Understanding the solar dynamo from numerical simulations

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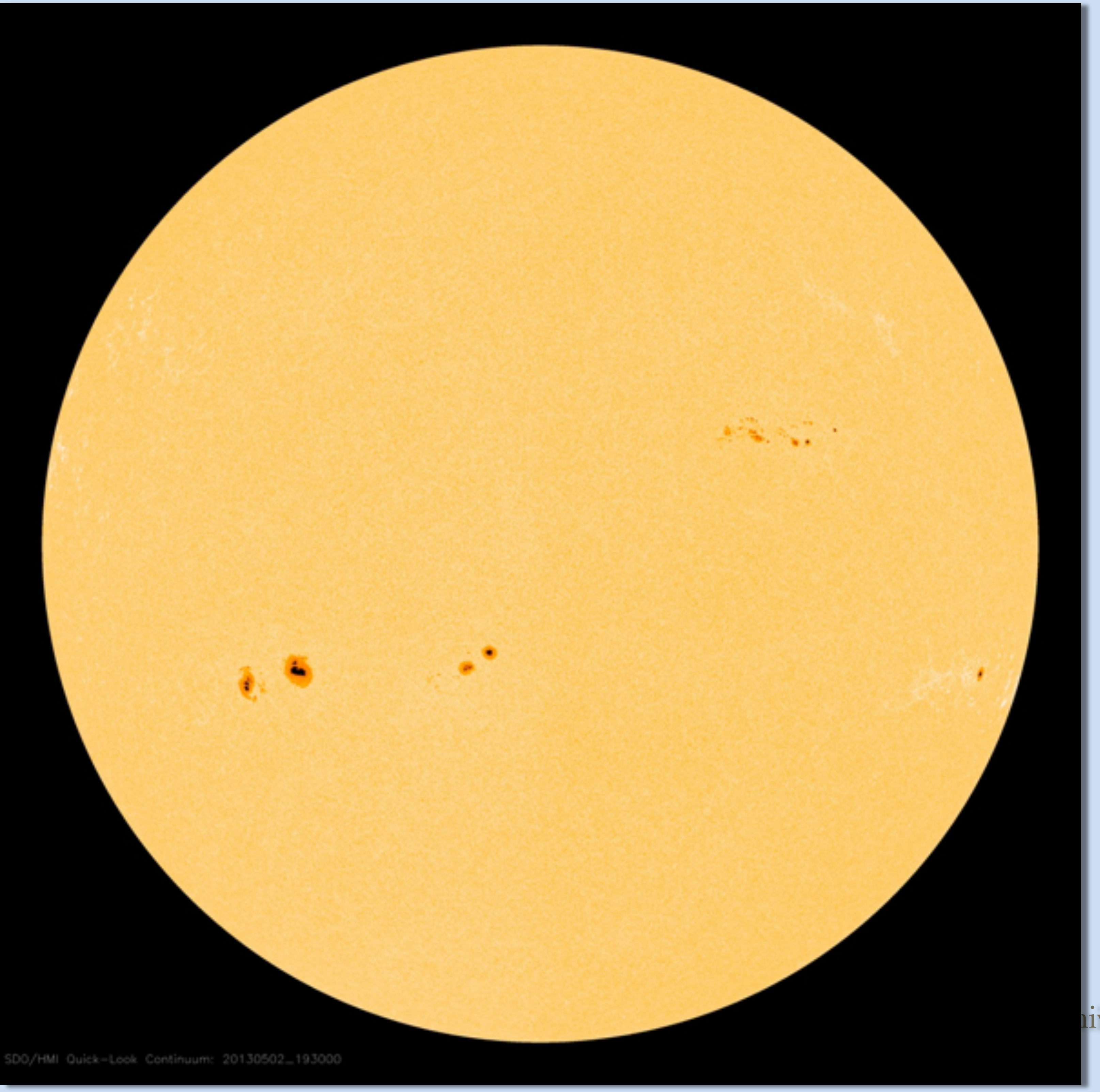
The Sun

The Sun



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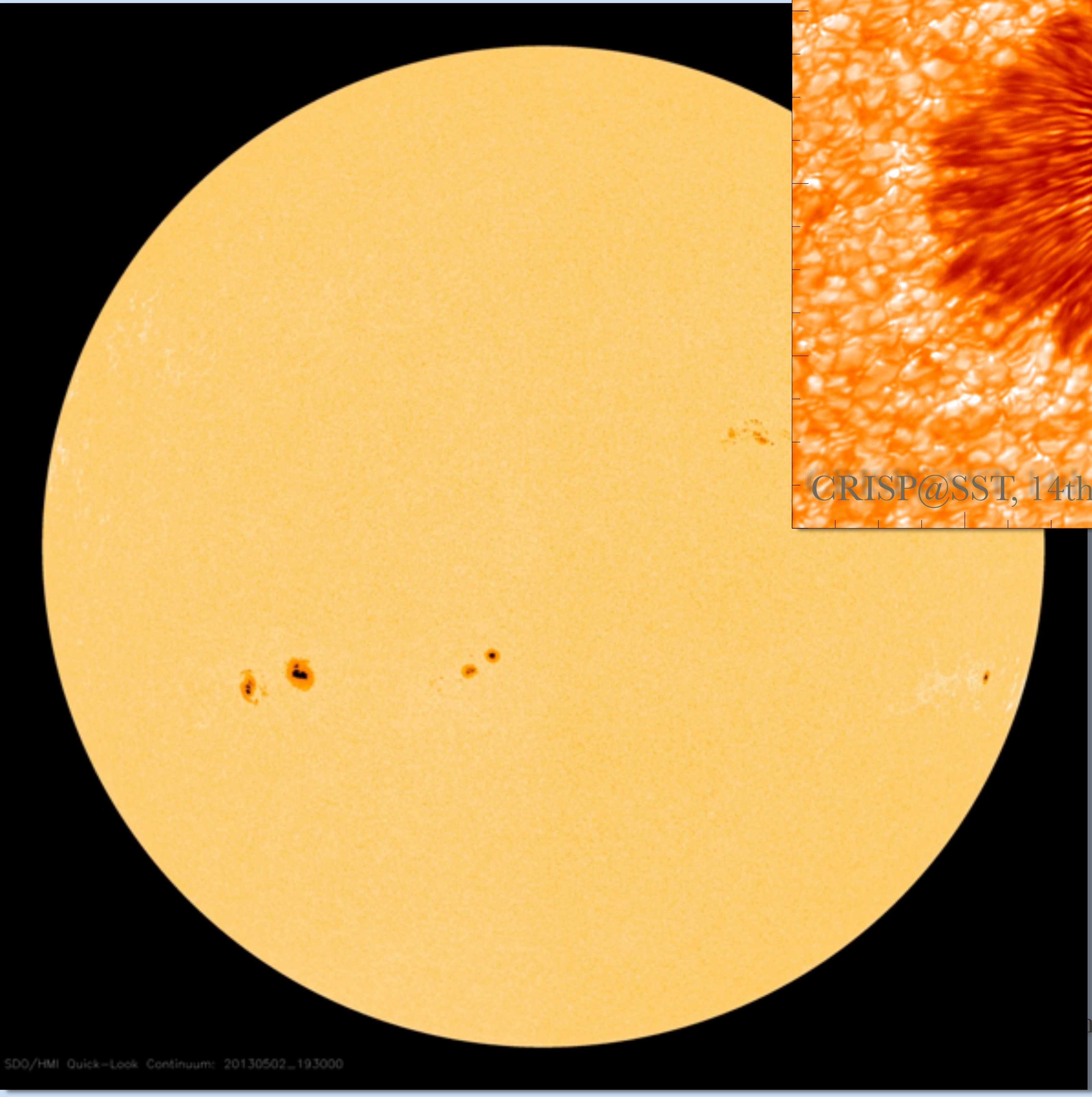
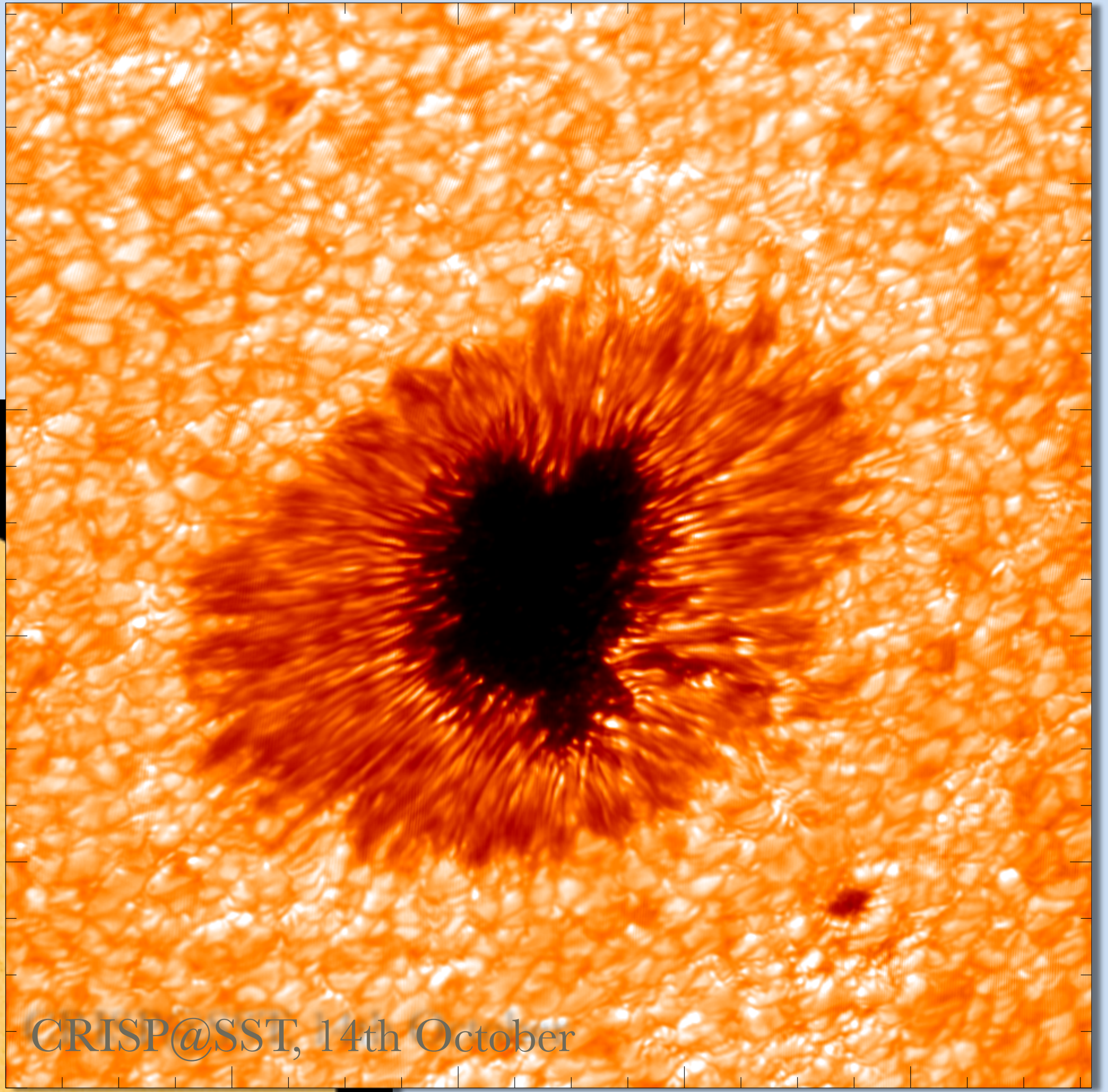
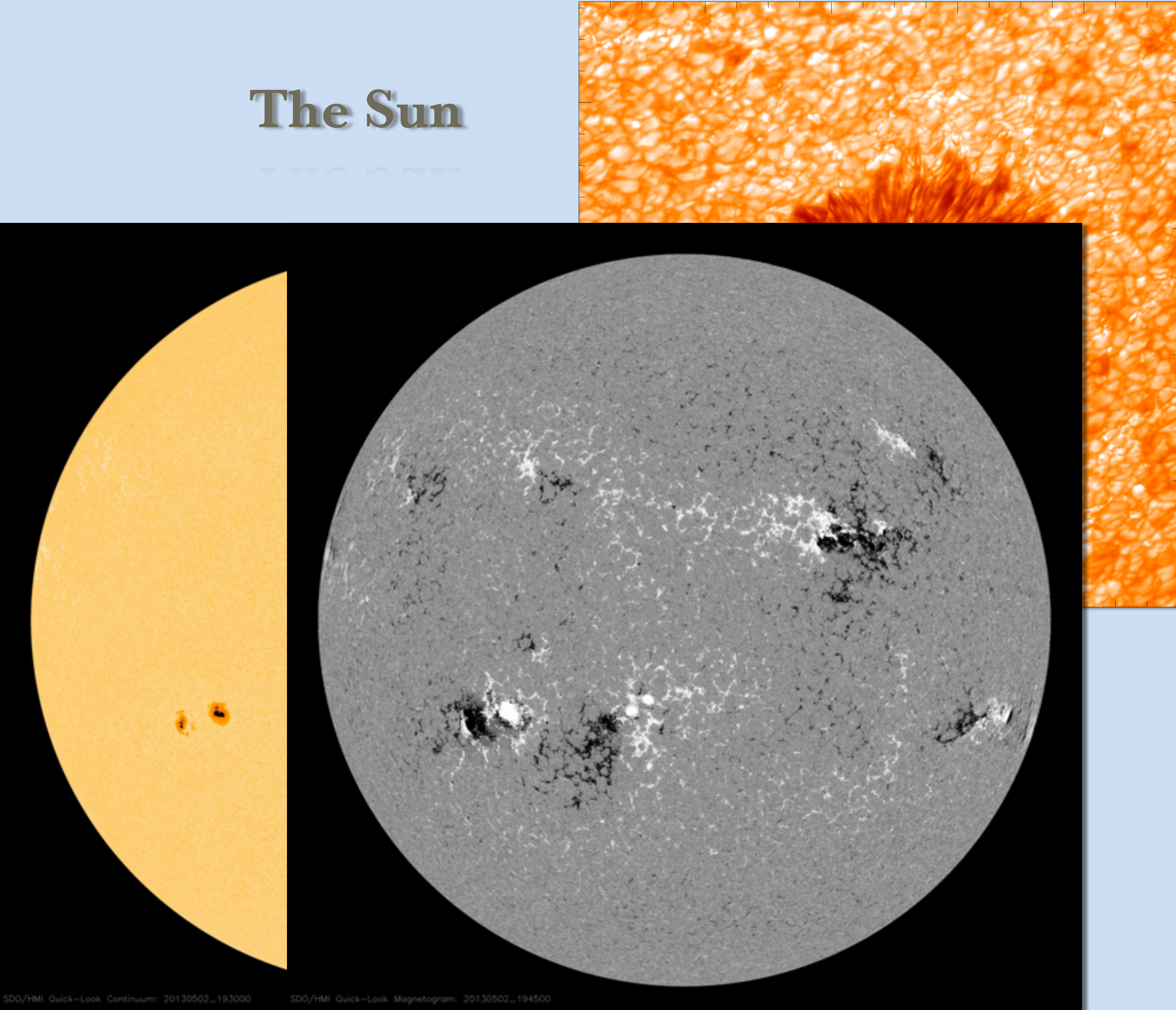
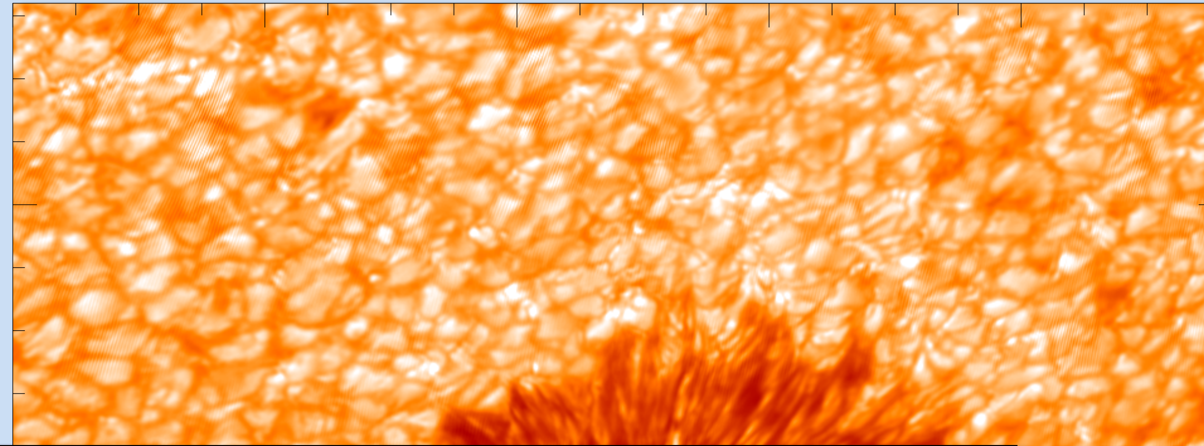

SDO/HMI Quick-Look Continuum: 20130502_193000

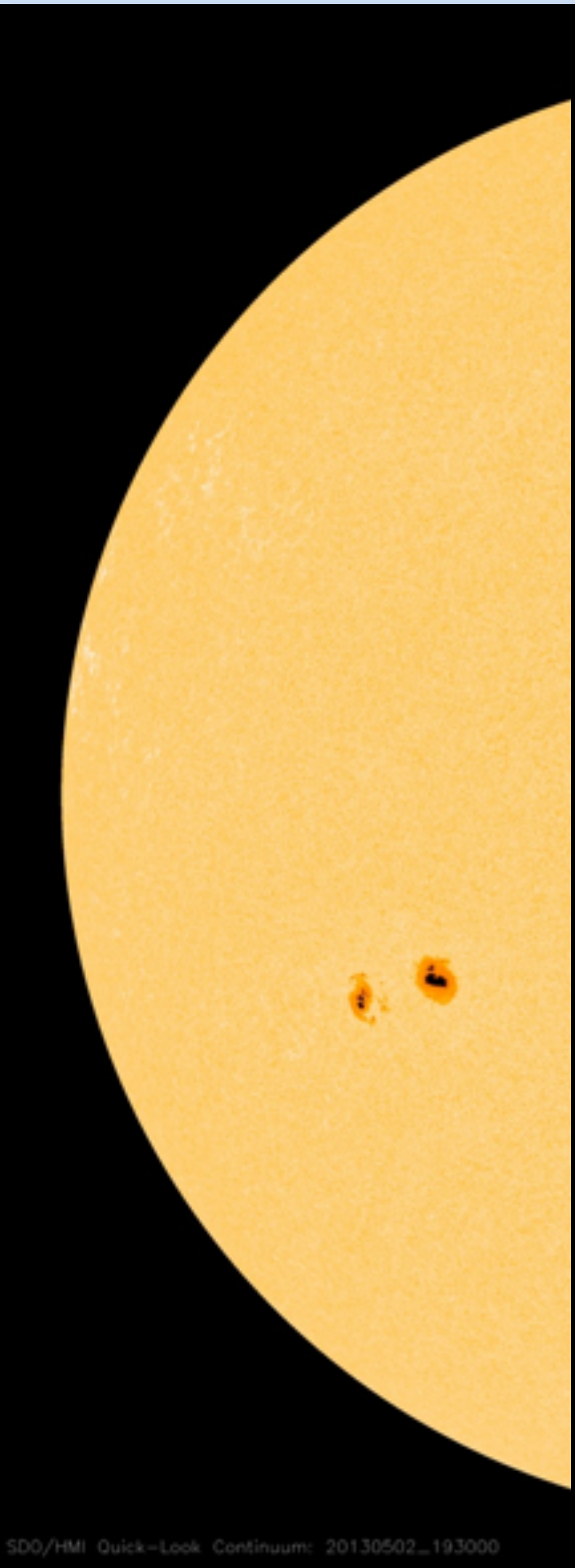

CRISP@SST, 14th October

The Sun


SDO/HMI Quick-Look Continuum: 20130502_193000
SDO/HMI Quick-Look Magnetogram: 20130502_194500

The Sun

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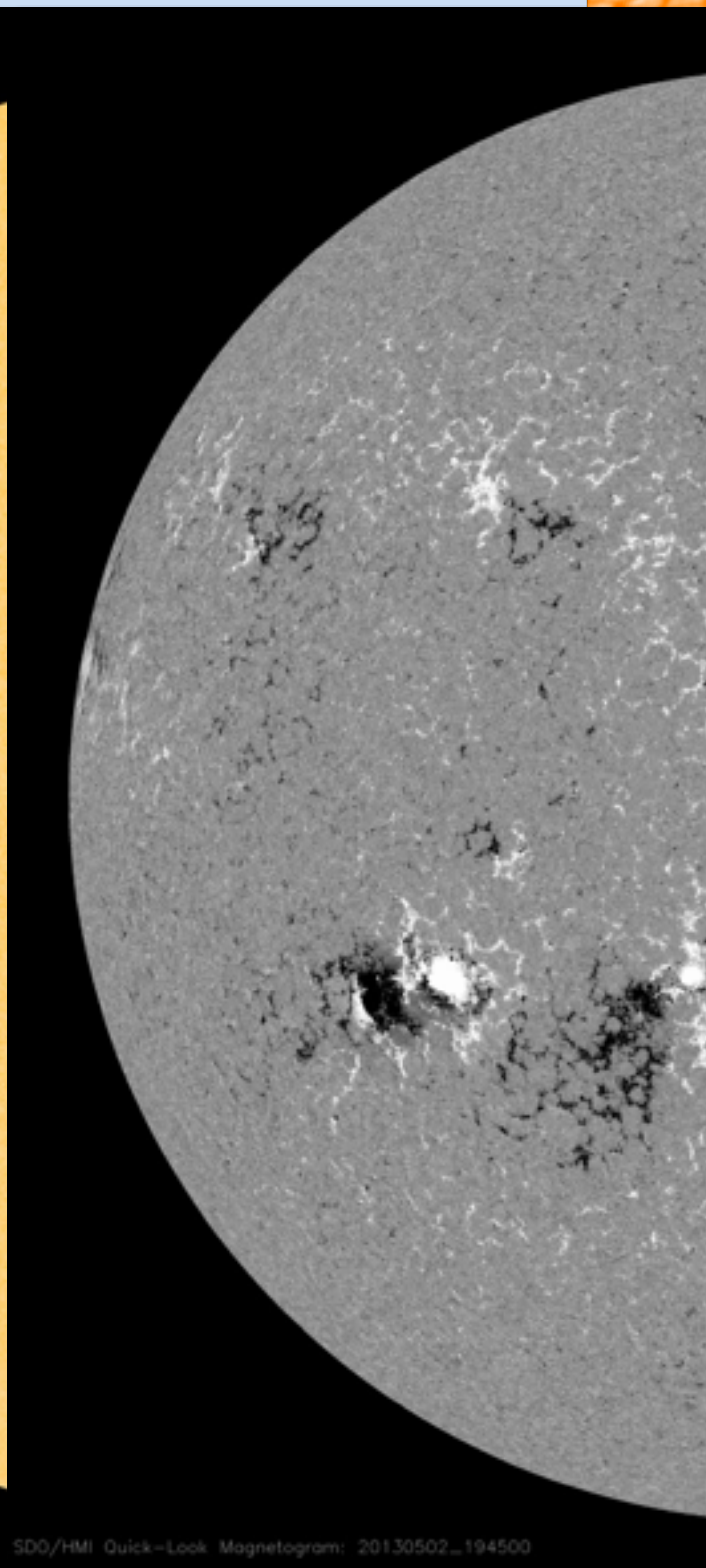
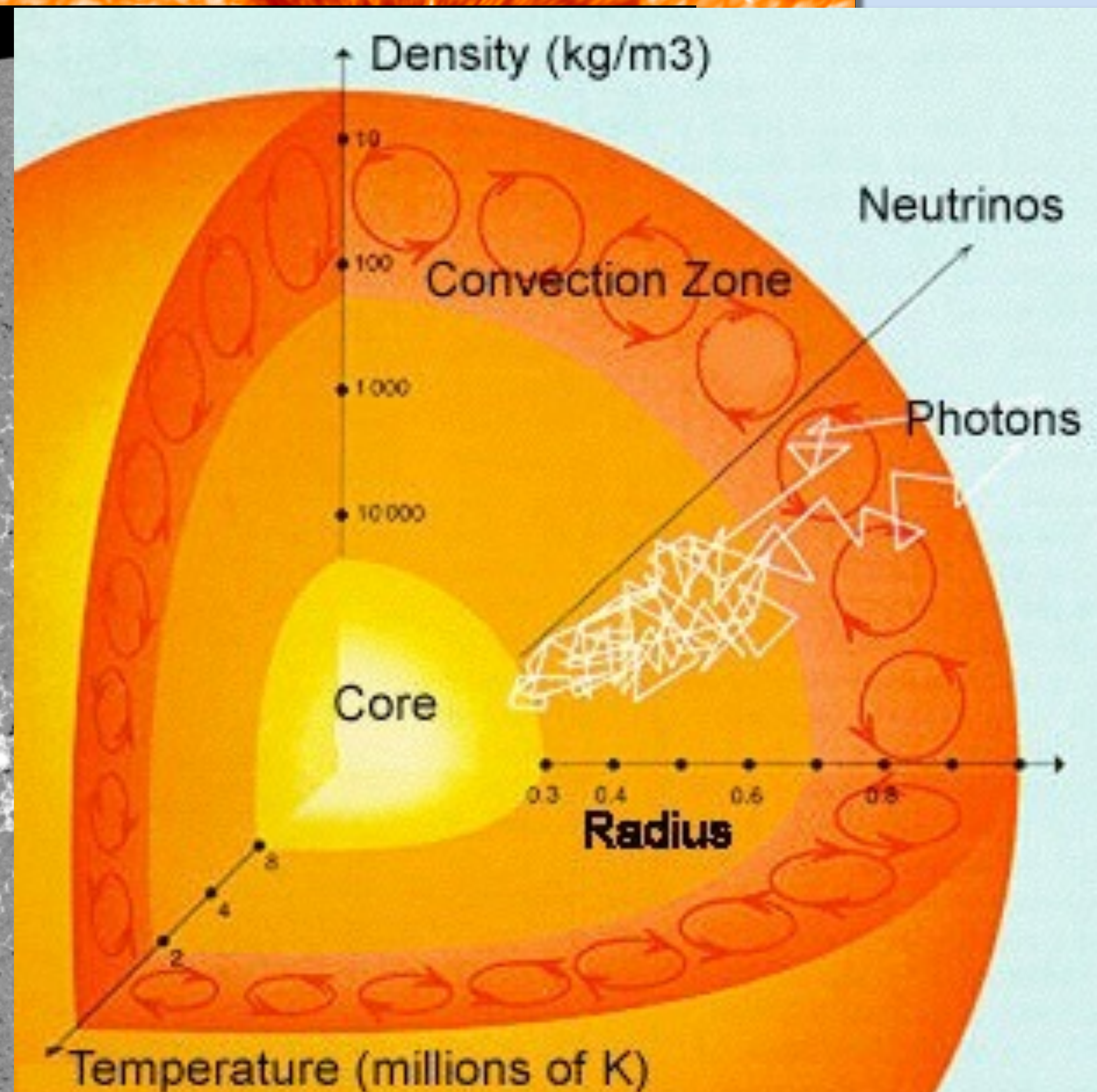
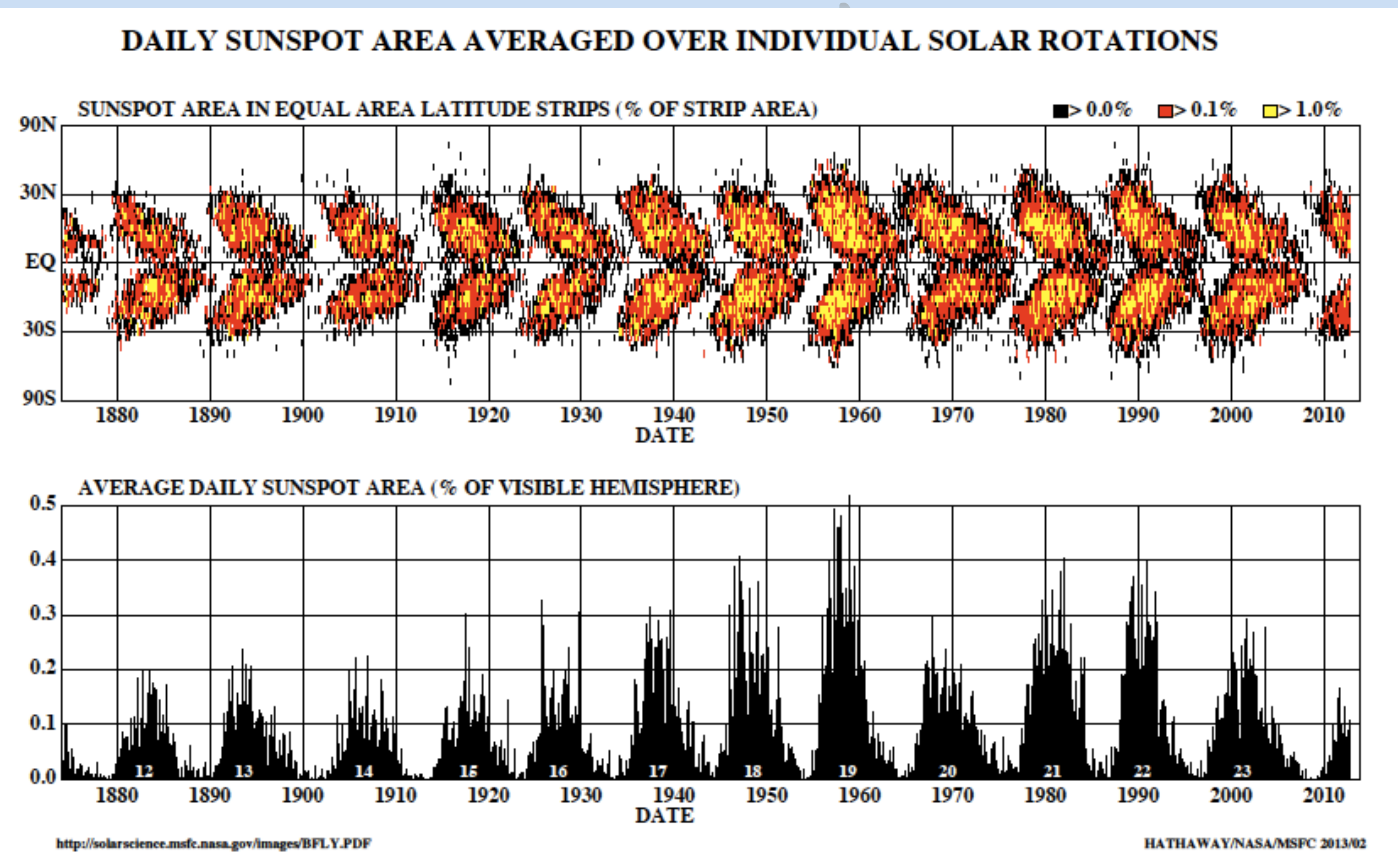
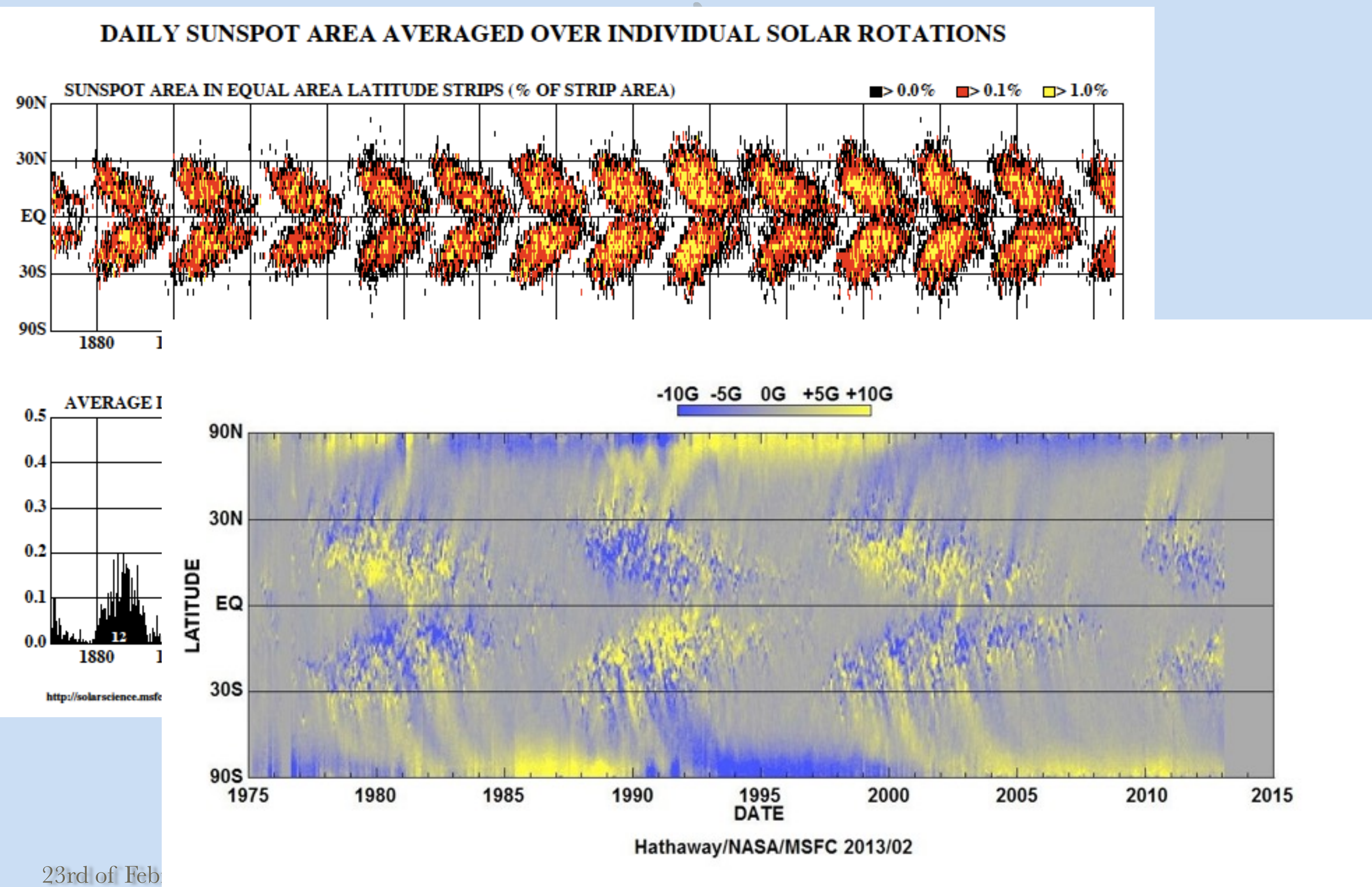

