The Equation of State of Dense Matter and Neutron Star Observations

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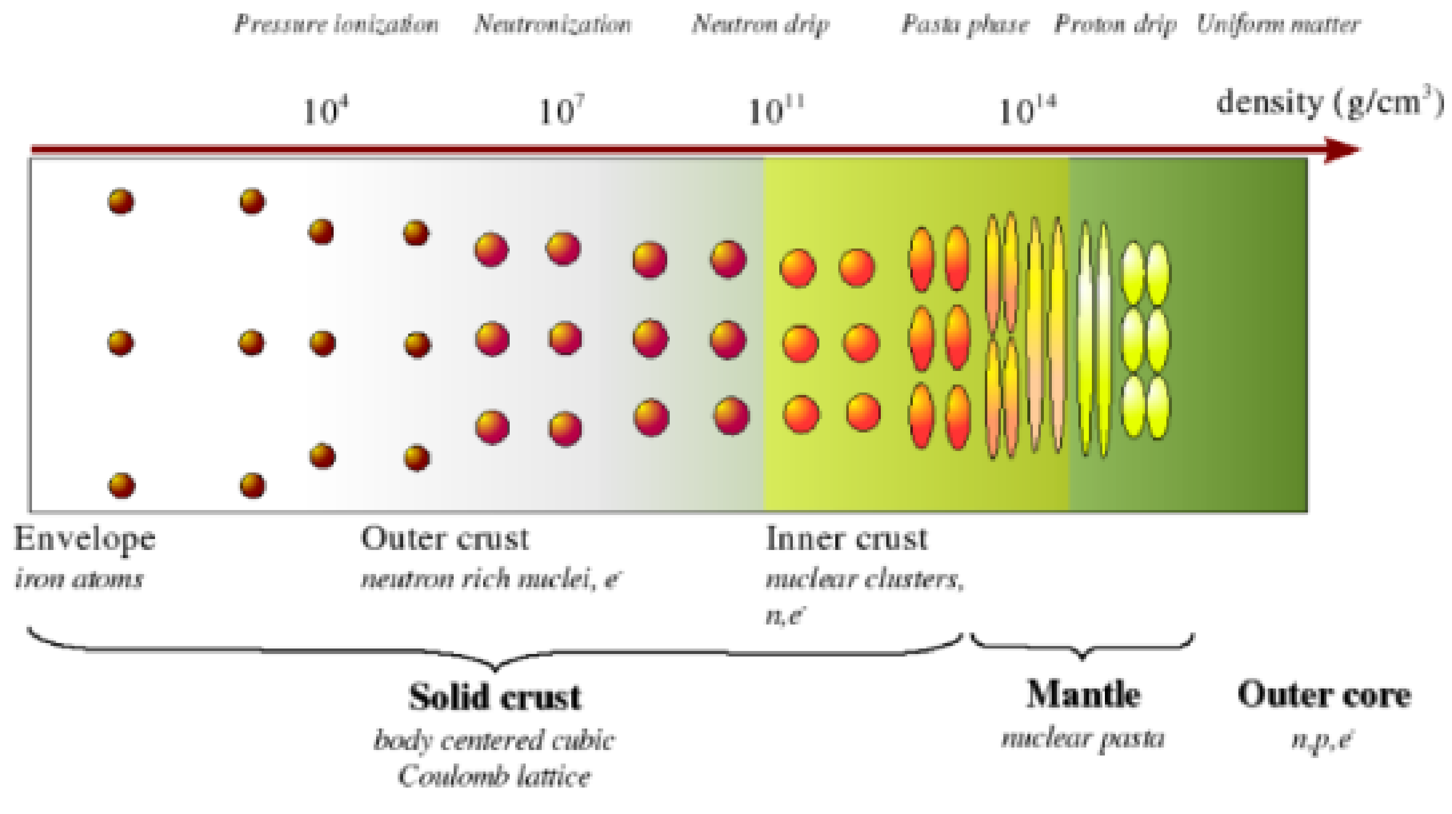
Outline

- NS crust and pasta
- Pulsar glitches and superfluidity
- Magnetar flares, EOS and superfluidity
- X-ray bursts and superbursts
- r-process nucleosynthesis

The Neutron Star Crust



Chamel (2008)

- Nuclei → nuclei + neutrons → core (n, p, and e fluid)

Remember:

$$E(Z,N) = -BA + E_{\rm surf}A^{2/3} + CZ^2A^{-1/3} + S\frac{(N-Z)^2}{A}$$

- Coulomb modified at high density by lattice corrections

Crust of an Isolated Neutron Star

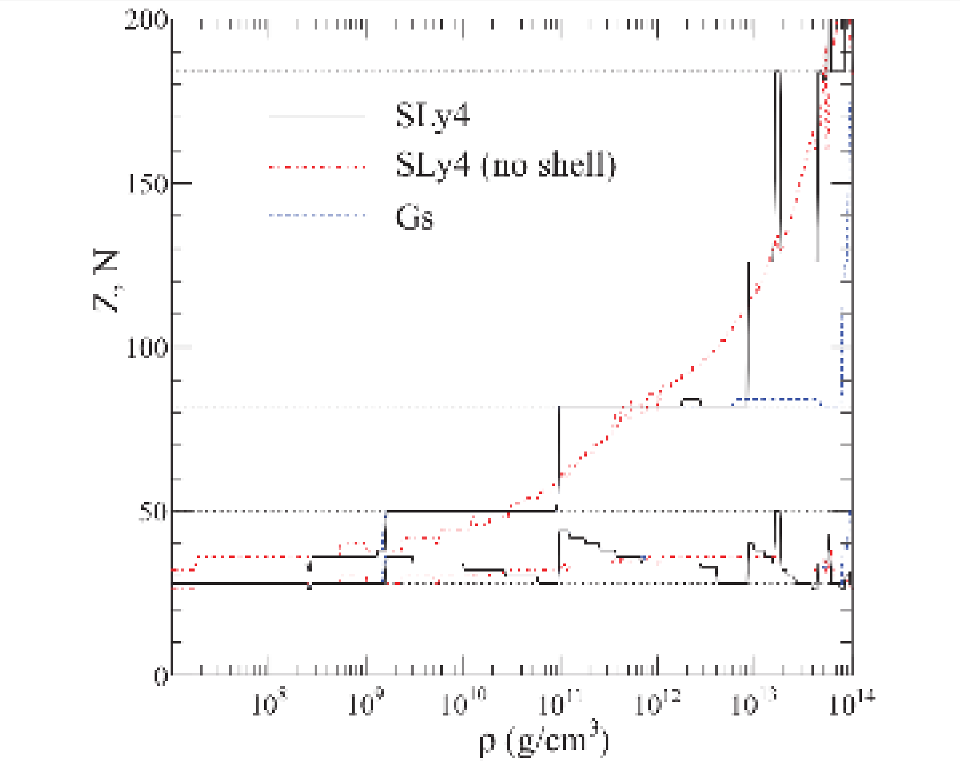
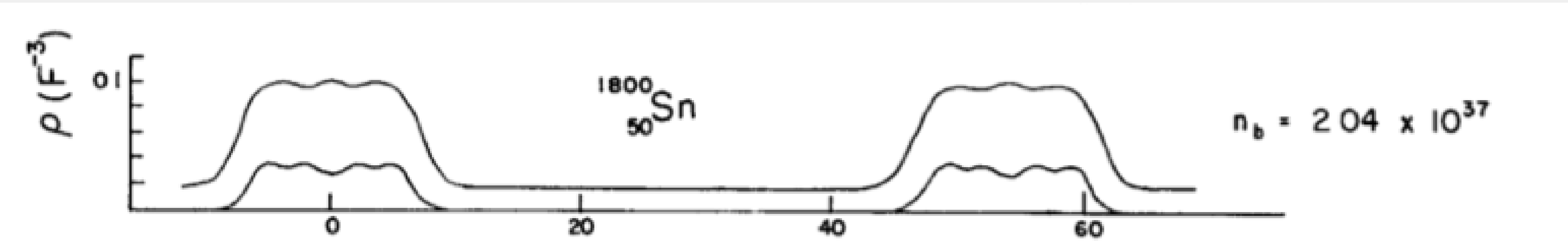


FIG. 1. (Color online) The composition of the equilibrium neutron star crust as a function of density. Deviations originate primarily because of the symmetry energy: models where the symmetry energy depends more steeply with density have larger Z and smaller N, i.e., a composition closer to the valley of stability. The smoother curves labeled "no shell" do not include shell effects.

Rüster et al. (2006), this plot from Steiner (2012)

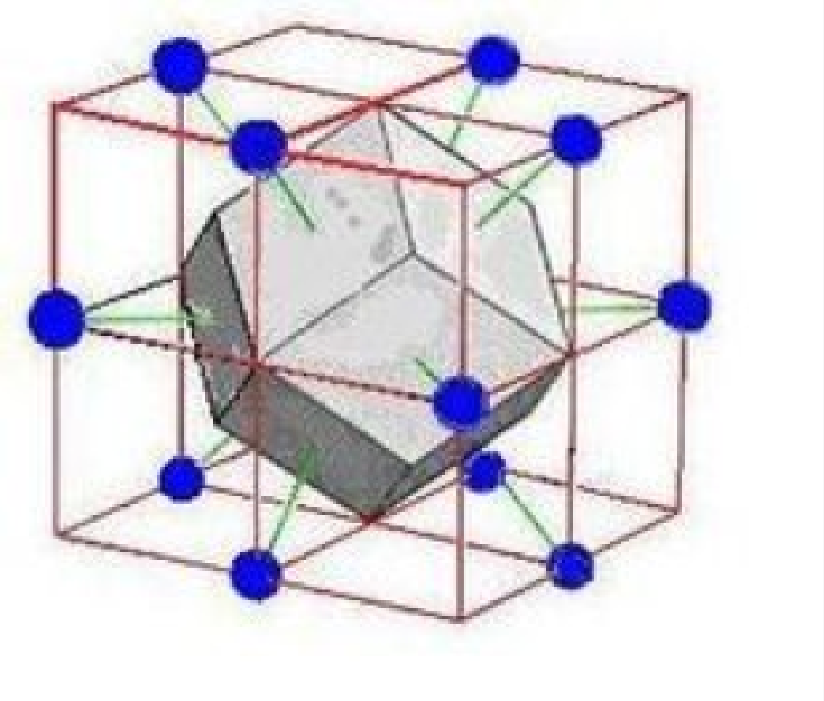
- Ground state of matter well determined, except at the highest densities

$$\mu_n = \mu_p + \mu_e$$



Negele and Vautherin (1973)

