Evolution of internal magnetic field in solar-like stars during the PMS

Constance Emeriau-Viard
Sacha Brun

CEA Saclay, AIM

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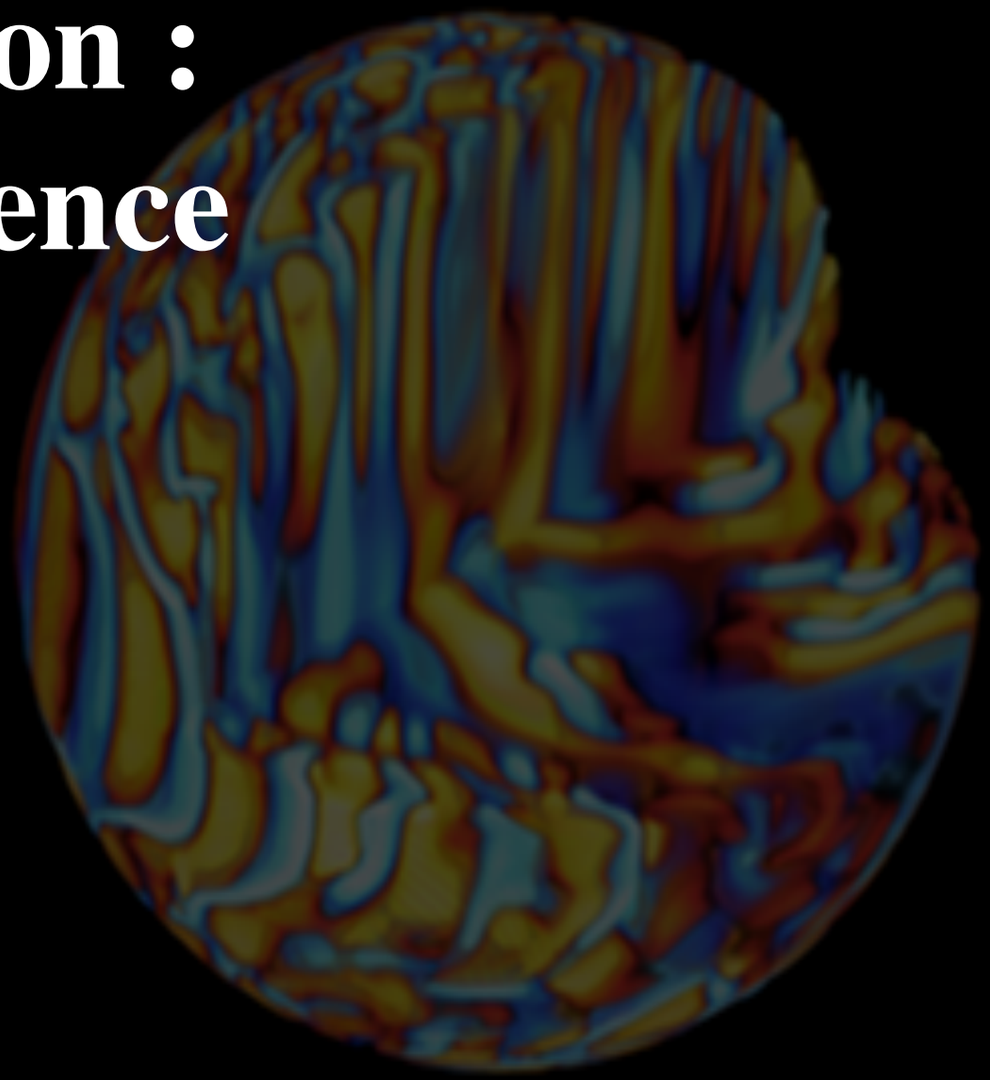
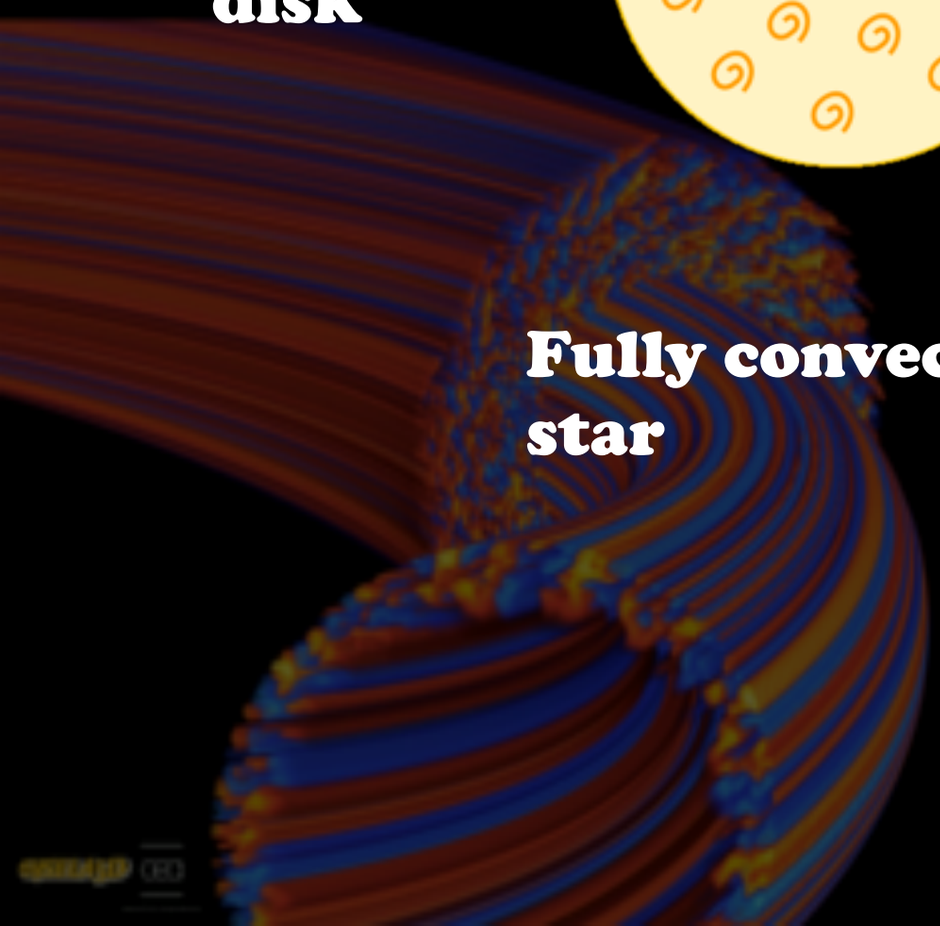
Stellar evolution :
Pre main sequence



