



Formation of intense bipolar regions in spherical dynamo

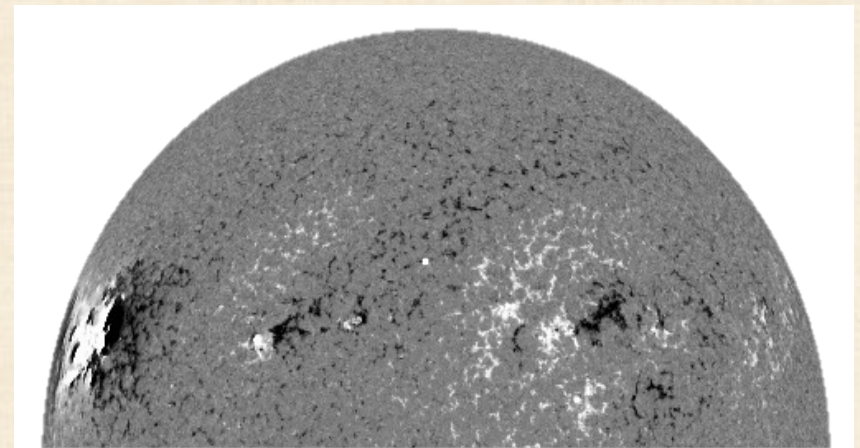
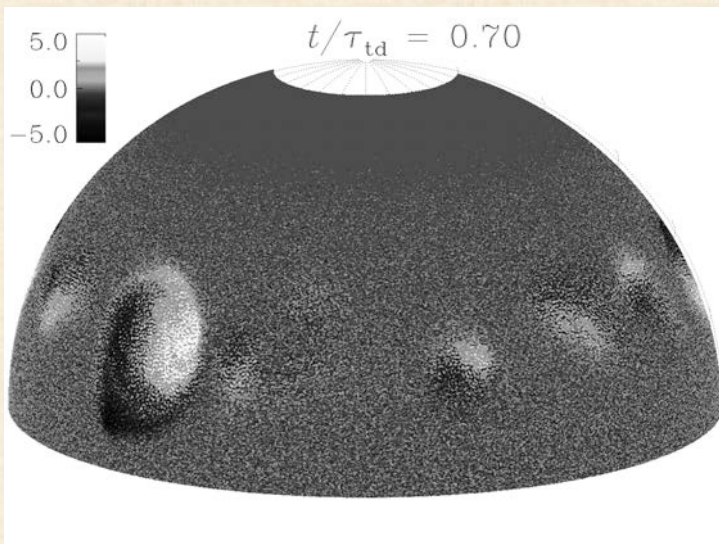
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Nathan Kleeorin ^{3,1,4}, **Dhrubaditya Mitra** ¹ & **Igor Rogachevskii** ^{3,1,4}

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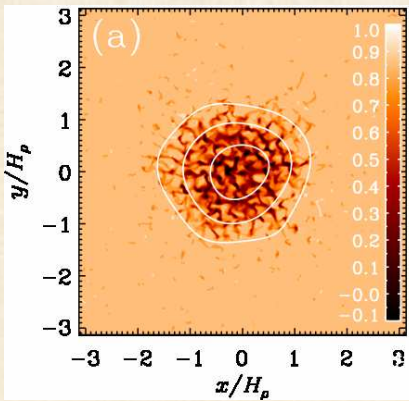


November 2014, Pune, India

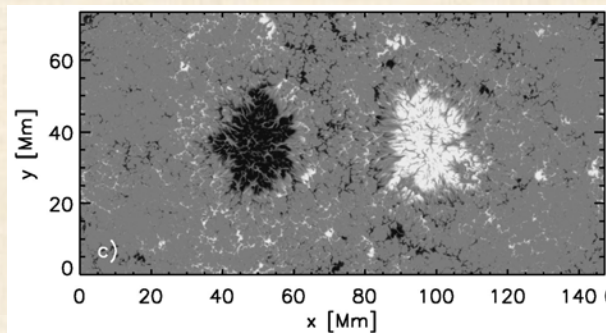


The origin of active regions and sunspots?

