3D helioseismic inversions of ring-analysis flow measurements

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Goals of this Talk

- Announce that our long promised 3D inversion procedure is now fully functional and ready for implementation in the HMI pipeline.
- Show you all how it works.
- Show some preliminary inversions around sunspots. (Strong Outflows to deep layers!)

Local Helioseismology

Two Basic Techniques to Measure Flows

- Time-Distance Helioseismology

Root Measurement

$$\Delta\tau \approx \frac{2U}{c} d$$

Travel Time Difference

- Ring Analysis

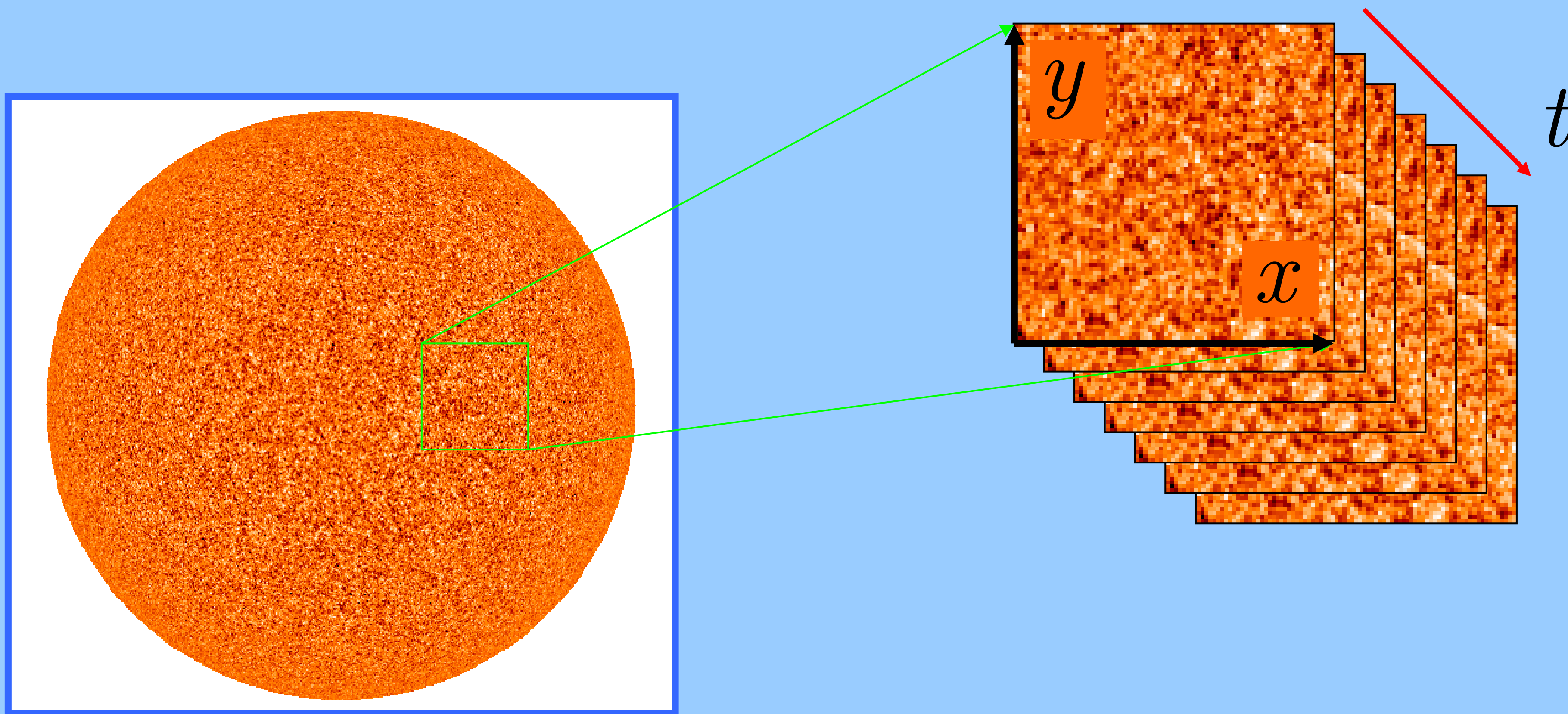
Root Measurement

$$\Delta\omega = \vec{k} \cdot \vec{U}$$

Frequency Shift

Horizontal flow

Plane Wave Decomposition

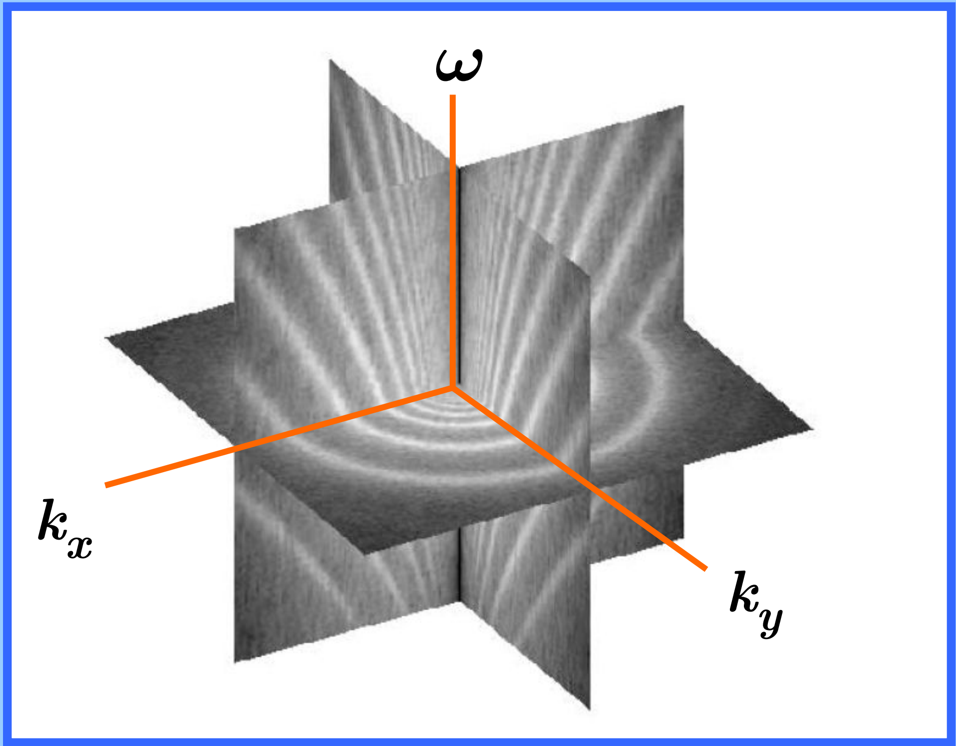


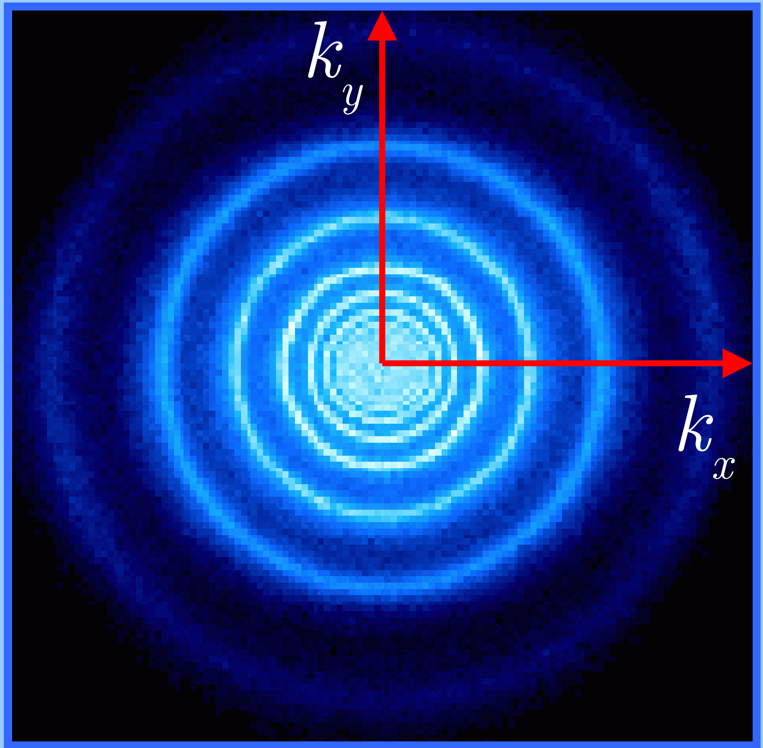
$$v(k_x, k_y, \omega) = (2\pi)^{-3/2} \iiint e^{-i\vec{k}_\mathrm{h}\cdot\vec{x}} e^{i\omega t} v_\mathrm{los}(x, y, t)$$

Power Spectra

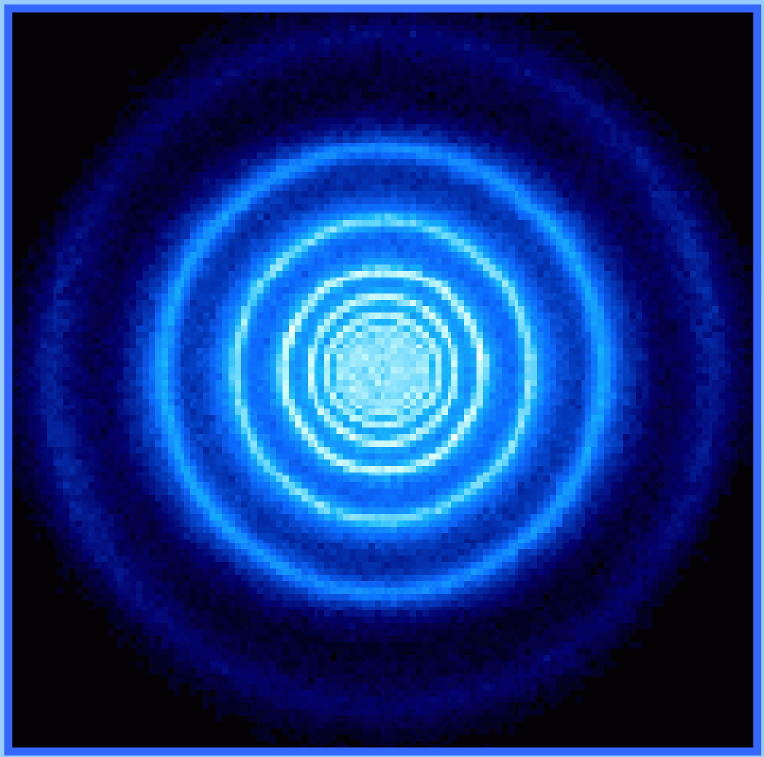
Power $= \left| v(k_x, k_y, \omega) \right|^2$

Since there are two spatial dimensions (x, y), and the time dimension t, the spectra are 3D.



