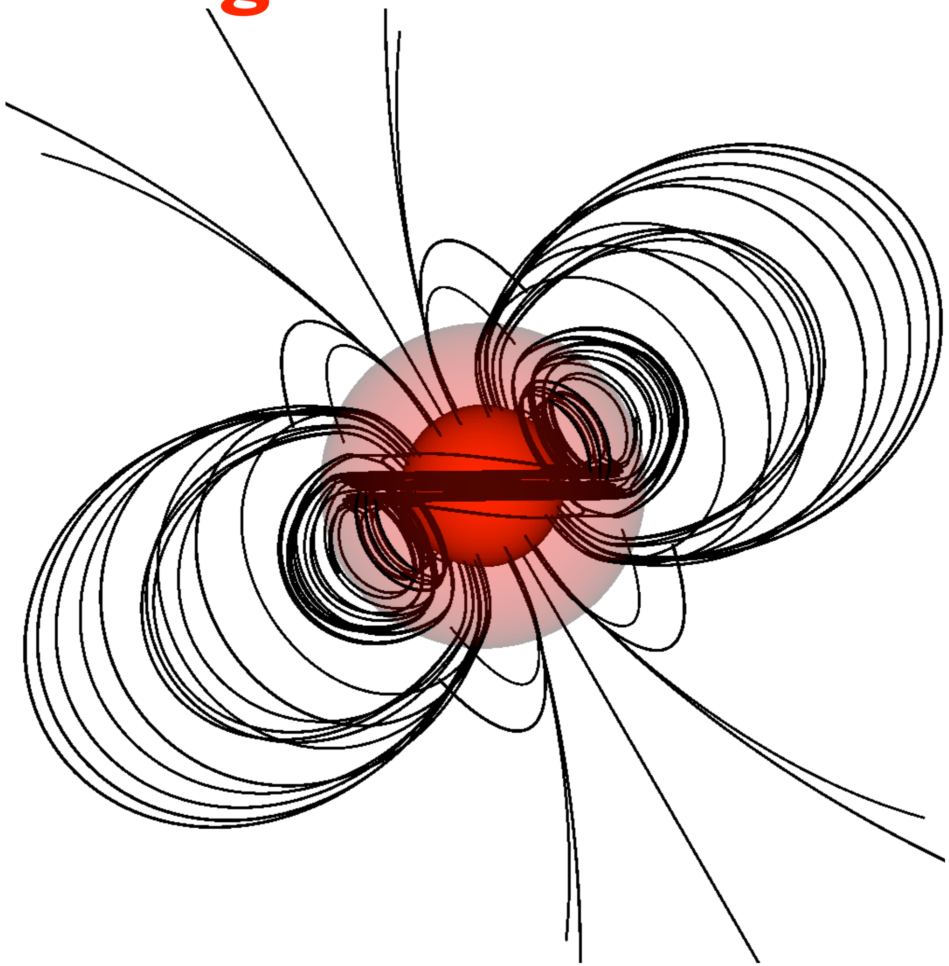
MONASH University

MoCA
Monash Centre for Astrophysics

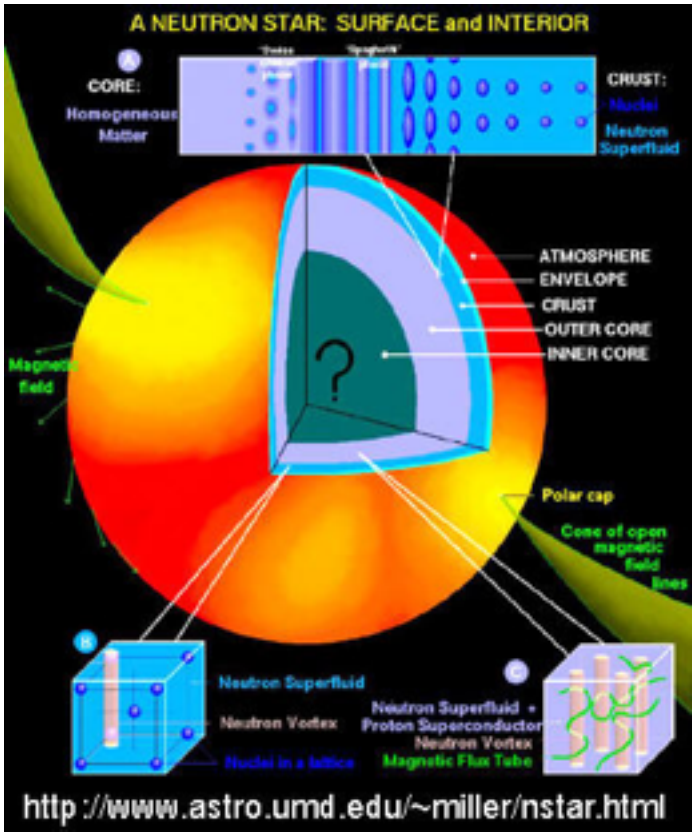
Determining observational properties of neutron stars by modelling their interiors

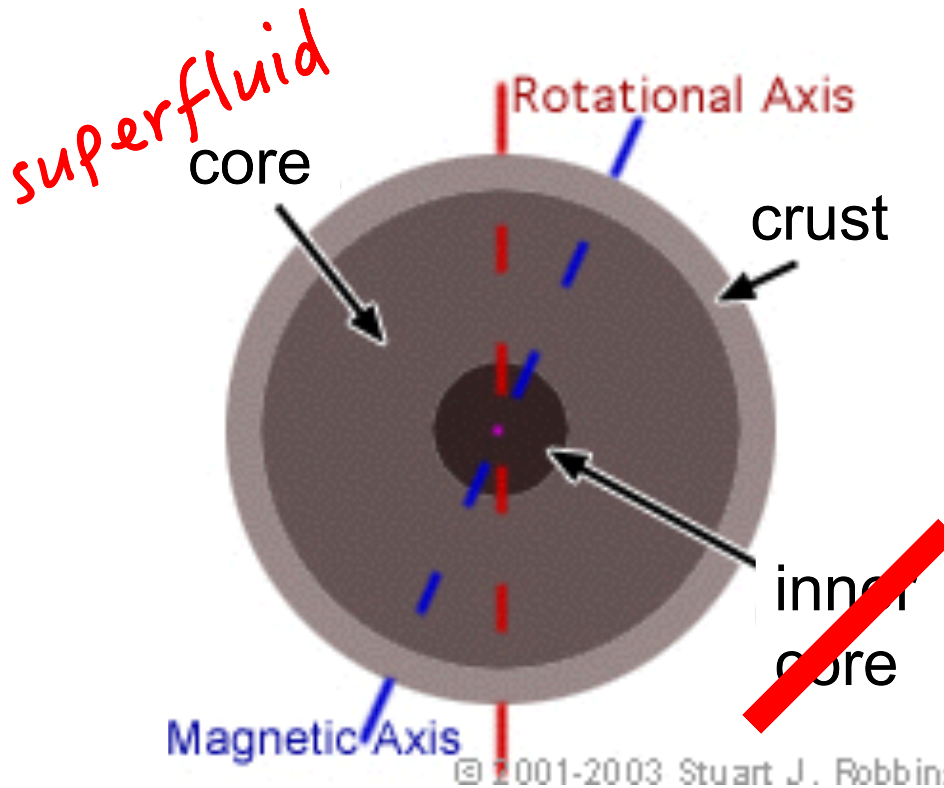
Paul Lasky



Neutron Star Anatomy

Fiducial neutron star talk	**This** neutron star talk



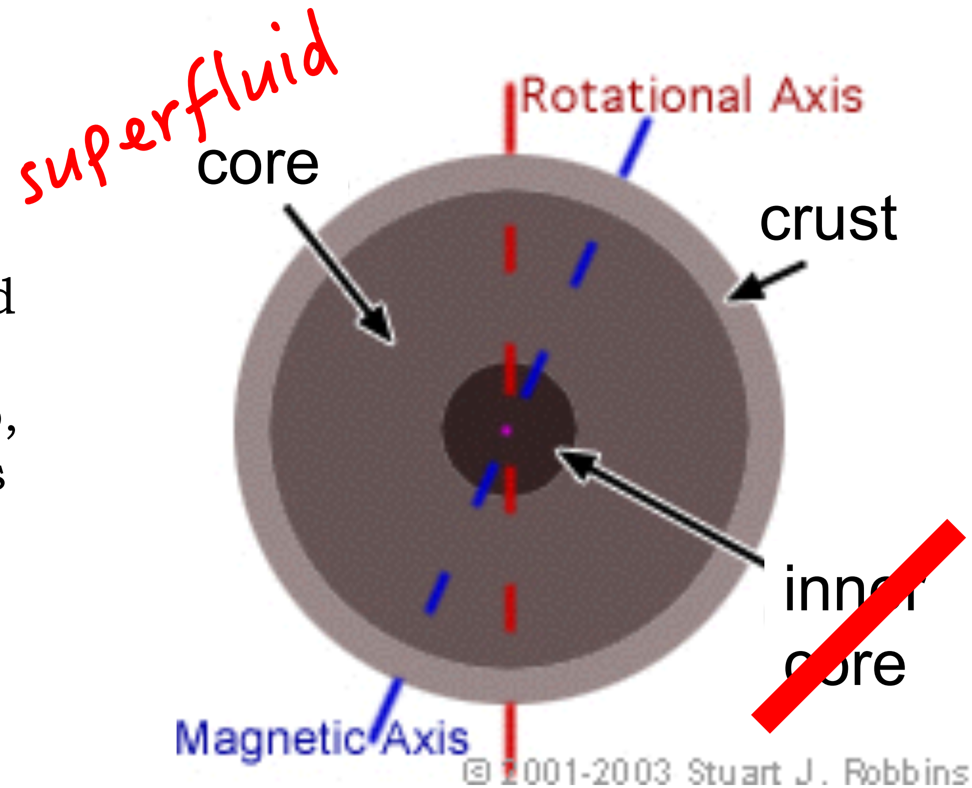


Neutron Star Anatomy

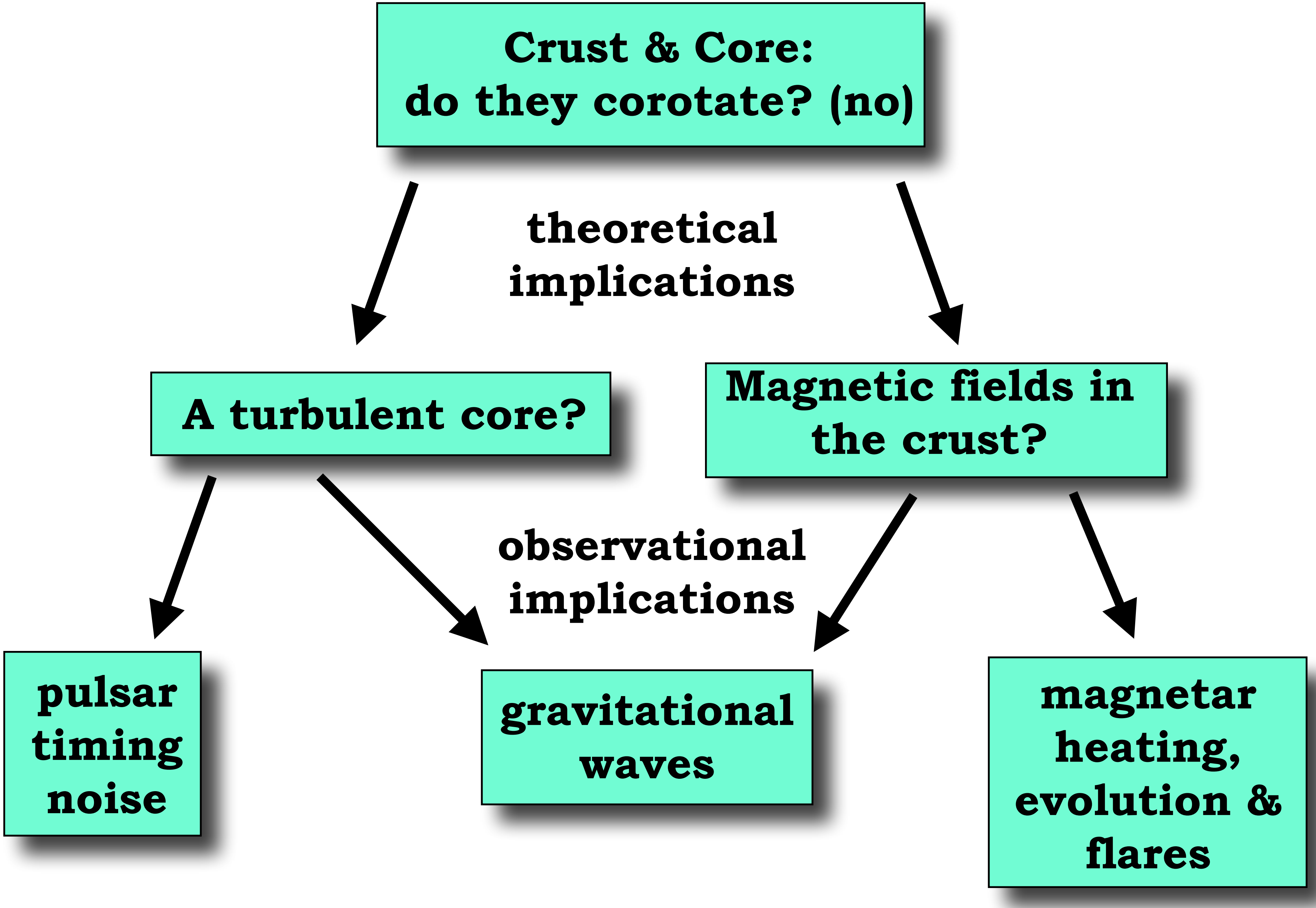
This neutron star talk

Greenstein (1970; Nature)

