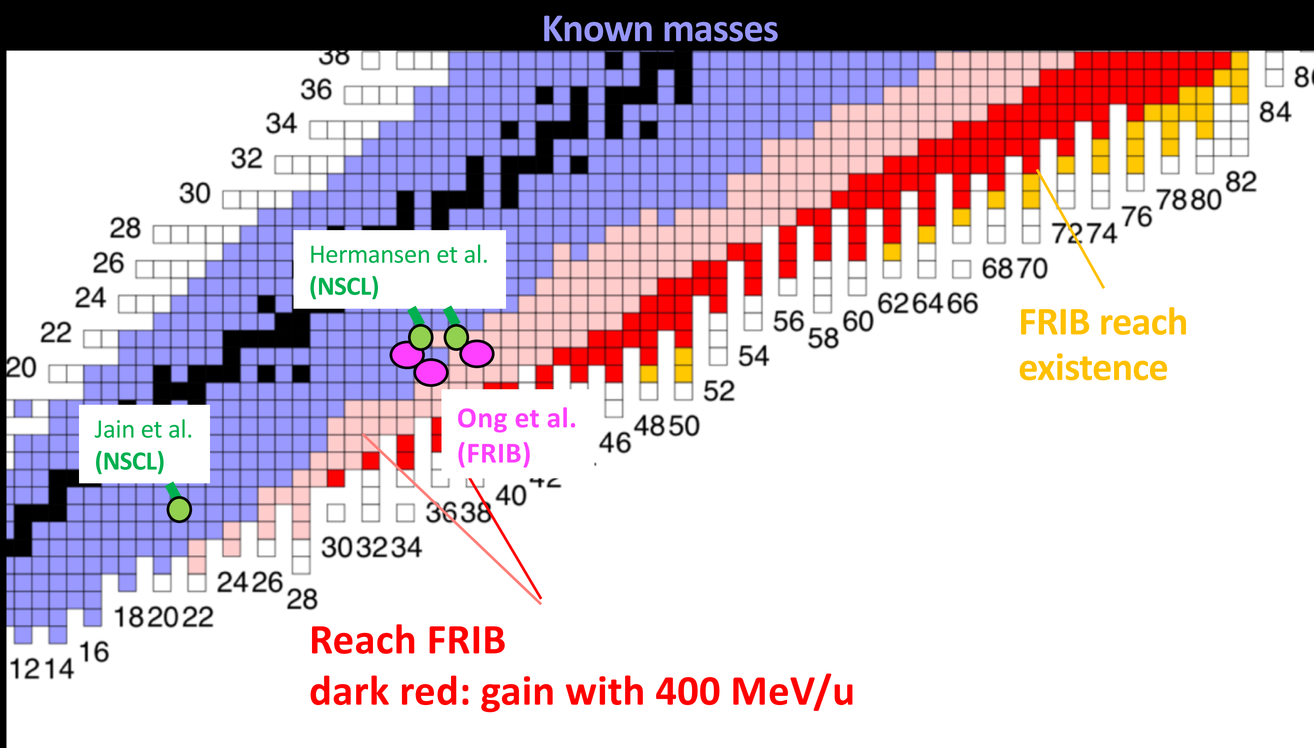
- **EC/β^- strength:** QRPA (S. Gupta, P. Moeller, W. Hitt) + Exp W.-J. Ong
- **Masses:** AME2012, FRDM (P. Moeller)
- **n-capture rates:** TALYS (S. Goriely, Y. Xu) with corrections from P. Shternin
- **Pycnonuclear fusion rates:** M. Beard, A. Afanasjev, L. Gasques, M. Wiescher, D. Yakovlev
- **Code:** 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)

Accreting Neutron Stars as Quasi Persistent Transients Probe Neutron Star Physics





All Rare Isotopes in Neutron Star Crusts Within Reach at FRIB



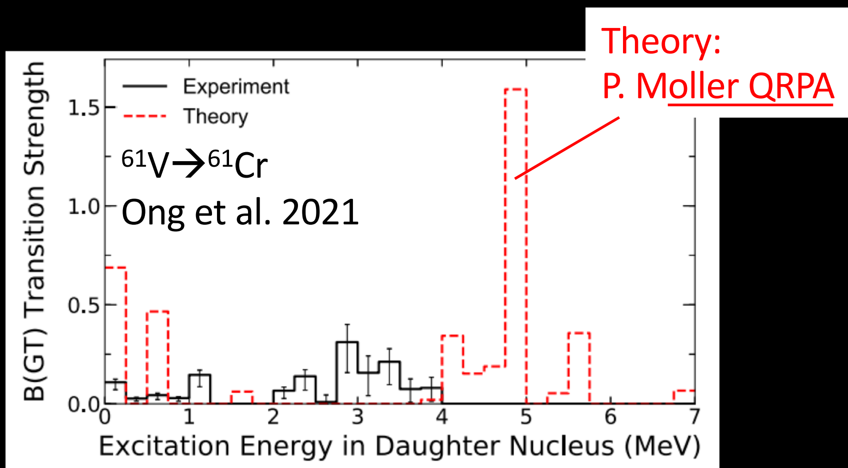
New theory data available:

