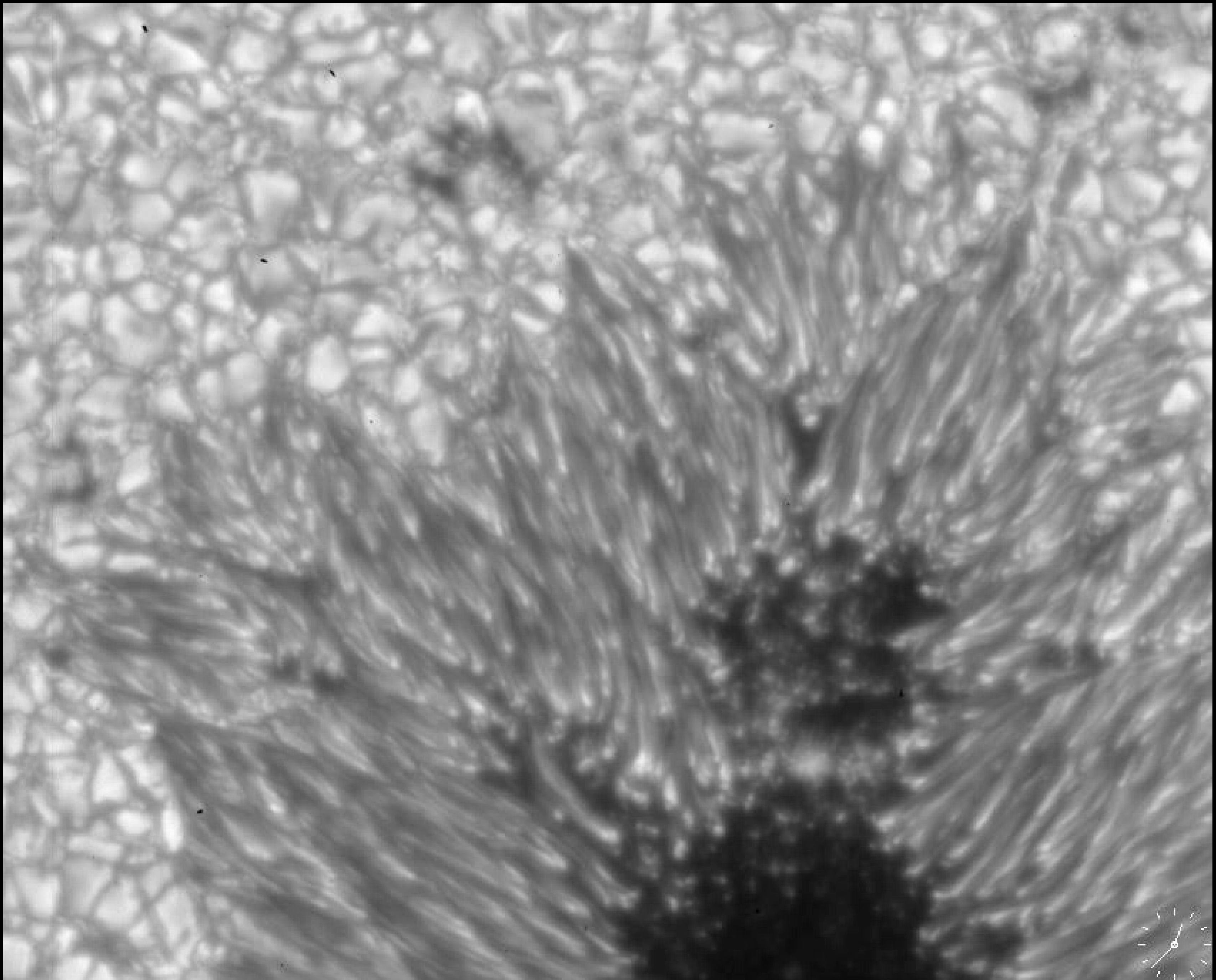
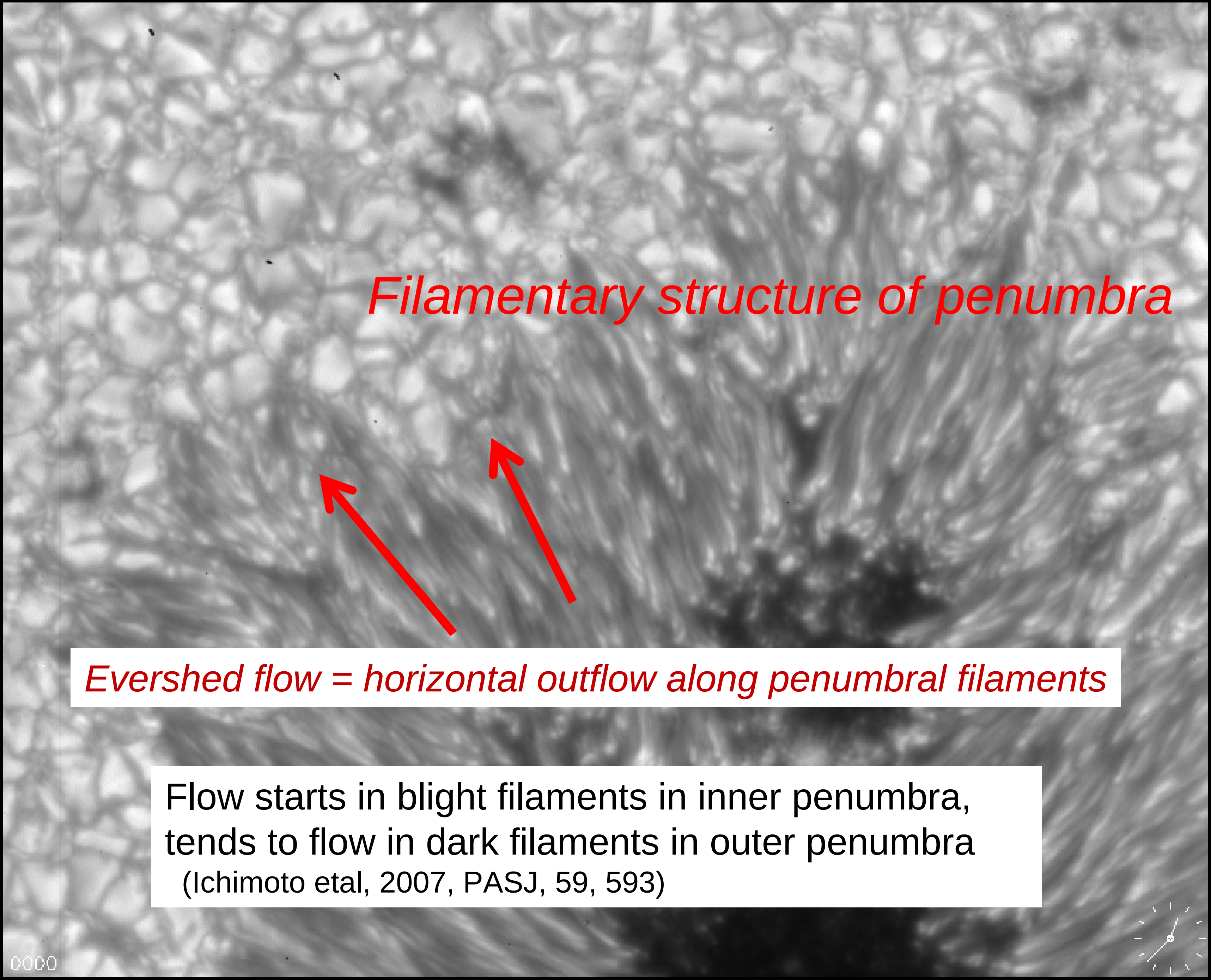
Convective nature of the Evershed Effect observed by SOT/Hinode

Kiyoshi Ichimoto (Kyoto Univ.)
and
Hinode/SOT team

Hinode 2 in Boulder, 2008.9.30 – 10.4





Filamentary structure of penumbra

Evershed flow = horizontal outflow along penumbral filaments

Flow starts in blight filaments in inner penumbra,
tends to flow in dark filaments in outer penumbra
(Ichimoto etal, 2007, PASJ, 59, 593)

Issues addressed in this talk are,,

- what is the nature of the Evershed flow?

- what is the origin of the filamentary structure of the penumbra?

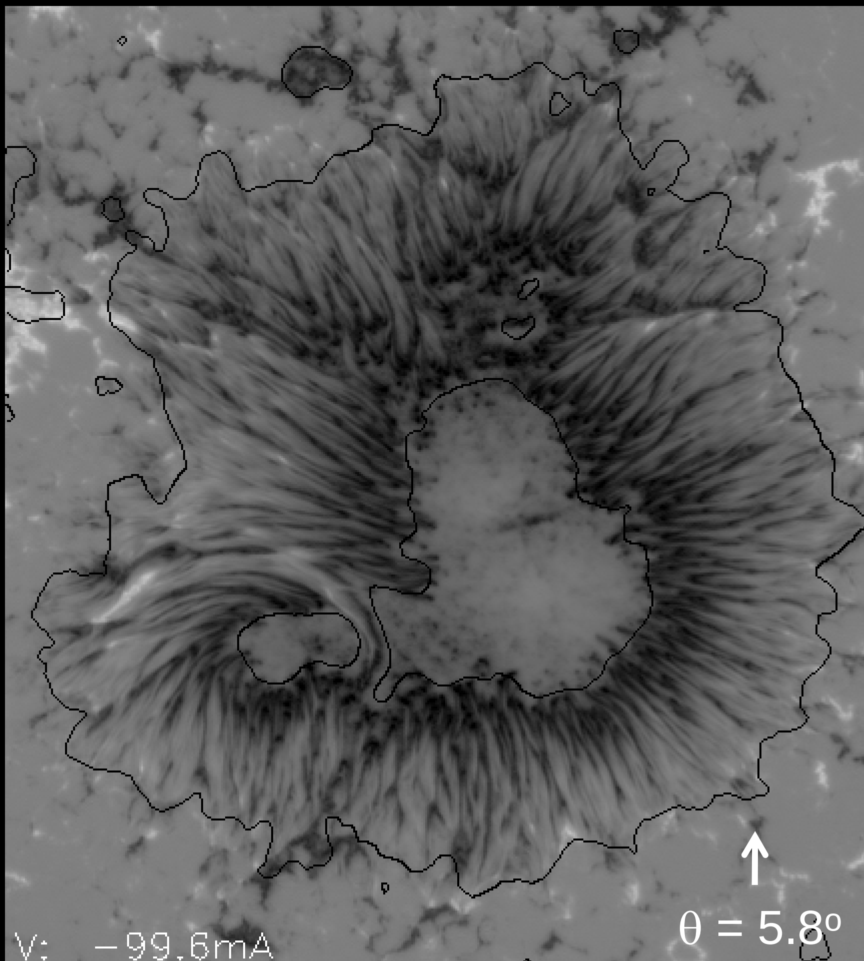
Answers (?)…. ‘flux tube model’ or ‘gap model’

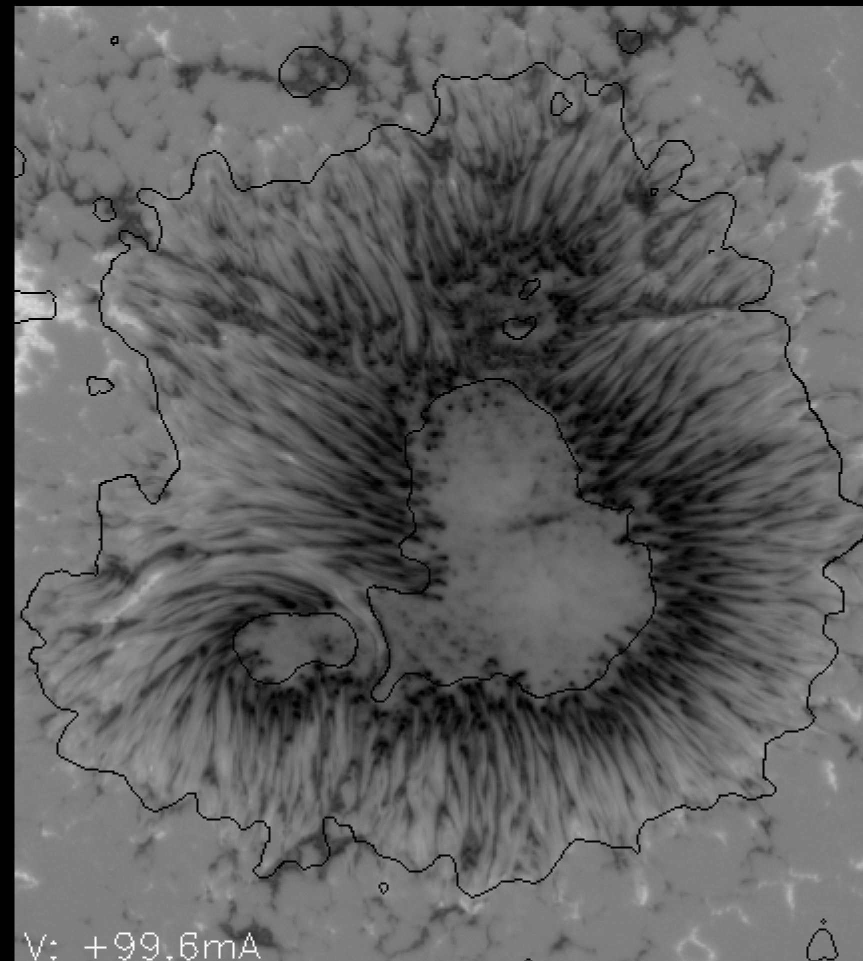
Let’s start with a magnetogram of a sunspot at DC to see the 3D structure of Evershed flow.

Stokes-V at 6302.5A ±100mA

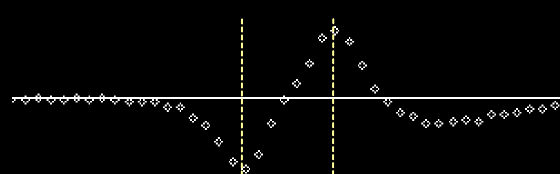
2007.5.1

(sign reversed)



