Magnetic Field in Galaxies and clusters

Kandaswamy Subramanian

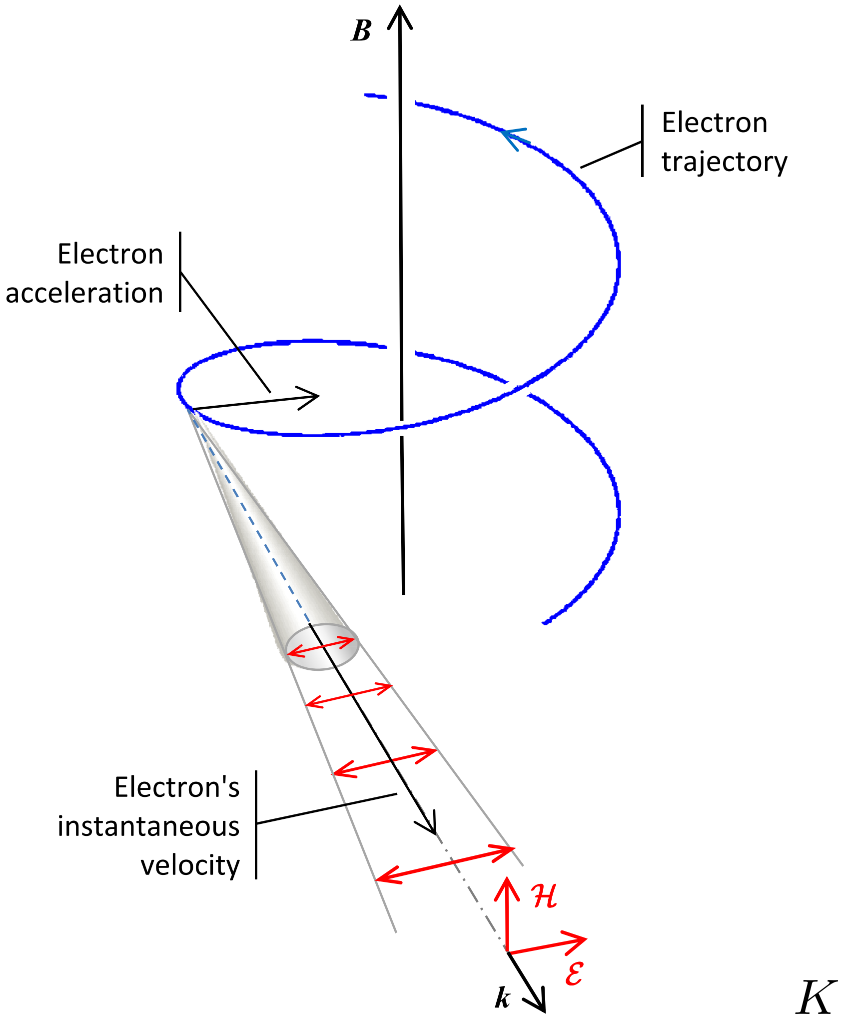
Inter-University Centre for Astronomy and Astrophysics,
Pune 411 007, India.

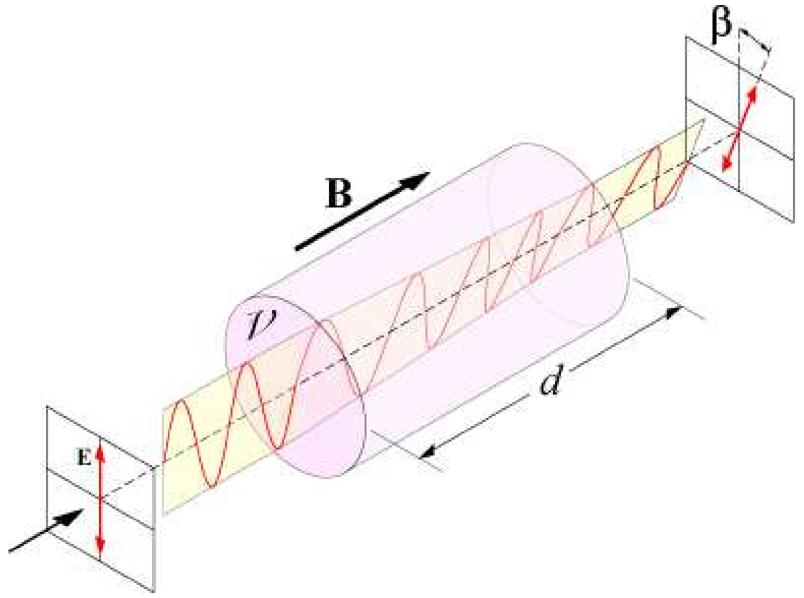
Plan

- Observing galactic and cluster B: **Radio crucial**
- The fluctuation dynamo, Young galaxies/Old clusters
- The large scale galactic dynamo

K. Subramanian, "Magnetizing the Universe", PoS proceedings, arXiv:0802.2804
http://ned.ipac.caltech.edu/level5/March08/Subramanian/frames.html

Measuring B fields:Synchrotorn Radiation





Faraday Rotation gives $B_{\|}$

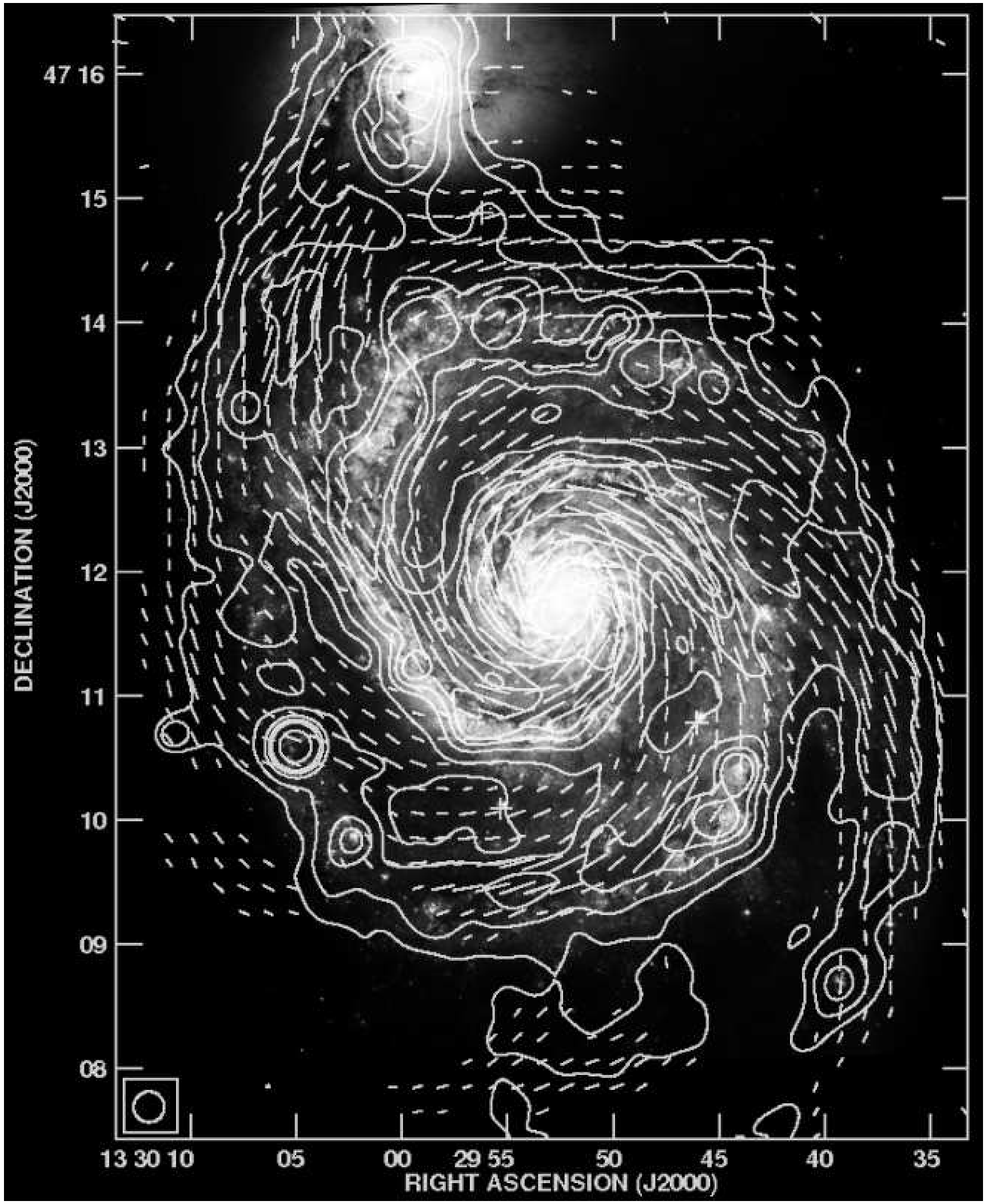
$$\Delta\phi = \lambda^2 \times RM = \lambda^2 \times K \int n_e \boldsymbol{B} \cdot \mathbf{dl}$$

$$K = 0.81 \text{ rad m}^{-2} \, (\mu G)^{-1} \, (\text{pc})^{-1} \text{ cm}^{-3}$$

