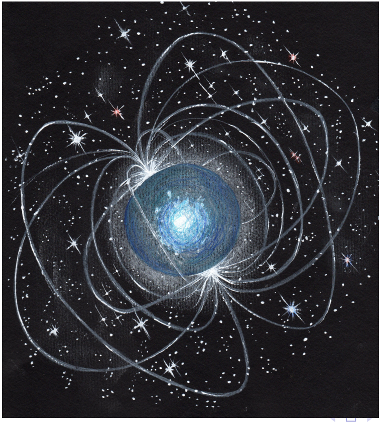
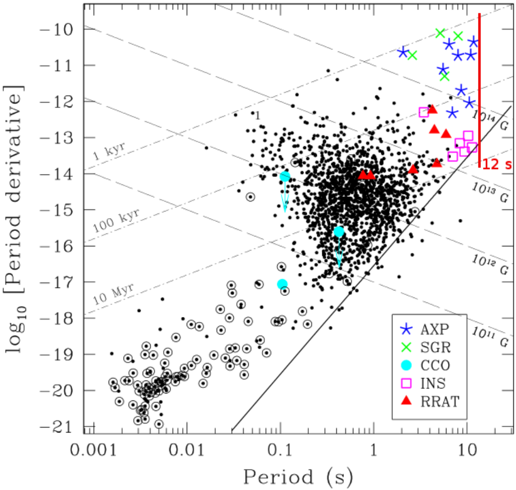
# The maximum period of pulsars as a probe of fundamental physics

Daniele Viganò (U. of Alicante)

in collaboration with J.A. Pons and N. Rea - arXiv:1304.6546 - The Fast and the Furious, Madrid, May 23, 2013



# Maximum period of isolated neutron stars?




*[adapted from Kaspi 2010]*

# Selection effects

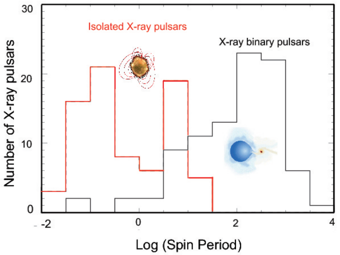
**RADIO**

Intrinsec mechanisms of radio emissions, although not understood, loses efficient for increasing period $\rightarrow$ narrow beams, low luminosity
Beaming fraction $f = 9[\log(P/10\text{s})]^2 + 3$ (phenomenological fit, Tauris & Manchester 1998)

---

**X-RAY**

No beaming selection effects against long $P$. Hot magnetised stars are more detectables.




---

**Evolved magnetars should reach periods of several tens of seconds and still be X-ray detectable.**

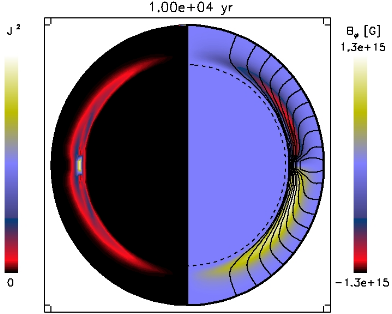
Why no evolved magnetars ($t \gtrsim 10^4 - 10^5$ yr) or XDINS are seen with, e.g., $P = 30$ or 50 s?
Why all the magnetars period (also the oldest ones, like SGR 0418) cluster in the same region?

# Evolution of magnetic field

**Magnetic field dissipation makes the spin-down inefficient at late ages**
$\Rightarrow$ **Asymptotic maximum period** [see, e.g., phenomenological model by Colpi+ 2000]

**Main results from magneto-thermal evolution [J.Pons' talk]**

• Large magnetic fields sustained by crustal currents keep the star detectable longer (Myr).
• Magnetic, rotational and thermal evolution agree with timing and spectral observations of magnetised neutron stars.
• The bulk of crustal currents circulate in the dense, inner crust due to the Hall drift.




**Bottomline**

Physics of INNER CRUST directly regulates the observed TIMING properties!

