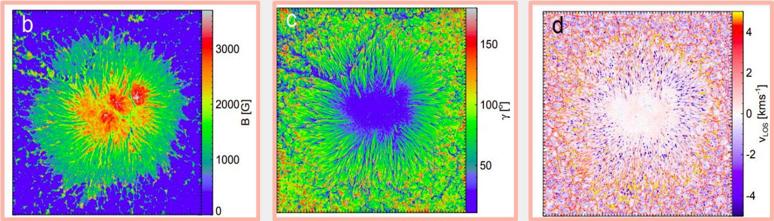
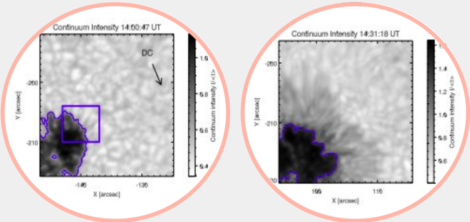
ISSS school:

"The different spatio-temporal scales of the solar magnetism"



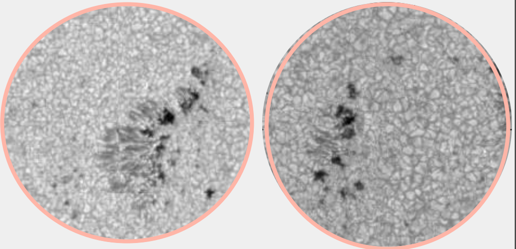
Tiwari et al. 2013



Murabito et al. 2016

STRUCTURE AND EVOLUTION OF THE PENUMBRA

Mariarita Murabito, INAF Capodimonte, 13 April 2022



Murabito et al. 2021

OUTLINE

Part I

Penumbral Structure

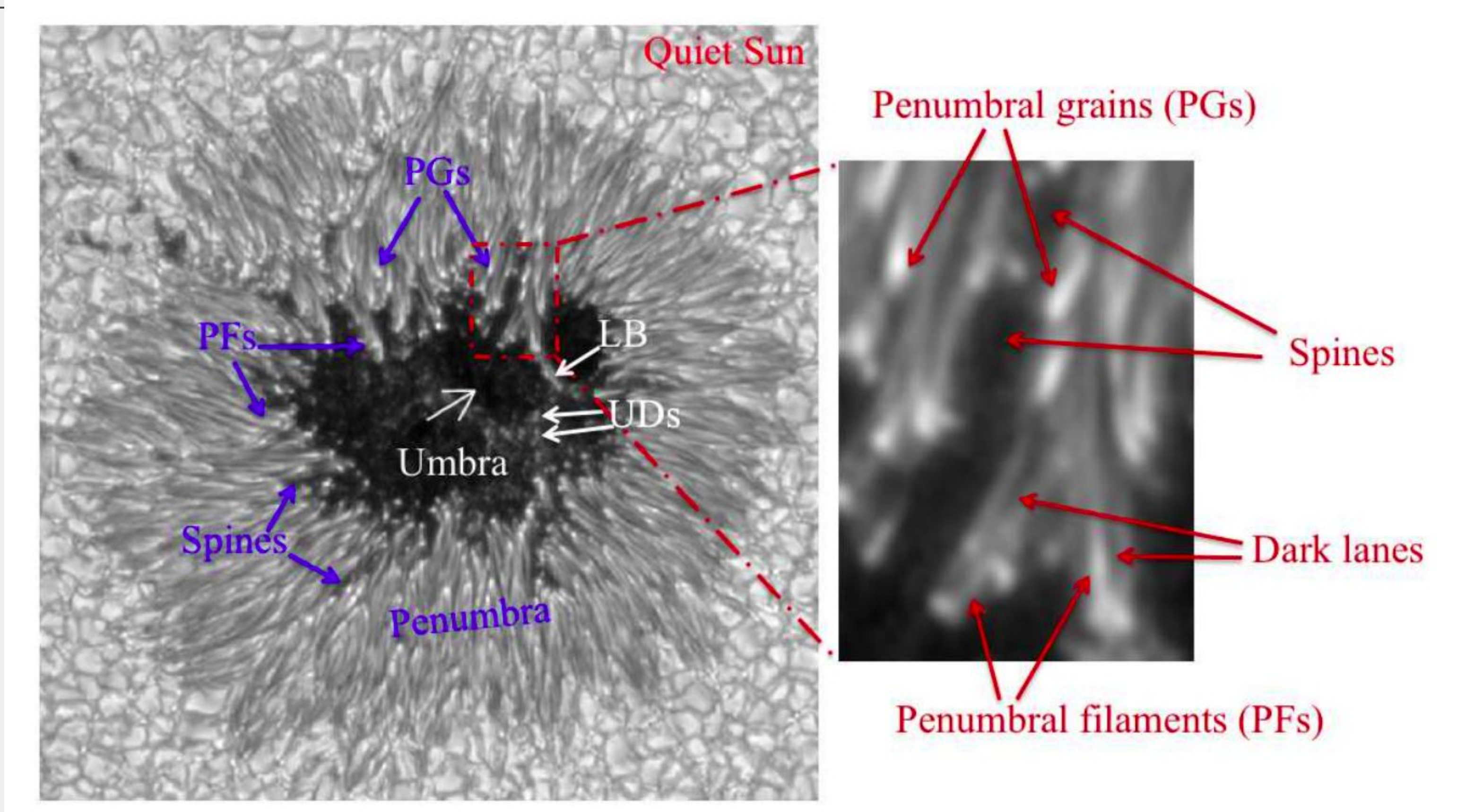
- ❑ Thermal & magnetic fine properties
- ❑ Evershed flow & magnetoconvection

Part II

Penumbra Evolution

- ❑ Formation
- ❑ Decay

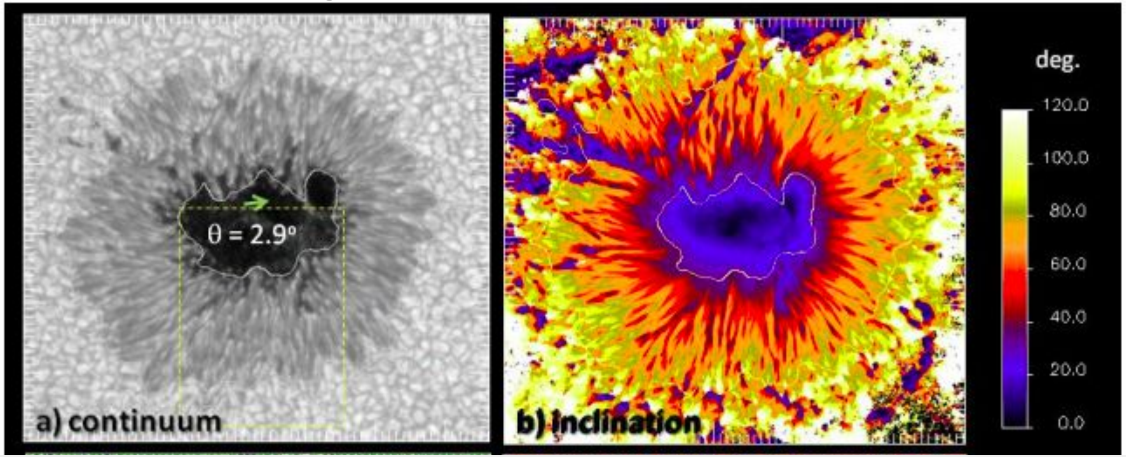
With the presence of rapidly **varying fine-scale field**, **flow, and thermal properties,** both in radial and azimuthal directions, sunspot **penumbra** represents, undoubtedly, the most complicated and challenging structure on the solar surface.



Taken from Tiwari et al. 2017 part of Hinode review.

Filaments structure

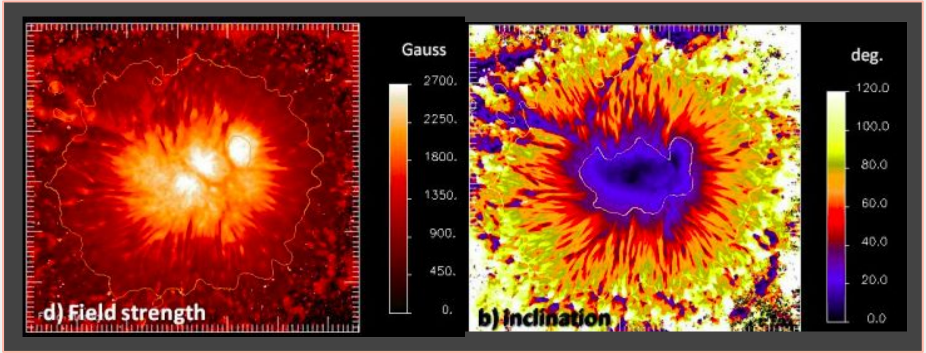
Borrero & Ichimoto 2011 Living review



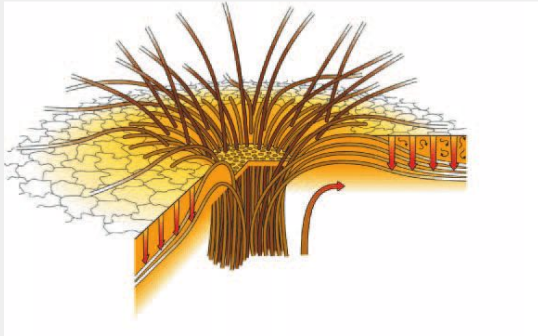
- The penumbra consists of radial channels with alternative larger and smaller field inclination.
- More horizontal field channels are associated with bright filaments in the inner and dark in the outer penumbra.

Filaments structure

- Two major magnetic field components:
  - **Spines** → stronger and more vertical. This magnetic field component possibly connects with regions far from the sunspot to form coronal loops over the active region.
  - **Intraspines** → weaker and more horizontal. This magnetic component turns back into the photosphere at the outer border of the sunspot or extend over the photosphere to form a canopy.
- Overall magnetic field structure referred to as **uncombed penumbra** (Solanki and Montavon, 1993) or **interlocking comb structure** (Thomas and Weiss, 1992).



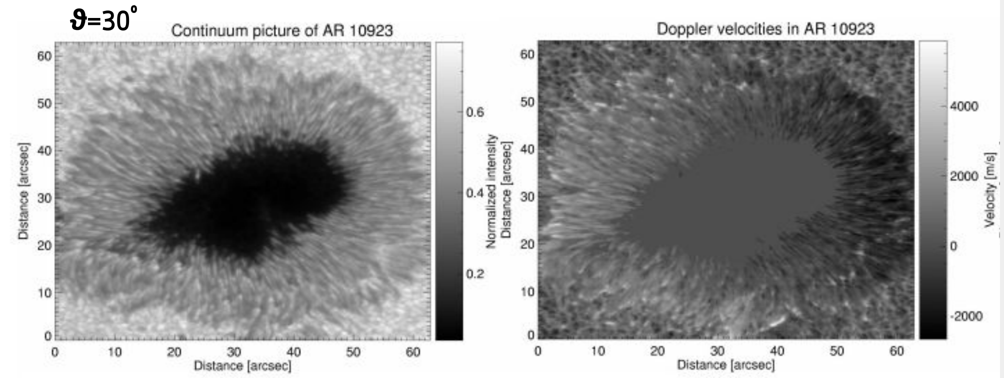
Borrero & Ichimoto 2011 Living review

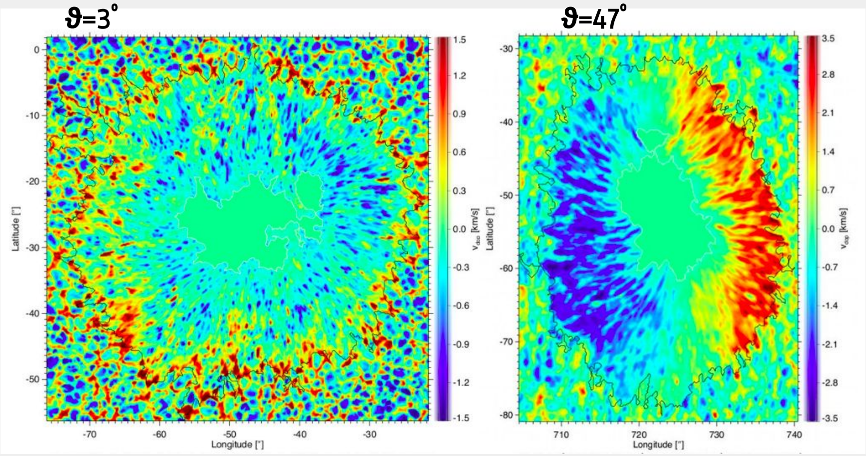


Evershed Flow & Magnetoconvection

The **EVERSHED flow** is a nearly horizontal outflow in the photosphere along the penumbral filaments

- At **disk center** → horizontal velocity components do not contribute to the LOS velocity then the vertical velocity component is prominent
- **Off disk center** → horizontal velocity component becomes visible. The velocity map is dominated by the horizontal Evershed flow, producing a blueshift on the center-side penumbra, and a redshift on the limb-side penumbra.

