Deep Structure of Meridional Circulation: Time-Distance Helioseismic Inferences from HMI (4 years)

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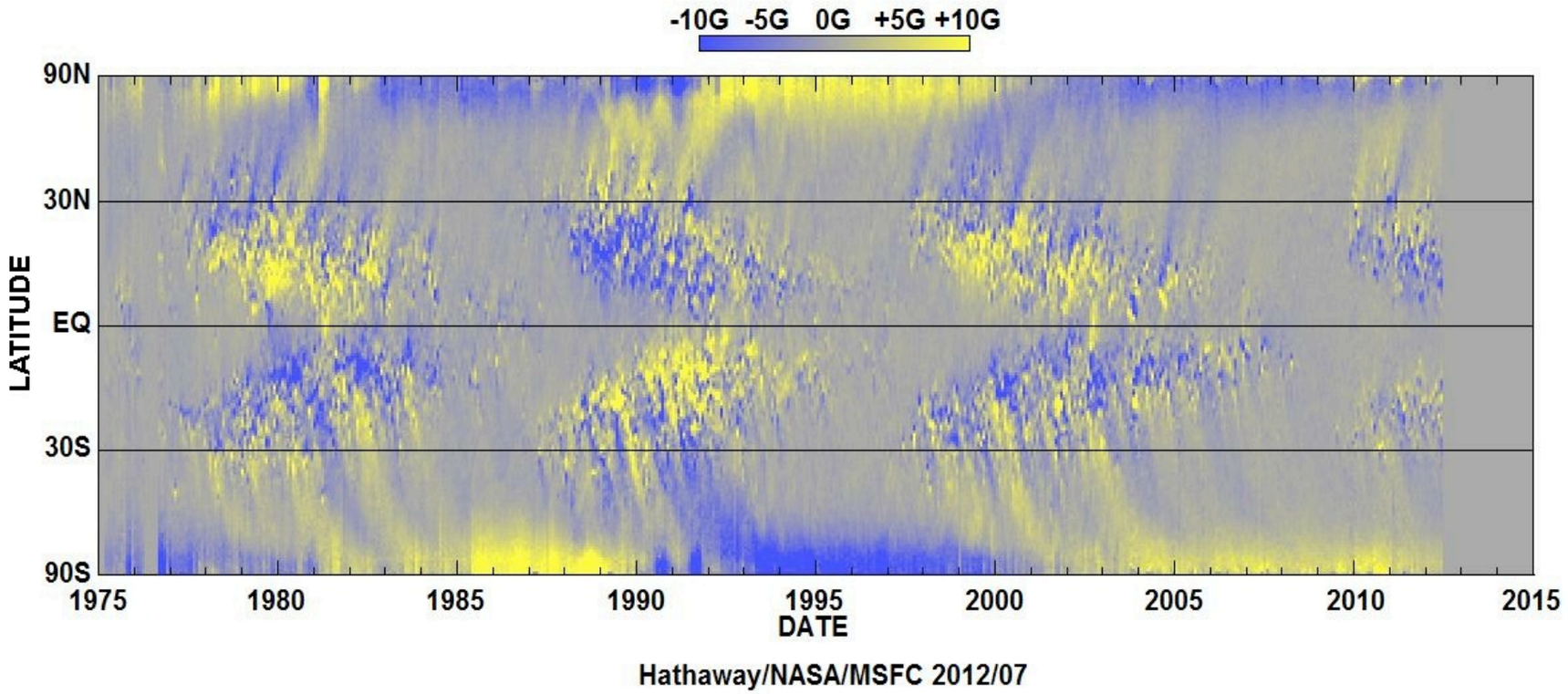
Solarnet III/Helas VII/SpaceInn, Freiburg.
31 Aug - 4 Sep, 2015

Meridional flows: surface observations, well established



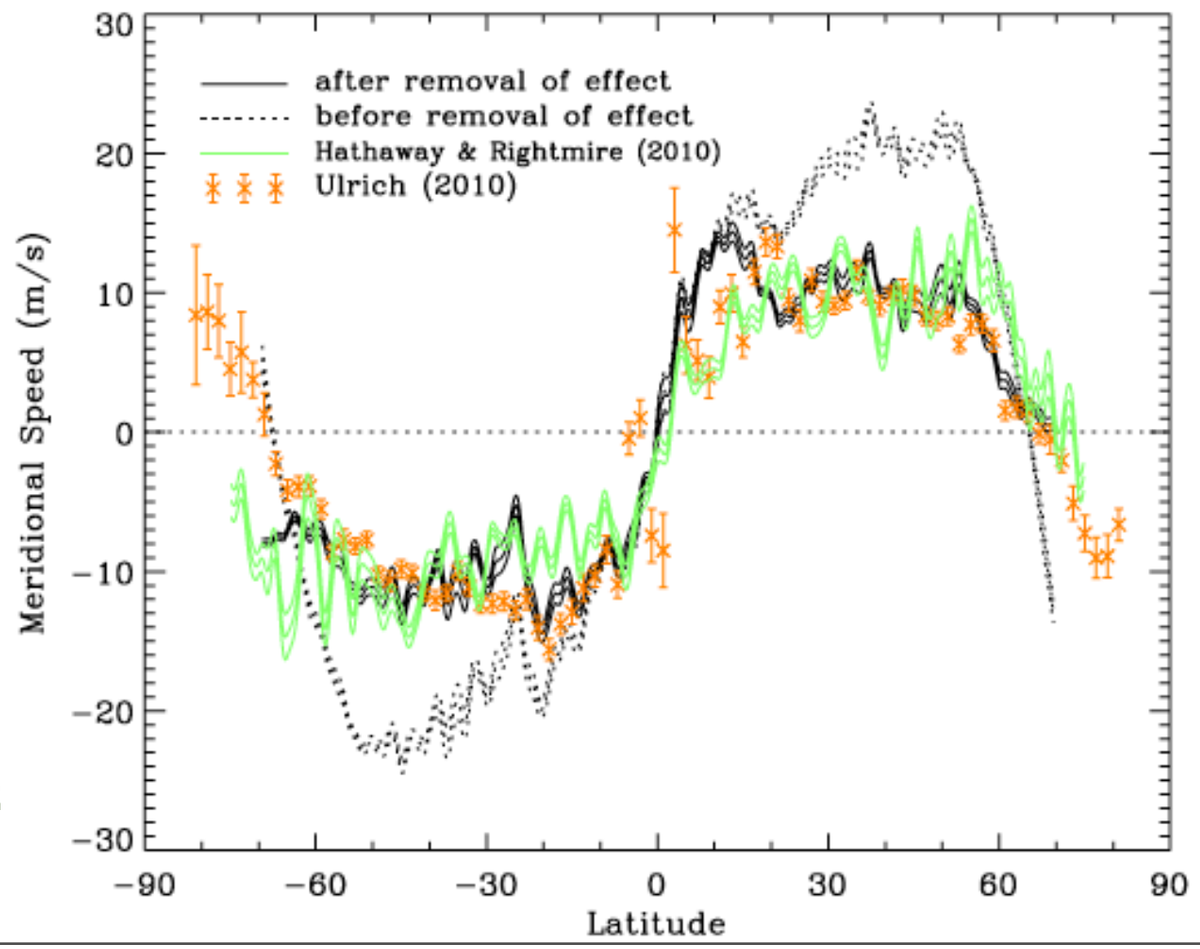
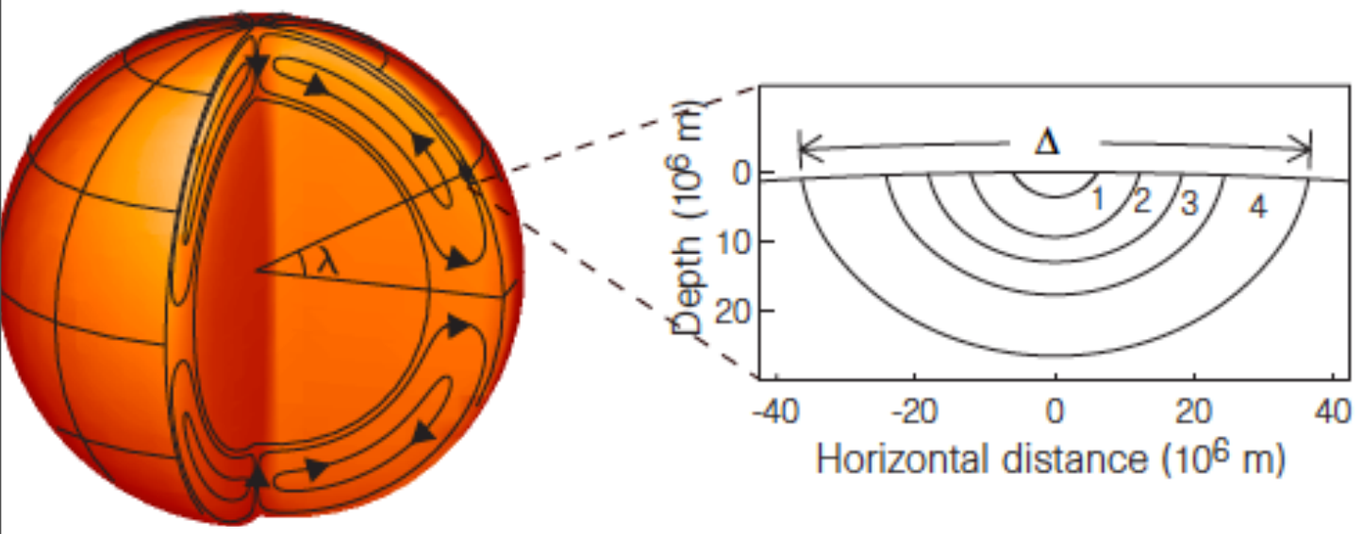
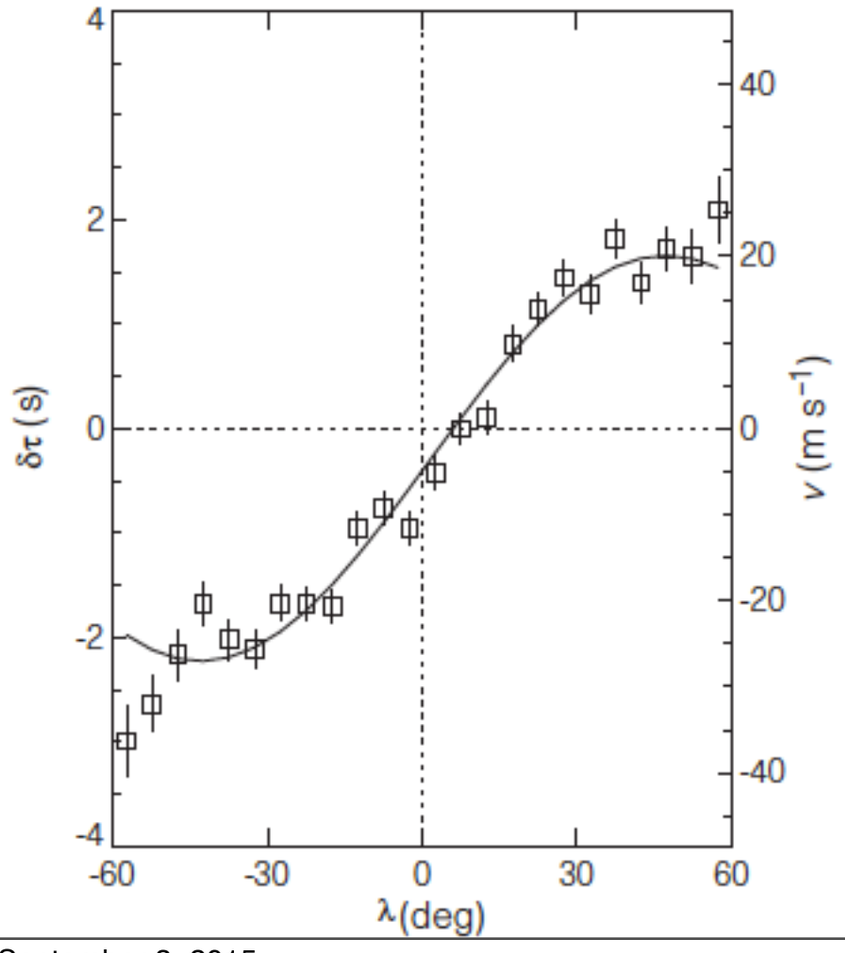


