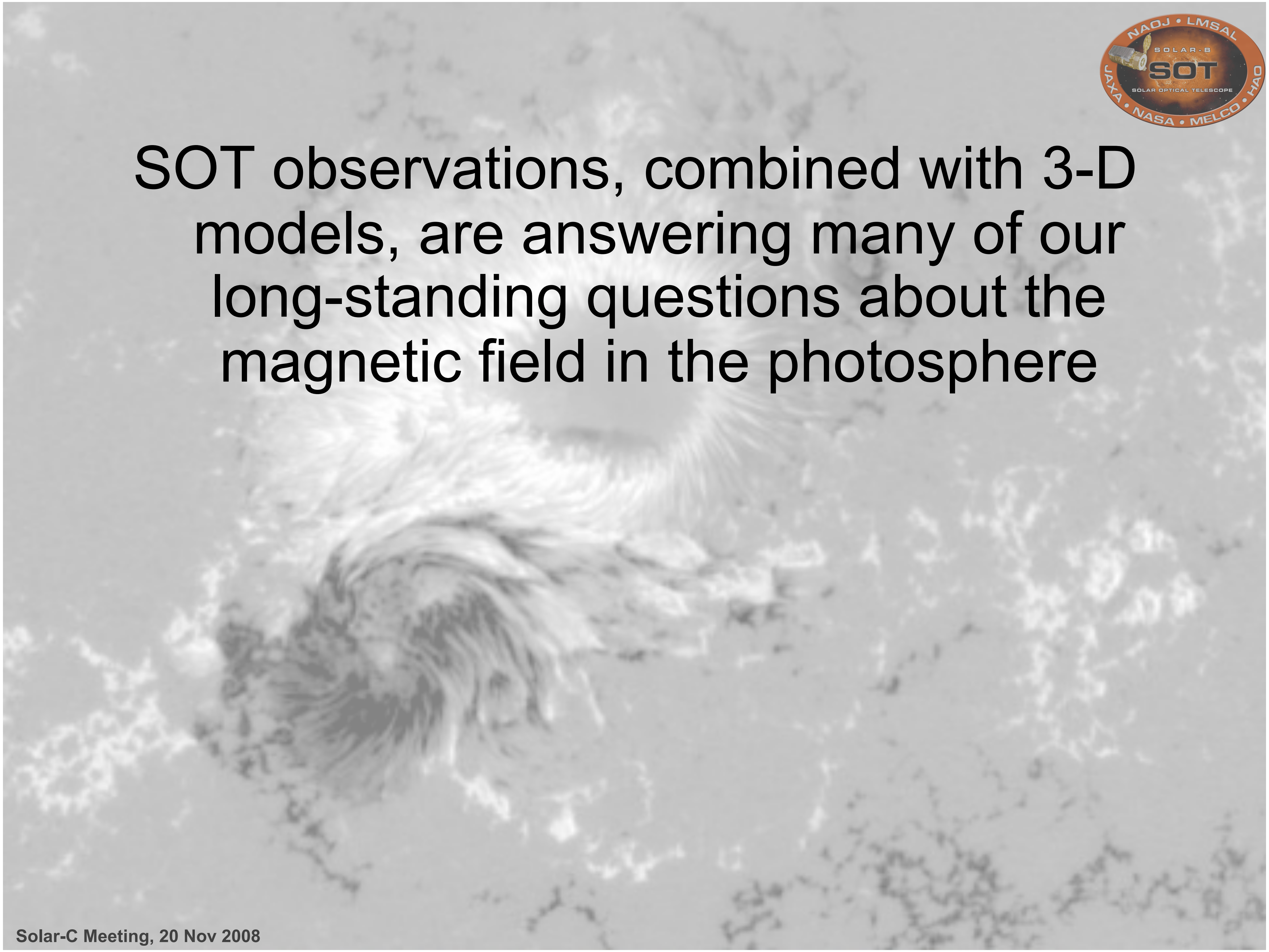
SOT Highlights on Photospheric Magnetic Fields

Ted Tarbell
LMSAL



SOT observations, combined with 3-D models, are answering many of our long-standing questions about the magnetic field in the photosphere

SOT Highlights & Discoveries

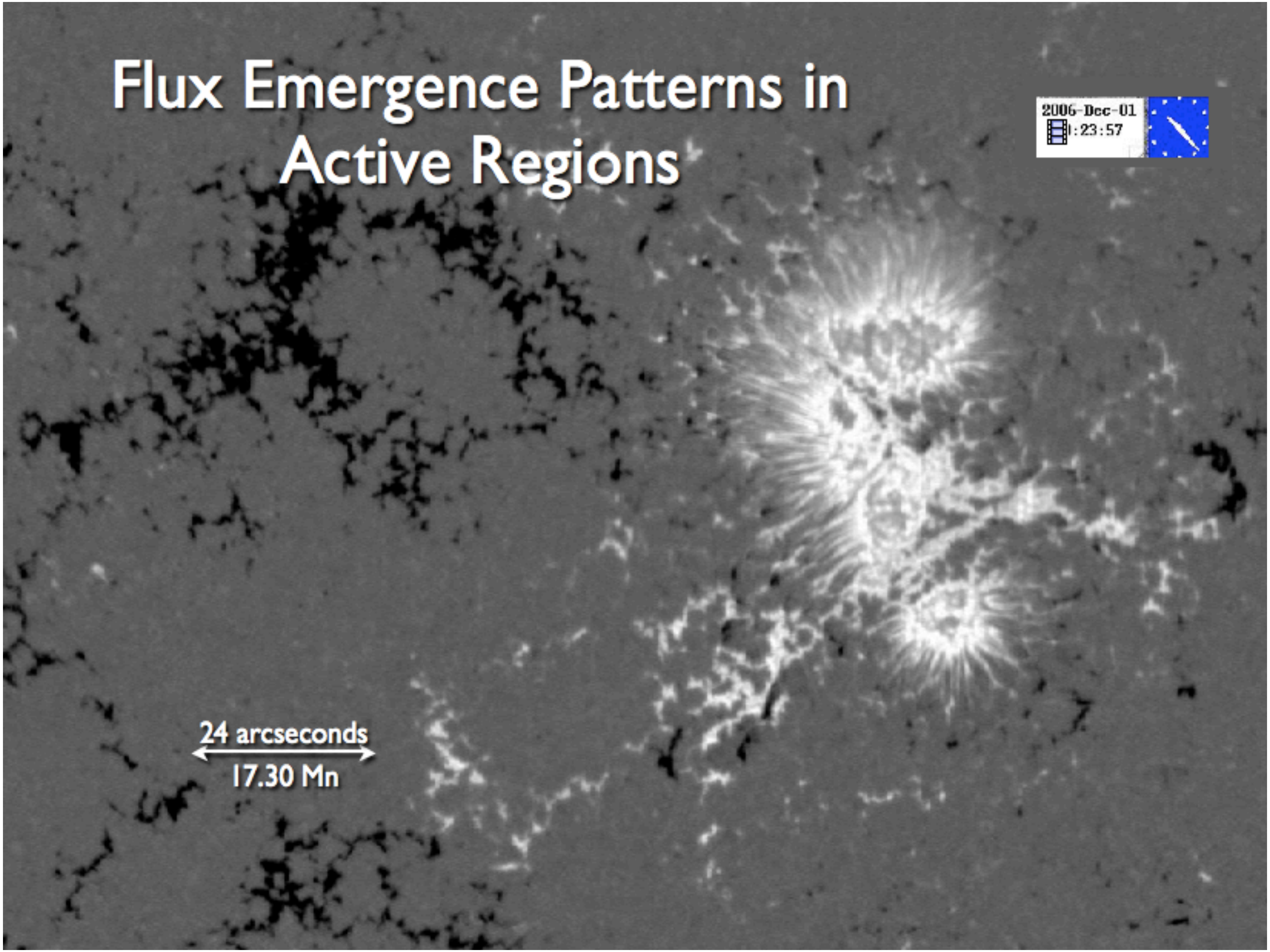
- Flux Emergence on Many Scales
- Turbulent and Transient Horizontal Magnetic Fields
- Convective Collapse
- Polar Magnetic Fields -- you have seen Tsuneta’s talk
- Reconnections & Jets Everywhere
- Penumbral Structure
- Flux Budget of a Decaying Sunspot
- Fields, Currents & NLFF Extrapolations -- see Schrijver’s talk

Flux Emergence on Many Scales

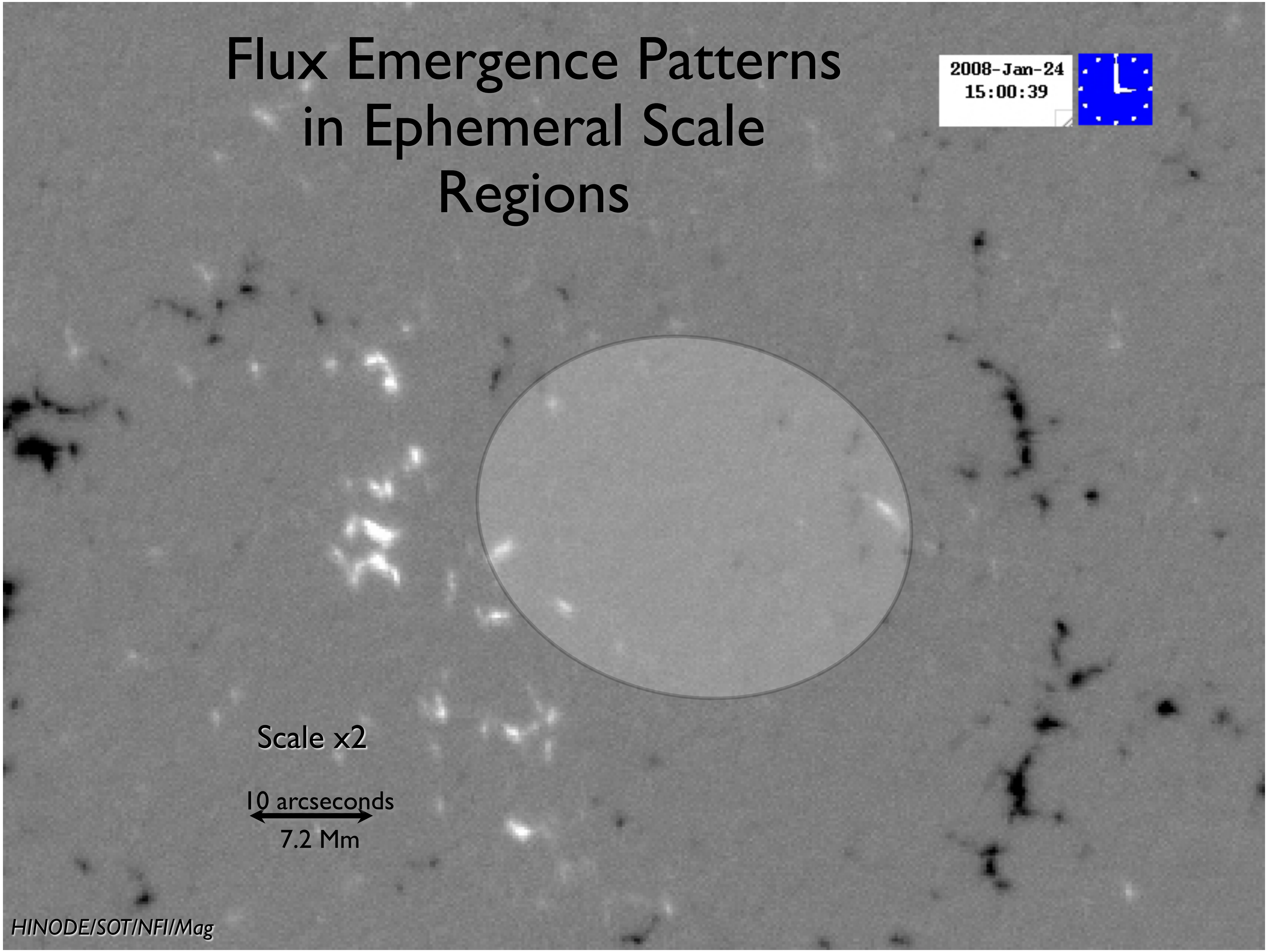
- A. Title, “Ponds, Fragments, and the Distribution of the Surface Magnetic Field,” 2nd Hinode Science Meeting, Boulder, Oct 2008
- M. Cheung et al, “Solar Surface Emerging Flux Regions: a Comparative Study of Radiative MHD Modeling and Hinode SOT Observations”

- Flux emerges in similar patterns at all scales of convection: super granulation (20 Mm), mesogranulation (6 Mm), and granulation (1 Mm) as well as active regions (100 Mm).
- Flux does not appear as simple bipoles, but rather a sea of mixed polarity structures.

