Coupling of the solar atmosphere by small-scale fields - Part I

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International School of Space Science
"The different spatio-temporal scales of the solar magnetism"
12 April 2022

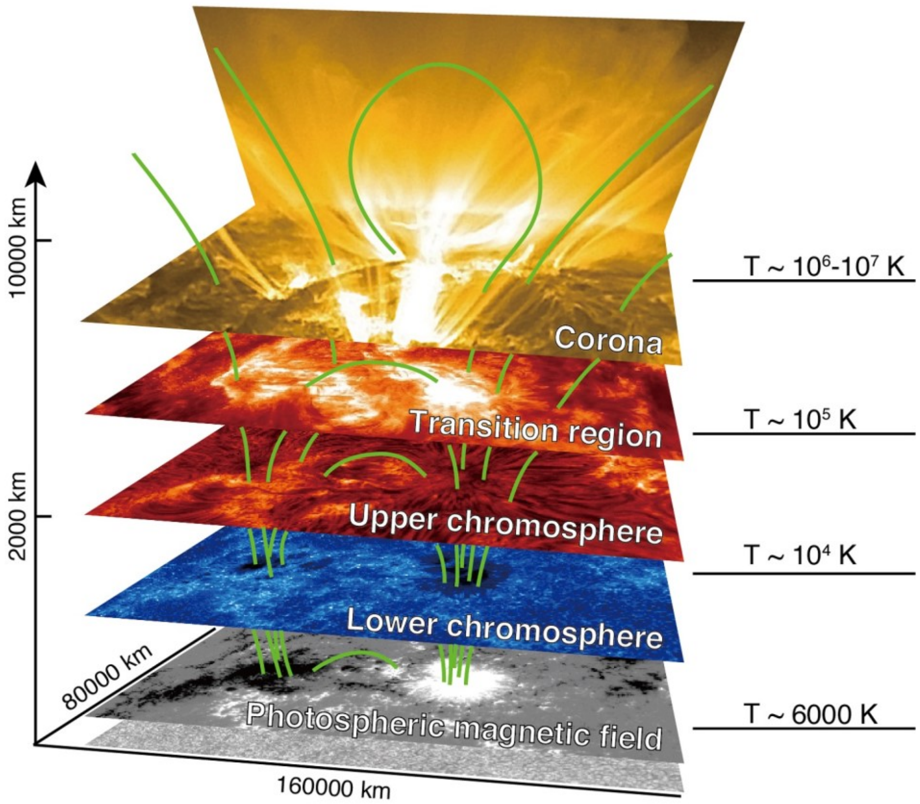
Outline

- **Magnetic coupling**
  1. from large scale … to small-scale features
  2. current view of the solar atmospheric structure
- **Interactions**
  - magnetic reconnection
- **Scientific cases**
  1. Case study: *Hinode* observations near pores
  2. Coronal heating
- **Interactions in the *IRIS* era**
  1. UV bursts
  2. Case study: *IRIS* observations in a plage
  3. Case study: penumbral brightenings
- **Conclusions**
  - perspectives

From large scales…

10^{21} – 10^{23} Mx

Coupling in multi-wavelength observations

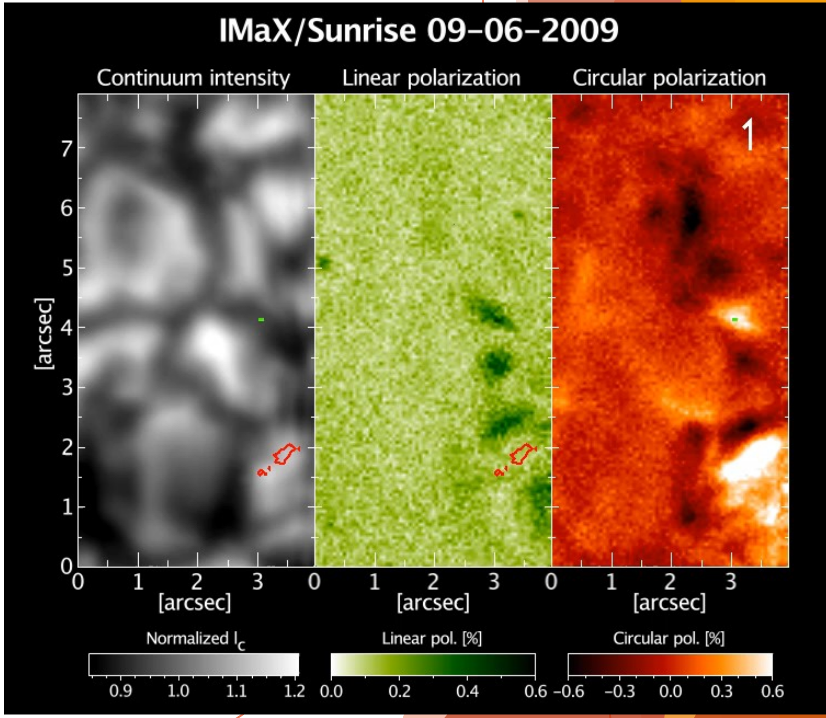


… down to small scales!

$10^{16} - 10^{19}$ Mx

Magnetic coupling: sub-arcseconds scale

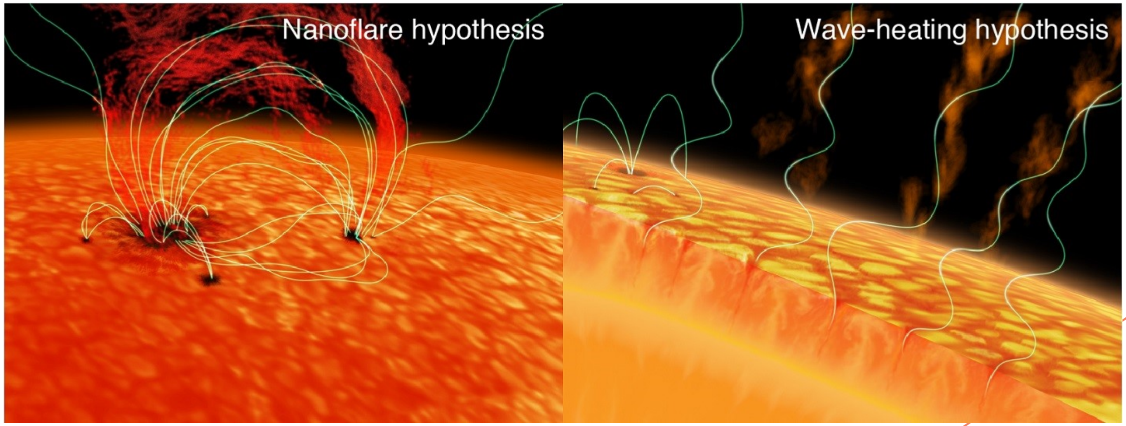
- Sub-arcseconds flux concentrations appear **everywhere** on the solar surface, down to the limit of the present instrumental capabilities
- High-resolution observations (at least <0″.3) showed that magnetic flux concentrations at different atmospheric heights are linked
  - ground-based: TIP@VTT, IBIS@DST, SOUP-CRISP-CHROMIS@SST, NST …
  - space-based: SOT@*Hinode*, IMaX&-SuFI@SUNRISE, *IRIS* …
- Also, the **quiet Sun** is far from being quiet (**see yesterday's lessons**)…



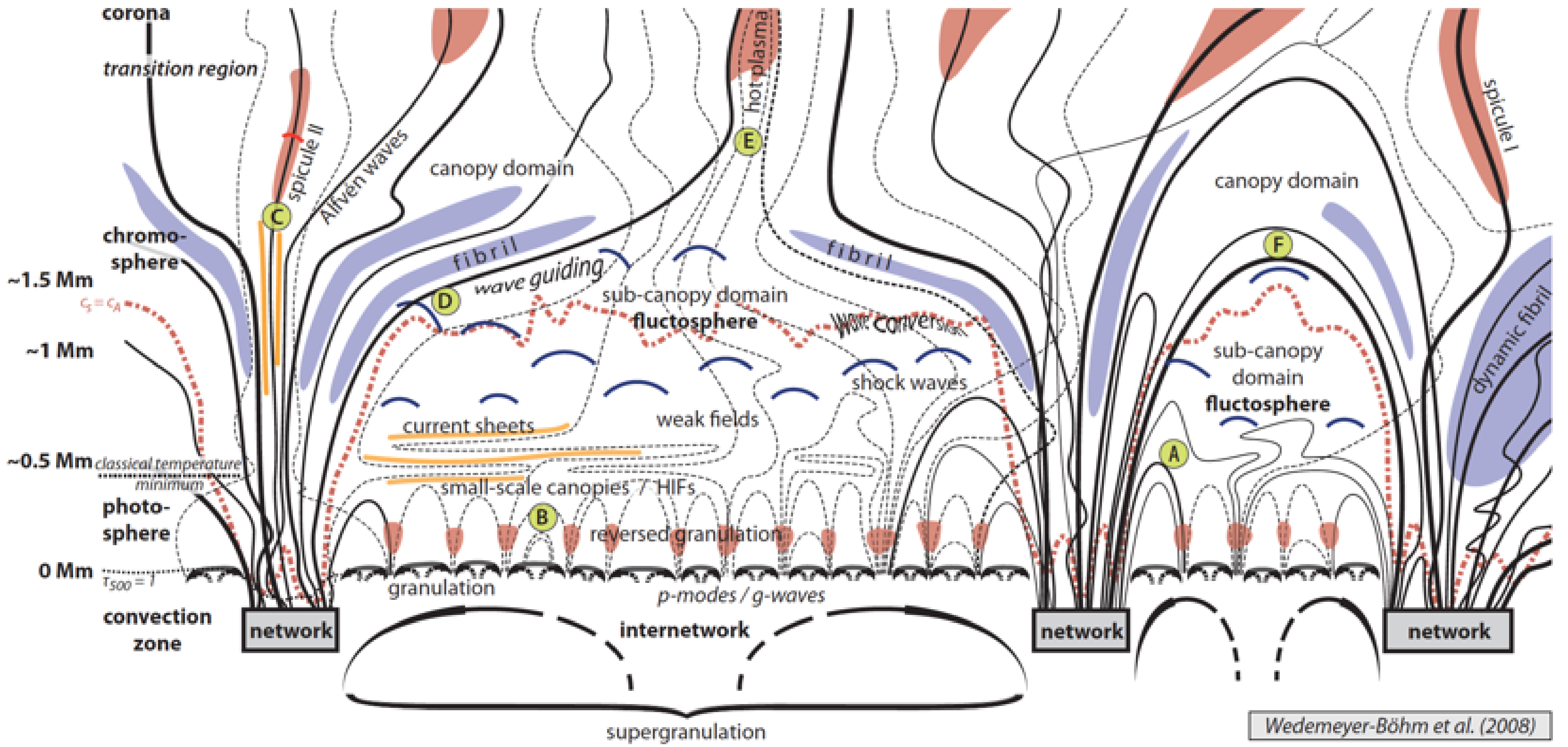
Magnetic coupling: sub-arcseconds scale

Questions

- Do small-scale flux concentrations interact with each other or with the ambient fields?
- Do they play a role in the chromospheric/coronal heating?
- How is the magnetic flux channeled into higher heights?



