Neutron star magnetic fields and rotational dynamics

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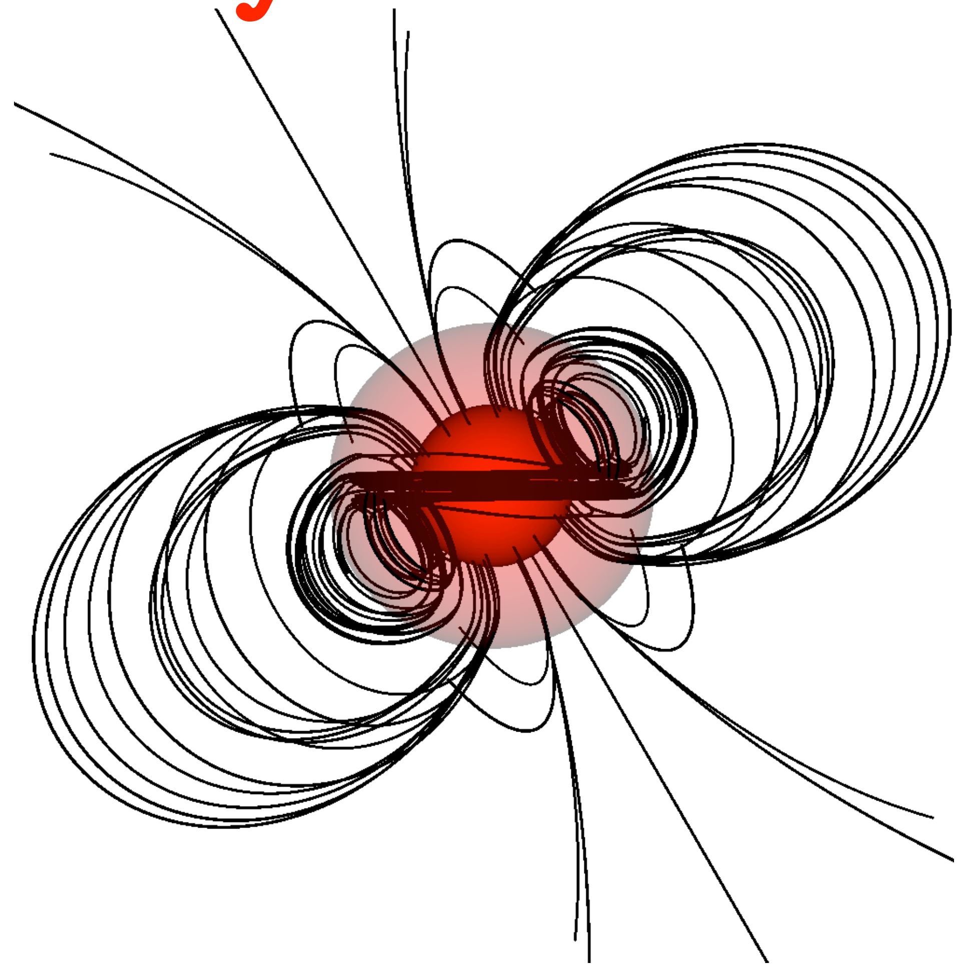
arXiv:1501.05473



summary

Conventional wisdom:

- Neutron star's crust & core *corotate*

- 2 mechanisms:
  - viscous coupling (Ekman pumping)

  - magnetic coupling (usually considered dominant)

The conventional wisdom is wrong!

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

- Observational implications

- A numerical challenge

Glampedakis & Lasky (arXiv:1501.05473)

Neutron stars rotate. We don't know how.

Glitches:

- impulsive spin up events
- large, almost instantaneous transfer of angular momentum from core to crust.

Timing noise:

- stochastic, time-correlated fluctuations of crust's angular momentum

Understanding these provides a window into neutron star interiors.