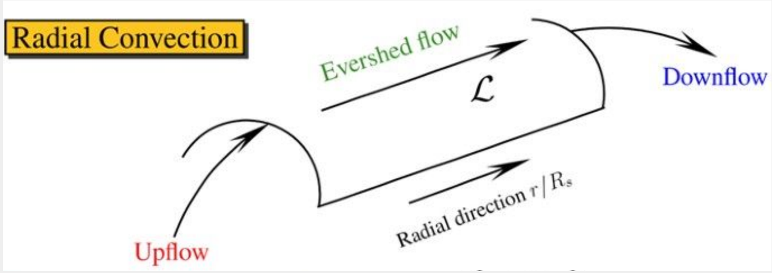




Rempel & Schlichenmaier 2011, Living Review

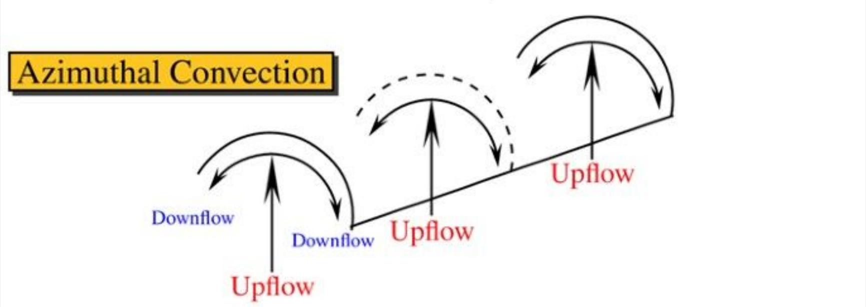
Filaments structure

- Penumbrae are made of copious thin bright filaments (Title et al. 1993, Borrero & Ichimoto 2011) and dark spines (Lites et al. 1993).
- The strong magnetic field (of 1-2 kG) should prohibit convection in sunspot penumbrae, keeping them dark, similar to umbrae.
- Penumbrae have 75% brightness of quiet-Sun intensity → some form of convection takes place
    - **Hot rising flux tube model** (Schlichenmaier et al. 2002): → radial, upflows in the inner penumbrae and downflows in the outer penumbrae (as evidenced by e.g., Rimmele & Marino 2006, Ichimoto et al. 2007b, Tiwari et al. 2013, and Franz & Schlichenmaier 2009, 2013).
    - The heat supplied is sufficient only if the upflowing hot plasma at the inner flux tube's footpoint travels only a small radial distance L before tuning into a downflow



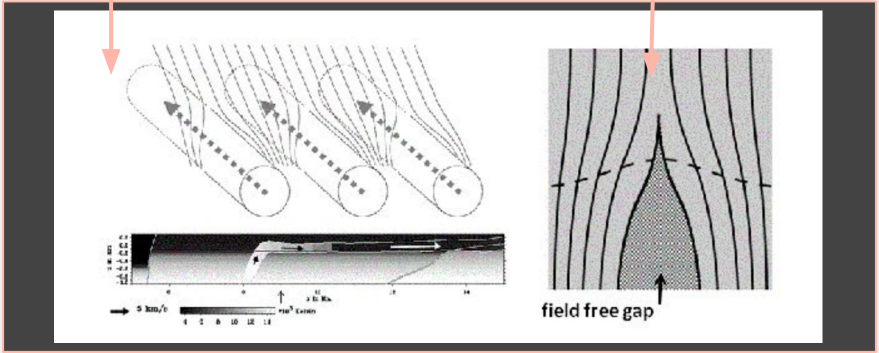
Filaments structure

- **Field-Free gap model:** ⟶ azimuthal/lateral convection, upflows along the central axis and downflows along the sides of the filament (found by Ichimoto et al. 2007b, Zakharov et al. 2008, Bharti et al. 2010, Joshi et al. 2011, Scharmer et al. 2011, Scharmer & Henriques 2012, Tiwari et al. 2013, and Esteban Pozuelo et al. 2015).
- Very efficient heat transport because the convective motions are over the entire length of the bright penumbral filaments.
- It does not readily offer an explanation for the EF



Models explaining the filamentary structure

- **Embedded flux tube model** (Solanki & Montovan 1993)
  - Nearly horizontal magnetic flux tubes forming the intraspines embedded in more vertical background magnetic field (spines).
- **Field-free gap model** (Choudhuri 1986, Spruit & Scharmer 2006, Scharmer & Spruit 2006)
  - Penumbral bright filaments as a manifestation of the protrusion of non-magnetized, convecting hot gas into the background oblique magnetic fields.



Borrero & Ichimoto 2011 Living review

Proposed mechanism for EF

- Inside the Embedded flux tube model or the rising flux-tube model (Schlichenmaier et al. 1998a,b), it was proposed the **siphon flow model** as driver (Meyer & Schmidt 1968, Thomas 1988, Degenhardt 1991, Montesinos & Thomas 1993)
    - A difference in the magnetic field strength between the two footpoints causes a differences of gas pressure driving the flow in a direction towards the footpoint with a higher magnetic field strength (i.e., the footpoint outside the sunspot to account for the Evershed outflow)
- Thermally driven or convective flow (Schlichenmaier et al. 1998a,b;Rempel 2011)
- NO possible to use the field-free gap model because the EF has been seen to be equally strong in Stokes V as in Stokes I (Solanki et al. 1994)

The results presented in Bellot Rubio et al. 2004, Borrero et al. 2004, Borrero et al. 2005 supported the siphon flow model.

Rempel & Schlichenmaier 2011, Living Review

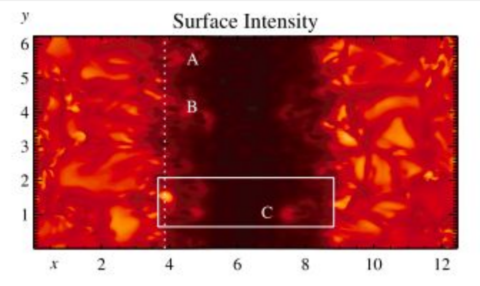
MHD simulations (see Thursday’s lessons)

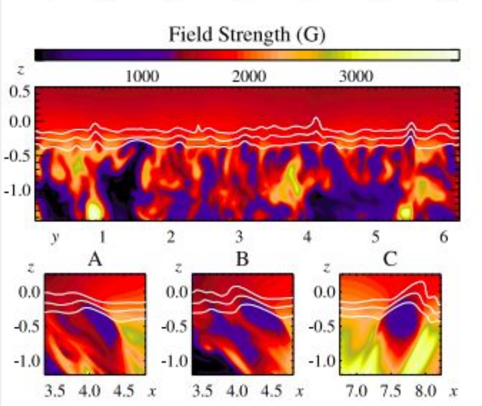
Heinemann et al. 2007

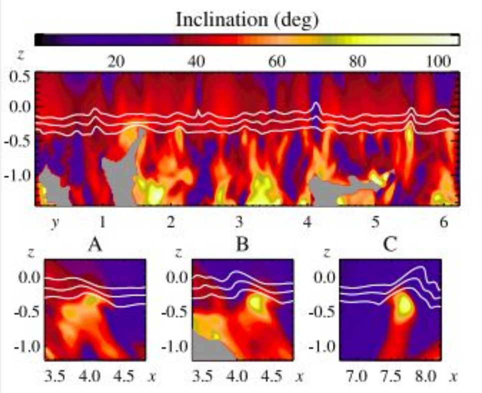
MHD simulations have been successful in reproducing many aspects of the fine scale structure of sunspot penumbra (Heinemann et al. 2007, Rempel et al. 2009; Rempel 2011, 2012).

- Several properties in common with observed filaments. They propagate into the umbral magnetic field, and have a dark core overlying the center.
- The filamentary structures are quite short
- The simulated filaments form and disappear within a typical time span of 30 minutes not in agreement with the observation (on the order of 1/2 hr)

Heinemann et al. 2007





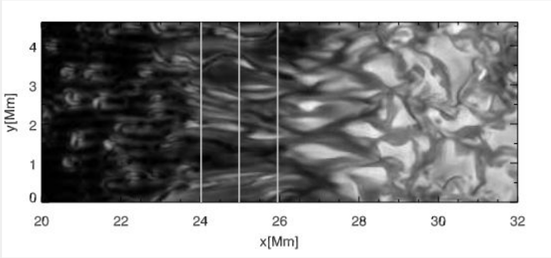


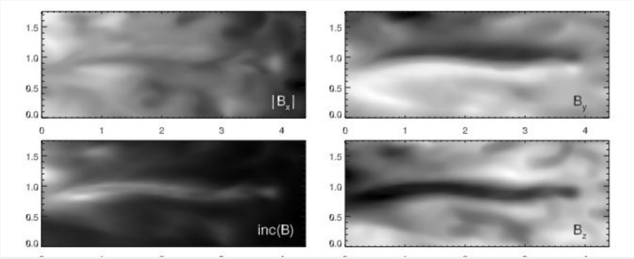
MHD simulations (see Thursday’s lessons)

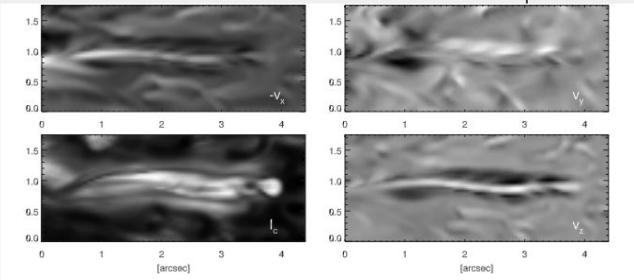
Rempel et al. 2009

- Penumbral filaments results from magnetoconvection in the form of upflow plumes, which become elongated by the presence of an inclined magnetic field

- Good agreement with the observationally interlocking-comb structure of the magnetic field with Evershed outflows along dark-laned filaments with nearly horizontal magnetic field and overturning perpendicular motion, which are embedded in a background of stronger and less inclined field.



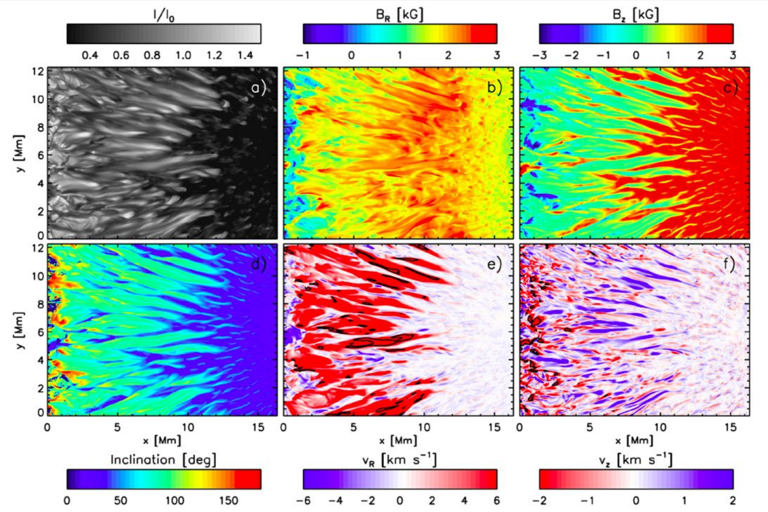


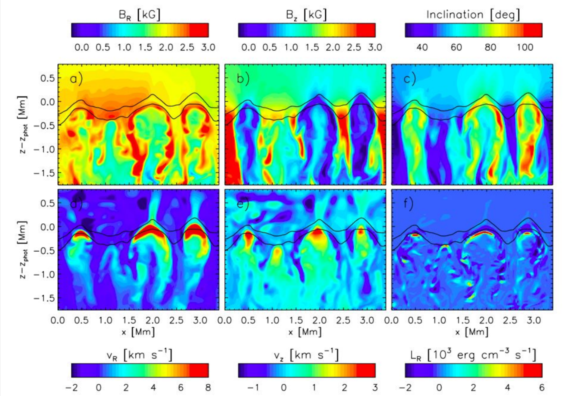


Rempel et al. 2009

MHD simulations (see Thursday's lessons)

Rempel 2011





- reinforces conclusions that the penumbra is anisotropic magnetoconvection and that the EF can be understood as convective flow component in the direction of the magnetic field
- The EF seems to be completely Lorentz force driven while horizontal flow is entirely pressure driven.
- The simulated EF is a deep photospheric flow as a direct consequence of its convective origin

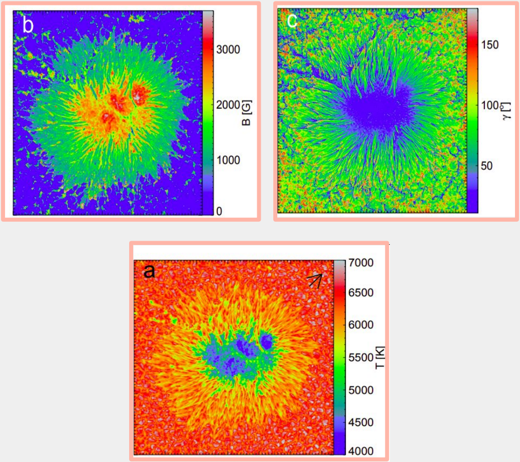
Filaments at higher spatial resolution

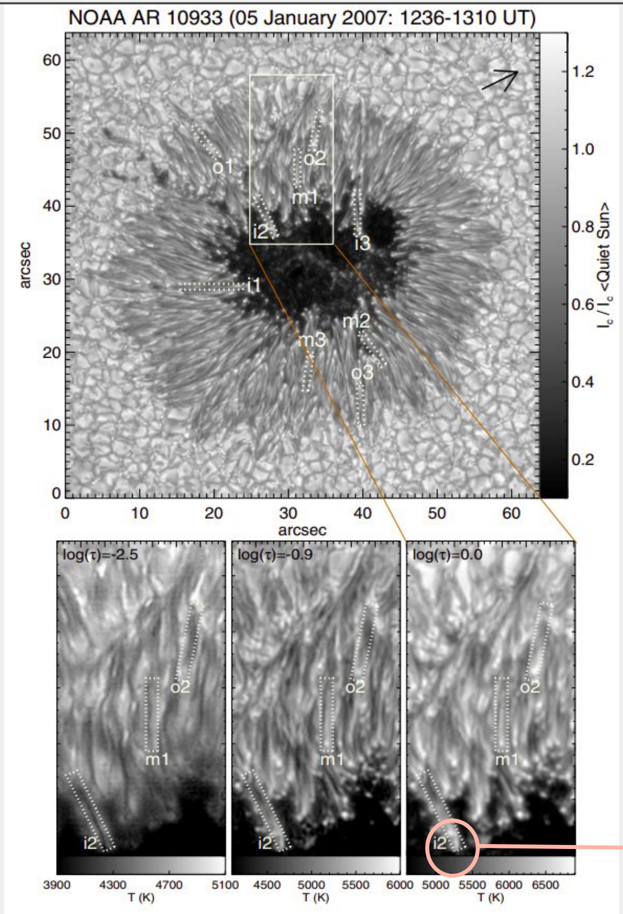
Thermal & Magnetic properties

Tiwari et al. 2013

Tiwari et al. 2015

- Hinode/SOT-SP (2007) at μ = 0.99
- Fe I 630 nm line pair (full stokes)
- Use of the spatially coupled inversion using the SPINOR code (Frutiger et al. 2000).
- Selection of the filaments using the LOS velocity and the magnetic field inclination.
- Creation of a standard filament averaging all selected penumbral filaments



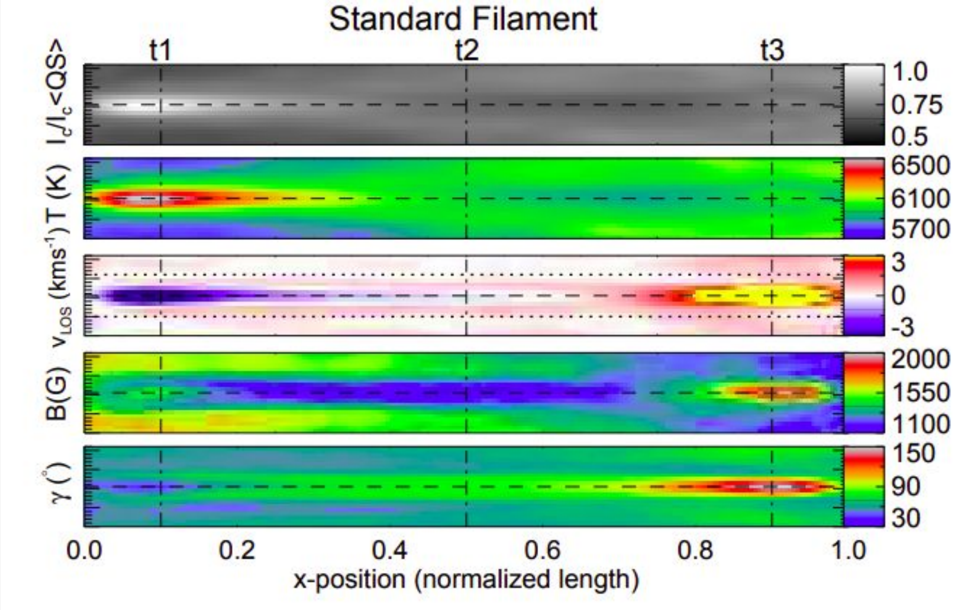


- A bright head (T ~6500 K) that rapidly fall in temperature (and intensity) along a central axes towards the tail.
- From heads to tails the difference in the temperature is up to 800 K.
- The teardrop-shaped heads were earlier referred to as penumbral grains (Muller 1973; Sobotka et al. 1999; Rimmele & Marino 2006; Zhang & Ichimoto 2013).

