Sensitivity of X-ray burst models to thermonuclear reaction rates

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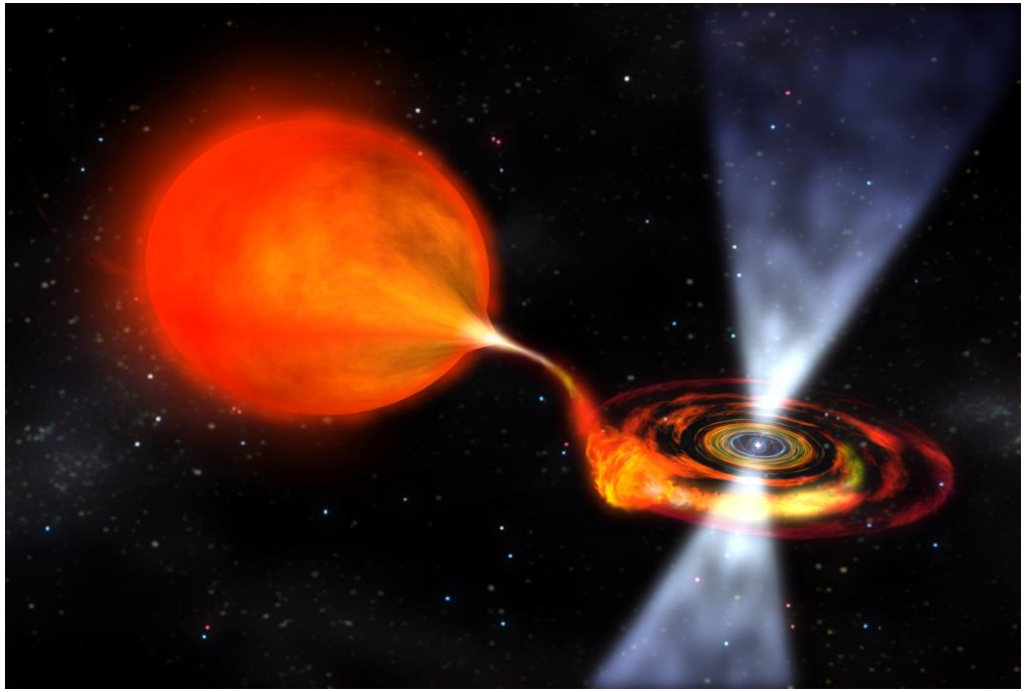
Outline

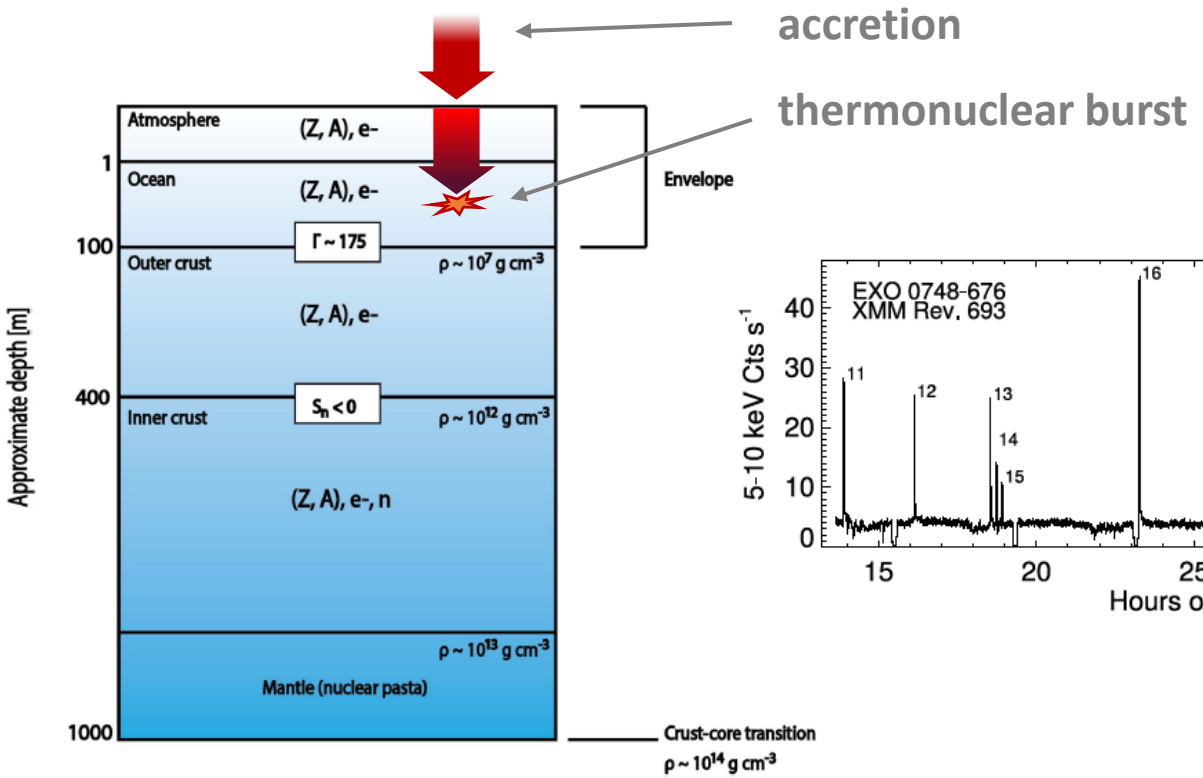
- Connection between observations of accreting neutron stars and nuclear physics processes.
- Sensitivity studies as a tool to identify key nuclear physics uncertainties in the modeling of X-ray bursts
- Results for models of two *standard* X-ray burst sources: *GS 1826-24* and *SAX J1808.4*

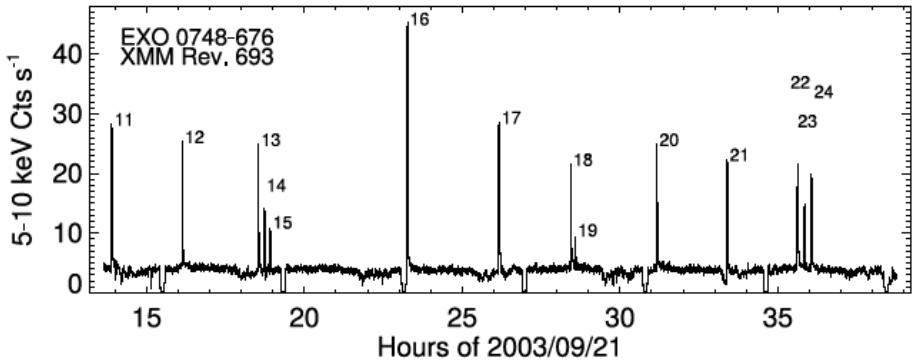
Neutron star in a low-mass X-ray binary system

