Superfluidity in Neutron Stars and Pulsar Glitches

Aurélien Sourie

Institute of Astronomy and Astrophysics
Université Libre de Bruxelles, Belgium

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1. Superconductivity and superfluidity in the laboratory
2. Superconductivity and superfluidity in neutron stars
3. Pulsar glitches as a strong support for the presence of superfluid matter in neutron stars
4. Other observational manifestations
5. Conclusion

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2. Superconductivity and superfluidity in neutron stars
3. Pulsar glitches as a strong support for the presence of superfluid matter in neutron stars
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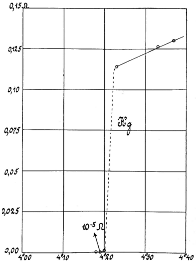
Discovery of superconductivity

In 1911, Onnes and his collaborators discovered that the **electric resistance of mercury dropped** to almost zero at $T_c \sim 4.2$ K.

The also noticed the existence of **persistent electric currents** in 1914.



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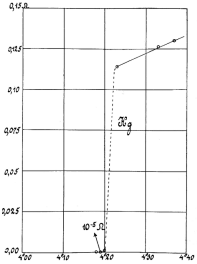

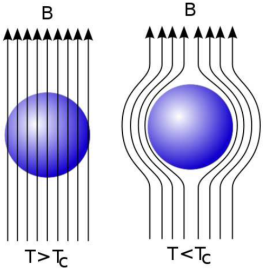

In 1933, **expulsion of magnetic flux** is observed by Meissner & Ochsenfeld, for $H < H_c(T)$ and $T < T_c$.

⇢ new thermodynamic state!

Contrary to type I, type II superconductors exhibit **incomplet Meissner effect** for $H_{c1}(T) < H < H_{c2}(T)$.

Discovery of superfluidity

During the 1930s, several groups found that, below $T_c \sim 2.17$ K, helium-4 **does not behave** like an ordinary liquid.

The term **superfluidity** was coined by Kapitsa in 1938 by analogy with superconductors.

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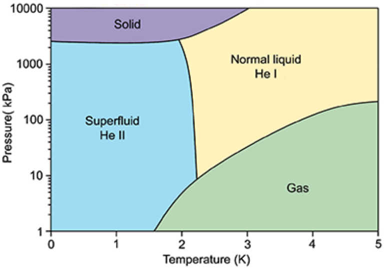

Persistent currents in HeII were observed during the 1950s and **Hess-Fairbank effect** was discovered in 1967.

--→ new thermodynamic state!

Tisza-Landau two-fluid model

The association between Bose-Einstein condensation and superfluidity was first advanced by London (1938).

Tisza & Landau postulated that He II contains two distinct components:

- a superfluid that carries no entropy,
- a normal viscous fluid [non-condensed atoms **or** quasi-particles].

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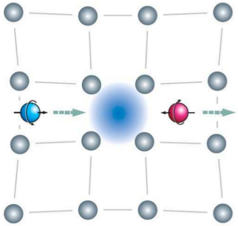
This two-fluid model was **extended** to superconductors by Gorter (1955).

BCS theory (1957)

In a superconductor, the dynamical distorsions of the crystal lattice can induce an attractive effective interaction between e^- of opposite spins.

Roughly speaking, e^- can thus form pairs and undergo a BEC below some critical temperature.



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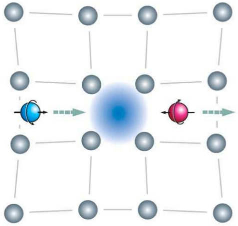

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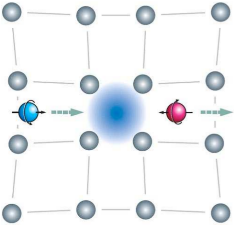
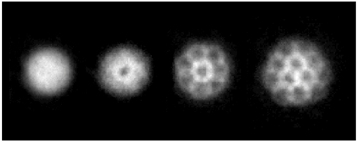


Rk: The BEC and BCS transition are now understood as two different limits of the same phenomenon.

⇢ **fermionic atoms** could become superfluid, as was confirmed by the discovery of superfluid helium-3 below $T_c \sim 2.5$ mK in 1971.

Vortex lines & flux tubes

A superfluid can only rotate by forming an array of *quantized vortices*.



