Geo/Astrophys. Fluid Dynamics Seminar

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Neutron Stars: Astrophysical Superfluids

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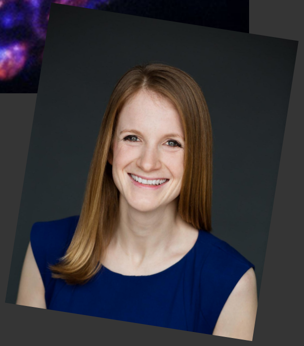
Oct 10th, 2023

Cassiopeia A supernova remnant
(credit: NASA/CXC/SAO)



NEUTRON STARS IN A NUTSHELL

formed in supernova explosions

mainly contain neutrons

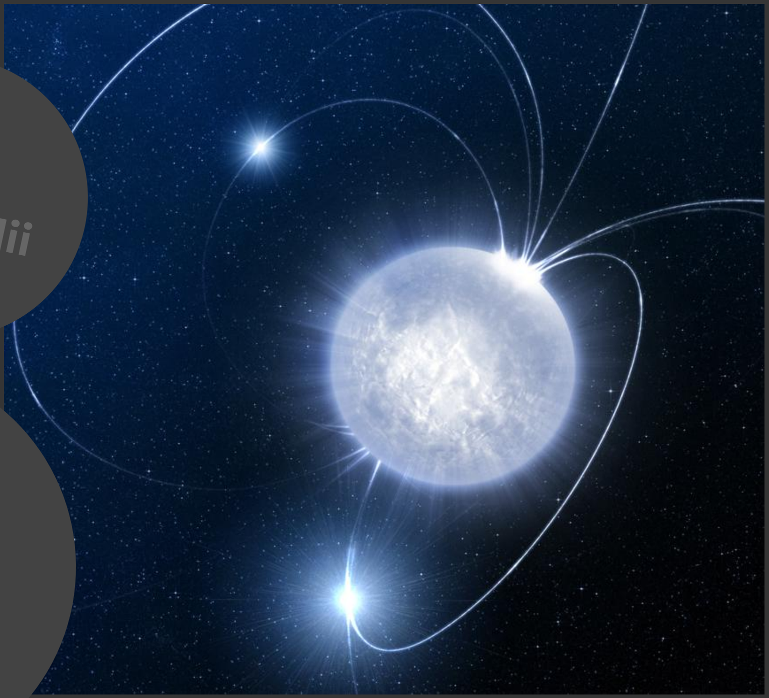
strongest known magnets

~1-2 solar masses

~10 km radii

rotate up to ~700 times per second

densities exceed those of atomic nuclei



credit: ESO, L. Calçada

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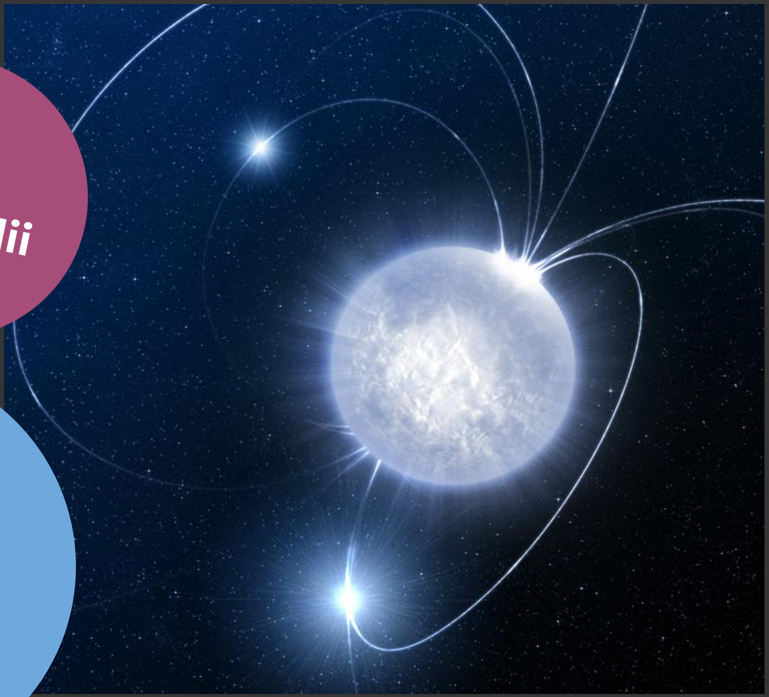

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NEUTRON STARS IN A NUTSHELL

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

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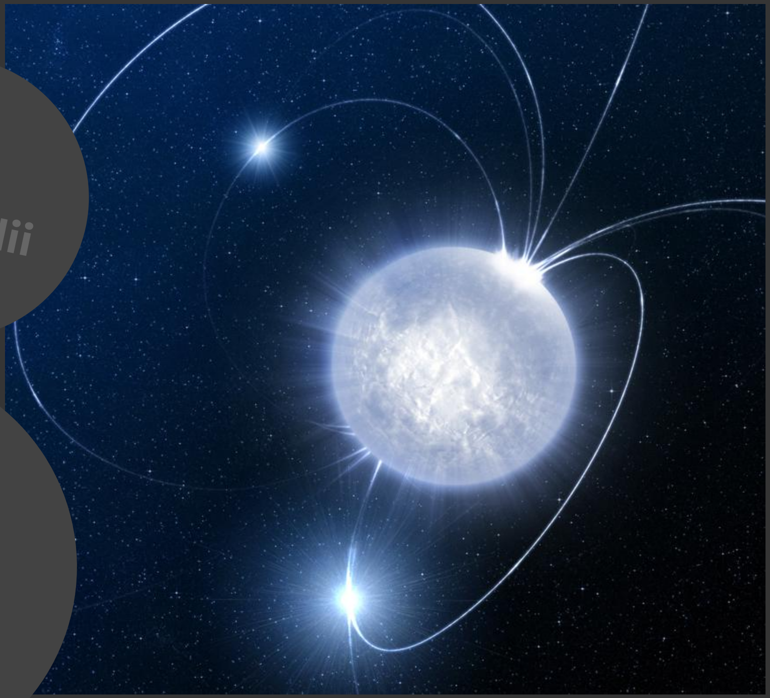

