# helioseismic holography of solar subsurface flows : progress & prospects

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# with input from:

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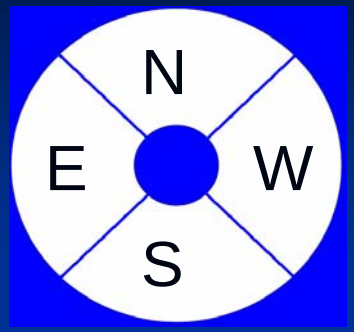
# outline

- "calibrated" (near-surface) flows CR1988
  - supergranulation
  - AR flows (see Braun, et al. 2004 GONG/SOHO 14)
- AR flows vs. depth: travel-time asymmetries
- inversions
  - zonal and meridional flows
- what's needed?

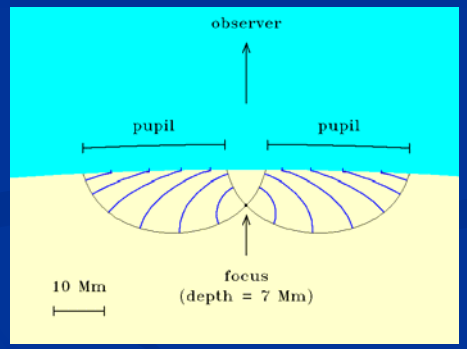
# phase-sensitive holography of flows

egressions and ingressions in 4 quadrants:




$$H_{\pm}^{E,W,N,S}(\mathbf{r},z,\nu) = \int_{E,W,N,S} d^2\mathbf{r}'\, G_{\pm}(\mathbf{r},\mathbf{r}',z,\nu)\, \psi(\mathbf{r}',\nu)$$

e.g. E-W correlation phase:




$$C^{E\to W} \equiv H_{+}^{E}\, H_{-}^{W*}$$

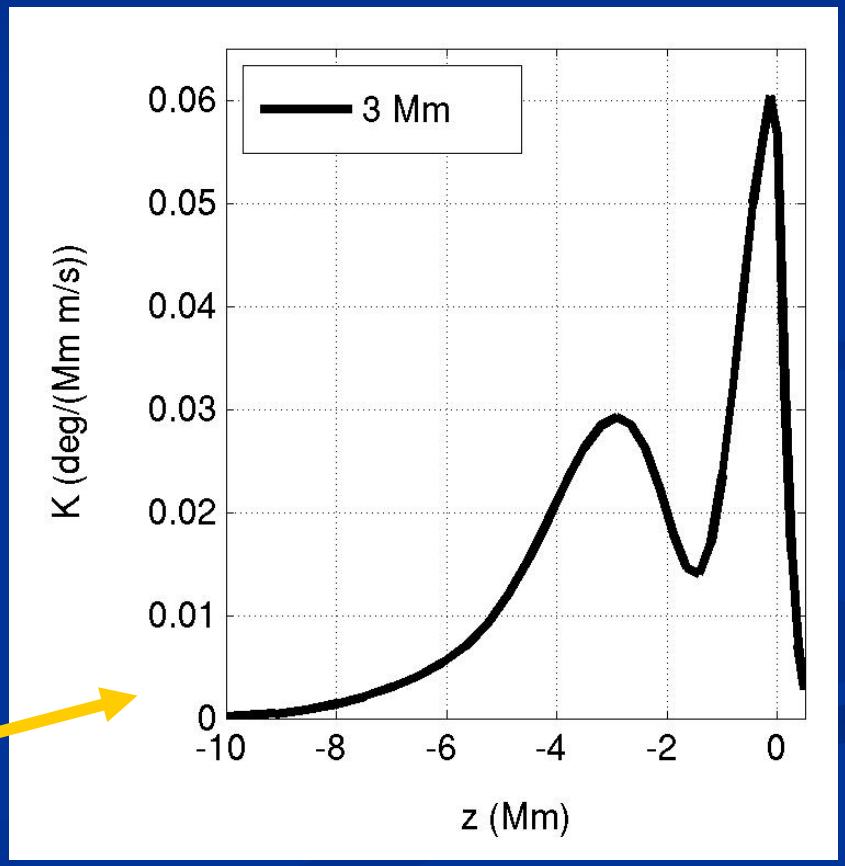
$$\phi^{E\to W} = \arg\left(\left\langle C^{E\to W}\right\rangle_{\Delta\nu}\right)$$

# "calibrated" near surface flows

- assume velocity proportional to phase differences

$$V_x \propto -\tfrac{1}{2}\left(\phi^{E\to W} - \phi^{W\to E}\right), \text{etc}.$$

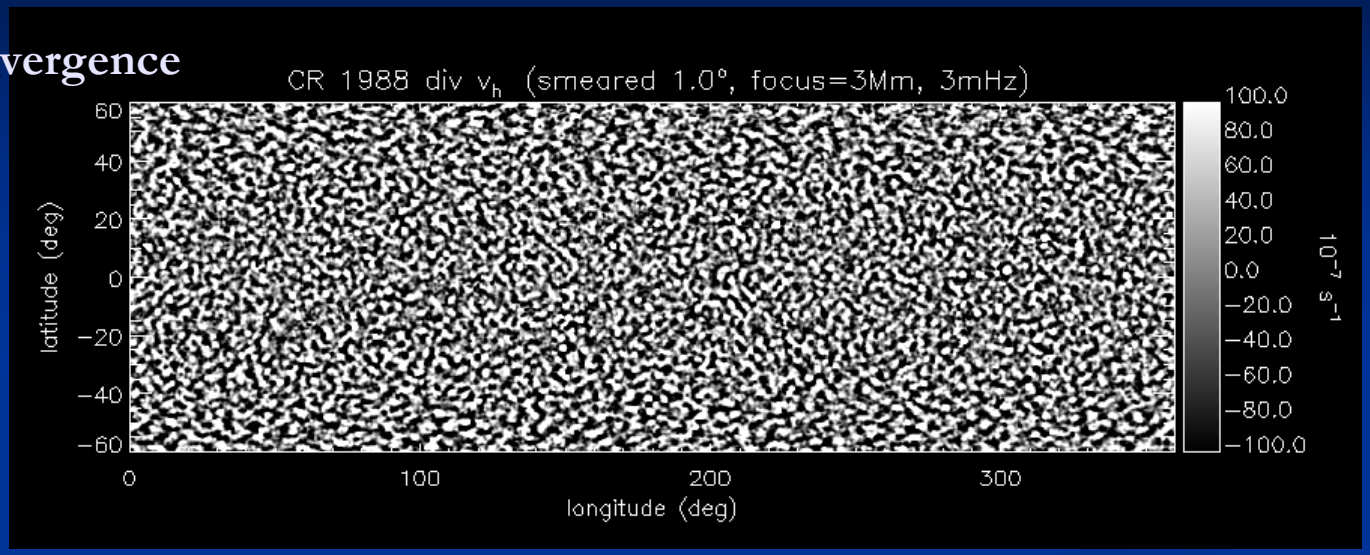
- will show results for focus=3Mm, calibrated from difference between two tracking rates
- actual averaging kernel for 3 Mm focus:



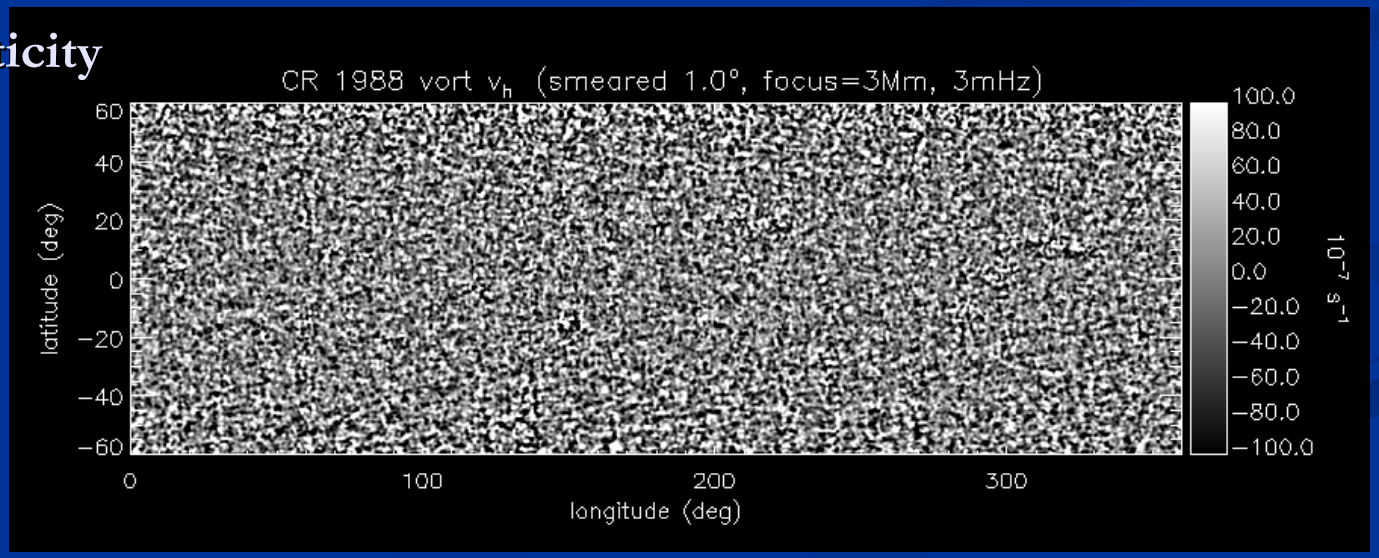
# supergranulation:

**horizontal divergence**

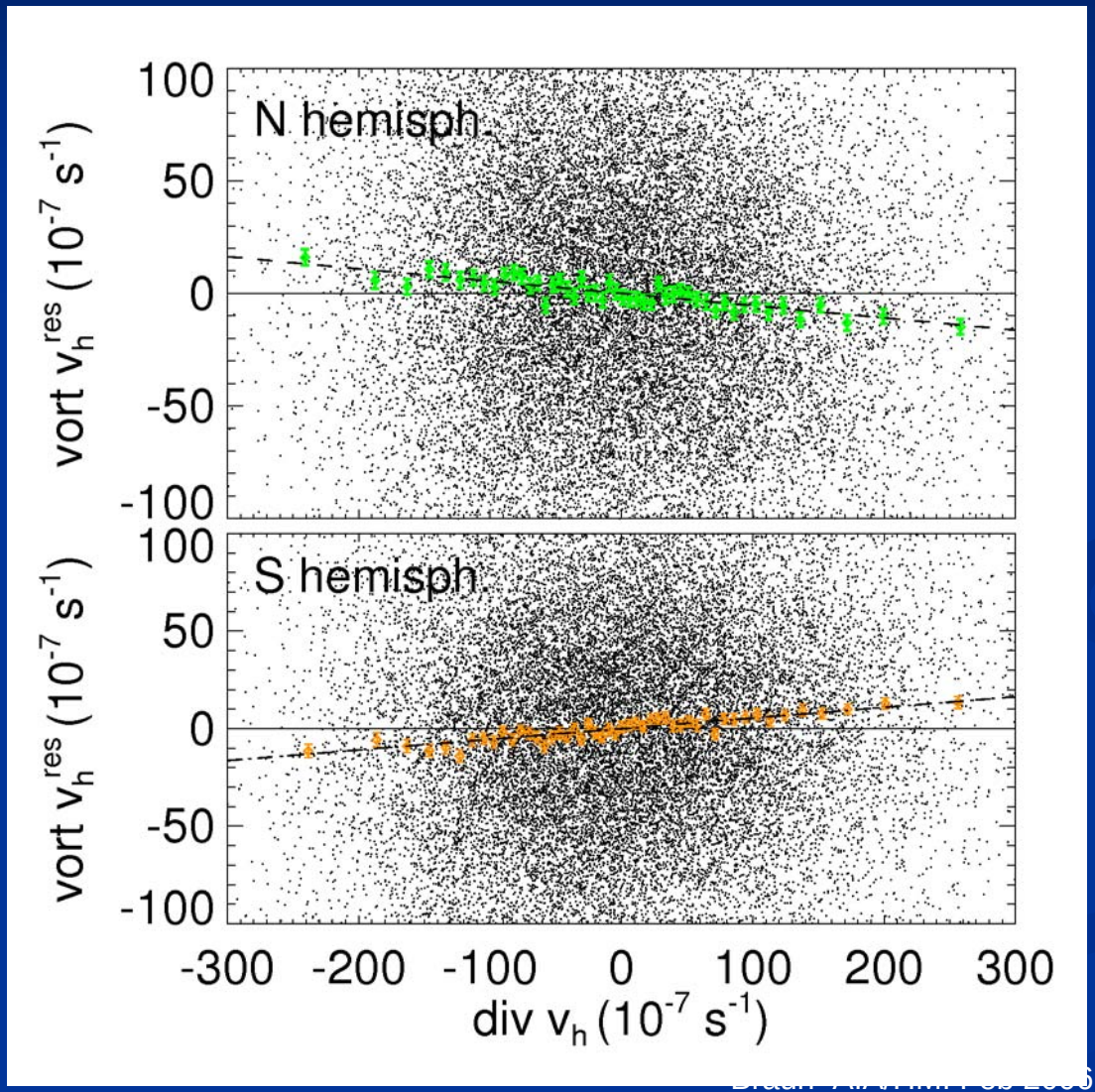
27-hr
time
averages

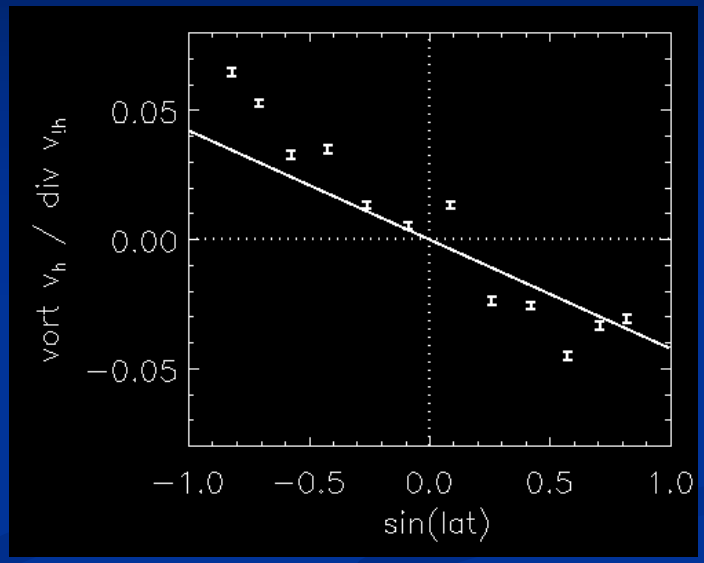



**vertical vorticity**



# vertical vorticity of SG as a result of Coriolis force on divergence:

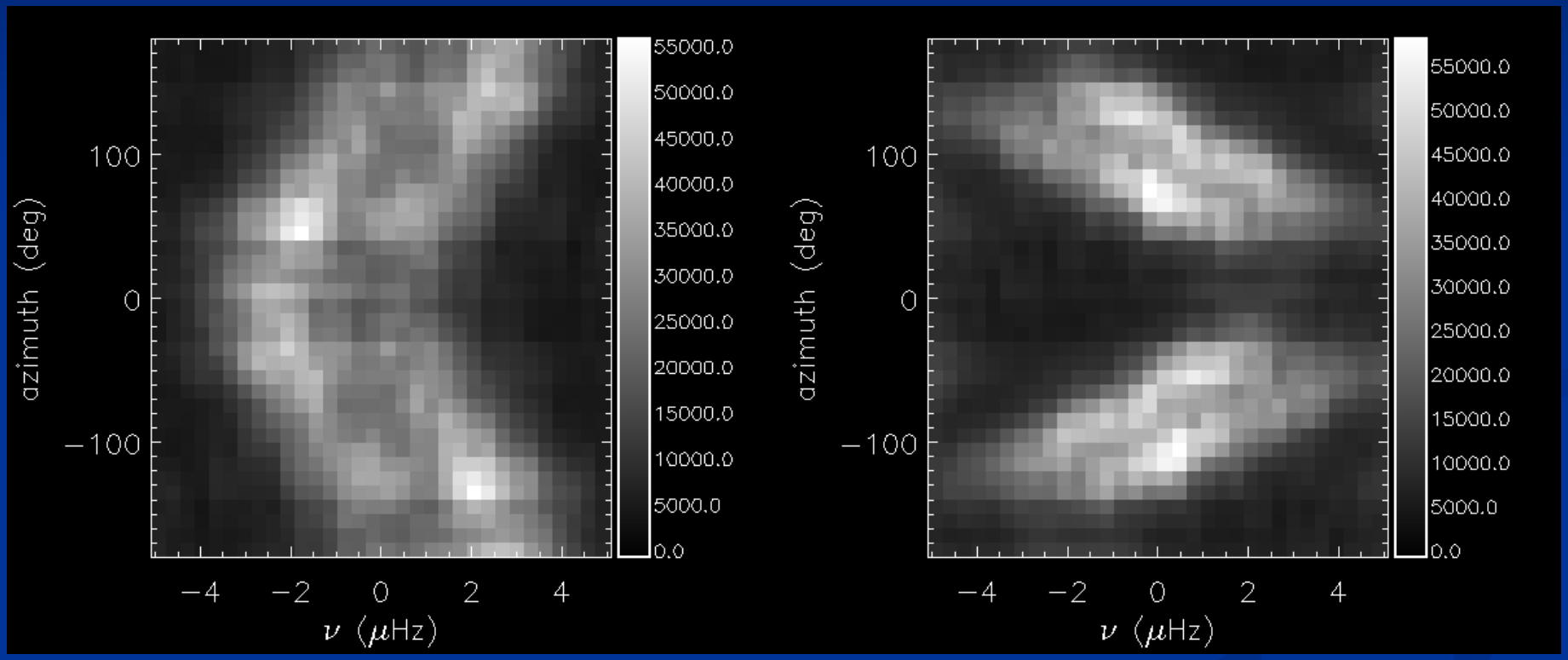



confirms time-distance f-mode results of Duvall & Gizon (2000)

# power spectra of supergranulation (divergence)

in the fashion of Gizon, Duvall & Schou (2003)