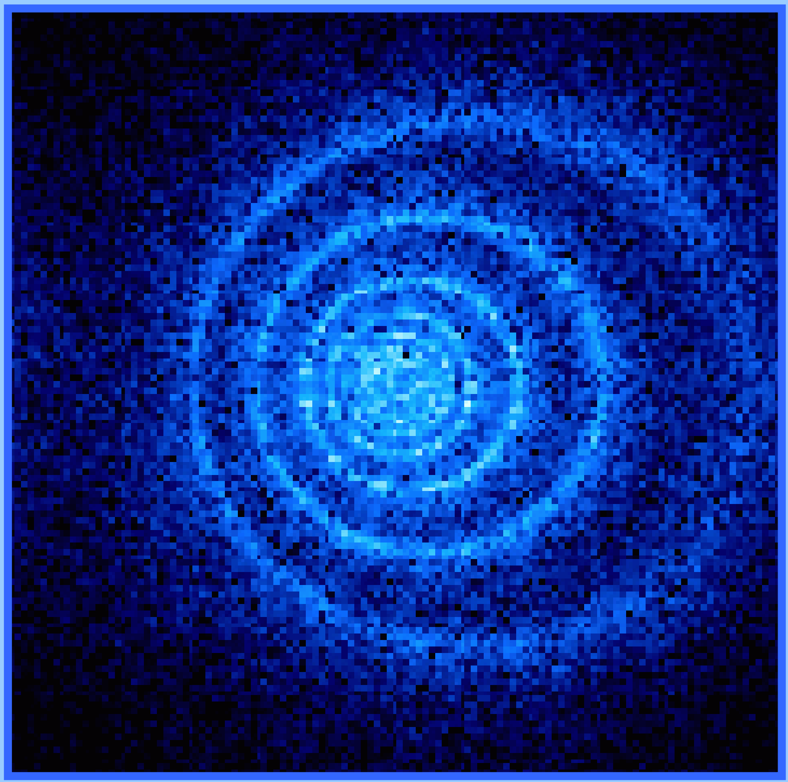


The Effects on p-Mode Spectra



Tracked at the rotation rate

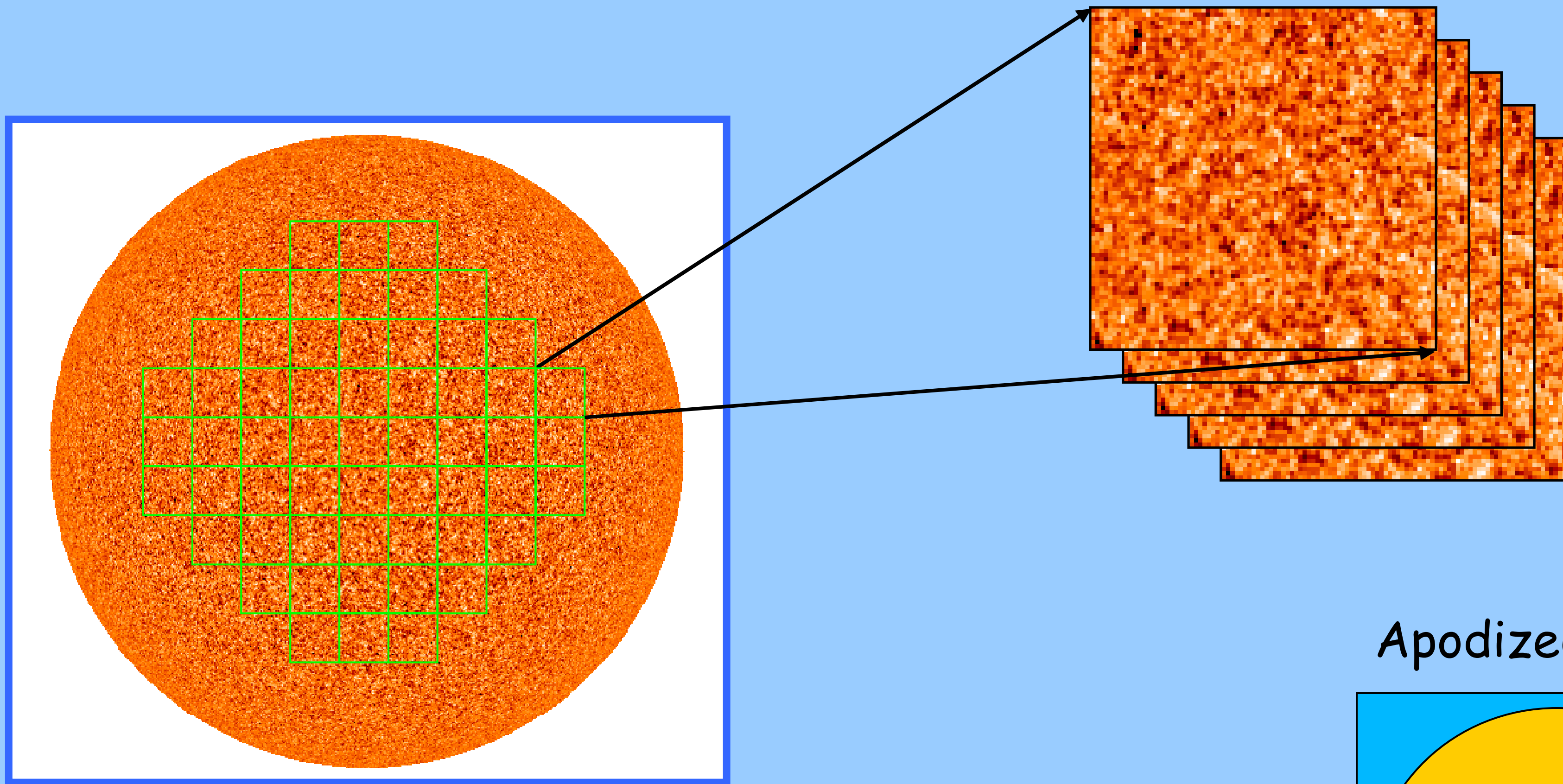
The above spectra was obtained by following the same patch of fluid as it rotates across the solar disk. This removes the large rotational velocity.

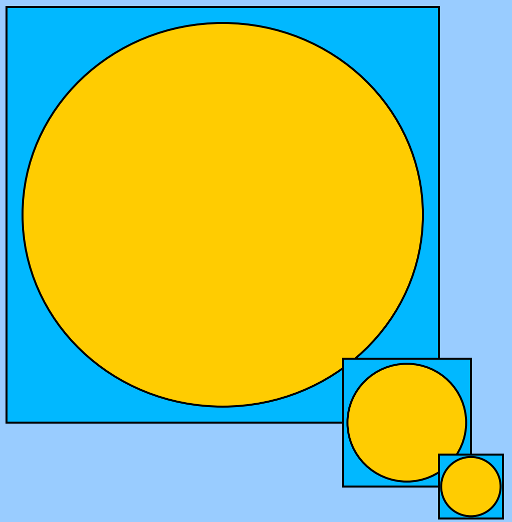


No Tracking

The above spectra was obtained by studying the same area on the solar disk. Equatorial rotation results in a speed of ~ 2000 m/s.

Building Mosaics





Three Tile Sizes

- 2°×2° (22 Mm in diameter)
- 4°×4° (45 Mm in diameter)
- 16°×16° (183 Mm in diameter)

Standard Ring-Analysis Data

For every tile the procedure obtains

Mode frequencies $\omega(n,l)$

Zonal Doppler Shifts $u_x(n,l)$

Meridional Doppler Shifts $u_y(n,l)$

3-D Inversion Implementation

RLS (Regularized Least Squares)

$$\chi^2 = \sum_i \frac{1}{\sigma_i^2}\left[u_{x,i} - \iiint d^3x\ K_i(\vec{x})v_x(\vec{x})\right]^2 + \iiint d^3x\ \mathrm{D}v_x$$

Sum over all data (all modes for all tiles)