SDO/HMI Quick-Look Magnetogram: 20130502_194500


Density (kg/m3)
10
100
1000
10000
Convection Zone
Neutrinos
Photons
Core
0.3
0.4
0.6
0.8
Radius
2
4
6
Temperature (millions of K)

Solar Cycle


DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS
SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)
> 0.0%
> 0.1%
> 1.0%
90N
30N
EQ
30S
90S
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
DATE
AVERAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)
0.5
0.4
0.3
0.2
0.1
0.0
12
13
14
15
16
17
18
19
20
21
22
23
http://solarscience.msfc.nasa.gov/images/BFLY.PDF
HATHAWAY/NASA/MSFC 2013/02

Solar Cycle



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-10G -5G 0G +5G +10G
LATITUDE
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30N
EQ
30S
90S
1975
1980
1985
1990
1995
2000
2005
2010
2015
DATE
Hathaway/NASA/MSFC 2013/02

Maxwell's equations

Hydrodynamics

Maxwell's equations

Hydrodynamics

Magnetohydrodynamics

Maxwell's equations

Hydrodynamics

Magnetohydrodynamics

1. quasi-neutrality
2. non-relativistic
3. no EM waves

Maxwell's equations

Hydrodynamics

1. quasi-neutrality
2. non-relativistic
3. no EM waves

Magnetohydrodynamics

$$\frac{\partial B}{\partial t} = \nabla \times (u \times B) - \nabla \times \eta J$$

$$\frac{D \ln \rho}{Dt} = -\nabla \cdot u$$

$$\frac{Du}{Dt} = g + \frac{1}{\rho}(J \times B - \nabla p + \nabla \cdot 2\nu\rho S)$$

+ energy equation

+ equation of state

Governing Parameters

Reynolds number

$$\mathrm{Re} = u_{\mathrm{rms}}/\nu \mathrm{k_f}$$

In the Sun:

10^{12} ... 10^{13}

magnetic Reynolds number

$$\mathrm{Re_M} = u_{\mathrm{rms}}/\eta \mathrm{k_f}$$

10^{8} ... 10^{9}

Dynamos

$$\frac{\partial B}{\partial t} = \nabla \times (u \times B) - \nabla \times \eta J$$

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$$\frac{\partial \overline{B}}{\partial t} = \nabla \times (\overline{U} \times \overline{B} + \overline{u' \times b'}) - \nabla \times \eta \overline{J}$$

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$$\nabla \times (\overline{U} \times \overline{B}) = (\overline{B} \cdot \nabla)\overline{U} - \overline{B}(\nabla \cdot \overline{U}) - (\overline{U} \cdot \nabla)\overline{B}$$

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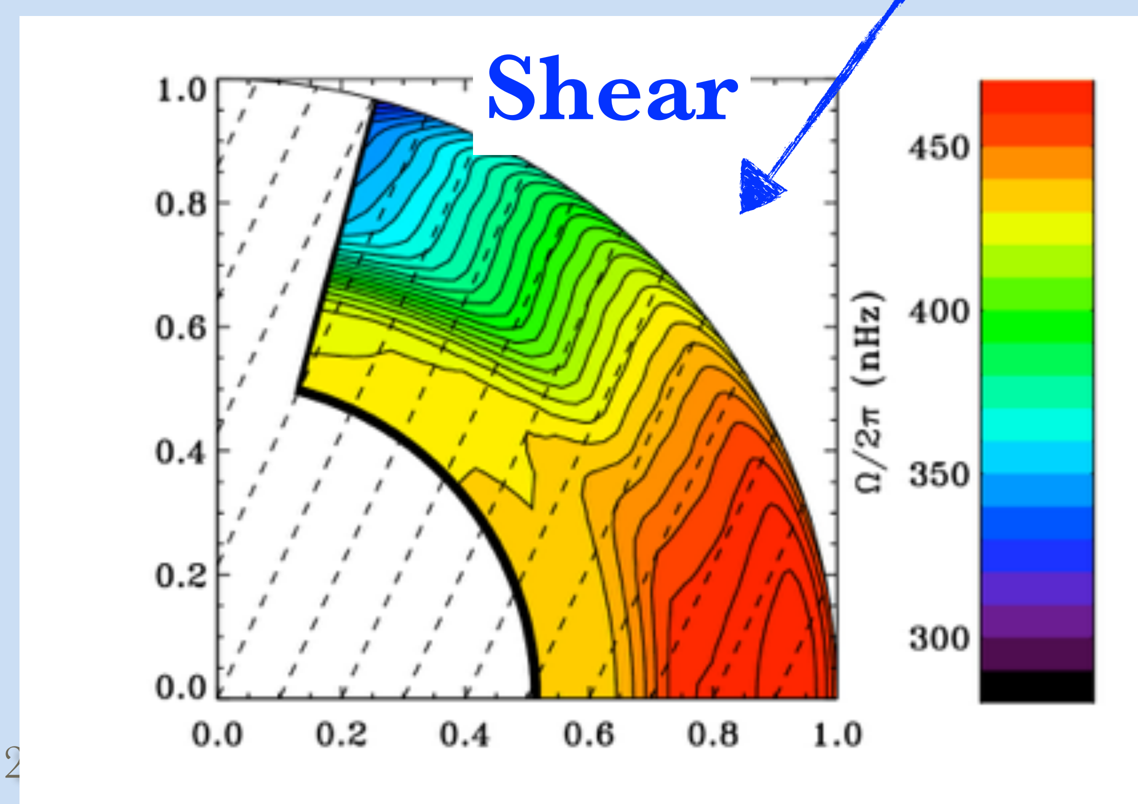

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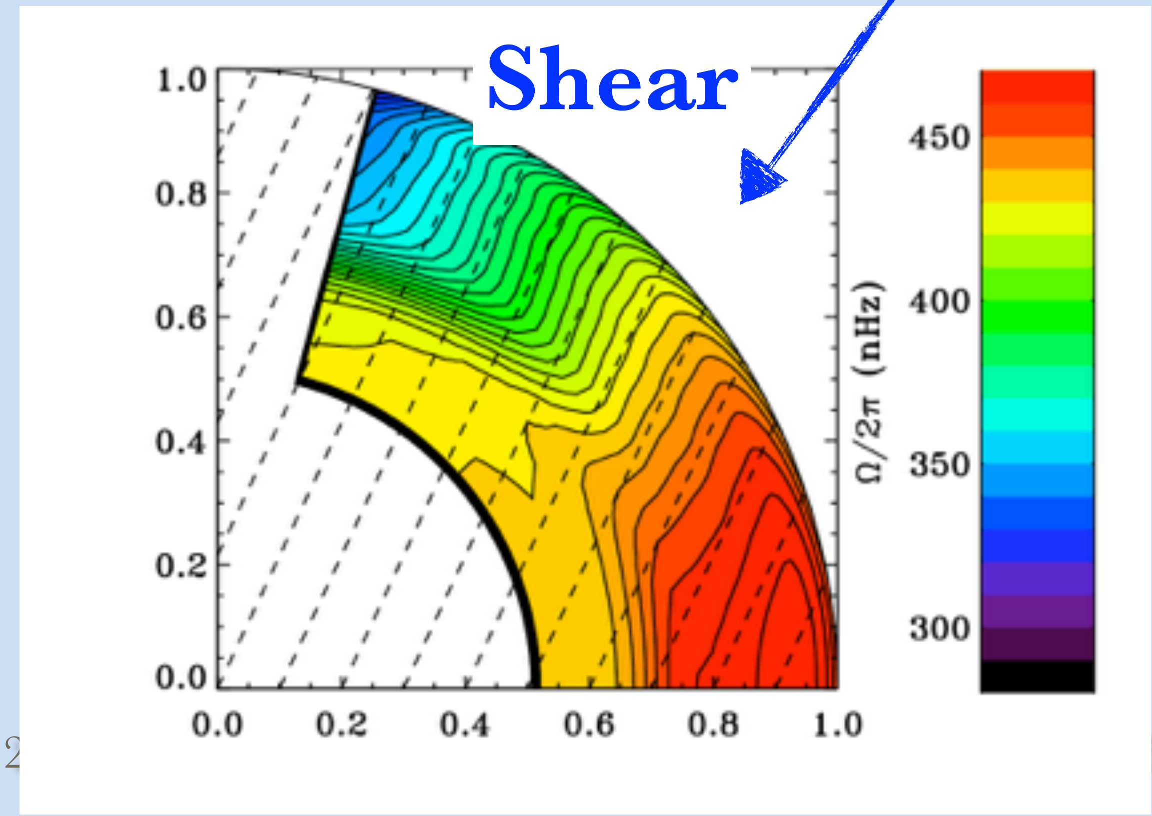

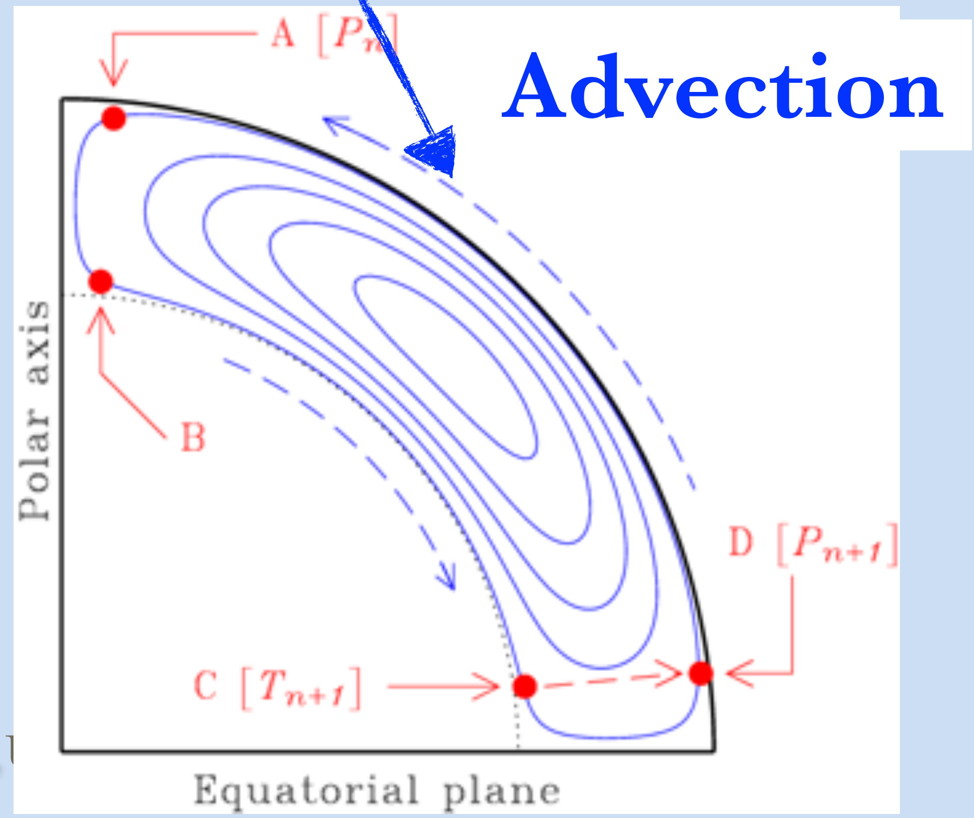

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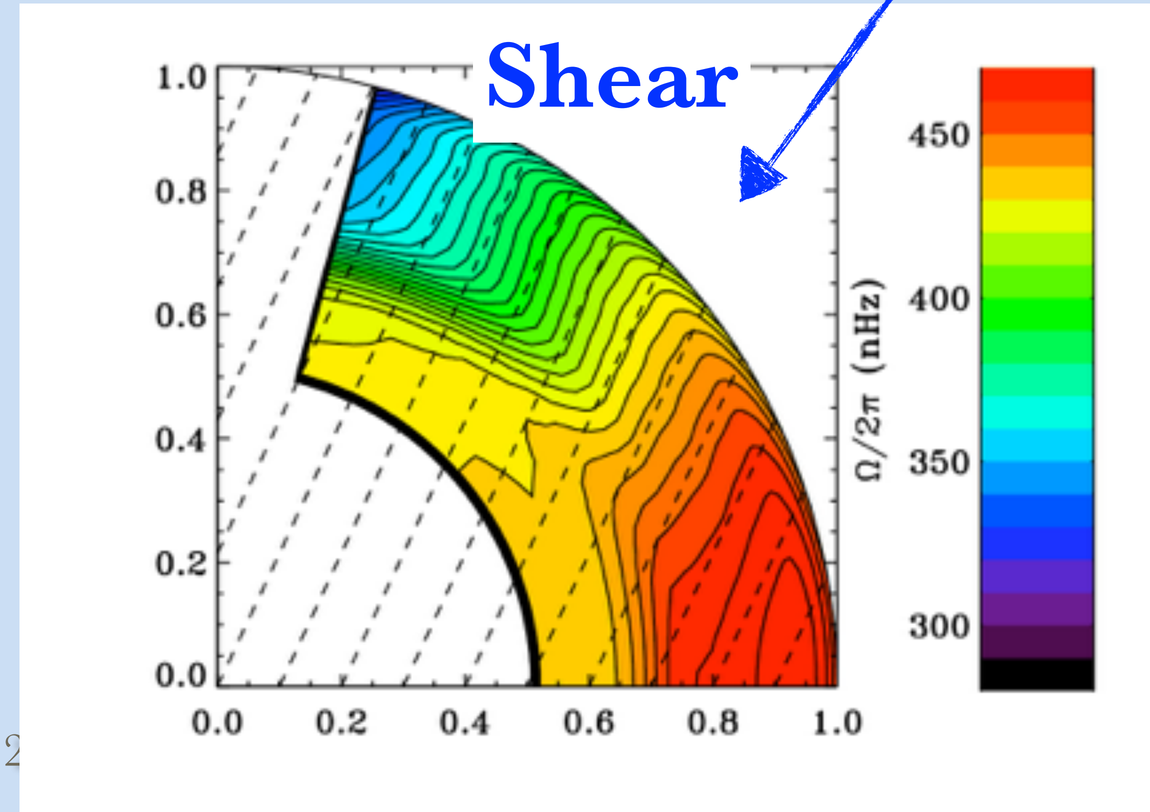
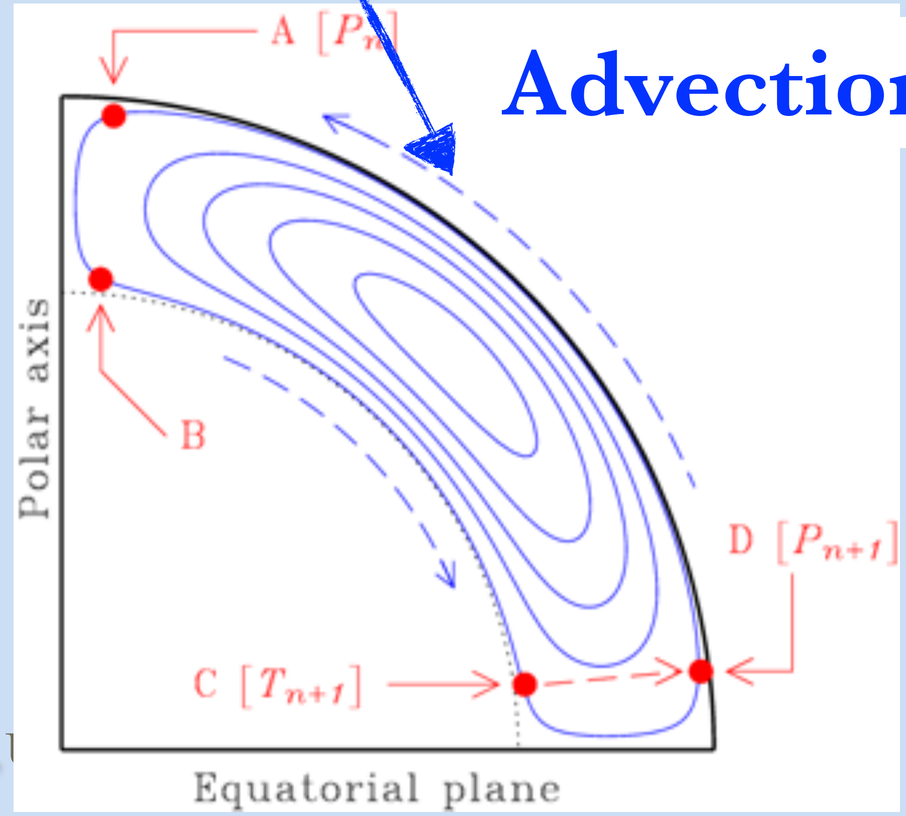
$$\nabla \times (\overline{U} \times \overline{B}) = (\overline{B} \cdot \nabla)\overline{U} - \overline{B}(\nabla \cdot \overline{U}) - (\overline{U} \cdot \nabla)\overline{B}$$

Shear



Advection



Electromotive force

$$\overline{\mathcal{E}} = \overline{u' \times b'}$$

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Simplifications:

Electromotive force

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Simplifications:

$$\alpha = \frac{\tau_{\mathrm{c}}}{3}\left(-\overline{\boldsymbol{\omega}\cdot\boldsymbol{u}} + \frac{\overline{\boldsymbol{j}\cdot\boldsymbol{b}}}{\overline{\rho}}\right)$$

Pouquet et al. 1976

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Simplifications:

$$\alpha = \frac{\tau_c}{3} \left(-\overline{\boldsymbol{\omega} \cdot \boldsymbol{u}} + \frac{\overline{\boldsymbol{j} \cdot \boldsymbol{b}}}{\overline{\rho}} \right)$$

Pouquet et al. 1976

$$\overline{B} = \overline{B}_{\mathrm{pol}} + \overline{B}_{\mathrm{tor}}$$

$$\frac{\partial \overline{B}_{\mathrm{pol}}}{\partial t} = \alpha \nabla \times \overline{B}_{\mathrm{tor}} + \eta_T \Delta \overline{B}_{\mathrm{pol}}$$

$$\frac{\partial \overline{B}_{\mathrm{tor}}}{\partial t} = (\overline{B}_{\mathrm{pol}} \cdot \nabla) \overline{u}_{\mathrm{tor}} + \alpha \nabla \times \overline{B}_{\mathrm{pol}} + \eta_T \Delta \overline{B}_{\mathrm{tor}}$$

How to solves the problem I

How to solves the problem I

1. Observational constrains

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    a) Surface observations + solar cycle evolution

How to solves the problem I

1. Observational constrains

   a) Surface observations + solar cycle evolution

   b) Helioseismology

How to solves the problem I

1. Observational constrains

   a) Surface observations + solar cycle evolution

   b) Helioseismology

   c) Other stars

How to solves the problem I

1. Observational constrains

   a) Surface observations + solar cycle evolution

   b) Helioseismology

   c) Other stars

→ Tail of the dog?

Not everything, but more than we think!

How to solves the problem II

How to solves the problem II

2. Mean-field modeling

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- Put physics in as you want.

How to solves the problem II

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- Put physics in as you want.
- Control experiments.

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- Put physics in as you want.
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- Tunable parameters.

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- Put physics in as you want.
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- Good parameters come from observations or fundamental theories.

How to solves the problem II

2. Mean-field modeling

- Put physics in as you want.
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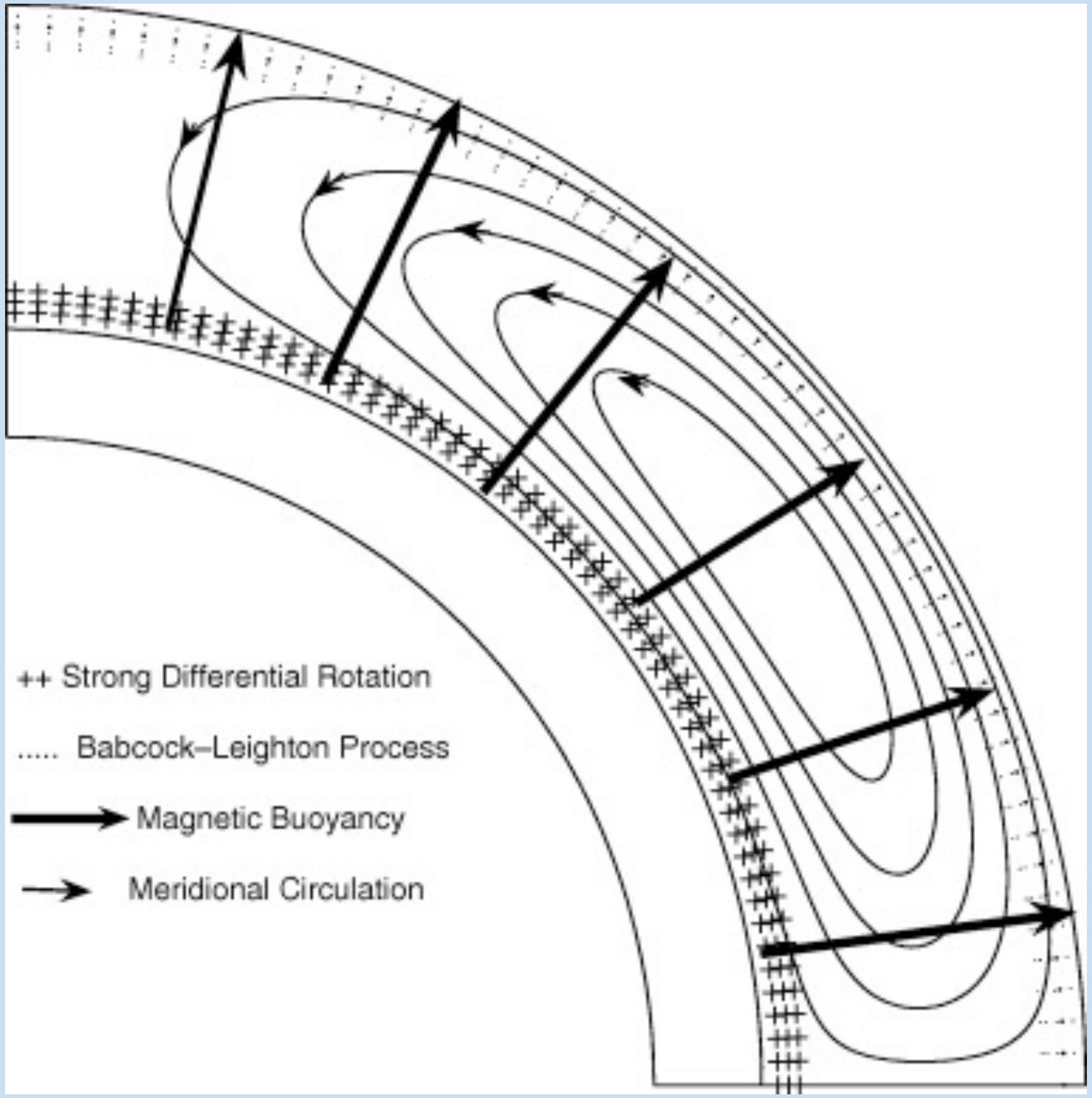
- Good parameters come from observations or fundamental theories.

→ Reproducing the Sun’s magnetic field is possible with many different approaches.

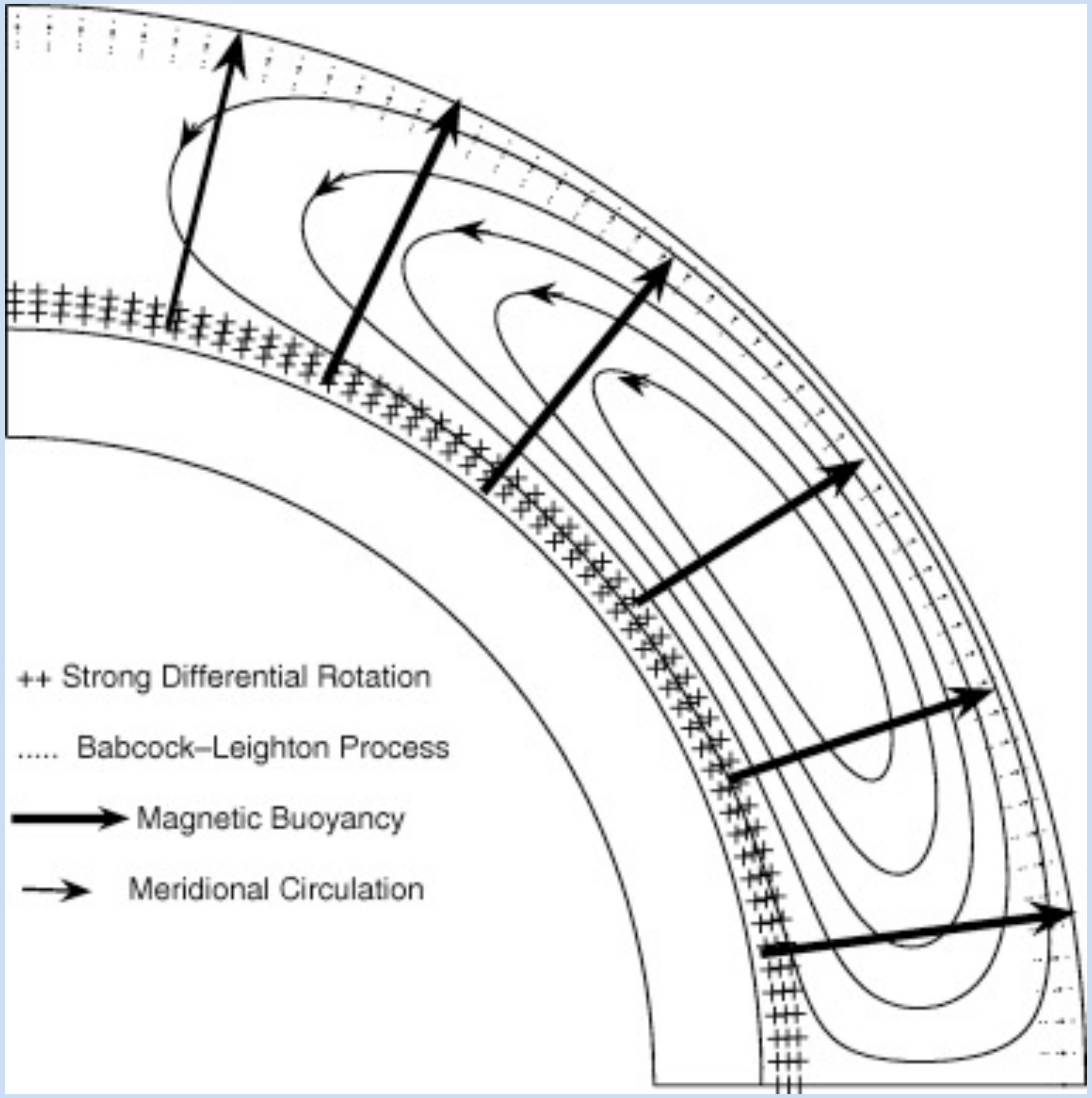
Babcock-Leighton Flux-Transport-Dynamo

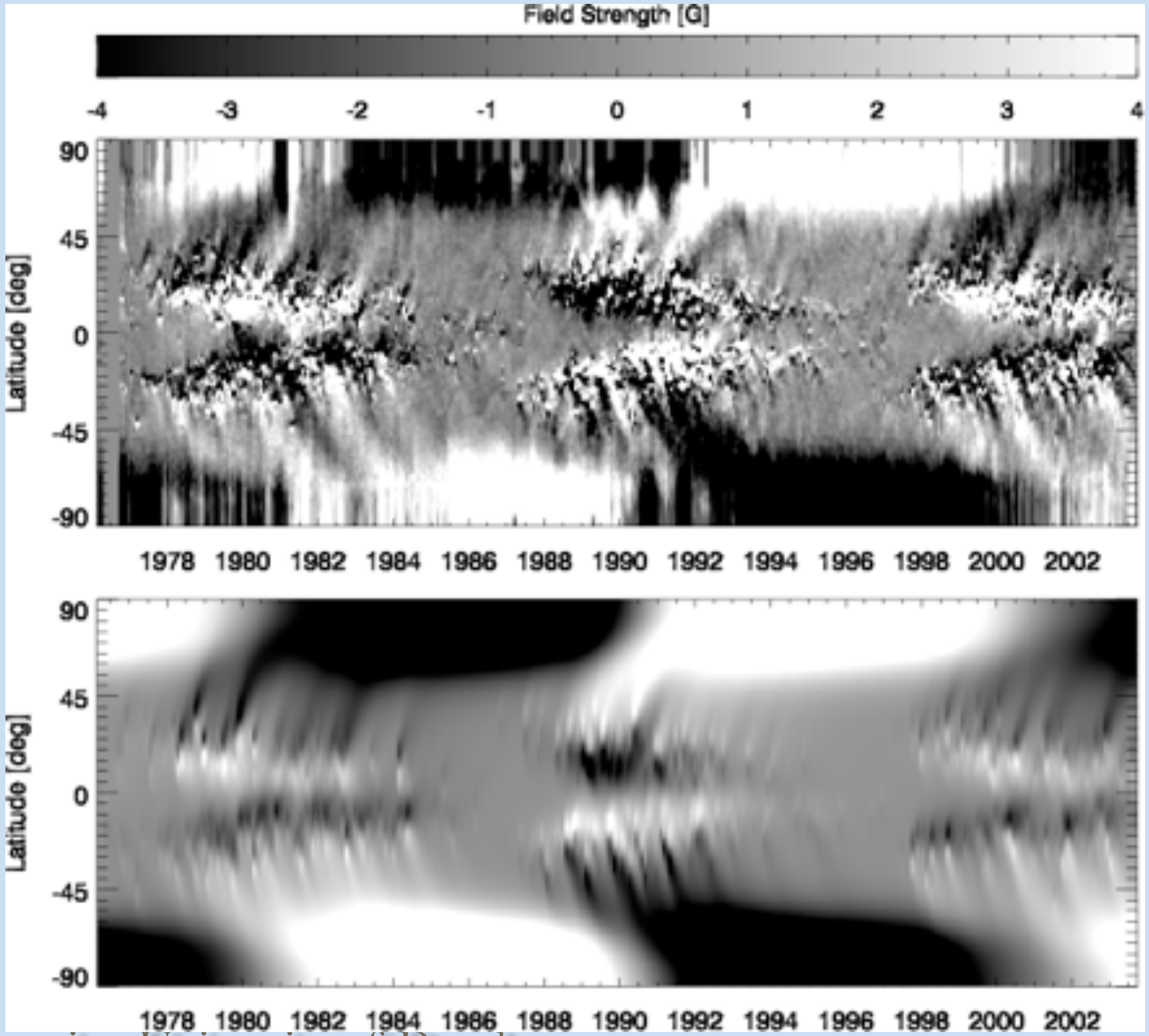
Babcock-Leighton
Flux-Transport-Dynamo



Dikpati & Charbonneau (1999)
Choudhuri, Schüssler & Dikpati (1995)
Nandy & Choudhuri (2002)

