Precession as a probe of the neutron star interior

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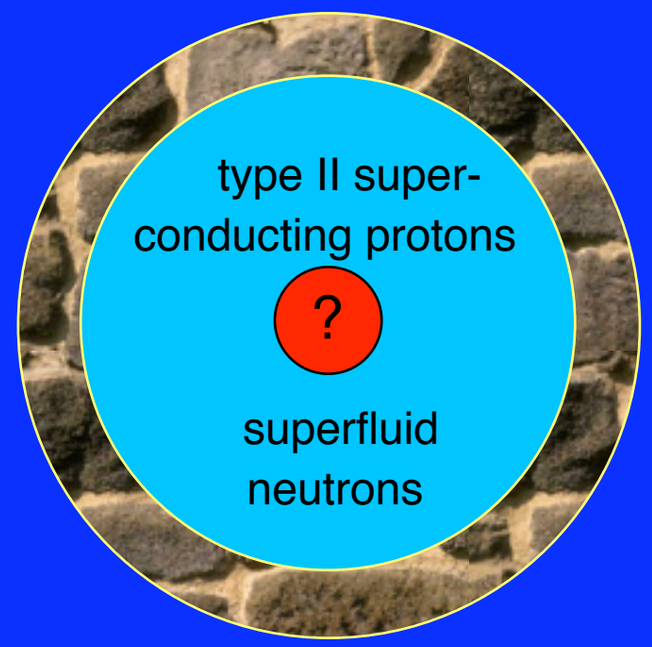
Evidence that neutron stars precess (or “wobble” or “nutate”)

Implications for:
- nuclear physics
- cooling theory
- glitch models
- modes (r, etc.)

State of the quantum liquid core is constrained

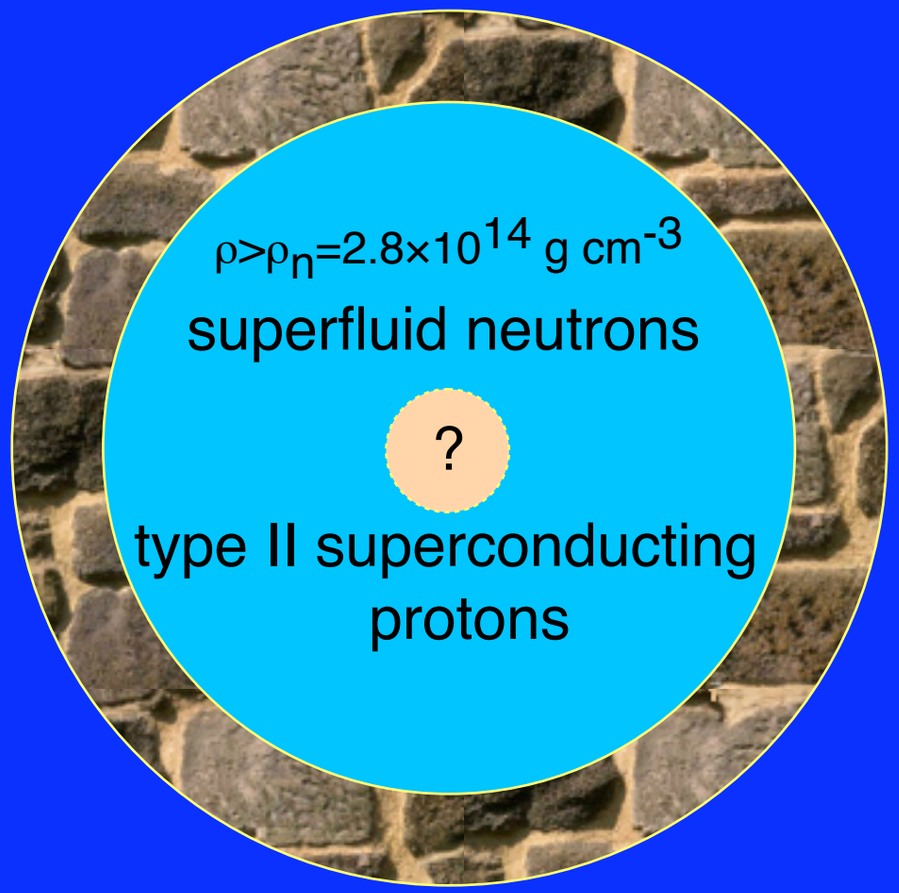
something wrong with...