Figure from Zhao et al. 2012

Time-distance helioseismic measurements of meridional flow

Early measurements by Giles, Duvall et al. 1997, Nature, using MDI/SOHO data





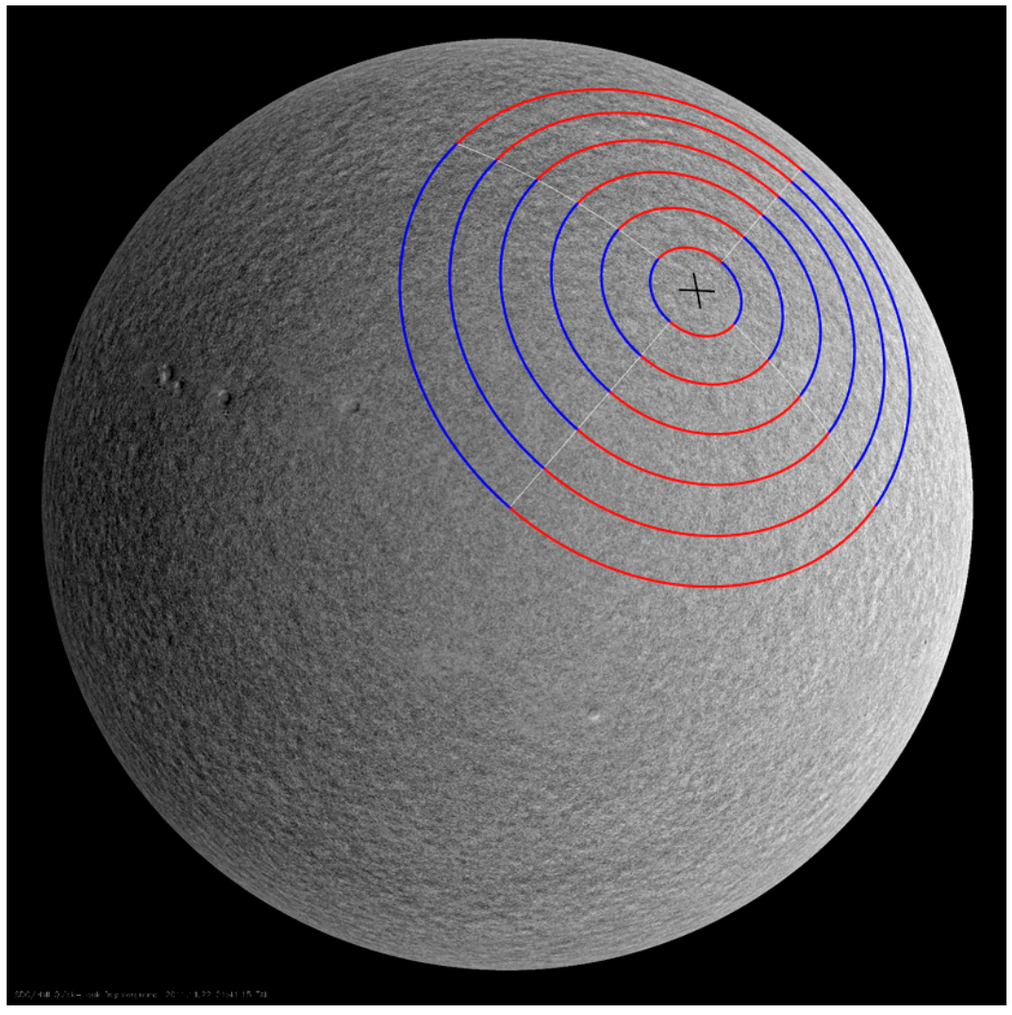
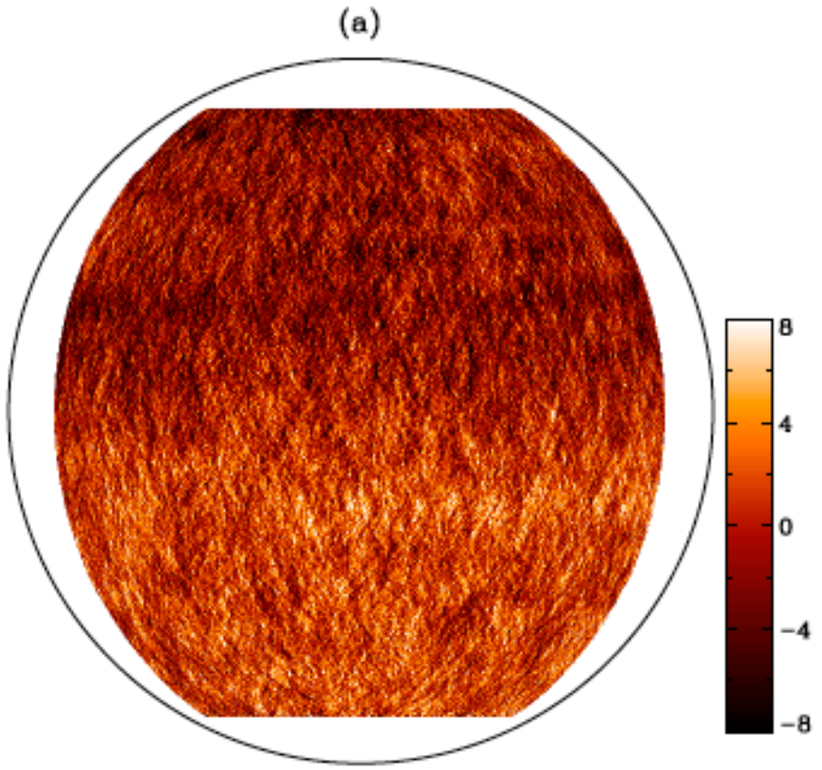


Figure Credit: Hanasoge et al. 2011

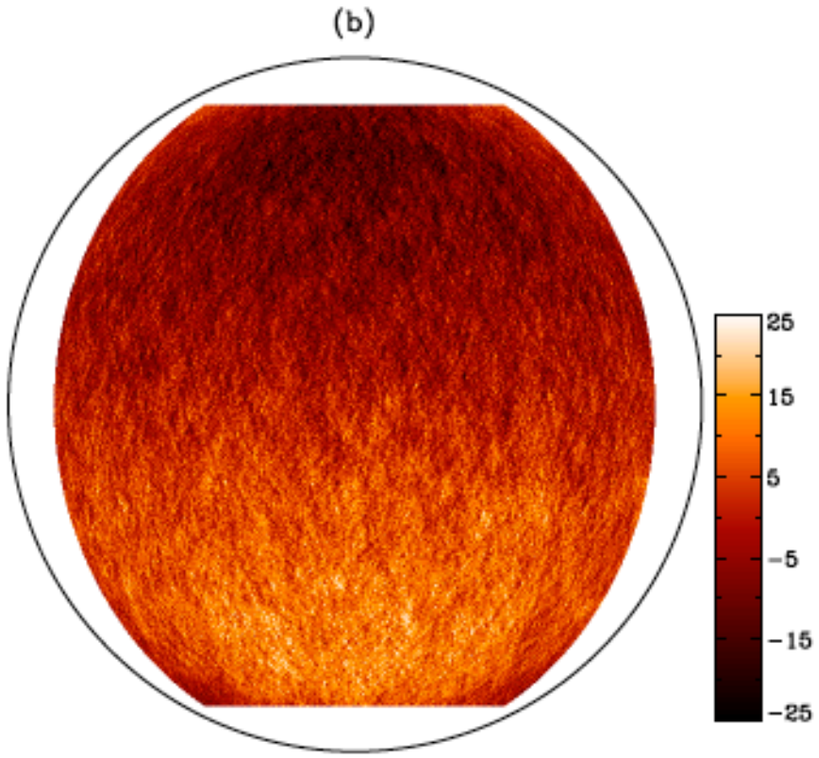
Center-to-limb Systematics in Helioseismic Travel Times

