Open Questions in Nuclear Astrophysics
(at some Intersection with Plasma Physics)

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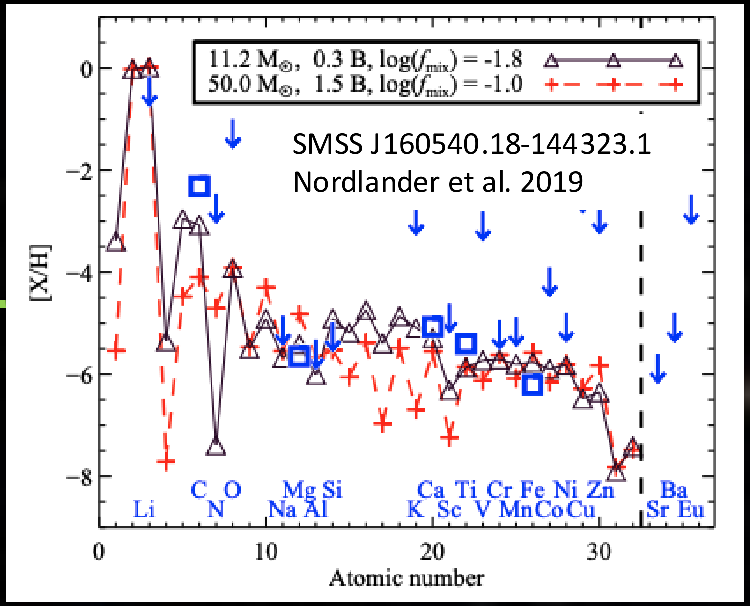
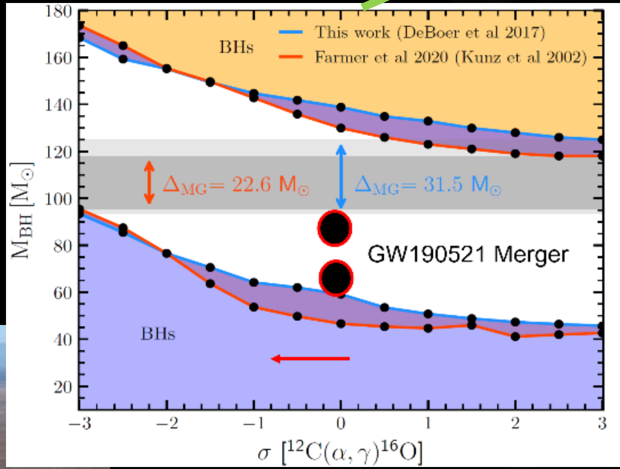
U.S. DEPARTMENT OF ENERGY | Office of Science

Stars

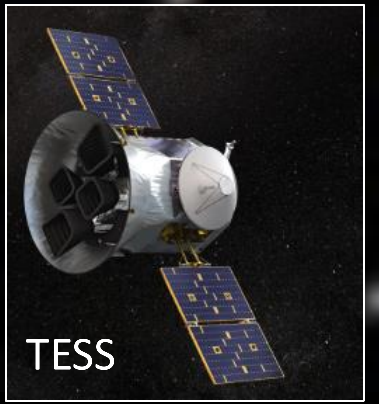
Signature of first massive stars in ultra-metal poor stars

- What do solar neutrinos tell us?
- What is the origin of odd-Z elements (Cl, K, Sc ., ...)?
- What elements did the first stars create?
- What is the structure of white dwarfs?
- What is the outcome of a core collapse supernovae?

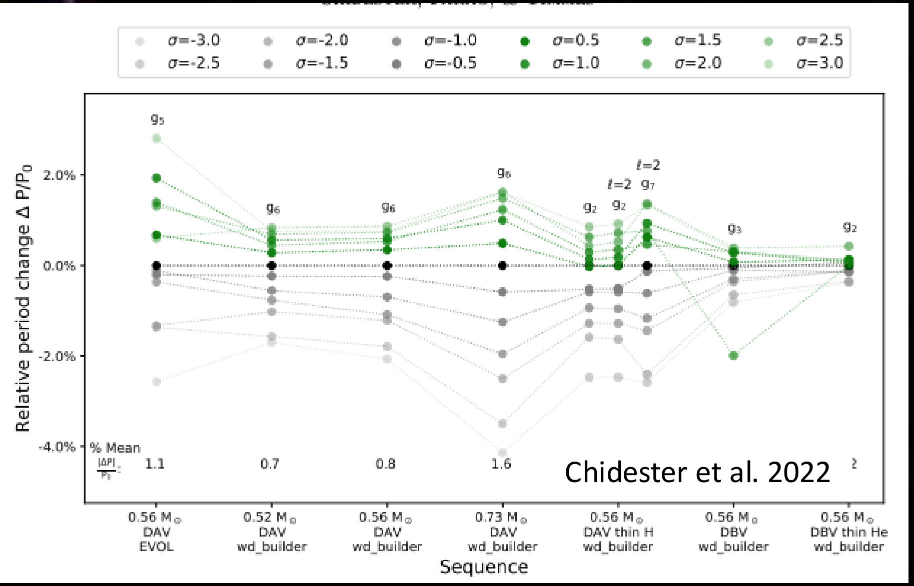




White Dwarf Asteroseismology



Impact of $^{12}C(\alpha,\gamma)$ rate on periods

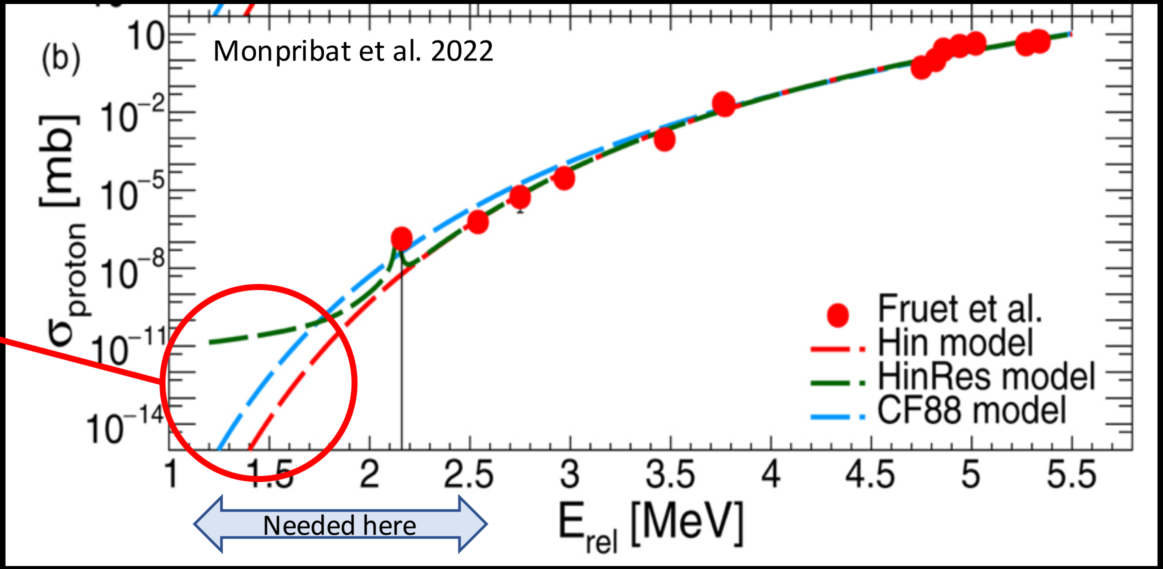


Nuclear Physics Challenge: Reactions at low energies (Thresholds) Expected to Exhibit Suprising Properties but are Hard to Measure

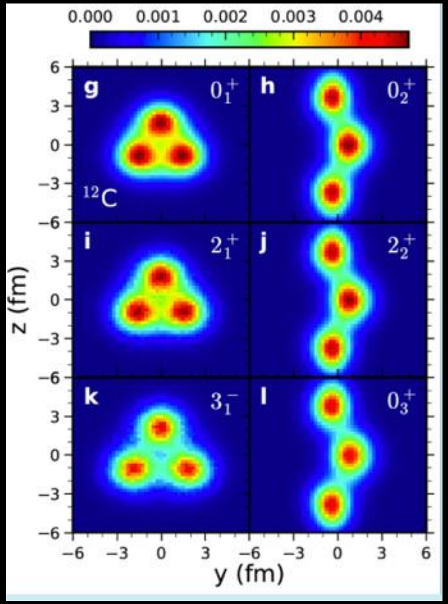
Experimental Challenge:
Cross section drops by > x10,000 from last data point

Theoretical Challenge:
3-4 orders of magnitude uncertainty in prediction due to quantum effects at low energies (e.g. clustering)