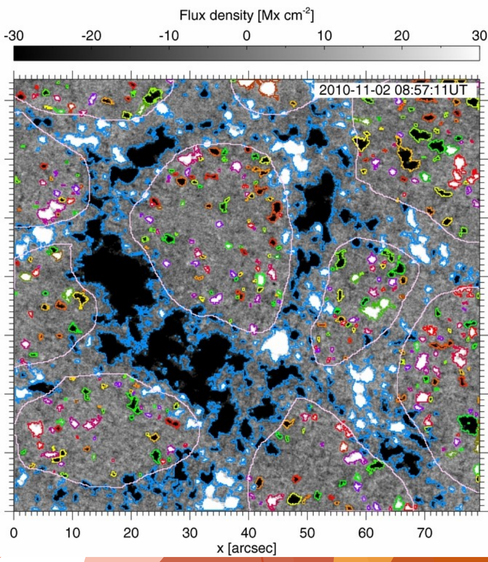
Current view



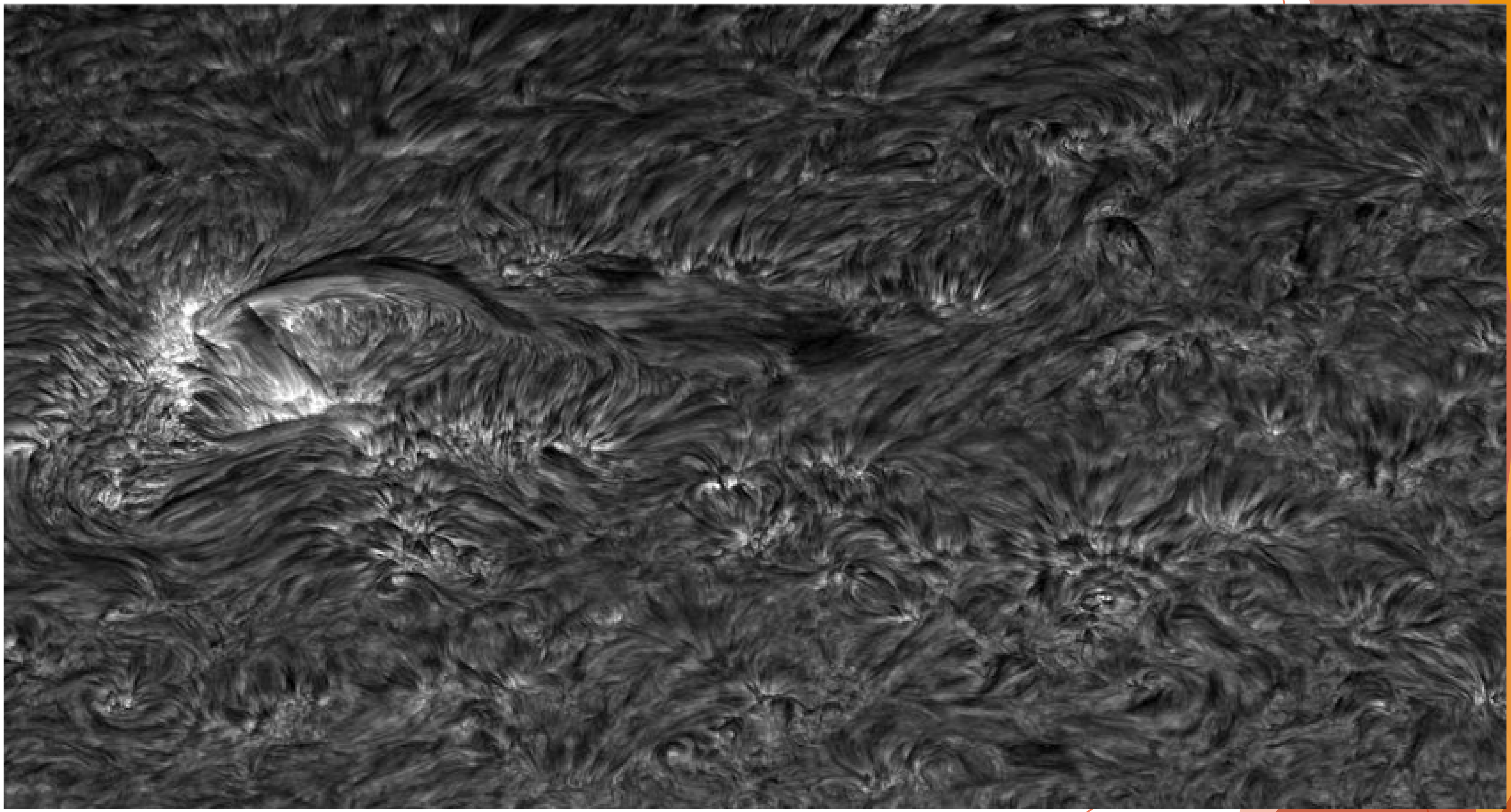
Current view

- The large-scale building blocks of the quiet Sun atmosphere are the **magnetic network patches**, which outline supergranulation cells
  - The magnetic field is highly structured and concentrated close to the "surface" (τ_{500} = 1) with **kG fields**
  - Network patches consist of a **conglomerate** of smaller magnetic elements or "flux bundles" of different field strength with a wealth of **substructure**
- The magnetic field spreads out in the layers above the patches, enclosing the weak-field internetwork and forming the "***magnetic canopy***"
  - Depending on the polarity of neighboring flux concentrations, the patches can form funnels or be connected via loops

Gošić et al. (2014) ApJ, 797, 49



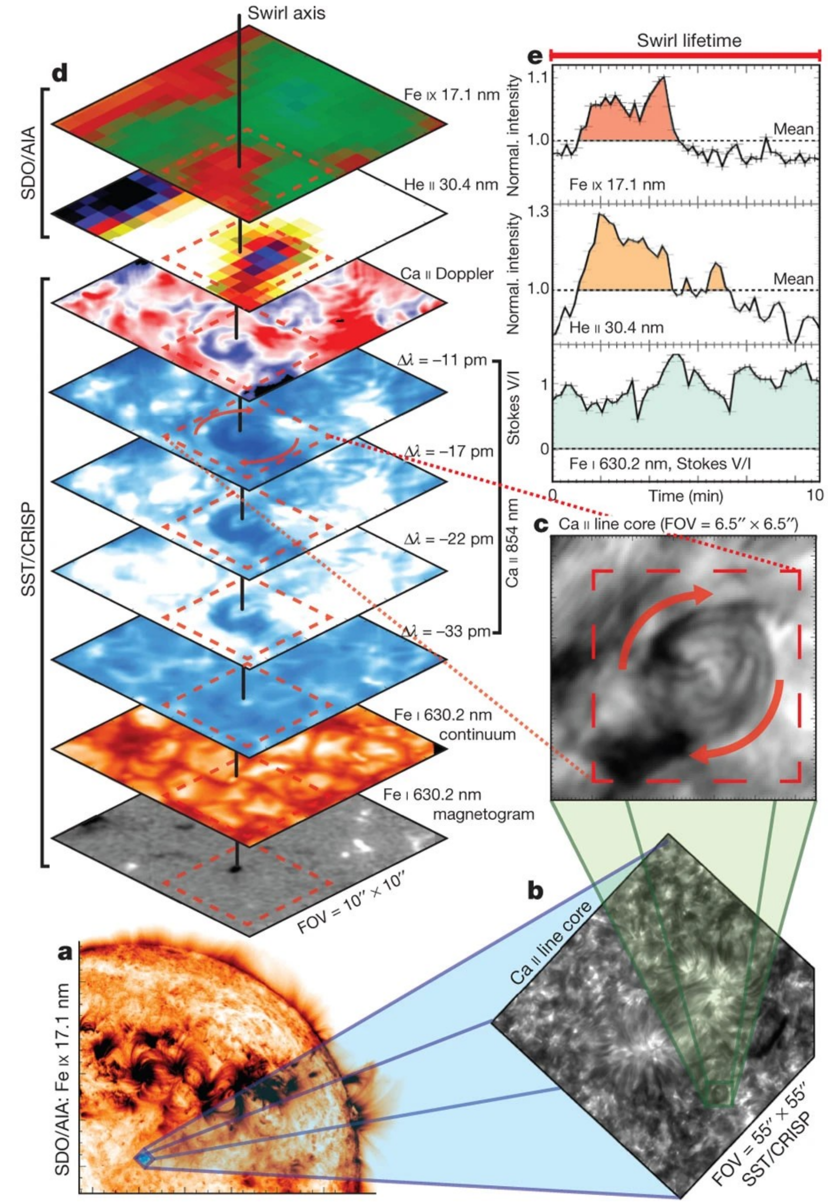
The canopy domain



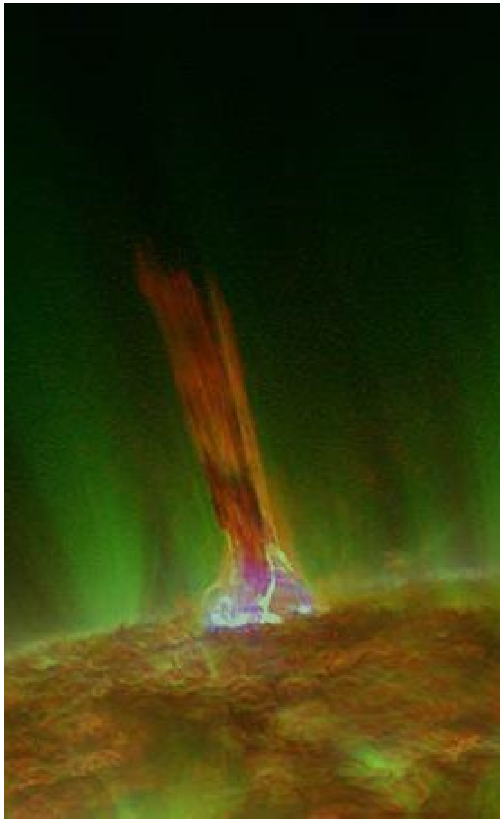
Wedemeyer-Böhm et al. (2012)
Nature, 486, 505