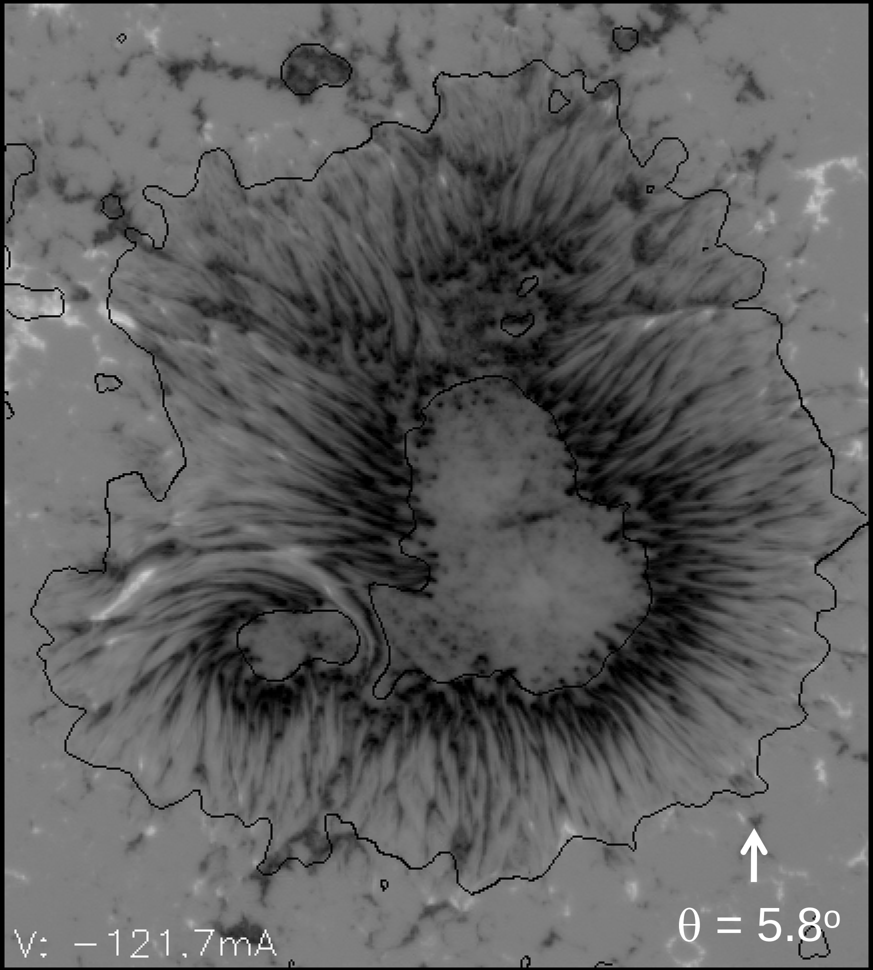


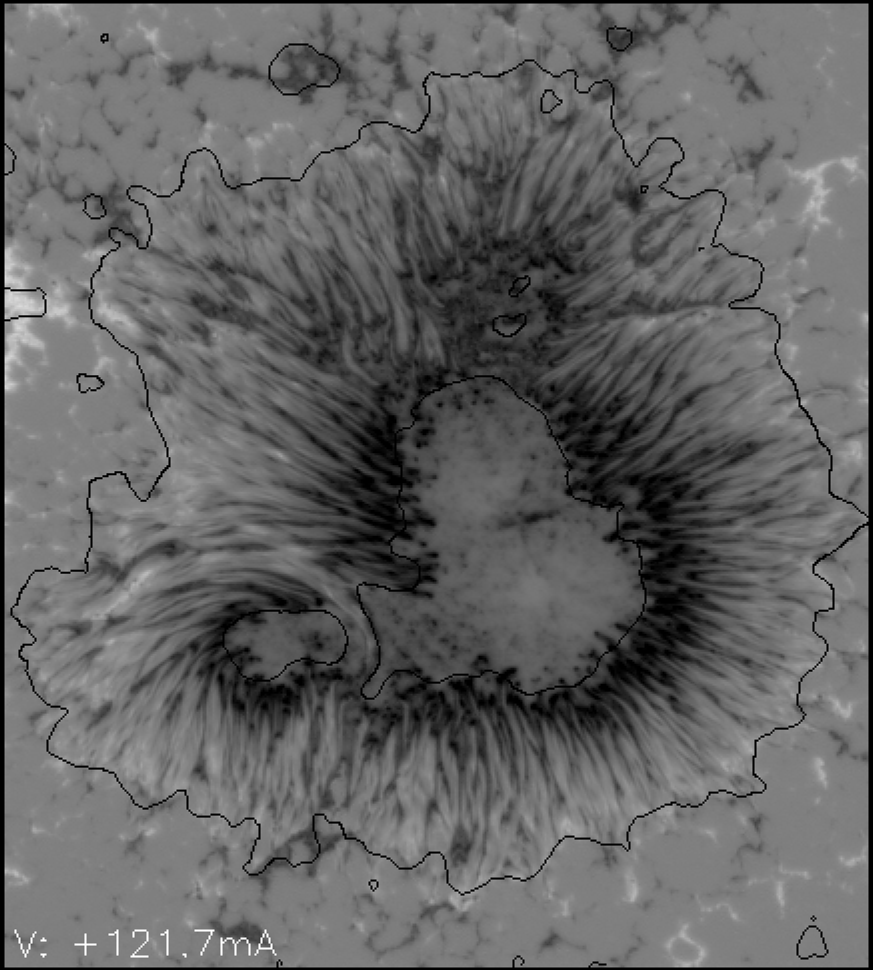
-100mA



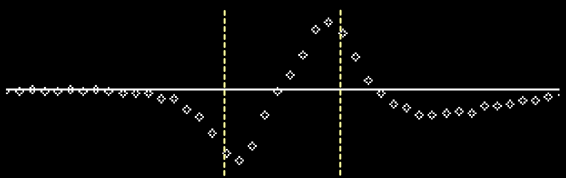
+100mA

Stokes-V at 6302.5A ±120mA



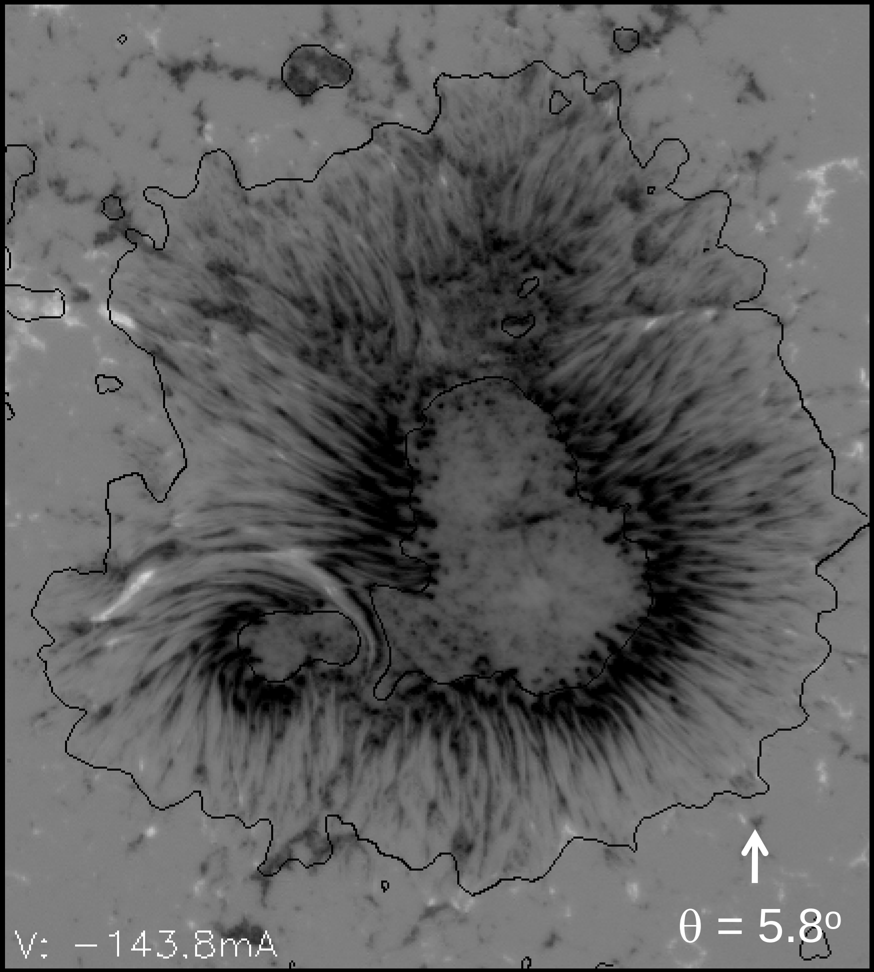


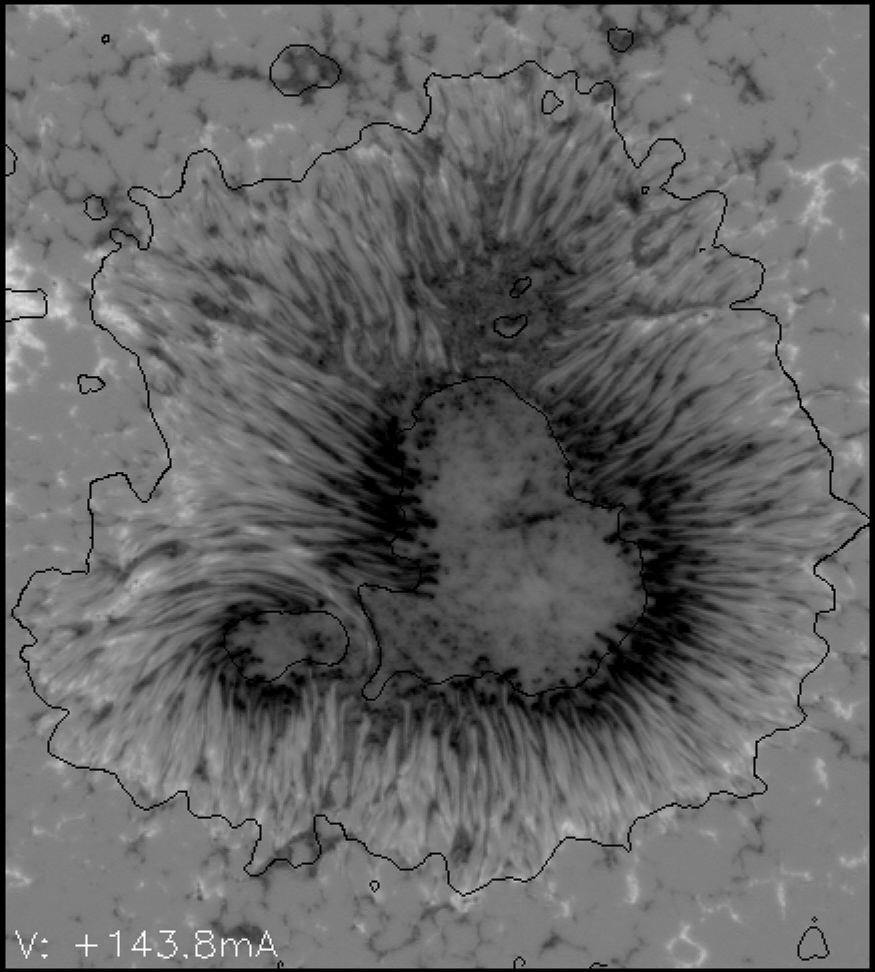
-120mA



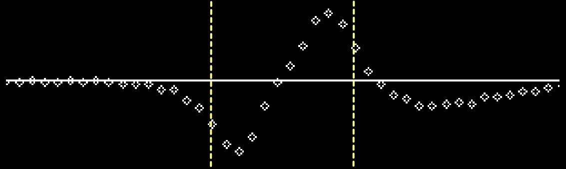
+120mA

Stokes-V at 6302.5A ±144mA



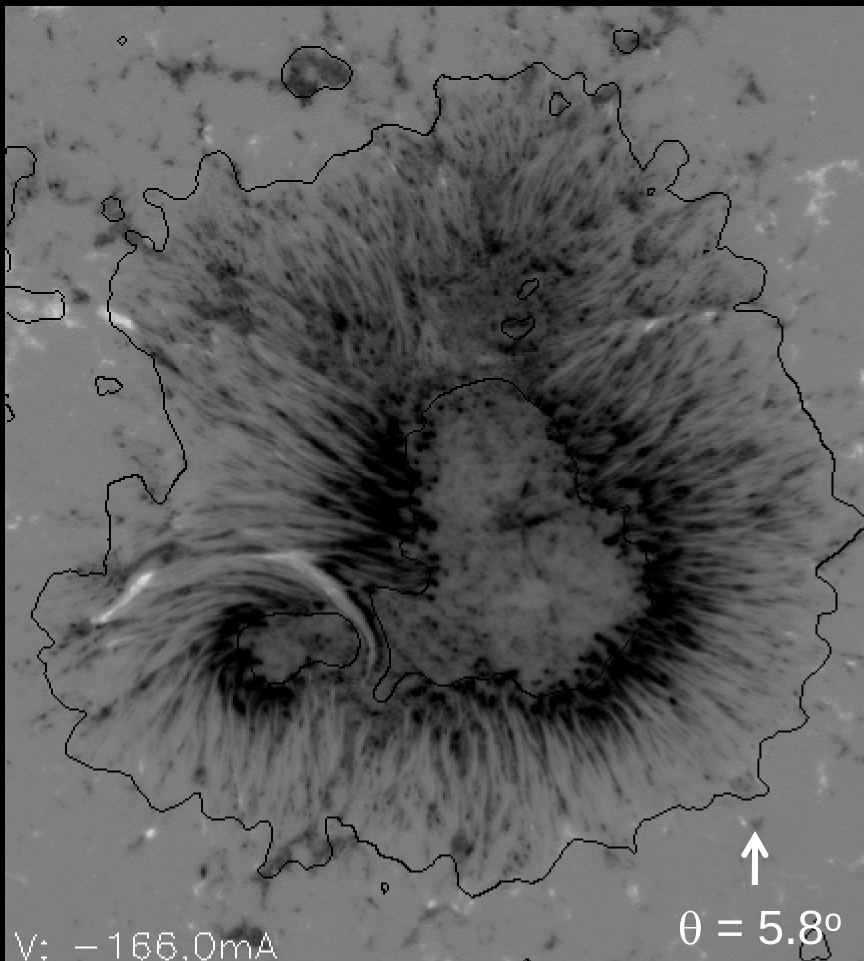


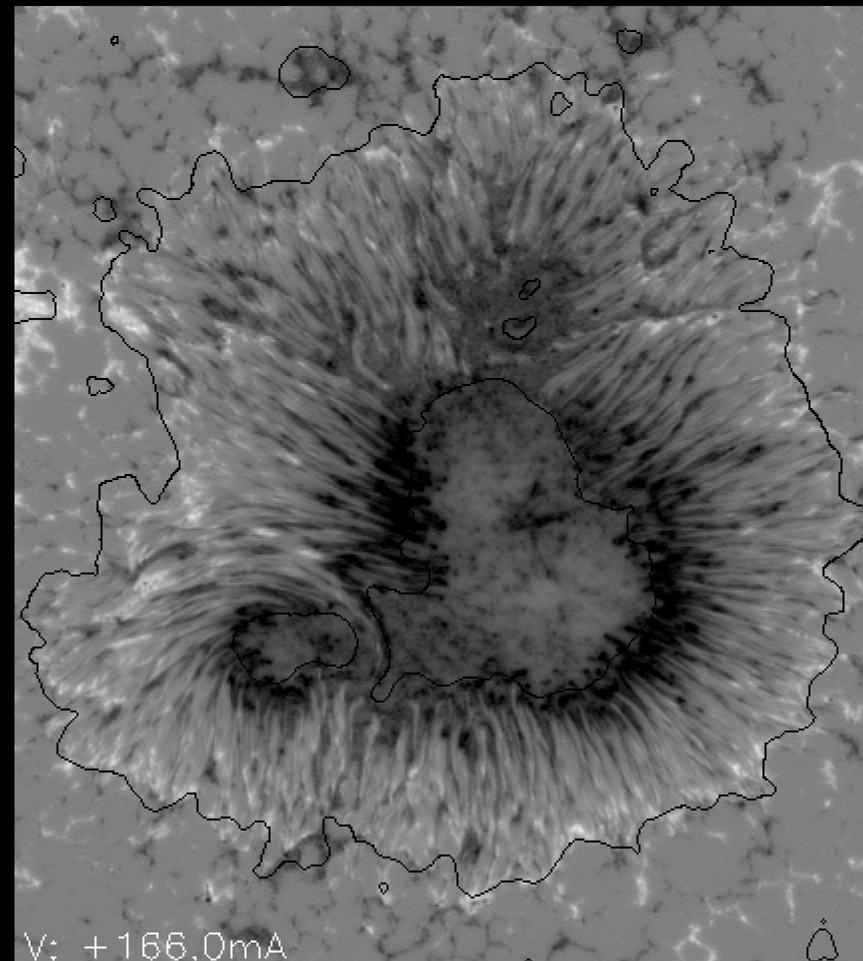
-144mA



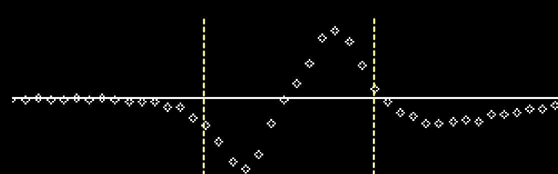
+144mA

Stokes-V at 6302.5A ±166mA



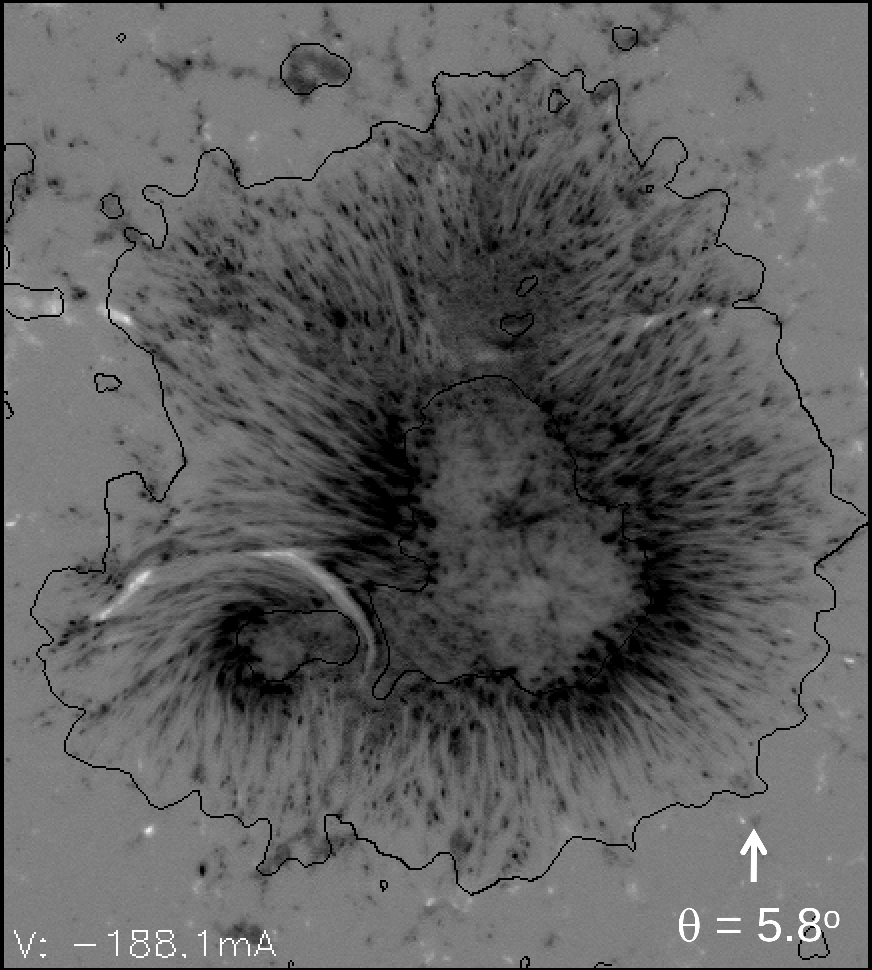


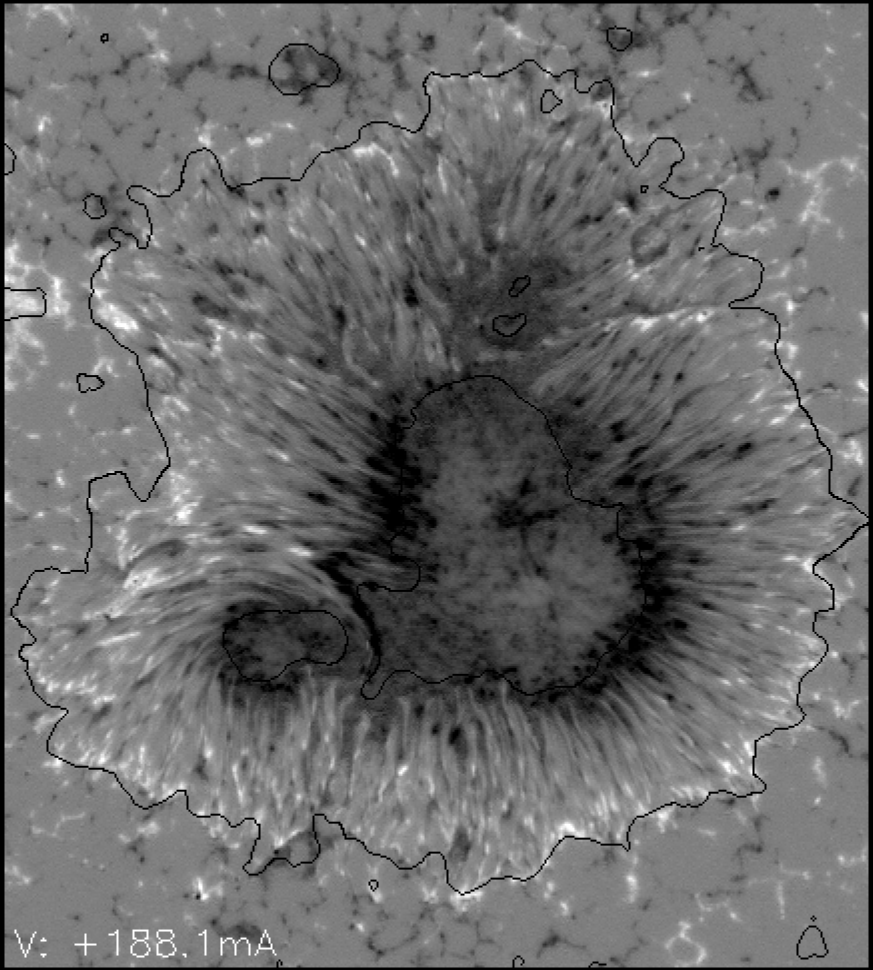
-166mA



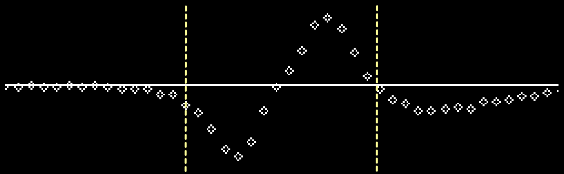
