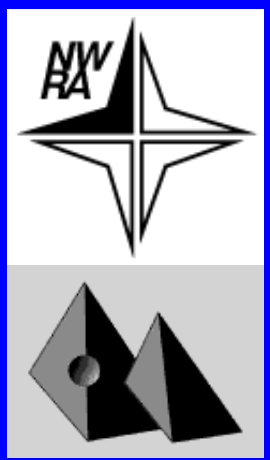
Probing the interior and far side of the Sun

Doug Braun

NorthWest Research Associates, Inc.
Colorado Research Associates Division



collaborators & contributors:

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A. Donea, H. Schunker, P. Cally (*Monash U.)*

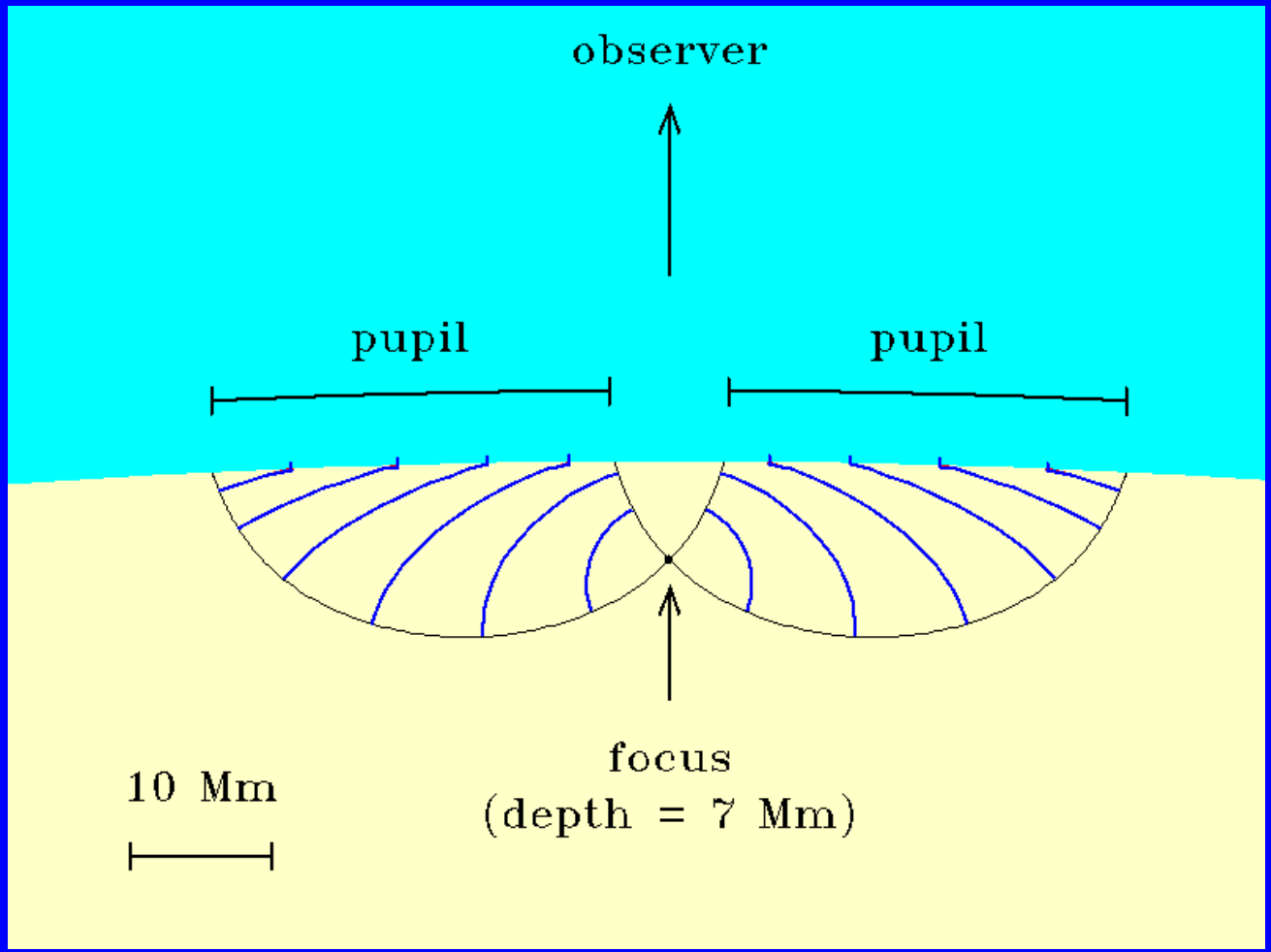
A. Malanushenko (*NSO & St Petersberg U*)

J. Werne (*NWRA*) & K. Julien (*CU*)

outline

- acoustic signatures of solar flares
- holography of active regions
  - looking through the showerglass
  - farside imaging
- holography of flows
  - supergranulation
  - larger-scale flows
- hare-and-hound exercises

helioseismic holography



H_- = ingression

H_+ = egression

acoustic power holography

(space-time domain)

egression,ingression: $$H_{\pm}(\mathbf{r},z,t) = \int_P d^2\mathbf{r}'\; G_{\pm}(\mathbf{r},\mathbf{r}',z,t)\,\psi(\mathbf{r}',t)$$

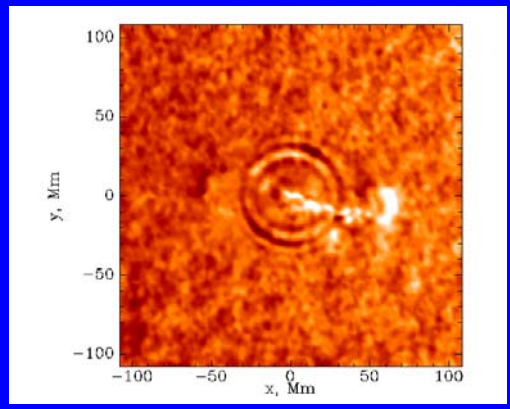
(z = depth,**r** = horizontal position, ψ= surface amplitude, $G_{\pm}$= Greens' functions)

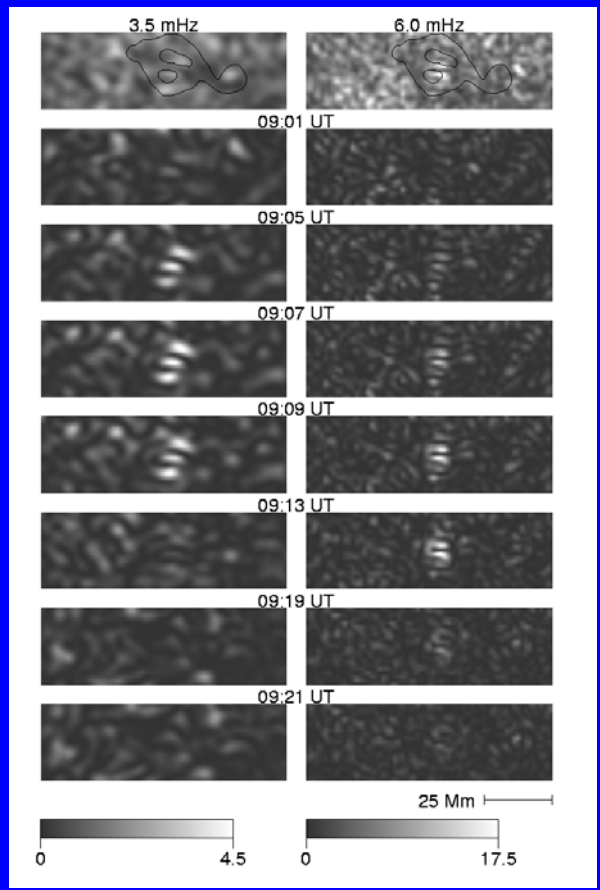
egression,ingression power: $$P_{\pm}(\mathbf{r},z,t) = H_{\pm}^2(\mathbf{r},z,t)$$

sensitive to sources, sinks at focus

Seismic images of a solar flare

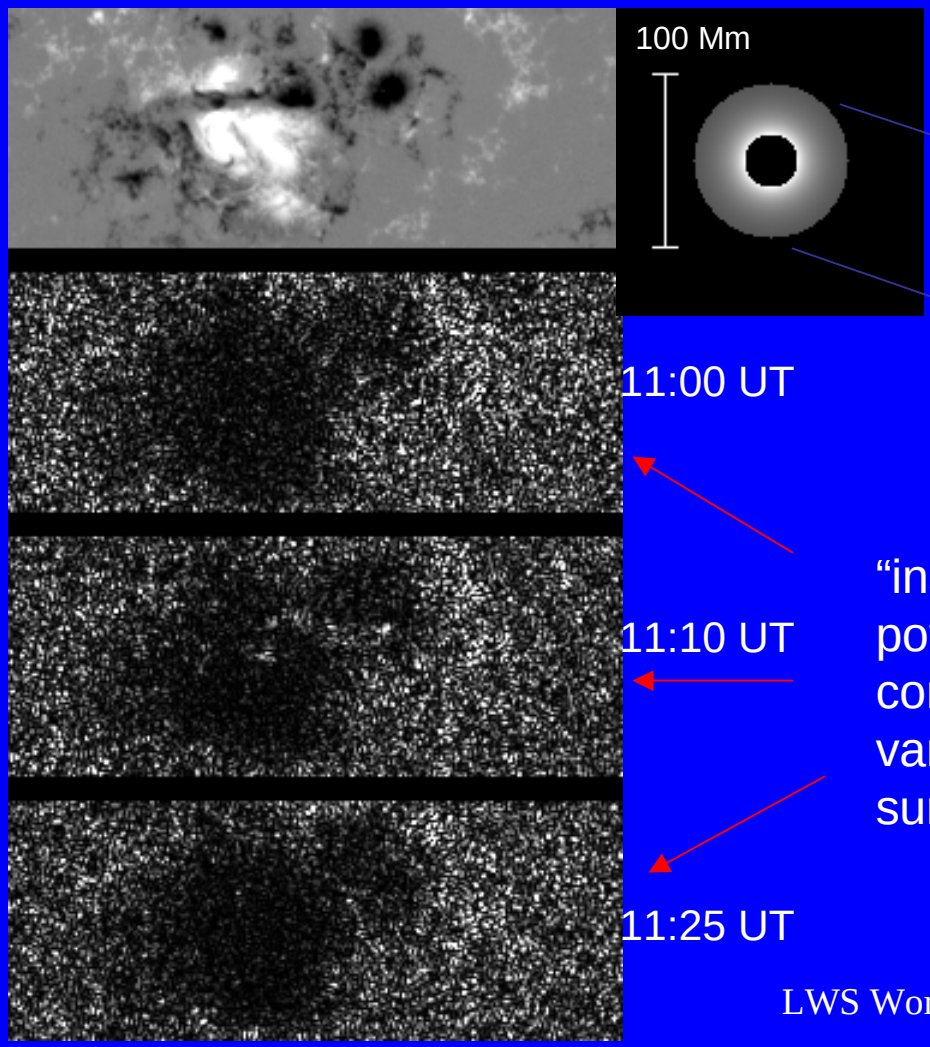
- X2.6 1996 July 7 (AR 7978)
- propagating waves (Kosovichev & Zharkova 1998, *Nature,* **393**, 317)
- acoustic power holography to image source (Donea, Braun & Lindsey 1999, *ApJ*, **513**, L146)
- only acoustic flare signature until…

