Fundamental Physics of HEDP Astrophysical Phenomena

Frederick K. Lamb
University of Illinois

High Energy Density Physics Workshop
Gaithersburg, Maryland, May 25–27, 2004

Fundamental Physics of HEDP Astrophysical Phenomena Question

How does matter and energy behave under conditions of extreme temperatures, pressures, and densities, *in astrophysical settings?*

HEDP Some HEDP Astrophysical Regimes

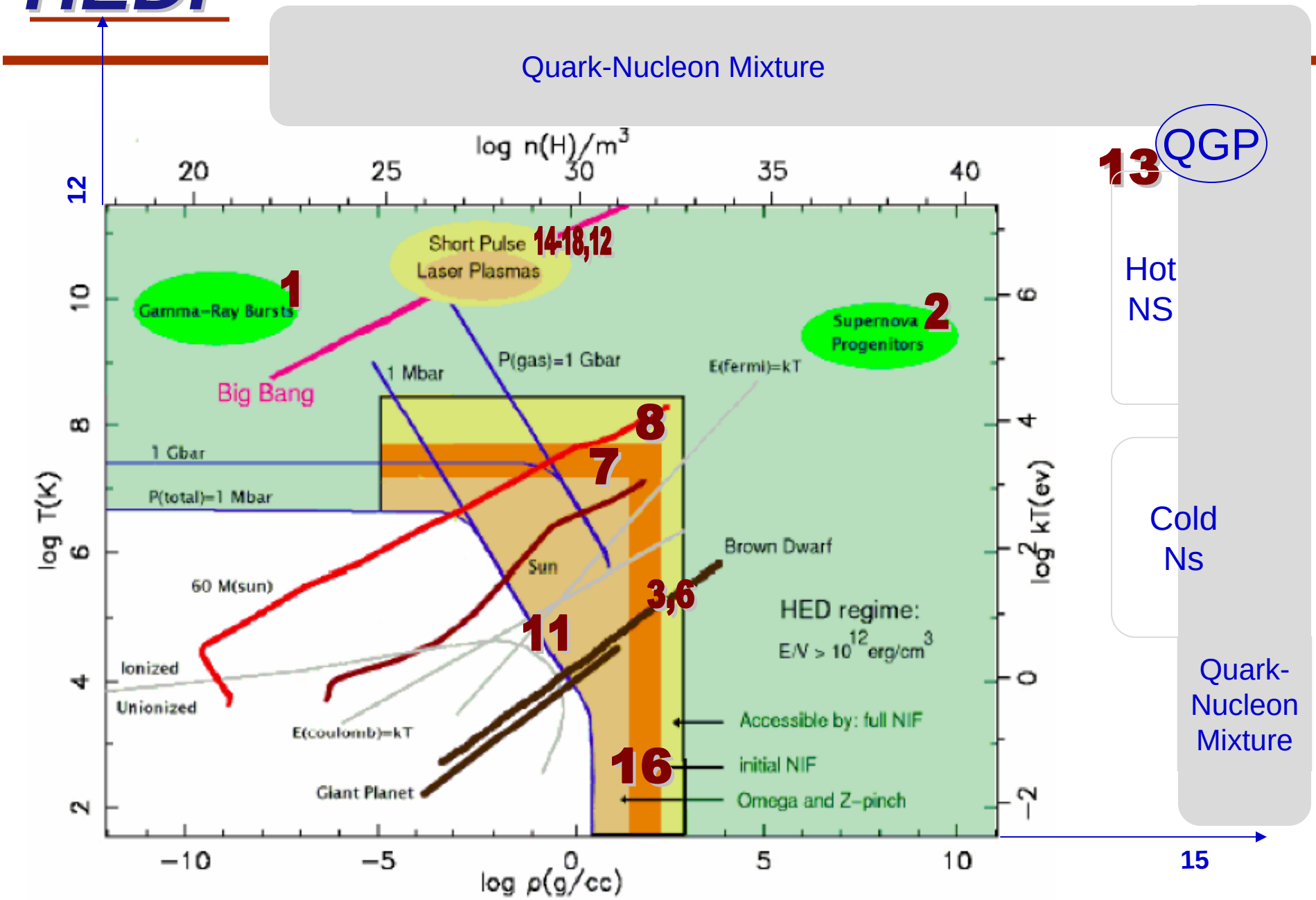
- Ultradense matter —
  - Hot neutron stars ($T \sim 10^{12}$ K)
    - » $n = 10^{38}$ cm^{-3} = 10^{44} m^{-3}
      ($\rho = 10^{14}$ g cm^{-3} = 10^{17} kg m^{-3})
    - » $\varepsilon = 10^{34}$ ergs cm^{-3} = 10^{33} J m^{-3}
  - Cold neutron stars ($T \sim 10^{8}$ K)
    - » $n = 10^{40}$ cm^{-3} = 10^{46} m^{-3}
      ($\rho = 10^{16}$ g cm^{-3} = 10^{19} kg m^{-3})
    - » $\varepsilon = 10^{34}$ ergs cm^{-3} = 10^{33} J m^{-3}