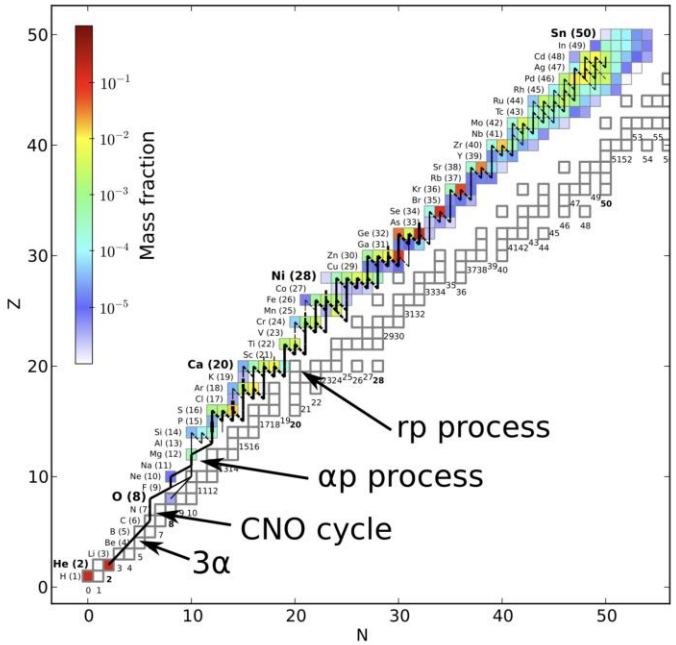


NASA/Dana Berry

X-ray bursts in accreting neutron stars





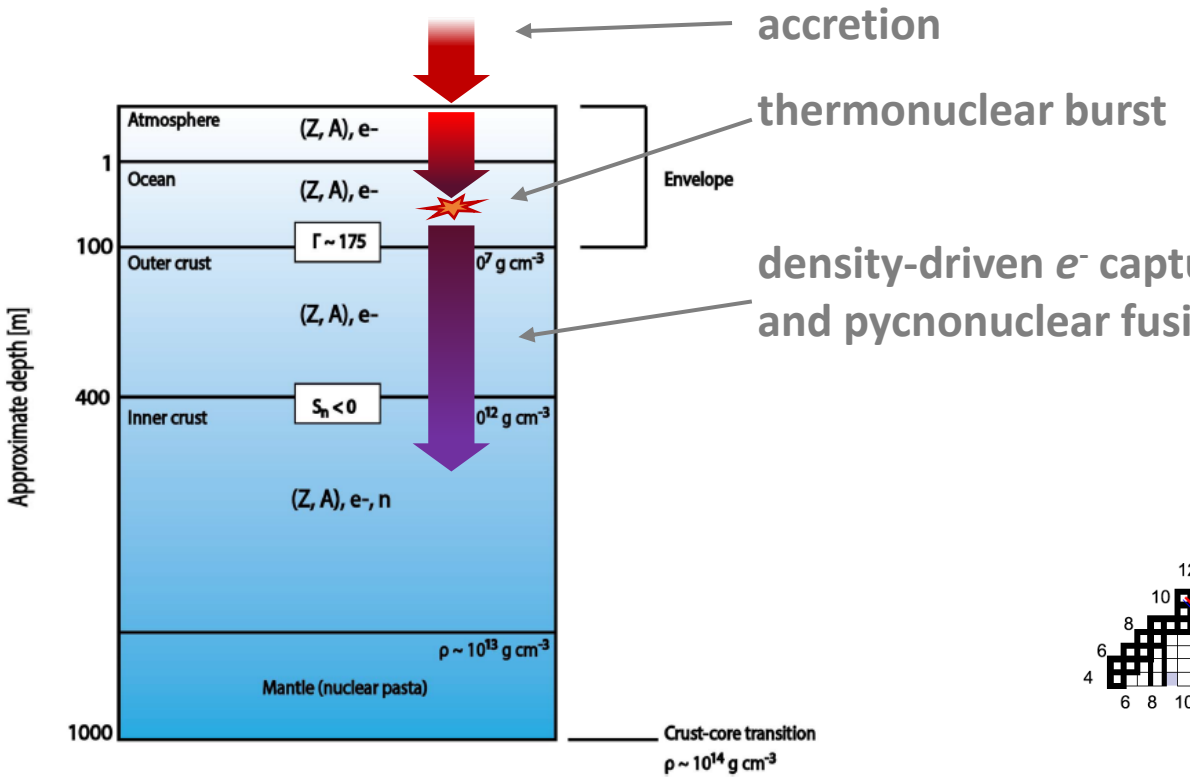


Outer layers of a neutron star

Meisel++, Jour. Phys. G, 45 (2018)

Galloway and Keek, arXiv:1712.06227 (2017)

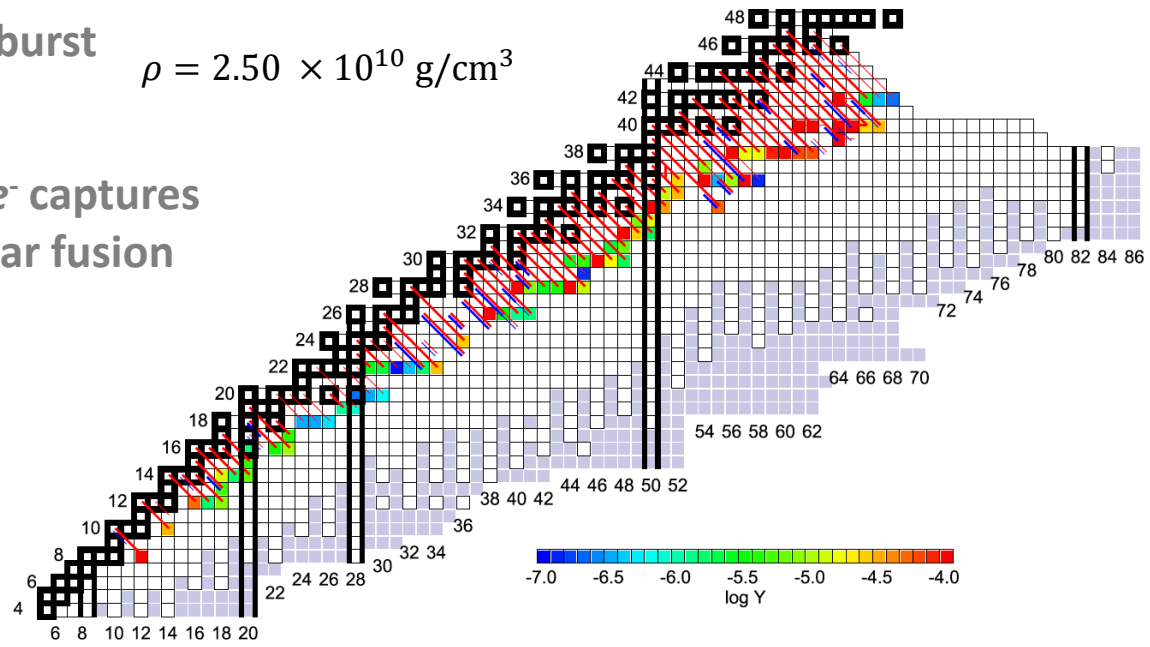
Nuclear processes in the crust of accreting neutron stars



Outer layers of a neutron star

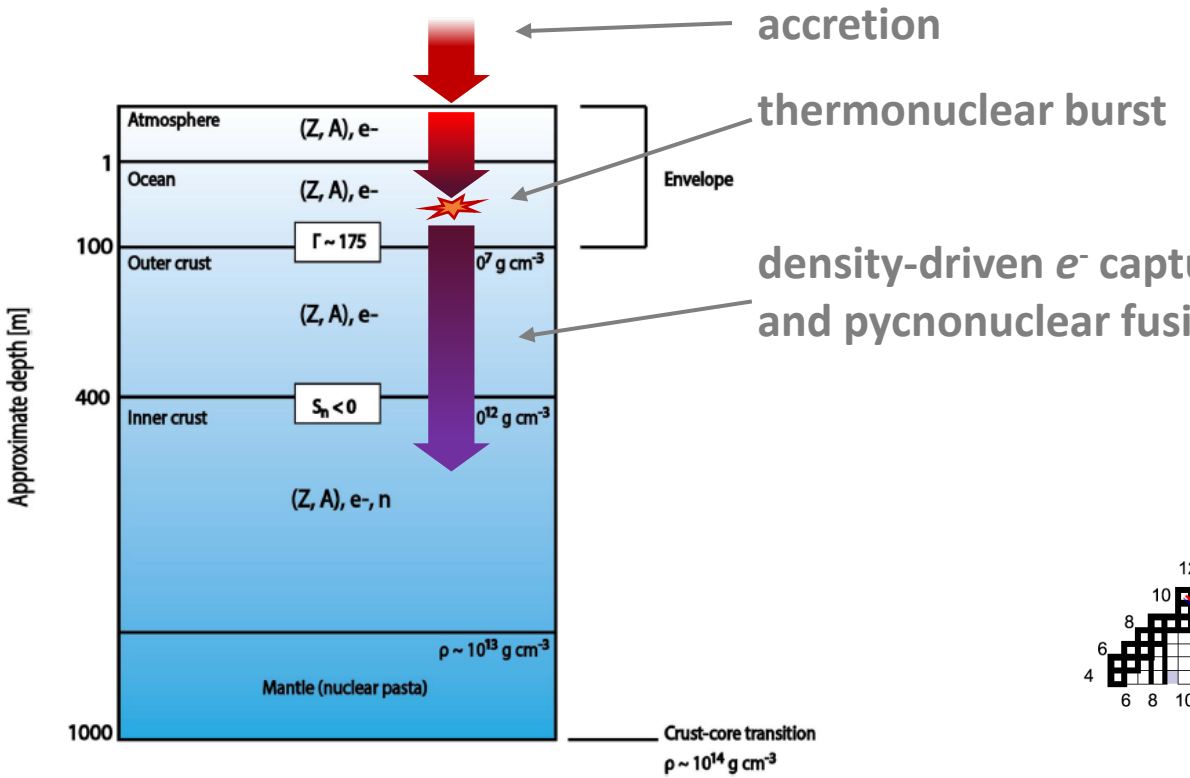
Meisel++, Jour. Phys. G, 45 (2018)