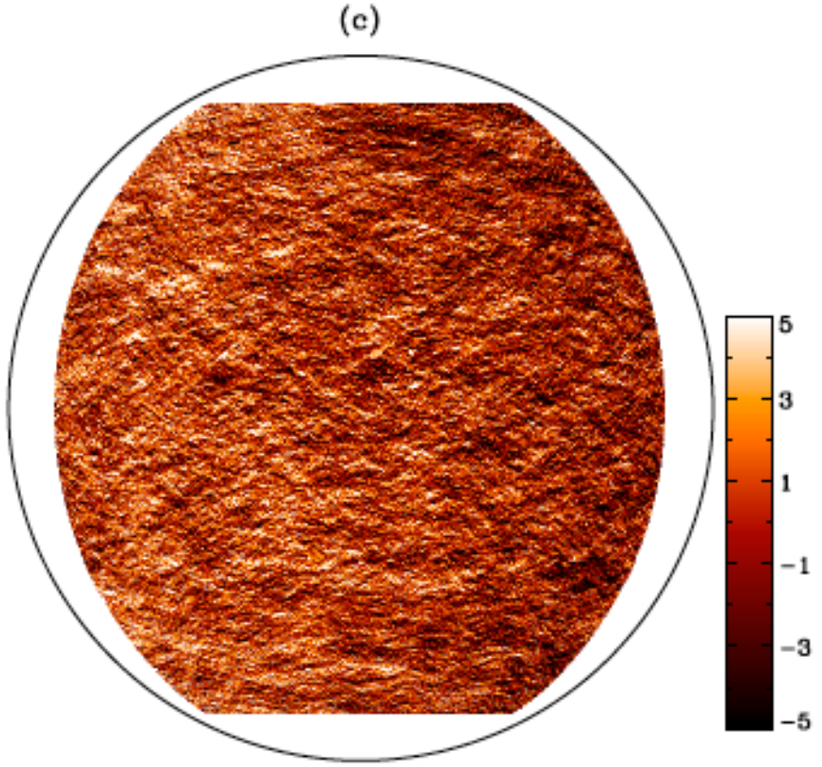
-- Zhao et al. 2012, ApJ

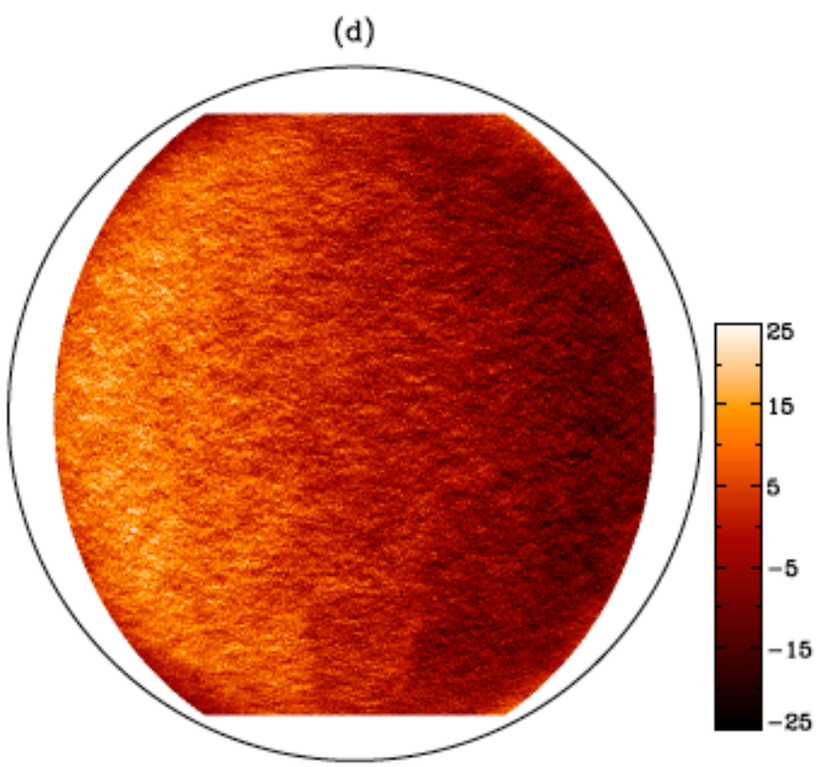
from HMI Doppler Velocities



from HMI continuum intensities

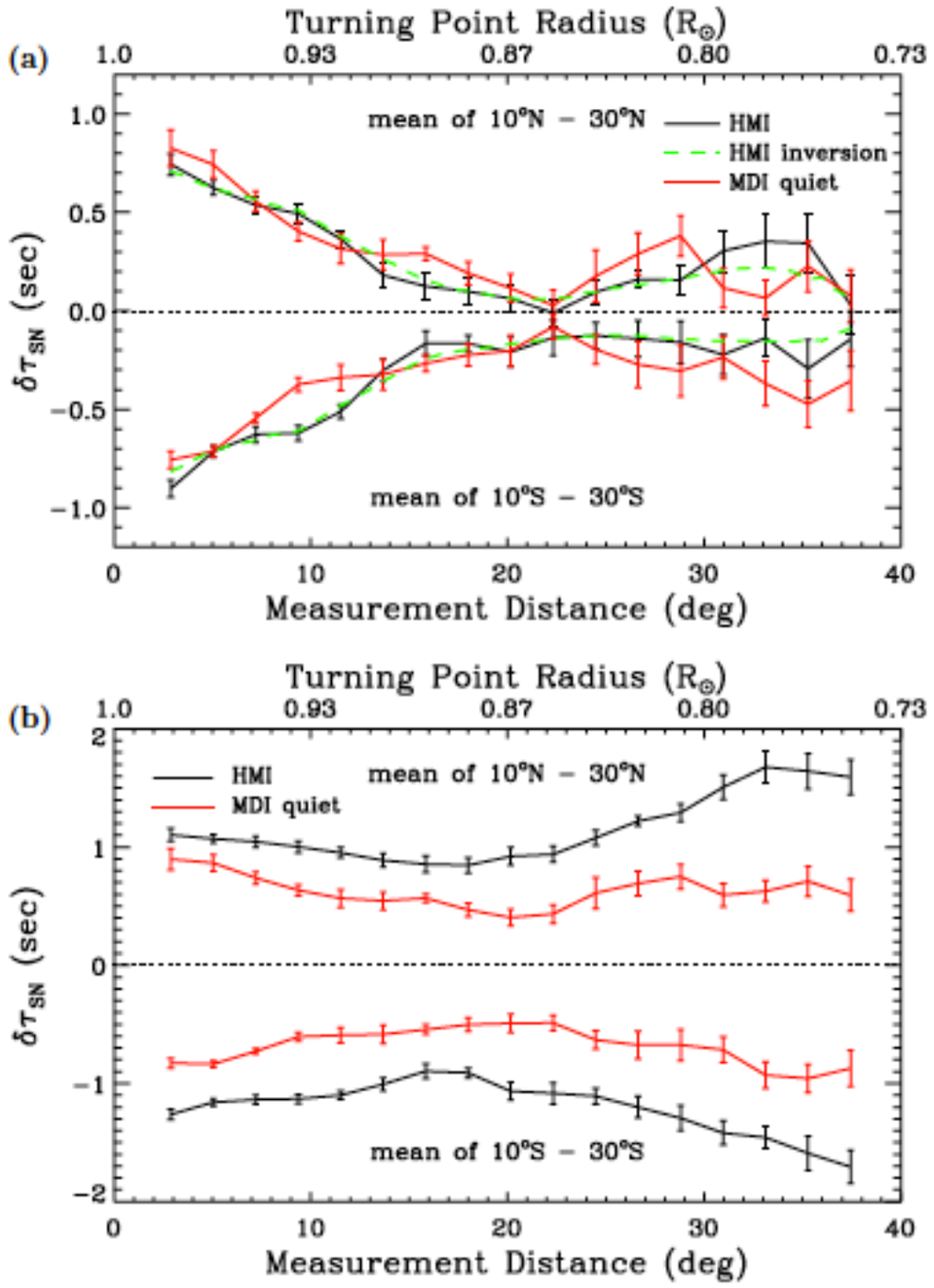


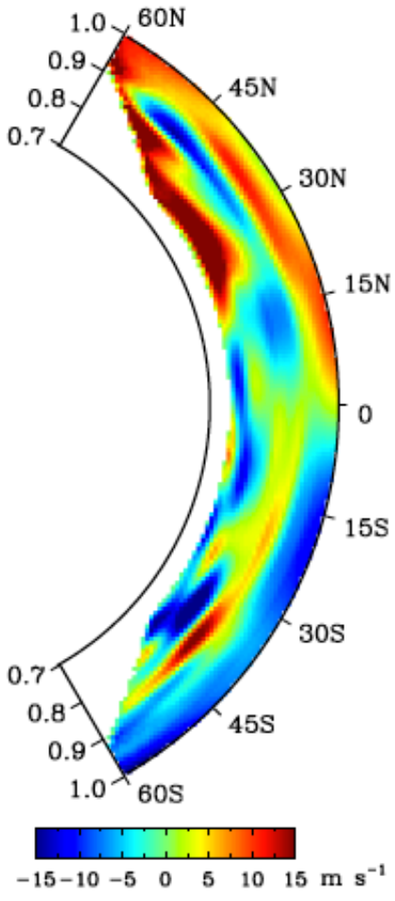


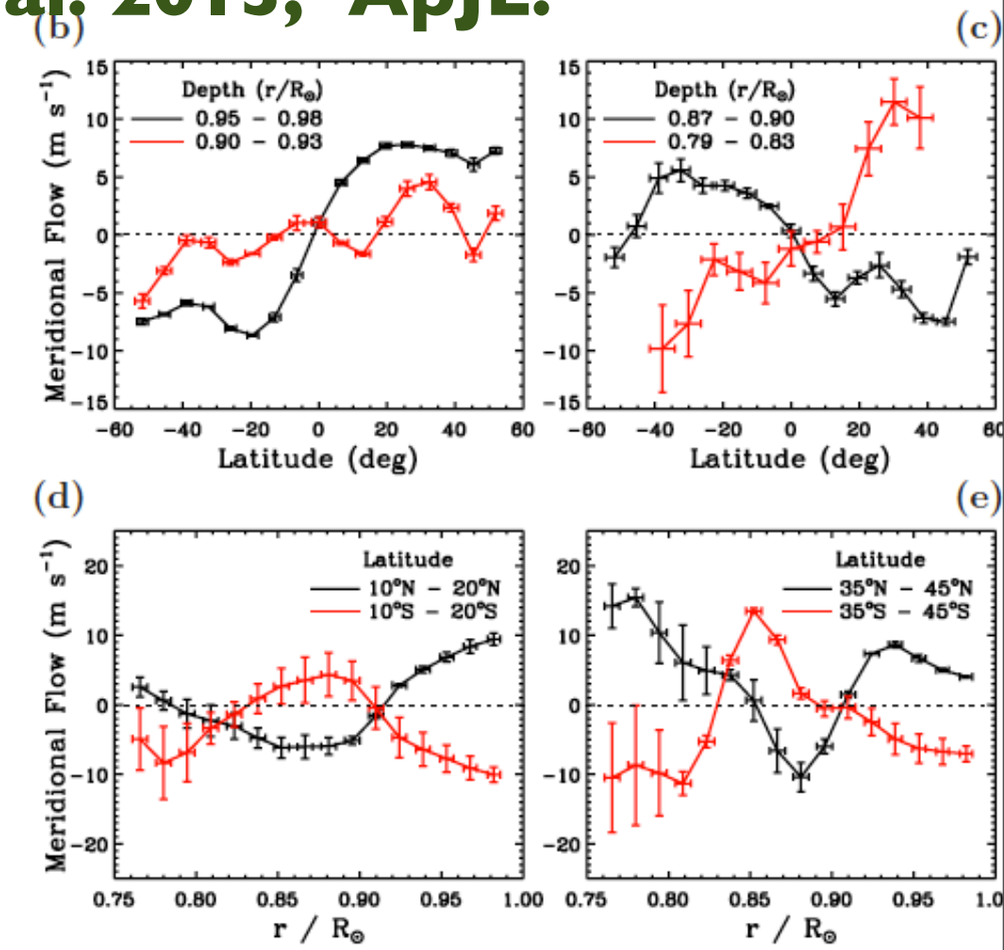


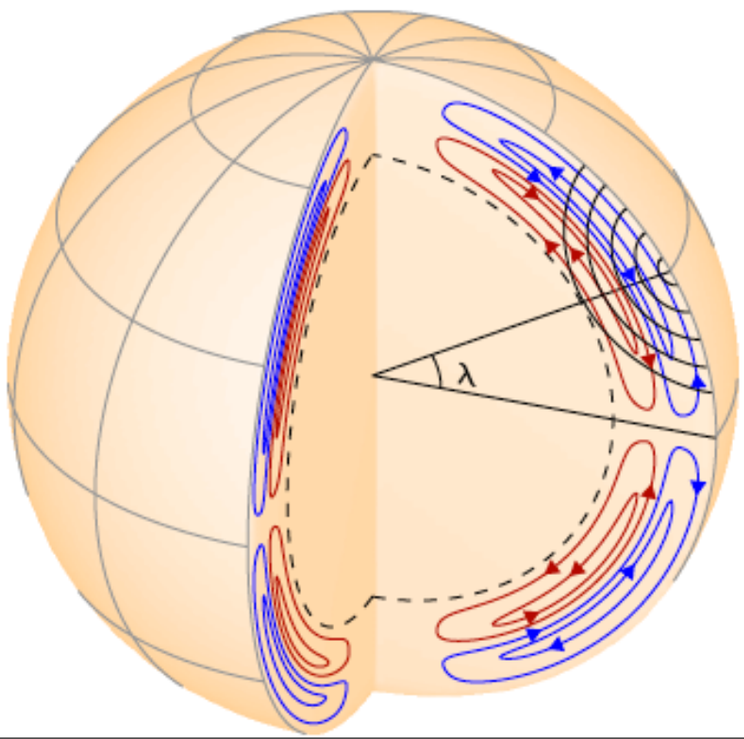
Shallow return-flow and double-cell signature after removing CTL systematics.

Zhao et al, 2013, ApJL.



