Superfluidity in the crust of Neutron Stars: why should we care?

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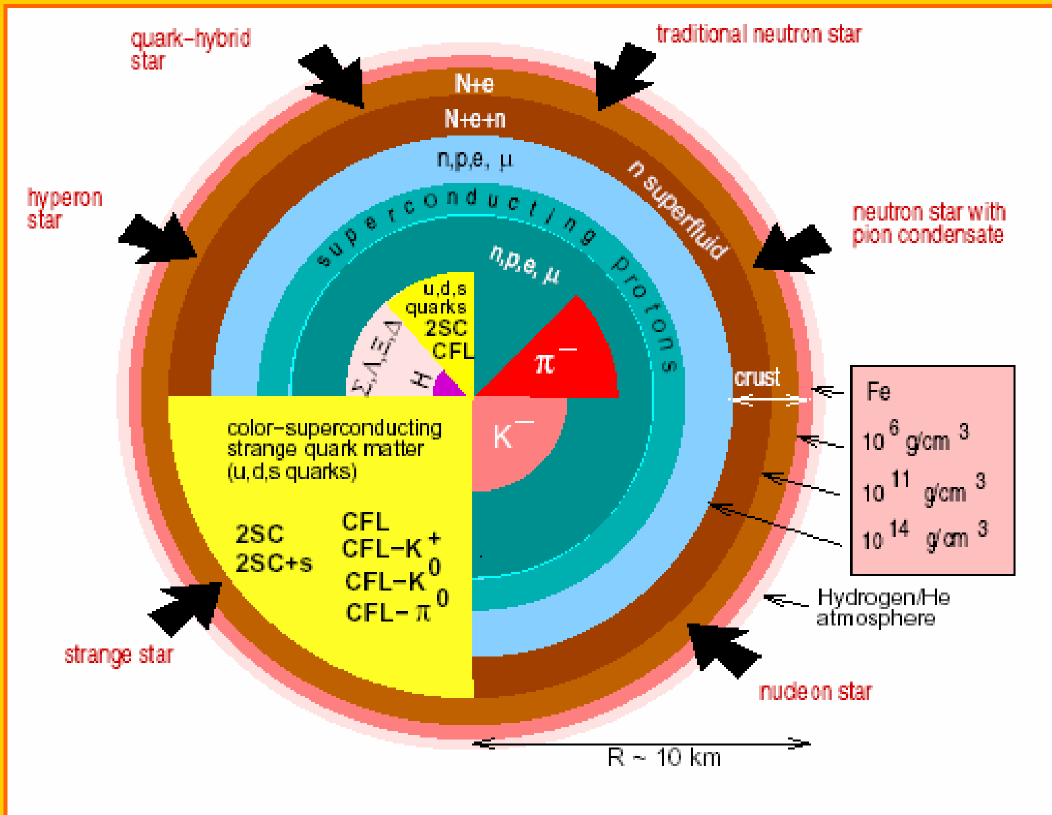
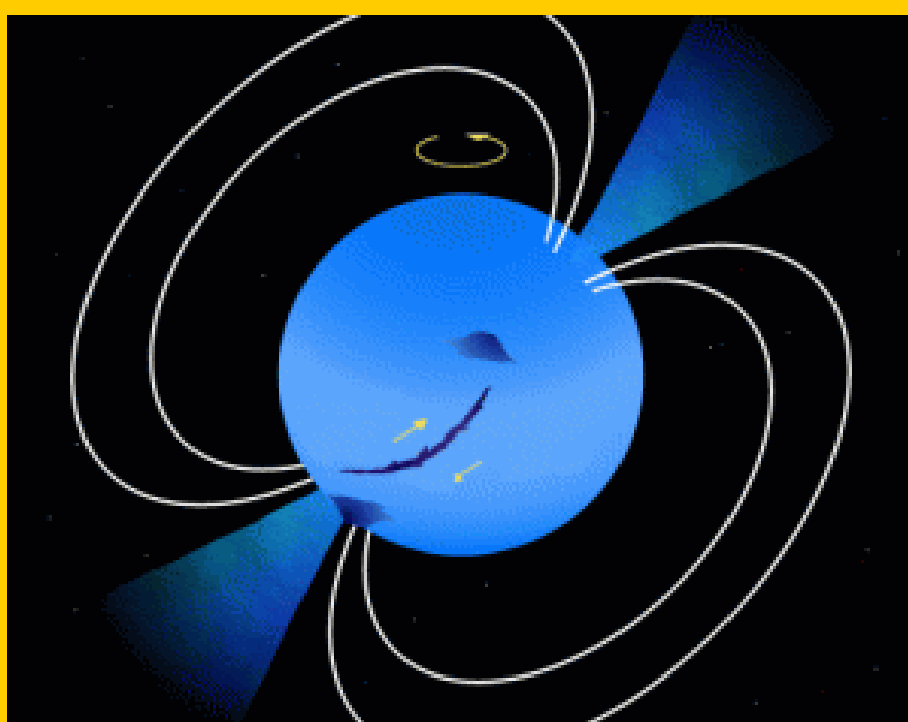
The most exotic laboratory in the Universe…



…can only be observed from the outside!



