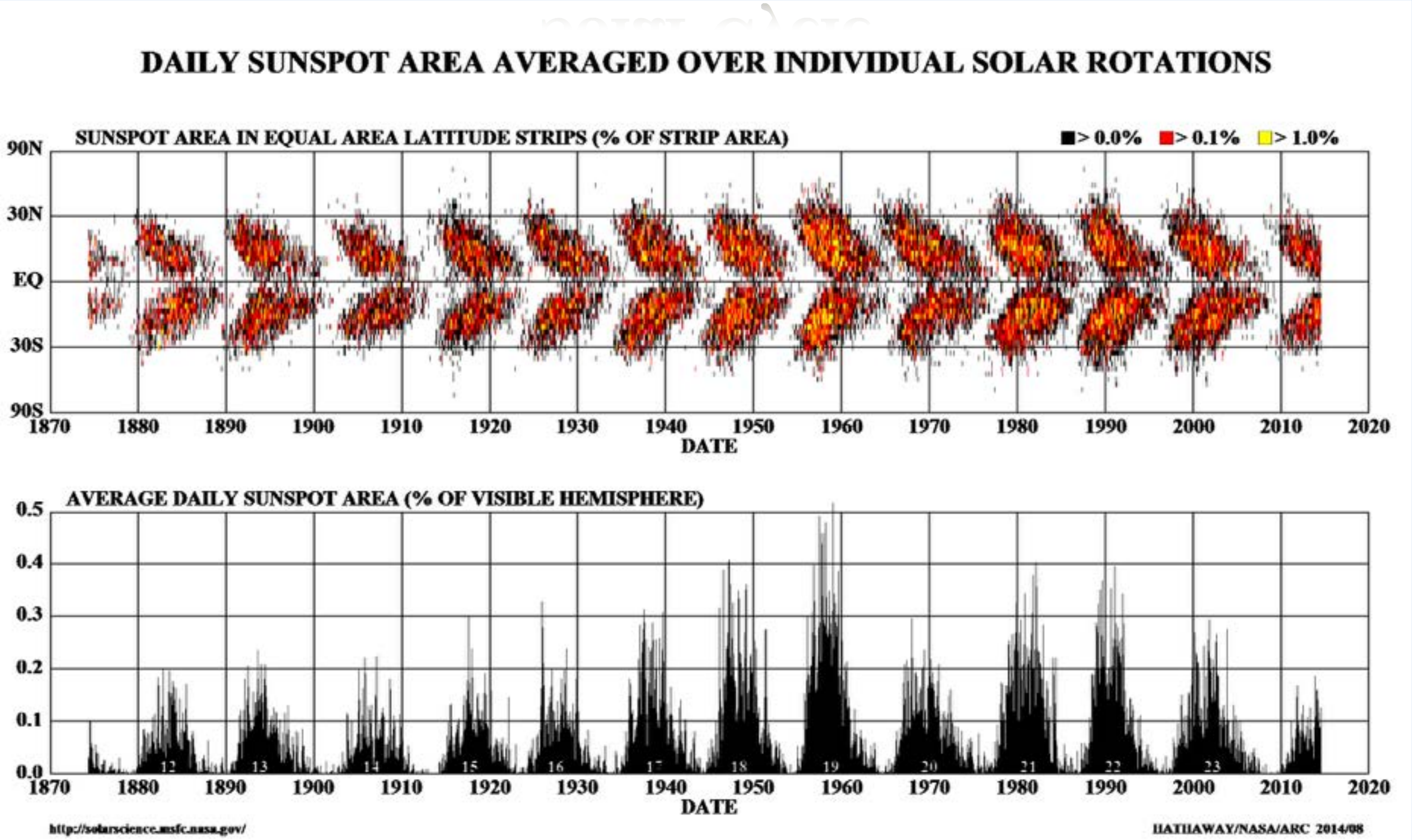
The importance of a coronal envelope for modeling the global turbulent dynamo of the Sun

Jörn Warnecke

Max Planck Institute for Solar System Research

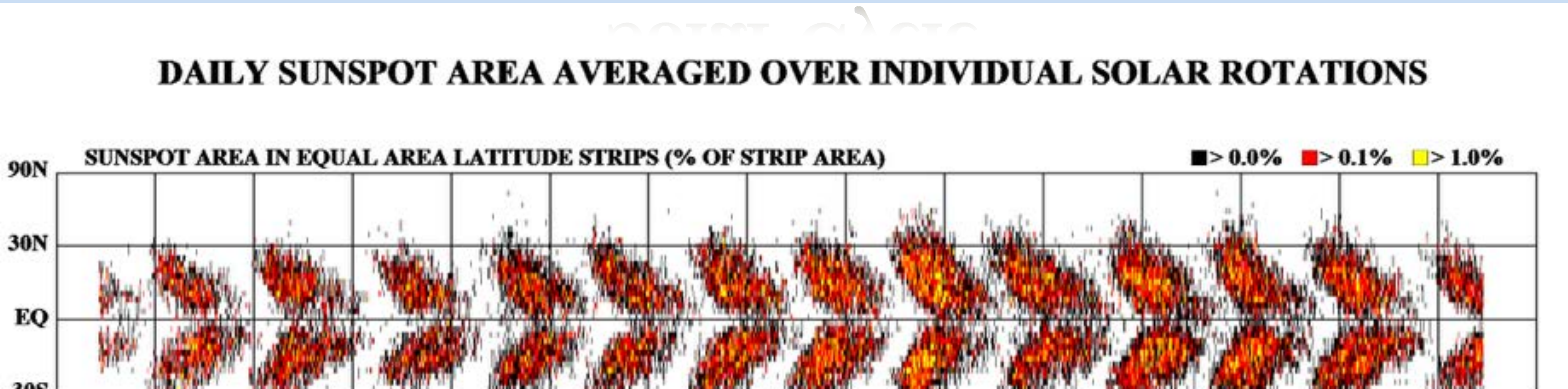
Axel Brandenburg, Nordita
Petri J. Käpylä, Helsinki University
Maarit J. Käpylä, Aalto University

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
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
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
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
DATE
http://solarscience.msfc.nasa.gov/
HATHAWAY/NASA/ARC 2014/08

Solar Cycle



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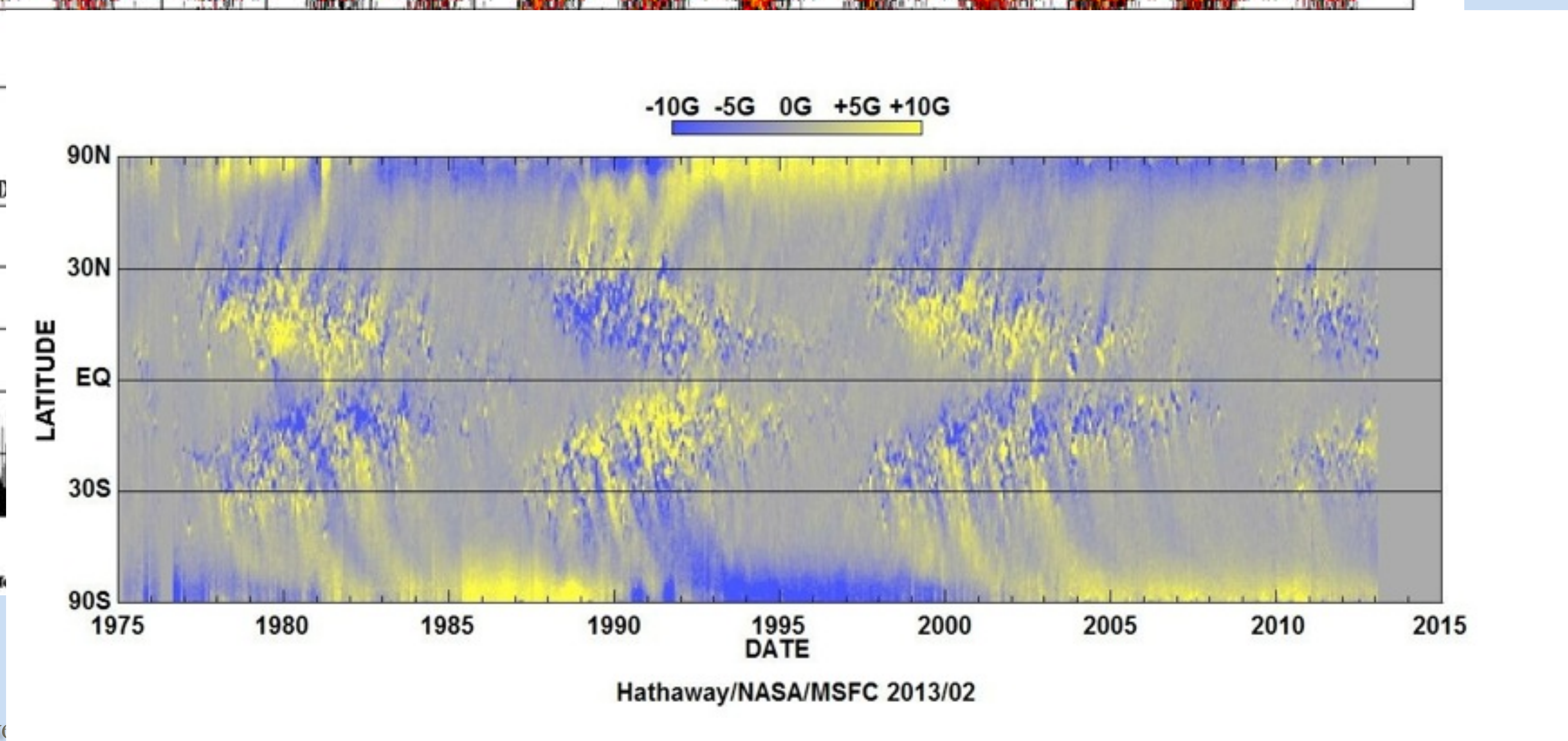
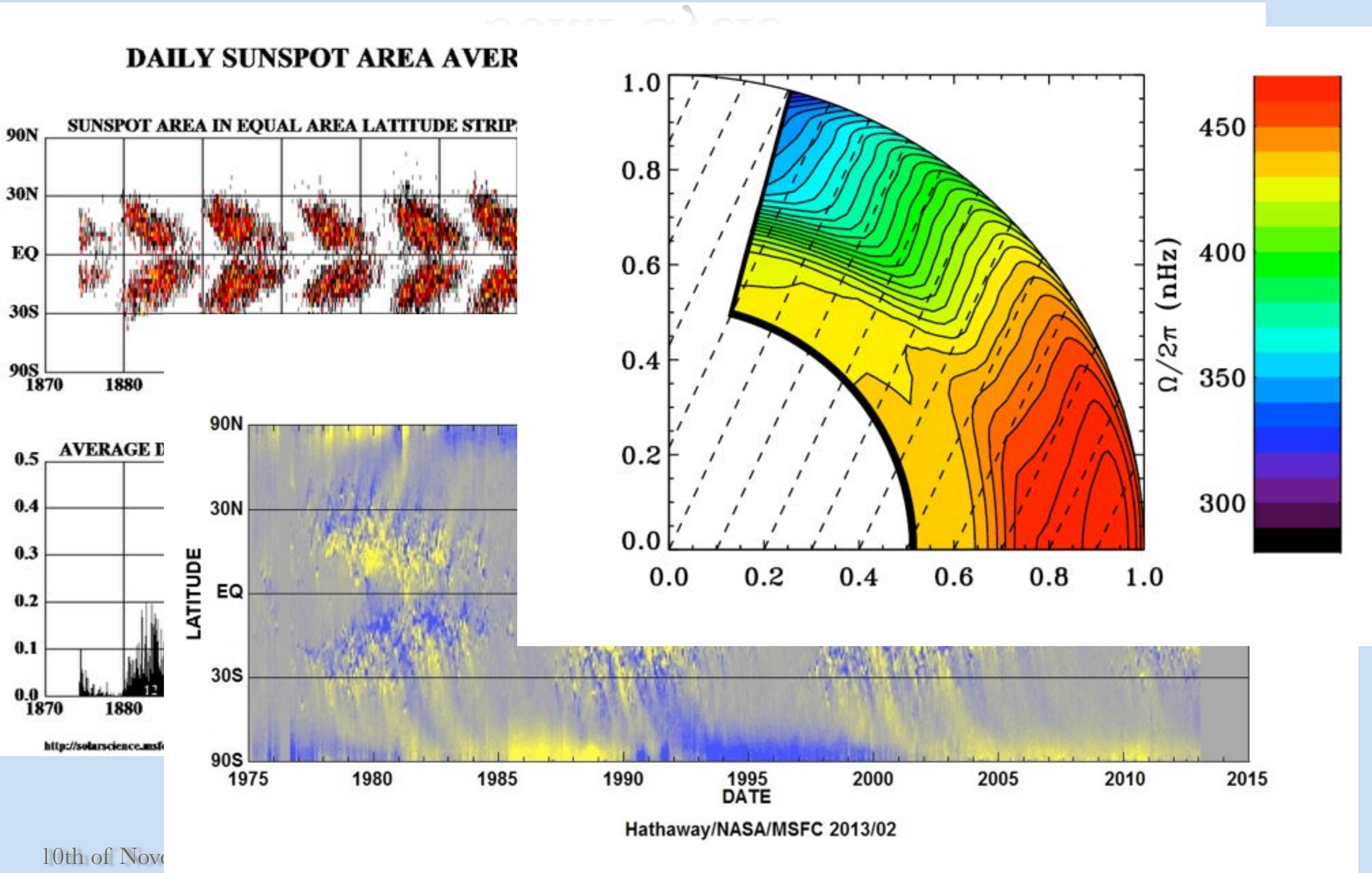
■ > 0.0% ■ > 0.1% □ > 1.0%
90N
30N
EQ
30S
90S
1870
1880
AVERAGE D
0.5
0.4
0.3
0.2
0.1
0.0
1870
1880



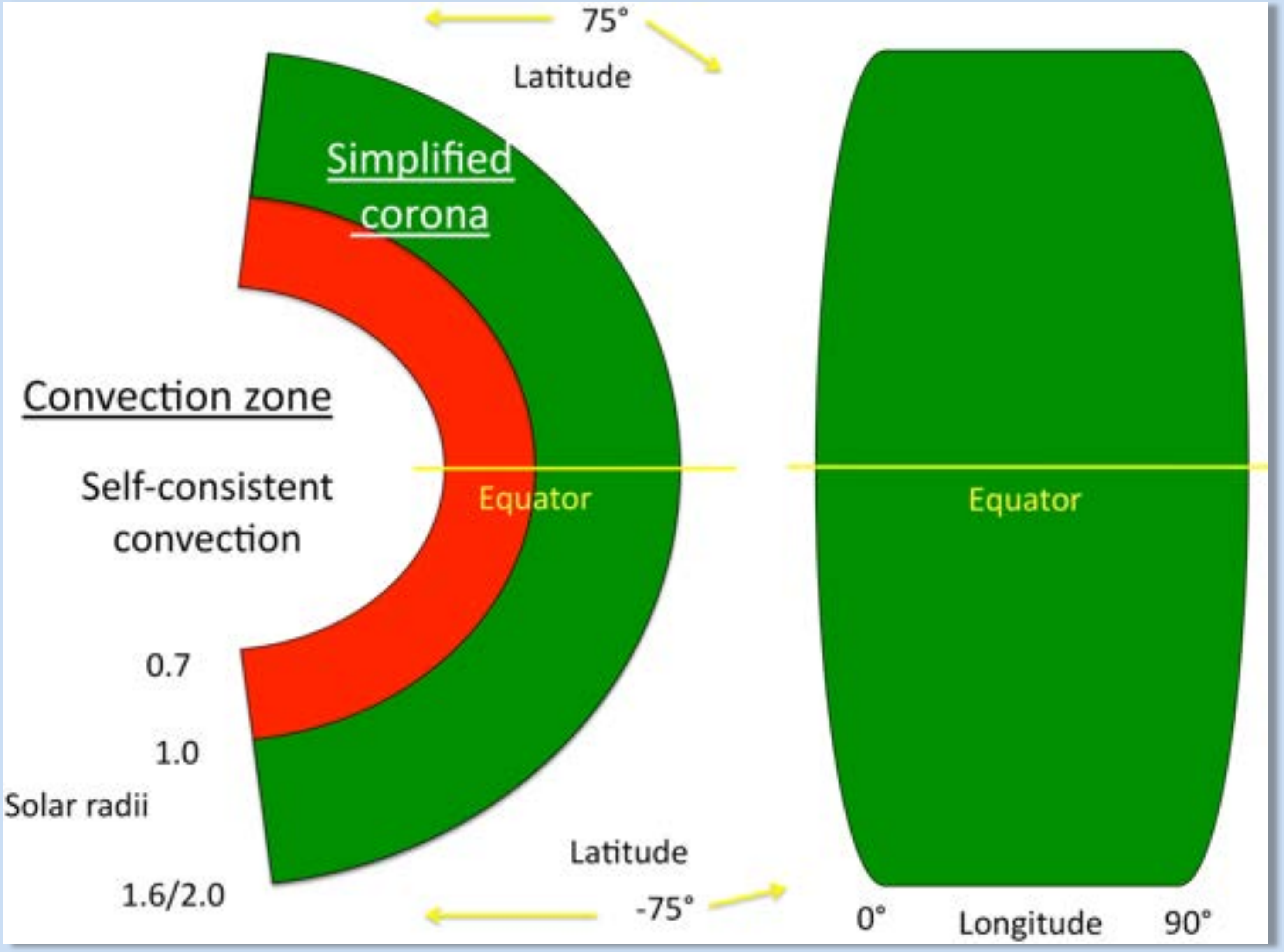
-10G -5G 0G +5G +10G
90N
30N
EQ
30S
90S
LATITUDE
1975
1980
1985
1990
1995
2000
2005
2010
2015
DATE
Hathaway/NASA/MSFC 2013/02

Solar Cycle



DAILY SUNSPOT AREA AVER
SUNSPOT AREA IN EQUAL AREA LATITUDE STRIP
90N
30N
EQ
30S
90S
1870
1880
AVERAGE D
0.5
0.4
0.3
0.2
0.1
0.0
http://solarscience.msf
LATITUDE
1975
1980
1985
1990
1995
2000
2005
2010
2015
DATE
Hathaway/NASA/MSFC 2013/02
1.0
0.8
0.6
0.4
0.2
0.0
$\Omega/2\pi$ (nHz)
450
400
350
300

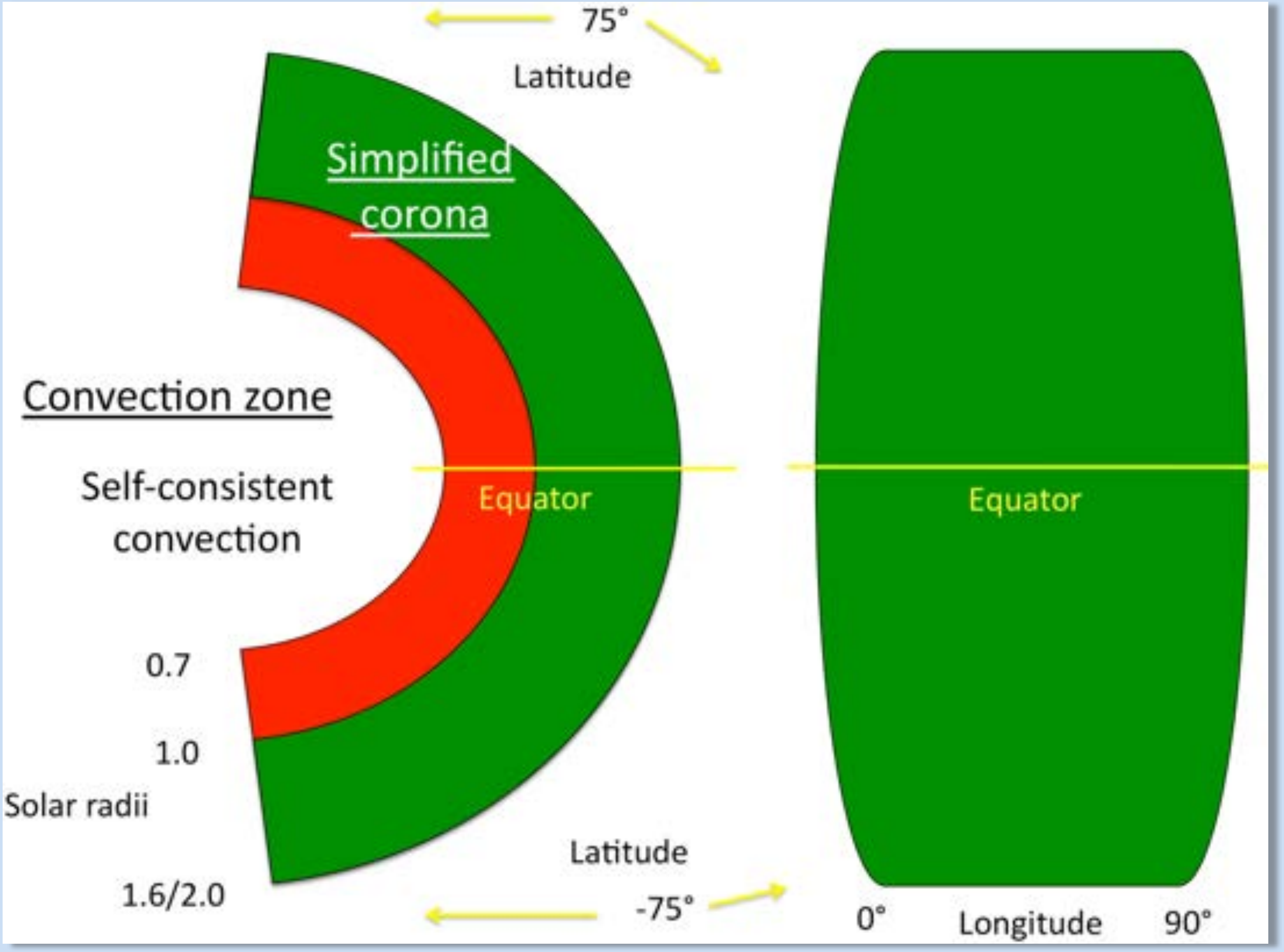
Setup



75°
Latitude
Simplified corona
Convection zone
Self-consistent convection
Equator
Equator
0.7
1.0
Solar radii
1.6/2.0
Latitude
-75°
0°
Longitude
90°

