Evershed Effect Observed by SOT/Hinode

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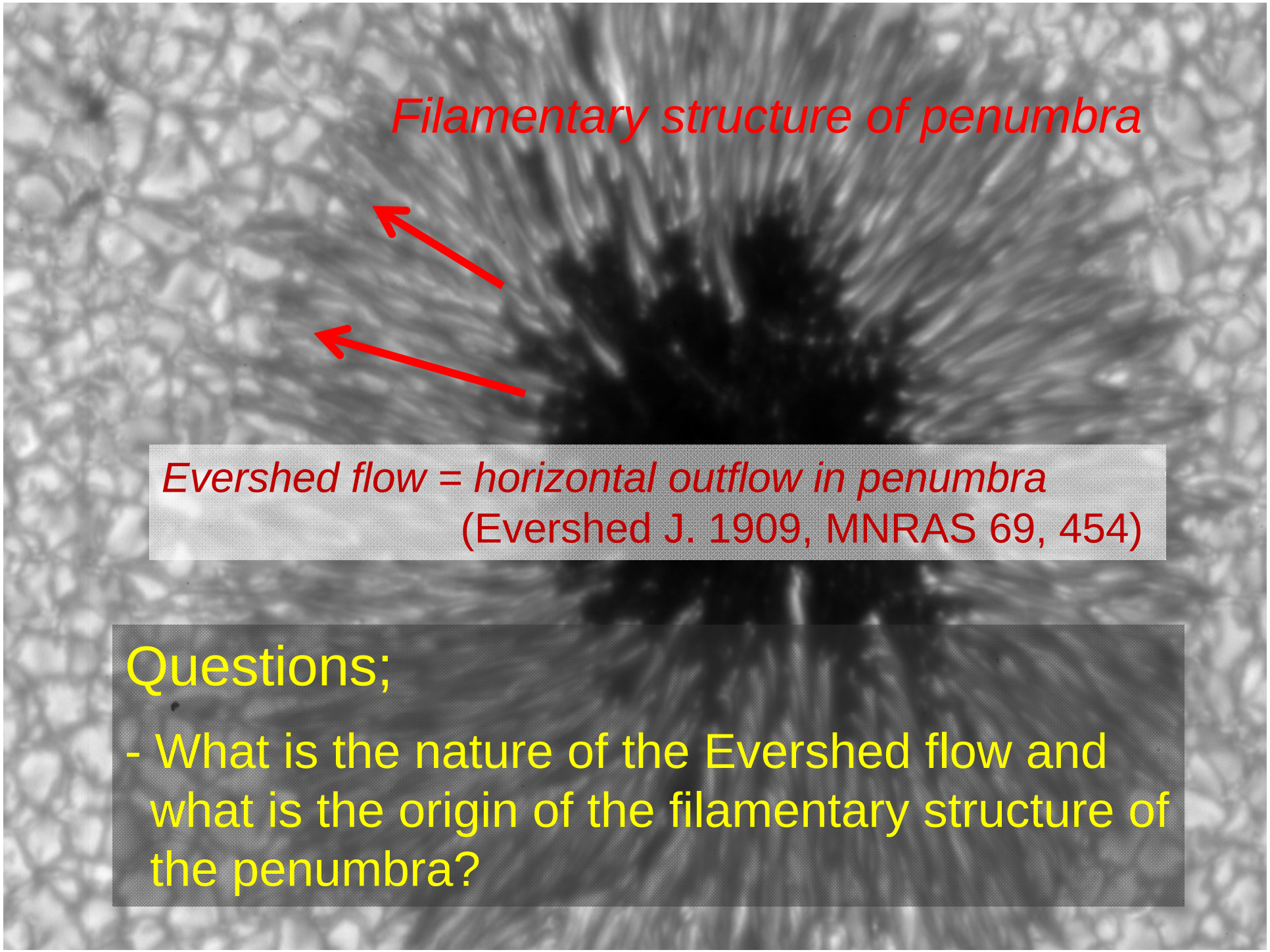
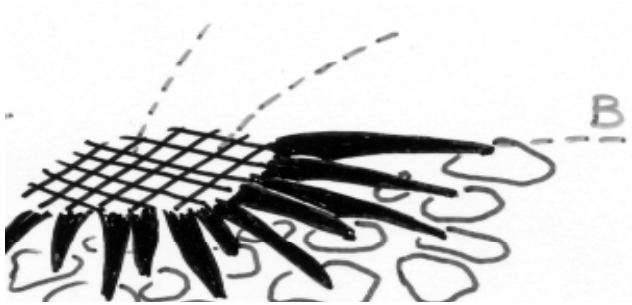
and
SOT/Hinode team

Evershed meeting in Bangalore IIA, 2008.12.2 – 12.5


Filamentary structure of penumbra
Evershed flow = horizontal outflow in penumbra
(Evershed J. 1909, MNRAS 69, 454)
Questions;
- What is the nature of the Evershed flow and what is the origin of the filamentary structure of the penumbra?

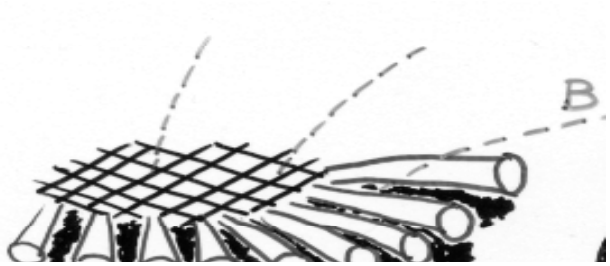
Penumbra/Evershed flow models in 1960-1980th

elevated dark filament



Obs ➔ B ⟂ *v*

rolling convection



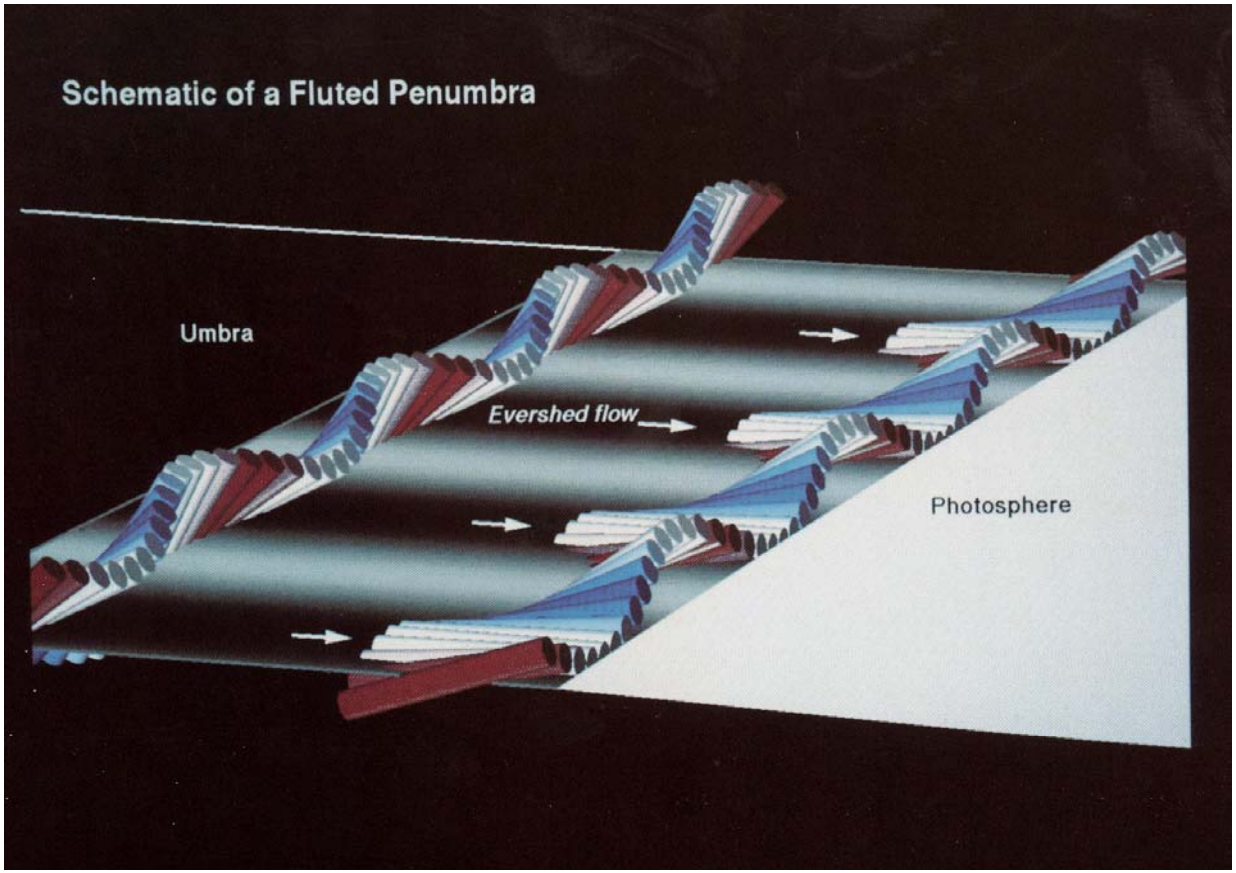
spot loses B in short time

driving force: ∇P_G (siphon flow) $\quad j \times B$

eg. Meyer and Schmidt (1968) Thomas (1981) Danielson (1961)

Progress in 1990th

Interlocking comb structure

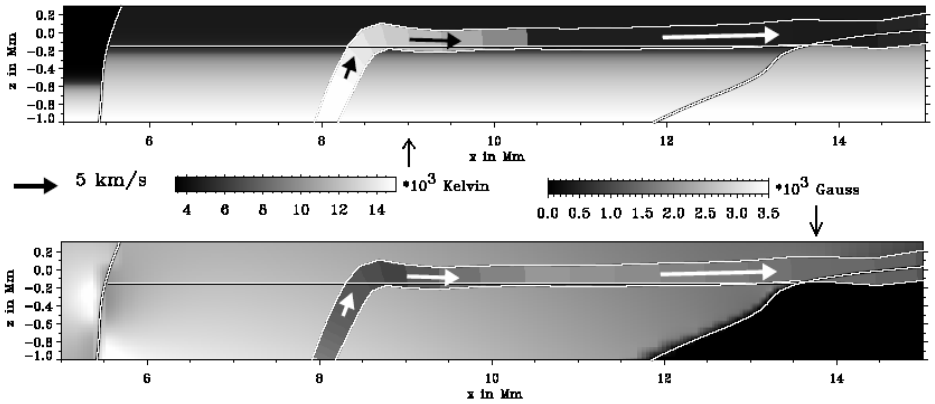


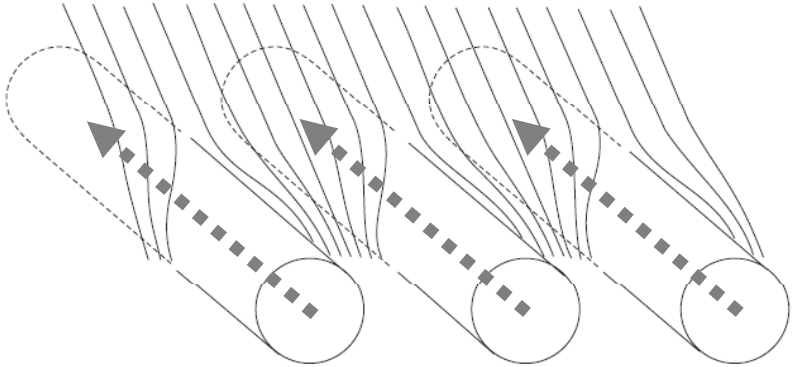
Title et al. 1993, ApJ, 403, 780

Two representative scenarios at present

Embedded flux tube model

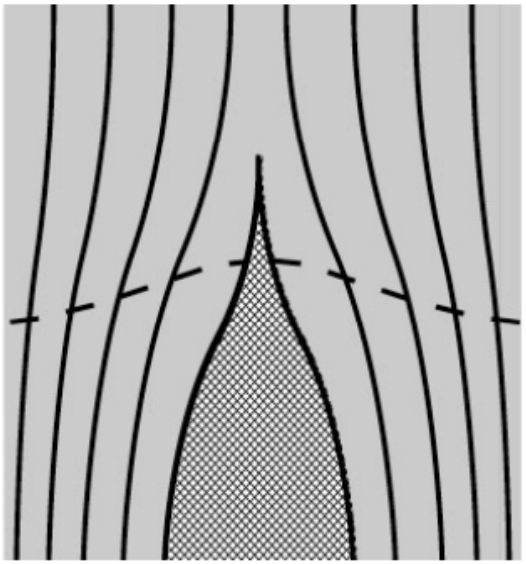
(e.g., Solanki & Motavon 1993
Schlichenmaier etal 1998)





Gappy model

(e.g., Spruit & Schermer 2006)



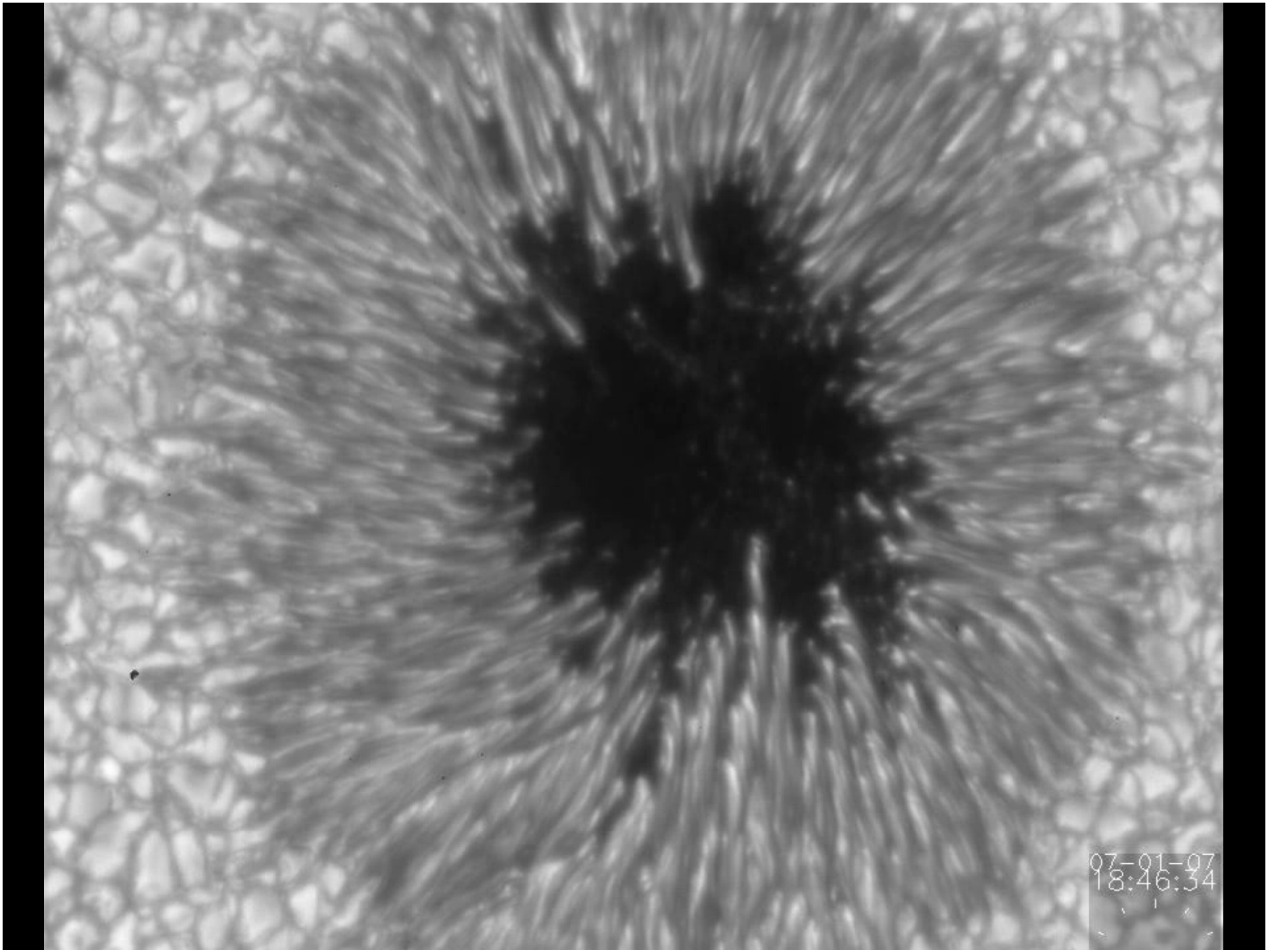
Bright filaments = field free gap
= protrusion of convection

Contents of this talk:

1) Identification of elementary structures of the Evershed flow.

2) Convective nature of Evershed flow.

