Time-distance Measurements of the Meridional Circulation Deep in the Convection Zone

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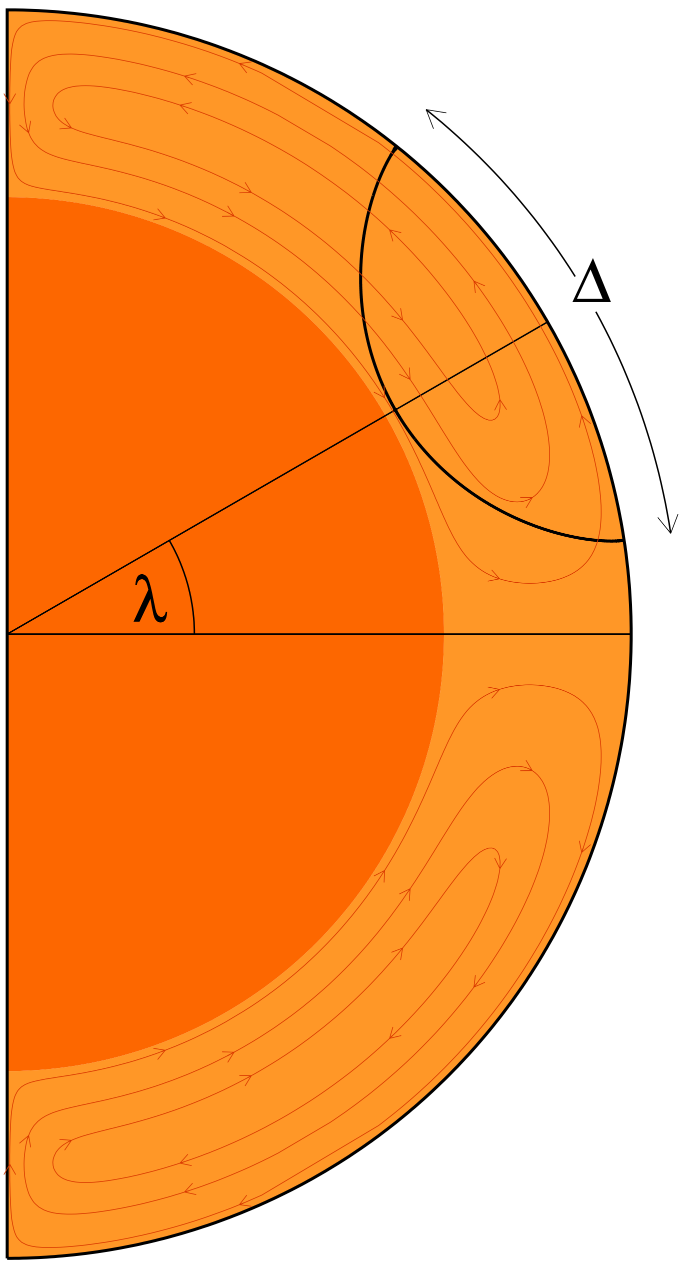
Measuring Meridional Flows

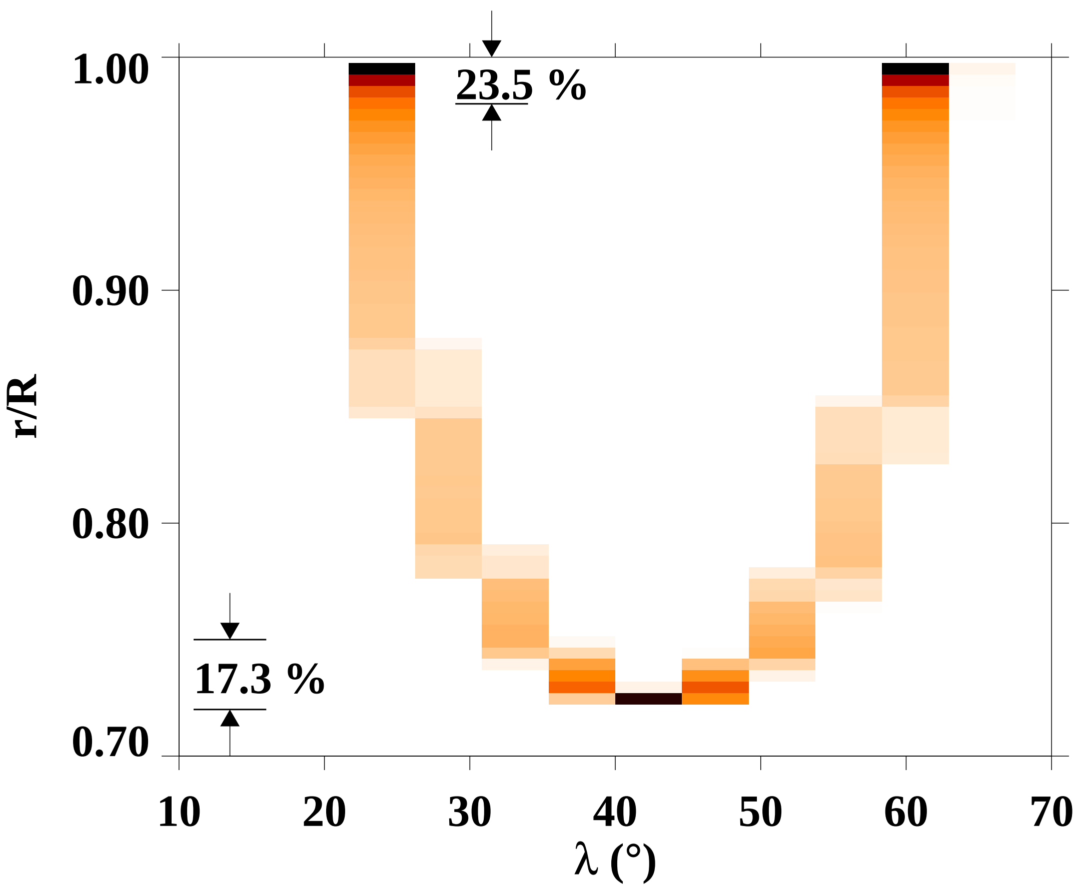


Time-distance helioseismology: measure the travel times for northward- and southward-propagating waves.