+166mA

Stokes-V at 6302.5A +188mA



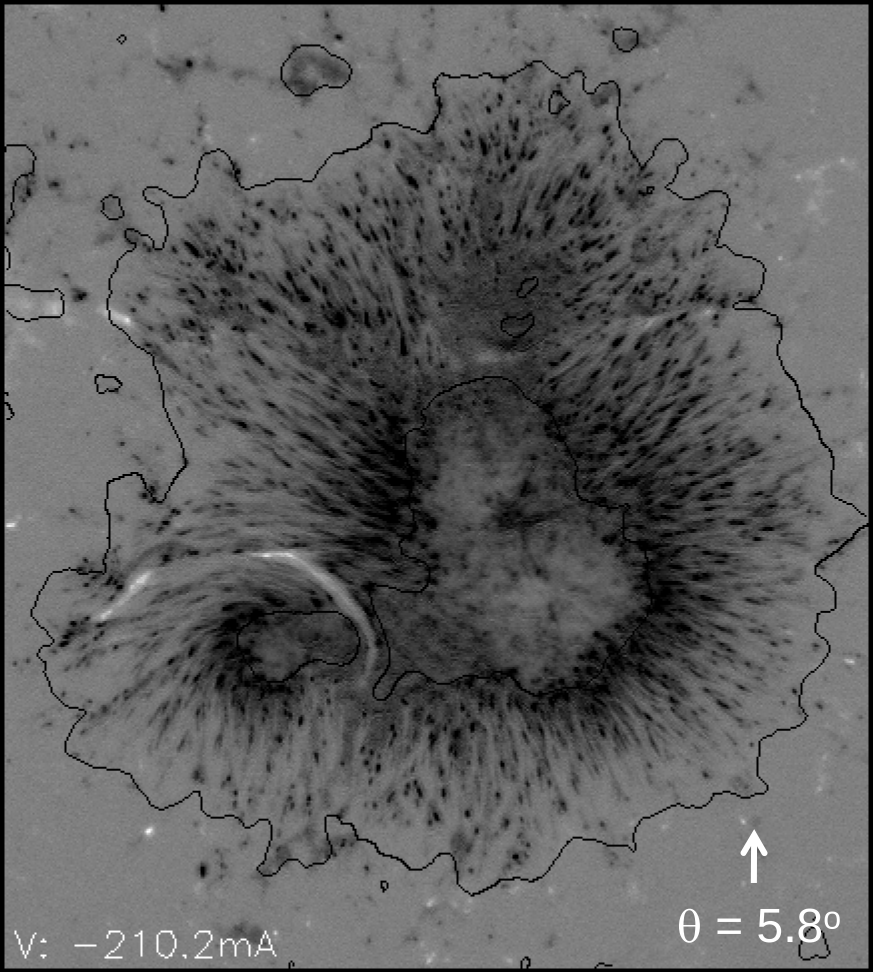


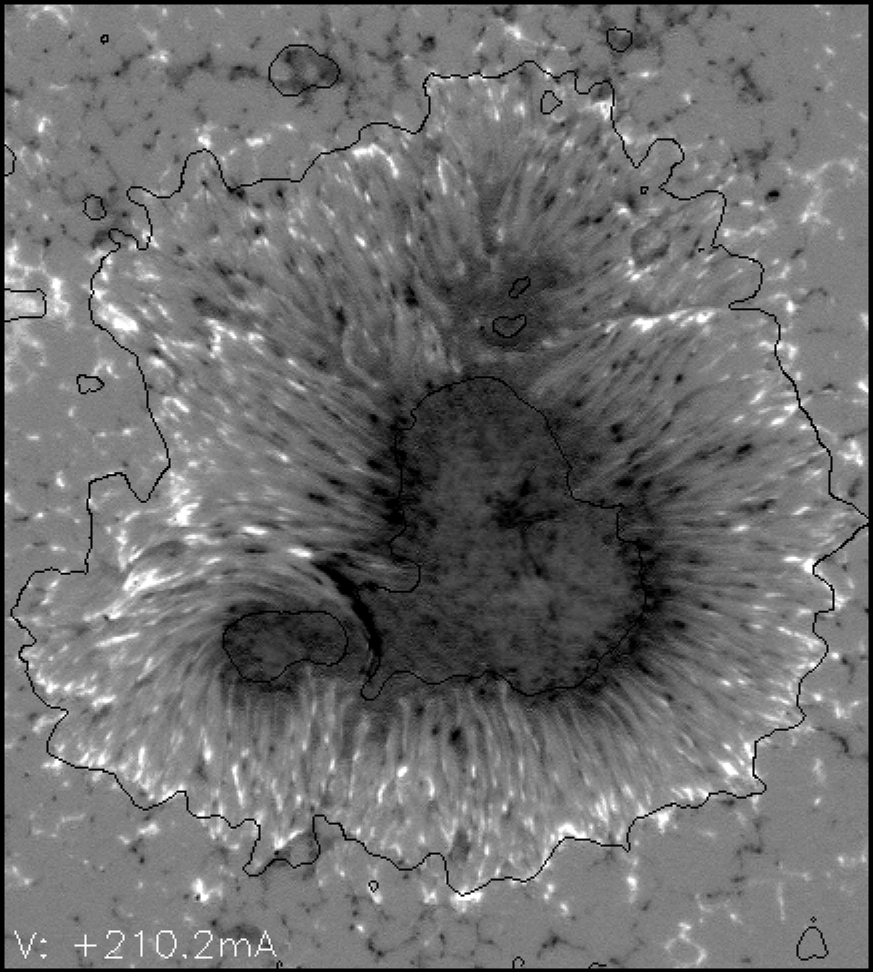
-188mA



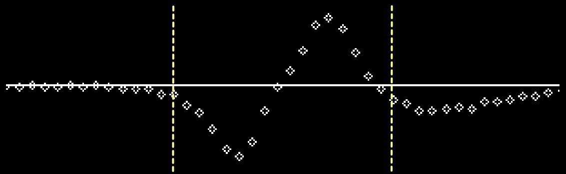
+188mA

Stokes-V at 6302.5A ±210mA



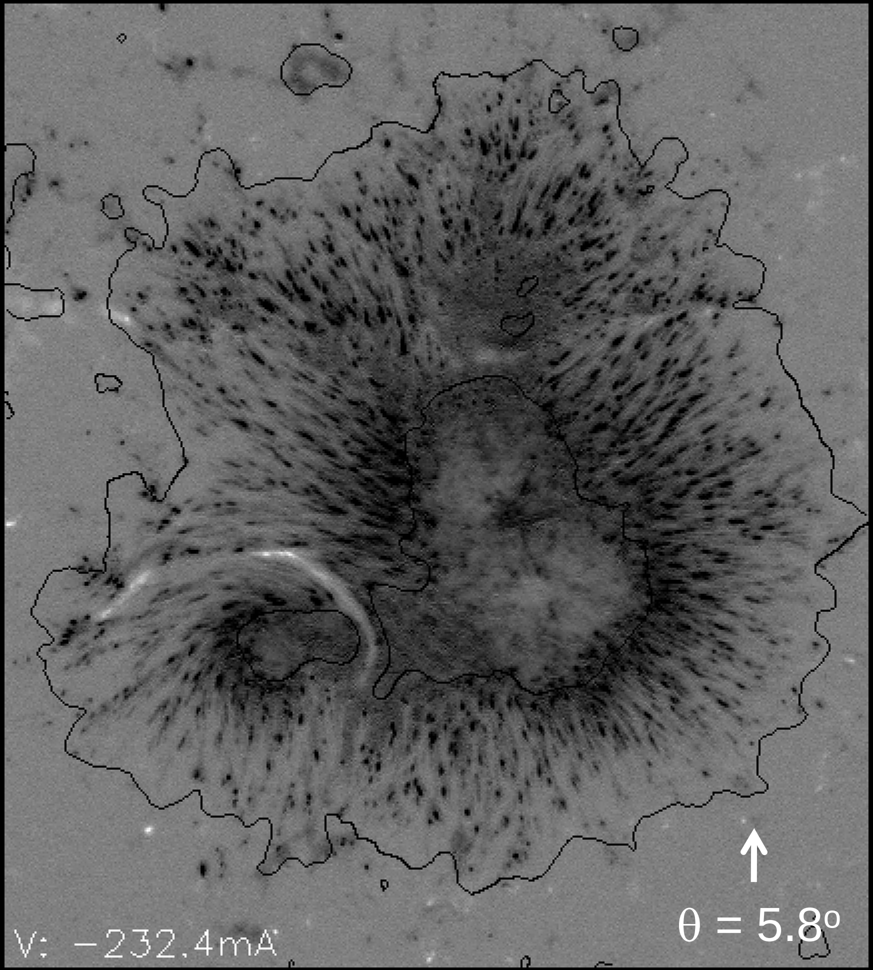


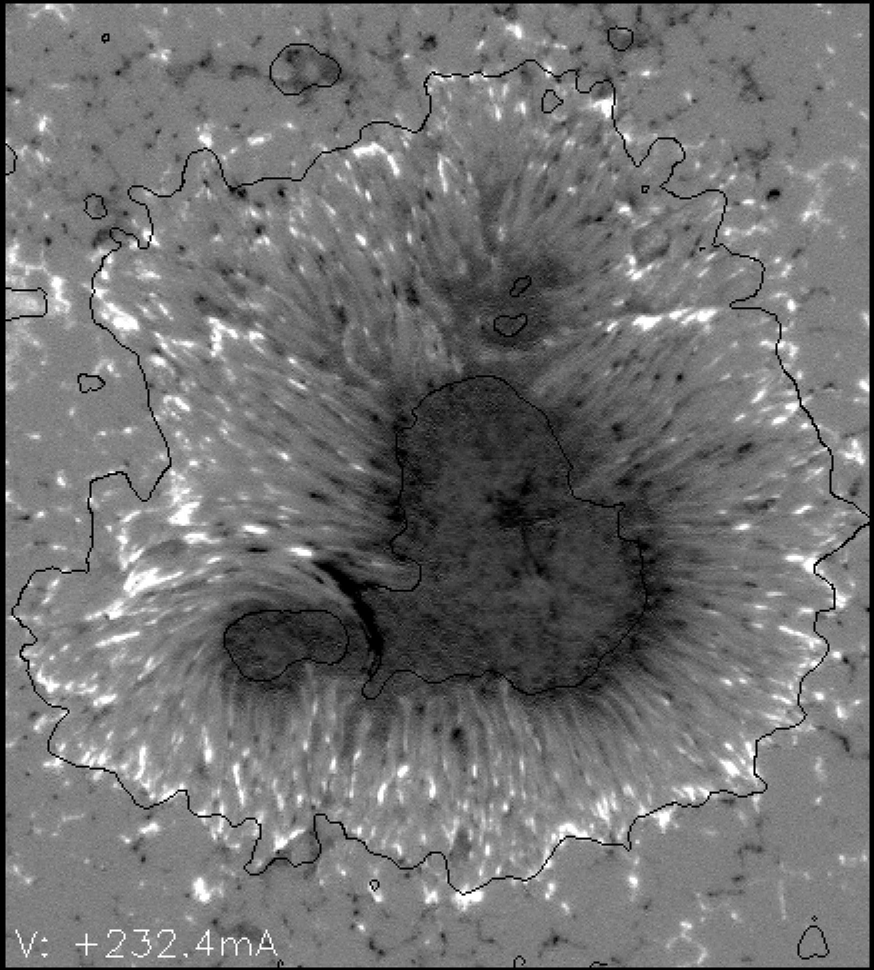
-210mA



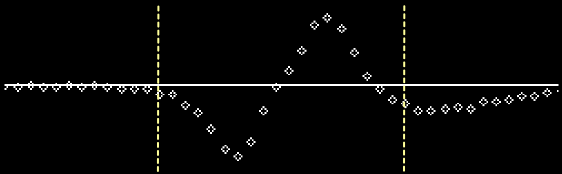
+210mA

Stokes-V at 6302.5A ±232mA



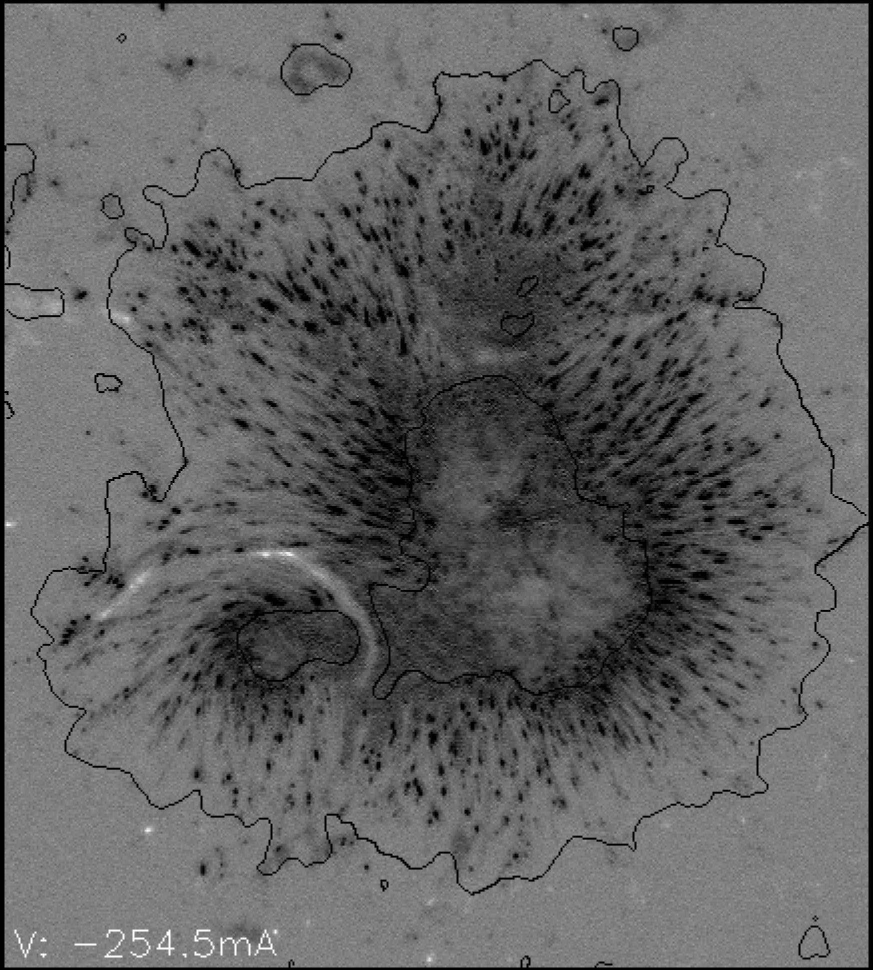


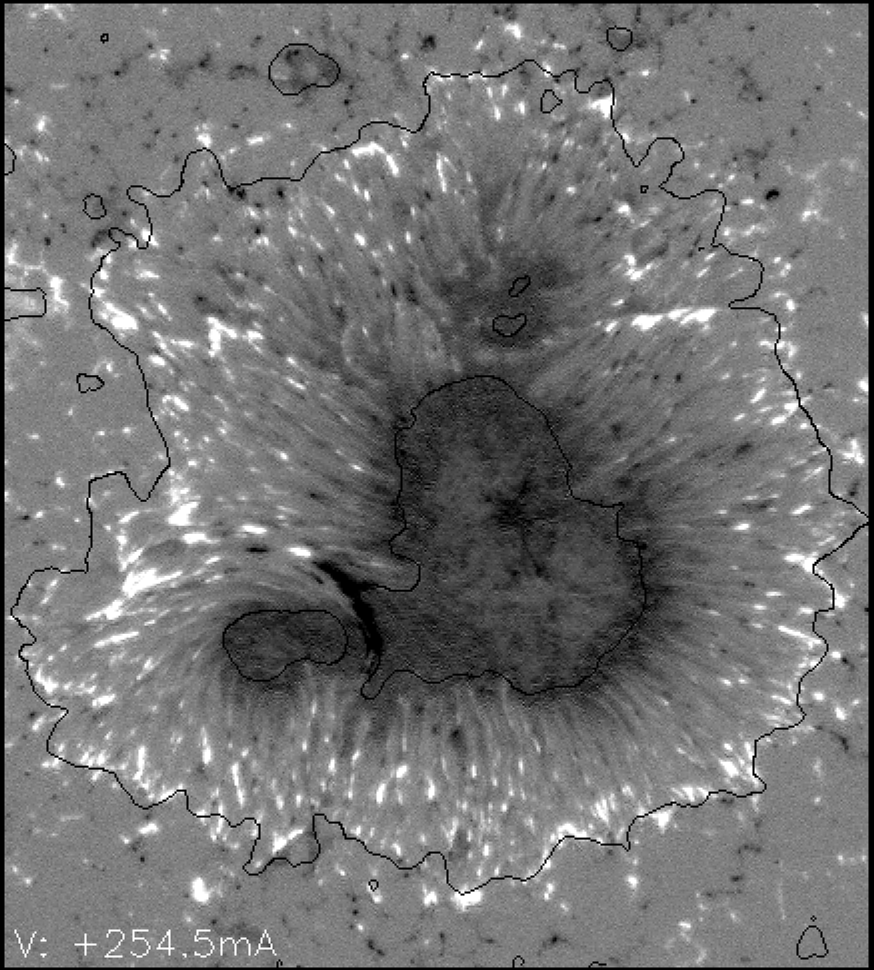
-232mA



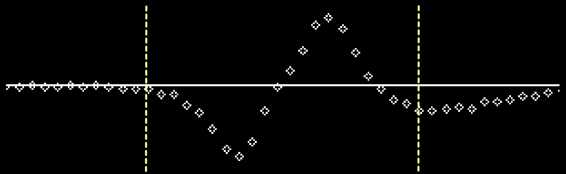
+232mA

Stokes-V at 6302.5A ±254mA



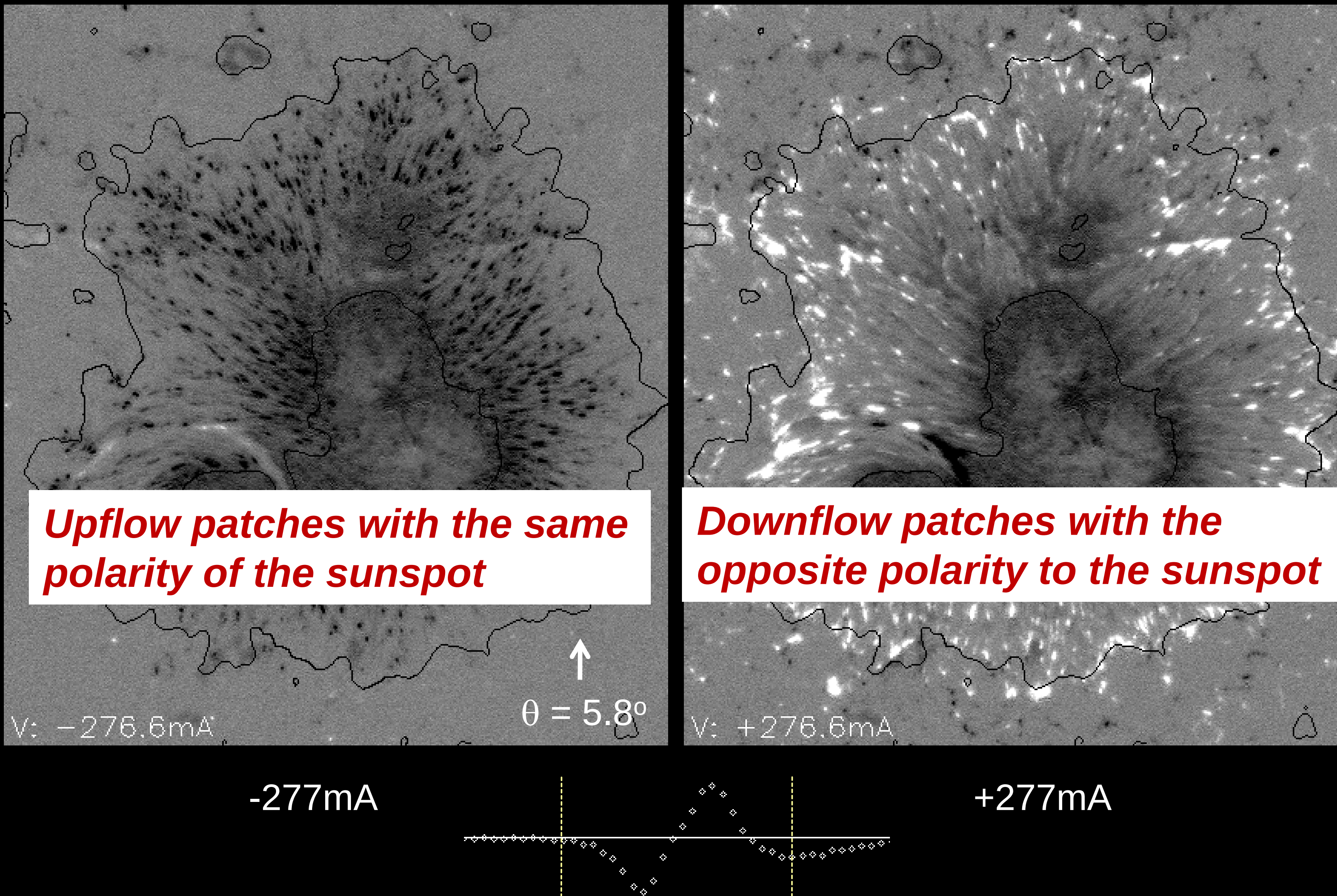


-254mA

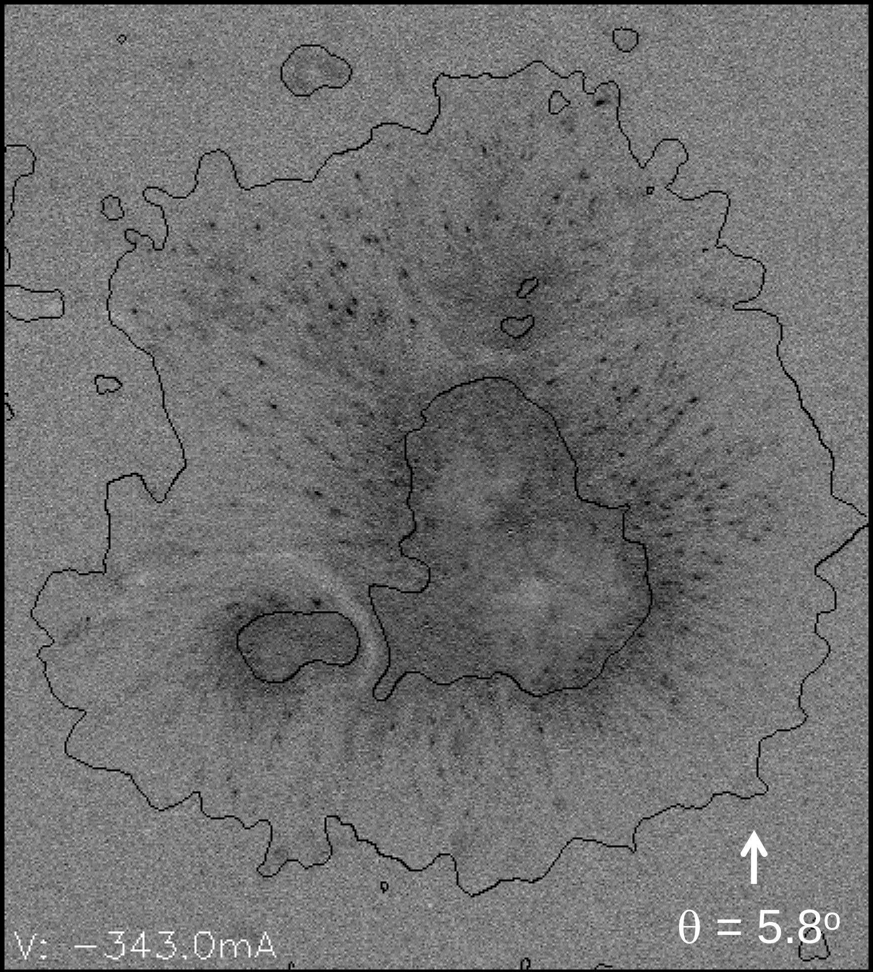


