Heavy neutron rich nuclei in astrophysics

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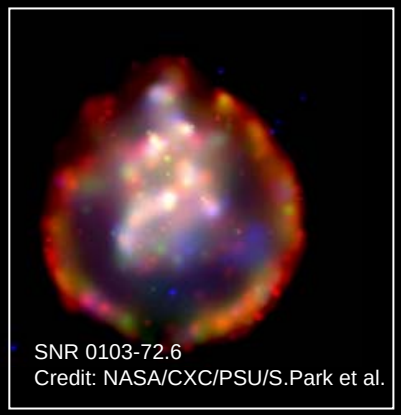
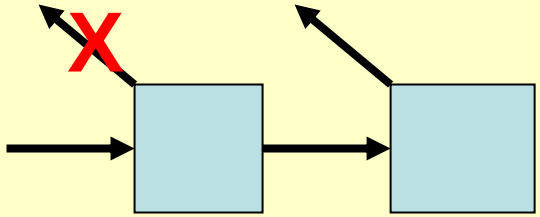
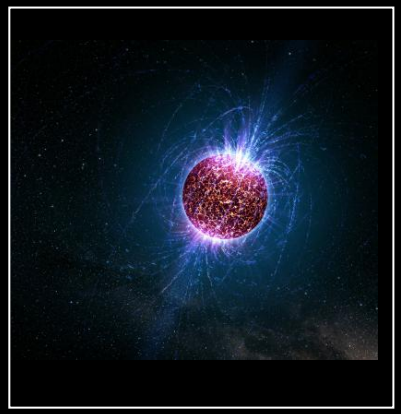


SNR 0103-72.6
Credit: NASA/CXC/PSU/S.Park et al.

High free neutron density
- r-process
- (inhomogeneus big bang?)

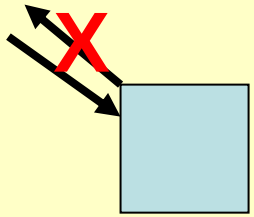
β-decay prevented
by more rapid neutron capture





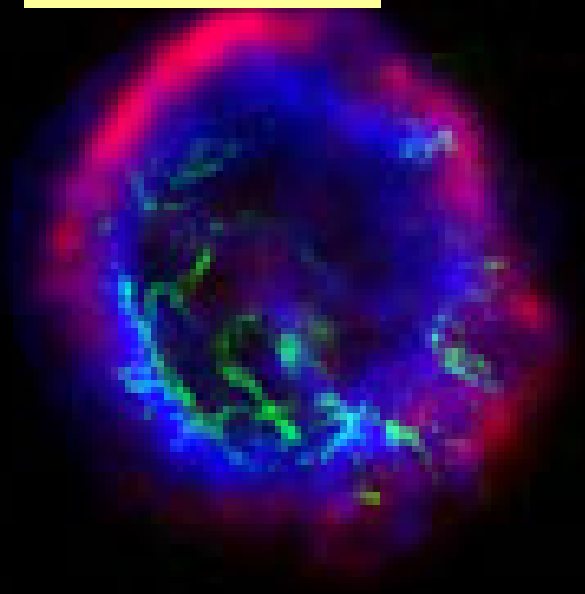
High electron density
- neutron stars

β-decay blocked
by degenerate electron gas
with high Fermi energy



r (apid neutron capture) process

Supernovae ?

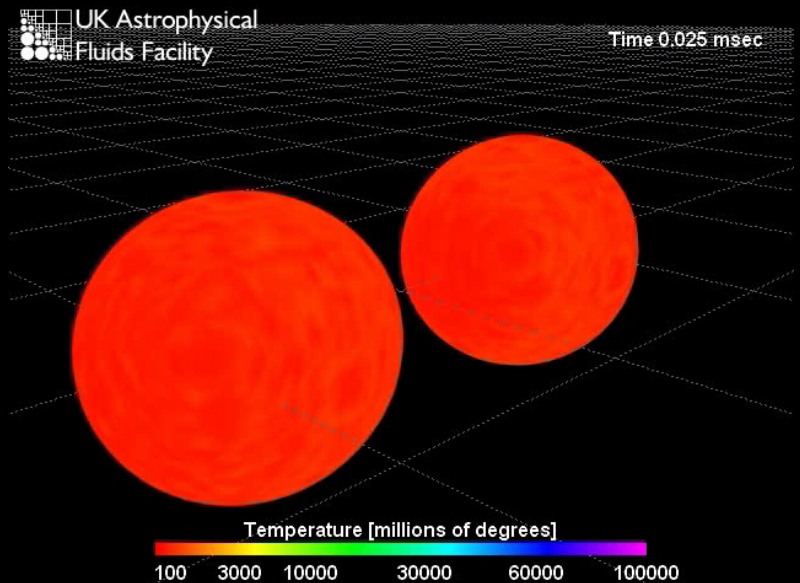


The origin of about half of elements > Fe (including Gold, Platinum, Silver, Uranium)

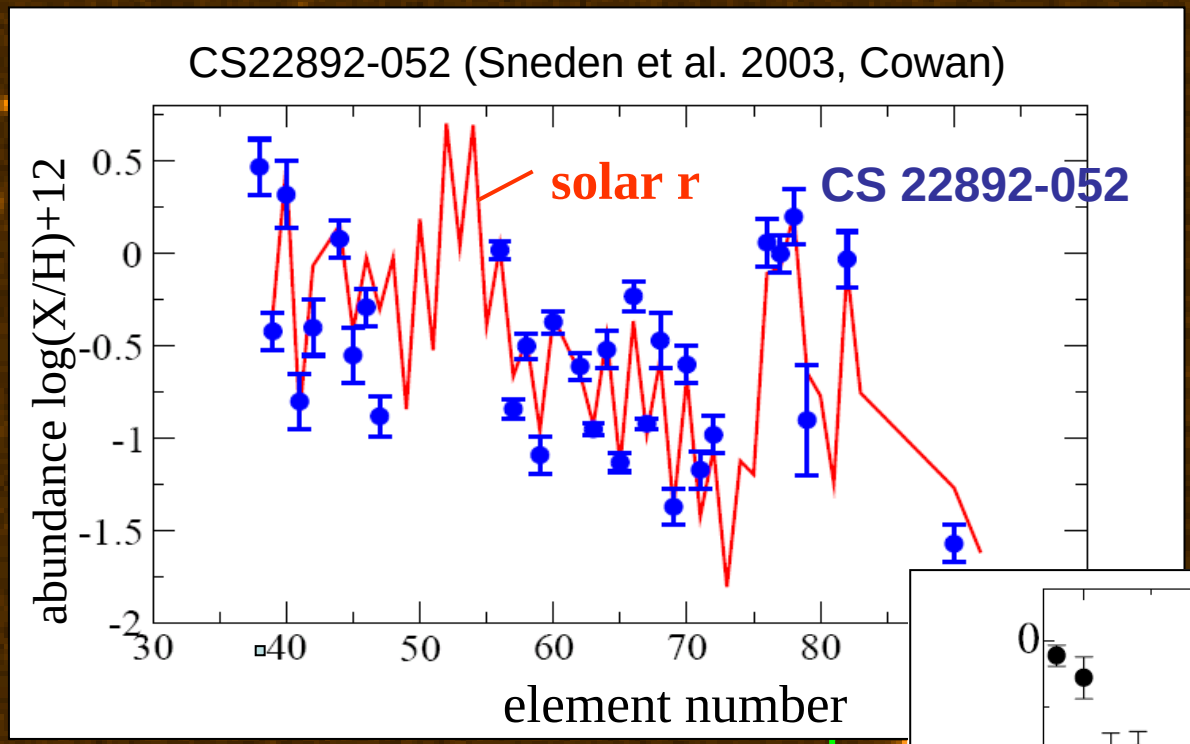
Open questions:

- **Where does the r process occur ?**
- **What are the actual reaction sequences ?**
- **Are there multiple r-processes and what are their individual contributions ?**
- **What can the r-process tell us about the physics of extreme environments ?**

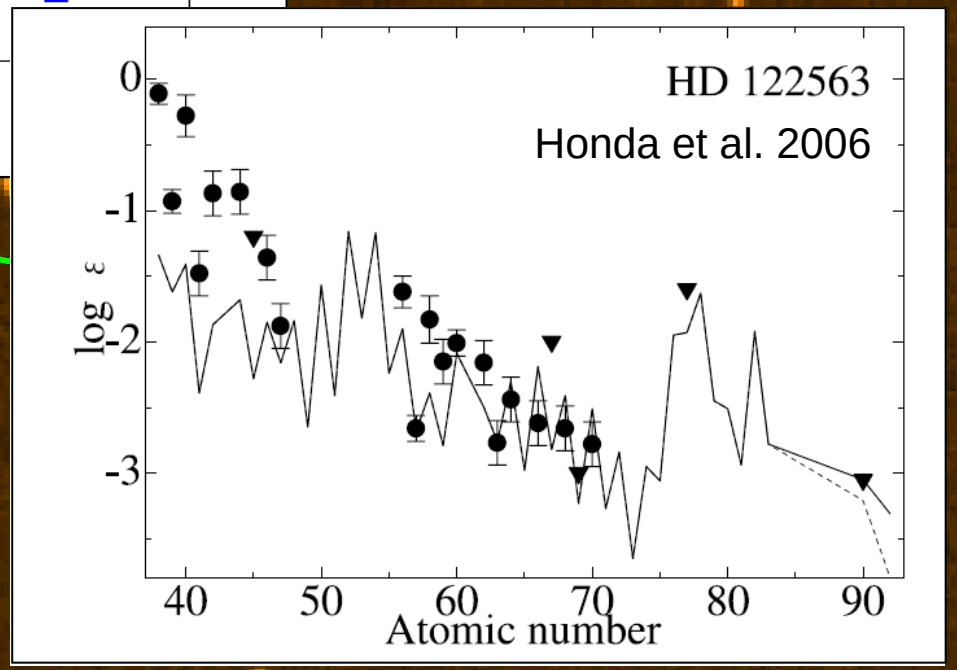
Neutron star mergers ?



Signature of the r-process



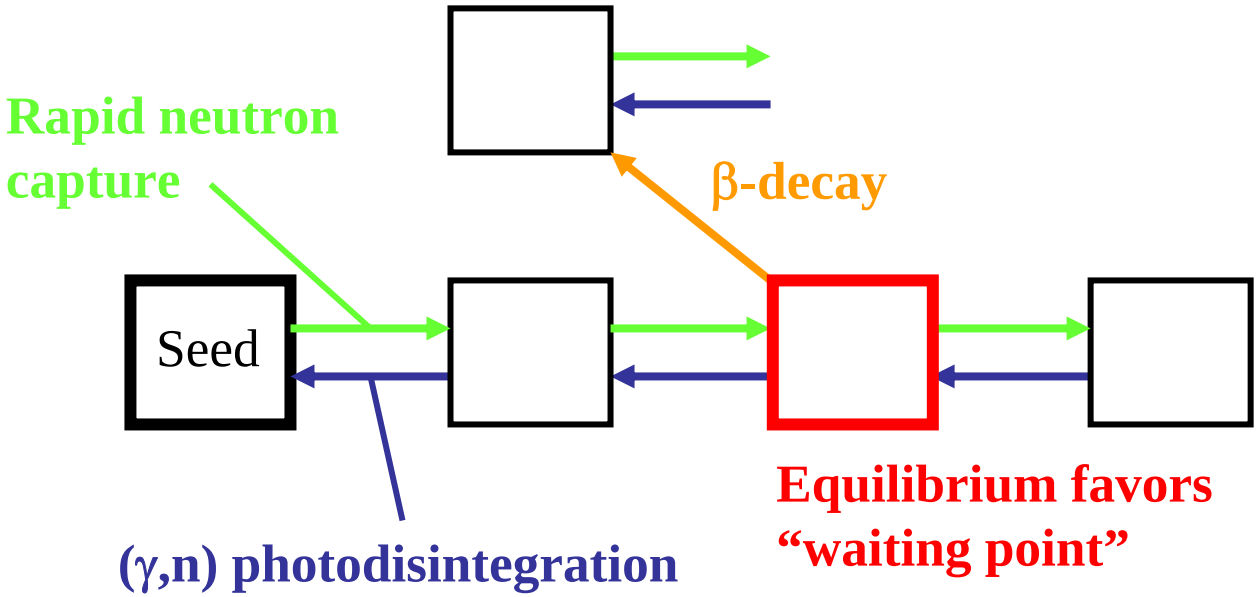
… and the LEPP (Montes et al. 2007)



Stars show usually mix of the two Solar system too?
→need to model them both to disentangle by isotope