3) Revisit to the two models.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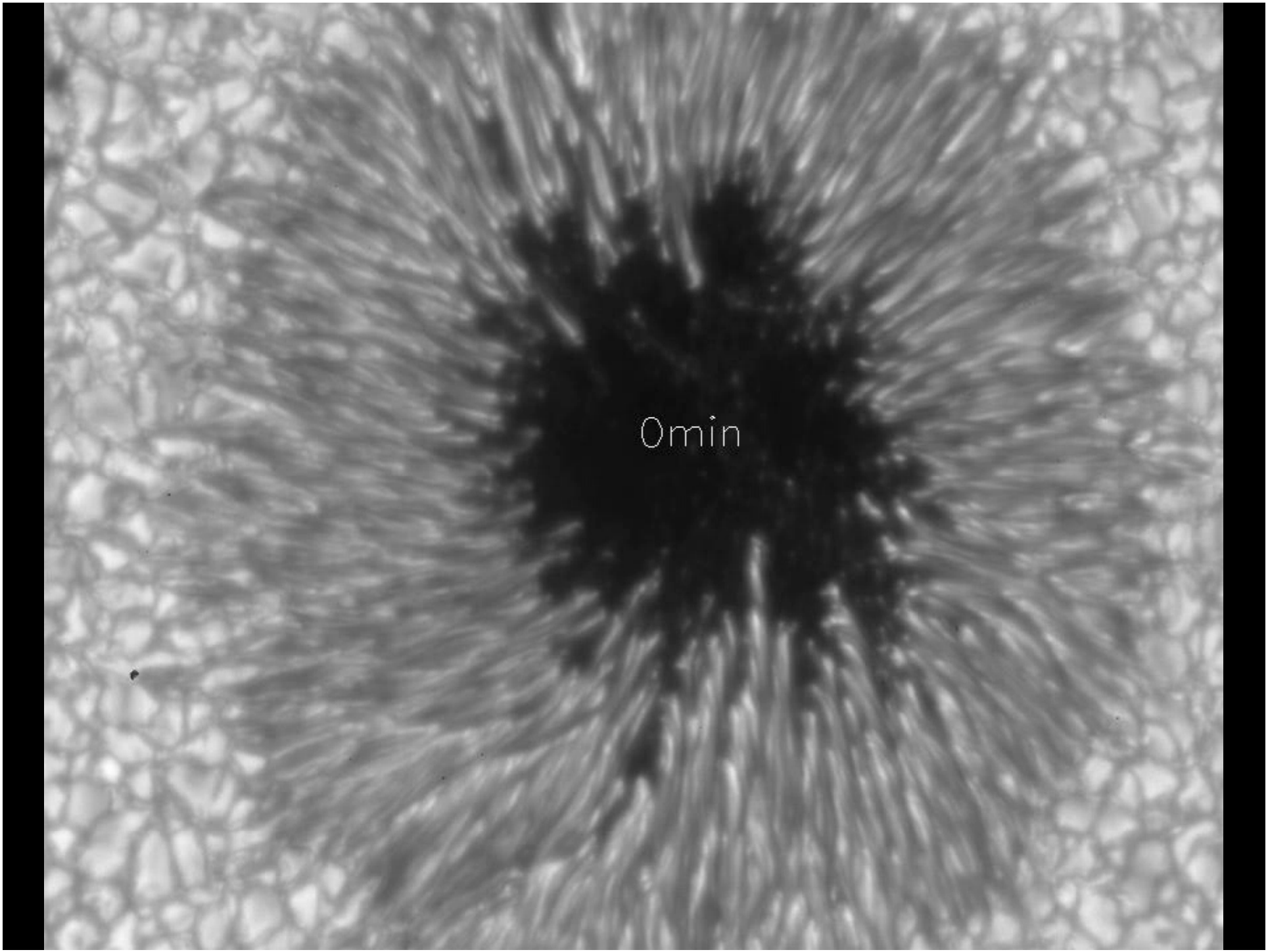
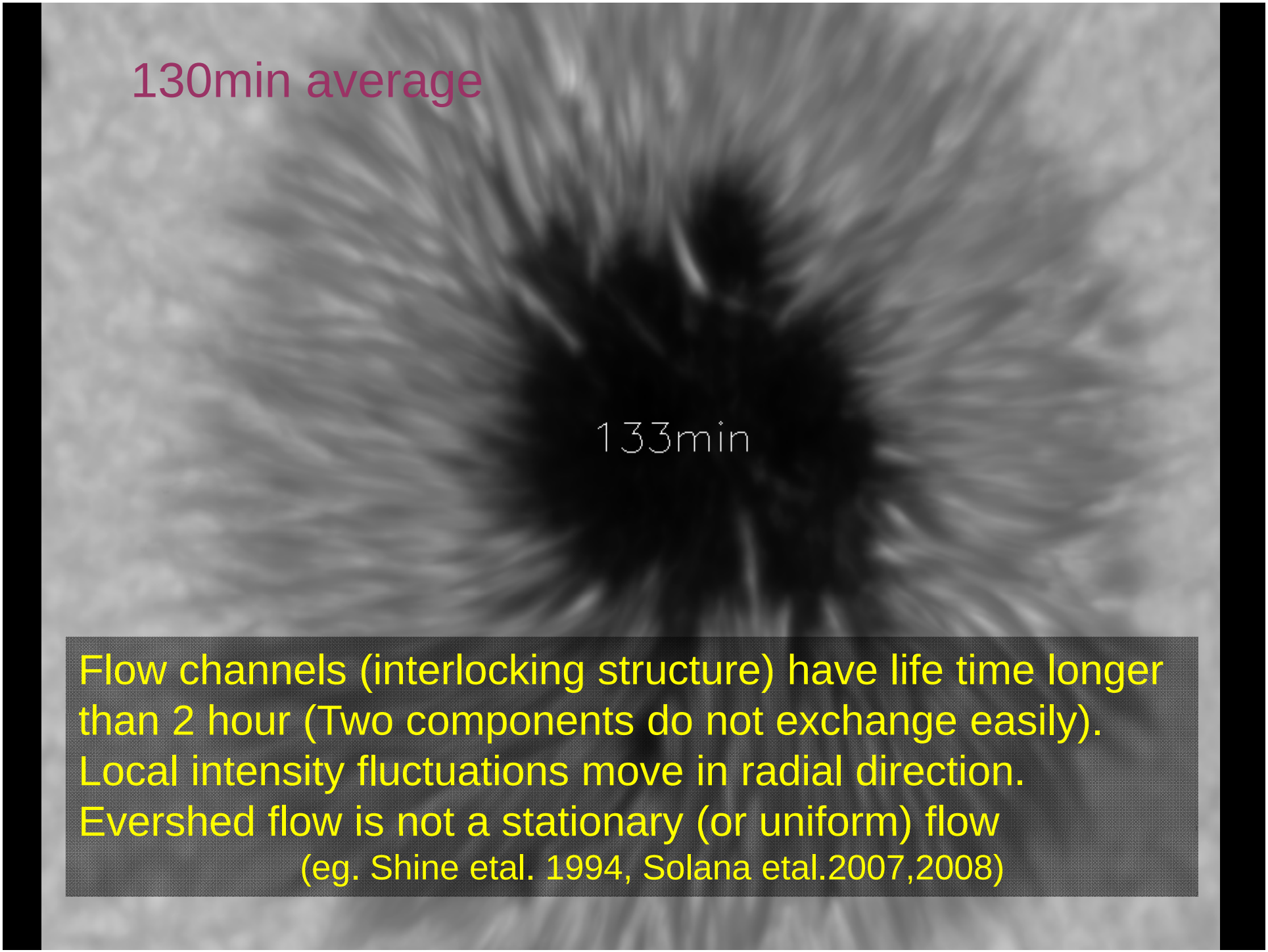
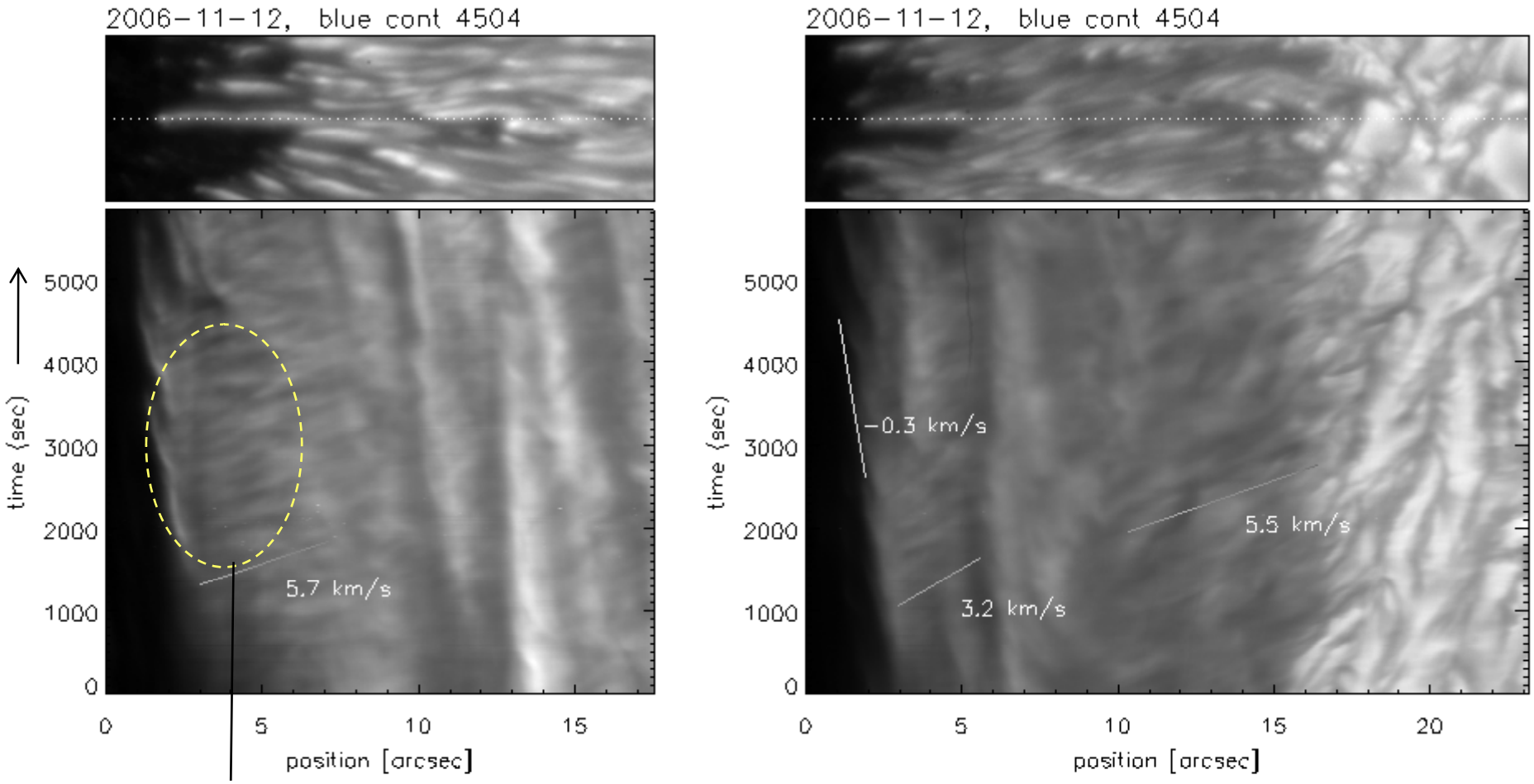

0min



Flow channels (interlocking structure) have life time longer than 2 hour (Two components do not exchange easily).
Local intensity fluctuations move in radial direction.
Evershed flow is not a stationary (or uniform) flow
(eg. Shine etal. 1994, Solana etal.2007,2008)

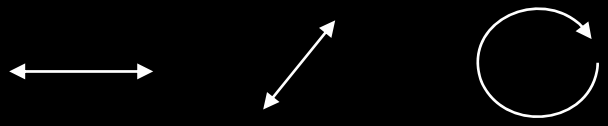
Where the Evershed flow takes place?



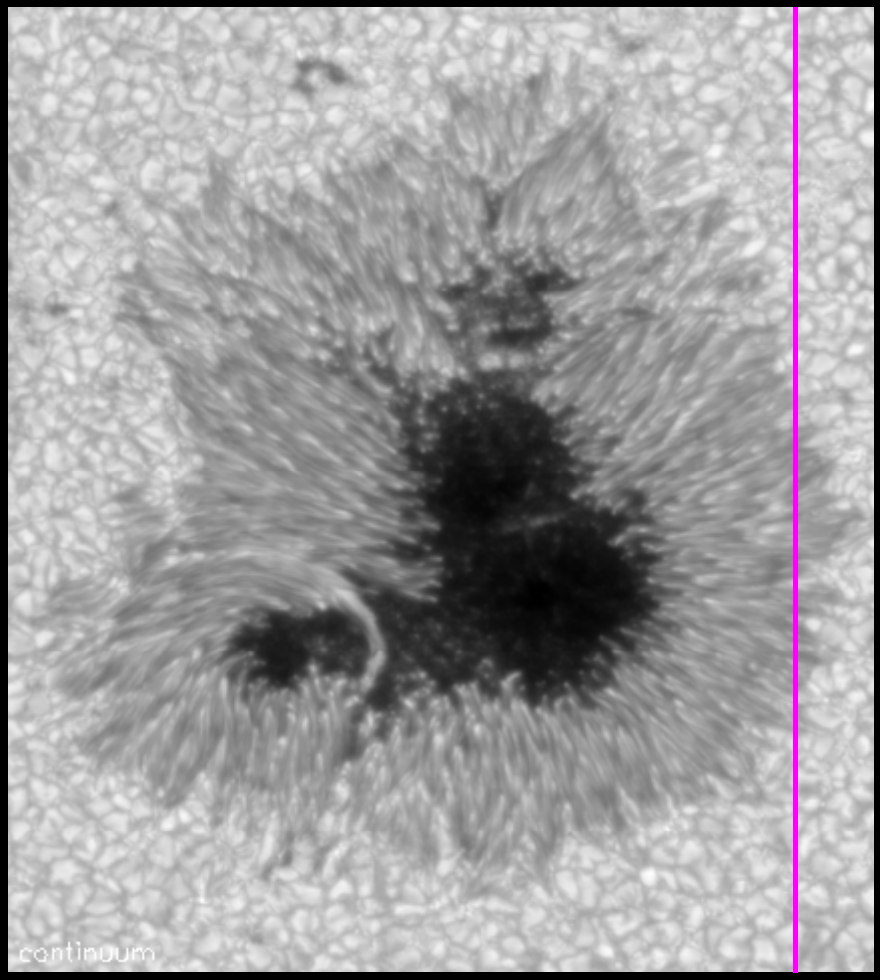
Evershed flow starts from the leading edge of bright penumbral filaments, and preferentially flows in dark filaments in outer penumbra. v = 3 ~ 6km/s。
Periodic variation of brightness, P = 3 ~5min

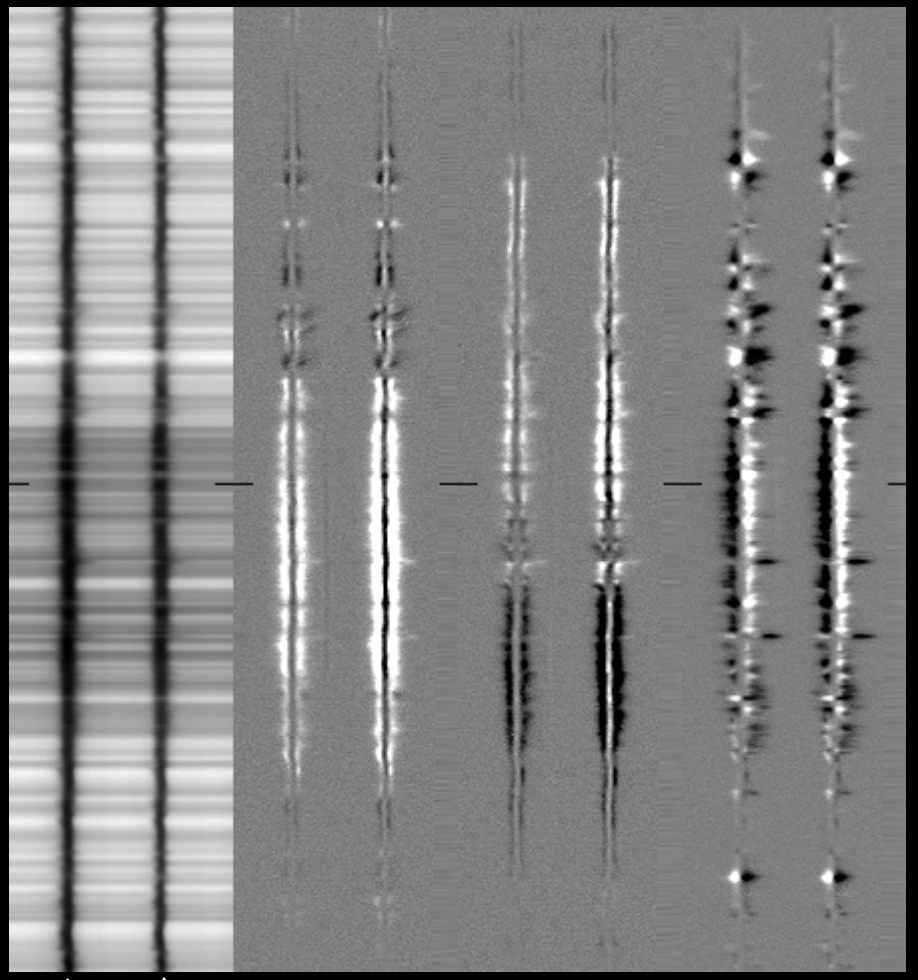
Ichimoto etal, 2007, PASJ, 59, 593

SOT spectro-polarimeter



I *Q* *U* *V*





Zeeman effect of spectral line
（SOT/Spectro-polarimeter）

FeI6301.5A
g = 1.67

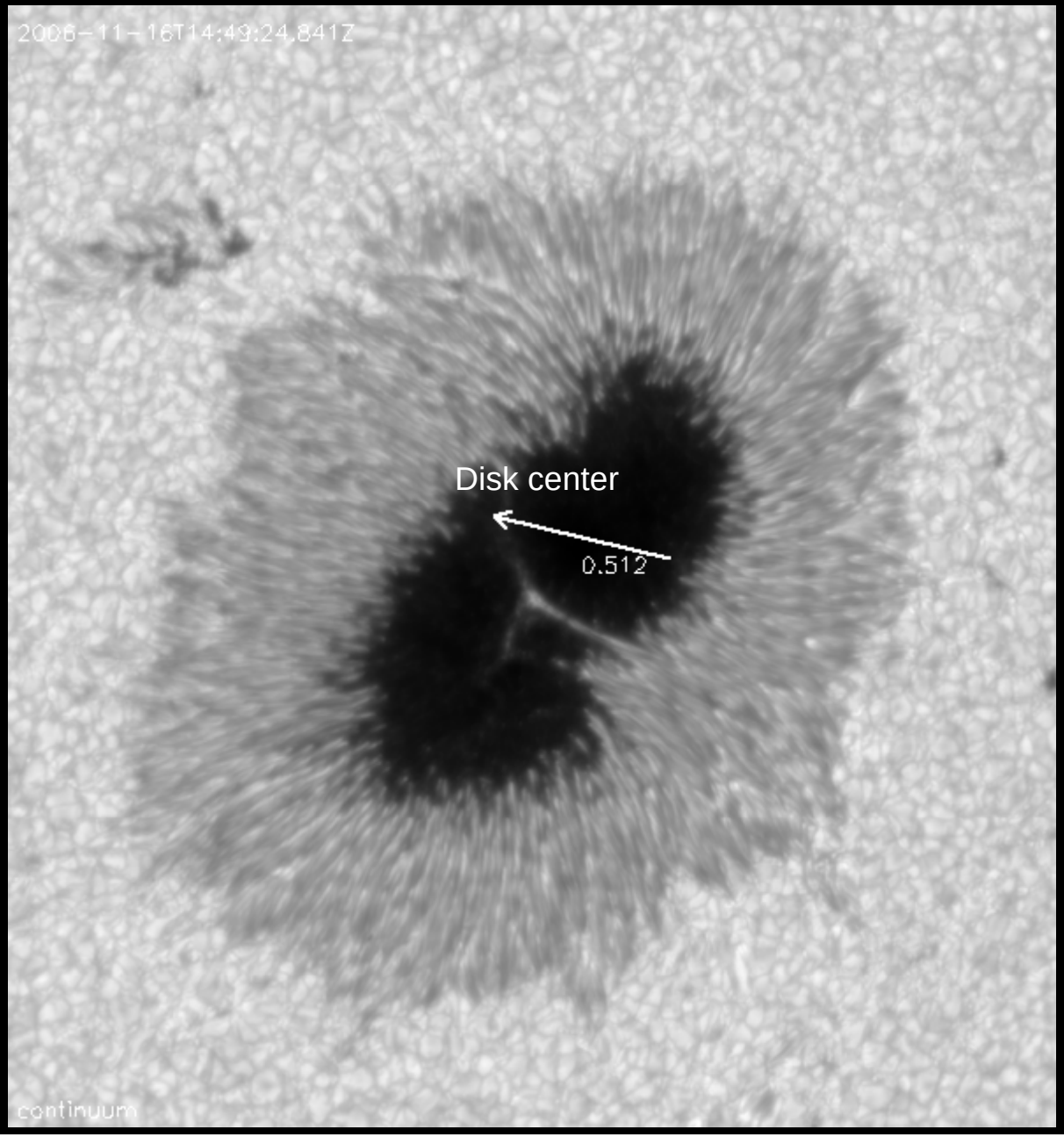
FeI6302.5A
g = 2.5

Where the gas flows? Dark or bright filament?

2006.11.16

Sin θ = 0.512
LOS → ~31deg.

Doppler shift is dominated by horizontal flow.

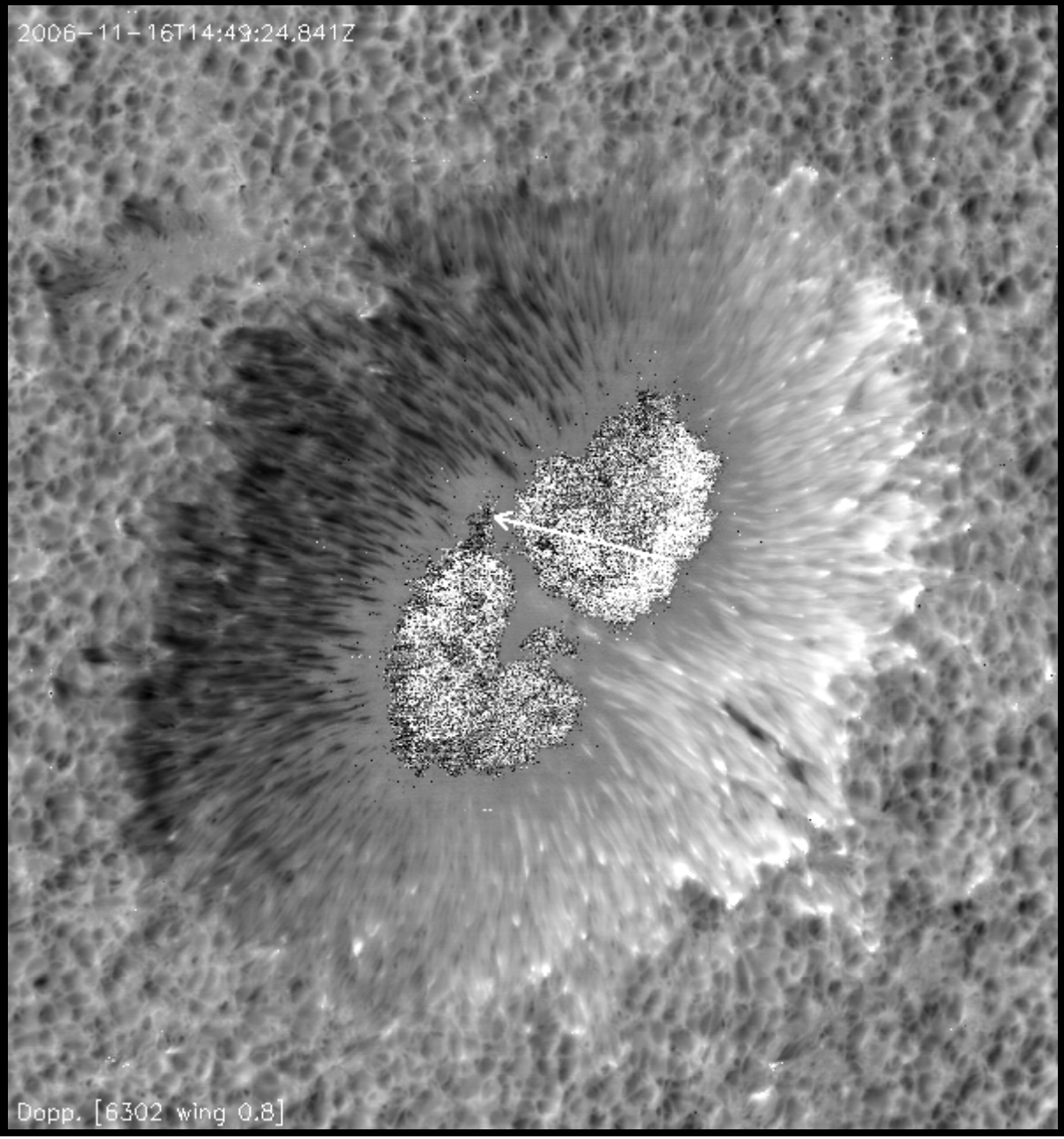


Dopplergram from SP; Flow field is also filamentary.