# The inner crust: pasta phase

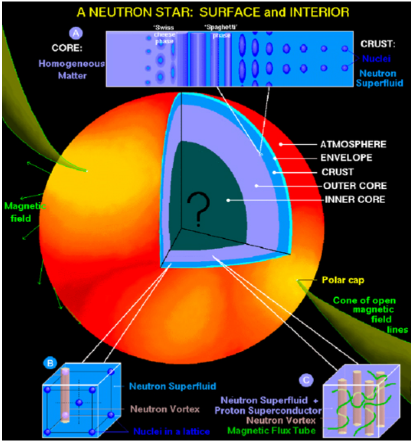
## What we know

• Density: $\rho \sim 4 \times 10^{11} - 10^{14}$ g cm$^{-3}$
• Composition: relativistic degenerate electrons, free (superfluid) neutrons, lattice made of ions (ground state with large $A$ and impurities)
• Pasta phase: in the 50-100 m innermost layer of the crust ($\rho \gtrsim 5 \times 10^{13}$ g cm$^{-3}$), the large Coulomb energy cost can favour nuclei in pasta shapes (rods, slabs, bubbles).

---

## Observational imprint of pasta phase

• Cooling? Outer crust is more important.
• Gravitational waves (mountains, modes)? [Gearheart+ 2011]
• TIMING PROPERTIES OF PULSARS!

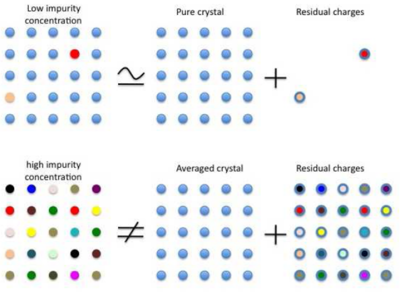



*[Page & Reddy 2006]*

# Impurity parameter

**Lattice properties in inner crust are poorly known**

- Structure? Concentration and localization of defects? Effects of magnetic fields?
- Disordered [Jones 2004]? Crystalline [Horowitz group]? Heterogeneous [Magierski & Heenen 2001]?
- Transport properties of pasta phase are largely unexplored.




[Daligault 2009]

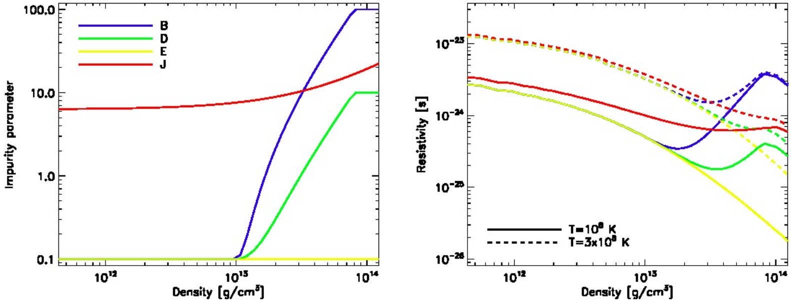
**IMPURITY PARAMETER**

$$Q_{imp} = \langle Z^2 \rangle - \langle Z \rangle^2$$

In absence of more detailed calculations, $Q_{imp}$ parametrizes the crystal structure.

# Conductivity of inner crust

- Crystalline lattice: $e^-$-phonon scattering (strongly $T$-dependent).
- Disorder resistivity (pasta phase or impurity) is almost independent on $T$

