# DYNAMO ACTION IN STARS

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*Joint work with:*

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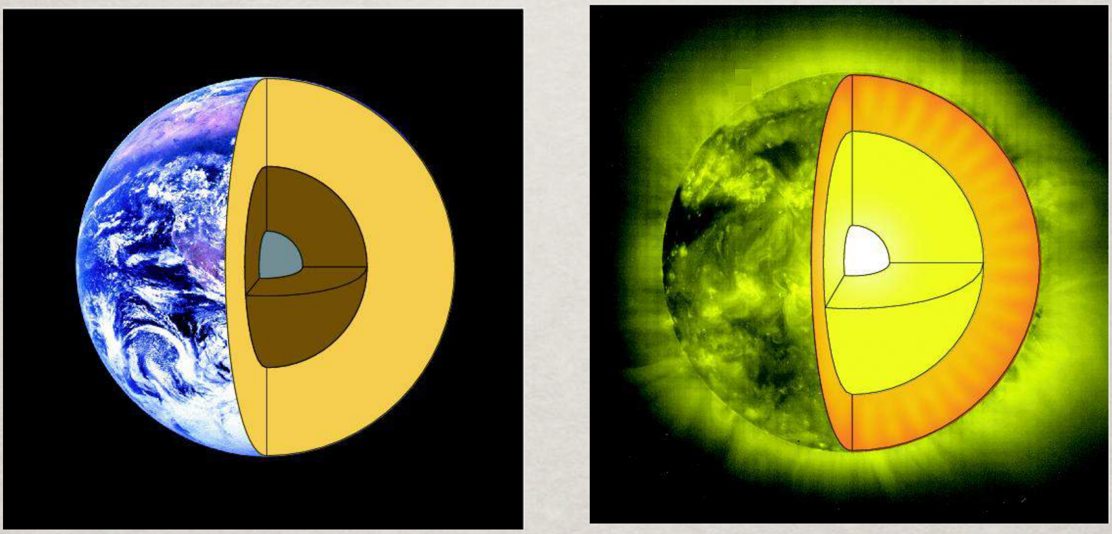
Raphaël Raynaud
Julien Morin
Jean-François Donati

$$
\begin{cases}
E_\eta \left( \dfrac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \boldsymbol{\nabla}) \mathbf{u} \right) = -\boldsymbol{\nabla} \pi + E \, \Delta \mathbf{u} - \mathbf{e}_z \wedge \mathbf{u} \\
\qquad\qquad\qquad + Ra \, T \mathbf{g} + (\boldsymbol{\nabla} \wedge \mathbf{B}) \wedge \mathbf{B} \, , \\
\boldsymbol{\nabla} \cdot \mathbf{u} = 0 \, , \\
\dfrac{\partial T}{\partial t} + \mathbf{u} \cdot \boldsymbol{\nabla} T = q \Delta T \, , \\
\dfrac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \wedge (\mathbf{u} \wedge \mathbf{B}) + \Delta \mathbf{B} \, , \\
\boldsymbol{\nabla} \cdot \mathbf{B} = 0 \, .
\end{cases}
$$

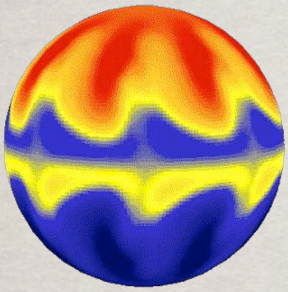
$$
E_\eta = \frac{\eta}{2\Omega \mathcal{L}^2} \, , \quad E = \frac{\nu}{2\Omega \mathcal{L}^2} \, , \quad q = \frac{\kappa}{\eta} \, .
$$

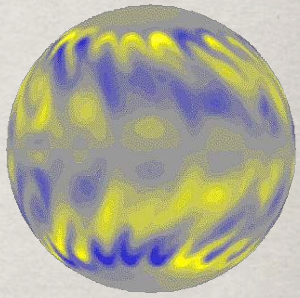
From the Earth to the stars…

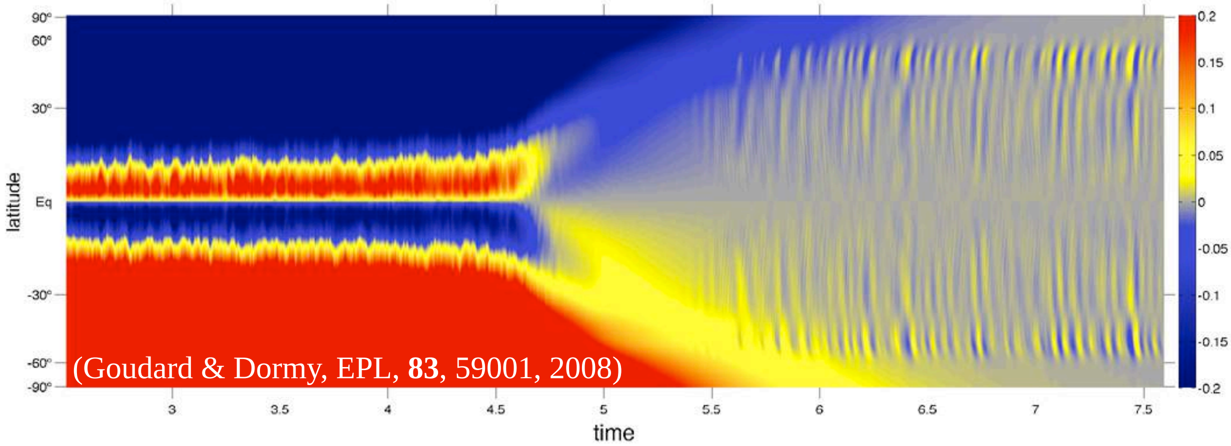


Goudard & Dormy, Europhysics Letters EPL, **83**, 59001, 2008

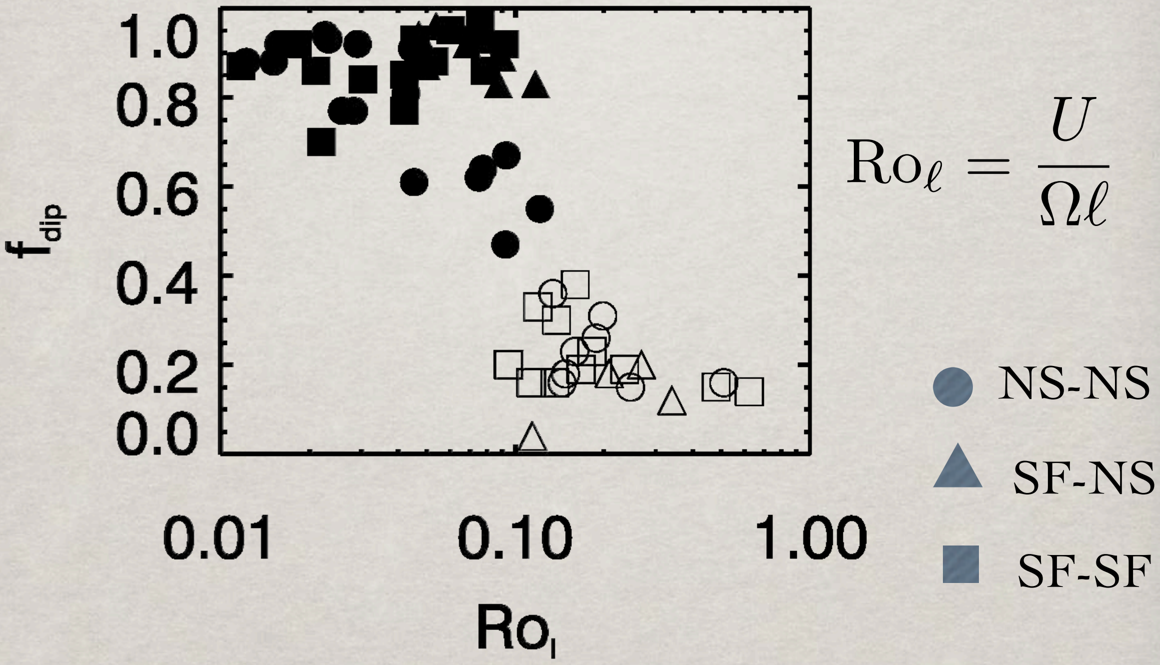
# From the Earth to the stars…








Transition between both dynamo modes
as a function of the local Rossby number




$$\mathrm{Ro}_\ell = \frac{U}{\Omega \ell}$$

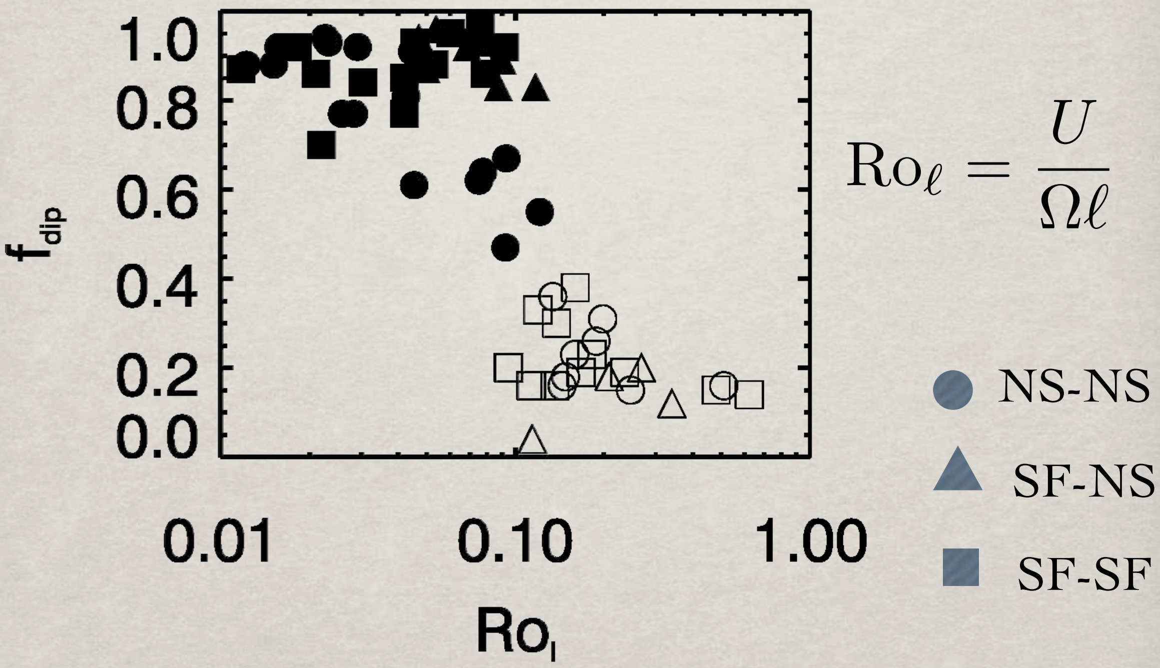
Schrinner, Petitdemange, Dormy, ApJ, 2012

Transition between both dynamo modes
as a function of the local Rossby number

| r_i/r_o | l_mean | E_kin | Ro_l |
|---|---|---|---|
| 0.5 | 11.0 | 90 | $4.7\,10^{-2}$ |
| 0.55 | 13.2 | 82 | $5.4\,10^{-2}$ |
| 0.6 | 16.4 | 86 | $6.9\,10^{-2}$ |
| 0.65 | 20.1 | 160 | $1.1\,10^{-1}$ |

Schrinner, Petitdemange, Dormy, ApJ, 2012

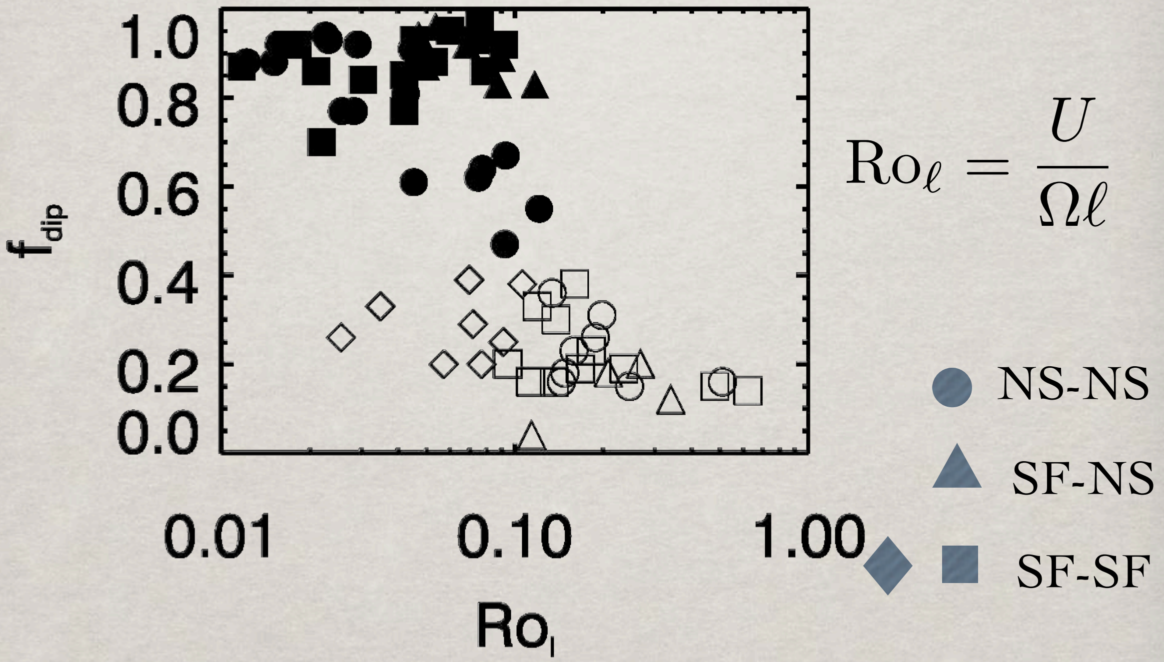
Transition between both dynamo modes
as a function of the local Rossby number




$$Ro_\ell = \frac{U}{\Omega \ell}$$

Schrinner, Petitdemange, Dormy, ApJ, 2012

## Transition between both dynamo modes as a function of the local Rossby number




$$\mathrm{Ro}_\ell = \frac{U}{\Omega \ell}$$

Schrinner, Petitdemange, Dormy, ApJ, 2012

## Bistability with the anelastic model:

THE ASTROPHYSICAL JOURNAL, 705:1000–1018, 2009 November 1 doi:10.1088/0004-637X/705/1/1000


