Grand Minima of Sunspots and Dynamo Models

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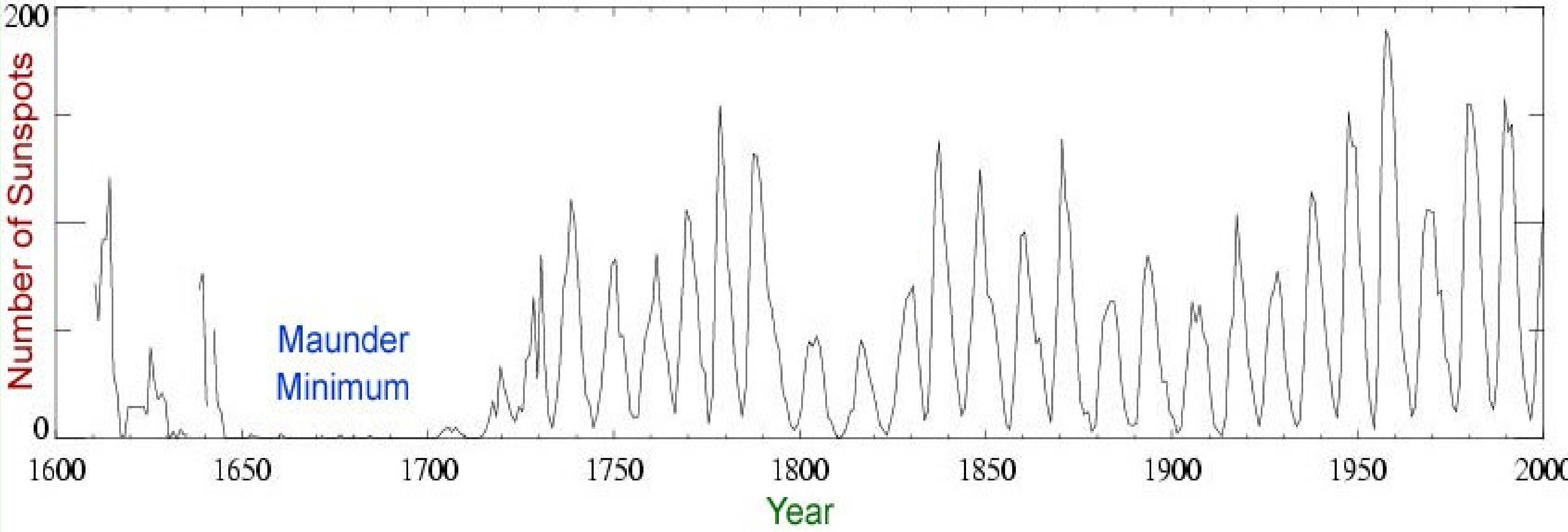
Maunder minimum



- **Maunder minimum period = 1645 to 1715** (Eddy, 1976; Foukal, 1990; Wilson, 1994)

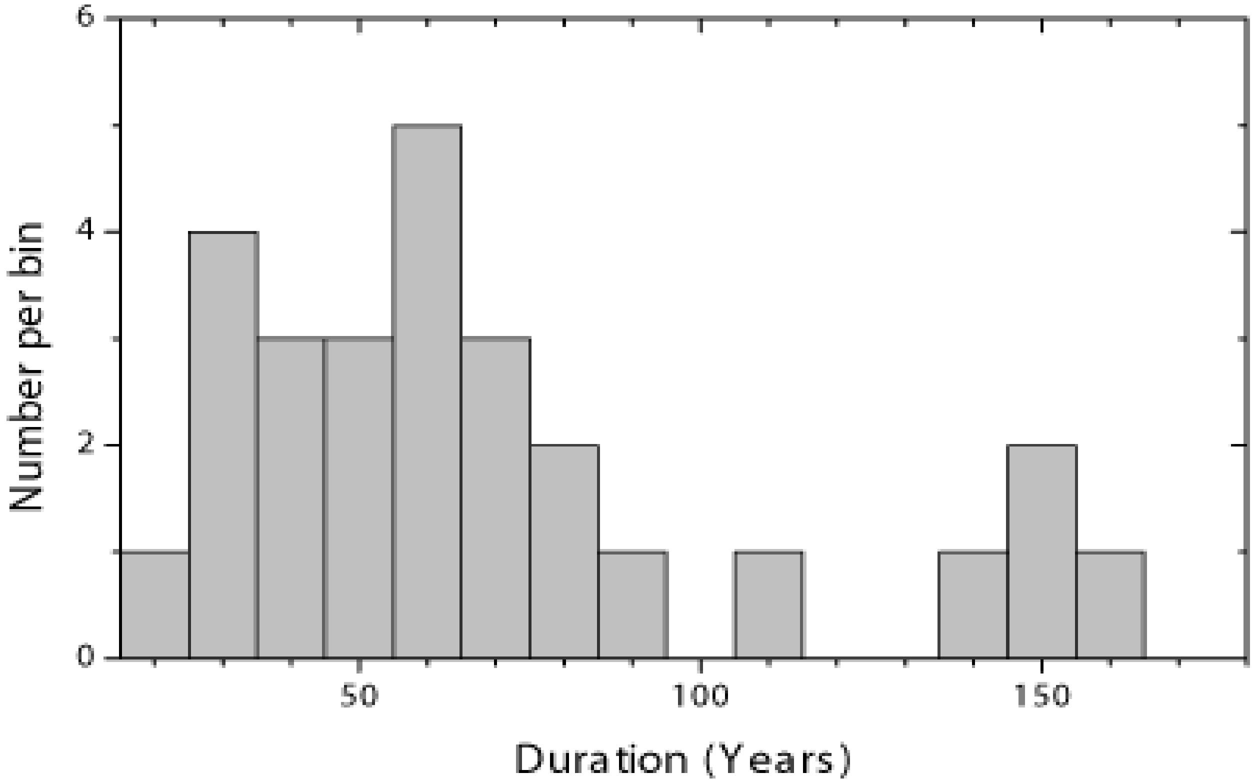
It is a real phenomenon! (Sokoloff & Nesme-Ribes 1994; Hoyt & Schatten 1996; …………….)

Solar activity in past

Results from C^{14} data in old tree ring:

- **27 grand minima in last 11,000 years**

(Usoskin et al. 2007)



Theoretical models of grand minima

The story started as early as in 1980s.

All the studies are done using mean-field dynamo models because the global simulations were not even successful to produce 11-year solar cycle (Gilman 1983; Glatzmaier 1985)!

Two broad approaches of grand minima:

=> Amplitude modulation

=> Stochastic noise

Amplitude modulations in nonlinear dynamo models

- **Nonlinearity due to back-reaction of *B* on *v***
- **Lambda quenching can produce grand mimima**(Kitchatinov et al. 1994; Kuker et al. 1999)

→ **Not expected in Sun!**

- **α-quenching:** $$\alpha = \frac{\alpha_0}{1 + |\overline{B}|^2}$$

→ **stabilizing effect!**
(Long history – Stix 1972; Ivanova & Ruzmaikin 1977; Yoshimura 1978; Schmitt & Schussler 1989).