Abstract: The neutron superfluid in most neutron stars should be in a highly turbulent state. If so, this turbulence drastically alters its rotational properties.



summary


Crust & Core:
do they corotate? (no)
theoretical
implications
A turbulent core?
Magnetic fields in
the crust?
observational
implications
pulsar
timing
noise
gravitational
waves
magnetar
heating,
evolution &
flares

The core and the crust

Conventional wisdom:

- Neutron star's crust & core *corotate*

- 2 mechanisms:
  - viscous coupling (Ekman pumping)

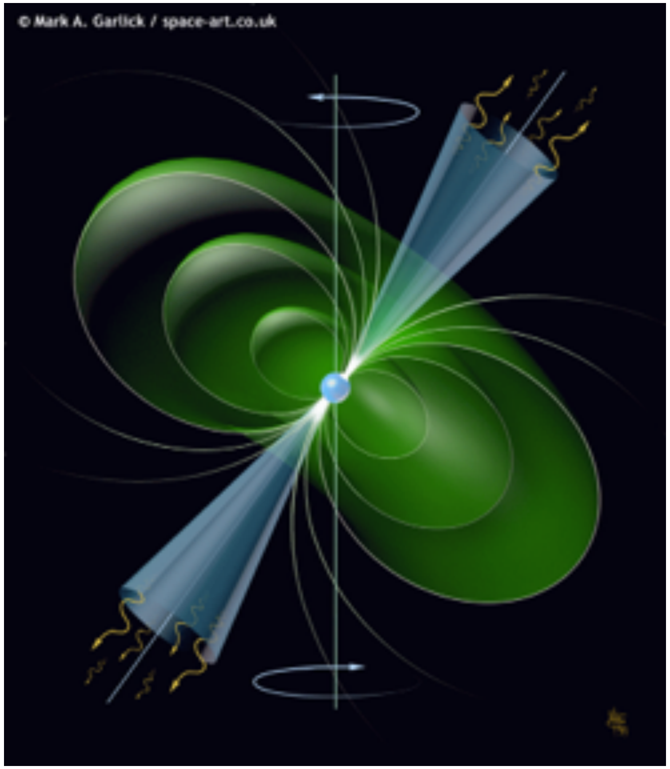
  - magnetic coupling (commonly considered dominant)

The conventional wisdom is wrong!

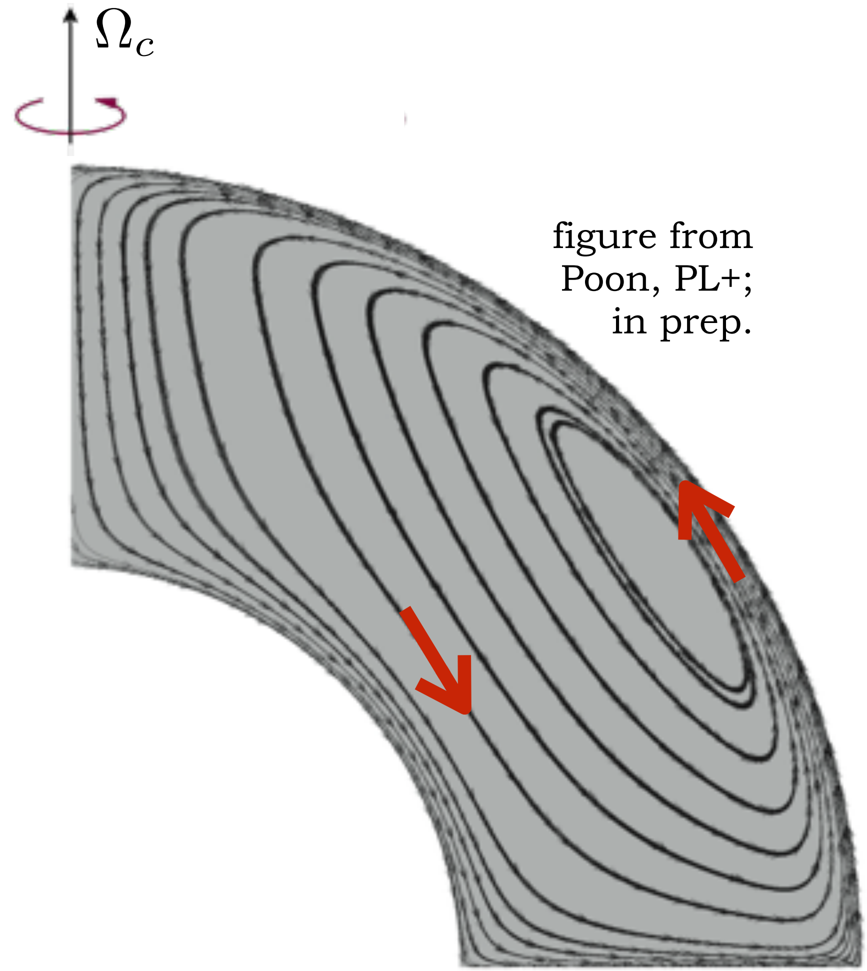
Neither mechanism can effectively enforce crust-core corotation (Melatos 2012; Glampedakis & PL 2015)

- Theoretical & Observational implications

Ekman pumping



magnetic field spins down crust



Ekman pumping spins down fluid in core

Ekman pumping

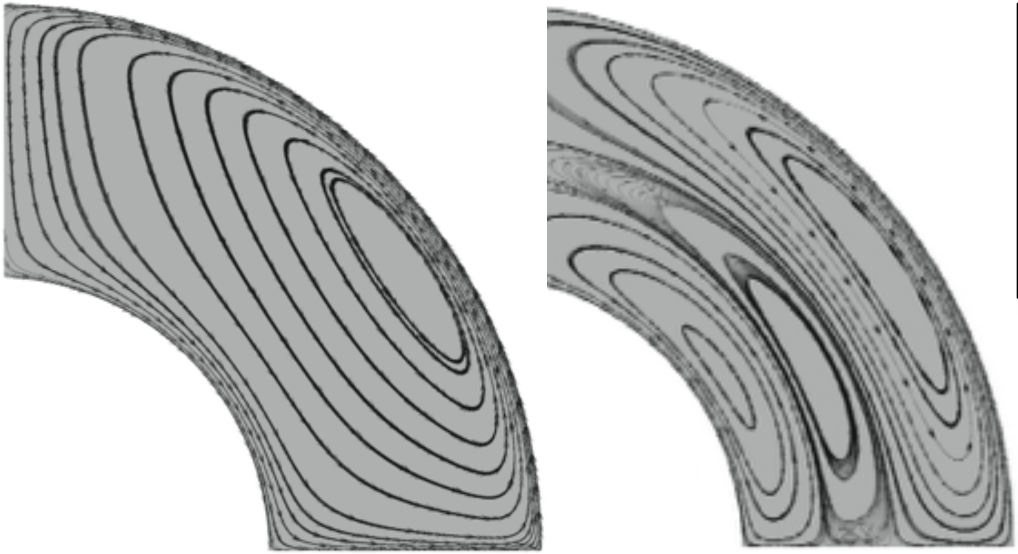
Vortex flow at the Canberra airport

"this is something that only physicists can get excited about..."

Alexander Heger

stratified Ekman pumping

- Ekman flow hindered by stratification (Abney & Epstein 1996)
- Only effective in thin layer near crust-core boundary
- Rest of core couples on much longer timescale (~ 10^3 yr; Melatos 2012)



figures from Poon, PL+; in prep.

Melatos 2012: neutron stars have super-rotating cores!

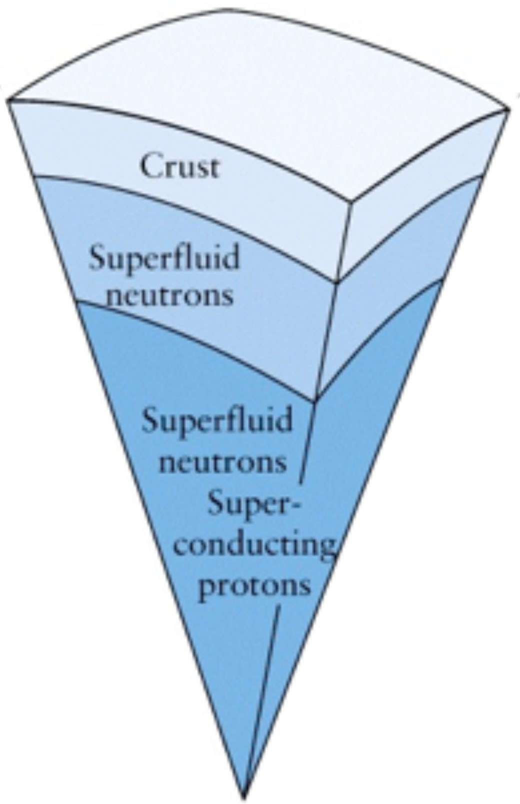
caveat:
the magnetic field!

magnetic crust-core coupling

Glampedakis & PL (2015)

Model

- Two-fluid core (charged proton-electron fluid + neutron superfluid) magnetically coupled to the crust.



http://www.ualberta.ca/

- in crust's instantaneous rest frame, the secular dynamics of charged component is

$$2\boldsymbol{\Omega} \times \mathbf{v_p} + \dot{\boldsymbol{\Omega}} \times \mathbf{r} + \nabla \Psi_p = \frac{1}{\rho_p} (\mathbf{F}_{\rm mag} - \mathbf{F}_{\rm cpl})$$

$$2\boldsymbol{\Omega} \times \mathbf{v}_n + \dot{\boldsymbol{\Omega}} \times \mathbf{r} + \nabla \Psi_n = \frac{1}{\rho_n} \mathbf{F}_{\rm cpl}$$

Ψ : chemical + gravitational potentials

$\mathbf{F}_{\rm mag}$: magnetic force

$\mathbf{F}_{\rm cpl}$: coupling force with neutrons

magnetic crust-core coupling

Glampedakis & PL (2015)

The punch line

- Degree of coupling between the crust and the core depends sensitively on the magnetic field **geometry!**

magnetic crust-core coupling

Glampedakis & PL (2015)

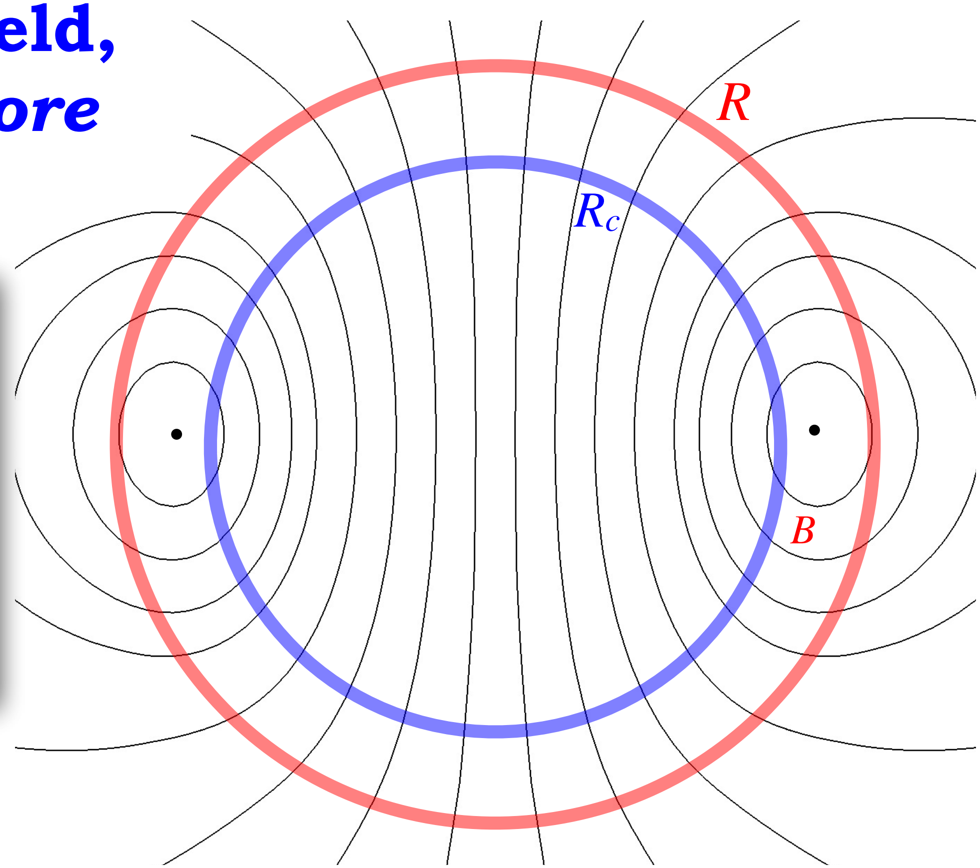
The punch line

- Degree of coupling between the crust and the core depends sensitively on the magnetic field **geometry!**

Case 1: purely poloidal field,
no closed field lines in core

Entire core couples to crust and corotates.

