



X-ray bursts, Neutron Stars, Crusts, and the EOS of Dense Matter

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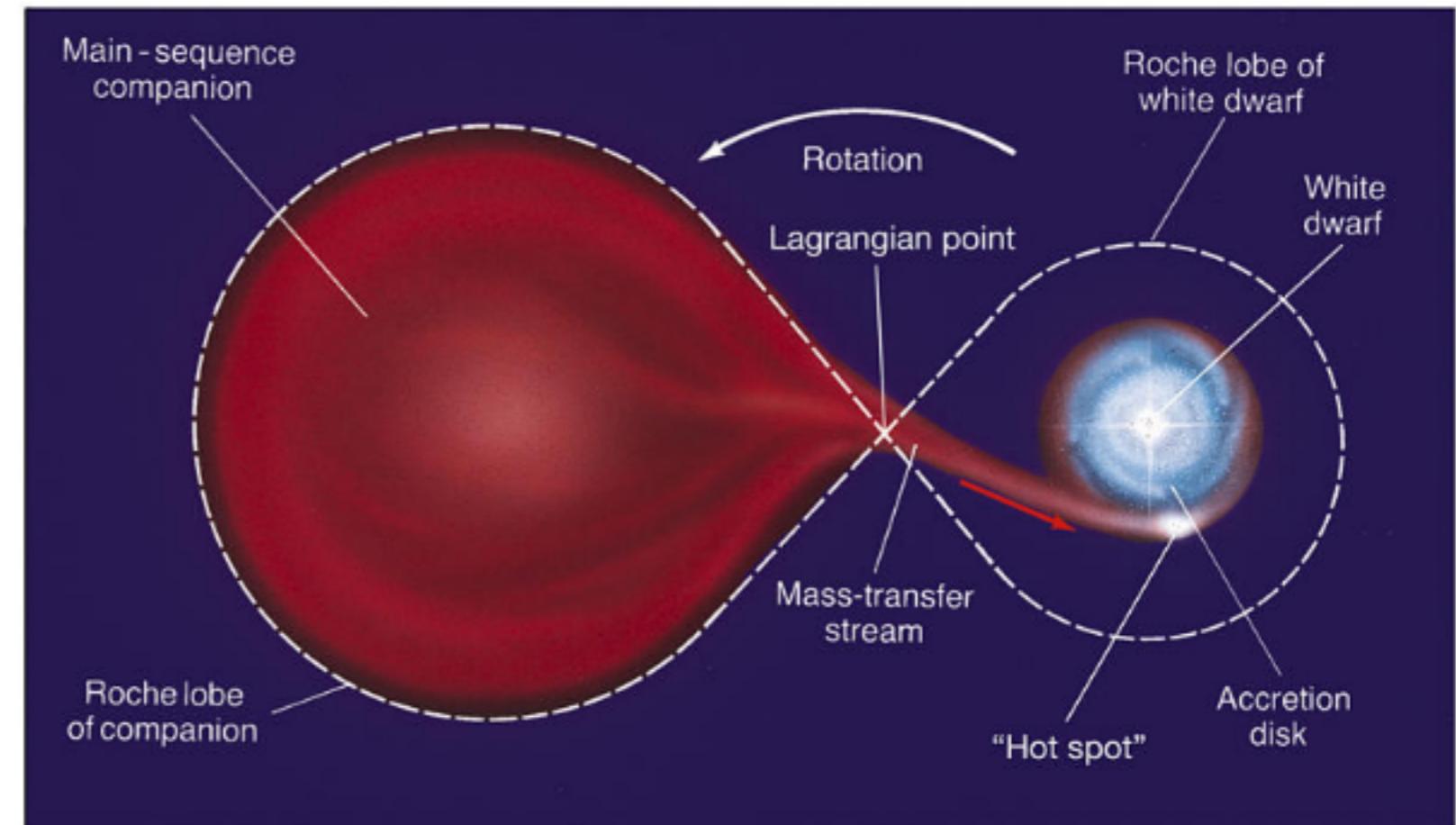
Outline

- Isolated and Accreting Neutron Stars
- X-ray Bursts
- The Crust
- Superbursts
- The EOS of Dense Matter
- PRE X-ray Bursts
- Neutron Star Masses and Radii

Neutron Star Zoology



RXJ 1856-3754



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- Thermal evolution
- Potentially large magnetic fields: i.e. Magnetars
- Some are radio and X-ray pulsars (e.g. AXPs)
- Binary pulsars and gravitational waves
- Heated by accretion, often intermittent
- Likely small magnetic fields, Burying B
- X-ray bursts: Unstable burning of light elements
- Burst oscillations
- LMXBs: progenitors of millisecond pulsars
- HMXBs, Type II X-ray bursts