Some isolated neutron stars that appear to be precessing

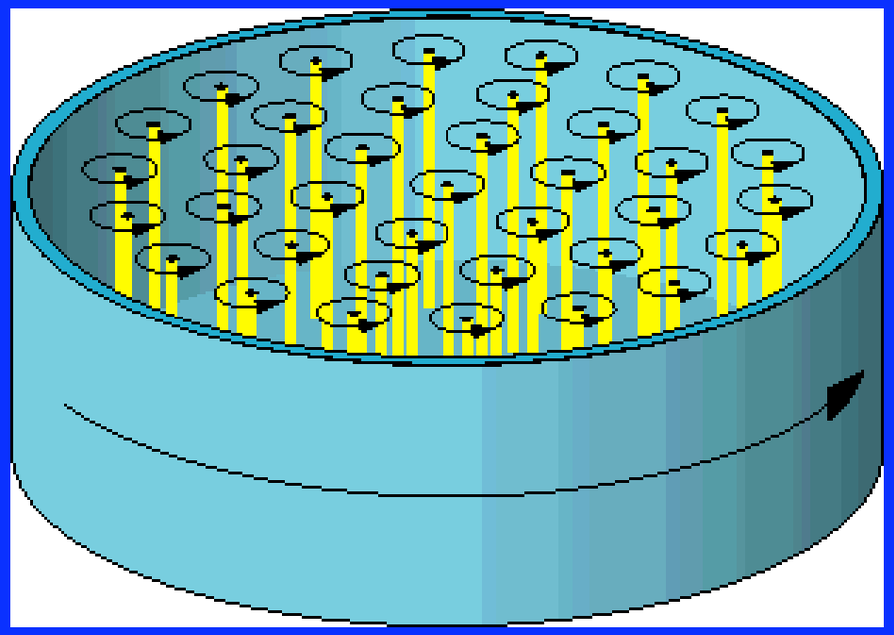
- PSR 1828-11 (Stairs, Lyne, Shemar 00)
  period of ~500 d.
- PSR B1642-03 (Shabanova, Lyne, Urama 01)
  period of ~3 yr.
- RX J0720.4 (Talks by Haberl, Kaplan)
  period of ~4-7 yr.

Nucleon pairing calculations predict...

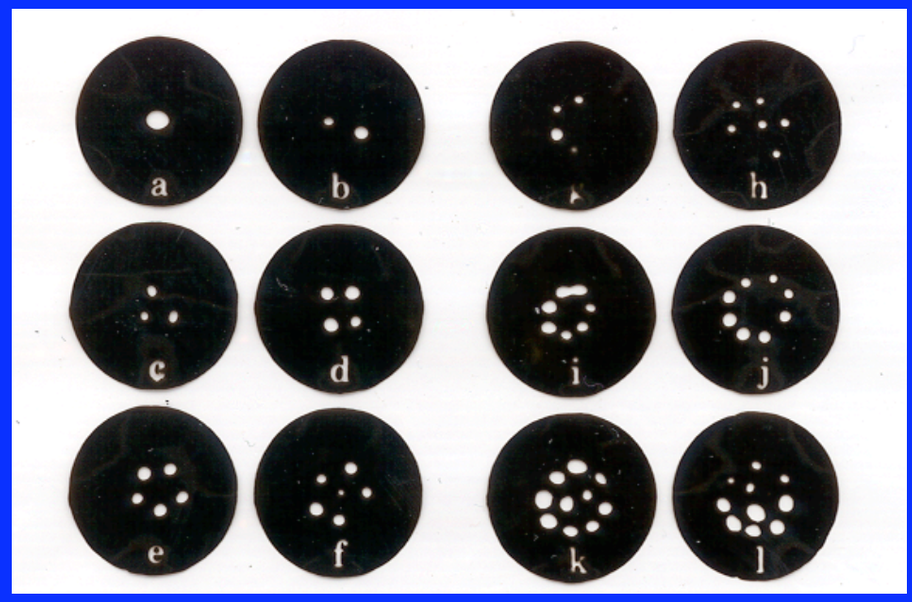


How does the quantum liquid of the core affect precession?

