

Nuclear Structure and the Neutron Star Crust

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Hydrodynamics

- Initially, I thought I would start out with a bit on hydrodynamics...

- But the Angra dos Reis waves were too much for me



Today

- Back to Skyrme and RMF models
- Nuclear Symmetry Energy
- Isolated Neutron Star Crust
- Accreted Neutron Star Crust and X-ray Bursts
- Speed of Sound in Neutron Stars

Skyrme Interaction

[Skyrme \(1959\)](#), [Negele and Vautherin \(1972\)](#), [Stone and Reinhard \(2007\)](#)

- Best way to describe heavy nuclei
- Based on a zero-range two-body force
- Three-body force from density-dependent two-body interaction
- Final Hamiltonian is an energy density functional
- Updates from chiral EFT?
[Stoitsov et al. \(2010\)](#)
- Not likely appropriate to extrapolate this far beyond nuclear saturation

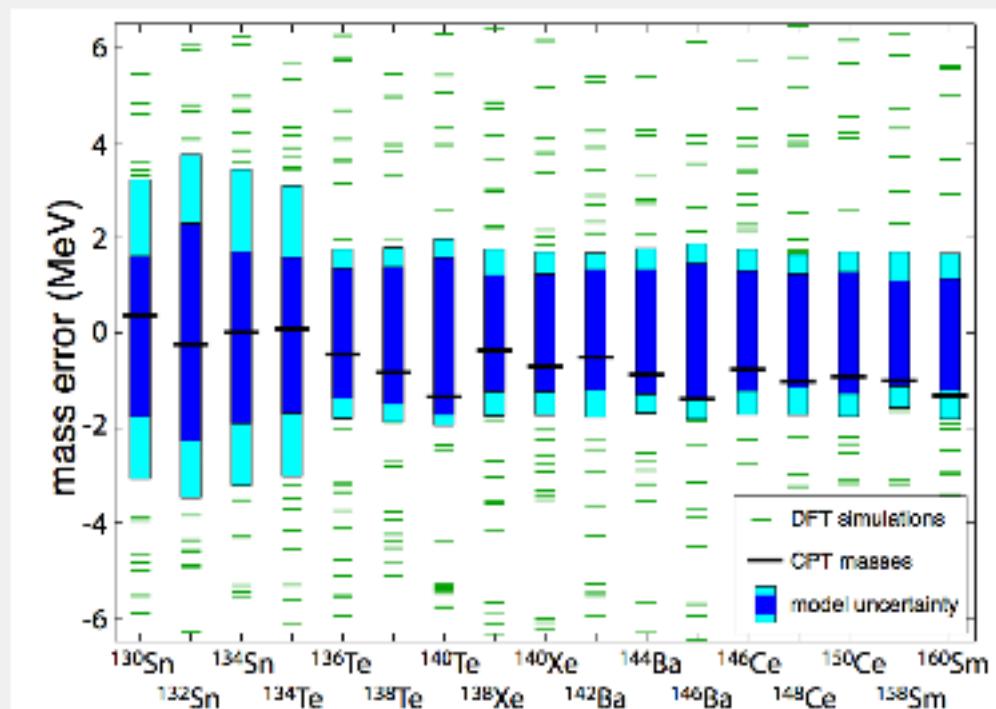


FIG. 2. (Color online) Estimated theoretical error bars for the masses of the even-even nuclei measured in Refs. [28–30], using the posterior for UNEDF1. Dark blue bands represent the 90% confidence bands obtained from the posterior; larger, light blue bands also account for model error; black bars show mass residuals.

[McDonnell et al. \(2015\)](#)

$$\mathcal{H} = \mathcal{H}(n_n, n_p, \nabla n_n, \nabla n_p, \dots)$$

Covariant mean-field theory

- Walecka model:

$$\begin{aligned}\mathcal{L} = & \bar{\psi}_i \left(i\partial - m_i + g_\sigma \sigma - g_\omega \omega - \frac{g_\rho}{2} \vec{\rho} \cdot \vec{\tau} \right) \psi_i \\ & + \frac{1}{2} (\partial^\mu \sigma) (\partial_\mu \sigma) - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{bM}{3} (g_\sigma \sigma)^3 - \frac{c}{4} (g_\sigma \sigma)^4 \\ & + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{1}{2} m_\rho^2 \rho^\mu \rho_\mu - \frac{1}{4} f_{\mu\nu} f^{\mu\nu} - \frac{1}{4} \vec{B}_{\mu\nu} \vec{B}^{\mu\nu}\end{aligned}$$

[Serot and Walecka \(1997\)](#)

- Mean-field approximation; Dirac equation for nucleons and meson field equations
- Relativistic, so in principle can go to higher densities
- Spin-orbit force appears more naturally
- No problem with $c_s^2 > c$
- In this form, limited control of symmetry energy
- Natural generalization to include hyperons

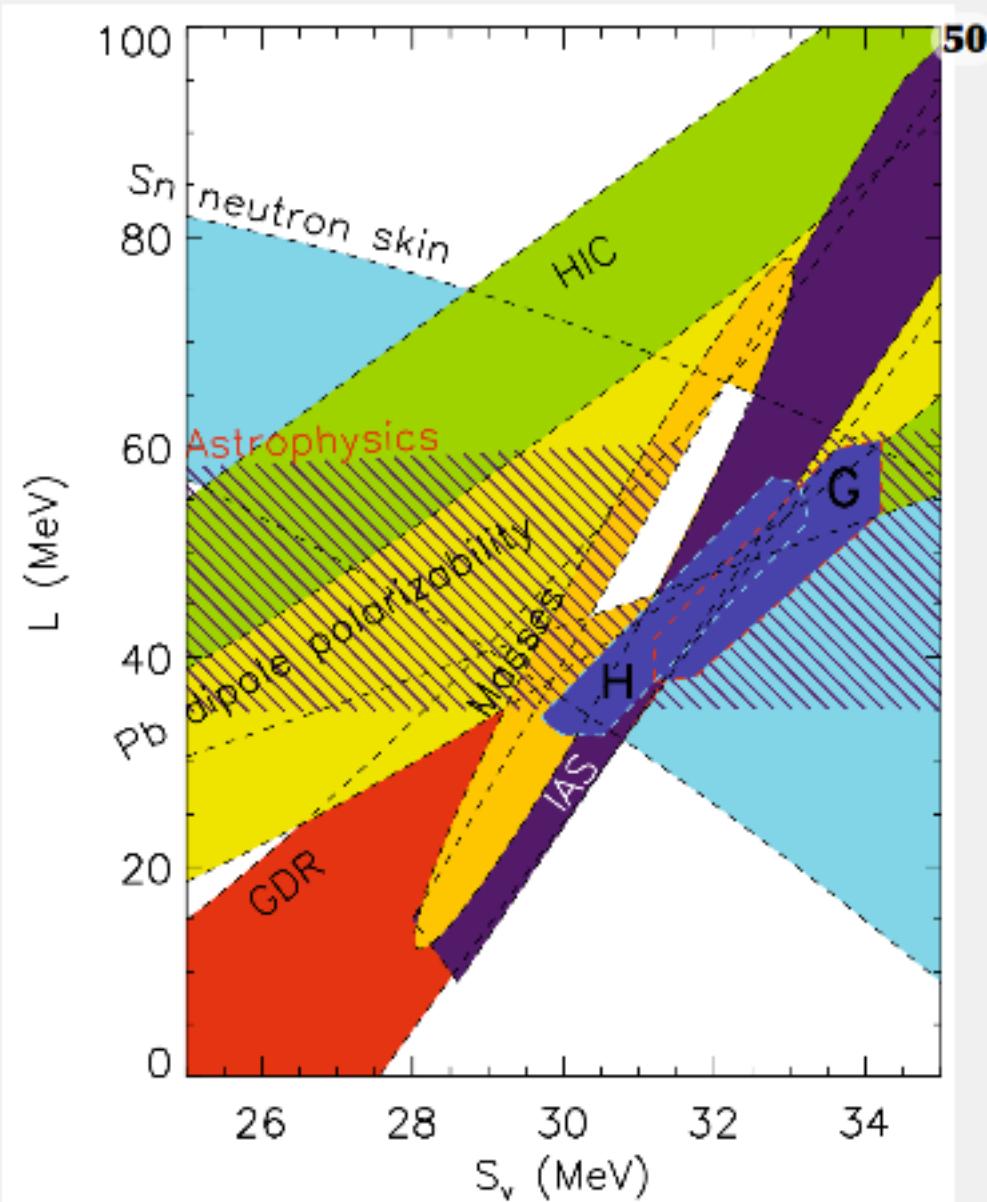
Density-dependent couplings

- Promote couplings g_σ , g_ω and g_ρ to functions of density
[TypeI and Wolter \(1999\)](#)
- More parameters and more control
- Not as much work on nuclear structure side
- Not as successful as modern energy density functionals,
e.g. Skyrme
- But not necessarily any farther from QCD

Symmetry Energy and its Derivative

- n_n, n_p are number densities of neutrons and protons
- $n_B \equiv n_n + n_p ; x \equiv n_p/n_B$
- $E/A = \frac{\epsilon(n_n, n_p)}{n_B}$
- Constraints from a large number of experiments