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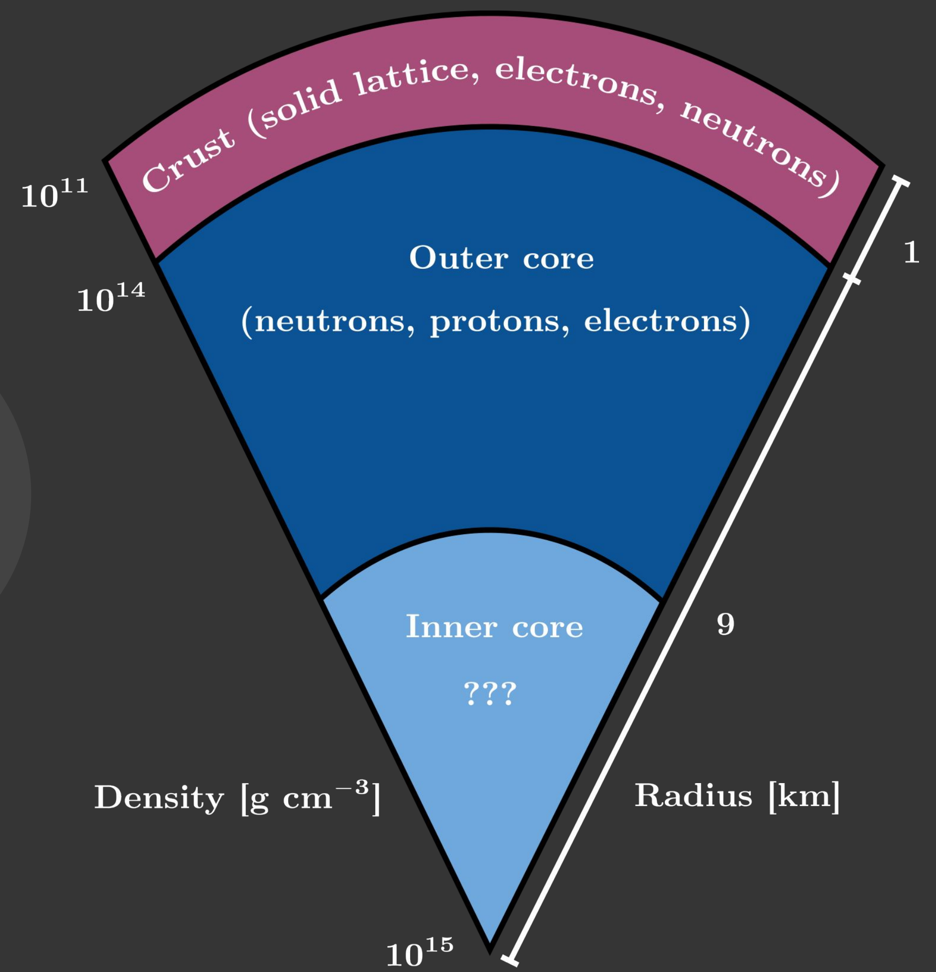
NEUTRON STAR INTERIORS

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

after 10^4 yrs temperatures reach ~10^6-10^8 K

structure is layered much like the Earth

decompose into solid crust and fluid core



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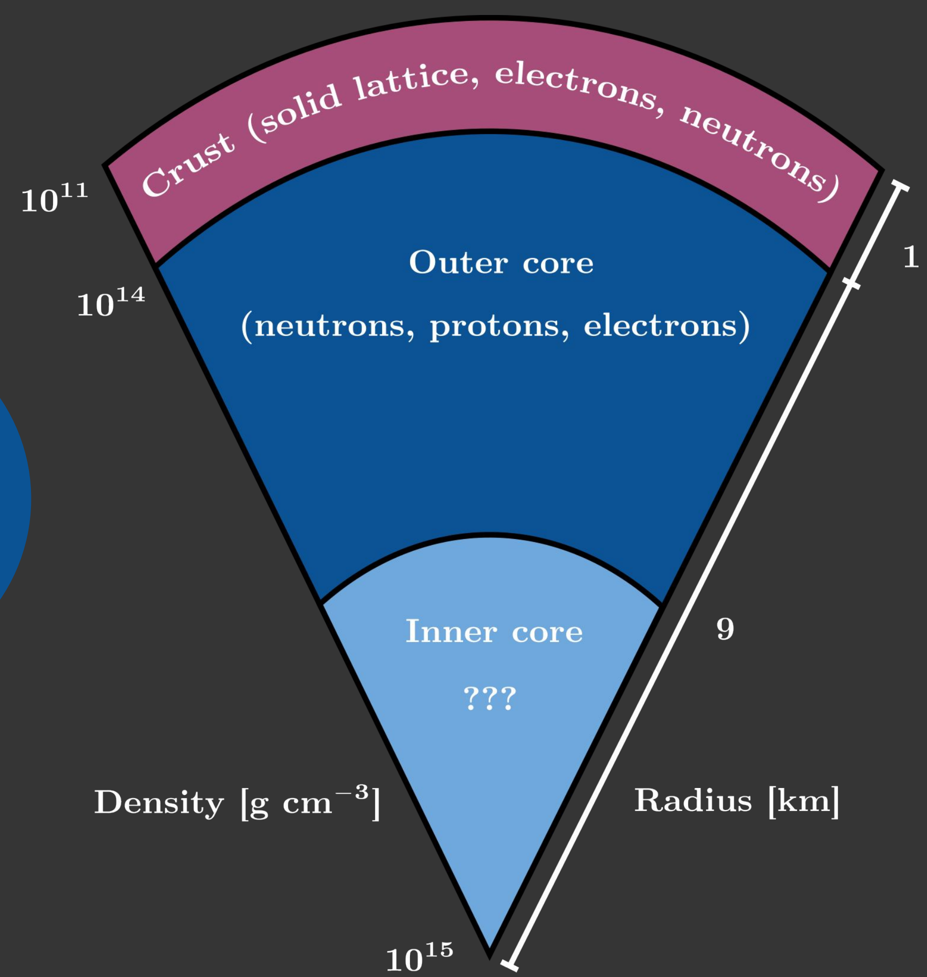