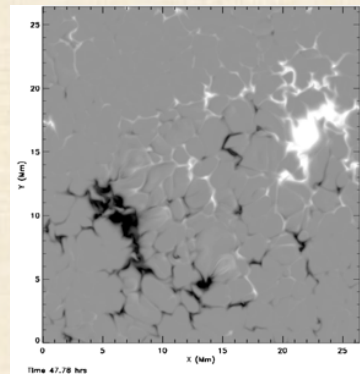
- Rising flux tube (Parker 55,79)
- Negative effective magnetic pressure instability (NEMPI) (Kleeorin+89,90)



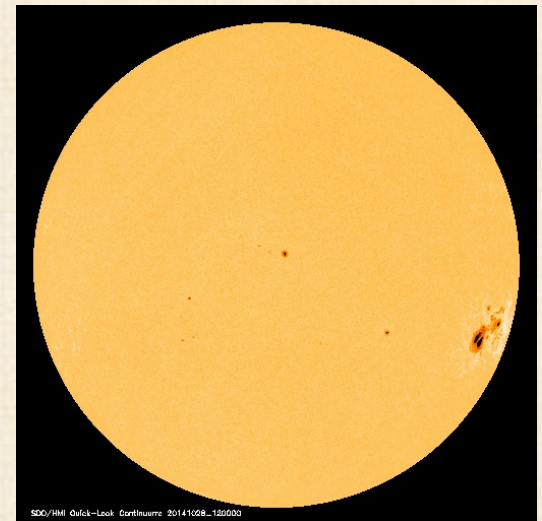
Brandenburg et al 2014



Rempel & Cheung 2014

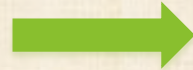


Steinl & Nordlund 2012



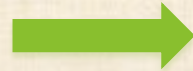
Motivation for the project

- Convenient results of Mean field simulations (MFS) by **Jabbari et al (2013)**

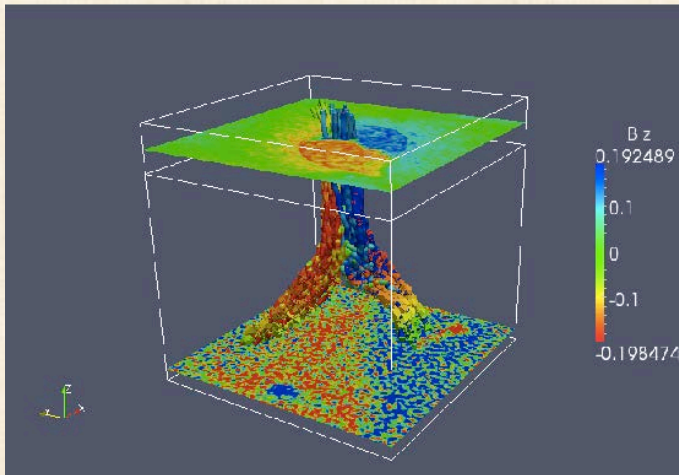


3D Direct numerical simulations (DNS)

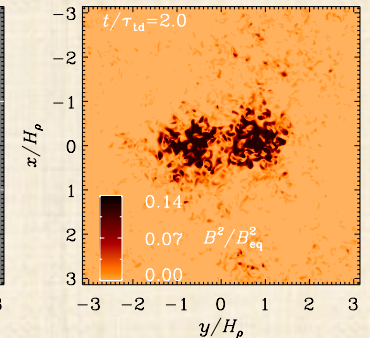
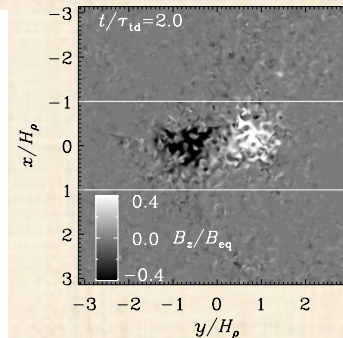
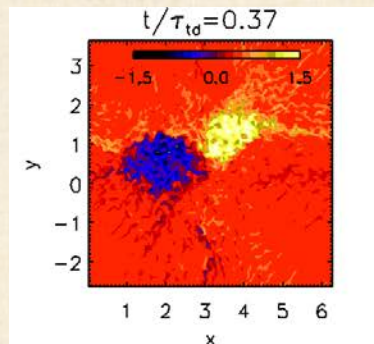
- Formation of bipolar regions with Superequipartition magnetic field



Spherical geometry
Physical boundary condition
Computing Negative effective magnetic pressure



Mitra et al 2014



Warnecke et al 2013

Two layer model

Two layer model with helical and no-helical forcing:

$$\rho \frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - c_s^2 \nabla \rho + \nabla \cdot (2\nu \rho \mathbf{S}) + \rho(\mathbf{f} + \mathbf{g}),$$

