Spoke-like Differential Rotation in a convective Dynamo with a Coronal Envelope

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together with

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A realistic boundary condition for the magnetic field is important

The Two Layer Model

Lower layer:

Convection zone

Dynamo action

⇨ Generation of magnetic field

Upper layer:

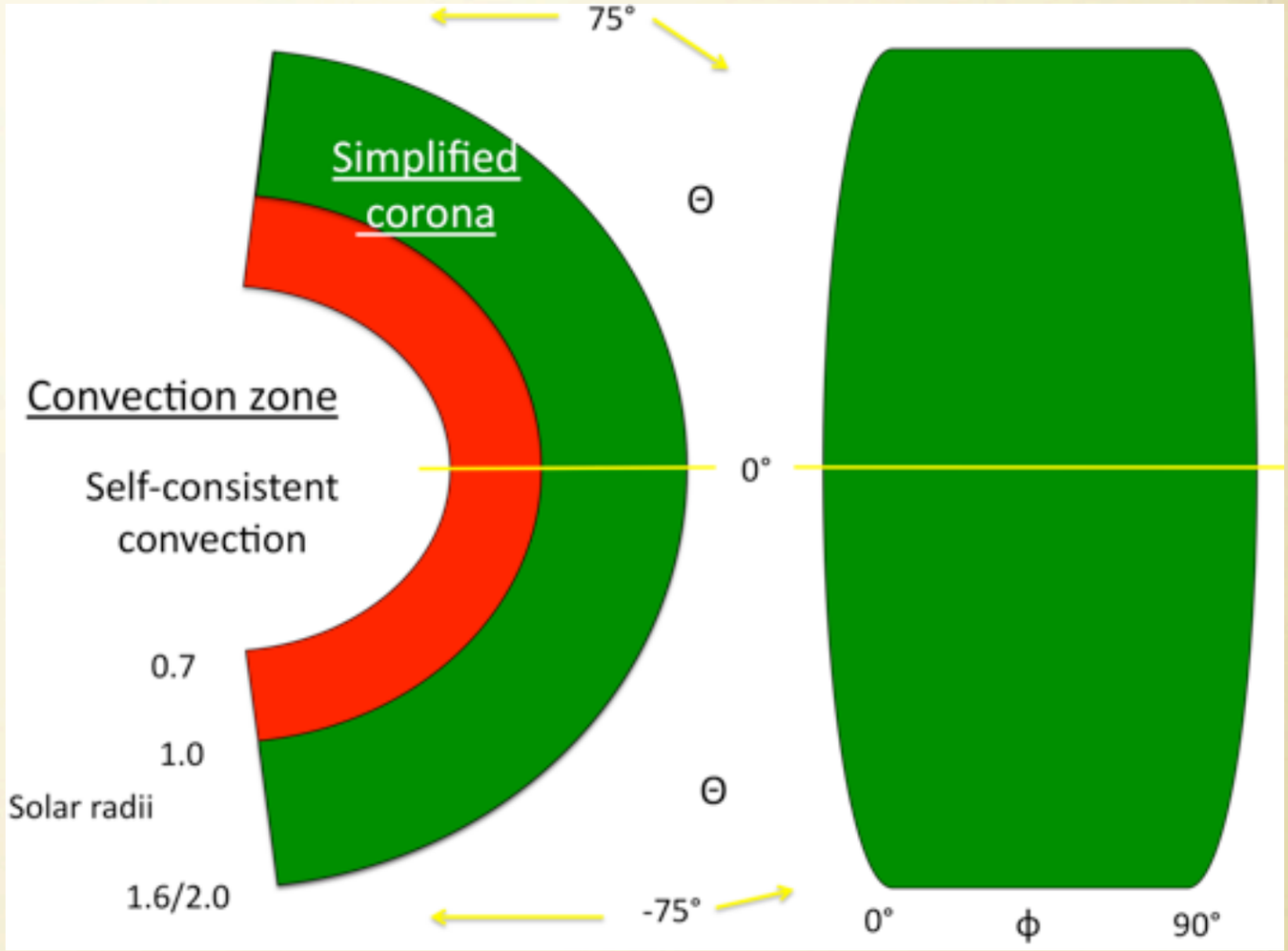
Simplified coronal model

Magnetic (helicity) flux emerges from the lower layer and gets ejected.

Both layers are in one simulation.

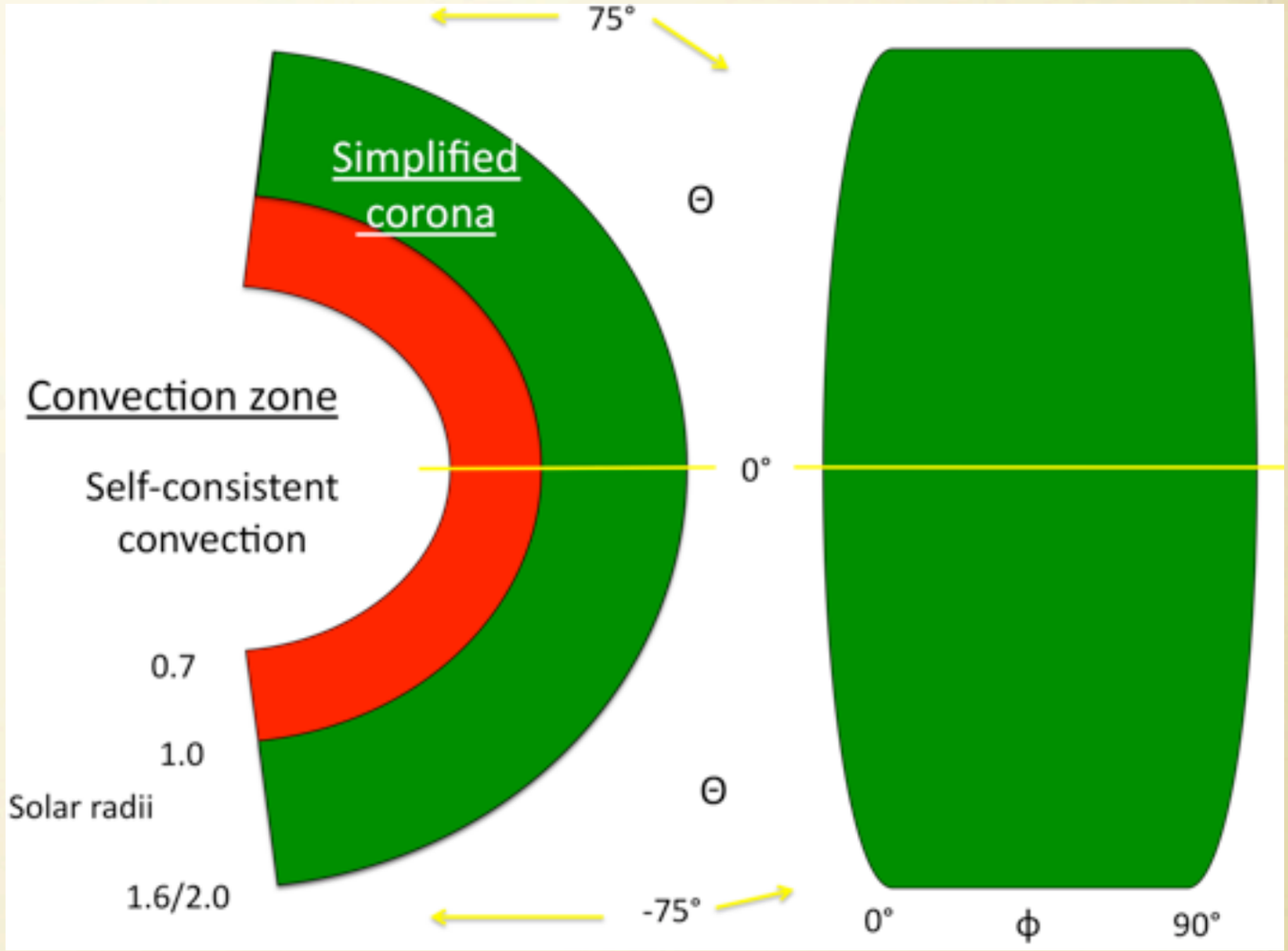
The Setup

Setup


75°
Simplified corona
Θ
Convection zone
Self-consistent convection
0°
0.7
1.0
Solar radii
Θ
1.6/2.0
-75°
0°
ϕ
90°

Setup

Self-consistent convection with a coronal layer



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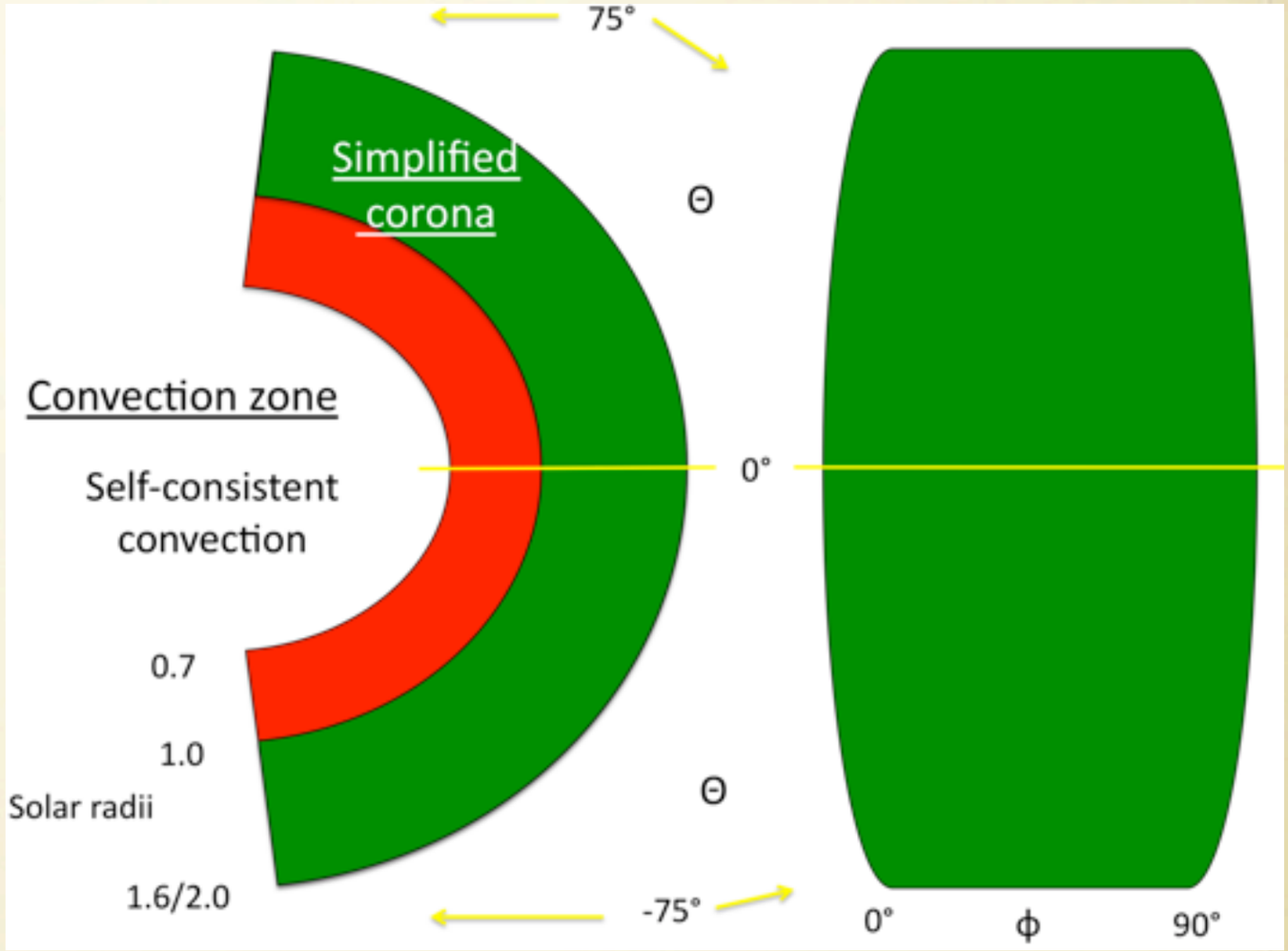
Equations:



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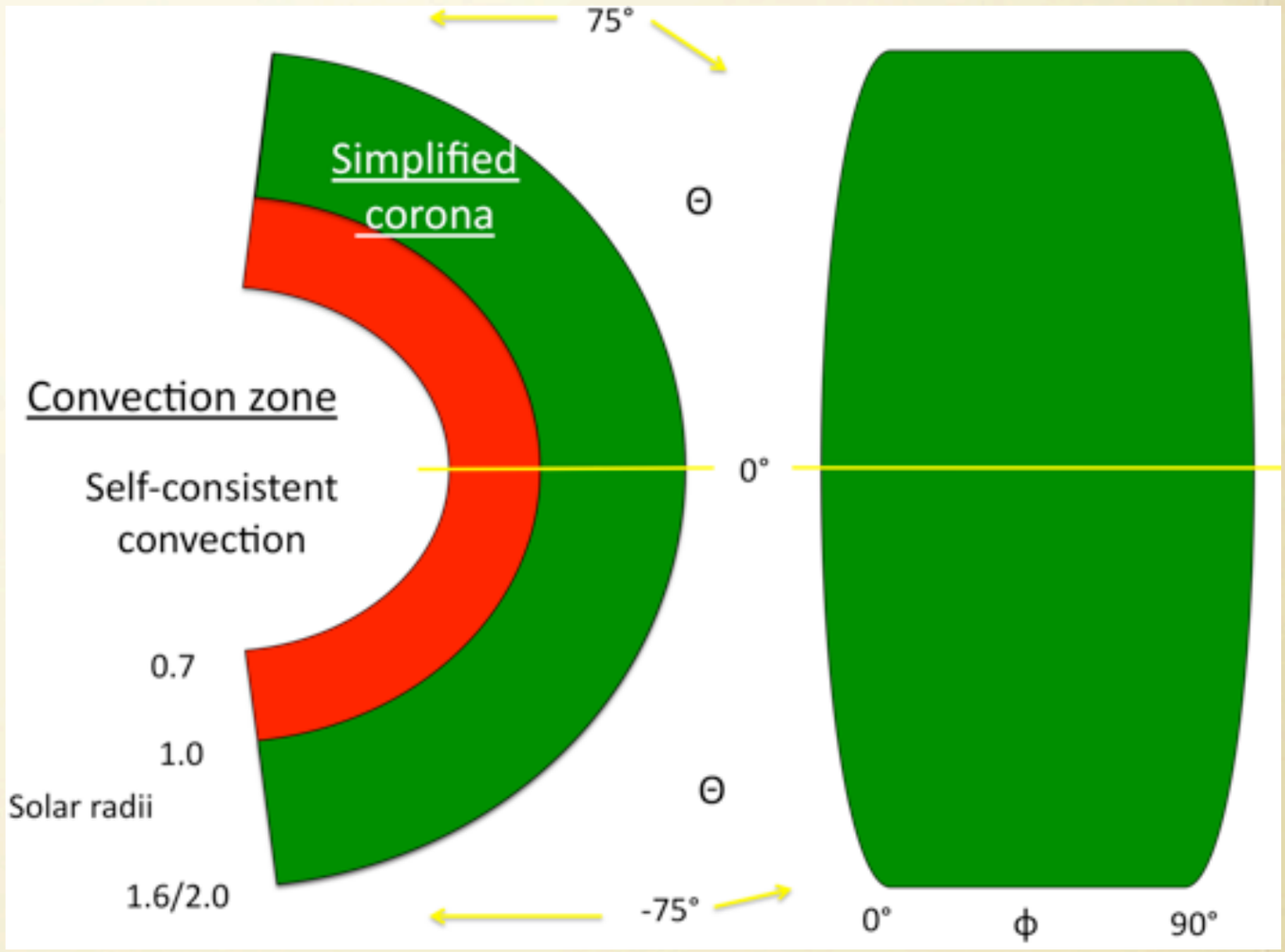
Self-consistent convection with a coronal layer

Equations:

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



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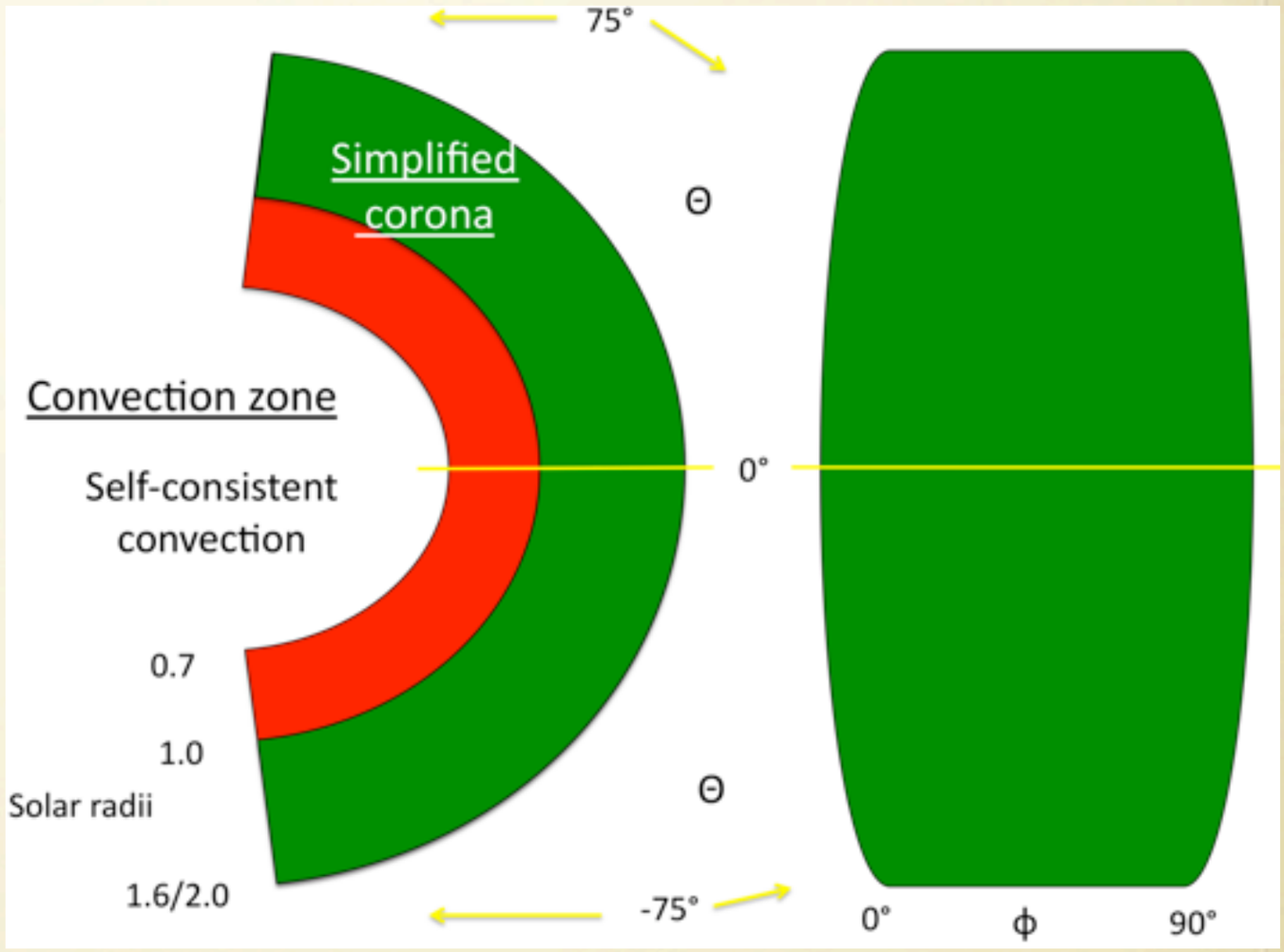

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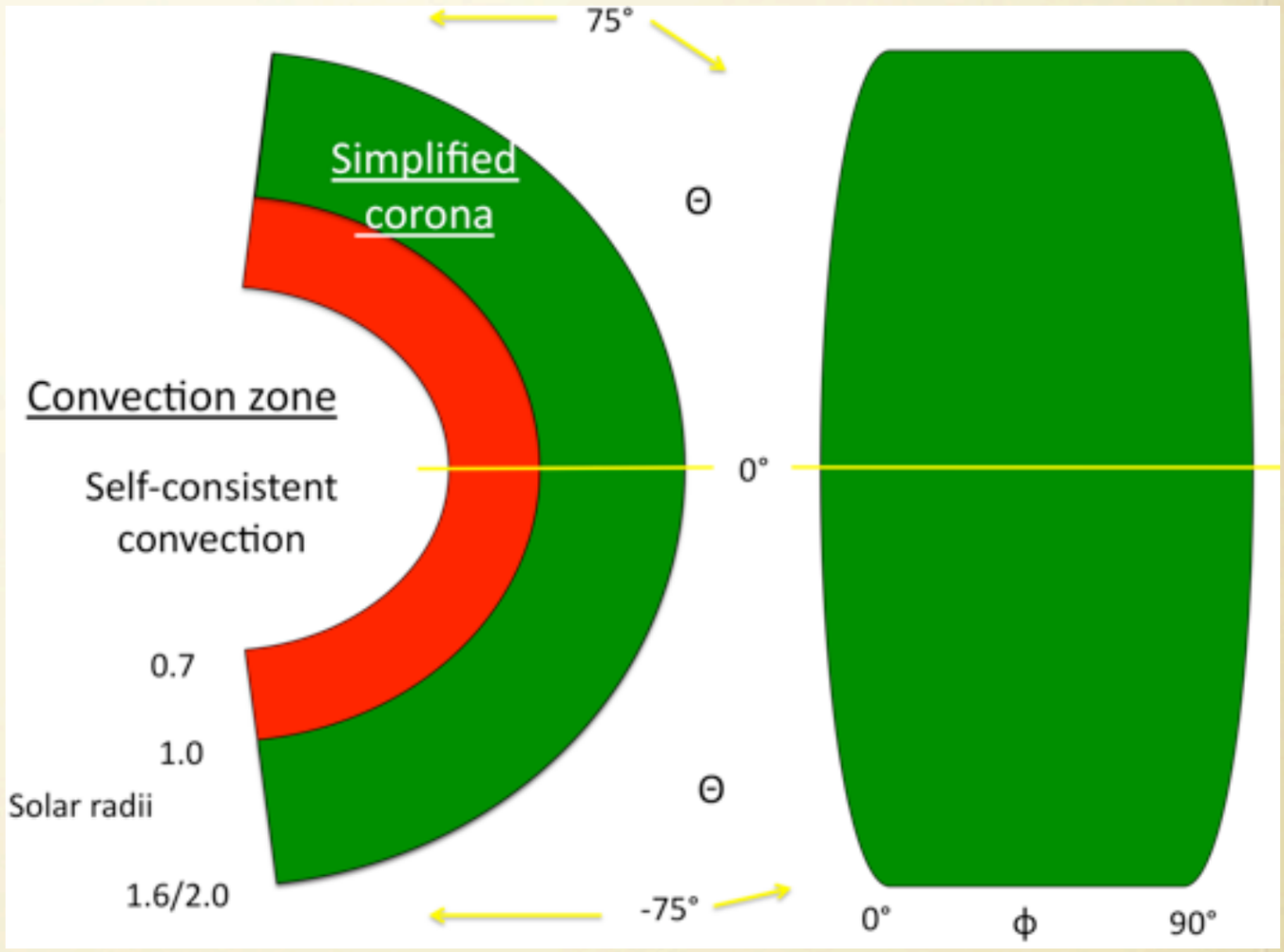


