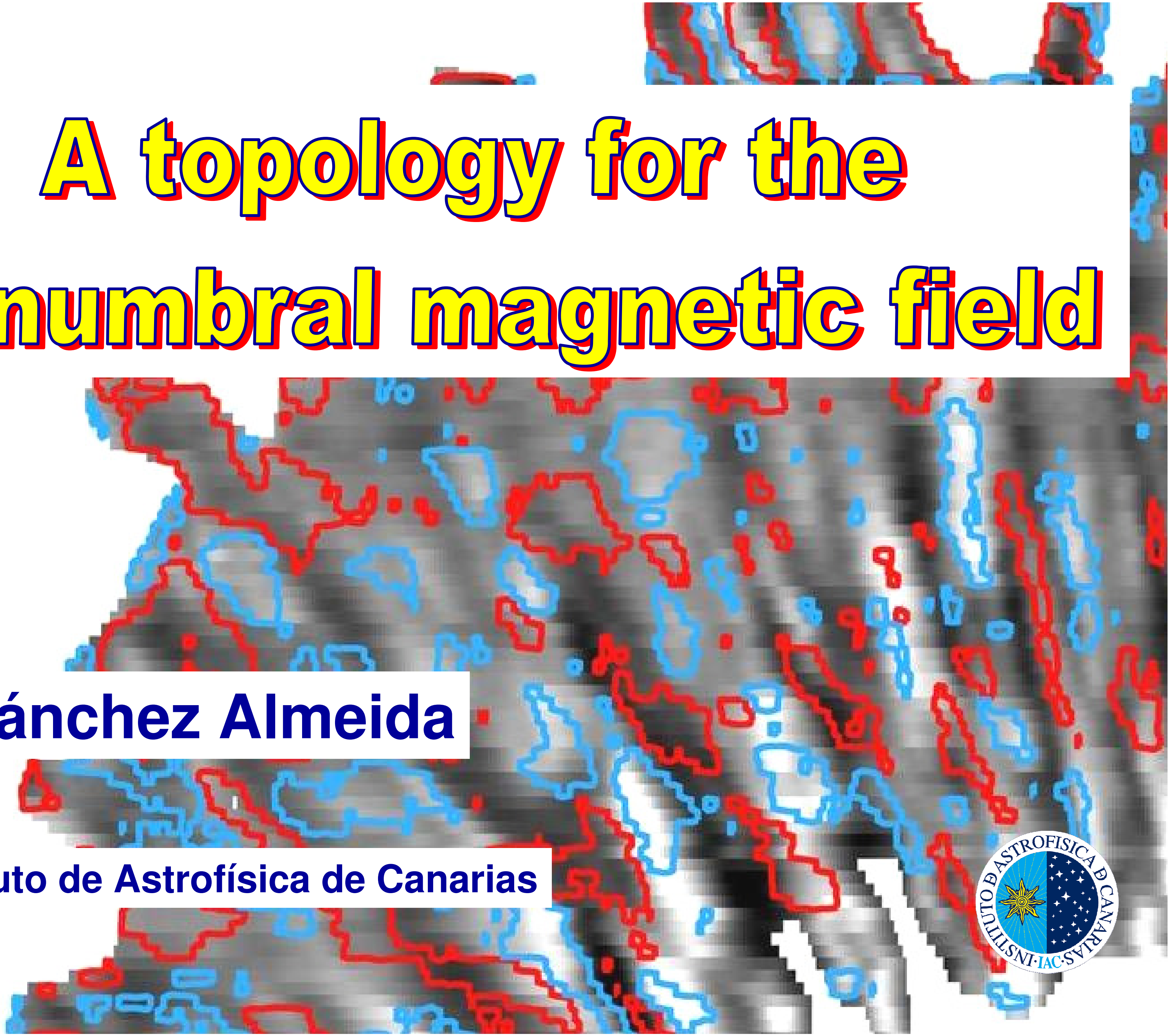
A topology for the penumbral magnetic field



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I know how the Evershed effect works .
It is surprising. exciting, ... and
very different from what most people think

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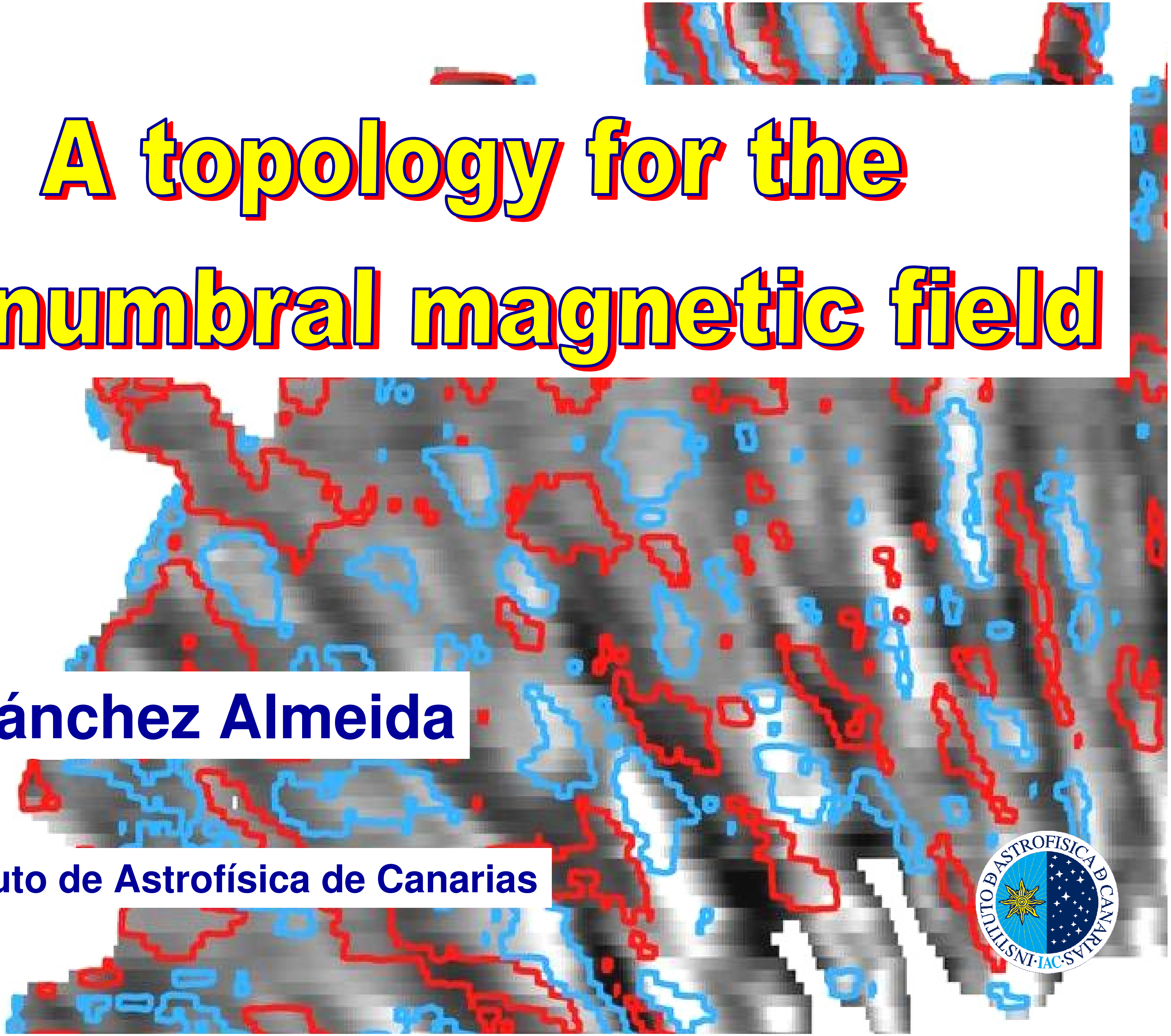
A topology for the penumbral magnetic field



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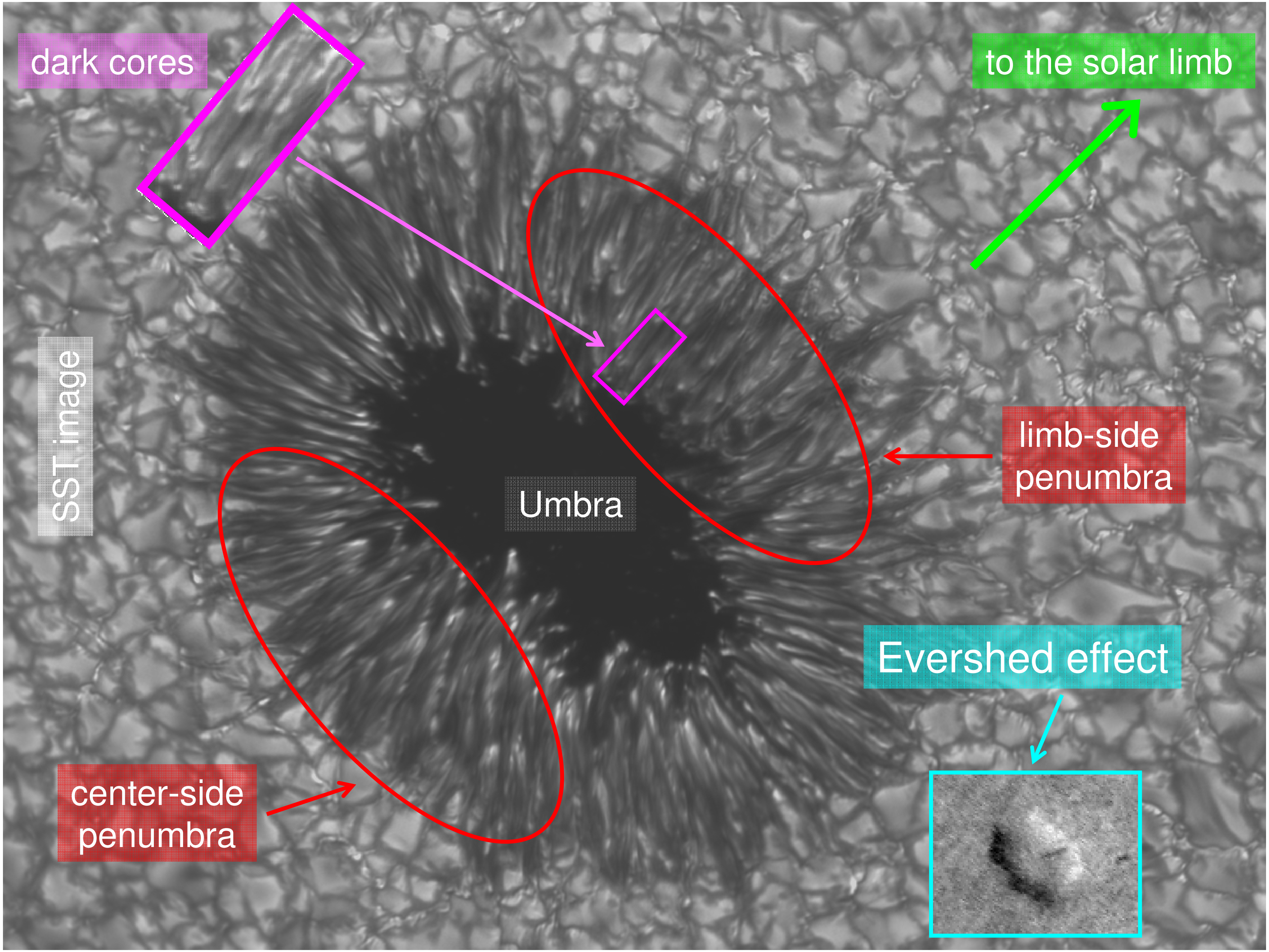
Outline

- Introduction to the Evershed effect
- Selected observational results
- Scenario emerging from these observations
- Comment on the gappy penumbra models
- Remarks + Request

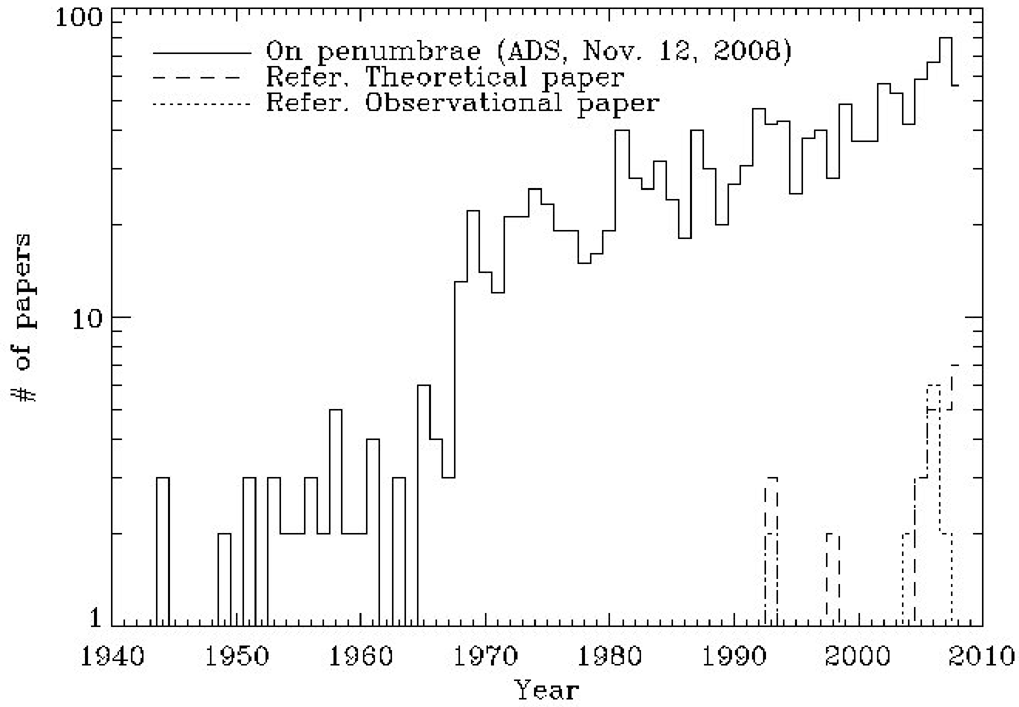
Introduction

[...]


dark cores
to the solar limb
SST image
Umbra
limb-side
penumbra
center-side
penumbra
Evershed effect