Crust and core spin down in unison



magnetic crust-core coupling

Glampedakis & PL (2015)

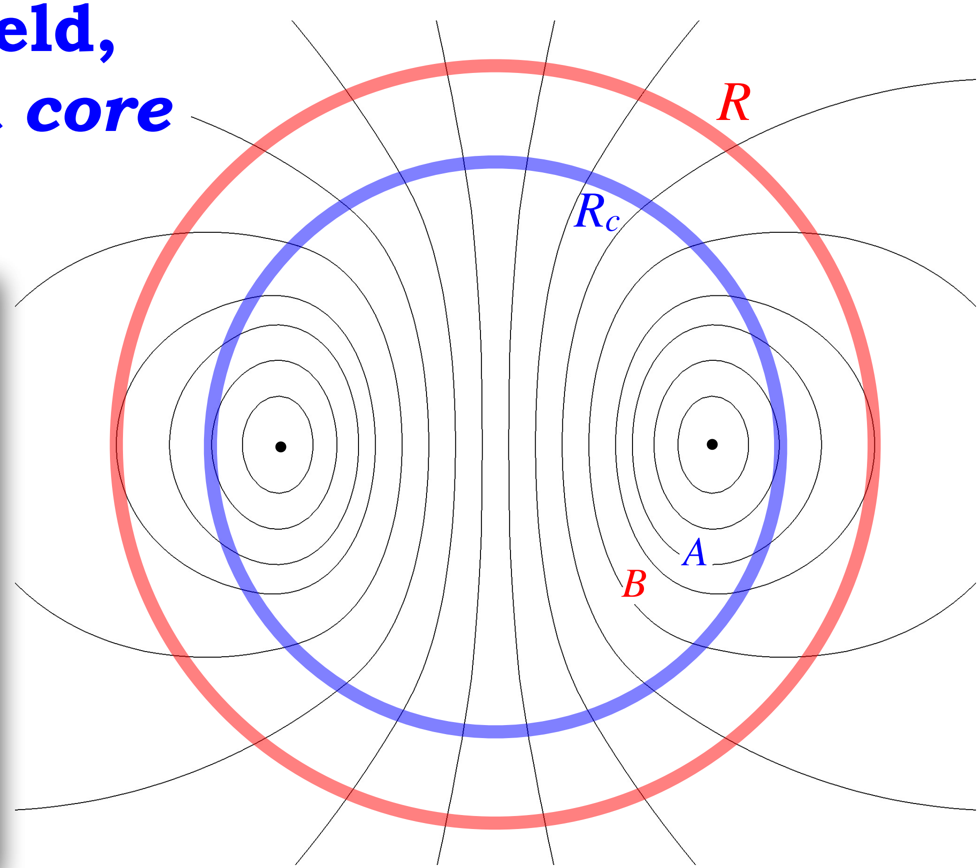
The punch line

- Degree of coupling between the crust and the core depends sensitively on the magnetic field **geometry!**

Case 2: purely poloidal field, *with* *closed field lines in core*

Only core region threaded by open field lines corotates with the crust

Rest of the core is decoupled



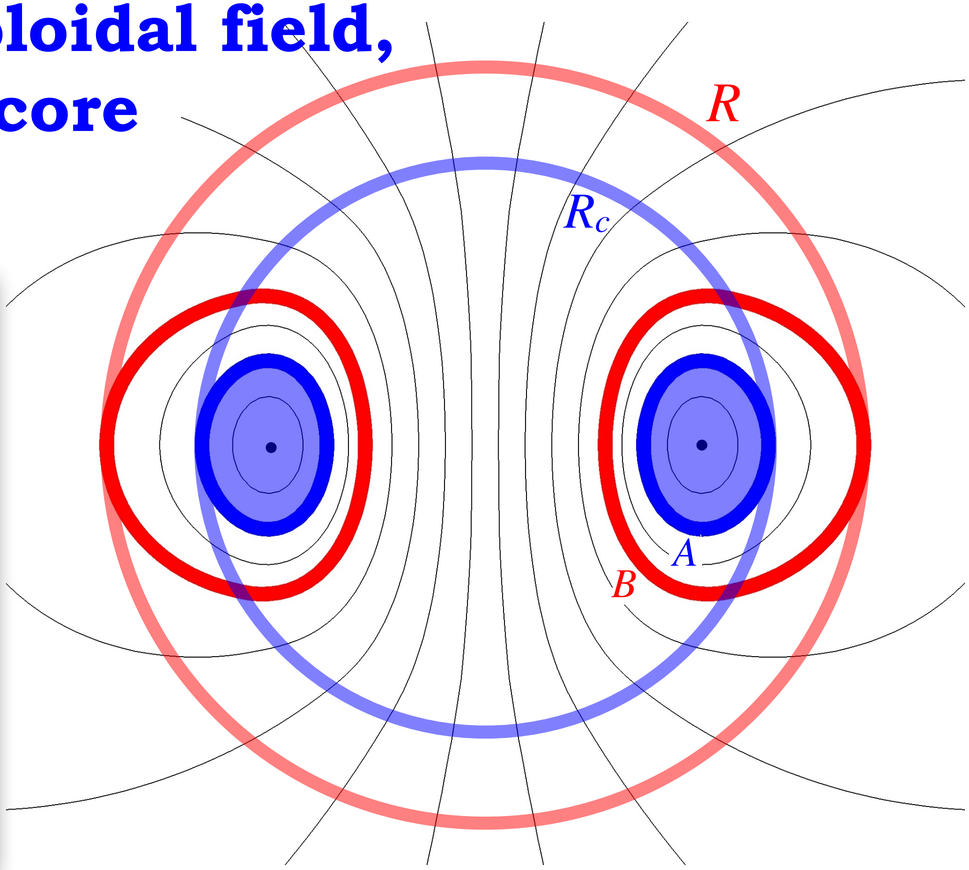
magnetic crust-core coupling

Glampedakis & PL (2015)

The punch line

- Degree of coupling between the crust and the core depends sensitively on the magnetic field **geometry!**

Case 3: mixed toroidal-poloidal field, with closed field lines in core



Only core region threaded by open field lines corotates with the crust

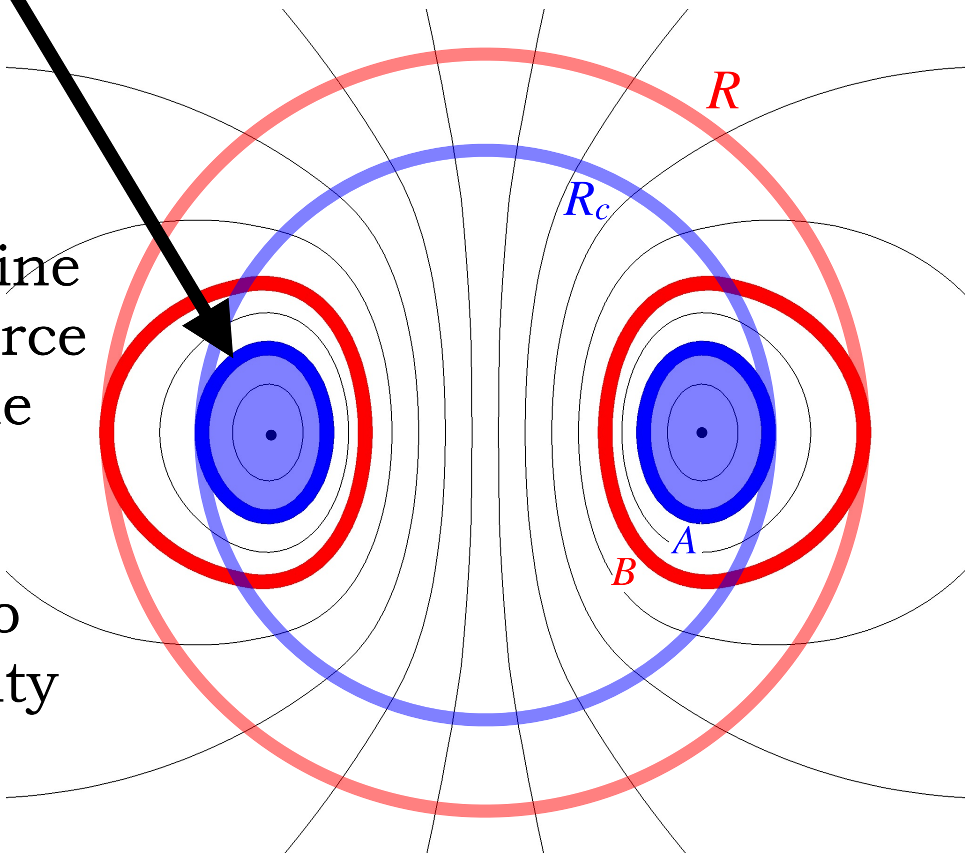
Rest of the core is decoupled

the super-rotating core region

Glampedakis & PL (2015)

- Following birth, neutron stars could have a **super-rotating, torus-shaped region in the core!**

- Almost certainly unstable:
  - velocity jump along field line A induces local Lorentz force that will try to displace the super-rotating region
  - also should be unstable to Kelvin-Helmholtz instability



Two Possible Outcomes

i) core remains in constant turbulent state

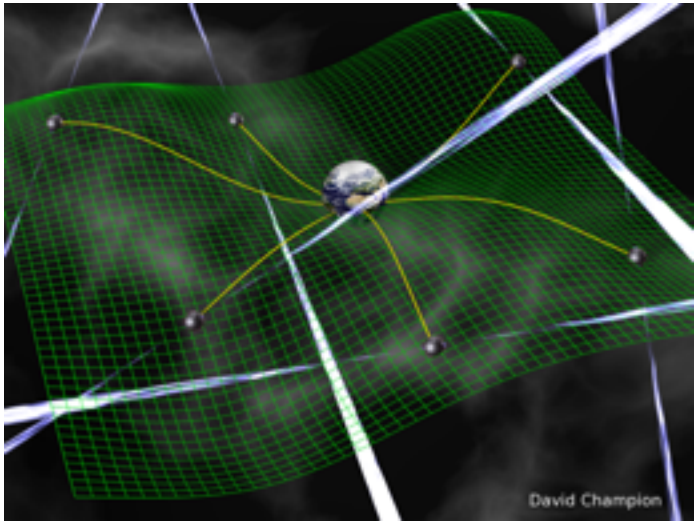
ii) magnetic field evicted to crust

Peralta, Melatos, et al.