$^{12}C+^{12}C$ →Massive Star Nucleosynthesis/SN Ia/Superbursts



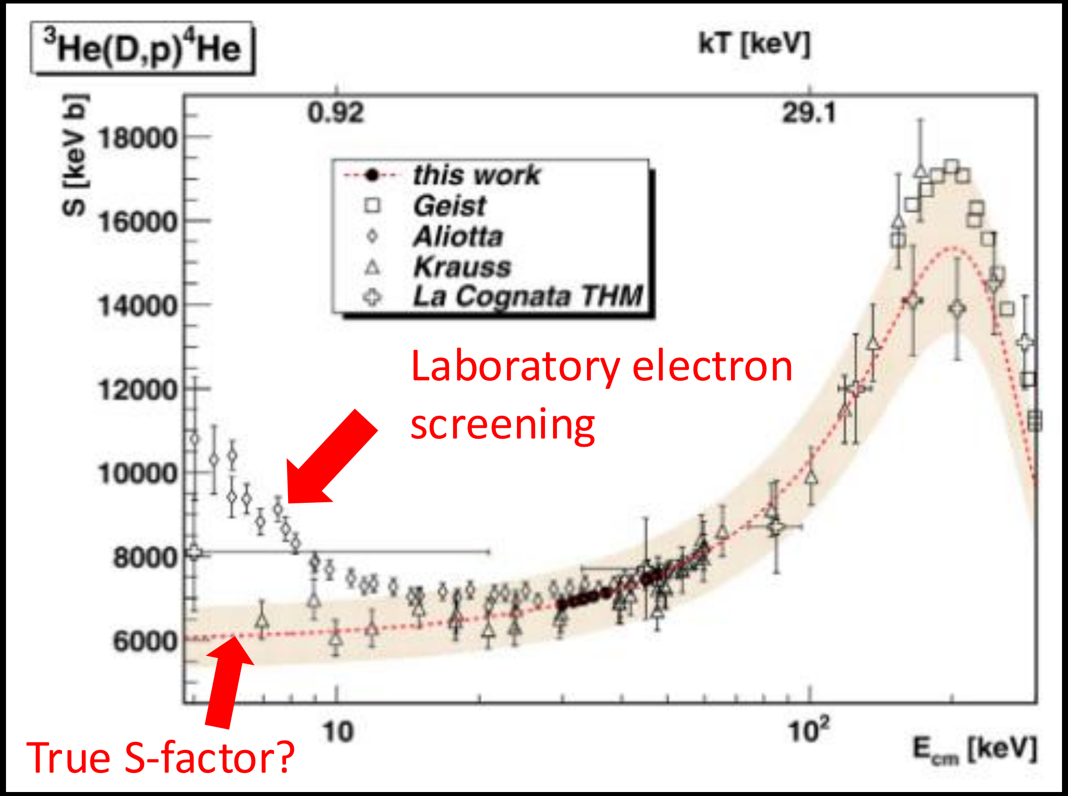
Example of possible cluster structure at low energies (here Hoyle state)



→ This affects reactions on stable and unstable nuclei in stellar evolution, X-ray bursts, Type Ia, Supernovae, i/n process neutron production …

Screening and Other Low Energy Frontiers Challenges

Aliotta & Langanke 2022



Electron cloud reduces Coulomb barrier

3 challenges:

1. Tiny signal to background: go underground? (LUNA, CASPAR, JUNA)
2. Lab screening from target not well understood and correction needed
3. Stellar screening has to be applied to get stellar rates and is not measured

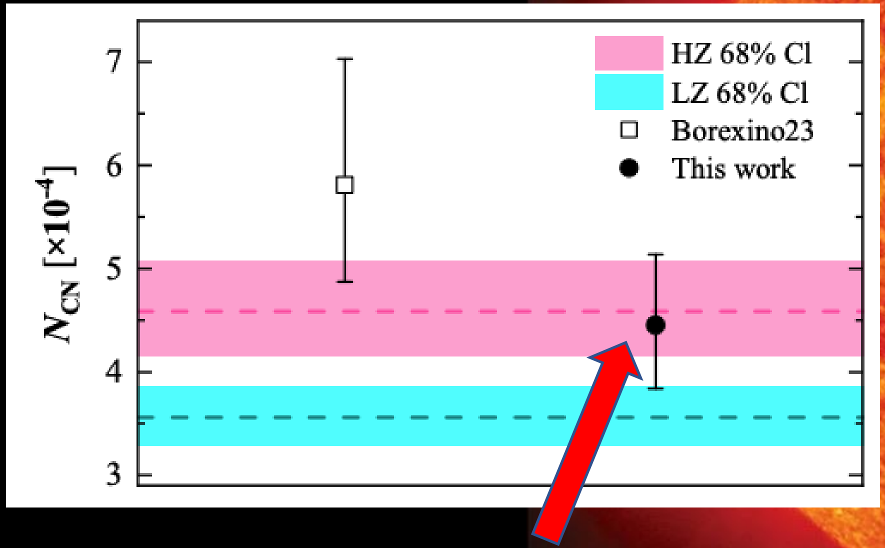
Direct measurements in laser heated plasma can address all three!

Accurate pp-chain and CNO Reactions in the Sun

Why do we need this?

- What do solar neutrinos tell us about the sun?
- Accurate standard solar model is critical
- What is the composition of the sun ?

C,N abundance in the Sun



New ^{14}N(p,g) rate (14% change)

Chen et al. 2024

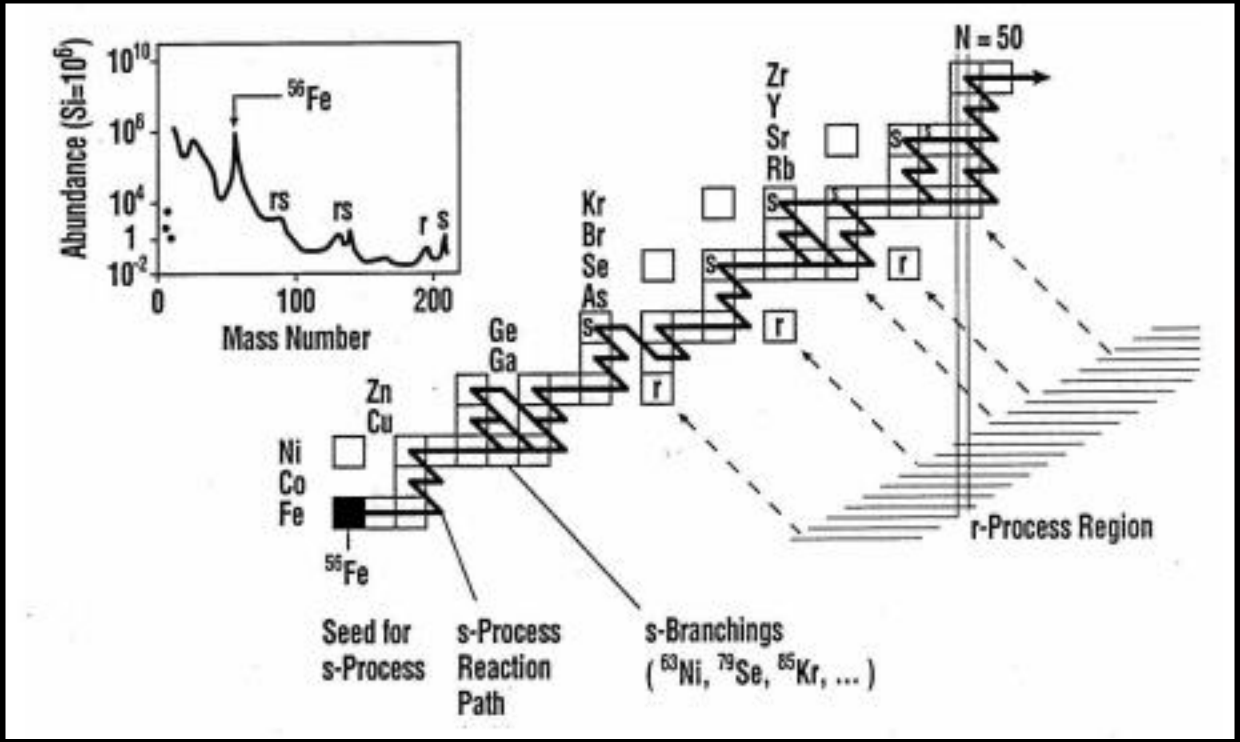
Stellar Electron Screening Effect:

- 5% correction for p+p
- ~13% for ^{14}N+p
- There is a controversy whether dynamical effects greatly reduce screening or not (Aliotta & Langanke 2022)

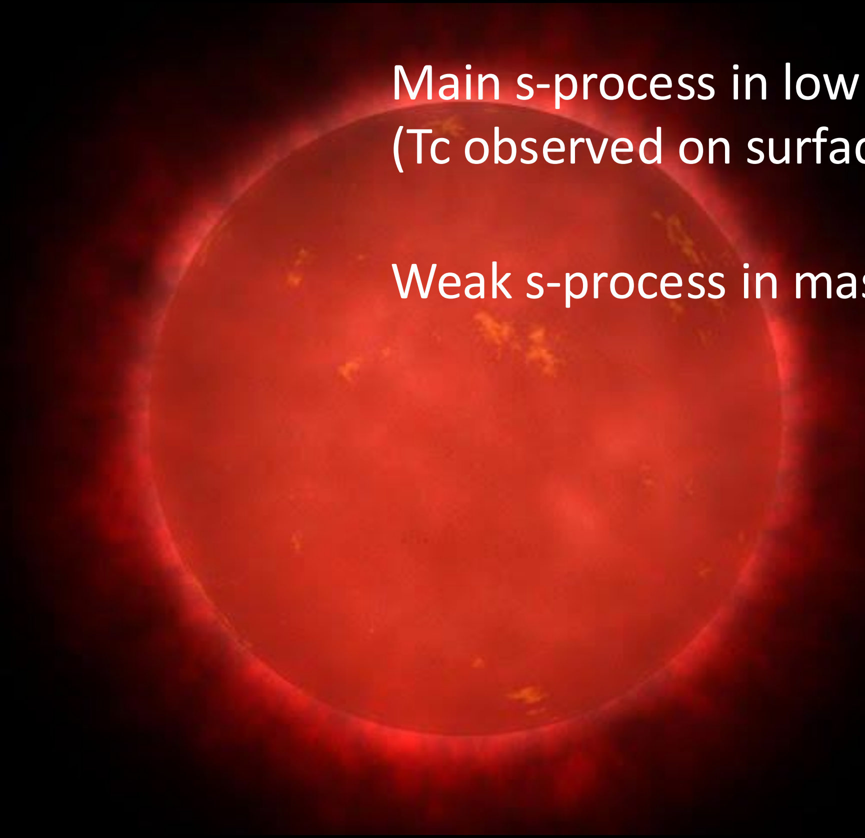
→ Measurements would be important

The Slow Neutron Capture Process – What we Know

S-process is responsible for half of the heavy elements in the universe



Käppeler et al. 2010



Main s-process in low mass red giants (Tc observed on surface)