The neutron superfluid's rotation



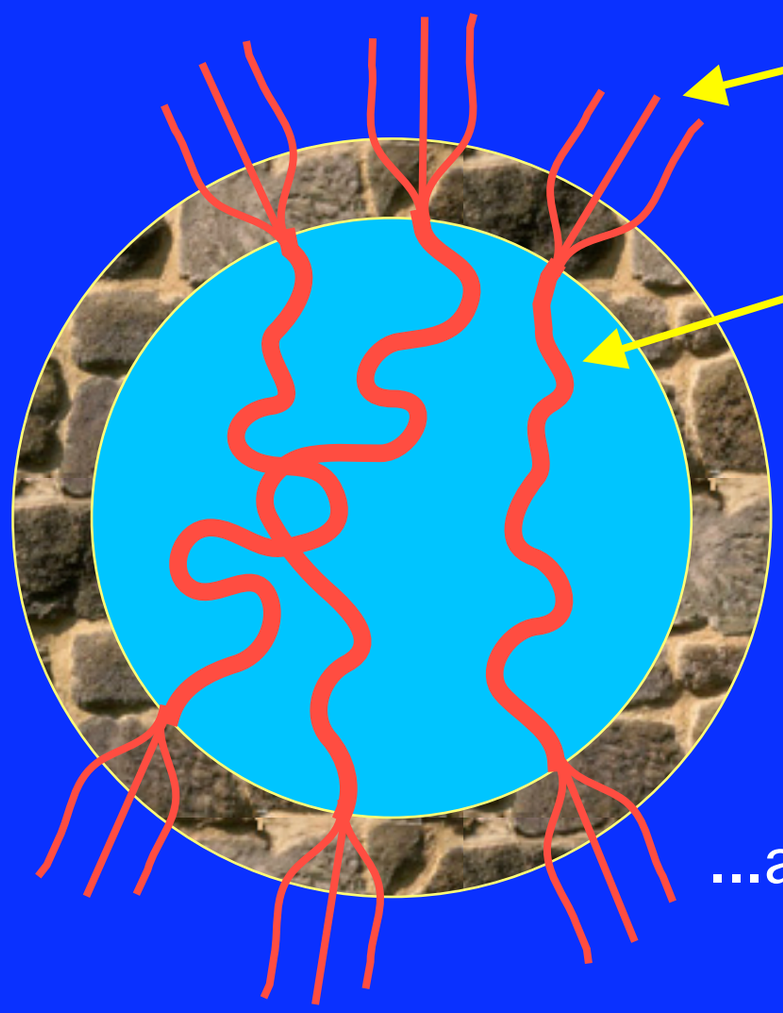
Rotating superfluid He



Distribution of vortices determines the fluid's angular momentum.

These stable structures give the superfluid gyroscopic properties.

