Nuclear Astrophysics at FRIB and Accreting Neutron Stars

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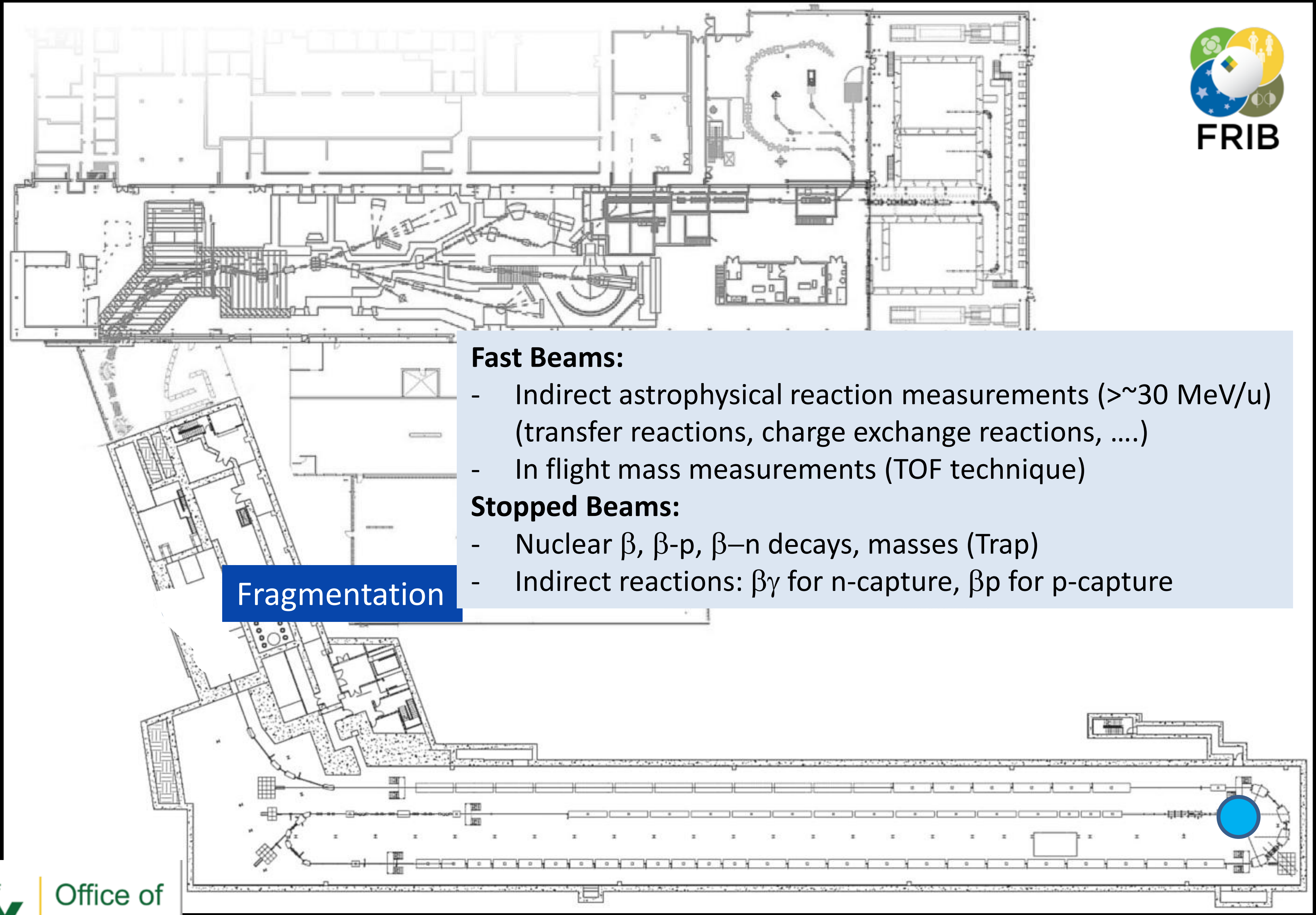
U.S. DEPARTMENT OF ENERGY | Office of Science

FRIB Radioactive Beam Facility at MSU

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

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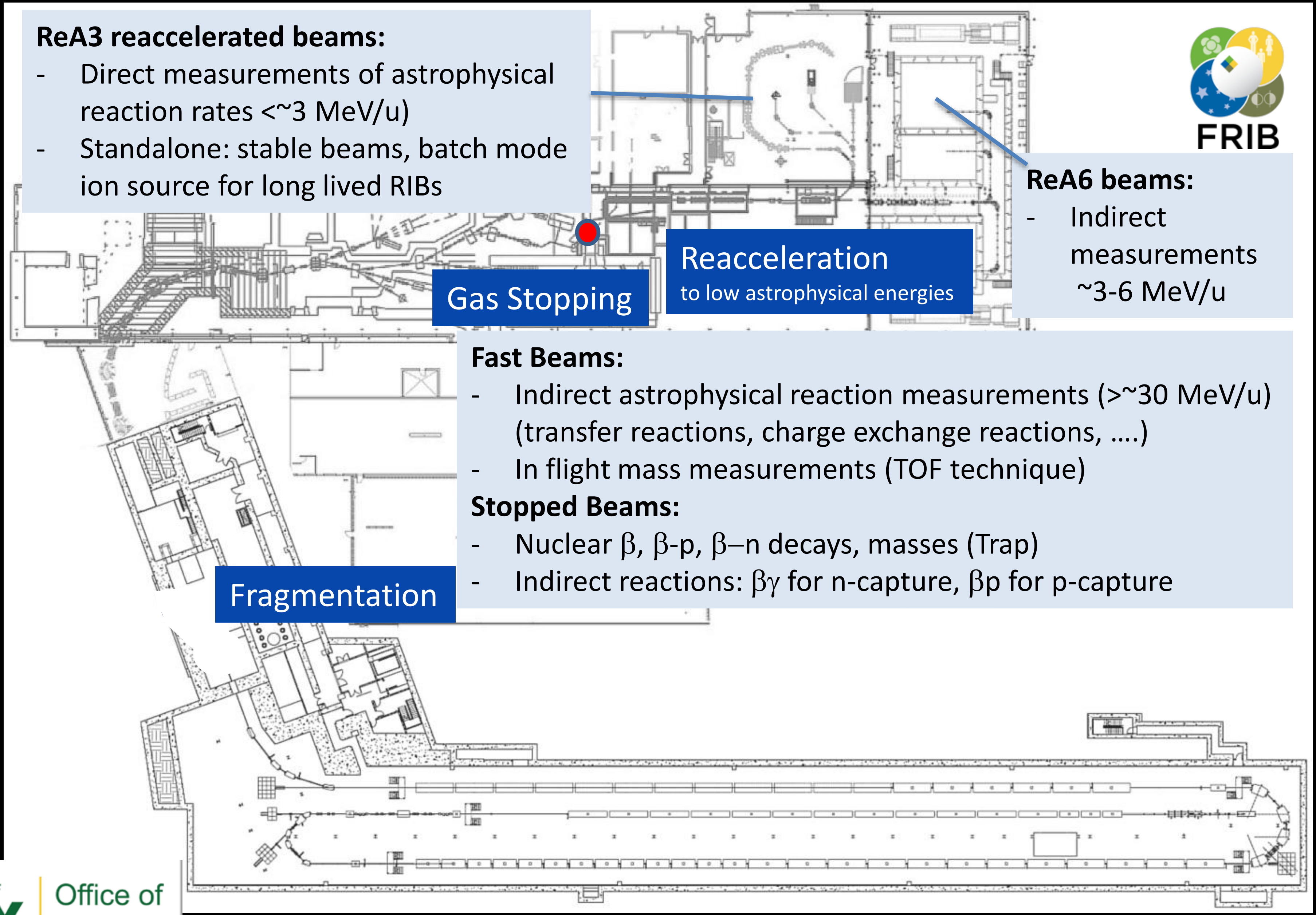
FRIB Provides Fast, Stopped, and Reaccelerated Beams



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

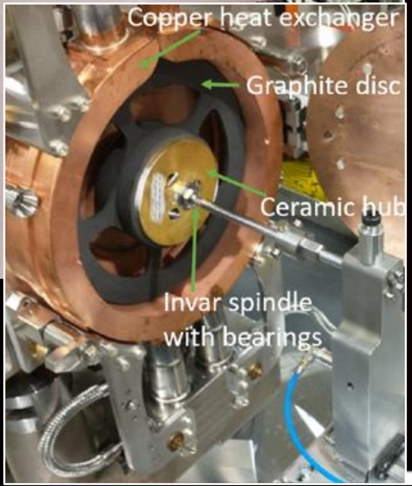
Fast Beams:
- Indirect astrophysical reaction measurements (>~30 MeV/u) (transfer reactions, charge exchange reactions, ….)
- In flight mass measurements (TOF technique)

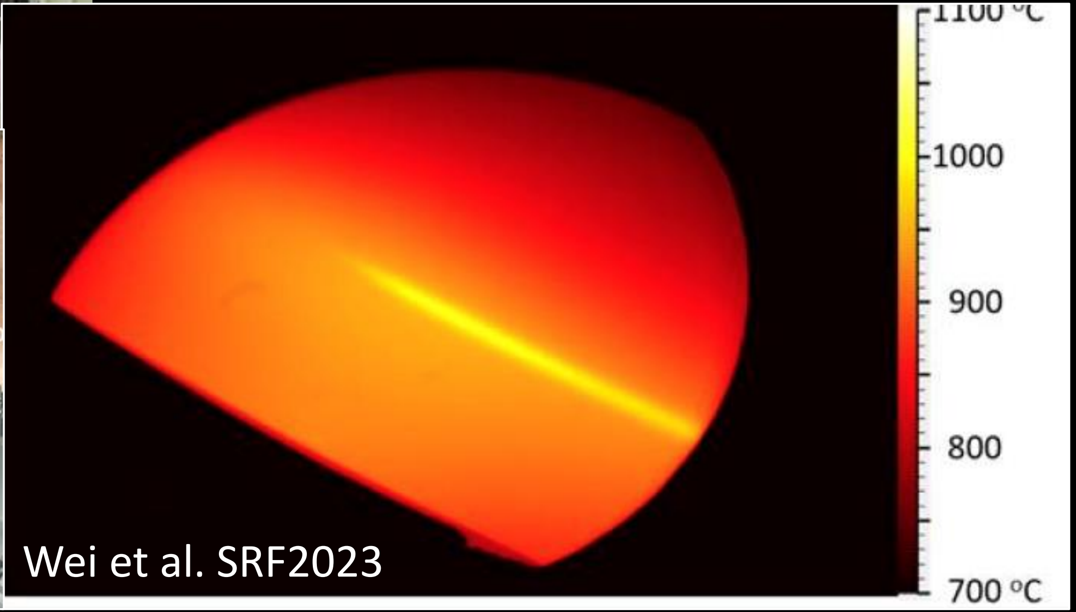
Stopped Beams:
- Nuclear β, β-p, β–n decays, masses (Trap)
- Indirect reactions: $\beta\gamma$ for n-capture, βp for p-capture

FRIB On Track for 400 kW

FRIB Status:

- First experiment May 2022 at 1 kW
- Since then two PACs, routine operation
- Power ramp up to 10 kW now
- 400 kW over next few years (~2028)
- 400 MeV upgrade planned