Flux Emergence Patterns in Active Regions

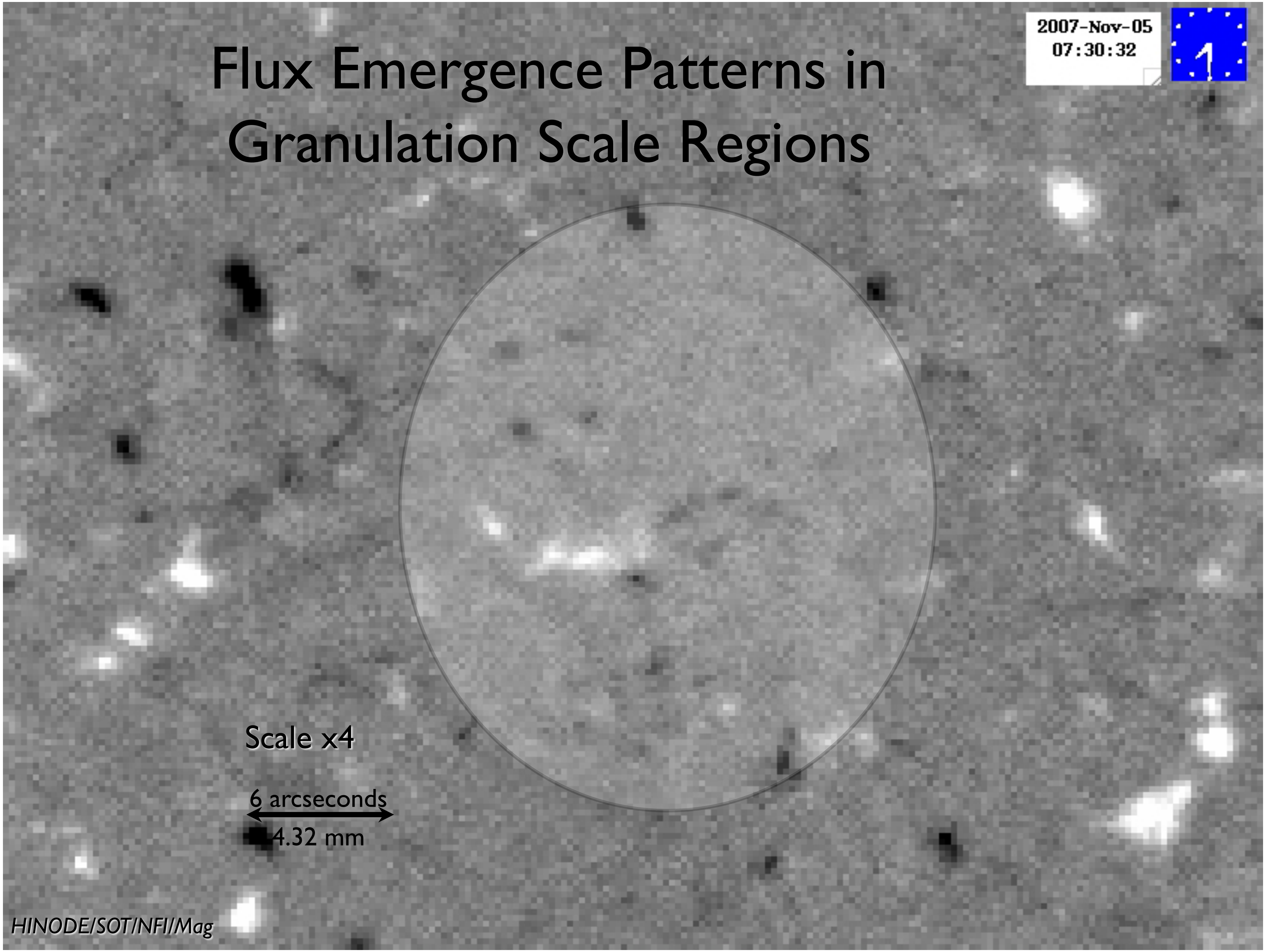


Flux Emergence Patterns in Ephemeral Scale Regions



HINODE/SOT/NFI/Mag

Flux Emergence Patterns in Granulation Scale Regions

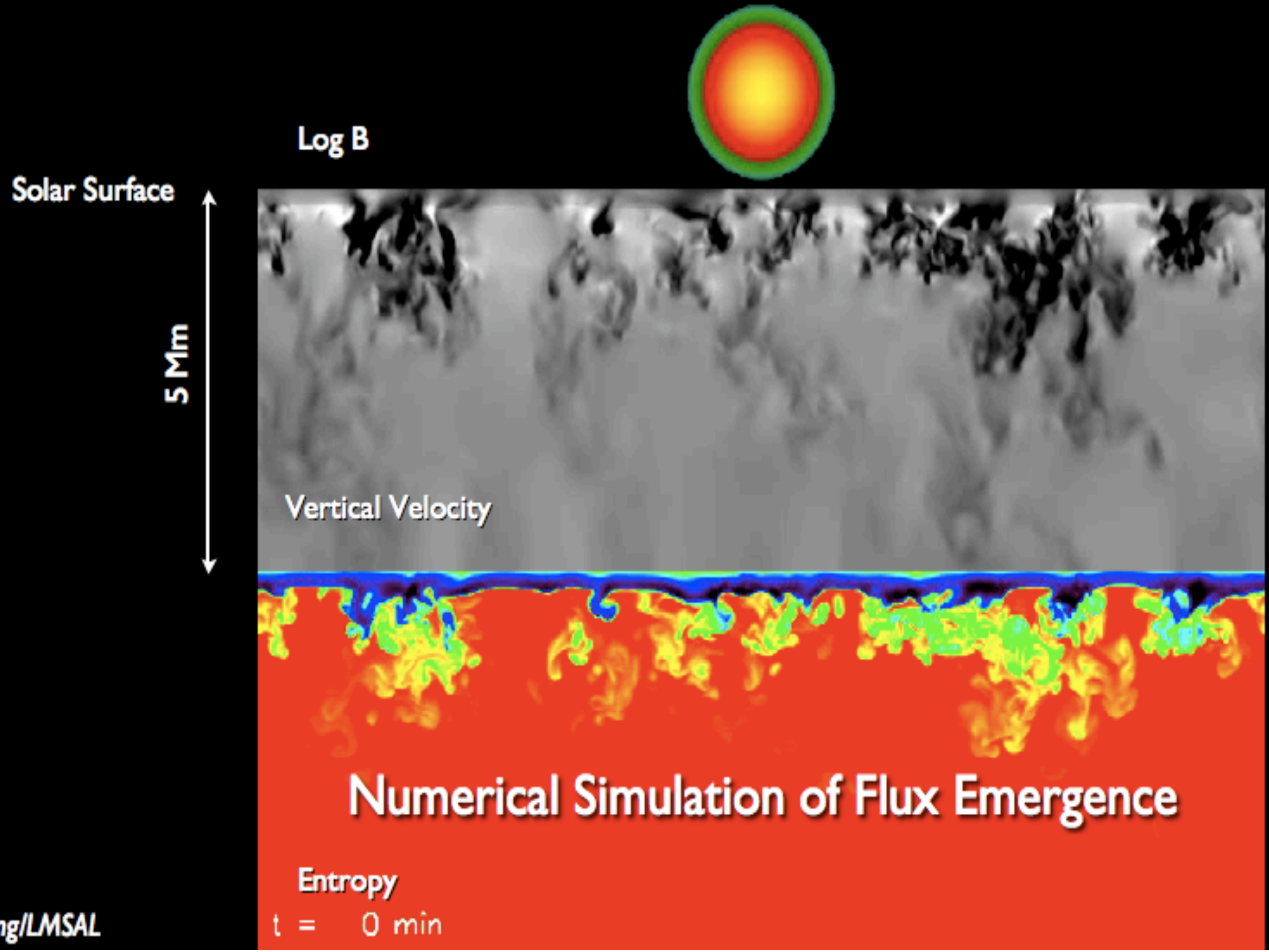


Scale x4

6 arcseconds

4.32 mm

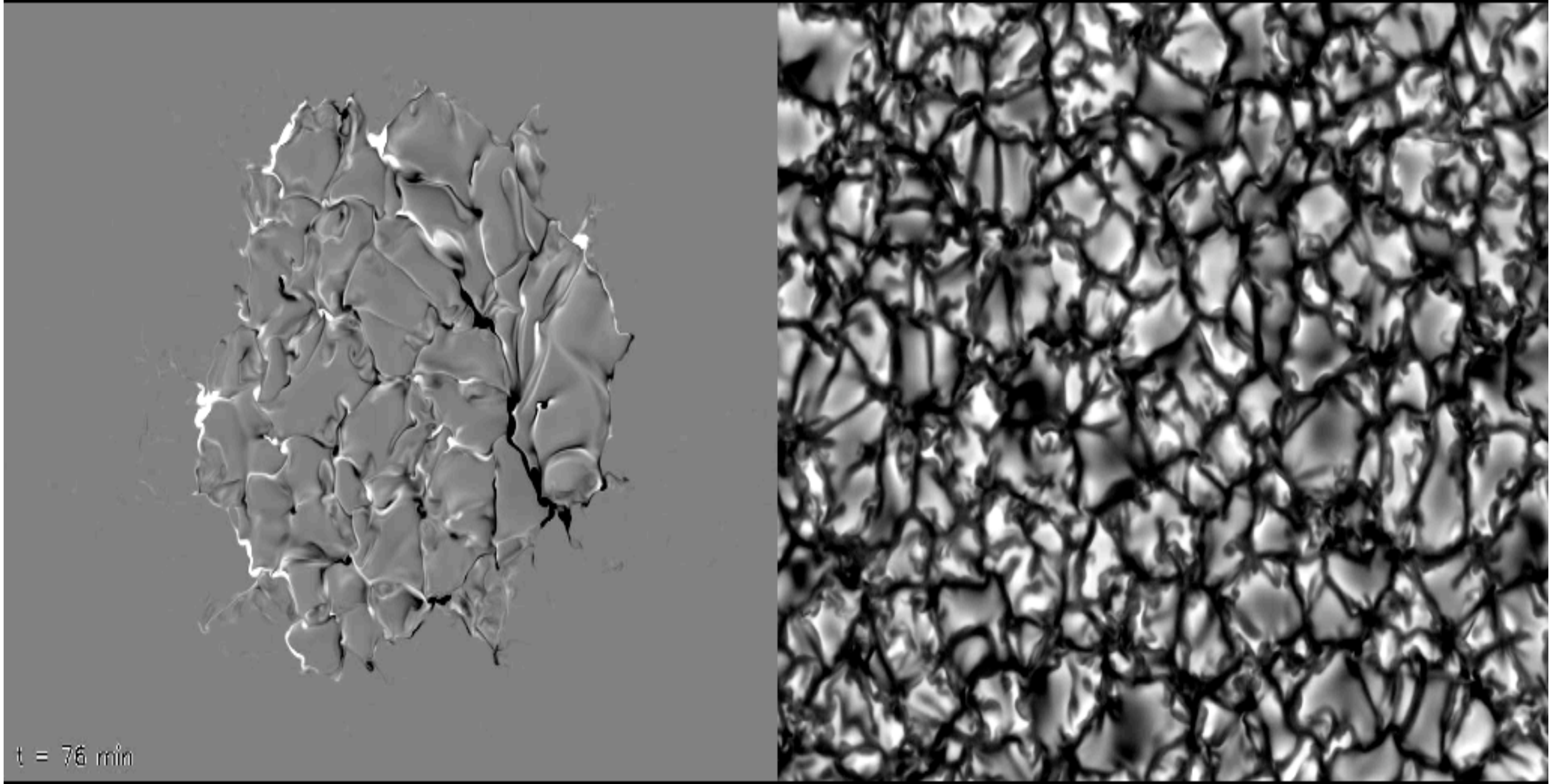
HINODE/SOT/NFI/Mag



Numerical Simulation of Flux Emergence

Cheung/LMSAL

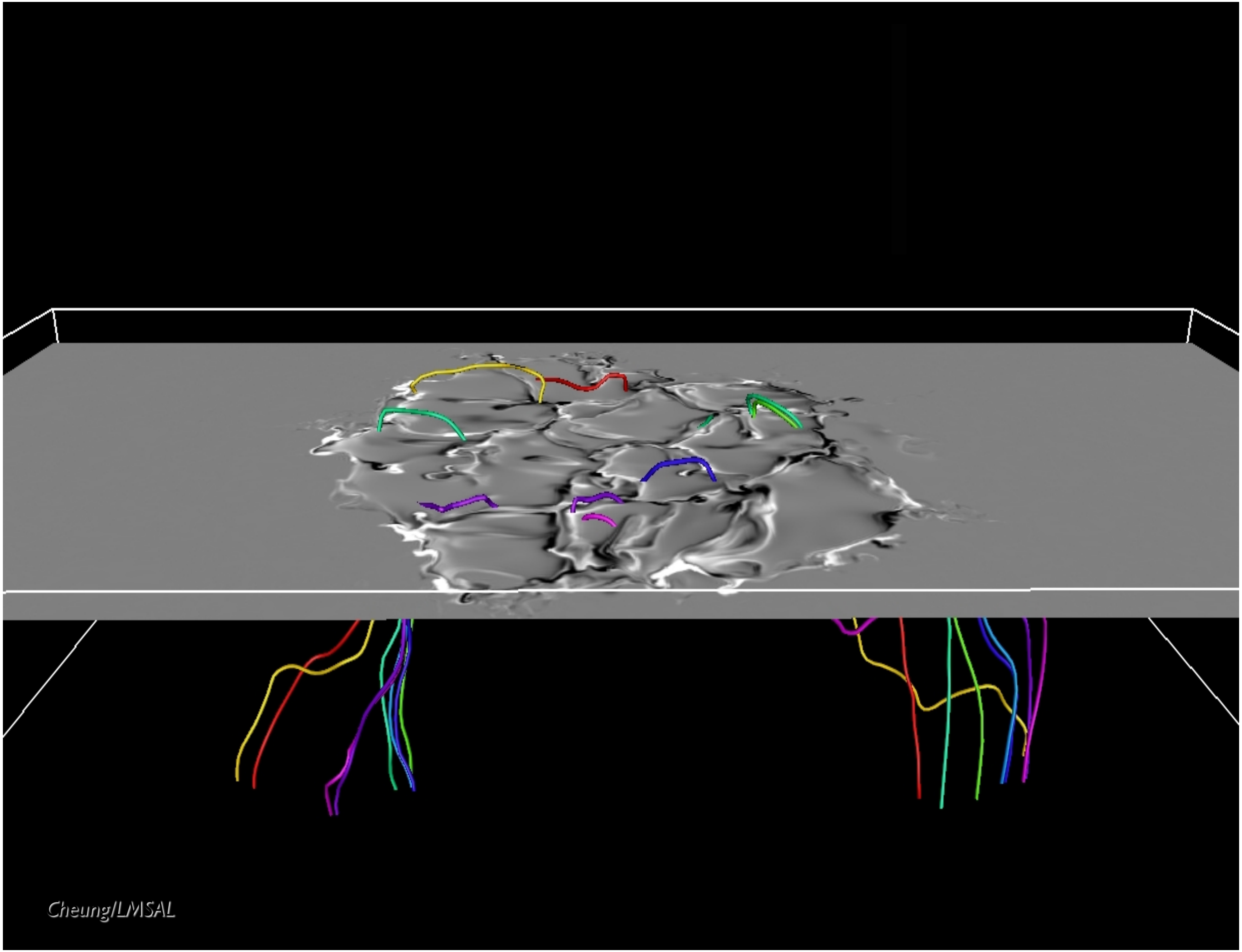
Numerical Simulation of Flux Emergence



Magnetic Field

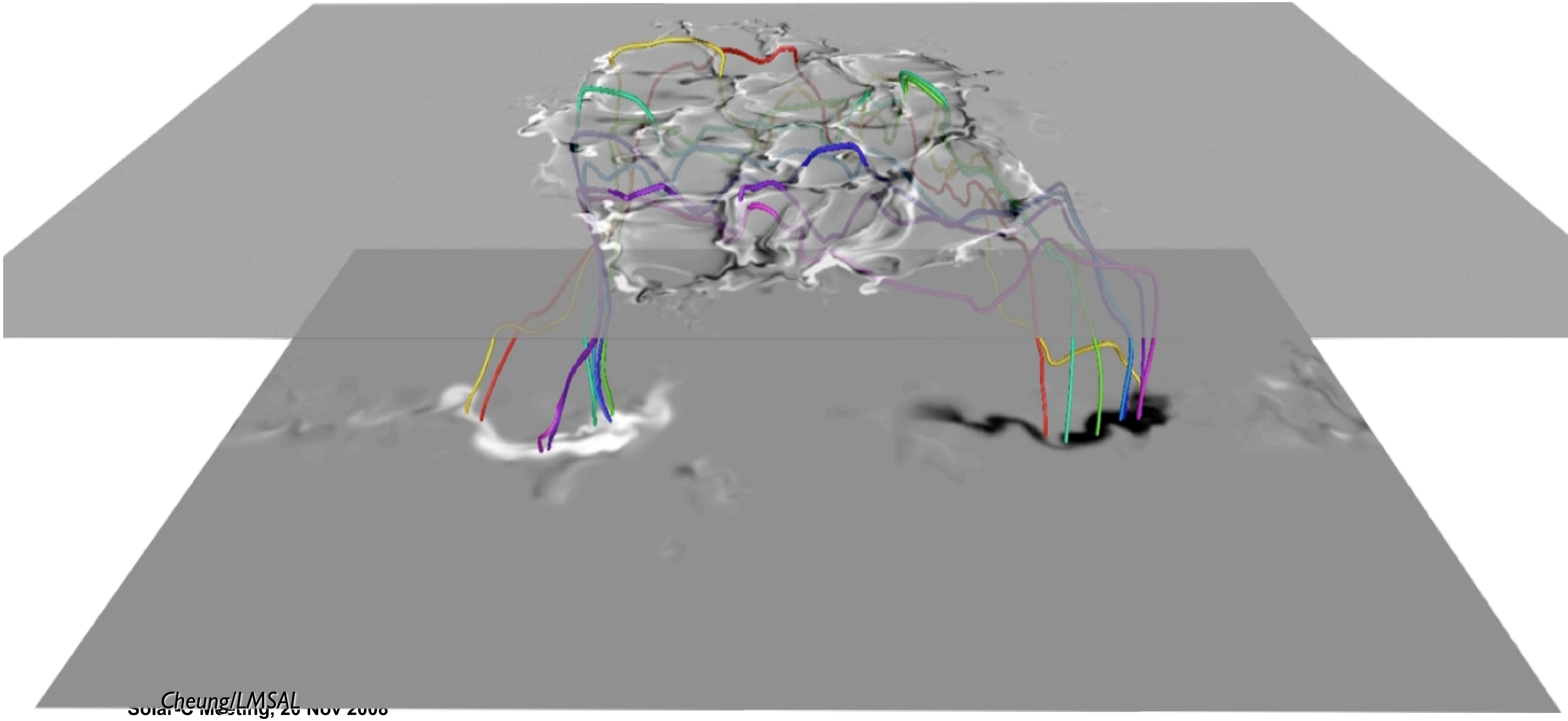
Granulation + Magnetic Field

Cheung/LMSAL



Cheung/LMSAL

View of Surface and - 5 Mm

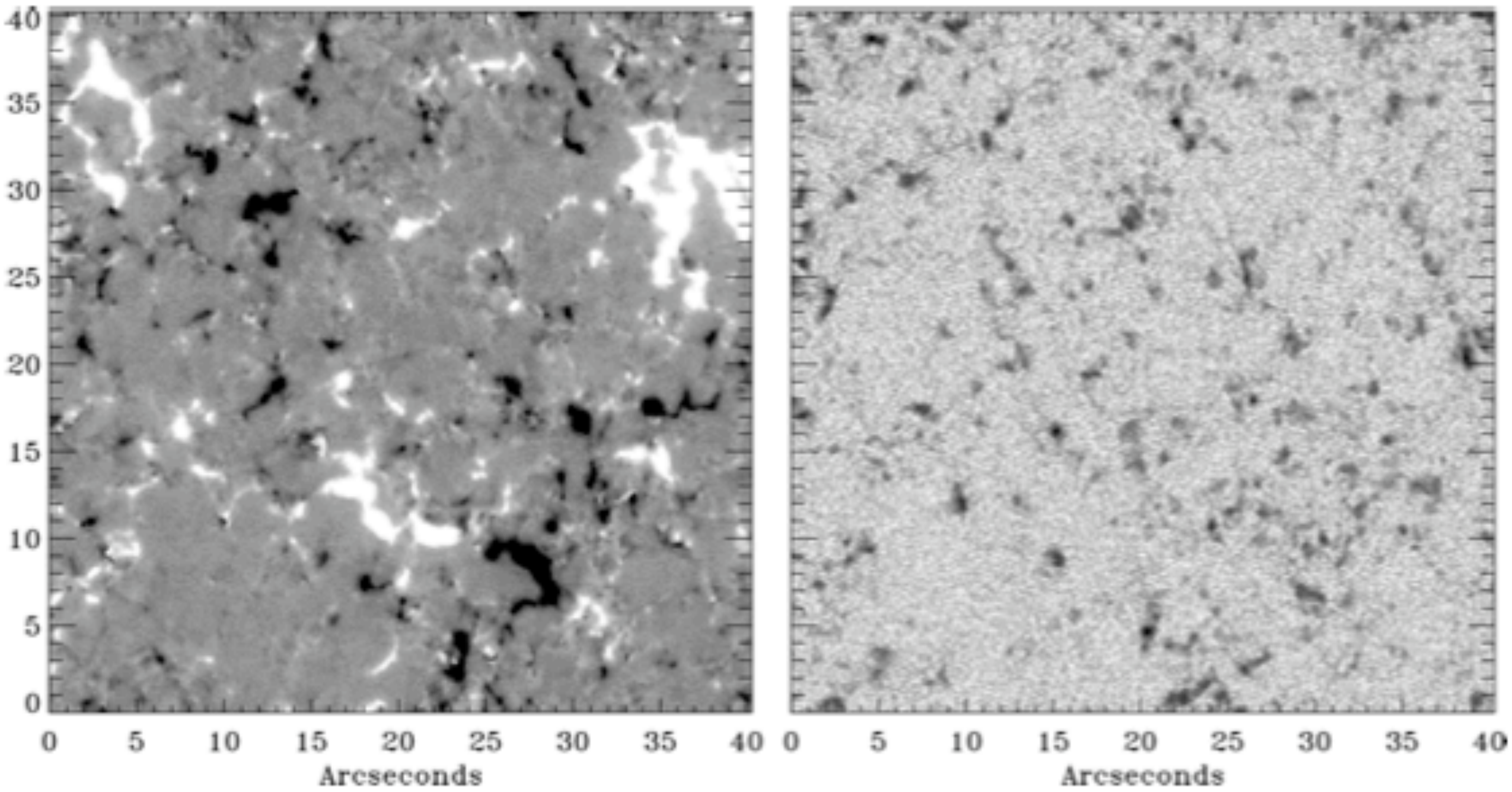


Cheung/LMSAL

Turbulent & Transient Horizontal Fields

- R. Ishikawa, “Statistical Properties of Transient Horizontal Fields,” 2nd Hinode Science Meeting, Boulder, Oct 2008
- B. Lites, “Is Flux Submergence an Essential aspect of Flux Emergence”
- J. Pietarila Graham, “The Solar Surface Dynamo”
- O. Steiner, “The Horizontal Internetwork Field: Numerical Simulations in Comparison to Observations with Hinode”

Pervasive horizontal magnetic flux (Lites et al. 2008)



$< |B^L_{app}| > \approx 11\,\mathrm{Mx\,cm^{-2}}$

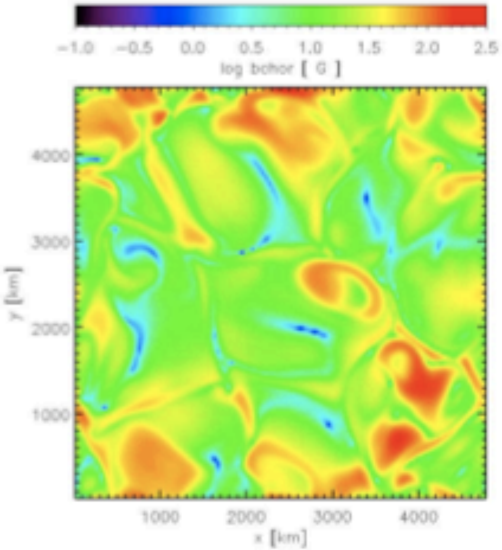
$< B^T_{app} > \approx 55\,\mathrm{Mx\,cm^{-2}}$

$|B^L_{app}| \leq 50\,\mathrm{Mx\,cm^{-2}}$

$B^T_{app} \leq 200\,\mathrm{Mx\,cm^{-2}}$

Numerical simulations (cont.)

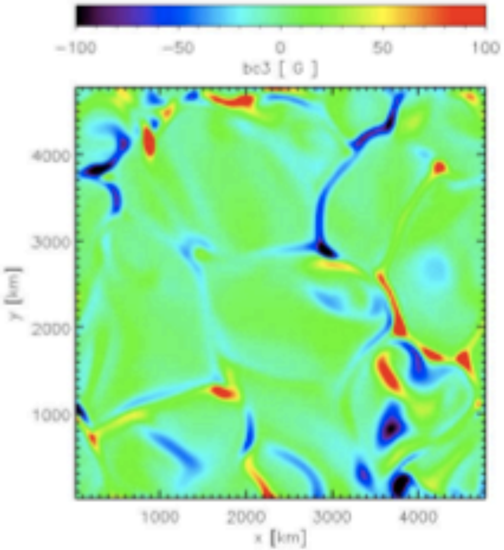
Snapshot of B_{hor}, B_{ver}, and the continuum intensity at 630 nm from *run h20* in the horizontal section of $\langle \tau_{500\,\mathrm{nm}} \rangle = 1$.



B_{hor}

area fraction with

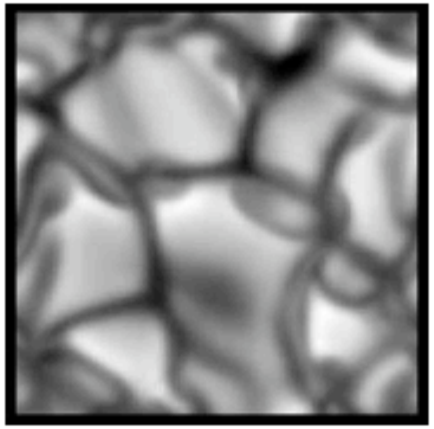
$B_{\mathrm{hor}} > 5$ mT $= 17\%$



B_{ver}

area fraction with

$B_{\mathrm{ver}} > 5$ mT $= 2.2\%$



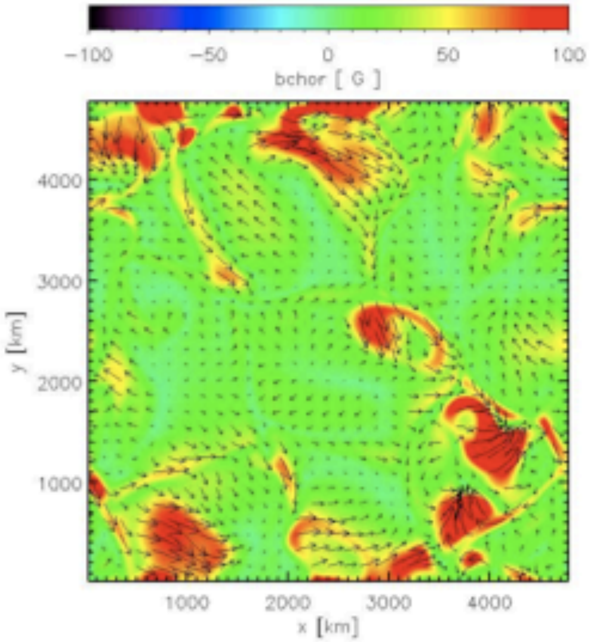
$I_{630\,\mathrm{nm}}$

$v_z(\langle \tau_{500\,\mathrm{nm}} \rangle = 1)$

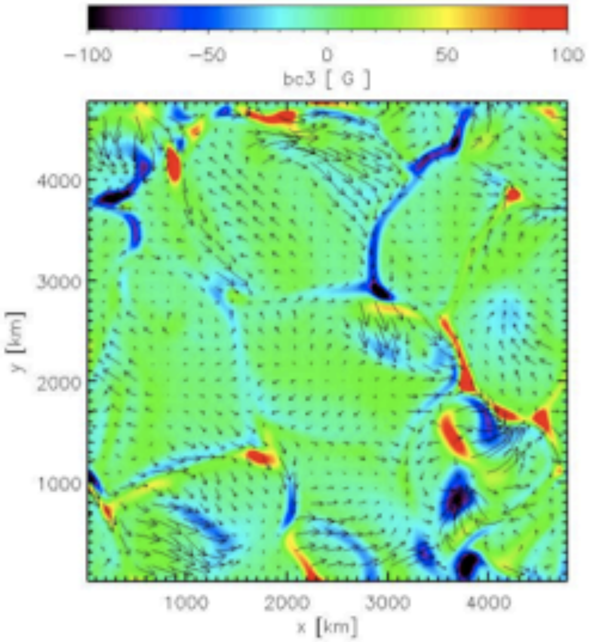
Movie

Polarimetry (cont.)

The vertical field component is more subject to apparent flux cancellation than the horizontal component, because ....



B_{hor}

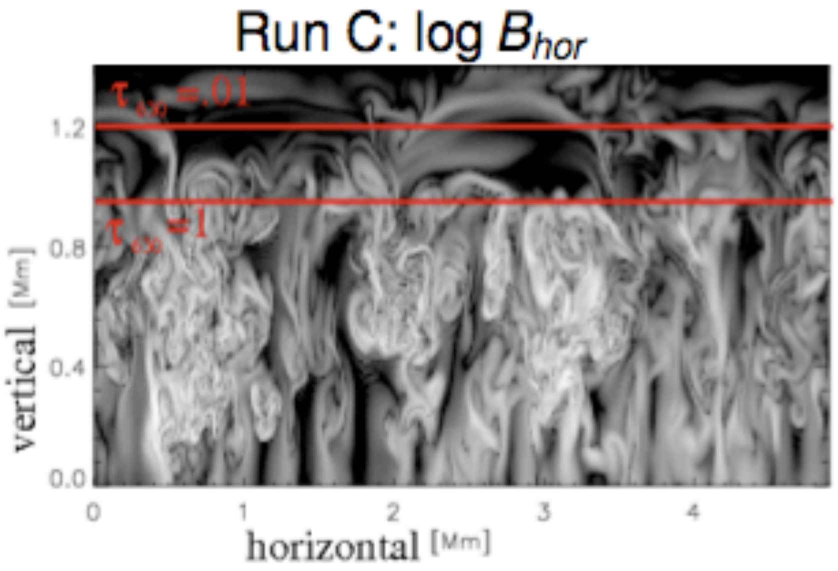


B_{ver}

..... the vertical field component has smaller scales and higher intermittency than the horizontal component.