[Madison et al., *PRL*, 2000]

Quantum of circulation:

$$\kappa = h/m_s$$

Mean surface density of vortex lines:

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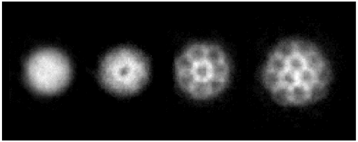

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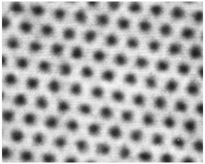
Likewise, a type II superconductor is threaded by *flux tubes* (or *fluxoids*).



[Hess et al., *PRL*, 1989]

Quantum magnetic flux:

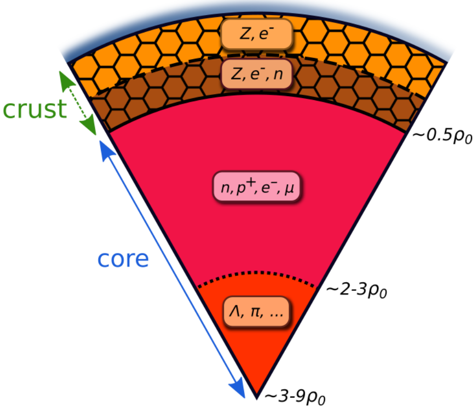
$$\phi_0 = h/q_s$$

Mean surface density of fluxoids:

$$n_\Phi = \frac{B}{\phi_0} = \frac{q_s\, B}{h}$$

Internal composition of a neutron star

- outer crust: ions forming a regular crystal lattice & degenerate e^-,



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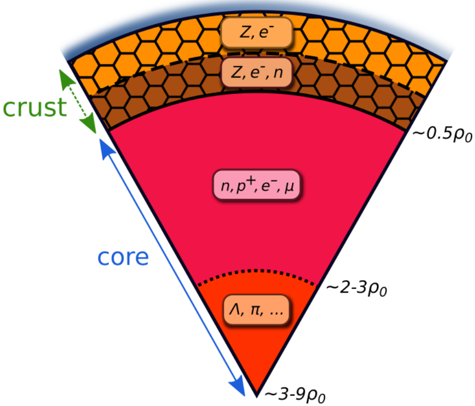

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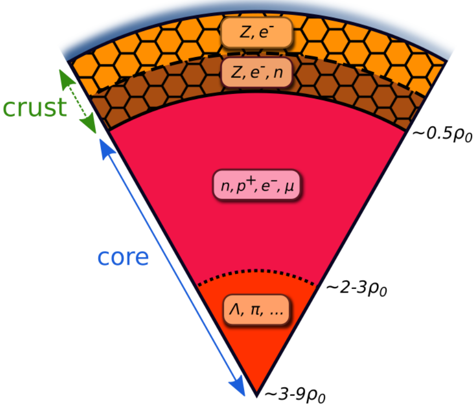

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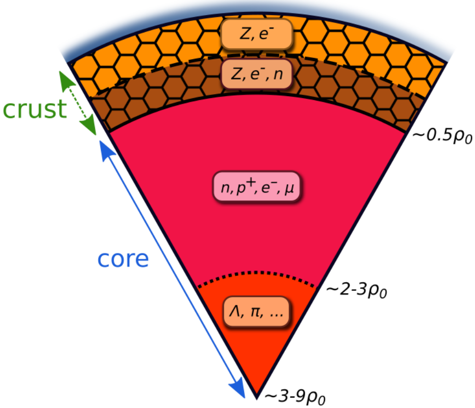

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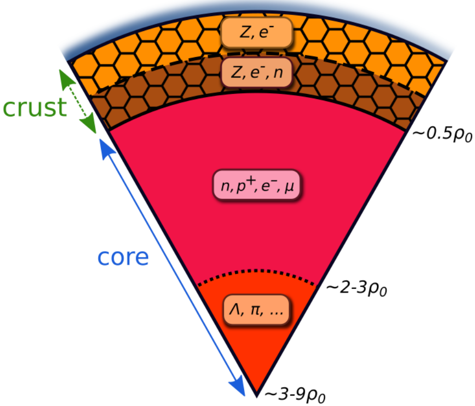

Rk: electrons in neutron stars are **not** superconducting ($T_c \sim 0$).