Weak s-process in massive stars

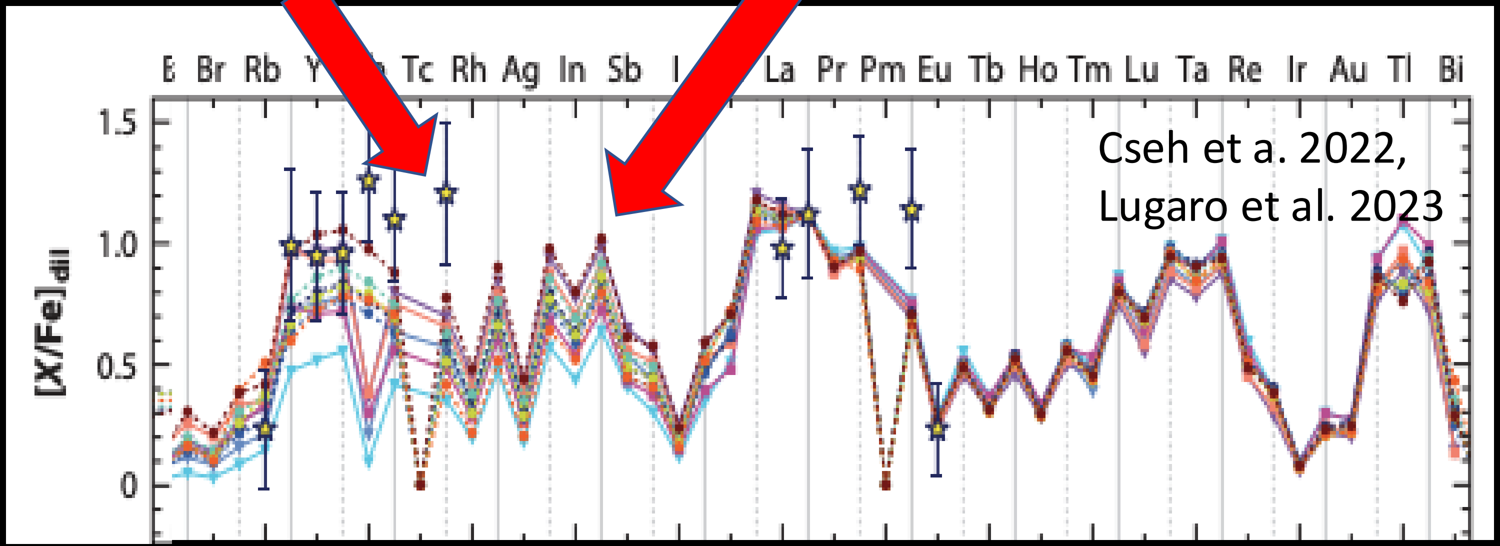
Mixed H and He burning, e.g.
$^{12}C+p \rightarrow {}^{13}N \rightarrow {}^{13}C + \alpha \rightarrow {}^{16}O + n$

Open Questions in the Slow Neutron Capture Process

- What is rate of neutron source reactions $^{13}C(\alpha,n)$, $^{22}Ne(\alpha,n)$ (close to being addressed)
- Relative contribution and heaviest elements produced in weak s-process
- How does mixing in stars work?
  Can observations plus precision nuclear physics be a precision probe of stellar physics?

Red giant surface abundances:
CD −42°2048

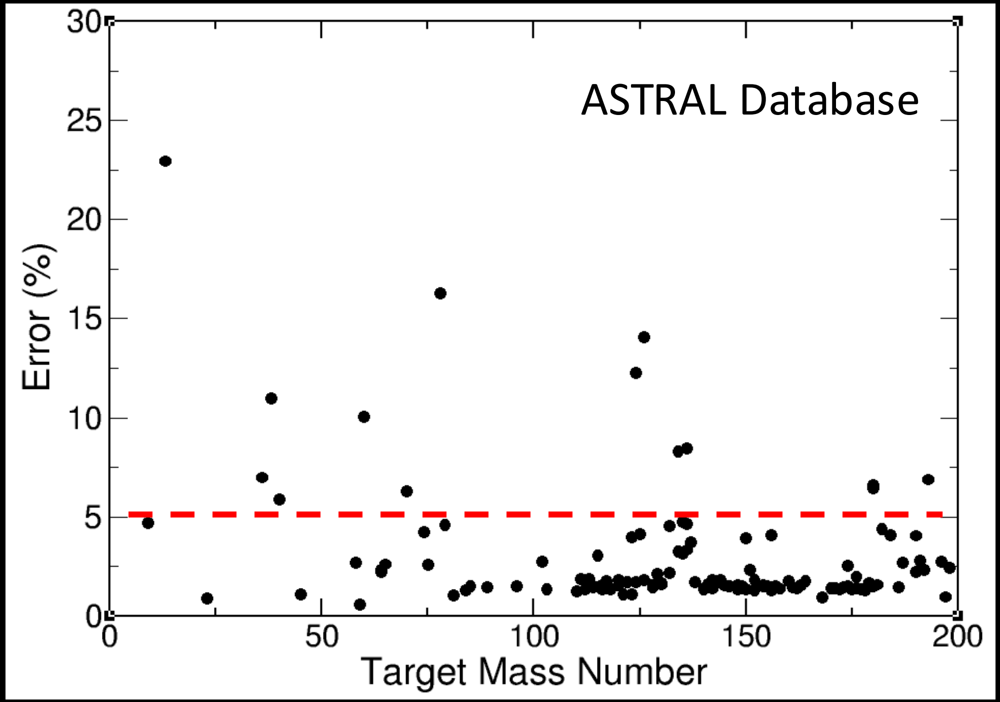
Lines are different models



→ Are neutron capture rates known well enough?

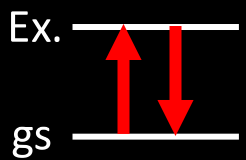
Precision of Nuclear Physics – (n,γ) rates

