Probing dense matter physics with precision X-ray timing

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LOFT
Large Observatory for X-ray Timing

the dense matter challenge

Neutron stars may be the most exotic objects we have in the Universe.

They are associated with a range of phenomena, most of which remain to be understood.

The extreme physics involved cannot be tested in the laboratory.

There are **no** models on the market that can deal with **all** the physics.

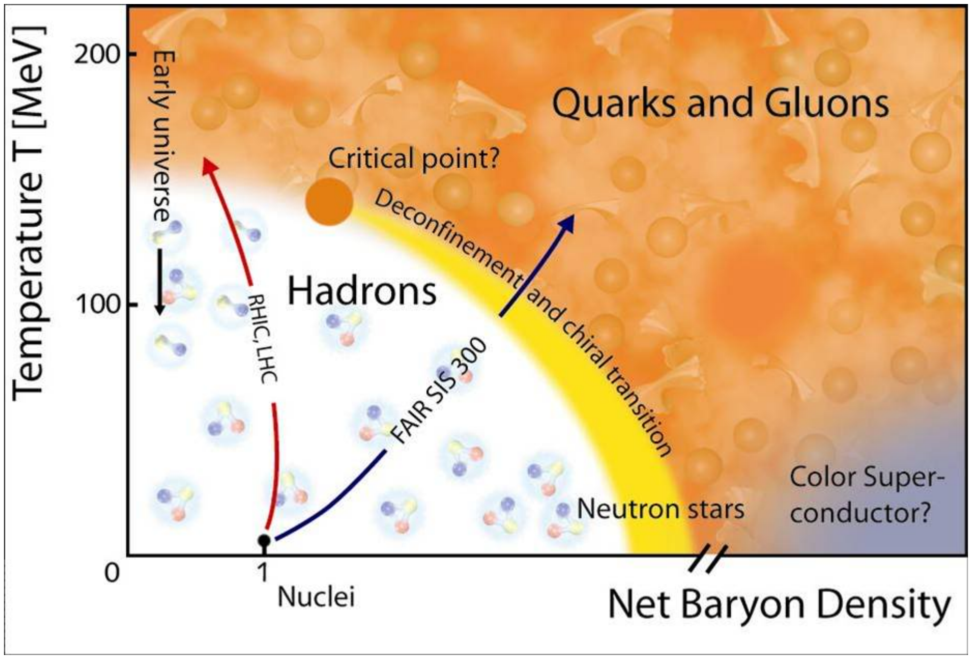
For any proposed model/scenario you need to ask what is included and what is not!

Main focus here will be on issues relating to X-ray timing, but keep in mind that the effort will benefit greatly from, perhaps even rely on, multi-messenger efforts.

the bigger picture

The desire to understand how matter behaves under extreme conditions is a key motivation for neutron star astrophysics.

The problem involves all four of the fundamental forces in Nature.



Gravity, holds the star together (gravitational waves?)
Electromagnetism, makes pulsars pulse and magnetars flare
Strong interaction, prevents collapse and determines the internal composition
Weak interaction, affects reaction rates, which lead to cooling and internal viscosity

Simplistically, neutron stars observations complement data gleaned from colliders like the LHC and RHIC.

the RXTE legacy

The LOFT concept builds on the immense success of RXTE.

Accurate X-ray timing has helped improve our understanding of neutron star physics.

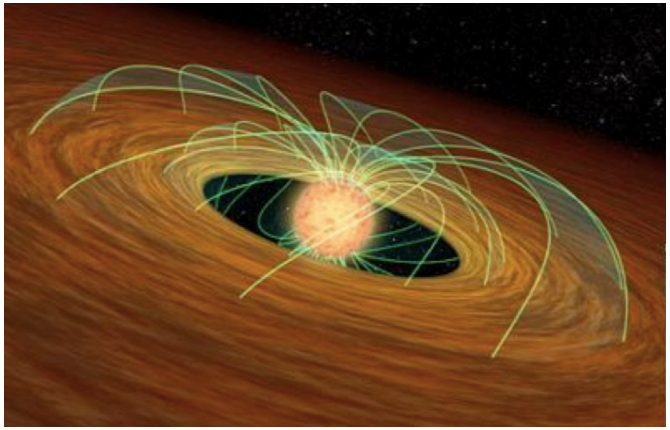
We are beginning to take the fingerprint of these objects, but need better resolution to make further progress.