Strong horizontal photospheric magnetic field in SSD

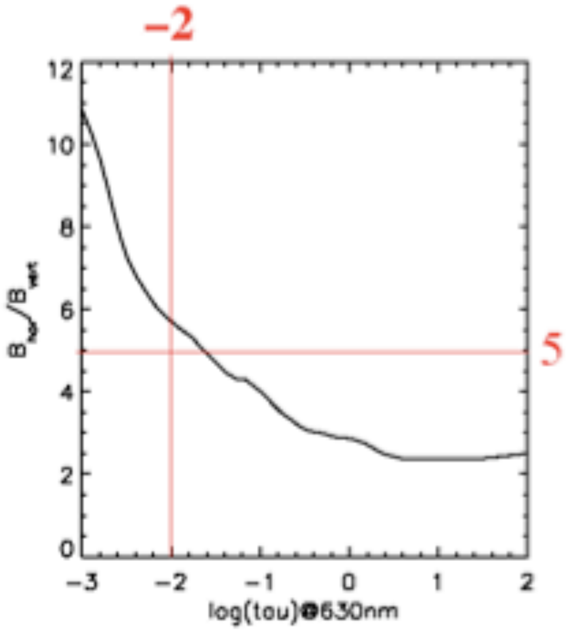
(Schüssler & Vögler 2008)


Run C: log B_{hor}

Shallow narrow loops (integranular lanes)

Extended loops (above granules)

(see also Steiner et al. 2008)

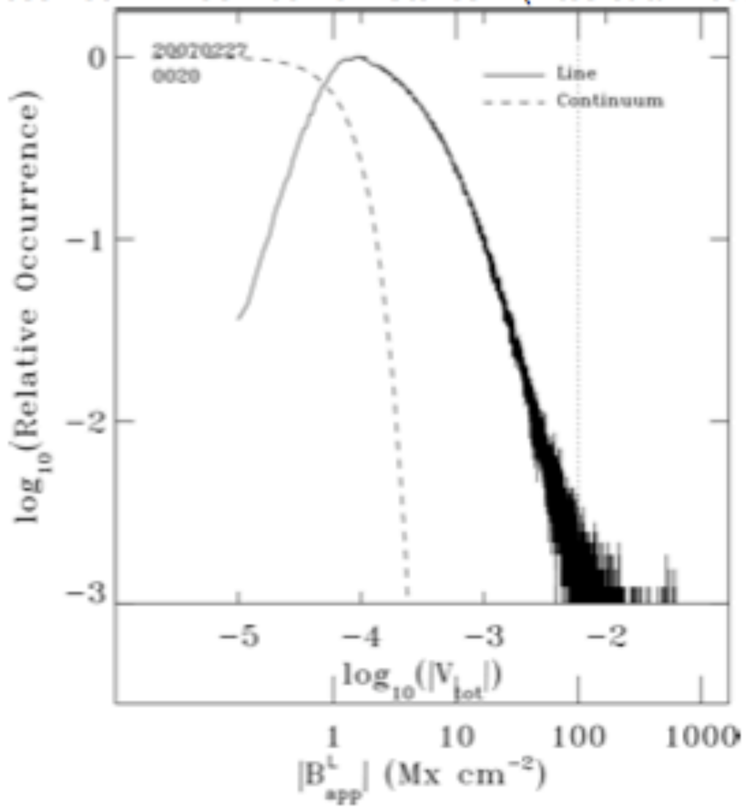


Average vertical field decreases faster with height than

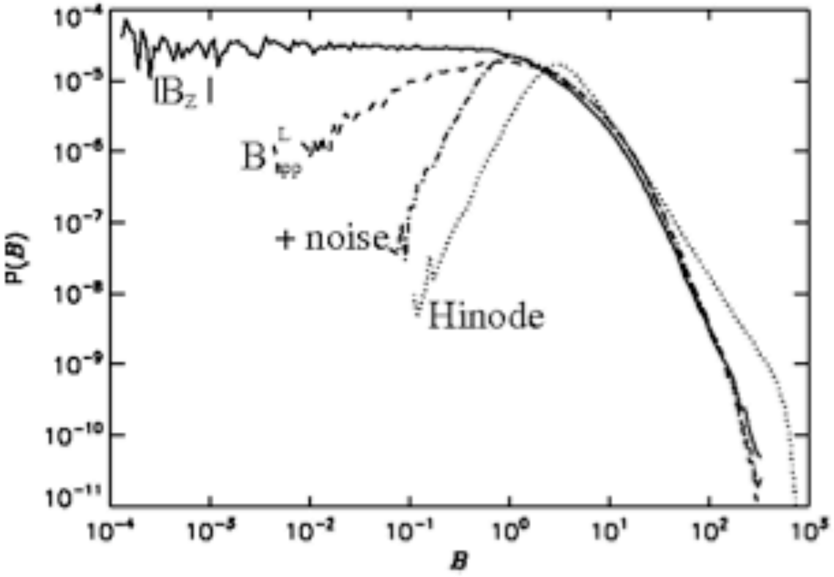
horizontal field

Prevalent weak vertical field

Observed PDF derived from Stokes V (Lites et al. 2008)



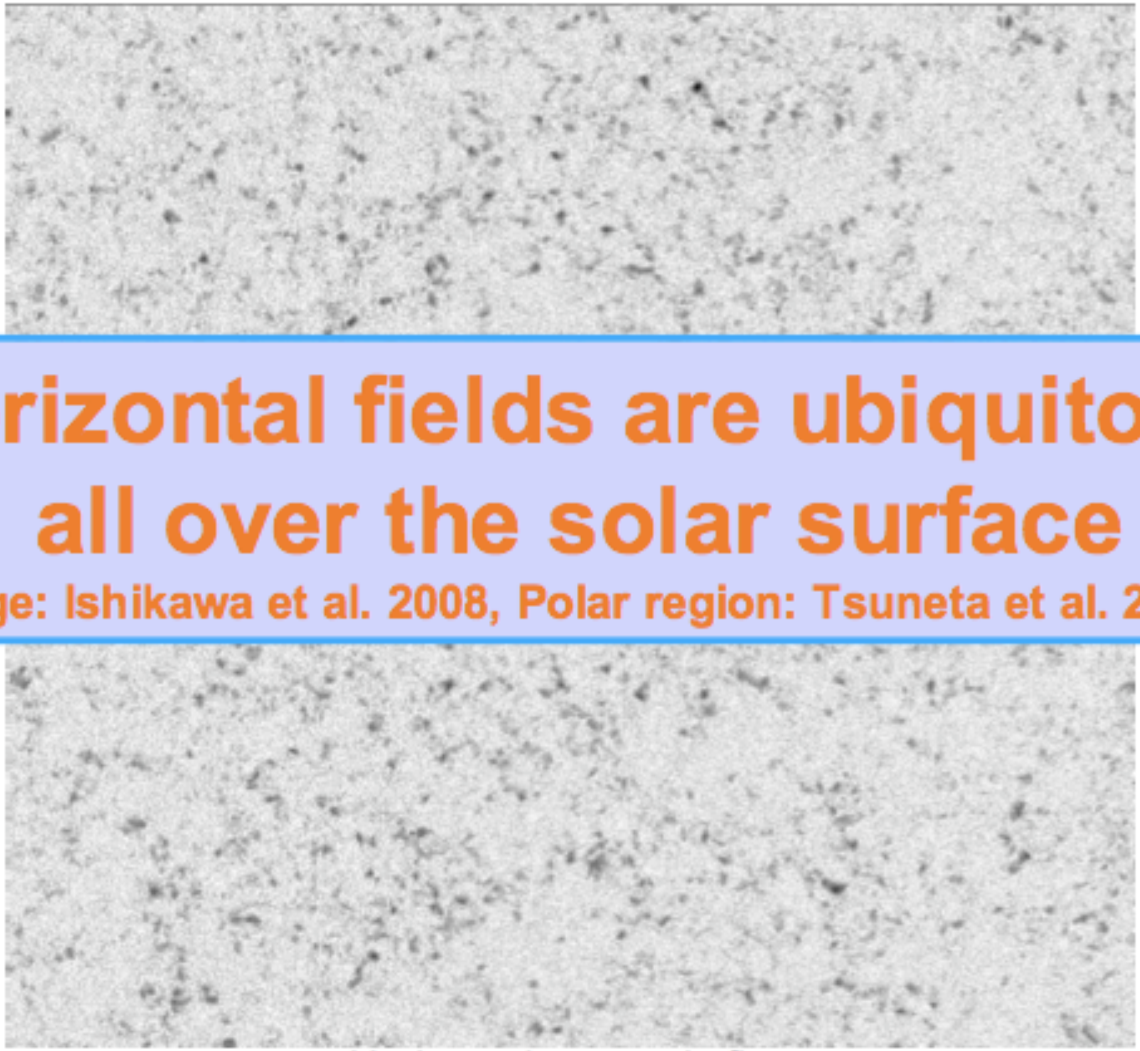
Simulated PDFs



Observed PDF is compatible with monotonic PDF of the *actual* field

Horizontal fields dominate the quiet Sun

Lites etal. 2008
Orozco Suarez etal. 2007
Centeno etal. 2007



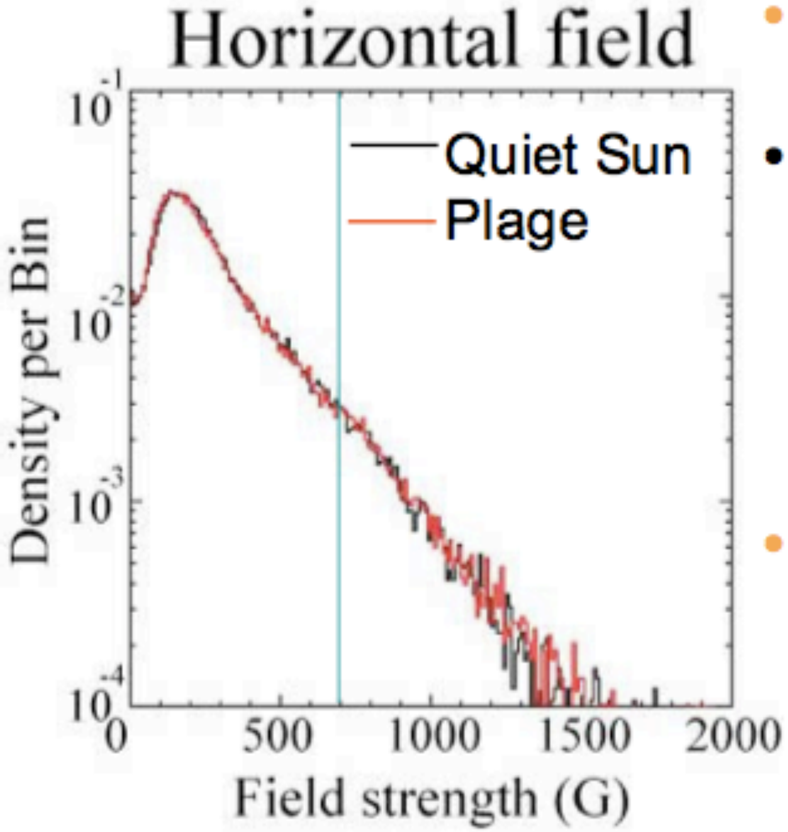
Horizontal fields are ubiquitous all over the solar surface

(Plage: Ishikawa et al. 2008, Polar region: Tsuneta et al. 2008)

Taken by Hinode/SP

Horizontal magnetic flux

Similar properties of THMFs in both regions



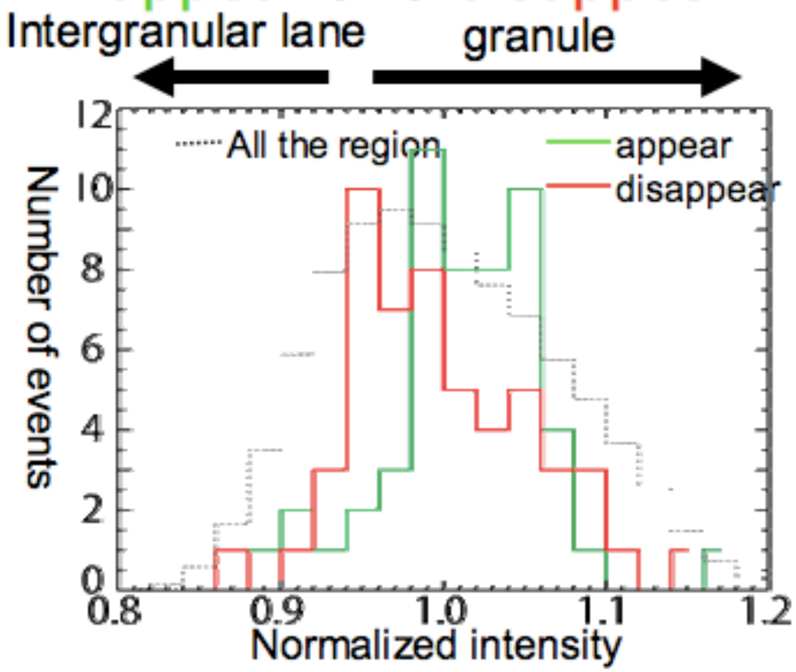
Ishikawa and Tsuneta, A&A, accepted

- No difference in field strength distribution
- 93% has field strength smaller than 700G, which is the equipartition field corresponding to the granular (convective) motion.
- Same occurrence rate between the plage and quiet regions in spite of x8 difference in vertical flux

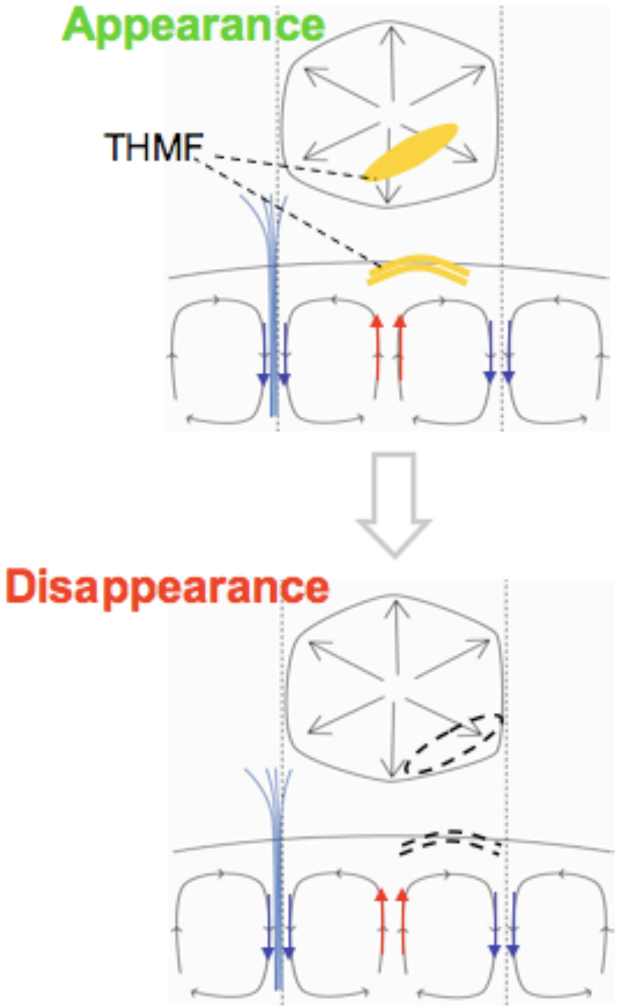
Note that network region, which has persistent strong vertical flux, are removed for the plot of the plage.

Location of THMFs appearance and disappearance

Intensity where THMFs appear and disappear



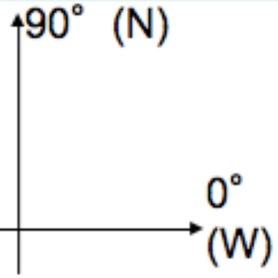
Active region THMFs



All events: no clear preferred orientation

$$Threshold:$$
$$LP > 0.22\% \;\&\; Area \geq 3\,pixels$$

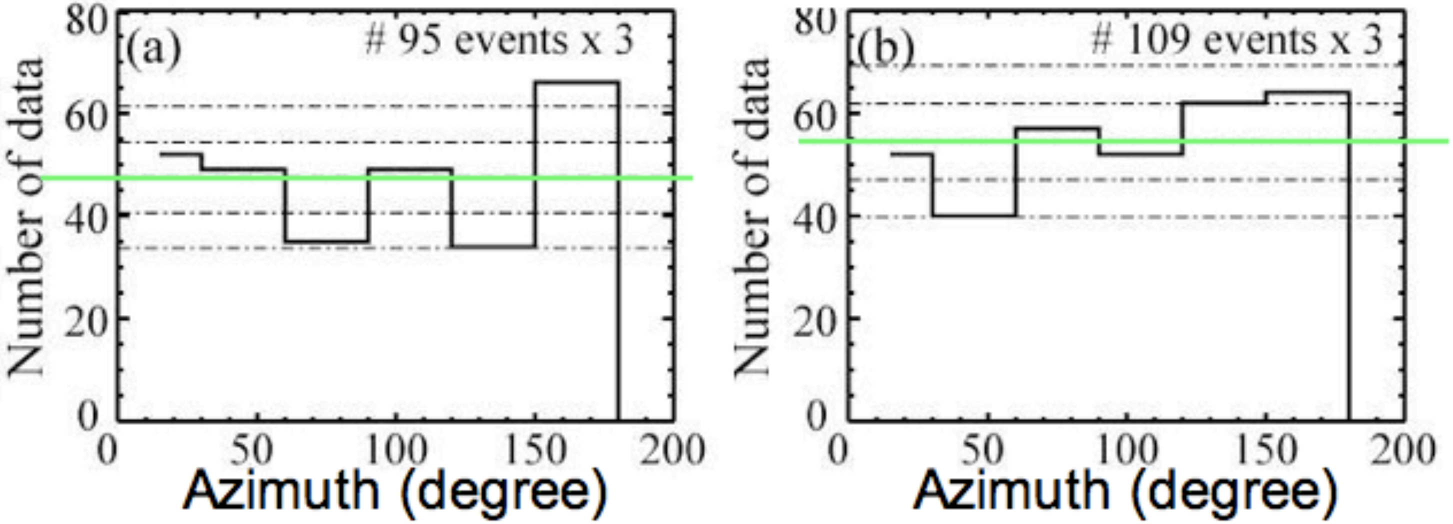
Definition



Azimuth: $\chi = \frac{1}{2}\arctan\left(U / Q \right)$

Quiet Sun

Active (plage) region



Ishikawa and Tsuneta, A&A, accepted

Properties of THMFs

- Very transient, and frequent
- The lifetime and size are smaller than those of granules
- Appear inside bright granules

→**Receptive to the convective motion**

- THMFs are found in the quiet Sun, plage region, and polar region, and the properties are the same.
- Magnetic field strength lower than equipartition field corresponding to granules
- Same occurrence rate between active (plage) region and QS in spite of x8 difference in vertical flux
- Essentially no preferred orientation for all events

→**The properties of THMFs are independent from global magnetic fields**

Local dynamo process would be generating THMFs all over the Sun

Open questions

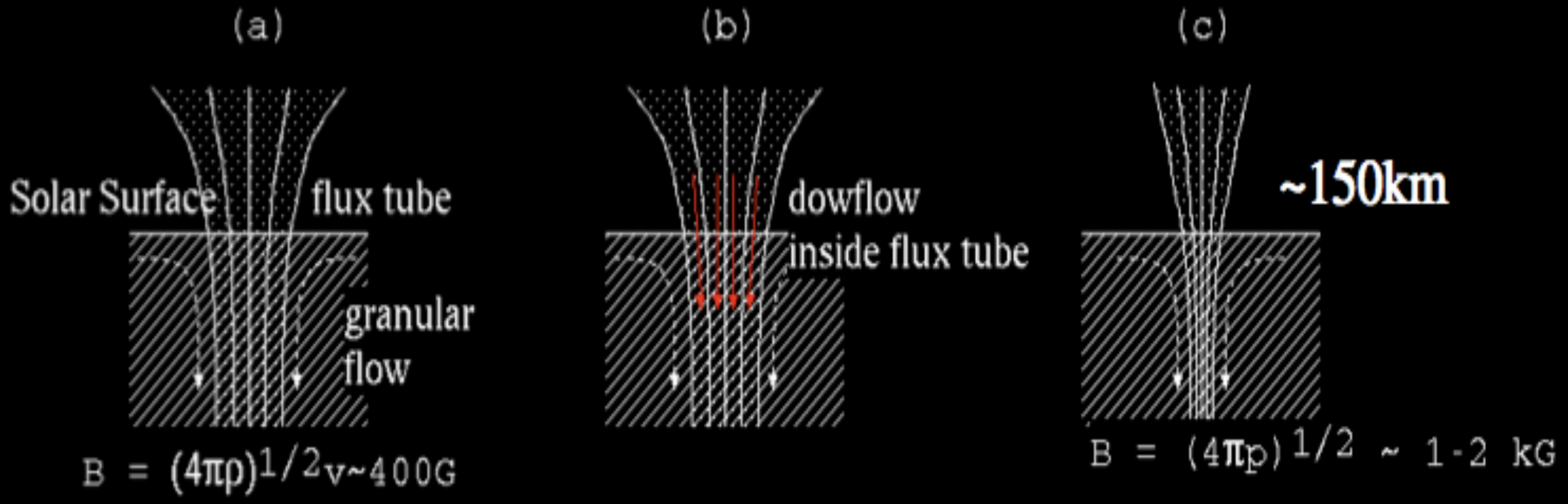
- ***When THMFs disappear, they do not necessarily reach the inter granular lane. Where do THMFs go? Do THMFs reach the chromosphere?***
- ***What is the magnetic configuration of THMFs?***

Convective Collapse to form Flux Tubes

- S. Nagata, “Convective Instability and the Formation of Solar Magnetic Flux Tubes,” 2nd Hinode Science Meeting, Boulder, Oct 2008
- C. Fischer, “Analysis of High Cadence Hinode SP Quiet Sun Time Series”

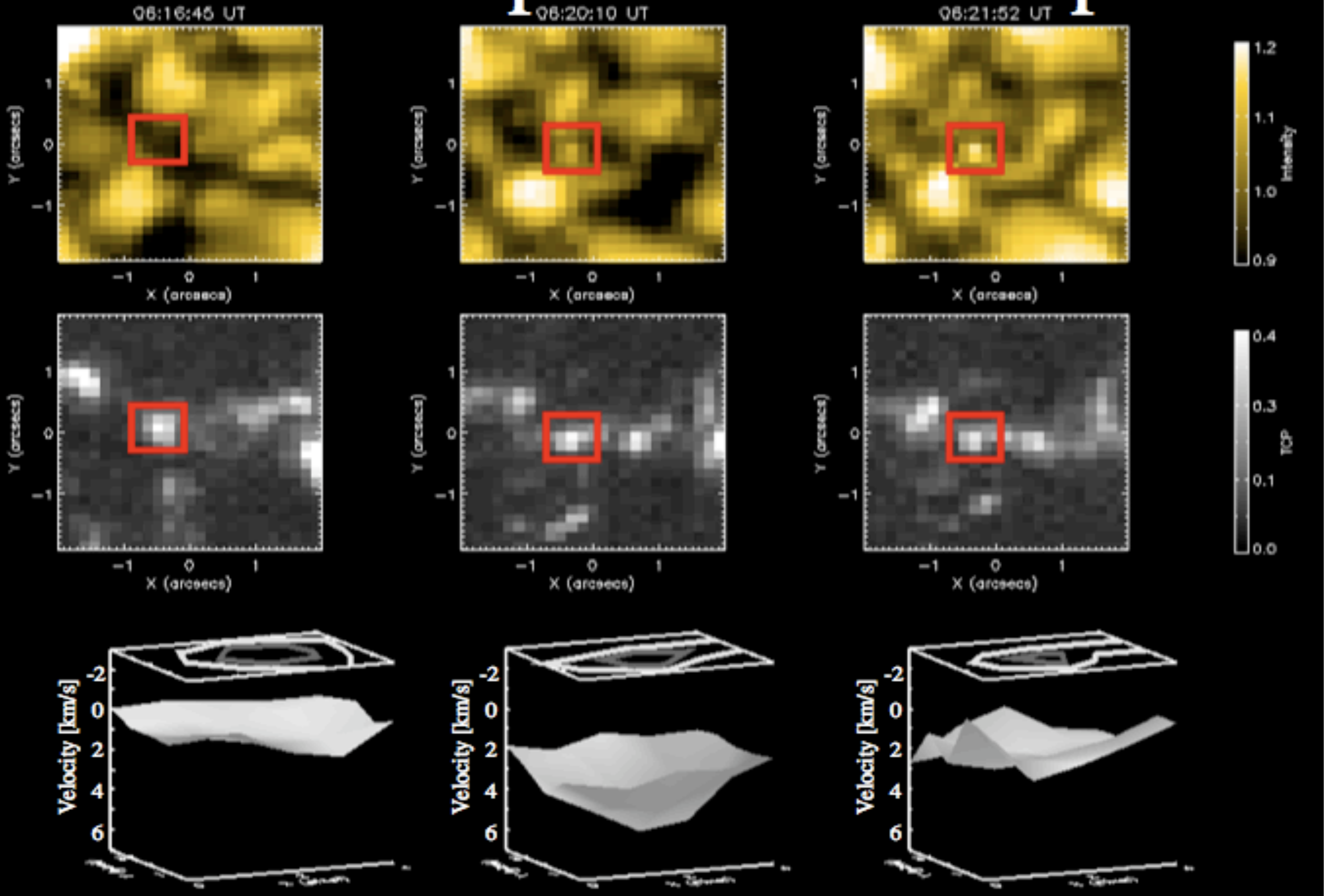
Convective Collapse

A model to explain the formation of kilo-gauss field flux tube on the Sun
Parker (1978); Webb & Roberts (1978); Spruit & Zweibel (1979)