HEDP Some HEDP Astrophysical Regimes

- High energy density radiation fields —
  - Sun's surface ($T \sim 10^4$ K)
    - » $F = 10^{11}$ ergs cm^{-2} s^{-1} = 10^4 W m^{-2} s^{-1} = 10^8 W m^{-2} s^{-1}
  - X-ray star (neutron star) surface ($T \sim 10^9$ K)
    - » $F = 10^{29}$ ergs cm^{-2} s^{-1} = 10^{22} W m^{-2} s^{-1} = 10^{26} W cm^{-2} s^{-1}
- High energy density magnetic fields —
  - $B \sim 10^{15}$ G neutron star

$$\varepsilon = 10^{28} \text{ ergs cm}^{-3} = 10^{27} \text{ J m}^{-3}$$

HEDP Map of Density-Temperature Plane



HEDP

Astrophysics Thrust Areas
Fundamental HEDP

Fundamental physics that enters astrophysical modeling —

- Often, fundamental physics questions are raised by modeling needs (e.g., the need to model pulsars)
- These physics questions can then turn into (e.g., the equation of state of ultradense matter)
    - Neutron star matter at densities much higher than is accessible in laboratory nuclei

HEDP

Astrophysics Thrust Areas
Fundamental HEDP

1. Fundamental properties of HED matter
   - EOS of degenerate and partially-degenerate matter at high and ultrahigh densities, high and low T
     - White dwarfs and neutron stars
     - Brown dwarfs, interiors giant gaseous planets
   - Properties of matter at high densities and temperatures
     - Interaction of high-intensity radiation fields with matter
     - Opacities of matter at high densities and temperatures, especially for complex abundances

HEDP

Astrophysics Thrust Areas
Fundamental HEDP

2. The origins and effects of ultrastrong magnetic fields

- How does matter behave in the presence of extremely strong (~ 10^9 – 10^{15} G or higher) magnetic fields?
- How are superstrong magnetic fields generated?
- How are magnetic fields dissipated under HEDP conditions?

(Neutron stars can in principle have B ~ 10^{18} G)