Magnetic tornadoes

- **Ubiquitous** structures that reach from the convection zone into the upper solar atmosphere
  - Convectively driven vortex flows that harbour magnetic fields are observed in the **photosphere**
  - Corresponding swirling motions have been discovered in the **chromosphere**
  - Imprints of these chromospheric swirls have been also revealed in the **TR and low corona**
- They provide an alternative mechanism for **channelling energy** into the upper solar atmosphere
- Relevant scientific interest



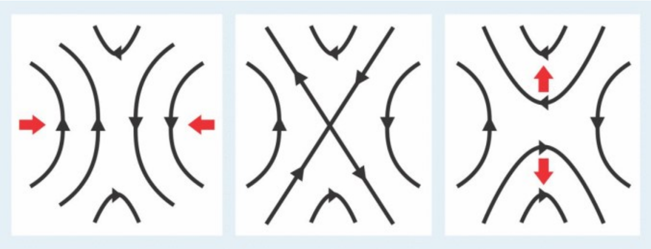
Interactions between new and pre-existing flux

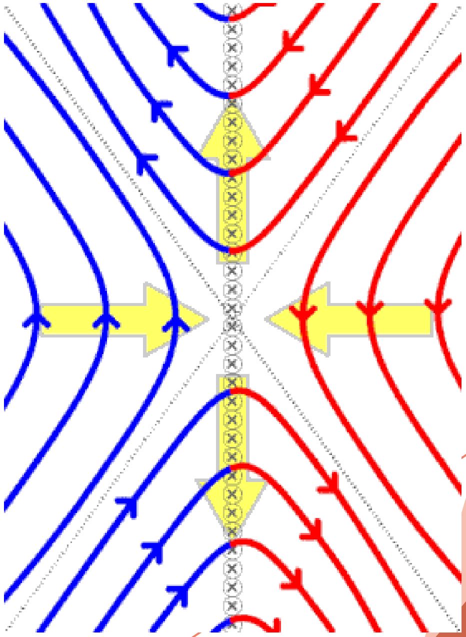


- A "hot" topic is the impact of **emerging flux regions (EFRs)** on the atmosphere
- Many phenomena occur when EFRs meet the pre-existing ambient field
  - **brightening, ejections (surges)**
  - **coronal heating (e.g., campfires)**
  - **flaring events, CMEs**
- The main responsible appears to be **magnetic reconnection**

Magnetic reconnection

- In the Sun, magnetic field lines are generally **“frozen”** into the highly conducting plasma
- **Magnetic reconnection** is a process arising due to the local increase of electrical resistivity
- Magnetic topology is **rearranged** and during the process magnetic energy is converted to
  - kinetic energy
  - thermal energy
  - particle acceleration



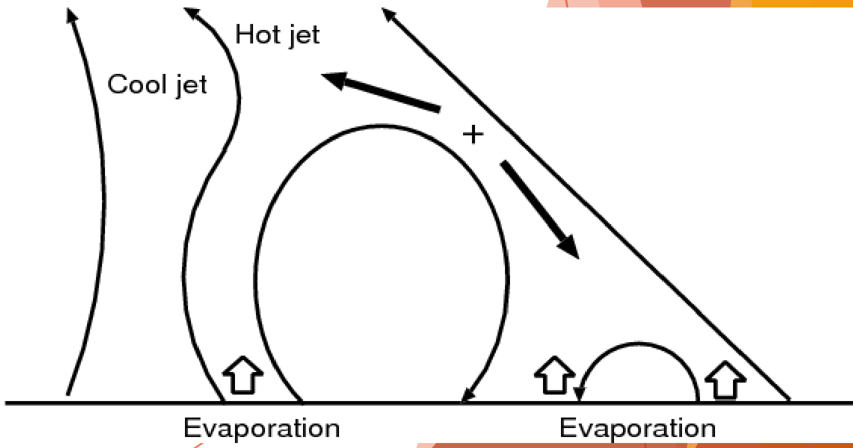


Interactions and magnetic reconnection

- Seminal works

Shibata et al. (1992), PASJ, 44, 265
Yokoyama & Shibata (1995), Nature, 375, 42

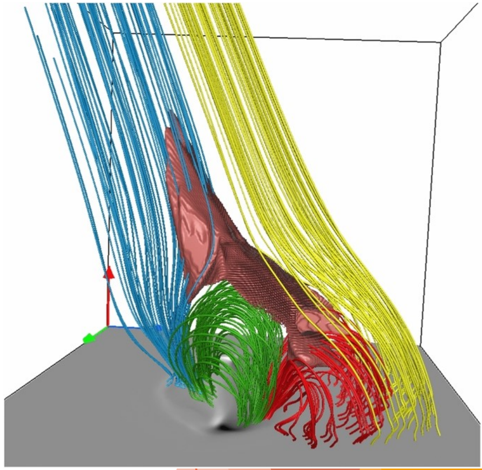
- Reconnection between emerging flux and an overlying field
- “the cutting of stressed magnetic field lines, which is associated with a violent release of energy”
  - **X-ray jets and Hα/Hβ surges can be ejected simultaneously**
  - **heating -> brightening**



Numerical models

(see Thursday's lessons)

Moreno-Insertis & Galsgaard (2013)



Numerical models show that the interaction between flux systems depends on:

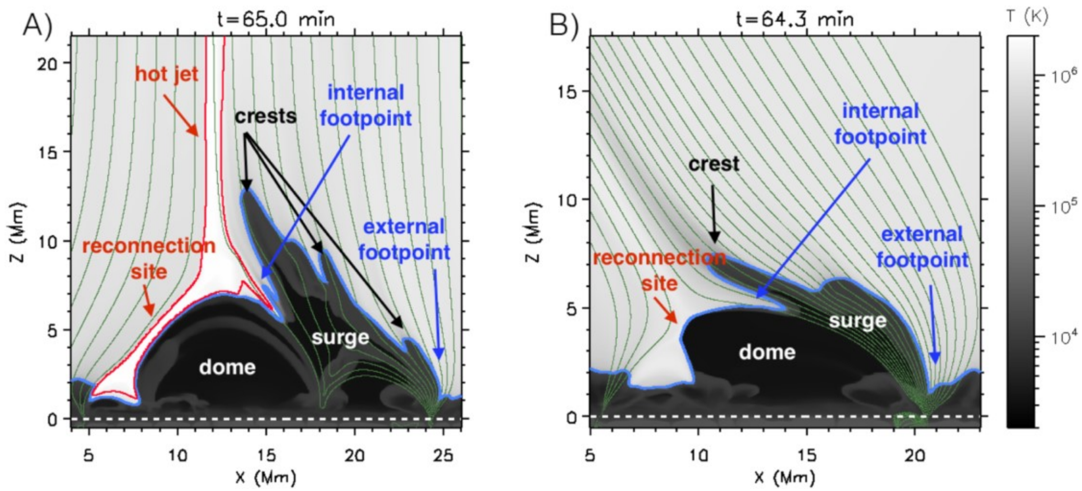
1) the strength of the fields involved
2) the total amount of flux
3) the relative angle between them
4) the height at which reconnection occurs

e.g. **Archontis et al.** (2004); **Galsgaard et al.** (2005), 2007); **Isobe et al.** (2007); **MacTaggart et al.** (2015); **Ni et al.** (2015, 2016, 2018a,b,c, 2020, 2021); **Hansteen et al.** (2017, 2019); **Isliker et al.** (2019); **Peter et al.** (2019), **Priest's group** (2018, 2019, 2020)

review **Cheung & Isobe** (2014)

Numerical models

(see Thursday's lessons)



- **Nóbrega-Siverio et al.** (2016, 2017, 2018) carried out small-scale 2.5MHD radiative numerical simulations, considering total magnetic flux $\Phi \approx 10^{19}$ Mx, and demonstrated the occurrence of **surges** and **brightenings** when emerging fields interact with ambient fields

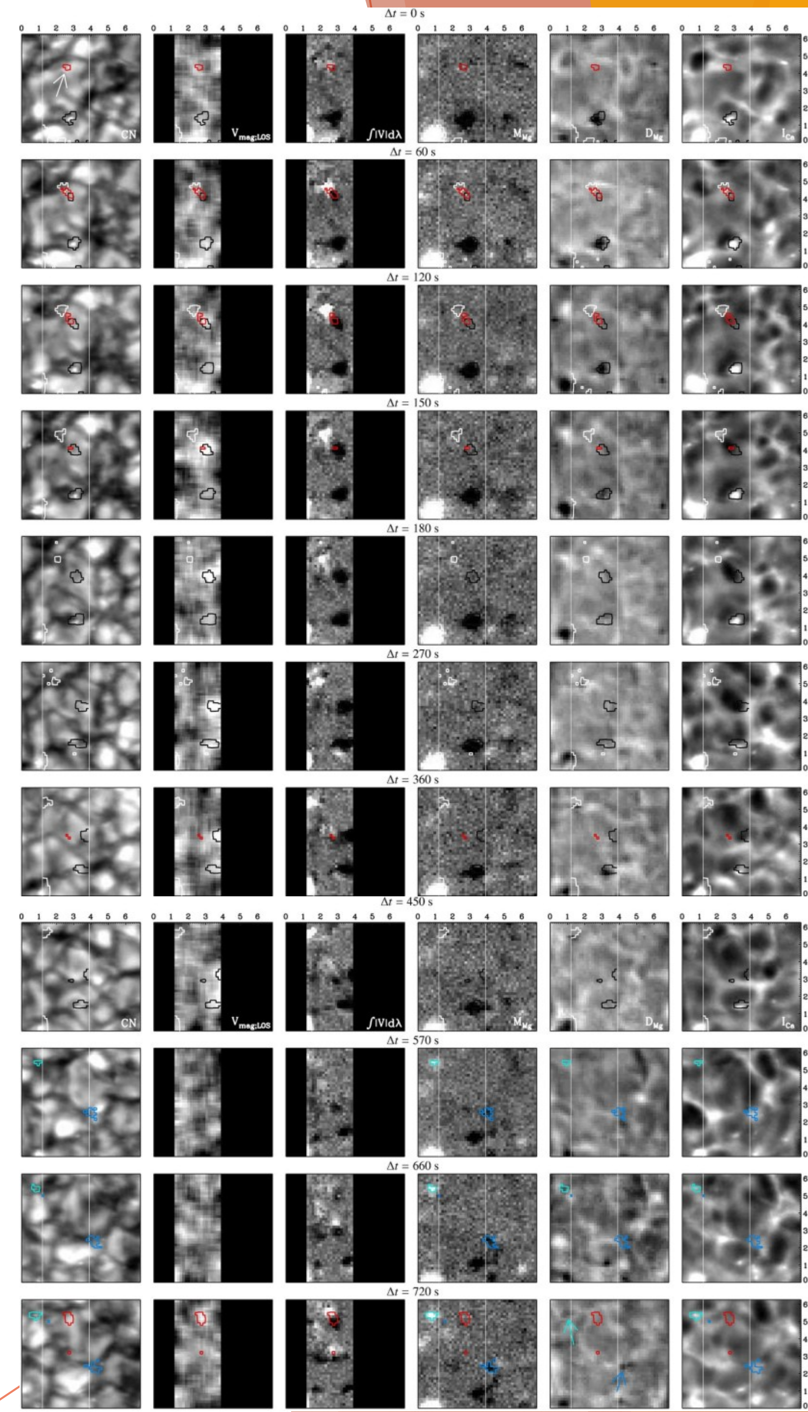
Scientific cases

Small bipoles in the chromosphere

- *Hinode*/SOT (2007)
- Simultaneous observation:
  - CN band (intensity)
  - Fe I 630nm line pair (full Stokes)
  - Mg I b 517.3nm (I&V only)