Accuracy of n-capture rates on stable nuclei

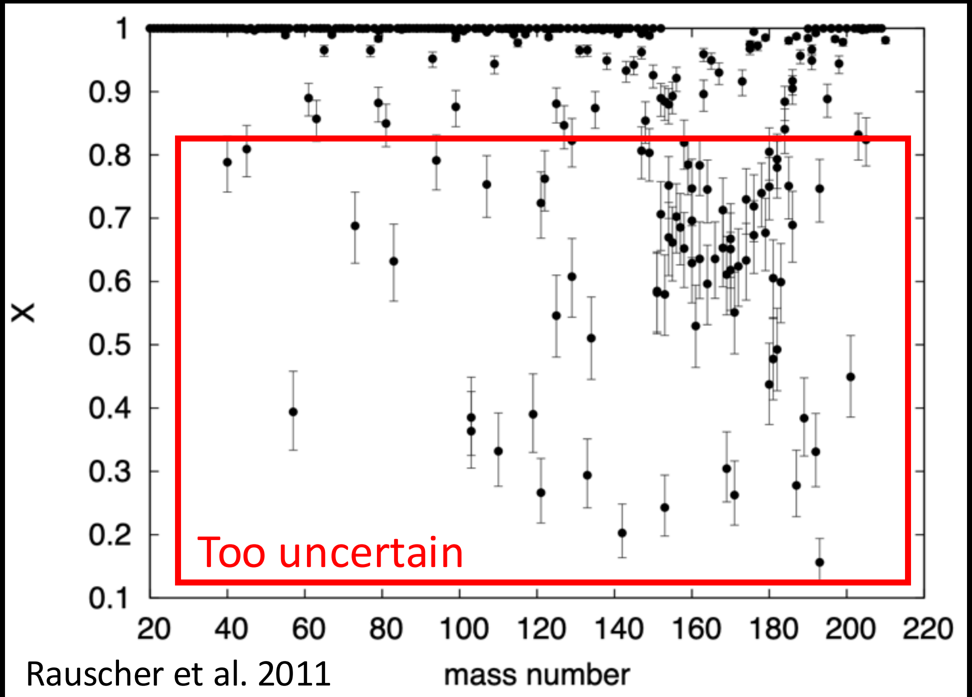


Population $e^{-Ex/kT}$

s-process
kT~30 keV



X: Fraction of Rate Determined by gs

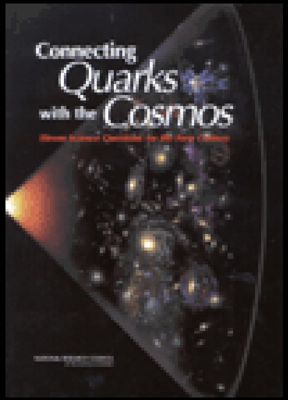


Example: ^{187}Os(n,γ)^{188}Os 9.8 keV excited state X=0.28

→ Direct n-capture measurements with n-beams have greatly reduced uncertainties

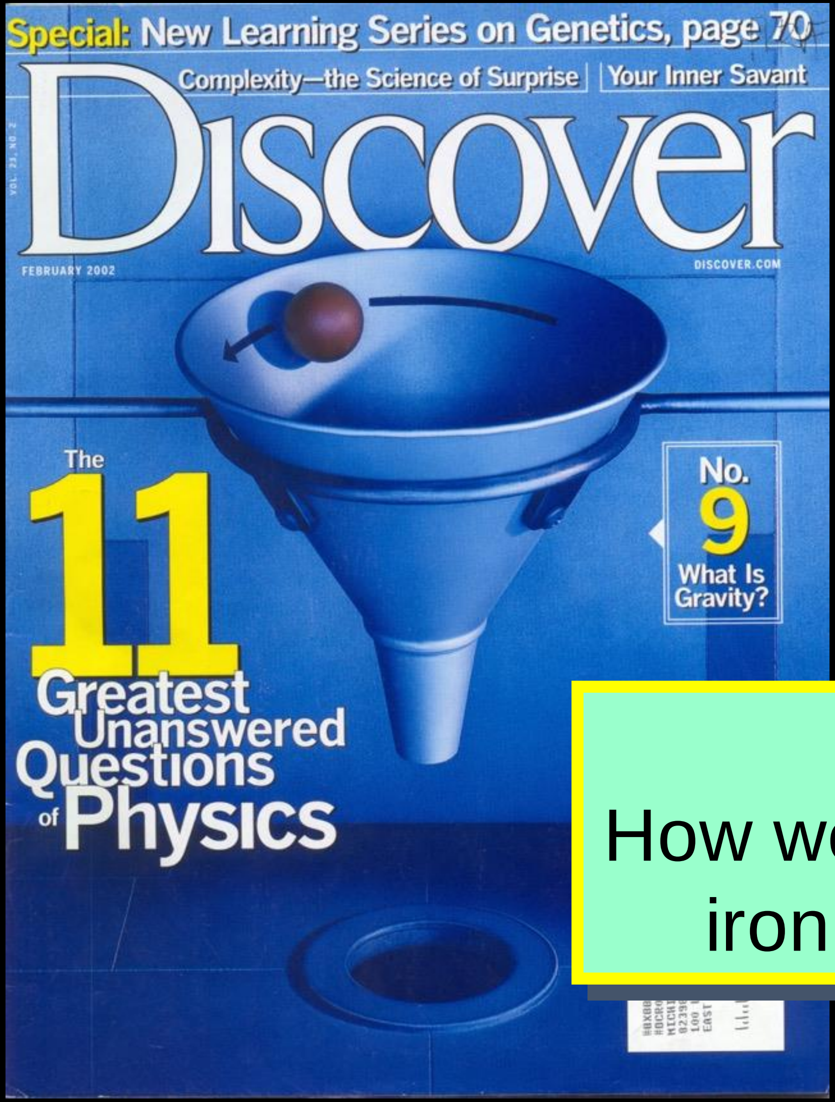
→ Unique opportunity to measure capture on short-lived excited states using laser induced plasma

→ Also advantages for capture on radioactive nuclei? (branchings)



Committee for the Physics of the Universe (NRC/NAS)

“Connecting Quarks with the Cosmos” – 11 science questions for the new century



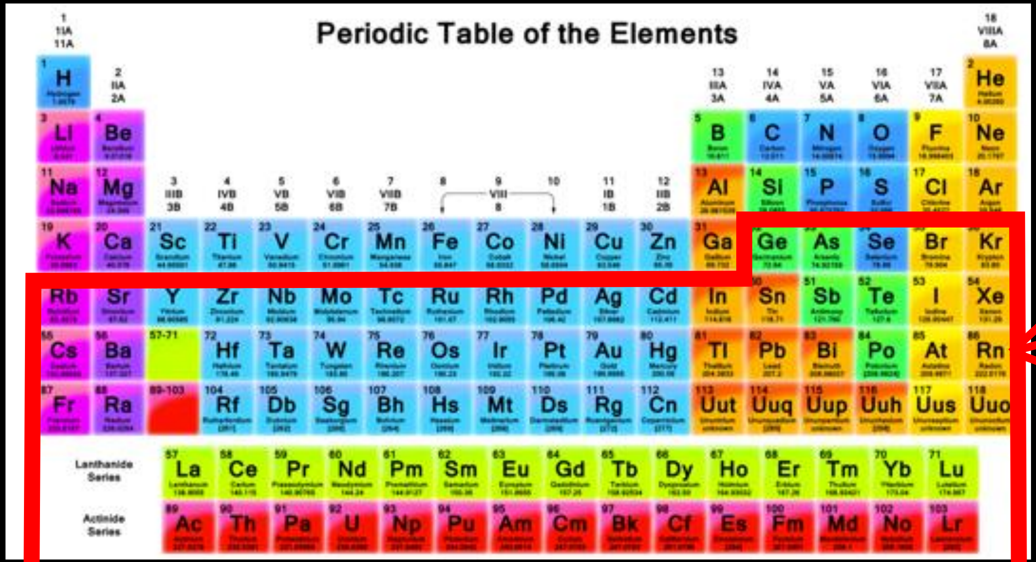
What they meant:
What is the site of the rapid neutron capture process (r-process)?

Question 3
How were the elements from iron to uranium made ?

CeNAM

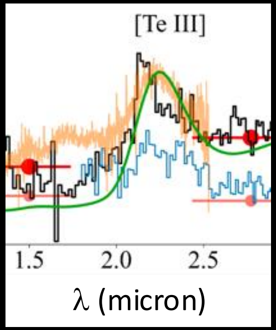
The Origin of the Heavy Elements Traditionally Attributed to the r-process More Complex than Anticipated

FRIB



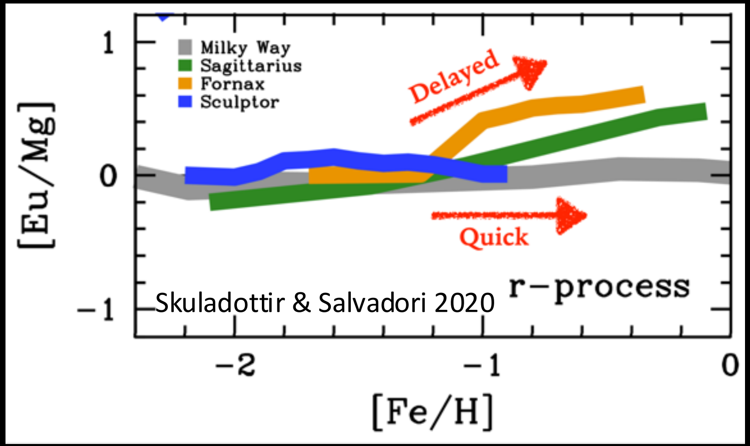
- Dynamical ejecta
- Wind ejecta
- Disk ejecta

GW170817 associated kilonova:
Reddining proves heavy elements are created
And ejected by NS mergers (short GRBs)

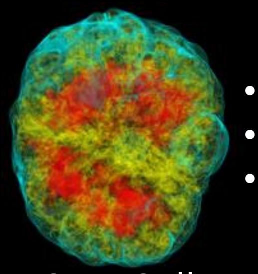


Levan et. al.
JWST detection of Te
in GRB230307 afterglow

Quite a bit of evidence for multiple main r-process sites

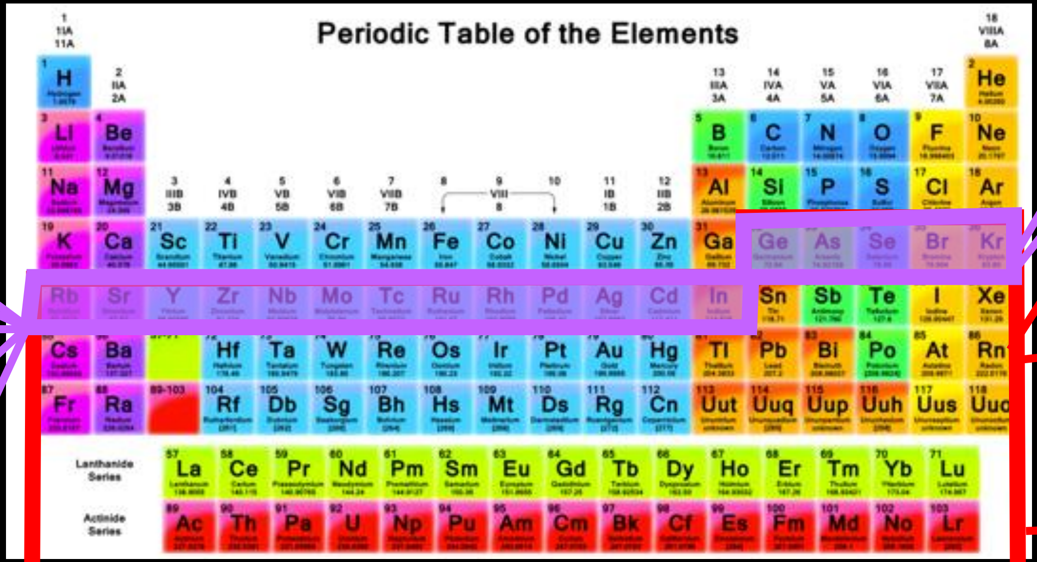


Even More Complex than That:



Core Collapse Supernovae

- n-process
- νp-process
- weak r-process



Rapid neutron capture process:

- Dynamical ejecta
- Wind ejecta
- Disk ejecta

NS Merge

λ (micron)

Collapsars

Jet Supernovae

Stars: H mixing i-process

Rapidly Accreting White Dwarfs - i-process

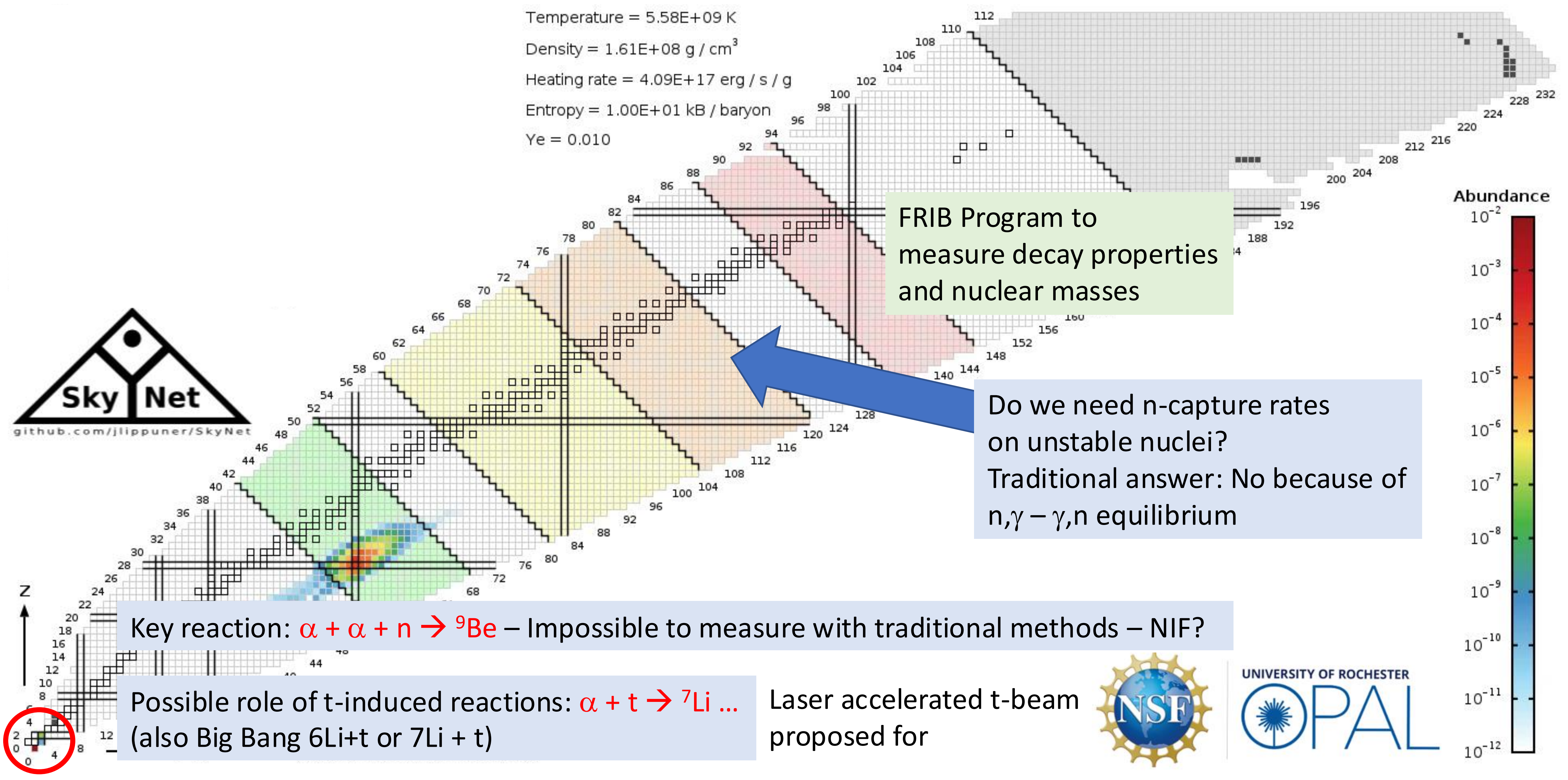
→ Now we are asking the right questions

→ Now we need the nuclear physics for all these sites to

→ To "interpolate" sparse observations and determine what each site makes

→ Disentangle individual contributions

R-Process Involves Extremely Unstable Nuclei



FRIB Program to measure decay properties and nuclear masses

Do we need n-capture rates on unstable nuclei?
Traditional answer: No because of $n,\gamma - \gamma,n$ equilibrium

Key reaction: $\alpha + \alpha + n \rightarrow {}^{9}Be$ – Impossible to measure with traditional methods – NIF?

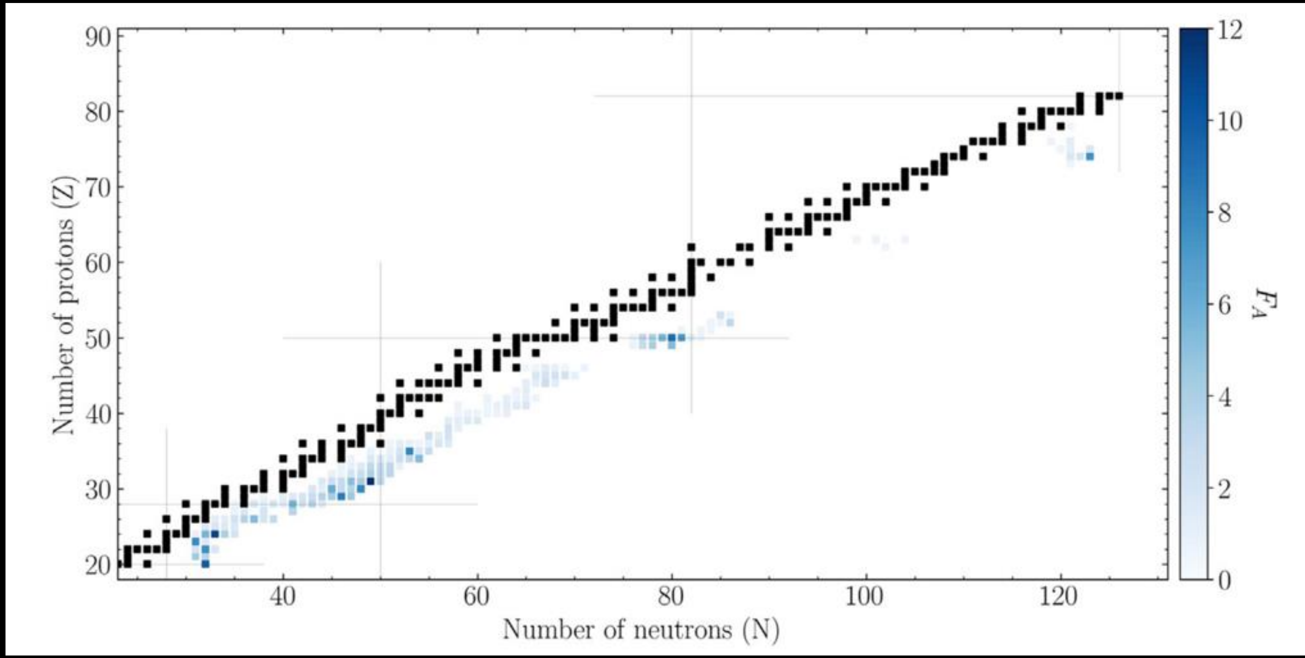
Possible role of t-induced reactions: $\alpha + t \rightarrow {}^{7}Li$ …
(also Big Bang 6Li+t or 7Li + t)