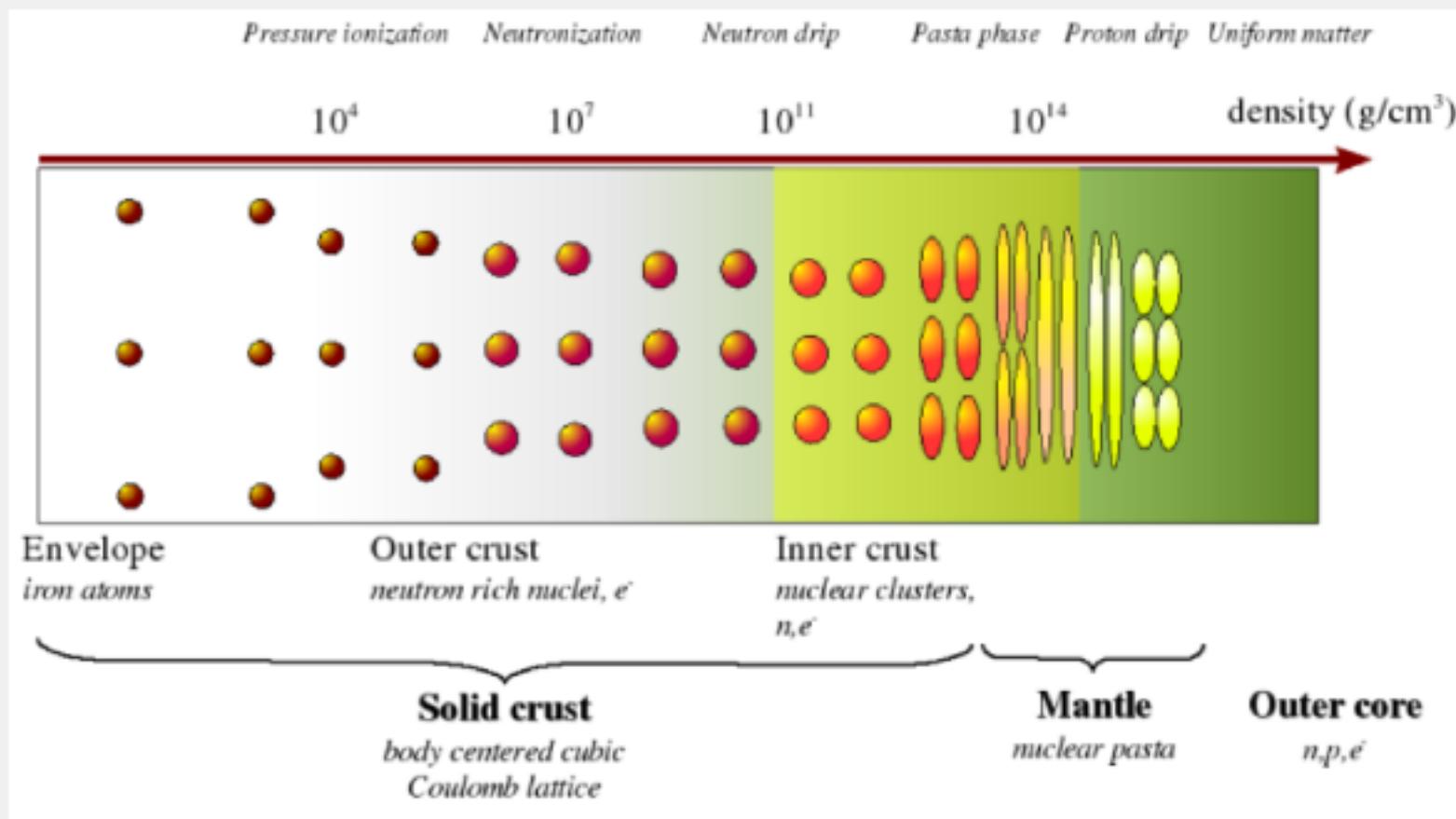
$$L \equiv 3n_0 S'(n_0)$$



[Lattimer and Steiner \(2014\)](#)

$$E/A = -B + \frac{K}{18n_0^2} (n_B - n_0)^2 + S(n_B)(1 - 2x)^2$$

The Neutron Star Crust



[Chamel \(2008\)](#)

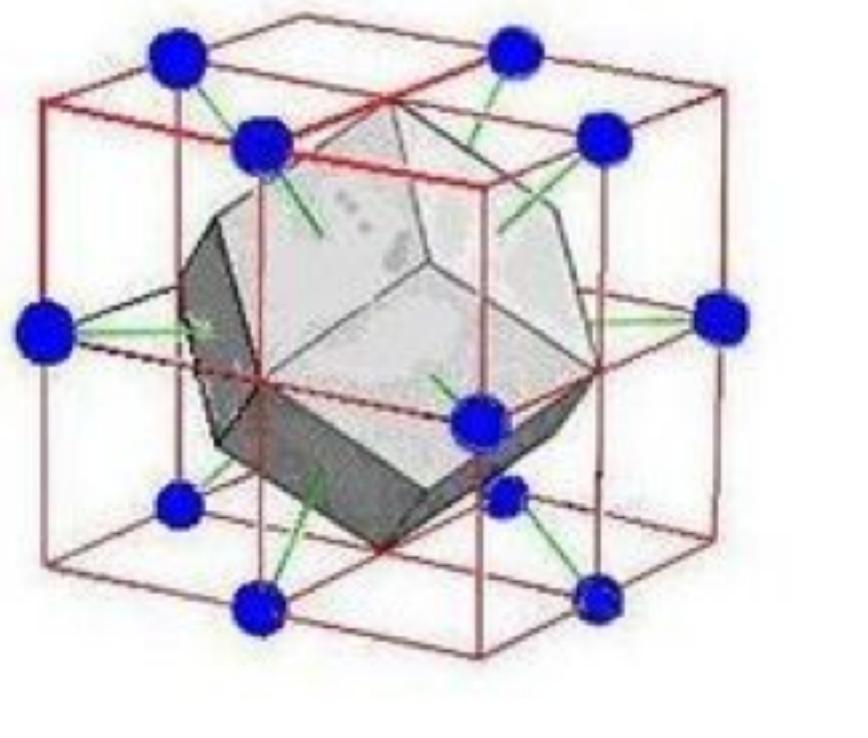
- Nuclei → nuclei + neutrons → core (n, p, and e fluid)

Remember:

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

- Coulomb modified at high density by lattice corrections

Wigner-Seitz Approximation



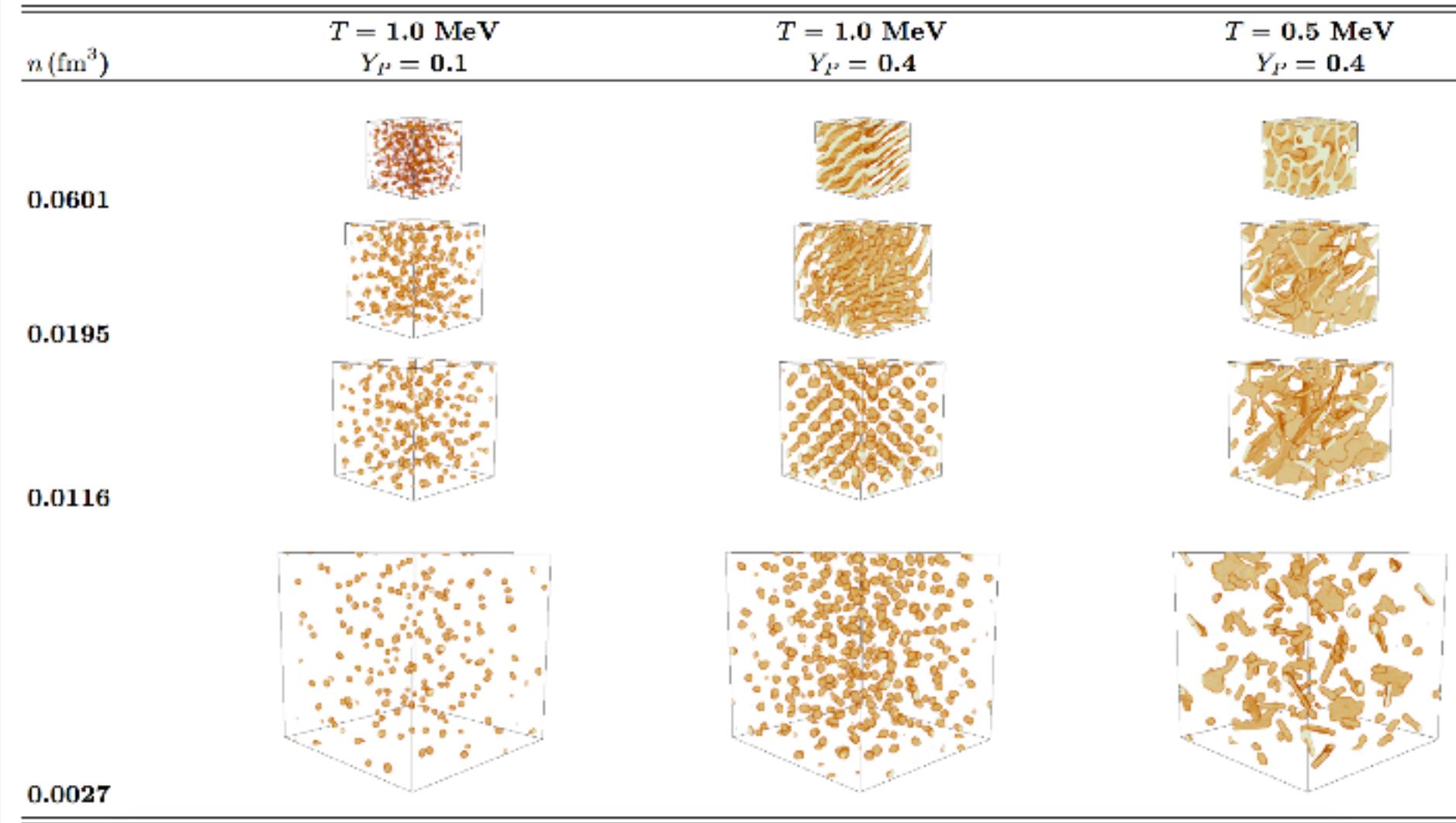
- Compute one nucleus in a unit cell and extrapolate
- Pasta represented by variable dimensionality
[Ravenhall et al. \(1983\)](#)
- Use Gauss' law to compute Coulomb energy

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

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

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.



