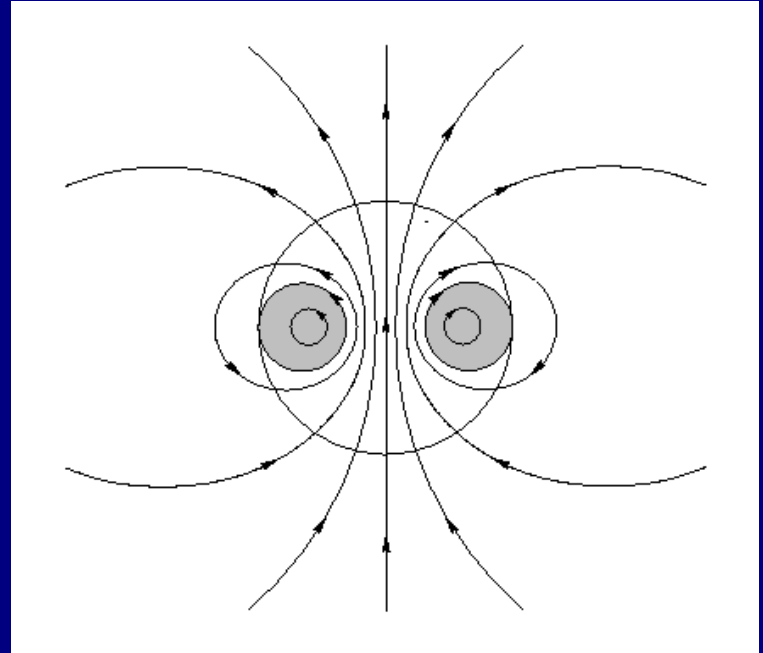


# What happens in a star when convection stops?

G2000

24<sup>th</sup> October 2007



*Jonathan Braithwaite  
CITA, Toronto*

# Which stars?

*Stars which went through a convective phase, but are now non-convective*

Main-sequence,  $> 1.5 M_{\text{sun}}$ : convection during protostellar phase. On MS, convection confined to core ( $\sim 1\%$  of volume)

Higher-mass white dwarfs: form out of convective core of MS star

Neutron stars: after formation, neutrino-driven convection lasting  $\sim 100\text{s}$

# What does the convection do?

- Drives differential rotation
- Convection and differential rotation are ingredients for a magnetic dynamo
- Dynamo will eventually saturate..

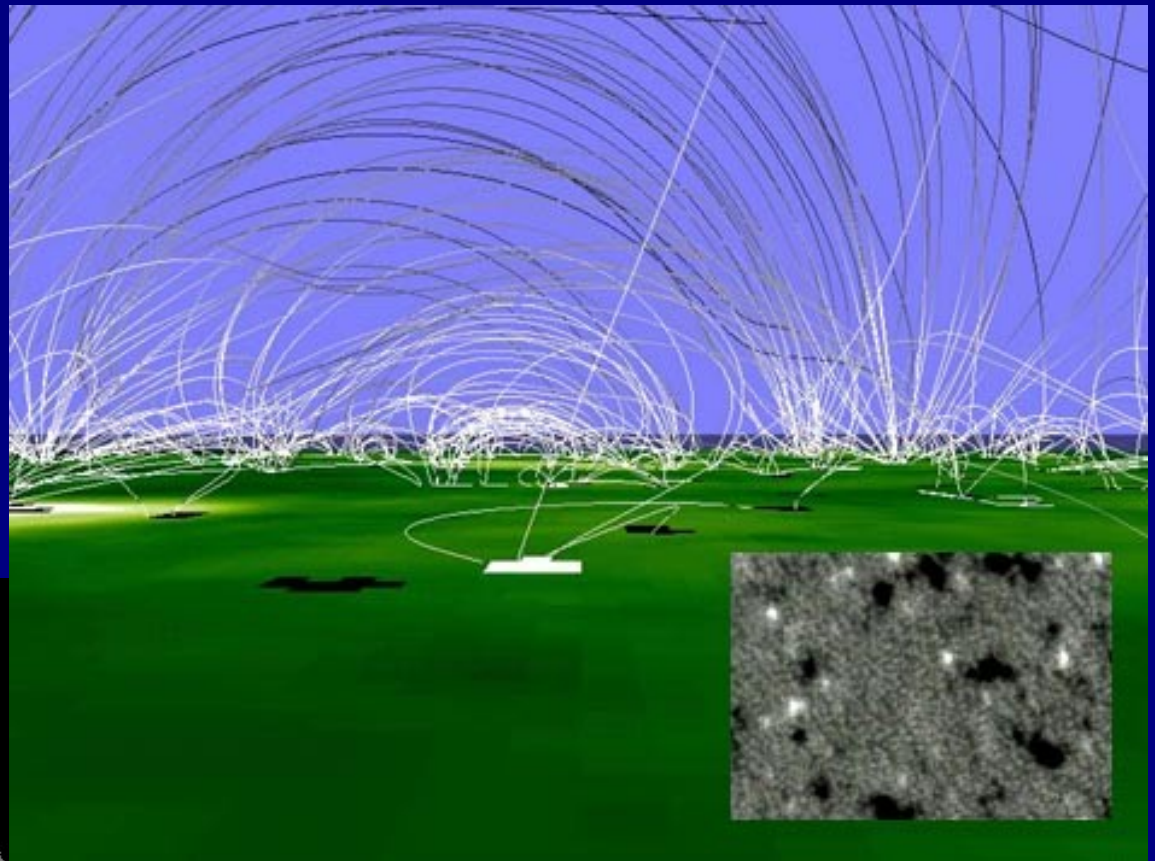
# Example of dynamo in stellar convective zone: the Sun

