Are neutron stars turbulent?

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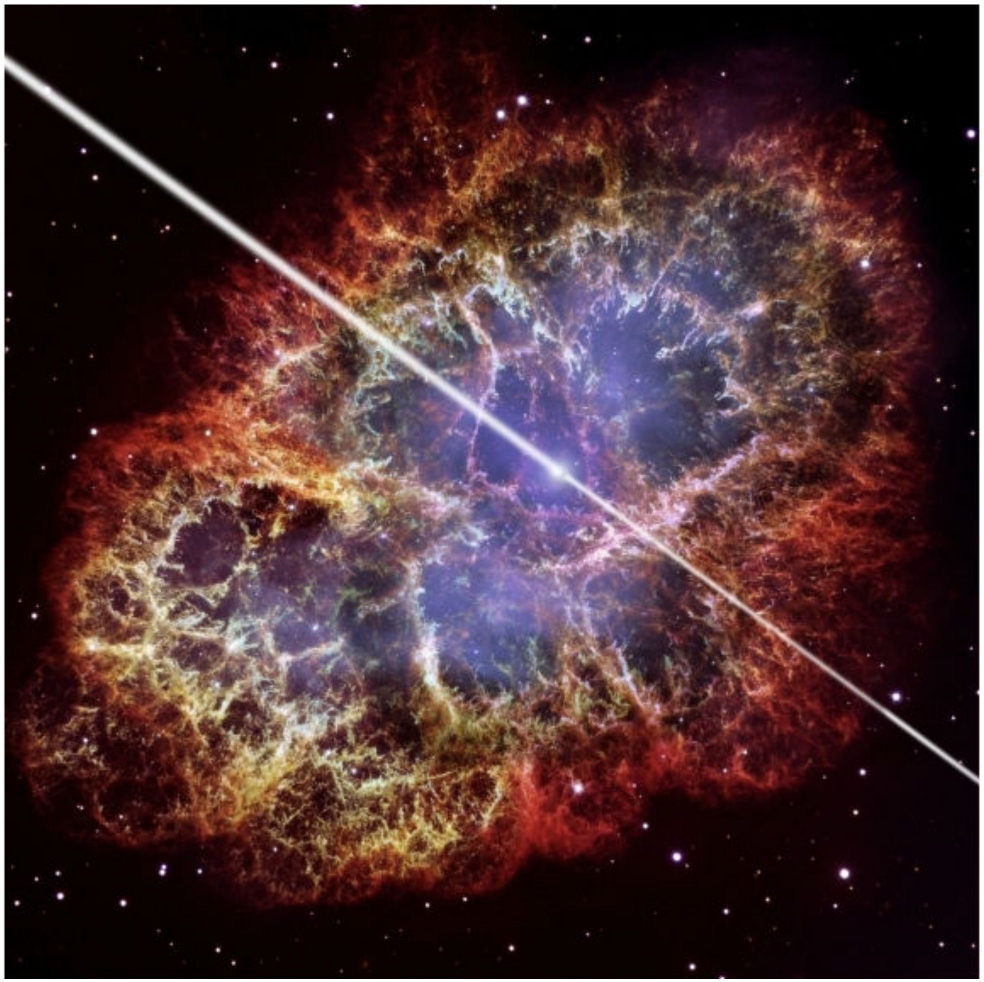
Outline

- Neutron star observations
- Convective turbulence
- Rotation-powered instabilities
- General picture and conclusions