[Caplan et al. \(2015\)](#)

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

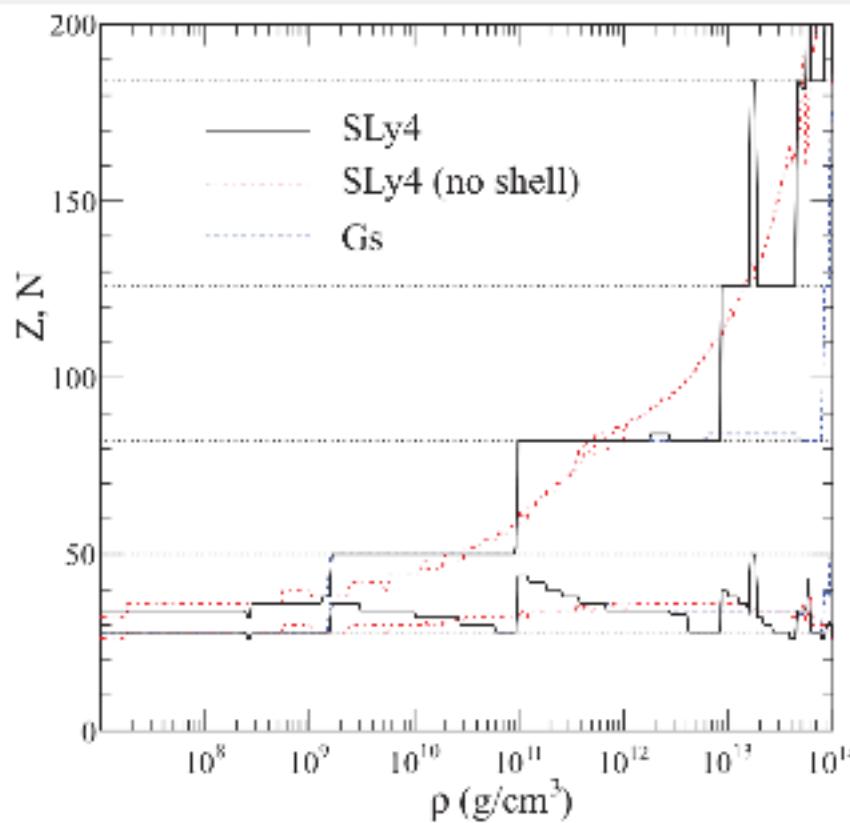


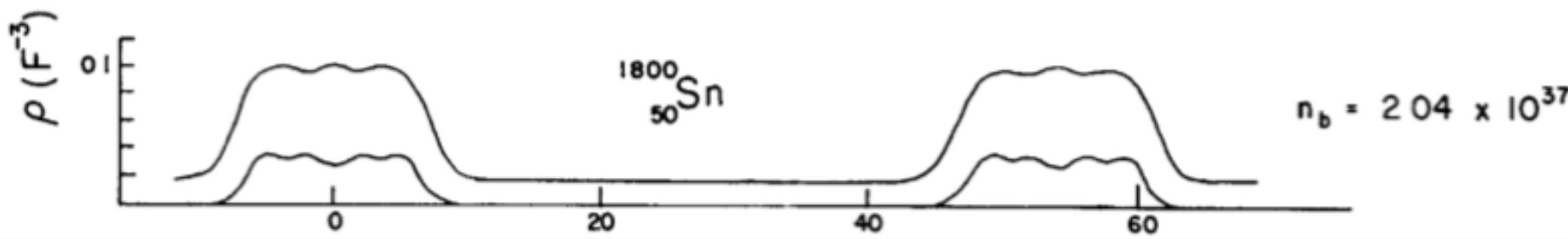
FIG. 1. (Color online) The composition of the equilibrium neutron star crust as a function of density. Deviations originate primarily because of the symmetry energy: models where the symmetry energy depends more steeply with density have larger Z and smaller N , i.e., a composition closer to the valley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

[Rüster et al. \(2006\)](#), this plot from
[Steiner \(2012\)](#)

Crust of an Isolated Neutron Star

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

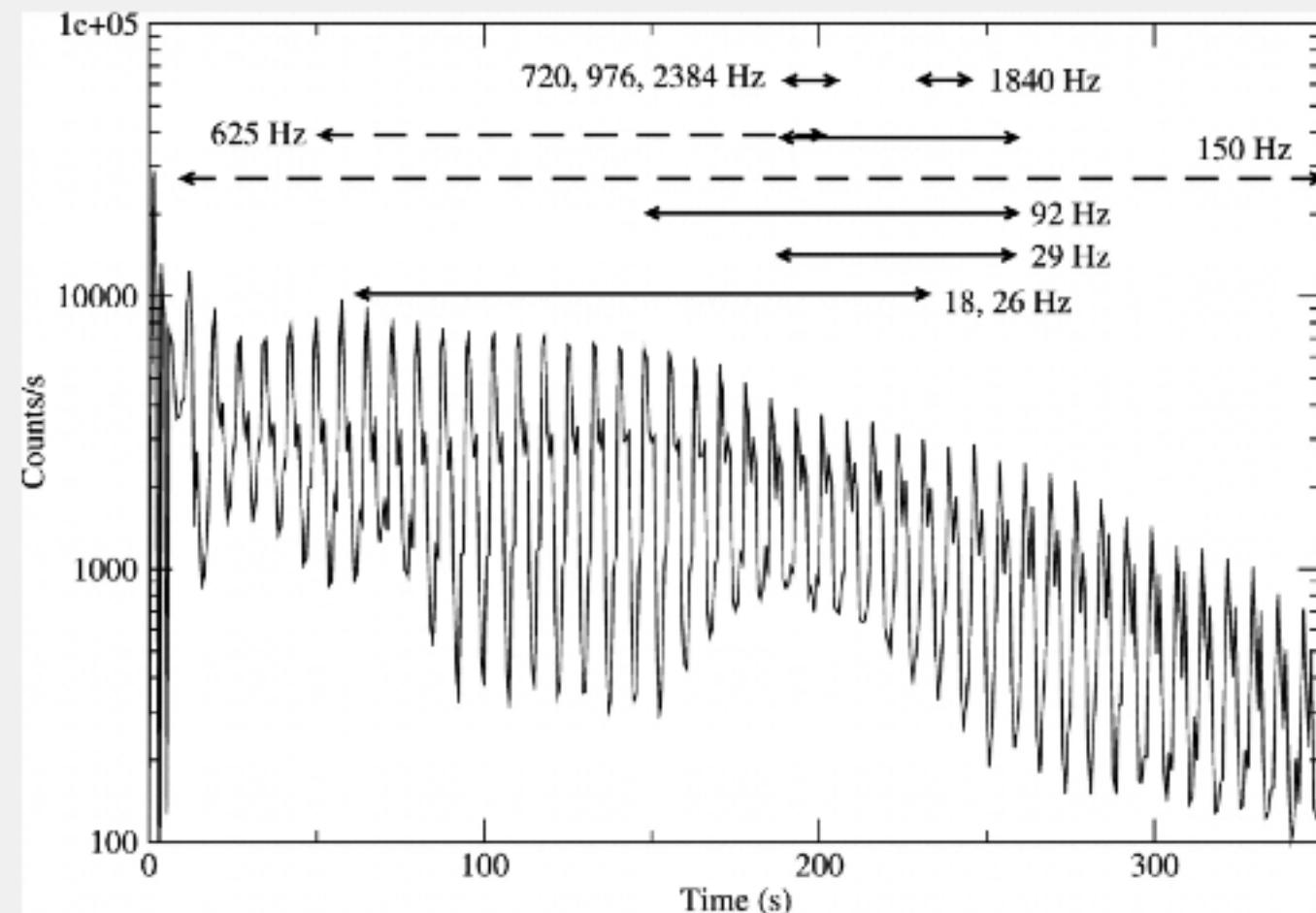
$$\mu_n = \mu_p + \mu_e$$



[Negele and Vautherin \(1973\)](#)