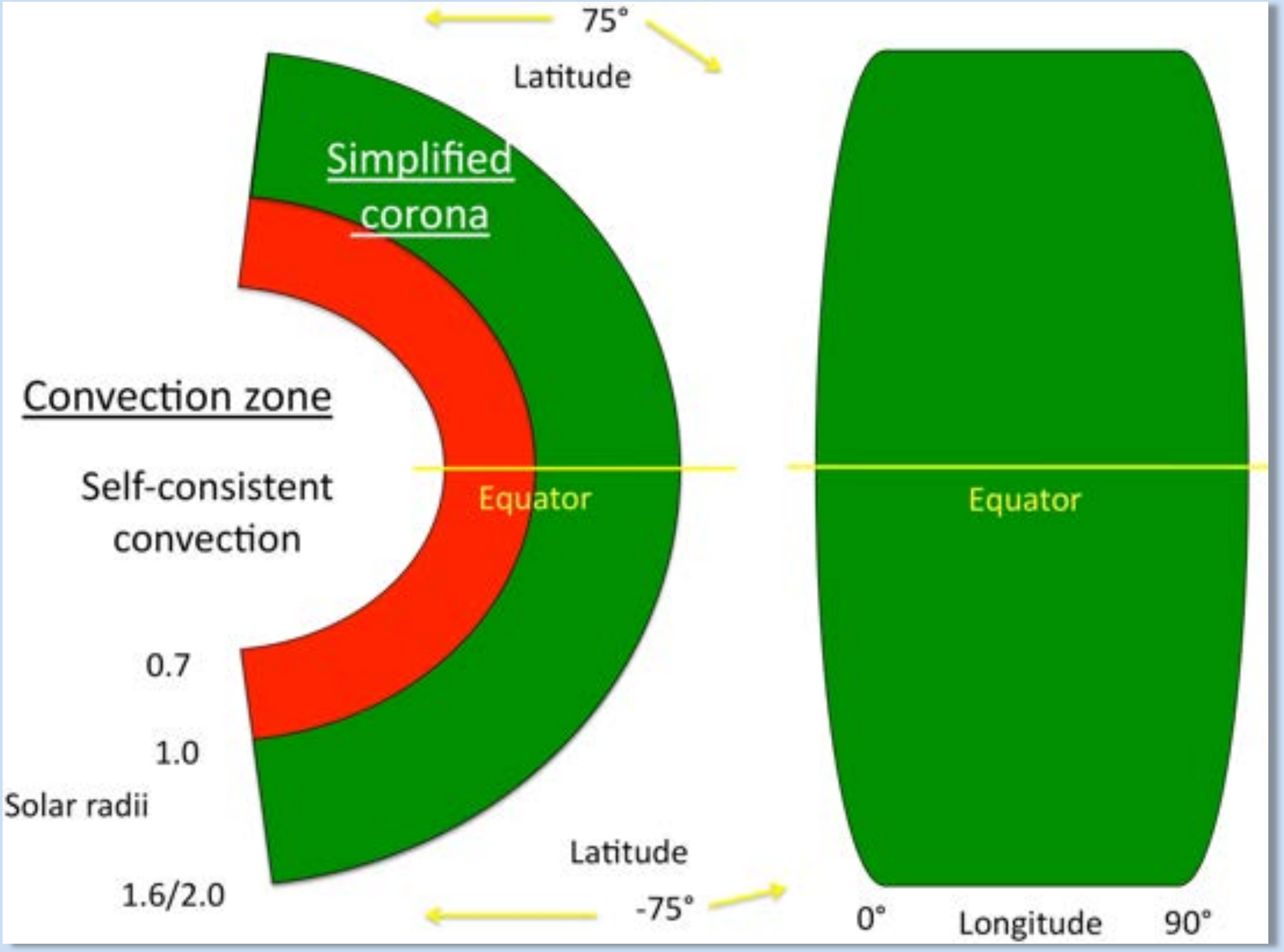
Setup

Self-consistent convection with a coronal layer



Setup

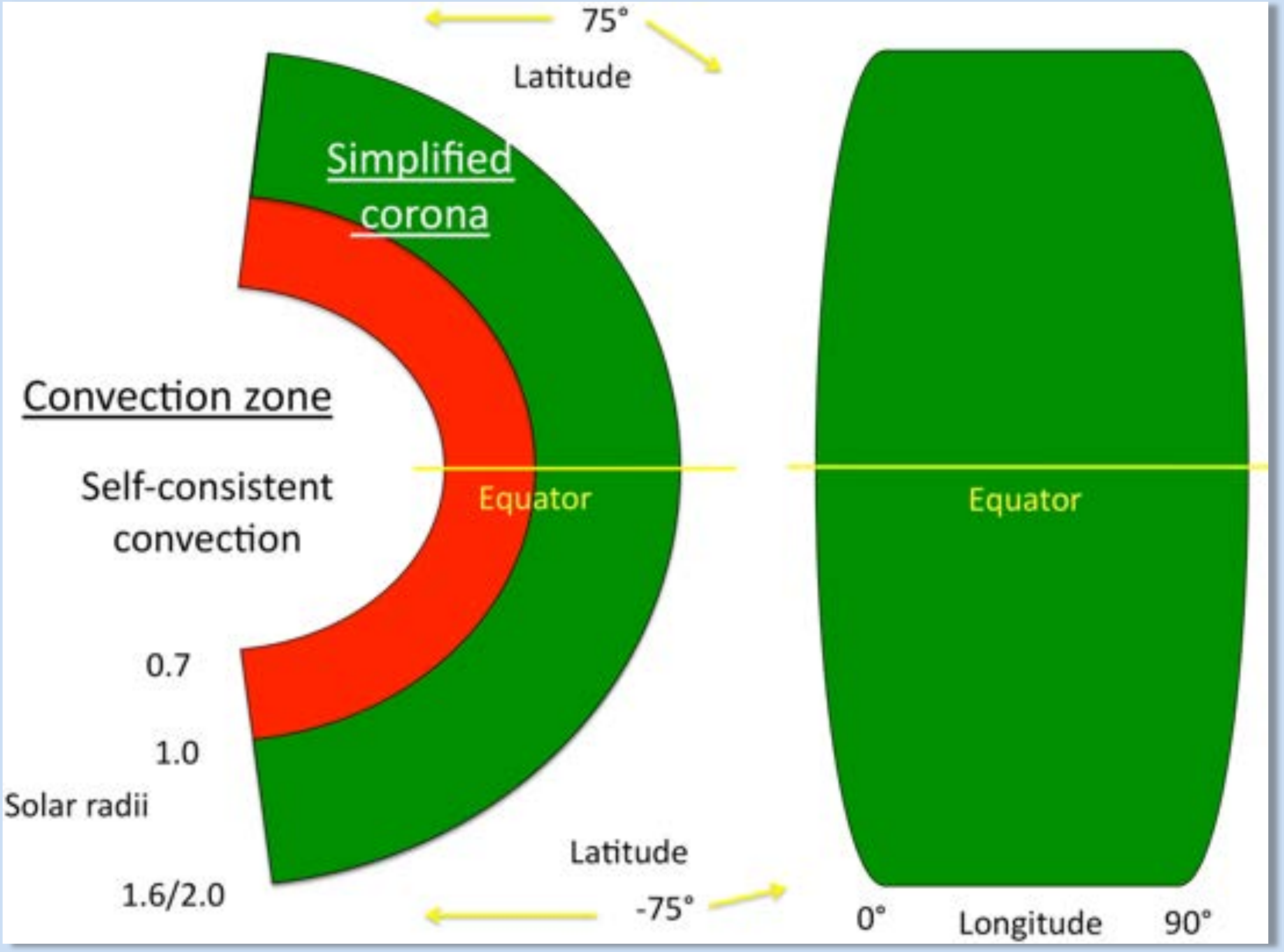
Self-consistent convection with a coronal layer



Equations:

Setup

Self-consistent convection with a coronal layer

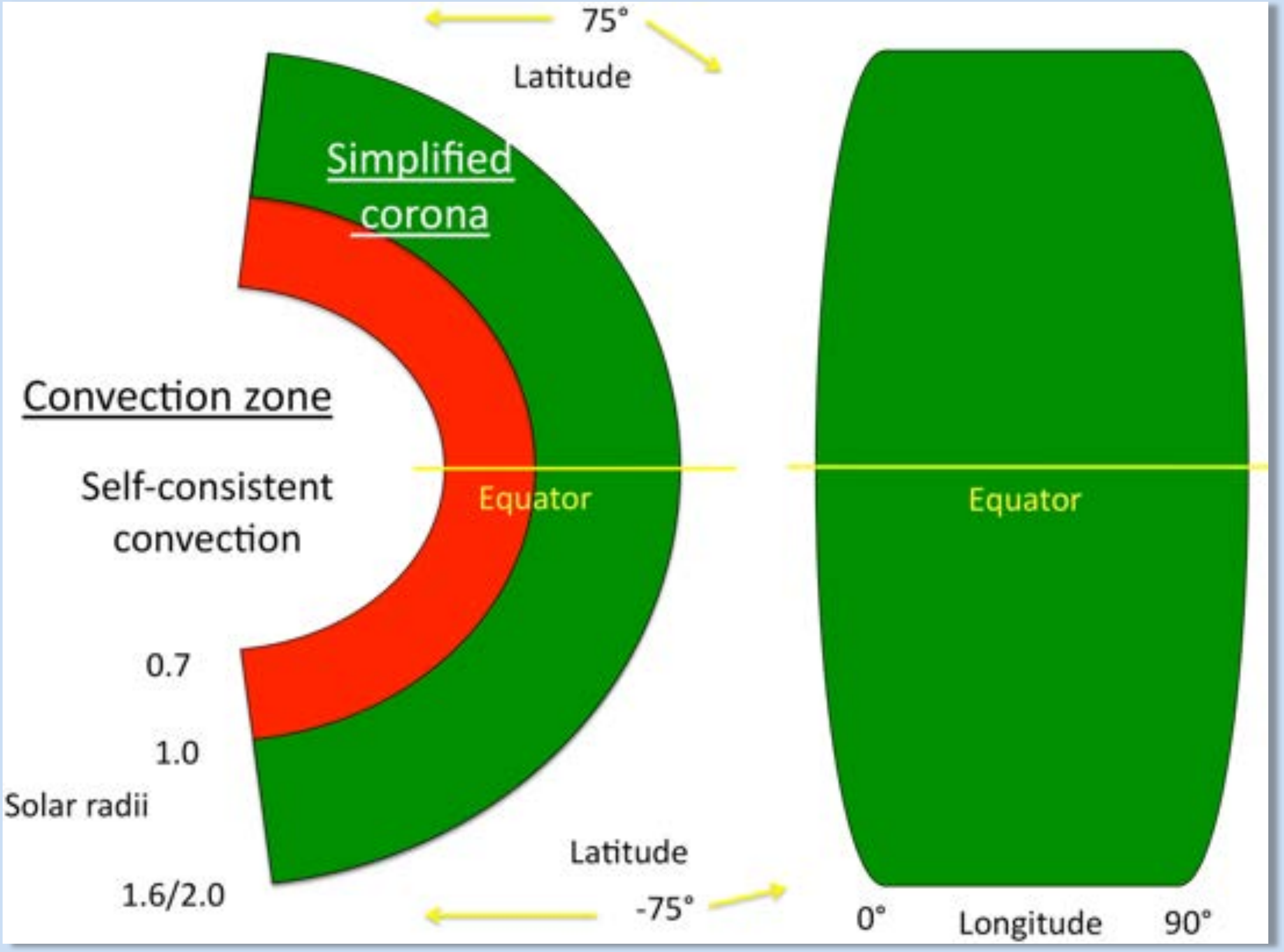


Equations:

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

Setup

Self-consistent convection with a coronal layer



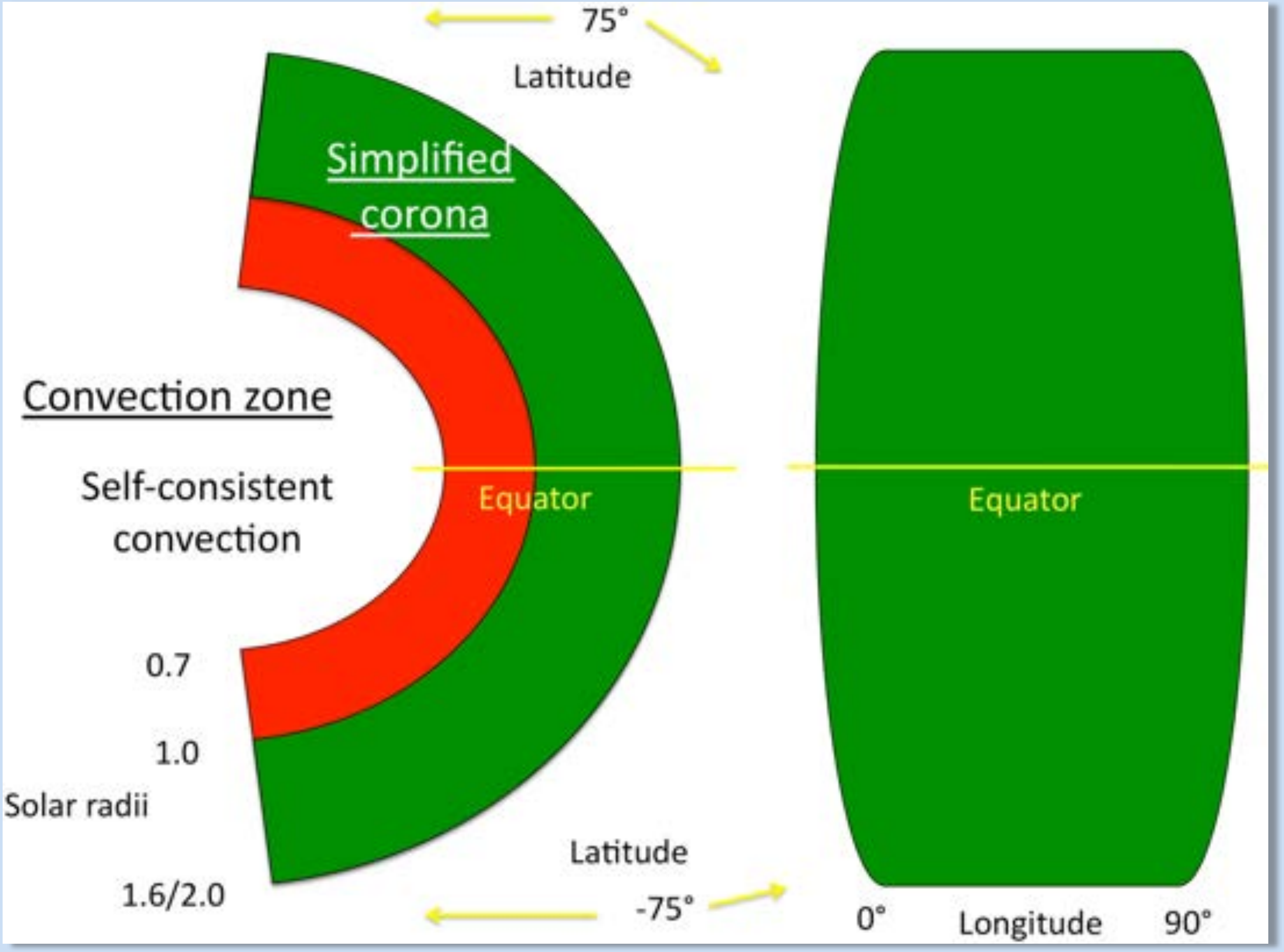
Equations:

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

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

Setup

Self-consistent convection with a coronal layer



Equations:

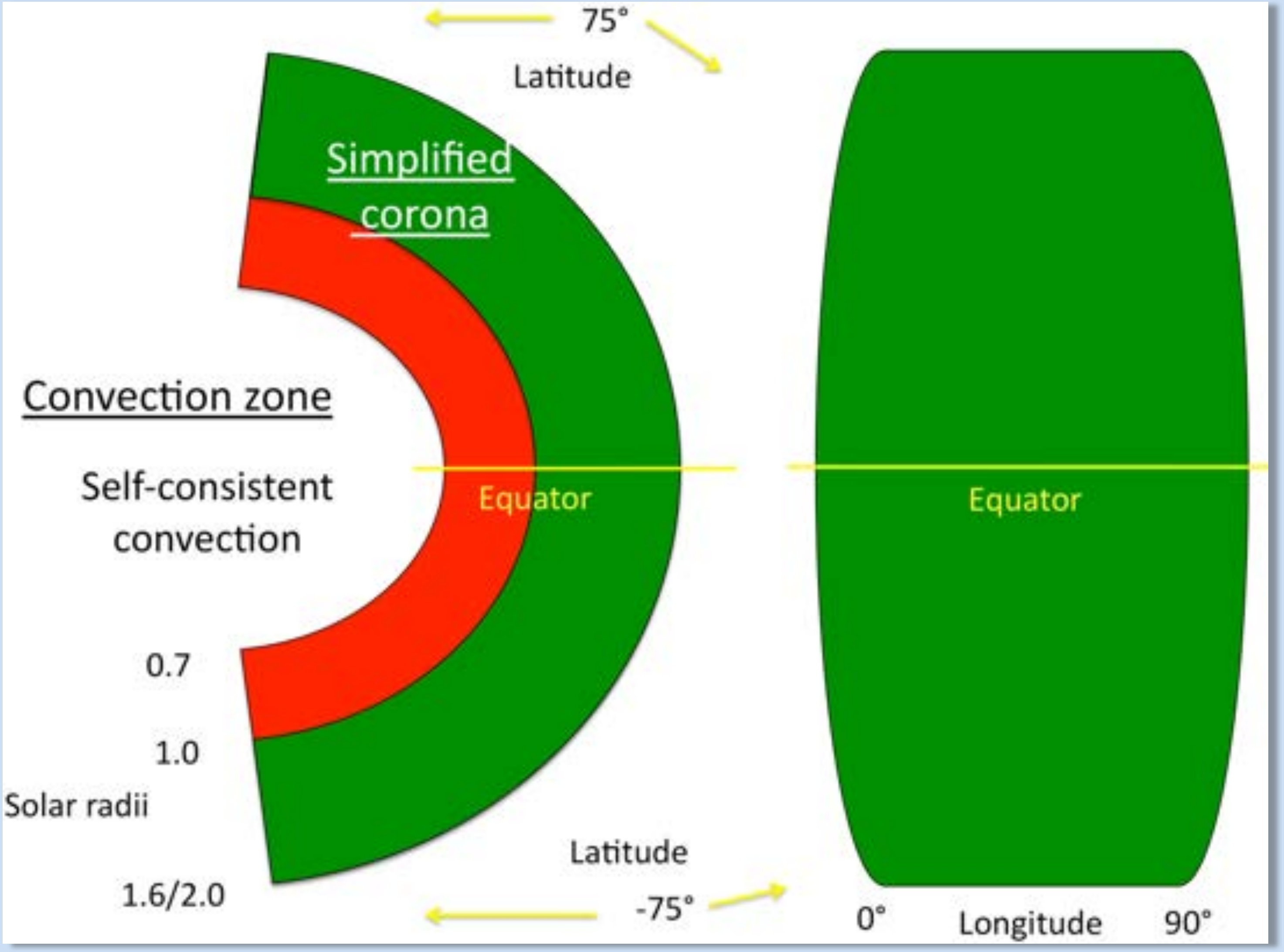
$$\frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A$$

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

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

Setup

Self-consistent convection with a coronal layer



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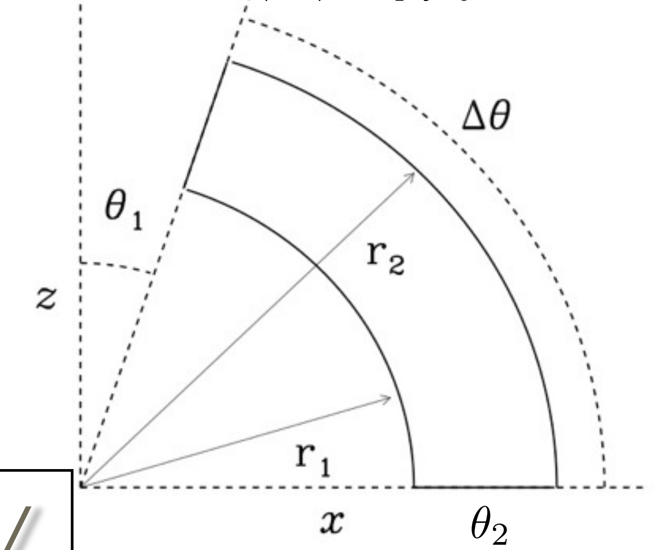
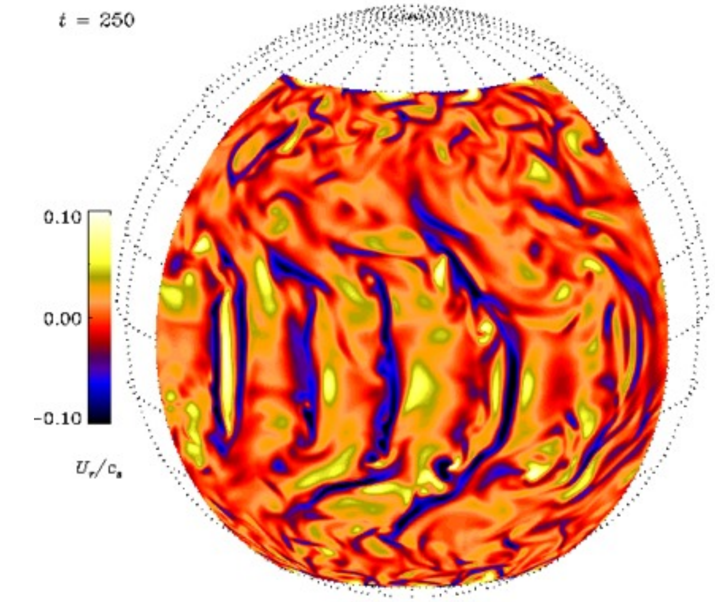
$$\frac{Du}{Dt} = g - 2\Omega_0 \times u + \frac{1}{\rho}(J \times B - \nabla p + \nabla \cdot 2\nu\rho S)$$

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

Global convective dynamo simulations

Mitra et al, (2009), *Astrophys. J.*, 697, 923





Käpylä et al. (2010b), *Astron. Nachr.*, 331, 73

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

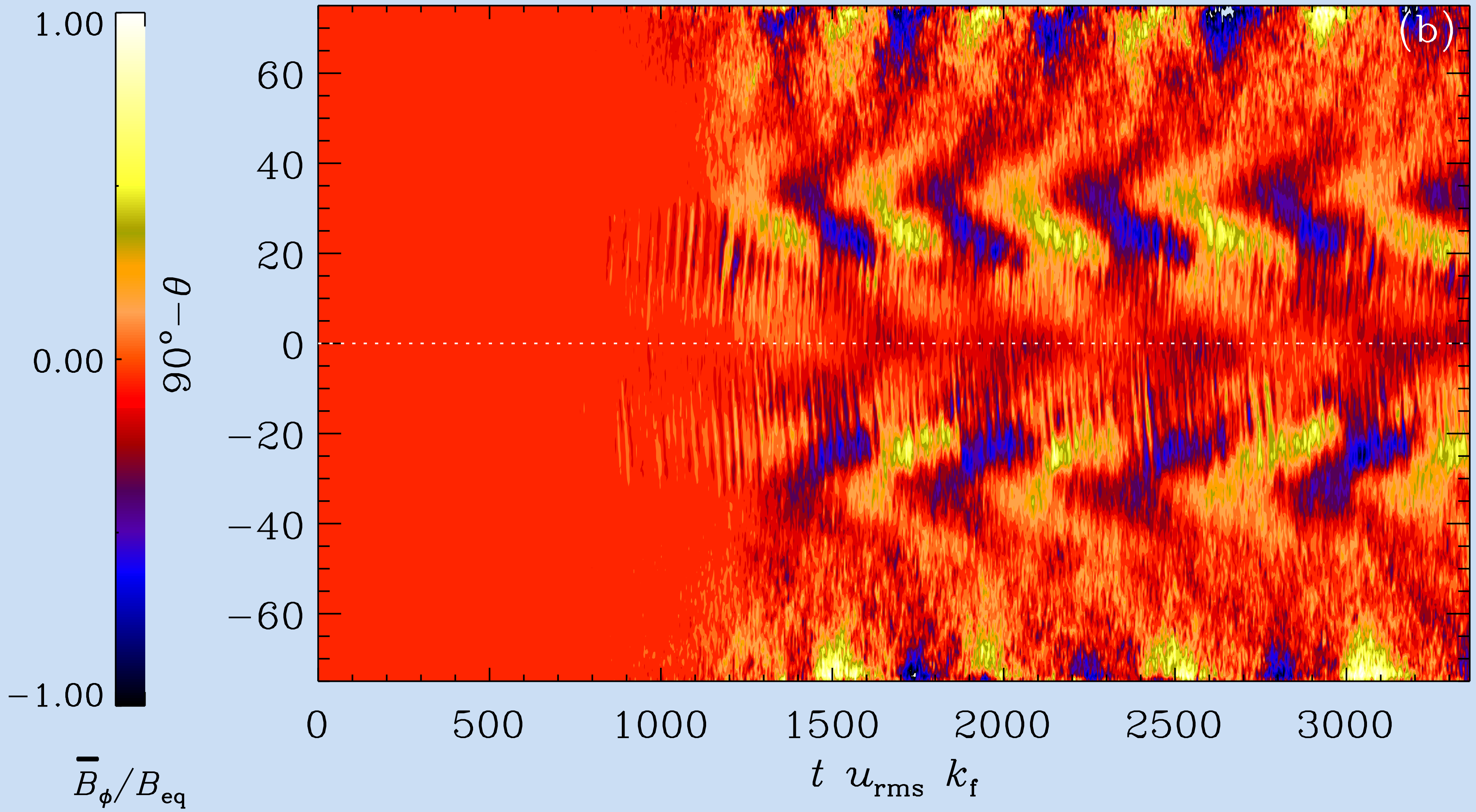
- high-order finite-difference code
- scales up efficiently to over 60.000 cores
- compressible MHD

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

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

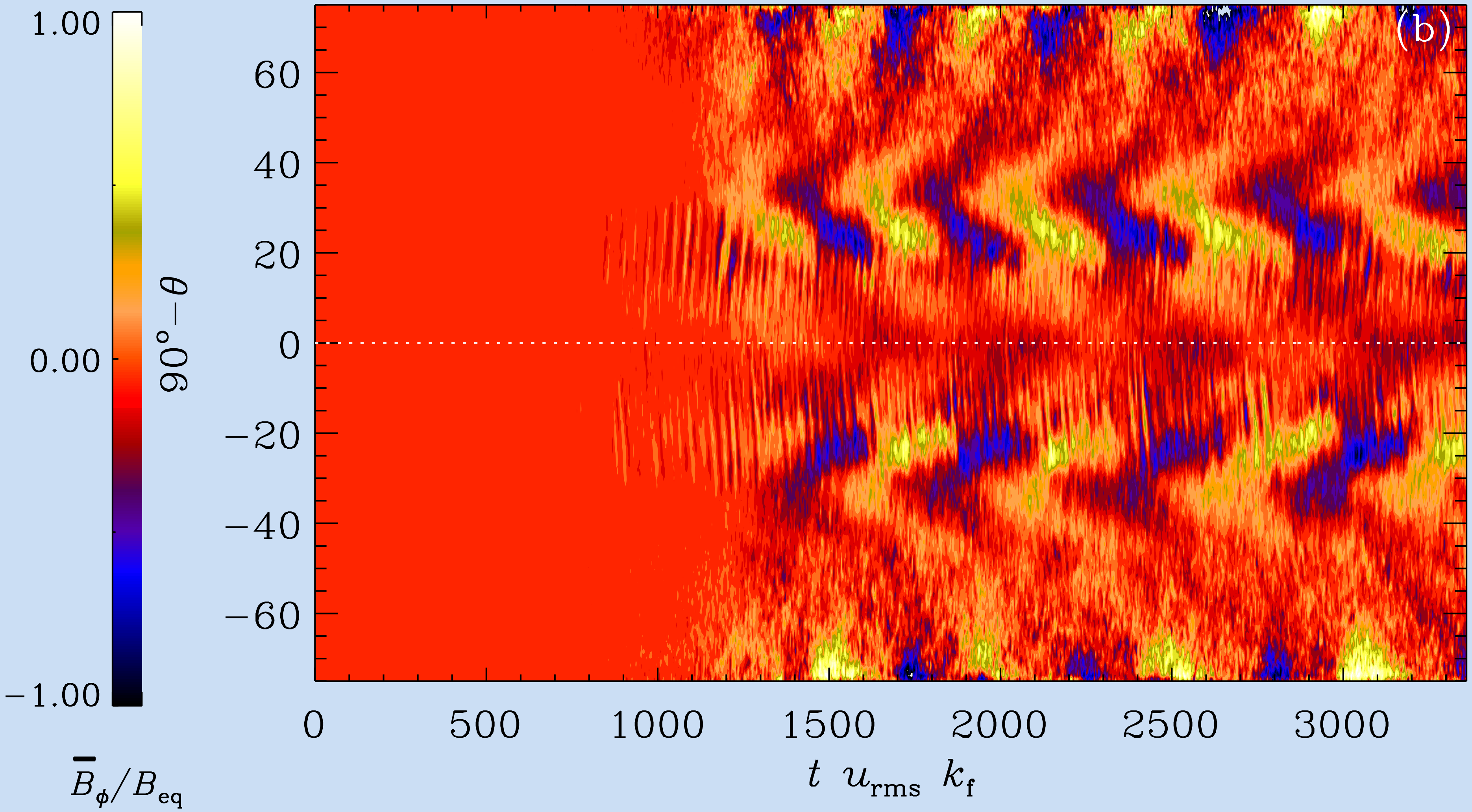
Normal field condition for *B* at the outer radial boundary and perfect conductor at all other boundaries. Impenetrable stress-free boundaries on all boundaries.

