Origin of B in magnetars

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when generated?
- fossil (inherited from MS)
- created during progenitor evolution
- created in core collapse

processes:
- ‘flux freezing’ during * evolution
- ‘winding-up’
- convection (dynamo)
- MRI (dynamo)

evolution to a stable ‘endproduct’

What field strength to explain?

pulsar fields .... magnetar fields: same process?

If continuous, need a mechanism that
explains a range of 5 decades in B
(e.g. equal numbers per decade, or lognormal)

- suggests mechanism includes exponential sensitivity
  of outcome on the controlling parameter

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- convection (dynamo)
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flux freezing:
magnetic flux inherited from MS progenitor

Magnetic flux in a magnetar:

$$B_{\rm m} = 10^{15},\ \ R = 10^{6}\ \ \rightarrow \Phi = 3\,10^{27}\,{\rm Mx}$$

$1.4 M_\odot$ core of O star:

$$R = 10^{11}\,{\rm cm} \rightarrow B_O = \Phi/\pi R^2 = 10^5\,{\rm G}$$

Statistics: 10% of N* forming O** must have such field

Requires that field remains frozen during entire pre-SN evolution. Problem: convective phases causing effective diffusion of the field.

field inherited from pre-collapse core, + flux freezing

collapse from 3000 km to 15 km:
final field of $10^{15}\,\mathrm{G}$ requires
(dipole component of) initial field $10^{10} - 10^{11}\,\mathrm{G}$

no plausible process known ....

processes during core collapse

- neutrino-driven convection

- magnetorotational dynamo from differential rotation

Field produced by convective dynamo in proto-NS

- Equipartition of energies → intrinsic field strength
- Rossby number → filling factor

$$B_{\rm eq} = (4\pi\rho)^{1/2} v_{\rm conv}$$

$$\mathrm{Ro} = 1/\Omega\tau_{\rm conv}$$ *(small for fast rotation)*

Sun: $B_{\rm e\odot} \approx 3\,10^3$ G $\quad v_{\rm c} \approx 4\,10^3$ cm/s, $\tau_{\rm conv} \approx 10^6$ s

$\mathrm{Ro}_\odot \approx 3$

SN: $B_{\rm e} \approx 1.5\,10^{15}$ $\quad v_{\rm c} \approx 4\,10^8$ Duncan & Thompson

$\mathrm{Ro} \approx 1.5 P_{-3}$

observed dipole field Sun: $B_{\rm dip} \approx 20\,\mathrm{G} = 10^{-2} B_{\rm e\odot}$

scaled to core collapse: $\approx 10^{13}\mathrm{G}$

Dynamo by differential rotation

1. exponential growth (faster than winding up)
2. does not need convection, but needs a magnetic instability:
   - magneto-rotational instability (MRI)
   - magnetic buoyancy ('Parker instability)
   - Tayler instability

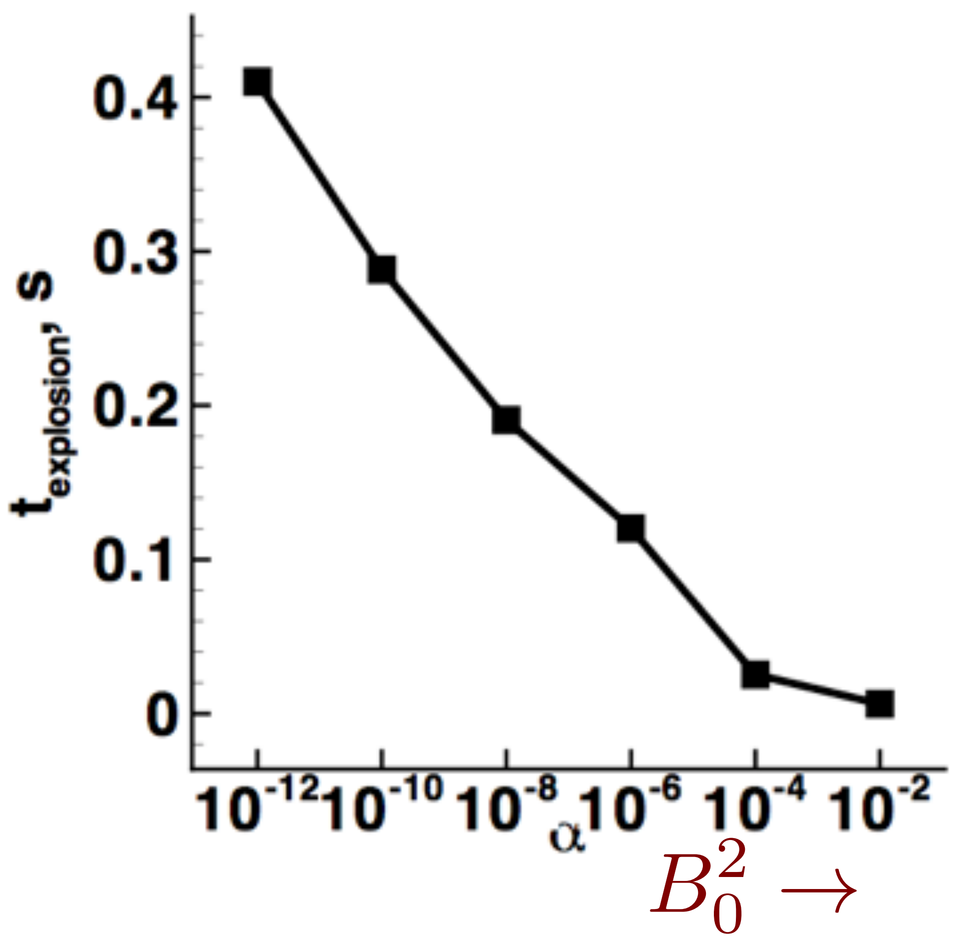
MRI: Akiyama+ 2003

MRI operating on $\partial\Omega/\partial\theta$:
Ardelyan, Moiseenko & Bisnovatyi-Kogan 05, 06

ν-cooling ➔ convection disappears, increasingly stable stratification, ➔ strength required for the field to appear at the surface increases (magnetic buoyancy).