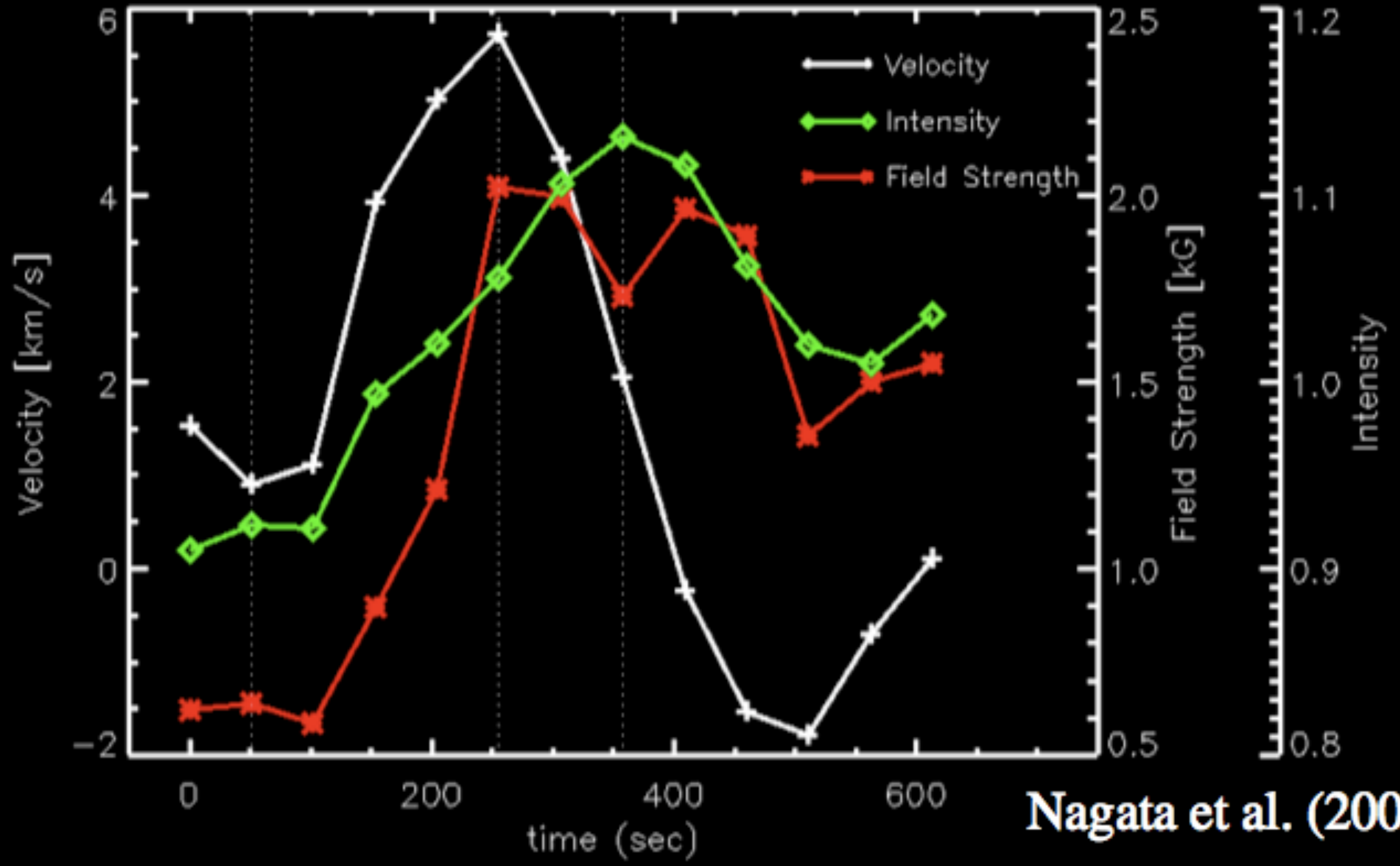
- a) Magnetic Fields are swept into the inter granular lanes; flux expulsion. The field strength archived in this process is ~ 400 G. (Equipartition field)
- b) Convective instability inside the flux tube lead to the down flow.
- c) The evacuated flux tube shrinks to balance the magnetic pressure with the surrounding gas pressure, the resultant field strength is kilo gauss.

The most prominent example



Nagata et al. (2008)

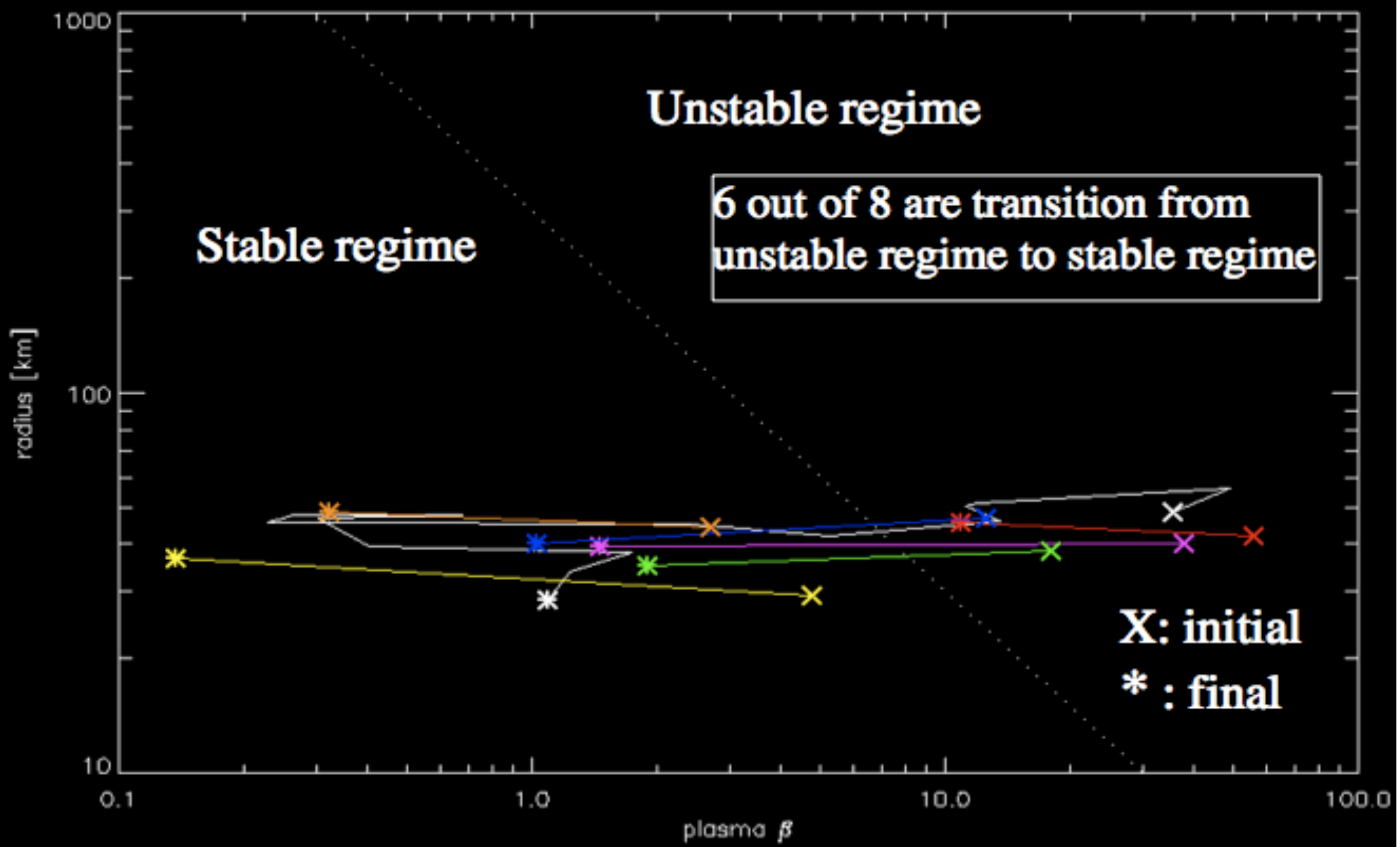
The most prominent example



Nagata et al. (2008)

The field strength intensification along with the growing downflow is *qualitatively* consistent with the theoretical prediction.

Evolution curve on β-a diagram



6 out of 8 are transition from unstable regime to stable regime

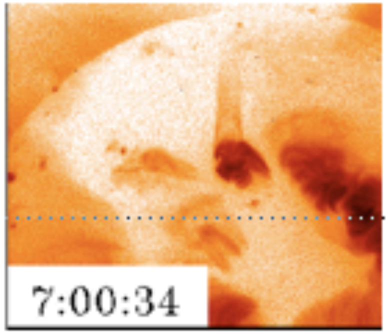
X: initial

* : final

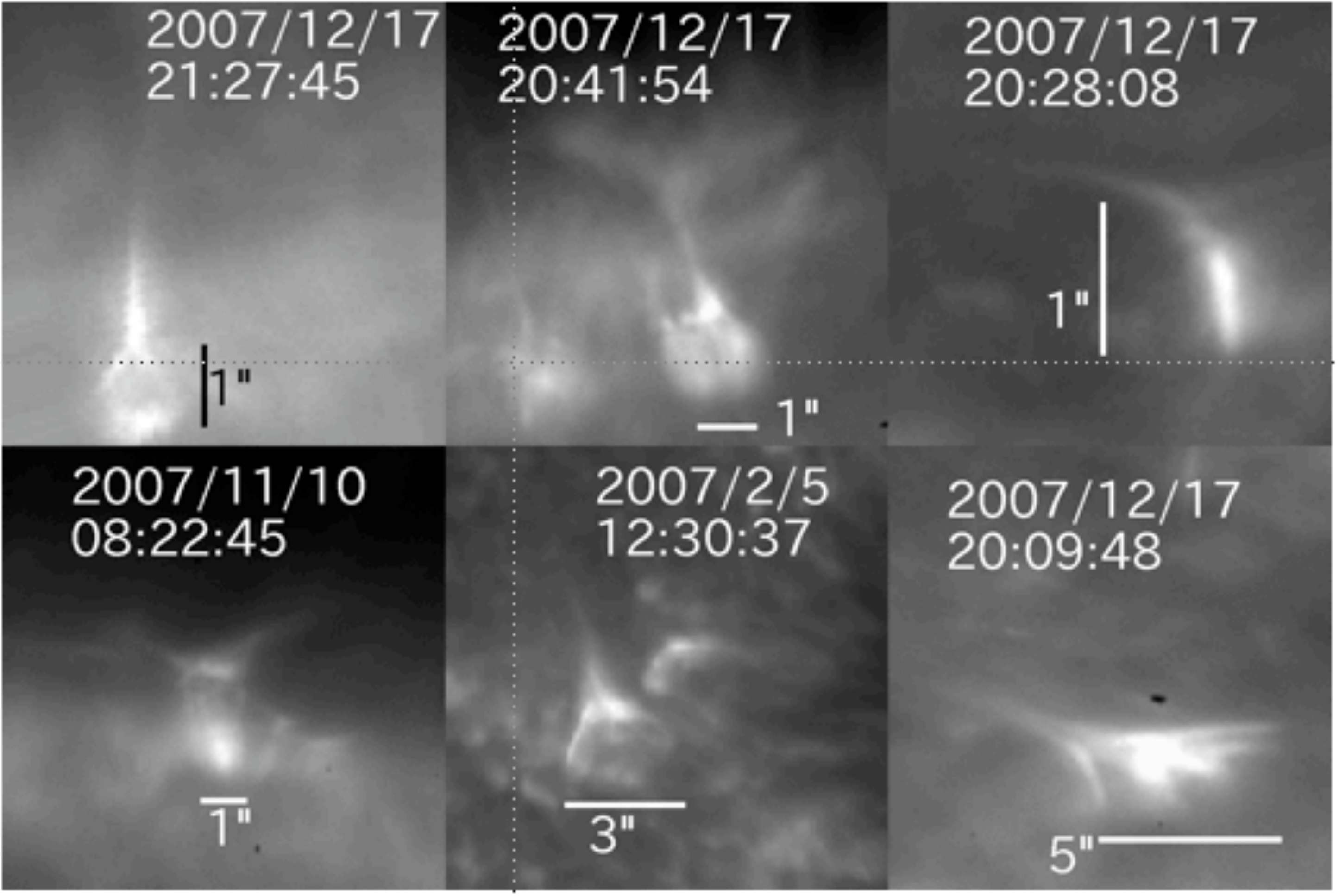
Reconnections & Jets Everywhere

- K. Shibata, “Ubiquitous Magnetic Reconnection in the Solar Atmosphere,” 2nd Hinode Science Meeting, Boulder, Oct 2008
- M. Shimojo, “The Relationship between the Magnetic Field and the Coronal Activities in the Polar Region”
- R. Kano et al, “Photospheric Magnetic Activities to Trigger Micro-flares Observed with Hinode SOT and XRT”
- Y. Katsukawa & J. Jurcak, “Chromospheric Activity at the Smallest Scales Obtained by Hinode: Small Scale Activities in Penumbrae”
- T. Shimizu, “Hinode Observation of the Vector Magnetic Fields in a Sunspot Light Bridge Accompanied by Chromospheric Plasma Ejections”

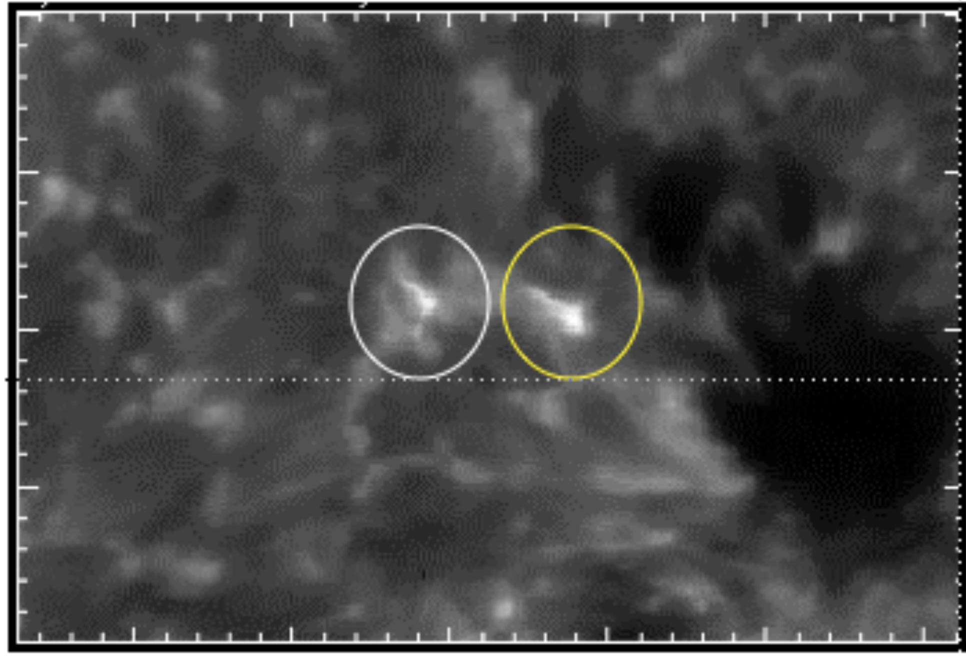
Various Ca II H jets



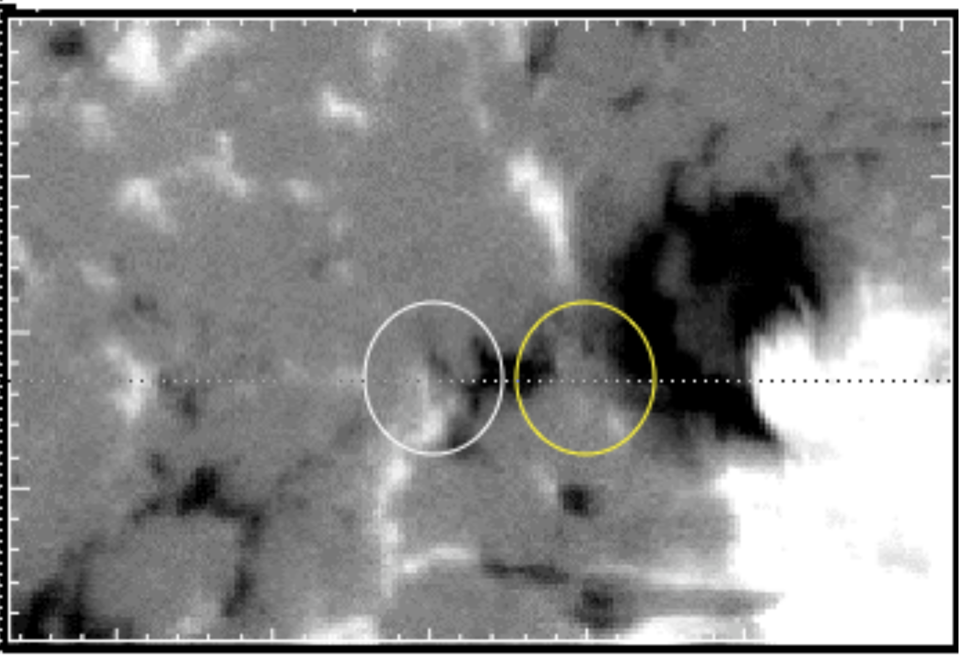
Yohkoh
Anemone
X-ray jet



Relation to magnetic field



CaII H



FG Stokes V

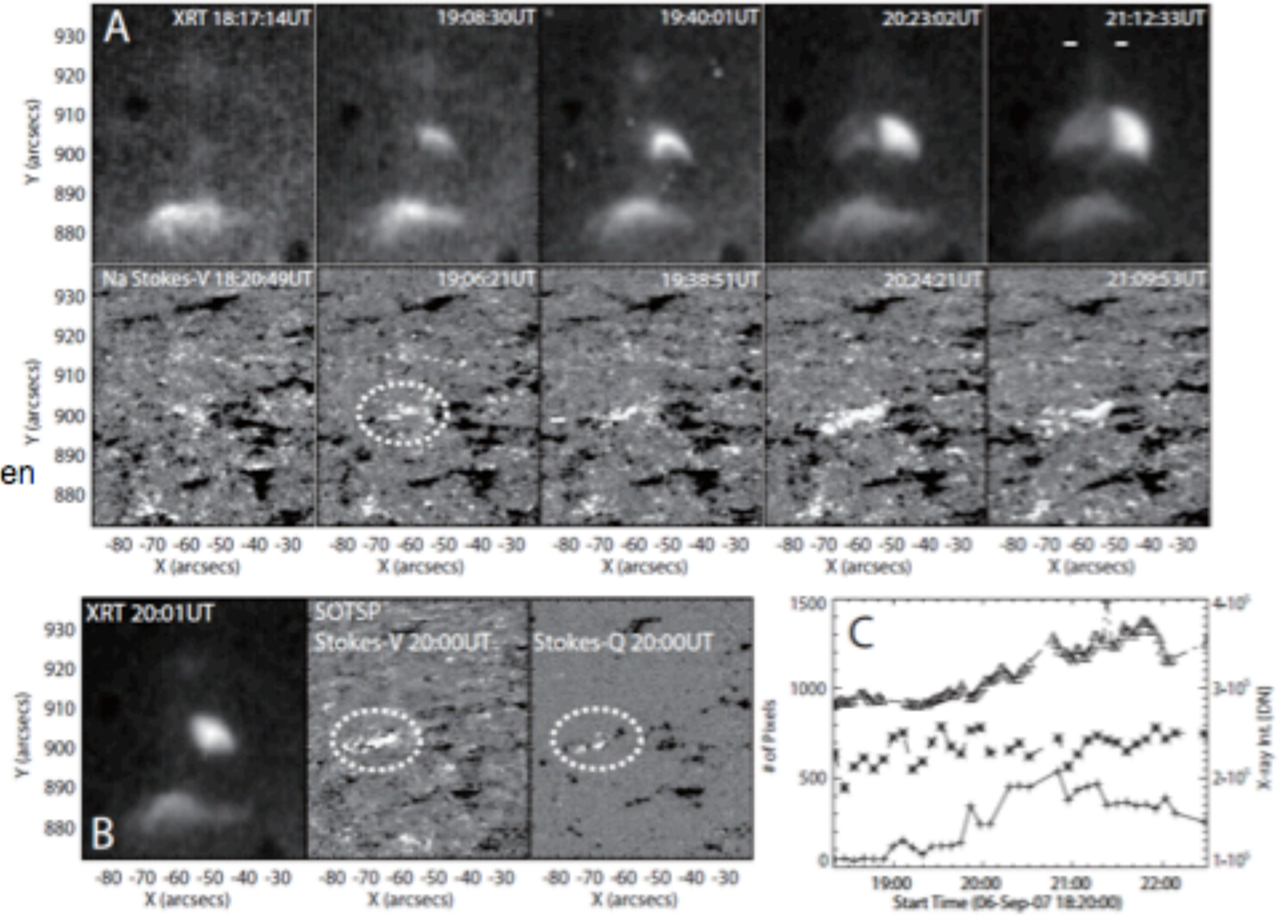
Result:2

The magnetic fields of the jet regions around the pole.