Magnetar flares

- 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

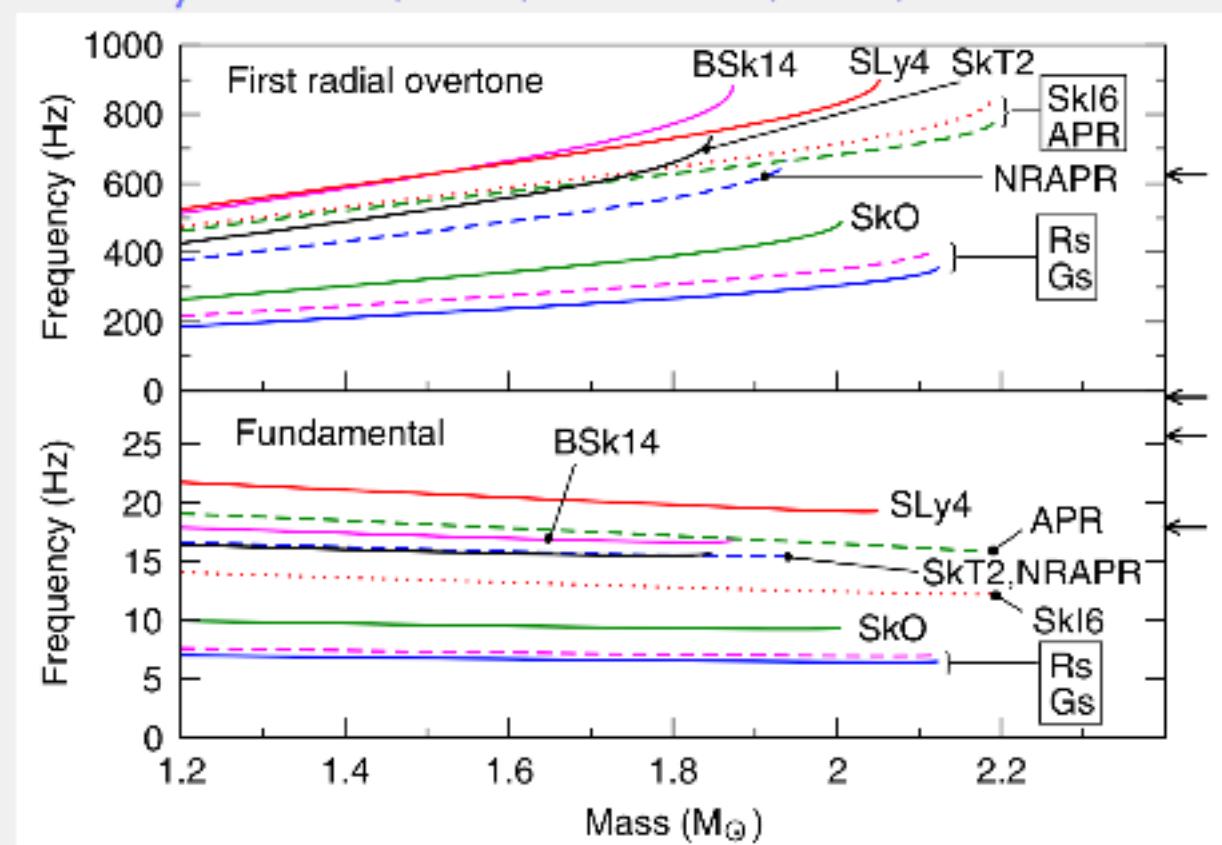


Shear Modulus

The shear modulus is

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

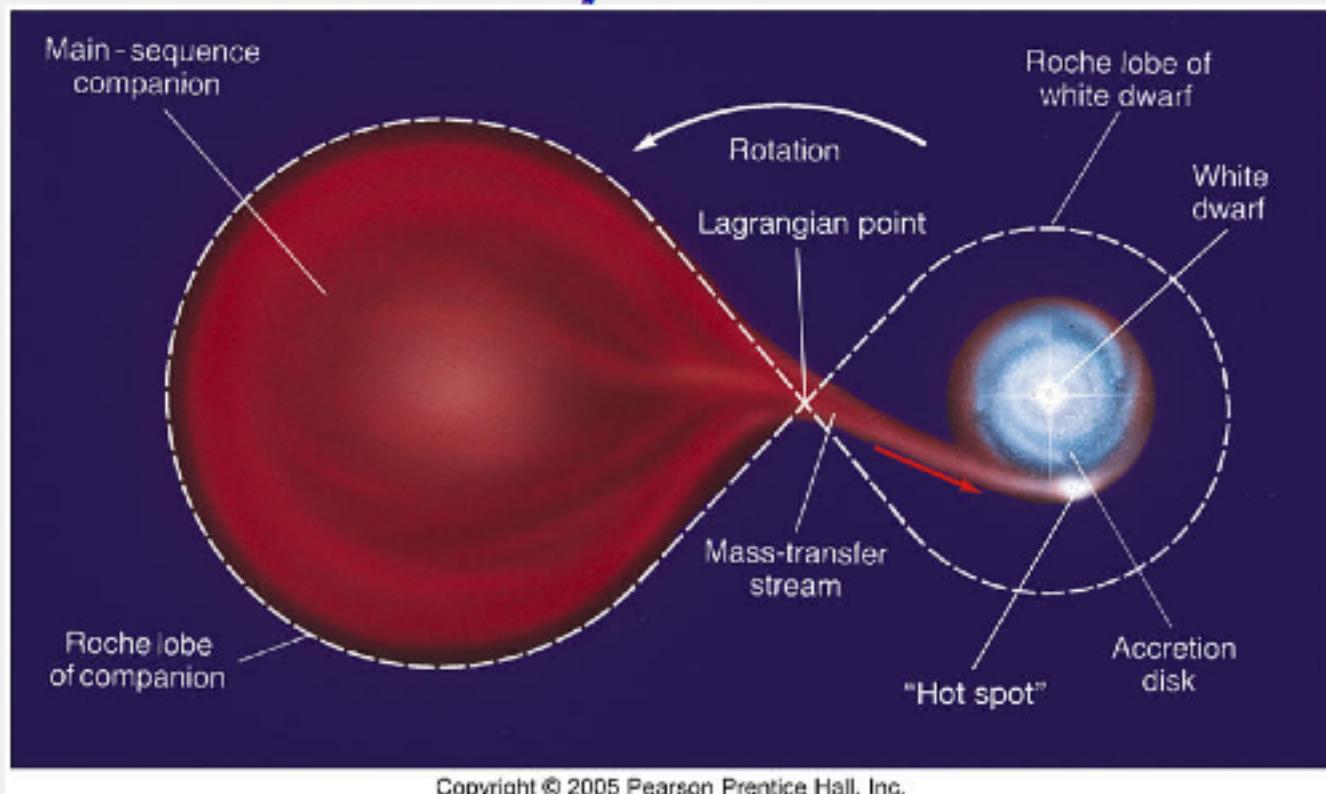
Stromayer et al. (1991) and Piro (2005)



- Skyrme models for the crust
- Found that larger values of L had larger shear speeds

Steiner and Watts (2009)

X-ray Bursts



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

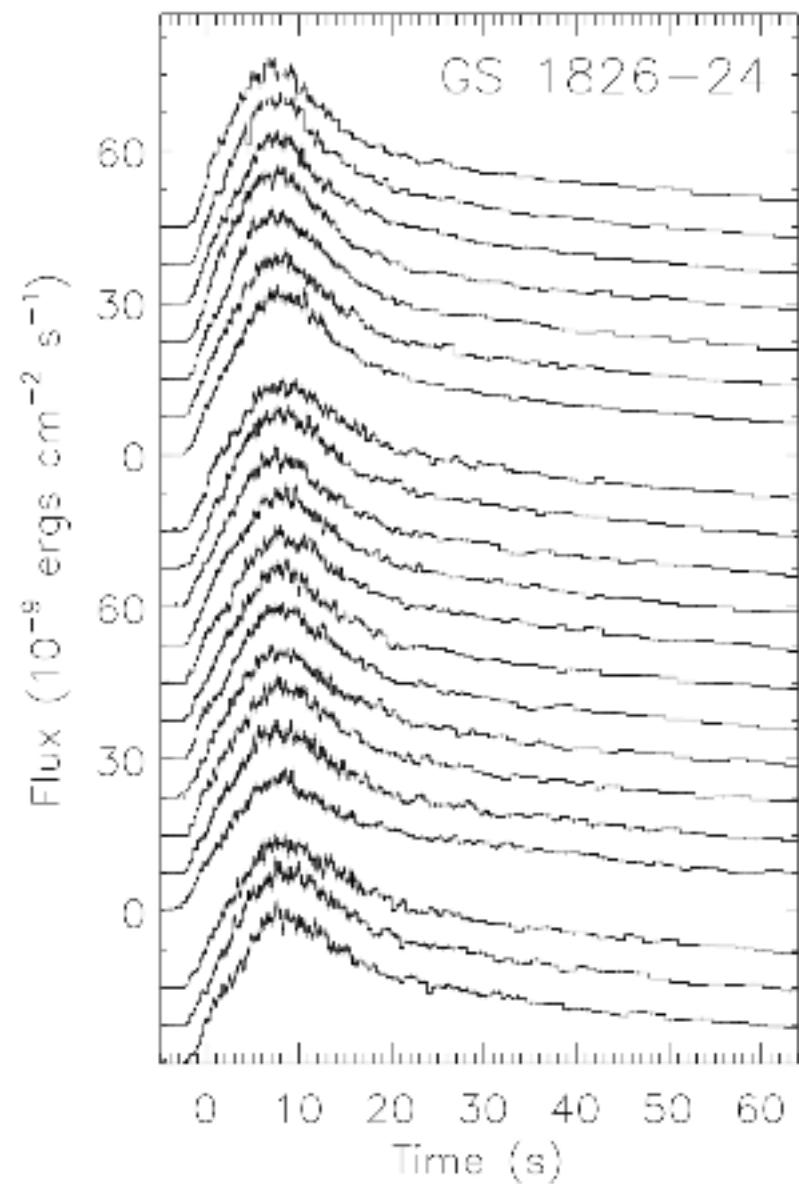
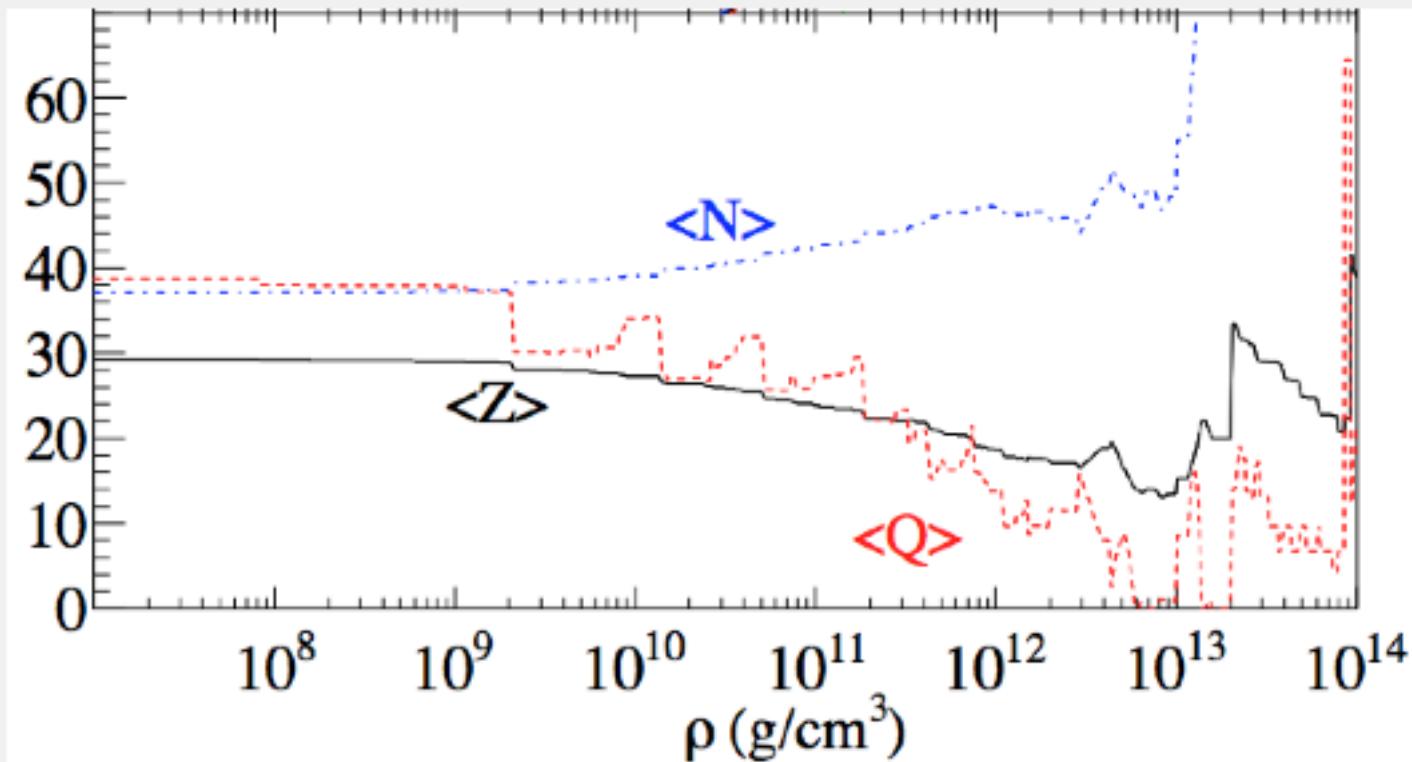