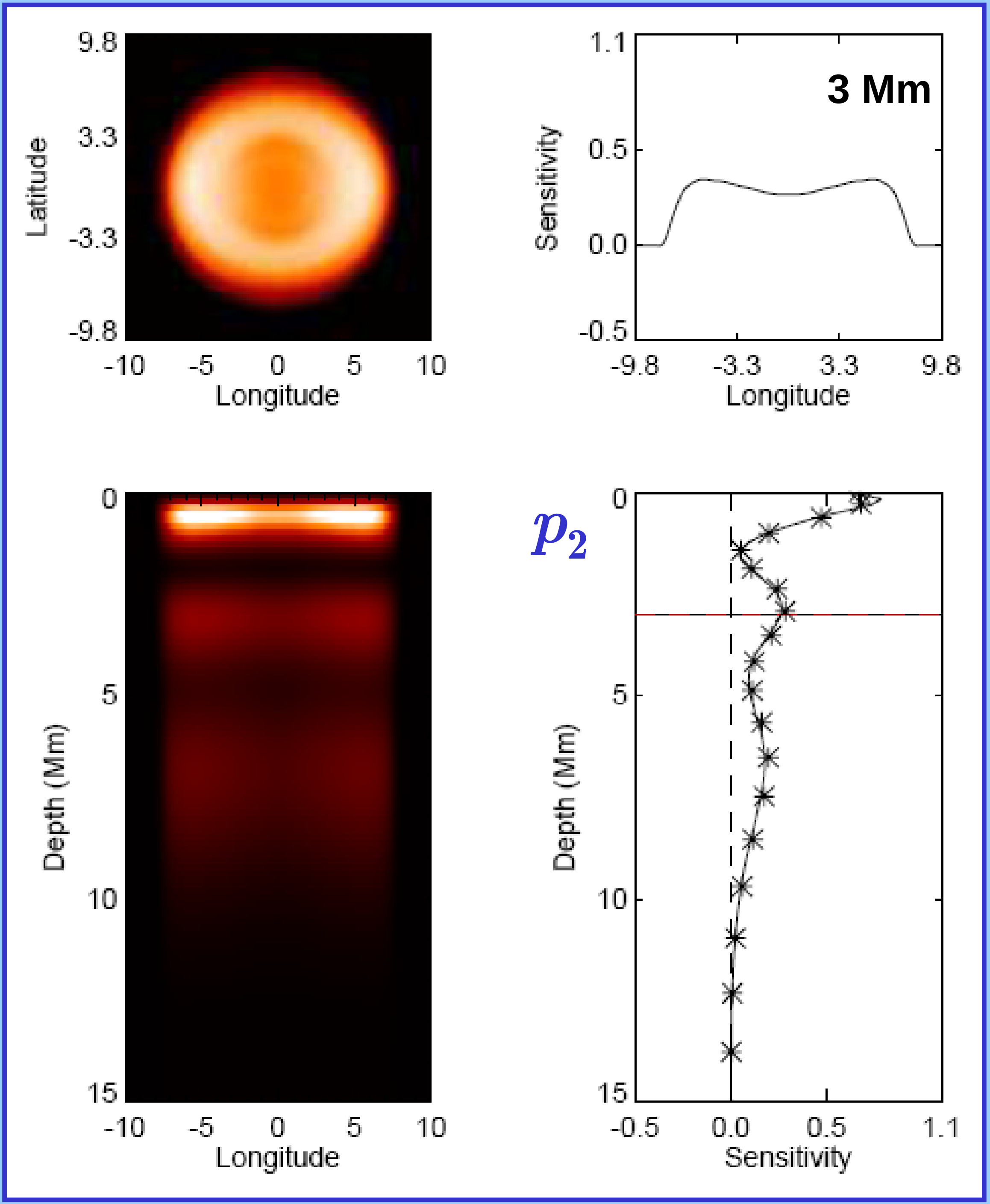
Measurement

Sensitivity Kernel

Flow field to deduce

Regularization

$$\mathrm{D}v_x = \lambda_x\left(\frac{\partial v_x}{\partial x}\right)^2 + \lambda_y\left(\frac{\partial v_x}{\partial y}\right)^2 + \lambda_z\left(\frac{\partial v_x}{\partial z}\right)^2$$



Sensitivity Kernels

The sensitivity kernels are computed using a code written by Aaron Birch which utilizes the Born approximation to describe the wave propagation.

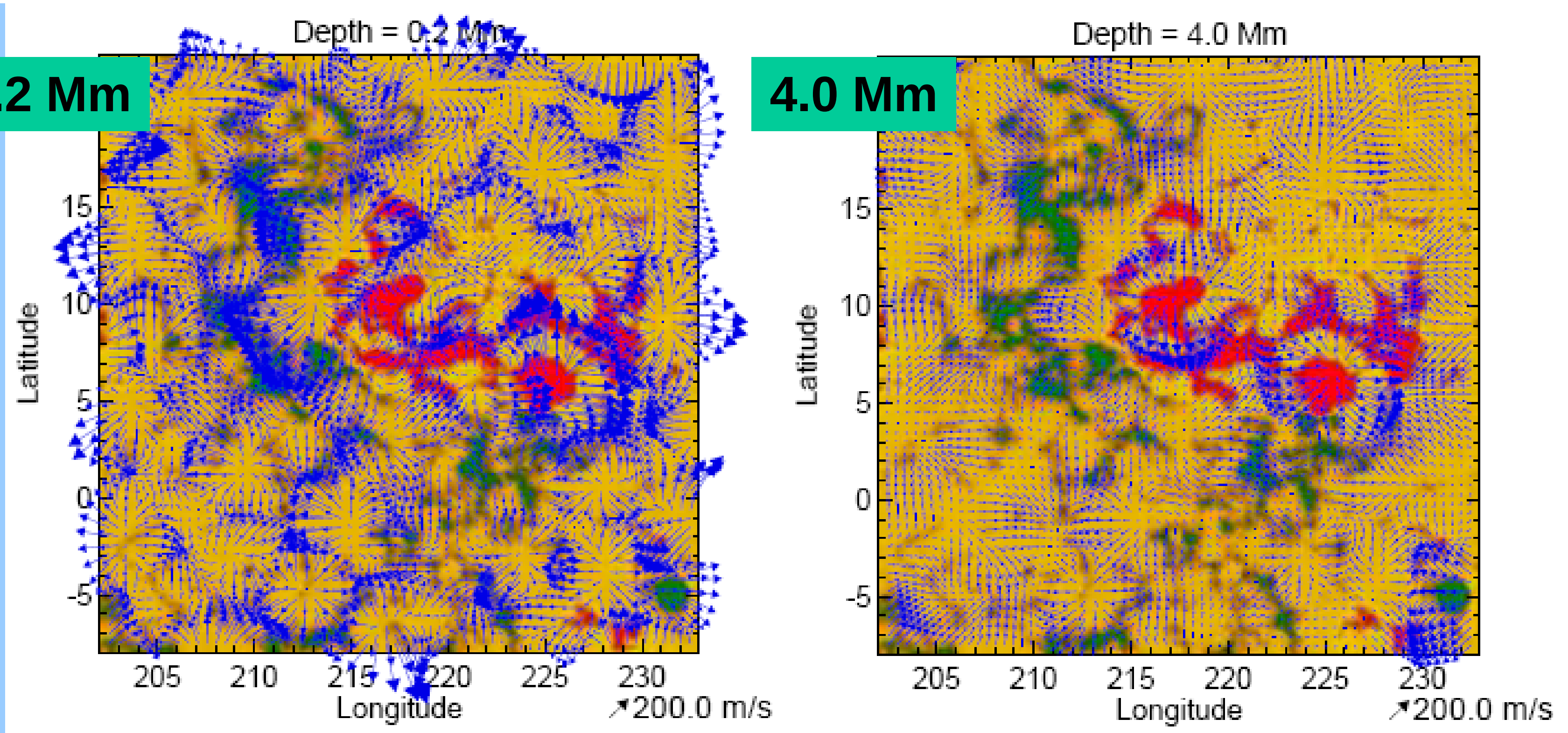
The structure of the kernels depends on the manner in which the ring-fitting is performed.