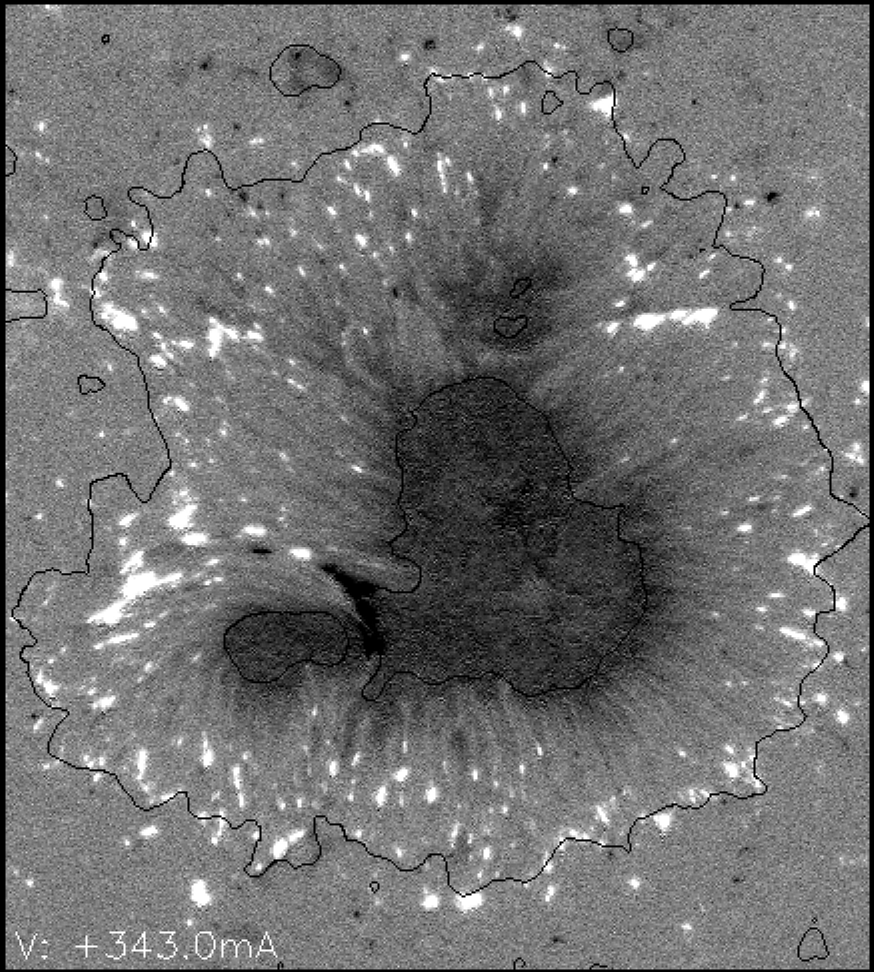
+254mA

Stokes-V at 6302.5A $\pm$277mA

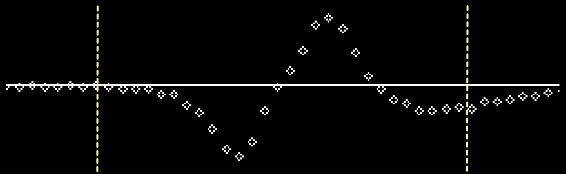


Stokes-V at 6302.5A +343mA



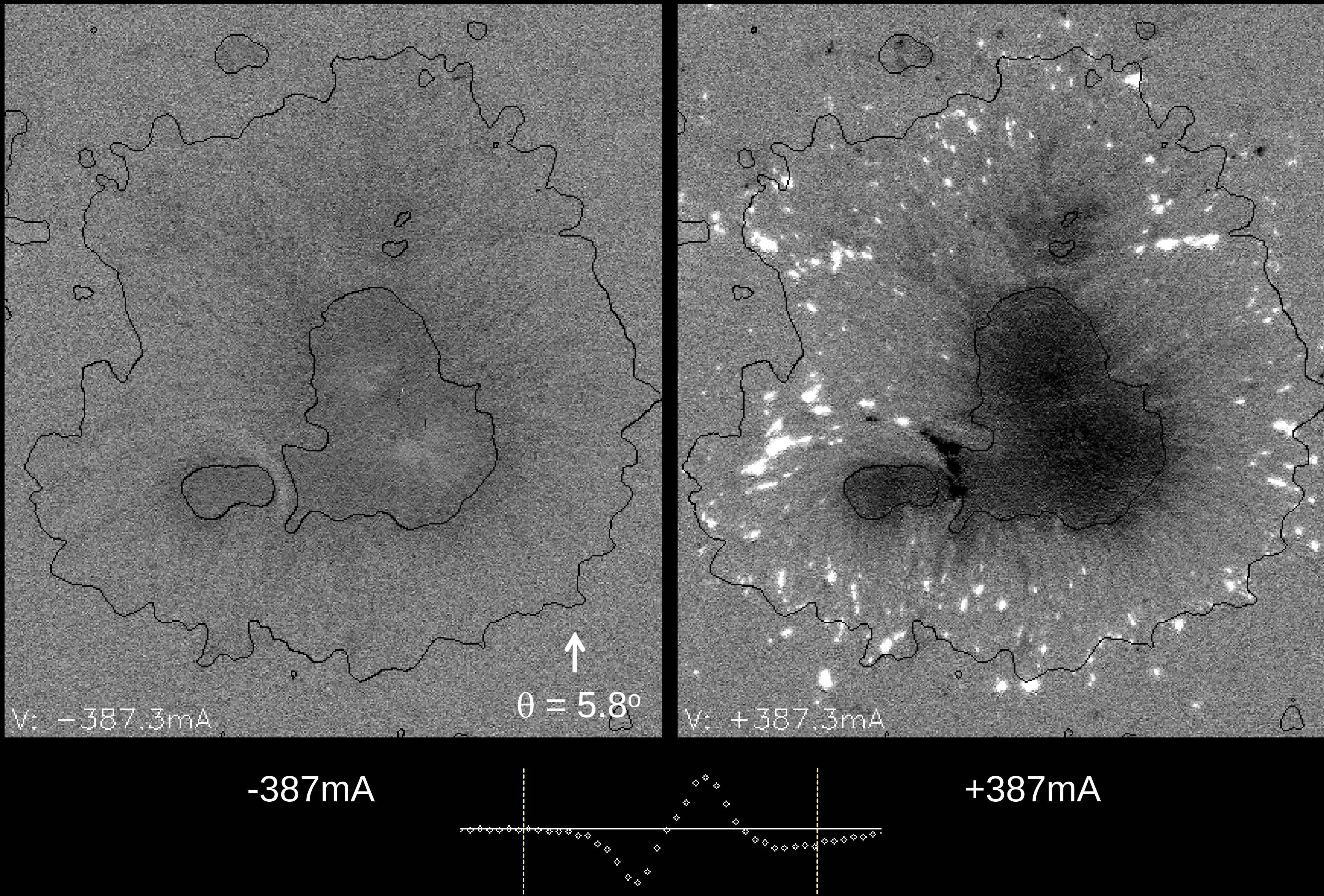


-343mA

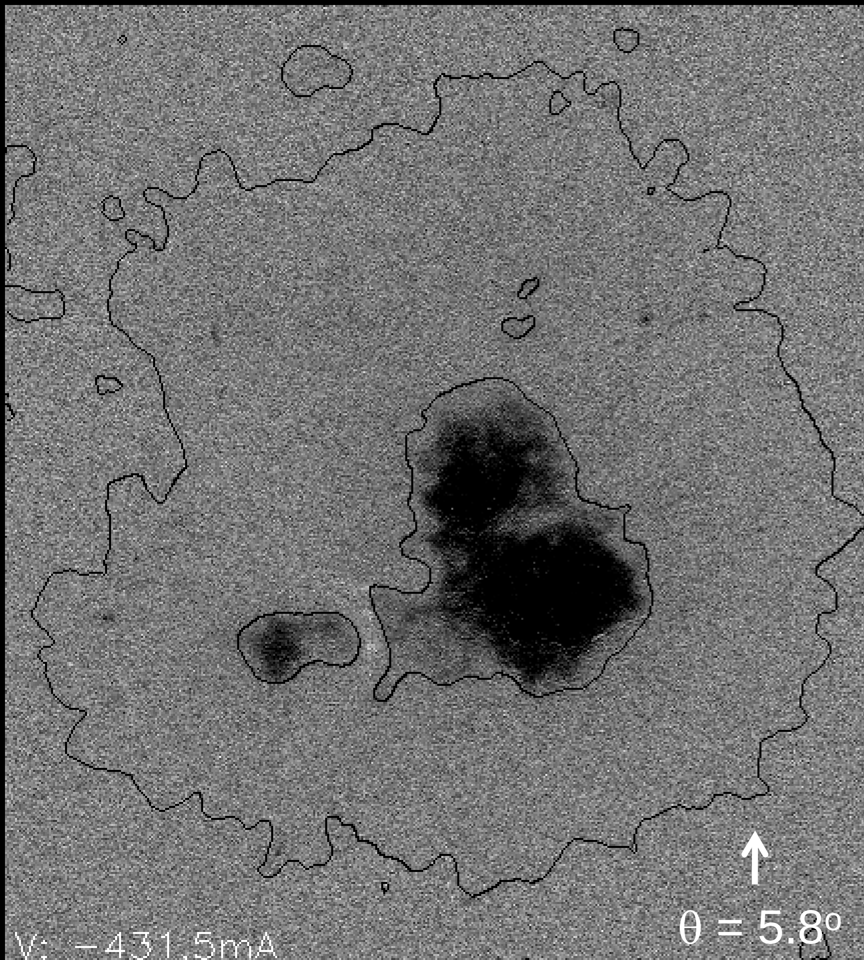


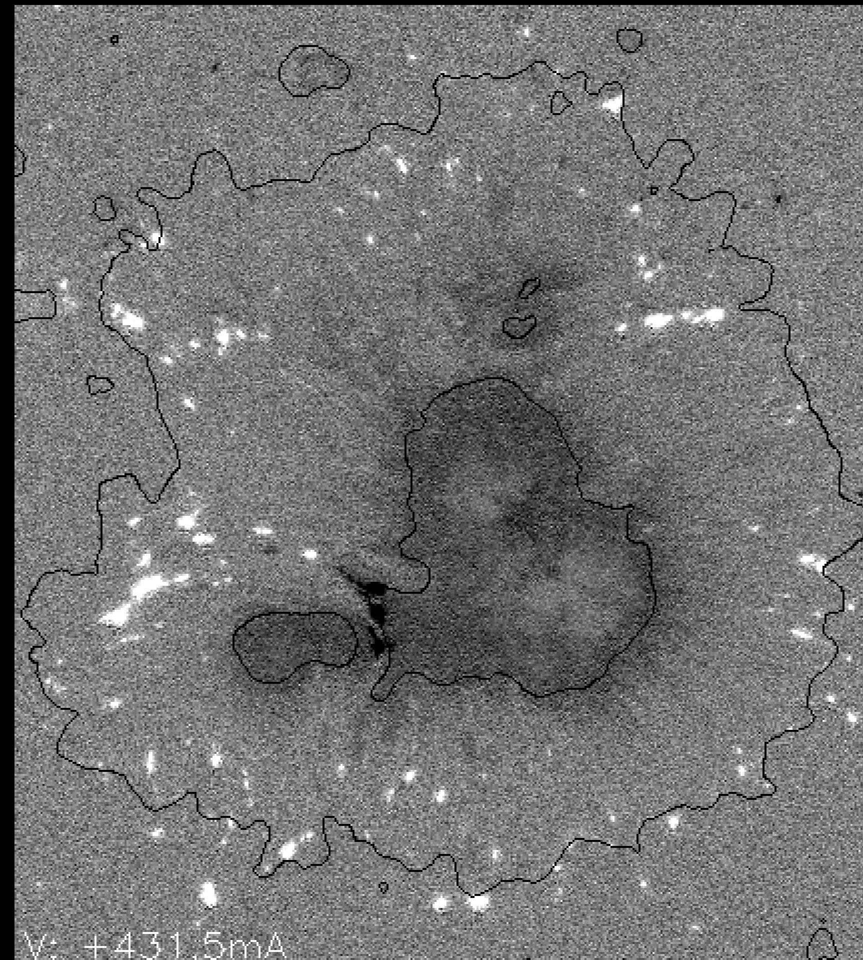
+343mA

Stokes-V at 6302.5A ±343mA

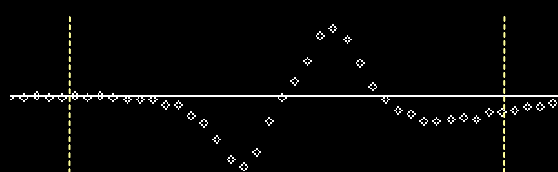


Stokes-V at 6302.5A ±343mA



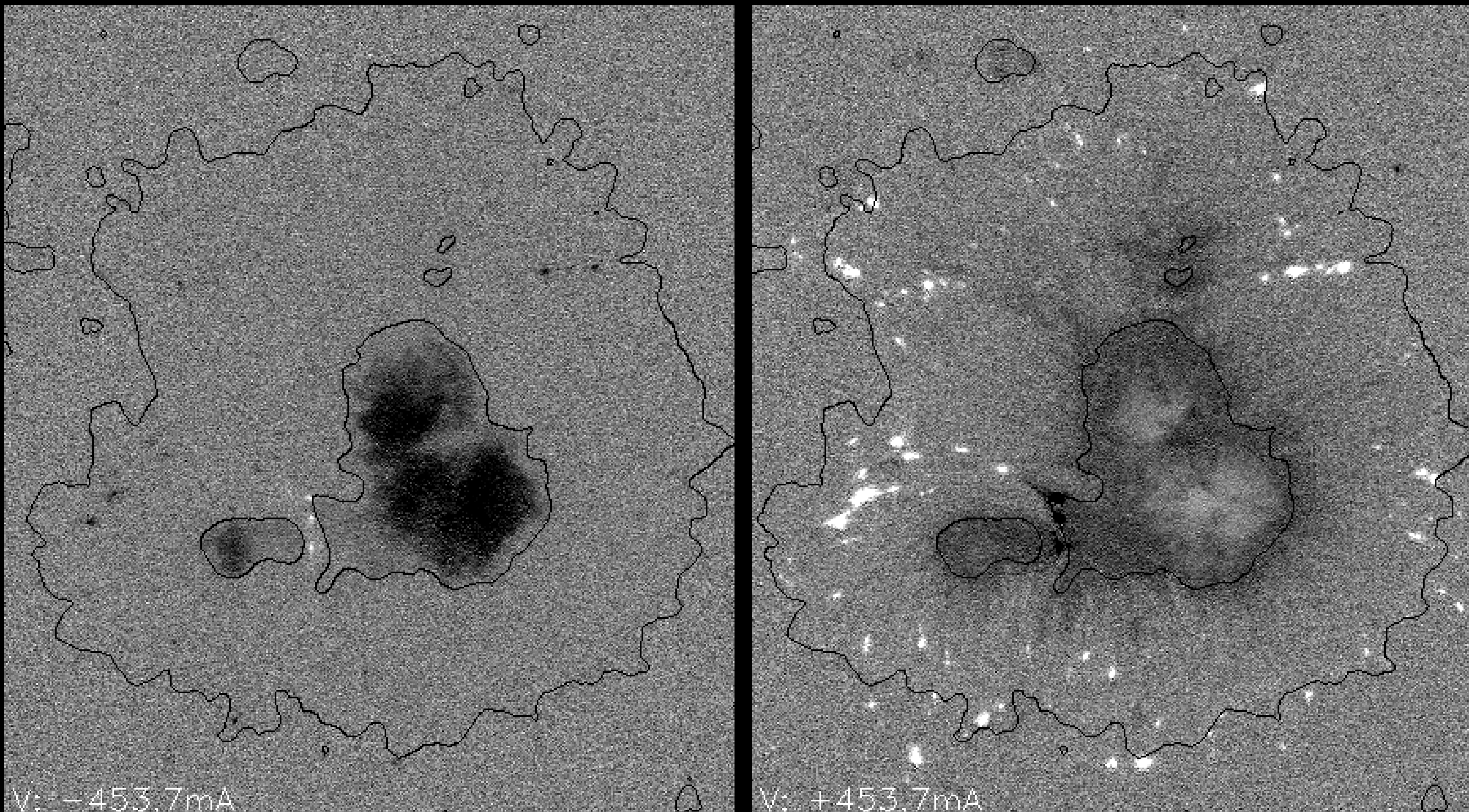


-431mA

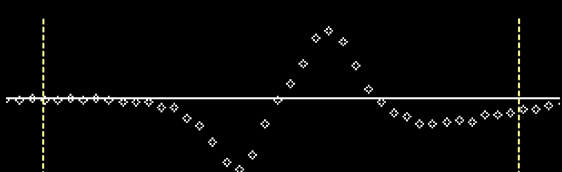


+431mA

Stokes-V at 6302.5A ±454mA

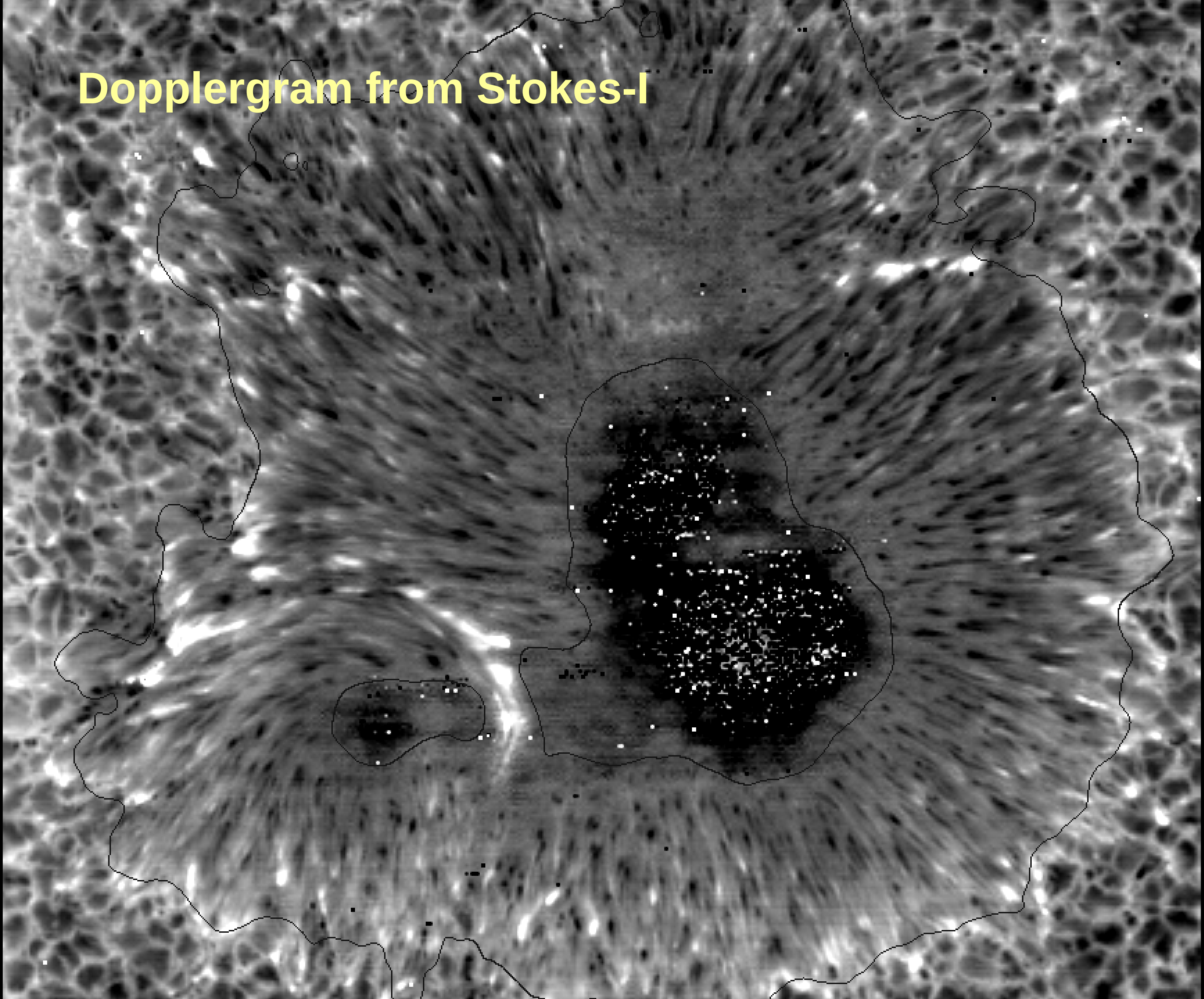


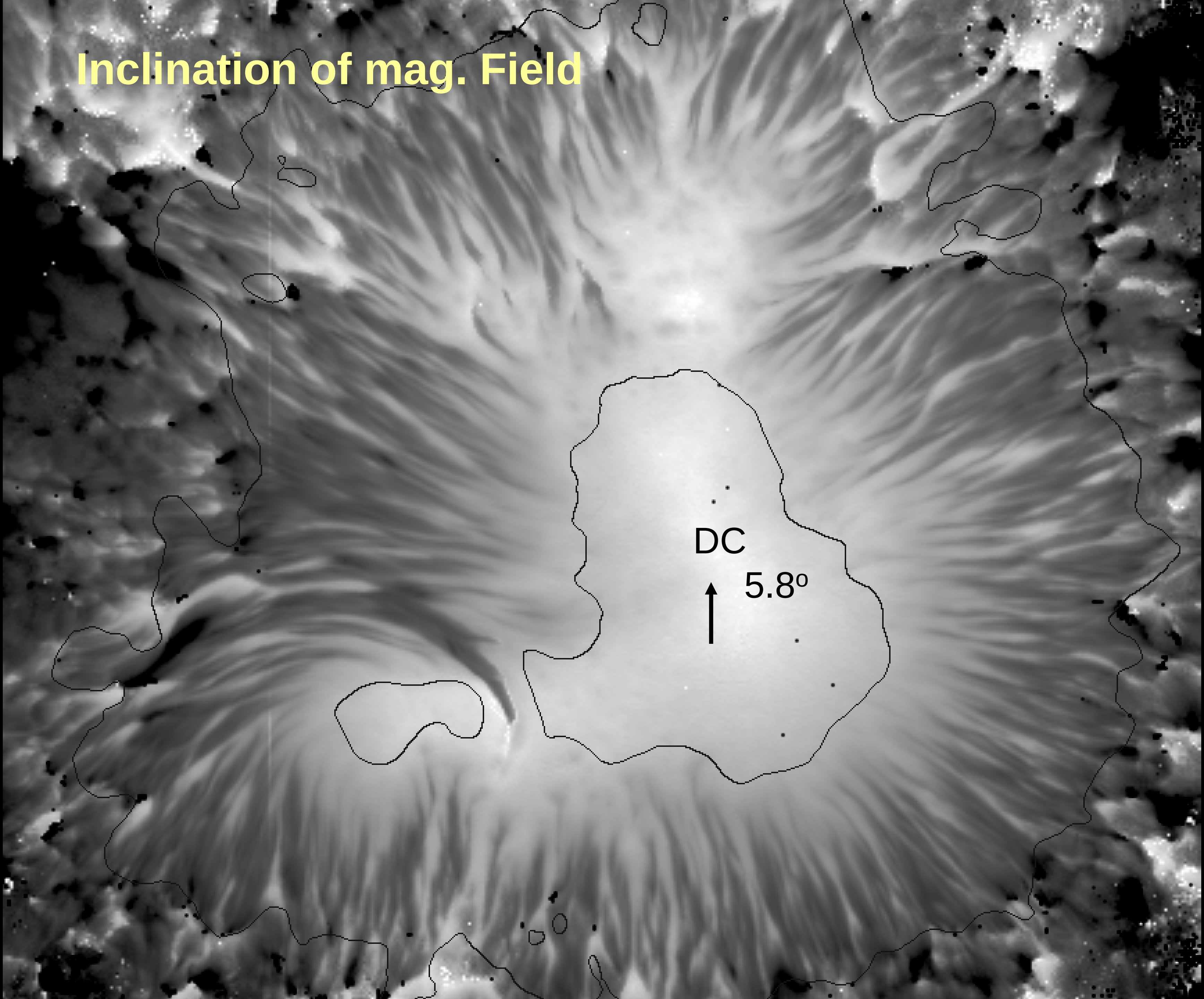
-454mA