Wigner-Seitz Approximation



- Compute one nucleus in a unit cell and extrapolate
- Use Gauss' law to compute Coulomb energy

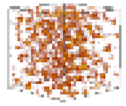
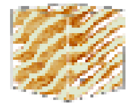
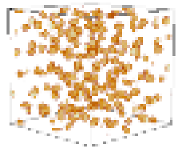
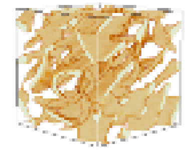
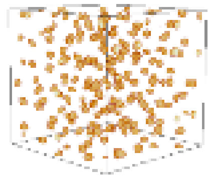
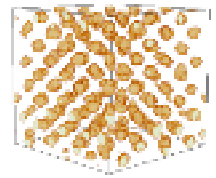
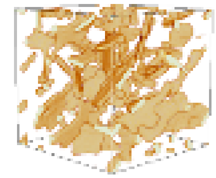
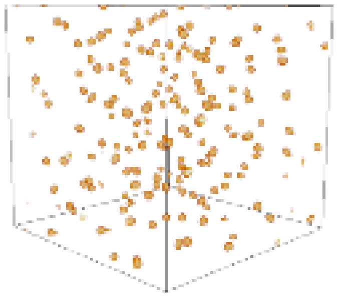
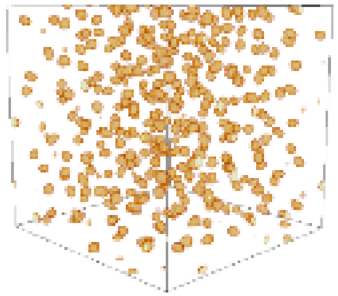
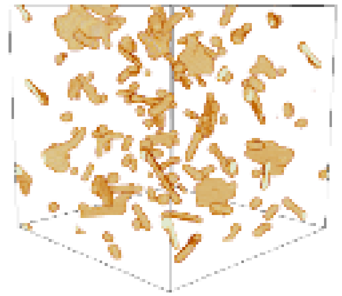
- At high densities, competition between Coulomb and surface energies gives rise to pasta
  Ravenhall et al. (1983)

$$E_{\rm surf} = \chi \sigma d / r \quad ; \quad E_{\rm Coul} = 2\pi n_p^2 e^2 r^2 \chi$$

$$f_d(\chi) = \left\{ 2/(d-2) \left(1 - \frac{1}{2} d u^{1+2/d} \right) + u \right\} / (d+2)$$

The Pasta

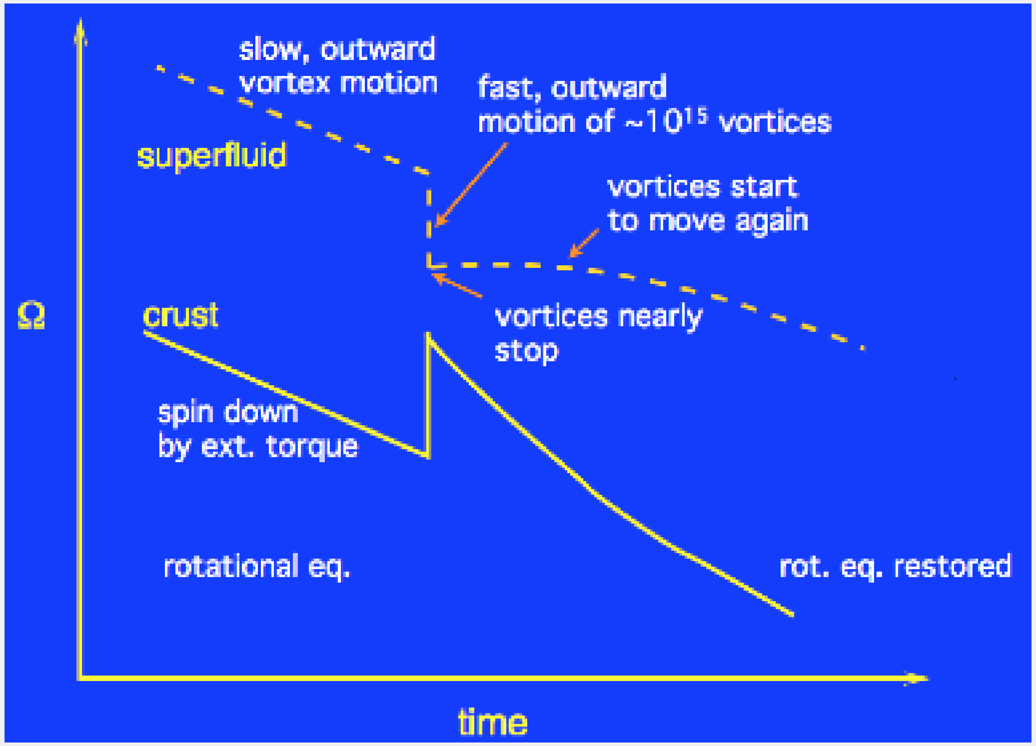
TABLE III: (Color online) Comparisons of configurations at several densities obtained from three different simulations, shown to scale. The figures are generated in Paraview by finding isosurfaces of charge density. The dark surfaces are generated where $n_Z = 0.03\,\text{fm}^{-3}$, and the lighter surfaces at the boundary show where $n_Z > 0.03\,\text{fm}^{-3}$. The first column shows the density of the configurations in each row.

$n\,(\text{fm}^3)$	$T = 1.0$ MeV, $Y_P = 0.1$	$T = 1.0$ MeV, $Y_P = 0.4$	$T = 0.5$ MeV, $Y_P = 0.4$
0.0601			
0.0195			
0.0116			
0.0027			

Caplan et al. (2015)

- Molecular dynamics is classical, but goes beyond Wigner-Seitz approximation
- Transport properties of crust are still uncertain

Pulsar Glitch Mechanism



Picture from B. Link

- Superfluid component, decoupled from rotation at the surface
- Natural to associate the superfluid component with the superfluid neutrons in the crust
- What is the mechanism for the sudden change?

- Superfluid vortices pinned to the lattice
- Neutron star spins down, vortices bend creating tension, eventually they must shift lattice sites
- Quasi-free neutrons are entrained with the lattice
  Chamel (2012), Chamel (2013)

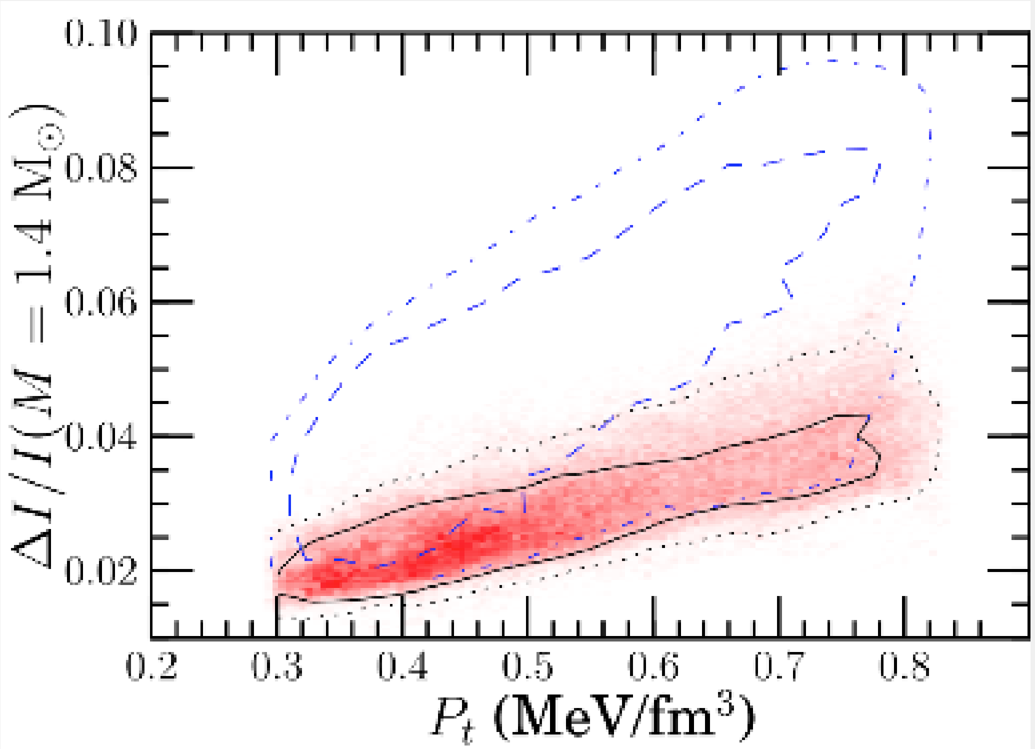
Is There Enough Superfluid in the Crust?