Synchrotron polarization gives $B_\perp$

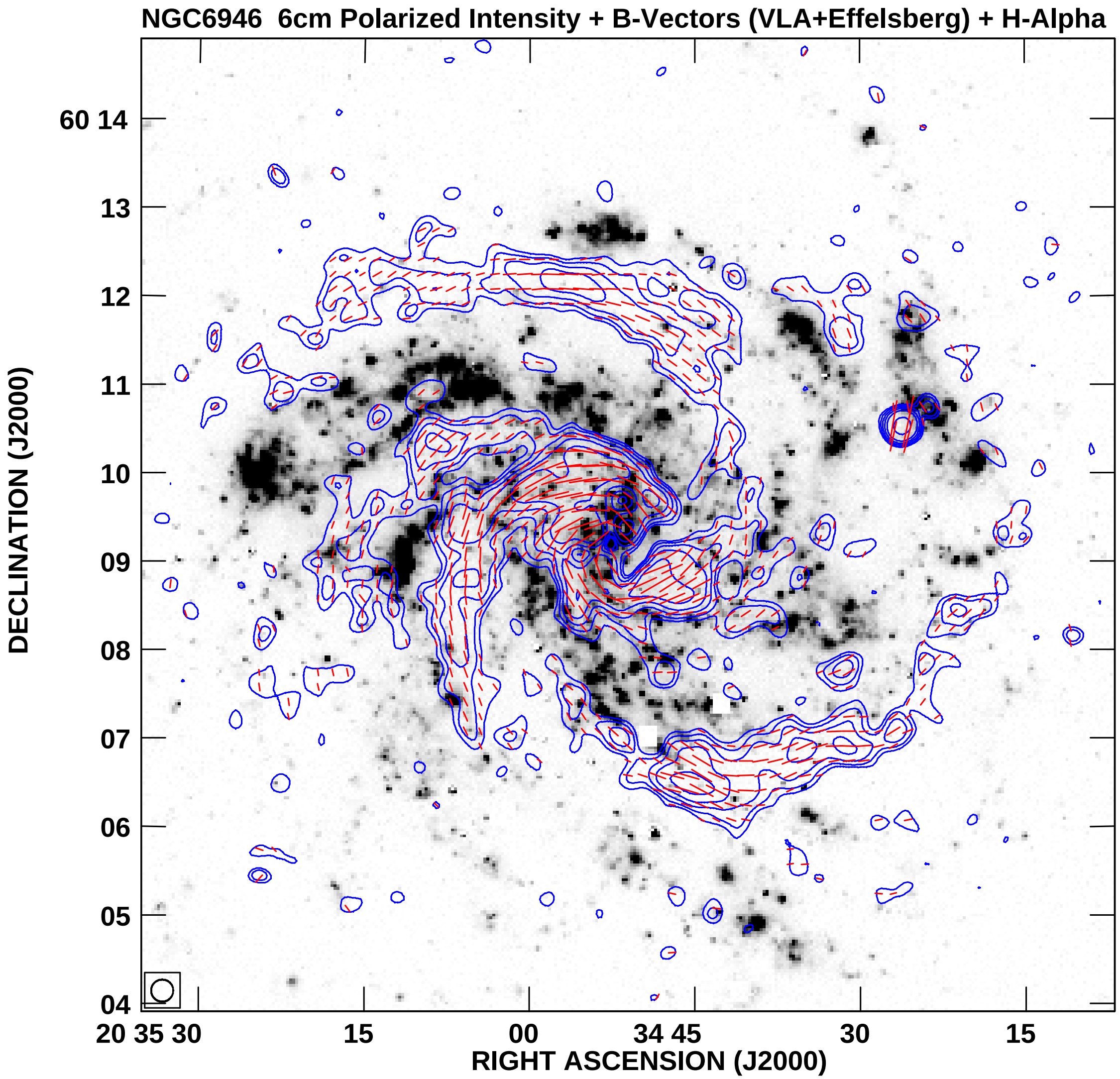
$$\boldsymbol{E} \propto \hat{\boldsymbol{n}} \times [(\hat{\boldsymbol{n}} - \vec{\beta}) \times d\vec{\beta}/dt] \propto d\vec{\beta}/dt$$

Galactic Magnetic Fields: Observations



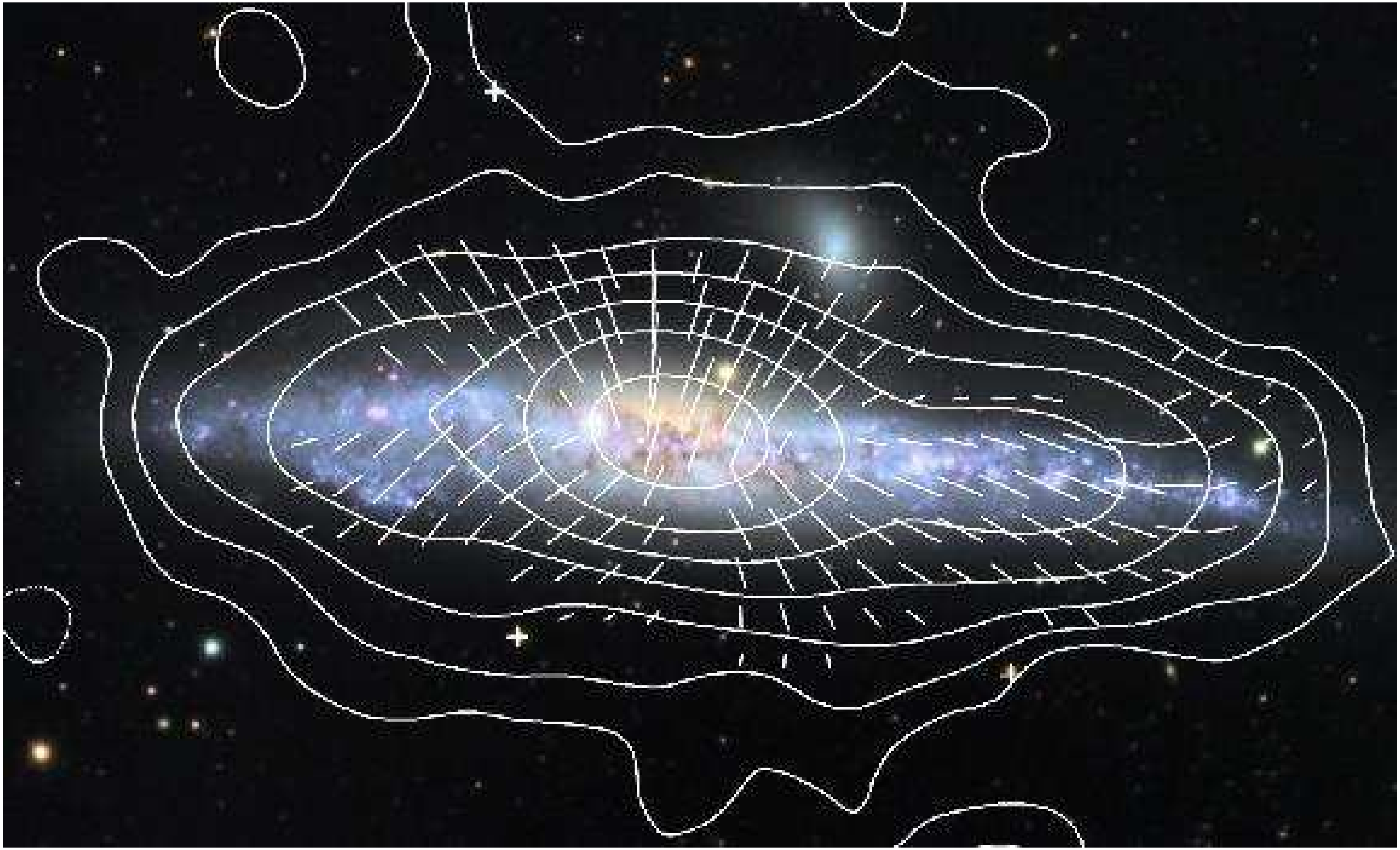
- **Synchrotron polarization and Faraday rotation probe B fields.**
- **M51 at 6 cm (Fletcher and Beck)**
- **Few μG mean Fields coherent on 10 kpc scales**
- **Correlated with optical spiral**

Magnetic Spirals: NGC6946



Why are optical and magnetic spirals correlated?