Coupling between various modes with close frequencies (Krause & Meinel 1988; Brandenburg et al. 1989a,b; Sokoloff & Nesme-Ribes 1994; Beer et al. 1998; Brooke et al. 1998)

- Weiss, Cattaneo & Jones (1984) found chaos in some highly truncated models with suppression of differential rotation

Stochastic noise

Since turbulence is the driver of dynamo action in stars, grand minima through the resulting noise can be possible!

$$\frac{\partial \bar{\mathrm{B}}}{\partial t} = \nabla \times (\bar{\mathrm{V}} \times \bar{\mathrm{B}}) + \nabla \times \varepsilon + \lambda \nabla^2 \bar{\mathrm{B}}$$

Where $\varepsilon = \overline{\mathrm{v}' \times \mathrm{B}'}$

After approximation: $\mathcal{E} = \alpha \bar{\mathrm{B}} - \beta \nabla \times \bar{\mathrm{B}}$

Fluctuations in α is indeed expected!

(Hoyng 1988; Choudhuri 1992; Moss et al. 1992; Hoyng 1993; Ossendrijver et al. 1996; Moss et al. 2008; Brandenburg et al. 2008)

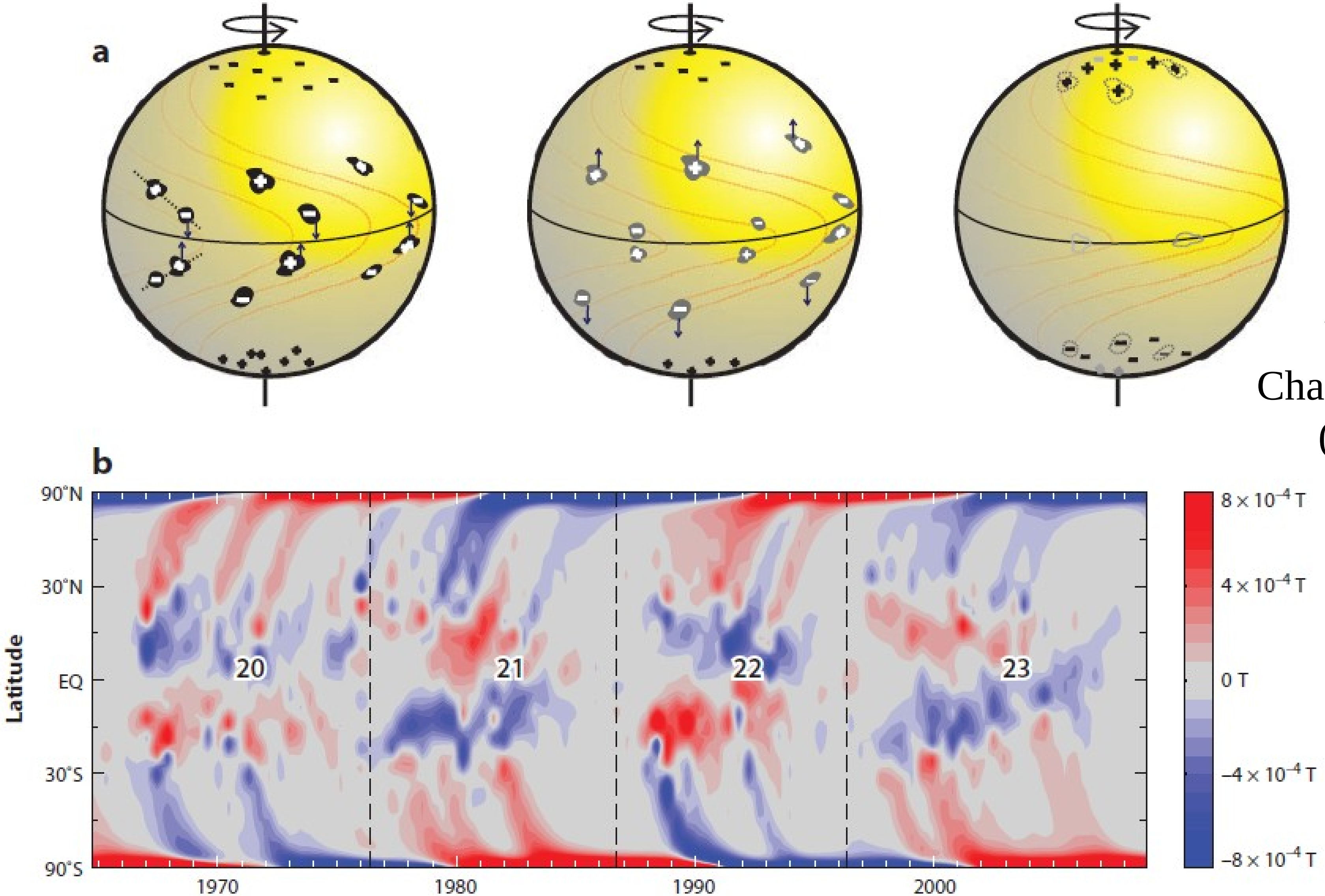
-- fluctuations in dynamo parameters are naturally invoked to explain the origin of grand minima.

Turbulence also introduces "magnetic noise" that affects the mean electromotive force directly (Brandenburg & Spiegel 2008).

Fluctuations in flux transport dynamo model:

Poloidal field generation:–Babcock–Leighton alpha effect:

(Babcock 1961; Leighton 1969; Dasi-Espuig et al. 2010; Munoz-Jaramill



From Charbonneau (2014)

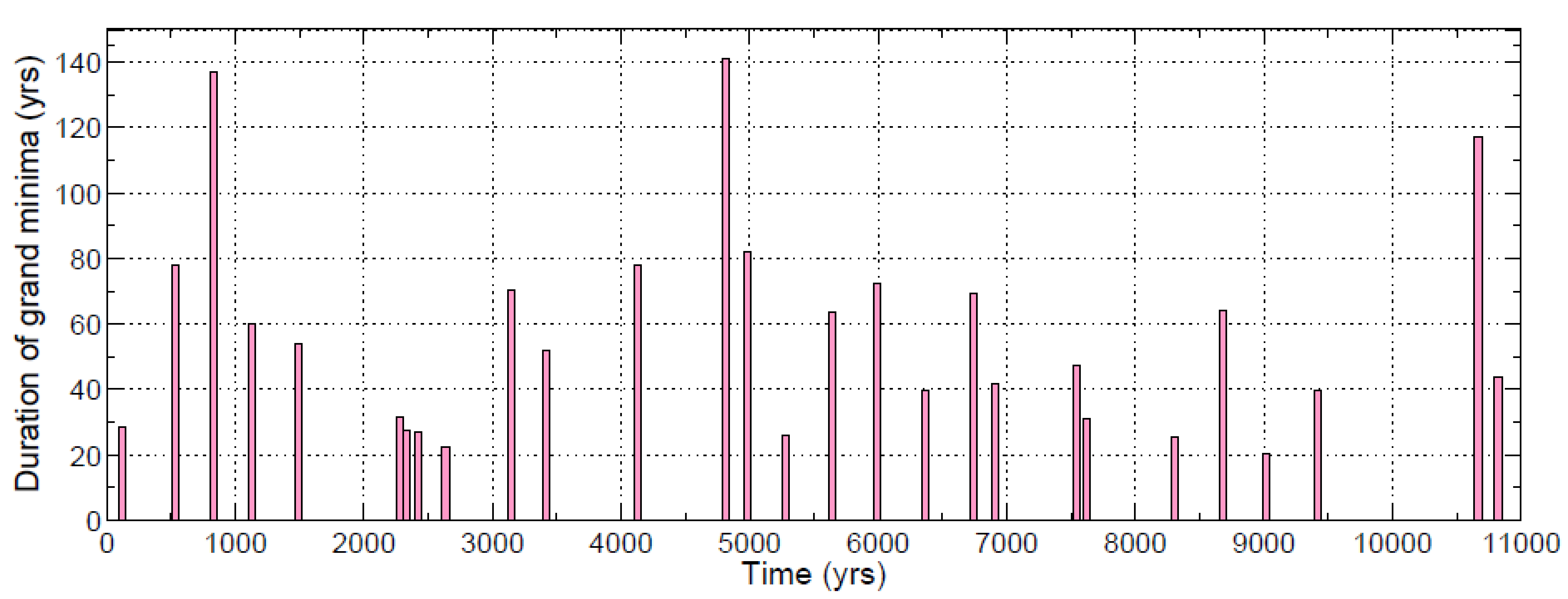
Possible mechanisms for producing grand minima under flux transport dynamo model