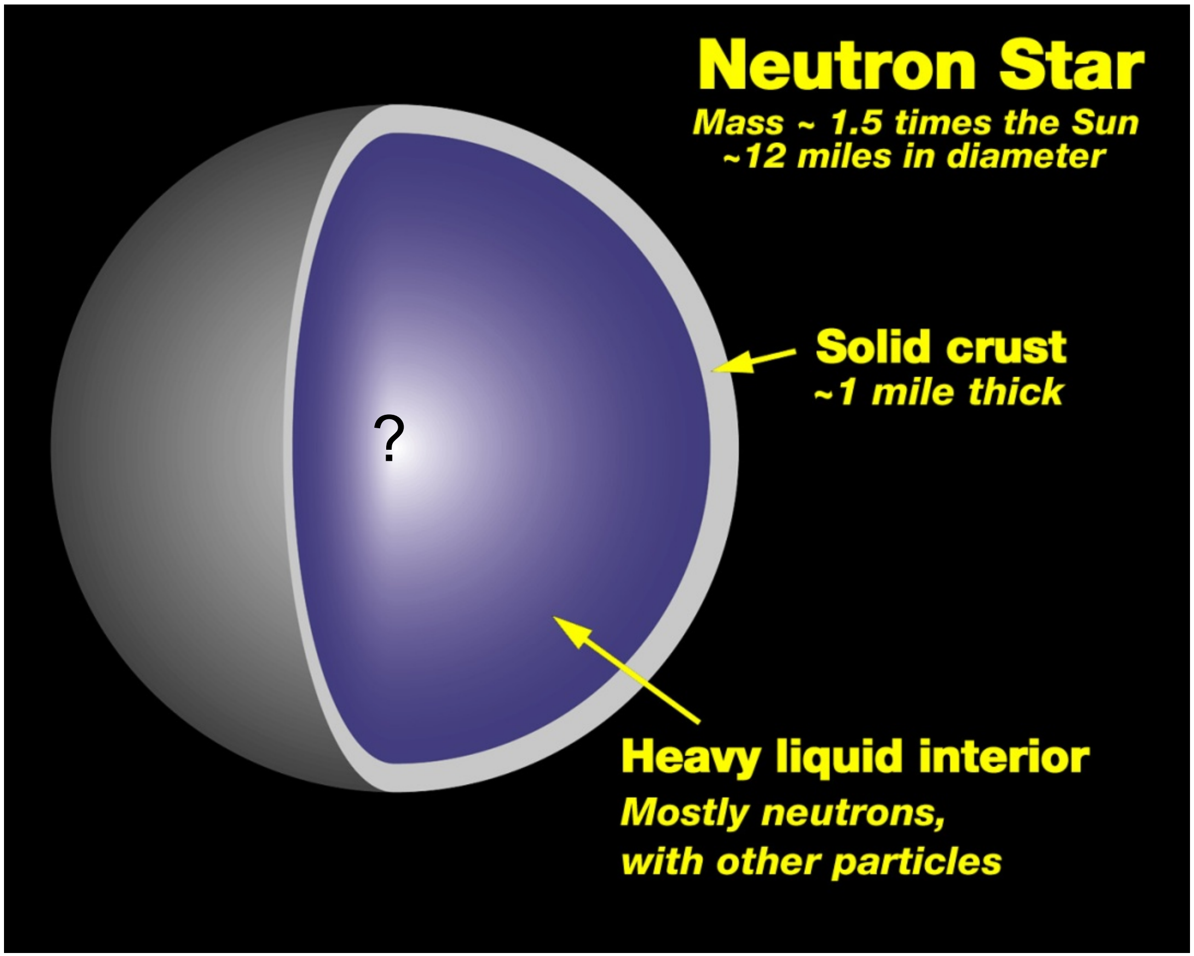
Neutron stars



Crab Nebula

- Ultra-compact stellar corpses
- Stable rotators
- Radio emission

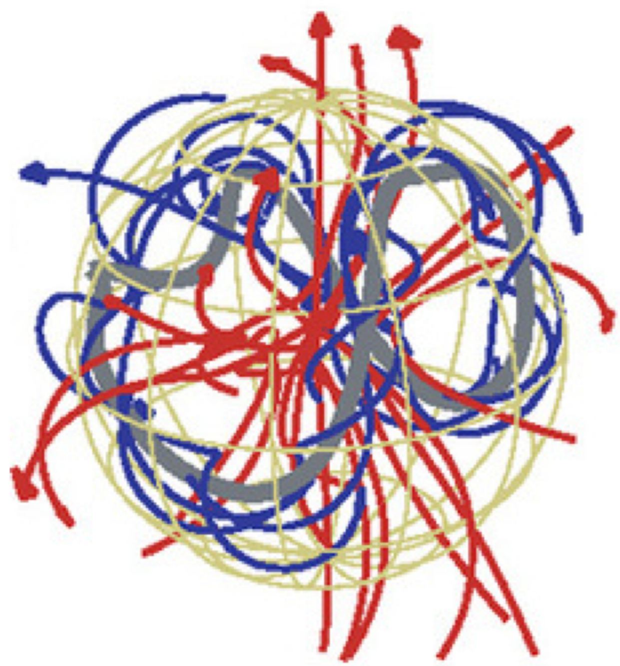
Neutron star interiors



- Outer crust for densities below nuclear saturation
- Outer core is nuclear fluid (5% protons and electrons)
- Inner core unknown
- Is this turbulent?

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

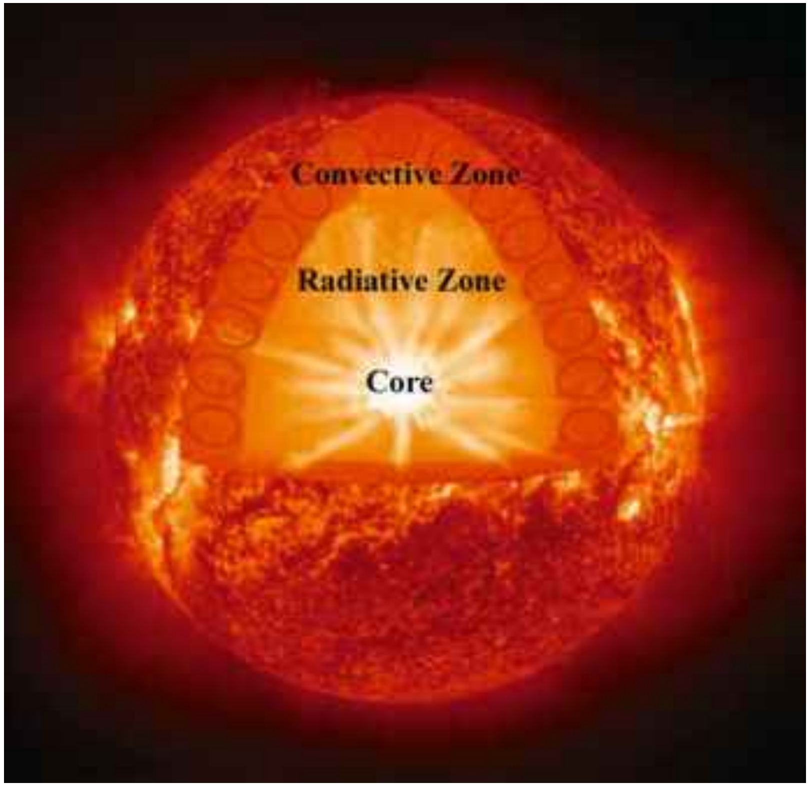
Why is turbulence interesting?

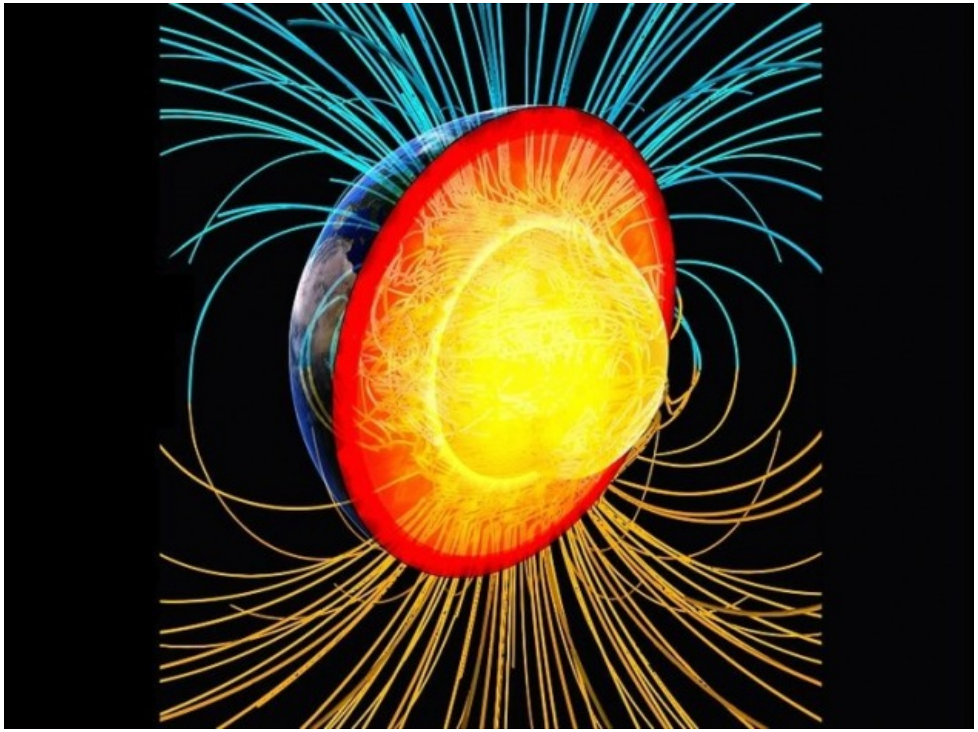
- Explain irregularities in radio timing data
  - Timing noise (e.g., Link 2012, Melatos & Link 2014)
  - Pulsar glitches (e.g., Melatos & Peralta 2007, Glampedakis & Andersson 2009, Andersson et al 2013)
- Gravitational wave emission
  - e.g., Melatos & Peralta 2010
  - stochastic background (Lasky et al 2015)

Are neutron stars turbulent?