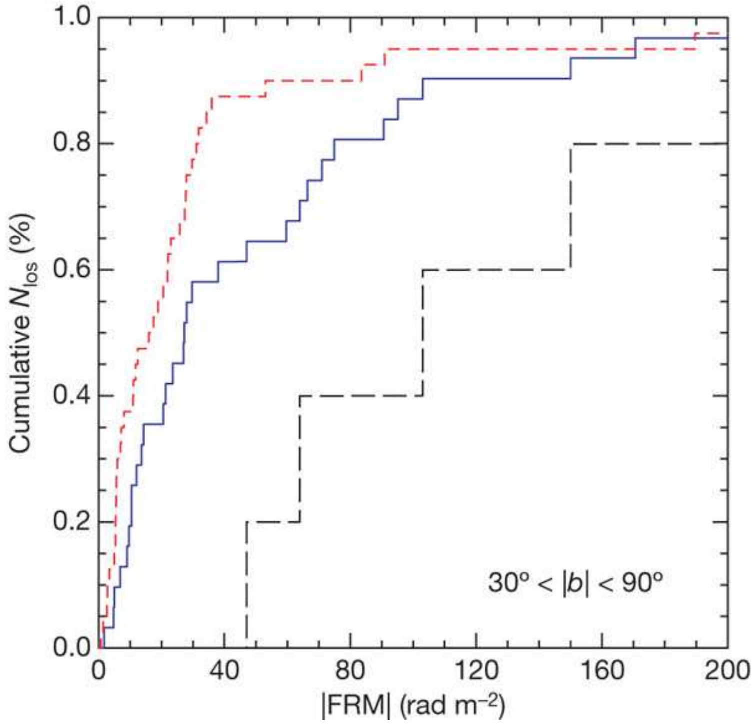
Edge on Galaxies: NGC4631



Halo magnetic fields

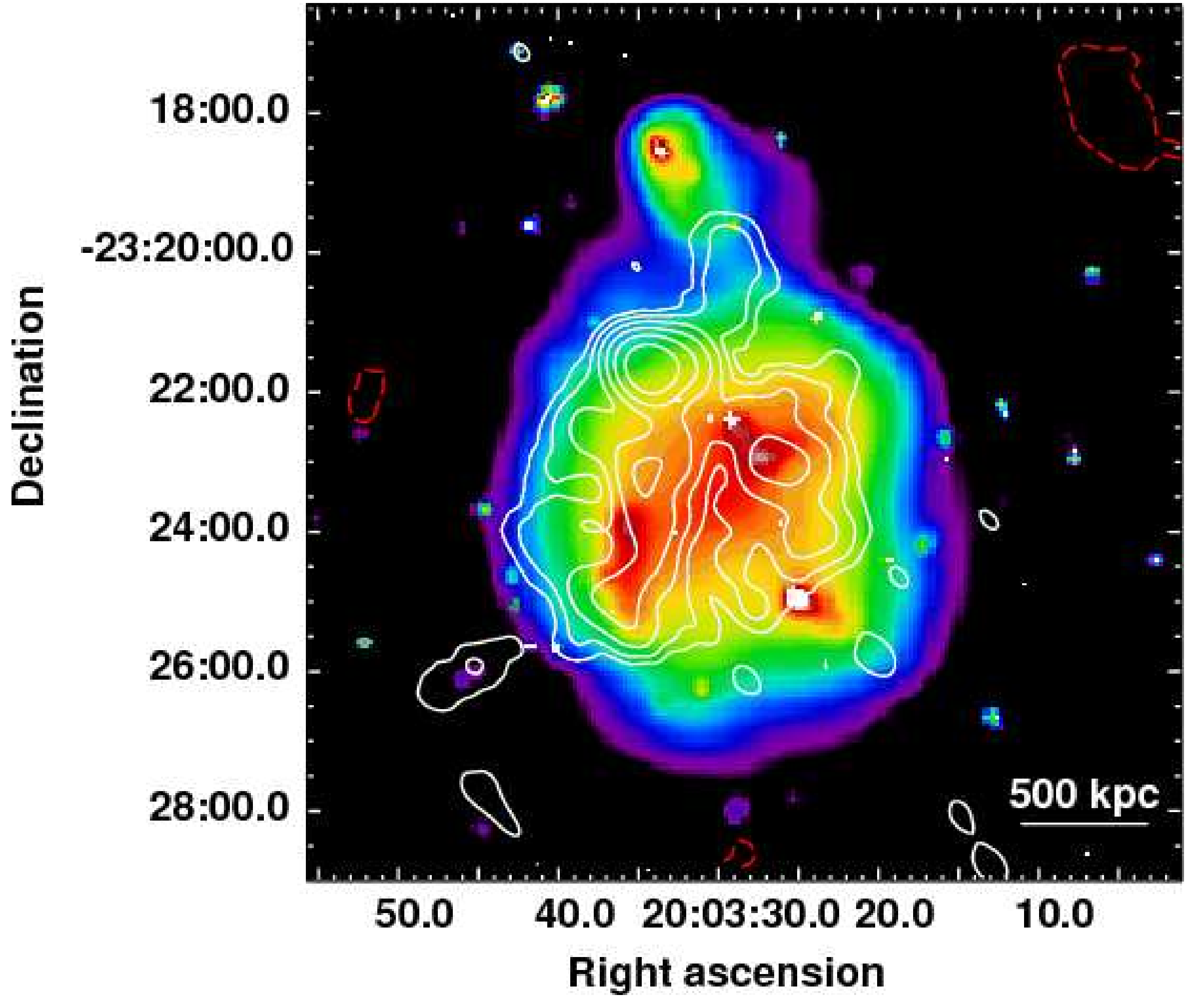
B in high z galaxies?

Cumulative FRM distributions for sightlines with and without strong Mg II absorption line systems.



ML Bernet *et al.* *Nature* **454**, 302-304 (2008) doi:10.1038/nature07105

Cluster Radio halos

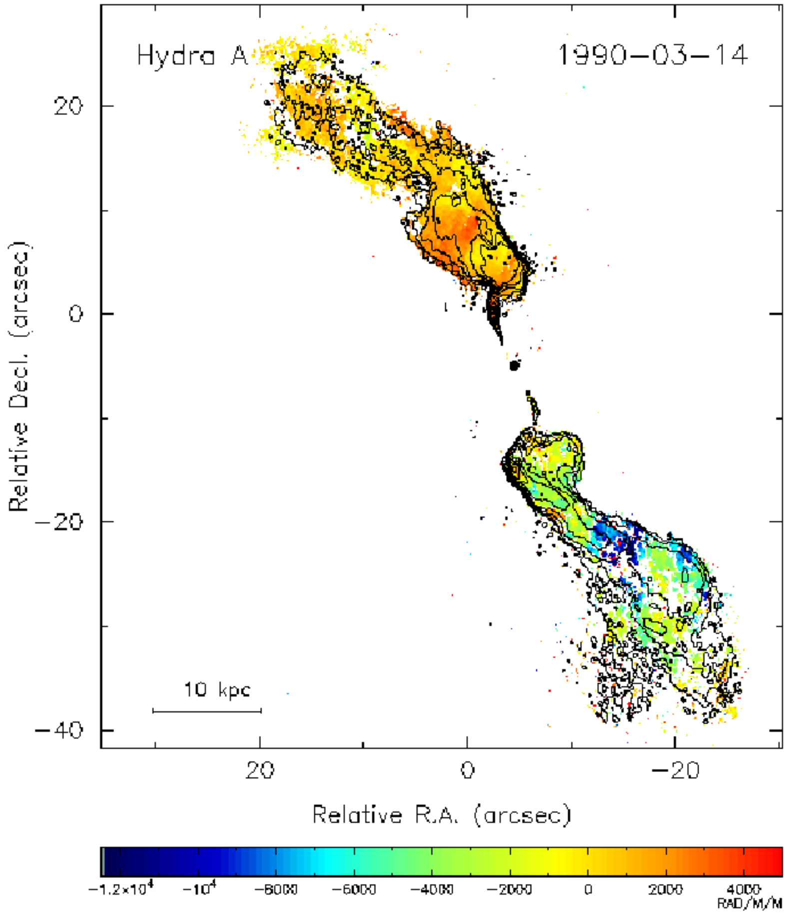


Chandra (X-Ray)-GMRT (235 Mhz): Giant radio halo in RXC J2003.5-2323

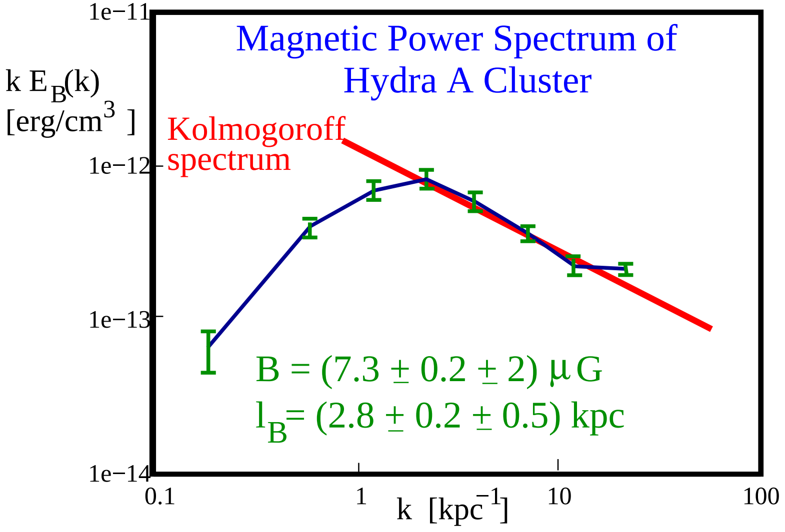
Giacintucci et al. A & A, 505, 45, 2009

Cluster Magnetism: Observations

Radio halos and Faraday Rotation probe cluster B fields



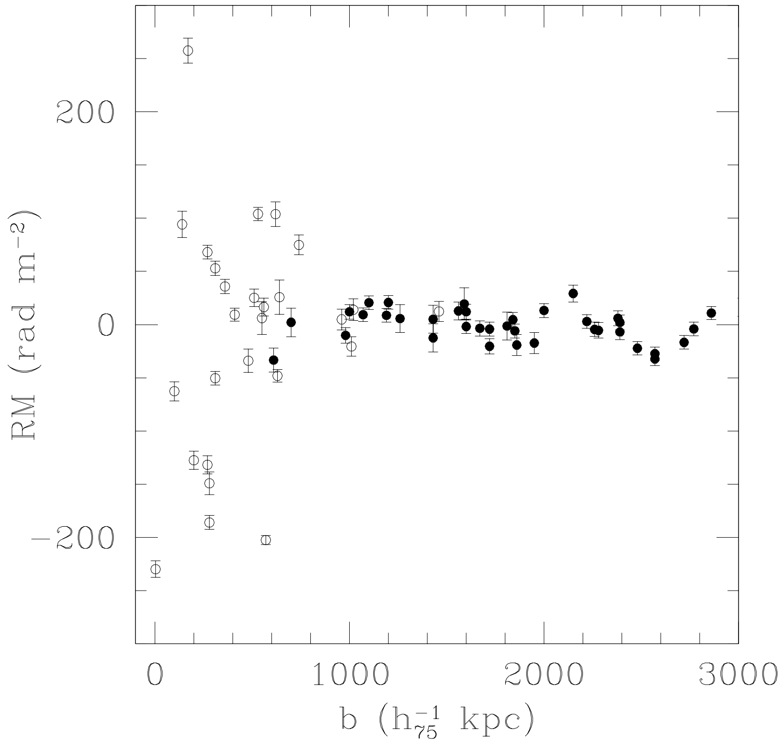
Vogt & Ensslin, A&A, 434, 67, 2005

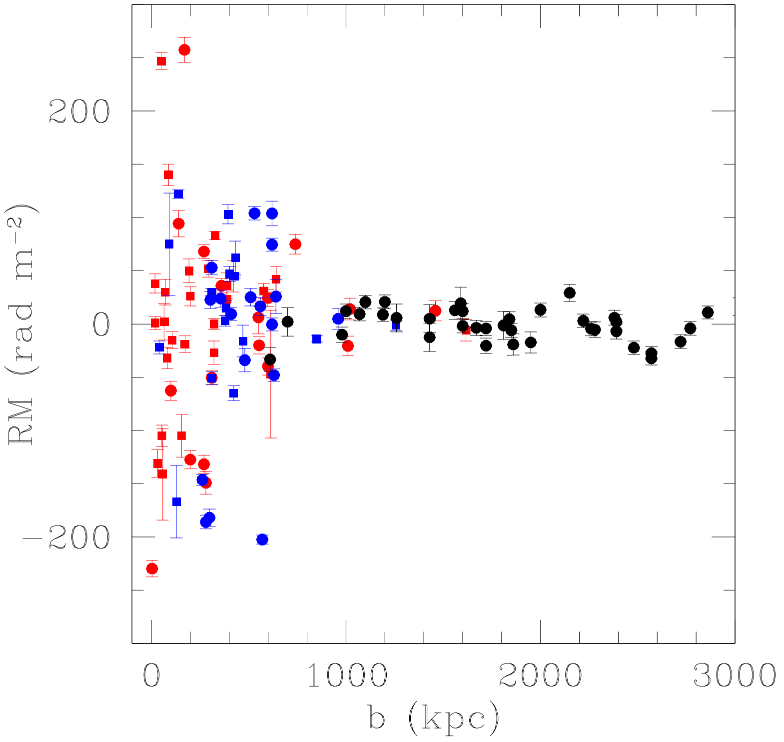


Hydra Cluster $B \sim 7\mu$G coherent on 3 kpc scale

Cluster Magnetism: Observations

Clarke et al., ApJ, 547, L111, 2001





- **Statistical RM study**
- $B \sim 5(l/10kpc)^{-1/2}\mu G$

- **embedded sources**
- **background sources**

How are cluster fields generated/maintained against turbulent decay?

