Fluids ECR Forum
University of Leeds

The Superfluid Neutron Star Interior

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Institute of Space Sciences (ICE-CSIC)

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NEUTRON STARS IN A NUTSHELL

formed in supernova explosions

mainly contain neutrons

strongest magnets known

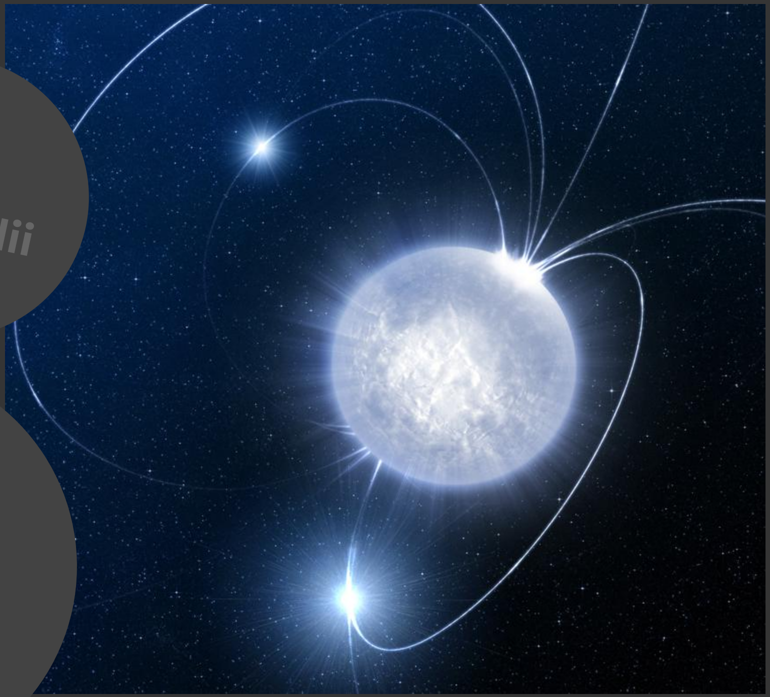
~1.4 solar masses

~10 km radii

rotate up to ~700 times per second

densities exceed those of atomic nuclei

Artist illustration of a neutron star and its dipolar magnetic field.



Credit: ESO, L. Calçada

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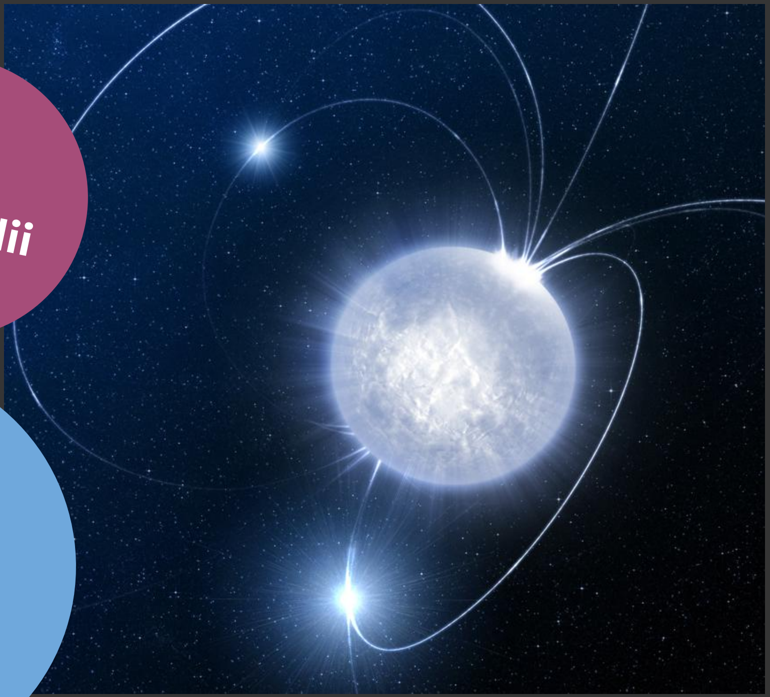