Fluctuations in Babcock-Leighton process may make the poloidal field weak (Charbonneau et al. 2004; Choudhuri & Karak 2009, 2012; Passos et al. 2014)

Fluctuations in meridional circulation may make it very weak (Karak 2010; Karak & Choudhuri 2013)

Results of simulation of grand minima

(adding stochastic fluctuations in
Babcock-Leighton α and meridional circulation)



We get 20–30 grand minima in 11,000 years

Observational value = 27

Choudhuri & Karak (2012)

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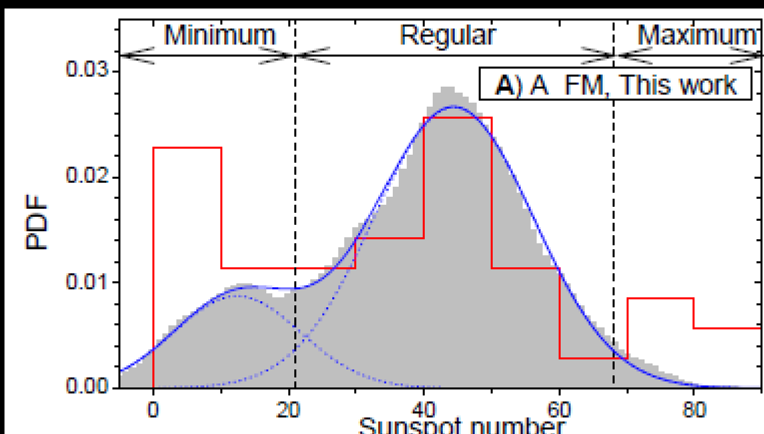
Astronomy & Astrophysics

Letter to the Editor

Evidence for distinct modes of solar activity*

I. G. Usoskin[1], G. Hulot[2], Y. Gallet[2], R. Roth[3], A. Licht[2], F. Joos[3], G. A. Kovaltsov[4], E. Thébault[2], and A. Khokhlov[2,5]



Results. The distribution of solar activity is clearly bi-modal, implying the existence of distinct modes of activity. The main regular activity mode corresponds to moderate activity. The existence of a separate Grand minimum mode with reduced solar activity, which cannot be explained by random fluctuations of the regular mode, is confirmed at a high confidence level.

Conclusions. The Sun is shown to operate in distinct modes – a main general mode, a Grand minimum mode corresponding to an inactive Sun, and a possible Grand maximum mode corresponding to an unusually active

Grand minima in 3D MHD simulations???

$$\frac{DU}{Dt} = -SU_x\hat{y} - c_s^2\nabla \ln\rho + \rho^{-1}\left[J \times B + \nabla\cdot(2\rho\nu\mathbf{S})\right] + f, \quad (2)$$

$$\frac{D\ln\rho}{Dt} = -\nabla\cdot U, \quad (3)$$

$$\frac{\partial A}{\partial t} + \overline{U}^{(S)}\cdot\nabla A = -SA_y\hat{x} + U \times B + \eta\nabla^2 A. \quad (4)$$

$$f(x,t) = \mathrm{Re}\{N f_{k(t)} \exp[\mathrm{i}k(t)\cdot x + \mathrm{i}\phi(t)]\}$$

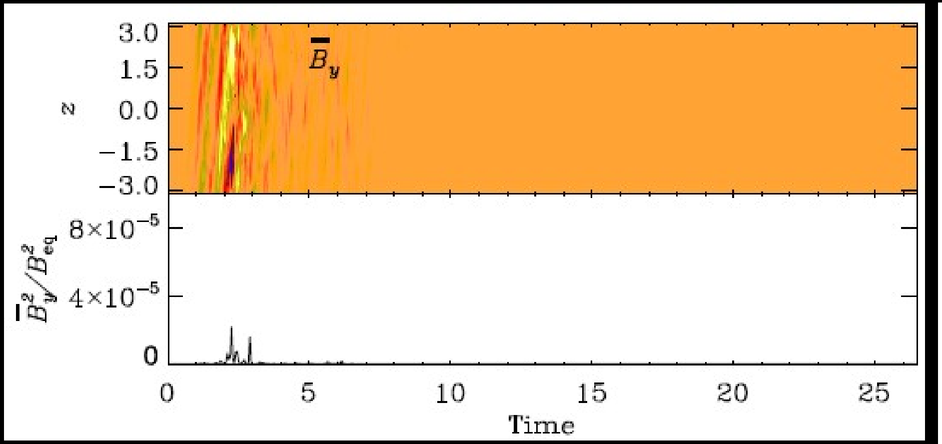
$$f_k = \mathsf{R}\cdot f_k^{(\mathrm{nohel})} \quad \text{with} \quad \mathsf{R}_{ij} = \frac{\delta_{ij} - \mathrm{i}\sigma\epsilon_{ijk}\hat{k}_k}{\sqrt{1+\sigma^2}}$$

Here $D/Dt = \partial/\partial t + (U + \overline{U}^{(S)})\cdot\nabla$ is the advective time derivative, $\overline{U}^{(S)} = (0, Sx, 0)$ with $S = \mathrm{const}$ is the