Fluctation/Small scale turbulent dynamo

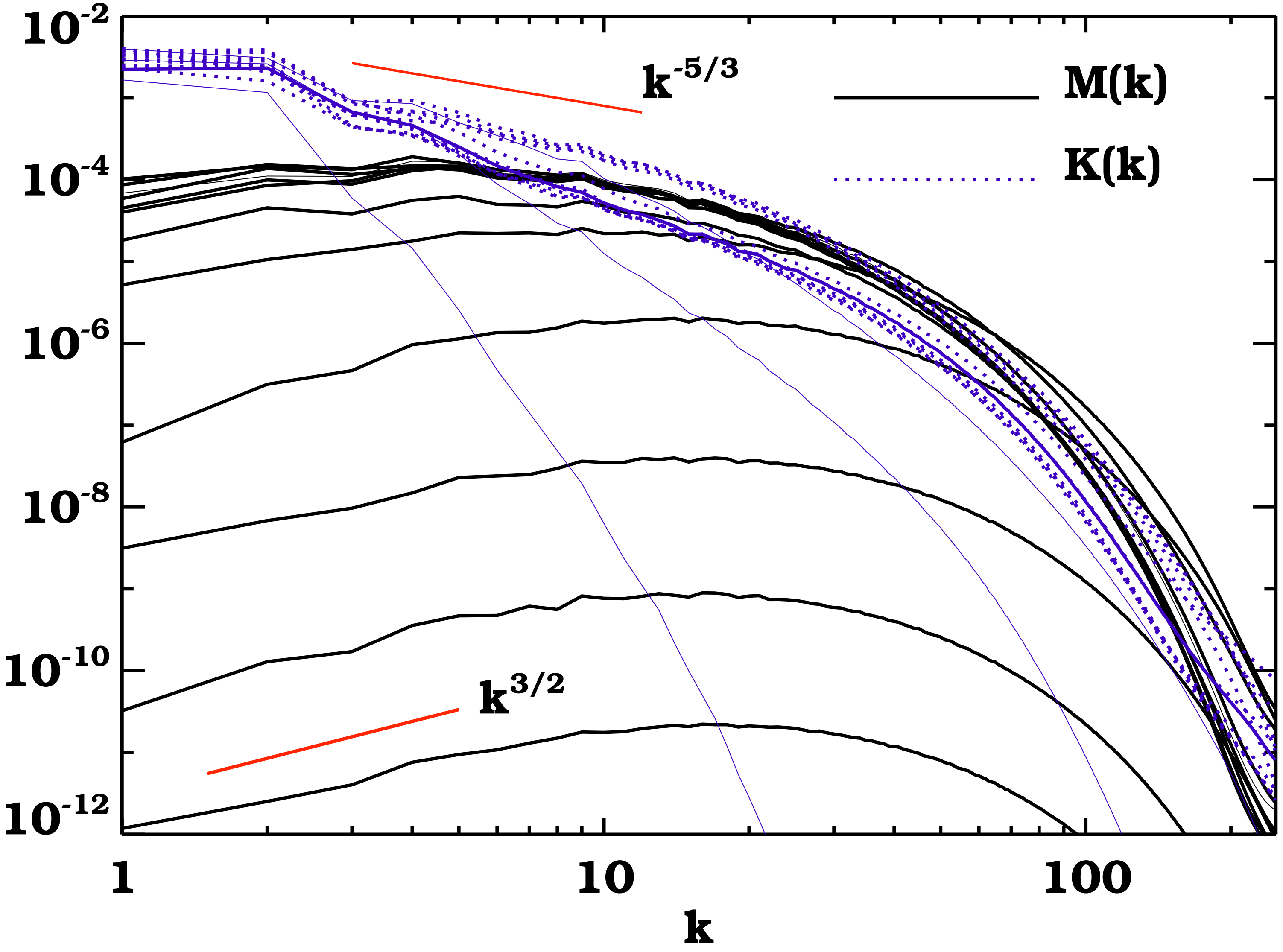
- Turbulence common: Stars, galaxies, galaxy clusters: leads to Random Stretching + "Flux freezing" $\Rightarrow$ Growth of B
- Cancellation (Eyink, 2011) and Resistance limits growth.
- Random B grows if $R_{\mathrm{M}} = vL/\eta > R_{crit} \sim 30 - 100$ (Kazantsev 1967)
  Eigenmode solutions of form: $\Psi(r)\exp(2\Gamma t) = r^2\sqrt{\eta_{\mathrm{T}}}M_{\mathrm{L}}$

$$-\Gamma\Psi = -\eta_{\mathrm{T}}\frac{d^2\Psi}{dr^2} + U_0(r)\Psi$$

- Growing modes if there are bound states in potential $U_0(r)$.
- Growth rate fast $\sim \epsilon\, v/L$ (10^7 yr: Galaxies; 10^8 yr clusters).
  Field intermittent: Eddy scale L, to "resistive" scale $\sim L/R_m^{1/2} \ll L$
- How does it saturate? Important for young galaxy/cluster/IGM Faraday RM and mean field dynamos?