EFFECTS OF FOSSIL MAGNETIC FIELDS ON CONVECTIVE CORE DYNAMOS IN A-TYPE STARS

NICHOLAS A. FEATHERSTONE[1], MATTHEW K. BROWNING[2], ALLAN SACHA BRUN[3], AND JURI TOOMRE[1]
[1] JILA and Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309-0440, USA; feathern@solarz.colorado.edu
[2] Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S3H8, Canada
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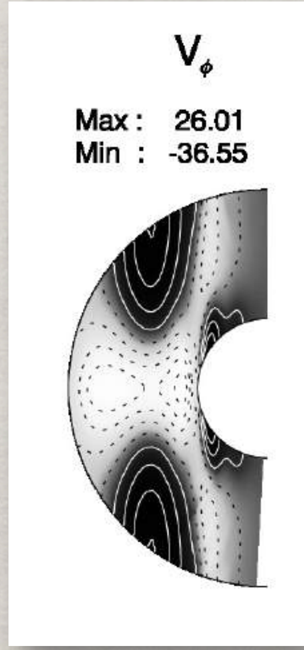
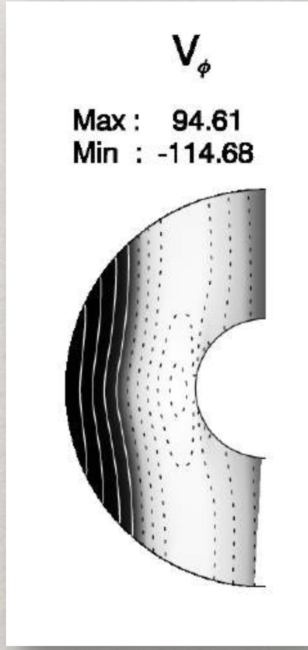
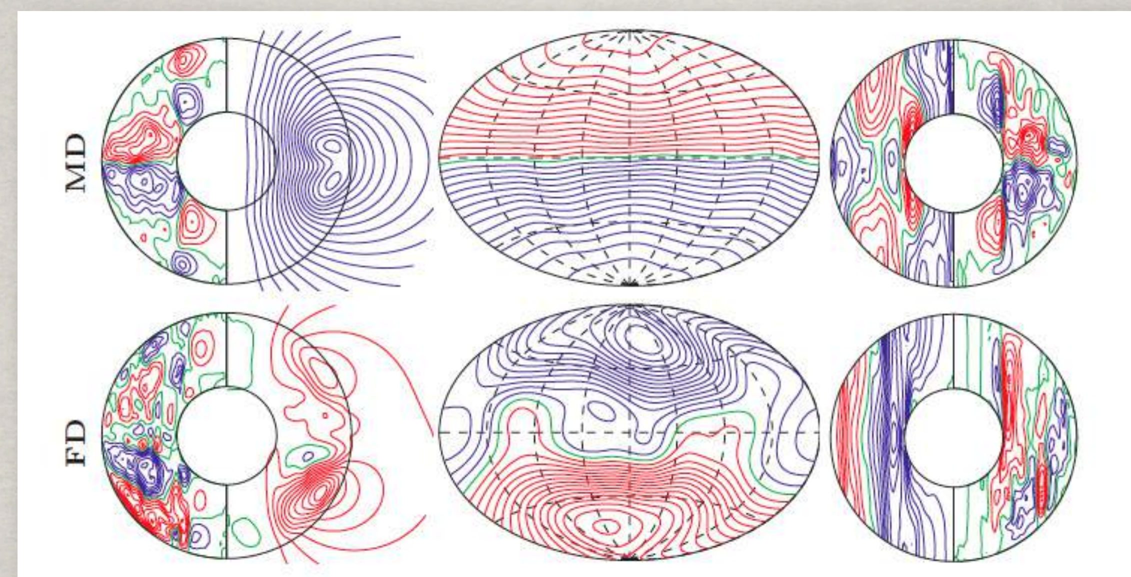
*Received 2009 May 8; accepted 2009 September 3; published 2009 October 16*