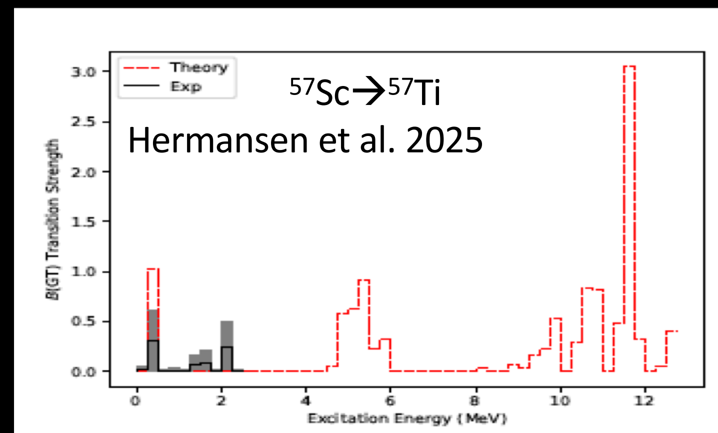
- New n-capture rates for degenerate neutrons (Knight et al. 2024)
- New shell model EC rates (Rahman et al. 2025)

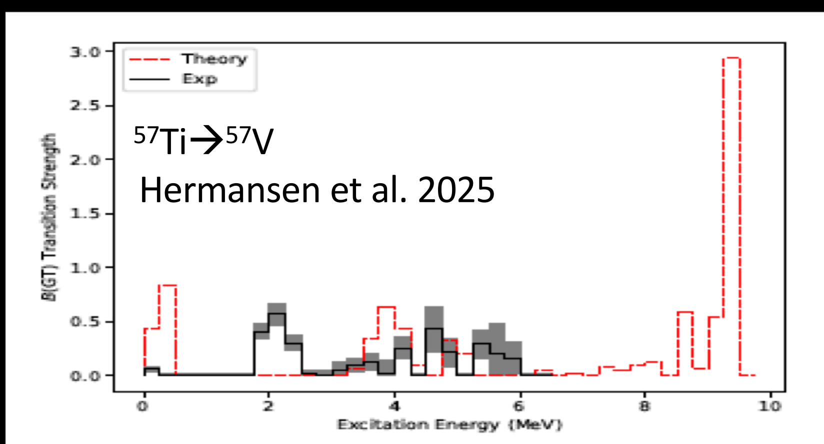
Experiments needed:

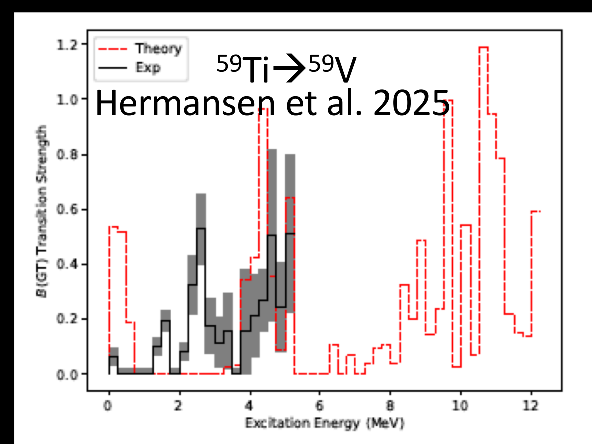
- Mass measurements
- Gs-gs b-decay transition strengths

Recent Results from Total Absorption β-delayed γ-Spectroscopy with SuN at NSCL/FRIB



