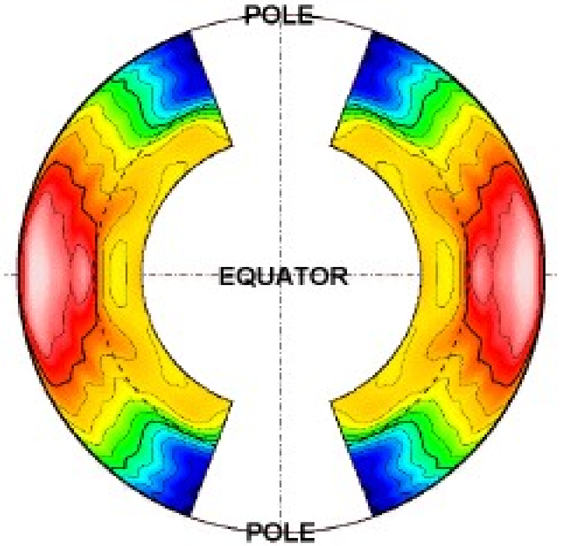
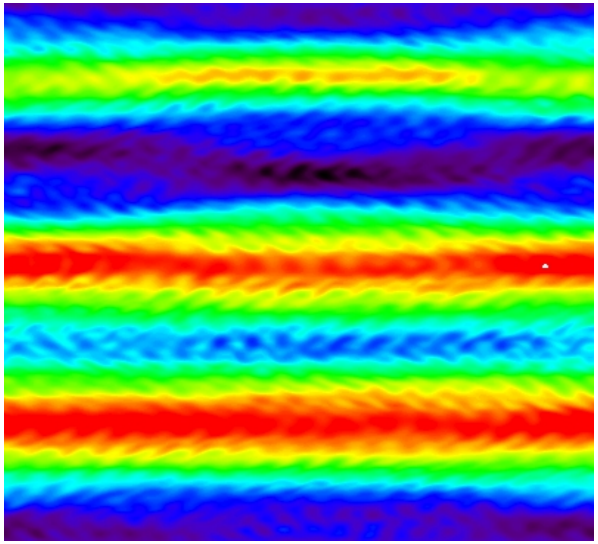
Tachocline Discussion: Questions?





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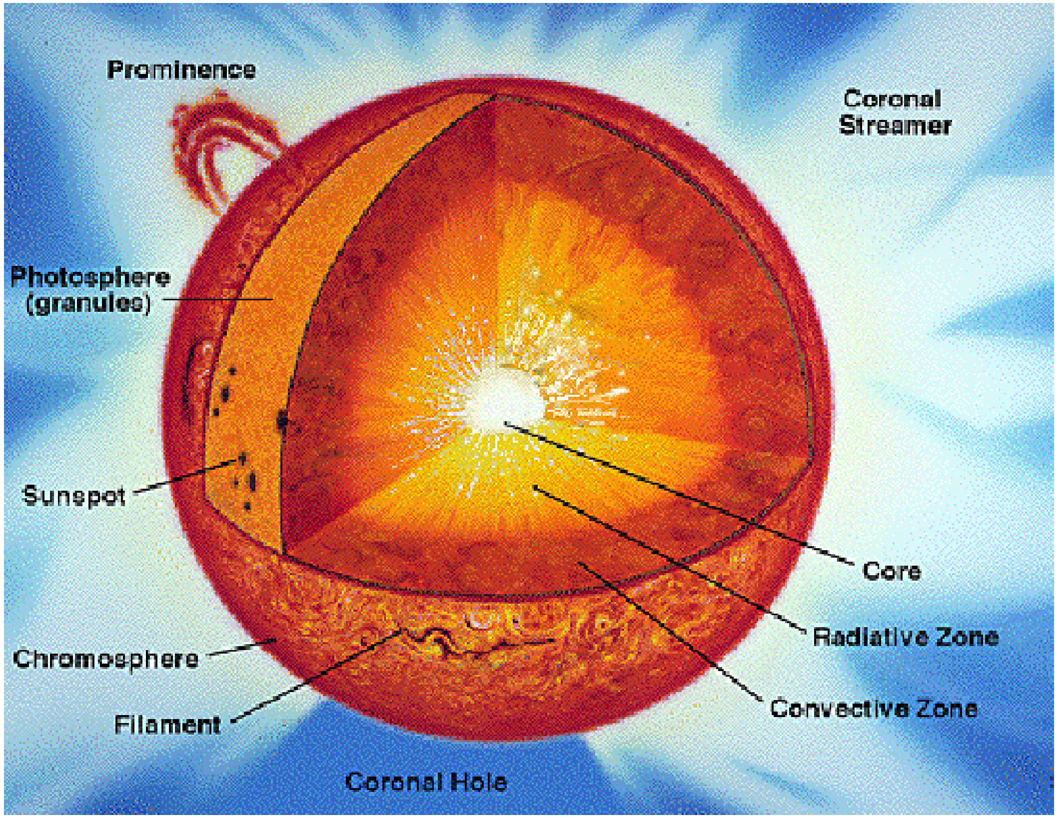
Solar Structure