Type II superconductivity in the core



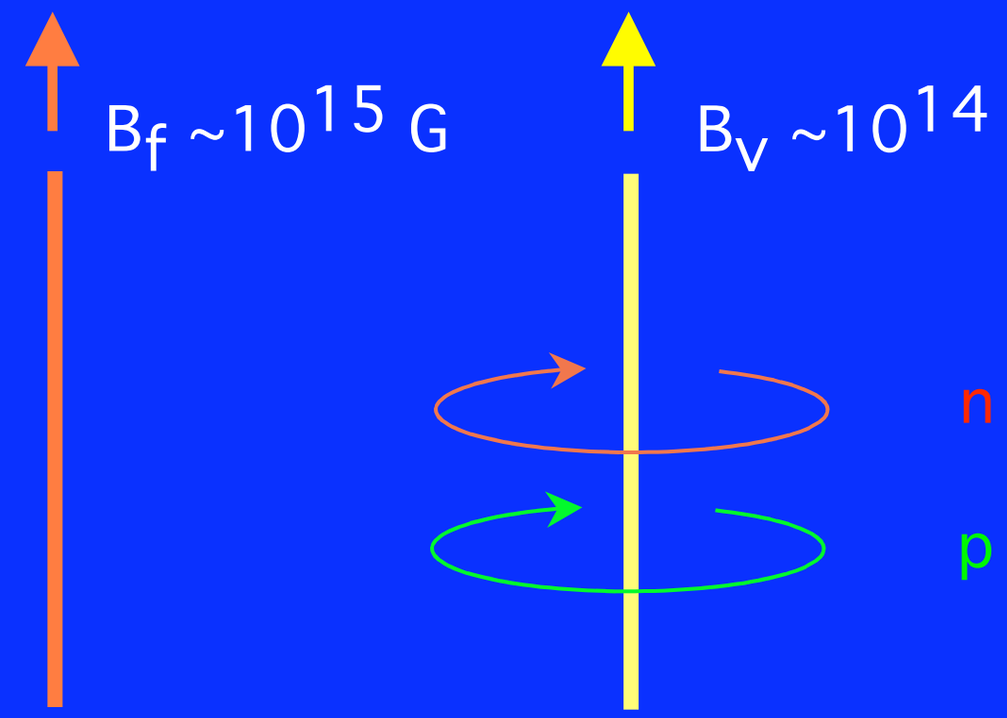
Normal field
$B \sim 10^{12}$ G

Flux tube
$B \sim 10^{15}$ G

A neutron star contains $\sim 10^{31}$ flux tubes, frozen to the charged fluid.

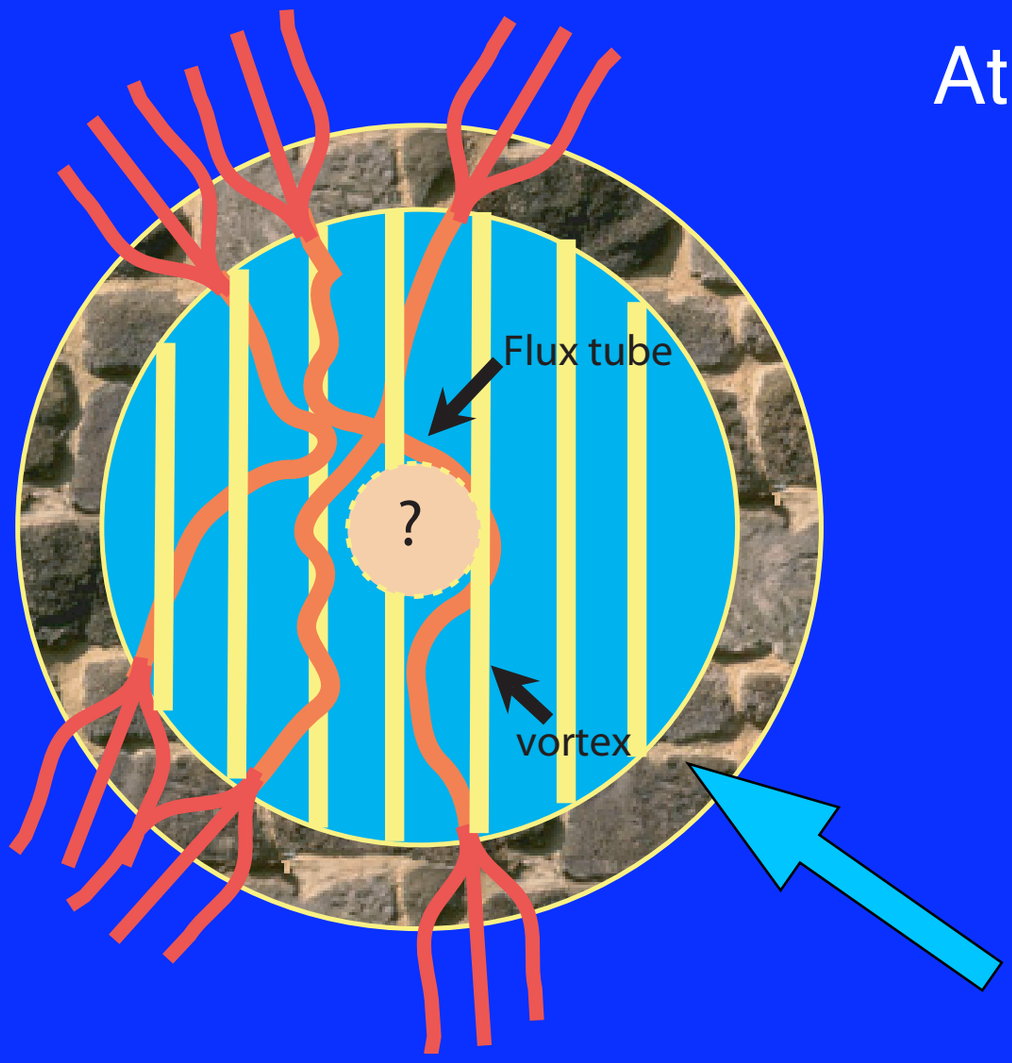
...and $\sim 10^{17}$ neutron vortices.