Equations:

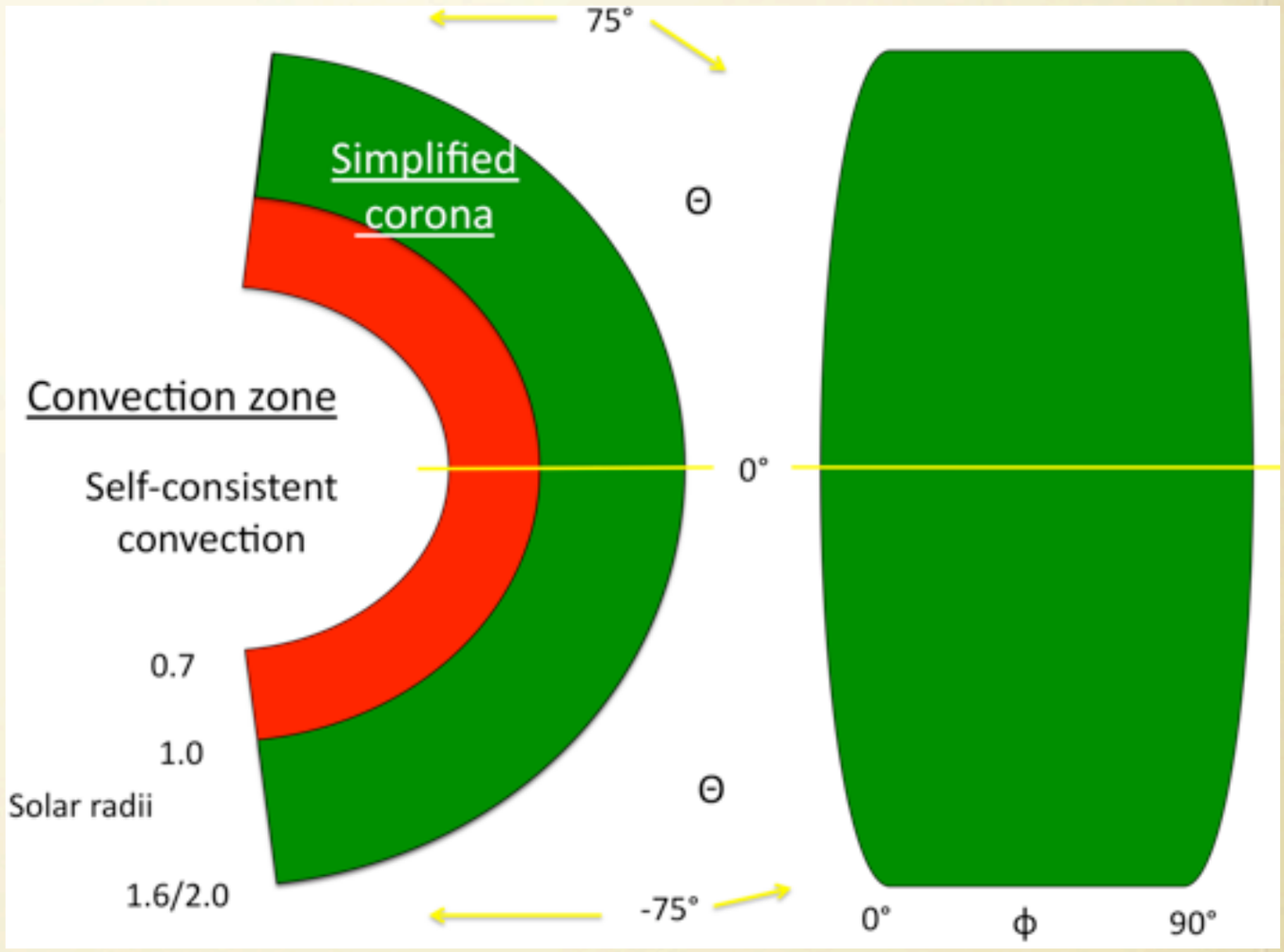
$$\frac{\partial A}{\partial t} = u \times B + \eta \nabla^2 A$$

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

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

Setup

Self-consistent convection with a coronal layer



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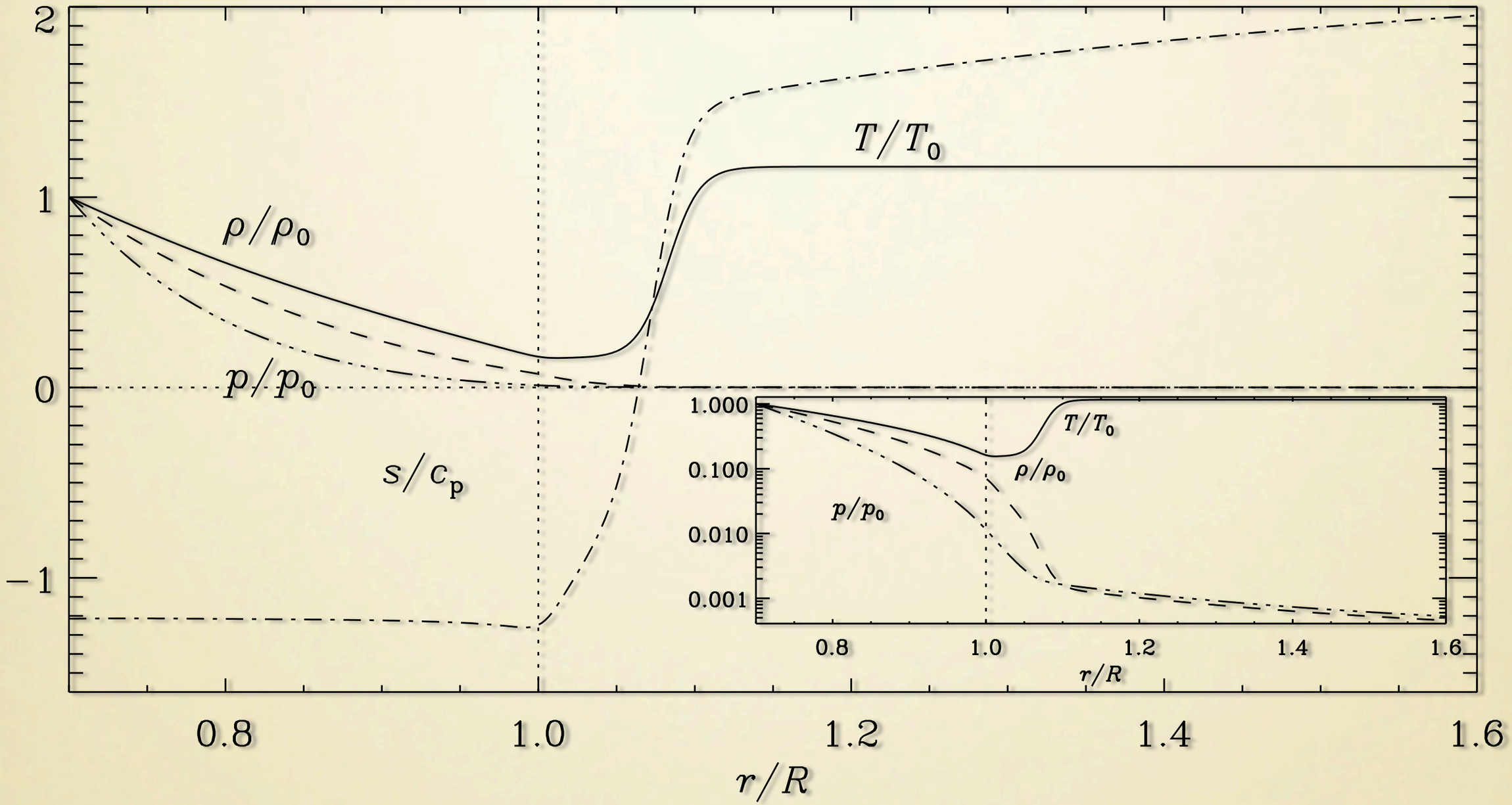
$$T\frac{Ds}{Dt} = \frac{1}{\rho}\nabla \cdot (K\nabla T + \chi_t \rho T \nabla s) + 2\nu S^2 + \frac{\mu_0 \eta}{\rho} J^2 - \Gamma_{\rm cool}(r),$$

Stratification



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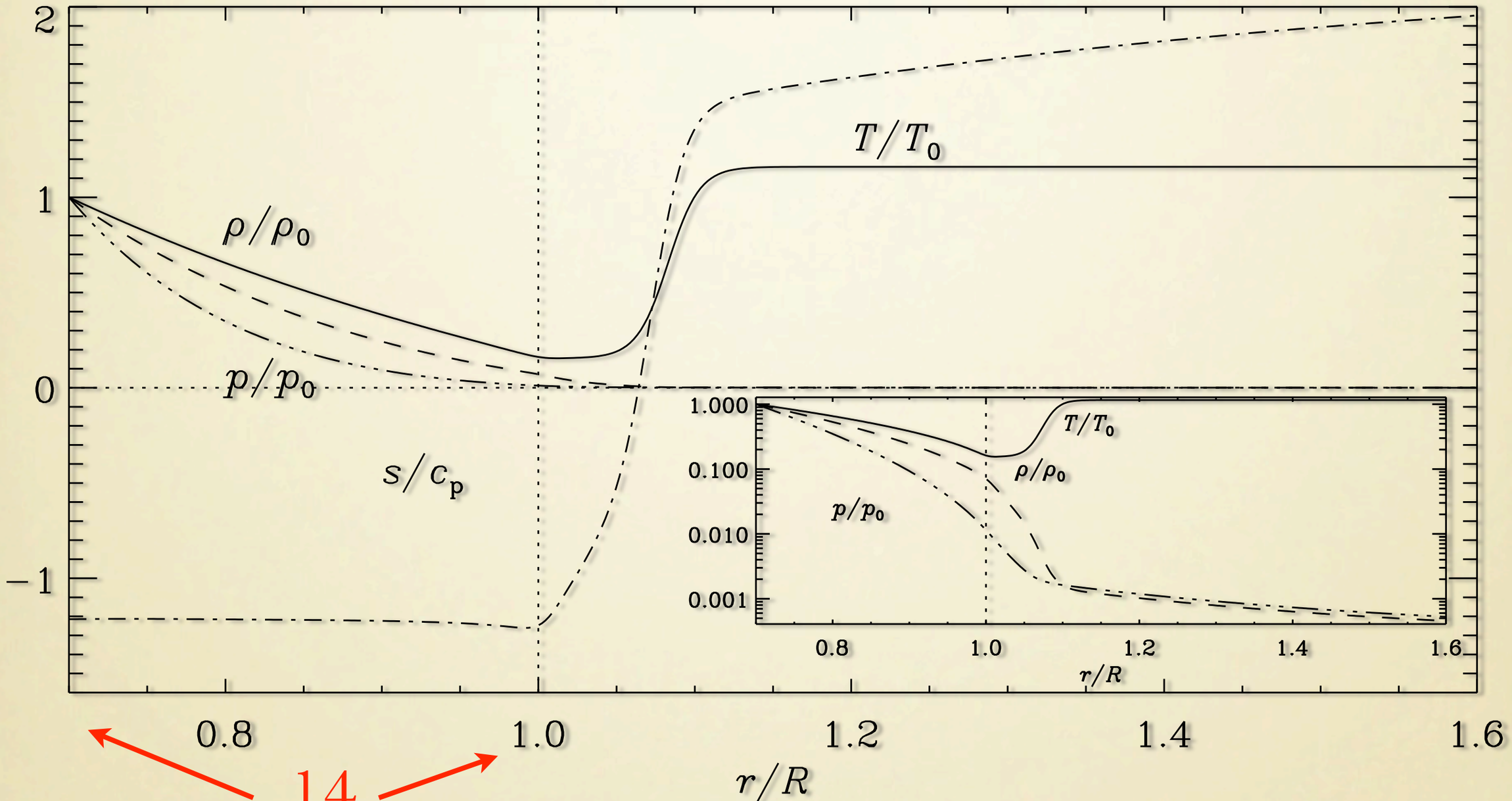

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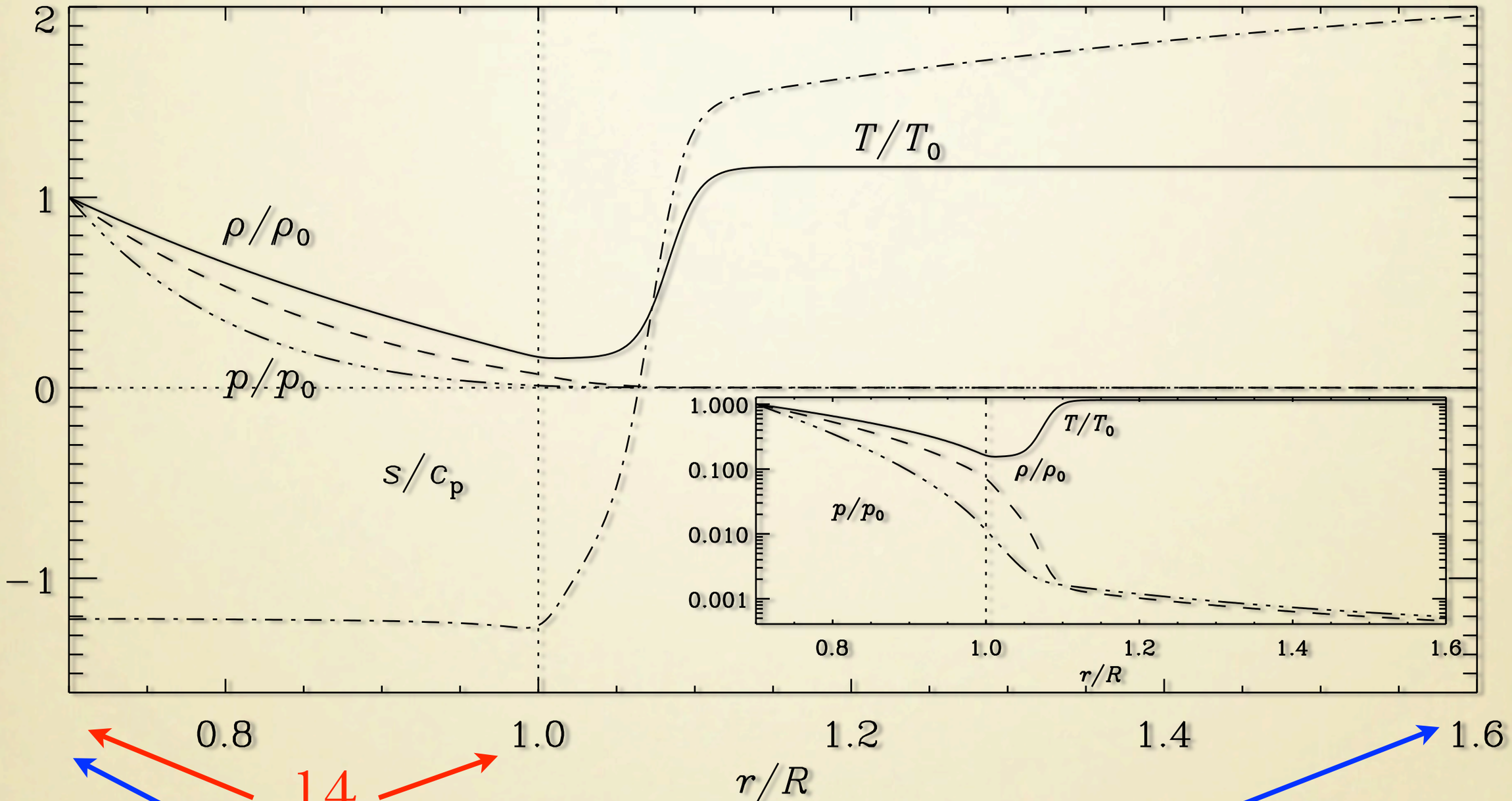
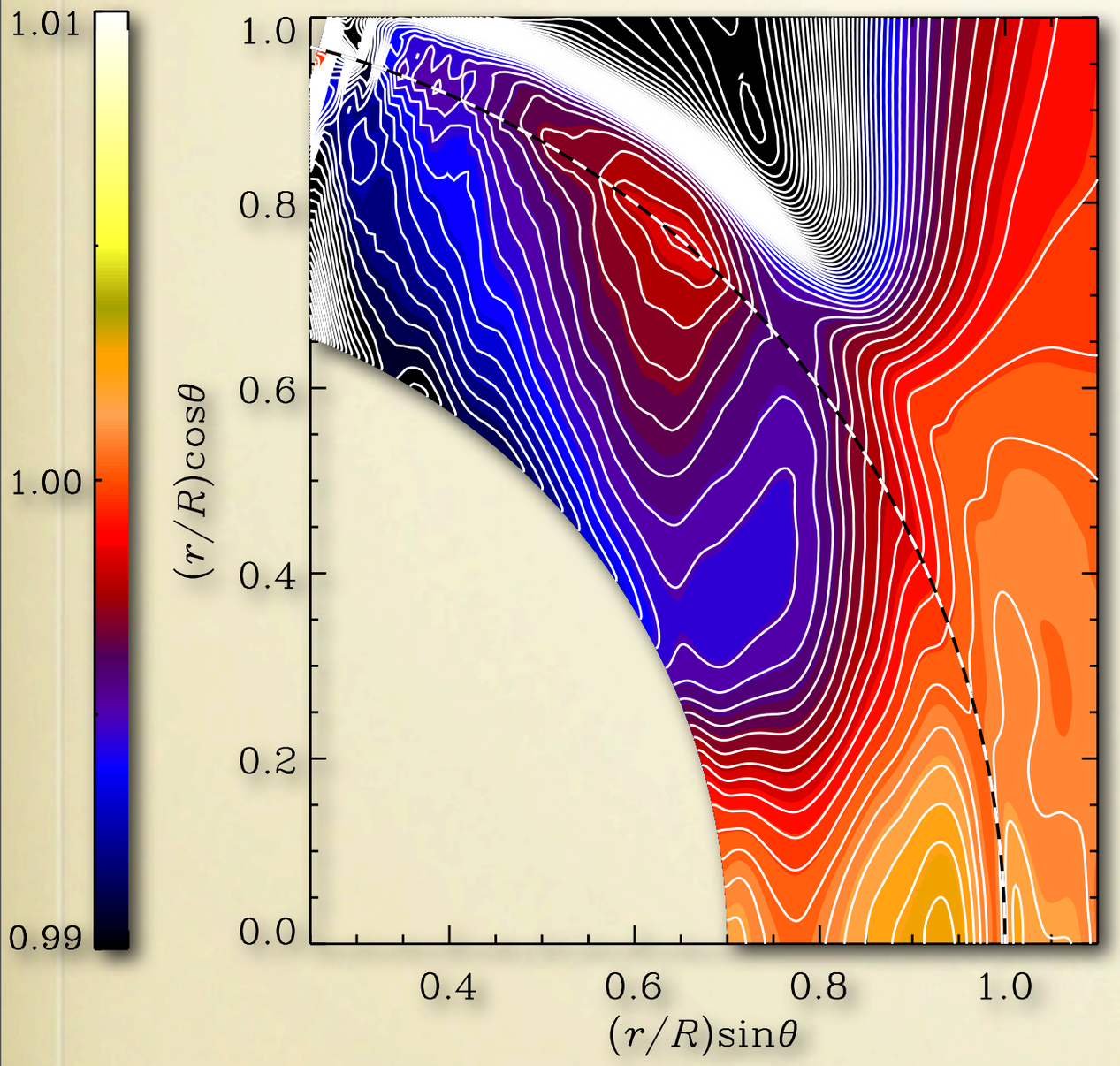