Nuclear superfluidity and superconductivity in NSs

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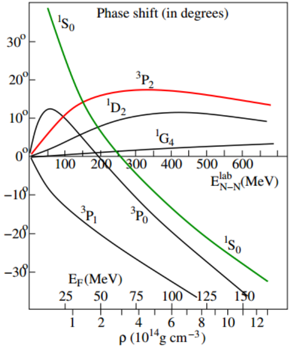
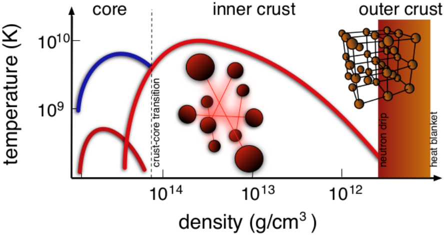
Most attractive pairing channels:

- $^1S_0$ at low densities
  $\hookrightarrow$ similar to e^- in a superconductor
- $^3P_2$ at high densities
  $\hookrightarrow$ similar to superfluid ^{3}He



Critical temperatures



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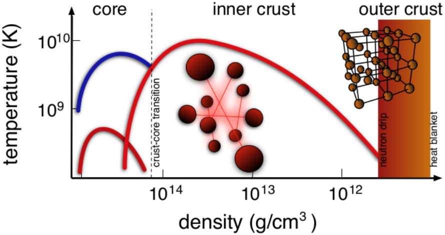

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Since NSs **rapidly cool down** below T_c^{max}, they are expected to contain:

- an *isotropic* $(^1S_0)$ neutron superfluid in the inner crust and in the outer core,
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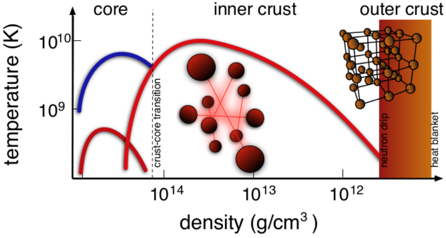

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Rk: other superfluid phases may be present in NSs (e.g. np, $n\Lambda$, $\Lambda\Lambda$, ...)

Dynamics of superfluid NSs

Neutron stars contain (at least!) **two dynamical components**:

- a plasma of charged particles (e^-, nuclei in the crust and p^+ in the core) locked together by the magnetic field,
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Fluid momenta:

$$\begin{cases} \boldsymbol{p}_{\rm n} & = \mathcal{K}^{\rm nn}\boldsymbol{v}_{\rm n} + \mathcal{K}^{\rm np}\boldsymbol{v}_{\rm p} \\ \boldsymbol{p}_{\rm p} & = \mathcal{K}^{\rm pn}\boldsymbol{v}_{\rm n} + \mathcal{K}^{\rm pp}\boldsymbol{v}_{\rm p} \end{cases}$$

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⇢ entrainment effects

The hydrodynamic equations of any **relativistic** superfluid mixtures have been derived by Carter et al., using a *variational formalism*.

Quantized lines

- Neutron superfluid:

$$\kappa = h/(2m_{\rm n}) \quad \dashrightarrow \quad n_v \simeq 6 \times 10^5 \left(\frac{P}{10 \text{ ms}}\right)^{-1} \text{cm}^{-2}$$

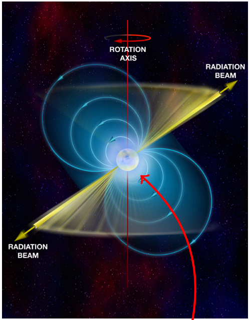
A typical NS contains $\sim 10^{18}$ vortices, which are generally assumed to be **aligned with the rotation axis**.

- The proton superconductor is usually thought to be of type II with $H_{c1} \sim 10^{15}$ G and $H_{c2} \sim 10^{16}$ G.

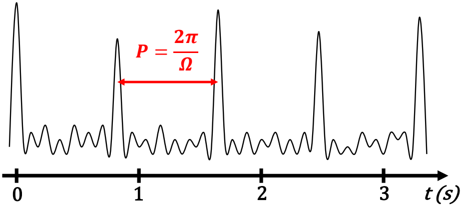
$$\phi_0 = h/(2e) \quad \dashrightarrow \quad n_\Phi \simeq 5 \times 10^{18} \left(\frac{B}{10^{12} \text{ G}}\right) \text{cm}^{-2}$$

A typical NS contains $\sim 10^{30}$ fluxtubes, which may have a **very complex structure**.