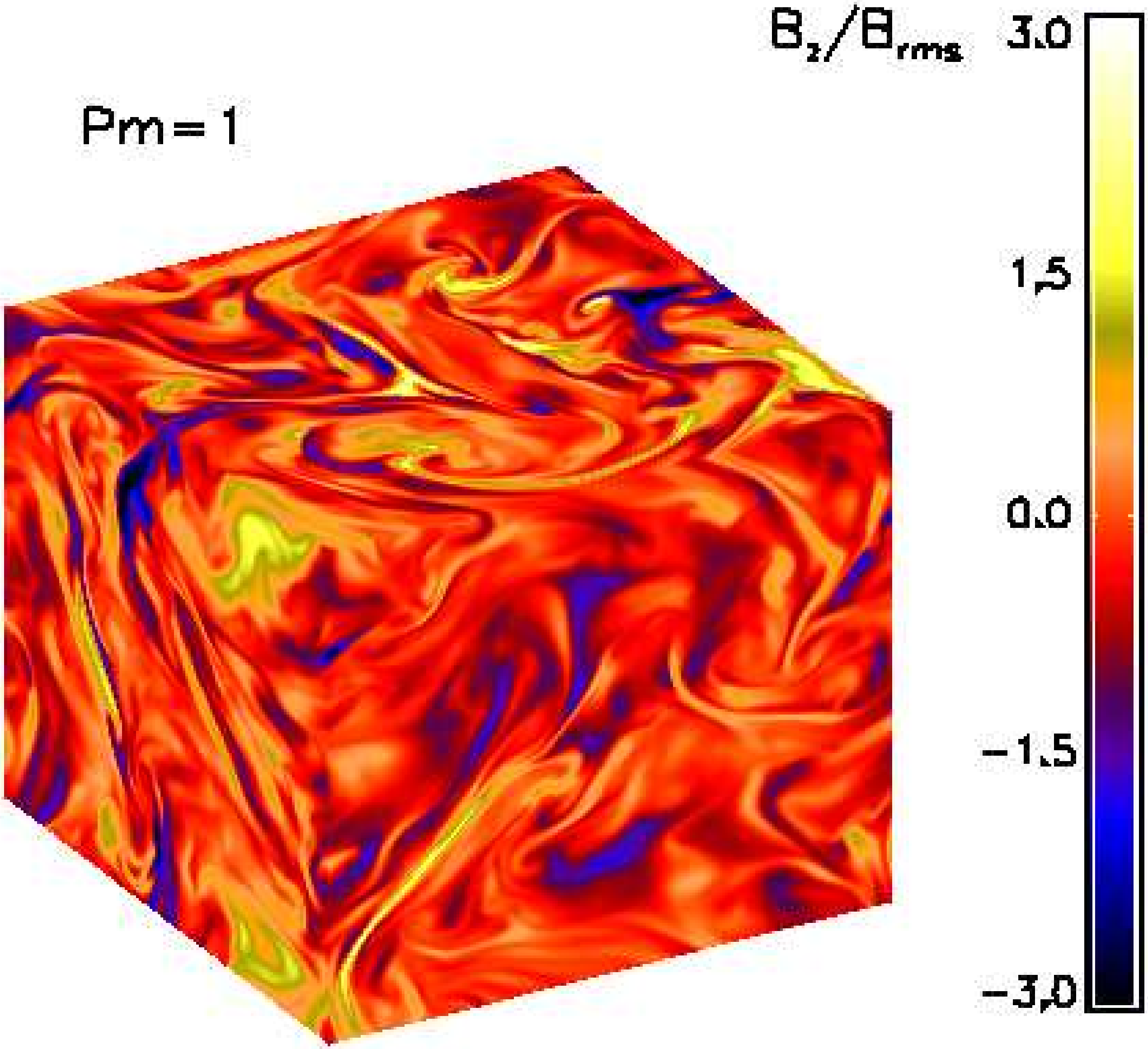
The fluctuation dynamo Simulations

Simulations by Pallavi Bhat, 2012, $P_m = \nu/\eta = 1$



The fluctuation dynamo

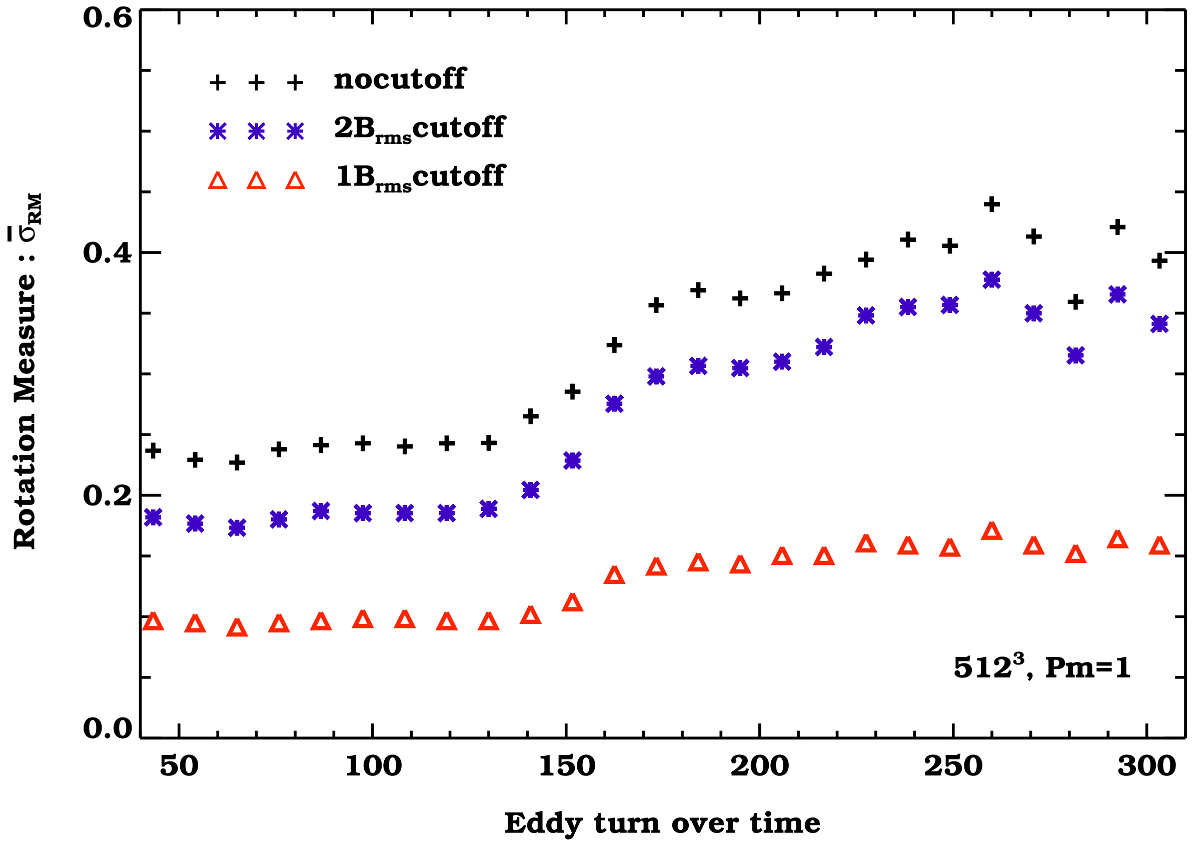
Generated **B** intermittent (Pallavi Bhat, 2012)



Faraday RM from Fluctuation dynamo

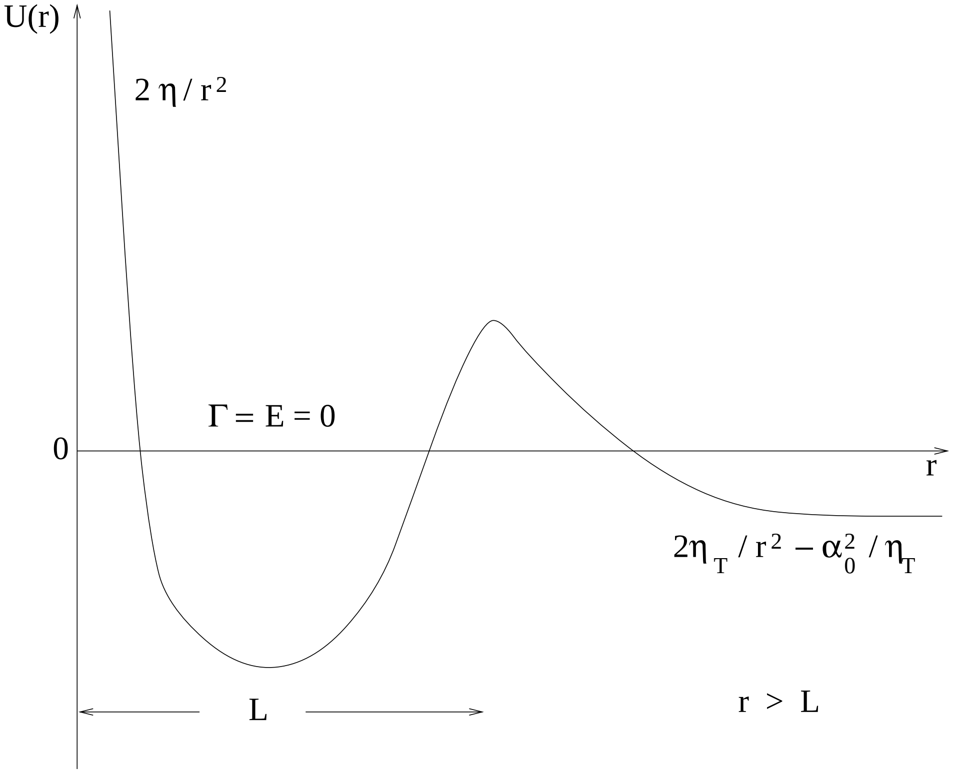
(Pallavi Bhat, KS, MNRAS, 429, 6429, 2013)

- RMS Faraday RM σ_{RM} by shooting lines of sight through the simulation box. Normalize by $\sigma_0 = K n_e (B_{rms}/\sqrt{3})\sqrt{Ll}$
- $\sigma_{RM} \approx 0.4 - 0.5\ \sigma_0$ for various R_m and P_m explored. Rare structures contribute $< 20\%$ to σ_{RM}

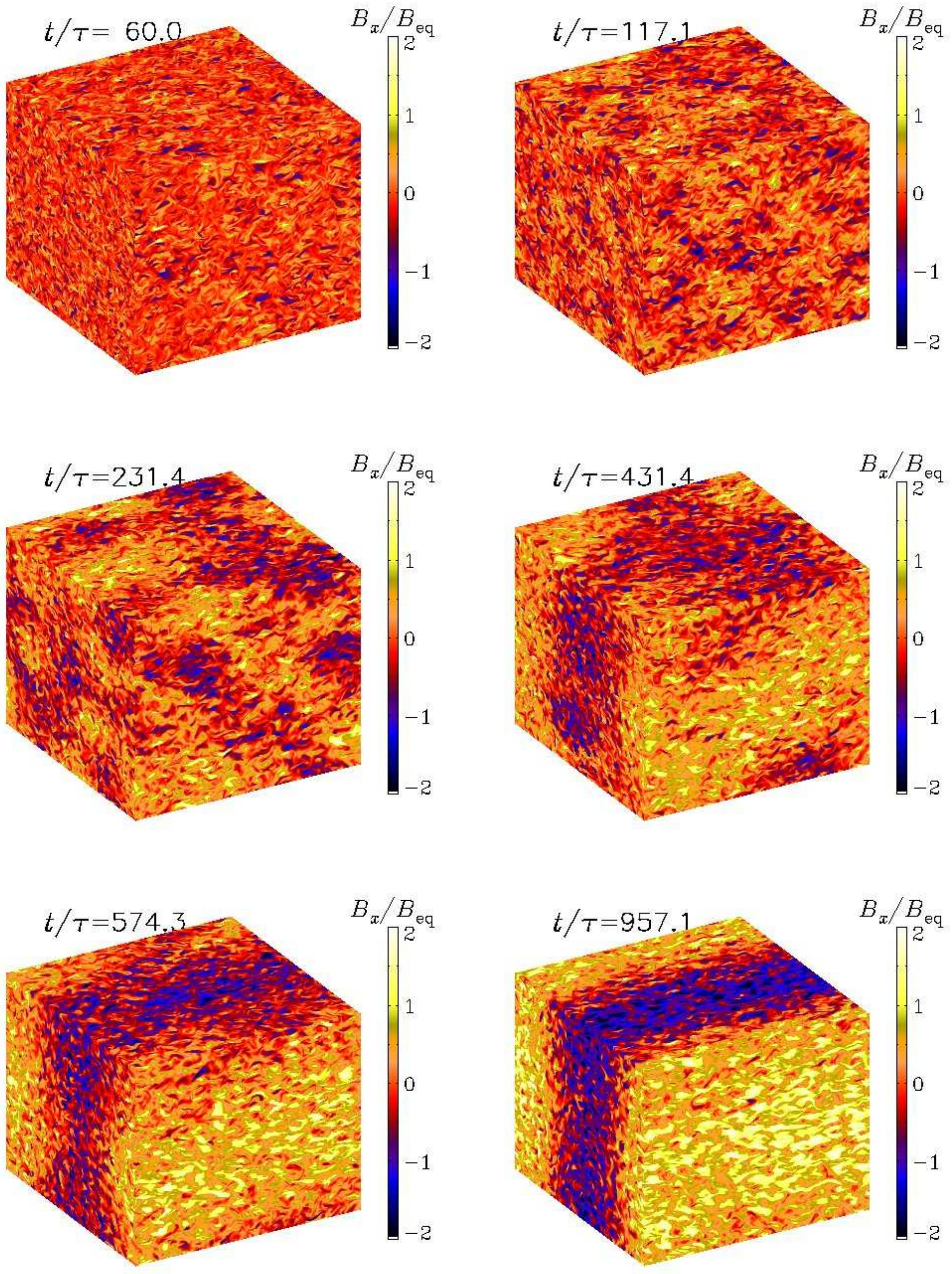


Kazantsev with Helicity: Tunneling?

