Rotationally induced mixing in solar-type stars

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In collaboration with:
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Evidence for / constraints on mixing in the Sun

- Surface abundances of He/Li/Be
- Interior profile of mean molecular weight
  - Sound speed anomaly at base of convection zone
  - Compositional stratification below convection zone

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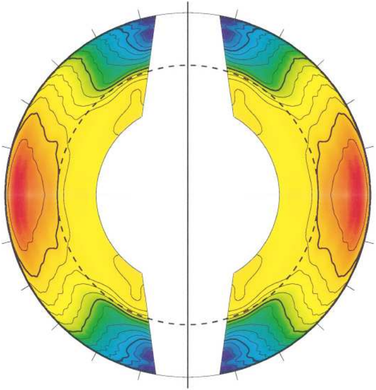
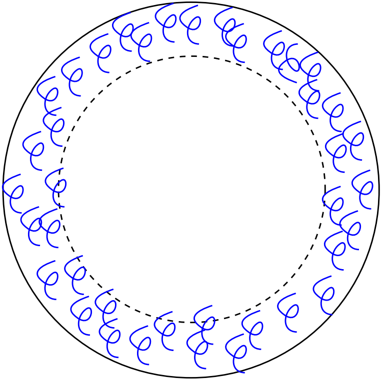
- Differential rotation



Causes of "mixing"

Heavy elements (and angular momentum) are transported by

- Turbulence
  - Thermally driven (convection, semi-convection, overshoot)
  - Shear driven (KH, GSF, MRI, ...)
- Meridional advection



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- Internal waves
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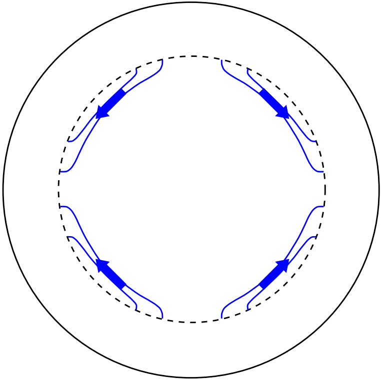

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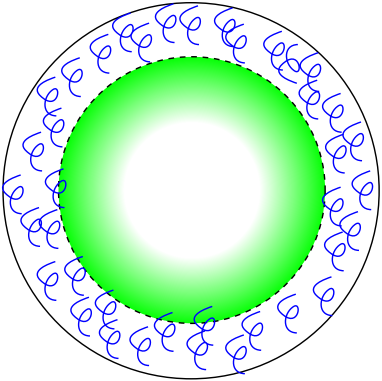

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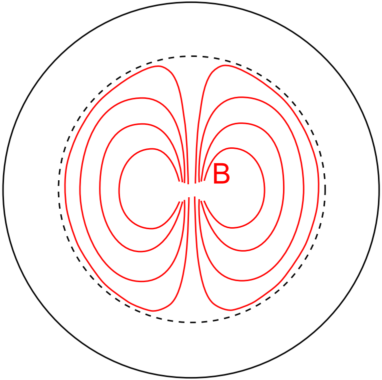

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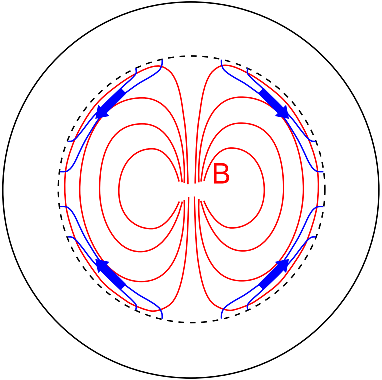
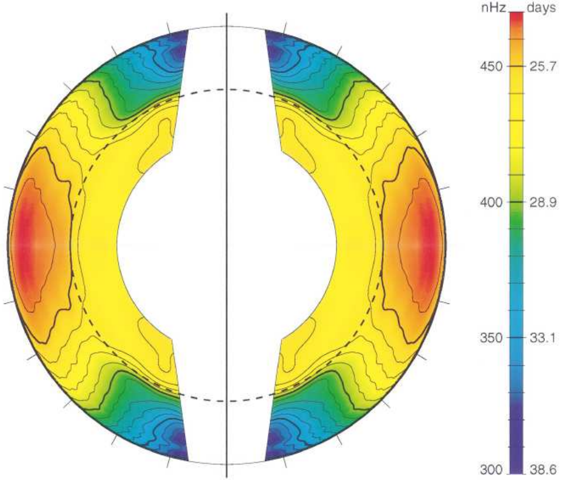


Neither of these is diffusive, or spherically symmetric

What drives meridional circulations?