$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{U} \times \mathbf{B} + \eta \nabla^2 \mathbf{A},$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{U},$$

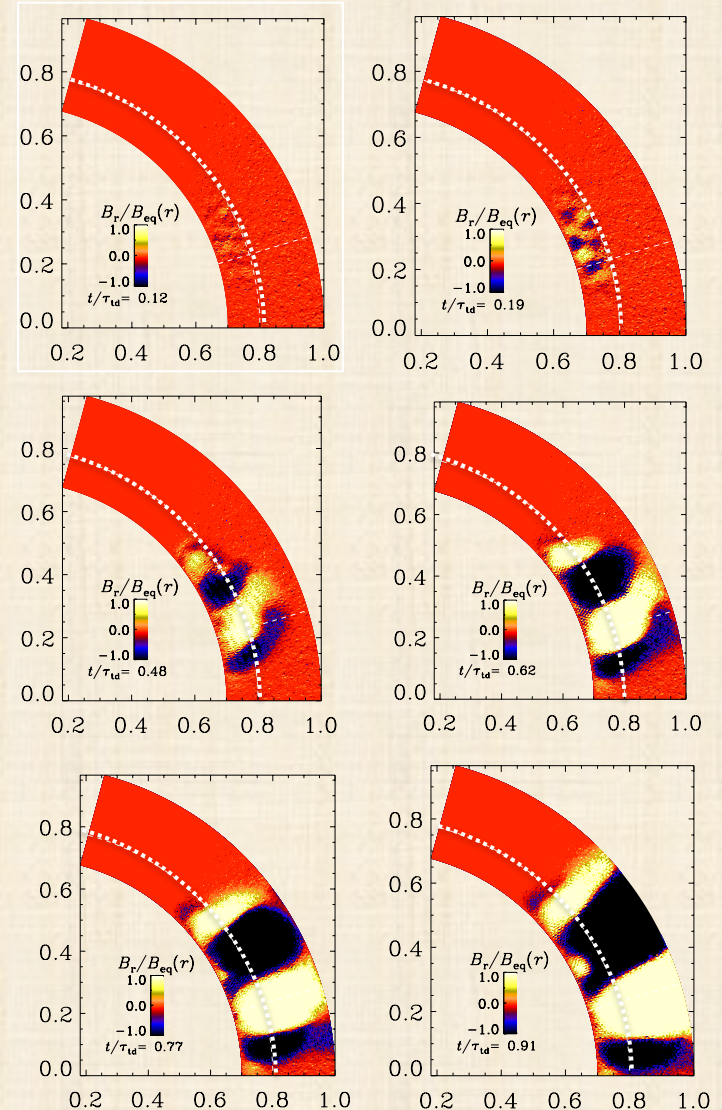
$$\mathbf{f}(\mathbf{x}, t) = \text{Re} \left[N \tilde{\mathbf{f}}(\mathbf{k}, t) \exp(i\mathbf{k} \cdot \mathbf{x} + i\varphi) \right]$$

$$\tilde{\mathbf{f}}(\mathbf{k}) = \mathbf{R} \cdot \tilde{\mathbf{f}}(\mathbf{k})^{(\text{nohel})} \quad \text{with} \quad R_{ij} = \frac{\delta_{ij} - i\sigma \epsilon_{ijk} \hat{k}}{\sqrt{1 + \sigma^2}},$$

$$\tilde{\mathbf{f}}(\mathbf{k})^{(\text{nohel})} = (\mathbf{k} \times \hat{\mathbf{e}}) / \sqrt{\mathbf{k}^2 - (\mathbf{k} \cdot \hat{\mathbf{e}})^2}$$

$$\sigma(r, \theta) = \frac{\sigma_{\max}}{2} \left[1 - \text{erf} \left(\frac{r - r_*}{w_f} \right) \right] \cos \theta \sin^n \theta$$