- First evidence that **small-scale bipoles** emerging through the photosphere are able to reach the **chromosphere**

Martínez González & Bellot Rubio (2009)
ApJ, 700, 1391



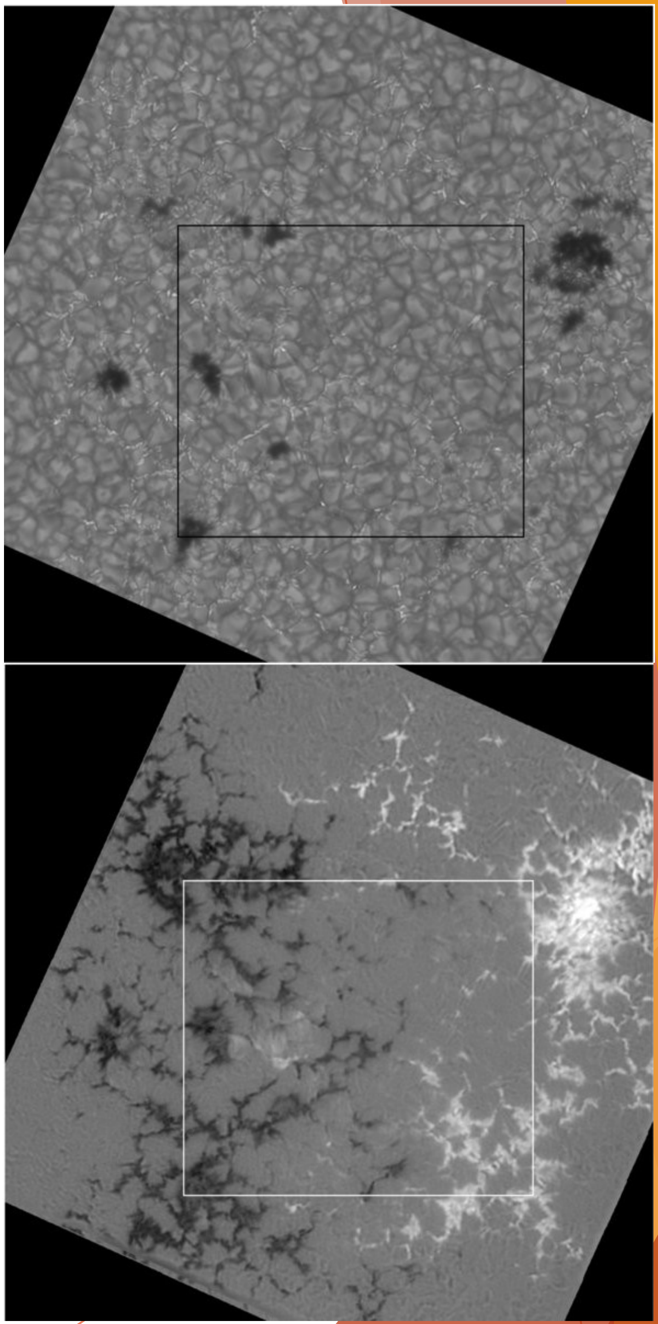
Hinode observations: an EFR close to pores

ACTIVE REGION NOAA 10971 – SEPTEMBER 2007

Guglielmino et al. (2008), ApJL, 688, L111
Guglielmino et al. (2010), ApJ, 724, 1083

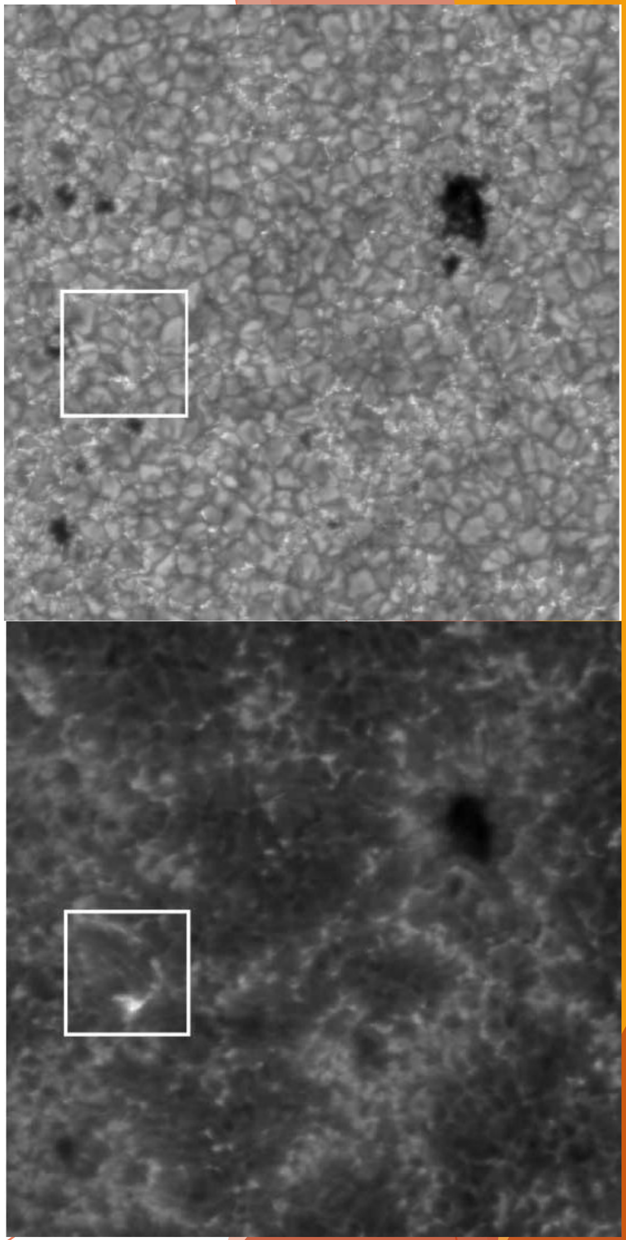
Data and context

- **SST** filtergrams data
  - Ca II H line core 396.85 nm
  - **G band 430.56 nm**
  - **Fe I 630.25 nm Stokes I&V (LOS magnetograms)**
  - Hα line core 656.29 nm
  - Fe I and Hα continua (reference channels)
- Diffraction-limited resolution: 0.2" (MOMFBD reconstruction)



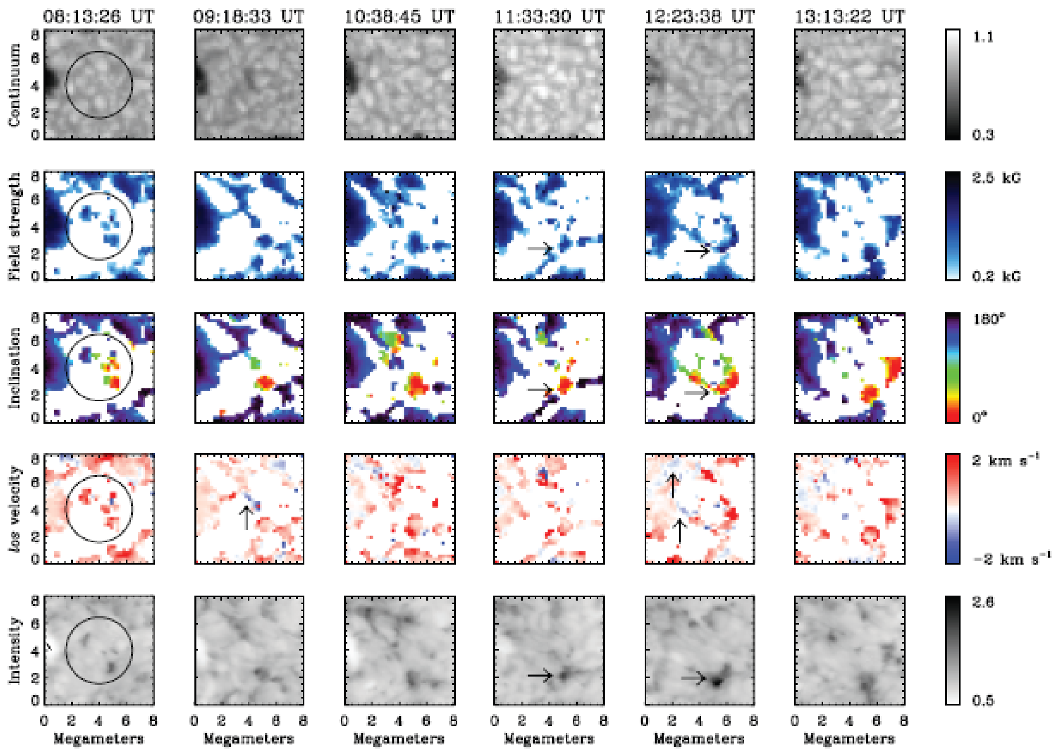
Data and context

- *Hinode* SOT/FG
  - G band 430.56 nm
  - Ca II H 396.85 nm
  - Na I D1 589.59 nm Stokes I&V
- *Hinode* SOT/SP
  - Full Stokes IQUV along Fe I at 630.2 nm pair
- *Hinode* EIS raster scans at 18 – 26 nm
  - O VI 184.12 Å, Fe XII 195.12 Å
  - He II 256.32 Å, Mg VII 278.39/280.75 Å, Si X 258.37 Å
- *Hinode* XRT
  - Filters: Carbon polyimide, Be thin/thick