Schou et al. 1998

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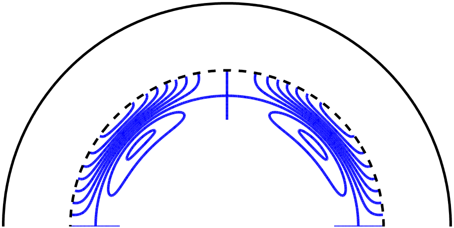
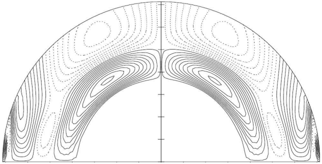


Spiegel & Zahn 1992



Elliott 1997

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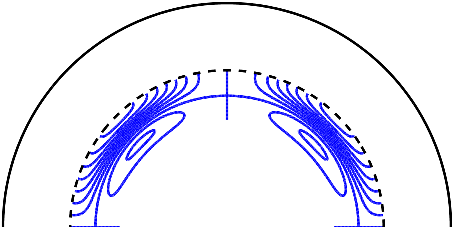

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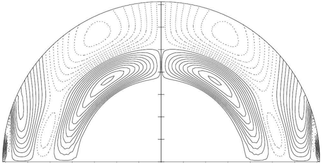

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Good for lithium, bad for rotation

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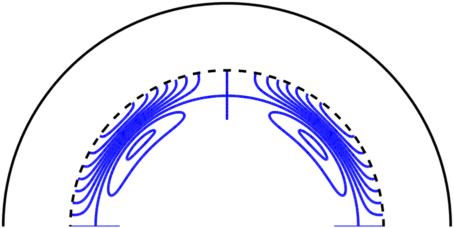

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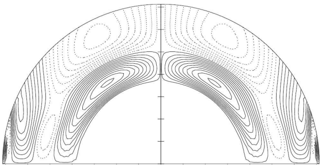


Elliott 1997

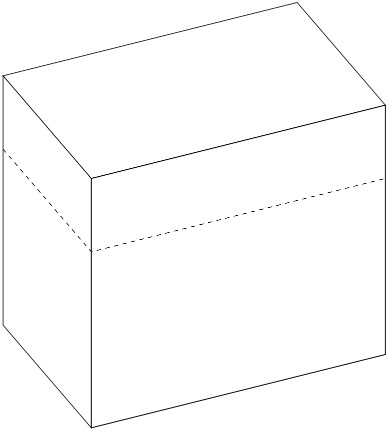
Good for lithium, bad for rotation
BUT
axisymmetric, no waves, no turbulence

Local Cartesian model

Rotating, compressible convection (Brummell, Hurlburt & Toomre 1996, Brummell, Clune & Toomre 2002)

- Ideal gas
- Fully compressible
- 3D
- (MHD)

- Horizontally periodic
- Pseudospectral



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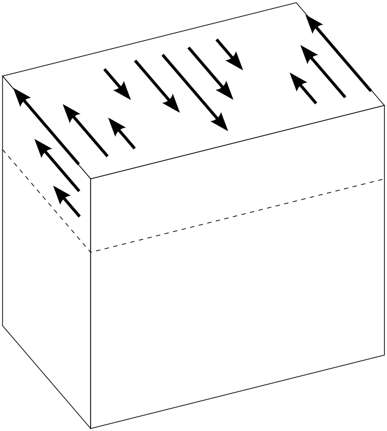

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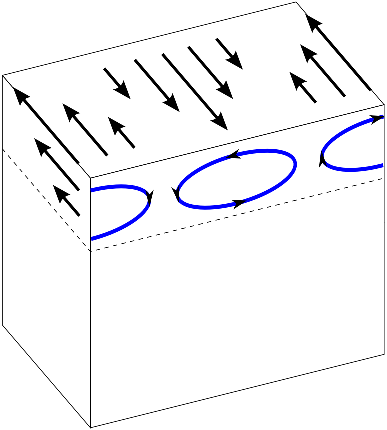

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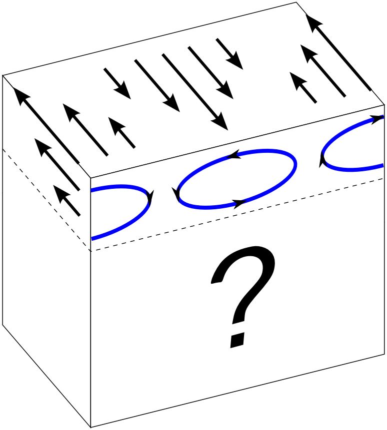