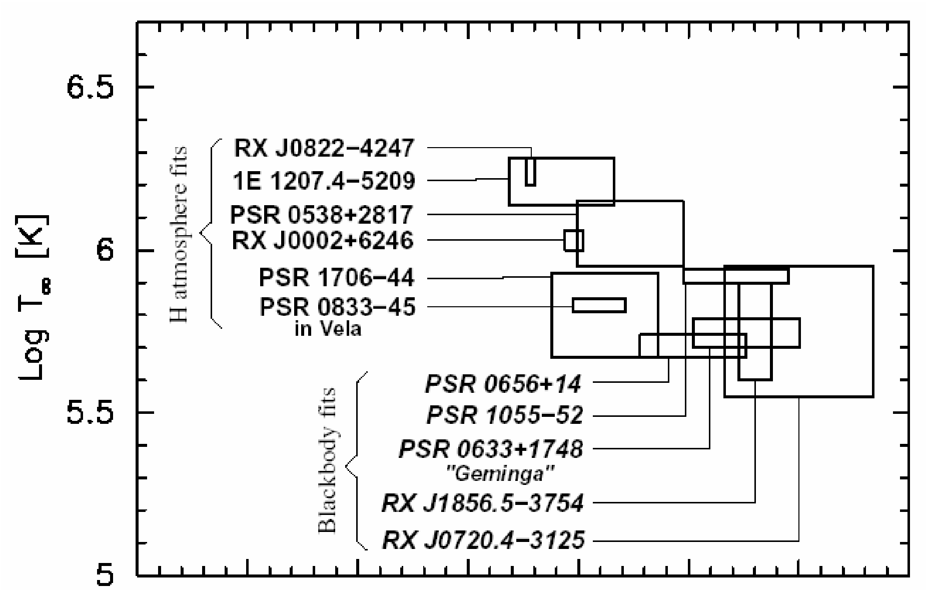
Understanding superfluidity in the crust is crucial because:

1) Crust superfluidity directly determines how properties of the exotic inside are observed from the outside
(cooling of Neutron Stars)

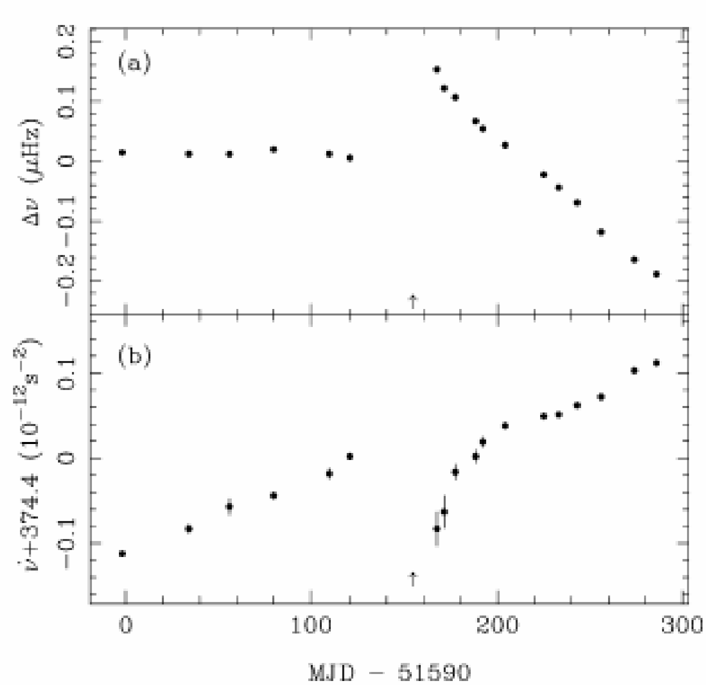
2) Crust superfluidity directly affects additional observables, thus further constraining the structure of Neutron Stars
(fast cooling & Pulsar glitches)