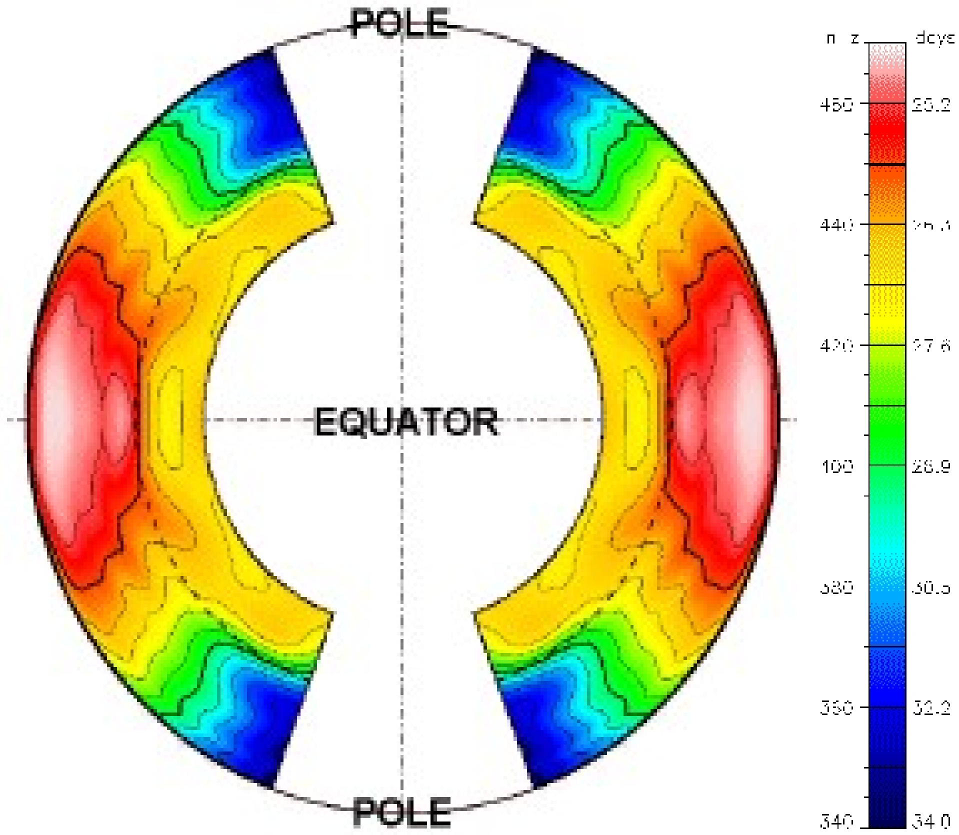
Solar Interior

1. Core
2. Radiative Interior
3. (Tachocline)
4. Convection Zone

Visible Sun

1. Photosphere
2. Chromosphere
3. Transition Region
4. Corona
5. (Solar Wind)

Helioseismology: The tachocline

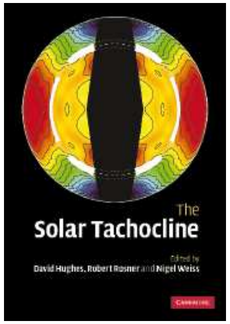


Schou et al (1998)

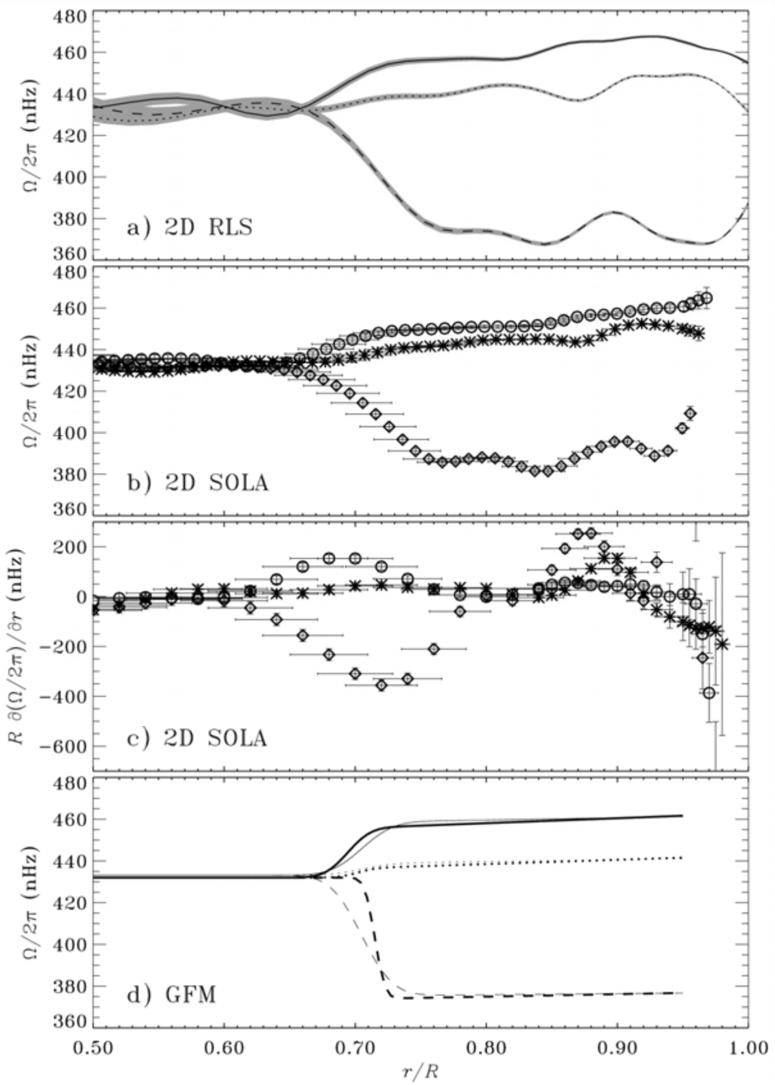
Review: Tobias S.M. (2005) in “Fluid Dynamics and Dynamos in Astrophysics and Geophysics” eds A.M. Soward et al.