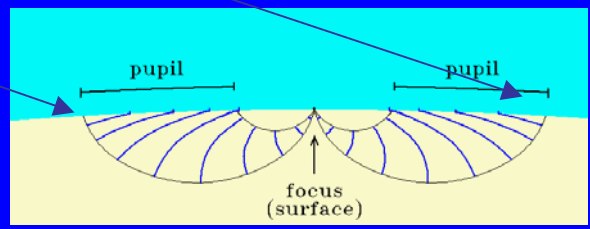




2003 Oct 28, X17 flare (AR 486)

A. Donea (Monash U.)

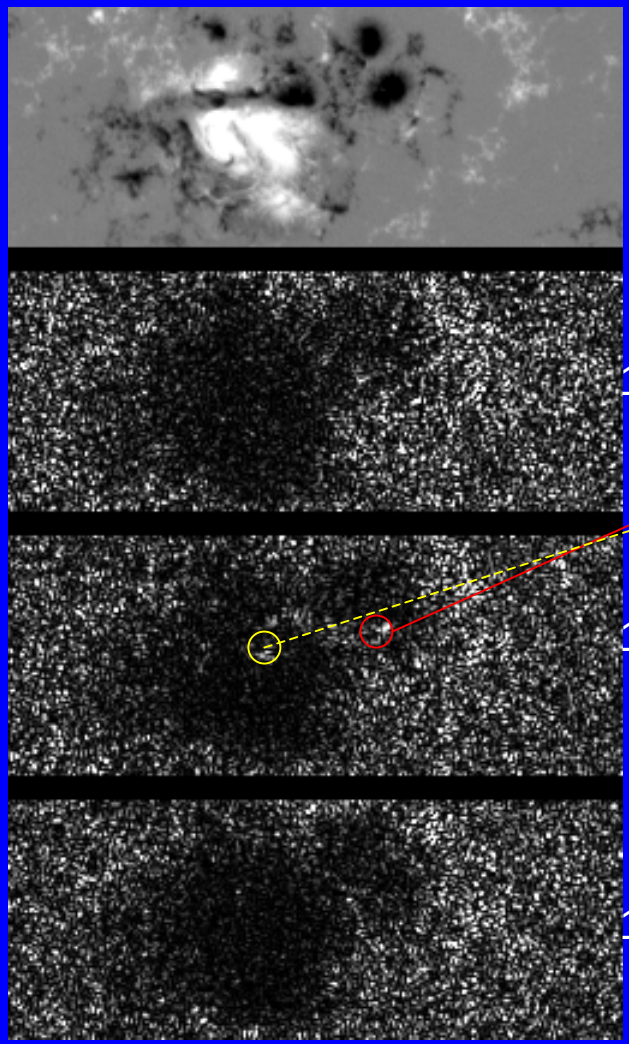


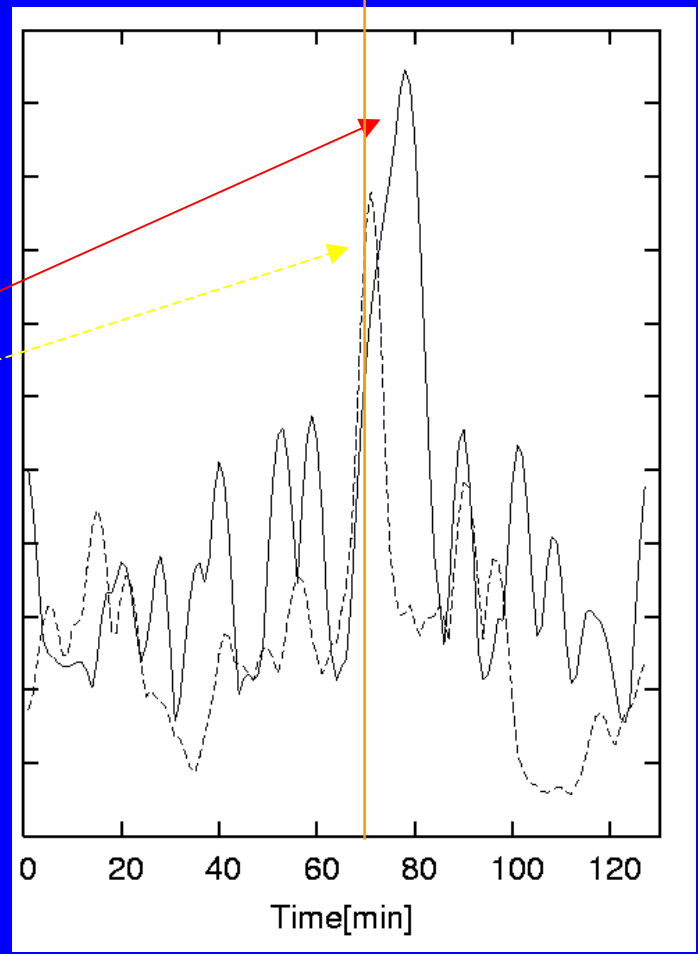


"instantaneous" egression power between 5-7 mHz computed in subjacent vantage with focus at surface.

2003 Oct 28, X17 flare (AR 486)

A. Donea (Monash U.)





phase-correlation holography

(space-frequency domain)

egression, ingression: $H_{\pm}(\mathbf{r}, z, \nu) = \int_P d^2\mathbf{r}'\ G_{\pm}(\mathbf{r}, \mathbf{r}', z, \nu)\, \psi(\mathbf{r}', \nu)$

correlation: $C(\mathbf{r}, z, \nu) \equiv H_{+}(\mathbf{r}, z, \nu)\ H^{*}_{-}(\mathbf{r}, z, \nu)$

correlation phase: $\phi(\mathbf{r}, z) = \arg\left(\left\langle C(\mathbf{r}, z, \nu)\right\rangle_{\Delta\nu}\right)$

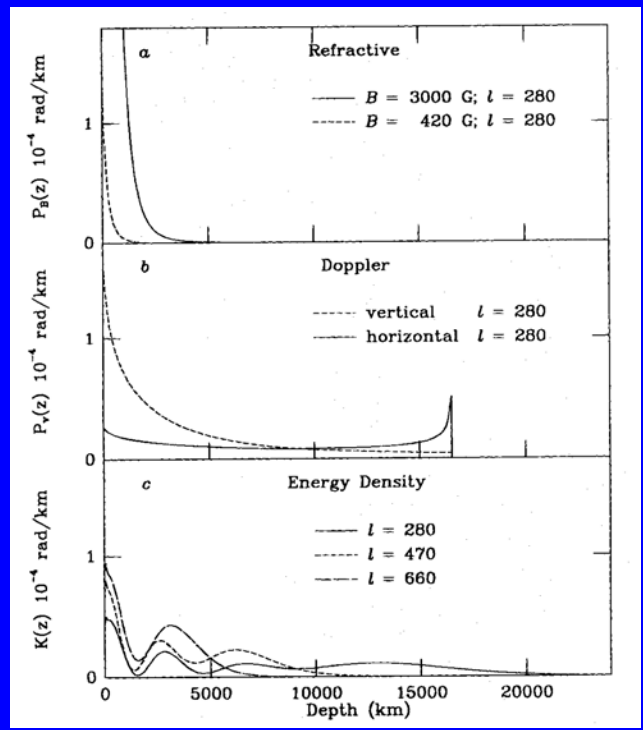
travel-time perturbation: $\delta t(\mathbf{r}, z) = \phi(\mathbf{r}, z)/2\pi\nu$ 。

sensitive to refractive perturbations at focus

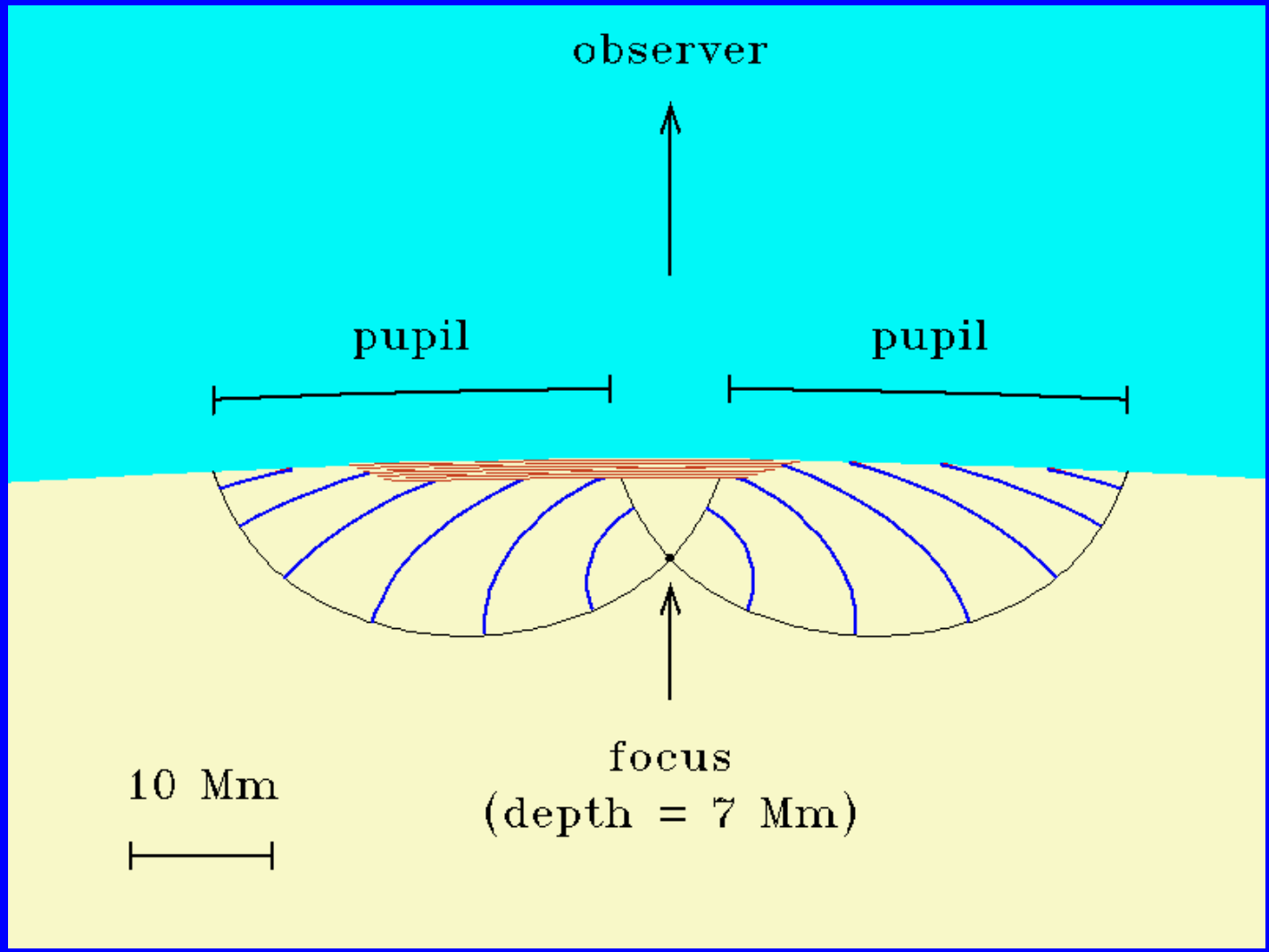
active regions

understanding (and removing?) surface contribution

- *dominate* influence of magnetic fields on acoustic waves is likely *at surface* ($\beta \approx 1$)
- theoretical expectations
  - Cally, Bogdan & Zweibel (1994, *ApJ*, **437**, 505)
  - Lindsey et al. (1996, *ApJ*, **470**, 636)
  - Cally & Bogdan (1997, *ApJ*, **486**, L67)
- observational evidence
  - Fan, Braun & Chou (1995, *ApJ*, **451**, 877)
  - Cally, Crouch & Braun (2003, *MNRAS,* **346**, 381)
  - Lindsey & Braun (2004, *ApJ*, submitted)