Wei et al. SRF2023

Neutron Stars as Unique Probes of Dense Matter

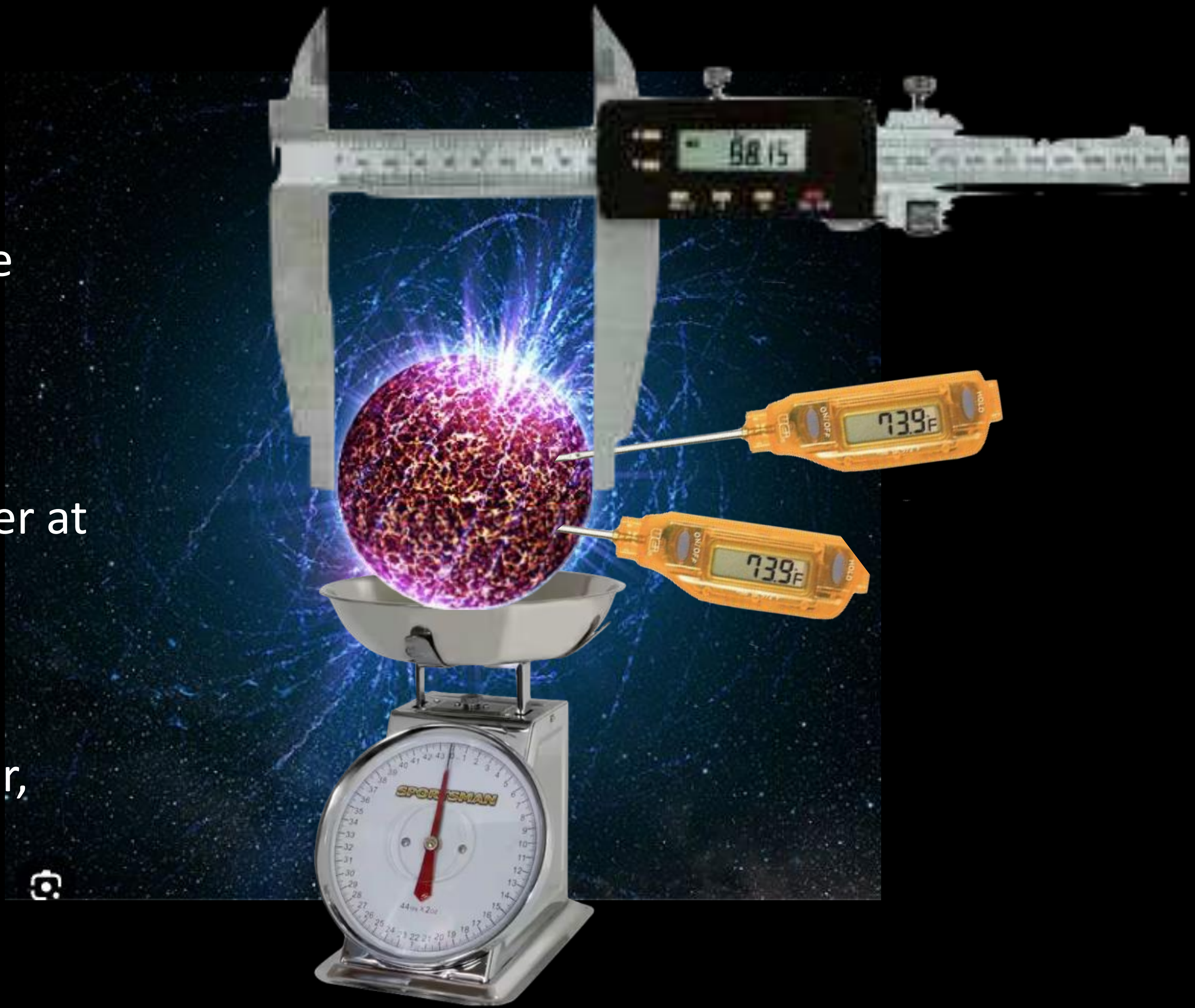
~10 km radius

~1.4 solar masses

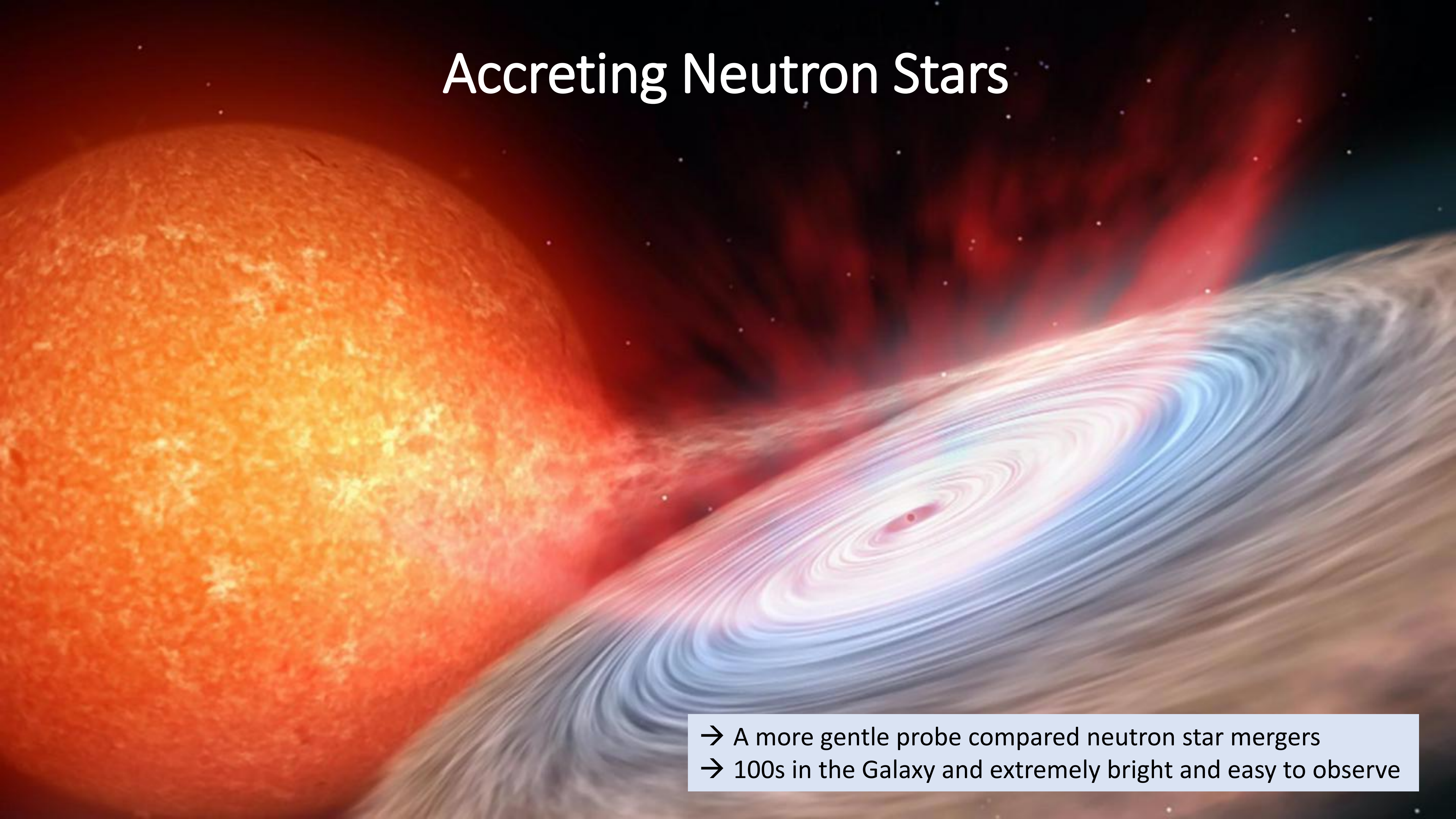
→Densest sample of matter in the universe

Questions:

- What are the properties of matter at extreme densities?
- What does that tell us about the nuclear force?
- Are there exotic phases of matter, especially in the center?



Accreting Neutron Stars



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

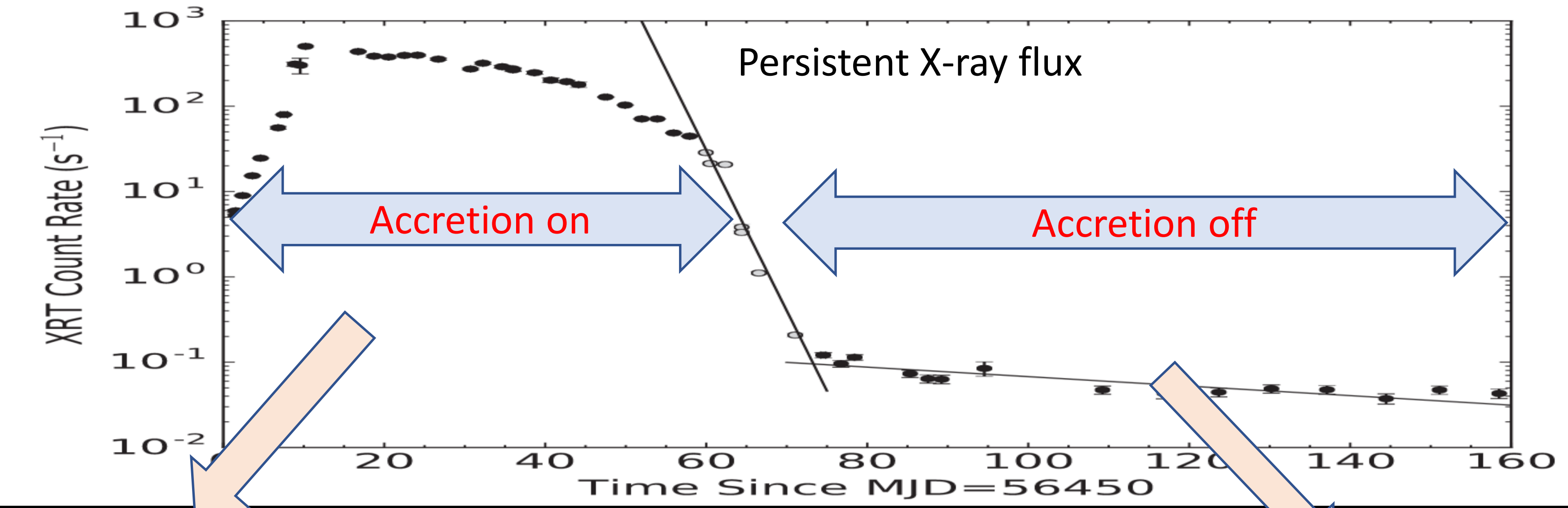
Accreting Neutron Stars are Observed as X-ray Binaries

Bright persistent X-ray source powered by gravitational energy.

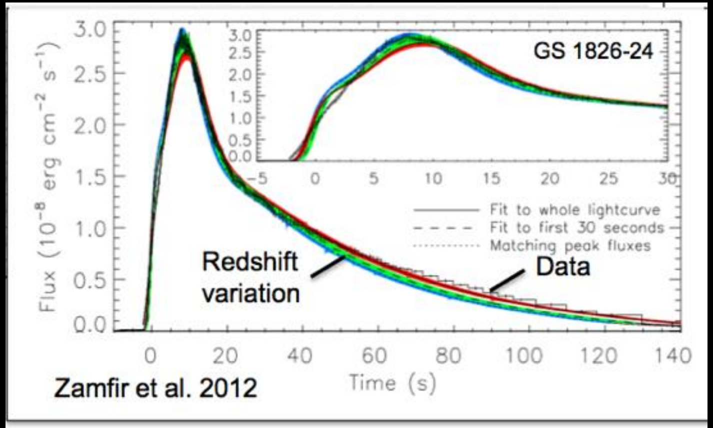
Brief X-ray bursts on top of persistent flux powered by nuclear reactions

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

Quasi Persistent Transients Probe Neutron Star Physics



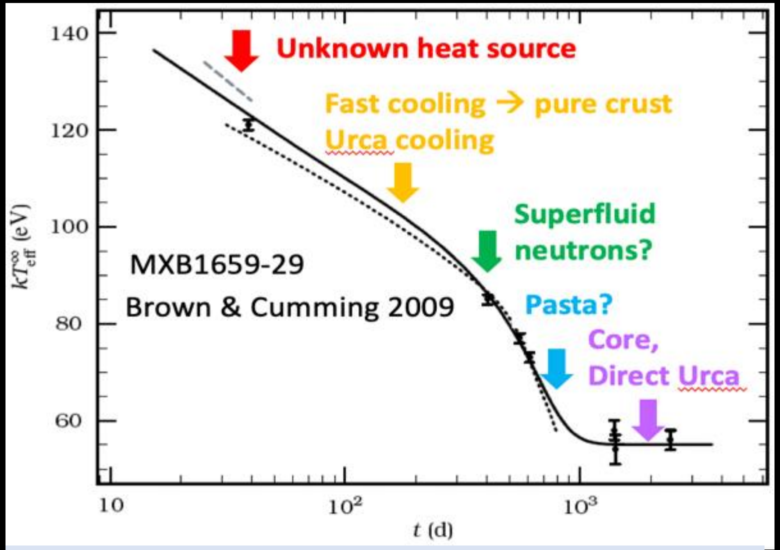
X-ray bursts – on top of persistent flux



→ NS compactness (mass, radius)
→ Burst frequency probes surface heat

Both observables are powered by rare isotope physics that needs to be understood accurately

Crust cooling



→ Temperature as function of depth

Open Questions Related to Bursts: Basic Burst Behavior

<u>A zoo of type I X-ray bursts:</u>

Short Bursts (~10s) He fuel

Rp-process bursts (~100s) H+He fuel

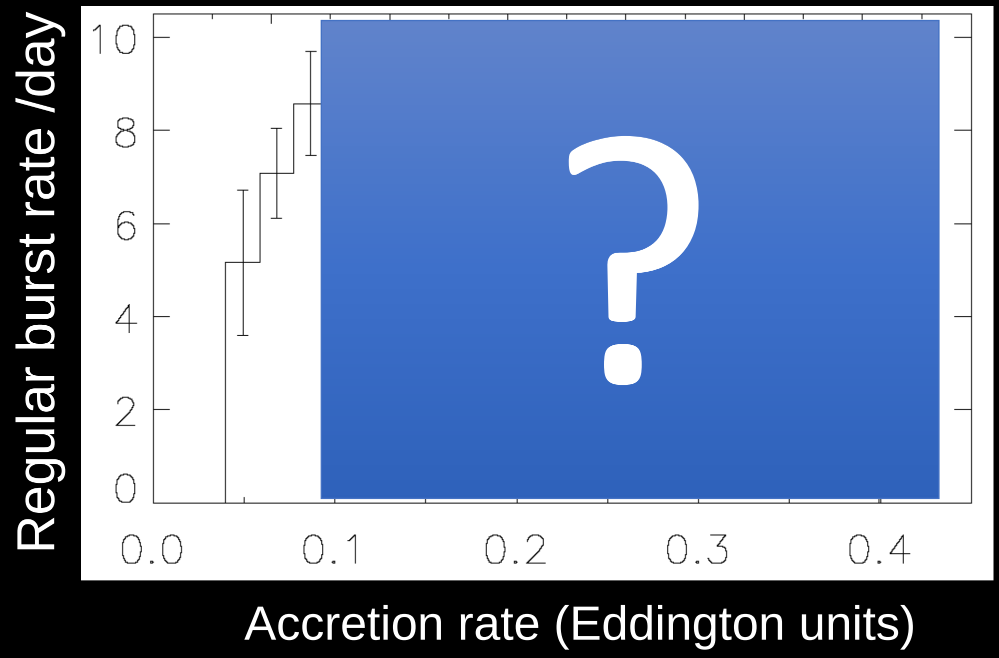
Intermediate long bursts (min-hours) Deep He fuel

Superbursts (hours-days) Deep C fuel?