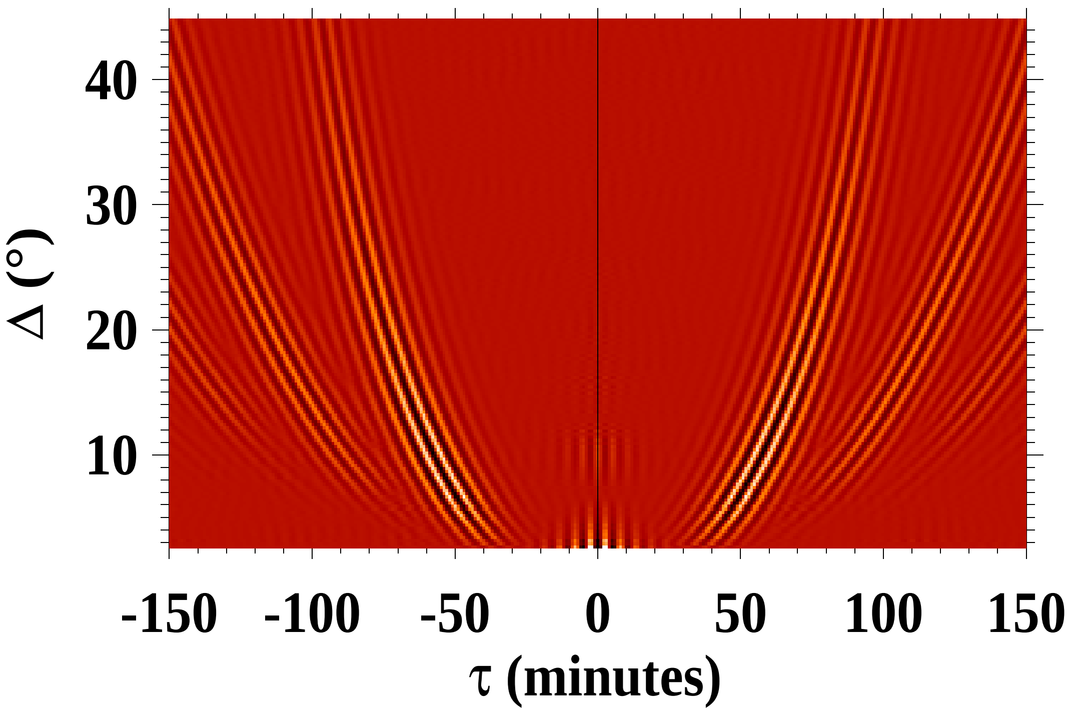
$$\delta\tau(\Delta, \lambda) \simeq 2\int_{\Gamma} \frac{\mathbf{u}\cdot\hat{\mathbf{n}}}{c^2}\, ds$$

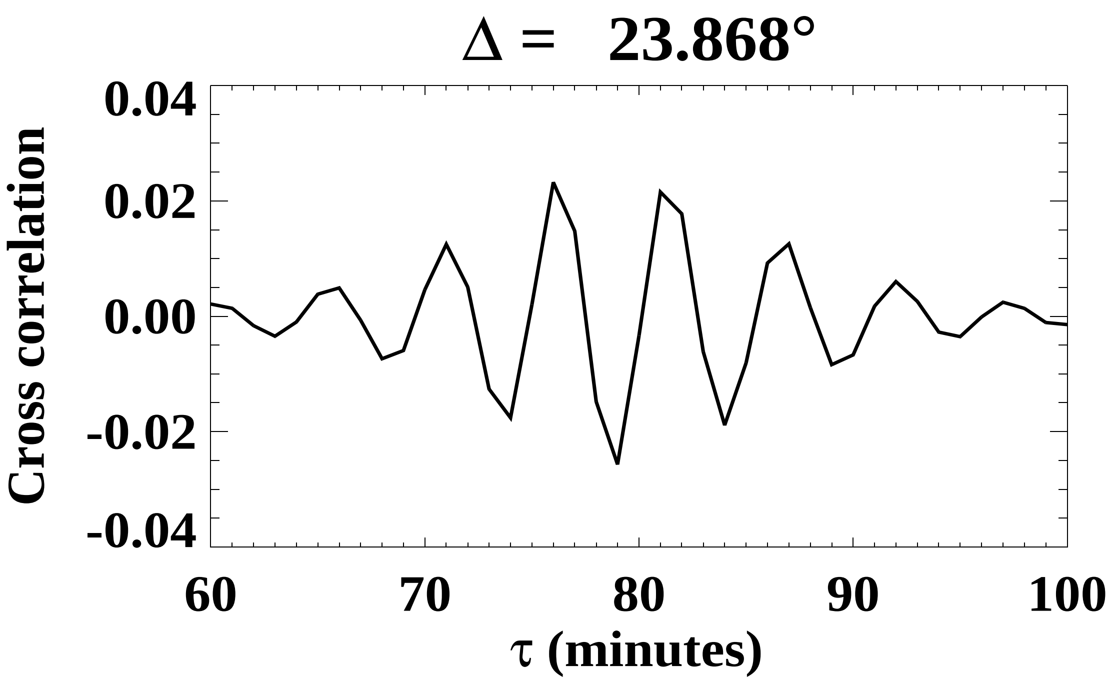
How Deep Can We Go?