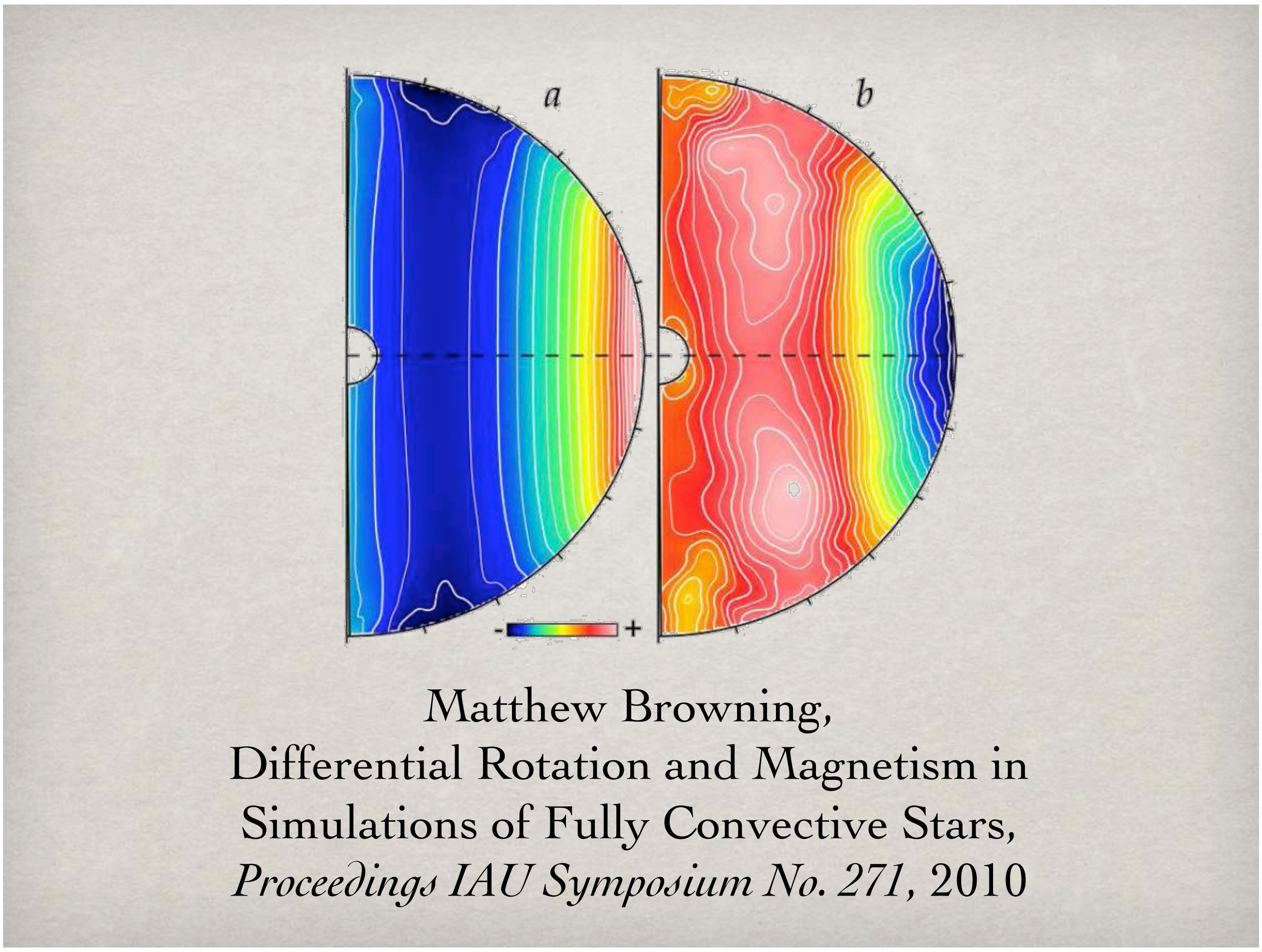
Steady Dipolar Mode Oscillating Mode

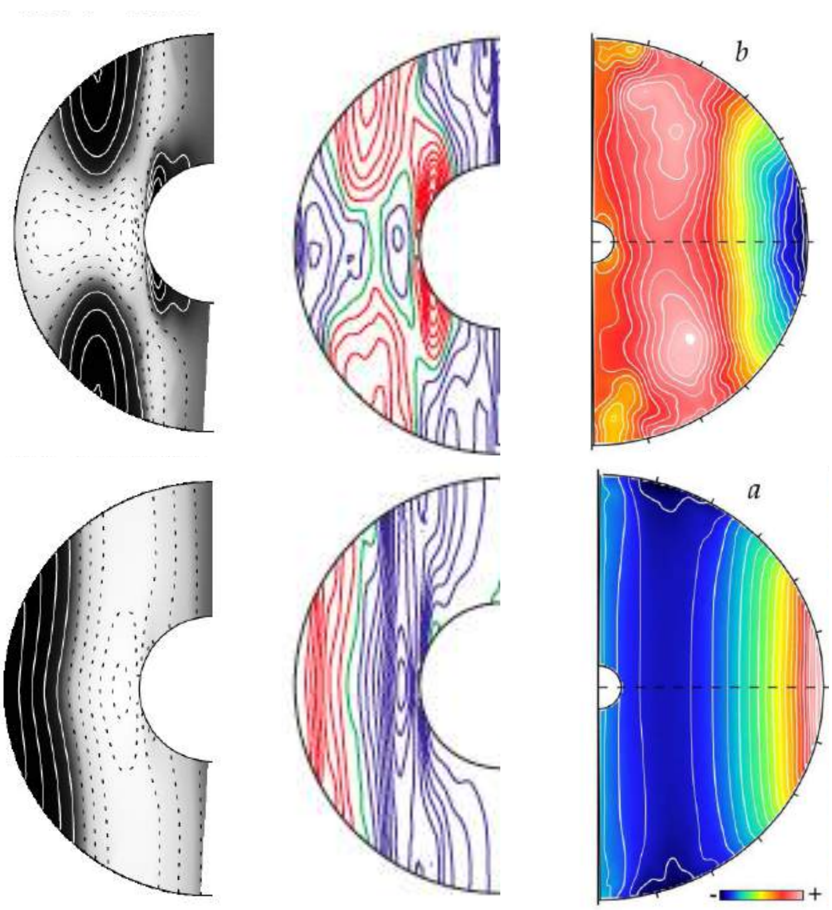


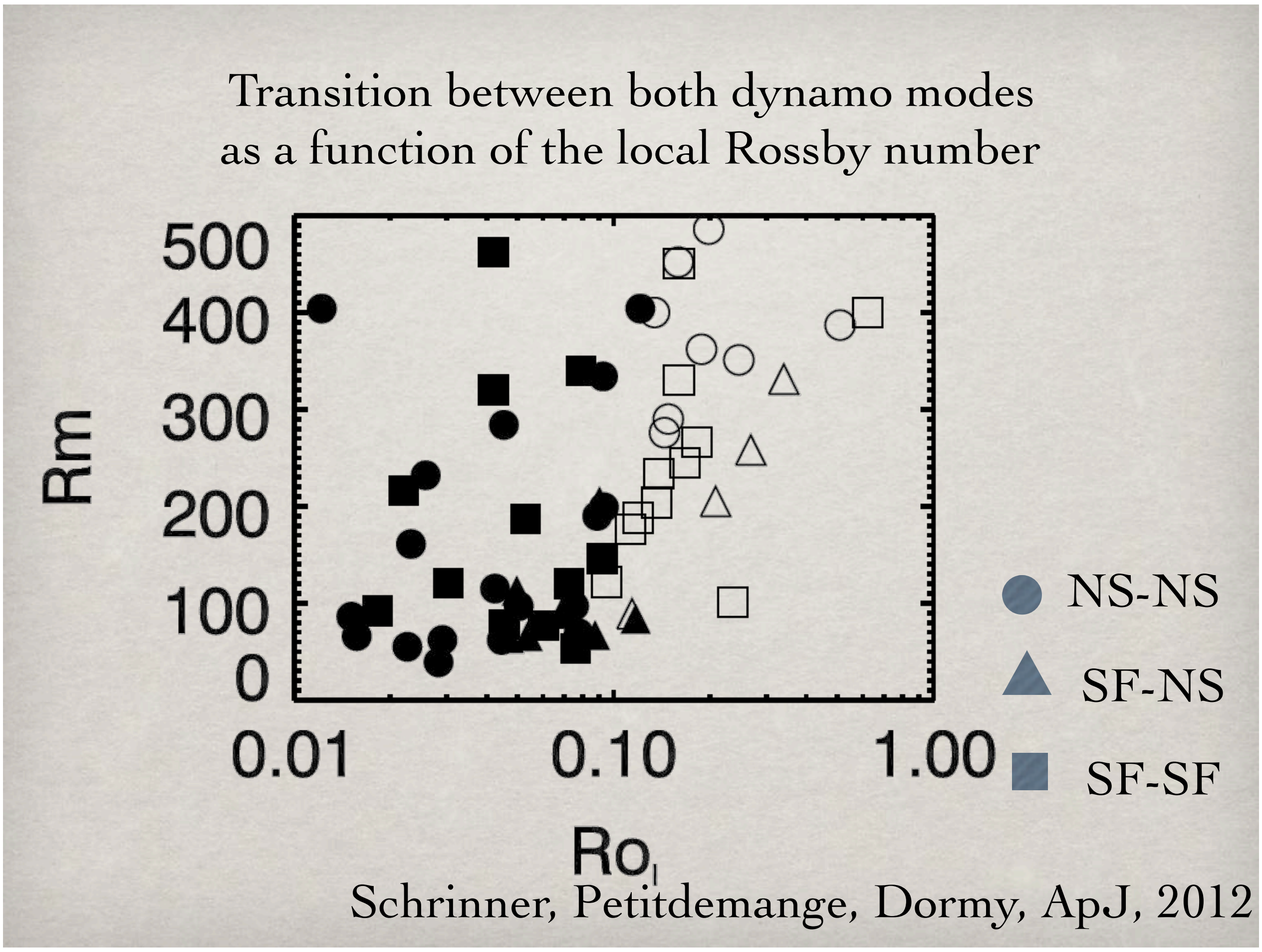



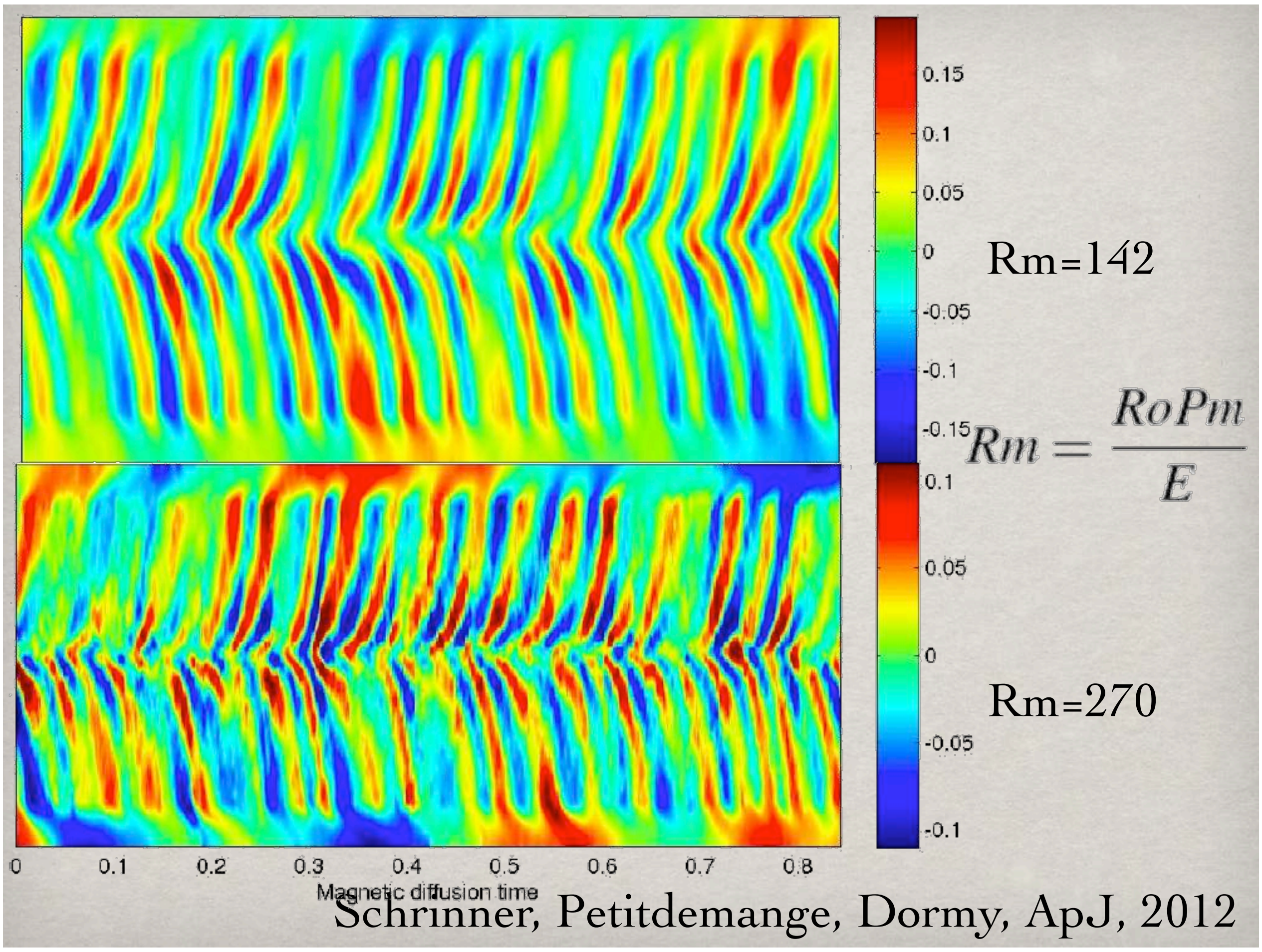



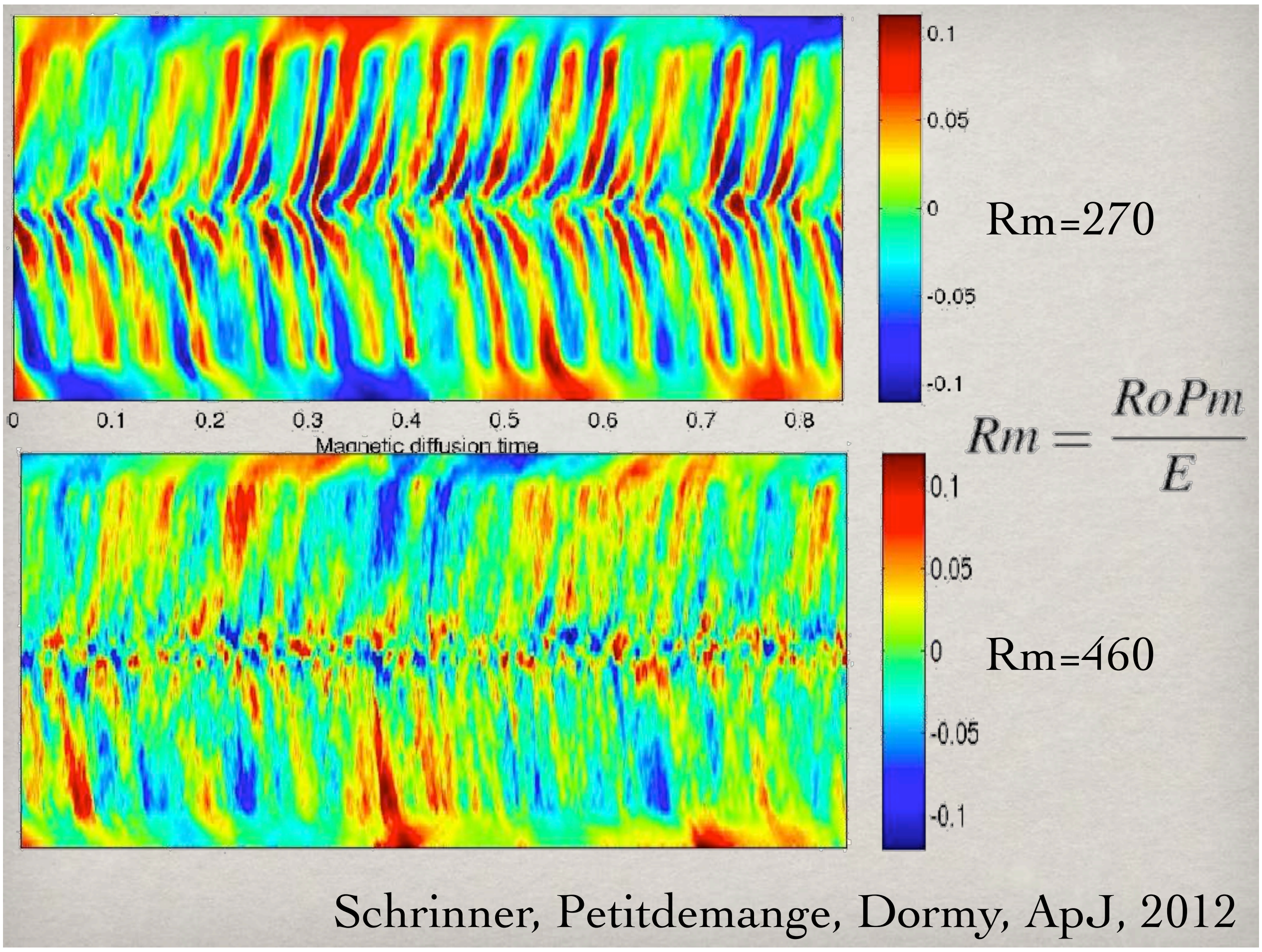

Simitev & Busse,
Bistability and hysteresis of dipolar dynamos generated by turbulent convection in rotating spherical shells,
*Europhysics Letters (EPL)*, 85 (2009) 19001

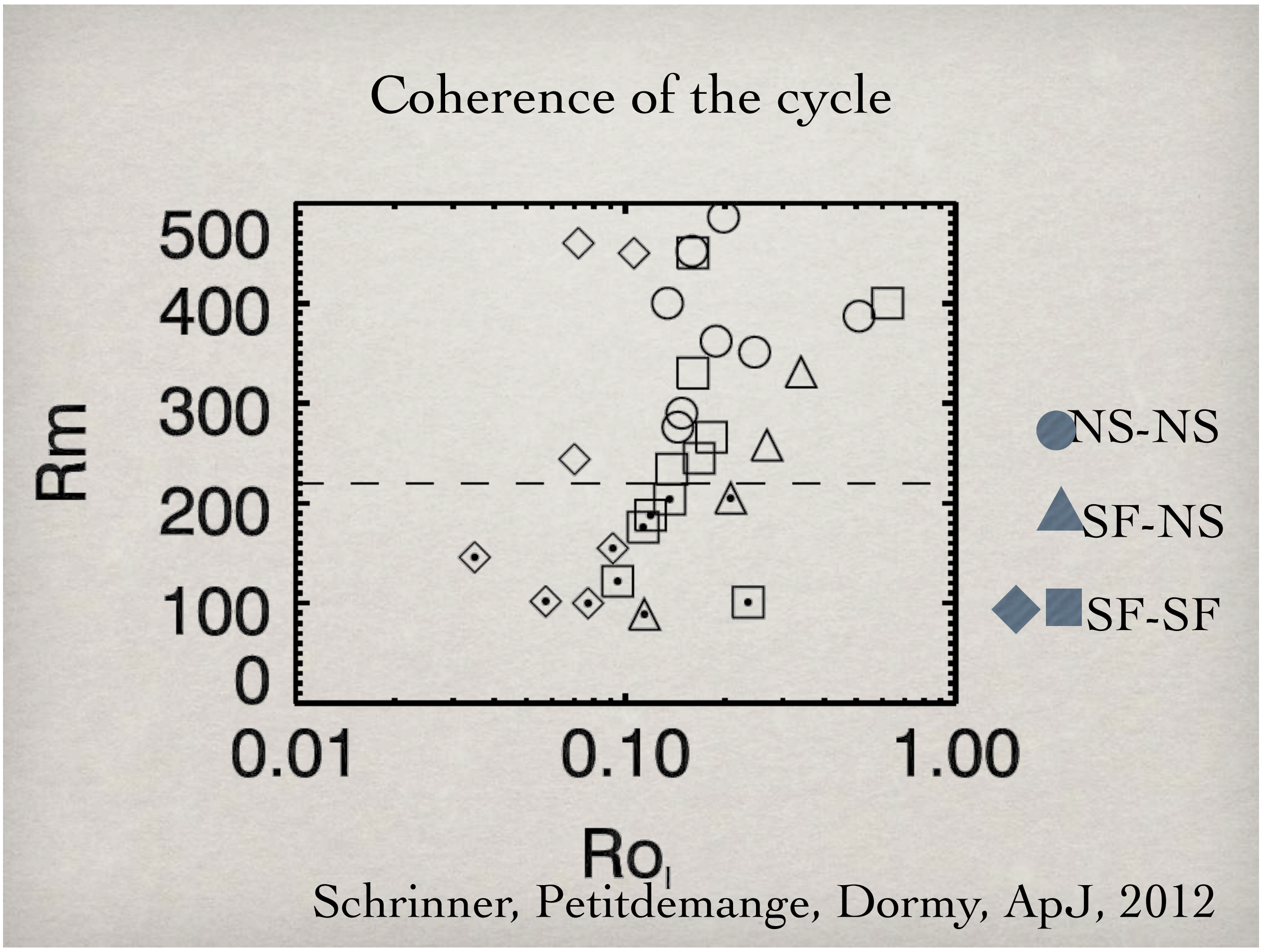

a
b
-
+
Matthew Browning,
Differential Rotation and Magnetism in
Simulations of Fully Convective Stars,
*Proceedings IAU Symposium No. 271,* 2010


b
a
-
+


Transition between both dynamo modes
as a function of the local Rossby number
Rm
500
400
300
200
100
0
0.01
0.10
1.00
Ro_l
NS-NS
SF-NS
SF-SF
Schrinner, Petitdemange, Dormy, ApJ, 2012

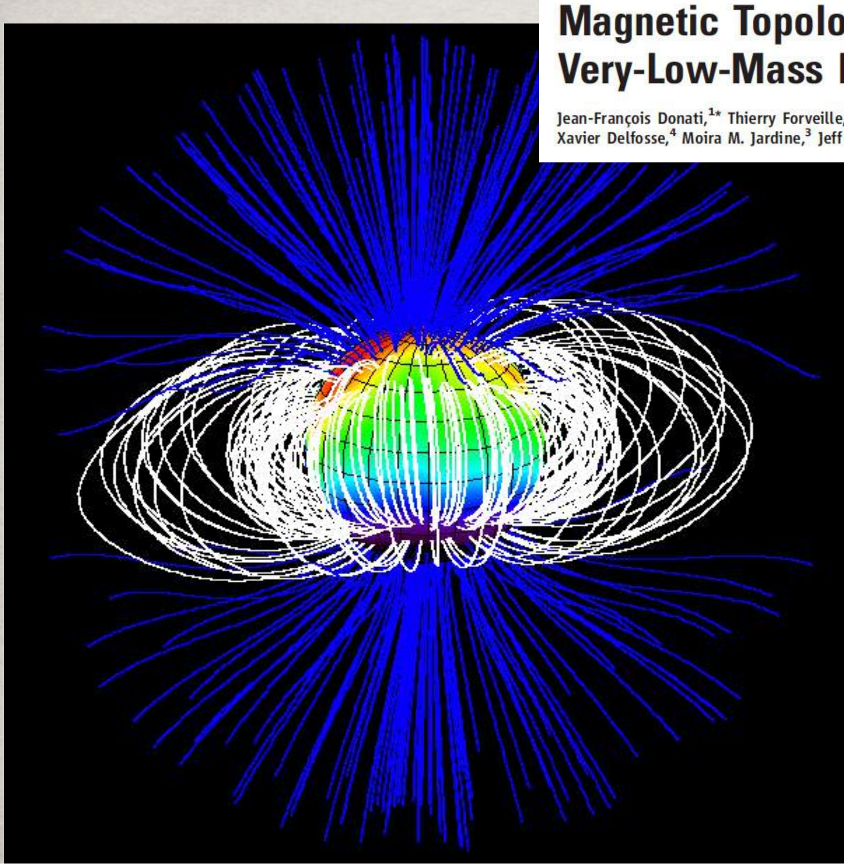

0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Rm=142
$Rm = \frac{Ro Pm}{E}$
0.1
0.05
0
-0.05
-0.1
Rm=270
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Magnetic diffusion time
Schrinner, Petitdemange, Dormy, ApJ, 2012


