Hydrodynamic stability of neutron star cores

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Why study stability?

- What is the underlying state of a spinning-down neutron star?

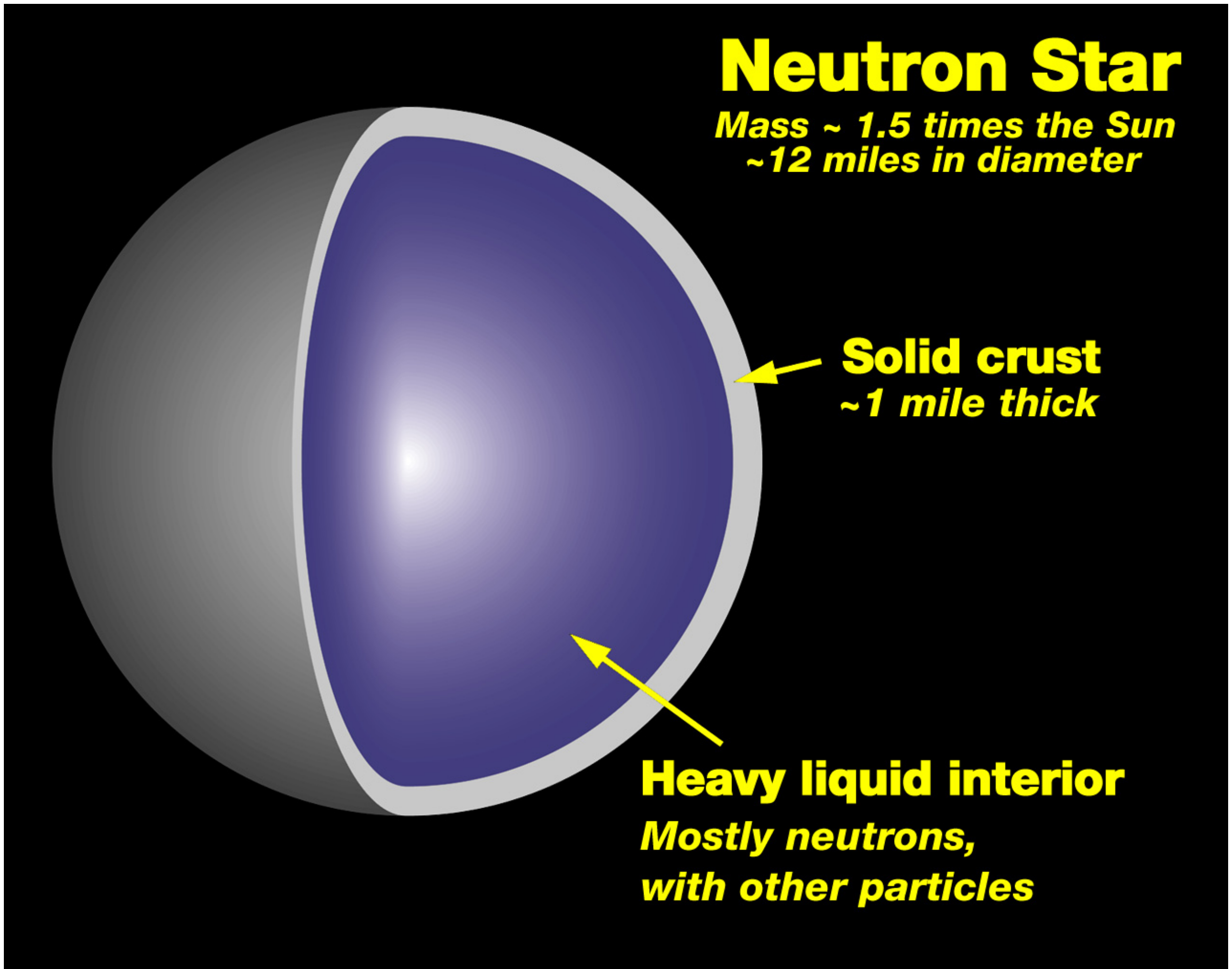
- Turbulence may be connected with timing noise (random fluctuations in pulsar spin frequency)

  see e.g., Melatos & Peralta, Link (2012a,b), Melatos & Link (2014)