Results

Differential rotation

Differential rotation



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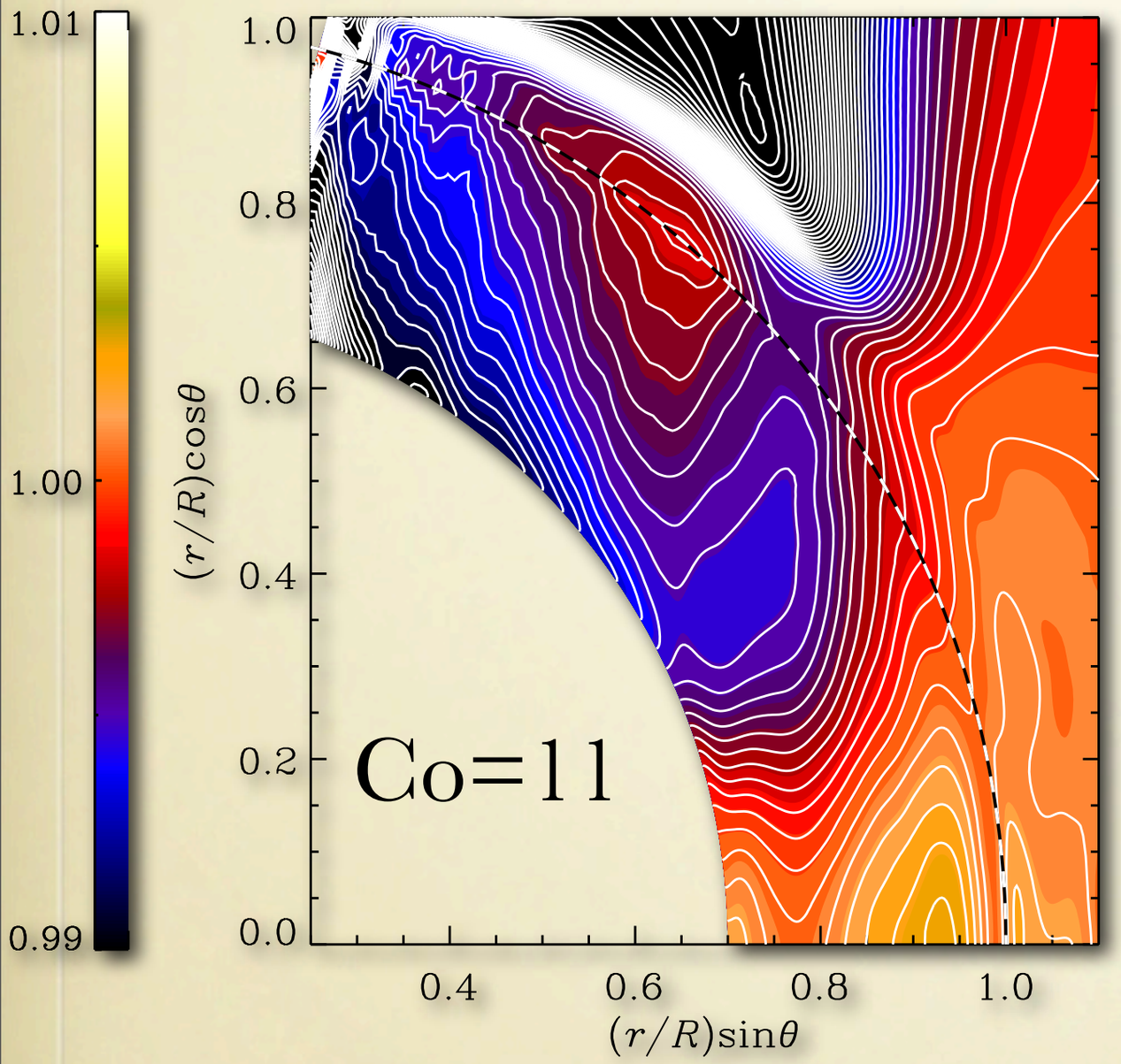

$$\mathrm{Co} = \frac{2\Omega_0}{u_{rms} k_f}$$

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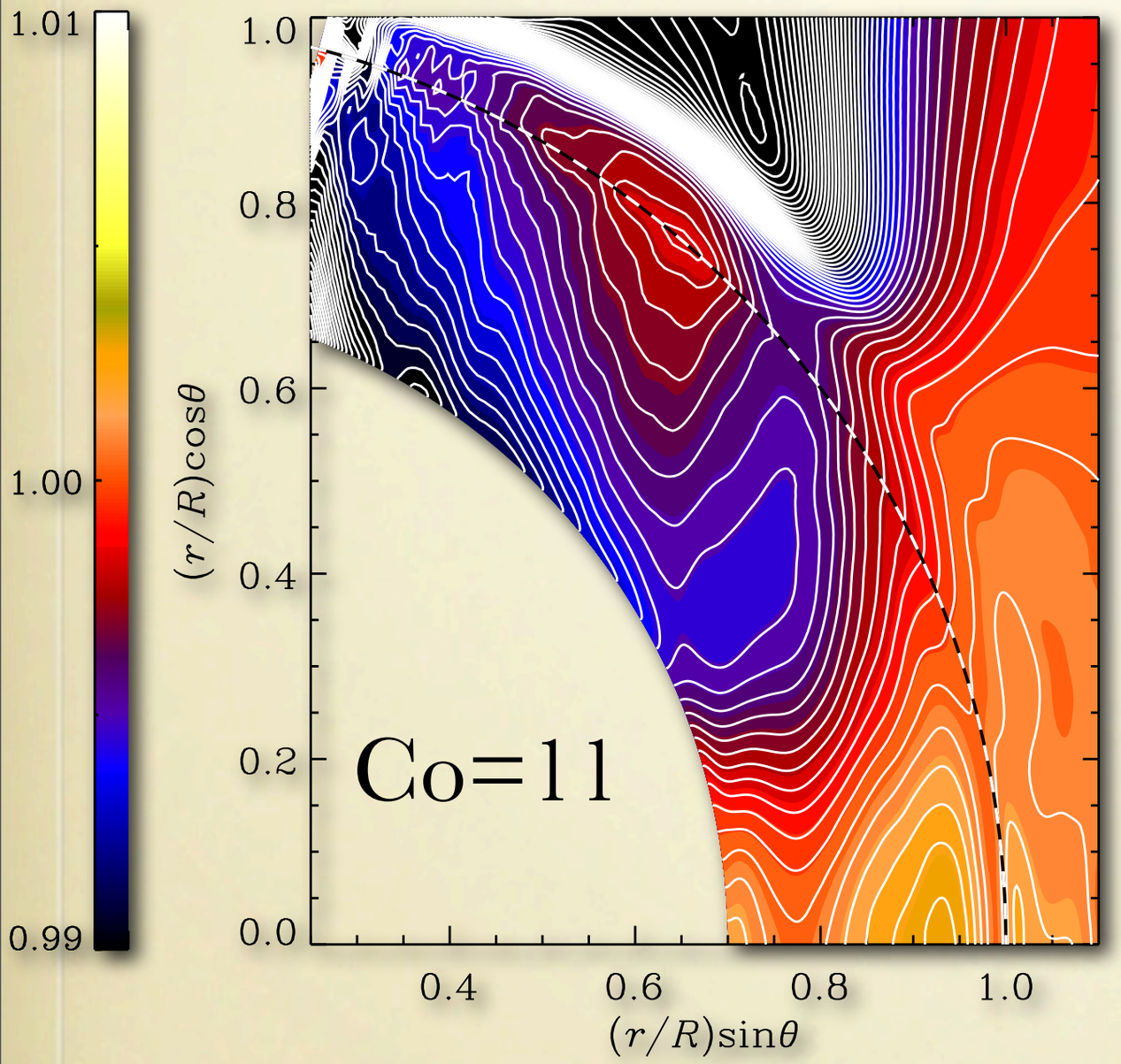

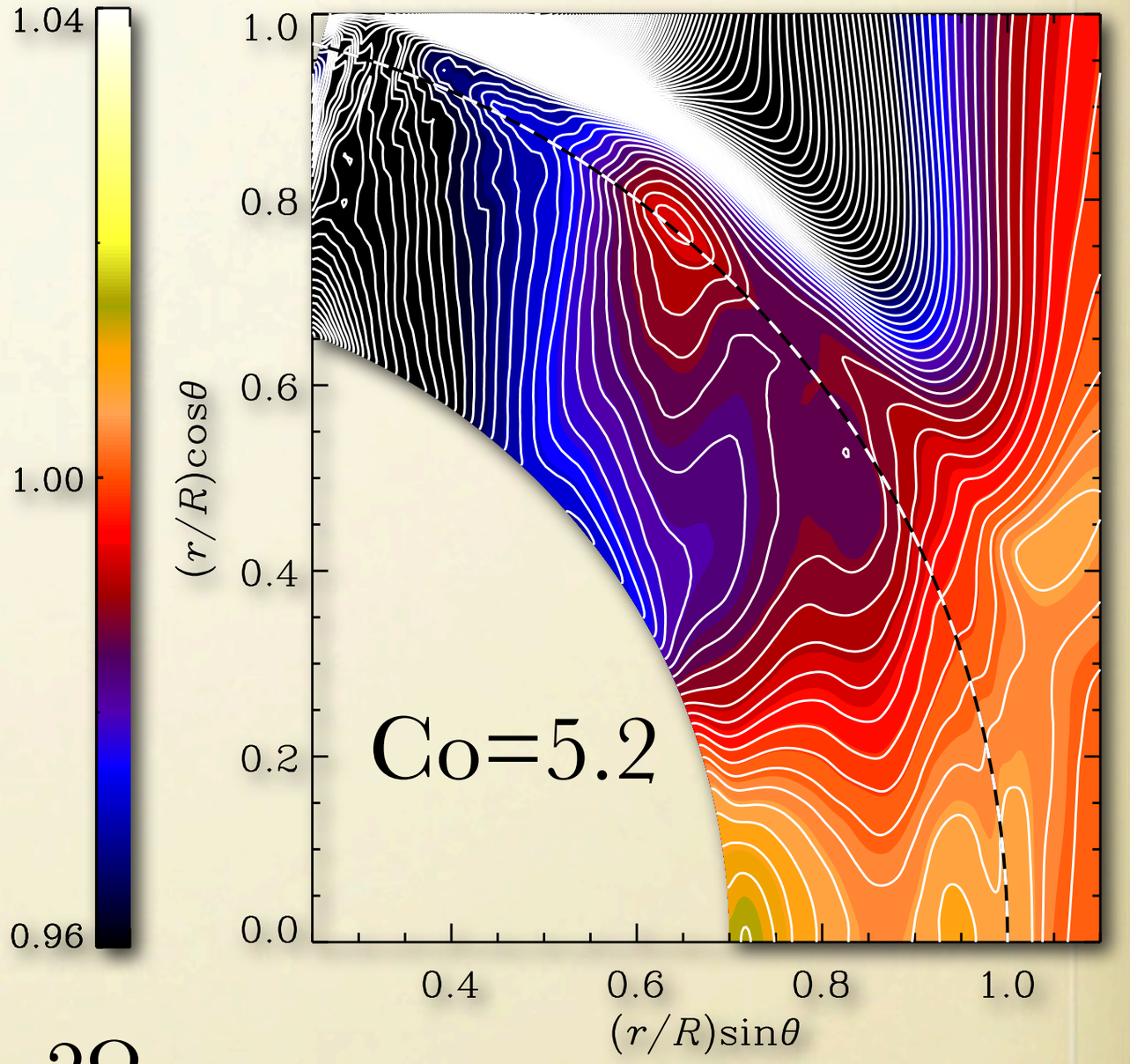

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The Baroclinic Term

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

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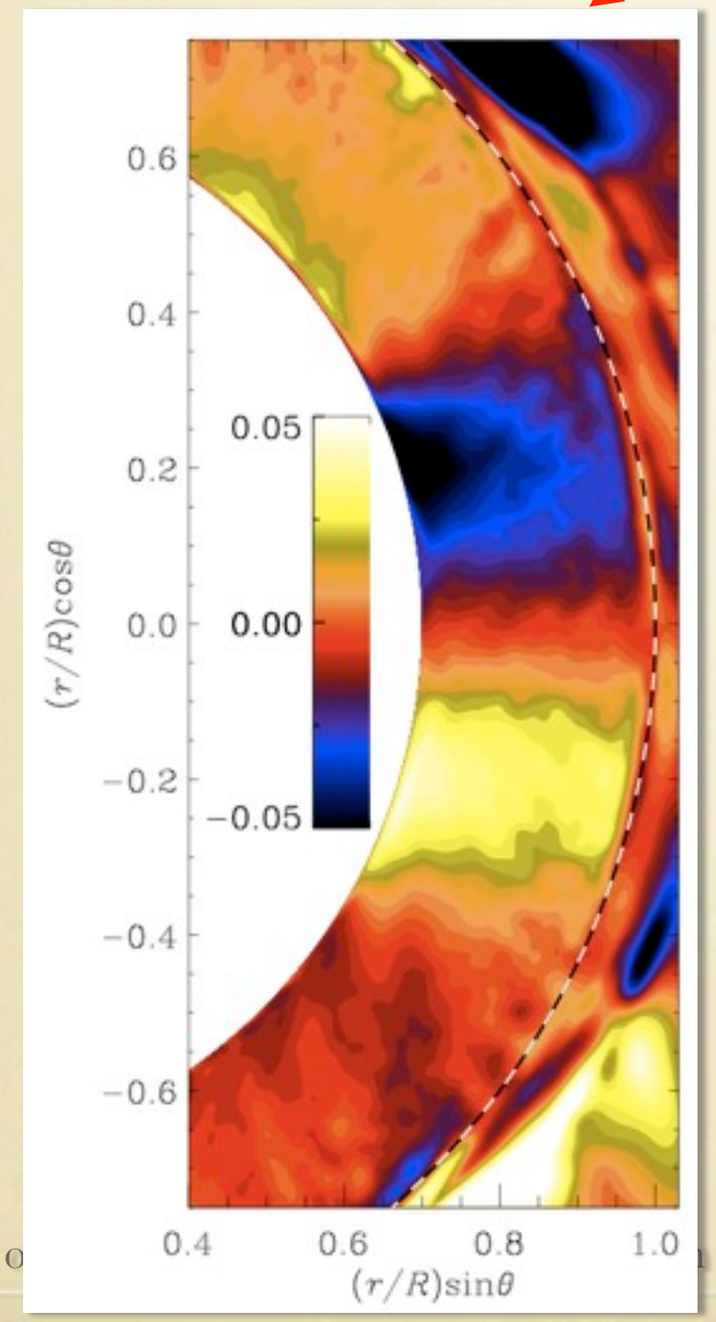

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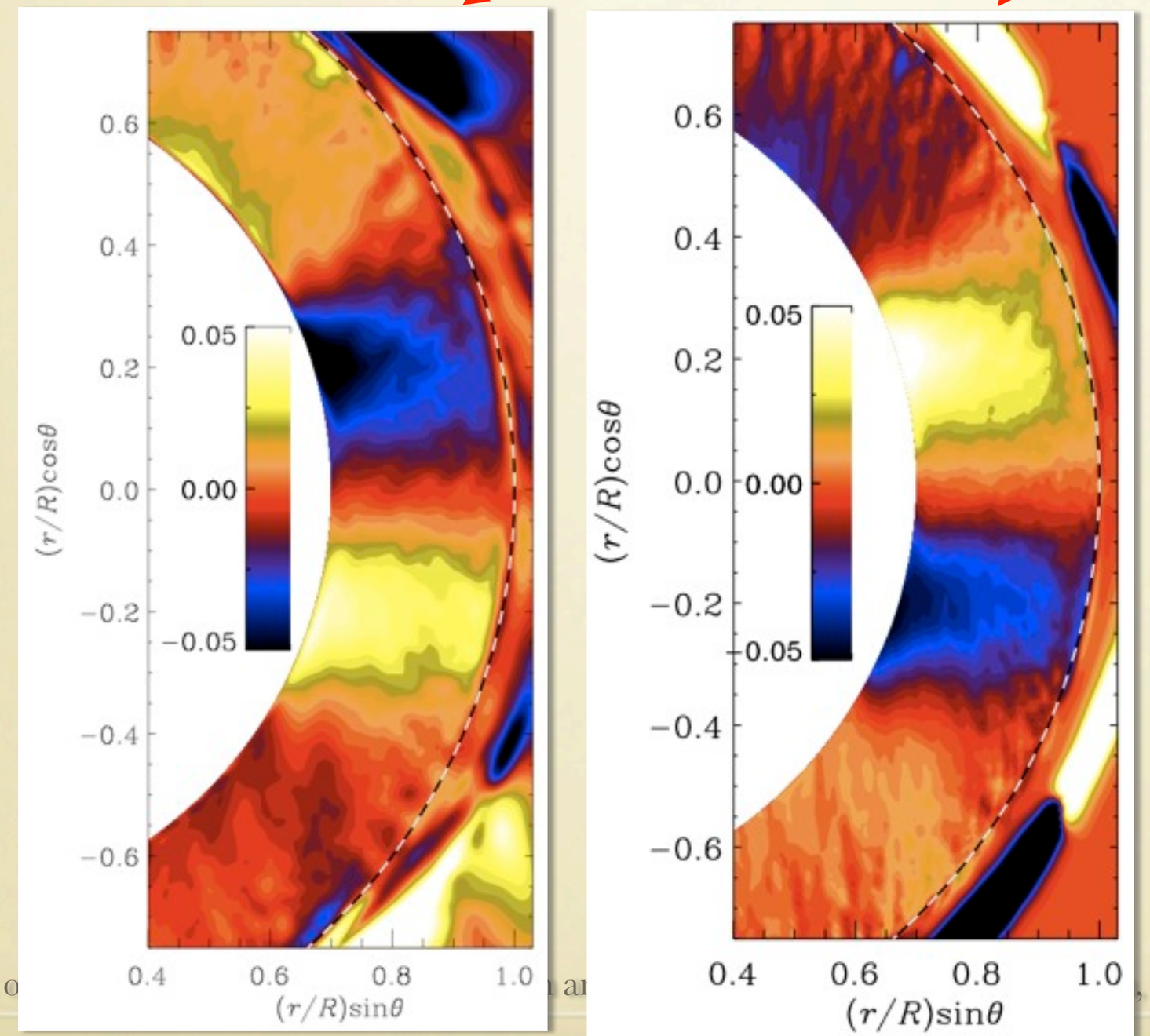

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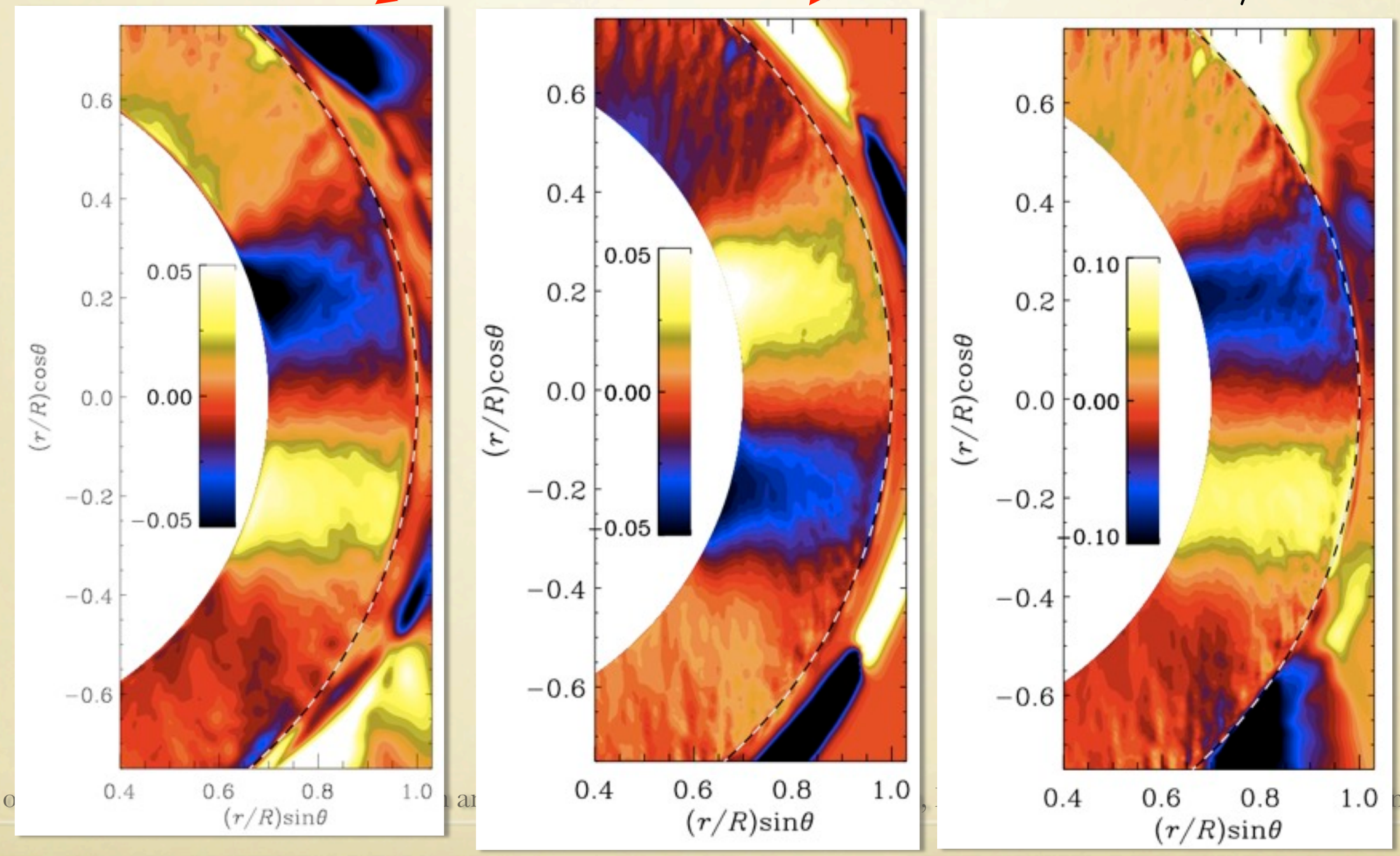
$R\nabla_\theta \overline{s}/c_\mathrm{P}$



Turbulent heat conductivity

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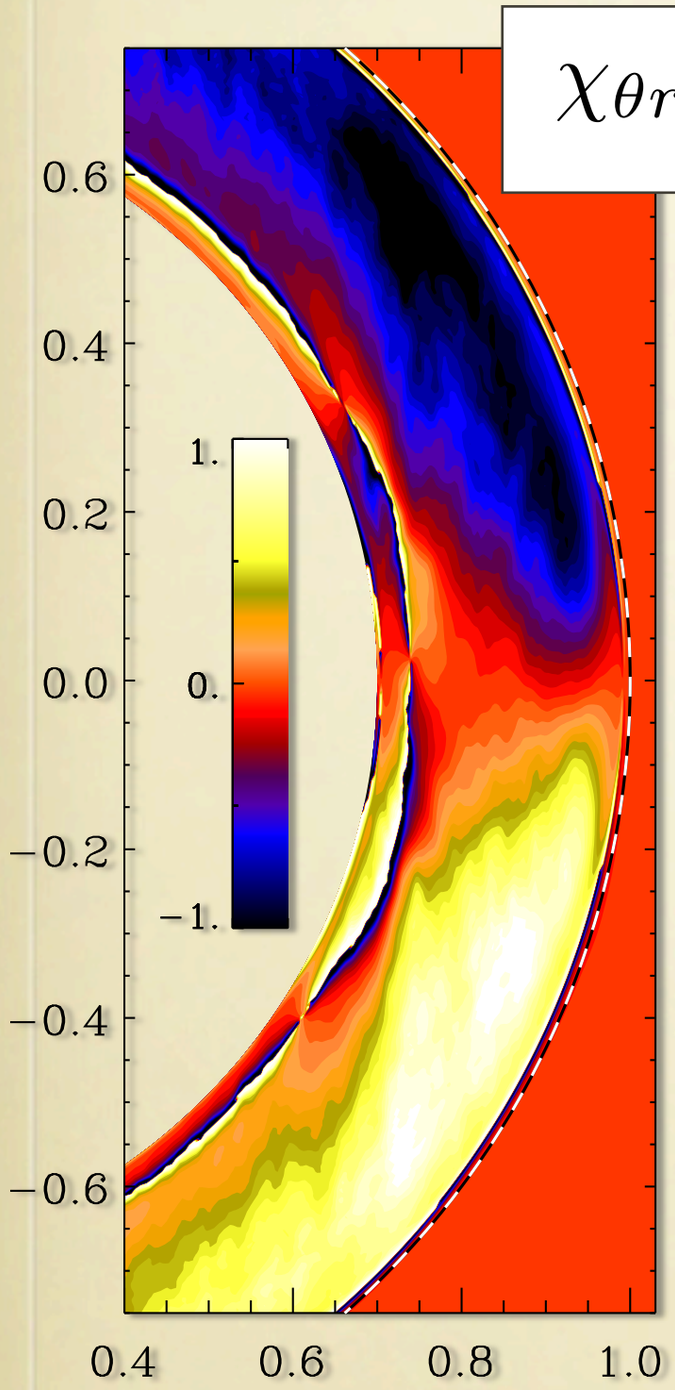