Introduction

• Literature impossible to follow: 1430 papers in ADS, with over 70 papers/year



• Frequent unacknowledged rediscoveries…

• Past findings and conclusions are often ignored in the current literature

• Hard to distinguish between superfluous and fundamental

• Misunderstandings among researchers, unintentional omissions …

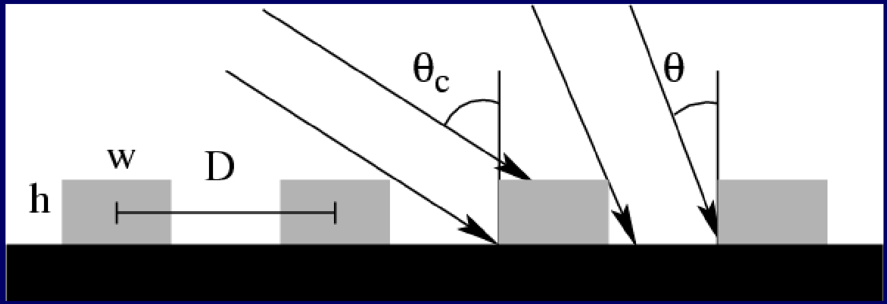
• Obviously, the explanation cannot be simple

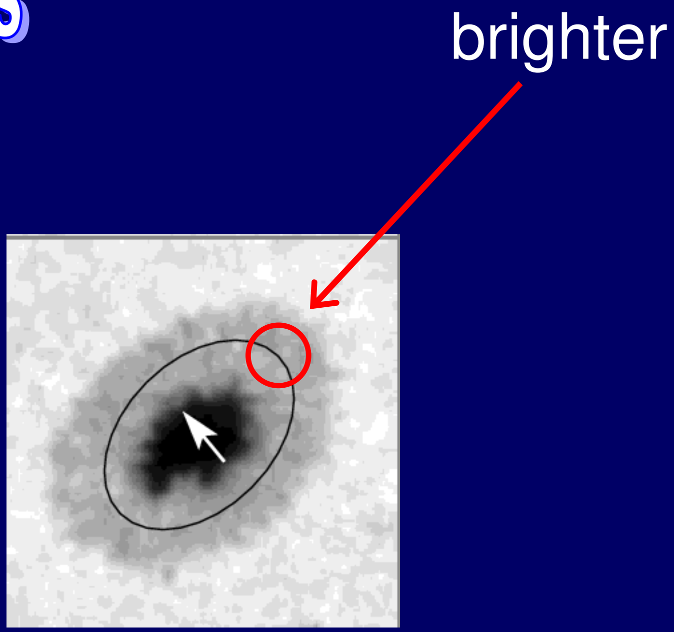
• Claims of problem solved hard to trust

• Apologies for overlooking citations during this presentation

Selected observational results

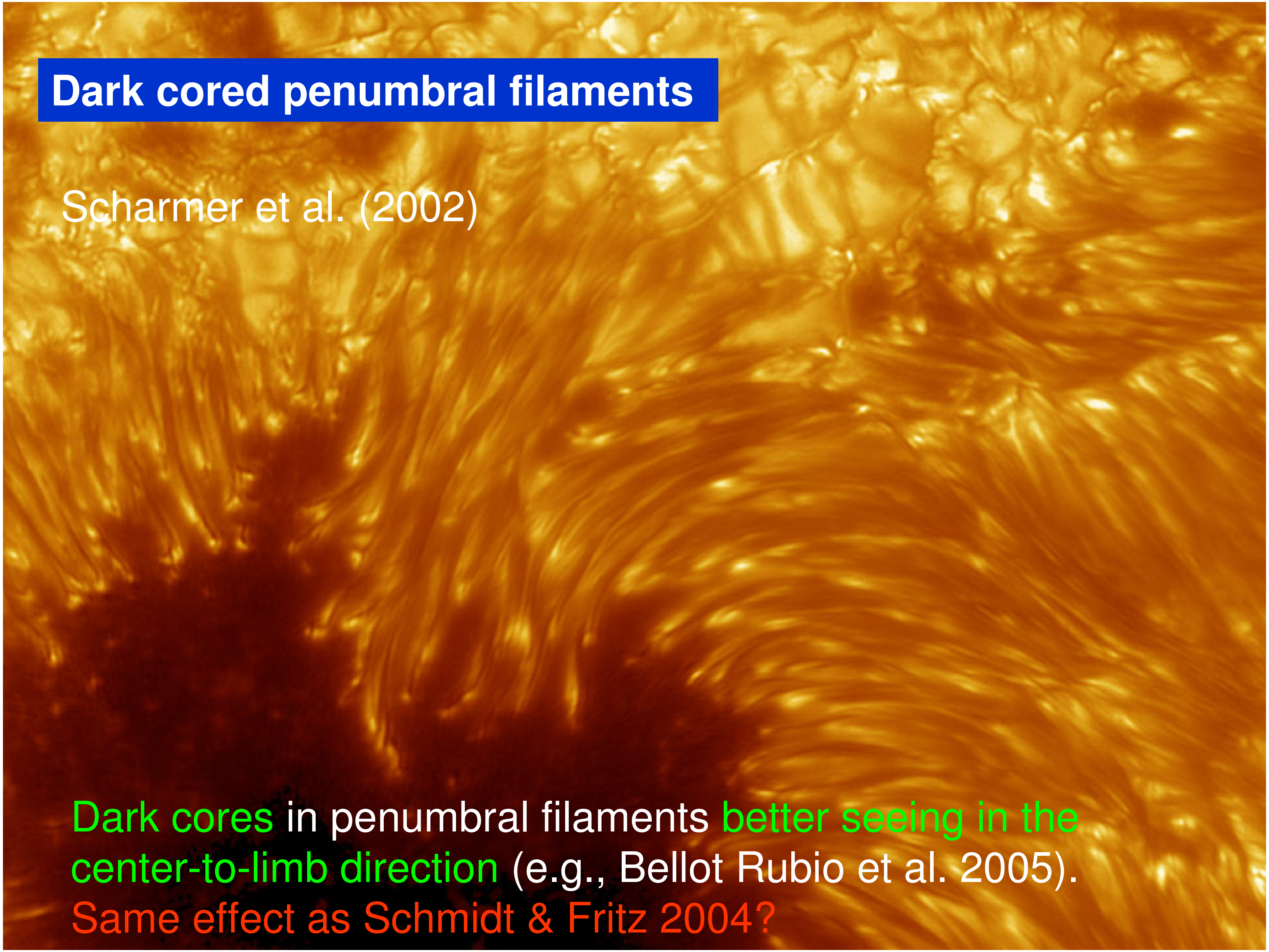
Bright features are elevated





At constant distance from the sunspot center, the limb side penumbra and the center side penumbra are darker than the rest of the penumbra (Schmidt & Fritz 2004). Low resolution observation.

Dark cored penumbral filaments



Scharmer et al. (2002)

Dark cores in penumbral filaments better seeing in the center-to-limb direction (e.g., Bellot Rubio et al. 2005).

Same effect as Schmidt & Fritz 2004?

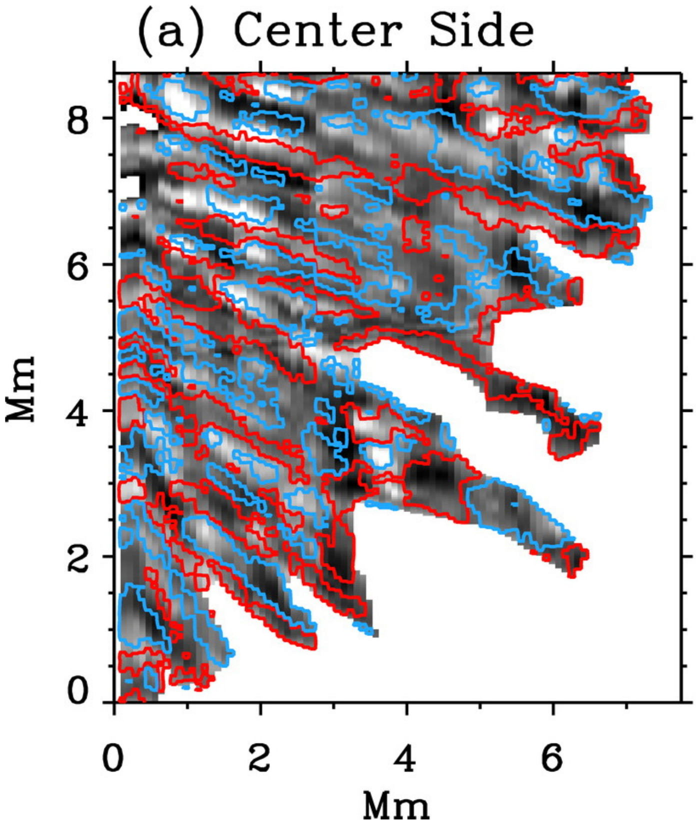
Correlation between Doppler shift and intensity

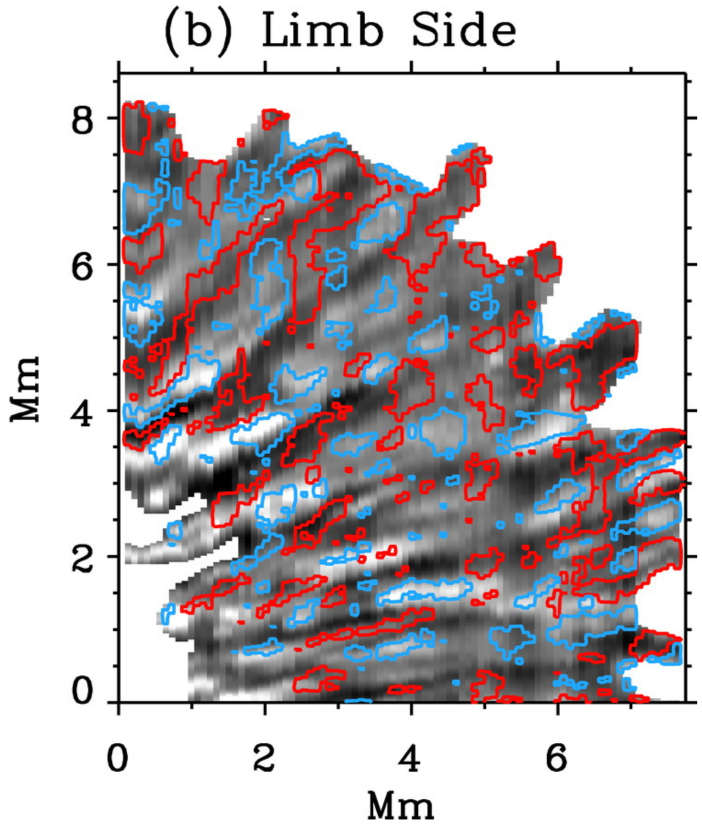
There is a horizontal outflow that affects both the bright features and the dark features (Evershed 1908 effect.)

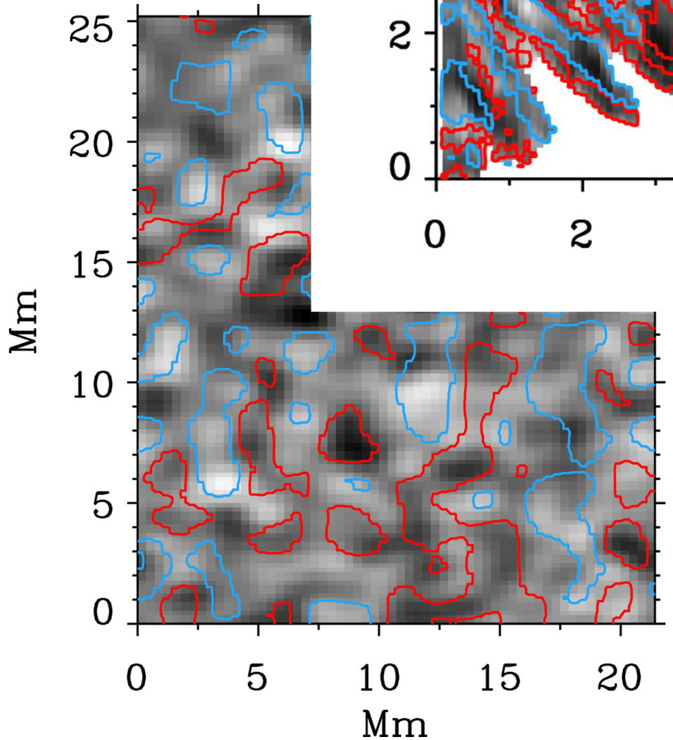
This horizontal outflow occurs preferentially in the dark filaments, so that the darker the filament the larger the flow (undisputed in the current literature).

There is a less well known but equally well documented correlation between the vertical component and the intensity, so that bright features show larger vertical velocities than the horizontal features. Same correlation as the solar granulation. Originally point out by Beckers & Schröter 1969, as a local correlation which do not reverse sign from the limb side penumbra to the center side penumbra.

SA et al. 2007. SST. Non-magnetic line spectroscopy at 0.2´´ resolution. μ=0.82





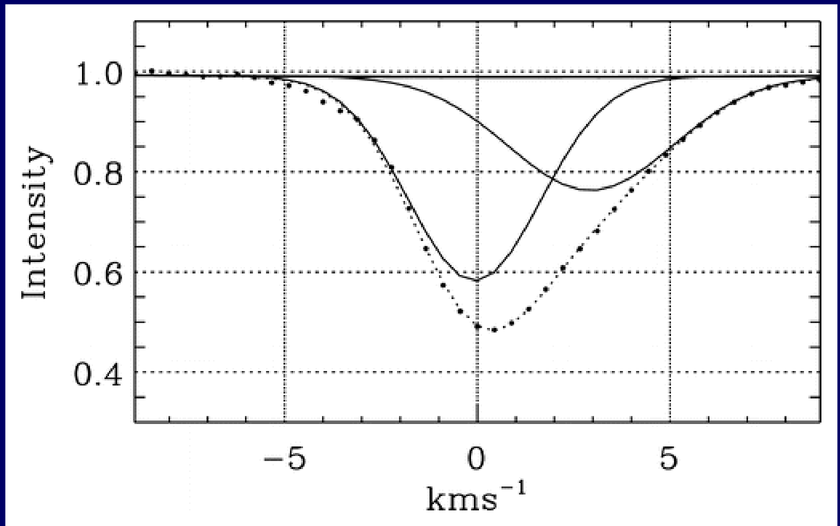


Local blueshifts associated with bright features whereas local redshifts are associated with dark features (No 121 relationship, though).