X-ray Bursts

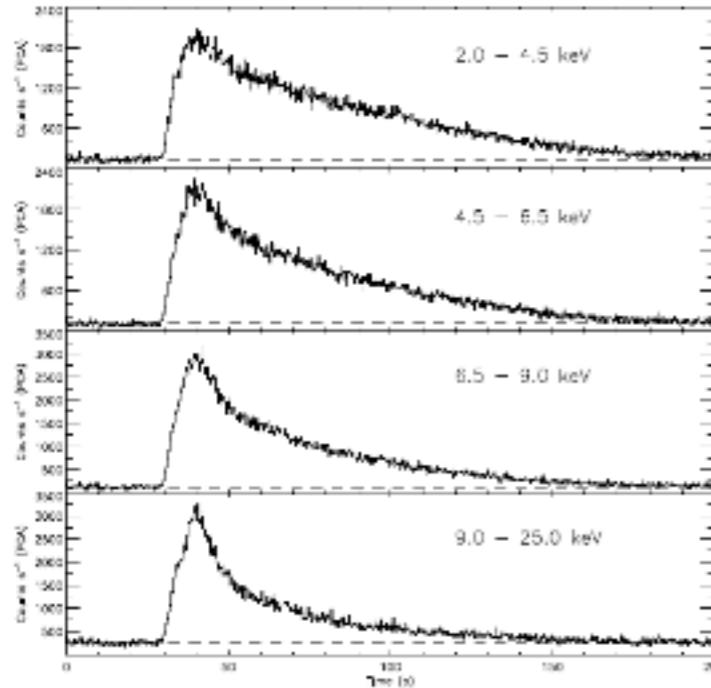


Fig. 3.3. An X-ray burst from GS 1826-238 seen with the RXTE/PCA. The burst is shown in four different energy bands. The long duration is indicative of the delayed energy release from the rapid proton (rp) process. The dashed line marks the preburst flux level (see also Kong et al. 2000).

X-ray burst

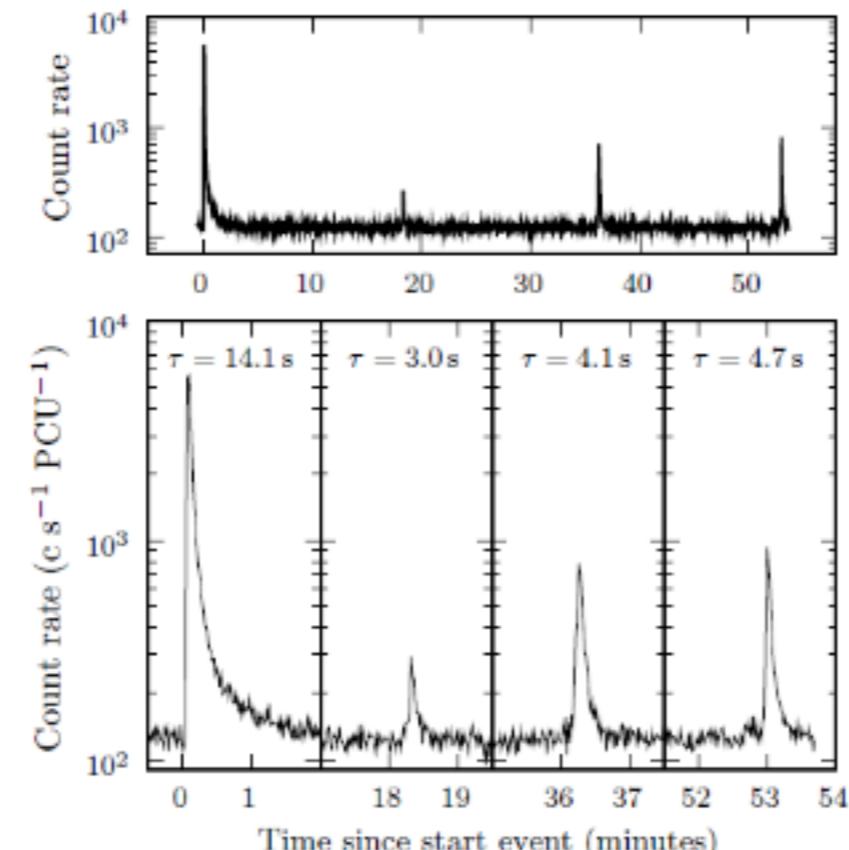


FIG. 14.— Quadruple burst from 4U 1636-53 as observed with the RXTE PCA on MJD 52286. Light curve at 2 s time resolution (top) and zoomed in on each burst at 1 s time resolution (bottom). For each burst we indicate the (longest) exponential decay time τ .

Quadruple bursts

- rp-process nucleosynthesis drives the long tail
- Reaction rates, nuclear masses
- Radiation transport, hydrodynamics, GR effects
- Magnetic fields, rotation

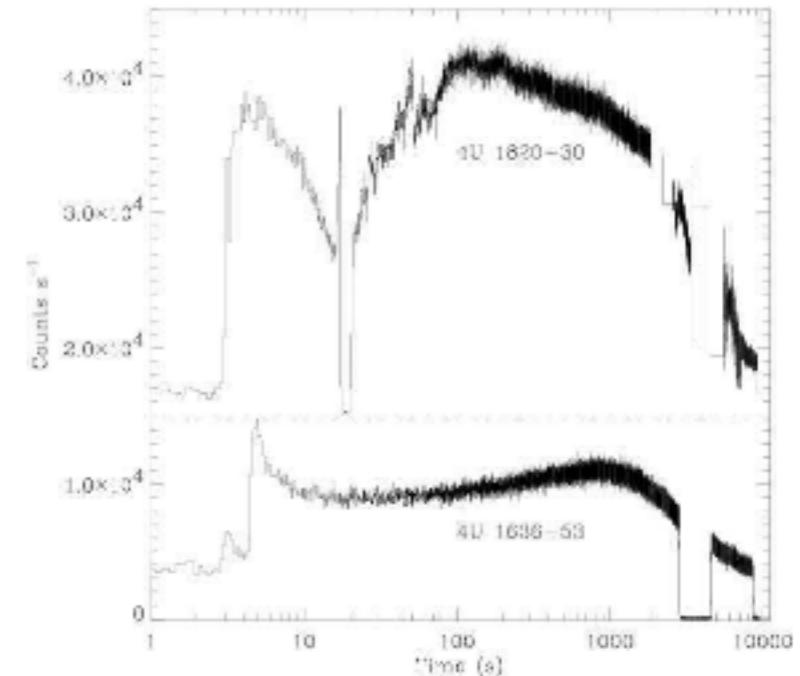


Fig. 3.15. Two superbursts observed with the RXTE/PCA. Shown are the 2 - 30 keV count rate histories observed in the PCA. Note the shorter precursor events prior to the superbursts. The event from 4U 1820-30 has been displaced vertically for clarity. The horizontal dashed line shows the zero level for this event. The time axis is logarithmic (after Strohmayer & Brown 2002; Strohmayer & Markwardt 2002).