FIG. 1.— Profiles of 20 X-ray bursts from GS 1826–24 observed by *RXTE* between 1997–2002, plotted with varying vertical offsets for clarity. The upper group of 7 bursts were observed in 1997–98, the middle group of 10 bursts in 2000, while the lower group of 3 were observed in 2002. The bursts from 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

Crust of an Accreted Neutron Star



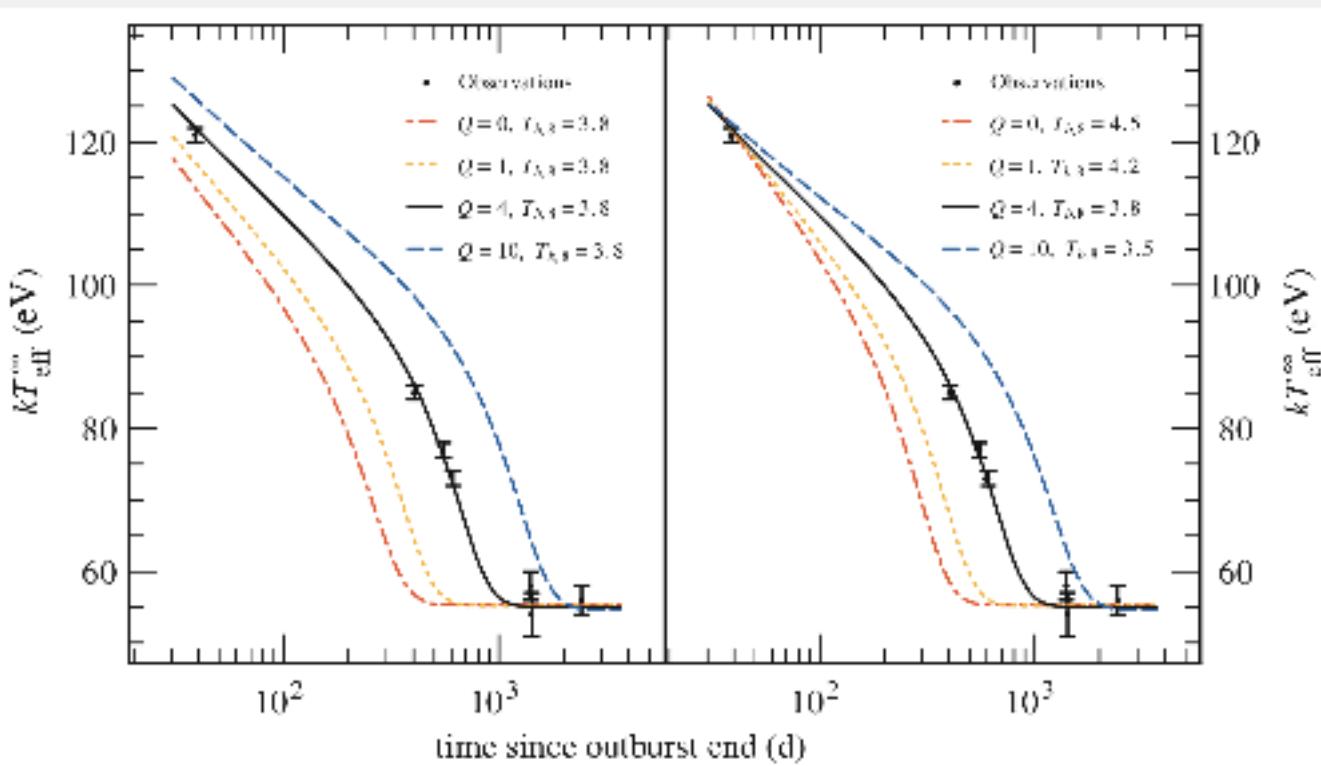
[Steiner \(2012\)](#)

- 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

How do we observe the crust?

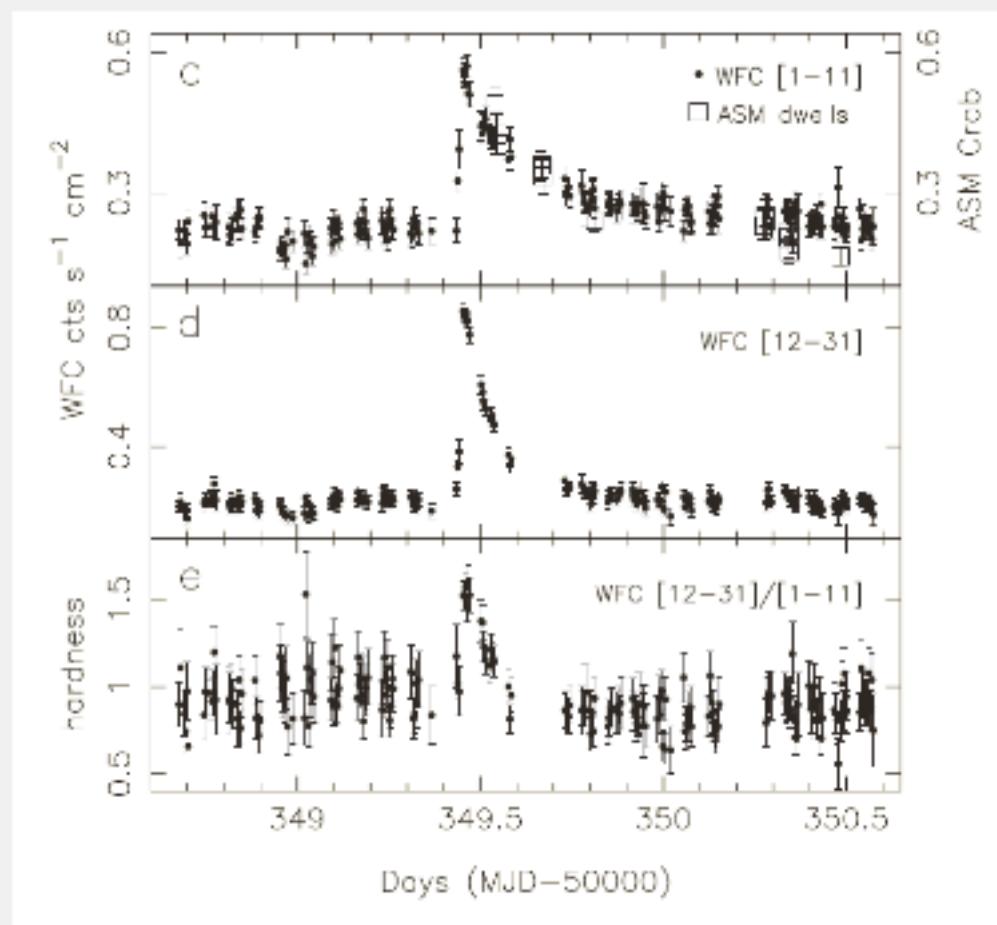


Brown and Cumming (2009)

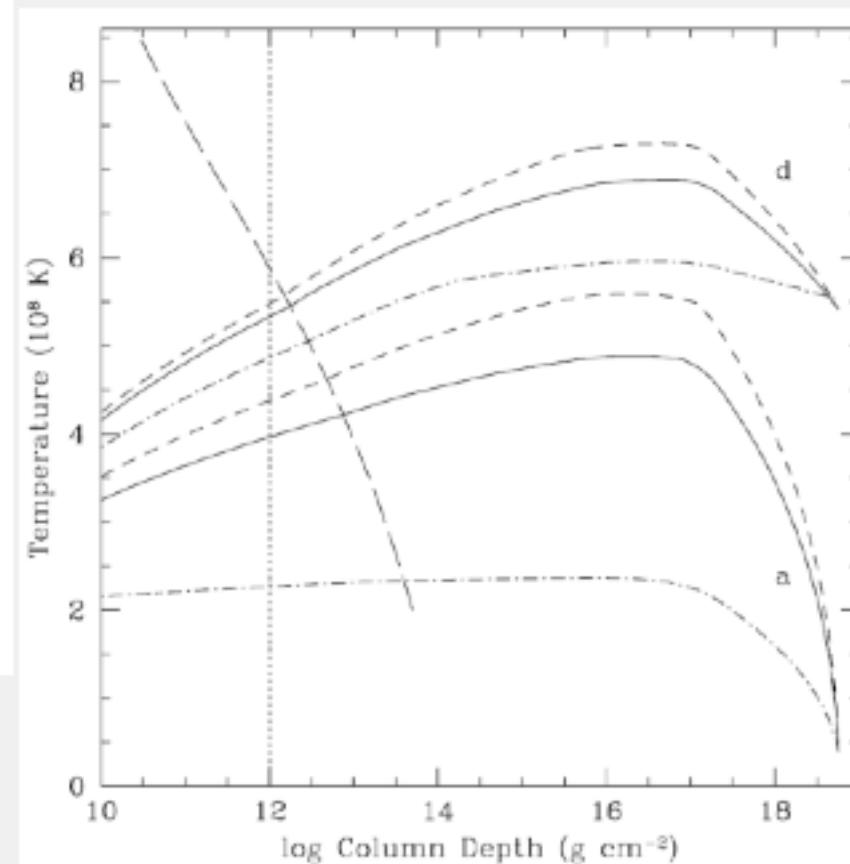
- Accretion generates 200 MeV/nucleon and heats up the crust
- When accretion shuts off, the crust cools down
- Cooling wave starts at the outer layers and proceeds inwards
- Found that the crust must be relatively pure

X-ray Superbursts

- Larger energies and longer times
- What fuels superbursts? Unstable carbon ignition.
- Crust temperature smaller than critical temperature for unstable fusion.