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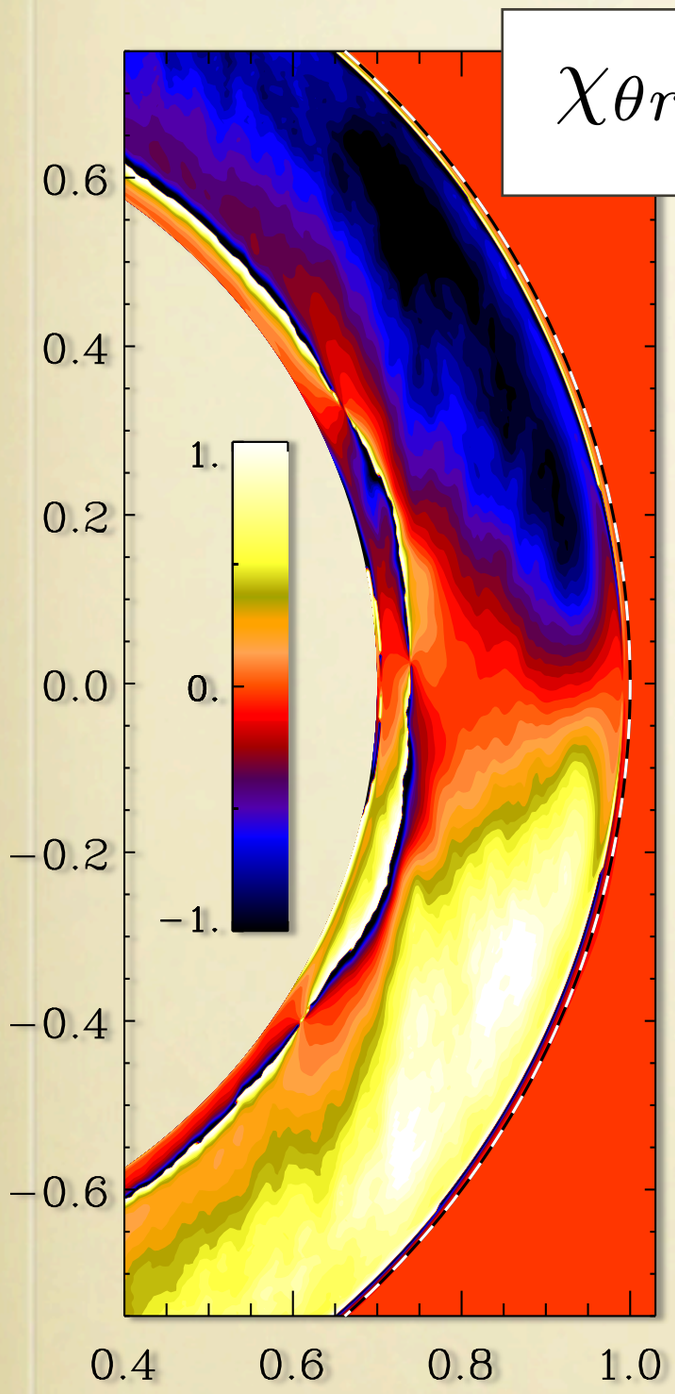

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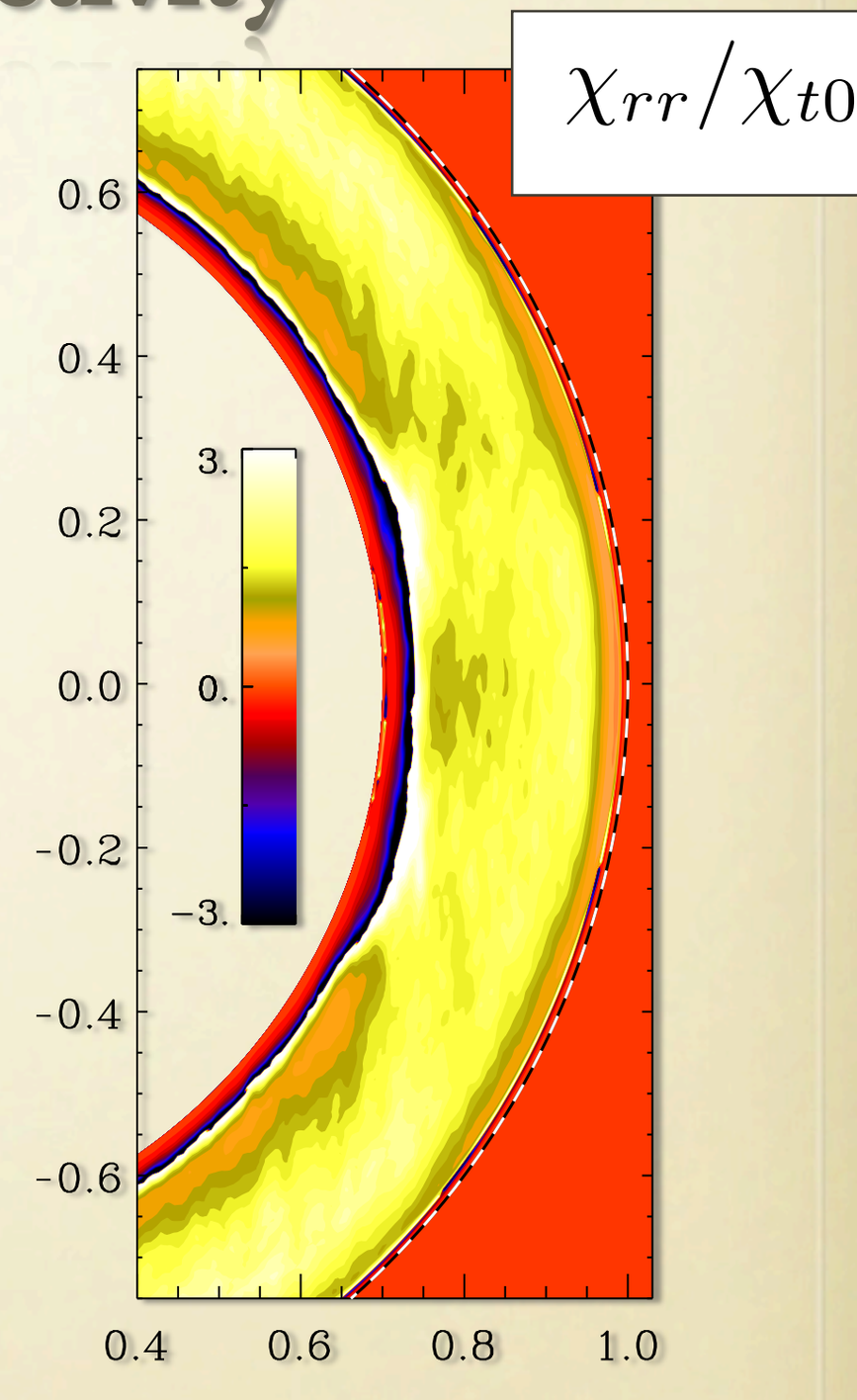
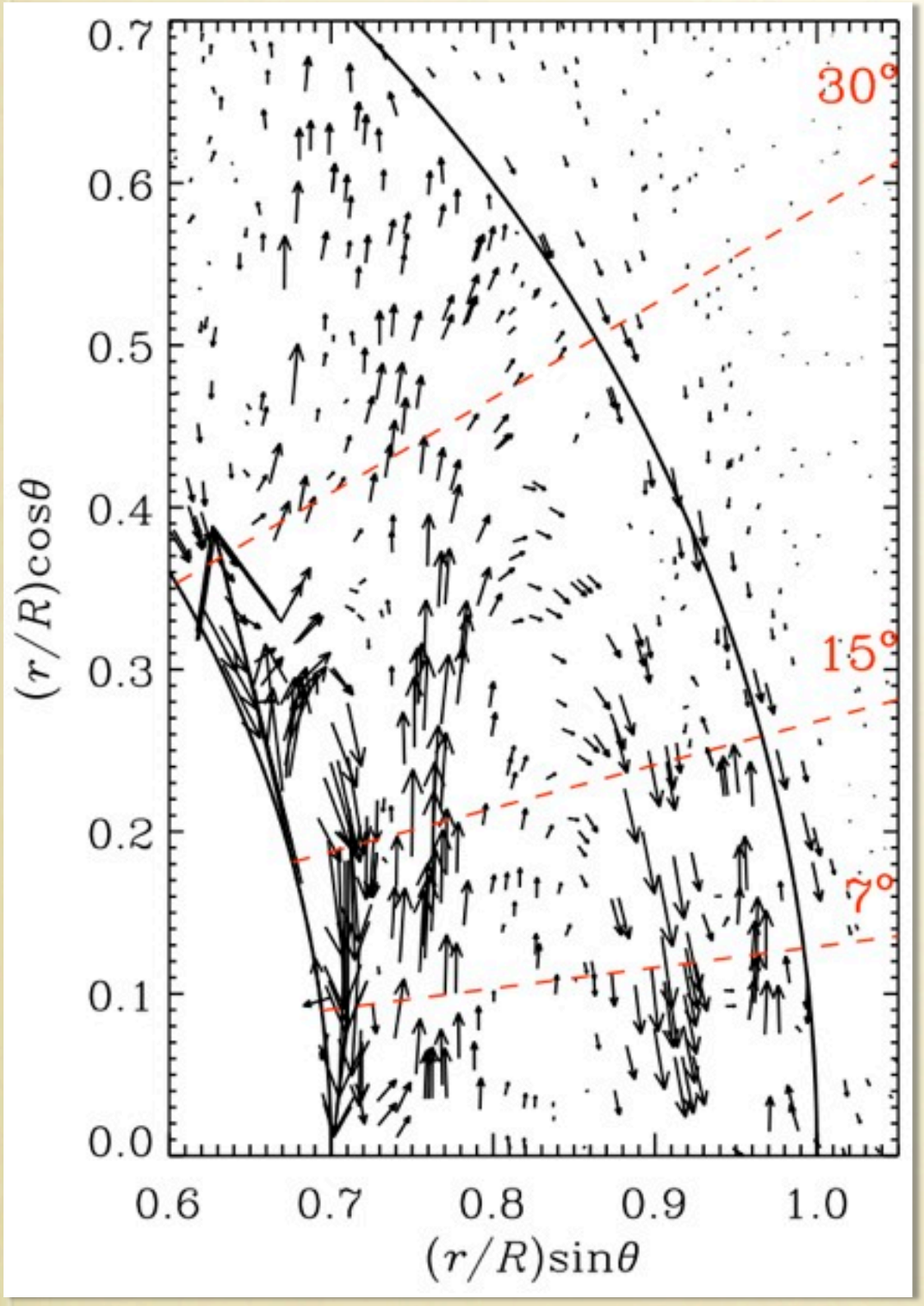


$$\chi_{\theta r} \approx -c_{\rm P}\overline{u_\theta' T'} \Big/ \overline{T}\nabla_r\overline{s}.$$

$$\chi_{rr} \approx -c_{\rm P}\overline{u_r' T'} \Big/ \overline{T}\nabla_r\overline{s}.$$

Meridional circulation

Co=11



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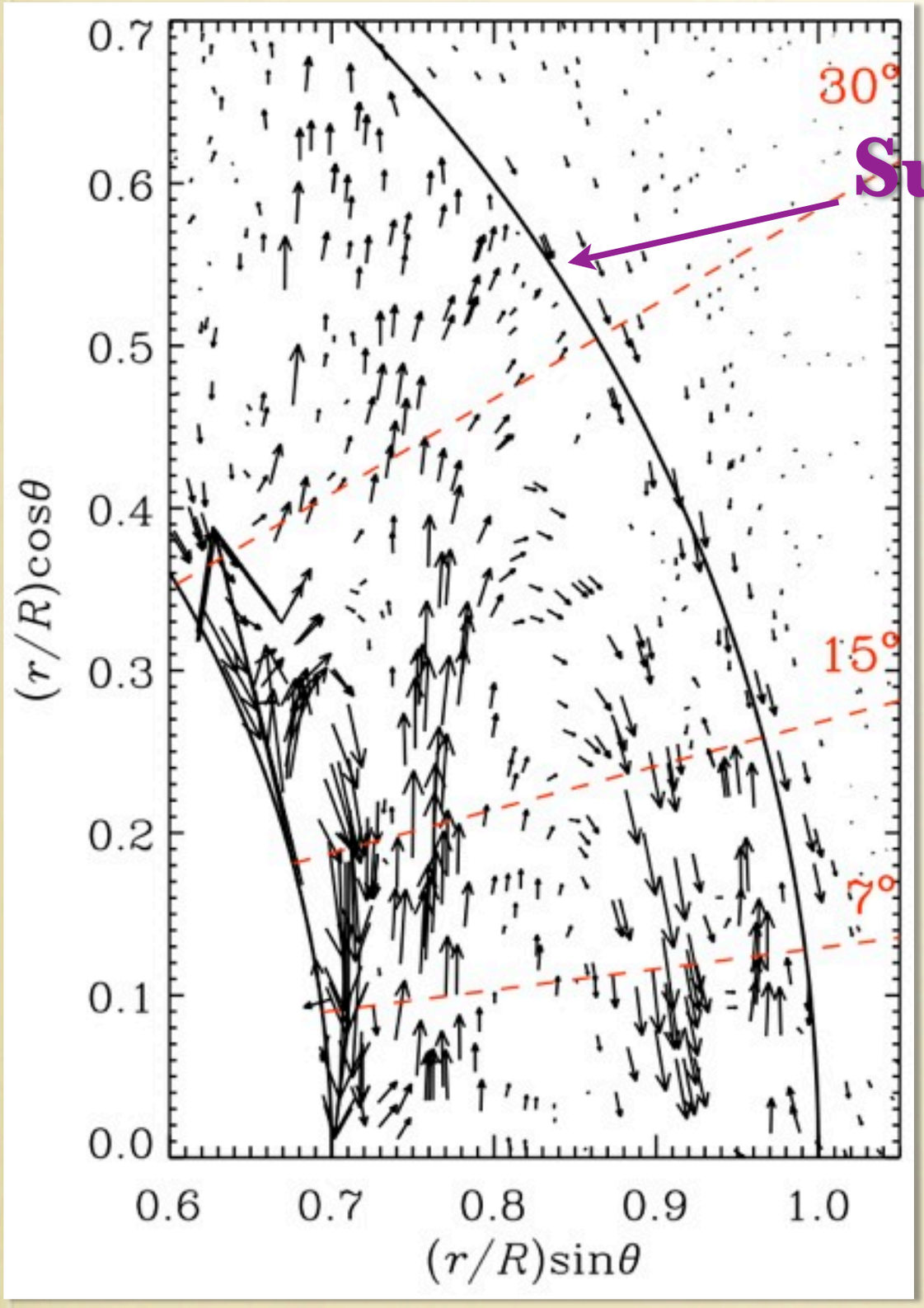
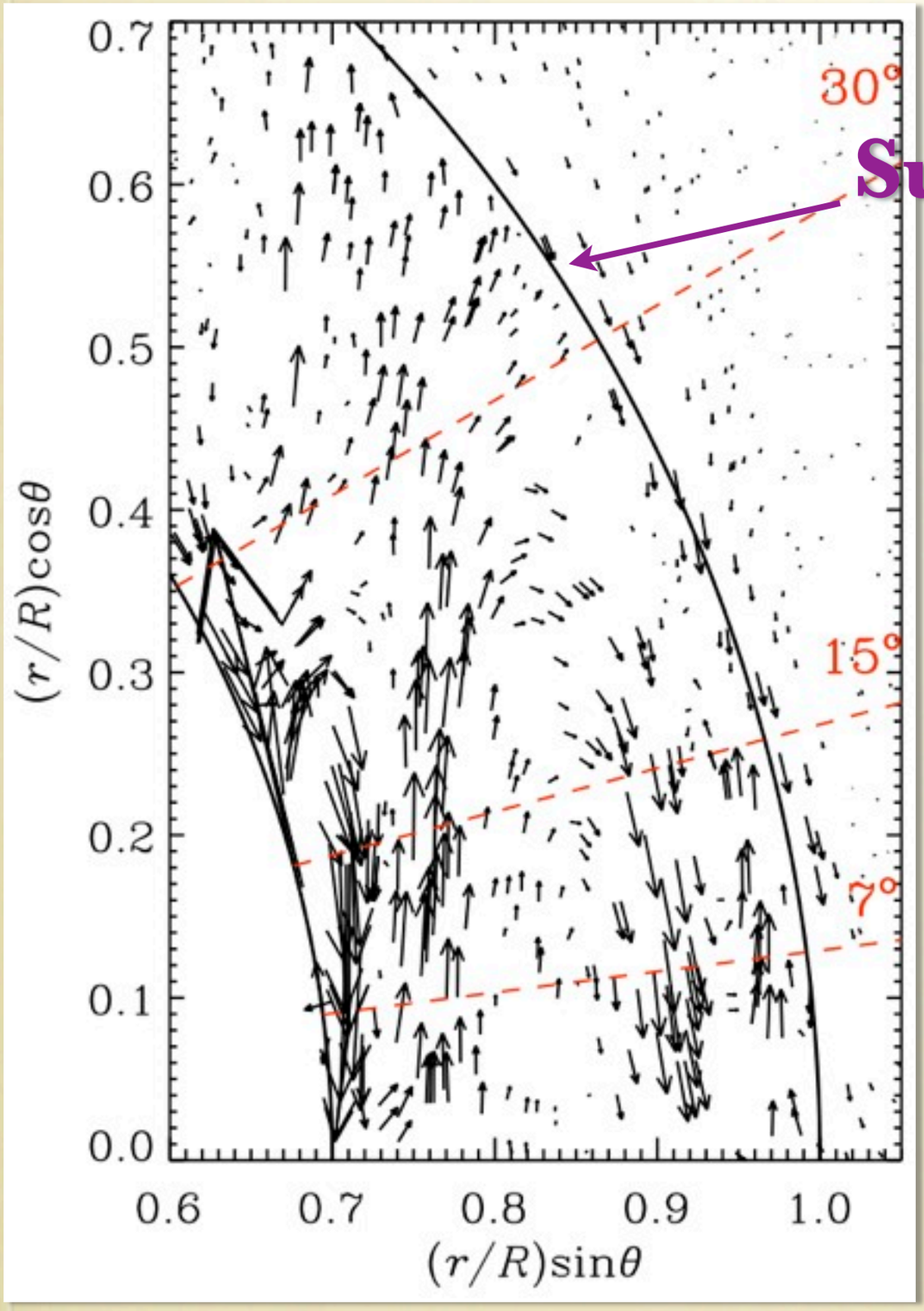


Surface

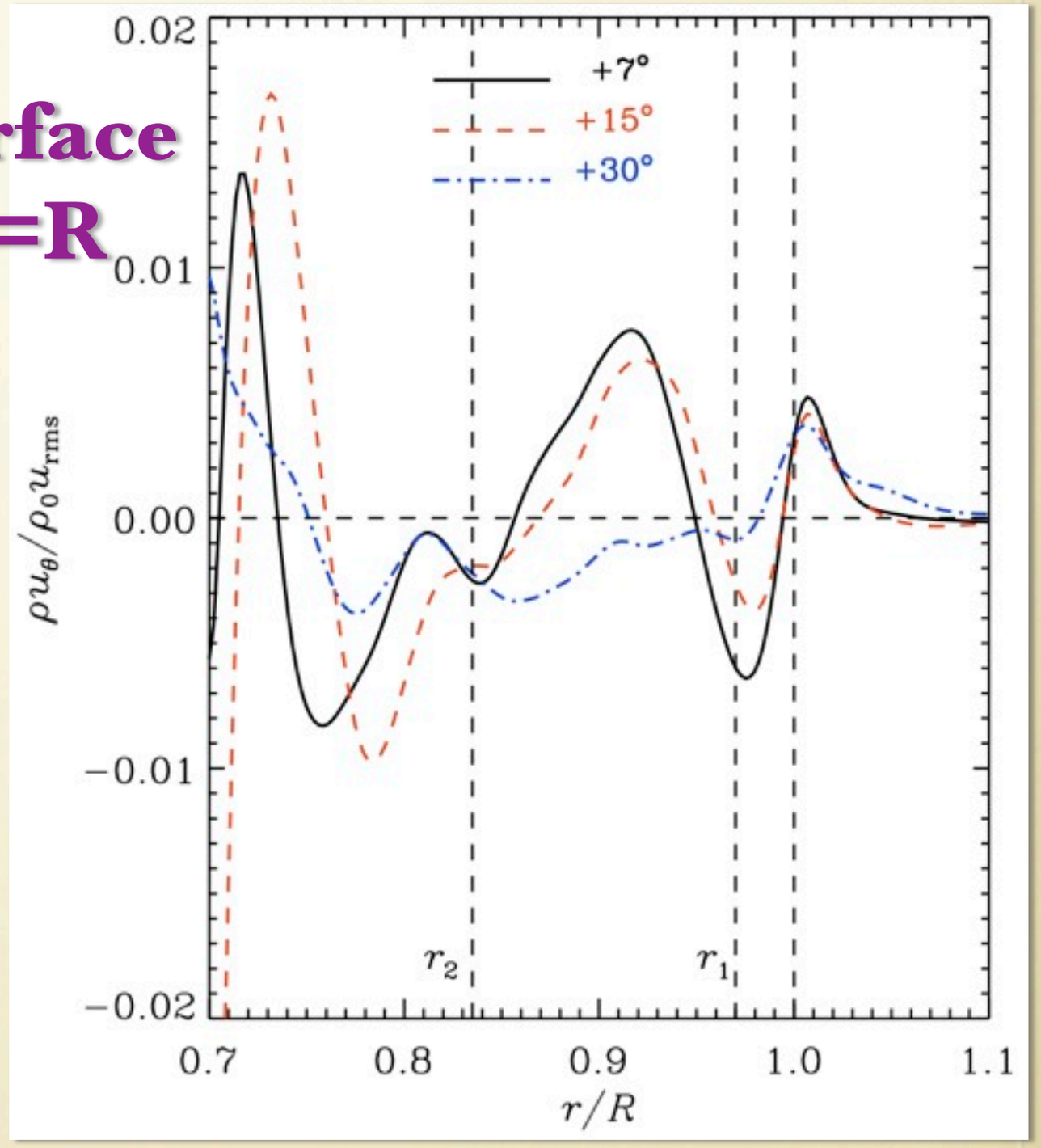
r=R

Meridional circulation

Co=11



Surface r=R



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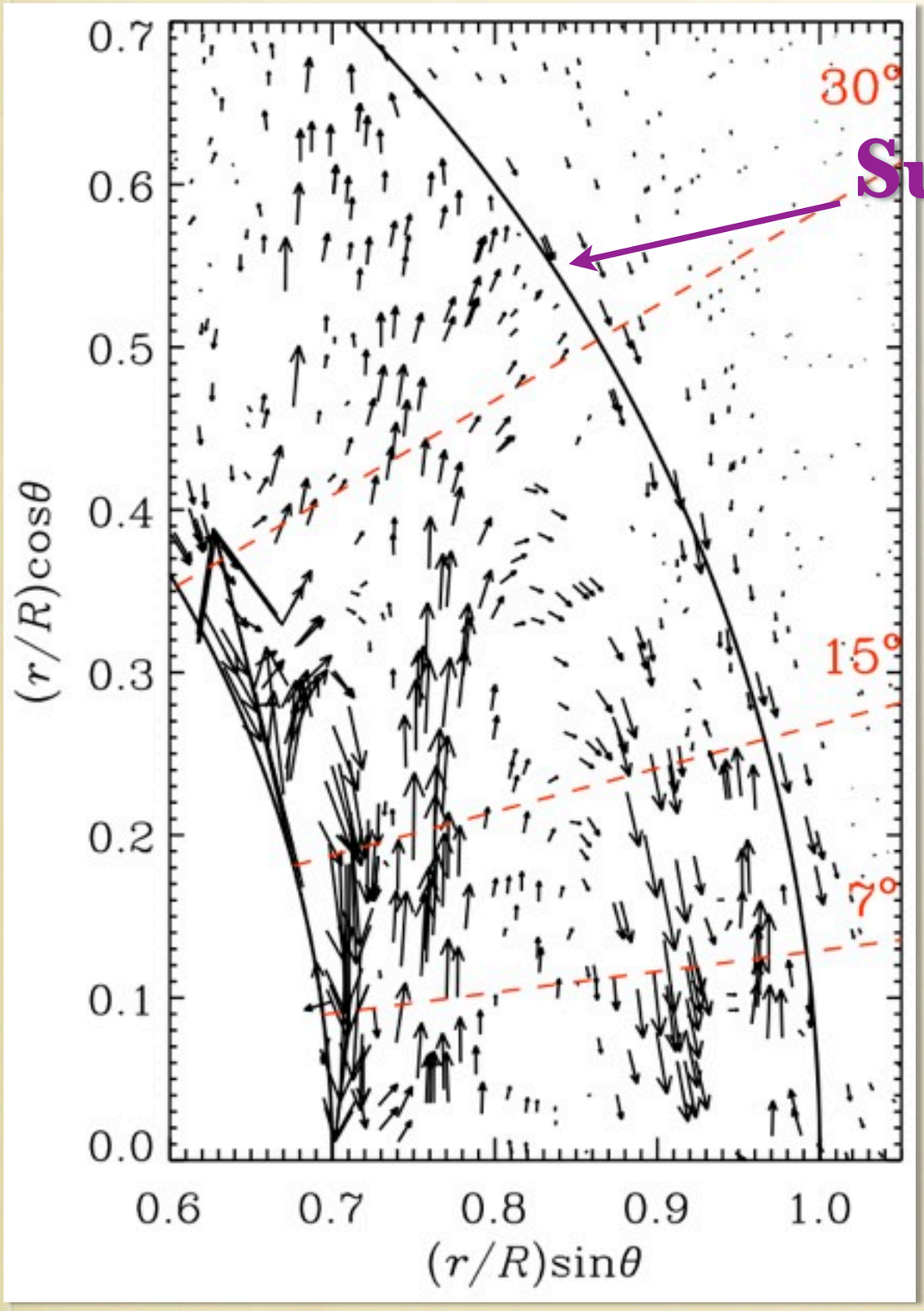