HEAD

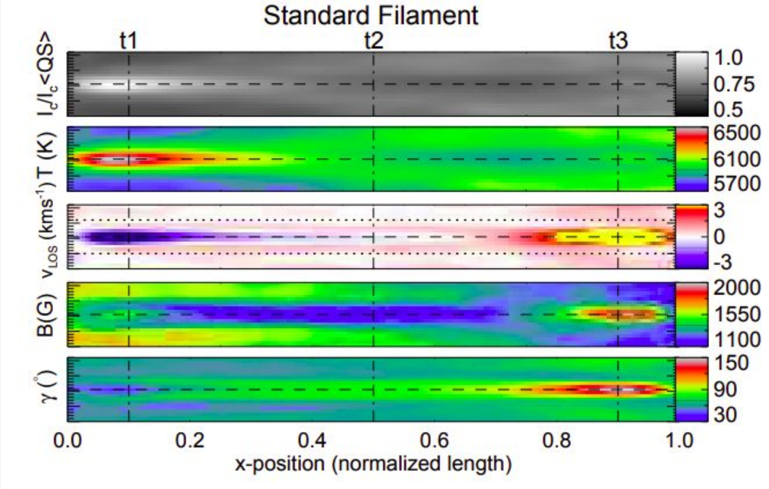
- Length varies from 2″ to 9″, and an average width of 0. ″8.

- Dark core along the central axis visible in the middle and higher photospheric layers
    - Locations with weak and more horizontal field resulting in a higher gas pressure.



- The inclination changes from more vertical (γ ~10-40° at the head) and stronger field to horizontal in the middle (where the field is weaker), and then to downward (γ ~140-170°) in the tail (where the field is stronger), thus making an inverse U shape.

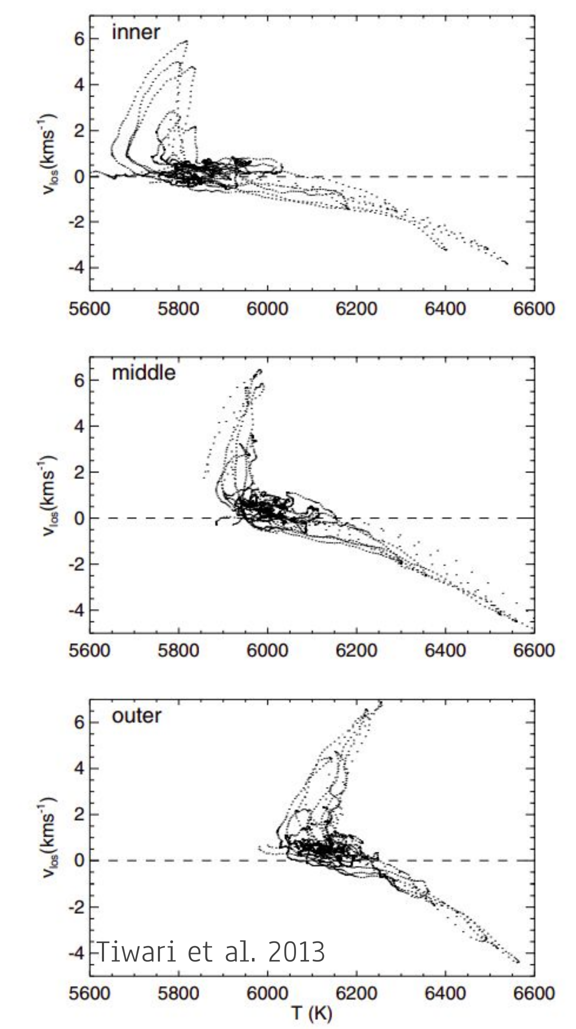
- They could form a sea-serpent, bipolar structure (Sainz Dalda & Bellot Rubio 2008; Schlichenmaier et al. 2010a), could remain below and disperse (Tiwari et al. 2013), or return back to the surface well outside the sunspot (Thomas et al. 2002).



Convective nature of penumbral filaments

- Clear convection (radial and azimuthal)
- Head's and along the central axis up to more than half of a filament upflows (~5 km/s).
- Strong downflows in the tail (~7 km/s)
- Weak downflows (~0.5 km/s) along the side edges of filaments (Joshi et al. 2011; Scharmer et al. 2011; Scharmer & Henriques 2012; Ruiz Cobo & Asensio Ramos 2013; Scharmer et al. 2013, and Esteban Pozuelo et al. 2015).

- Upflows are systematically hotter than downflows by 800 K in the scatter plots between T and vLOS ⟶ quantitative support of the convective nature.



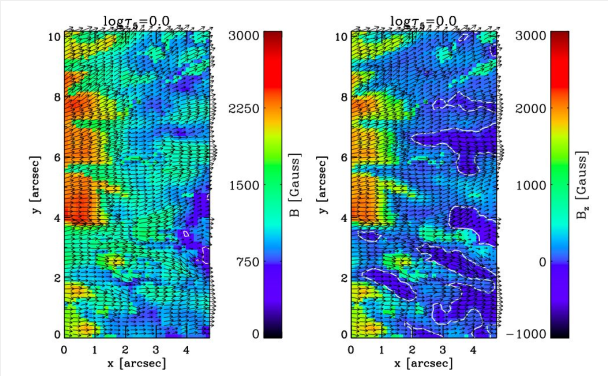
Tiwari et al. 2013

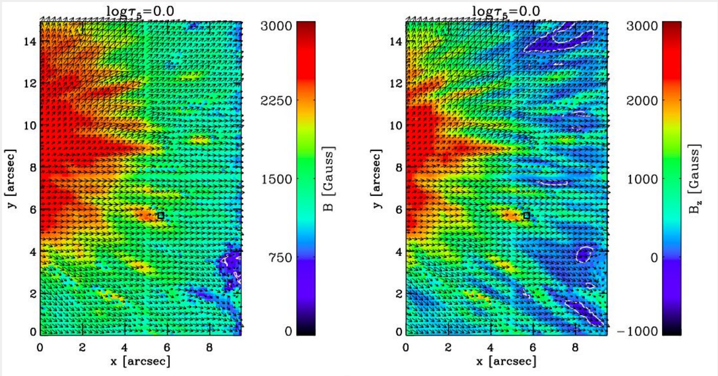
Conclusions

- Systematic temperature decrease of 400-800 K from the head to the tail of the filament → compatible with the convective driver scenario.
- The systematic excess magnetic field strength (500 G) in the tail over that in the head → the siphon flow mechanism could drive the EF.
- The flux tube models are supported by the measured strength and inclination of the magnetic field. → These models can reproduce the tear-shaped bright heads, but they have difficulty in explaining the observed upflows along more than half of the length of the filaments and downflows containing downward-pointing magnetic field along the sides.
- Complex picture emerges from these high resolution observations → combining aspects of both the models and bears a strong resemblance to the results of numerical simulations (Rempel et al. 2009b; Rempel 2012), although some quantitative differences appear to be present.

- The weaker (still ~1 kG) magnetic field strength in the filament's central part –>
    - the flow in filaments is not field-free ⟶ this supports the view that the EF is magnetized (Solanki et al. 1994; Borrero et al. 2005; Ichimoto et al. 2008a; Rempel 2012).
    - Recent infrared photospheric observations found no evidence of regions with weak (B<500 G) magnetic fields (Borrero et al. 2016). ⟶ In agreement with previous observations (Borrero & Solanki 2008, 2010) & 3D MHD simulations (Rempel et al. 2009; Nordlund & Scharmer 2010; Rempel 2011, 2012).

Only 19% and 3% with Bz <0





Borrero et al. 2016

Only 0.5% and 0.2% with B <500

Conclusions - unresolved problems

- The velocity pattern well know → but how this global pattern is related to the velocity structure in individual penumbral filaments has remained unresolved.

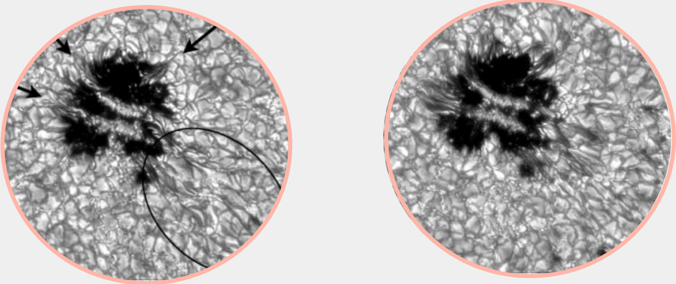
- Unclear what happens to the magnetic field that submerges at the ends of the filaments.
  - It may remain below the solar surface (Thomas et al. 2002),
  - form a structure similar to a U-loop, returning to the surface within the penumbra (Schlichenmaier et al. 2010) and possibly moving outwards (Sainz Dalda & Bellot Rubio 2008), appearing as a pair of MMF outside the penumbra (Zhang et al. 2003).

- NO evolution of penumbral filaments with time

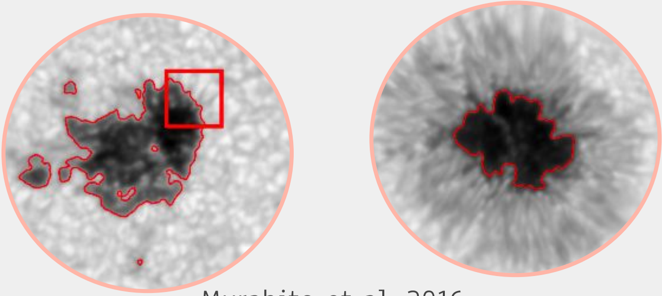
Although stable penumbrae seem to be a well characterised phenomenon from both the observational and modelling point of view, the mechanisms behind their onset and establishment in the photosphere has not been studied in detail.

Penumbral Evolution

- Introduction on formation process
- Simulation studies
- In-depth studies :
    - Murabito et al. 2016,
    - Murabito et al. 2017,
    - Murabito et al. 2018.
- Simulation studies



Schlichenmaier et al. 2012



Murabito et al. 2016

Introduction on formation process

A&A 512, L1 (2010)
DOI: 10.1051/0004-6361/201014112

Astronomy & Astrophysics

LETTER TO THE EDITOR

The formation of a sunspot penumbra★

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A&A 537, A19 (2012)
DOI: 10.1051/0004-6361/201117485

Astronomy & Astrophysics

The formation of sunspot penumbra

Magnetic field properties

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THE ASTROPHYSICAL JOURNAL LETTERS, 747:L18 (5pp), 2012 March 10 doi:10.1088/2041-8205/747/2/L18

PRECURSOR OF SUNSPOT PENUMBRAL FORMATION DISCOVERED WITH *HINODE* SOLAR OPTICAL TELESCOPE OBSERVATIONS

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ABSTRACT

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VELOCITY AND MAGNETIC FIELD DISTRIBUTION IN A FORMING PENUMBRA

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ABSTRACT

HOW and **WHY** the penumbra forms are two of key questions, and their study requires long time series observations (several hours) with the highest temporal, spatial, and spectral resolution available.

When?

- Threshold of the magnetic flux: 1-1.5x10^{20} Mx (Leka & Skumanich 1998)

- Critical value of the magnetic field intensity and inclination $\gamma \geq 60^{\circ}$ and $B_{crit} \leq 1.6$ kG (Rezaei et al. 2012)

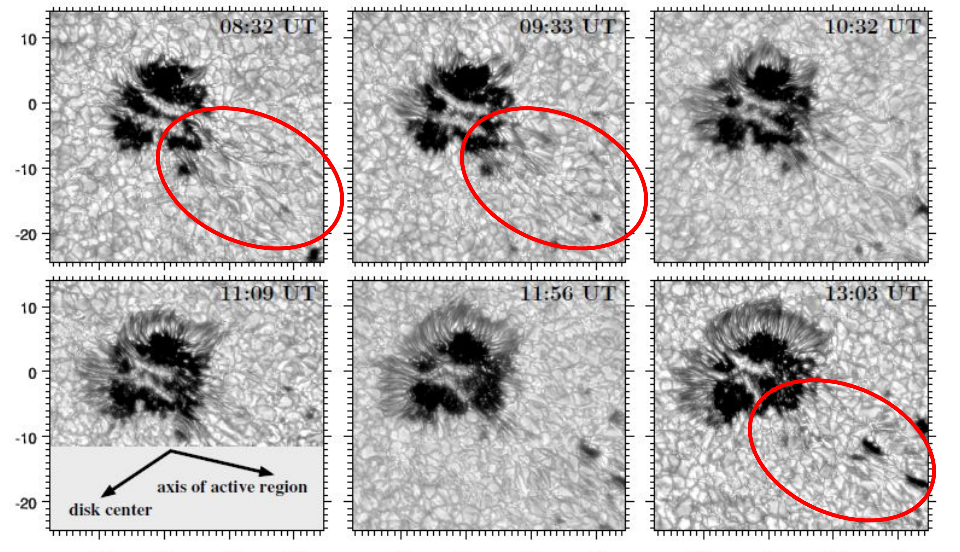
- Umbra-penumbra (UP) boundary ($B_{ver} \sim 1980 \pm 190$ G) migrates towards the umbra (Jurcak 2011)

- Jurcak et al. 2015 proposed two modes of magneto-convection.

  Depending if $B_{ver} < (>) B_{ver}^{stable}$ a penumbral/umbral mode will work.

How?

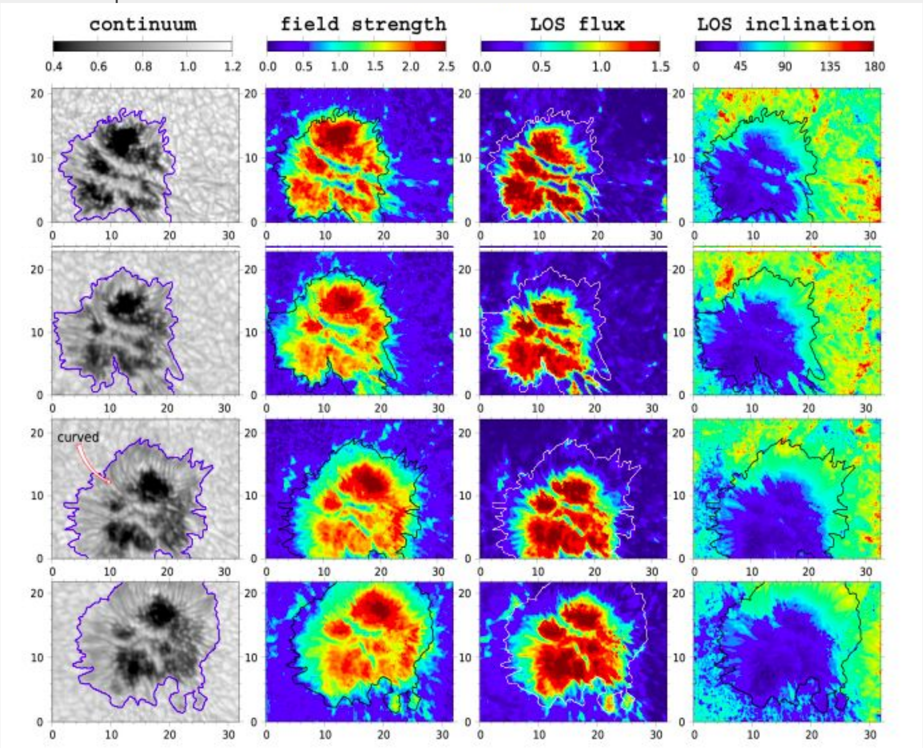
- VTT (2009)
    - G-band (403 nm) and Ca II K (393 nm) images
    - GFPI polarimetric Fe I 617.3 nm
    - TIP II polarimetric Fe I 1089.6 nm



- It forms in sectors
- Elongated granules towards the opposite polarity
- First sector appears on the side away the opposite polarity

Schlichenmaier et al. 2010

How?