0.1
0.05
0
-0.05
-0.1
Rm=270
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Magnetic diffusion time
$Rm = \frac{RoPm}{E}$
0.1
0.05
0
-0.05
-0.1
Rm=460
Schrinner, Petitdemange, Dormy, ApJ, 2012

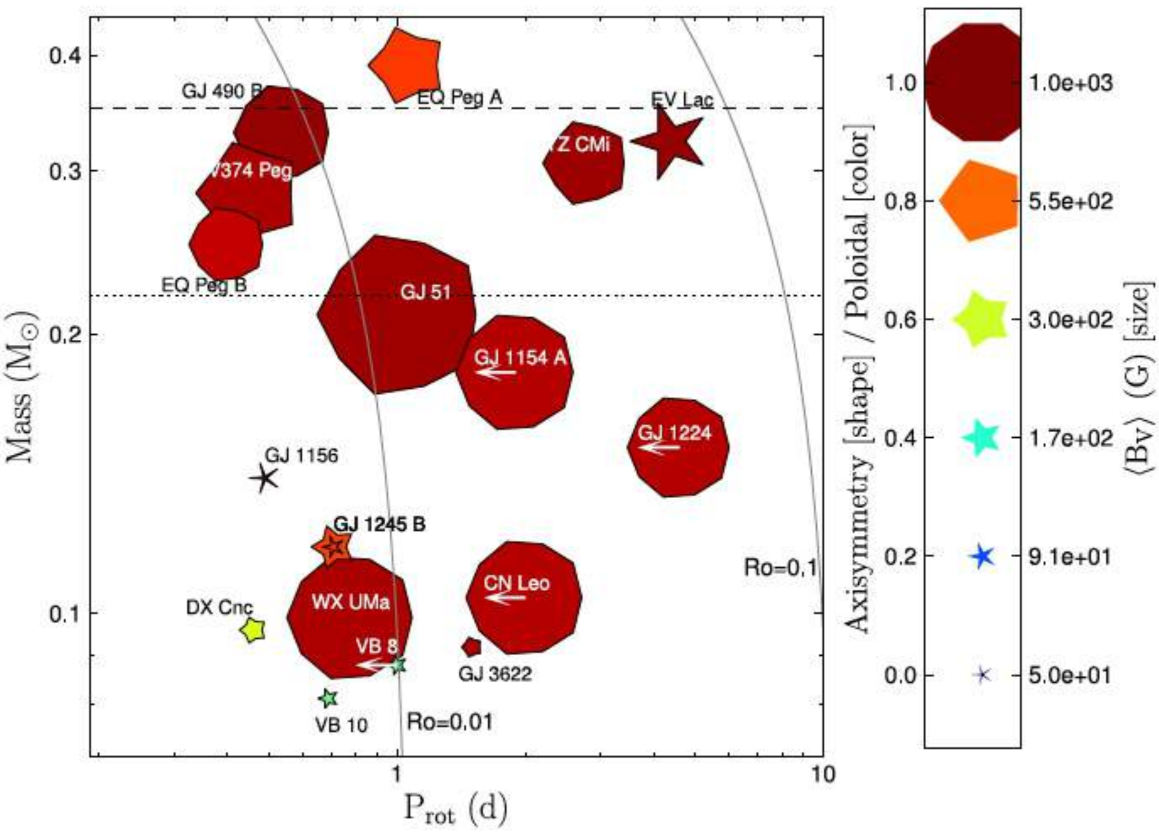

Coherence of the cycle
Rm
500
400
300
200
100
0
0.01 0.10 1.00
$Ro_l$
NS-NS
SF-NS
SF-SF
Schrinner, Petitdemange, Dormy, ApJ, 2012

**The Large-Scale Axisymmetric Magnetic Topology of a Very-Low-Mass Fully Convective Star**

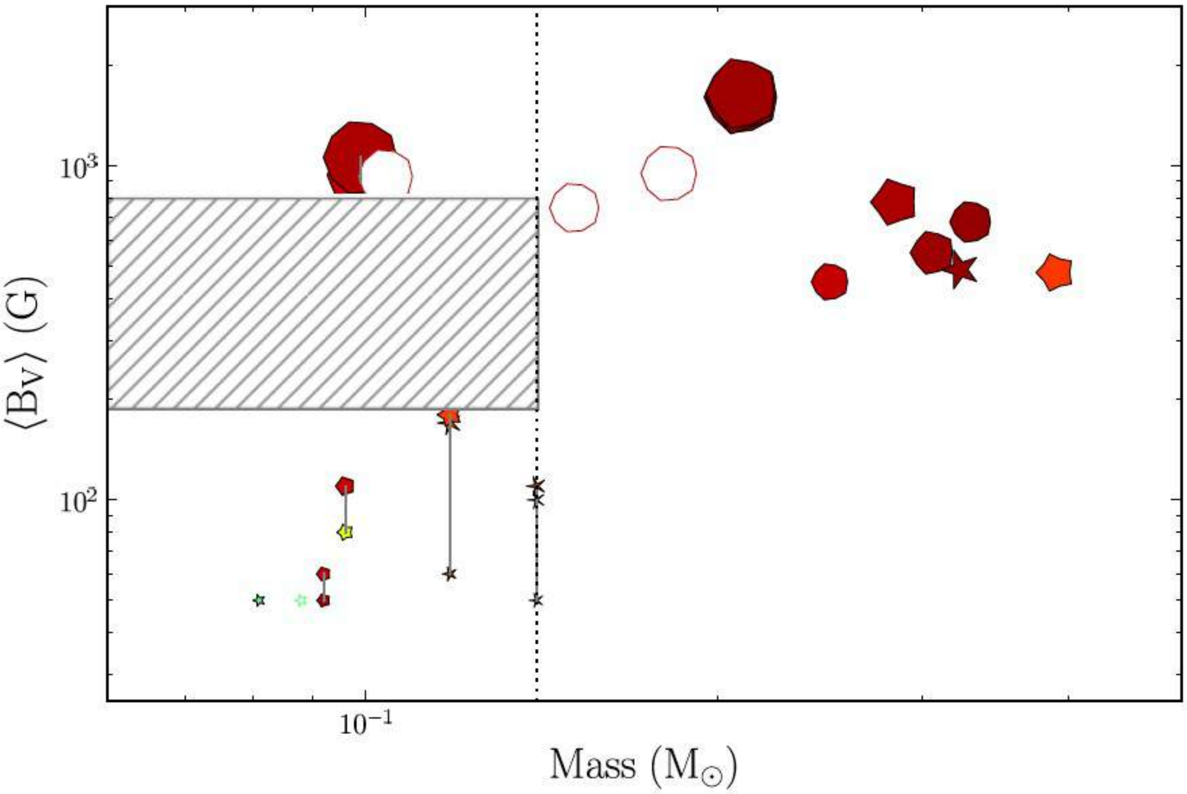
Jean-François Donati,[1*] Thierry Forveille,[2] Andrew Collier Cameron,[3] John R. Barnes,[3] Xavier Delfosse,[4] Moira M. Jardine,[3] Jeff A. Valenti[5]



Magnetic map of v374Peg (Donati et al, 2006, Science, 311,633)




J. Morin, Dormy, Schrinner, Donati, MNRAS, 2011.



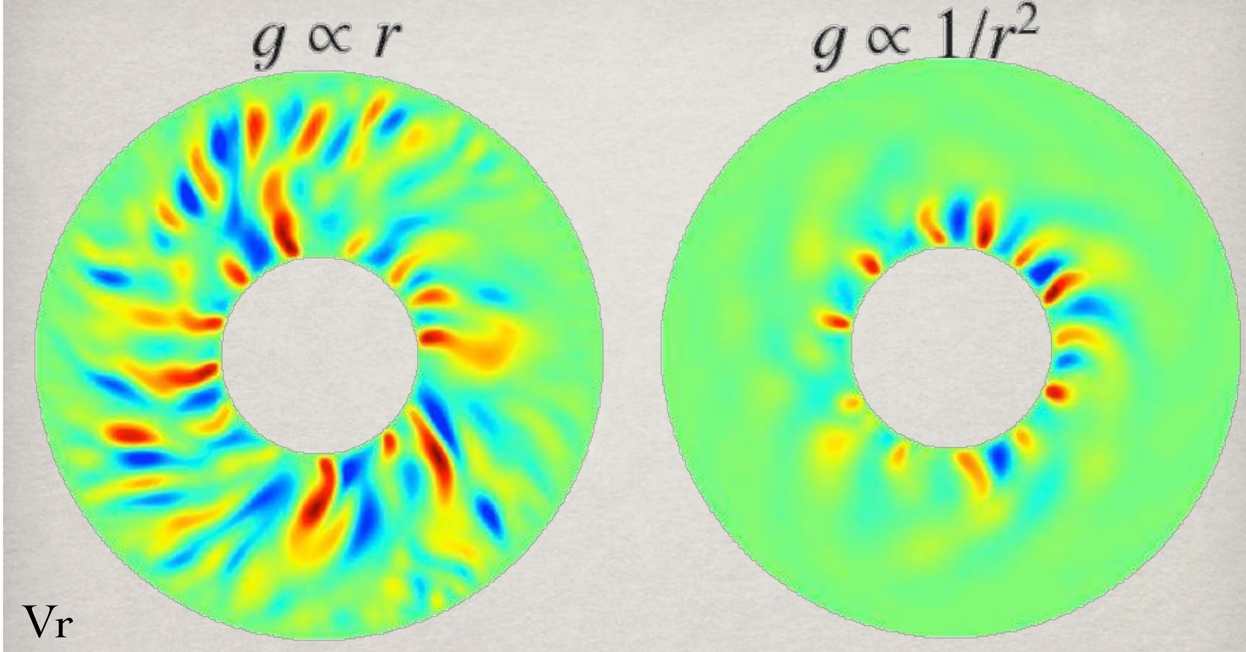

J. Morin, Dormy, Schrinner, Donati, MNRAS, 2011.

**ANELASTIC MODELS**

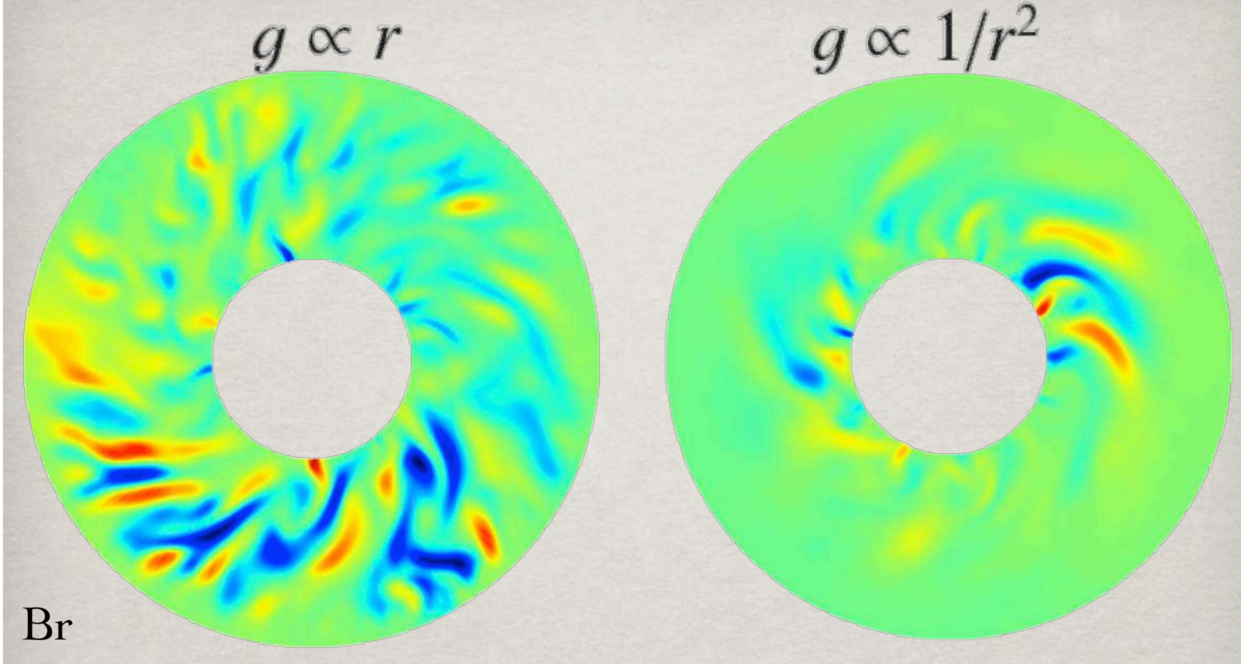
C.A.Jones *et al*
Anelastic convection-driven dynamo benchmarks
Icarus, **216**, Issue 1, 2011

$$\nabla \cdot \bar{\rho}\mathbf{u} = 0.$$

Schrinner, Petitdemange, Raynaud, and Dormy
Topology and field strength
in spherical, anelastic dynamo simulations
A&A 564, A78 (2014)




R. Raynaud, L. Petitdemange and E. Dormy
Influence of the mass distribution
on the magnetic field topology
A&A 567, A107 (2014)