$\rho = 2.50 \times 10^{10}$ g/cm^3



R. Lau et al, ApJ 859, 62 (2018)

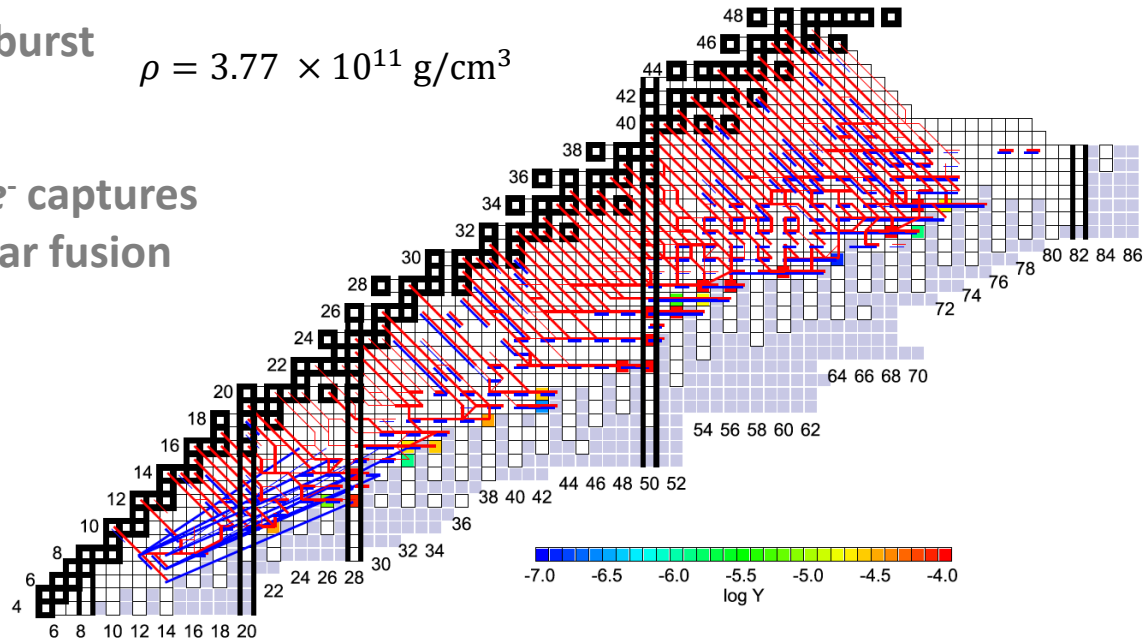
Nuclear processes in the crust of accreting neutron stars



Outer layers of a neutron star

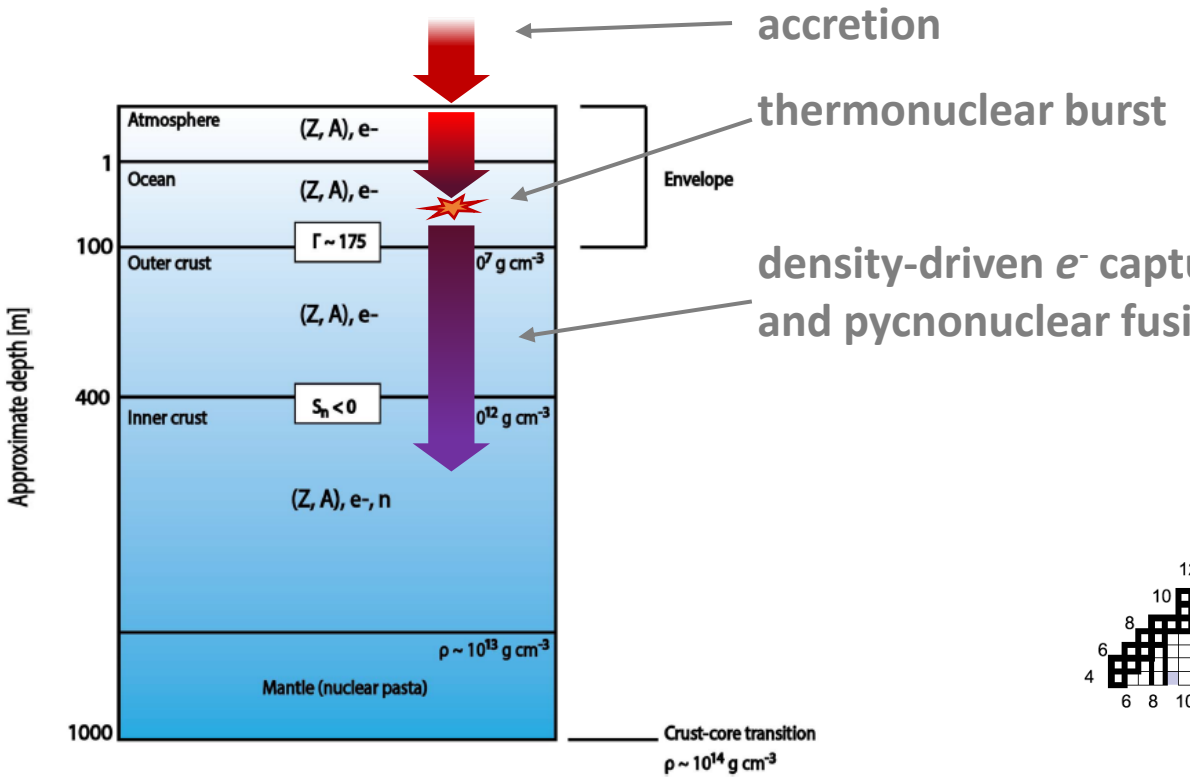
Meisel++, Jour. Phys. G, 45 (2018)