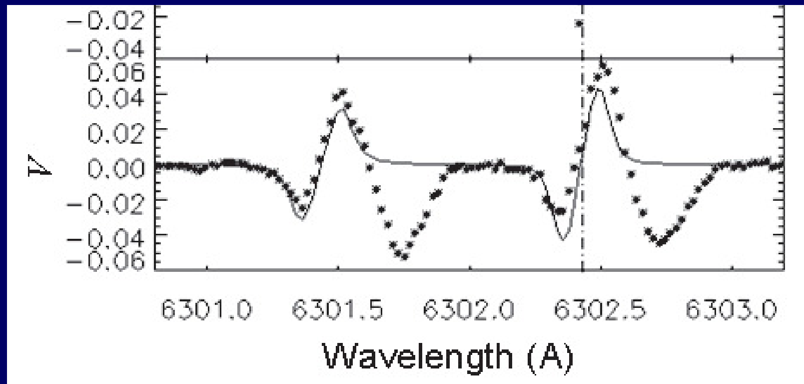
granulation at 2´´ resolution

Impossible to resolve the fine-scale structure of the magnetic fields and velocities in penumbrae

(1) Even the best angular resolution achieved nowadays yield asymmetric line profiles.



SA et al. 2007, SST, 0.2´´



Ichimoto et. al. 2007, HIN0DE, 0.32´´

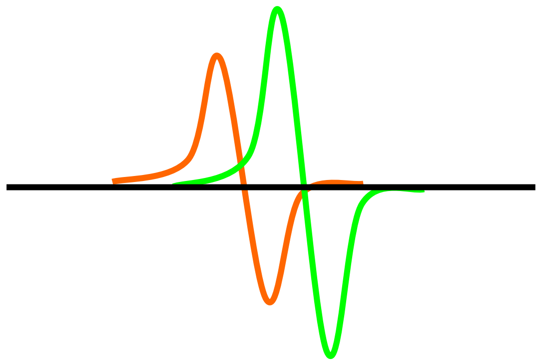
(2) Penumbrae show Broad-Band-Circular Polarization (BBCP; Illing et al. 1974a,b) which is produced by the Net Circular Polarization of individual lines (NCP,Makita 1986). This necessarily imply large gradients of magnetic field and velocity in ~100 km along the line of sight (LOS). We will not be able to resolve these large gradients by improving the spatial resolution. Very old but still valid argument!

$$\mathrm{BBCP} \propto \mathrm{NCP} = \int_{band-width} V(\lambda)d\lambda \neq 0$$

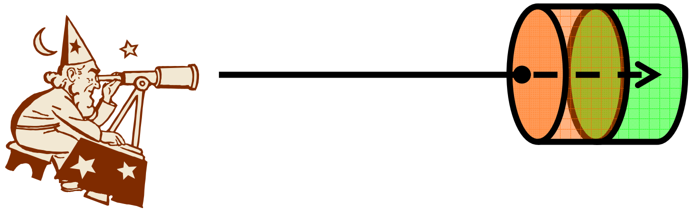
The NCP cannot be produced by two 2 laterally unresolved components, but the components must overlap along the LOS.

if $\int V(\lambda)d\lambda = 0$ and $\int V(\lambda)d\lambda = 0$

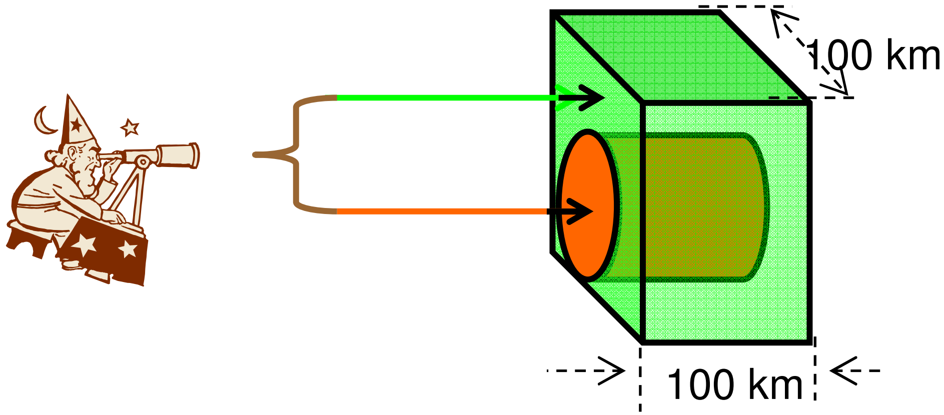
then NCP = $\int [V(\lambda) + V(\lambda)] d\lambda = 0$



NCP

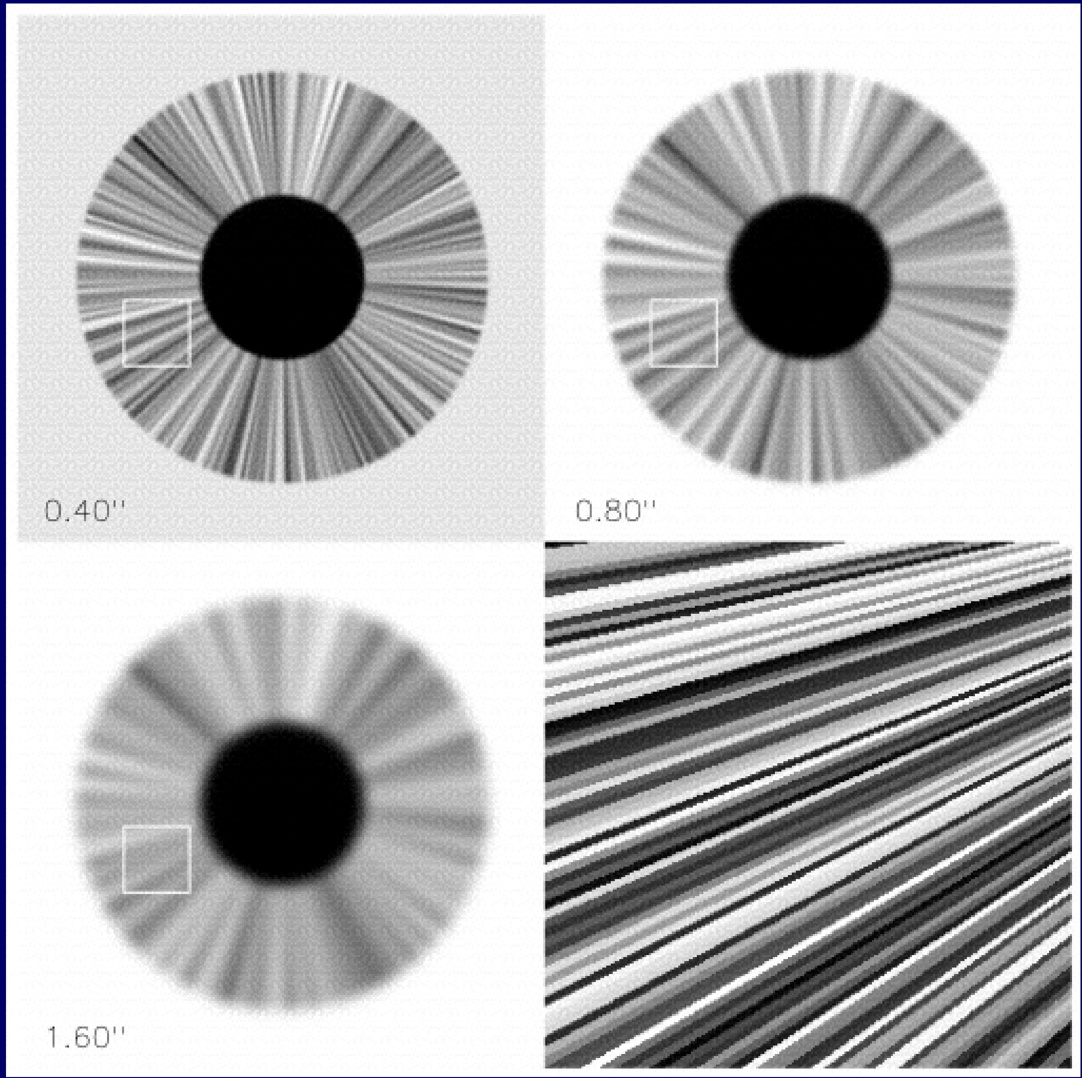


NO NCP



Bottom line: one have to be cautious of measurements based on assuming that the magnetic and velocity fields are uniform in the resolution element.

What is a bright and a dark filament depends on the angular resolution of the observation



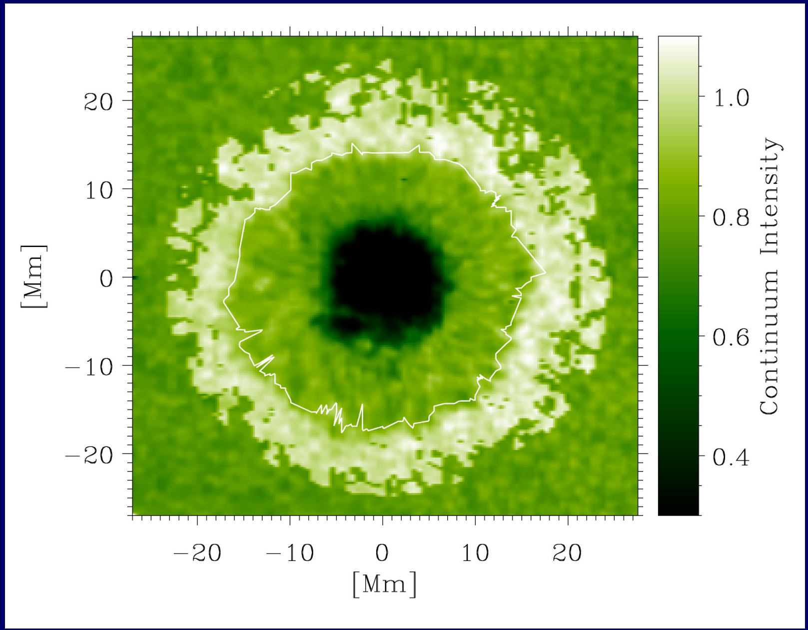
SA & Bonet (1998)

Explaining line asymmetries

SA, 2005, ApJ, 622, 1292

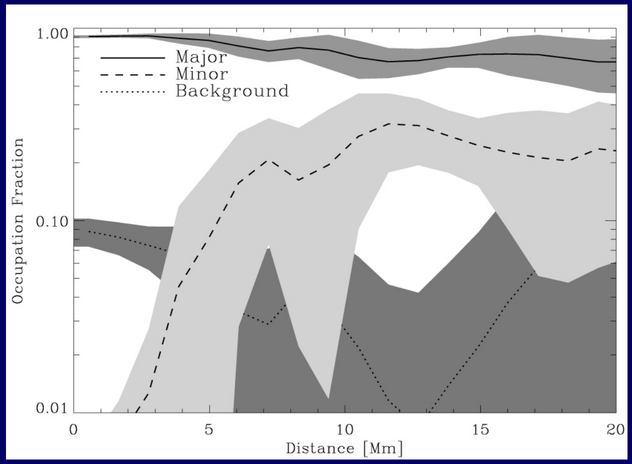
The results to be described follow up, and are consistent with,

- Bumba (1960), line flags in the penumbrae.
- Grigorjev & Katz (1972). Golovko (1974) X-over effect.
- Illing et al. (1974). Auer & Heasly (1978). BBCP
- Makita (1986) BBCP = NCP, and @ neutral line
- SA & Lites (1992). $\Delta\theta$ mechanism
- Title et al. (1993). Lites et al. (1993). Fluted penumbra
- Solanki & Montavon (1993). NCP due to uncombed fields
- SA et al. 1996, MISMA hypothesis



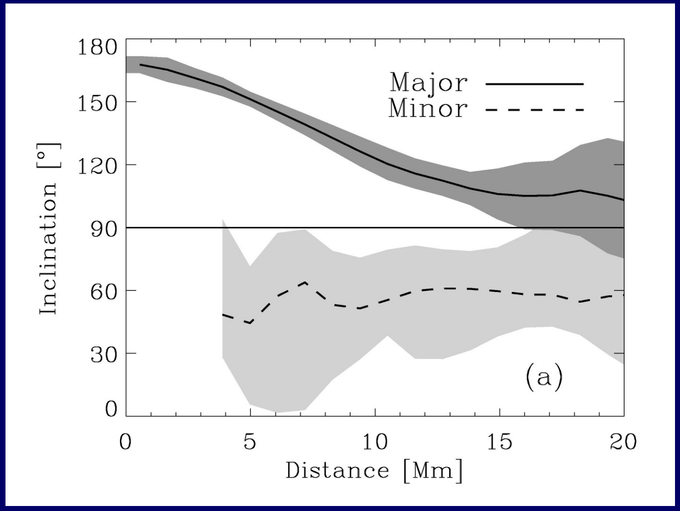
- ASP, Stokes I, Q, U, V, Fe I 6301 Å, Fe I 6301 Å
- NOAA 7912 @ μ=0.96
- 1” angular resolution
- 10000 spectra were fitted
- MISMA Inversion Code (SA, 97)

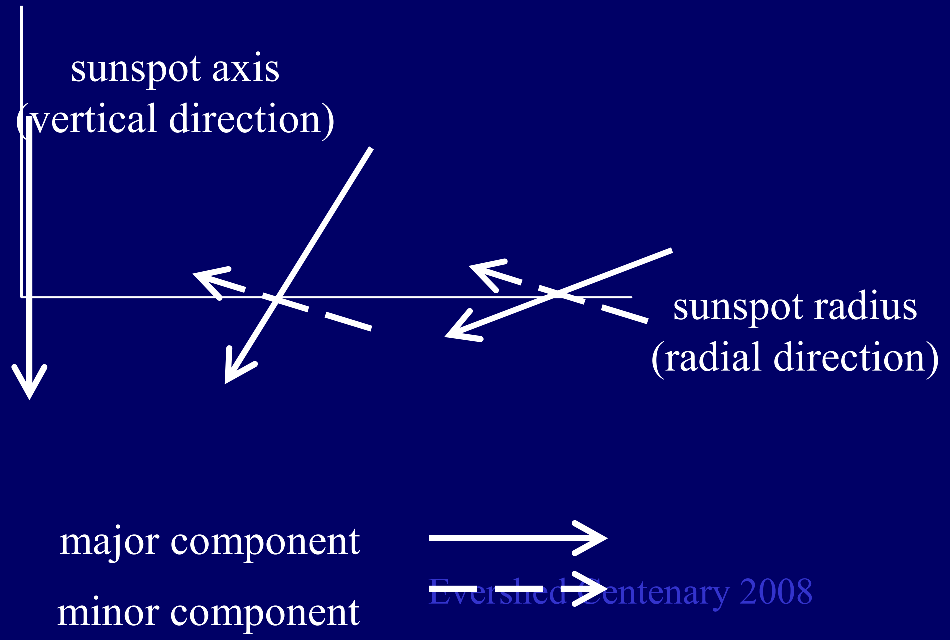
- 2 magnetic components, in mechanical balance along and across the magnetic field lines
- Velocities and magnetic fields are forced to be aligned
- magnetic flux conserved: $\nabla \cdot \vec{B} = 0$
- right NCP, including FeI 15649 Å (Schlichenmayer et al. 2002), right Wilson depression, right mean velocities (by Rimmele 1995), …