Turbulent Consequences

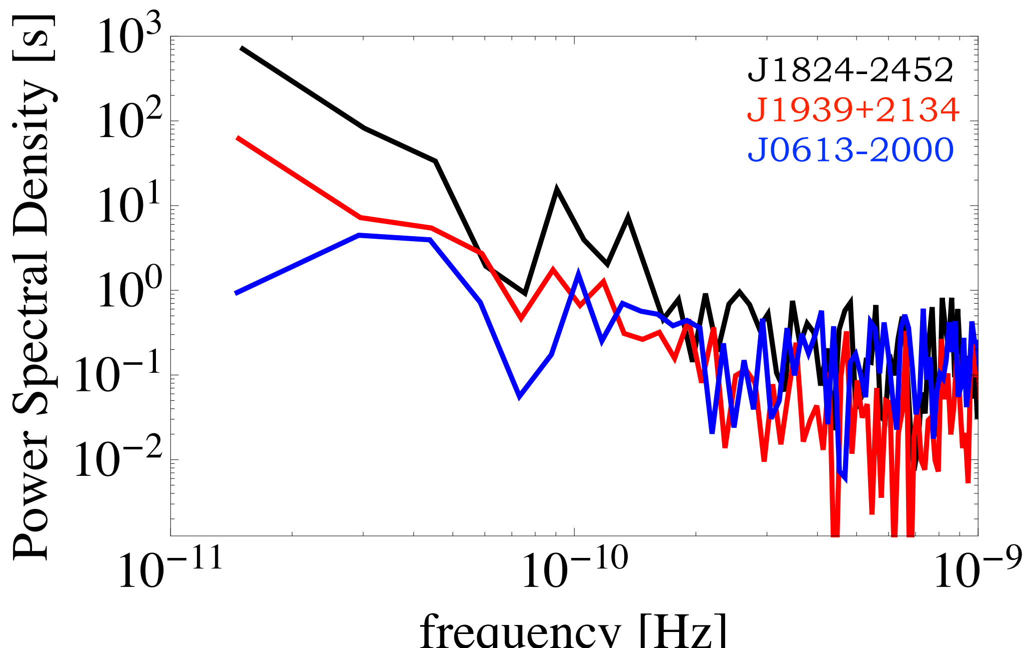
- ## Pulsar timing noise
  - Is pulsar timing noise from turbulence?
  - Quantifying the effect on gravitational wave detection with Pulsar Timing Arrays
- ## Gravitational waves - LIGO
  - Single Neutron Star
  - Stochastic Background

Pulsar Timing Arrays



- Time millisecond pulsars with EXTREME precision
- Look for correlated timing residuals as GW signature
  - **Timing Residual: difference between measured and modelled phase of pulse.**

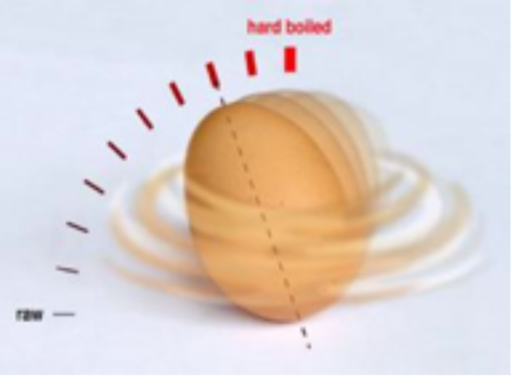
- Timing noise:
  - Stochastic wandering of pulse arrival times
  - stochastic torque fluctuations exerted on crust by turbulent fluid in core



Timing Noise Due to Turbulence

Greenstein
(1970; Nature)

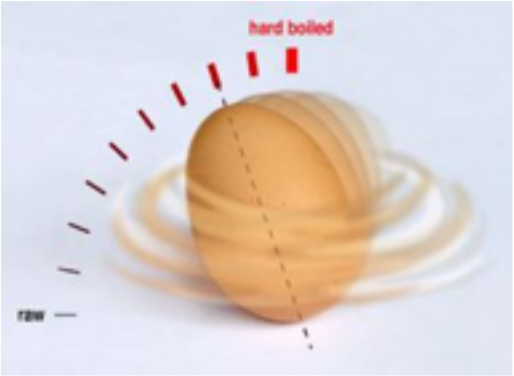
‘My final point is a speculative one. When an uncooked egg rotates it does so irregularly. The yolk inside moves about erratically, and in order to conserve angular momentum the rotation rate of the shell must also fluctuate. The rotating turbulent neutron superfluid must exhibit something like the same phenomenon.



Timing Noise Due to Turbulence

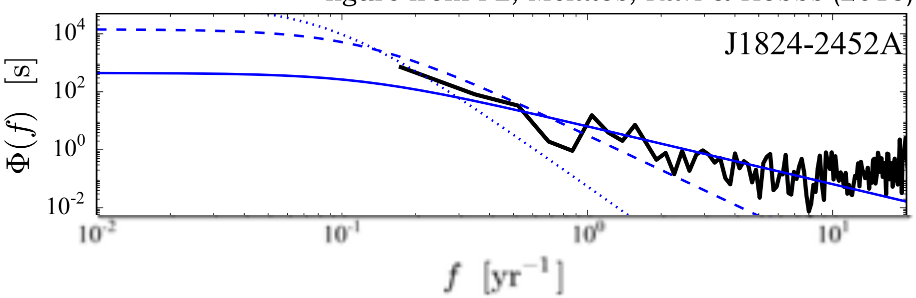
Greenstein
(1970; Nature)

'My final point is a speculative one. When an uncooked egg rotates it does so irregularly. The yolk inside moves about erratically, and in order to conserve angular momentum the rotation rate of the shell must also fluctuate. The rotating turbulent neutron superfluid must exhibit something like the same phenomenon.



Melatos & Link (2014)
calculated angular momentum fluctuations on NS crust from core

figure from PL, Melatos, Ravi & Hobbs (2015)

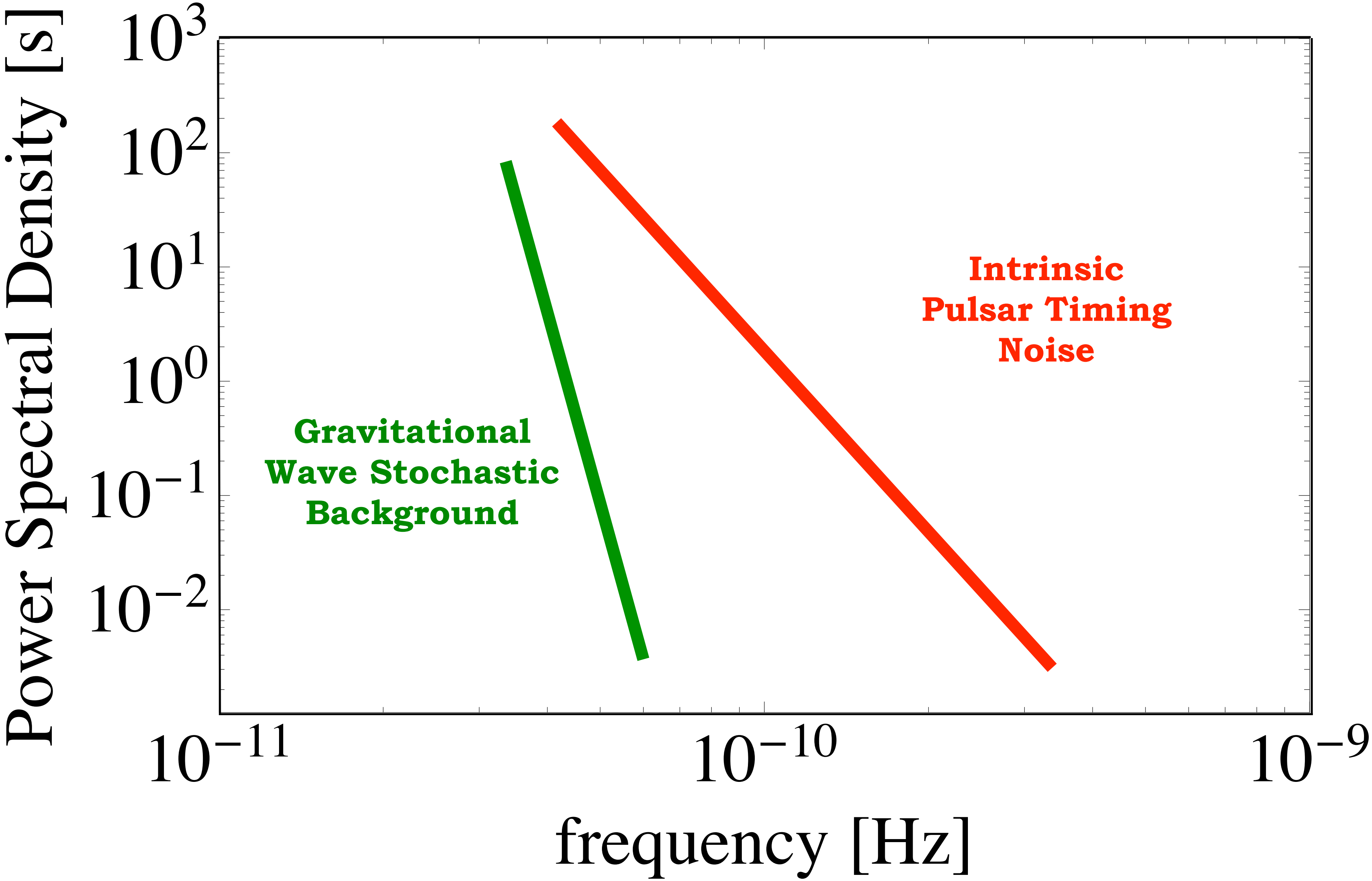


Small number of (relatively unconstrained) parameters 'fit' timing noise spectra.

Prediction: low-frequency plateau in timing noise spectrum

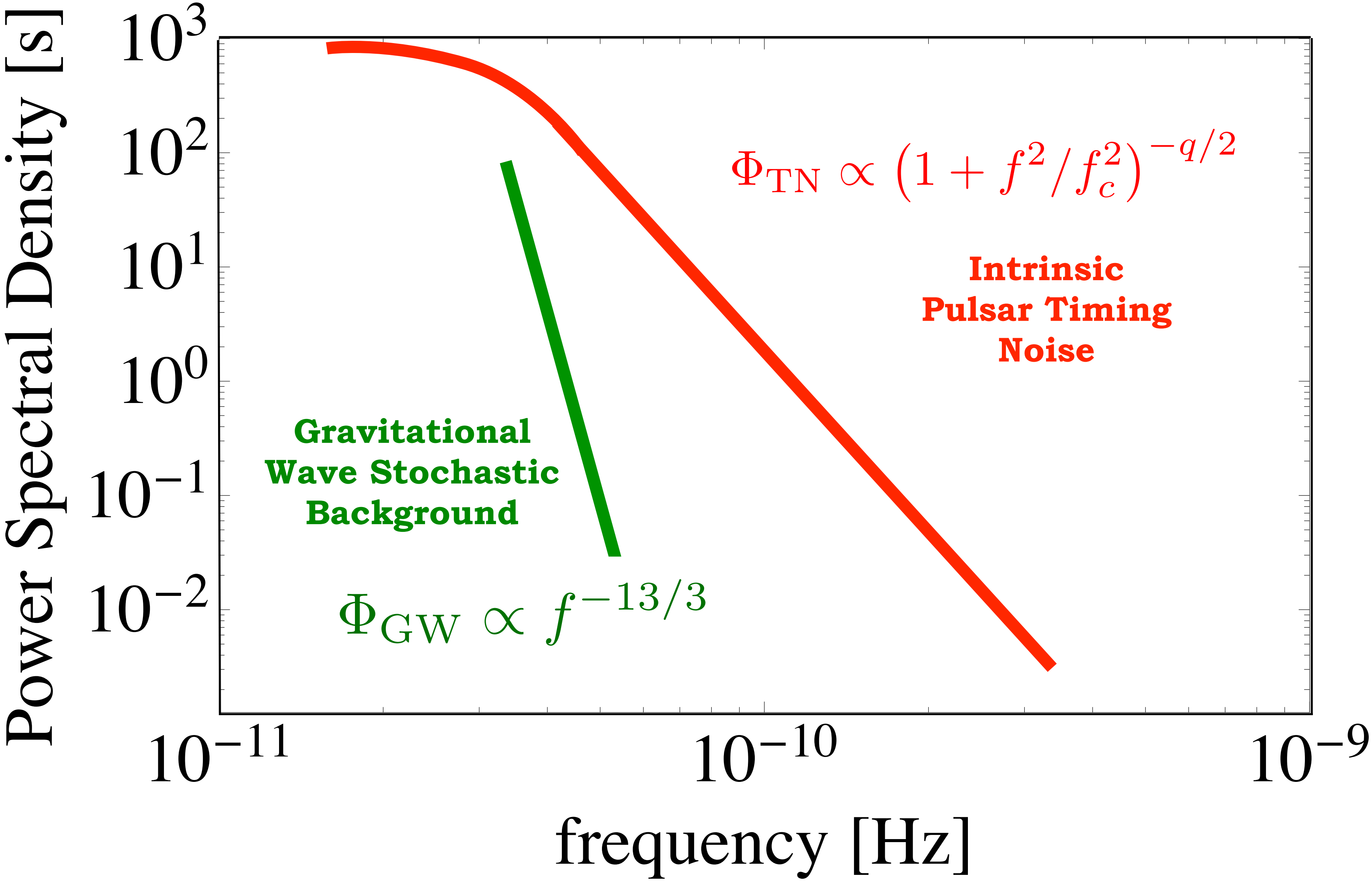
Quantifying the effect on GW detection with PTAs

PL, Melatos, Ravi & Hobbs (2015)