Superburst

Accretion Rates and Unstable Burning

TABLE 1. Nuclear Burning Regimes at High Accretion Rates

Range in Local Accretion Rate	Type of Nuclear Burning
$\dot{m} > \dot{m}_{st}$ $\dot{M} > 2.6 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$	Stable hydrogen/helium burning in a mixed H/He environment [Equations (24) and (26)]
$\dot{m}_{st} > \dot{m} > \dot{m}_{c1}$ $2.6 \times 10^{-8} > \dot{M}/(M_{\odot} \text{ yr}^{-1}) > 10^{-9}$ (FHM Case 1)	Thermally unstable helium ignition in a mixed H/He environment [Equation (35)]
$\dot{m}_{c1} > \dot{m} > \dot{m}_{c2}$ $10^{-9} > \dot{M}/(M_{\odot} \text{ yr}^{-1}) > 2 \times 10^{-10}$ (FHM Case 2)	Thermally unstable pure He ignition after complete hydrogen burning [Equation (36)]
$\dot{m}_{c2} > \dot{m}$ $2 \times 10^{-10} M_{\odot} \text{ yr}^{-1} > \dot{M}$ (FHM Case 3)	Thermally unstable hydrogen burning triggers combined flash

Bildsten, 1998

• Ignition condition: $\frac{\partial \varepsilon_{\text{Heat}}}{\partial T} \geq \frac{\partial \varepsilon_{\text{Cool}}}{\partial T}$

• Parameter alpha: ratio of recurrence time to persistent luminosity

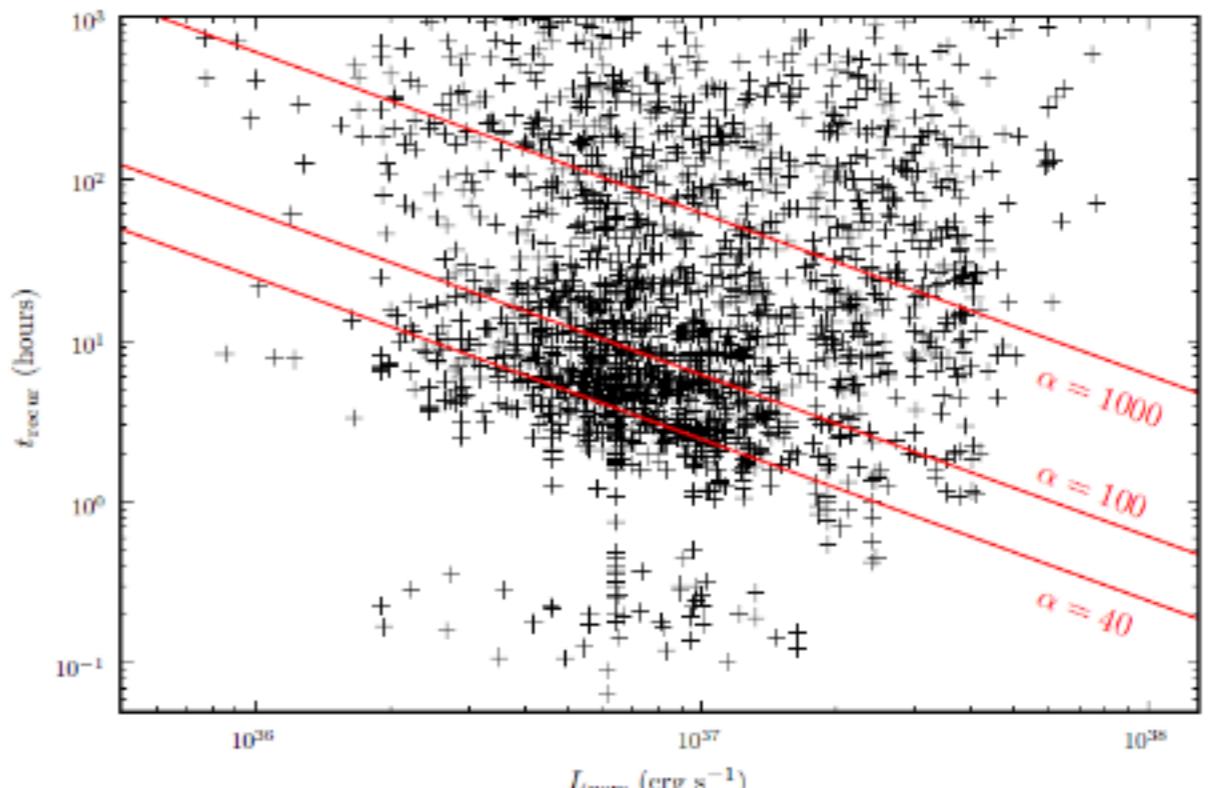


FIG. 5.— Observed recurrence time t_{recur} as a function of the persistent luminosity L_{pers} for 2415 bursts from 44 LMXBs. Due to the presence of data gaps, values of t_{recur} exceeding one hour are upper limits to the real recurrence time. We show bursts with $t_{\text{recur}} < 10^3$ hour. The lines represent constant values of the average α -parameter as indicated (see text). Note that the crosses indicate only the positions of the data points, not the uncertainties. The shortest recurrence time is 3.8 minutes.

