Constraining properties of dense matter with precision radio timing measurements

Bennett Link

- What spin variations have revealed about:
  - the ground state of NS matter
  - its dynamics

- Future directions (and wishes)
The central question of nuclear physics

What are the properties of matter above nuclear density
\((\sim 3\times10^{14} \text{ g cm}^{-3})\)?

Such dense matter exists in neutron stars

\begin{itemize}
  \item \(M \approx 1.4 \, M_{\text{Sun}}\)
  \item \(R \approx 10 \, \text{km}\)
\end{itemize}

\[\Rightarrow \rho = \frac{M}{(4\pi R^3/3)} = 5\times10^{14} \text{ g/cm}^3 \approx 2 \, \rho_{\text{nucleus}}.\]
The central question in neutron star physics

Atmosphere: H, He, C....
Crust: heavy elements Fe, Ni...

WHAT IS IN HERE?
The NS ground state (according to theory)

**Predictions:**
- Most of the interior is liquid, with
- SF neutrons + SC protons (type II)

**Questions:**
- Is this right?
- What are the implications?

\[ \rho > \rho_n = 2.8 \times 10^{14} \text{ g cm}^{-3} \]

Superfluid neutrons

Superconducting protons (type II)

\( e^-, \mu \)
Constraining the ground state of NS matter

Some NSs **precess** (nutate) with periods of years

PSR 1828-11

(Stairs et al. 00)
Inconsistent with this **theoretical** prediction

\[ \rho > \rho_n = 2.8 \times 10^{14} \text{ g cm}^{-3} \]

superfluid neutrons

Superconducting protons (type II) \( e^-, \mu \)

which would precess with a period of **at most seconds**, rather than years. (Link 03).

⇒ the current picture of ground state of the interior is seriously challenged
Want $M$ and $R$ for the **same object**.

Rapid rotators: **fastest observed is 716 Hz. Discovery of a kHz pulsar would be very constraining.**
Constraining internal dynamics with spin variations

- Glitches

Statistically, \( \frac{I_{\text{loose}}}{I} \approx 1\% \) suggestive of inner-crust origin (Link, Epstein & Lattimer 99)
Constraining internal dynamics with timing noise
Evidence for a damped rotational mode

⇒ damped mode with $\tau \sim 10$ d.

(Price, Link, Shore, Kramer & Lyne, in preparation)
Two pay-offs of precision pulsar timing

Discovery of precession

Discovery of correlated structure in timing noise

challenges

superfluid neutrons

SC protons (type II)

detection of crust-liquid dynamics?
Key ingredients for further progress

- EOS: Need more masses $\Rightarrow$ SURVEYS!
- Internal dynamics: Need frequent (daily) timing of choice pulsars to identify modes.