2006.11.16

Sin θ = 0.512
LOS → ~31deg.

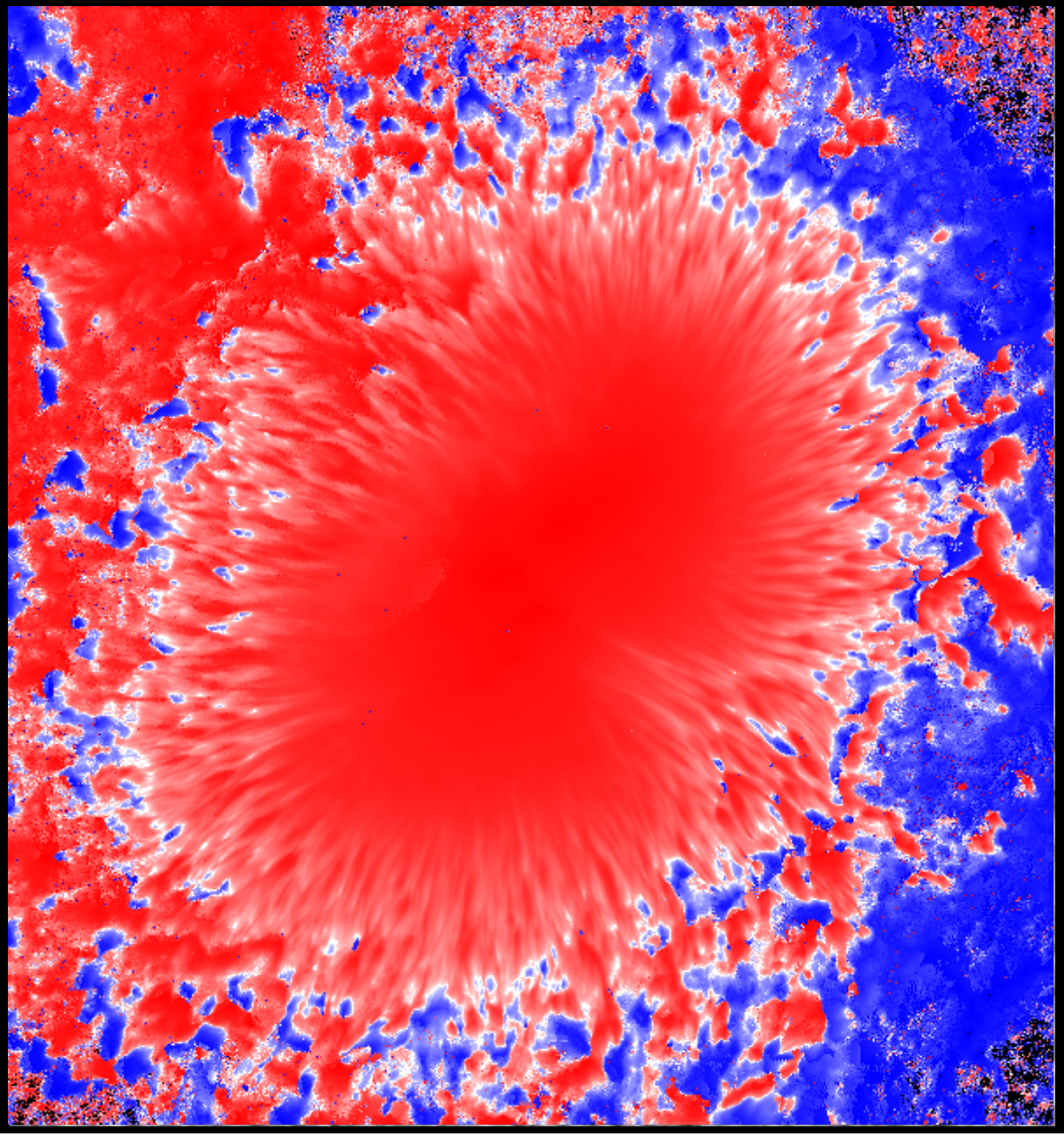
Doppler shift is dominated by horizontal flow.



Field inclination seen from top;

2006.11.16

Sin θ = 0.512
LOS → ~31deg.

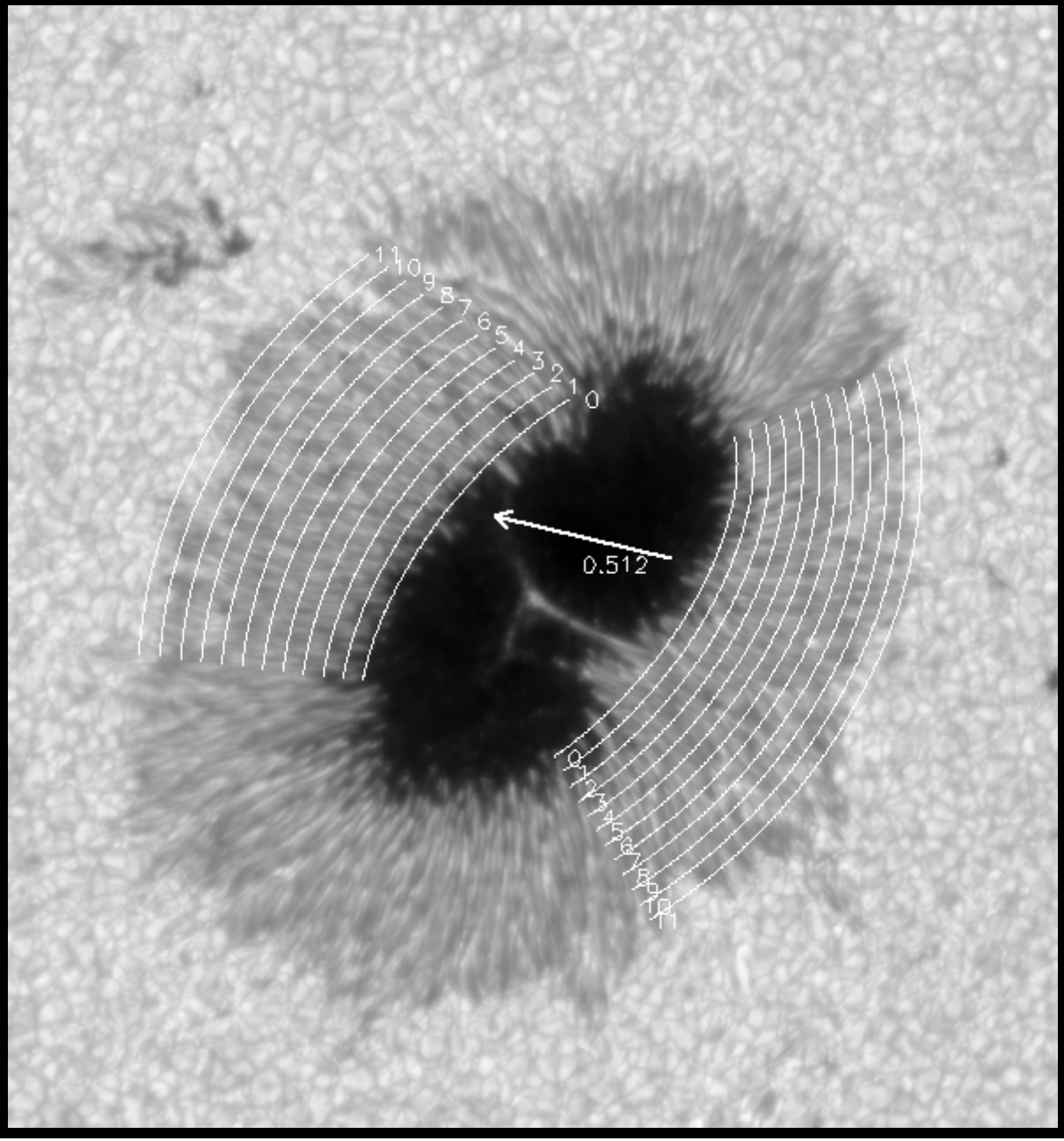


Correlation study between Doppler shift and Ic, γ

2006.11.16

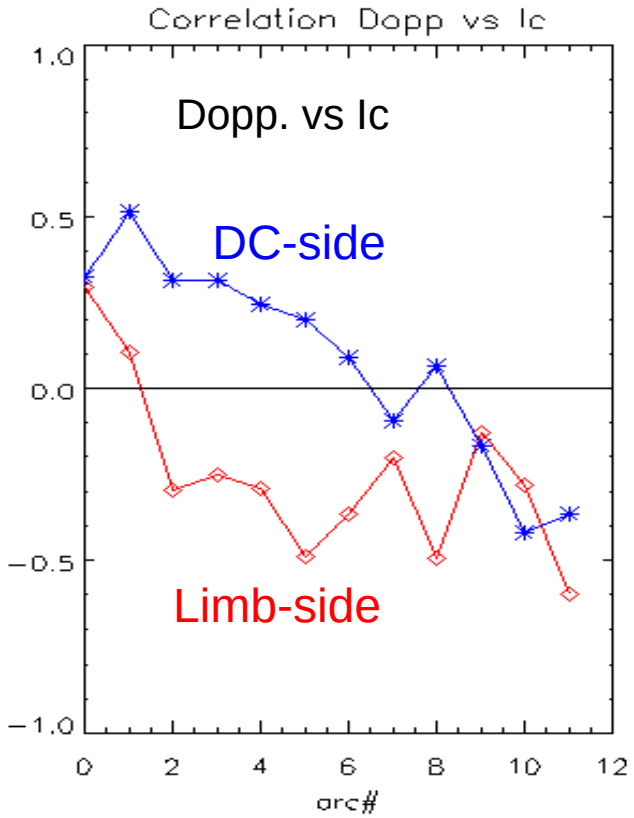
Sin θ = 0.512
LOS → ~31deg.

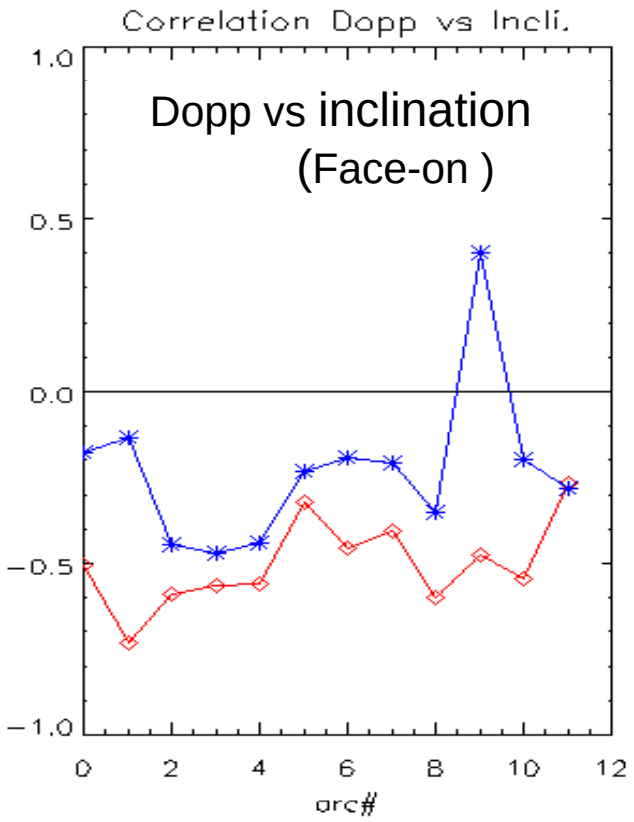
Doppler shift is dominated by horizontal flow.



Correlation coeff. vs. distance from sunspot center, 2006.11.16

DC-side blue shift =positive
Limb-side red shift =positive



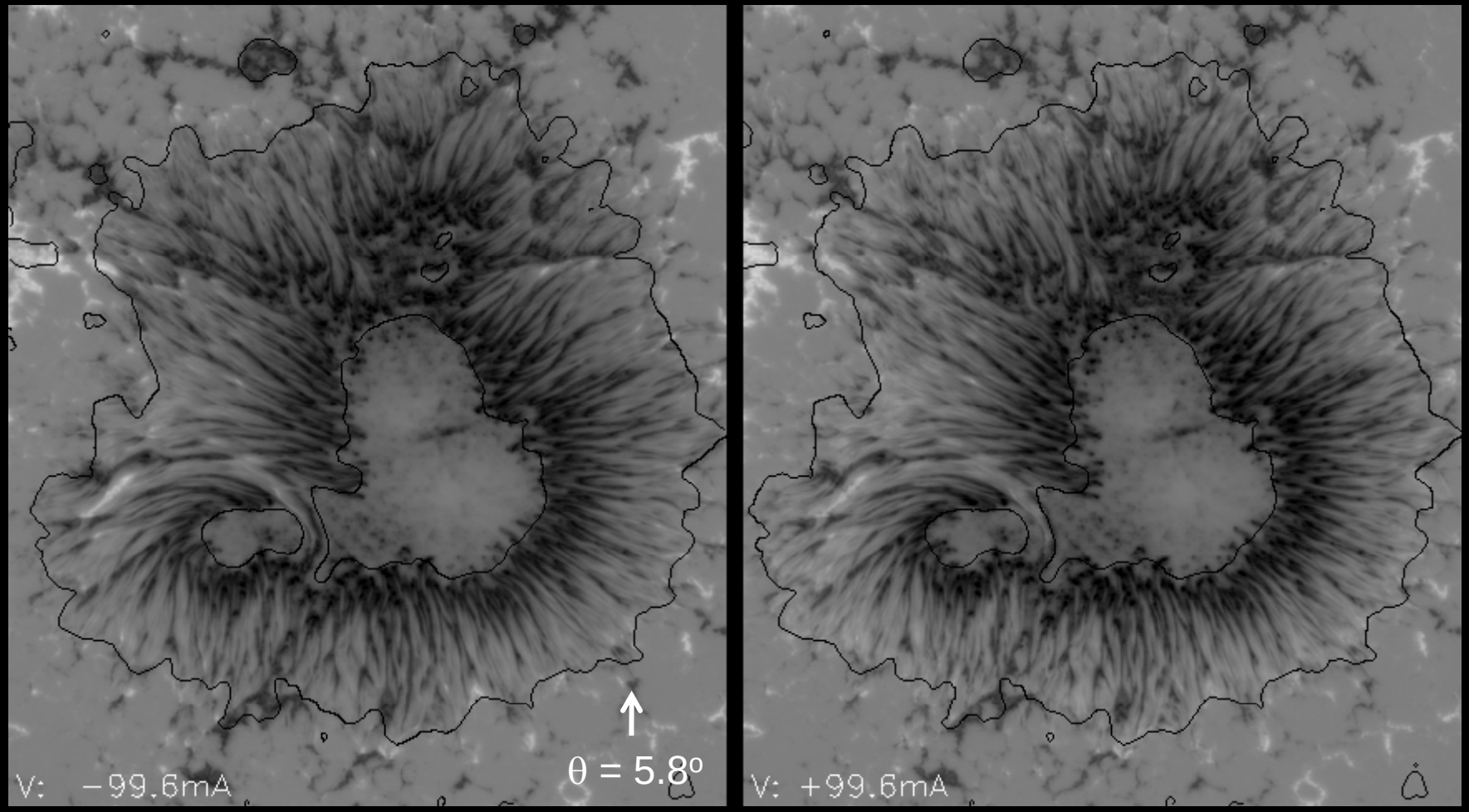


Evershed flow tends to be contained
in *horizontal magnetic field channel*,
in *bright filaments* in inner penumbra,
in *dark filaments* in outer penumbra.
Difference of DC & Limb → presence of vertical comp. of flow.

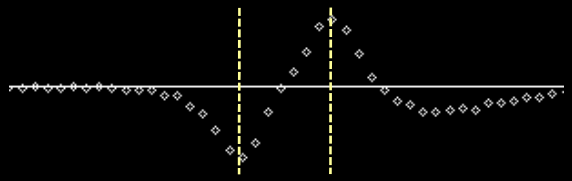
2007.5.1

Stokes-V at 6302.5A ±100mA

(sign reversed)