What can be observed

- **Surface temperatures (isolated NS)**

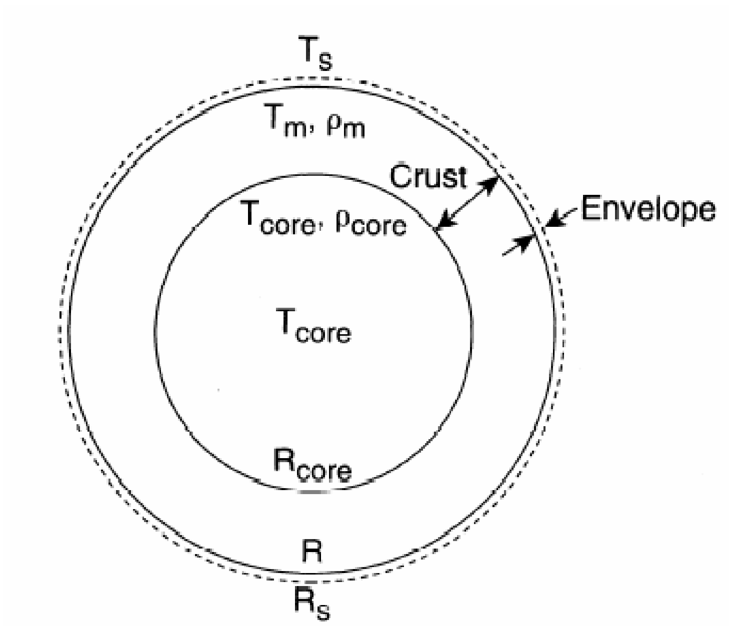


- **Glitches in rotational frequency (Pulsars)**



Inside a neutron star

- **Neutron star structure**



Crust ($\rho > \sim 10^6$ g/cm^3) → relativistic electrons

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neutron-rich nuclei + sub-nuclear neutron matter

- **Crust properties**

thermal → specific heat, emissivity

transport → thermal & electric conductivity, viscosity

nuclear → equilibrium nuclides, pairing

mechanical → elasticity, superfluid motion

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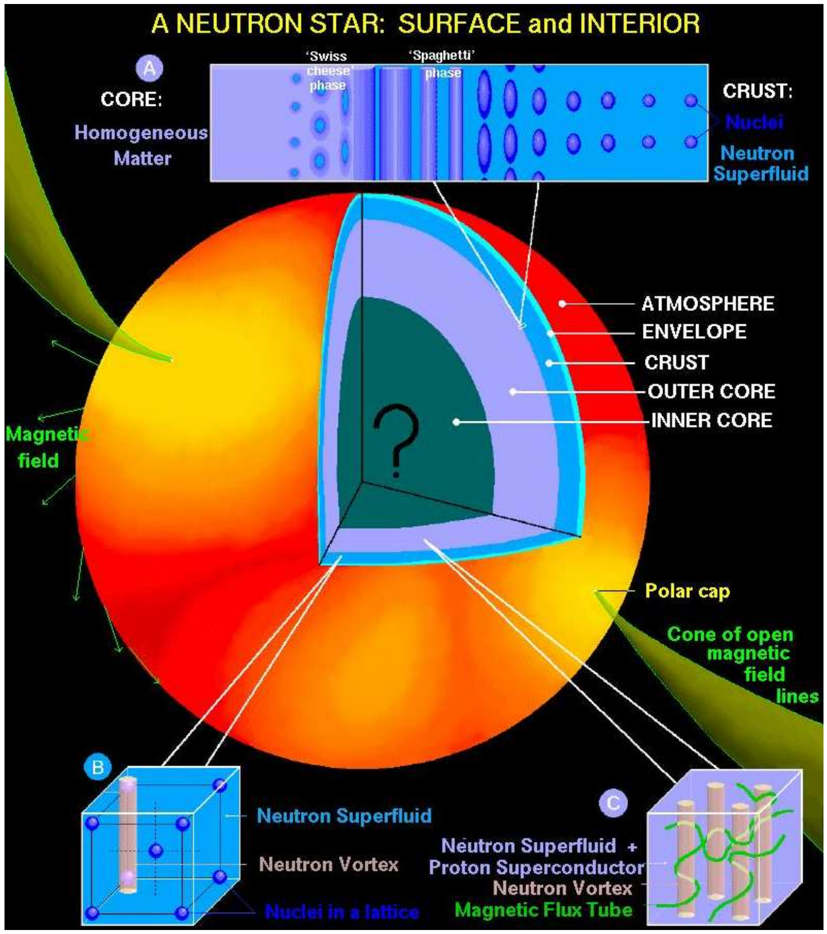
nuclear core ⇒ crust ⇒ observable surface