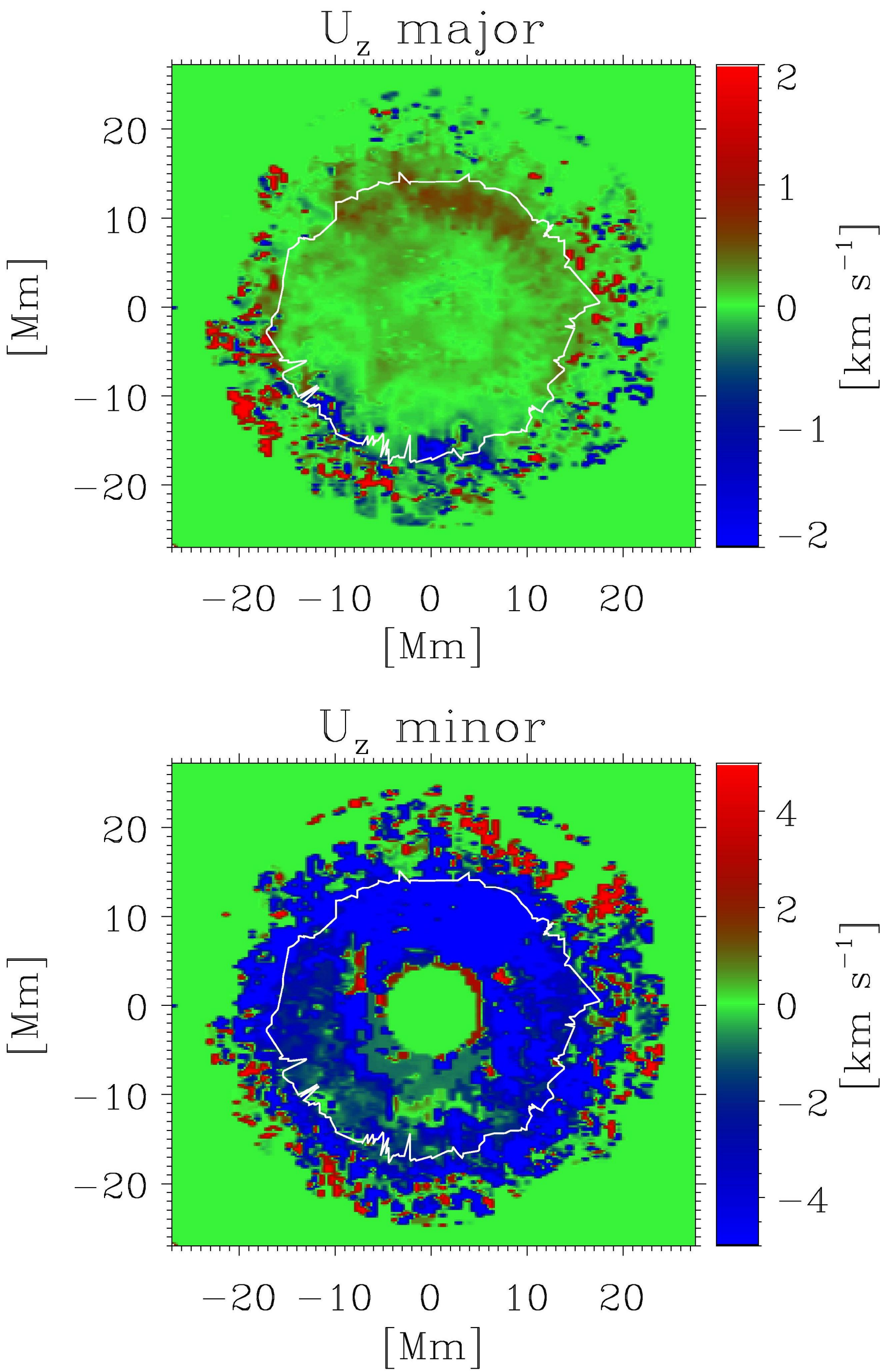


The major component occupies some 70 % of the penumbra.
The minor component accounts for the remaining 30 %. Absent in the umbra.

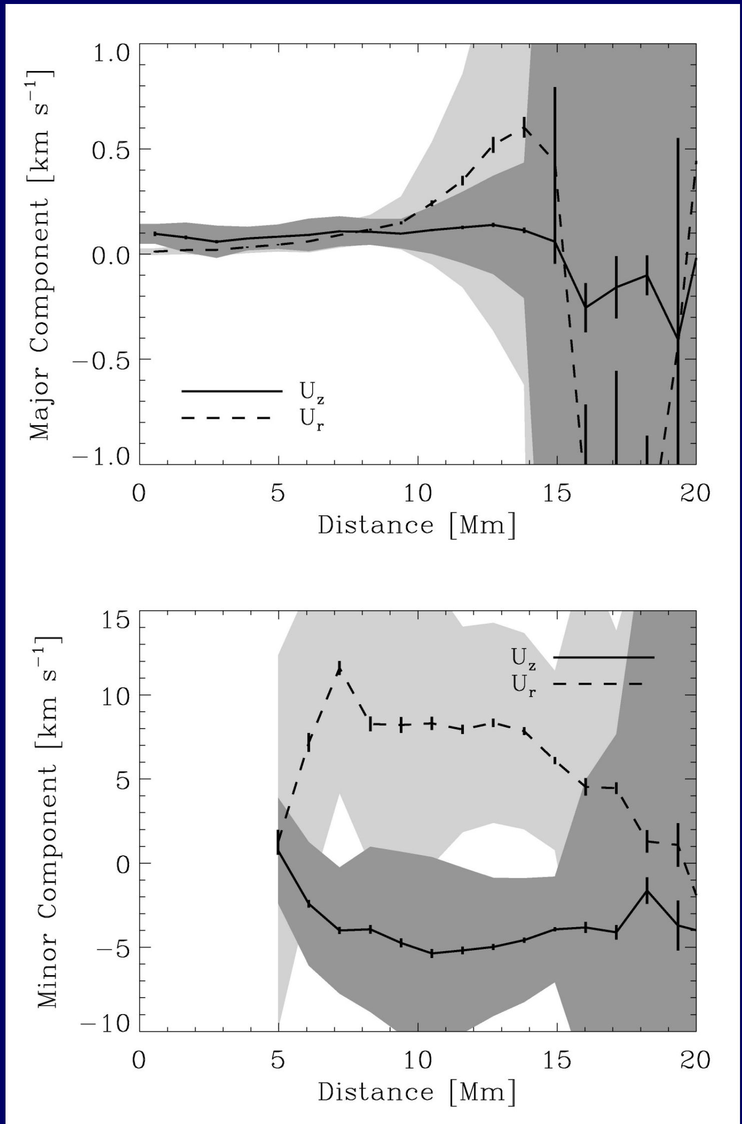
The minor component has a polarity opposite to that of the sunspot. The field lines of the minor component return to the solar interior within the penumbra. The flows along the minor component field lines also return.







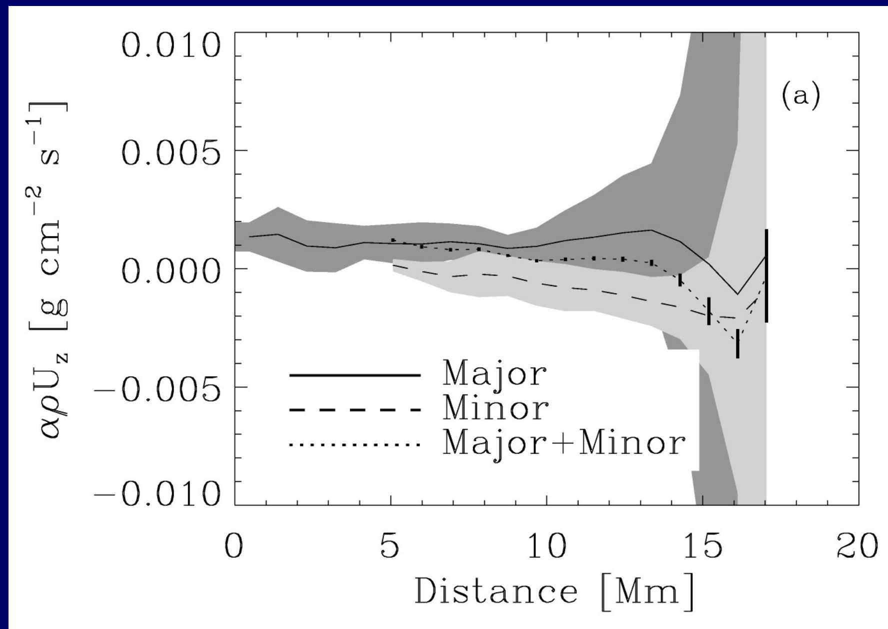
U_z major
[Mm]
[Mm]
[km s^{-1}]
U_z minor
[Mm]
[Mm]
[km s^{-1}]