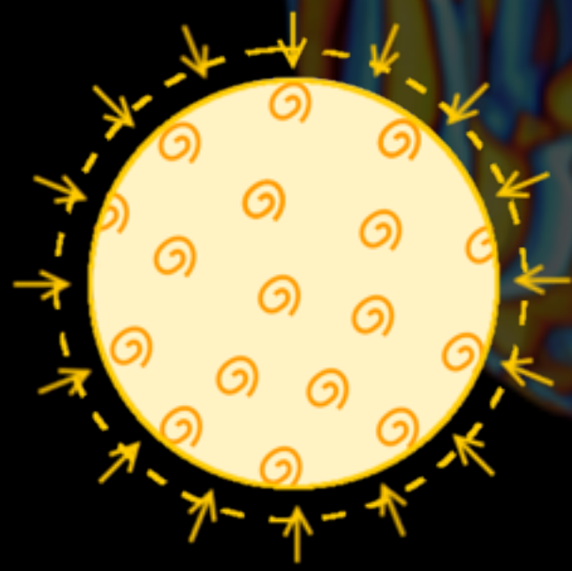
Protostellar disk



Fully convective star

Stellar evolution : Pre main sequence

Protostellar disk



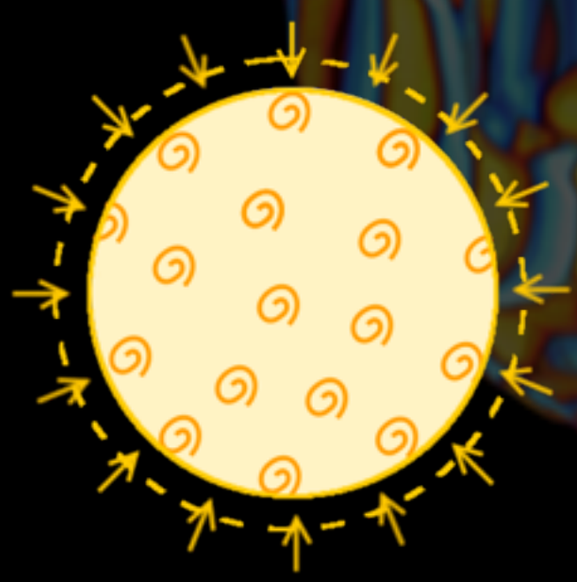
Increase of T and ρ in the core

Fully convective star

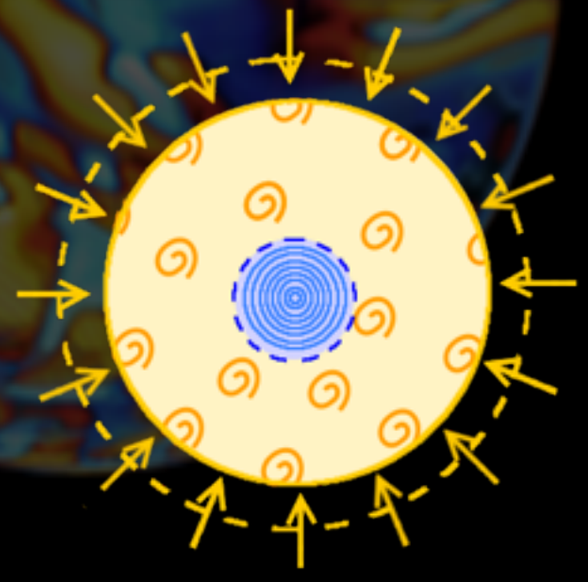
Stellar evolution : Pre main sequence

Protostellar disk

Fully convective star



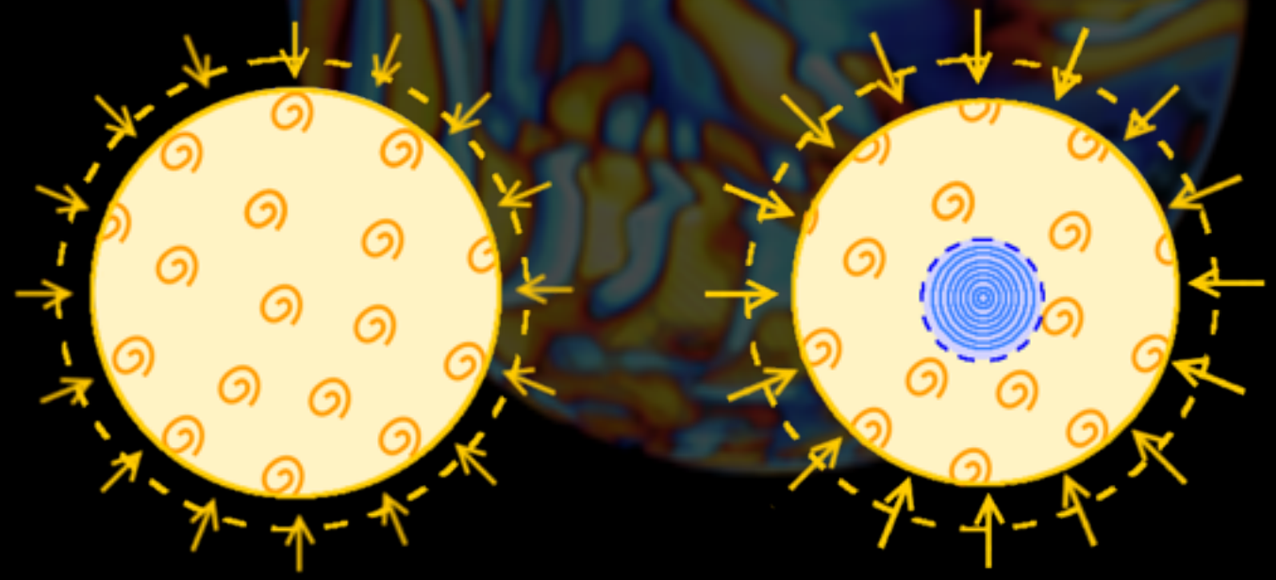
Increase of T and ρ in the core



Opacity drops

Stellar evolution : Pre main sequence

Protostellar disk



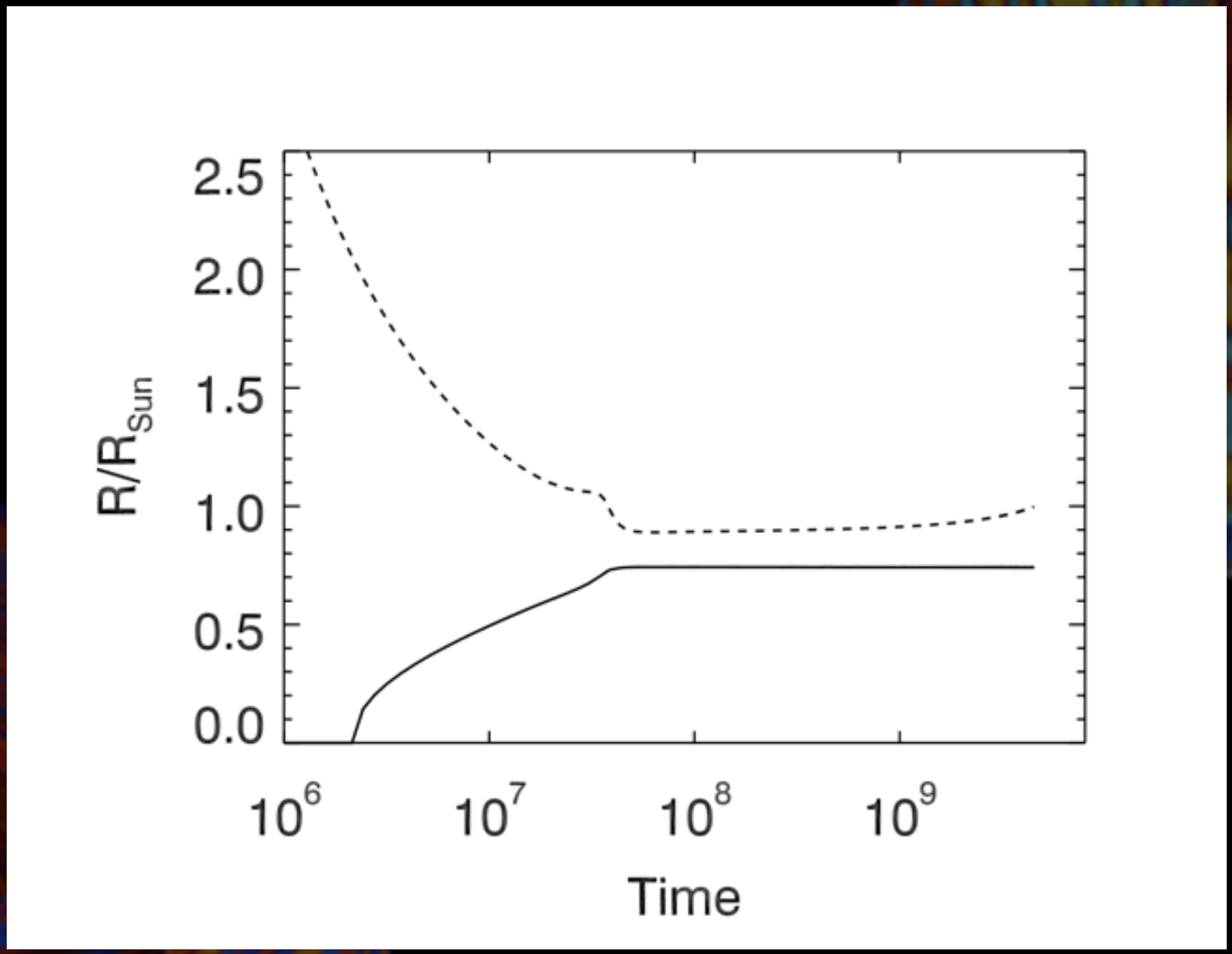
Fully convective star

Increase of T and ρ in the core

Opacity drops

Radiative core appears and grows

Stellar evolution : Pre main sequence

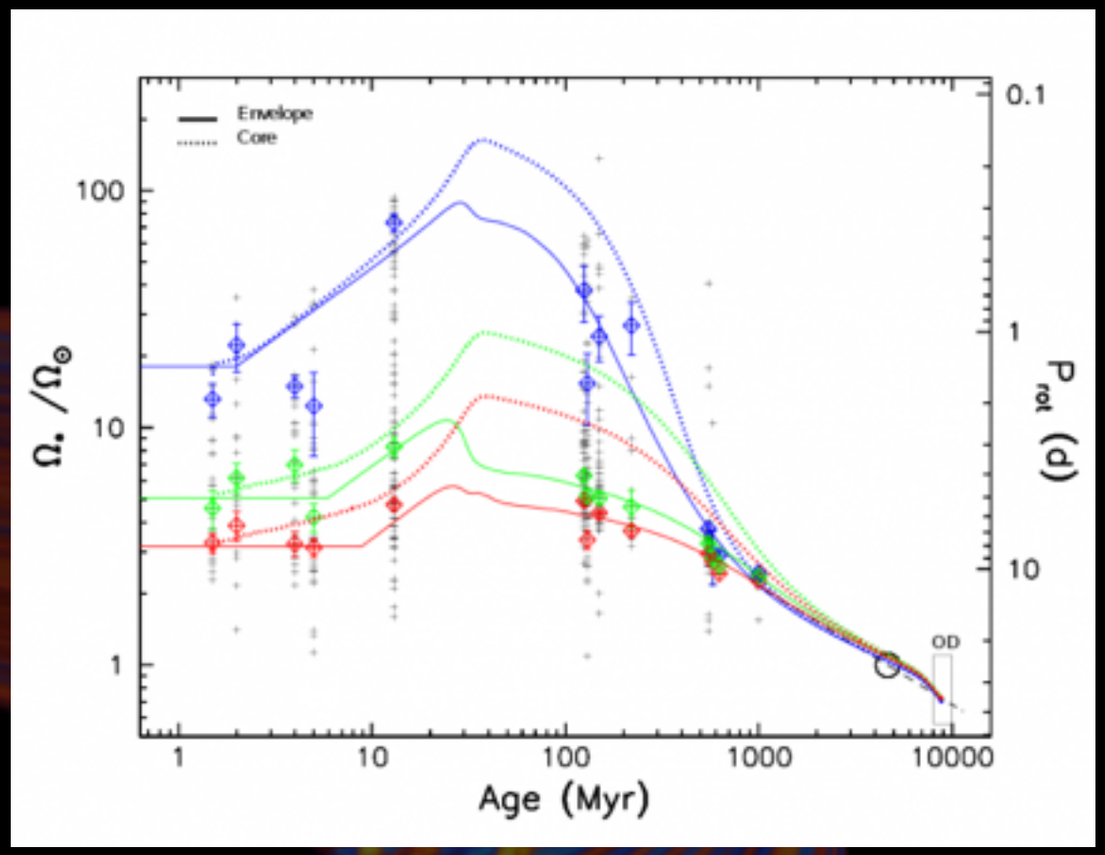


Radiative core appears and grows

Stellar evolution :
Pre main sequence

Gyrochronologie

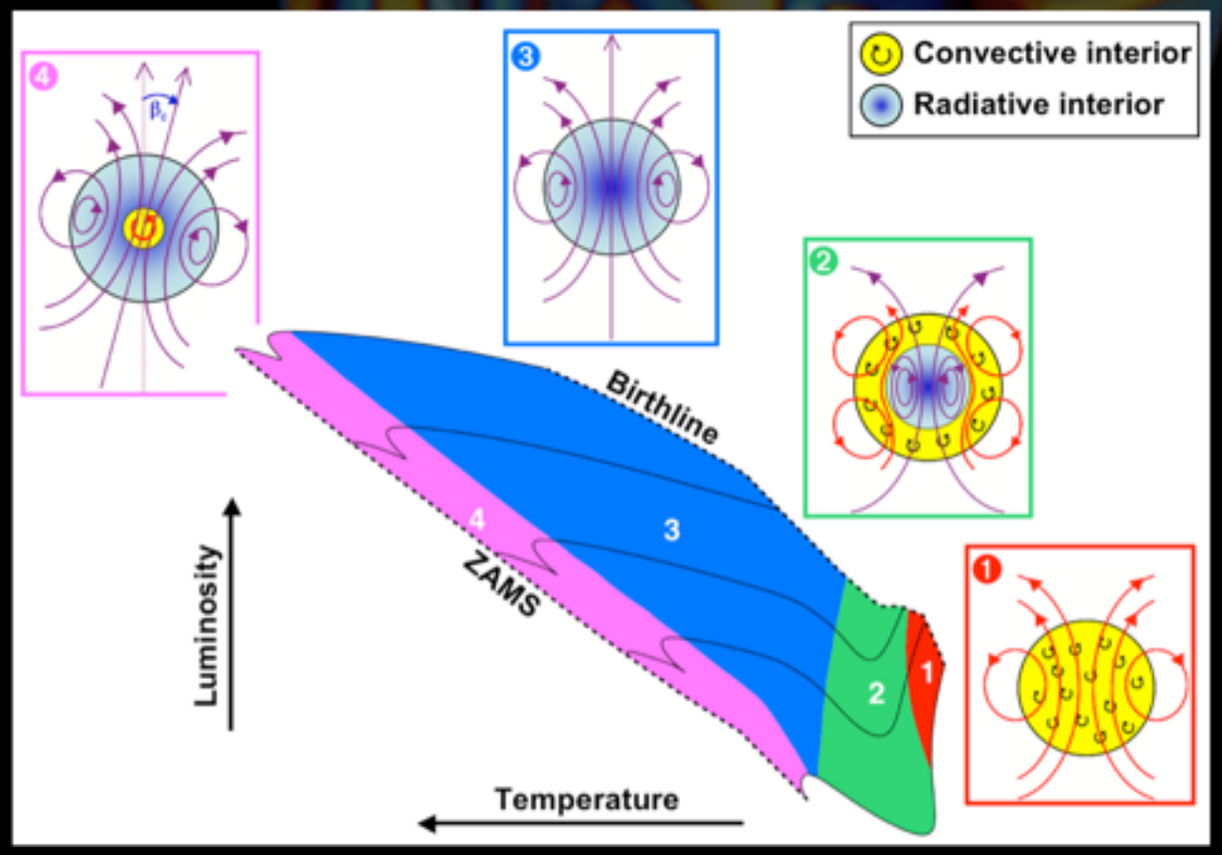
$$\Omega \propto t^{-\frac{1}{2}}$$



Gallet et Bouvier (2013)
Skumanich (1972)

Magnetochronologie

$$B \propto t^{-0.655 \pm 0.045}$$



Alecian (2013)
Vidotto et al. (2014)

ASH code

- Anelastic equations for a conductive plasma in a rotating sphere

$$\frac{\rho}{\bar{\rho}} = \frac{P}{\bar{P}} - \frac{T}{\bar{T}} = \frac{P}{\gamma \bar{P}} - \frac{S}{c_p}$$

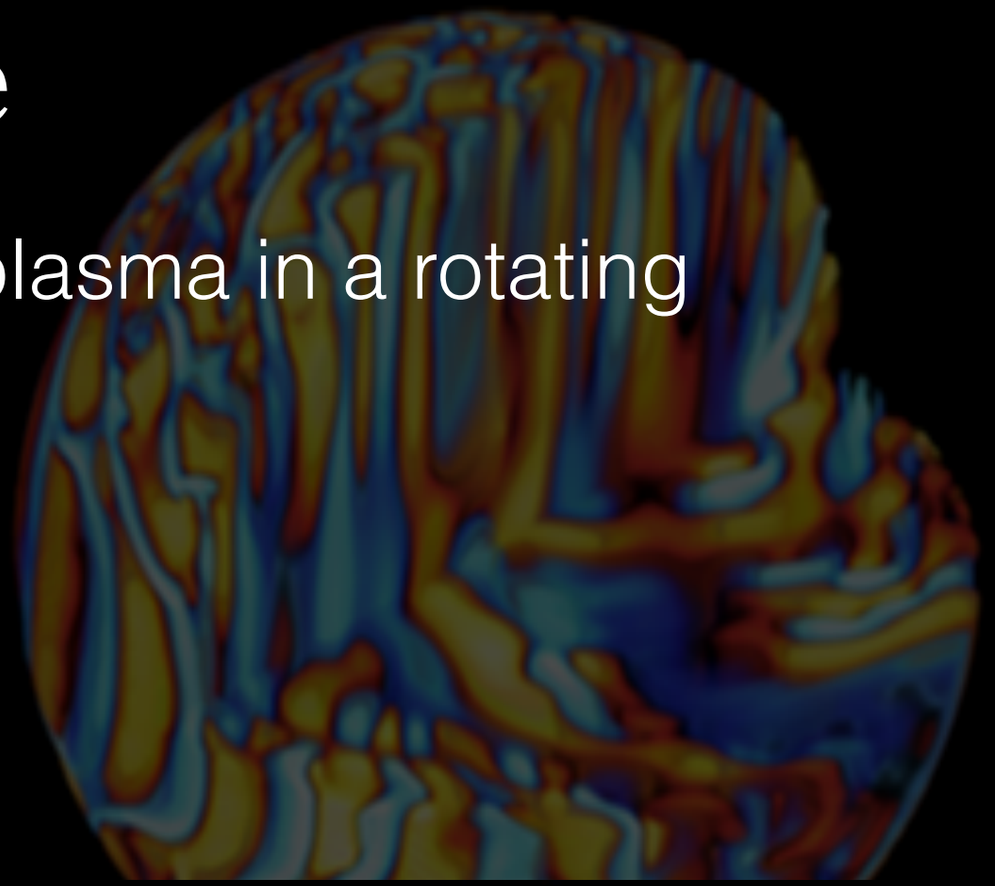
$$\vec{\nabla}.\left(\bar{\rho}\vec{\mathrm{v}}\right) = 0$$