Keek et al., 2010

Superbursts

- Observed in several sources
- Sensitive to the properties of the crust and possibly a probe of the core
- Many X-ray burst models do not generate sufficient Carbon
- Require sufficiently high temperatures for unstable Carbon ignition
- Cooper et al. (2009) suggested a resonance in $^{12}\text{C} + ^{12}\text{C}$ may solve this problem

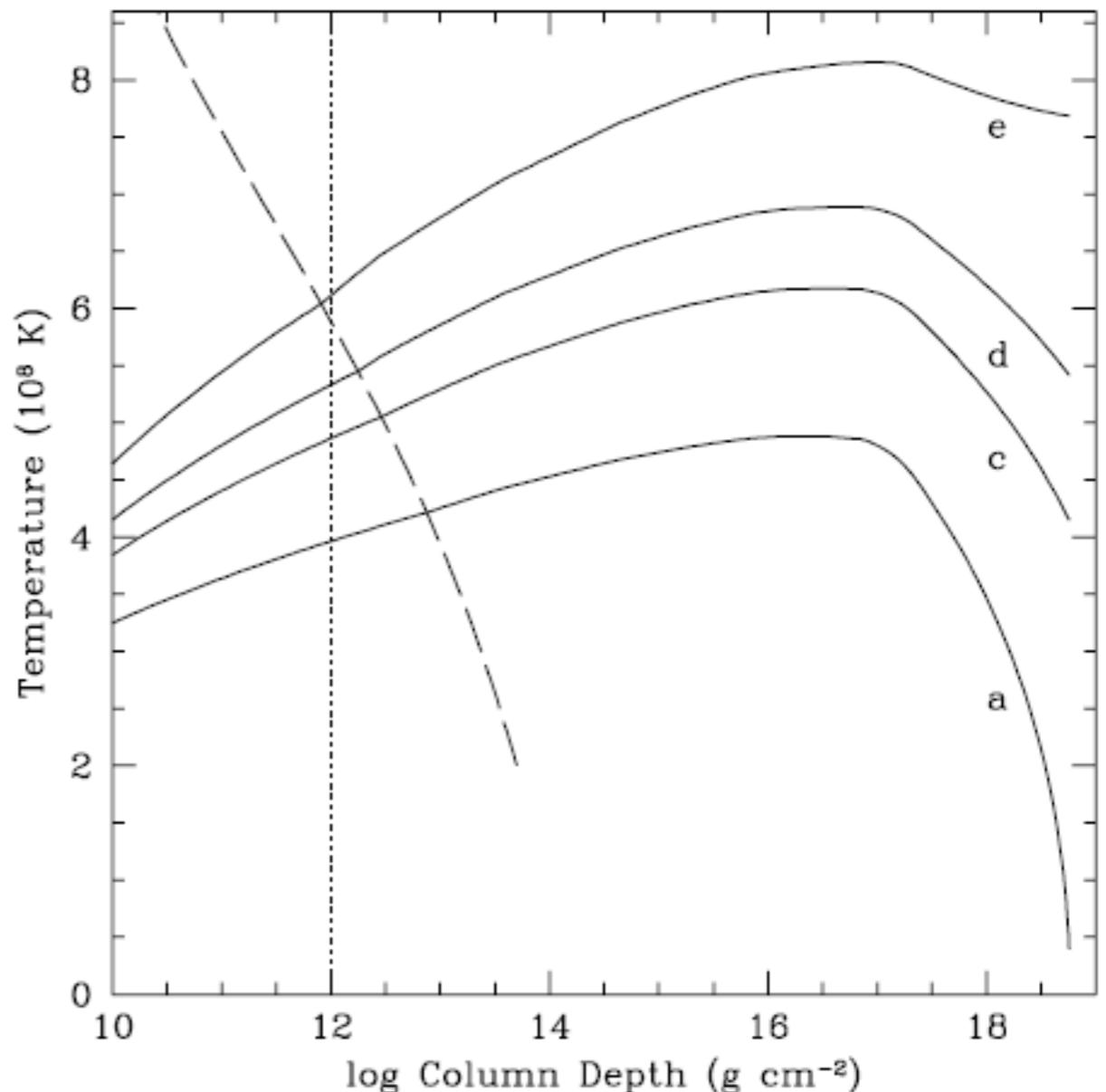
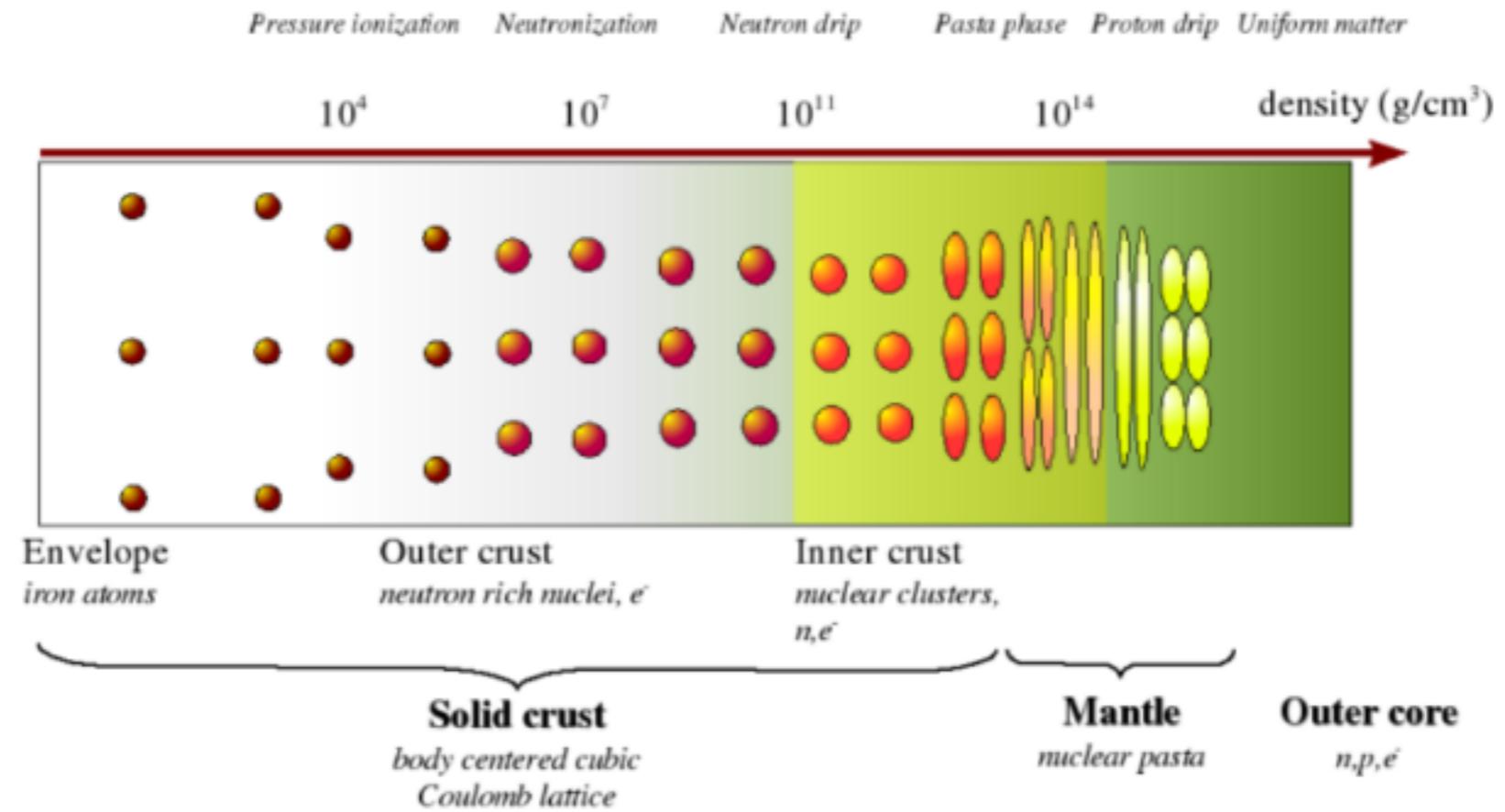


