

Local Helioseismic Inferences of Sub-surface Magnetism and Dynamics

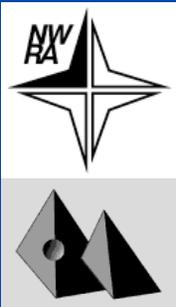
Doug Braun

NWRA / CoRA

With input from: A.-C. Donea¹, C. Lindsey², A.
Birch²

¹Monash U. / CSPA (AUS)

²NWRA / CoRA

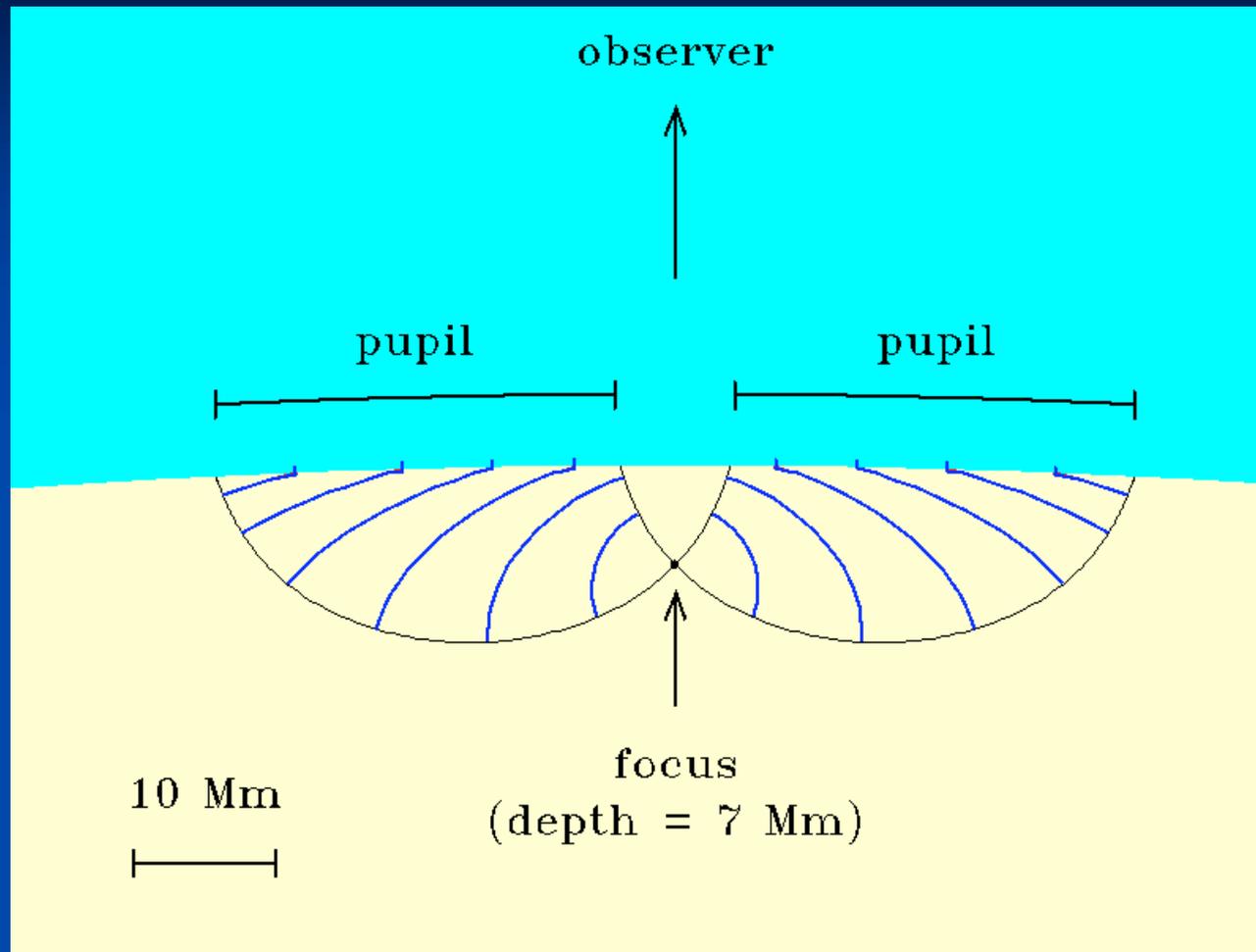


*NorthWest Research Associates, Inc.
Colorado Research Associates Division*

outline

- Acoustic egression from flares
- Farside imaging
- Flows (near surface; around ARs)
 - time-averaged properties (div, vort)
 - Time evolution of AR 9906, 10486 , 10488
- supergranulation (time permitting)

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

egression signatures from flares

- X2.6 flare of 1996 July 9
 - Ripples observed by Kosovichev & Zharkova (1997)
 - Subsequently “imaged” by holography by Donea, Braun & Lindsey (2000)
- (almost) All X-class flares observed by MDI have been analyzed by **Besilu & Donea**:
 - **12+ NEW sun-quakes discovered**
 - **~20 negative results** (does not include those unfavorably positioned for seismic analysis)
- M-class survey in progress (**3 detections so far**)

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Seismic radiation from solar flares

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Charlie Lindsey
Colorado Research Associates Division,
NorthWest Research Associates
Boulder

Helioseismic holography is a technique used to image the sources of seismic disturbances observed at the solar surface. It has been used to detect acoustic emission, known as sun quakes, radiated from three X-class solar flares. The detection of seismic waves from powerful flares has opened a new and promising connection between helioseismology and flare physics. To understand the physics of the acoustic radiation responsible for sun quakes we have undertaken a systematic survey covering a large number of X-class solar flares observed by SOHO-MDI. We will present a statistical study of the solar quakes detected so far.

We will address questions such as:

- Why are some large flares acoustically active while most are acoustically inactive?
- Is photospheric heating by high-energy protons a major factor in seismic emission from flares?
- What is the effect of magnetic fields in flare acoustics?

SQ = SEISMIC RADIATION SOURCE QUAKE

Year	Month	Day	AR	LO	BO	Begin (UT)	Max (UT)	End (UT)	Type	Observations	Proton Event	White Flare	SQ Begin (UT)	SQ Max (UT)	SQ End (UT)	Seismic Energies 3 mHz (erg)	Seismic Energies 6 mHz (erg)	GOES Xray (J/m ²)
1996	7	9	7978	248.5	-10.5	09:01	09:12	09:49	X 2.6	First sunquake discovered by Kosovichev; its acoustic source detected by A.C.Donea & C. Lindsey	-	-	09:01	09:13	09:19	7.50E+27	8.90E+26	7.30E-02
1997	11	4	8100	-	-	05:52	05:58	06:02	X 2.1	No data	X	-	-	-	-	-	-	5.60E-02
1997	11	6	8100	-	-	11:49	11:55	12:01	X 9.4	HR centred on another AR	X	-	-	-	-	-	-	3.60E-01
1997	11	27	8113	-	-	12:59	13:17	13:20	X 2.6	Not enough data	-	-	-	-	-	-	-	7.00E-02

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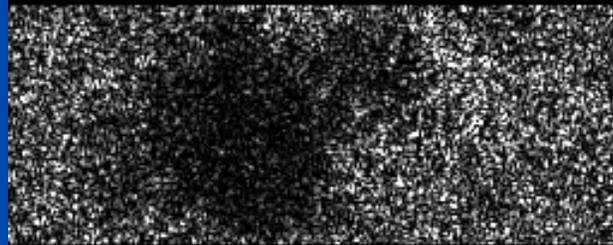
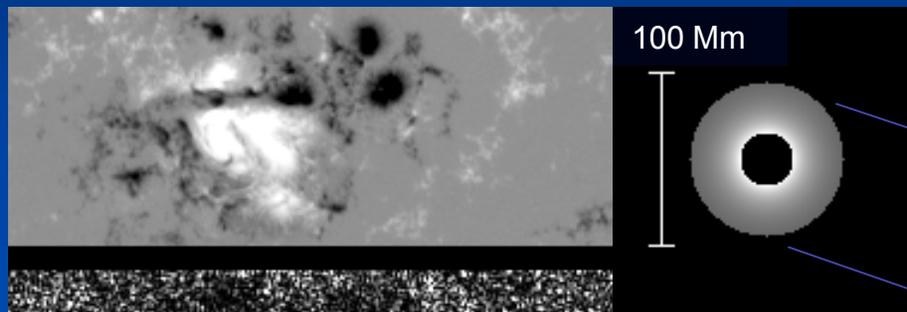
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2003	10	28	10486	288	-19	09:51	11:10	11:24	X 17.2	SQ discovered by A.C.Donea&C.Linsday	X	-	11:00	11:07	11:12	1.00E+27	9.40E+26	1.80E+00
2003	10	29	10486	288	-19	20:37	20:43	21:01	X 10	SQ discovered by A.C.Donea&C.Linsday	-	-	20:35	20:43	20:50	1.10E+27	2.70E+26	8.70E-01
2003	11	2	10486	-	-	17:03	17:25	17:39	X 8.3	At the limb	-	-	-	-	-	-	-	9.10E-01
2003	11	3	10486	-	-	01:09	01:30	01:45	X 2.7	At the limb	-	-	-	-	-	-	-	3.60E-01
2003	11	3	10486	-	-	09:43	09:55	10:19	X 3.9	At the limb	-	-	-	-	-	-	-	5.60E-01
2003	11	4	10486	-	-	19:29	19:50	20:06	X 28	After the limb	X	-	-	-	-	-	-	2.30E+00
2003	11	20	10501	2	360	07:35	07:47	07:53	M 9.6	In progress	-	-	-	-	-	-	-	6.00E-02
2004	2	26	10564	-	-	01:50	02:03	02:10	X 1.1	No data	-	-	-	-	-	-	-	7.00E-02
2004	7	15	10649	42	-10	01:30	01:41	01:48	X 1.8	Negative	-	-	-	-	-	-	-	8.50E-02
2004	7	15	10649	42	-10	18:15	18:24	18:28	X 1.6	Negative	-	-	-	-	-	-	-	4.90E-02
2004	7	16	10649	44	-10	01:43	02:06	02:12	X 1.3	Negative	-	-	-	-	-	-	-	6.20E-02
2004	7	16	10649	44	-10	10:32	10:41	10:46	X 1.1	Negative	-	-	-	-	-	-	-	4.00E-02
2004	7	16	10649	44	-10	13:49	13:55	14:01	X 3.6	SQ	-	-	13:48	13:56	14:01	7.31E+26	3.06E+25	1.40E-01
2004	7	17	10649	44	-10	07:51	07:57	07:59	X 1	Negative	-	-	-	-	-	-	-	2.20E-02
2004	8	13	10656	88	-14	18:07	18:12	18:15	X 1	SQ	-	-	18:07	18:10	18:16	0	1.02E+25	2.70E-02
2004	8	15	10656	85	-14	12:34	12:41	12:43	M 9.4	SQ	-	-	12:36	12:42	12:47	0	3.01E+26	2.20E-02
2004	8	18	10656	-	-	17:29	17:40	17:54	X 1.8	At the limb	-	-	-	-	-	-	-	1.80E-01
2004	10	30	10691	-	-	11:38	11:46	11:50	X 1.2	HR centred on quiet Sun	-	-	-	-	-	-	-	3.70E-02
2004	11	7	10696	26	8	15:42	16:06	16:15	X 2	Negative	X	-	-	-	-	-	-	2.00E-01
2004	11	10	10696	-	-	01:59	02:20	02:13	X 2.5	At the limb	-	-	-	-	-	-	-	1.60E-01
2005	1	1	10715	-20	4	00:01	00:31	00:39	X 1.7	In progress	-	-	-	-	-	-	-	9.20E-02
2005	1	15	10720	180	13	00:22	00:43	01:02	X 1.2	SQ	-	X	00:33	00:42	00:47	1.78E+27	9.50E+26	1.20E-01
2005	1	15	10720	-	-	22:25	23:02	23:31	X 2.6	Not enough data	X	-	-	-	-	-	-	6.30E-01
2005	1	17	10720	-	-	06:59	09:52	10:07	X 3.8	Not enough data	-	-	-	-	-	-	-	8.40E-01
2005	1	19	10720	-	-	08:03	08:22	08:40	X 1.3	Not enough data	-	-	-	-	-	-	-	2.20E-01
2005	1	20	10720	-	-	06:36	07:01	07:26	X 7.1	Not enough data	-	-	-	-	-	-	-	1.30E+00

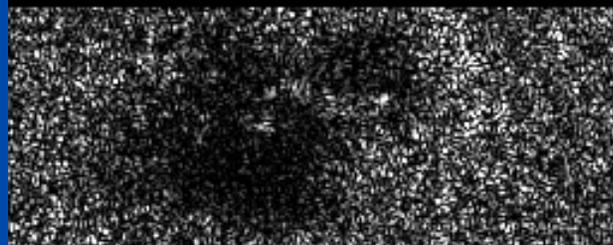
All Times are expressed in UT
L0/B0 Carrington Coordinates For AR