- **Fluctuation dynamo → bound state problem** (Kazantsev, 1967)
- **Helicity of turbulence allows 'tunneling' to larger scales than L** (Subramanian, PRL, 1999; Brandenburg, Subramanian, A&A Lett, 2000)
- **For** $\dot{M}_{\rm L} \approx 0$, $\dot{H} \approx 0 \rightarrow -\eta_{\rm T}(d^2\Psi/dr^2) + \Psi\left[U_0 - (\alpha^2(r)/\eta_{\rm T}(r))\right] = 0$,
- $r \gg L$, $M_{\rm L}(r) = \bar{M}_{\rm L}(r) \propto r^{-3/2} J_{\pm 3/2}(\mu r)$,

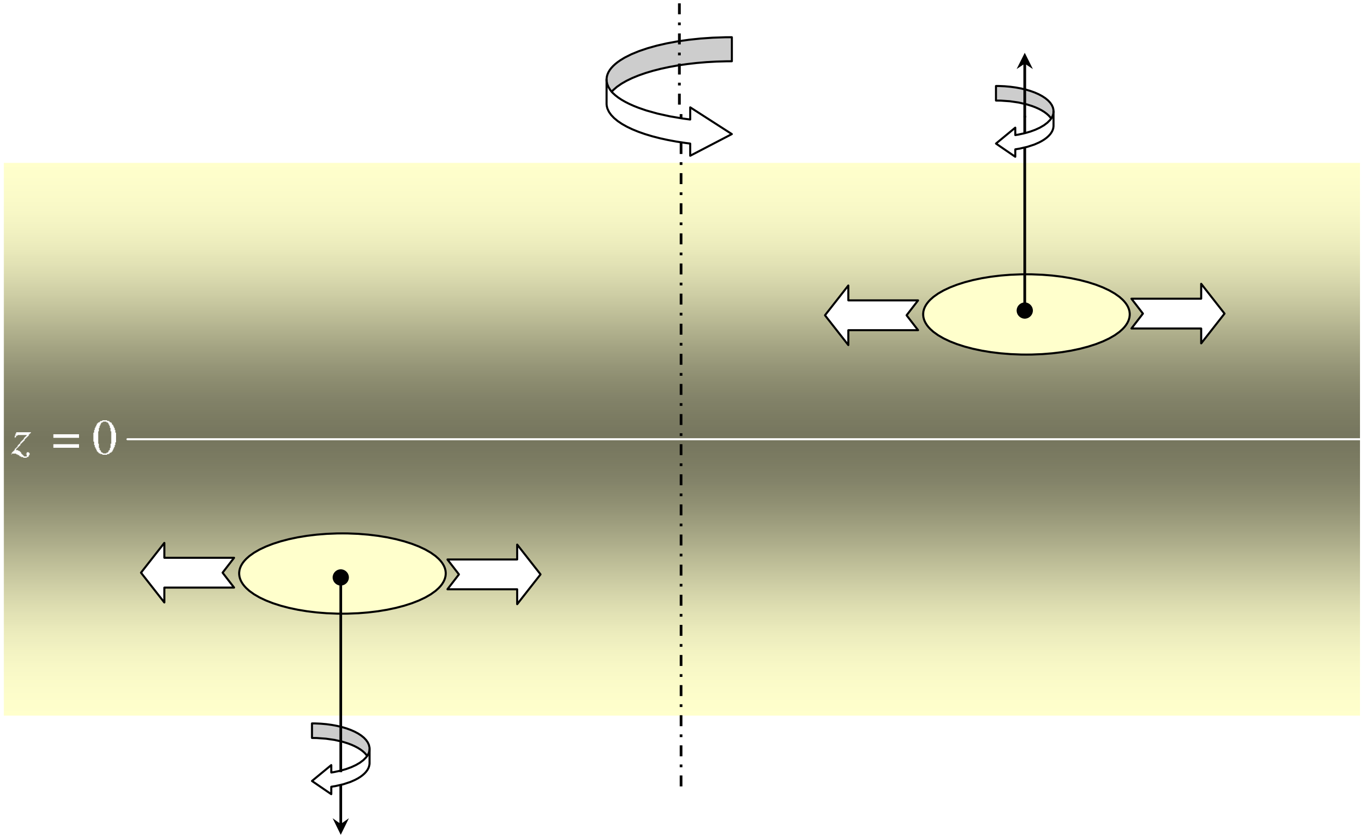


Helically forced turbulent dynamos

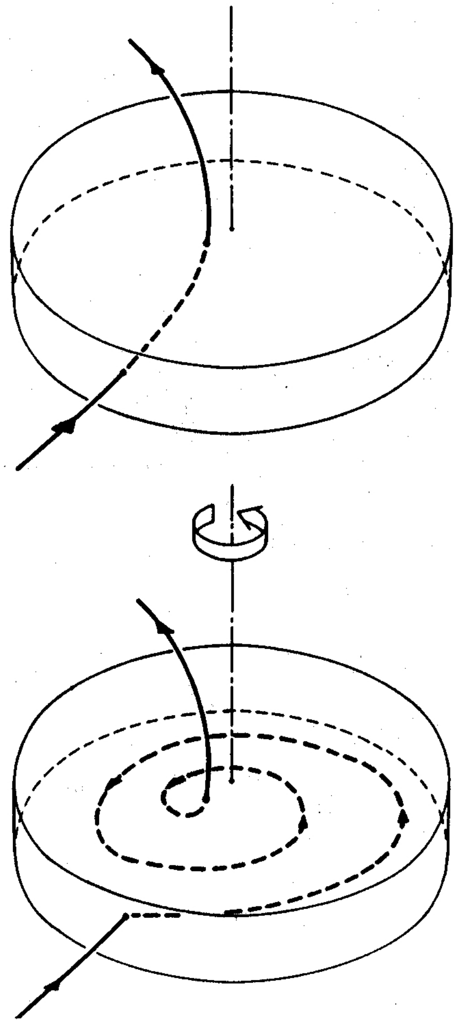


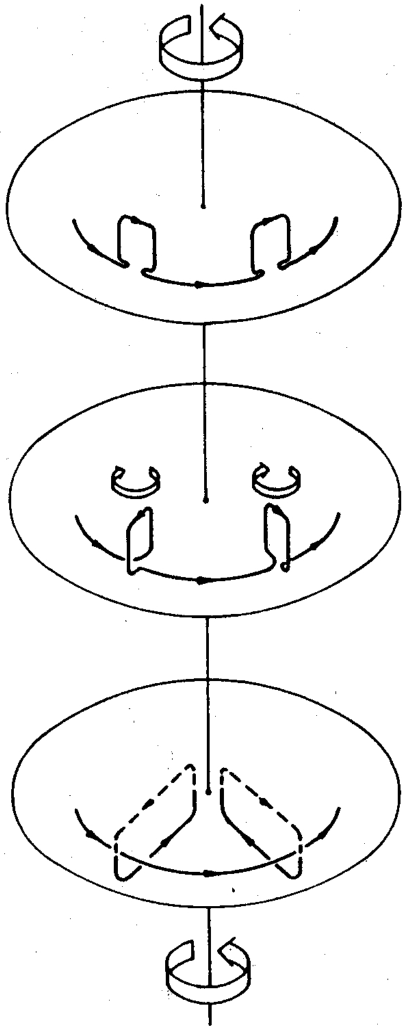
- Axel Brandenburg, 2001....2012; $k_f = 15$
- **Rapid growth in kinematic stage conserving magnetic helicity.**
- **Further Slow Growth on resistive timescale (dissipating small-scale helicity)**
- **Can be understood in terms of magnetic helicity conservation;** (Field and Blackman, 2002).

Supernovae Drive Helical turbulence



Galactic Shear and α effect





Kinematic Limit?

Helicity (links) conservation? Competing Fluctuation dynamo?

Turbulent Mean-Field Dynamo

- **Consider flow with large-scale velocity $\overline{\mathbf{V}}$ and a 'turbulent' stochastic velocity $\mathbf{v}$**
- $\mathbf{V}=\overline{\mathbf{V}}+\mathbf{v}$, $\mathbf{B}=\overline{\mathbf{B}}+\mathbf{b}$: **Mean + Stochastic fields**
- **Average can be volume average over 'intermediate' scales or ensemble average**
- **Averages satisfy Reynolds rules**

$$\overline{\boldsymbol{V}_1+\boldsymbol{V}_2}=\overline{\boldsymbol{V}}_1+\overline{\boldsymbol{V}}_2, \quad \overline{\overline{\boldsymbol{V}}}=\overline{\boldsymbol{V}}, \quad \overline{\overline{\boldsymbol{V}}\boldsymbol{v}}=0, \quad \overline{\overline{\boldsymbol{V}}_1\,\overline{\boldsymbol{V}}_2}=\overline{\boldsymbol{V}}_1\,\overline{\boldsymbol{V}}_2,$$

$$\overline{\partial\boldsymbol{V}/\partial t}=\partial\overline{\boldsymbol{V}}/\partial t, \quad \overline{\partial\boldsymbol{V}/\partial x_i}=\partial\overline{\boldsymbol{V}}/\partial x_i.$$

- **Average now the induction equation**

Turbulent Mean-Field Dynamo

- $\mathrm{V} = \overline{\mathbf{V}} + \mathrm{v}, \mathrm{B} = \overline{\mathrm{B}} + \mathrm{b}$: **Mean + Stochastic fields**
- **Mean satisfies DYNAMO equation, with** $\overline{\mathcal{E}} = \overline{\mathbf{v} \times \mathrm{b}}$**:**