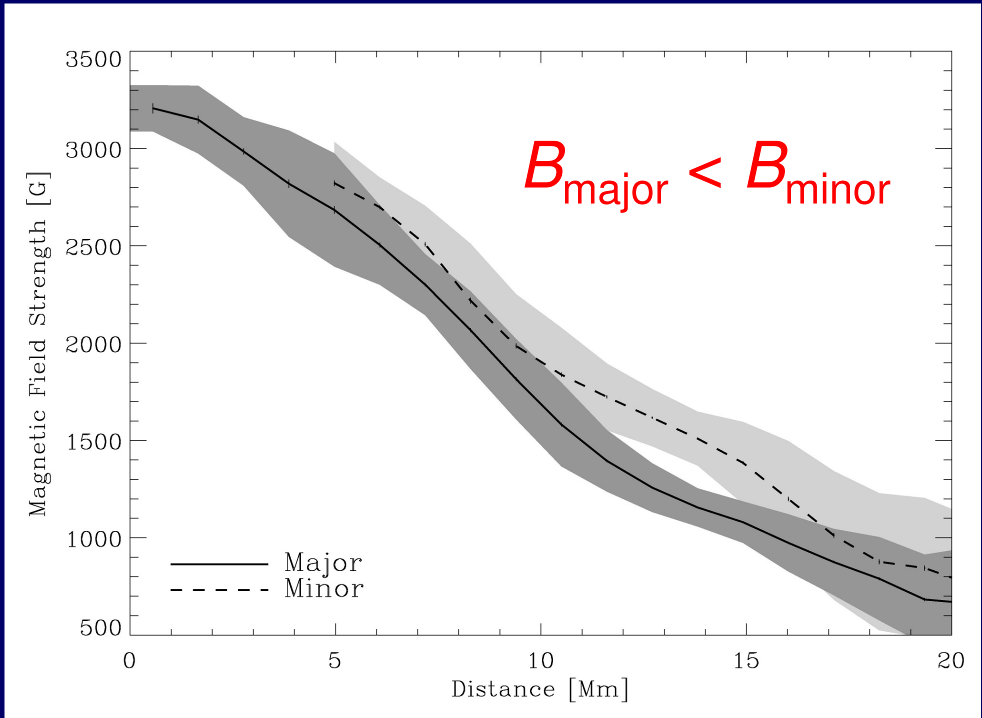


Major component: low velocity (< 1km/s) + high mass density

Minor component: high velocity (< 5km/s) + high mass density

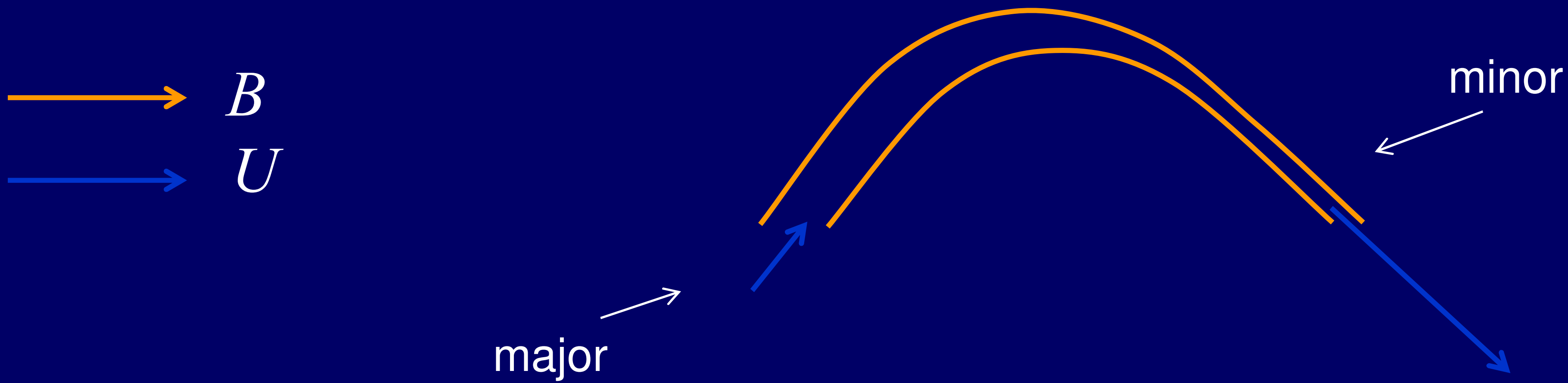
Major and minor transport the same mass

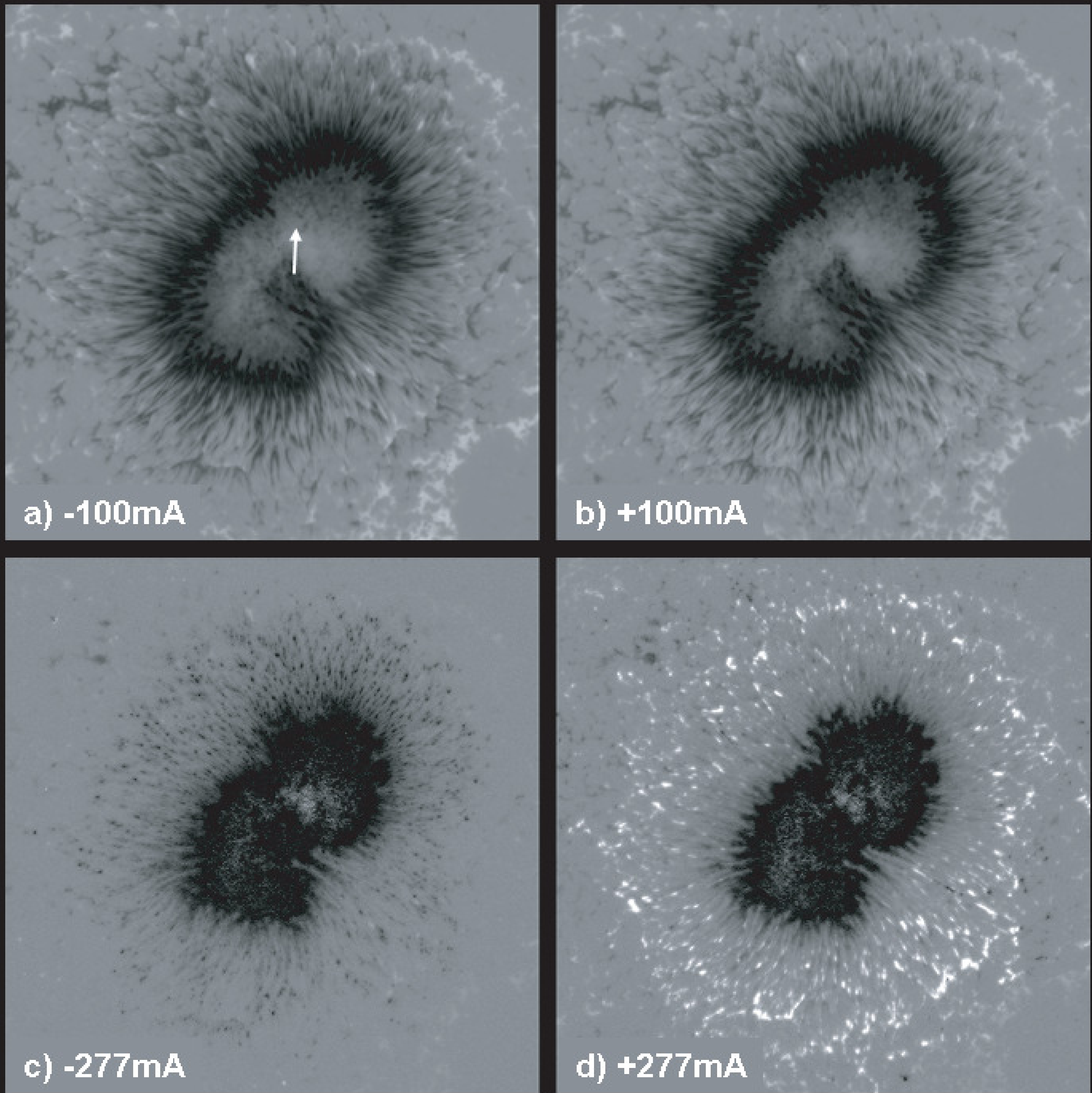




This magnetic field strength difference is able to drive a siphon flow of several km/s

$$\Delta U^2 \approx \frac{B^2}{2\pi\rho}\frac{\Delta B}{B}$$





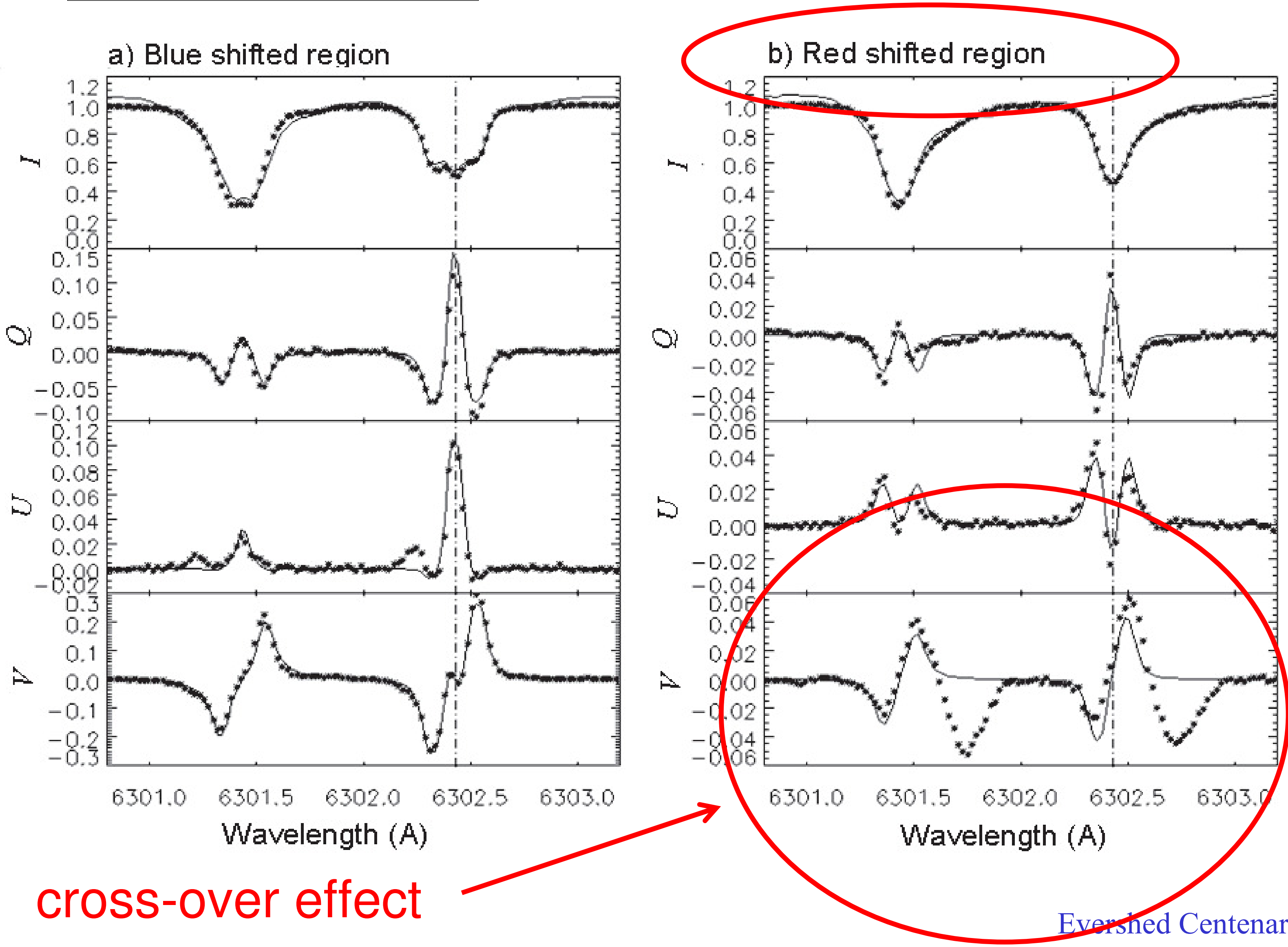
Hinode
Ichimoto et al. 2007

Magnetograms at various wavelengths

Fe I 6302 Å

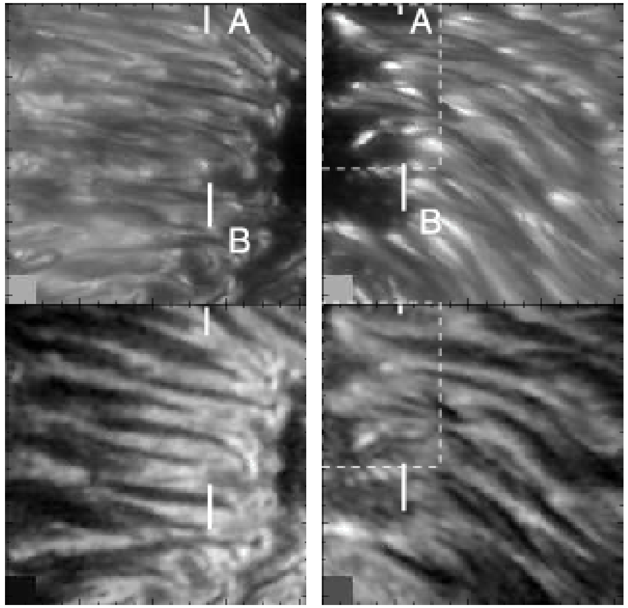
0.32´´ resol.

Hinode
Ichimoto et al. 2007



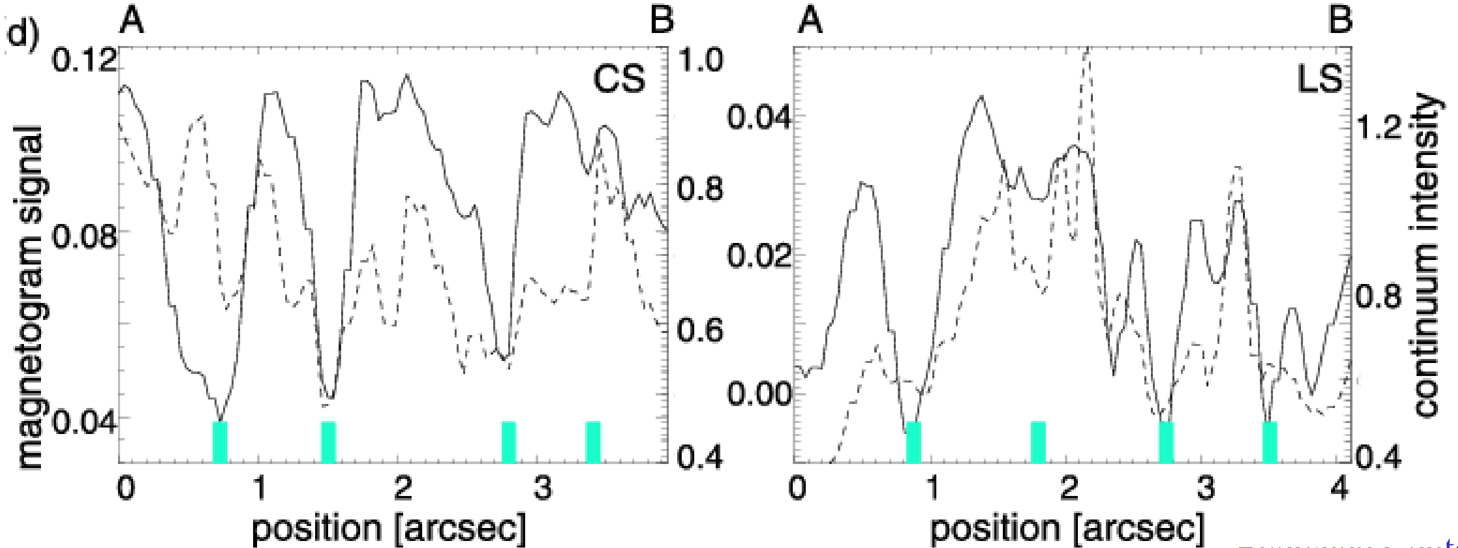
cross-over effect

The opposite polarity is not observed with the SST
(Langhans et al. 2005, 2007)!!!!



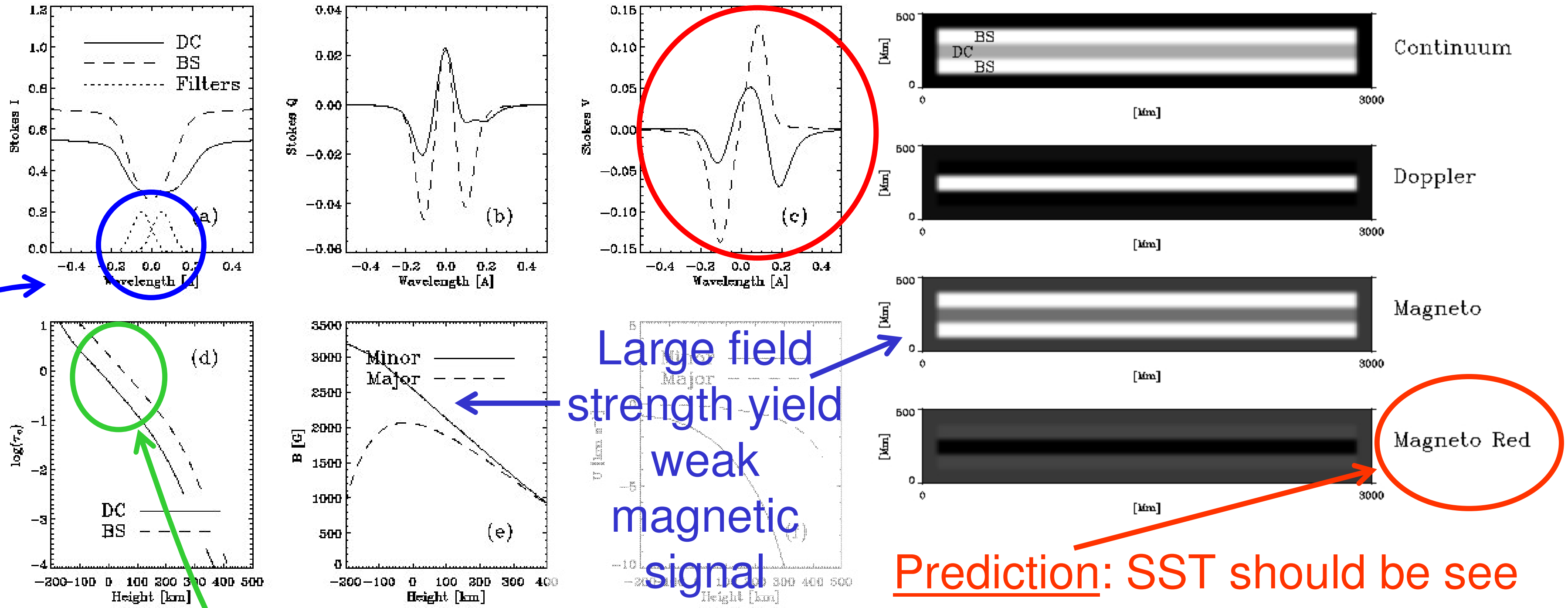
(a) center side, CS (b) limb side, LS

The dark cores in penumbral filaments show a reduced polarization signal, but it is not opposite to the main sunspot polarity



The model MISMA from SA(2005) naturally produce these profiles. Moreover, it easily explains the lack of magnetic signals in dark cores if the dark cores are locations where the minor component dominates, i.e., where plasma returns to the solar interior.