2003 Oct 28, X17 flare (AR 10486)

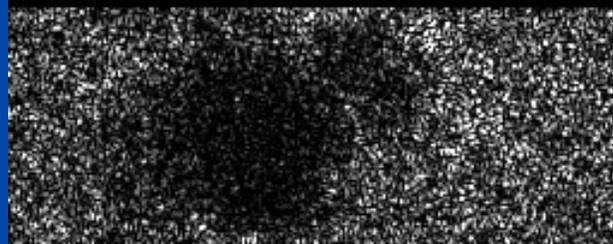
Donea & Lindsey 2005 ApJ (in press)



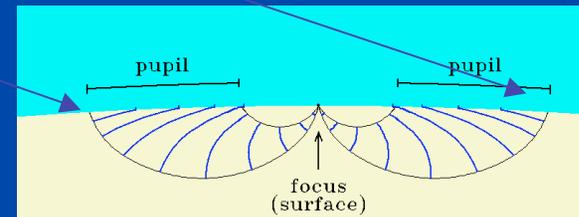
11:00 UT



11:10 UT



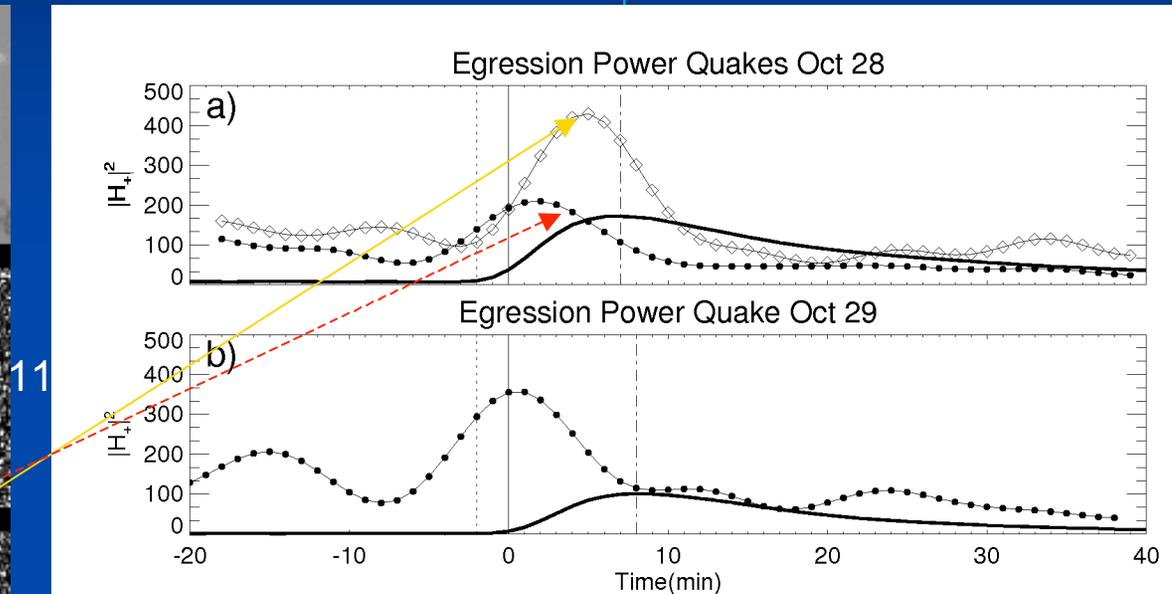
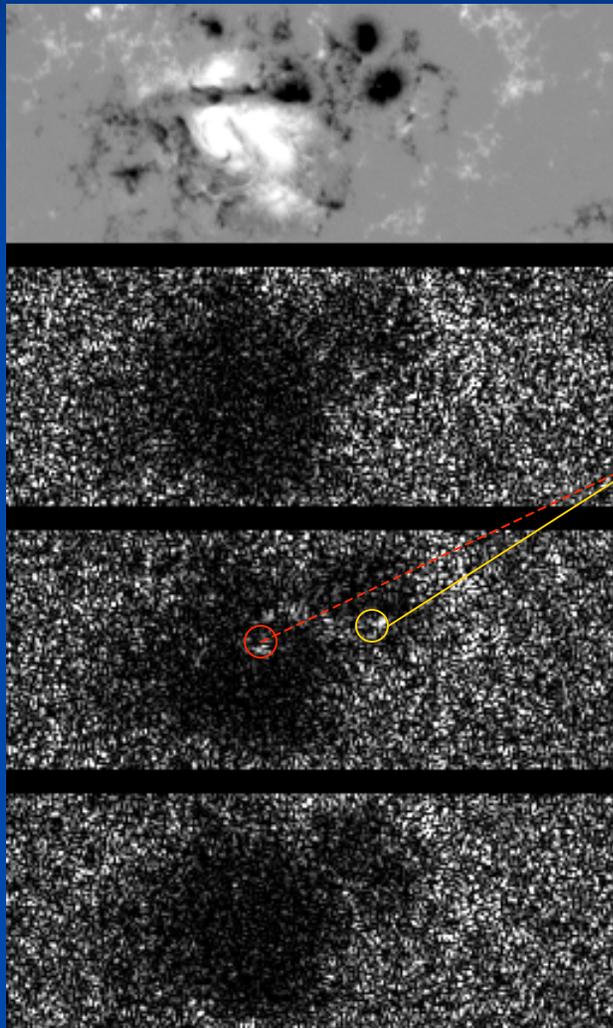
11:25 UT



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

2003 Oct 28, X17 flare (AR 10486)

GOES 10:peak X-ray flux



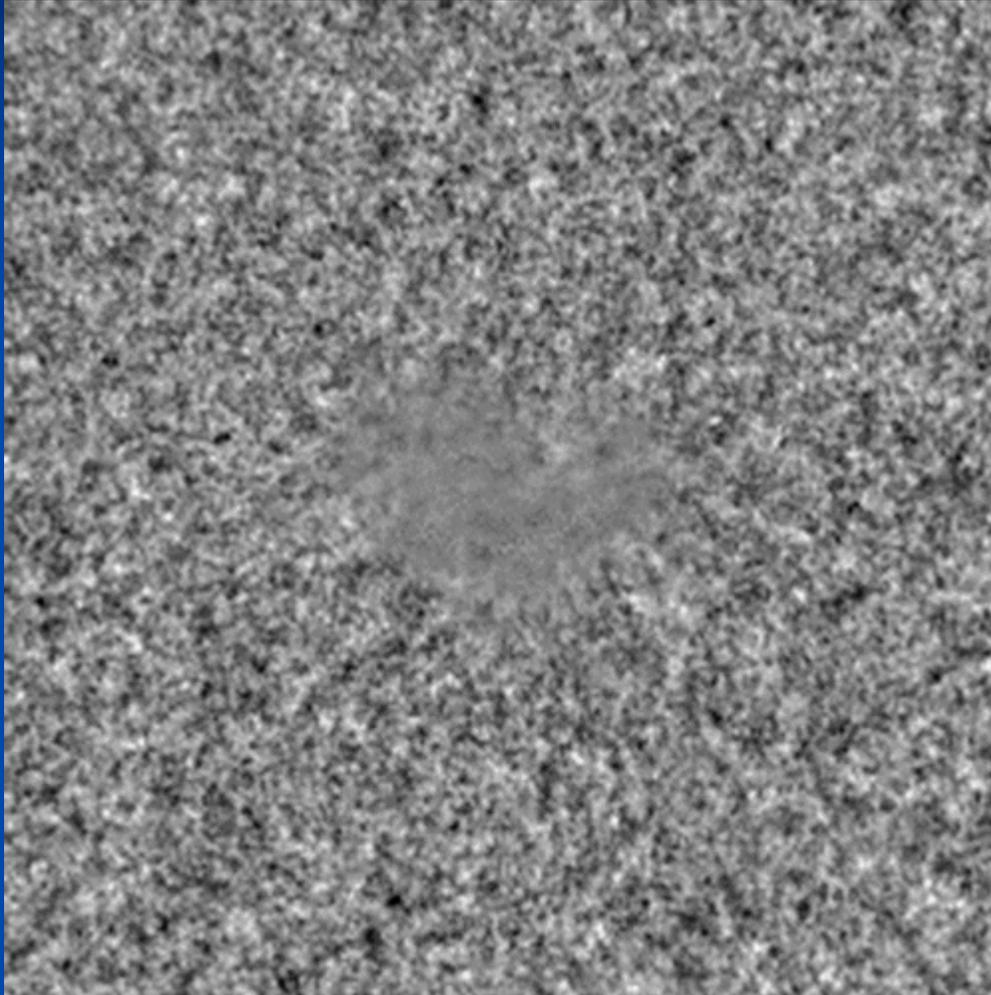
11

11:10 UT

5-7 mHz egression power

11:25 UT

AR 10720; raw (difference) images



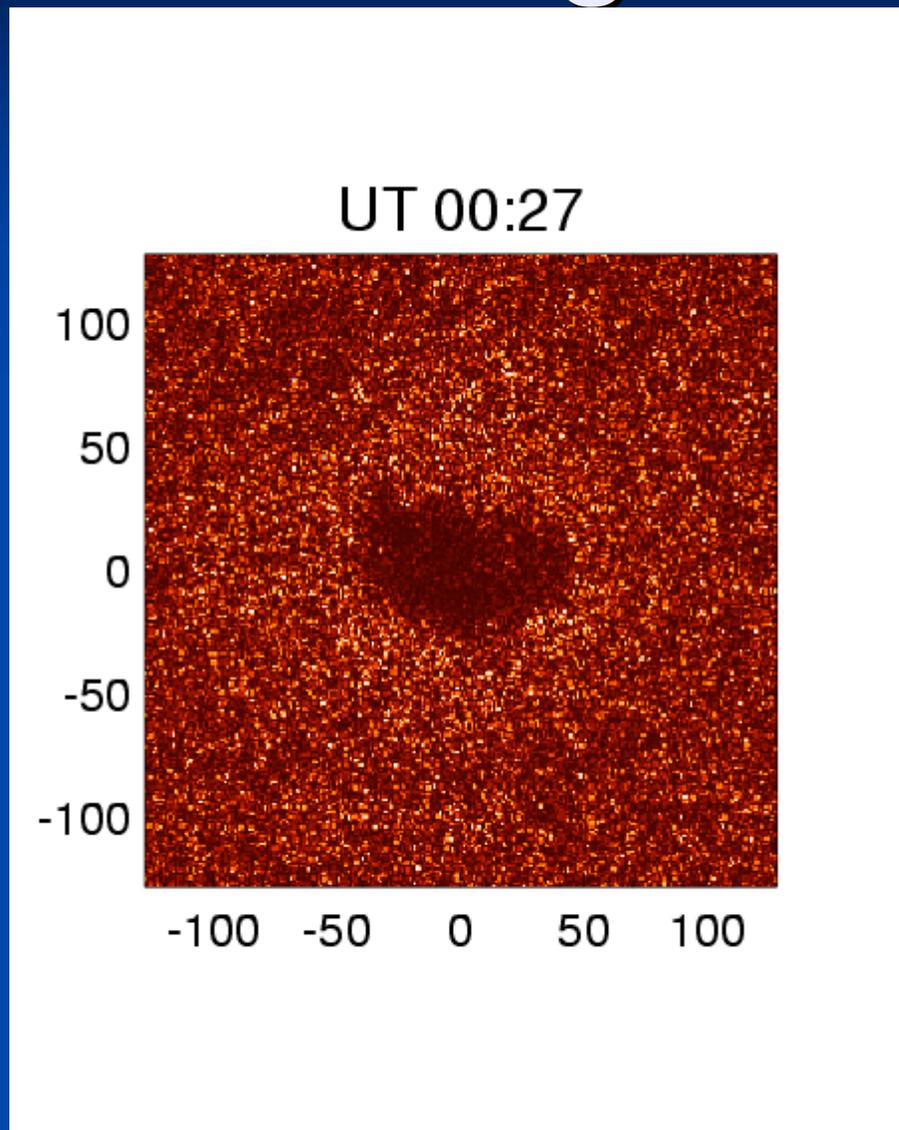
X1.2 flare: 2005 Jan 15

Like the original “sun quake” of 1996 (AR 7976), **shows rare “ripple” signature in minimally filtered (or raw) data.**

most *seismically* energetic flare known

movie courtesy A.-C. Donea

AR 10720 egression images



6mHz egression power (no observable egression signatures at other frequencies)

movie courtesy A.-C. Donea

goals of holographic flare studies

- understand why flares are so acoustically quiet?
- understand role of protons in acoustic emission
- “control source” in magnetic region for comparison with convection-driven p-mode propagation for probing subsurface of ARs