Book: eds D.W. Hughes, R. Rosner, N.O. Weiss (2007)

Tobias, Diamond & Hughes (2007) ApJL



Fine detail of tachocline structure



Charbonneau et al (1999)

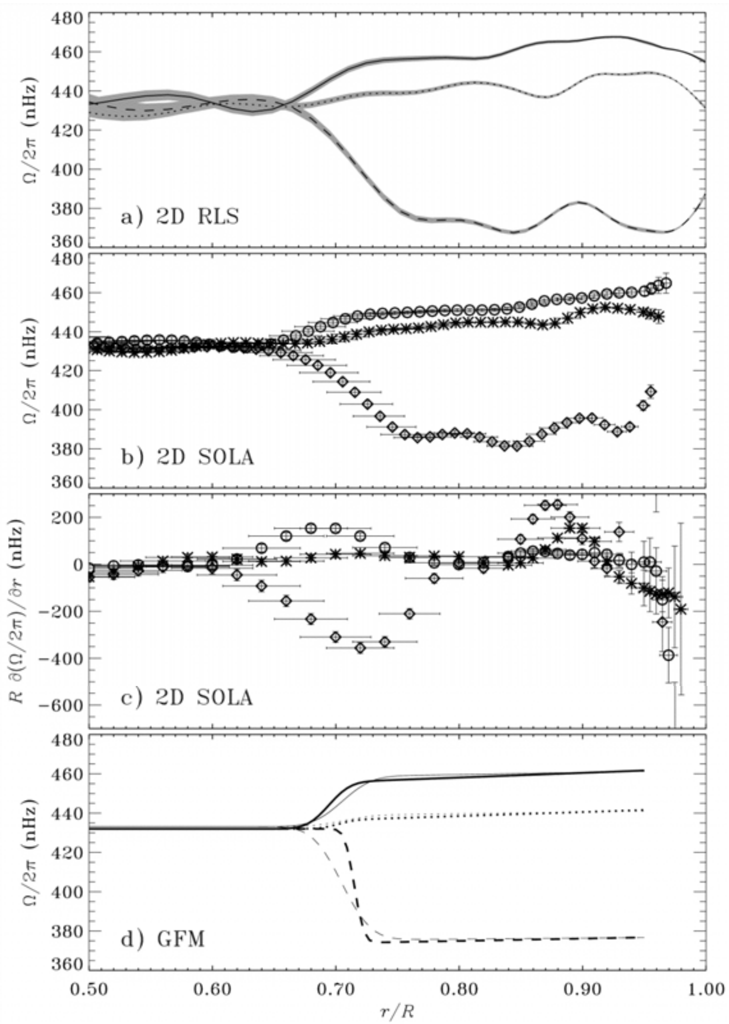
- 30 nHz at equator
- Position
  - $R_c/R_S = 0.693$
- Prolateness
  - R_c/R_S varies by 0.02
- Thickness
  - $R_{tach}/R_S = 0.039$ (no lower bound) (Charbonneau et al 1999)
    $R_{tach}/R_S = 0.019$ (Elliott & Gough 1999)
- Latitudinal dependence

$$\omega = \omega_{eq}(1 - a_2\mu^2 - a_4\mu^4)$$

$$a_2 \approx a_4 \approx 0.15$$

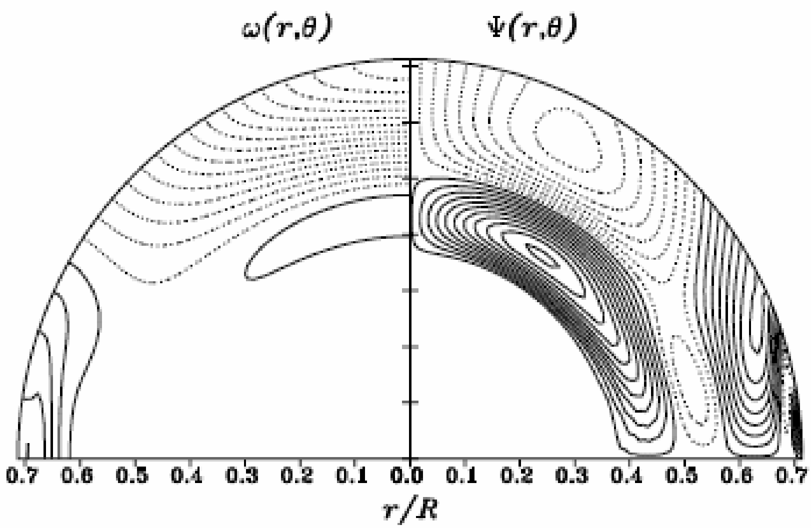
- Oscillation 1.3yr period?
  - Howe et al (2000)