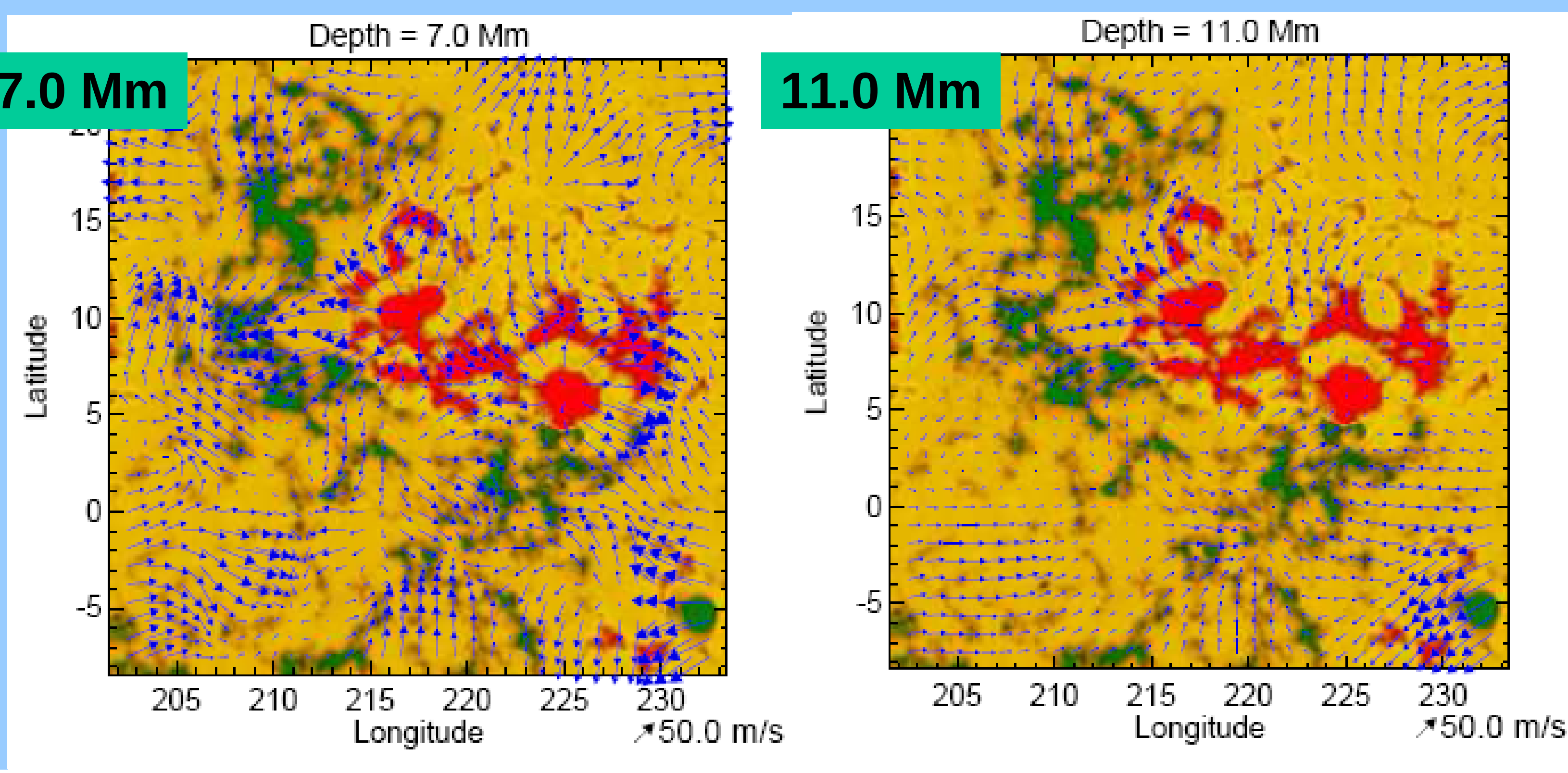
We preferentially get higher sensitivity in a ring with a size that is roughly the apodization radius.