Babcock-Leighton Flux-Transport-Dynamo





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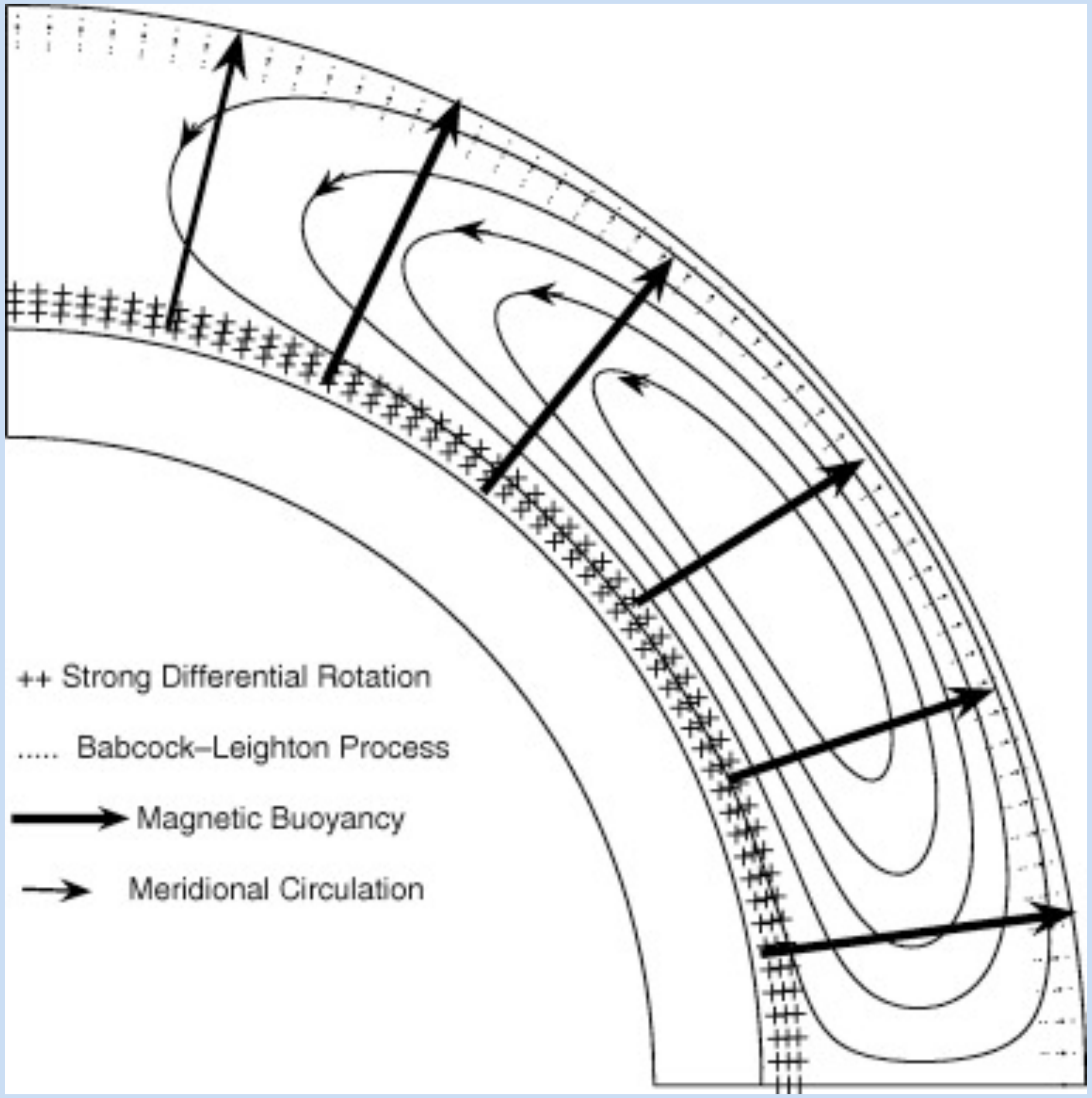
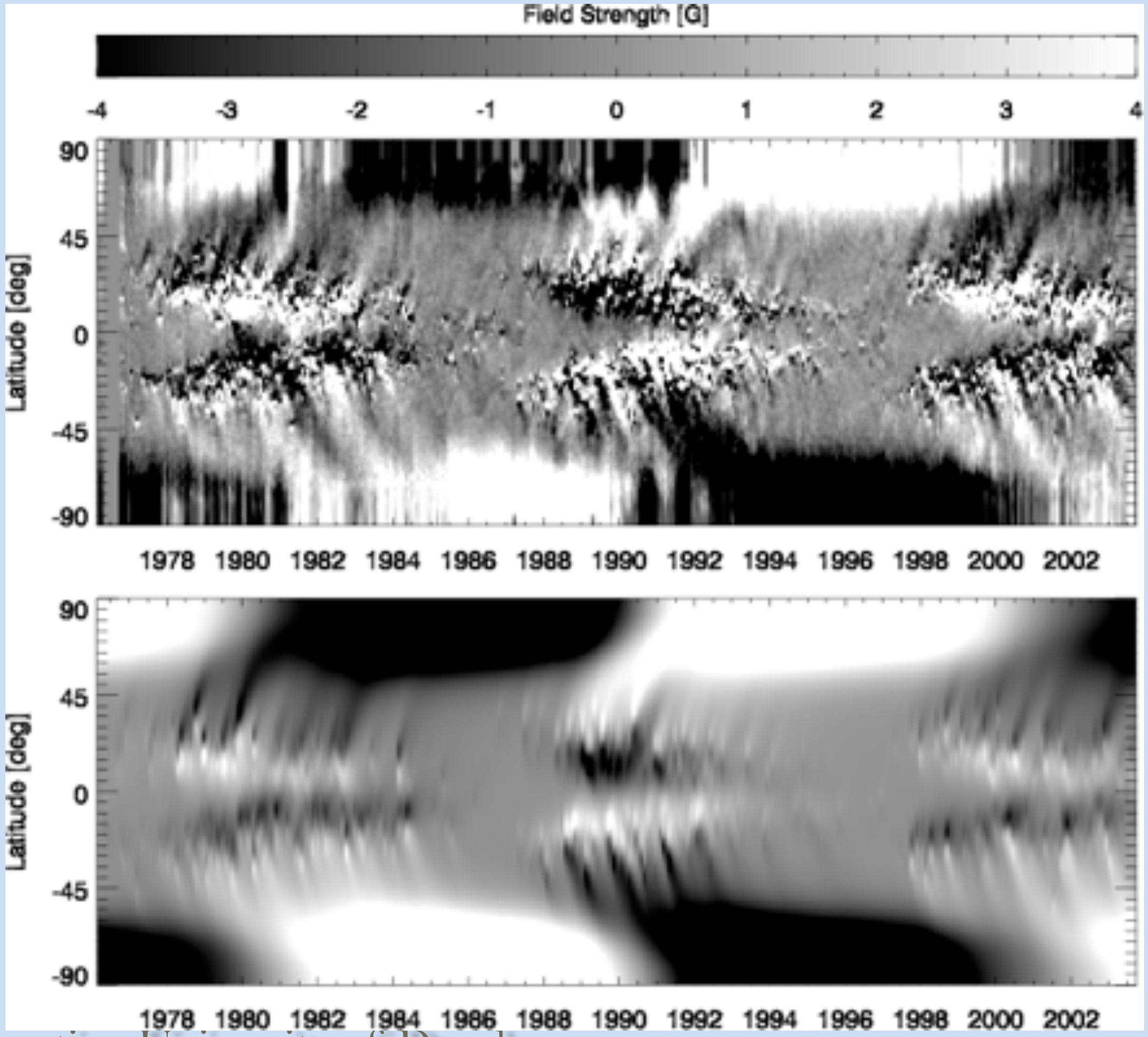


1. Meridional circulation
2. Low magnetic diffusivities
3. Sunspot formation critical



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Rising flux tubes?

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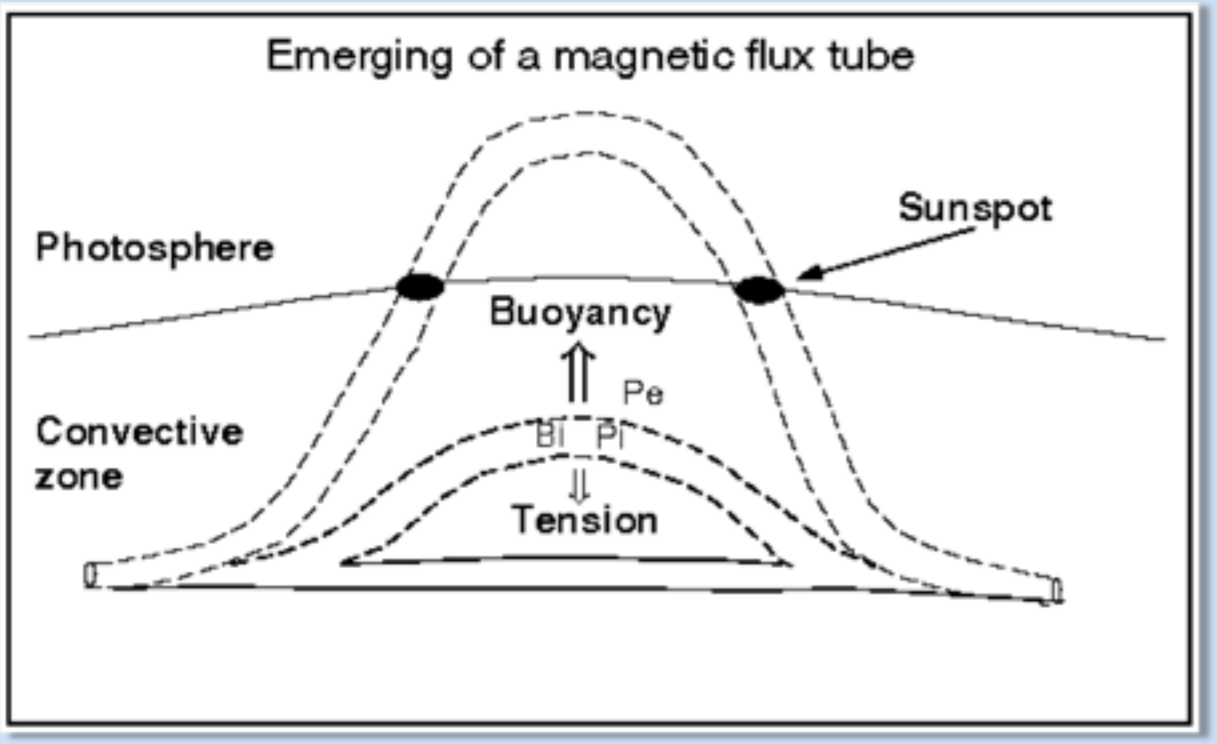

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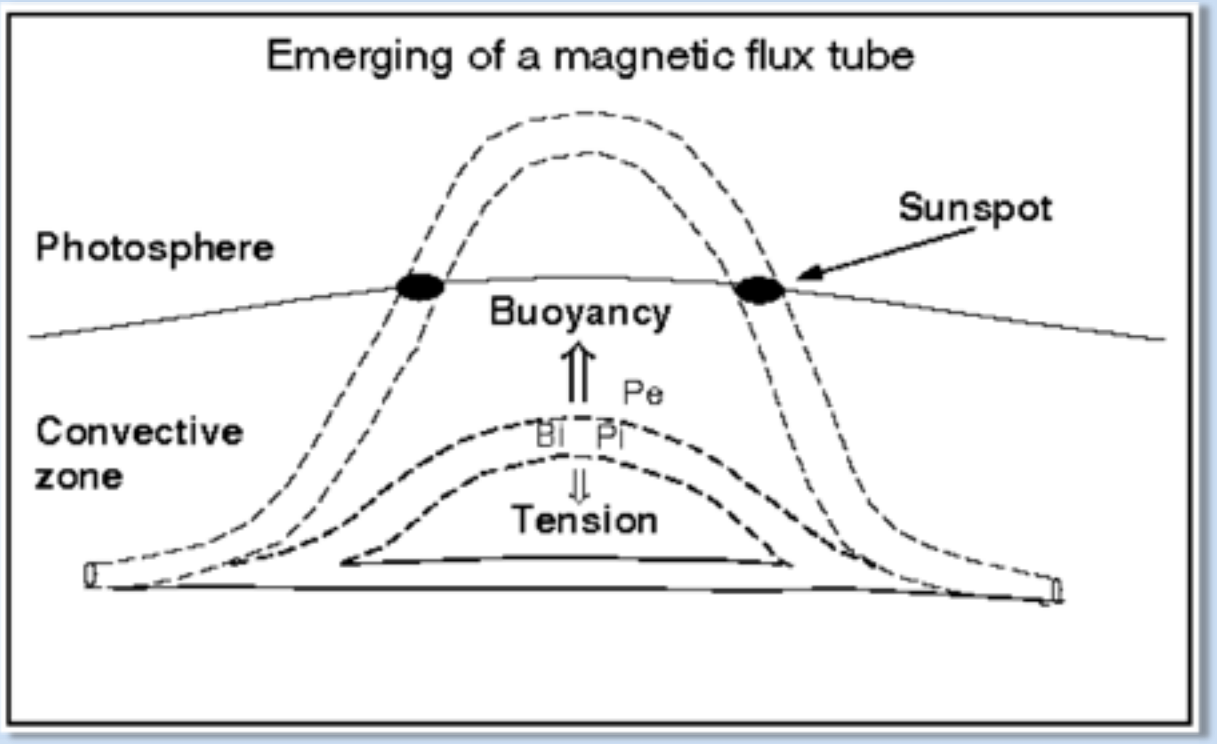
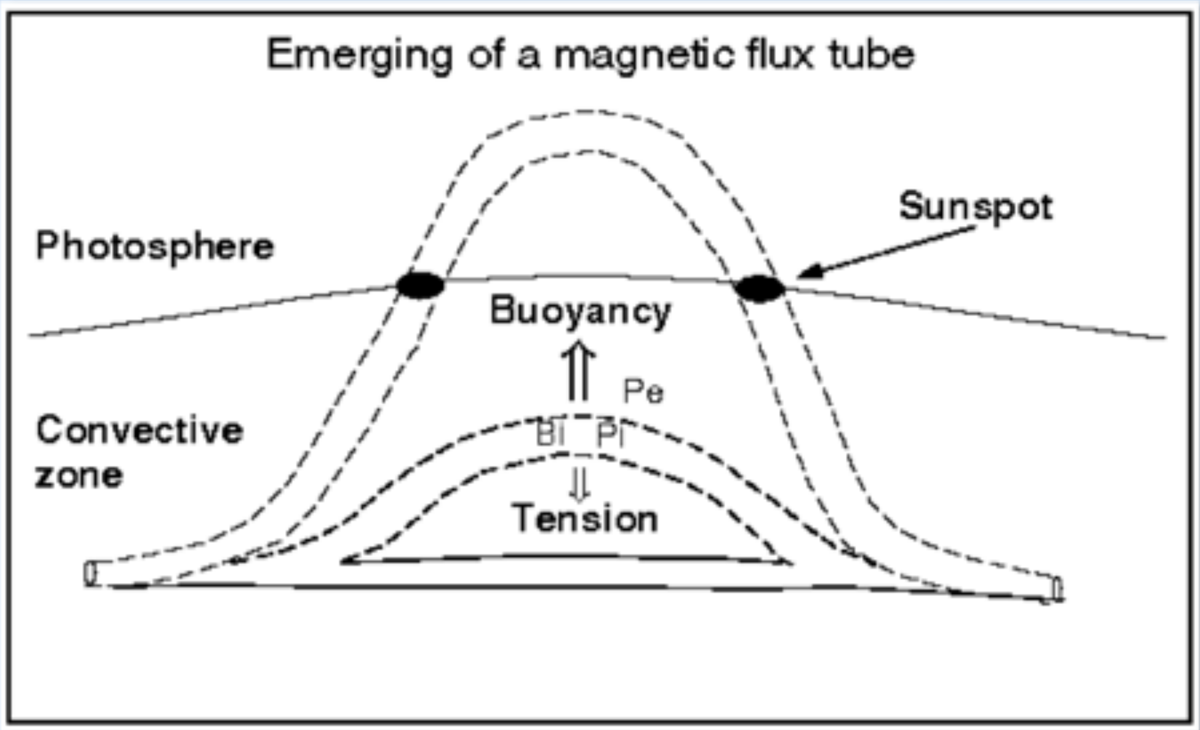


Rising flux tubes?



- Can flux tubes be generated? — Arlt et al. (2007)
- Do flux tubes survive? — Guerrero & Käpylä (2011)
- No detection by helioseismology yet.
- Is the dynamo at the tachocline? — Brandenburg (2005)

How to solves the problem III

How to solves the problem III

3. Global convective dynamo simulations

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- Numerical experiments.

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- Numerical experiments.
- Parameters far from realistic.

How to solves the problem III

3. Global convective dynamo simulations
   - Numerical experiments.
   - Parameters far from realistic.
   - Testing mean-field theories.

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- Numerical experiments.
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- Testing observational contraints.

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→ Interpreting this simulations helps us to understand the solar dynamo!

Global convective dynamo simulations

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

$$\frac{D \ln \rho}{Dt} = -\nabla \cdot u$$

$$\frac{Du}{Dt} = g - 2\Omega_0 \times u + \frac{1}{\rho} \left(J \times B - \nabla p + \nabla \cdot 2\nu\rho S \right)$$

$$T \frac{Ds}{Dt} = \frac{1}{\rho} \nabla \cdot \left(K \nabla T + \chi_t \rho T \nabla s \right) + 2\nu S^2 + \frac{\mu_0 \eta}{\rho} J^2 - \Gamma_{\mathrm{cool}}(r),$$

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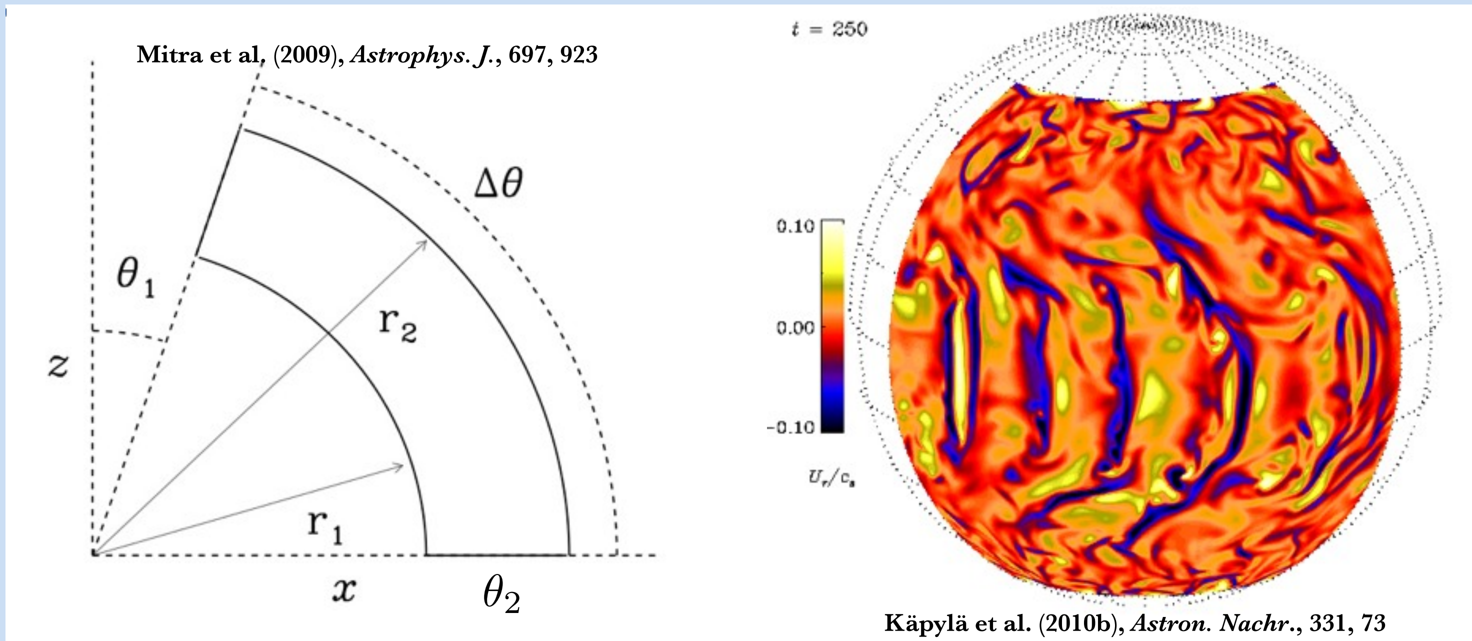
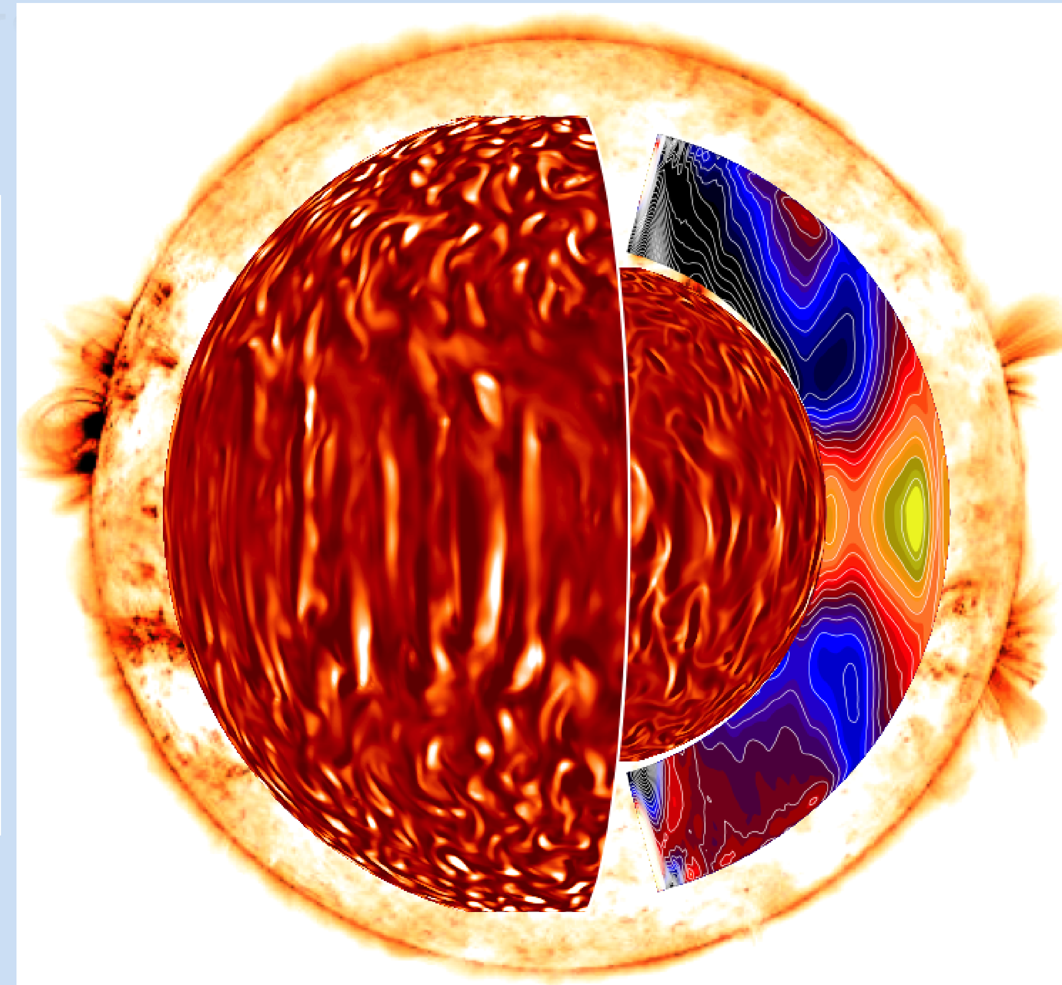
- high-order finite-difference code
- scales up efficiently to over 60.000 cores
- compressible MHD

http://pencil-code.google.com/

Global convective dynamo simulations



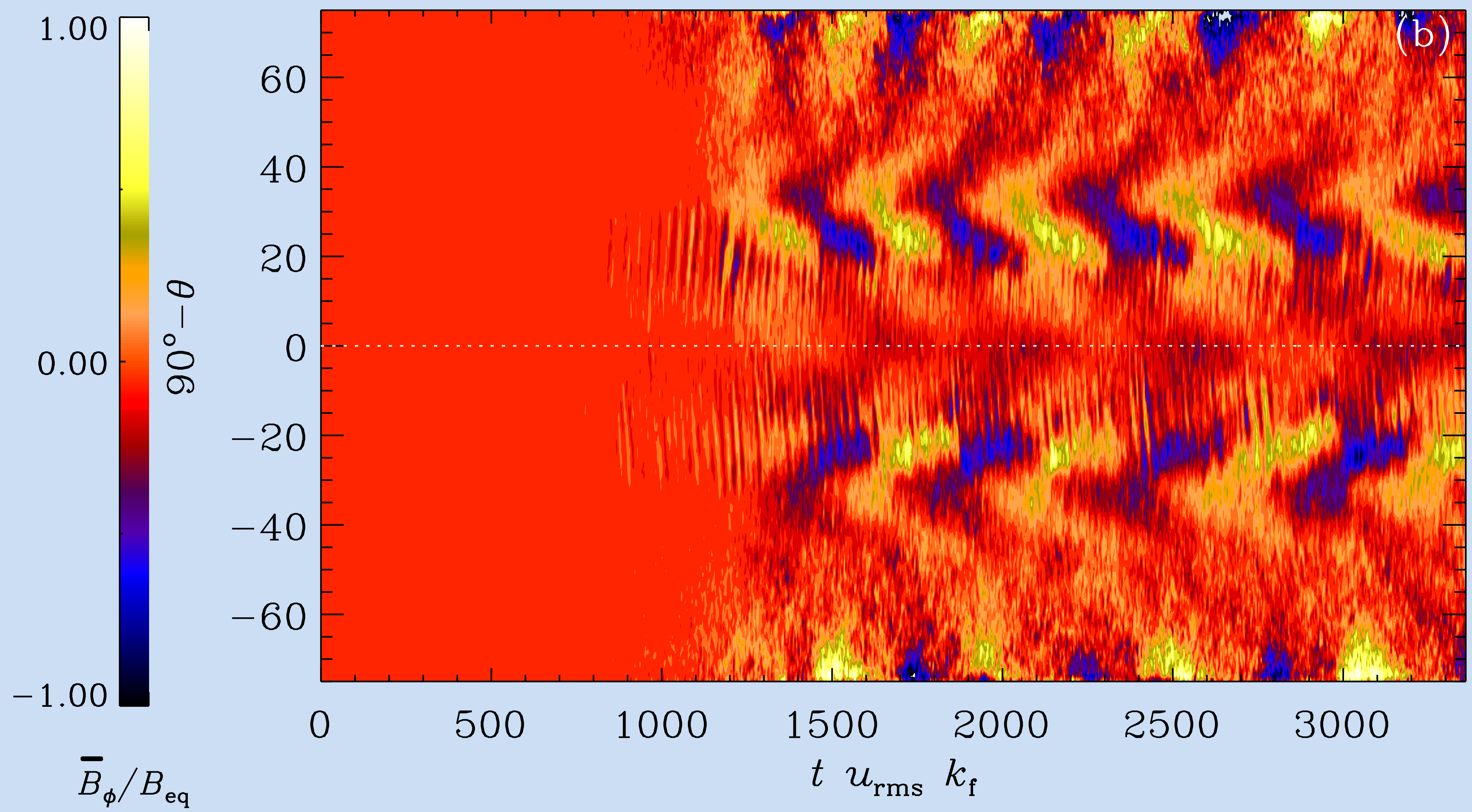


$0.7R < r < R \qquad \theta_1 < \theta < \theta_2 \qquad 0 < \phi < \Delta\phi \qquad k_{\rm f} = 2\pi/\Delta R$

We model a spherical sector (`wedge') where only parts of the latitudinal and longitudinal extents are taken into account.

Normal field condition for *B* at the outer radial boundary and perfect conductor at all other boundaries. Impenetrable stress-free boundaries on all boundaries.