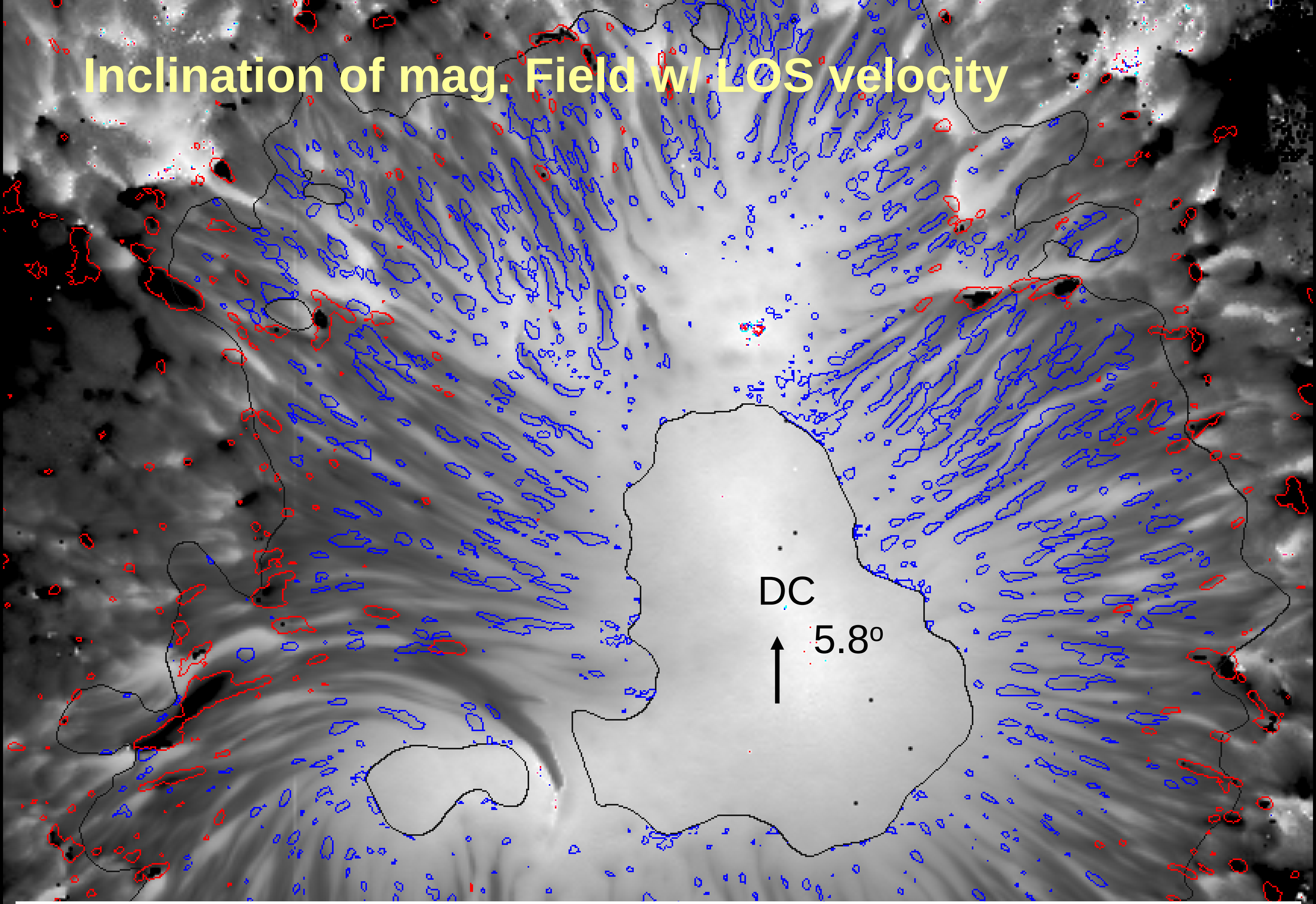
+454mA

➔ 22km/s (supersonic?)


Dopplergram from Stokes-I

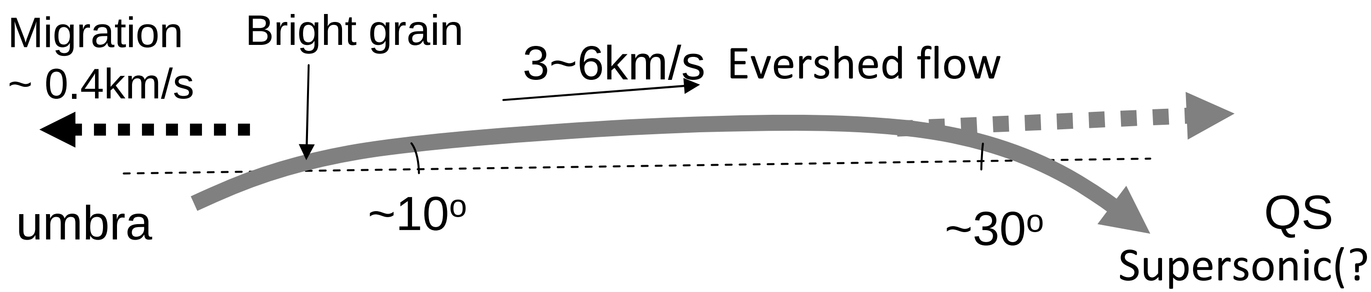

Inclination of mag. Field
DC
5.8o

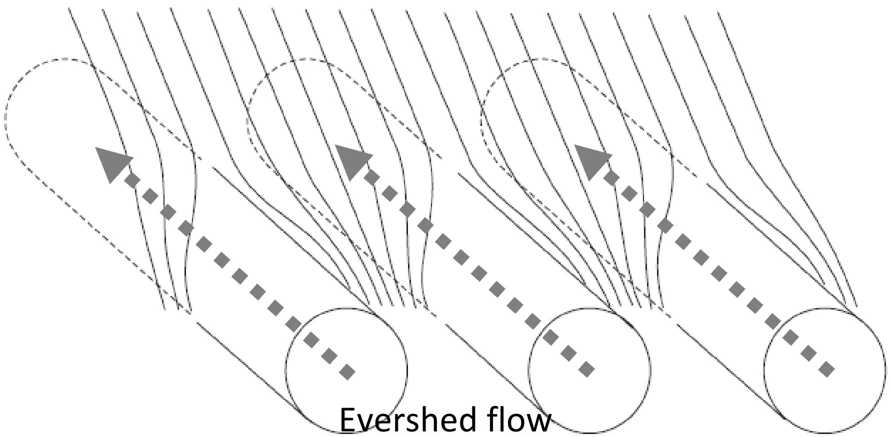
Inclination of mag. Field w/ LOS velocity



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

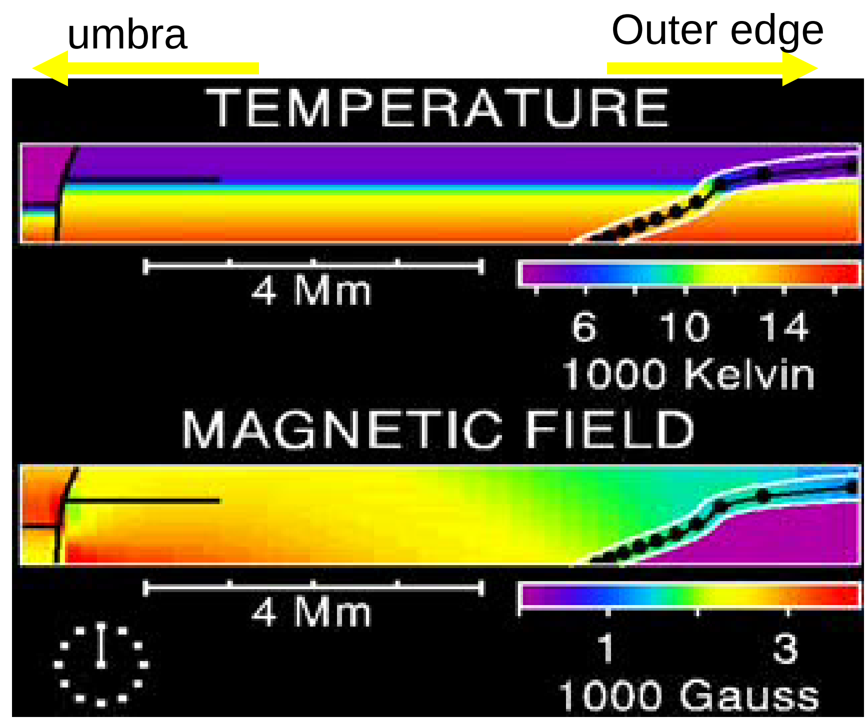
Individual Evershed flow channels consistent with the rising flux tube model w/ uncombed structure.





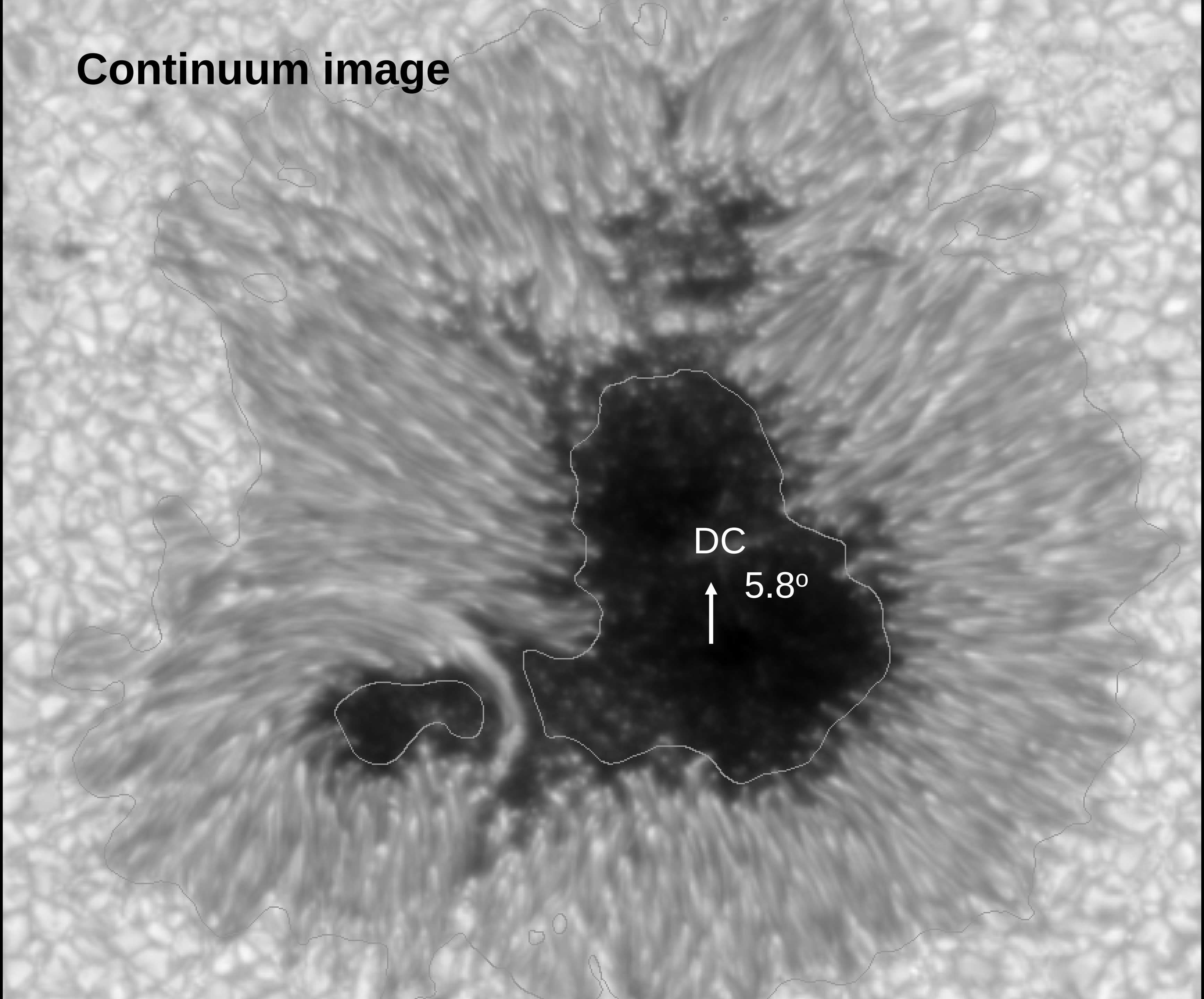
‘uncombed’ penumbral model

Solanki & Motavon 1993

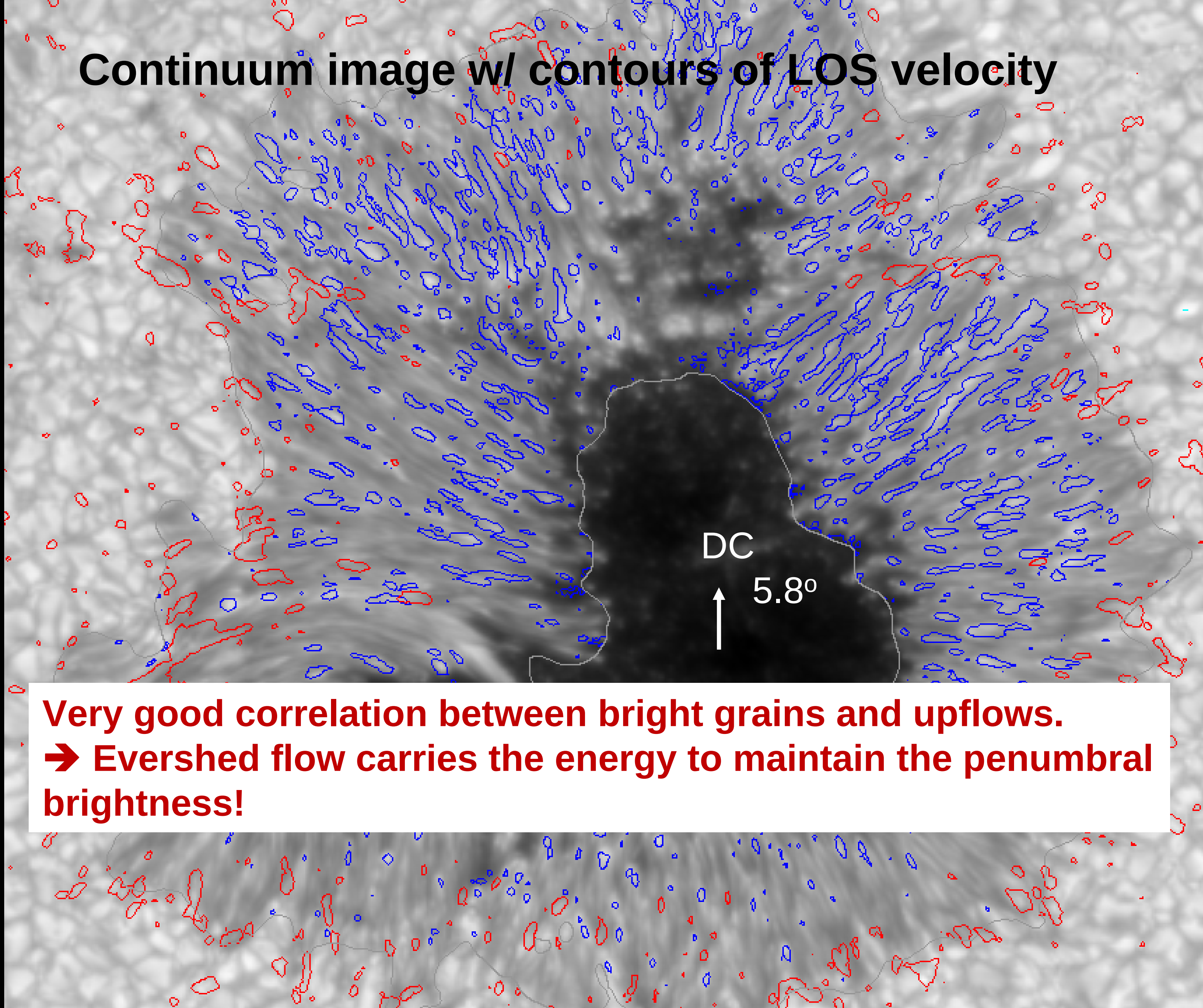


flux tube model （Schlichenmeier etal 1998)