- We require 1.6% of I to explain glitches in Vela
  Link, et al. (1999)

- Entrainment: 75-85% of otherwise superfluid neutrons 'connected' to the lattice
  Chamel (2012)

- Current M and R observations suggest there is not enough I in the crust
  See Andersson et al. (2012)

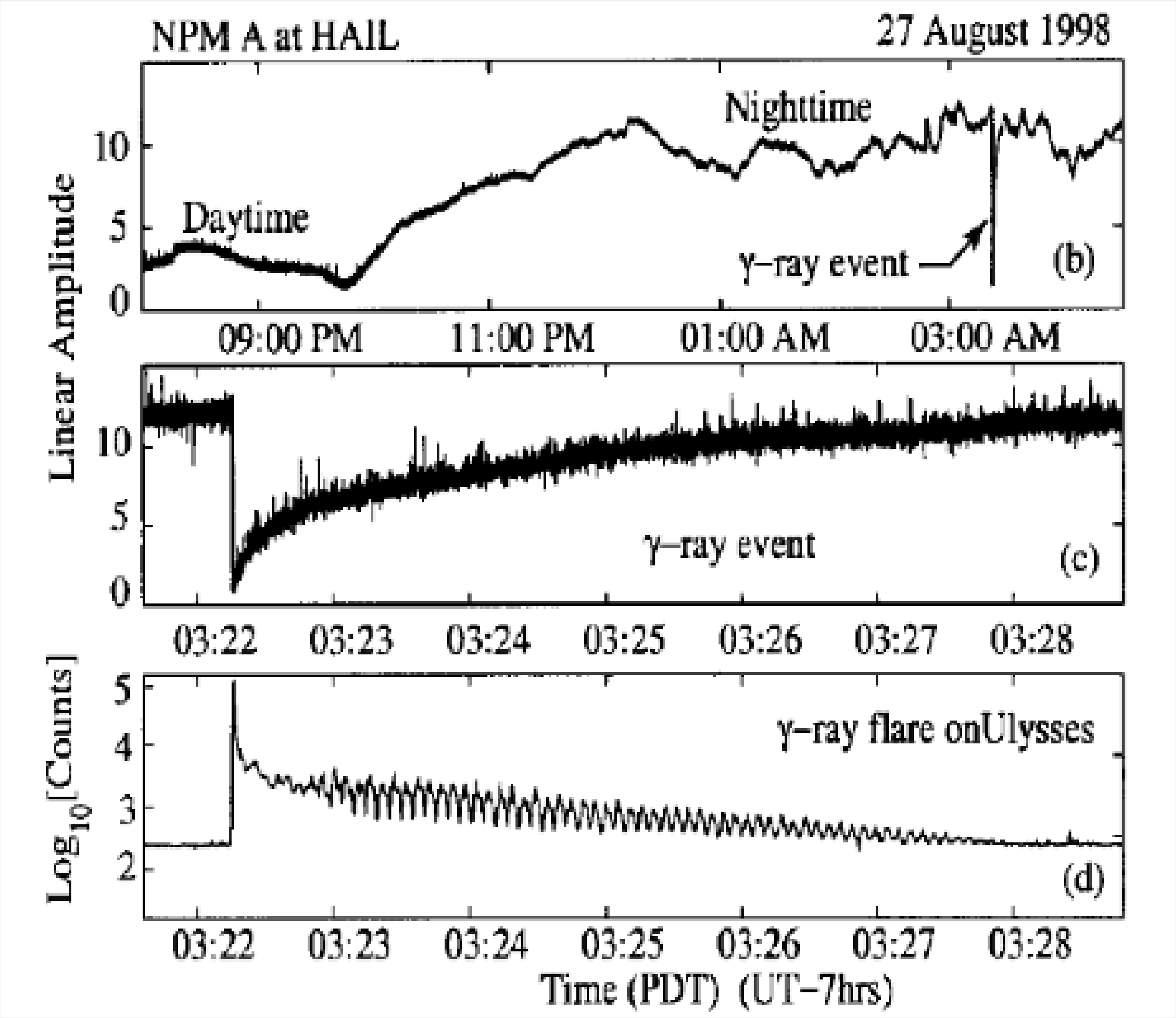
- Unless the systematics force much larger neutron star radii and P_t is large



Steiner et al. (2015); black and red are with M & R observations, blue contours are with $I = 70\ M_\odot\ km^2$

Magnetar Flares

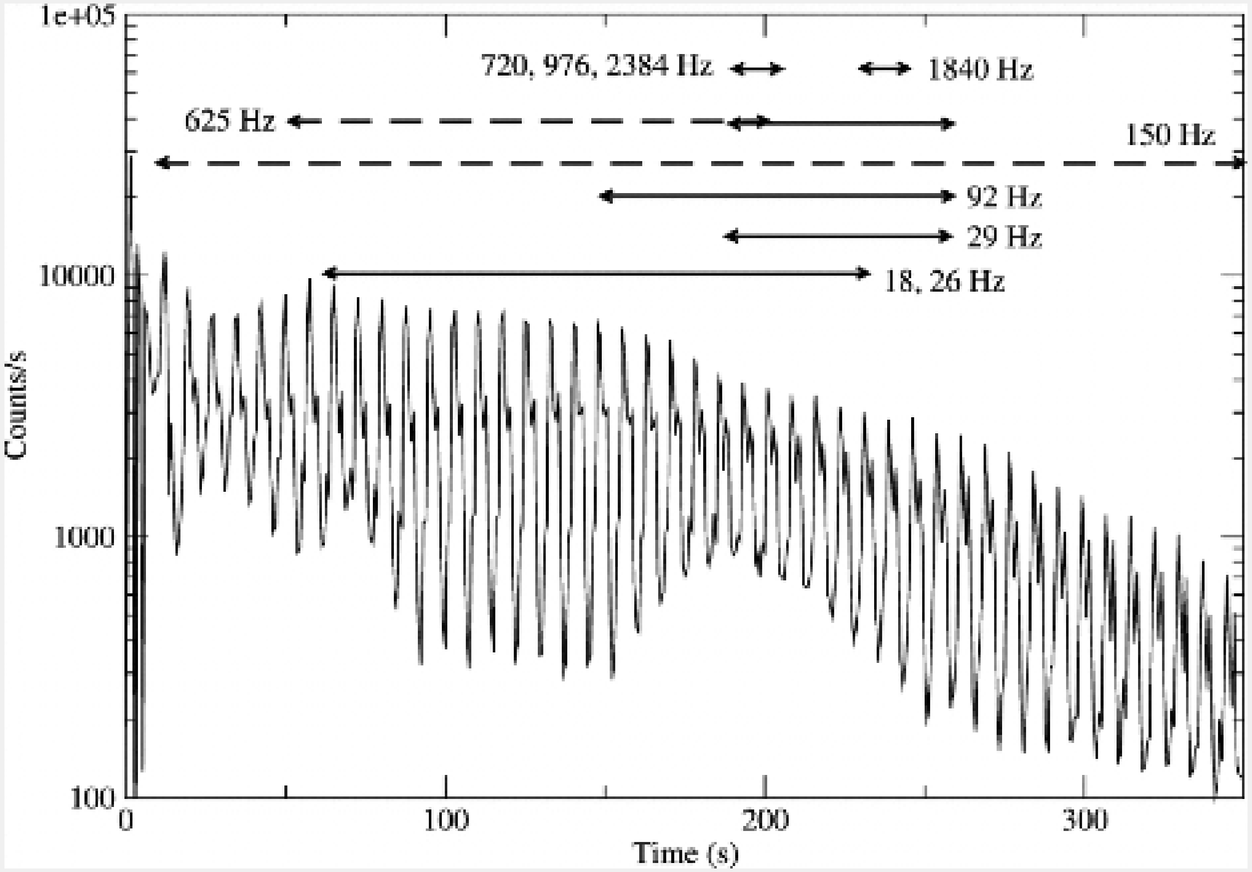
- Magnetars are highly magnetized neutron stars
- Star quakes generate gamma-ray flares
- Catastrophic breaking of the crust, due to stress generated by the 10^{15} G magnetic field
- Aug. 1998 flare of SGR 1900 (45k lyrs)
- Earth's ionosphere: ionization varies with sunlight



Inan et al. (1999)

Flare QPOs

- Emit (up to 10^{46} ergs) flares of hard X-rays/gamma rays
- Flares obey log-normal distribution also observed in terrestrial earthquakes
- Seismic energy contained in the crust is sufficient to drive the flares
- Flares originate in reconfigurations of a magnetized crust
- Quasi-periodic oscillations are embedded in the giant flares
- Some of the oscillation frequencies are thought to be shear modes of the crust