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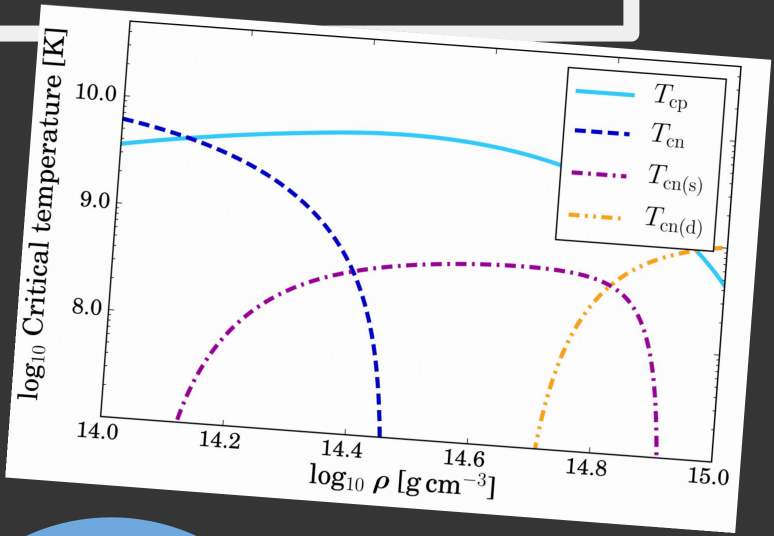
SUPERFLUID COMPONENTS



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

superfluids can flow without friction

at least 3 SF components

fermionic nucleons can form Cooper pairs

transition analogous to lab SCs

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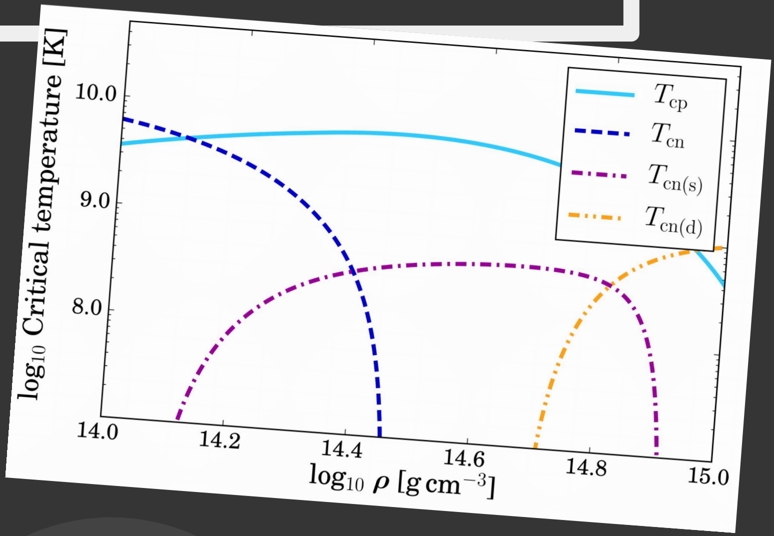

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at least 3 SF com-ponents

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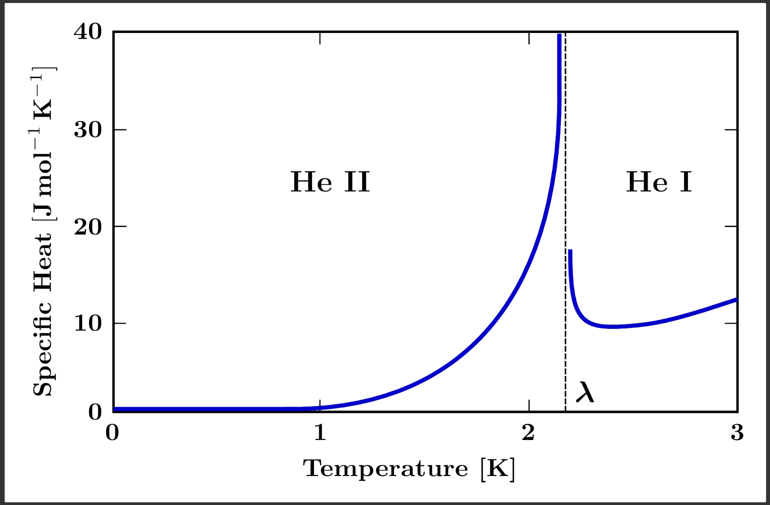
transition analogous to lab SCs

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

SUPERFLUID HELIUM



At low temperatures, helium-4 does not solidify but enters a new fluid phase.

- heat capacity resembles the Greek letter λ
- helium II behaviour explained by two-fluid model
- normal component: viscous properties & heat transport
- inviscid component: SF features

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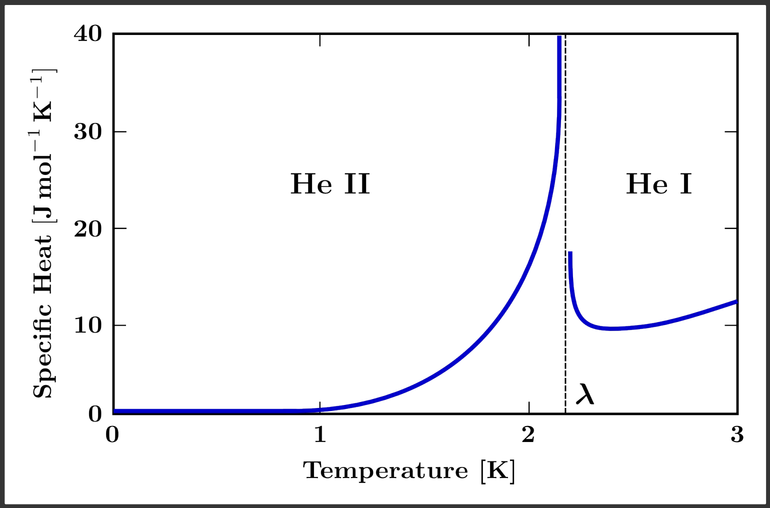
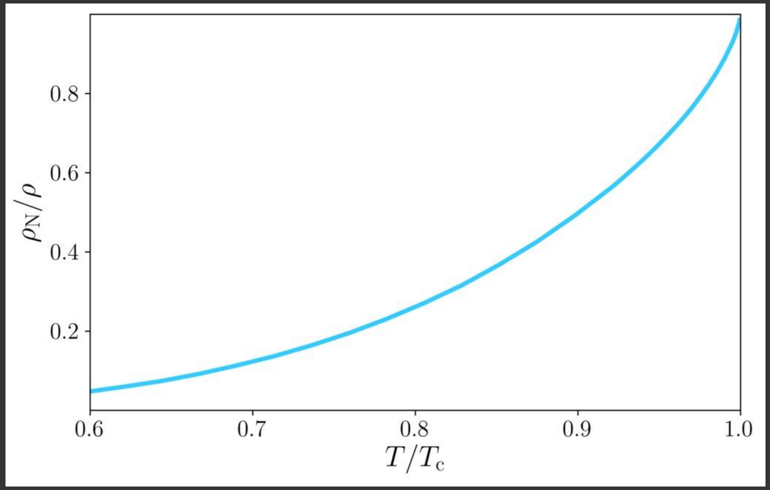
SUPERFLUID HELIUM





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normal component: viscous properties and heat transport

inviscid compo-nent: SF features

QUANTUM VORTICES

Superfluids are characterised by a QM wave function $\Psi = \Psi_0 e^{i\varphi}$, which satisfies the Schrödinger equation.