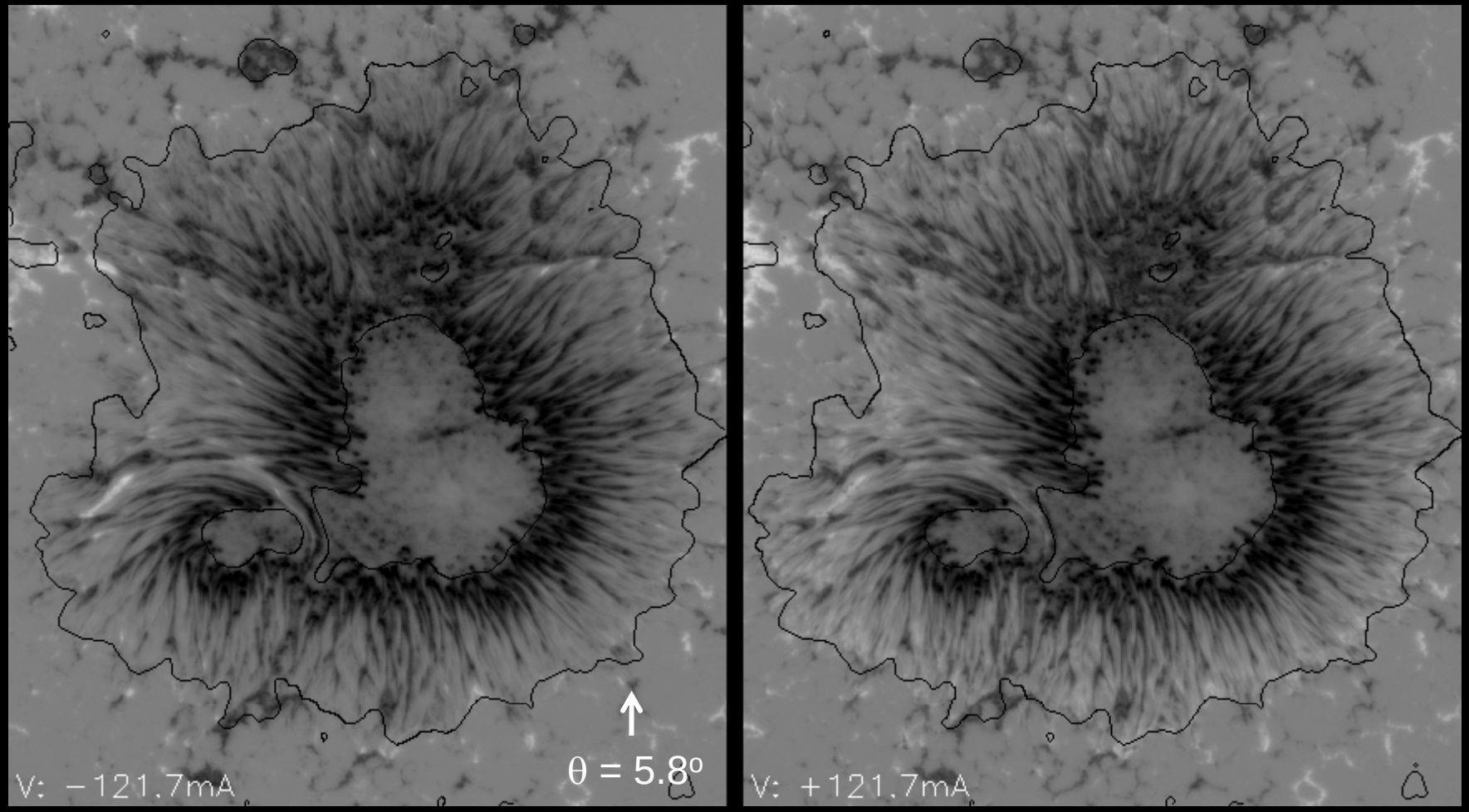


-100mA

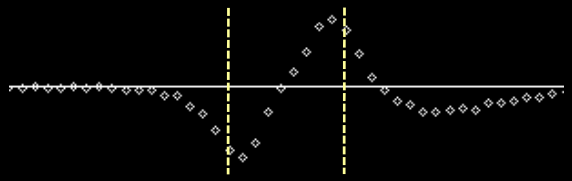


+100mA

Stokes-V at 6302.5A ±120mA

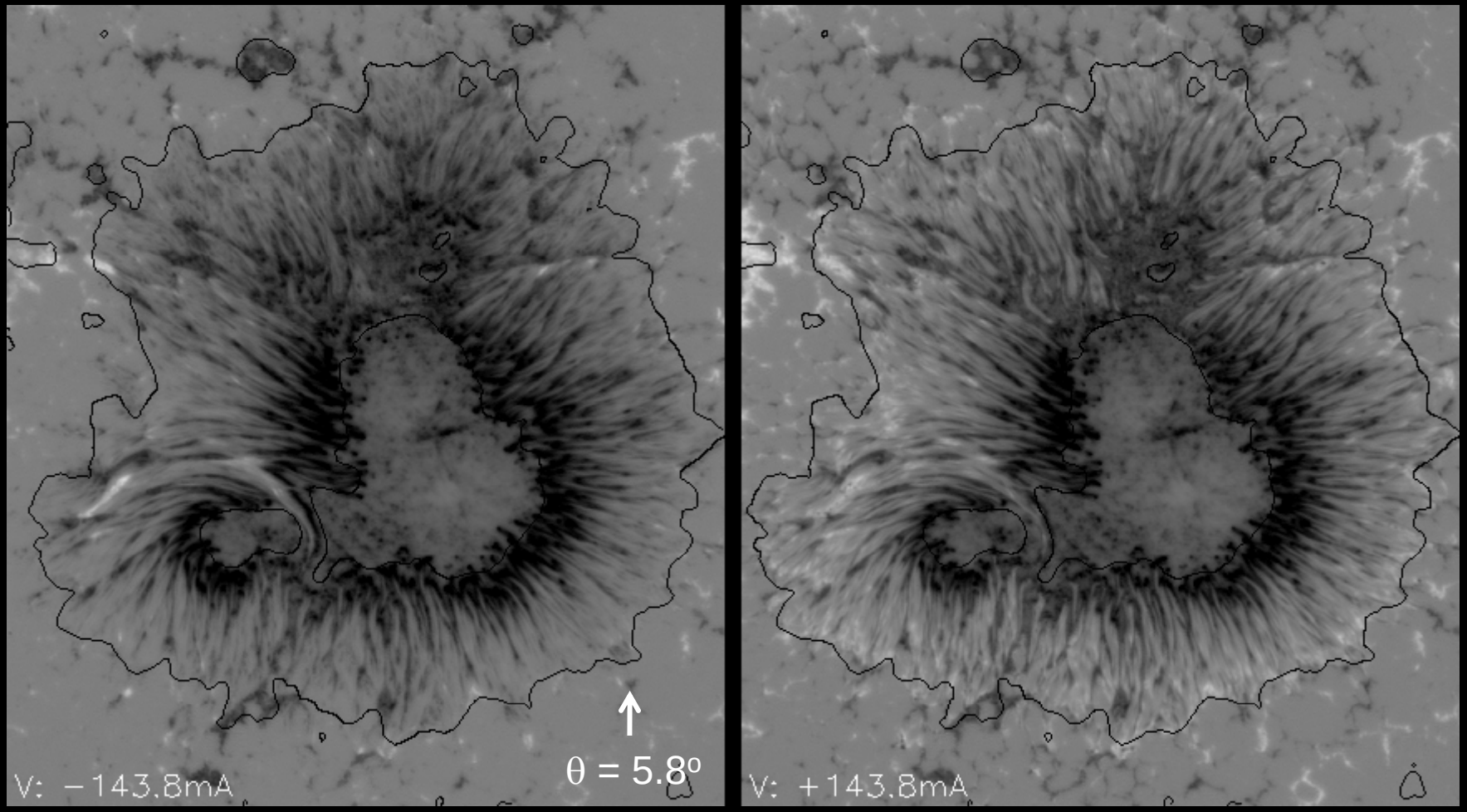


-120mA

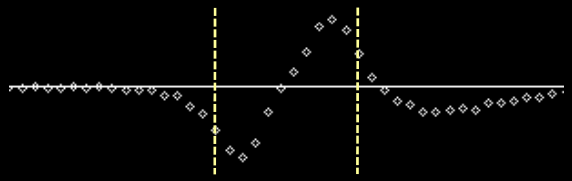


+120mA

Stokes-V at 6302.5A ±144mA

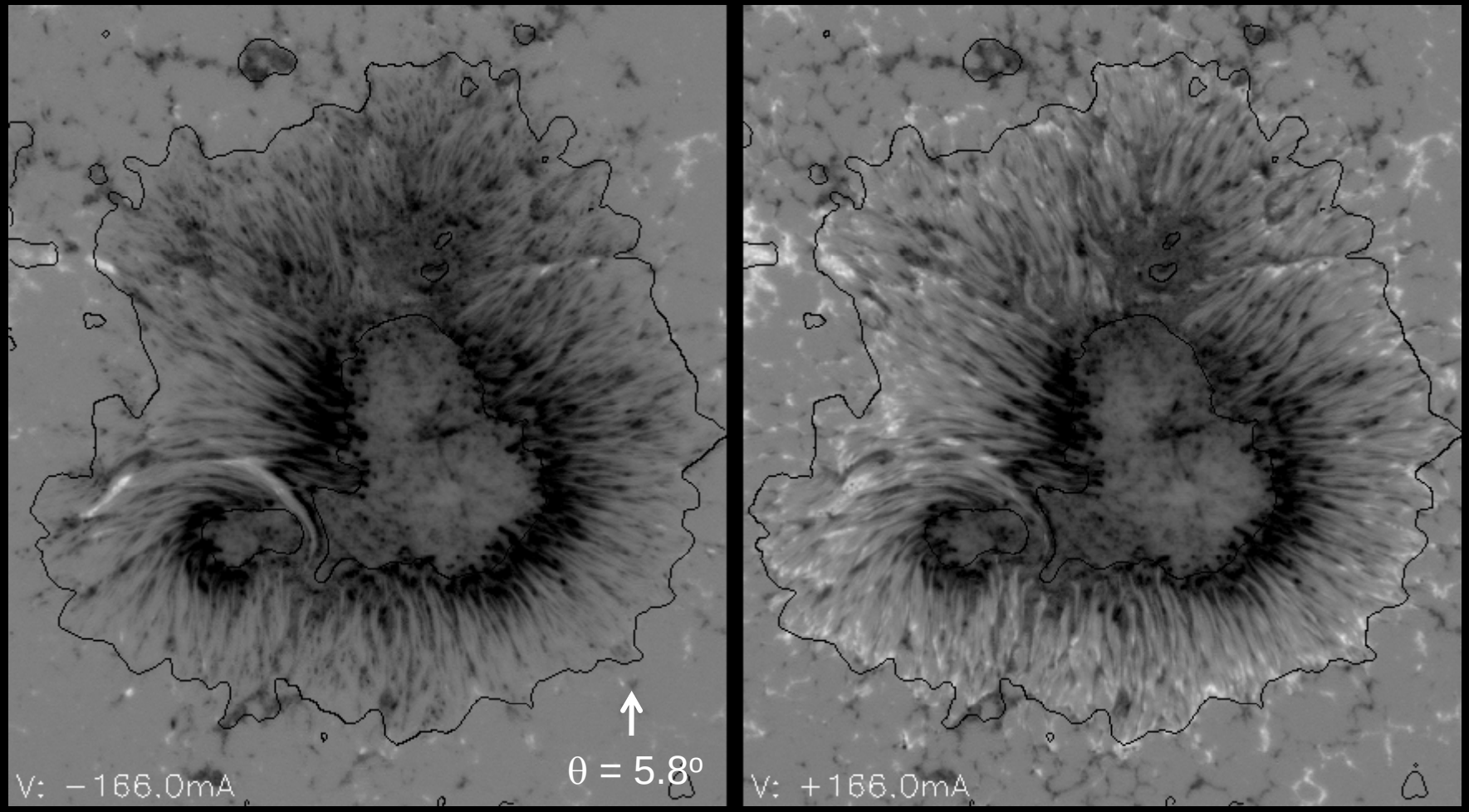


-144mA

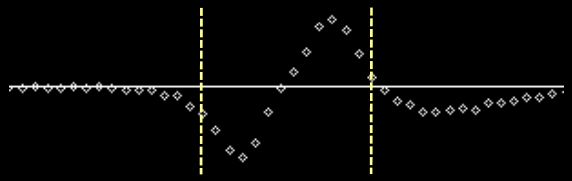


+144mA

Stokes-V at 6302.5A ±166mA

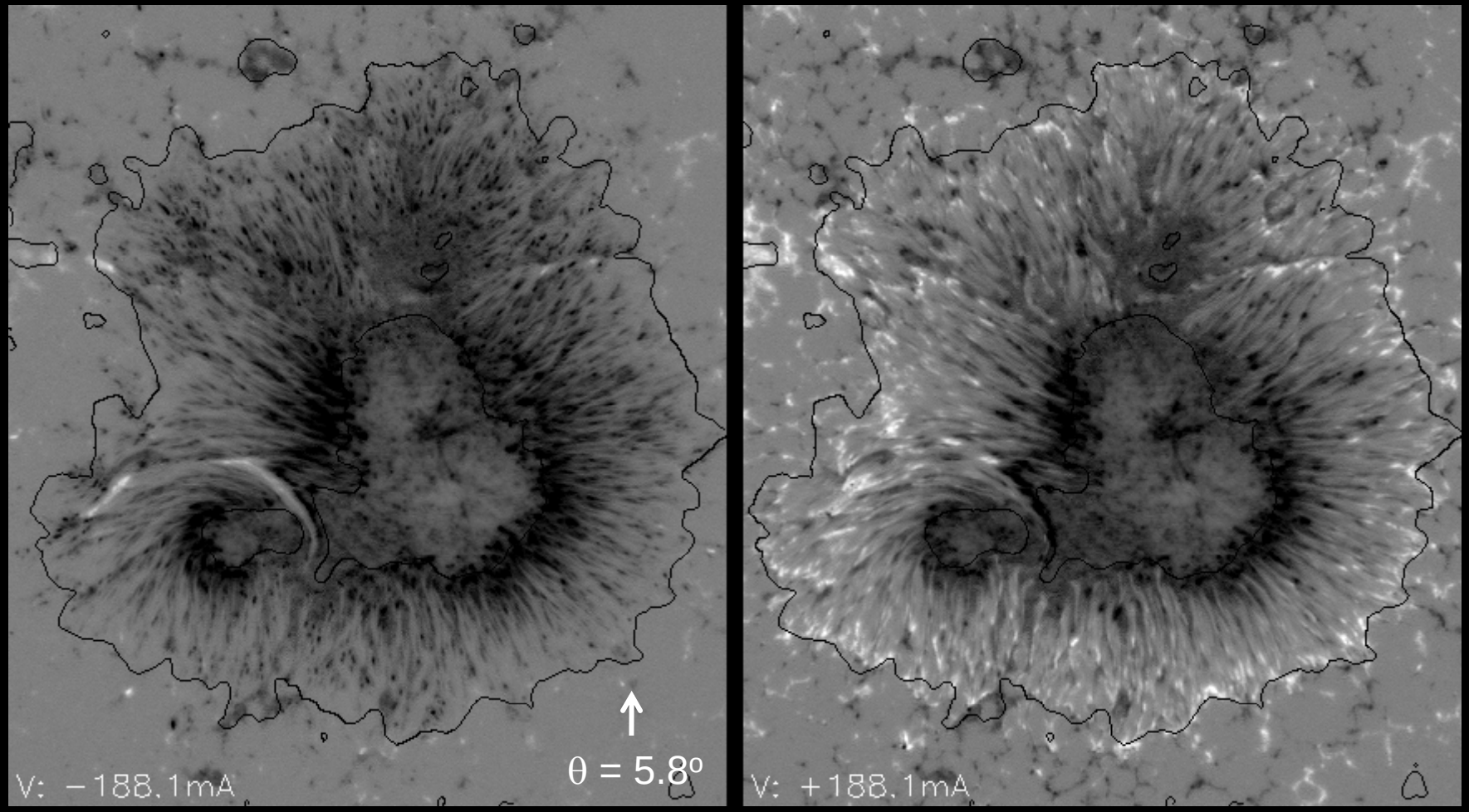


-166mA

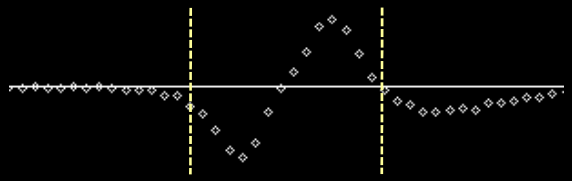


+166mA

Stokes-V at 6302.5A ±188mA

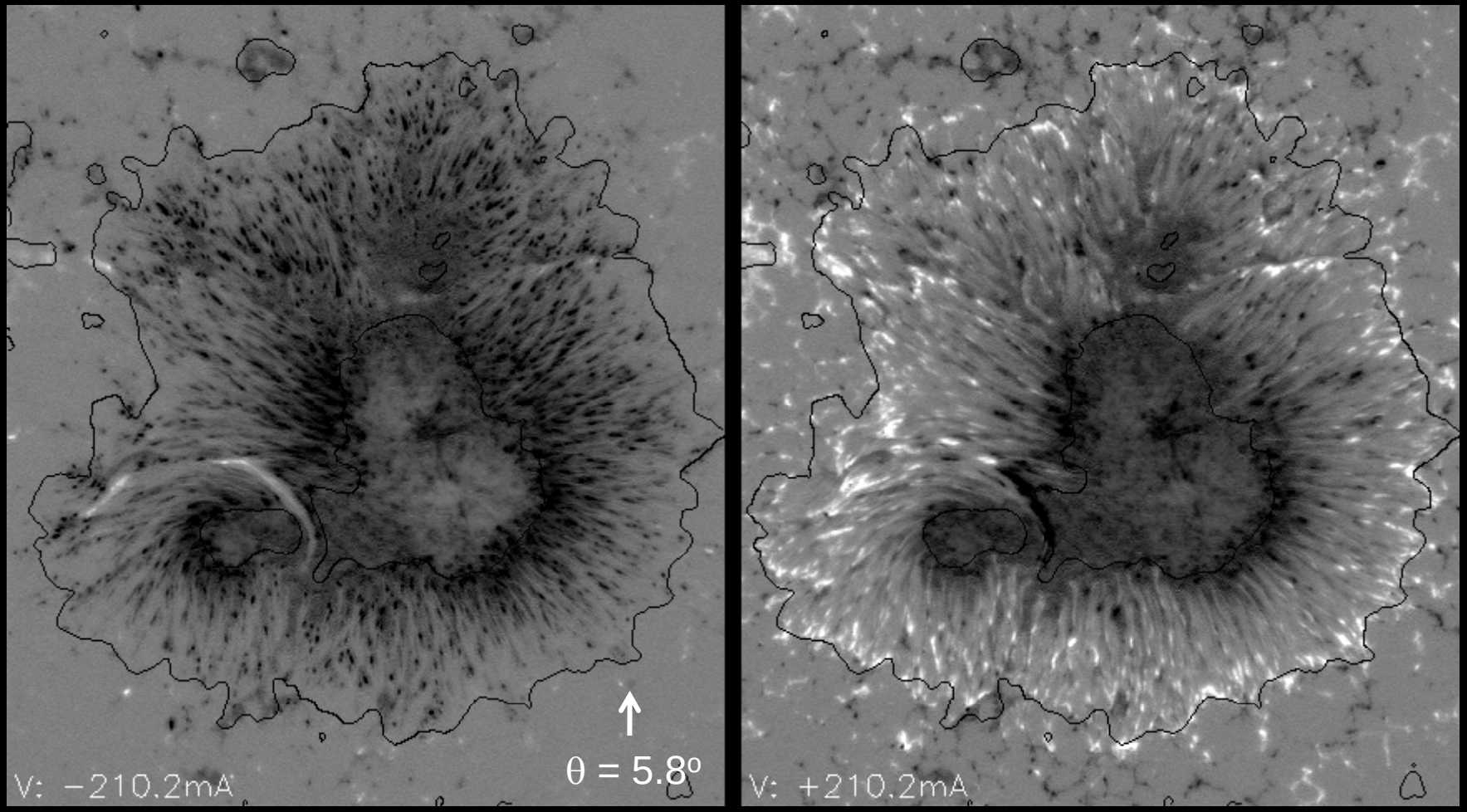


-188mA

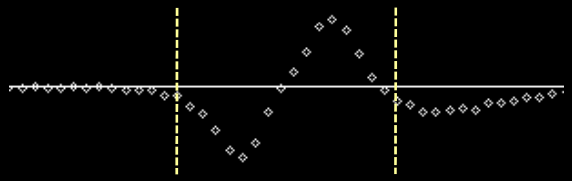


+188mA

Stokes-V at 6302.5A ±210mA

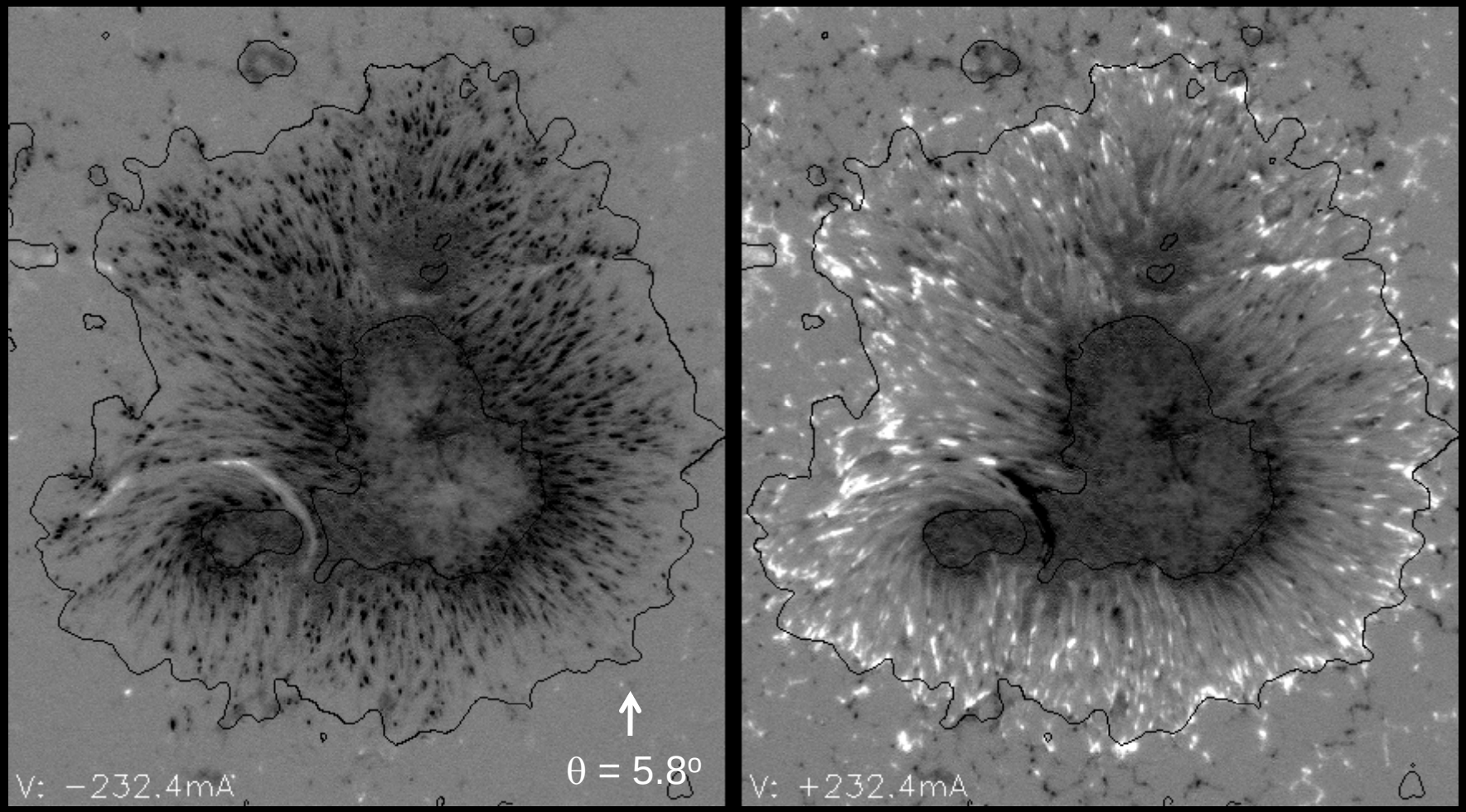


-210mA