Photospheric evolution of EFRs and atmospheric response

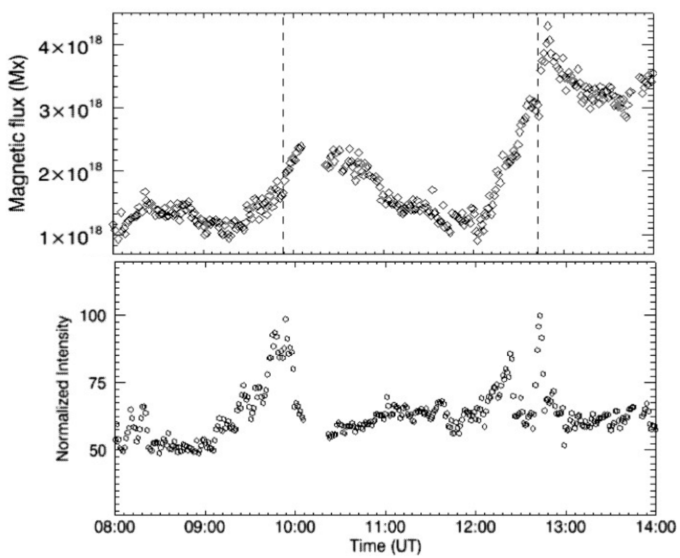
- Magnetic flux emergence detected using **SOT/SP & SOT/FG** in the middle of the AR
  - **emergence zone** with upflows (1.5 km s^{-1}) and B_h fields (1 kG)
  - **bipolar footpoints** with downflows (2 km s^{-1}) Bz fields (2 kG)
- Magnetic flux content: ≈1.4×10^{19} Mx
- Lifetime: ≈6 hours

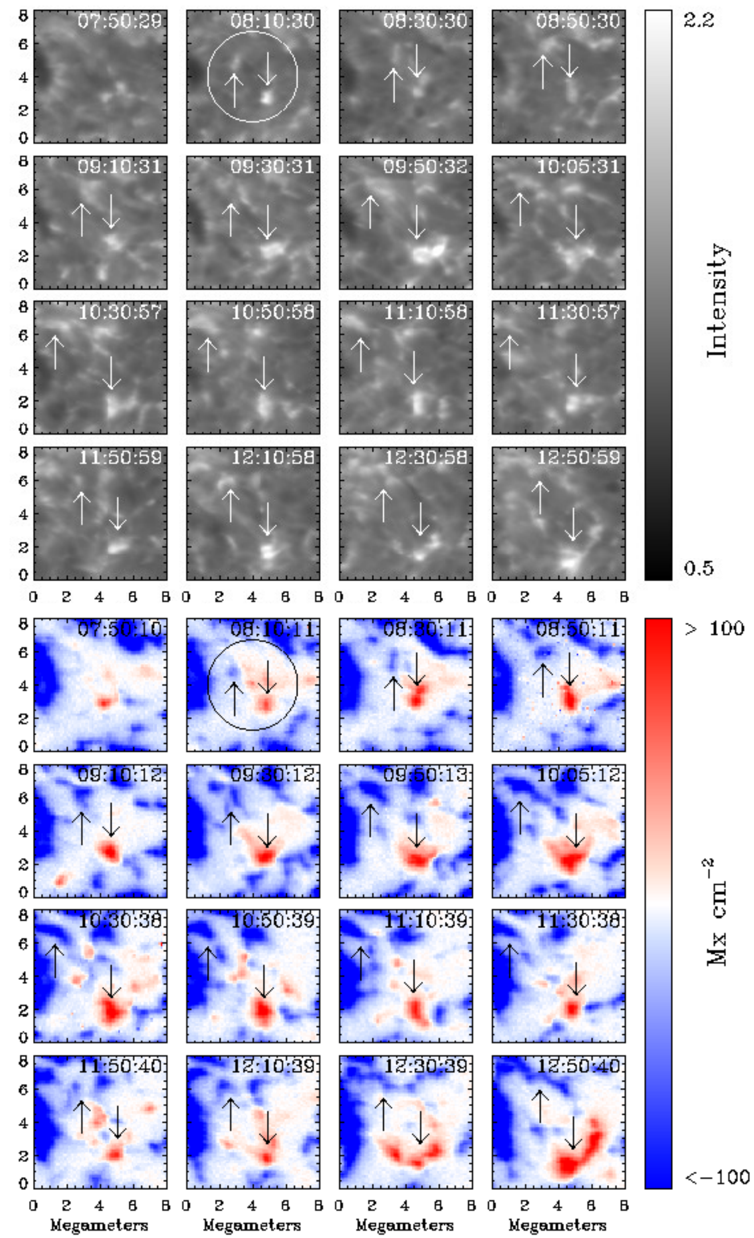


Guglielmino et al. (2008) ApJL, 688, L111

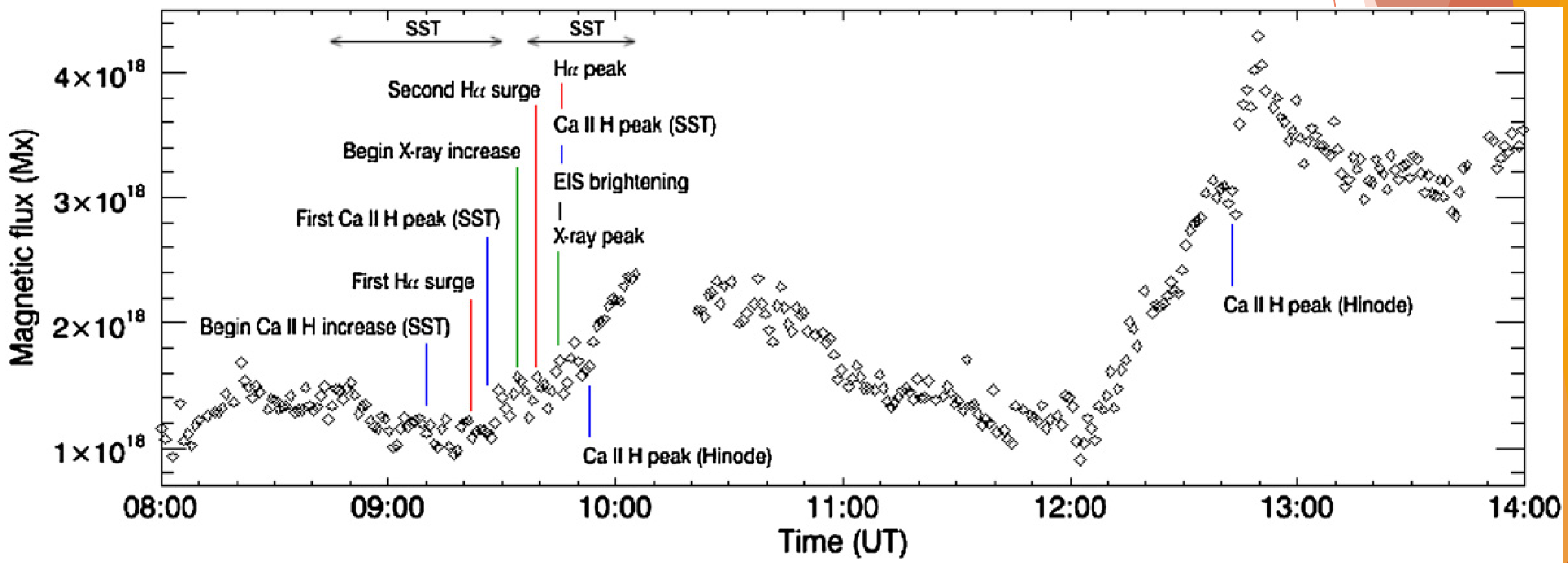
Response to EFR in the chromosphere

- Intensity peaks of chromospheric origin observed in the **Ca II H** line-core, with a small delay with respect to the magnetic flux increase





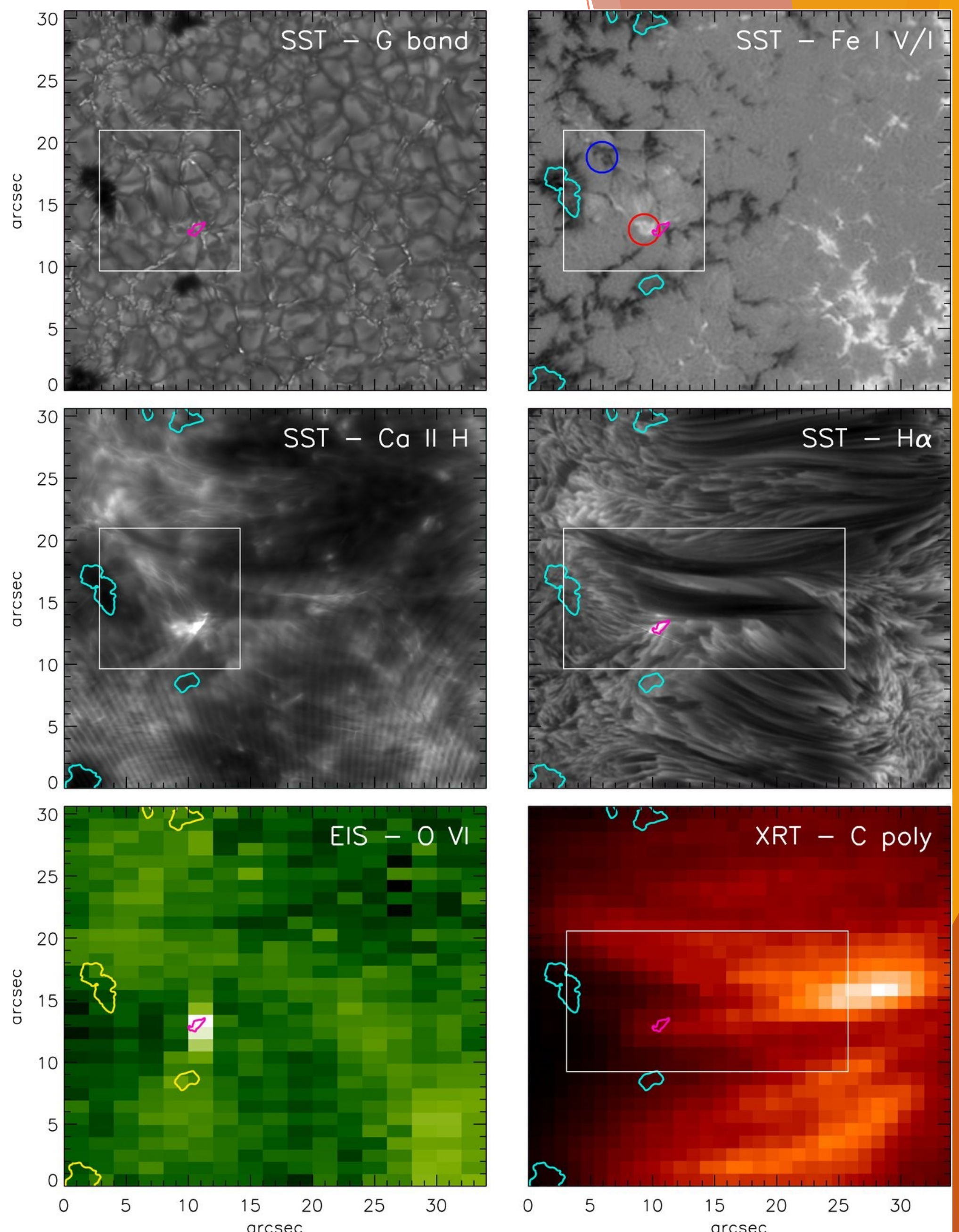
Flux history and full atmospheric response from the photosphere to the corona