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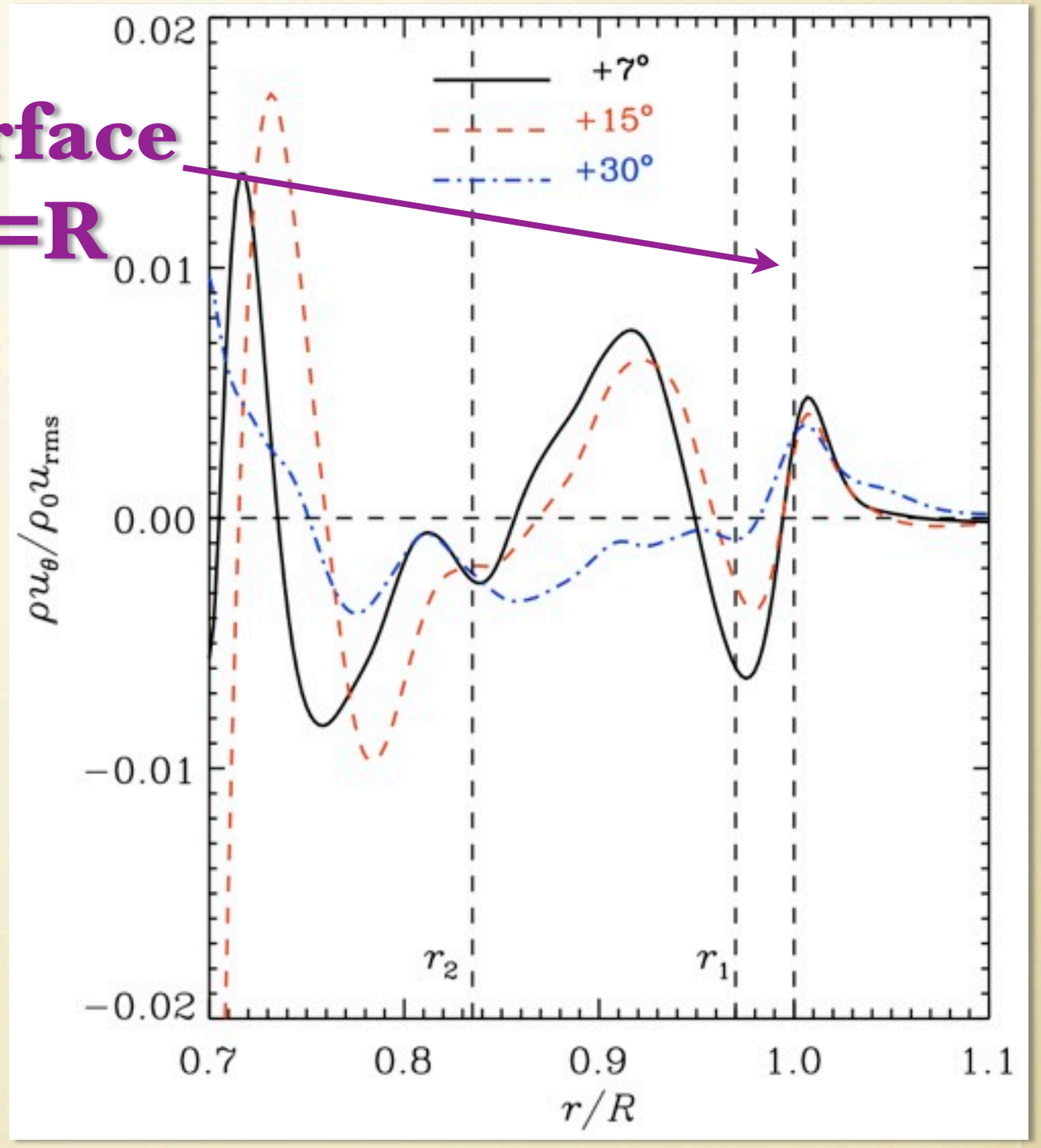

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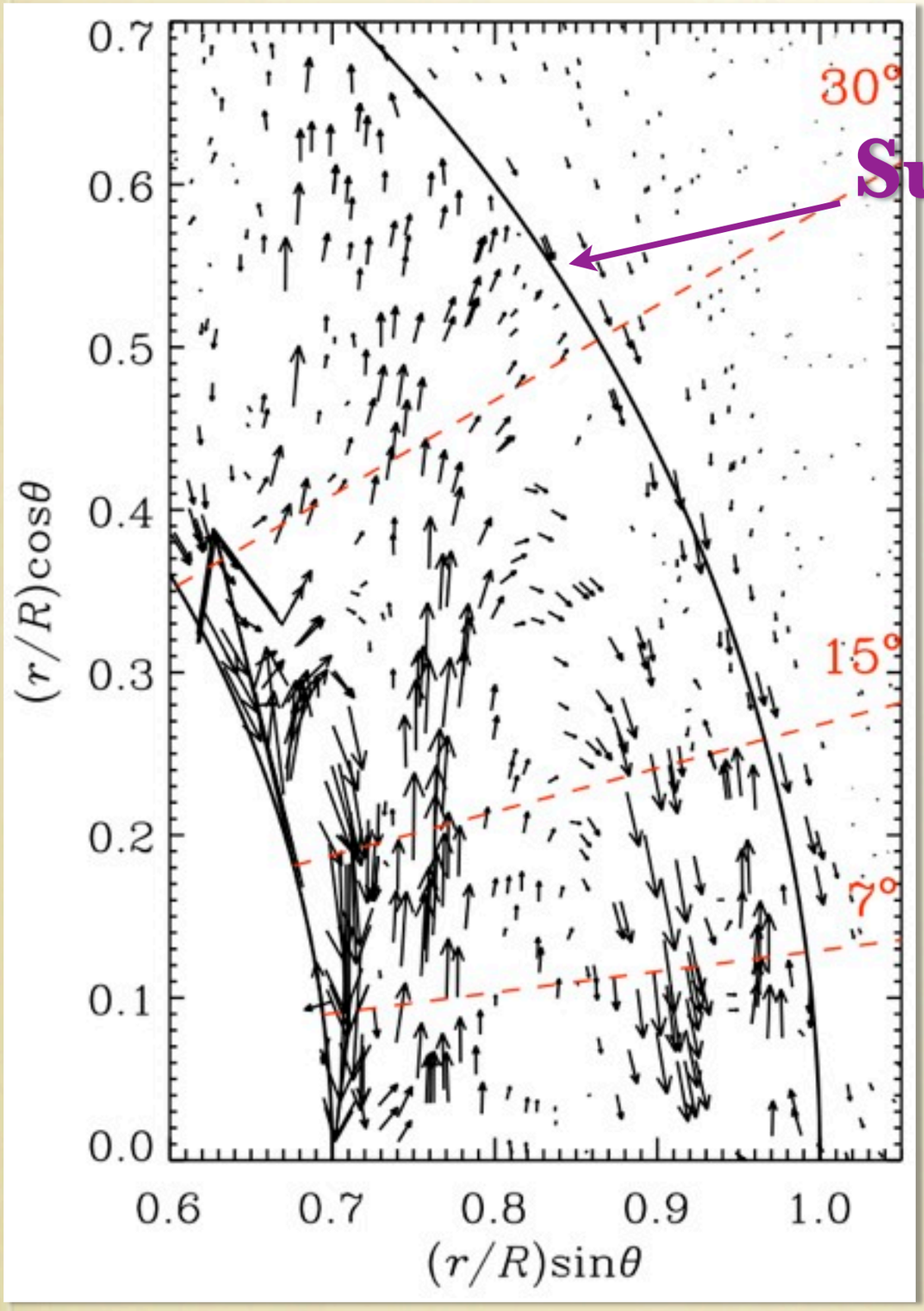

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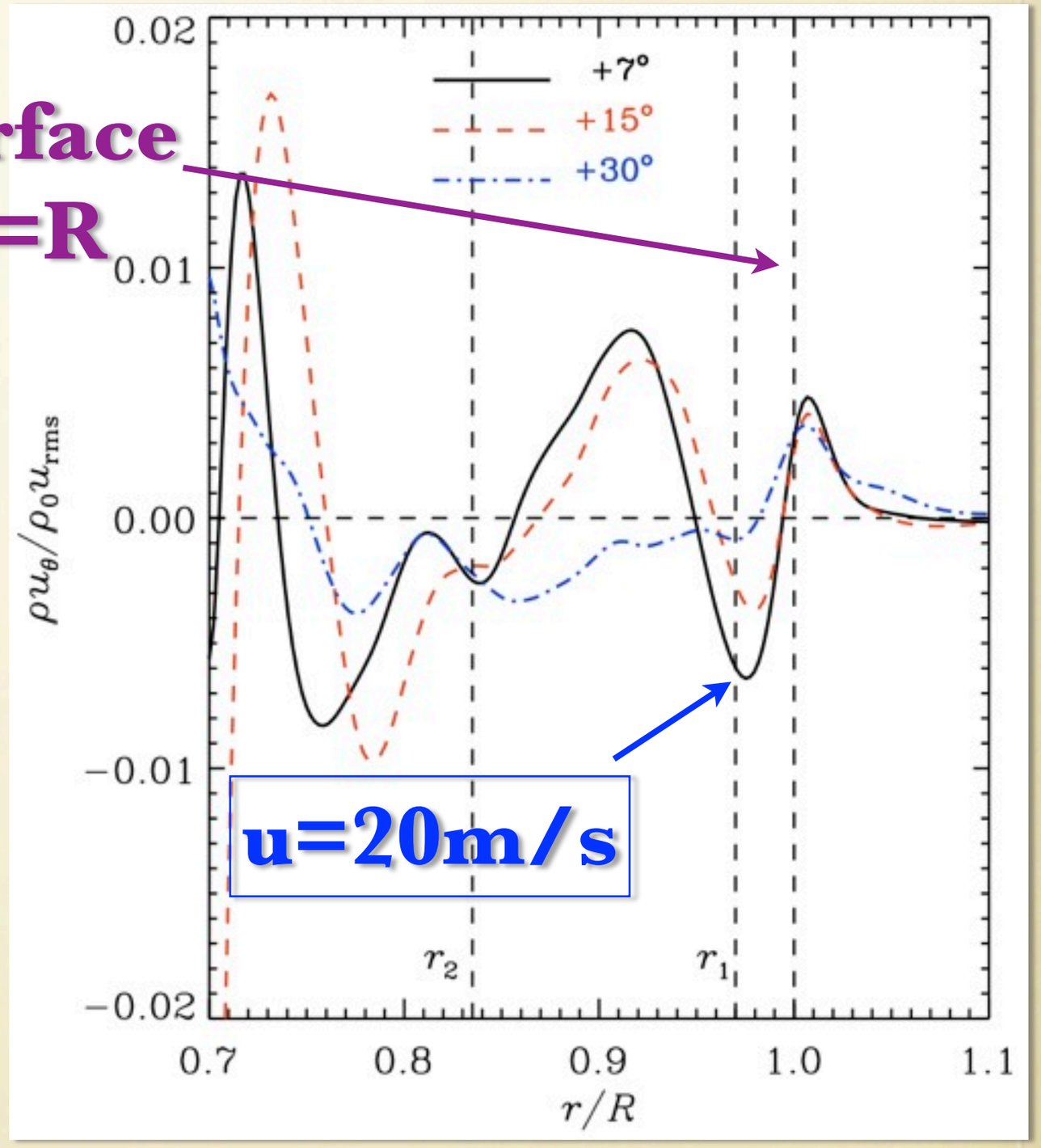
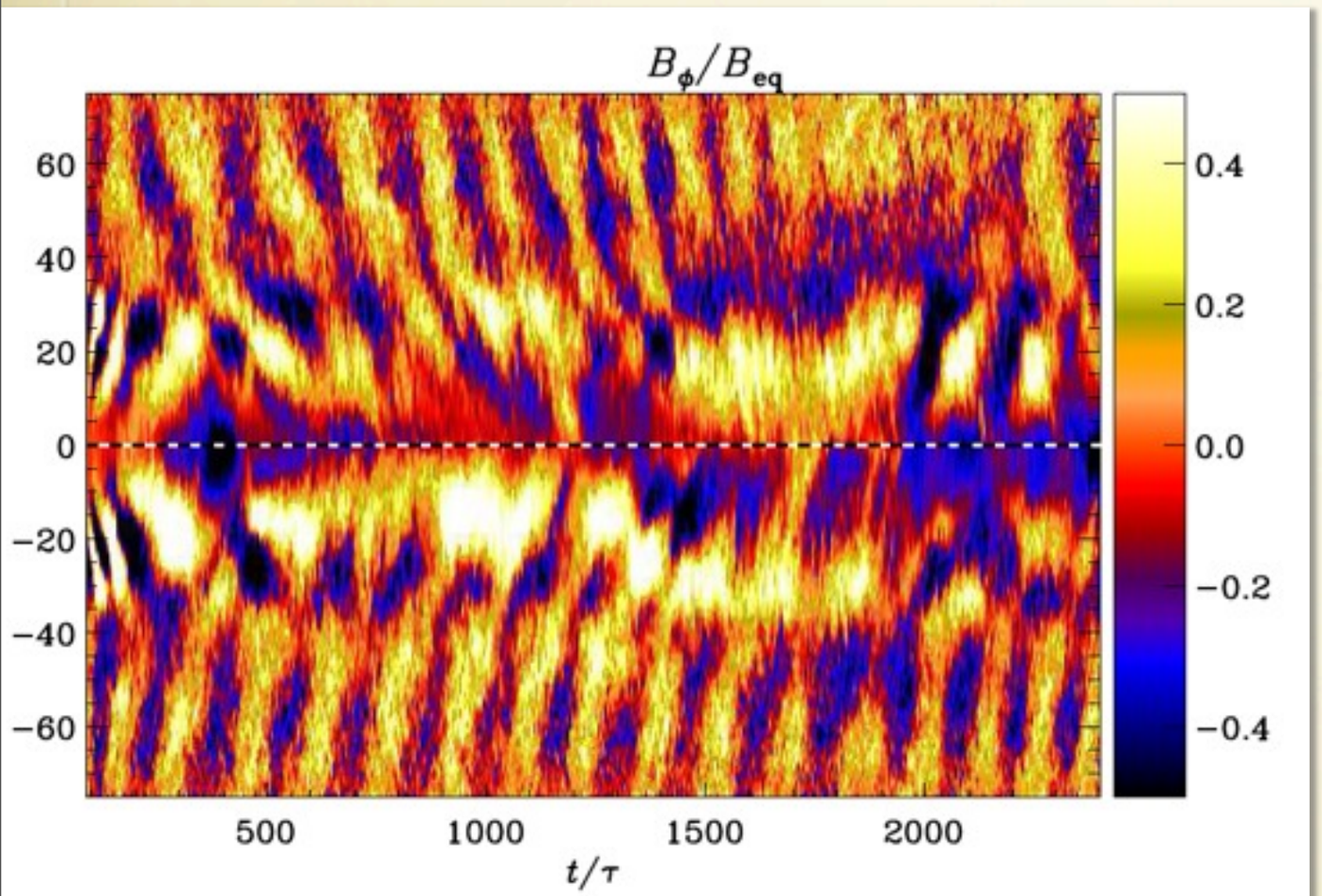


What is new?

What is new?

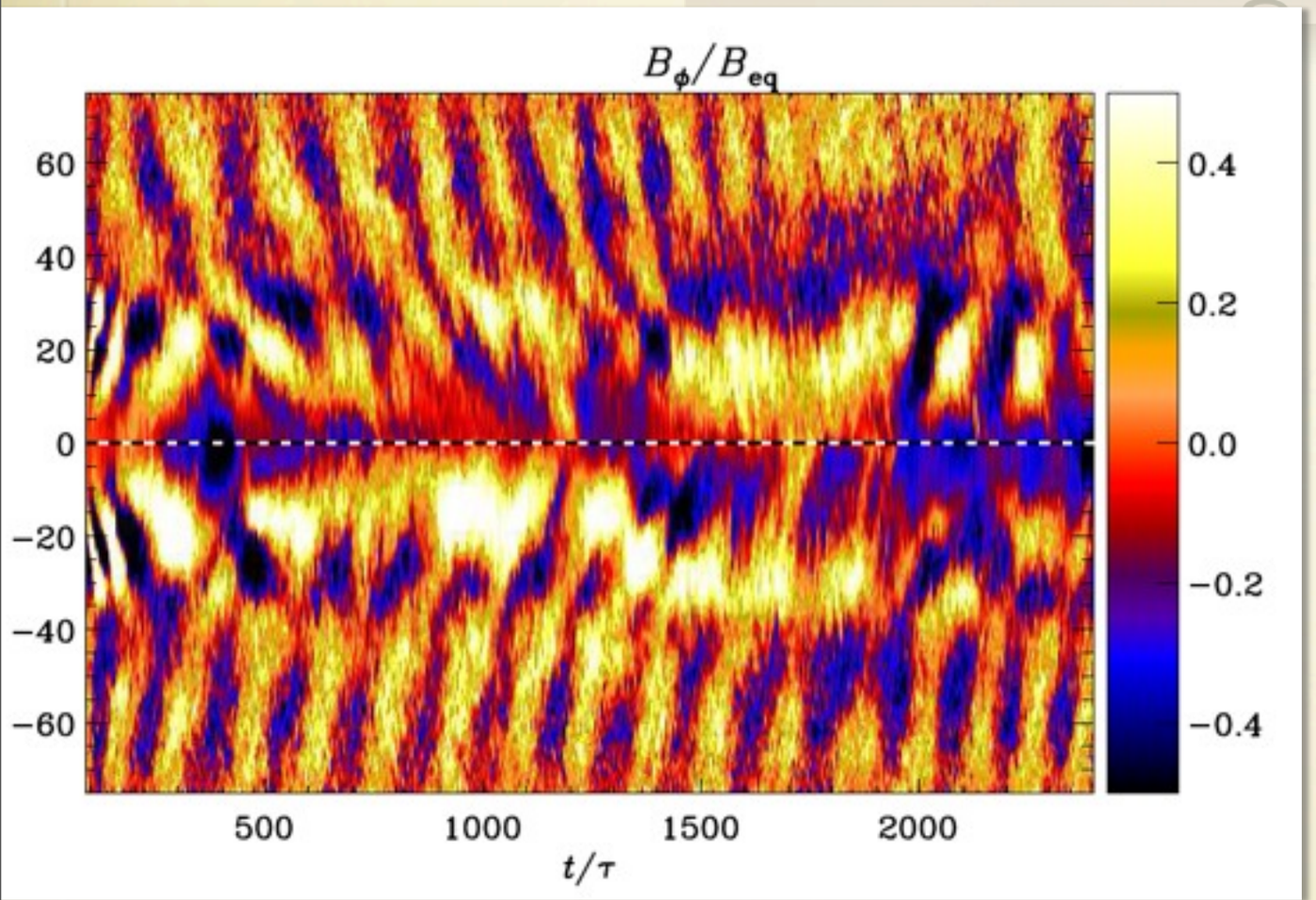
Magnetic fields

What is new?