Equatorward Migration



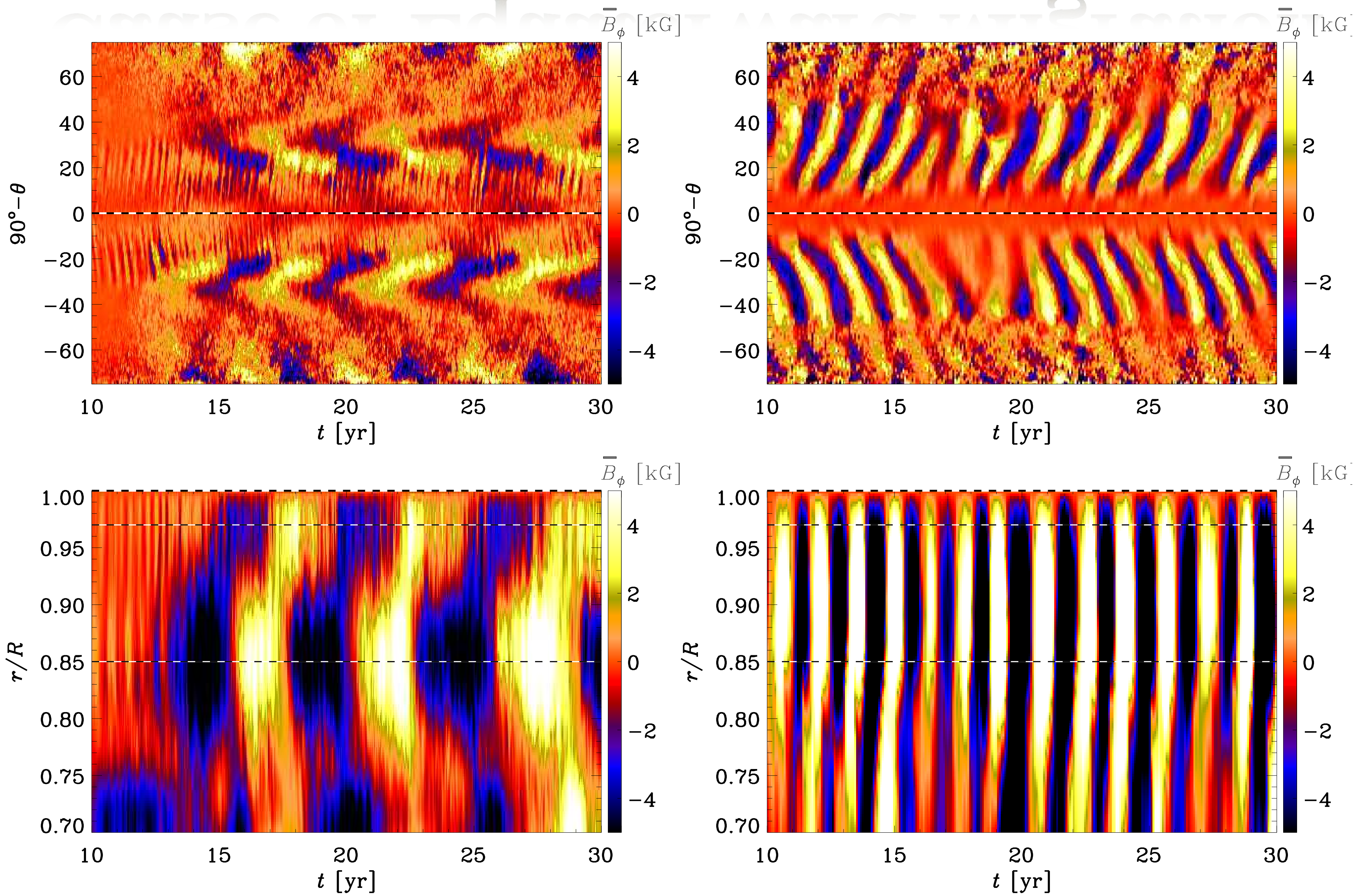
Käpylä, Mantere & Brandenburg 2012 (ApJL 755, L22)

Equatorward Migration



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

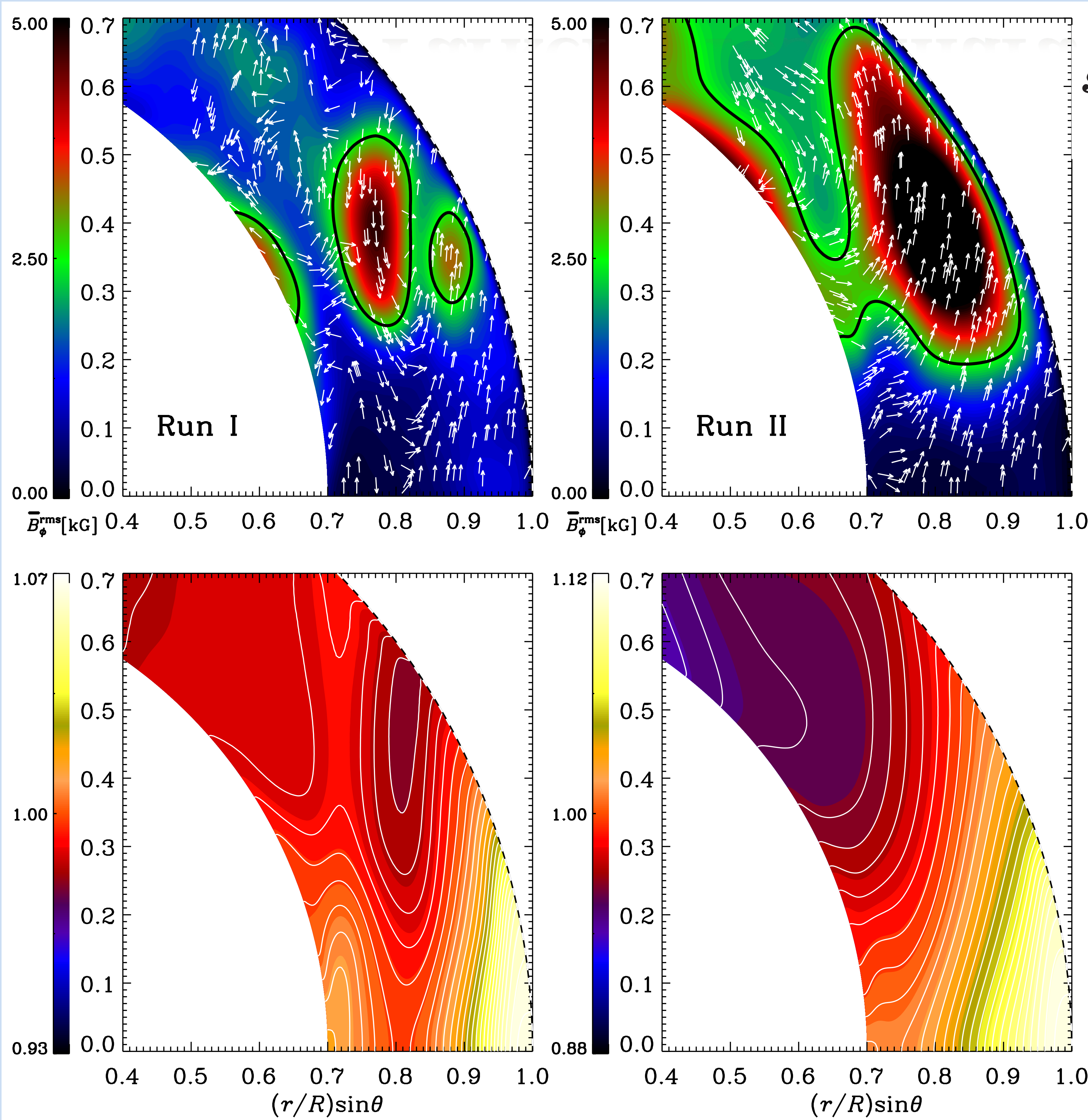
Cause of Equatorward Migration



Pr=ν/χ=2.5
Pm=ν/η=1

Pr=0.5
Pm=0.5

Parker—Yoshimura—Rule



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

Parker 1955

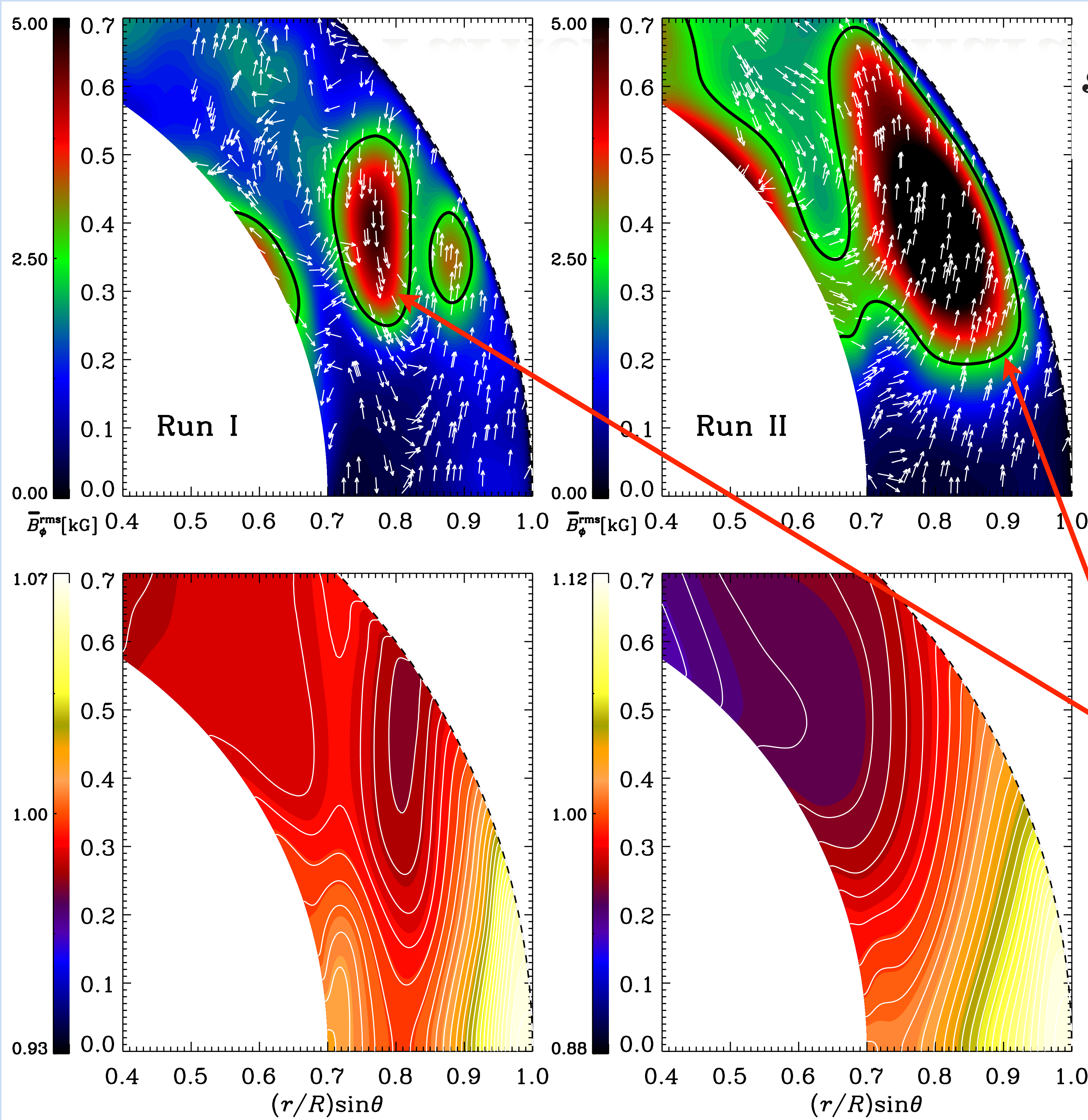
Yoshimura 1975

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

Pouquet et al. 1976

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

Parker—Yoshimura—Rule



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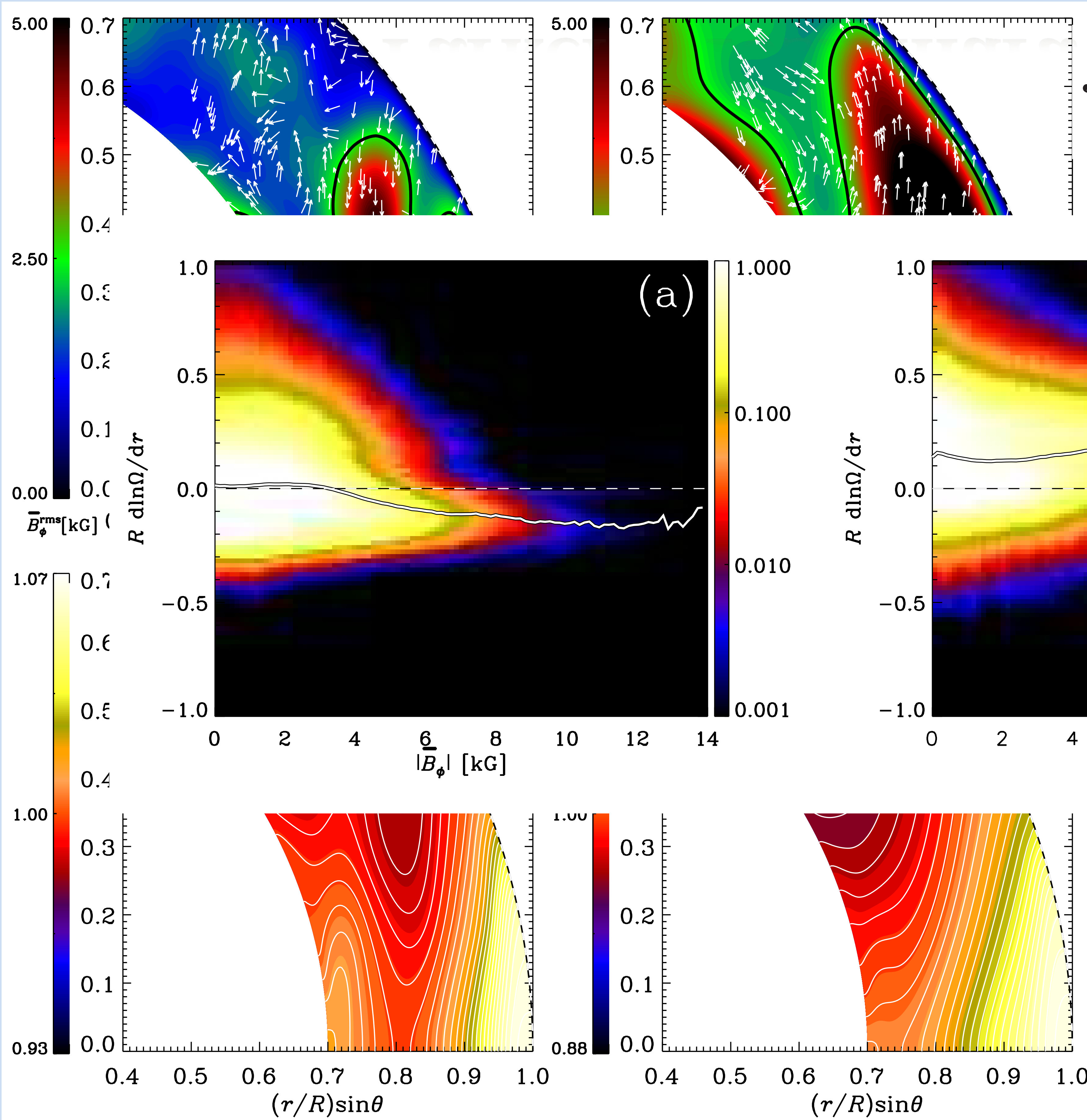
Pouquet et al. 1976