the showerglass effect



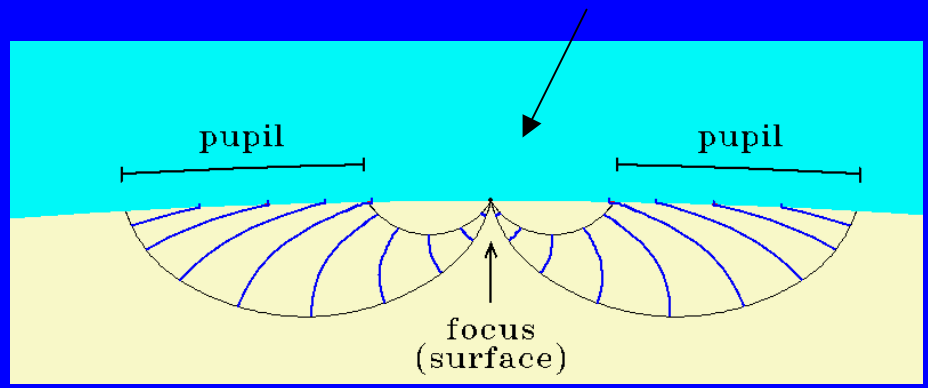
showerglass assessment: *local control* correlations

$$C_{-}(\mathbf{r}) \equiv \left\langle \psi(\mathbf{r},\nu) H_{-}^{*}(\mathbf{r},\nu) \right\rangle_{\Delta\nu}$$

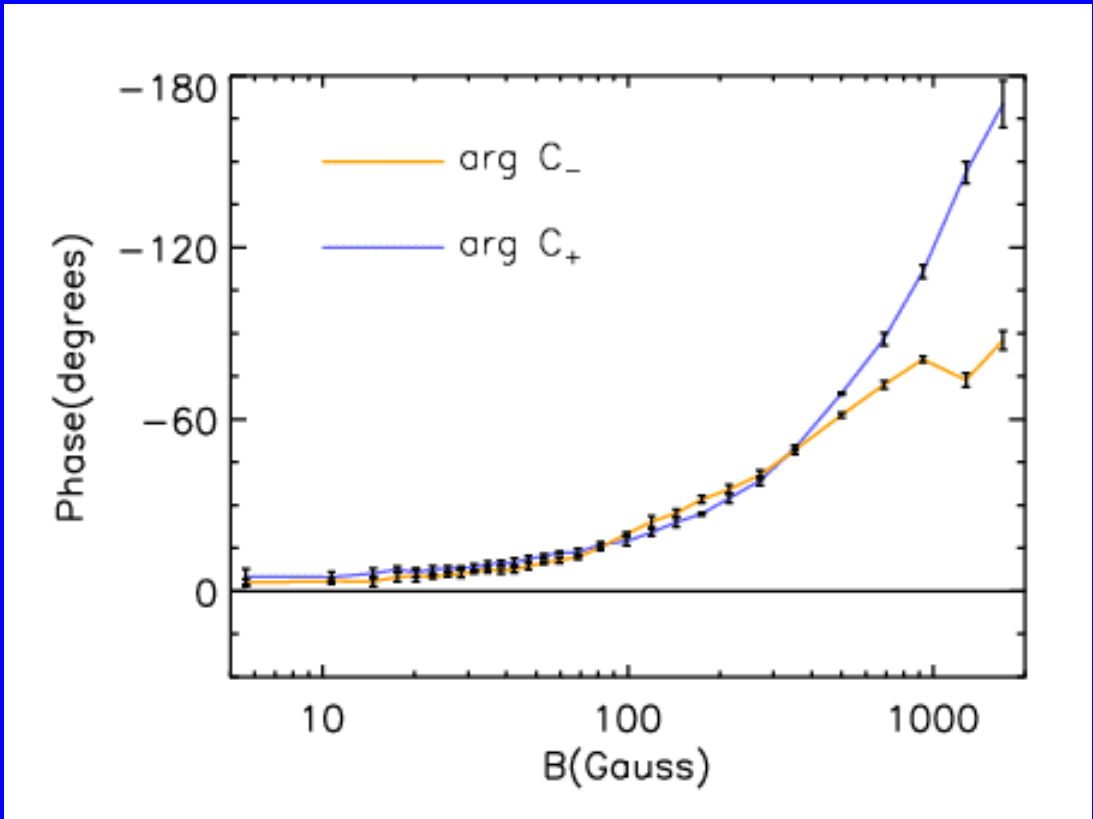
$$C_{+}(\mathbf{r}) \equiv \left\langle H_{+}(\mathbf{r},\nu) \psi^{*}(\mathbf{r},\nu) \right\rangle_{\Delta\nu}$$

- quiet Sun:
  - control (expect $C_{\pm} = 1$)
- magnetic region:
  - C_{-} describes how surface fields shift phase and amplitude of local photospheric signature of incoming waves
  - C_{+} describes influence of field on outgoing waves