$\rho = 3.77 \times 10^{11}$ g/cm^3



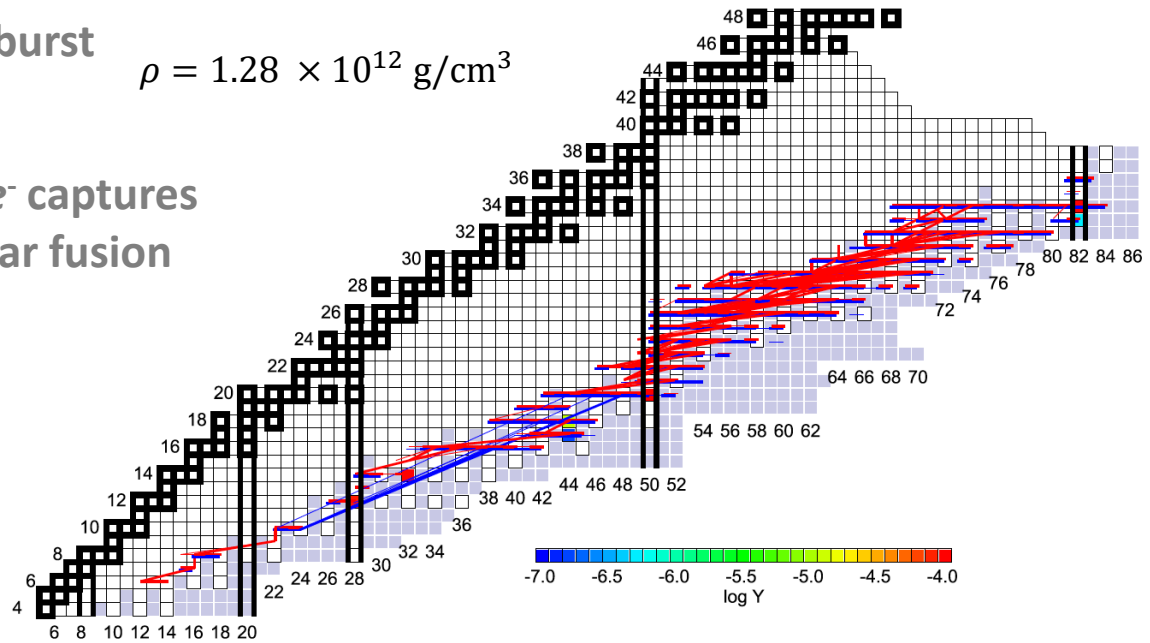
R. Lau et al, ApJ 859, 62 (2018)

Nuclear processes in the crust of accreting neutron stars



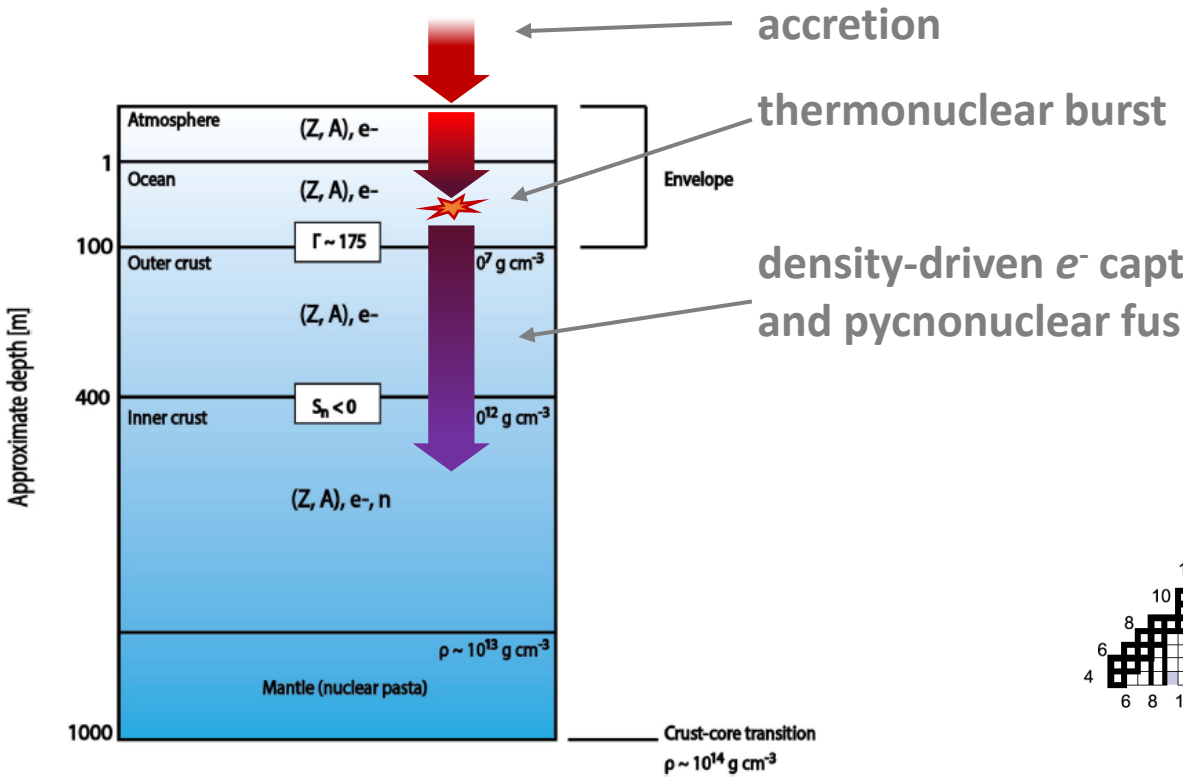
Outer layers of a neutron star

Meisel++, Jour. Phys. G, 45 (2018)



R. Lau et al, ApJ 859, 62 (2018)

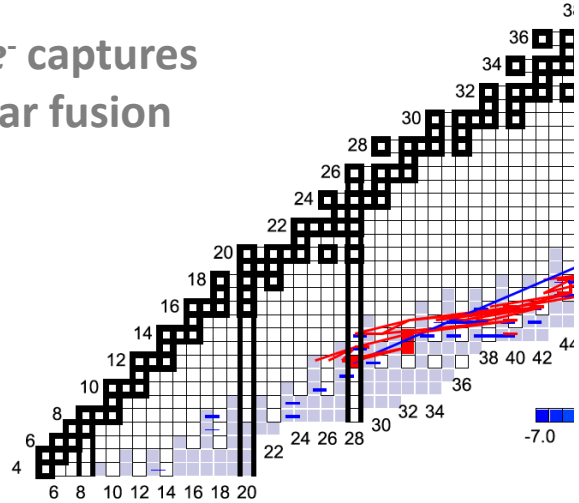
Nuclear processes in the crust of accreting neutron stars



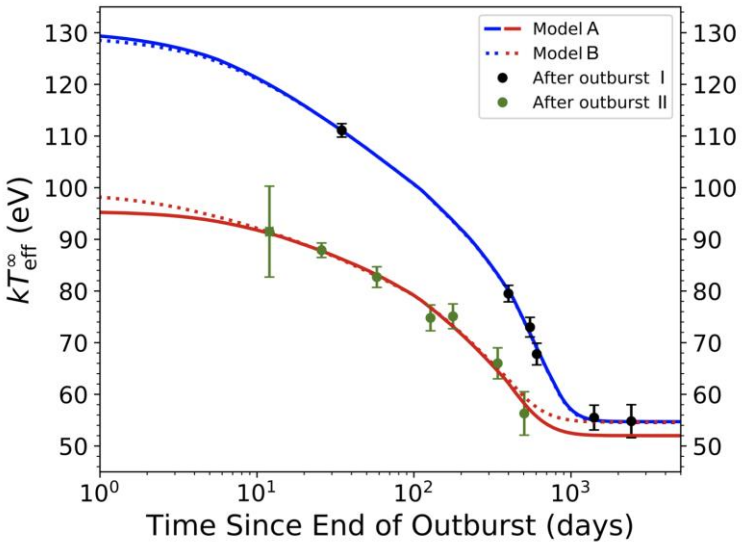
Outer layers of a neutron star

Meisel++, Jour. Phys. G, 45 (2018)

$\rho = 2.49 \times 10^{12}$ g/cm^3



Cooling of MXB 1659−29 following accretion outbursts

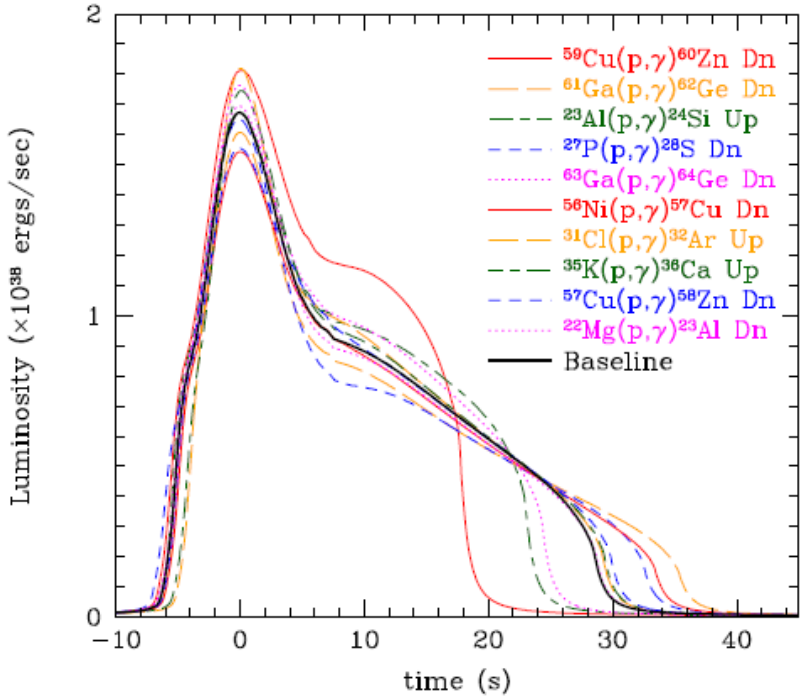


A. Parikh et al, A&A 624, A84 (2019)

Sensitivity studies are a tool to identify key nuclear reaction rates in nucleosynthesis processes

- Sensitivity studies vary the rate of reactions in a network to isolate those with higher impact on the results.