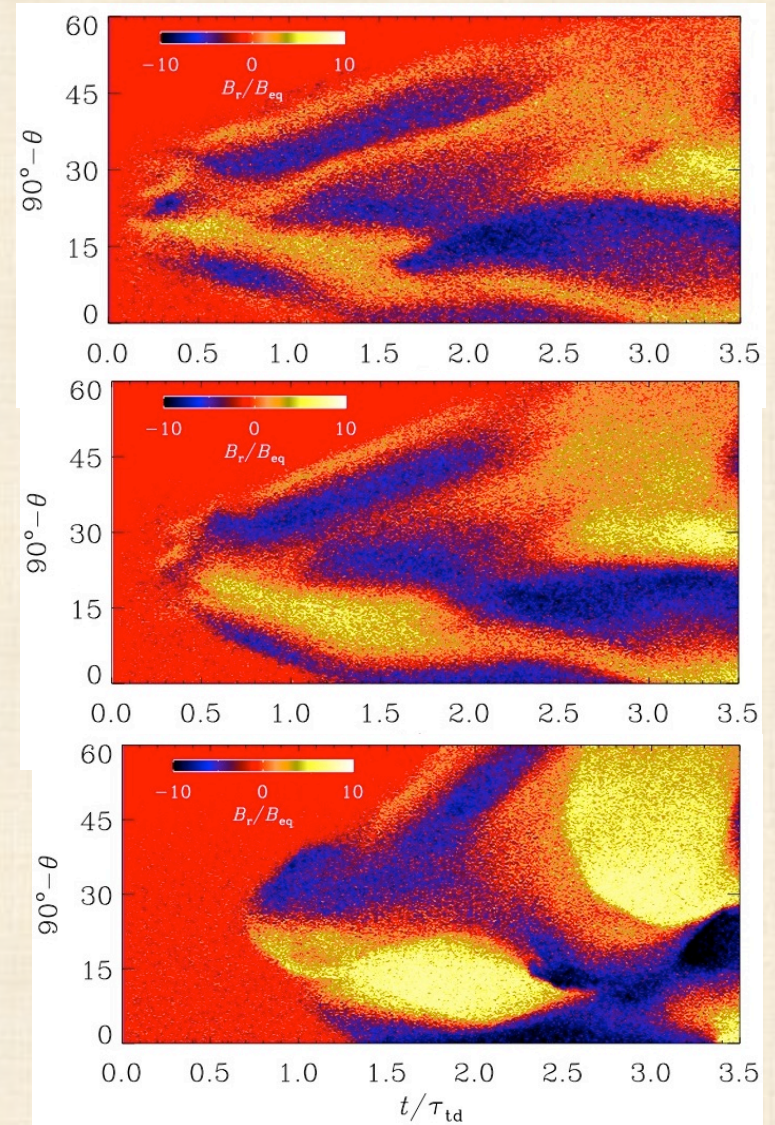
- High stratification
- Isothermal equation of state
- Pencil-Code simulation
- with resolution of 288×1152×1152
- No rotation