Small-scale turbulent velocity field

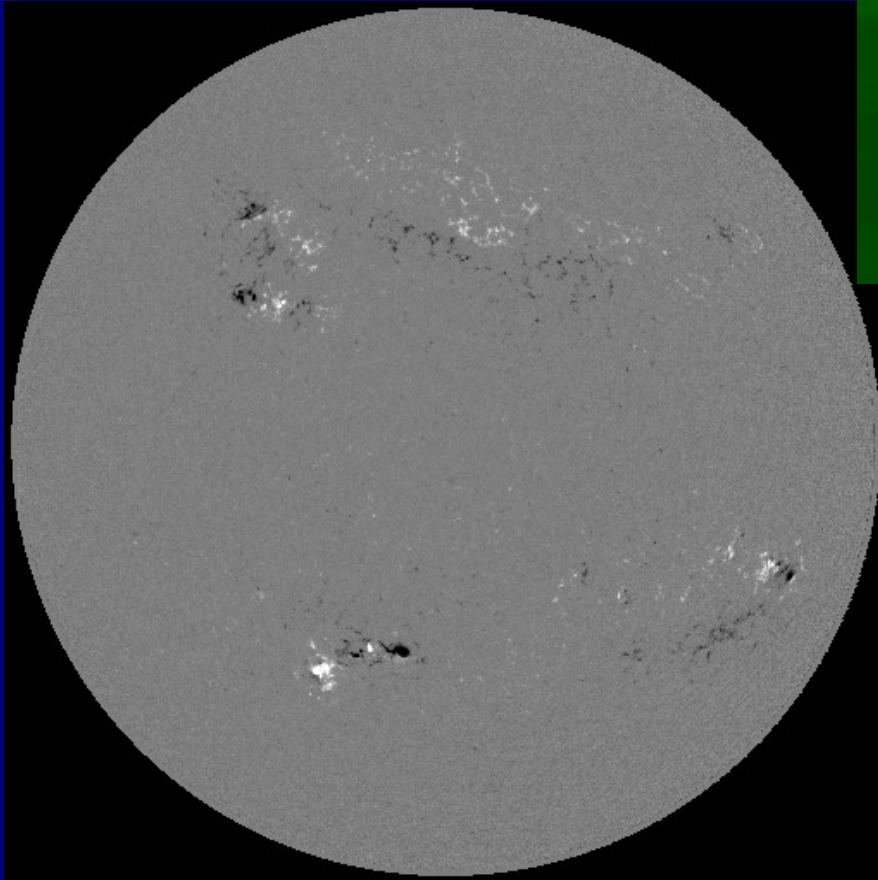


Small-scale, turbulent magnetic field

# Solar magnetic field



Small-scale field in non-active region



Distribution of magnetic field on solar surface (Michelson Doppler Imager experiment on SOHO).  
Black/white = field pointing into/out of Sun