Hyperbursts (years) Deep O,Ne fuel?

Why?

Burst rate as function of accretion rate?

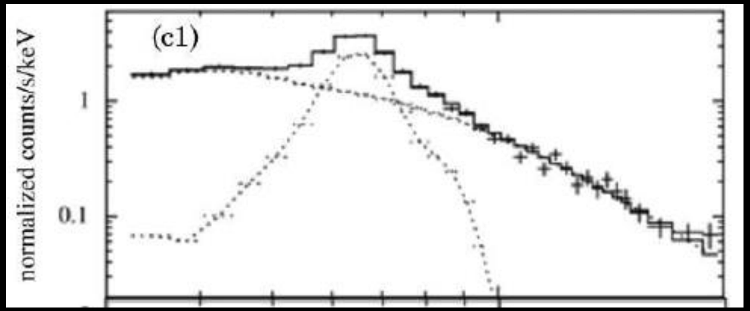


Cornelisse et al. 2003

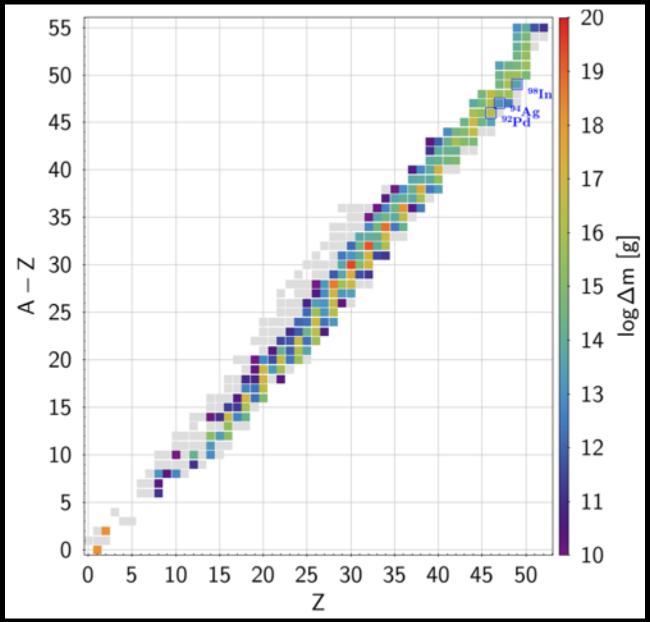
Open Questions Related to Bursts: What Isotopes are Created and What Observables are affected?

- 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

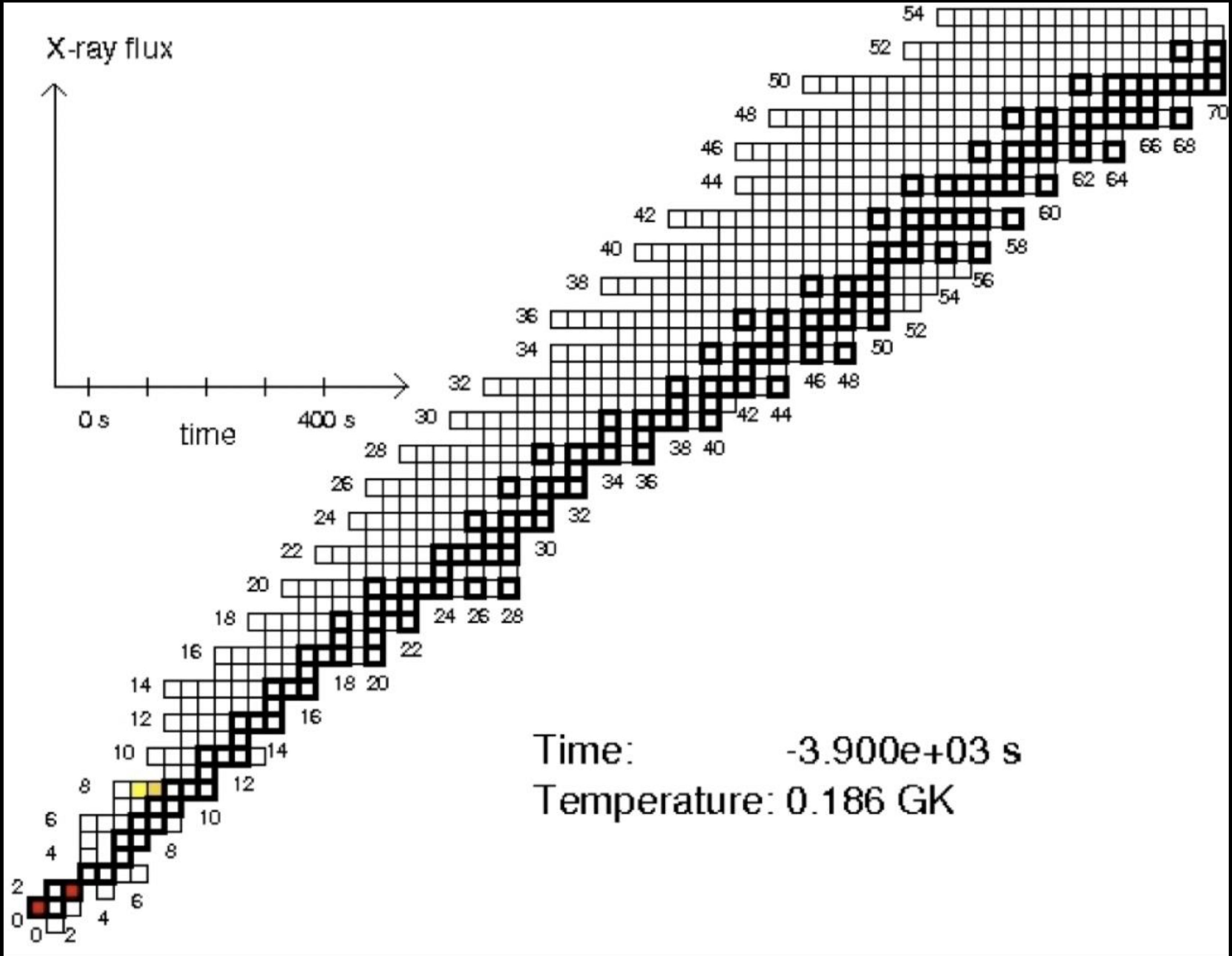


Also Weinberg et al. 2002:
~few % ^{28}Si, ^{60}Zn, ^{62}Zn

→ 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

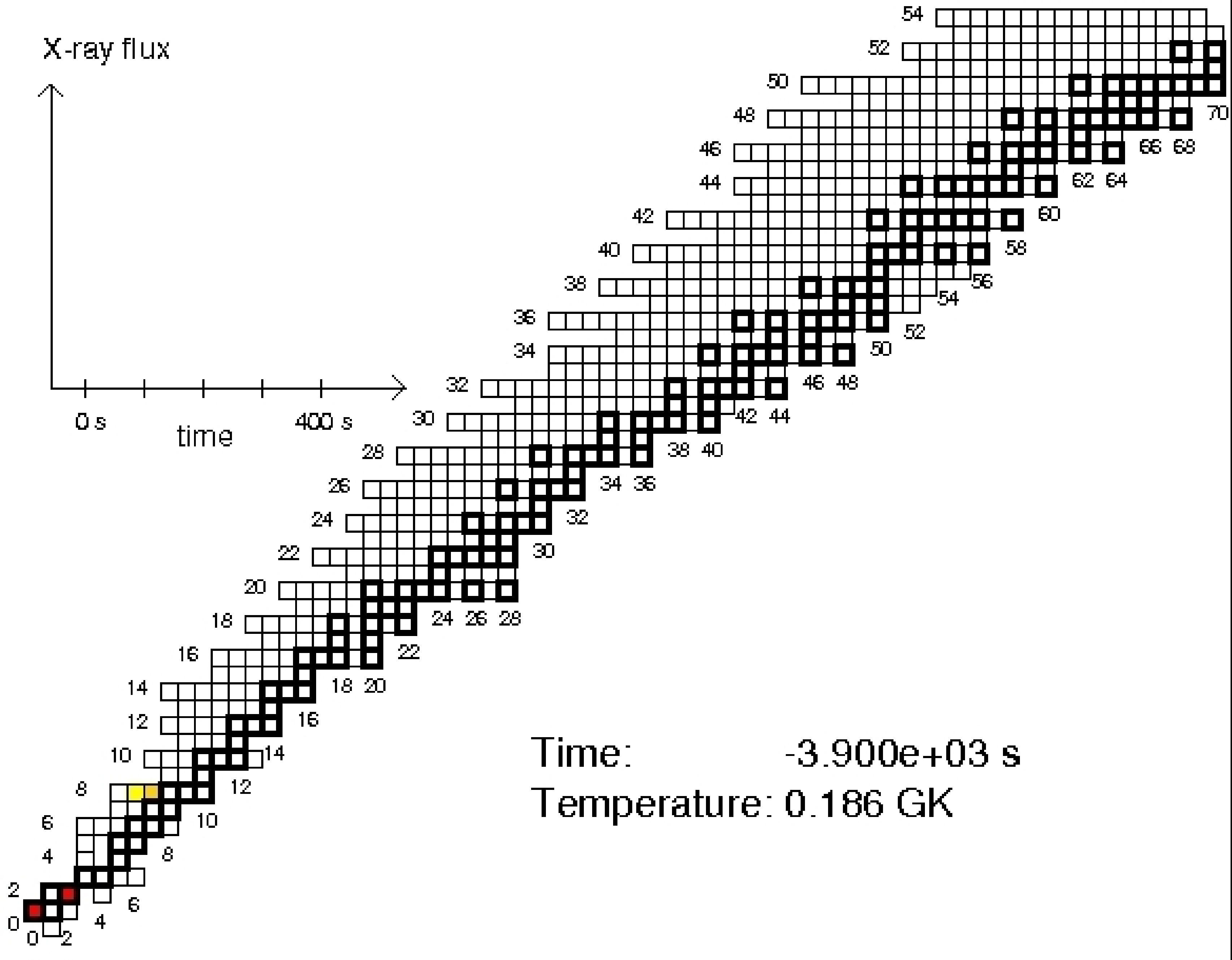
Also: Not ejected material→ Sets Composition of Neutron Star Crust



A. Heger

Steady State Abundances in Cycles

After R. Longland



A. Heger

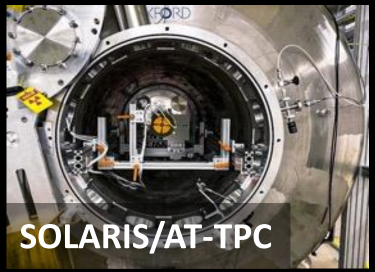
p,α induced reactions on n-deficient nuclei for X-ray bursts, novae, supernovae (νp- and p-process)