Equatorward Migration I



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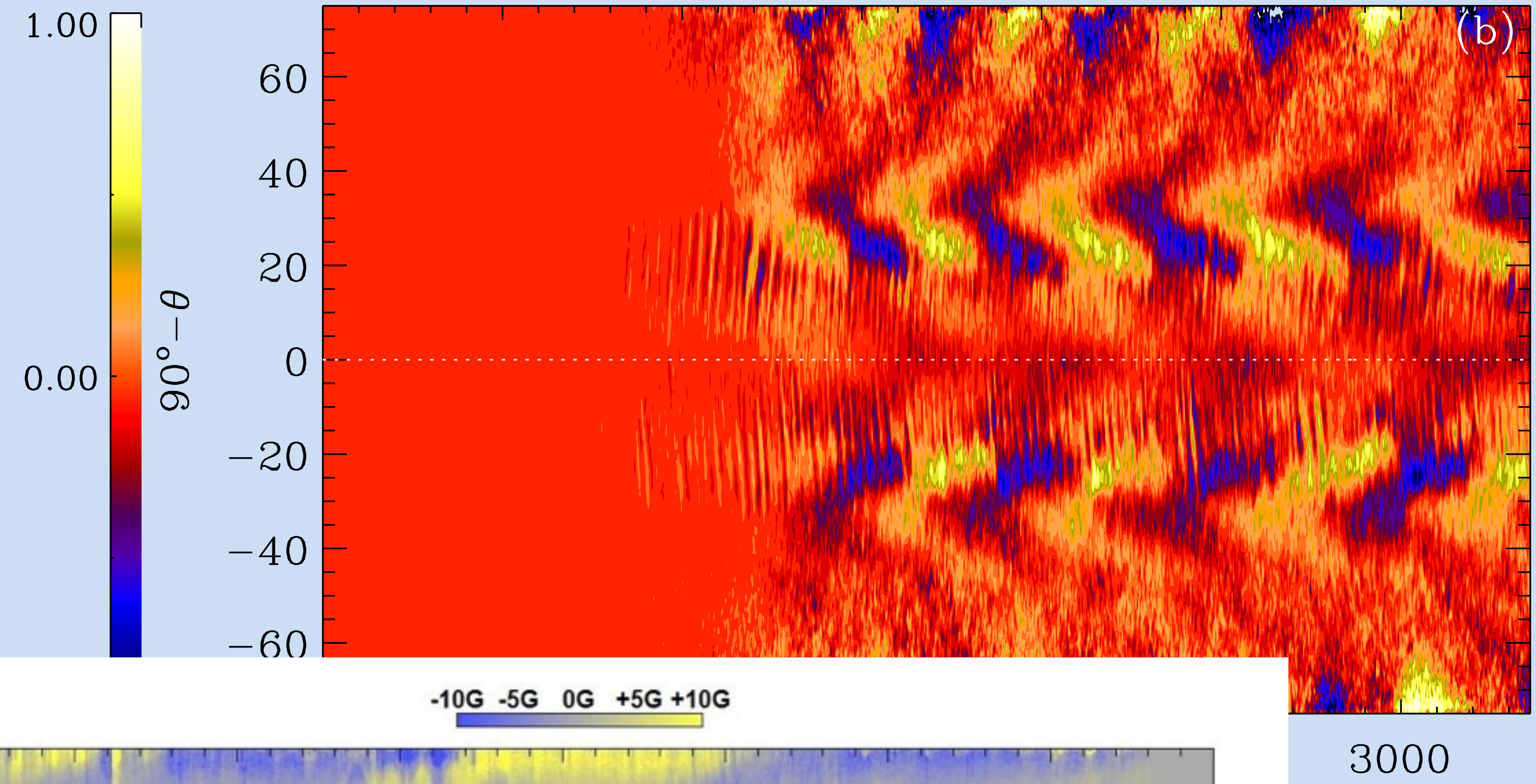

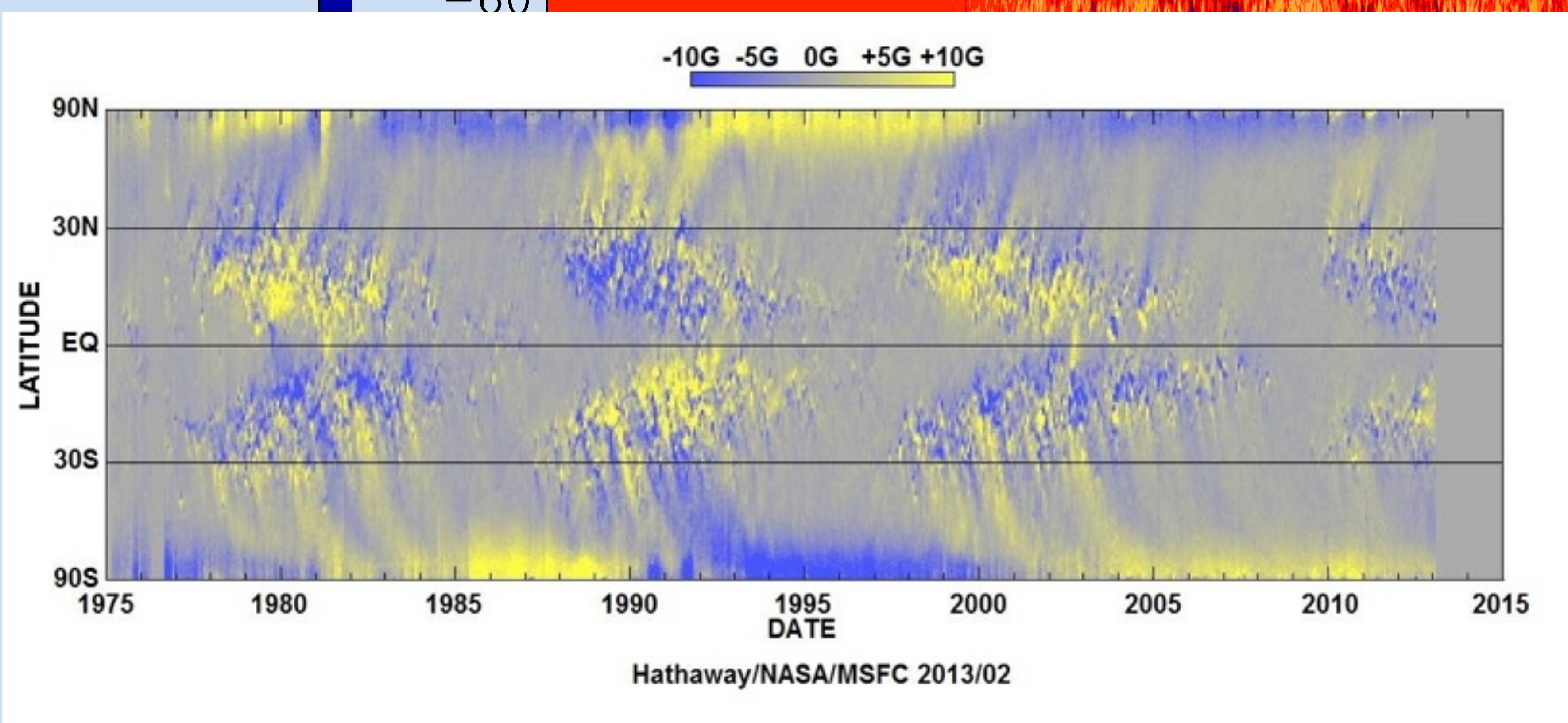

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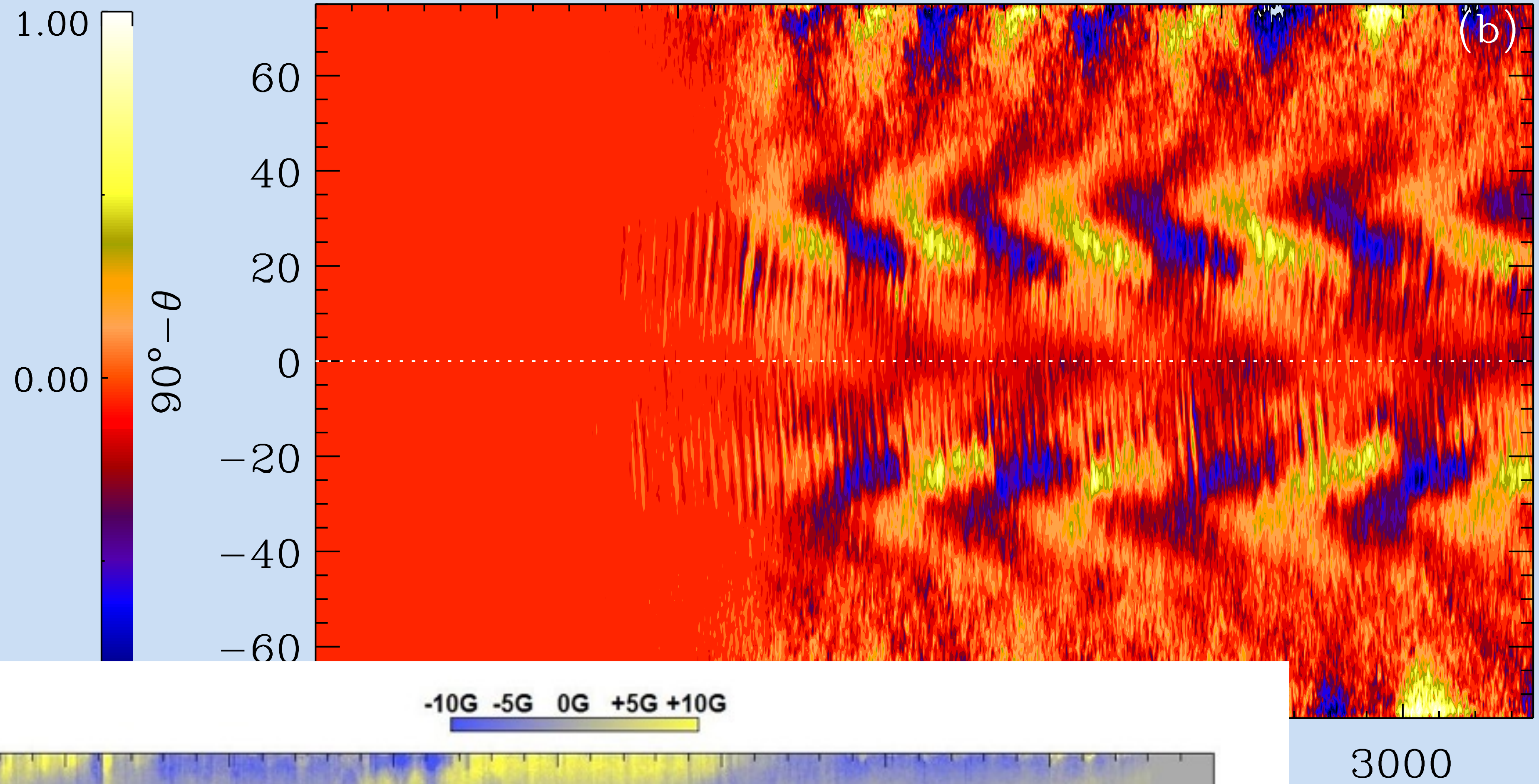
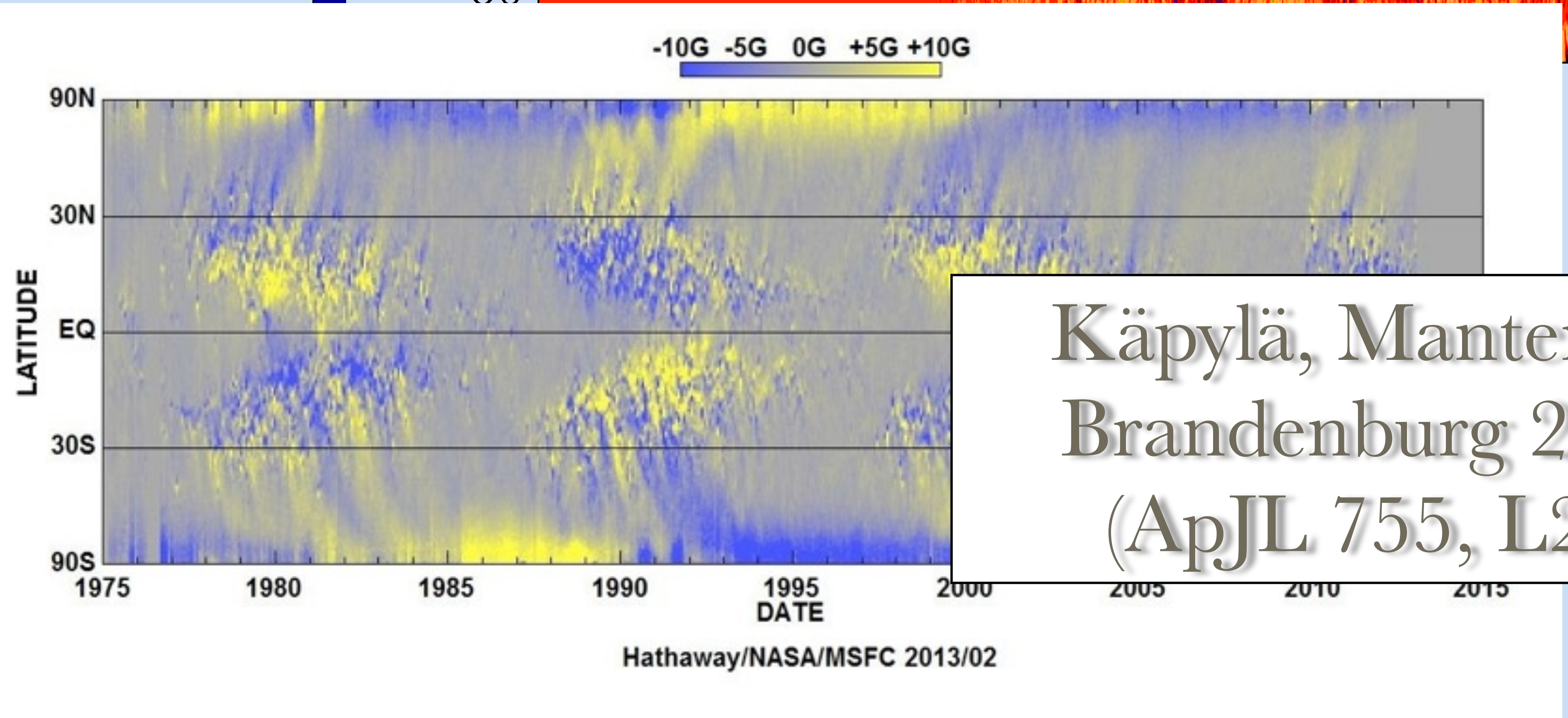
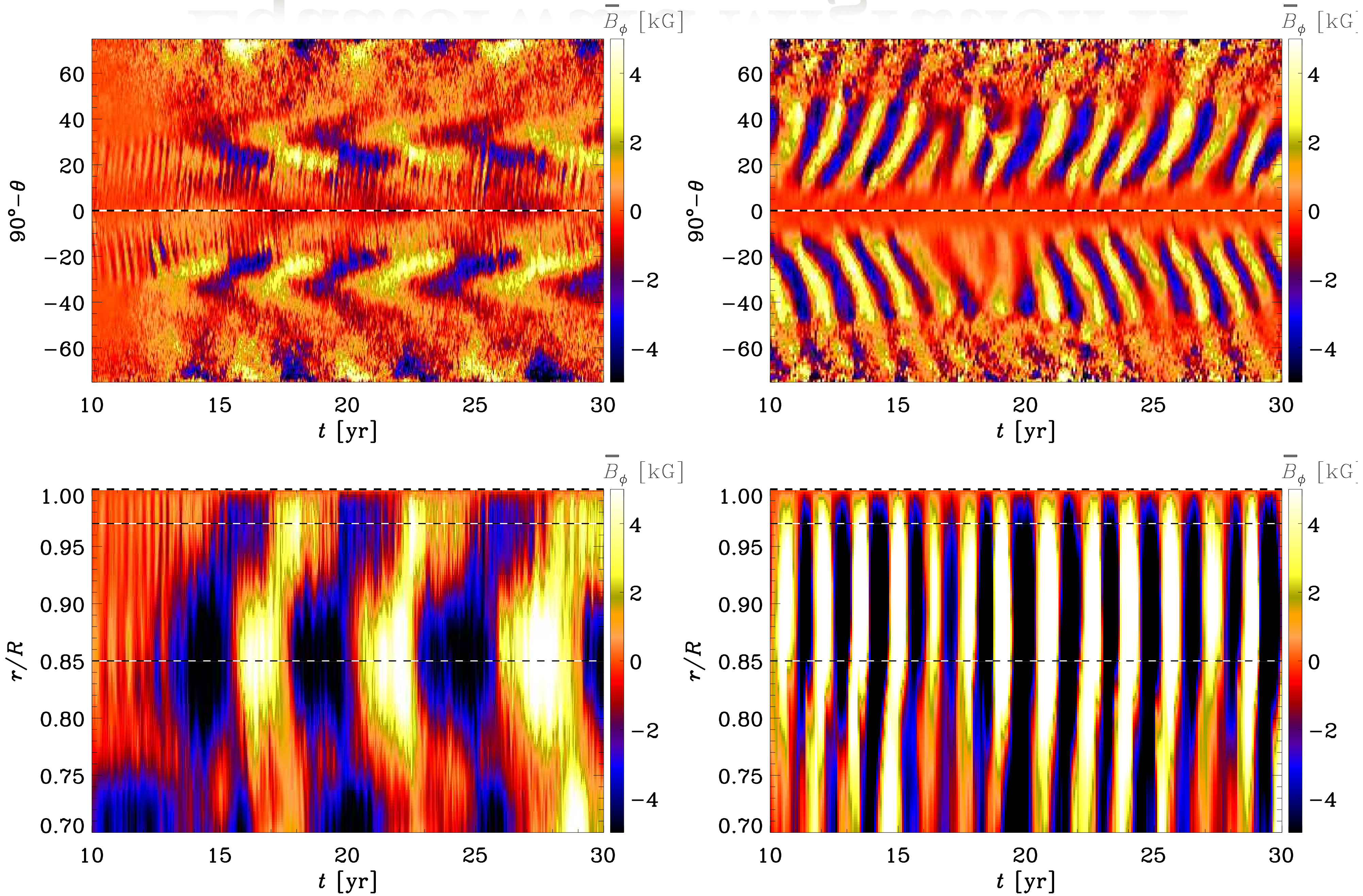




Käpylä, Mantere & Brandenburg 2012 (ApJL 755, L22)

Equatorward Migration II



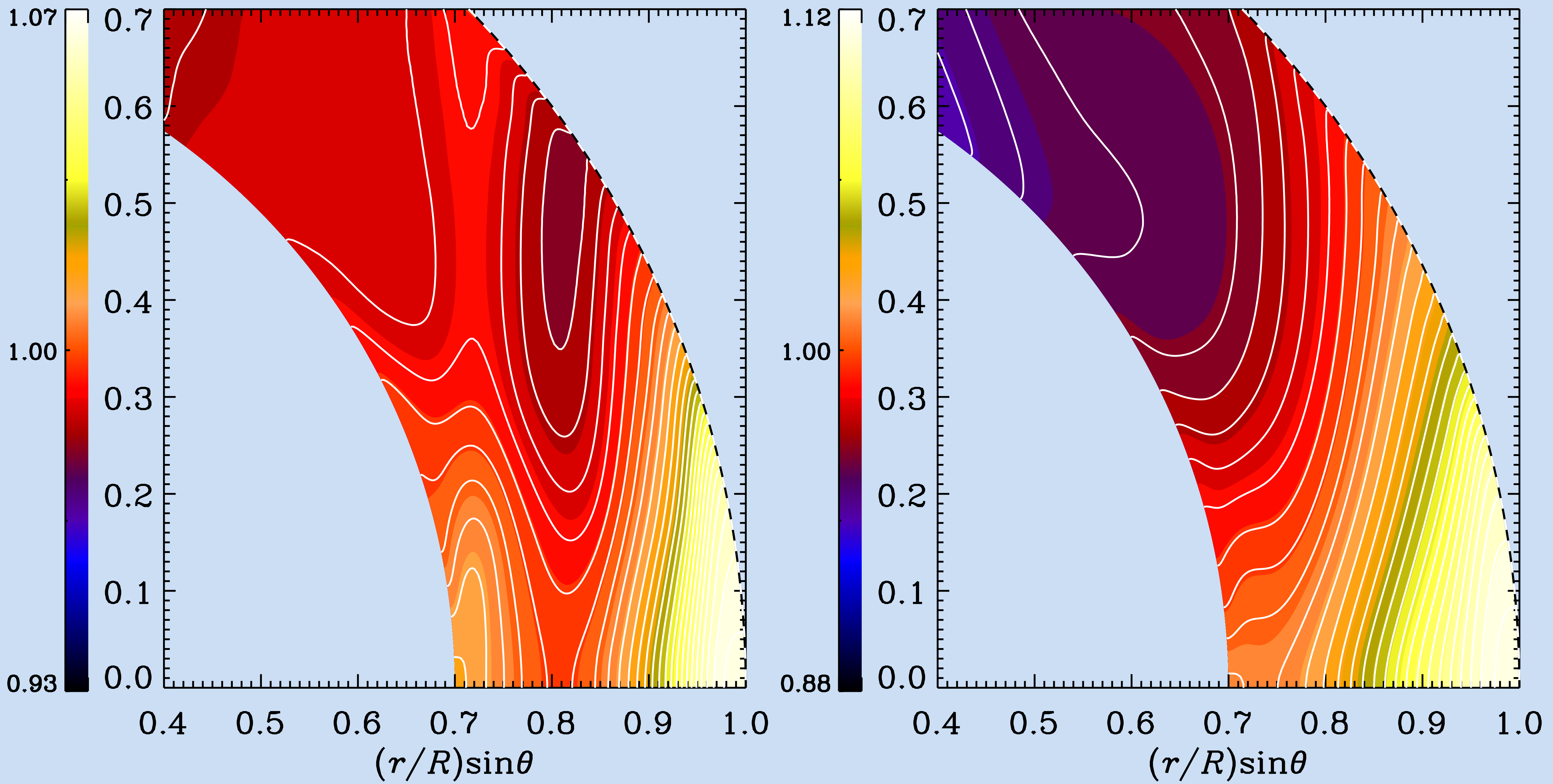
Pr=ν/χ=2.5

Pm=ν/η=1

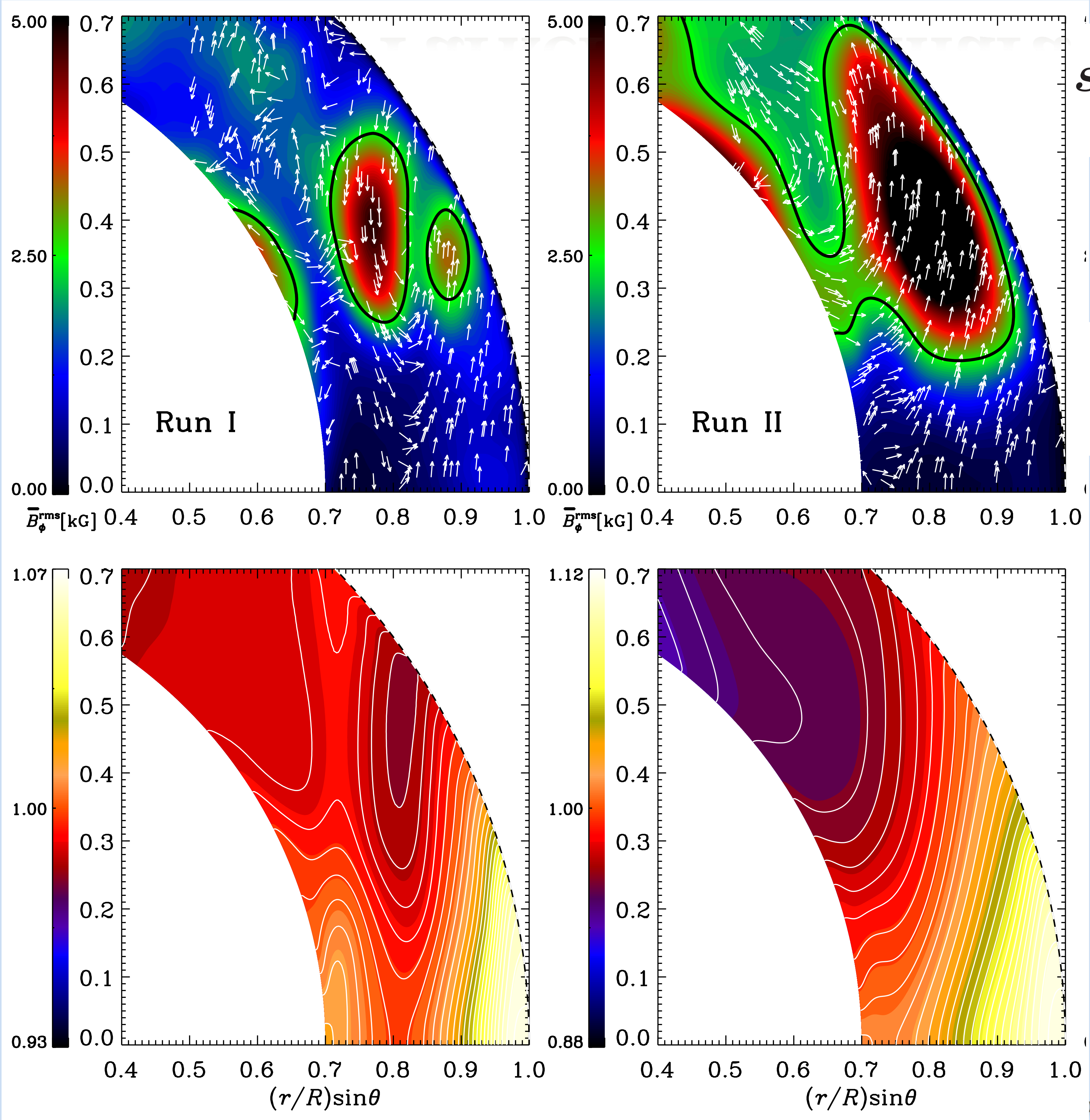
Pr=0.5

Pm=0.5

Differential rotation



Parker—Yoshimura—Rule



$$\boldsymbol{s}_{\rm mig}(r,\theta) = -\alpha \hat{\boldsymbol{e}}_\phi \times \boldsymbol{\nabla}\Omega,$$

Parker 1955

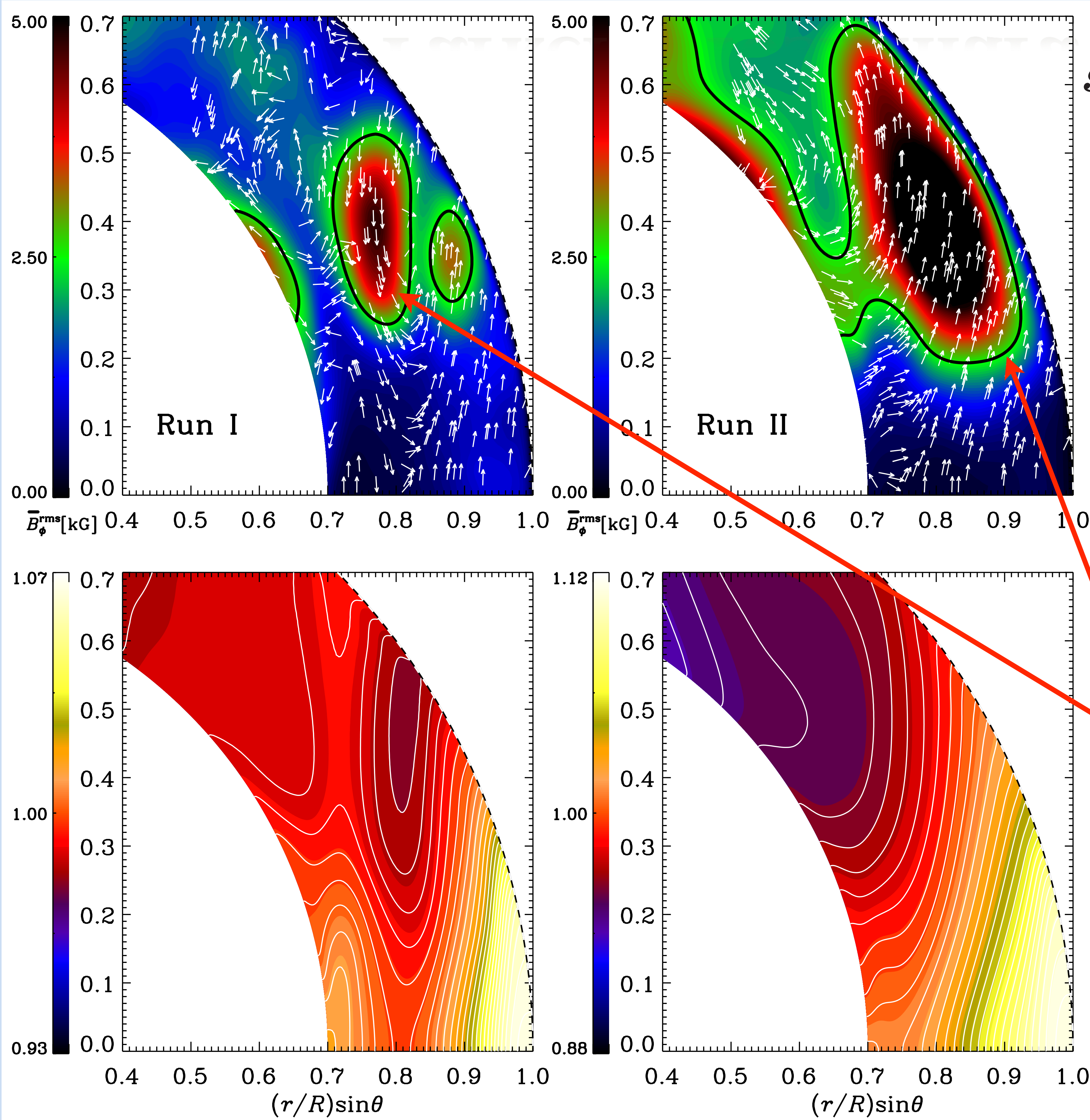
Yoshimura 1975

$$\alpha = \frac{\tau_c}{3}\left(-\overline{\boldsymbol{\omega}\cdot\boldsymbol{u}} + \frac{\overline{\boldsymbol{j}\cdot\boldsymbol{b}}}{\overline{\rho}}\right)$$

Pouquet et al. 1976

Warnecke et al. 2014a (ApJL 796, L12)

Parker—Yoshimura—Rule



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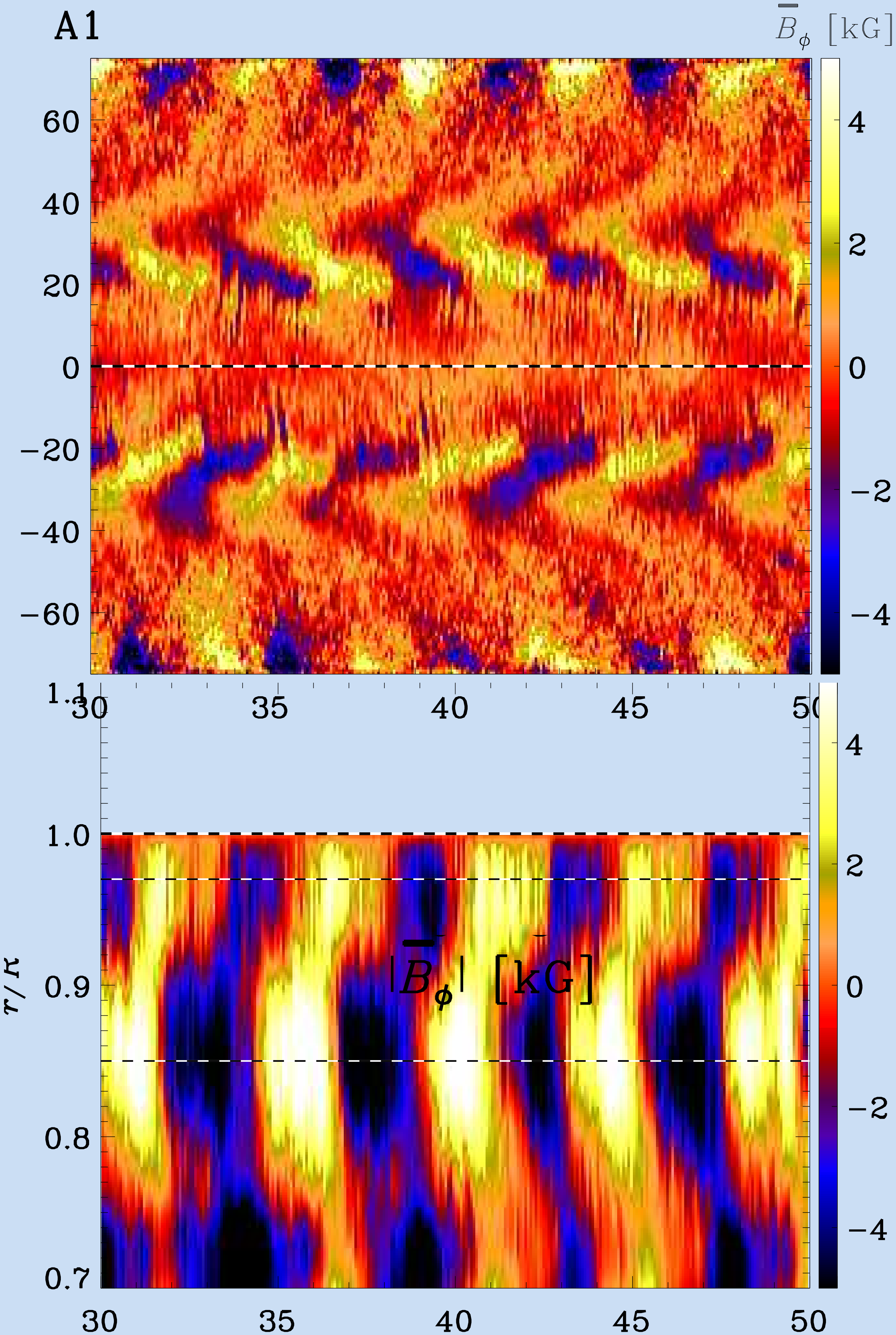
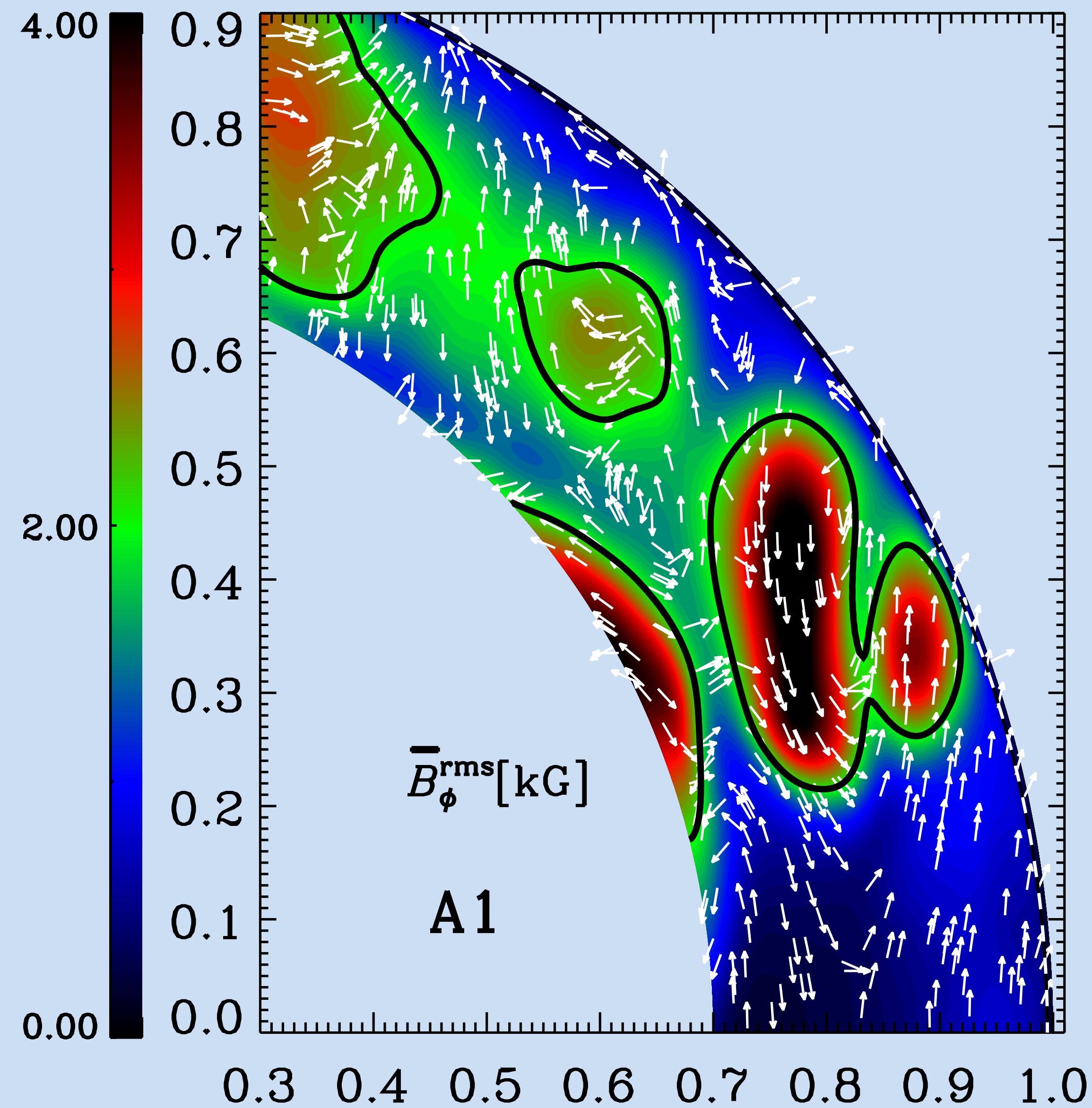
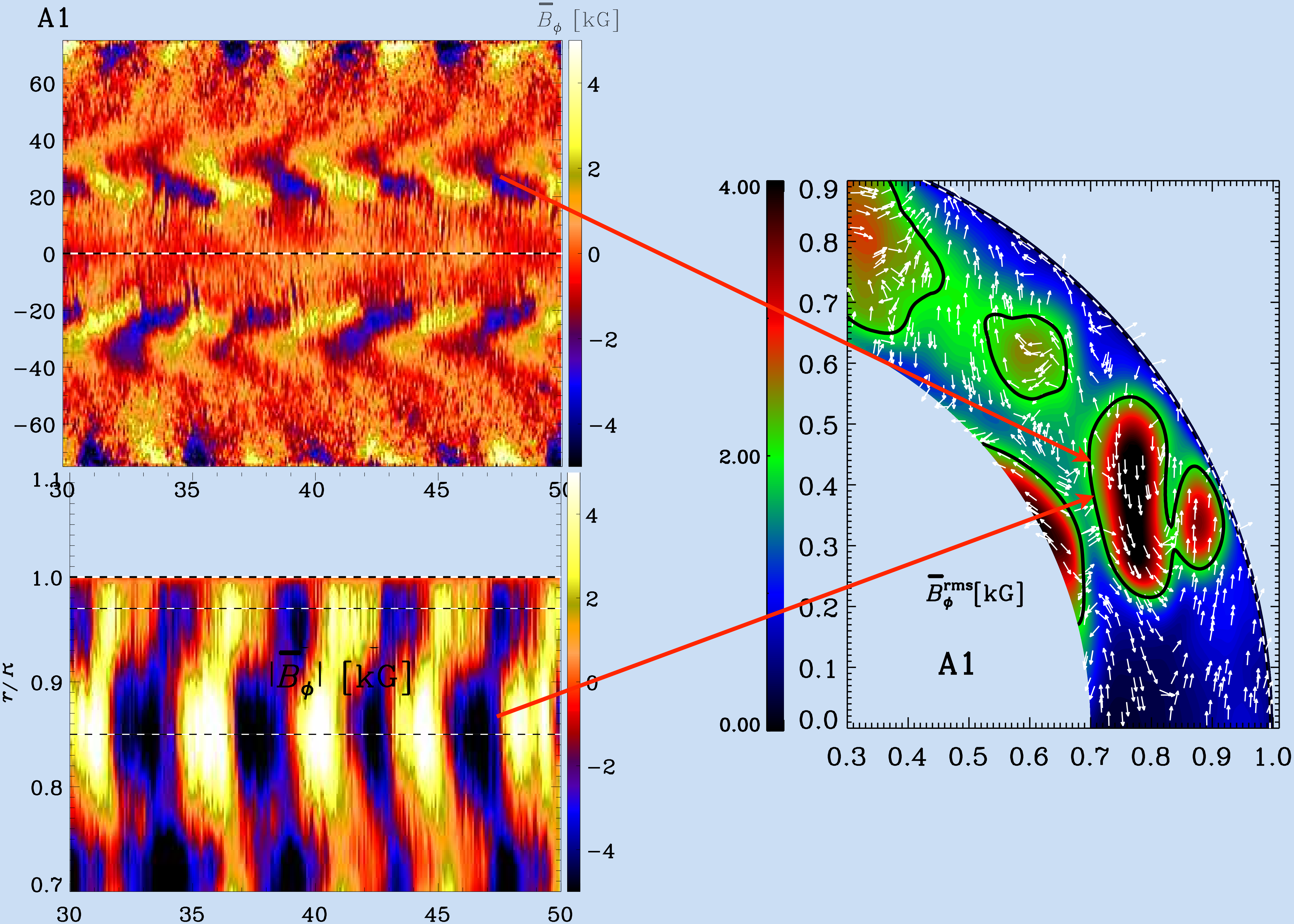
Pouquet et al. 1976