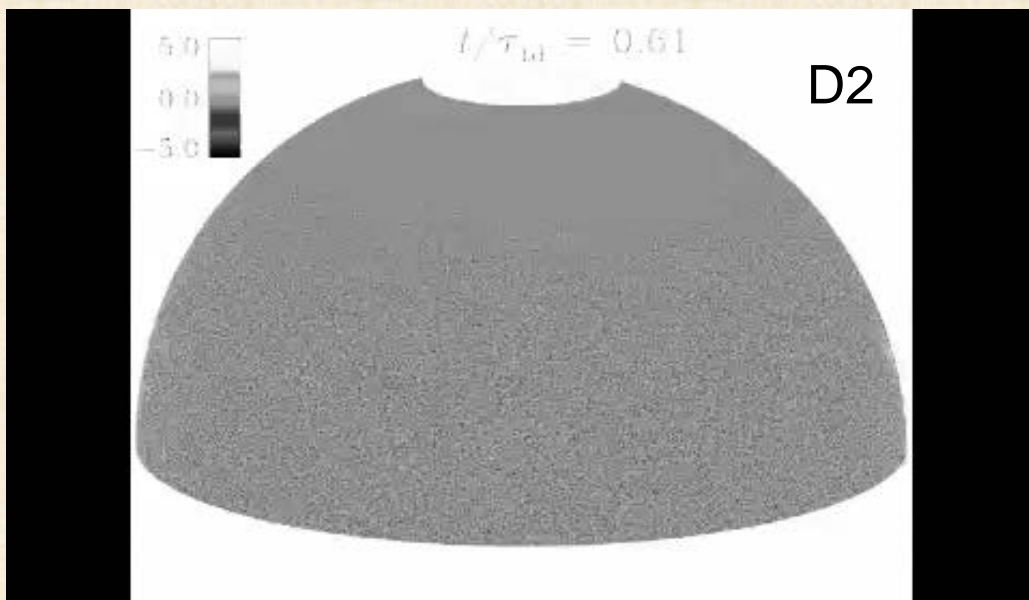
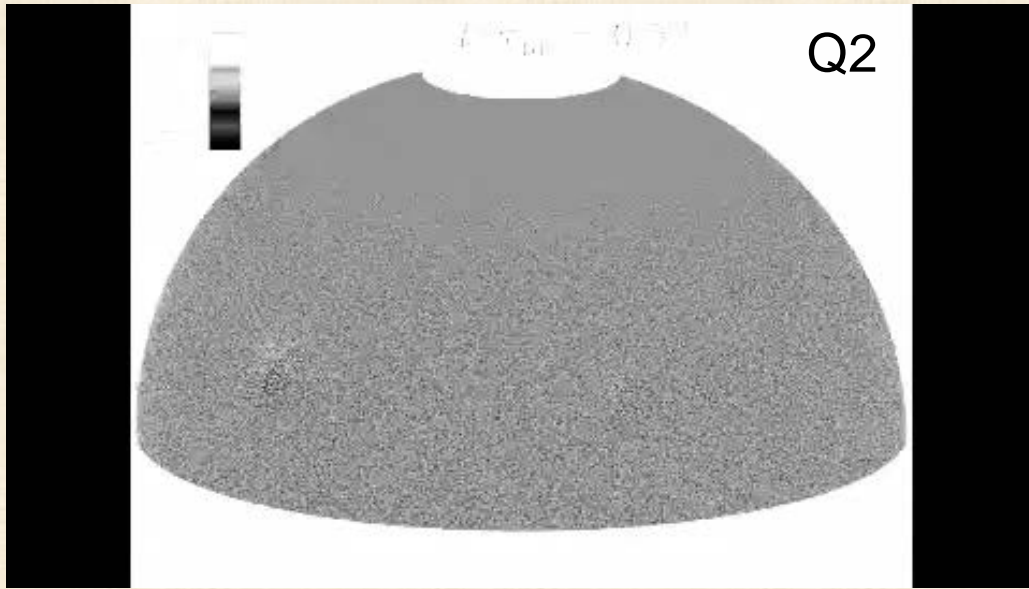
The results: nature of the dynamo

Butterfly diagram for our reference run (Run Q2 with $\Gamma\rho = 450$) at $r/R = 0.75$ (top), 0.8 (middle), and 0.95 (bottom).

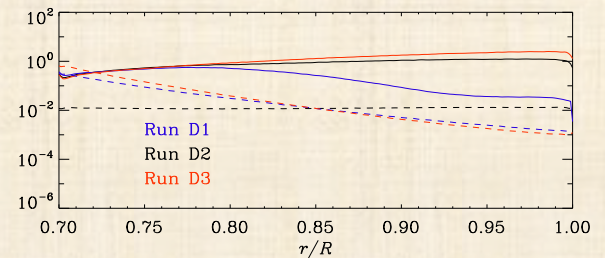
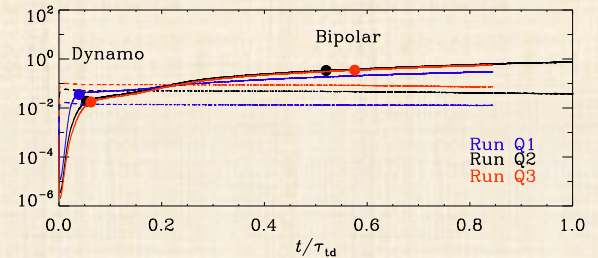
Run	Γ_ρ	r_*	ϕ ext.	Re_M	n	b.c.	σ_{\max}	$\tilde{\lambda}$
Q1	2	0.8	π	20	6	Q	1	0.079
Q2	450	0.8	π	20	6	Q	1	0.084
Q3	1400	0.8	π	20	6	Q	1	0.04
Q4	450	0.75	π	20	6	Q	1	0.074
D1	2	0.8	π	20	6	D	1	0.087
D2	450	0.8	π	20	6	D	1	0.082
D3	1400	0.8	π	20	6	D	1	0.077
D4	450	0.8	π	20	6	D	0.2	0.11
R1	450	0.8	$\pi/4$	20	6	D	1	0.0083
R2	450	0.8	$\pi/4$	40	6	D	1	0.075
H1	2	0.8	π	20	0	Q	1	0.087
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H4	450	0.75	π	20	0	Q	1	0.081