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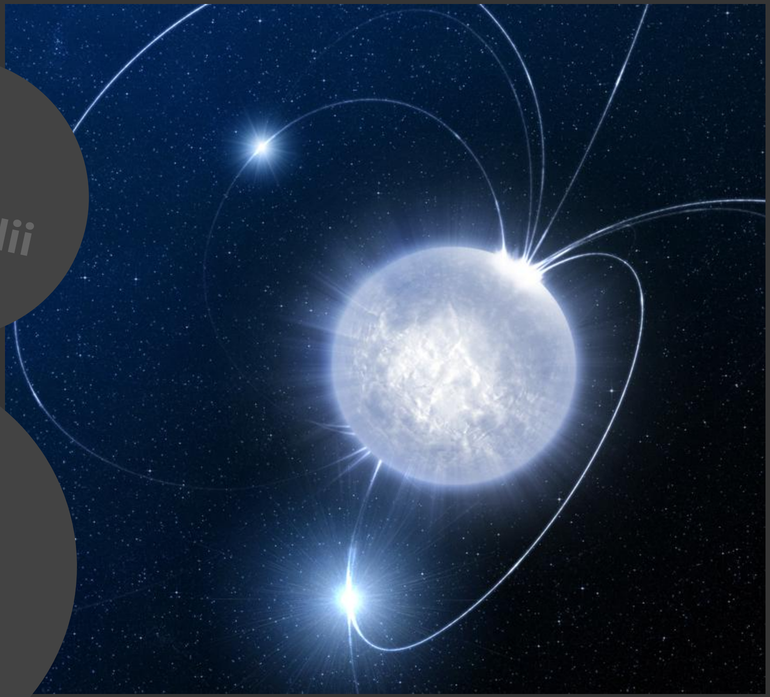

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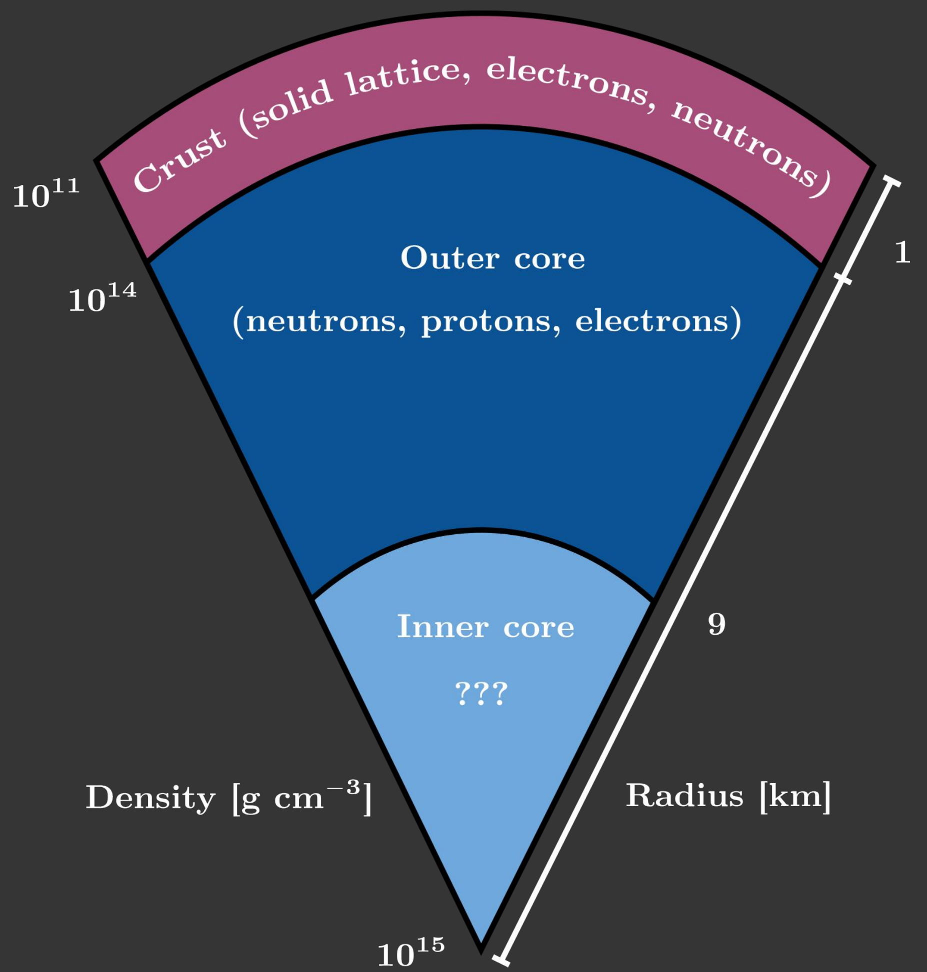
NEUTRON STAR INTERIORS