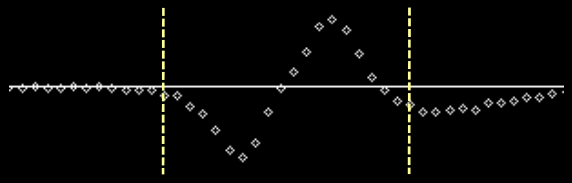


+210mA

Stokes-V at 6302.5A ±232mA

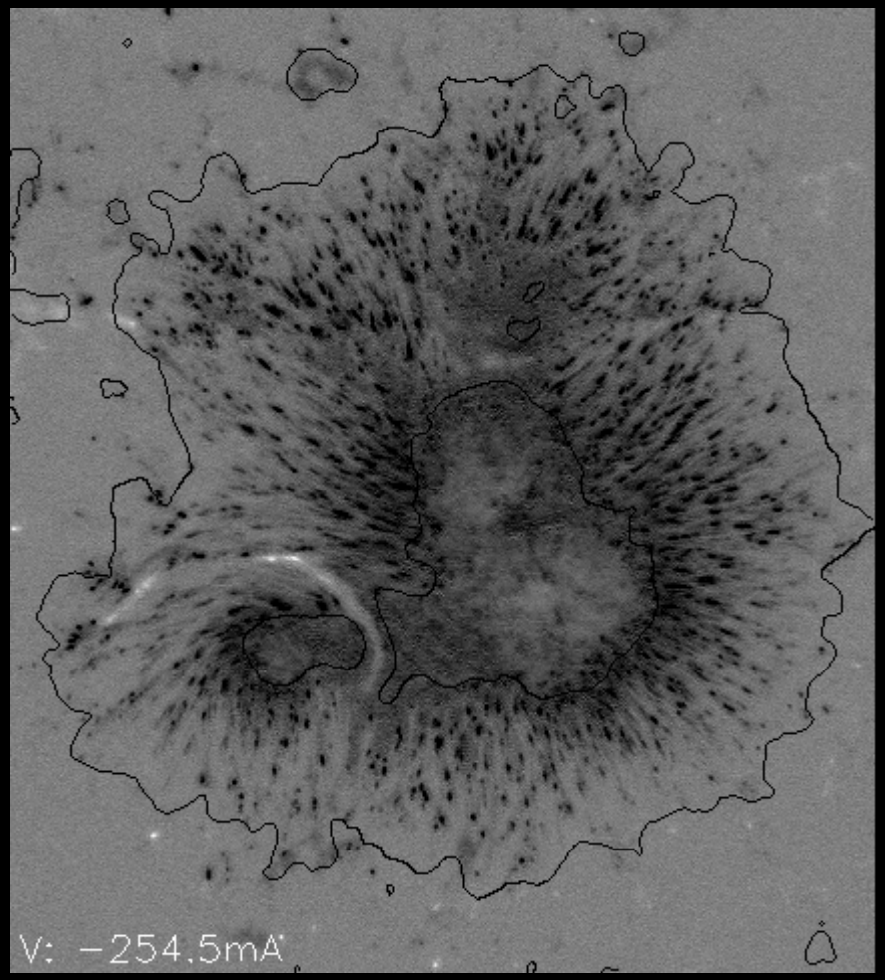


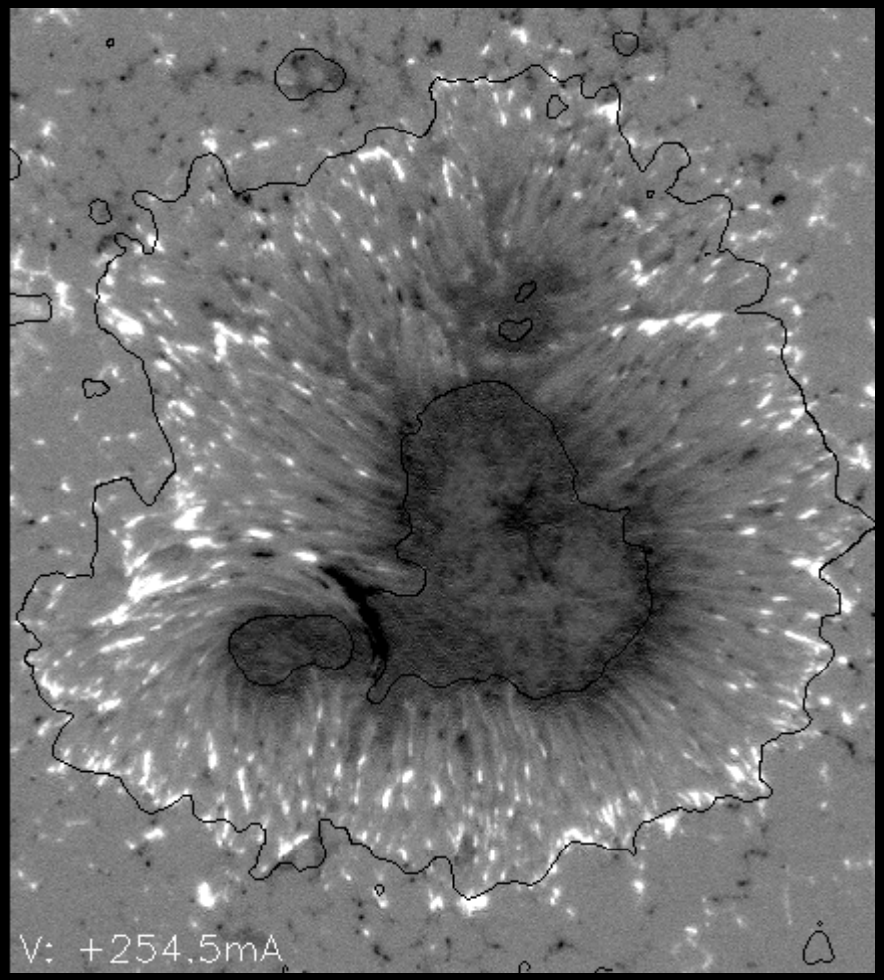
-232mA



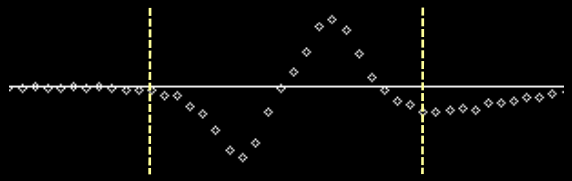
+232mA

Stokes-V at 6302.5A ±254mA



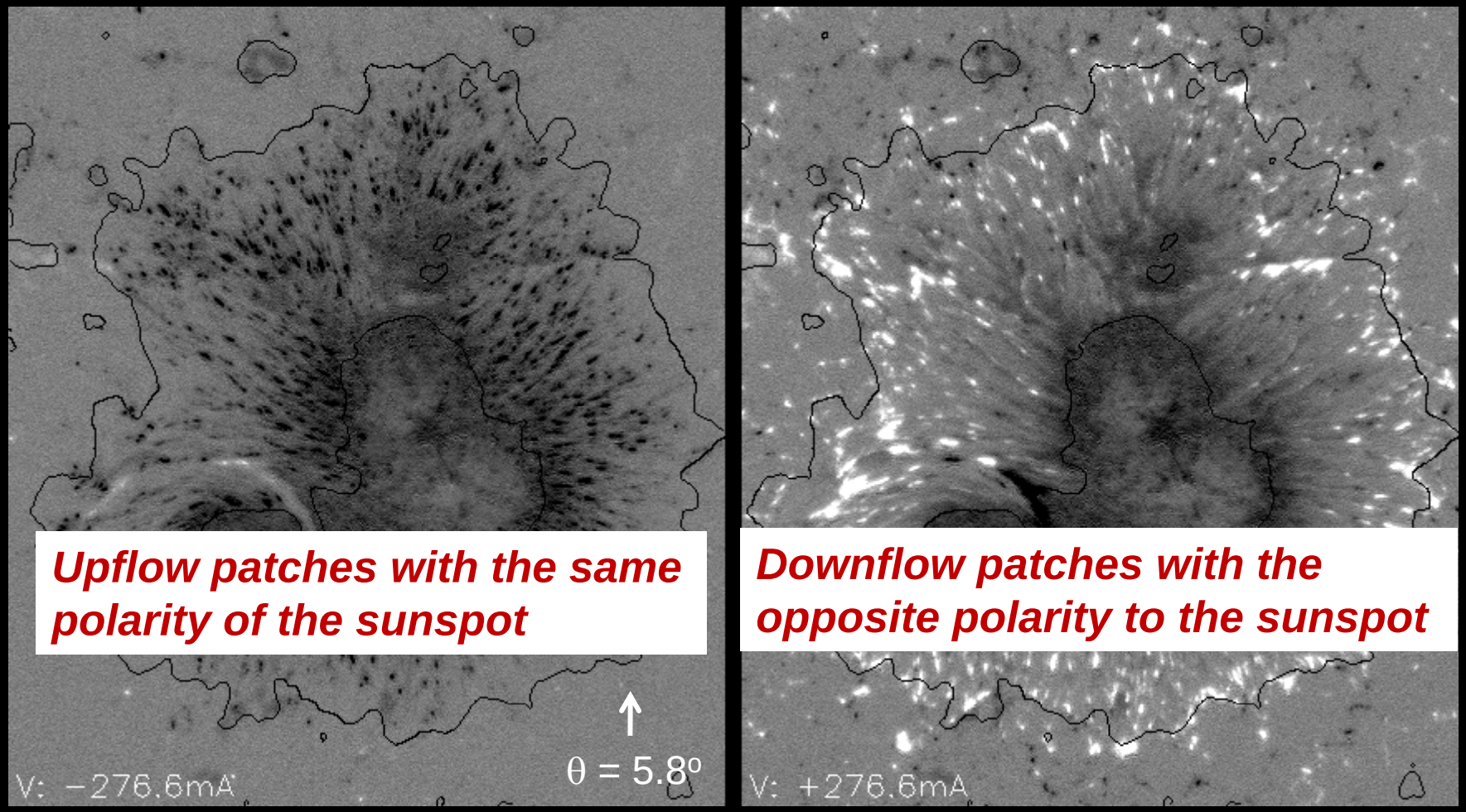


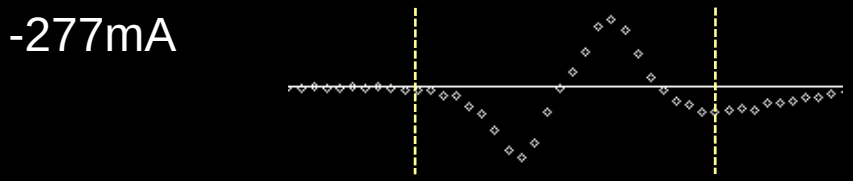
-254mA



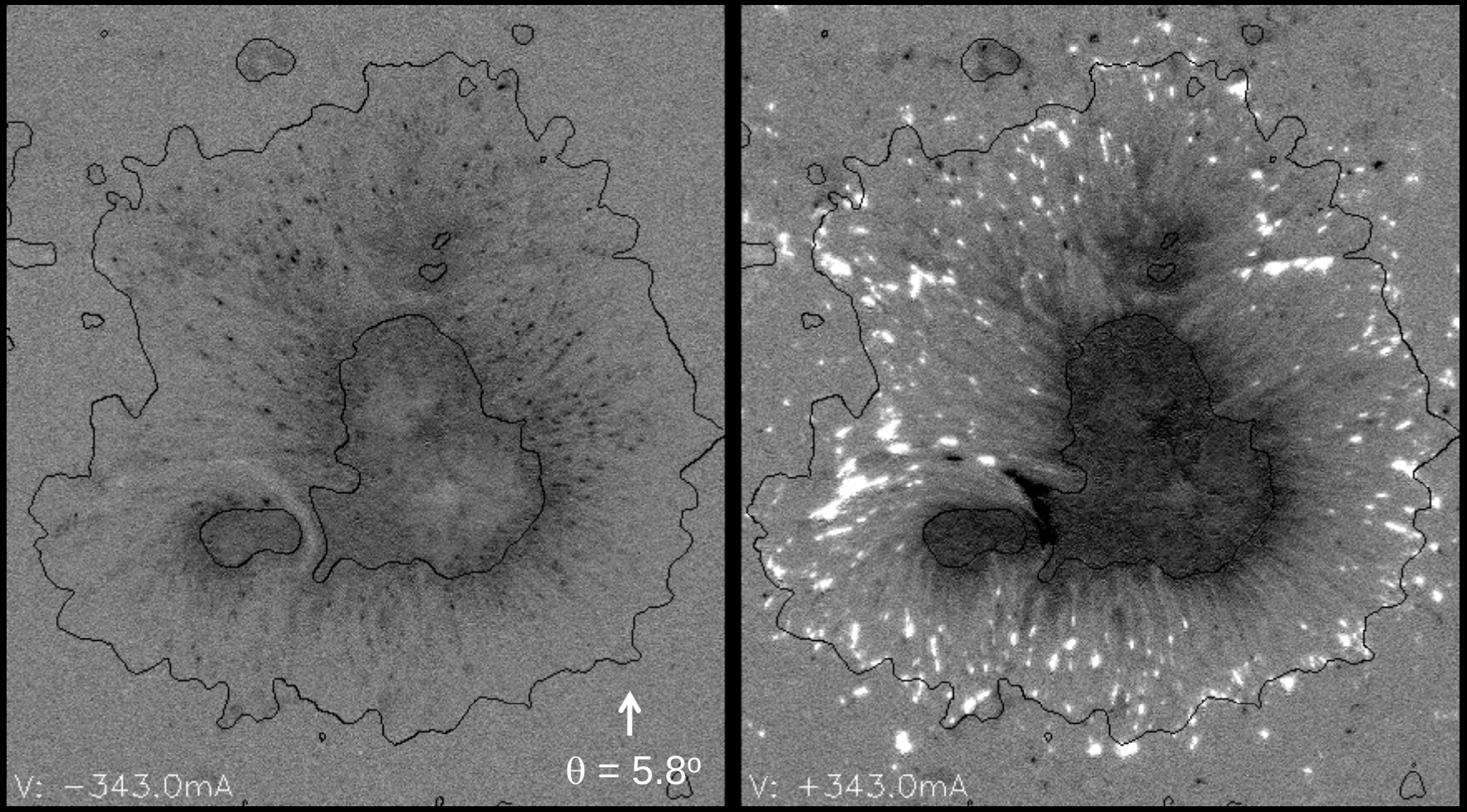
+254mA

Stokes-V at 6302.5A ±277mA

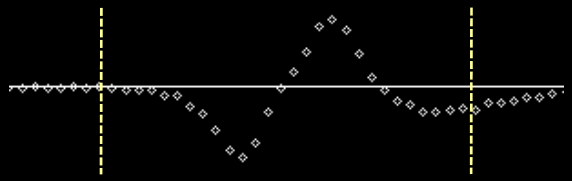




Stokes-V at 6302.5A ±343mA

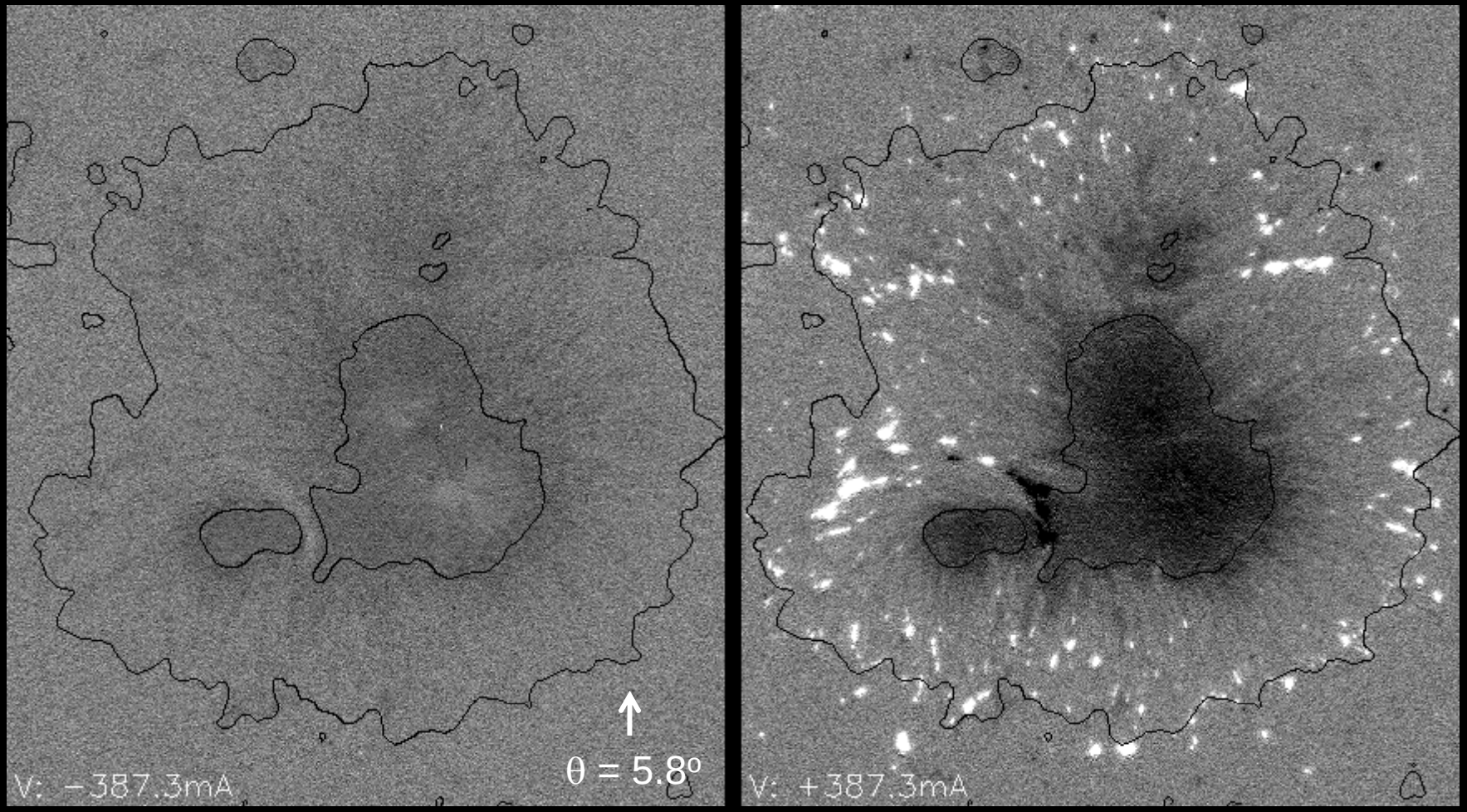


-343mA

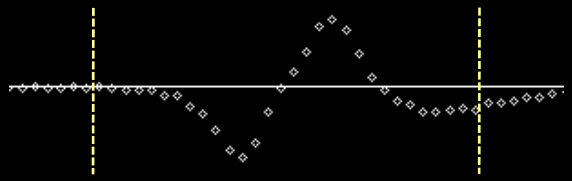


+343mA

Stokes-V at 6302.5A ±343mA

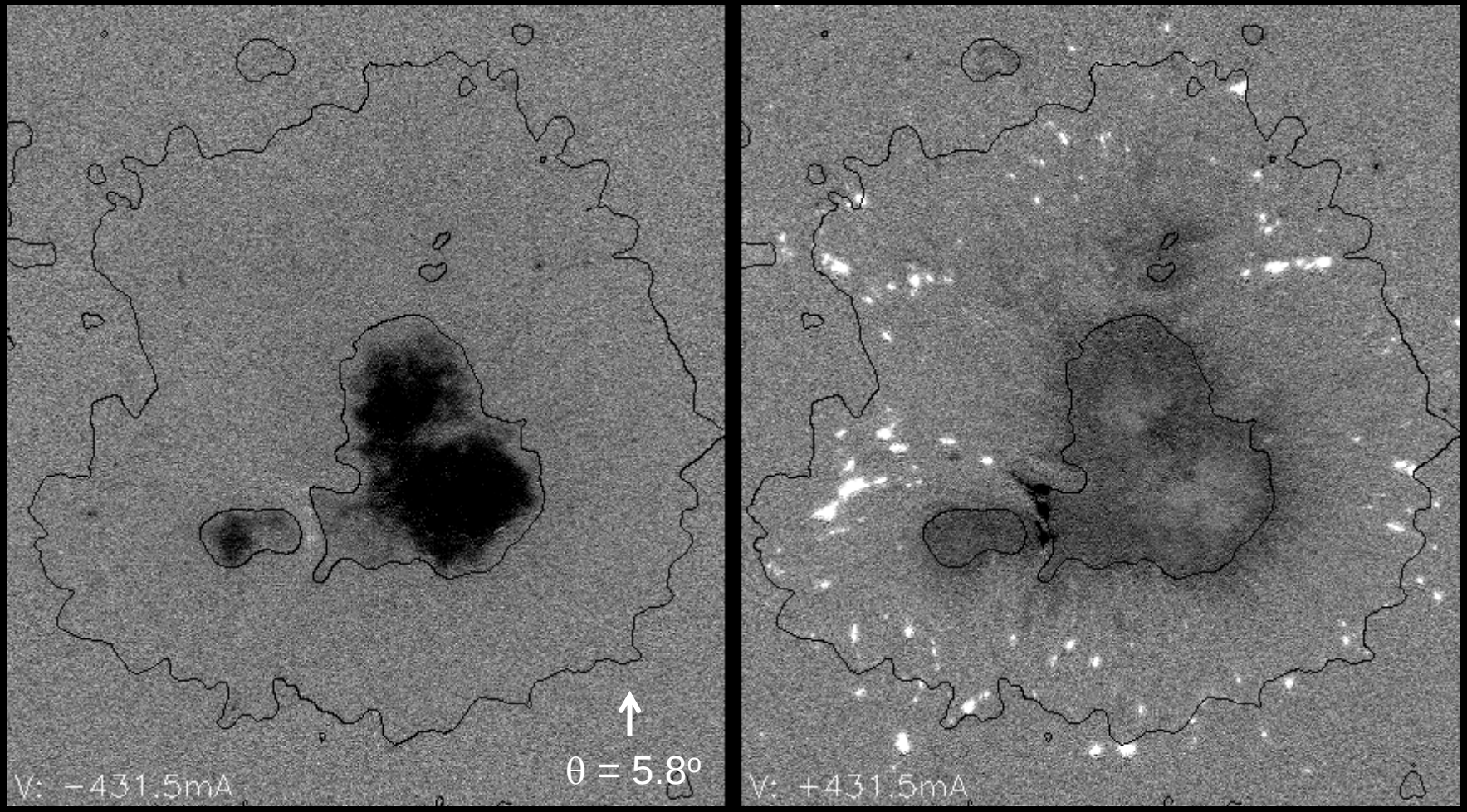


-387mA

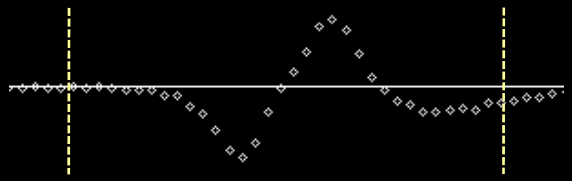


+387mA