Co=11

Equatorward migration of the magnetic field



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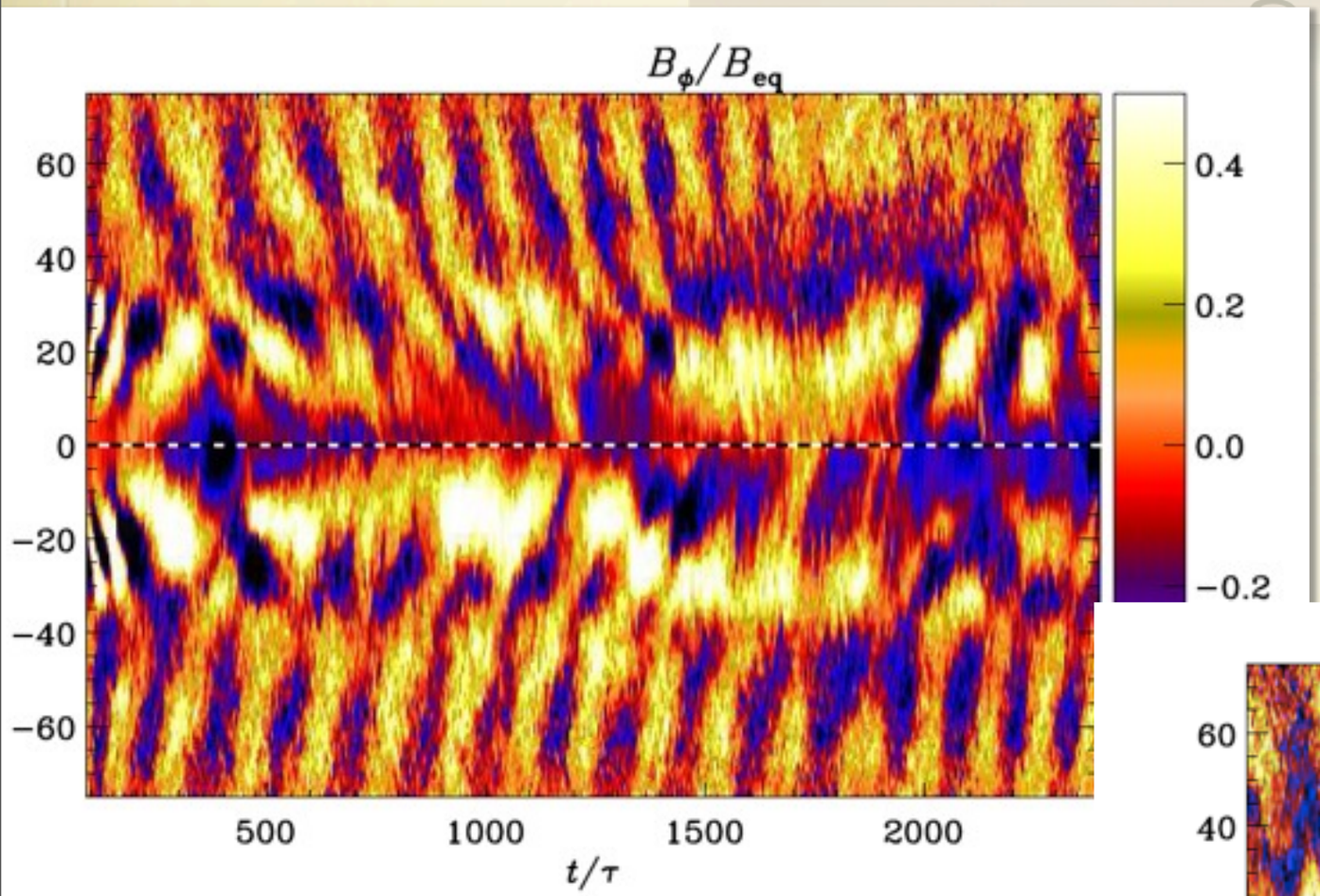

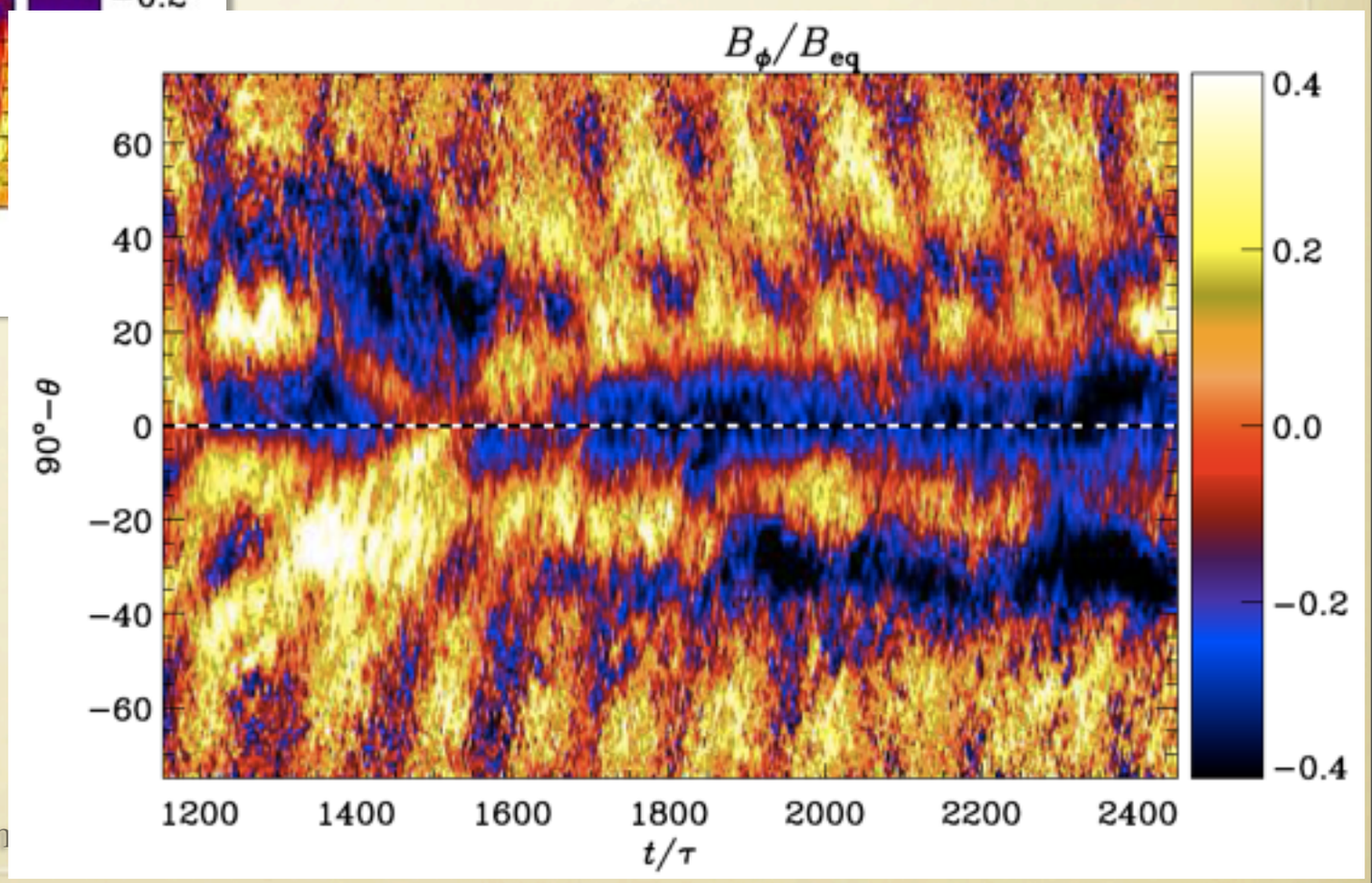

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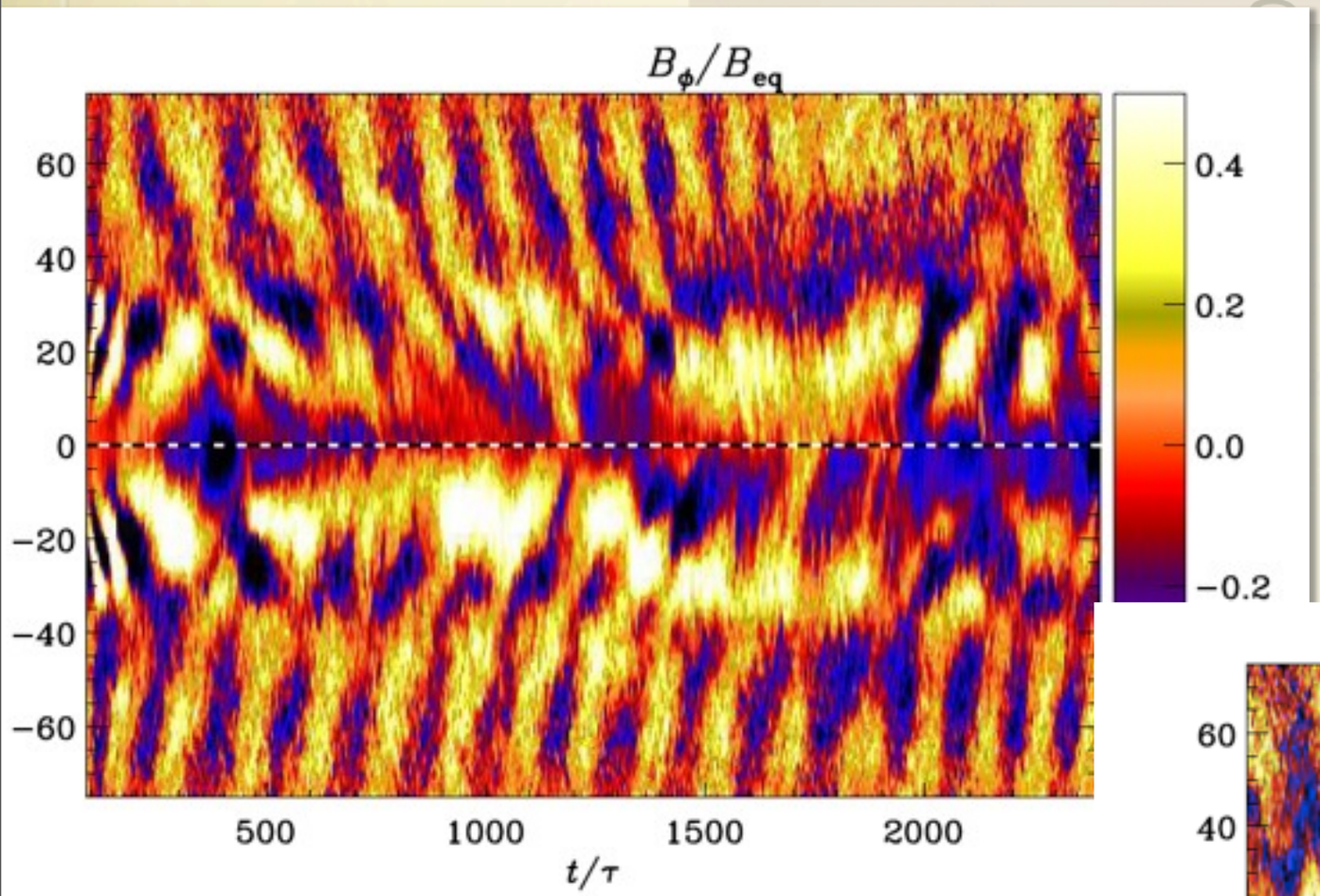
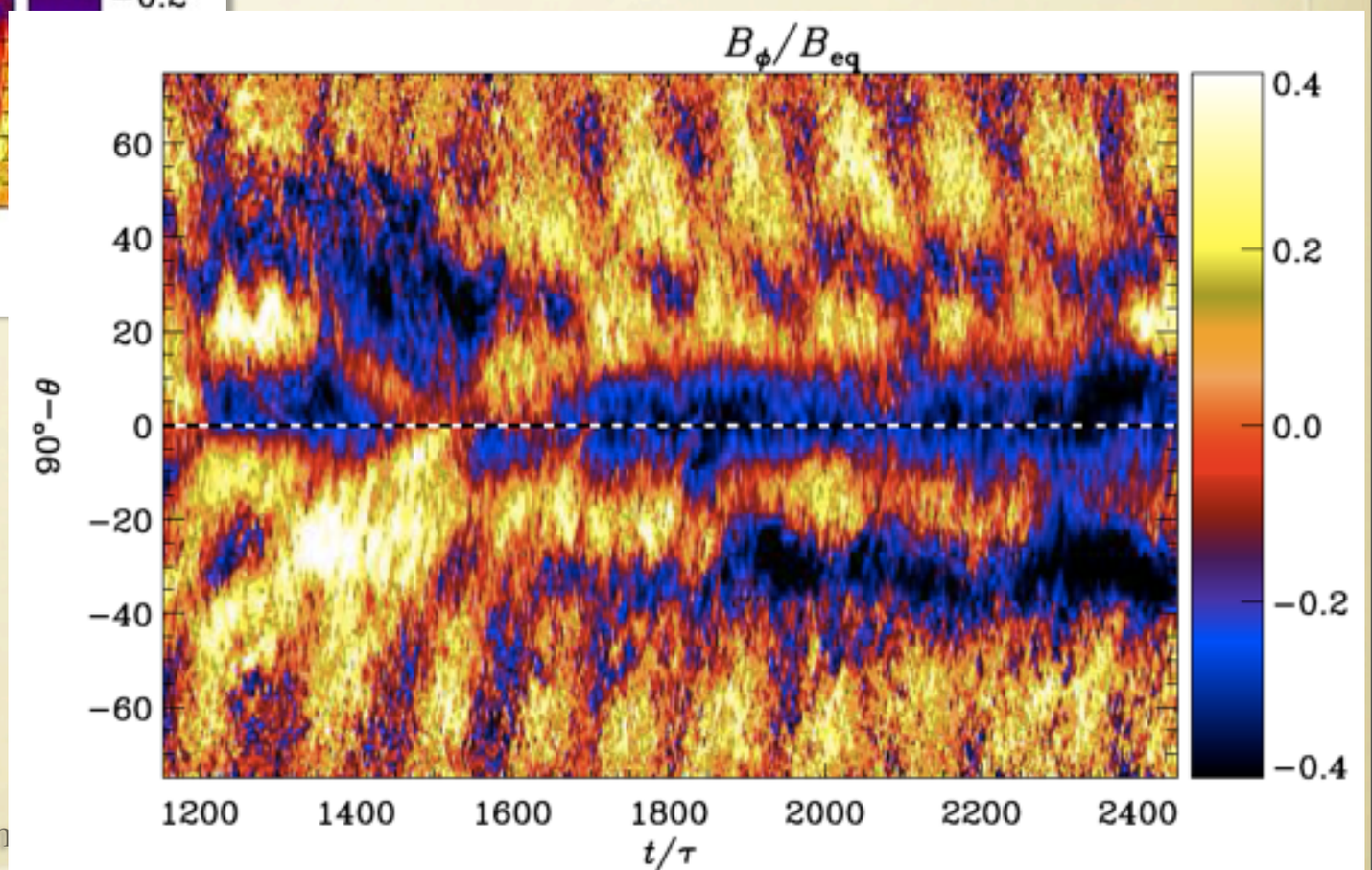
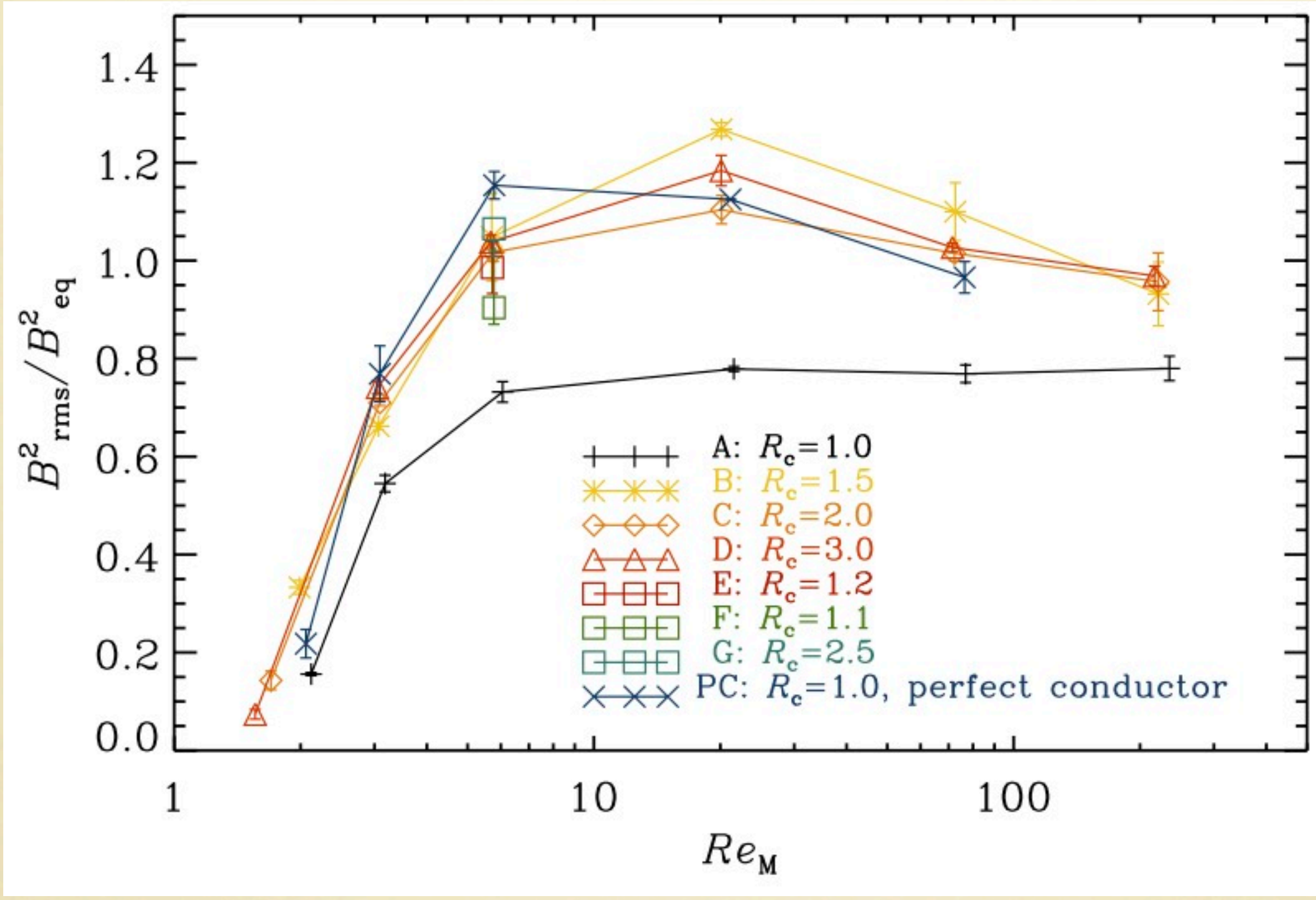


T_{cyl}=150 turnover times
≈ 12 years

Co=11



Corona supports dynamo action



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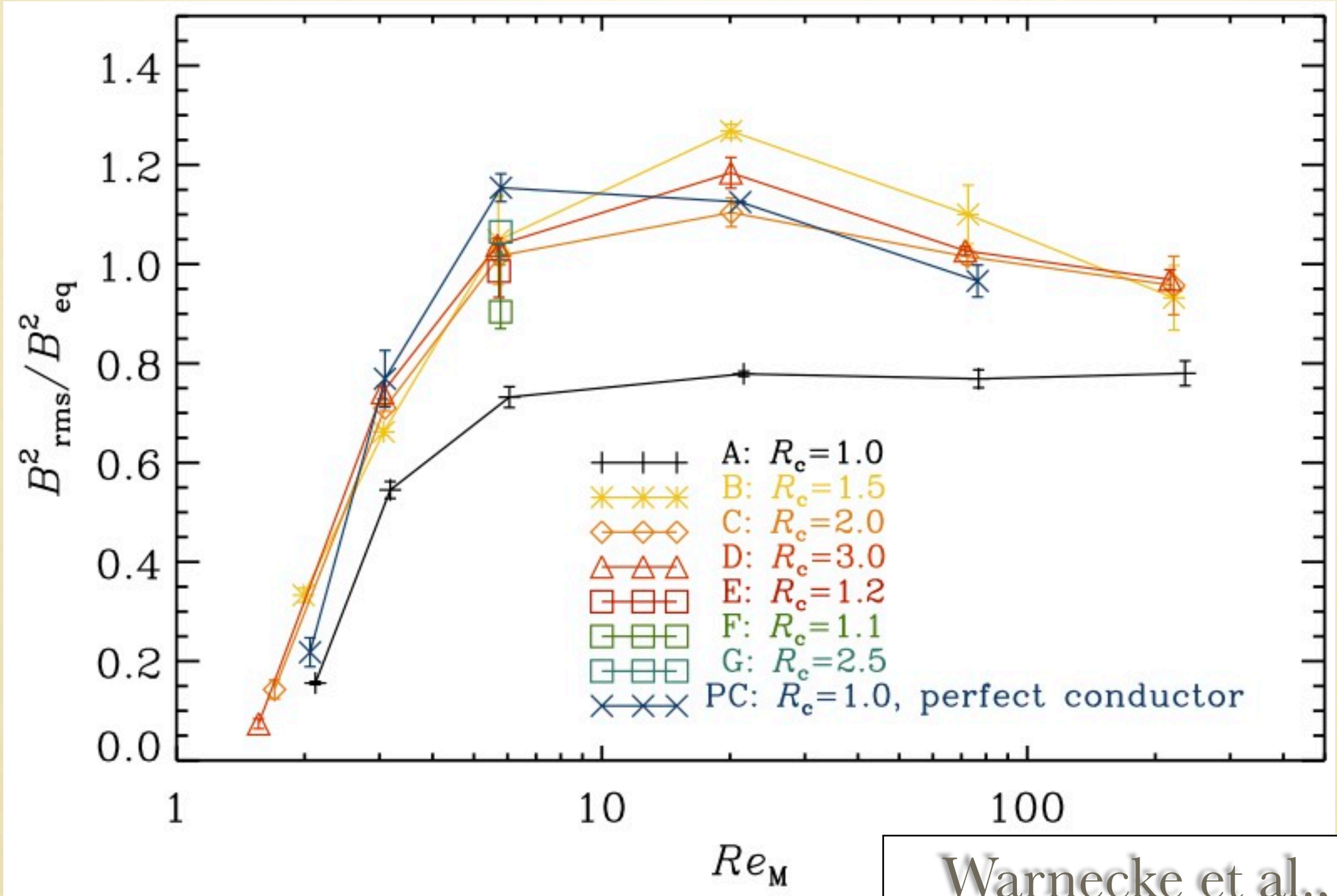
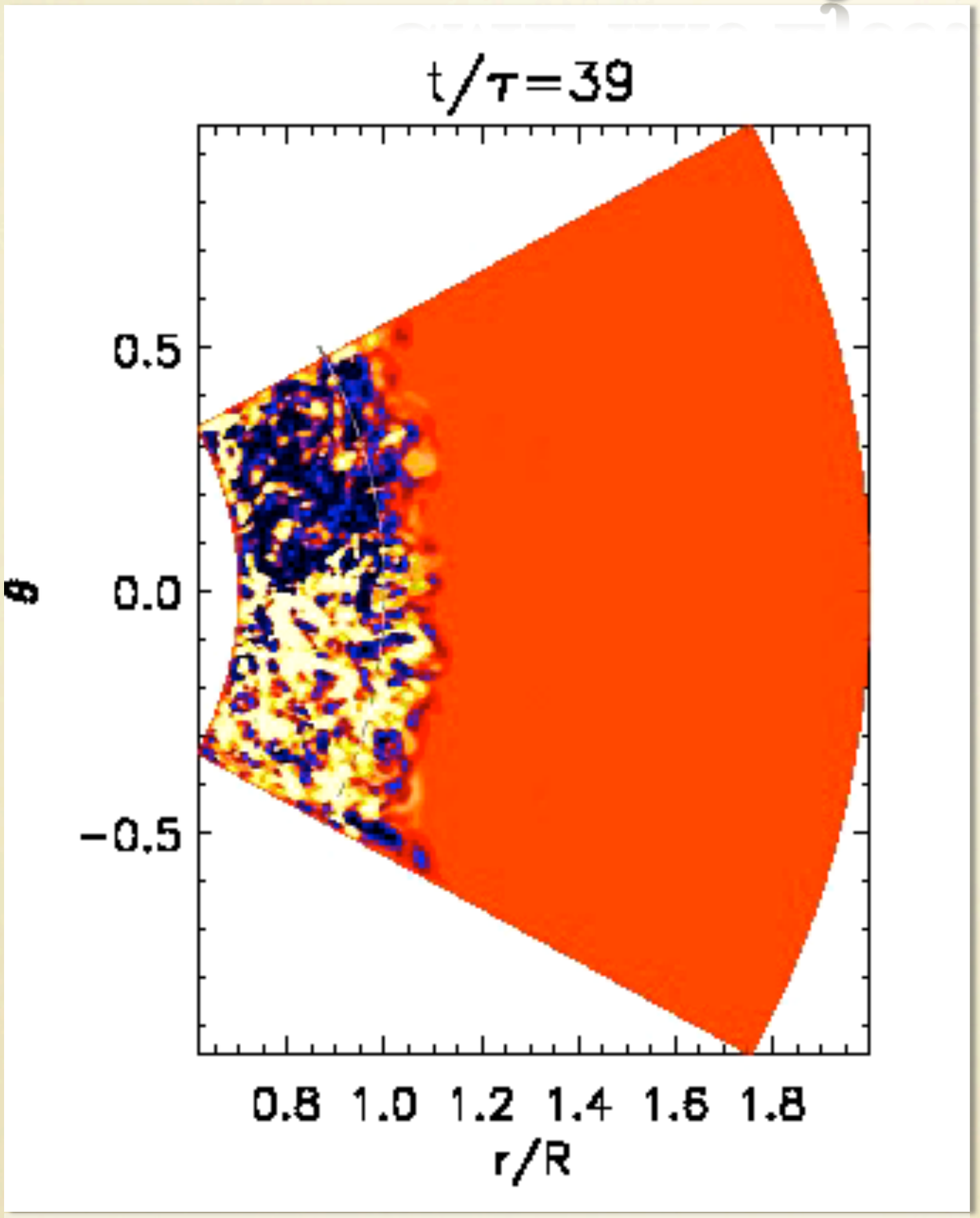


Warnecke et al., 2013b (in prep.)

