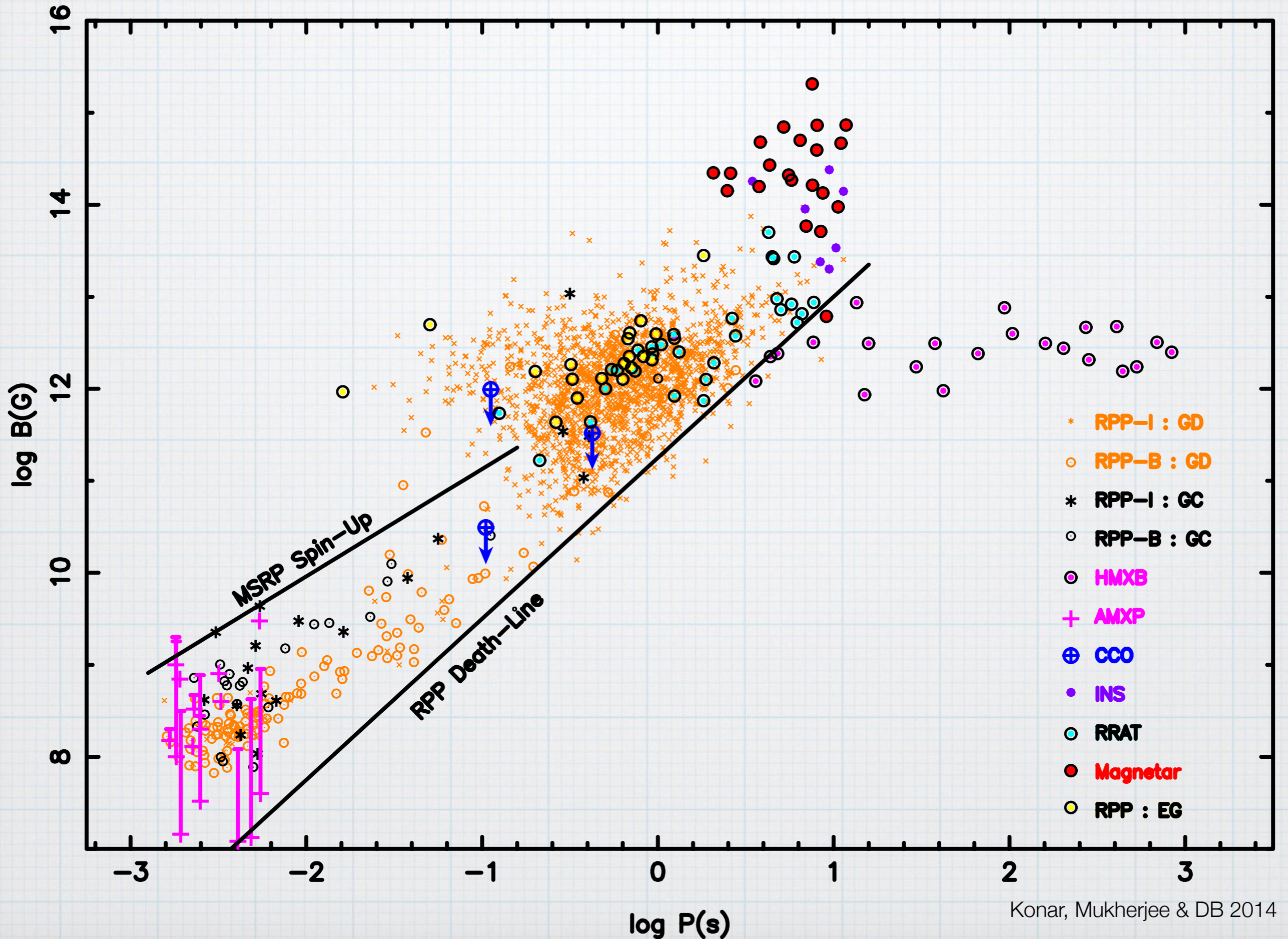


Magnetic Fields of Neutron Stars

Dipankar Bhattacharya
IUCAA, Pune

- * Neutron Stars harbour the strongest known magnetic fields in the universe:
 $\sim 10^8 - 10^{15} \text{ G}$**
- * Magnetic fields determine their interaction with their surroundings, their long-term evolution and their visibility**

Neutron star families and their magnetic field strengths



Open Questions

- * **Origin**
- * **Configuration**
- * **Evolution**

Origin of the Magnetic Field

Inheritance from progenitor (fossil field)

Flux conservation: $BR^2 = \text{constant}$

Cannot make magnetar strength, progenitor fields not strong enough

If pulsar strength fields result, pulsar spins won't - core's angular momentum would have been removed by magnetic coupling. (Spins from kicks? - correlation not evident)

Inherited field could be small ($\sim 10^8$ G?)

Origin of the Magnetic Field

Amplification in core collapse

Large amount of energy becomes available in differential rotation seconds before collapse
(max $\sim 10^{51}$ erg from SN constraint)

MRI could tap this energy to amplify field

$$B_{\max} \approx 10^{17} \text{G} \frac{\Delta\Omega}{\Omega} \frac{\Omega_{\text{NS}}}{\Omega_{\text{K}}} \quad (\text{Spruit 2007})$$

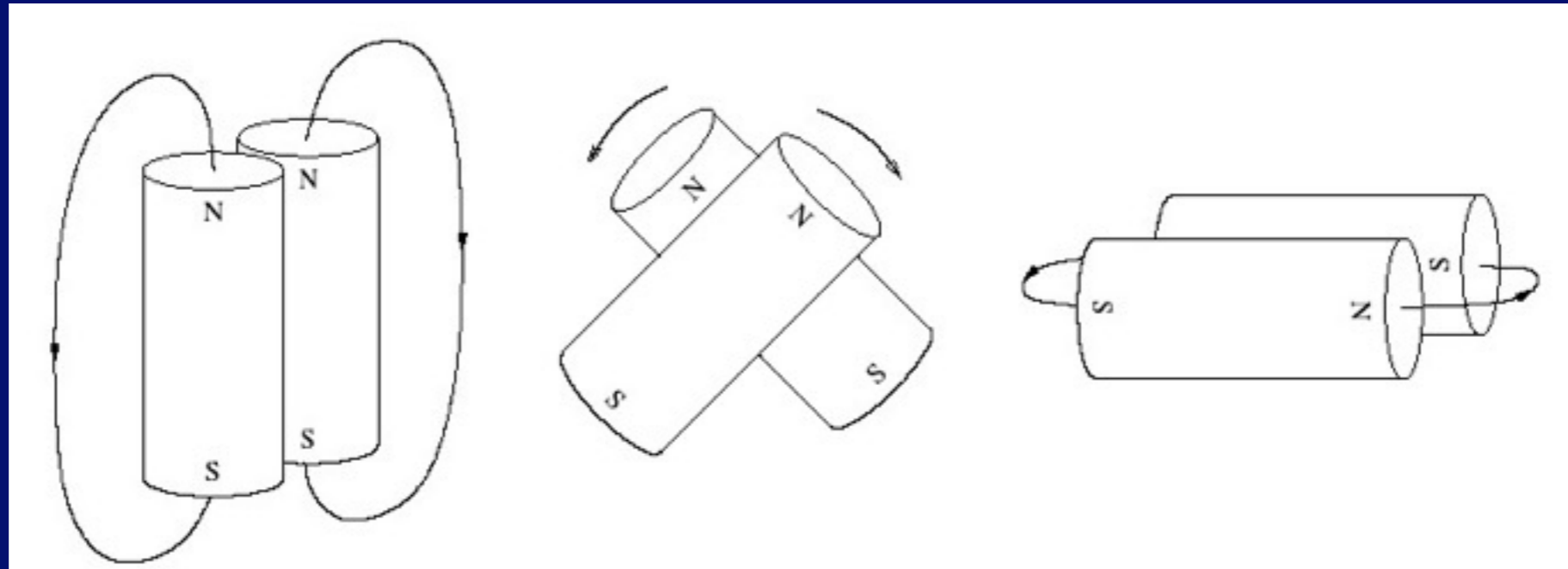
Magnetar strength field just about possible if the process is highly efficient

Origin of the Magnetic Field

Strong field in a fluid star will be subject to MHD instabilities

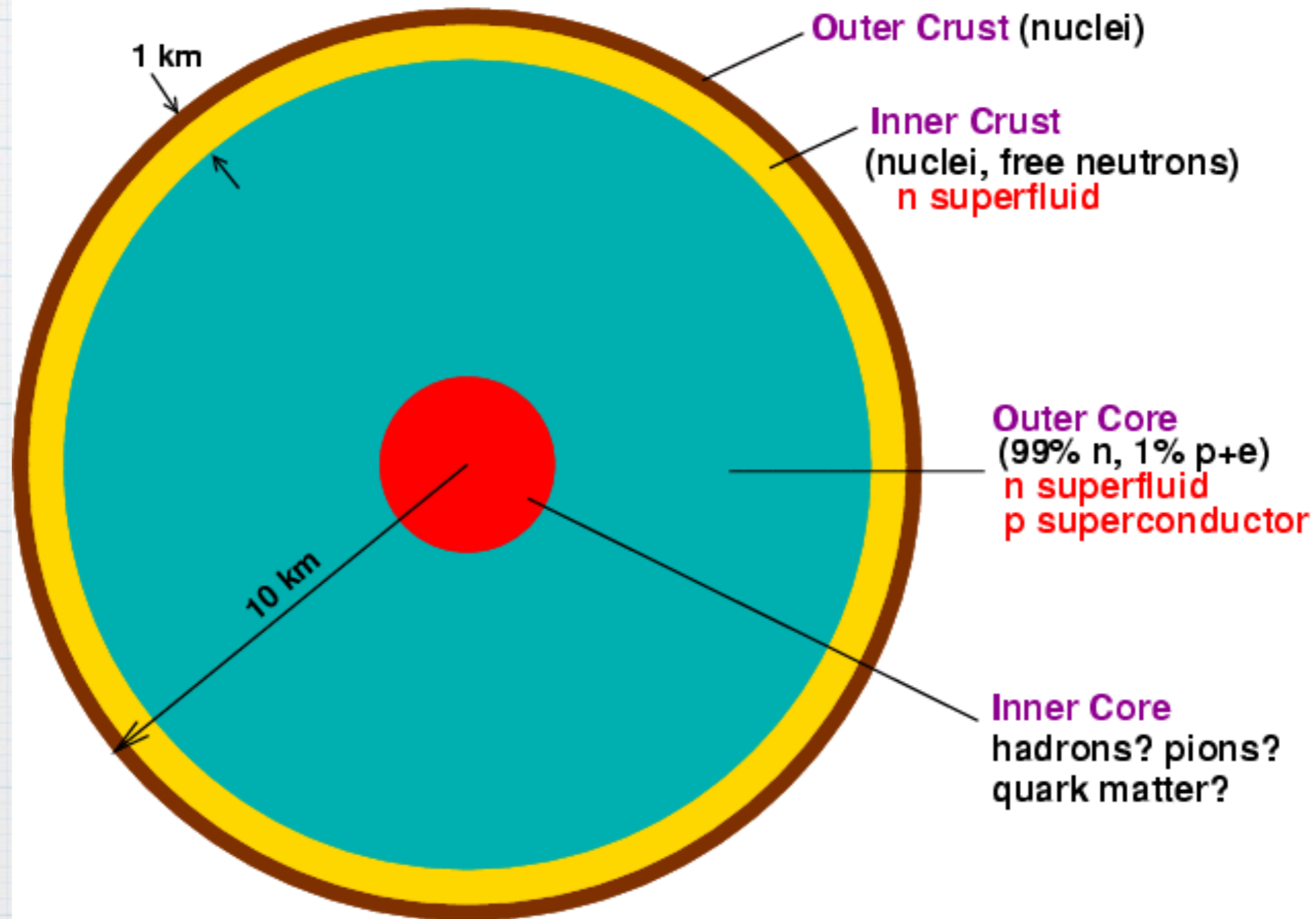
Buoyancy will cause loss of flux until stable stratification sets in

Overturn instability (*Flowers & Ruderman 1977*)



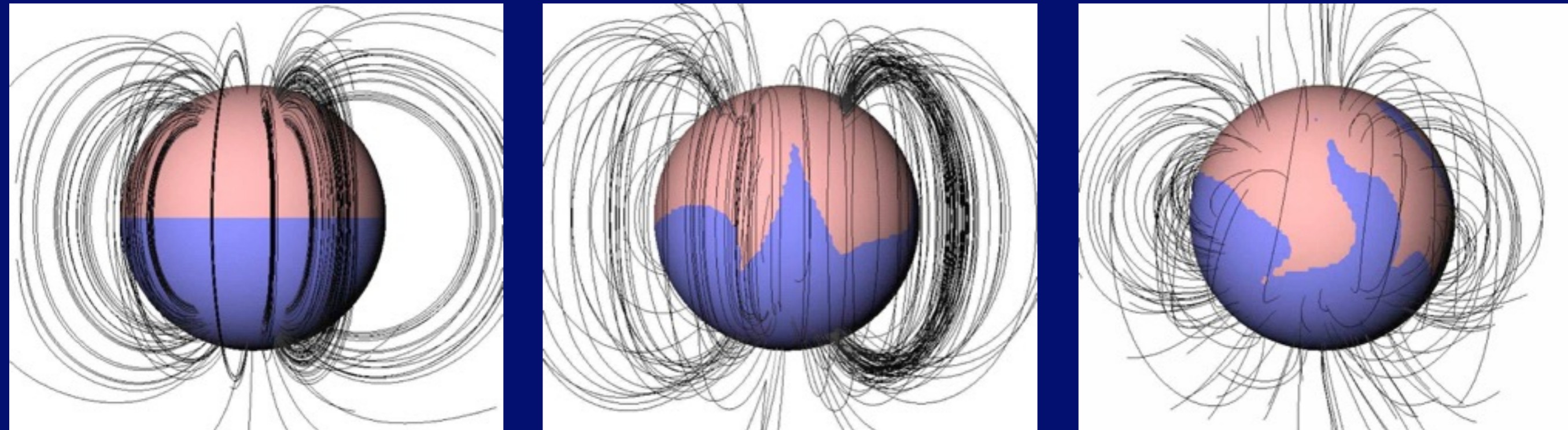
Would seriously reduce magnetic moment
in Alfvén time scale ($t_A \sim 3s / B_{14}$)