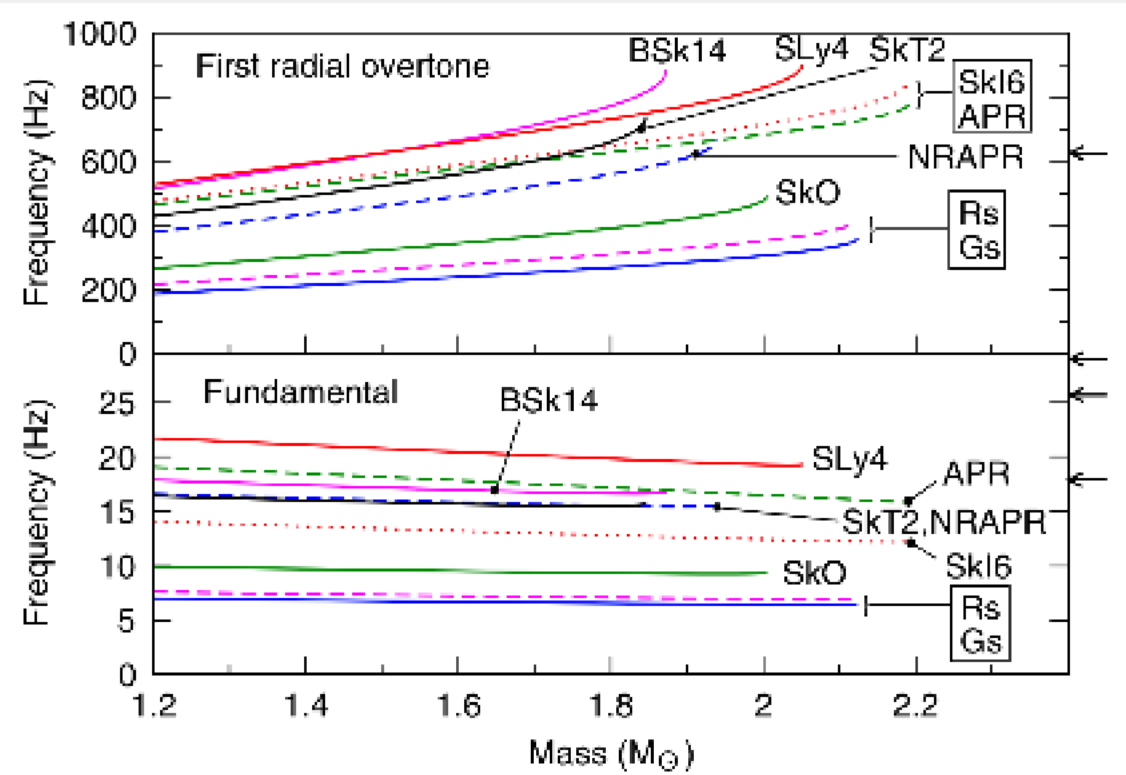


Shear Modulus in the Crust

- The shear modulus in the crust is is

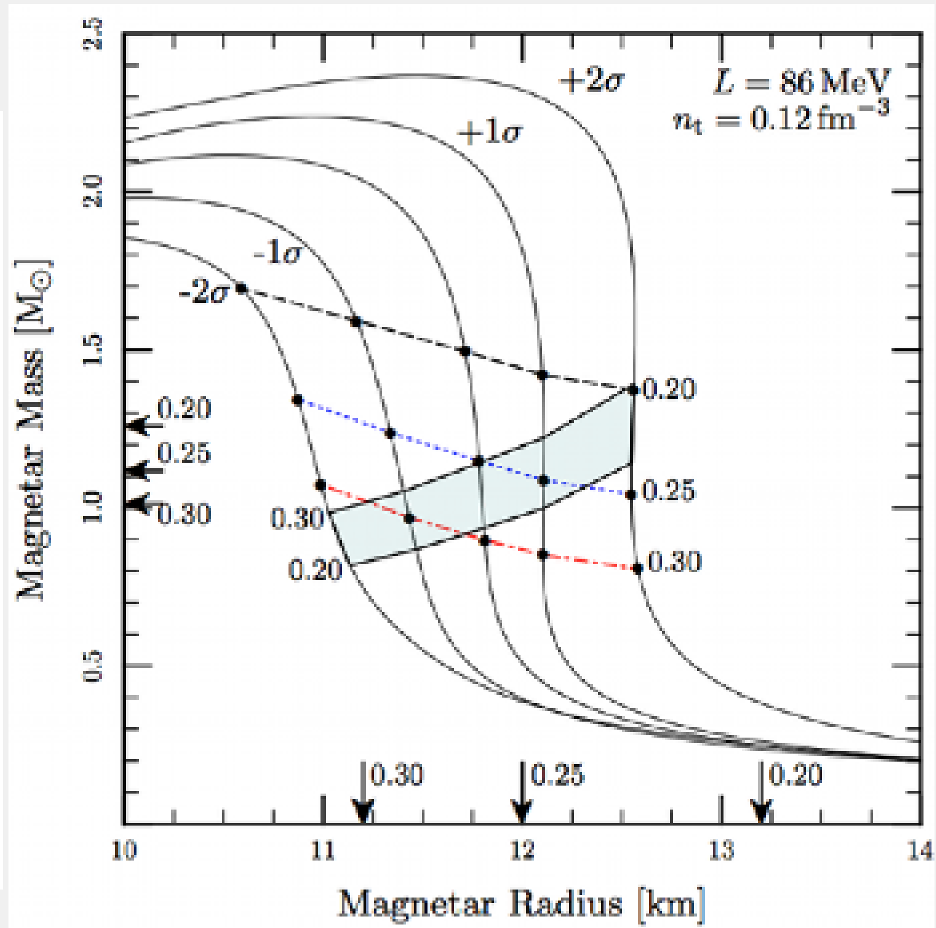
$$\mu = \frac{0.12}{1 + 0.6(173/\Gamma)^2} \frac{n(Ze)^2}{a} \quad ; \quad v_s = (\mu/\rho)^{1/2}$$

Stromayer et al. (1991) and Piro (2005)



Steiner and Watts (2009)

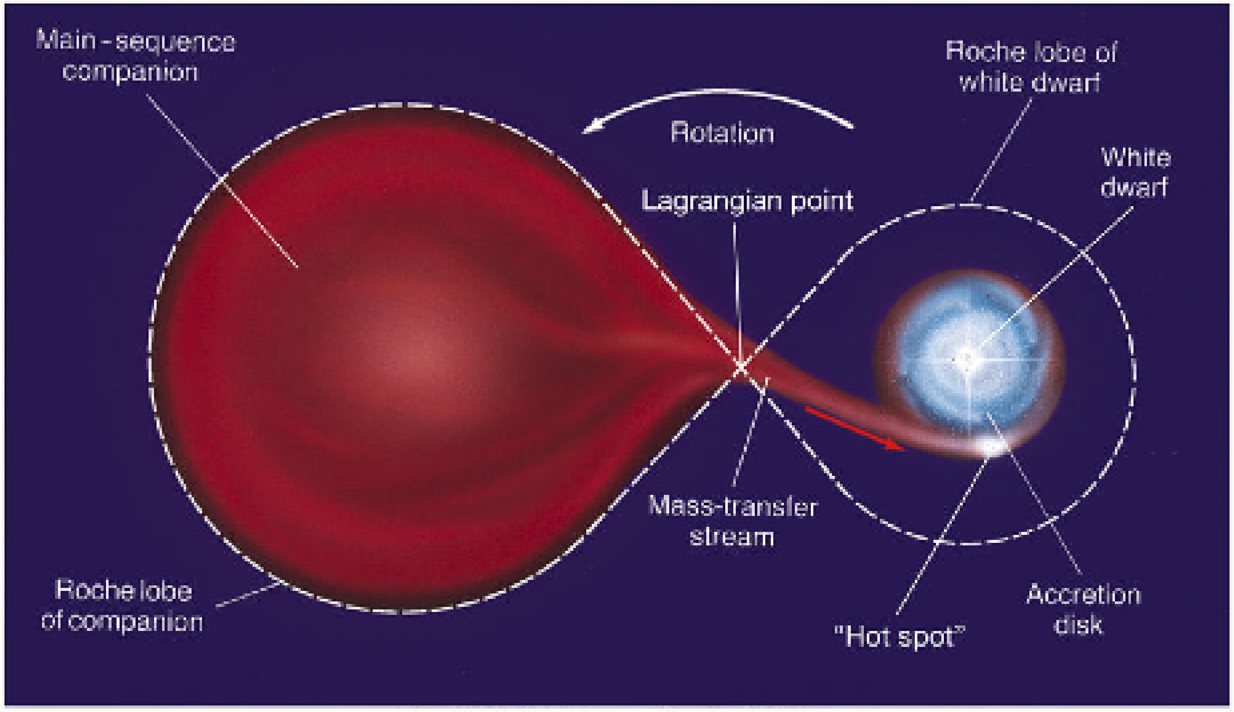
- Frequency of QPOs related to EOS



Deibel et al. (2014)

- Frequency of QPOs related to superfluid entrainment

X-ray Bursts



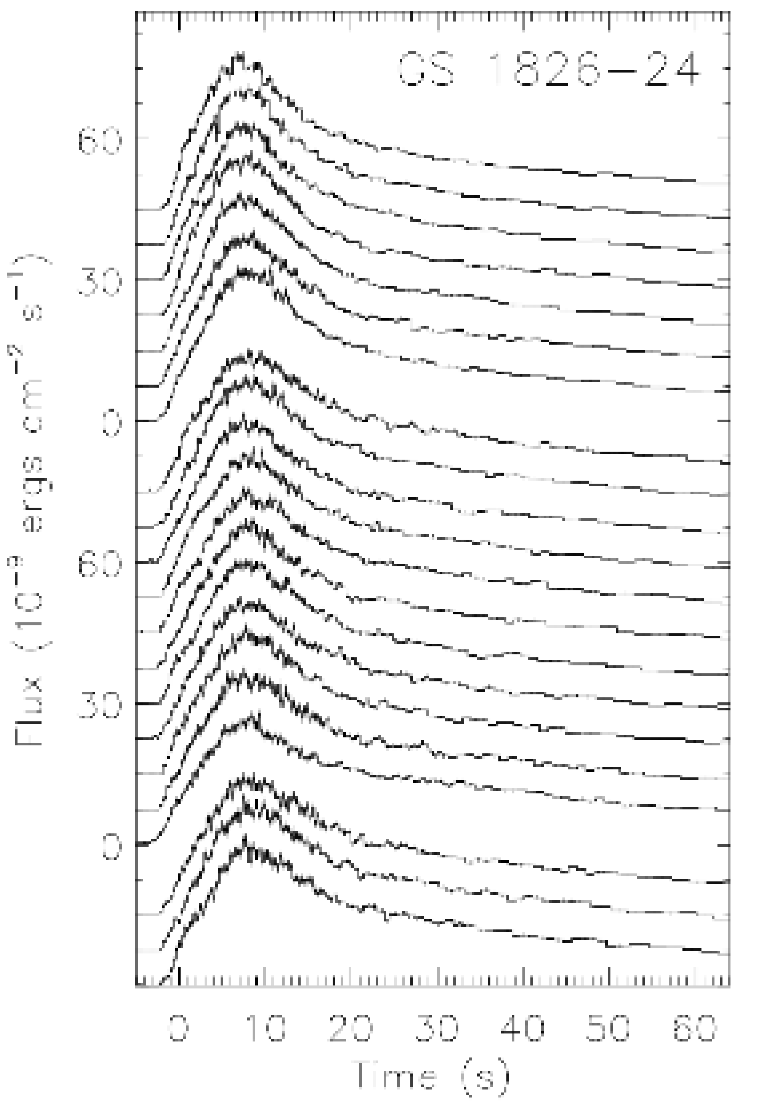
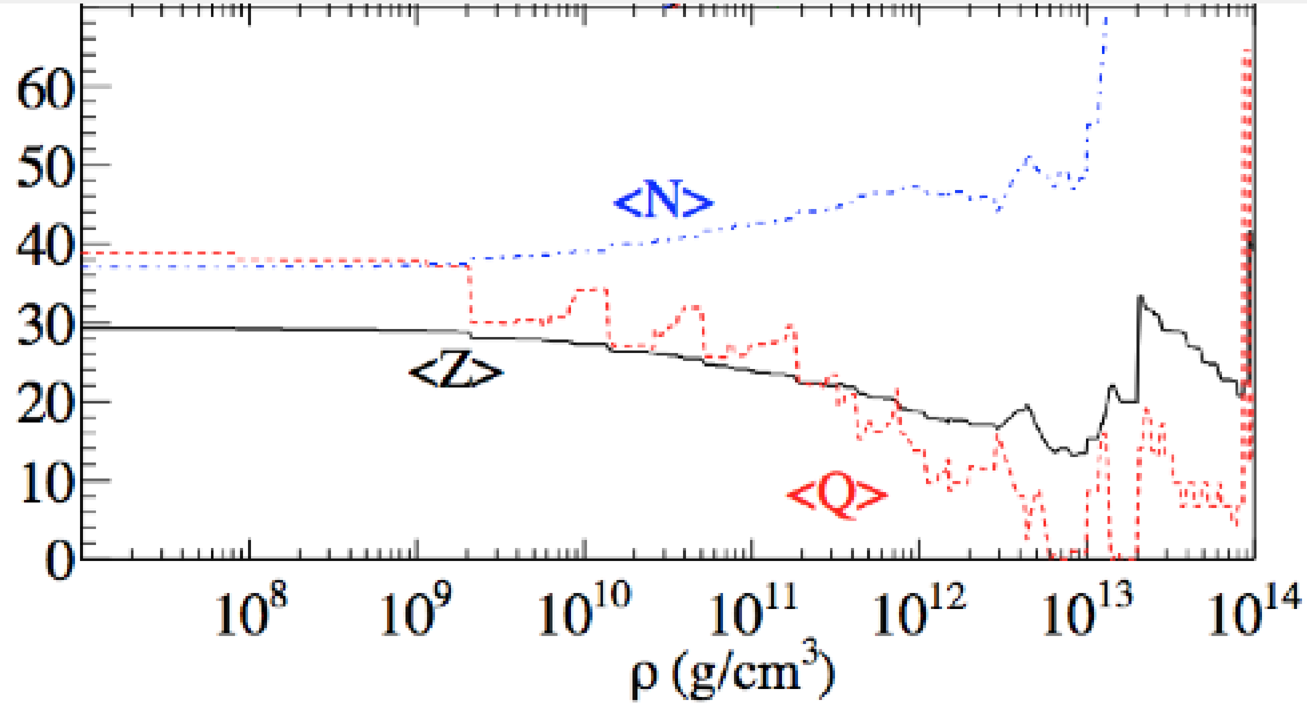