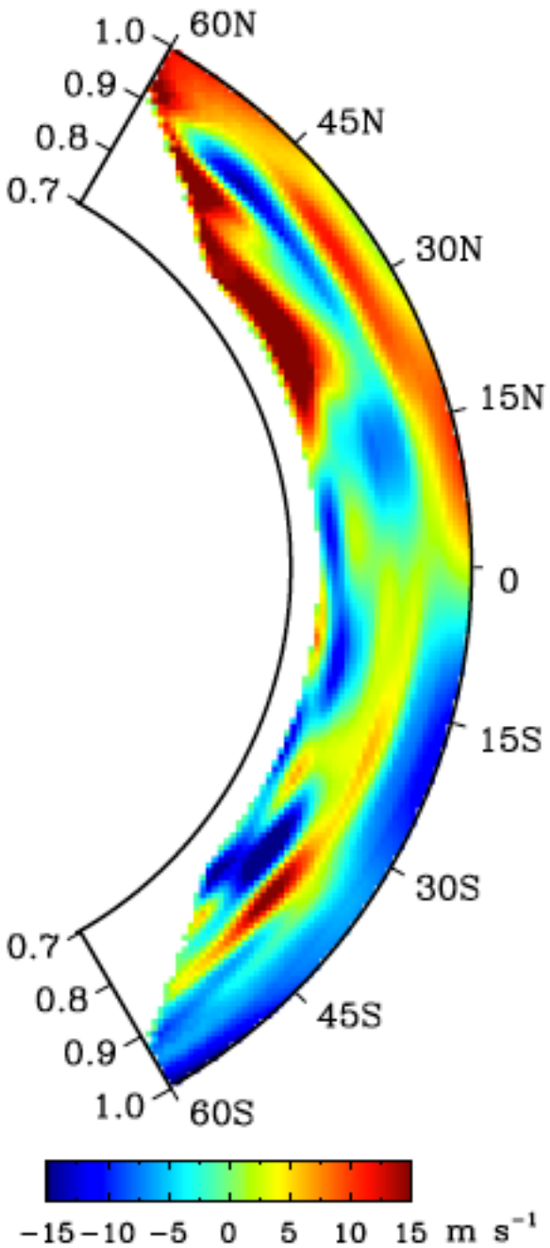




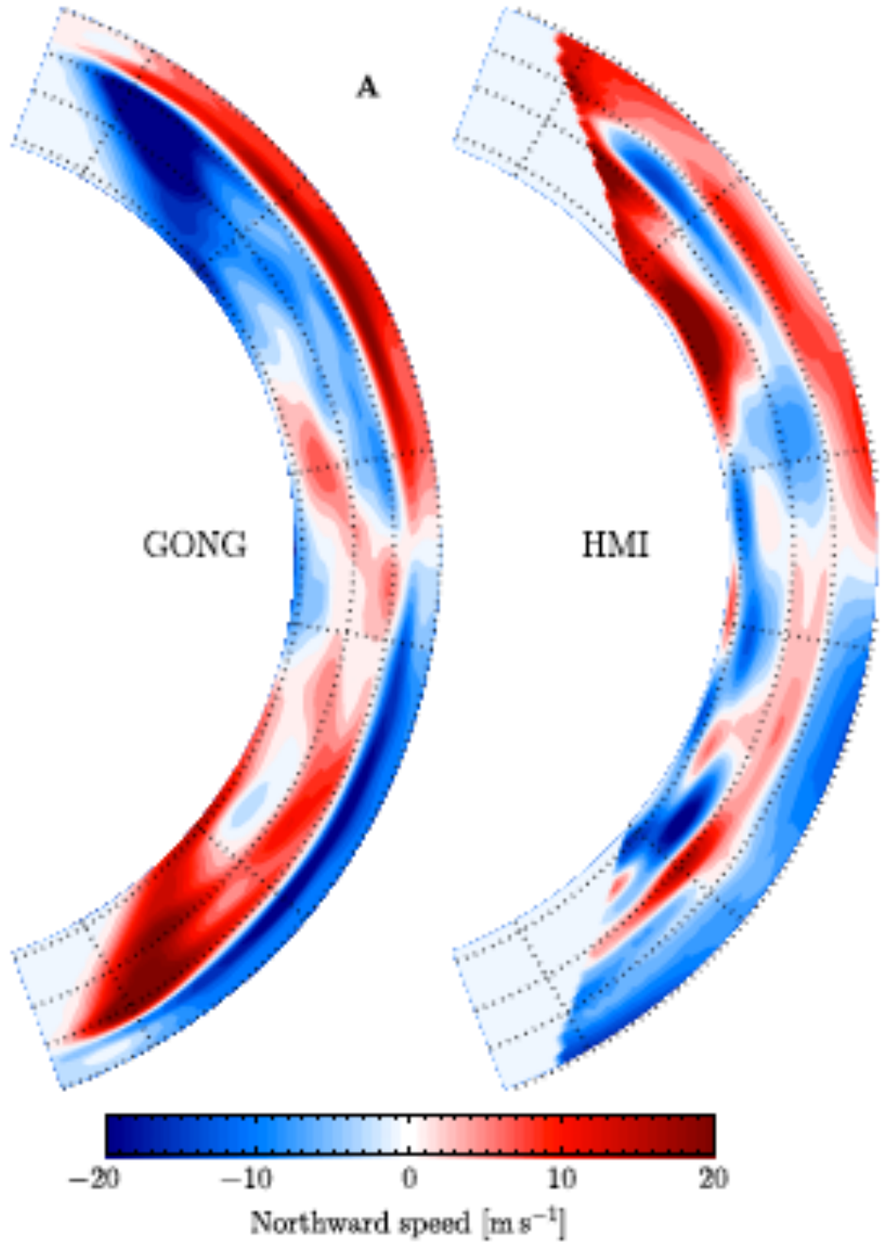


Meridional circulation without mass-conservation constraint in the inversions.