- Convective instability?

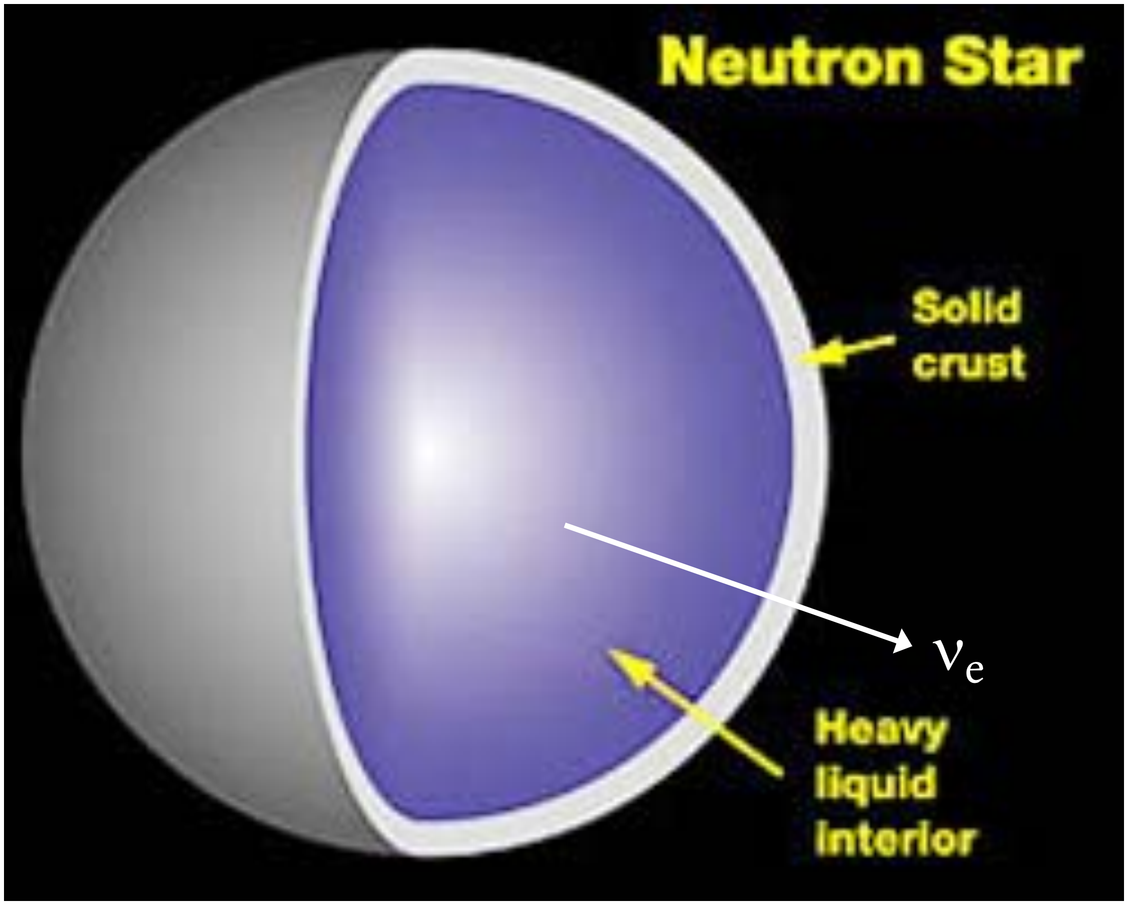
Convective turbulence





- Both the Sun and the Earth are convectively unstable

Neutron star cooling



- Neutron stars cool via neutrino emission (modified Urca process)

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e$$

$$n + p + e^- \rightarrow n + n + \nu_e$$

- Neutrinos free stream from interior

- Neutron star convectively stable (e.g., Gusakov and Kantor 2013, Passamonti et al. 2016)

Are neutron stars turbulent?

- Convective instability – neutrino cooled
- Kelvin-Helmholtz?