The sensitivity to horizontal flows goes like $1/c^2$, but also like $\mathbf{u} \cdot \hat{\mathbf{n}}$.

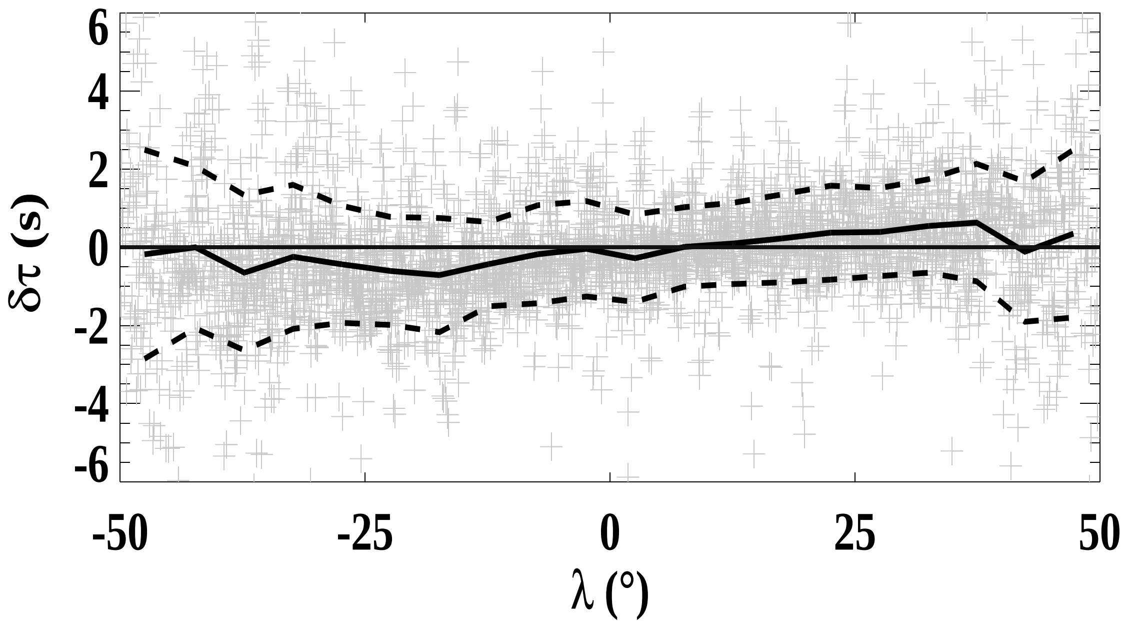


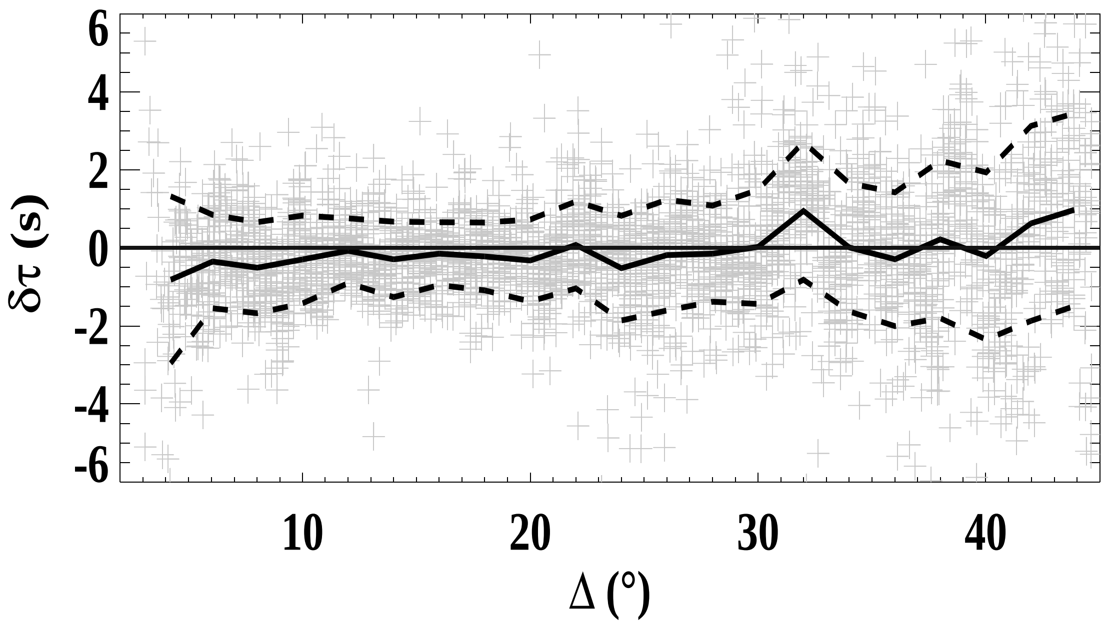
Cross Correlations





Travel Time Differences





Solar Dynamos and Meridional Circulation

Wang, Sheeley, & Nash (1991); von Rekowski, Rüdiger, Kitchatinov, Küker, ... (1998, 1999, ...); Dikpati, Charbonneau, Schüssler, Choudhuri, ... (1995, 1999, ...)

Models reproduce solar-like magnetic cycle by including a meridional circulation.

- poleward flow $\sim 10\,\mathrm{m/s}$ at the surface
- equatorward flow $\sim 1\,\mathrm{m/s}$ at the base of the convection zone.
- turning point $\sim 0.8\,R_\odot$ (?)
- cycle behaviour depends *critically* on the magnitude of the equatorward flow.