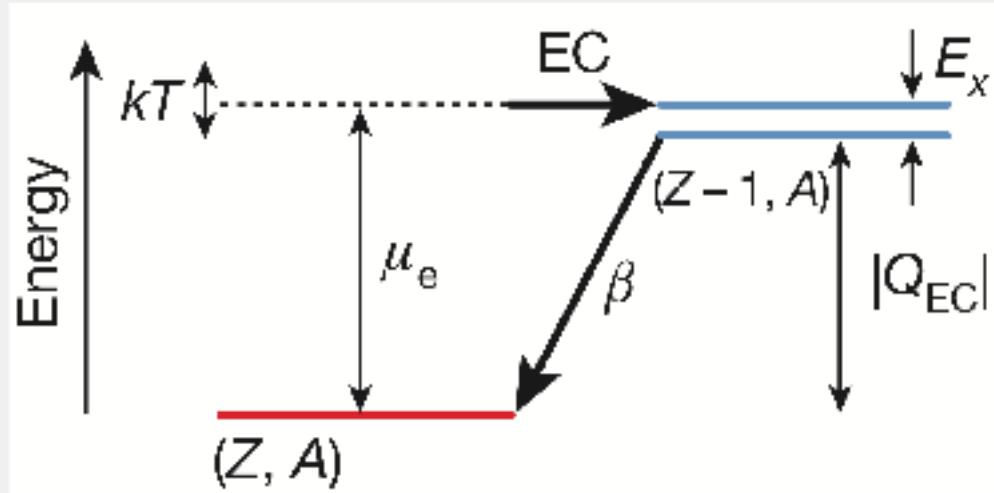
Superburst in KS 1731-260



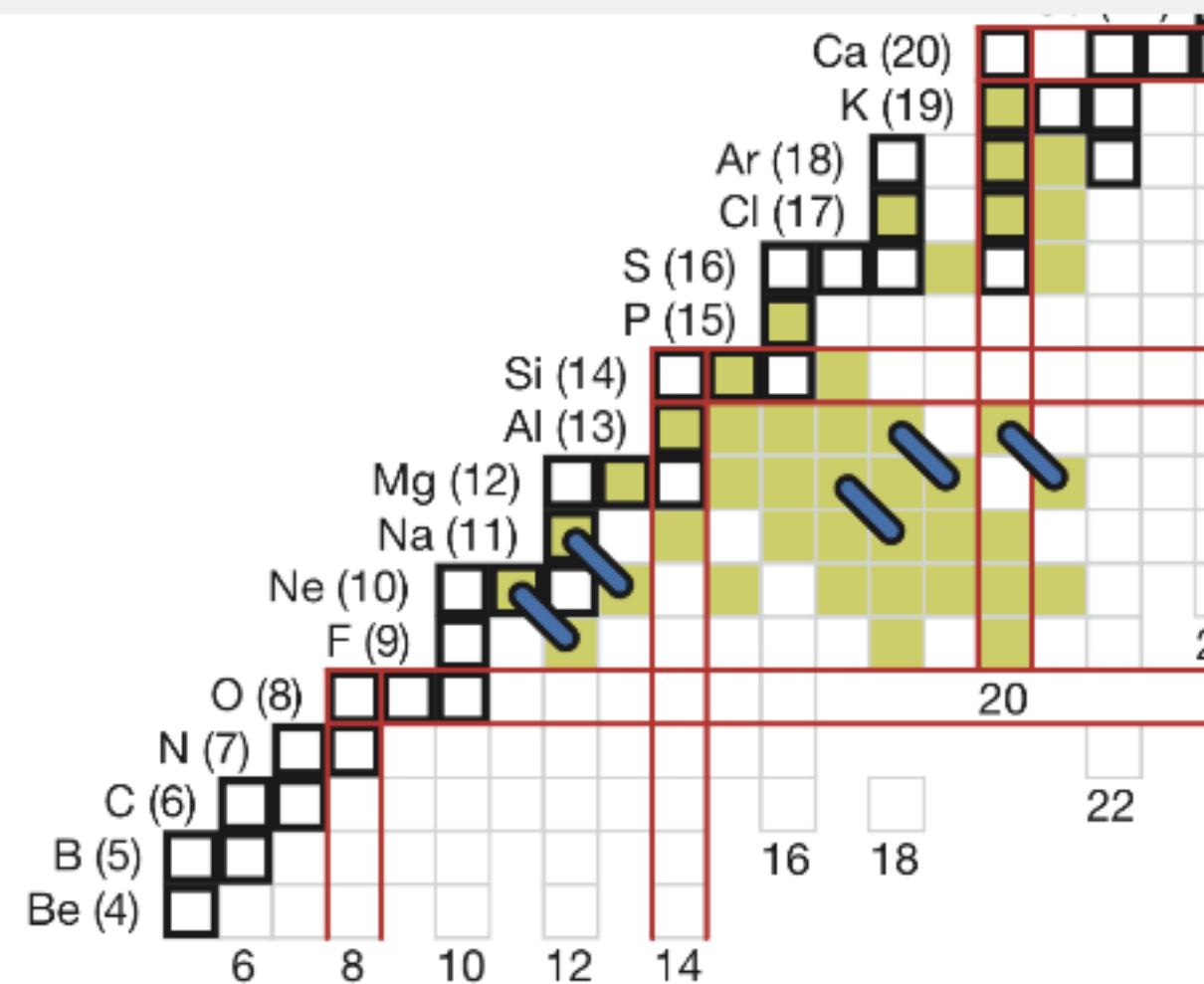
Cumming, et al. (2006)

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)