CME-like Ejections

Current helicity density

CME-like Ejections



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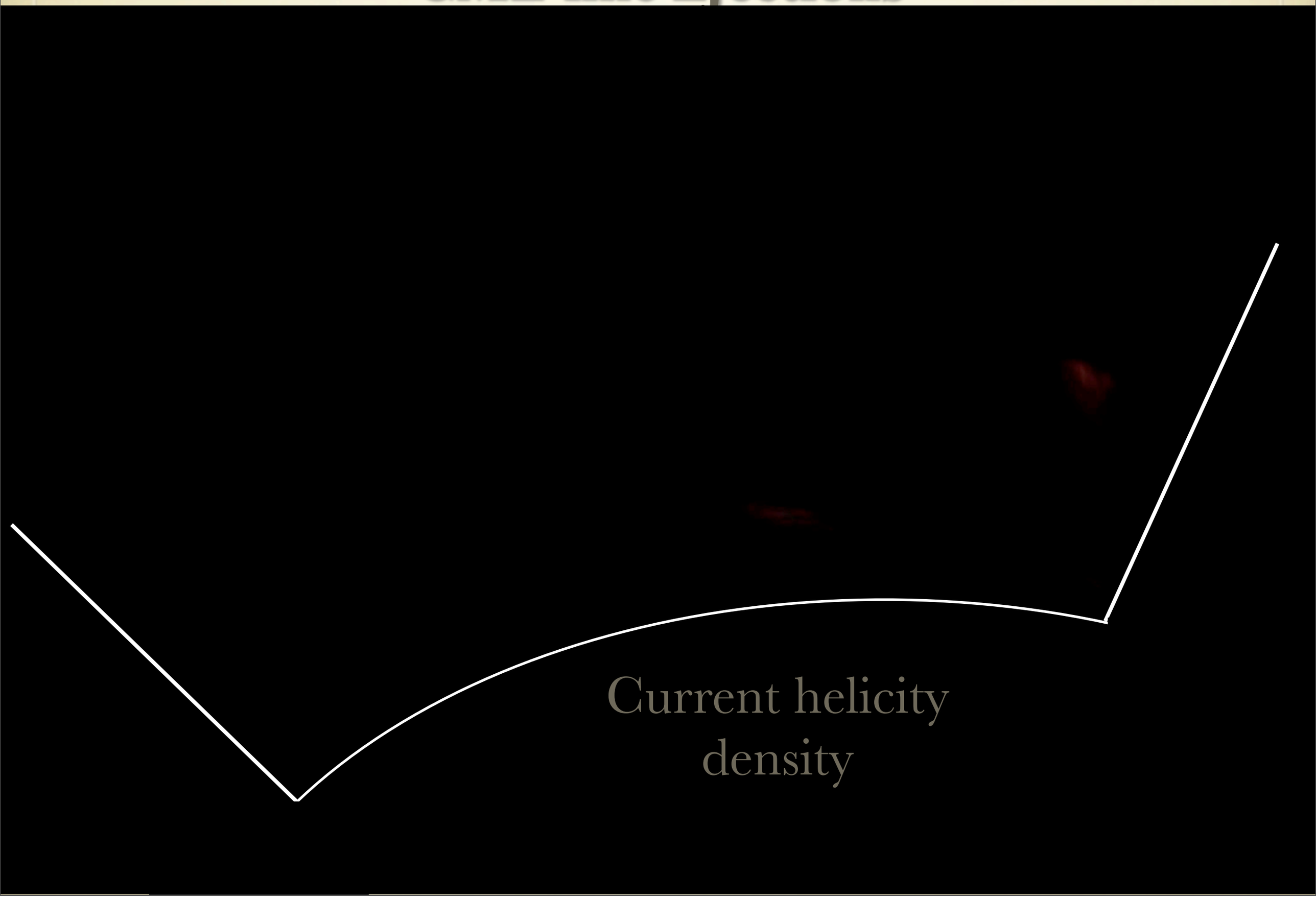

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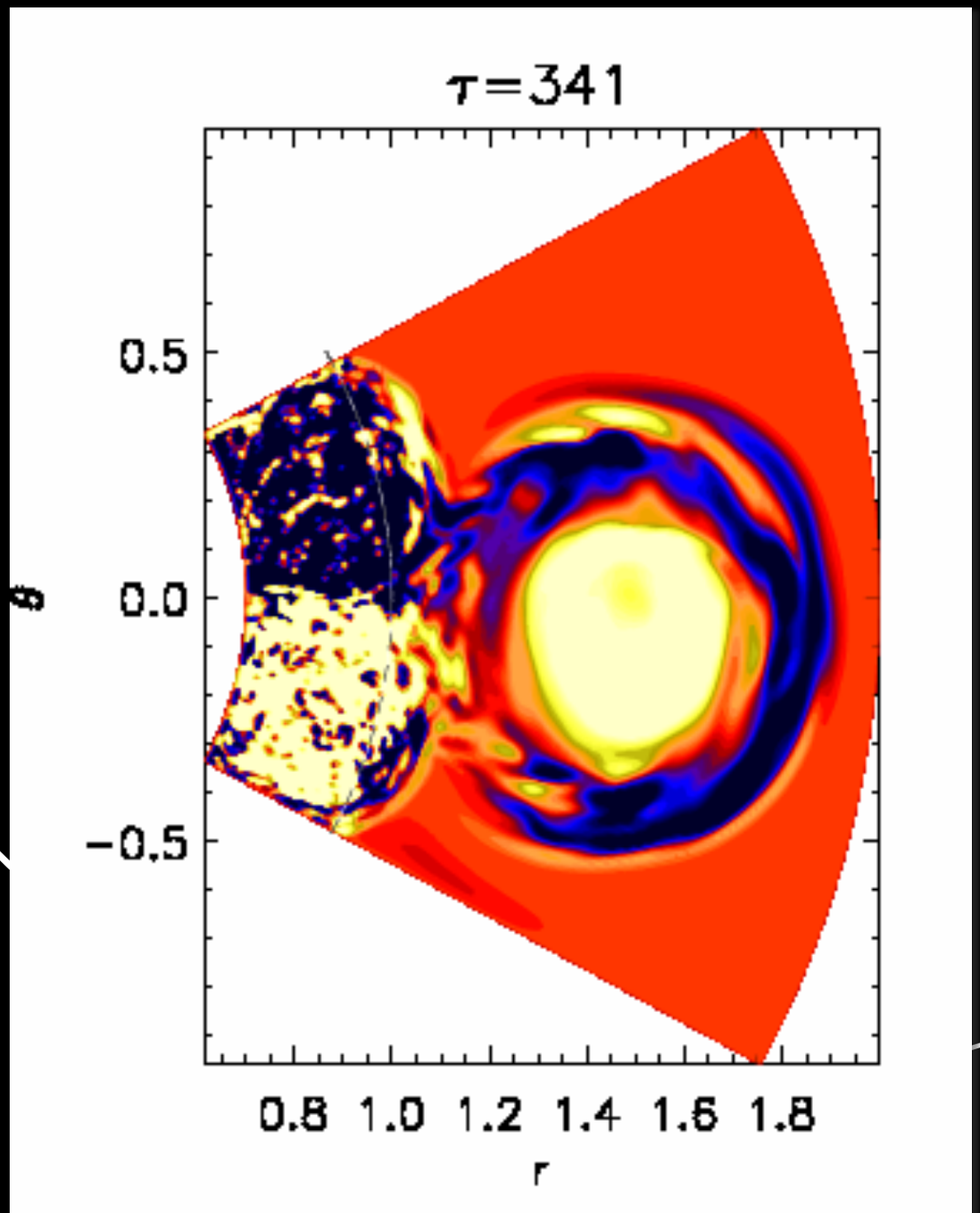

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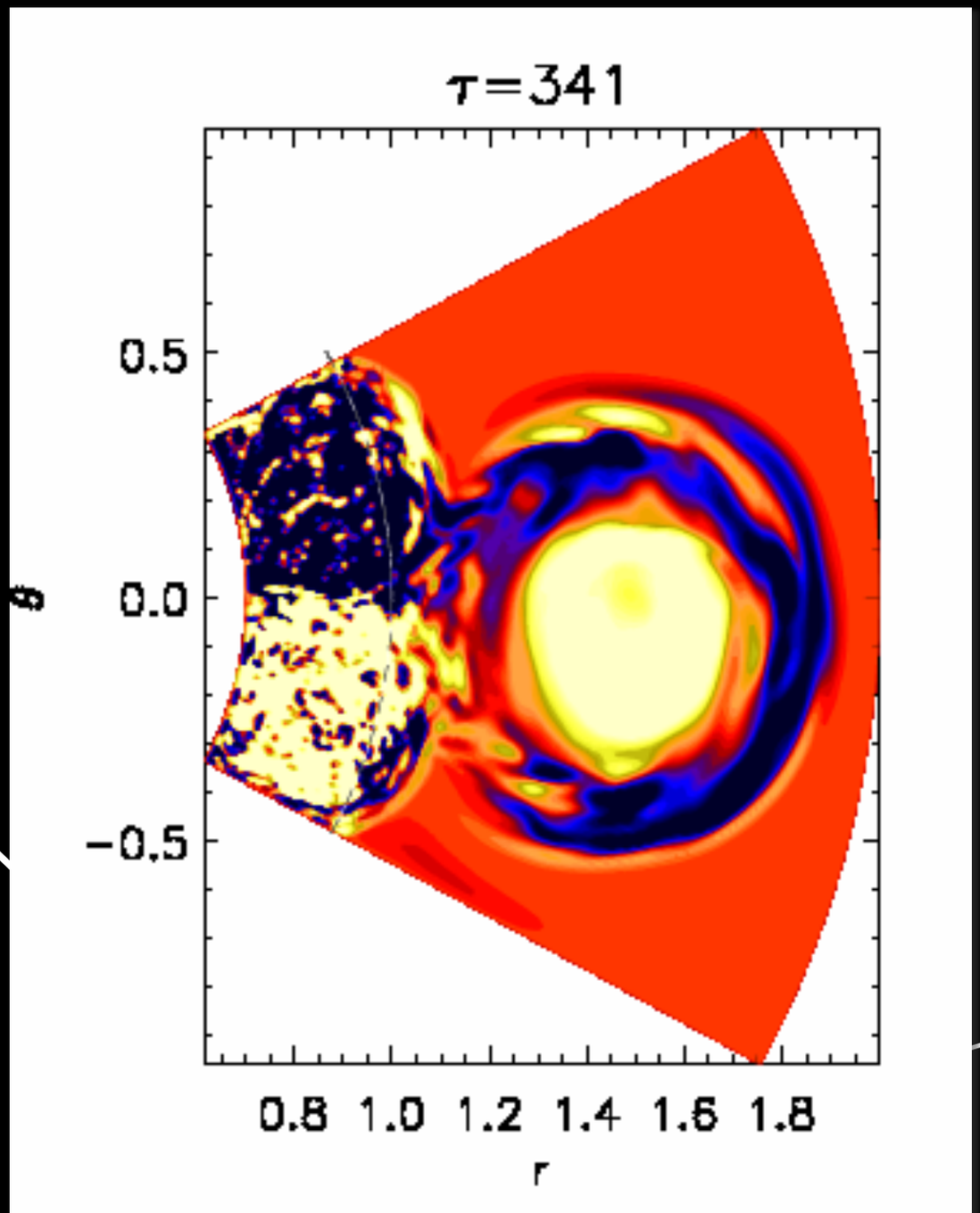

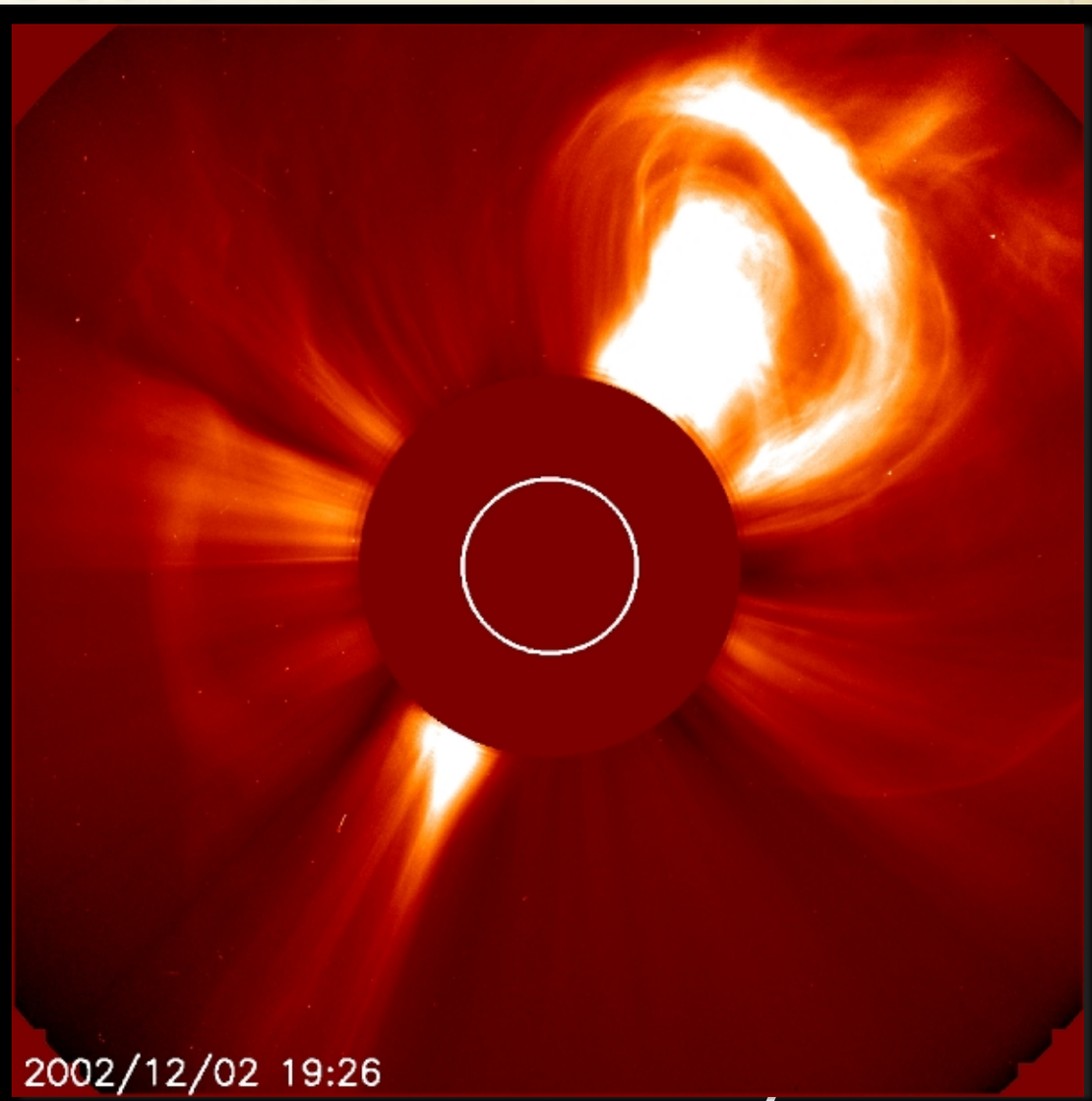

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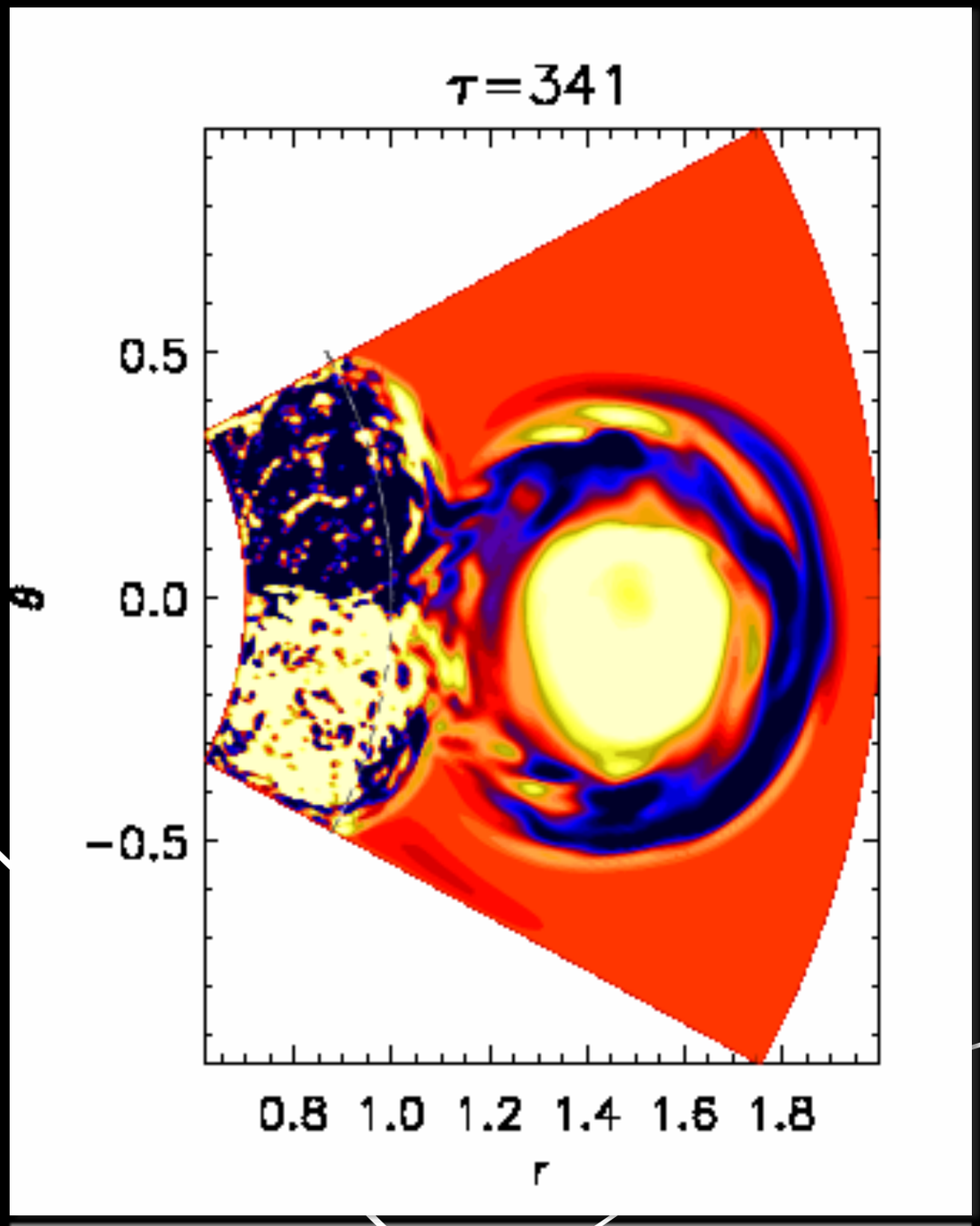