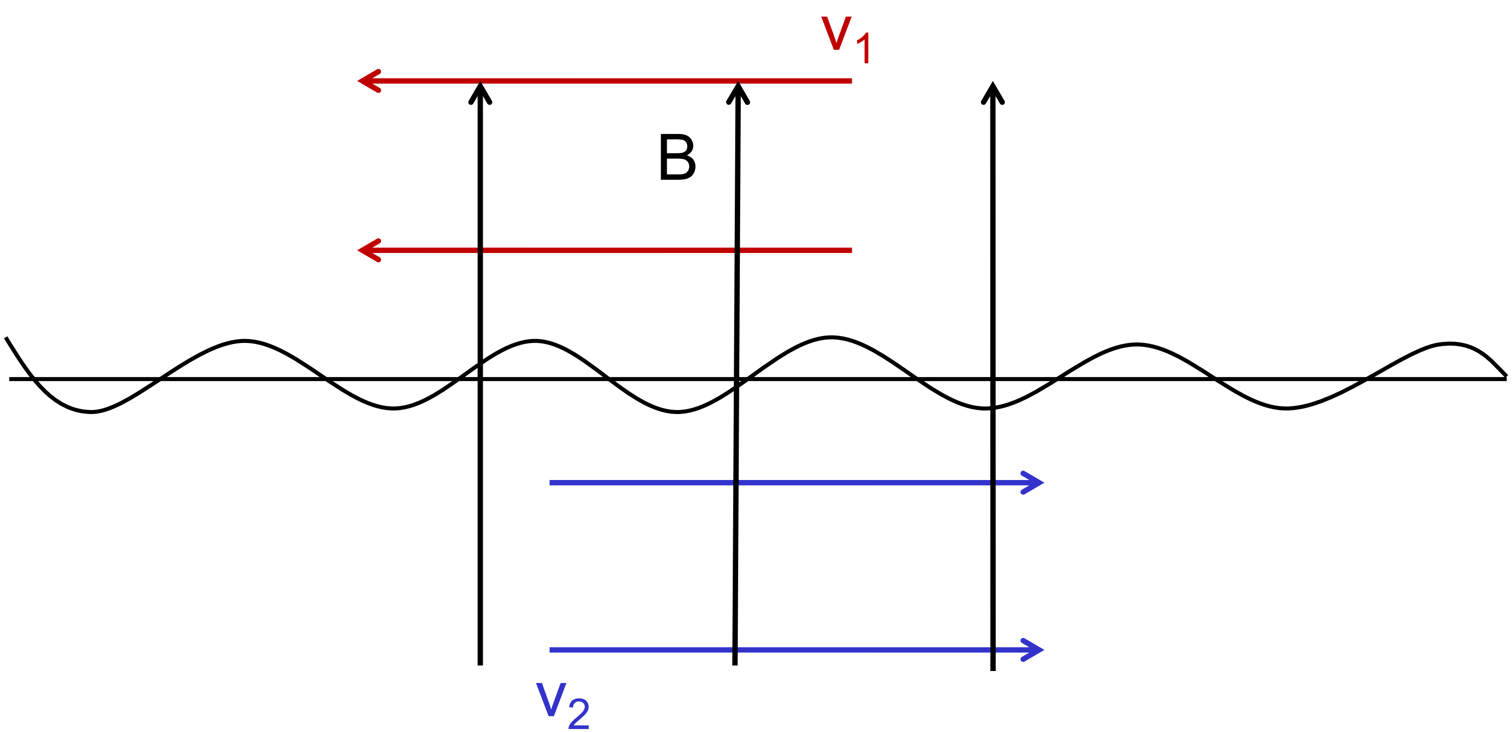
Kelvin-Helmholtz instability

- Two-stream interfacial instability

- Where? e.g, crust-core interface

Kelvin Helmholtz instability

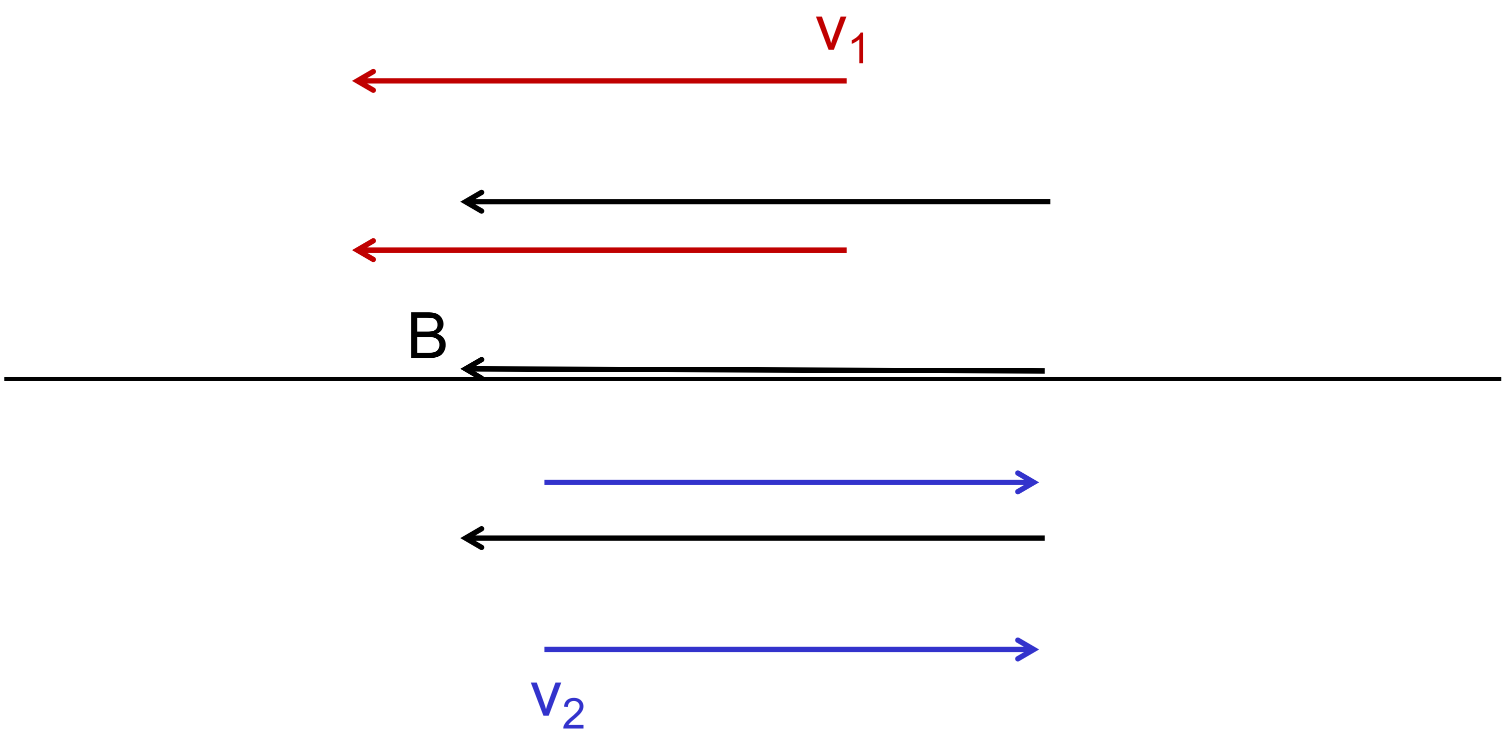
- Add transverse field



- No Effect!

Kelvin Helmholtz instability

- What about parallel field?



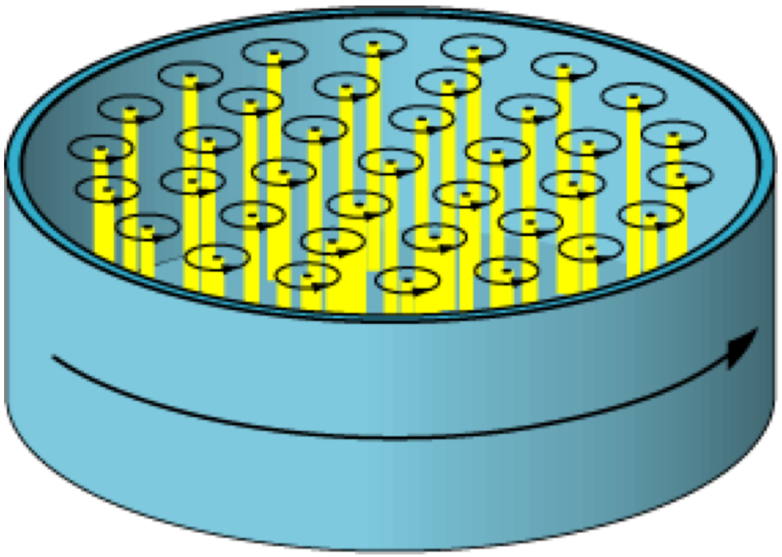
- Stabilized my magnetic tension for Alfven speed, $v_A > v_1\text{-}v_2$

Are neutron stars turbulent?