Their structure is complex and influenced by the (unknown) equation of state.

after 10^4 yrs tempera-tures reach ~10^6-10^8 K

structure is layered much like the Earth

decompose into solid crust and fluid core



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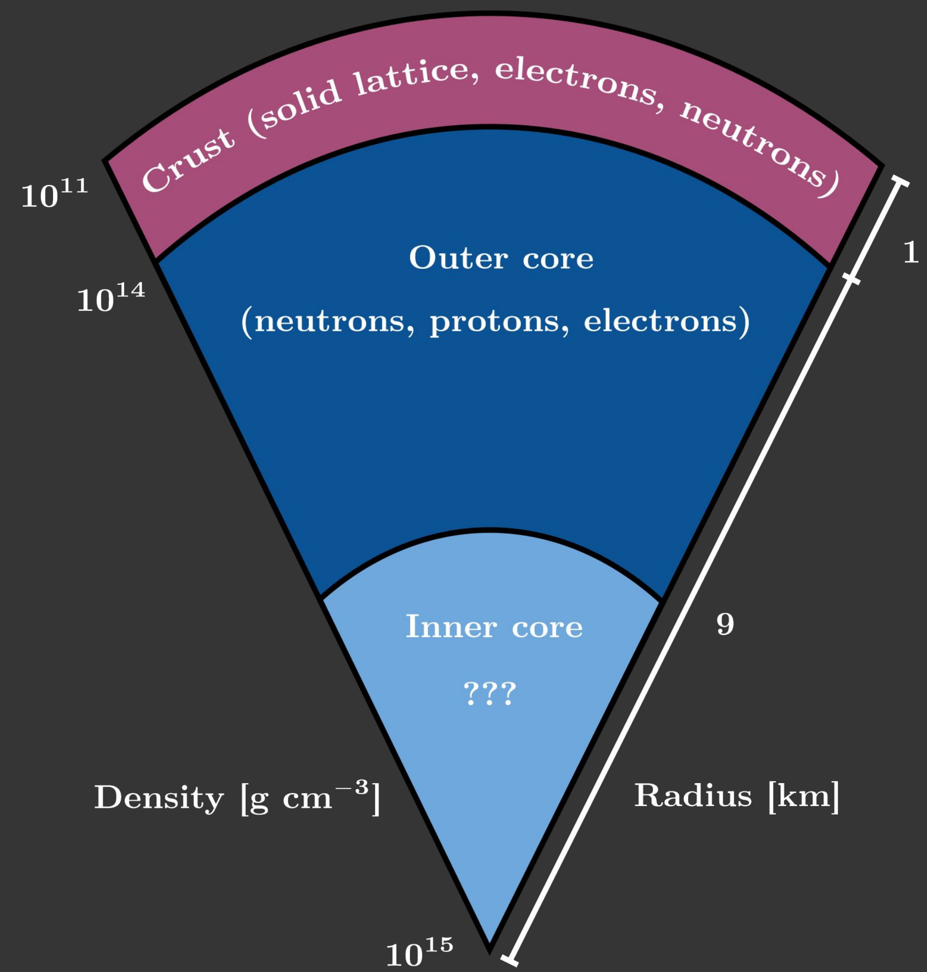

SUPERFLUID COMPONENTS

Although neutron stars are hot compared to laboratory experiments, they are very cold in terms of their densities.

nucleons can form Cooper pairs

transition analogous to lab SCs

at least 3 SF com-ponents

superfluids can flow without friction

Large numbers of particles condense into the same quantum state, which is characteristic for macroscopic quantum phenomena.

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Credit: NOAA Photo Library

Superfluids can be characterised by a QM wave function, which satisfies the Schrödinger equation.

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arrange in a regular lattice

Imagine vortices like tiny, rapidly rotating tornadoes.