Notre Dame /ORNL/ LSU/MSU led

Recoil Separator
→ Direct reaction measurements

ORNL/CSM led

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

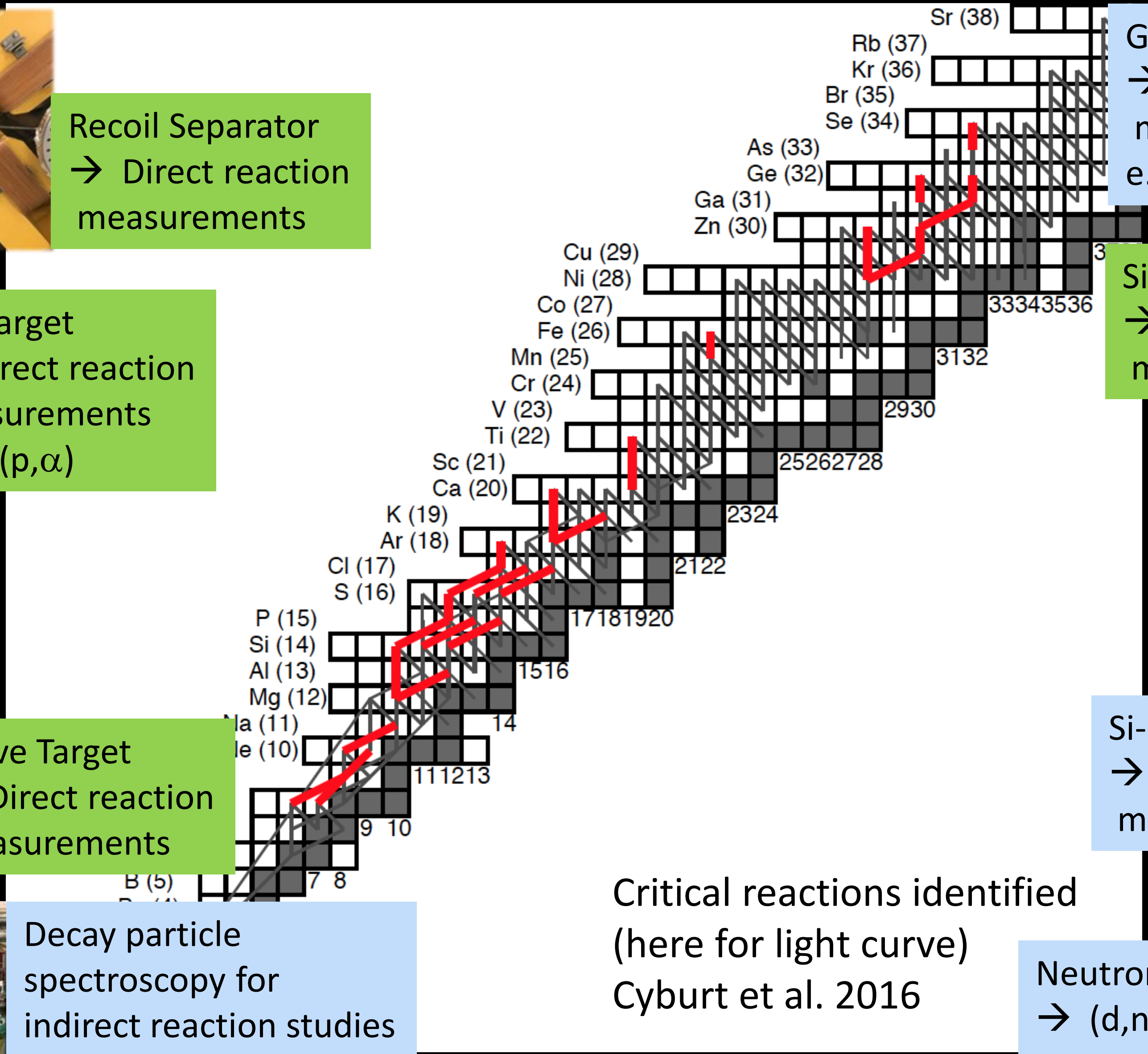


ANL/MSU led

Active Target
→ Direct reaction measurements

MSU led (Wrede)

Decay particle spectroscopy for indirect reaction studies

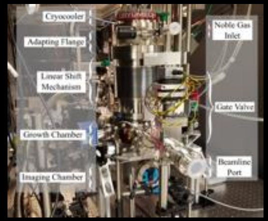


Critical reactions identified (here for light curve) Cyburt et al. 2016

LBNL/ANL/FSU/MSU/ORNL led

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

Single Atom Microscope
→ Direct reaction measurements



MSU led (Singh)

MUSIC
→ Direct reaction measurements

ANL led

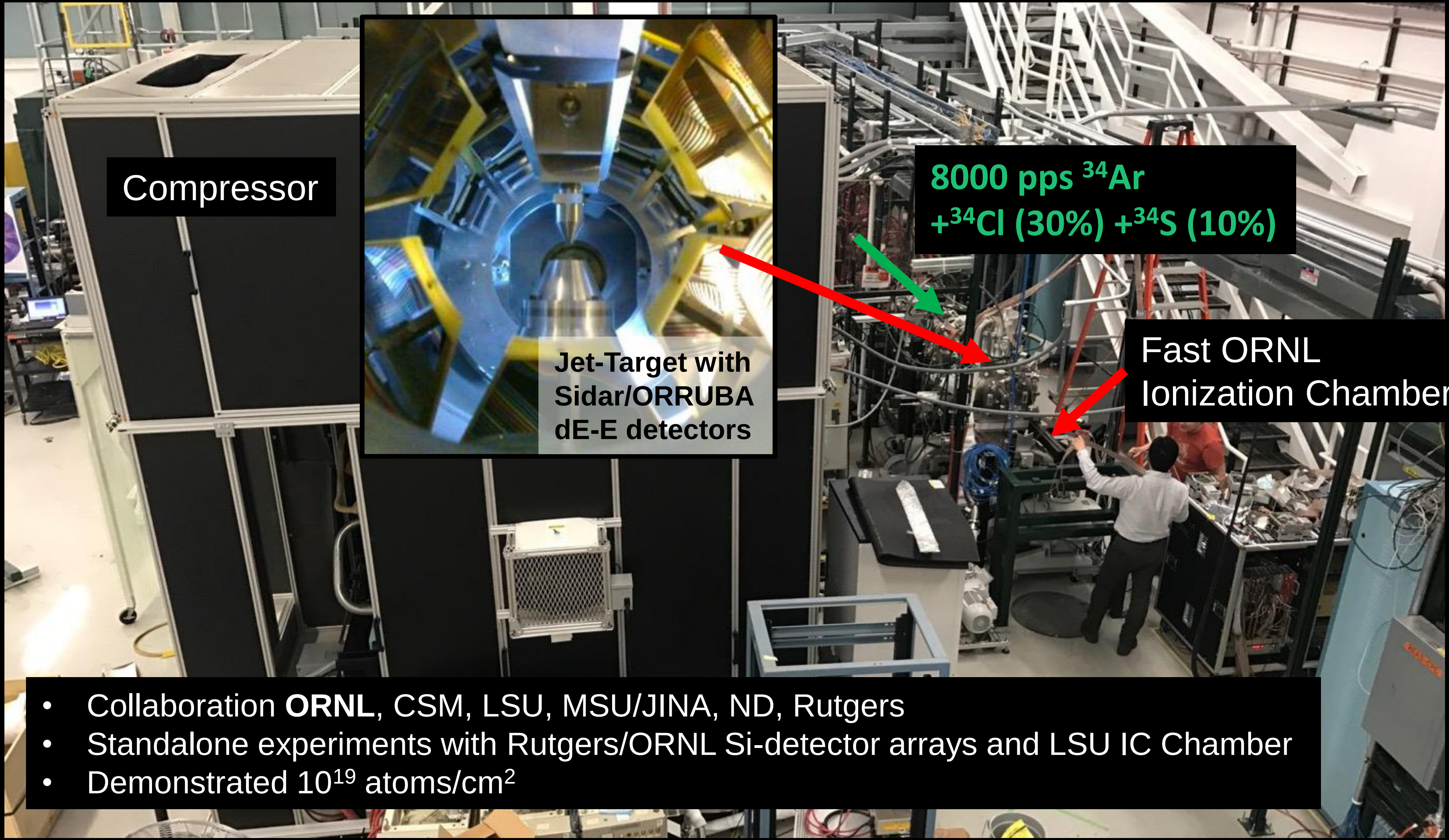
Si-Detector Array
→ Direct/Indirect reaction measurements

ORNL Rutgers

Neutron Detector
→ (d,n) Indirect reaction measurements

MSU led (Zegers)

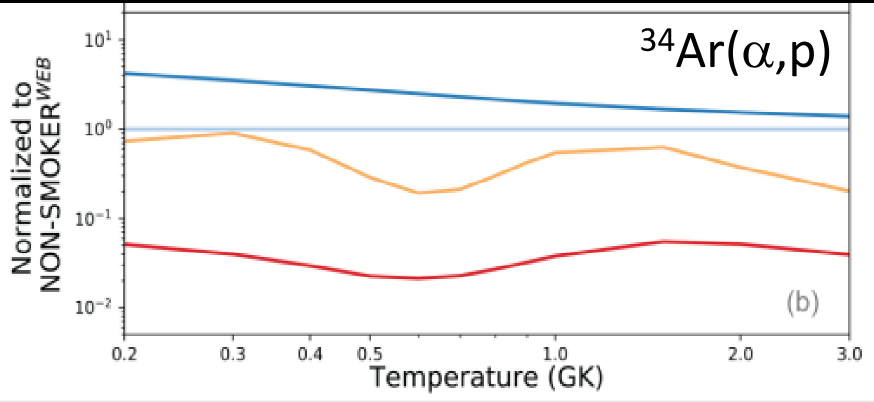
JENSA Gas Jet Target for (α,p) Measurements



- Collaboration **ORNL**, CSM, LSU, MSU/JINA, ND, Rutgers
- Standalone experiments with Rutgers/ORNL Si-detector arrays and LSU IC Chamber
- Demonstrated 10^{19} atoms/cm^2

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

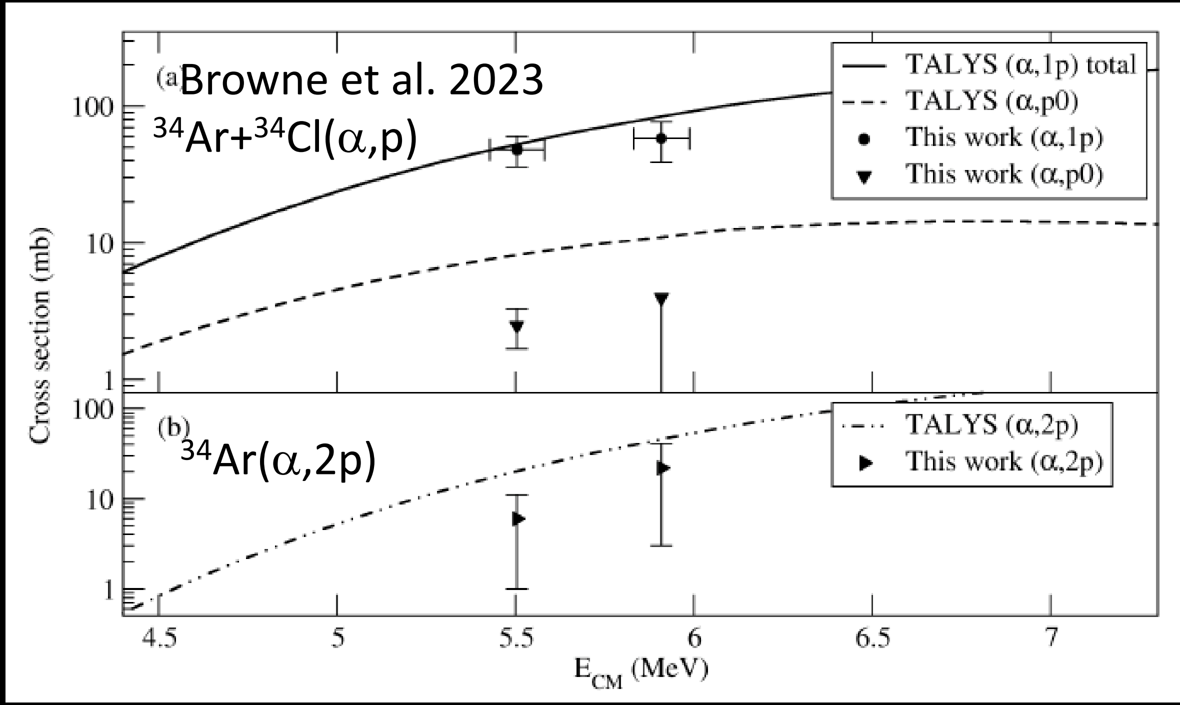
Open questions concerning these types of rates (Long et al. 2017)