The Structure of Neutron Stars



Origin of the Magnetic Field

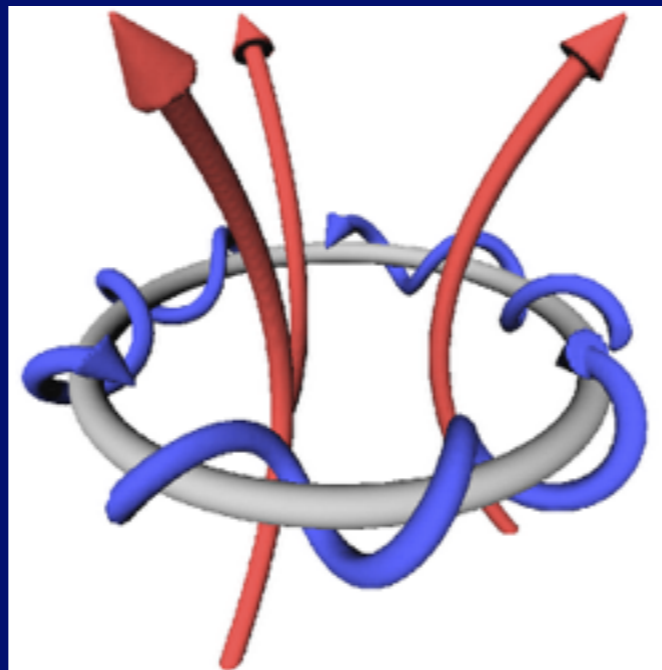
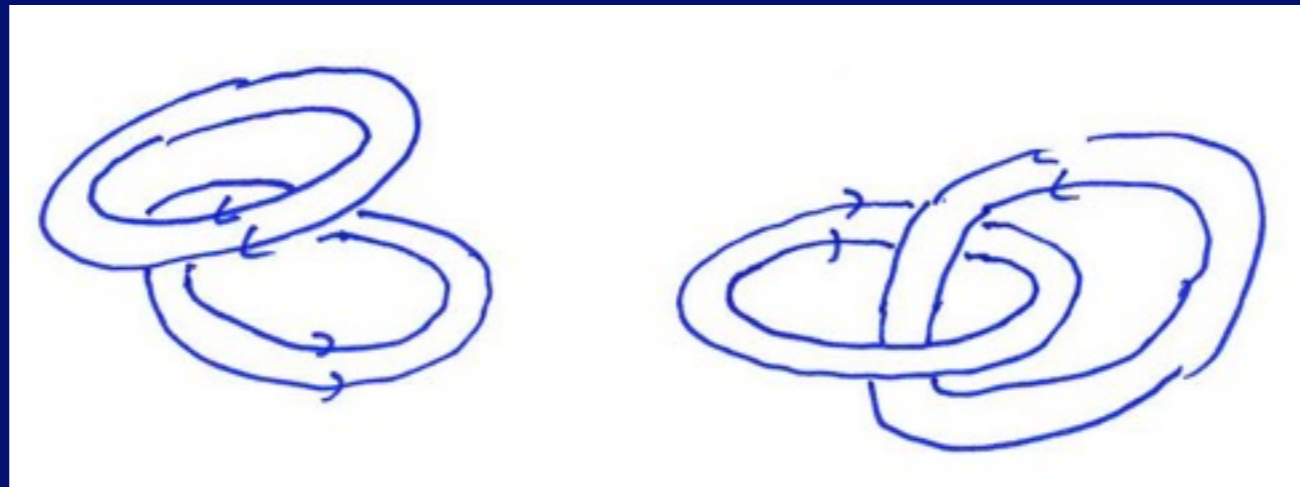
Simulation of overturn instability in a neutron star
(*Braithwaite & Spruit 2006*)



At the end of the run, poloidal field consistent with zero
Coriolis force can reduce the growth rate by a factor Ωt_A in
a fast rotating star. Max possible residual field $\sim 10^{13}$ G by
the time the solid crust forms and arrests further decay.

Origin of the Magnetic Field

Retention of MRI-generated Magnetar strength field would require non-zero helicity $\int \mathbf{B} \cdot \mathbf{A} dV$



(Braithwaite & Nordlund 2006)

Origin of the Magnetic Field

Crustal Thermoelectric Battery

Induction equation $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} - \frac{c^2}{4\pi\sigma} \nabla \times \mathbf{B})$

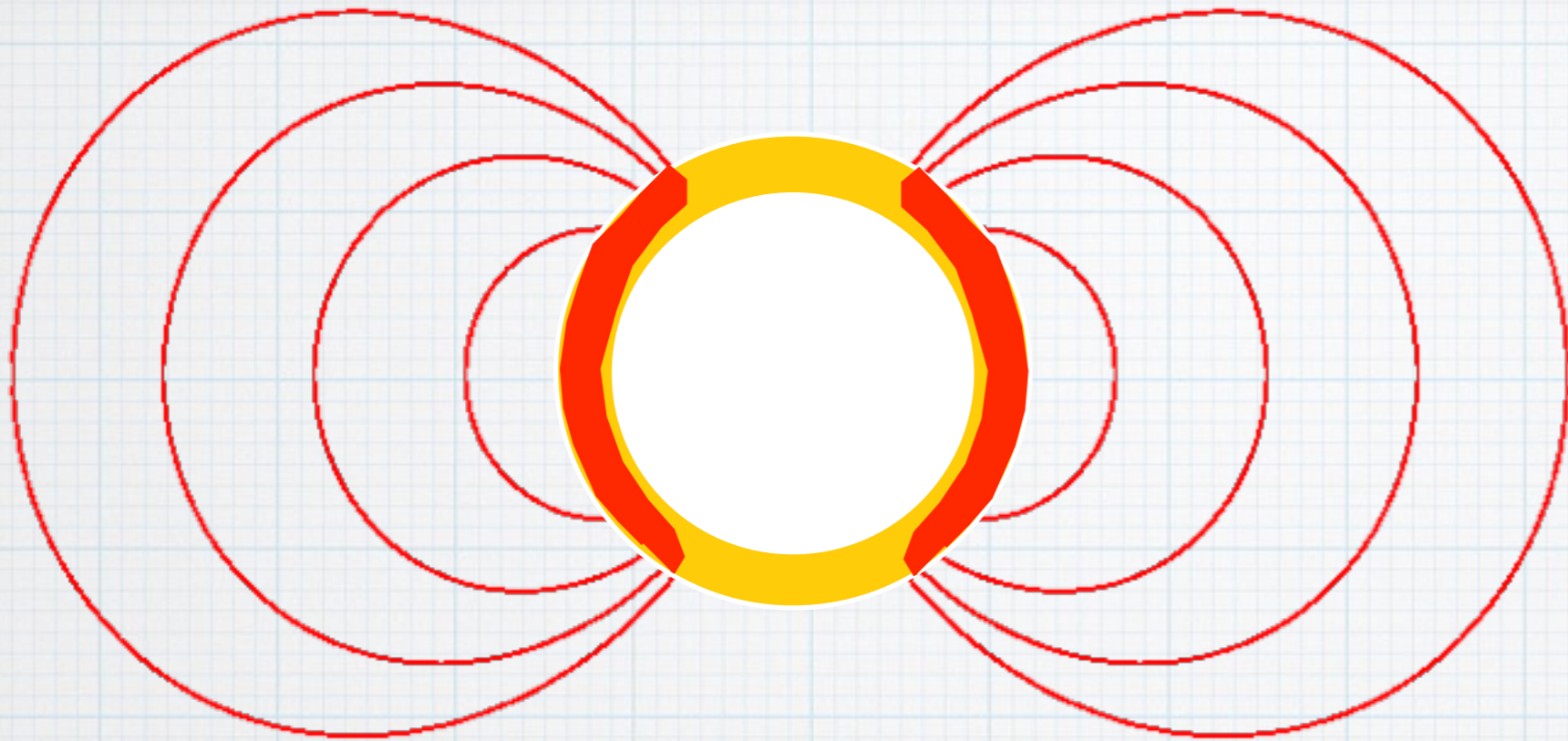
Contribution to \mathbf{V} may arise from

Ambipolar diffusion, Hall effect, **Heat flux**

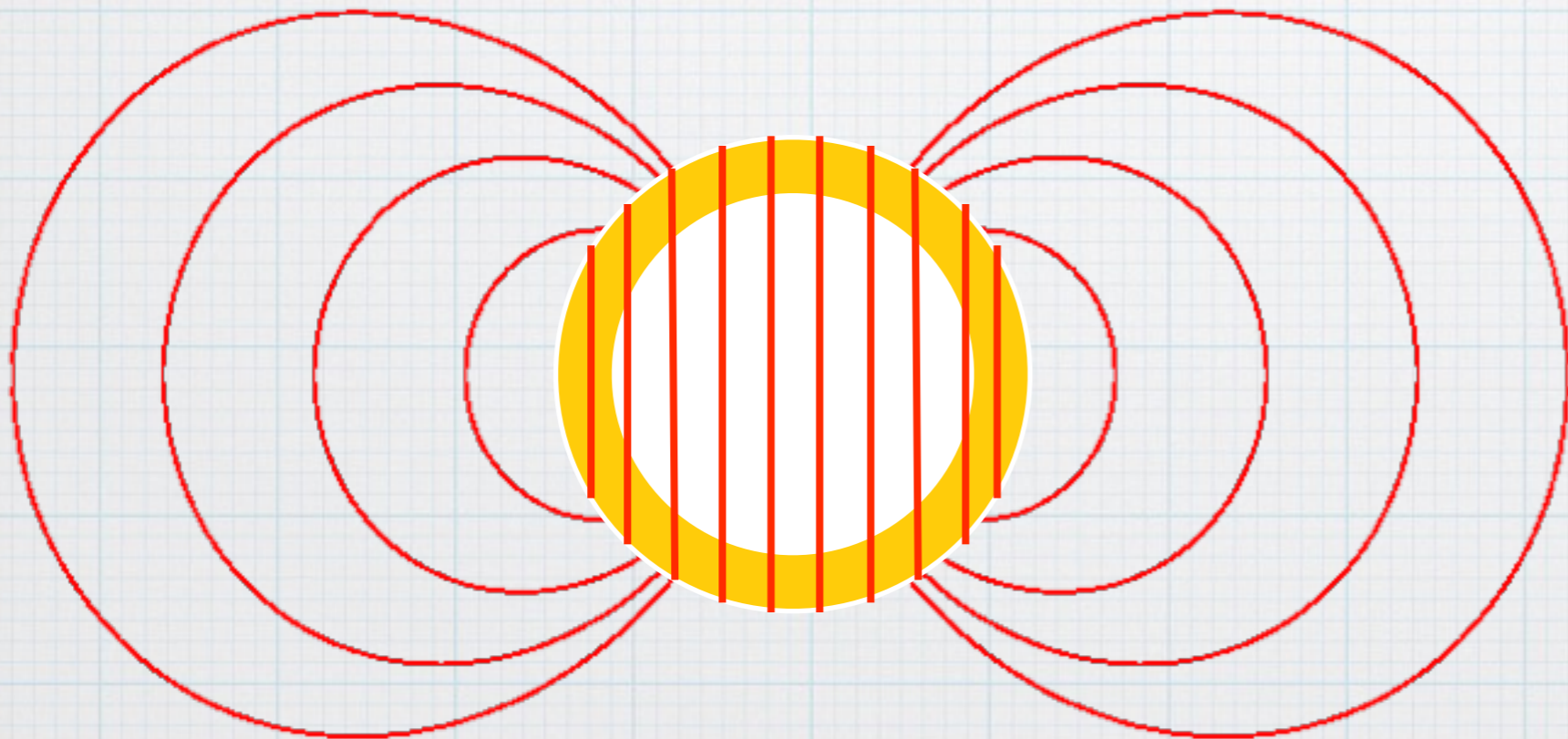
Heat flowing down density gradient can amplify pre-existing horizontal field (Blandford et al 1980)

Generation of $\sim 10^{12}$ G possible from initial $\sim 10^8$ G

Crustal stresses prevent further growth; currents confined to crust



Crystal Field



Uniform Field

The Magnetosphere

Strong electric field may be generated in the neutron star magnetosphere due to the combination of strong field with

- **Spin : pulsars**

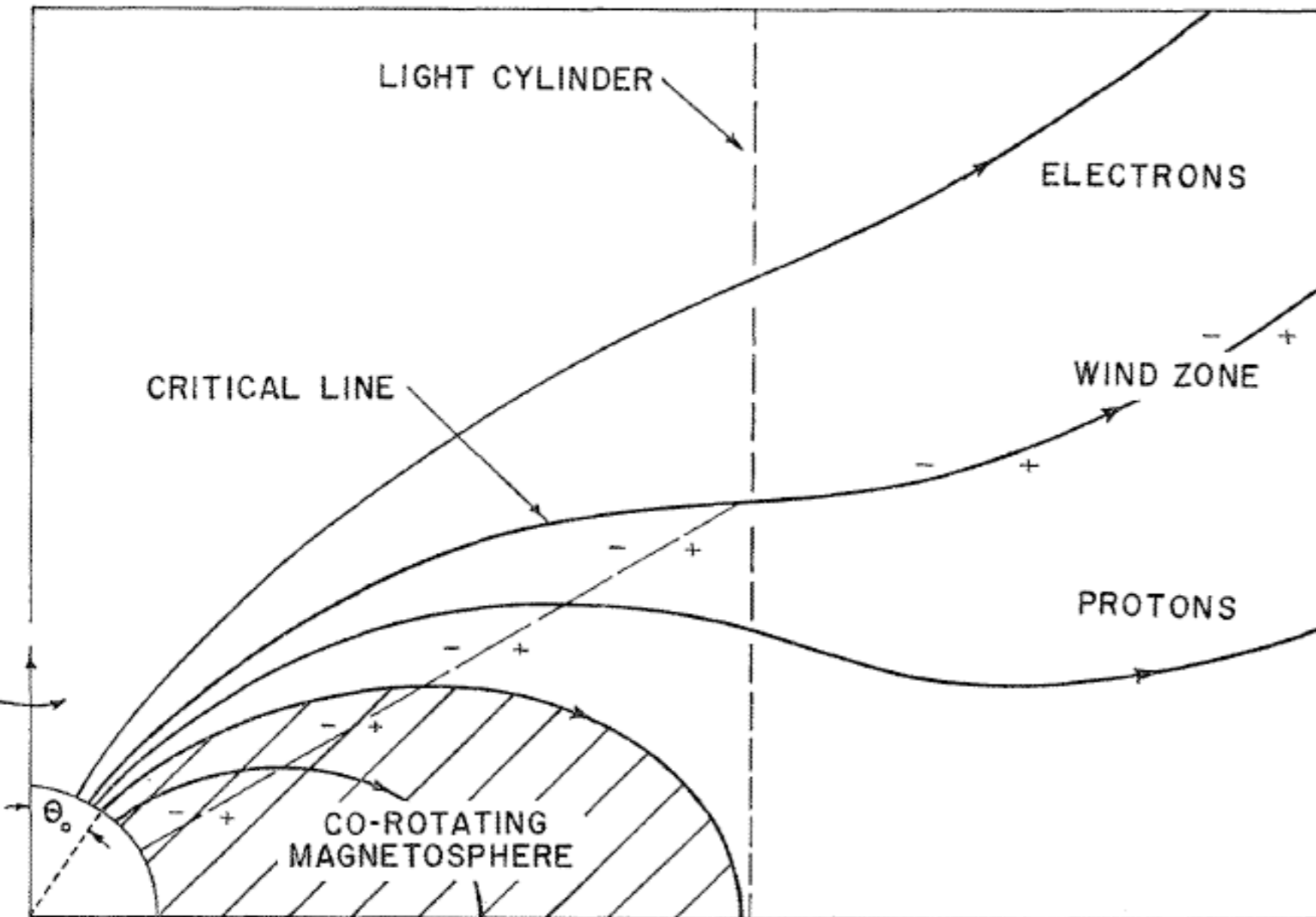
(radiation generated at the cost of rotational energy; $P\dot{P} \propto B_p^2$)

- **Magnetic reorganisation : Magnetars**

(radiation generated at the cost of magnetic free energy)

The Pulsar Magnetosphere: an outstanding problem

Basic concepts: Goldreich & Julian 1969



- A vacuum exterior would have potential drop exceeding 10^{15} V
- Space charge must exist, $E \cdot B = 0$
- Co-rotating magnetosphere can be maintained up to the light cylinder, $\rho \approx -\Omega \cdot B / 2\pi c$
- With pair production, no. density of charged particles may far exceed ρ
- ρ passes through 0 and changes sign in the magnetosphere

Plasma on open field lines cannot co-rotate. Current flows out along these lines, creates toroidal mag. field which provides the dipole spin-down torque.