Strong toroidal field

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

Parker—Yoshimura—Rule



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

Parker 1955

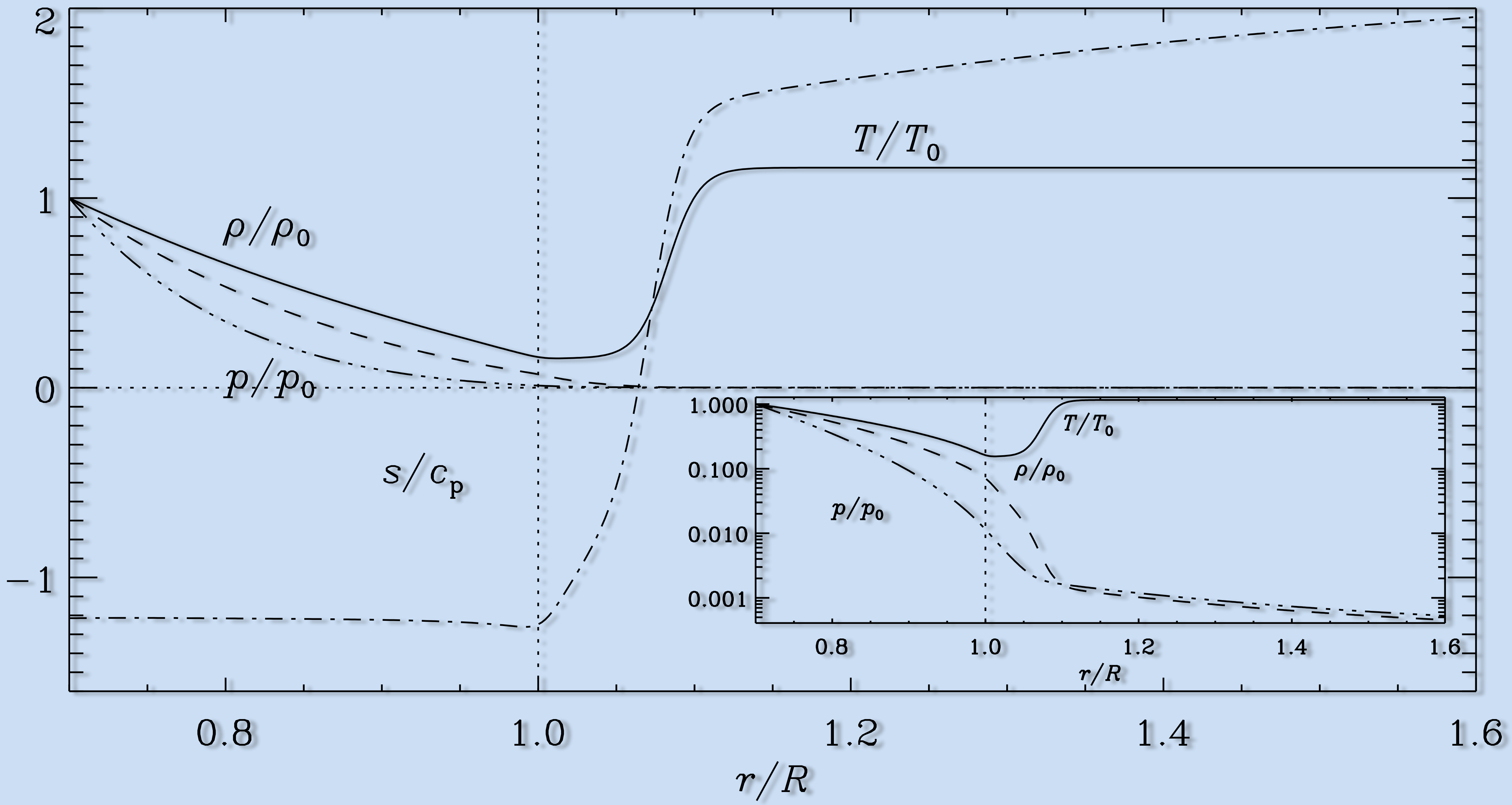
6

idal

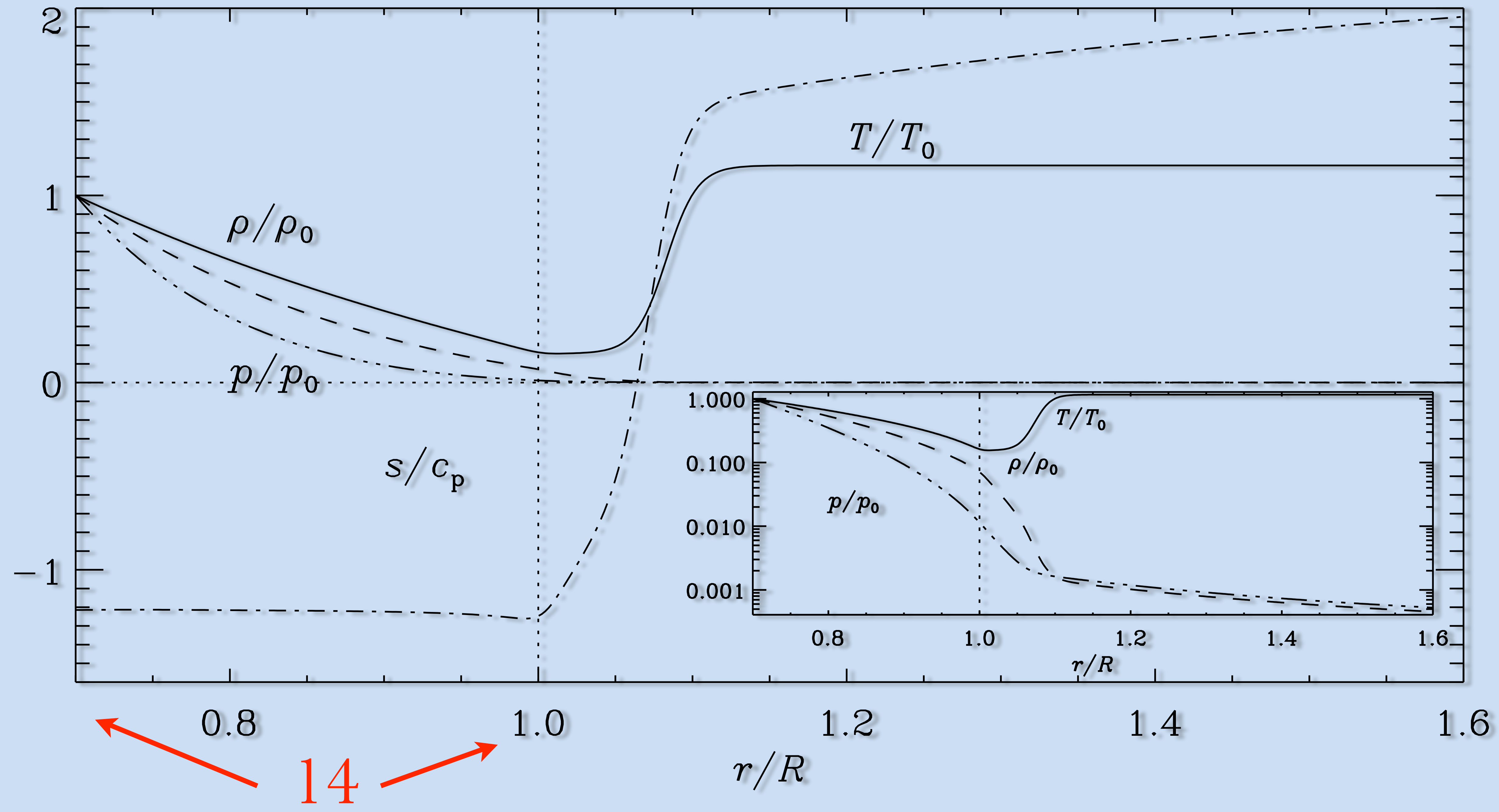
field

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

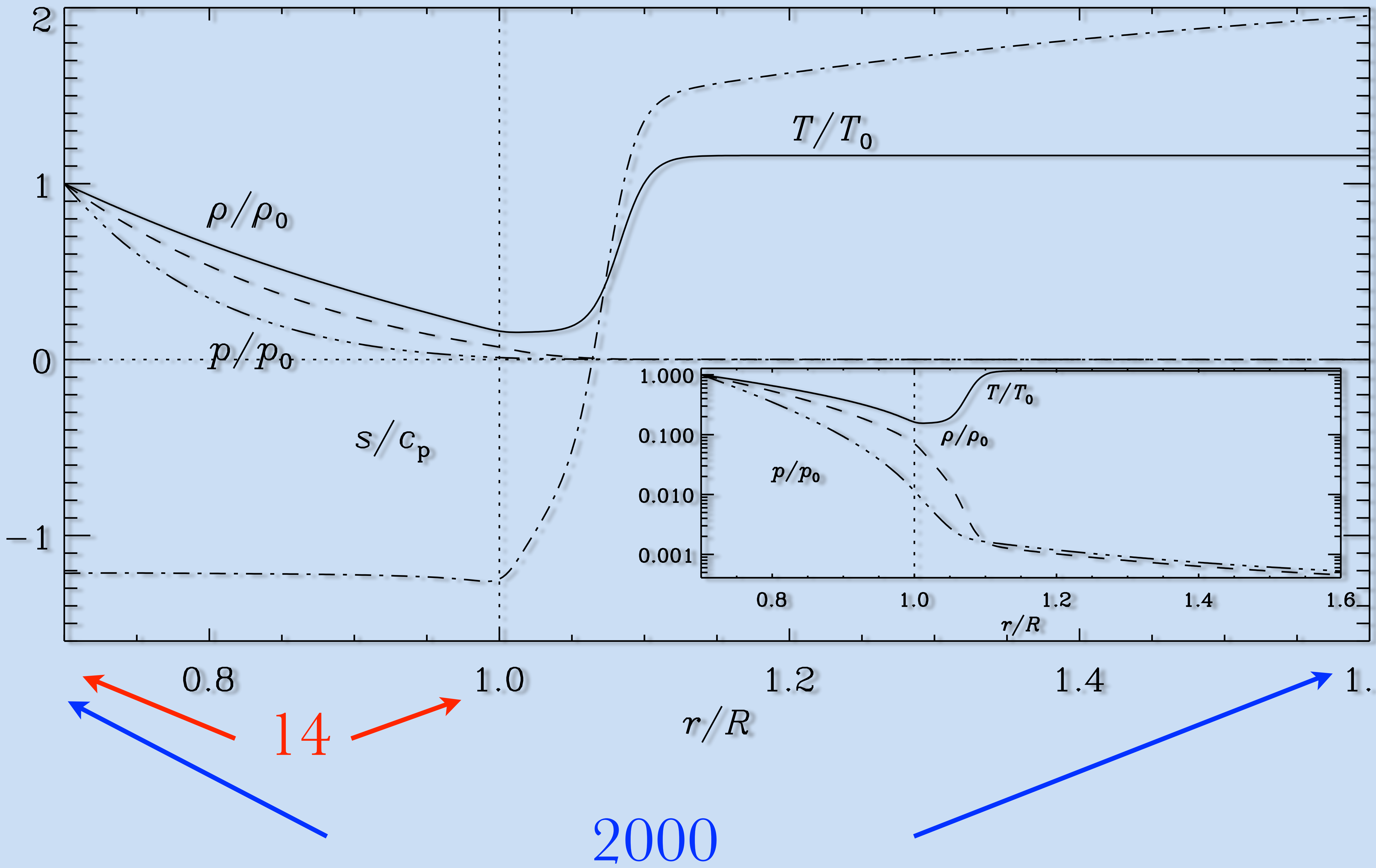
Stratification



Stratification

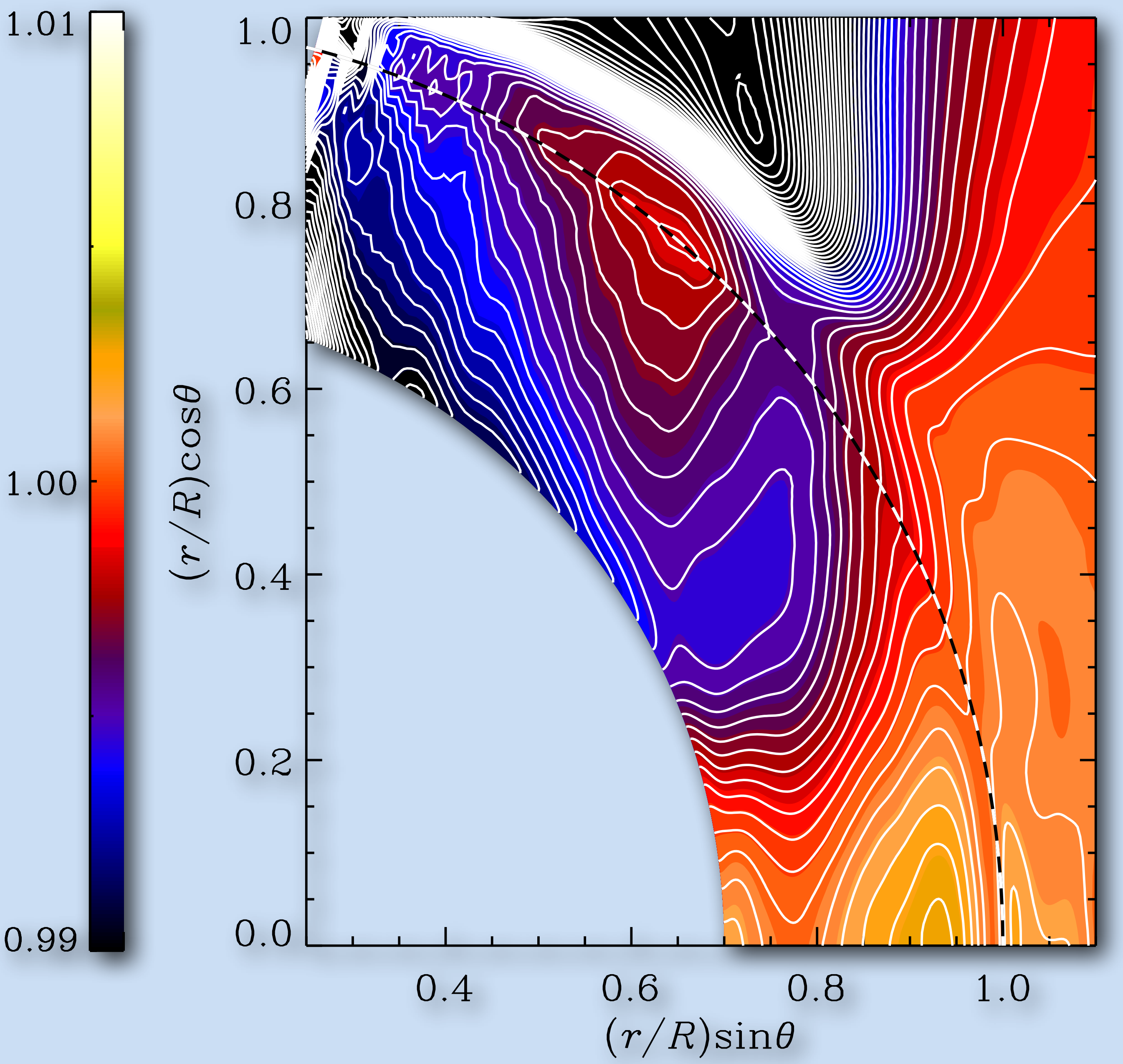


Stratification

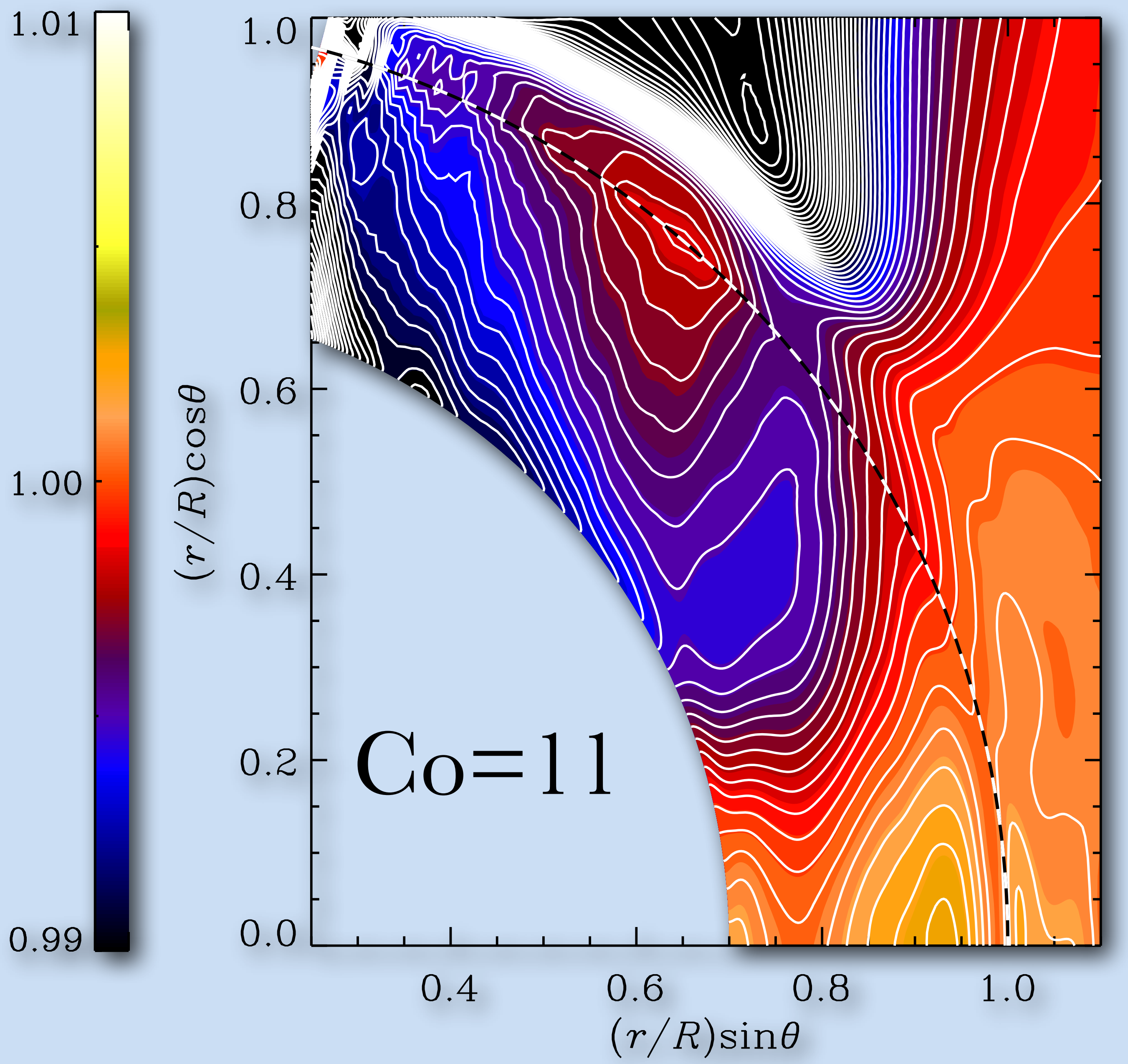


Differential rotation

Differential rotation

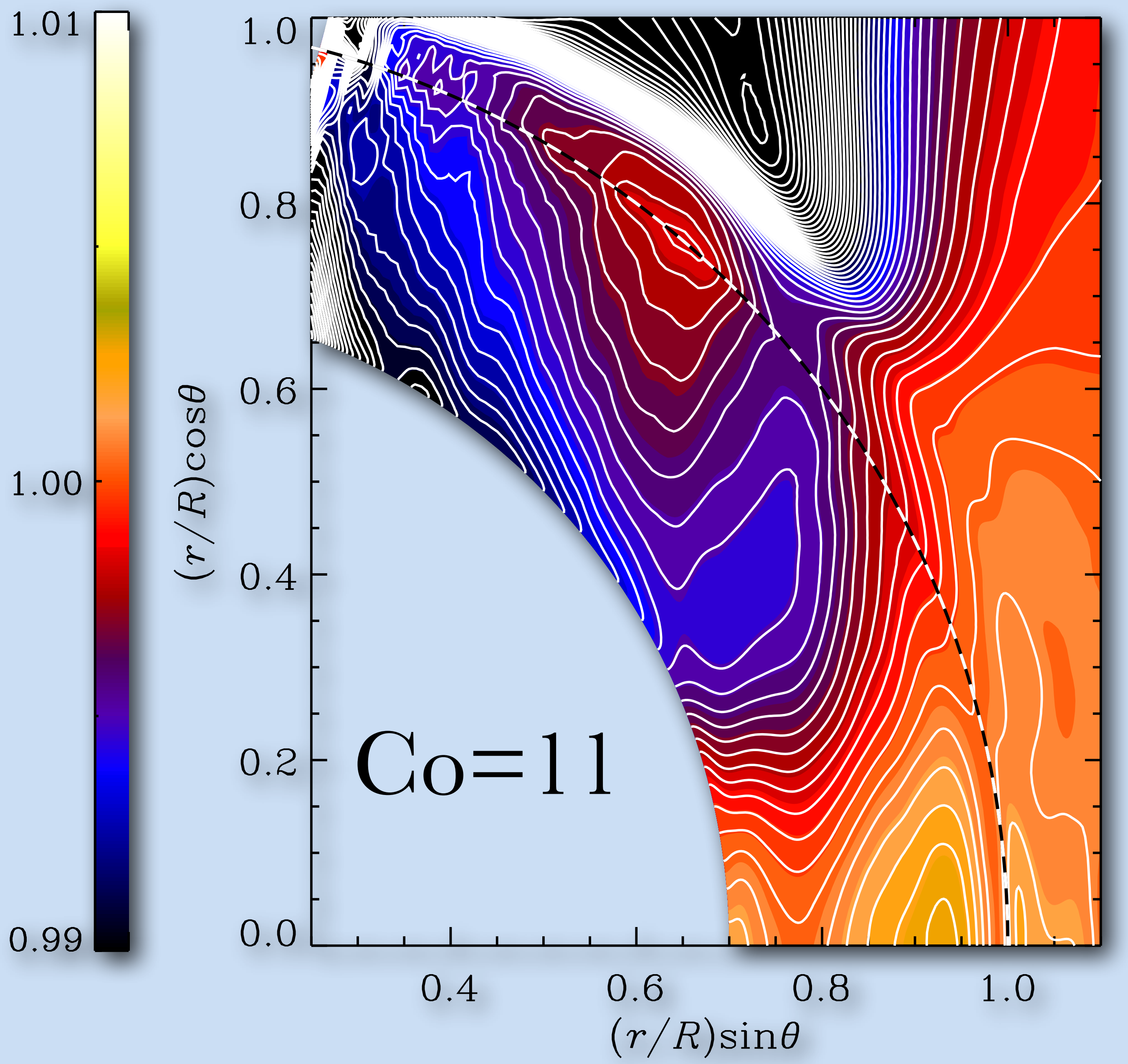


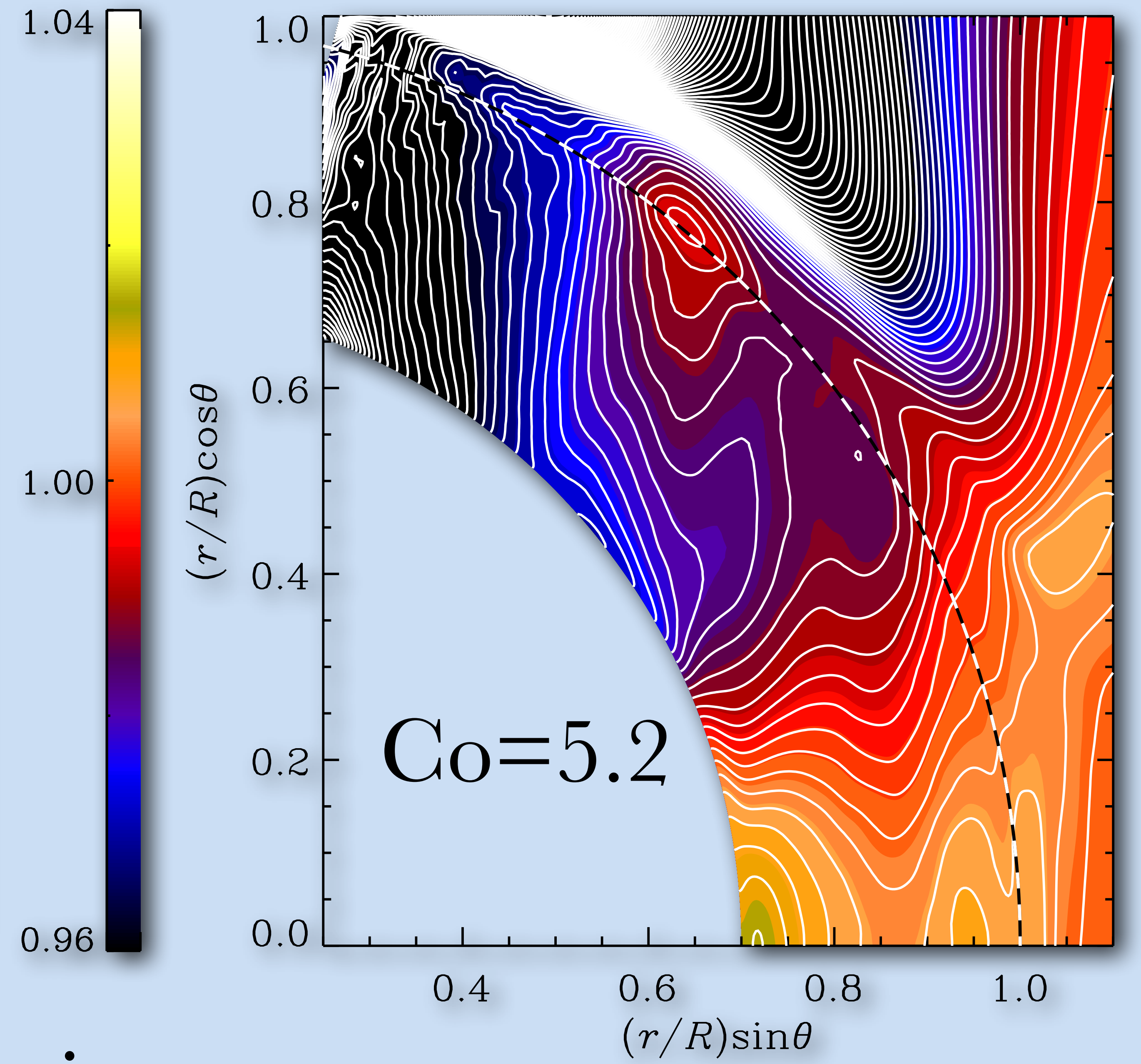
Differential rotation



$$\mathrm{Co} = \frac{2\Omega_0}{u_{rms} k_f} = \frac{\text{2 Rotation rate}}{\text{Turnover time}}$$

Differential rotation





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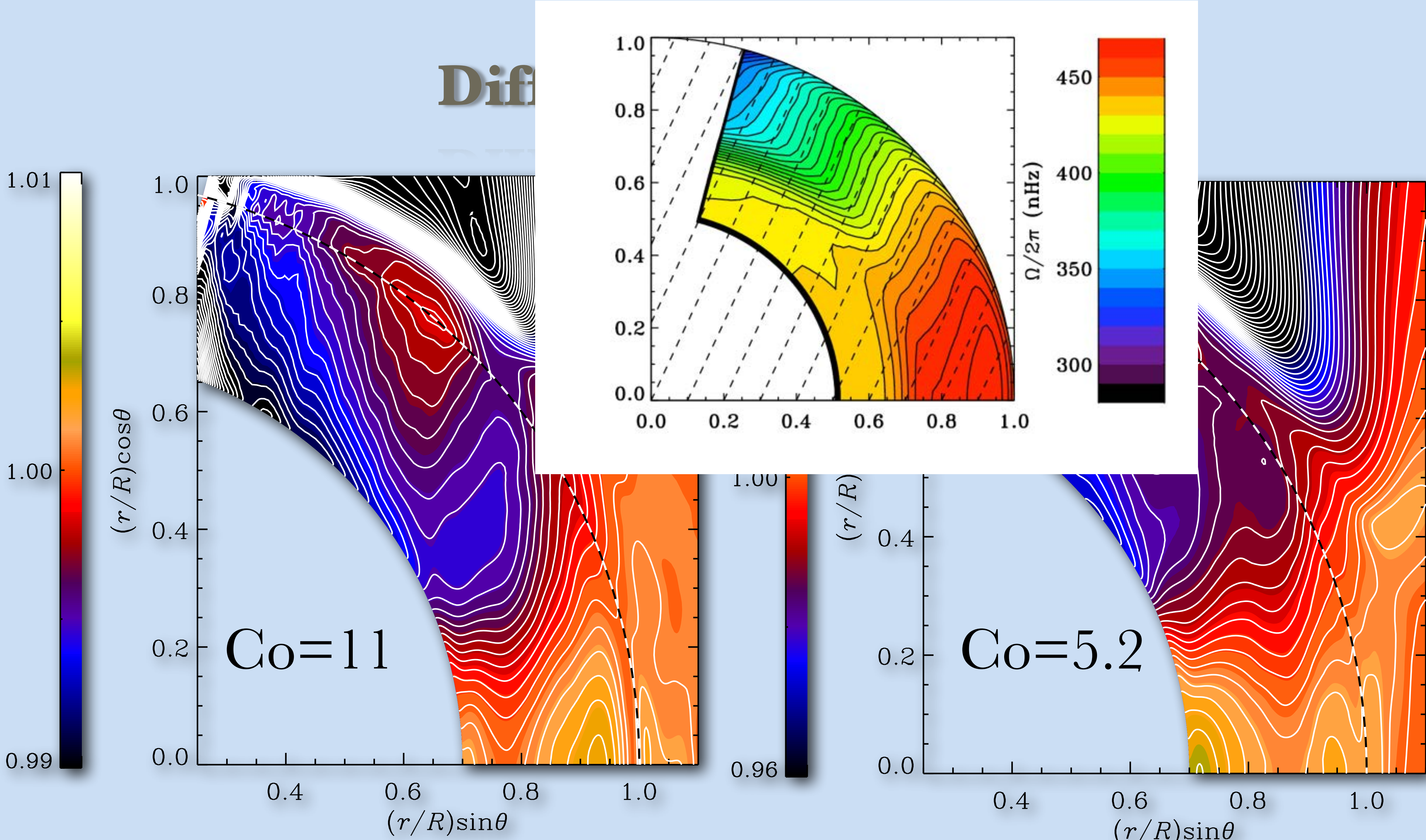
Diff



$$\mathrm{Co} = \frac{2\Omega_0}{u_{rms} k_f} = \frac{2 \text{ Rotation rate}}{\text{Turnover time}}$$