ψ = local acoustic amplitude



calibration of showerglass

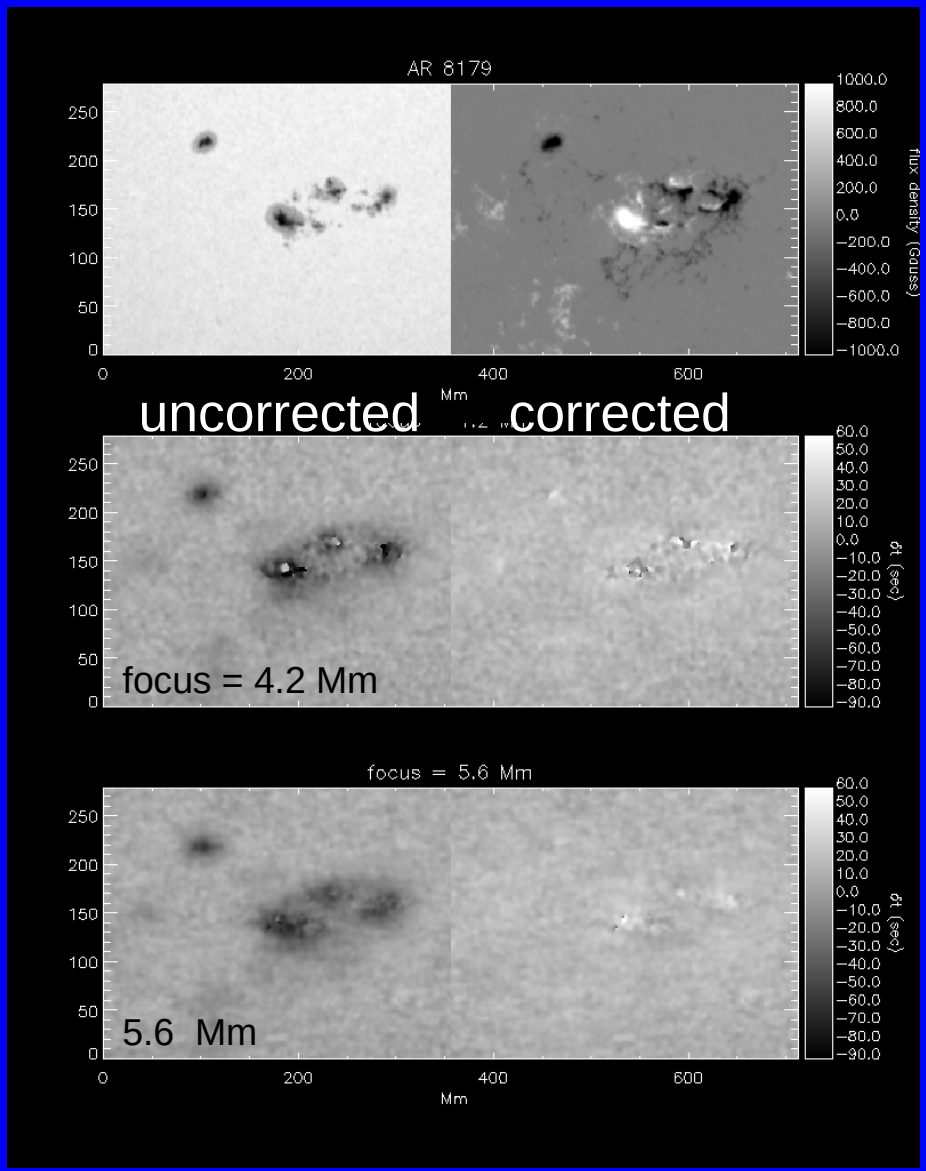


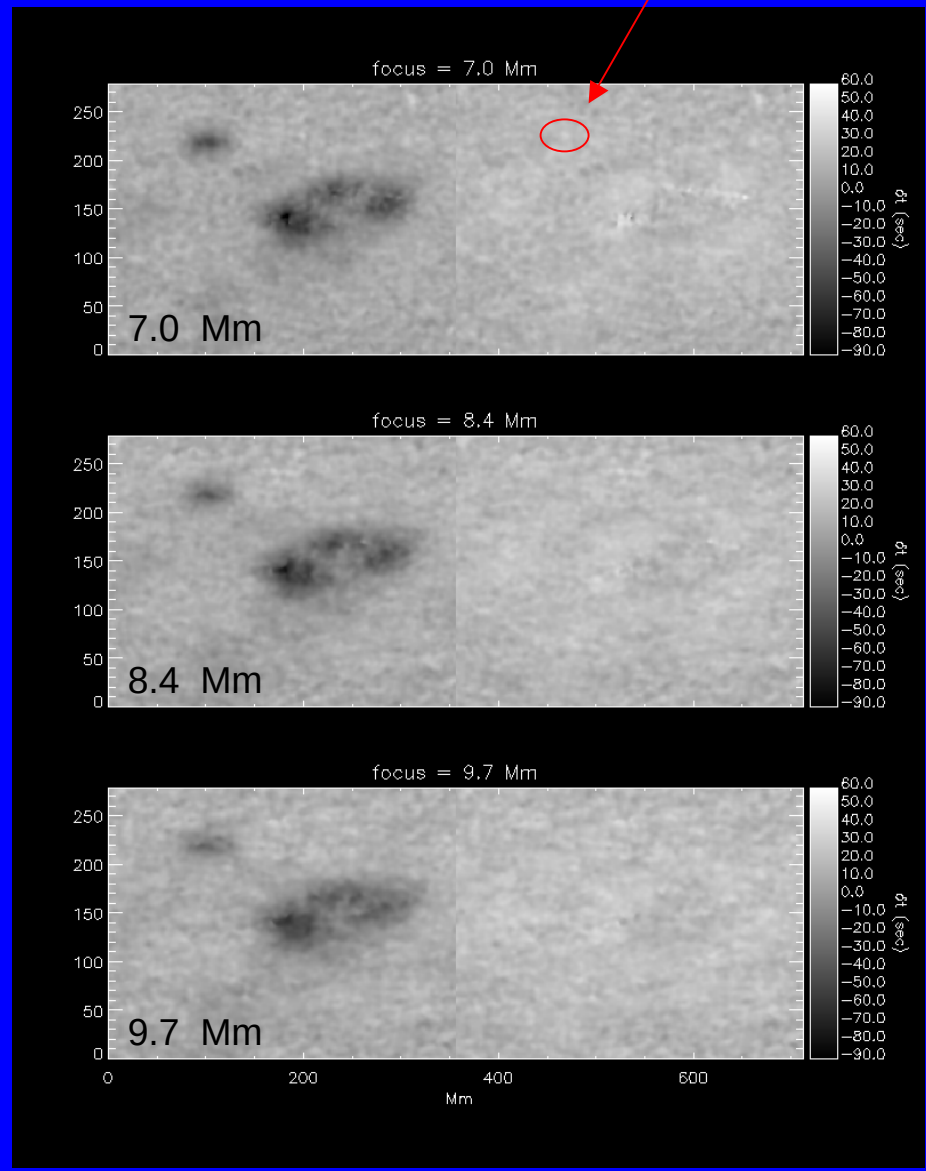
Lindsey & Braun 2004 (*ApJ* submitted, preprint available at www.cora.nwra.com/~dbraun)

see poster in session 5B

application of showerglass correction

$|\delta c| < 250$ m/s

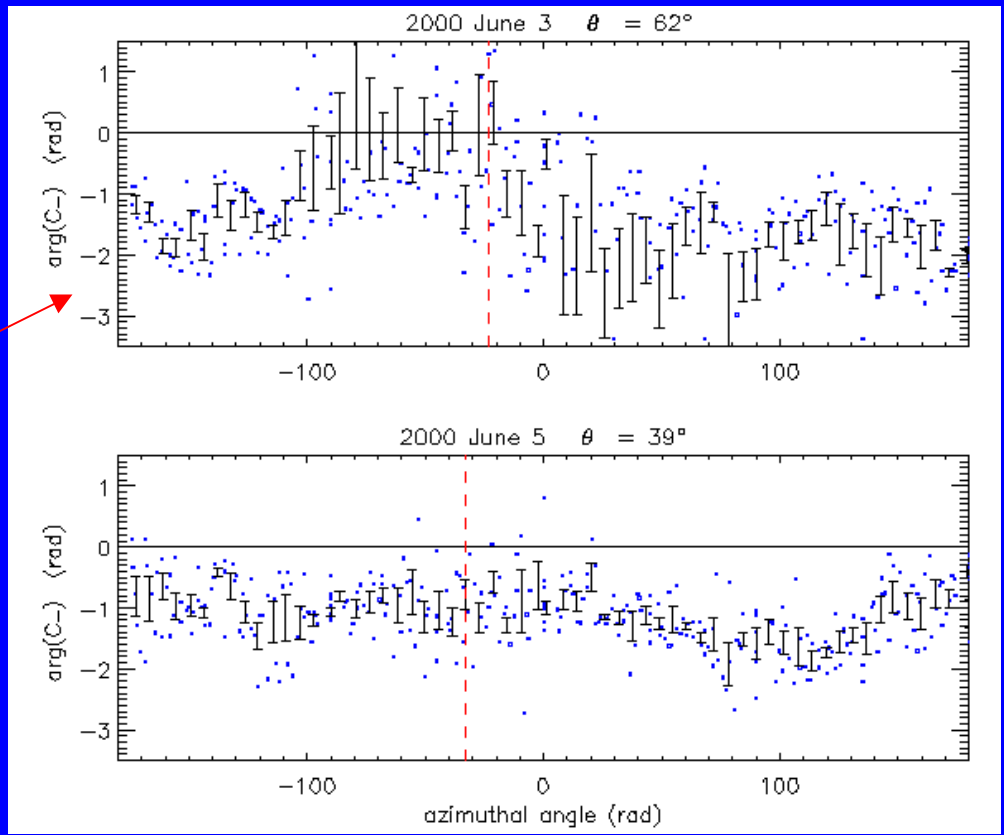




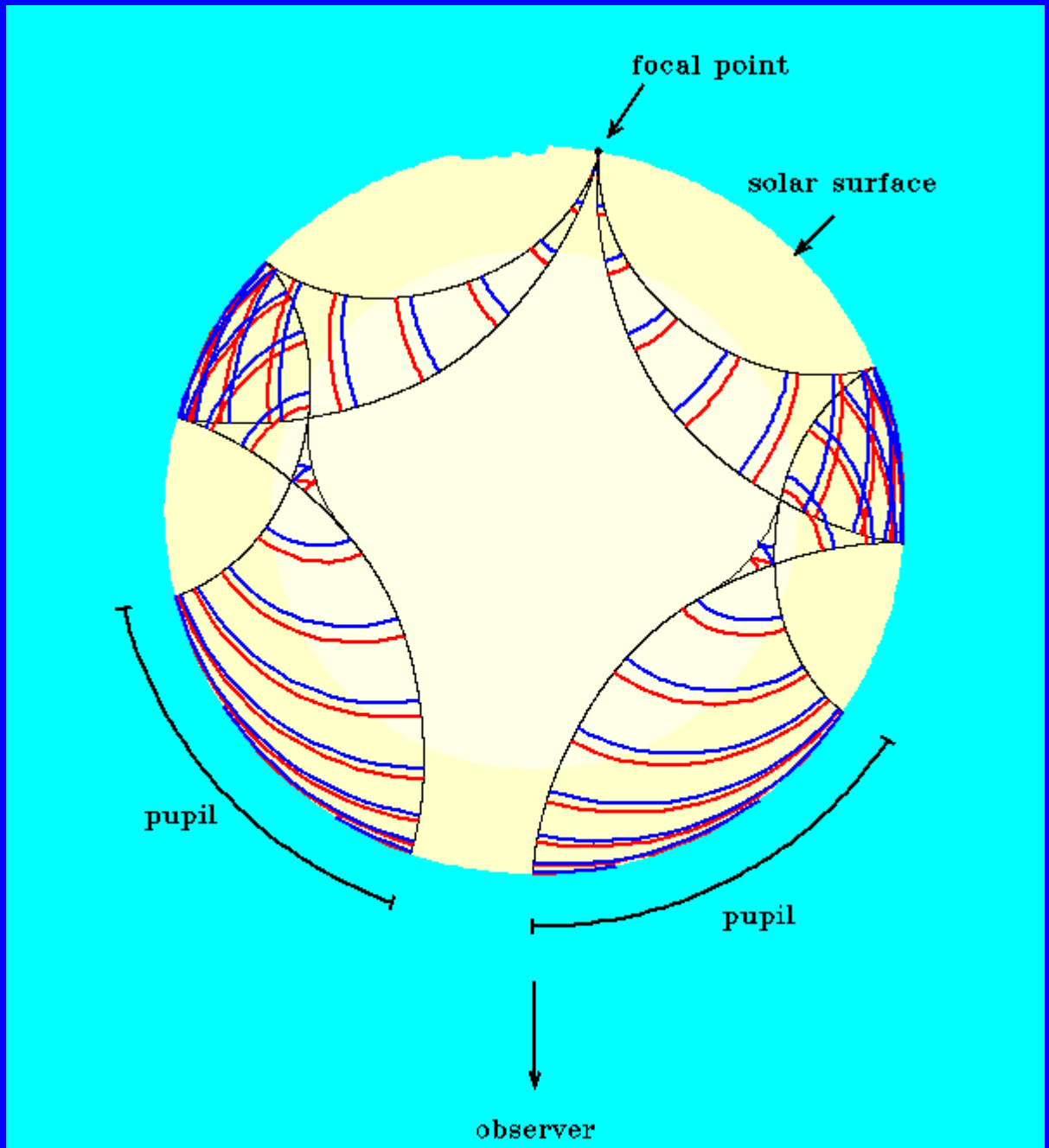
understanding the showerglass

w/ H. Schunker, P. Cally (Monash U.)

- arg(C_-) depends on magnetic field inclination w.r.t. vertical and line-of-sight
- observed as azimuthal variation of phase in penumbra close to limb
- hope to model in terms of slow-mode conversion