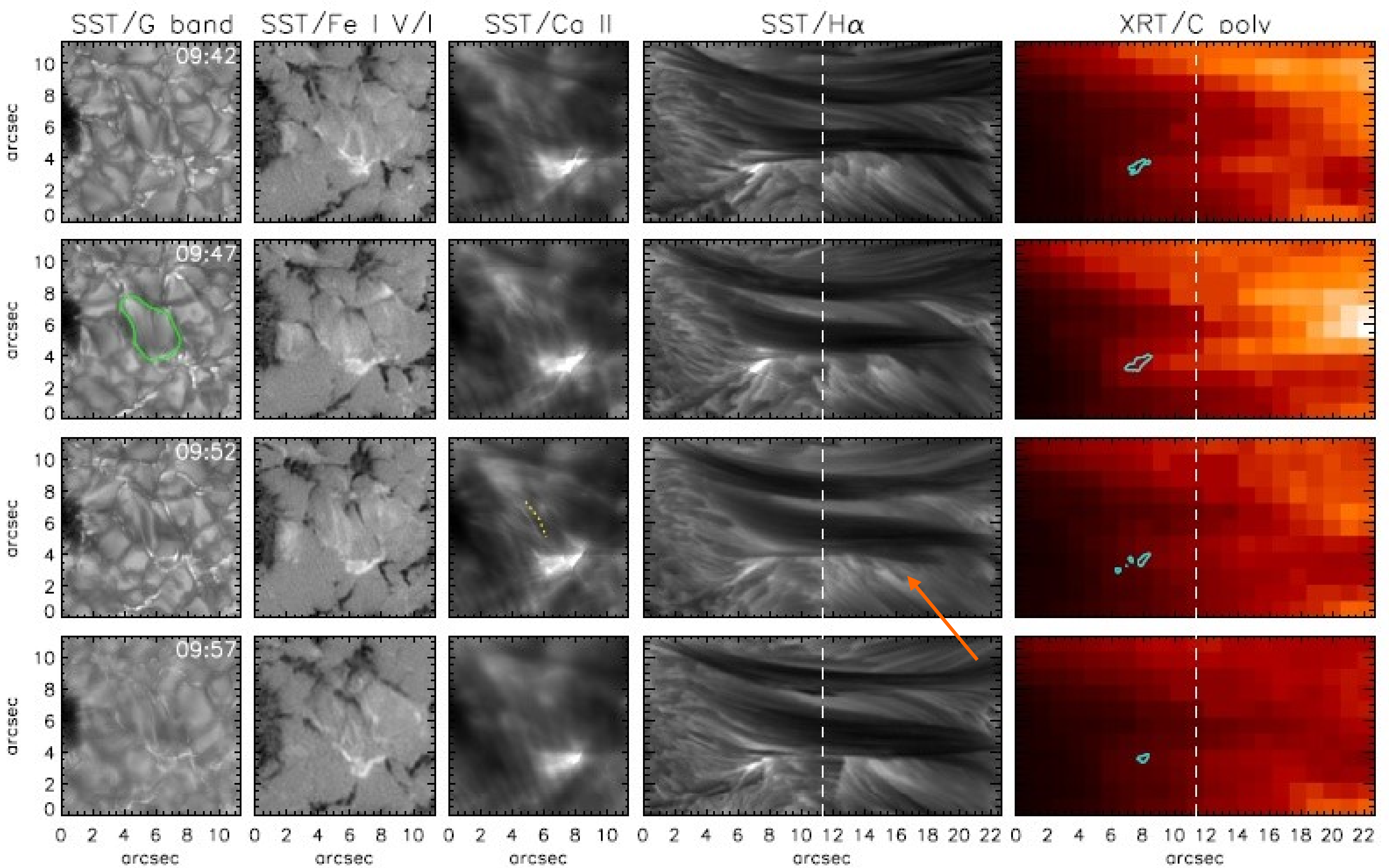
Guglielmino et al. (2010), ApJ, 724, 1083

Response in EUV and X-rays

- EFR observed at 9:45 UT by **SST** and ***Hinode*** (**SOT-EIS-XRT**)
- It shows clear signatures in **all the layers** of the solar atmosphere.
  - Localized **brightenings** in **Ca II H** and **Hα lines**
  - The enhancements begin in the **low atmosphere**
  - Chromospheric peaks, EUV brightenings and maximum X-ray intensity are **simultaneous**

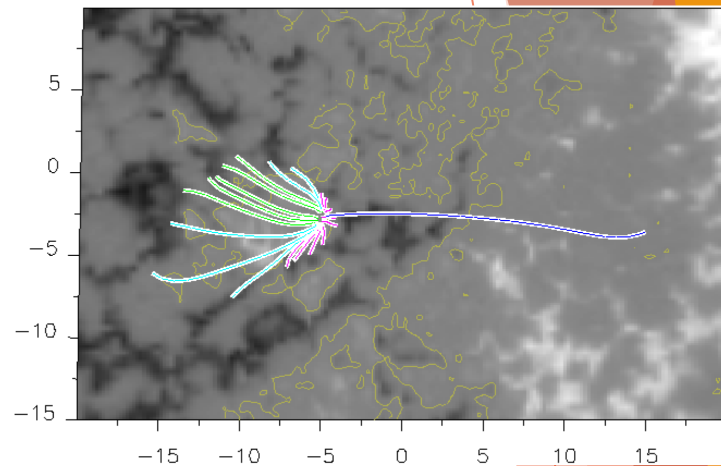


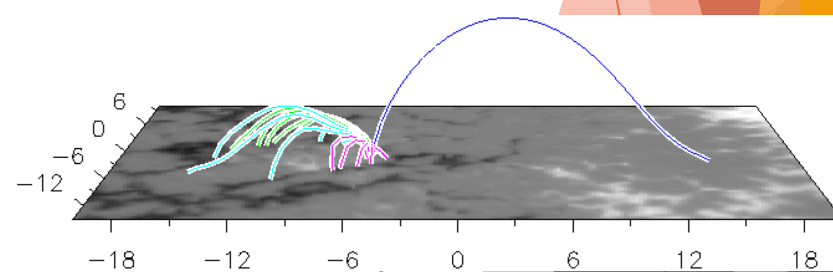
Response in Hα and X-rays: surge and loop enhancement



Magnetic topology inferred by extrapolations

- Potential and lfff extrapolations indicate that the EFR field lines reconnect with the ambient field
- The EFR emergence gives rise to a quadrupolar field topology, with a **fan-spine configuration**
- The **spine** is cospatial to the **surge**
- Extrapolations are not able to retrieve the correct connectivity between the EFR polarities
- Shear/twist would be needed

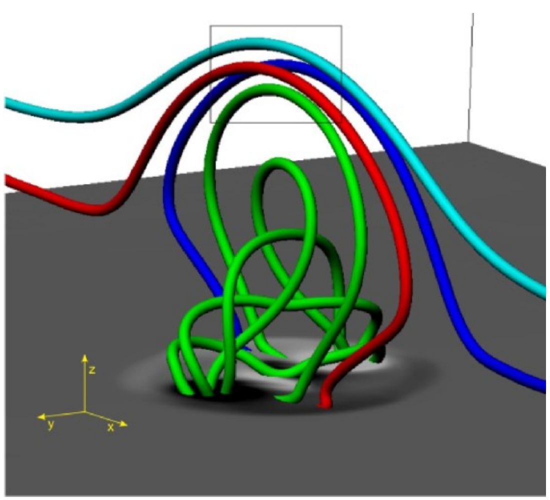


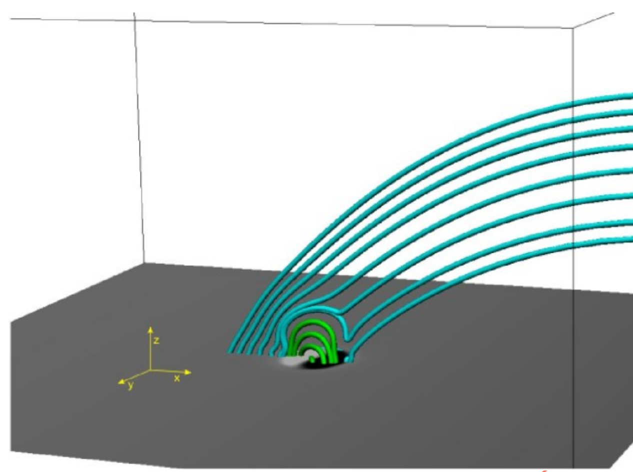


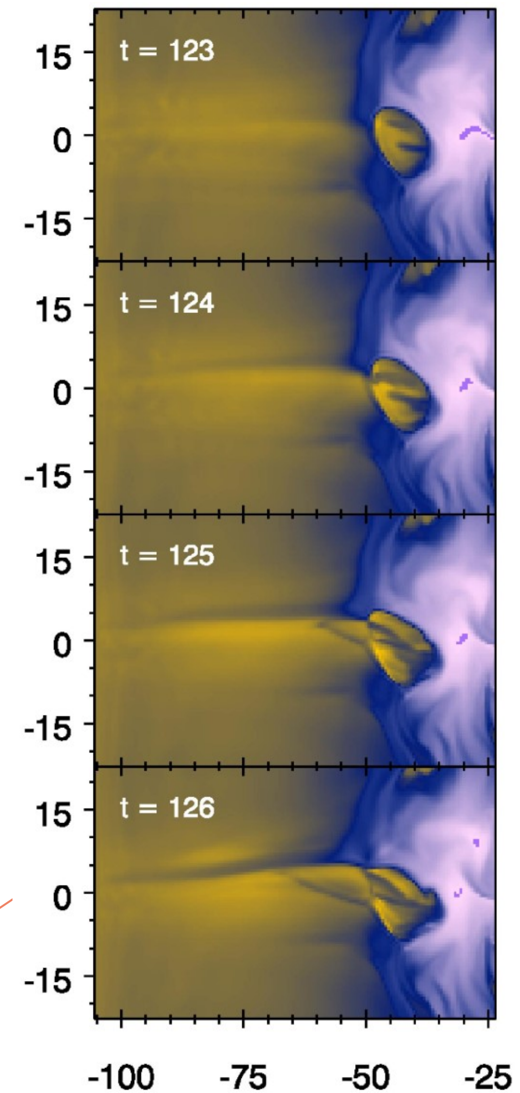
Data-driven simulations

MacTaggart et al. (2015) A&A, 576, A4

- MHD simulations were used to model this EFR, confirming the proposed scenario
- An **asymmetric** ambient field can result in preferred locations for reconnection, acting as a **guide field** for the surges