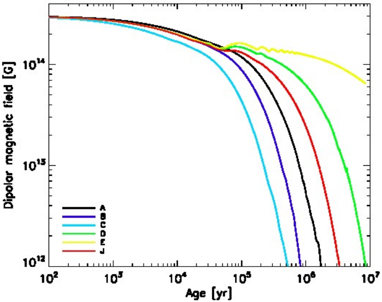


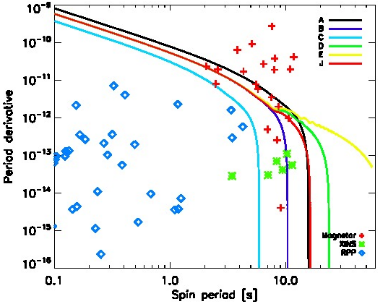

*[Conductivity calculated with St. Petersbourgh IOFFE group routines]*

http://www.ioffe.ru/astro/conduct/

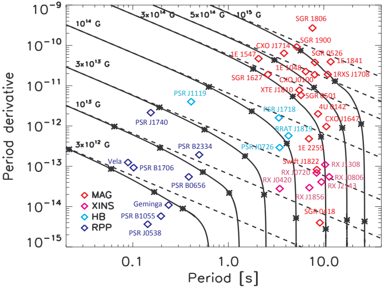
# Timing properties

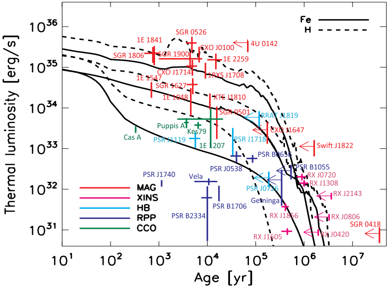
Initial magnetic field: $B = 3 \times 10^{14}$ G.
A and C models: same as B, with different mass



# Constraining models




## Constraining models

Data requires a large $Q_{imp} \gtrsim 10$ in the pasta phase (see also Pons' talk).
If $Q_{imp} \lesssim O(1)$, the evolved magnetars (XDINS) would have longer periods and would still be detectable.

# Conclusions

**Timing properties ⇔ Inner crust properties**

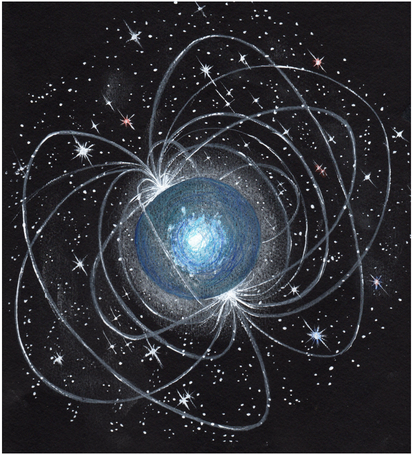
In highly magnetised objects, currents circulate in the inner crust.
Transport properties highly depends on the structure of the lattice: impurity degree, pasta phase.

**Maximum period of isolated neutron stars**

No isolated neutron star is seen with $P > 12$ s.
A highly resistive layer in the inner crust is consistent with observed properties.

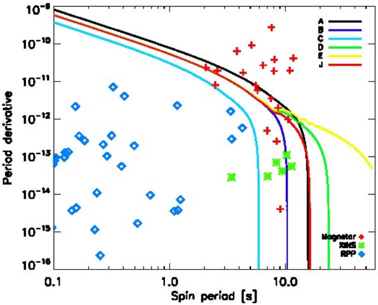
**PRECISE CONSTRAINTS NEED:**

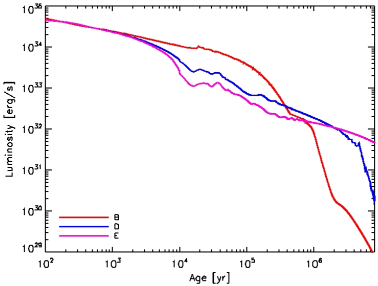
- Observations: more timing data of INSs (e.g., LOFT).
- Microphysical calculations of the transport properties for amorphous/heterogeneous inner crust can constrain its physics.
- Population synthesis of INSs.



[© A. Manzoni]

# Luminosity




## Constraining models

Large $Q_{imp}$: fast dissipation, brighter early phases, saturation of periods.
Loww $Q_{imp}$: slow dissipation, heat deposition is spread over longr timescales, periods keep increasing at late ages.
If $Q_{imp} \lesssim O(1)$, old magnetars and XDINS would have longer periods and would still be detectable at few Myr.