# Modelling stellar magnetic field

- Model star as ball of gas, with entropy profile stable against convection
- At  $t=0$ , magnetic field is small-scale and turbulent
- Evolve magnetic field in time, using numerical magnetohydrodynamics
- Two possible outcomes:
  - field decays indefinitely on Alfvén timescale
  - field finds equilibrium configuration

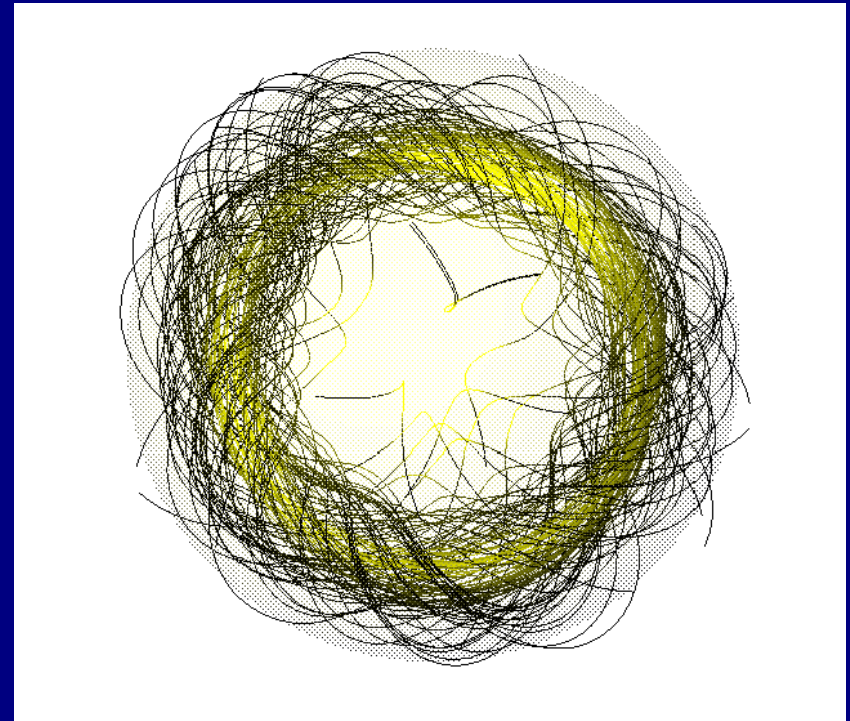
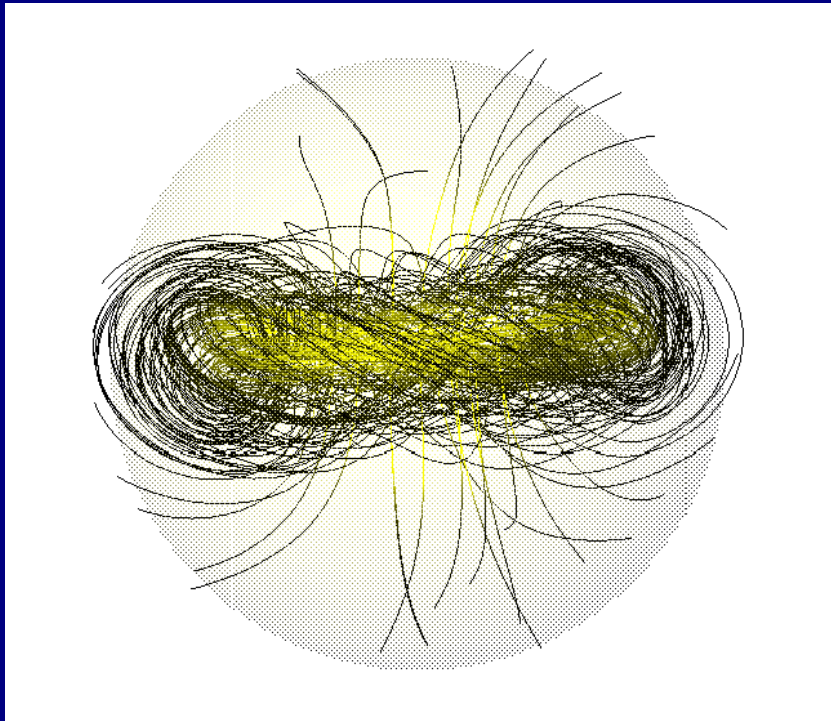
# Modelling stellar magnetic field