Zhao et al. 2013

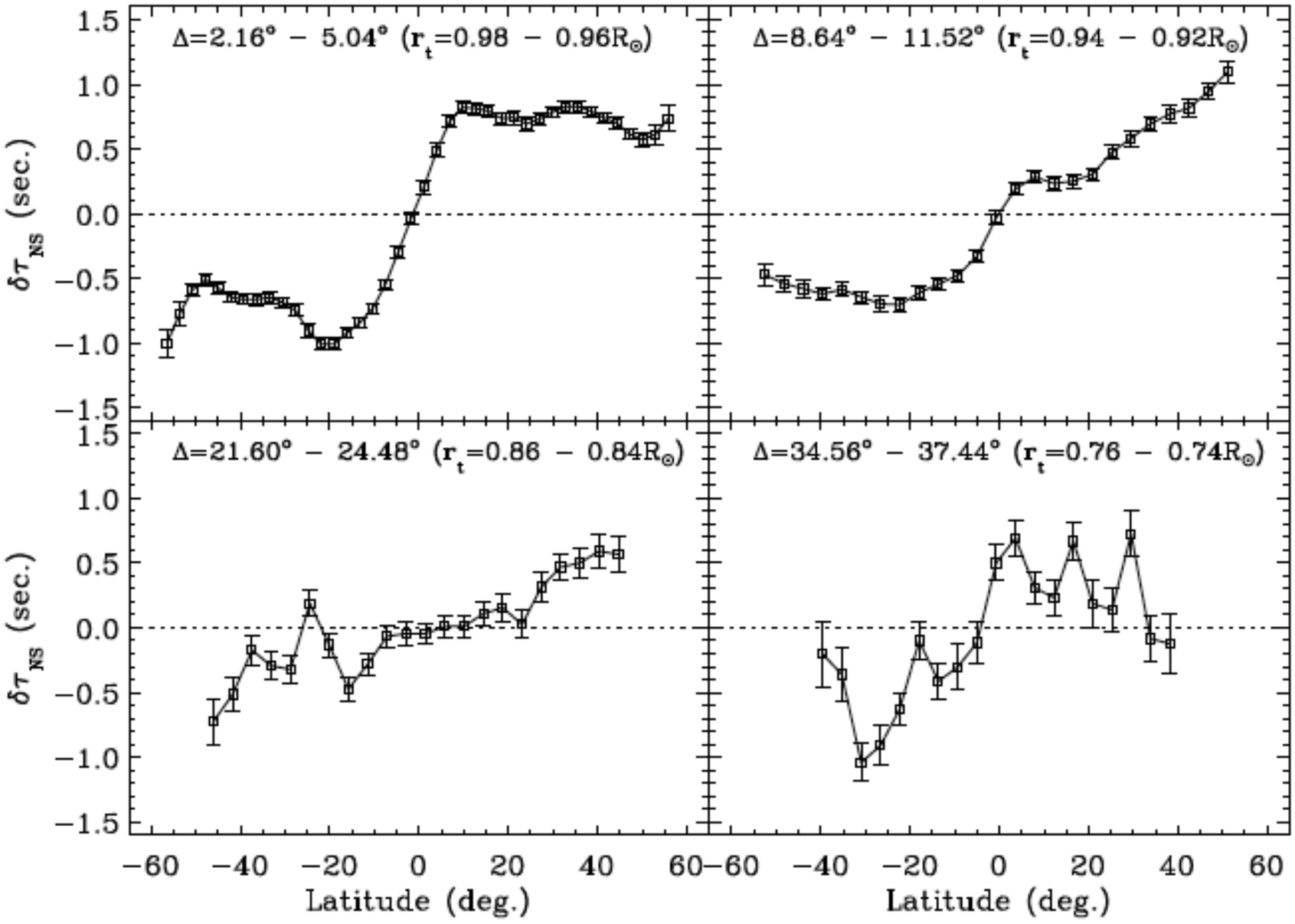


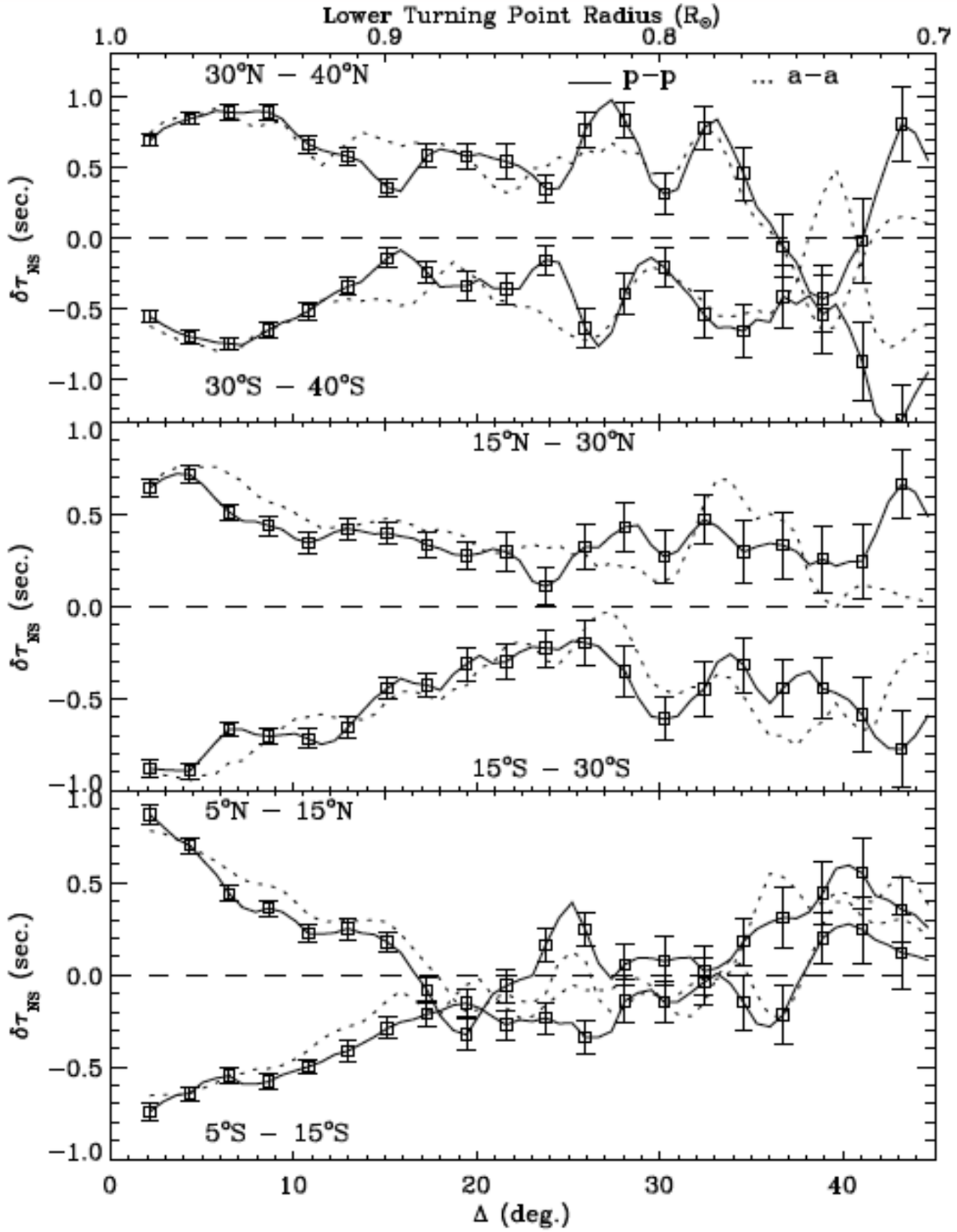
Jackiewicz et al. 2015

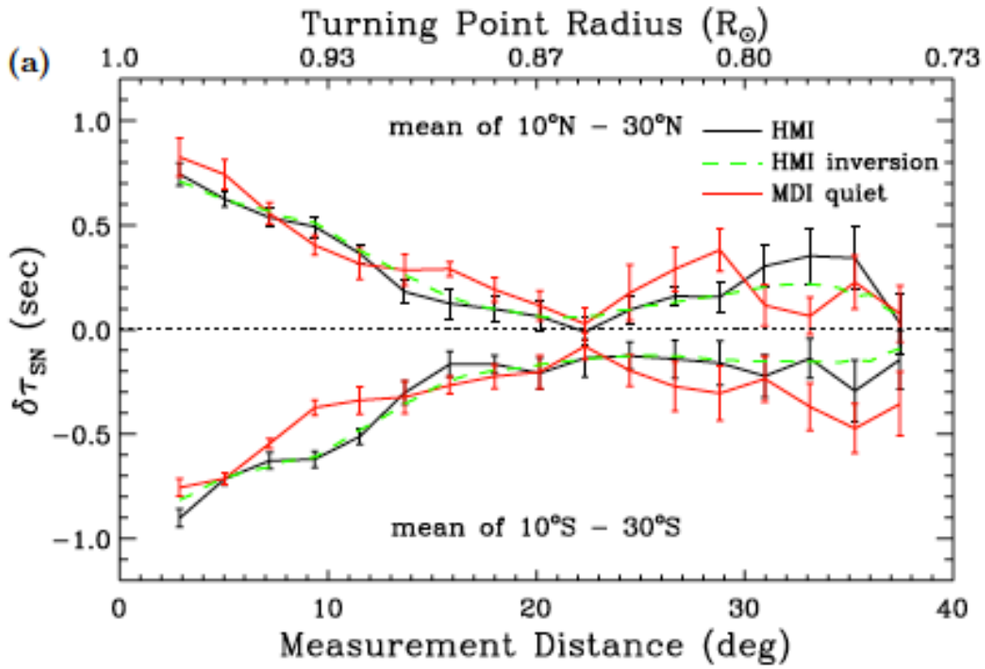


Travel-time differences from 4 years of HMI data

Rajaguru and Antia (2015, to be submitted to ApJ)




Lower Turning Point Radius (R⊙)
1.0
0.9
0.8
0.7
30°N – 40°N
p–p
a–a
30°S – 40°S
15°N – 30°N
15°S – 30°S
5°N – 15°N
5°S – 15°S
δτ_NS (sec.)
Δ (deg.)
0
10
20
30
40


(a)
Turning Point Radius (R⊙)
1.0
0.93
0.87
0.80
0.73
mean of 10°N – 30°N
HMI
HMI inversion
MDI quiet
mean of 10°S – 30°S
δτ_SN (sec)
Measurement Distance (deg)
0
10
20
30
40

Meridional flows with mass-conservation constraints in the inversions of travel times

$$\delta\tau = -2\int_{\Gamma_0} \frac{\mathbf{u}\cdot\hat{\mathbf{n}}}{c^2}\, ds, \qquad (1)$$

The solutions here are obtained by fitting stream functions satisfying mass conservation while inverting the travel times.

$$\rho u_r = \frac{1}{r}\frac{\partial\psi}{\partial\theta} + \frac{\cos\theta}{r\sin\theta}\psi,$$

$$\rho u_\theta = -\frac{\partial\psi}{\partial r} - \frac{\psi}{r},$$

$$\psi'(r,\theta) = \sum_i \sum_j a_{ij}\Phi_i^r(r)\Phi_j^\theta(\theta), \qquad \psi' = \psi/\rho$$

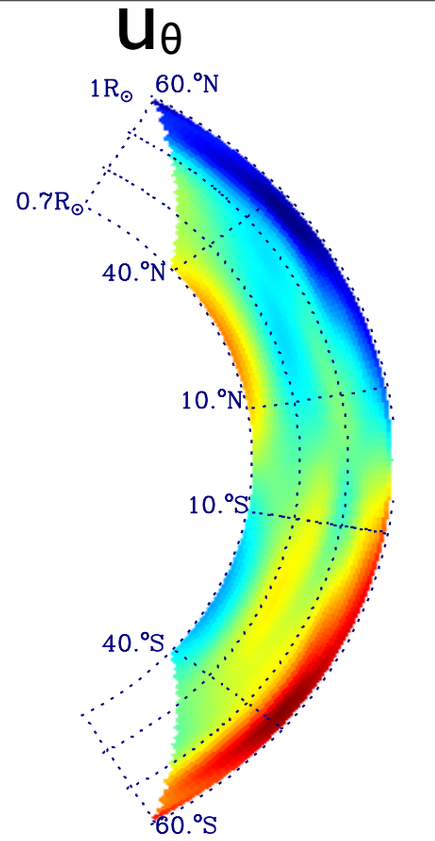
where $\Phi_i^r(r)$ are the cubic B-spline basis covering $0.7R_\odot \le r \le R_\odot$ and $\Phi_j^\theta(\theta)$ are the cubic B-spline basis covering $|\theta - \pi/2| \le 1.055$. We use 38 knots in r which are uniformly spaced in acoustic depth and 31 knots in θ which are uniformly spaced in θ to define the B-spline

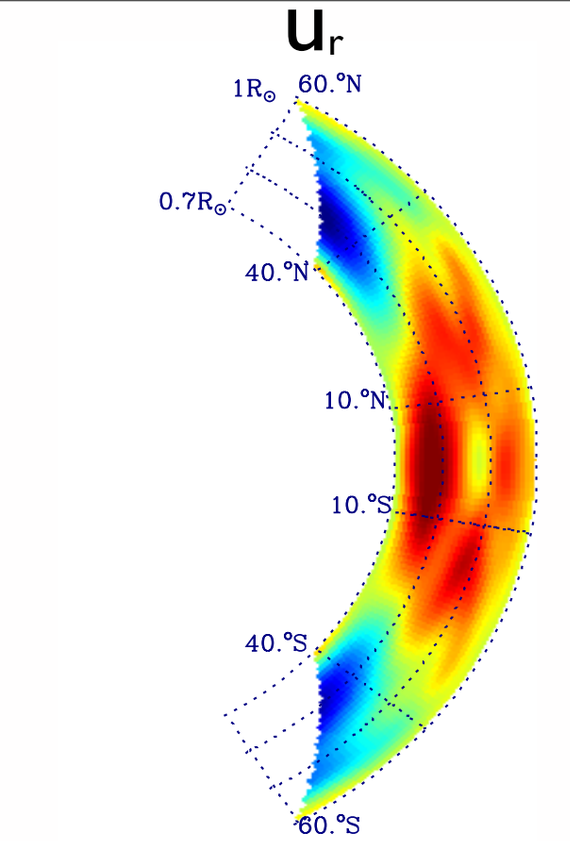
The coefficients a_{ij} determined using RLS with second derivative smoothing in both r and θ by minimizing

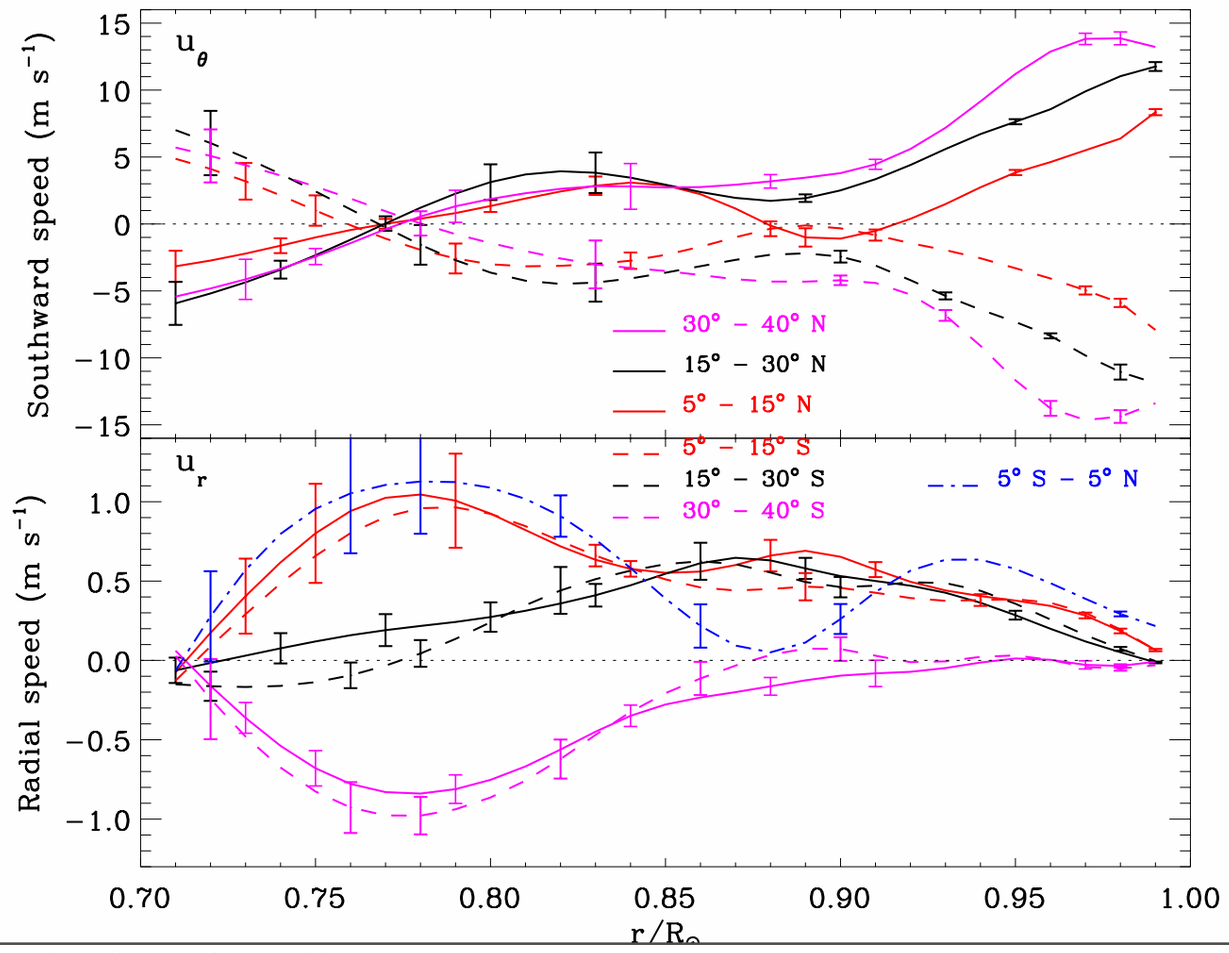
$$\sum_i \left(\frac{d_i}{\sigma_i}\right)^2 + \lambda_r^2 \sum \left(\frac{\partial^2\psi'}{\partial r^2}\right)^2 + \lambda_\theta^2 \sum \left(\frac{\partial^2\psi'}{\partial\theta^2}\right)^2$$