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

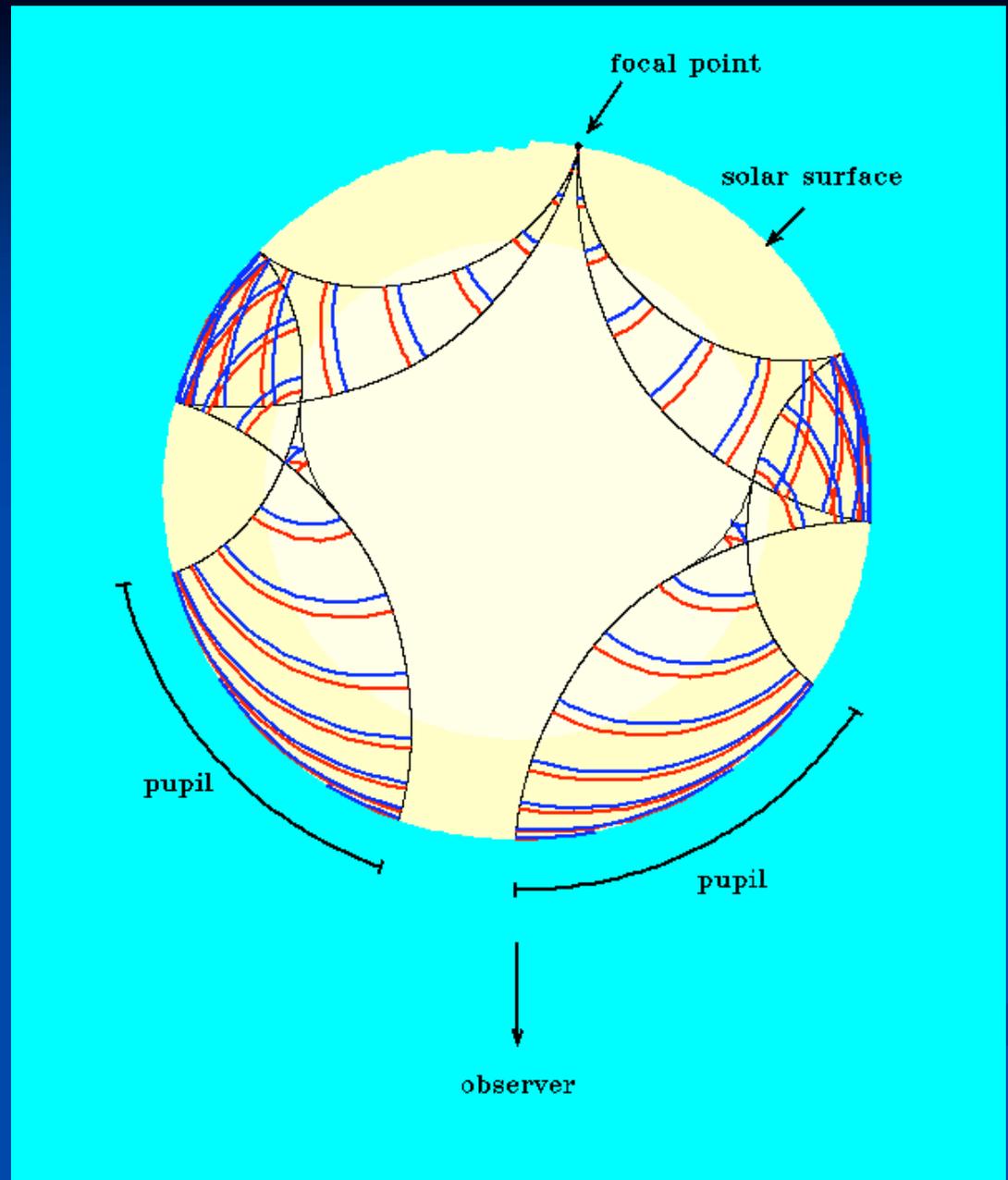
correlation phase: $\phi(\mathbf{r}, z) = \arg \left(\langle C(\mathbf{r}, z, \nu) \rangle_{\Delta\nu} \right)$

travel-time perturbation: $\delta t(\mathbf{r}, z) = \phi(\mathbf{r}, z) / 2\pi\nu_0$

sensitive to refractive perturbations at focus

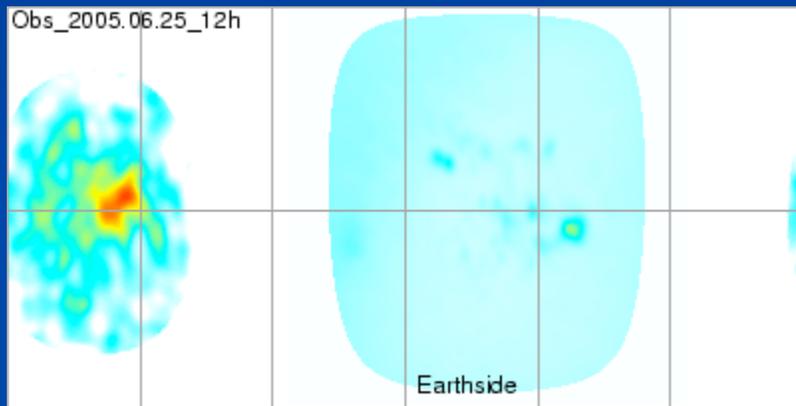
farside imaging with helioseismic holography

Lindsey & Braun 2000,
Science 287, 1799

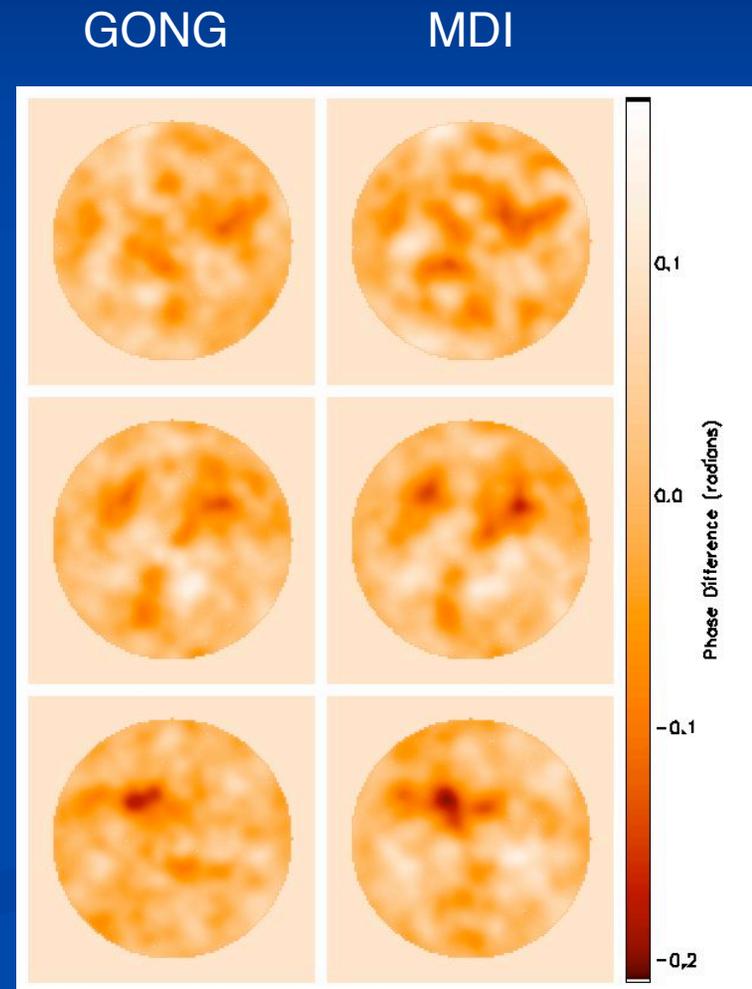


daily farside imaging websites:

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



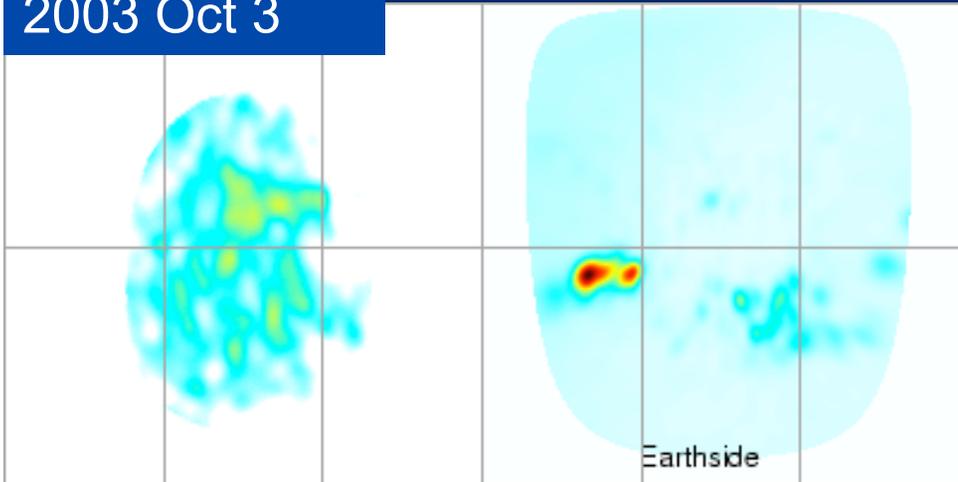
<http://gong.nso.edu/data/farside>



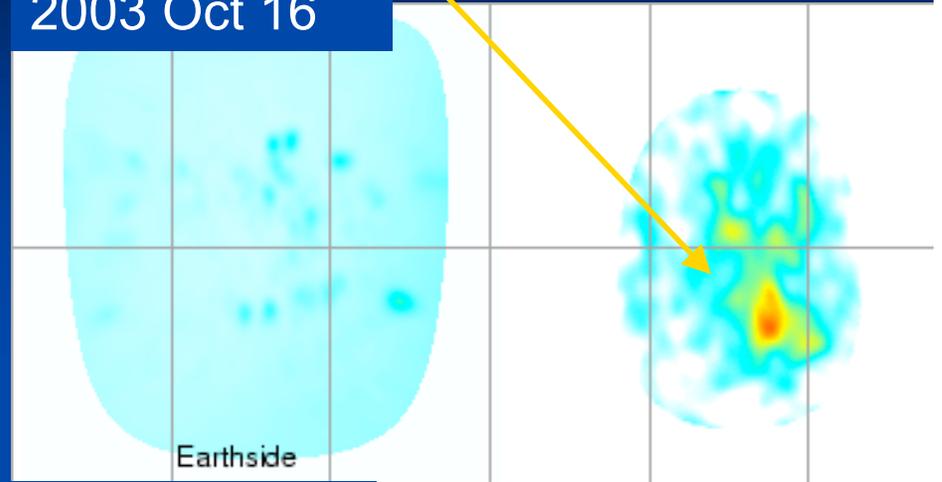
AR 10486

first appeared on farside

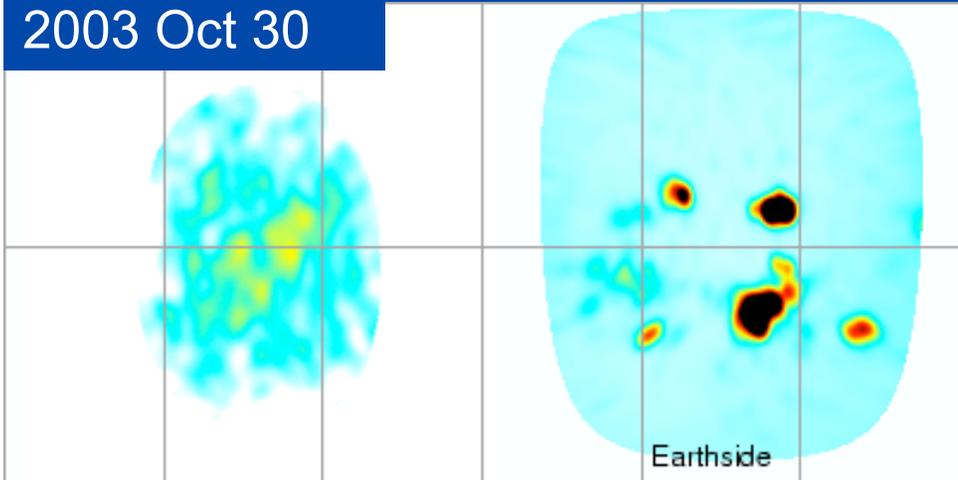
2003 Oct 3



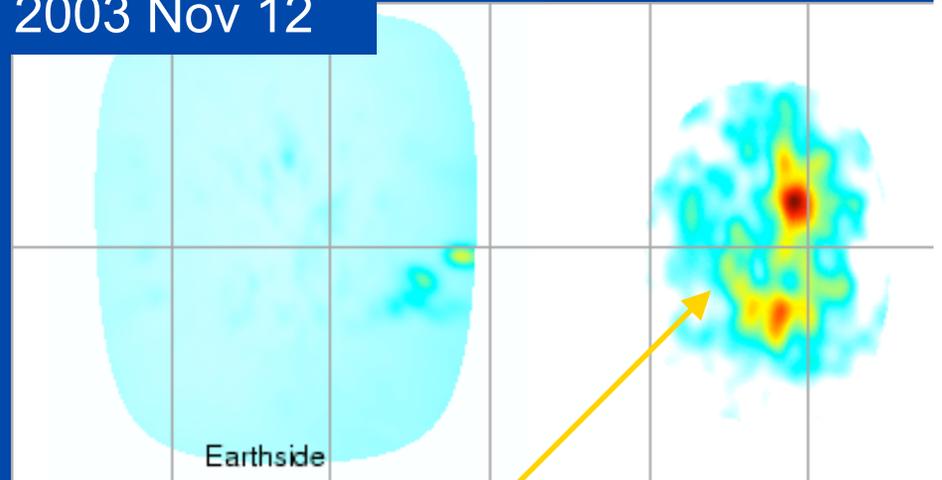
2003 Oct 16



2003 Oct 30

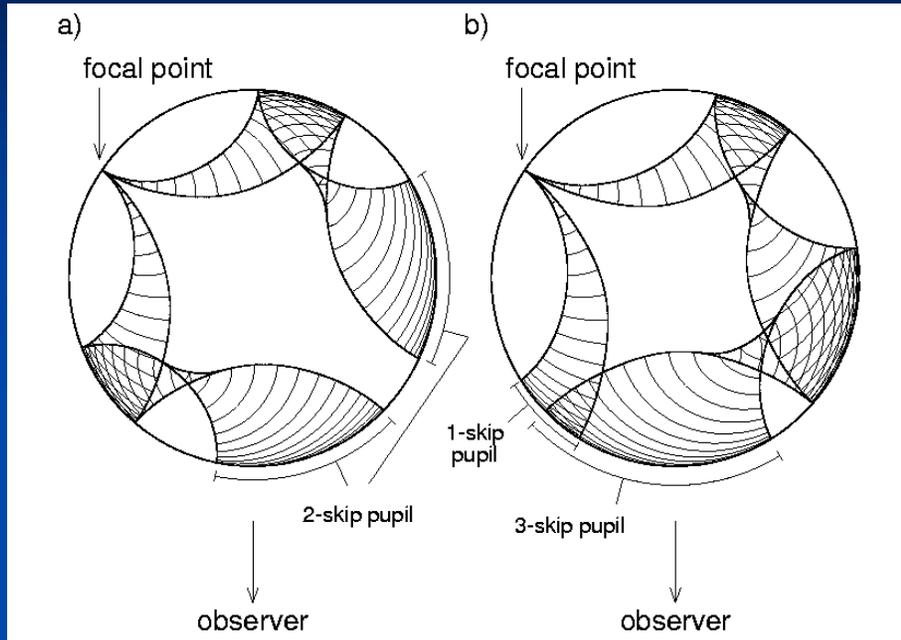


2003 Nov 12

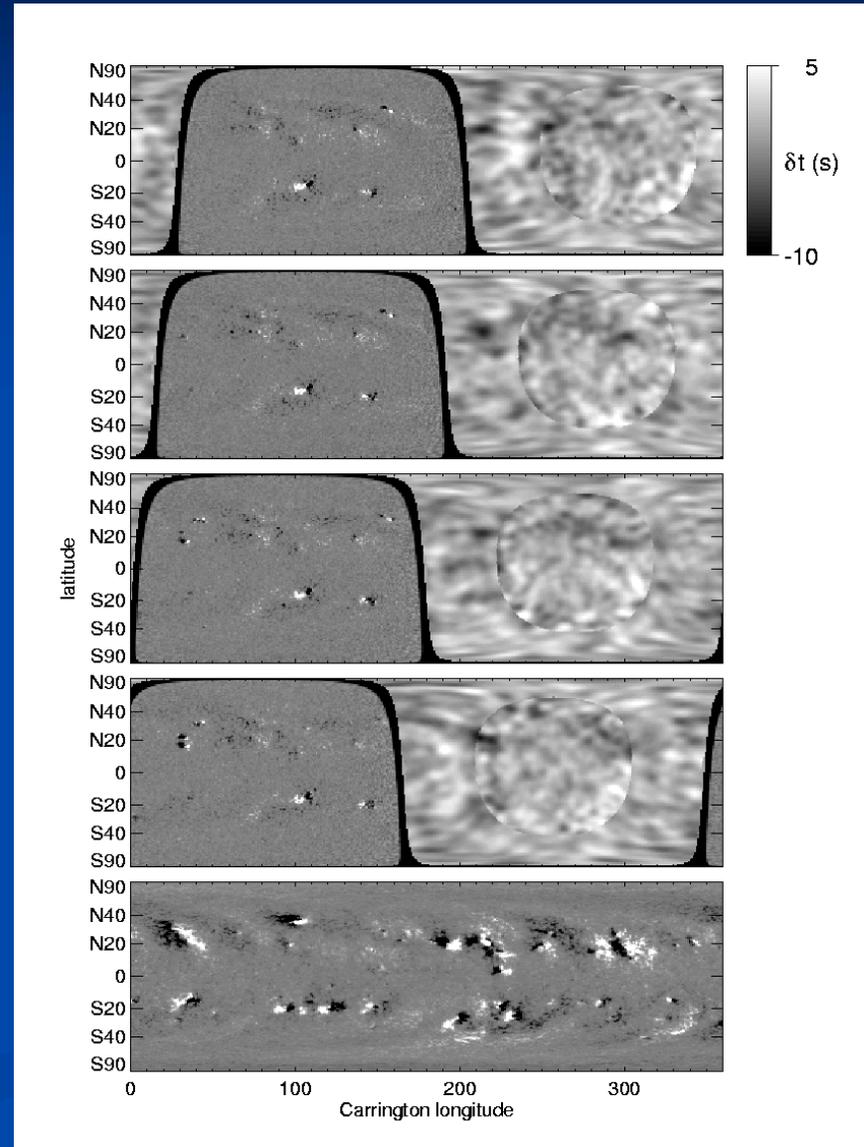


ARs 486,488 on farside

Imaging the full far hemisphere



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



flows

(near surface::; focus depth = 3 Mm)

- how we do this
- 5.8 day-average properties of flows for CR1988 (2002 Mar 30 – April 26)
- temporal variations in flows for:
 - AR 9906
 - AR10486, 10488
- supergranulation (time permitting)

phase-sensitive holography of flows



egressions and ingressions in 4 quadrants:

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

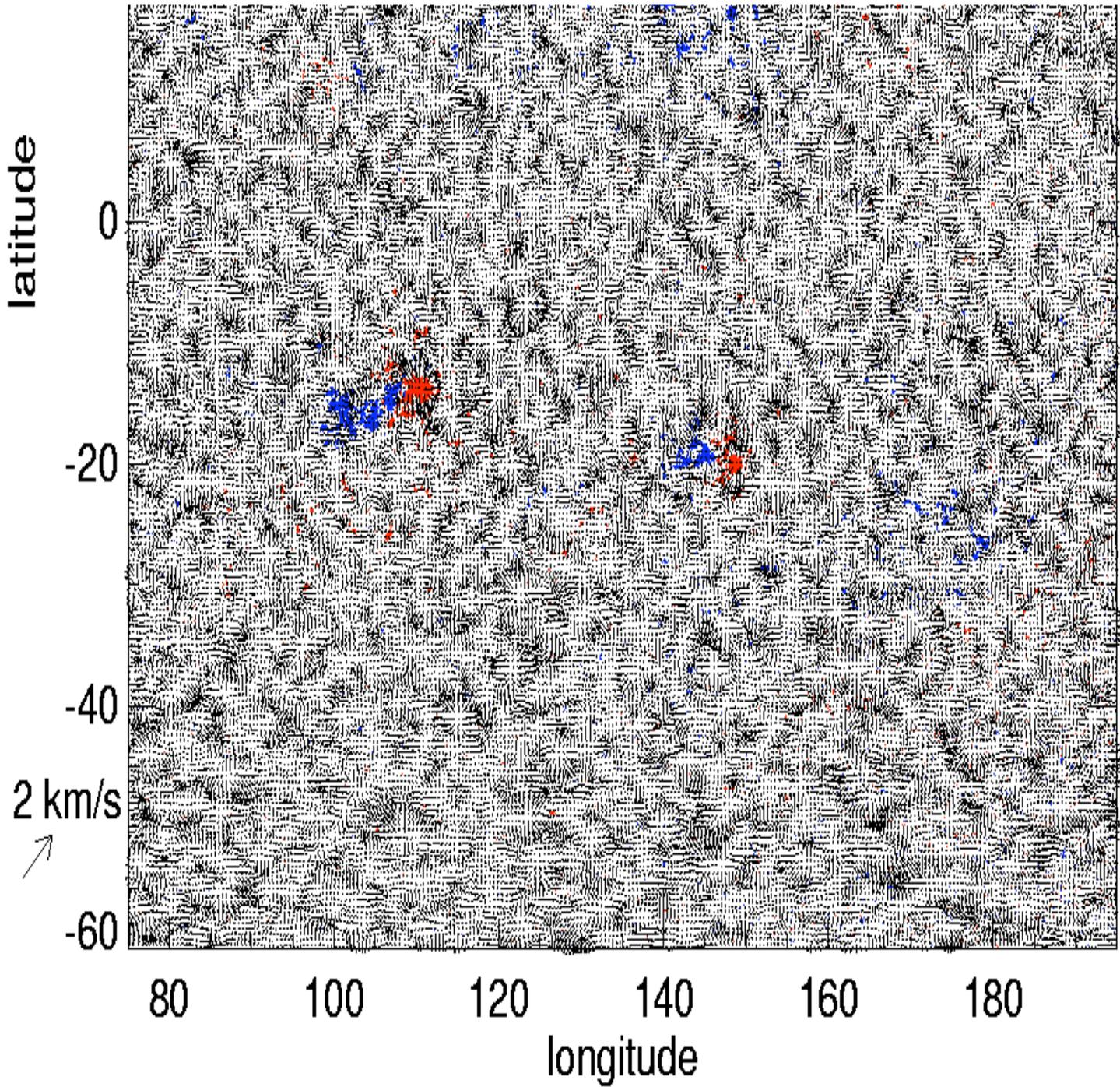
e.g. E-W correlation
phase:

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

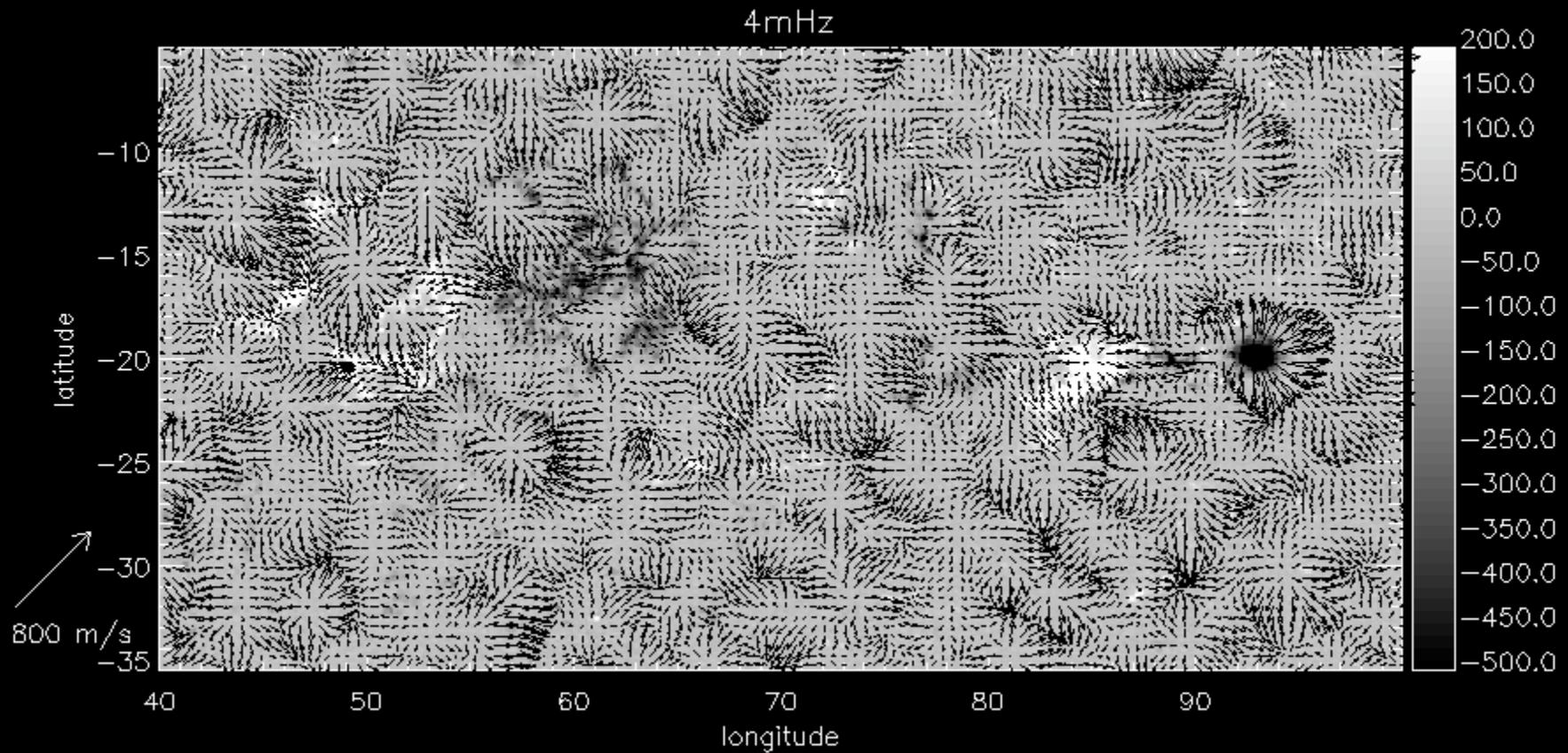
$$\phi^{E \rightarrow W} = \arg \left(\left\langle C^{E \rightarrow W} \right\rangle_{\Delta\nu} \right)$$