- Proposed as cause of glitches (impulsive increase in spin frequency)

  see e.g., Glampedakis & Anderson (2009)

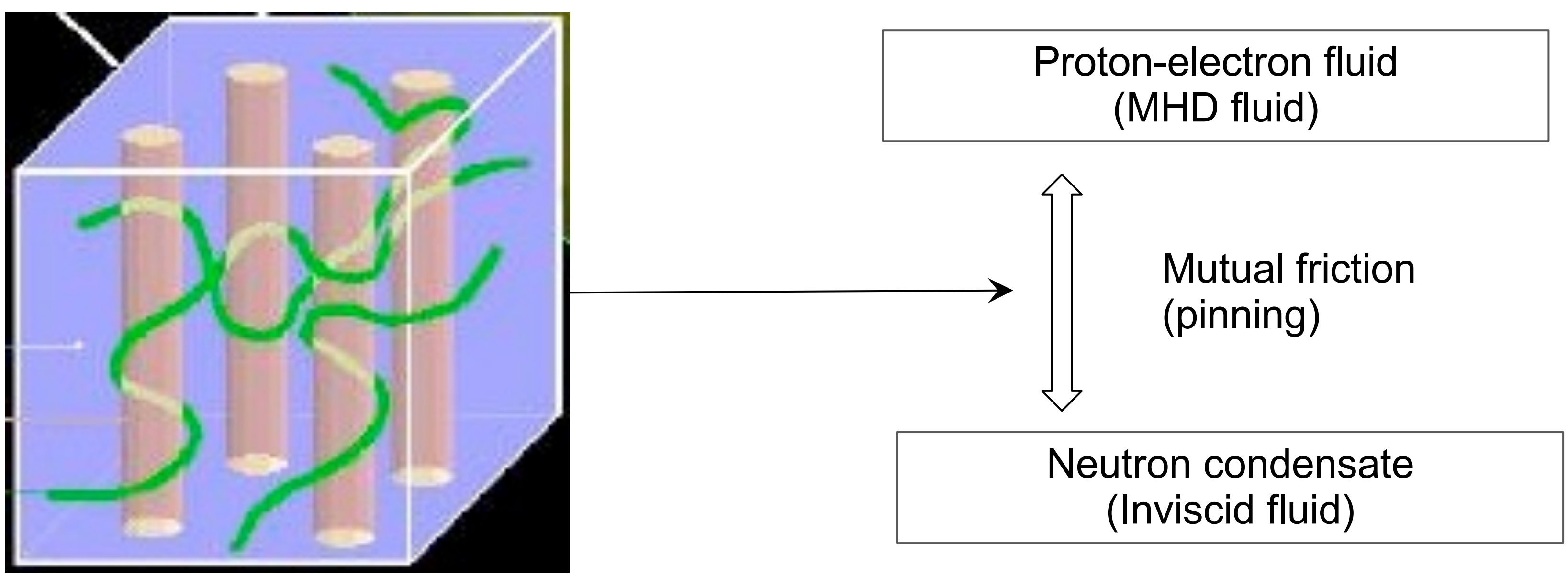
Neutron star hydrodynamics



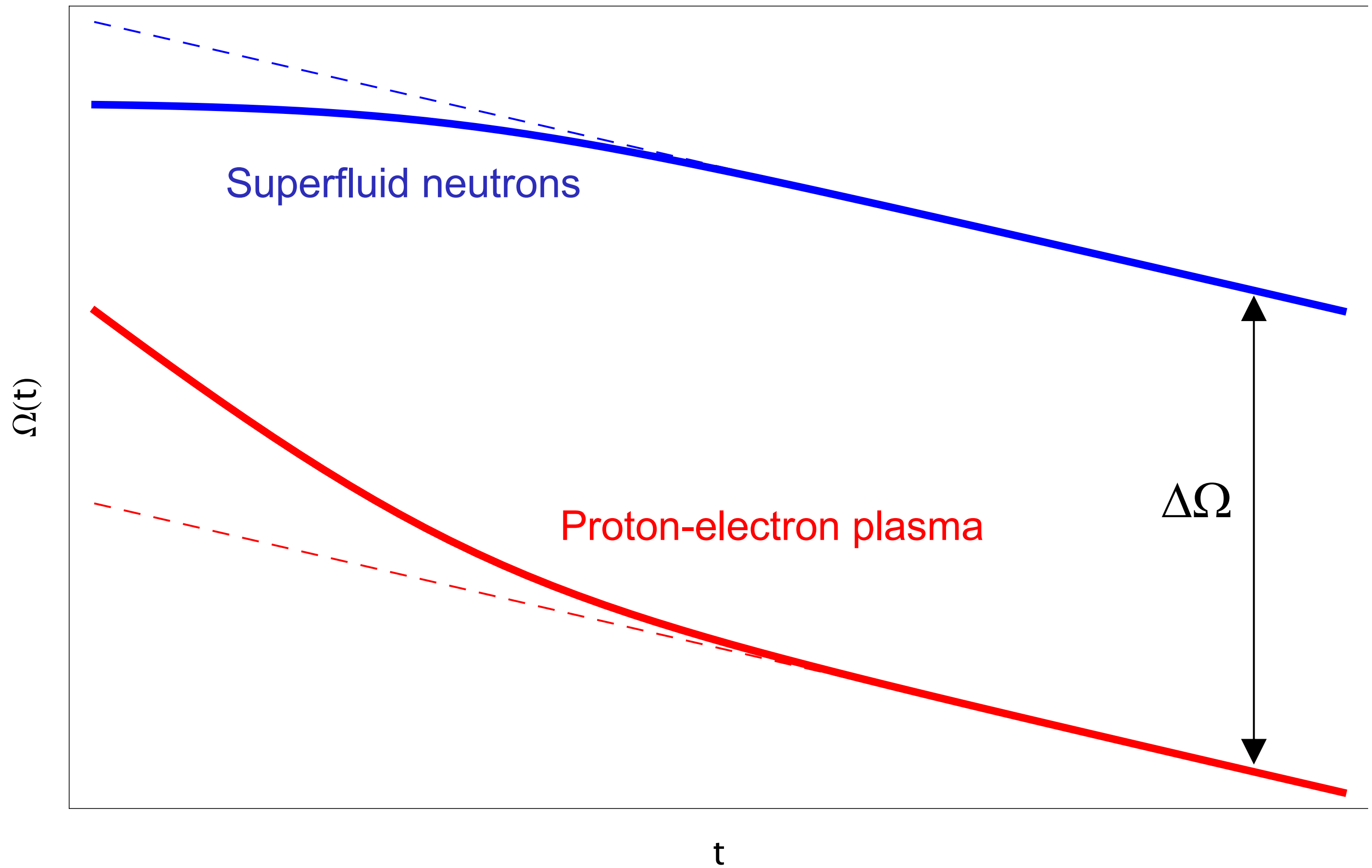
- 5% superconducting protons + electrons (MHD plasma)
- 95% superfluid neutrons

Superfluidity and superconductivity

- Vortices and flux tubes form to accommodate rotation and magnetic field
- Arrays pin due to magnetic forces



Spin-down equilibrium



- Rotational lag develops between neutrons and protons
- Is this stable?