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times \left(\overline{\mathbf{V}} \times \overline{\mathbf{B}} + \overline{\boldsymbol{\mathcal{E}}} - \eta (\nabla \times \overline{\mathbf{B}}) \right);$$

- **The stochastic small-scale field satisfies:**

$$\frac{\partial \boldsymbol{b}}{\partial t} = \nabla \times (\overline{\boldsymbol{V}} \times \boldsymbol{b} + \boldsymbol{v} \times \overline{\boldsymbol{B}} - \eta \nabla \times \boldsymbol{b}) + \boldsymbol{G}$$

- **Here G is the ”pain in neck” nonlinear term in v and b.**

$$\boldsymbol{G} = \nabla \times (\boldsymbol{v} \times \boldsymbol{b})' = \nabla \times [\boldsymbol{v} \times \boldsymbol{b} - \overline{\boldsymbol{v} \times \boldsymbol{b}}]$$

- **Finding $\overline{\mathcal{E}} = \overline{\mathbf{v} \times \mathrm{b}}$ is a closure problem:** $\overline{\boldsymbol{\mathcal{E}}} = \alpha \overline{\mathbf{B}} - \eta_{turb} (\nabla \times \overline{\mathbf{B}})$

The kinematic limit of $\overline{\mathcal{E}}$

- **For short correlation times ($\tau_{\rm cor}$), neglect G, also assume statistical isotropy of the random v :**

$$\overline{\mathcal{E}} = \overline{\boldsymbol{v} \times \int^t dt' (\partial \boldsymbol{b}/\partial\tau)} = \overline{\boldsymbol{v}(t) \times \int^t dt' [-\boldsymbol{v}(t') \cdot \nabla \overline{\boldsymbol{B}} + \overline{\boldsymbol{B}} \cdot \nabla \boldsymbol{v}(t')]}$$

$$\overline{\mathcal{E}}_i = \int_0^t \left[\epsilon_{ijk} \overline{v_j(t) v_{k,p}(t')}\, \overline{B}_p(t') + \epsilon_{ijp} \overline{v_j(t) v_l(t')}\, \overline{B}_{p,l}(t') \right] \mathrm{d}t',$$

- **So**: $\overline{\mathcal{E}} = \alpha \overline{\boldsymbol{B}} - \eta_t \nabla \times \overline{\boldsymbol{B}}$, where

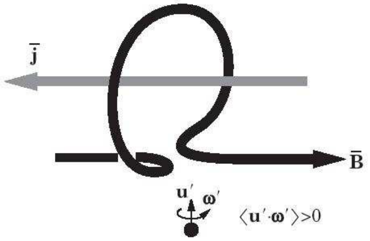
$$\alpha = -\tfrac{1}{3} \int_0^t \overline{\boldsymbol{v}(t) \cdot \boldsymbol{\omega}(t')}\, dt' \approx -\tfrac{1}{3} \tau_{\rm cor} \overline{\boldsymbol{v} \cdot \boldsymbol{\omega}},$$

$$\eta_{\rm t} = \tfrac{1}{3} \int_0^t \overline{\boldsymbol{v}(t) \cdot \boldsymbol{v}(t')}\, dt' \approx \tfrac{1}{3} \tau_{\rm cor} \overline{\boldsymbol{v}^2},$$

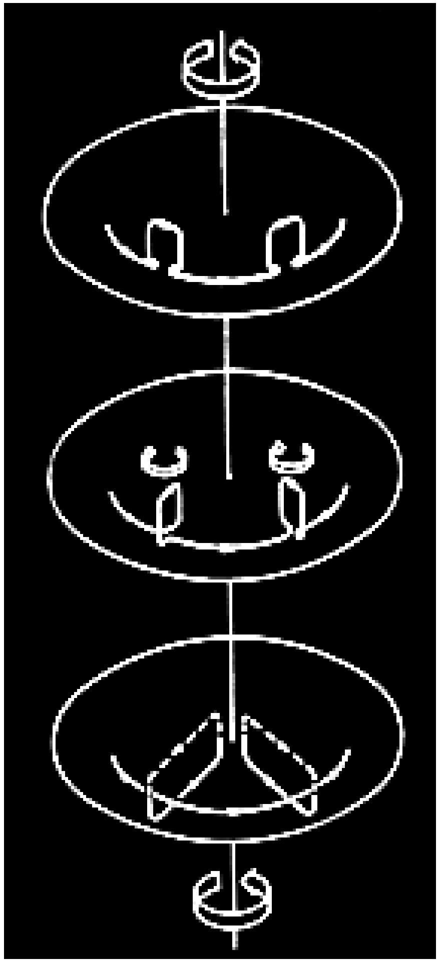
- $\partial \overline{\mathbf{B}}/\partial t = \nabla \times \left(\overline{\mathbf{V}} \times \overline{\mathbf{B}} + \alpha \overline{\mathbf{B}} - (\eta_{\rm t} + \eta)(\nabla \times \overline{\mathbf{B}}) \right);$

Mean-Field Dynamo: Galactic

- Galactic Shear generates B_ϕ from B_r
- Supernovae drive HELICAL turbulence (Due to Rotation + Stratification)
- Helical motions generate B_r from B_ϕ



α-effect (Parker, 55)



RSS, 1988

- Mean field satisfies dynamo equation

$$\frac{\partial\overline{\mathbf{B}}}{\partial t} = \nabla\times\left(\overline{\mathbf{U}}\times\overline{\mathbf{B}} + \overline{\boldsymbol{\mathcal{E}}} - \eta(\nabla\times\overline{\mathbf{B}})\right);$$

$$\overline{\boldsymbol{\mathcal{E}}} = \overline{\mathbf{u}\times\mathbf{b}} = \alpha\overline{\mathbf{B}} - \eta_{turb}(\nabla\times\overline{\mathbf{B}})$$

$$\alpha = -\frac{\tau_{corr}}{3}\langle\mathbf{u}\cdot\omega\rangle \quad \eta_{turb} = \frac{\tau_{corr}}{3}\langle\mathbf{u}^2\rangle$$

- Exponential growth of $\overline{\mathbf{B}}$, $t_{growth}\sim 10^9$ yr

A revised picture for α-effect

Anvar and Natasha Shukurov 2009

- $\overline{\mathcal{E}}$ transfers helicity: Oppositely signed WRITHE AND TWIST Helicities
- **Lorentz force of small-scale twist Helicity grows to cancel kinetic α**

Nonlinear saturation of helical dynamos

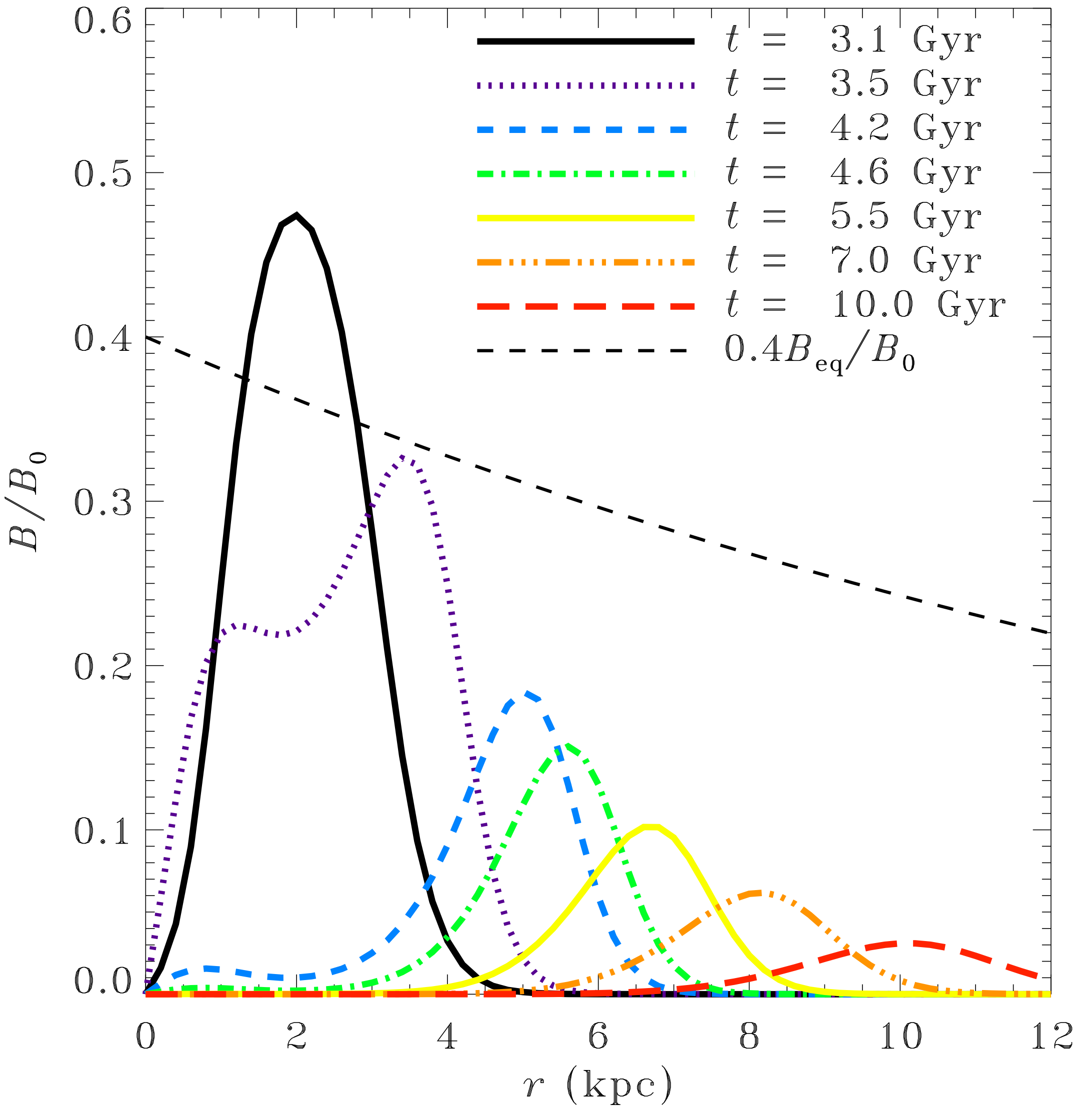
- $\overline{\mathcal{E}}$ transfers helicity between small-large scales
- Small scale current helicity grows to cancel kinetic α
- Nonlinear $\alpha = -(\tau/3)\langle \mathbf{v}\cdot\omega\rangle + (\tau/3\rho)(4\pi/c)\langle \mathbf{j}\cdot\mathbf{b}\rangle \rightarrow 0?$
- CATASTROPHIC QUENCHING OF DYNAMO?
- Need to get rid of small scale helicity, by Helicity fluxes?
  (Blackman & Field; Kleeorin et al).
  But what is gauge invariant helicity density and flux?
- Small scale helicity density h is density of correlated b field links (Subramanian & Brandenburg, ApJ Lett., 2006)

$$\partial h/\partial t + \nabla\cdot\mathbf{F} = -2\overline{\boldsymbol{\mathcal{E}}}\cdot\overline{\mathbf{B}} - 2\eta(4\pi/c)\overline{\mathbf{j}\cdot\mathbf{b}}$$