Continuum image

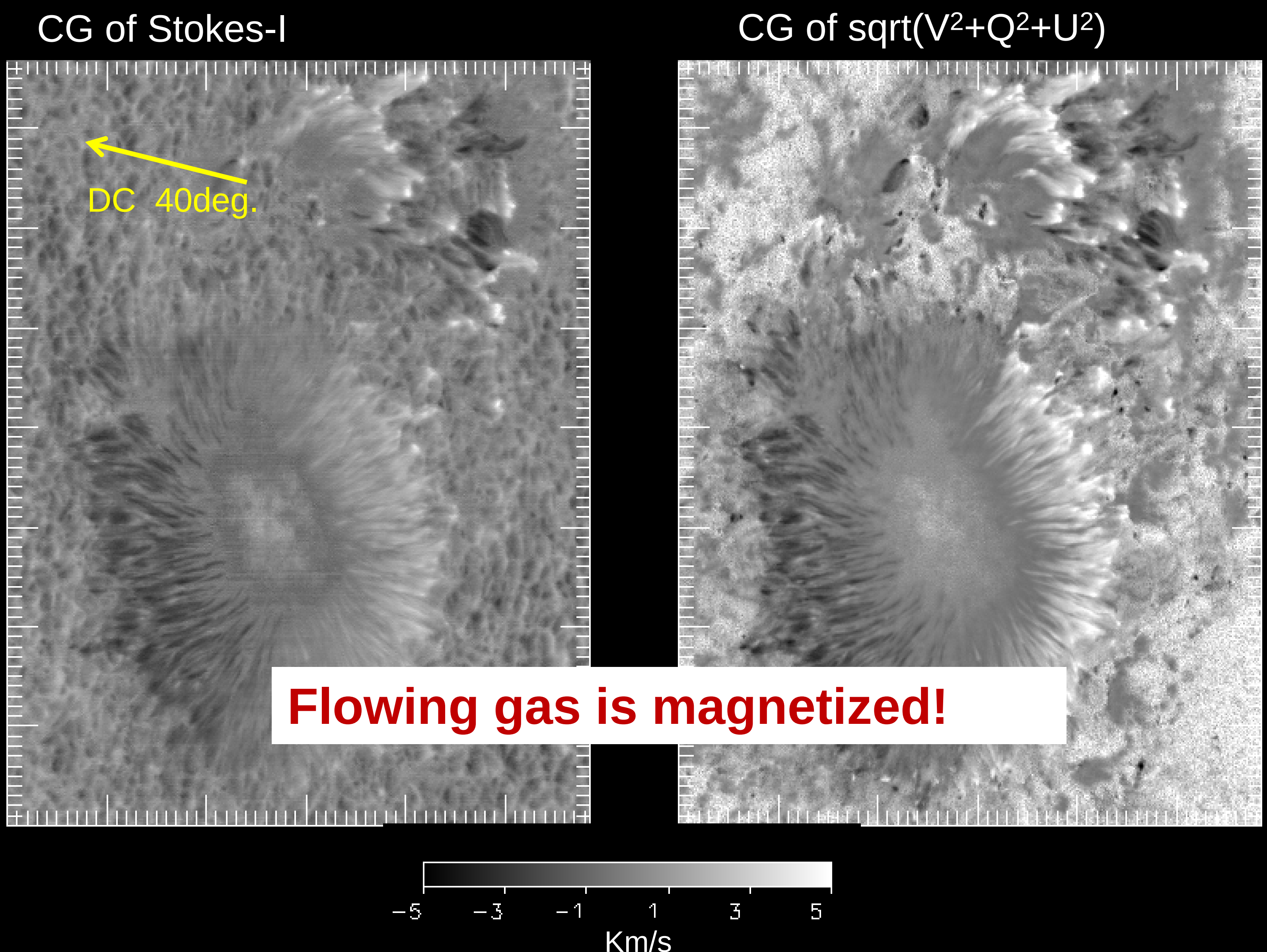


Continuum image w/ contours of LOS velocity



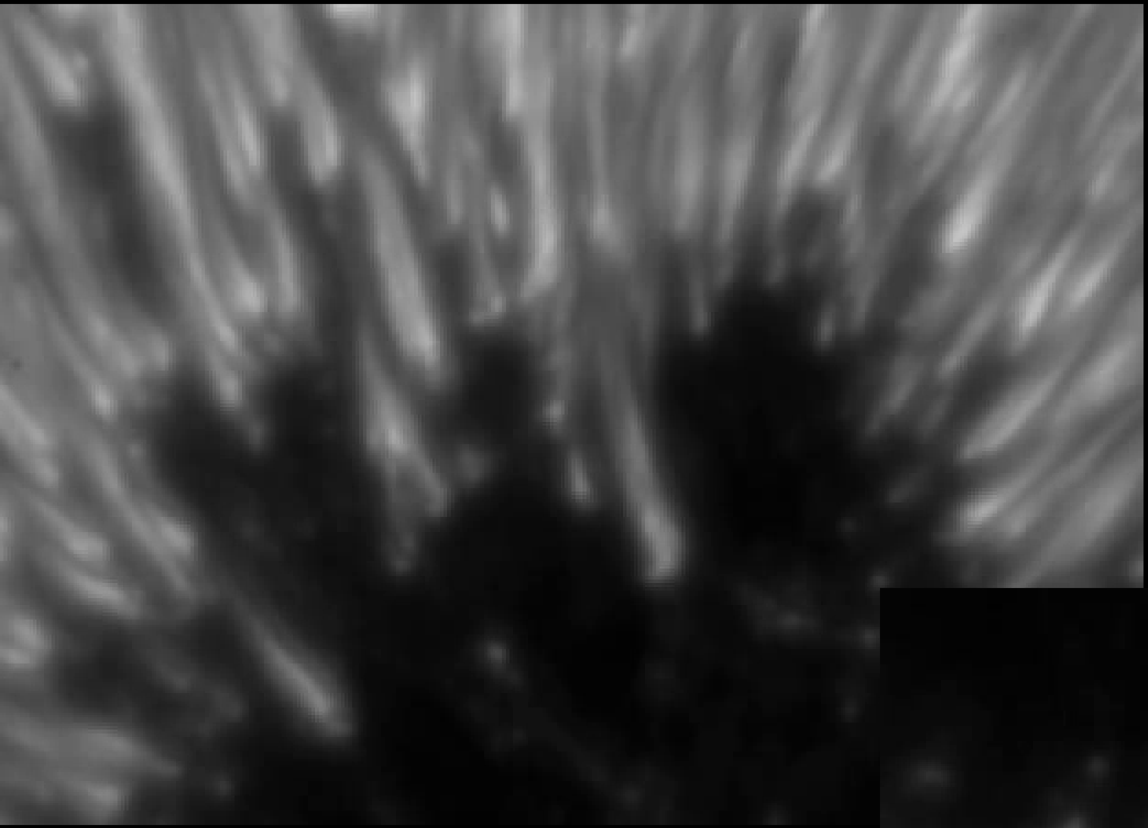
Very good correlation between bright grains and upflows.
➔ Evershed flow carries the energy to maintain the penumbral brightness!

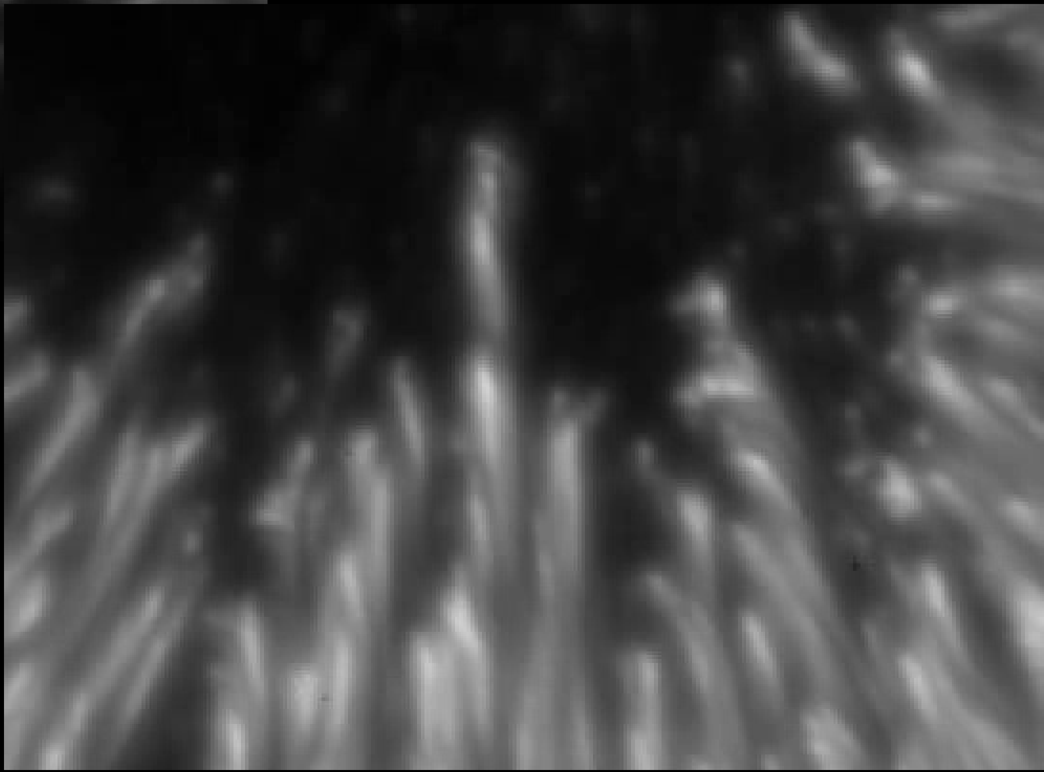
6302.5A Doopppler shift, 2007.1.8



Flowing gas is magnetized!

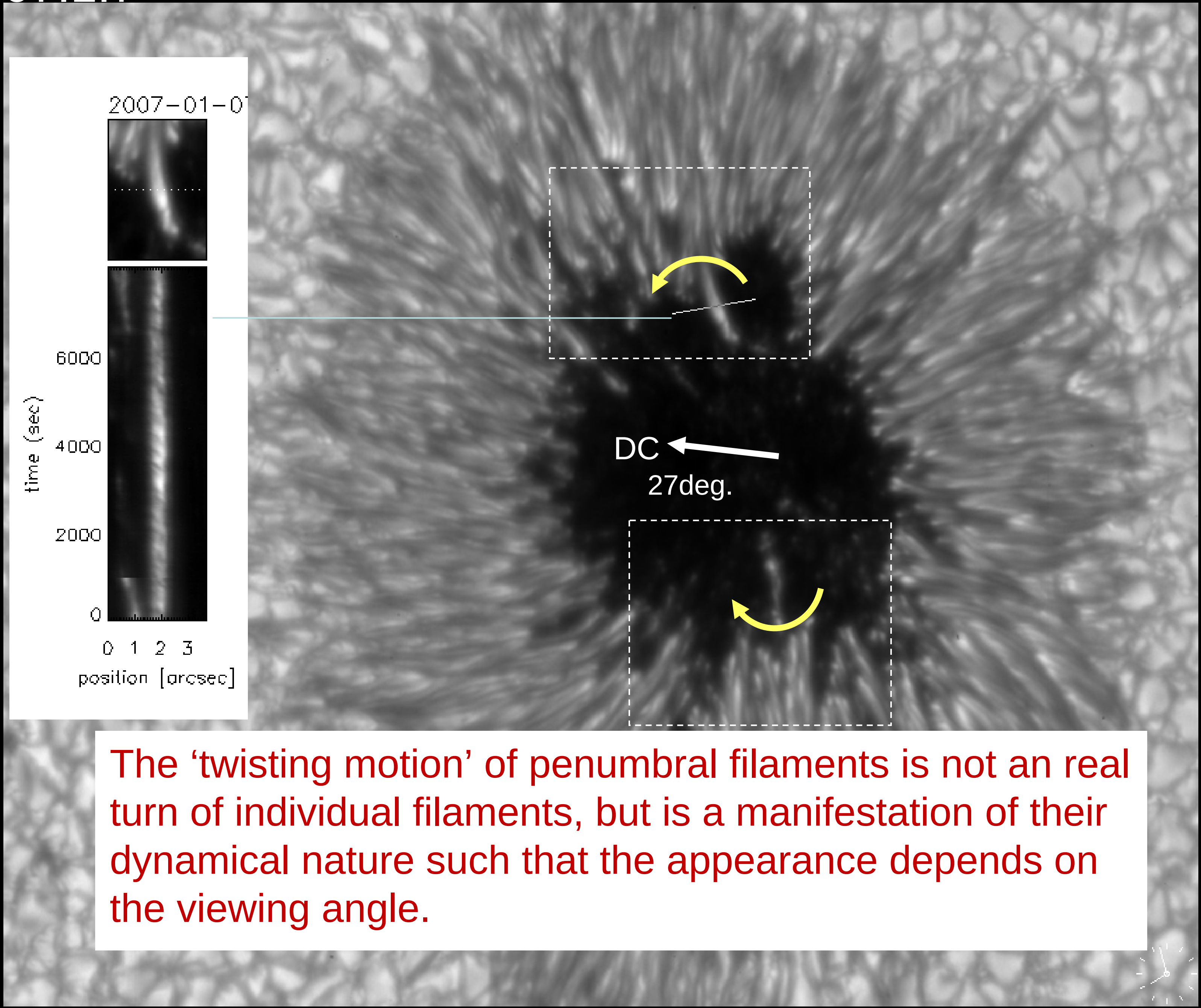
2007.1.7





Twisting filaments…

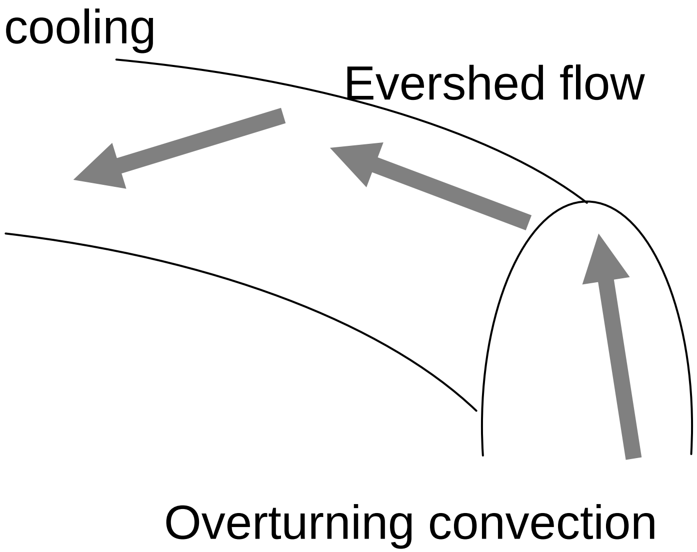
2007.1.7

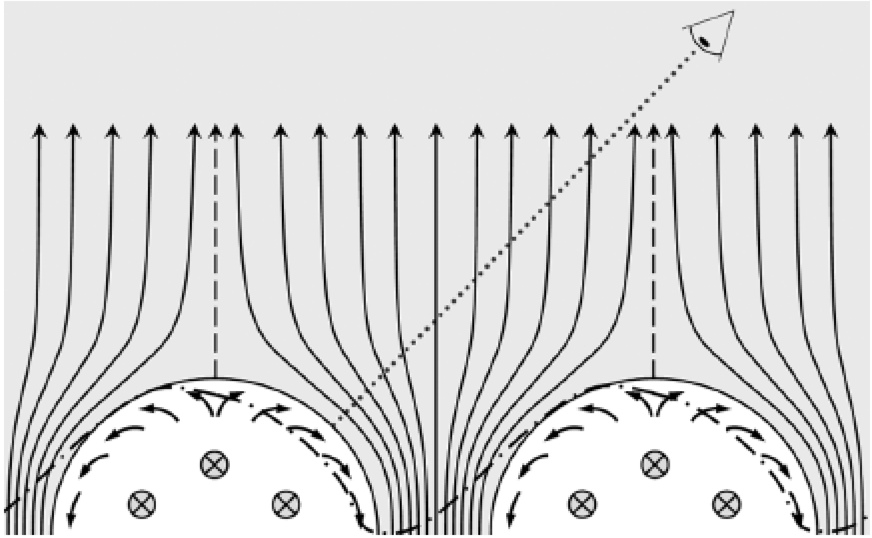


The 'twisting motion' of penumbral filaments is not an real turn of individual filaments, but is a manifestation of their dynamical nature such that the appearance depends on the viewing angle.

What is the origin of the twisting appearance?