farside imaging

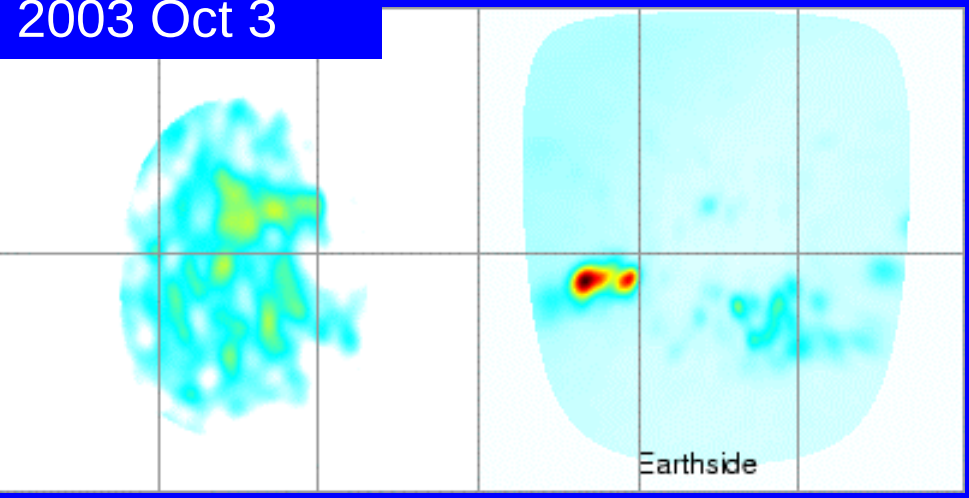


2004 March 25

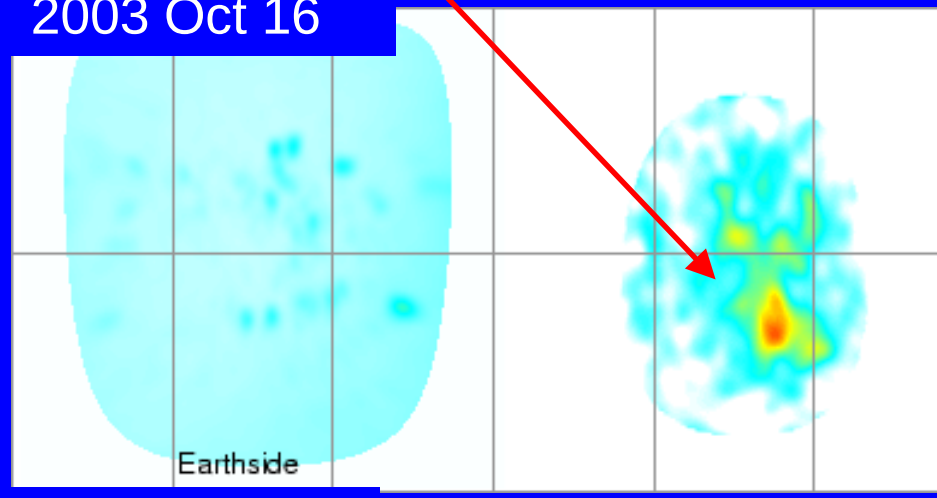
AR 486

first appeared on farside

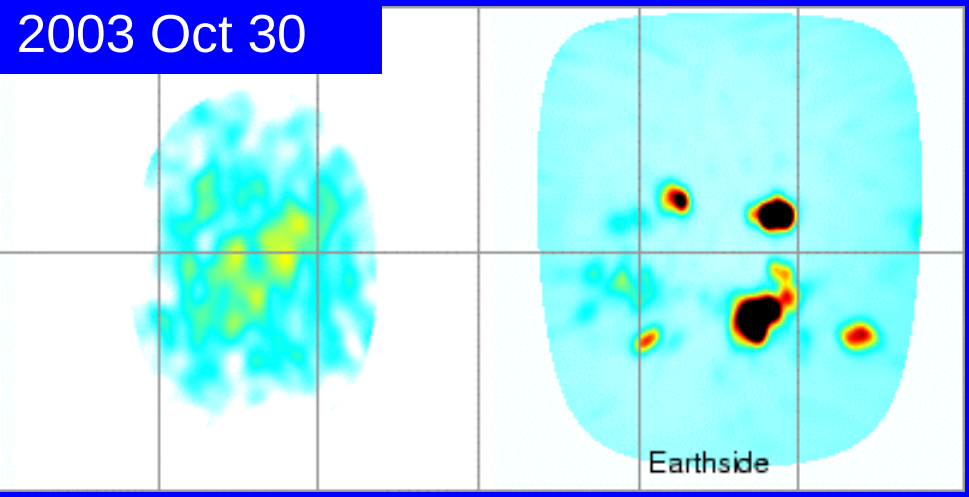
2003 Oct 3



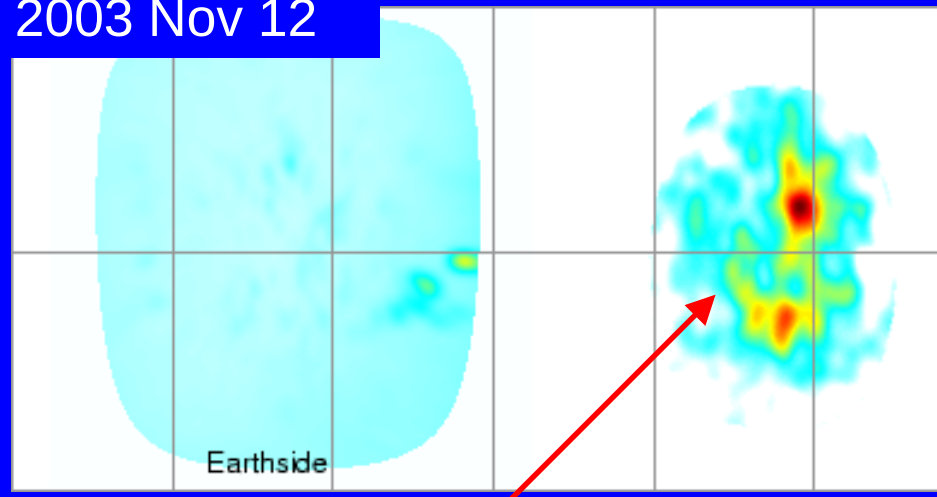
2003 Oct 16



2003 Oct 30



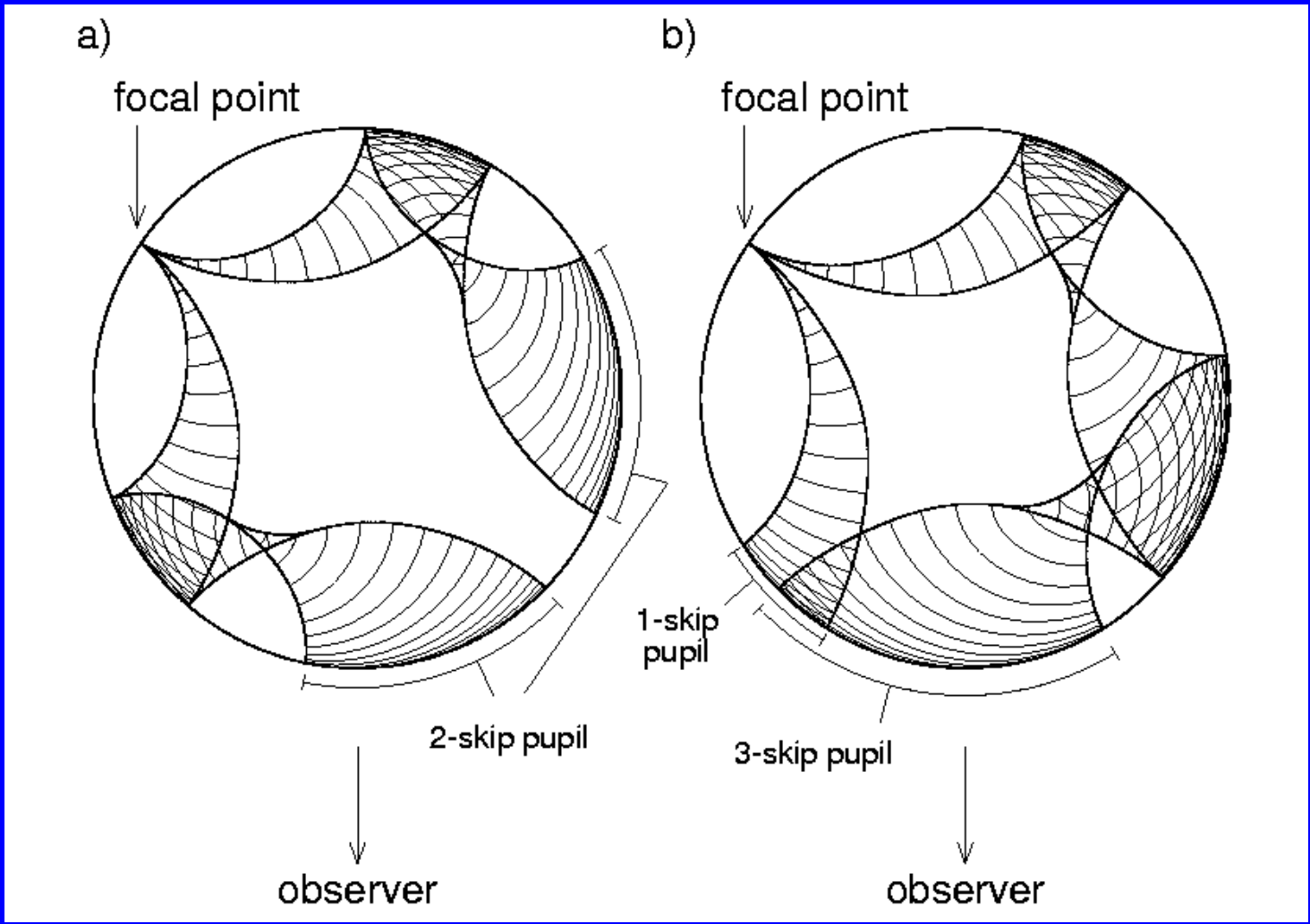
2003 Nov 12



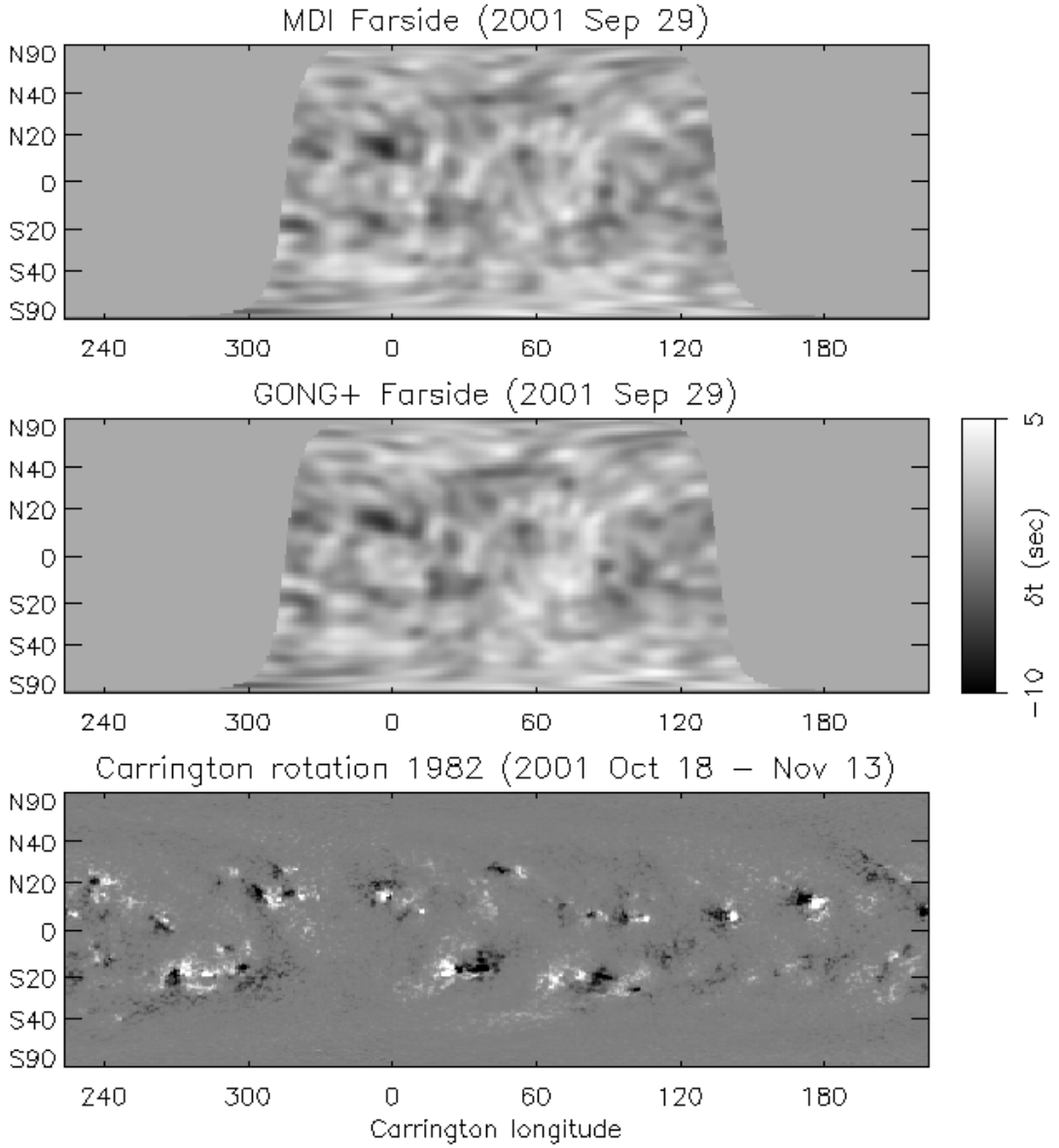
ARs 486,488 on farside

http://soi.stanford.edu/data/farside

increasing coverage of farside imaging