Pulsar timing – discovery of the first millisecond X-ray pulsar, and long-term timing of several systems

X-ray bursts – radius expansion bursts have provided constraints on equation of state through M-R relation

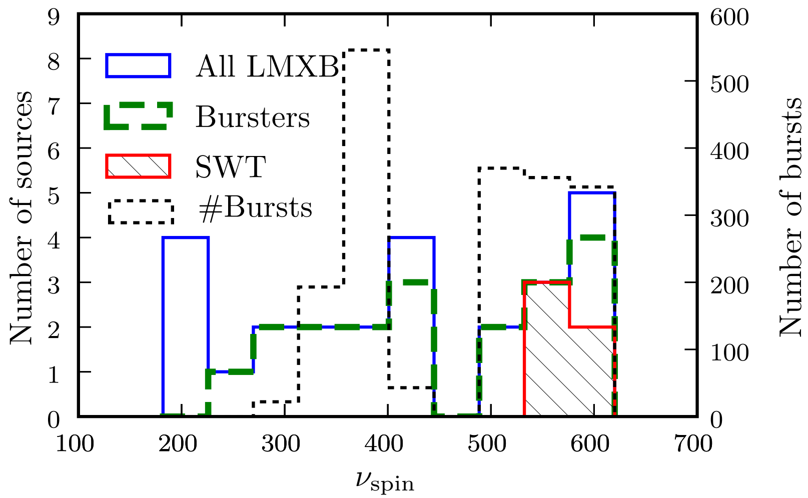
Magnetar dynamics – QPOs in tails of giant flares have led to first serious discussion of neutron star seismology. Spin glitches have been seen and compared to radio pulsar phenomenon.

timing



Millisecond pulsars, like the record holder J1748-2446ad at 716 Hz, form by accreting matter (and angular momentum) from a companion.

Only a few systems are seen as pulsars (in X-ray), like SAX J1808.4-3658 which has a spin period of 2.5 ms. In some systems the spin is inferred from oscillations associated with X-ray bursts.



The fastest system, 4U 1608, spins at 620Hz.

Is some kind of speed-limit is enforced?

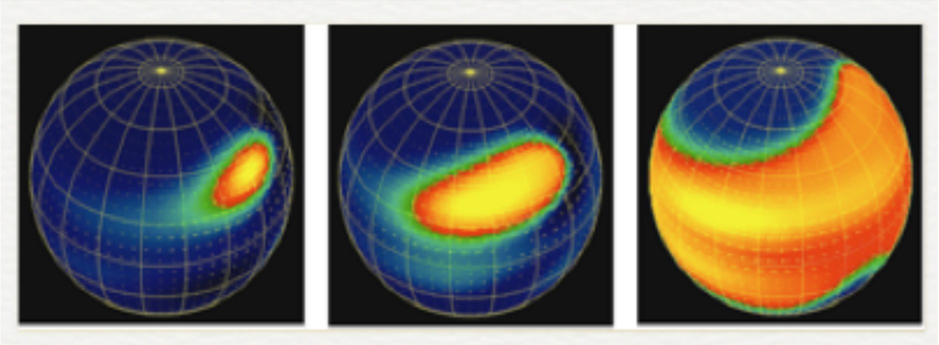
- "non-standard" accretion torque?
- additional gravitational wave torque?

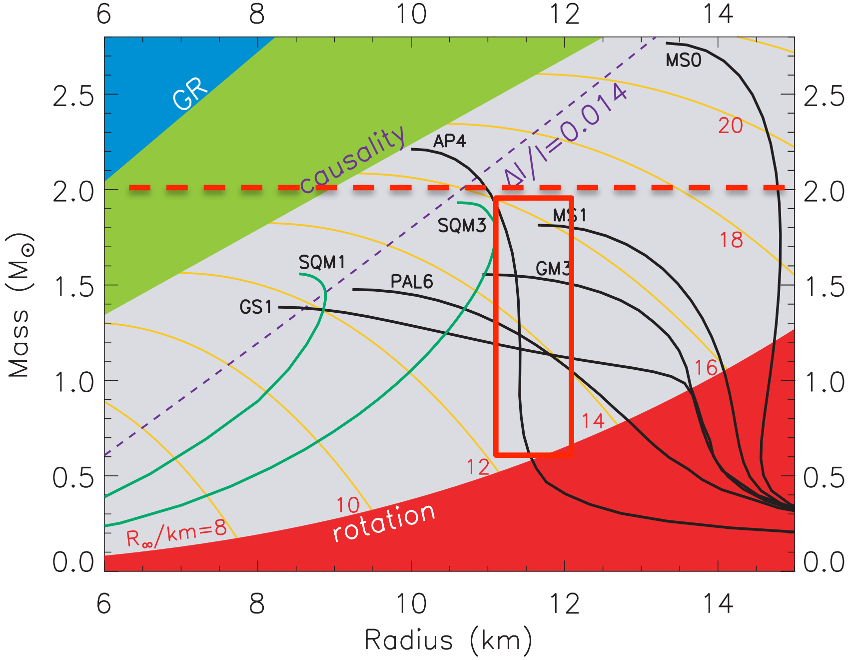
(e.g. r-modes probe interior viscosity)