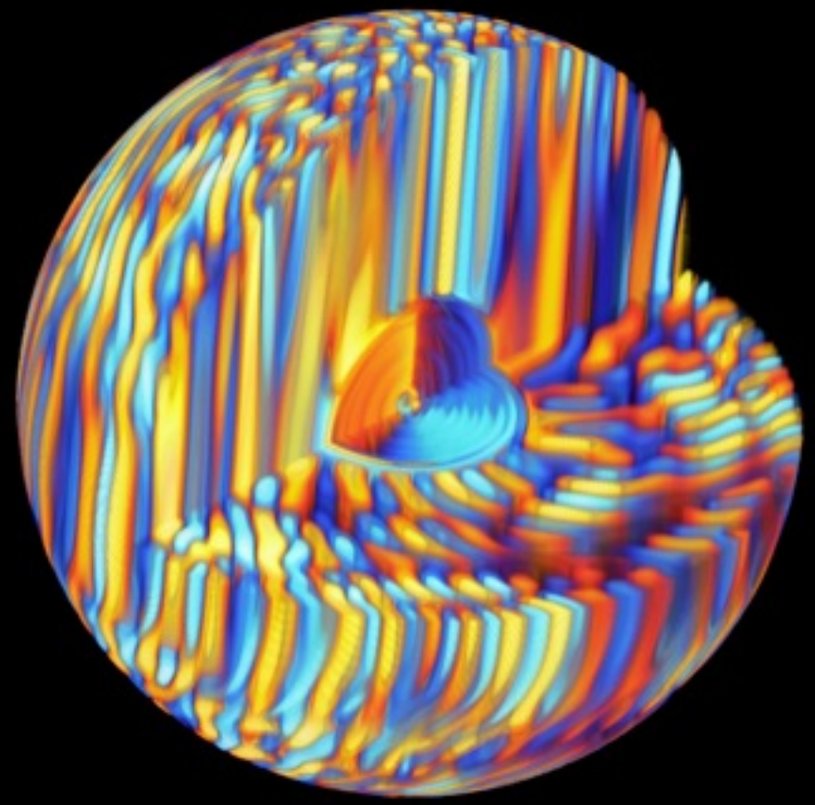
$$\bar{\rho}\left(\frac{\partial \vec{\mathrm{v}}}{\partial t} + \left(\vec{\mathrm{v}}.\vec{\nabla}\right)\vec{\mathrm{v}}\right) = -\bar{\rho}\vec{\nabla}\widetilde{\omega} - \bar{\rho}\frac{S}{c_p}\vec{g} - 2\bar{\rho}\vec{\Omega}_0 \times \vec{\mathrm{v}} - \vec{\nabla}.\vec{\mathcal{D}}$$

$$\bar{\rho}\bar{T}\frac{\partial S}{\partial t} + \bar{\rho}\bar{T}\vec{\mathrm{v}}.\vec{\nabla}\left(S + \bar{S}\right) = \bar{\rho}\epsilon + \vec{\nabla}.\left[\kappa_r \bar{\rho} c_p \vec{\nabla}\left(T + \bar{T}\right)\right.$$

$$\left. + \kappa \bar{\rho}\bar{T}\vec{\nabla}S + \kappa_0 \bar{\rho}\bar{T}\vec{\nabla}\bar{S}\right] + 2\bar{\rho}\nu\left[e_{ij}e_{ij} - 1/3\left(\vec{\nabla}.\vec{\mathrm{v}}\right)^2\right]$$

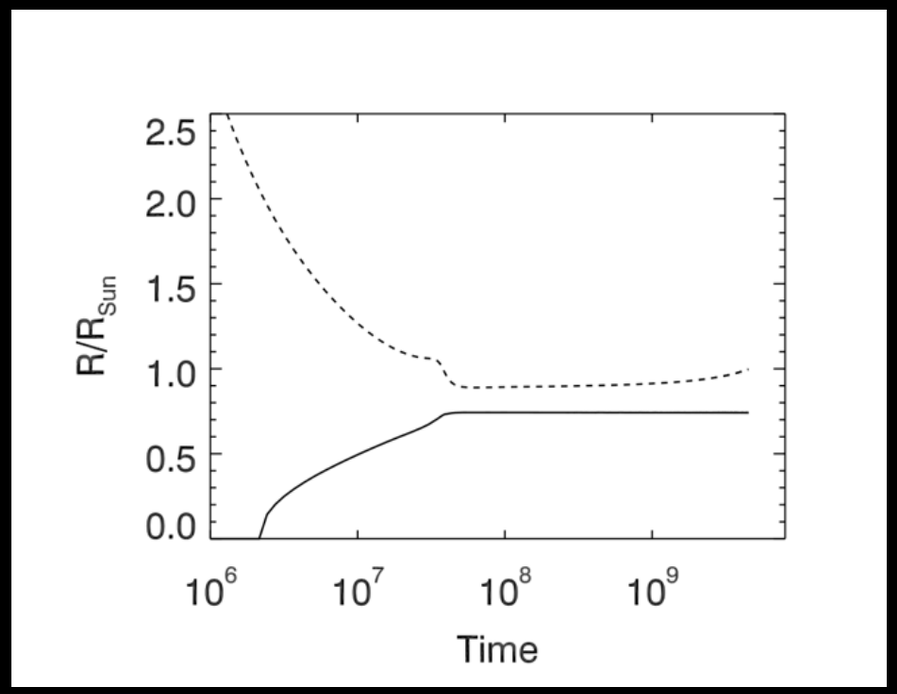
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B})$$

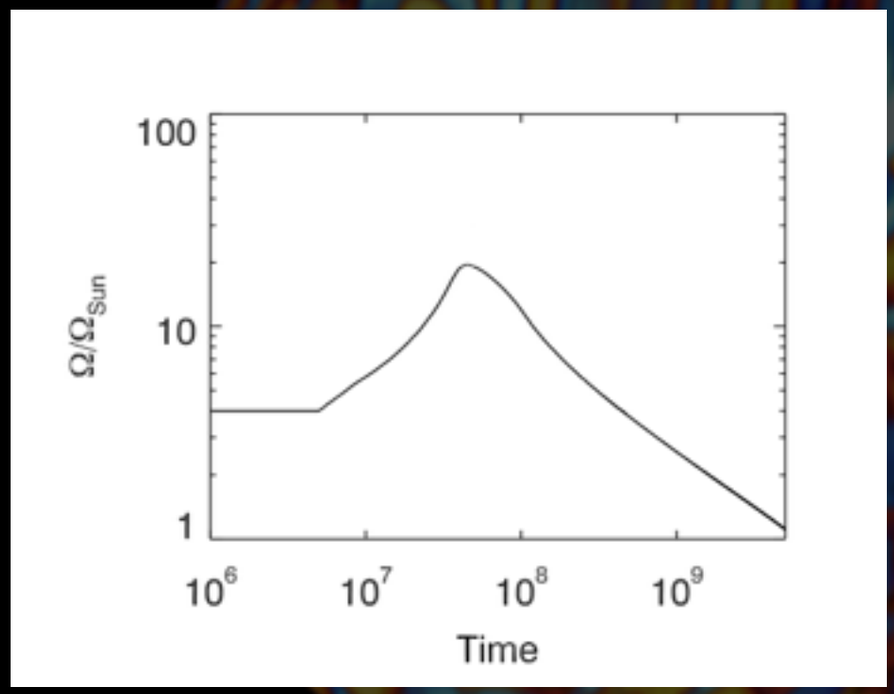


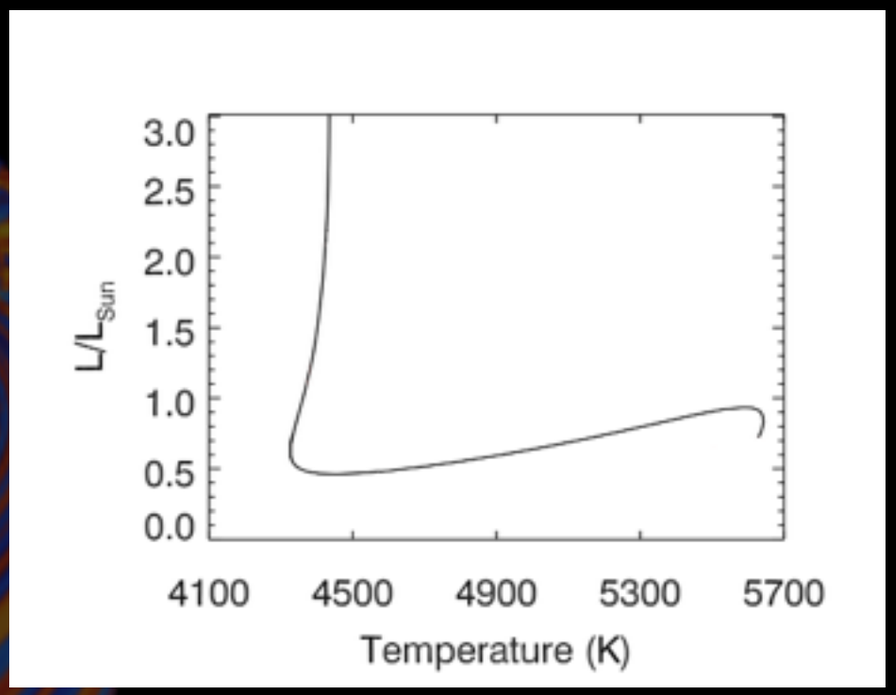


- Geometry : 3D full sphere
- Spherical harmonics : Θ,ϕ (FFT)
- Radiale structure : finite differences (order 4 or 6)