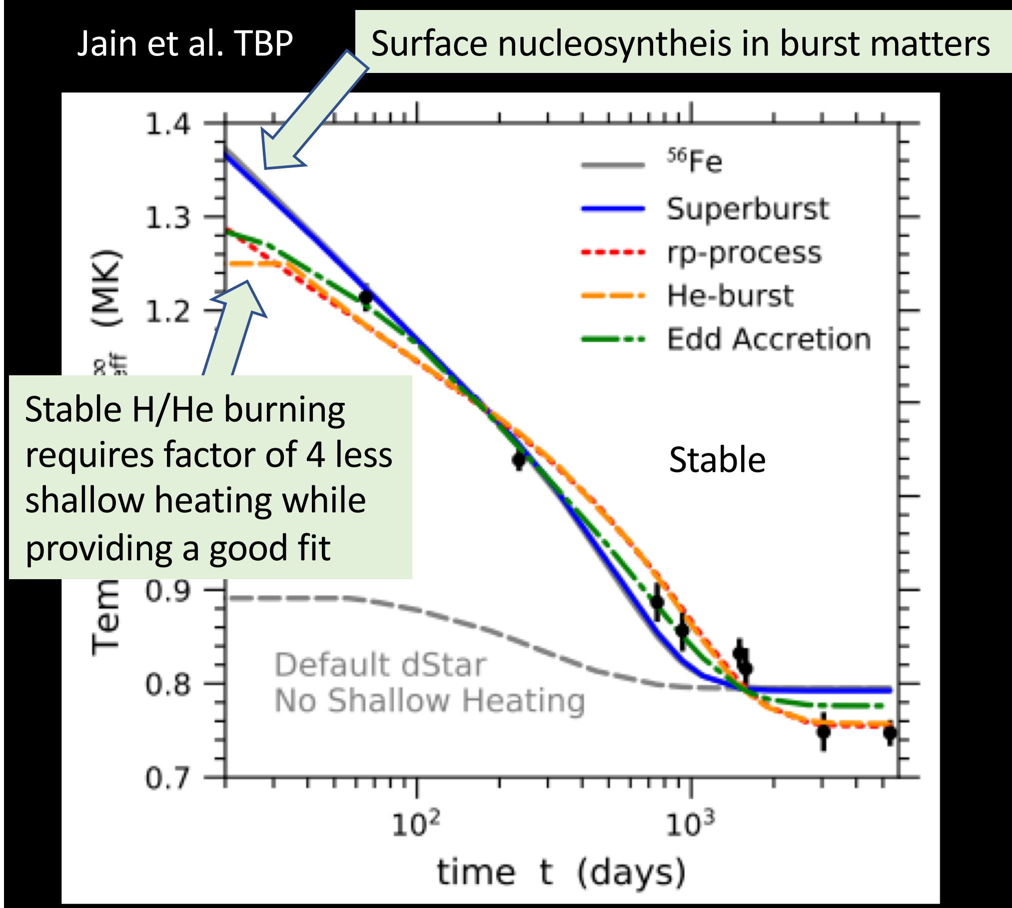


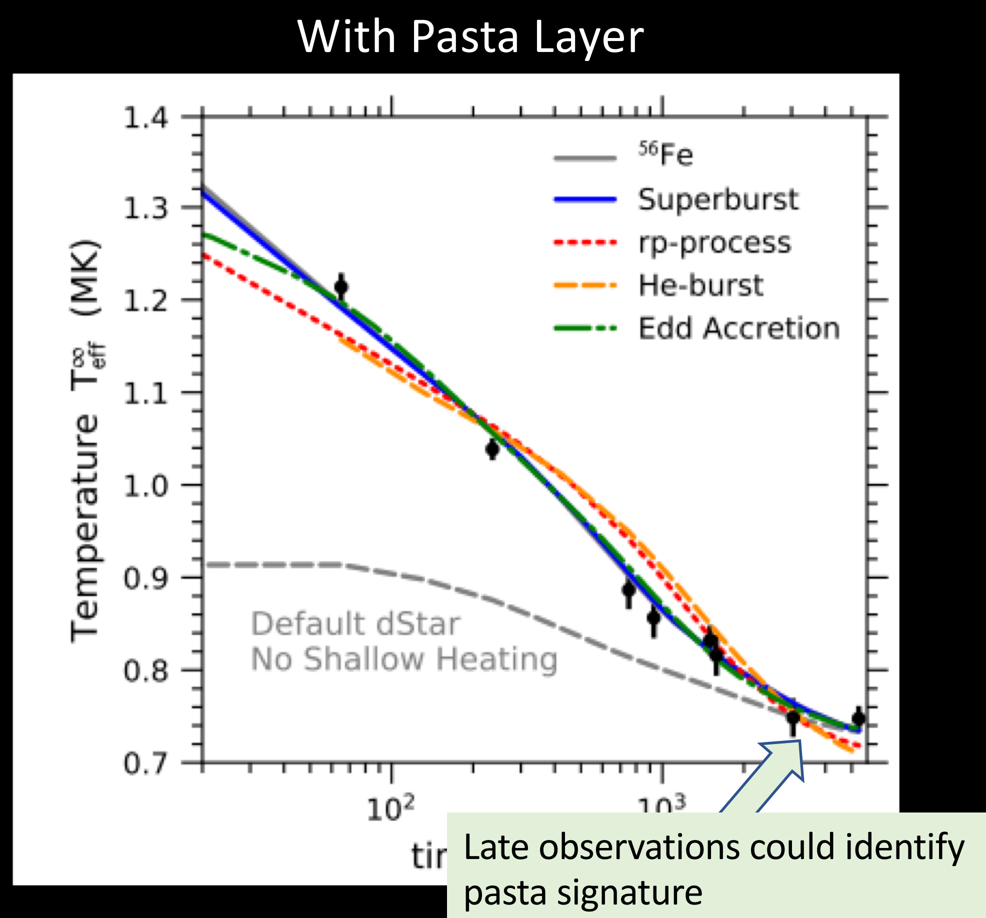




Trend:
Weaker population of ground state than expected
→ Weaker Urca cooling

Cooling of KS1731-260 with Different Burst Ashes



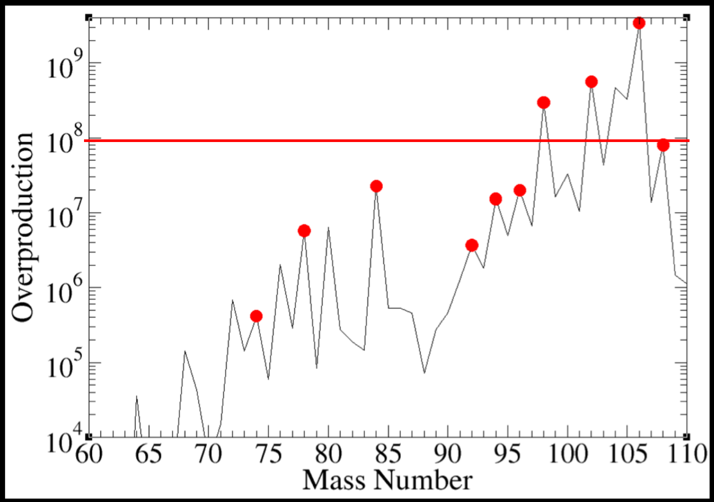


Summary

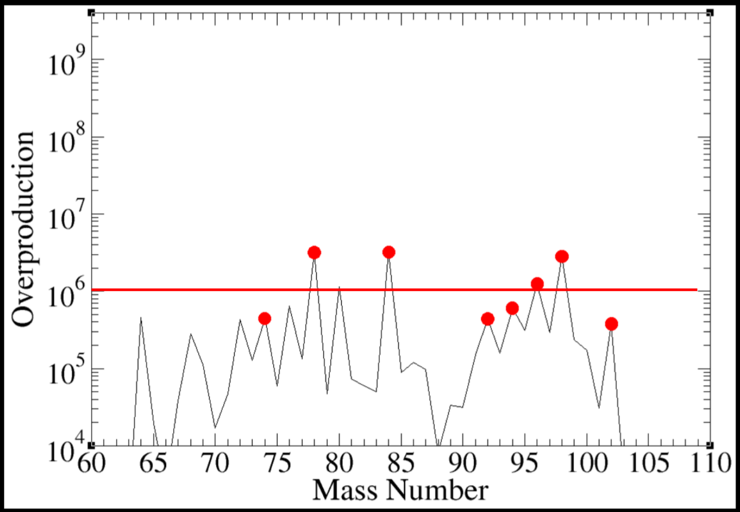
- Novae and X-ray bursts are interesting
  - Many open questions that require nuclear physics
  - A broad range of multi-messenger observables need to be interpreted
  - Provide insights into the origin of the elements, explosive hydrodynamics, and dense matter physics
  - They are the two most frequent thermonuclear explosive events in the galaxy
    - Unique laboratories for extreme physics at our ”doorstep”
- Addressing the outstanding problems requires
  - Progress in pinning down the nuclear physics from the proton drip line to the neutron drip line
    - Need a broad range of stable and radioactive beam facilities combined with nuclear theory – BUT with modern RIB facilities ALL nuclei should be within reach (eventually)
  - Advanced multi-D hydrodynamics studies
  - An advanced MeV g-ray mission – COSI would be an important first step; others are being planned

P-process Contribution?