$\mathbf{v}_{SF} = \hbar/m_c \nabla\varphi$
dictates
$\omega = \nabla \times \mathbf{v}_{SF} = 0$
(superflow is irrotational)

each vortex carries a quantum of circulation $\kappa = h/m_c$

SFs rotate by forming quantised vortices

array mimics solid-body rotation: $\omega = 2\Omega = N_v \kappa$

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Credit: NOAA Photo Library

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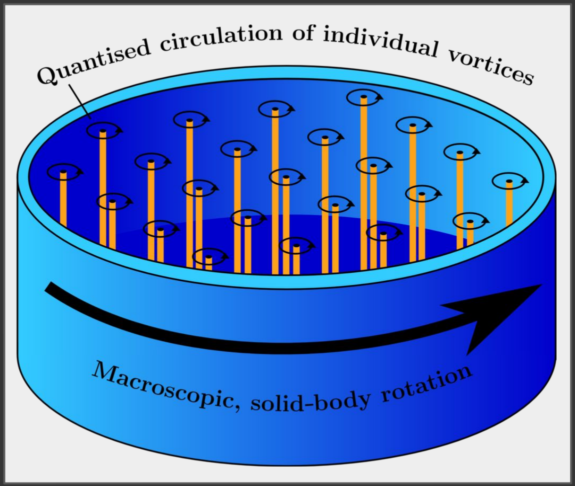

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HVBK EQUATIONS

Based on the two-fluid picture, Hall, Vinen, Bekarevich and Khalatnikov developed a vortex-averaged, hydrodynamic description of SF.

HVBK-type equations also apply to NSs: superfluid neutrons plus charged particle conglomerate

vortices enter via tension & mutual friction

momentum / continuity equations for macroscopic velocity fields

$$\rho_{\mathrm{S}} \frac{D\mathbf{v}_{\mathrm{S}}}{Dt} + \nabla\tilde{p}_{\mathrm{S}} - \frac{\rho_{\mathrm{S}}\rho_{\mathrm{N}}}{2\rho} \nabla(\mathbf{v}_{\mathrm{N}} - \mathbf{v}_{\mathrm{S}})^2 = \mathbf{T} + \mathbf{F}_{\mathrm{mf}}$$

$$\rho_{\mathrm{N}} \frac{D\mathbf{v}_{\mathrm{N}}}{Dt} + \nabla\tilde{p}_{\mathrm{N}} + \frac{\rho_{\mathrm{S}}\rho_{\mathrm{N}}}{2\rho} \nabla(\mathbf{v}_{\mathrm{N}} - \mathbf{v}_{\mathrm{S}})^2 - \eta\nabla^2\mathbf{v}_{\mathrm{N}} = -\mathbf{F}_{\mathrm{mf}}$$

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$$\mathbf{T} = -\rho_S \nu_S \, (\boldsymbol{\omega} \cdot \nabla) \, \hat{\boldsymbol{\omega}}$$

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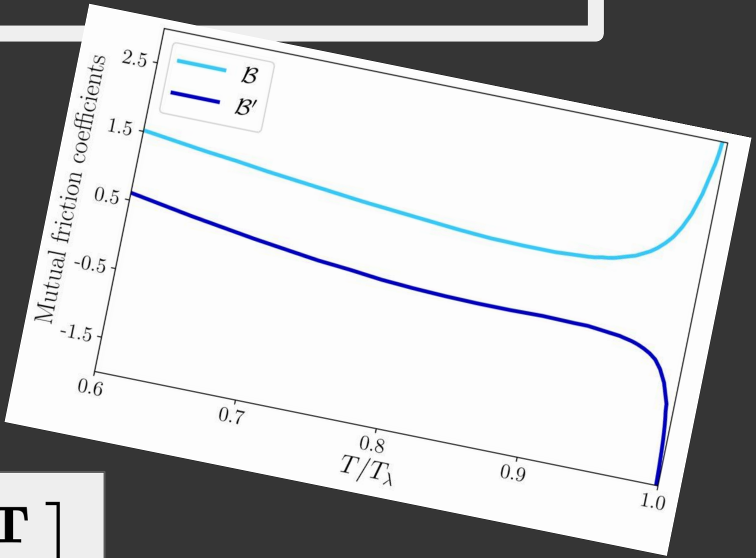
$$\rho_{\rm S}\frac{D\mathbf{v}_{\rm S}}{Dt} + \nabla\tilde{p}_{\rm S} - \frac{\rho_{\rm S}\,\rho_{\rm N}}{2\rho}\nabla(\mathbf{v}_{\rm N}-\mathbf{v}_{\rm S})^2 = \mathbf{T} + \mathbf{F}_{\rm mf}$$

$$\rho_{\rm N}\frac{D\mathbf{v}_{\rm N}}{Dt} + \nabla\tilde{p}_{\rm N} + \frac{\rho_{\rm S}\,\rho_{\rm N}}{2\rho}\nabla(\mathbf{v}_{\rm N}-\mathbf{v}_{\rm S})^2 - \eta\nabla^2\mathbf{v}_{\rm N} = -\mathbf{F}_{\rm mf}$$

MUTUAL FRICTION

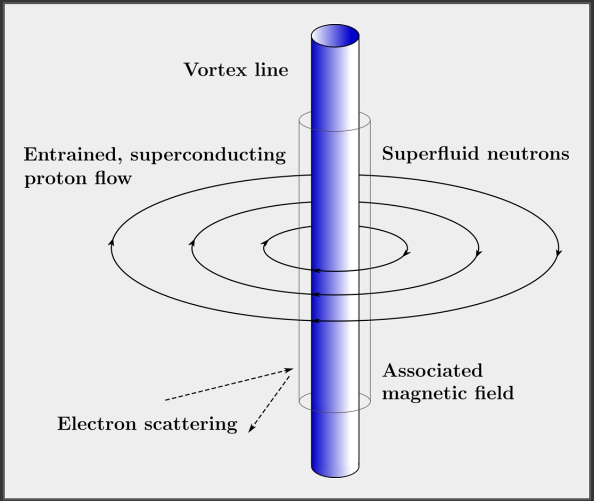


The inviscid fluid component experiences dissipation due to interactions between the vortices and the normal component.