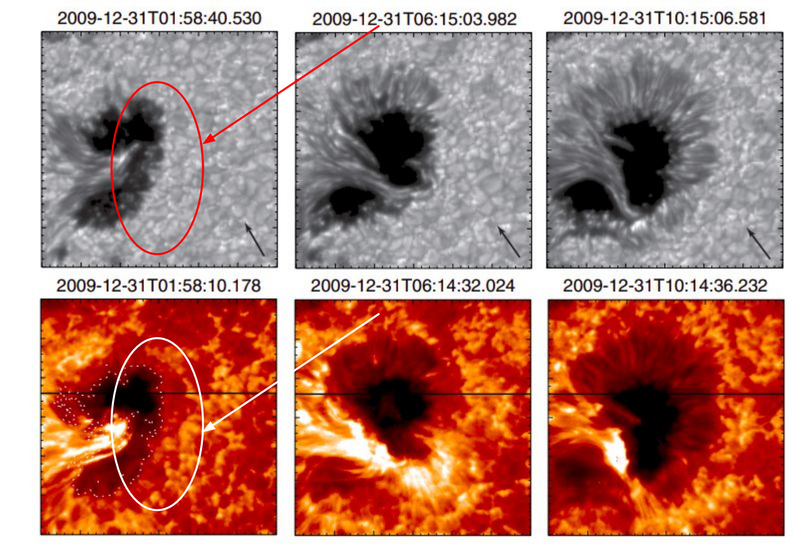


Rezaei et al. 2012

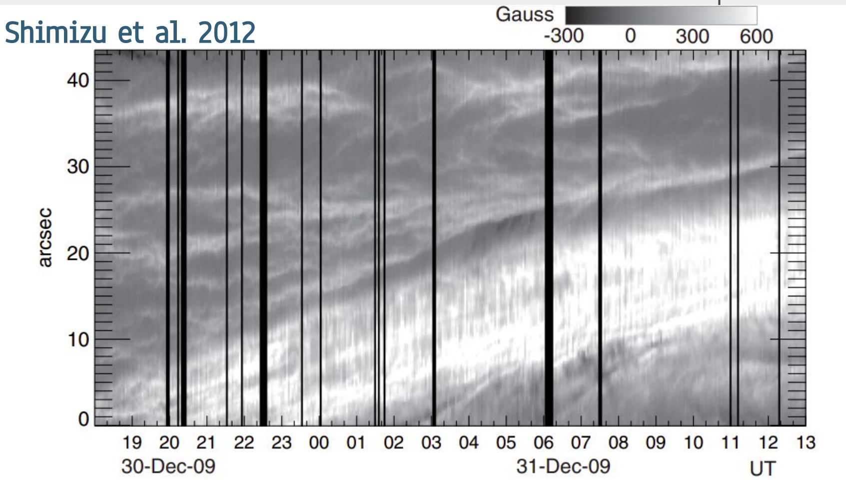
- Strong (≈1 kG) and inclined (45° - 60°) magnetic field before the penumbra forms.
- Umbra magnetic field constant during the penumbra formation.
- stable filaments only form away from the emergence site.

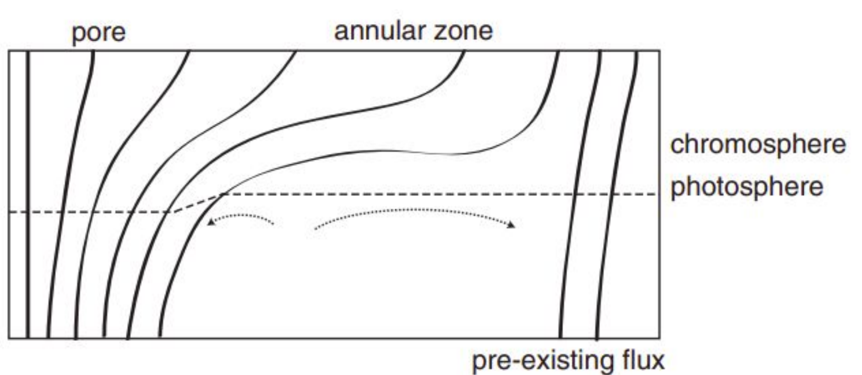
Chromospheric Precursor

- Hinode/SOT (2009-2010)
  - Ca II H (396.8 nm)
  - G-band (430 nm)
  - LOS magnetograms Na I D (589.6 nm)



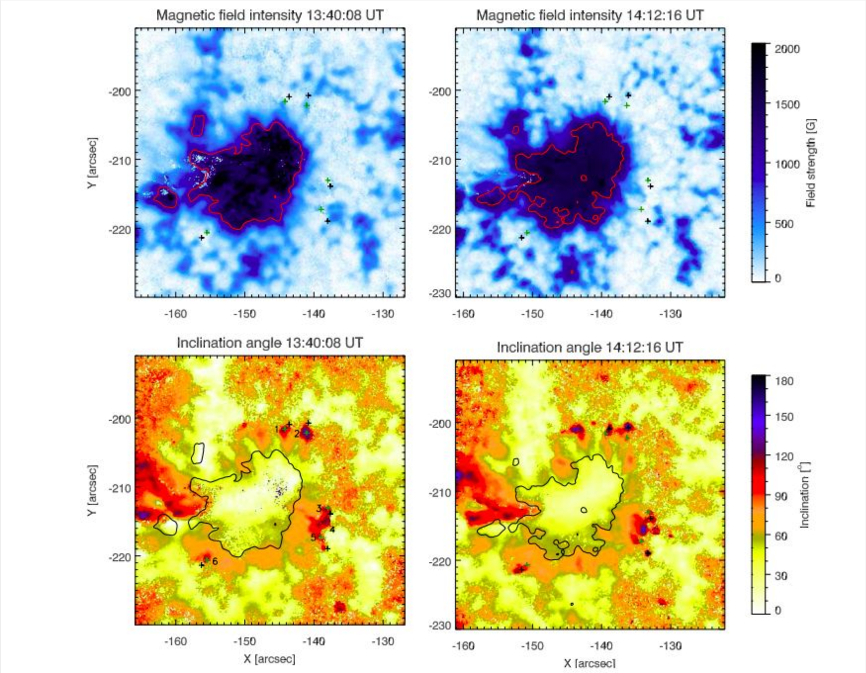
Shimizu et al. 2012

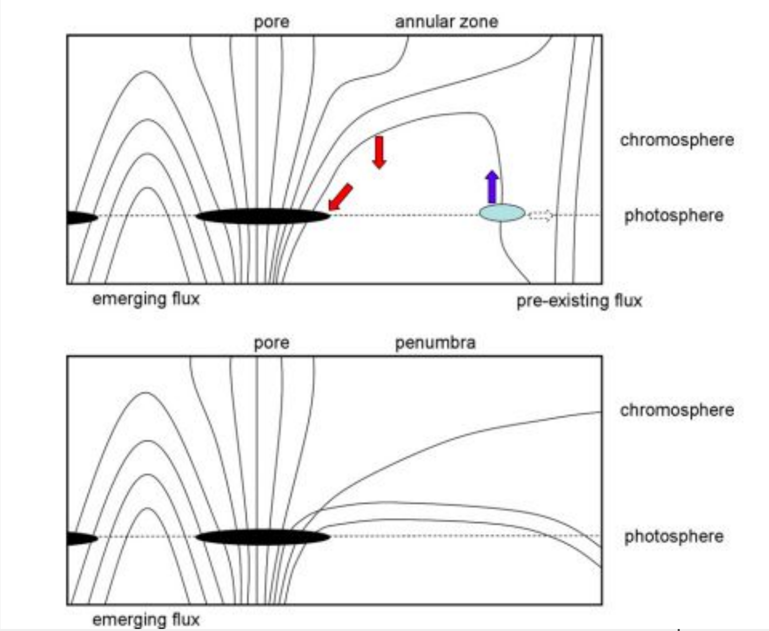




Why?

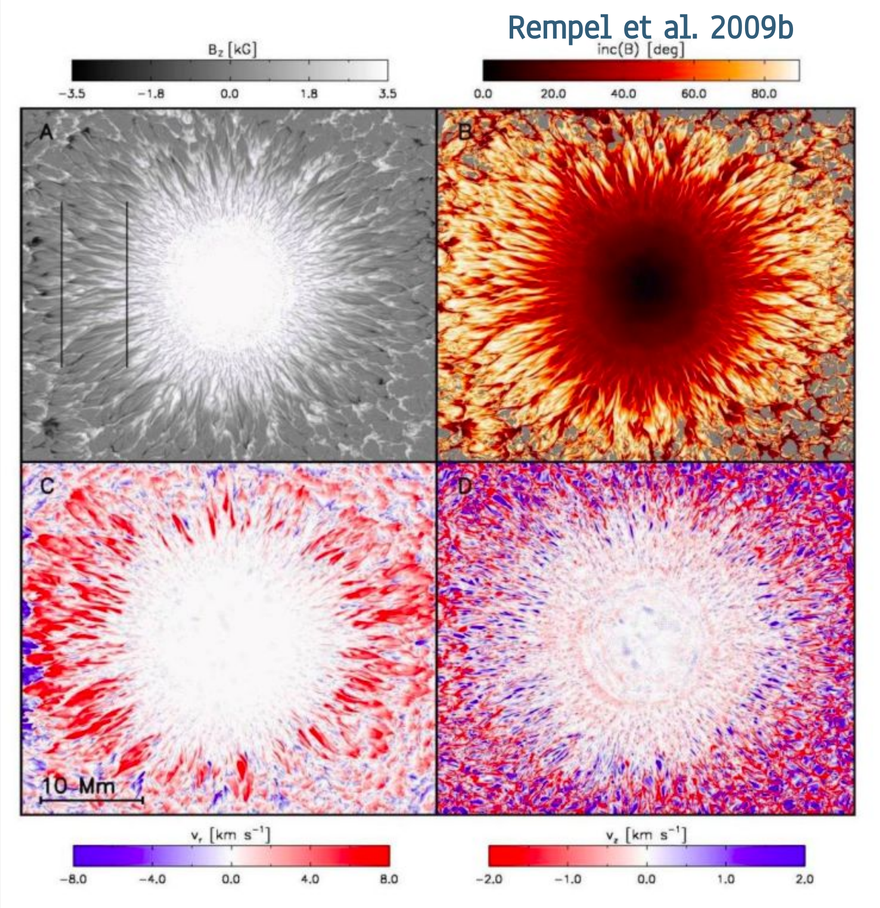
- DST/IBIS (2012)
  - Fe I 617.3 nm & Fe I 630.2 nm pair - Full stokes
  - Ca II 854.2 nm





Romano et al. 2014

Numerical models (see Thursday's lessons)



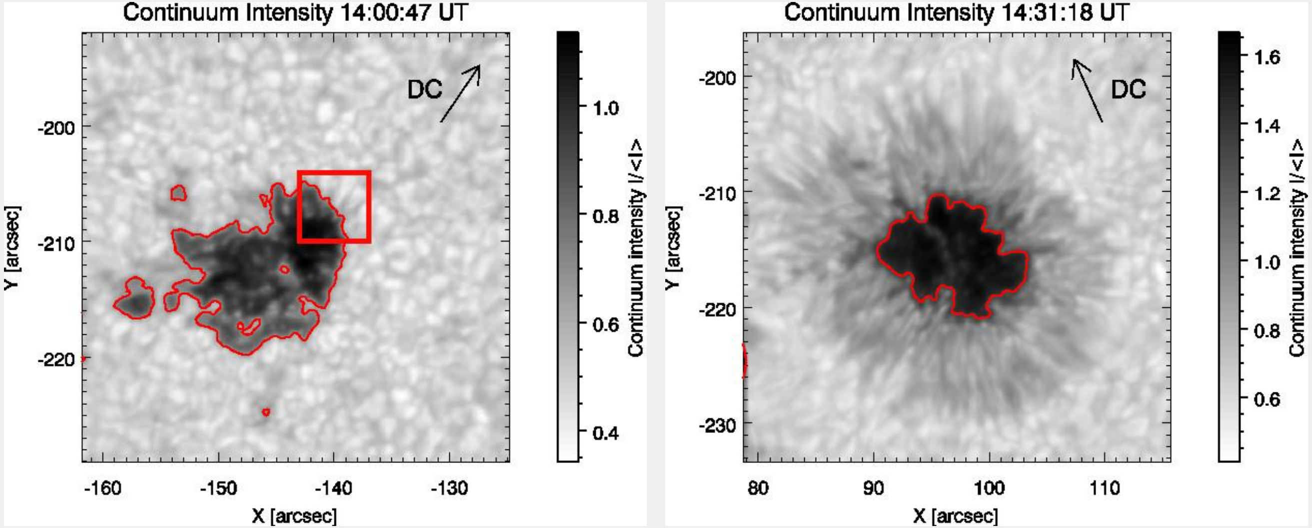
- MURaM simulation
- Extended outer penumbra with a strong radial outflow (up to 5 km s -1).
- The onset of the outflow is related to the magnetic field inclination.