The pulsar phenomenon

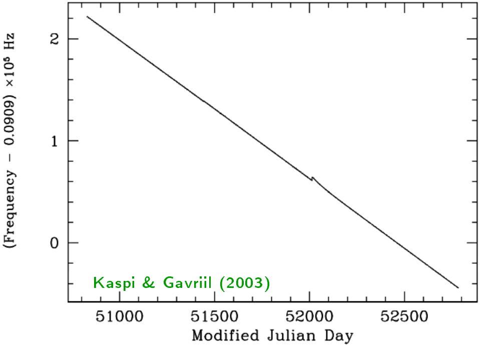


neutron star



The time evolution of P (or f) can be measured with a *very high precision*

Pulsar frequency *glitches*



- Slow *braking* in time
  ↪ emission of EM radiation in the magnetosphere.

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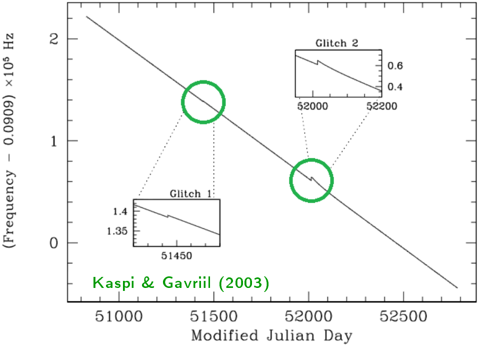

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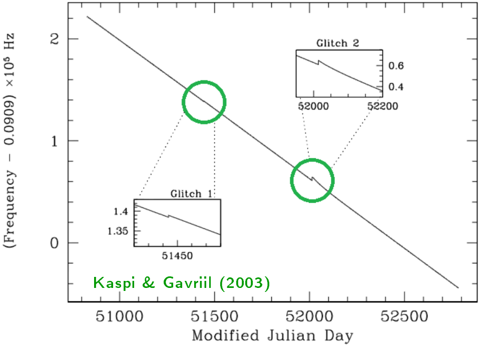

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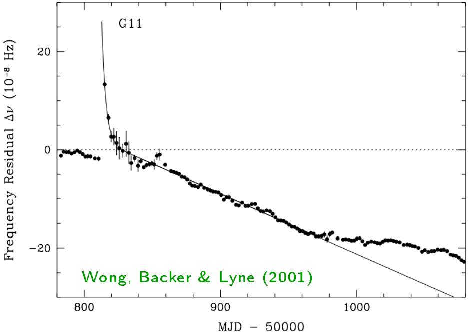
Since 1969, 531 glitches have been observed in 187 pulsars

Pulsar frequency *glitches*



- **amplitude:**

$$\Delta\Omega/\Omega \sim 10^{-11} - 10^{-5}$$

- short **rise time:**

$$\boxed{\tau_r < 30 \text{ s}}$$ ←-- Vela

- exponential **relaxation** on several days or months.

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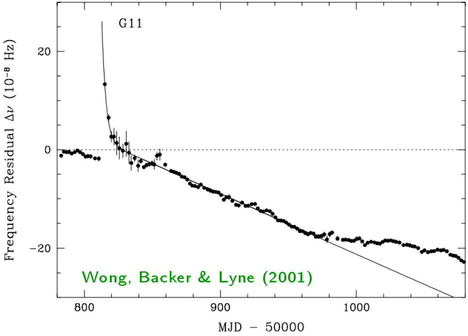

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→ **glitch** = manifestation of an **internal process**
probably related to the presence of **superfluid matter**

Vortex-mediated glitch theory

Anderson & Itoh, *Nature*, 1975

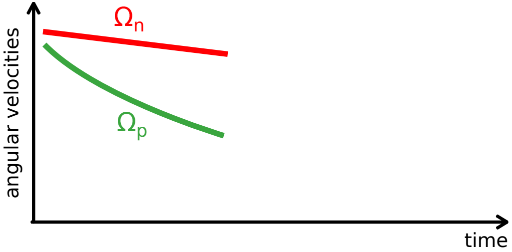
Two-fluid model

- Charged particles:

  $\Omega_p = \Omega \leftrightarrow$ pulsar

- Superfluid neutrons:

  $\Omega_n \gtrsim \Omega_p$



Key assumption: the vortices can **pin** to nuclei in the crust.

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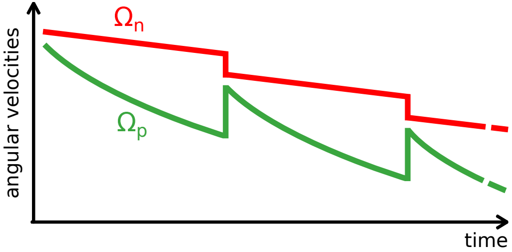

Once a threshold lag $\Omega_n - \Omega_p$ is reached, some vortices get **unpinned** and are allowed to move **radially** ($\Delta\Omega_n < 0$).