Laser accelerated t-beam proposed for

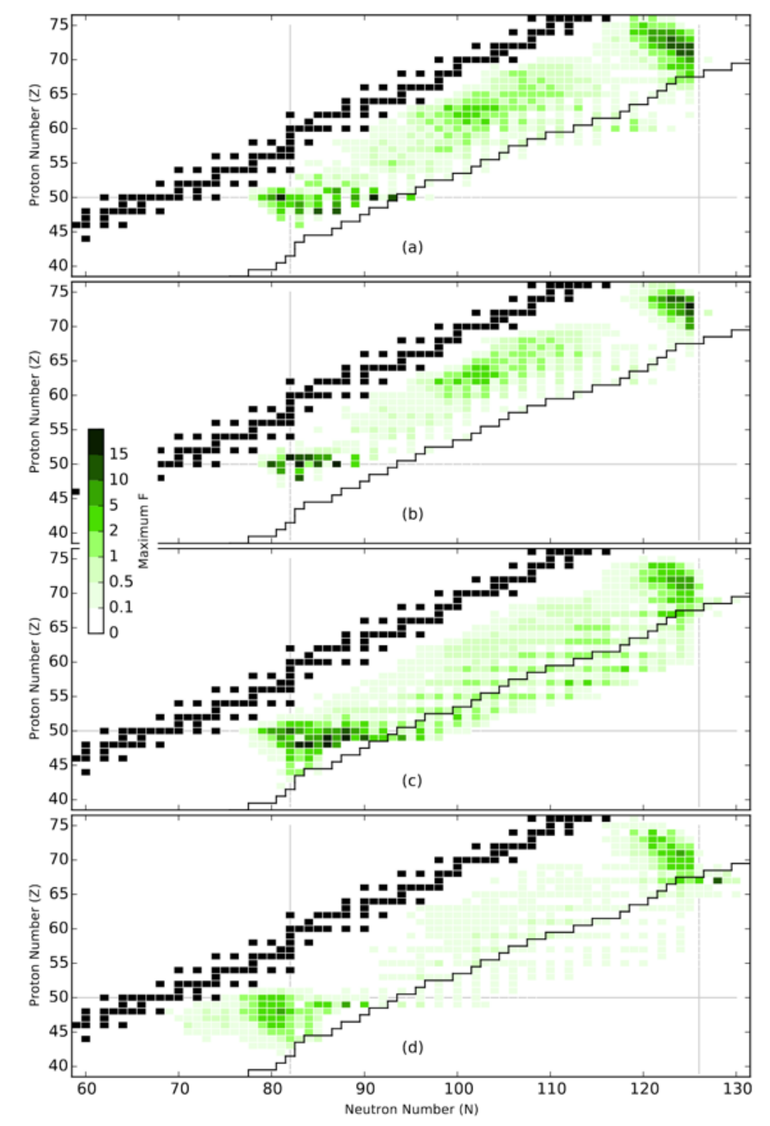
UNIVERSITY OF ROCHESTER OPAL

Sensitivity Studies Indicate Impact of n-capture Rates on Final Abundances

Mumpower et al. 2016



Vescovi et al. 2022



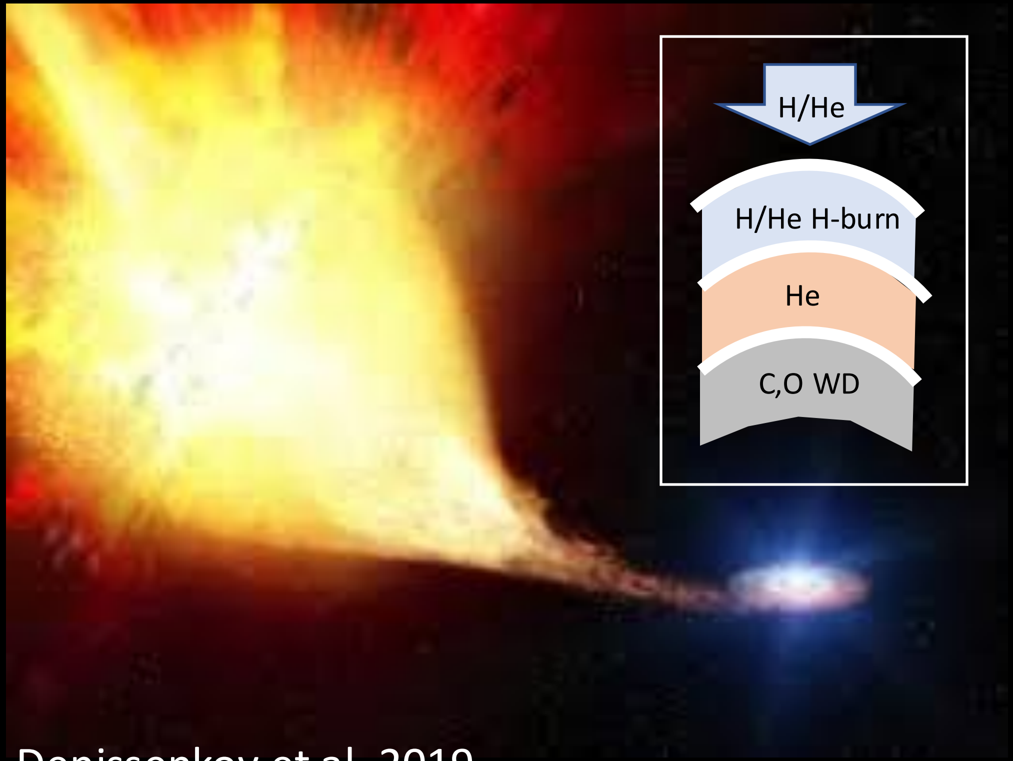
Mixing in Stars May Give Rise to Intermediate Neutron Capture Process (i-process)

Mixing of H into He burning:

3x ^{4}He → ^{12}C + p → ^{13}N → ^{13}C + ^{4}He → ^{16}O + n

Example: Rapidly Accreting White Dwarfs

He flashes every ~100,000 yrs



Denissenkov et al. 2019

Stephens, Herwig et al. 2020

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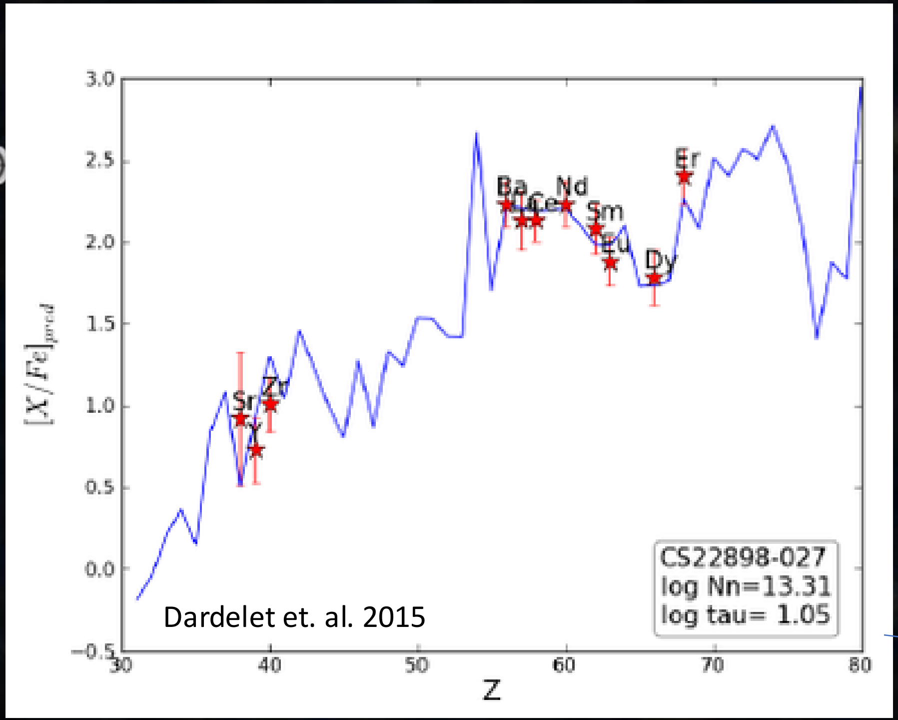
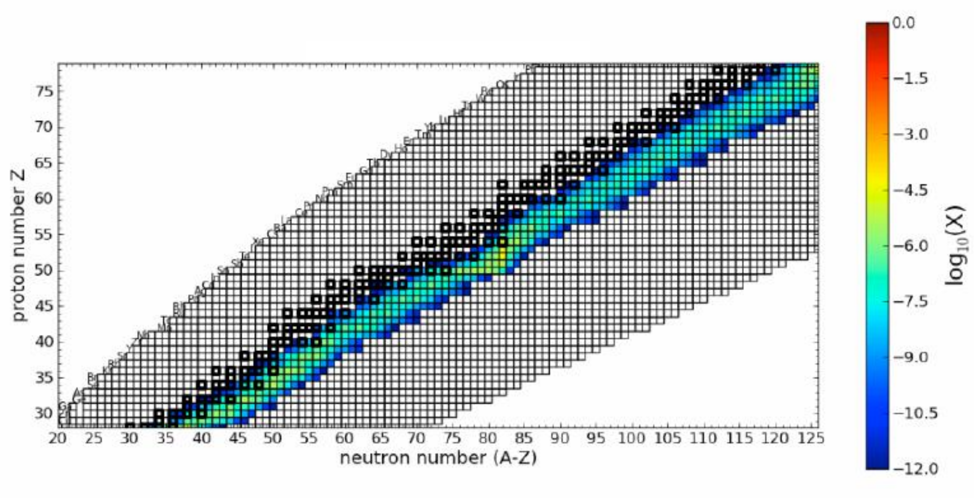
The i-process – a New Challenge for Nuclear Physics