Superfluidity in Neutron Stars



- **Inner crust** (~10^{11} g/cm^3 < ρ < ~10^{14} g/cm^3)

gas of unbound superfluid neutrons ($^1S_0$ pairing) → n_G

lattice of neutron-rich nuclei (Wigner-Seitz cells) → R_N, R_{WS}

ρ_B	1.5×10^{12}	9.6×10^{12}	3.4×10^{13}	7.8×10^{13}	1.3×10^{14}
n_G	4.8×10^{-4}	4.7×10^{-3}	1.8×10^{-2}	4.4×10^{-2}	7.4×10^{-2}
R_{WS}	44.0	35.5	27.0	19.4	13.77
R_N	6.0	6.7	7.3	6.7	5.2
a	0.77	0.83	0.94	1.12	1.25
N	280	1050	1750	1460	950
Z	40	50	50	40	32
N_{bound}	110	110	110	70	40

Cooling scenarios

- **Standard cooling of core**

modified URCA process ($\Delta t_9 \approx 1$ *yr*)

nucleon-nucleon bremsstrahlung ($\Delta t_9 \approx 40$ *yr*)

$\Downarrow$

low central density $\rightarrow$ low mass NS with stiff EOS

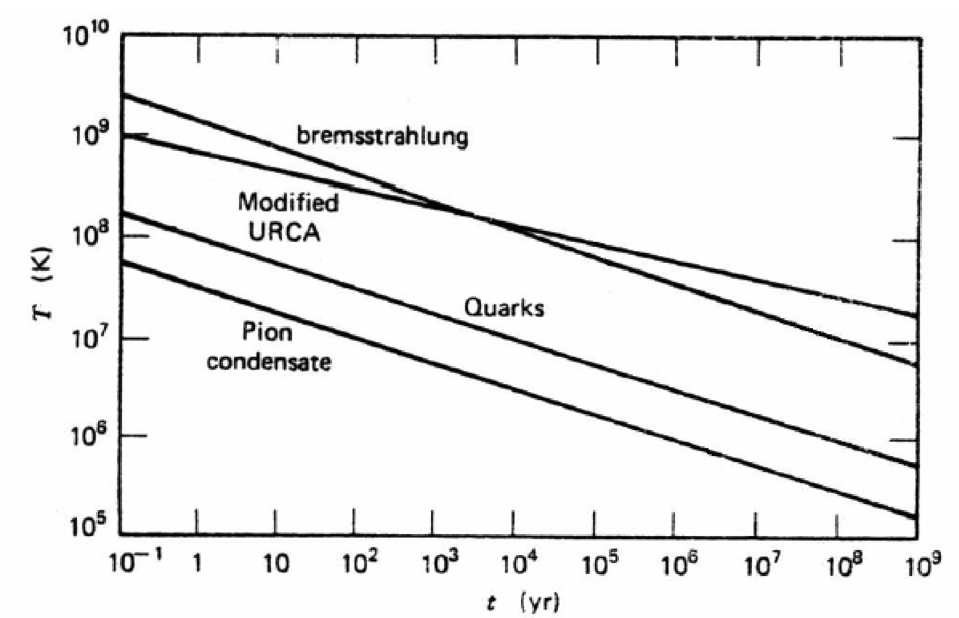
- **Rapid cooling of core**

direct URCA process ($\Delta t_9 \approx 1$ *min*)

exotic β-decays (deconfined quarks, hyperons, meson condensates, $\Delta t_9 \approx 1$ *hr*)

$\Downarrow$

high central density $\rightarrow$ high mass NS or low mass NS with soft EOS



Crust superfluidity and surface temperature

The *program*: cooling as a probe of NS structure

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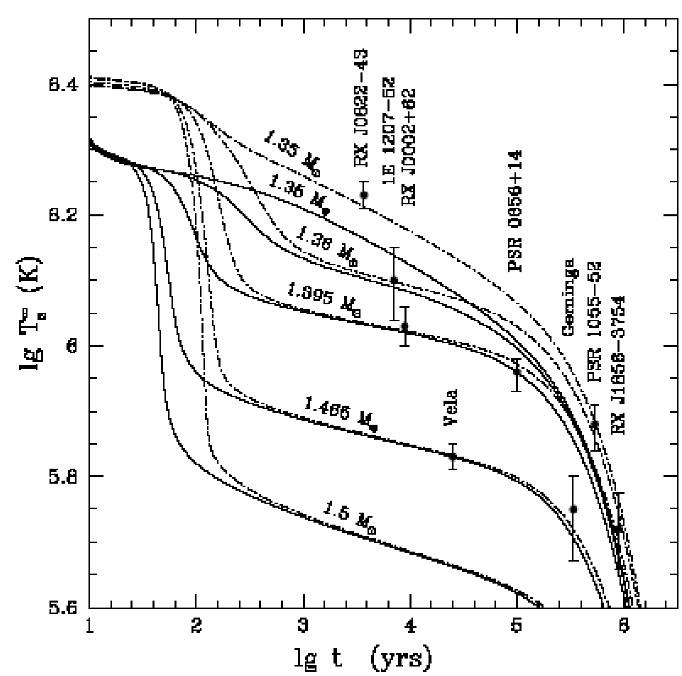