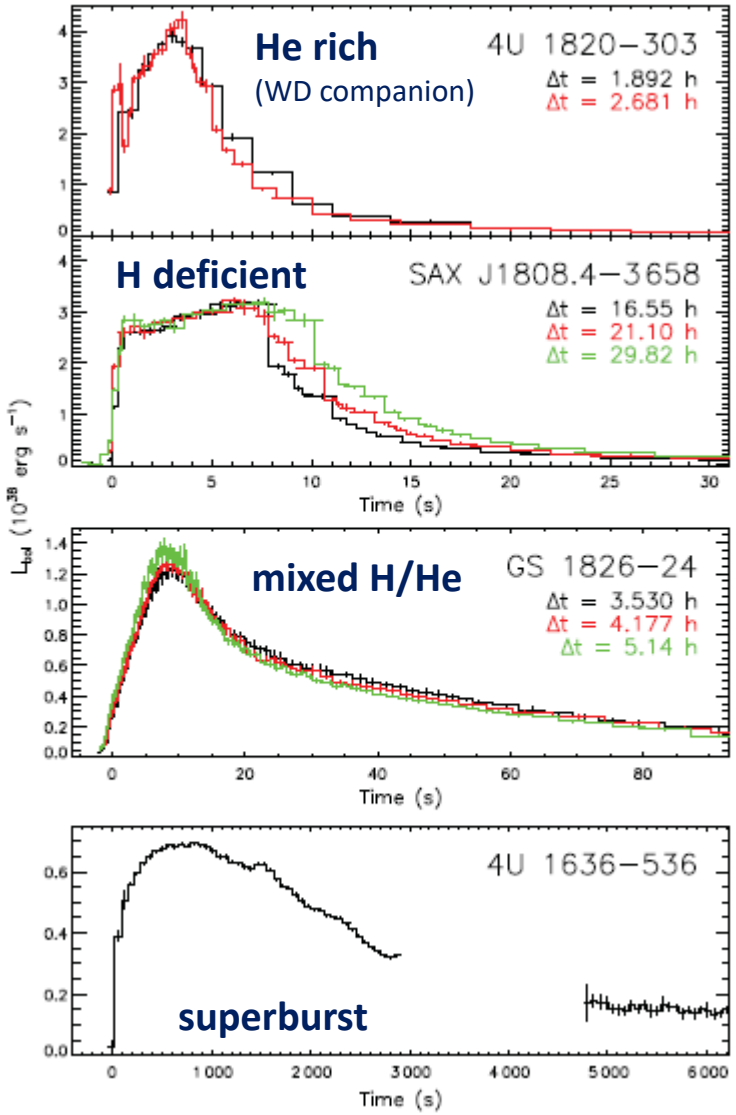
- They have been a valuable tool to guide experimental efforts for X-ray bursts – e.g. Cyburt et al ApJ (2016), Parikh et al NAR (2008), Lam et al EPJ WoC 260 (2022).



R. Cyburt et al, ApJ 830, 55 (2016)

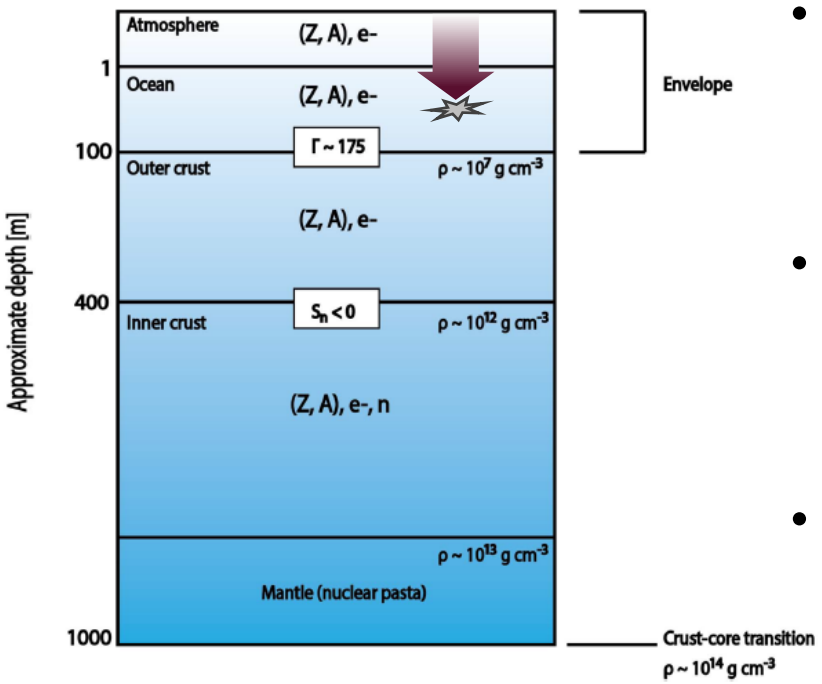
Our sensitivity study aims to cover the parameter space of observed sources

- The details of the X-ray burst depends on properties of the companion star and the accretion process
- We extend previous study (Cyburt et al) to a wide range in composition of accreted material and accretion rate
- In this presentation:
  - **GS 1826-24**: X= 70%, Z=2%, $\dot{m}$ =7% $\dot{m}_{\mathrm{Edd}}$
  - **SAX J1808.4**: X= 50%, Z=2%, $\dot{m}$ =5% $\dot{m}_{\mathrm{Edd}}$



D. Galloway et al, PASA 34 (2019) and ApJS 249 32 (2020)

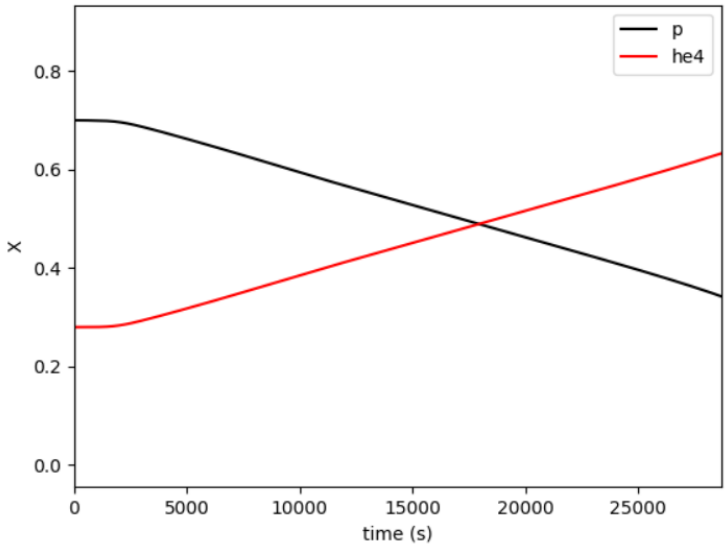
Network evolves by steady-state burning before ignition of burst



Meisel++, Jour. Phys. G, 45 (2018)