The results: bipolar structures

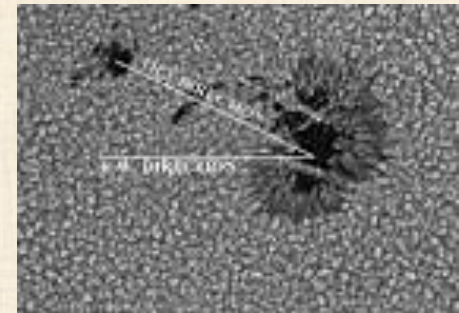
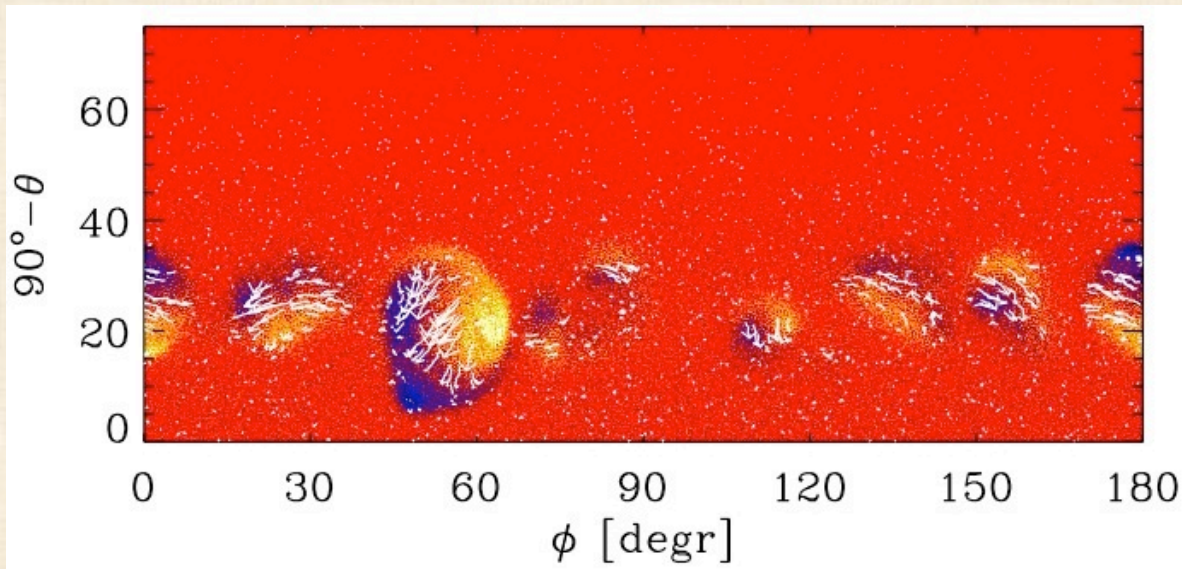


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The results: bipolar structures

- Our spots show a systematic East-West orientation with negative vertical field on the left and positive values on the right.
- Some of the regions also show a certain tilt.
- Most of the bipolar regions are oriented in a similar fashion.
- expected Ω loop scenario?