The *problem* to solve: superfluidity in the crust

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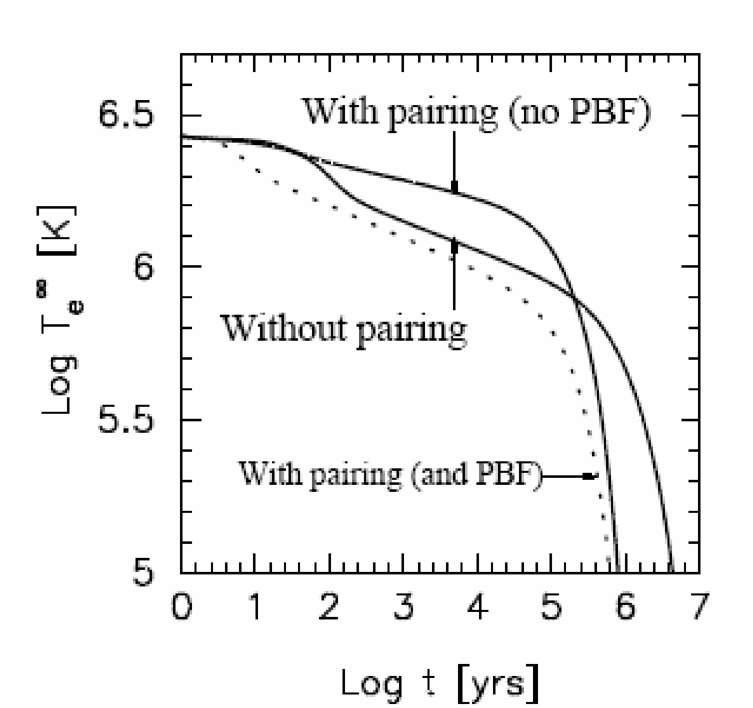
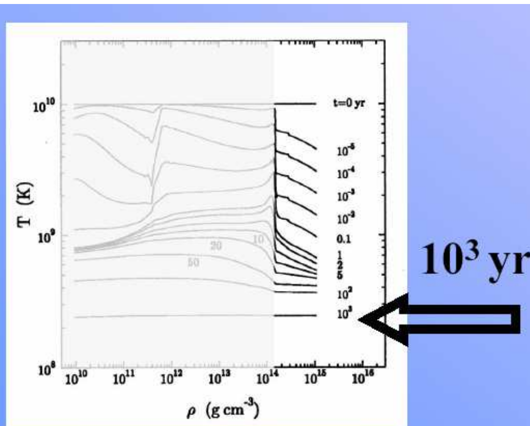


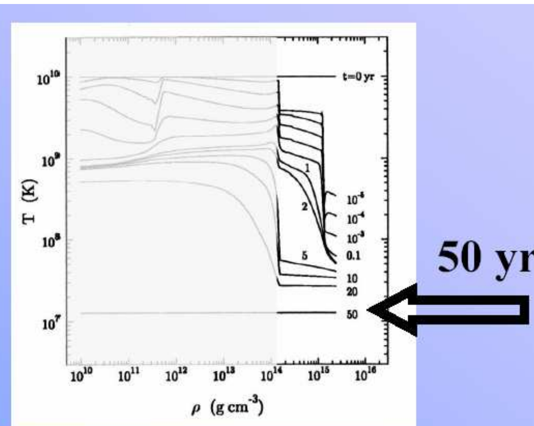
Rapid cooling

- **Temperature evolution**

Core temperature (internal properties)