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

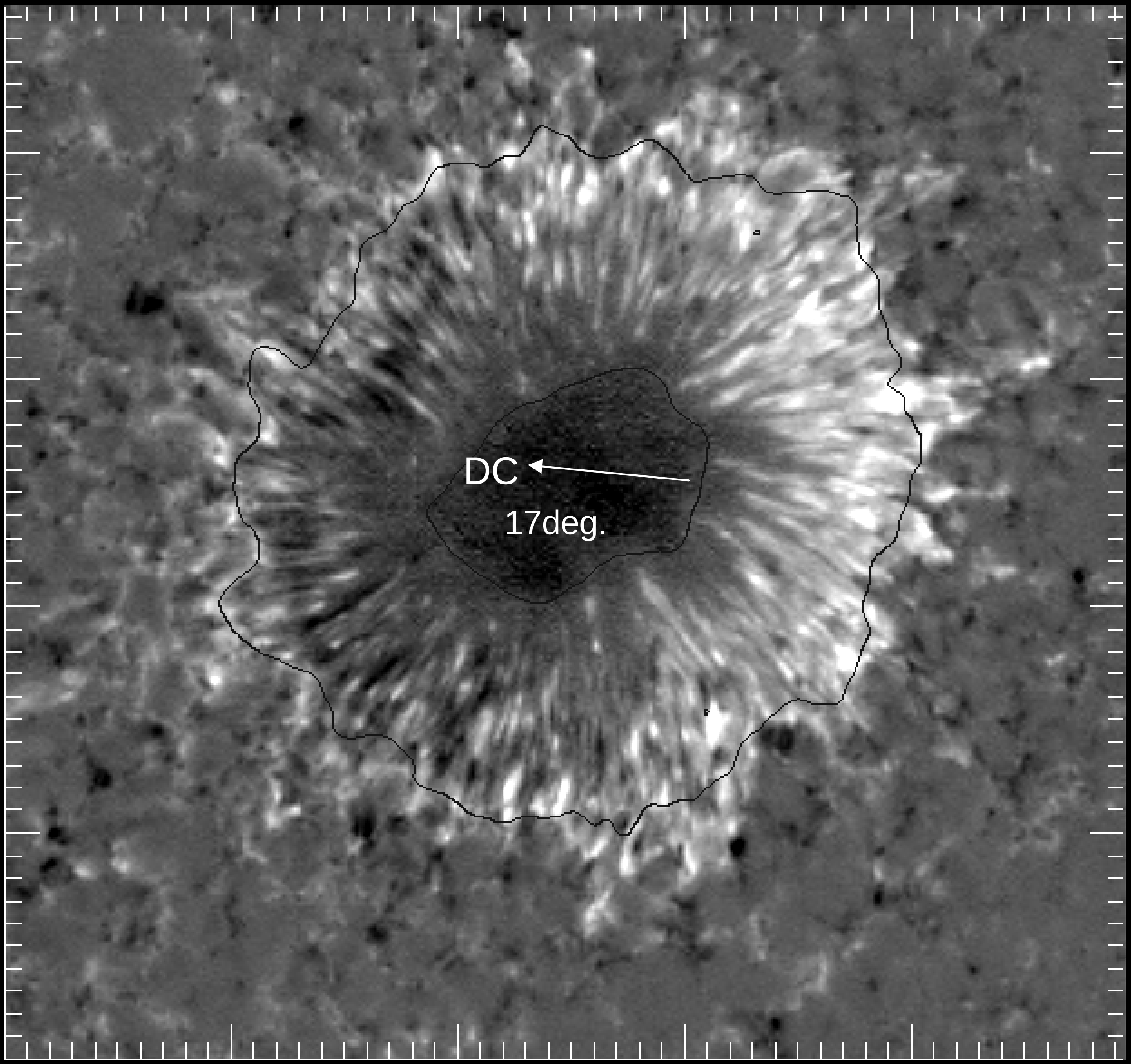




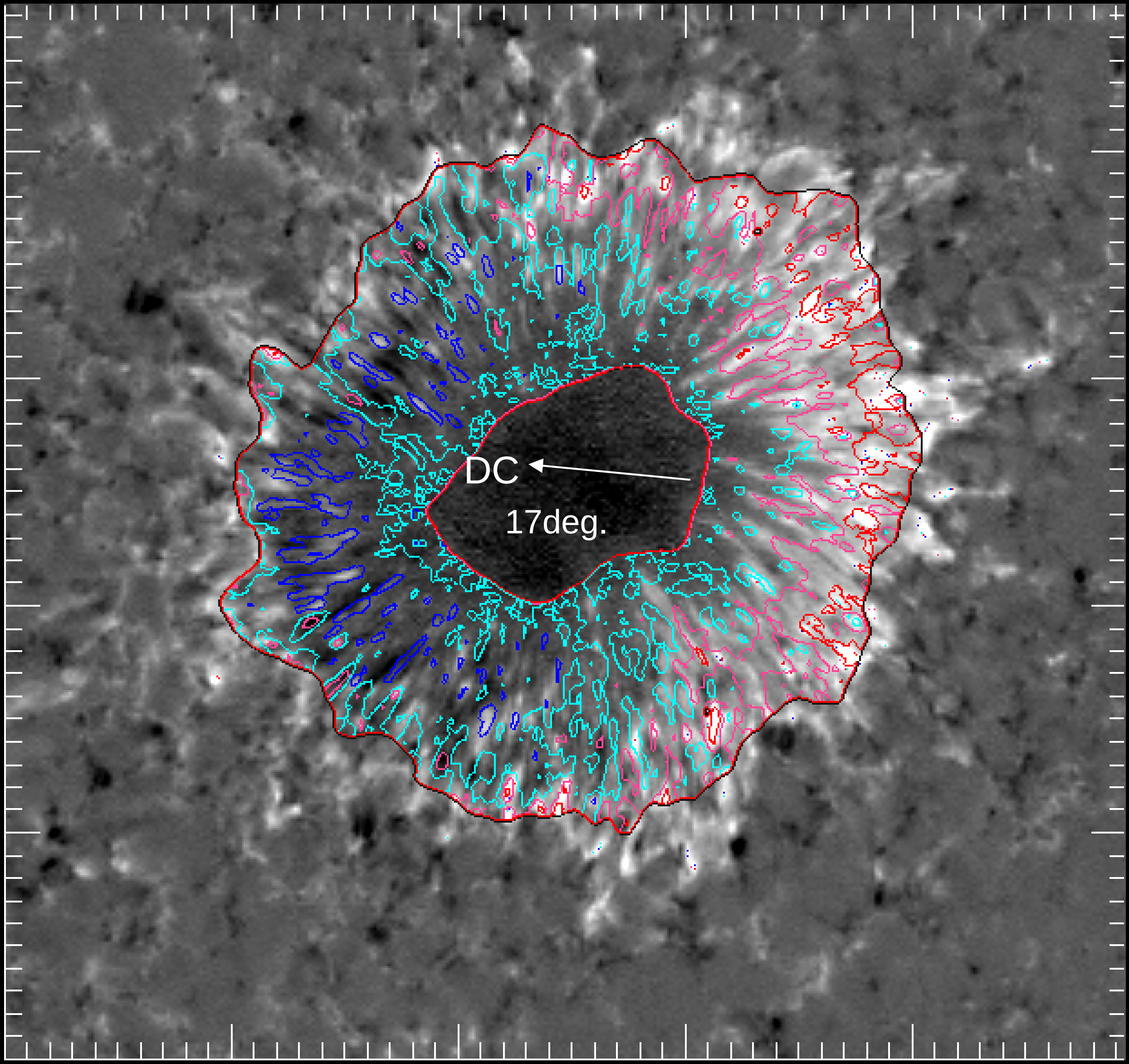
Ichimoto, etal., 2007, Science, 318, 1597

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

Net circular polarization in SOT resolution



Net circular polarization in SOT resolution



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

Summary (1):

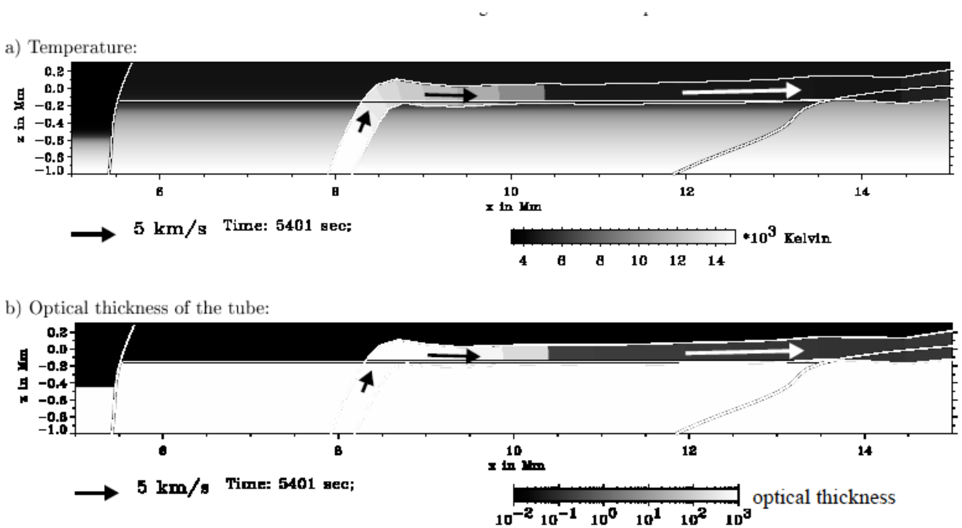
‘Convective nature of the Evershed Effect’

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

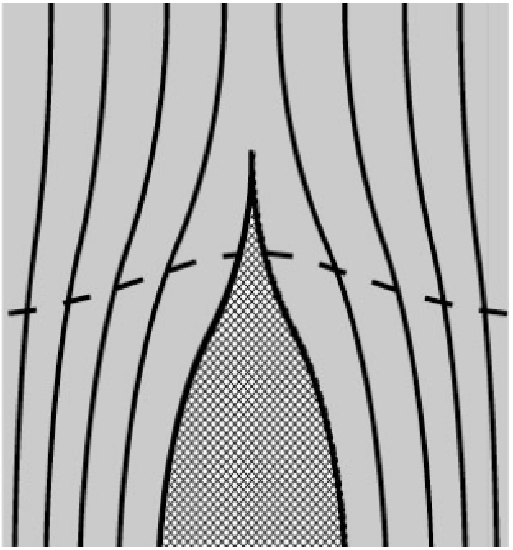
(e.g., Solanki & Motavon 1993
Schlichenmaier etal 1998)



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.

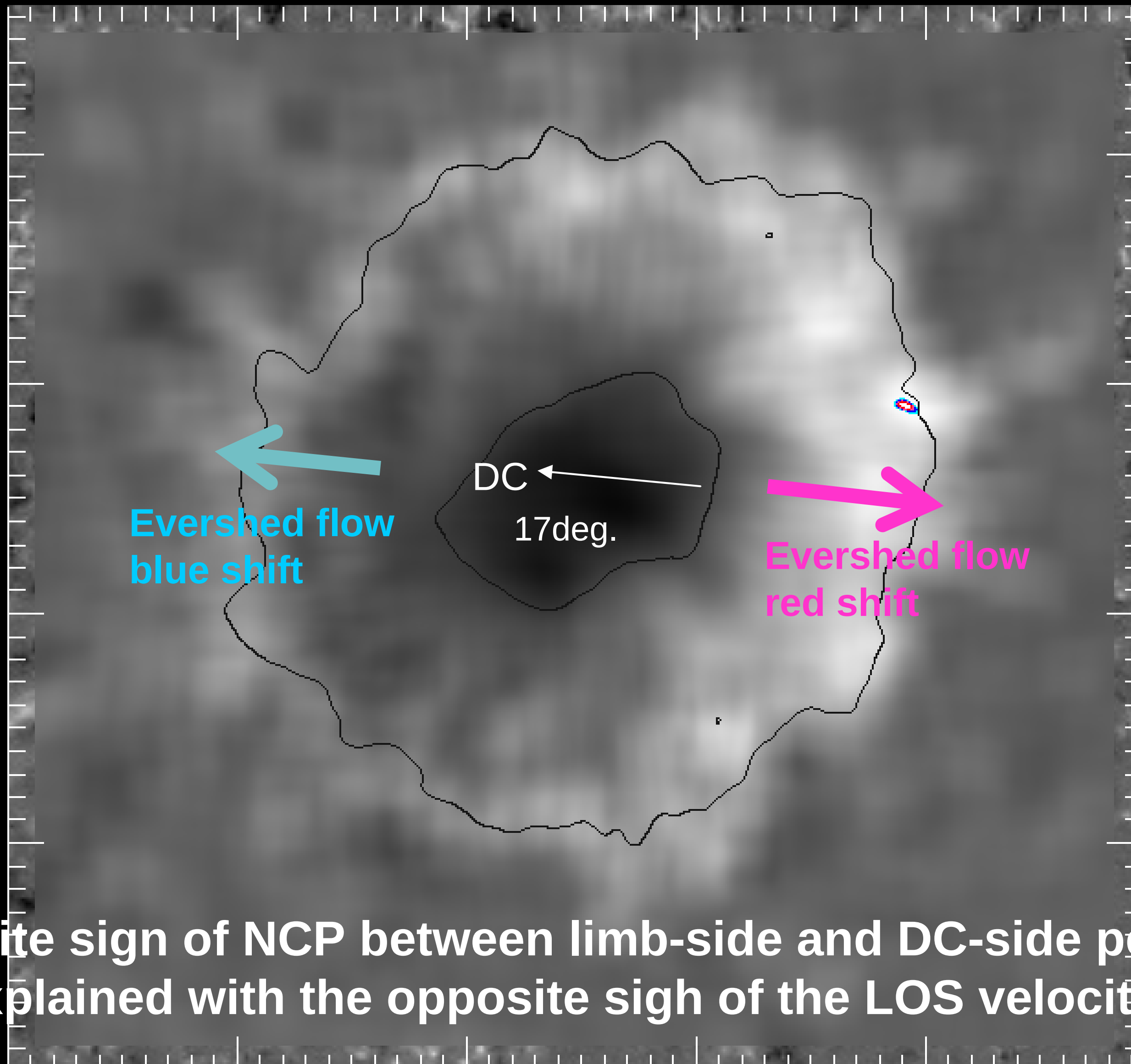
Summary (2):

- If the flux tube model allows vertically elongated ‘flux tubes’, 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!

Net circular polarization in low resolution



$$\int V d\lambda$$

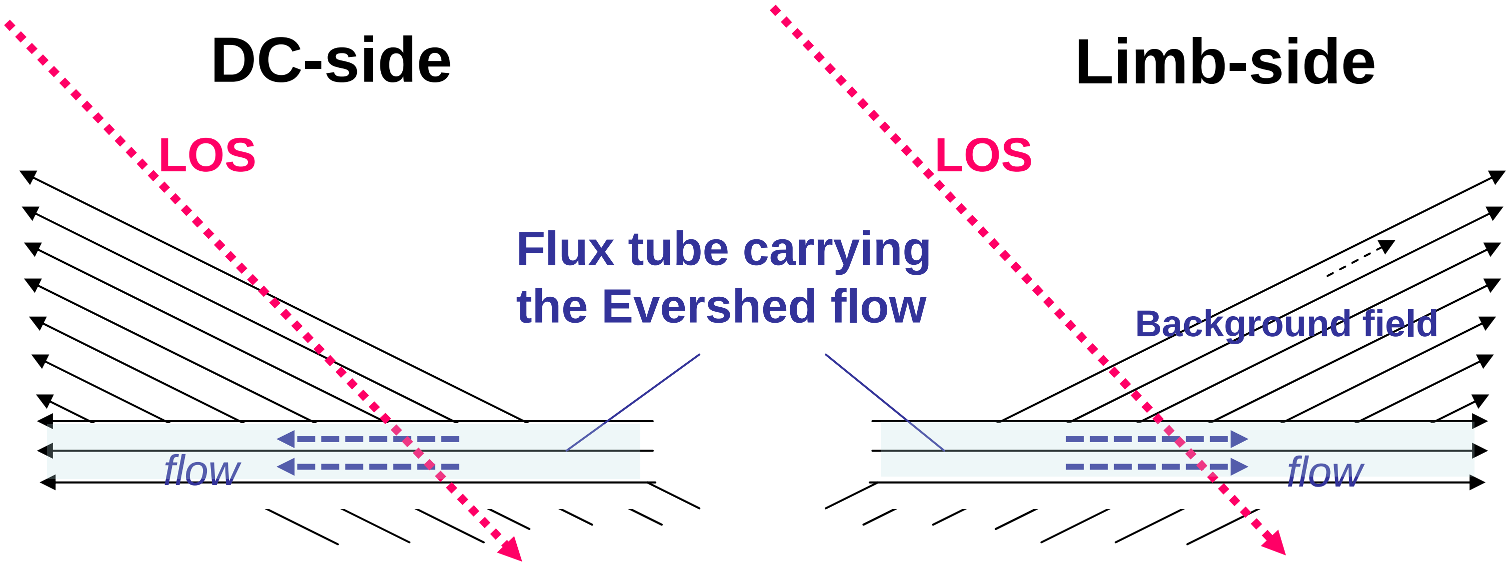
Depth veri.
$dv/d\tau$, $dB/d\tau$

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

Consistent with

Horizontal Evershed flow in deep layer, dγ/dz

Solanki and Montavon (1992), Martinez Pillet (2000), Muller et al (2002,2006)



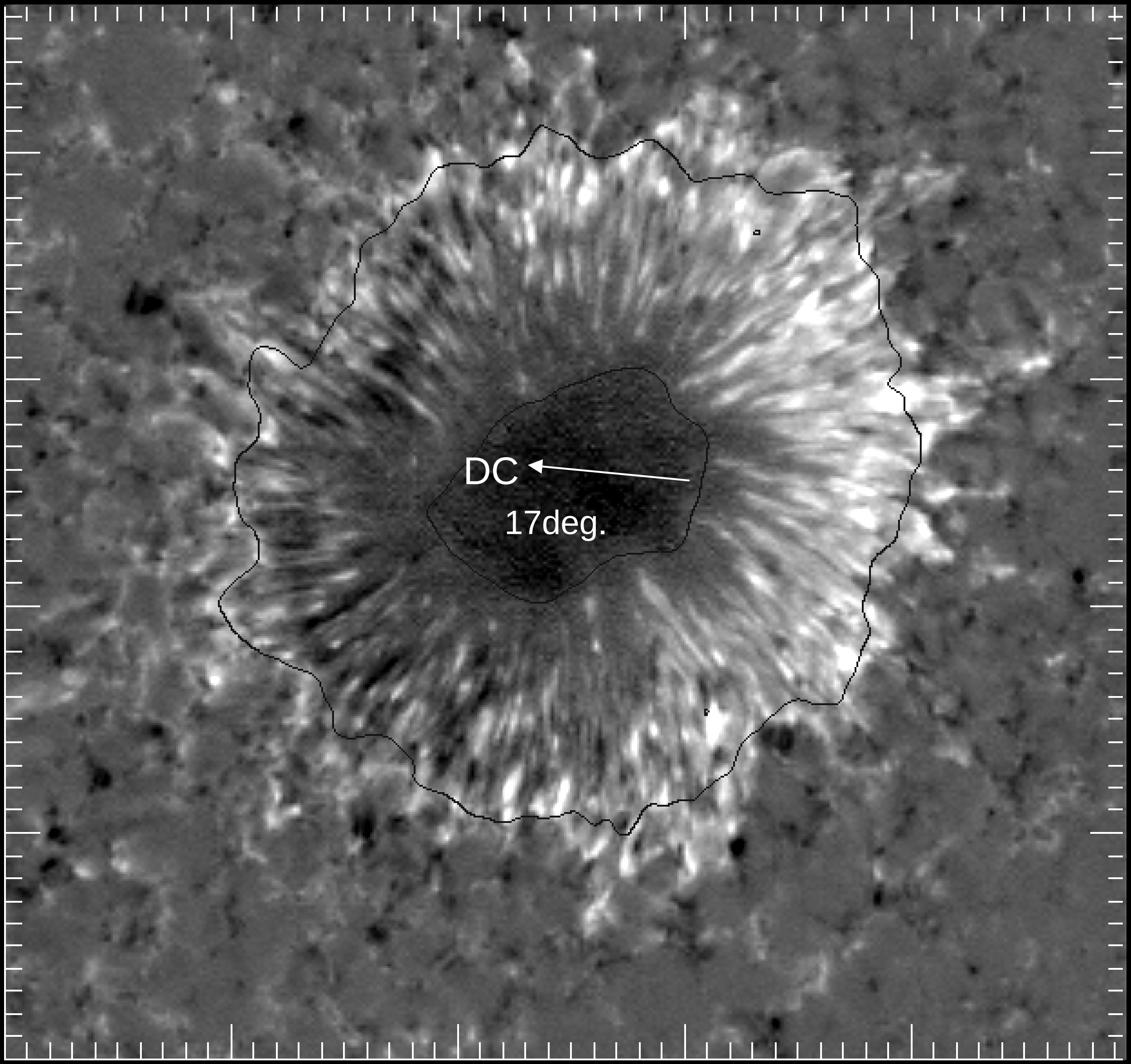
NCP < 0

NCP > 0

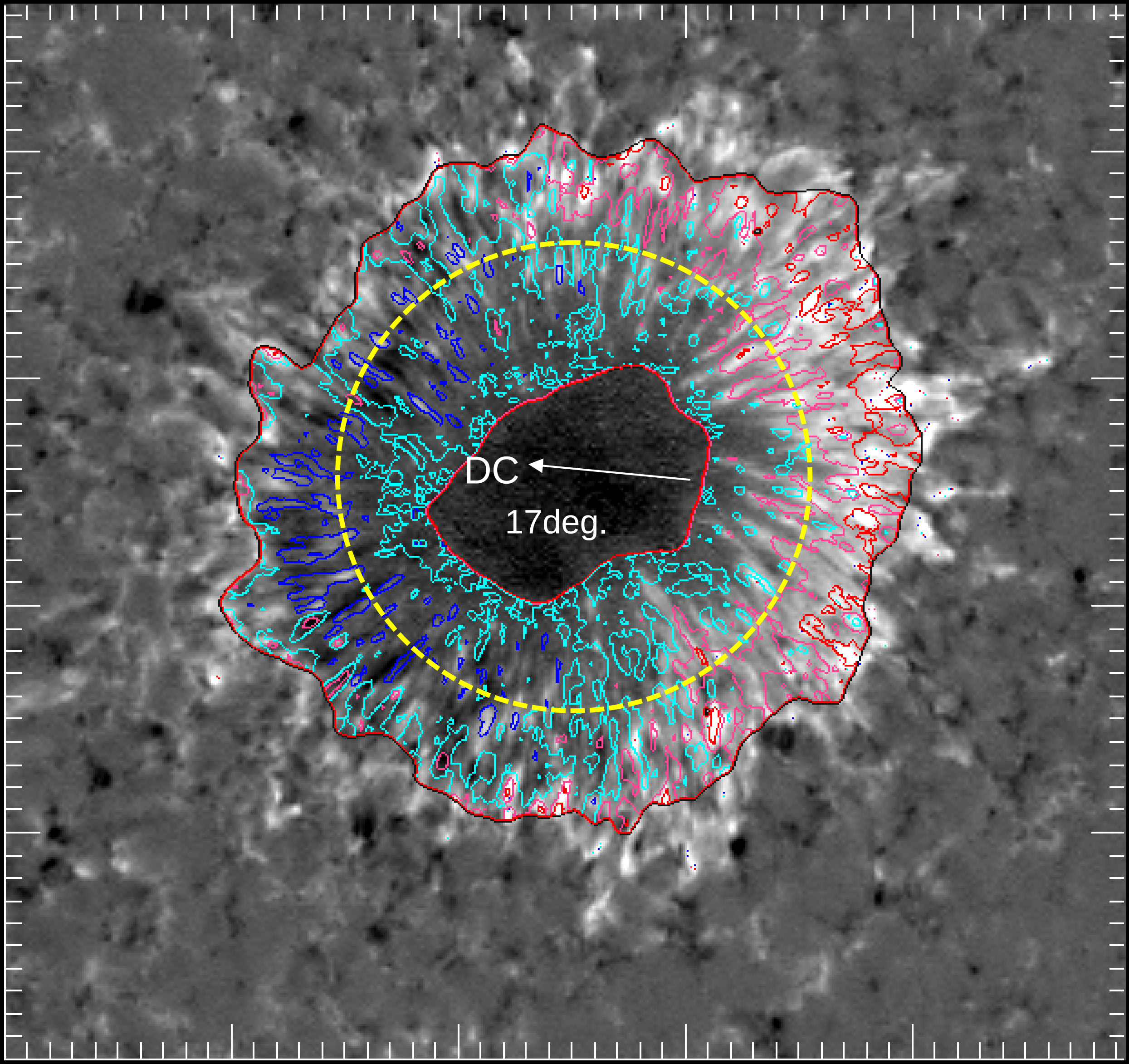
$$B_{\parallel} > 0, \quad \frac{d|\cos\gamma|}{d\tau} < 0, \quad \frac{d\upsilon_{LOS}}{d\tau} < 0$$

$$B_{\parallel} < 0, \quad \frac{d|\cos\gamma|}{d\tau} > 0, \quad \frac{d\upsilon_{LOS}}{d\tau} > 0$$