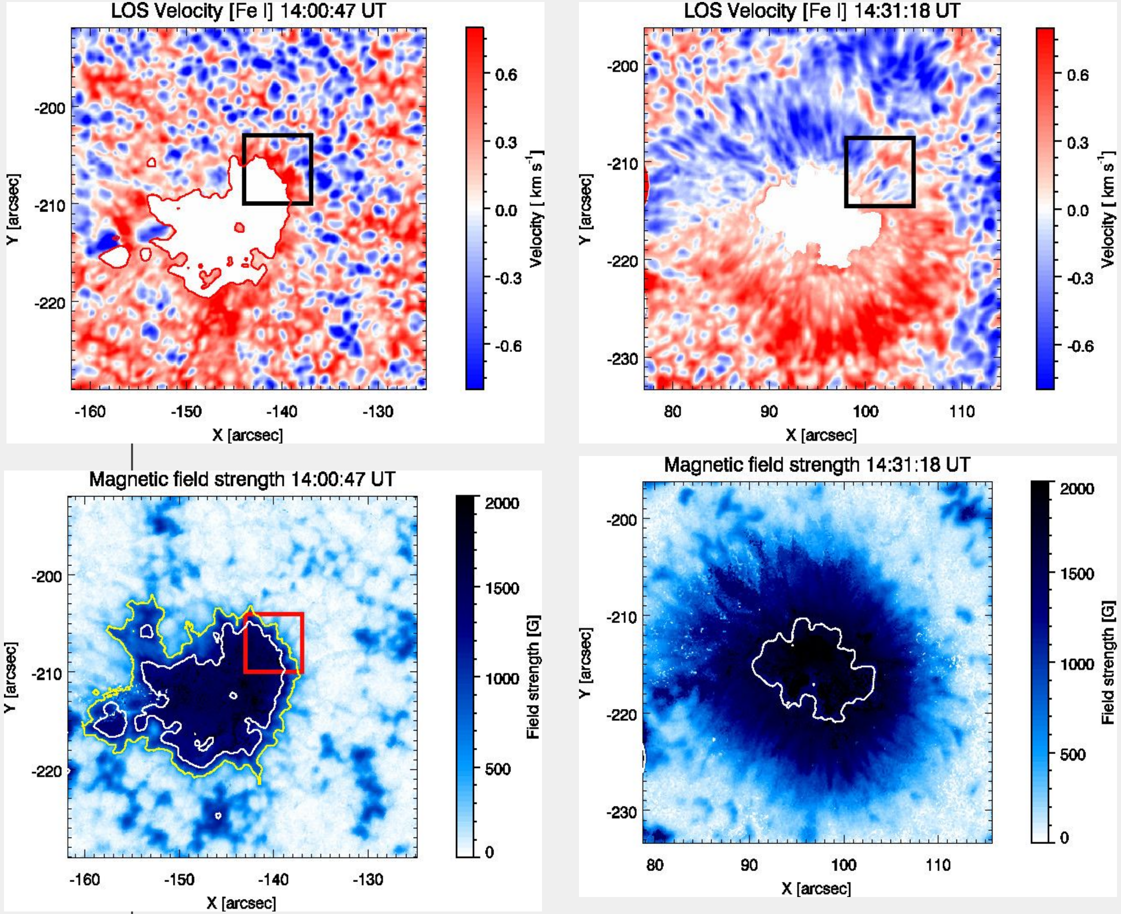
BUT

- The size of penumbral regions are still downgraded
- The inner penumbra appear to be too fragmented and short
- The initial condition of the magnetic field is quite arbitrary

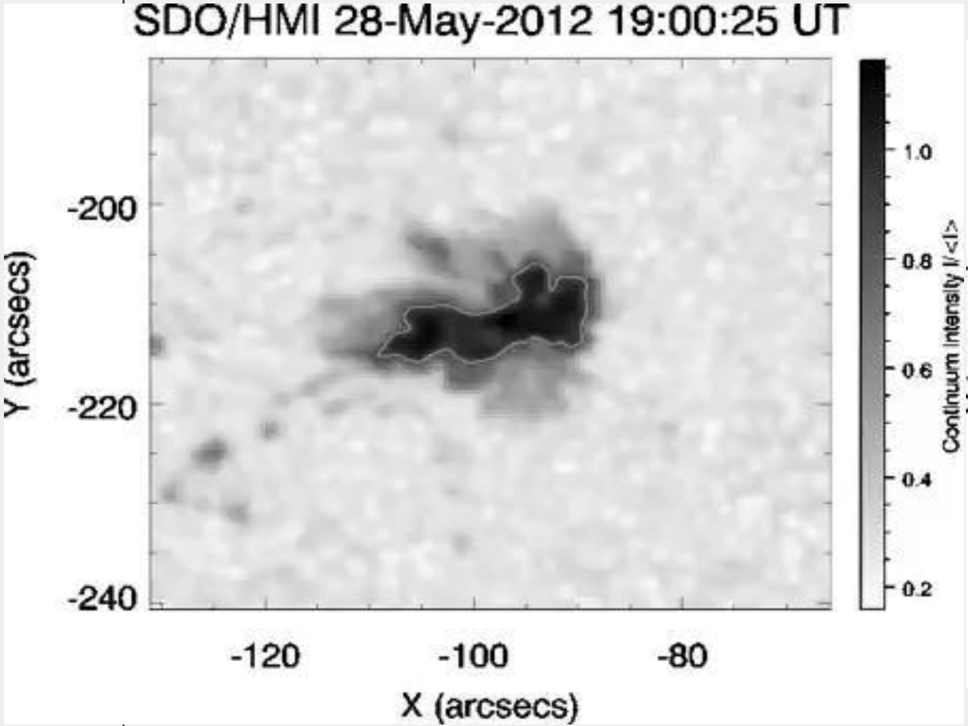
In-depth studies: Murabito et al. 2016

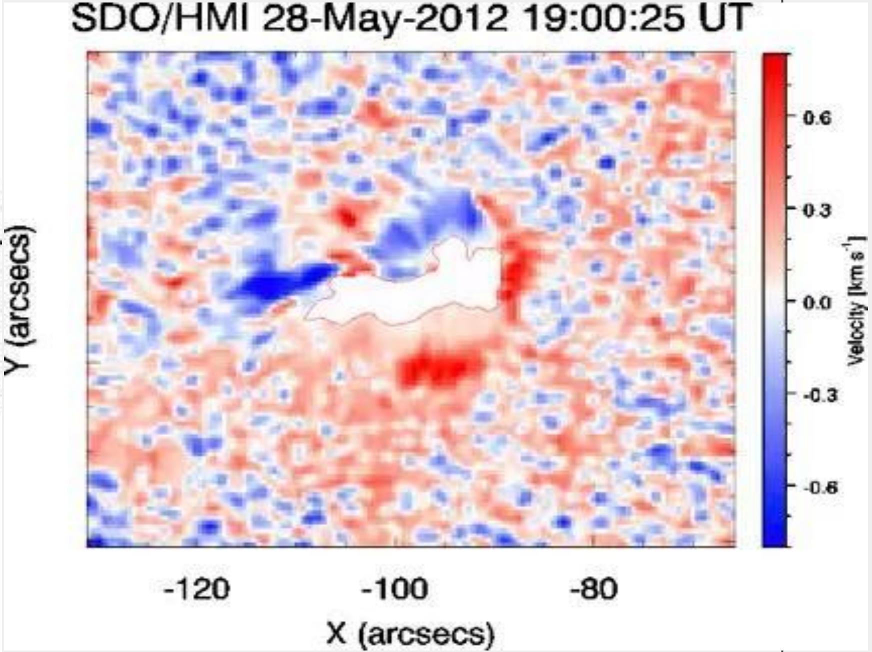
- DST/IBIS (2012)
  - Fe I 617.3 nm & Fe I 630.2 nm pair - Full stokes
  - Ca II 854.2 nm

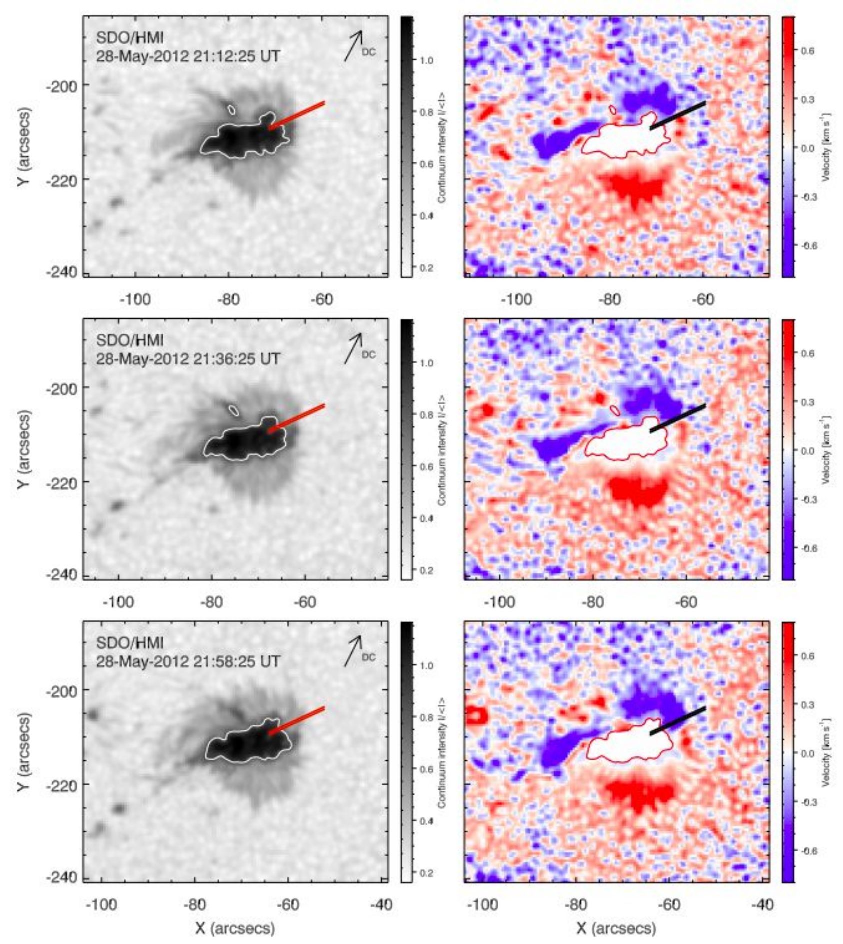


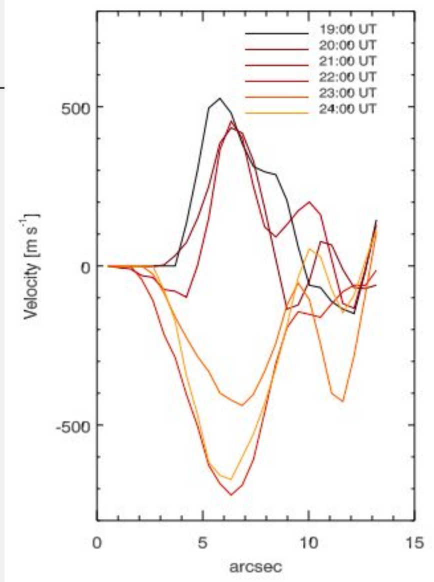


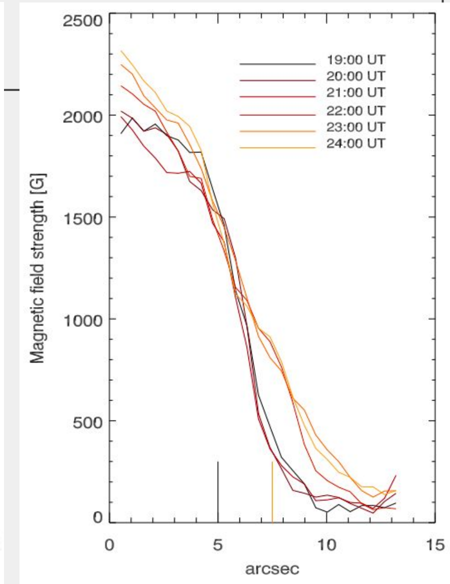
- Downflows ≥ 1 km/s, elongated “cells” in intensity and inhomogeneous field strength in the annular zone.


SDO/HMI 28-May-2012 19:00:25 UT
-200
-220
-240
Y (arcsecs)
-120
-100
-80
X (arcsecs)
1.0
0.8
0.6
0.4
0.2
Continuum Intensity I/<I>


SDO/HMI 28-May-2012 19:00:25 UT
Y (arcsecs)
-120
-100
-80
X (arcsecs)
0.6
0.3
0.0
-0.3
-0.6
Velocity [km s-1]

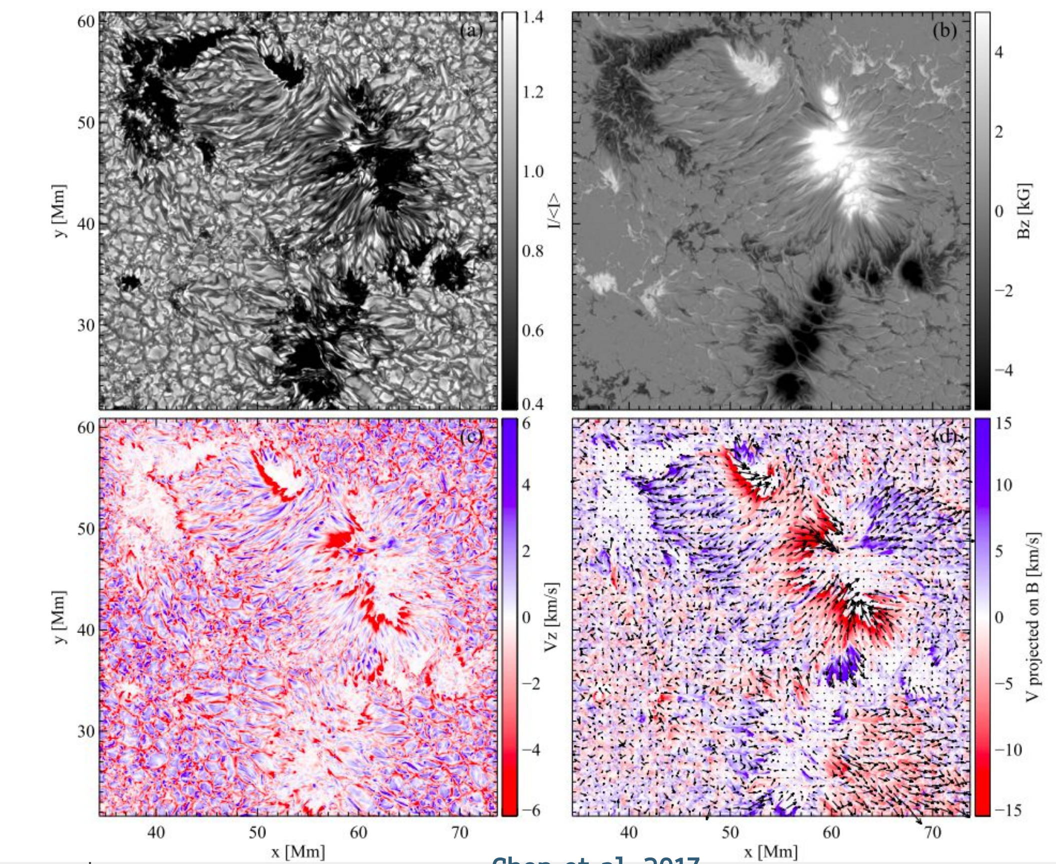






- With time the blueshifted region covers a larger range, while the redshifted region decreases.
- The velocity field changed sign in 1–3 hr
- The field increased only some minutes after the Evershed-like flow had already been established.