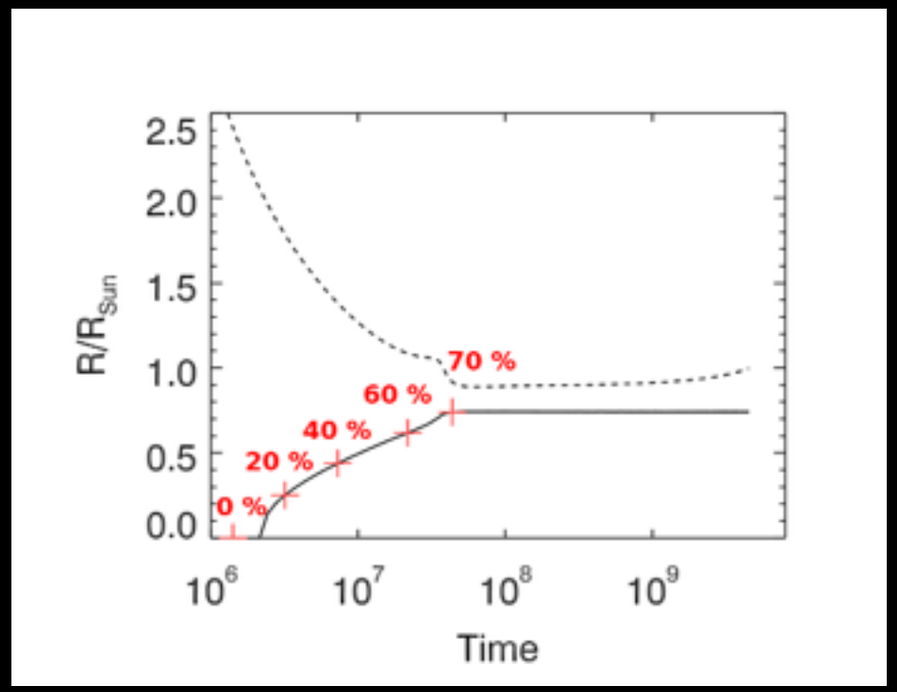
1D secular evolution

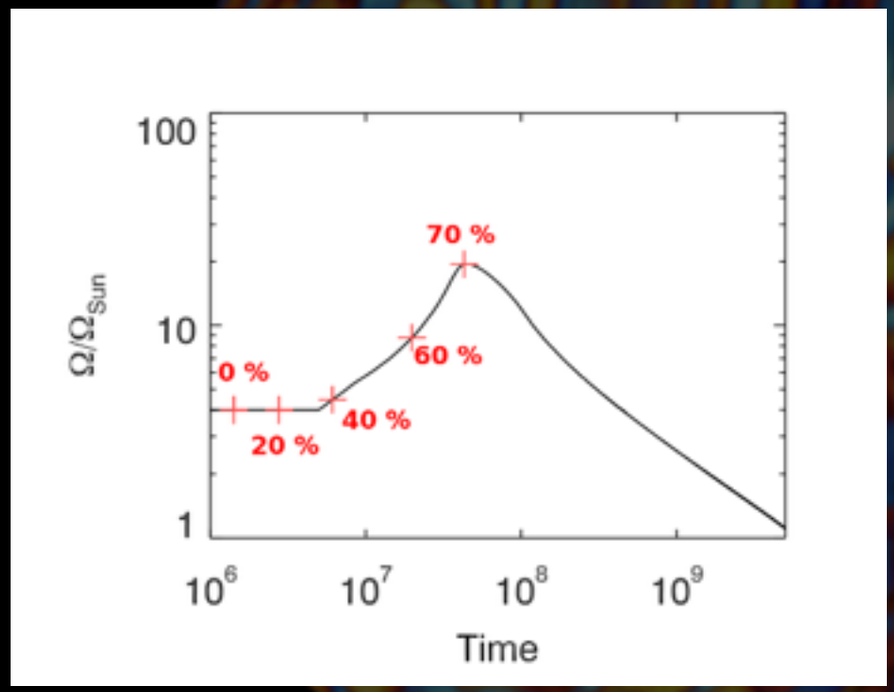


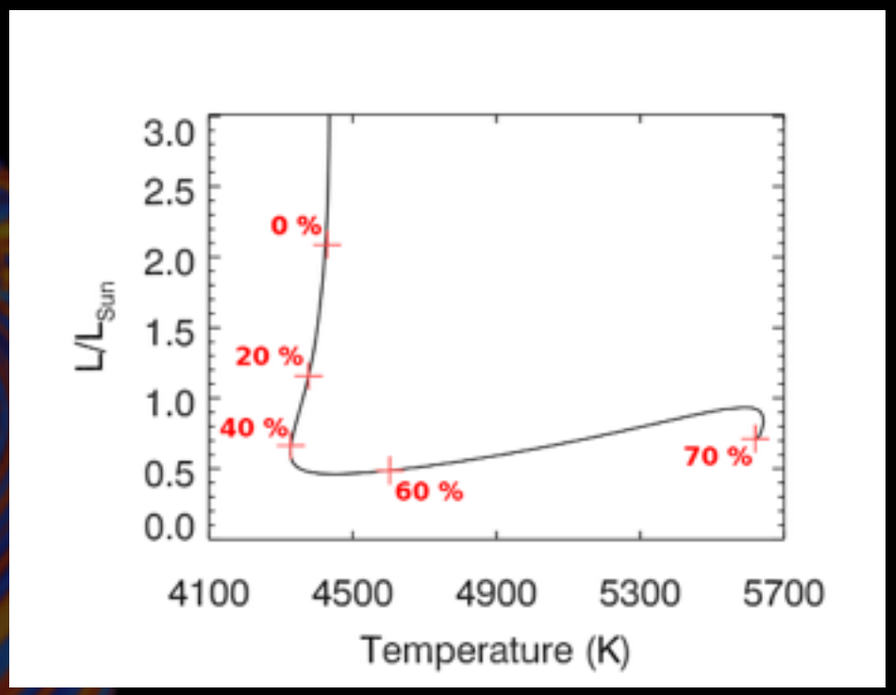




Choice of our ASH models

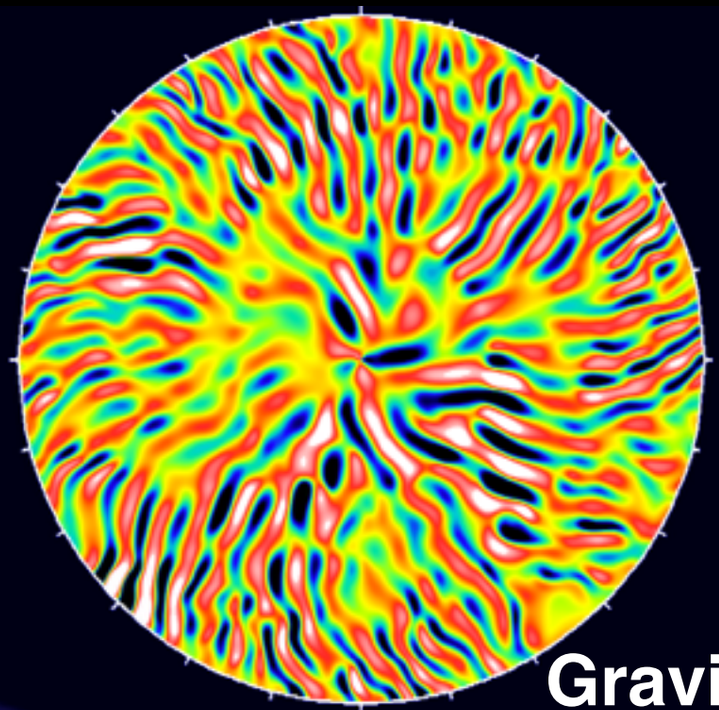




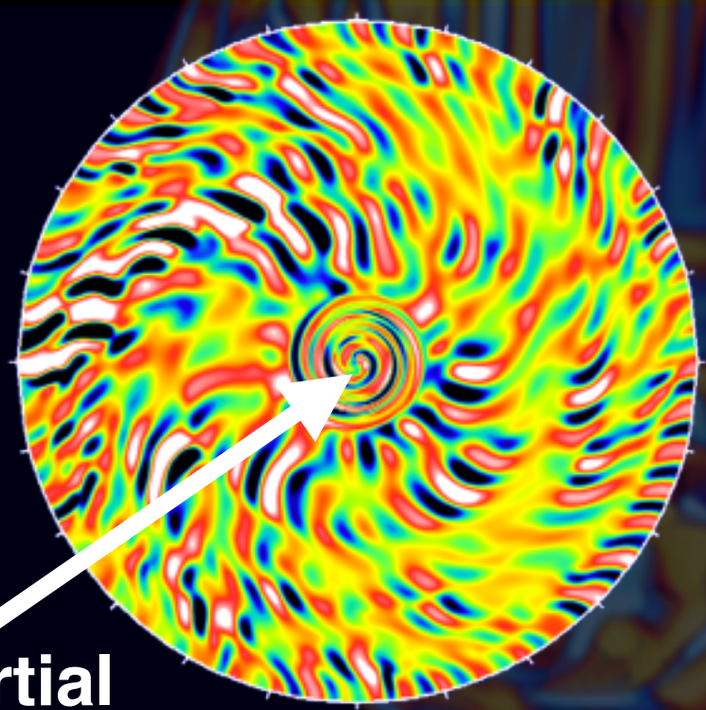


Hydrodynamical models

FullConv

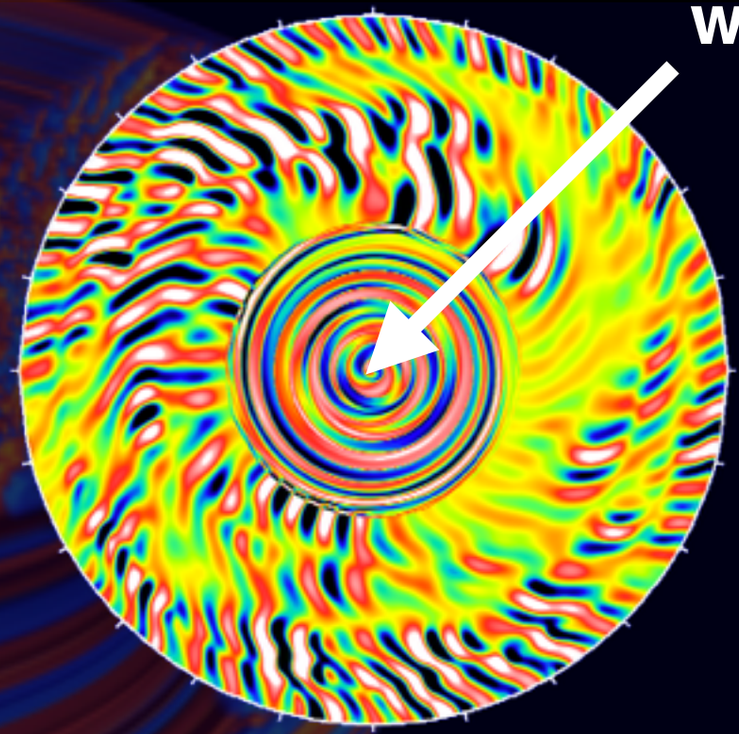


20% RZ

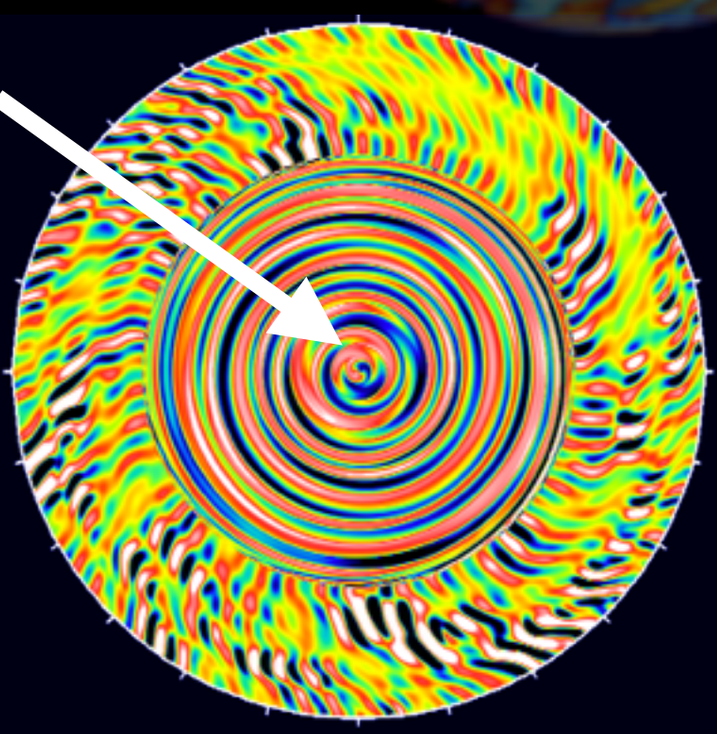


Gravito-inertial waves

40% RZ



60% RZ



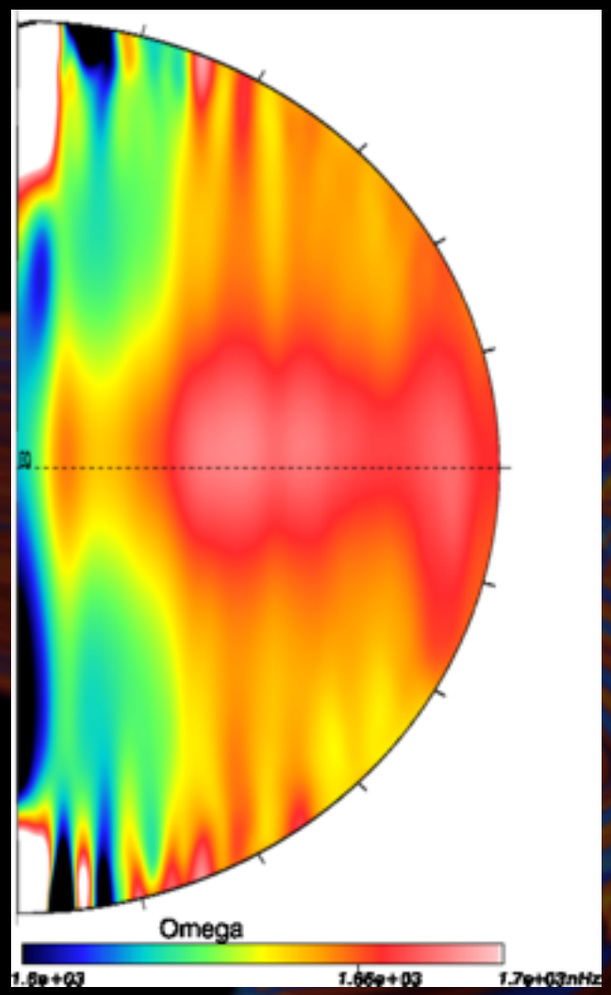
Hydrodynamical models

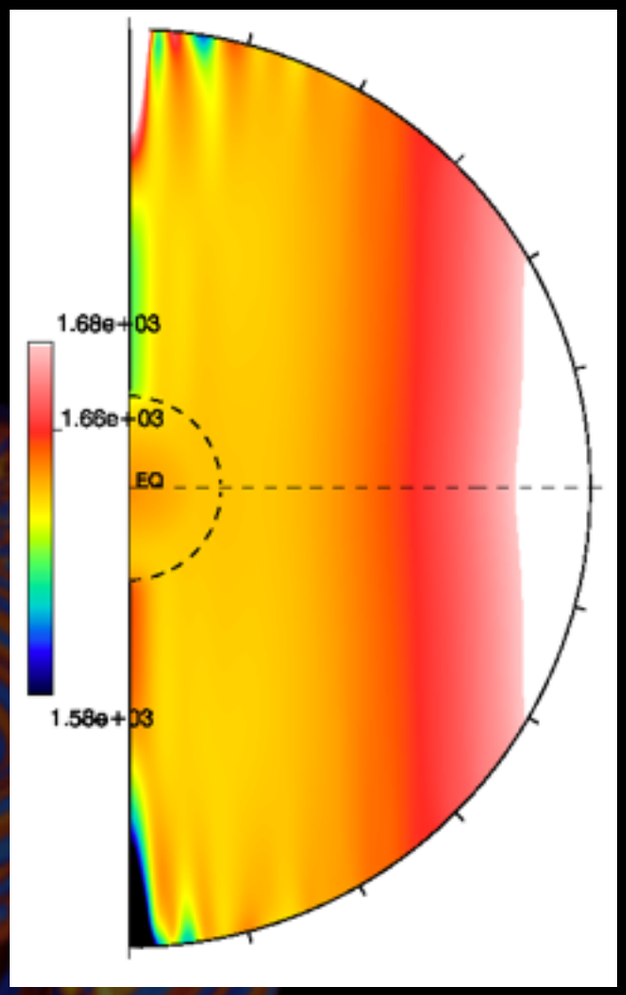
FullConv
4 Ω_{sun}

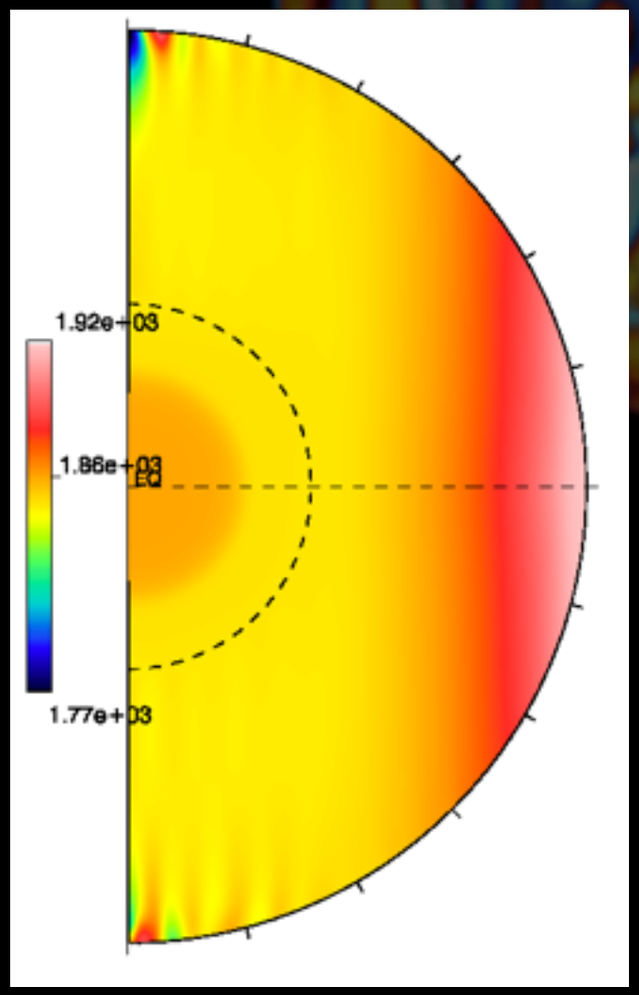
20% RZ
4 Ω_{sun}

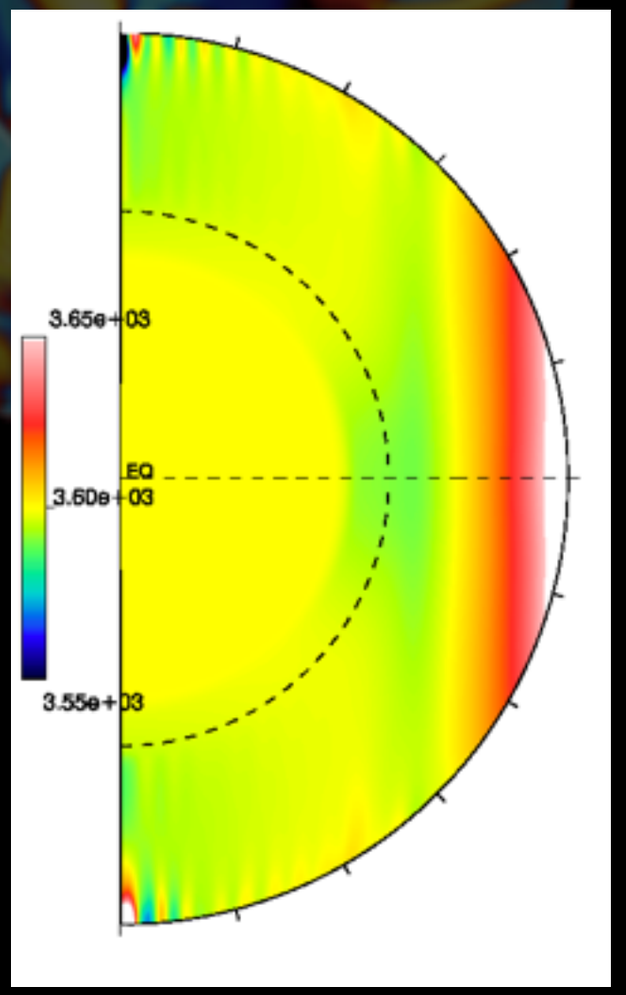
40% RZ
4.5 Ω_{sun}

60% RZ
8.7 Ω_{sun}

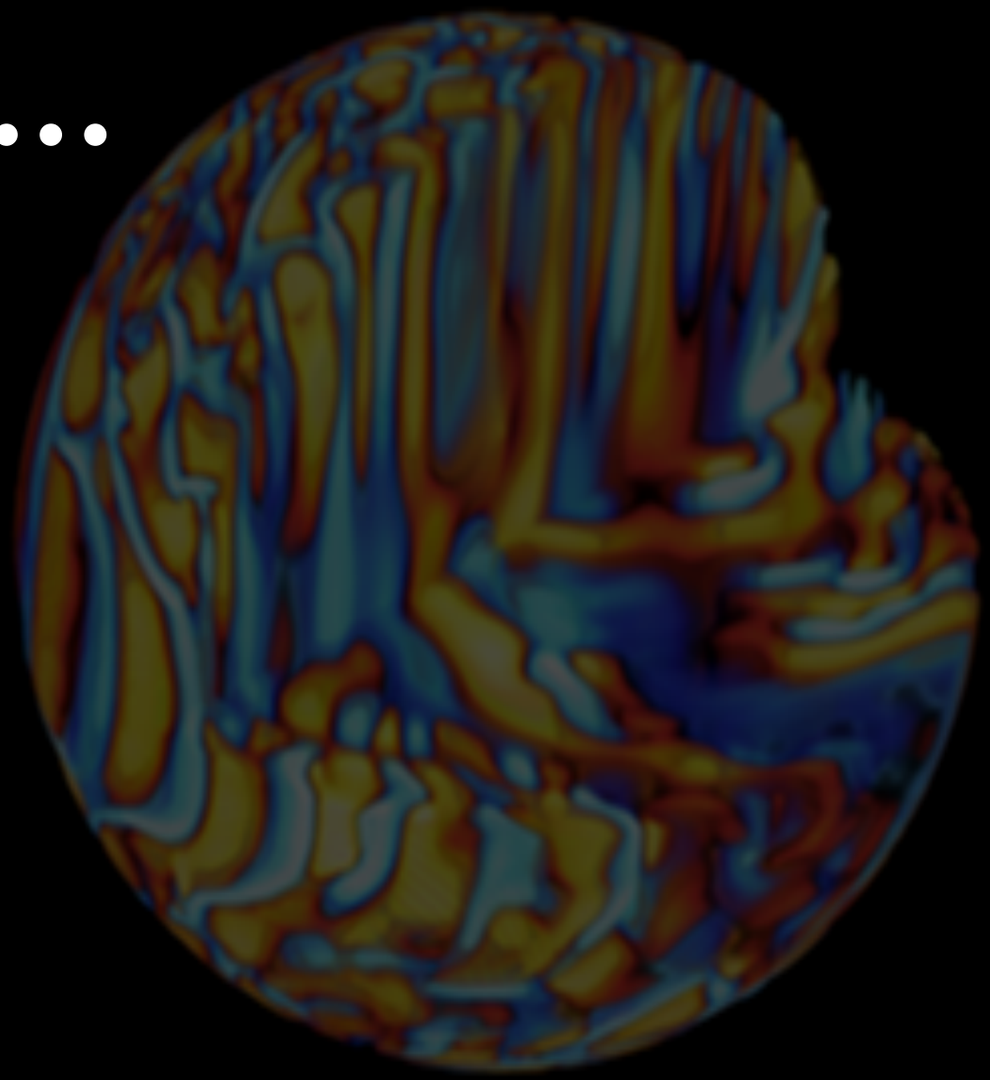








How to …



Seed magnetic field
(confined dipole)

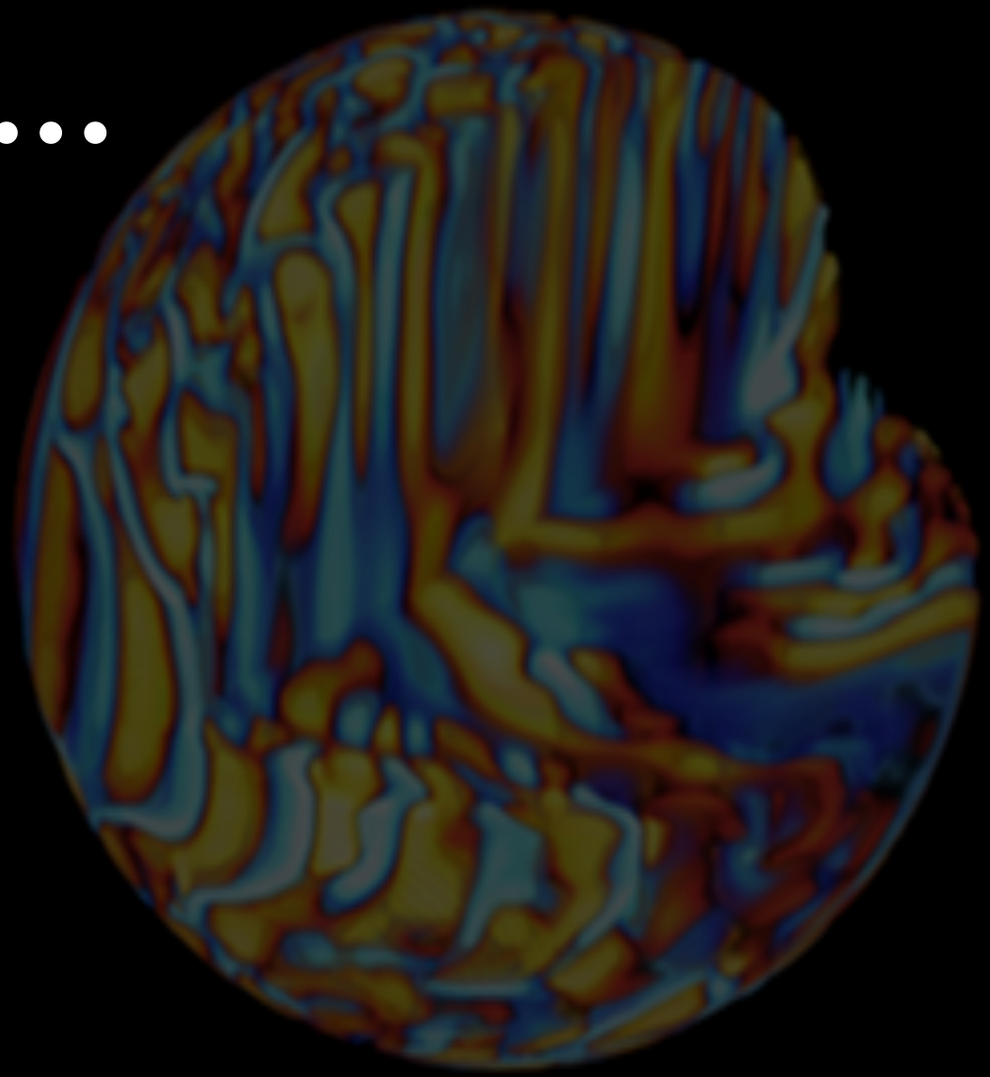