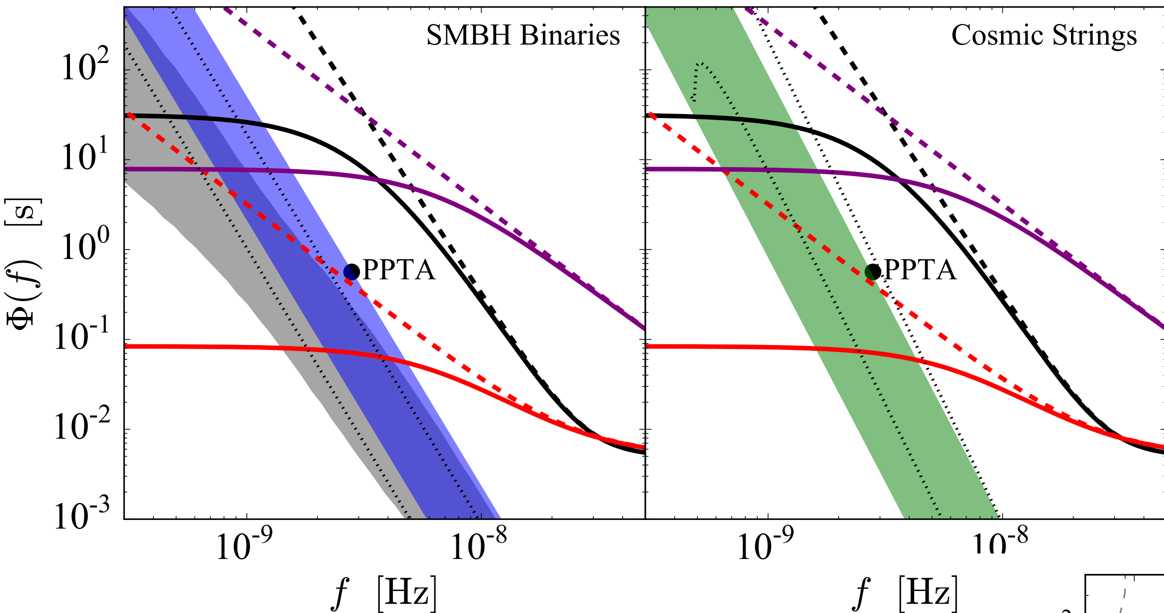
Quantifying the effect on GW detection with PTAs

PL, Melatos, Ravi & Hobbs (2015)

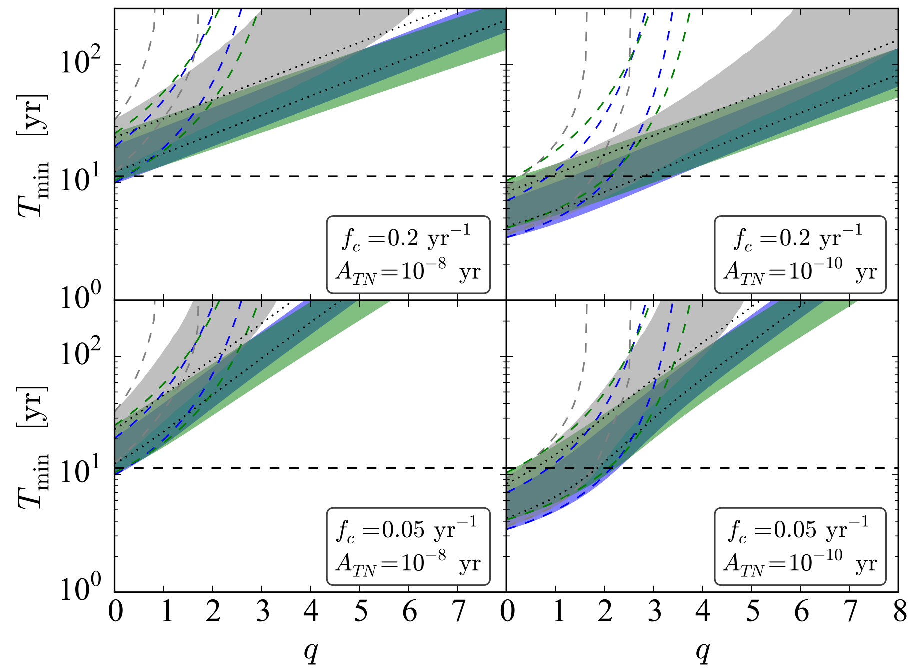


Quantifying the effect on GW detection with PTAs

PL, Melatos, Ravi & Hobbs (2015)

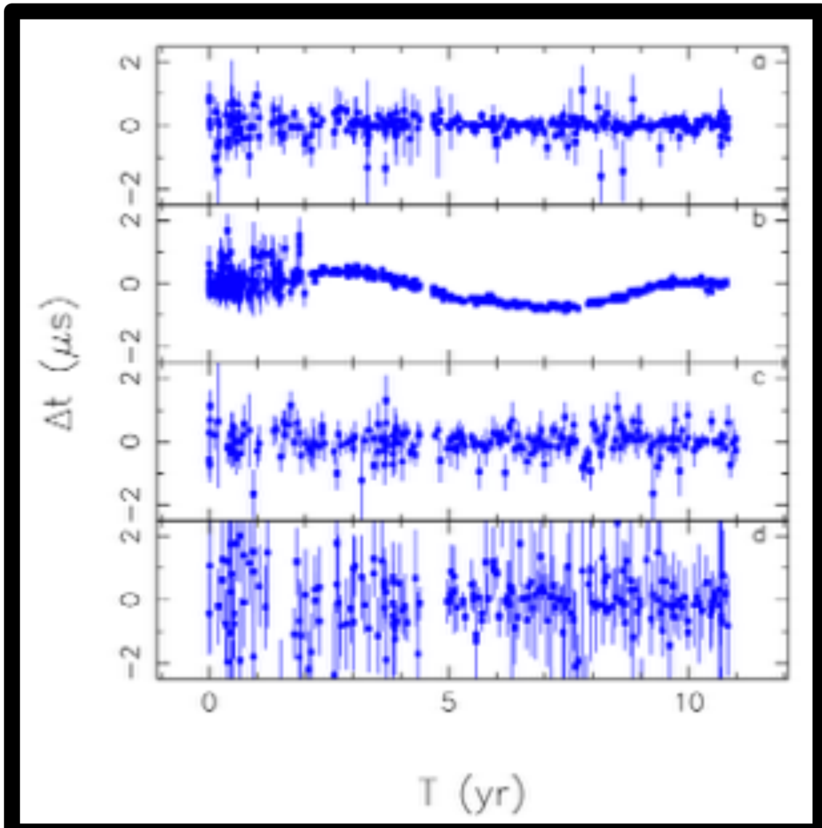


- ➡ Punch line:
  - ➡ A low-frequency turnover is great for PTAs
  - ➡ evidence for one is hard to find

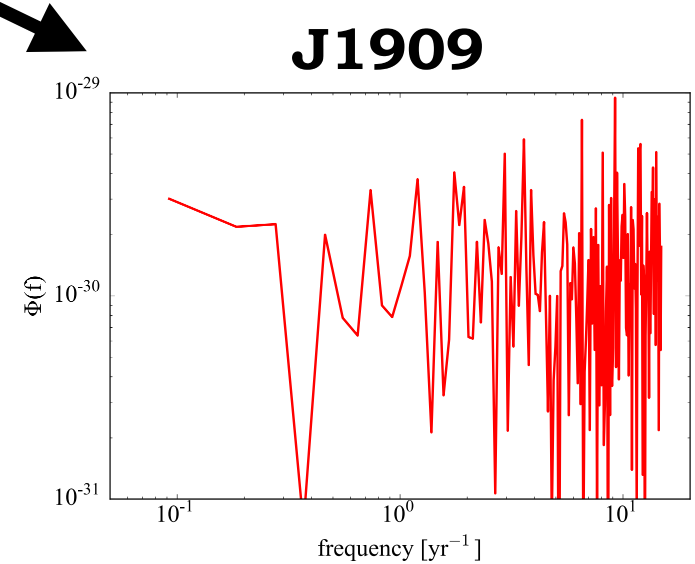


Quantifying the effect on GW detection with PTAs

This may not matter for a number of years... Shannon et al. (in prep)

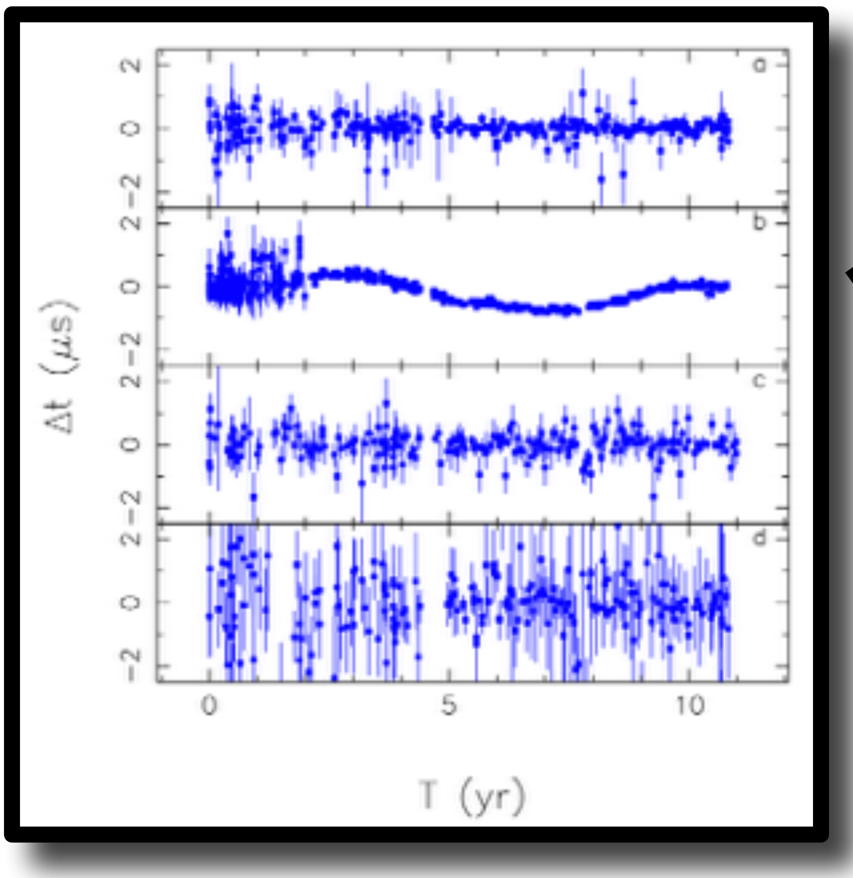


Bayesian analysis: No evidence for red noise in the two pulsars that are biggest contributors to new GW limit

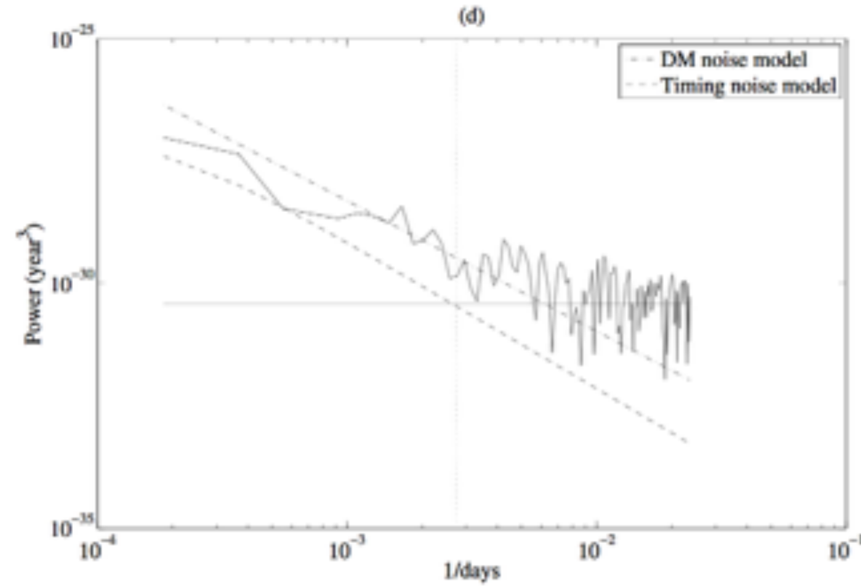


What about the level of red noise?

Red noise in PSR0437 is *NOT* a gravitational wave background!



J0437



Reardon et al. (in prep)

Search for evidence of a plateau in the spectrum to (potentially) understand neutron star core physics!