HEDP

High-Frequency Neutron Star X-ray Oscillations

3 Basic Types

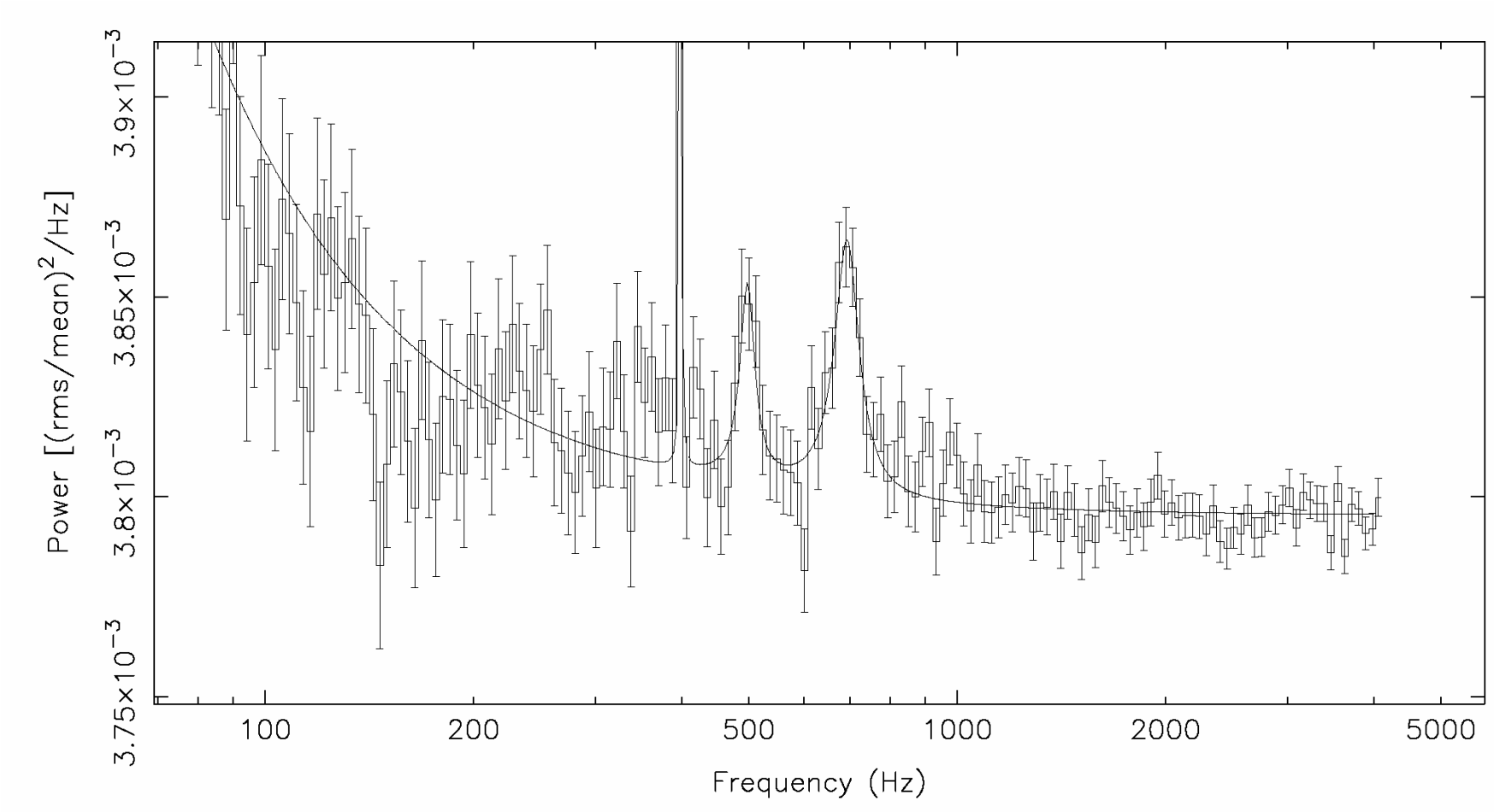
- **Persistent oscillations** at the neutron star's spin frequency ("X-ray pulsations"); 5 accretion-powered millisecond X-ray pulsars are now known, with frequencies ranging from 185 Hz to 435 Hz

- **Oscillations during thermonuclear X-ray bursts** ("burst oscillations") Generated by the spin of the star; 16 such "nuclear-powered pulsars" are known.

- **Accretion-powered kilohertz oscillations** (kilohertz QPOs) Basic frequency is that of orbital motion skimming the neutron star's surface; detected in some 25 neutron stars so far.