A charge-starved gap is likely on the null ρ surface at the boundary of the closed magnetosphere: The Outer Gap (Cheng et al 86, Romani 94)

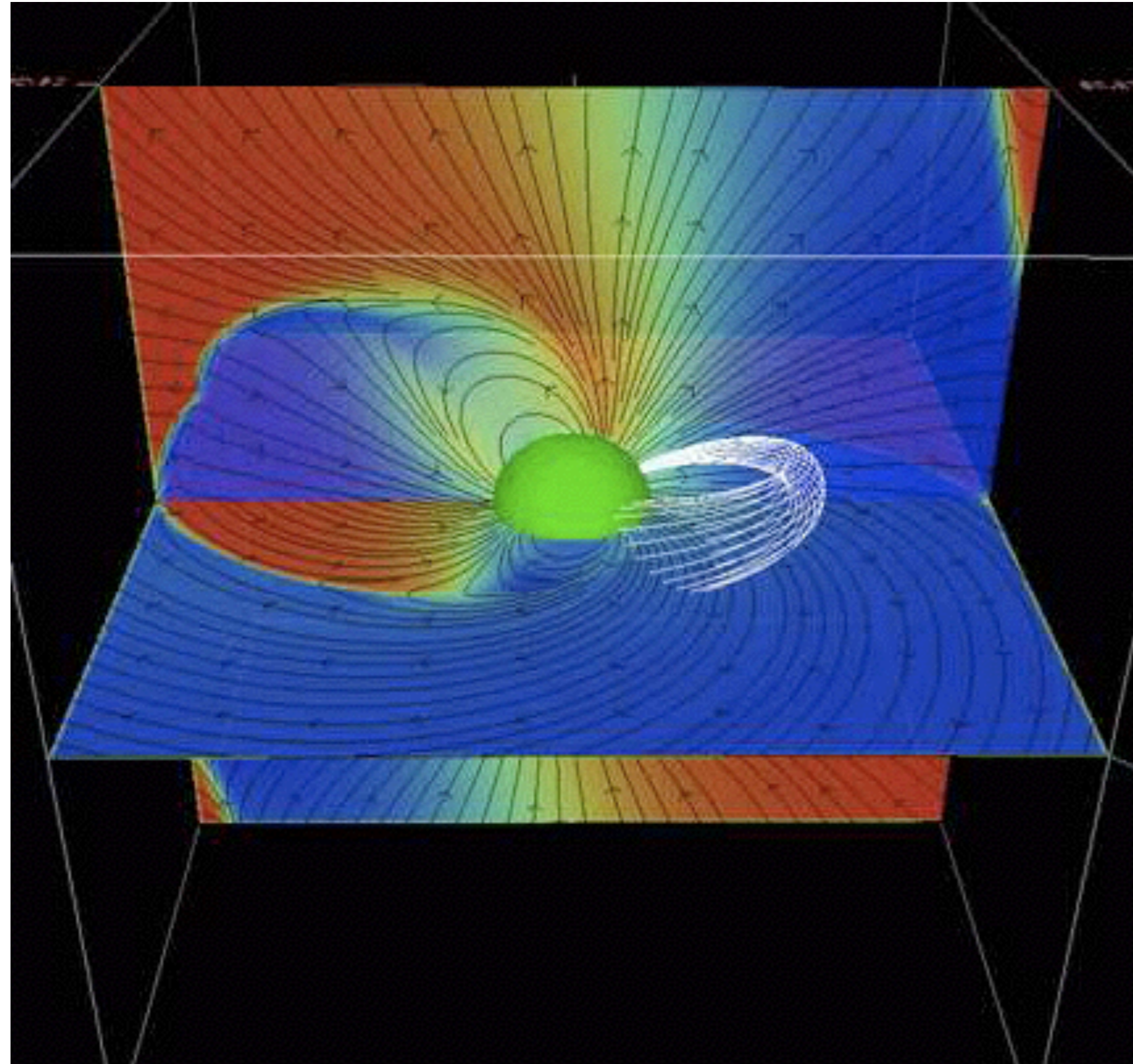
Force-free magnetosphere

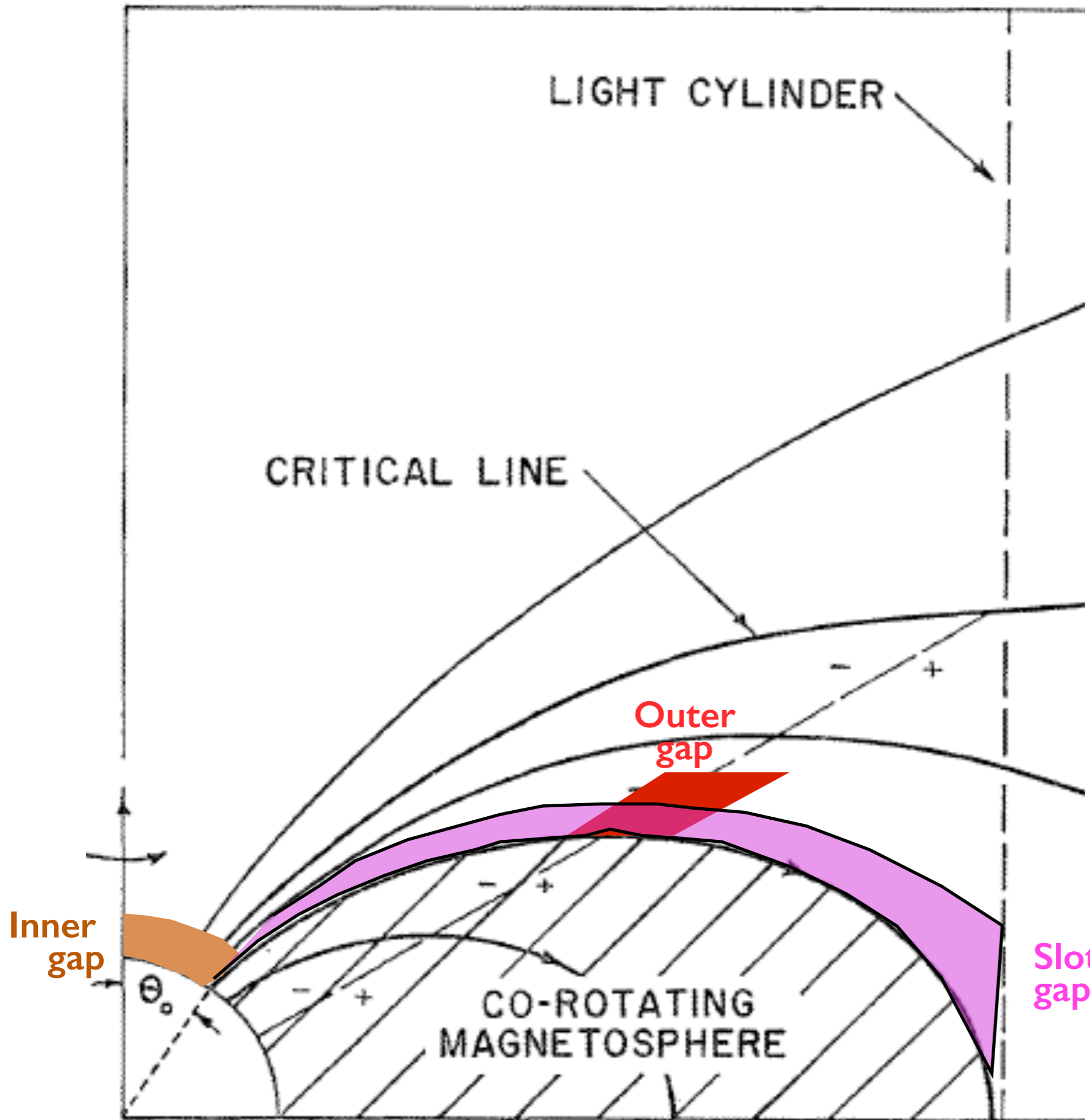
(Spitkovsky 2006)

$$\rho E + (j \times B) / c = 0$$

everywhere

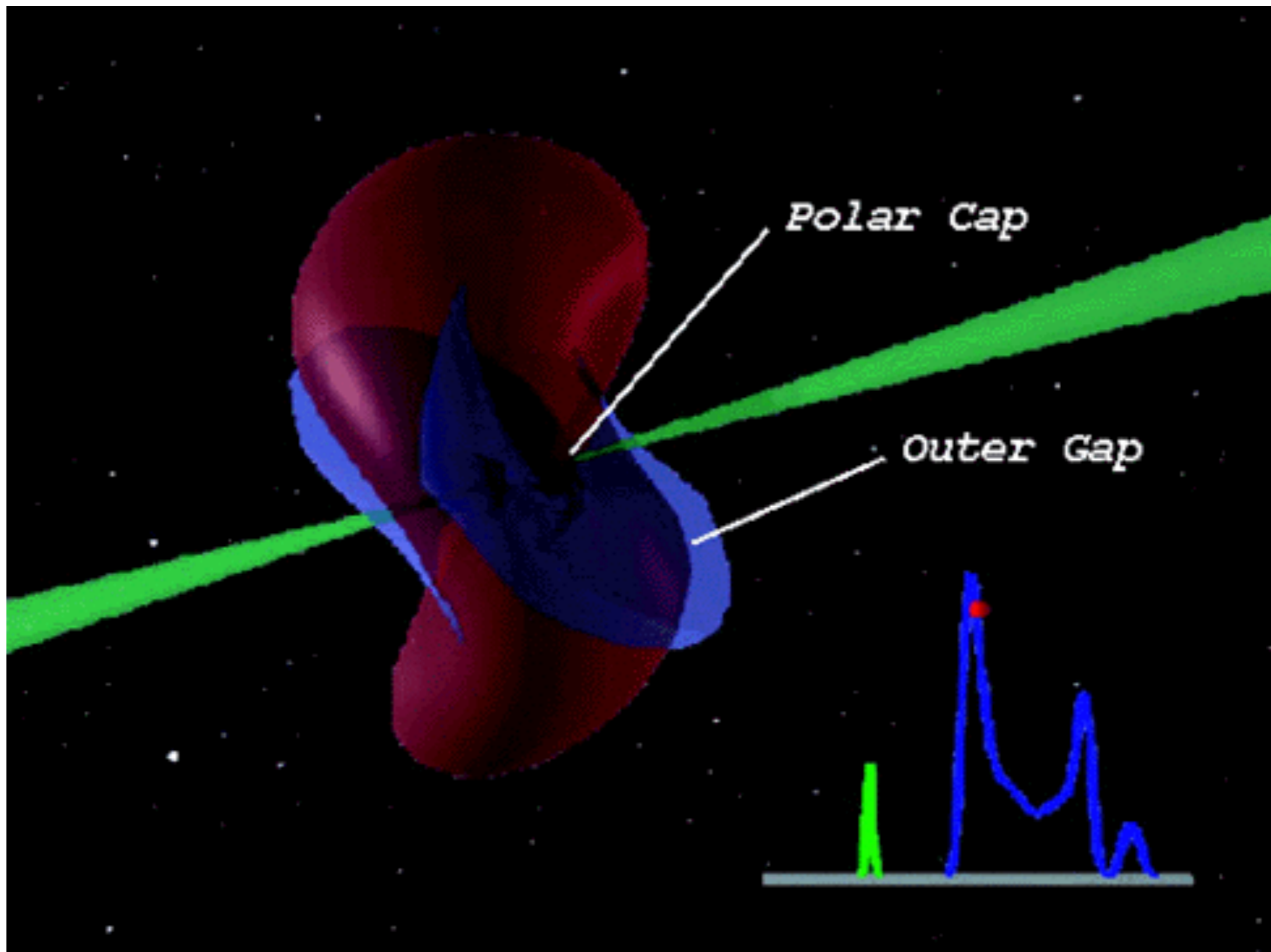
*poor approximation near
LC, current sheets*