RLS Inversion

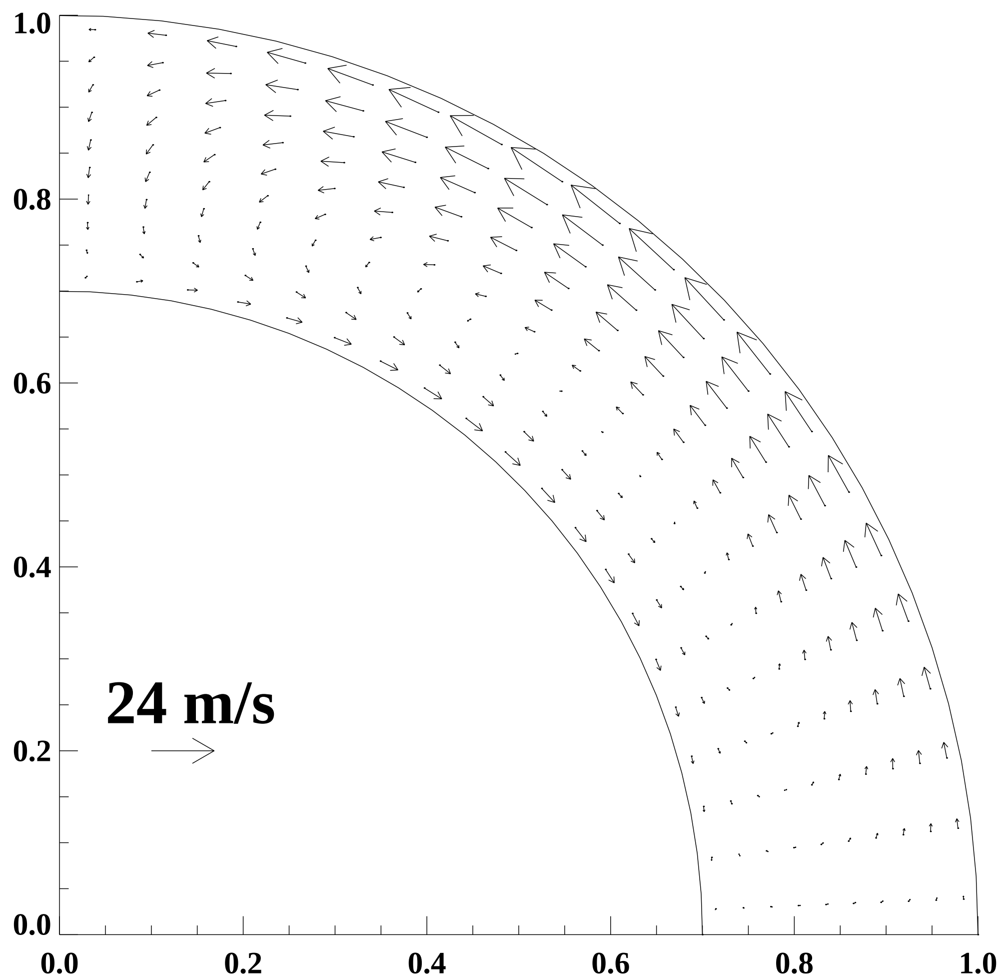
This RLS inversion uses a first-derivative regularization: minimize

$$\sum_i \left[\frac{\delta\tau_i - 2\int_i \frac{\mathbf{u}\cdot\hat{\mathbf{n}}}{c^2}\,ds}{\sigma_i} \right]^2 + \gamma \int |\nabla u|^2 \, r\,dr\,d\theta$$

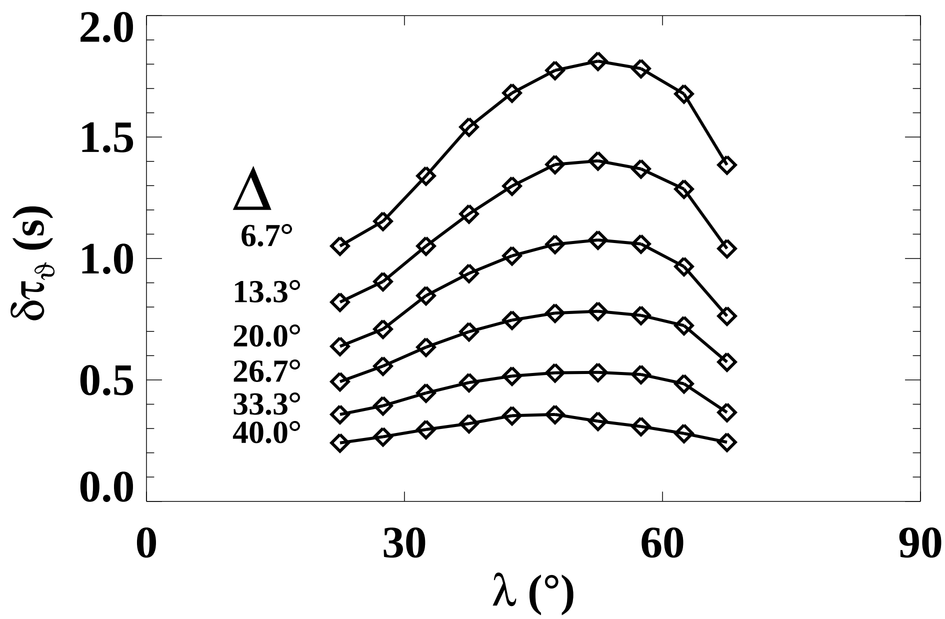
The radial component of the flow is assumed to be zero. Some might ask (during the question period, for example), "isn't that a dangerous assumption?"