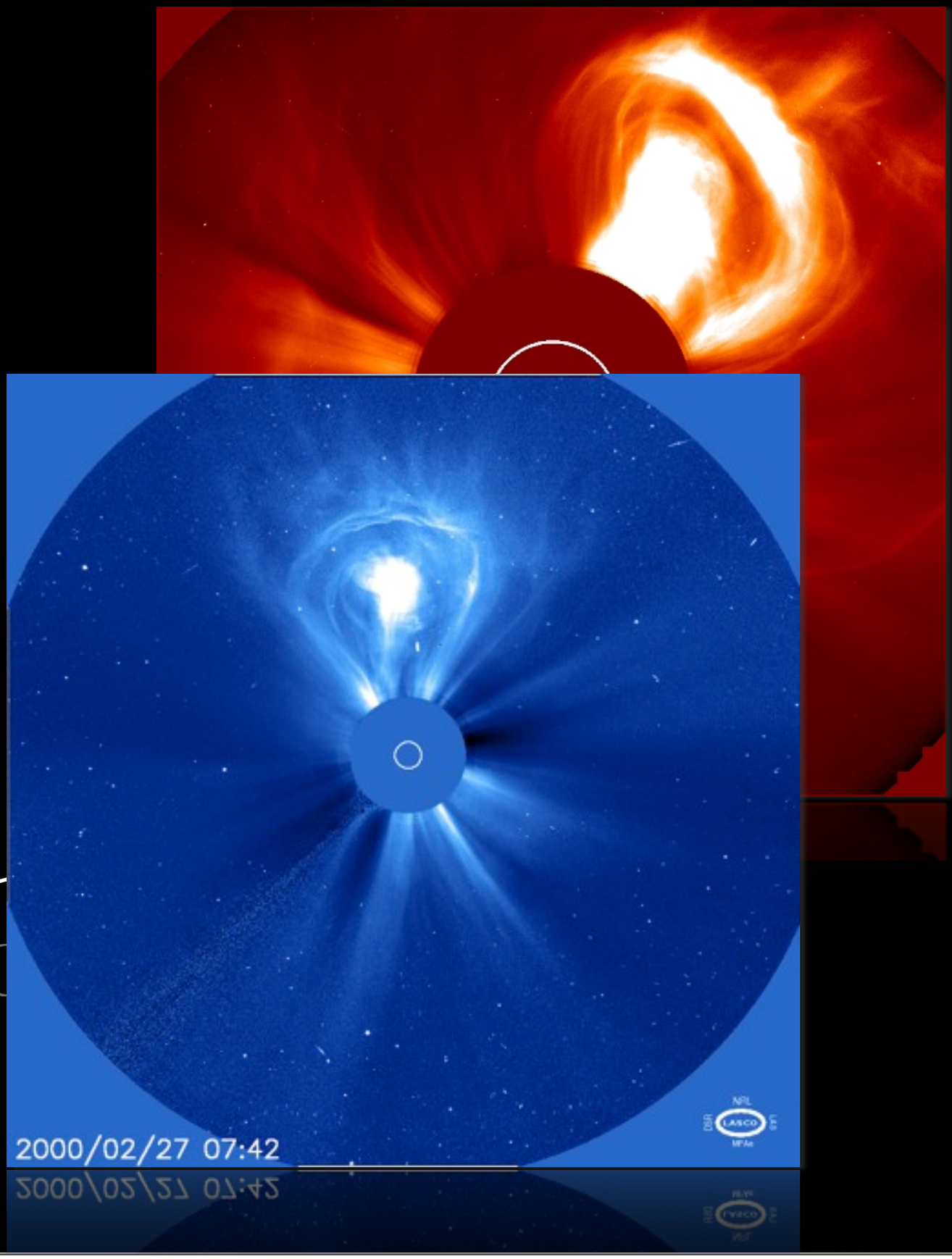

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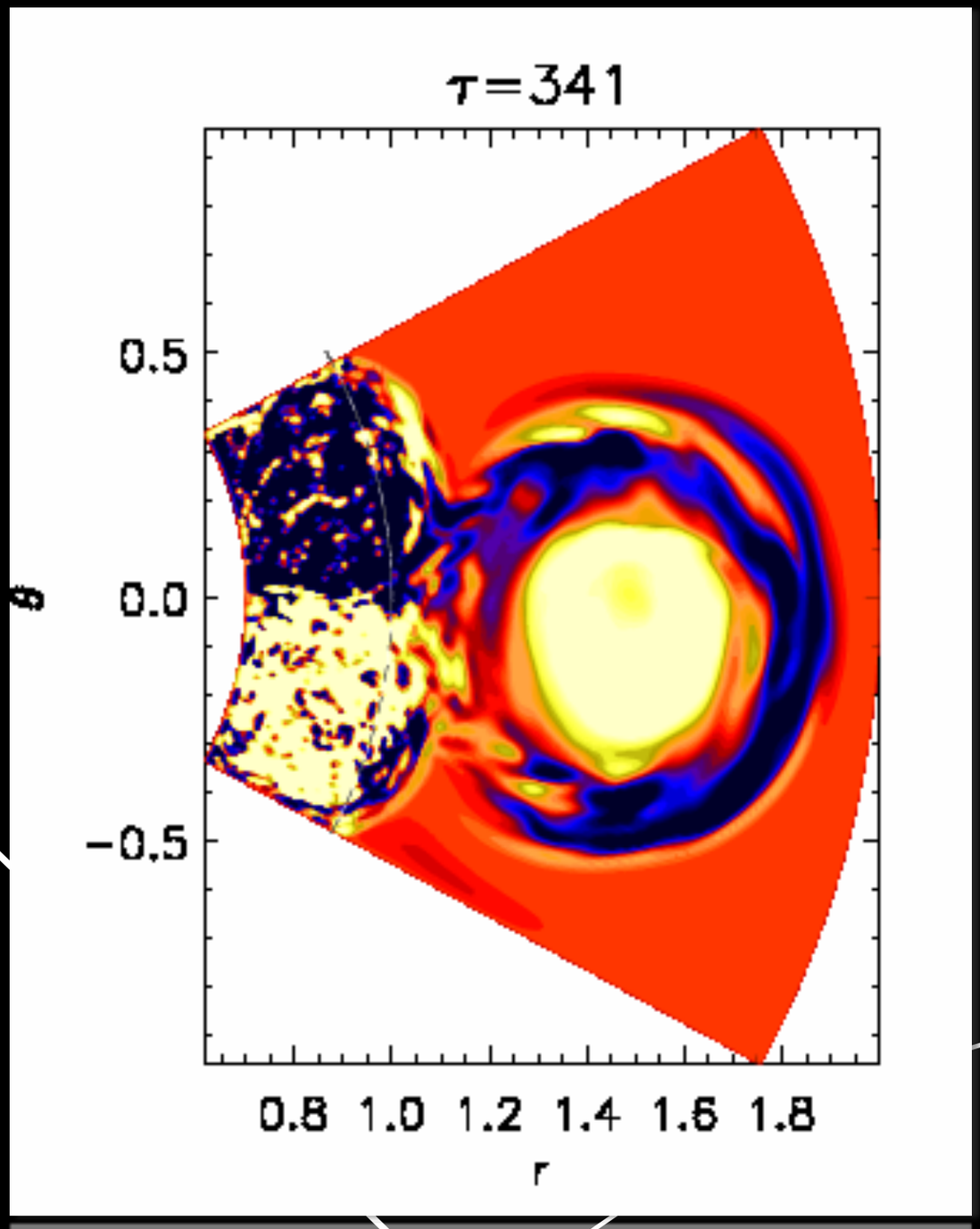
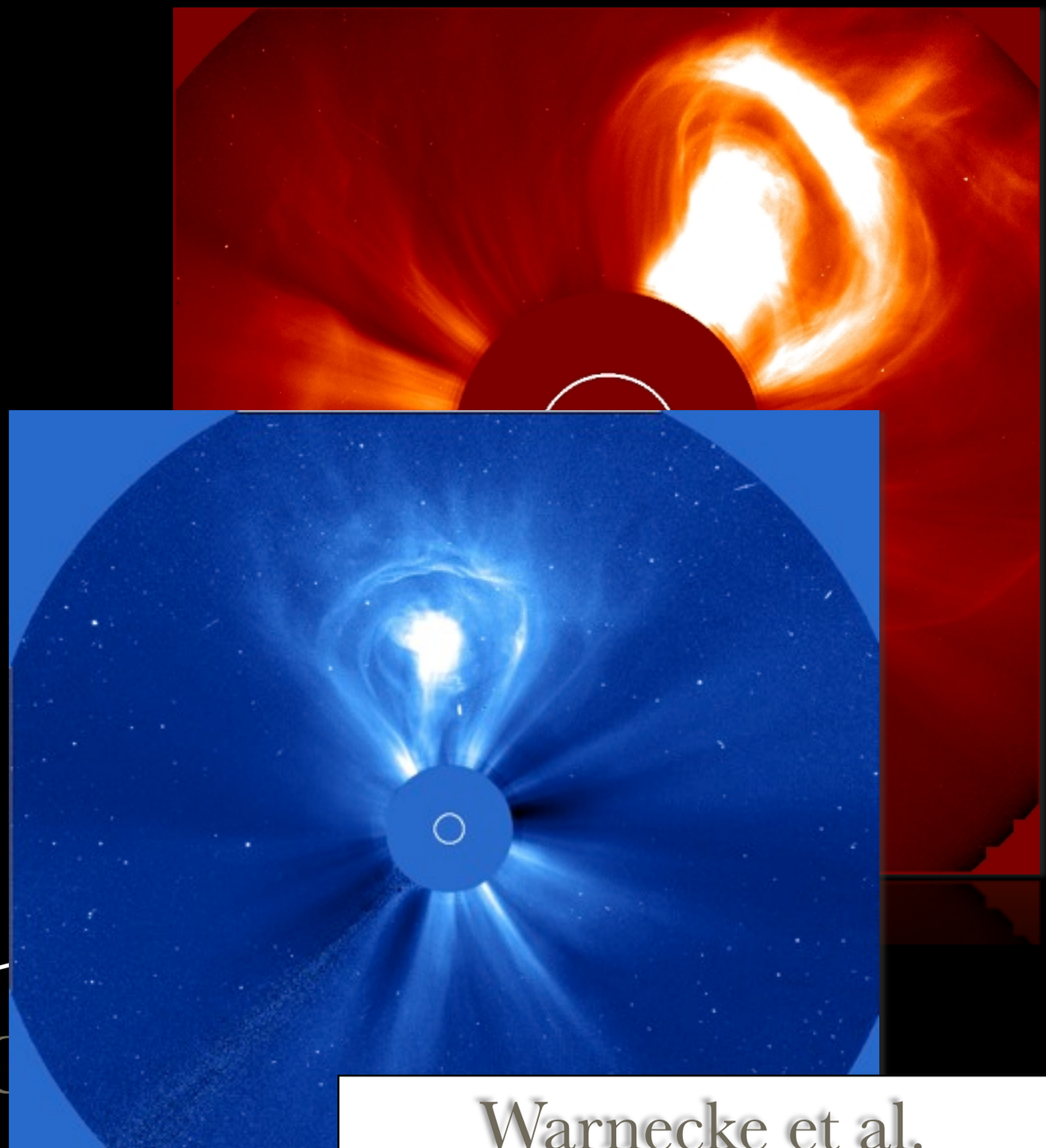
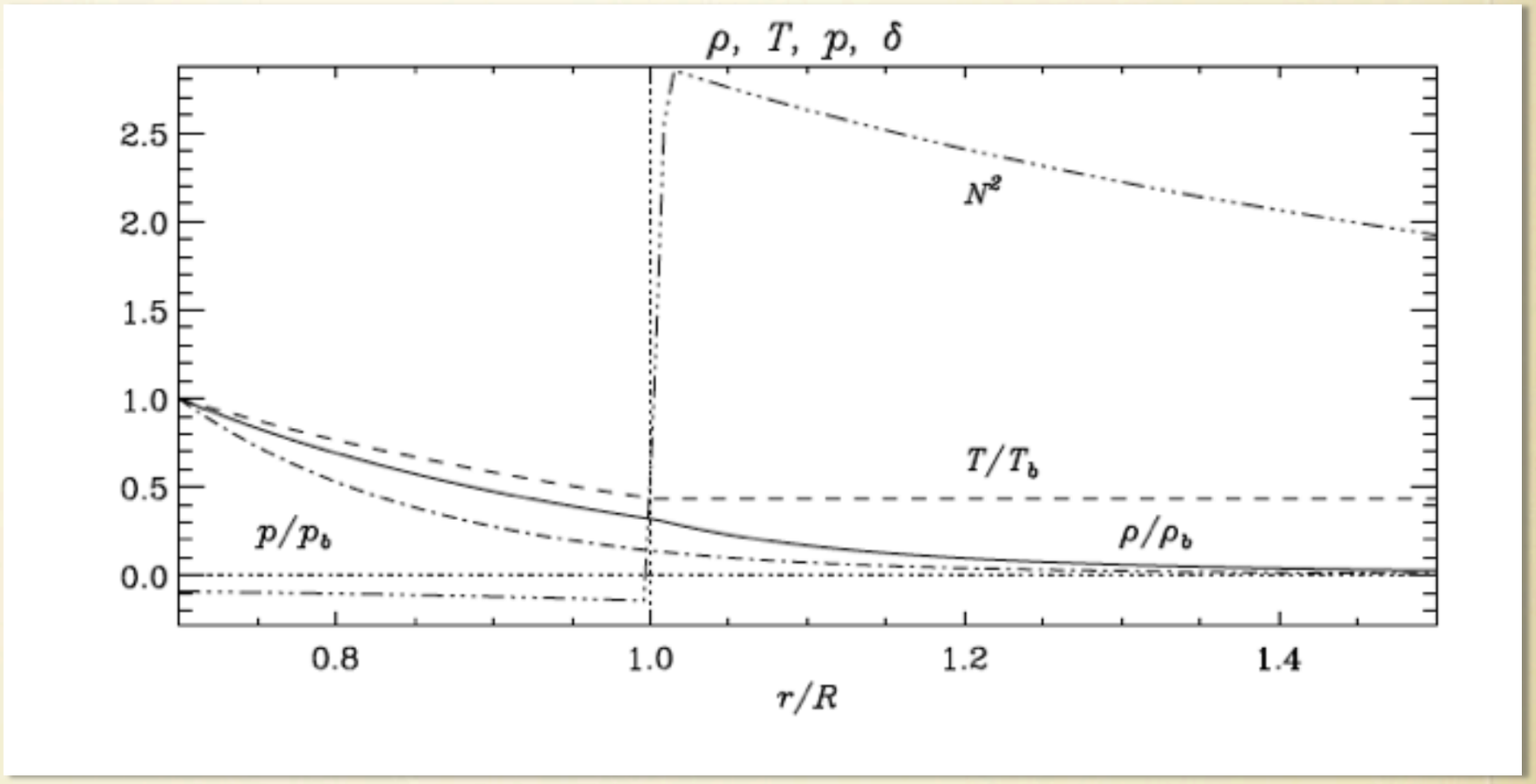




Warnecke et al.
2011
(A&A 534, A11)

Self-consistent convection with a coronal layer



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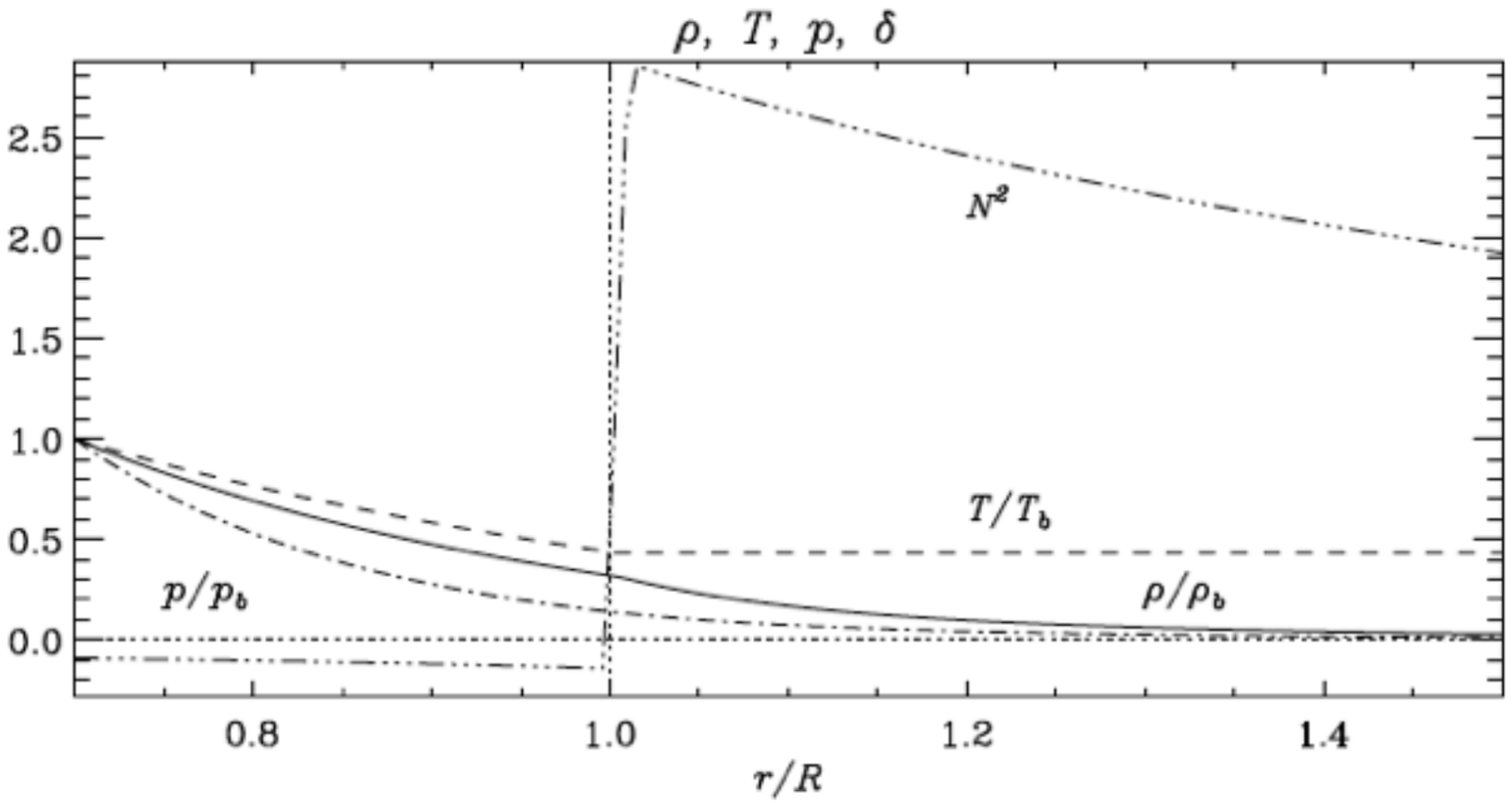
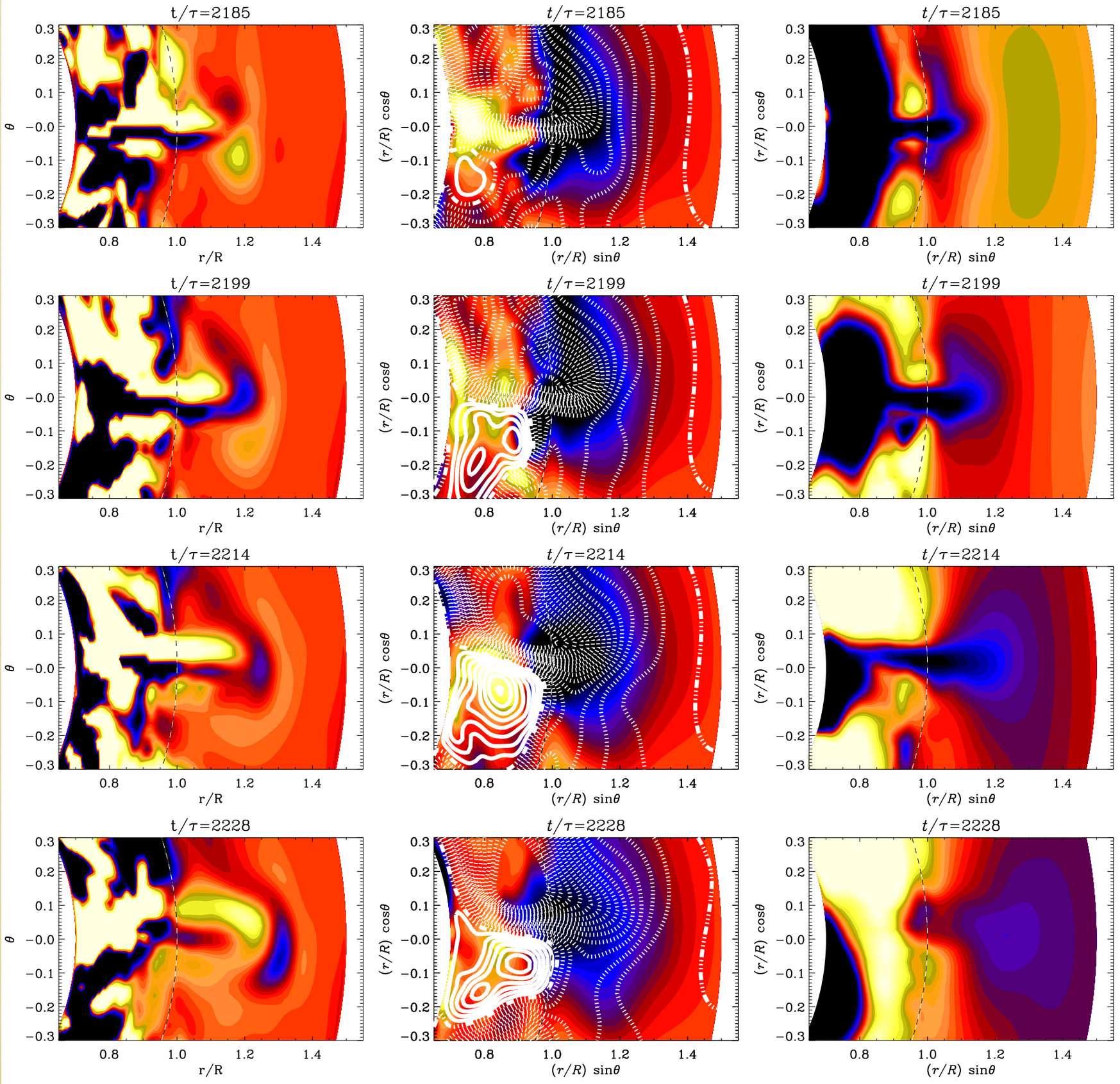
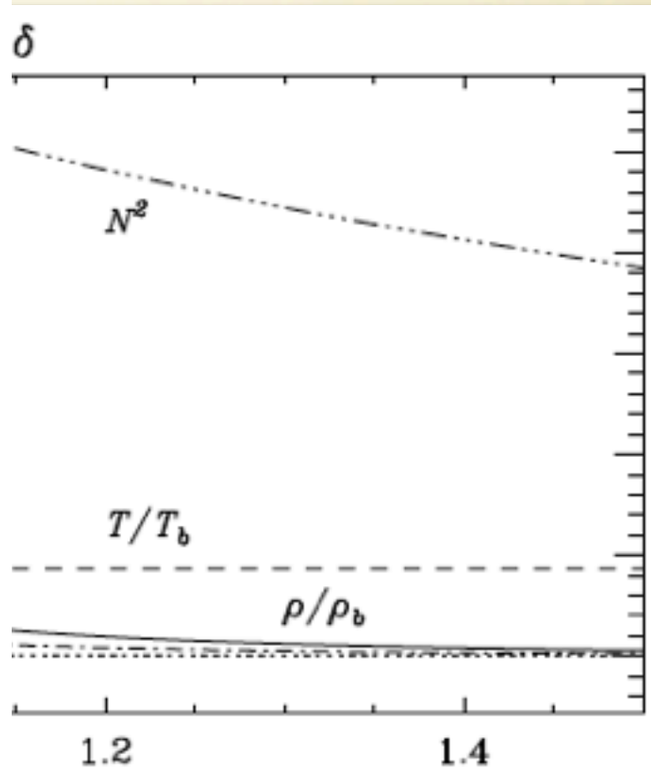


Self-consistent convection with a coronal layer

Warnecke et al. 2012 (Sol. Ph. 280, 299)

Convection driven Ejections





Warnecke et al.
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- Including solar wind