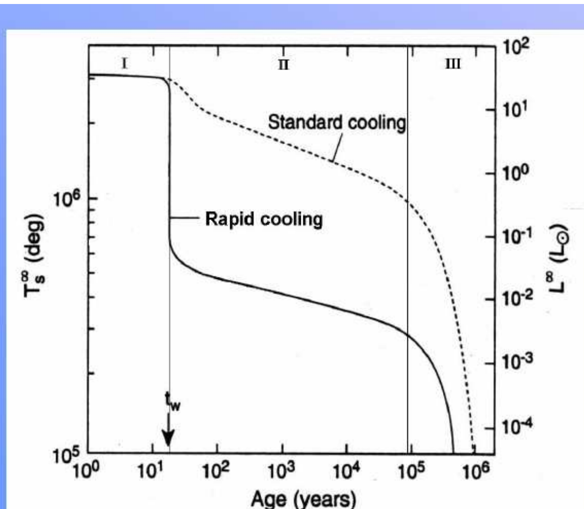


standard cooling



rapid cooling

Surface temperature (observed)



I. Core relaxation epoch
II. Neutrino cooling epoch
III. Photon cooling epoch

crust properties $\Rightarrow$ duration of epoch I (plateau)

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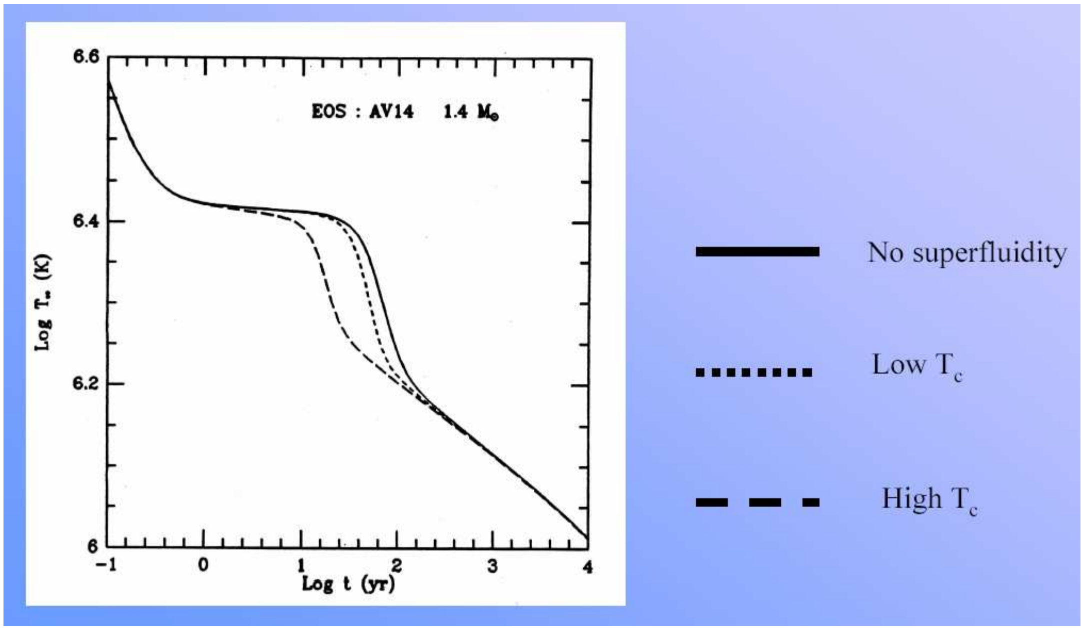
if rapid cooling $\Rightarrow$ observe $\mathbf{t_w}$

Crust superfluidity and rapid cooling



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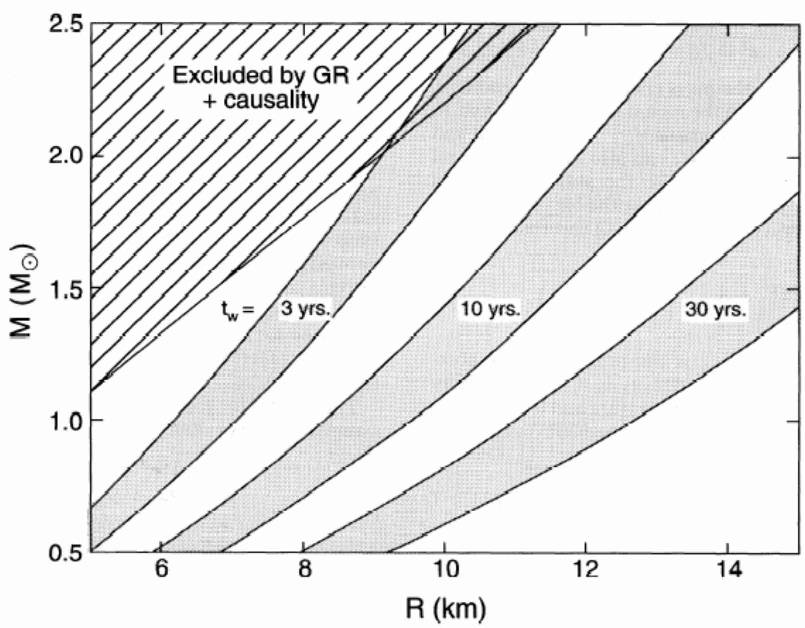
superfluidity ⇒ decrease of C_V ⇒ shorter $\mathbf{t_w}$