Parameter selection

acoustic time		buoyancy time		rotation time		Eddington–Sweet time		viscous time
$\dfrac{L}{c}$	$\ll$	$\dfrac{1}{N}$	$\ll$	$\dfrac{1}{\Omega}$	$\ll$	$\left(\dfrac{N}{\Omega}\right)^2 \dfrac{L^2}{\kappa}$	$\ll$	$\dfrac{L^2}{\nu}$

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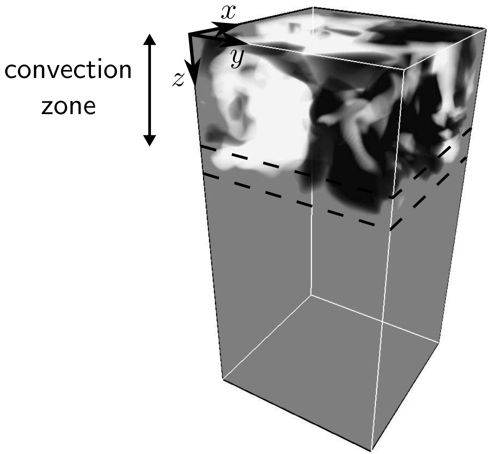
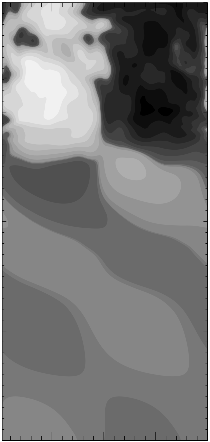
$$\Rightarrow \quad \frac{\nu}{\kappa} \ll \left(\frac{\Omega}{N}\right)^2 \ll 1$$

The burrowing regime





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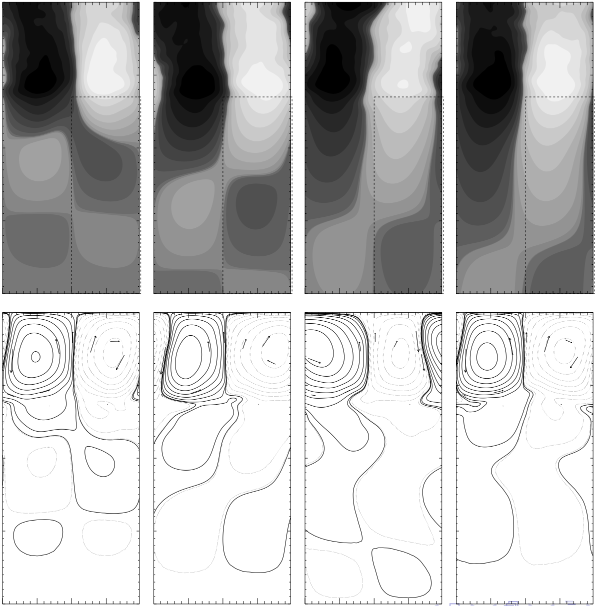
Burrowing with and without turbulence



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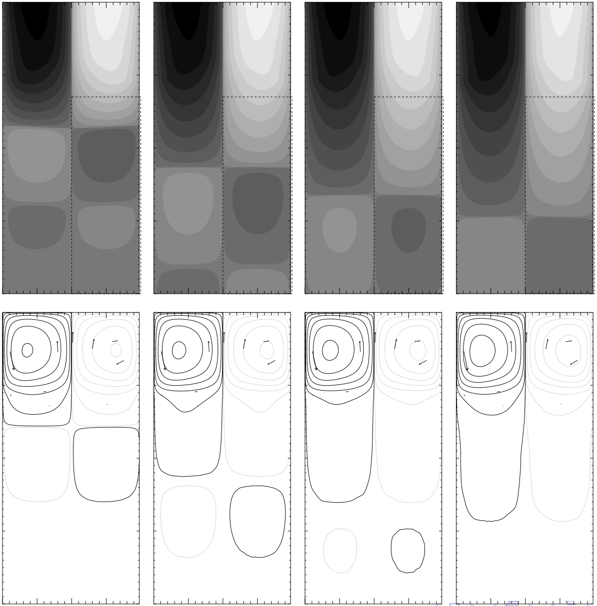