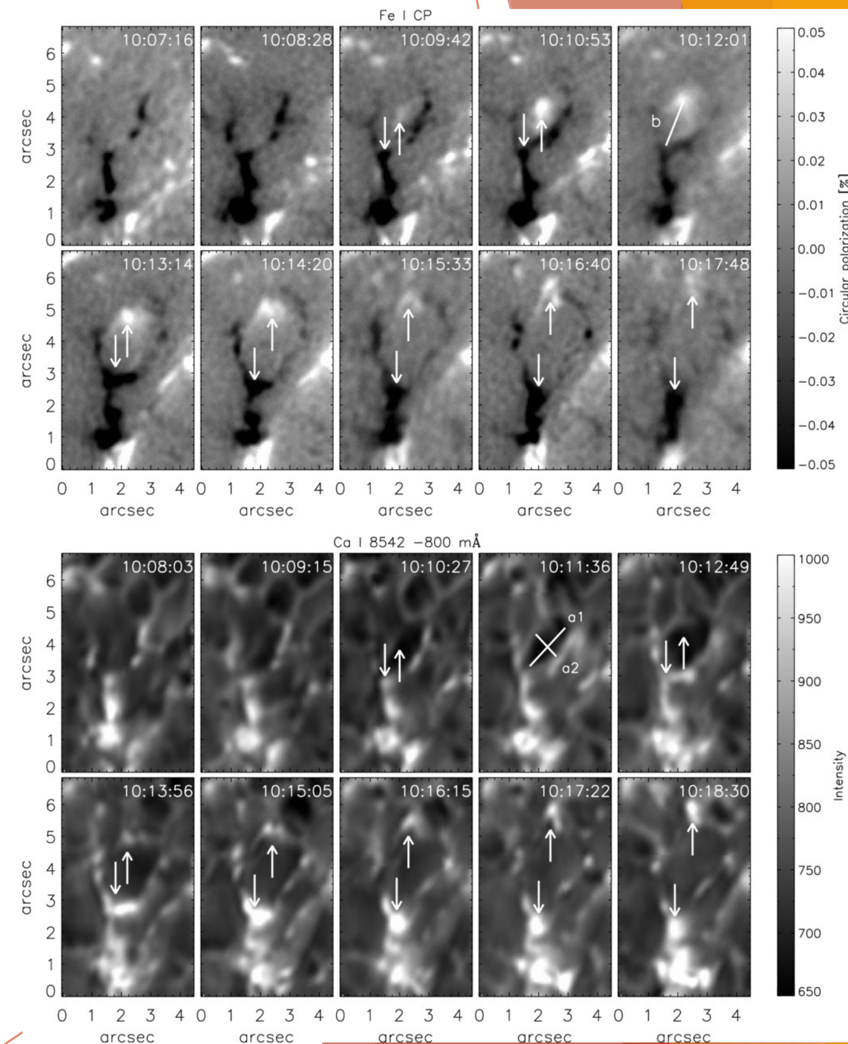


Other scientific cases

Emergence of magnetic bubbles through the solar atmosphere

Ortiz et al. (2014), ApJ, 781, 126

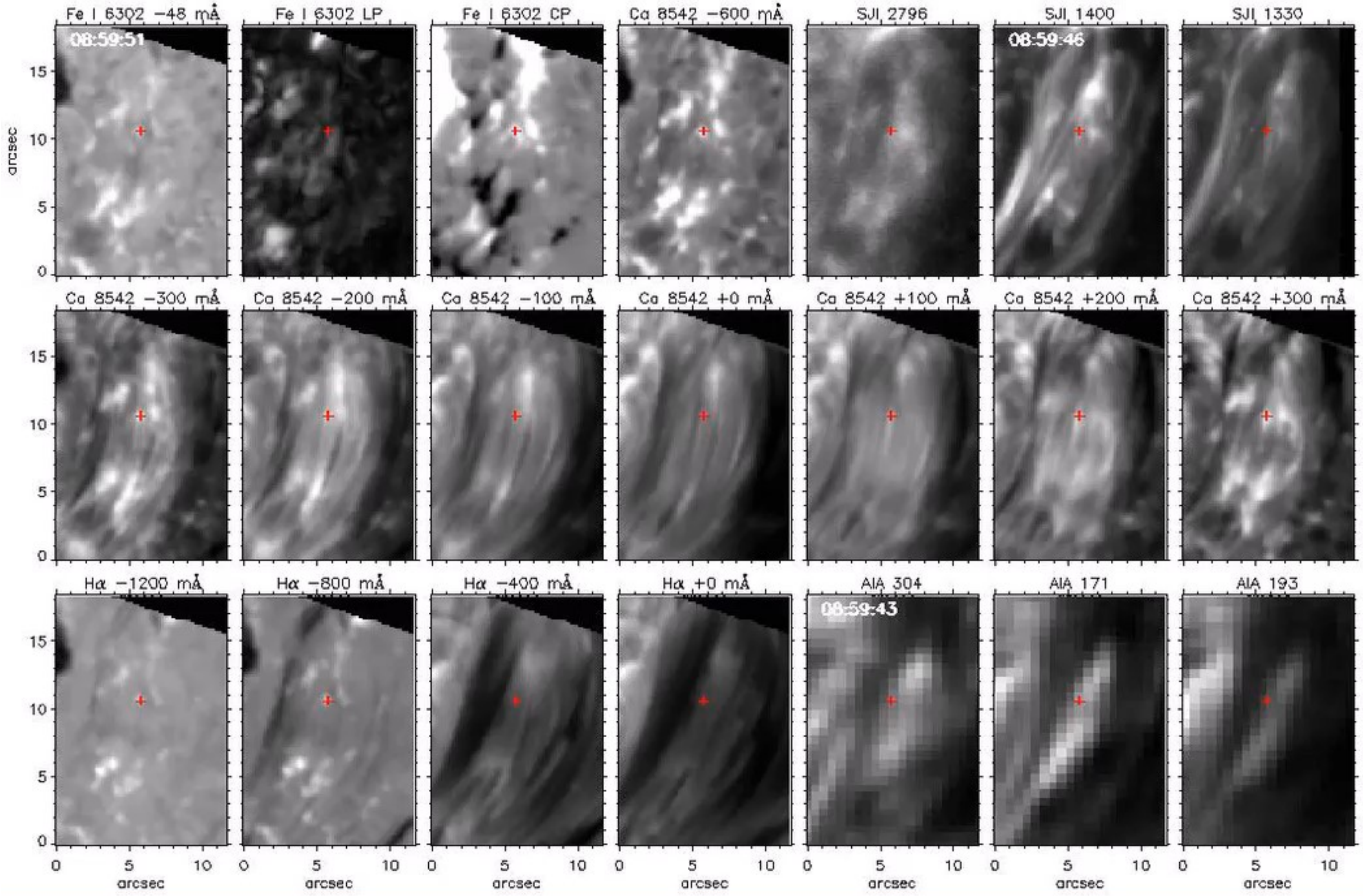
- High resolution observations of SST/CRISP along the Fe I 630.2 and Ca II 854.2 nm lines
  - abnormal granulation, separation of opposite polarities, and brightenings at chromospheric heights
  - Ca II **dark bubbles** in coincidence of horizontal magnetic field patches
  - the dark bubble rise in a few minutes into the chromosphere, with a speed of **-5 km s^{-1}**
  - temperature deficit of **250 K**