Turbulent Consequences

- **Pulsar timing noise**
  - Is pulsar timing noise from turbulence?
  - Quantifying the effect it has on gravitational wave detection with PTAs
- **Gravitational waves - LIGO**
  - Single Neutron Star
  - Stochastic Background

Turbulent flows emit gravitational waves

Melatos & Peralta (2010)

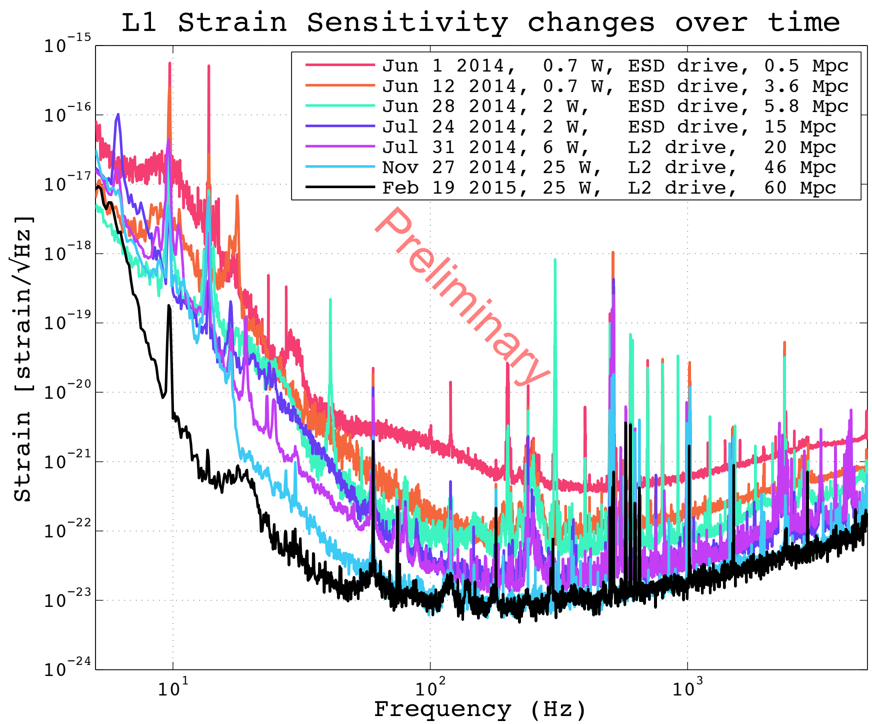
Turbulence: On average - axisymmetric

Instantaneously non-axisymmetric

$$h_{\rm rms} = 5 \times 10^{-28} \left(\frac{M_\star}{1.4\,M_\odot}\right) \left(\frac{R_\star}{10\,{\rm km}}\right)^3 \left(\frac{d}{1\,{\rm kpc}}\right)^{-1} \left(\frac{\Delta\Omega}{10\,{\rm rad\,s^{-1}}}\right)^3$$

← **Shear**
(difference in angular velocity between crust and core)

Only of potential interest to LIGO for nearby (d ~10 pc) fast rotators (P ~ 1 ms => ΔΩ ~ 30)



One neutron star does not emit a detectable gravitational wave signal

What about ALL the neutron stars in the Universe?

PL, Bennett & Melatos (2013)

Consider 2 Populations

- **Naive:**
  - all NSs in Universe have same $\Delta\Omega$. i.e. $\Delta\Omega$ is independent of Ω

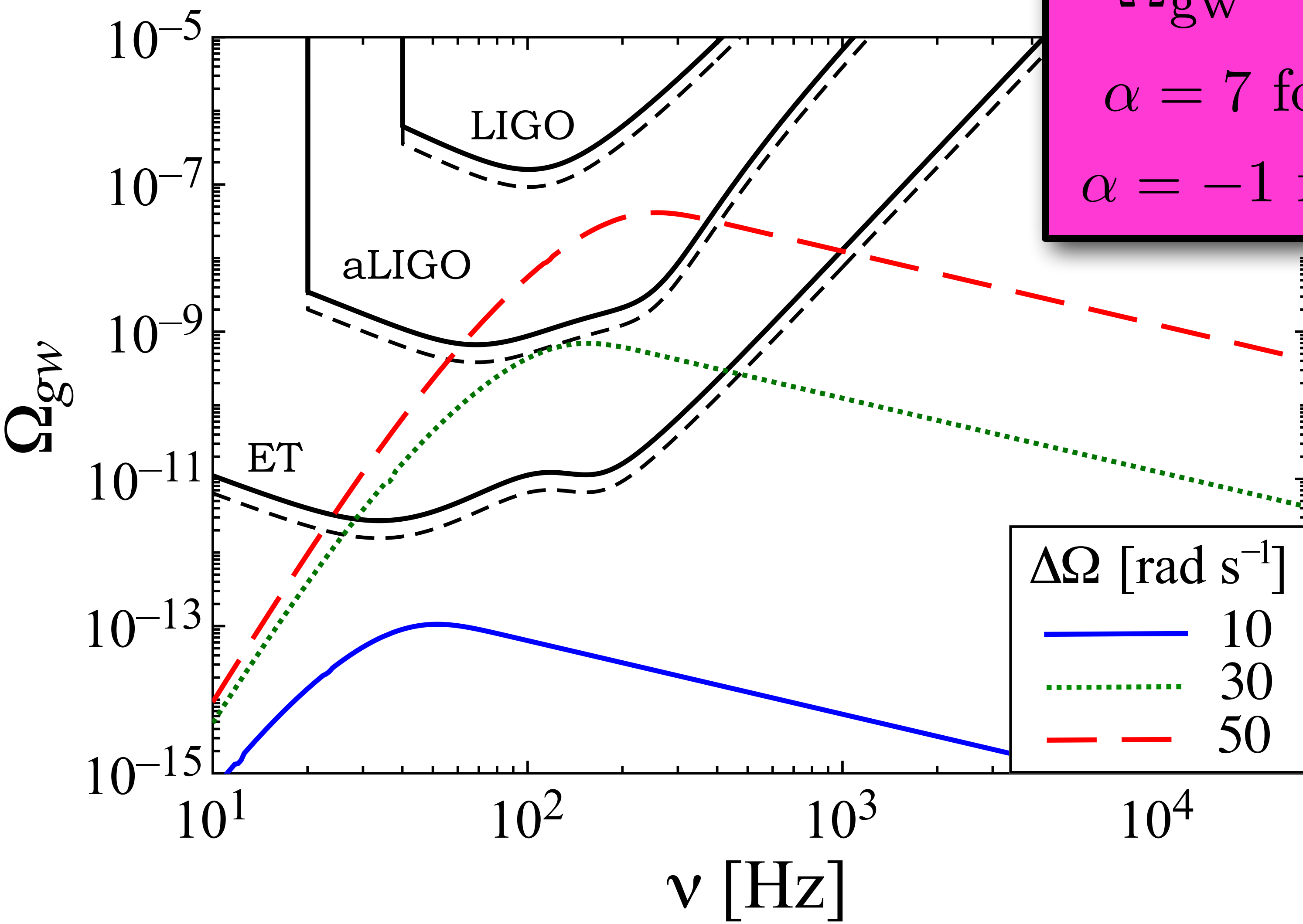
- **Radio pulsars:**
  - Broad distribution of $\Delta\Omega$, where $\Delta\Omega$ is proportional to spindown rate

Unique ΔΩ

$$\Omega_{\rm gw} = \Omega_\alpha \nu^\alpha$$

$$\alpha = 7 \text{ for } \nu \lesssim \nu_c$$

$$\alpha = -1 \text{ for } \nu \gtrsim \nu_c$$



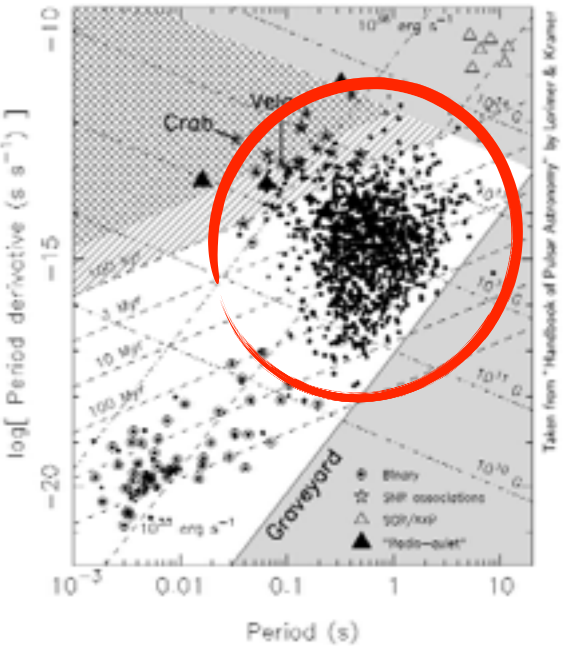
PL, Bennett & Melatos (2013)

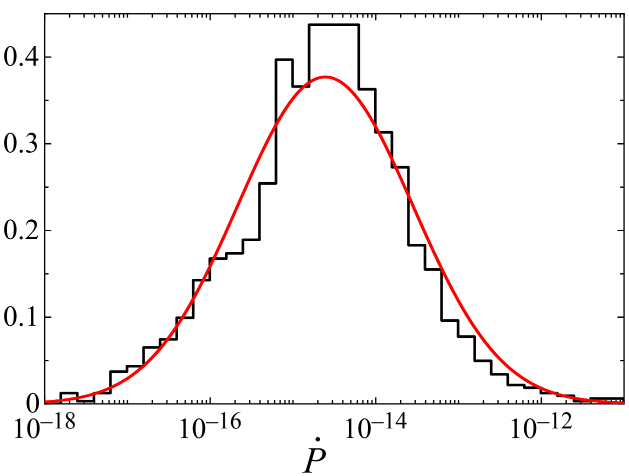
Pulsar Population

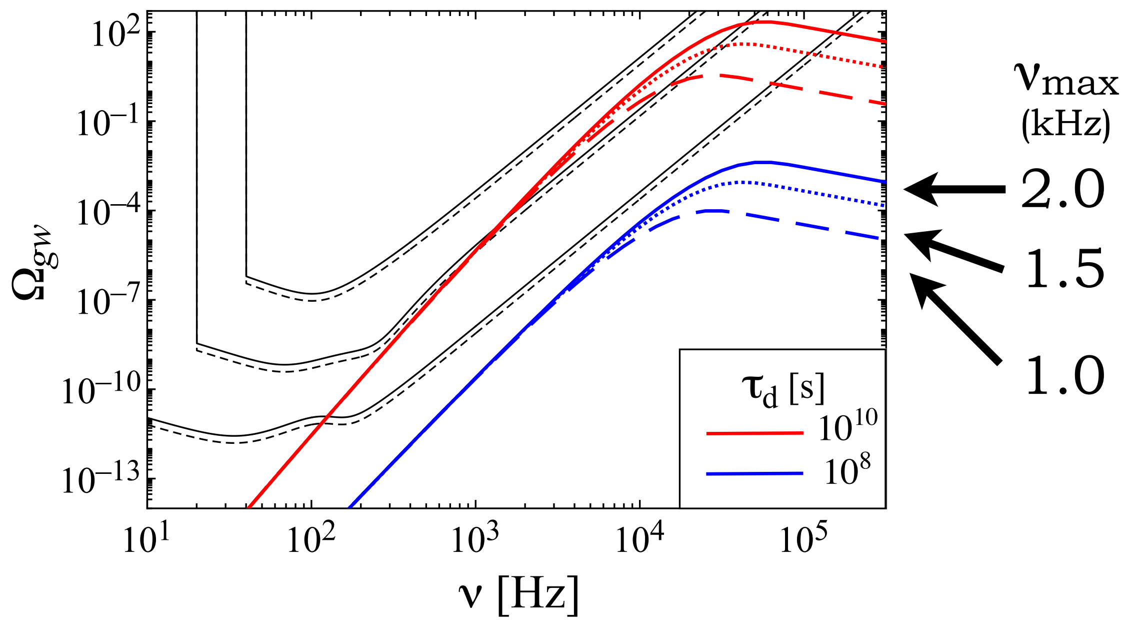
take galactic distribution of known pulsars and assume the same throughout the Universe

$$\Delta\Omega = \tau_d \dot{\Omega}$$

atnf.csiro.au







PL, Bennett & Melatos (2013)

Detection unlikely

"Things sometimes happen to me that are very, very unlikely. Does it mean that I don't exist with high Bayesian probability?"
(Levin 2015, Facebook)

Non-detections give interesting constraints on shear damping times, etc.

$$\Omega_{\rm gw} = \Omega_\alpha \nu^\alpha$$
$$\alpha = 7 \text{ for } \nu \lesssim \nu_c$$
$$\alpha = -1 \text{ for } \nu \gtrsim \nu_c$$

It is worth searching for this.