$$\mathbf{F}_{\rm mf} = \mathcal{B}_{\rm He}\frac{\rho_{\rm S}\rho_{\rm N}}{2\rho}\,\hat{\boldsymbol{\omega}}\times\left[\boldsymbol{\omega}\times(\mathbf{v}_{\rm S}-\mathbf{v}_{\rm N})-\frac{\mathbf{T}}{\rho_{\rm S}}\right] + \mathcal{B}'_{\rm He}\frac{\rho_{\rm S}\rho_{\rm N}}{2\rho}\left[\boldsymbol{\omega}\times(\mathbf{v}_{\rm S}-\mathbf{v}_{\rm N})-\frac{\mathbf{T}}{\rho_{\rm S}}\right]$$

two coefficients determine dissipation strength

In helium, coefficients can be directly measured. In NSs, they must be calculated.



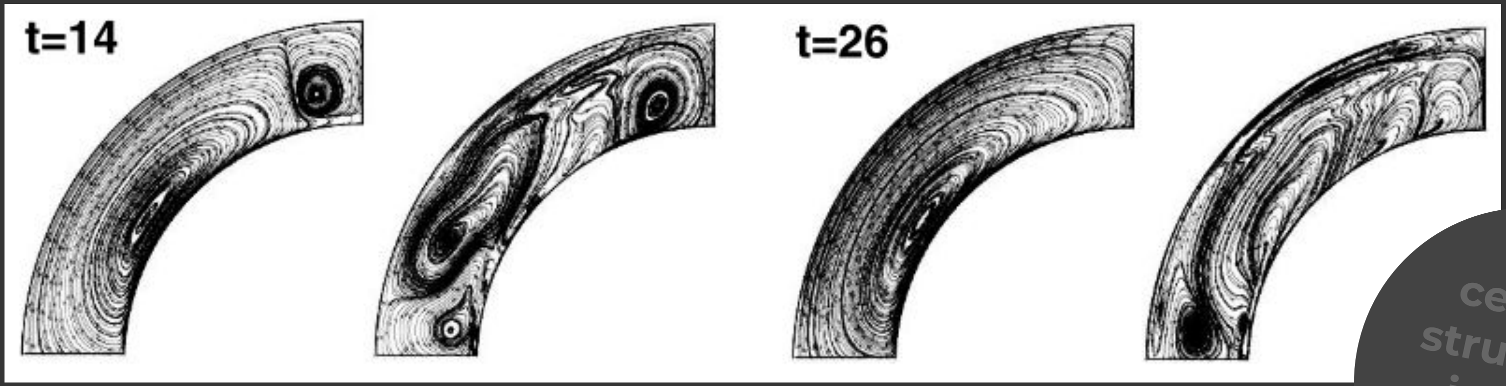
SPHERICAL NEUTRON STAR SHELL

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

model outer NS core dynamics

evolution following steady differential rotation

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



cell-like structures in both fluids

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

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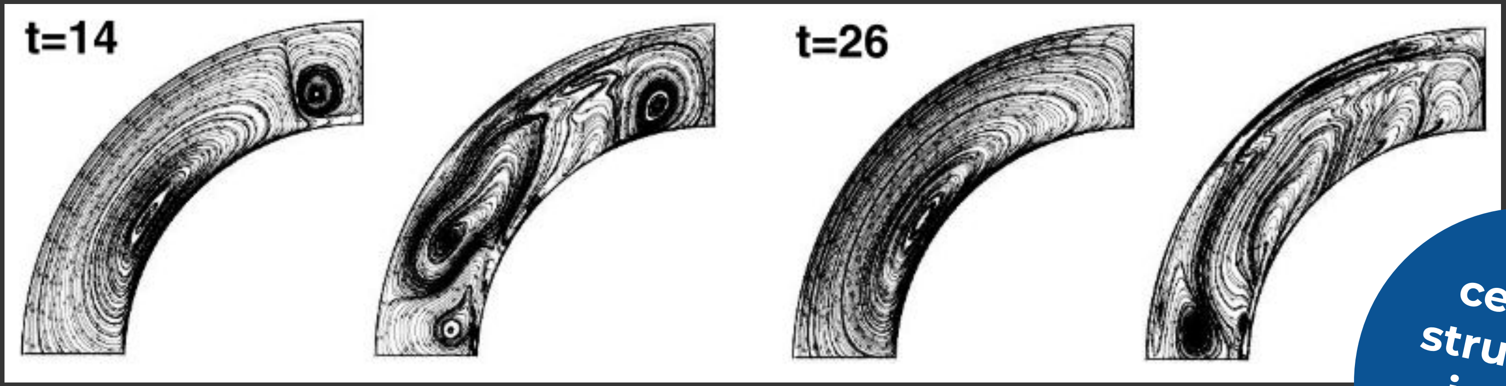

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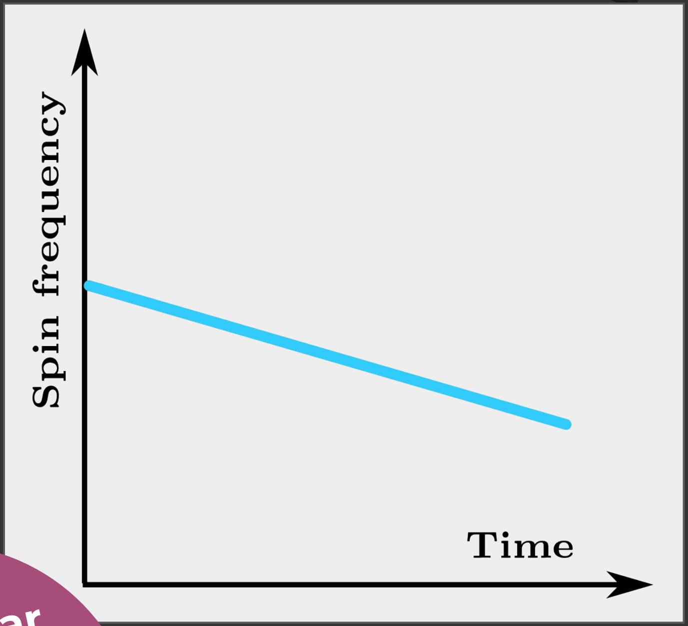
RADIO PULSAR TIMING