FIG. 1.— Profiles of 20 X-ray bursts from GS 1826−24 observed by *RXTE* between 1997–2002, plotted with varying vertical offsets for clarity. The upper group of 7 bursts were observed in 1997–98, the middle group of 10 bursts in 2000, while the lower group of 3 were observed in 2002. The bursts from each epoch have been time-aligned by cross-correlating the first 8 seconds of the burst. Error bars indicate the 1σ uncertainties.

X-ray bursts from GS 1826-24

- H and He accreted is unstable
- X-ray burst, burns H and He to heavier elements

Crust of an Accreted Neutron Star



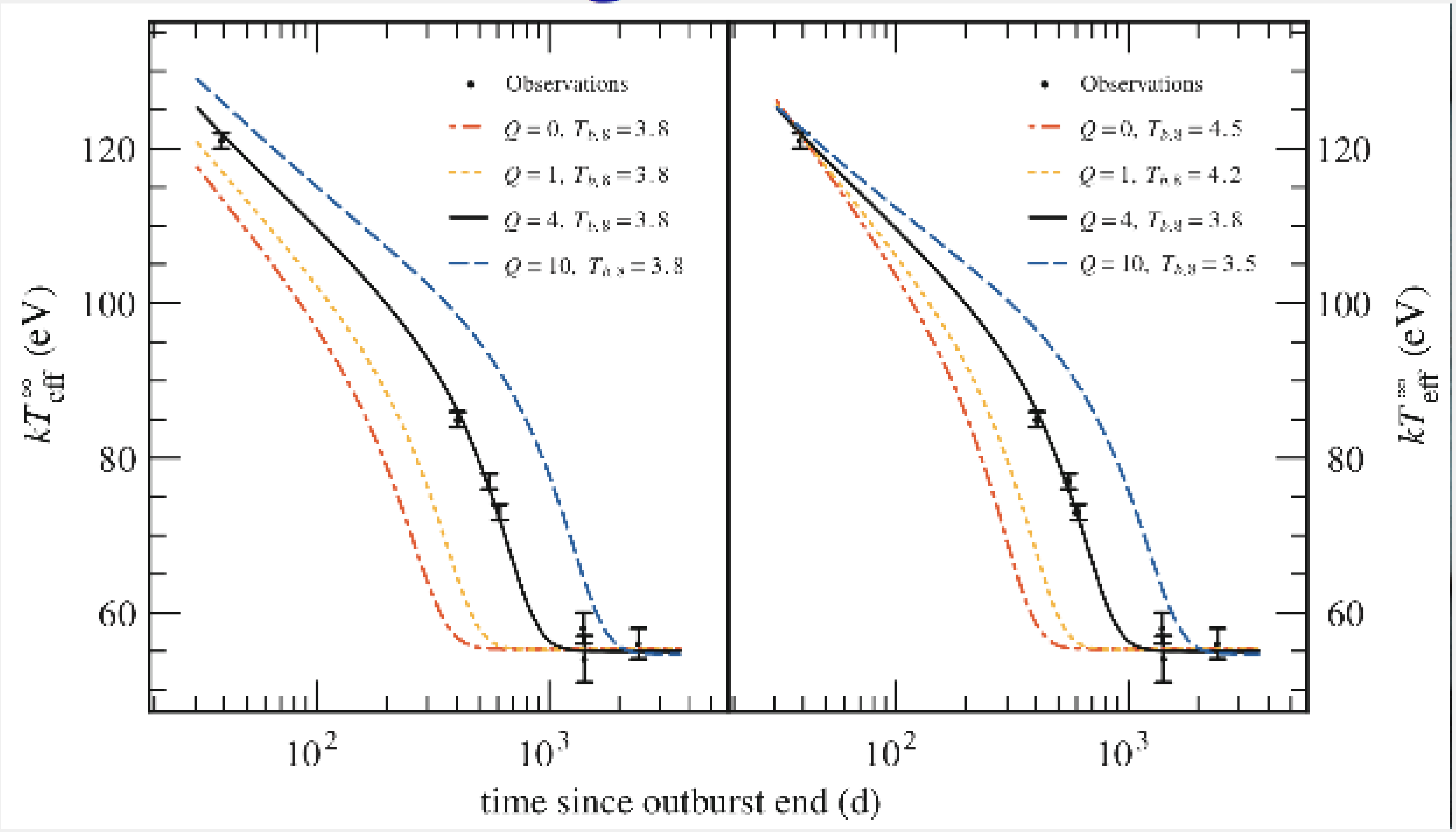
Steiner (2012)

- X-ray burst ashes consist of an ensemble of nuclei
- Nucleons driven to higher densities as matter accretes on top

$$\langle Q \rangle = \left[\sum_i n_i (Z_i - \langle Z \rangle)^2 \right] \left[\sum_i n_i \right]^{-1}$$

- Series of electron capture, neutron emission, and fusion reactions proceed at high densities