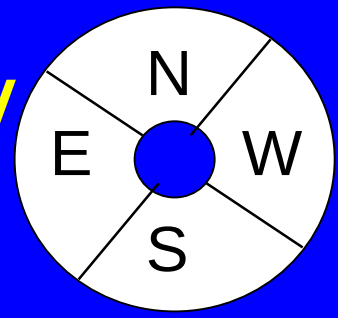


Braun & Lindsey (2001, *ApJ*, **560**, L189)



GONG+ to provide near real-time full-hemisphere farside imaging (see poster in session 4B; Braun, et al.)

Doppler-sensitive holography



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:

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

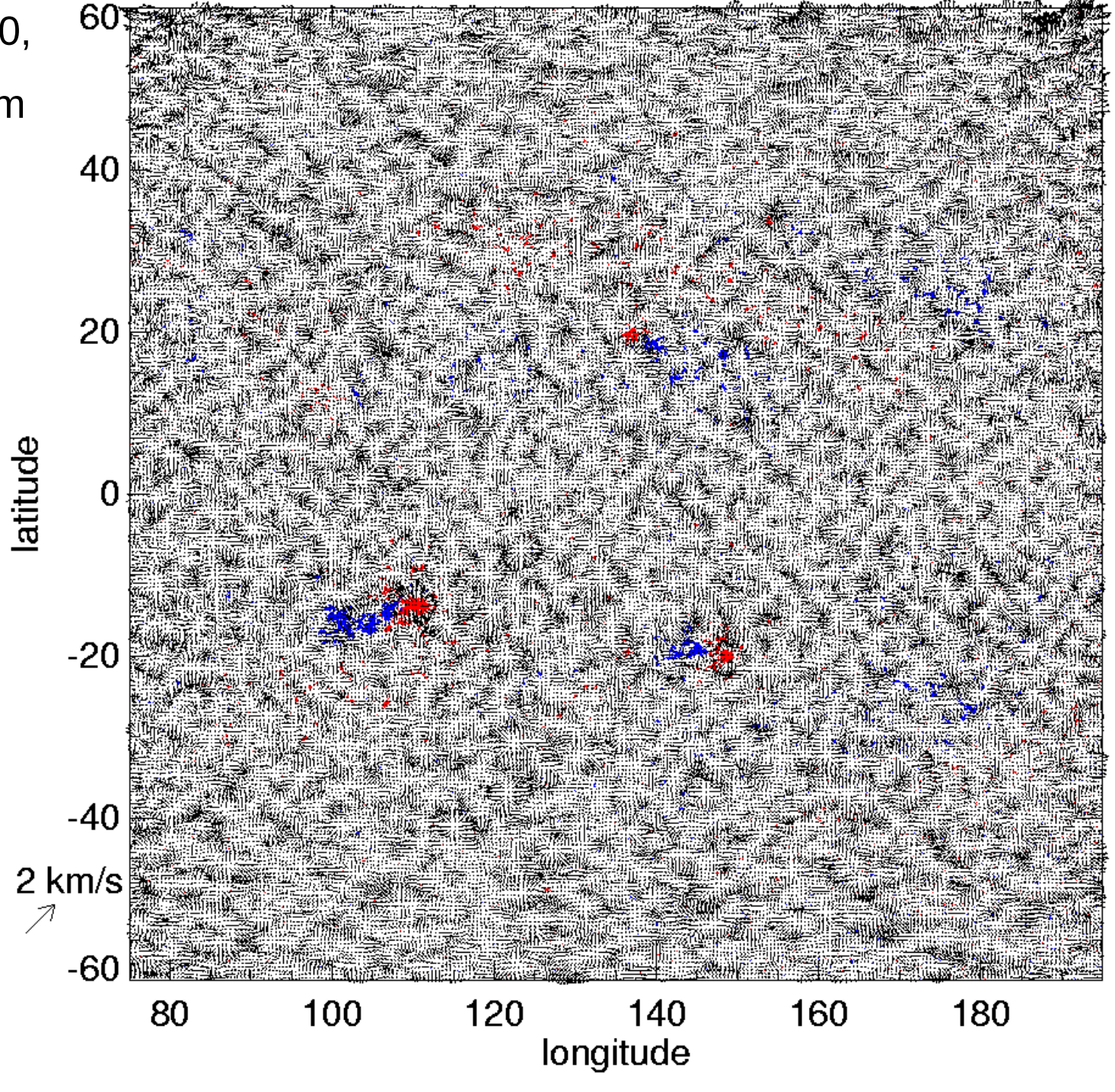
$$\phi^{E\to W} = \arg\left(\left\langle C^{E\to W}\right\rangle_{\Delta\nu}\right)$$

velocity:

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

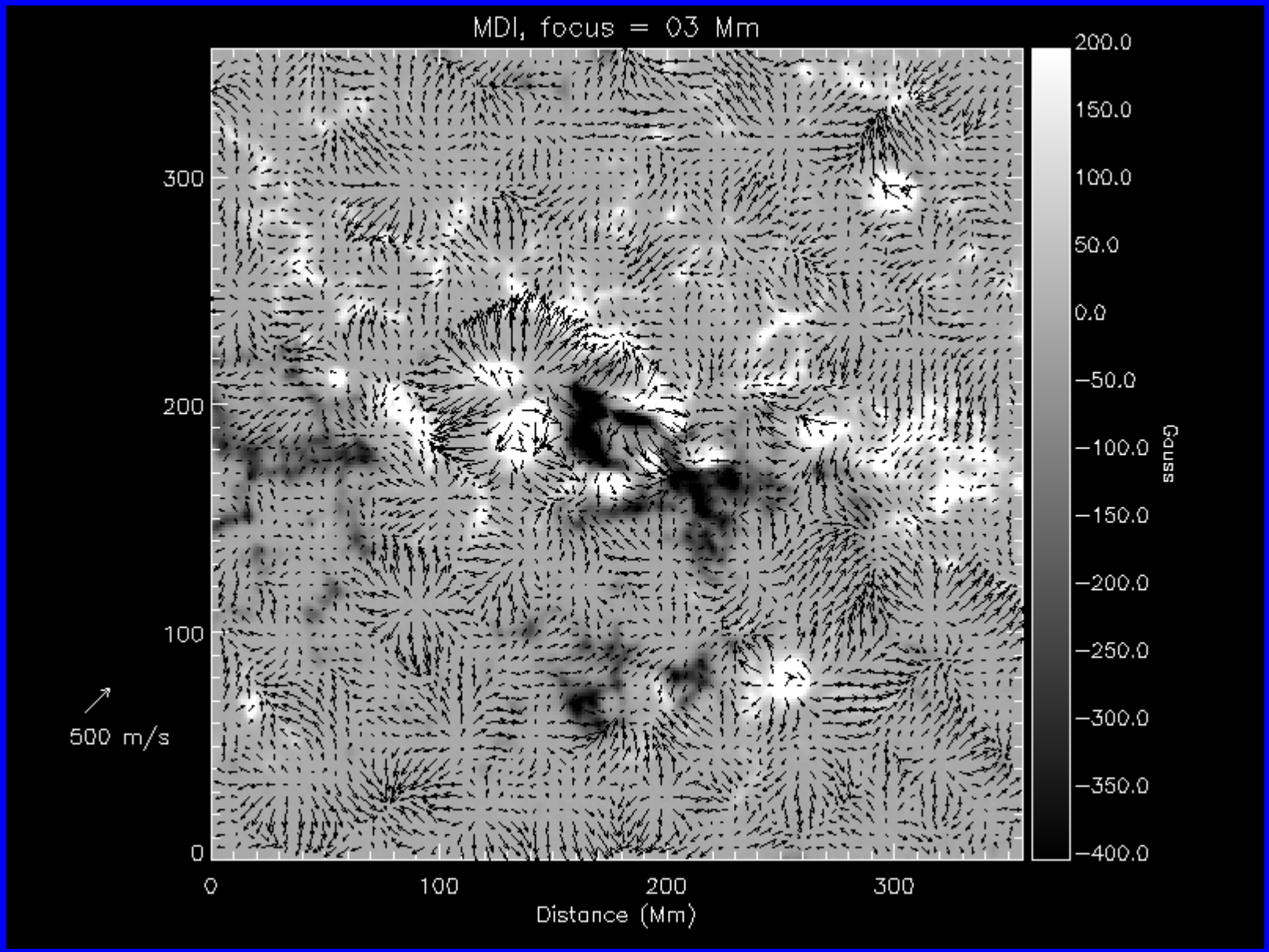
1999 April 20,

focus = 3 Mm

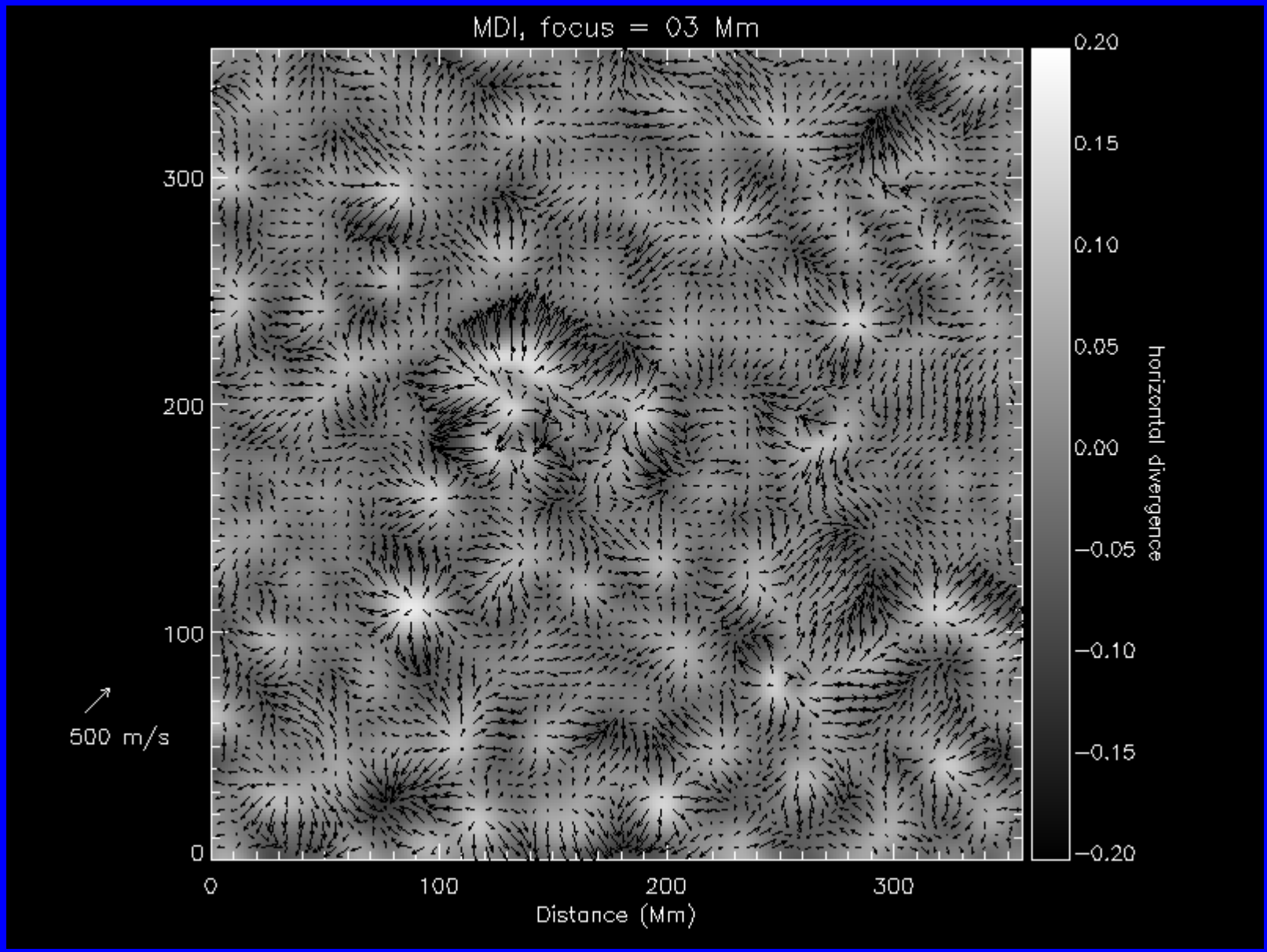


holography of solar dynamics

- nature and depth of supergranulation
- temporal variations of meridional circulation
- other large-scale flows and ARs
- acoustic properties of tachocline

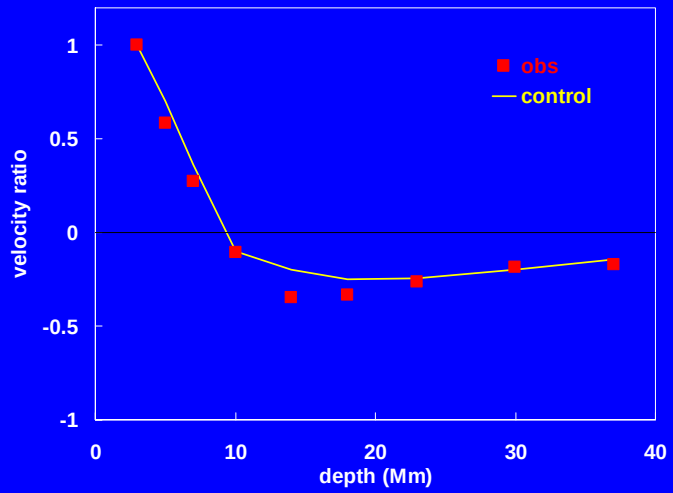

MDI, focus = 03 Mm
300
200
100
0
0
100
200
300
Distance (Mm)
500 m/s
200.0
150.0
100.0
50.0
0.0
−50.0
−100.0
−150.0
−200.0
−250.0
−300.0
−350.0
−400.0
Gauss

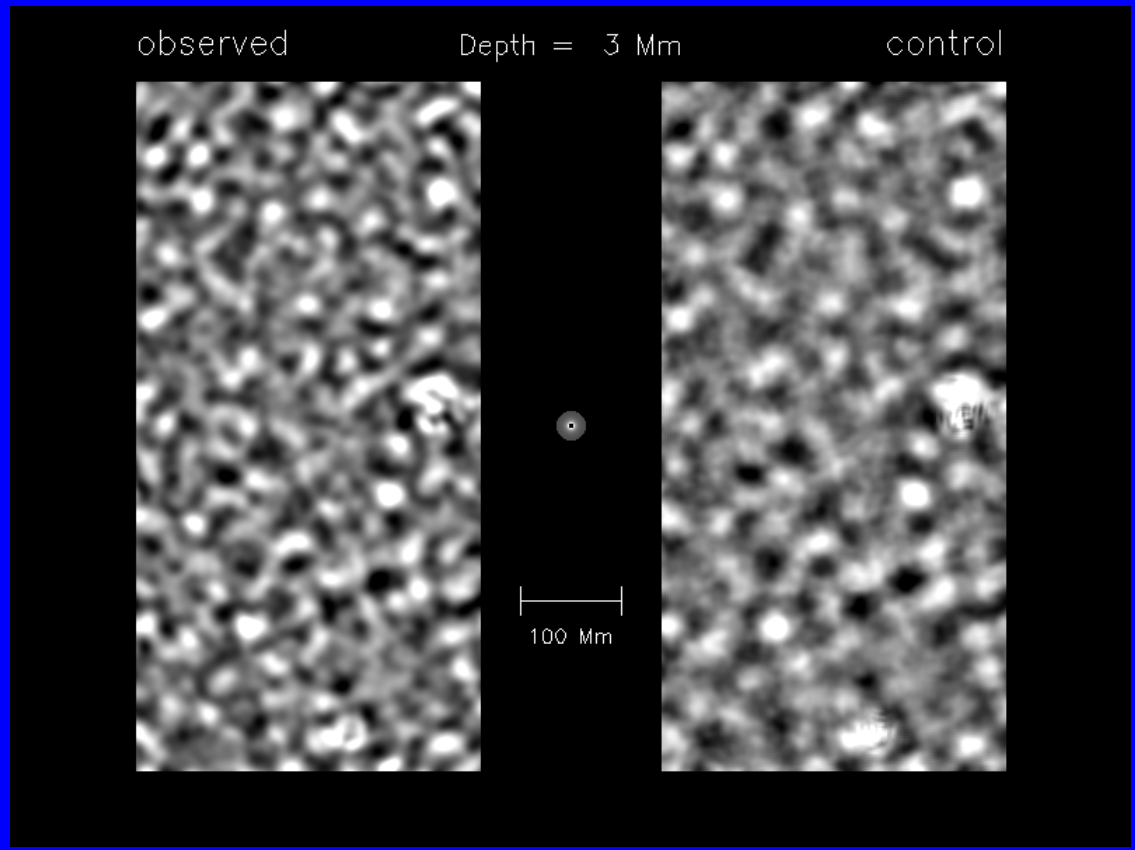
anticorrelation of flow patterns between 3 and 14 Mm?



observations are consistent with control model of *superficial* SG flows

(Braun and Lindsey 2002, *SOHO 12 proceedings*)