Intermediate Neutron Capture Process (i-process)



i-process star element abundances

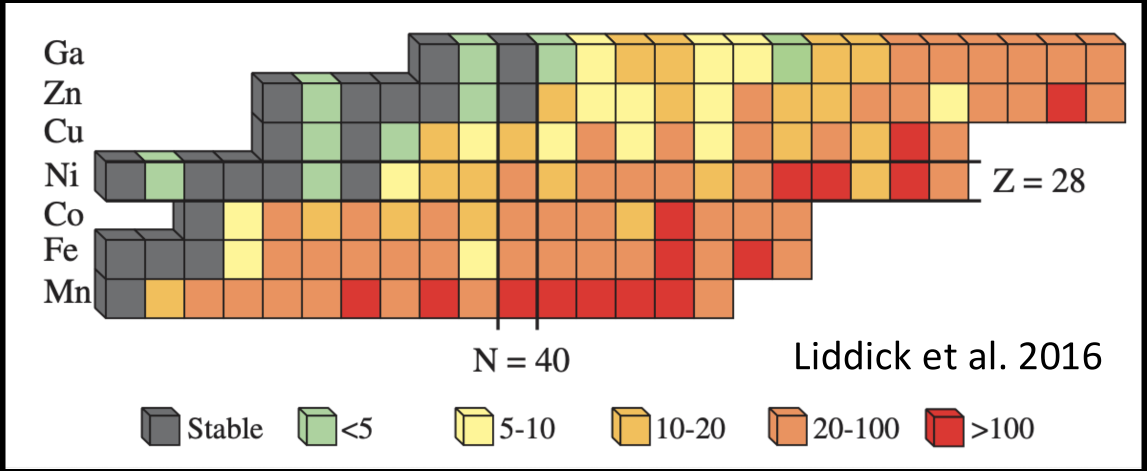
→ Explains abundance signatures in some metal poor stars

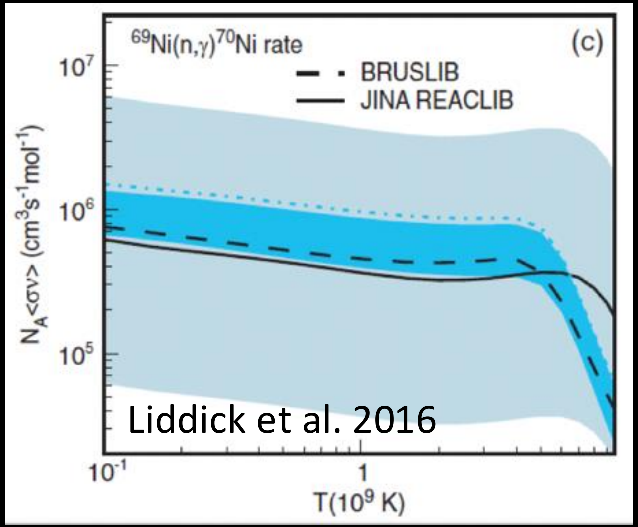
→ Need nuclear physics to model the i-process to
- → identify viable models (stars, accreting white dwarfs)
- → determine nucleosynthesis contribution
- → Like s-process abundances are determined by n-capture rates

FoV: 3.98'

How Can One Measure n-capture on Unstable Nuclei

Uncertainty of Predicted Neutron Capture Rates



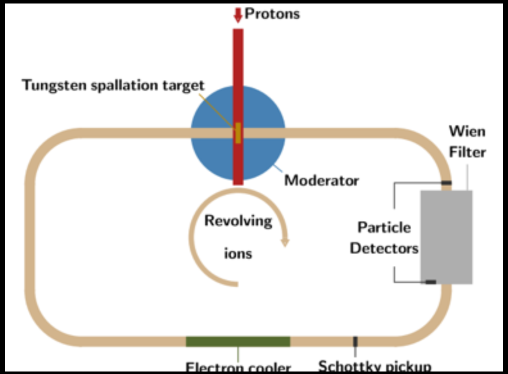


β-Oslo method at FRIB: determines γ-strength and level density from β-decay γ-spectroscopy

+ Surrogate reaction technique, transfer reactions

→ Indirect and model dependencies

Far future: ion storage ring with neutron beam (Development work at LANL)



Mosby, Reifarth, et. al.

Advantage of laser induced plasma reactions: high density

→ Can measure 2n capture with second capture on unstable nucleus

→ Already 1 isotope away from stability significant increase in theory uncertainty –can obtain important constraints

Neutron spectrum?

Accreting Neutron Stars are Observed as X-ray Binaries

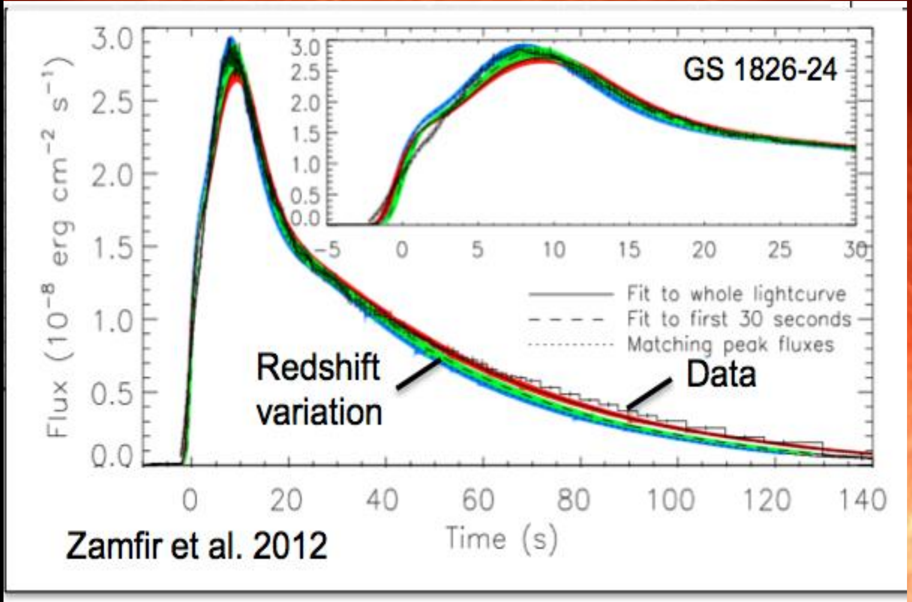
Bright persistent X-ray source powered by gravitational energy.

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

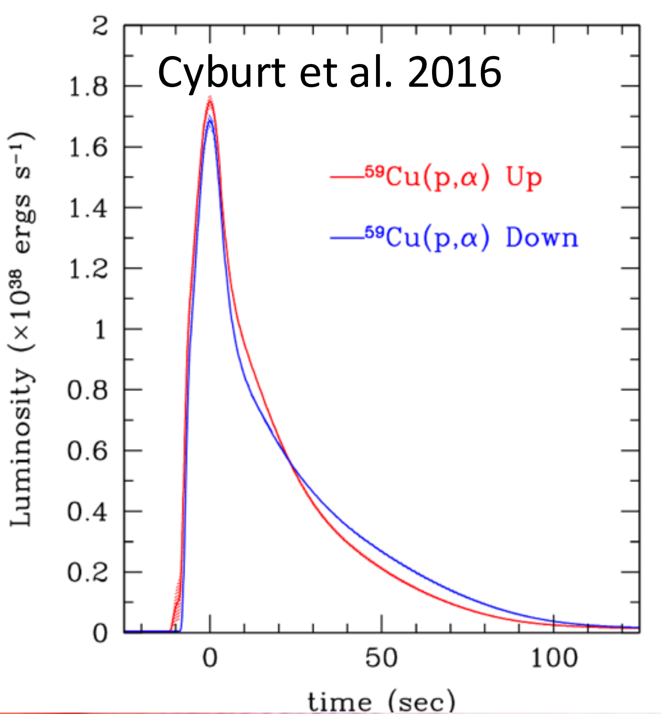
- Durations: 10-100~s
- Recurrence time: hours-days

→ 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

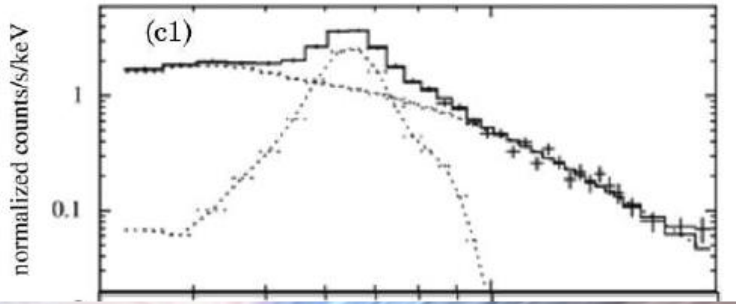


→ Extract surface redshift to constrain compactness (mass, radius)
→ Burst properties probes surface heat