d_i are the residuals in the fit to eqn.(1) and σ_i are the corresponding errors in the travel-time differences. λ_r and λ_θ are the two smoothing parameters.

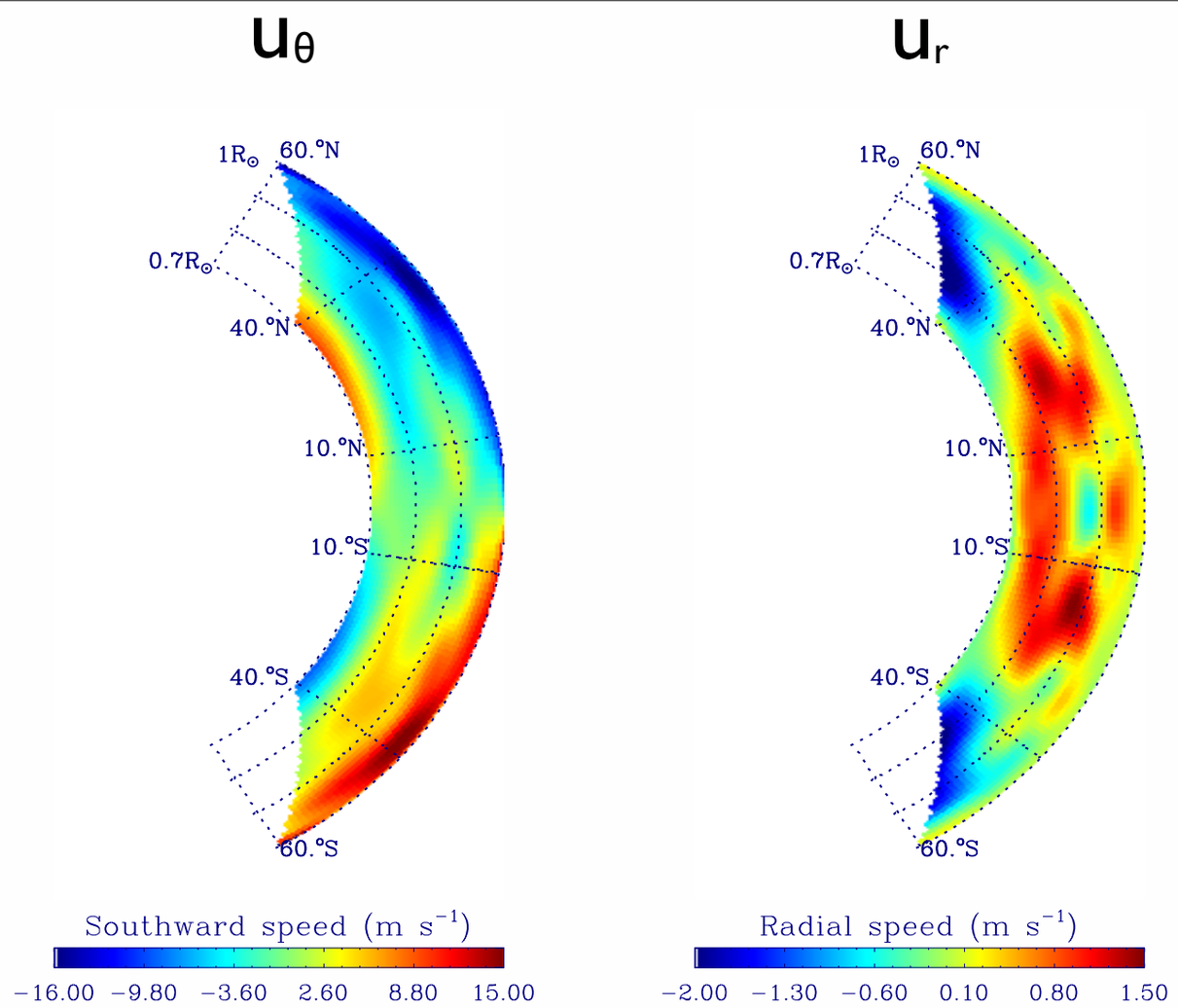
A solution with higher smoothing and lower errors.

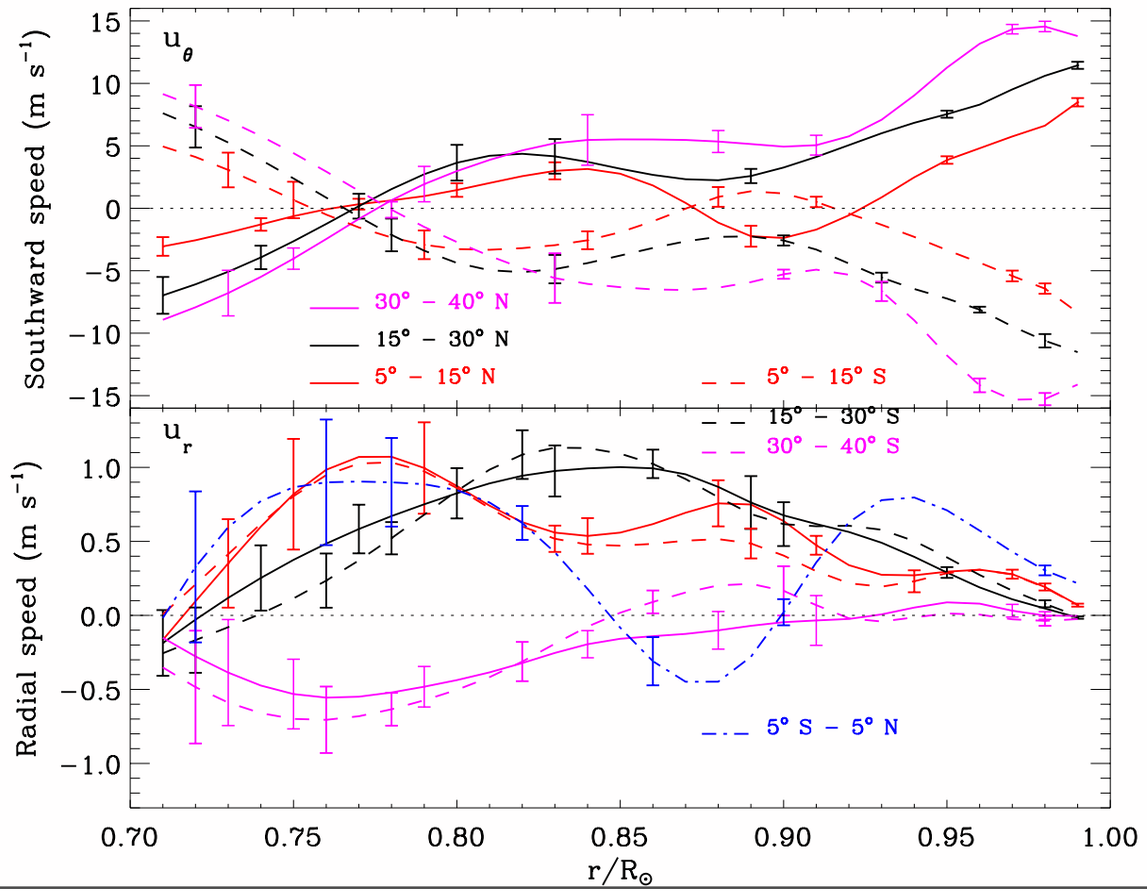






A solution with lower smoothing and higher errors.

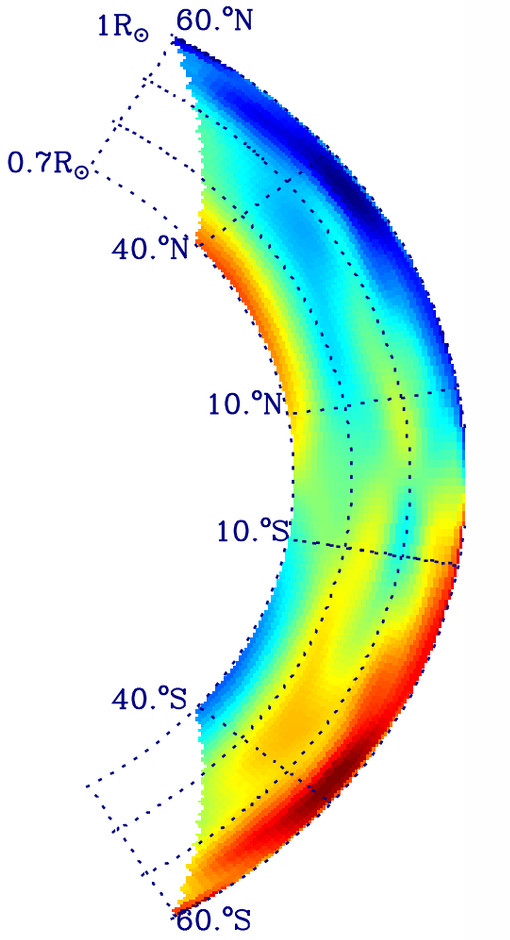




Meridional flows with mass-conservation constraints in the inversions of travel times

Rajaguru and Antia (2015)

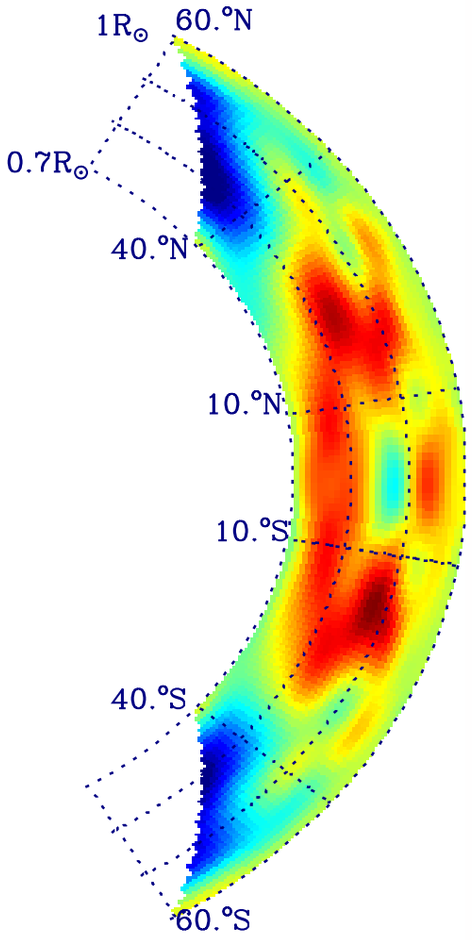
u_θ



Southward speed (m s^{-1})