(numerical) evidence for MRI dynamo action in core collapse

Akiyama et al. 2003



MRI simulation finds

$$B = B_0 \exp(t/t_0),$$
$$t_0 \approx 0.05$$

Ardelyan, Moiseenko & Bisnovatyi-Kogan MNRAS 2006

exponential sensitivity to *rotation rate*

MRI: $B \sim \exp(\Delta\Omega t)$

numbers that work,
assuming : $\Delta\Omega/\Omega \sim 0.3$,
initial field $B_0 = 10^5\,\mathrm{G}$,
duration $t = 1\,\mathrm{s}$:

$10^{16}\,\mathrm{G}$ $P = 10\,\mathrm{ms}$

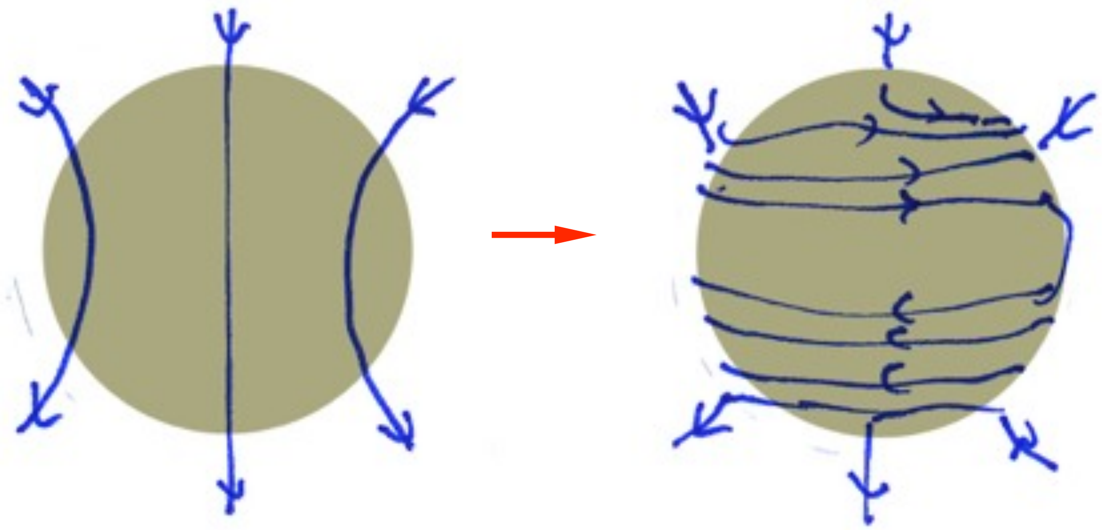
$10^{10}\,\mathrm{G}$ $P = 20\,\mathrm{ms}$

- field-amplification processes don't produce dipole fields
- fields produced evolve on Alfvén time scale

→ stable dipole involves more than an amplification process

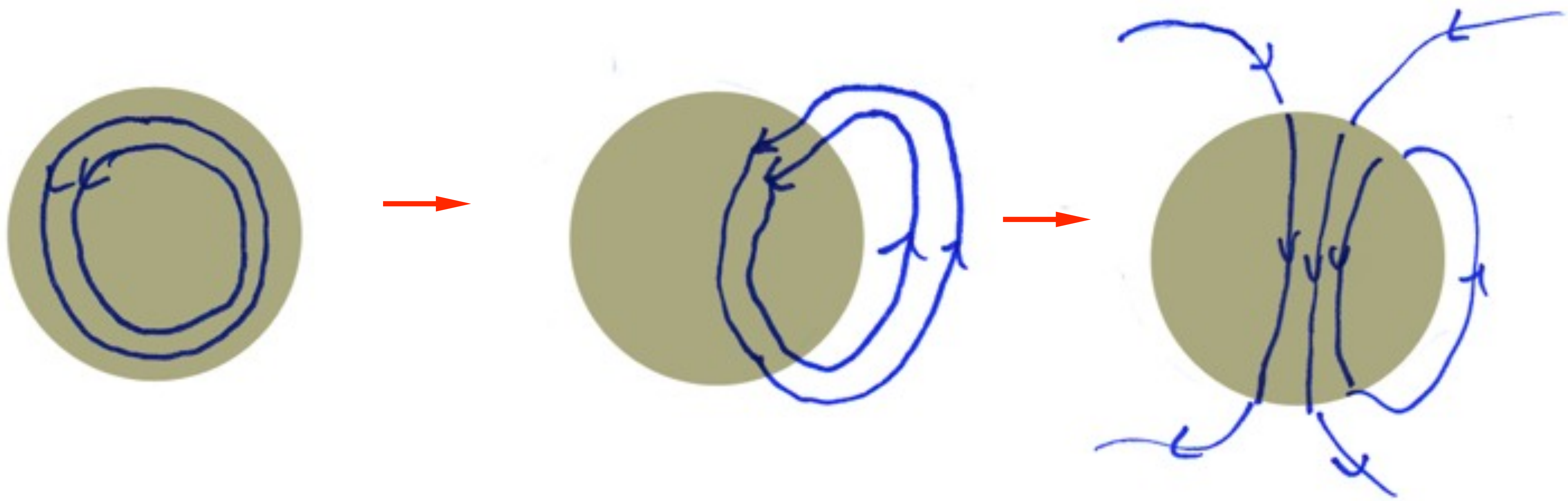
- relaxation to a magnetic equilibrium
- magnetar: $10^{15}\,\mathrm{G}$ → Alfvén crossing time $\tau_\mathrm{A} = 0.1\,\mathrm{s}$
- pulsar $10^{12}\,\mathrm{G}$ → $\tau_\mathrm{A} = 100\,\mathrm{s}$
- compare: crust formed @ $\approx 100\,\mathrm{s}$
  field freezes into crust

Field amplification: *how to make a strong, stable dipole moment*



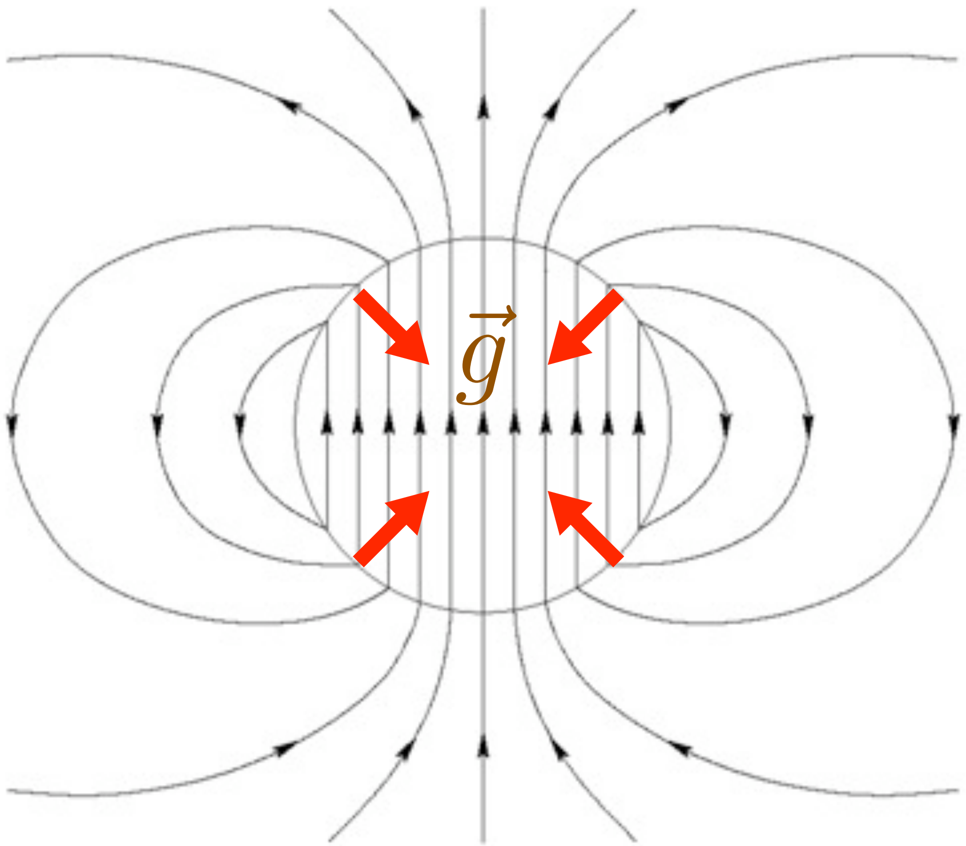
Winding-up:
1. does not change dipole moment
2. takes time ...