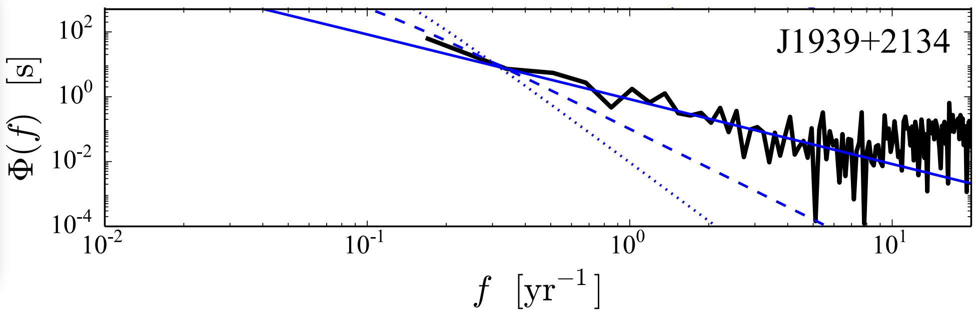


figure from Lasky et al. (2015; submitted)

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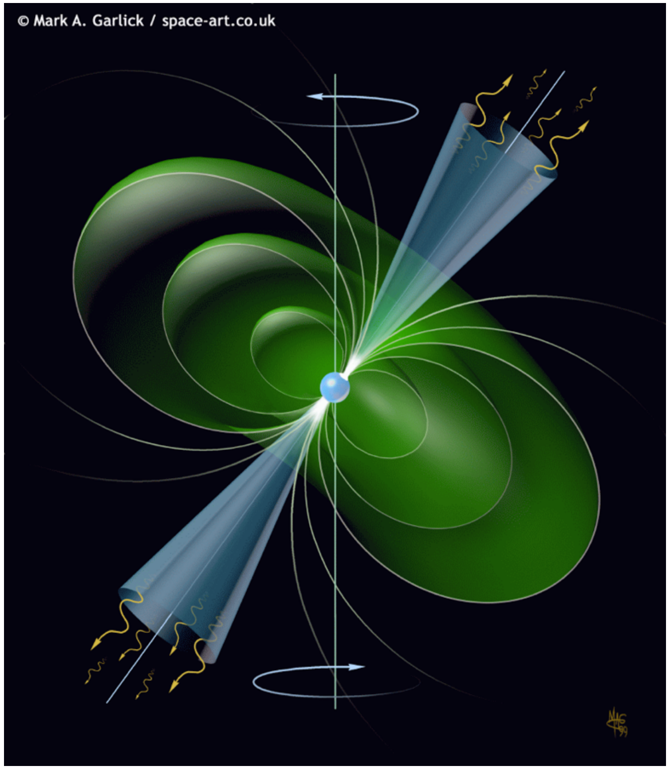
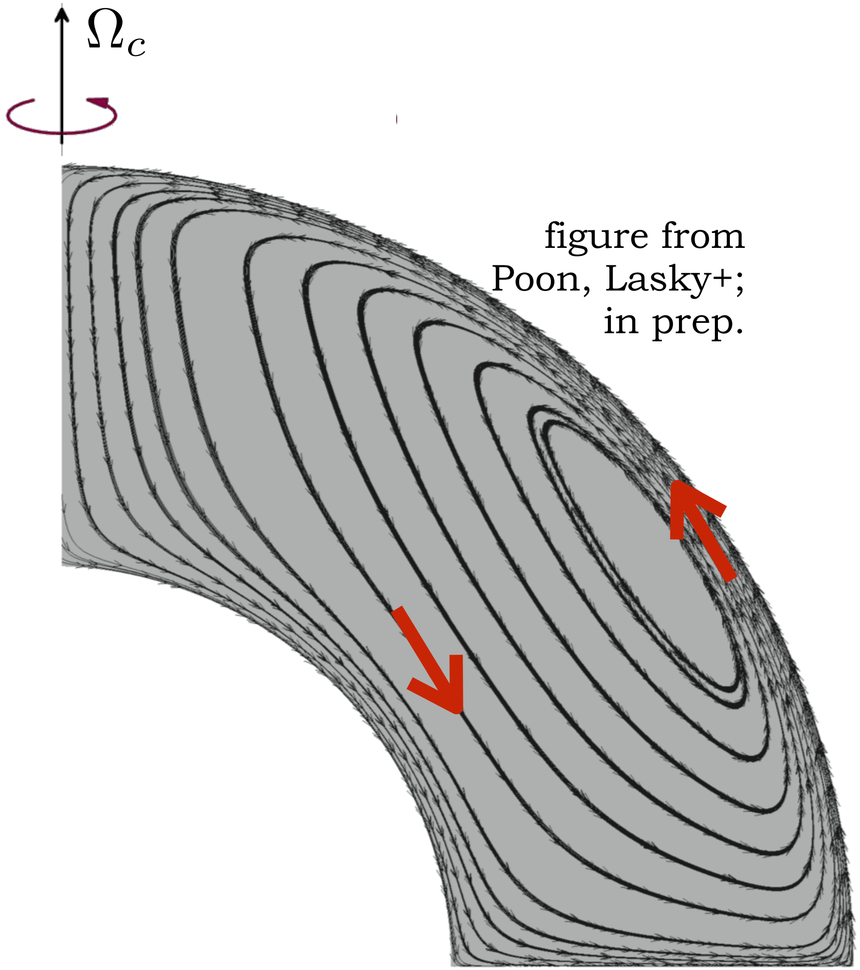
Ekman pumping