No magnetic field: two-stream instabilities

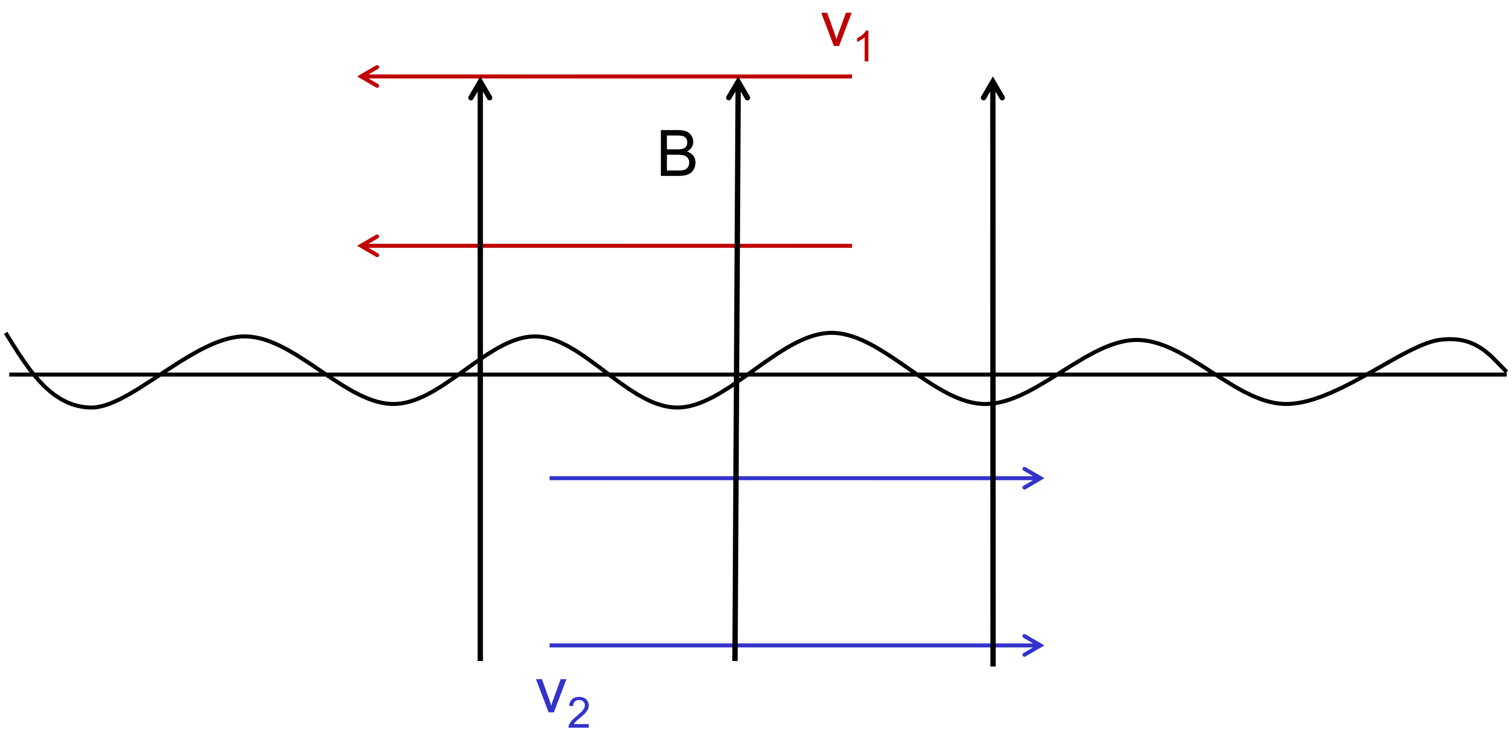
- Perfect pinning: Glampedakis & Andersson (2009)
- Inertial modes coupled by mutual friction produce two-stream instabilities
- What about magnetic fields?