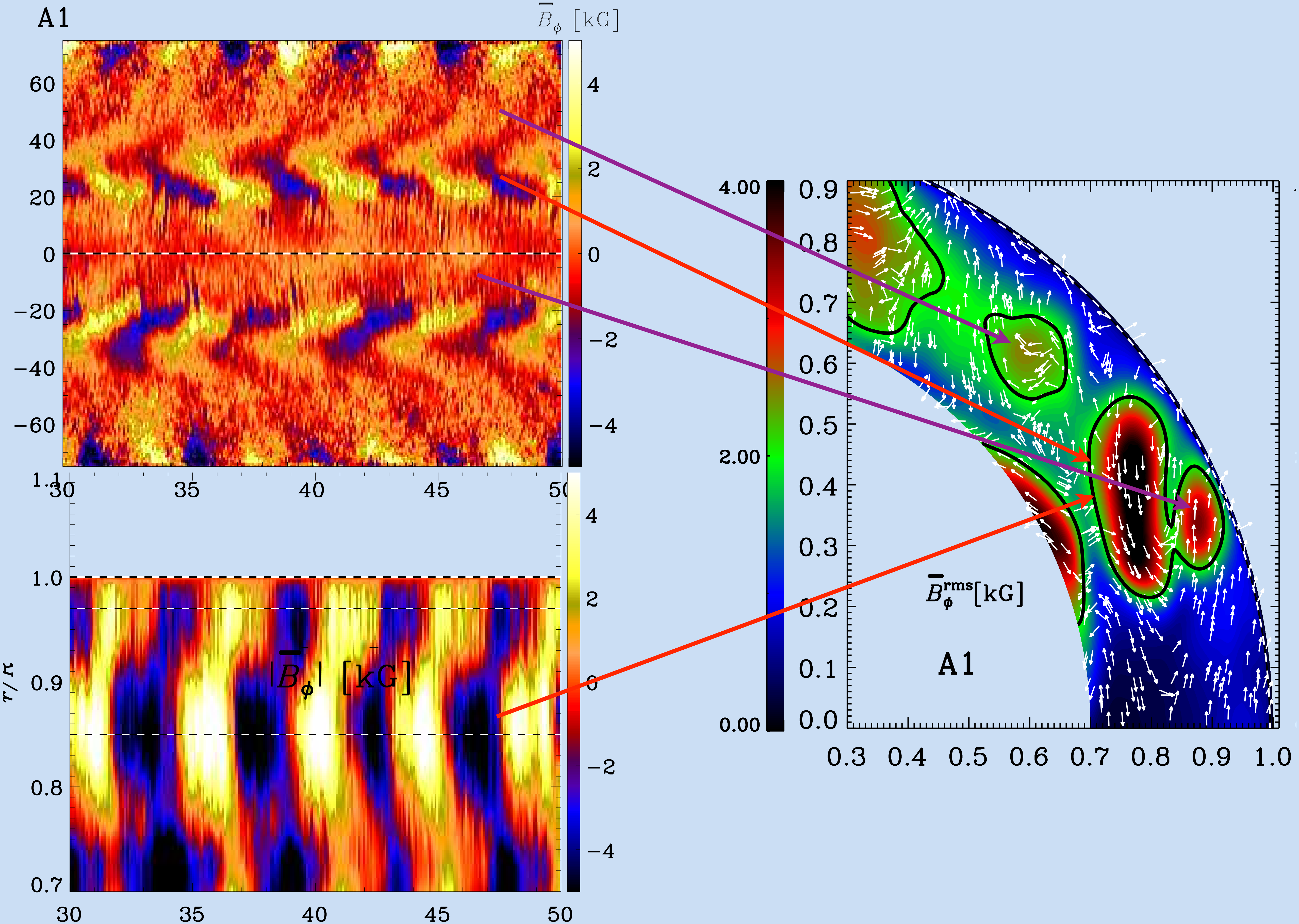
Strong toroidal field

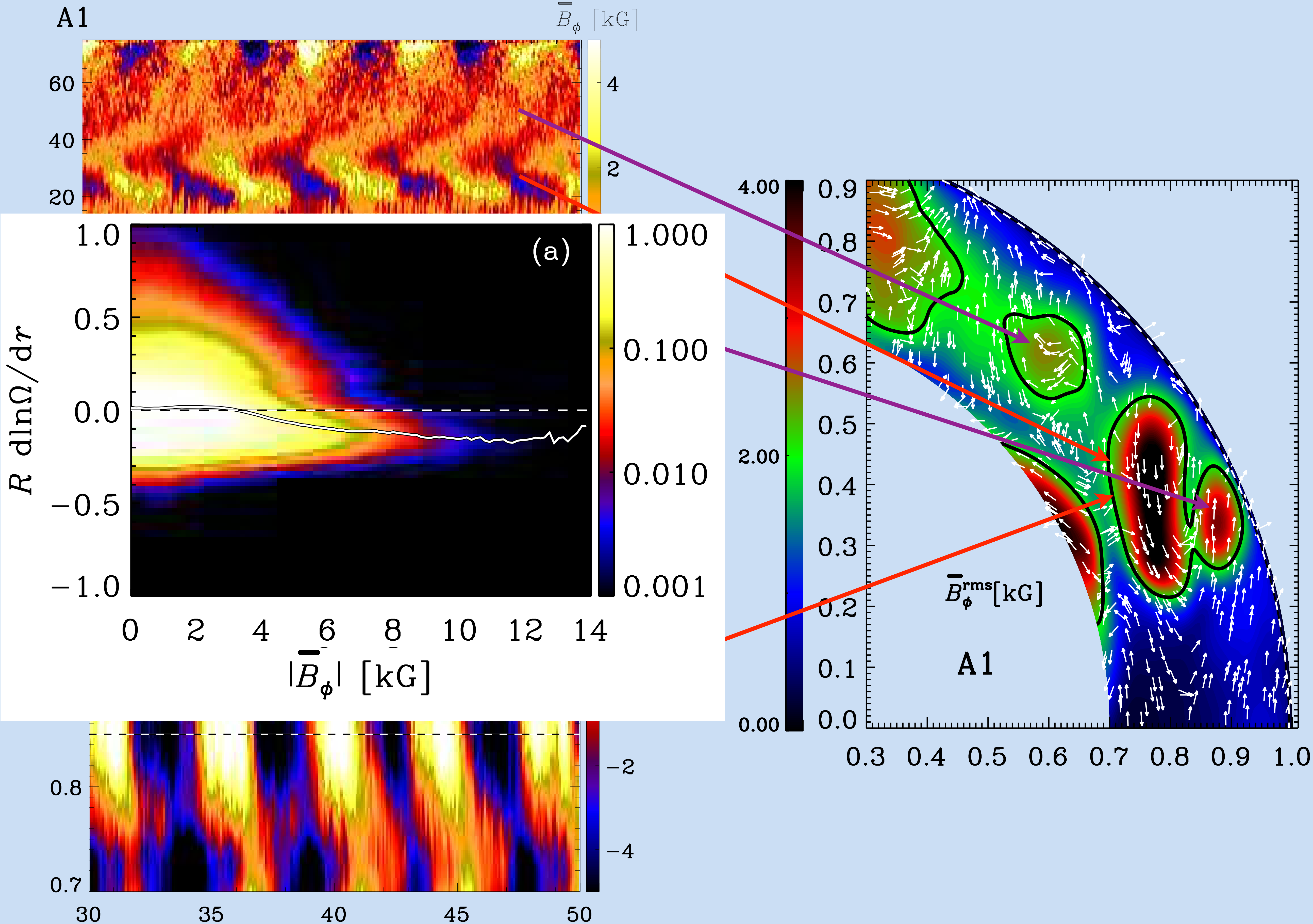
Warnecke et al. 2014a (ApJL 796, L12)


A1
$\overline{B}_\phi$ [kG]
60
40
20
0
−20
−40
−60
4
2
0
−2
−4
30
35
40
45
50
1.1
1.0
0.9
0.8
0.7
r/R
$\overline{B}_\phi$ [kG]

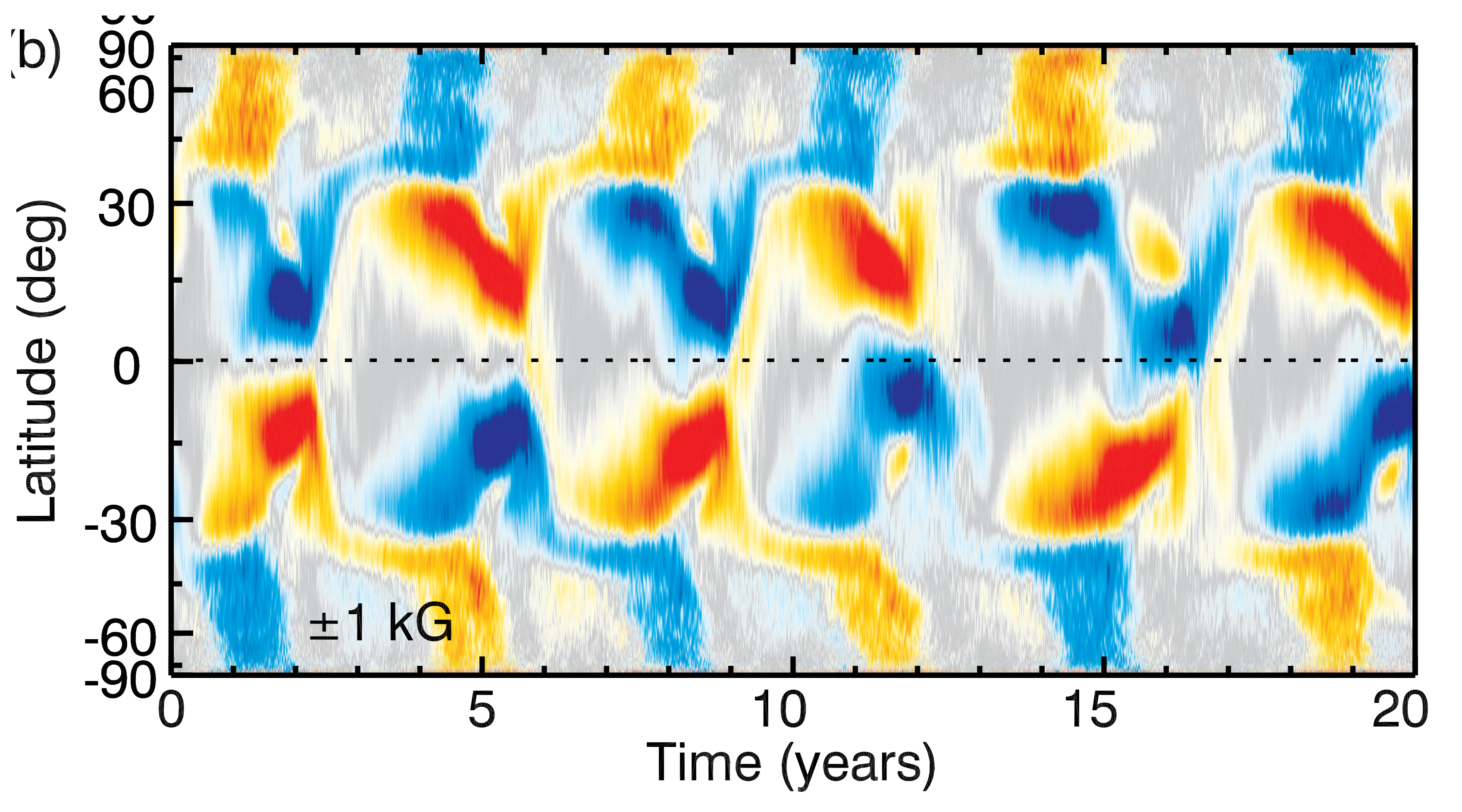

4.00
2.00
0.00
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\overline{B}_\phi^{\rm rms}$[kG]
A1

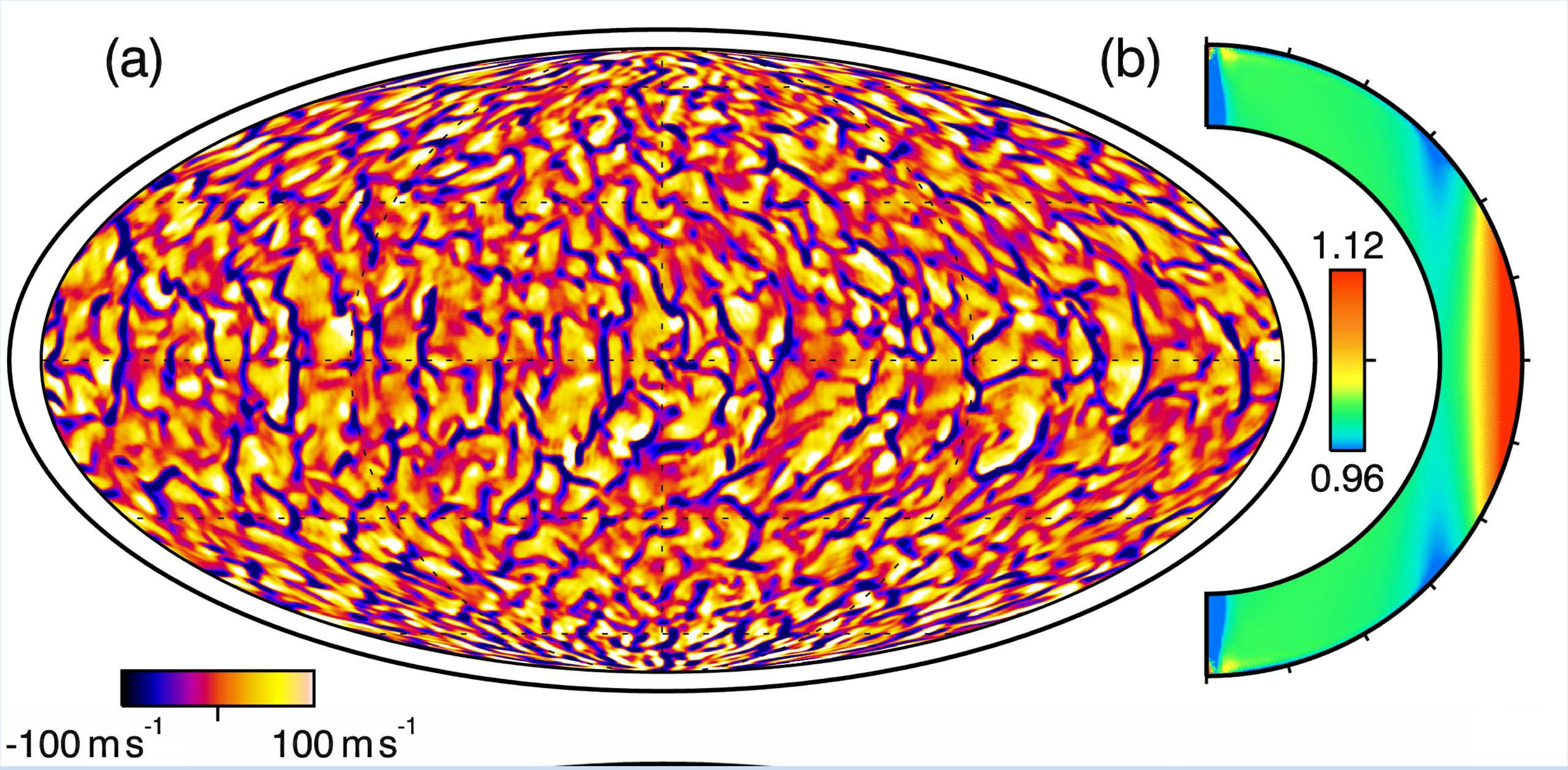

A1
$\overline{B}_\phi$ [kG]
$|\overline{B}_\phi|$ [kG]
r/R
$\overline{B}_\phi^{\rm rms}$[kG]
A1


A1
$\overline{B}_\phi$ [kG]
60
40
20
0
−20
−40
−60
30
35
40
45
50
4
2
0
−2
−4
1.1
1.0
0.9
0.8
0.7
r/R
$|\overline{B}_\phi|$ [kG]
4.00
2.00
0.00
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\overline{B}_\phi^{\rm rms}$[kG]
A1



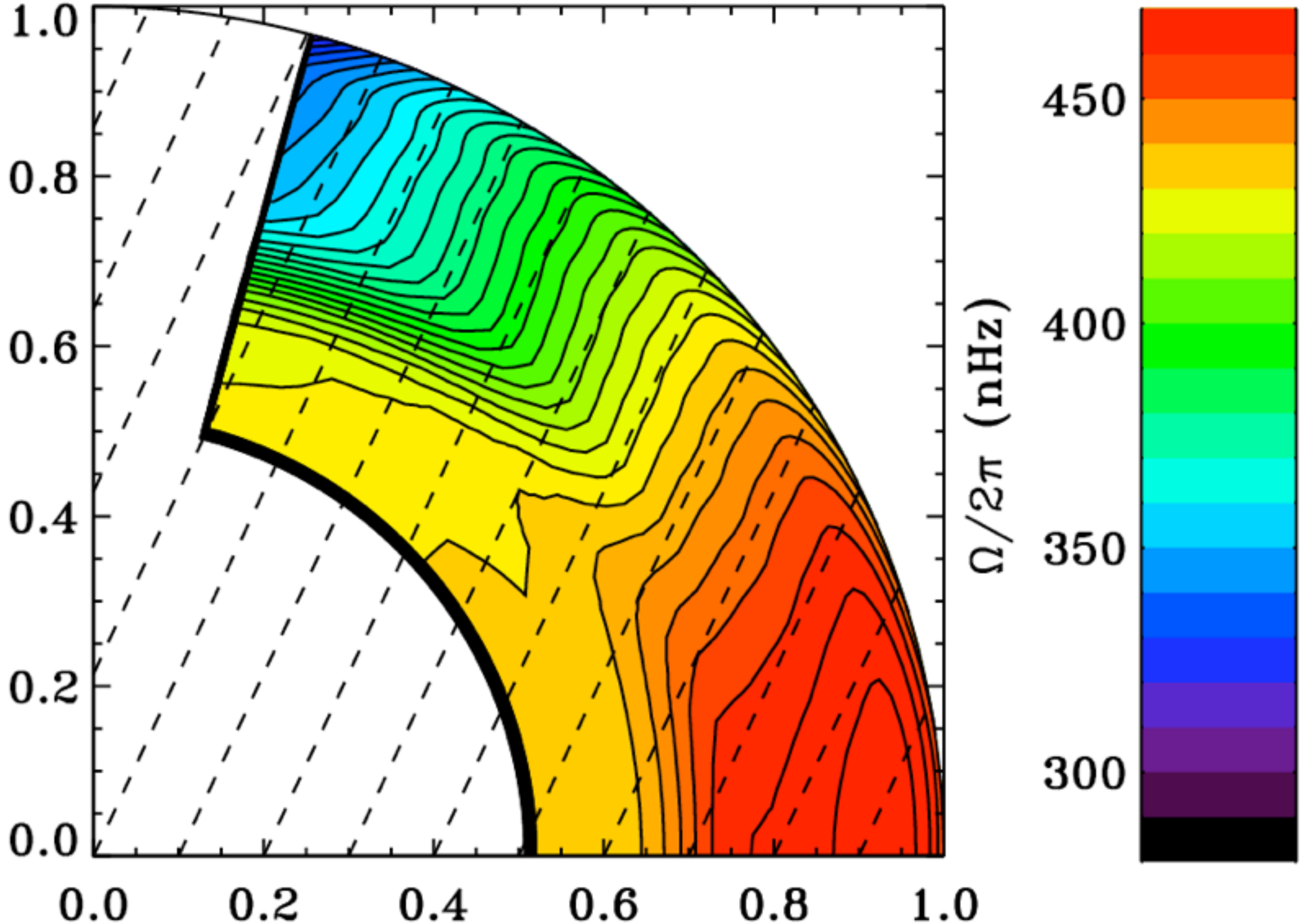
A1
$\overline{B}_\phi$ [kG]
60
40
20
4
2
1.0
0.5
0.0
−0.5
−1.0
(a)
R dlnΩ/dr
1.000
0.100
0.010
0.001
0 2 4 6 8 10 12 14
$|\overline{B}_\phi|$ [kG]
0.8
0.7
−2
−4
30 35 40 45 50
4.00
2.00
0.00
0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
$\overline{B}_\phi^{rms}$[kG]
A1





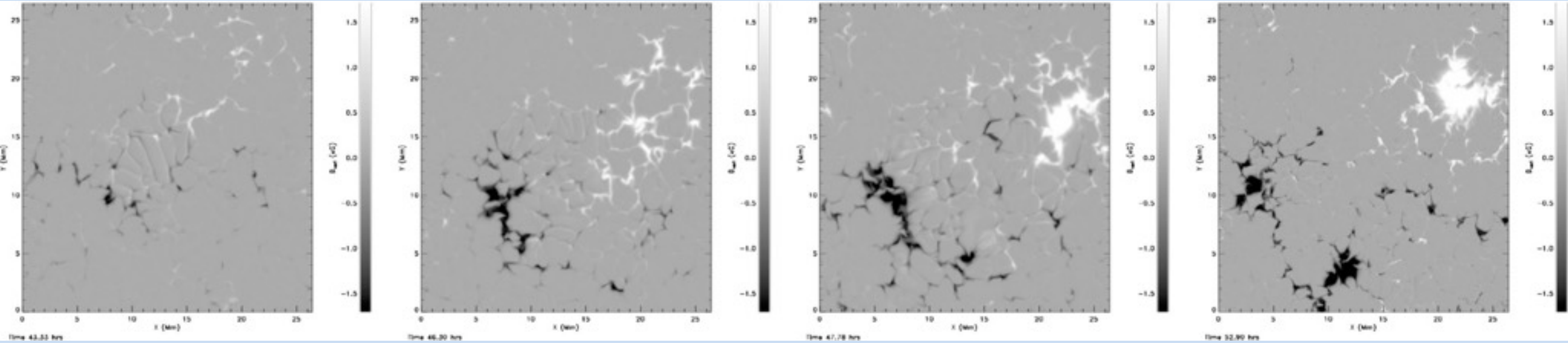
Augustson et al. 2014

Propagation direction of mean toroidal magnetic field can be entirely explain by the Parker—Yoshimura—Rule



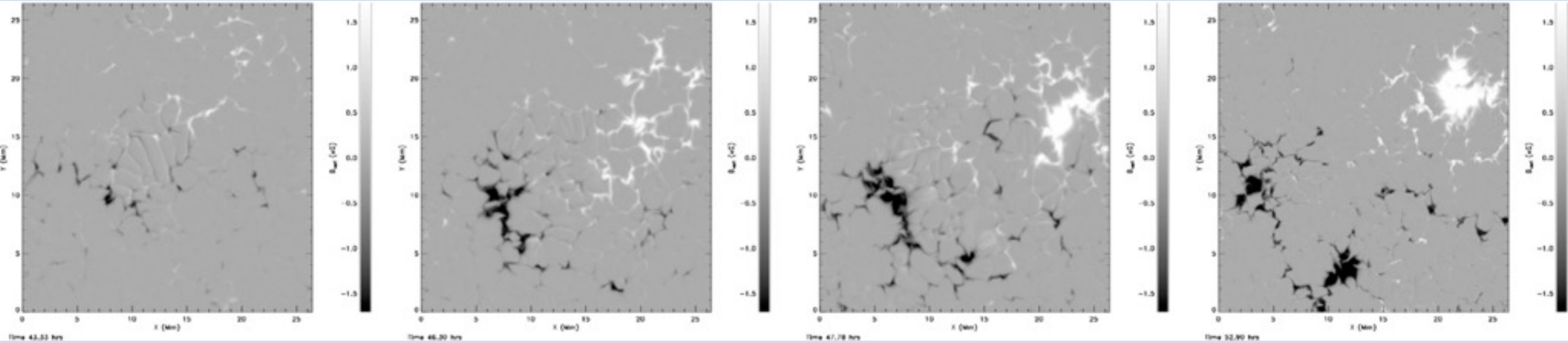
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Ω/2π (nHz)
450
400
350
300

Forming flux concentrations near the surface



Stein & Nordlund, 2012

Forming flux concentrations near the surface



Stein & Nordlund, 2012

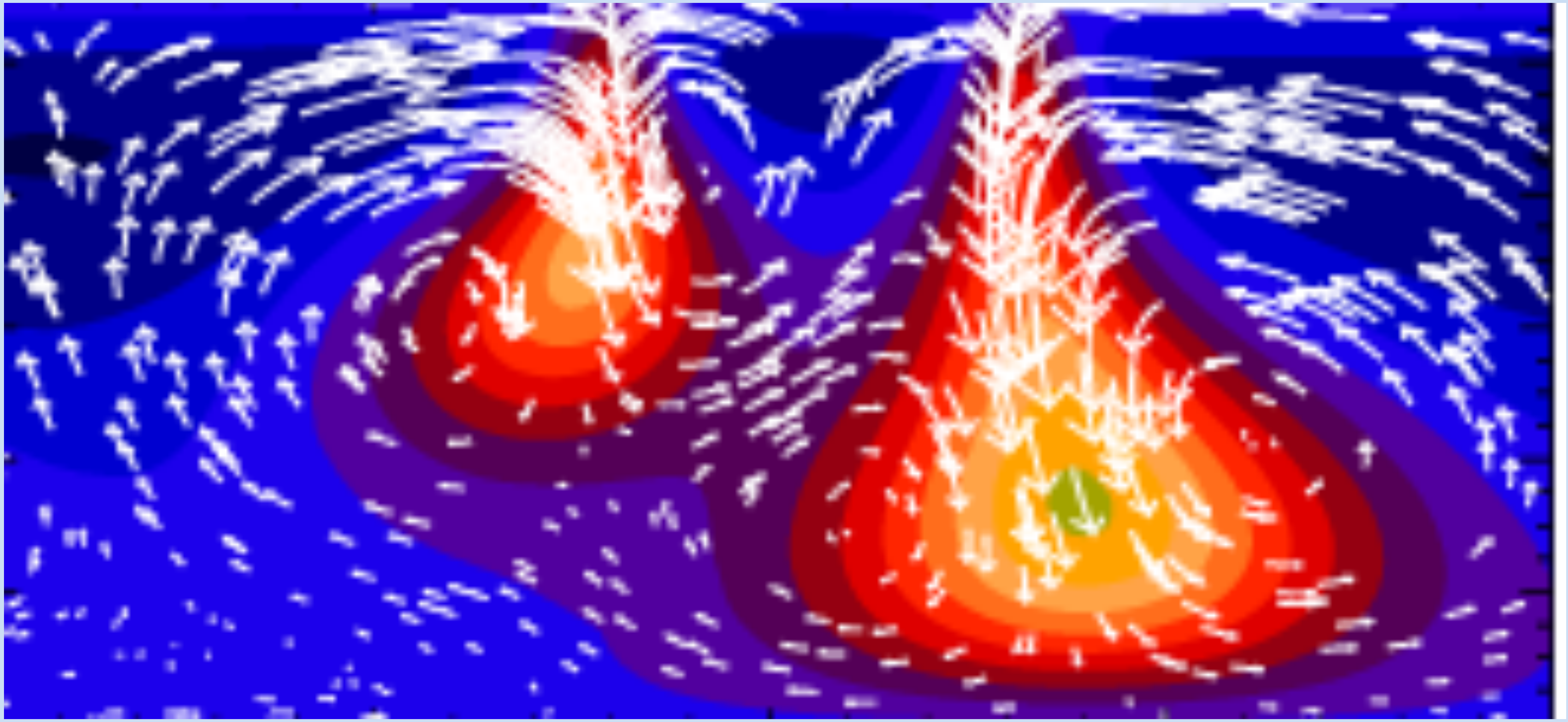
- Near-Surface simulation
- Radiative transfer
- Realistic convection
- Super-granulation determine separation

Negative Effective Magnetic Pressure Instability

Negative Effective Magnetic Pressure Instability
NEMPI

Negative Effective Magnetic Pressure Instability NEMPI

Negative Effective Magnetic Pressure Instability
NEMPI



Negative Effective Magnetic Pressure Instability NEMPI

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Pressure: $$P_{tot} = P_{gas} + \frac{B^2}{2\mu}$$

Negative Effective Magnetic Pressure Instability
NEMPI

Pressure: $P_{tot} = P_{gas} + \frac{B^2}{2\mu}$ $\qquad \overline{P}_{tot} = \overline{P}_{gas} + \frac{\overline{B}^2}{2\mu} + \overline{P}_{turb}$