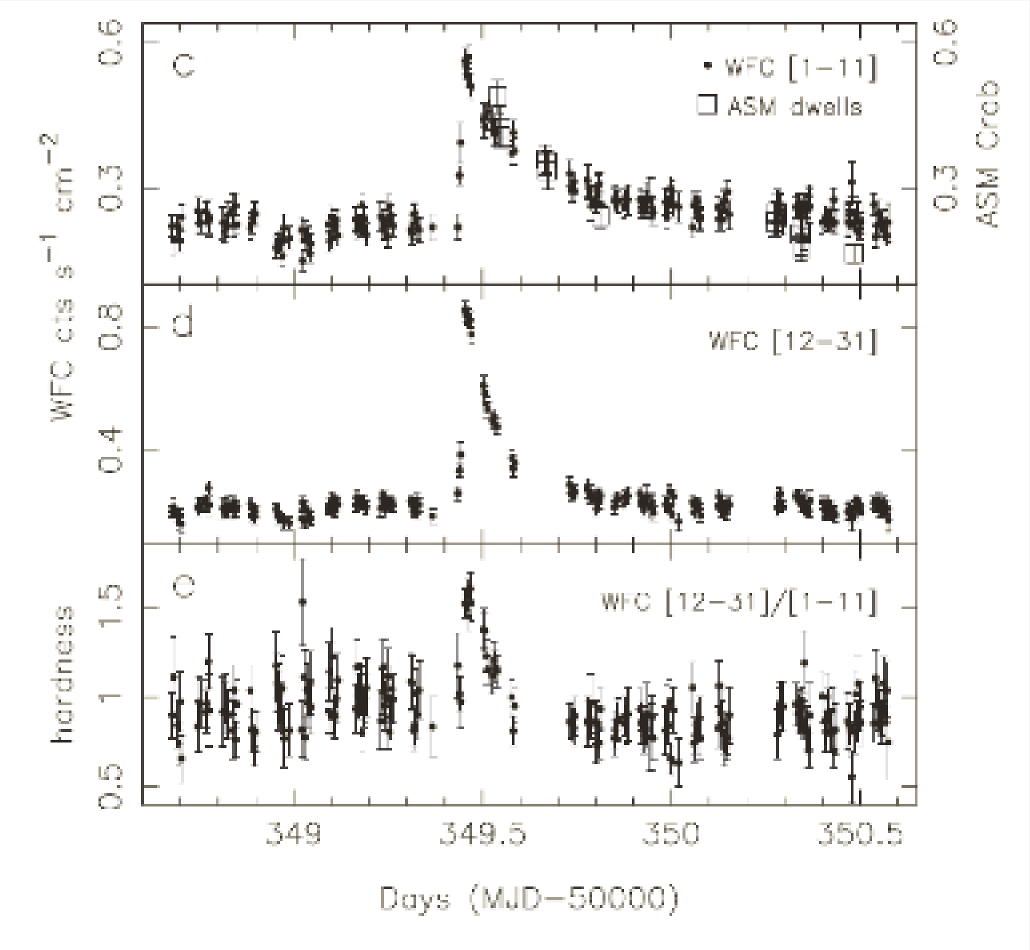
Cooling of the Crust



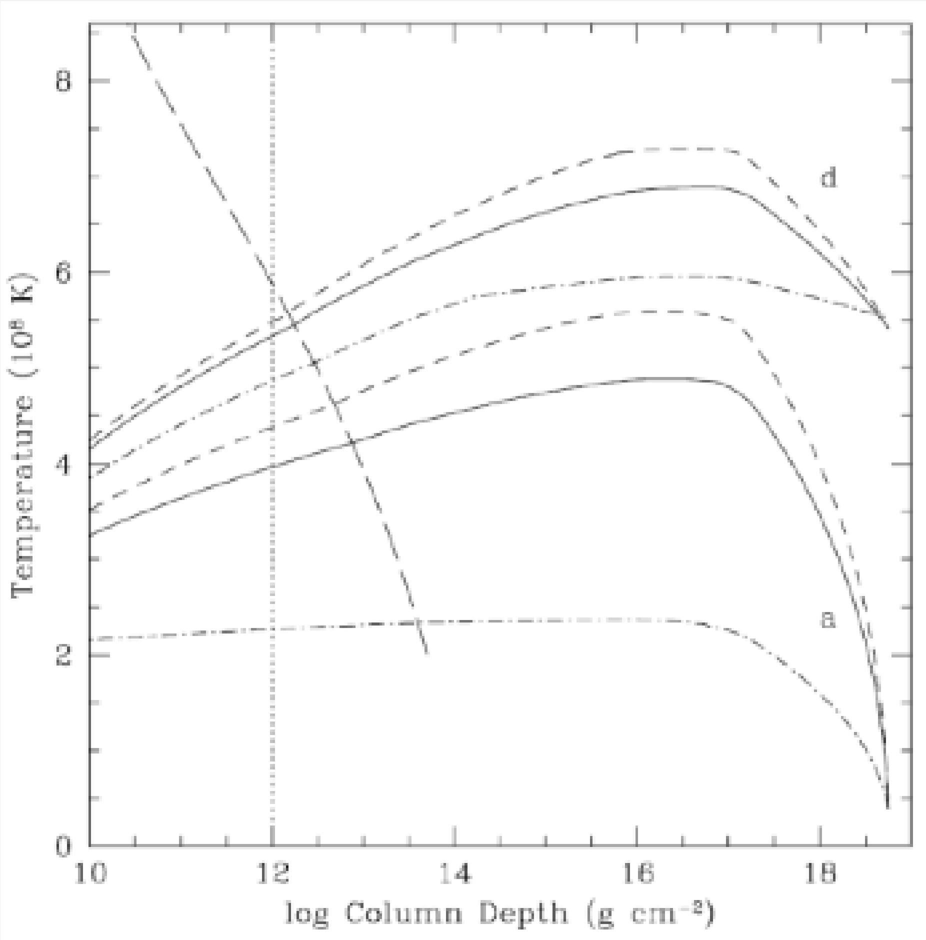
Brown and Cumming (2009)

- Accretion generates 200 MeV/nucleon and heats up the crust
- When accretion shuts off, the crust cools down
- Cooling wave starts at the outer layers and proceeds inwards
- Found that the crust must be relatively pure

X-ray Superbursts



Superburst in KS 1731-260

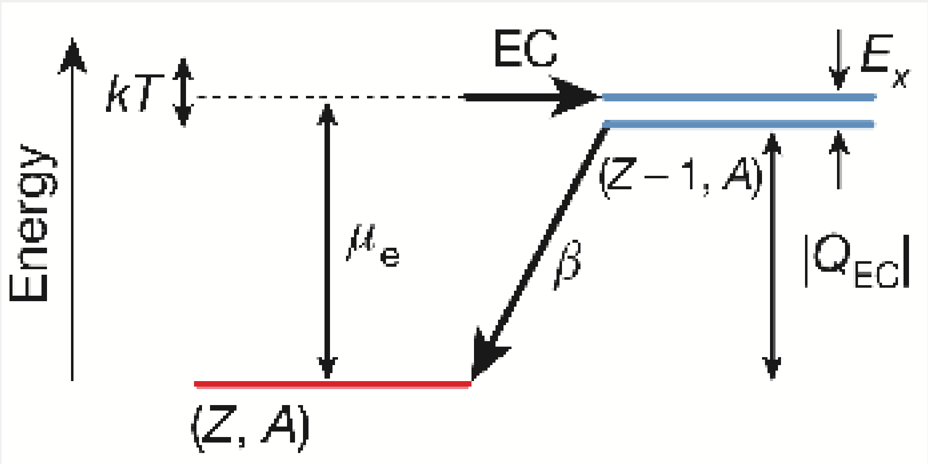


Cumming, et al. (2006)

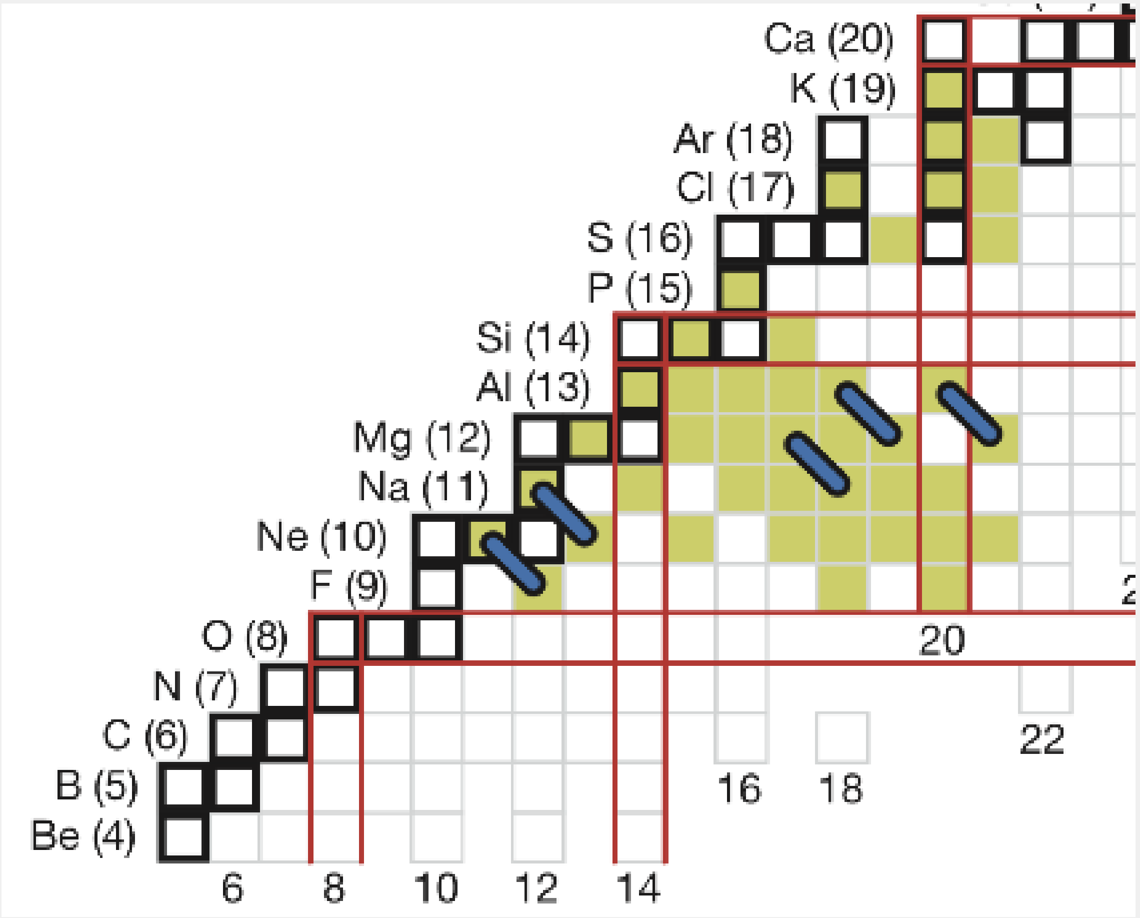
- Larger energies and longer times; unstable carbon ignition
- Crust temperature smaller than critical temperature for unstable fusion.

More Problems with Superbursts

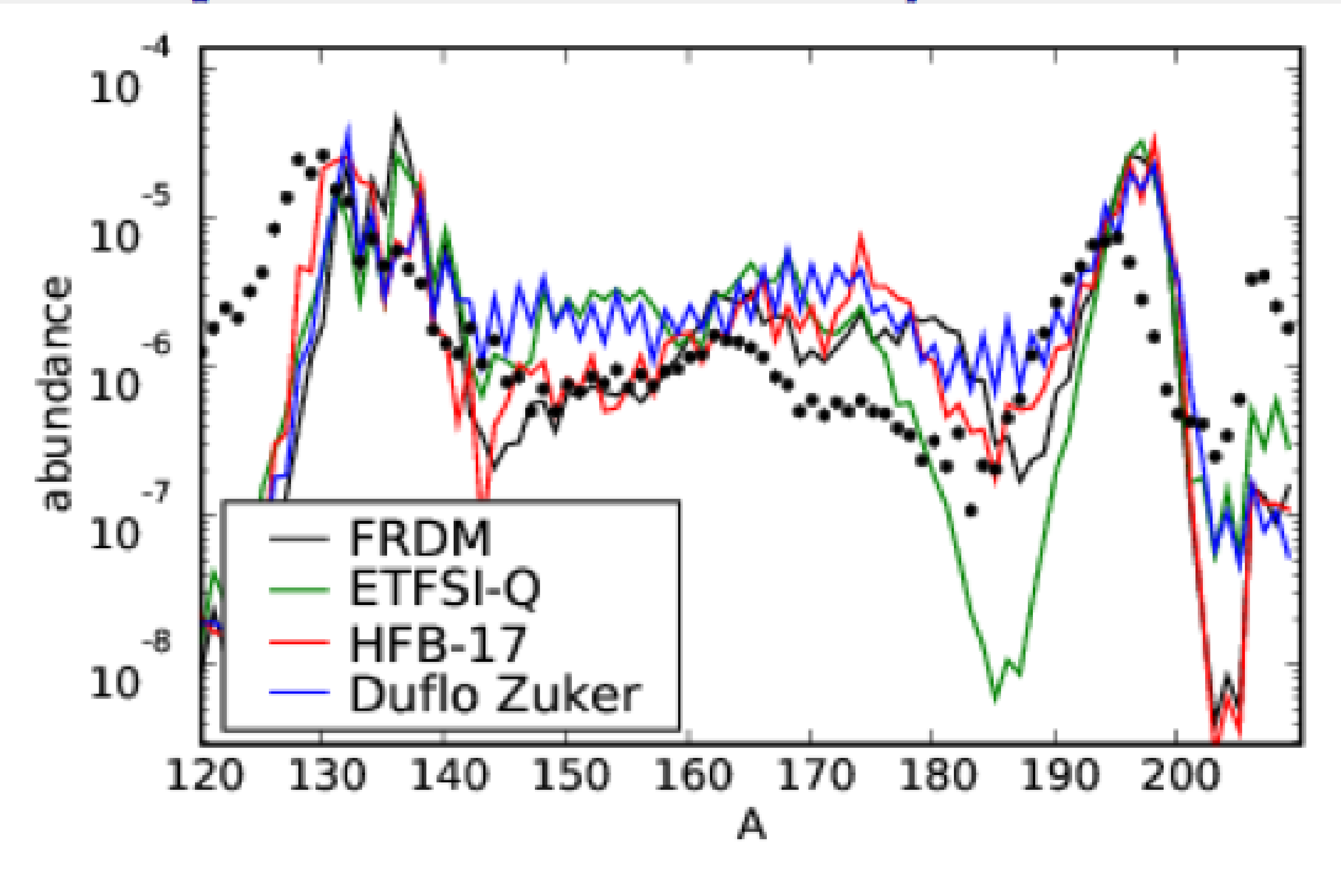
- Urca shell cooling
- Electron capture into an excited state, within T of daughter ground state
- Leads to even cooler crusts!