- An ephemeral region in the polar region with an X-ray jet

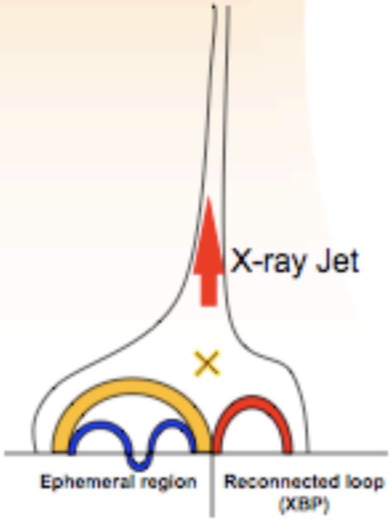
White: ⊙ toward us

Black: ⊗ toward the screen

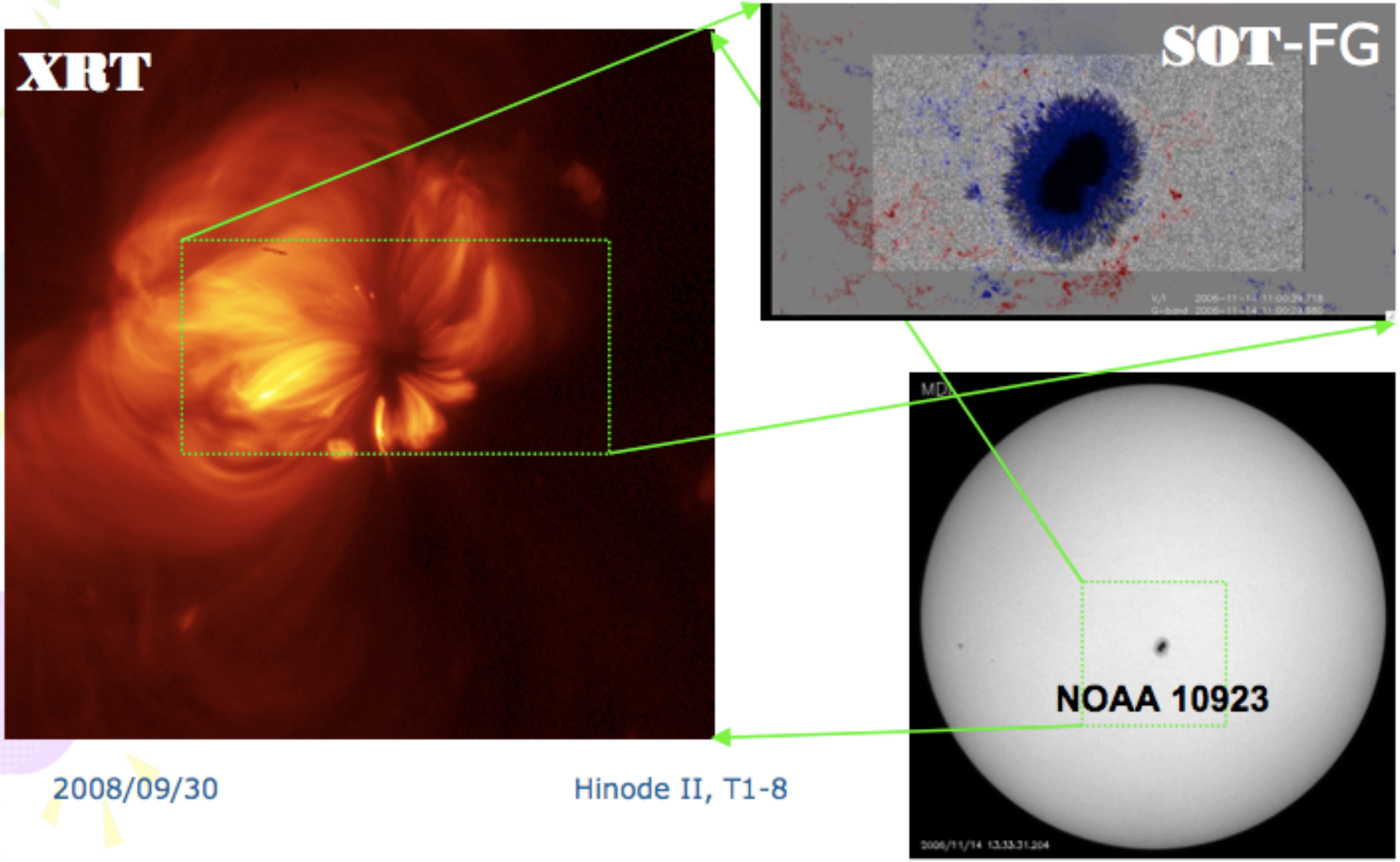


White: ↔

Black: ↕

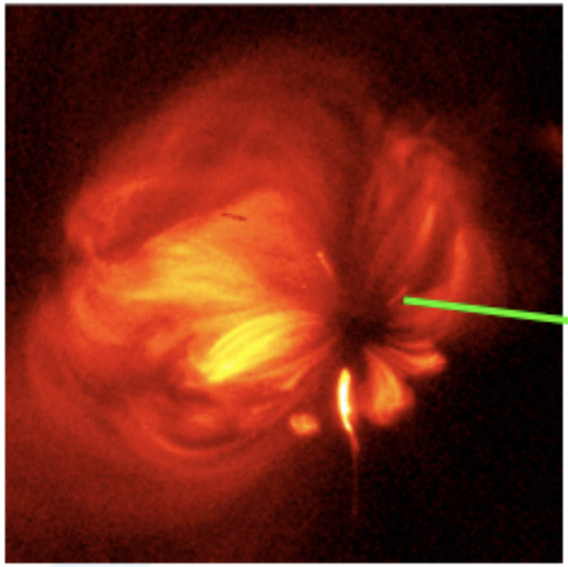


Micro-flares observed with Hinode

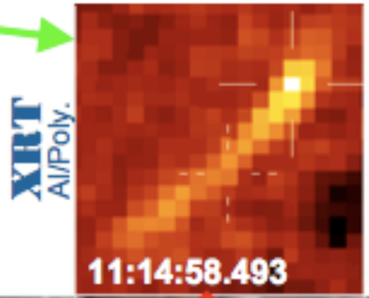


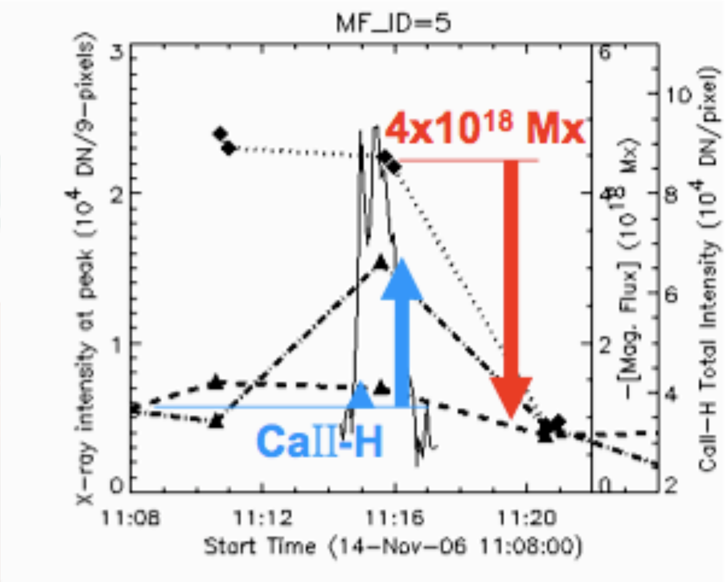
2008/09/30

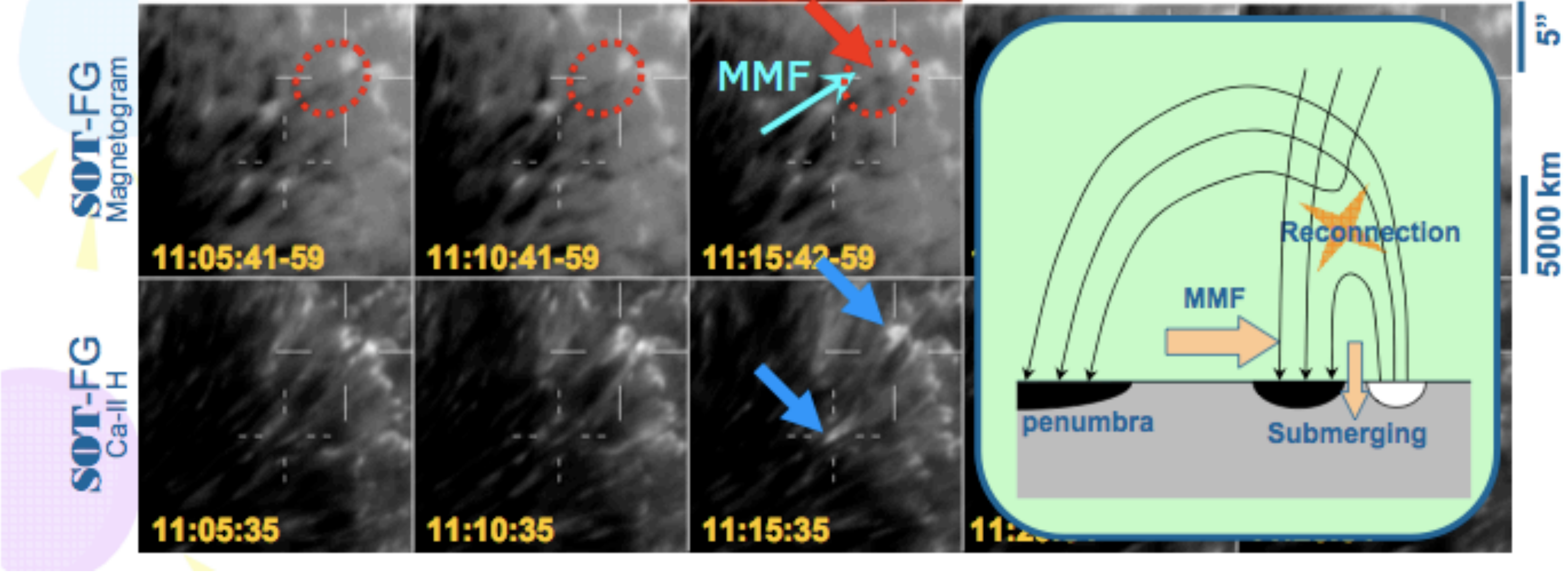
Hinode II, T1-8



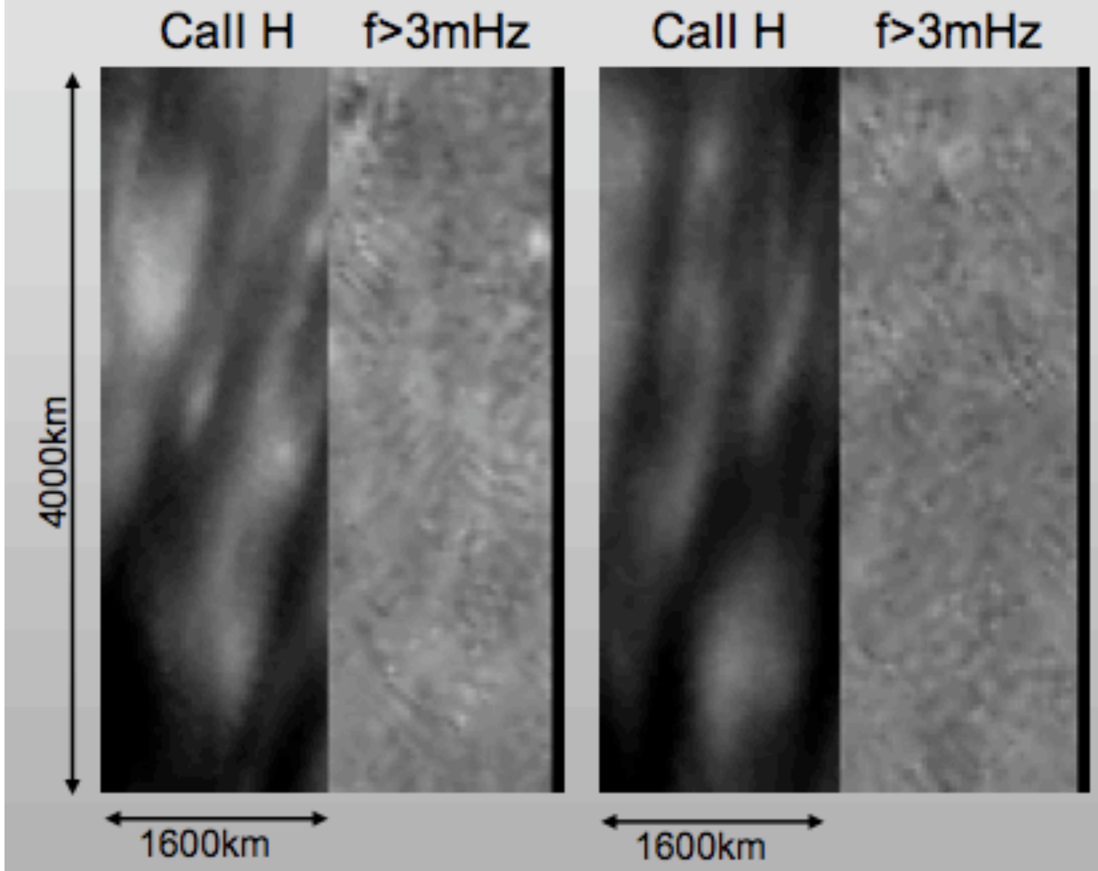
event-(

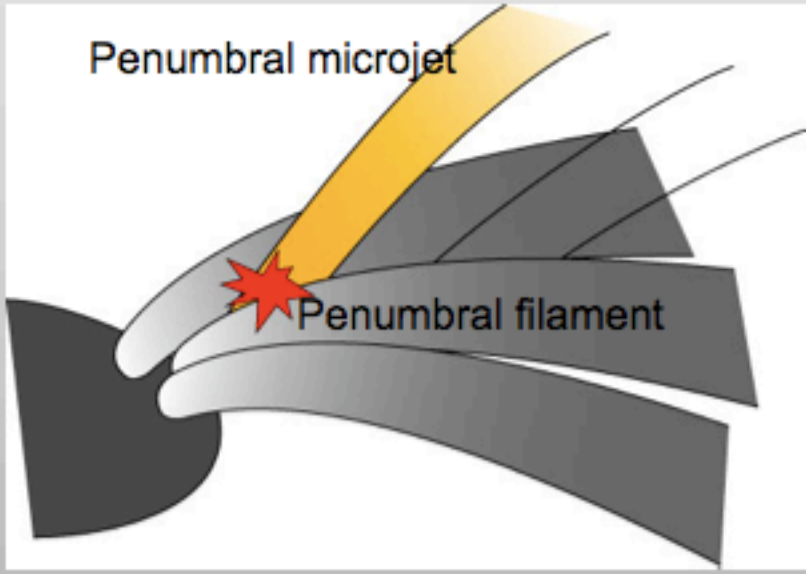

XRT
Al/Poly.
11:14:58.493


MF_ID=5
4x10¹⁸ Mx
CaII-H
X-ray intensity at peak (10⁴ DN/9-pixels)
-[Mag. Flux] (10¹⁸ Mx)
Ca II-H Total Intensity (10⁴ DN/pixel)
0
1
2
3
0
2
4
6
2
4
6
8
10
11:08
11:12
11:16
11:20
Start Time (14-Nov-06 11:08:00)


SOT-FG
Magnetogram
SOT-FG
Ca-II H
MMF
11:05:41-59
11:10:41-59
11:15:42-59
11:05:35
11:10:35
11:15:35
11:2
Reconnection
MMF
penumbra
Submerging
5"
5000 km

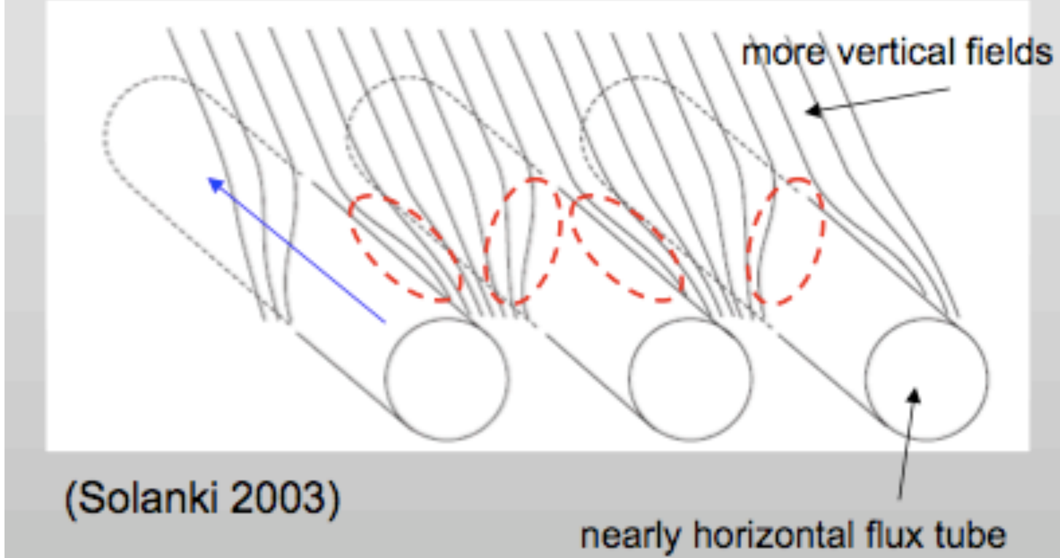
Detailed structure of penumbral micro-jets



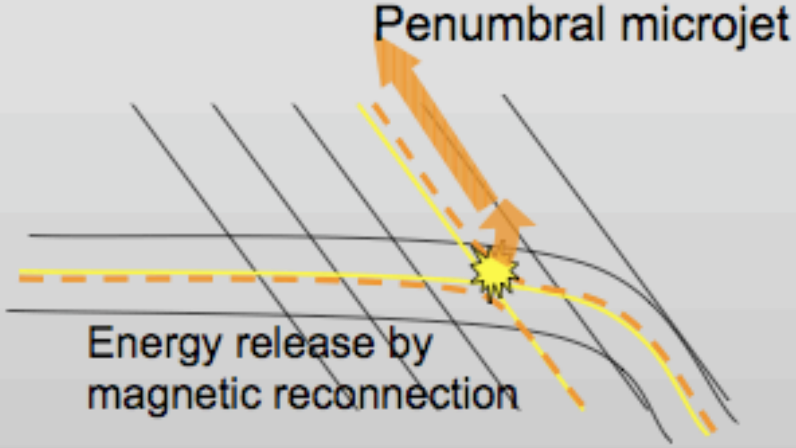


- Emanate from between two penumbral filaments, suggesting the penumbral microjets are following background vertical fields.
- Happen near penumbral grains migrating to an umbra.

Possible mechanism of the penumbral microjets



(Solanki 2003)



- The uncombed magnetic configuration may cause magnetic reconnection between the two magnetic components, and makes jet-like transient brightenings.
- The discovery of the penumbral microjets are important:
  - Consumption of magnetic energies and restructuring of sunspot magnetic fields
  - There is a possibility that we can directly measure magnetic configuration around magnetic reconnection sites.
- Are there any photospheric signatures?

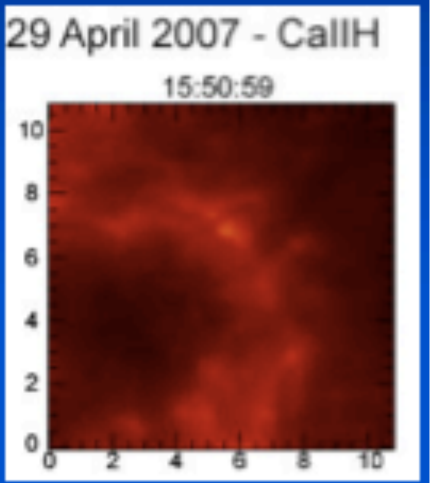
Recurrent chromospheric plasma ejections

- Recurrent ejections
  - 29 April Nothing happened before 19:50UT.
  - 30 April Occurred in almost all the periods. Continued until 1 May.

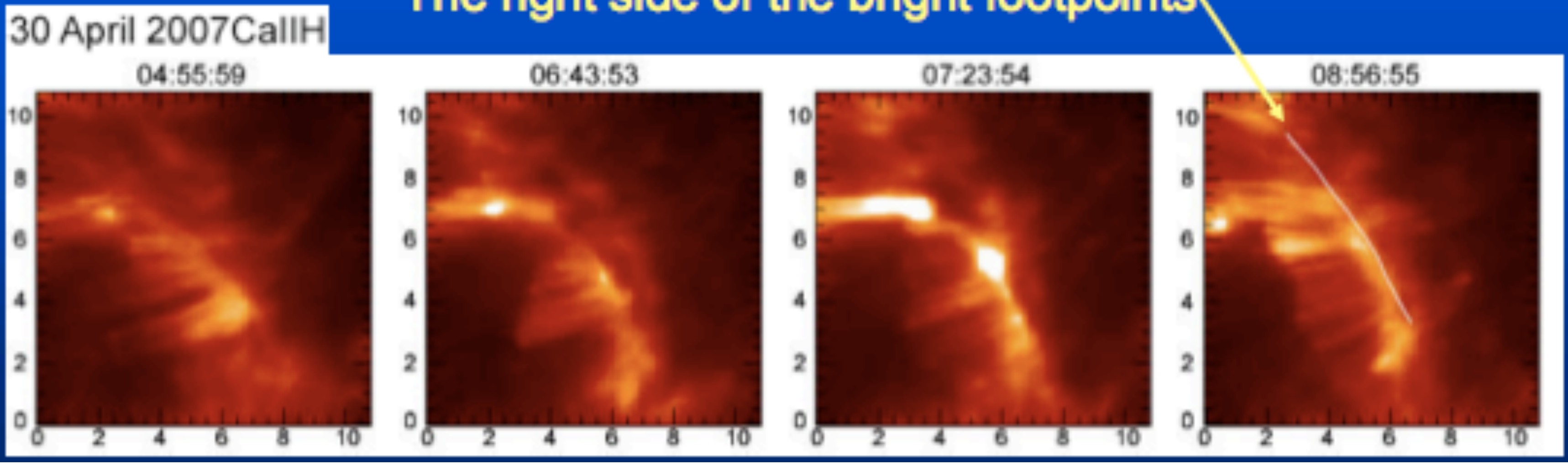
  ※ What changed magnetically from 29 April to 30 April?
- Physical parameters of ejections
  - Apparent length: 1,500-3,000km, speed: 6-40km/s
  - Inclination of magnetic field at the footpoints (SP data)

    166.7deg from LOS direction
    - Estimated length 6,500-13,000km
    - Estimated upward speed 26-180km/s

NOAA10953


29 April 2007 - CaIIH

The right side of the bright footpoints


30 April 2007CaIIH

Activities in the LB : Interpretation

- Long-lasting chromospheric plasma ejections
  - Indication of magnetic reconnections at the very low altitude
  - Close to the height where the magnetic fields are measured with SP
    - Providing the magnetic field structure near reconnection points

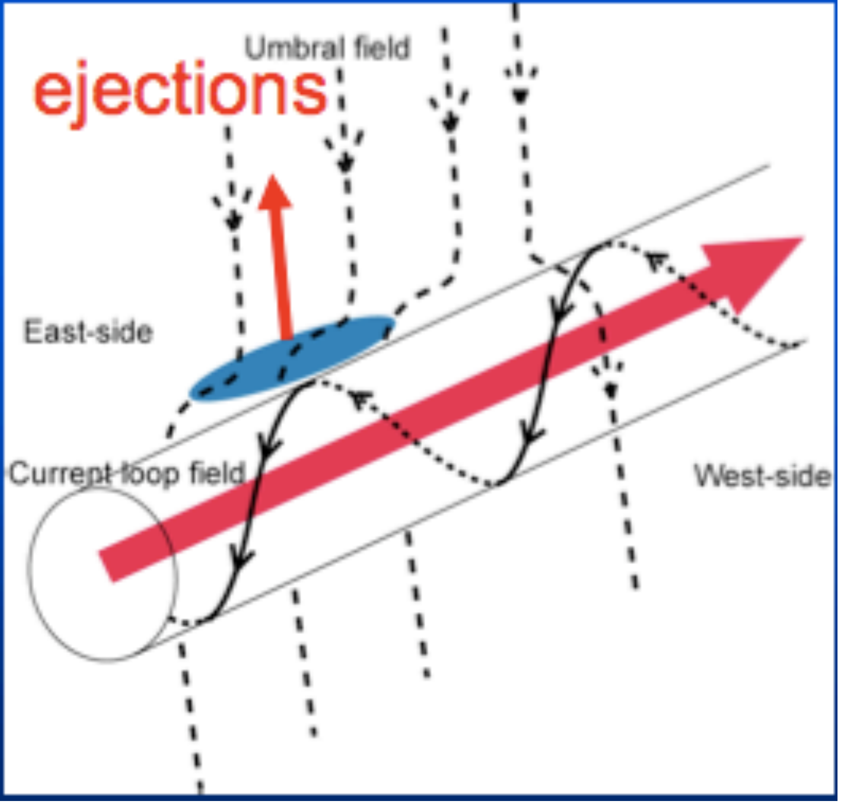
    c.f. Loop microflares

- Lying "twisted" magnetic flux (current carrying) loop
  - Red current "line" = Current loop
  - Upward current loop is trapped below the cusp-like magnetic field
  - Ejections were observed only at the east side of the current loop