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

credit: J. Christiansen



time pulsar radiation to learn about their interiors

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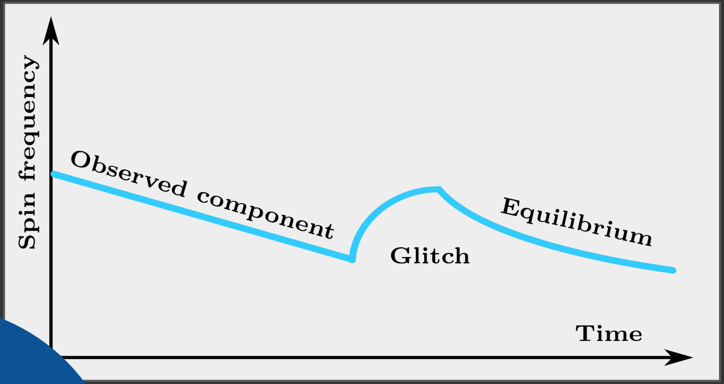
PULSAR GLITCHES

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



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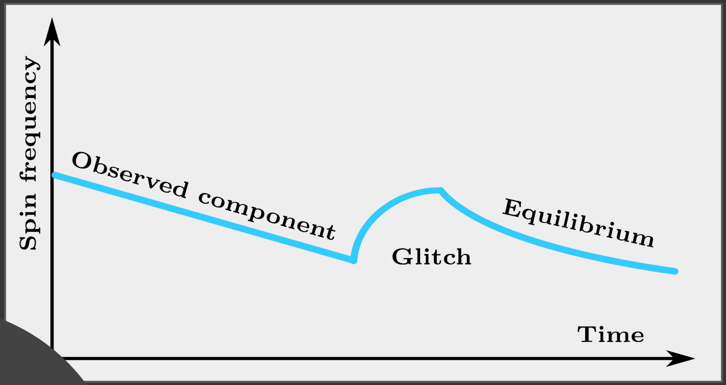

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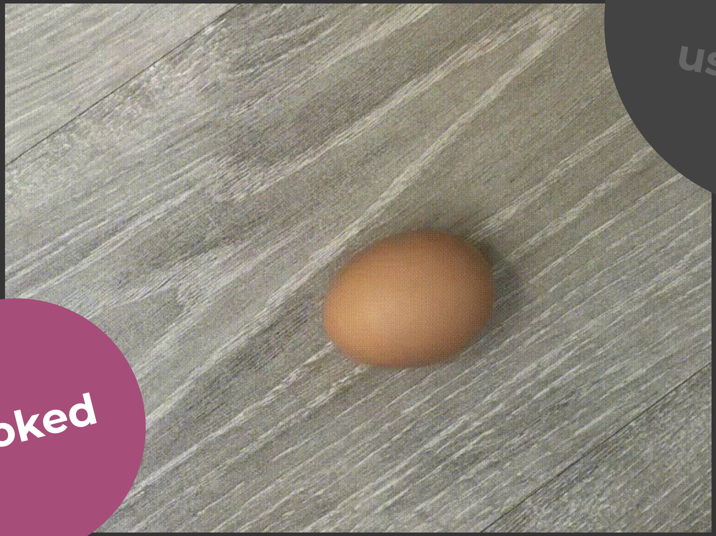


cooked

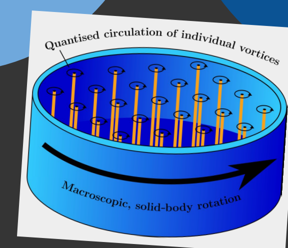
raw

MANIFESTATION OF SUPERFLUIDITY

Spin-up glitches are naturally explained in a two-component model.

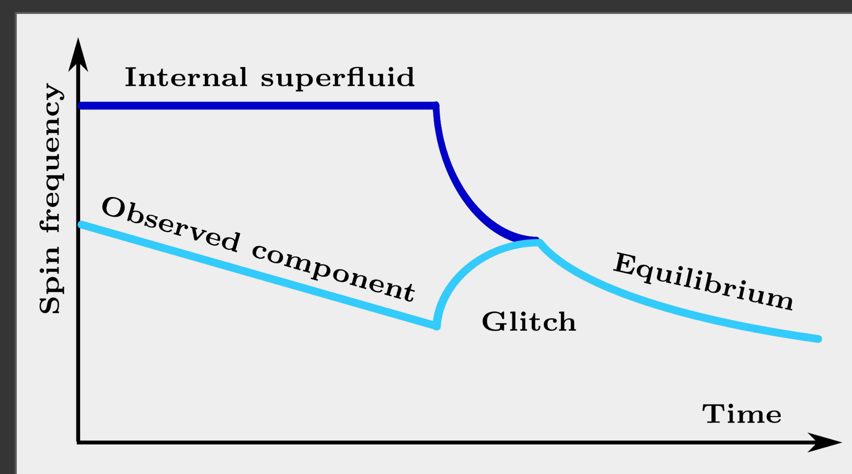
superfluid provides angular momentum reservoir

superfluid spin-down can be prevented by vortex pinning



glitches are macroscopic manifestation of quantum vortices

the shape of the glitch encodes the (hidden) internal NS physics



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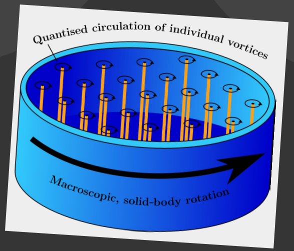