r-process and nuclear physics

10-100 g/cm^3 neutrons →neutron capture timescale: ~ 0.2 μs



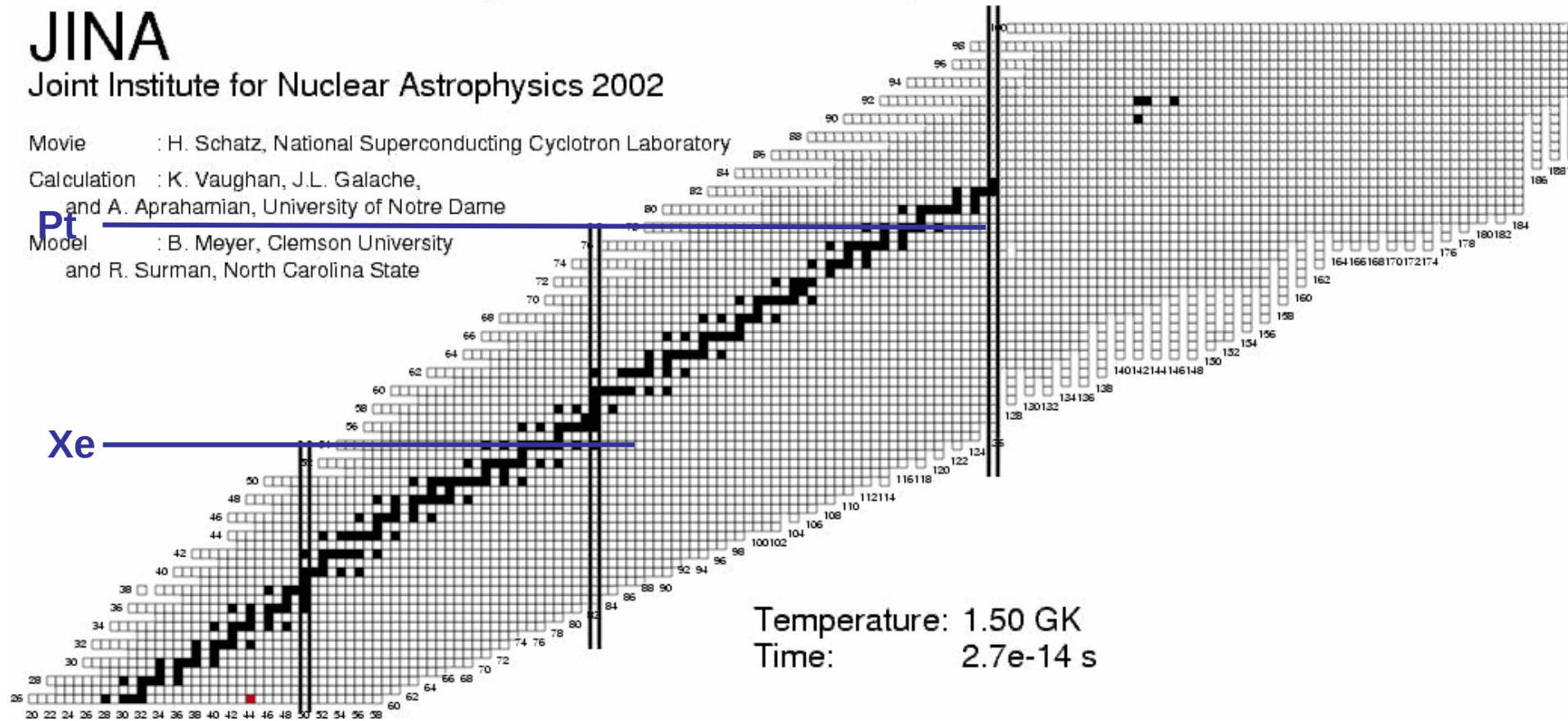
Location of path: $S_n = T_9/5.04 \times (34.08 + 1.5 \log T_9 - 1.5 \log n_n) = 2\text{-}4$ MeV

Need:

- masses (β-endpoint, traps)
- half-lives (Si detector stacks, combine with γ-spectroscopy)
- neutron emission probabilities (neutron detector)
- maybe fission and neutrino interaction rates
- neutron capture rates

Origin of the heavy elements in nature ?

Nucleosynthesis in the r-process



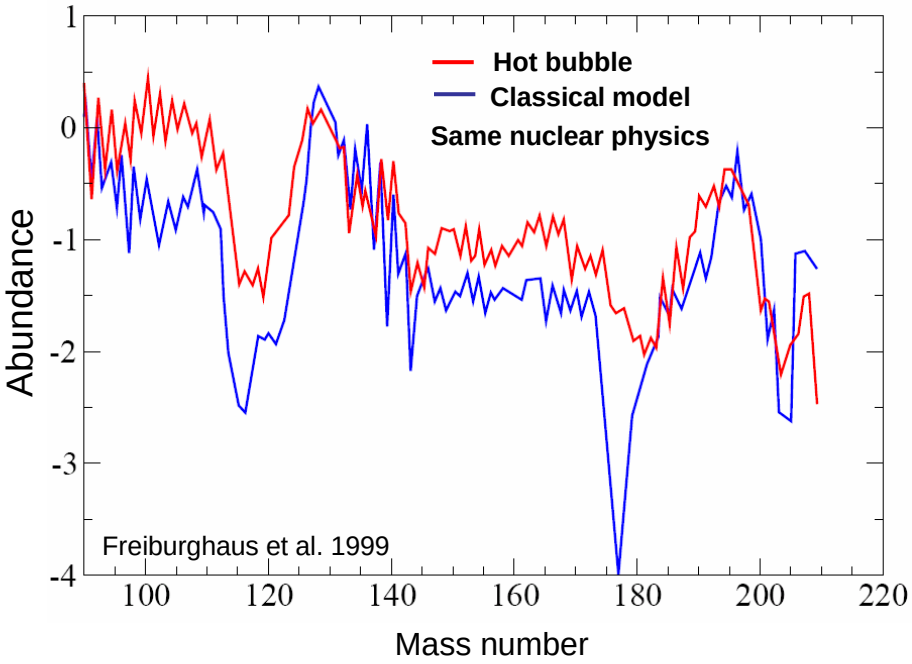
Compare calculated results with many precision abundance observations ?

→ Masses and half-lives determine final abundances in specific model

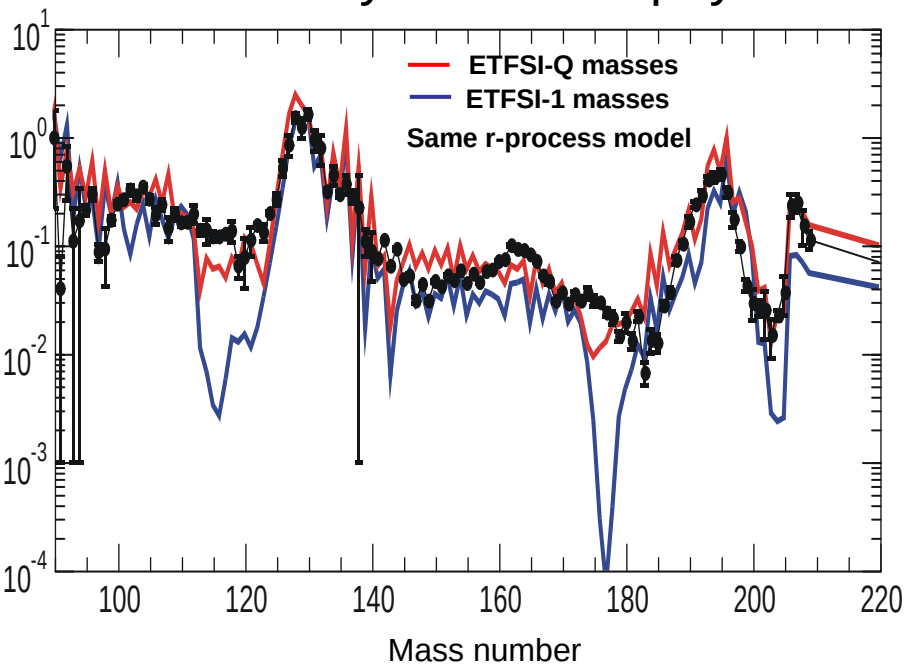
→ They are needed to compare details, not just major peaks, with observations

Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Sensitivity to nuclear physics



Contains information about:

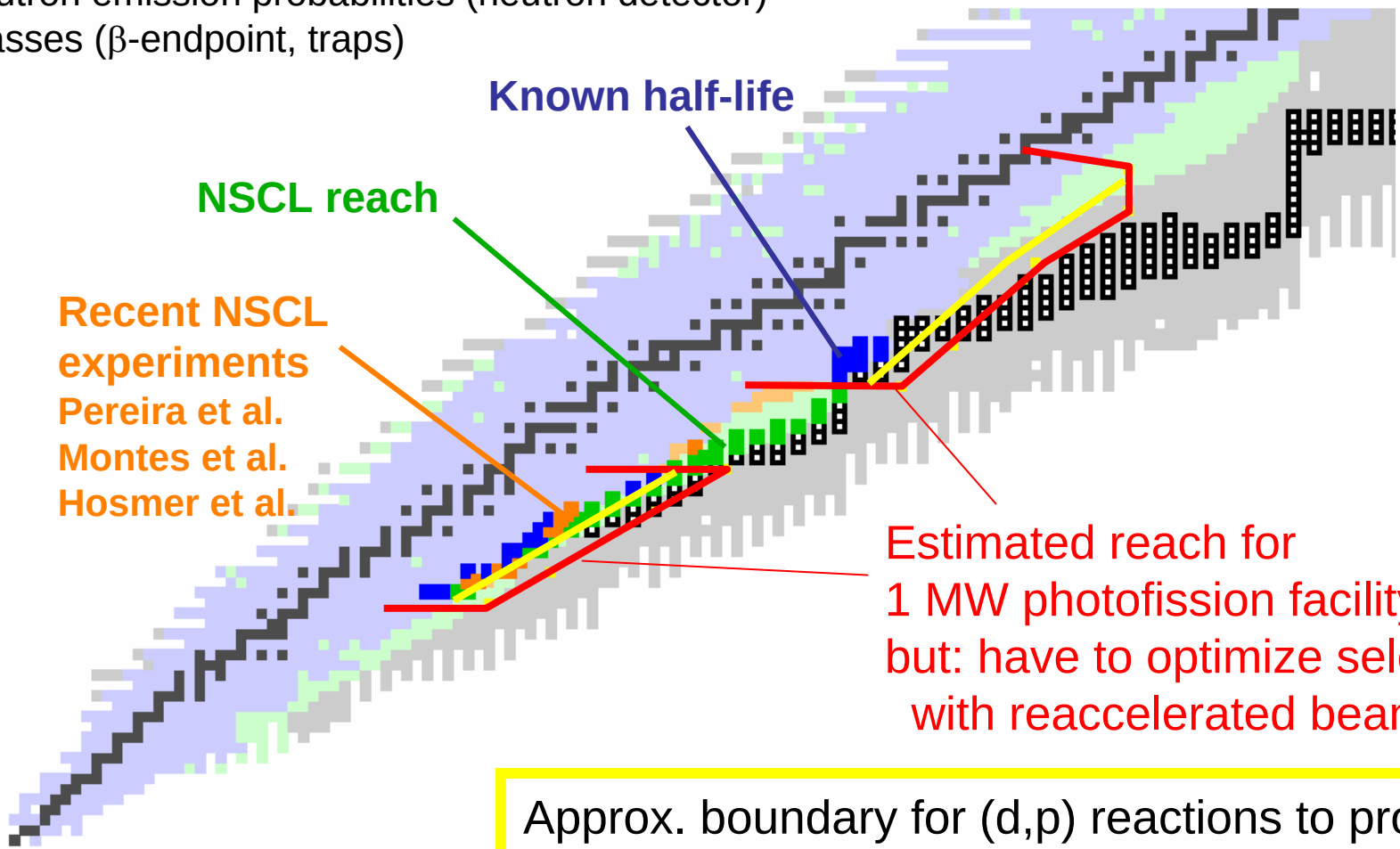
- n-density, T, time (fission signatures)
- freezeout
- neutrino presence
- which model is correct

But convoluted with nuclear physics:

- masses (set path)
- $T_{1/2}$, Pn (Y ~ $T_{1/2(prog)}$, key waiting points set timescale)
- n-capture rates
- fission barriers and fragments

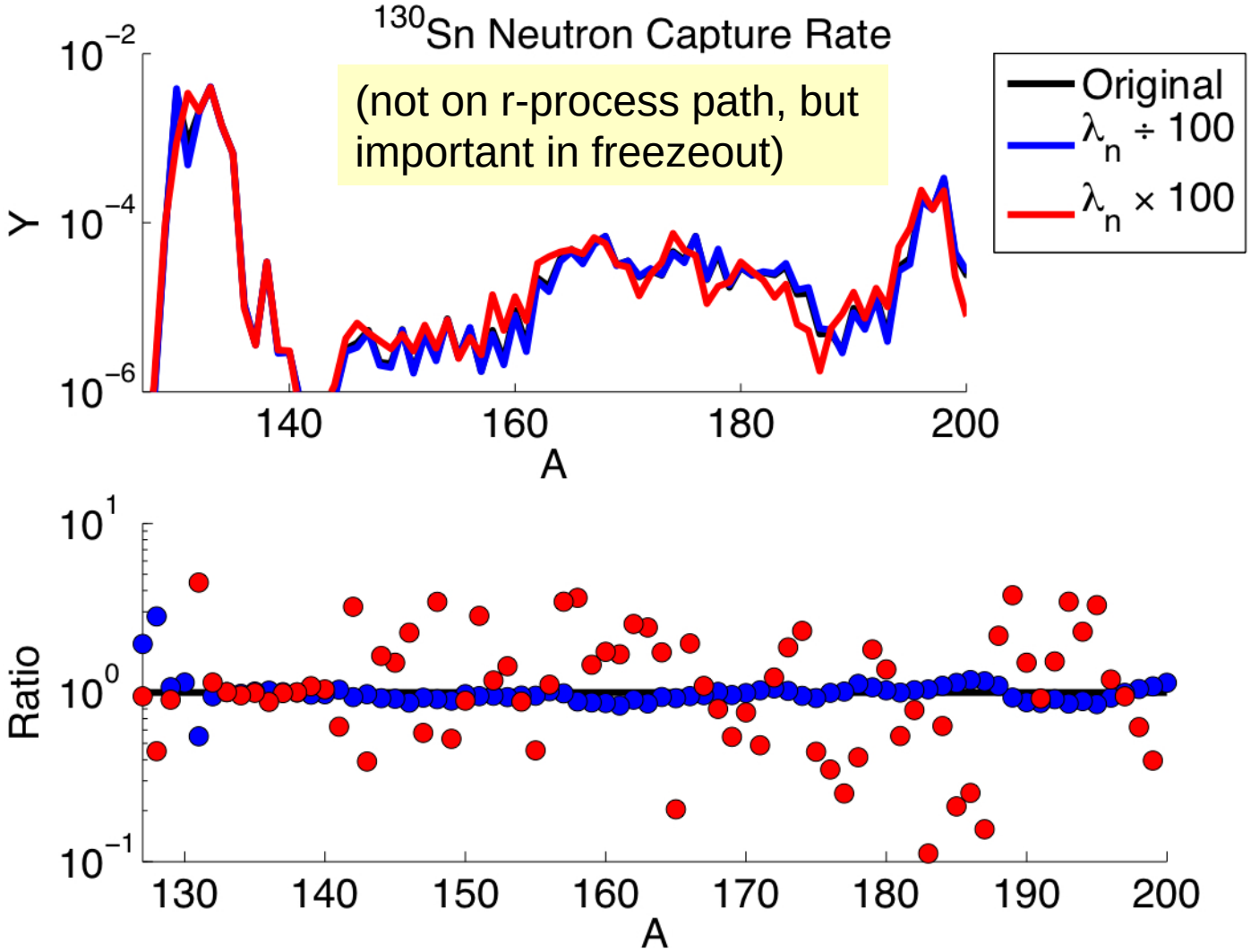
Facility reach into the r-process

- half-lives (Si detector stacks, combine with γ-spectroscopy)
- neutron emission probabilities (neutron detector)
- masses (β-endpoint, traps)