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# Equilibria

- Twisted flux-tube loop(s). Large length scales
- Two types of equilibrium
  - simple axisymmetric: flux tube is a circle around the equator
  - non-axisymmetric: flux tube has more complex shape
- Which type is produced depends on initial central concentration and magnetic helicity of field

# Shape of axisymmetric equilibrium



*Braithwaite & Nordlund 2006*

# Radial profile of initial field

- Run simulations where initial field is tapered as  $B \sim \rho^p$
- If star forms from a uniform magnetised cloud and flux loss fraction is independent of radius, we expect  $p=2/3$
- Threshold at  $p \sim 0.5$

# Properties of non-axisymmetric equilibria

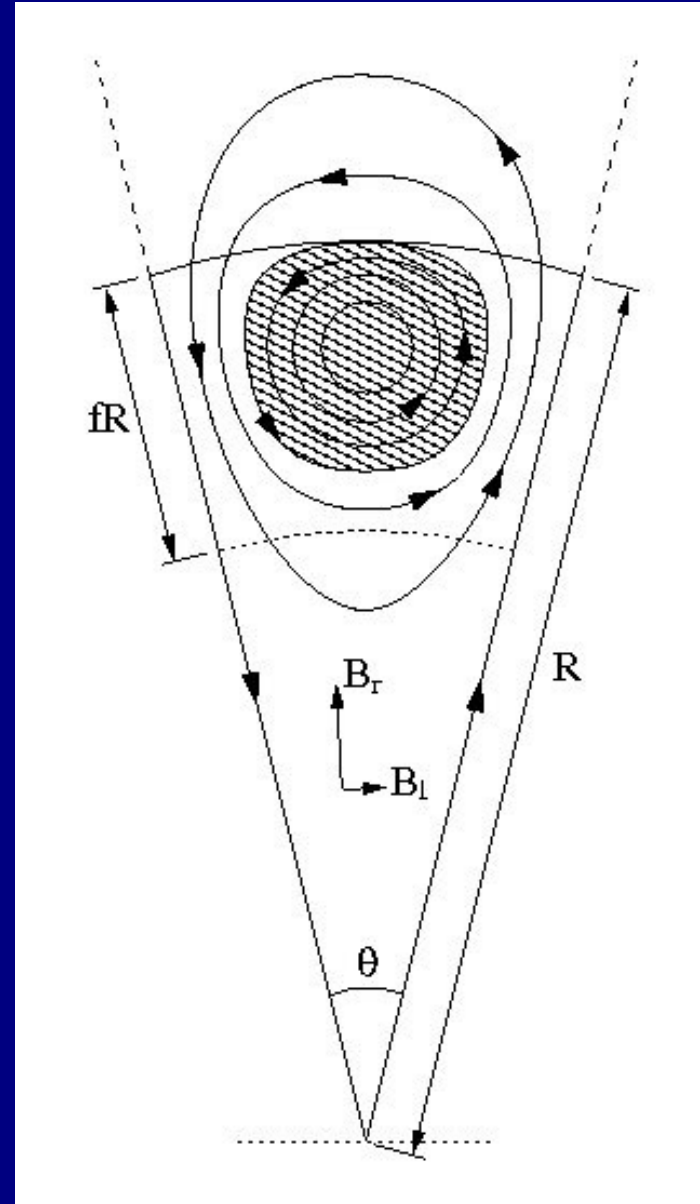
- Consist of twisted flux tube(s) below the stellar surface
- Toroidal flux confined to largest closed poloidal loop
- Energy of tube,  $E \approx \frac{ARf}{8\pi} (B_l^2 + B_r^2 + B_t^2)$
- If we allow length & width of tube to change adiabatically (with fixed length x width), we find that since