Rapid cooling and EOS (LVPP 1994)



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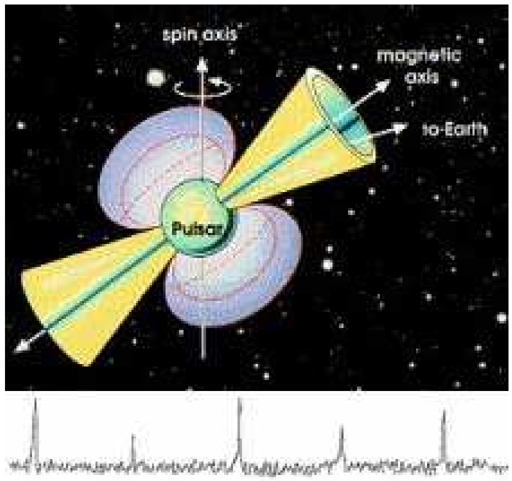
$\mathbf{t_w}$ ⇒ M=M(R) ⇒ constraint on EOS

Pulsar glitches

- **Pulsar slow-down**



emission of e.m. and gravitational waves $\rightarrow \dot{E}_{em} > 0$

isolated neutron star $\rightarrow \dot{E}_{tot} = \dot{E}_{em} + \dot{K}_{rot} = 0$

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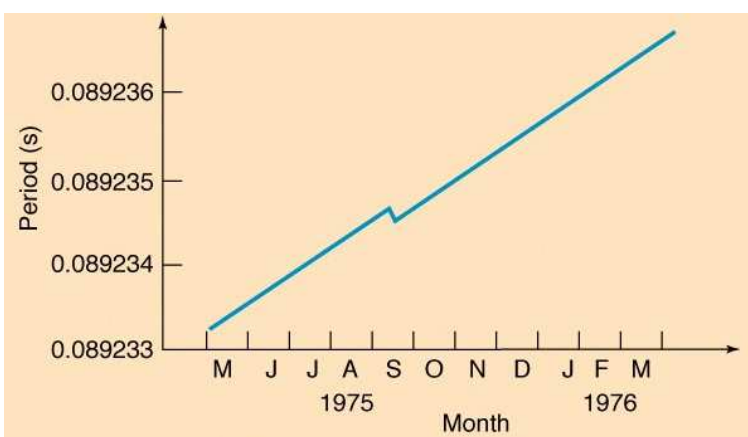
decrease of rotational frequency $\rightarrow \dot{\Omega} < 0$

- **Rotational glitches**

spin-ups $\rightarrow \frac{\Delta\Omega}{\Omega} \approx 10^{-6}$ (Vela) $\frac{\Delta\Omega}{\Omega} \approx 10^{-8}$ (Crab)

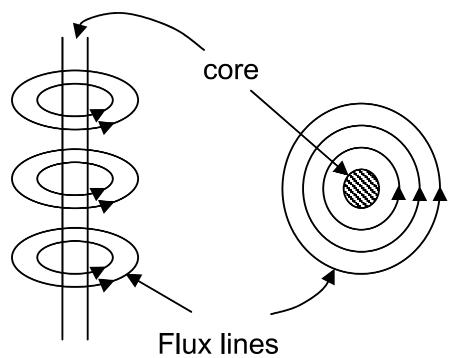


Vortex theory for glitches

- **Quantized vortex lines**

superfluid $\rightarrow$ irrotational flow $\rightarrow$ $\vec{\nabla}\times\vec{v}_s = 0$

classical vortex $\rightarrow$ $\vec{v}_s = \frac{C}{r}\hat{e}_\theta$ $\rightarrow$ $\vec{\nabla}\times\vec{v}_s = 2\pi C\,\delta^{(2)}(\vec{r})\hat{e}_z$