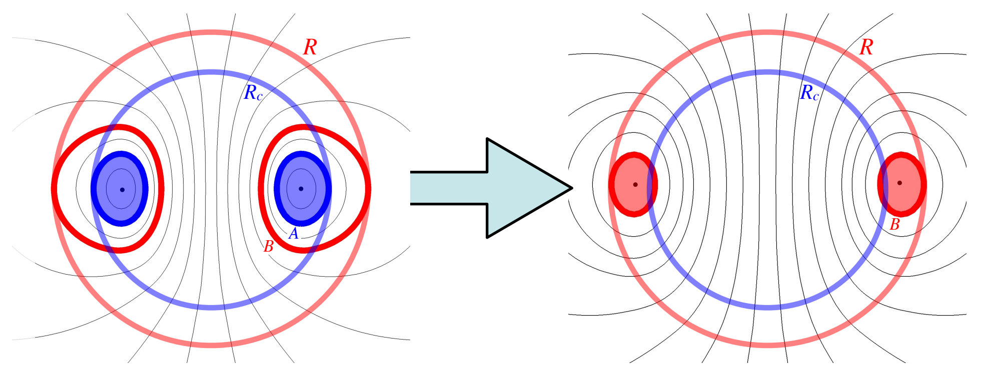
PL, Bennett & Melatos (2013)

Two Possible Outcomes

i) core remains in constant turbulent state

Peralta, Melatos, et al.

ii) magnetic field evicted to crust

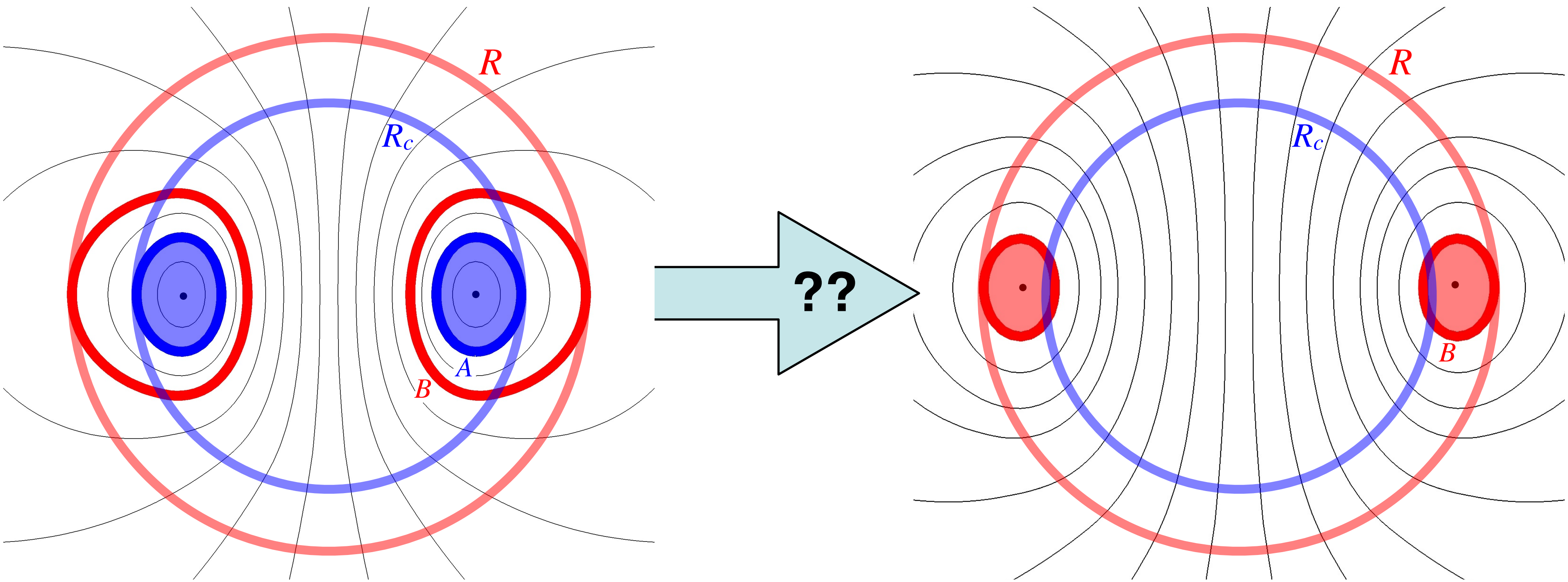


the crust as a magnetic field depository

Glampedakis & PL (2015)

- A Conjecture:

the system will evict the closed field lines + toroidal region into the crust

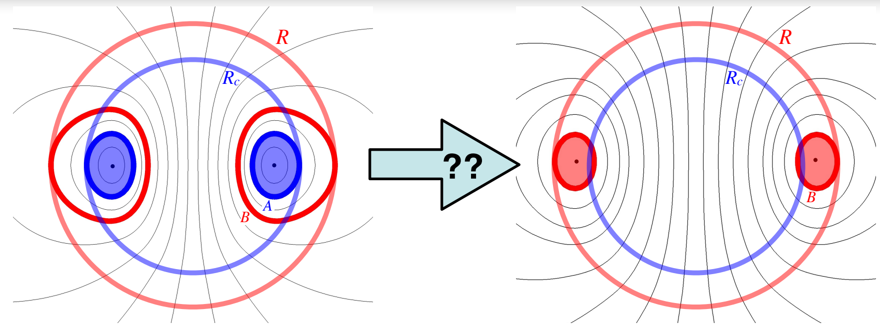


the crust as a magnetic field depository

Glampedakis & PL (2015)

- A Conjecture:

the system will evict the closed field lines + toroidal region into the crust



- *young magnetars:*

$B \gtrsim 10^{15}$ G: star spins down before crust forms (~1 day)
$B \lesssim 10^{15}$ G: our model applies

hydrodynamic instability timescale

$$t \sim t_{\rm sd} \approx 4.7 \left(\frac{B_p}{10^{15}\,{\rm G}}\right)^{-2} \left(\frac{P}{10\,{\rm ms}}\right)^{2} {\rm d}$$

$t \lesssim t_{\rm sd}$: gravitational wave emission

$t \gg t_{\rm sd}$: eviction of the magnetic field to the core

$t \lesssim t_{\rm sd}$: gravitational wave emission

- Strong toroidal field wound up in core

$$h_0 \propto \frac{I \epsilon \nu^2}{D}$$

- ε due to magnetic deformations

$$\epsilon \sim 10^{-6} \left(\frac{B_{\rm t}}{10^{15}\,{\rm G}} \right)$$

e.g., Cutler (2002)
Haskell et al. (2008, erratum 2009),
Mastrano et al. (2011)

$t \lesssim t_{\rm sd}$: gravitational wave emission

- Strong toroidal field wound up in core

$$h_0 \propto \frac{I\epsilon\nu^2}{D}$$

- ε due to magnetic deformations

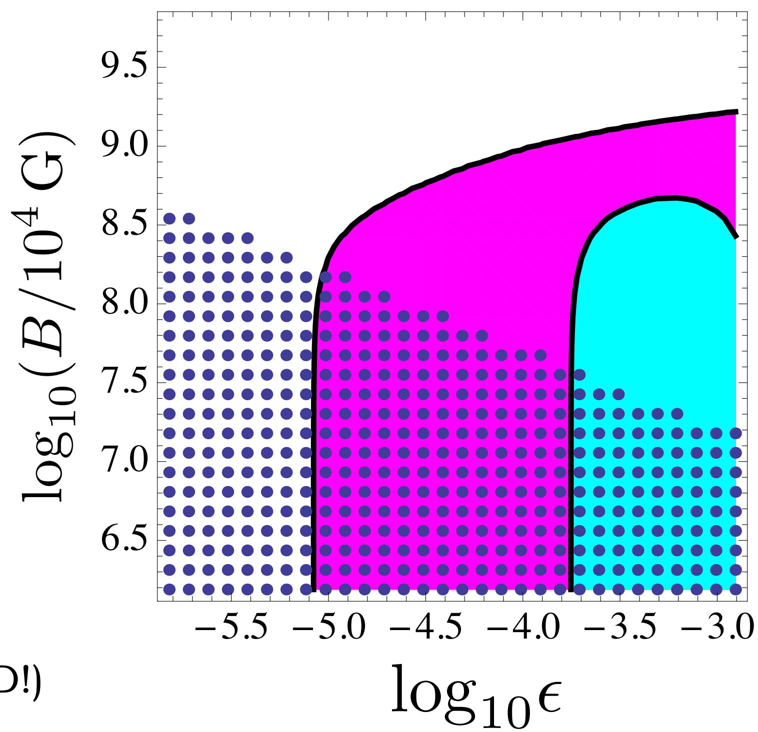
$$\epsilon \sim 10^{-6}\left(\frac{B_{\rm t}}{10^{15}\,{\rm G}}\right)$$

e.g., Cutler (2002)
Haskell et al. (2008, erratum 2009),
Mastrano et al. (2011)

unfortunately, need long integration times:

SN1987A: ~ 1 yr integration

Chung, Melatos, et al. (2011)



(important: other emission mechanisms possible that make this search worthwhile — Lilli Sun's PhD!)

$t \lesssim t_{\rm sd}$: gravitational wav

- Strong toroidal field wound u

$$h_0 \propto \frac{I \epsilon \nu^2}{D}$$

- ε due to magnetic deformatic

$$\epsilon \sim 10^{-6} \left(\frac{B_{\rm t}}{10^{15}\ {\rm G}} \right)$$ Haskell

unfortunately, need lon integration times:

SN1987A: ~ 1 yr integrati

Chung, Melatos, et al. (2011)

(important: other emission mechanisms possible that make this search worthwhile — Lilli Sun's PhD!)

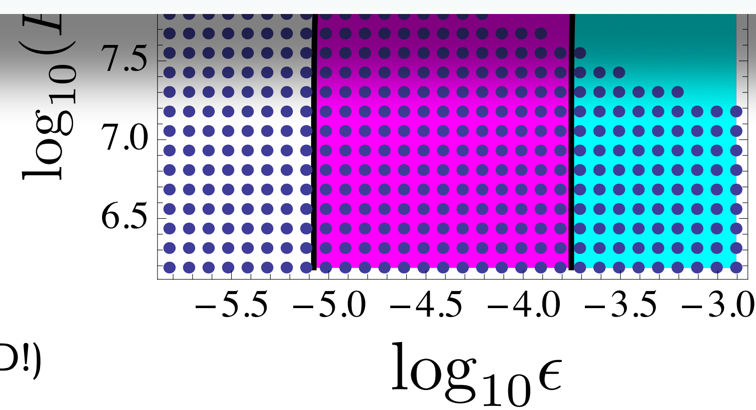
Unless....

$$\epsilon^{2SC} \sim 8.0 \times 10^{-5} \left(\frac{\langle B_t \rangle}{10^{15}\ {\rm G}} \right)$$

$$\epsilon^{CFL} \sim 2.5 \times 10^{-4} \left(\frac{\langle B_t \rangle}{10^{15}\ {\rm G}} \right)$$

This is potentially a nuclear physics experiment!

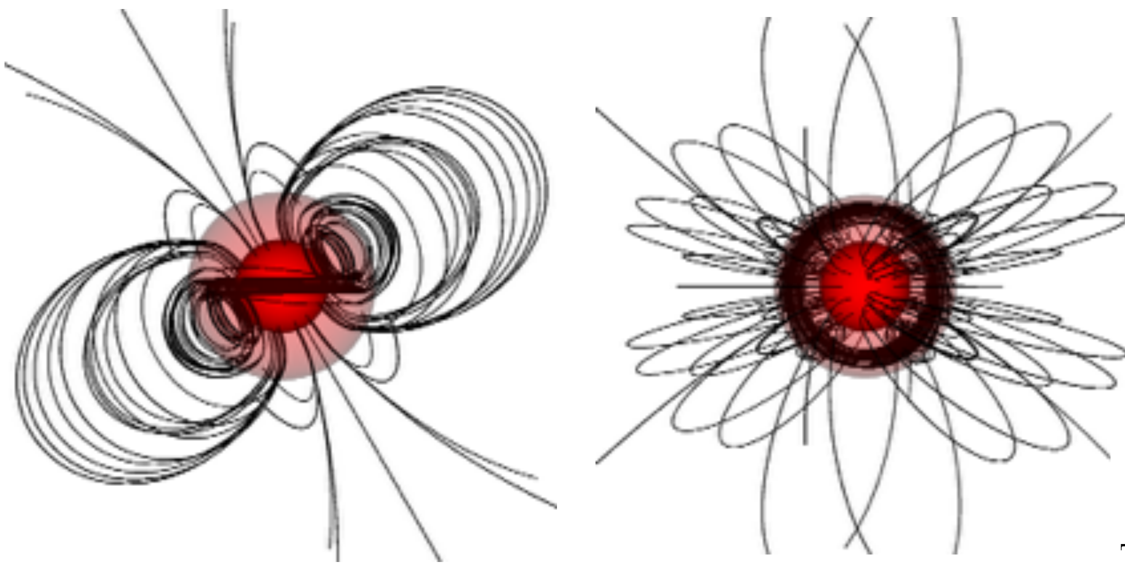
Owen (2004), Glampedakis et al. (2012)



$t \lesssim t_{\rm sd}$: gravitational wave emission

- a positive detection also allows us to probe the stellar geometry

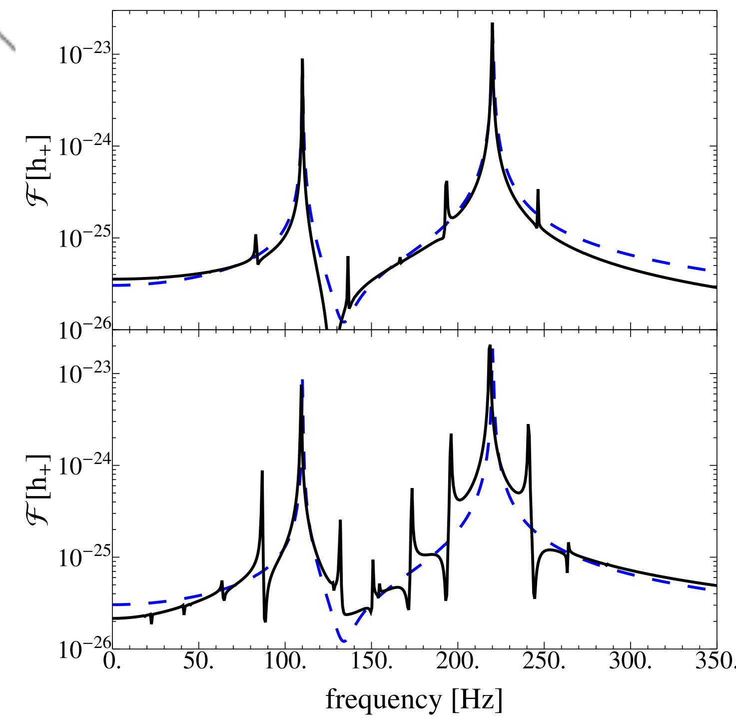
(e.g., Mastrano, PL & Melatos 2013 for multipolar fields)



e.g., *twisted-torus*

PL & Melatos (2013)