1-zone Model: Extreme rp-process burst



1-zone Model: Typical H/He Burst



GCE "Model:"

- 100 Sources at all times
- For 10^{10} years
- 10^{-8} solar masses/yr accretion

→ 10^4 solar masses processed

- Mass of Galactic Disk 6×10^{10} solar masses
- Overproduction 10^8

→ Need to process 6×10^2 solar masses

→ 6% ejection (Herrera et al. 3%, Weinberg et al. few%)

Issues:

- Typical burst much lower overproduction (x100)
- Base of layer is most enriched, not necessarily what is ejected
- Not all bursts eject all the time

→ Would need unrealistic number of sources (Herrera et al.)

But: Lots of uncertainties, maybe ^{92}Mo, ^{94}Mo, ^{96}Ru, ^{98}Ru not enhanced everywhere?

Setup to Determine gs-gs β-Decay Branches

Measure all γ-branches with SuN Total Absorption Spectrometer

Measure all n-branches with NERO

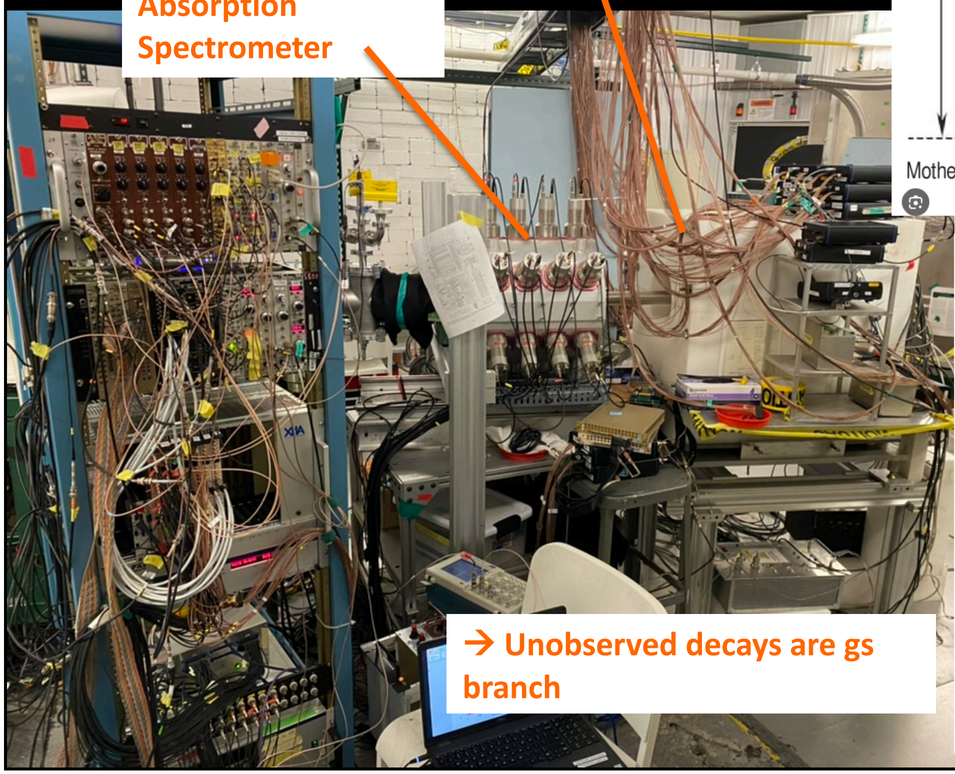
→ Unobserved decays are gs branch

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

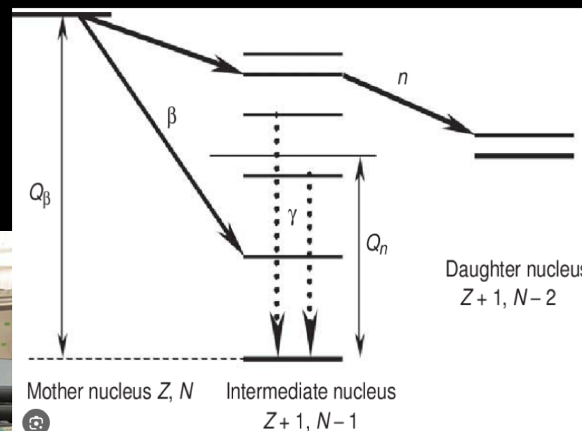
Setup at NSCL@MSU

Measure all γ-branches with SuN Total Absorption Spectrometer

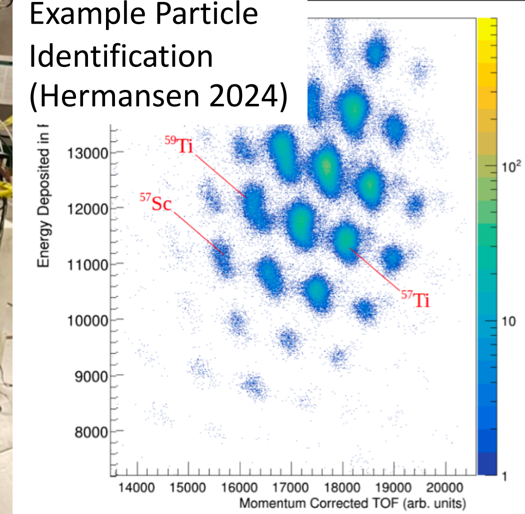
Measure all n-branches with NERO



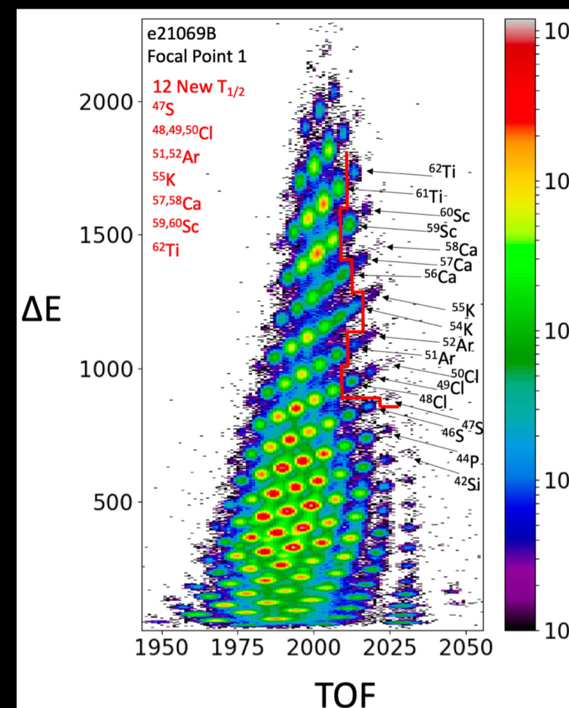
→ Unobserved decays are gs branch