The Results: effective pressure

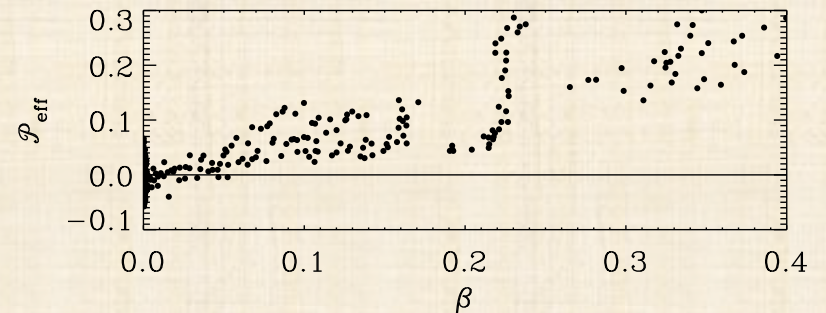
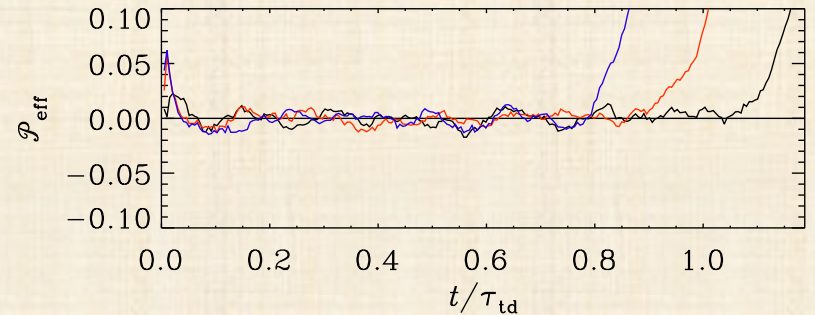
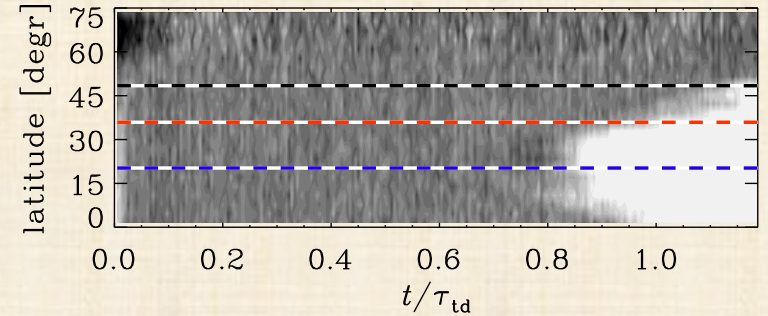
$$\Delta \bar{\Pi}_i^f = \bar{\rho} (\overline{u_i^2} - \overline{u_{0i}^2}) + \frac{1}{2} (\overline{b^2} - \overline{b_0^2}) - (\overline{b_i^2} - \overline{b_{0i}^2}),$$

$$\Delta \bar{\Pi}_i(r, \theta, t) = \bar{\Pi}_i(r, \theta, t) - \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \bar{\Pi}_i(r, \theta, t') dt'$$

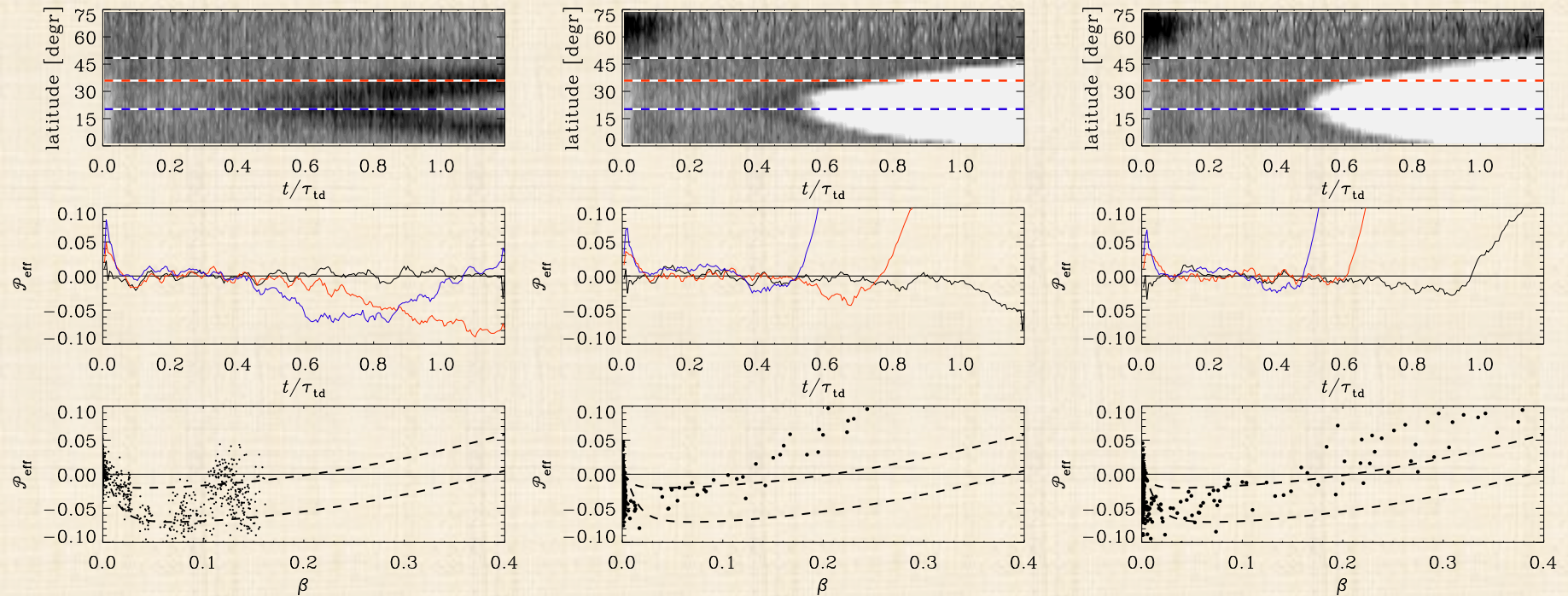
$$q_p = - (\Delta \bar{\Pi}_\theta + \Delta \bar{\Pi}_\phi) / \bar{B}^2$$