- Thermodynamic trajectory for neutron star ocean calculated with *Settle.* Cumming and Bildsten, ApJ 544, 453 (2000).
- Composition evolved by coupling *NucNet Tools* reaction network to *Settle* trajectory. B. Meyer, PoS, NIC XII:096 (2013).
- Settling process dominated by hot CNO cycle significantly alters composition of accreted material

Change of H/He fraction during settling process

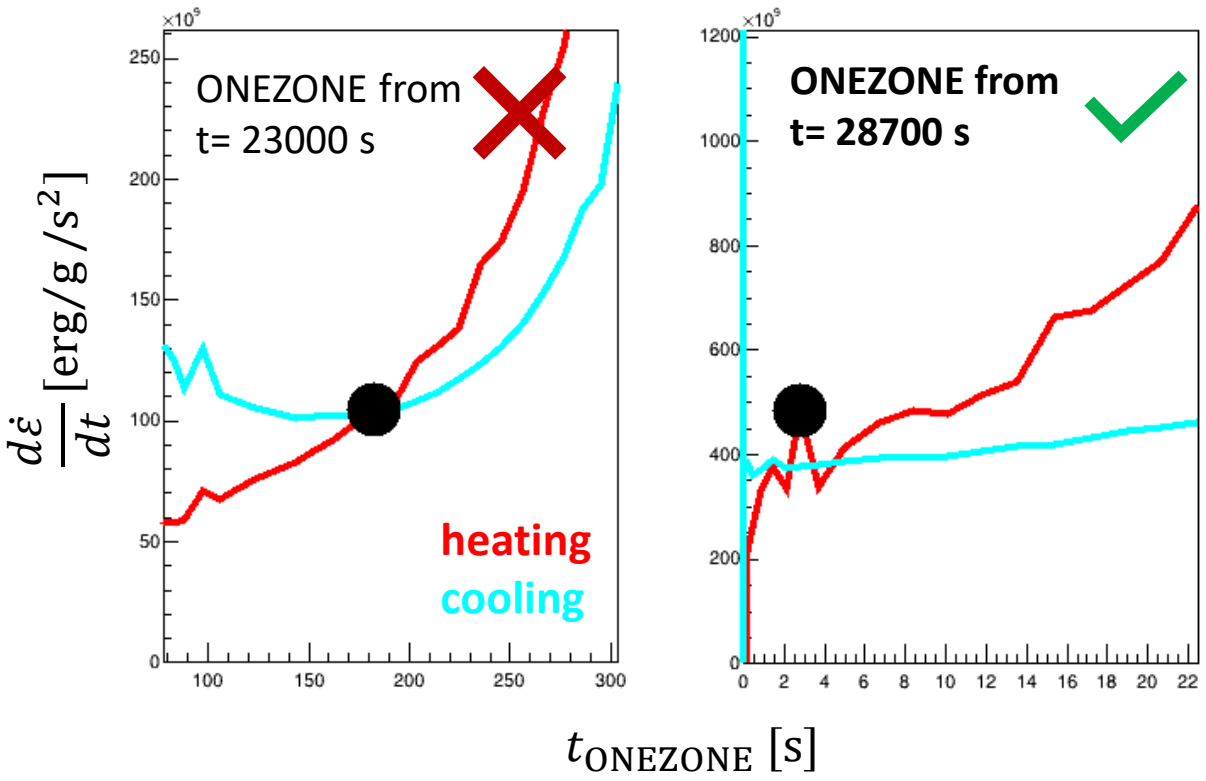


GS 1826-24

(X_{acc}= 70% → X_{ign}= 34%)

X-ray burst modeled with ONEZONE

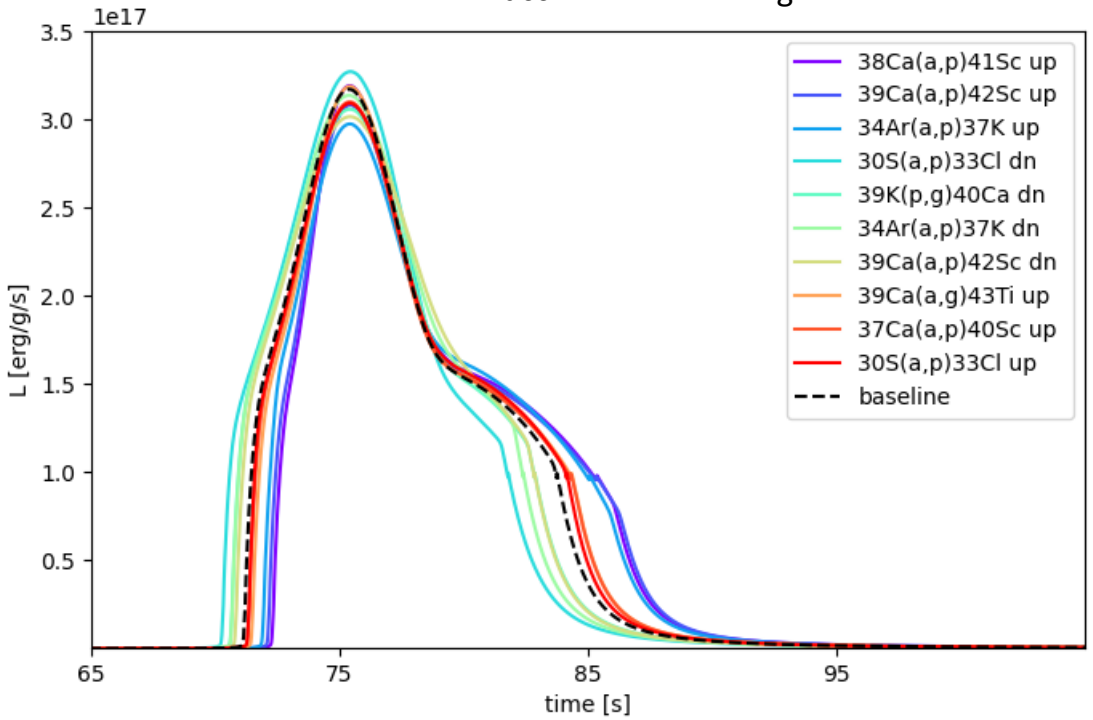
- ONEZONE: reaction network that can evolve thermodynamic conditions in a single zone.
- Criteria to estimate burst ignition depth: derivative of heating rate > derivative of cooling rate. Cumming++ ApJ 544 (2000)
- Sensitivity study:
  - Vary individually all (α, p), (α, γ), and (p, γ) rates by factor of x100 and x0.01
  - Impact of reaction measured by change of burst luminosity and abundances vs model with standard rates (JINA Reaclib)