Some Physical Parameters



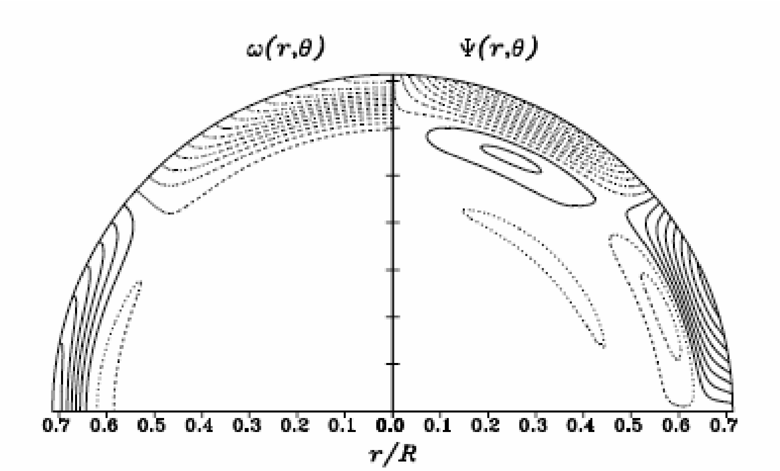
- High density
  - $\rho \sim 0.2$ g/cm^3
- High Temperature
  - T ~ 2.0 x 10^6 K
- P ~ 6 x 10^{12} Pa
- Magnetised
  - Field 10^4 – 10^5 G
  - plasma $\beta = 10^5$
- Very stably stratified
  - Ri ~ 10^2 - 10^4

Why is there an angular momentum problem? (Spiegel & Zahn picture)



- What is the mechanism that leads to the formation of this thin shear layer?
- Take the differential rotation of the convection zone as given (transport of angular momentum by stresses of turbulence)
- Spiegel & Zahn (1992): a radiation driven meridional circulation transports angular momentum from the convection zone into the interior along cylinders → no tachocline.
- NOTE THIS MERIDIONAL FLOW IS SLOW: T~10^6years
- So what keeps the tachocline thin?

Why is there a tachocline? (Spiegel & Zahn Scenario)



$$< u'_r u'_\phi > = -\nu_v r \sin\theta \frac{\partial \Omega}{\partial r}$$

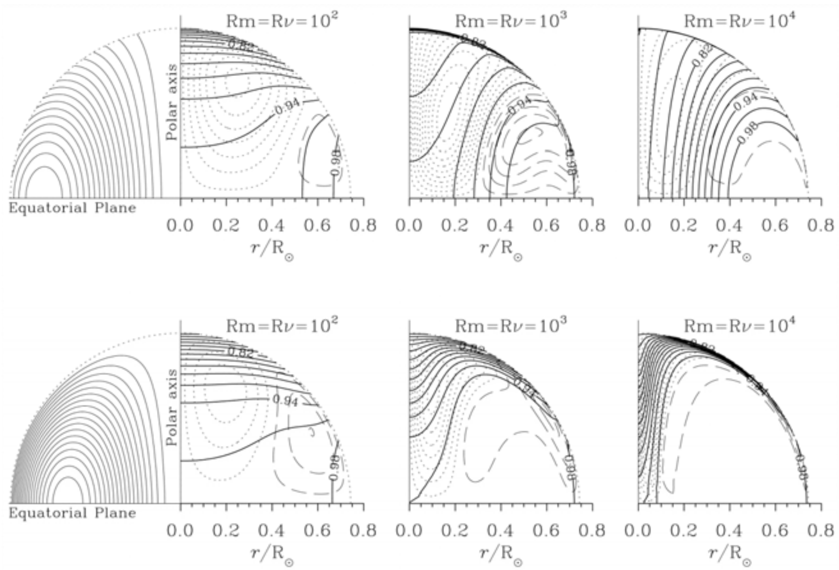
$$< u'_\theta u'_\phi > = -\nu_h r \sin\theta \frac{1}{r} \frac{\partial \Omega}{\partial \theta}$$

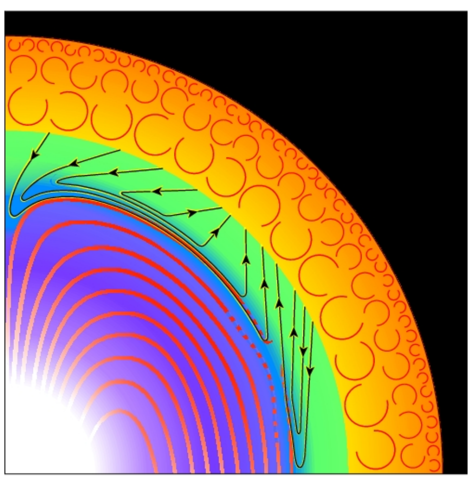
- Stable stratification → 2 dimensional turbulence (if there is any turbulence)
- 2D turbulence → anisotropic turbulent viscosity (drives system towards constant angular velocity) ("TURBULENCE ACTS AS A FRICTION") prevents tachocline spreading into the interior.
- TURBULENCE (A FAST PROCESS) IS INVOKED TO STOP THE SPREADING OF THE DIFFERENTIAL ROTATION (A SLOW PROCESS)