  Formation of anti-parallel magnetic field lines

  → Magnetic reconnection

  → Chromospheric plasma ejections

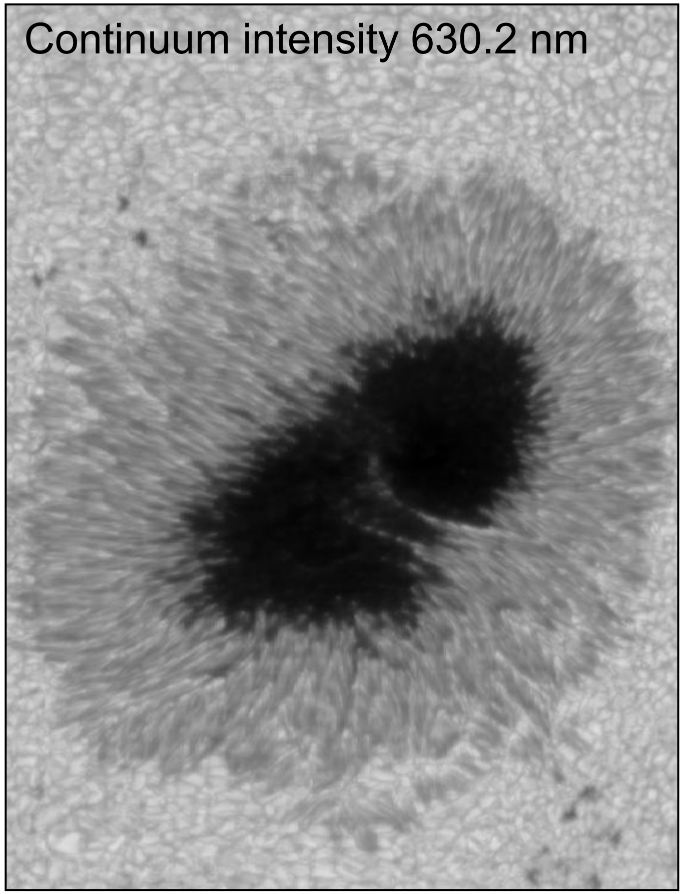


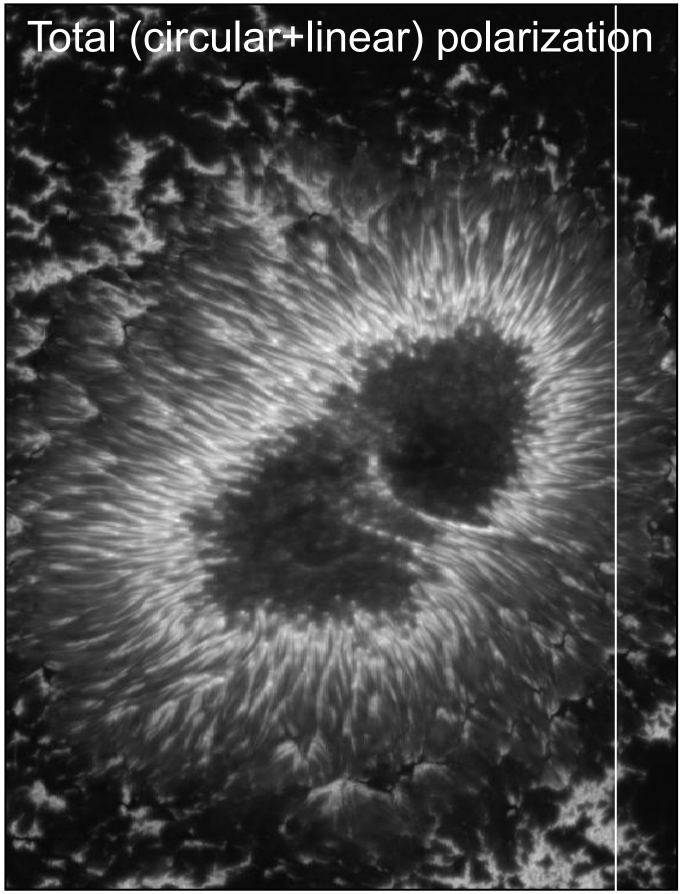
Penumbral Field Structure

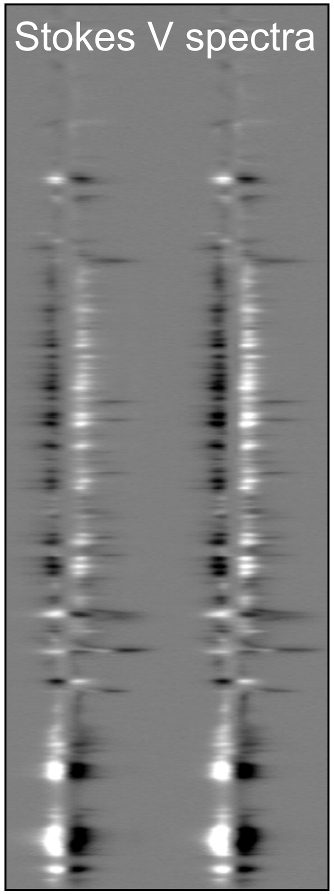
- L. Bellot Rubio, “Sunspot Magnetic Fields near the Diffraction Limit: the Hinode View,” 2nd Hinode Science Meeting, Boulder, Oct 2008

- K. Ichimoto, “Convective Nature of the Evershed Observed by SOT/Hinode,” ibid.

Hinode/SP: full Stokes spectropolarimetry at 0.3"


Continuum intensity 630.2 nm


Total (circular+linear) polarization


Stokes V spectra

2006-11-14
Target: NOAA 10940
Heliocentric angle: 8°
Mode: normal map

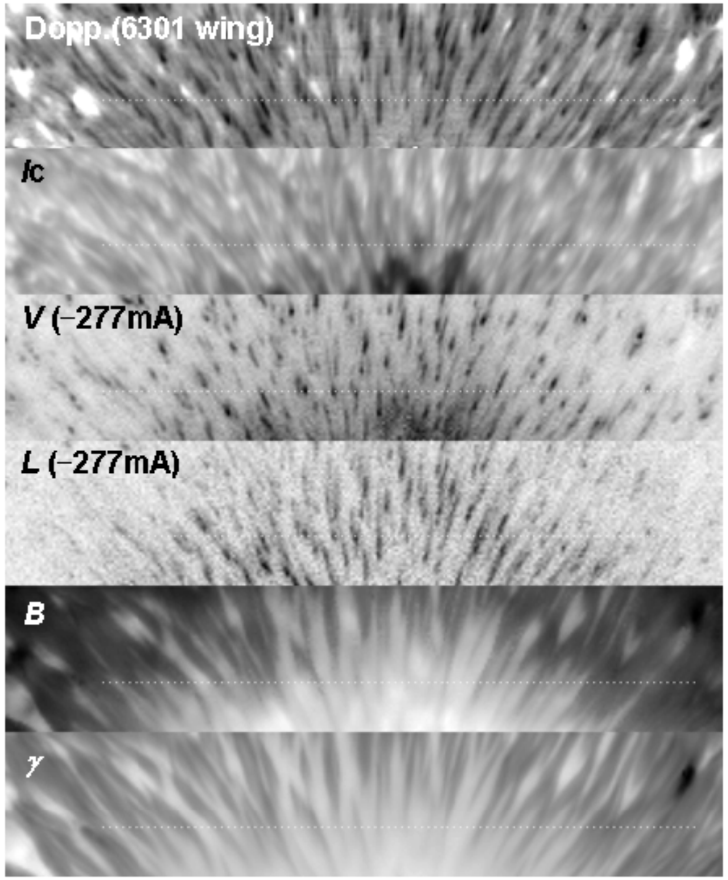
Exposure time:	4.8 s/slit
Slit width and length:	0.16″, 164″
Noise level:	$1.1 \times 10^{-3}\ I_c$
Spatial resolution:	0.3″

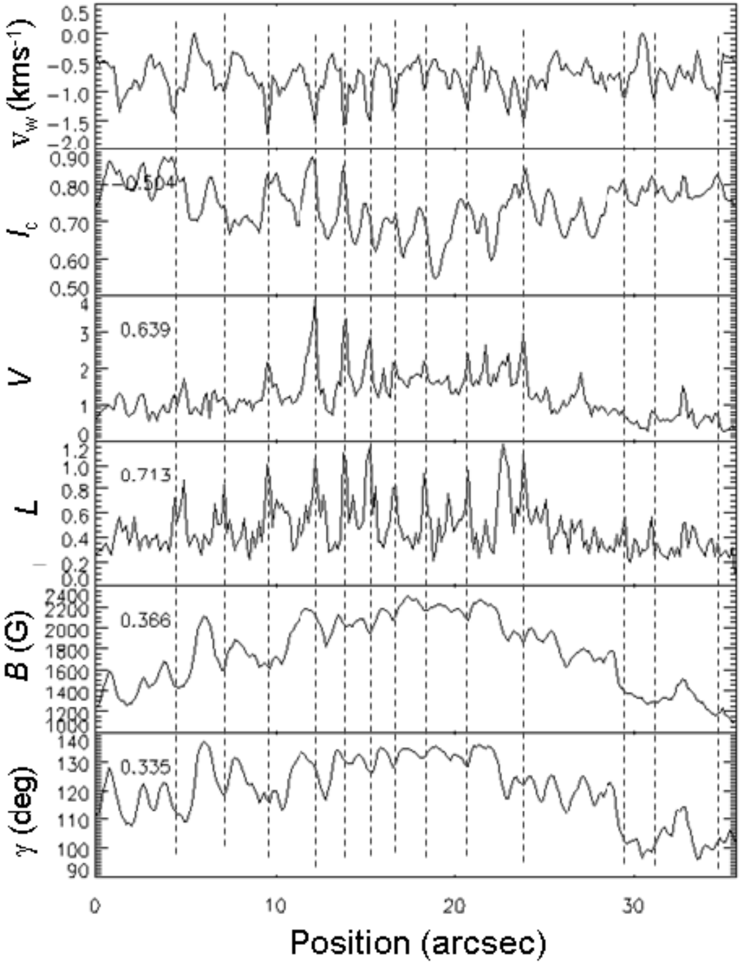
Horizontal interlacing of different magnetic components

Ichimoto et al., 2007, PASJ, 59, 593

Milne-Eddington inversion

At 0.3", two magnetic components show up prominently in the field strength and inclination maps derived from ME inversions

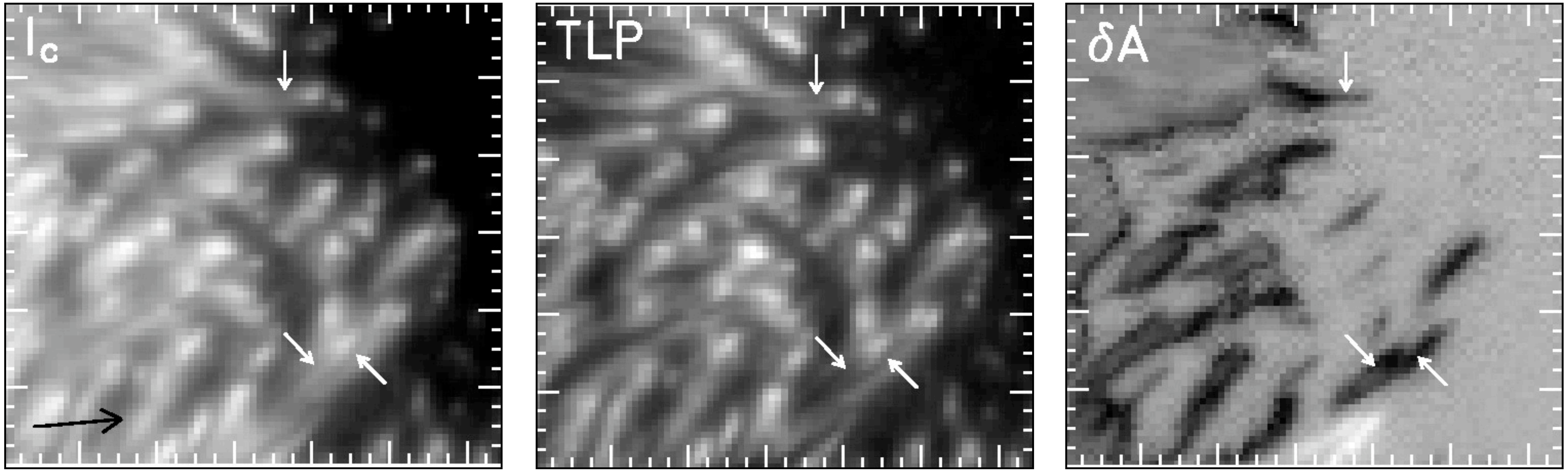




Vertical interlacing of different magnetic components

Bellot Rubio et al., 2007, ApJ, 668, L91

Bright filaments in inner limbside penumbra



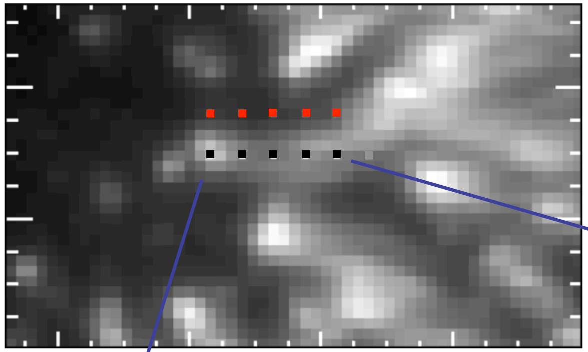
The NCP of spectral lines is not zero and shows correlation with penumbral filaments, confirming results of Tritchler et al. (2007) and Ichimoto et al. (2008)

Bright filaments are distinct structures (with flows) embedded in ambient sunspot field

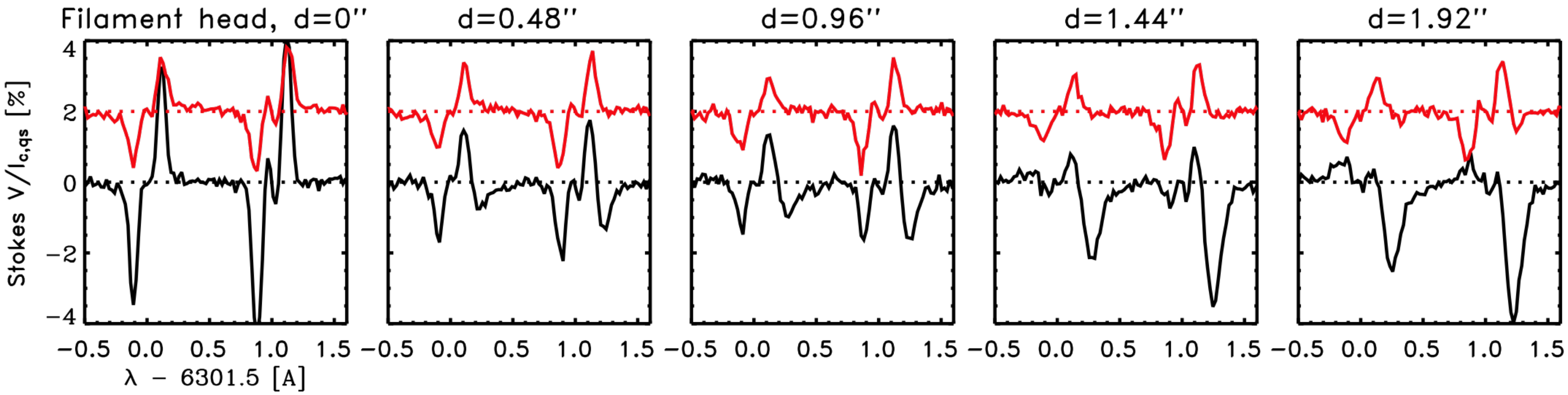
Multi-lobed Stokes V profiles reflect vertical interlacing

Bellot Rubio et al., 2007, ApJ, 668, L91

Limb-side penumbra, θ = 50°



Multi-lobed Stokes V profiles still occur, but now it is less likely that they are due to horizontal interlacing of different magnetic components

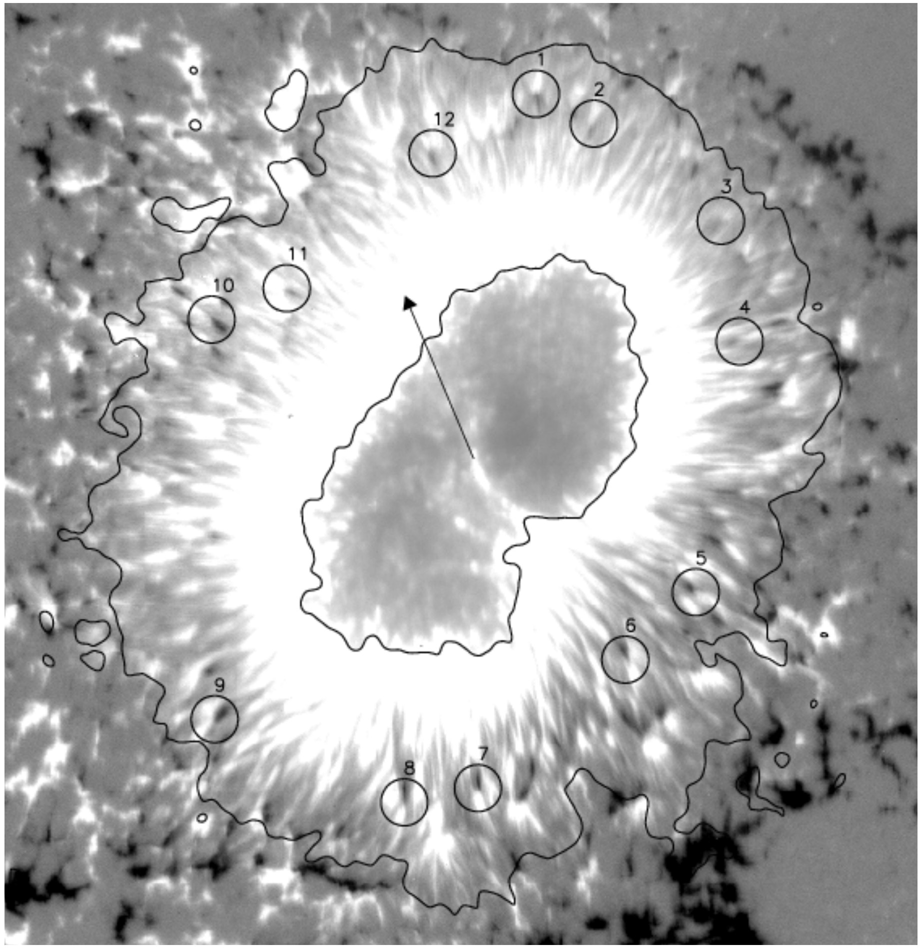


***Magnetic* components of opposite polarity exist along the LOS: one is strongly Doppler-shifted to the red**

Penumbral field lines return back to solar surface

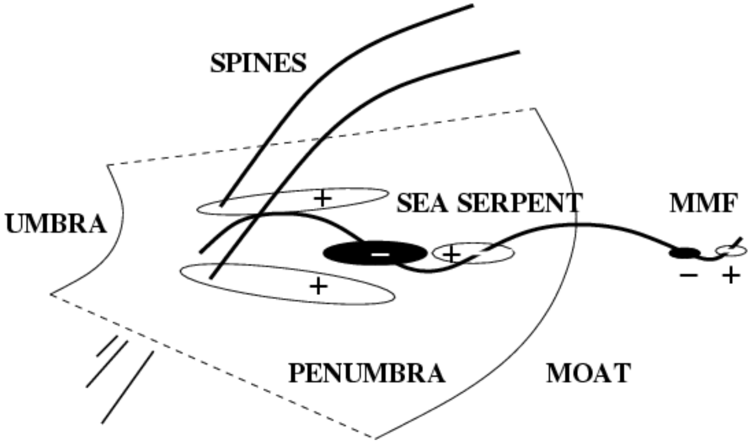
Sainz Dalda & Bellot Rubio, 2008, A&A, 481, L21

Hinode/NFI Fe I 630.2 nm, Δλ = −120 mÅ



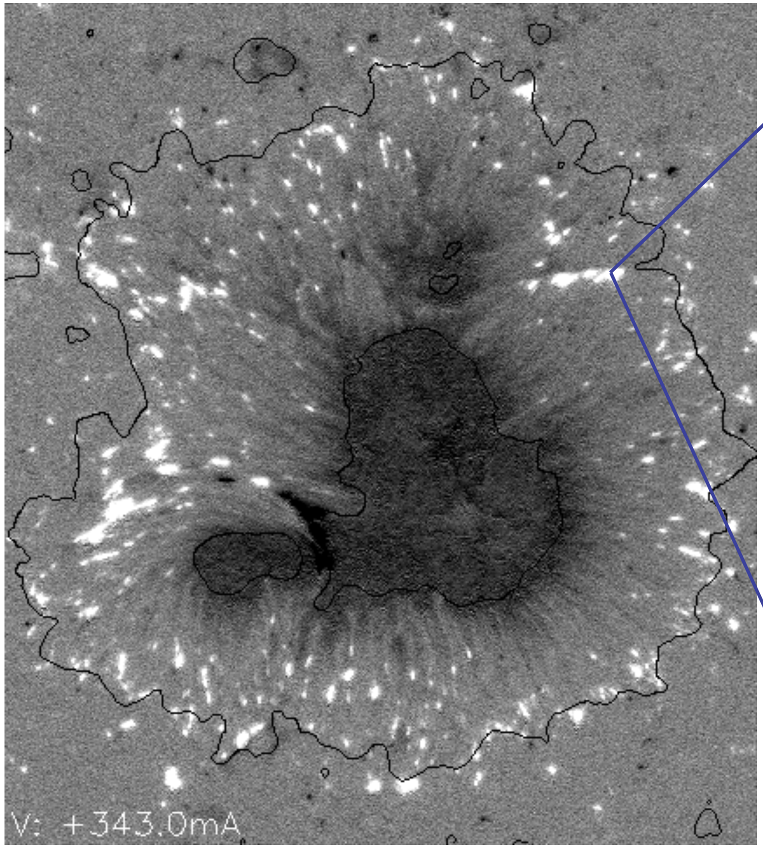
Opposite-polarity field lines occur everywhere in the mid and outer penumbra

First time that they are imaged directly (confirming earlier inversion results….)