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

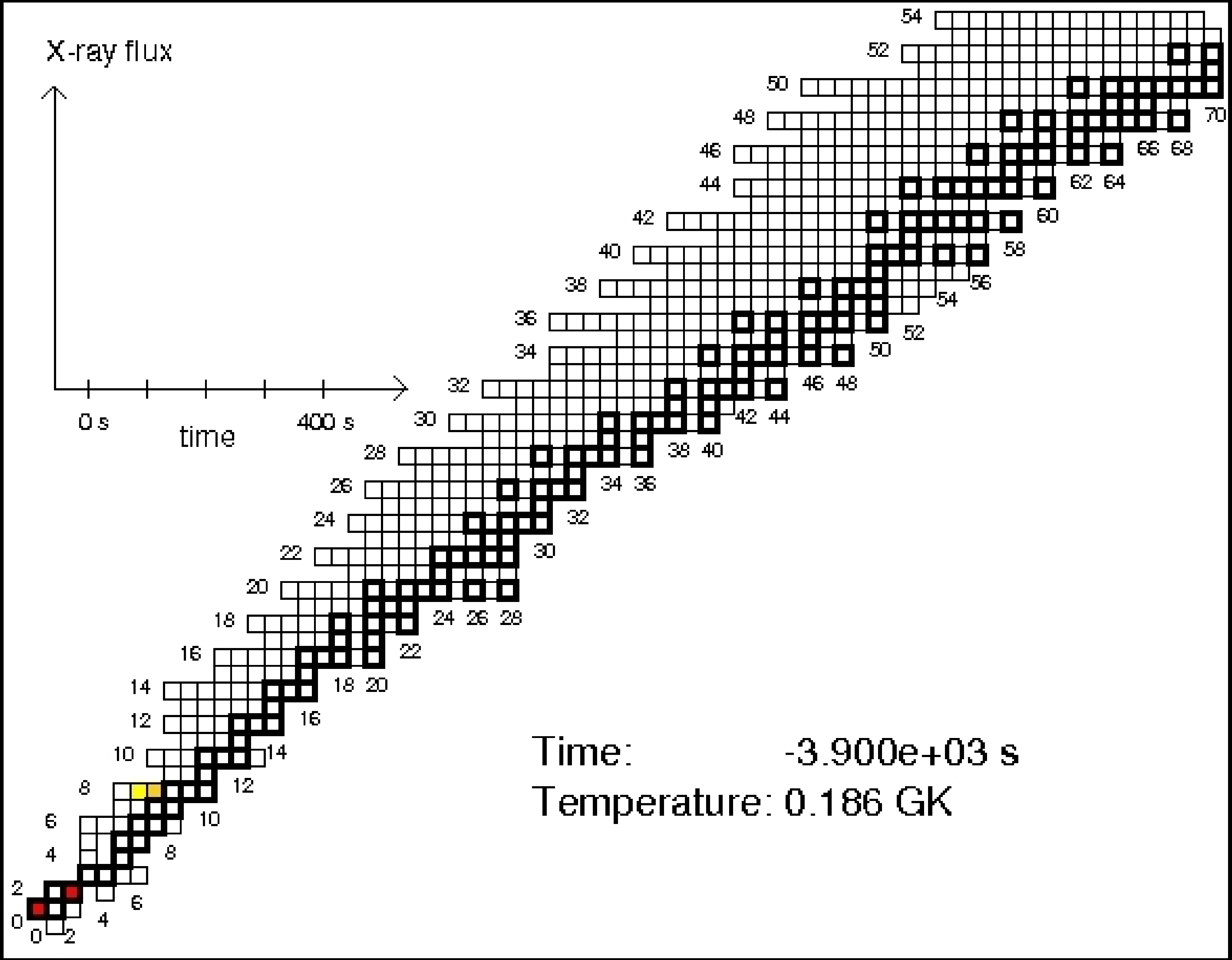
Can we detect element signatures in spectra?



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

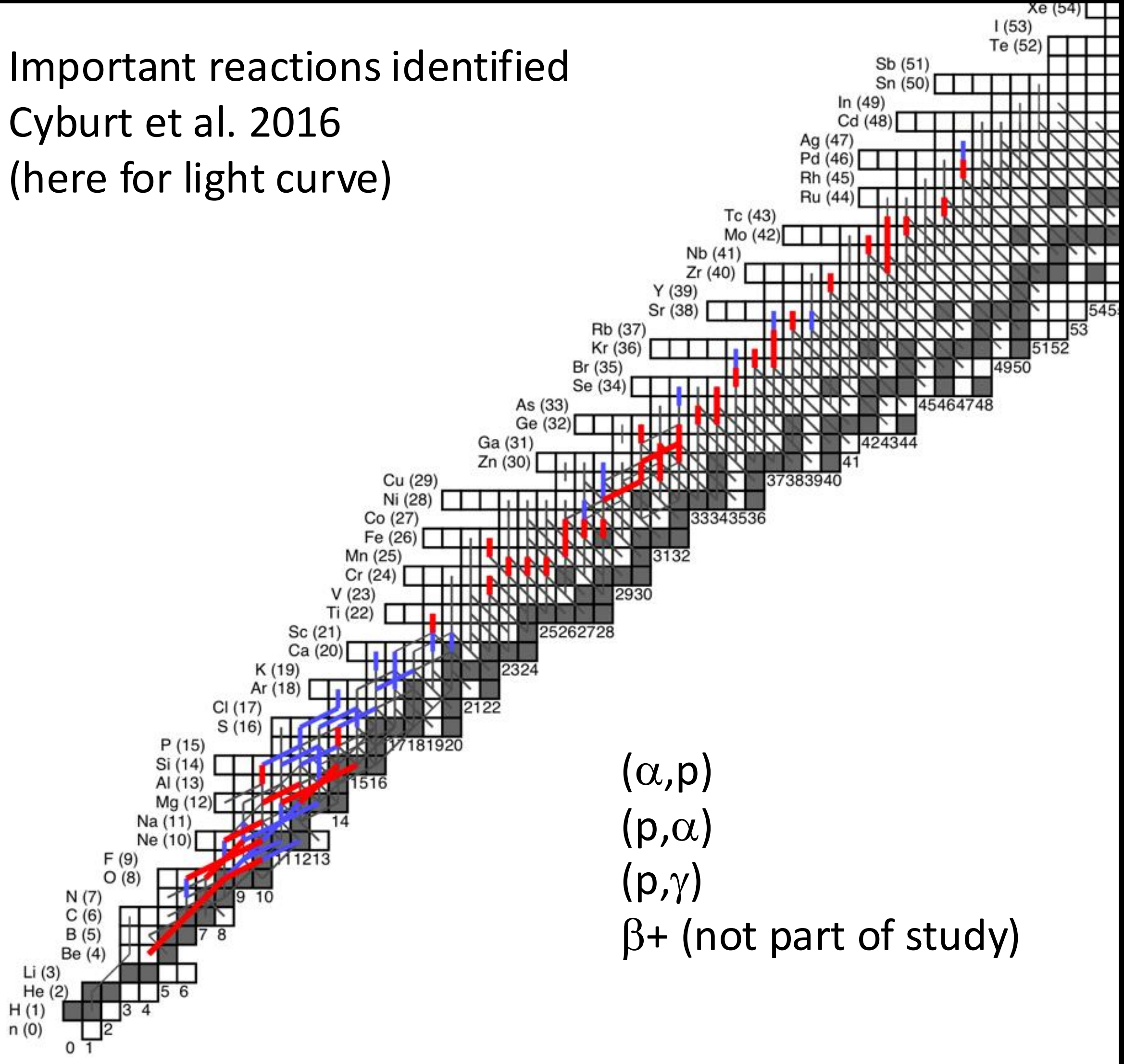
→ Need nuclear physics to predict candidates and aid in identification



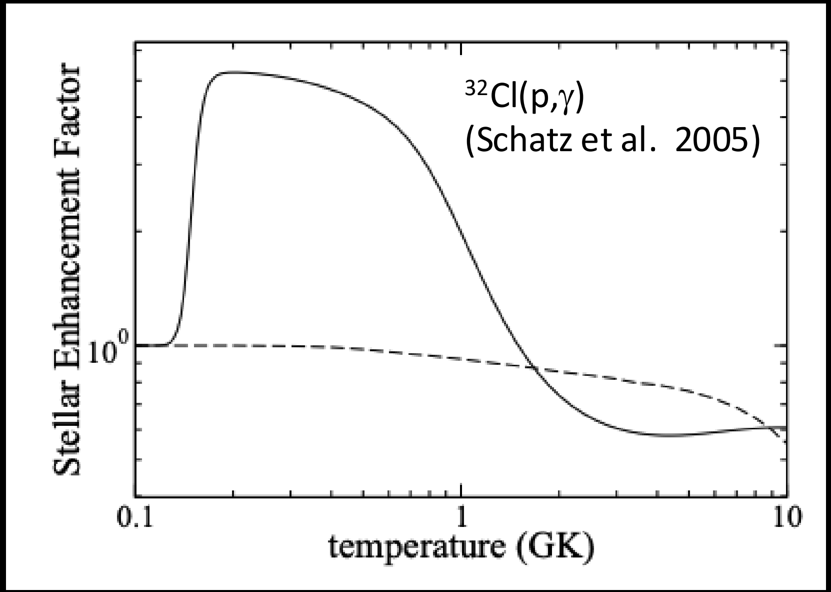
Based on model
By A. Heger

X-ray Burst Reactions

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



Capture on thermally excited states also important here



89.9 keV excited state in ^{32}Cl target

Shell model rate – informed by measured level excitation energies – highly uncertain

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

CeNAM

IReNA

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

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

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 OF NUCLEAR ASTROPHYSICS
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

Summary

- "Low density" plasma effects are important for many open questions in nuclear astrophysics and need to be addressed experimentally
  - Electron screening
  - Reactions on short lived excited states
- Laser heated plasmas also offer advantages for measuring nuclear reactions
  - n-capture on unstable nuclei
  - Higher/complementary sensitivity to low cross sections
  - t-beams
- There are also important weak interaction effects at higher density
  - Continuum electron capture in neutron stars, supernovae, ...
  - Plasmon decay neutrino emission in white dwarfs and neutron stars
  - More screening
- Interdisciplinary networks like CeNAM and IReNA are critical for taking advantage of new complementary capabilities and developments