Some Comments

- Is there a linear instability leading to turbulence?
  - Yes there are many possible instabilities including joint differential rotation and magnetic field instabilities (Gilman & Fox 1997 and follow up papers), magnetic buoyancy
- Is this turbulence 2D?
  - Not necessarily – depends whereabouts in tachocline.
- If this turbulence is 2D does it really act so as to transport angular momentum towards a state of constant differential rotation?—i.e does the turbulence act as anisotropic viscosity?
  - Analogy with atmospheric models says that (hydrodynamic) 2D turbulence of this type acts so as to mix PV and drive the system away from solid body rotation (Gough & McIntyre 1998, McIntyre 2003)
  - ***Anti-friction***
  - ***What is role of stably stratified MHD turbulence in transporting angular momentum?***

Alternative: Magnetic models





- A relic field in the interior can keep the interior rotating as a solid body (Mestel & Weiss 1987 $10^{-3} - 10^{-2}$ G)
- But if magnetic coupling spins down the radiative interior, why doesn't angular velocity propagate in along field lines
- MacGregor & Charbonneau (1999) suggested that all the field lines must be contained in the radiative interior (no magnetic coupling)
- Gough & McIntyre (1998) propose that a two-cell meridional flow can keep the field down where necessary – delicate balance (Garaud 2002)
- Clearly a weak field can also be kept down by turbulent magnetic pumping (Tobias et al 1998, Dorch & Nordlund 2001) or turbulent diamagnetism (see e.g. Rädler)
- But if field is kept down, how do you spin down the interior?

Current Thinking…

NOMINAL BASE

OVERSHOOTING (AND MAYBE PENETRATIVE) CONVECTION
TURBULENCE IS 3D
MAGNETIC
STRONG MEAN DYNAMO FIELD…
MAGNETIC BUOYANCY INSTABILITIES

FAST

END OF OVER-SHOOTING

MHD TURBULENCE DRIVEN FROM ABOVE / INSTABILITIES?
VERY STABLY STRATIFIED – 2D
WEAK MERIDIONAL FLOW
LATITUDINAL ANGULAR MOMENTUM TRANSPORT
WEAK MEAN FIELD, BUT MHD IMPORTANT?

FAST/SLOW?

BASE OF TACHOCLINE

Parameter Regime

- Strongly stratified
  - Ri ~ 10^3 in lower tachocline

- Not rotationally constrained, though rotationally influenced
  - Ro ~ 0.1 – 1.0 (high degree of uncertainty)

- Molecular Viscosity Small (cf Coriolis Force)
  - Ek ~ 10^{-11}

- High Rm, Re
  - Rm~10^5, Re~10^{10}

β-plane MHD

Set $\mathbf{B} = B_0\hat{\mathbf{x}} + \nabla \times (A\hat{\mathbf{z}})$

$$\partial_t \omega + J(\psi, \omega) + \beta \partial_x \psi = B_0 \partial_x \nabla^2 A + J(A, \nabla^2 A) + \upsilon \nabla^2 \omega + F_\omega$$
$$\partial_t A + J(\psi, A) = B_0 \partial_x \psi + \eta \nabla^2 A$$

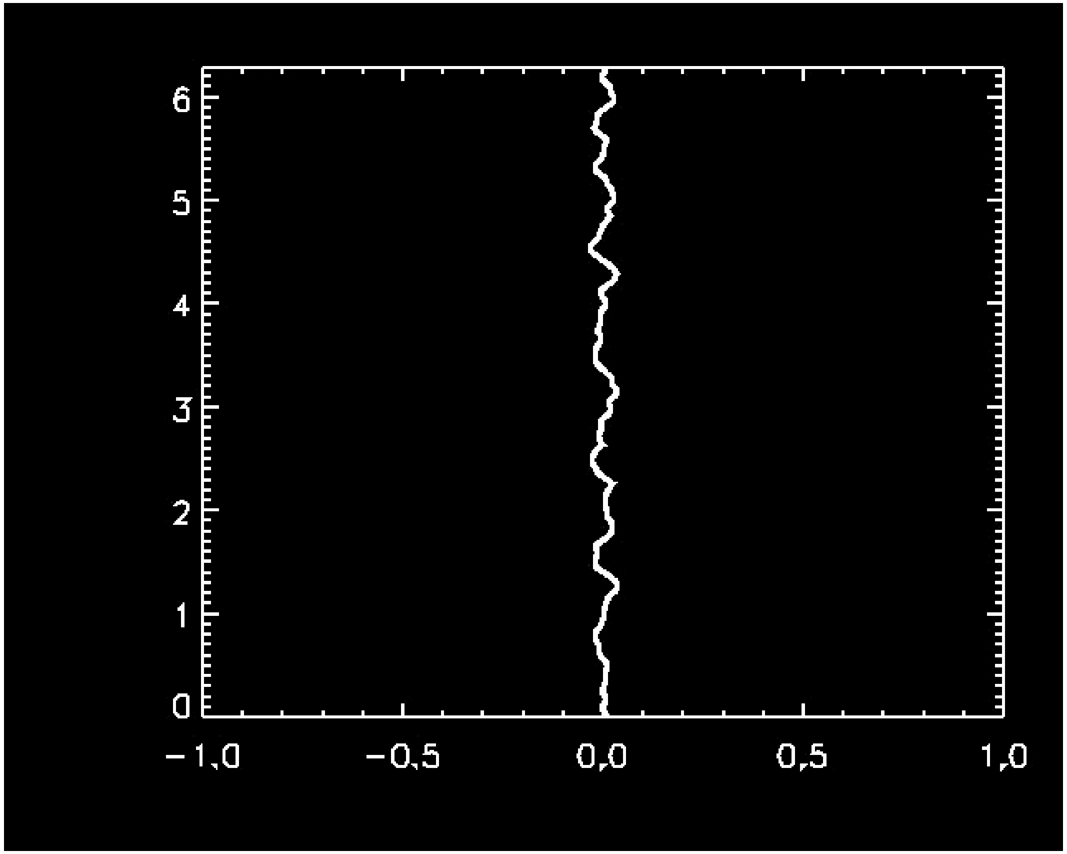
- and potential for magnetic field (A)
- In the absence of magnetic field any turbulence that is driven at a small scale inverse cascades to give a mean (zonal) flow (in the x-direction) (cf some theories for Jupiter’s jets)
- The scale in latitude is set by a balance between decorrelation rate and frequency of Rossby Waves.