Kelvin-Helmholtz instability

- Two-stream interfacial instability

Kelvin Helmholtz instability

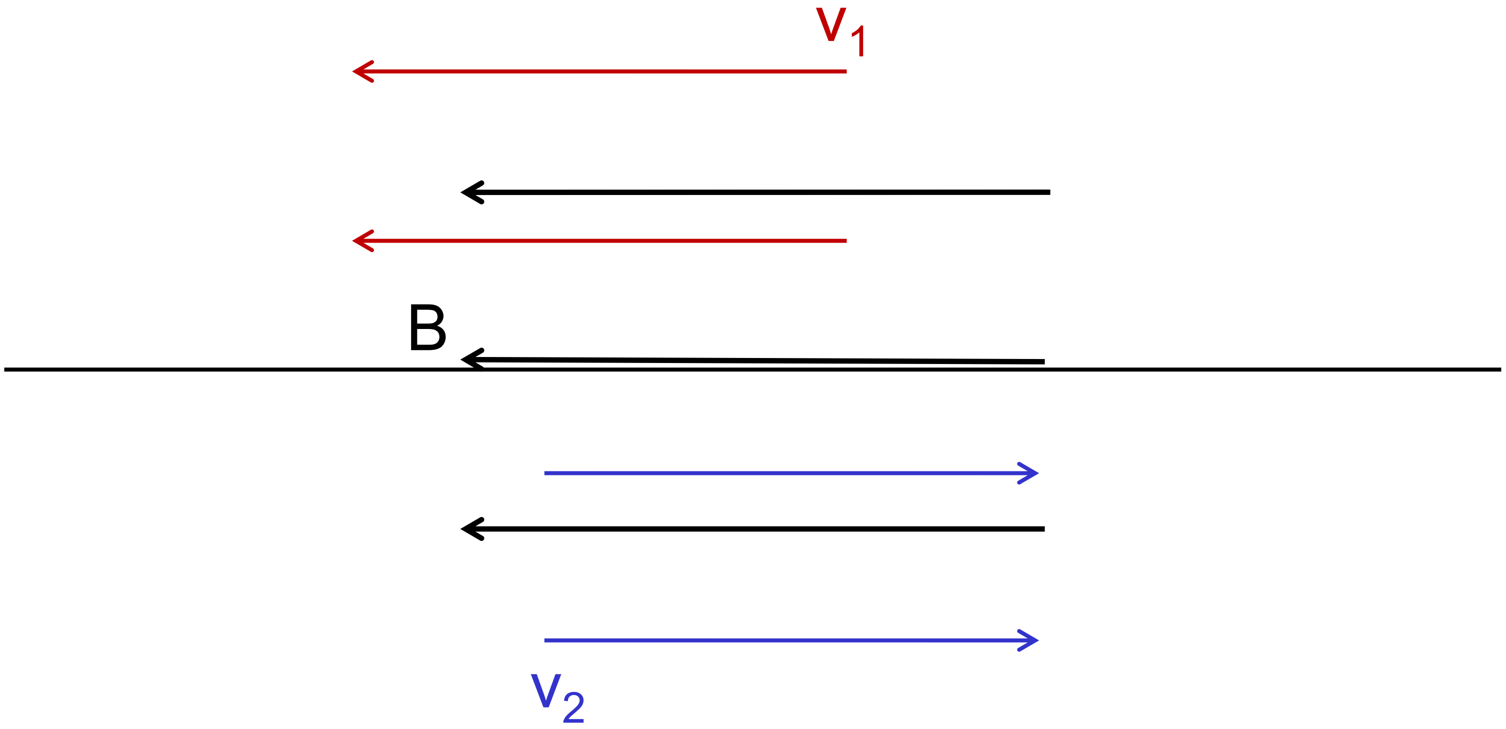
- Add transverse field



- No Effect!

Kelvin Helmholtz instability

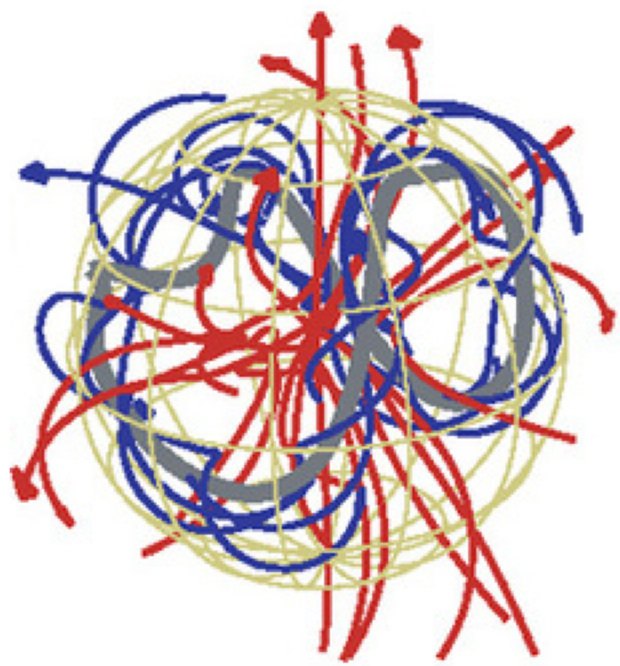
- What about parallel field



- Stabilized for Alfven speed, $v_A > v_1 - v_2$

Magnetic field structure

- Pure dipole field is unstable (Flowers and Ruderman '77)