Schatz et al. (2014)



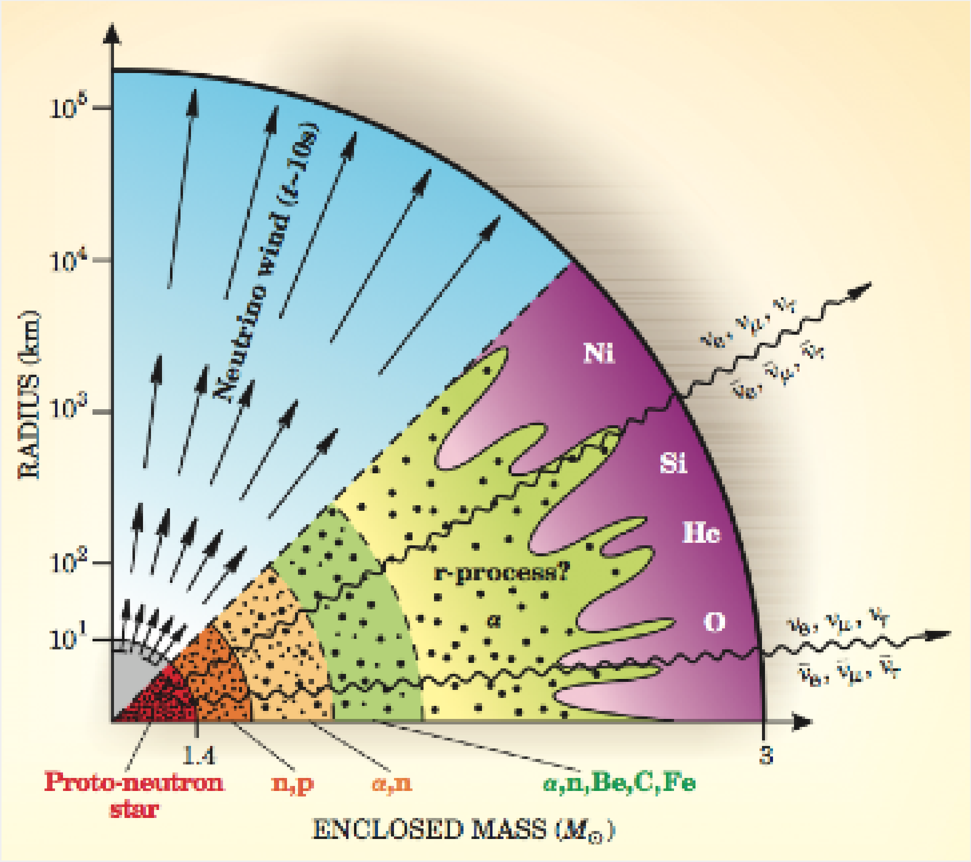
R-process Nucleosynthesis



- Two ways of synthesizing heavy elements: s- and r-process

- What is the astrophysical site of the r-process? 

Neutrino-driven wind for the r-process



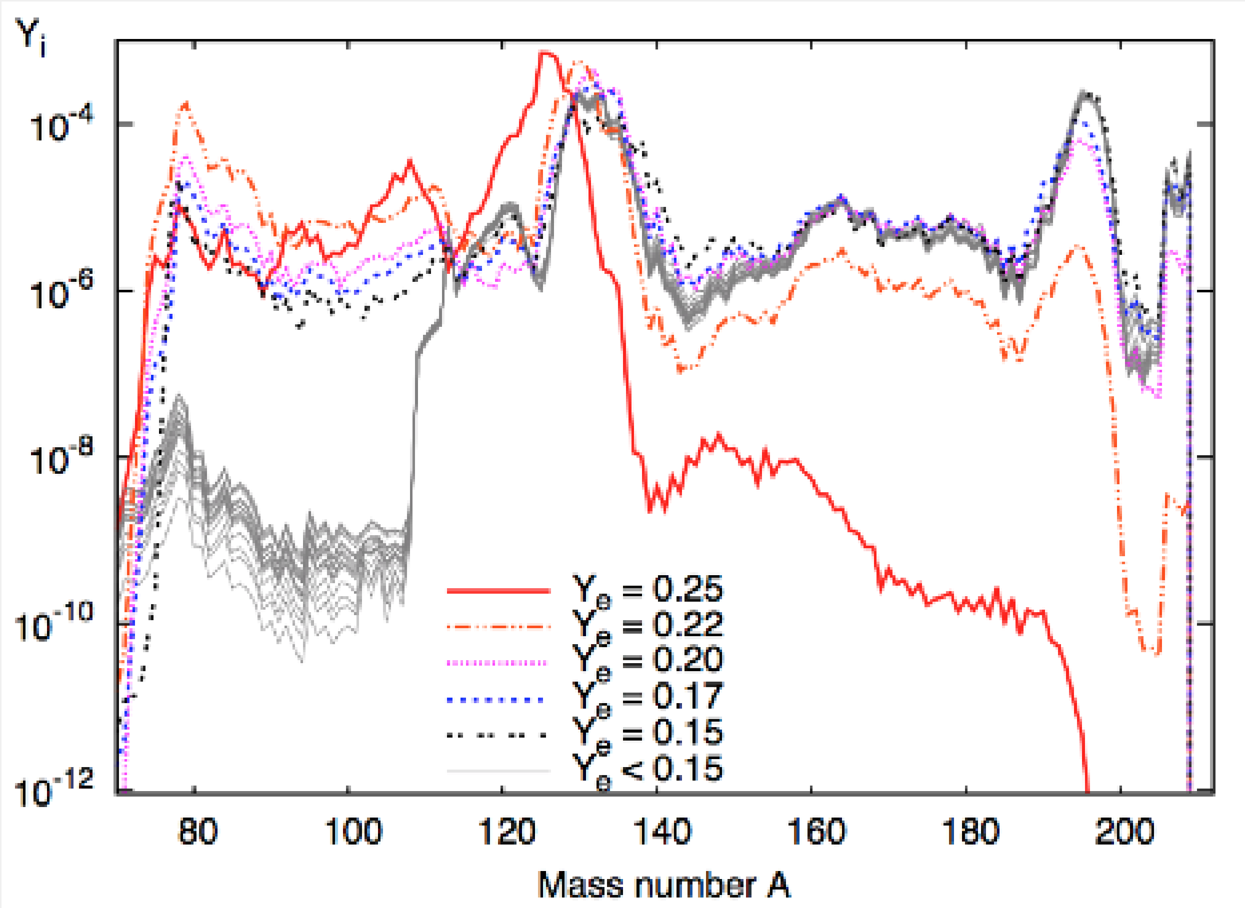
Cowan and Thielemann (2004)

- Copious neutrinos emitted from hot proto-neutron star create a hydrodynamic wind
- Electron fraction and temperature (entropy)
- Simulations typically predict entropies which are insufficient to generate the heaviest r-process
- Still a leading site, especially for low A r-process elements

- Caveats: fall back, rotation, magnetic fields, multi-D effects, jets
- Neutrino opacity depends on the nuclear interaction
  Roberts, et al. (2012)

R-process Nucleosynthesis from Neutron Star Mergers

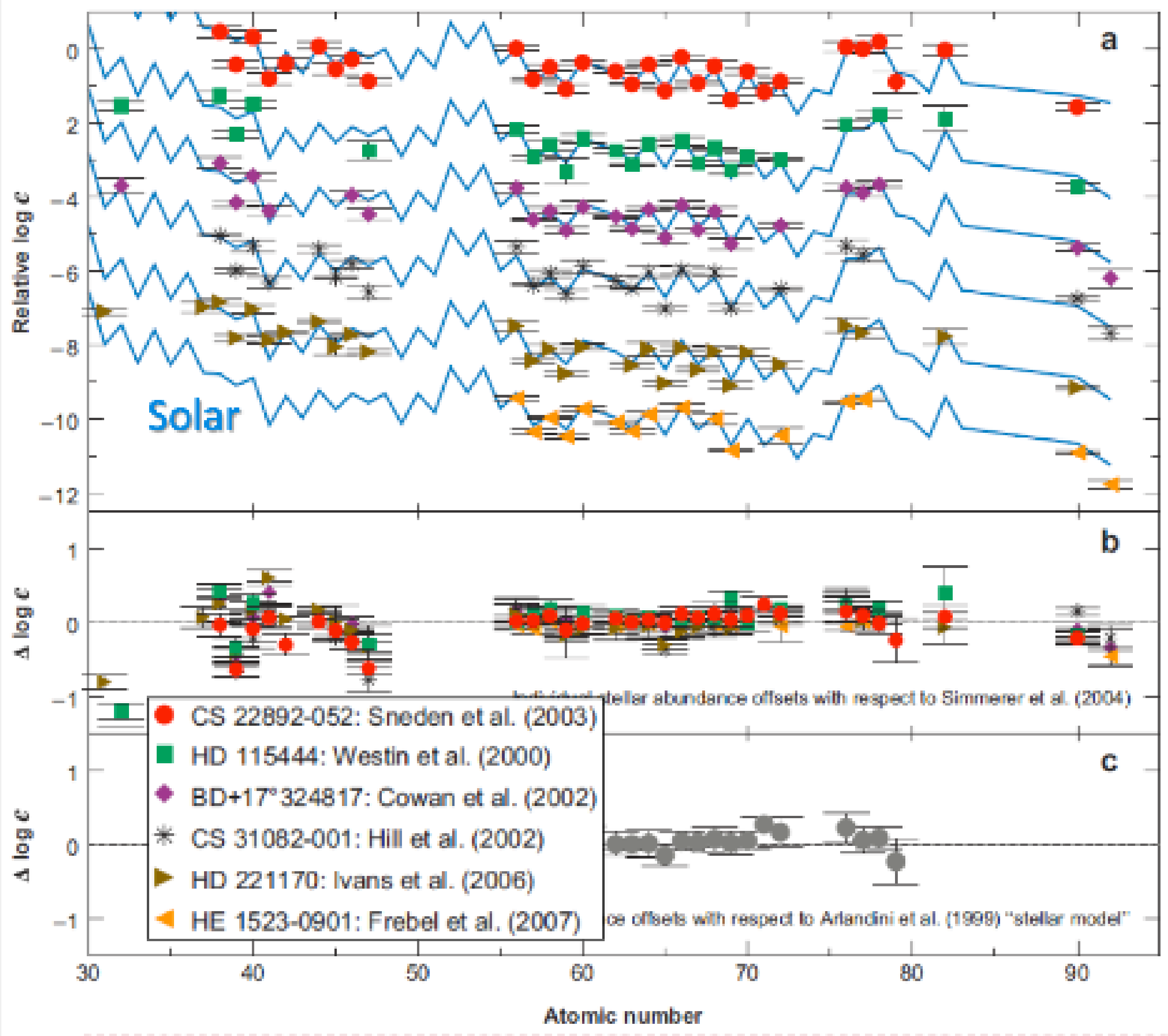
- Nucleosynthesis nearly independent of the electron fraction of the ejected material