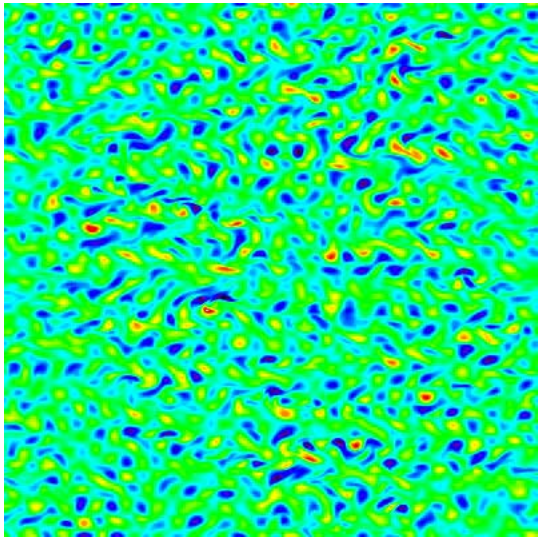
$$k_y = \left(\frac{\beta}{U}\right)^{1/2}$$

Rhines Scale

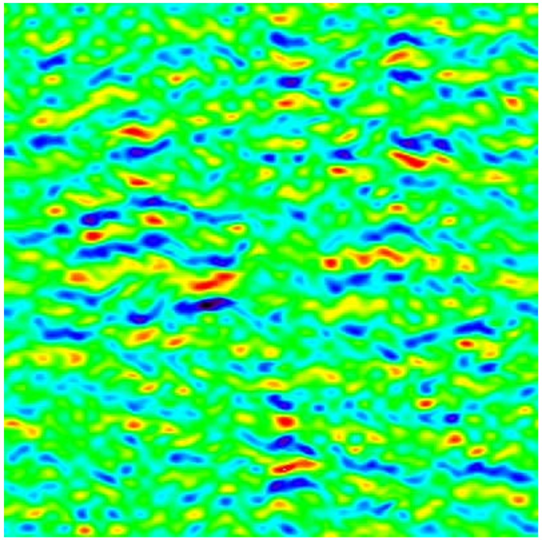
β-plane (hydro example)