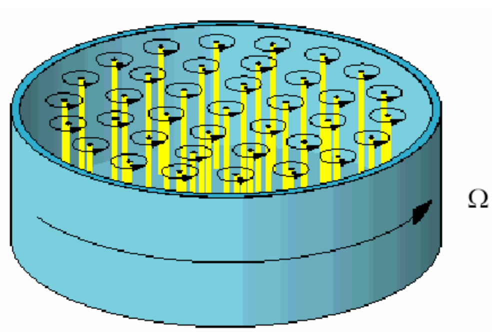
quantized vortex lines $\rightarrow$ $C = k\,\frac{\hbar}{2m_N}$ $\quad (k = 1,2,\cdots)$

quantized vorticity $\rightarrow$ $\oint \vec{v}_s \cdot d\vec{l} = k\,\frac{h}{2m_N}$ $\quad (k = 1,2,\cdots)$

- **Rotating vessel: Feynman-Onsager formula**

$\vec{\nabla}\times(\vec{\Omega}\times\vec{r}) = 2\vec{\Omega} \neq 0$ $\rightarrow$ no rigid rotations $\vec{\Omega}$

array of parallel vortices (if $\Omega >> \Omega_{cr}$) $\rightarrow$ $<\vec{v}_s> = \sum_i \vec{v}_{si}$



E_Ω minimized by $<\vec{v}_s> = \vec{\Omega}\times\vec{r}$

$\Downarrow$

uniform density of vortices $\rightarrow$ $n_v = \frac{N_v}{\pi R^2} = \frac{4m_N}{h}\Omega$

$\Downarrow \Downarrow$

superfluid angular momentum quantized in vortices

Vortex pinning and Magnus force

if superfluid vortices are pinned $\rightarrow$ $\dot{n}_v = 0$ $\rightarrow$ $\dot{\Omega}_s = 0$

but slow-down of normal component $\rightarrow$ $\dot{\Omega}_n < 0$

$\Downarrow$

rotational lag of components $\rightarrow$ $\Delta\Omega = \Omega_s - \Omega_n > 0$

outward drag force on vortex $\rightarrow$ $f_{mag} \propto \Delta\Omega$

Vortex un-pinning and glitches

since $\Delta\dot{\Omega} > 0$ $\rightarrow$ f_{mag} increases with time

pinning energy $\rightarrow$ maximum pinning force f_{pin}

when $f_{mag} \geq f_{pin}$ $\rightarrow$ unpinning of many vortices

$\Downarrow$

transfer of angular momentum to the star surface

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normal component spin-up $\Rightarrow$ pulsar glitch

Vortex energy in the inner crust

inner crust (nuclei + neutron gas) $\rightarrow$ $n_N >> n_G$

vortex energy density is density-dependent $\rightarrow$ $\varepsilon_s = \varepsilon_s(n)$

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presence and position of nuclei modify $\varepsilon_s(n)$

Vortex-nucleus interaction and pinning

vortex-nucleus configurations in nuclear lattice

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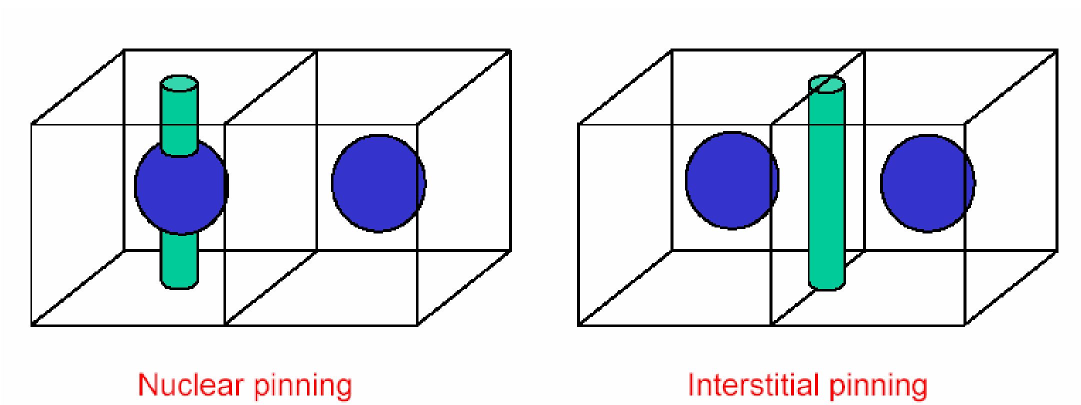

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E_{NP} E_{IP}

pinning energy $\rightarrow$ $\Delta E_{pin} = E_{NP} - E_{IP}$

$\Downarrow$

$\Delta E_{pin} < 0 \Rightarrow$ nuclear pinning

$\Delta E_{pin} > 0 \Rightarrow$ interstitial pinning (*superweak*)

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Glitches as evidence of macroscopic superfluidity!