Dipole produced by (off-centered) rise of toroidal loop

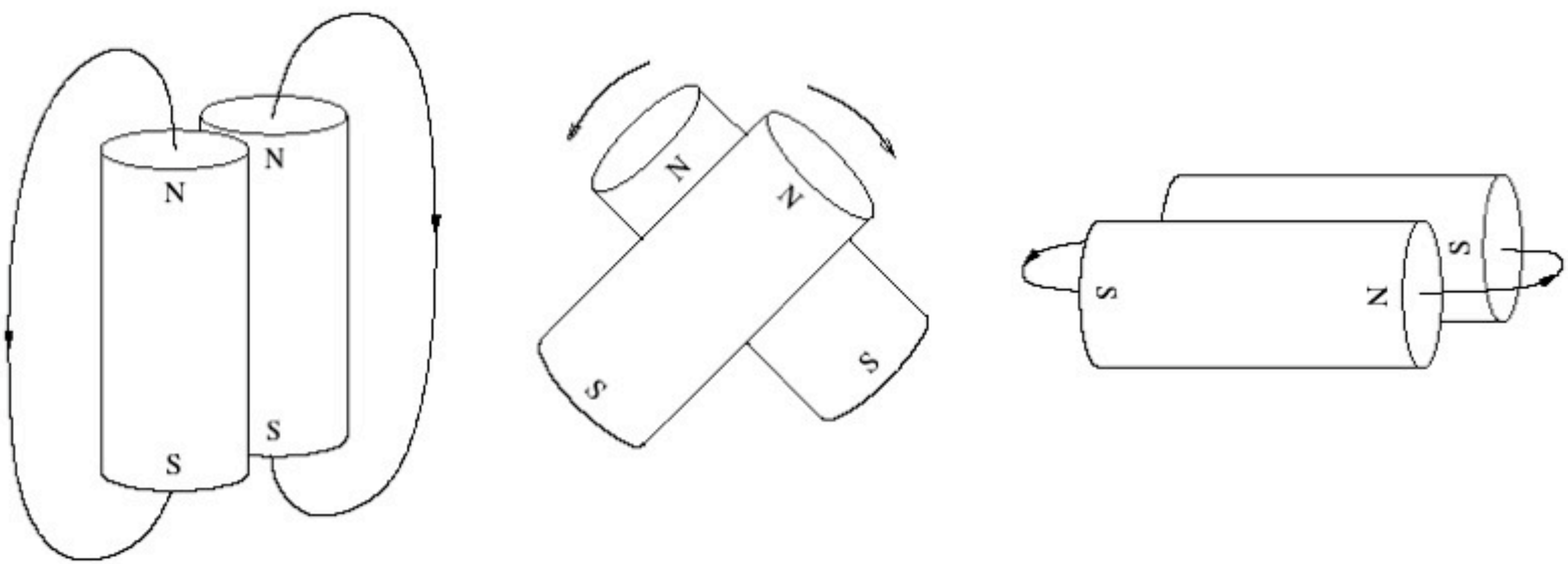


- Limited by ***stable stratification***, once neutrinos escaped
- dipole produced is unstable (Flowers-Ruderman)

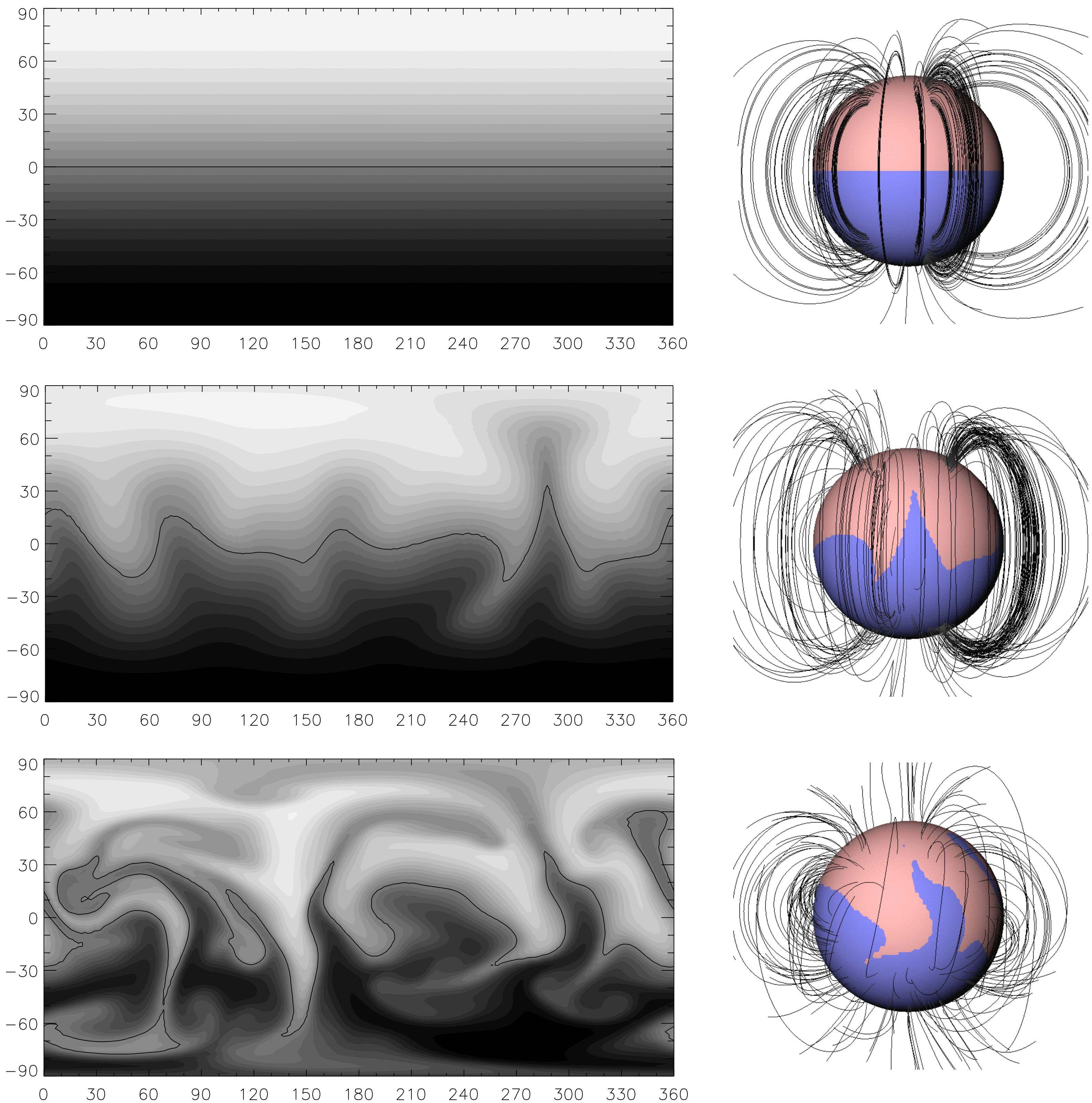
Magnetic stars: instability of a poloidal field