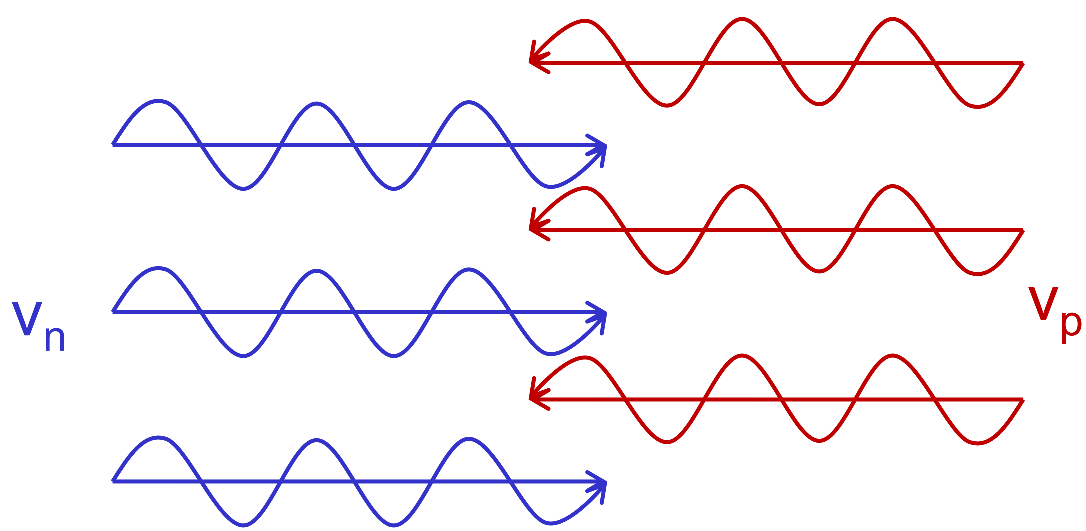


Braithwaite and Spruit (2004)

- Only known stable configuration is the twisted torus
- Toroidal field at least equal to dipole field for stability

Bulk two-stream instability

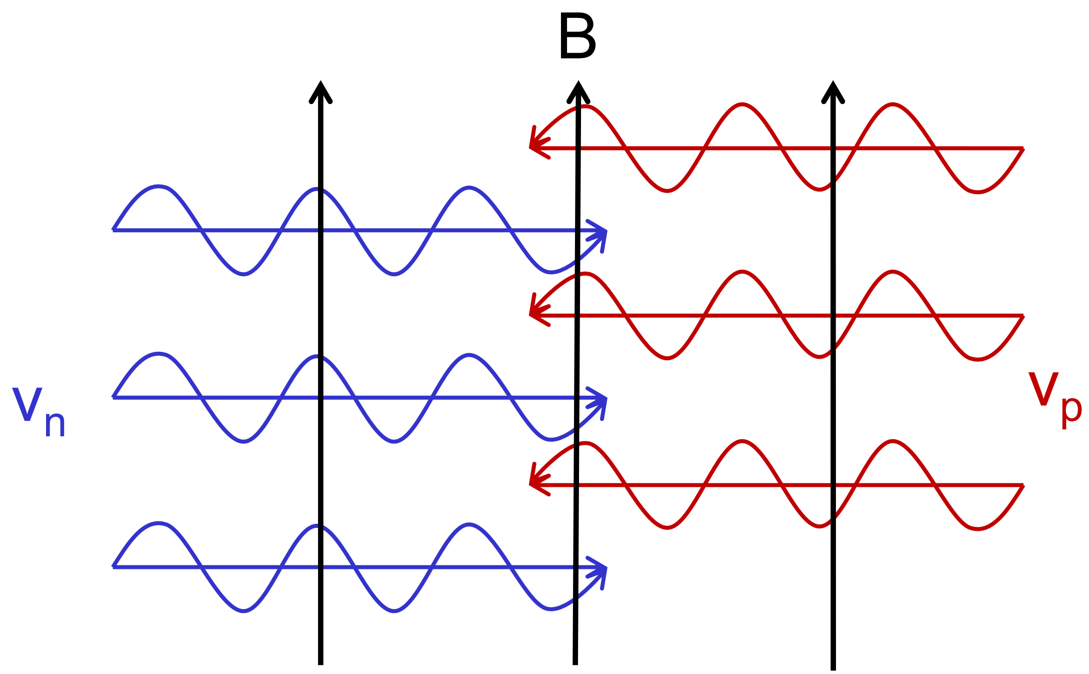
- Perfectly pinned flux tubes and vortices