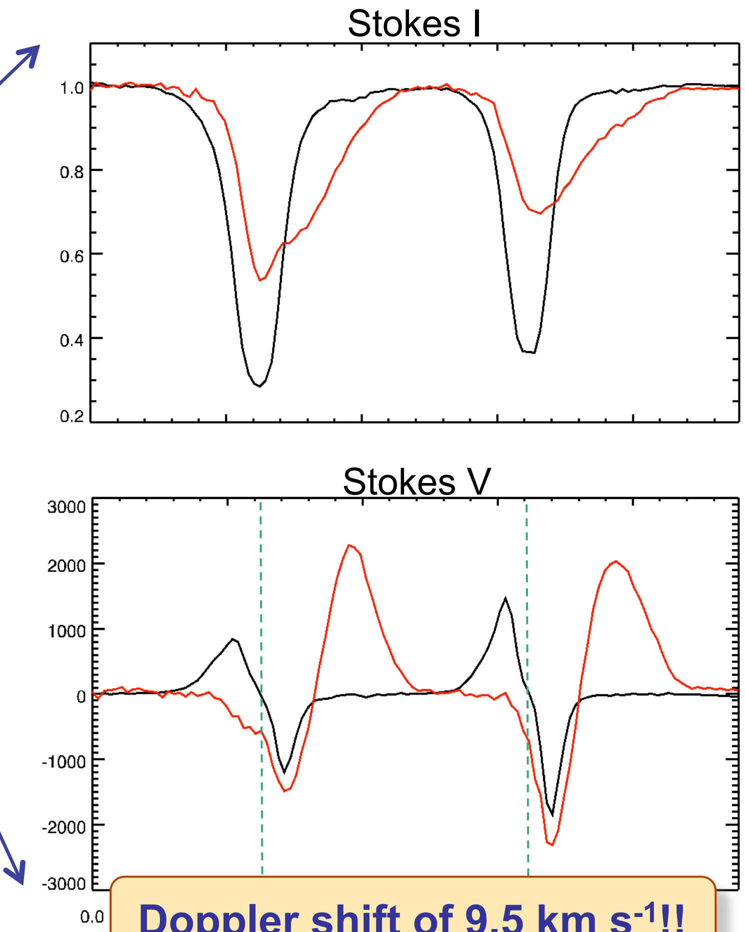


Supersonic Evershed flows occur in the penumbra

Stokes V signal at +343 mÅ (~12 km s^{-1})



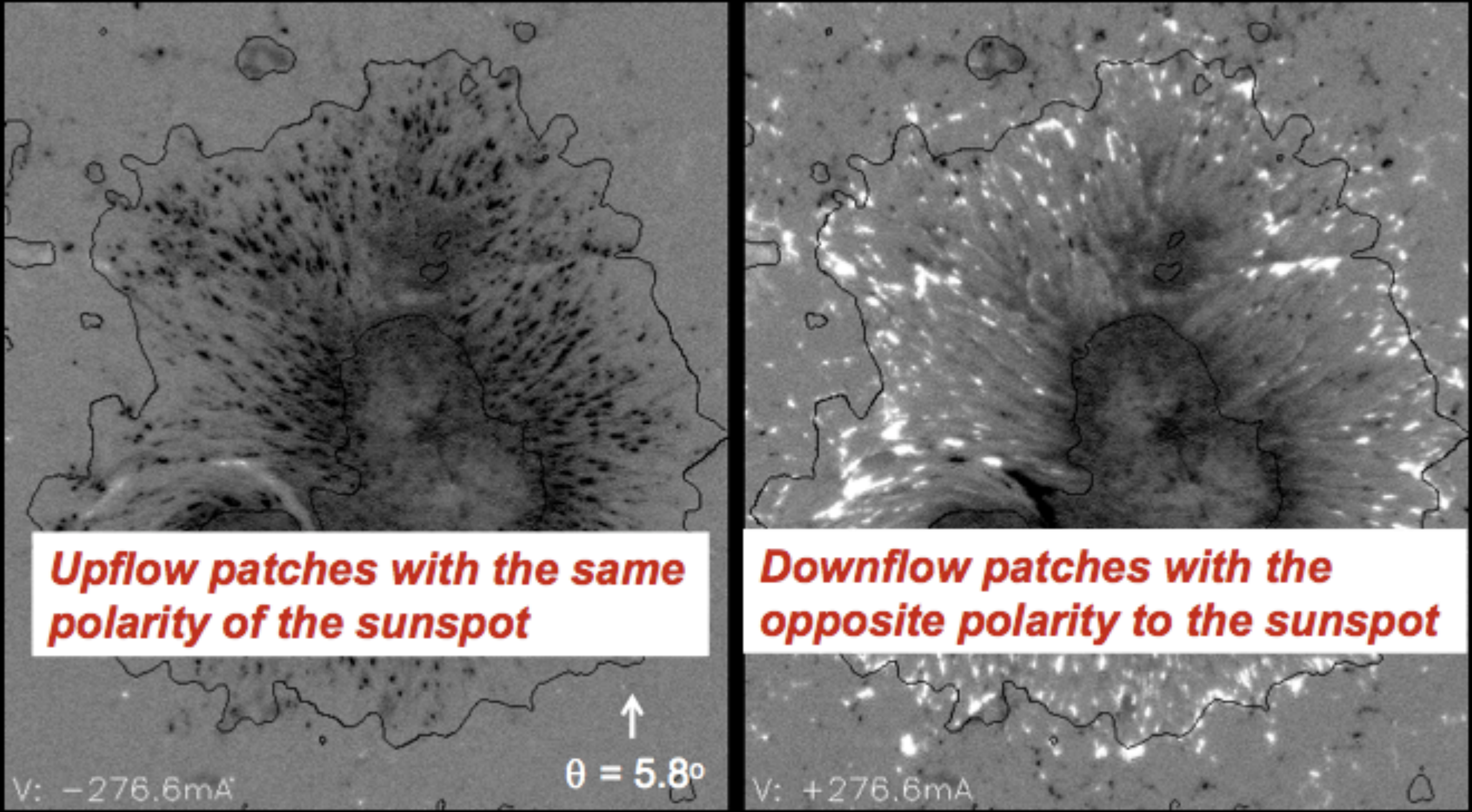
NOAA 10973, θ ~ 5°, courtesy K. Ichimoto



Doppler shift of 9.5 km s^{-1}!!

Patches with supersonic flows are observed everywhere in the middle and outer penumbra (as also reported by Shimizu et al. 2008)

Stokes-V at 6302.5A ±277mA



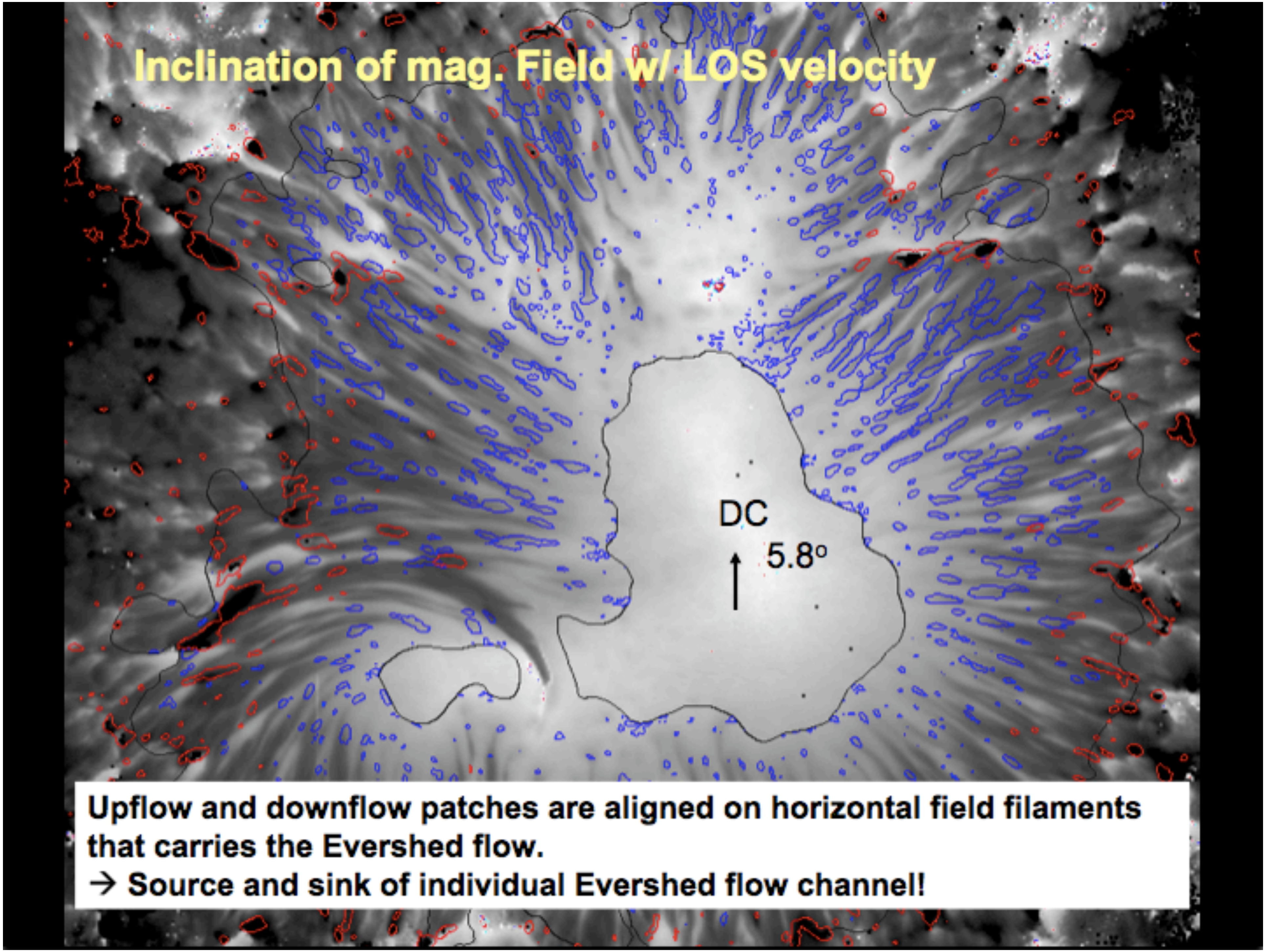
Upflow patches with the same polarity of the sunspot

Downflow patches with the opposite polarity to the sunspot

-277mA

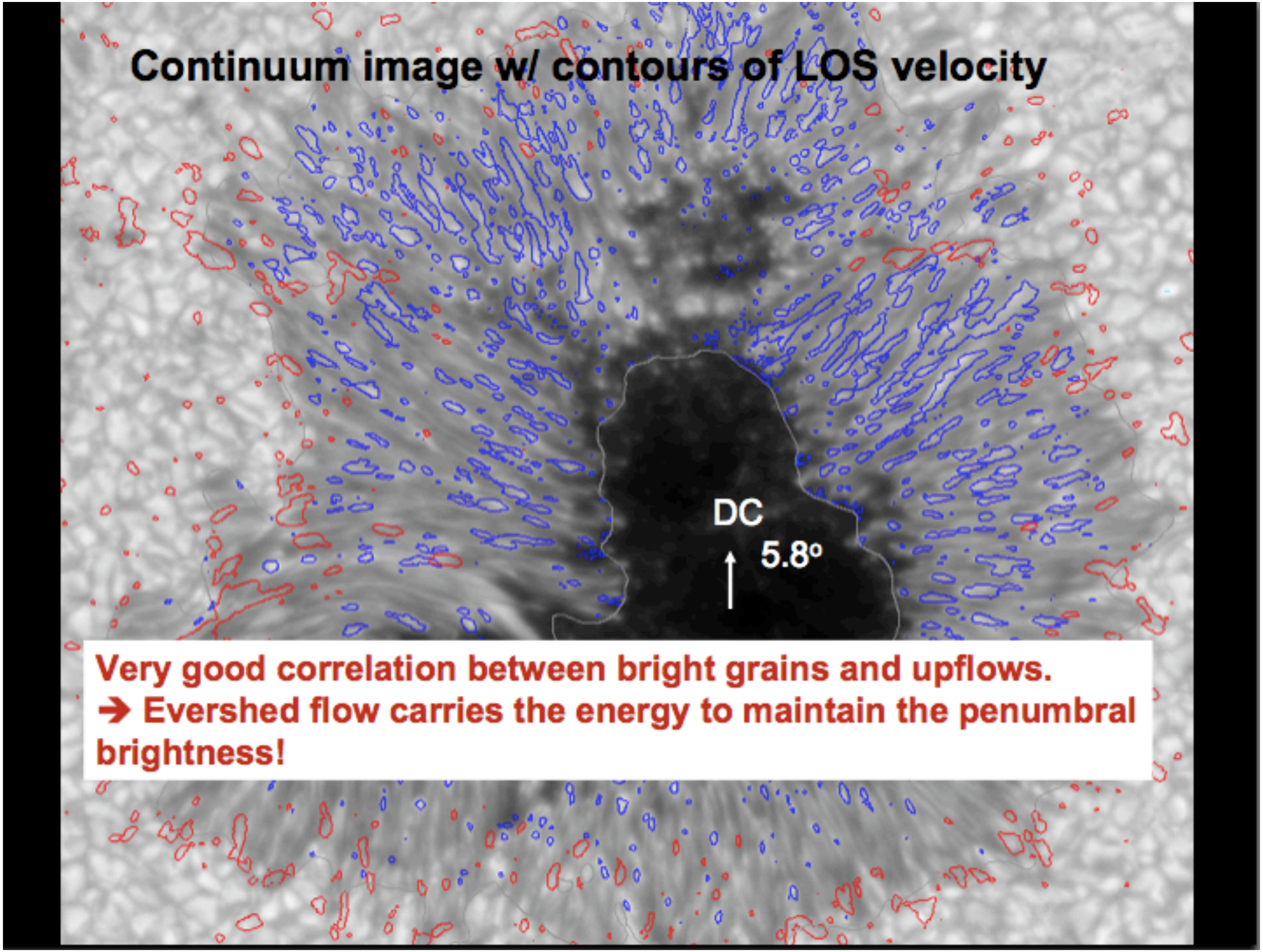
+277mA

Inclination of mag. Field w/ LOS velocity



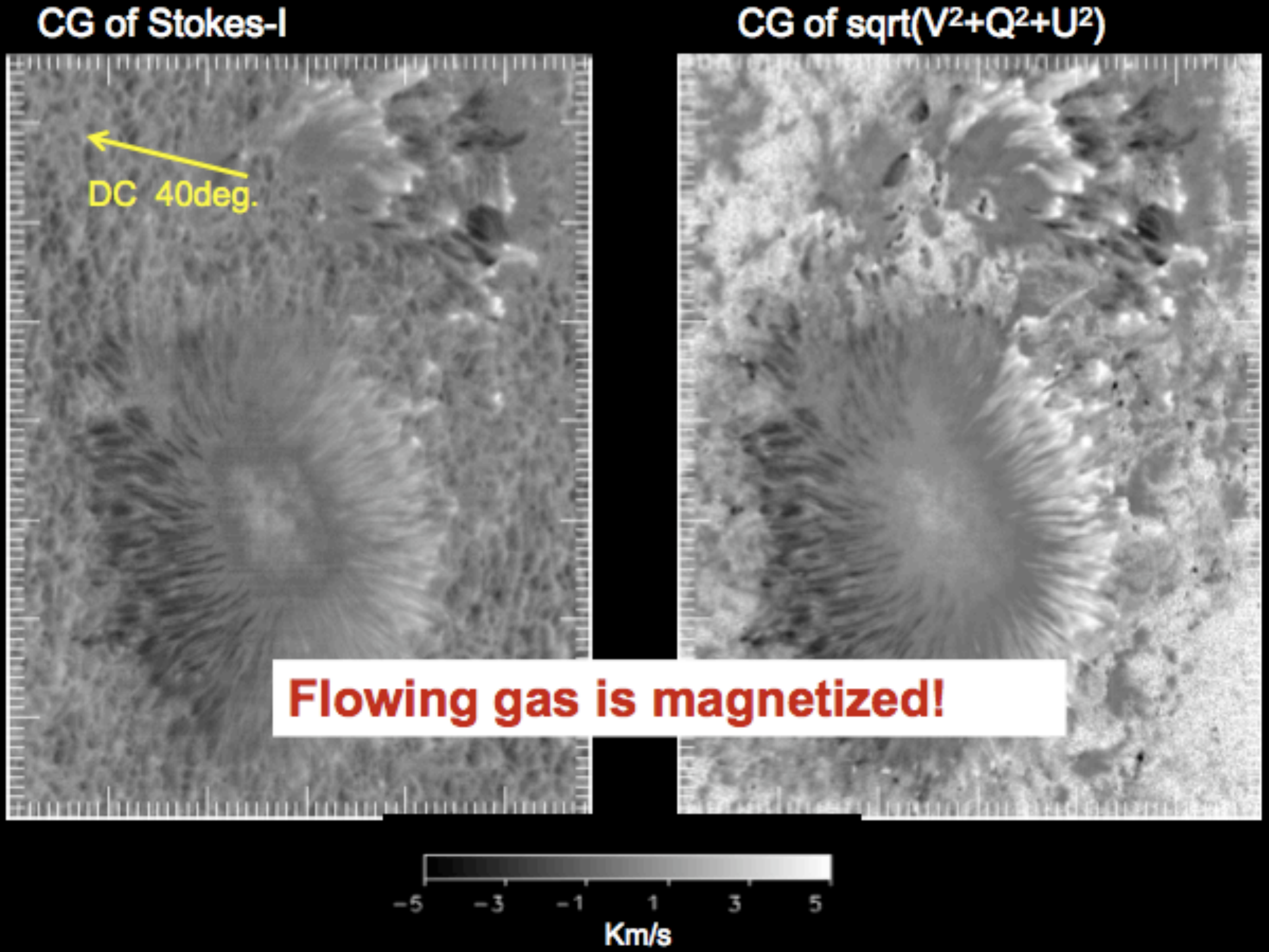
Upflow and downflow patches are aligned on horizontal field filaments that carries the Evershed flow.
→ Source and sink of individual Evershed flow channel!

Continuum image w/ contours of LOS velocity



Very good correlation between bright grains and upflows.
➔ Evershed flow carries the energy to maintain the penumbral brightness!

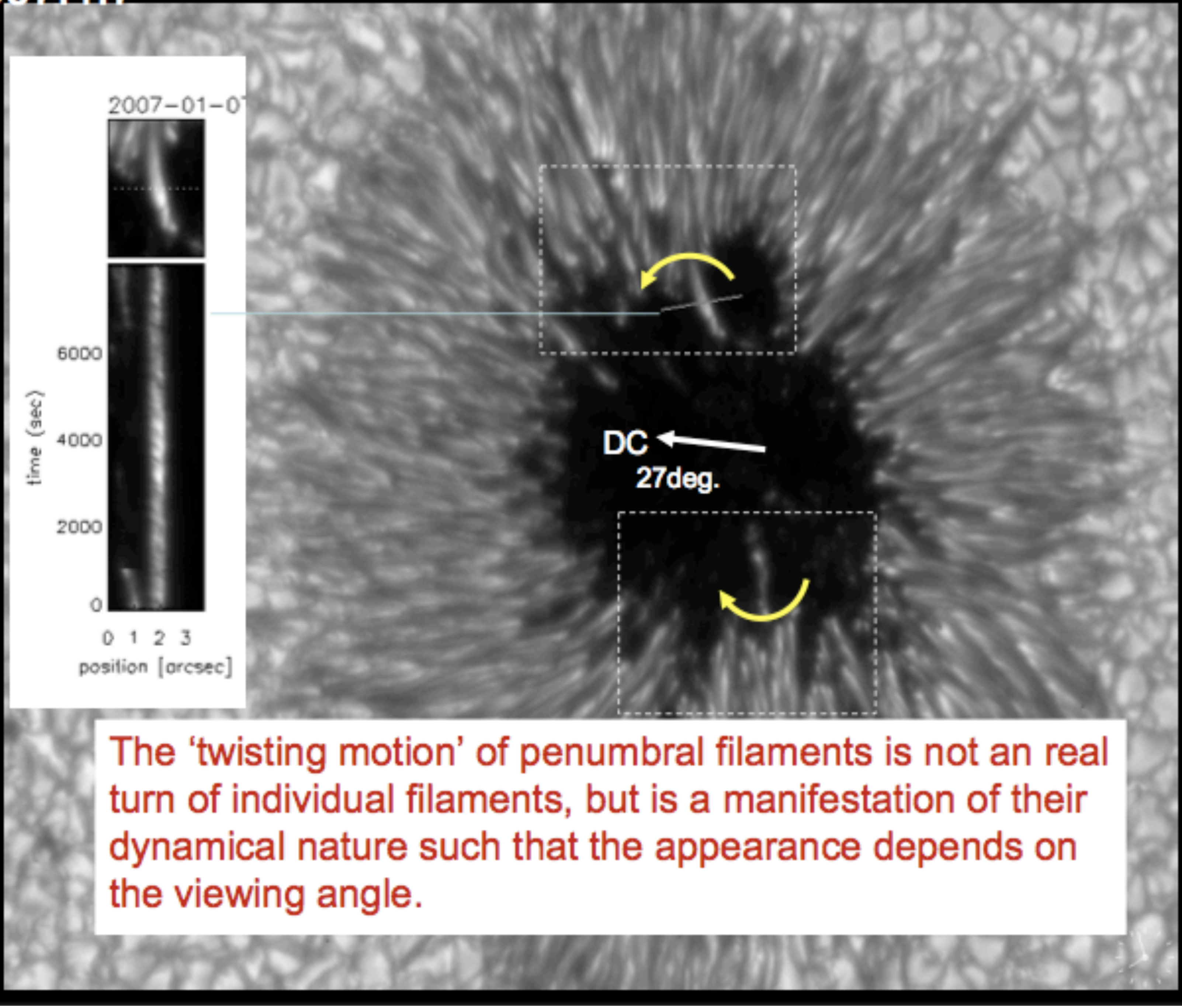
6302.5A Dooppler shift, 2007.1.8


CG of Stokes-I

CG of sqrt(V²+Q²+U²)

Flowing gas is magnetized!

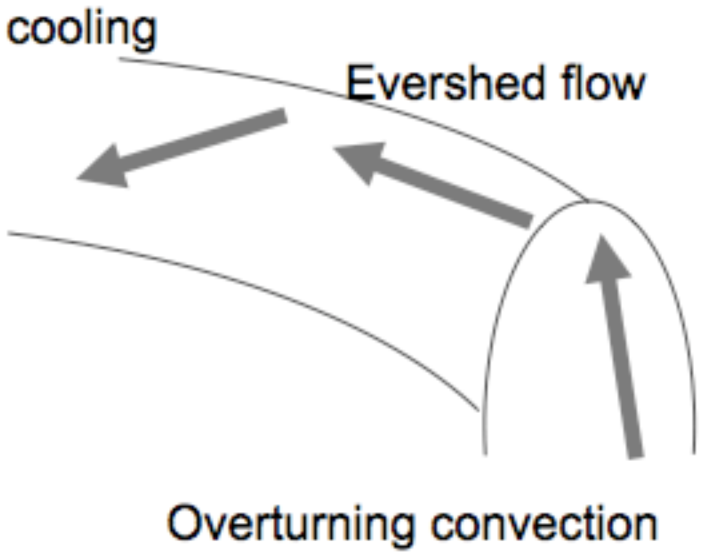
2007.1.7



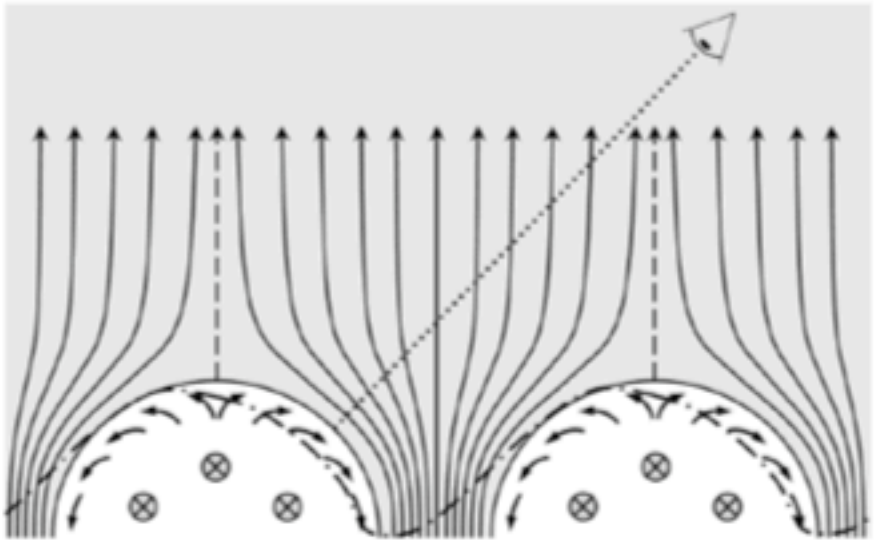
The 'twisting motion' of penumbral filaments is not an real turn of individual filaments, but is a manifestation of their dynamical nature such that the appearance depends on the viewing angle.