⇝ angular momentum transfer between the fluids:

$$\Delta\Omega = -I_n/I_p \times \Delta\Omega_n > 0$$

Vela glitch puzzle

Andersson et al., *PRL*, 2012 & Chamel, *PRL*, 2013

Glitches have been thought to originate from the **crust**.

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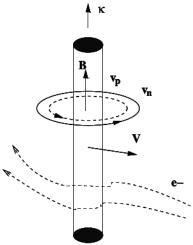

picture from K. Glampedakis

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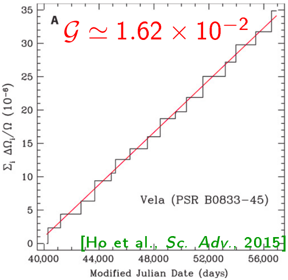

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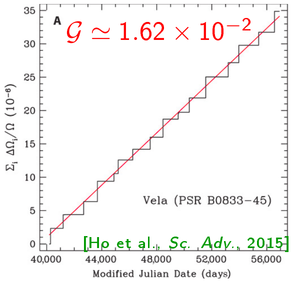

However, this scenario has been recently **challenged** by considering **crustal entrainment effects** ⇢ *the crust is not enough!*

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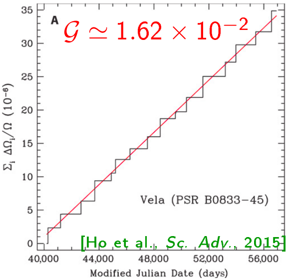

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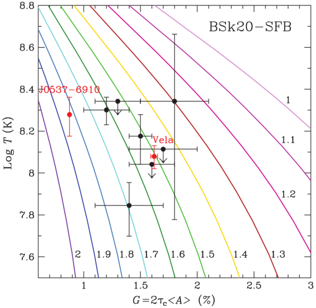
⇢ possible role of the outer core...

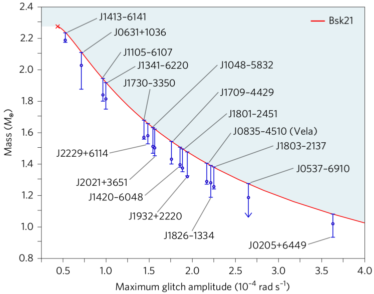
Mass estimates for giant glitchers

Two recent studies have proposed **complementary** methods to constrain pulsar masses from glitch observations.



From T_s^∞/age and $\mathcal{G}$

[Ho et al., *Sc. Adv.*, 2015]



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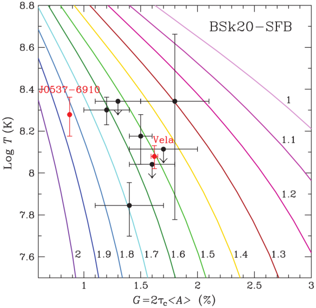

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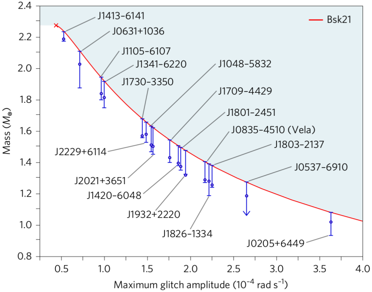

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[Pizzochero et al., *Nat. Astr.*, 2017]

Many ingredients are still poorly known:
⇢ error bars are *largely* underestimated!

Other possible observational manifestations

- rapid cooling of Cassiopeia A,
- thermal relaxation of transiently accreting NSs during quiescence,
- quasi-periodic oscillations in soft gamma-ray repeaters, ...

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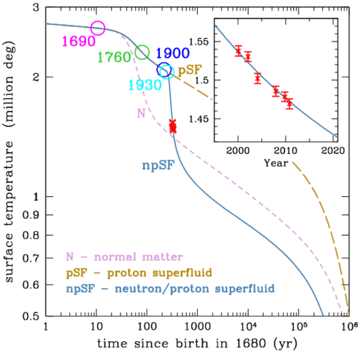
- quasi-periodic oscillations in soft gamma-ray repeaters, ...