Flowers and Ruderman 1977



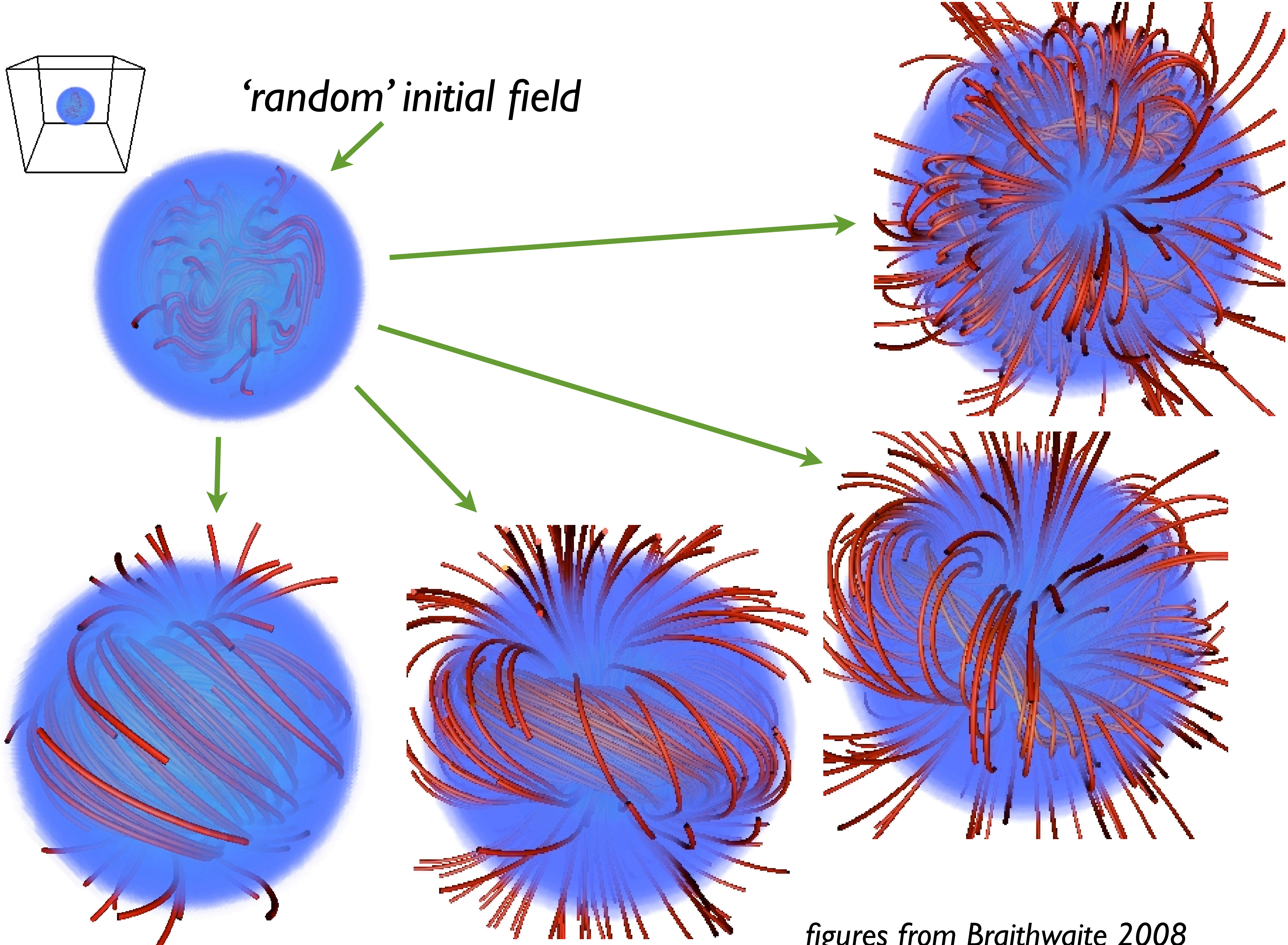
Numerical simulation of Flowers-Ruderman instability of a dipole field



End result:

$$B \downarrow 0$$

(Braithwaite and HS A&A 2005)