Took at random on of these models, and (1) increase to contribution of the minor component → BP, and (2) decrease the contribution → BS.



Large field strength yield weak magnetic signal

Prediction: SST should be see opposite polarities in the far red wing

SST filters

~100 km Wilson depression of the DCs

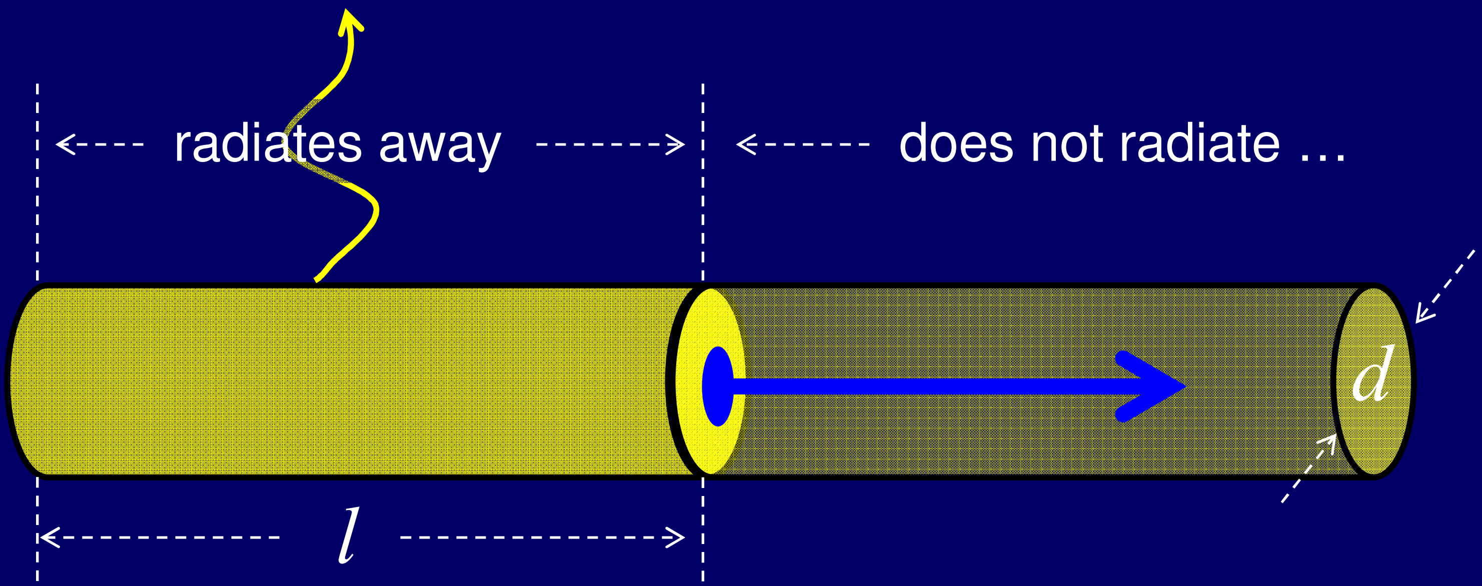
Brightness, vertical velocities, and length of the filaments

(1) Penumbra radiative flux ≈ 75% of photospheric flux

If transported by convective motions then (e.g., Spruit 1987)

- fill factor up ≈ fill factor down (≈50%)
- U_z up ≈ - U_z down ≈ 1 km s

(2) Bright penumbral filaments are not tracing flows tubes (not traicing individual streams). Danielson (1960).

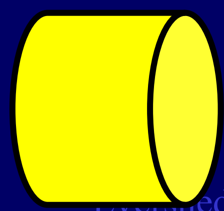


$$\left\{ \begin{array}{l} l \approx U t_c \\ t_c \approx 30\,\mathrm{s}\,(d\,/\,200\,\mathrm{km})^{1.5} \quad \text{(← Schlichenmaier et al. 1999)} \\ t_c \ : \text{cooling time} \\ U \ : \text{flow speed (~5 km/s)} \end{array} \right.$$

Aspect ratio of the bright filament ≈ 1

$$l\,/\,d = 0.8(d\,/\,200)^{0.5}$$

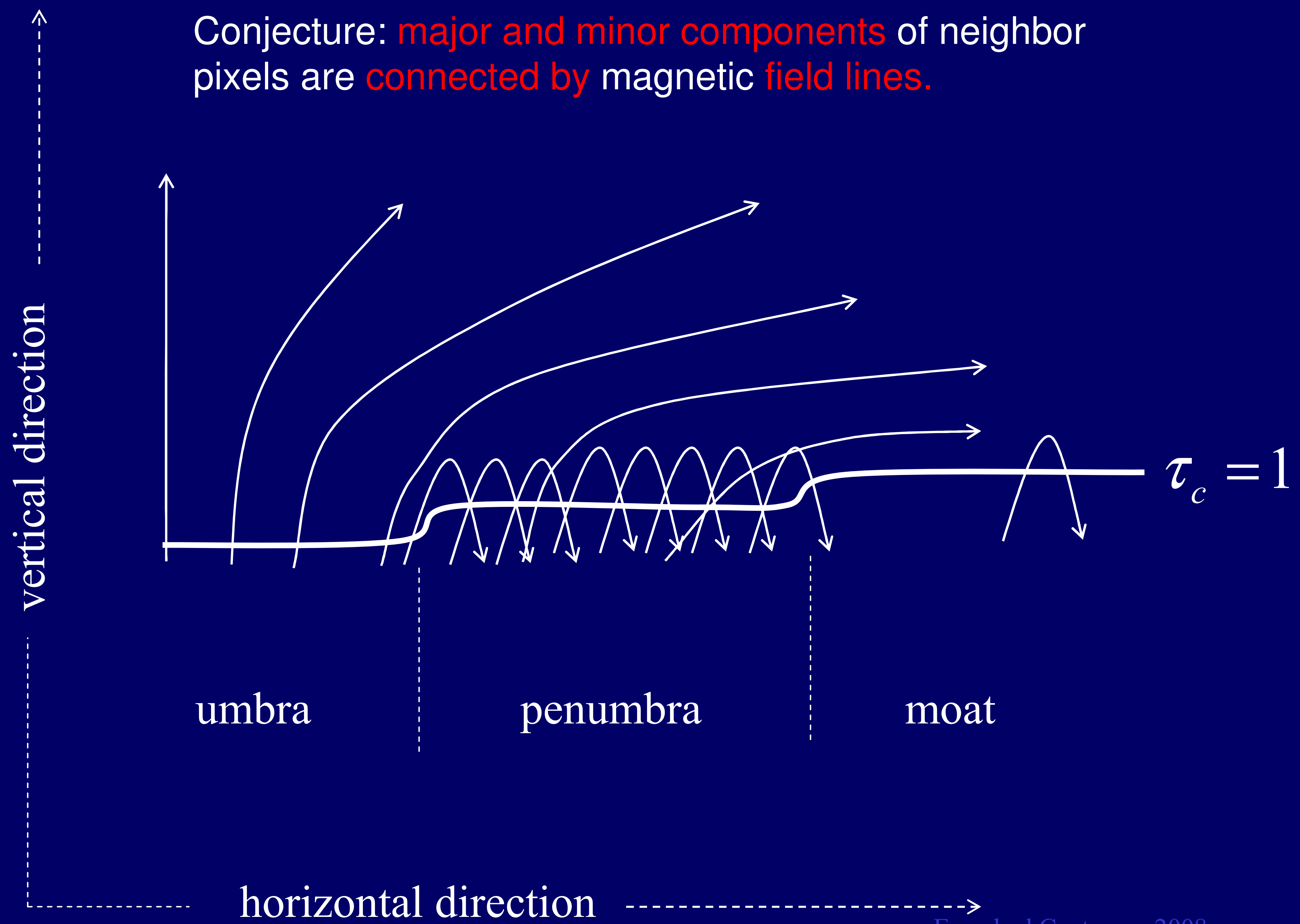
It is a blob, rather than a filament!

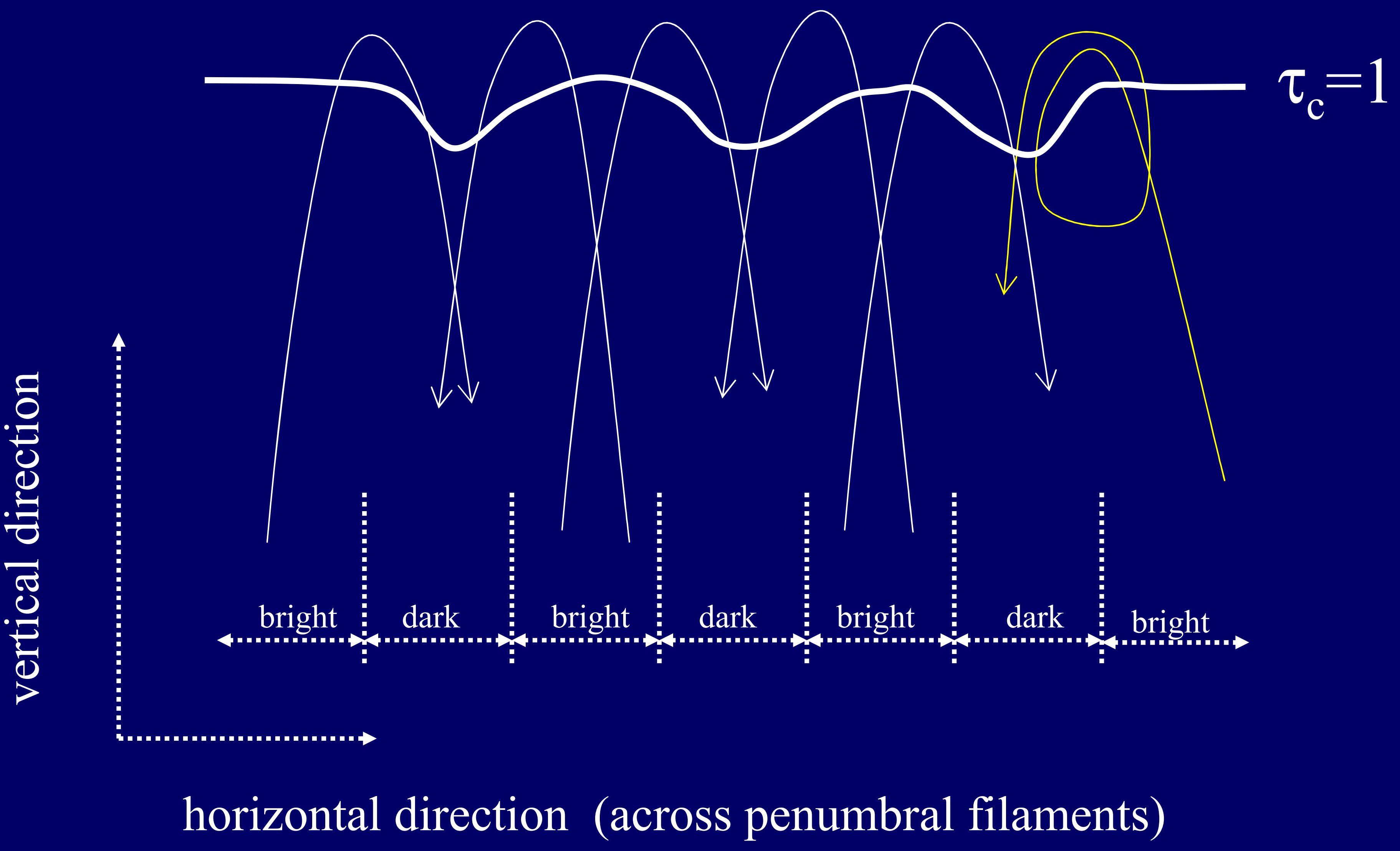


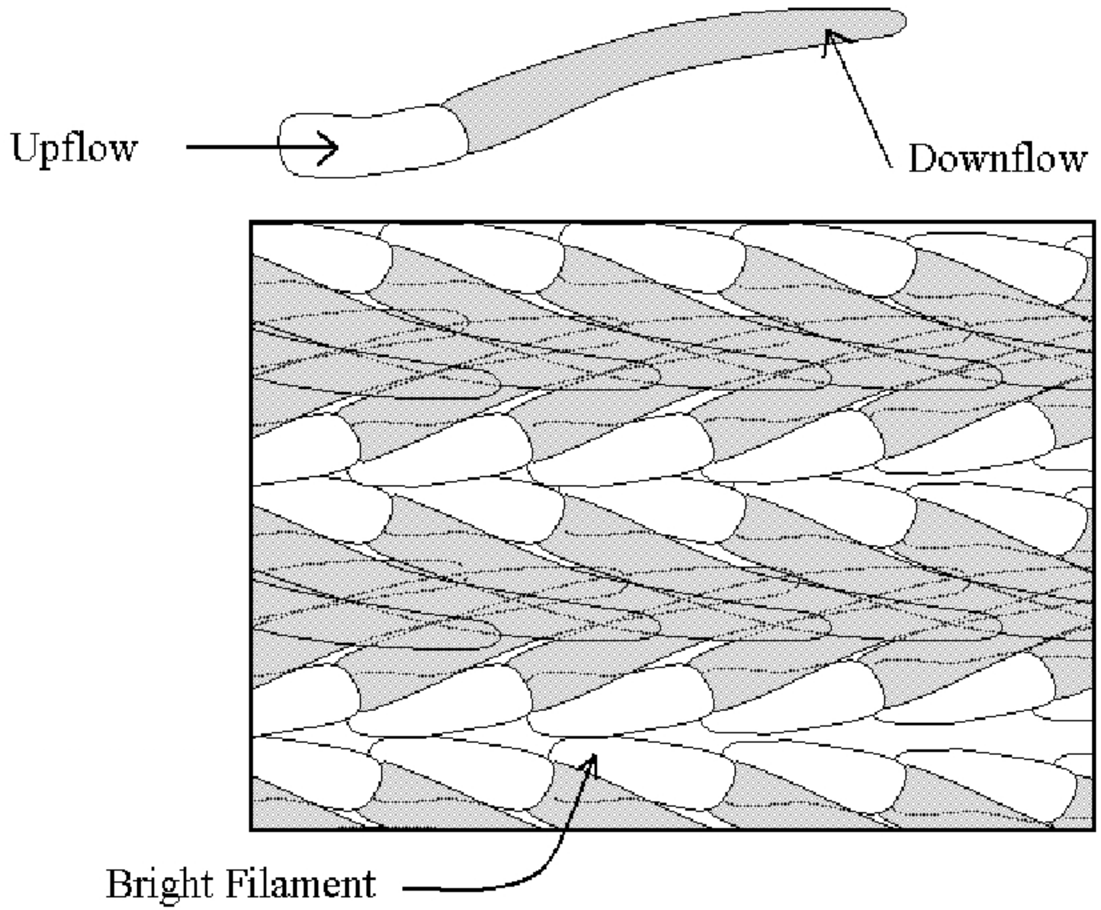
Scenario emerging from these observations combined