- triaxial deformation
- 'naturally motivated'
- Enriches GW signal

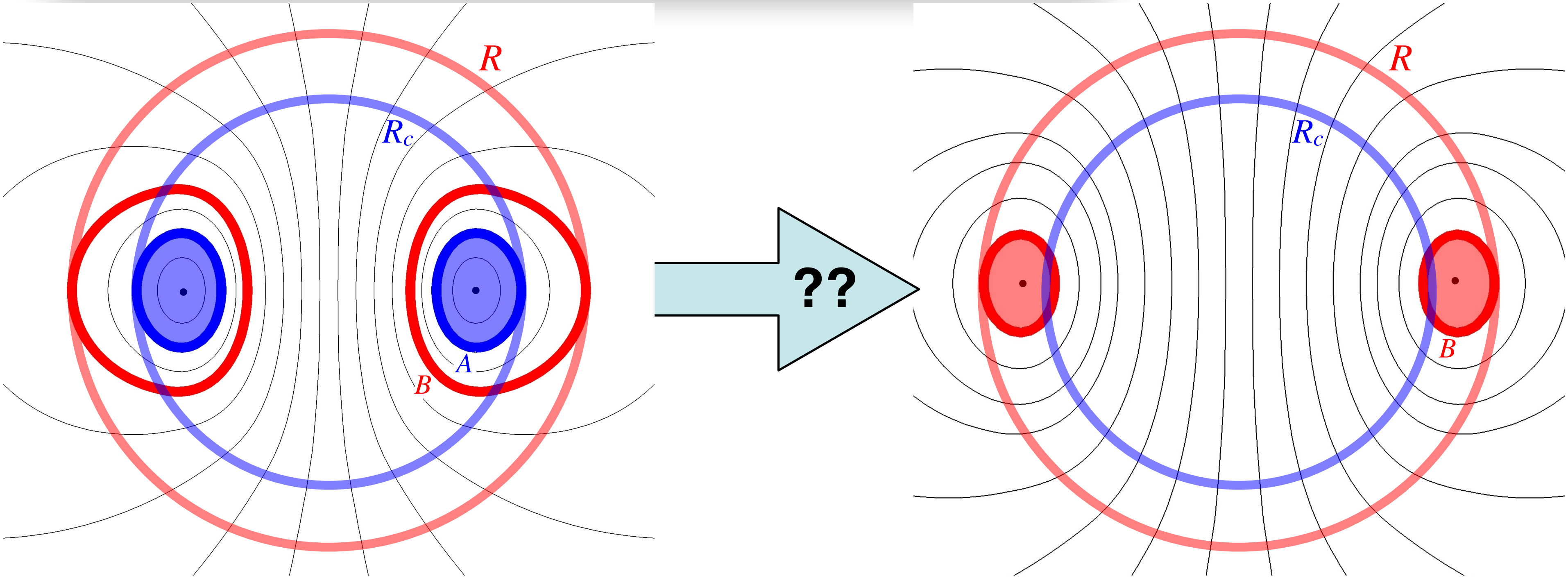


e.g., NS born with:

- Virgo cluster (~20 Mpc)
- $B_p = 10^{14}$ G
- $\langle B_t \rangle = 10^{16}$ G

Triaxiality must last ~ one month for SNR~3 in aLIGO

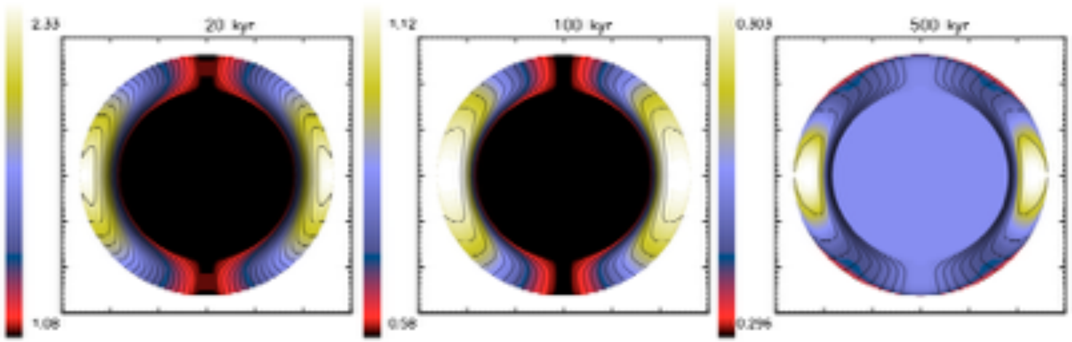
$t \gg t_{\rm sd}$: eviction of the magnetic field



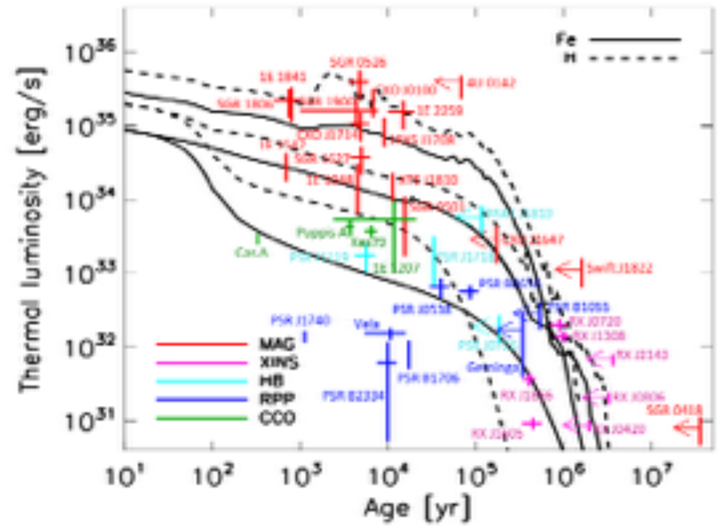
✓existence of strong toroidal field in crust is key for magnetar heating, fast magnetic evolution and flares!

$t \gg t_{\mathrm{sd}}$: eviction of the magnetic field

- magnetar heating
    - e.g., series of papers by Pons & collaborators, Ho et al. 2012
    - magneto-thermal evolution of strong crustal fields



Pons, Miralles & Geppert (2009)



Viganó, Pons, Miralles & Rea (2015)

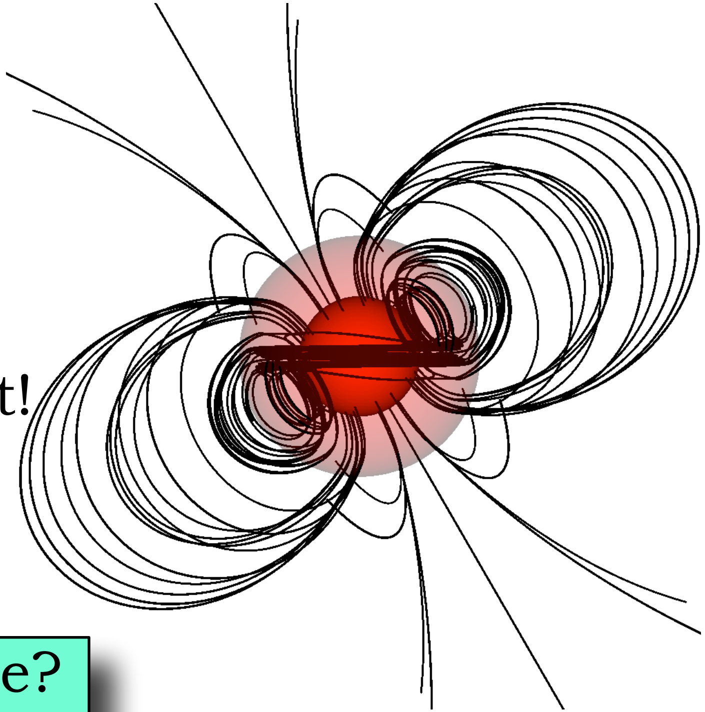
- magnetar flares
    - giant flares - is crust-fracturing by strong B-field involved?
      (e.g., Thompson & Duncan series)

the future?

magnetic field does not couple the core and crust of a neutron star.

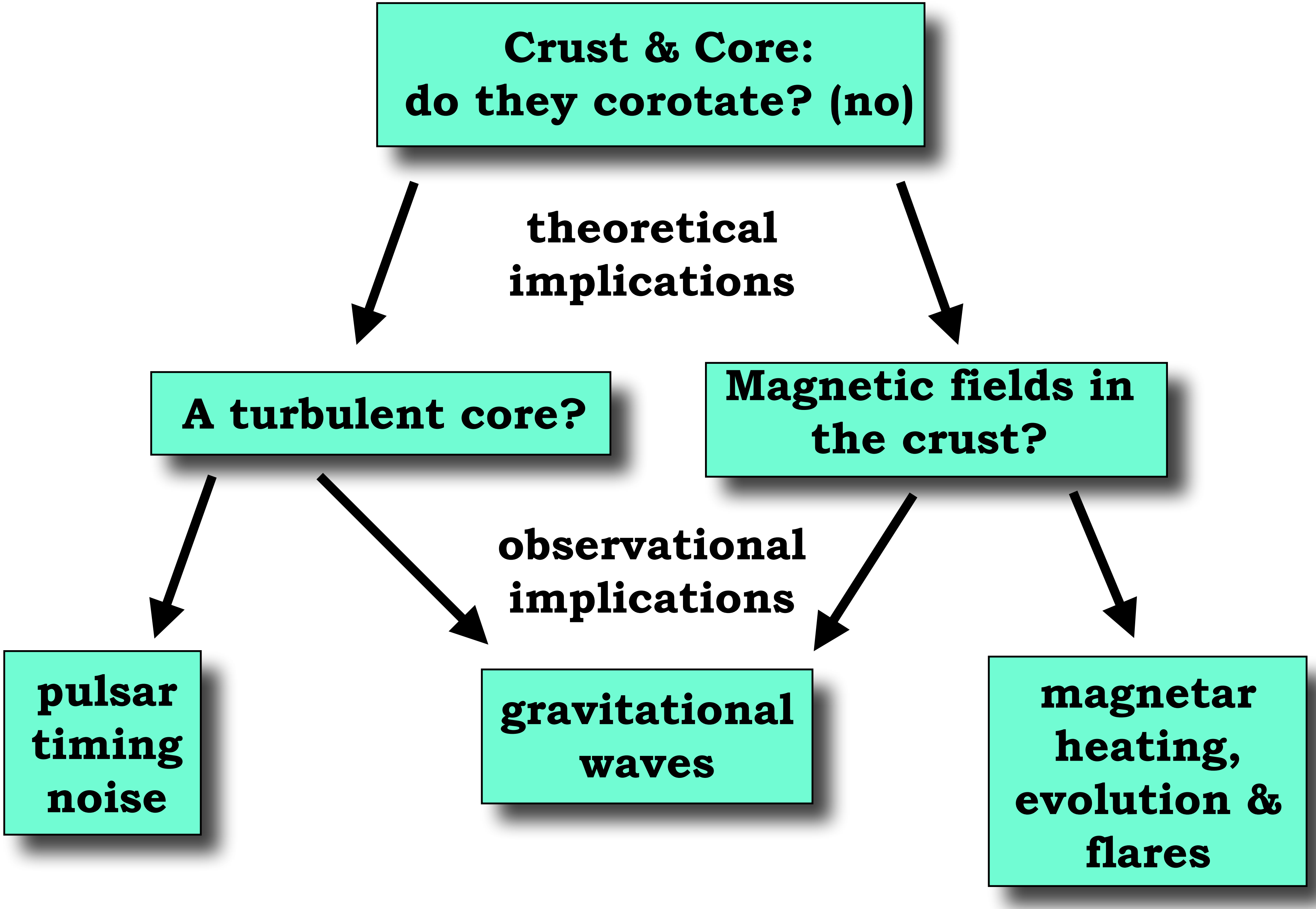
Conjecture: *stability is reached when closed field lines + toroidal field are evicted into crust.*

- what's next?
  - more general B-field geometry
    - easy to generalise to higher-order multipoles
    - non-axisymmetric more difficult!
  - superconducting MHD



- how does the system *actually* evolve?

summary


Crust & Core:
do they corotate? (no)
theoretical
implications
A turbulent core?
Magnetic fields in
the crust?
observational
implications
pulsar
timing
noise
gravitational
waves
magnetar
heating,
evolution &
flares