Fully convective
hydrodynamical
model

Relaxation

Fully convective
MHD model

final relaxed
magnetic field

How to …



Seed magnetic field
(confined dipole)

Fully convective hydrodynamical model

Relaxation

Fully convective MHD model

final relaxed magnetic field

20% radiative hydrodynamical model

Relaxation

20% radiative MHD model

final relaxed magnetic field

How to …

Seed magnetic field (confined dipole)

Fully convective hydrodynamical model

Relaxation

Fully convective MHD model

final relaxed magnetic field

20% radiative hydrodynamical model

Relaxation

20% radiative MHD model

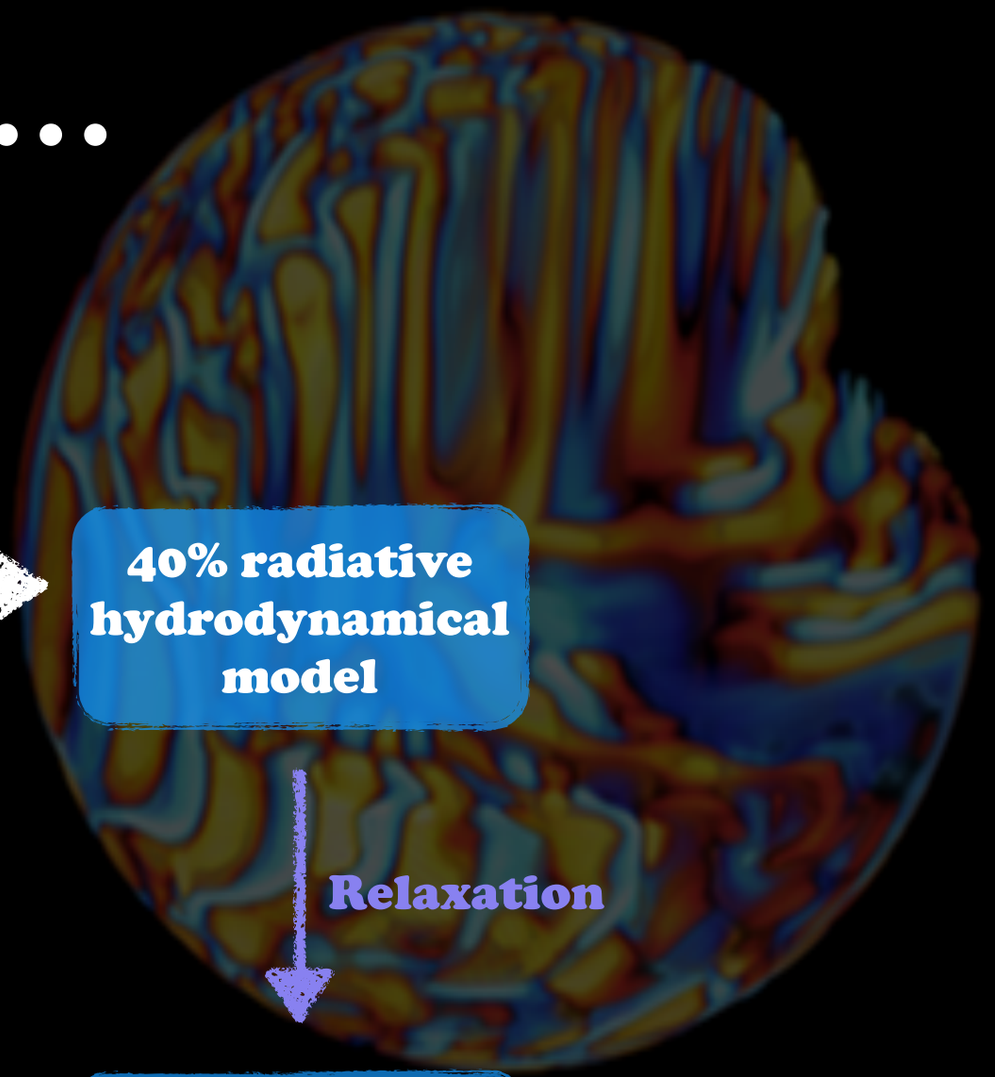
final relaxed magnetic field

40% radiative hydrodynamical model

Relaxation

40% radiative MHD model

final relaxed magnetic field



How to …

Seed magnetic field (confined dipole)