$n = 2$

$l = 428$

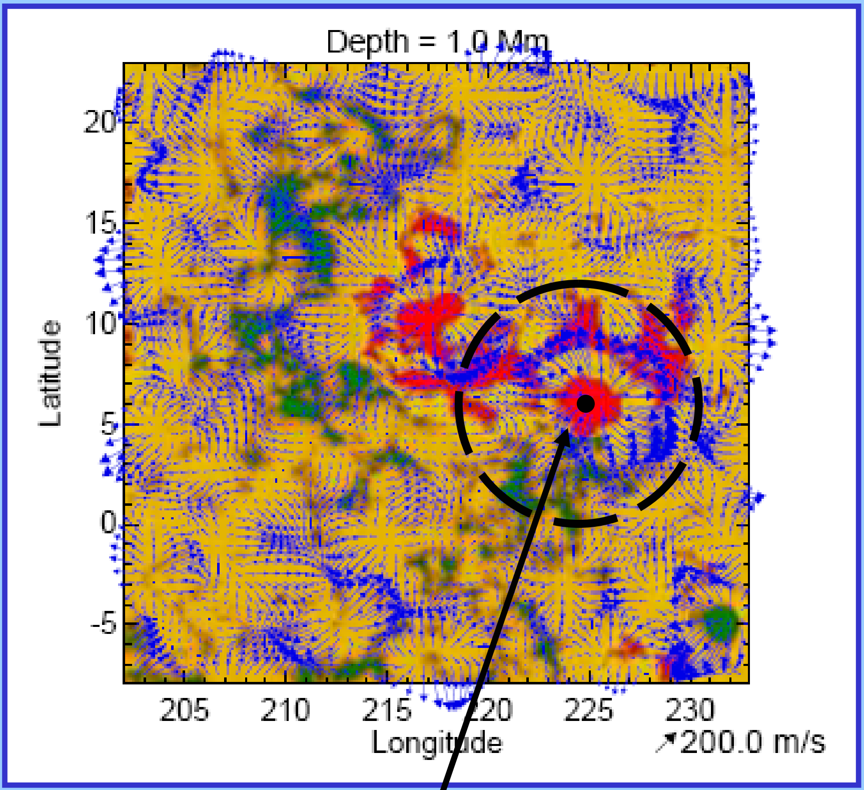
16° tile



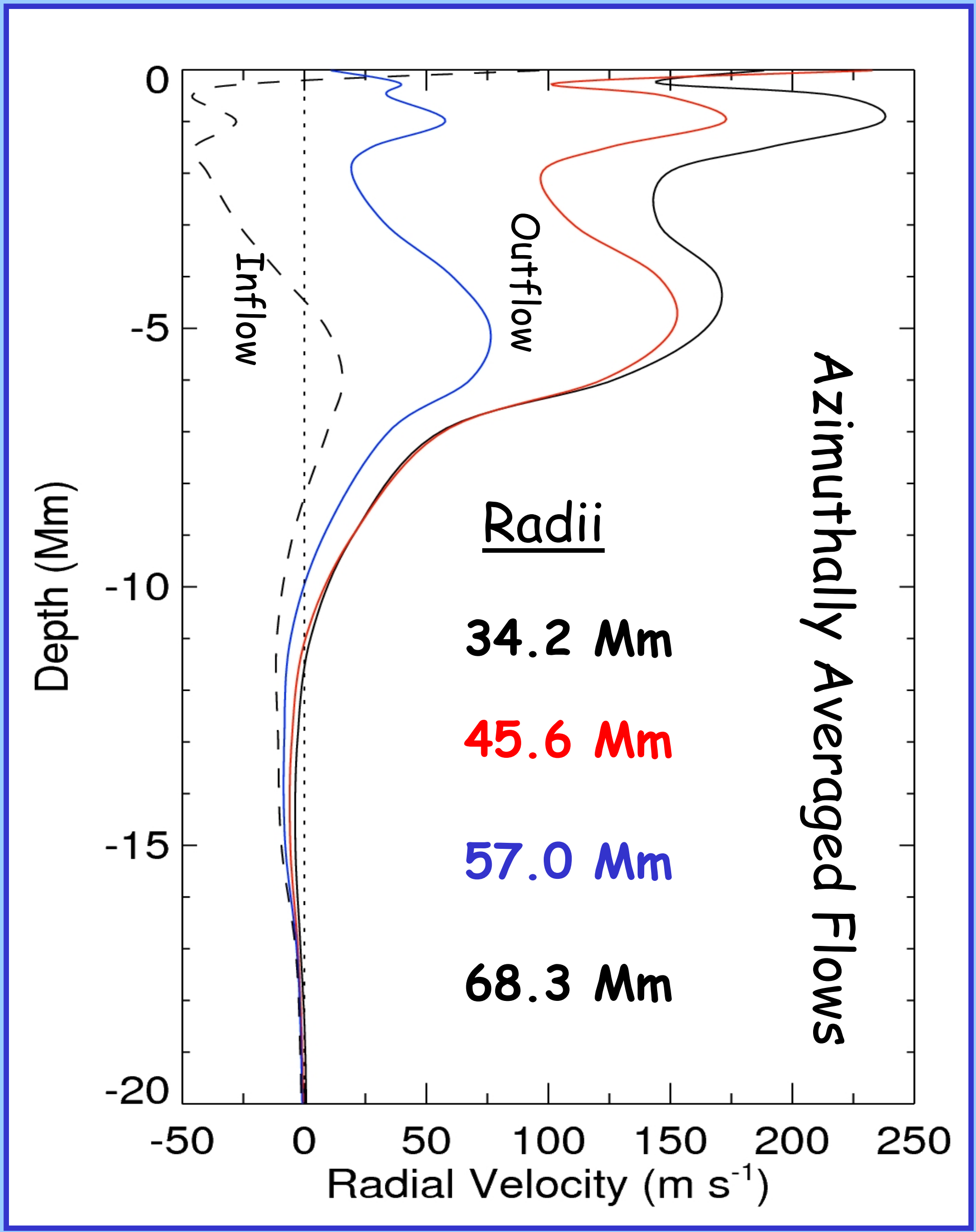


January
2002