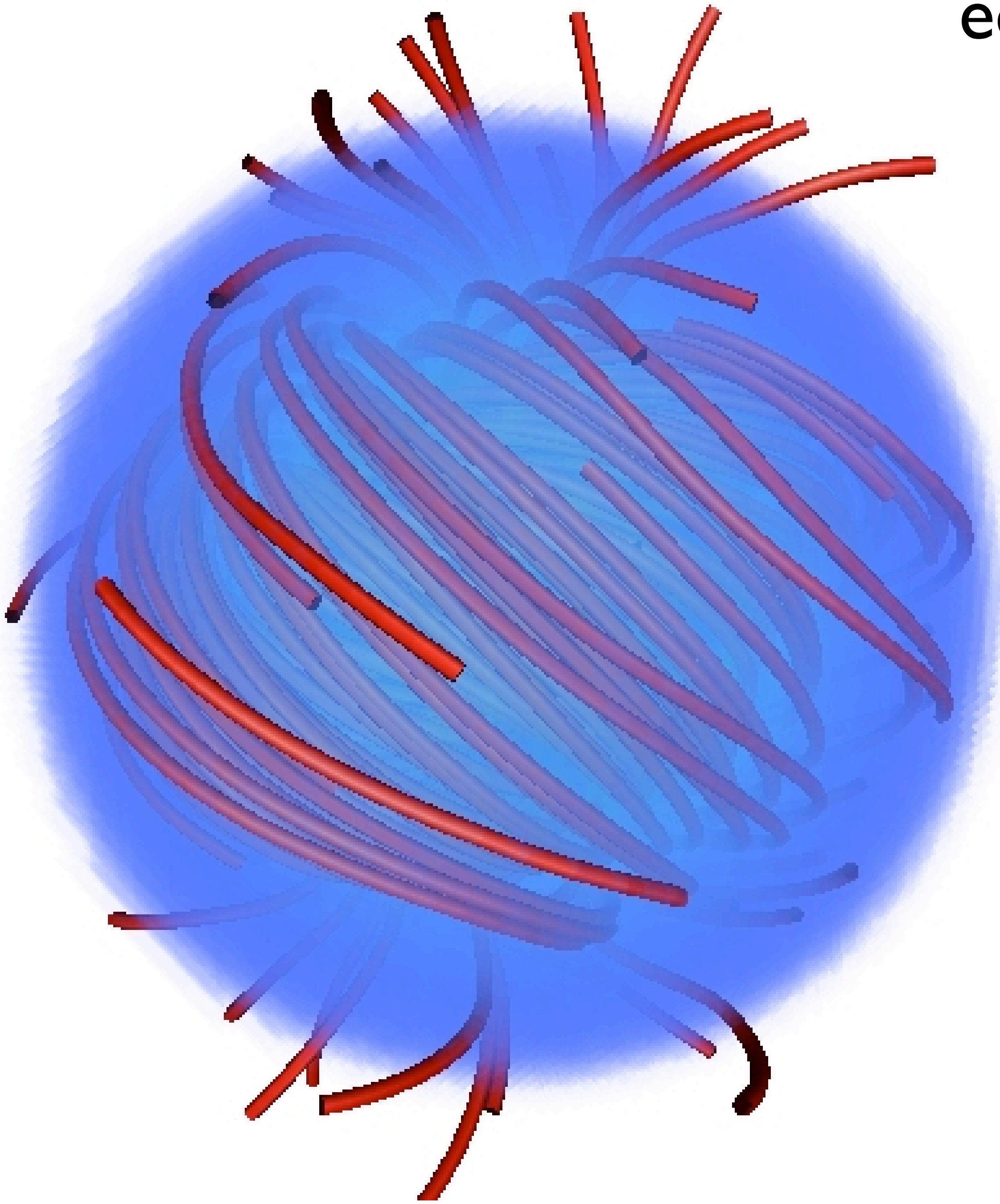


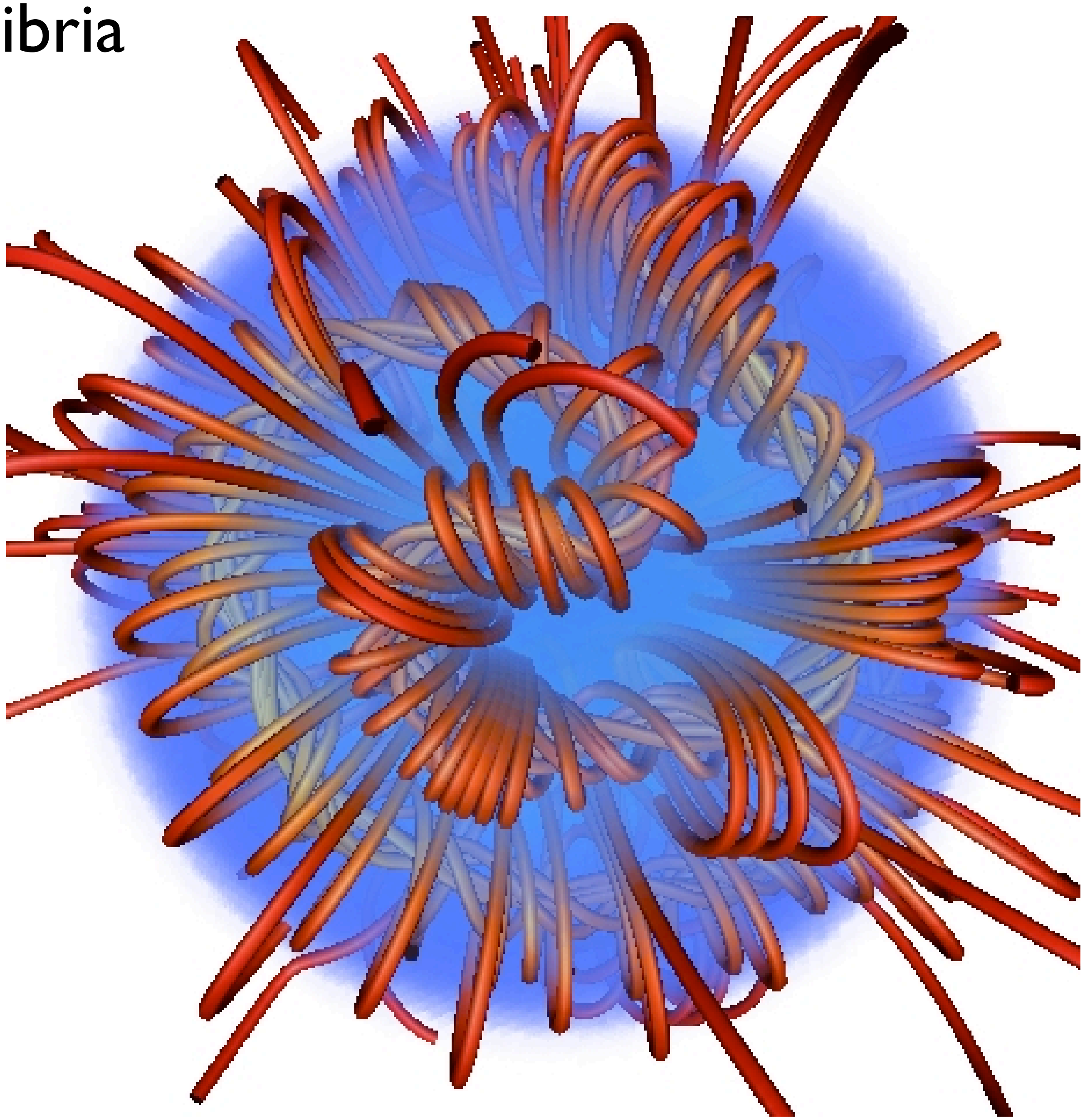
figures from Braithwaite 2008

Simulations of magnetic relaxation to equilibrium

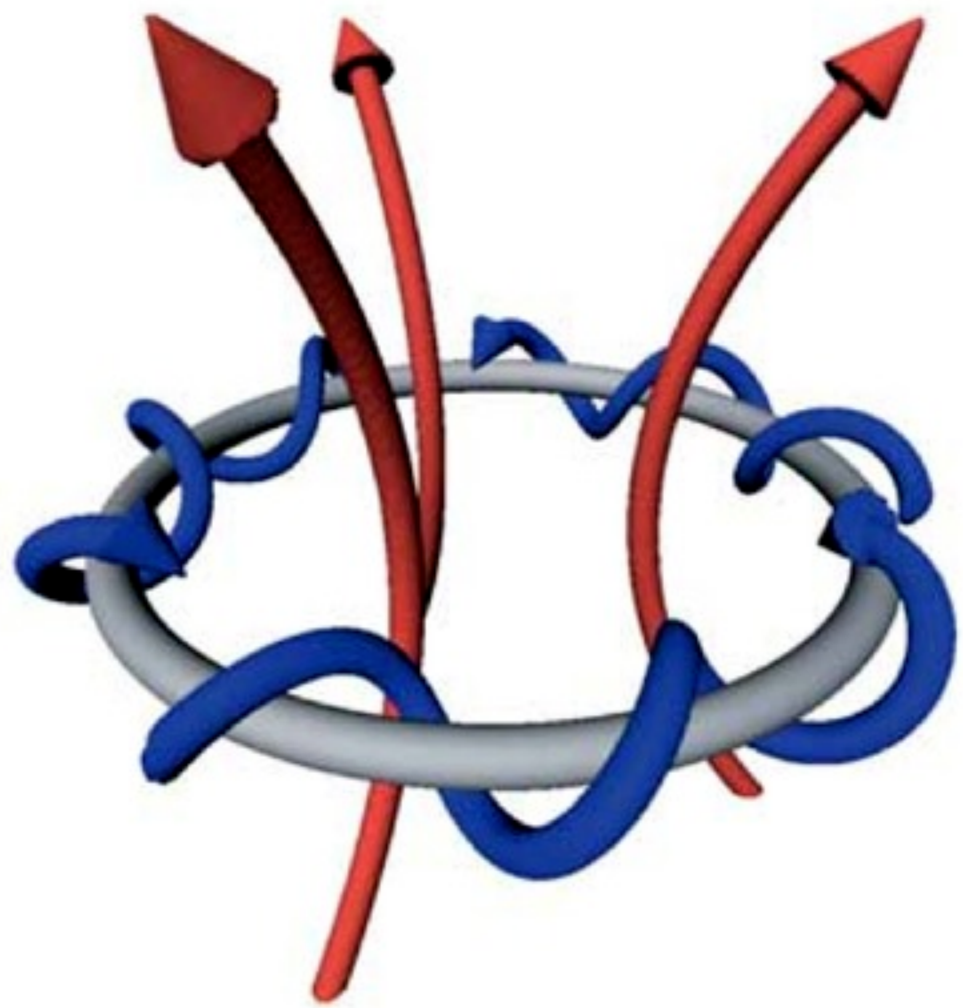
Braithwaite 2008

Axisymmetric and
non-axisymmetric
equilibria





poloidal field bundle stabilized by twisted torus



configuration has nonzero *magnetic helicity*

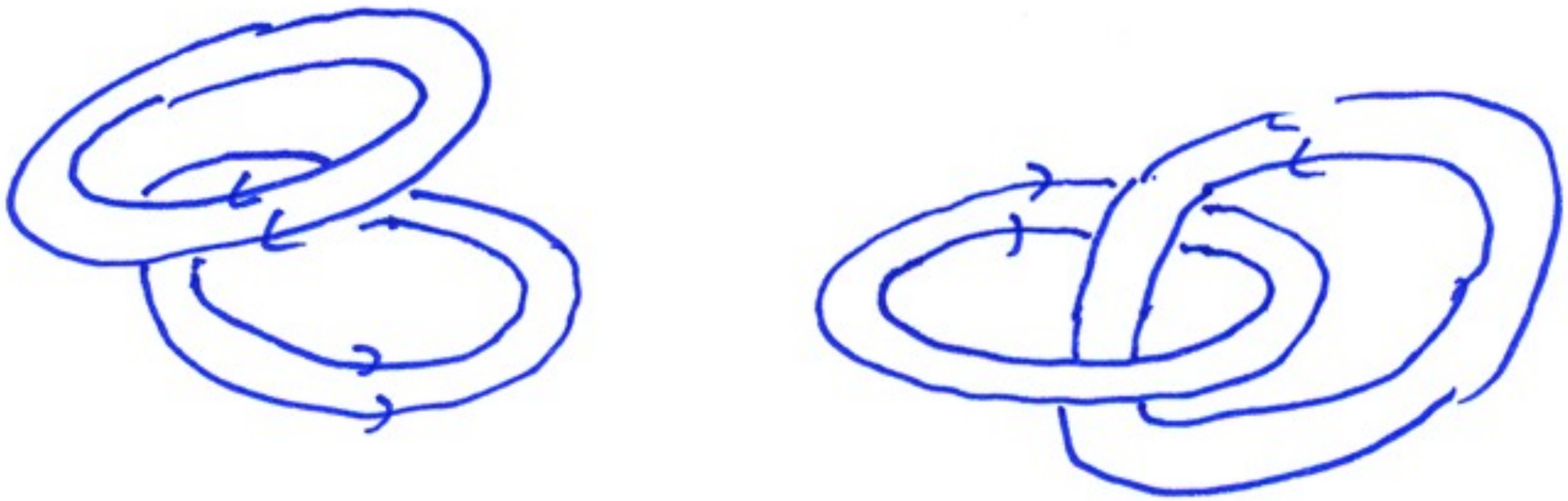
Helicity:
- global, topological quantity
- twist + ‘knottedness’