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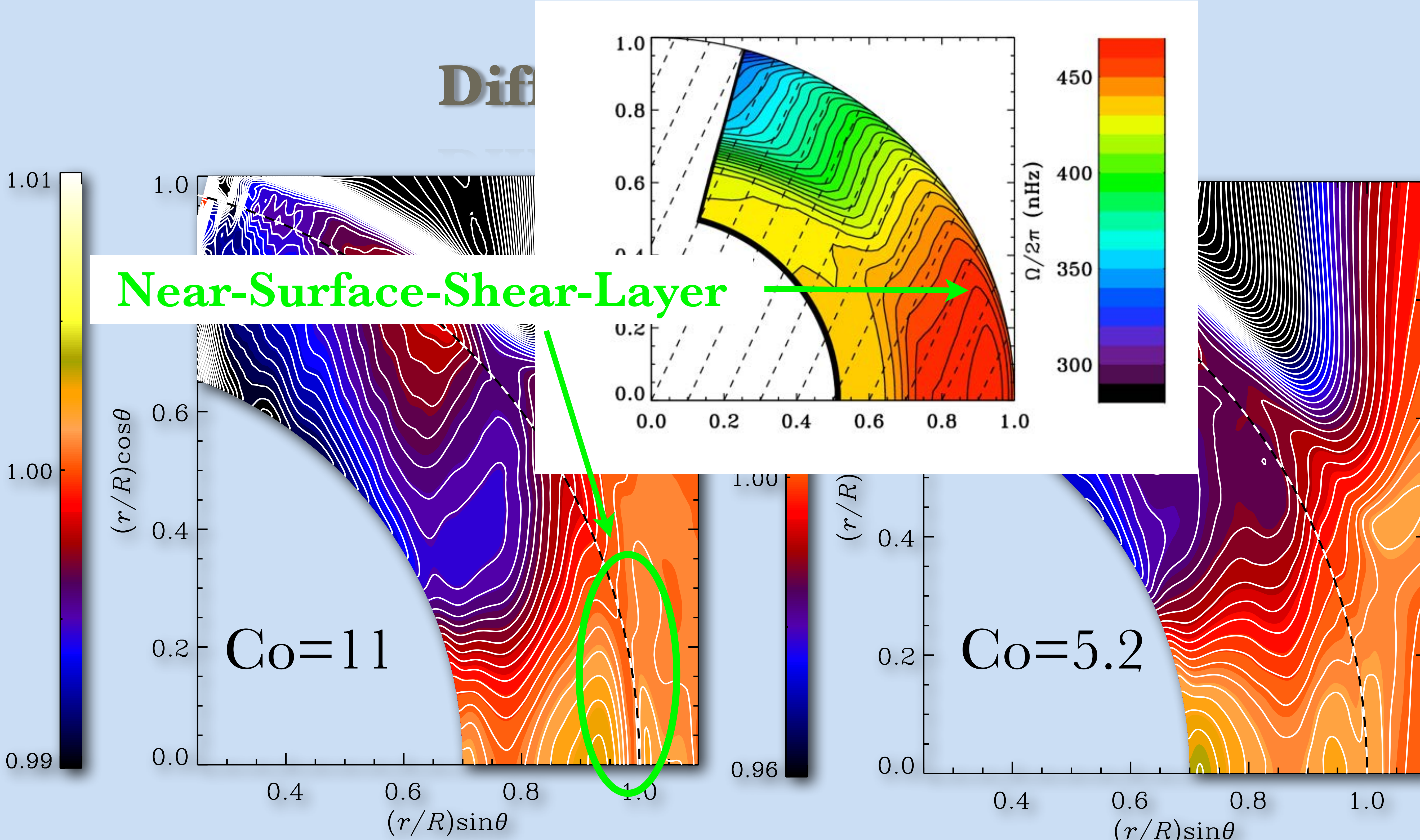

$$\mathrm{Co} = \frac{2\Omega_0}{u_{rms} k_f} = \frac{2\ \text{Rotation rate}}{\text{Turnover time}}$$

The Baroclinic Term

$$\frac{\partial \overline{\omega_\phi}}{\partial t} = r\sin\theta \frac{\partial \overline{\Omega}^2}{\partial z} + \left(\overline{\nabla T \times \nabla s}\right)_\phi + ...$$

The Baroclinic Term

Co=11

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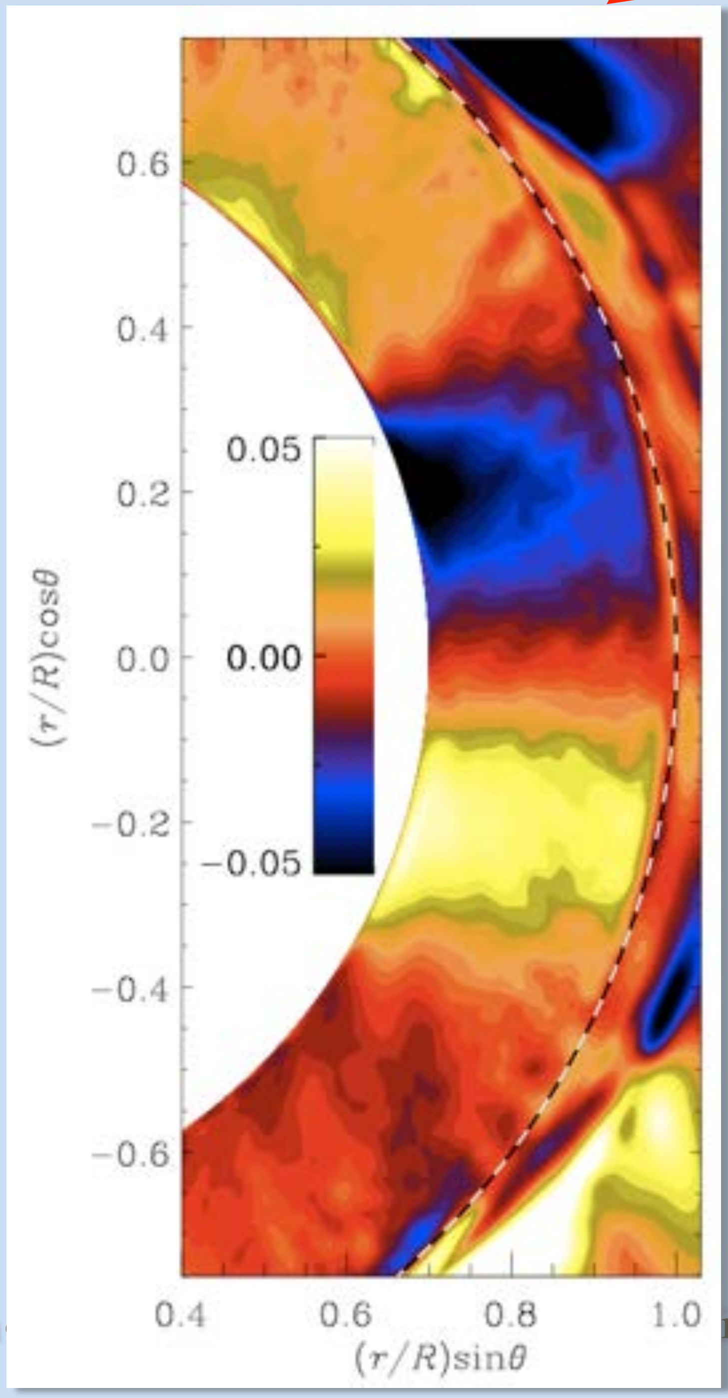

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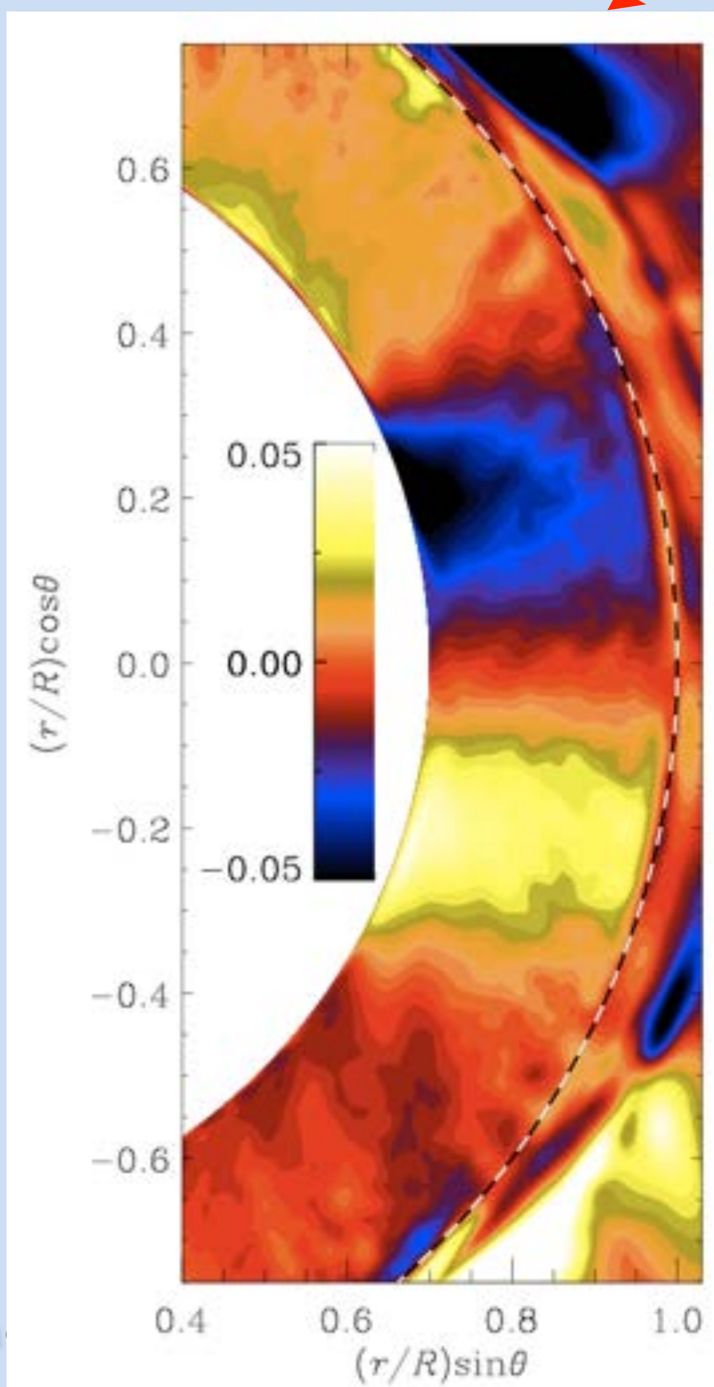

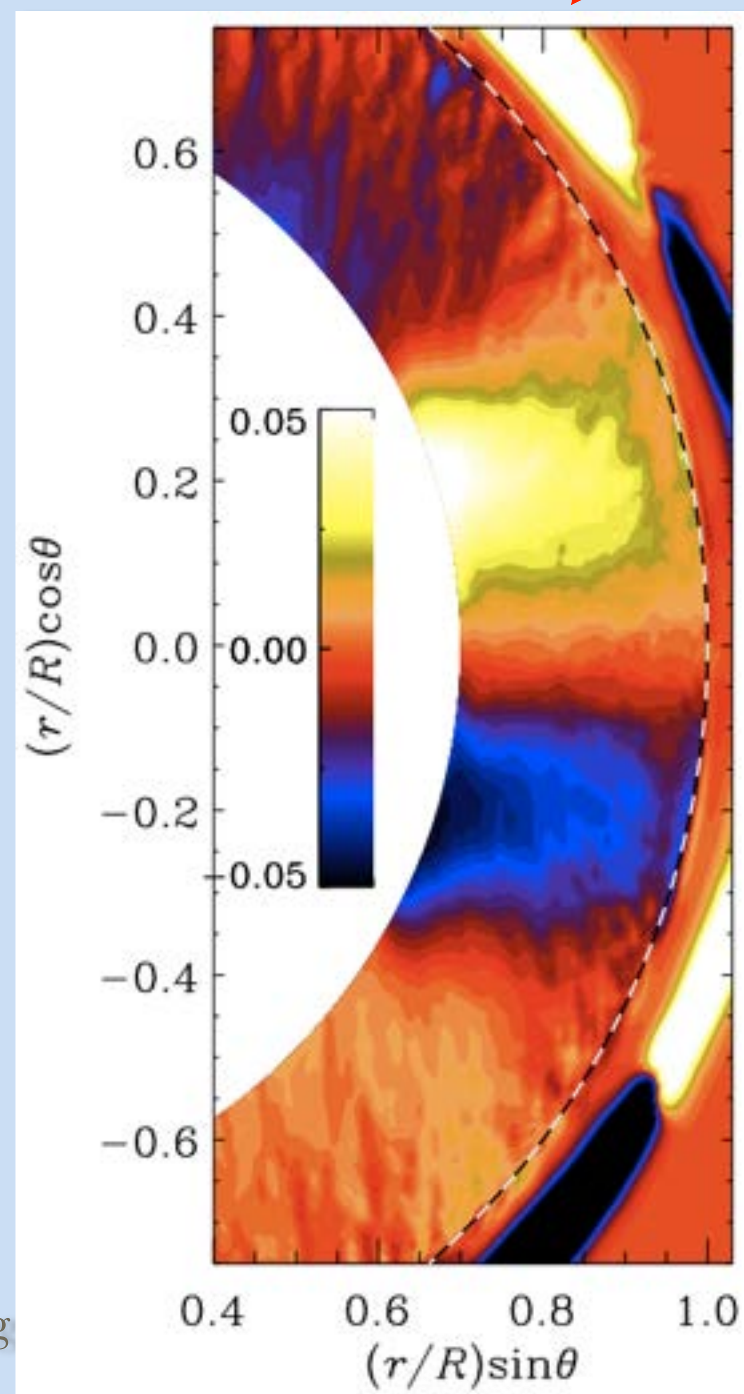

The Baroclinic Term

Co=11

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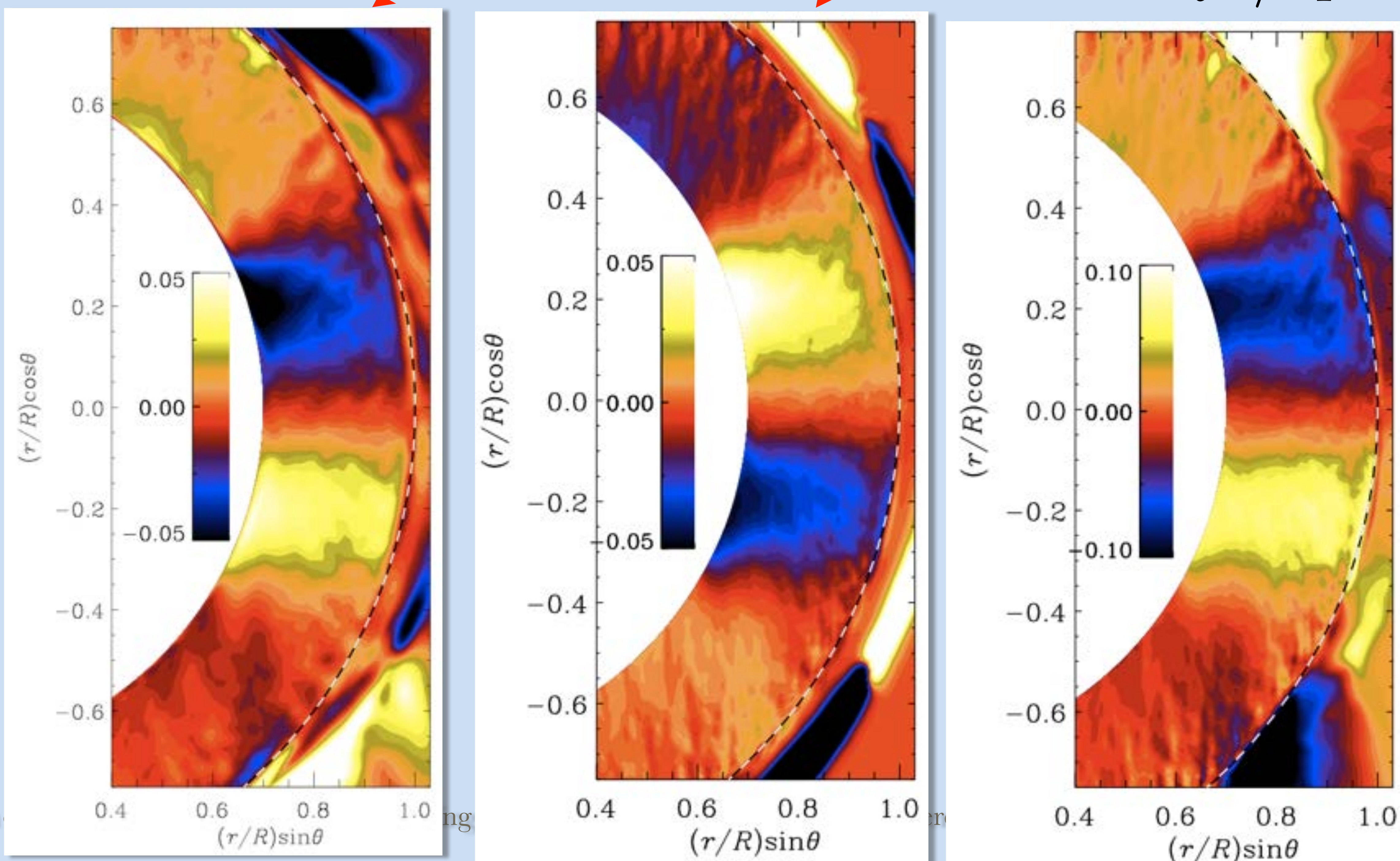
$R\nabla_\theta \overline{s}/c_\mathrm{P}$



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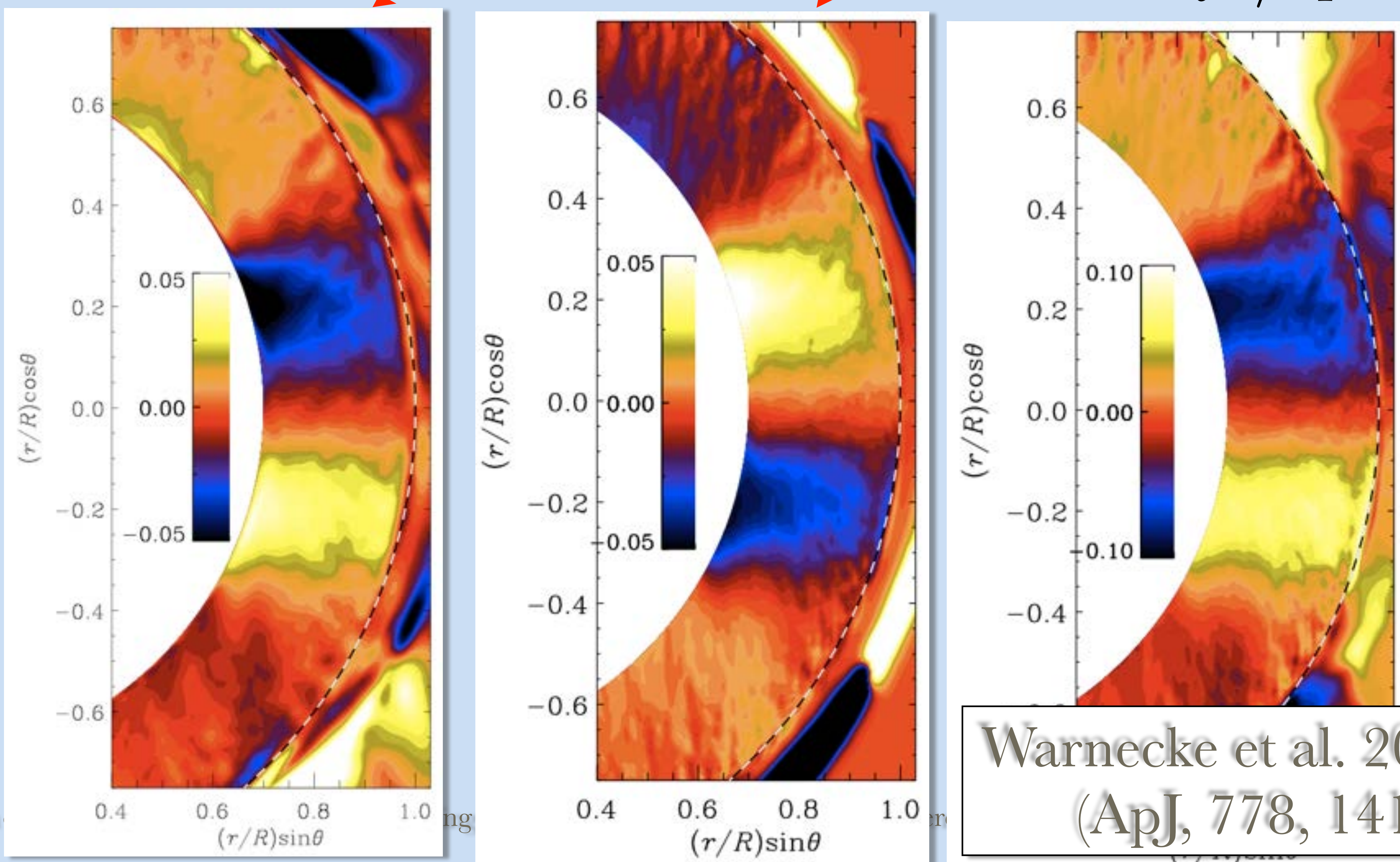
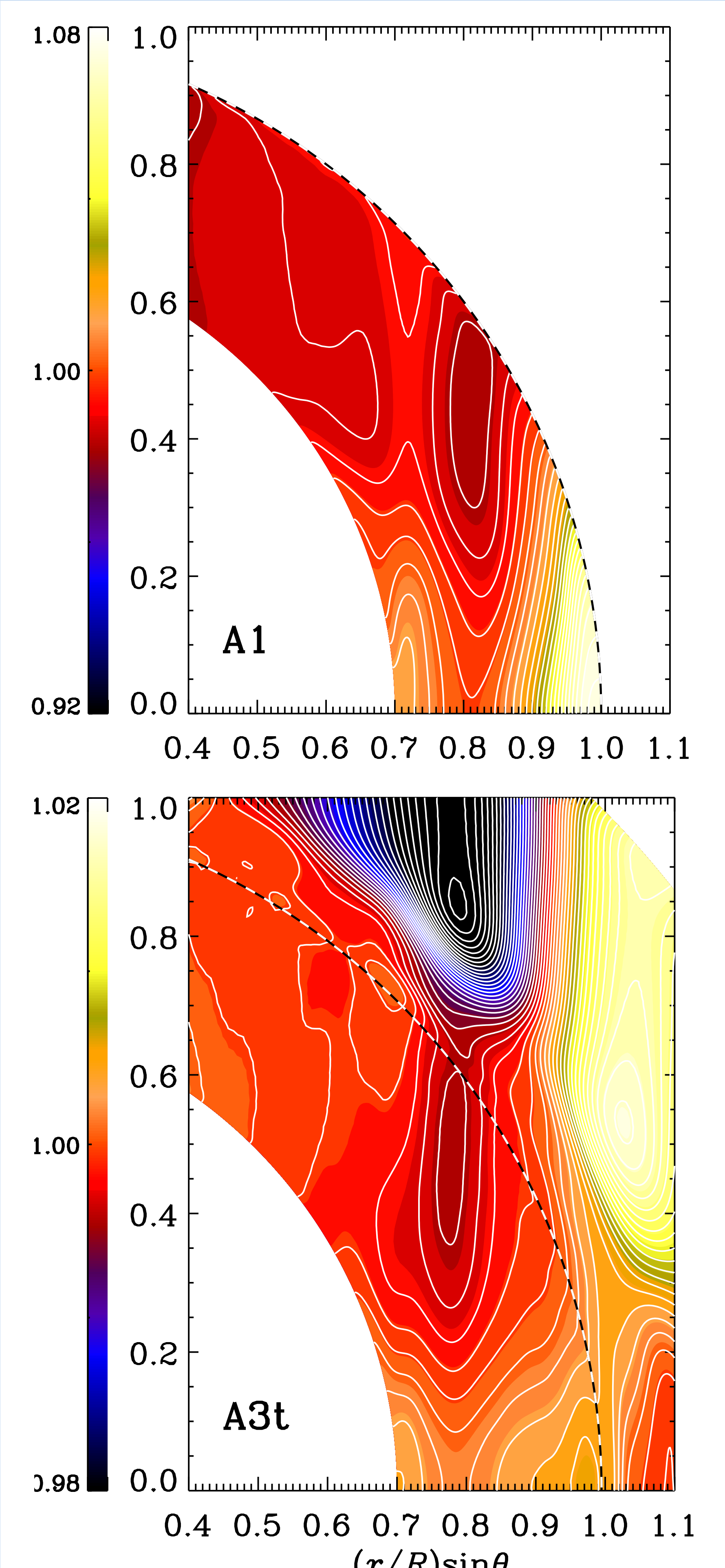
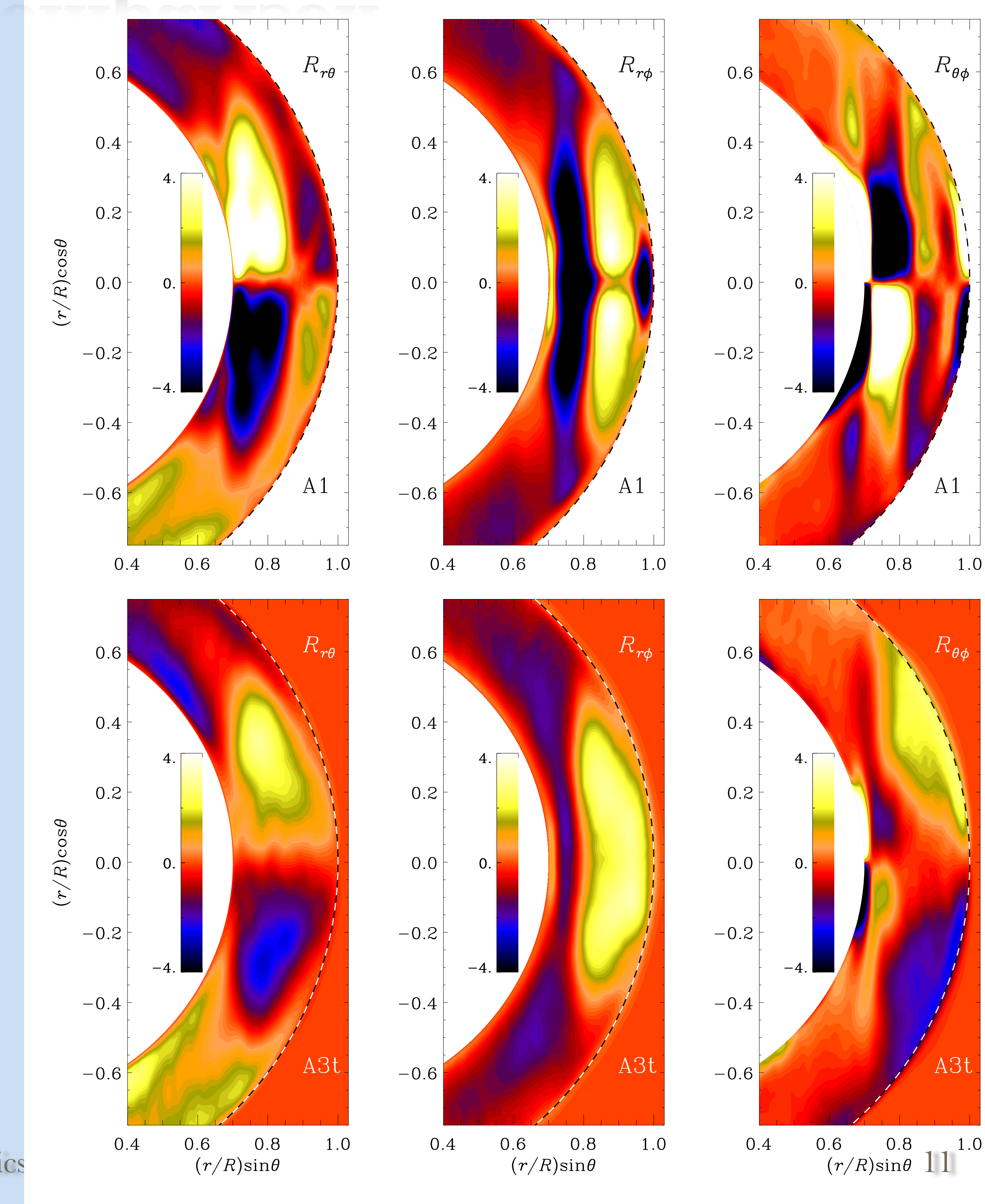