[Ho et al., *PoS*, 2013]

Other possible observational manifestations

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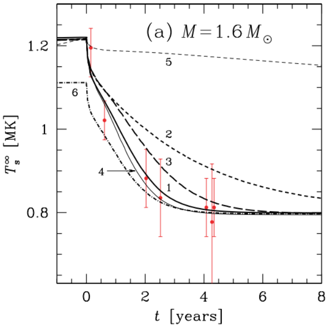

[Shternin et al., *MNRAS*, 2007]

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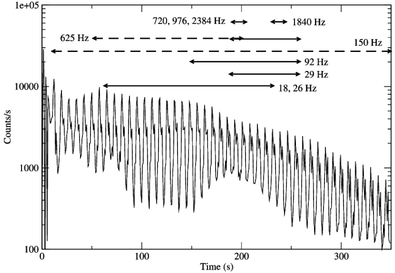

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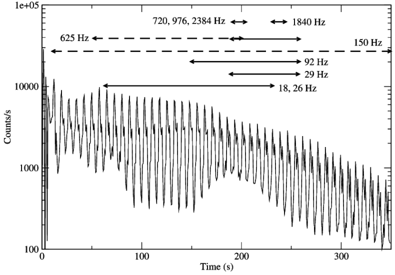


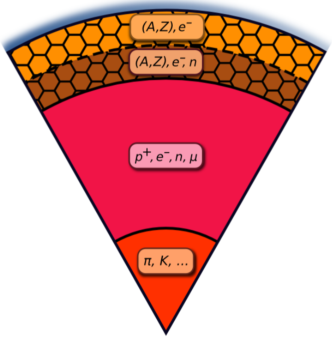
[Strohmayer & Watts, *ApJL*, 2005]

However, many aspects of these phenomena are poorly known...

Conclusion

Nuclear superfluidity in NSs was **predicted** long before the discovery of pulsars. Still, some aspects remain **not very well understood**. (e.g. pairing phases, T_c, hydrodynamics, ...).

What we know with confidence:



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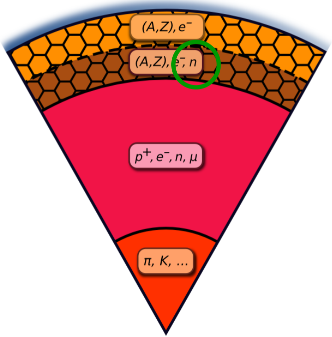

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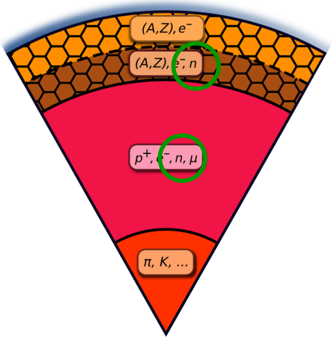

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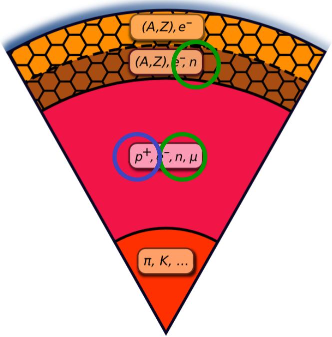

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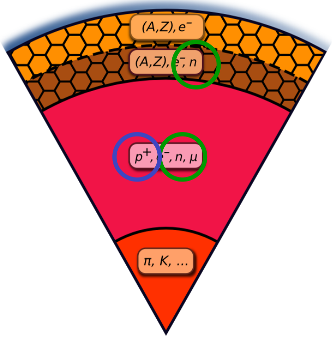

Fortunately, superfluidity leaves its imprint on various astrophysical phenomena: **glitches**, oscillations, cooling, ...

Some references

On superfluidity & superconductivity in NSs:

- J. Sauls, *NATO ASI Series C* **262**, 457- 490 (1989)
- N. Chamel, *Journal of Astrophysics and Astronomy* **38**, 43 (2017)

On glitch models and observations:

- B. Haskell & A. Melatos, *Int. J. of Mod. Phys. D* **24**, 1530008 (2015)
- C. Espinoza et al., *MNRAS* **414**, 1679-1704 (2011)

On cooling:

- D. Yakovlev & C. Pethick, *ARA&A* **42**, 169-210 (2004)

On the impact of superfluidity on the GW emission of NSs:

- K. Glampedakis & L. Gualtieri, *arXiv:1709.07049* (2017)

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Thank you!