Fully convective hydrodynamical model

Relaxation

Fully convective MHD model

final relaxed magnetic field

20% radiative hydrodynamical model

Relaxation

20% radiative MHD model

final relaxed magnetic field

40% radiative hydrodynamical model

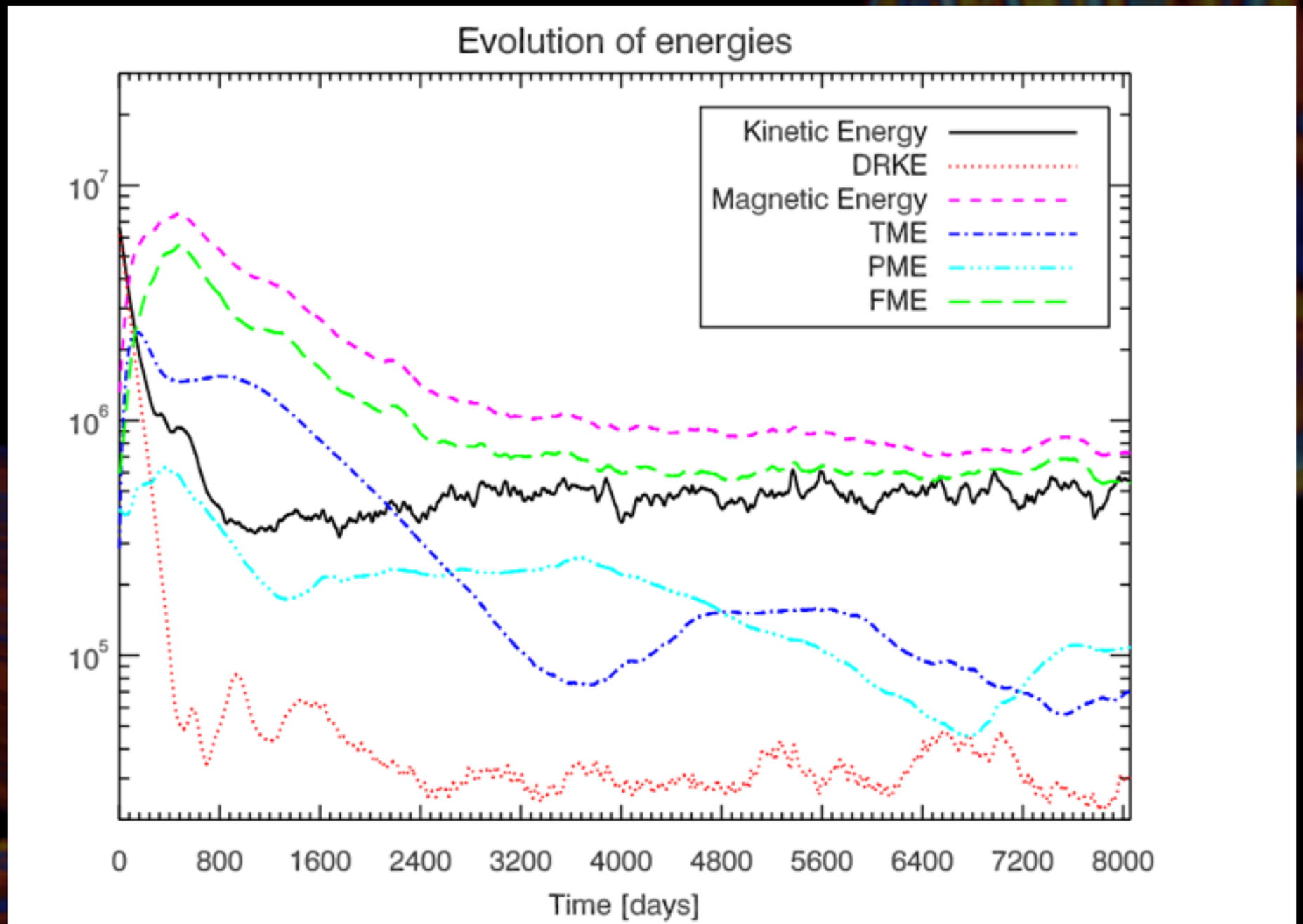
Relaxation

40% radiative MHD model

final relaxed magnetic field

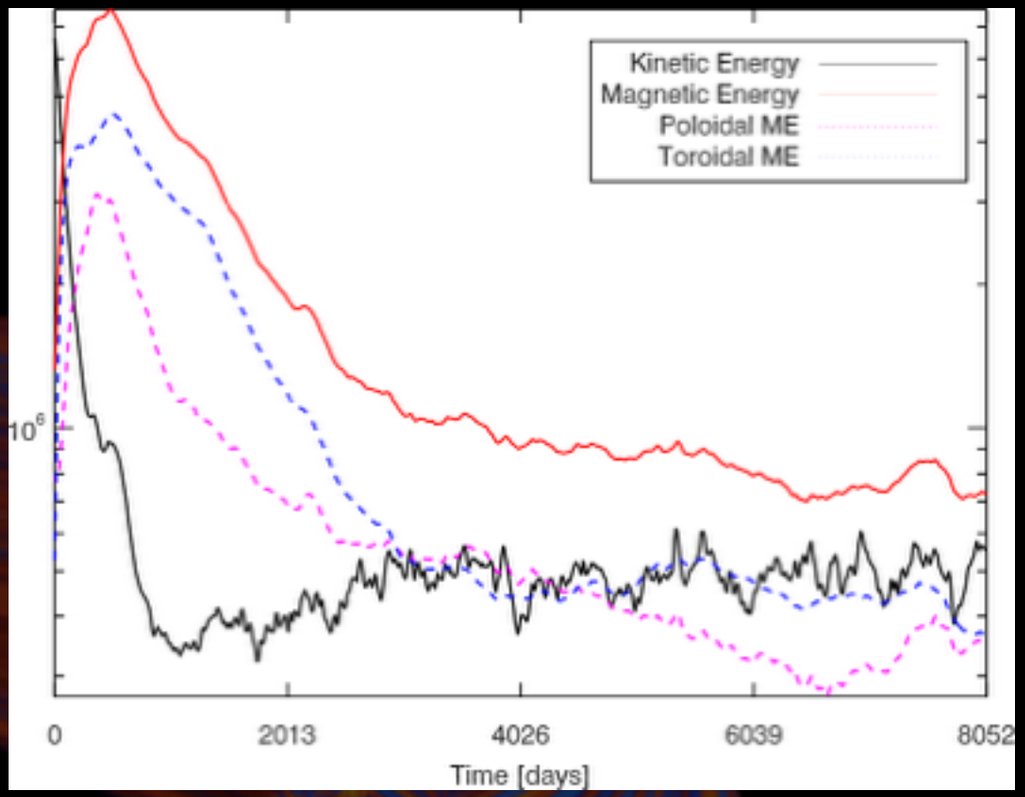
…

Energy relaxation

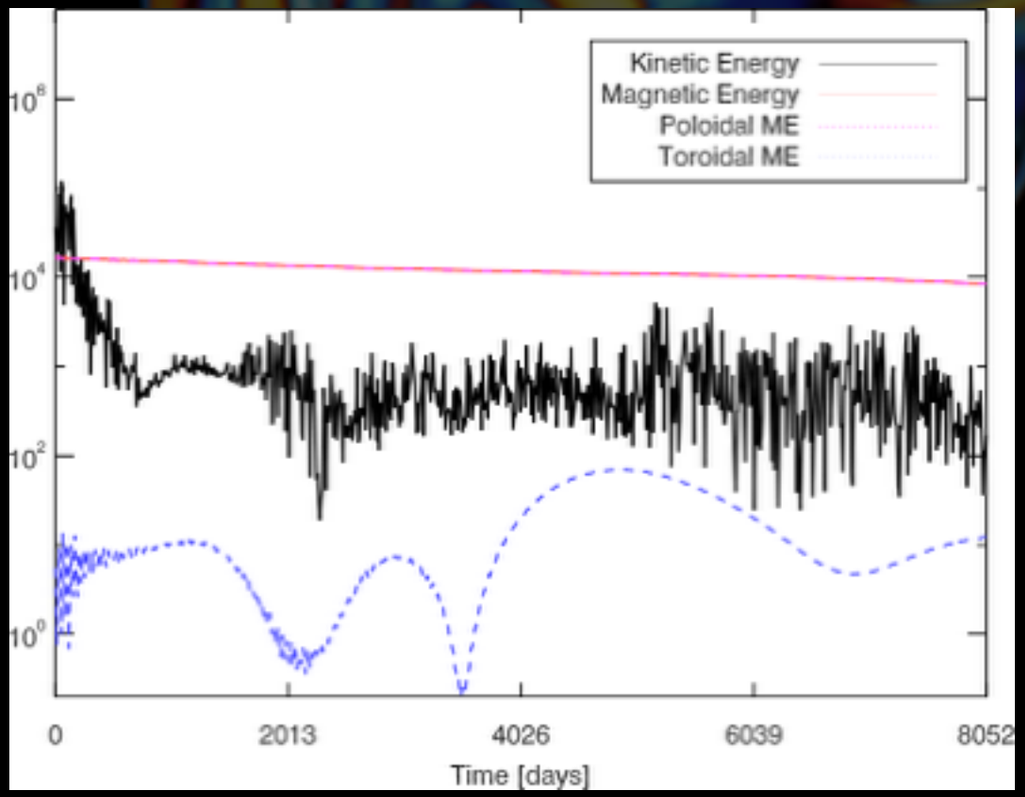


Energy relaxation

Convective zone

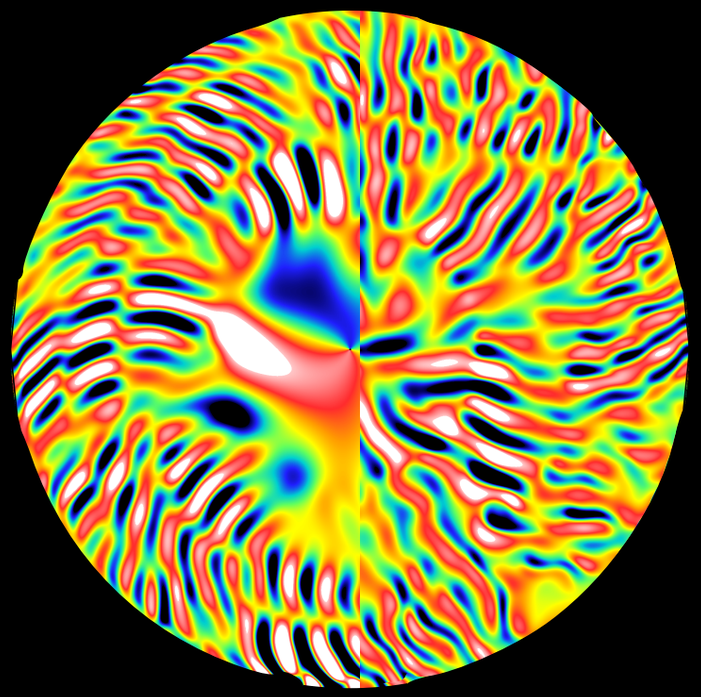


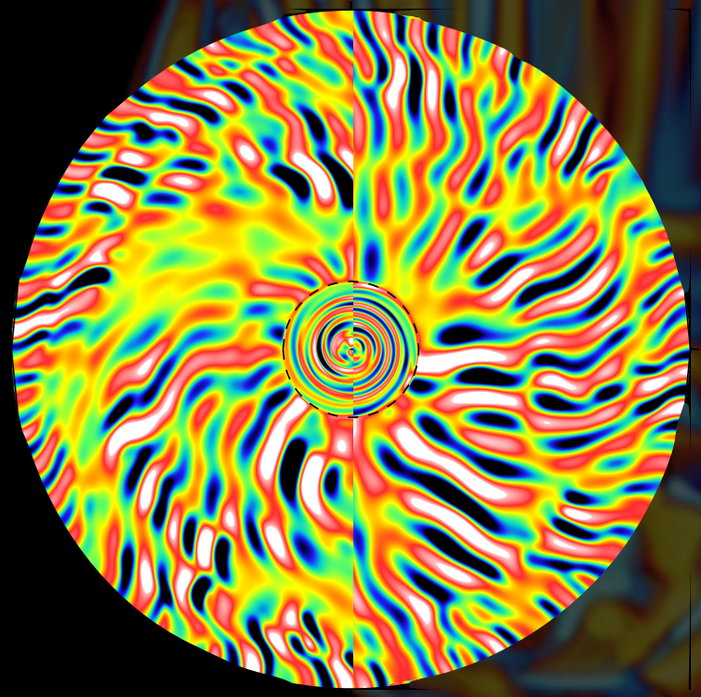
Radiative zone



HD vs MHD Convection

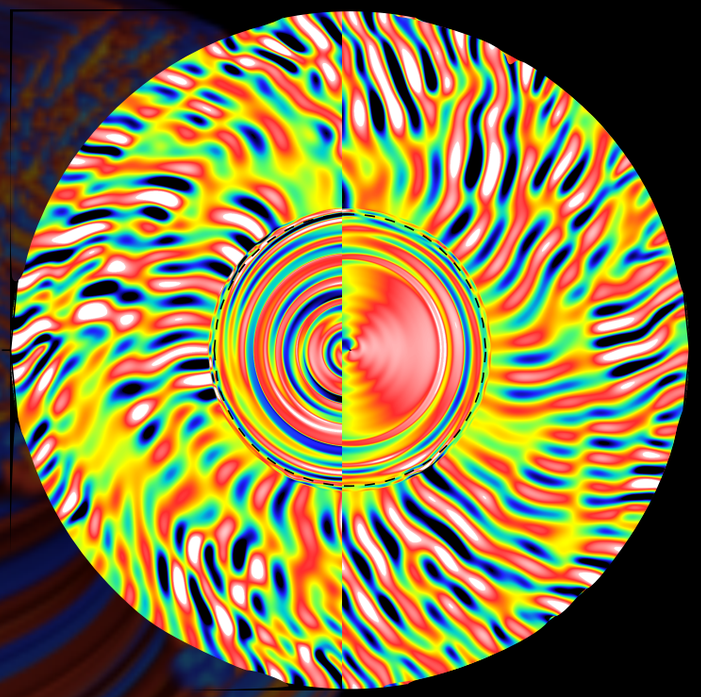
FullConv