Stokes-V at 6302.5A ±343mA

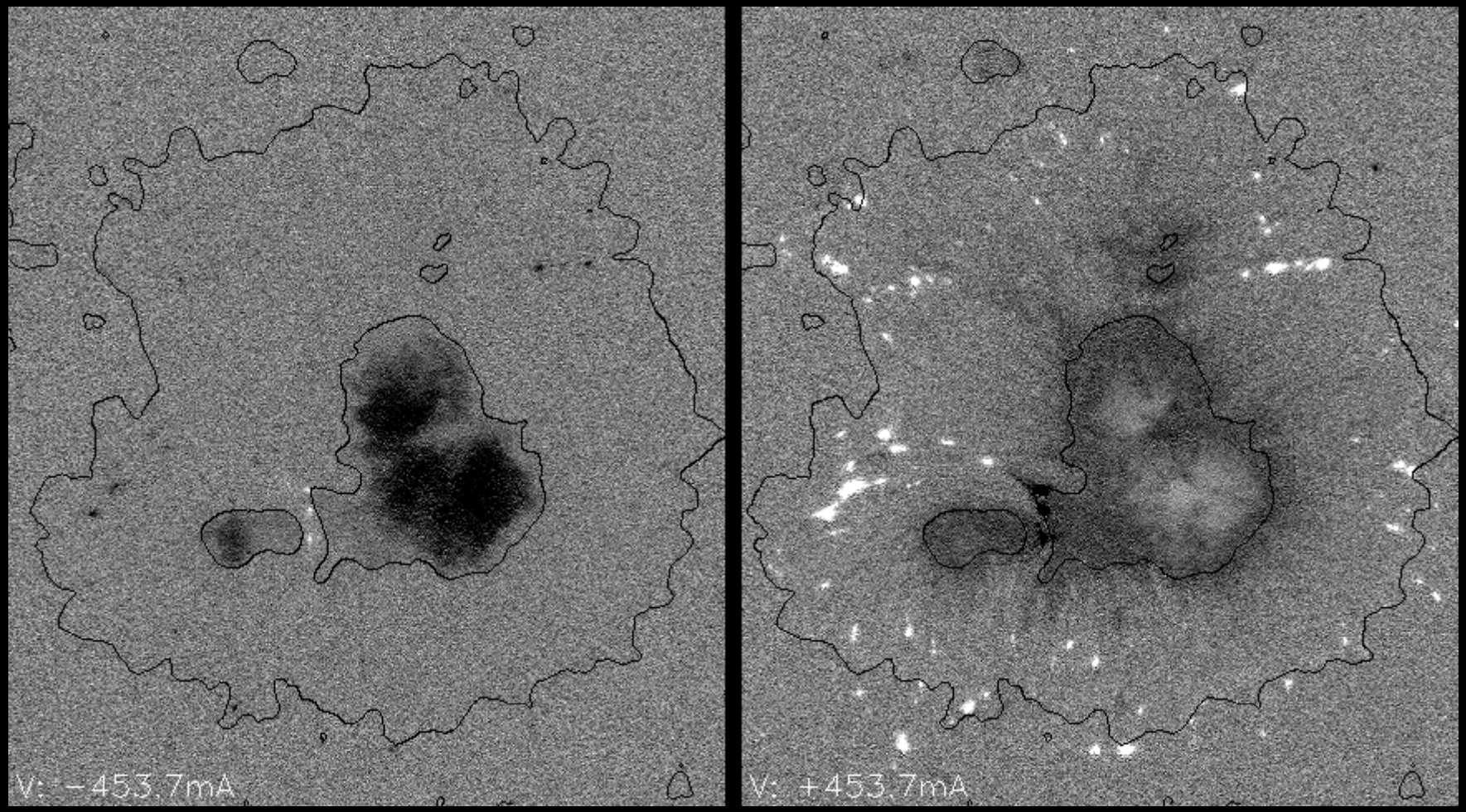


-431mA

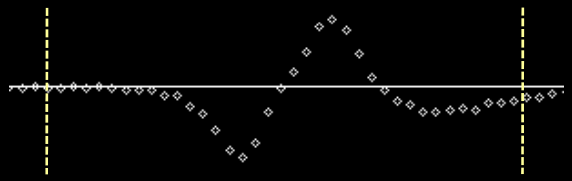


+431mA

Stokes-V at 6302.5A ±454mA

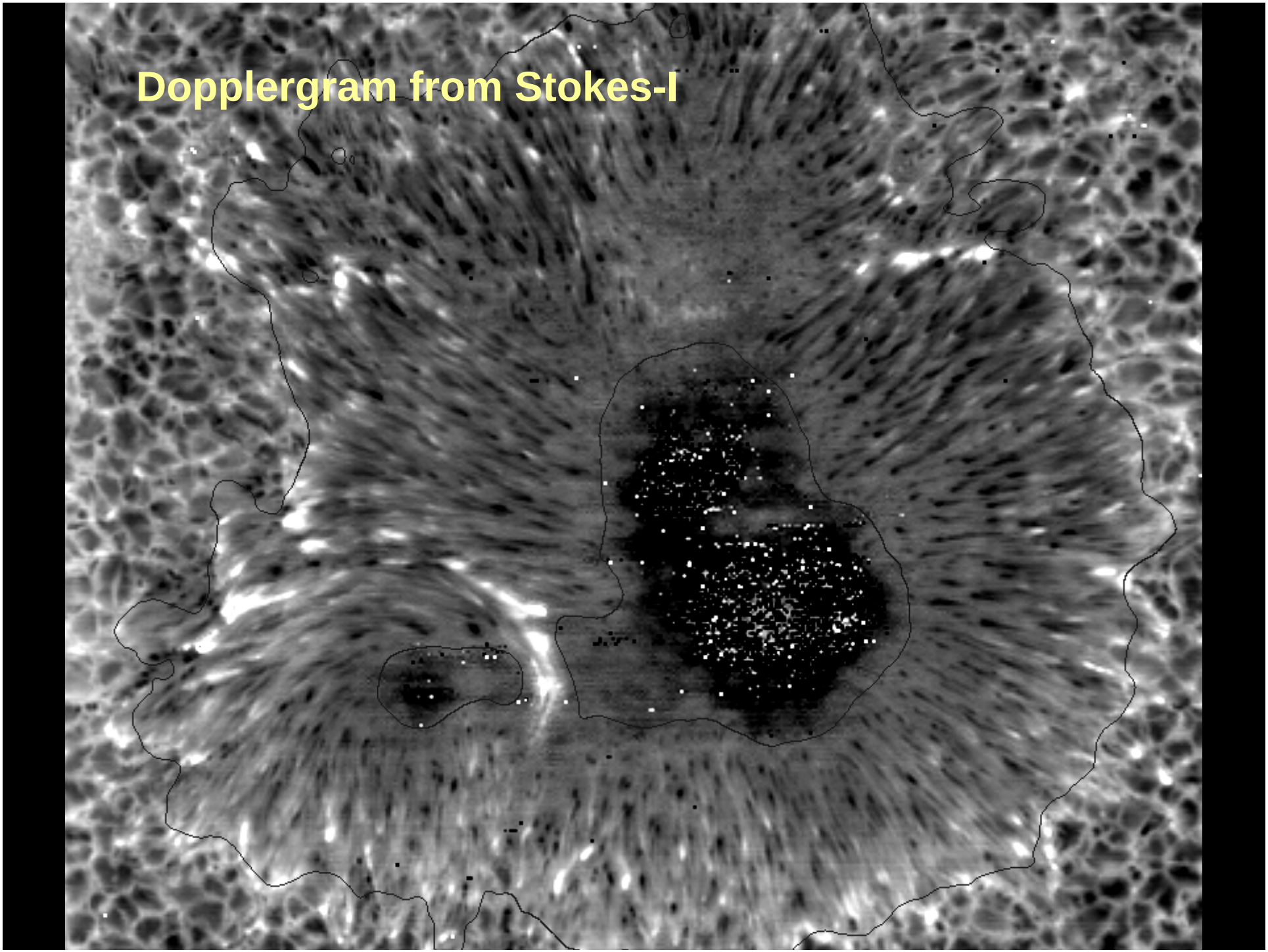


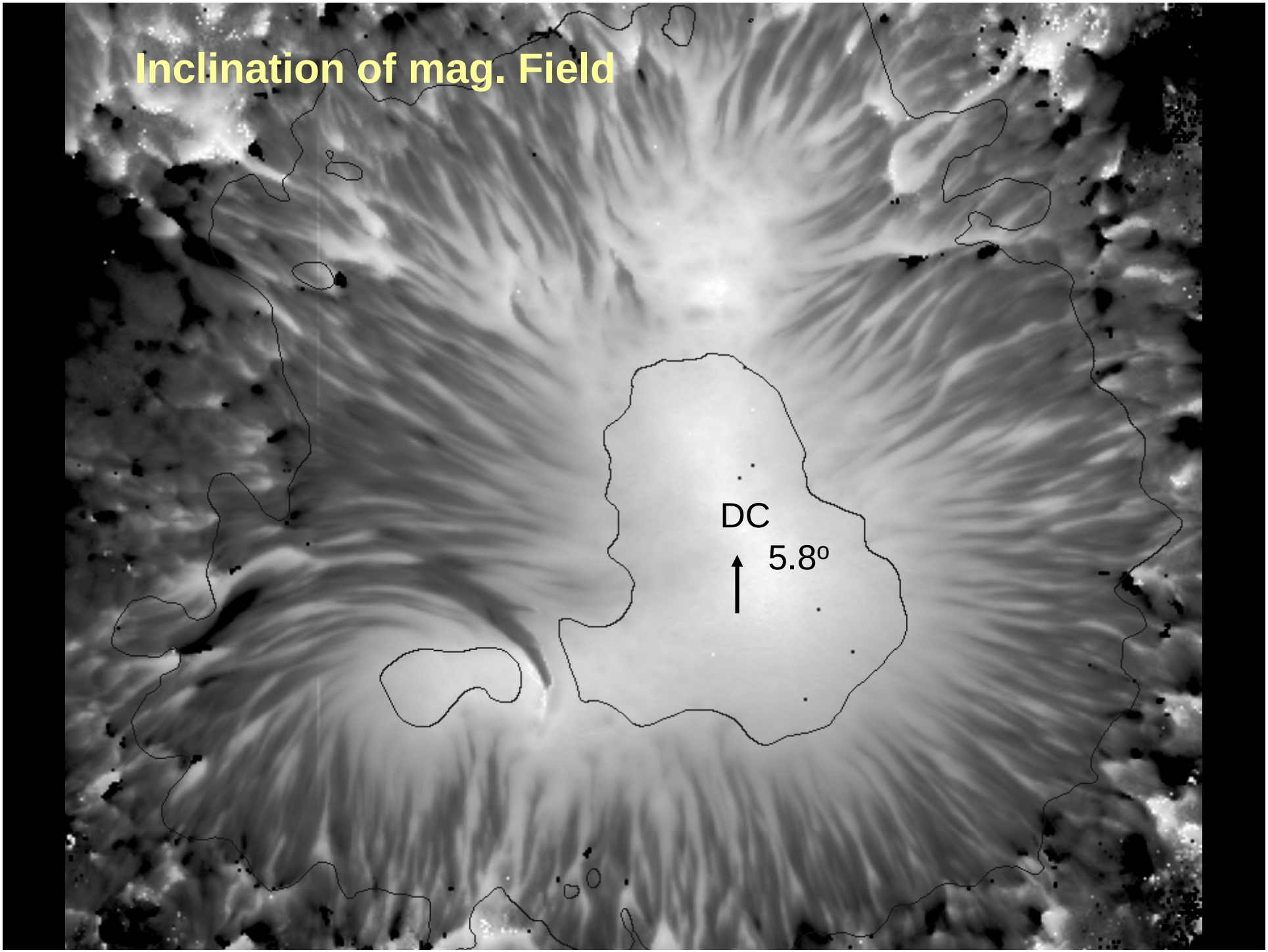
-454mA



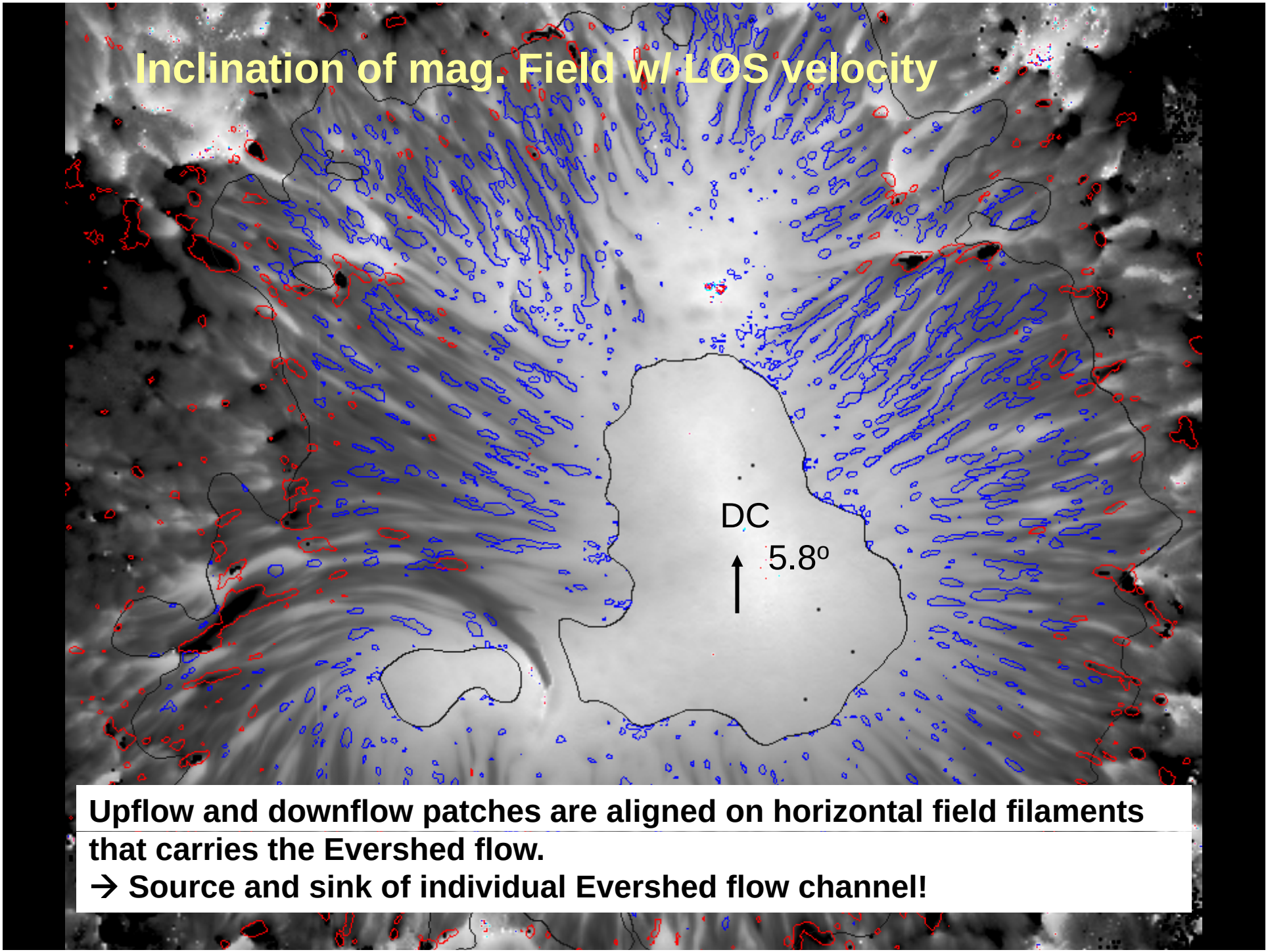
+454mA

➔ 22km/s (supersonic!)


Dopplergram from Stokes-I


Inclination of mag. Field
DC
5.8o

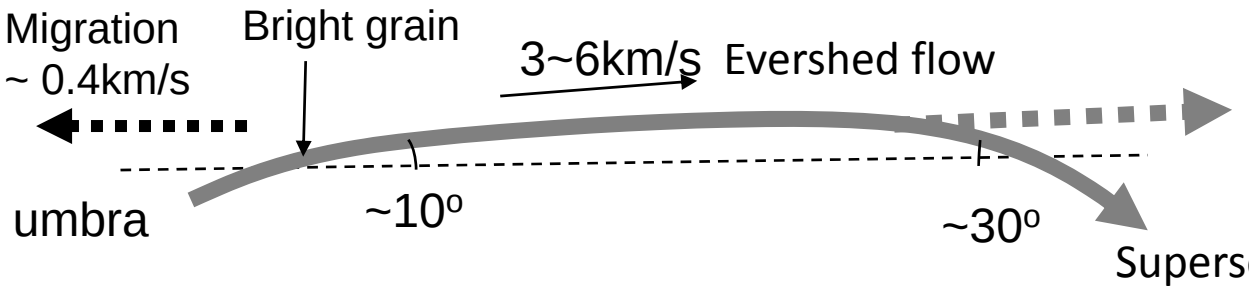
Inclination of mag. Field w/ LOS velocity

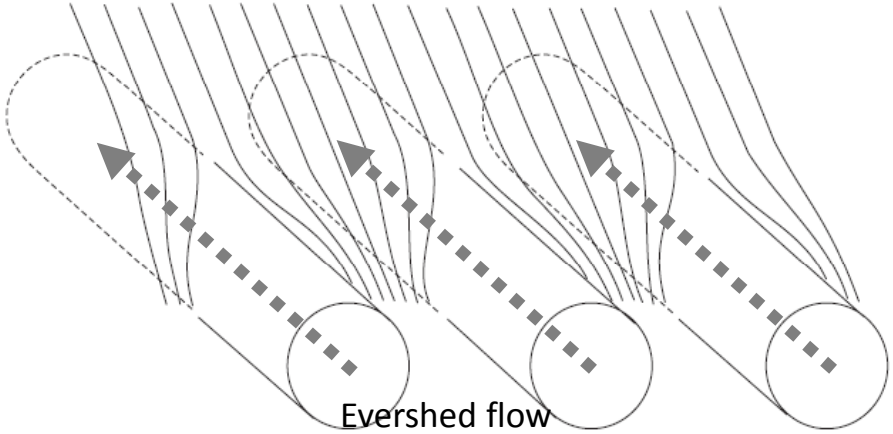


Upflow and downflow patches are aligned on horizontal field filaments that carries the Evershed flow.

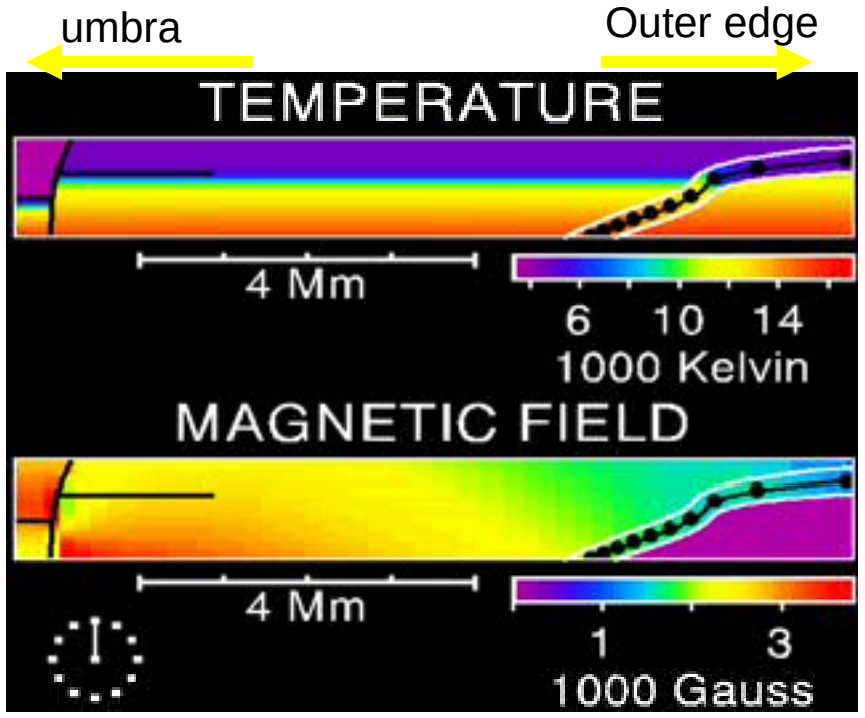
→ Source and sink of individual Evershed flow channel!