Theory

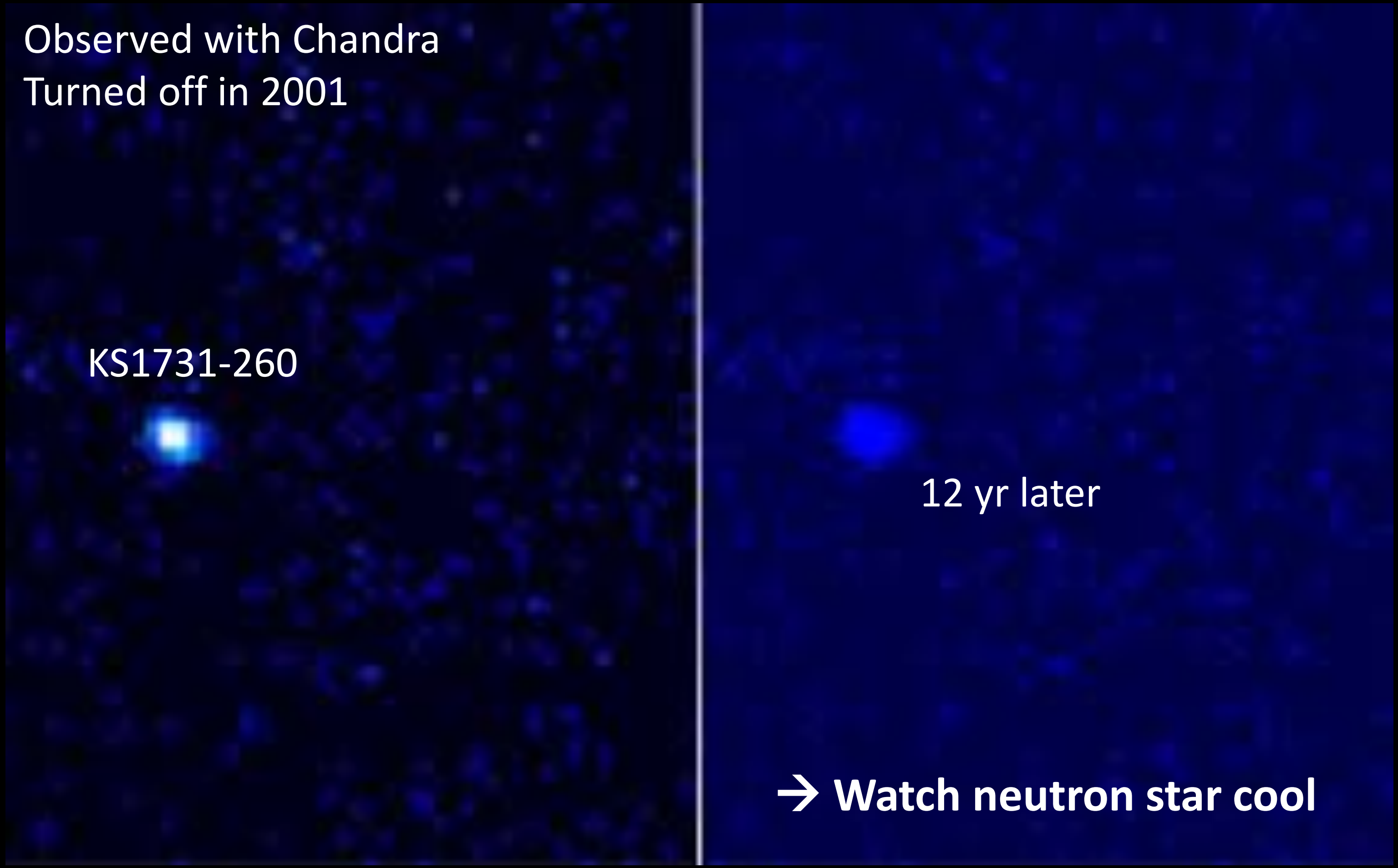
Clustering enhancement

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



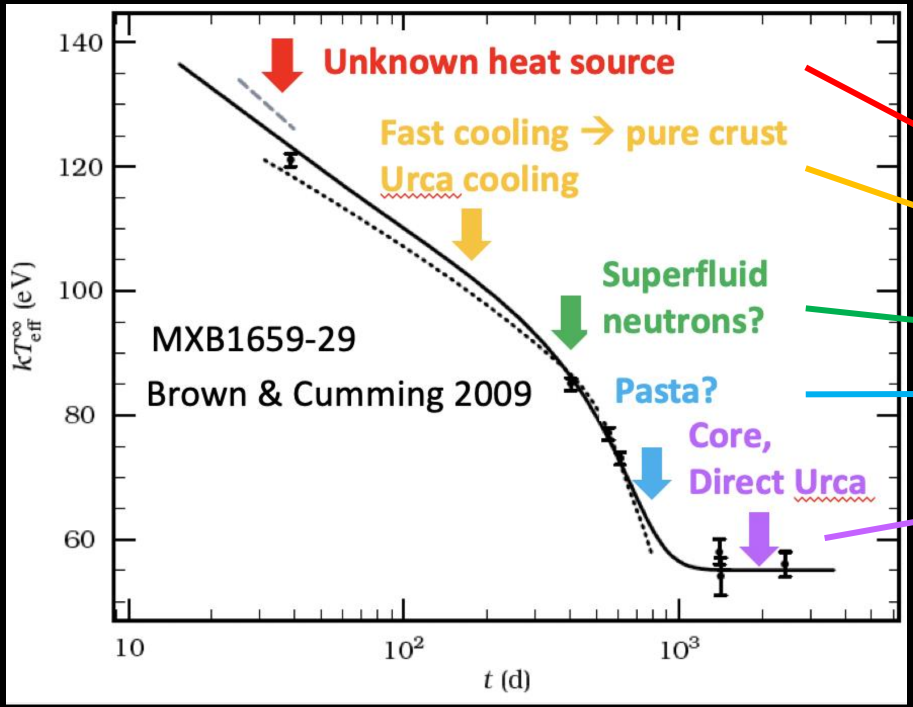
→ Current theory surprisingly good
→ Issues compensated with cluster effects?
→ Need to push to lower energies
(probe upper end of Gamow Window at 3 GK)

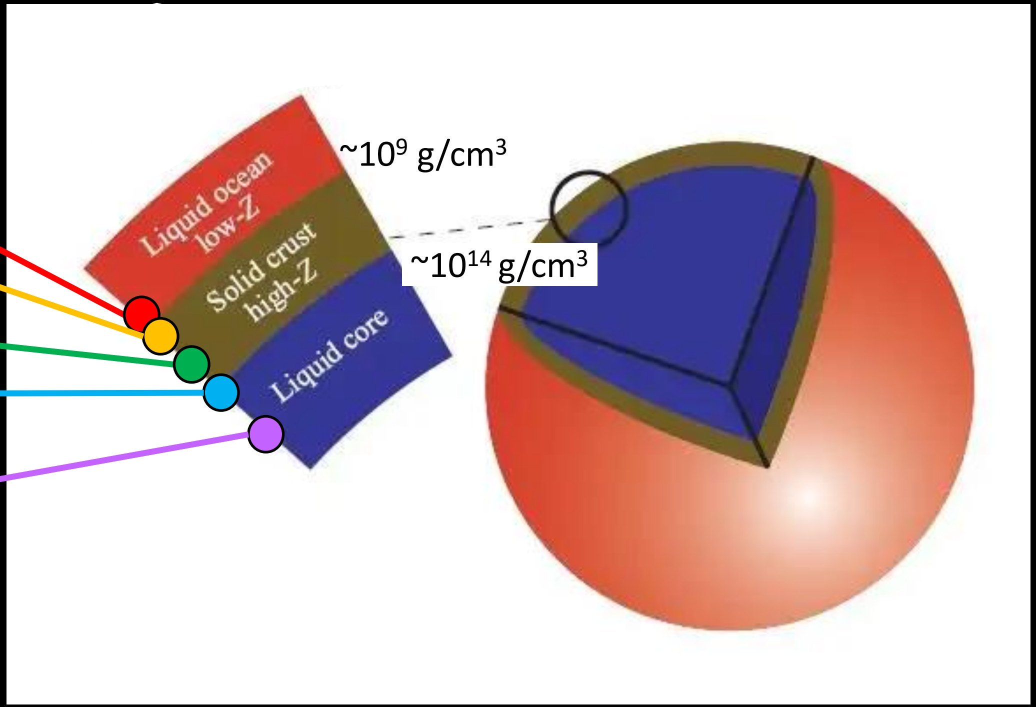
Accreting Neutron Stars Cool Within Months-Years!



NASA/Chandra/Wijnands et al.

Cooling Observations Probe Neutron Star Interior

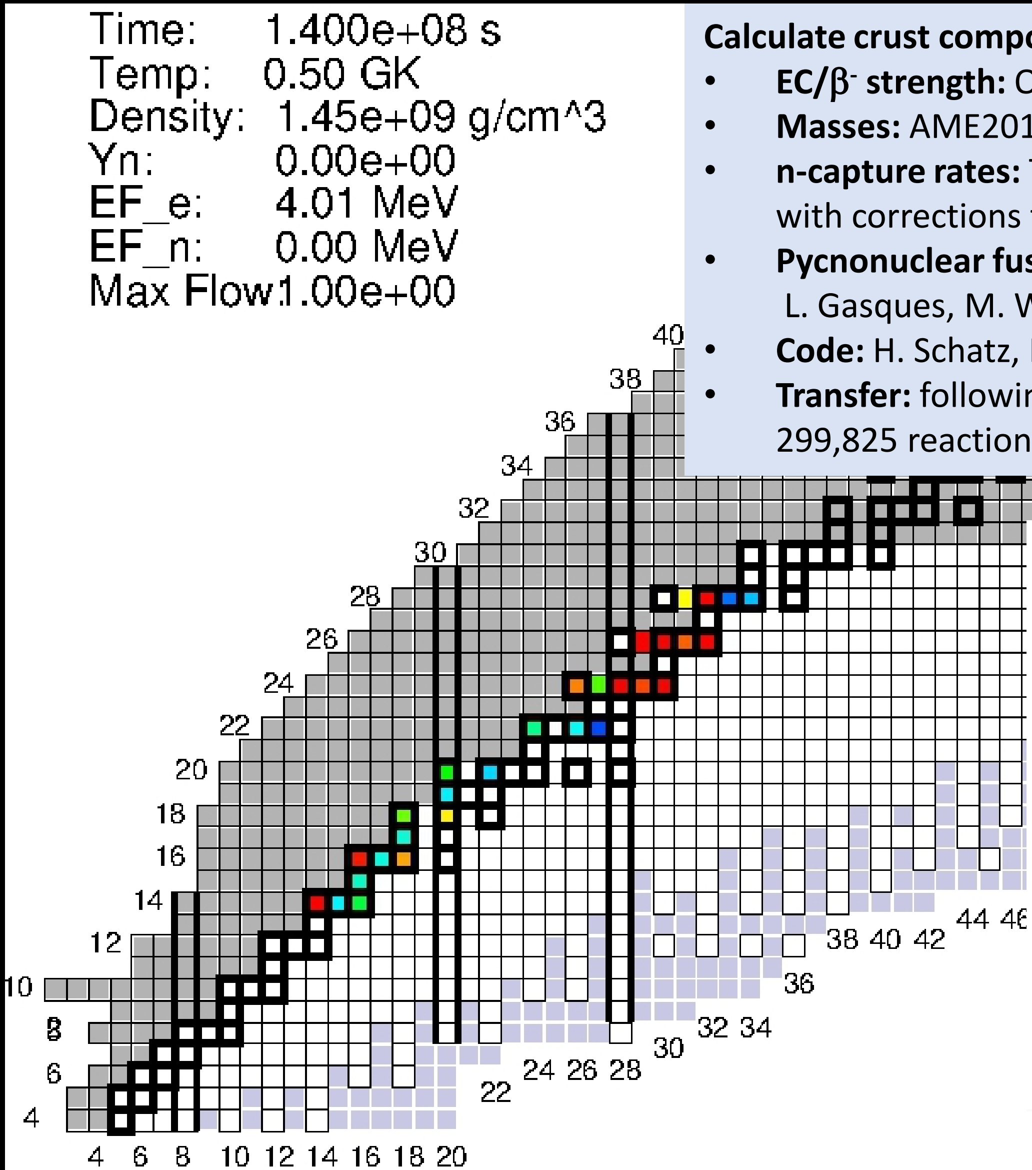




→ Need to understand the nuclear reactions that heat the crust during accretion

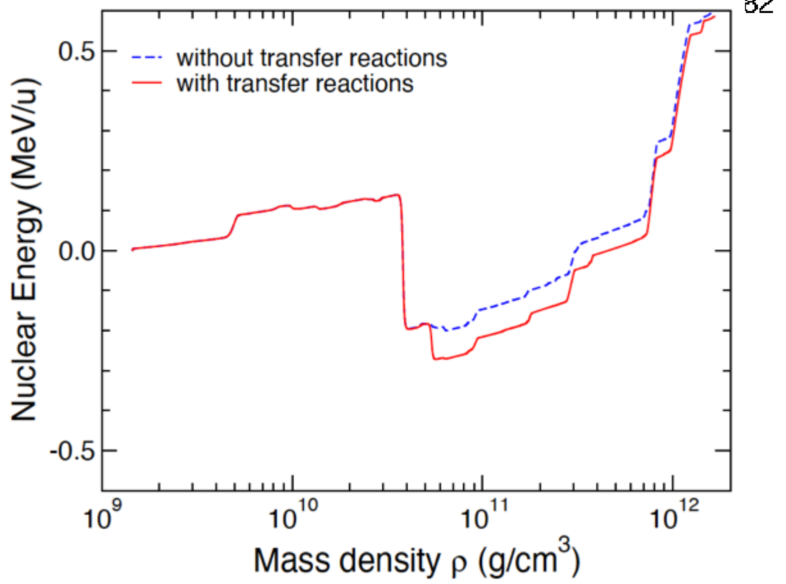
→ Need to understand initial composition of burst ashes – different types of bursts produce different compositions