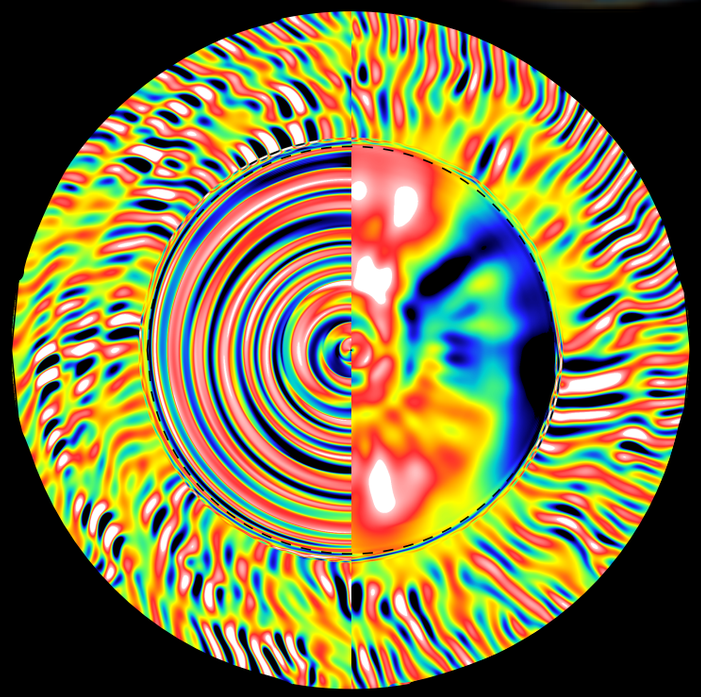




20% RZ

40% RZ



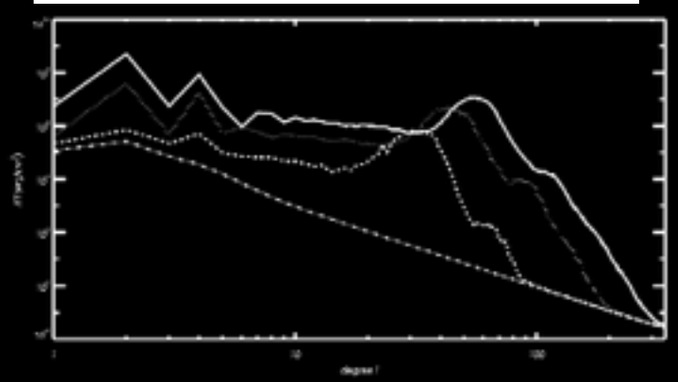


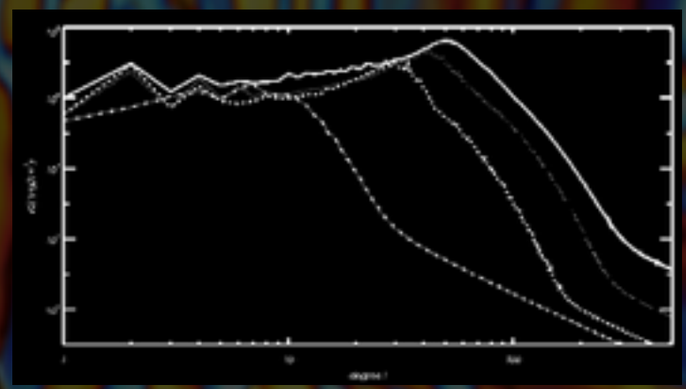
60% RZ

HD vs MHD

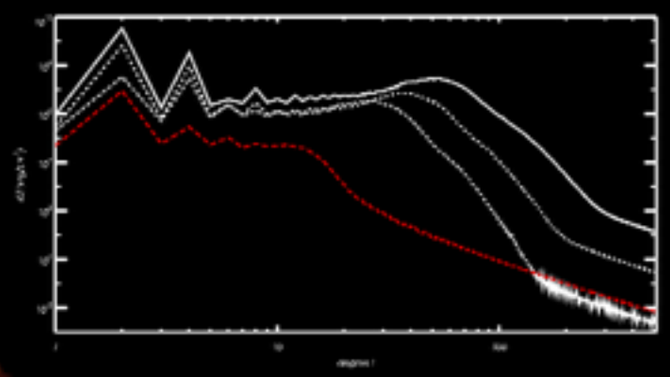
Kinetic energy spectra

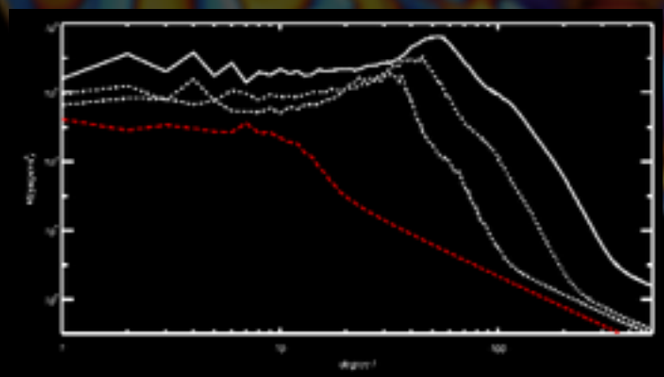
FullConv



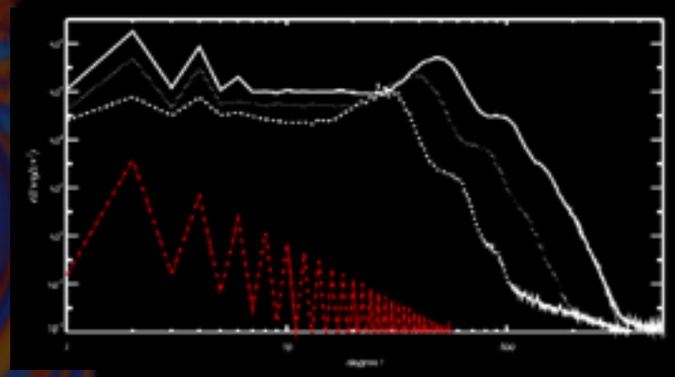


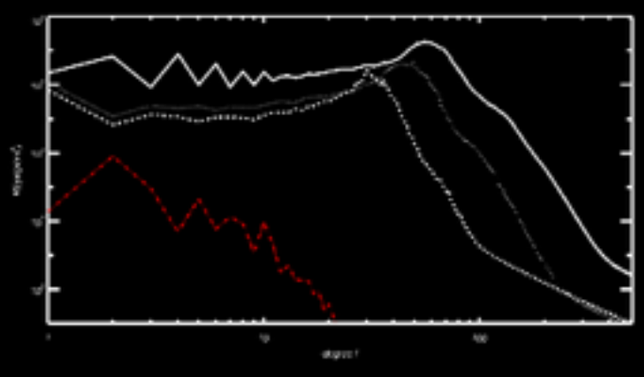
20% RZ





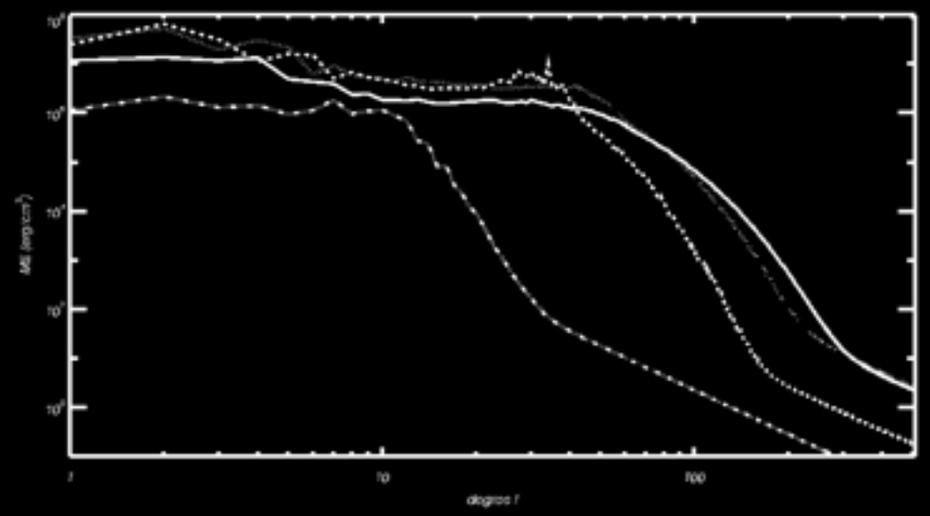
40% RZ

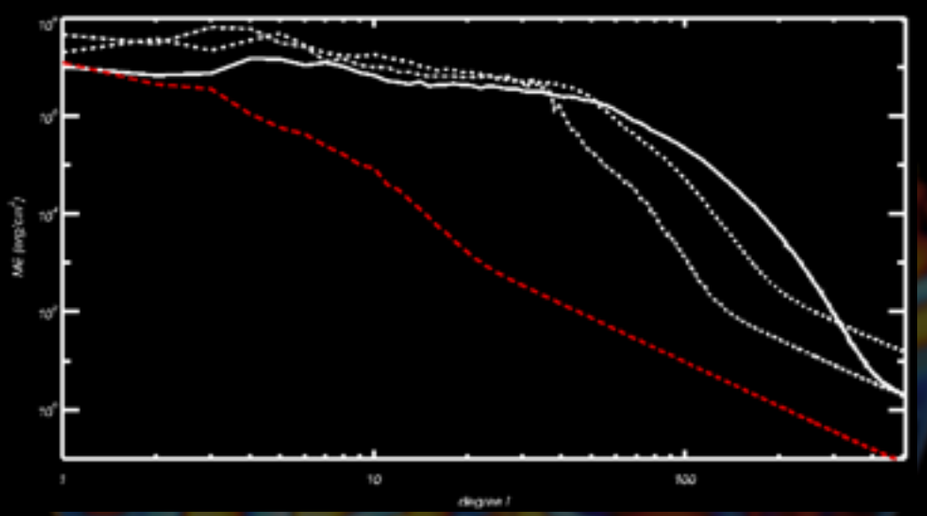




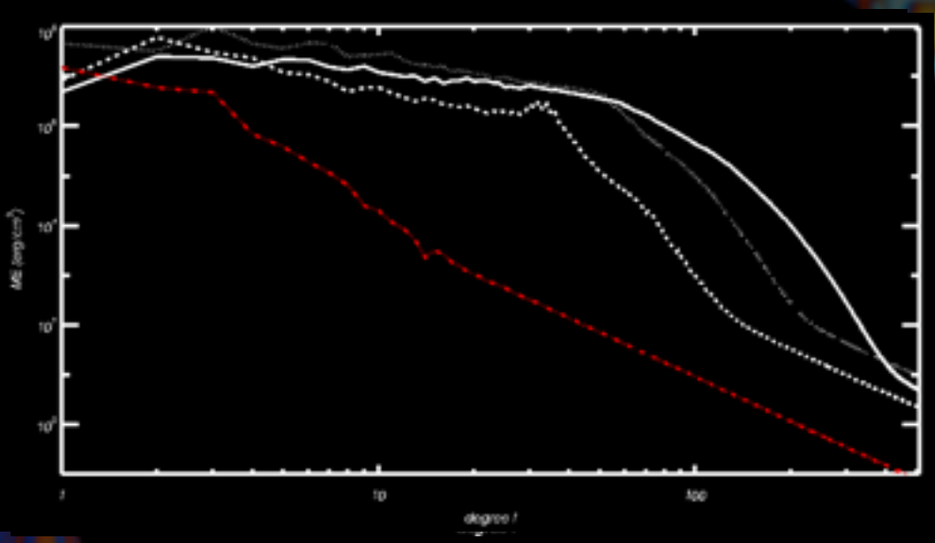
Radii : 95 % - 75 % - 60 % - 4 %

Magnetic energy spectra





FullConv

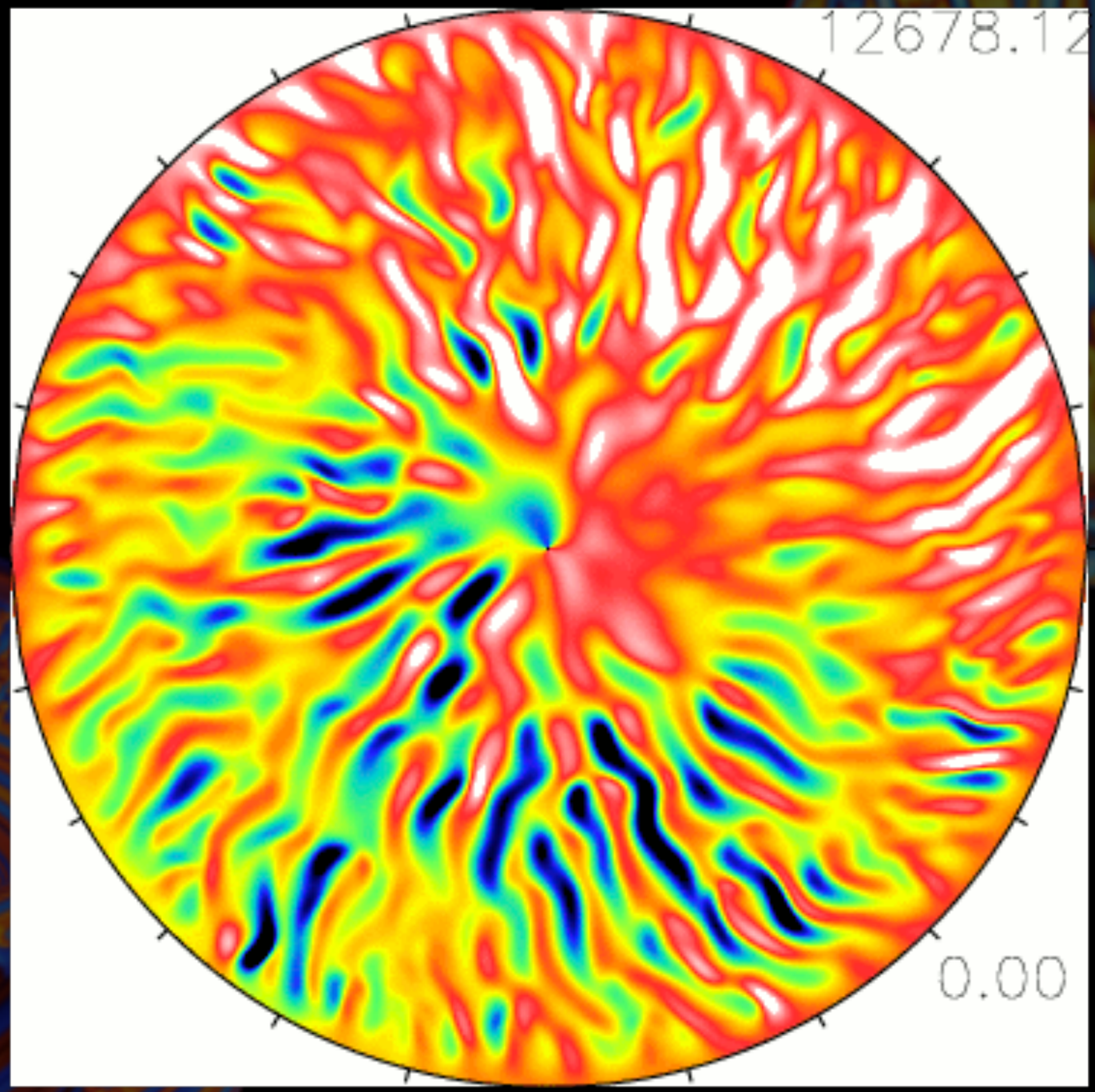


20% RZ

40% RZ

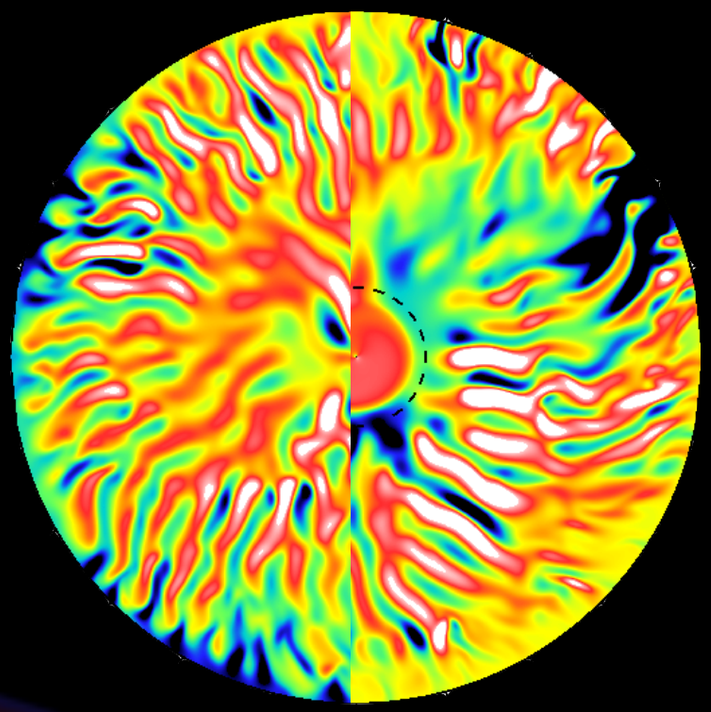