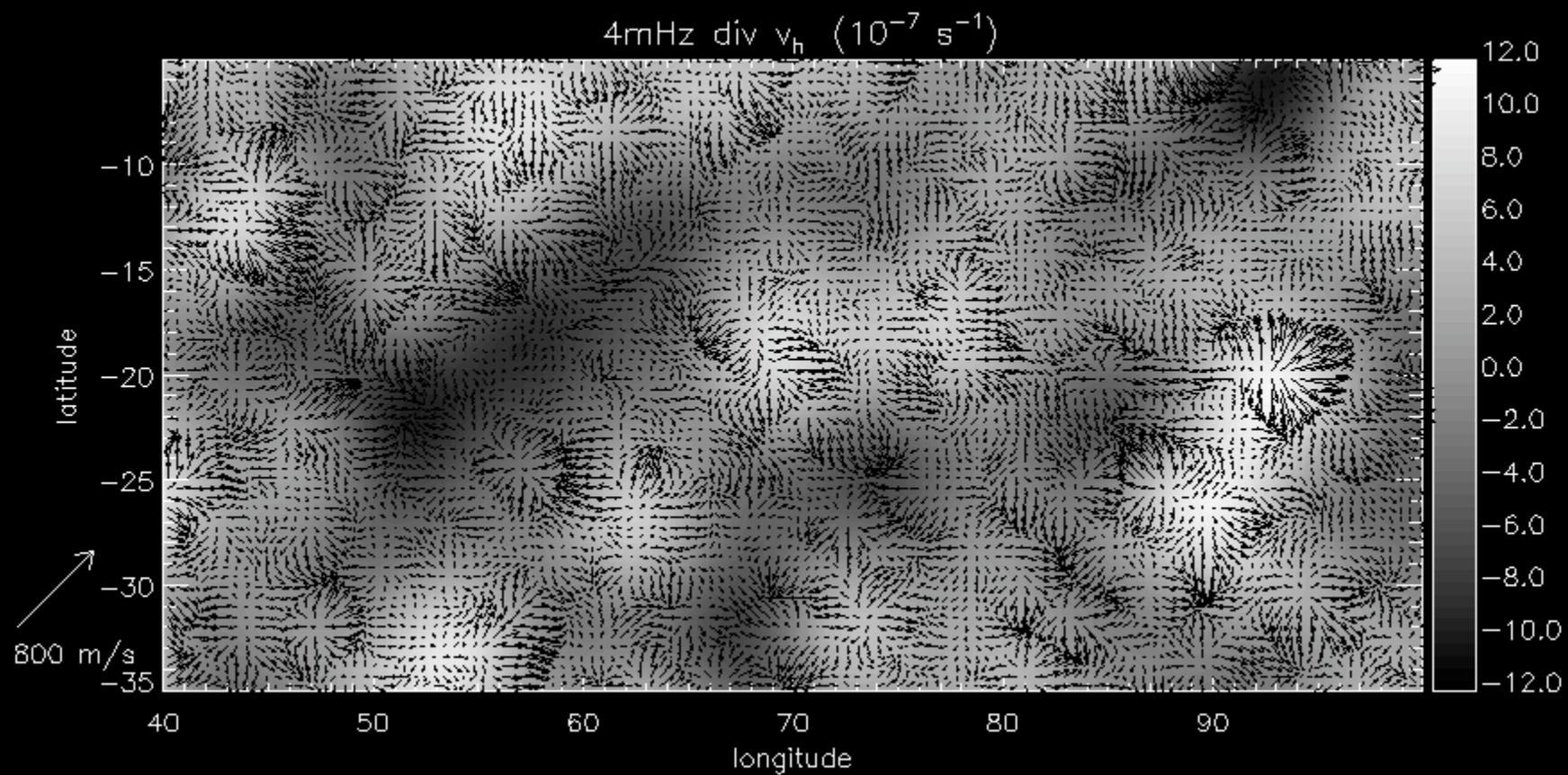
velocity:

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



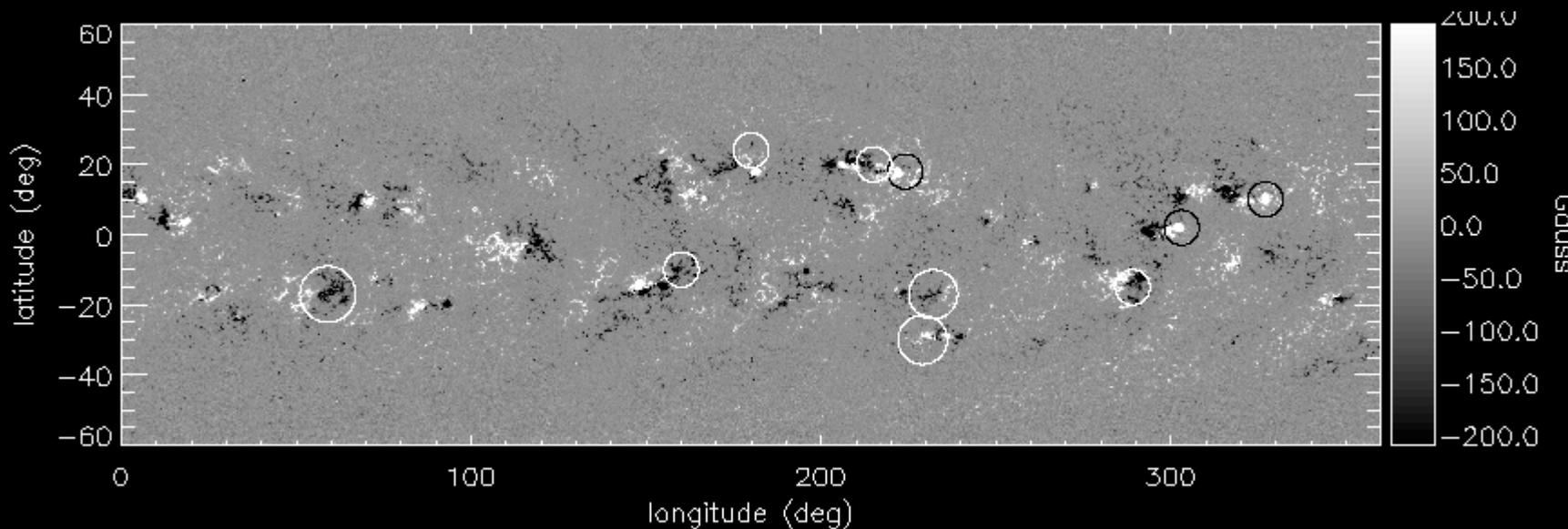
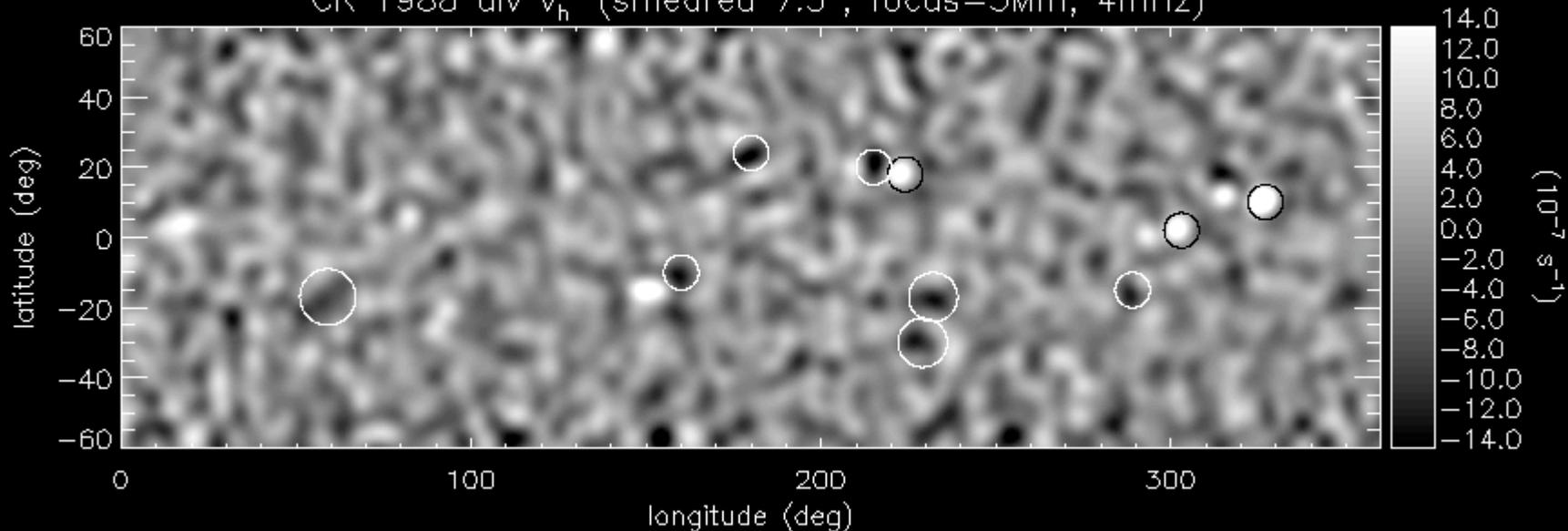
Inflows and outflows in ARs



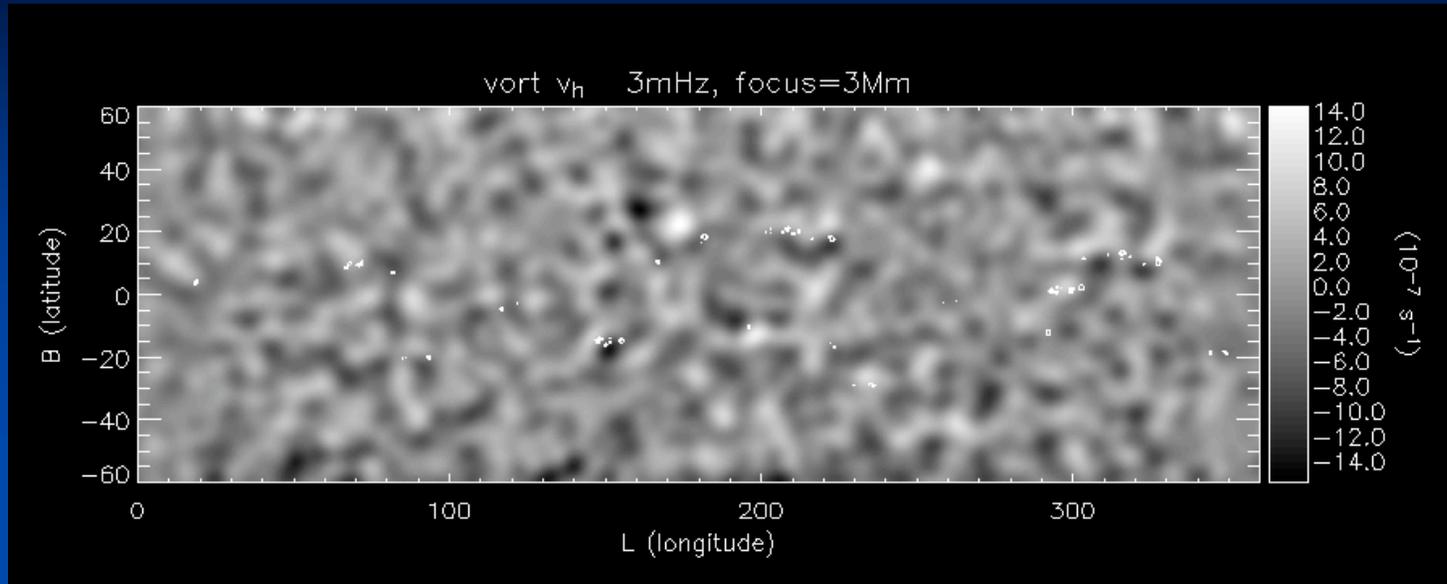


Carrington rotation 1988

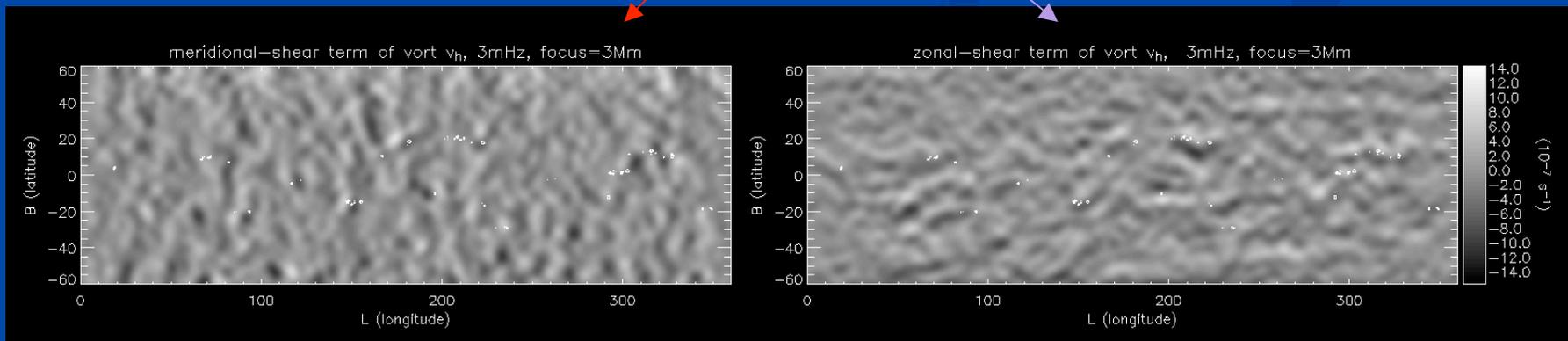
CR 1988 div v_h (smeared 7.5° , focus=3Mm, 4mHz)



vertical vorticity (smeared to 7.5°)



$$\text{vort } v_h = \underbrace{(1/\cos B) \partial(\cos B v_B) / \partial L}_{\text{meridional-shear term}} - \underbrace{(1/\cos B) \partial v_L / \partial B}_{\text{zonal-shear term}}$$