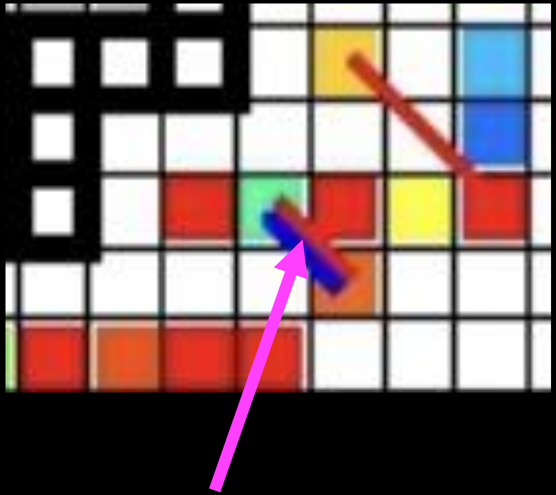
Reactions Heating the Crust During Accretion Identified



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)



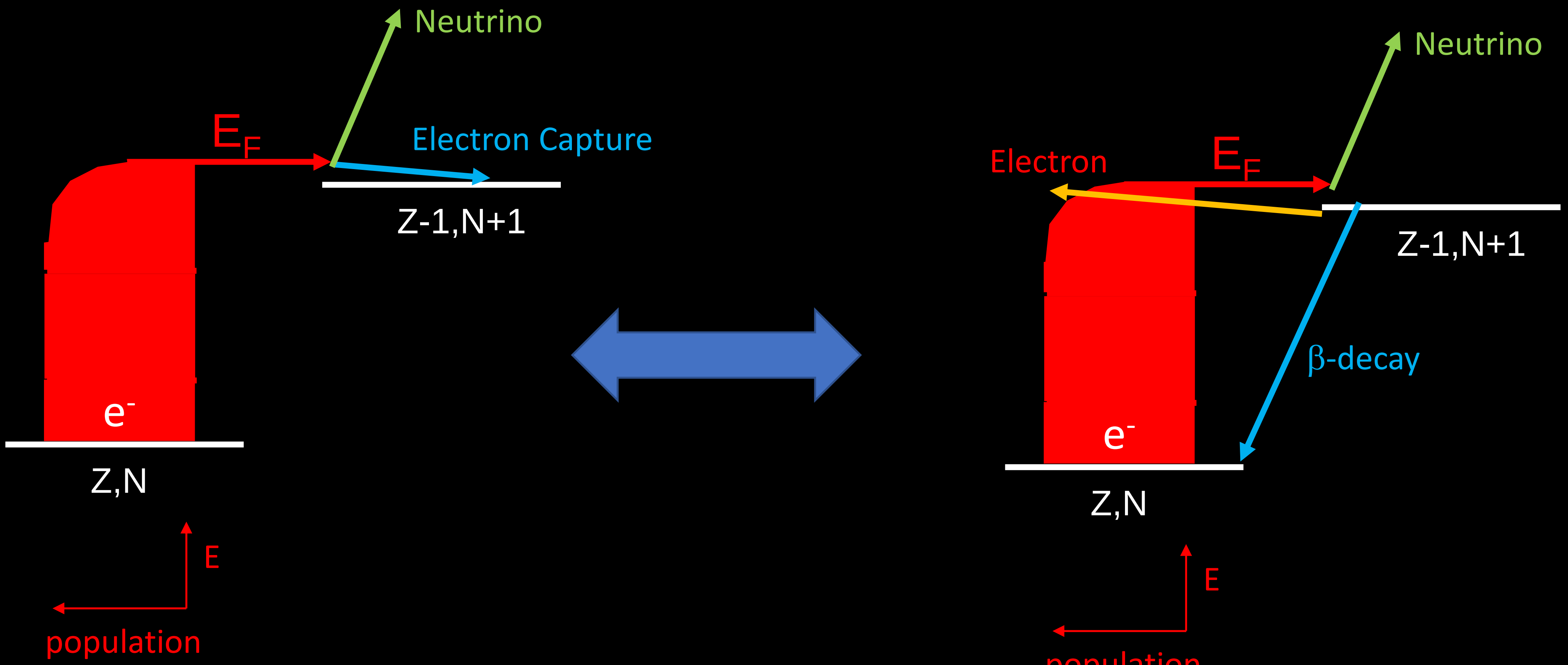


Urca Cooling

For gs-gs electron capture inverse b-decay is not completely Pauli blocked

→ EC and b-decay Rapidly alternate

Urca Cooling in the Accreted Neutron Star Crust



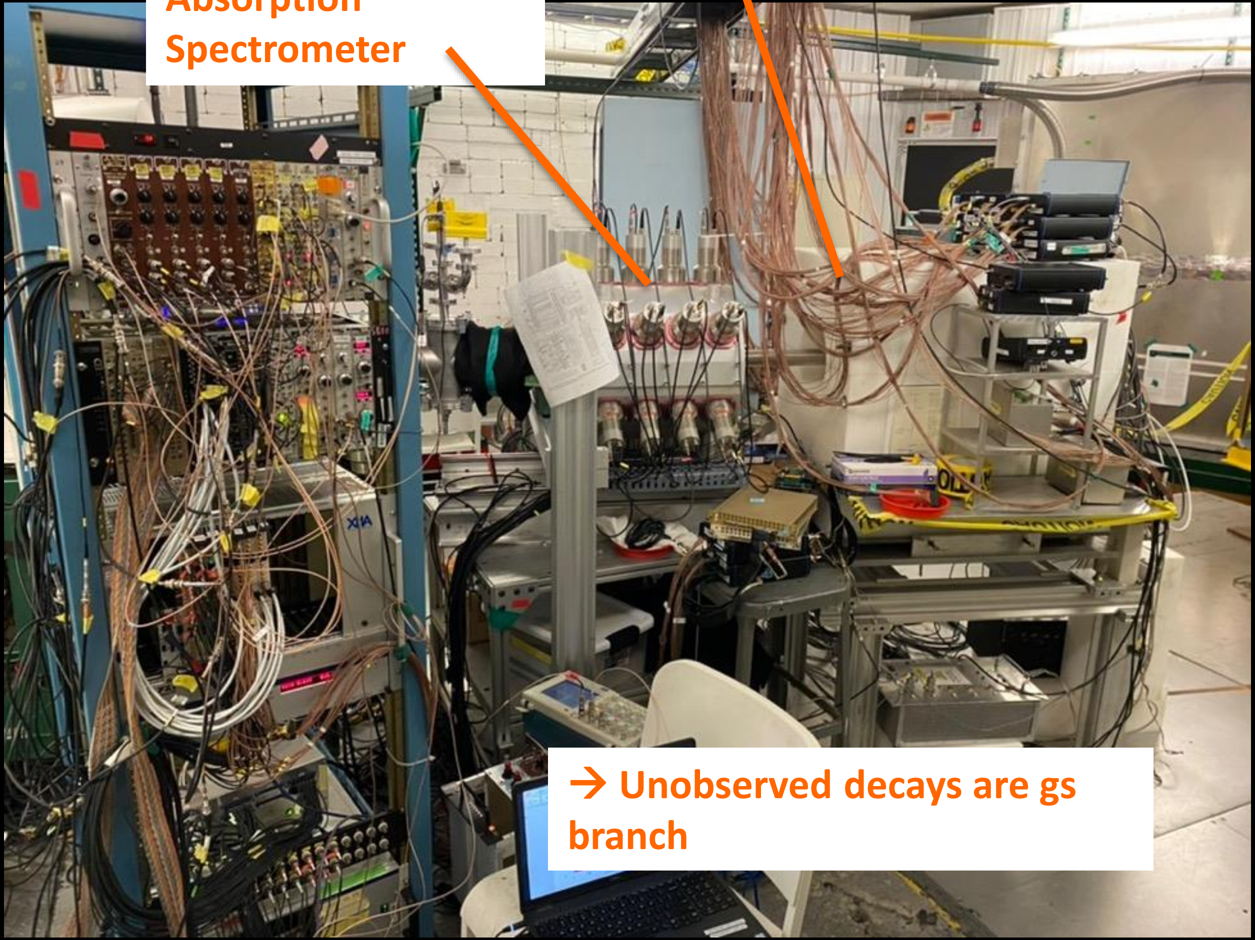
Cooling rate determined by **gs-gs** β-decay transition strength