Mean field approach: $U = \overline{U} + u$

Negative Effective Magnetic Pressure Instability NEMPI

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Turbulent pressure: $$\overline{\Pi}_{ij}^{B} = \overline{\rho u_i u_j} + \frac{\overline{b^2}}{2}\delta_{ij} - \overline{b_i b_j}$$

Negative Effective Magnetic Pressure Instability NEMPI

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Negative Effective Magnetic Pressure Instability NEMPI

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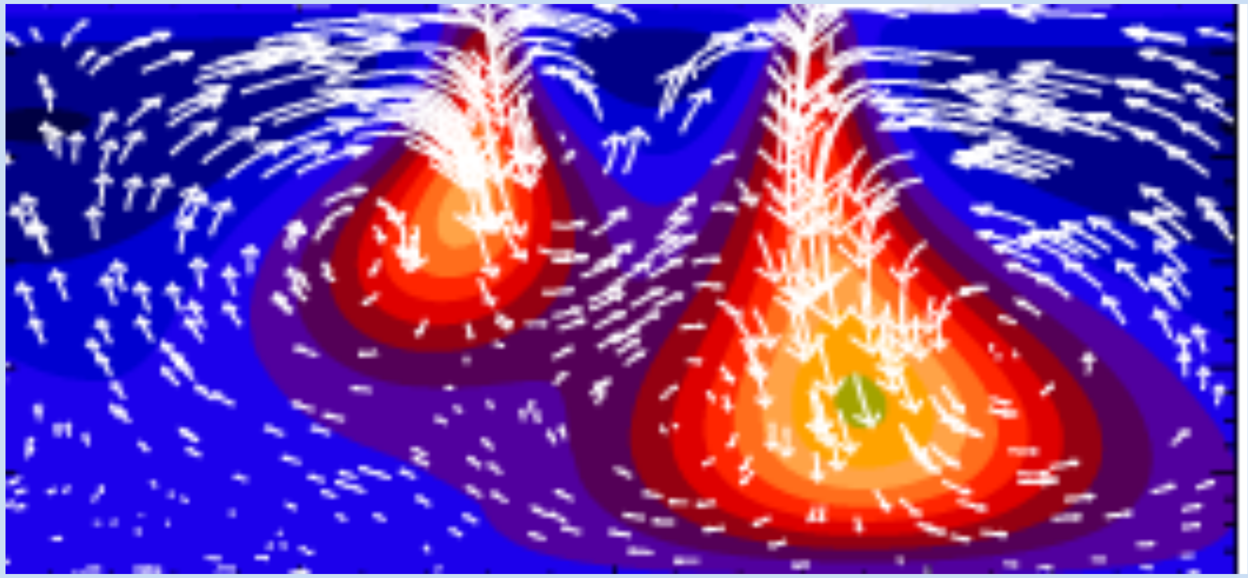
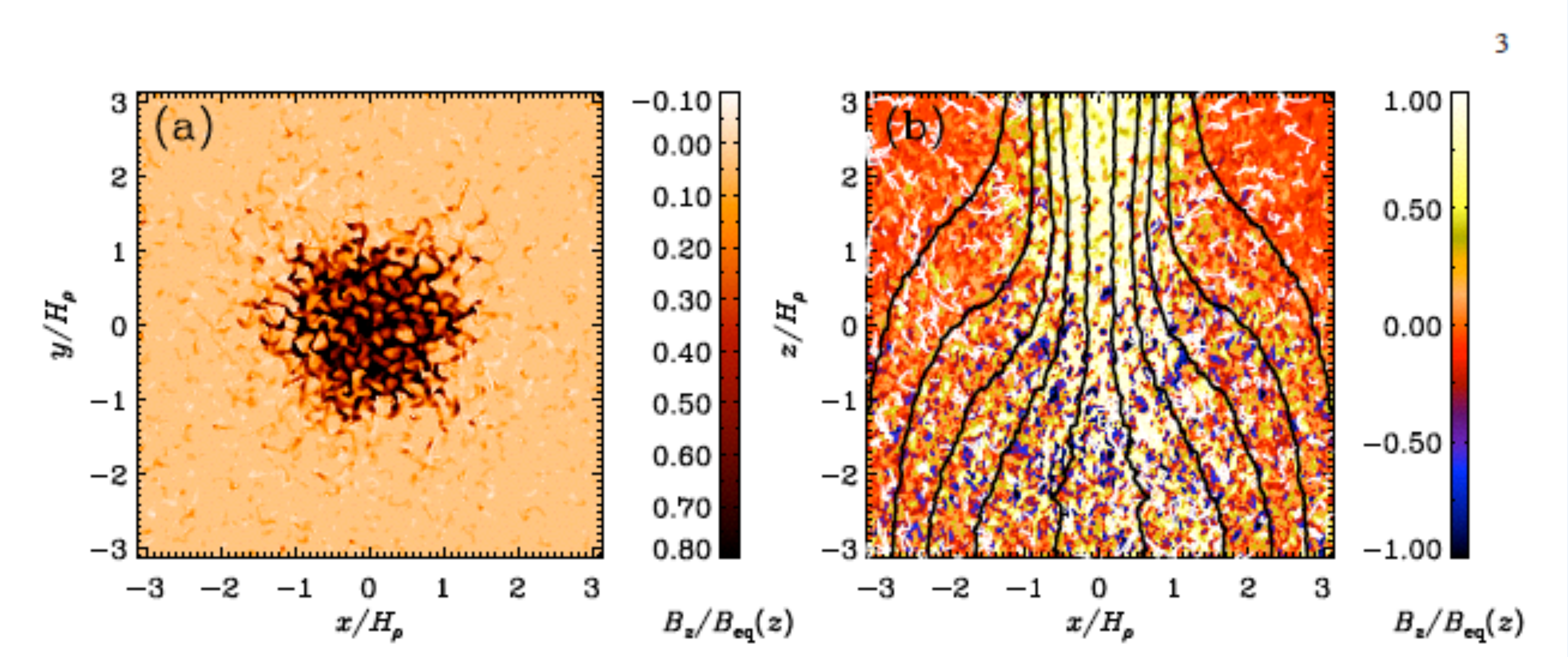


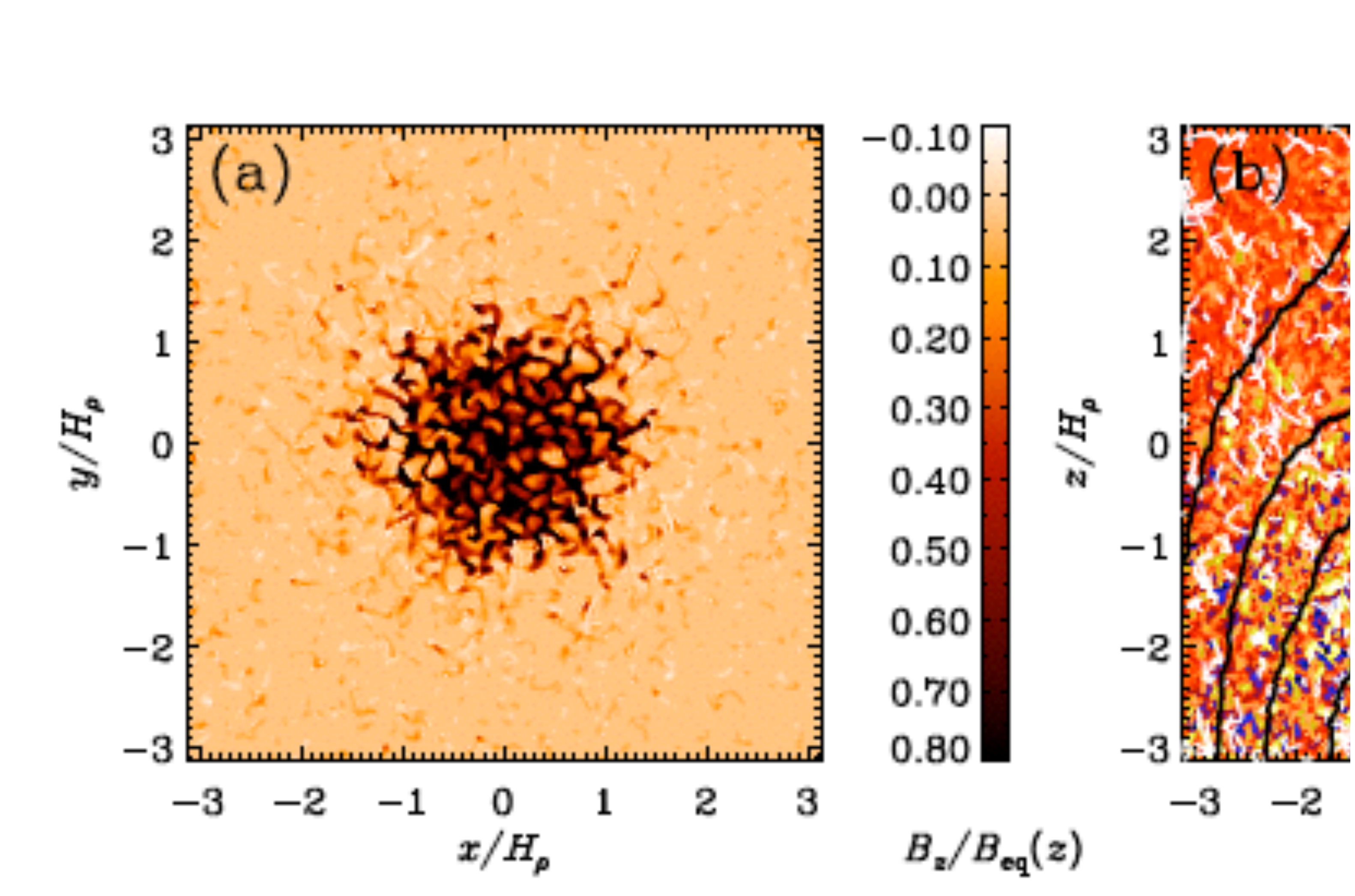
Kleeorin et al. 1989, 1990
Brandenburg et al., 2011, 2012, 2013
Kemel et al. 2012a,b, 2013a,b

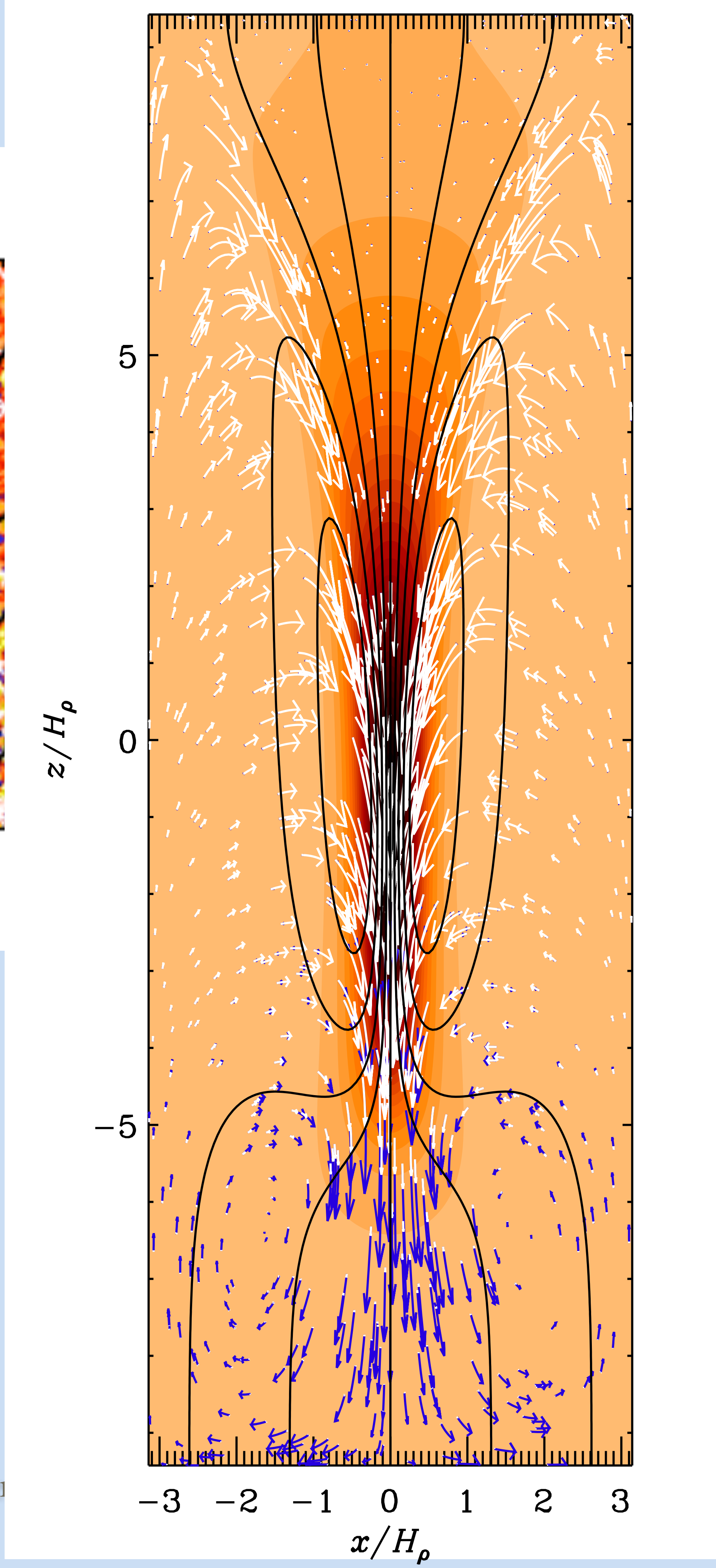
NEMPI



Brandenburg et al., 2013

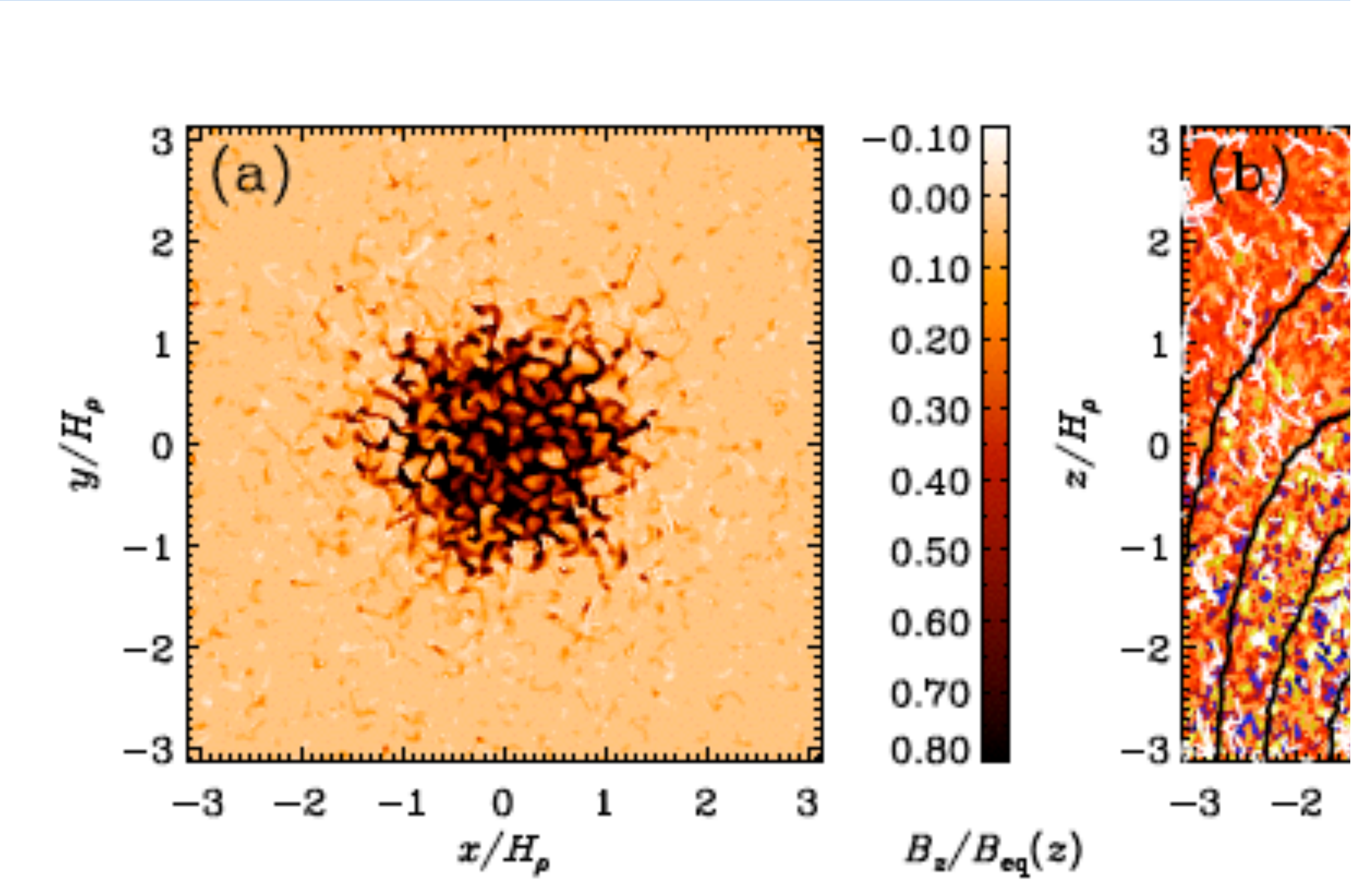
NEMPI

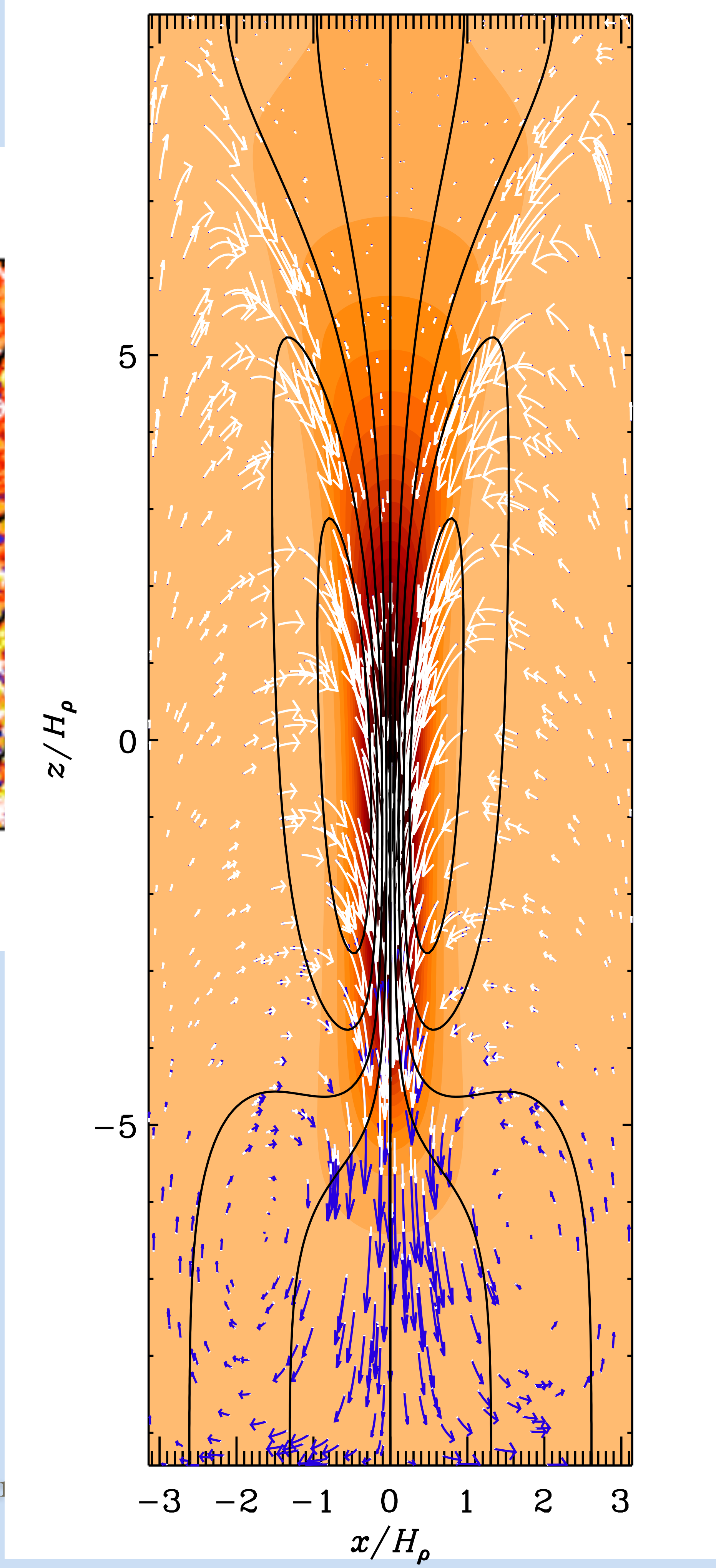




Brandenburg et al., 2013

NEMPI

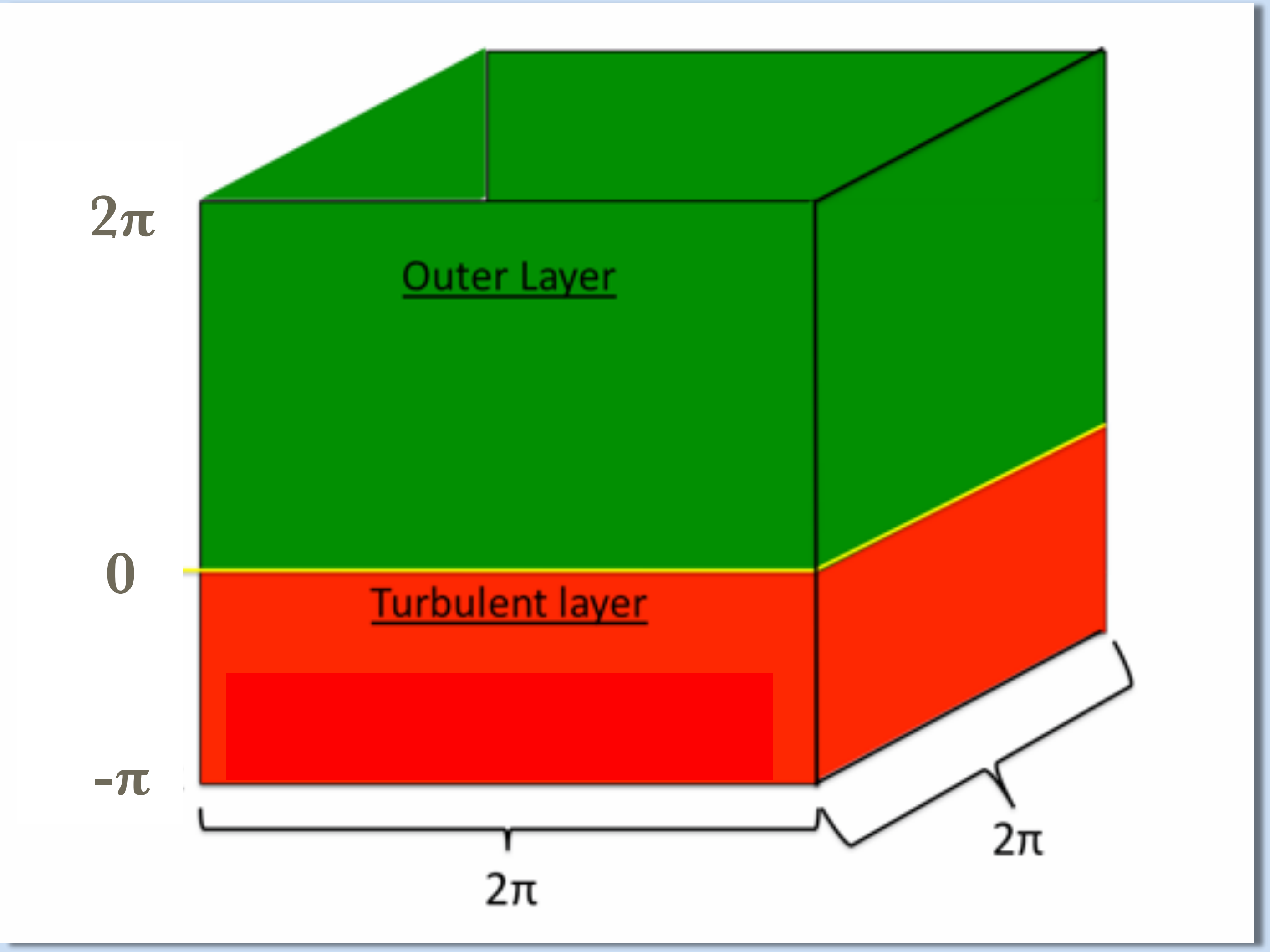




Brandenburg et al., 2013

- Turbulent magnetic instability
- Scale separation important
- No bipolar region yet

Cartesian Setup

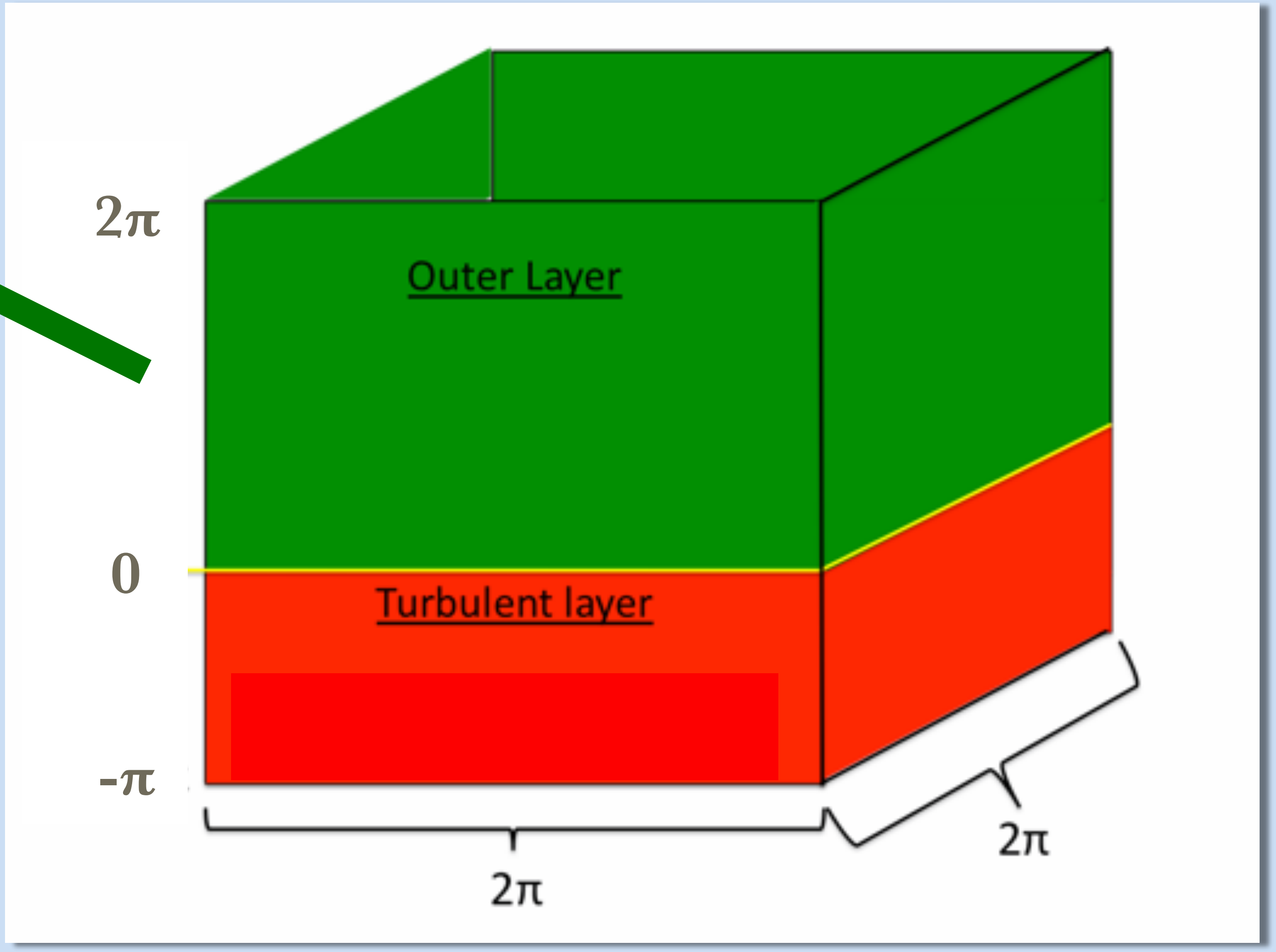


Cartesian Setup

Simplified corona:

Isothermal

density stratification



Cartesian Setup

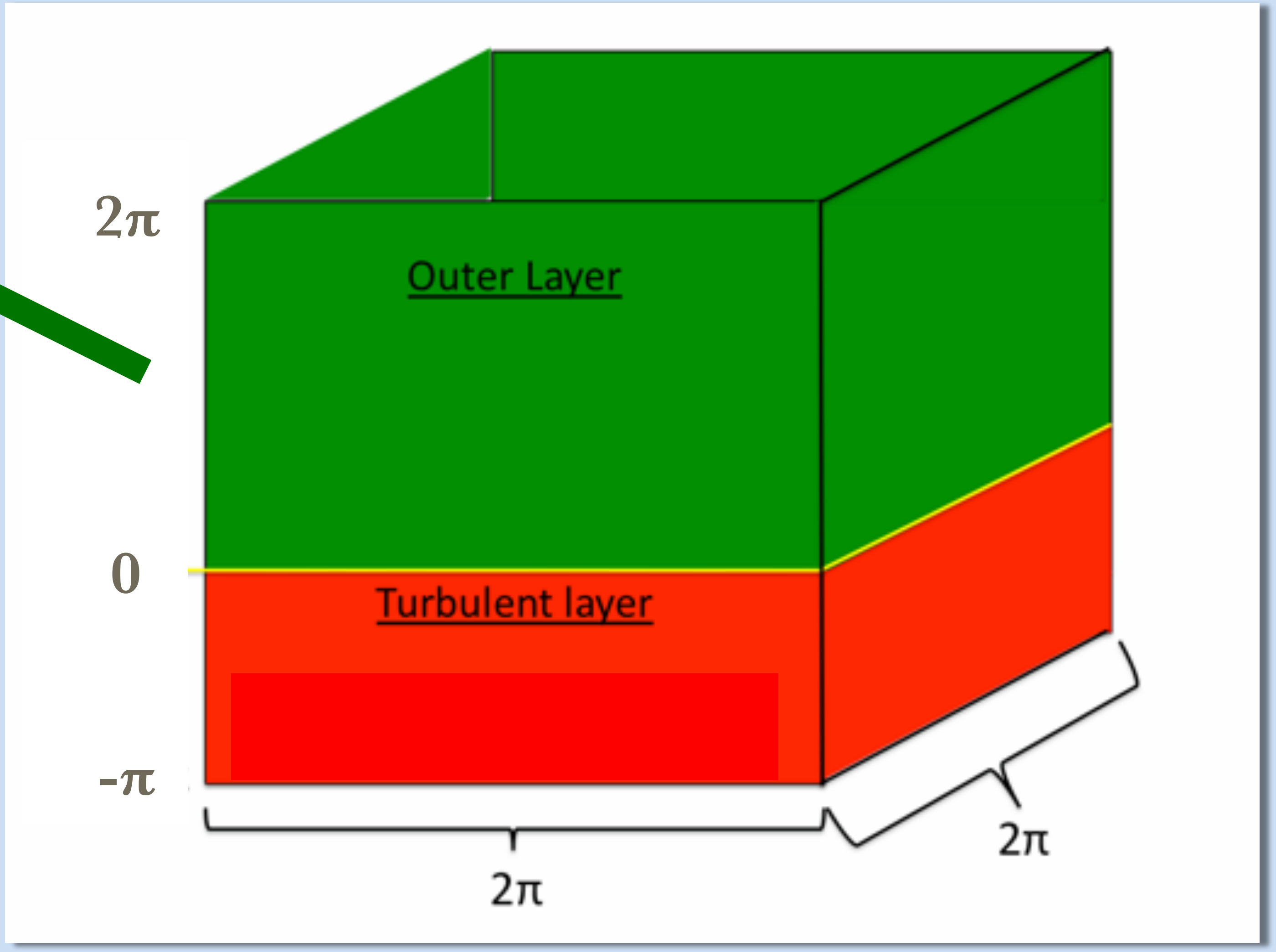
Simplified corona:

Isothermal

density stratification

Imposed magnetic field:

$B_y = B_0 = 0.02\ B_{eq0}$



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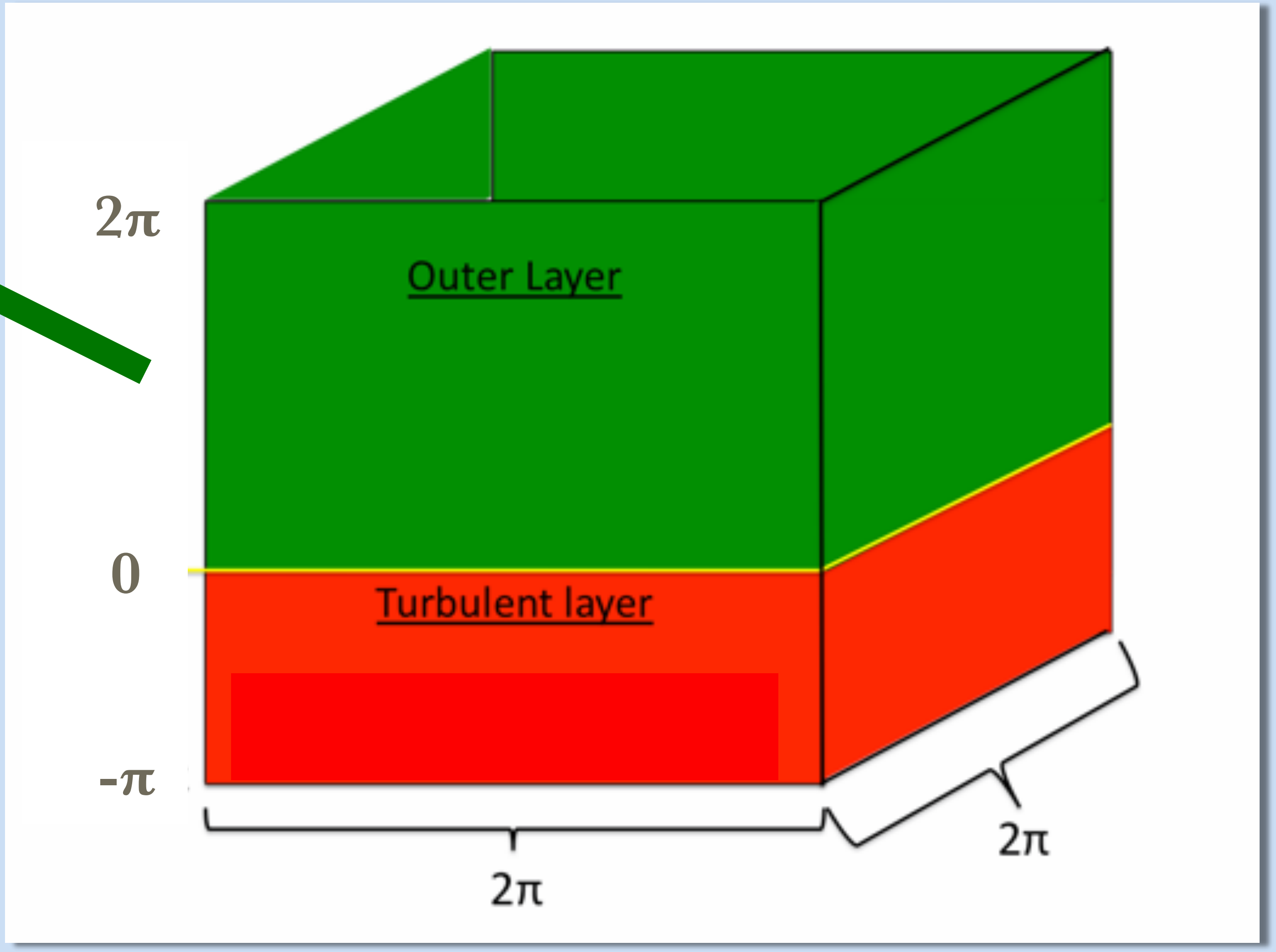

Imposed magnetic field:

$B_y = B_0 = 0.02\ B_{eq0}$

Equations:

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

$$\frac{D \ln \rho}{Dt} = -\nabla \cdot U$$

$$\frac{DU}{Dt} = g + \theta_w(z) f + \frac{1}{\rho}[-c_s^2 \nabla \rho + J \times B + \nabla \cdot (2\nu\rho S)]$$

Cartesian Setup

Simplified corona:

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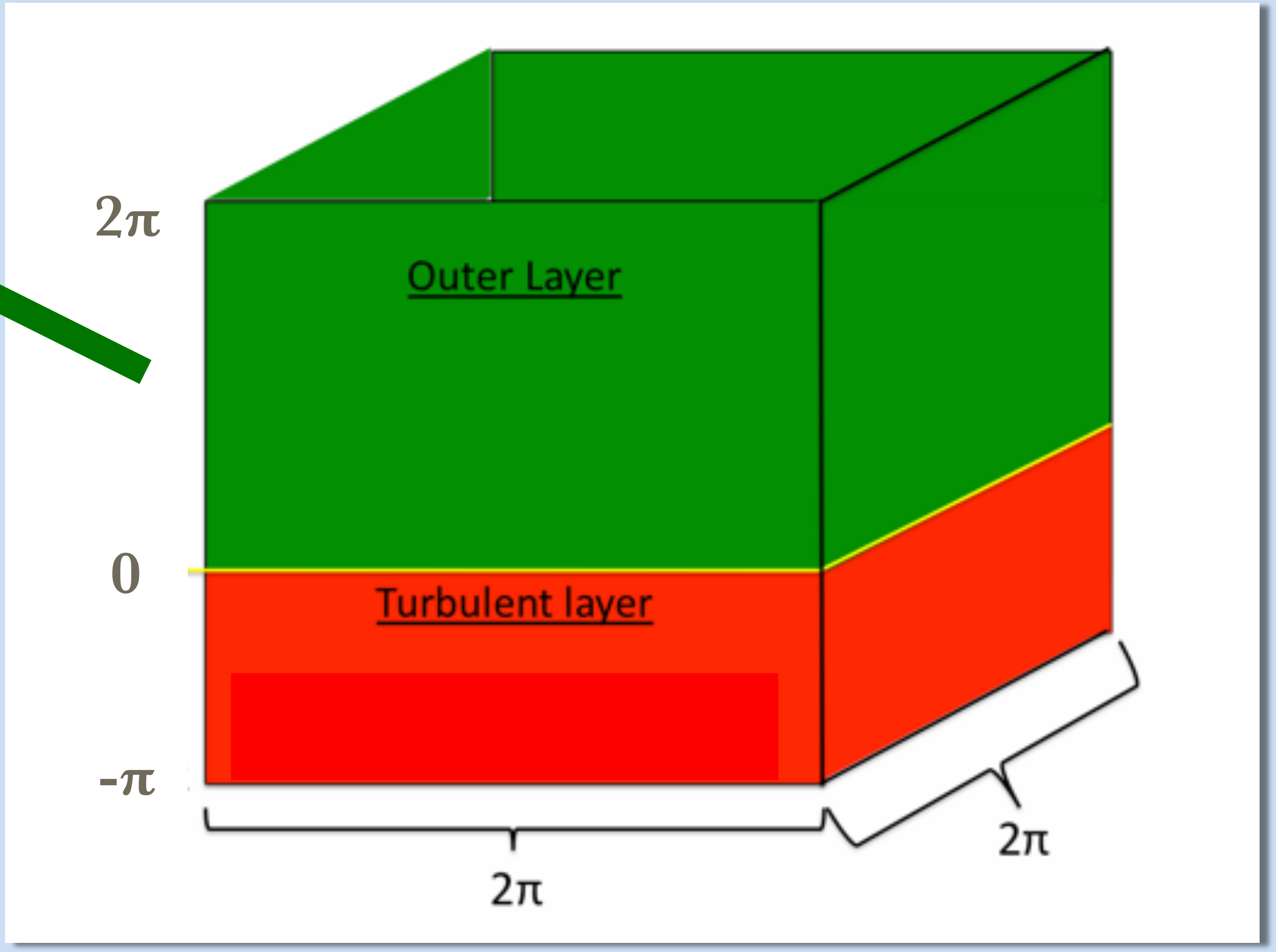

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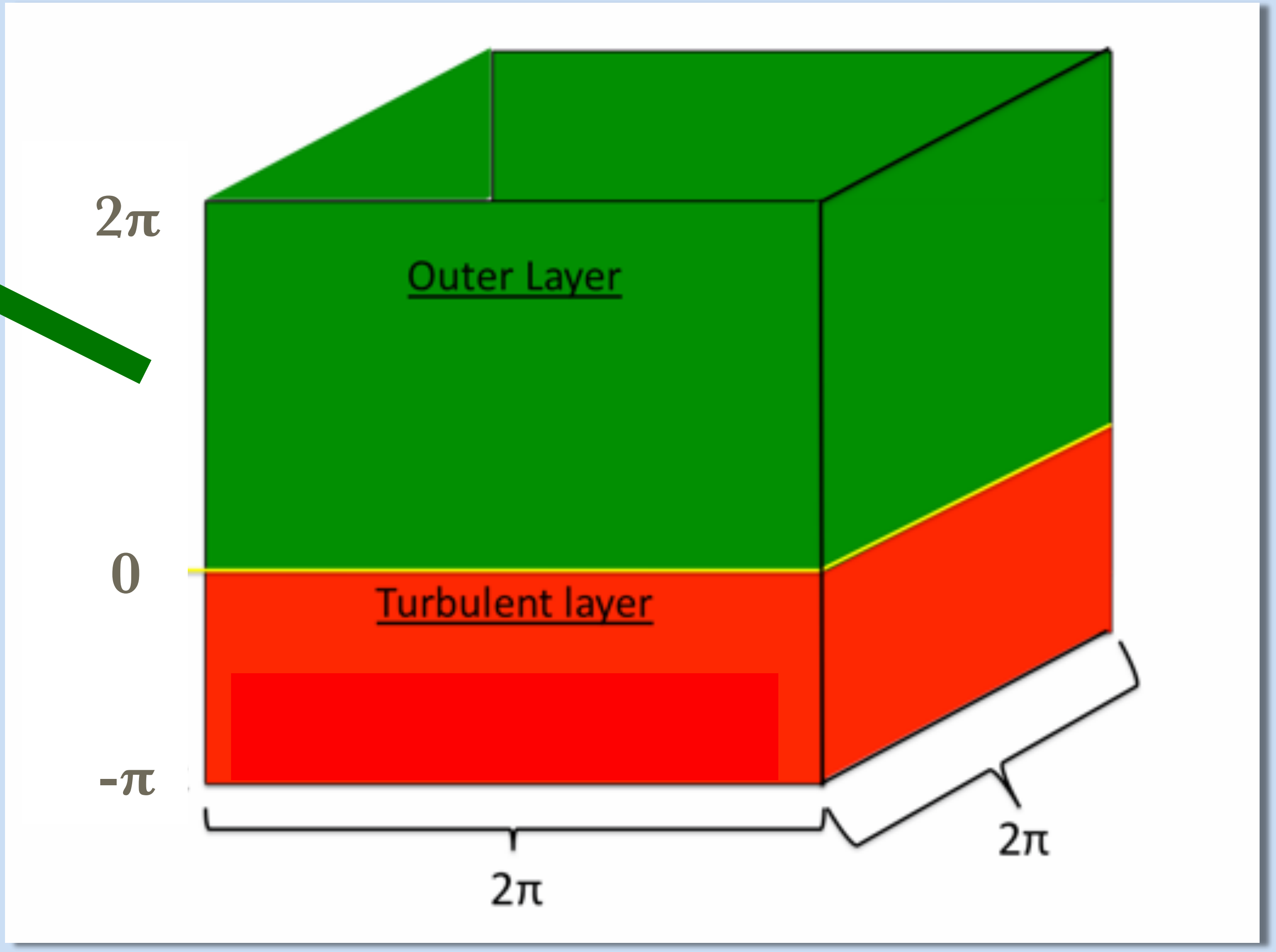
Forcing f with non-helical transverse plane waves with wave numbers around $k_f = 30$.

Cartesian Setup

Simplified corona:

Isothermal

density stratification



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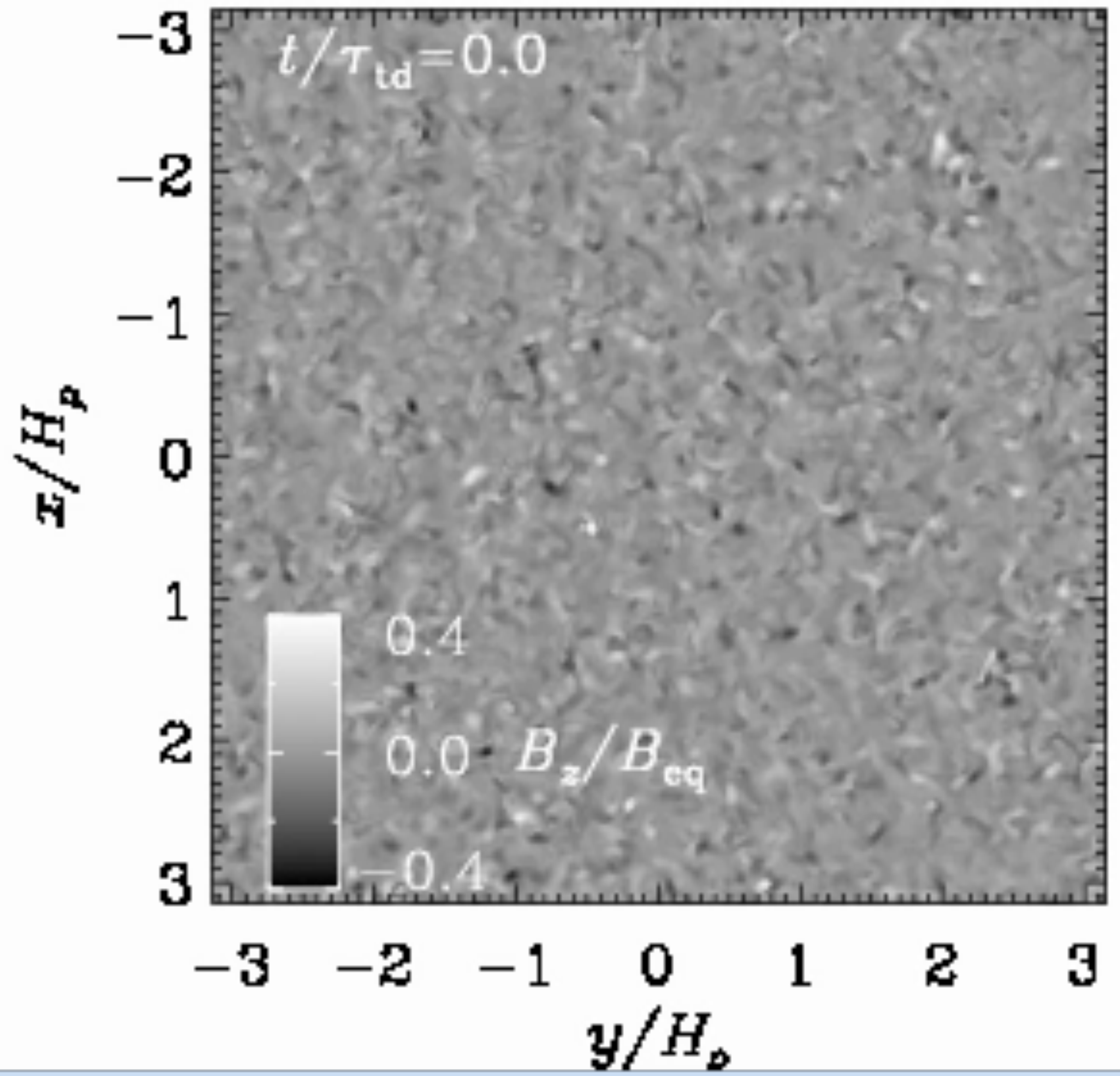
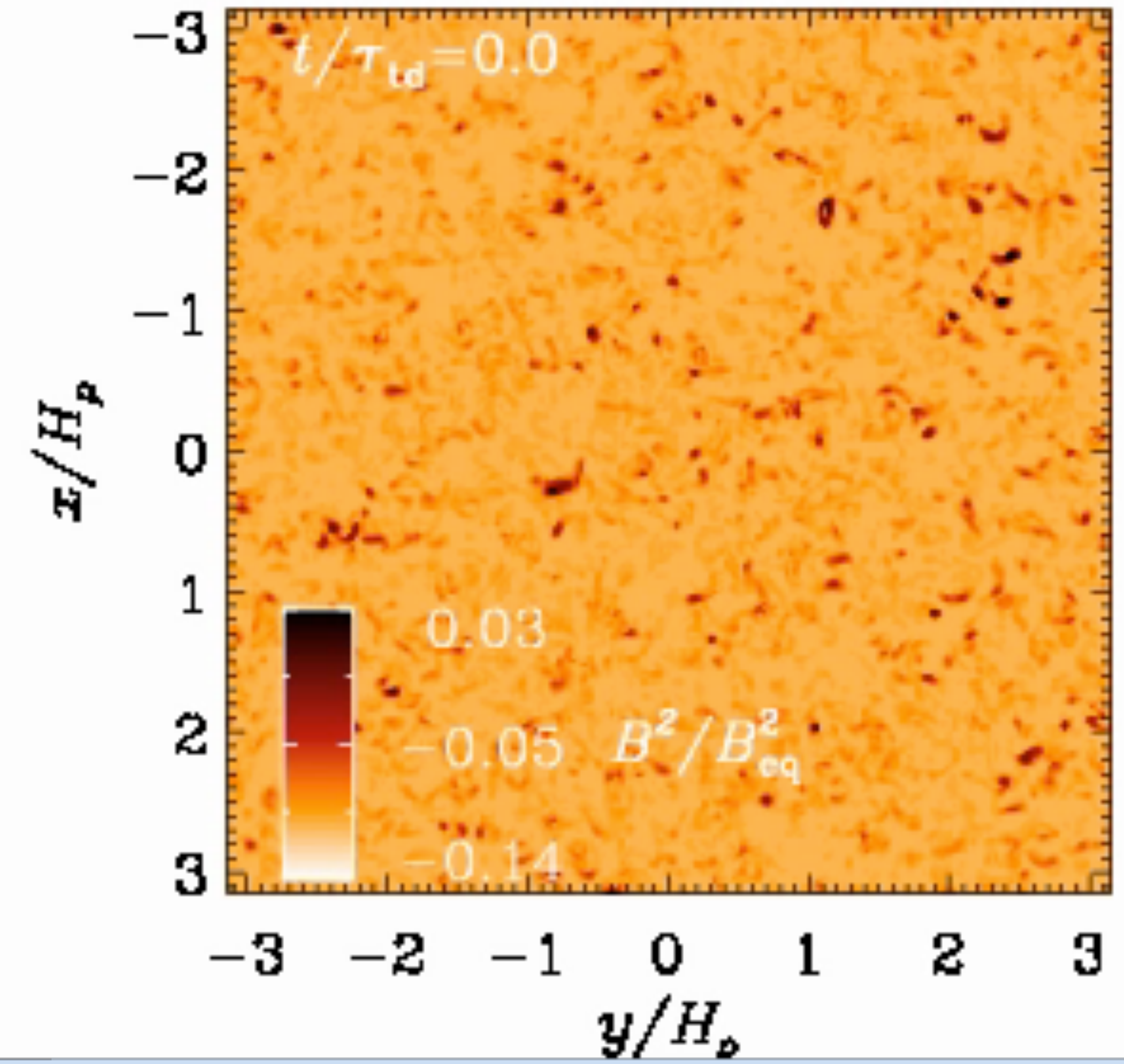
$$\Theta_w(z) = \frac{1}{2}\left(1 - \mathrm{erf}\,\frac{\mathrm{z}}{\mathrm{w}}\right)$$

Forcing f with non-helical transverse plane waves with wave numbers around $k_f = 30$.

Results



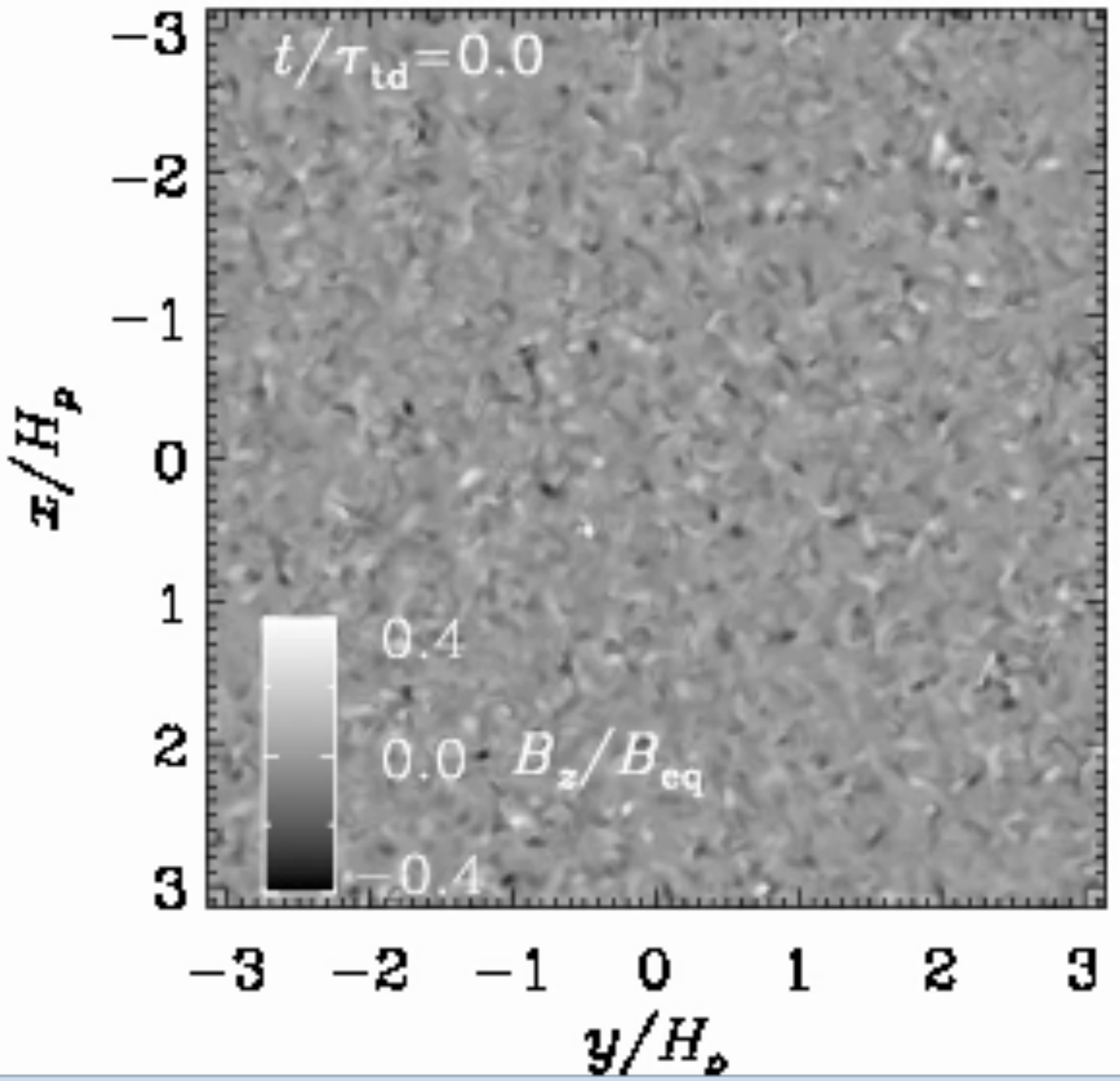


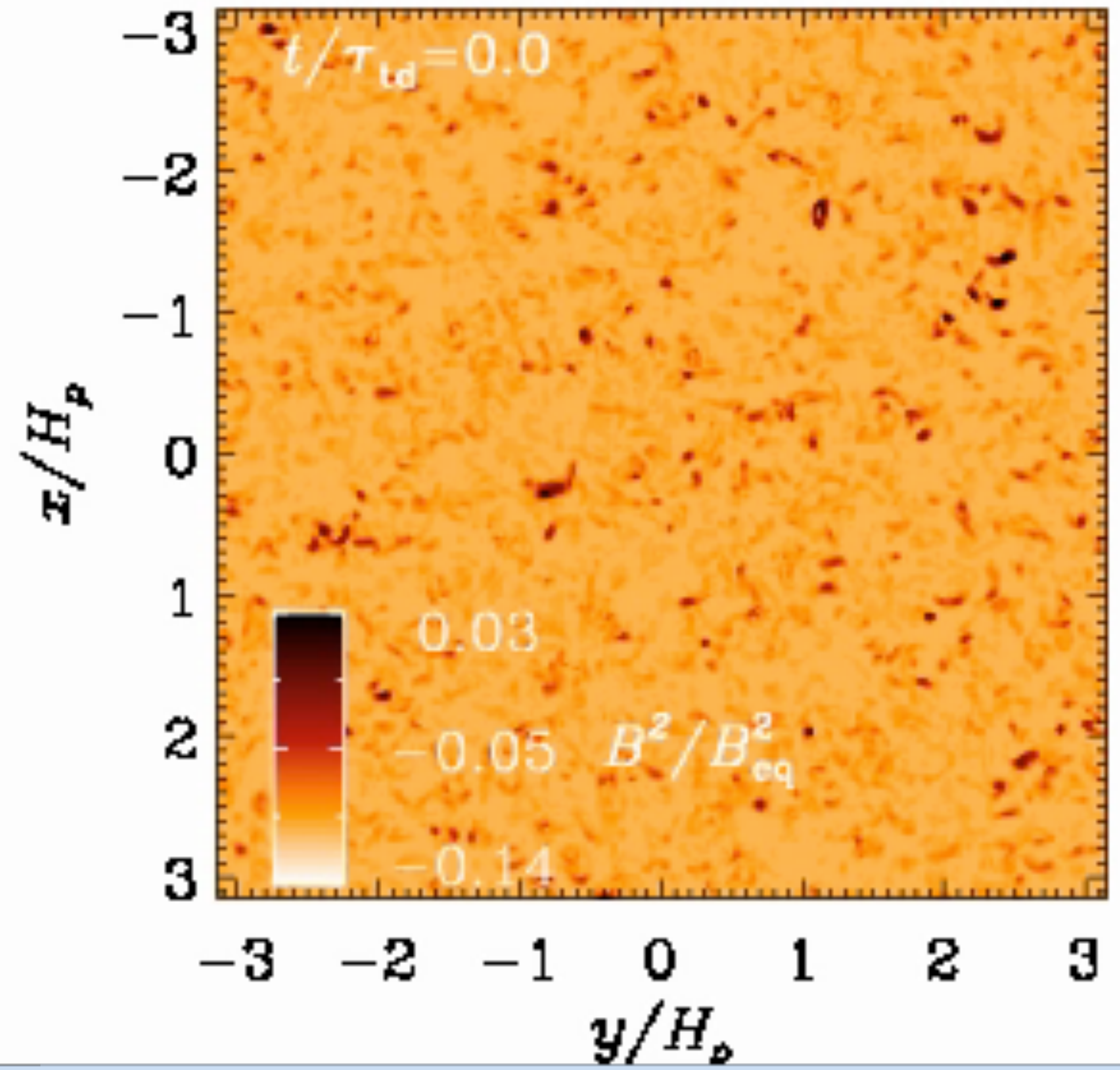
B_z

B^2

$\tau_{td}=3k_f/(u_{rms}\, k_1{}^2)$

Results





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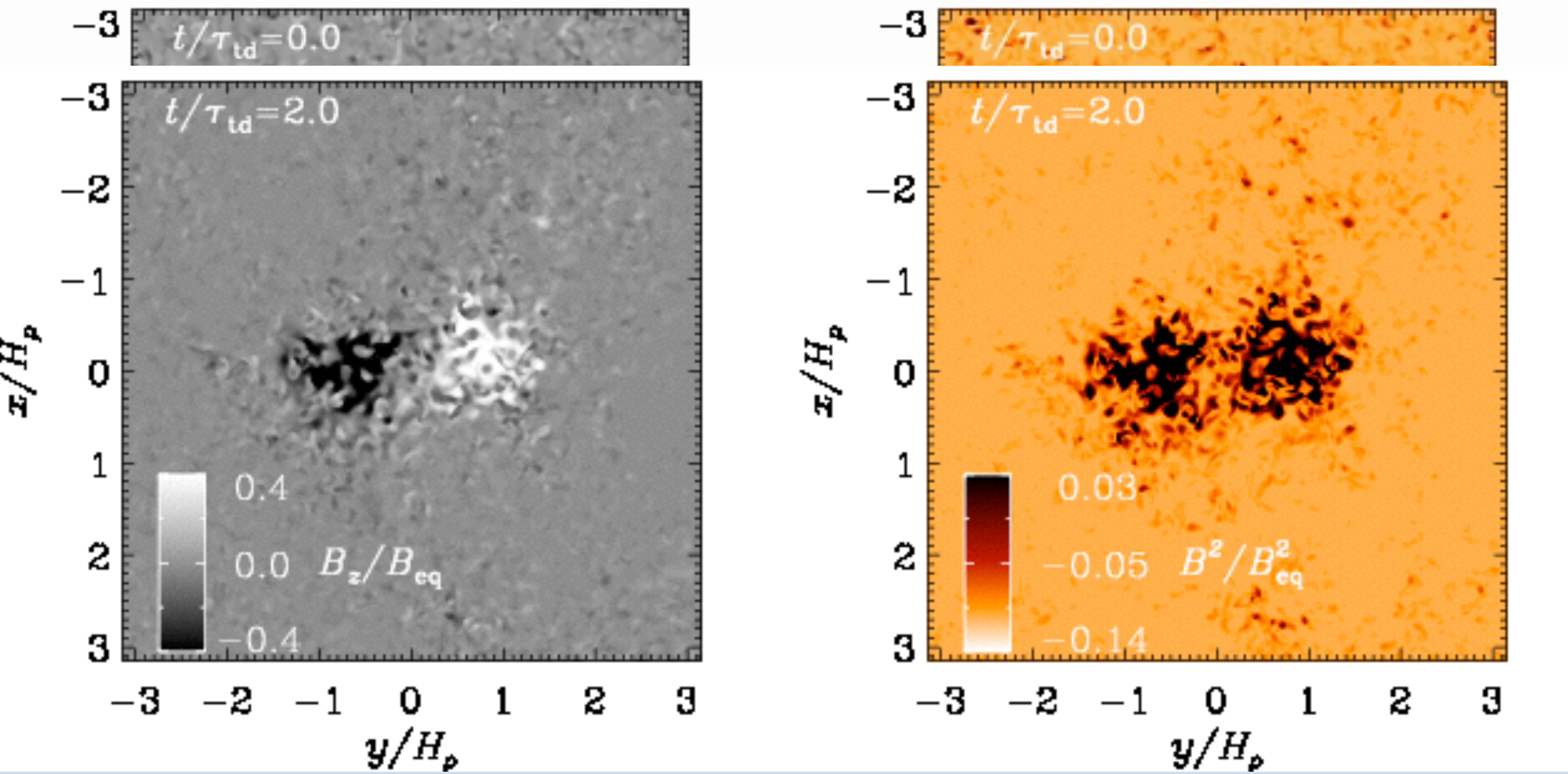