Field line sweepback strongly distorts the flux surfaces near the light cylinder

Some models place the acceleration & emission region in the wind zone



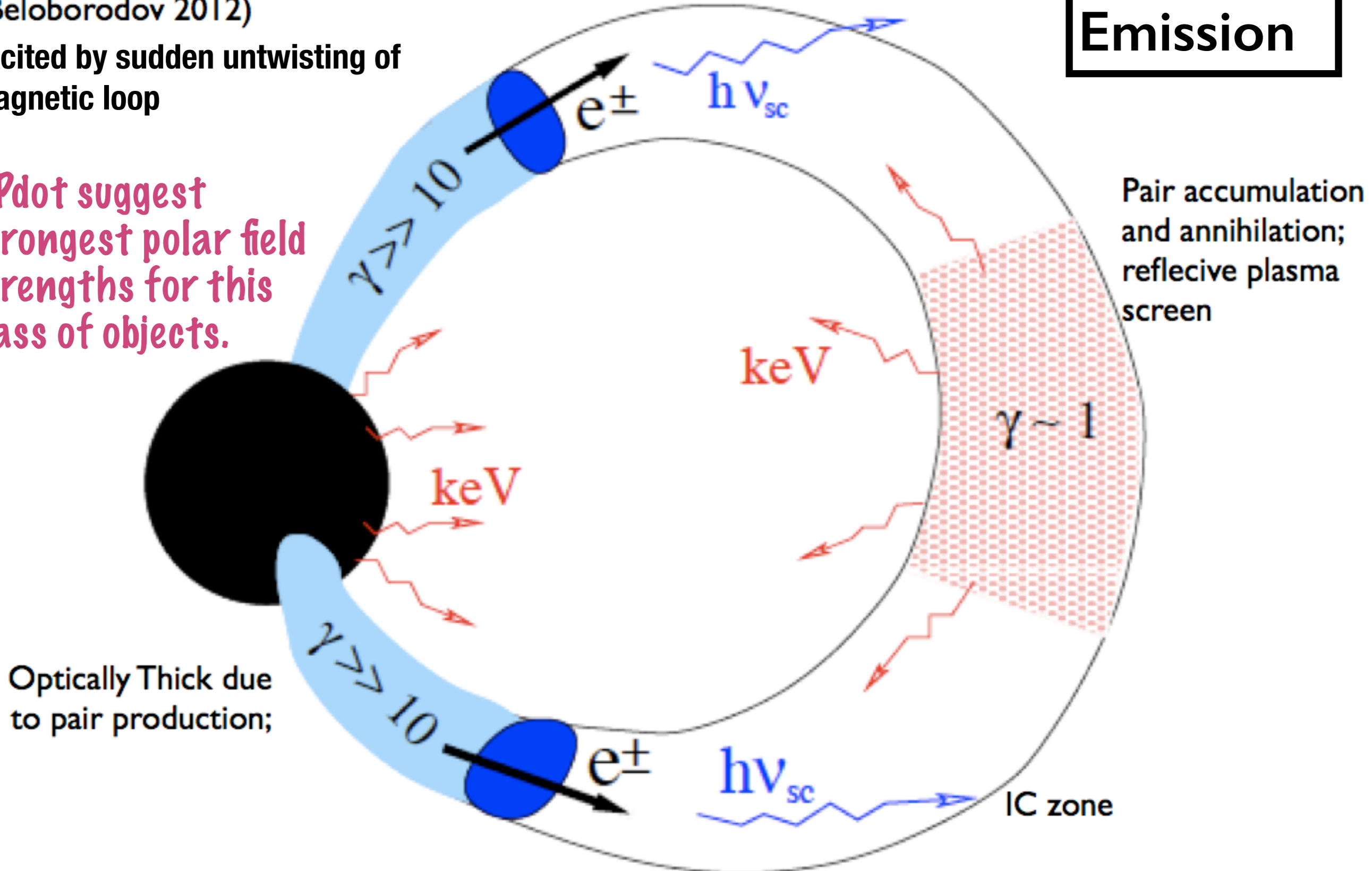
Radiation in a current bundle

(Beloborodov 2012)

Excited by sudden untwisting of magnetic loop

Magnetar Emission

P , \dot{P} suggest strongest polar field strengths for this class of objects.



Stored magnetic energy is released to generate emission. Magnetic field strength would reduce with time (no direct observational evidence yet of this happening).

Evolution

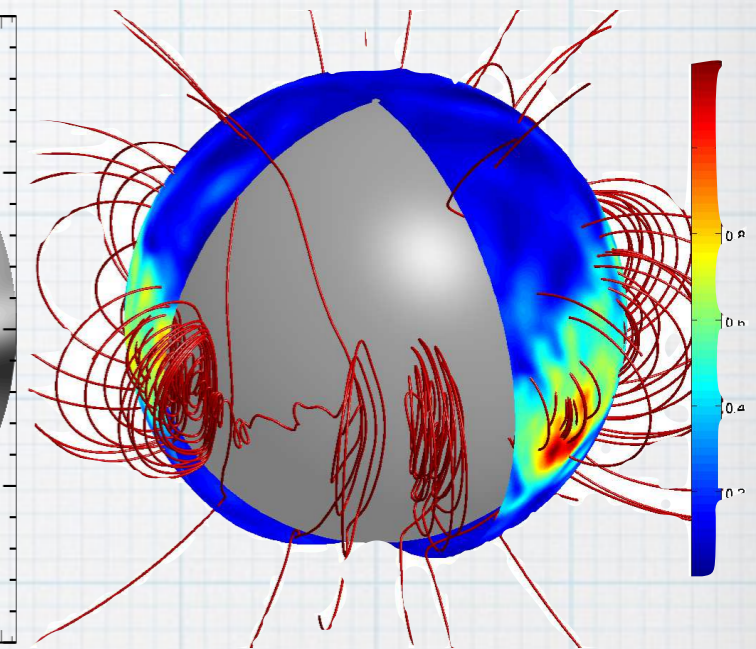
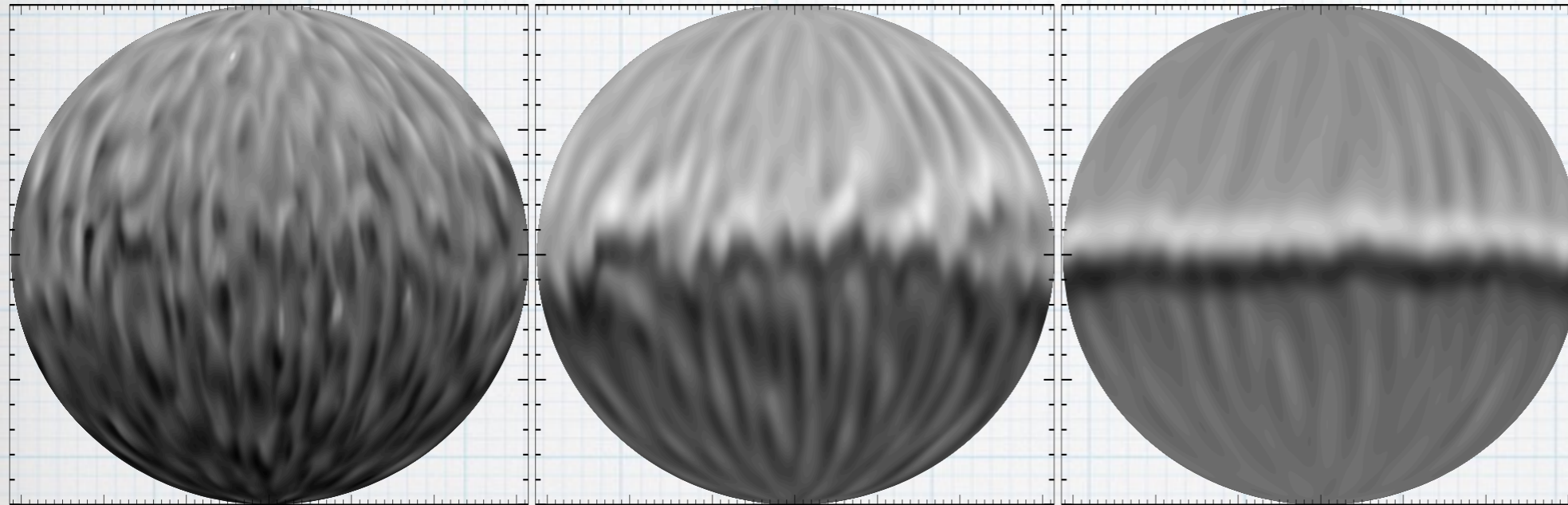
- * Evolution of the magnetic field may hold clues to the origin of the field
- * How does the field evolve?
- * Agents of evolution:
 - Lorentz forces
 - Ohmic diffusion
 - Ambipolar diffusion
 - Hall effect

Hall-mediated Magnetar field evolution in the crust

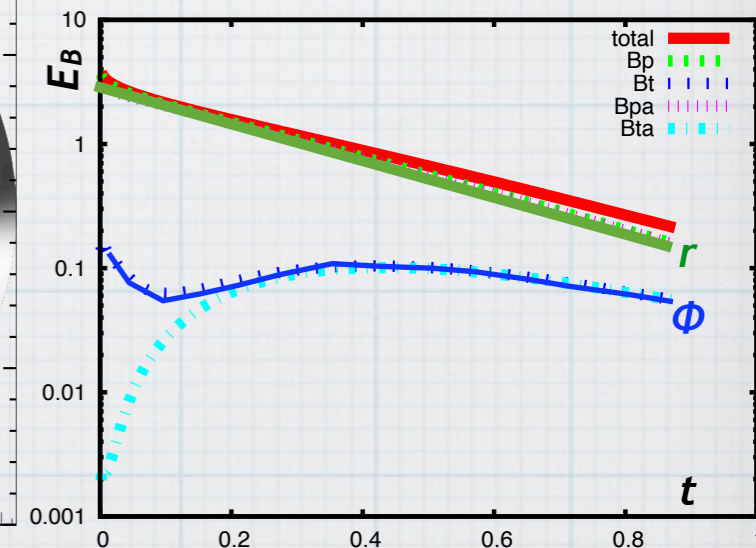
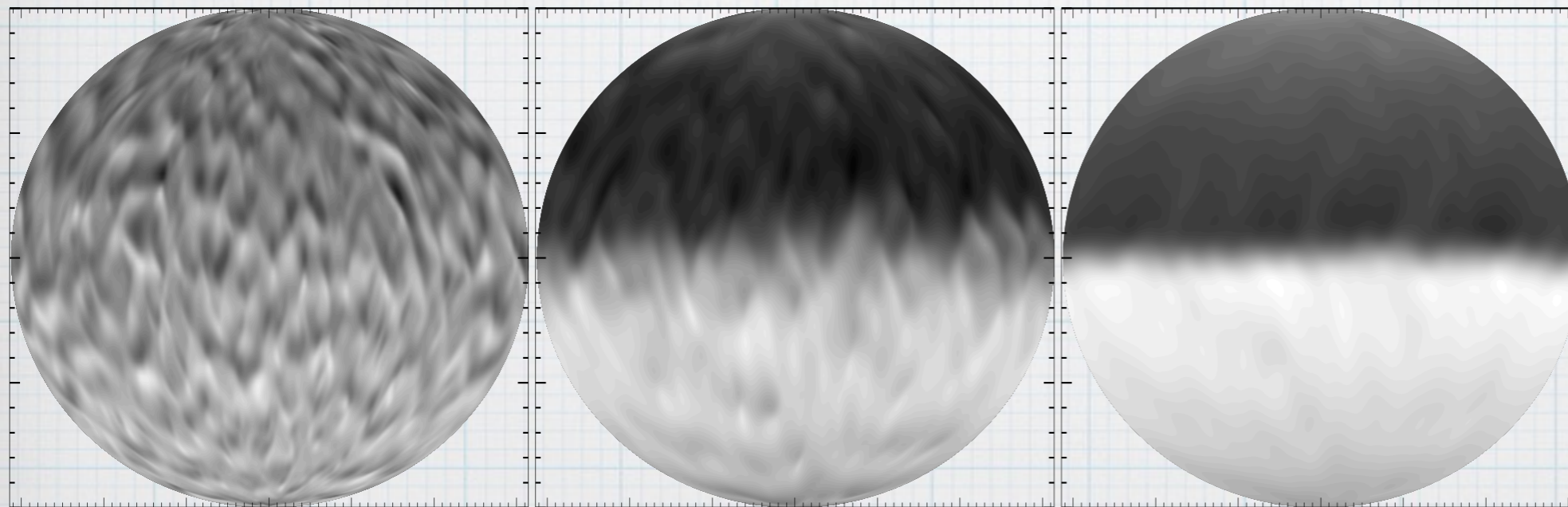
0.21 My