Example Particle Identification (Hermansen 2024)



Recent FRIB experiment (Ong et al.)



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

ChETEC INFRA

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

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

JINA-CEE
Joint Institute for Nuclear Astrophysics

Becoming

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

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

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

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

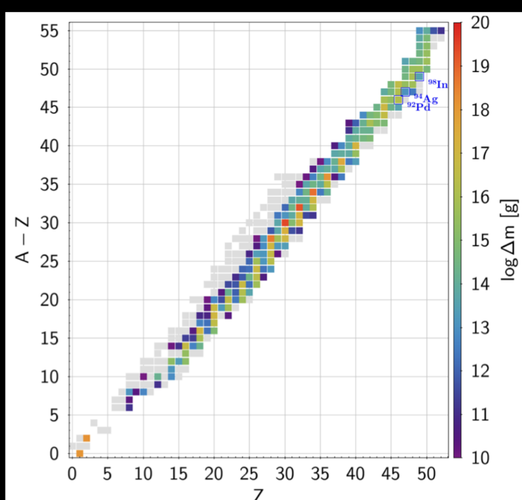
Supports:
- Joint workshops
- Schools
- Visits/Exchanges
- Online Seminar
- Professional Development
- Young Researchers Organization
- Blog!

More at irenaweb.org - Join there

Open Questions Related to Bursts: Is Material Ejected?

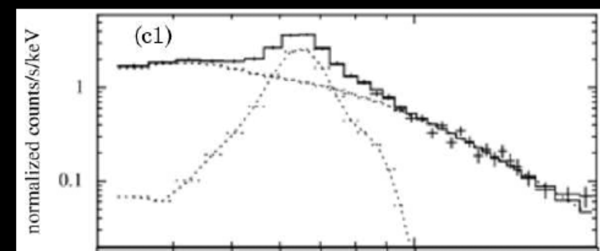
- Do bursts eject material?
- Observable features in spectra?
- Contribution to nucleosynthesis (A=92-98 p-nuclei)?

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



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

Spectral features:
Many tentative observations in literature



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

Jordi et al.2013

Bardayan