Net circular polarization in SOT resolution

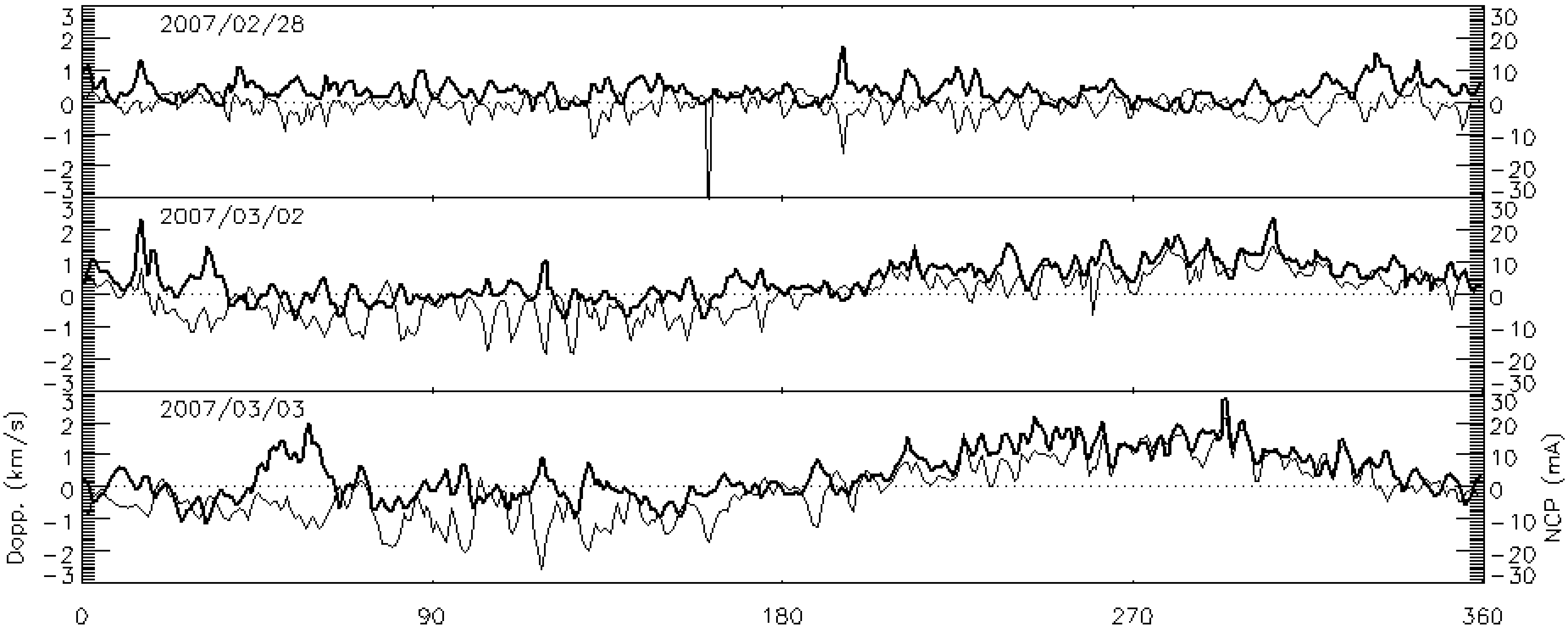


Net circular polarization in SOT resolution



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

Thick: NCP
Thin: Doppler



DC side リムside

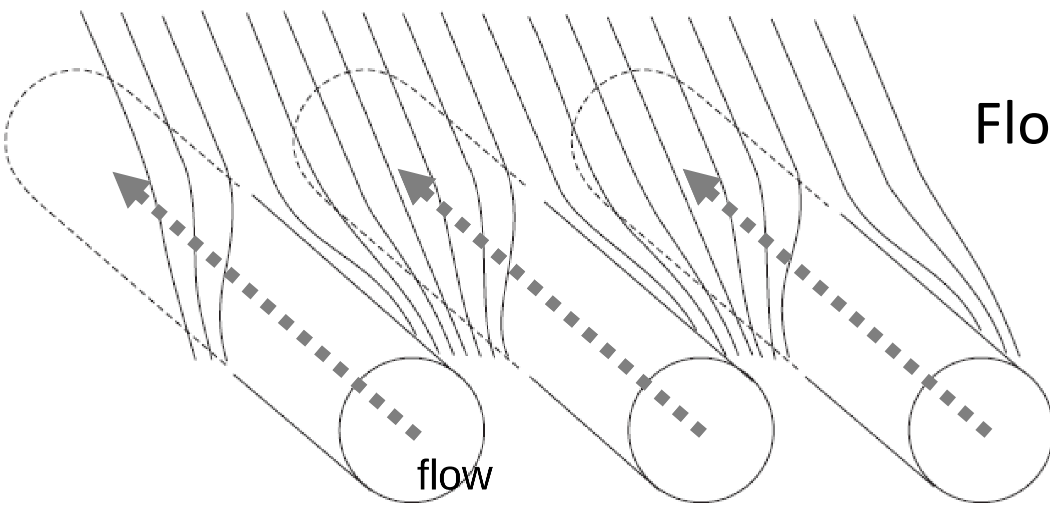
Thus penumbral NCP cannot be explained by dγ/dτ effect, but require a positive correlation between $|v_{LOS}|$ and $|B|$ along the LOS.

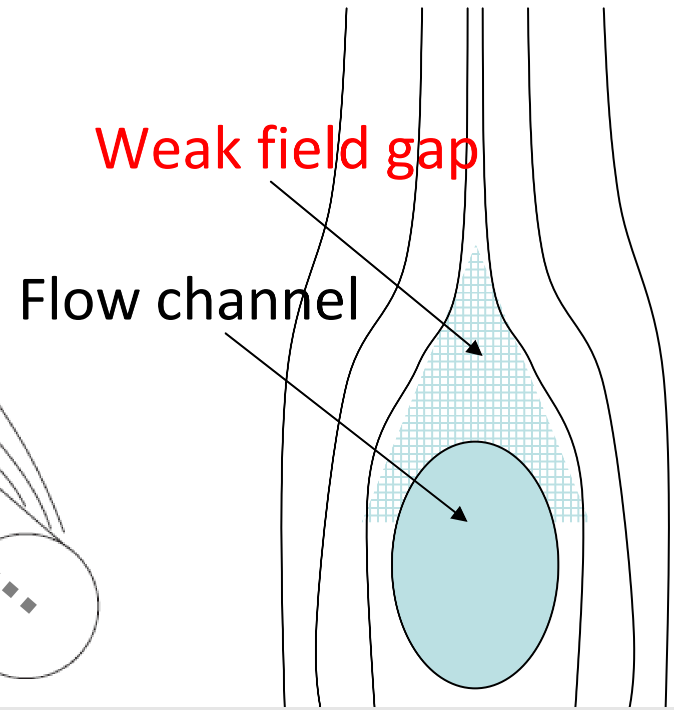
Suggesting the presence of
weak field gap above the flow channel

Ichimoto etal. 2008, A&A, 481, L9

Uncombed structure

Solanki & Motavon 1993

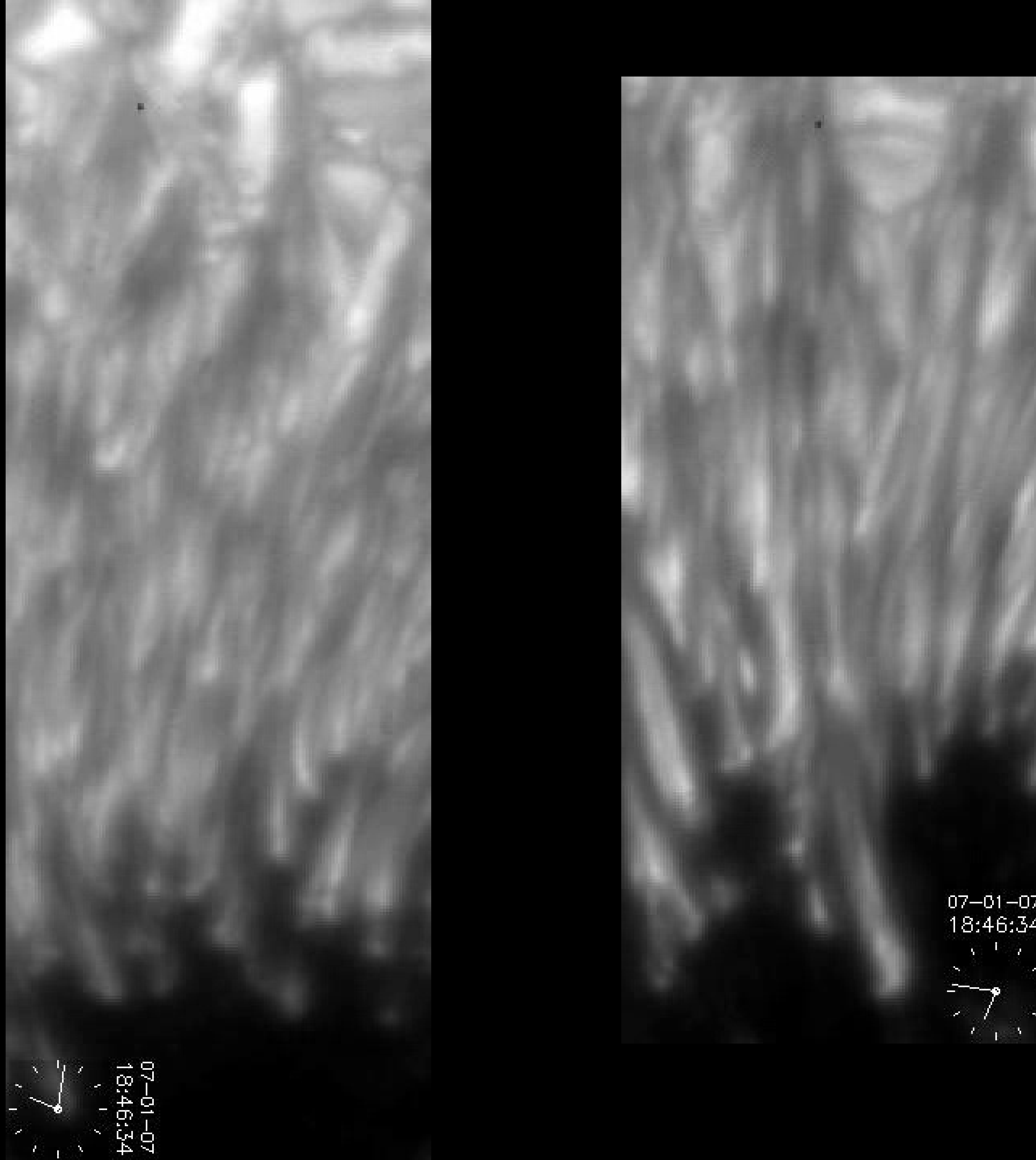




Flowing gas is not field free, but magnetized!

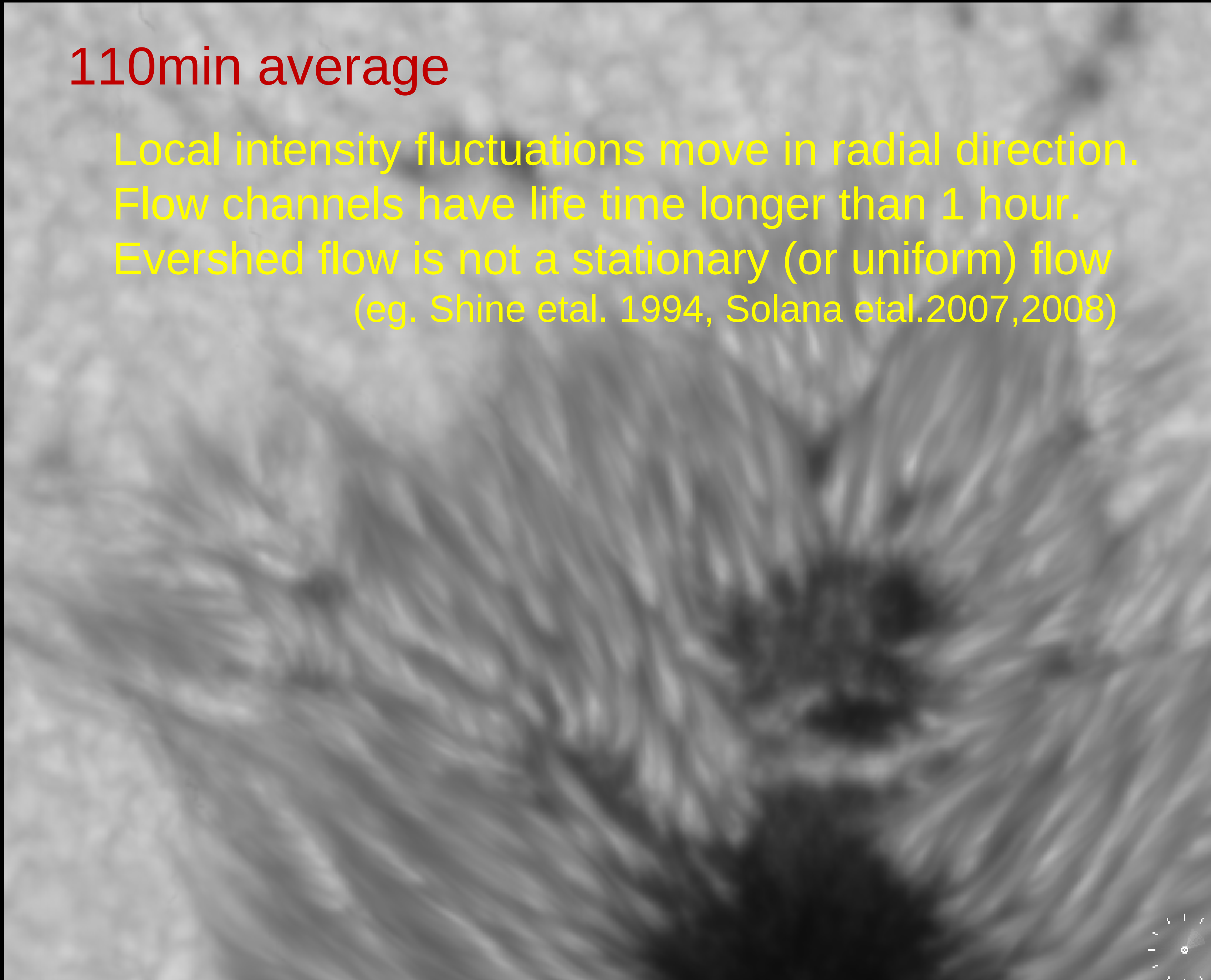
Positive correlation between v_{LOS} and B at

Negative NCP in DC-side penumbra is produced in inter-Evershed flow channels! → presence of flows there too!


07-01-07
18:46:34

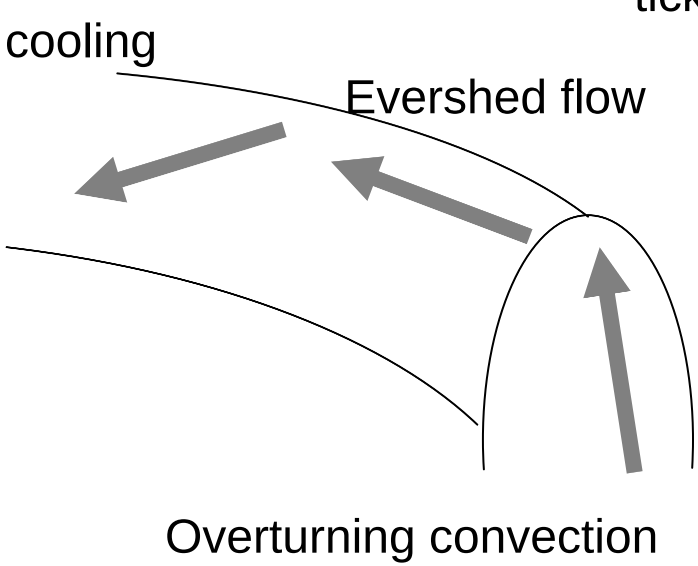
110min average

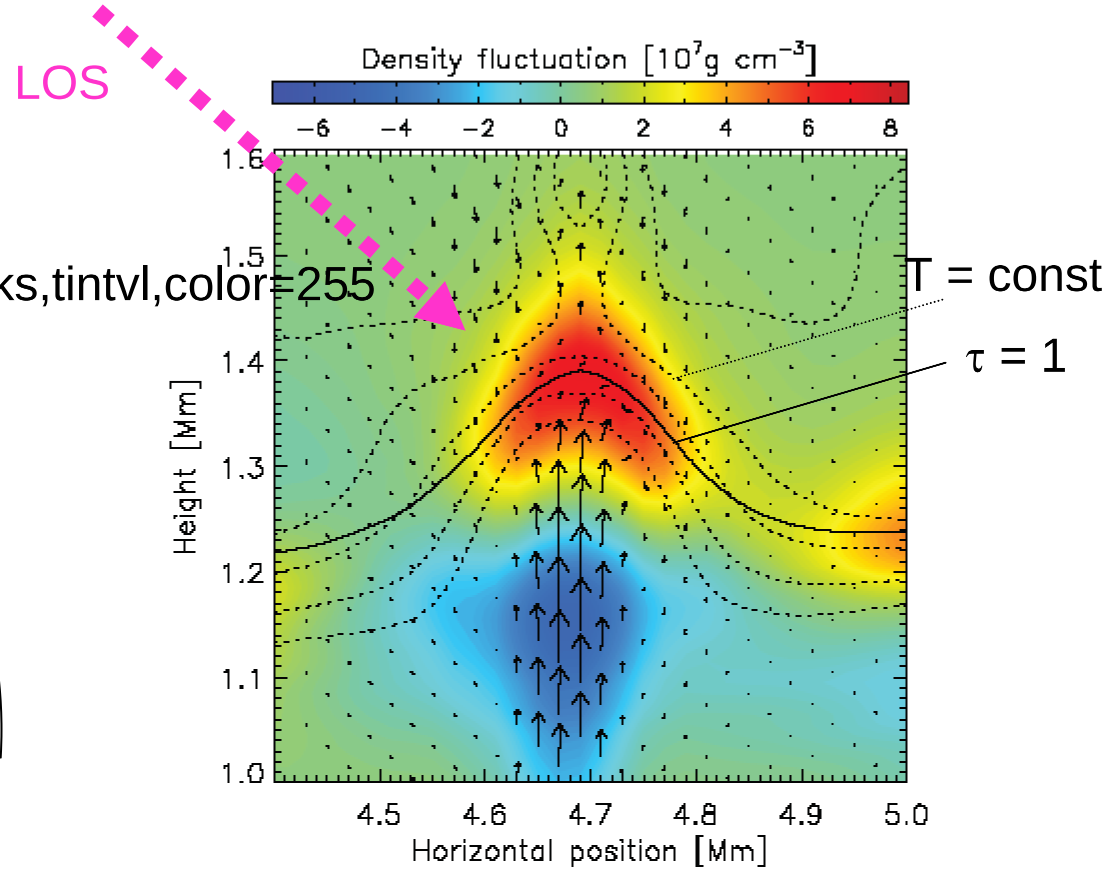
Local intensity fluctuations move in radial direction.
Flow channels have life time longer than 1 hour.
Evershed flow is not a stationary (or uniform) flow
(eg. Shine etal. 1994, Solana etal.2007,2008)



What is the origin of the twisting appearance?

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





Umbral dot simulation

Schussler and Vogler, 2006, ApJ, 641, L73