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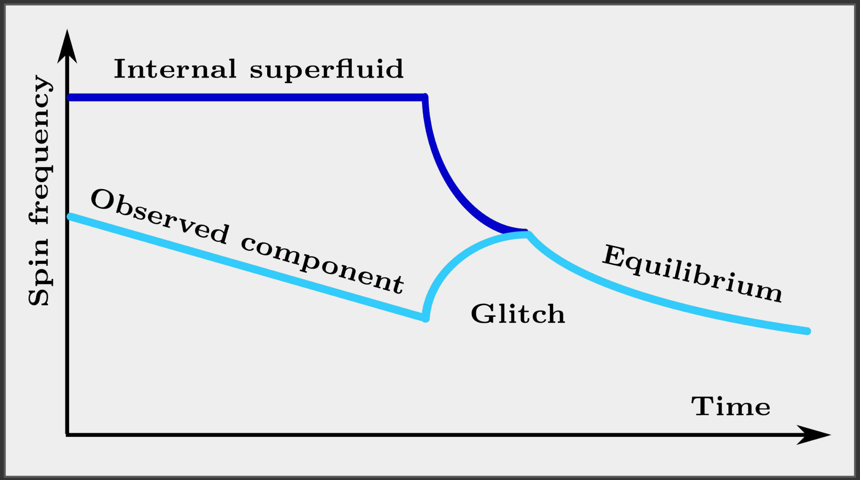
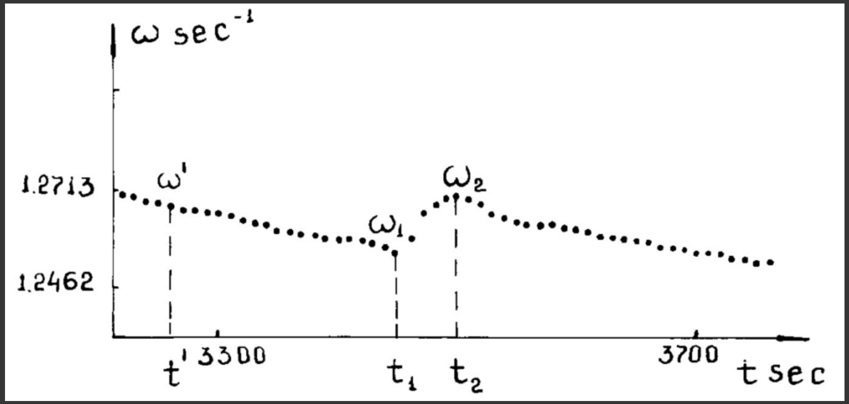
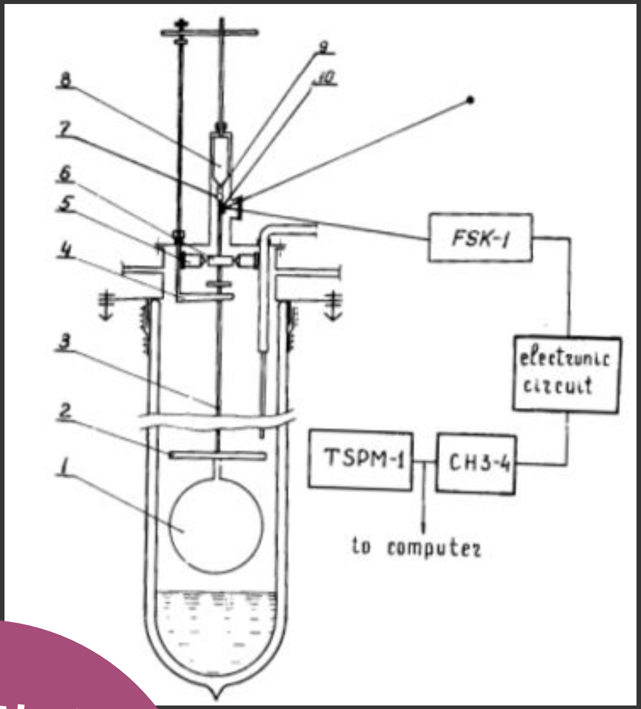


LABORATORY HELIUM GLITCHES

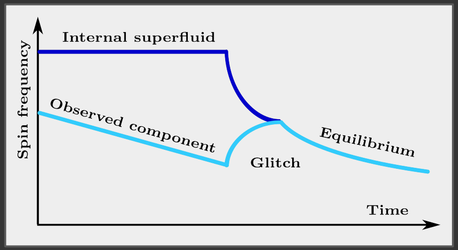
In the 1970s, Tsakadze and Tsakadze performed a systematic analysis of Helium II spin-up.



credit: Tsakadze & Tsakadze (1980)



credit: Tsakadze & Tsakadze (1980)



with their very basic set-up they might have detected one (!) glitch

NEW 3D SPIN-UP SIMULATIONS

Take a new look at numerically modelling glitch behaviour in 3D: Solve HVBK equations with Dedalus.

$$\frac{\rho_{\rm S}}{\rho} = 0.95, \quad \frac{\rho_{\rm N}}{\rho} = 0.05$$

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no tension; Re_N = 100

start from co-rotation then accelerate outer boundary for normal fluid

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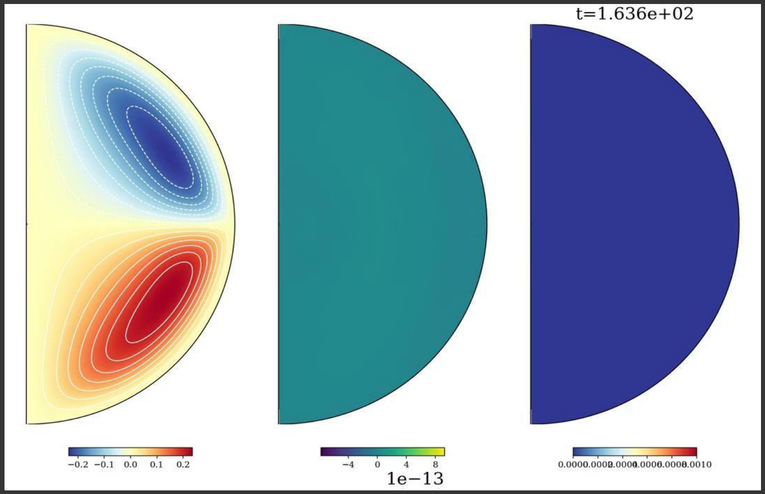
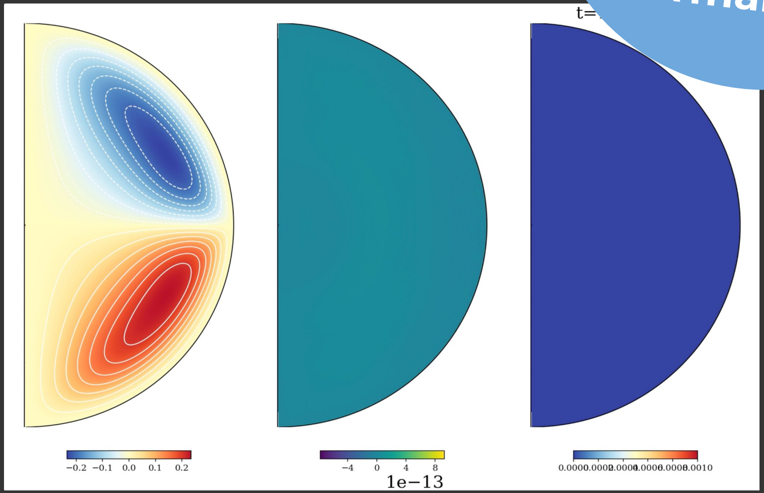