- no local ‘helicity density’
- conserved in perfect conductivity
  (reconnection changes H)

‘somewhat conserved’ at finite conductivity
(‘Taylor relaxation’)

- (to the extent that) H conserved: final state
  is a stable field configuration

Stability ($t > t_A$) requires:

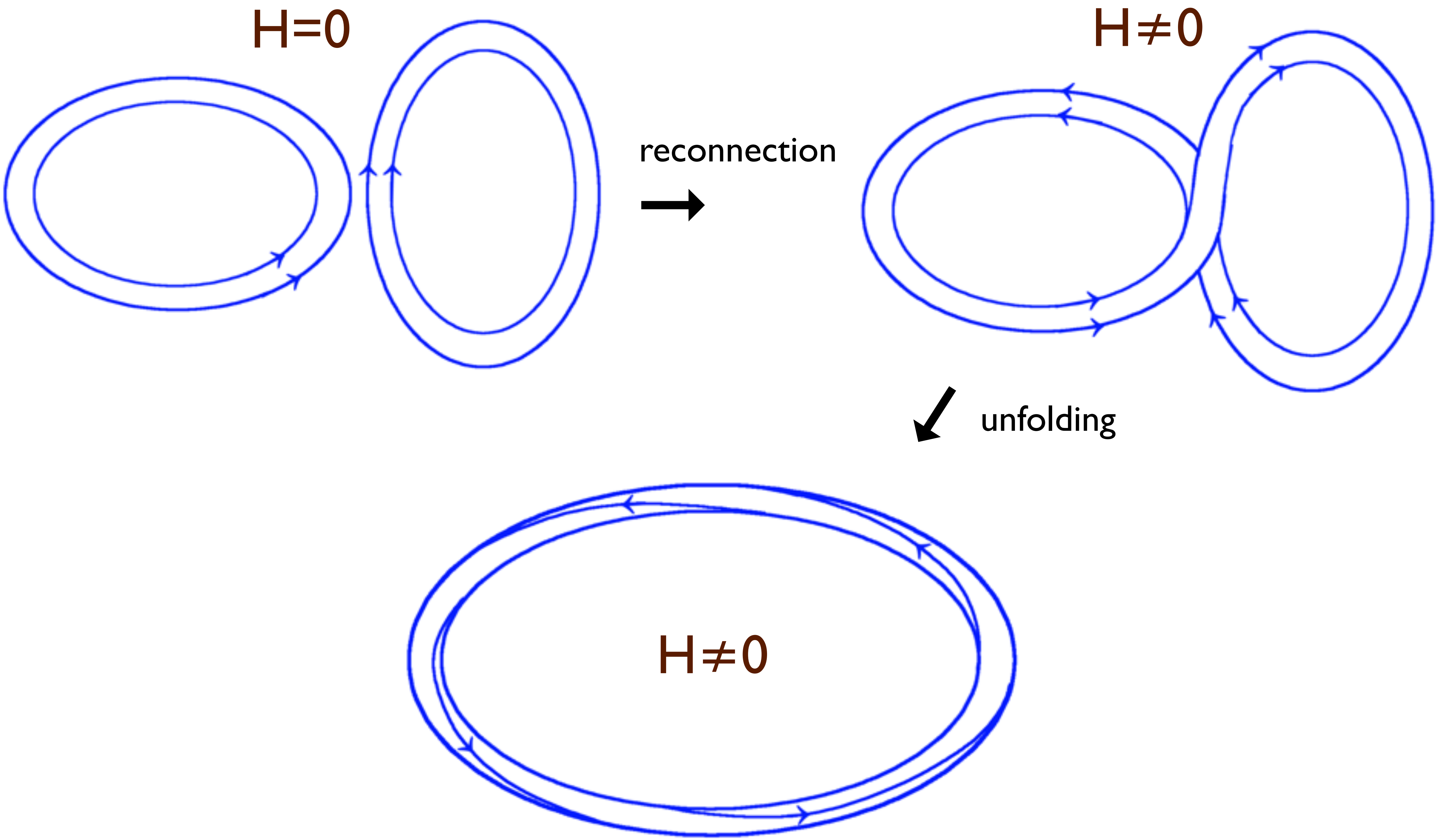
- 1. Stable stratification
- 2. Helicity $H = \int_V \mathbf{B} \cdot \mathbf{A}\, \mathrm{d}V \qquad (\mathbf{B} = \nabla \times \mathbf{A})$