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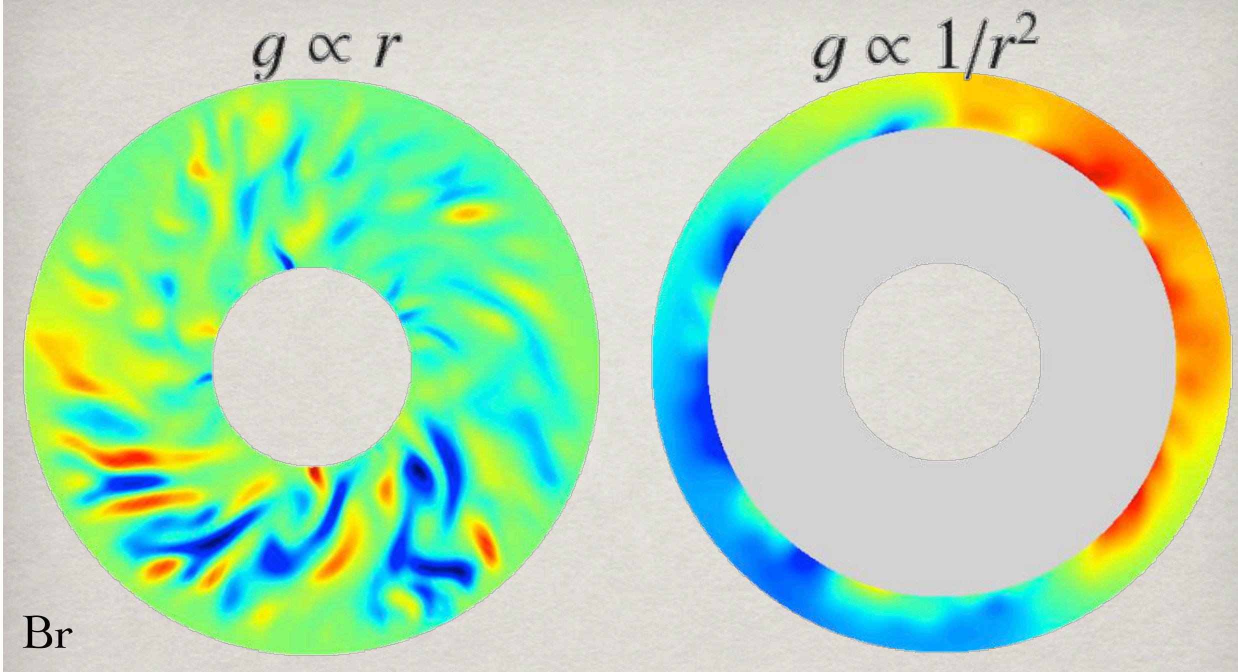


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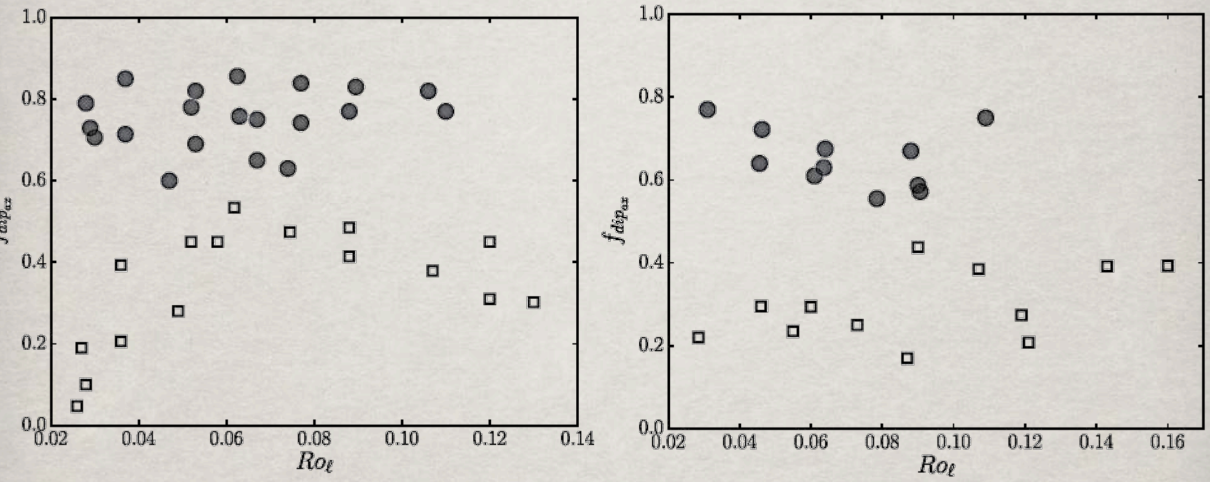



(d) $N_\varrho = 1.5$

(f) $N_\varrho = 2.0$

R. Raynaud, L. Petitdemange and E. Dormy
Dipolar dynamos in stratified systems
MNRAS 448, 2055–2065 (2015)

# Summary (1/2)

- Some properties of stellar dynamics seem robust enough to be described using simple Boussinesq models.
- In such models the transition between steady dipolar to fluctuating dynamos is controlled by the local Rossby number.
- M dwarfs characteristics suggest a connection with geodynamo theory (rapid rotation, strong dipole, bistability).

## The induction equation

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

$$\boldsymbol{\nabla} \cdot \mathbf{B} = 0$$

$$\tau_\eta = L^2/\eta \qquad \tau_U = L/U$$

## The induction equation

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

$$\boldsymbol{\nabla} \cdot \mathbf{B} = 0$$

$$\tau_\eta = L^2/\eta \qquad \tau_U = L/U$$

$$\mathrm{Rm} = \frac{UL}{\eta}$$

## The induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times \left(\mathbf{u} \times \mathbf{B} - \mathrm{Rm}^{-1}\, \boldsymbol{\nabla} \times \mathbf{B}\right)$$

$$\boldsymbol{\nabla} \cdot \mathbf{B} = 0$$

$$\tau_\eta = L^2/\eta \qquad \tau_U = L/U$$

$$\mathrm{Rm} = \frac{UL}{\eta}$$

# Fast and Slow dynamo action

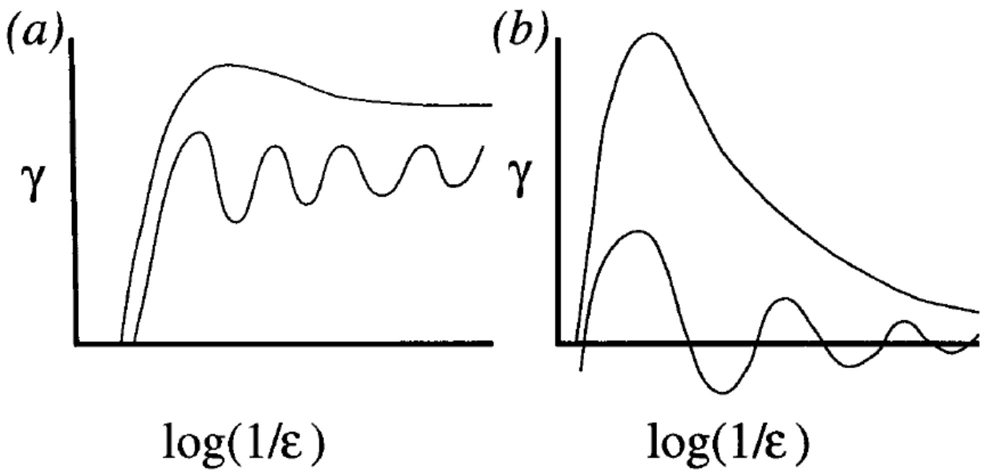
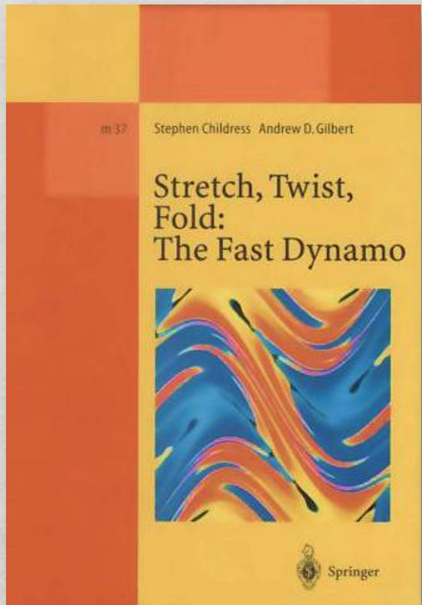



**Fig. 1.2** Schematic picture of possible growth rates for fast and slow dynamos: $\gamma(\epsilon)$ against $\log R = \log(1/\epsilon)$ for $(a)$ fast dynamos, and $(b)$ slow dynamos.

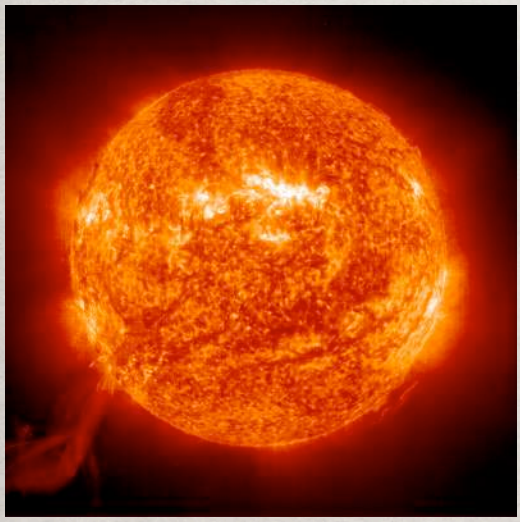
Childress, Gilbert,
"Stretch, Twist, Fold : The Fast Dynamo"
Springer 1995, p21
The x-axis is scaled with respect to the advective time

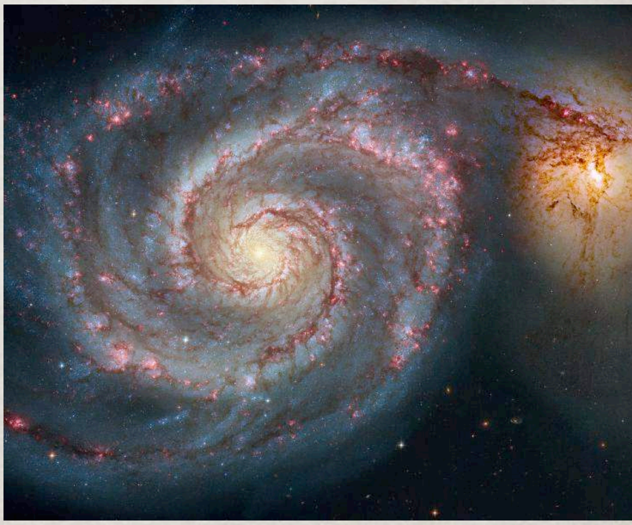
# Fast and Slow dynamo action




Childress, Gilbert,
"Stretch, Twist, Fold : The Fast Dynamo"
Springer 1995, p21
The x-axis is scaled with respect to the advective time

## Large Rm astrophysical dynamos…


SOHO - EIT Consortium, ESA, NASA


M51, NASA, HUBBLE

$\mathrm{Rm} \simeq 10^{10}$

$\mathrm{Rm} \simeq 10^{20}$

## The ABC Flow

Vladimir Arnold

$$\mathbf{u} = (A\sin z + C\cos y)\,\mathbf{e}_x + (B\sin x + A\cos z)\,\mathbf{e}_y + (C\sin y + B\cos x)\,\mathbf{e}_z$$

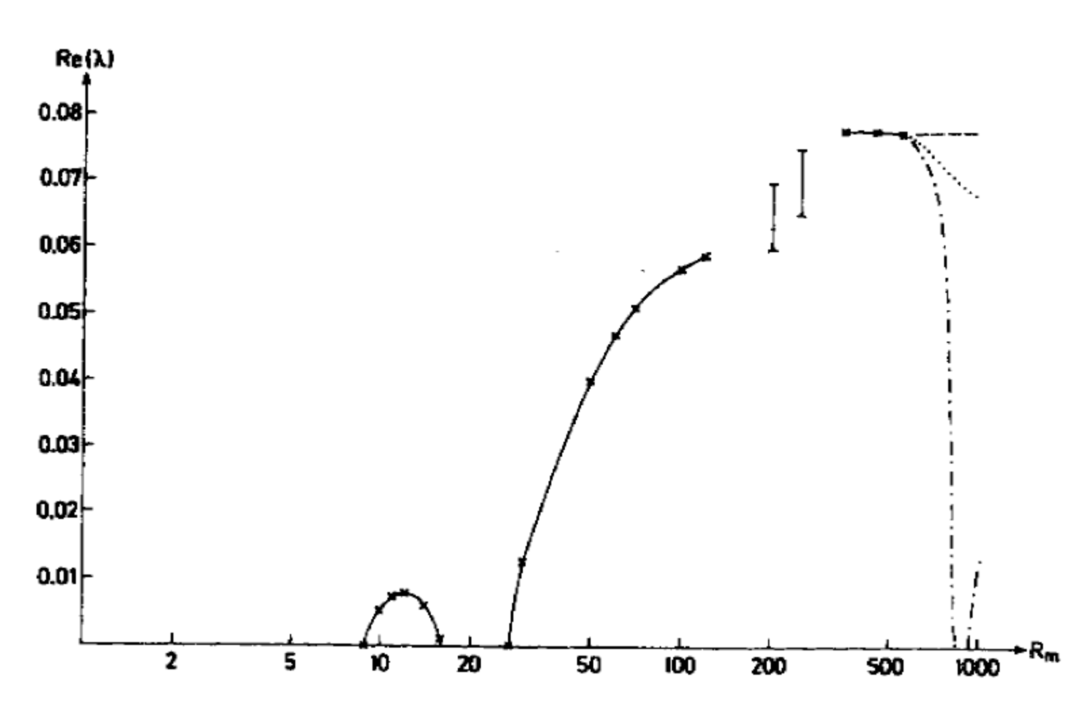
Chaos stretches line elements of a flow exponentially fast.