−16.00 −9.80 −3.60 2.60 8.80 15.00

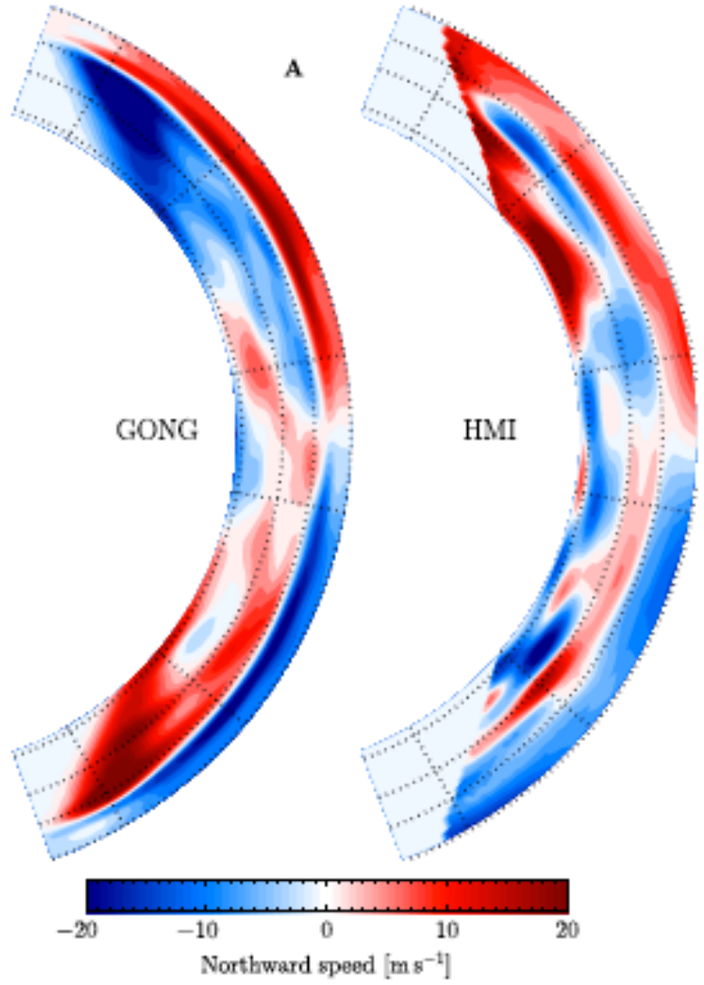
u_r

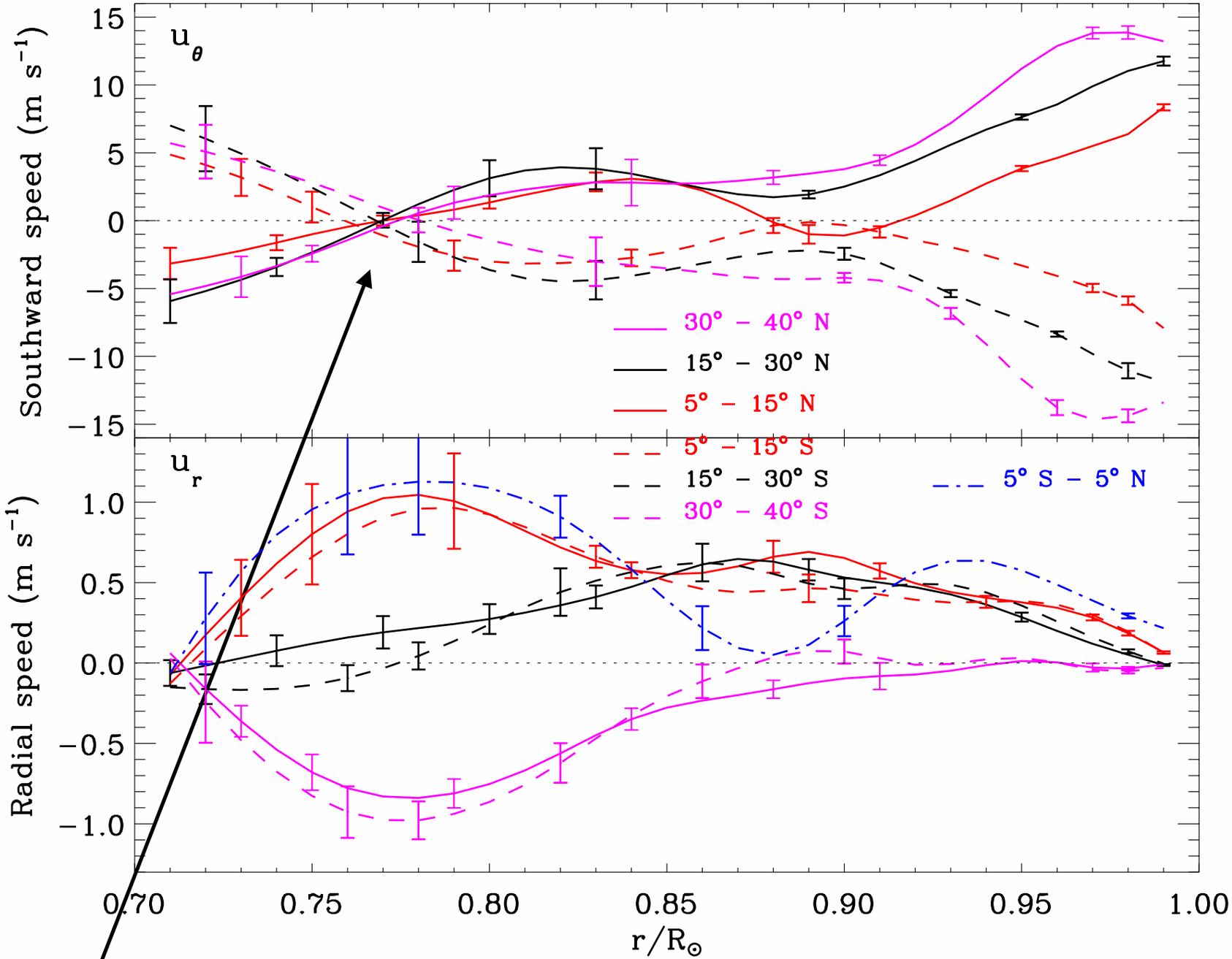


Radial speed (m s^{-1})

−2.00 −1.30 −0.60 0.10 0.80 1.50

u_θ





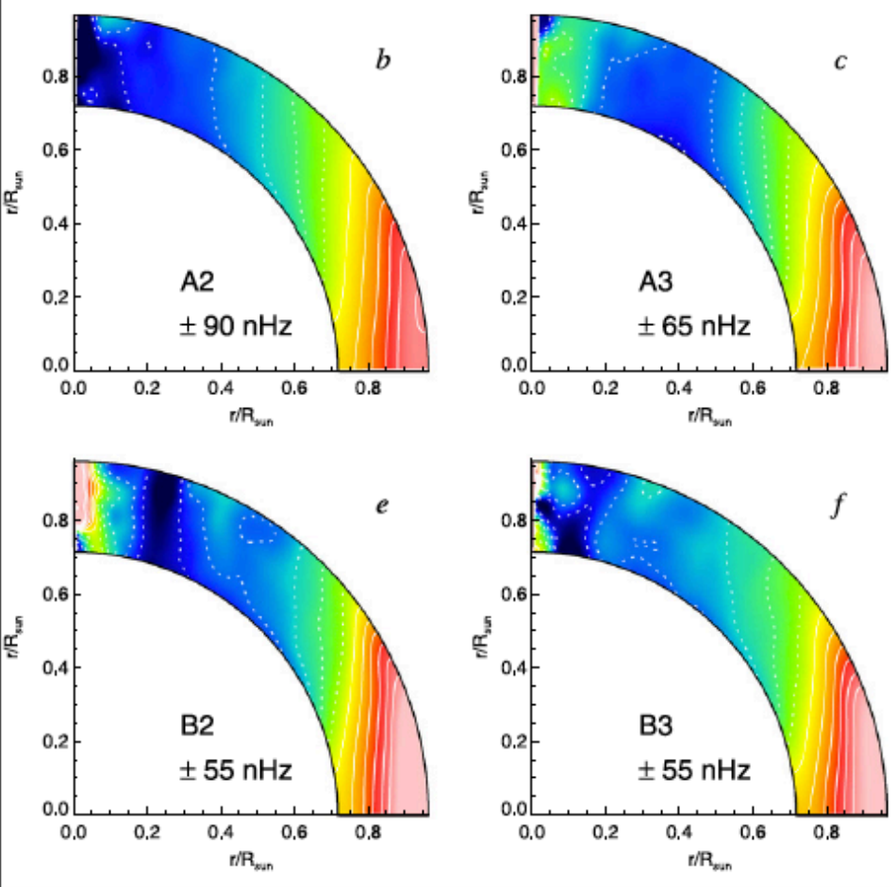
Likely reversal of flow at about 0.77 R_{sun} .

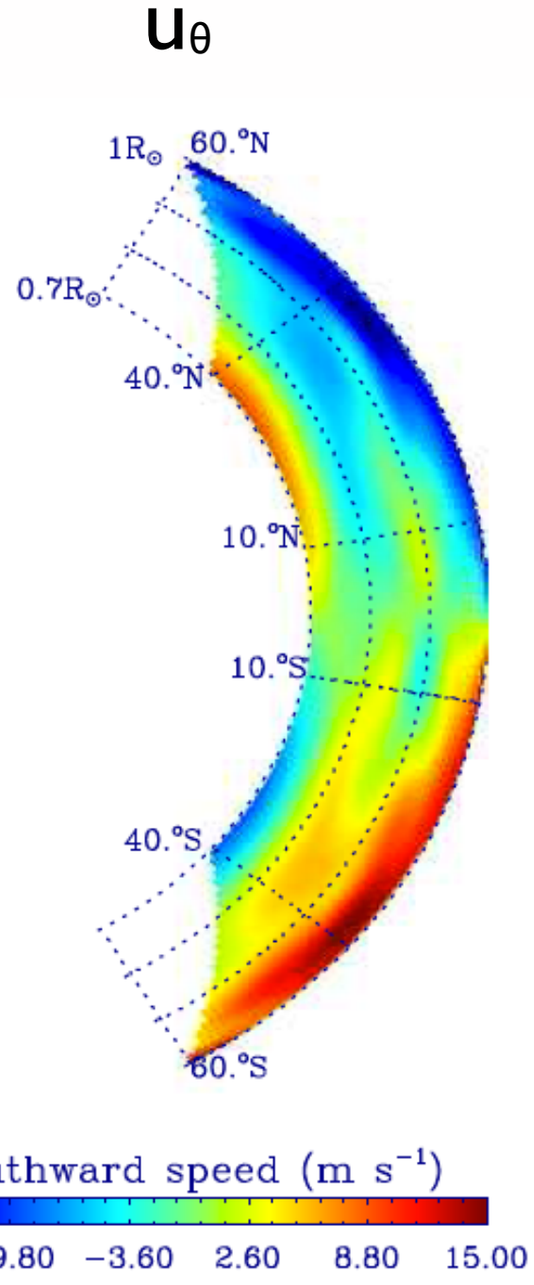
Hints of flow reversals at about 0.89 Rsun are not significant.