- Convective instability – neutrino cooled
- Kelvin-Helmholtz – magnetic field stabilizes charged fluids
- Bulk two stream instabilities?

Neutron stars are cold

- Neutrons and protons form superfluid and superconducting condensates

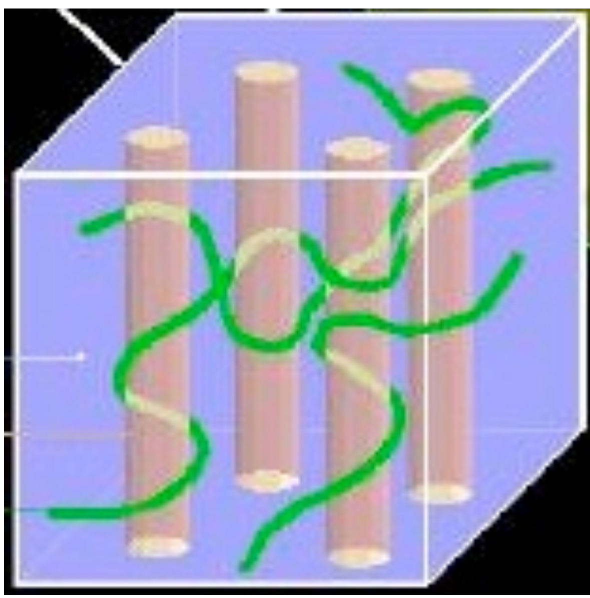


- Neutron superfluid forms quantized vortex array to rotate

- Type II superconducting protons form quantized flux tube array to support magnetic field

Pinning interactions

- Vortex and flux tube arrays pin due to magnetic forces

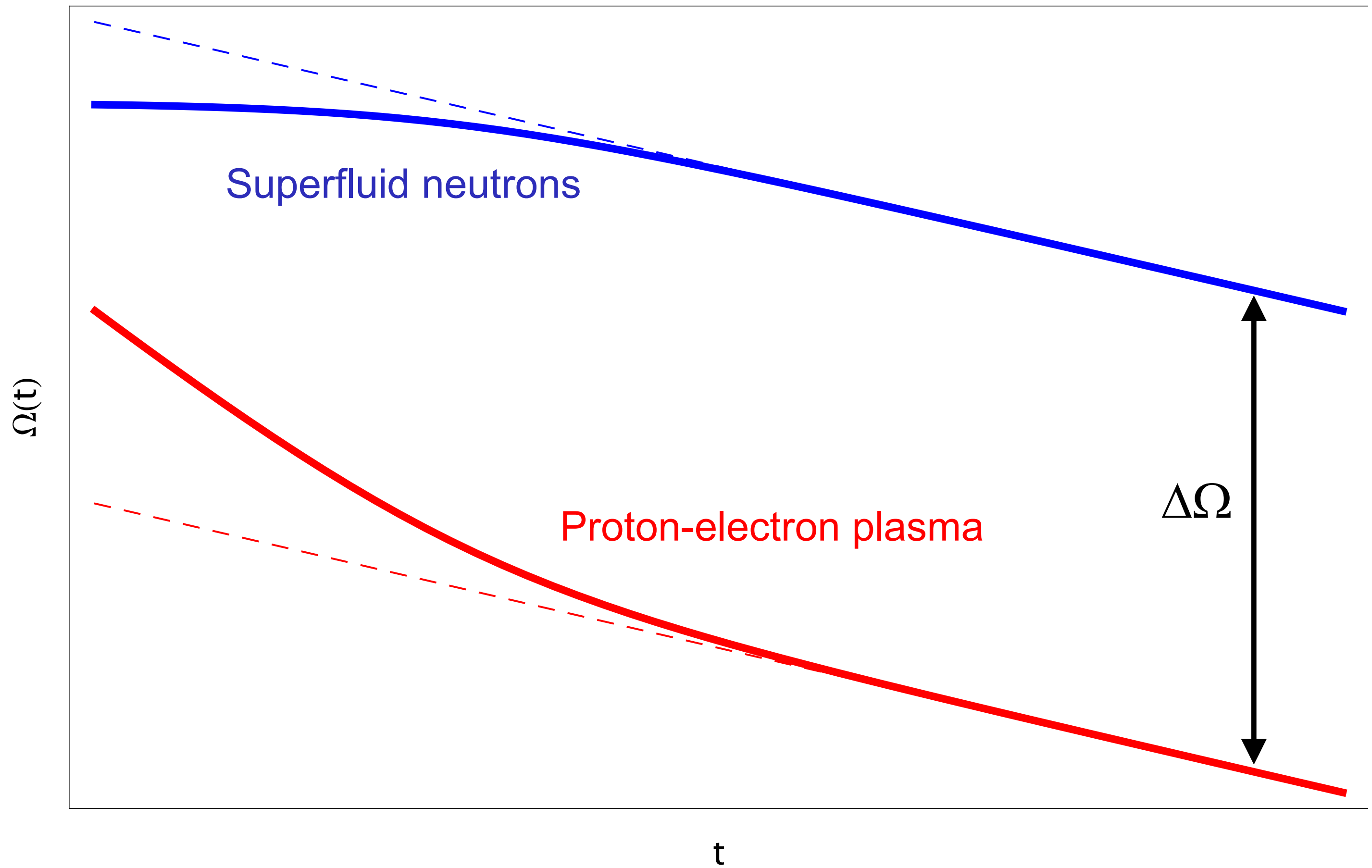


Proton-electron fluid
(MHD fluid)

Mutual friction
(pinning)

Neutron condensate
(Inviscid fluid)