$$\frac{\partial \ln B_l}{\partial \ln \theta} = 1 \quad \frac{\partial \ln B_r}{\partial \ln \theta} = 0 \quad \frac{\partial \ln B_t}{\partial \ln \theta} = -1$$

we have

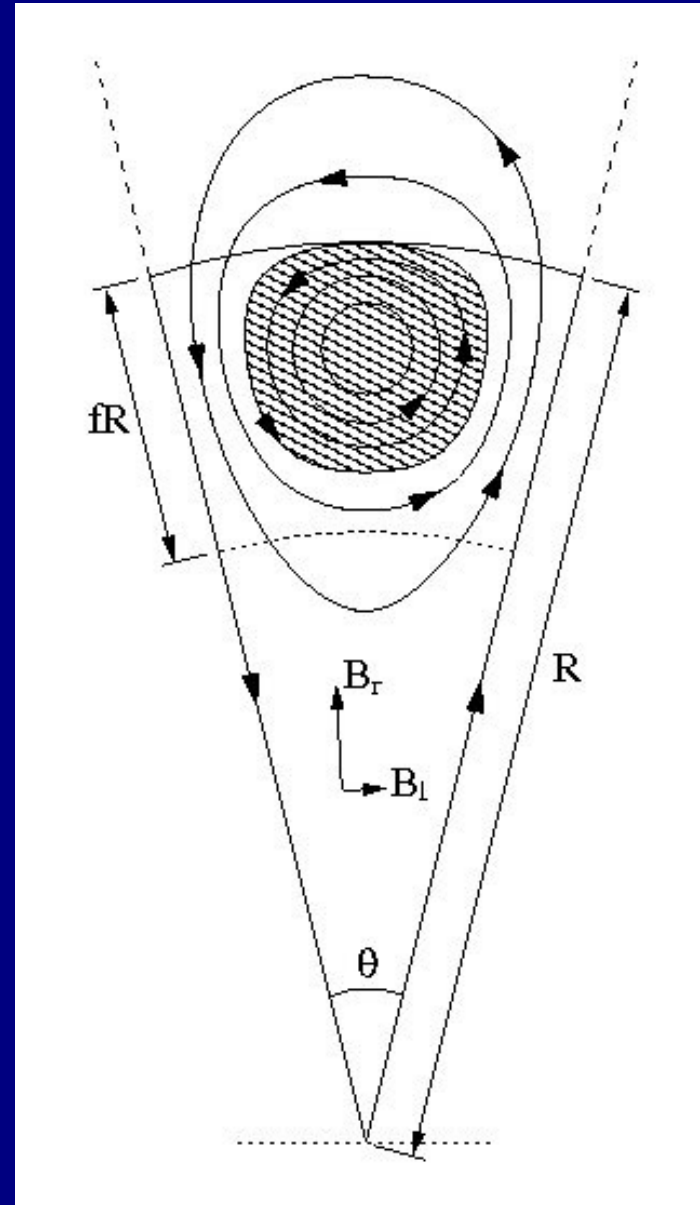
$$\frac{\partial E}{\partial \theta} \approx \frac{ARf}{4\pi} \left( \frac{B_l^2}{\theta} - \frac{B_t^2}{\theta} \right)$$

- Therefore:  $B_l \approx B_t$
- Energy lowest for circular tube, i.e.  $f=\theta$ , so  $B_r \approx B_l \approx B_t$



- Roughly equal toroidal & poloidal fluxes:
  - Too strong toroidal field  $\Rightarrow$  flux tube contracts and widens  $\Rightarrow$  toroidal field weakens
  - Too strong poloidal field  $\Rightarrow$  flux tube lengthens & becomes narrower  $\Rightarrow$  poloidal field becomes weaker
- At equilibrium:

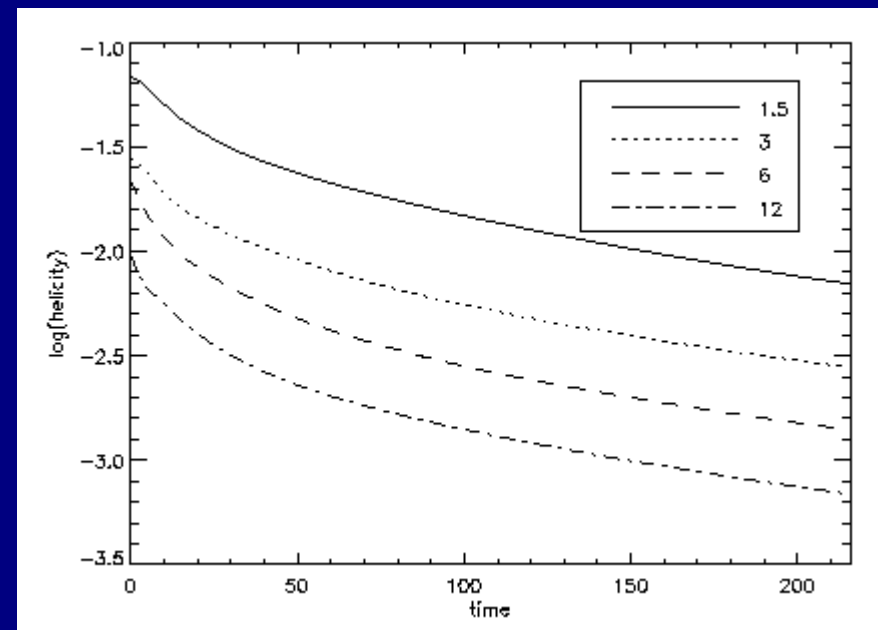
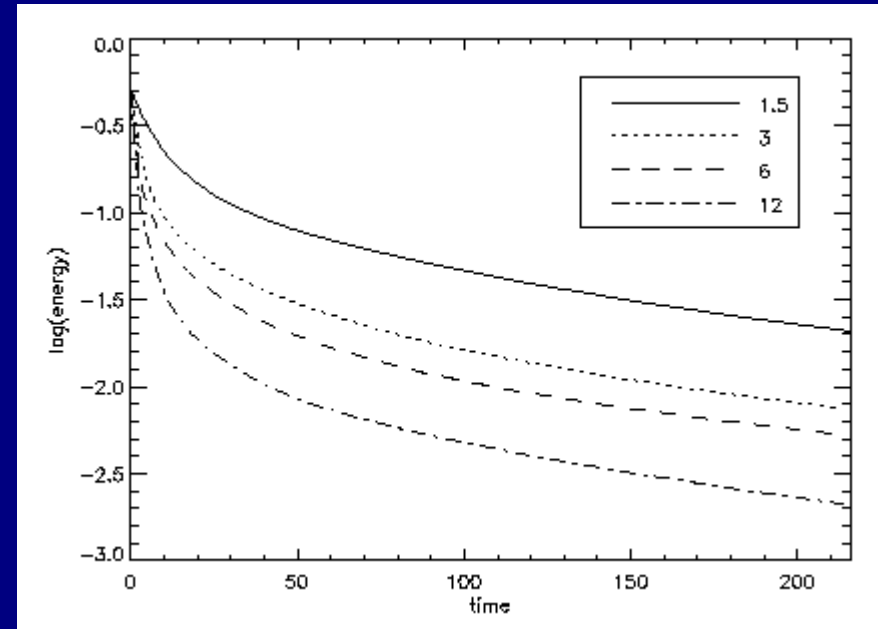
$$\theta^2 \approx \frac{A}{2R^2} \frac{\phi_t}{\phi_p}$$



# Magnetic helicity of initial field

- Initial random field contains wavenumbers up to  $k_{\max}$
- Simulations run with  $R_* k_{\max}/2\pi = 1.5, 3, 6$  and  $12$ .
- Helicity defined as  $H \equiv \int \mathbf{A} \cdot \mathbf{B} \, dV$ , where  $\mathbf{B} = \text{curl } \mathbf{A}$ . It is conserved in the limit of infinite conductivity
- Higher  $k_{\max}$  means lower helicity, because different regions cancel each other out
- Lower initial helicity results in a lower-energy field, since the equilibrium is the lowest energy state at that value of helicity

*Above right: magnetic energy against time  
Below right: magnetic helicity against time*



*Figures by Brandon Helfield*

# Comparison to observations

Upper-MS stars:

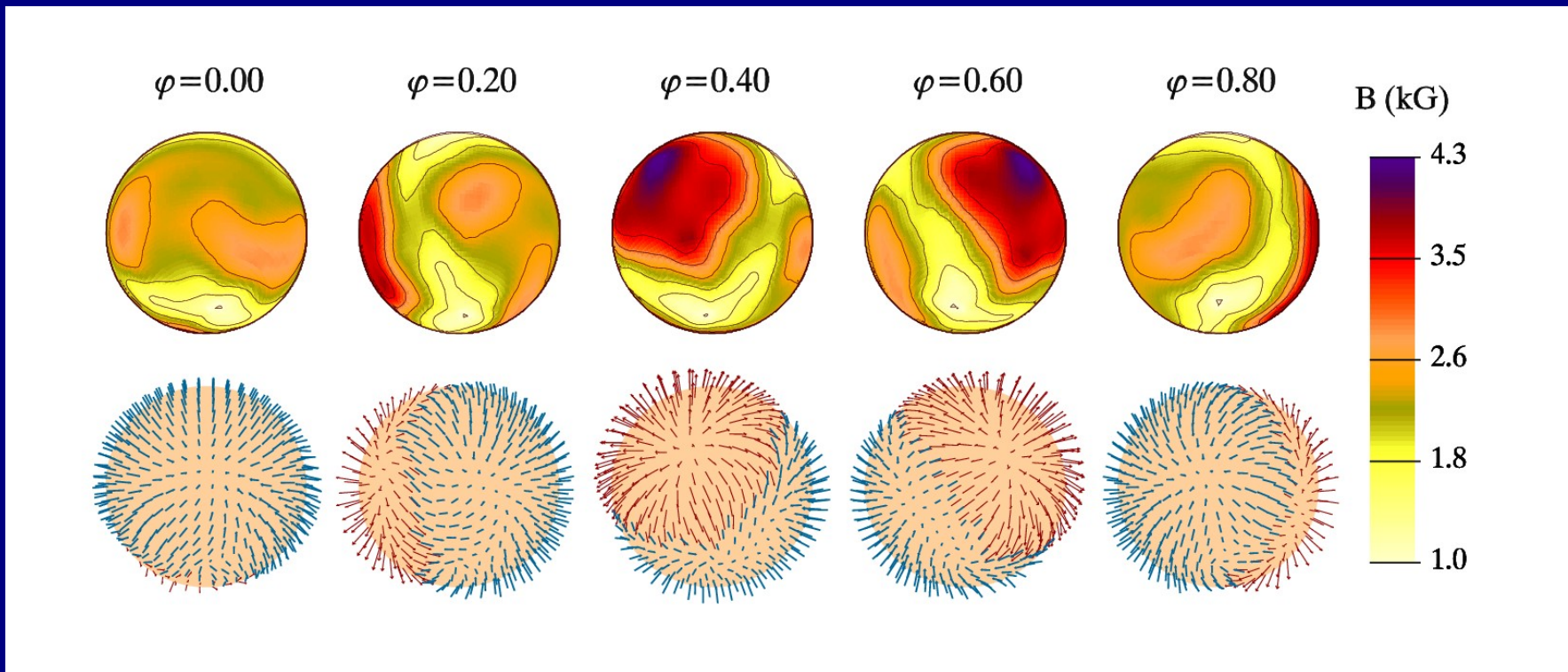
most stars have no field (upper limit  $\sim 3$  gauss)