Results: reactions that impact burst luminosity

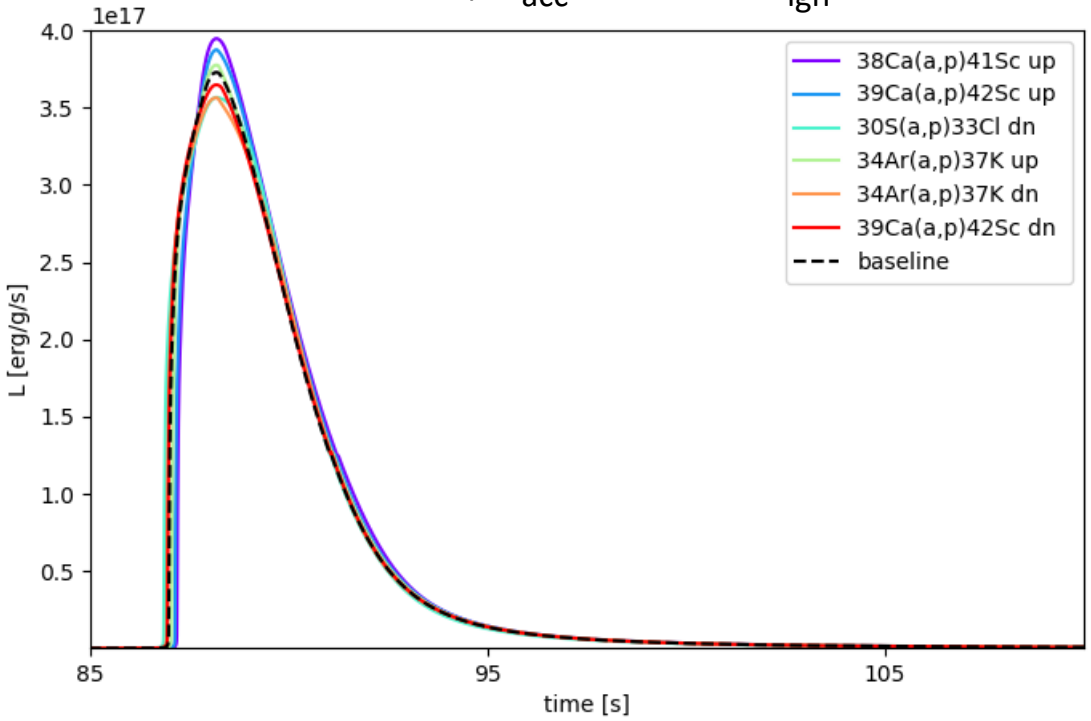
Mixed H/He

GS 1826-24, X_{acc}= 70%→ X_{ign}= 34%



H deficient

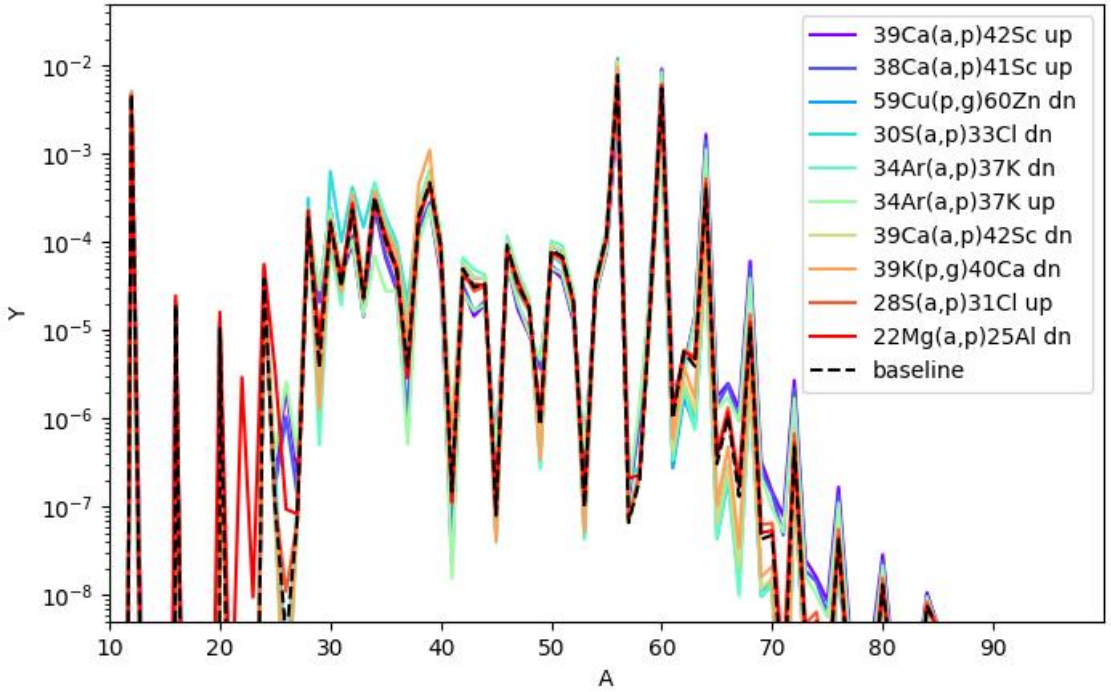
SAX J1808.4, X_{acc}= 50%→ X_{ign}= 6%



Results: reactions that impact burst nucleosynthesis

Mixed H/He

GS 1826-24, X_{acc}= 70%→ X_{ign}= 34%



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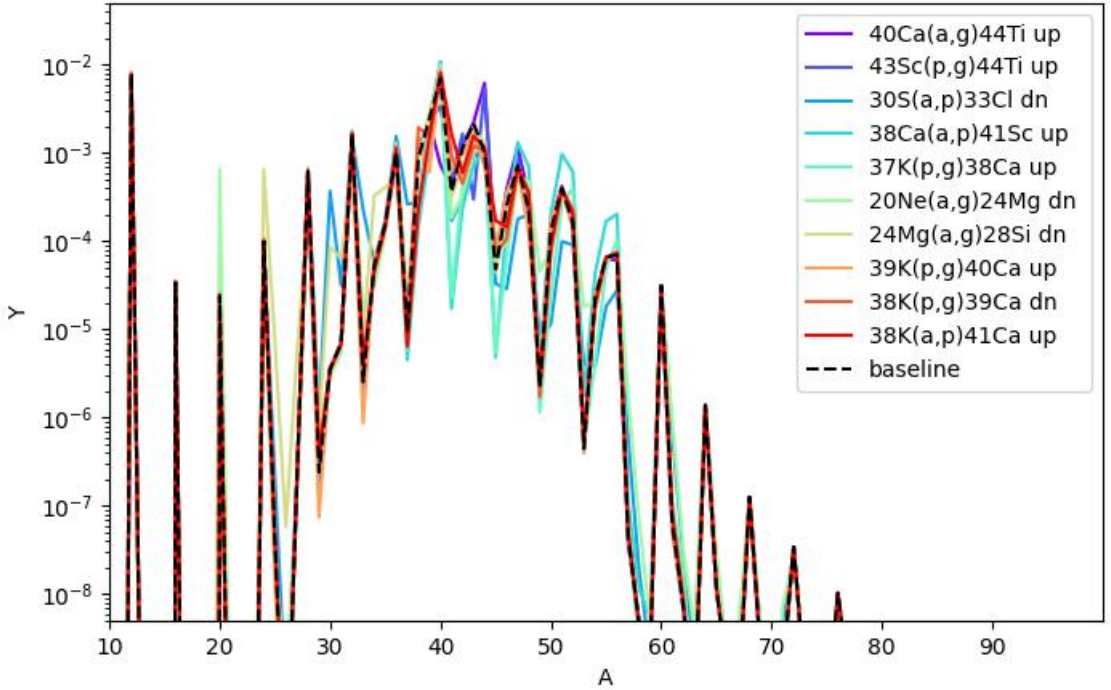
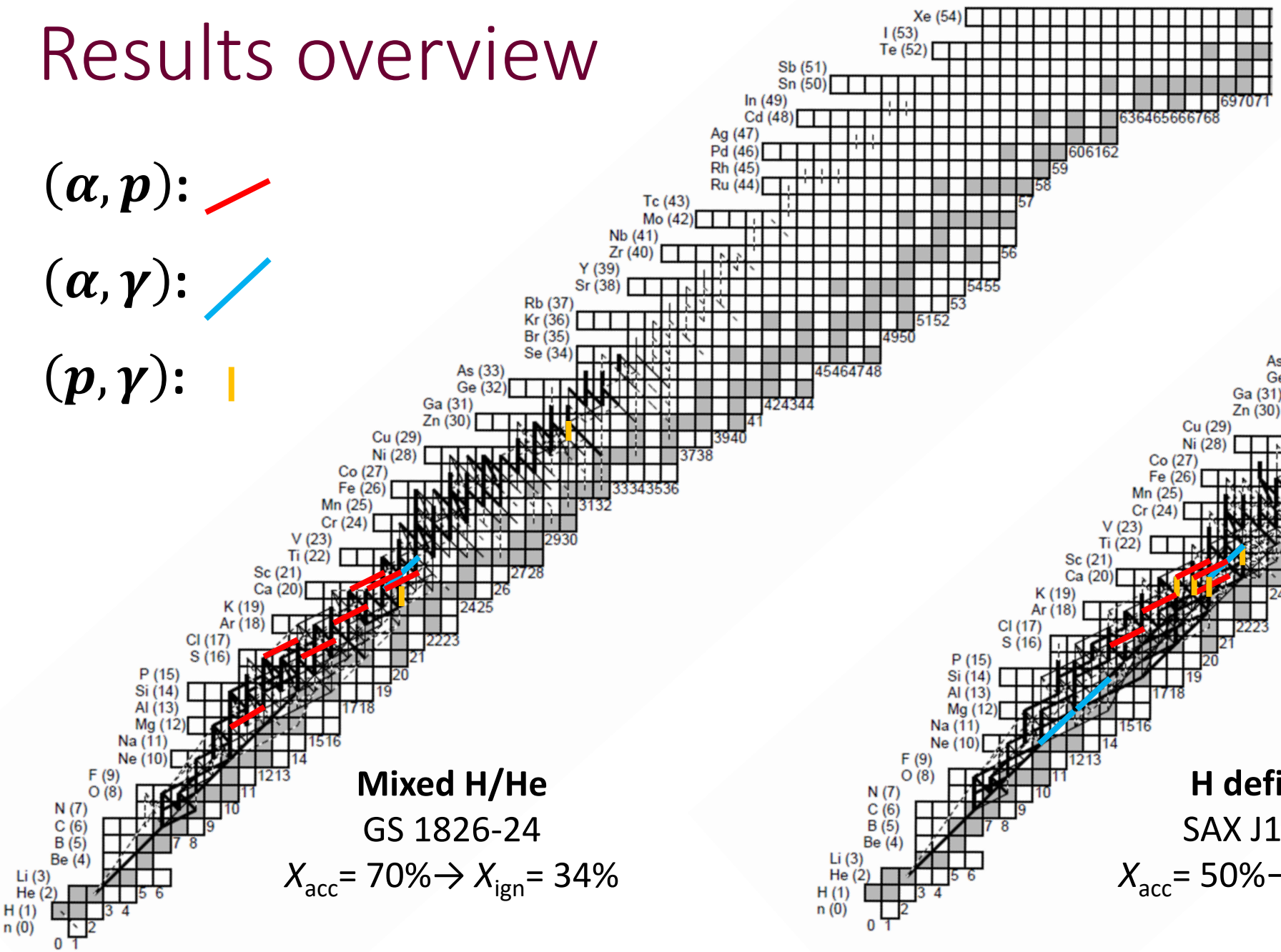