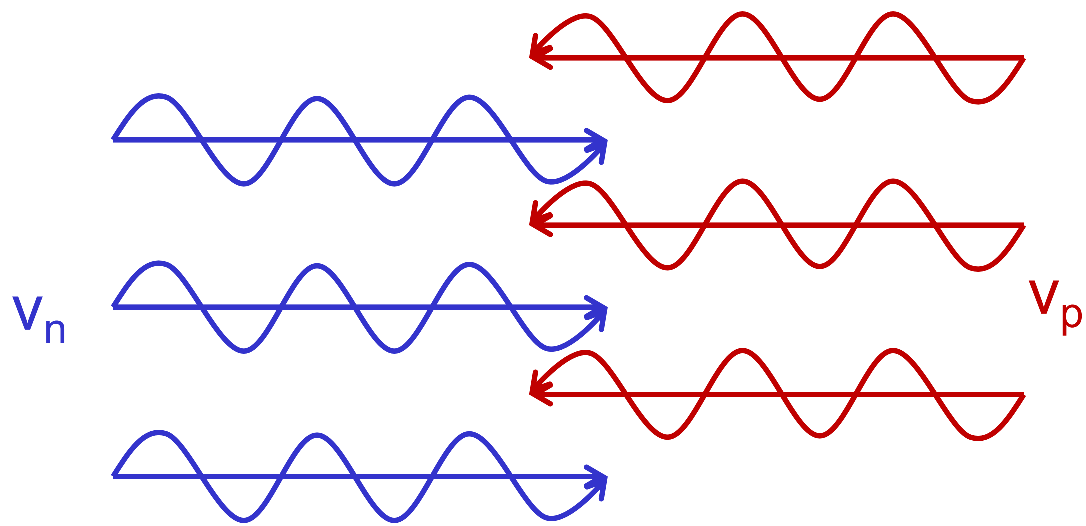
Spin-down equilibrium



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

Bulk two-stream instability

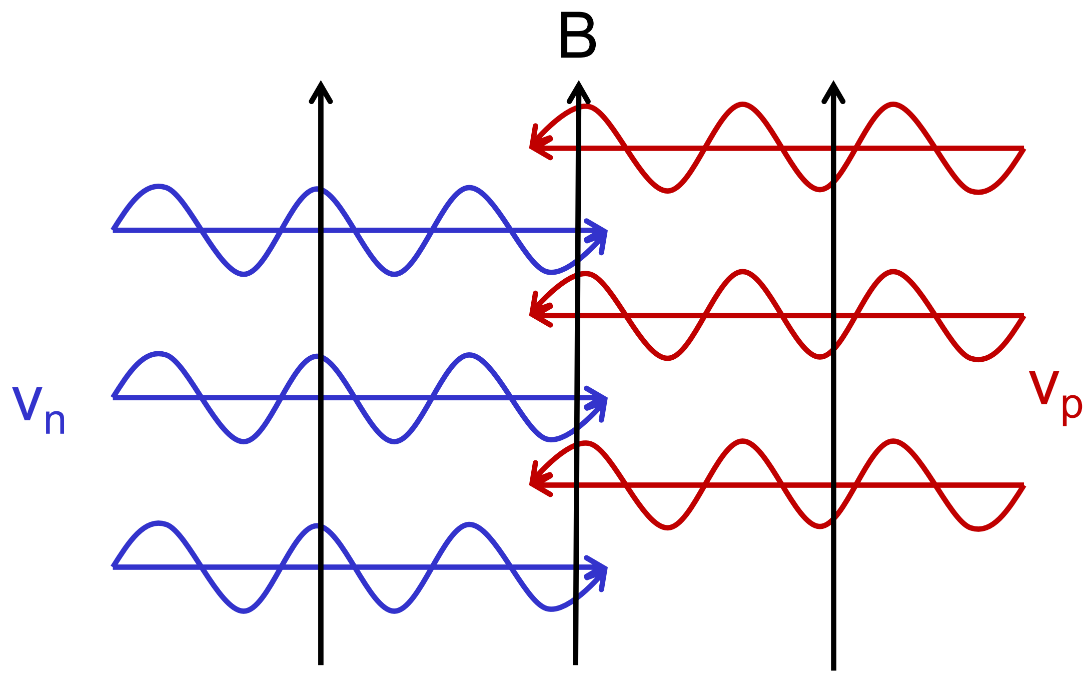
- Perfectly pinned flux tubes and vortices



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

What about magnetic fields?

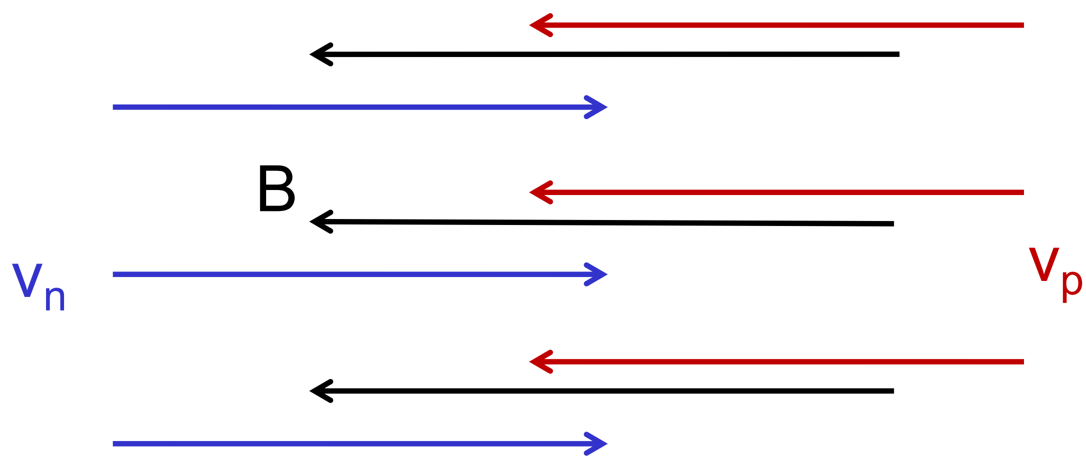
- Add poloidal (dipole field), what happens?



- No effect!

What about magnetic fields?

- What about toroidal field?



- Stabilized by magnetic stresses 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 two-stream instabilites?