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HVBK-TYPE EQUATIONS

Ideal superfluids often coexist with a second component, leading to distinct two-fluid behaviour.

nature of the second component depends on the system

obtain two momentum / continuity equations

vortices contribute directly via tension and mutual friction

Hydrodynamical / macroscopic description of both components:

inertial terms + pressure / temperature gradients **=** viscous terms + vortex tension + mutual friction + magnetic forces

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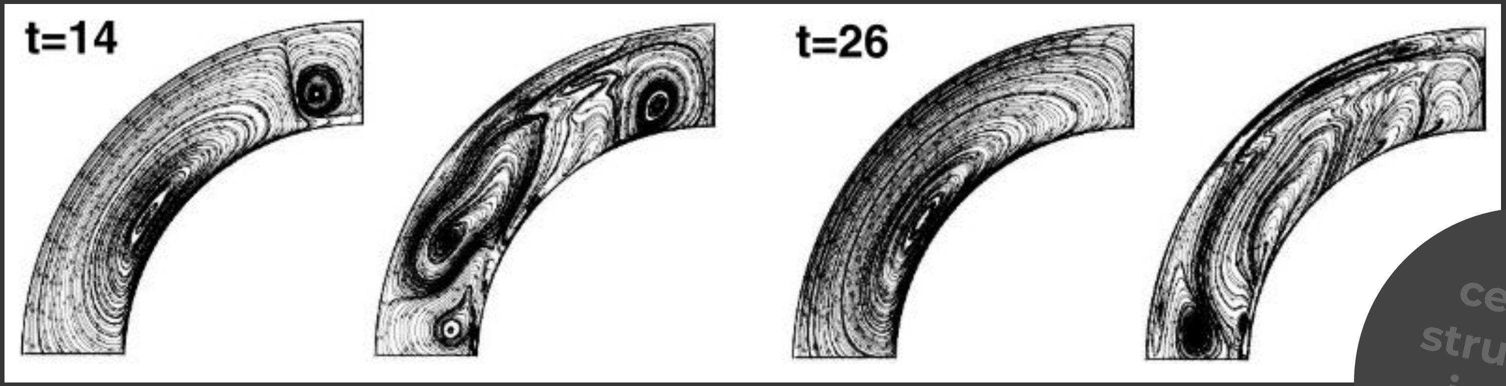
CRUSTAL NEUTRON STAR SHELL

Example: Peralta et al. (2005) evolved the NS HVBK equations for a rotating, spherical shell.

model crustal dynamics

evolution following steady differential rotation

Streamlines for normal (left) and superfluid (right):



Credit: see Fig. 1 in Peralta et al. (2005)

cell-like structures in both fluids

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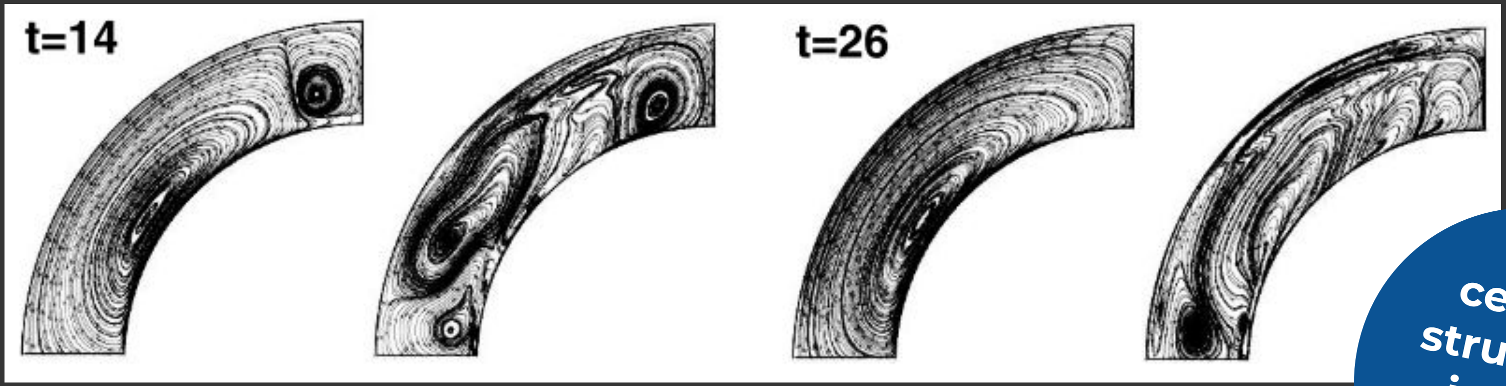