Warnecke et al. 2013a, (ApJ, 778, 141)

Comparison

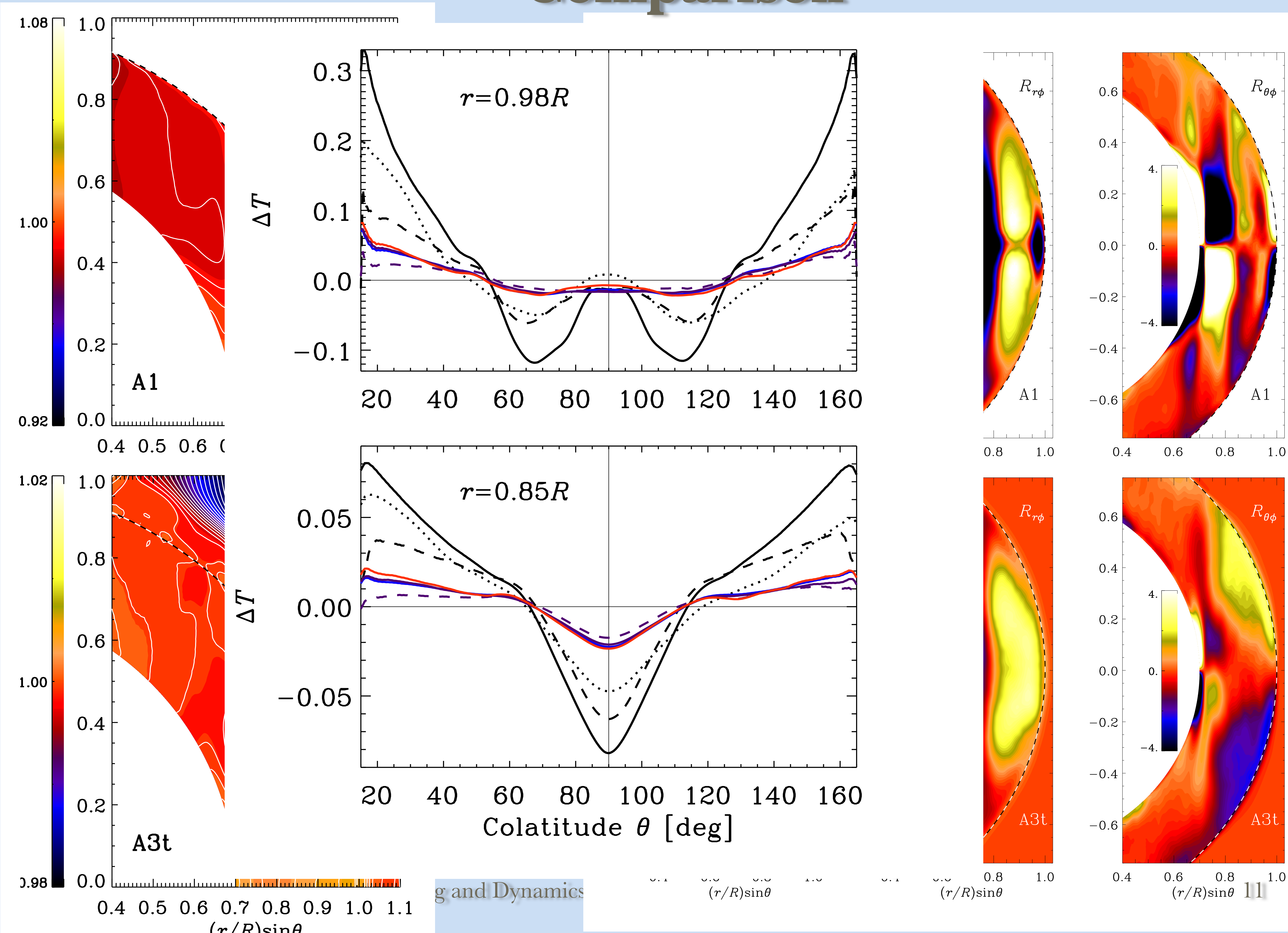


1.08
1.00
0.92
A1
1.02
1.00
0.98
A3t
0.0 0.2 0.4 0.6 0.8 1.0
0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
$(r/R)\sin\theta$



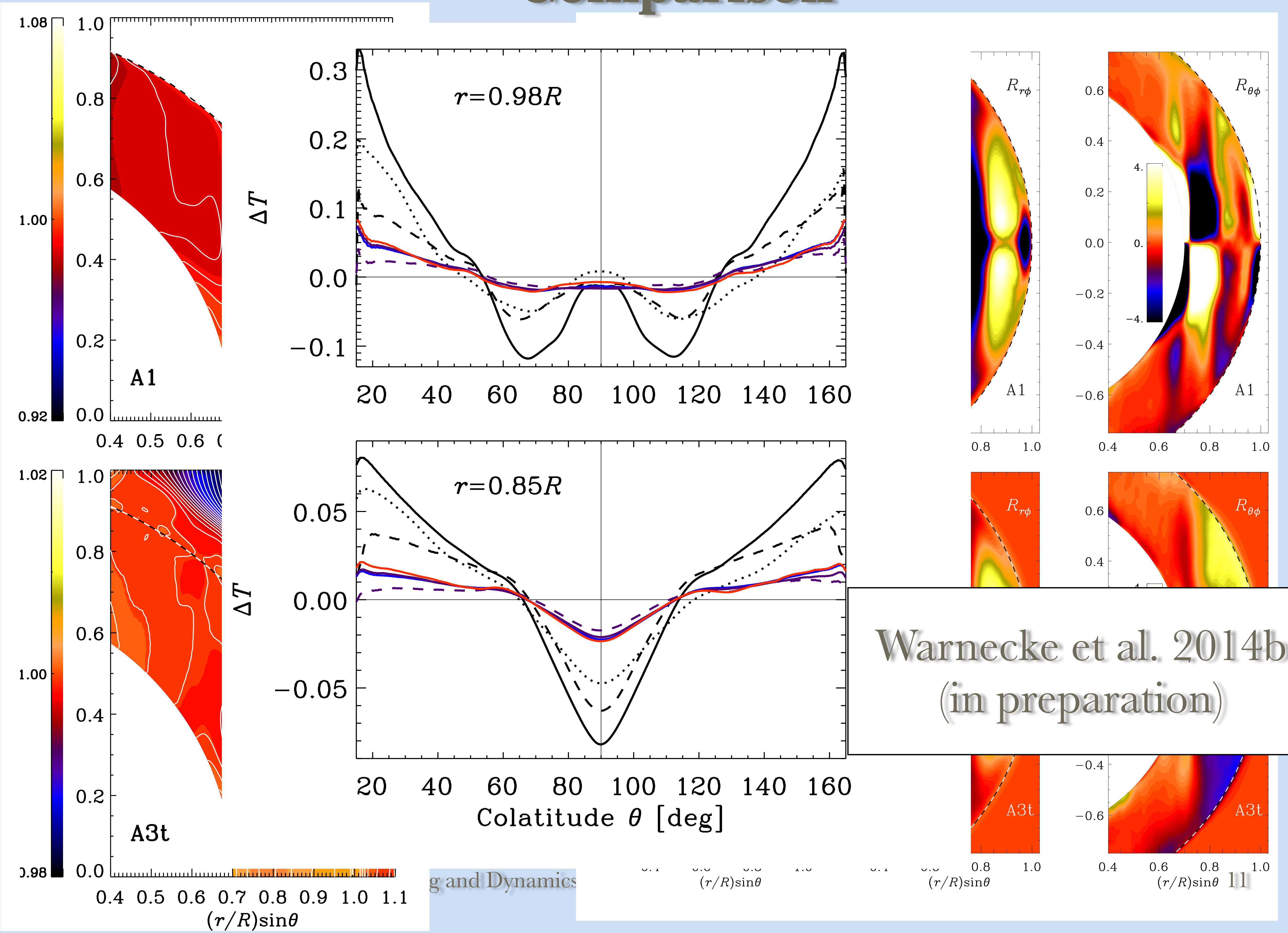
$R_{r\theta}$
$R_{r\phi}$
$R_{\theta\phi}$
A1
A3t
4.
0.
−4.
$(r/R)\cos\theta$
$(r/R)\sin\theta$

Comparison



$r=0.98R$
$r=0.85R$
ΔT
Colatitude θ [deg]
A1
A3t
$R_{r\phi}$
$R_{\theta\phi}$
$(r/R)\sin\theta$
g and Dynamics

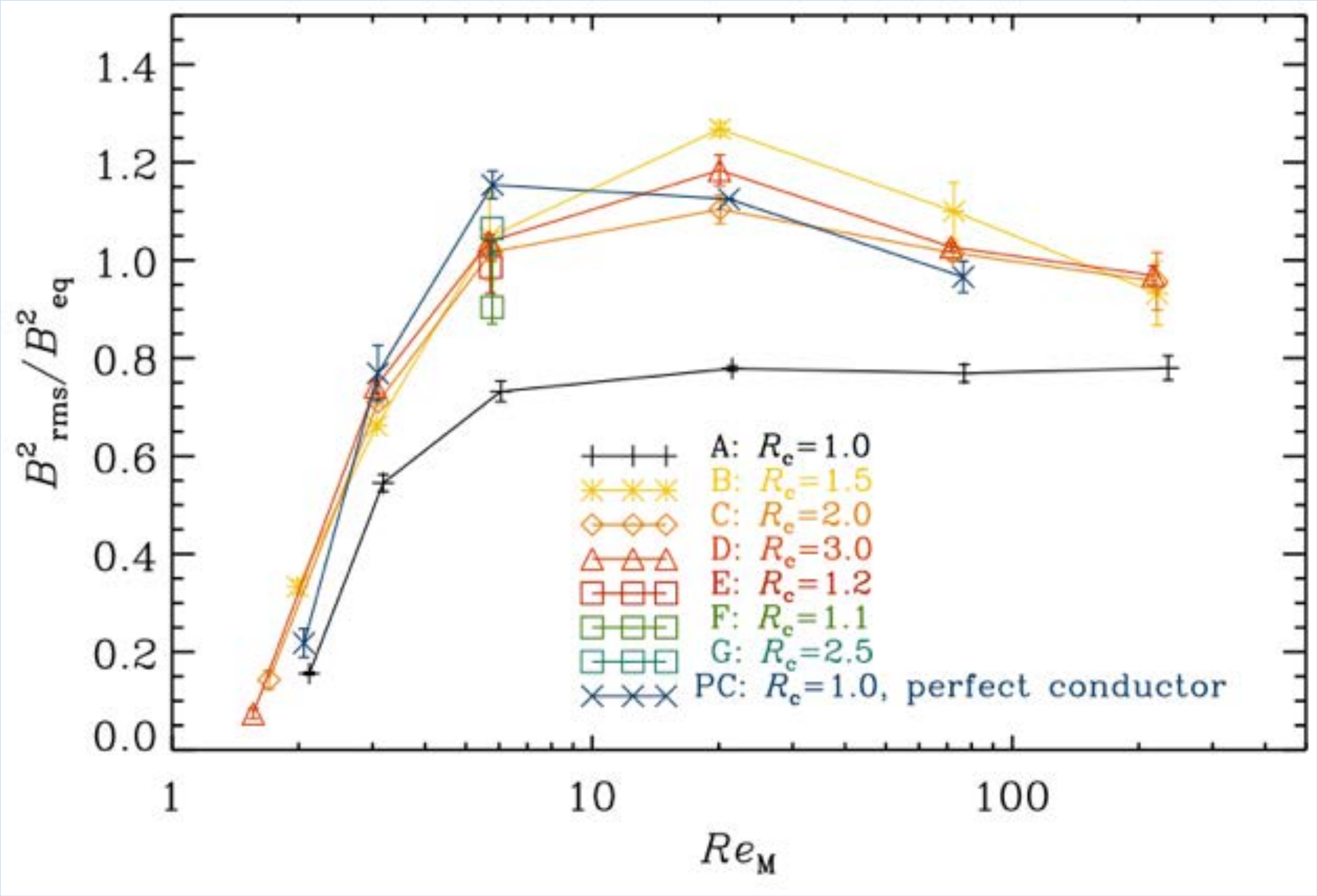
Comparison



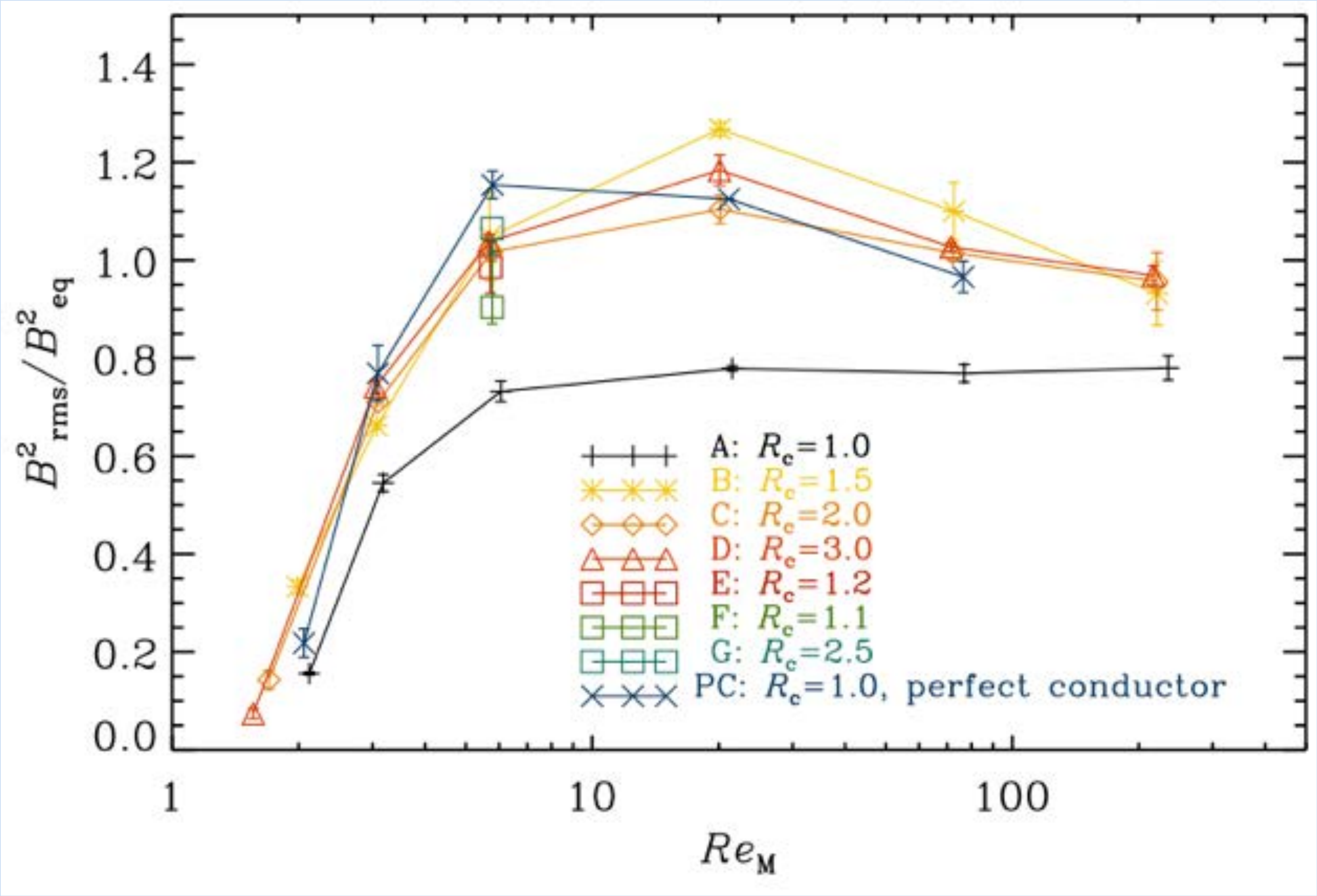
Warnecke et al. 2014b
(in preparation)