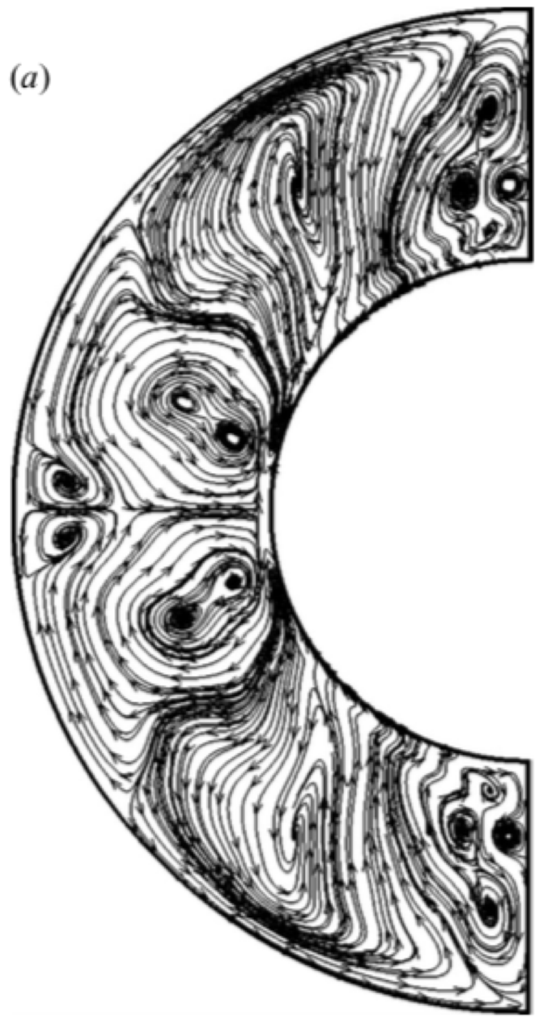
- Unstable sound waves (chemical coupling)?
  - Relative flow for instability unrealistically high (e.g., Andersson et al. 2004)

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

Are neutron stars turbulent?

- Convective instability – neutrino cooled
- Kelvin-Helmholtz – magnetic field stabilizes charged fluids
- Bulk two stream instabilities – stabilized by magnetic field
- Shear turbulence?

Shear turbulence

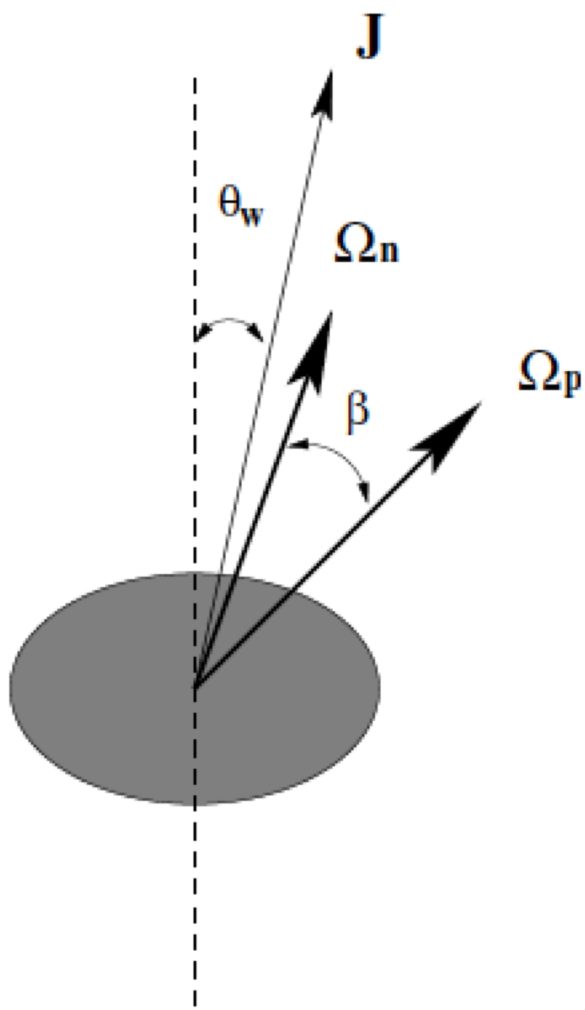


- Relative rotation between crust and core (e.g., Peralta & Melatos 2006,2007)
- Core composition unknown
- Decoupled from birth? (magnetic field) (Melatos 2012)

Are neutron stars turbulent?

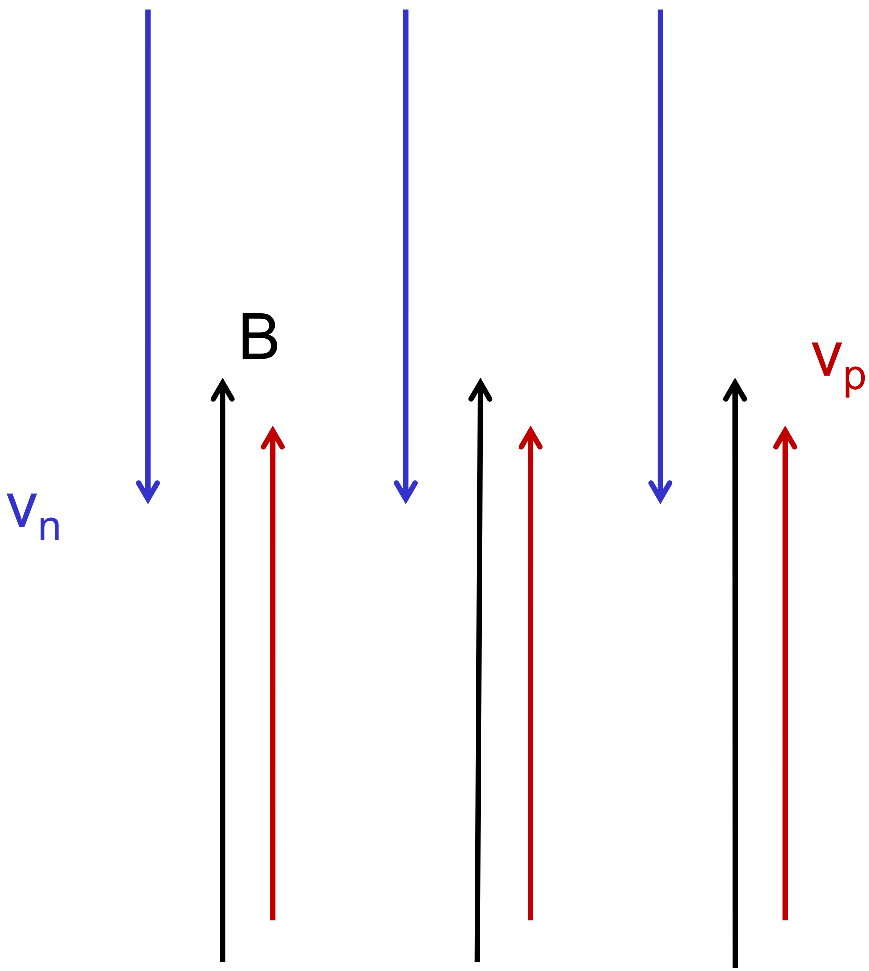
- Convective instability – neutrino cooled
- Kelvin-Helmholtz – magnetic field stabilizes charged fluids
- Bulk two stream instabilities – stabilized by magnetic field
- Shear turbulence – if core magnetically decoupled
- Free precession?