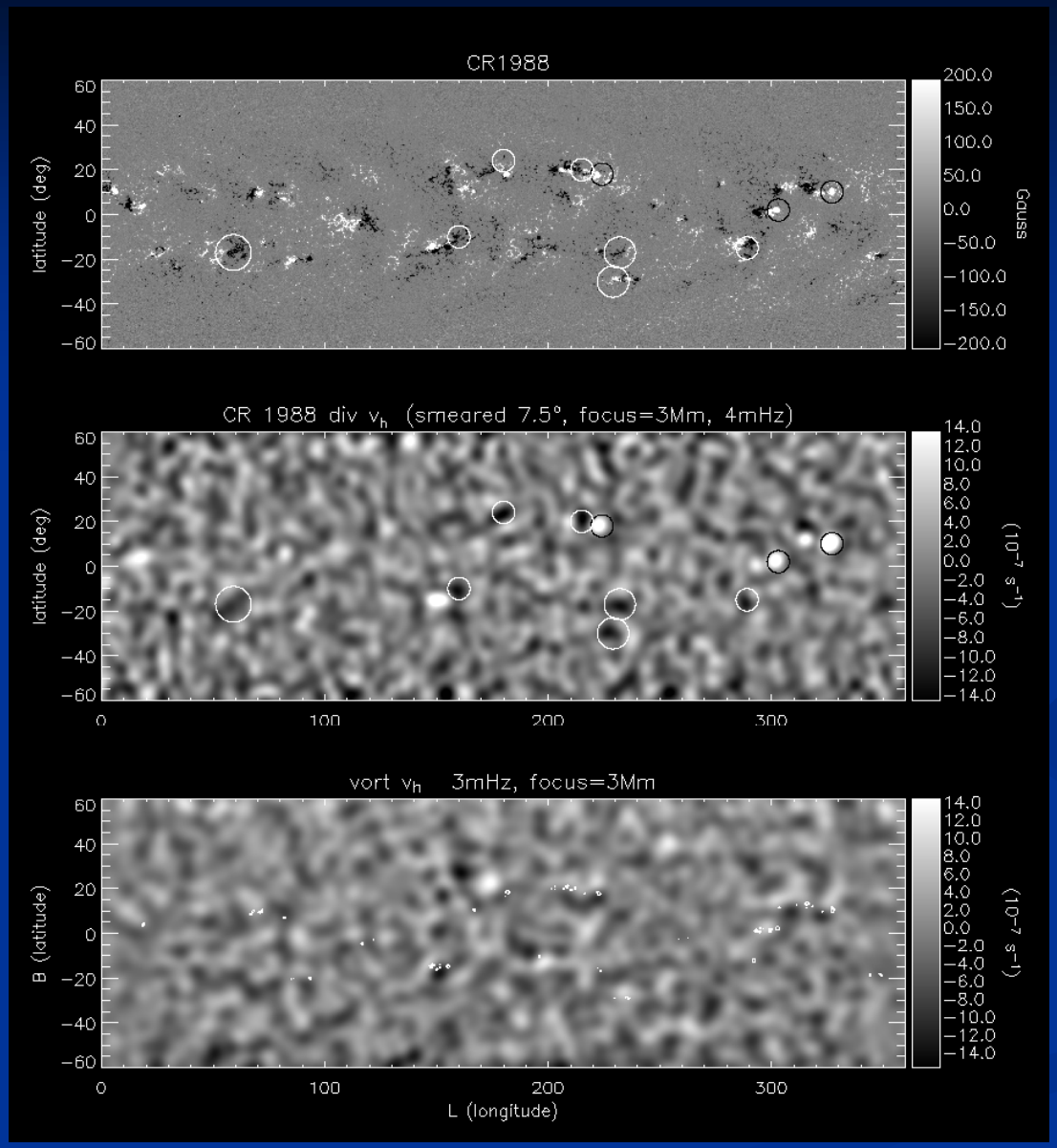



10° latitude strip @ B=0

B = 45°

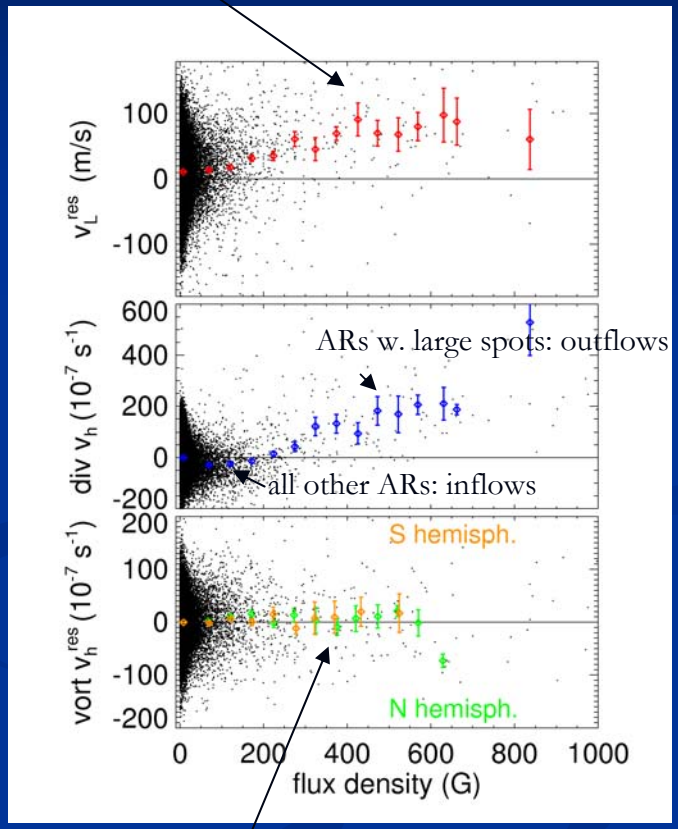
# AR scale flows (CR1988)

5 x 27-hr time averages




SEE Braun, et al.2004 SOHO 14

ARs: faster rotation

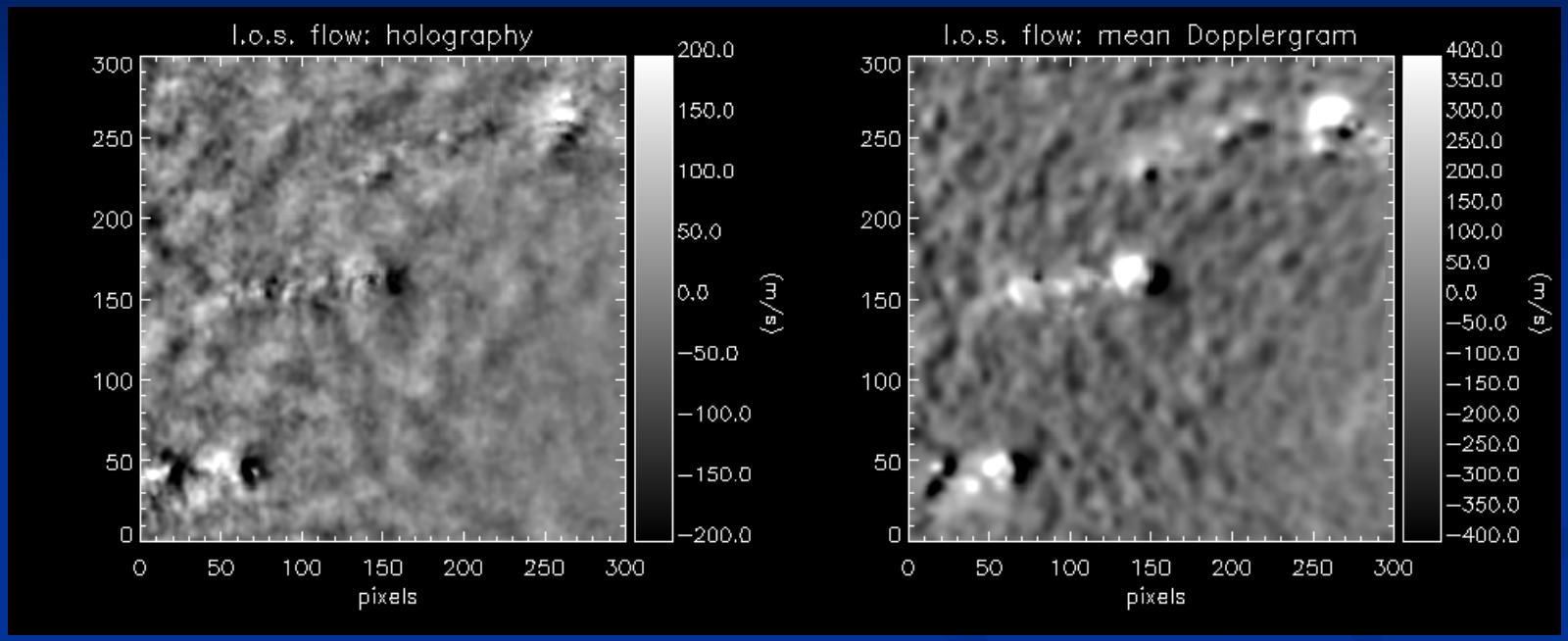


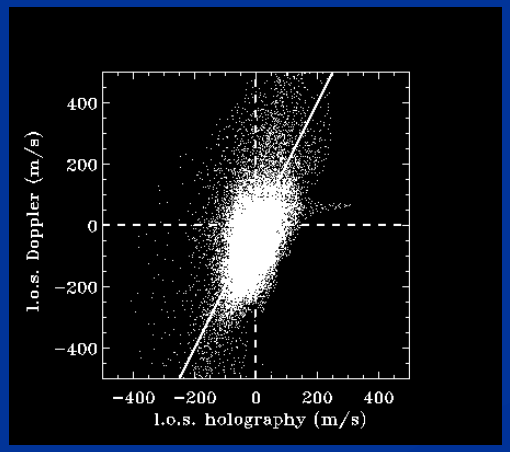

ARs: no net vorticity

# spot outflows: comparison with direct Dopplergrams

line-of-sight component of deduced HH calibrated flows (3Mm focus)

average of 28 hours of MDI Dopplergrams.