(5.8 day-averaged) flow properties of ARs in CR1988

For near-surface (e.g. 3Mm):

ARs rotate faster than quiet Sun (this shear can give rise to “bipolar” vorticity signature)

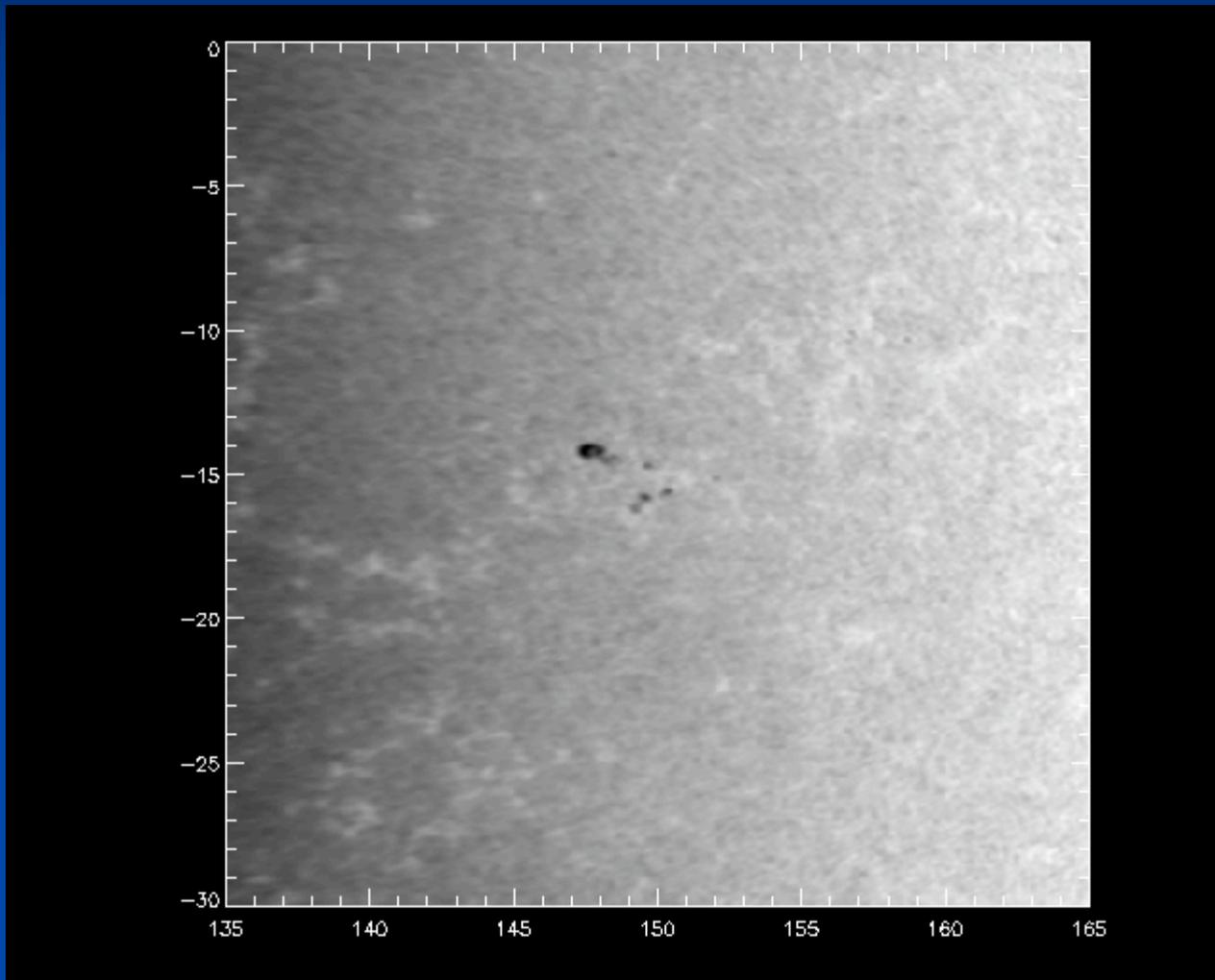
Inflows in plage; outflows in spots

No *net* vorticity signatures in ARs (but small number²⁴)

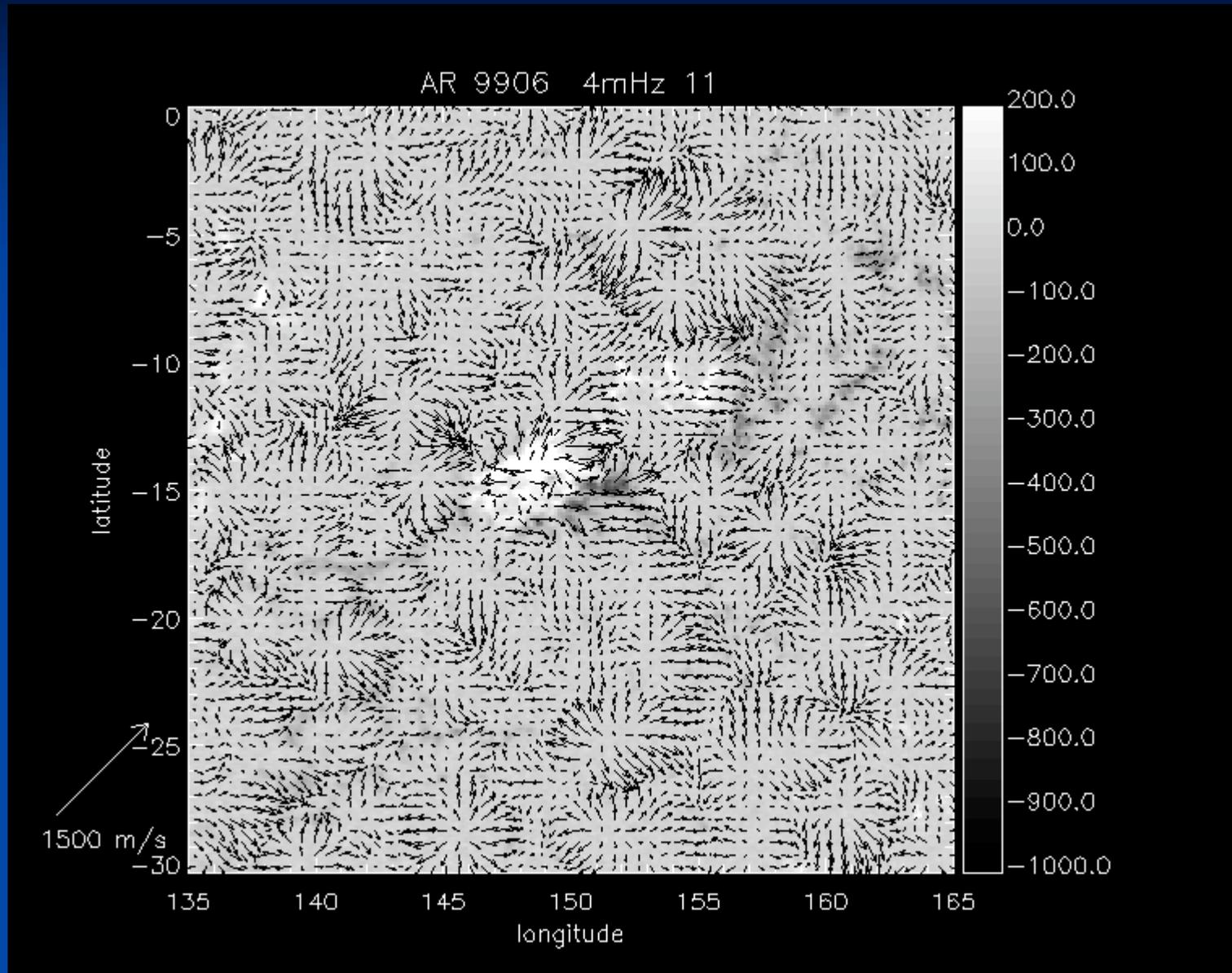
AR flows in time

- near-surface flow sequences over 8 days (7 x 28 hr sequences):
 - AR 9906 (2002 Apr 11-18)
 - AR 10486 & 10488 (2003 Oct 25-Nov 1)
- motivating questions:
 - Are helioseismic (near-surface) flows related to/consistent with morphology changes (e.g. what you might get by feature tracking)?
 - are there vorticity signatures which persist or are they “noisy” (like supergranulation)?
 - any sudden changes (e.g. flare related) ?