Vortices and flux tubes interact (entrainment)



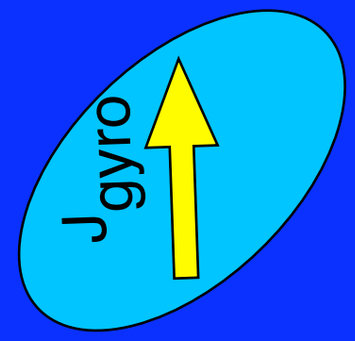
$E_{int} \sim B_f B_v V_{overlap} \sim 5\ \mathrm{MeV/intersection}$

Vortices are pinned to the flux tubes



At what frequency does the star precess?

(Link 03)



Disaster!

This object would precess

$\sim 10^9$ times faster than observed.

Requirement for precession to be slow

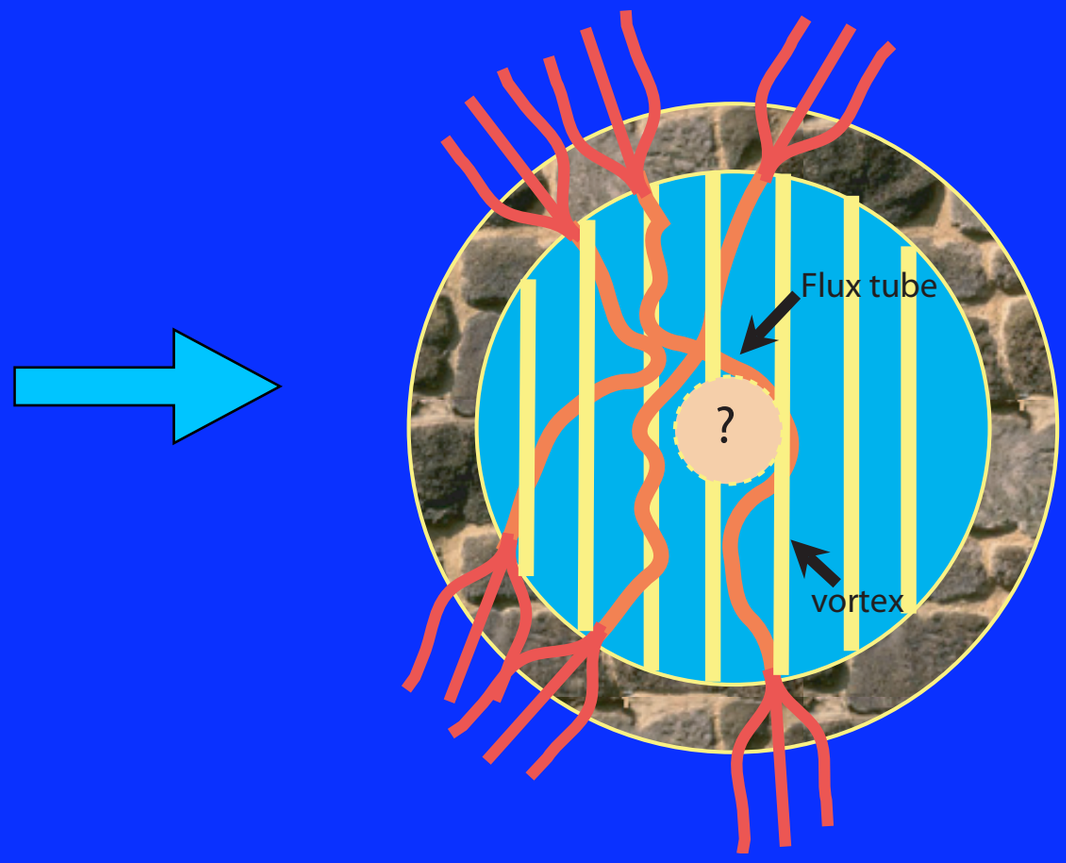
$\Omega_{\text{superfluid}}$ must be able to closely follow Ω_{body}, i.e.,

$$|\vec{v}_{vortex} - \vec{v}_{body}| \simeq |\vec{v}_{superfluid} - \vec{v}_{body}| \simeq 10^{-2}\ \text{cm s}^{-1}$$ (for PSR 1828-11)