$2\pi$-periodic in all directions of space

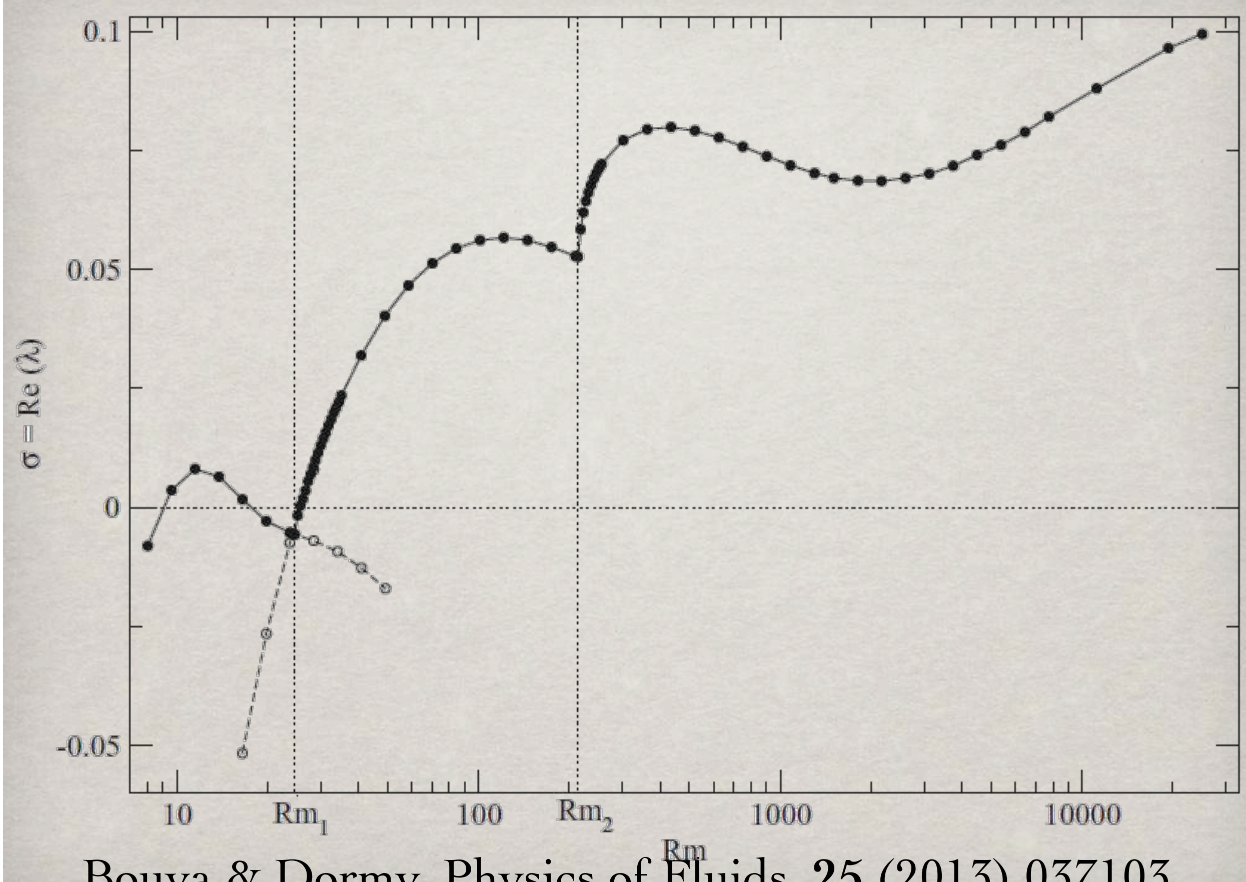
Most papers since Arnold and Korkina (1984) focus on

$$A = B = C \equiv 1$$

# A prototype for fast dynamo

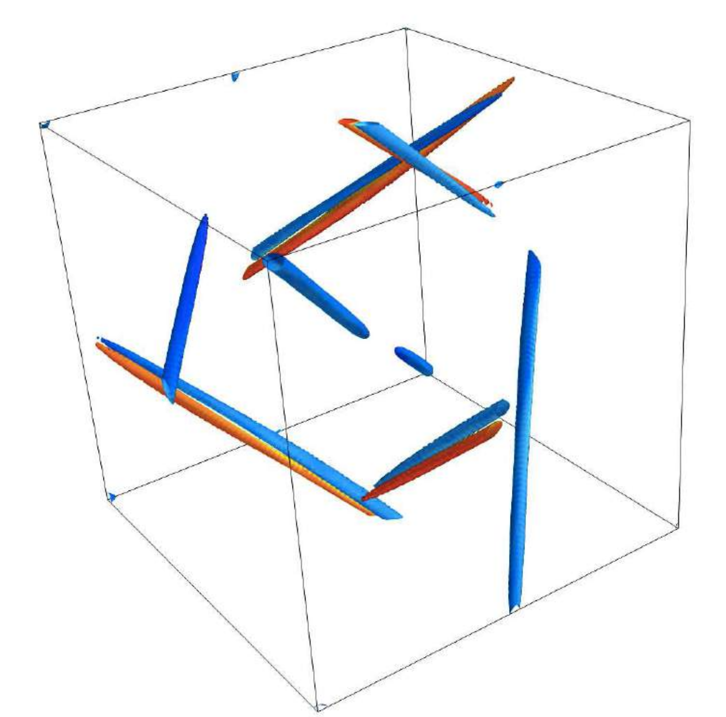



Galloway and Frisch (1984, 1986)