Numerical models

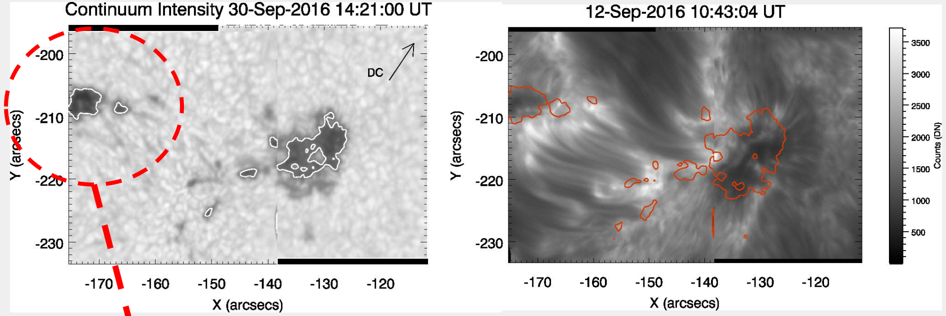


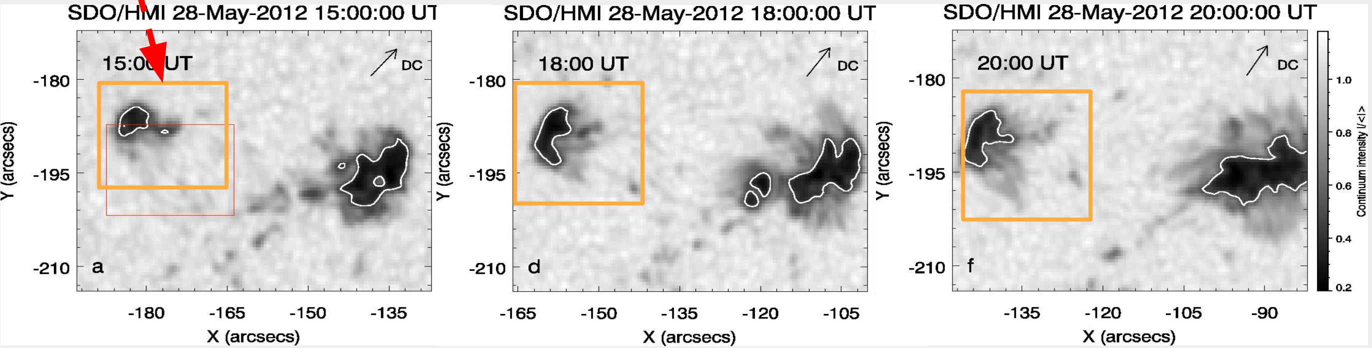
Chen et al. 2017

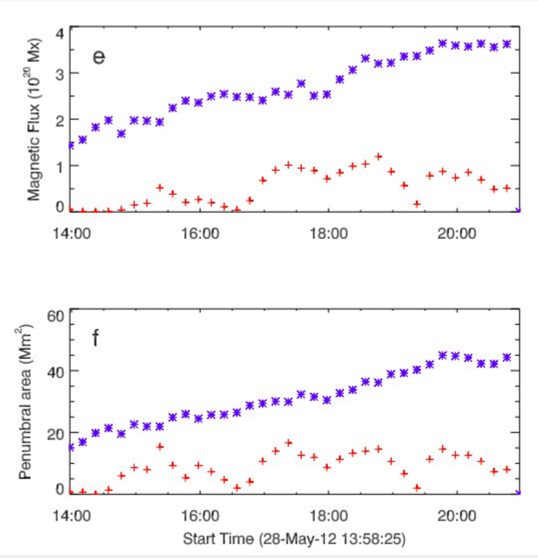
- **MURaM simulation** where magnetic and flow fields are adapted from a solar convective dynamo simulation (Fan & Fang 2014)
- Penumbral filaments form spontaneously.
- Counter EF is visible in a large section of the penumbra
- Long penumbral filaments appear in ongoing flux emergence regions (on the side of the opposite polarity spot).
- Fewer and shorter penumbra filaments grow on the side away from the opposite polarity

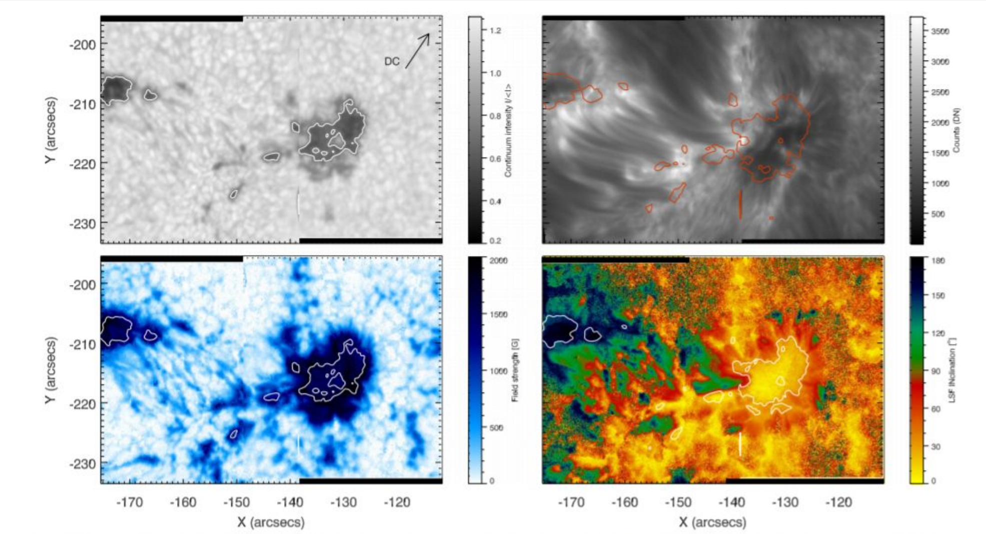
In-depth studies: Murabito et al. 2017

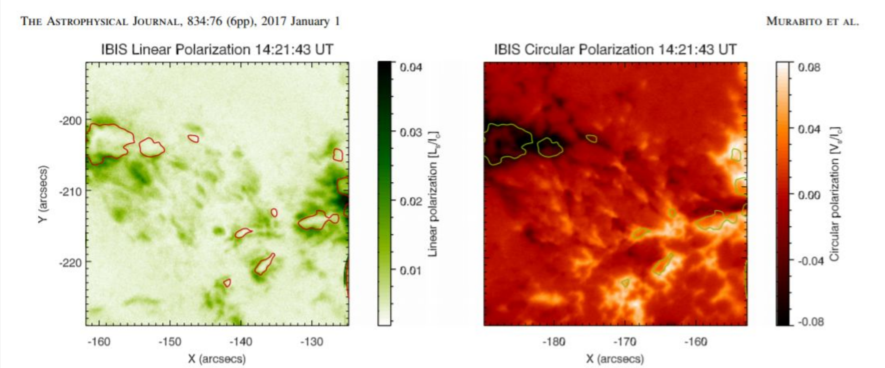
- **DST/IBIS (2012)**
- Study of the following part of AR
- The first penumbral sector grows as the negative magnetic flux increases
- The penumbral areas characterized by positive magnetic field are transient.







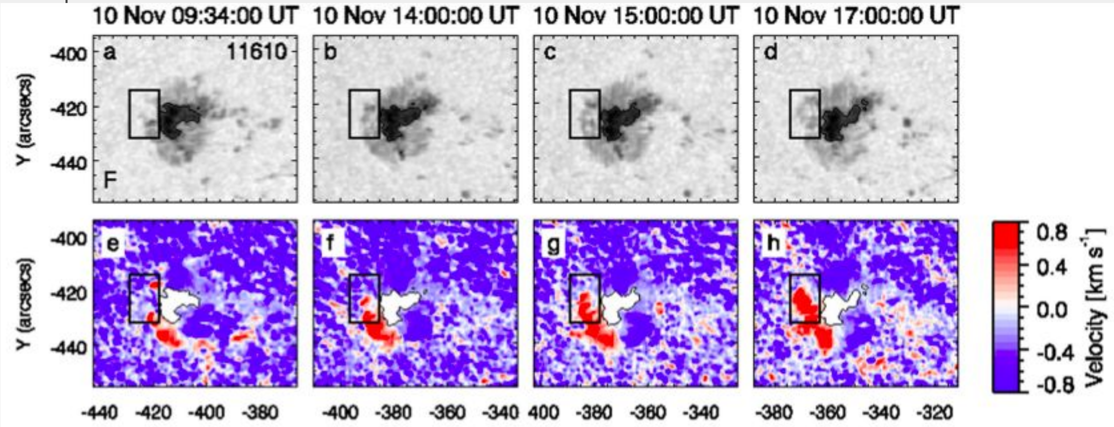


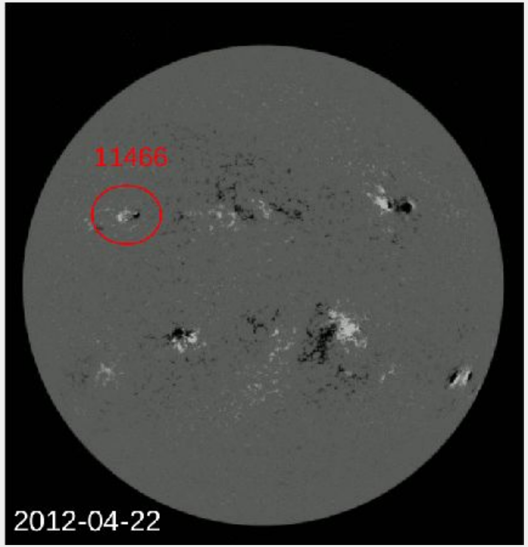


- Elongated granules are visible.
- Presence of an AFS ⟶corresponds to a EFR
- Filamentary magnetic configuration ⟶ a sea-serpent configuration
- The filamentary structure recognized in the linear and circular polarization maps
- Where later the first penumbral sector appears the values are larger than 4%
- In the northern part of the pore the linear polarization is smaller than about 1%.

In-depth studies: Murabito et al. 2018

- SDO/HMI (2011-2012)
- Selection of 12 simplest ARs
  - The formation occurs while the sunspots were visible on the solar disk.
  - β-type magnetic field configuration during the entire passage of the AR.
- **No preferred side where the penumbra starts to form.**
- **All exhibits counter EF**

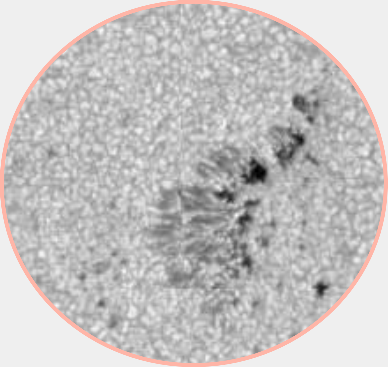


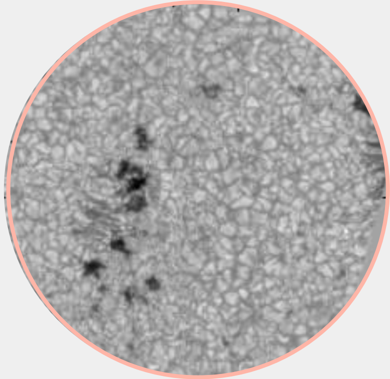


Penumbral Evolution

Decay process: the most elusive phenomenon

- Introduction on decay process
- Simulation studies
- In-depth studies :
    - Murabito et al. 2021

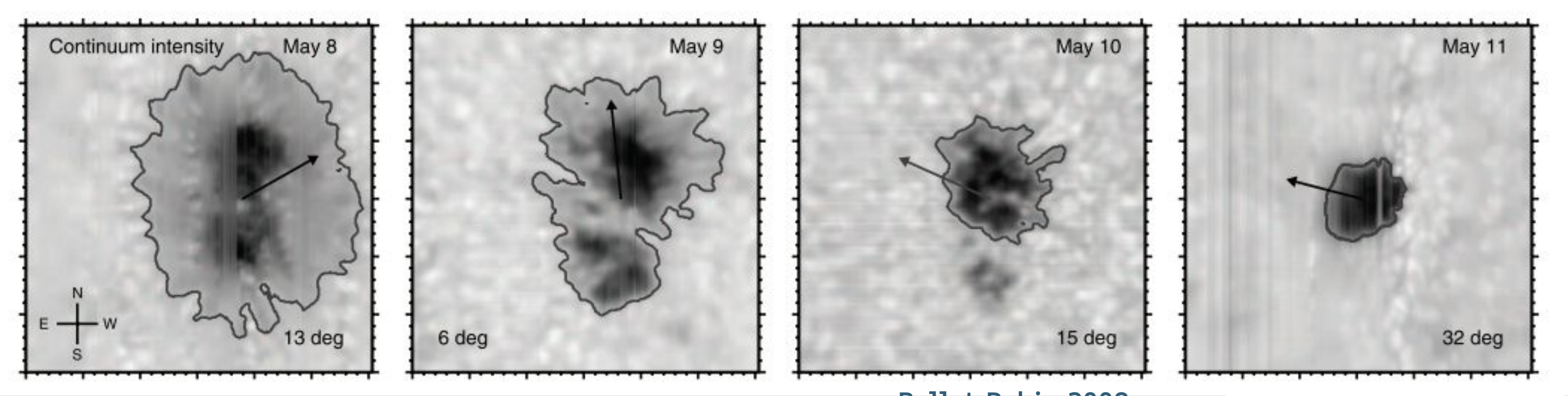




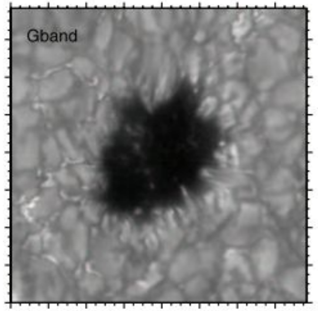
Murabito et al. 2021

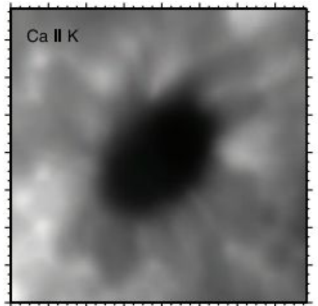
Introduction

- Slow (several days) process
- MMFs seems to be the responsible for the decay of ARs (Zhang et al. 1992, Deng et al. 2007)
- The penumbra disappearance may partly explain the removal of flux from mature spots (Martinez Pillet 2002)
- Energetic flares have been related to the disappearance of the penumbra (Wang et al. 2004; Deng et al. 2005; Sainz Dalda & Martı́nez Pillet 2008).