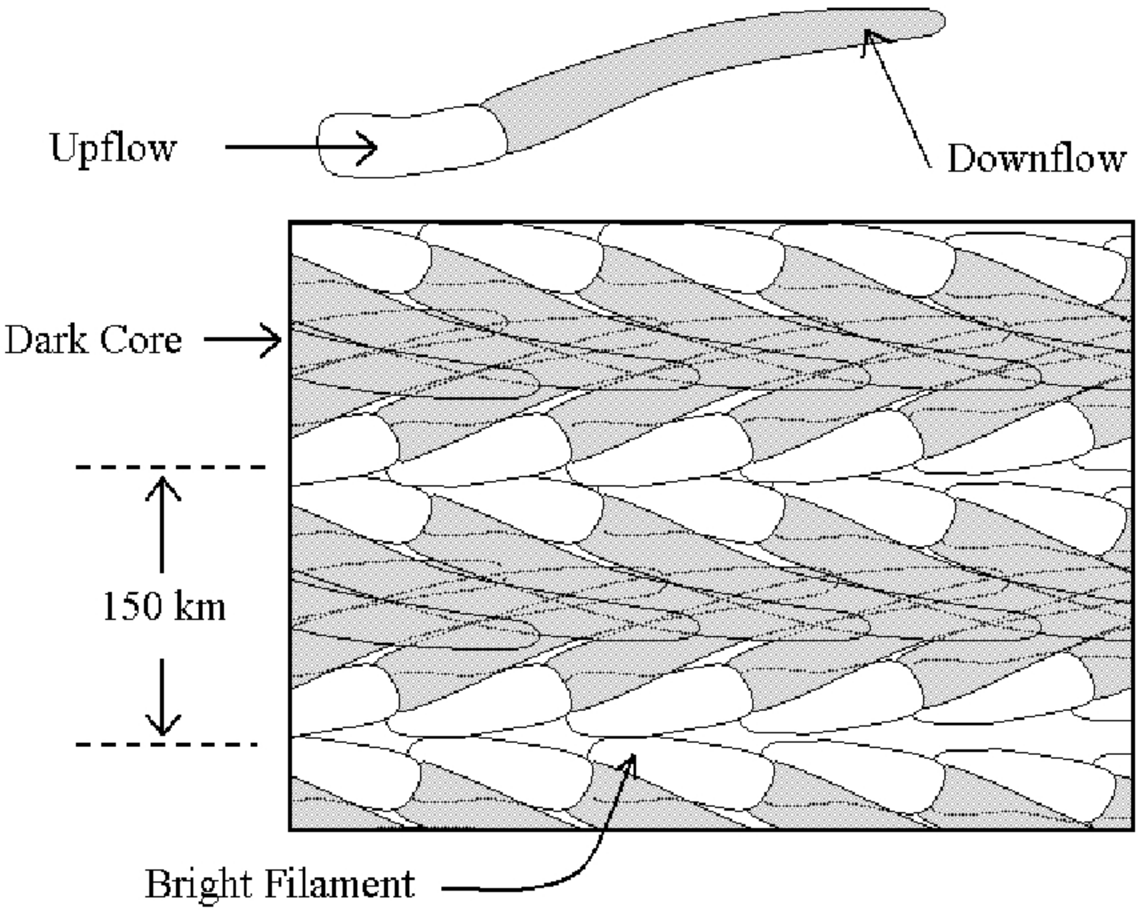
- Bright features are elevated with respect to the dark features. Dark cores best seeing in the center side and limb side penumbrae
- Like in quiet granulation, upflows are correlated with bright features, and downflows with dark features.
- Positive and negative polarities throughout the penumbrae.
- Upflows and downflows transport the same mass (per unit time).
- Magnetic field aligned mass flows.
- Unresolved structure, even with SST or Hinode (NCP). Beware of trivial interpretations of observations
- Bright filaments are not tracing the flow channels… but there are bright and dark filaments
- Conjecture: convection is responsible for the radiative flux.

Conjecture: major and minor components of neighbor pixels are connected by magnetic field lines.



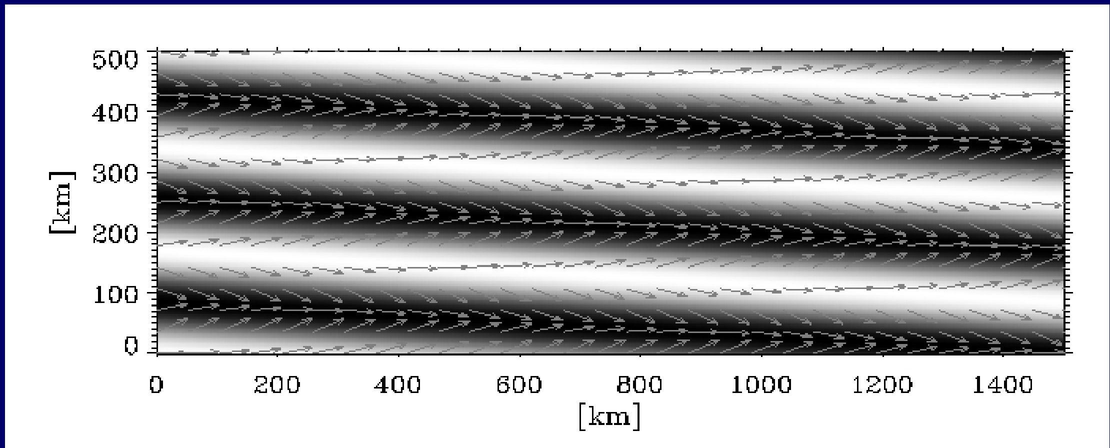

τc=1
vertical direction
bright
dark
bright
dark
bright
dark
bright
horizontal direction (across penumbral filaments)

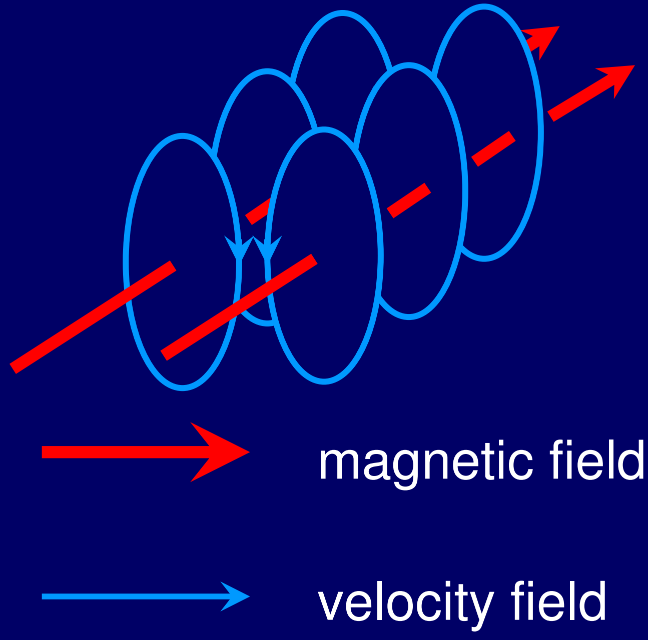

Upflow
Downflow
Bright Filament



the dark cores in penumbral filaments are one (dark) sink surrounded by the two (bright) upflows that the sink induces next to it.

When the magnetic field is almost horizontal, both theory and (oversimplified) numerical simulations tell that convection takes the form of rolls aligned with the field: convective rolls (Danielson 61, Weiss et al. 1990, Hulburt et al. 00, …)



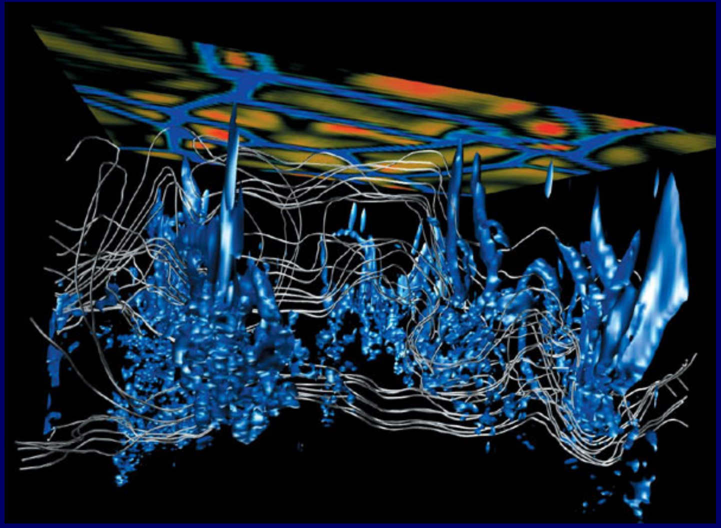


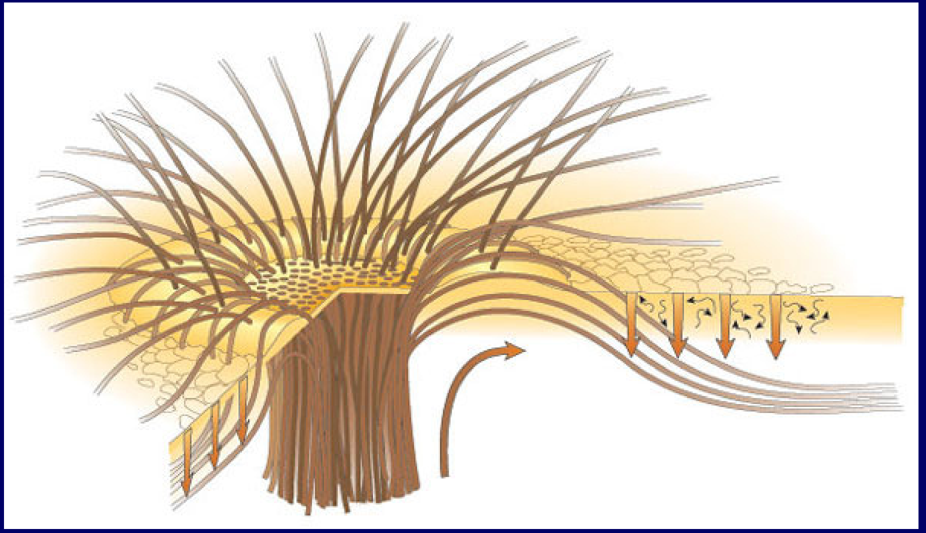
Convection takes place in the form of modified convective rolls. Dark cored penumbral filaments may be two paired convective rolls with the dark core the sinks (Priest 2003; SA 2004,2006).

Non-magnetic convection: driven by the downflows (the sinks)

Long lasting sinks in non-magnetic granulation.
Upflows induced by the sinks, next to the sinks.
(e.g., Nordlund 1984 , Rast 2003)

Some sort of magnetic pumping may allow submerging the magnetic field lines in the dark cores. (Like Thomas et al. 2002, in a fully magnetized environment.)

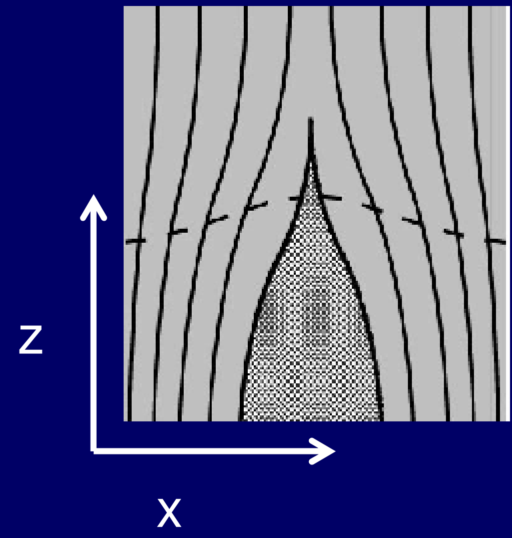




Further evidence: Zaharov et al (2008).

Some remarks on the field free gappy penumbra models

Spruit & Scharmer (2006), Scharmer & Spruit (2006) Energy is transported from below by (almost) magnetic field free gaps that intrude into a magnetized background.



´´The Evershed flow represents the horizontal-flow component of overturning convection in gaps with strongly reduced field strength (Scharmer et al. 2008)´´.

Supported by (beautiful) numerical simulations of magneto-convection in strong, inclined magnetic fields: Heinemann et al. 2007; Rempel et al. 2008.