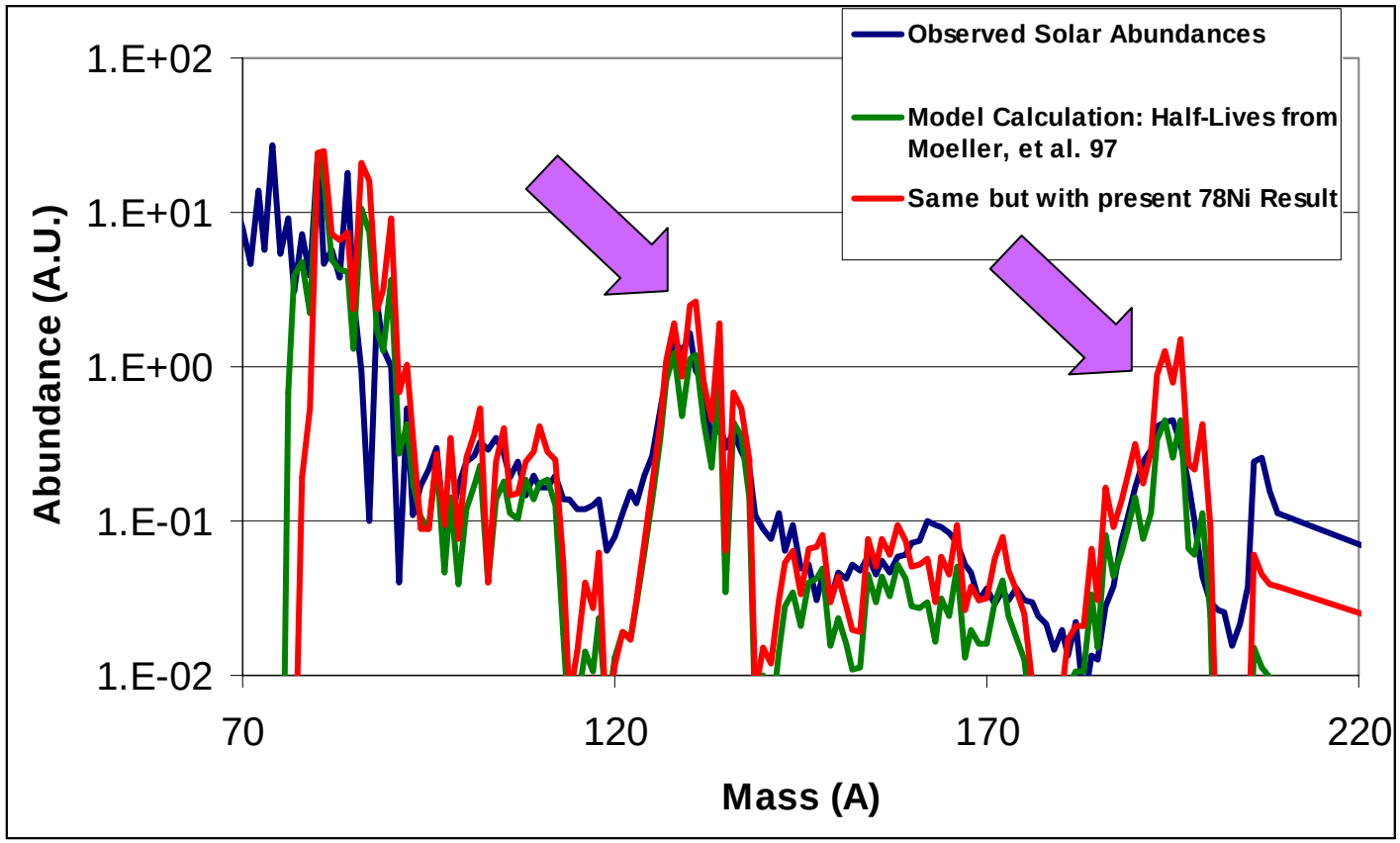
Approx. boundary for (d,p) reactions to probe neutron capture rates (during r-process freezout)