$\mathcal{B} = 0.375$



Fuentes & Graber (in prep)

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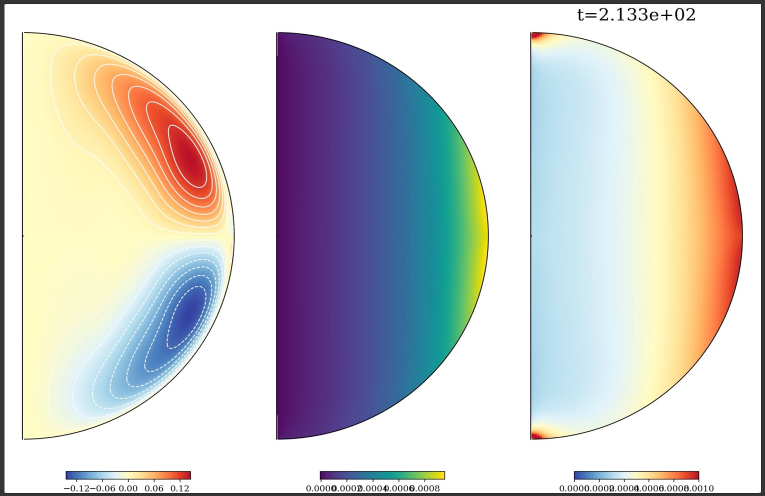

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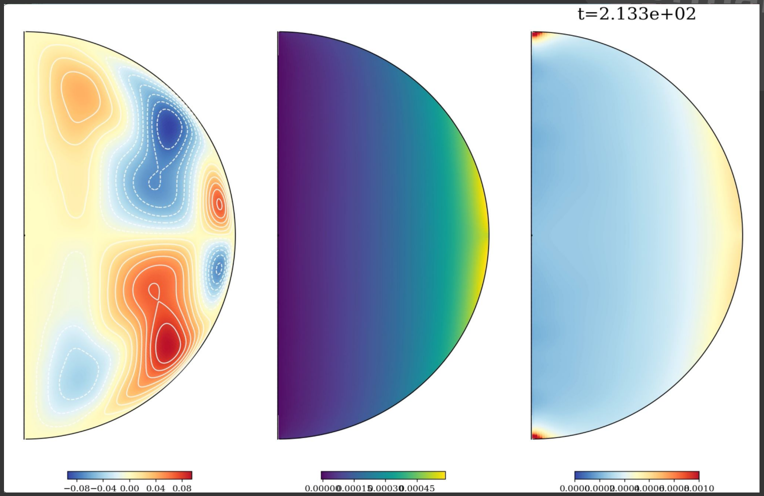

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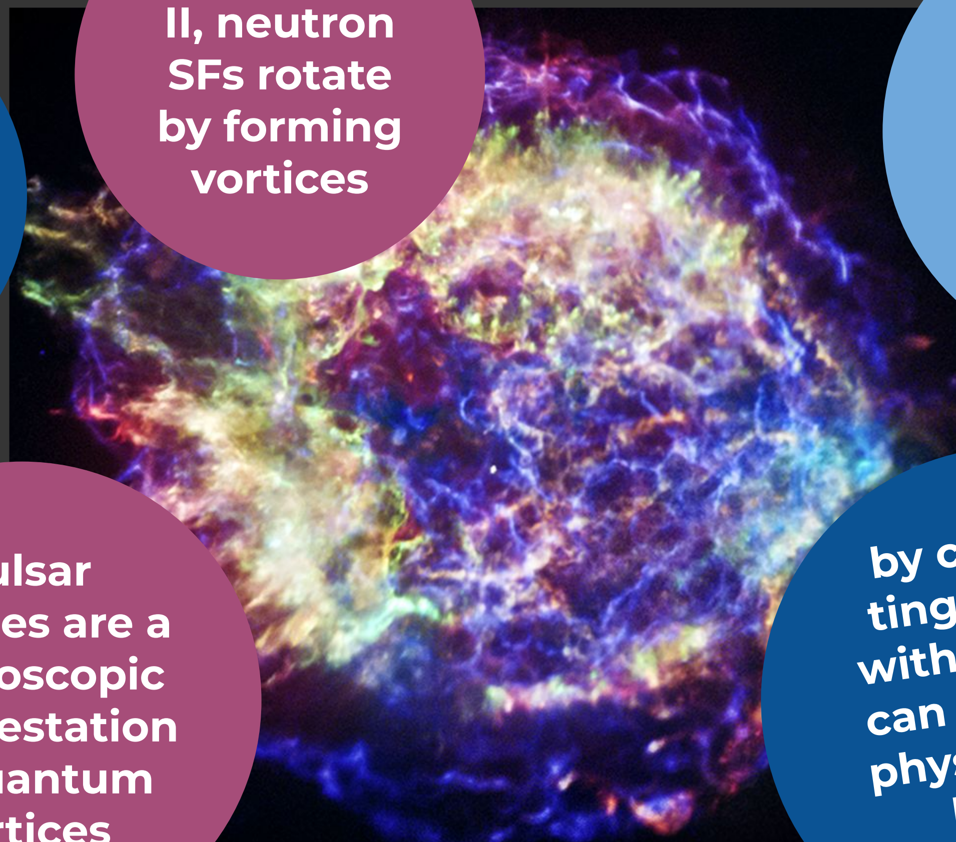
TAKE-HOME POINTS



NSs contain at least 3 SF compo-nents

like helium II, neutron SFs rotate by forming vortices

vortices affect large-scale dynamics via tension and mutual friction

pulsar glitches are a macroscopic manifestation of quantum vortices

by contras-ting models with data, we can constrain physics of the hidden interior

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