H=0 H≠0

Helical field configurations are not stable in themselves.
They don’t even exist in the absence of constraining forces.

Helicity can decrease , but also *created* by reconnection

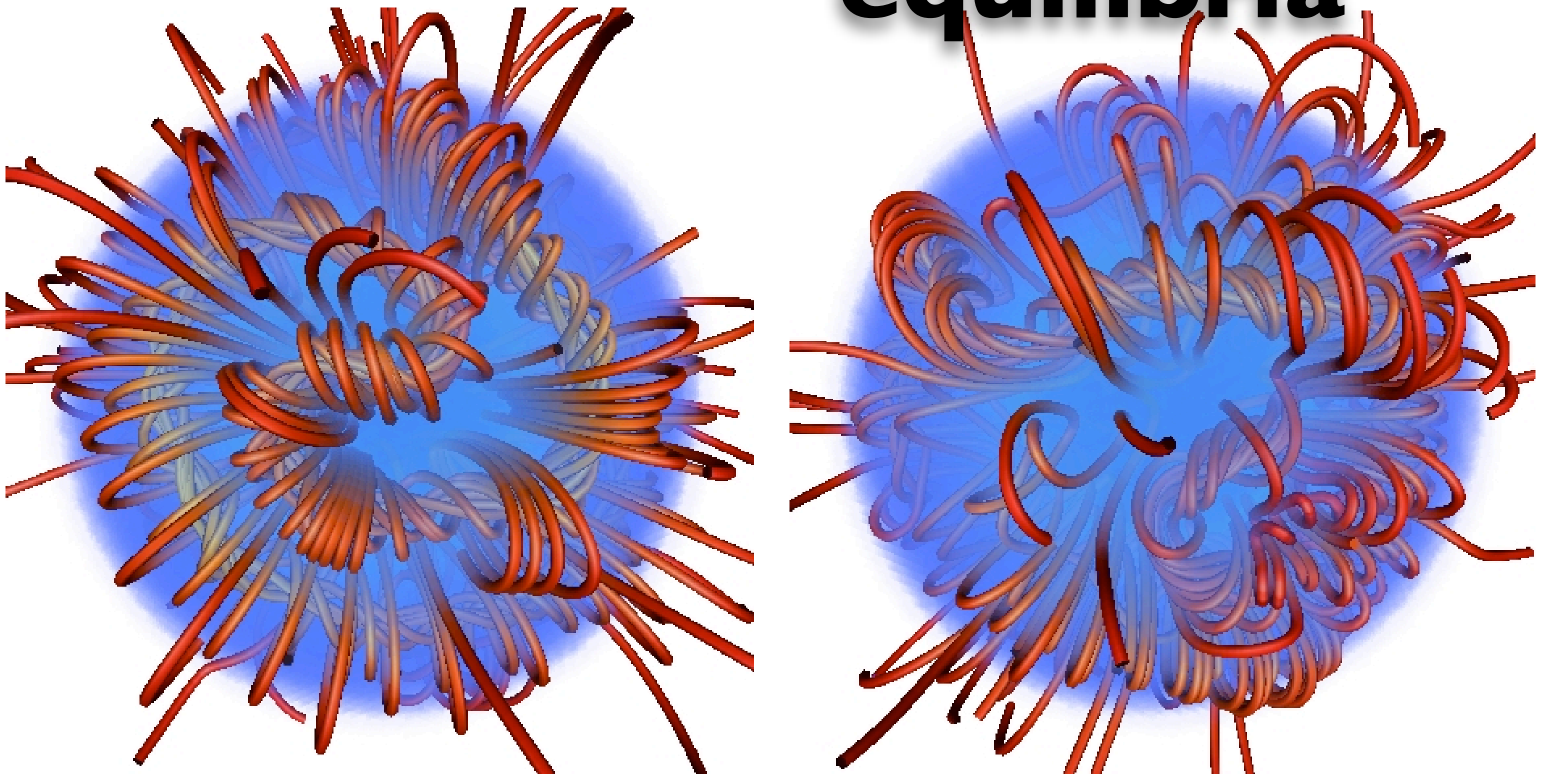


Summary

- fossil fields?
- convective dynamos: not likely
- exponential amplification during core collapse
- range of field strength:
  exponential sensitivity to a control parameter
- decay of amplified field by Alfvenic relaxation