most others have dipolar fields, some have more complex field

$10^2$ – $10^5$  gauss

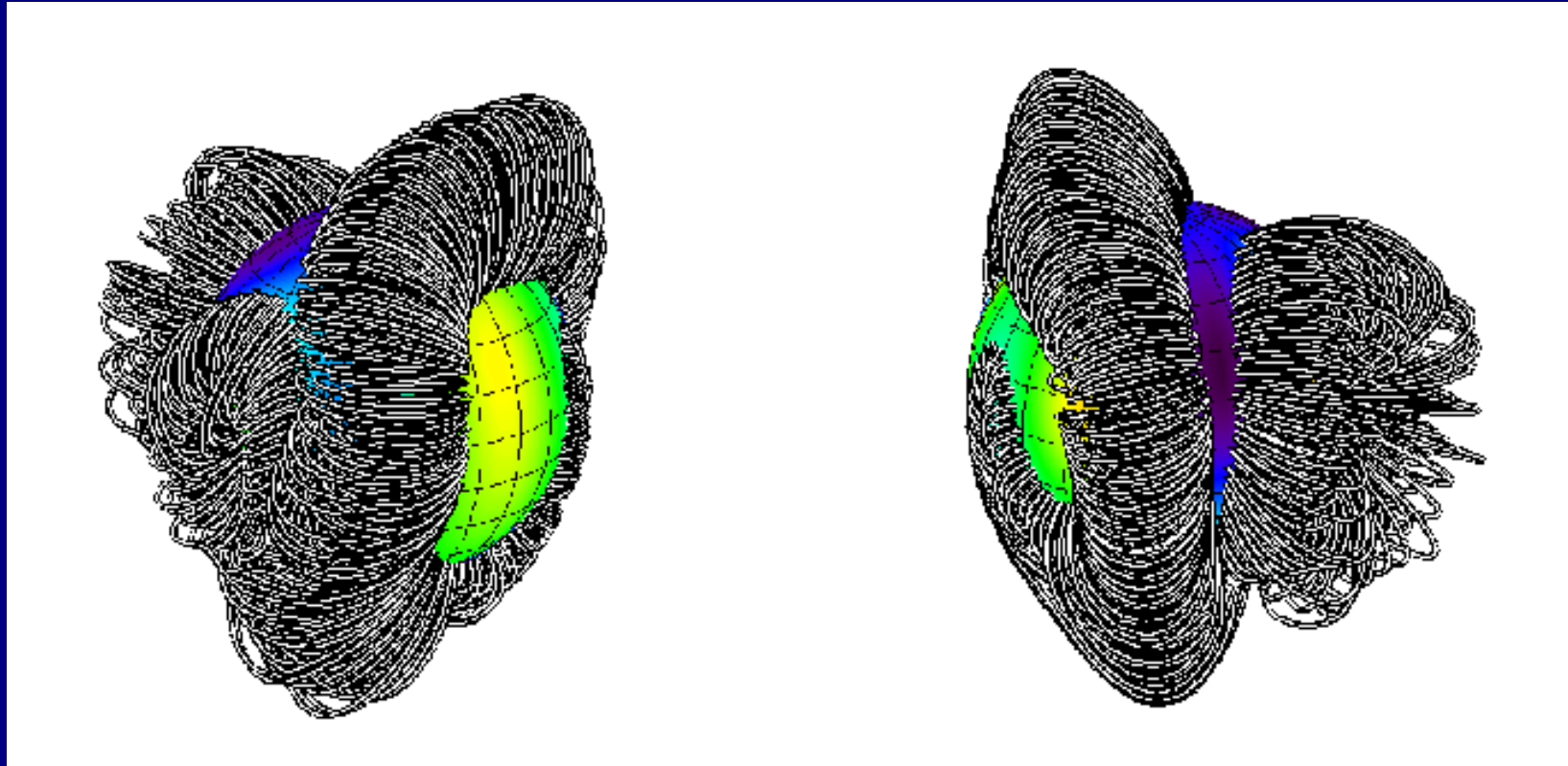
# Fields observed on intermediate-mass main-sequence stars (Ap stars)

Fields observed are steady,  
large scale. In most cases  
roughly dipolar



*Field on  $\alpha^2$  CVn. (Kochukhov et al., in prep.)*

# Non-dipolar field: example



Field topology on  $\tau$  Sco (*Donati et al. 2006*)

# Comparison to observations

## Upper-MS stars:

most stars have no field (upper limit  $\sim 3$  gauss)

most others have dipolar fields, some have more complex field

$10^2$ – $10^5$  gauss

## (Heavier) white dwarfs:

most are quadrupolar/octopolar (?)

$10^4$ – $10^9$  gauss

## Neutron stars:

large scale (but only dipole is measurable)

$10^{12}$ – $10^{15}$  gauss

## In general:

large-scale, either dipolar or other low-order multipoles

*makes sense*

wide range of field strengths, uncorrelated with rotation speed

*why? stars with active dynamos have  $B=B(\Omega)$*

*may have to do with helicity & central concentration of initial field*