magnetic field spins down crust

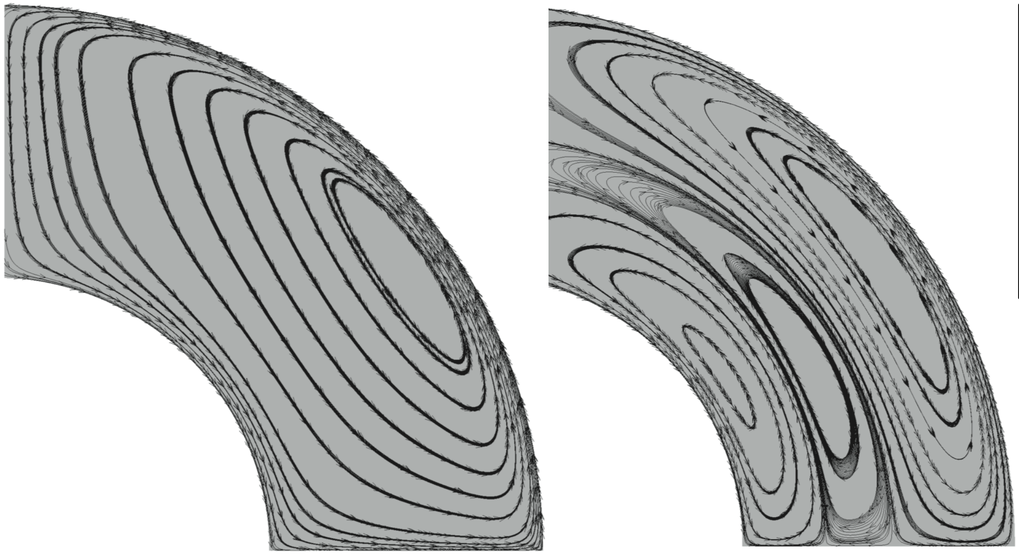


Ekman pumping spins down fluid in core

Glampedakis & Lasky (arXiv:1501.05473)

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, Lasky+; in prep.

Melatos 2012: neutron stars have super-rotating cores!

caveat:
the magnetic field!

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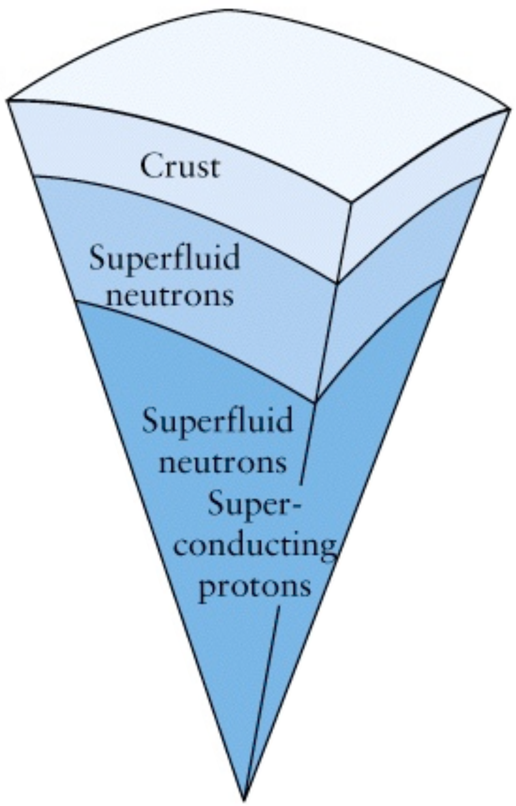
magnetic crust-core coupling