Free precession



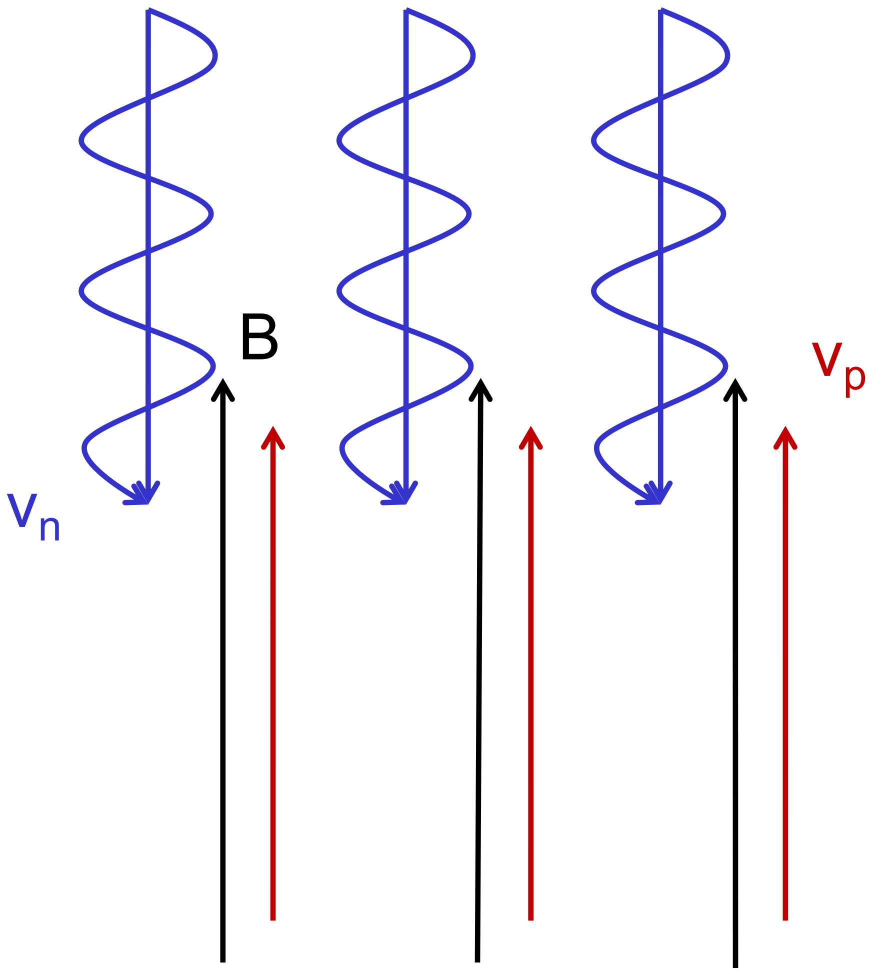
- Angular momentum vectors of protons and neutron misaligned
- Relative flow along the rotation axis
- Is this stable?

Stability of free precession



- Two stream instability
- Stabilized by poloidal field for wobble angles < 1 degree (van Hoven and Levin 2008)

Stability of free precession

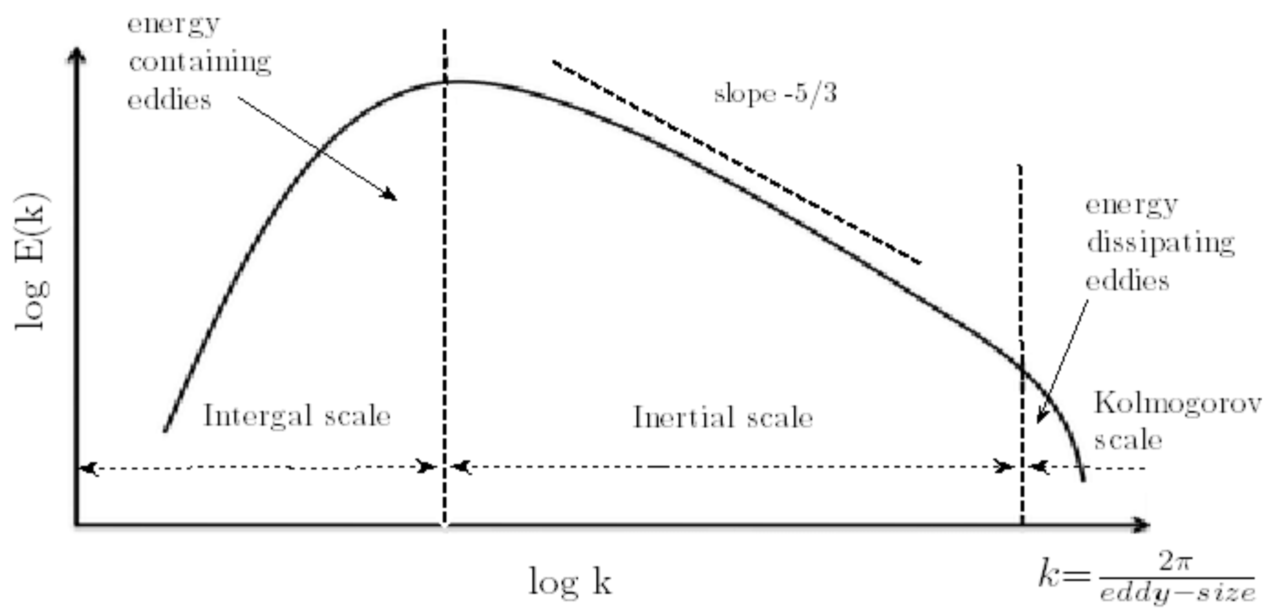


- Donnelly-Glaberson instability
- Growth time of days to years

Are neutron stars turbulent?

- Convective instability – neutrino cooled
- Kelvin-Helmholtz – magnetic field stabilizes charged fluids
- Bulk two stream instabilities – stabilized by magnetic field
- Shear turbulence – if core magnetically decoupled
- Free precession – DGI growth time of days
- Anything else?

What's driving turbulence?



- Magnetic braking is very weak

Conclusions

- Most candidate instabilities don't appear to be relevant in neutron stars
- What can drive global, quasi-steady turbulence in a neutron star?
- Something we haven't thought of?

Thanks!