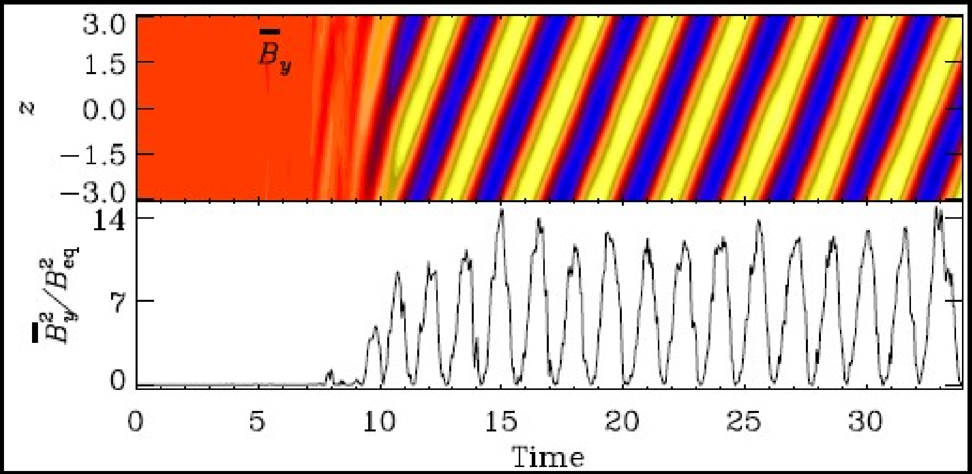
Periodic box, imposed large-scale shear,

turbulence is generated artificially by helically forced flow.

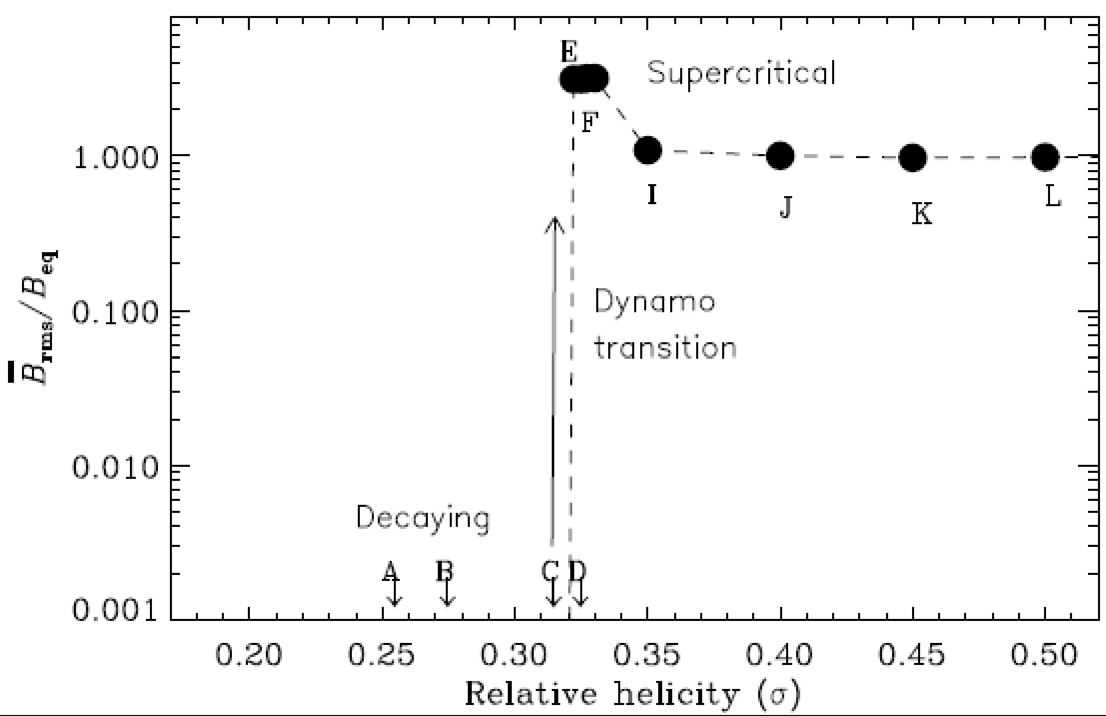
Results



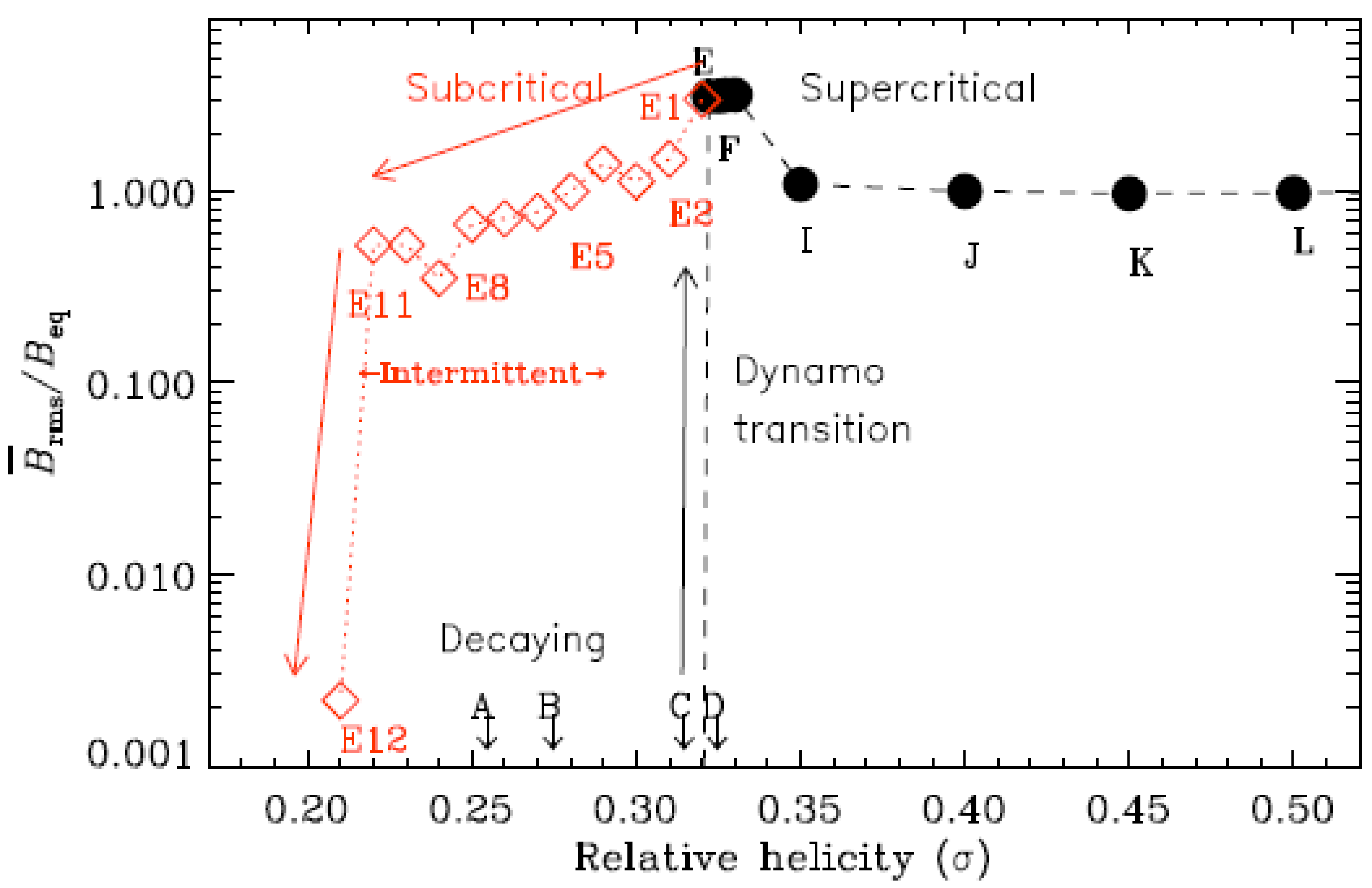
$\bar{B}_y$
z
3.0
1.5
0.0
−1.5
−3.0
$\bar{B}_y^2/B_{eq}^2$
8×10^{-5}
4×10^{-5}
0
0
5
10
15
20
25
Time