Impact of neutron capture rates on the r-process



J. Beun, R. Hix, G.C. McLaughlin, R. Surman (In Preparation)

Impact of ^{78}Ni half-life on r-process models

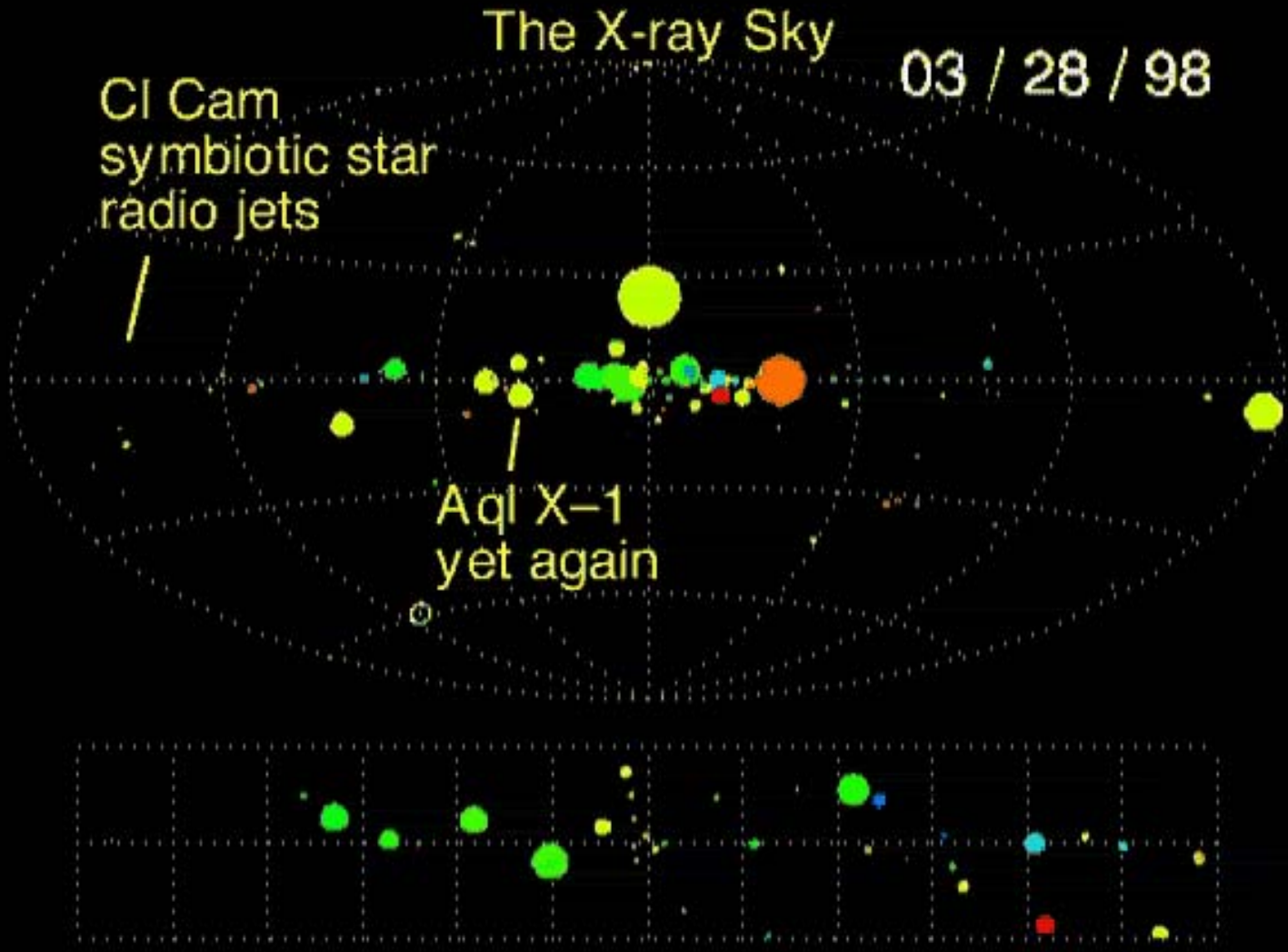


→need to readjust r-process model parameters

→Can obtain Experimental constraints for r-process models from observations and solid nuclear physics

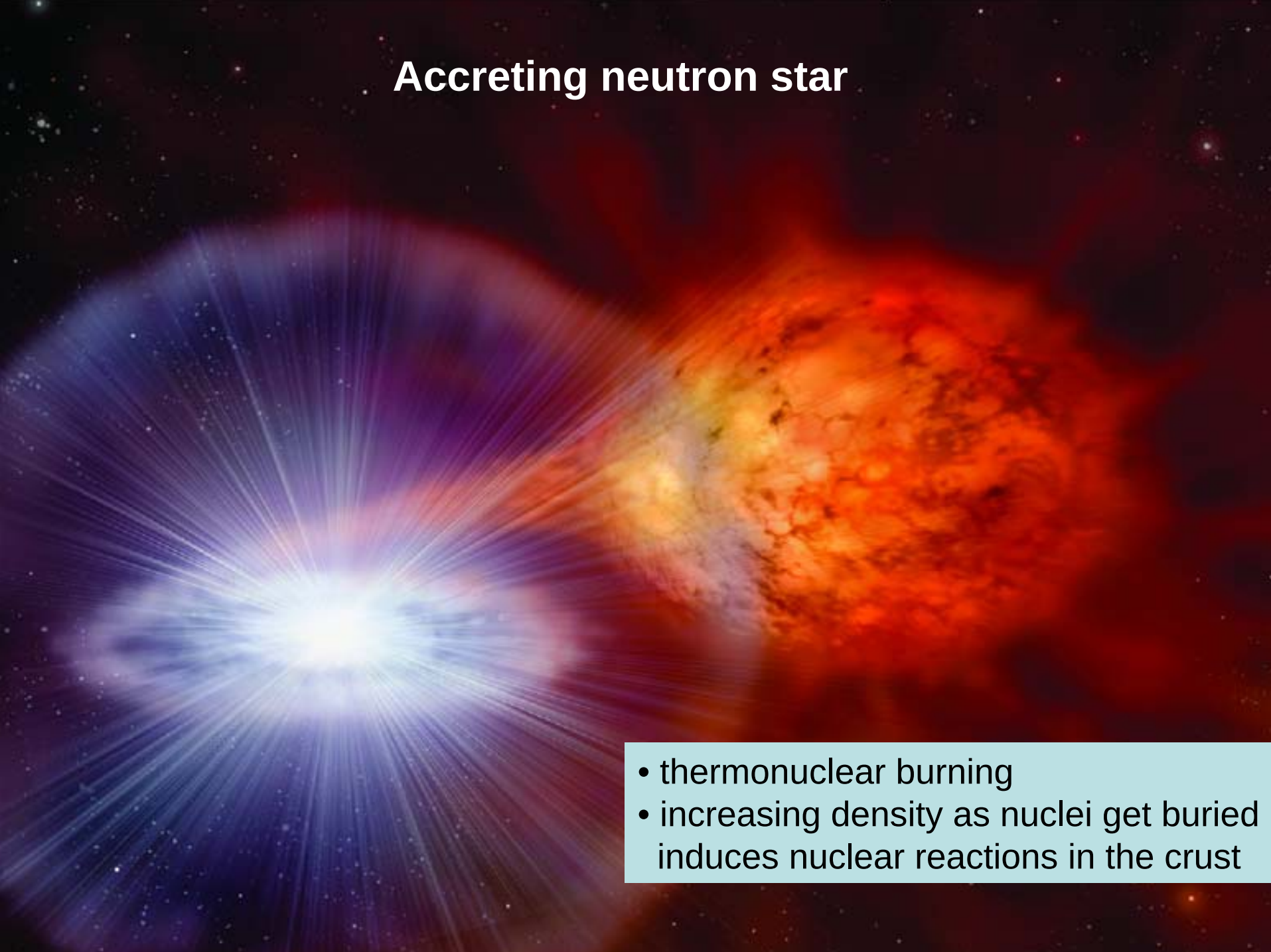
→ remainig discrepancies – nuclear physics ? Environment ? Neutrinos ? Need more data

Neutron rich nuclei in neutron stars



D.A. Smith, M. Muno, A.M. Levine, R. Remillard, H. Bradt 2002 (RXTE All Sky Monitor)

Accreting neutron star



- thermonuclear burning
- increasing density as nuclei get buried induces nuclear reactions in the crust

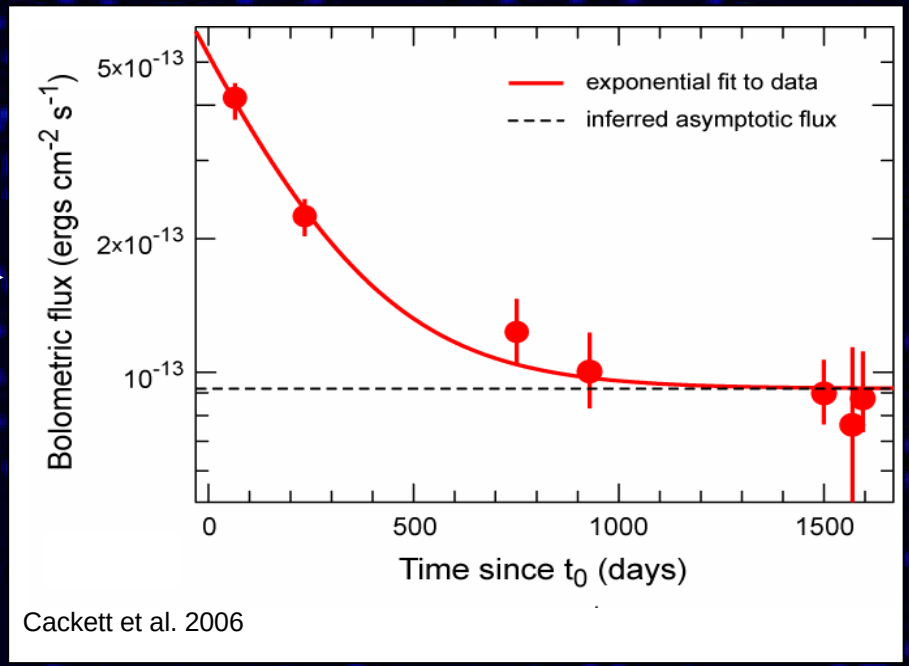
Crust heating in accreting neutron stars - observations