This requires that

$$\vec{v}_{vortex} \simeq \vec{v}_{superfluid}$$

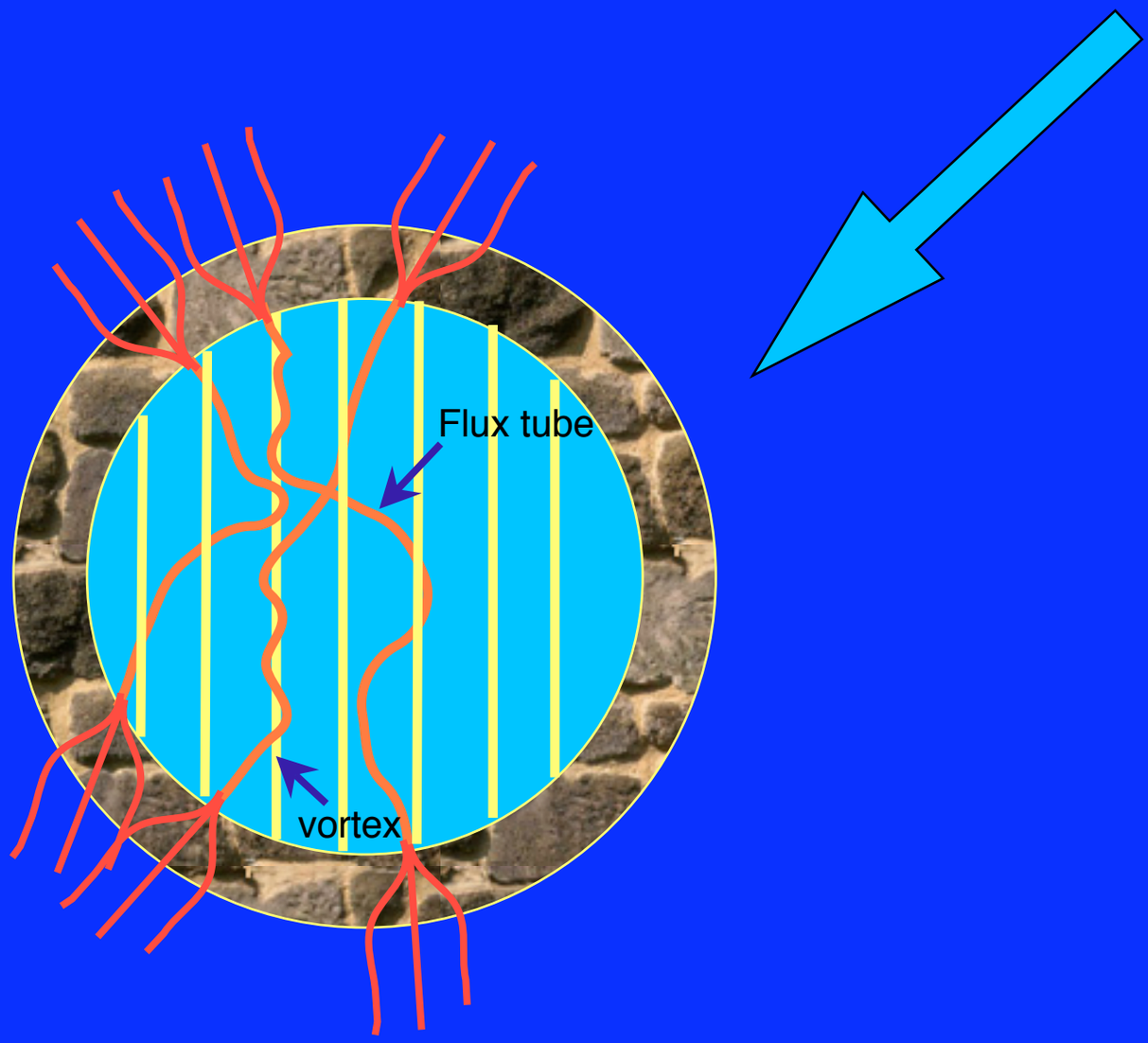
Cannot happen here



Impediments to vortex motion

- Hydrodynamic forces on pinned flux tubes are ~10^6 times too small to drive vortices through the flux tubes.
- Vortices cannot push the flux tubes fast enough.
  (Ruderman, Zhu, Chen 98; Jones 06)
- Vortices can move some, such as through "vortex creep"
  (Alpar, astro-ph/0505073), but in this case, precession is highly over-damped. It cannot happen.
  (see Sedrakian, Wasserman, Cordes 99 and these proceedings)