Periodic Oscillations and Kilohertz QPOs

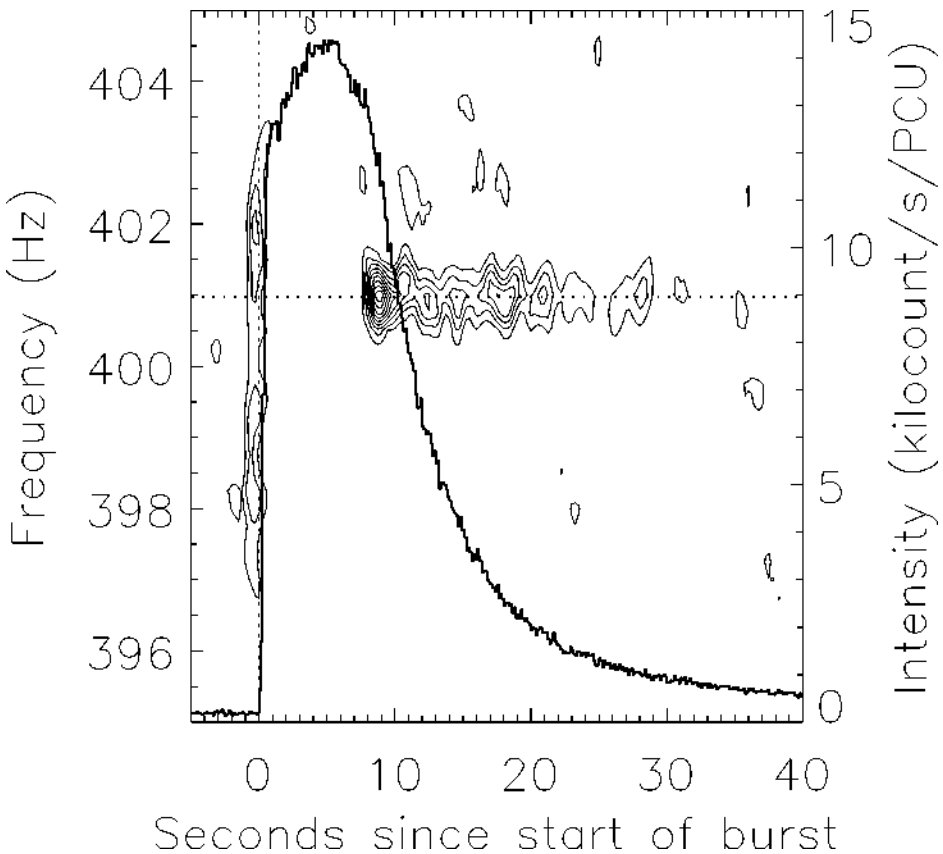
X-ray pulsar SAX J1808.4–3658



ν_{spin} = *401 Hz*, $\nu_{QPO1} \approx$ 500 Hz, $\nu_{QPO2} \approx$ 700 Hz, $\Delta\nu_{QPO} \approx$ *200 Hz*

HEDP Burst Oscillations in SAX J1808.–3658

$\nu_{burst} = \nu_{spin}$



Chakrabarty et al. 2003

- Four bursts were observed; all show 3–5% oscillations in the burst rise and the burst tail
- During the rise of the burst, ν_{burst} increases quickly, 10X faster than in any other X-ray burst source, and overshoots the spin frequency
- The oscillation disappears during the radius expansion that occurs at the peak of the burst
- The oscillation reappears in the tail of the burst, with a frequency $\nu_{burst} = \nu_{spin} + 6$ mHz
- The oscillation in the tail *begins in phase* with the magnetic pole, but *then drifts* by 0.1 in phase

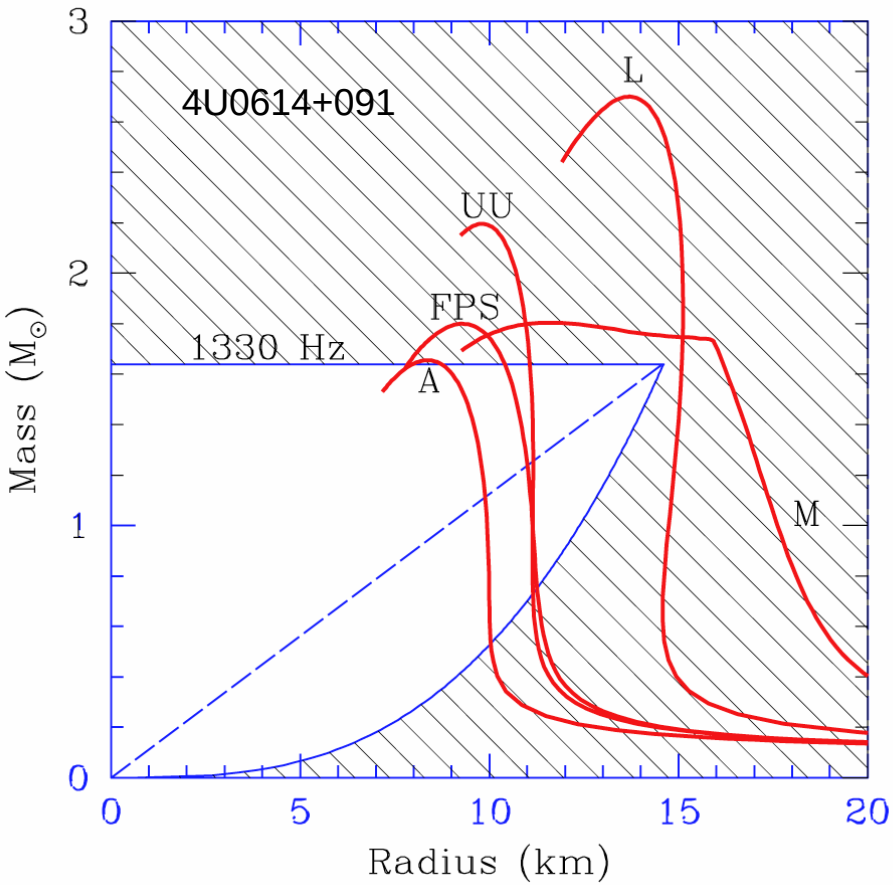
HEDP Burst Oscillations and kHz QPOs in Neutron Stars with Known Spins