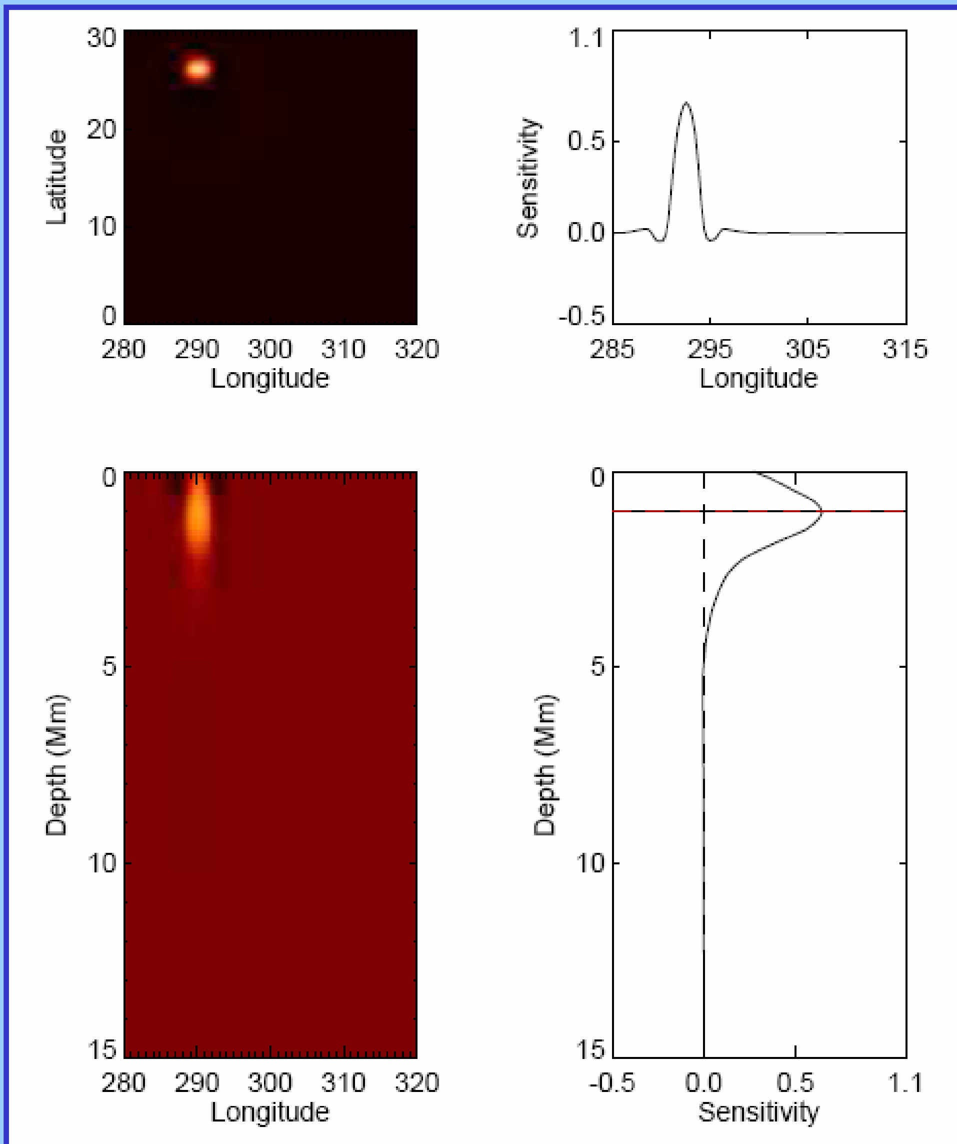
Outflow Speed



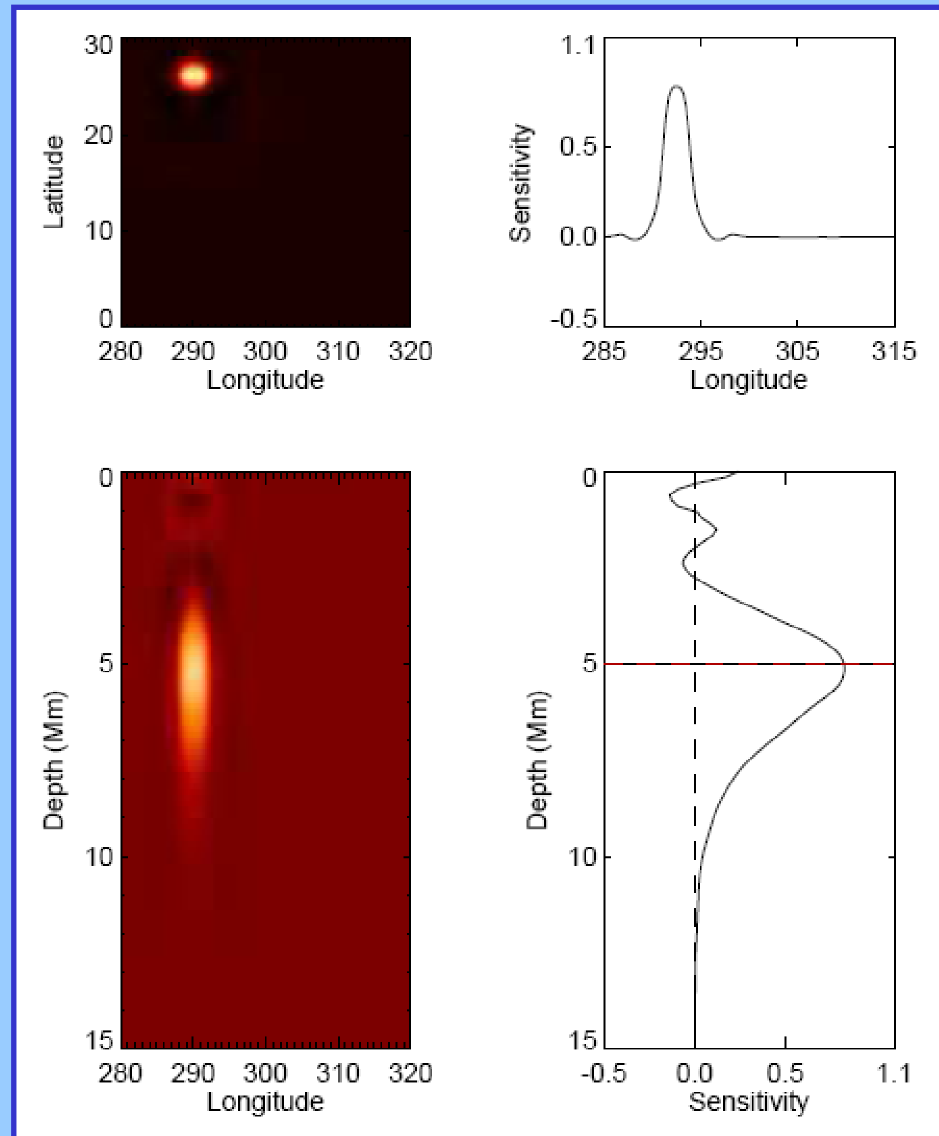
Azimuthal Averages are computed about this point