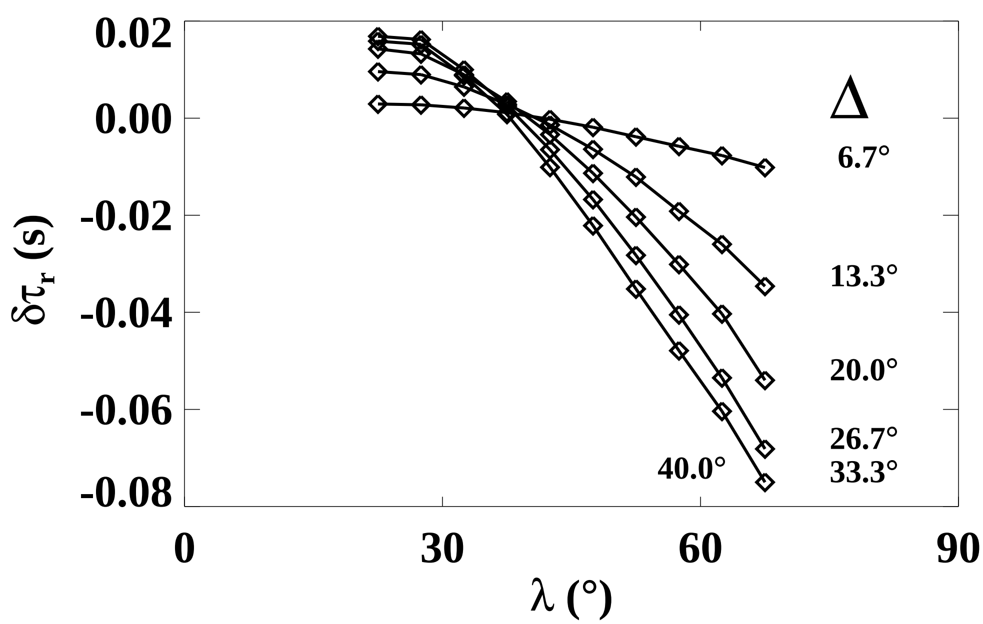
Is it Possible to Detect Radial Flow?

Using what we know about the horizontal flow near the surface, we can speculate on the rest of the profile and add in a radial flow which conserves mass:

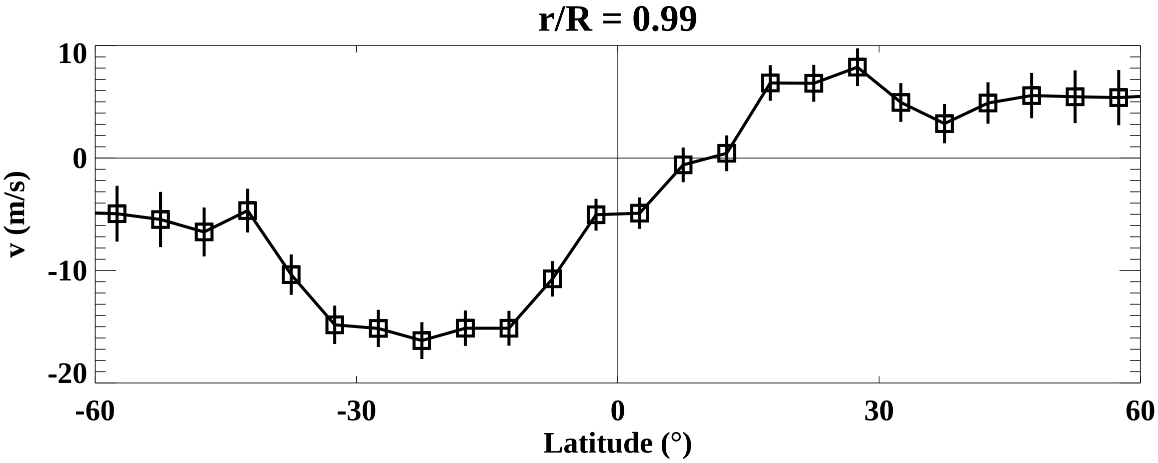


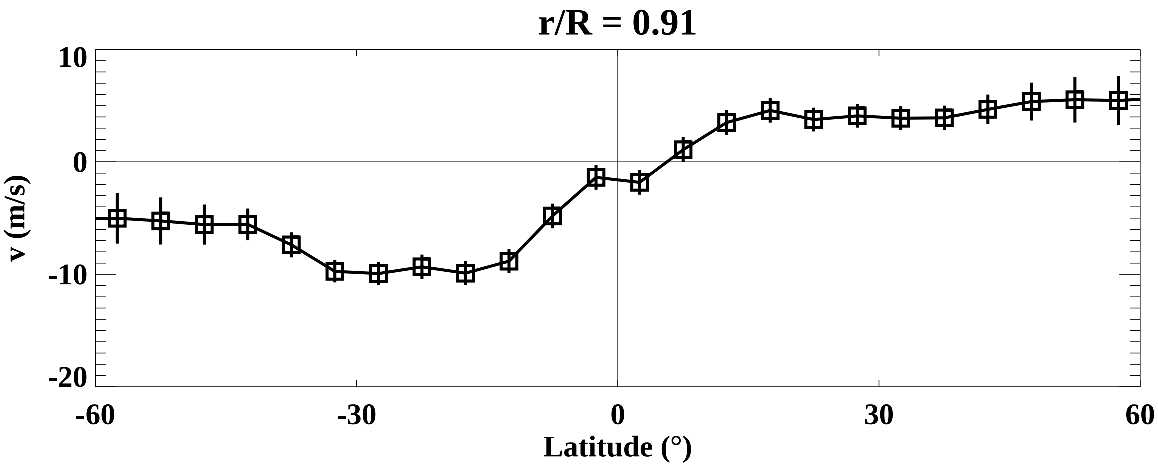
Given a set of rays described by (Δ, λ) we can compute the travel time differences due to this profile:

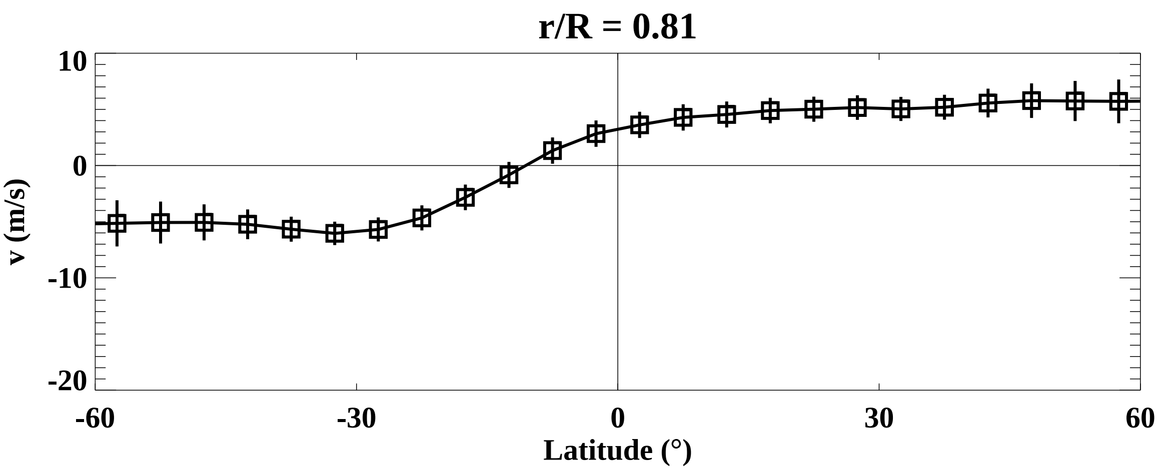


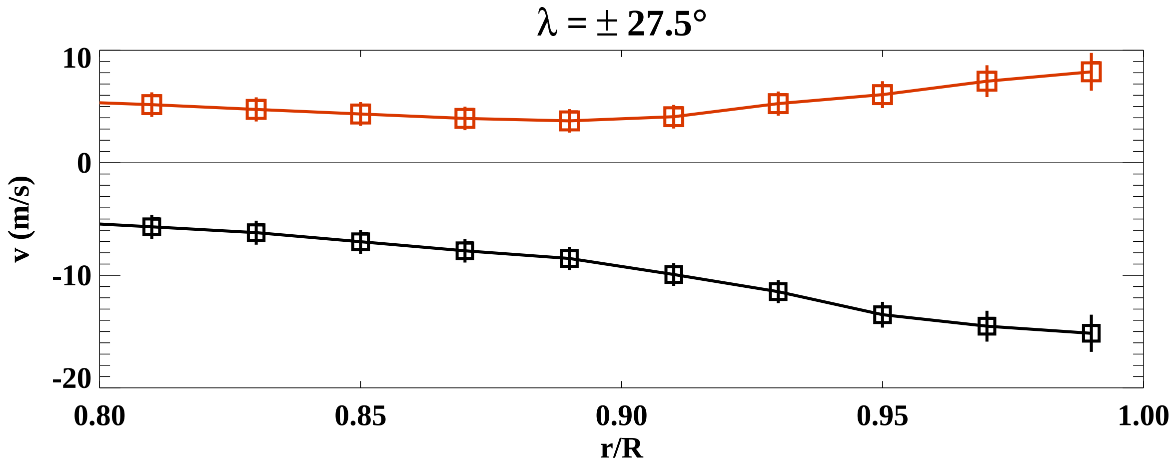


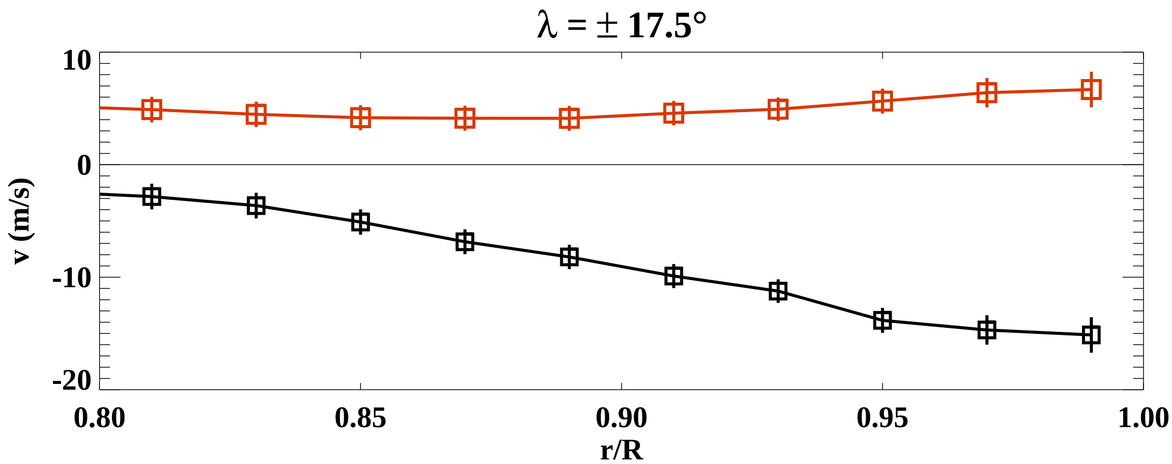
Meridional Flow Inversion Results

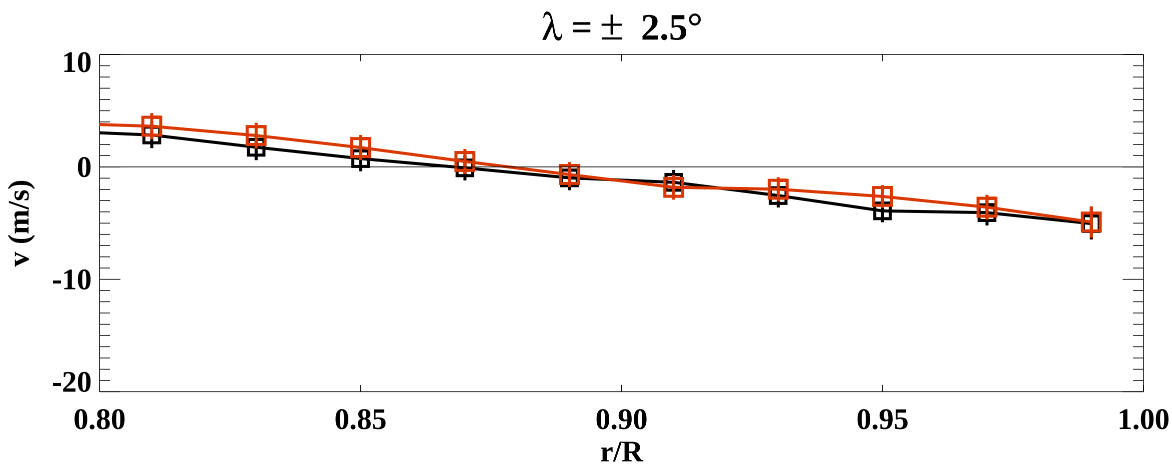


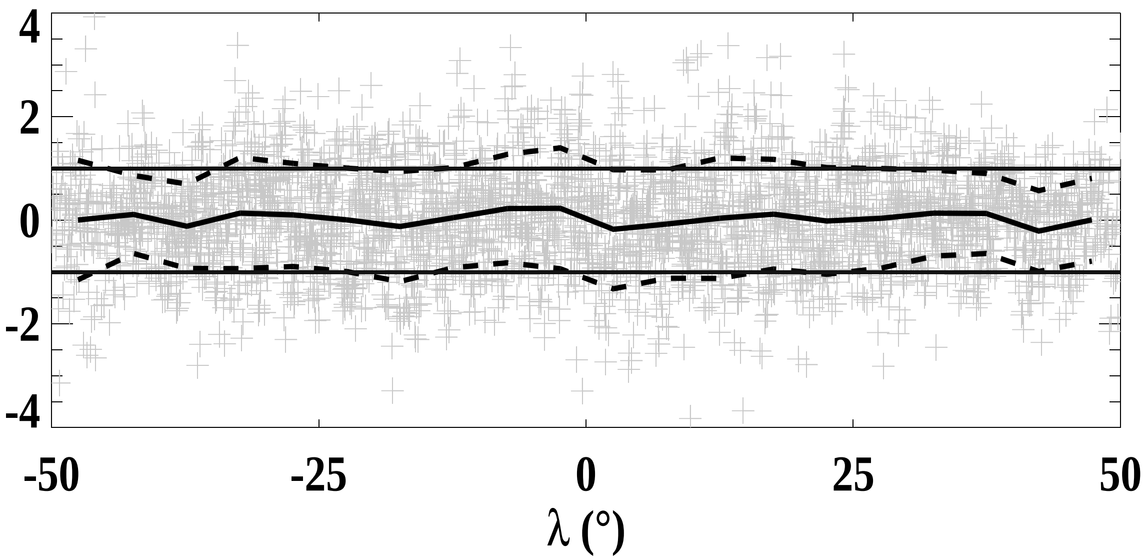




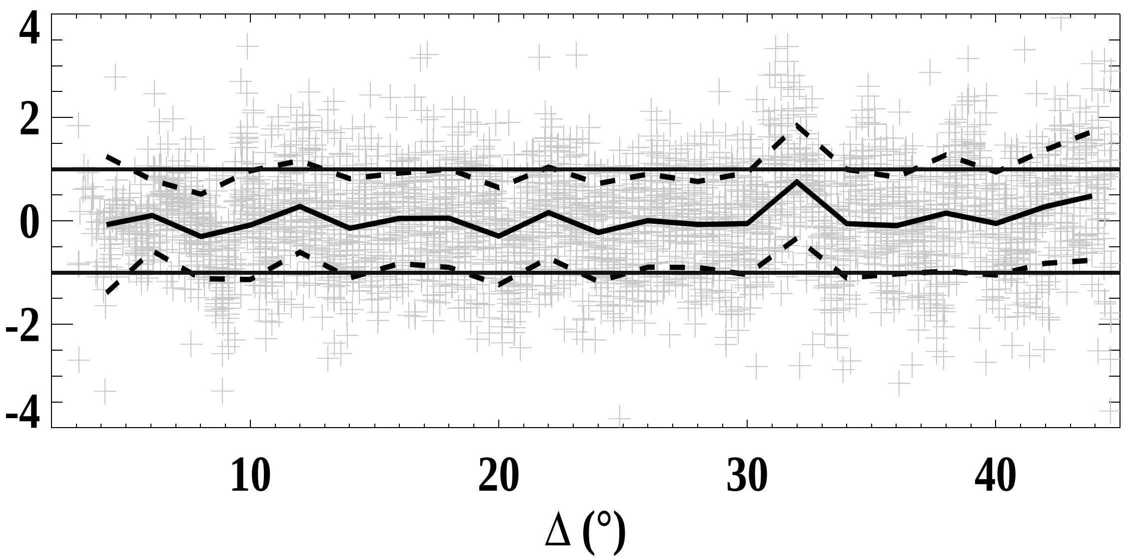

λ = ± 27.5°
10
0
-10
-20
v (m/s)
0.80
0.85
0.90
0.95
1.00
r/R


λ = ± 17.5°
10
0
-10
-20
v (m/s)
0.80
0.85
0.90
0.95
1.00
r/R


λ = ± 2.5°
10
0
-10
-20
v (m/s)
0.80
0.85
0.90
0.95
1.00
r/R

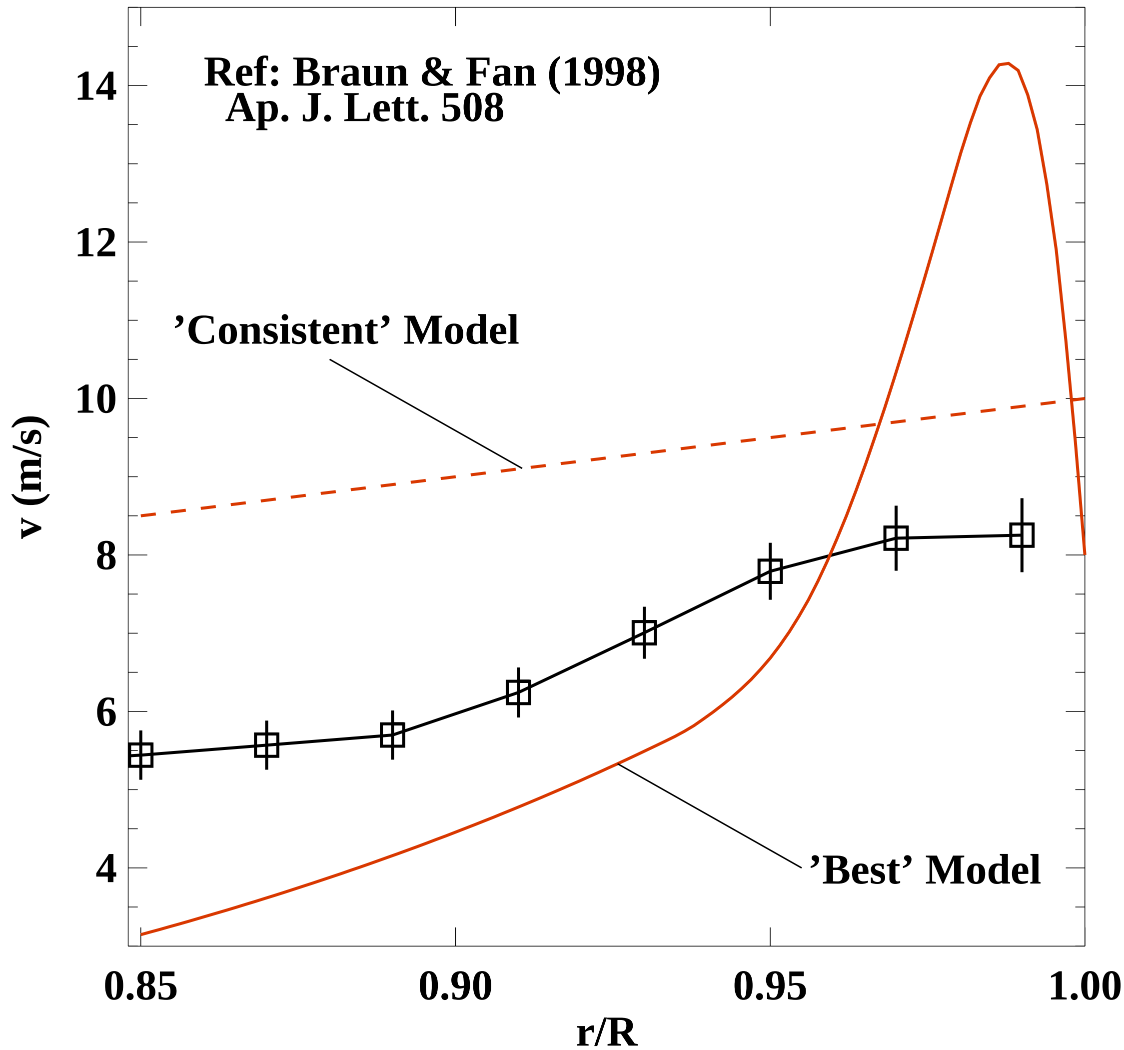


Normalized Residuals



$$\text{Residual} = \frac{\delta\tau_{\text{measured}} - \delta\tau_{\text{model}}}{\sigma}$$

Comparing Techniques



Braun & Fan measured the meridional flow using a wave decomposition technique. The result is an average over a large latitude range $(20^\circ \leq \lambda \leq 60^\circ)$ and over both hemispheres.

What About the Return Flow?

$$\frac{\int_{0.8R_\odot}^{R_\odot} \rho(r)\, r\, dr}{\int_{0.7R_\odot}^{0.8R_\odot} \rho(r)\, r\, dr} \approx 0.5$$

Continuity implies a return flow of $\sim 5\,\mathrm{m/s}$ (order of magnitude)

- Might actually be detectable (with luck ... and more data)
- Looks OK for some dynamos

Conclusions

Time-distance helioseismology: it's not just for small stuff!

Meridional circulation is poleward down to $0.8\,R_\odot$. The return flow must be $\sim 5\,\mathrm{m/s}$. Perhaps we are not too far from providing a useful constraint for dynamo theorists.

Cross-equator flow seems to depend on depth in a way that is inconsistent with a P-angle error. Perhaps we are seeing a component of the meridional circulation which spans both hemispheres.