Transients

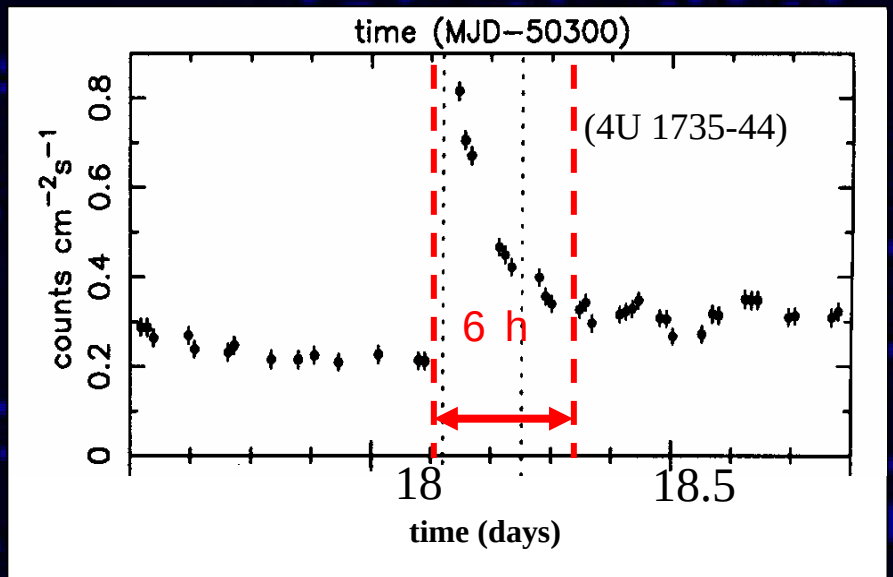
Off-state luminosity probes crust temperature profile directly

KS 1731-260

Bright X-ray burster for ~12 yr
Accretion shut off early 2001



Cackett et al. 2006

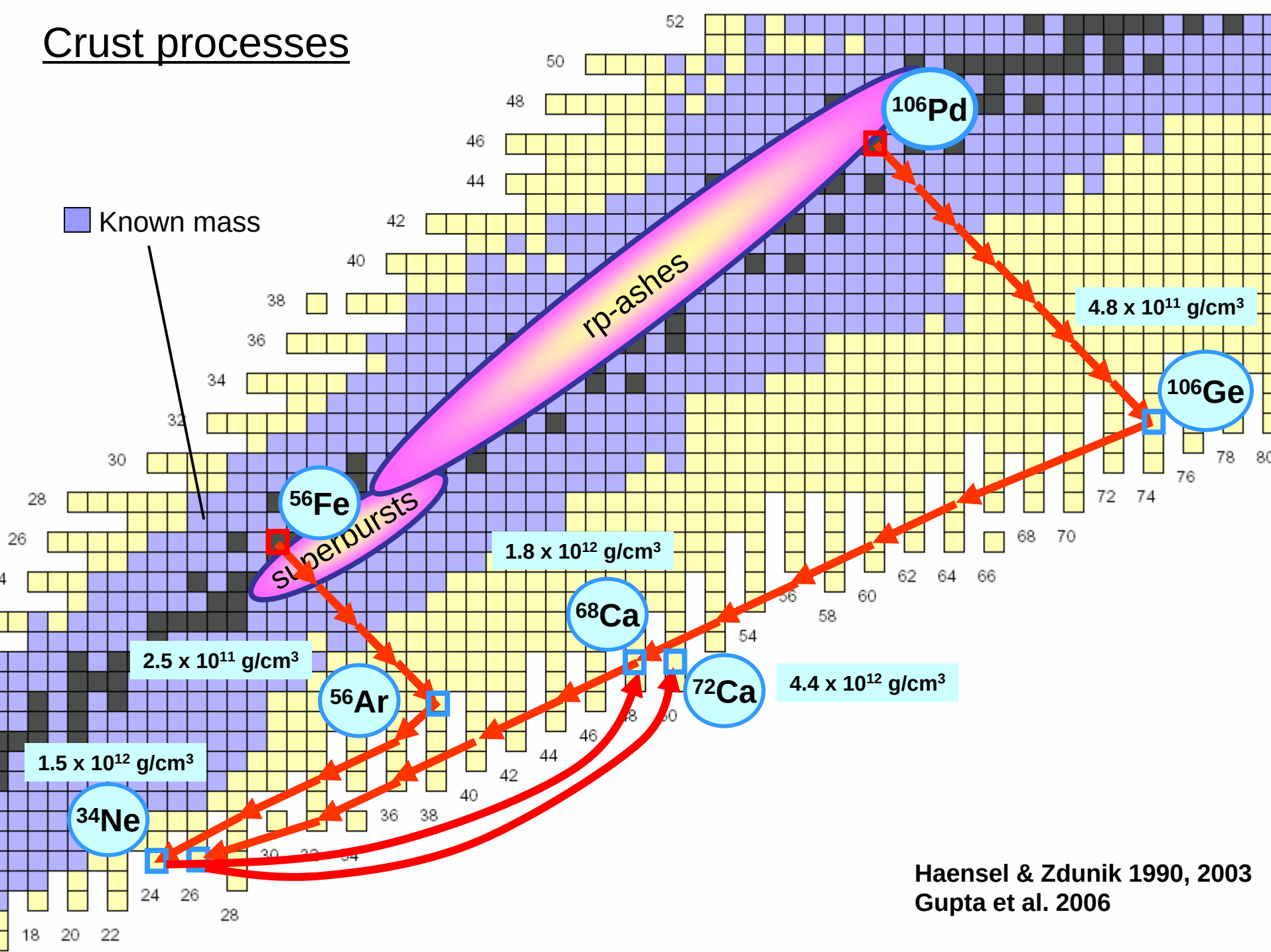


Superbursts

recurrence time ~1yr
is sensitive to crust temperature
(crust too cold in current models)