Results overview

(α, p):

(α, γ):

(p, γ):



Mixed H/He

GS 1826-24

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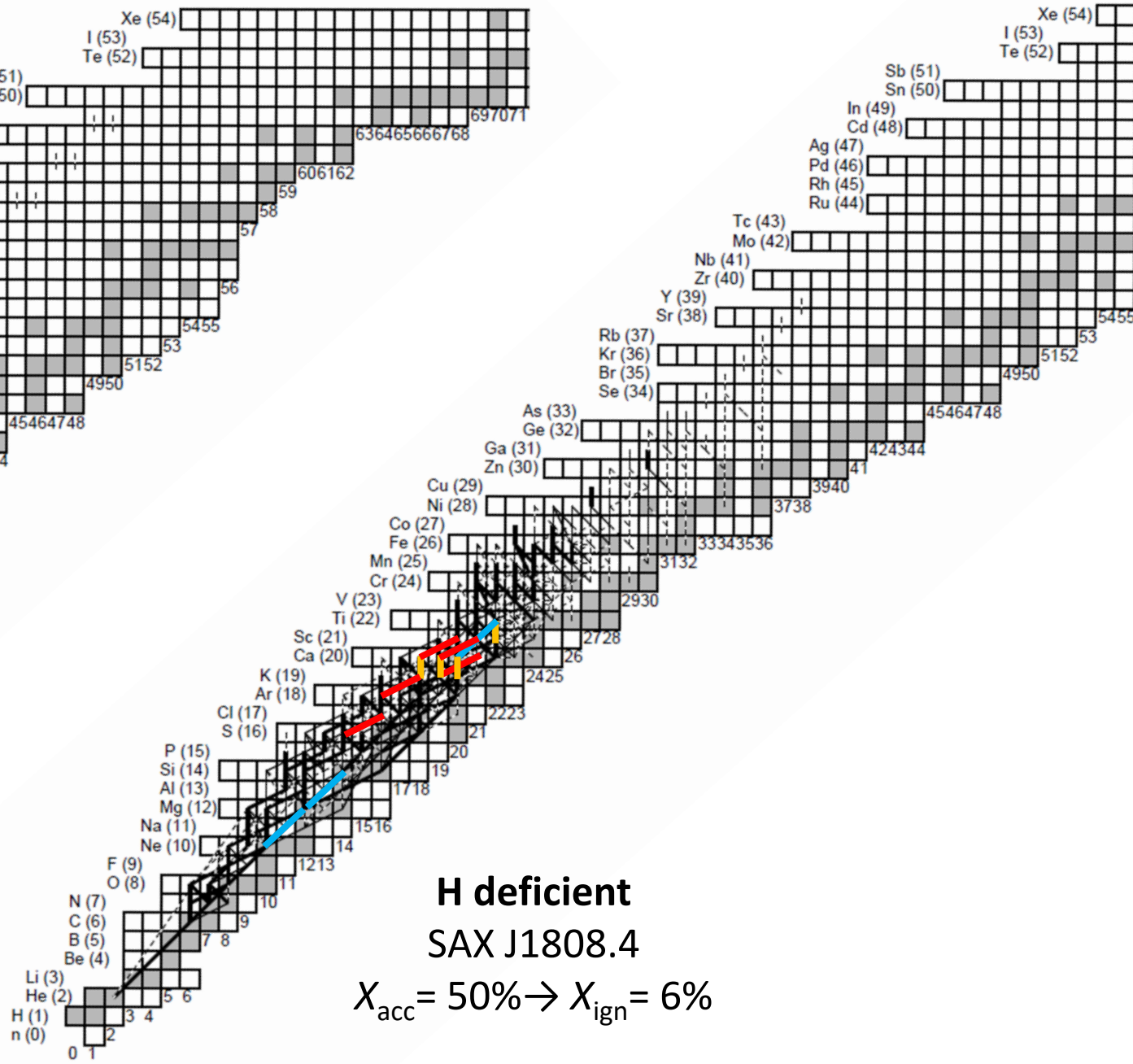


H deficient

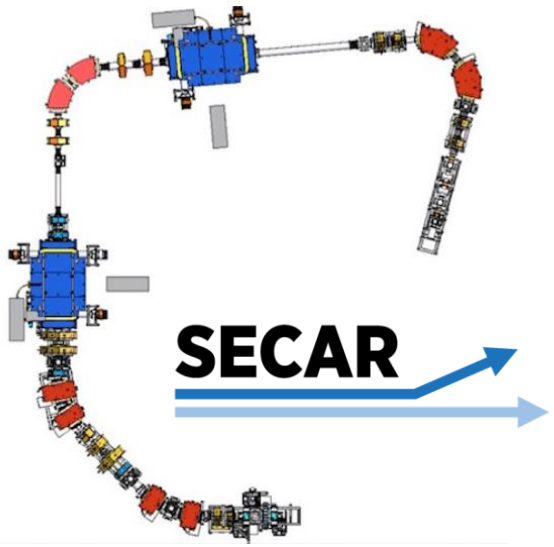
SAX J1808.4

X_{acc}= 50%→ X_{ign}= 6%

Conclusions and Outlook

- Develop the machinery for an X-ray burst sensitivity study based on fast single-zone reaction networks.
- Ongoing calculations for a grid of parameters of X-ray binary systems (H/He fraction, metallicity, accretion rate).
- He-rich bursts lightcurves are affected by small number of rates. Rate of settling process is important.
- Our sensitivity study will give an overview of how role of charge particle reactions evolves with the properties of accreting binary systems.

Thermonuclear reaction rate measurements in Michigan: SECAR @ FRIB (and others)



See: Ruchi Garg (poster), Pelagia Tsintari (Thu. session 3)

Join us @ CMU! Open postdoc in experimental nuclear astrophysics.

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