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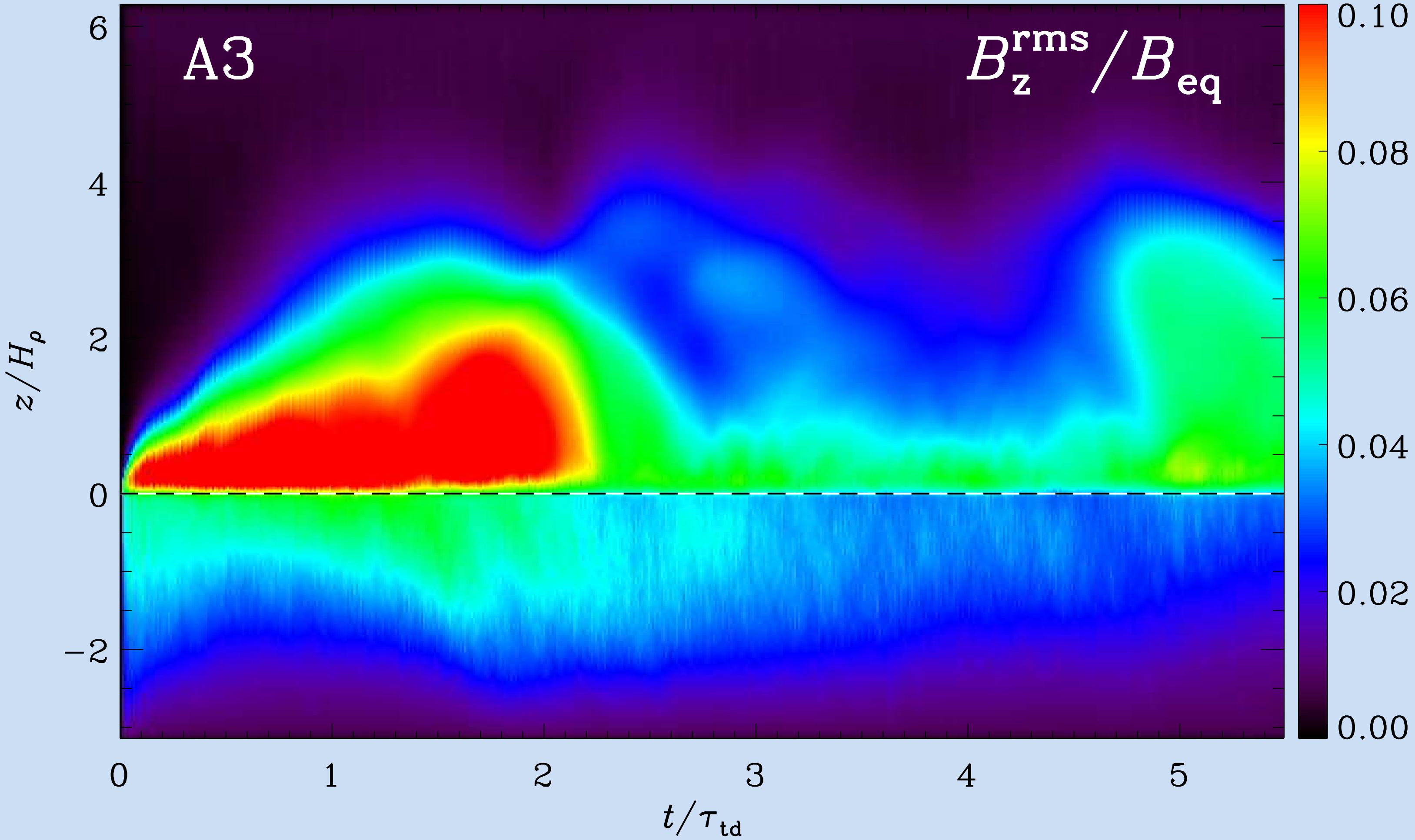
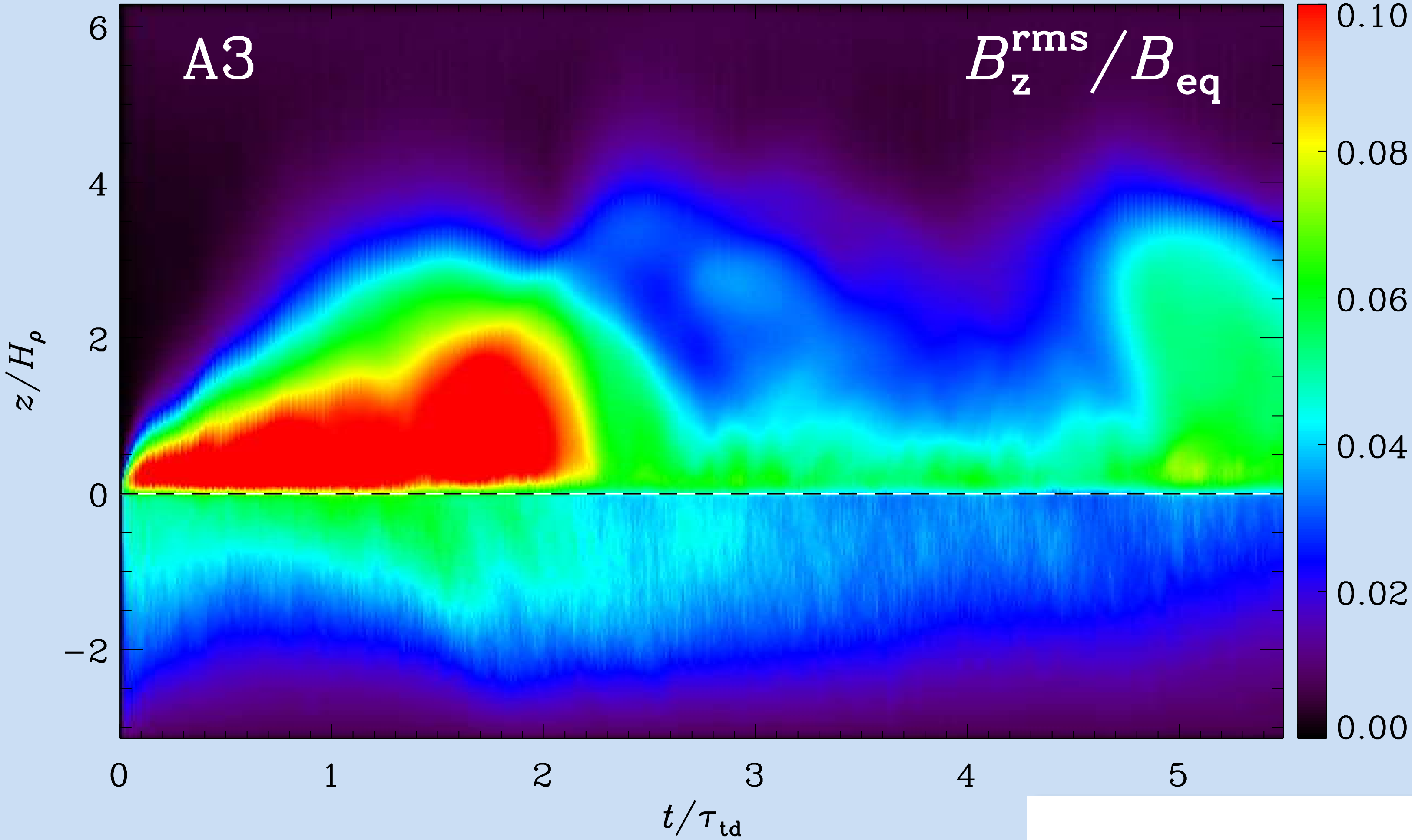
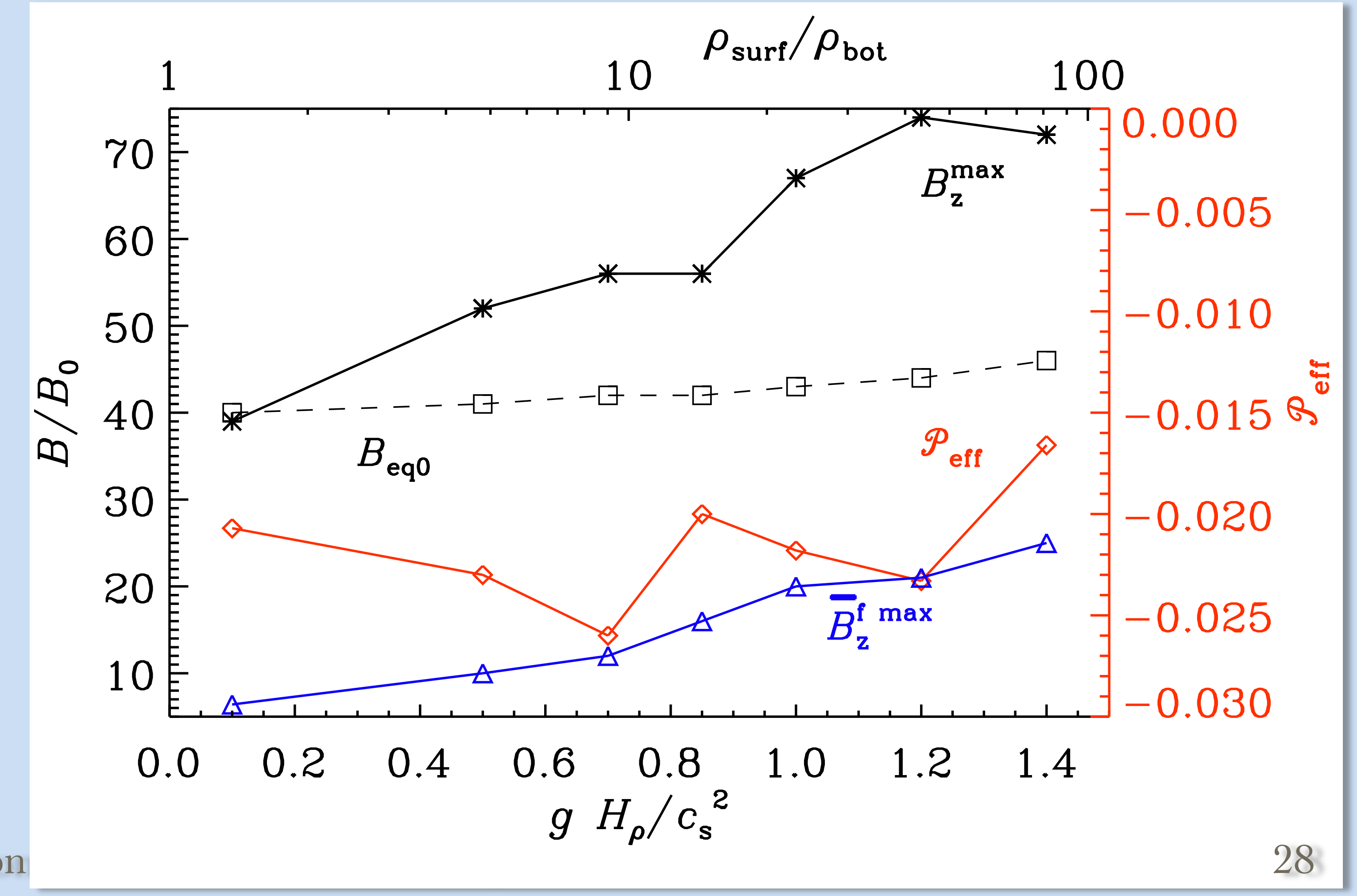


Emergence from the lower layer to the surface



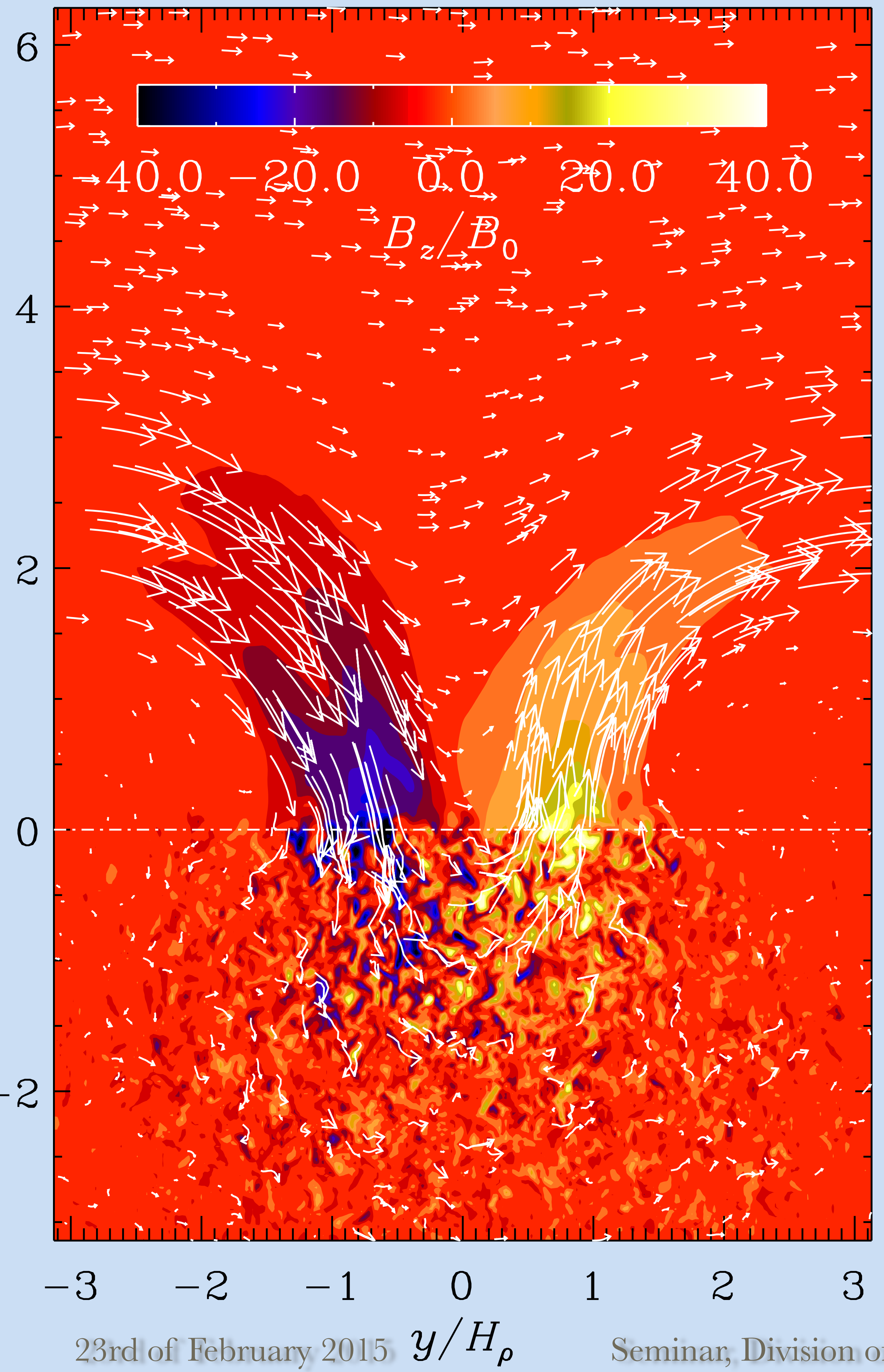
Emergence from the lower layer to the surface

Strong dependency with stratification

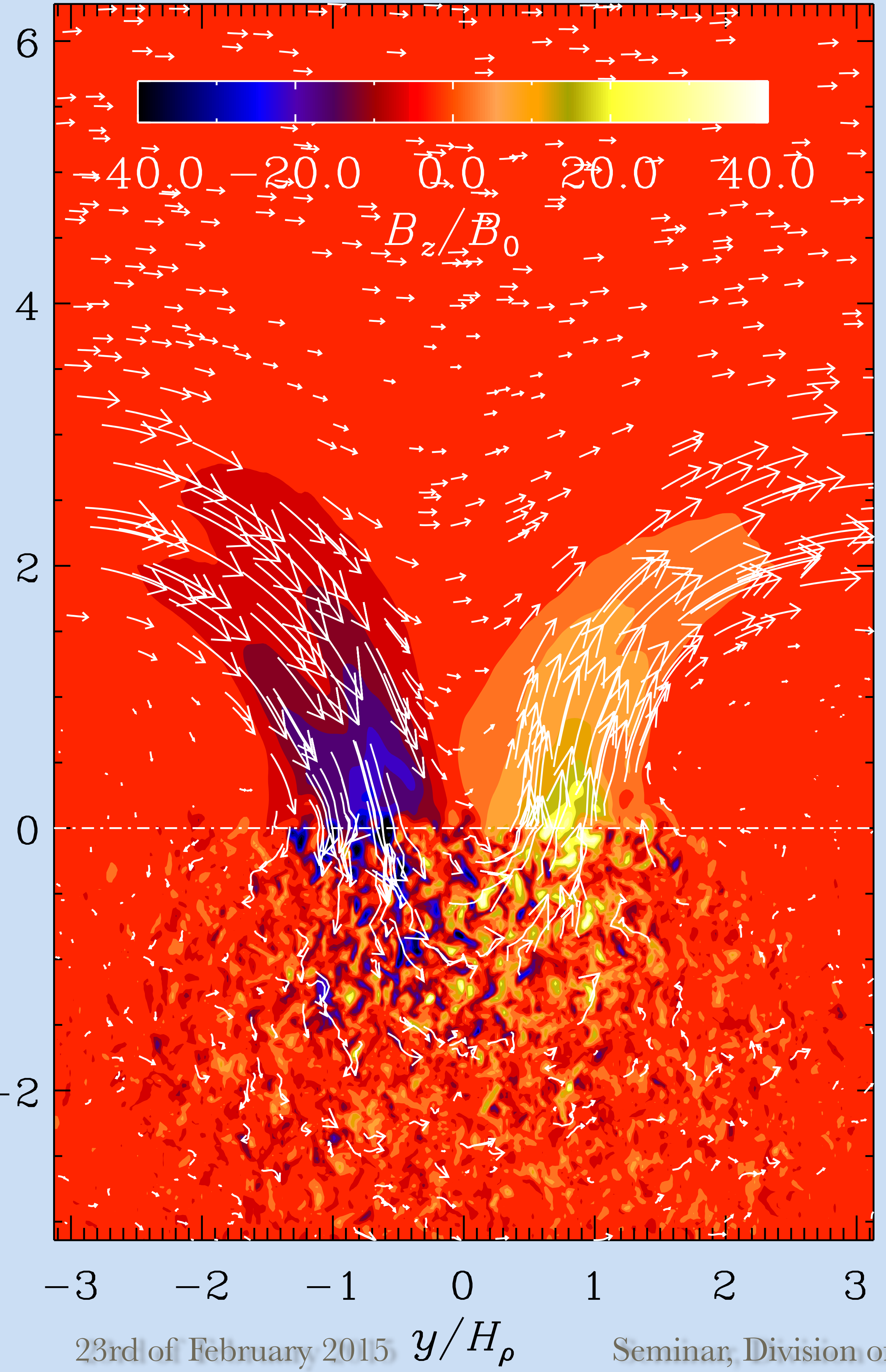


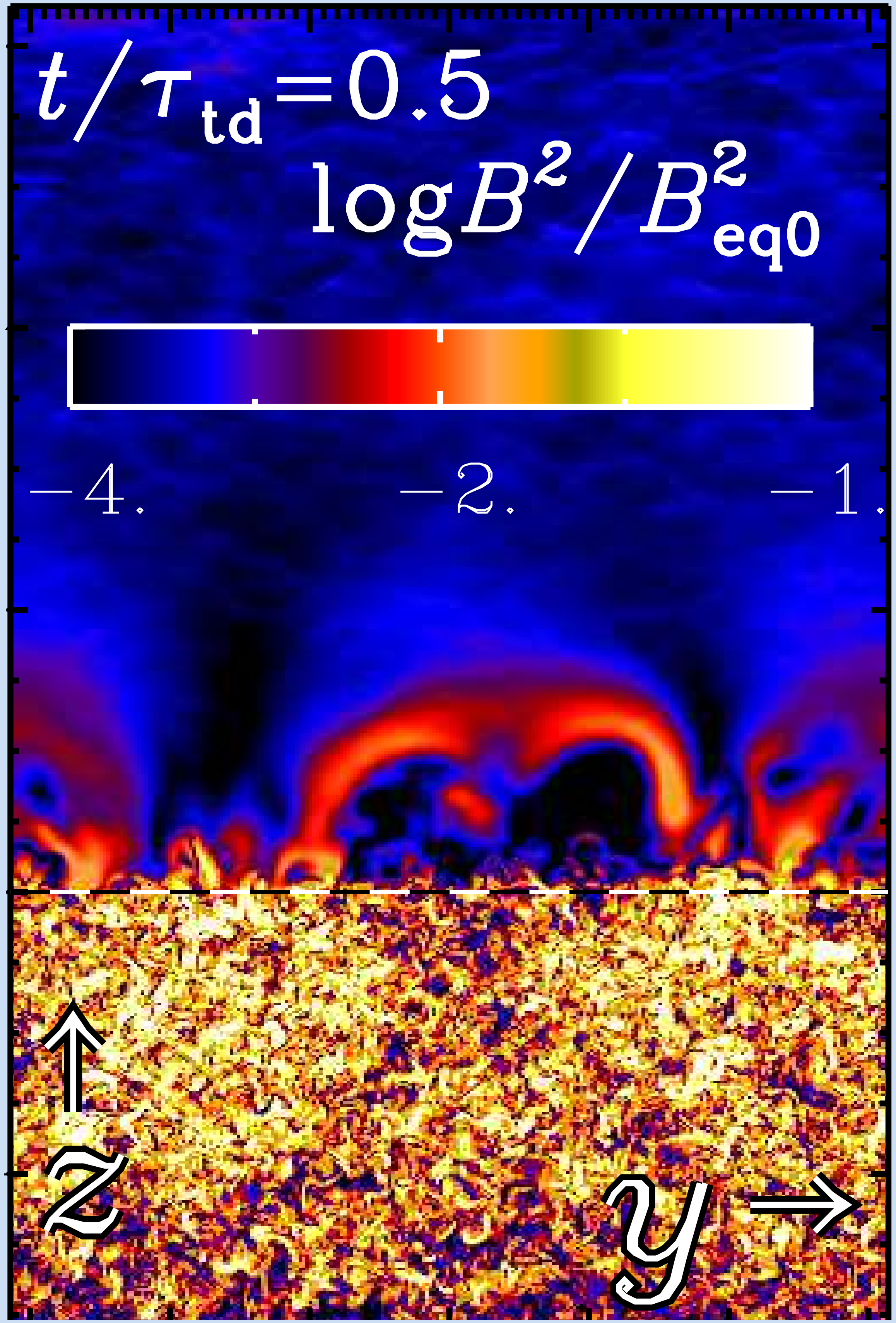
Warnecke et al. 2015 (submitted to A&A, arXiv:1502.03799)

Coronal extend

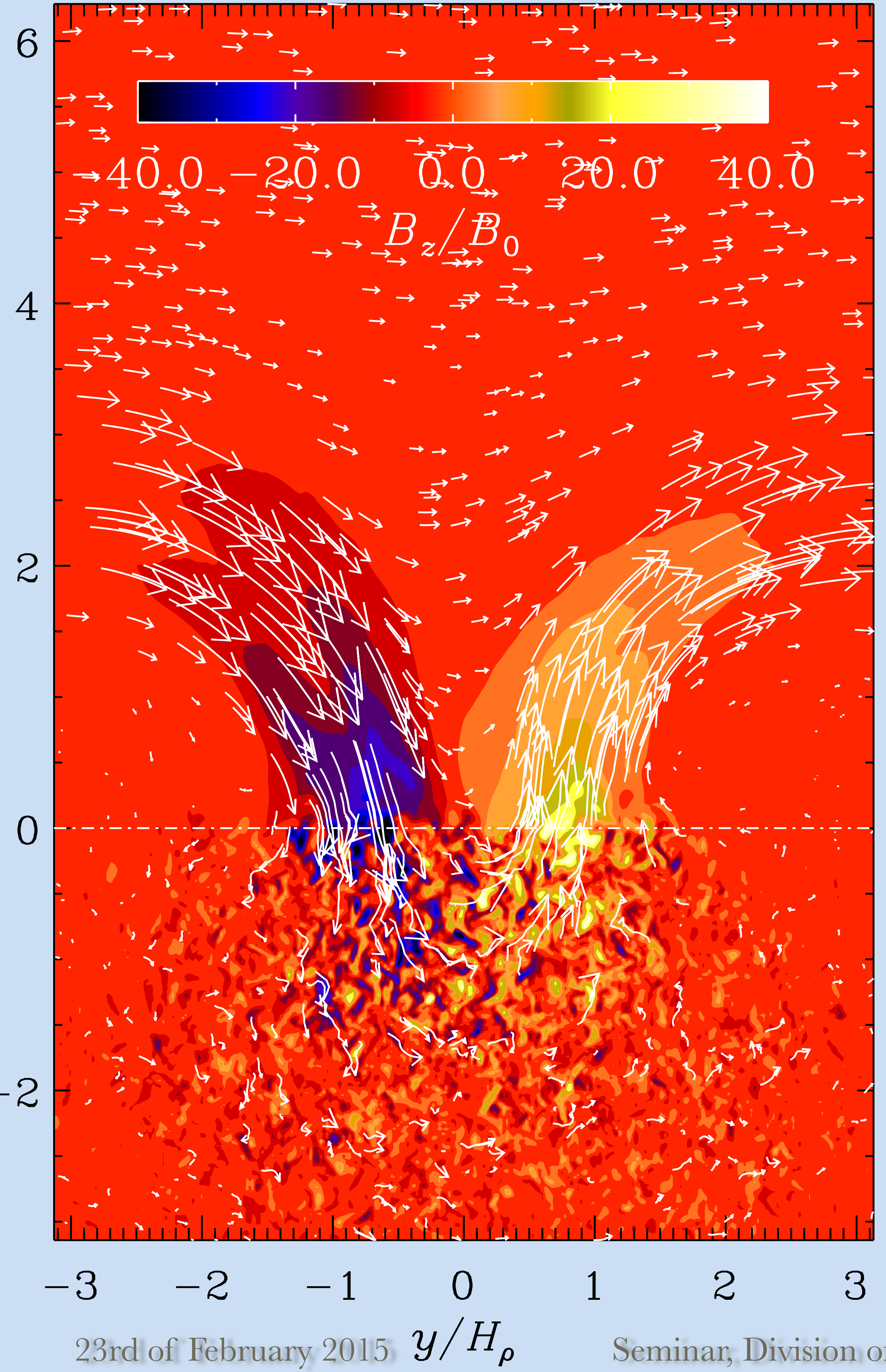


Coronal extend

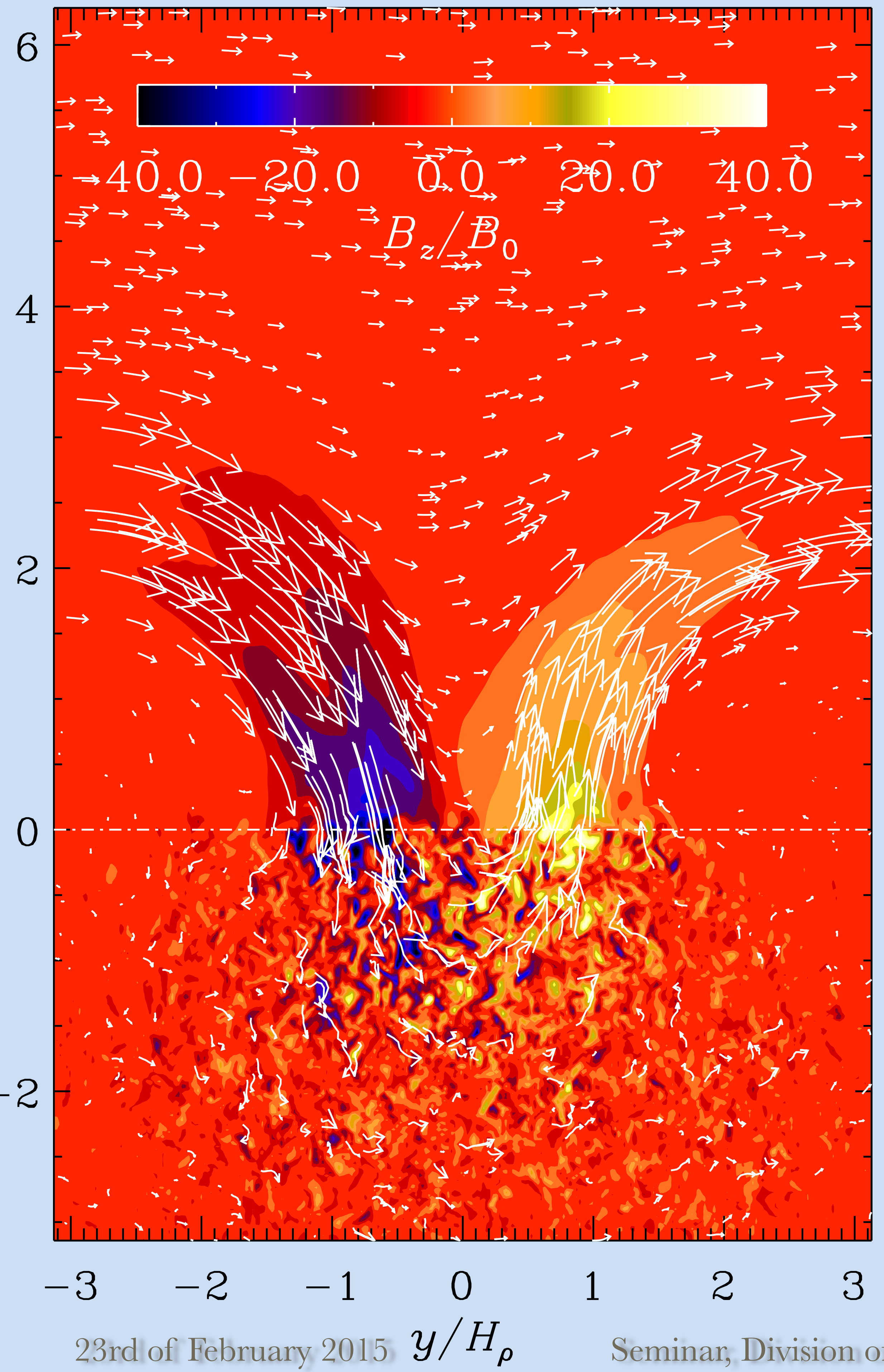


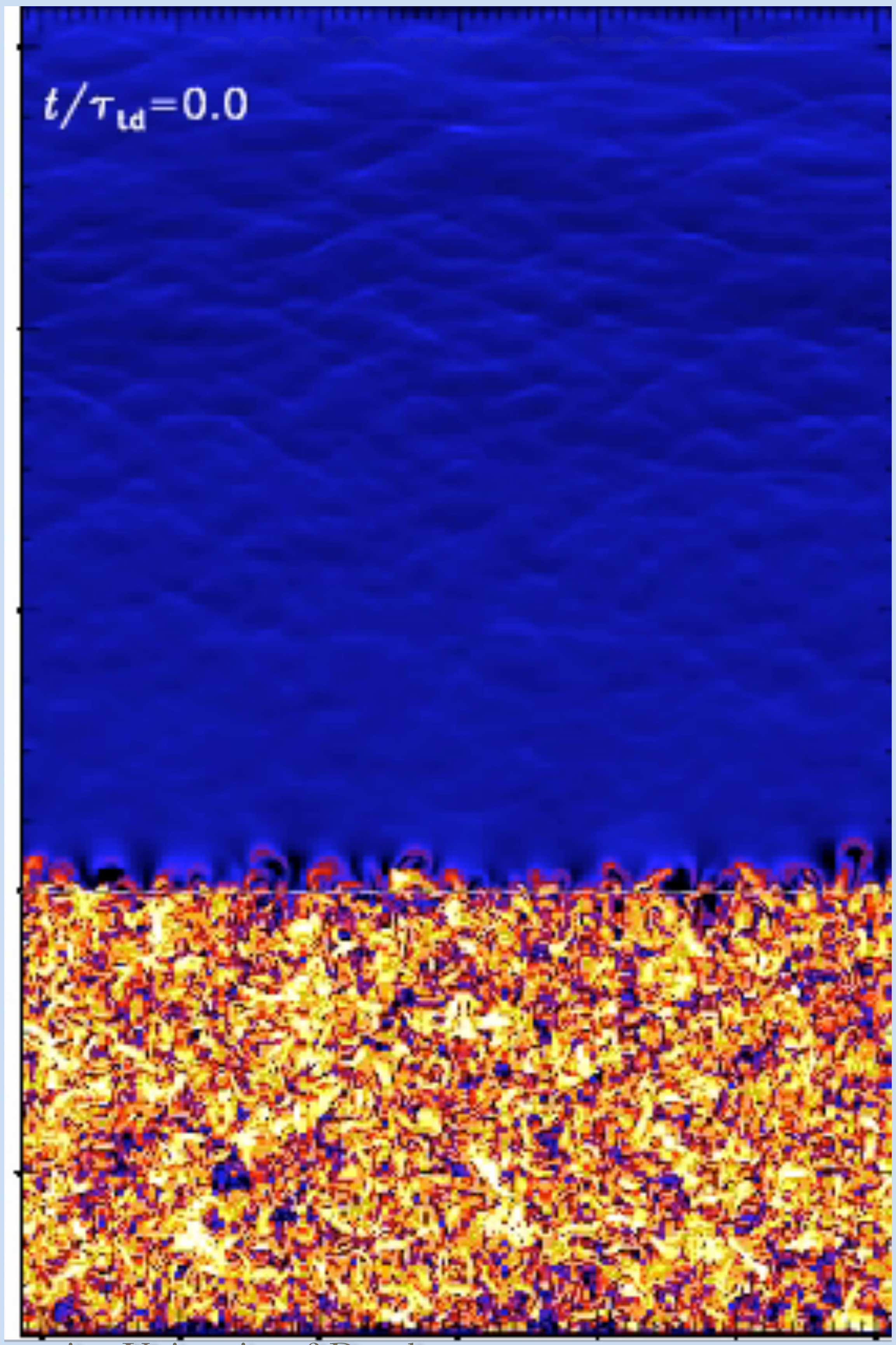


Coronal extend



Coronal extend





Conclusions

- Equatorward propagation in simulation are related to the negative shear.
- Migration of mean magnetic field can be entirely explained by an alpha-omega-dynamo wave
- Near-surface shear layer in the Sun might be important to produce the solar dynamo.
- Simple setup is enough for spontaneous formation.
- NEMPI might be a possibility for formation of sunspots