Probe Urca Cooling Rates Via β-delayed Total Absorption Gamma Spectroscopy

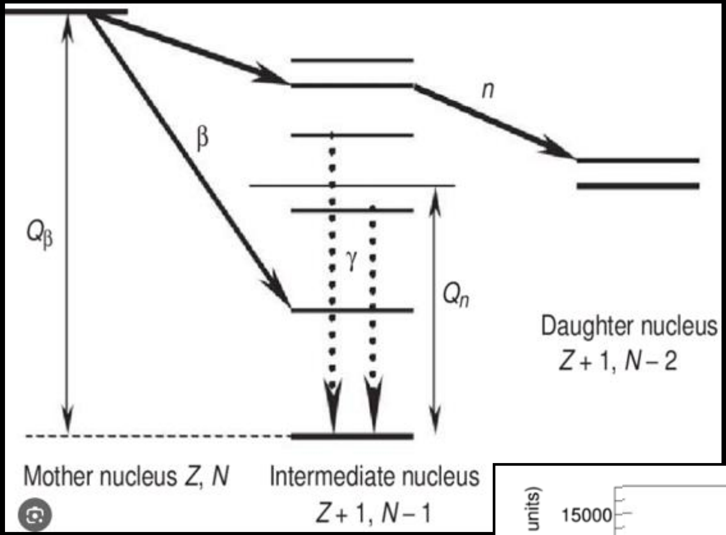
Setup at NSCL@MSU

Measure all γ-branches with SuN Total Absorption Spectrometer

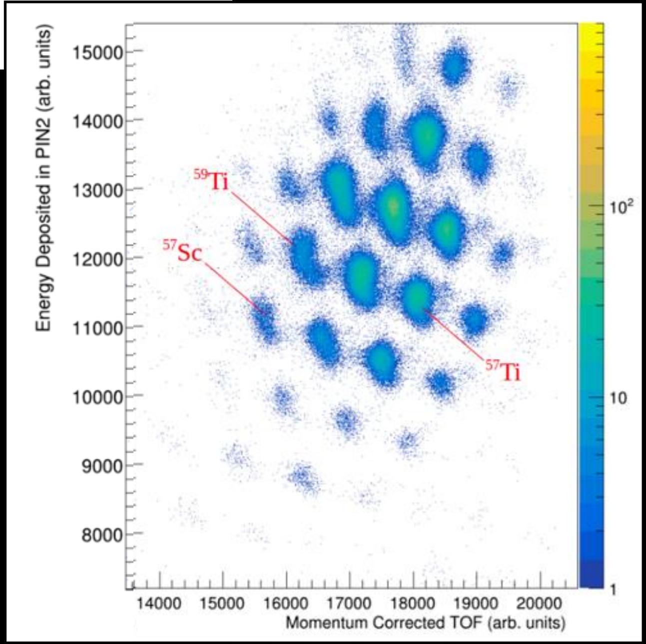
Measure all n-branches with NERO



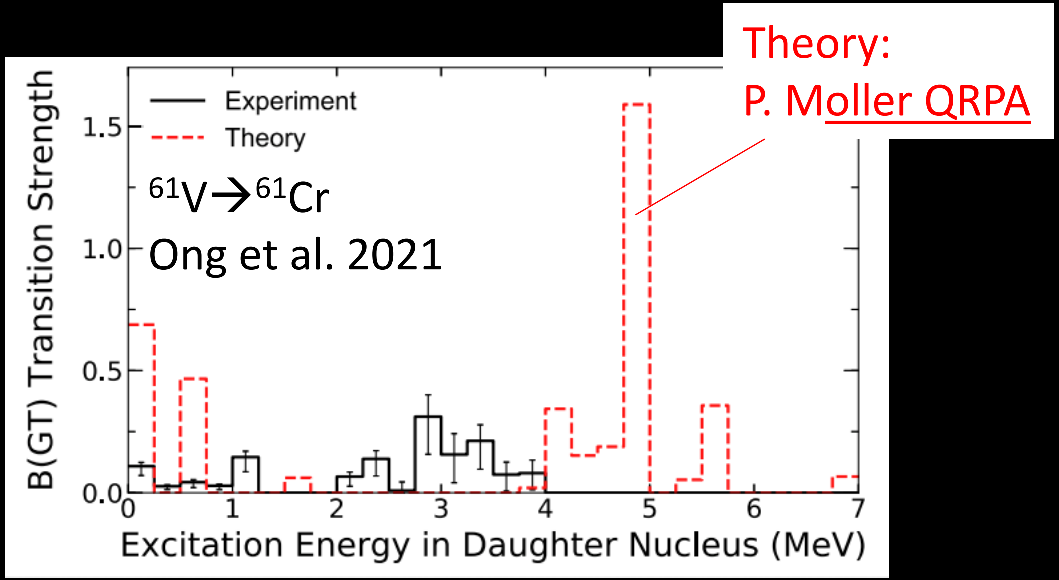
→ Unobserved decays are gs branch

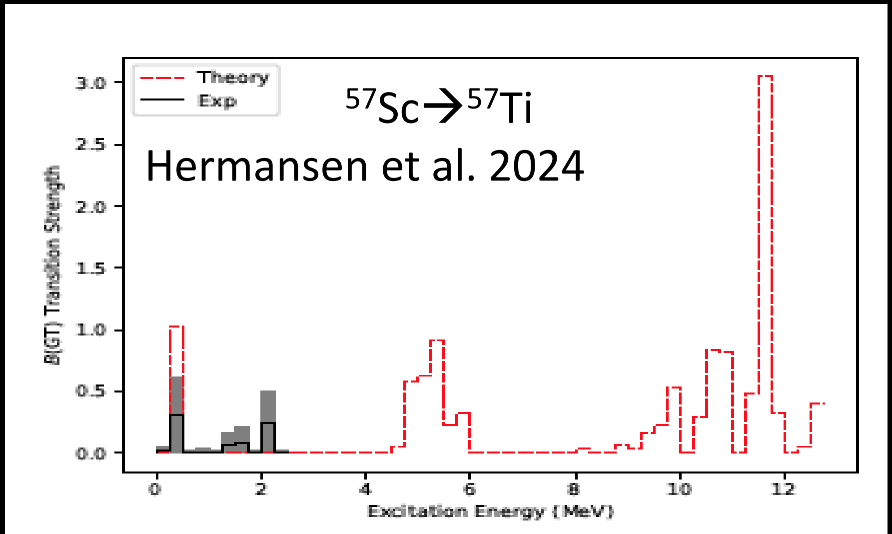


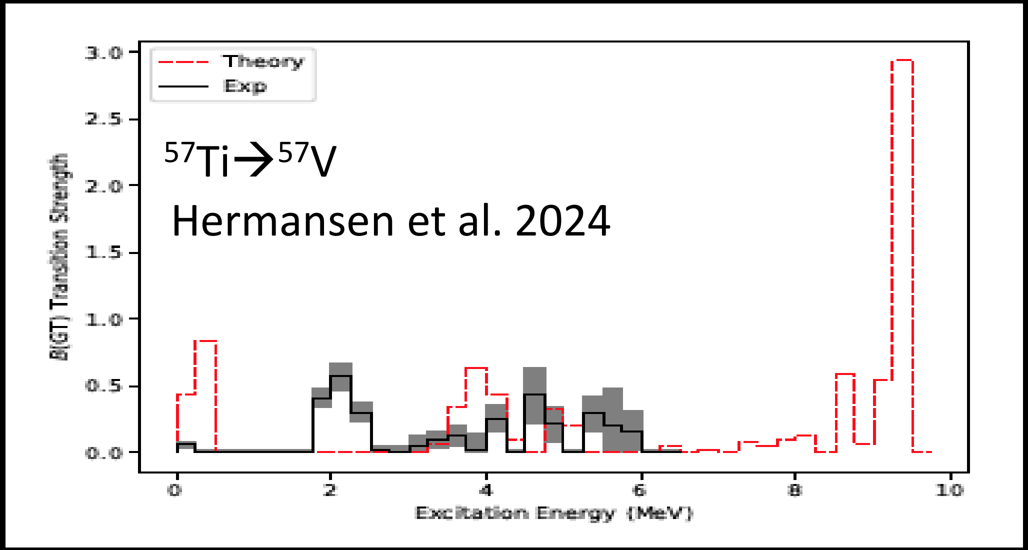
Example Particle Identification (Hermansen 2024)