0.67 My

1.40 My

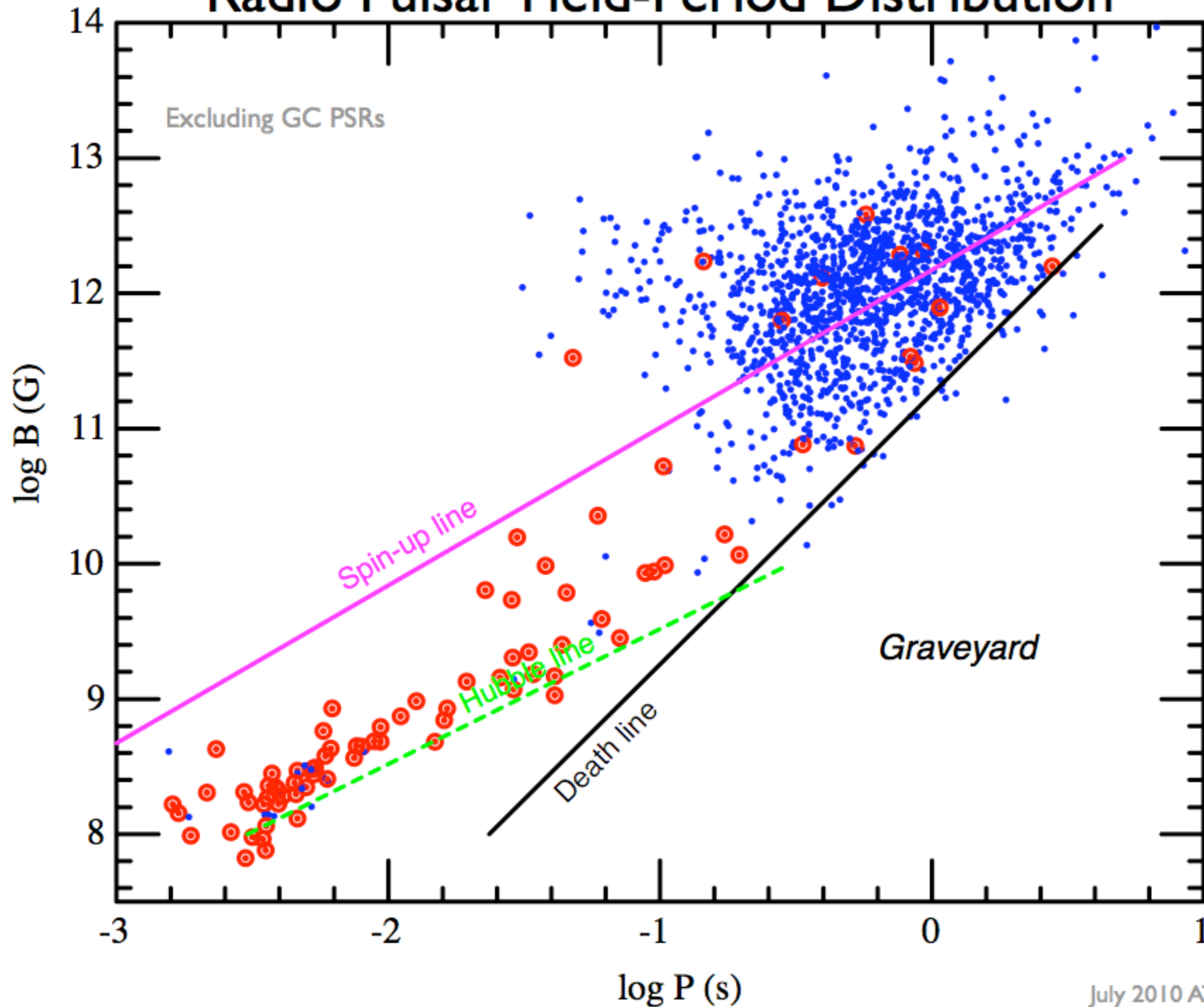


Radial

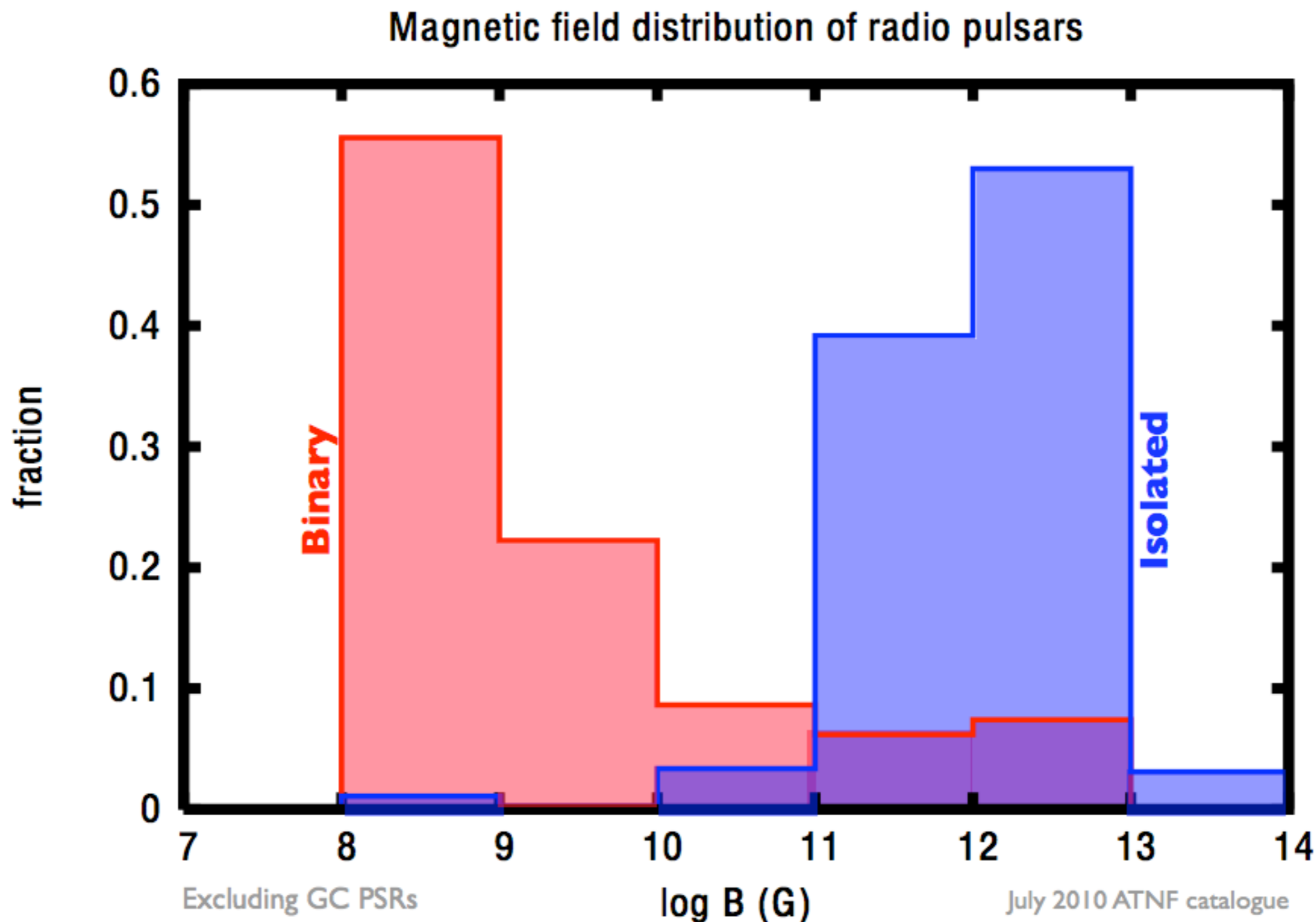


Azimuthal

Radio Pulsar Field-Period Distribution



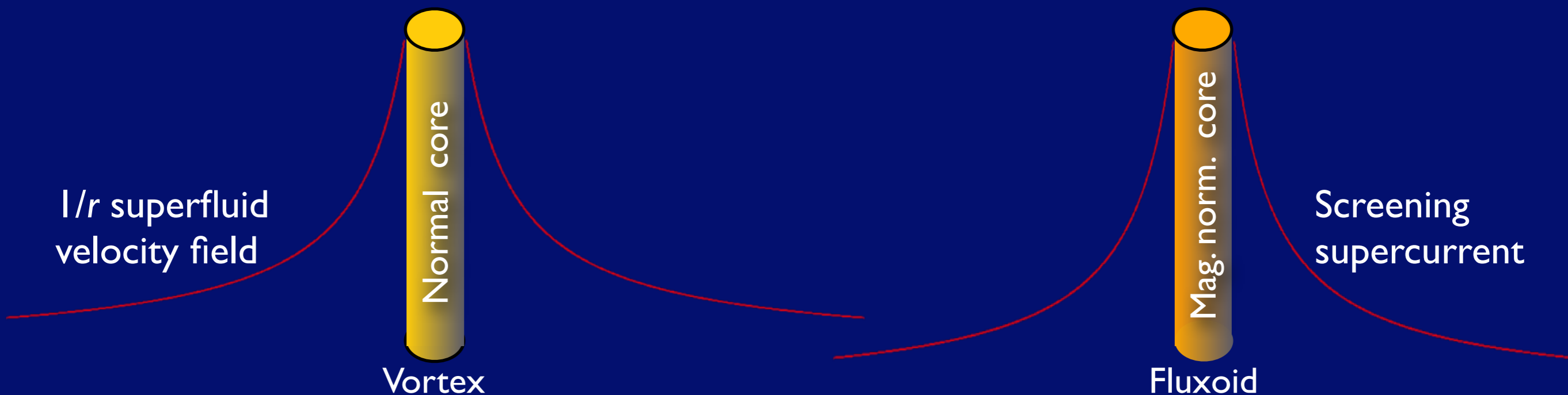
Evolution in a binary system appears to reduce a Neutron Star's Magnetic Field Strength



The Superfluid Interior

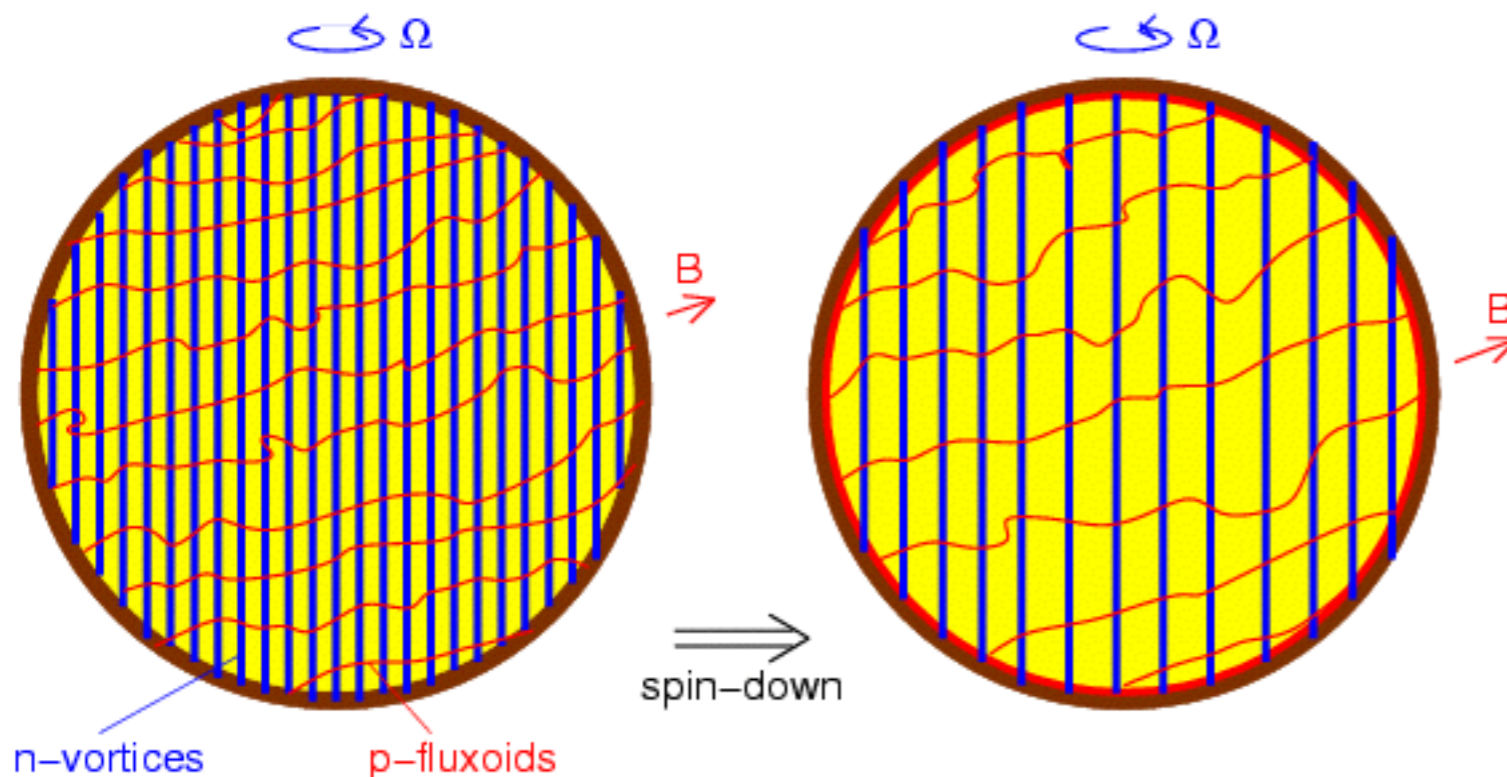
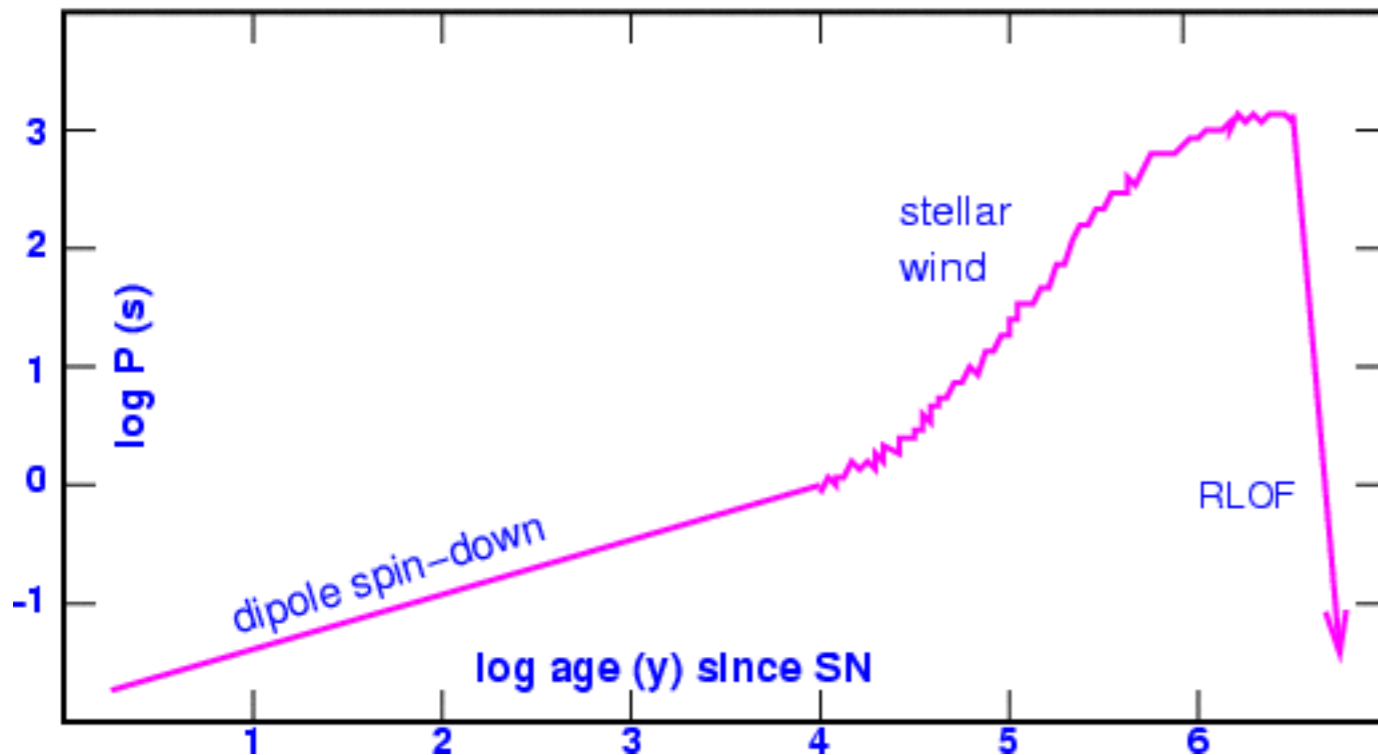
The rotating neutron superfluid is permeated by an array of vortices, each carrying a vorticity quantum $h/2m_n$. There are $\sim 2 \times 10^{16} / P(\text{s})$ such vortices.