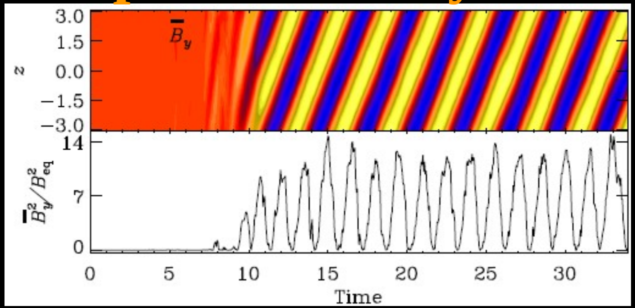
$\bar{B}_y$
z
3.0
1.5
0.0
−1.5
−3.0
$\bar{B}_y^2/B_{eq}^2$
14
7
0
0
5
10
15
20
25
30
Time



$\bar{B}_{rms}/B_{eq}$
1.000
0.100
0.010
0.001
E
F
Supercritical
I
J
K
L
Dynamo
transition
Decaying
A
B
C
D
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Relative helicity (σ)



Supercritical dynamo



Karak, Kitchatinov & Brandenburg (2015)

Turbulent transport coefficients are quenched due to magnetic field --

From quasi-linear approximation (Rudiger & Kitchatinov 1993; Kitchatinov et al. 1994)

Also seen in simulations: Karak et al. (2014b)

$$\eta_{\mathrm{T}} = \eta \phi_{\eta}(B), \qquad \alpha_{\mathrm{T}} = \alpha \phi_{\alpha}(B)$$

$$\phi_{\alpha}(B) = \frac{15}{32B^4}\left[1 - \frac{4B^2}{3(1+B^2)^2} - \frac{1-B^2}{B}\,\mathrm{arctg}(B)\right]$$

$$\phi_{\eta}(B) = \frac{3}{8B^2}\left[1 + \frac{4+8B^2}{(1+B^2)^2} + \frac{B^2-5}{B}\,\mathrm{arctan}(B)\right]$$

$$D = \frac{\alpha_{\mathrm{T}} \Omega R^3}{\eta_{\mathrm{T}}^2}$$

Effective dynamo number versus magnetic field

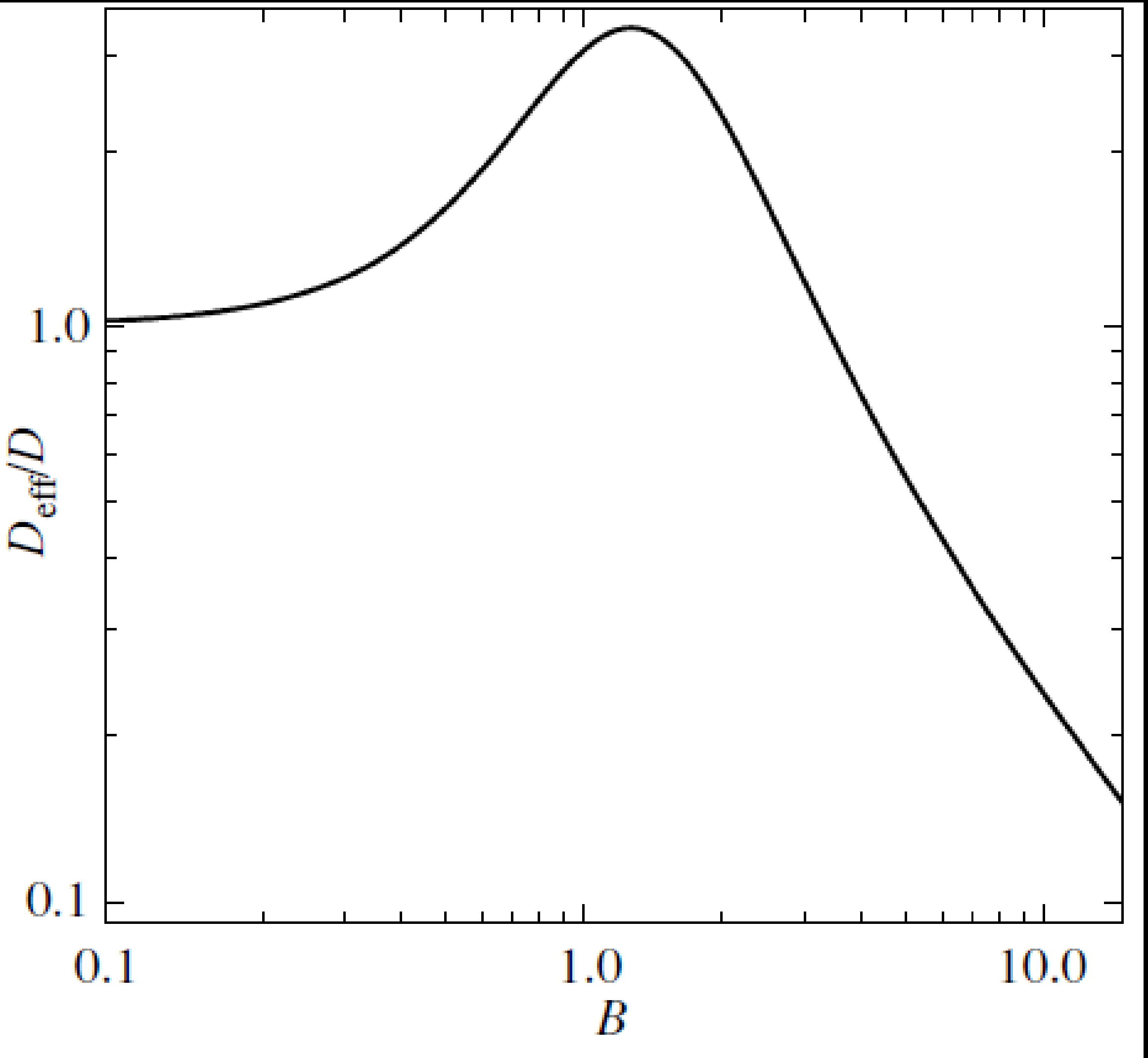
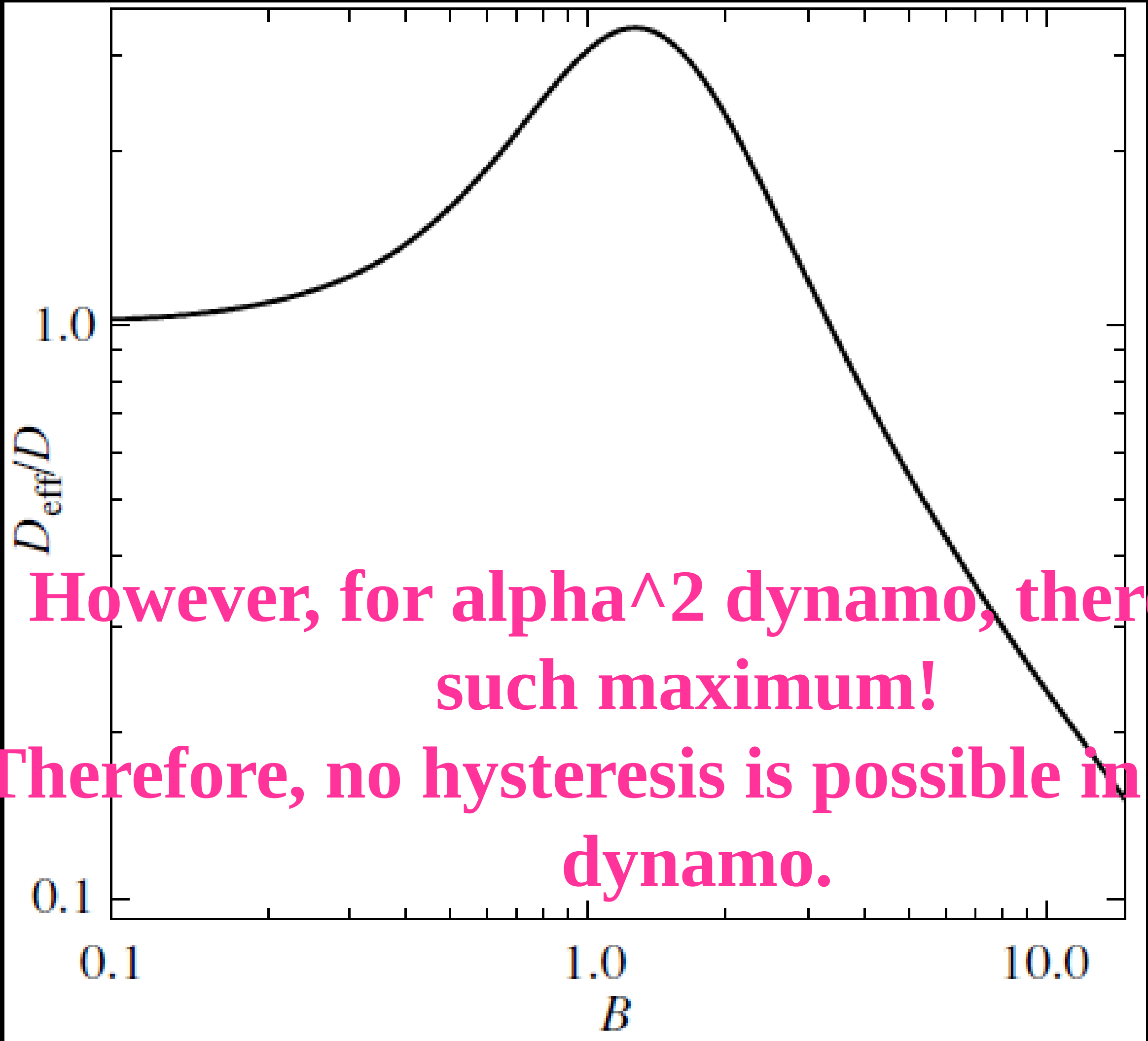