Radii : 95 % - 75 % - 60 % - 4 %

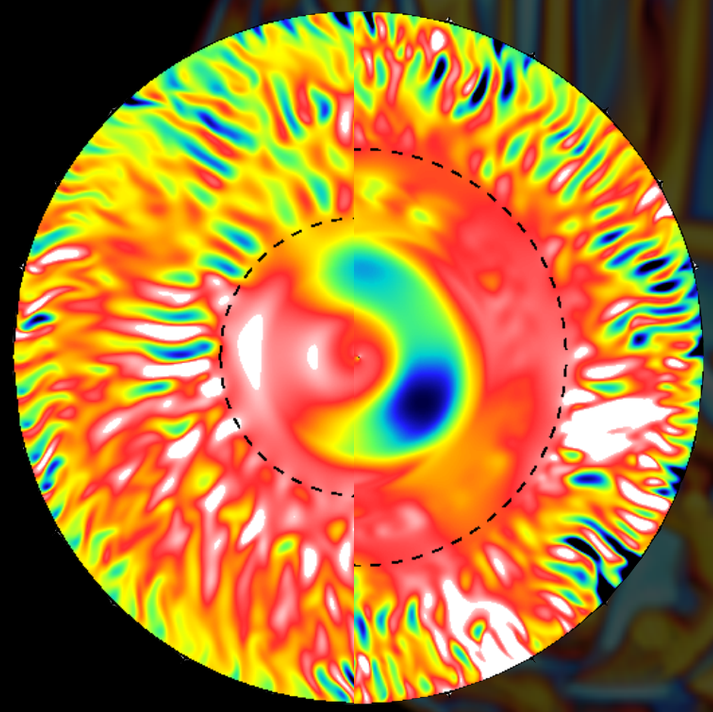
MHD magnetic field evolution



MHD magnetic field

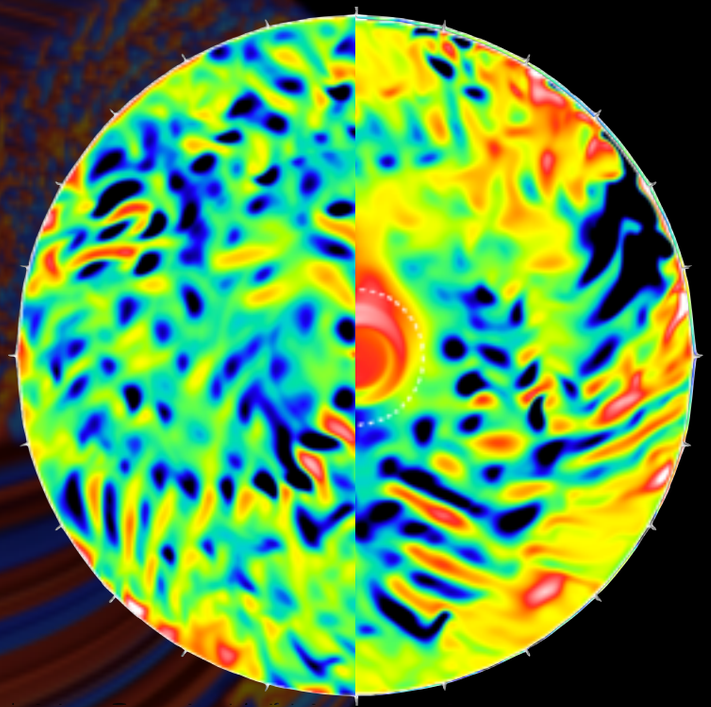
Br

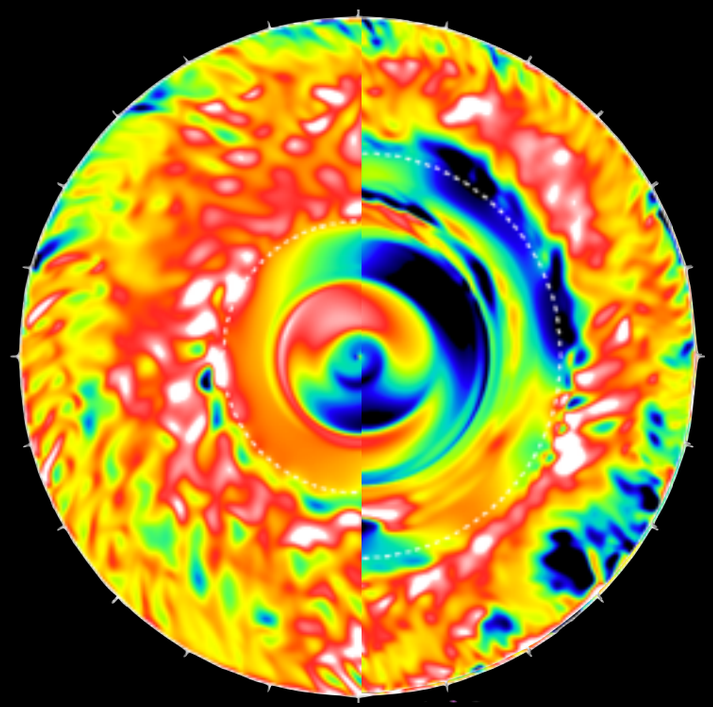




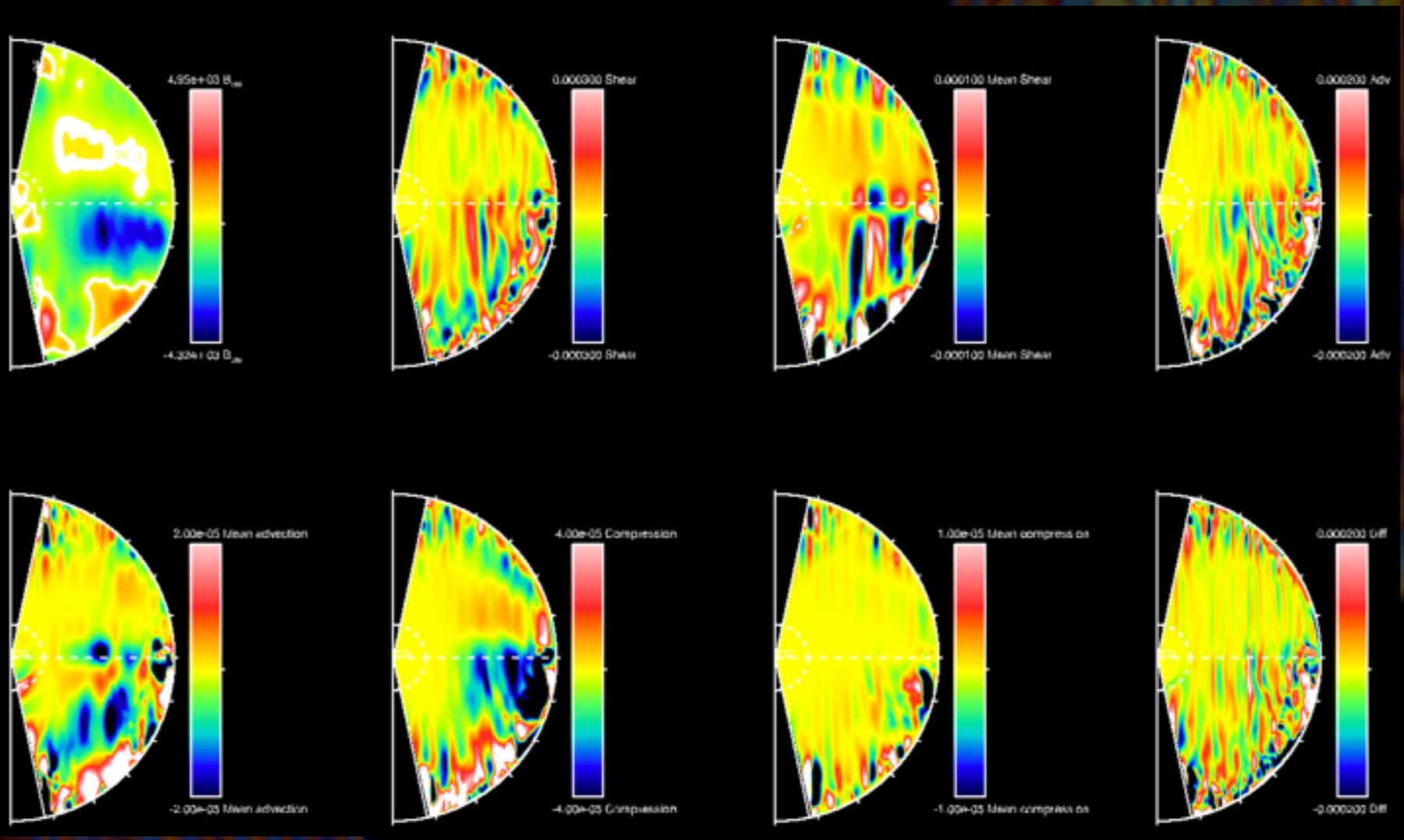
FC 20% 40% 60%

Bϕ





Magnetic field generation



$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = P_{FS} + P_{MS} + P_{FA} + P_{MA} + P_{FC} + P_{MC} + P_{MD}$$

Conclusion and perspectives

- Complete models with radiative zone at 60% and 70% to finish the PMS study

- Develop analysis of magnetic field dynamo (generation, α-Ω effect, butterfly diagram …)

- Deepen analysis of spectra

- Compute models for the MS study