Large scale dynamos need helicity fluxes

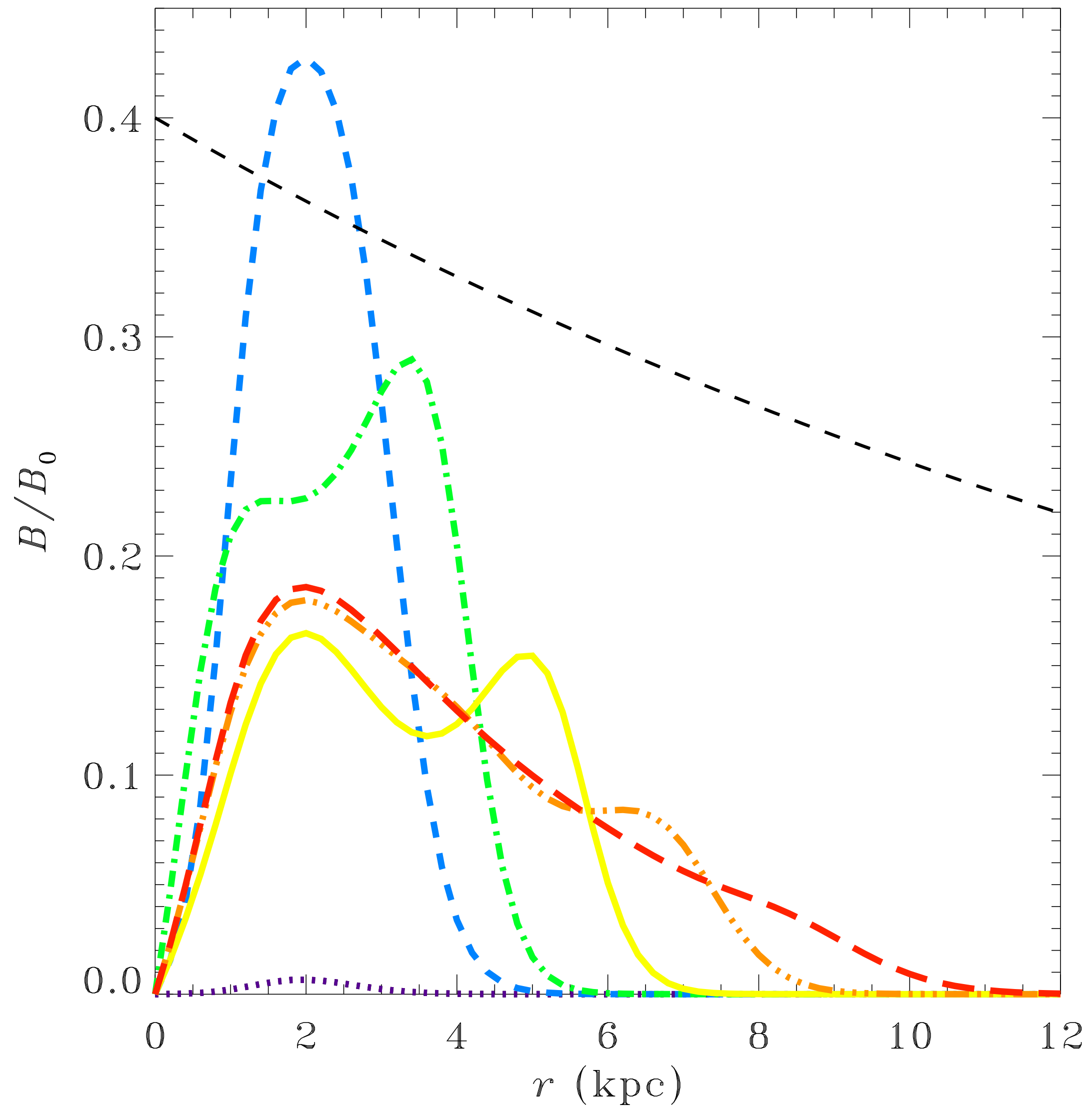
Effect of α-quenching in galaxy

Luke Chamandy, Subramanian, Shukurov, MNRAS, 428, 3569 (2013)



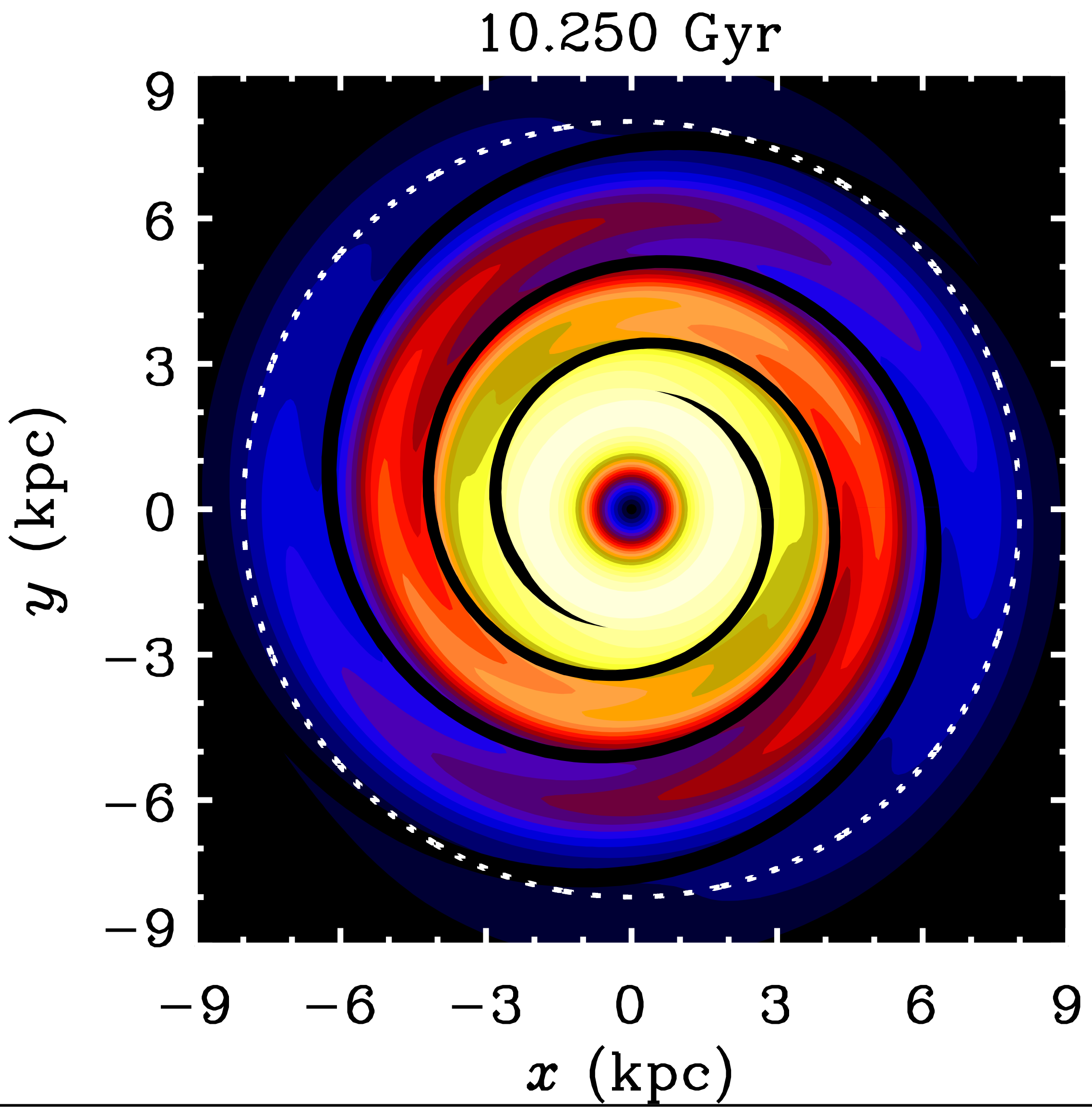
Effect of advective flux in galaxy

Luke Chamandy, Subramanian, Shukurov, MNRAS, 428, 3569 (2013)



Galactic outflows and magnetic spiral

Winding up Spiral with enhanced outflow along spiral (Chamandy, Shukurov, KS, 2014)



Questions

- When do the first fields arise?
- How do they evolve with redshift in galaxies and the IGM?
- Dynamos required to amplify/maintain fields.
- Fluctuation dynamo saturation?
- Galaxy cluster plasma nearly collisionless...how to treat?
- For mean field dynamos: α, η_t at large R_m?
- How do MFD′s saturate; helicity fluxes?
- Is an Early universe field needed? Is it inevitable?

SKA will be crucial to probe the Magnetic Universe.