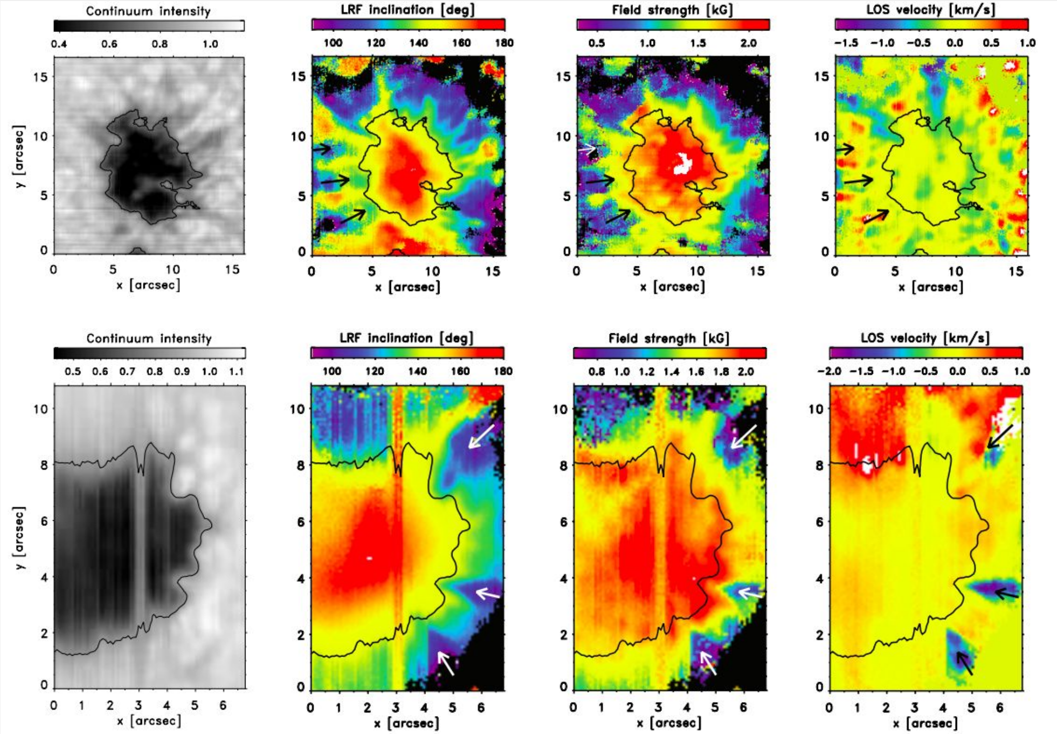


Bellot Rubio 2008





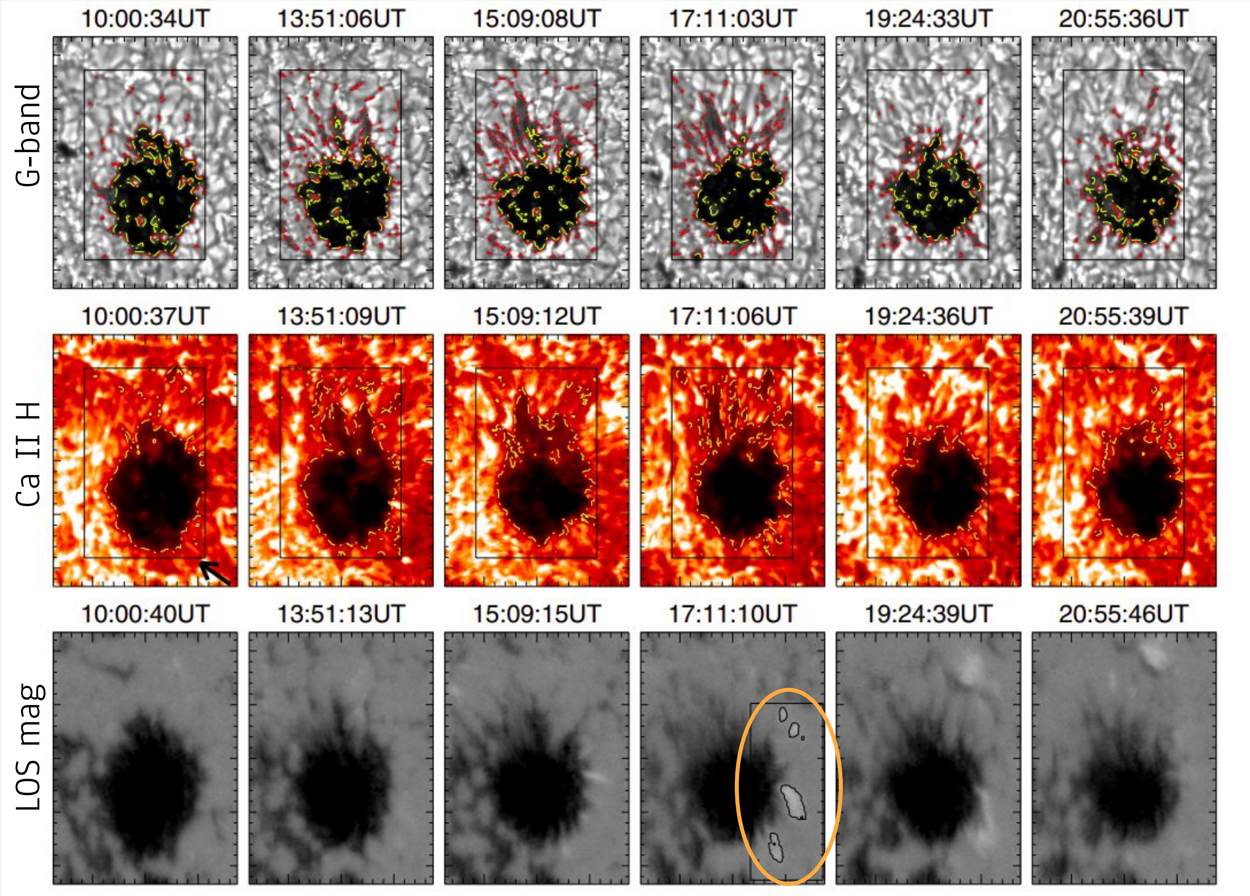
- DSLP@DST
- Full stokes from 630.0 to 630.4 nm containing Ti I and three Fe I
- Ca II K and G-band images
- The penumbra took 3 days to disappear
- Partly developed penumbra in Ca II K. → consistent with the scenario of an elevated magnetic canopy.



Bellot Rubio 2008

- finger-like structures with weak and more inclined fields.
- The fingers exhibit conspicuous blueshifts
- Seem to be associated with the disappearance of the penumbra.
- Bigger umbra than in the continuum → existence of **magnetic canopy.**

Decay of rudimentary penumbra



- HINODE/SOT (2007)
- LOS magnetograms of the Fe I 630.2 nm line.
- Ca II H and G-band images.
- Transient penumbra filaments

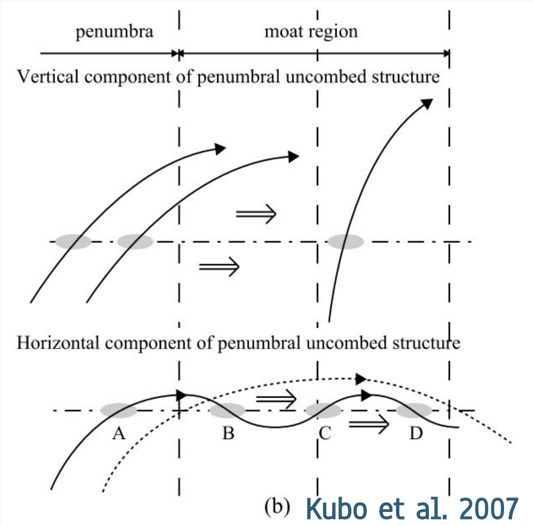
- ❑ $3x10^{19}$ Mx.
- ❑ Wider filaments in the chromosphere.
- ❑ opposite polarity patches

Watanabe et al. 2014

Processes involved in the decay

Three processes seem to be involved:

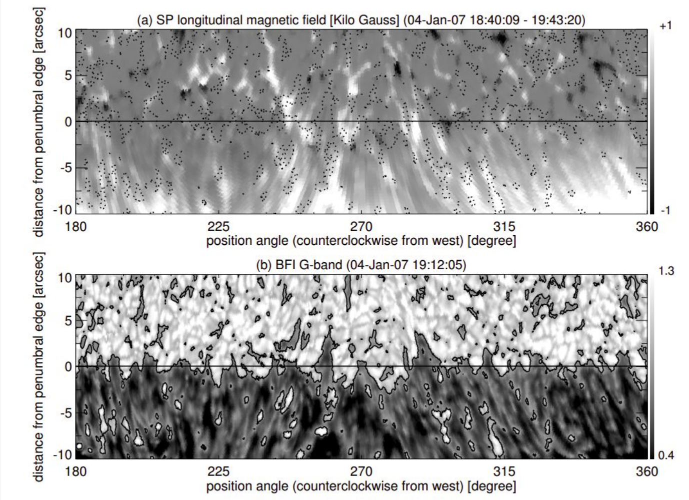
1. Displacement of MMFs (Kubo et al. 2003, Kubo et al. 2007)

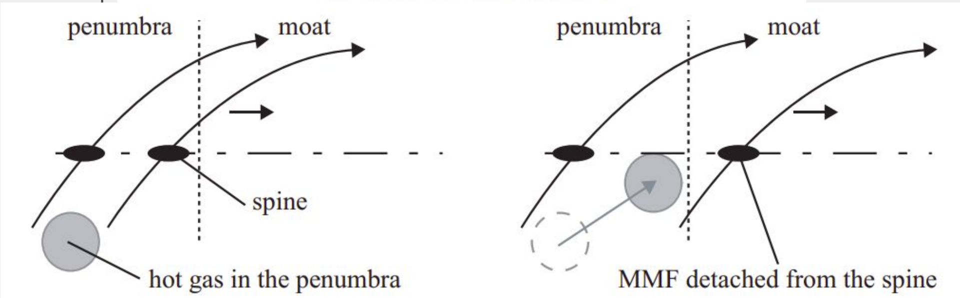


Kubo et al. 2007

- **ASP (2003)**, Fe I 630 nm line pair
- Detection of (non)isolated MMFs
- Moat fields as Nonisolated MMFs
- Isolated MMFs on the lines extrapolated from the horizontal component of the uncombed structure
- MMFs are detached from the spine (vertical) component
- Isolated vertical MMFs can transport sufficient magnetic flux and are responsible for the disappearance and disintegration of the sunspot

Processes involved in the decay





Kubo et al. 2008

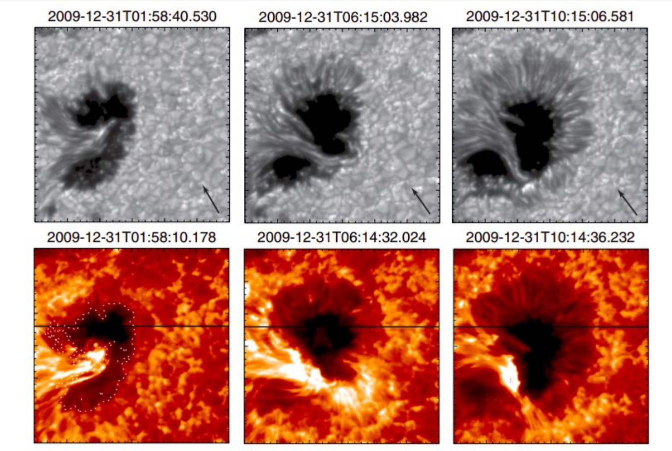
- Hinode/SOT (2007)

Higher spatial resolution

Processes involved in the decay

Three processes seem to be involved:

1. Displacement of MMFs (Kubo et al. 2003, Kubo et al. 2007)
2. Change of the inclination of the overlying magnetic canopy



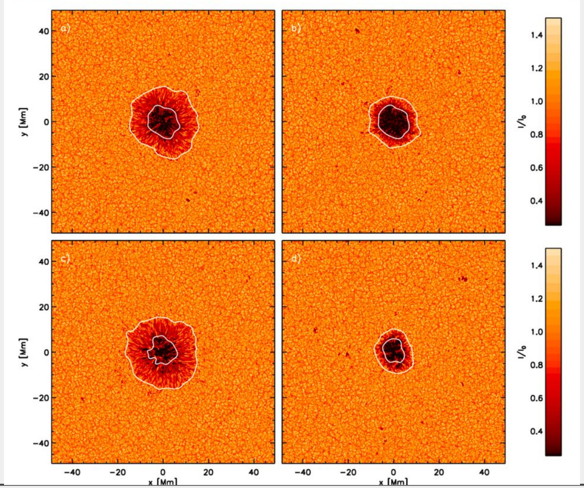
Romano et al. 2020 proposed an opposite process with respect to that of the penumbra formation.
The straightening up of field lines belonging to the **overlying magnetic canopy**

But, this process was never observed.

Processes involved in the decay

Three processes seem to be involved:

1. Displacement of MMFs (Kubo et al. 2003, Kubo et al. 2007)
2. Change of the inclination of the overlying magnetic canopy (Shimizu et al. 2012, Romano et al. 2020)
3. Convective motions

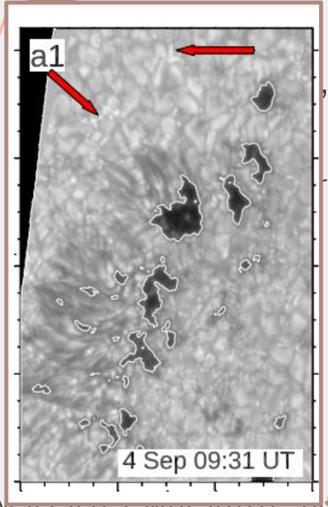


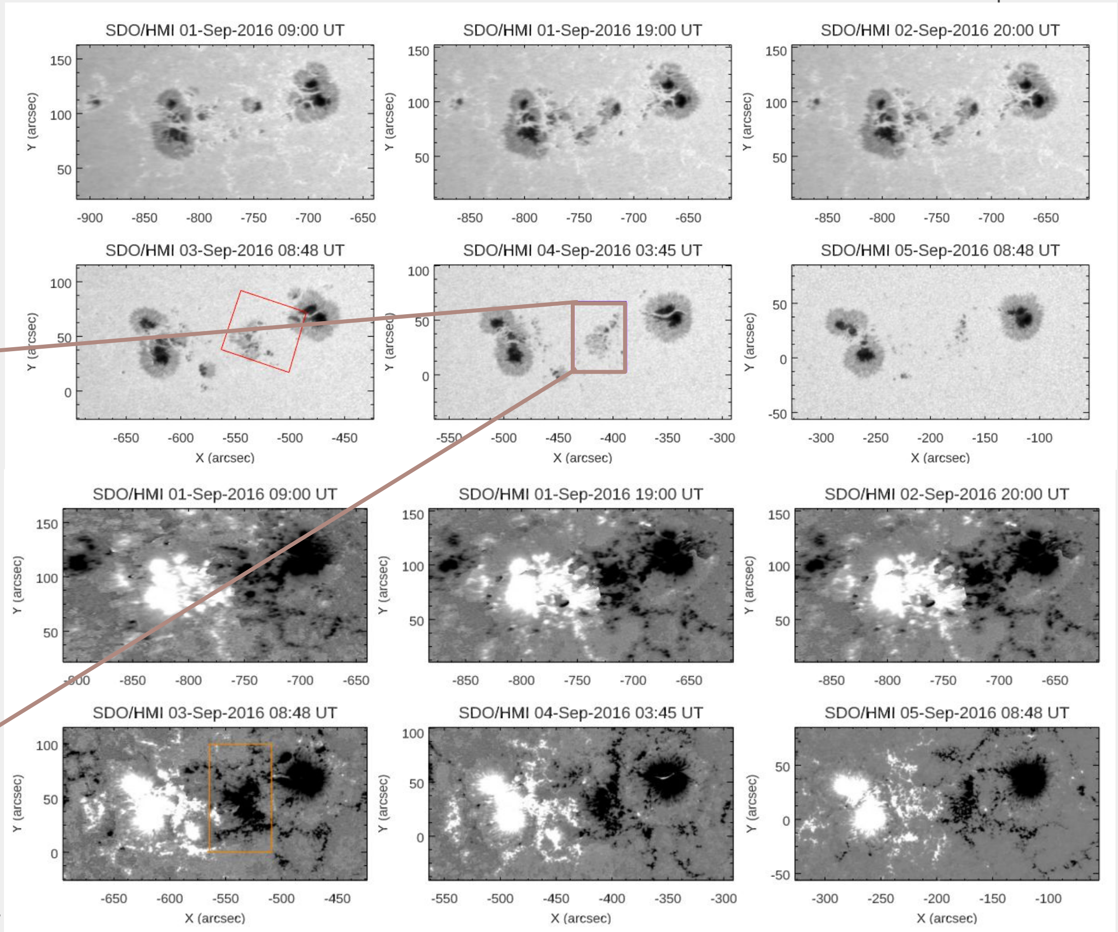
Rempel 2015

- Sunspot decay may result from **convective motions, placed deeper in the photosphere**
- The strength of the enhanced mixed polarity field in the moat region depends **on the strength of the overlaying magnetic canopy**.