Speed of sound

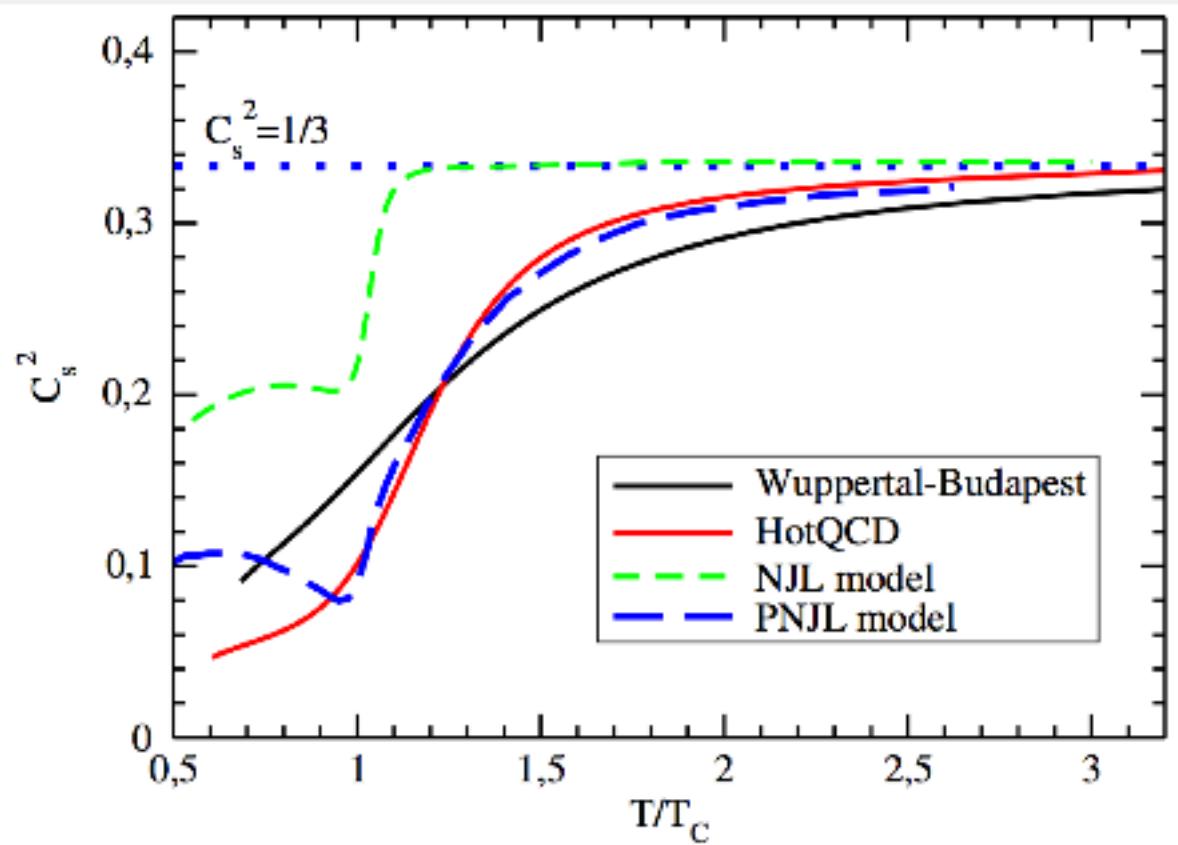
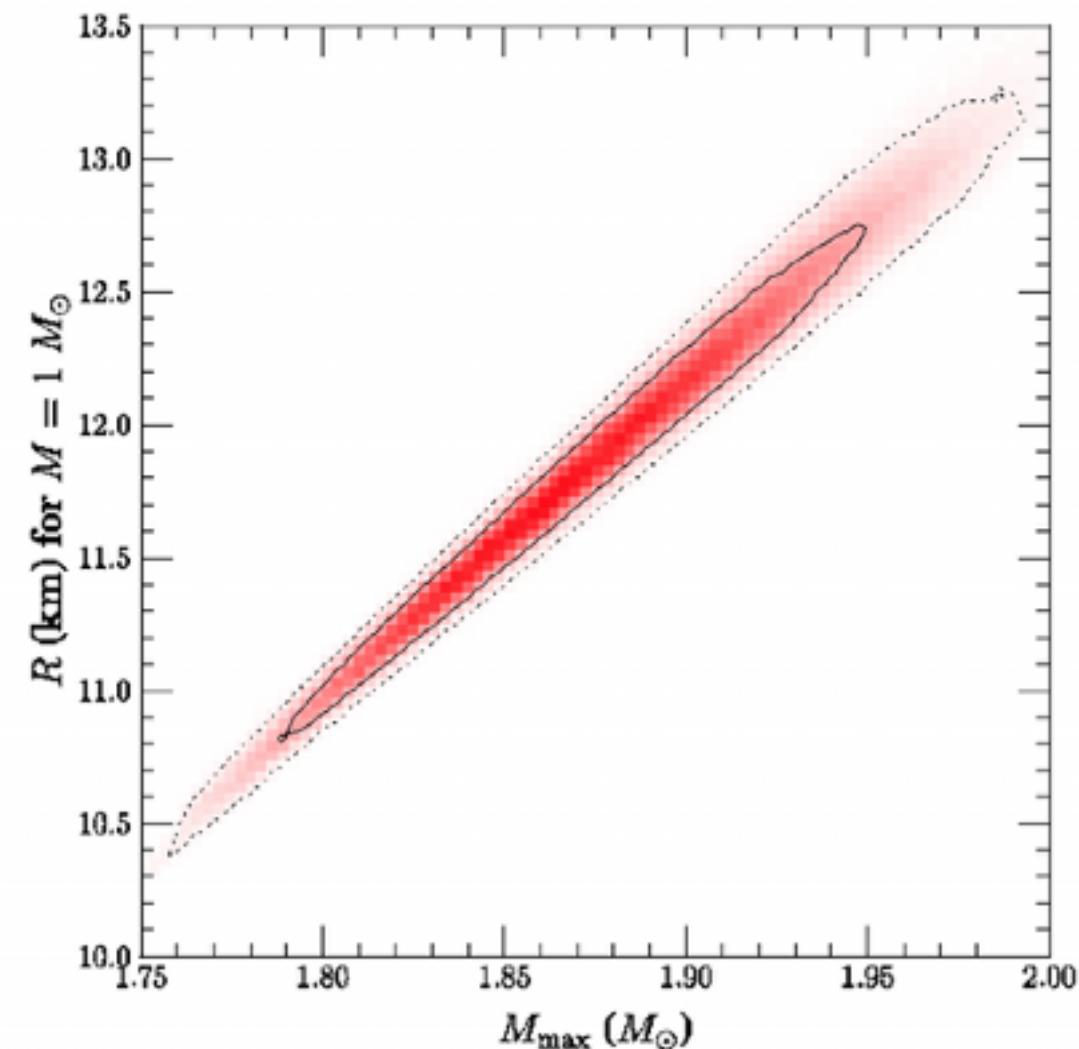
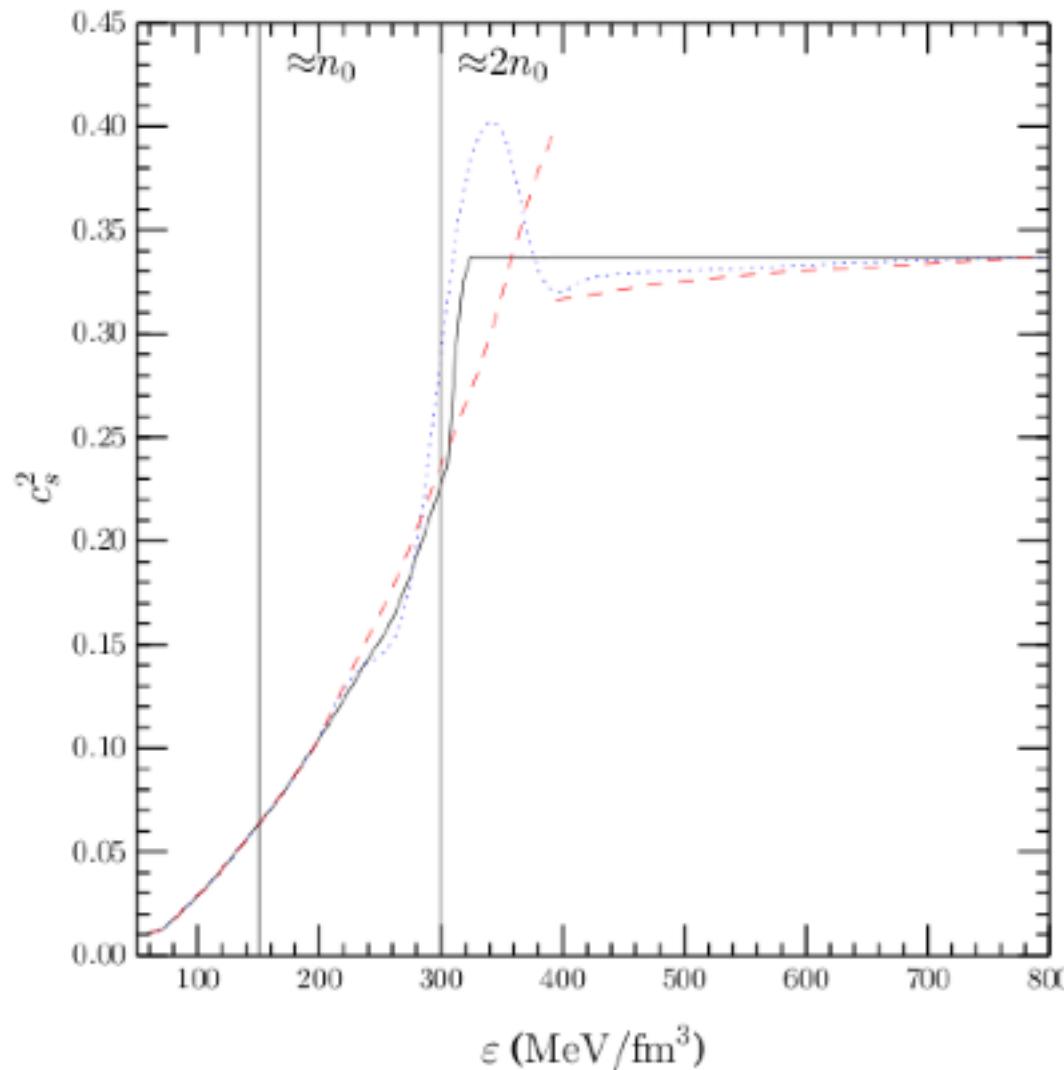


FIG. 4 (color online). Speed of sound squared as a function of T/T_C . The red solid curve corresponds to the HotQCD data, the black solid one to the Wuppertal-Budapest data, the short-dashed one to the NJL model, and the long-dashed one to the Polyakov loop extended NJL model fit to the HotQCD lattice data.

Plumari et al. (2011)

- The speed of sound at zero density and finite temperature: $c_s^2 \rightarrow 1/3$ as $T \rightarrow \infty$
- What happens at high density and zero temperature?
- $c_s^2 \approx 1/12$ in neutron matter at the saturation density
- Is $c_s^2 > 1/3$ anywhere in the universe?