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

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

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

Ψ : chemical + gravitational potentials

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

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

Glampedakis & Lasky (arXiv:1501.05473)

magnetic crust-core coupling

The punch line

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

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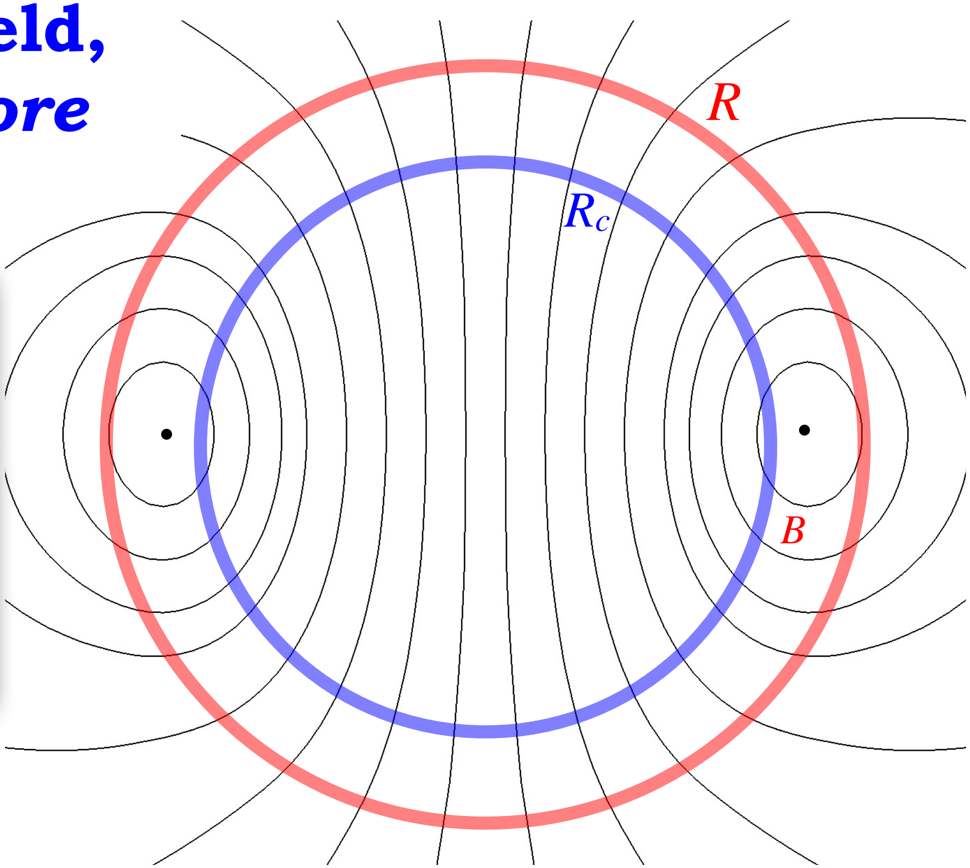
Case 1: purely poloidal field,
no closed field lines in core



Entire core couples to crust and corotates.

Crust and core spin down in unison

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magnetic crust-core coupling

The punch line

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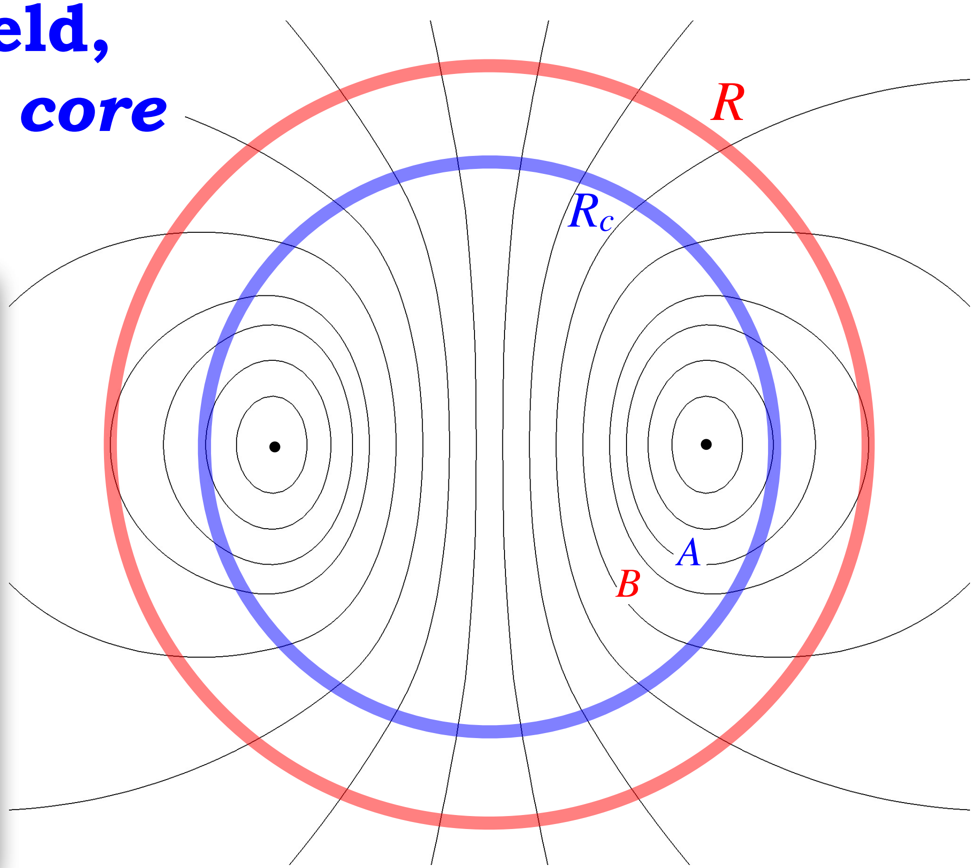
Case 2: purely poloidal field,
***with* closed field lines in core**