Individual Evershed flow channels consistent with the rising flux tube model w/ uncombed structure.

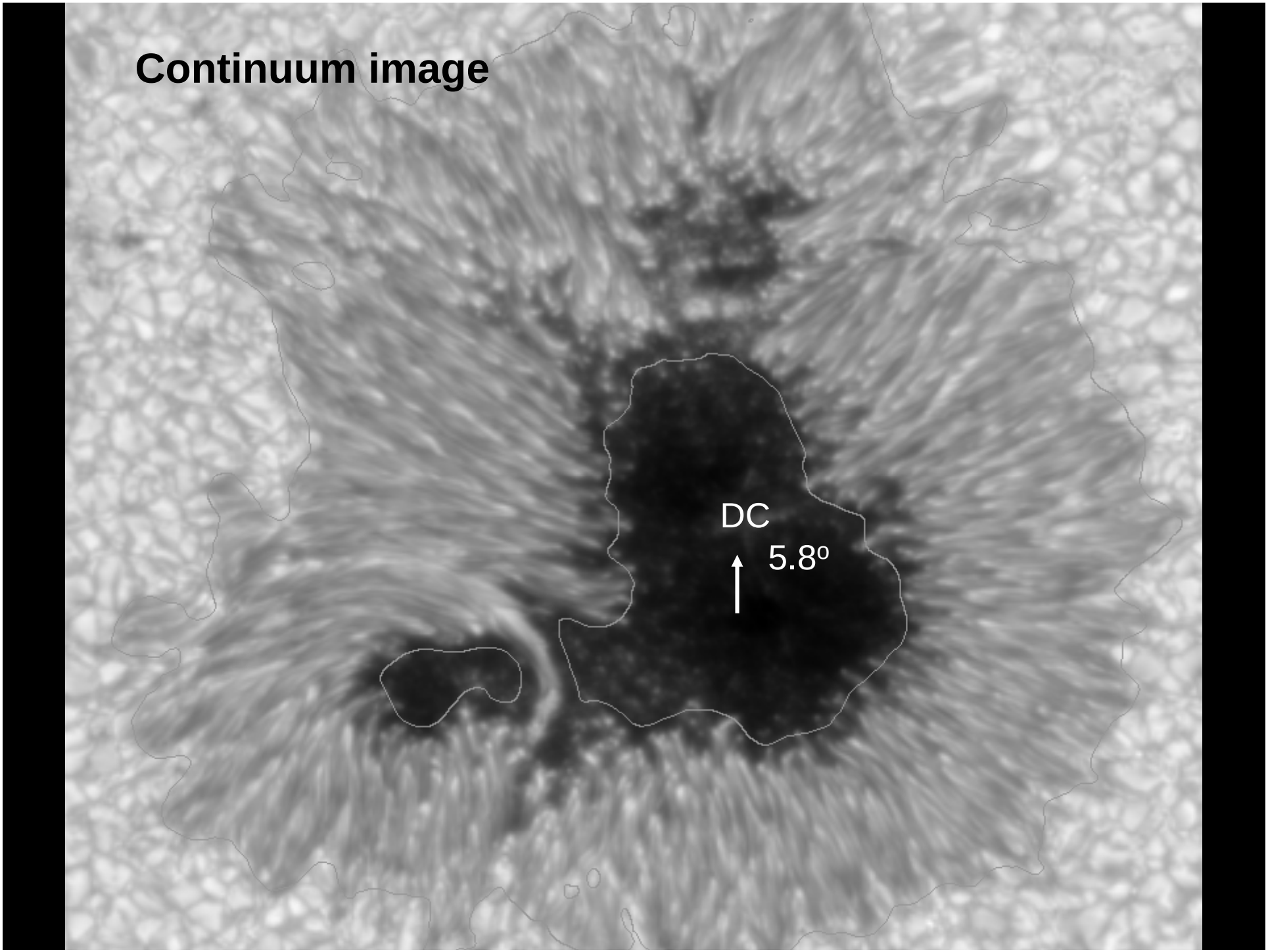




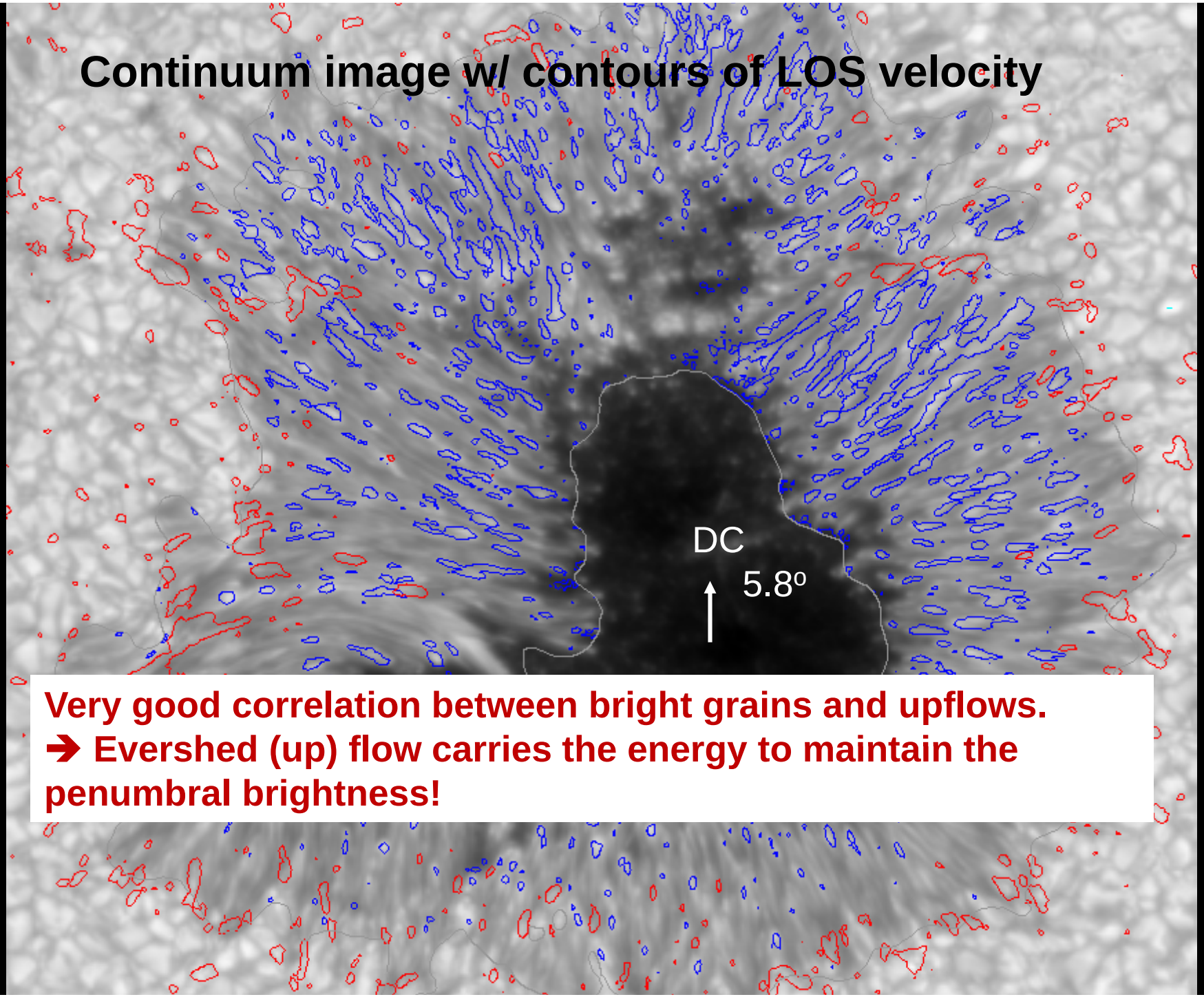
‘uncombed’ penumbral model
Solanki & Motavon 1993



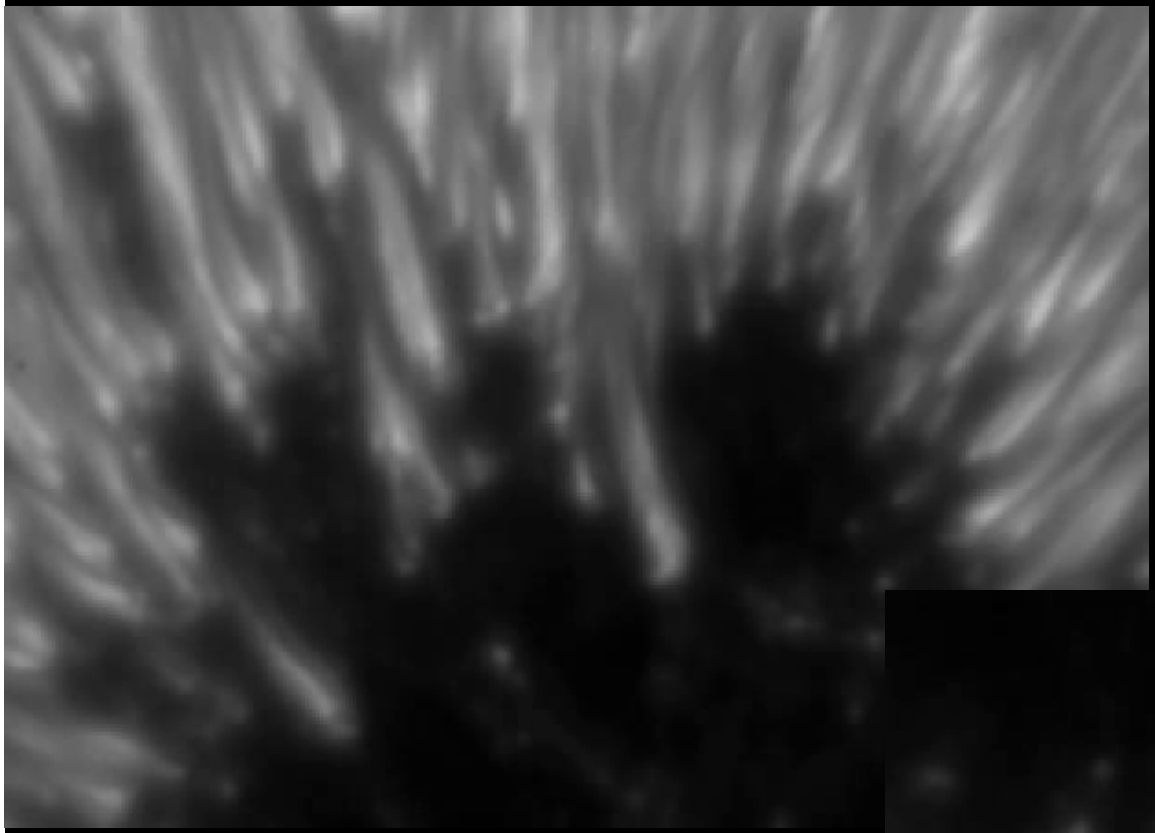
flux tube model （Schlichenmeier etal 1998)


Continuum image
DC
5.8º

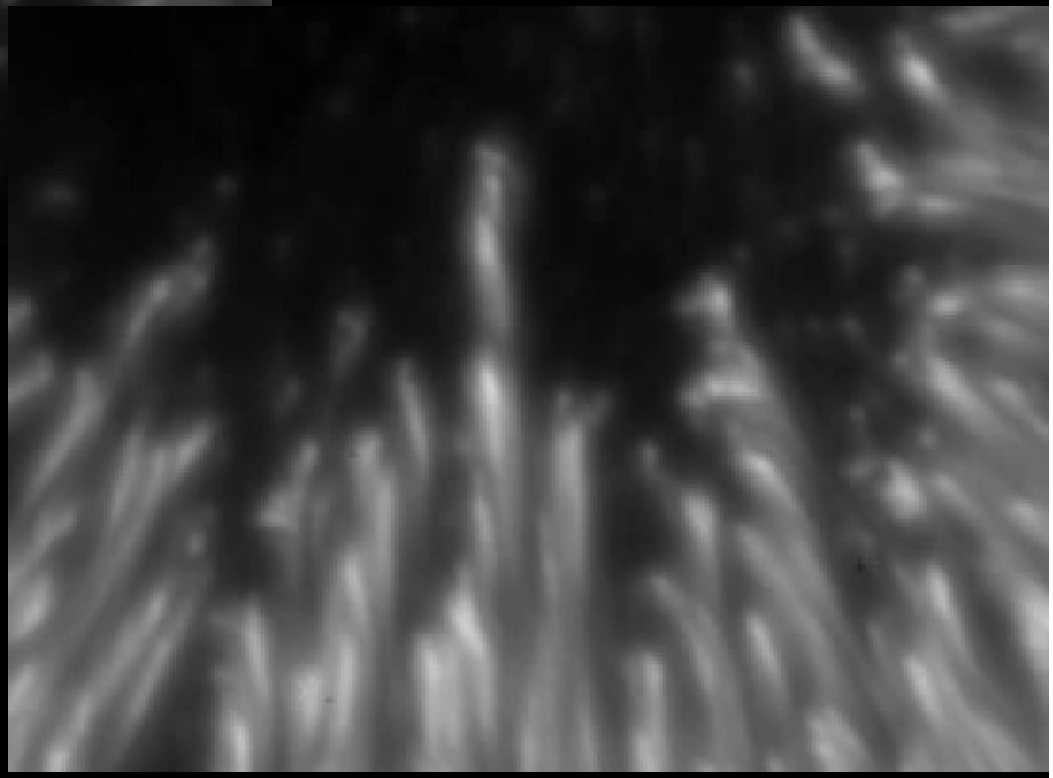
Continuum image w/ contours of LOS velocity



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



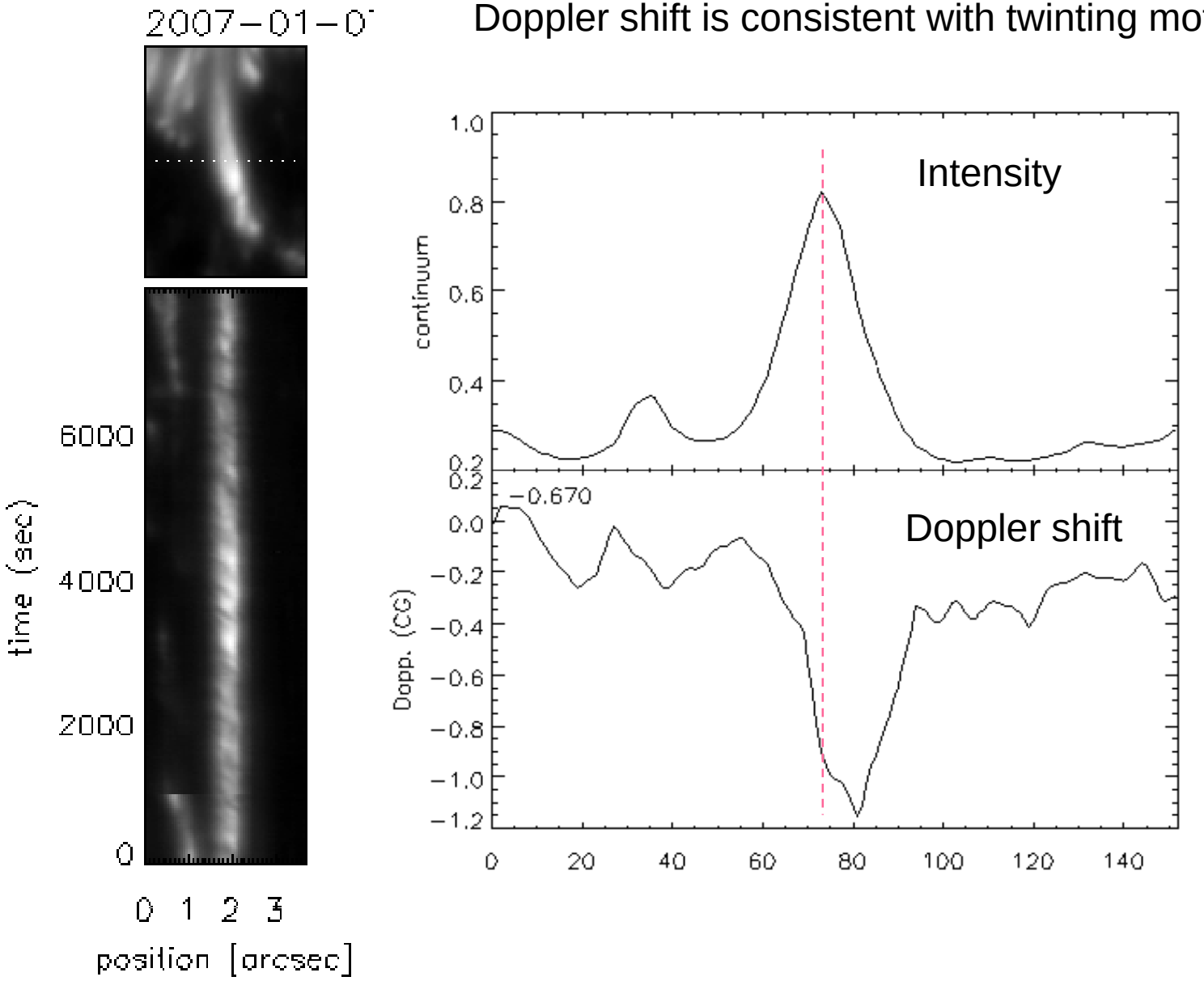
2007.1.7



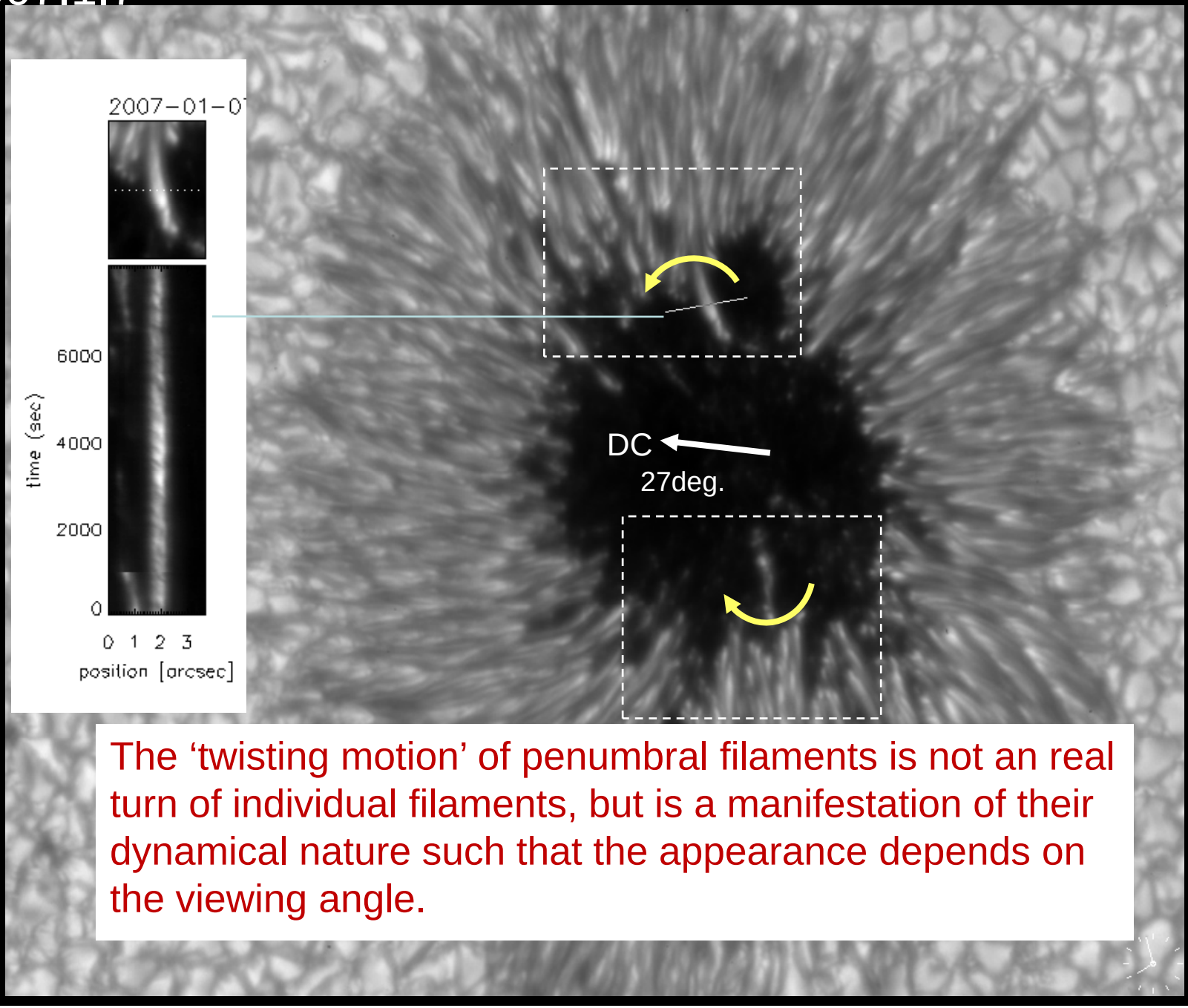
Twisting filaments…

2007.1.7

Doppler shift is consistent with twinting motion..