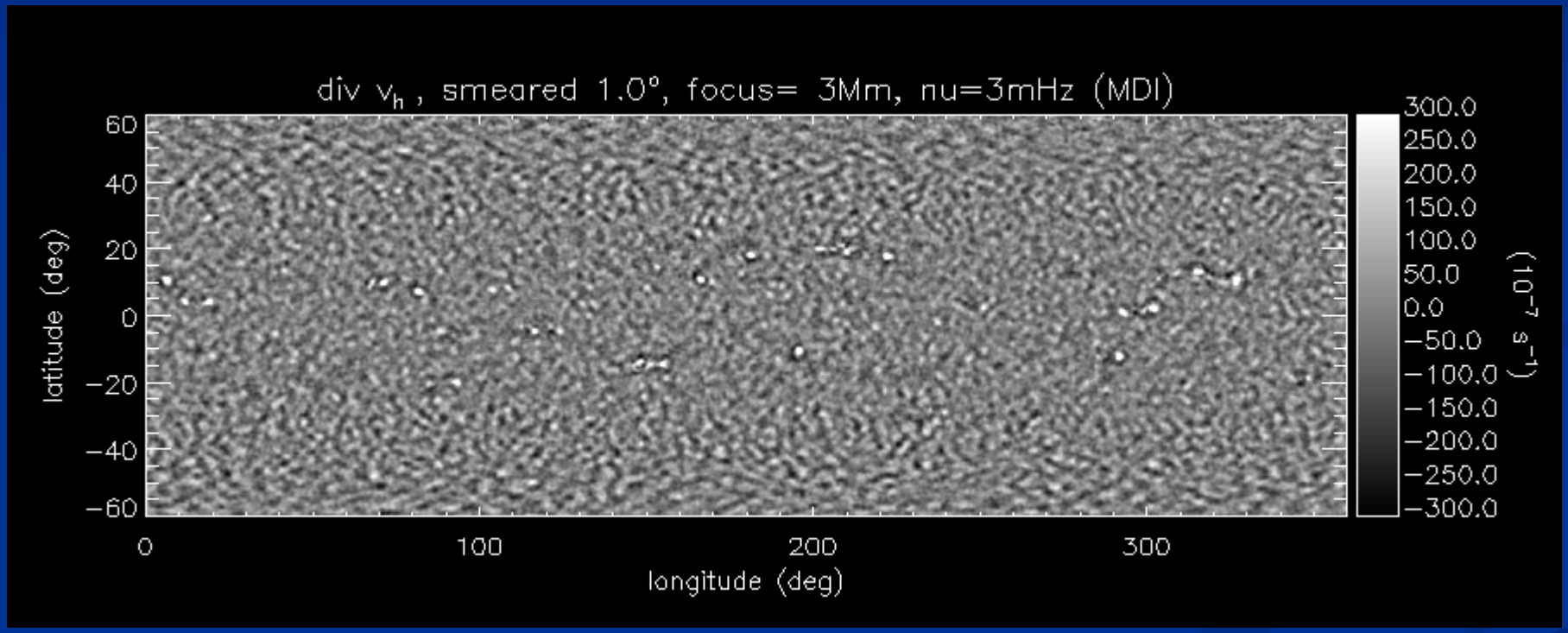



HH calibrated velocities in outflows at 3Mm focus are roughly one-half the magntitude of values in the photosphere

# horizonal divergence with depth
## (smeared 1°)

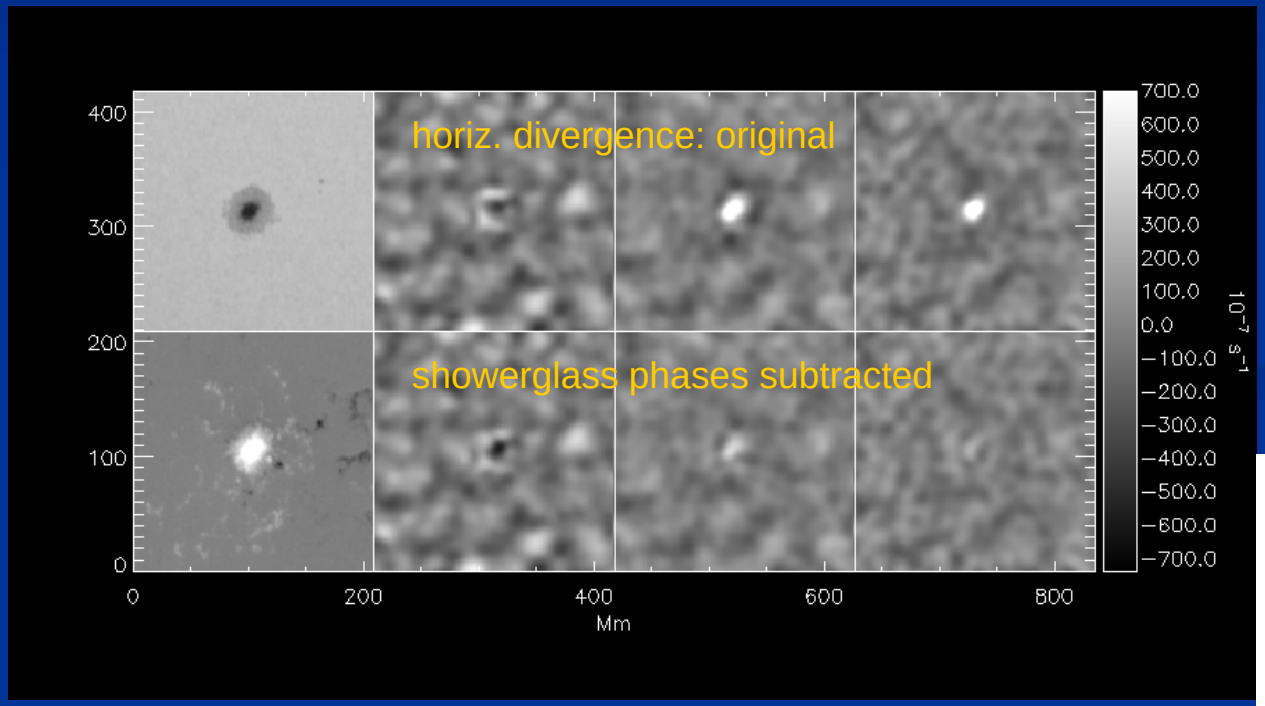
focus = 3 - 30 Mm

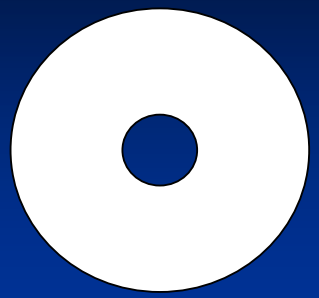


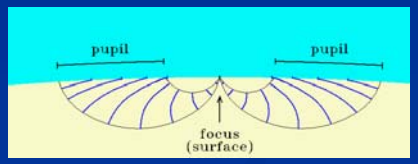

**At all depths, "outflow" signatures from sunspots dominate: are these actual deep outflows or due to magnetic effects?**