Corona supports dynamo action

Corona supports dynamo action

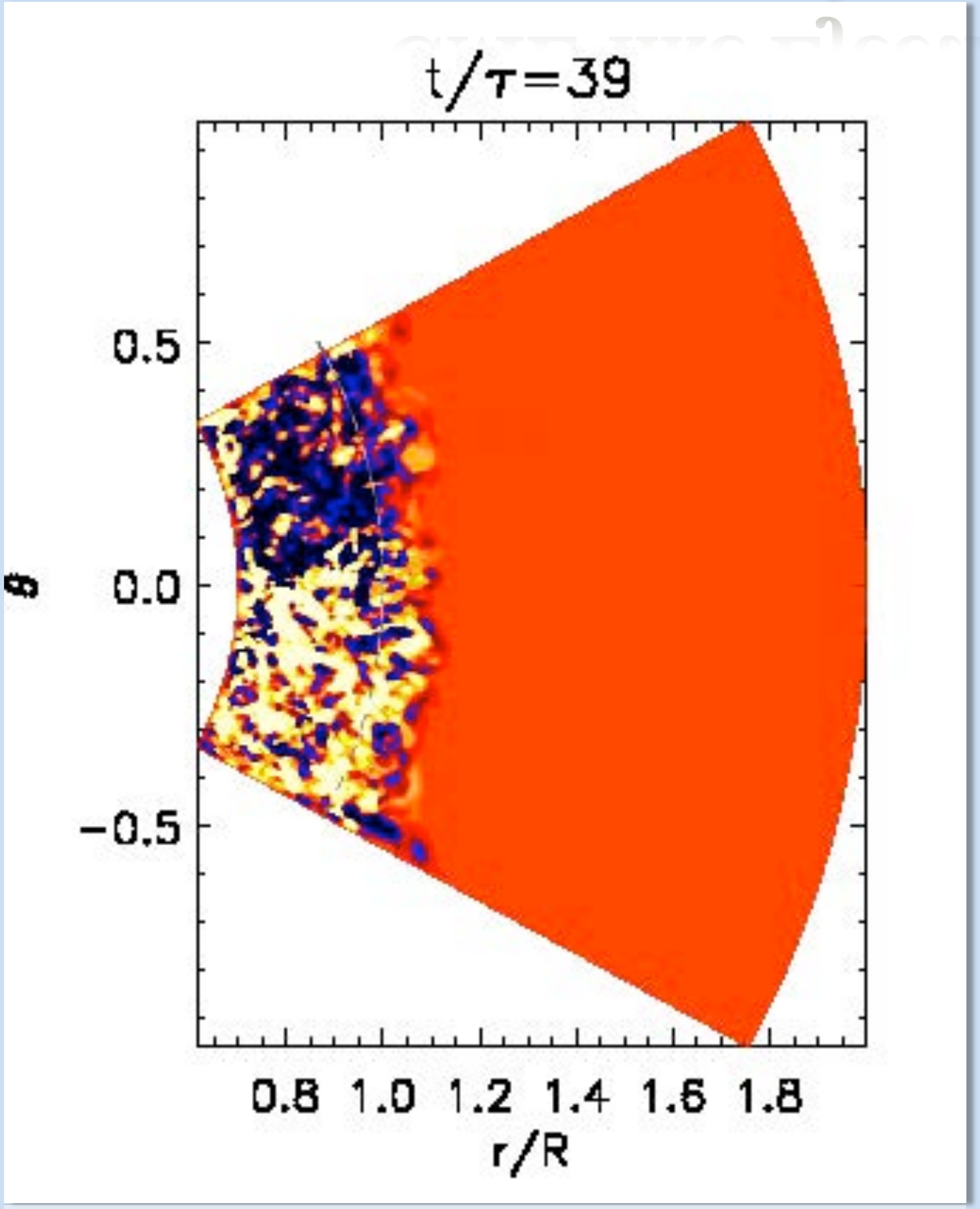


Corona supports dynamo action



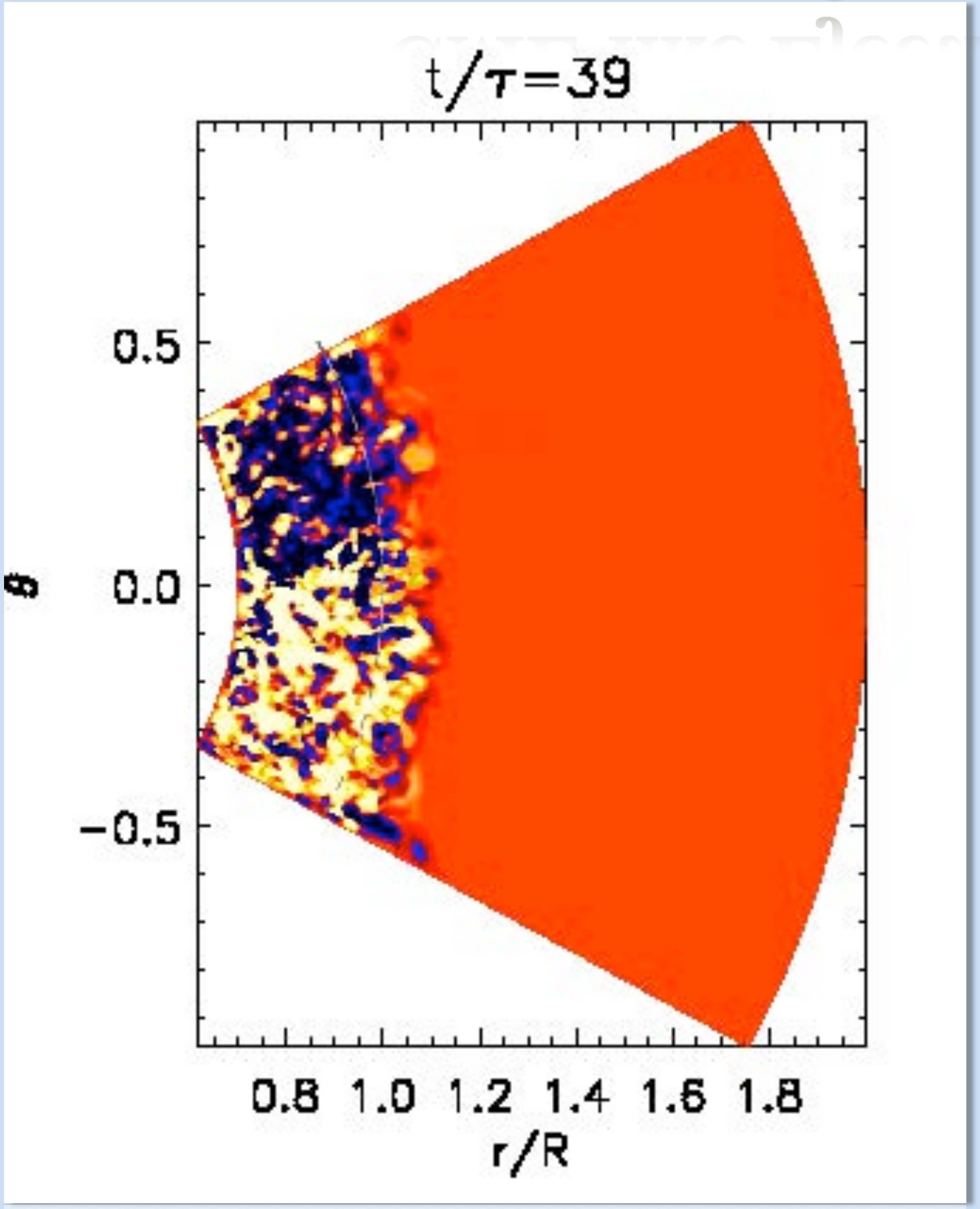
Warnecke et al., 2014
IAU proceeding

CME-like Ejections



Current helicity density

CME-like Ejections



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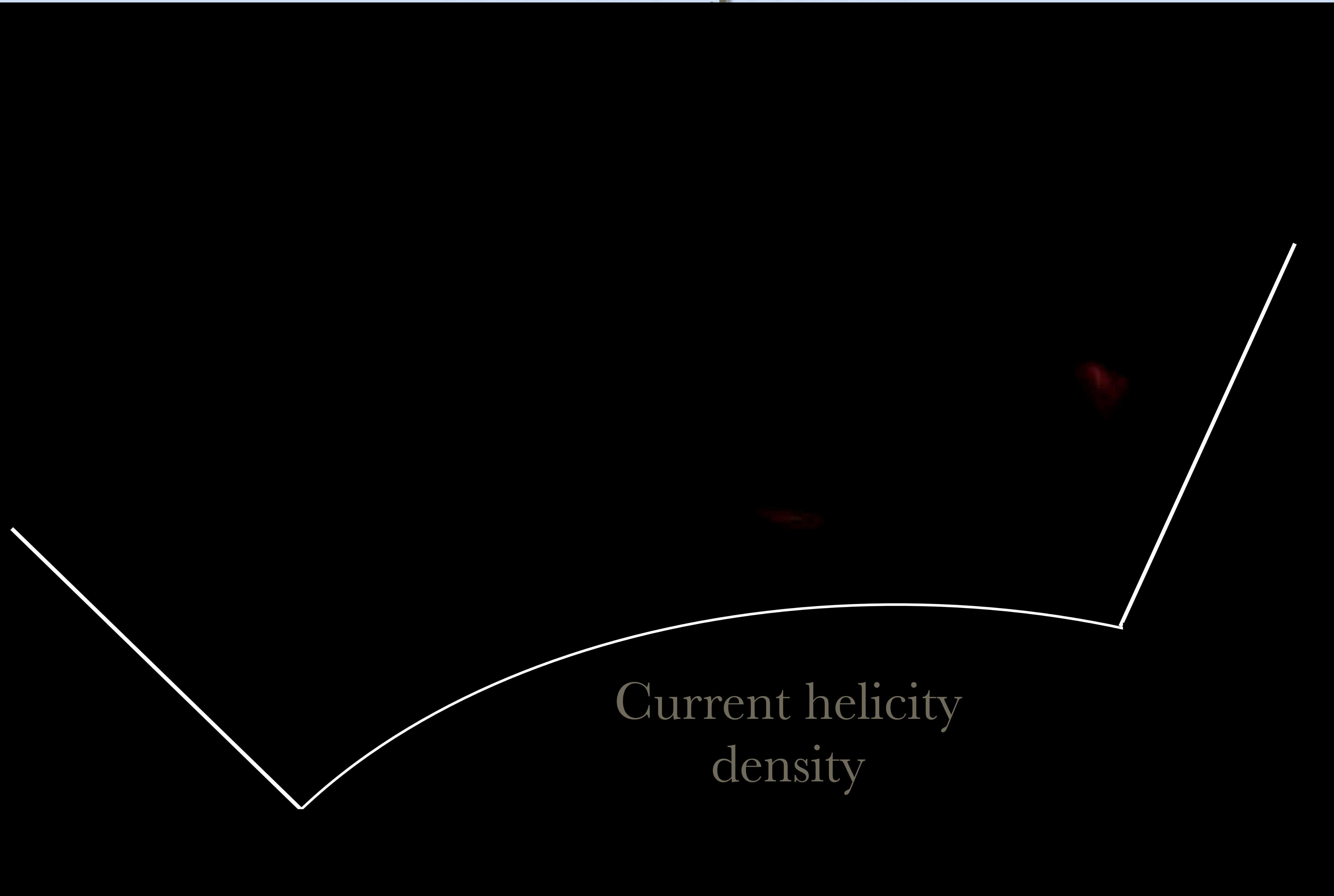
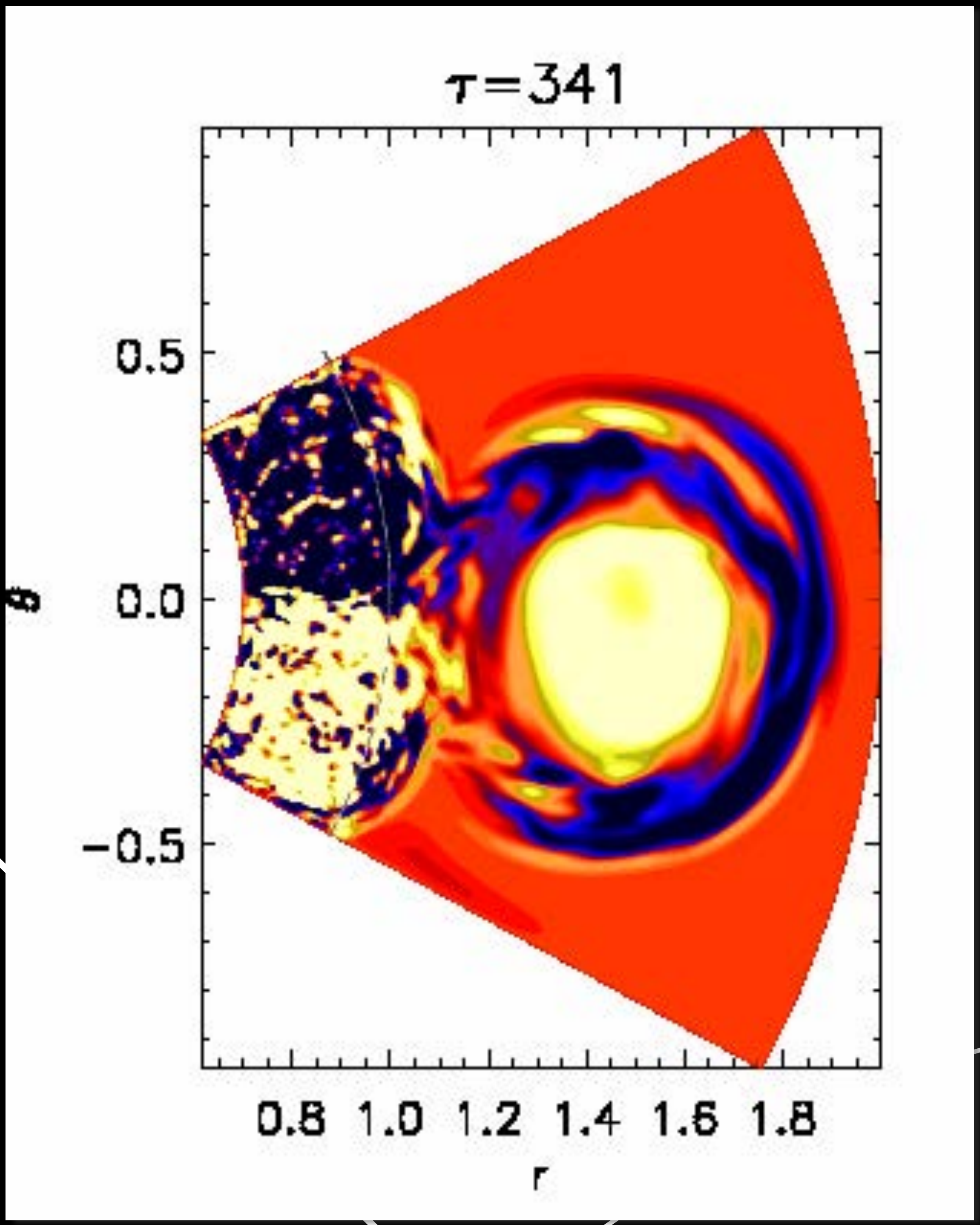
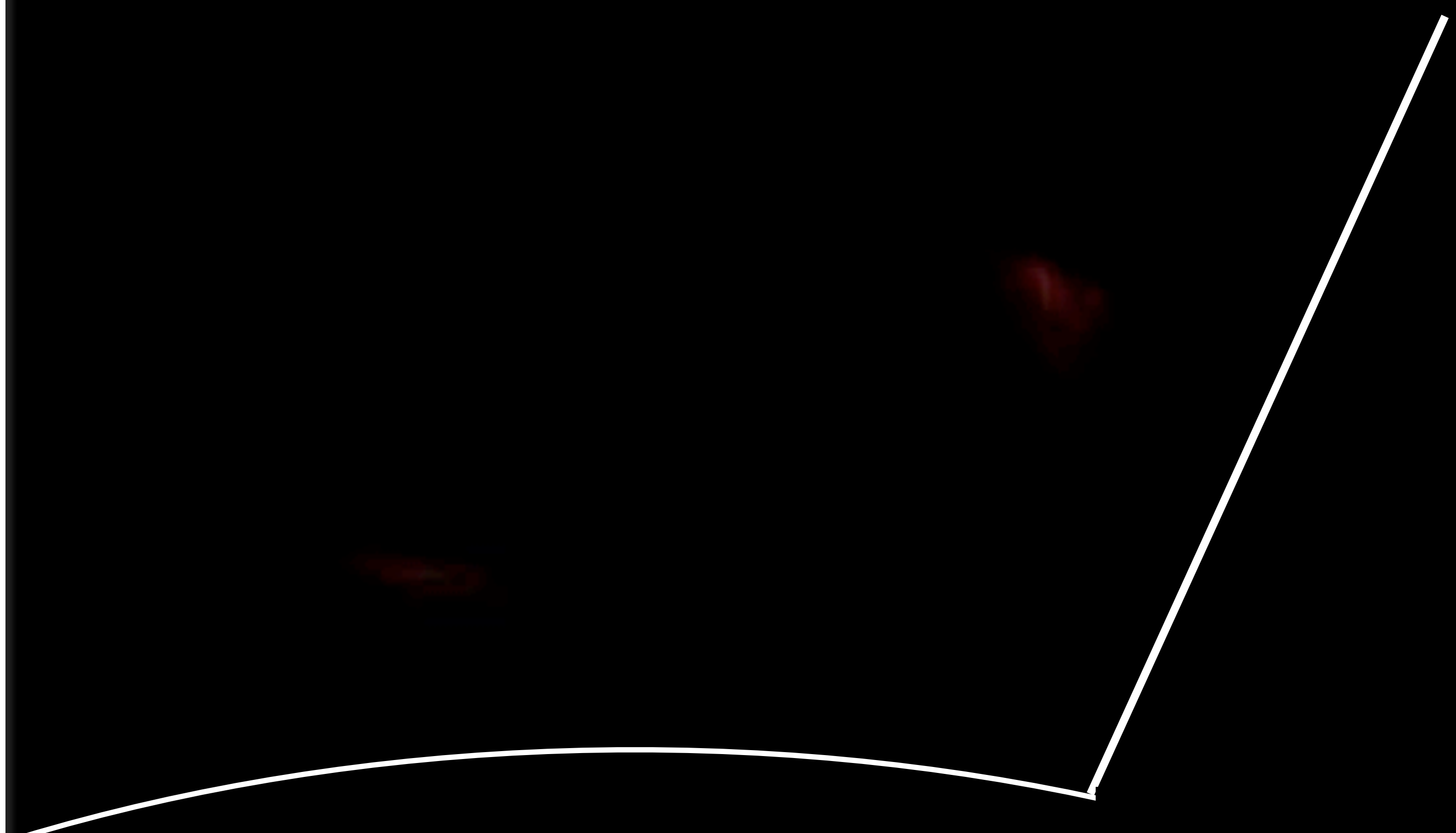


CME-like Ejections





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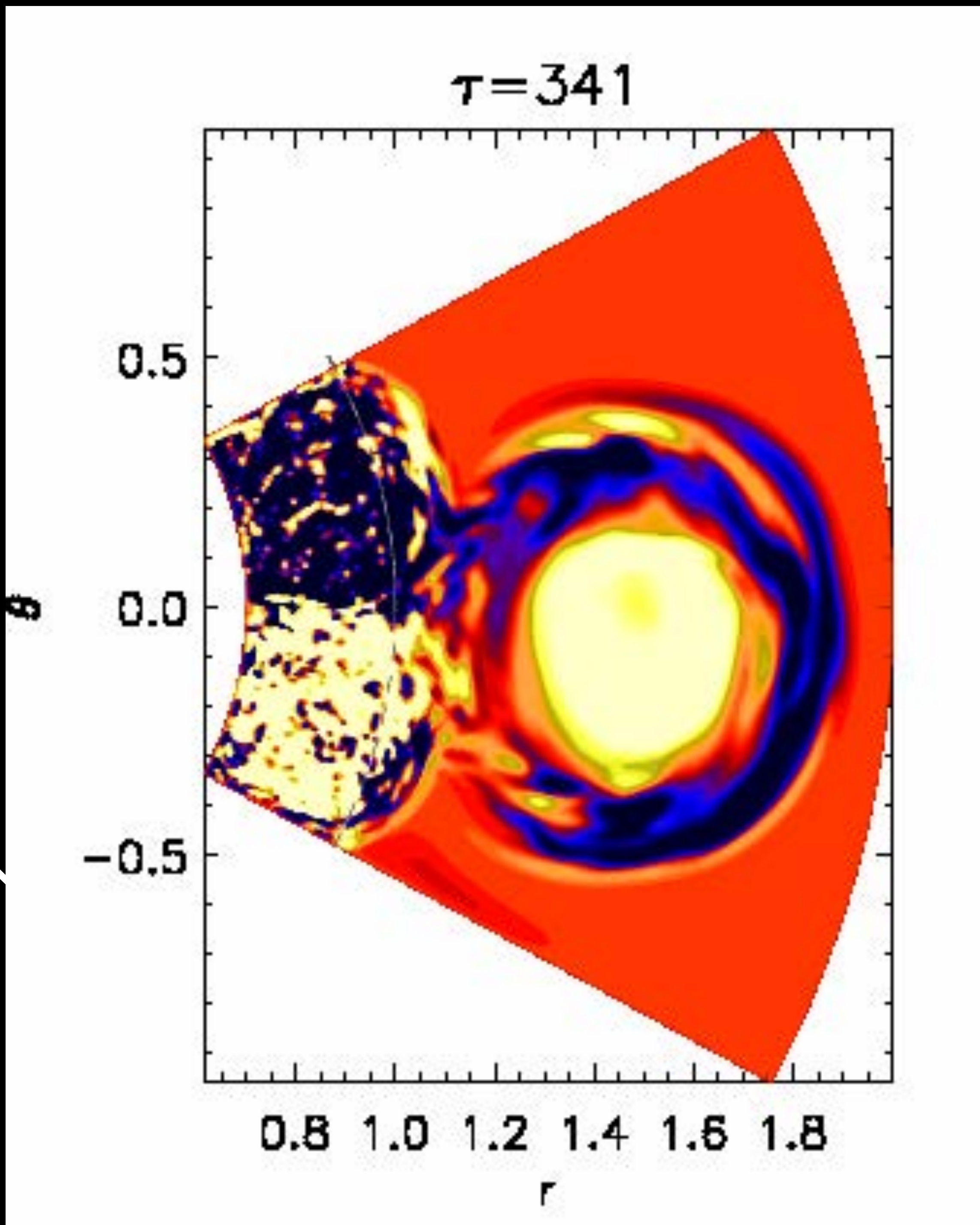
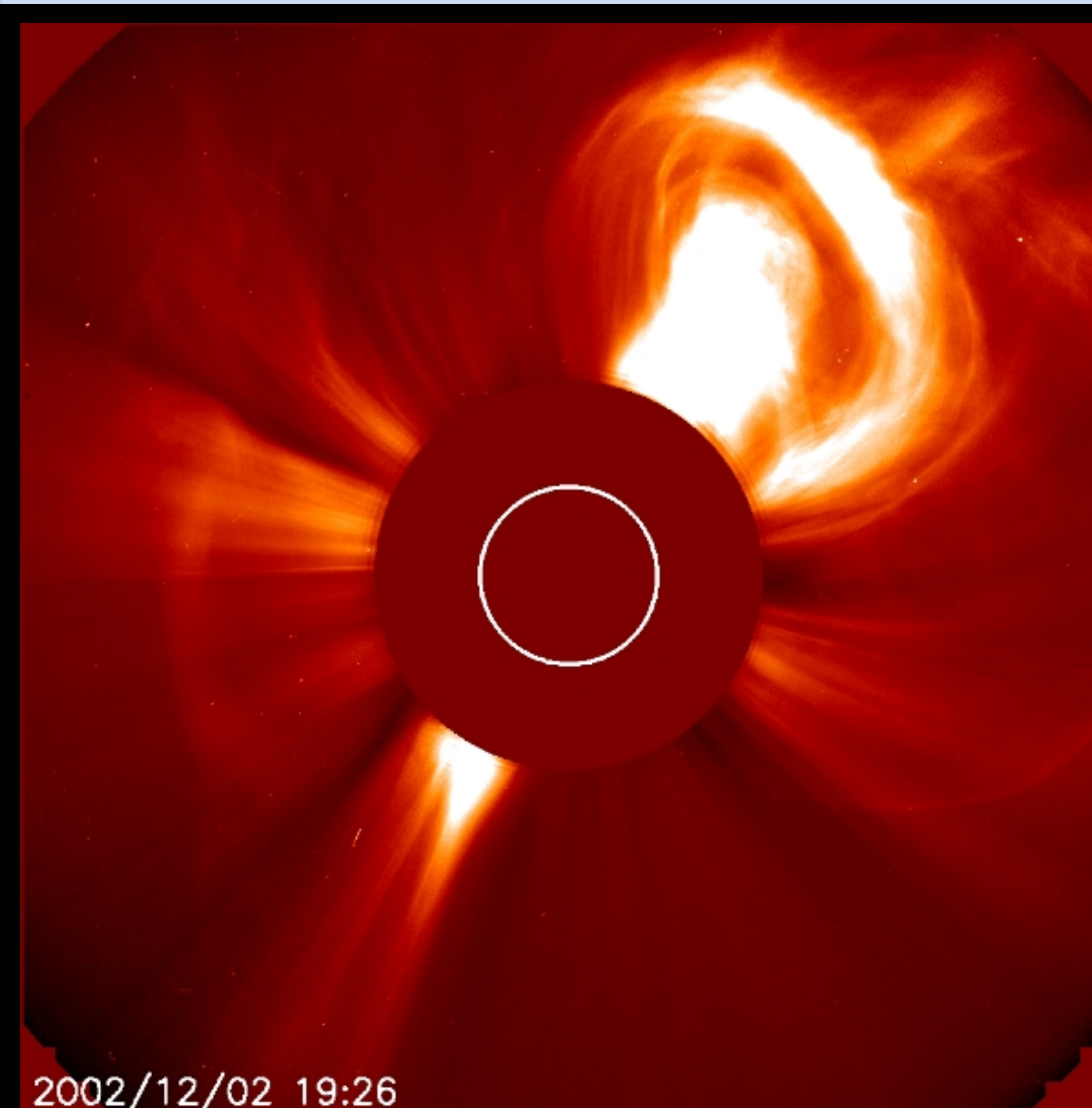
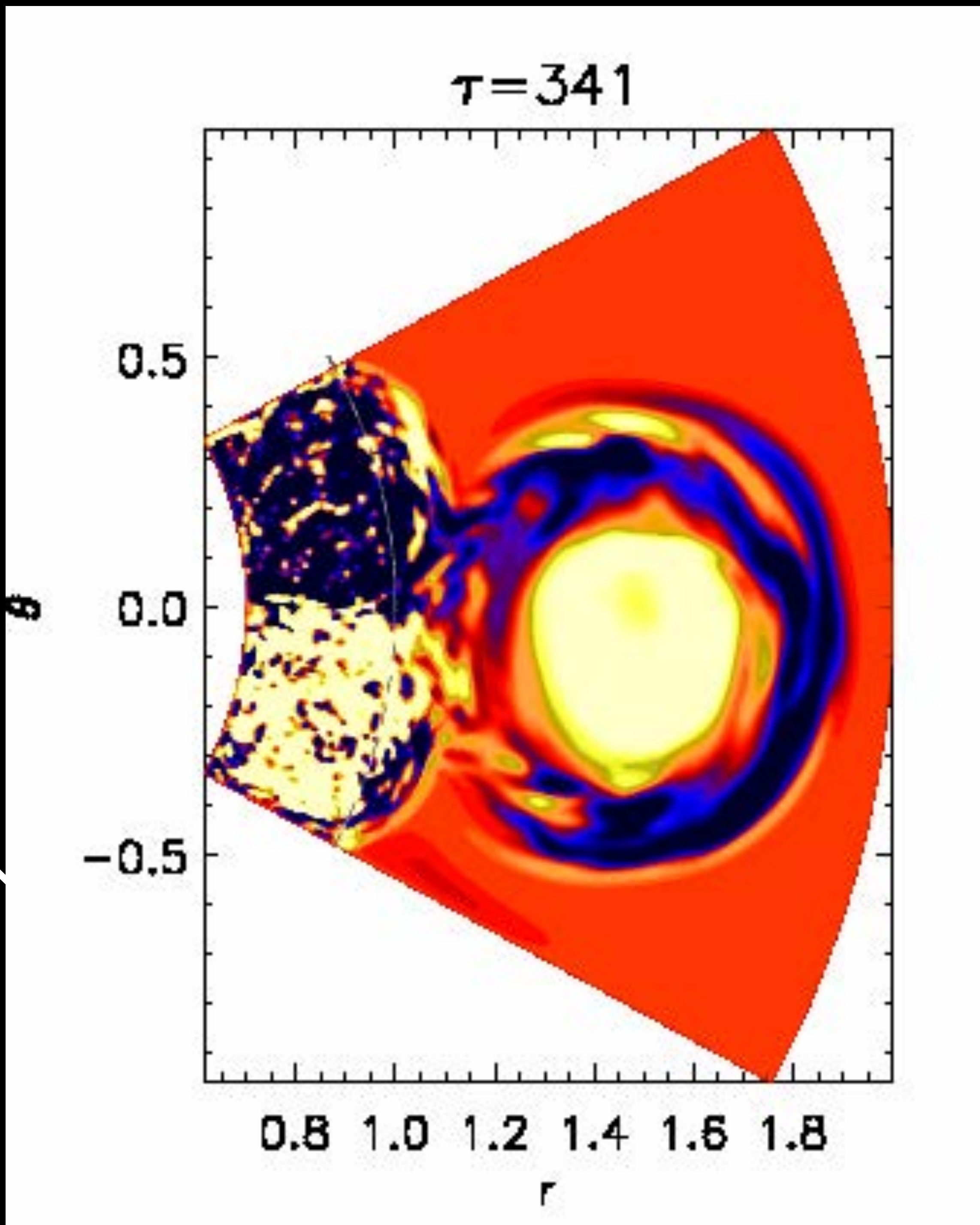
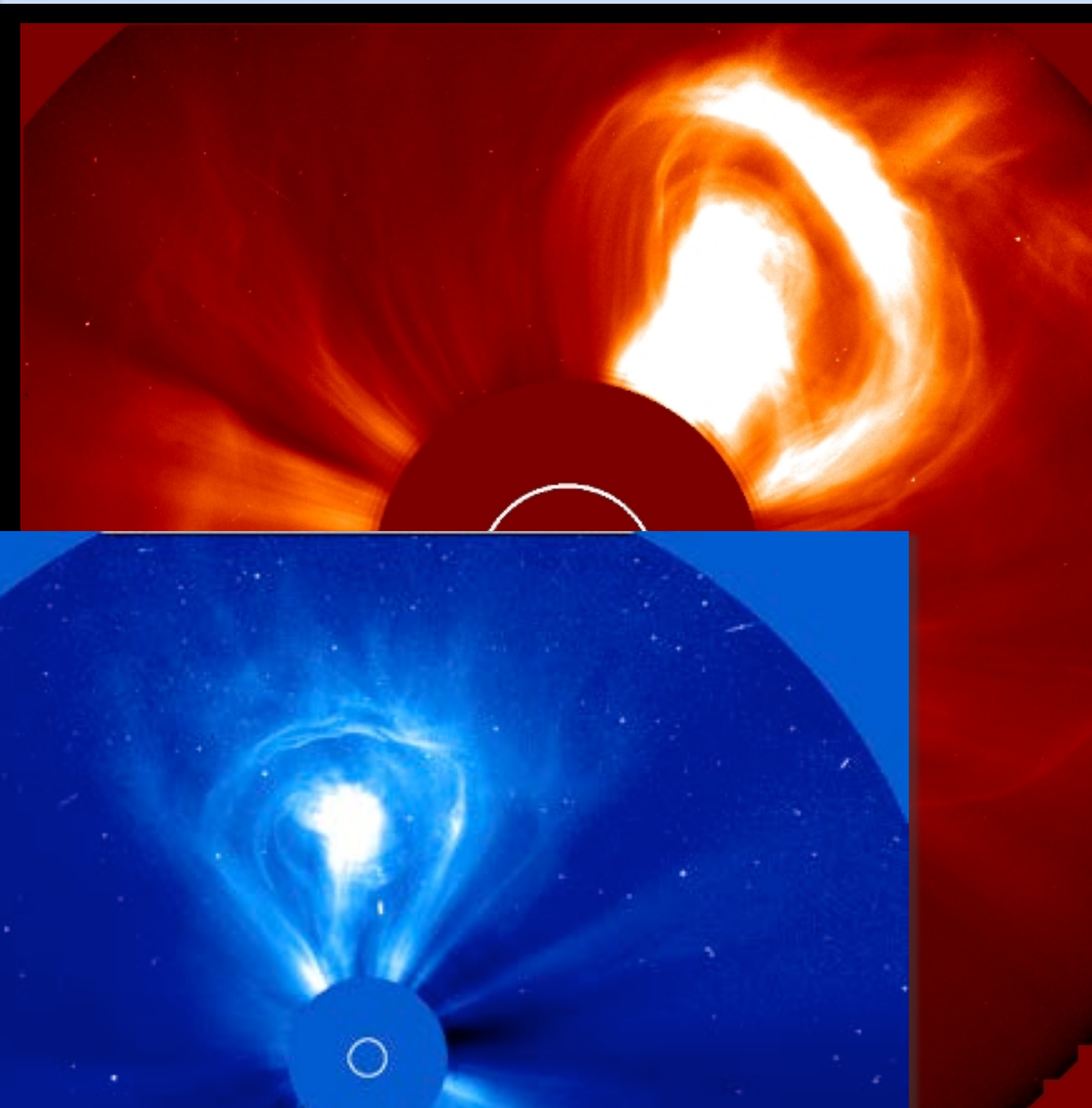