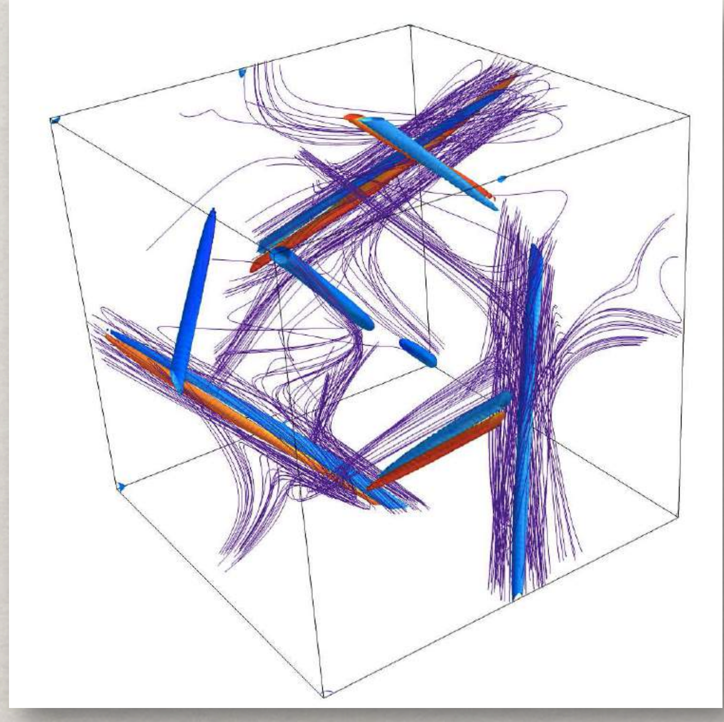

Bouya & Dormy, Physics of Fluids, **25** (2013) 037103

## $\mathrm{Rm} = 434$

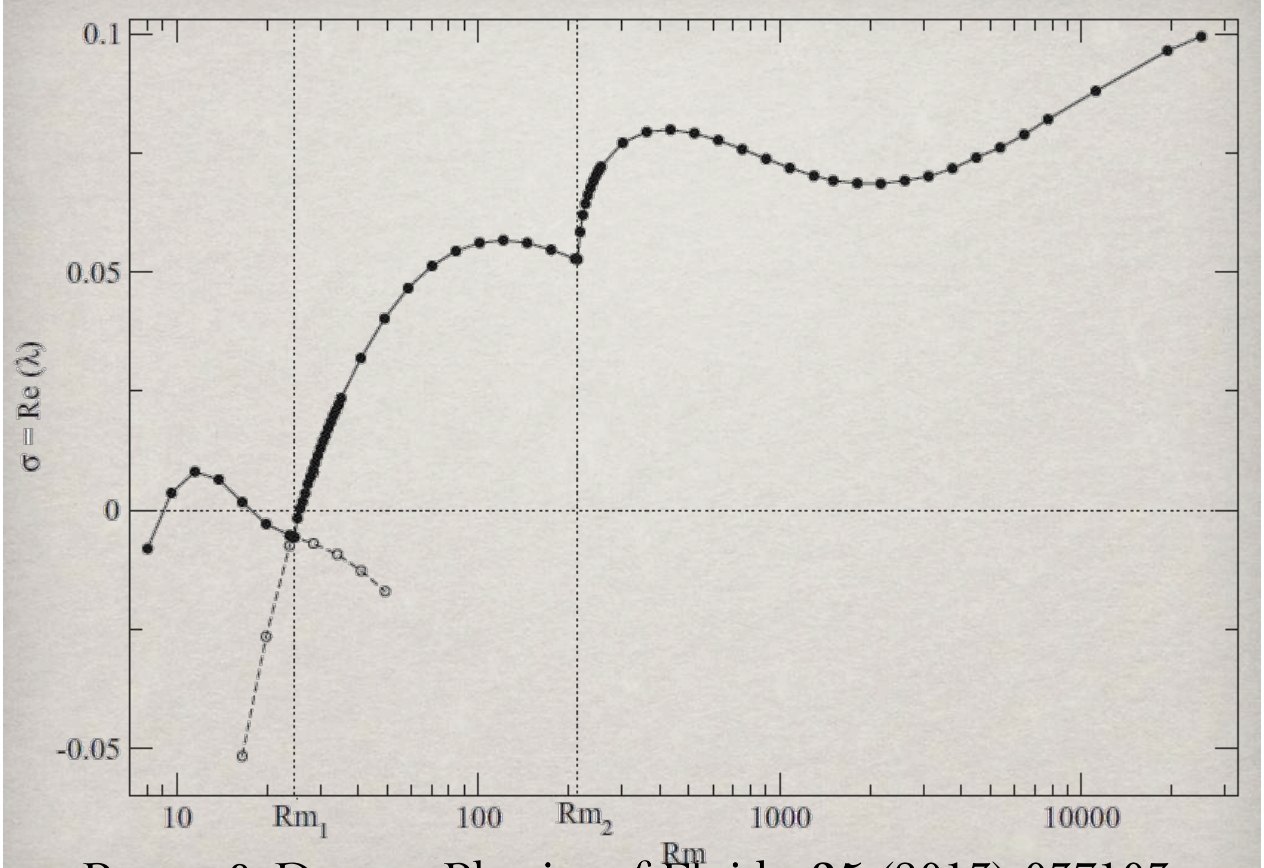


Bouya & Dormy, Physics of Fluids, **25** (2013) 037103

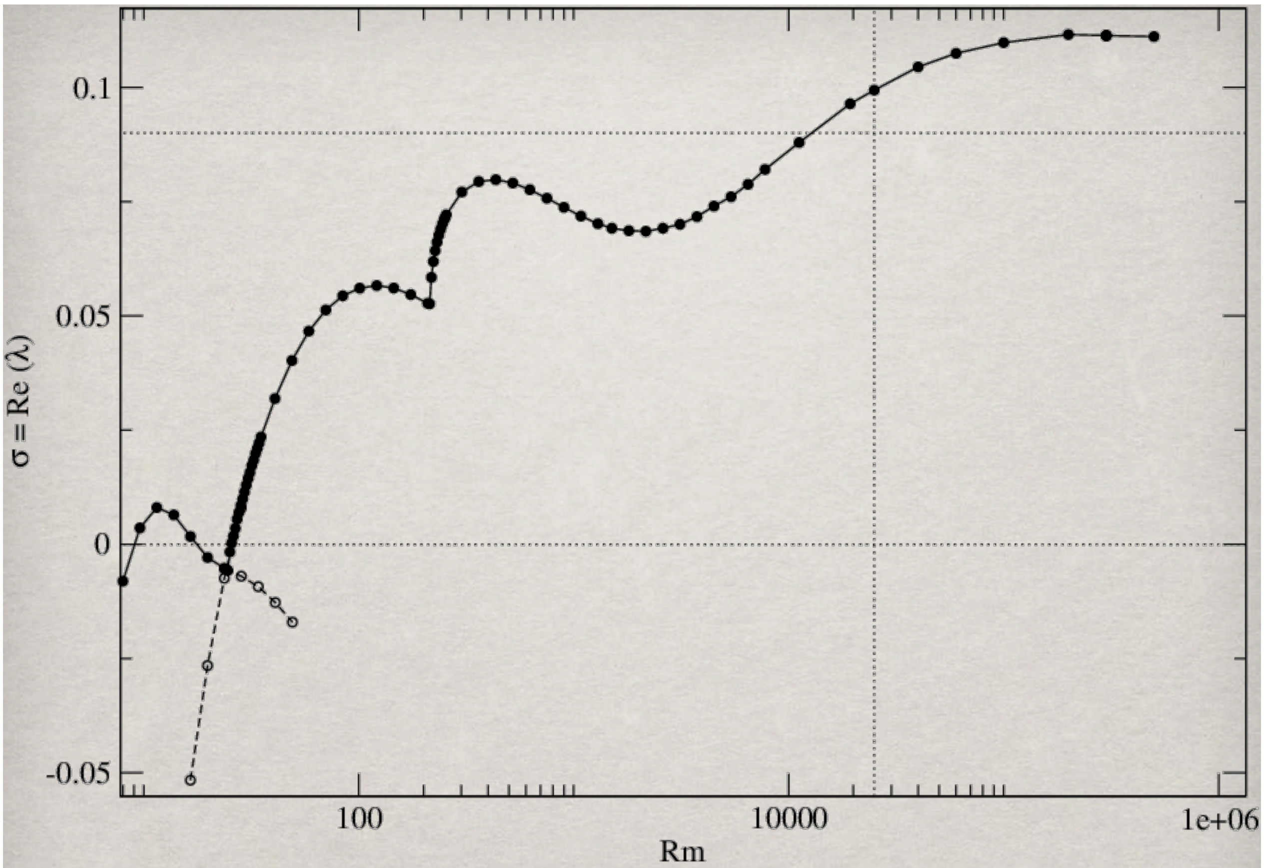
## $\mathrm{Rm} = 434$



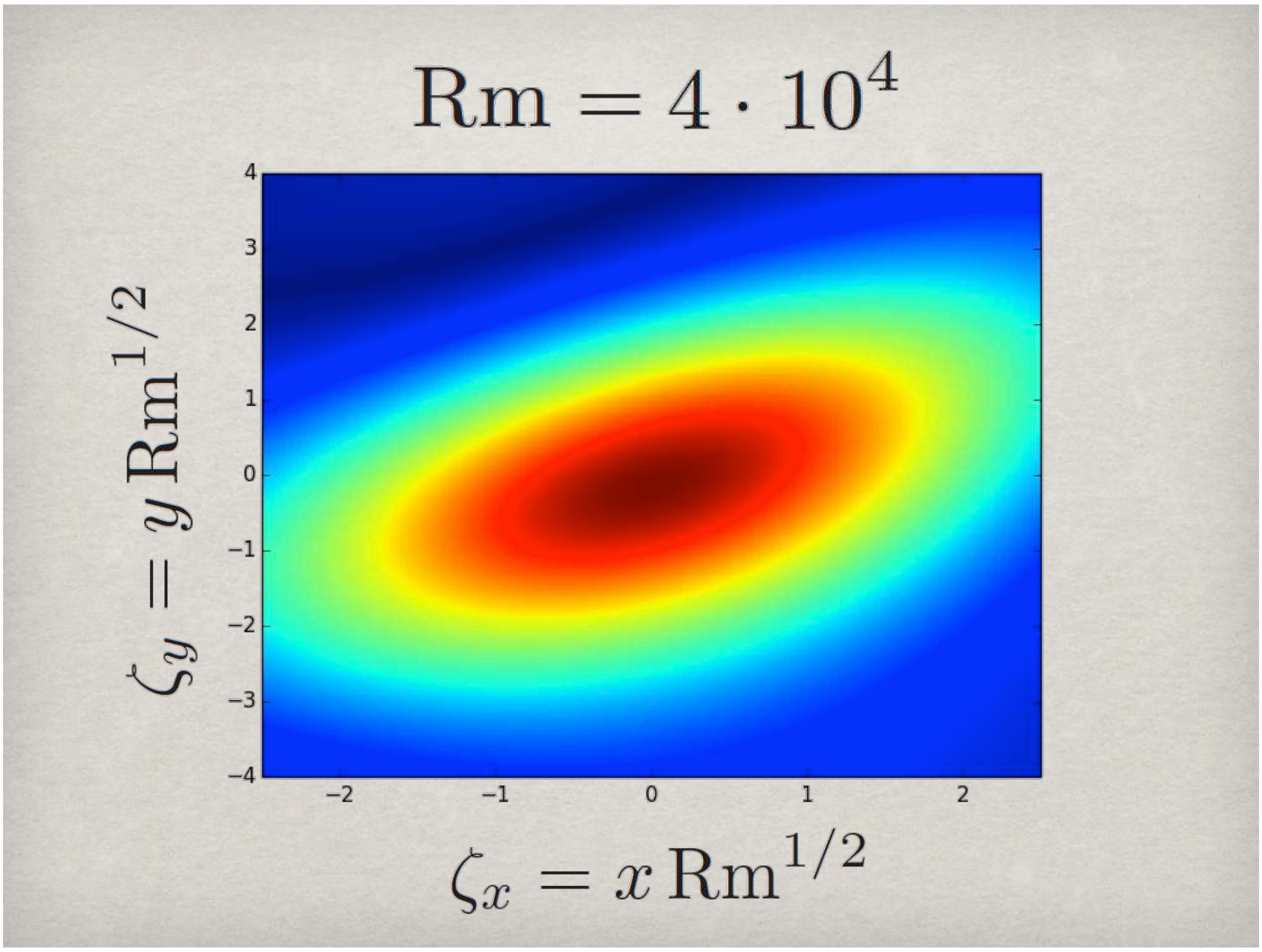
Bouya & Dormy, Physics of Fluids, **25** (2013) 037103