What is the origin of the twisting appearance?

➔ Overturning-convection seen from a side(!?)



Ichimoto, etal., 2007, Science, 318, 1597



V. Zakharov, etal., 2008,
A & A manuscript no. 0266 c ESO

Summary (1):

‘Convective nature of the Evershed Effect’

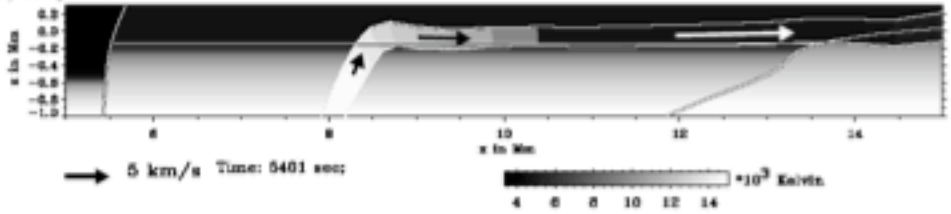
1) Source and sink of the Evershed flow are identified; The geometry is consistent with the 3D uncombed penumbral model.
2) Evershed flow carries the energy of penumbra.
3) Source region of Evershed flow channels shows a hint of overturning convection.
4) Flowing plasma is not field free, but magnetized.
5) Flow velocity (and magnetic field strength) increase with depth in flowing channel (← NCP).

Flux tube model vs. gap model

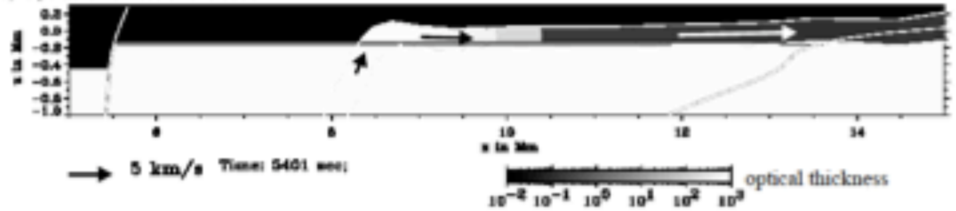
Embedded flux tube model

(e.g., Solanki & Motavon 1993
Schlichenmaier etal 1998)

a) Temperature:



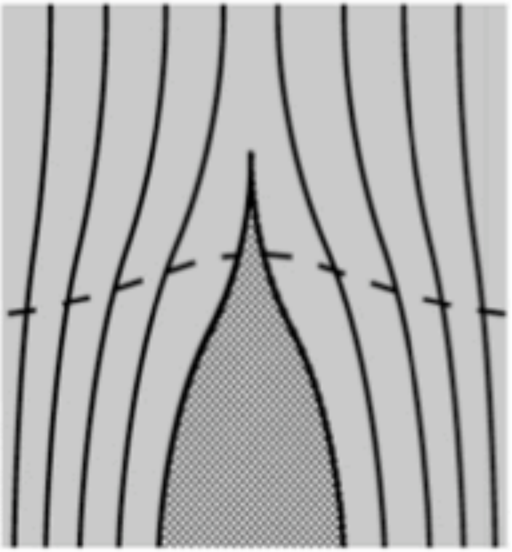
b) Optical thickness of the tube:



There is no observational evidence of the lower boundary of flux tubes.

Gap model

(e.g., Spruit & Schermer 2006)



Field free gap
Penetrating convection

Flowing gas is not field free.

In both models, buoyancy drives the rising motion.

Summary (2):

- If the flux tube model allows vertically elongated ‘flux tubes’, and if the gap model discard the word “field free”, then *there is no fundamental difference between the two models*. And SOT observations suggest this direction.

- Evershed effect may be interpreted as a natural consequence of ‘thermal convection’ under a strong, inclined magnetic fields.

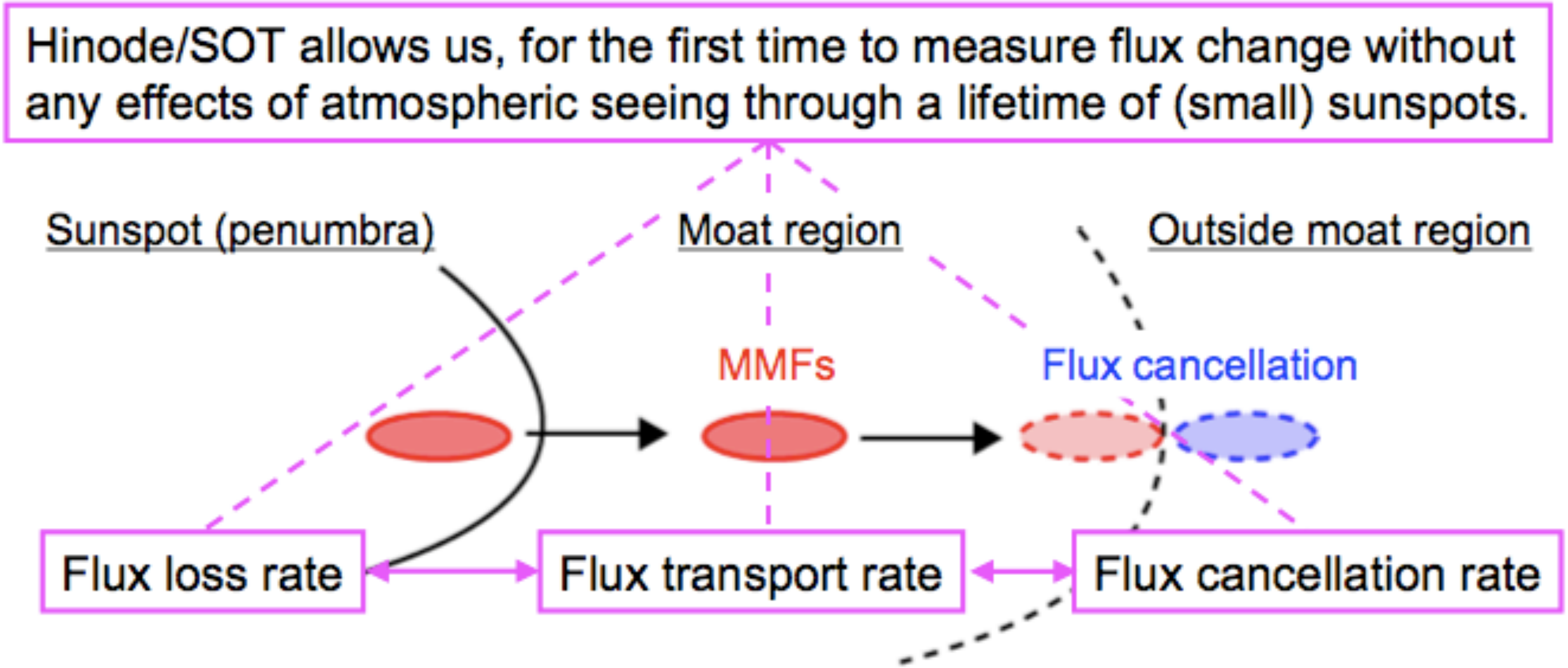
Thank you!

Flux Budget of a Decaying Sunspot

- Kubo et al, “Magnetic Flux Loss & Flux Transport in a Decaying Active Region,” 2nd Hinode Science Meeting, Boulder, Oct 2008

Flux Budget of a Decaying Sunspot

- How much magnetic flux is carried away from the sunspot to the outer boundary of the moat region?
- How much magnetic flux is removed from the photosphere?



Hinode/SOT allows us, for the first time to measure flux change without any effects of atmospheric seeing through a lifetime of (small) sunspots.

Sunspot (penumbra)

Moat region

Outside moat region

MMFs

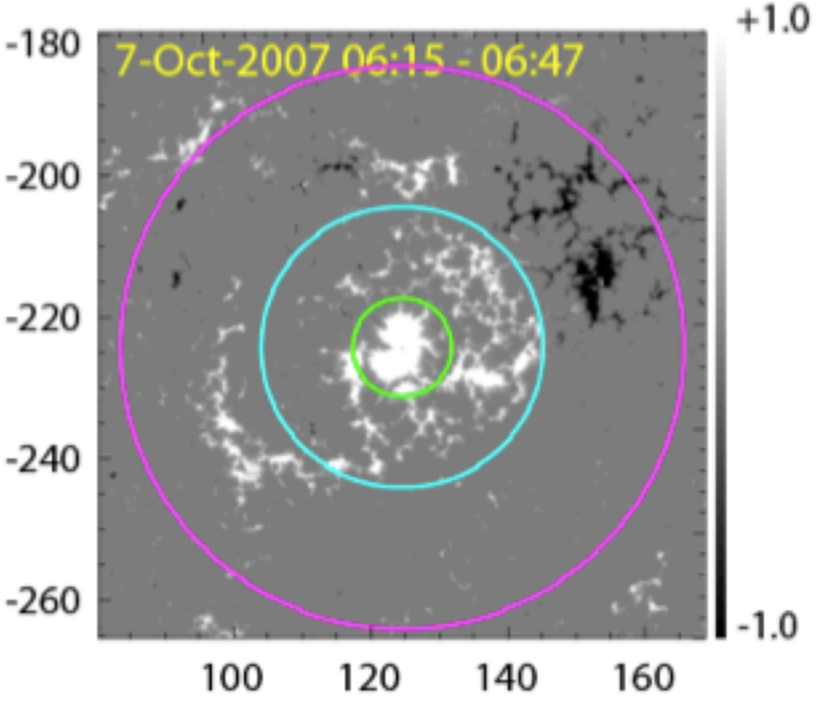
Flux cancellation

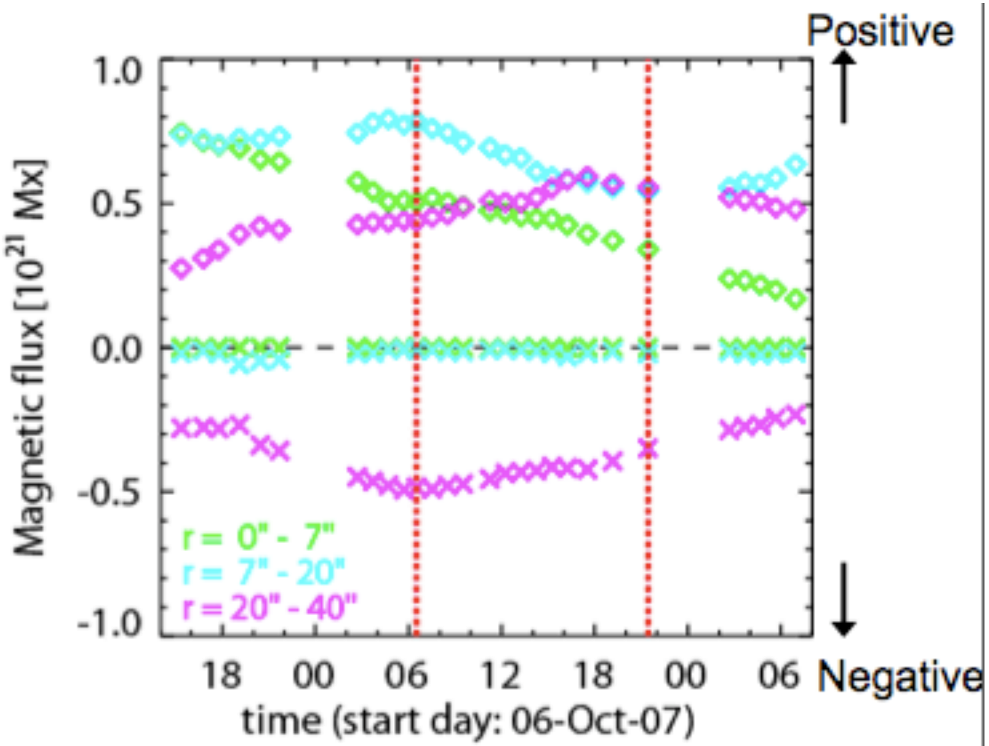
Flux loss rate

Flux transport rate

Flux cancellation rate

Flux Budget of a Decaying Sunspot





Flux change rates in the period between two red lines (06:15 – 21:26 on Oct 7)

- The sunspot significantly decayed (but still survived).
- No significant flux emergence (form visual inspection)

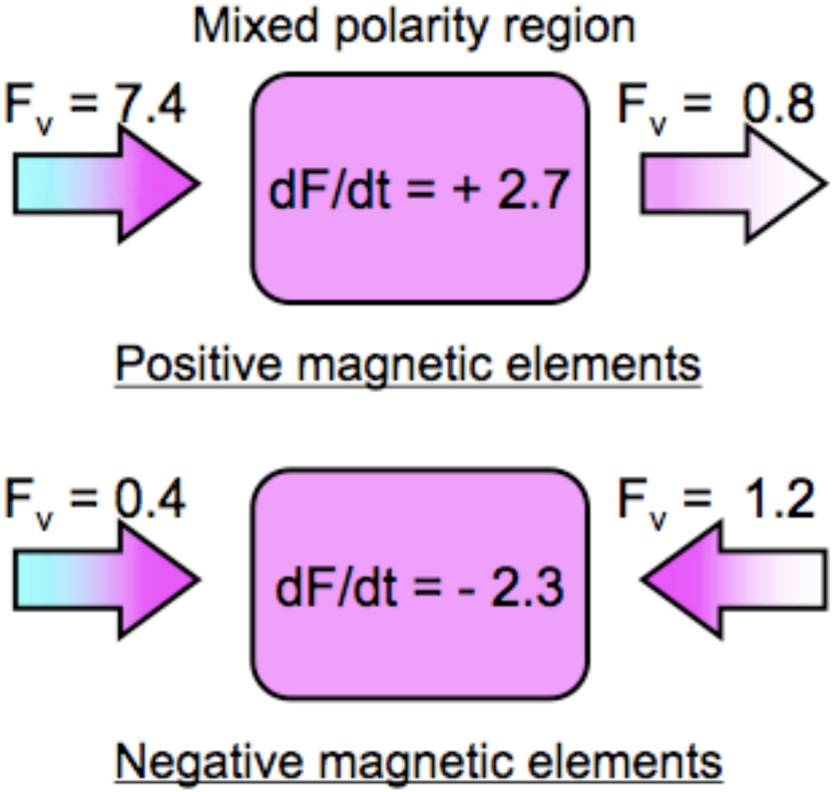
Magnetic flux cancellation at moat boundary

- Magnetic flux loss rate:

$$\left(\frac{dF}{dt}\right)_{Loss} = \cancel{\left(\frac{dF}{dt}\right)}_{Emerge} - \left(\frac{dF}{dt}\right)_{Obs} \pm (F_v)_{Obs}$$

Observations

- Positive: **3.9** [= -2.7 + 7.4 - 0.8] x 10^{15}
- Negative: **3.9** [= -(-2.3) + 0.4 + 1.2] x 10^{15}



Mixed polarity region

F_v = 7.4

dF/dt = + 2.7

F_v = 0.8

Positive magnetic elements

F_v = 0.4

dF/dt = - 2.3

F_v = 1.2

Negative magnetic elements

The flux loss rates of positive and negative elements balance each other in the mixed polarity region

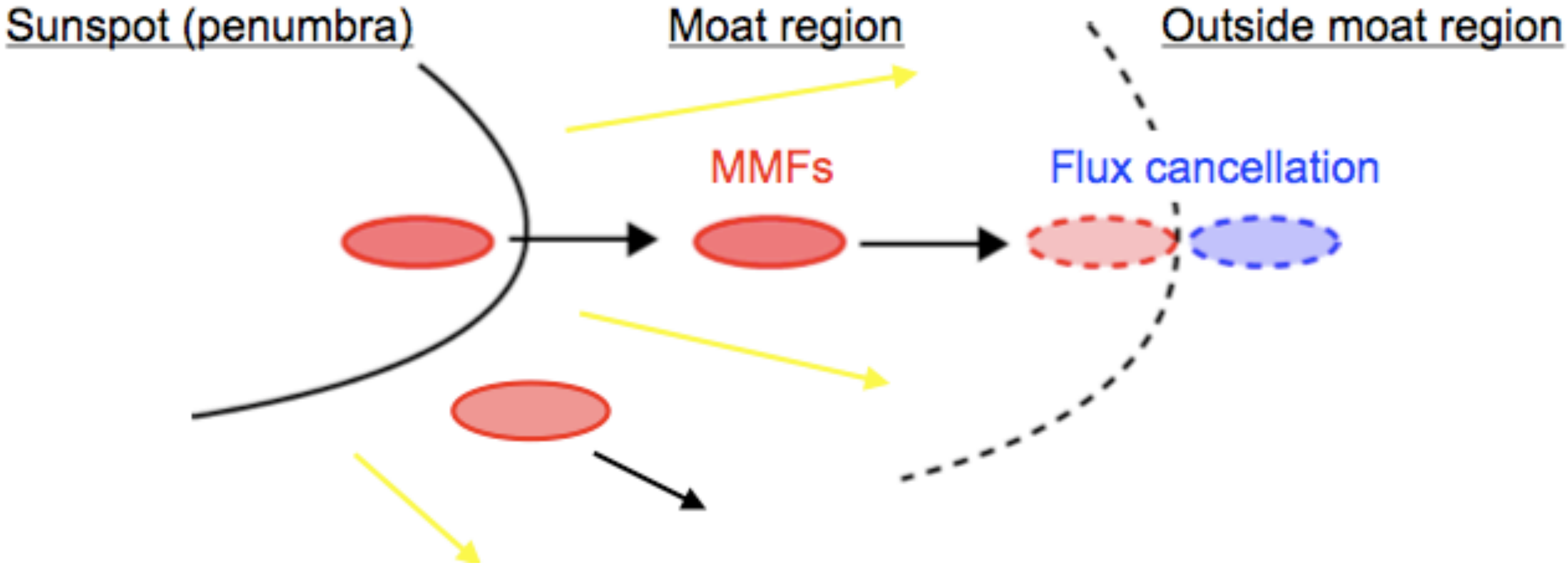
→ Magnetic flux cancellation!

Unit : [10^{15} Mx/sec]

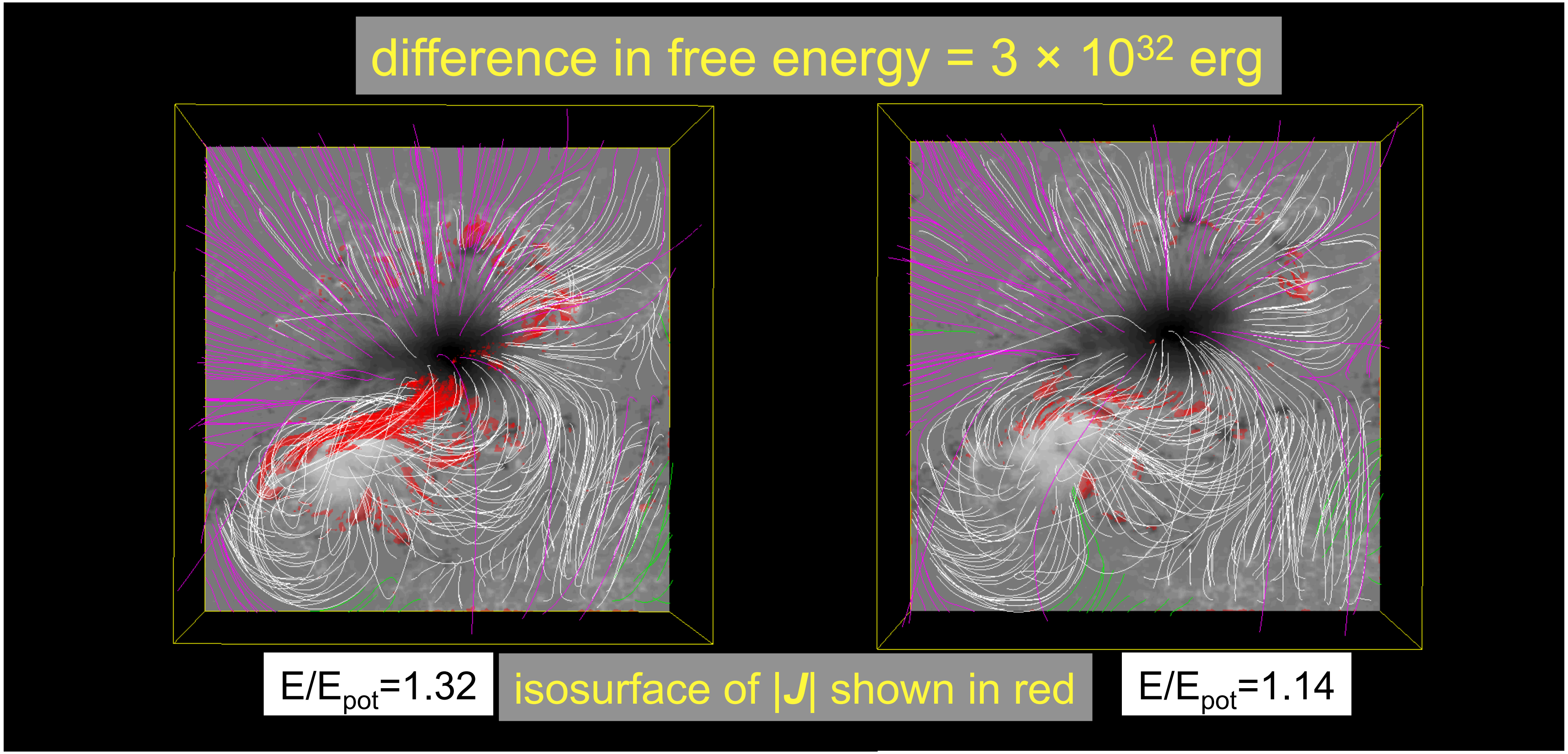
Flux Budget of a Decaying Sunspot

- Most of the magnetic flux removed from the sunspot (and inner moat region) is transported to the outer boundary of the moat region as moving magnetic features.

- The transported magnetic flux is removed from the photosphere by the flux cancellation at the outer boundary of the moat region.



Fields, Currents and NLFF Extrapolations



difference in free energy = 3 × 10^{32} erg

$E/E_{pot}=1.32$

isosurface of |*J*| shown in red

$E/E_{pot}=1.14$

- Stay tuned for talk by K. Schrijver later this afternoon