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

Rest of the core is decoupled

Glampedakis & Lasky (arXiv:1501.05473)

magnetic crust-core coupling

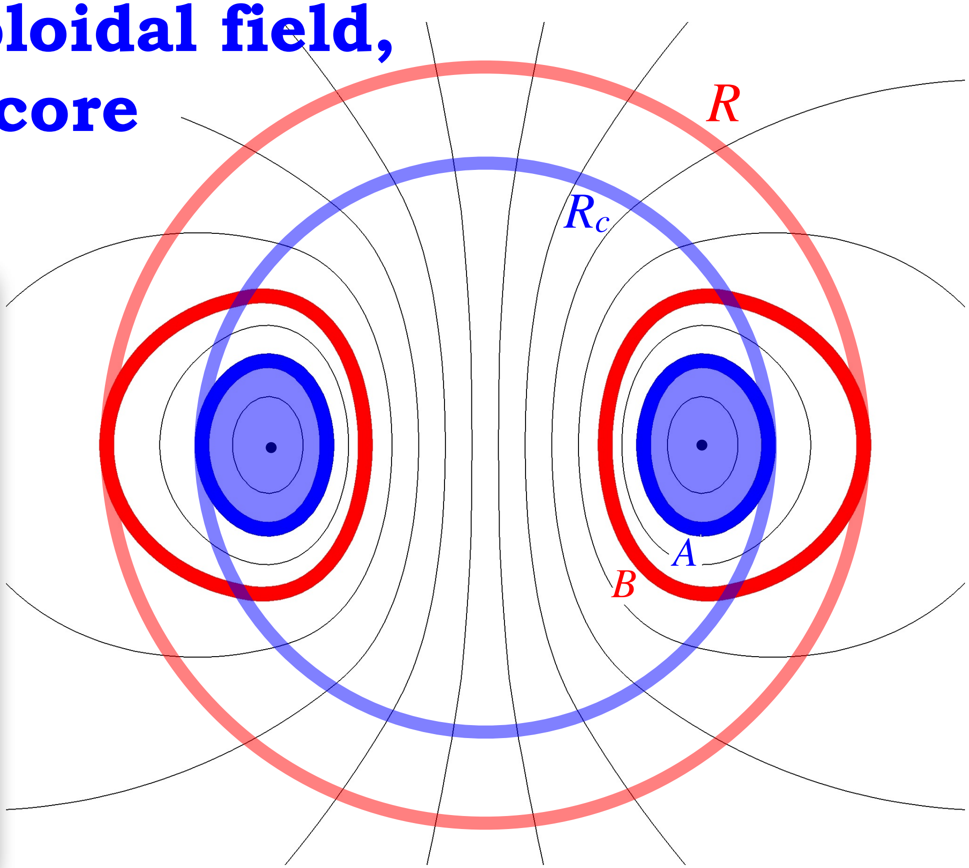