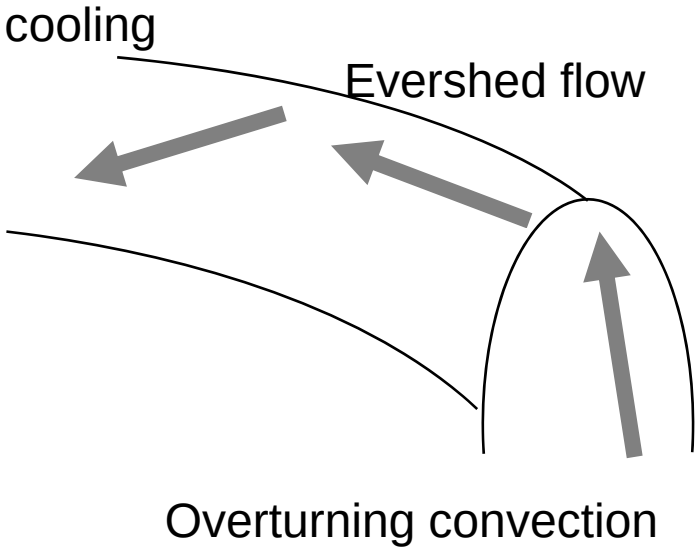
2007.1.7



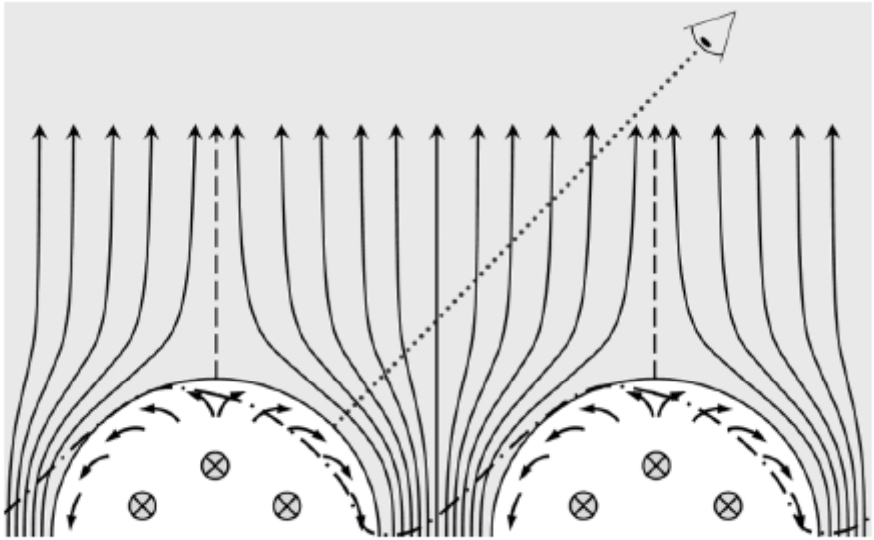
The ‘twisting motion’ of penumbral filaments is not an real turn of individual filaments, but is a manifestation of their dynamical nature such that the appearance depends on the viewing angle.

What is the origin of the twisting appearance?

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

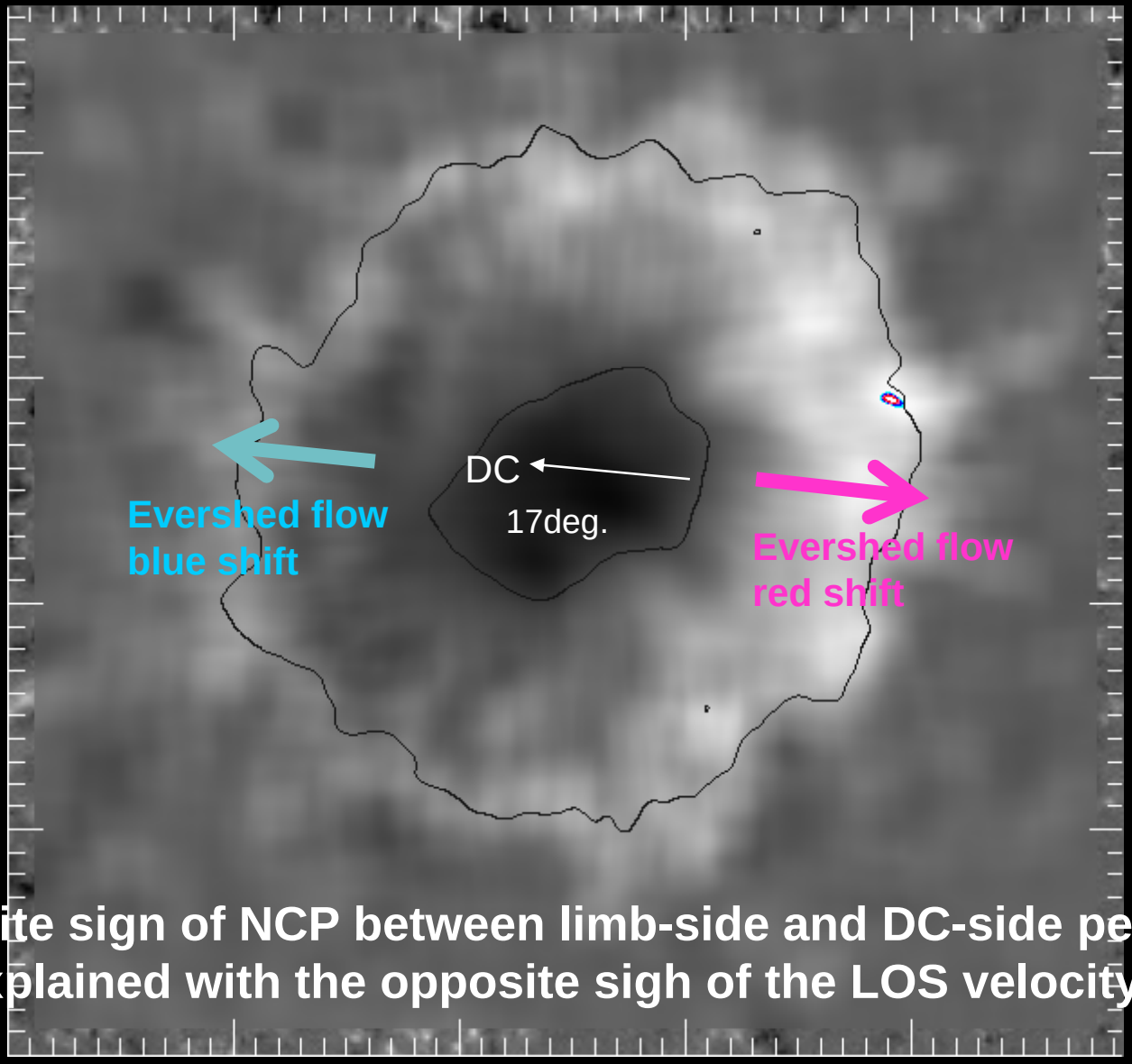


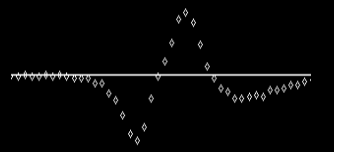
Ichimoto, etal., 2007, Science, 318, 1597



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

Net circular polarization in low resolution



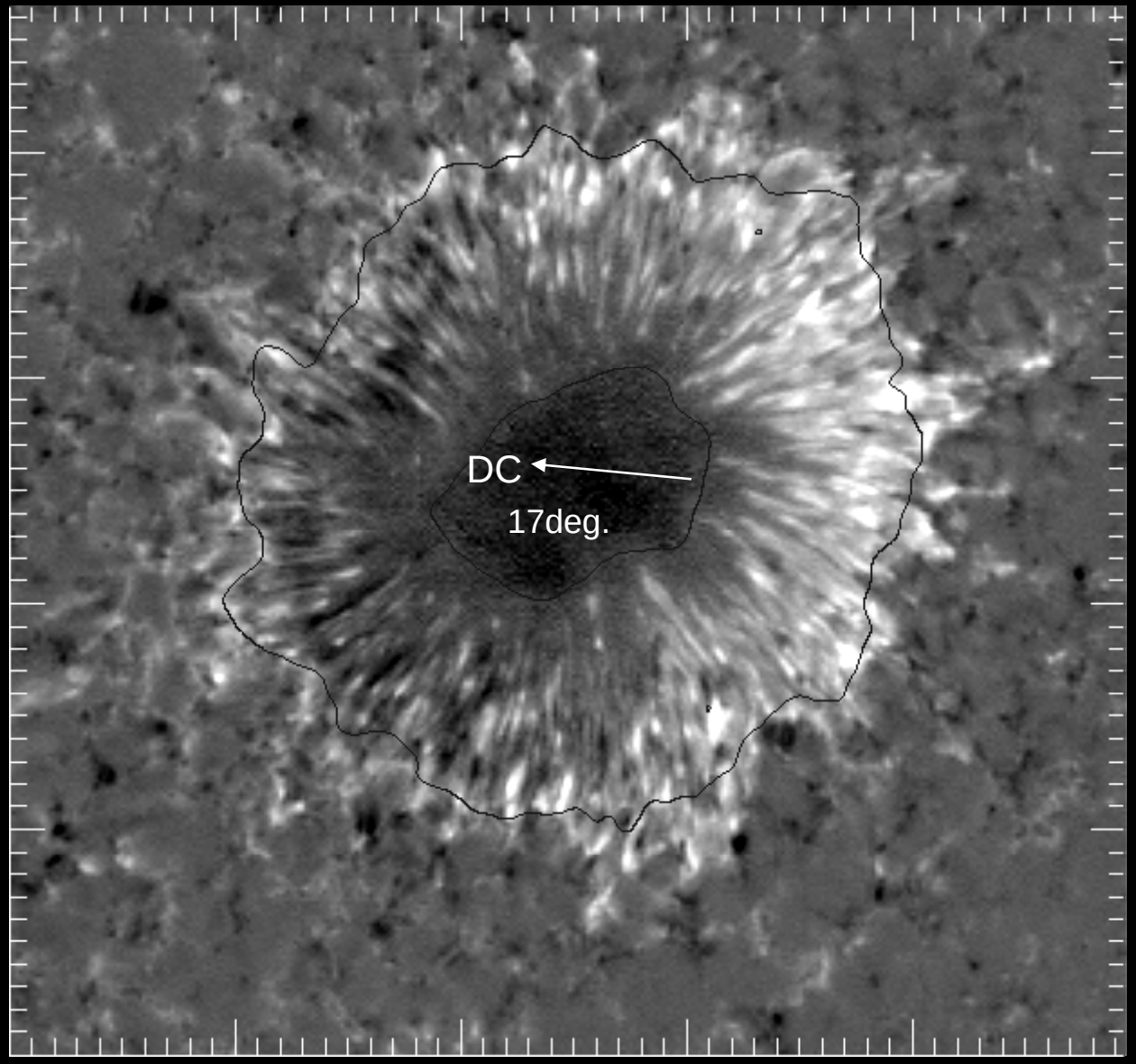


$$\int V d\lambda$$

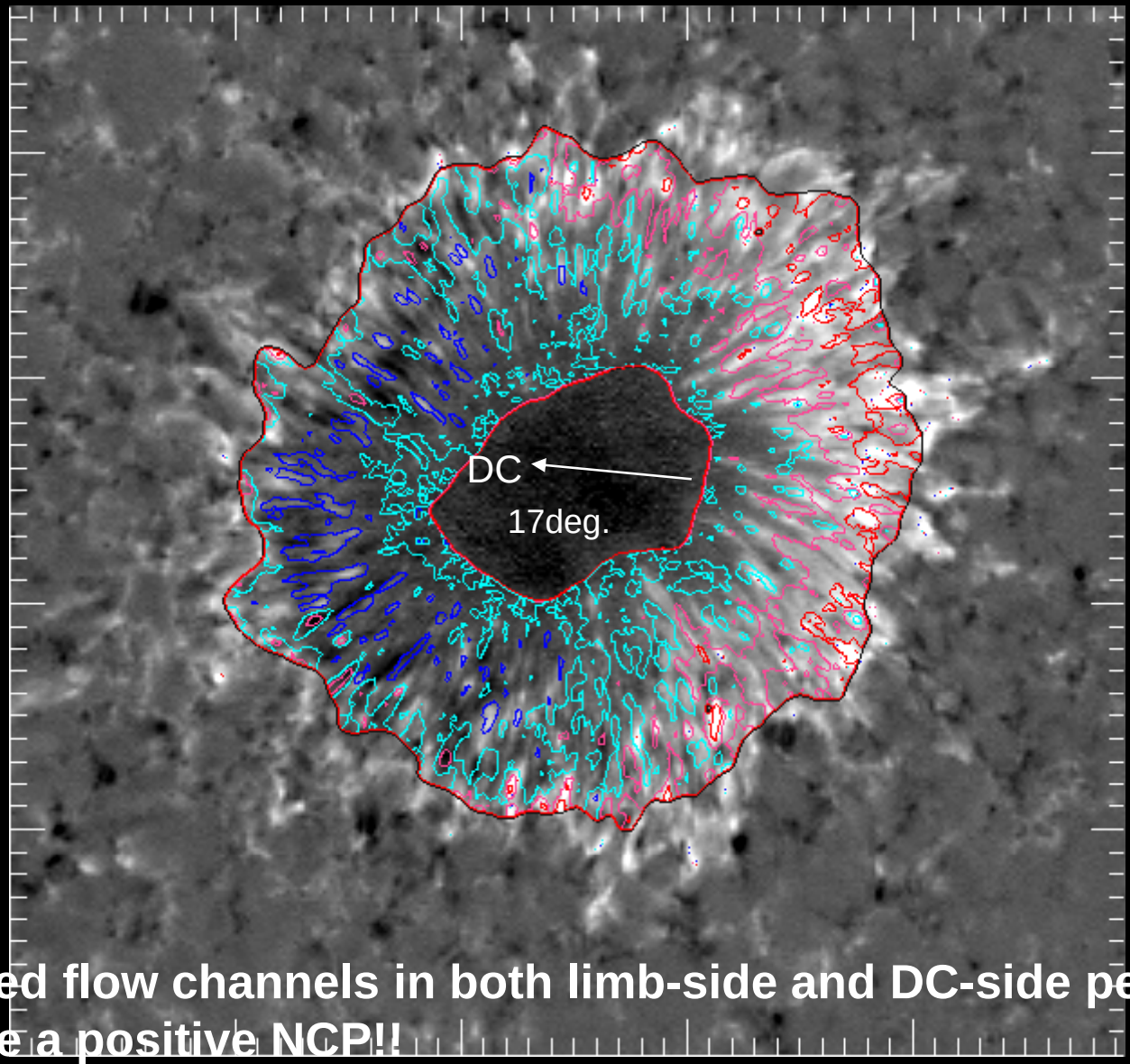
Depth veri.
dv/dτ, dB/dτ

Opposite sign of NCP between limb-side and DC-side penumbra was explained with the opposite sigh of the LOS velocity in deep layer.

Net circular polarization in SOT resolution



Net circular polarization in SOT resolution

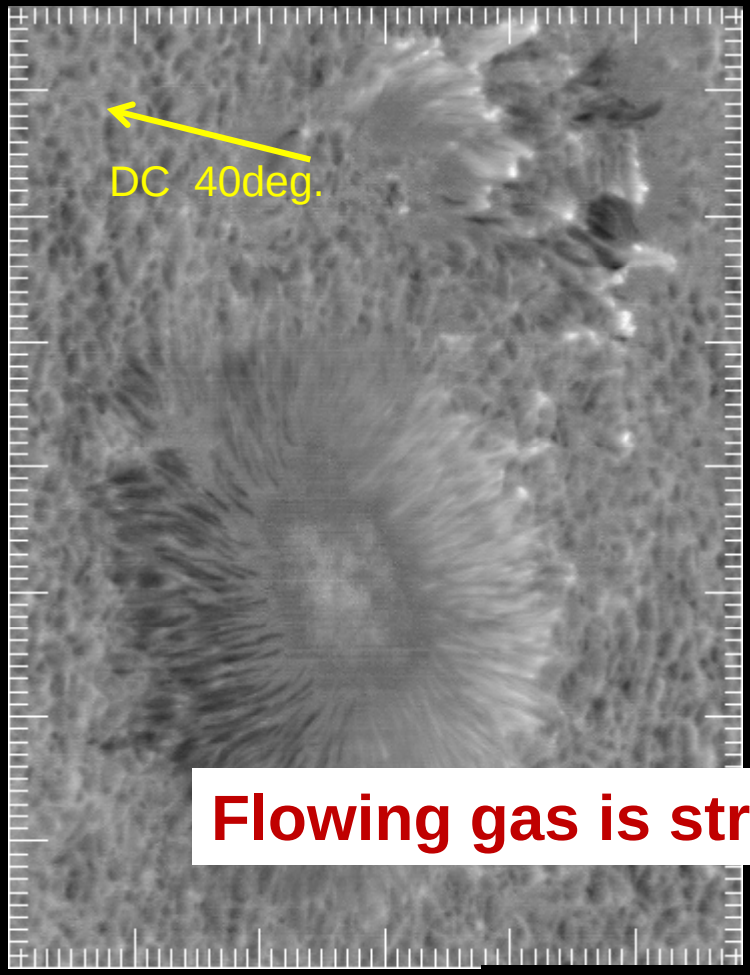


Evershed flow channels in both limb-side and DC-side penumbra produce a positive NCP!!

Positive correlation between flow velocity and field strength!

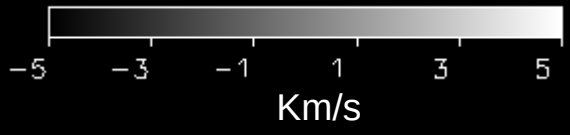
6302.5A Dooppler shift, 2007.1.8

CG of Stokes-I



CG of sqrt($V^2+Q^2+U^2$)

Flowing gas is strongly magnetized!



Summary (1):

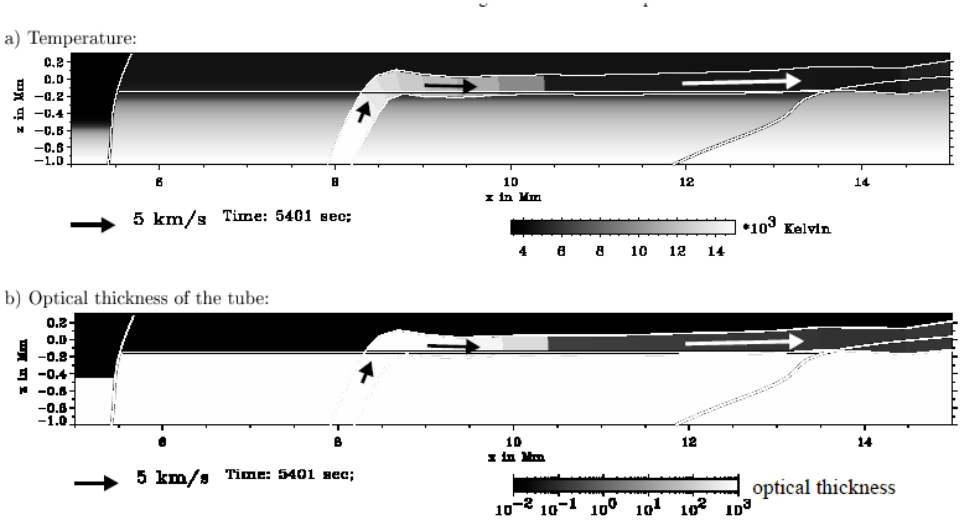
‘Convective nature of the Evershed Effect’

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

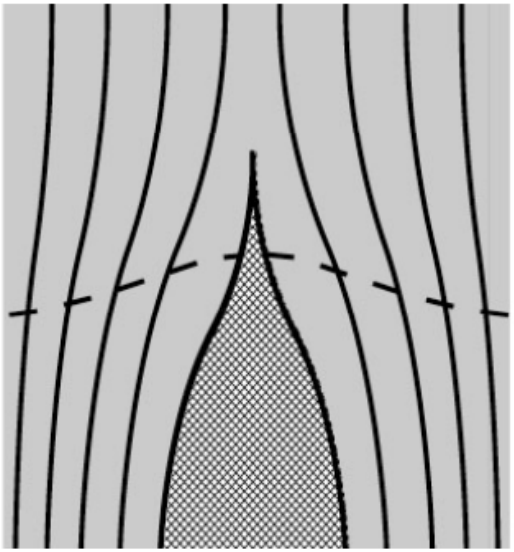
(e.g., Solanki & Motavon 1993
Schlichenmaier etal 1998)



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” (=slab), and if the gap model discard the word “field free”, then *there is no fundamental difference between the two models*. SOT observations suggest this direction.

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

Thank you!