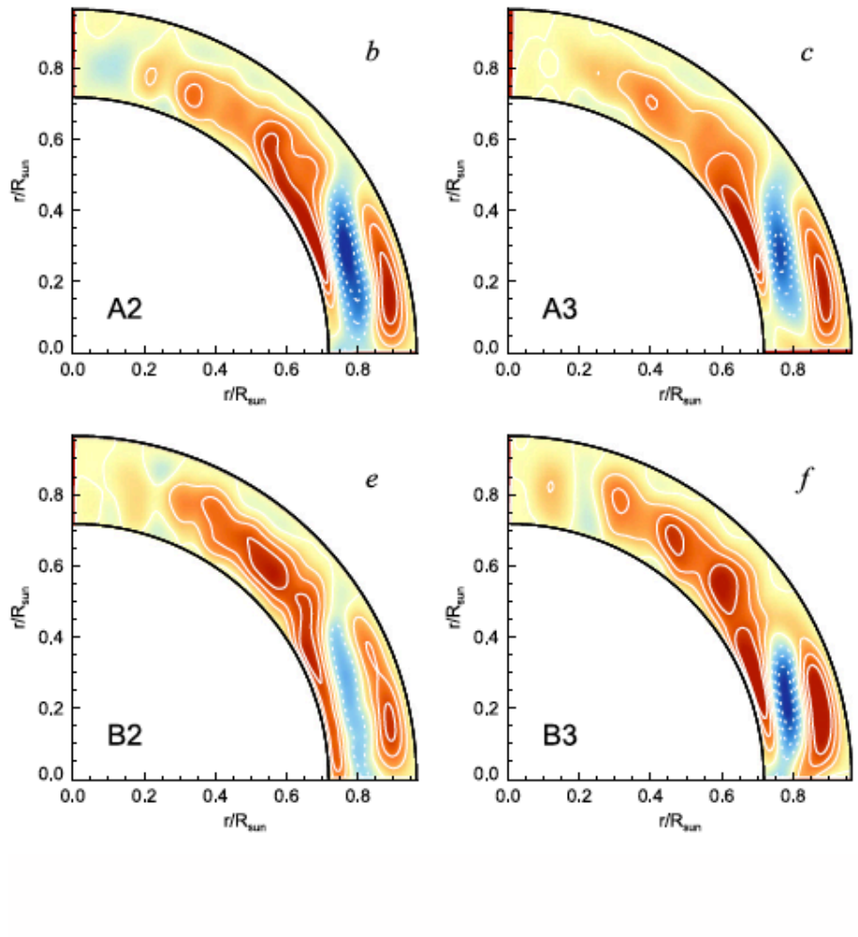
A single cell of meridional flow with return flow at about 0.77 R_{sun} is consistent with the above inversions.

Numerical models of differential rotation and MC

Featherstone & Miesch (2015)







Main inferences:

(1) Within errors, the measurements are consistent with a single deep cell of MC

- return-flow likely below 0.77 R_{sun}

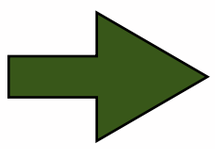
- broad upwellings near the equatorial regions (10°S - 10°N) with radial speeds of ~ 1 m/sec over the depth ranges of 0.7 - 0.8 R_{sun} and 0.9 - 0.97 R_{sun}

(2) There are signatures of multi-cellular structure at low latitudes (< 25 deg.) but the signals are close to error limits.

Reasons for the differences between inferences on the deep structure of MC:

(1) mass-conservation constraints

(2) differences in inversion strategy -- sensitivity to errors and systematics in measurements.

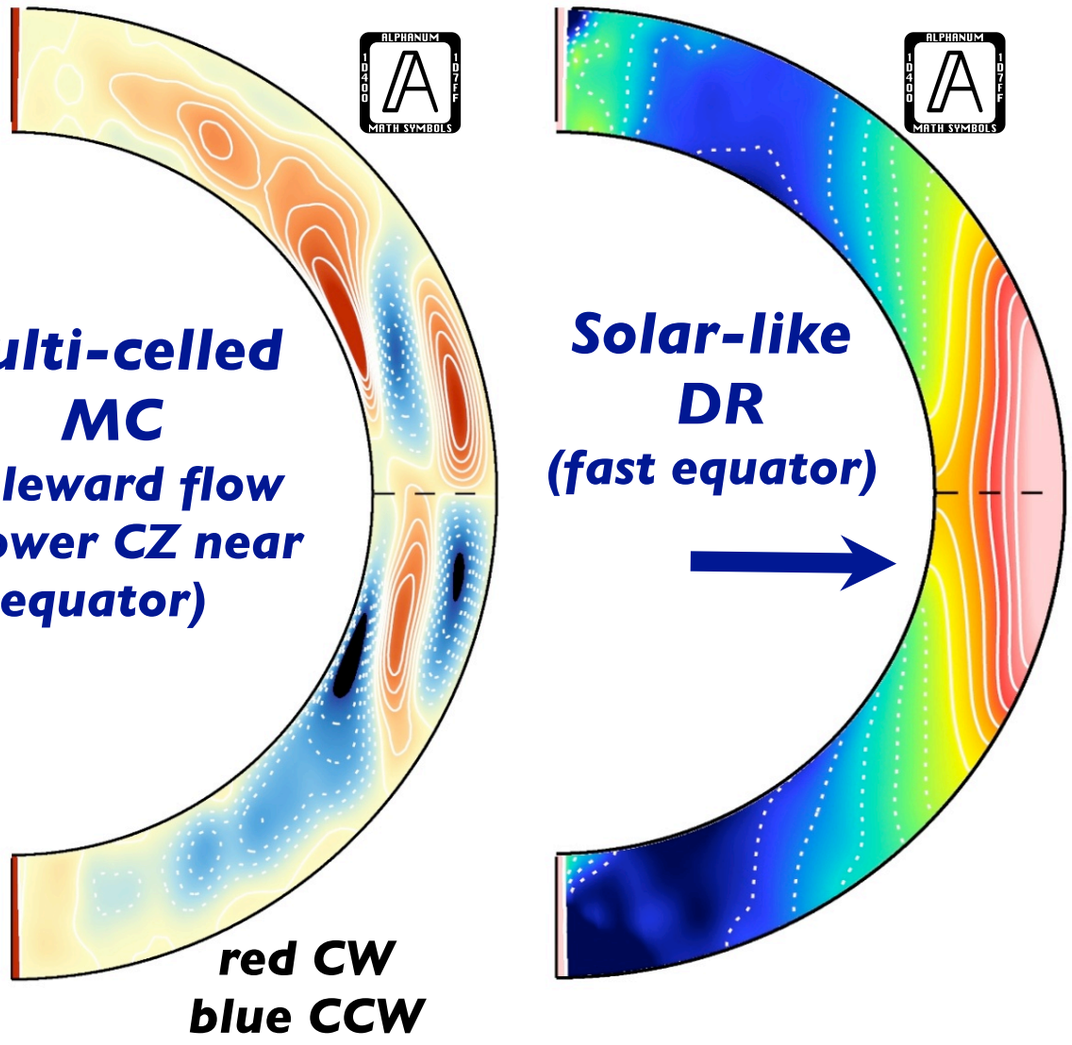


Significant improvements are needed to address the noise and systematics.

A Slide from M. Miesch (2012)

Simulations suggest two different regimes for the Mean Flows

Fast Rotation (Ro ≲ 0.3)

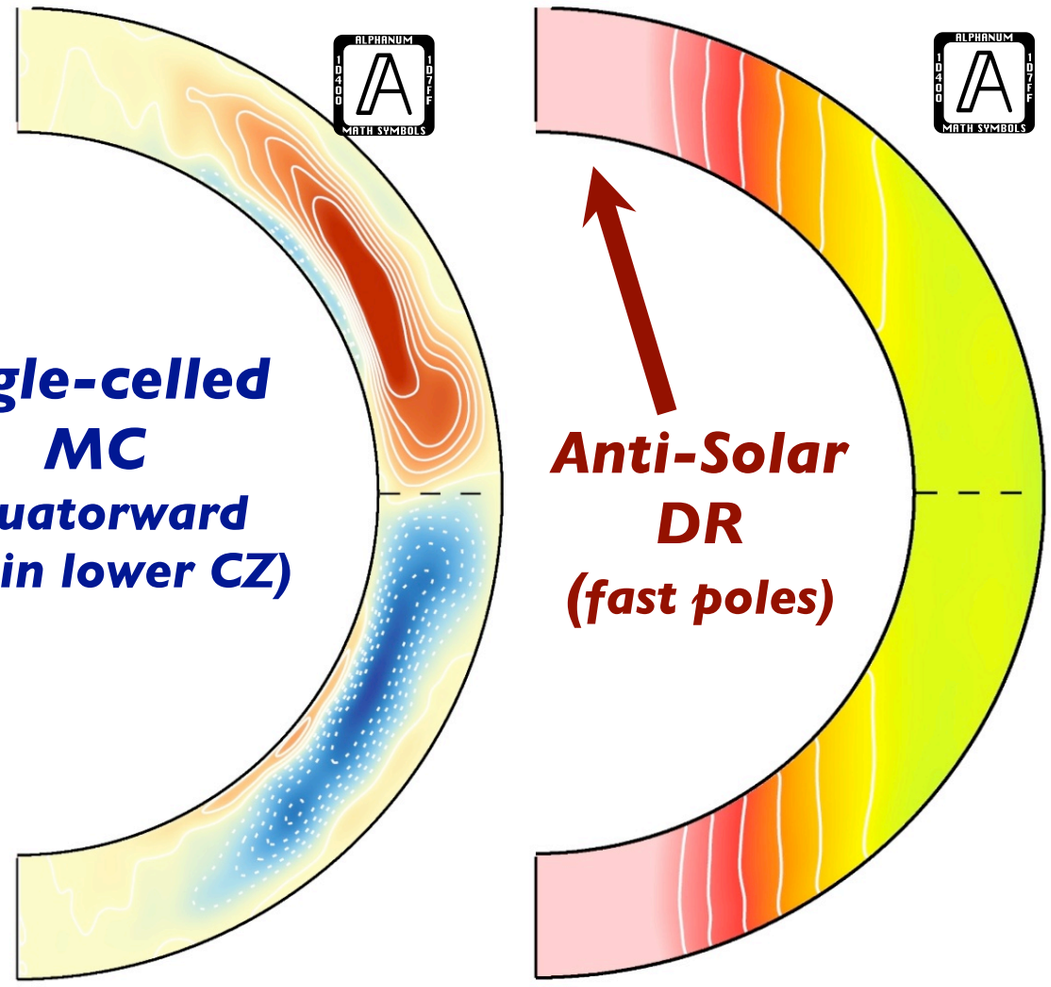


Multi-celled MC (poleward flow in lower CZ near equator)

Solar-like DR (fast equator)

red CW
blue CCW

Slow Rotation (Ro ≳ 0.9)



Single-celled MC (equatorward flow in lower CZ)

Anti-Solar DR (fast poles)

Featherstone & Miesch (2013)

$$R_o = \frac{U}{2\Omega_0 L}$$

Flux-Transport dynamo models may have difficulty operating in rapidly-rotating stars