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The non-burrowing regime

acoustic time	$\ll$	buoyancy time	$\ll$	rotation time	$\ll$	viscous time	$\ll$	Eddington–Sweet time
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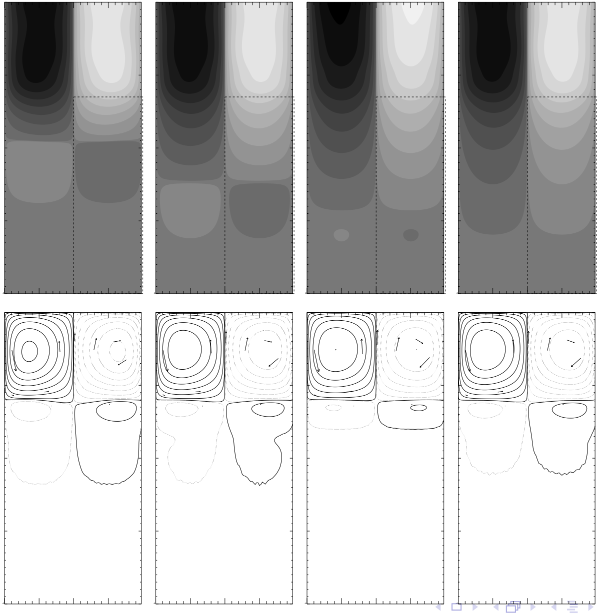
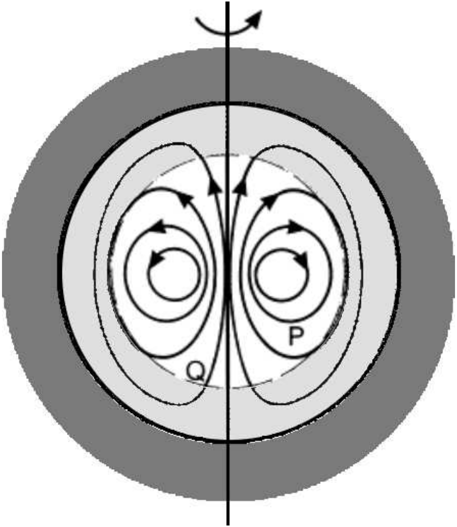


Summary

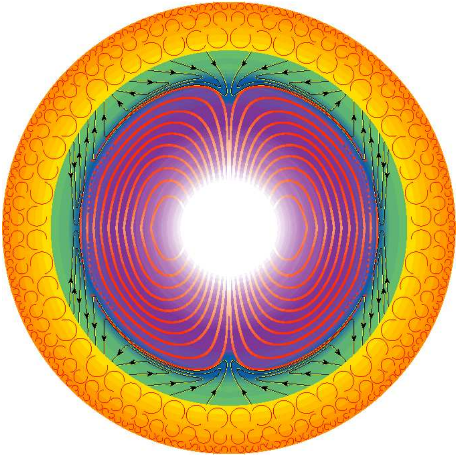
- Burrowing expected in solar interior, but not for late solar-type stars.
- Might explain solar lithium depletion.
- Yet solar interior rotates uniformly...

The Ferraro constraint



Mestel & Weiss 1987

The Ferraro constraint



Gough & McIntyre 1998

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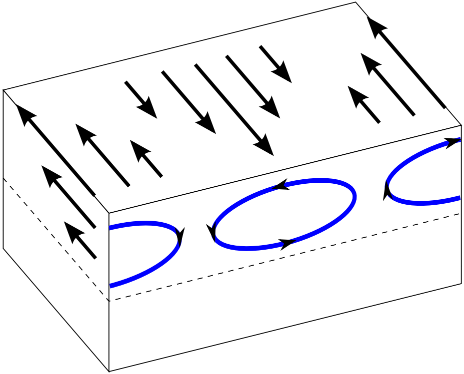

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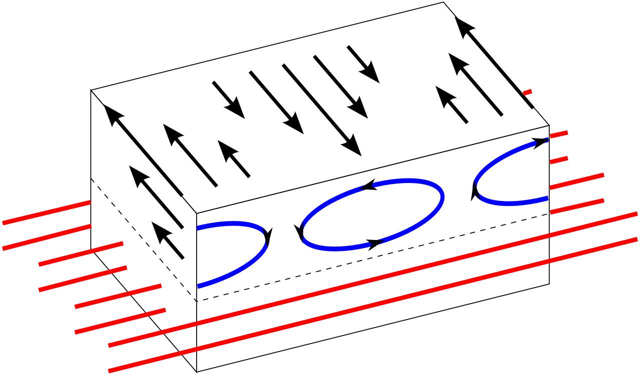

Can a magnetic field halt the burrowing?

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Conclusions

- Burrowing of meridional flows is robust in the absence of a magnetic field
- But a weak magnetic field can dominate the angular momentum transport, and halt the burrowing

The end

Thank you!