The punch line

- 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



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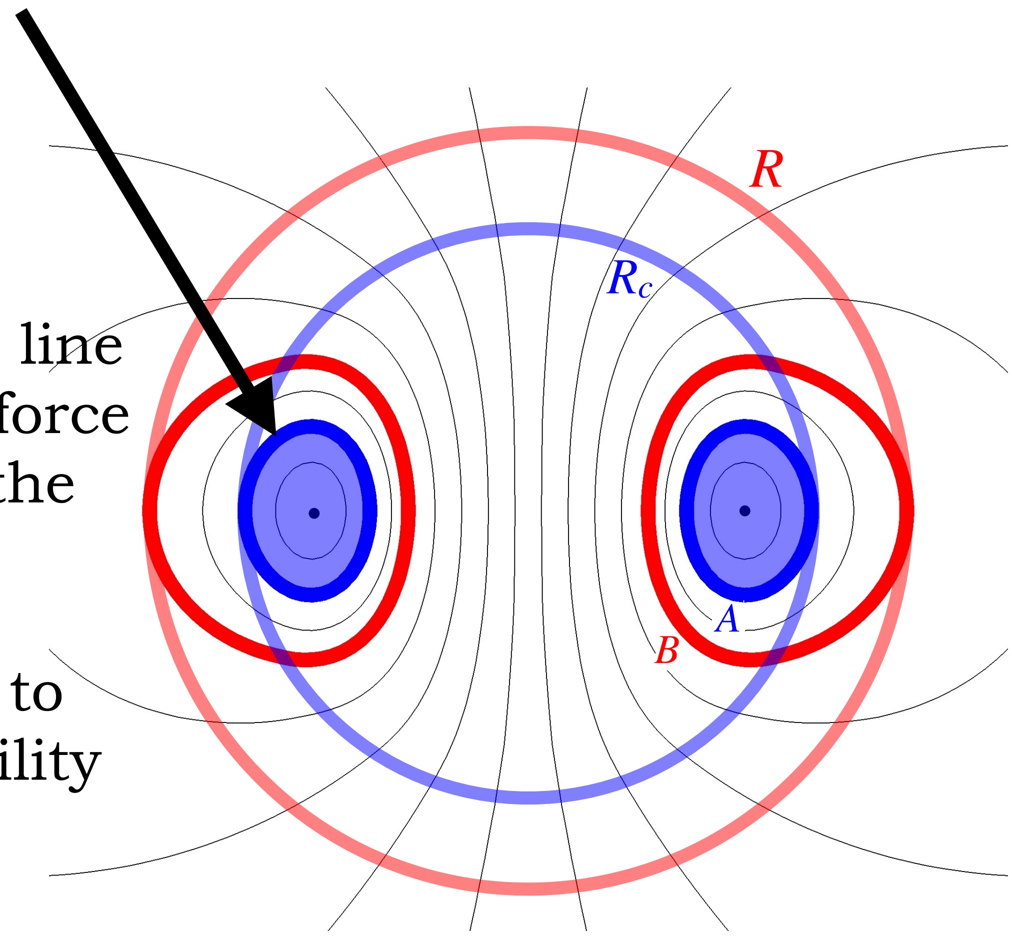
the super-rotating core region