# assessing (and subtracting) surface phase asymmetries

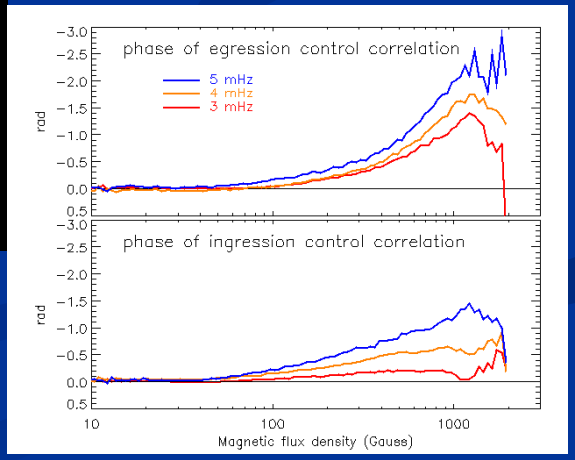
focus depth = 3 Mm 5Mm 7 Mm






showerglass phases from local control correlations

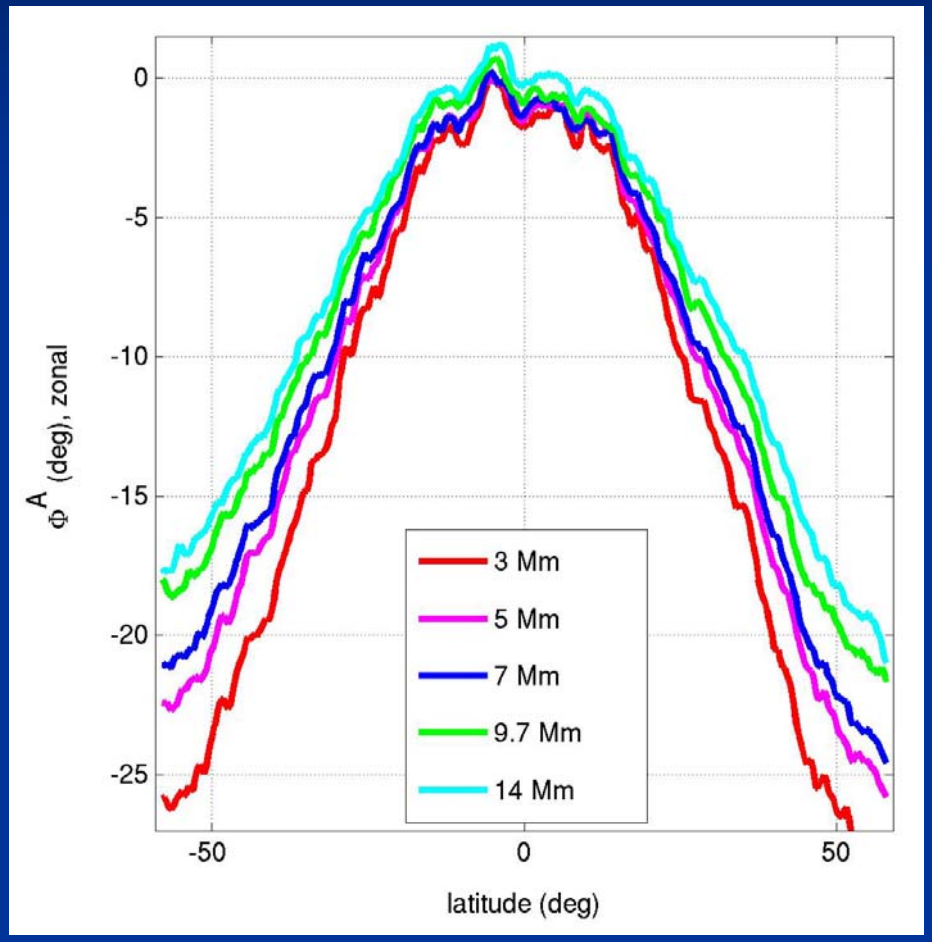


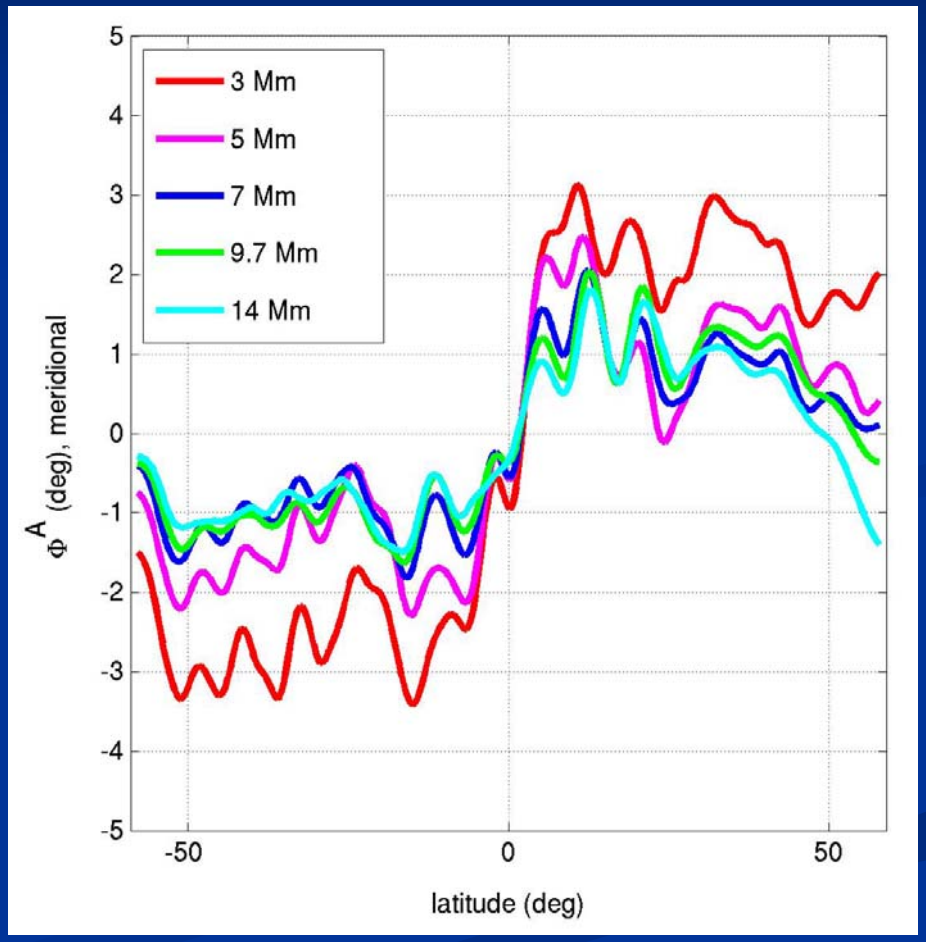

see Lindsey & Braun 2005a,b

# assessing magnetic effects

- subject of major, ongoing research at NWRA/CoRA and elsewhere
- models taking into account both flows and magnetic effects will probably not be in place by HMI launch
- for now, models of flows will retain flexibility of removing phase contributions based on empirical fits to local **B** (strength, inclination)