Averaging Kernels



Target Depth 1 Mm

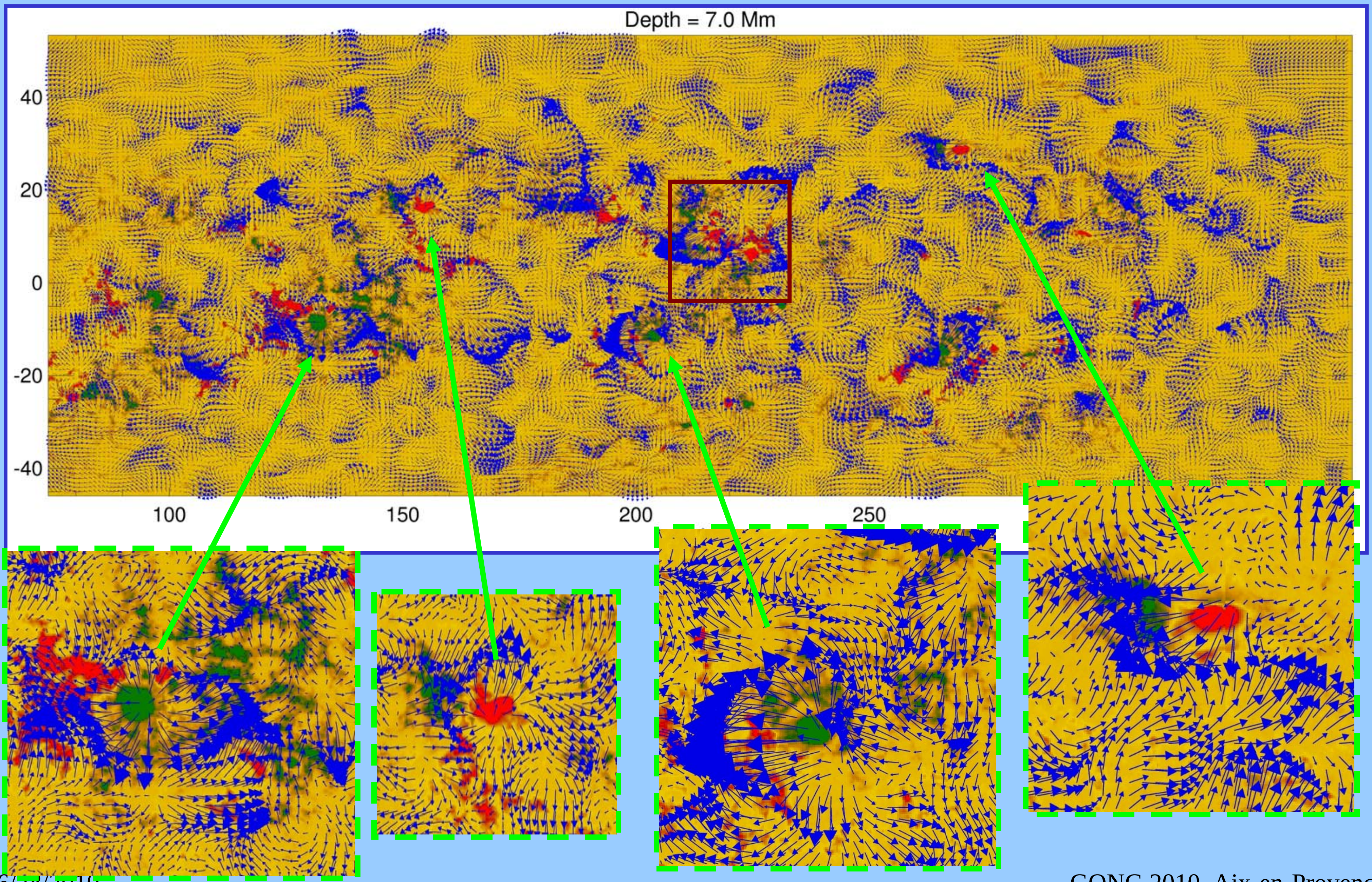


Target Depth 5 Mm

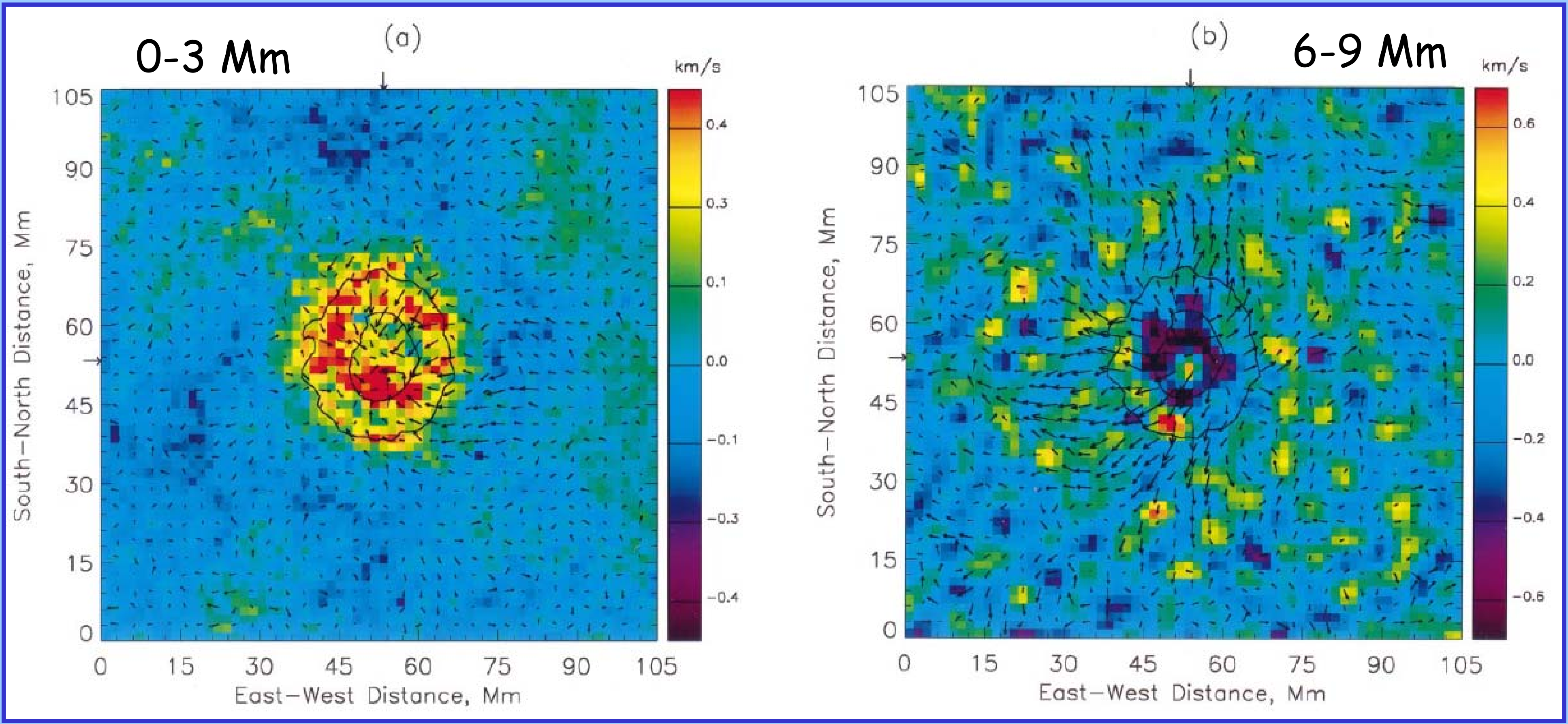
Synoptic Flow Map

11 – 20 January 2002

7 Mm



Time-Distance Results



Findings

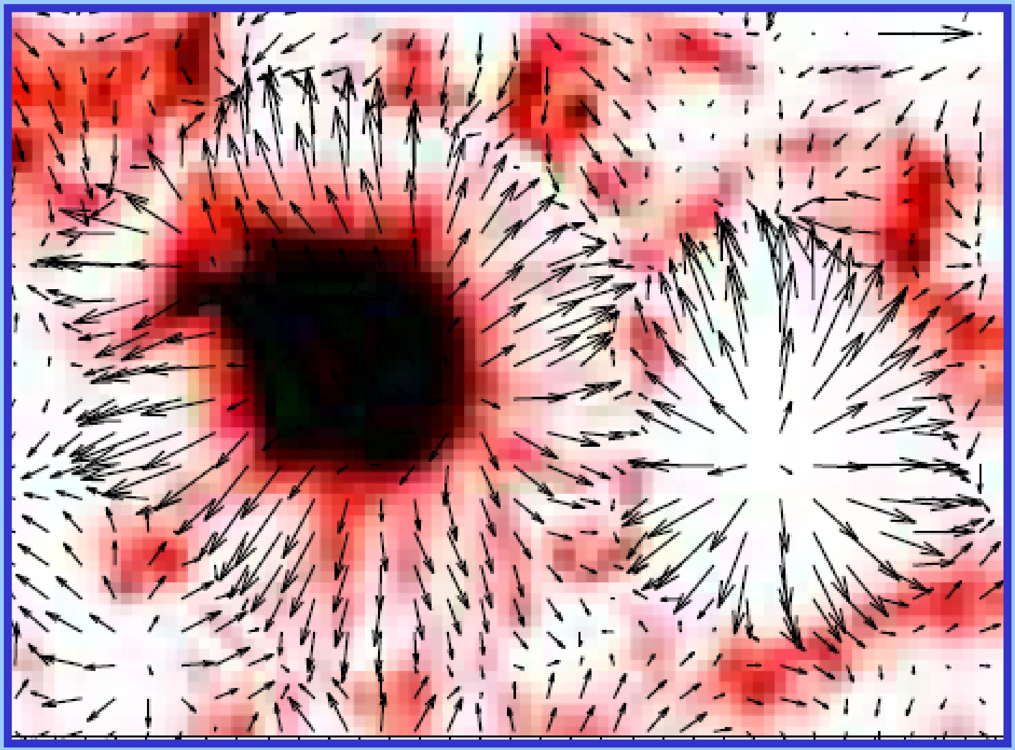
Inflows: 0-6 Mm
Outflows: 6-9 Mm
Neither: 9+ Mm

18 June 1998
MDI

Zhao et al. 2001

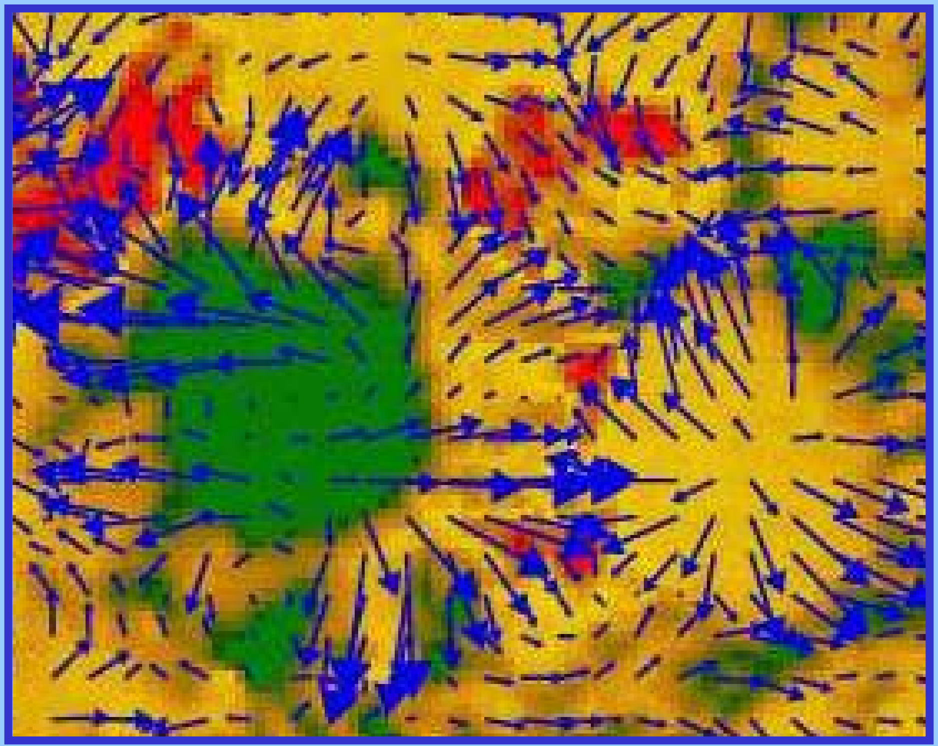
Moat Flows Obtained with *f* Modes

Time-Distance
Helioseismology



Jackiewicz et al. 200?

Ring Analysis



Haber 2009

4 January 2002

Advantages over the "Old" 1-D procedure

- Self-consistent treatment of horizontally varying flows
- Higher horizontal spatial resolution at all depths (but particularly at intermediate depths, 2 – 7 Mm).
- Can now connect surface structures with related deep structures (smoothly varying resolution with depth).

Conclusions

- The 3-D ring-analysis inversions are working well.
- They have been optimized for computational efficiency, and are ready for importation into the HMI pipeline.
- We detect 200 m/s outflows from sunspots all the way from the surface down to a depth of roughly 7 Mm.
- We agree with the f-mode time-distance measurements at the surface and the p-mode time-distance inversions at depth.