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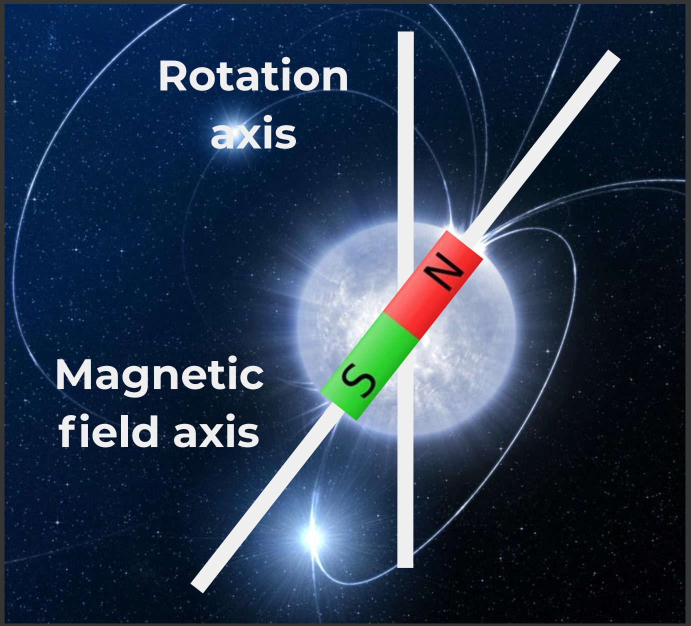
PULSAR TIMING

Because rotation and magnetic field axes are misaligned, NSs emit radio radiation like a lighthouse.



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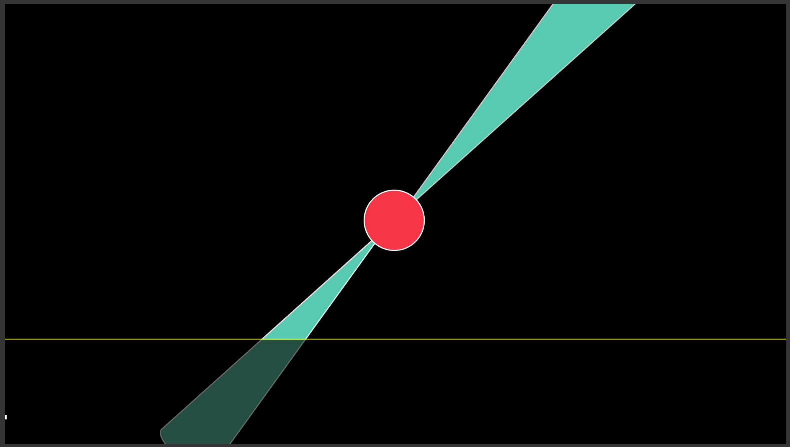

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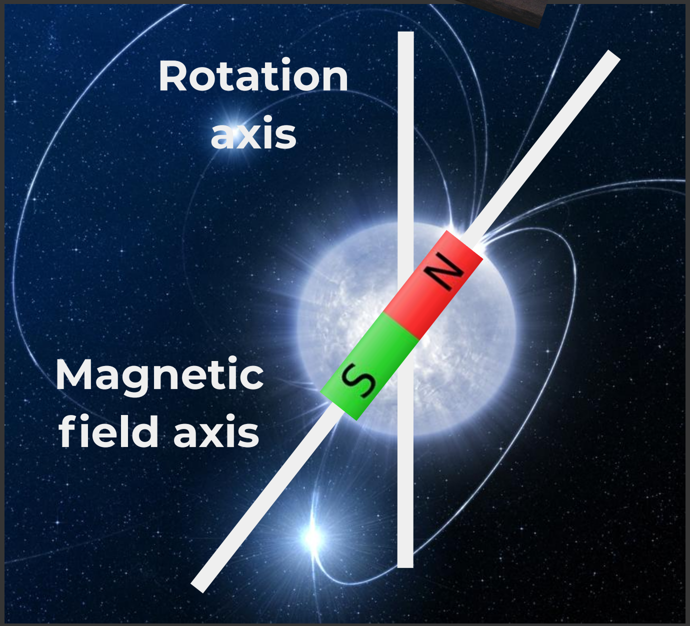