Magnetic flux through the proton superconductor is carried in such singular lines - each fluxoid carrying a quantum $hc/2e$. There are $\sim 10^3 B_{12}$ such fluxoids.

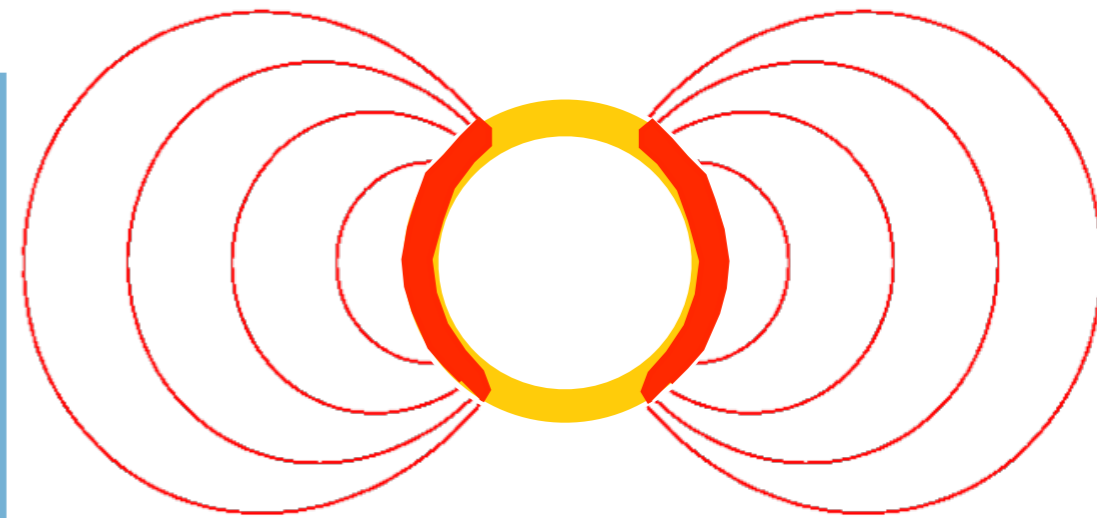


Field evolution in a binary neutron star

Expulsion of interior field to the crust



Srinivasan, Bhattacharya, Muslimov & Tsygan 1990



Field in the crust undergoes ohmic decay

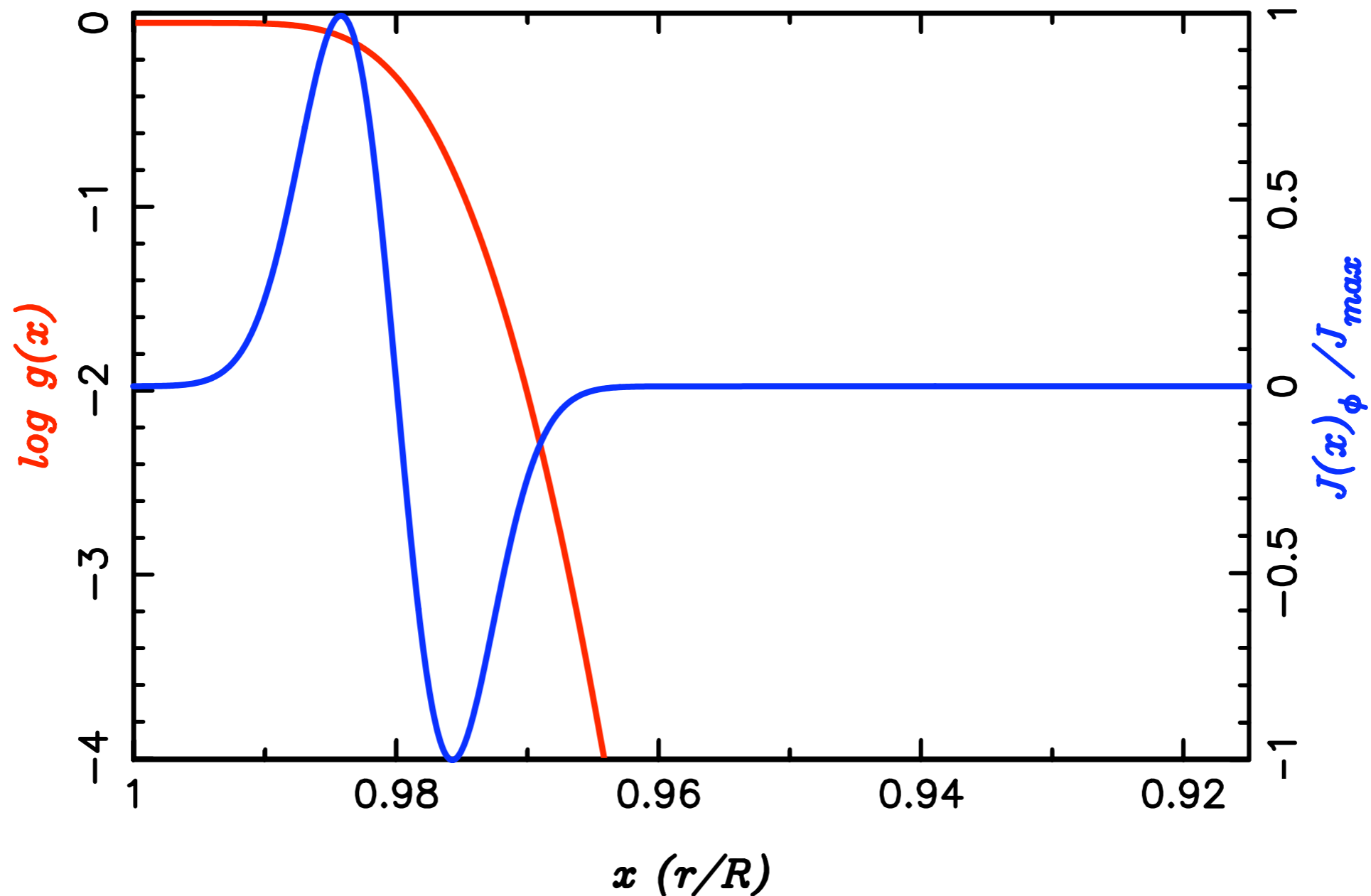
Decay can be enhanced due to heating caused by accretion

(Geppert & Urpin 1994; Konar & Bhattacharya 1997-...)

Matter accreted on the star may bury/screen its mag field

(Bisnovatyi-Kogan & Komberg 1974; Romani 1990, 1993; Litwin, Brown & Rosner 2001; Choudhuri & Konar 2002; Melatos et al 2001-2015)

Ohmic evolution of Crustal Field in an accreting neutron star



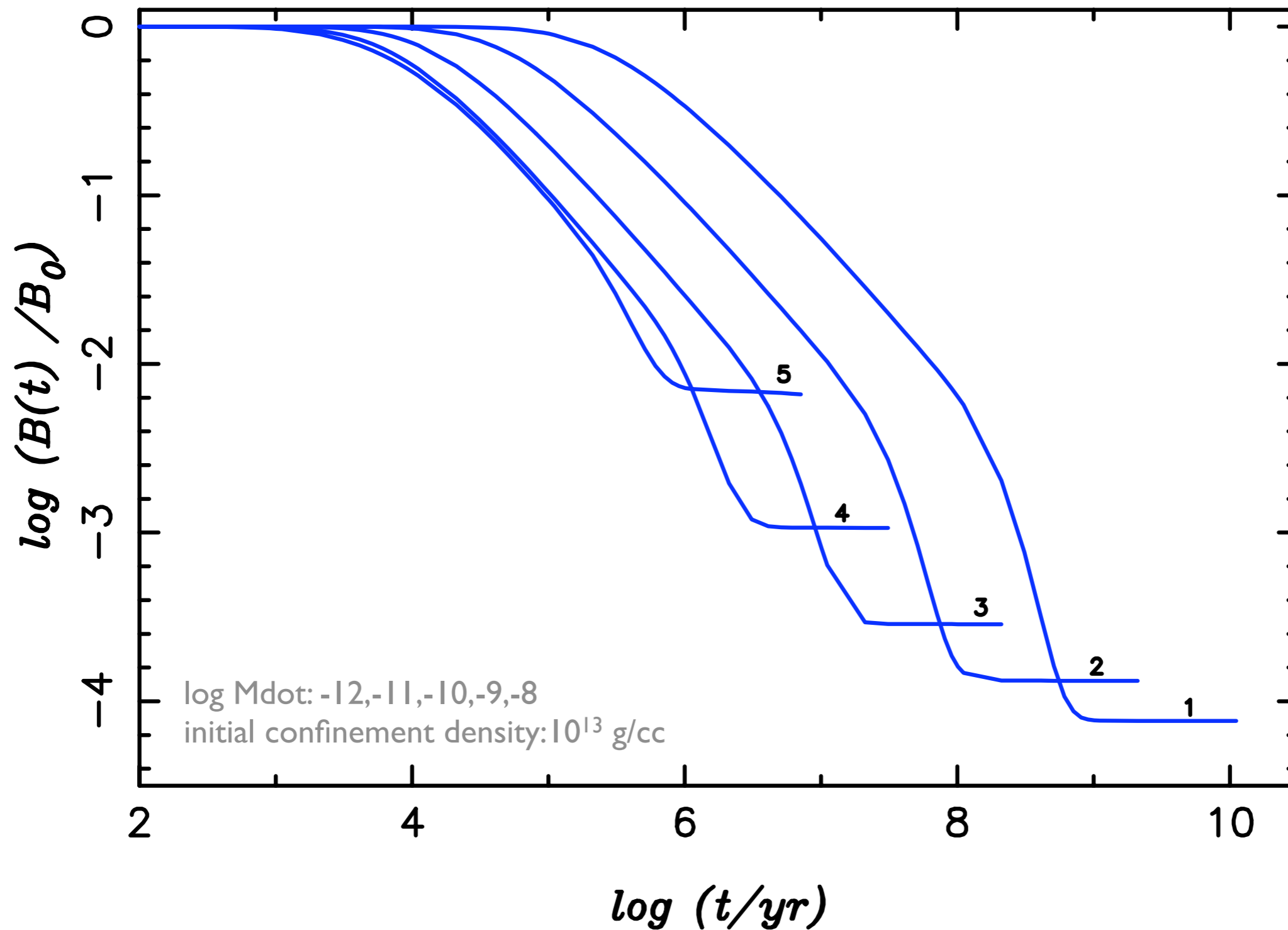
Accretion causes

- a) Rise in Temp \Rightarrow Decrease in conductivity
- b) Inward Migration \Rightarrow Higher conductivity