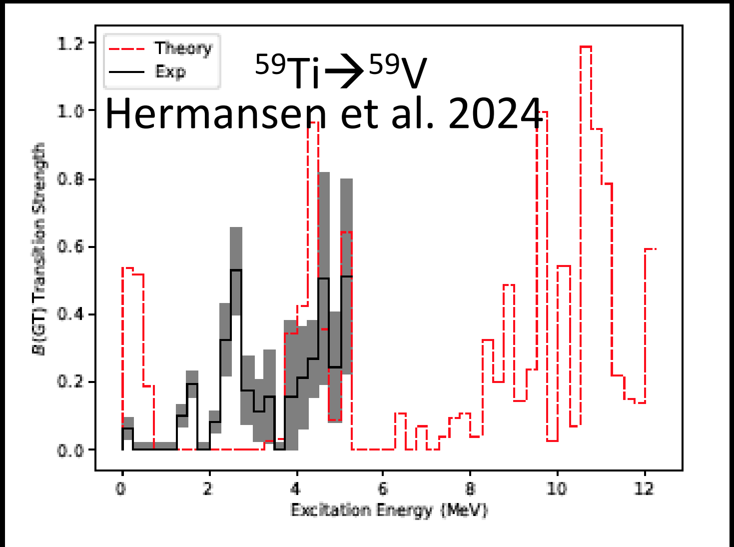


Recent Results





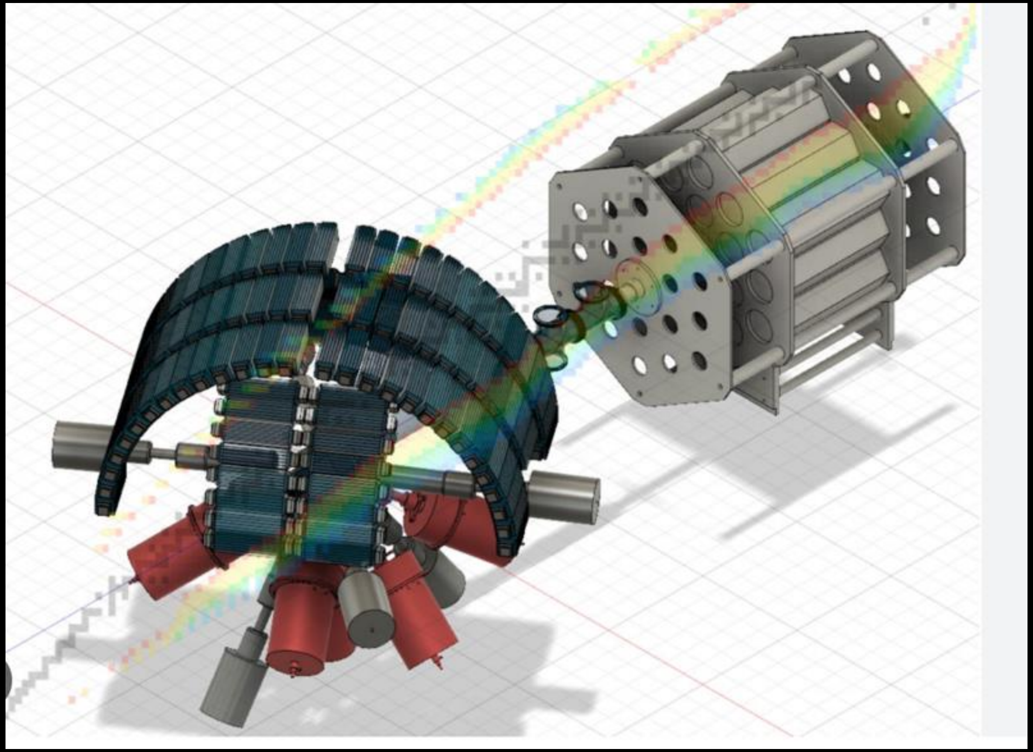


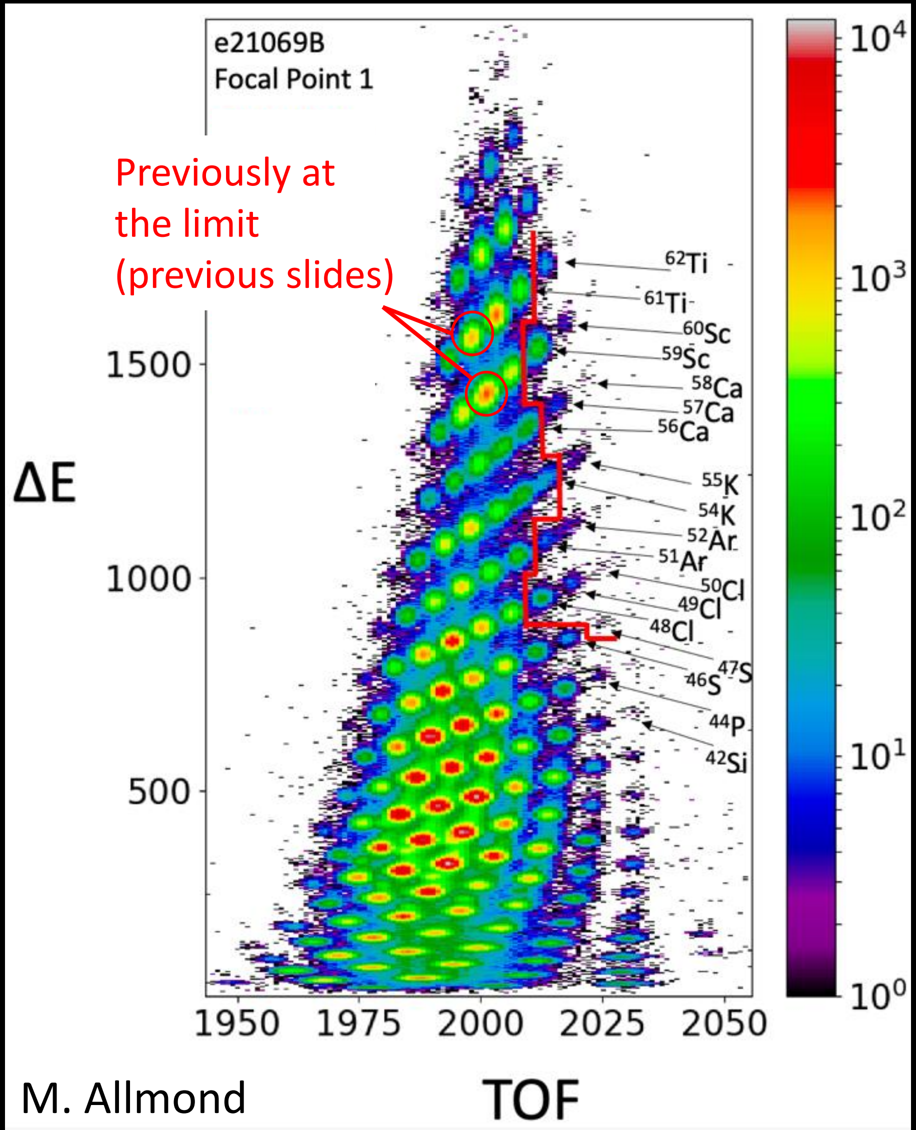


Trend:
Weaker population of ground state than expected
→ Weaker Urca cooling

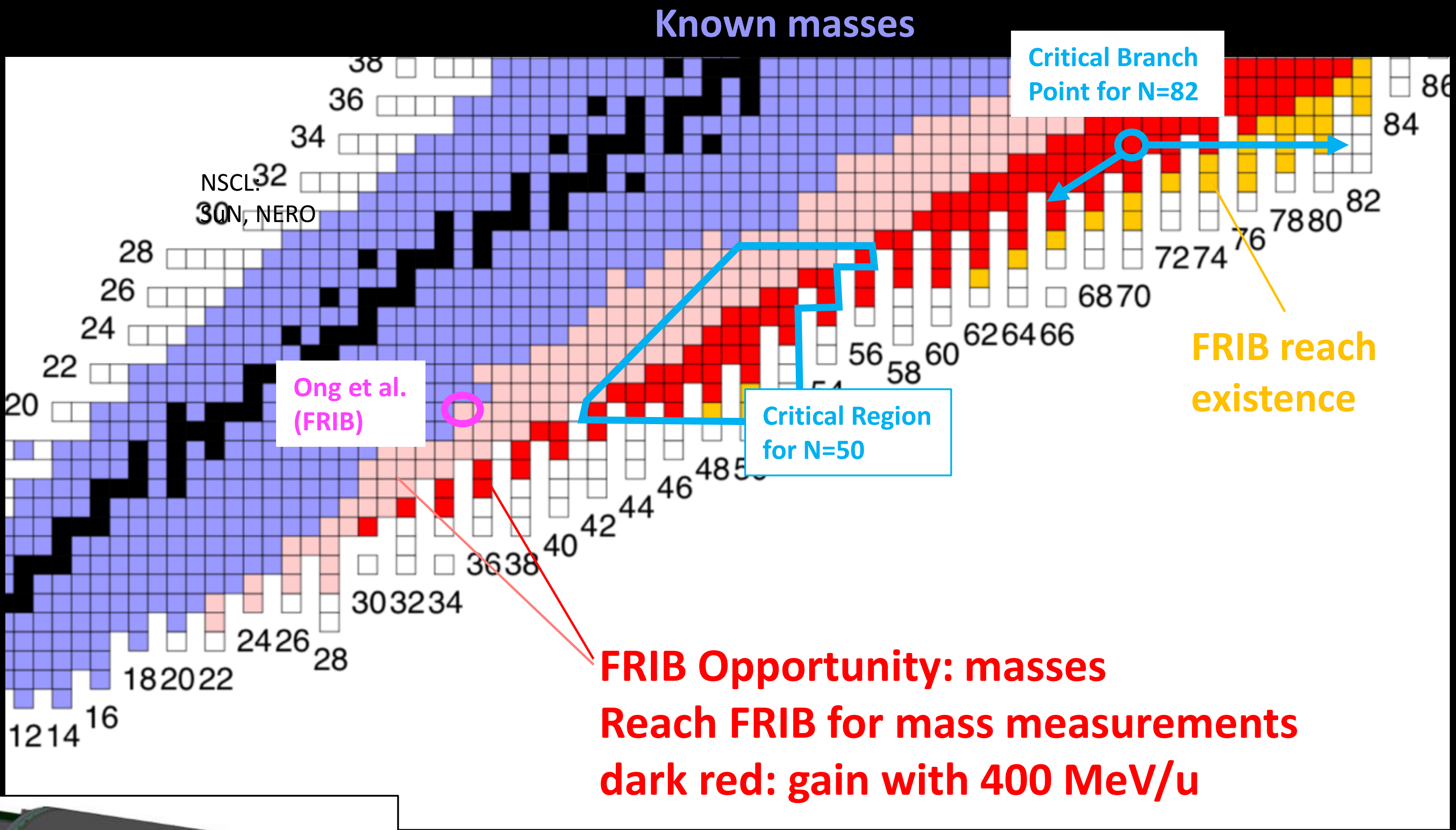
Recent FRIB results using FDSi Setup

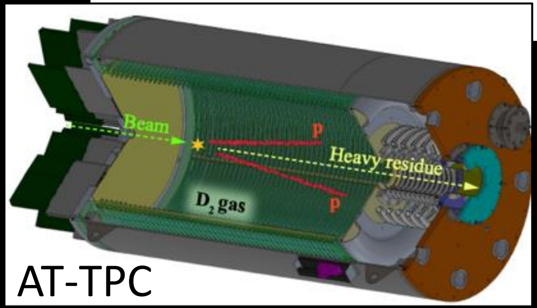
Spokesperson: W.-J. Ong





All Rare Isotopes in Neutron Star Crusts Within Reach at FRIB





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)

IReNA

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

BRIDGCE UK NETWORK
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
(Phasing out)

Being replaced by

CeNAM
Center for Nuclear Astrophysics across Messengers
(Proposal for funding pending)
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 OF NUCLEAR ASTROPHYSICS
Ibero American Network for Nuclear Astrophysics
27 Scientists from 6 accelerator laboratories in 6 countries.
New

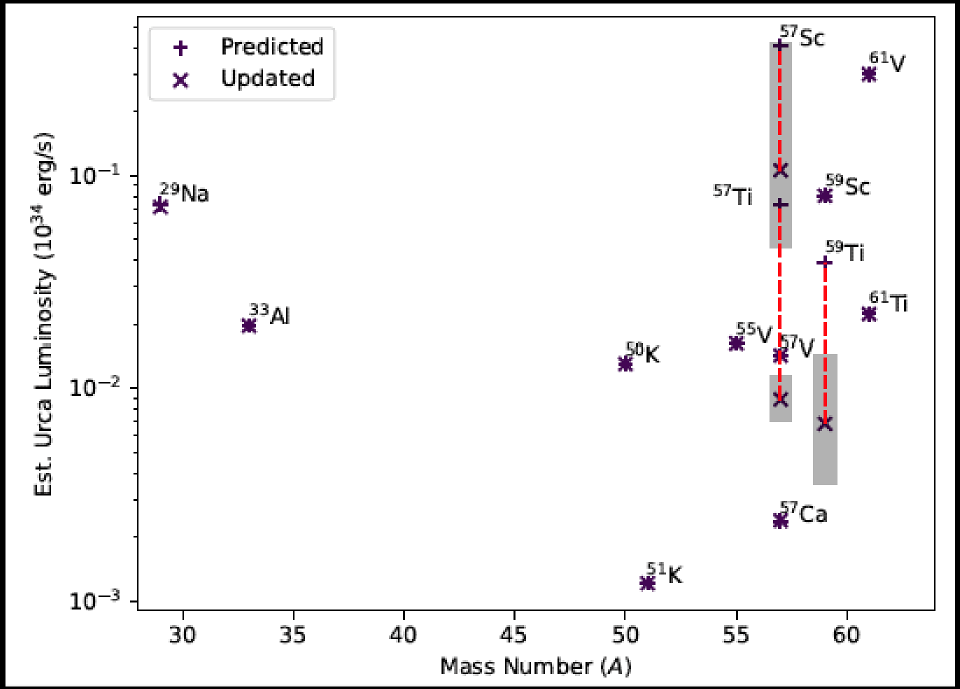
Supports:
- Joint workshops
- Schools
- Visits/Exchanges
- Online Seminar
- Professional Development
- Young Researchers Organization
- Blog!

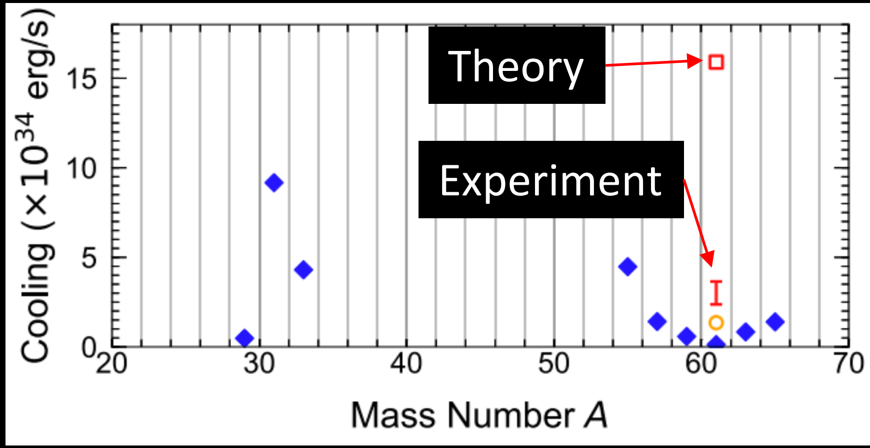
More at irenaweb.org - Join there

Summary

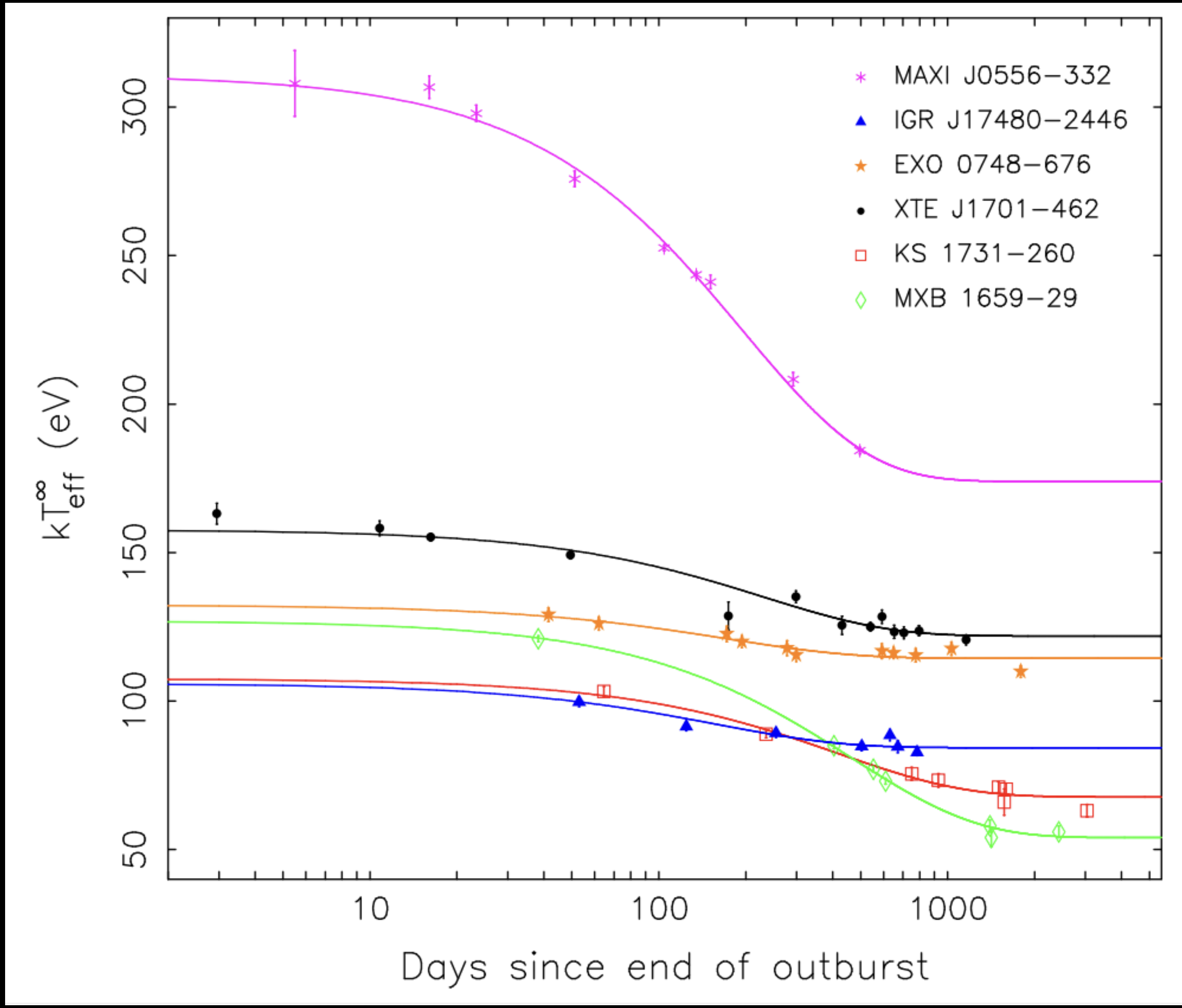
- A new generation of rare isotope beam facilities will offer major new opportunities for nuclear astrophysics – example FRIB in the US, many others under construction
- This is exciting as it coincides with major advances in astronomy, gravitational wave detection, and computational modeling
- Accreting neutron stars offer unique probes of neutron star physics
  - Need radioactive beam experiments
    - To quantitatively interpret observations
    - To solve the many physics puzzles
  - Stable beam experiments can also offer complementary information on unstable nuclei not too far from stability
  - New observational opportunities with XRISM, ATHENA, ….
- Join IReNA

Also add Kirby’s Result





Of decay chain in neutron star



MAXI J0556−332
IGR J17480−2446
EXO 0748−676
XTE J1701−462
KS 1731−260
MXB 1659−29
kT_{eff}^{∞} (eV)
50
100
150
200
250
300
10
100
1000
Days since end of outburst