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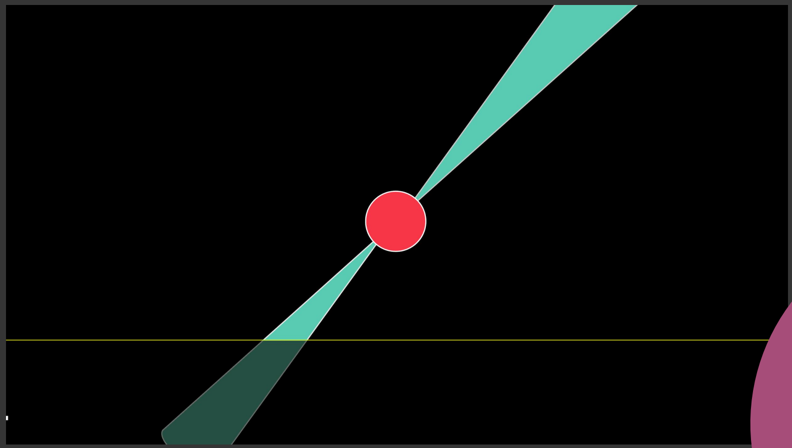

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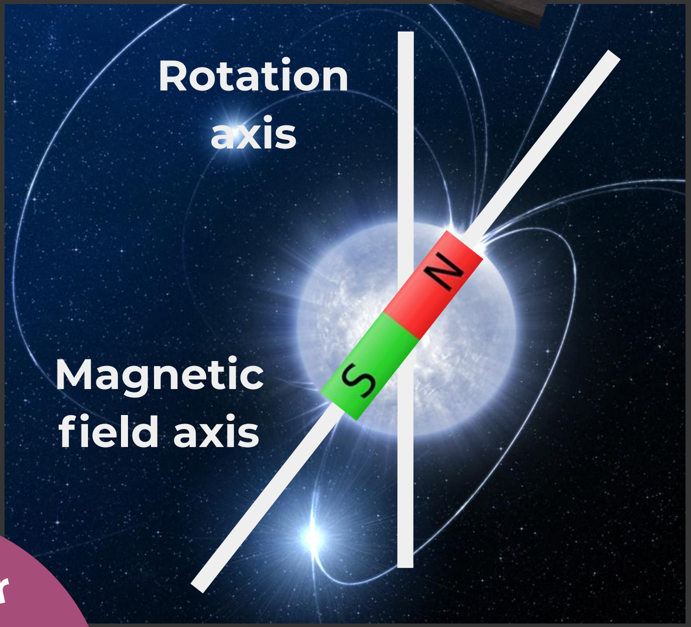
time pulsar radiation to learn about their interiors



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PULSAR GLITCHES

The regular spin-down of NSs can be interrupted by sudden spin-ups.

naturally explained in two-com-ponent models

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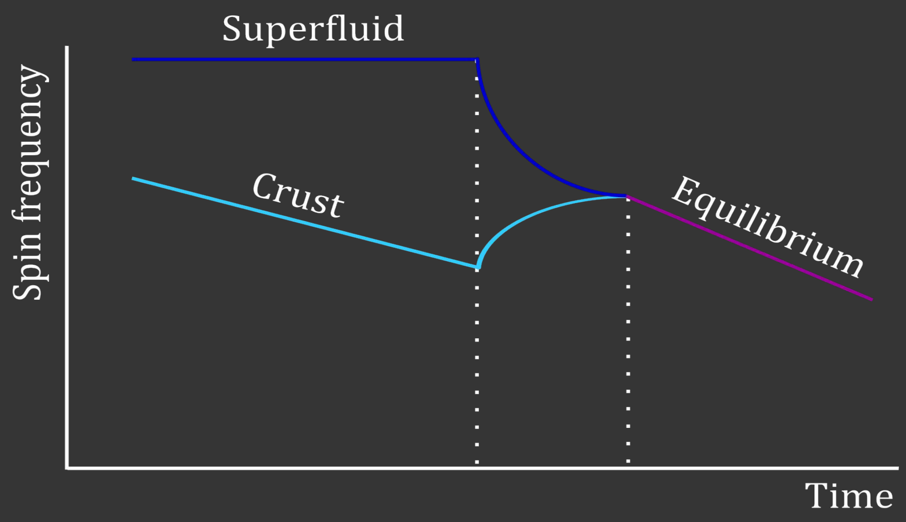
Superfluid spin-down can be prevented by vortex pinning.