FIG. 11.—Effect of core neutrino emissivity on superburst ignition conditions at $\dot{m} = 0.3\dot{m}_{\text{Edd}}$. We assume a disordered lattice in the crust, and do not include Cooper pairing. The accreted composition is 20% ^{12}C ($X_{\text{C}} = 0.2$) and 80% ^{56}Fe by mass. From top to bottom, the temperature profiles are for increasing core neutrino emissivity; the letters refer to Table 2. The long-dashed curve shows the carbon ignition curve for $X_{\text{C}} = 0.2$, and the vertical dotted line indicates a column depth of $10^{12} \text{ g cm}^{-2}$.

The Neutron Star Crust



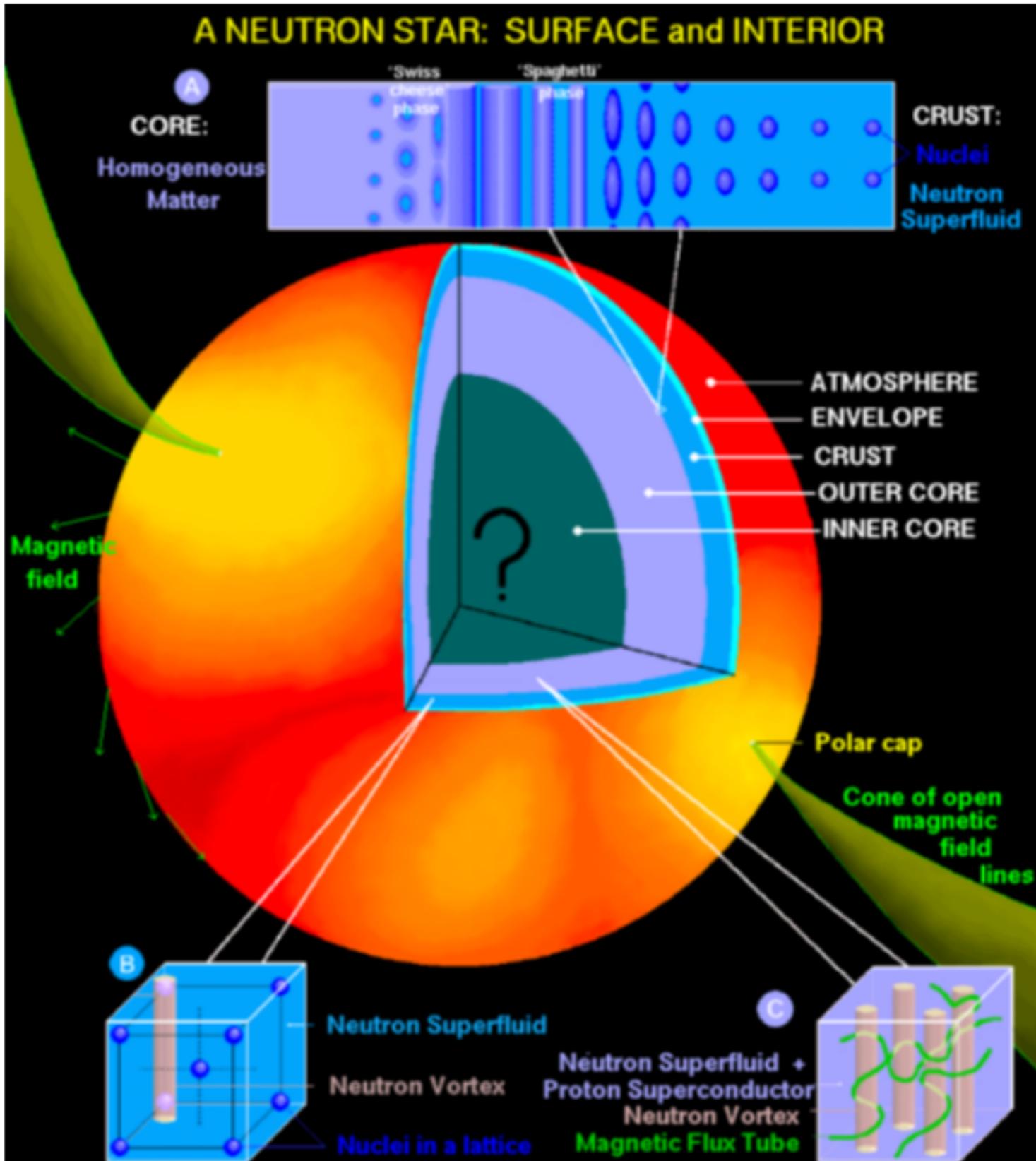
Composition:

Density (g/cm ³)	Isolated	Accreting
10 ⁶	⁵⁶ Fe	X – ray burst ashes
4 × 10 ¹¹	¹¹⁸ Kr	burst ashes + electron captures
10 ¹⁴	[100–400] [20 – 50]	[100–400] [20 – 50]

- Deep crustal heating: Electron captures, neutron emission and pycnonuclear reactions: important source of heat

Matter at High Densities

- Neutron stars are mostly neutrons! $\mu_n = \mu_p + \mu_e$
- Why might they contain exotic matter?
 - Large nucleon chemical potentials and/or small inter-nucleon densities



$$\mu_e \propto (1 - 2x)S$$

Figure by Dany Page



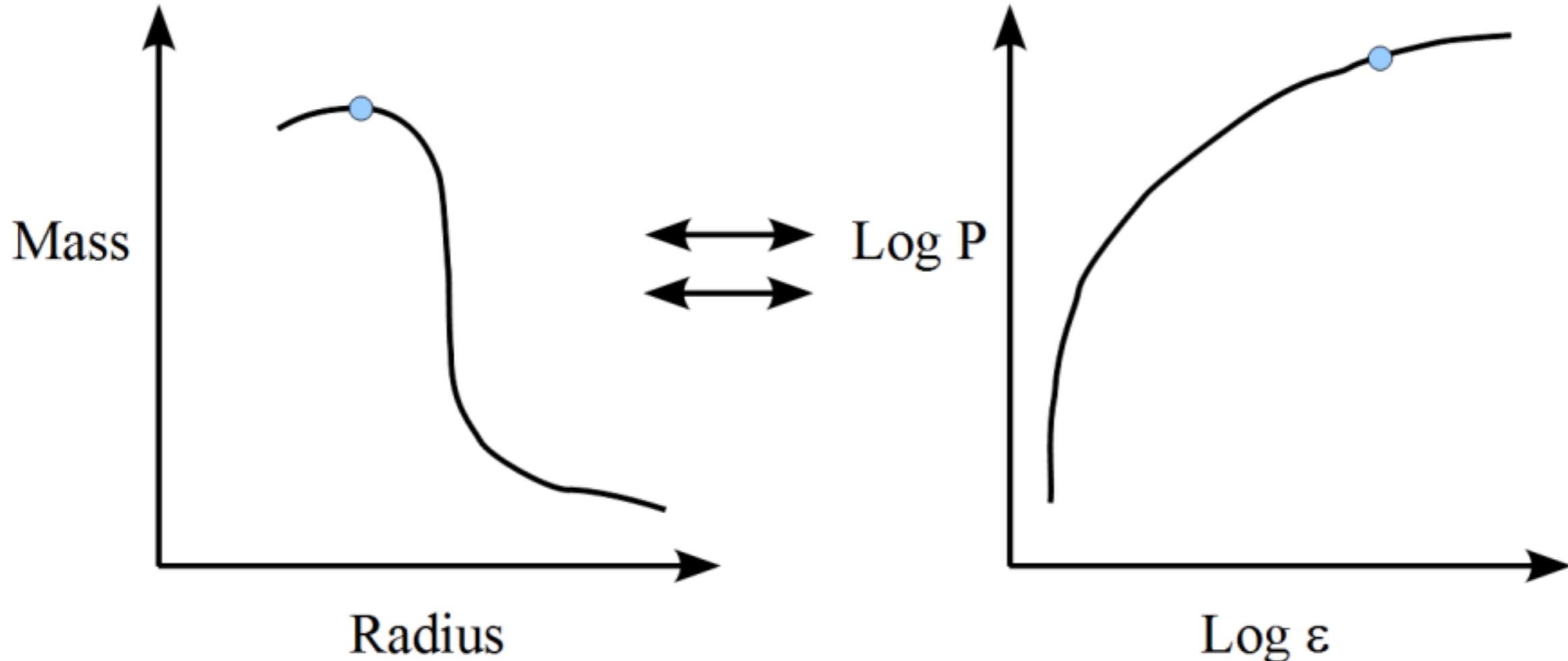
Schematic Equation of State

$$u \equiv n/n_0$$

$$\varepsilon = n_B \left\{ m_B + B + \frac{K}{18}(u-1)^2 + \frac{K'}{162}(u-1)^3 + (1-2x)^2 \left[S_k u^{2/3} + S_p u^\gamma \right] \right\} + \varepsilon_{\text{elec}}$$

- saturation density: nuclear masses
- nuclear binding: nuclear masses
- compressibility: giant resonances
- symmetry energy: giant resonances, heavy-ion collisions, etc.