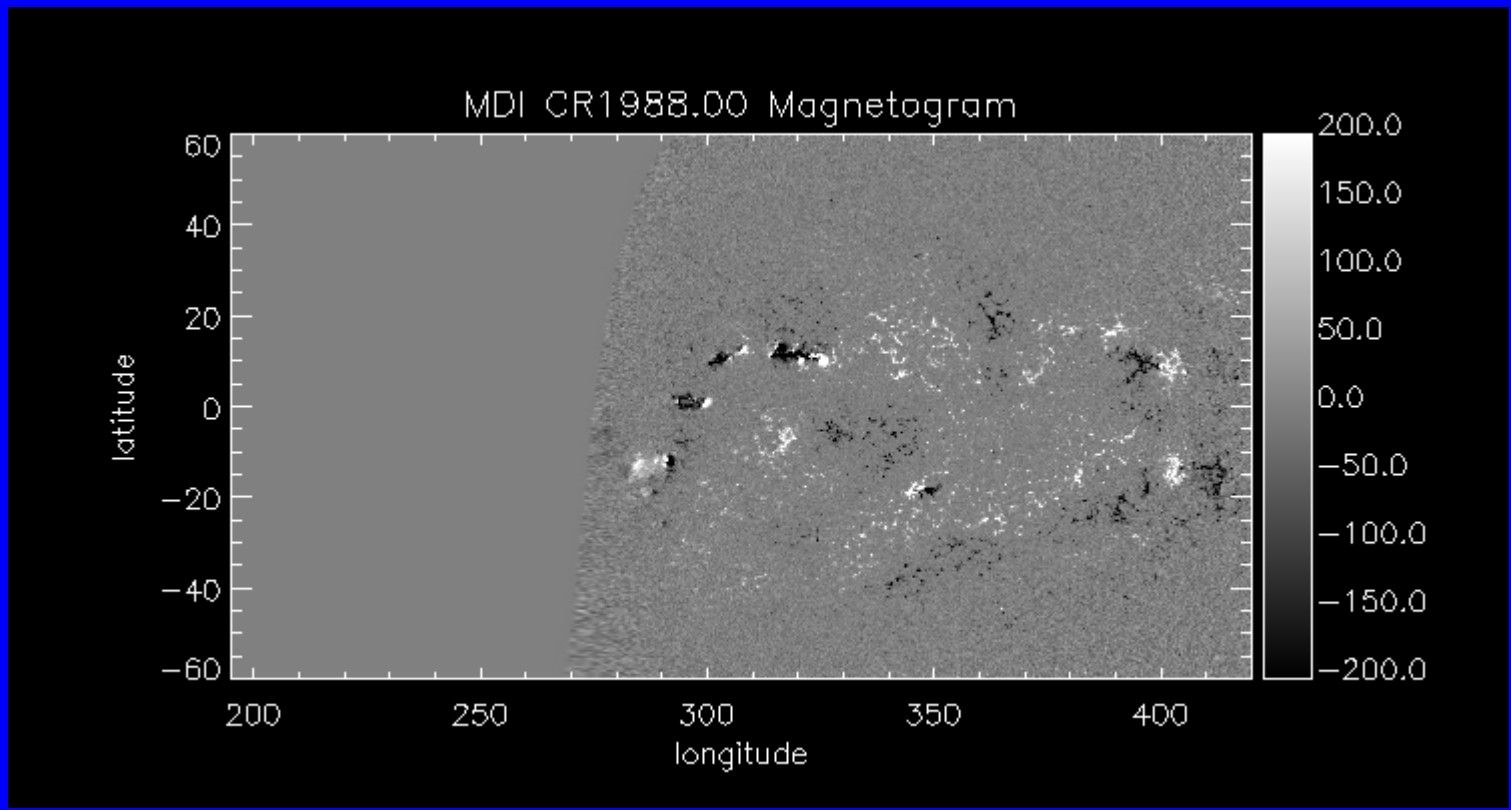
horizontal velocity divergence movie

bright=outflow, dark=inflow

sequence of 8 days, compared with magnetogram at start & end

flows averaged over 4° patches

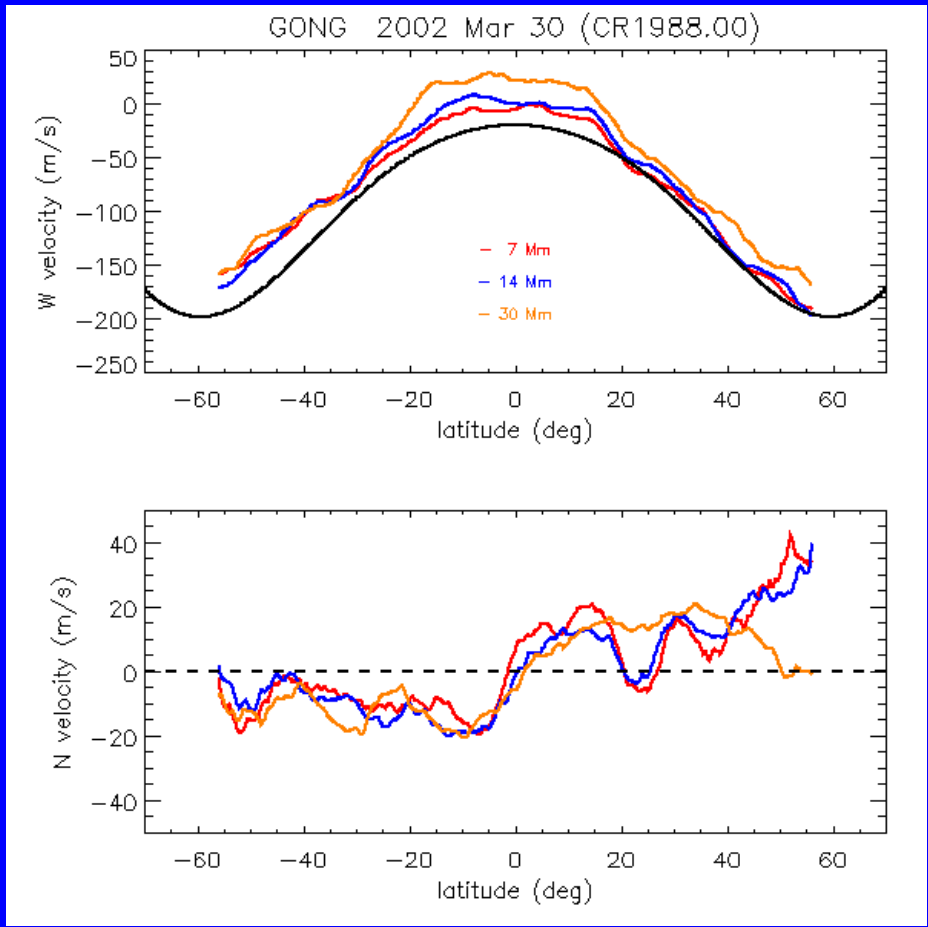
large spot groups show outflows, other ARs are inflows



longitude-averaged flows

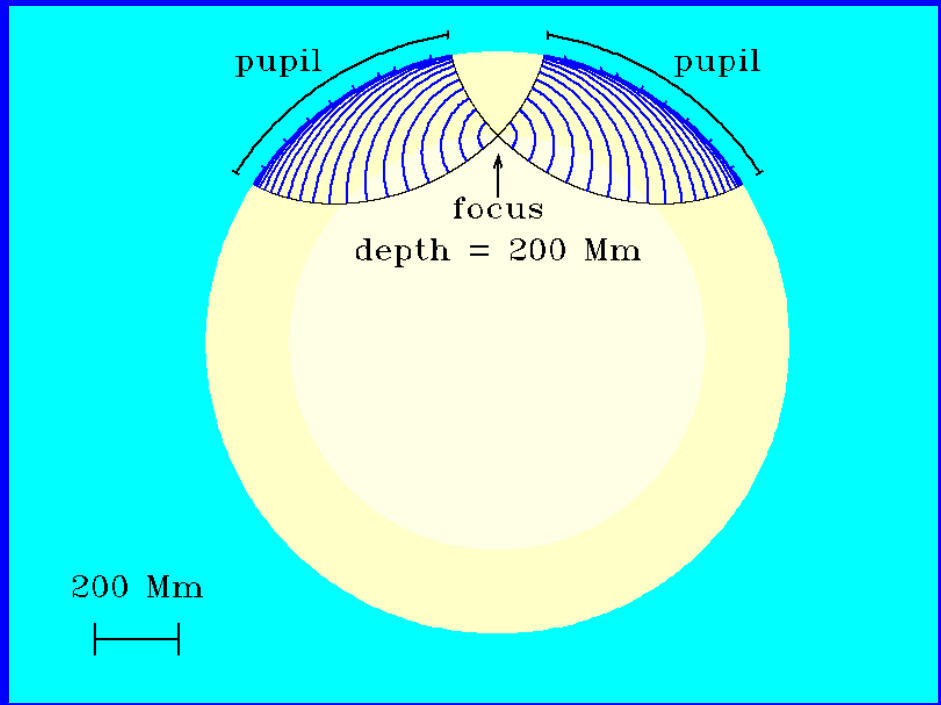
differential rotation

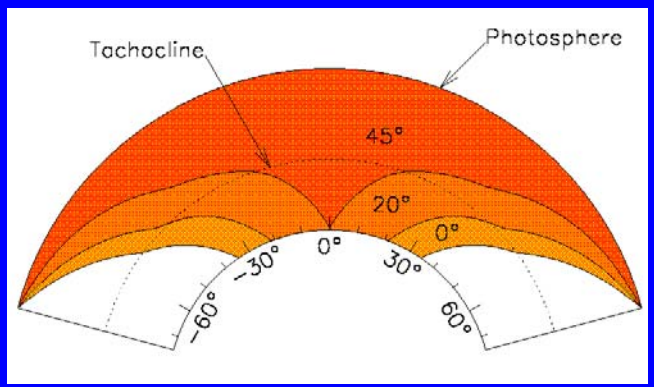
meridional flow



probing the tachocline and below

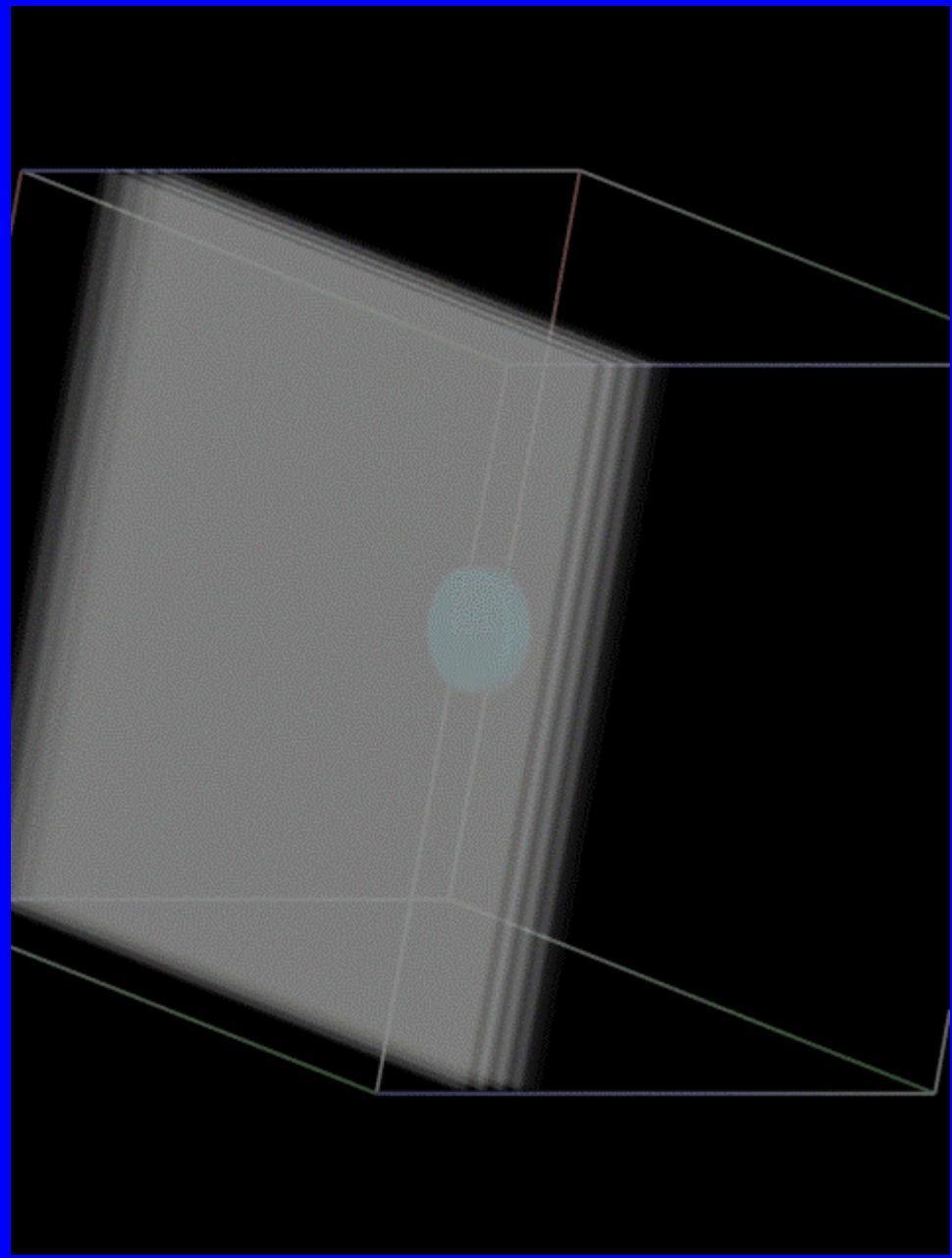
- coverage limited using single-skip correlations
- beyond *SDO*/HMI: farside seismic observations?





hare and hound exercises

- goal: compare and test local seismic analyses and inversions on artificial simulations
- extensive 3-D forward modeling by simulated acoustic propagation being proposed by several groups, e.g:
  - Mansour & Kosovichev (Stanford) - large-scale CZ simulations, etc.
  - Werne & Julien (NWRA,CU) - local, imposed perturbations, etc.



further information:

cora.nwra.com/~dbraun (holography, publications)

soi.stanford.edu/data/farside (farside synoptic program)

acknowledgments:

data: SOI-MDI (*SOHO),* P. Scherrer, et al.

GONG+, J. Leibacher, et al.

support: NASA (LWS and SR&T programs)

NSF (SAA program)