Fig. 1. $D_{eff}/D = \phi_\alpha(B)/\phi_\eta^2(B)$ versus magnetic field. In the region of weak fields, D_{eff} increases with B.

Effective dynamo number versus magnetic field

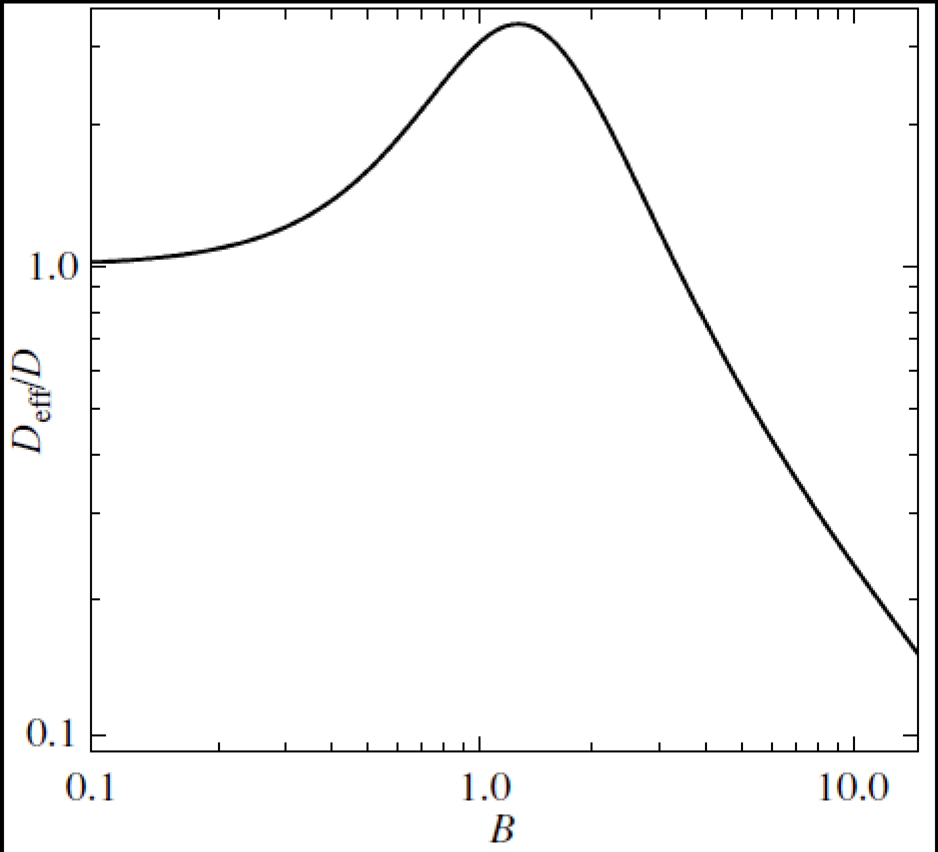


However, for alpha^2 dynamo, there is not such maximum!

Therefore, no hysteresis is possible in alpha^2 dynamo.

Fig. 1. $D_{\rm eff}/D = \phi_\alpha(B)/\phi_\eta^2(B)$ versus magnetic field. In the region of weak fields, $D_{\rm eff}$ increases with B.