Mean flow





ω



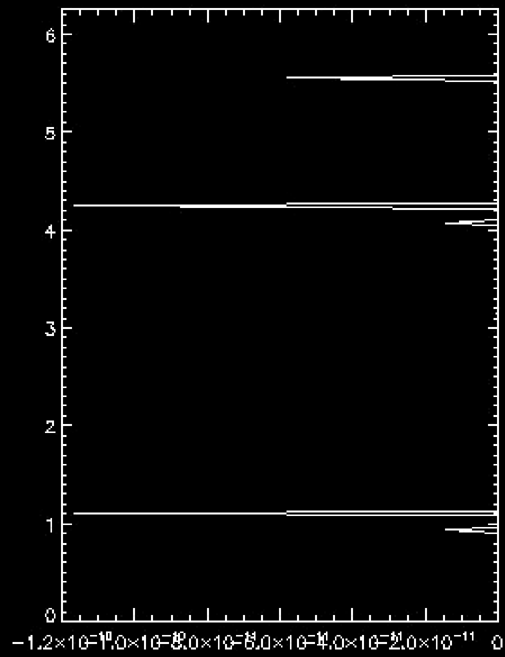
u

Antifriction β=50

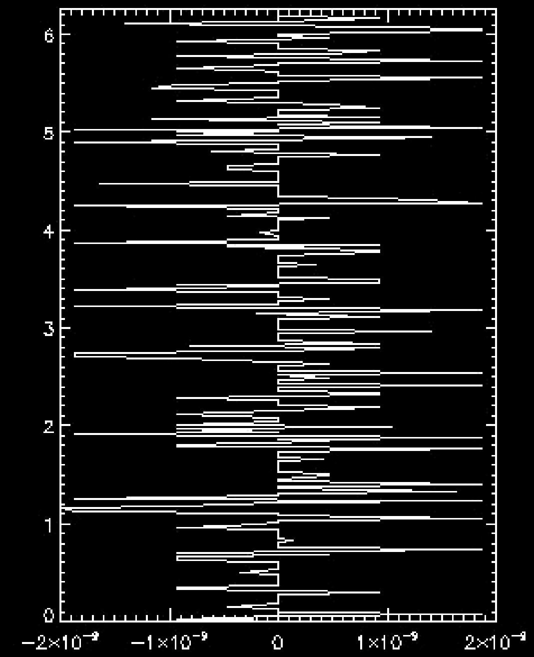
HYDRODYNAMIC

Mean Flows

Early Times

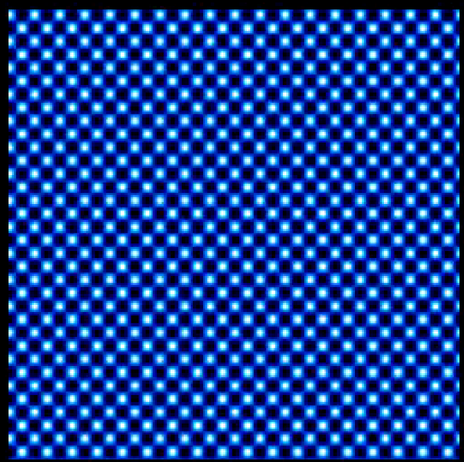


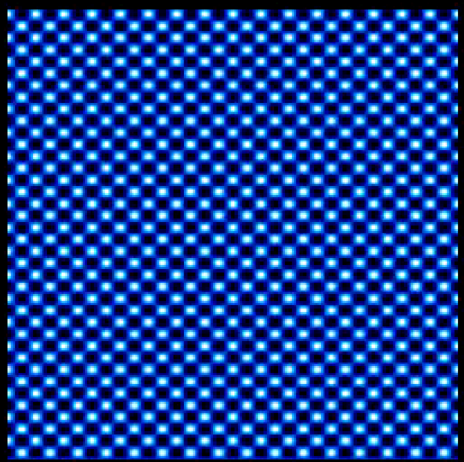
$\beta = 5$



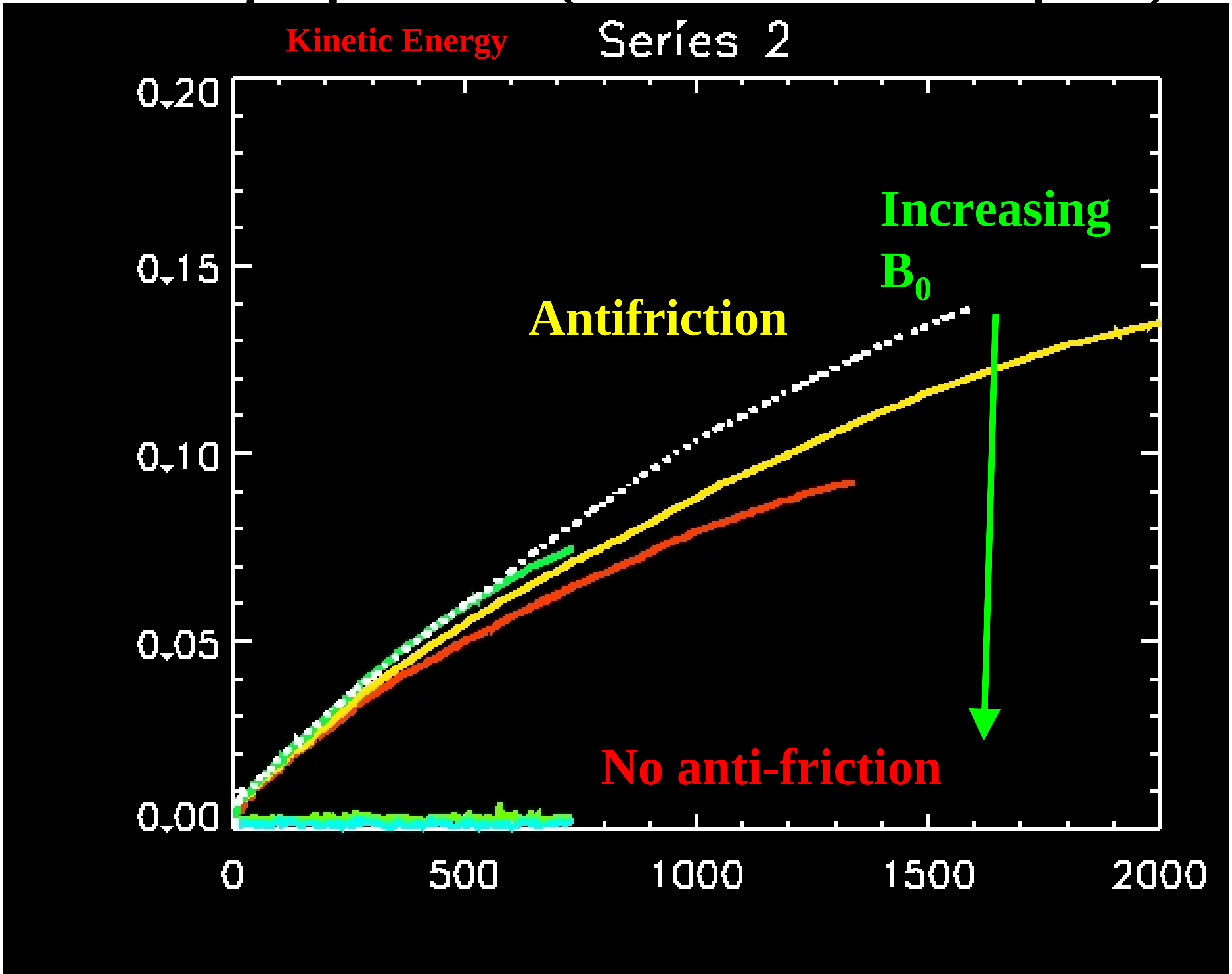
$\beta = 50$

Rossby Waves





β-plane (MHD example)