The Equation of State and Mass vs. Radius



As of 5 years ago:

- Accurate mass measurements from double pulsars (e.g. Hulse-Taylor pulsar)
- Limited radius information for a few sources (e.g. Rutledge et al.)

Now:

- 10-15 percent measurements of M and R for the same object from PRE bursts
- Until recently, no real quantitative constraints on the EOS

Photospheric Radius Expansion X-ray Bursts

- X-ray bursts sufficiently strong to blow off the outer layers - radiate at the Eddington limit

- Flux peaks, then temperature reaches a maximum, "touchdown"

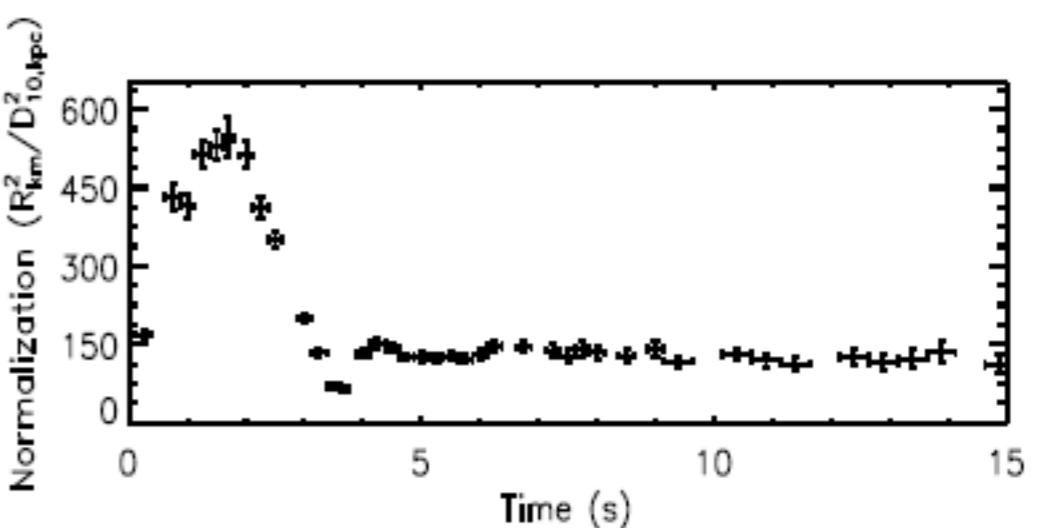
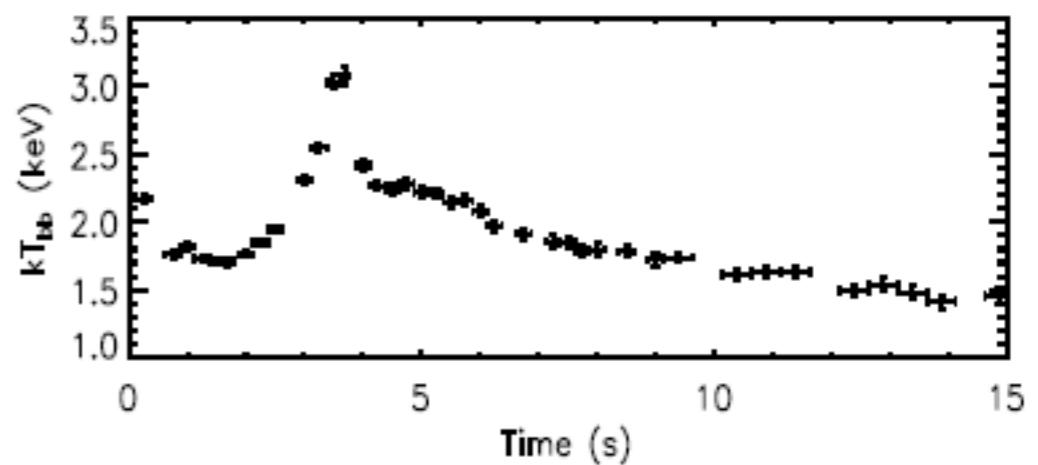
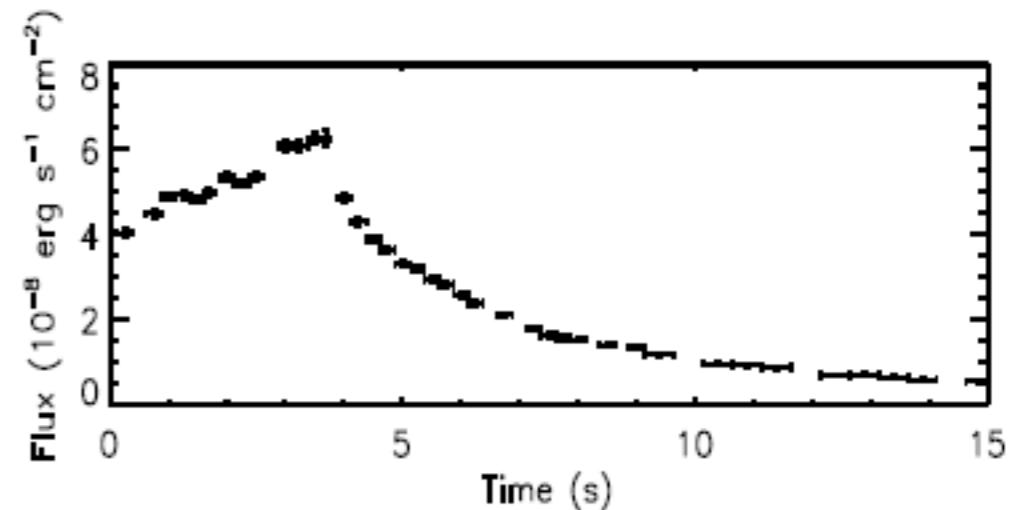
$$F_{TD} = \frac{GMc}{\kappa D^2} \sqrt{1 - 2\beta(r_{ph})}$$