We are beginning to piece together this story, but precision timing, especially of systems in quiescence, is needed to constrain the theory.

bursts

Observed X-ray bursts arise as an explosive burning front propagates around the star. The associated hot-spot helps pin down the star's spin.





Detailed modelling allows us to infer the star's radius.

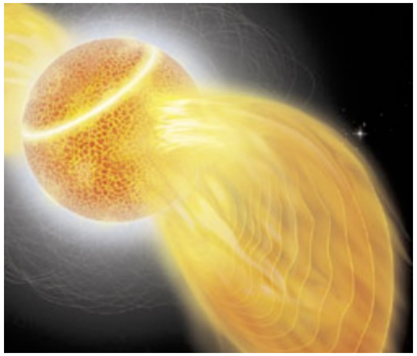
Current data suggests that the radius should be in the range 11-12 km.

The maximum mass is relatively large, 1.9-2.2 M_o

The data is beginning to constrain the nuclear physics!

To get to the next level (eg. an error box of a few percent), we need more accurate modelling of pulse profiles and higher precision timing.

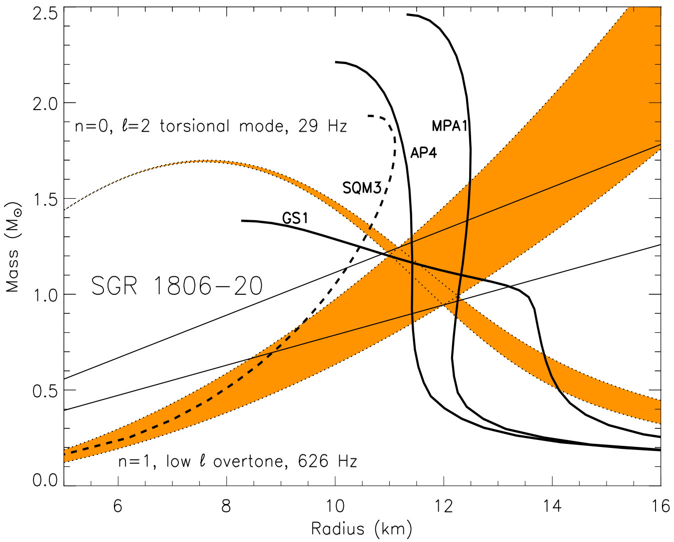
magnetars



Magnetars (SGR/AXP) are neutron stars with superstrong magnetic fields: $B \sim 10^{15}$ G, $P \sim$ 1-10 s

Field decay powers regular gamma-ray flares.

On rare occasions magnetars emit **giant** flares, thought to result from crust fractures leading to a rearrangement of the magnetic field.



Quasi-periodic oscillations seen in the X-ray tail of flares provide first evidence of neutron star oscillations and an opportunity for asteroseismology.

Should allow us to constrain both mass and radius, and probe crust physics as well.

However...

Modelling is difficult, especially since interior magnetic field and superfluidity may both be important.

Need more, and better, data if we are to make progress!

ESA's Cosmic Vision:

Probe gravity in the very strong environment of black holes and other compact objects, and the state of matter at supra-nuclear densities in neutron stars.

The science case for a large area X-ray instrument, like LOFT, is clear…

We need this kind of instrument to probe dense matter physics, at the level of the mass-radius relation and beyond.

We also have to make sure that we make maximal use of the multi-messenger opportunities (radio, gravitational waves, …)