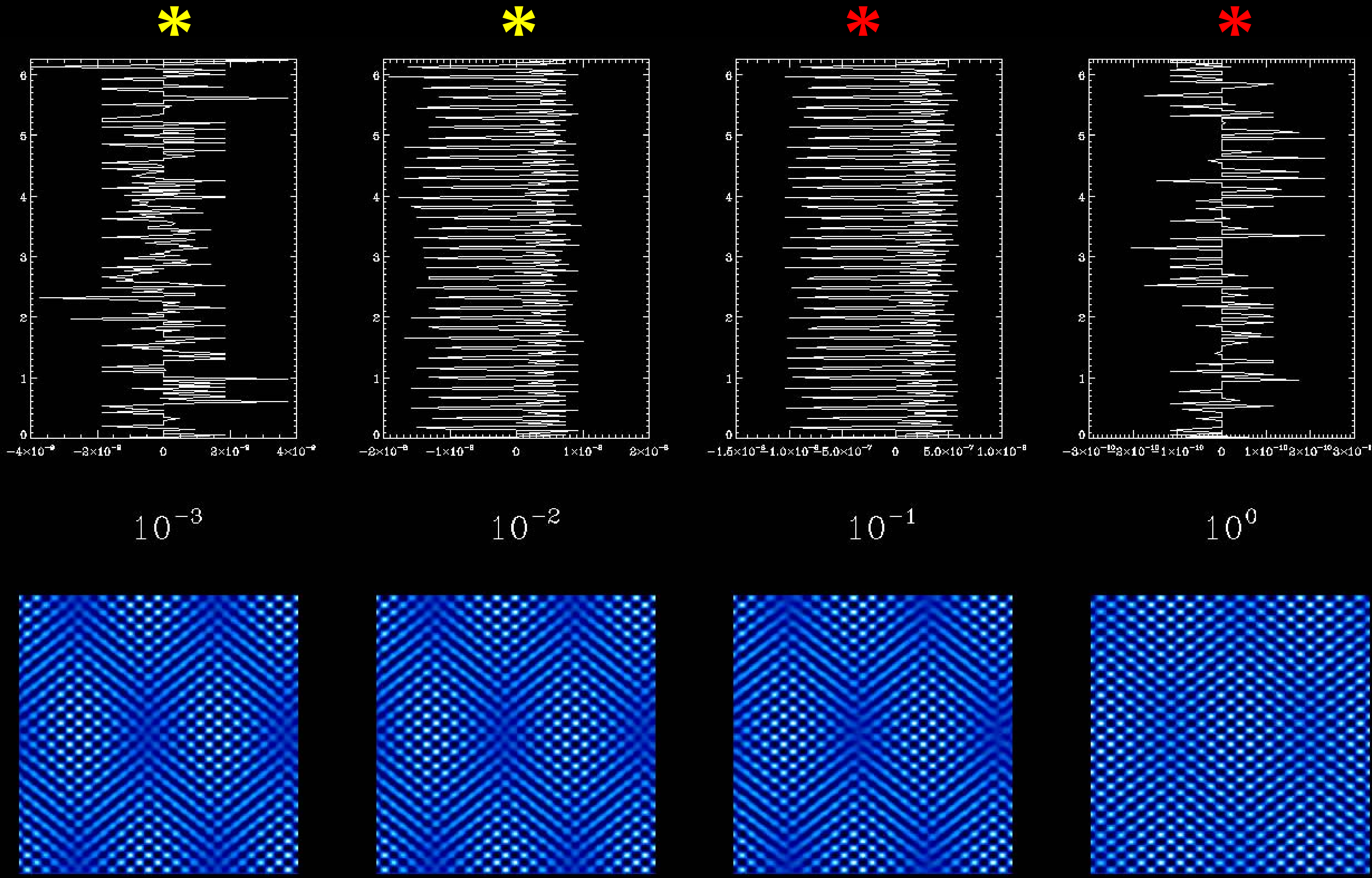
(fixed Rm)

How does it work?

- Mean flows $\overline{u}(y) = \int u(x,y)dx$ driven by Reynolds stresses and opposed by Maxwell Stresses.

$$\partial_t \overline{u} = -\partial_y (\overline{uv} - \overline{b_x b_y}) + \nu \partial_{yy}^2 \overline{u}$$

- Competition between Reynolds Stresses and Maxwell Stresses
- Competition between Rossby Waves and Alfvén Waves.



Rossby Waves

Rossby/Alfvén Waves

Alfvén Waves