- Growth time ~ $1/(\Omega_n - \Omega_p)$ ~ s (Glampedakis and Andersson 2009)

What about magnetic fields?

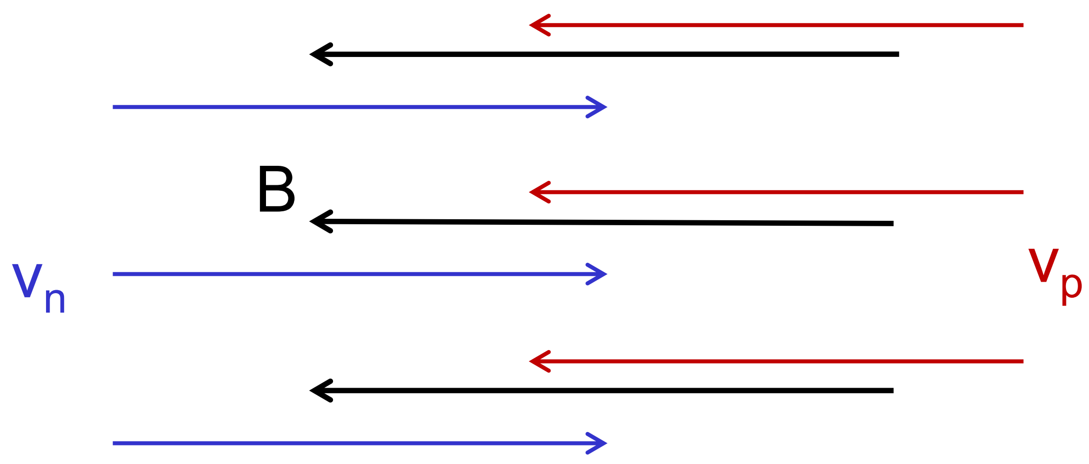
- Add poloidal (dipole field), what happens?



- No effect!

What about magnetic fields?

- What about toroidal field?



- Stabilized for Alfven speed, $v_A > v_n - v_p$
- Corresponds to $B=10^{10}$ G --> stable!

Imperfect pinning

- Vortices excited by thermal fluctuations overcome pinning barriers – vortex slippage (Link 2014)
- Additional class of instabilities arise
- Slower growth rates (days) - timing noise? (Link 2012, Andersson et al 2013)
- Also stabilized by the magnetic field

Other unstable modes?

- Unstable sound waves?
  - Relative flow for instability unrealistically high (e.g., Andersson et al. 2004)

- Entrainment (Fermi-liquid coupling)?
  - No instabilities in expected range of entrainment parameter (e.g., Andersson et al. 2004)

- Unstable g-modes (buoyancy), convective instability?
  - Weakly unstable thermal g-modes in young neutron stars (e.g., Gusakov and Kantor 2013, Passamonti et al. 2016)

Conclusions

- Outer core is stable in garden variety spinning down isolated neutron stars
- Turbulence unlikely to be responsible for timing irregularities in these objects
- Turbulence almost certainly relevant in freely precessing pulsars (Donnelly-Glaberson instability)