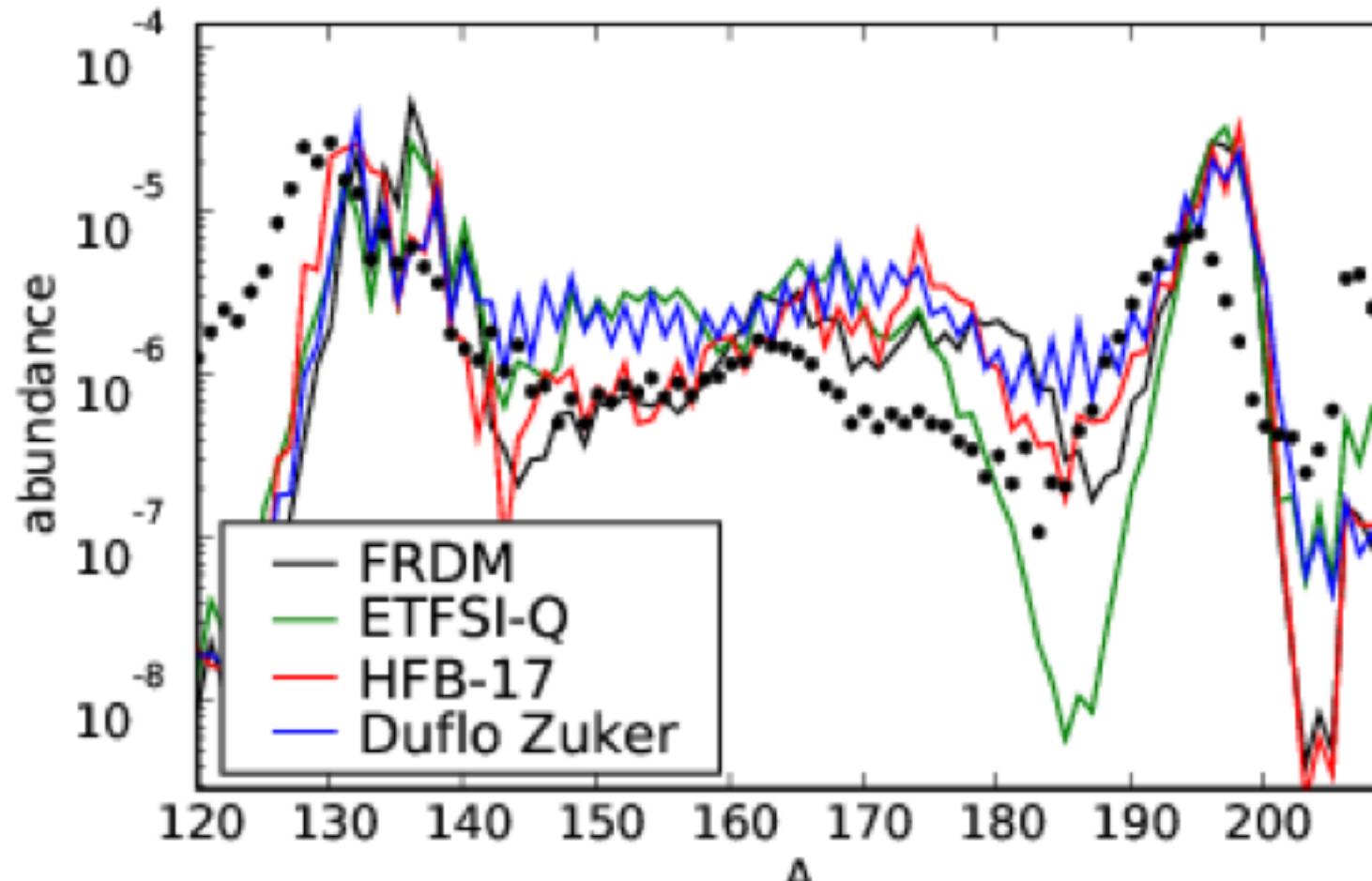
Assume $c_s^2 < 1/3$ everywhere



Bedaque and Steiner (2015)

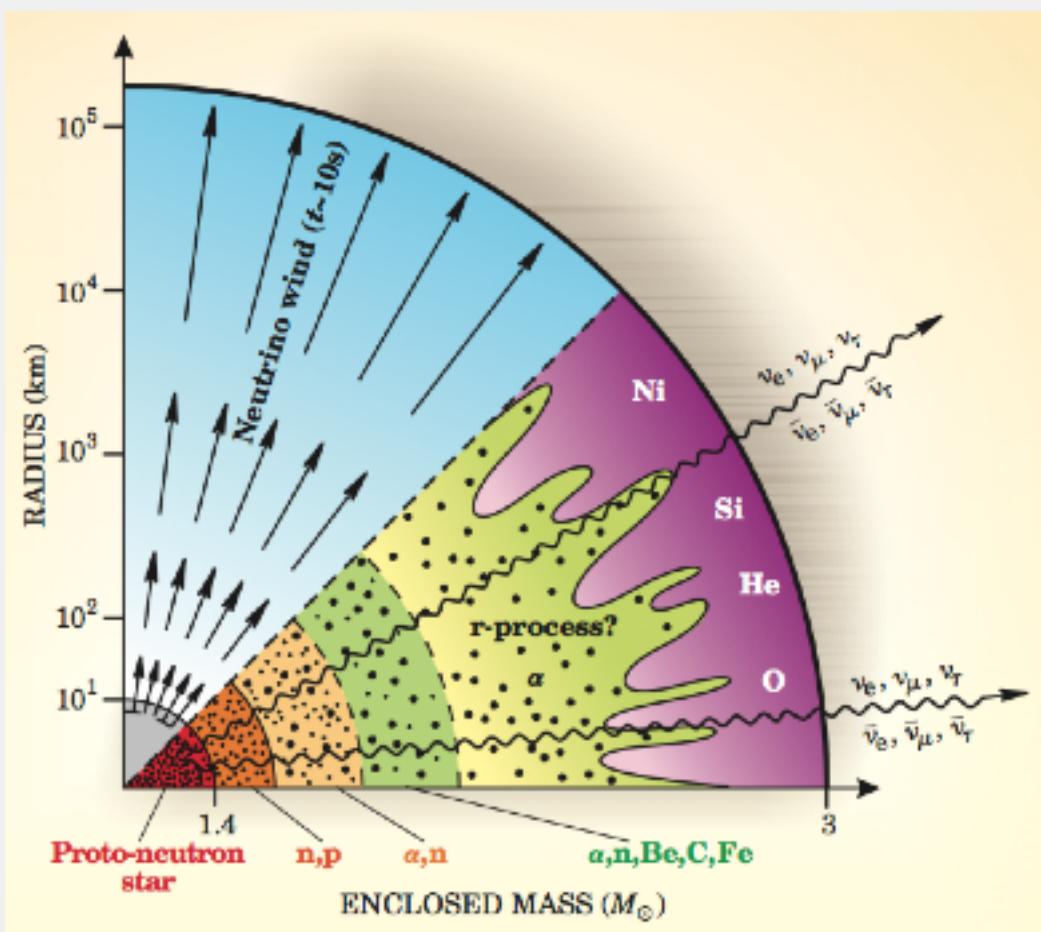
- Make the speed of sound as large as possible (black curve)
- Vary nuclear physics at low densities within limits allowed by the structure of nuclei
- Failure! c_s^2 must be non-trivial at high densities. Why?

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



- 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

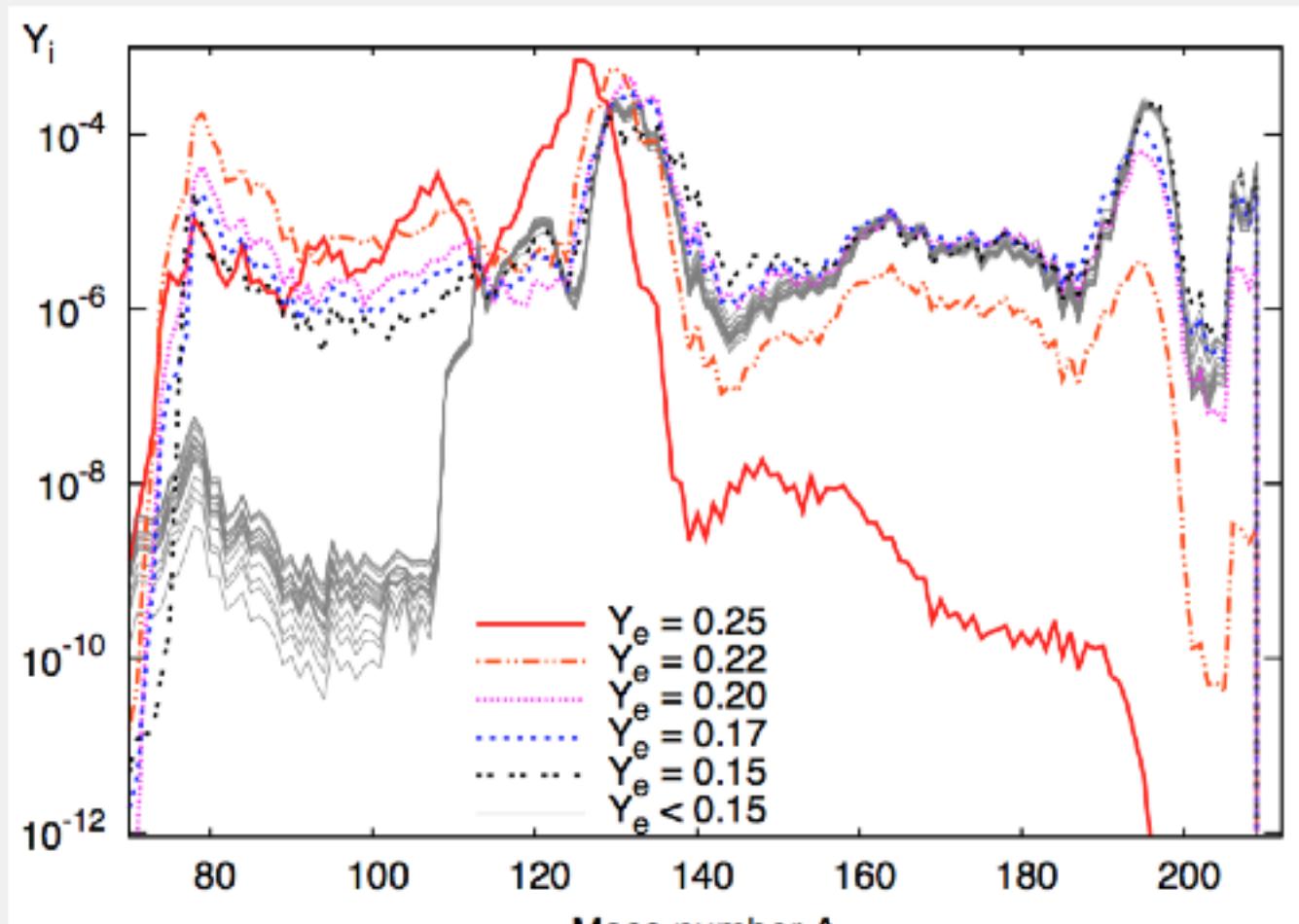
Cowan and Thielemann (2004)

- Caveats: fall back, rotation, magnetic fields, multi-D effects, jets
- Neutrino opacity depends on the nuclear interaction

Roberts, Reddy, and Shen (2012)

R-process Nucleosynthesis from Neutron Star Mergers ⁶⁶

- 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, Janka, and Marek, 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 \(2013\)](#)

Summary

- Nuclei and the nucleon-nucleon interaction
- Exotic matter and Gibbs phase transitions
- Equation of state and masses and radii
Neutron star radii are likely between 10-13 km
- Cooling of isolated neutron stars
May imply neutron triplet superfluidity in the core
- R-mode oscillations and pulsar glitches
- Neutron star crust and pasta
- Shear modulus
May be connected to magnetar QPOs
- Problems with superbursts
Urca shell cooling
- Sound speed in neutron stars
Neutron stars have the fastest sound in the universe
- R-process nucleosynthesis
Neutron star mergers may play an important role