- 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

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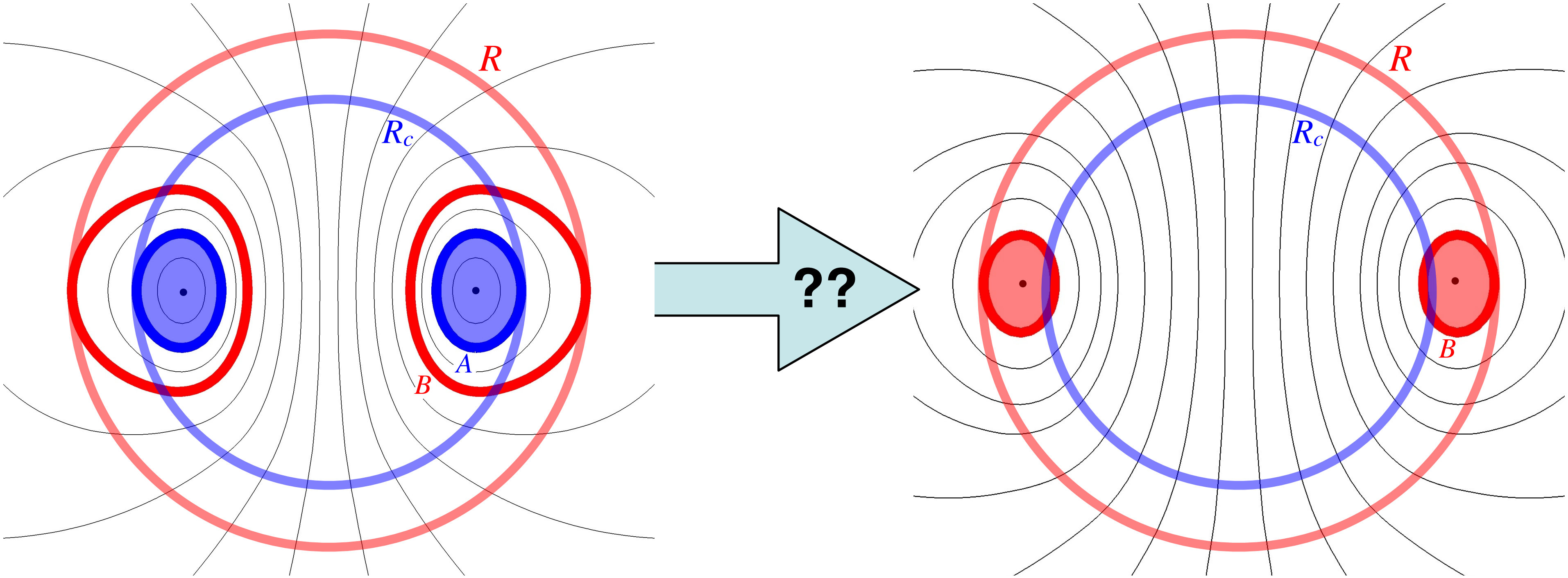
the crust as a magnetic field depository

- A Conjecture:

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



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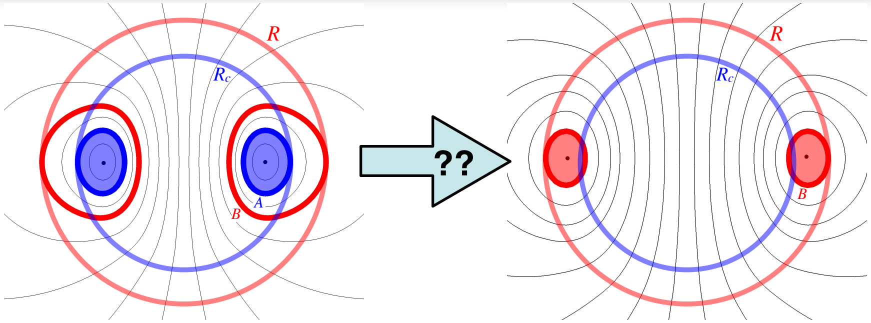

- *young magnetars:*

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

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

- *young pulsars:*
  Initial spindown is long (~10^3 yr); core likely couples to crust via viscosity or vortex-mediated mutual friction