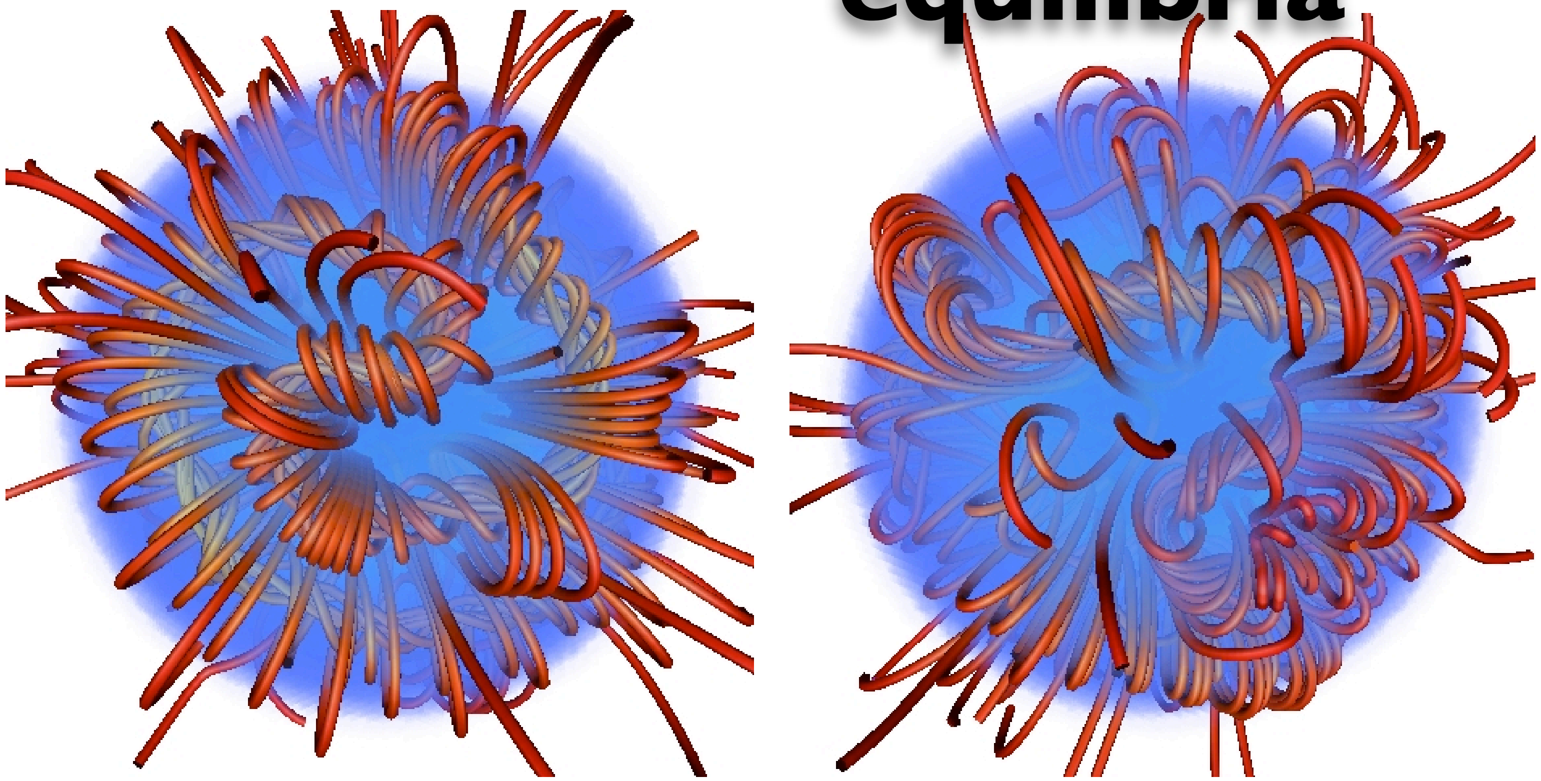
- importance of magnetic helicity

Non-axisymmetric equilibria



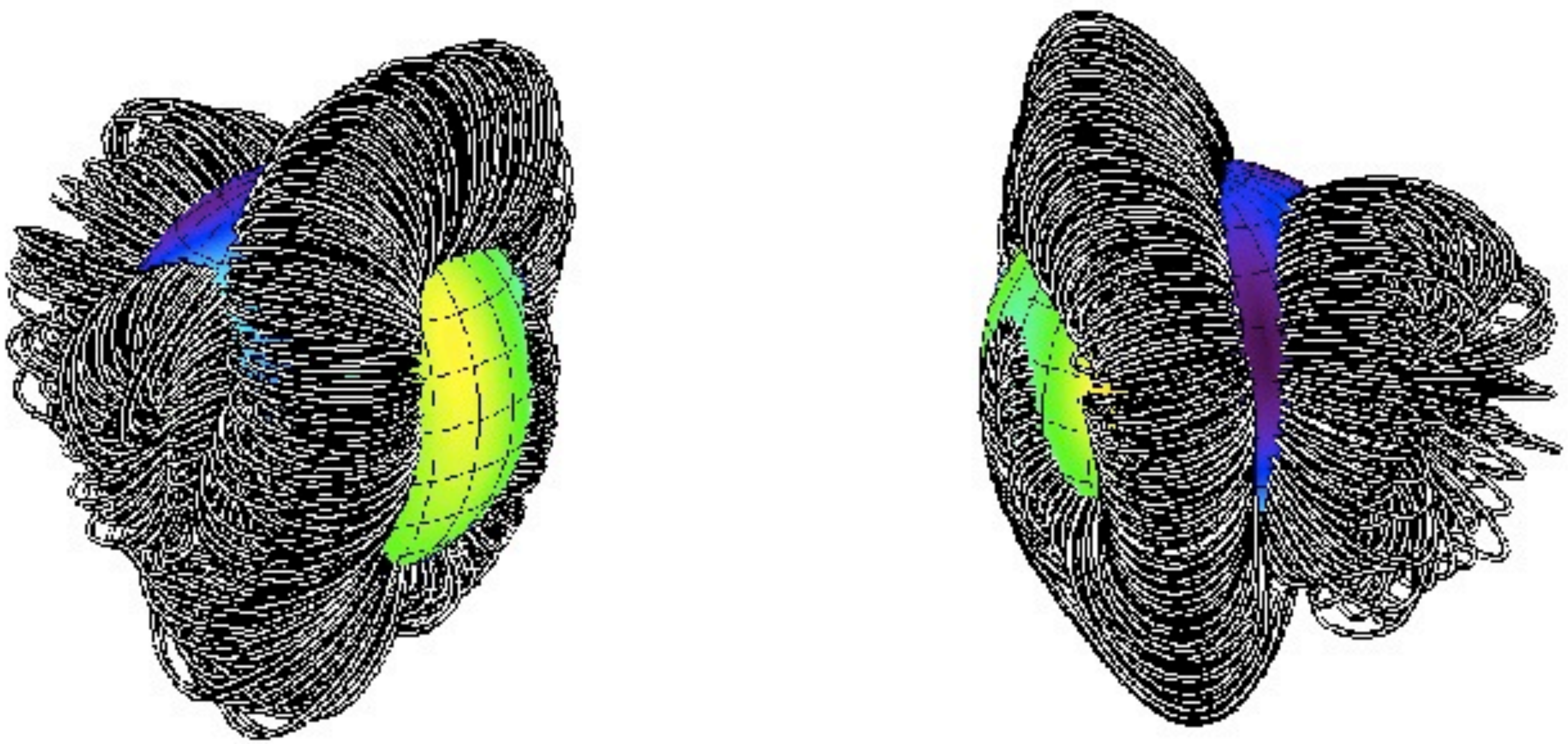
Simulations
(Braithwaite 2008)

Non-axisymmetric equilibria



Simulations

(Braithwaite 2008)



τ Sco

(Donati et al. 2006)