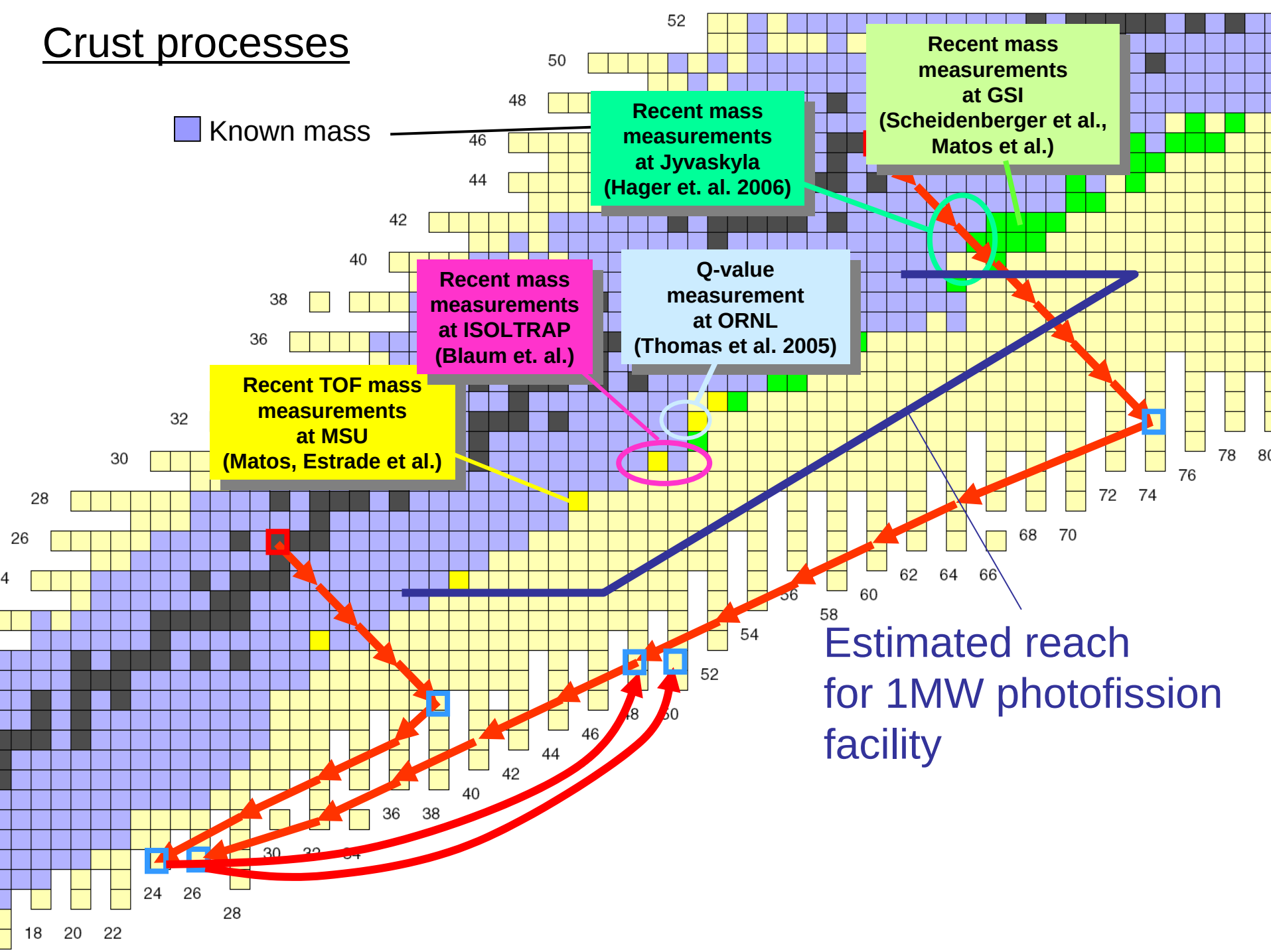
NASA/Chandra/Wijnands et al.

Crust processes

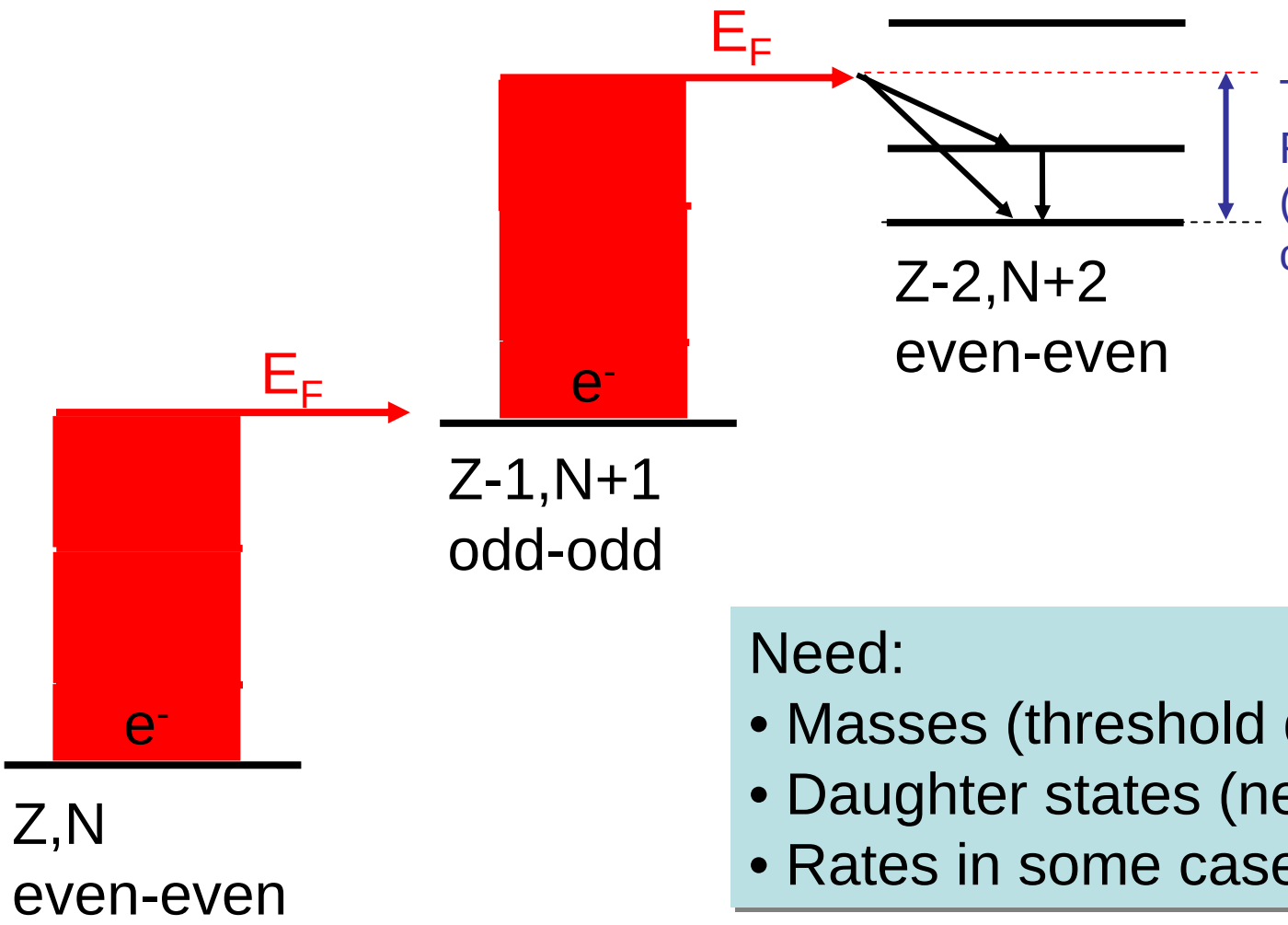


Haensel & Zdunik 1990, 2003
Gupta et al. 2006

Crust processes



Crustal heating by pairing



Need:

- Masses (threshold difference)
- Daughter states (neutrino loss)
- Rates in some cases?

Summary

- major advances in astronomy and astrophysics require similar advances in nuclear physics to address the many compelling scientific questions

- neutron rich nuclei far from stability are important in many astrophysical scenarios

- an e-beam photofission facility will enable the study of many nuclei relevant for the r-process and accreting neutron stars (transient cooling and superbursts)