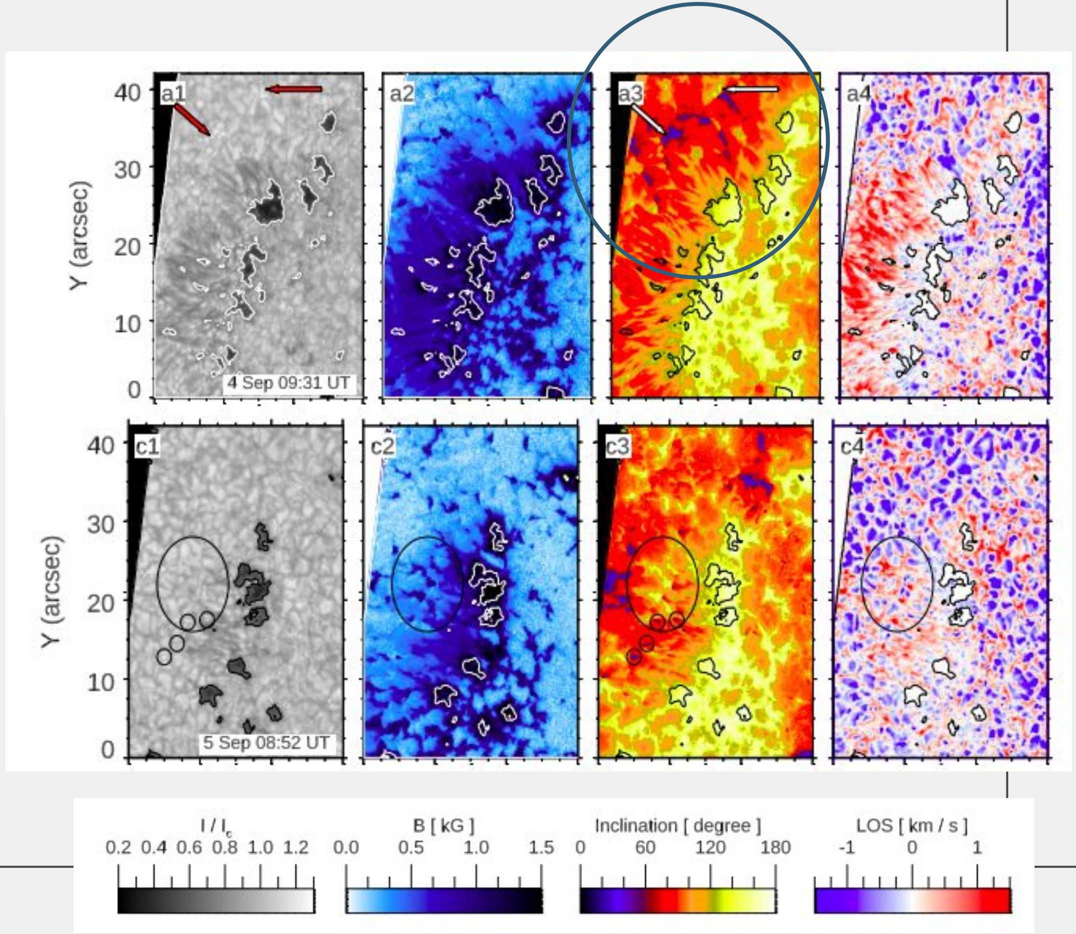
In-depth studies: Murabito et al. 2021

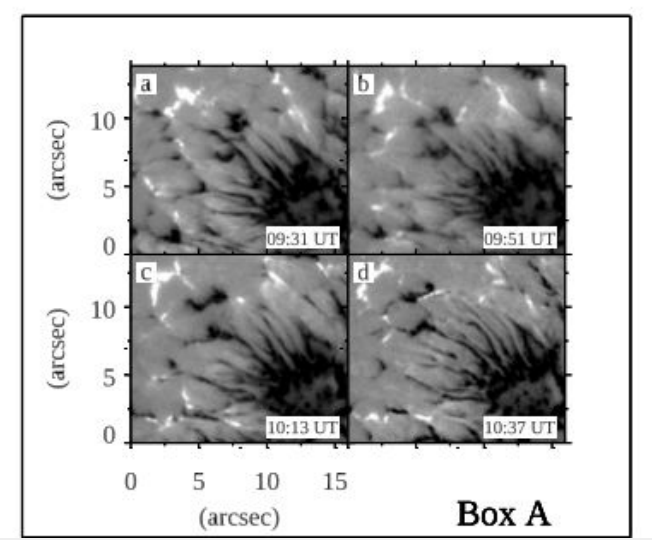
- SST/CRISP (2016)
  - Fe I 630.2 nm line pair full stokes
    - VFISV M-E inversions & CP/LP
- HINODE/SOT
  - Fe I 630.2 nm line pair full stokes
    - Level 2 as CP, LP and vLOS
- SDO/
  - , continuum
  - rapolartion

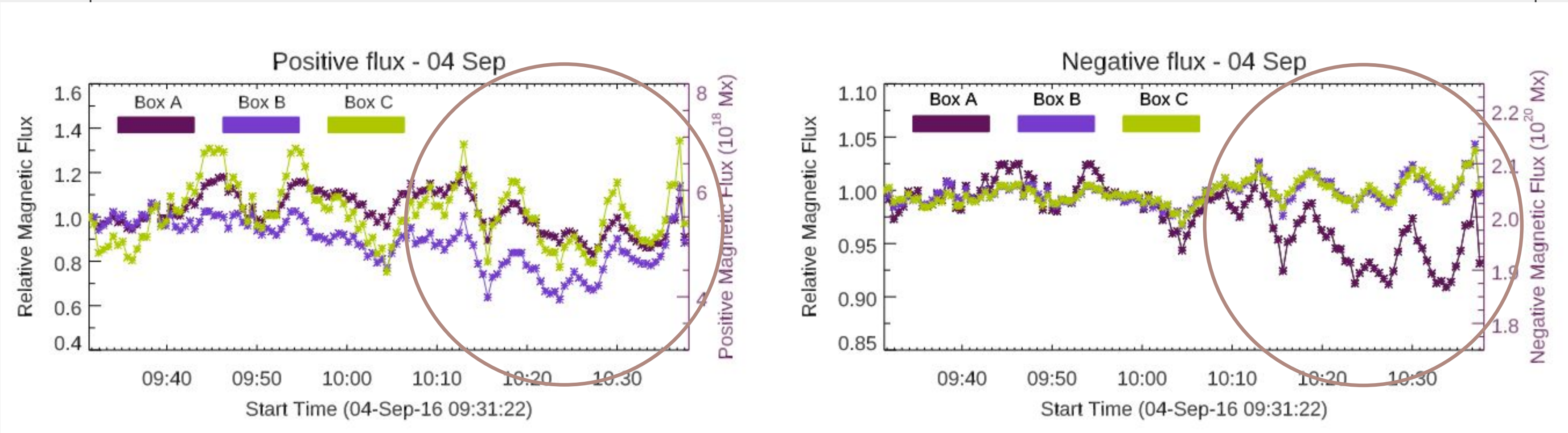


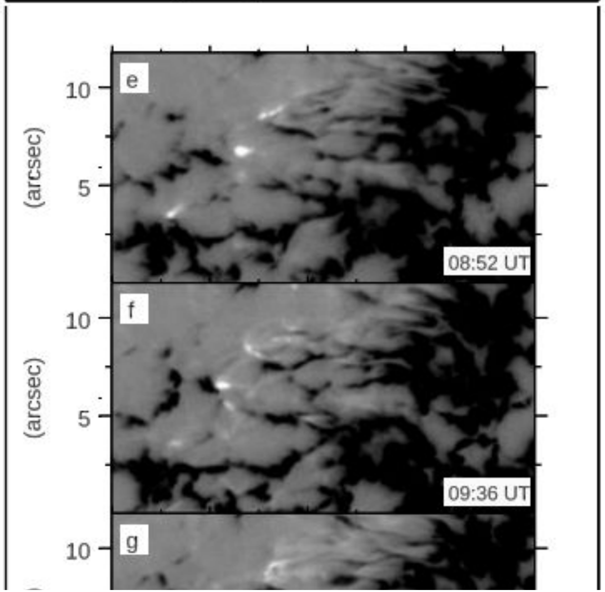


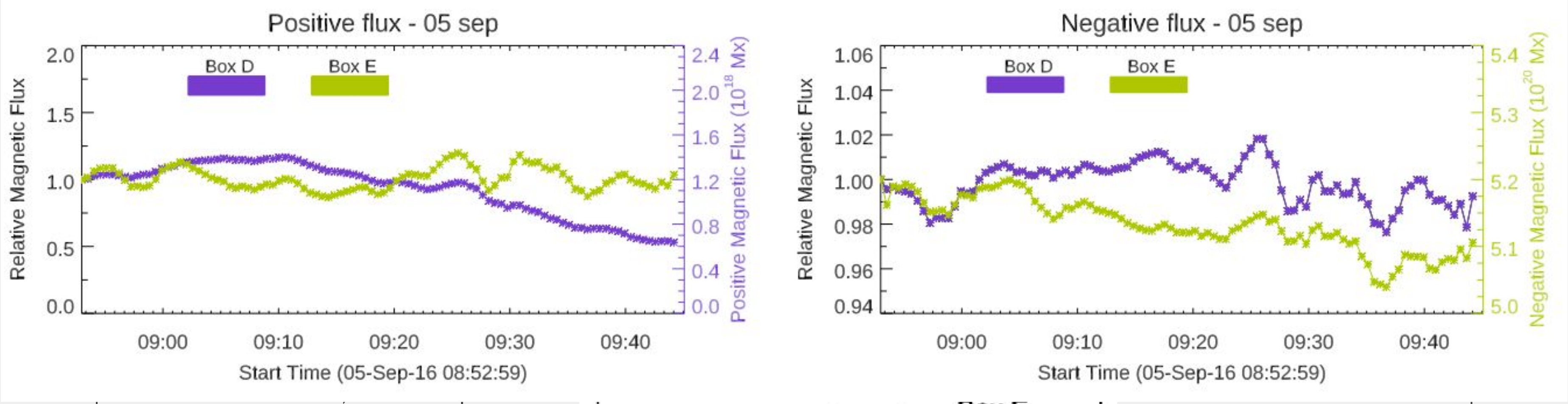
- Penumbra decay gradually
- Ring of patches of opposite polarity
- Sea-serpent configuration




a
b
c
d
09:31 UT
09:51 UT
10:13 UT
10:37 UT
(arcsec)
0 5 10
0 5 10 15
Box A

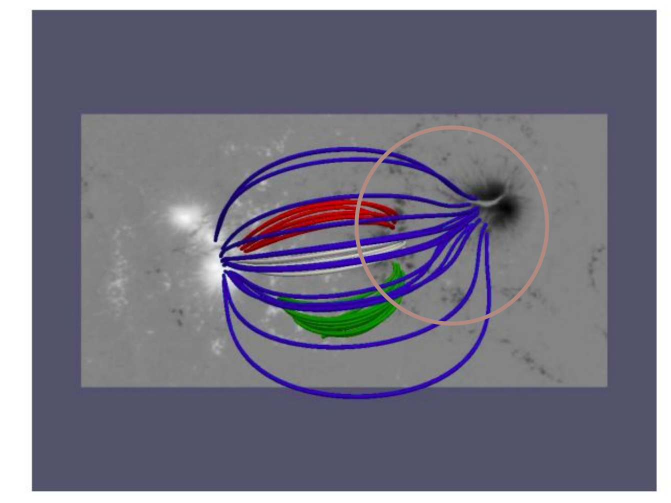

Positive flux - 04 Sep
Box A
Box B
Box C
Relative Magnetic Flux
Positive Magnetic Flux (10^{18} Mx)
1.6 1.4 1.2 1.0 0.8 0.6 0.4
8 6 4
09:40 09:50 10:00 10:10 10:20 10:30
Start Time (04-Sep-16 09:31:22)
Negative flux - 04 Sep
Box A
Box B
Box C
Relative Magnetic Flux
Negative Magnetic Flux (10^{20} Mx)
1.10 1.05 1.00 0.95 0.90 0.85
2.2 2.1 2.0 1.9 1.8
09:40 09:50 10:00 10:10 10:20 10:30
Start Time (04-Sep-16 09:31:22)


e
10
5
(arcsec)
08:52 UT
f
10
5
(arcsec)
09:36 UT
g
10


Positive flux - 05 sep
Box D
Box E
Relative Magnetic Flux
Positive Magnetic Flux (10^{18} Mx)
Start Time (05-Sep-16 08:52:59)
Negative flux - 05 sep
Box D
Box E
Relative Magnetic Flux
Negative Magnetic Flux (10^{20} Mx)
Start Time (05-Sep-16 08:52:59)

Box E

- We observed the formation of the penumbra only in the region towards the opposite polarity
    - In contrast with Schlichenmaier et al. 2010,2012 and Rezai et al.2012 but in agreement with Murabito et al. 2017
- Following the scenario proposed by Romano et al. (2013, 2014, 2020), in the side towards the negative polarity the penumbra cannot form for the absence of the overlying canopy.



- Before the penumbra disappears, opposite polarity patches associated with penumbral bright points.
- MMFs, located near the sectors which starts to disappear are detected.
- Penumbra disappeared in sectors, where the negative magnetic flux decreases → A robust suggestion that the interaction between type III MMFs and the penumbral field plays a key role.
- The different observed connectivities may play a role in the onset of the differential decay.

Not been able to disentangle between the three mechanisms, although the role of MMFs and overlying canopies seem to have different spheres of action.