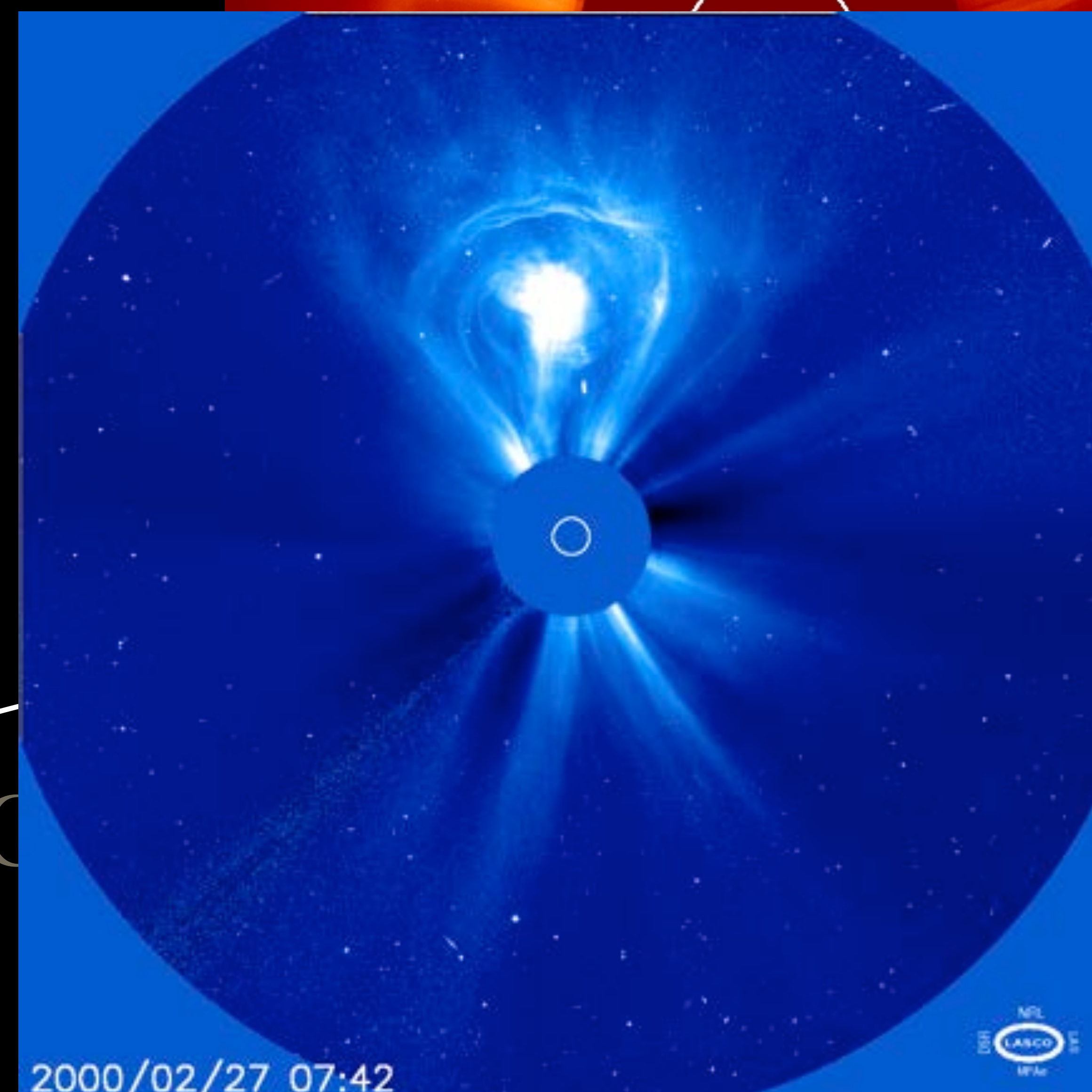


Current helicity density

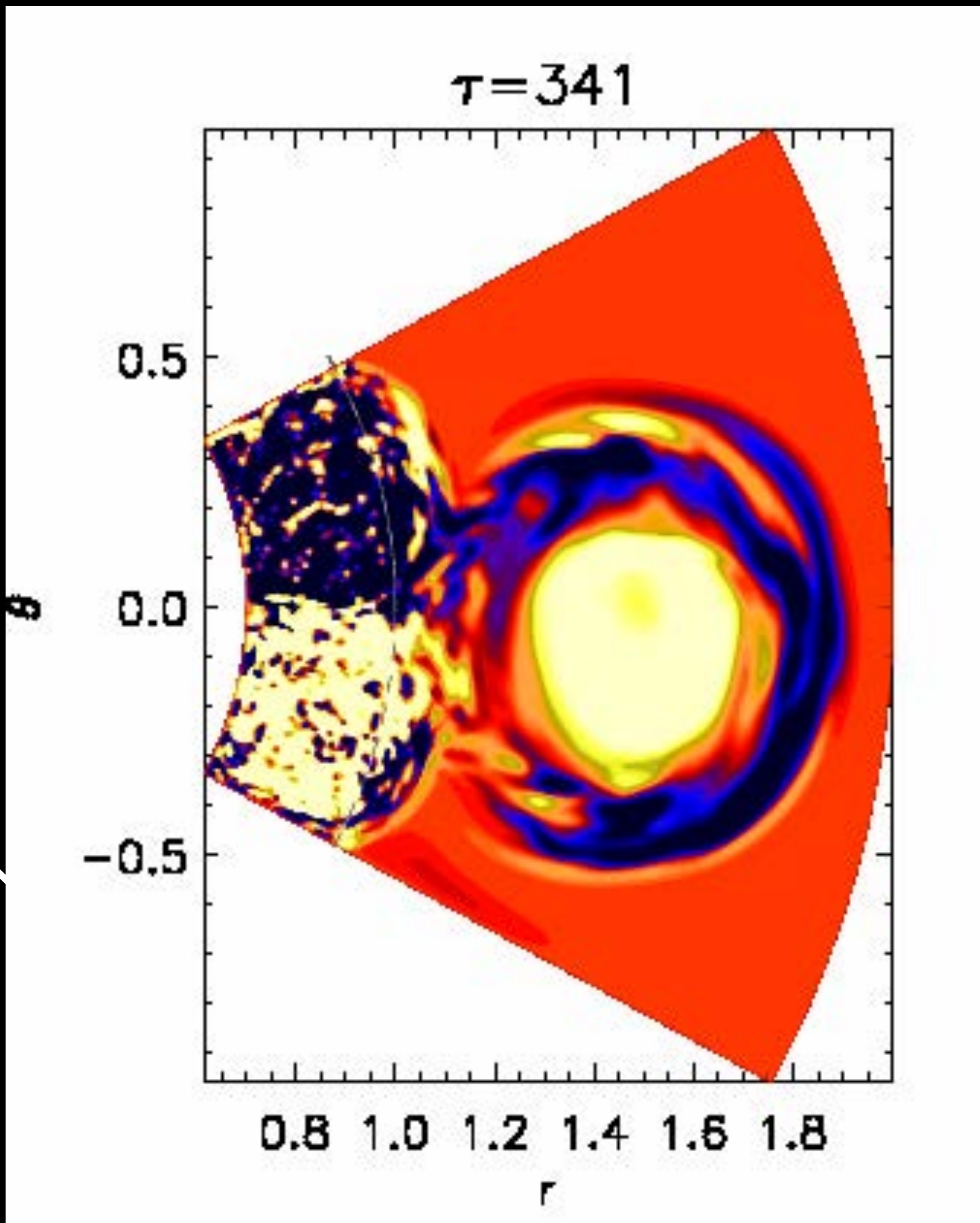
CME-like Ejections

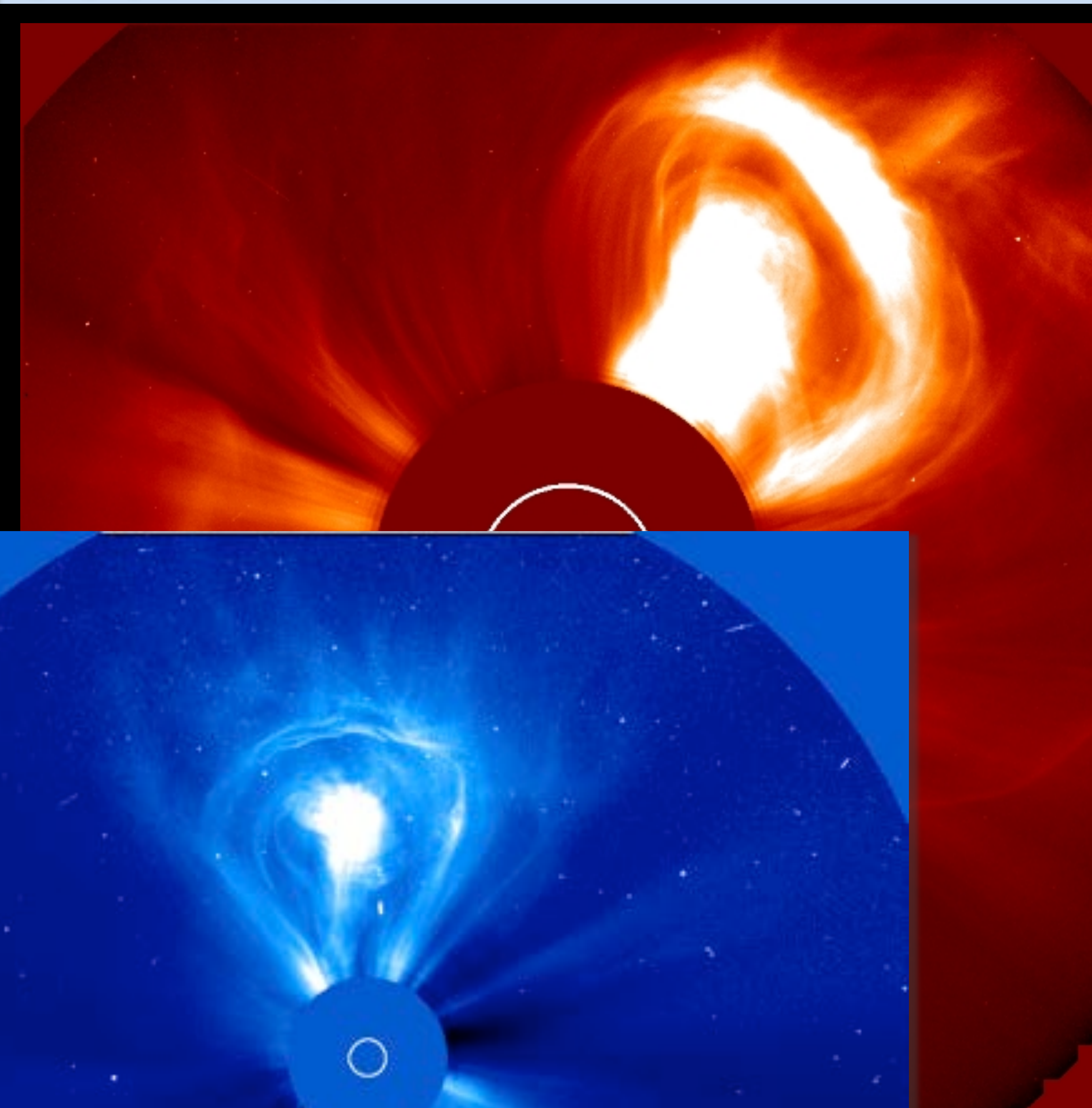


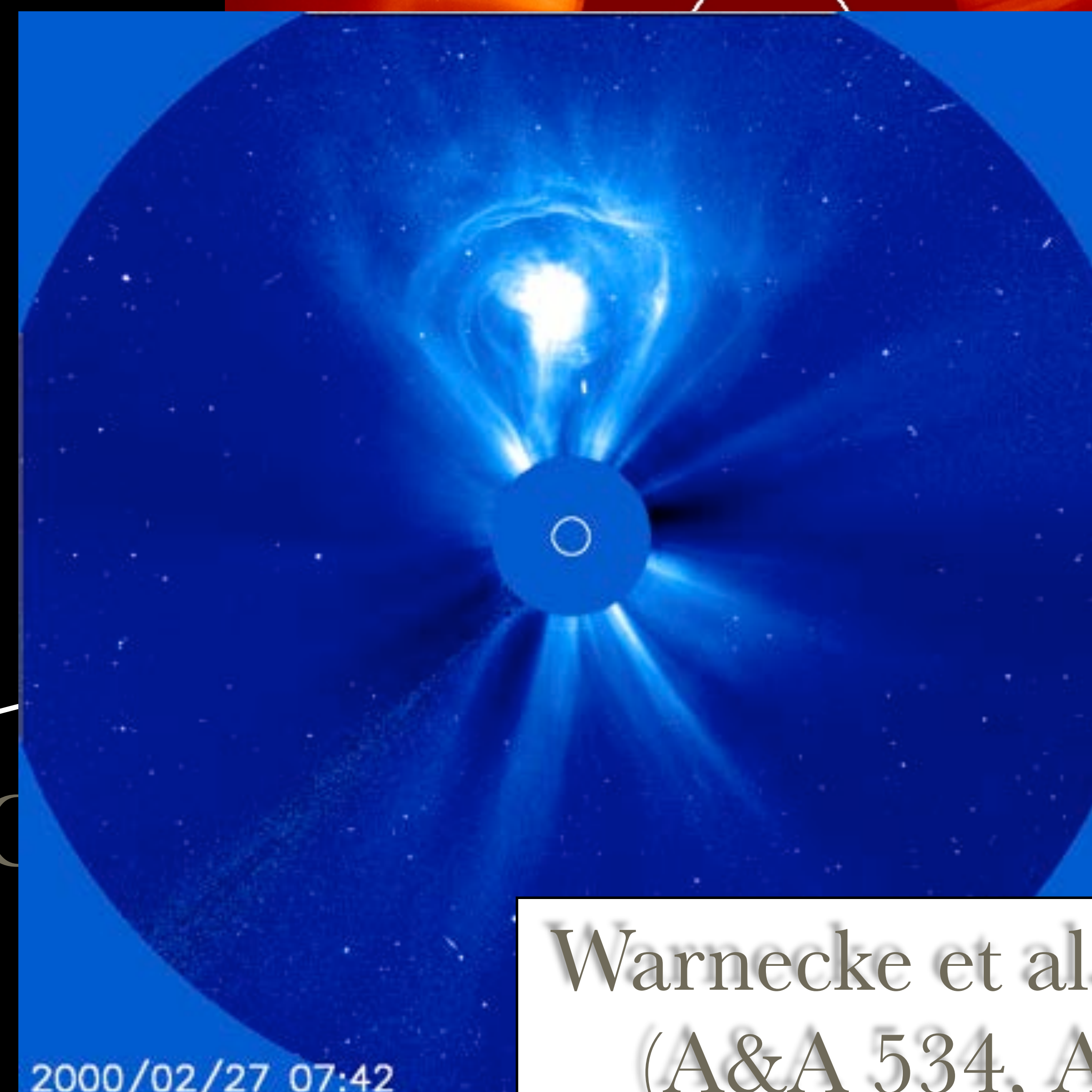




CME-like Ejections







Warnecke et al. 2011
(A&A 534, A11)

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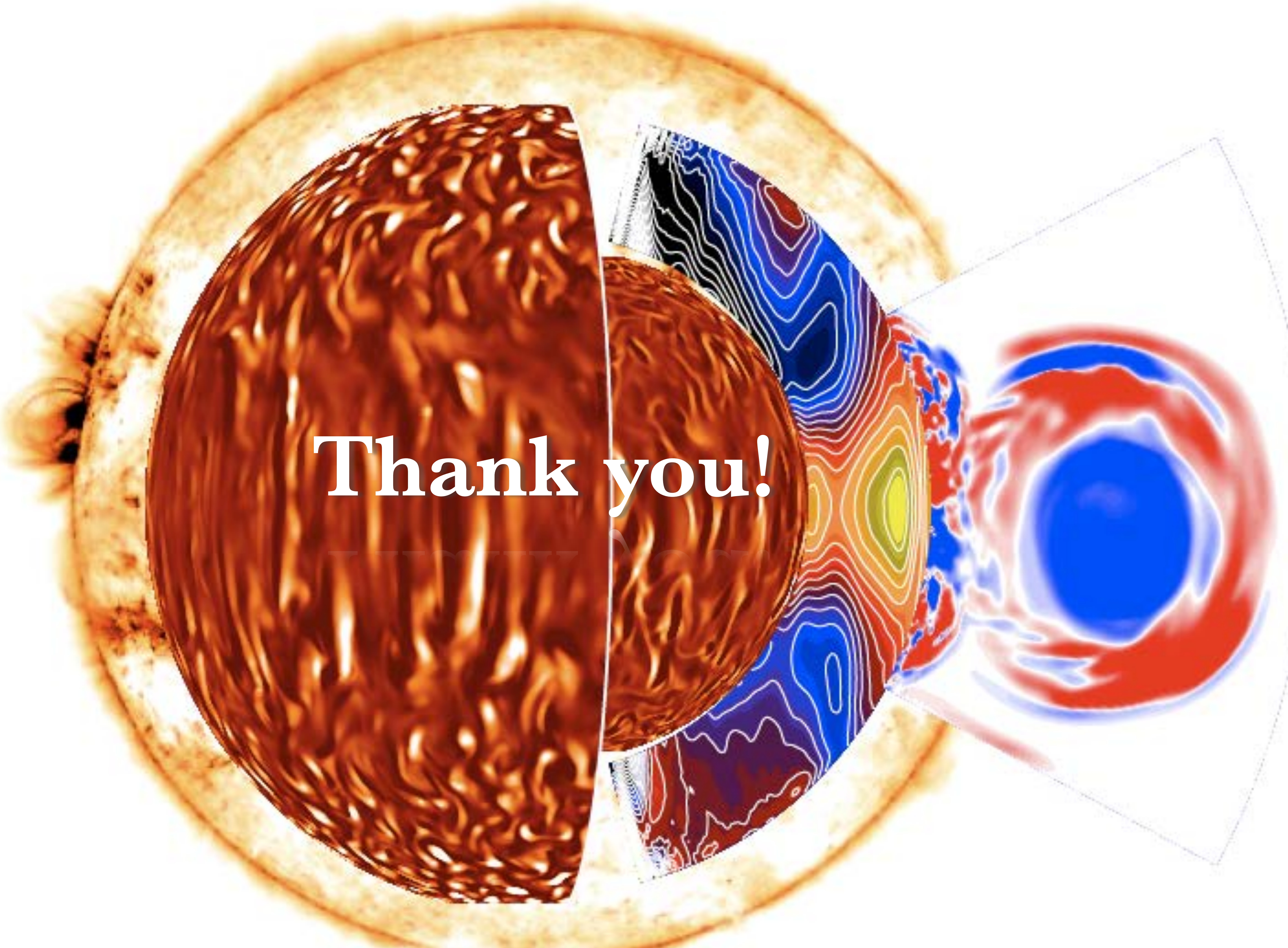
- It alters the Reynolds stress and the temperature distribution.
- It increased the dynamo efficiency.


Thank you!