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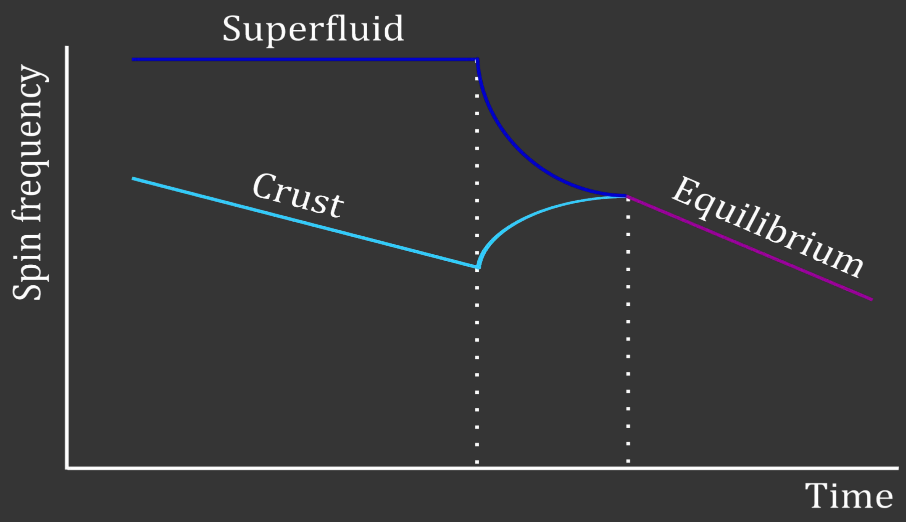

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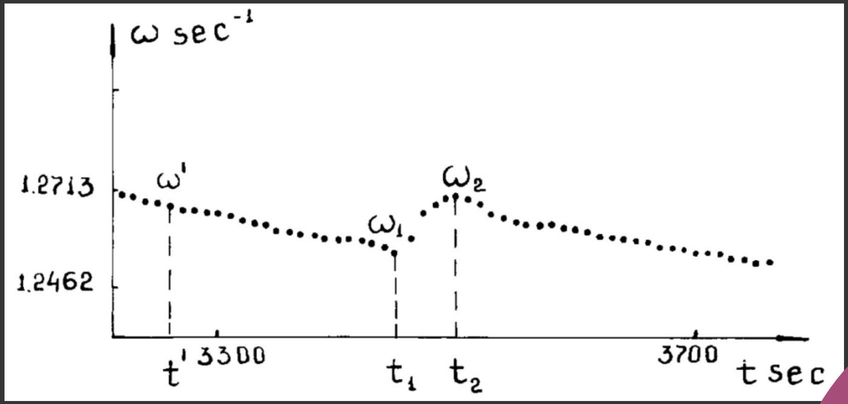
TAKE-HOME MESSAGES

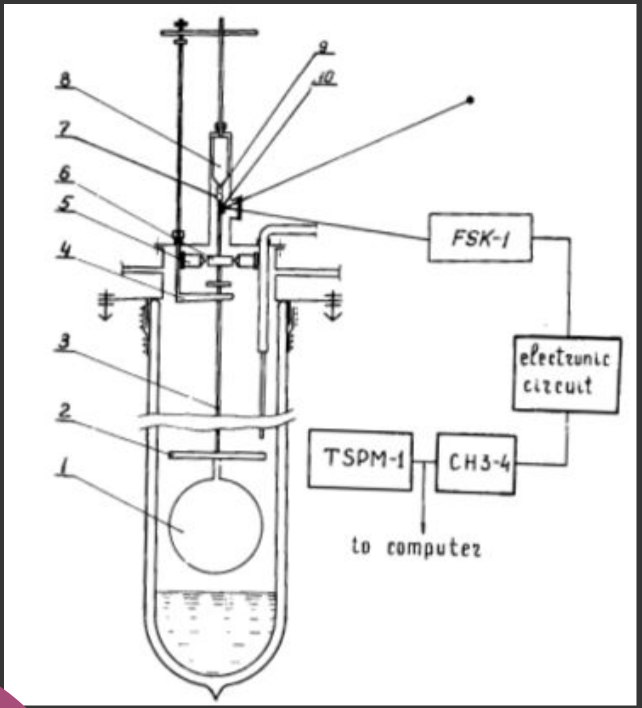
- NSs contain at least 3 SF compo-nents
- SFs rotate by forming vortices
- understan-ding vortex dynamics is crucial to model pulsar glitches
- vortices affect dynamics via tension and mutual friction
- pulsar glitches are a macroscopic manifestation of quantum vortices

LABORATORY ANALOGUES

In the 1970s, Tsakadze and Tsakadze performed a systematic analysis of Helium II spin-up.



Credit: Tsakadze & Tsakadze (1980)



Credit: Tsakadze & Tsakadze (1980)

with their very basic set-up they might have detected a glitch