$$\mathcal{P}_{\text{eff}} = \frac{1}{2} (1 - q_p) \beta^2$$

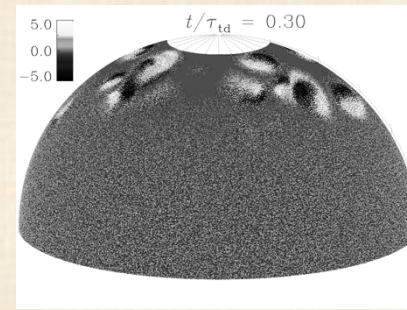
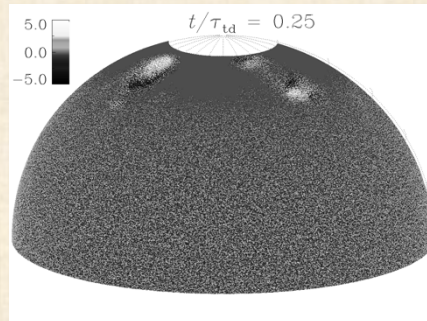
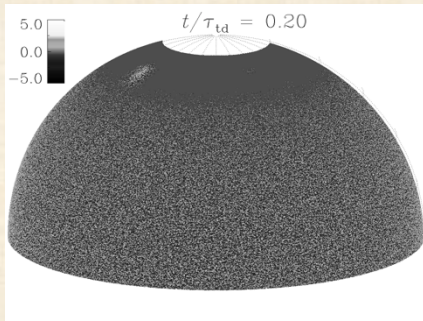
$$q_p(\beta) = \beta_*^2 / (\beta_p^2 + \beta^2)$$



The Results: Effective pressure



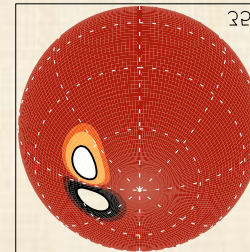
The results: high latitude spots



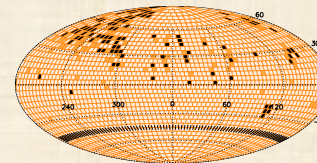
Jabbari et al 2013

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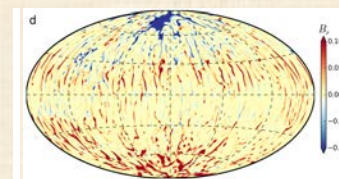
Isik et al 2007



August 7 - "6120 Å"

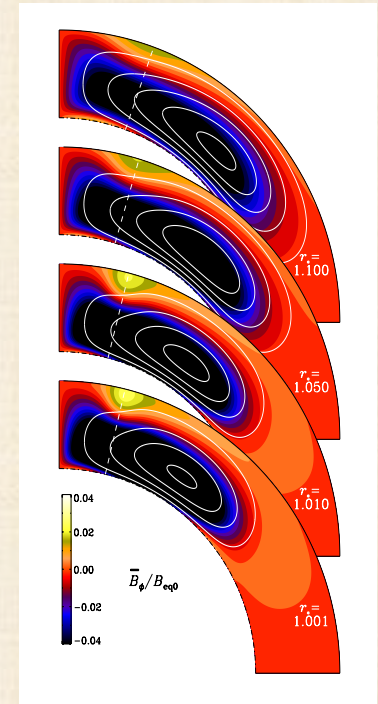


Wolter et al 2005



Yadav et al 2014

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Summary

- Formation of sharp spot-like structures in a strongly stratified two-layer spherical model with helical turbulence in the lower and non-helical turbulence in the upper one.
- Confirmation of the results of Mitra et al 2014 in spherical geometry and for a much larger domain
- For the first time, the bipolar magnetic spots have a finite size and more than 10 time equipartition field strength.
- Stratification as an essential element behind the spot formation
- Delayed appearance of the structure for weaker σ or smaller r_*
- The physics behind the spot formation?

THANKS FOR YOUR ATTENSTION