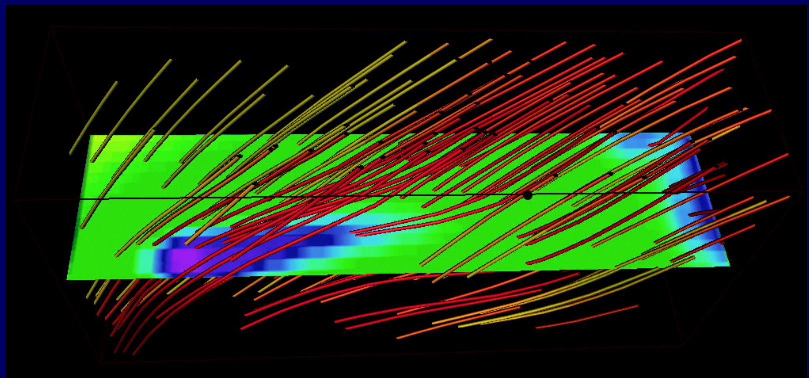
despite its beauty in reproducing the dark cores in penumbral filaments, it presents a number of difficulties when confronted with observations (only one fundamental …)

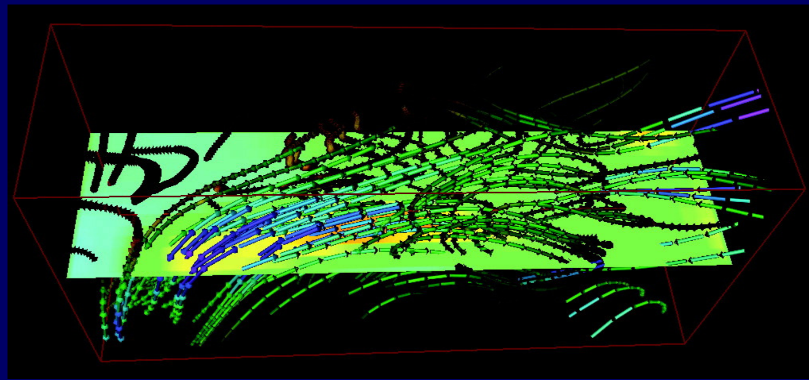
- If the Evershed effect occurs in field free gaps, it cannot displace the Stokes V zero crossing point (Grossman-Doerth et al. 1988, 1989). This is a general result that applies independently of the spatial resolution, spectral line, etc. Stokes V in penumbrae are shifted (e.g., Skumanich & Lites 1990).

  Workaround: allow the field free gaps to posses magnetic fields. But then the question of modeling the interaction between magnetic fields and flows arises. The current numerical simulations do not reach the magnetic Reynolds number required to treat this interaction properly, making their predictions to be taken with caution. (As the Reynolds number increases, we expect that magnetic and non-magnetic component to separate, worsening the problem. Simultaneously, mass flows and magnetic fields would tend to be aligned to minimize magnetic forces.)

❑ Magnetic field lines and stream lines are not aligned. This may be an artifact due to the unrealistically low Reynolds number, and the prediction may not apply to the real penumbrae.

Scharmer et al 2008

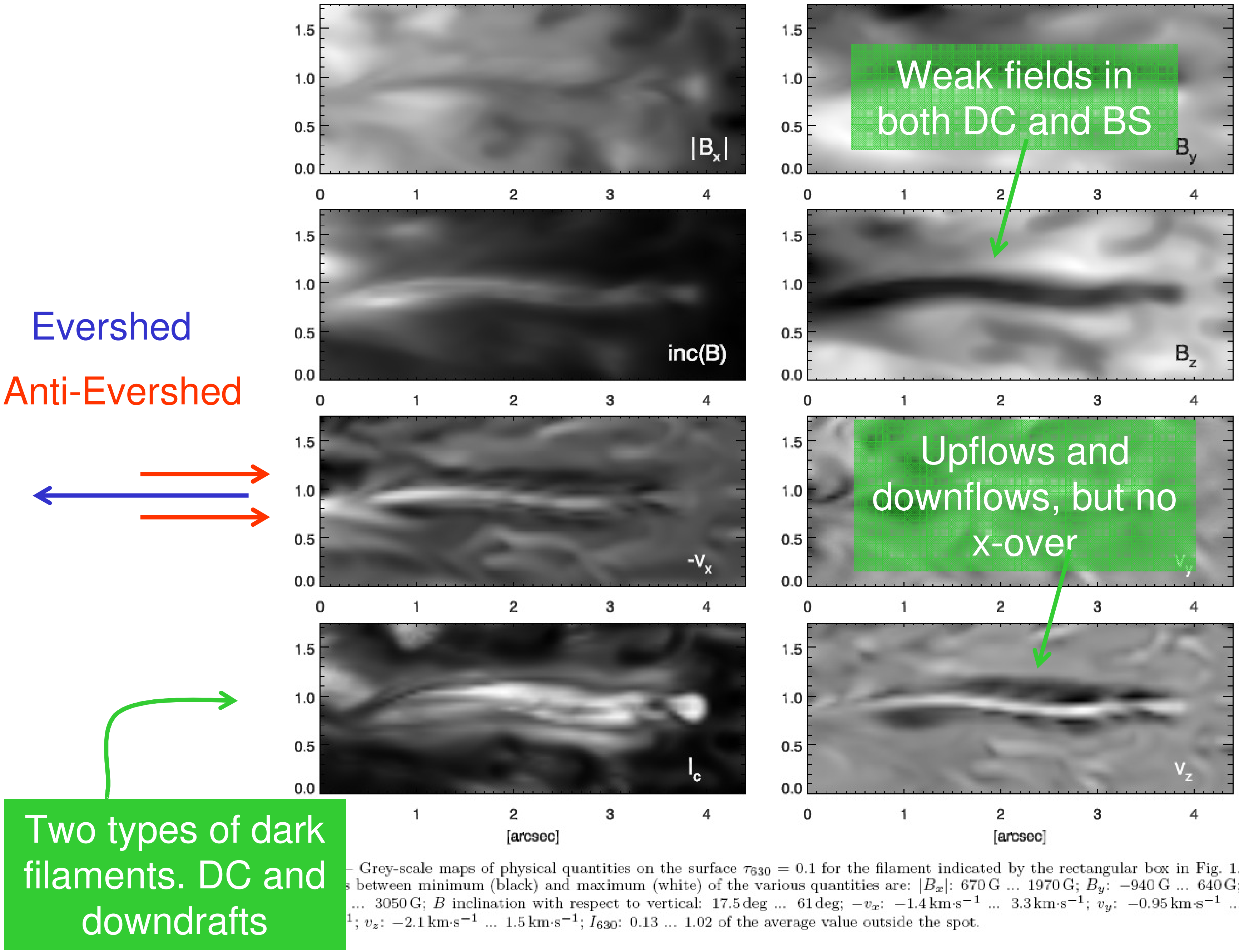




Mass moves across field lines, thus allowing convective transport of energy. Could this mode convection be an artifact due to the low Reynolds numbers?

❑ How can the gappy penumbra cope the presence of reverse polarities in penumbrae?

Rempel et al. 2008



– Grey-scale maps of physical quantities on the surface $\tau_{630} = 0.1$ for the filament indicated by the rectangular box in Fig. 1. s between minimum (black) and maximum (white) of the various quantities are: $|B_x|$: 670 G ... 1970 G; B_y: −940 G ... 640 G; ... 3050 G; B inclination with respect to vertical: 17.5 deg ... 61 deg; $-v_x$: $-1.4\,\mathrm{km{\cdot}s^{-1}}$ ... $3.3\,\mathrm{km{\cdot}s^{-1}}$; v_y: $-0.95\,\mathrm{km{\cdot}s^{-1}}$ ... ^{1}; v_z: $-2.1\,\mathrm{km{\cdot}s^{-1}}$ ... $1.5\,\mathrm{km{\cdot}s^{-1}}$; I_{630}: 0.13 ... 1.02 of the average value outside the spot.

Remarks

- Everywhere in the penumbra, there are structures with a magnetic polarity opposite to the sunspot polarity.

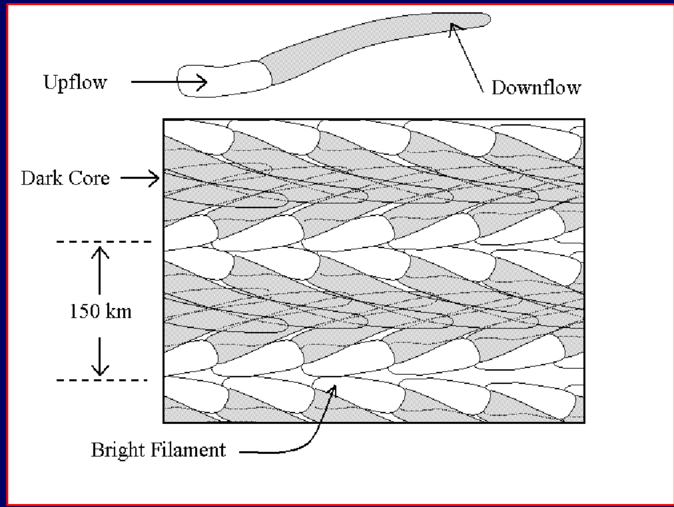
- Everywhere in the penumbra, there are upflows and downflows associated with bright and dark structures, respectively. Same correlation as the solar granulation

- The flows seems to be magnetic field aligned, so that the reverse polarity corresponds to downflows.

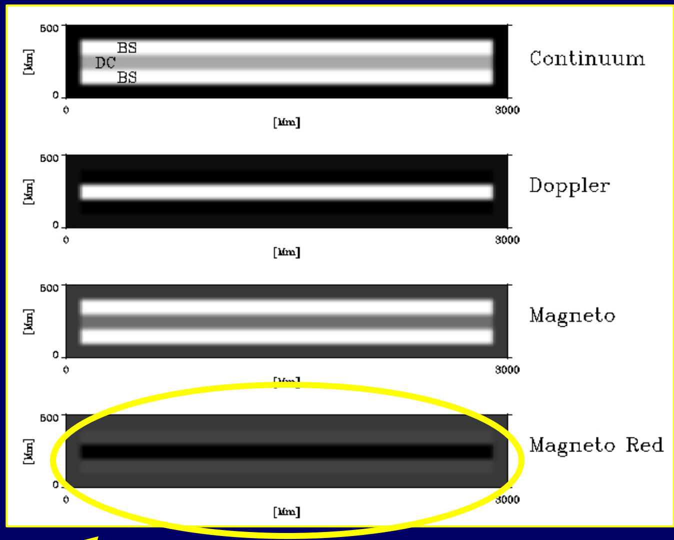
- The structuring of the fields remains spatially unresolved even to SST and HINODE (and probably will remain so forever → NCP)

- Magnetic field difference between upflows (weak) and downflows (strong) able to drive a siphon flow along the field lines with the speed and sense of the observed Evershed flow.

❑ Dark cored penumbral filaments may be two paired convective rolls with the dark core the sink



❑ Not inconsistent with the dark cores having weak magnetic signals



prediction

❑ In this scenario the dark cores play the role of the granulation downdrafts in the non-magnetic convection.

Request -- Proposal

100 later, we do not know what is the Evershed effect

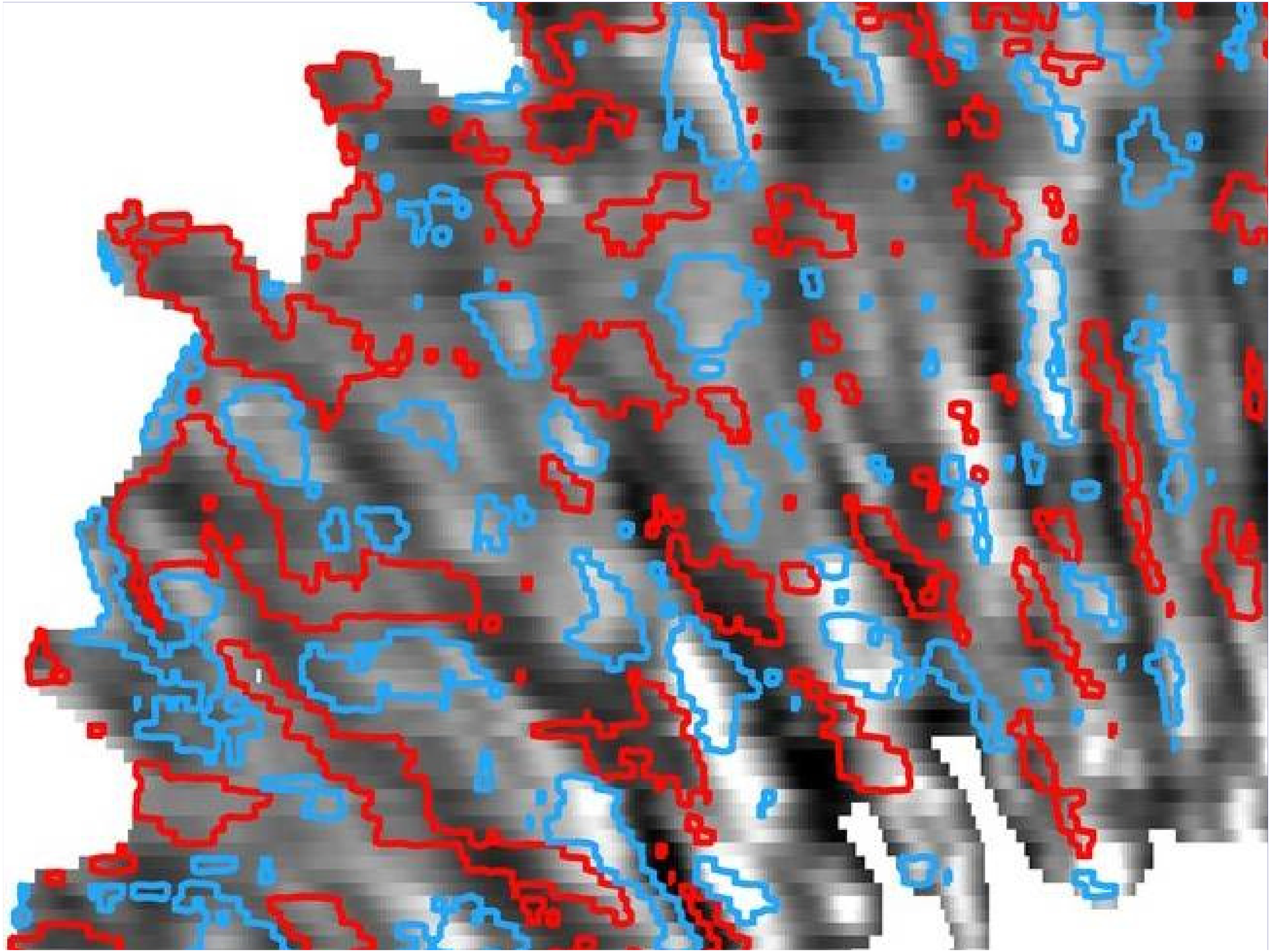
- Exciting …
- Sad … since, almost certainly, we have all the clues available

The time is ripe for solving the riddle.
A significant step would be organizing a workshop for Evershed freaks,

(1) Clear up misunderstanding between researchers

(2) Agree on the list of observables that characterize the Evershed effect (to be reproduced by any model that claims explaining the effect).

We should organize the workshop!



"I don't ask why
author's conclusions
lie, I just assume they
all do."

House, MD