Korobkin et al. (2012)

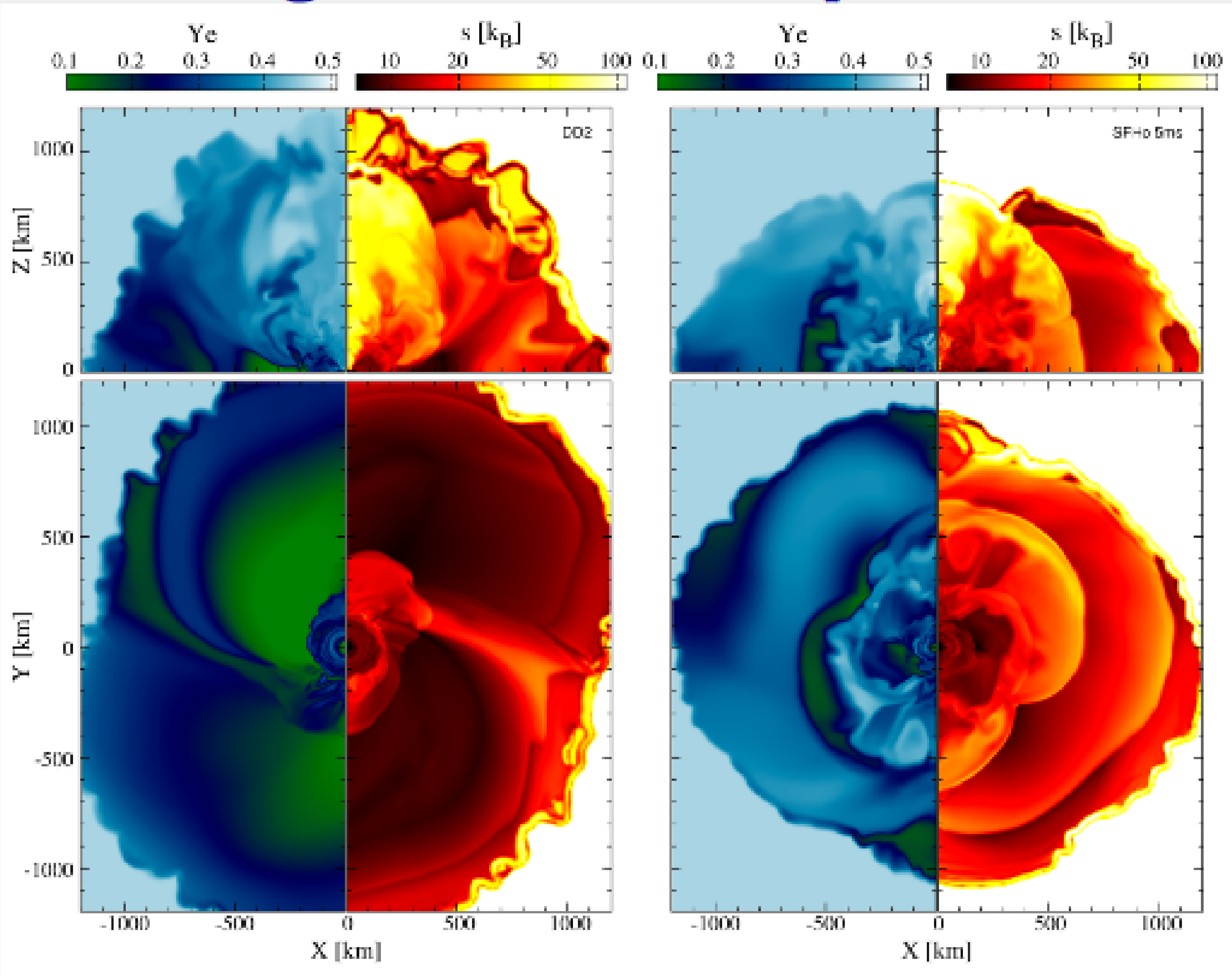
- However, it **is** dependent on amount of material ejected, thus depends on the EOS
  Oechslin et al. (2007); Roberts et al. (2011)
- Possibly accompanied by UV/optical signal
  e.g. Li and Paczynski (1998); Metzger et al. (2010); Berger, Fong, and Chornock (2013)

Mergers and the r-process



- r-process nuclei observed in stars is universal: same pattern from event to event
- May occur in neutron star mergers, but is it universal?

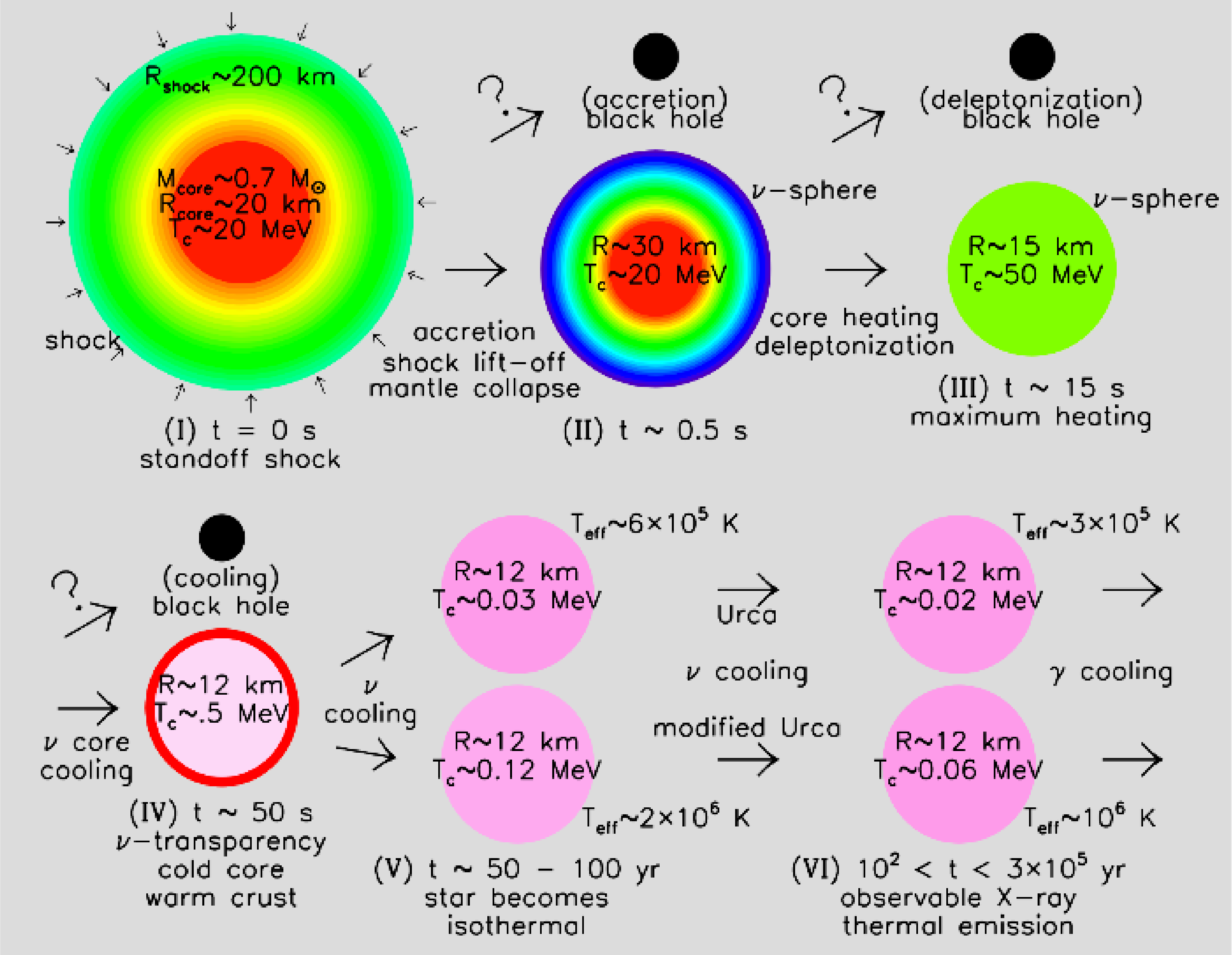
Mergers and the r-process



Sekguchi et al. (2015), DD2 (large radii) on left and SFHo (small radii) on right

- Small radii lead to higher Y_e and more universal r-process production
- Smaller radii also lead to larger amounts of ejected r-process material

Birth of a Neutron Star



Lattimer and Prakash (2004)

Taking computational nuclear theoretical physics to the next century

- Computation is ubiquitous, even mean-field calculations are run on the world's largest computers
- Old paradigm: closed-source. Either collaborate or compete.
- Alternative: open-source - create a nuclear physics community
- (But obviously not all codes should be open-source)
- See http://github.com/awsteiner for C++ code for
    - models of dense hadronic/quark matter (Skyrme, RMF, NJL, etc.)
    - TOV solver (including rotation based on RNS)
    - nuclear structure in Hartree approximation from covariant mean-field model
    - MCMC, including that for neutron star observations
- Or code at the Astrophysics Source Code Library

Summary

- Neutron stars are an excellent laboratory for nuclear physics
- Future lies in careful combinations of experiment, theory, and observation