Dynamo hysteresis observed in mean-field model with quenching in turbulent transport coefficients



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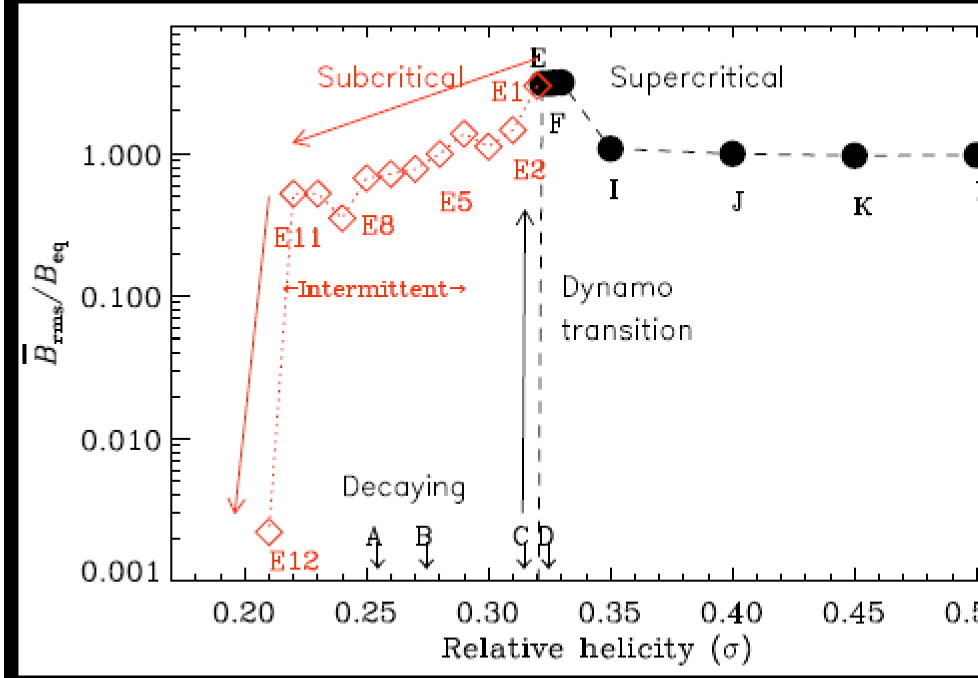