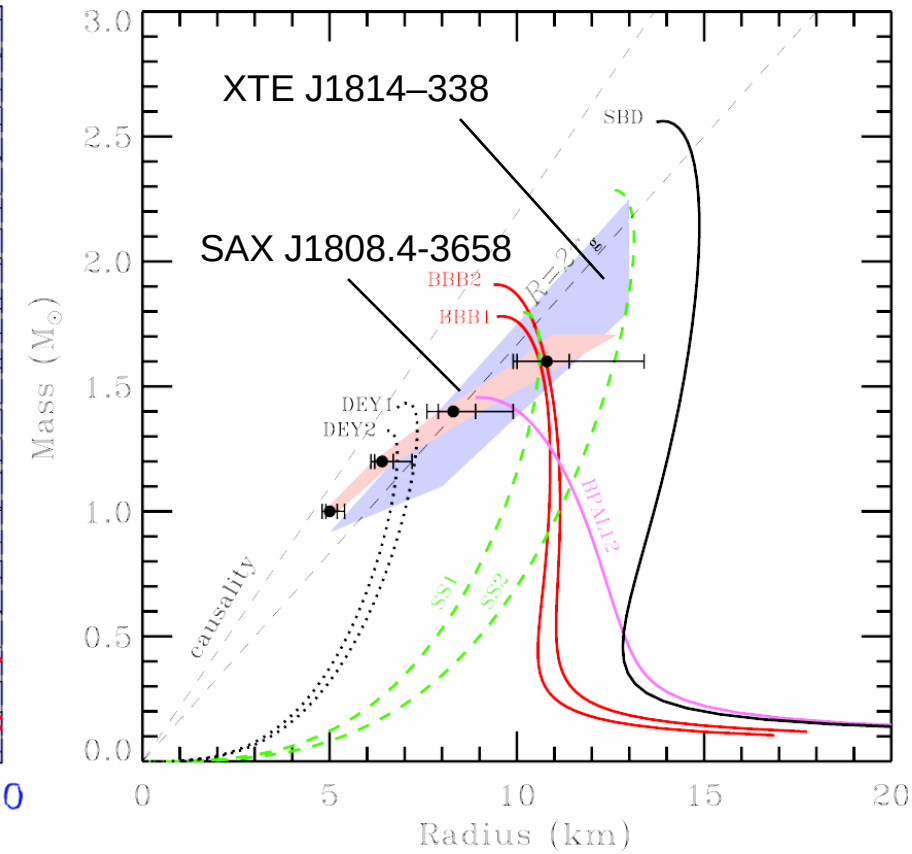
Spin Rate (Hz)	Object	Millisecond Pulsar References
185	XTE J0929–314	Galloway et al. 2002
191 •	XTE J1807–294	Markwardt et al. 2003a
270	4U 1916–05	
314	XTE J1814–338	Markwardt et al. 2003b
330	4U 1702–429	
363	4U 1728–34	
401 •	SAX J1808.4–3658	Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998
410	SAX J1748.9–2021	
435	XTE J1751–305	Markwardt et al. 2002
524	KS 1731–260	
549	Aql X-1	
567	X 1658–298	
581	4U 1636–53	
589	X 1743–29	
601	SAX J1750.8–2900	
619	4U 1608–52	

Boldface : known pulsars; • : pulsars with known kHz QPOs;
italics : neutron stars without known burst oscillations

HEDP

Properties of Dense Matter and General Relativistic Effects





Left: Comparison of upper kilohertz QPO frequency with NS EOS
Right: Comparison of illustrative burst oscillation data with NS EOS

HEDP

Possible New Instrumentation to Address HEDP Astrophysics

- Physics of ultradense matter and ultrastrong magnetic fields
  - Spins, accretion-powered and nuclear-powered kilohertz oscillations constrain the equation of state of cold dense matter
  - X-ray spectra and the waveforms of pulsars provide data on the structure of their magnetic fields and on quantum electrodynamic effects
- A follow-on X-ray timing mission
  - Cambridge, MA, Workshop, November 2003