- Normalization during the tail of the

$$A \equiv \frac{F_\infty}{\sigma T_{bb,\infty}^4} = f_c^{-4} \left(\frac{R}{D} \right)^2 (1 - 2\beta)^{-1}$$

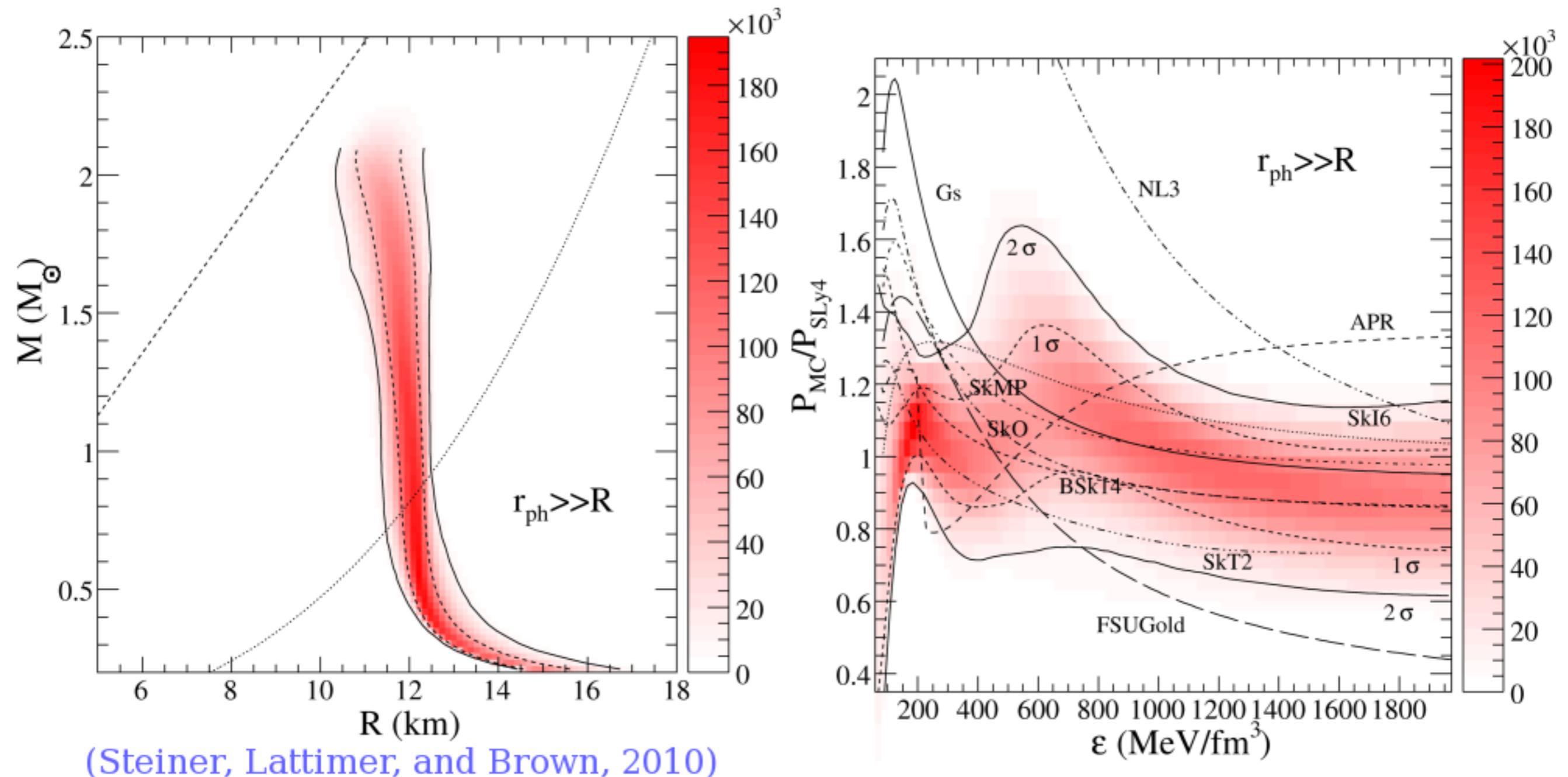
burst:

- If we have the distance, two constraints for mass and radius



(Ozel, Guver, and Psaltis, 2009)

The Mass and Radius Curve from Observations



(Steiner, Lattimer, and Brown, 2010)

- The mass and radius constraints provided by observations are much smaller when taking into account the fact that all objects must lie on the same curve



Summary

- X-ray bursts: probe physics of exotic nuclei and dense matter
- Still a lot of holes in our current understanding
 - Nuclear physics of the rp-process path
 - Astrophysics of a plethora of bursts
- *Almost all* neutron stars have radii between 11 and 12.5 km
- Some popular equations of state are already ruled out