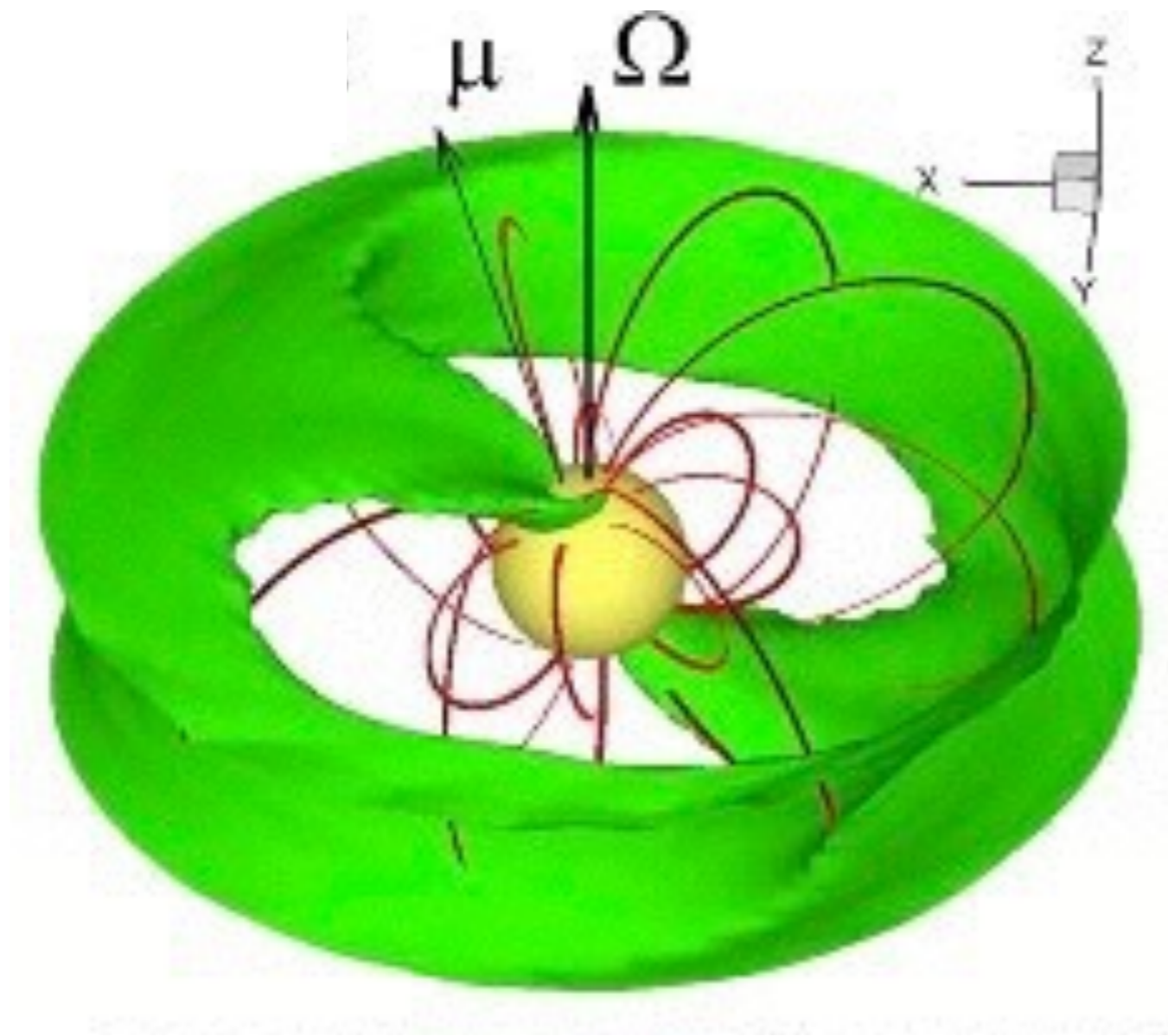
Konar & Bhattacharya 1997

Crustal Field in an accreting neutron star

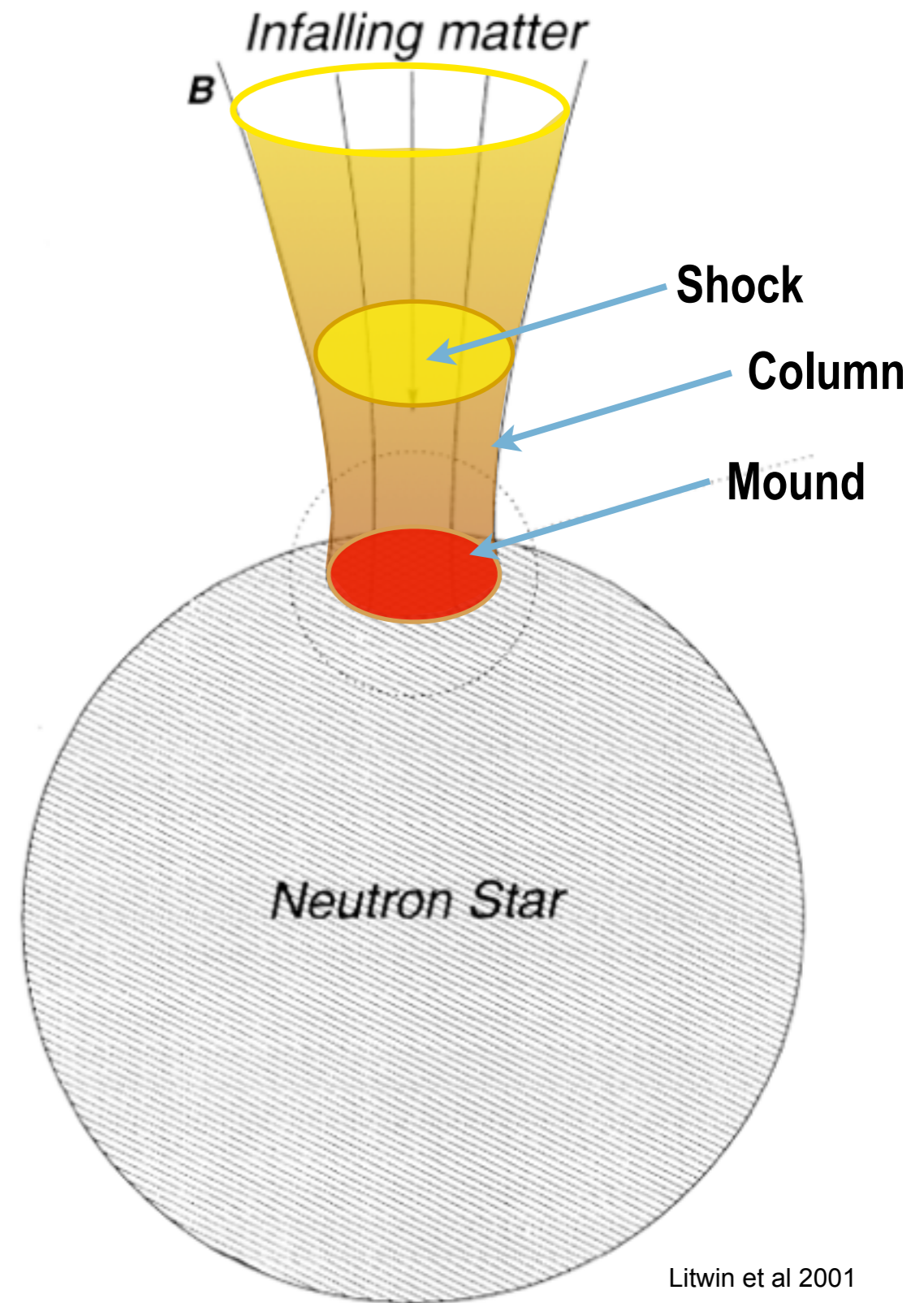
Ohmic Decay



Accretion onto the polar cap



Romanova, Kulkarni and Lovelace 2008



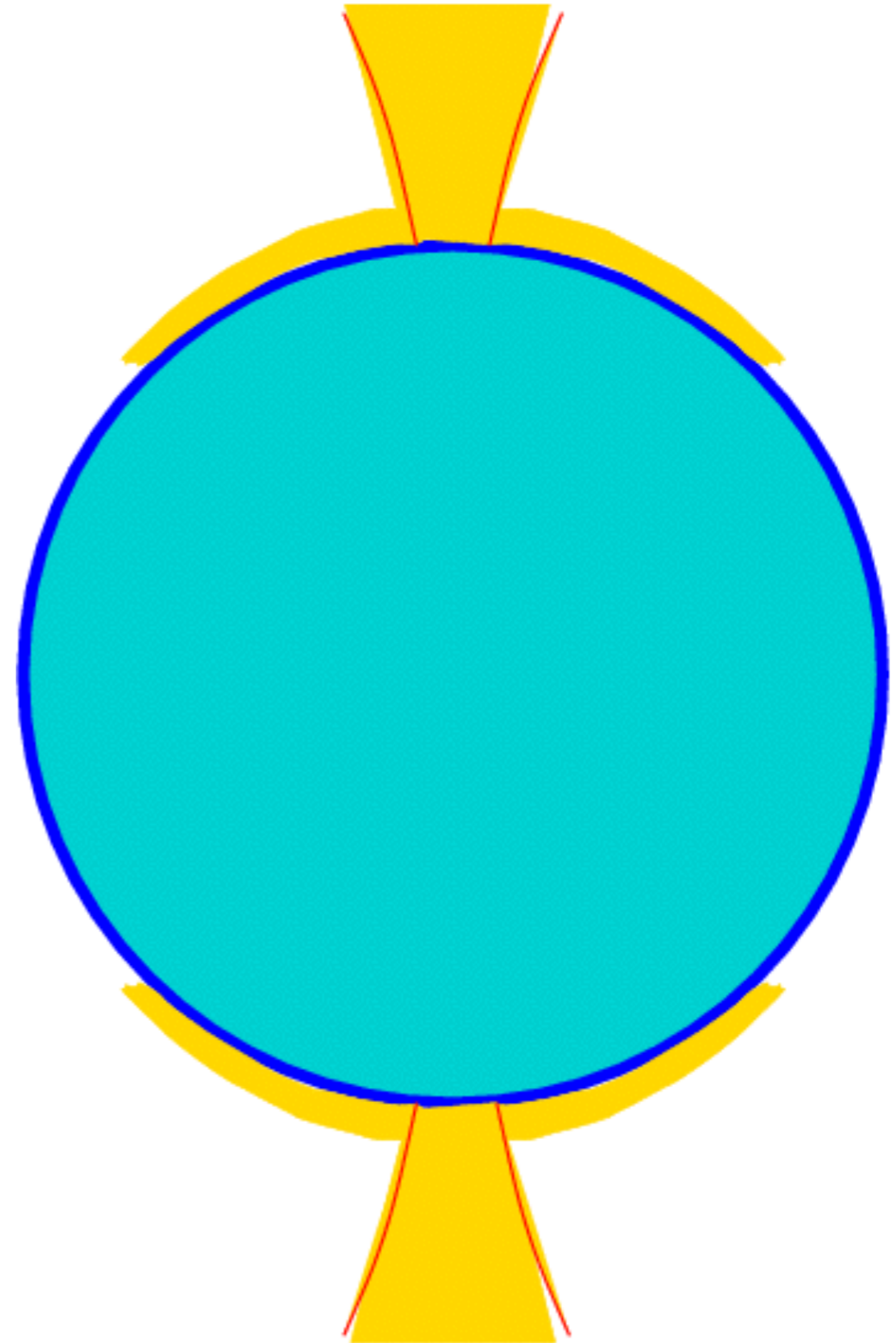
Litwin et al 2001

Polar accretion geometry

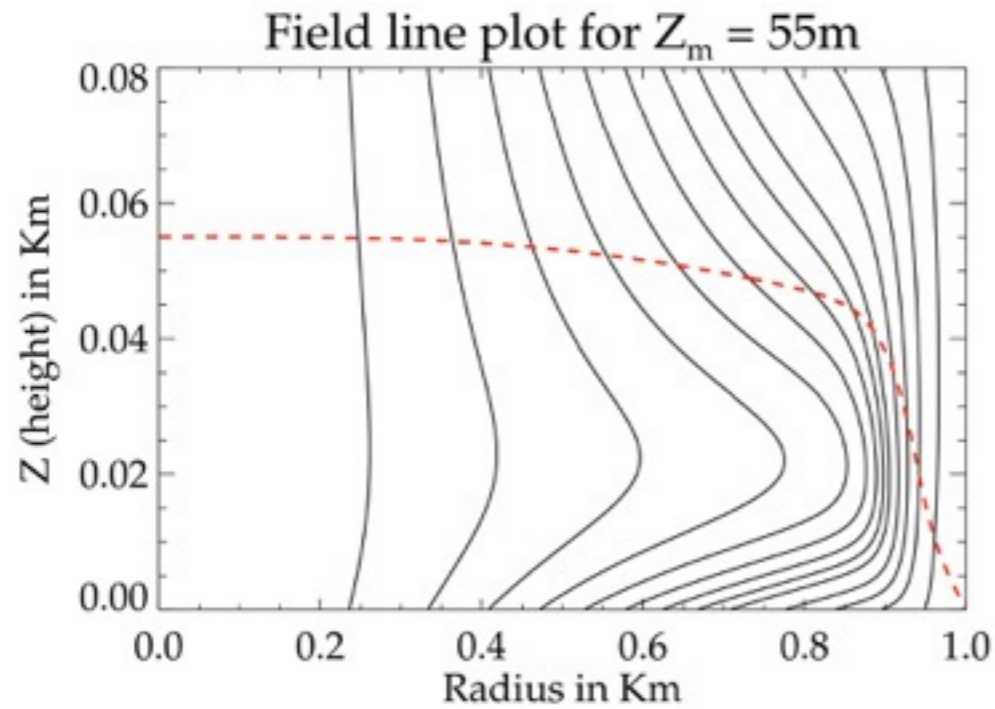
The Fate of the Mound

What happens to the mound with continued accretion?

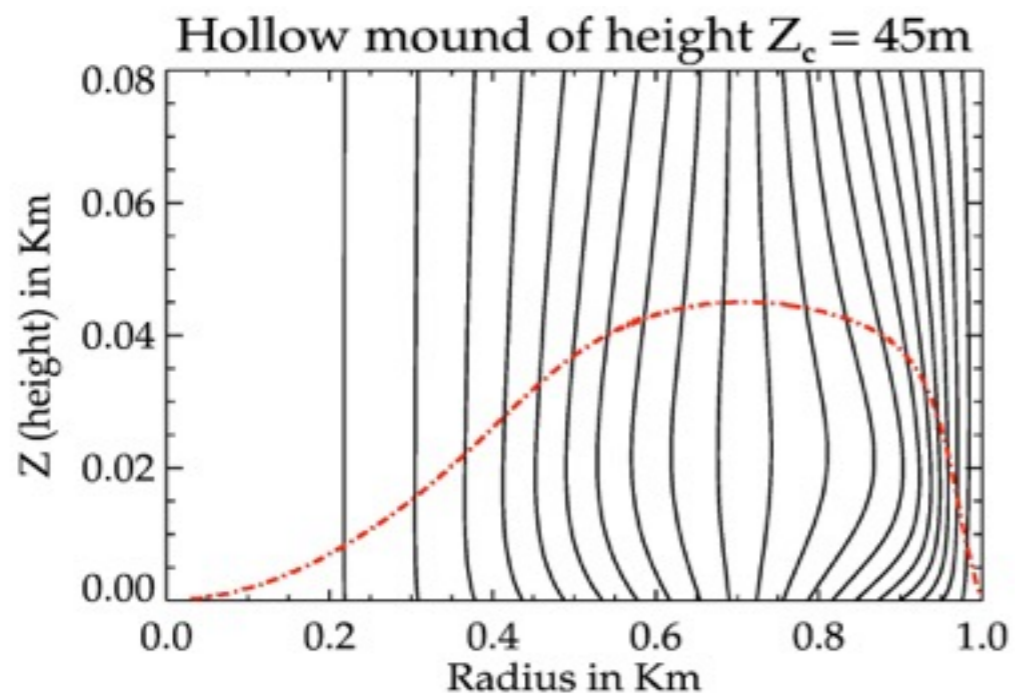
- Grow without bound?
- Spread over the surface, dragging the field?
- Spread over the surface, slipping through the field?
- The answer lies in plasma instabilities