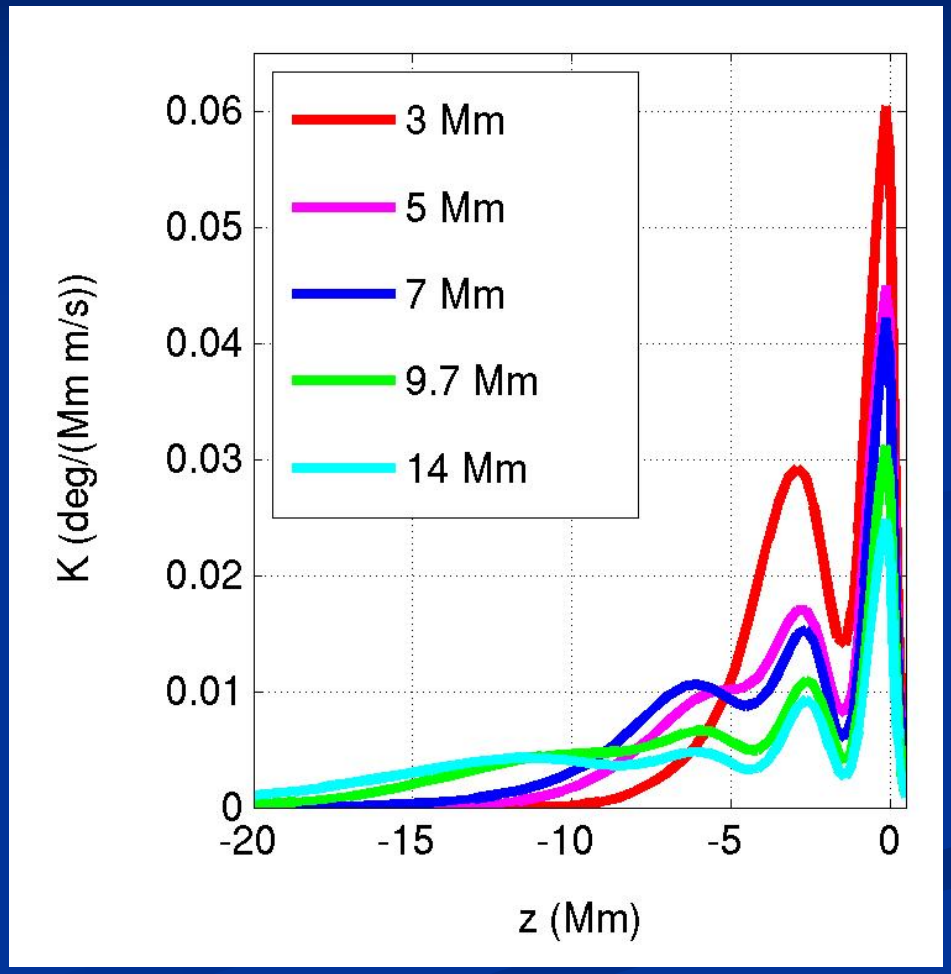
# zonal and meridional flows



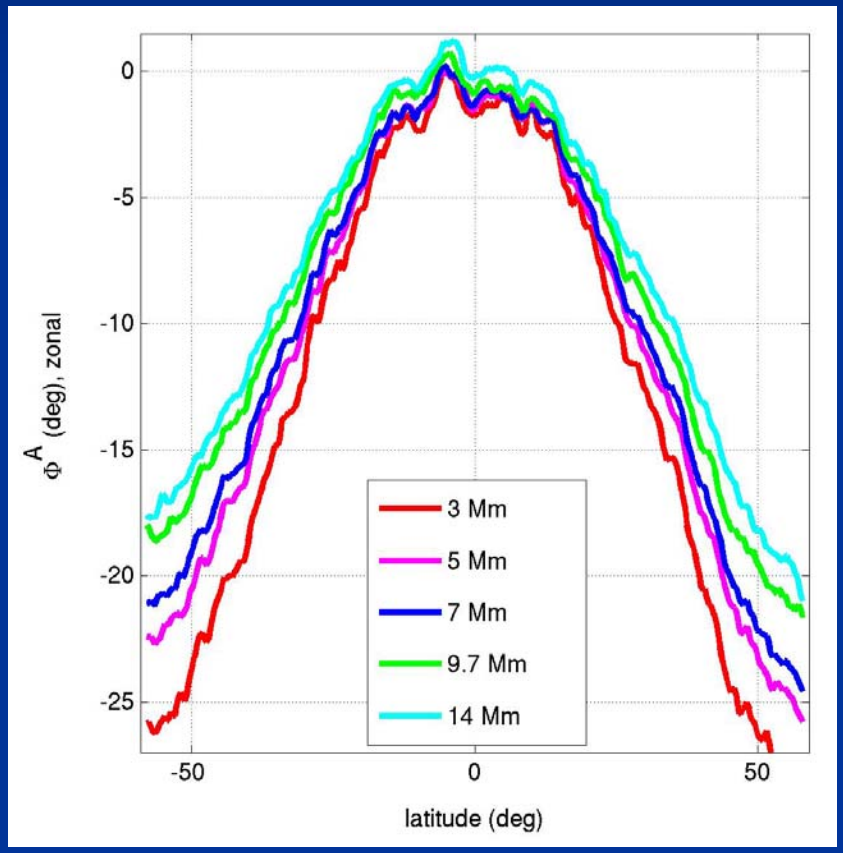



# inversions
## A. Birch

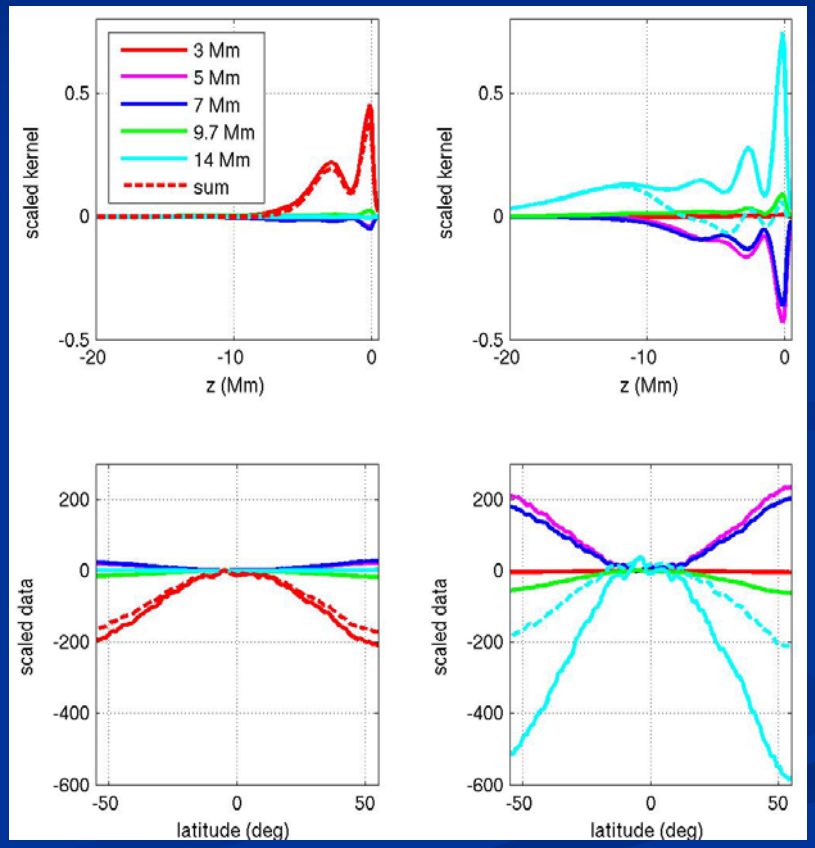
- multi-channel deconvolution algorithm (for 3D case)
- these rotation and meridional inversions are only 1D (depth) and only include horizontal flows
- averaging kernels (from Green's functions under Born approx.)
- OLA method
- regularization by hand
- solutions for two depths are shown (3Mm and 14 Mm)



# zonal data and inversions

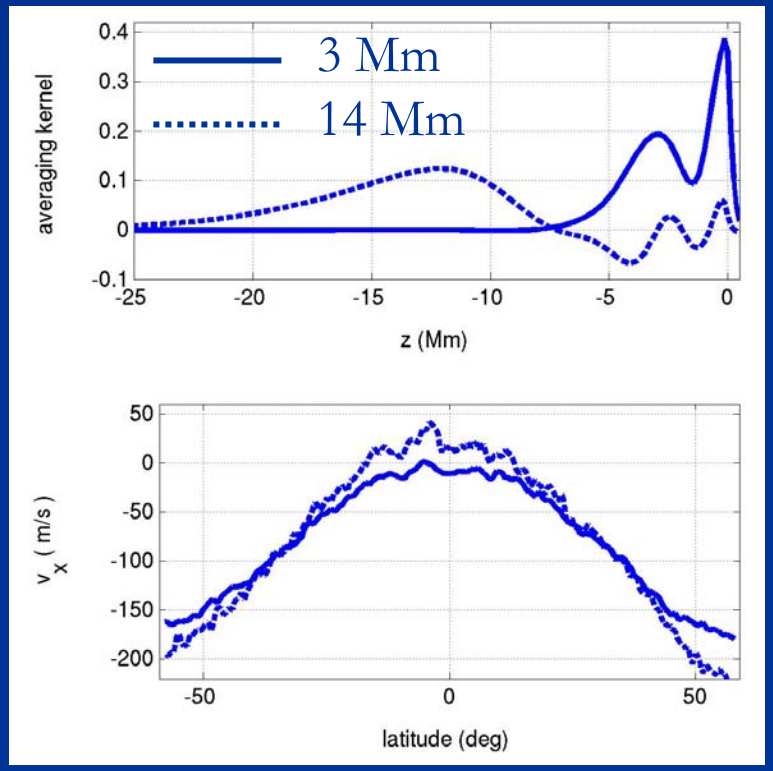



3 Mm 14 Mm

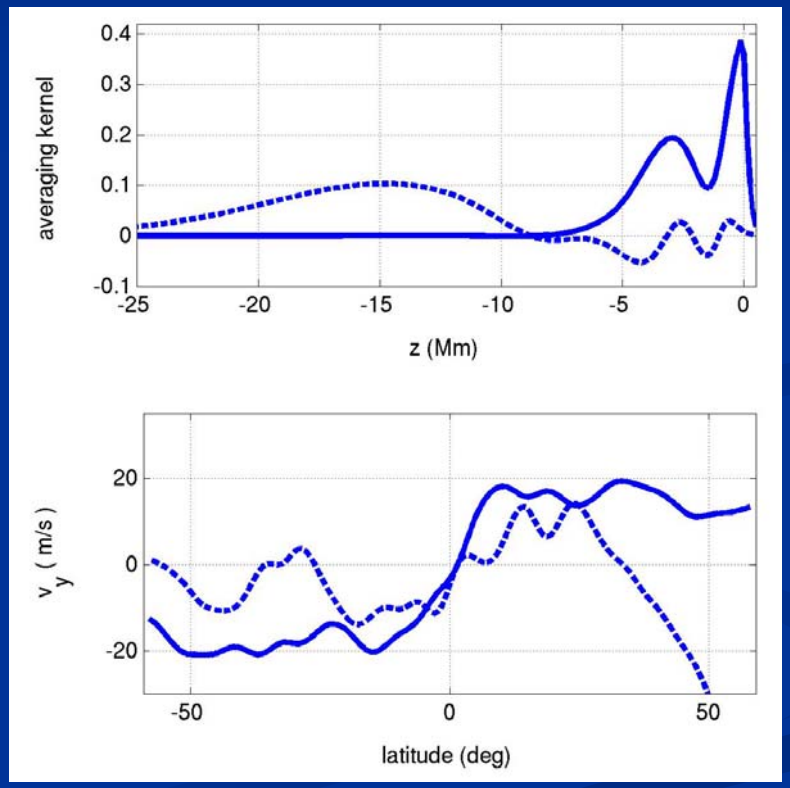


# inversion results

## zonal




## meridional



# HH code development needed for flows

- fix foreshortening & near-limb problems
- spherical coordinates
- inversions
  - f mode
  - higher frequencies

# larger (science-related) issues to address:

- travel-time asymmetries in magnetic regions
  - understanding physics
  - extracting flow signatures from other effects
- vertical flows? directly? assume mass-conservation?
- combining or using surface flows in inversions, models
- combining other measurements (TD,RD, etc.) in modeling

# further information:

http://cora.nwra.com/~dbraun

# support:

NASA (LWS and SR&T programs)

NSF (Stellar Astronomy and Astrophysics program)