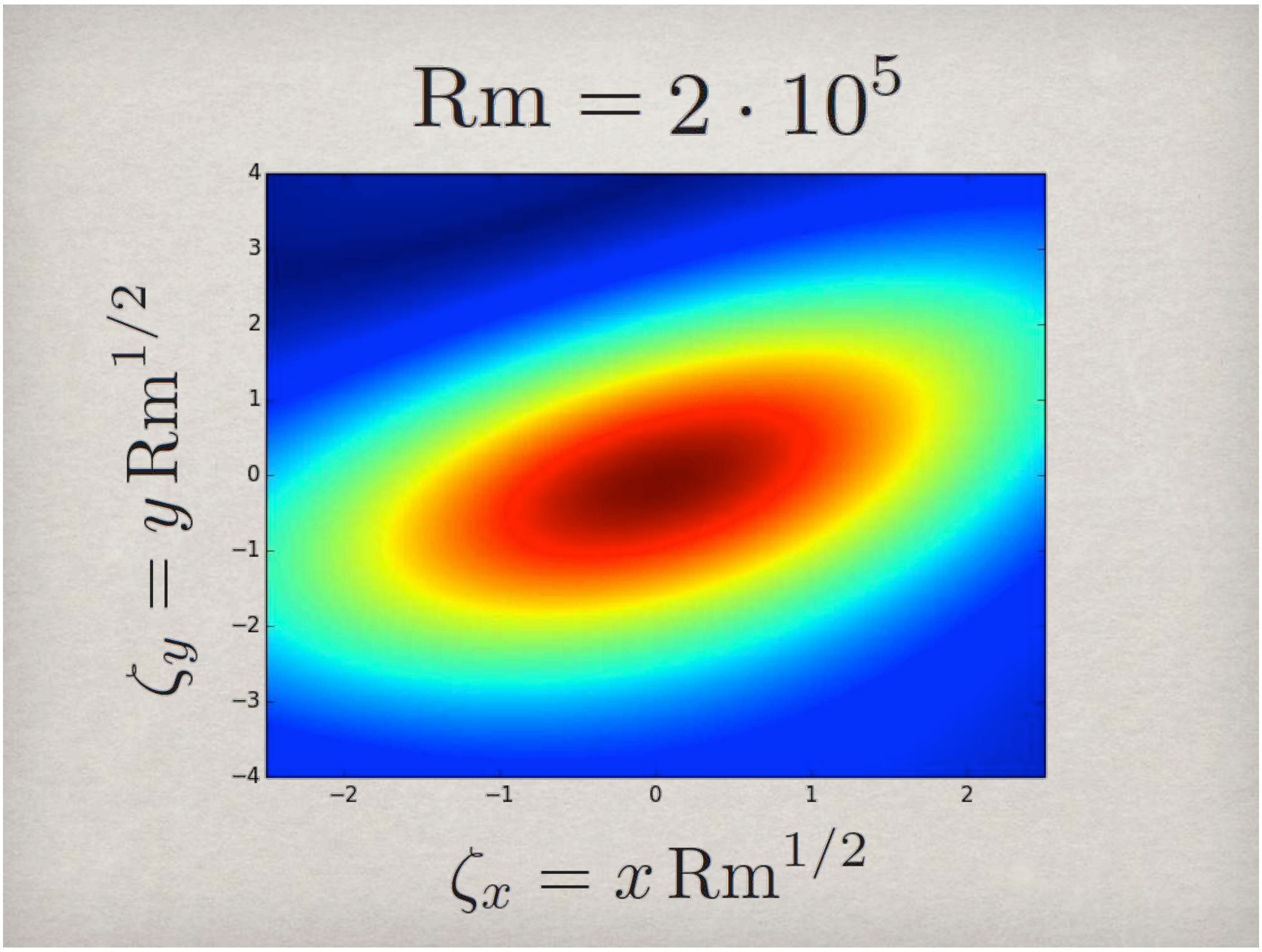


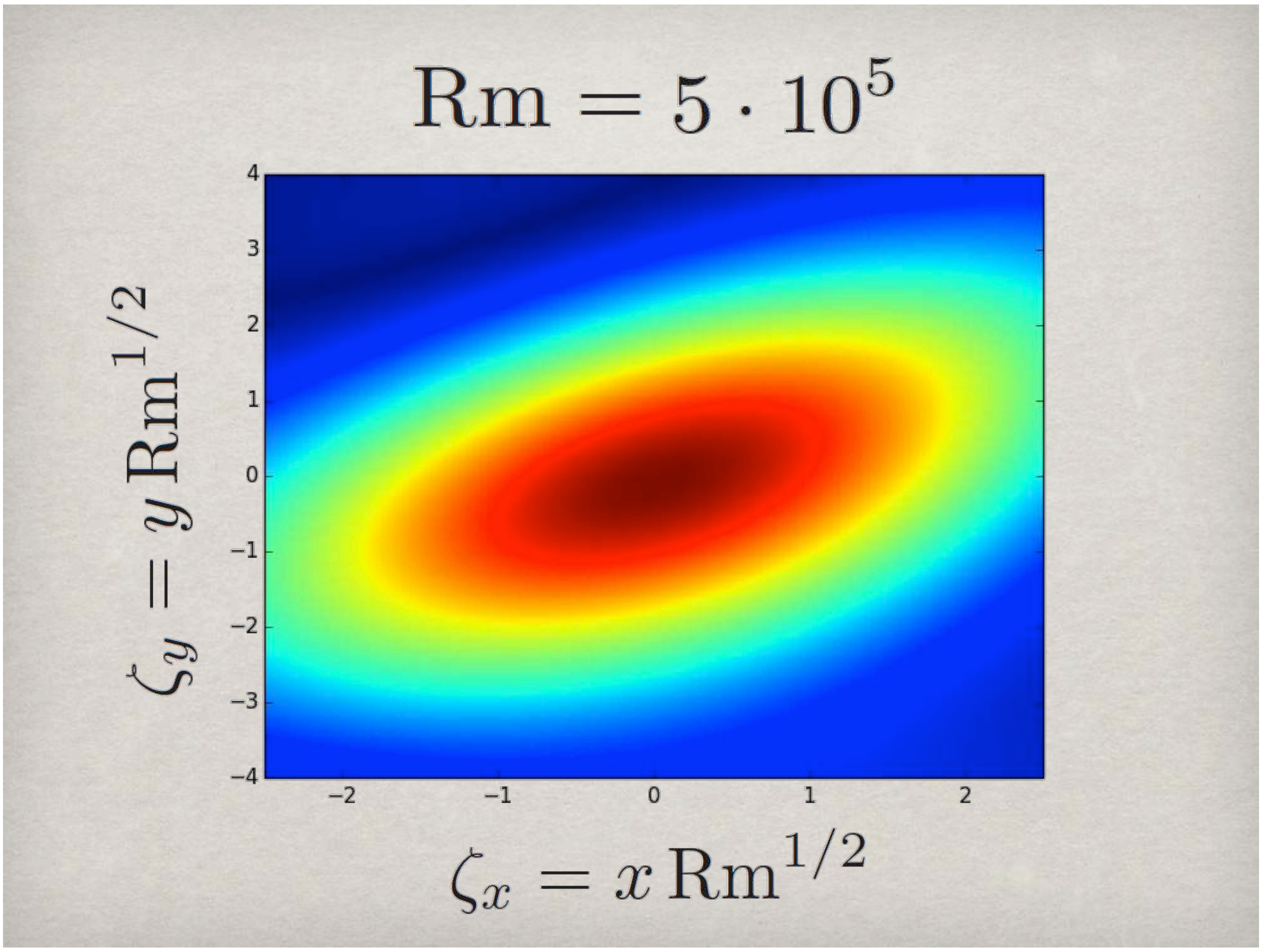

Bouya & Dormy, Physics of Fluids, **25** (2013) 037103

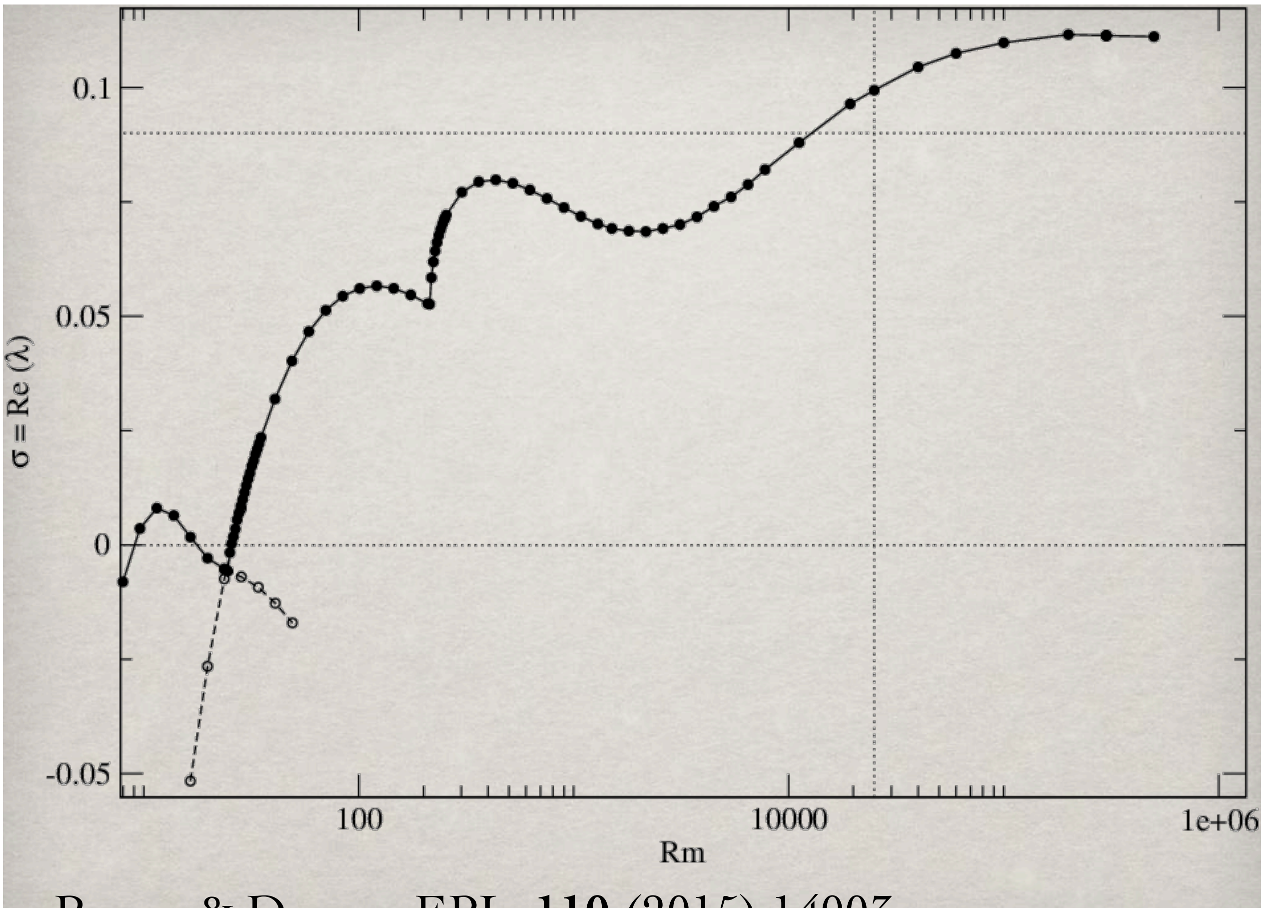



Bouya & Dormy, EPL, **110** (2015) 14003

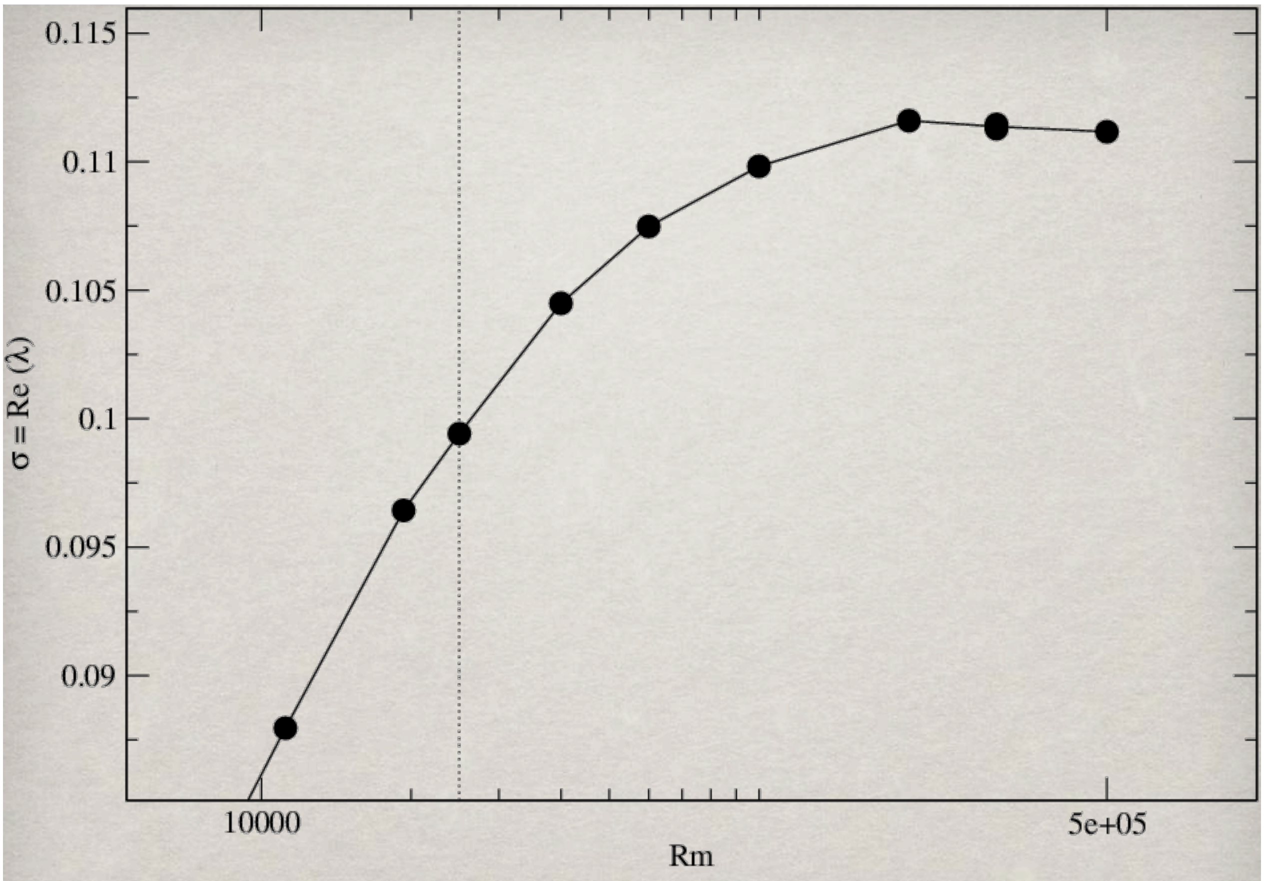

$\mathrm{Rm} = 4 \cdot 10^4$
$\zeta_y = y\,\mathrm{Rm}^{1/2}$
$\zeta_x = x\,\mathrm{Rm}^{1/2}$
4
3
2
1
0
−1
−2
−3
−4
−2
−1
0
1
2


$\mathrm{Rm} = 2 \cdot 10^5$
$\zeta_y = y\,\mathrm{Rm}^{1/2}$
$\zeta_x = x\,\mathrm{Rm}^{1/2}$
4
3
2
1
0
−1
−2
−3
−4
−2
−1
0
1
2



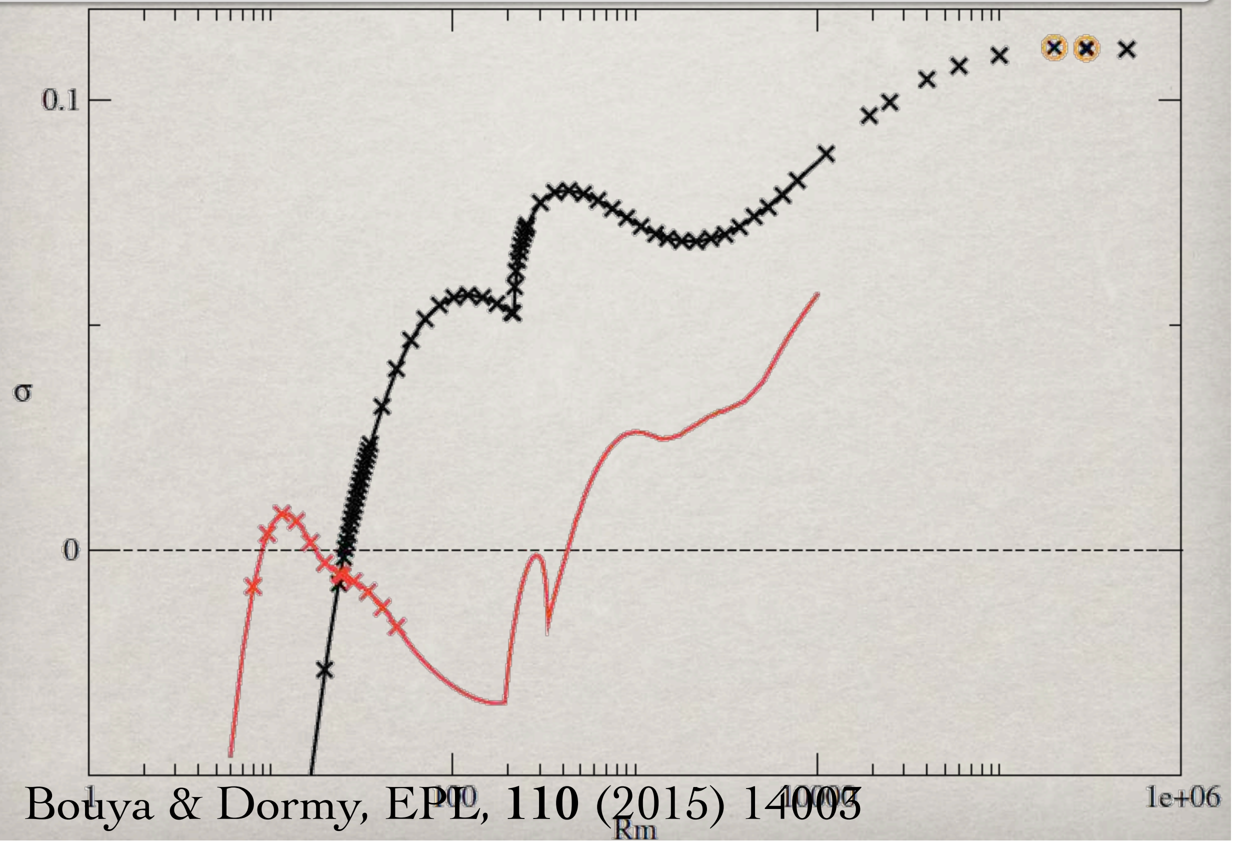




Bouya & Dormy, EPL, **110** (2015) 14003



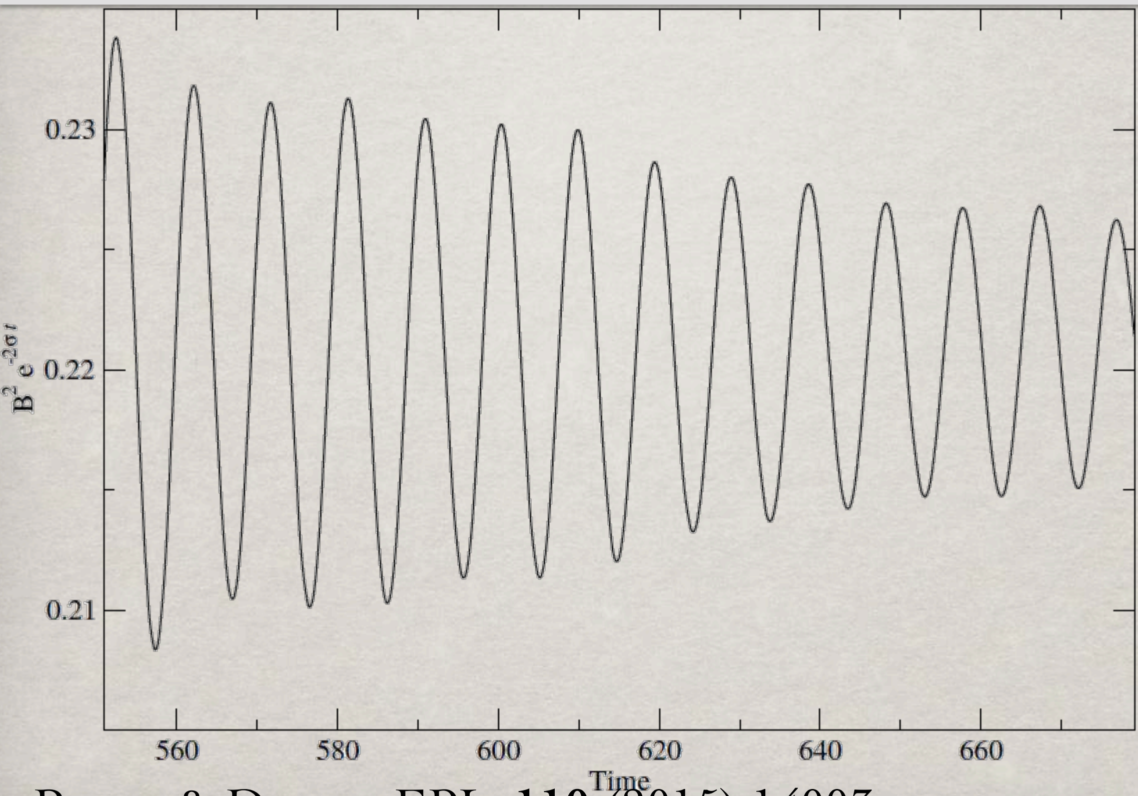

Bouya & Dormy, EPL, **110** (2015) 14003

## Toward an asymptotic regime



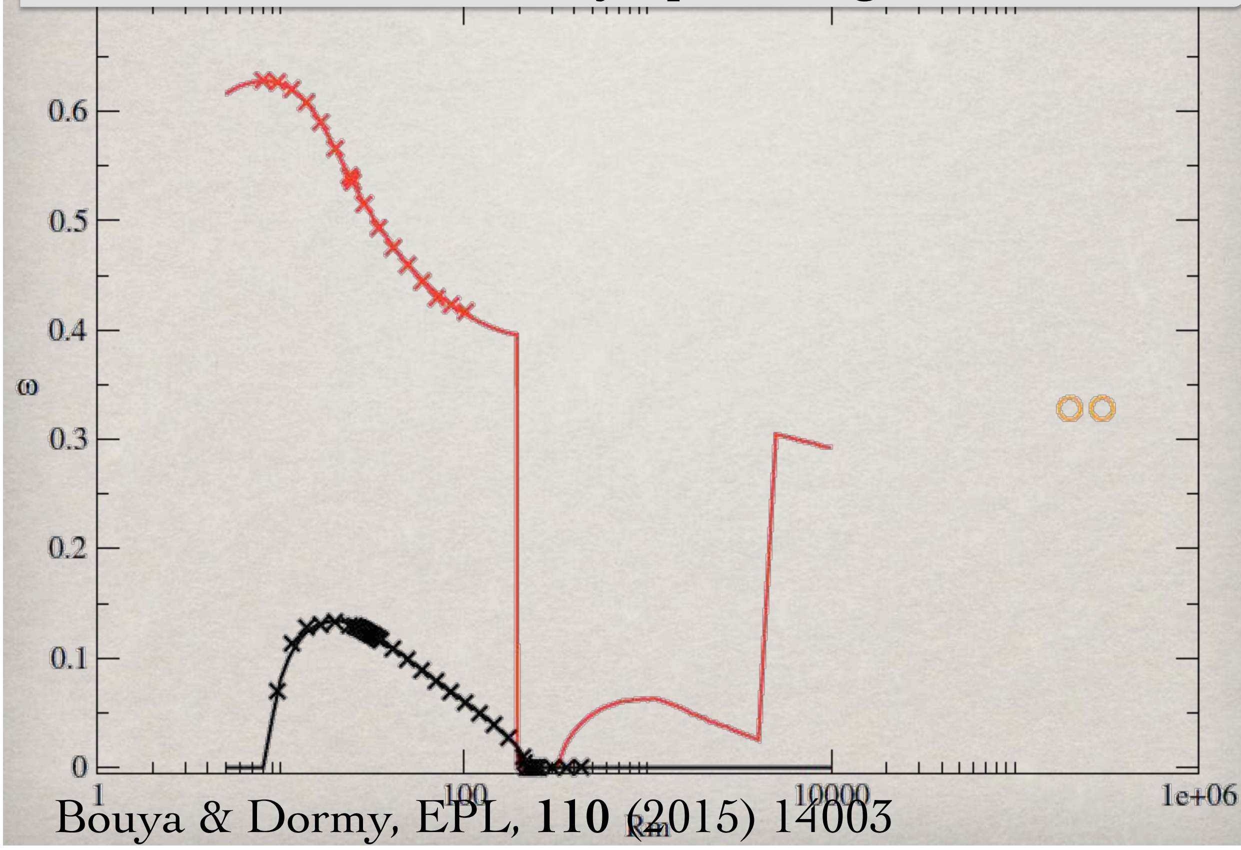

Bouya & Dormy, EPL, **110** (2015) 14003

# Toward an asymptotic regime




Bouya & Dormy, EPL, **110** (2015) 14003

# Toward an asymptotic regime




Bouya & Dormy, EPL, **110** (2015) 14003

# Summary (2/2)

- Fast dynamo action (amplification at a rate independent of the resistivity) is extremely challenging to achieve.
- Fast dynamo action is not yet clearly established for the most classical prototype (the ABC flow).

Bouya & Dormy, Physics of Fluids, **25** (2013) 037103
Bouya & Dormy, Europhysics Letters, **110** (2015) 14003