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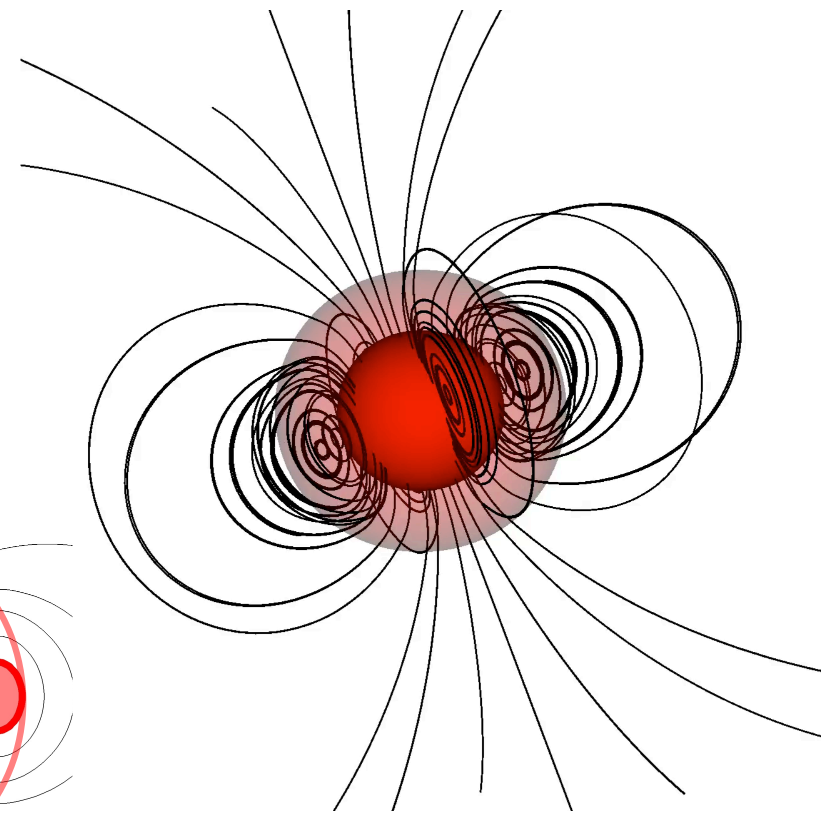
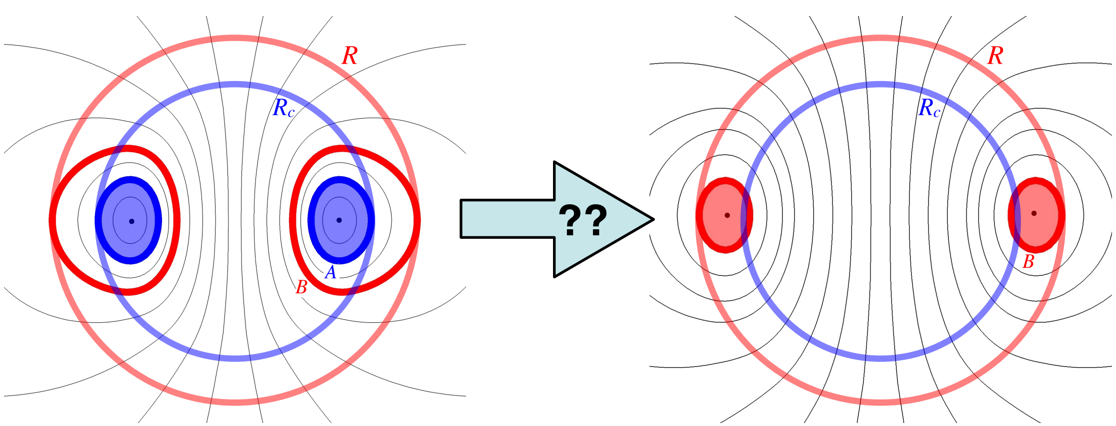
how does the system *actually* evolve?

a computational challenge

please discuss with me if you're interested!



movie from Lasky & Melatos (2013)



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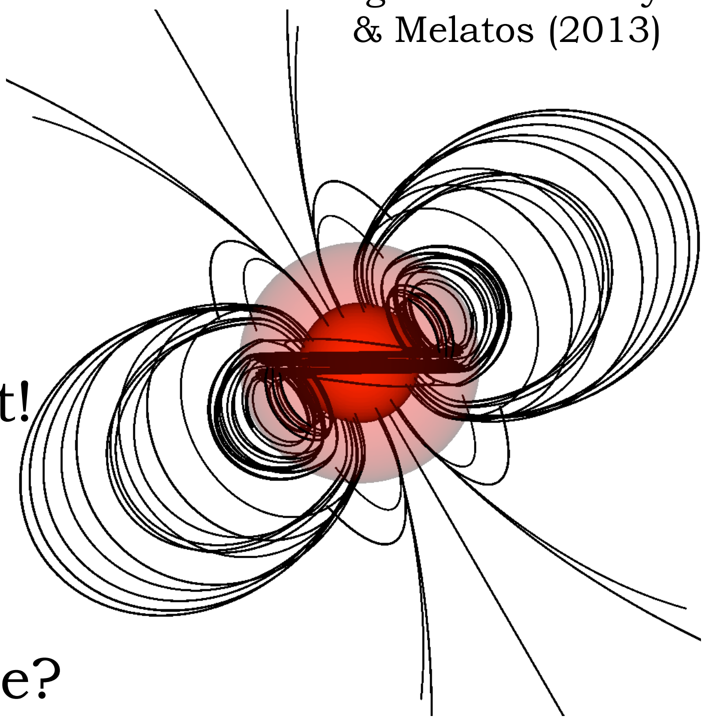
summary

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.*

figure from Lasky & Melatos (2013)



- 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?

Glampedakis & Lasky (arXiv:1501.05473)