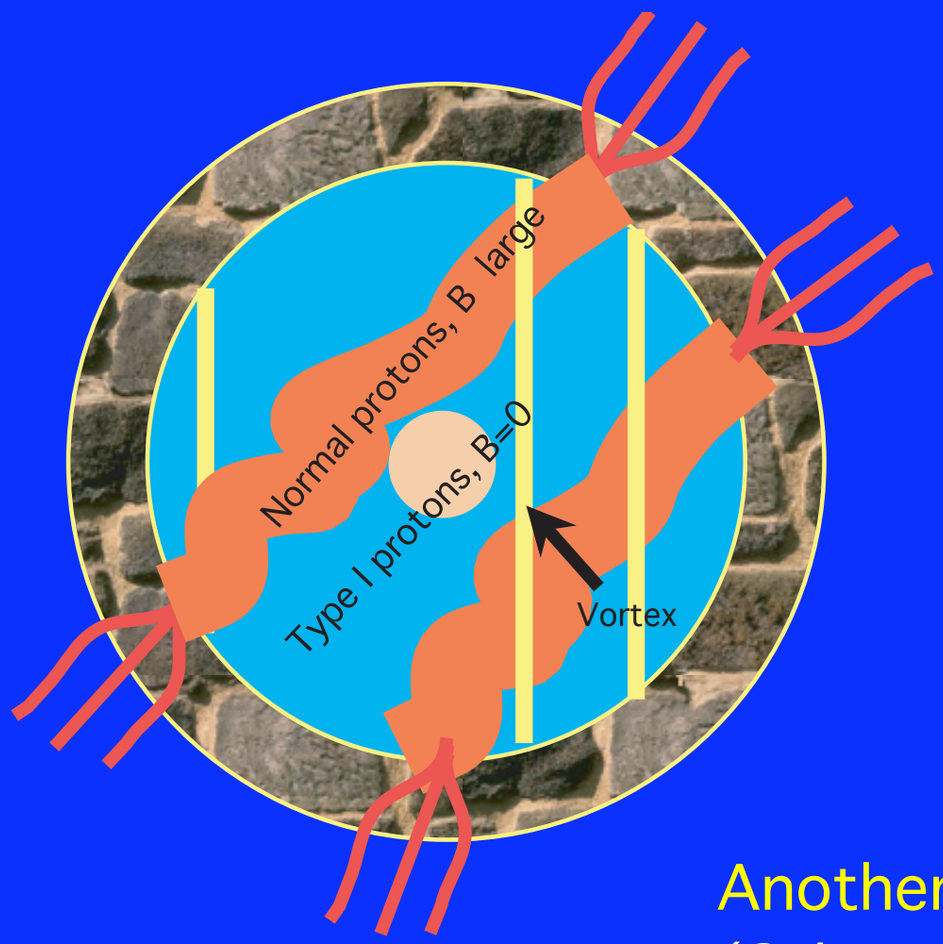
Conclusion: long-period, long-lived precession is impossible in this picture



Vortices and flux tubes cannot interact anywhere in the star.
Similar considerations apply to the inner crust.
(Shaham 77; Link & Cutler 02)

Possible resolutions

The core protons are not type II, but <u>type I.</u>



The magnetic flux would not be a significant impediment to vortex motion (Sedrakian 05)

⇒ <u>the crust would precess slowly.</u>

Another possibility: <u>the core neutrons are normal.</u>
(Schwenk & Friman 04)

Evidence that neutron stars precess

State of the quantum liquid core is constrained

Mountains of $\Delta R \sim 0.1$ mm exist on some neutron stars

MSPs with such deformation could be detectable GW sources!

The state of the core should be reconsidered.

Implications for:
- cooling theory
- core glitch models
- modes (r, etc.)