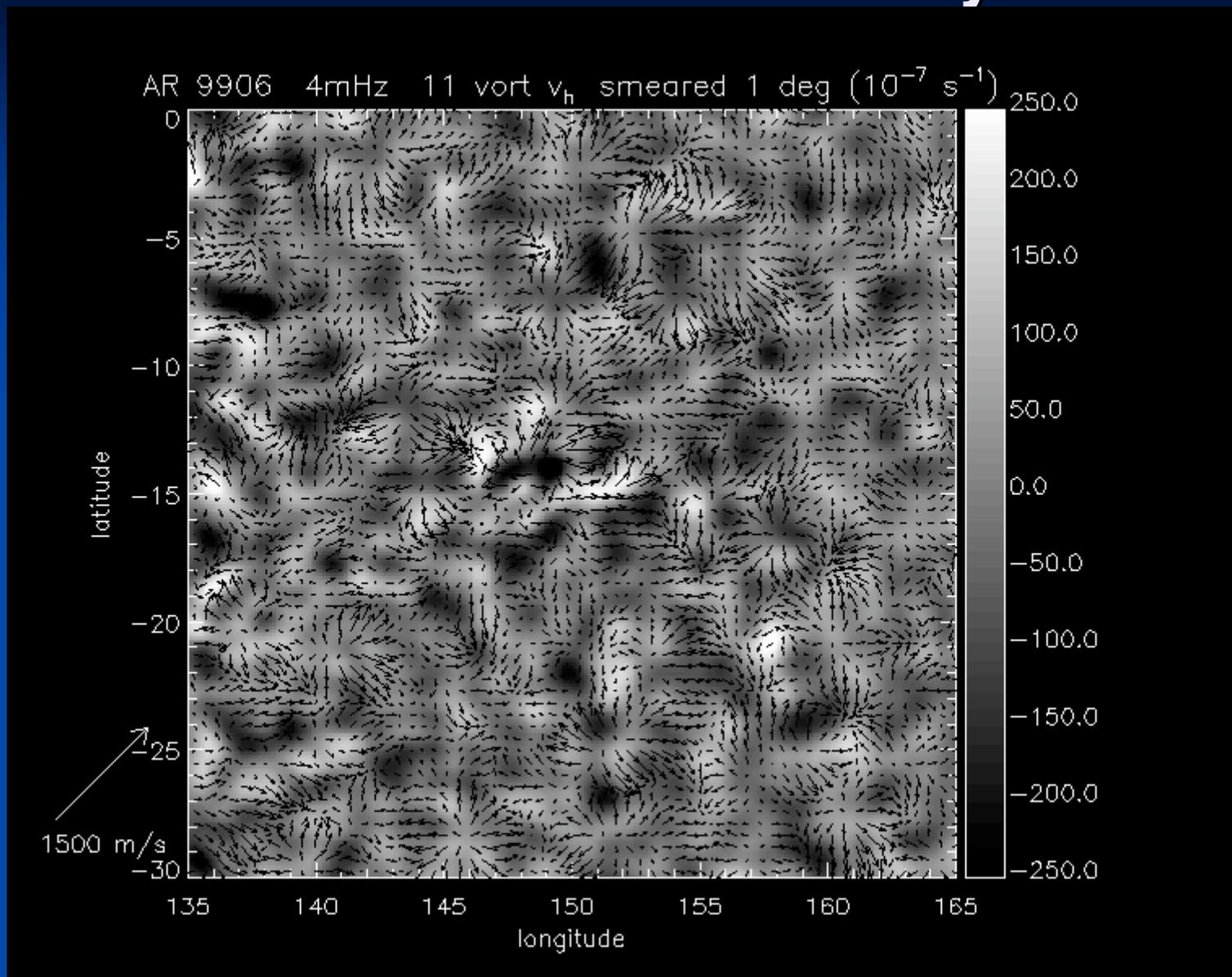
AR9906



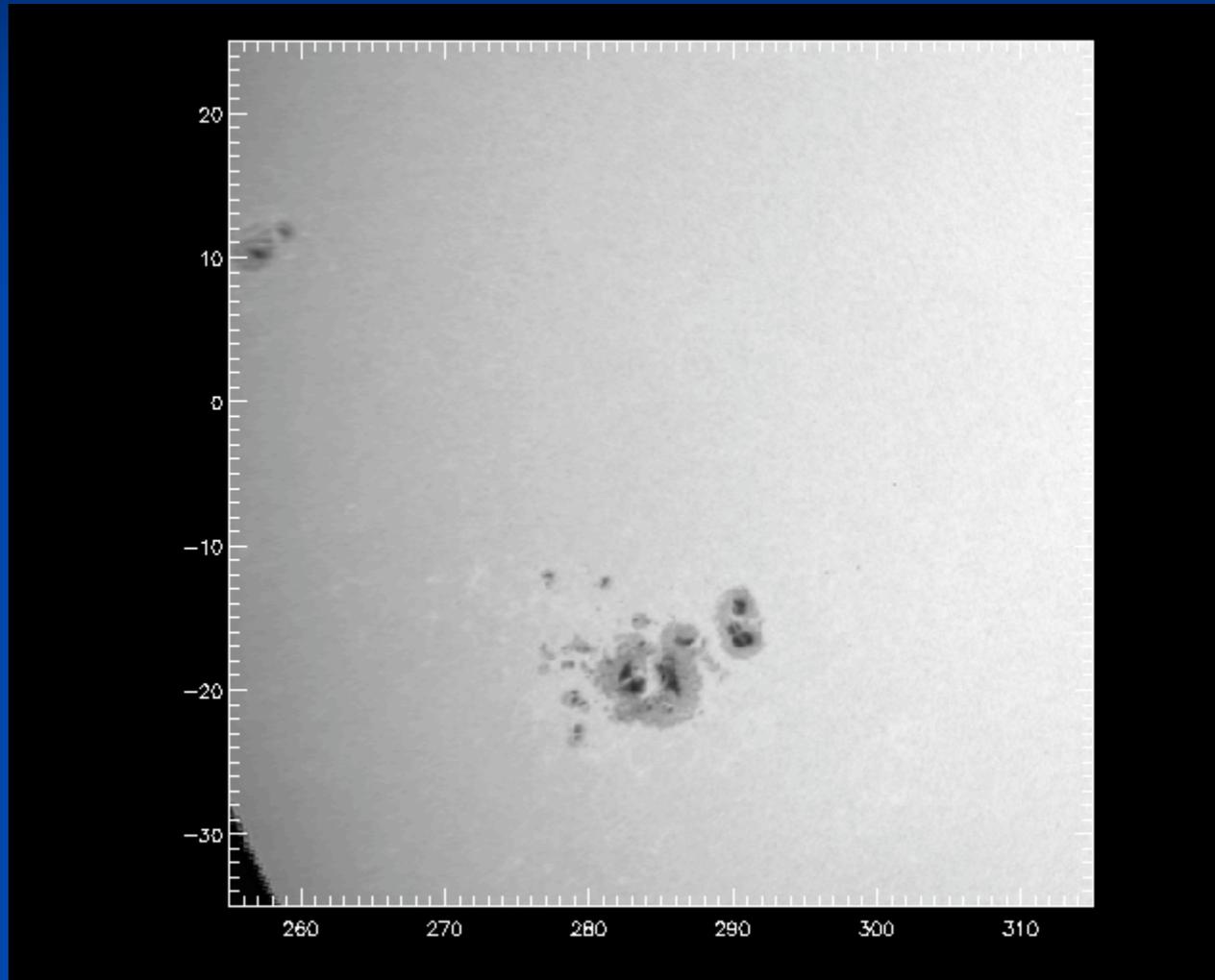
AR 9906 flows



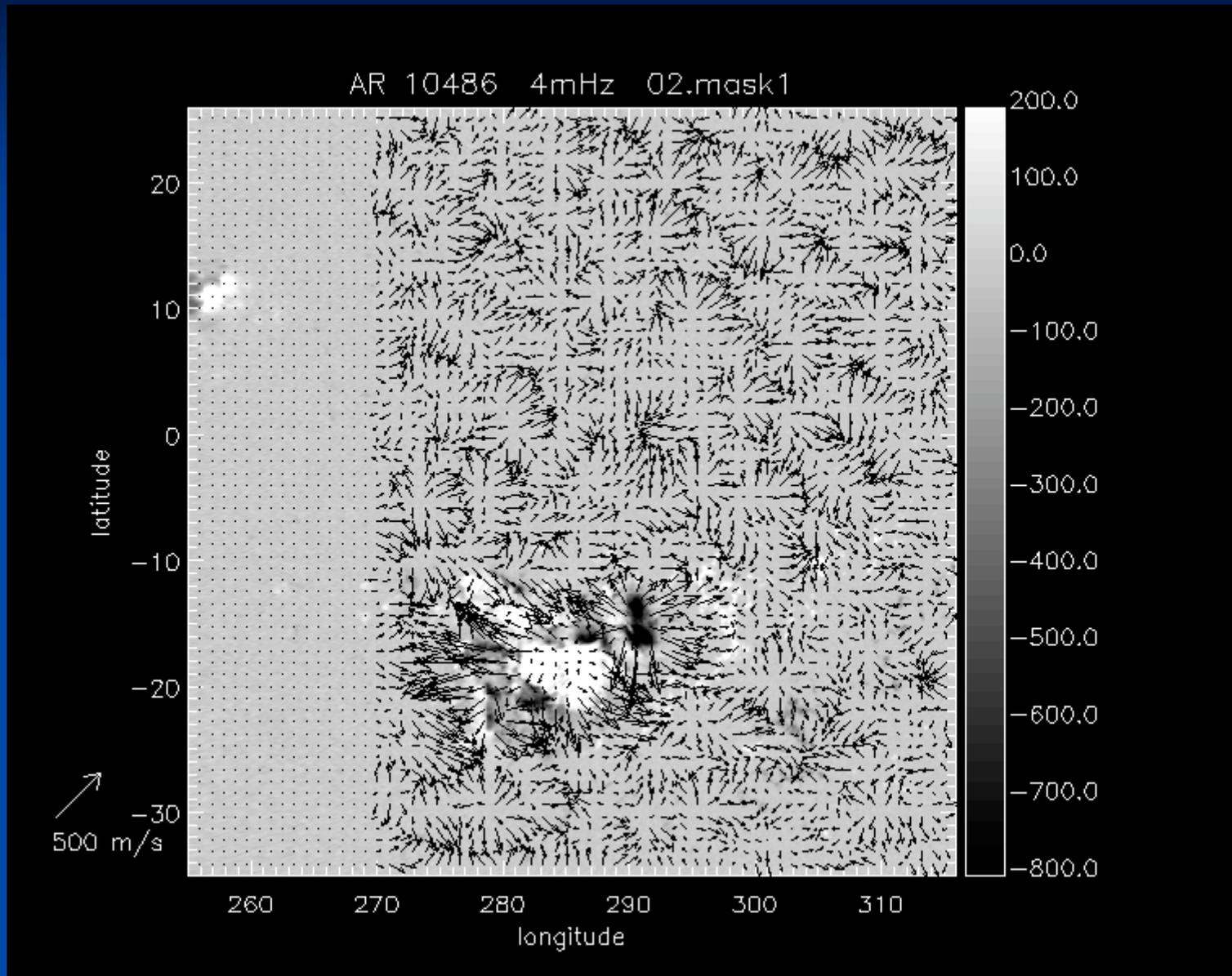
AR9906 vertical vorticity



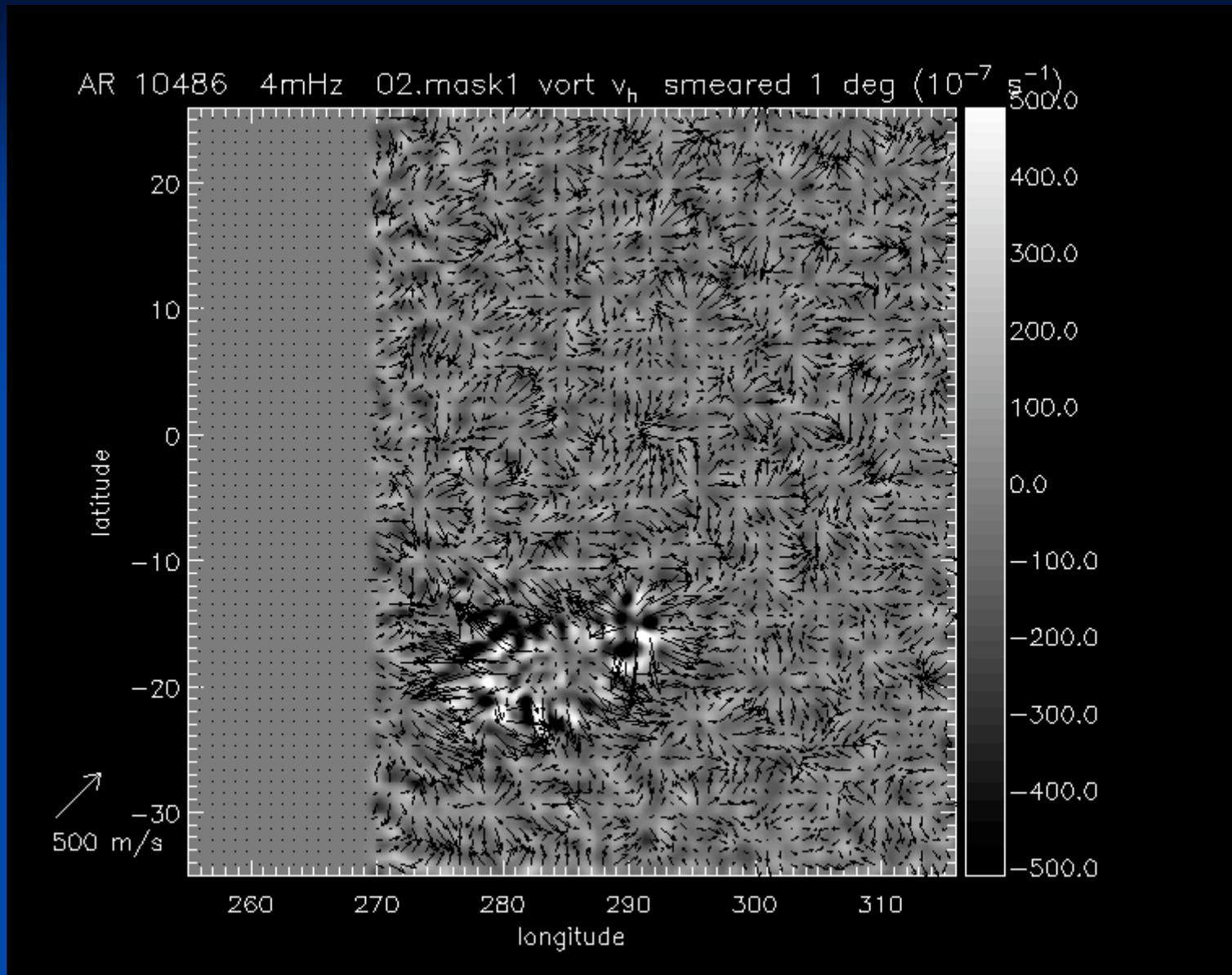
AR10486 & 10488



AR10486 & 10488 flows



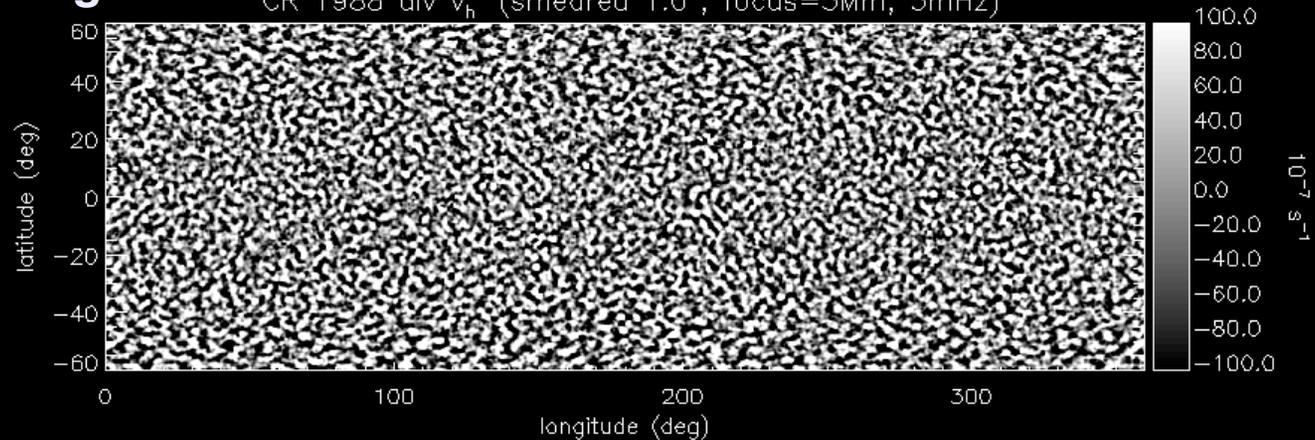
AR 10486 & 10488 vertical vorticity



supergranulation:

horizontal divergence

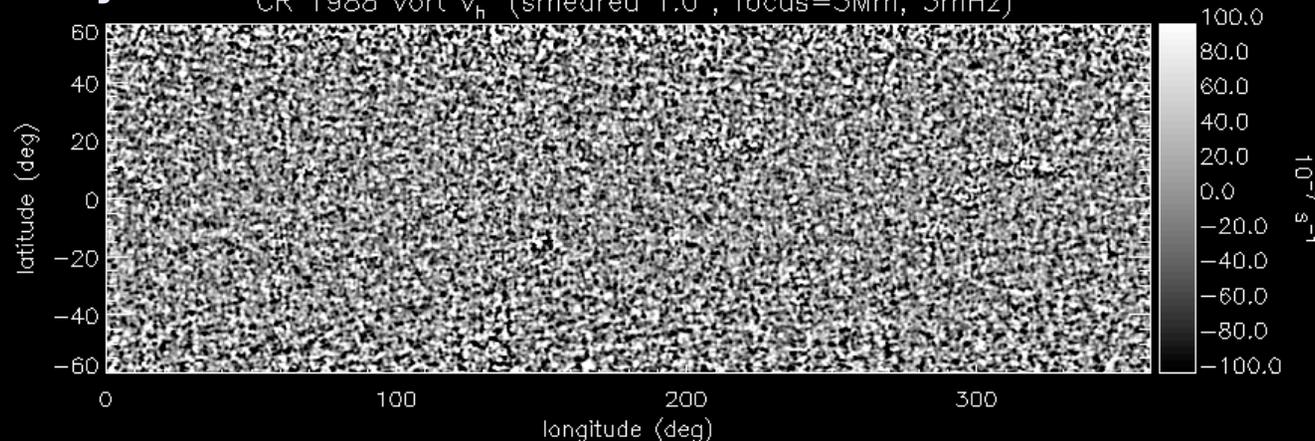
CR 1988 $\text{div } v_h$ (smeared 1.0° , focus=3Mm, 3mHz)



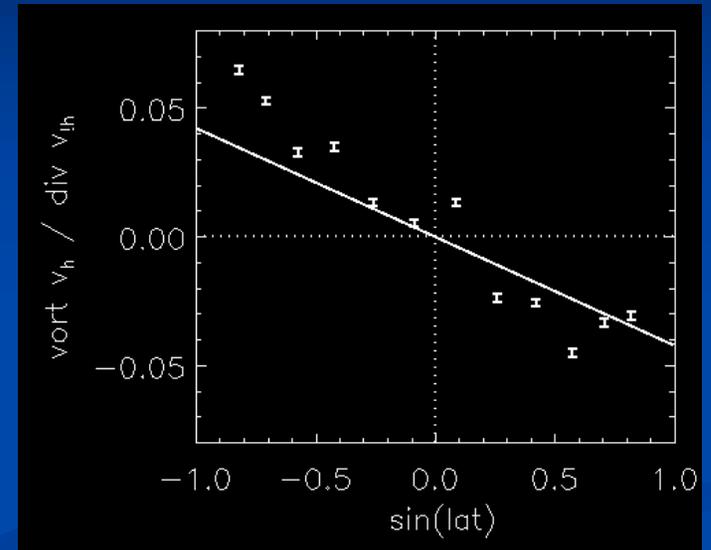
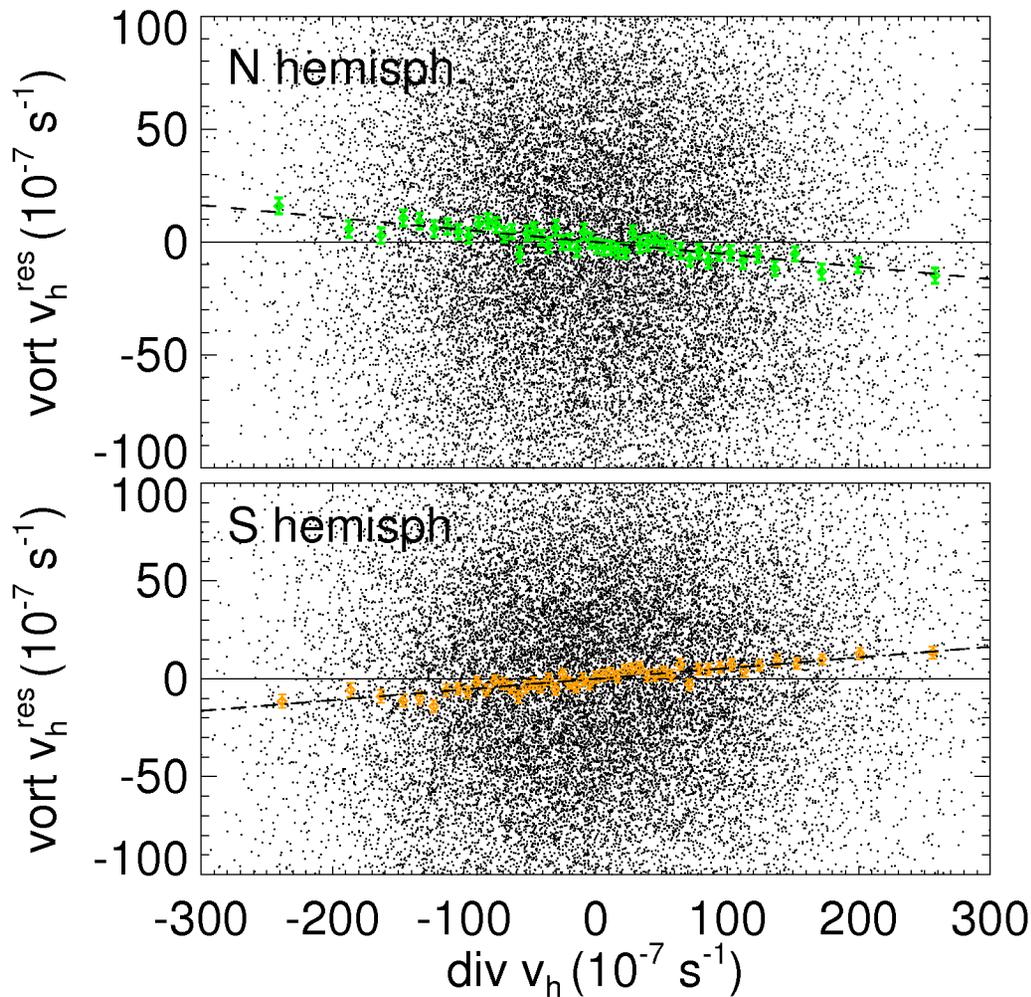
27-hr
time
average
s

vertical vorticity

CR 1988 $\text{vort } v_h$ (smeared 1.0° , focus=3Mm, 3mHz)

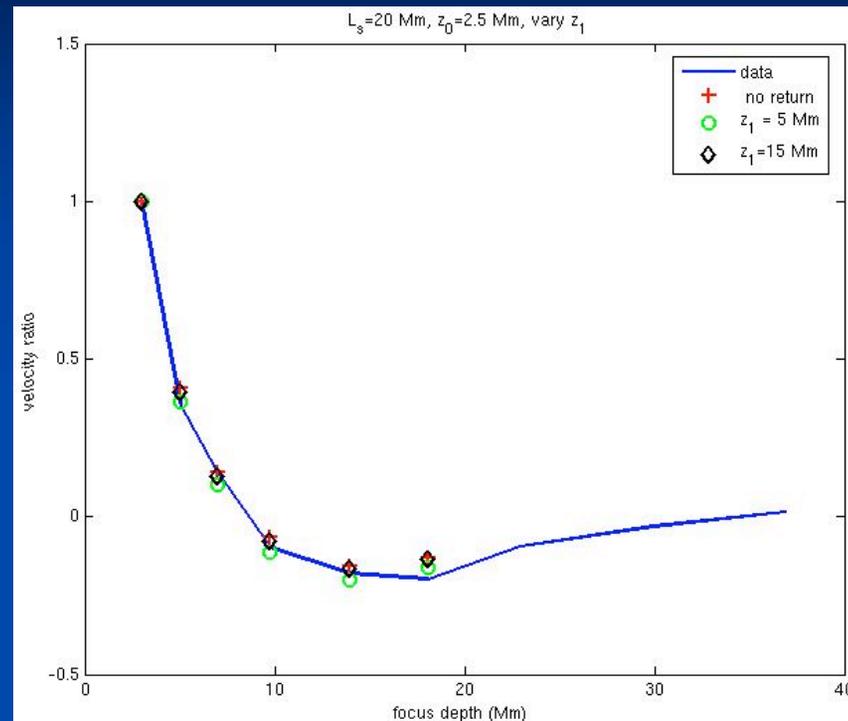
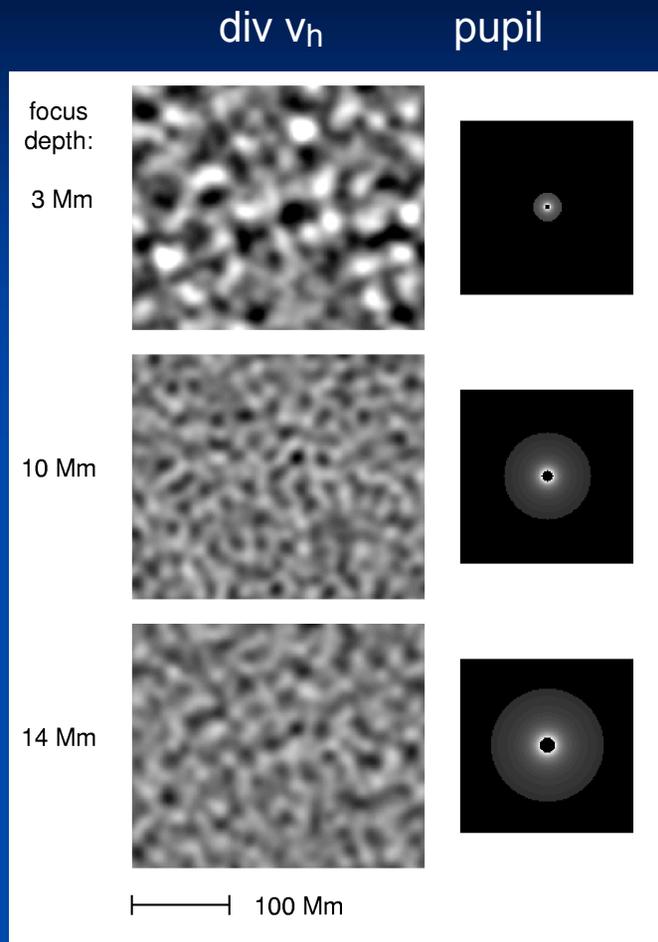


vertical vorticity of SG as a result of Coriolis force on divergence:



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

supergranular depth sensitivity



$v \propto e^{-z/z_0} \cos(\pi z/z_1) \quad z_0 = 2.5 \text{ Mm}.$

red crosses : no return flow ($z_1 \rightarrow \infty$).

green circles: $z_1 = 5 \text{ Mm}$

black diamonds: $z_1 = 15 \text{ Mm}.$

(Braun, Birch, & Lindsey 2004 SOHO/GONG Proceedings)

discussion points:

- sunspots have outflows; other magnetic regions have inflows. ARs rotate faster than quiet Sun
- evolving ARs do not obviously follow the inferred flow patterns around them
- would like to compare seismic flow signatures with “feature-tracking”
- effects of surface magnetism (“showerglass”)
- need for artificial data
- what would you folks like to see/do?

further information:

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

(includes links to farside and flare sites)

support:

NASA (LWS and SR&T programs)

NSF (Stellar Astronomy and
Astrophysics program)