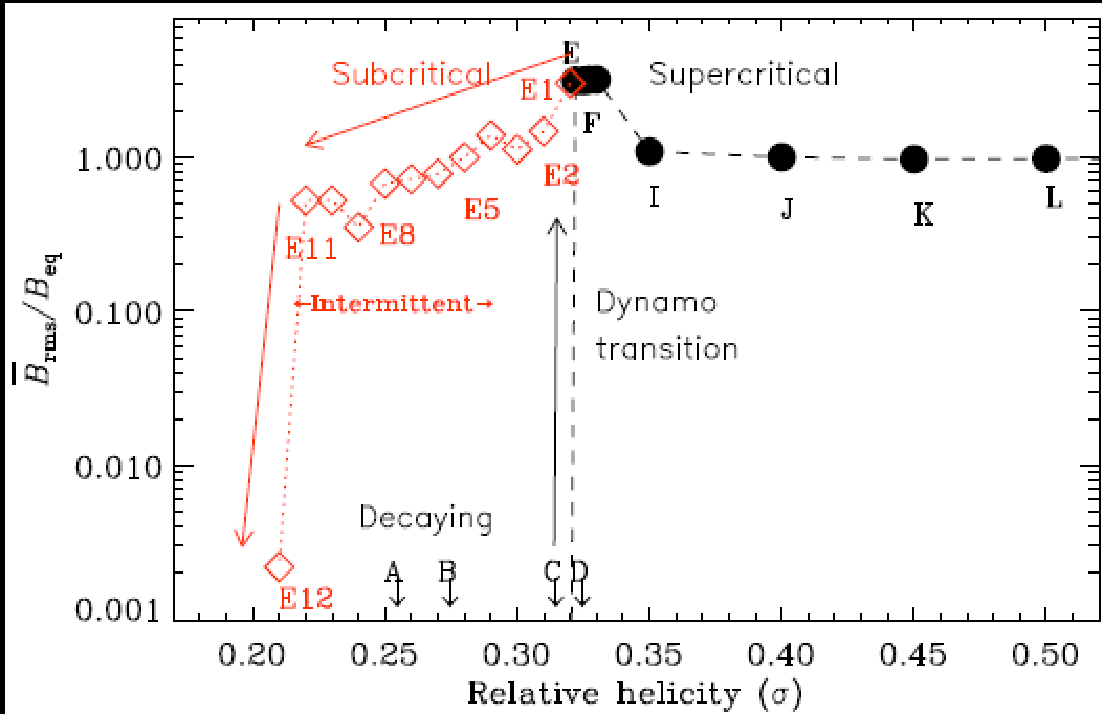

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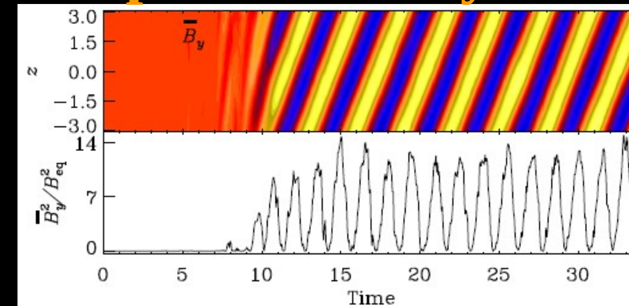
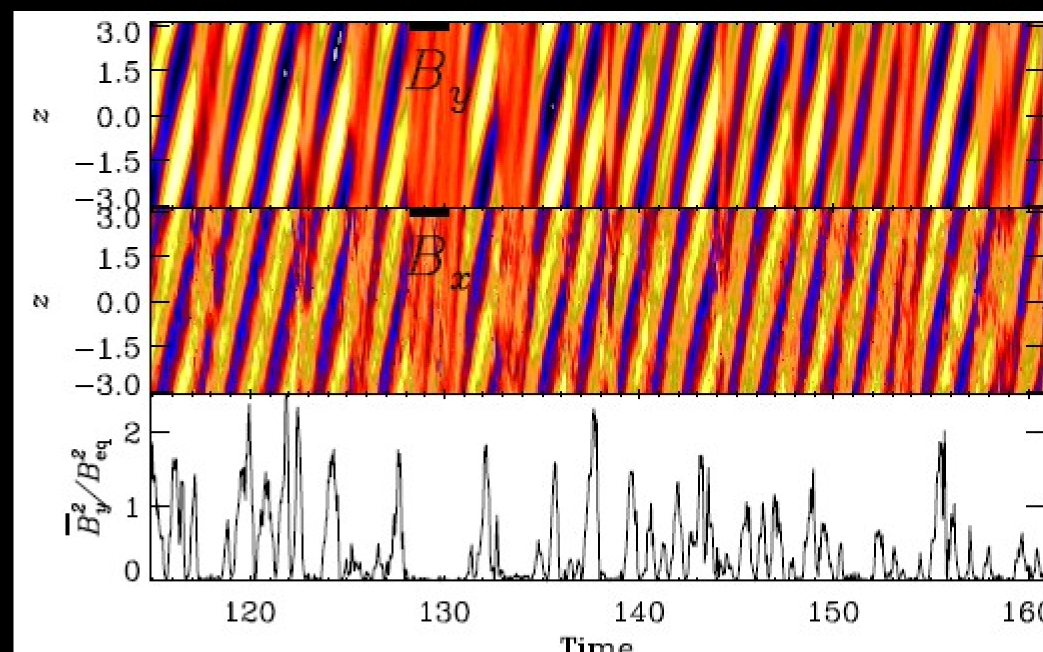
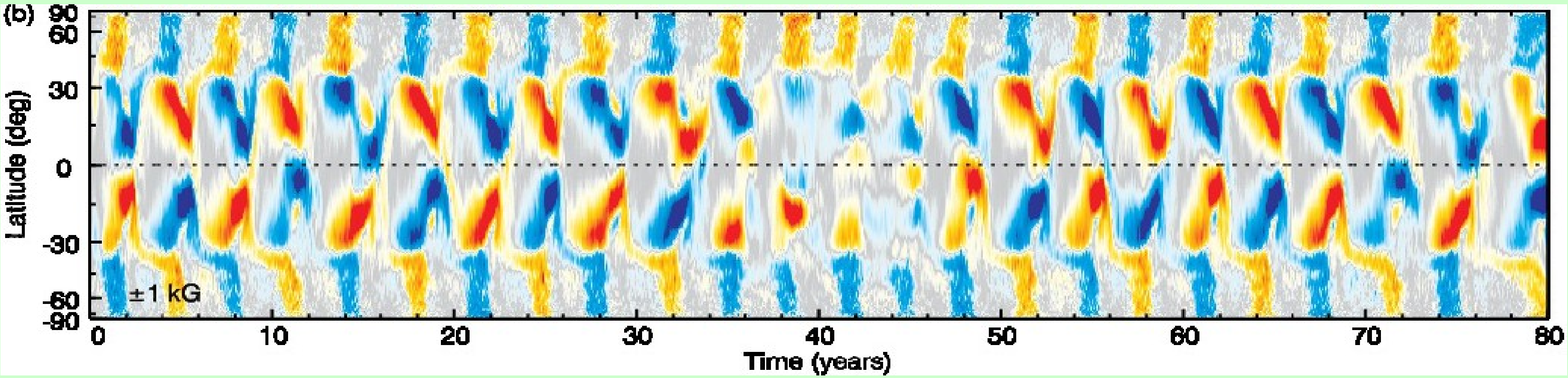


Intermittent



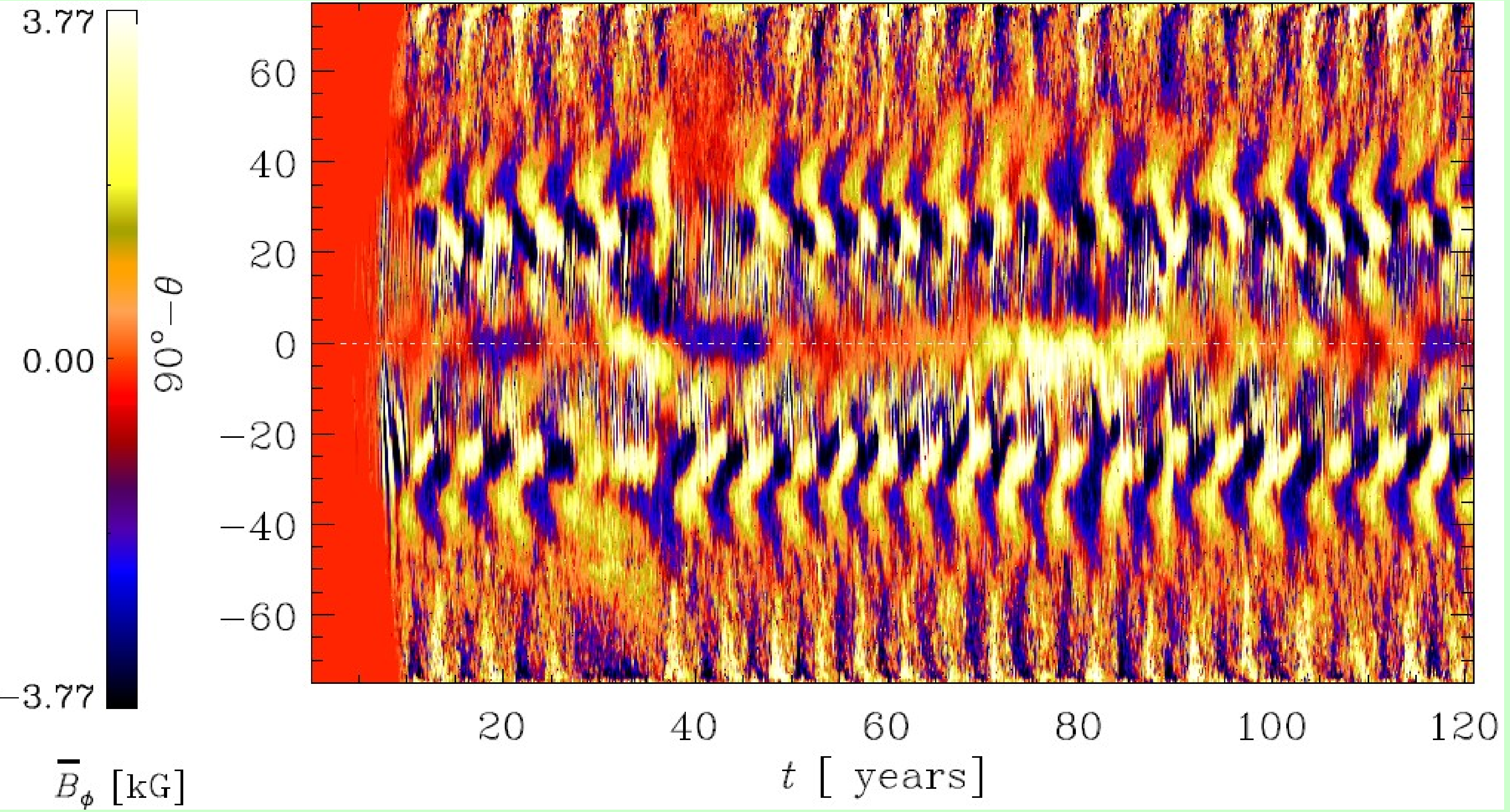
Karak, Kitchatinov & Brandenburg (2015)

People started seeing "grand minima-like" events in more realistic spherical global convection simulation!



Augustson et al. (2014)

"Grand minima-like" events in more realistic spherical global convection simulation



Kapyla et al. (in preparation)

Conclusion

1. We have found the evidence of dynamo hysteresis in turbulent simulations.

2. We have shown the intermittent magnetic cycles (which somewhat resembles the grand minima observed in Sun) in 3D simulations.
Intermittent magnetic cycle are only observed near the critical dynamo number only.

3. Two distinct modes of solar activity found in simulations are relevant to recently found in observations by Usoskin et al. (2014).

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Thank you