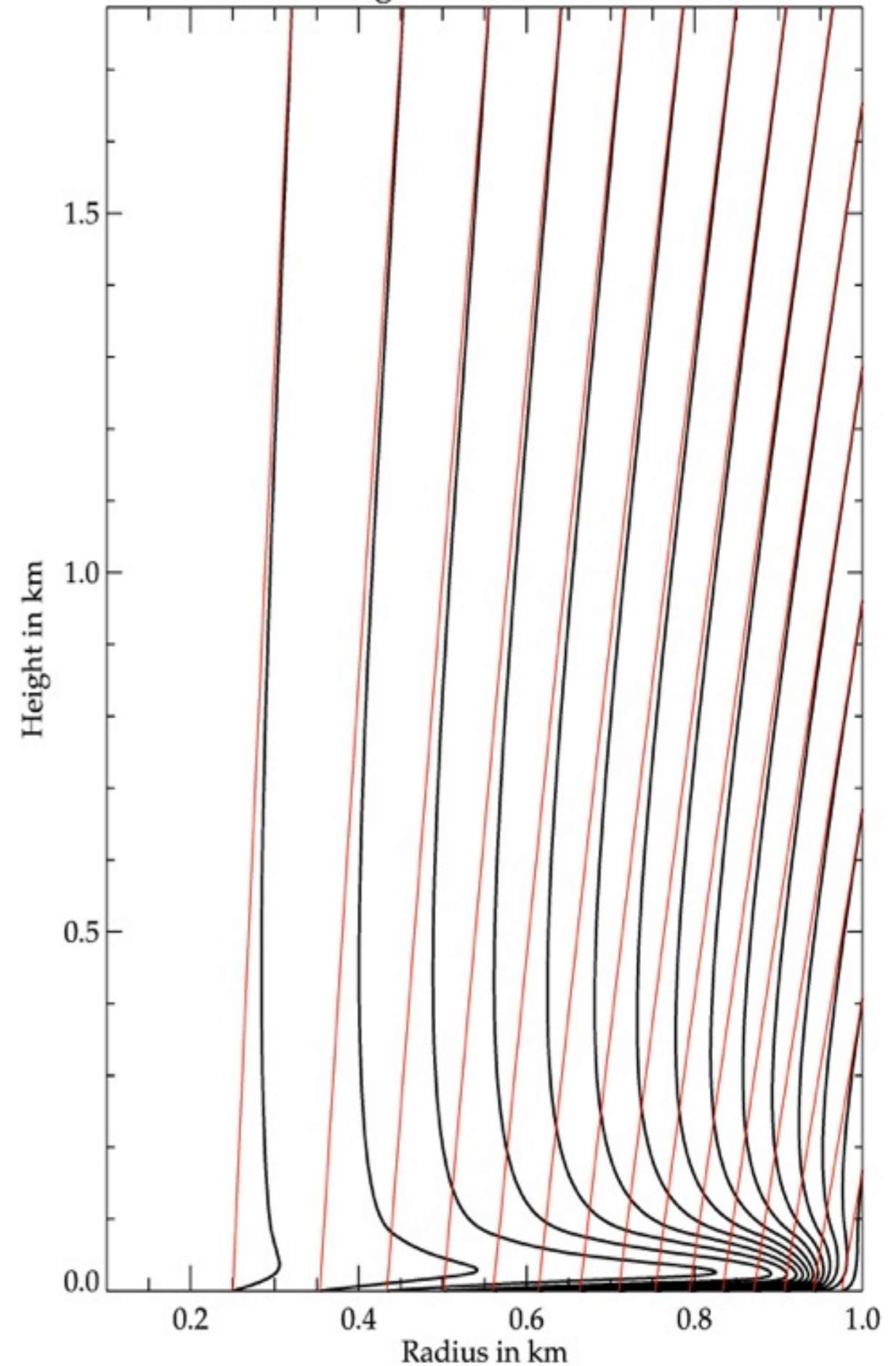
Filled mound : $Z_0(\psi) = Z_c \left(1 - \left(\frac{\psi}{\psi_p} \right)^2 \right)$



Hollow mound : $Z_0(\psi) = \frac{Z_c}{0.25} \left(0.25 - \left(\frac{\psi}{\psi_p} - 0.5 \right)^2 \right)$

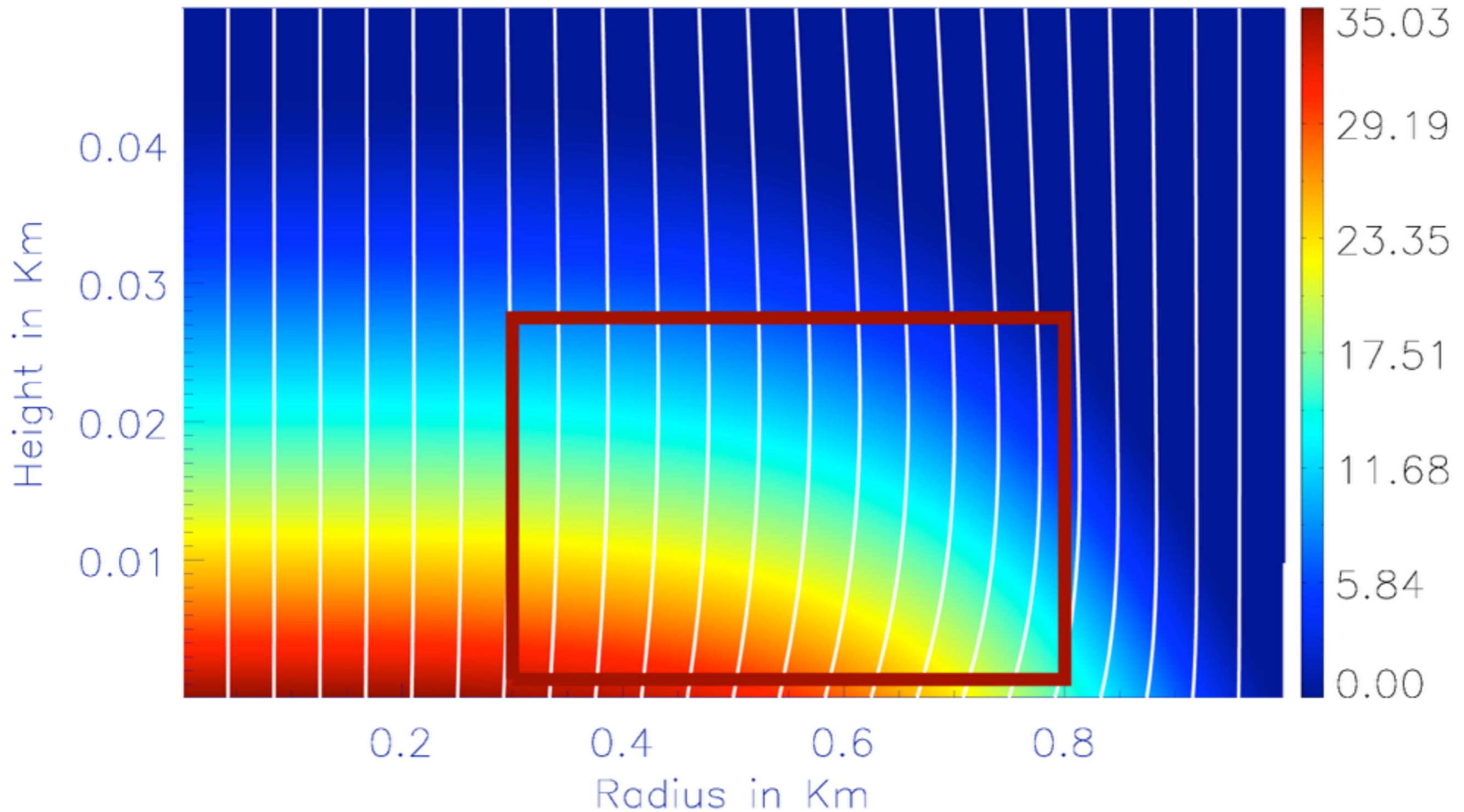


Field configuration for 55m mound



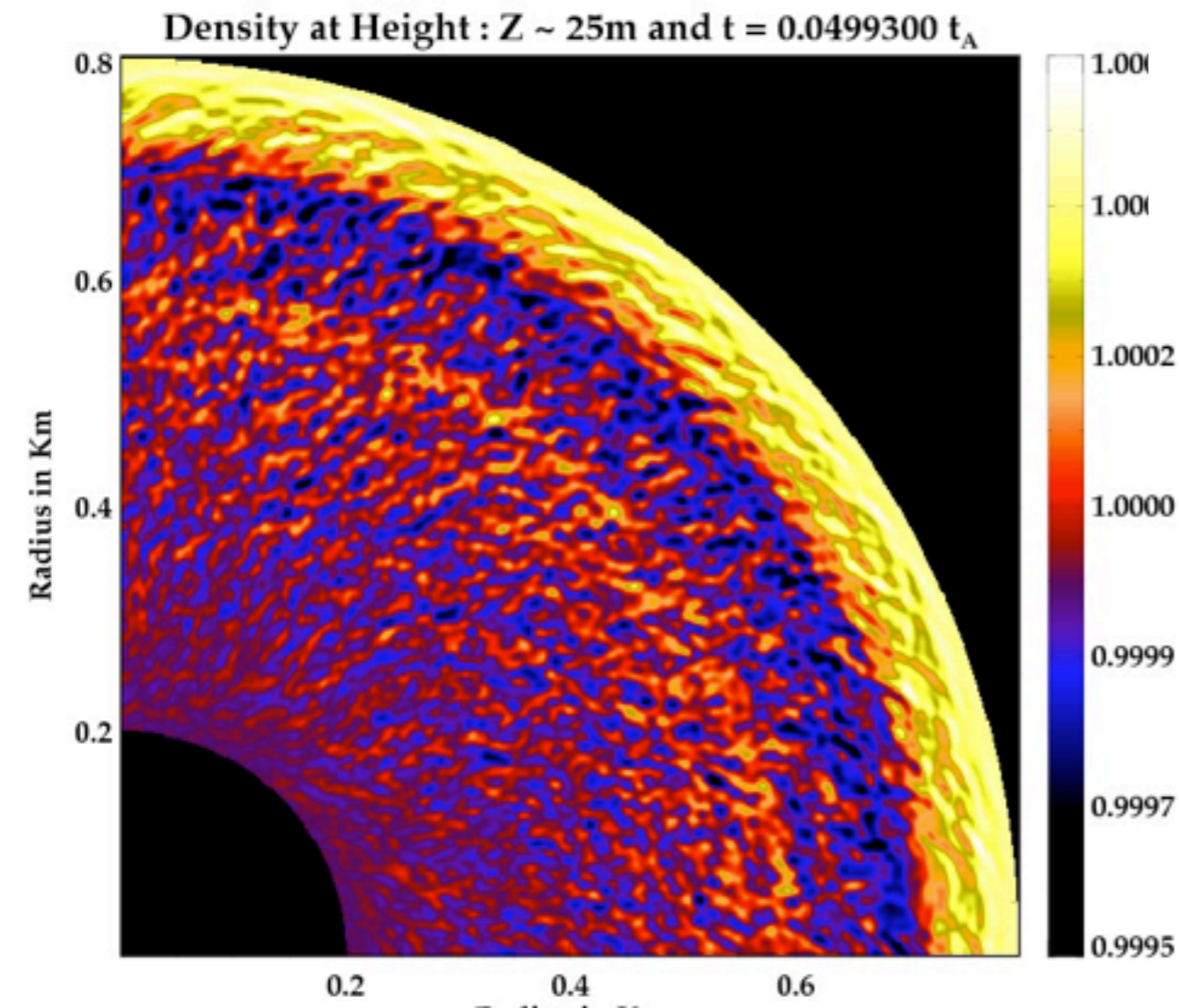
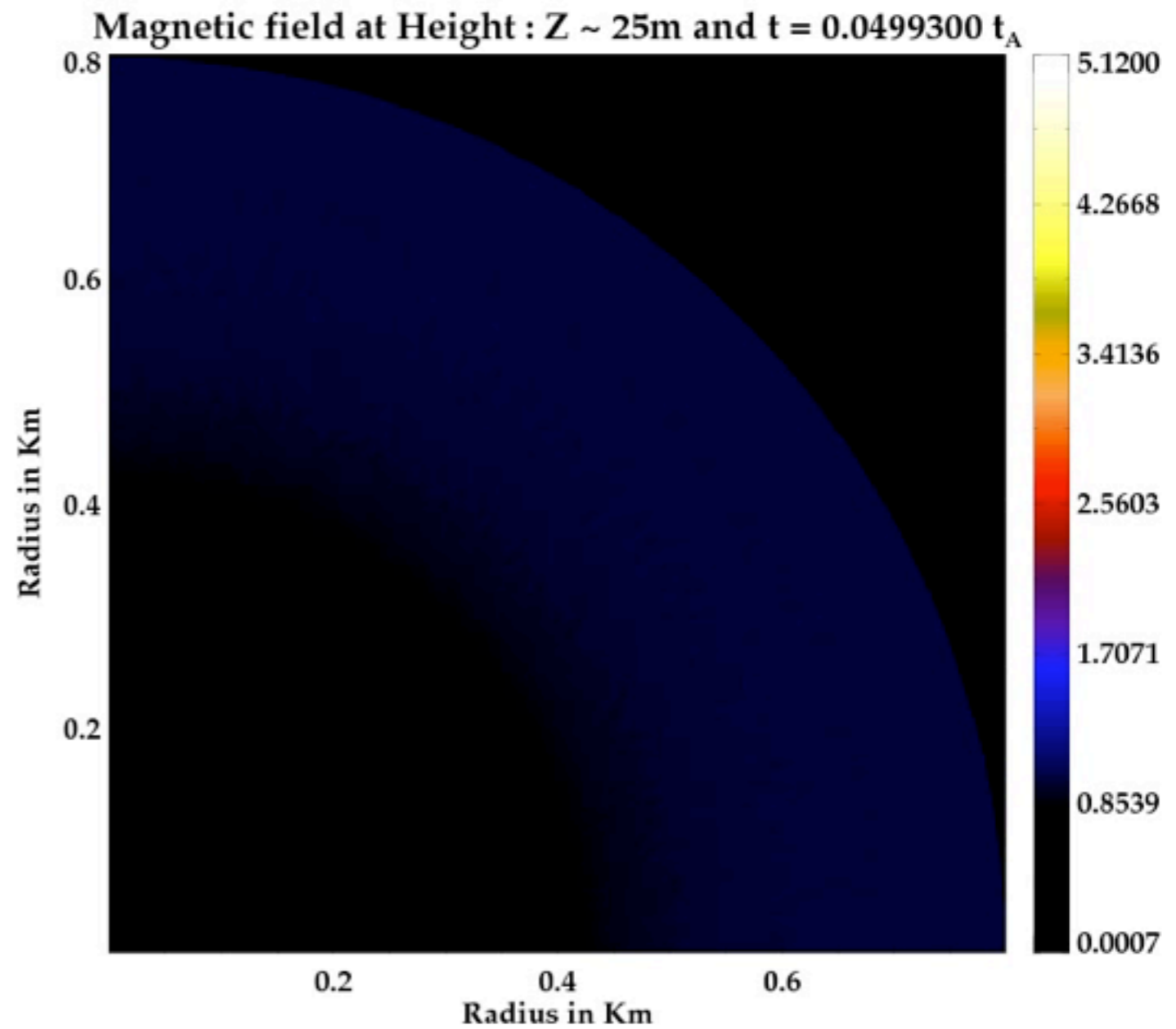
Mound Stability Analysis with PLUTO MHD code

Field lines and density contour



3-D simulations

- ▶ Filamentary structures develop due to interchange instabilities
- ▶ Matter leaks out at the sides through low-field regions
- ▶ Larger mounds go unstable quicker



Mound Height	Instability trigger time
70 m	$0.3 t_A$
50 m	$3.6 t_A$
45 m	stable till $10 t_A$

Summary

- * Neutron stars possess the strongest magnetic fields known, but their origin and evolution remain shrouded in mystery
- * A fascinating interplay of physical processes governs the behaviour of the magnetic field. Origin may be from pre-collapse dynamo, or post-formation crustal battery
- * Secular evolution of magnetar fields may involve hall-mediated ohmic decay, as well as reorganisation driven by Lorentz forces
- * Accretion appears to cause magnetic field decay. Several possible mechanisms may be at work. But which is the most important? Much work is still needed to answer this