Emergence of magnetic bubbles through the solar atmosphere

Ortiz et al. (2014), ApJ, 781, 126

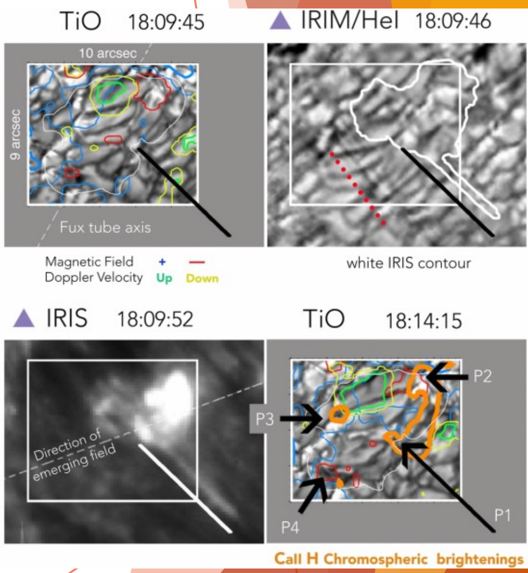
***SST* - IRIS - SDO**



Vargas Domínguez et al. (2014) ApJ, 794, 140

Emerging bipoles at granular scale and atmospheric response

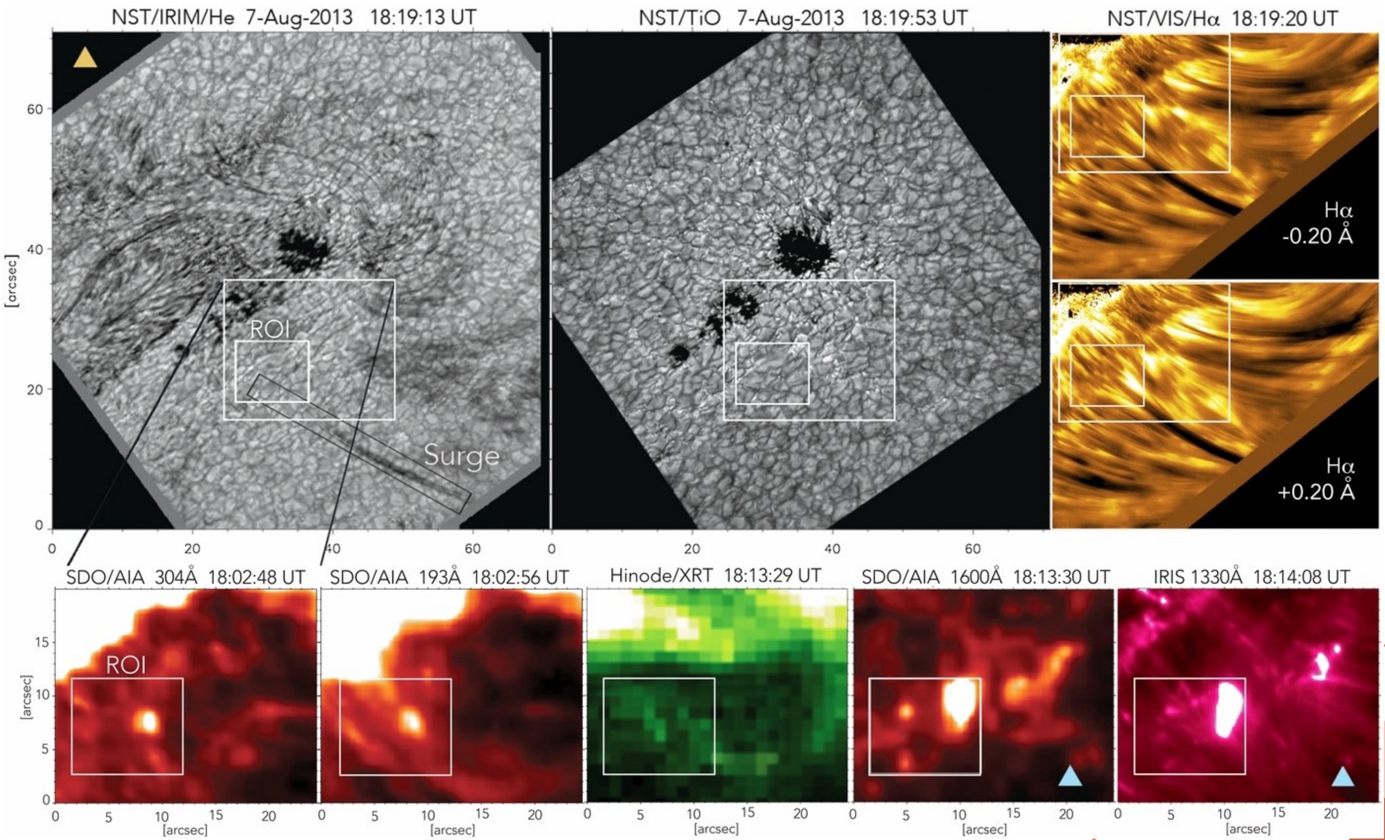
- A **small-scale** buoyant horizontal magnetic flux tube causes granular alignments and interacts with the preexisting field in the upper atmospheric layers, close to solar pores
- Sudden appearance of an extended **surge** in the He I line; a hot plasma jet is associated with
- Emerging magnetic loop-like structures
- The interaction of emerging twist field lines with the pre-existing overlying field generates **high-temperature emission** regions and boosts the **surge/jet** production



Vargas Domínguez et al. (2014)
ApJ, 794, 140

Emerging bipoles at granular scale and atmospheric response

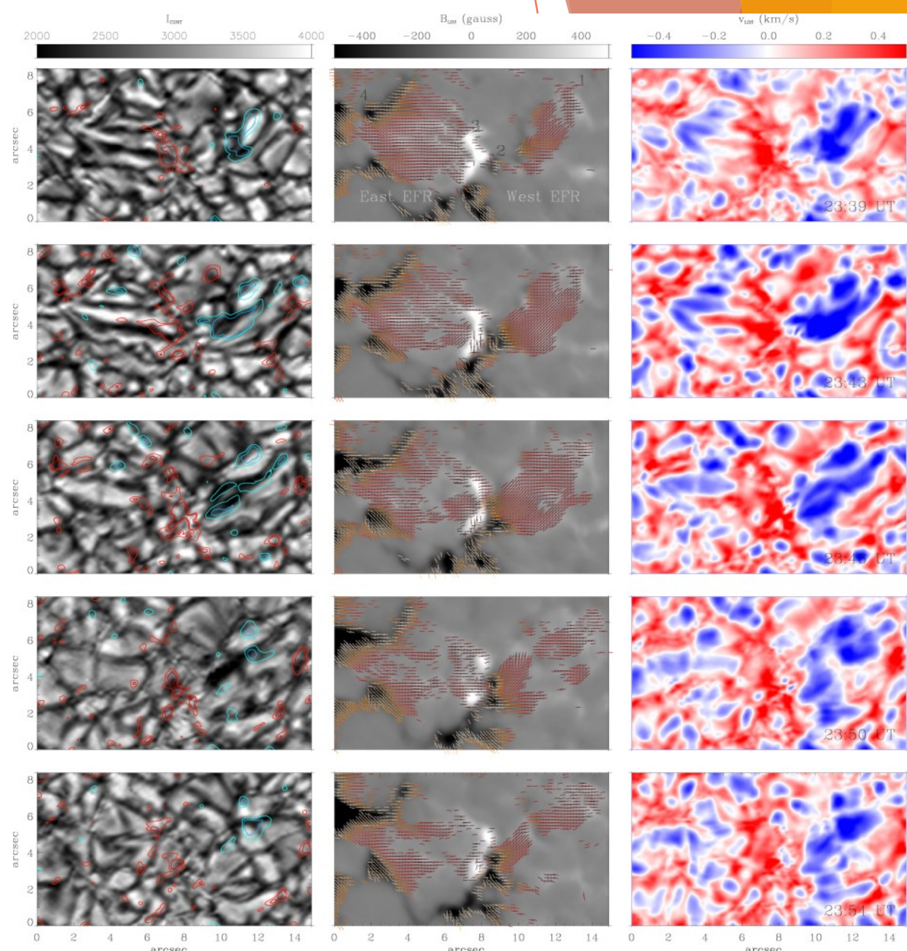
NST - IRIS – *Hinode* - SDO



Two small EFRs with a chromospheric response

Centeno et al. (2017) ApJSS, 229, 3

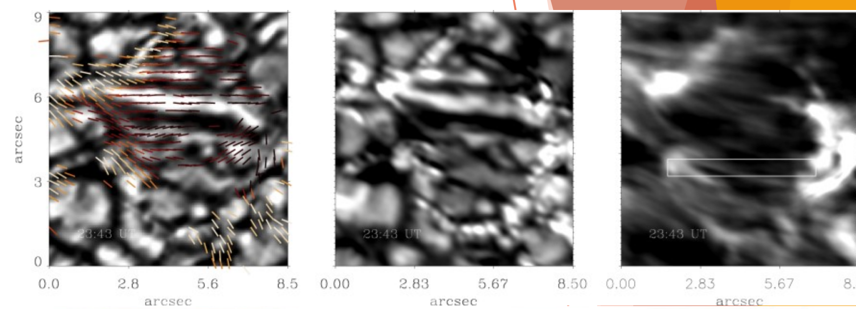
- Joint observation of Sunrise: **IMaX** and **SuFI**
- Two small (≈5") emerging flux photospheric patches, following their **chromospheric response**
  - The rising magnetic fields interact with the granulation
  - The plasma that is burdening the rising field slides along them, creating **fast downflowing channels**
  - This falling material shapes the field in an **undulatory fashion**
  - **Magnetic reconnection** enables the field to release itself from its anchoring, allowing it to continue its voyage up to higher layers

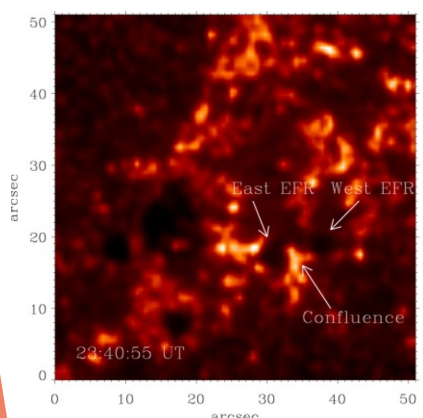


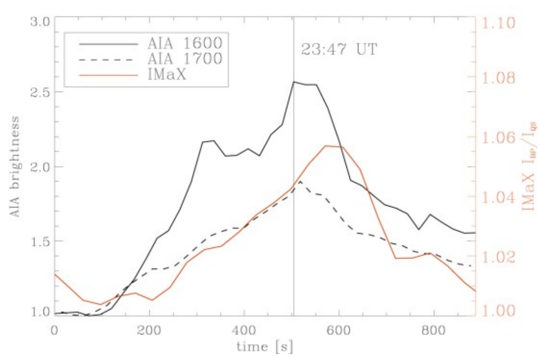
Centeno et al. (2017) ApJSS, 229, 3

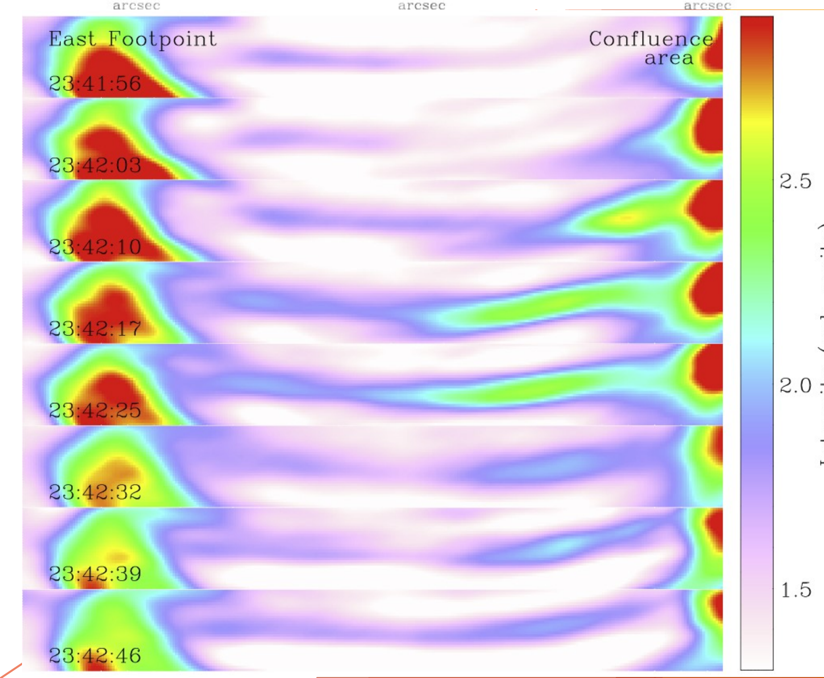
Two small EFRs with a chromospheric response

- Magnetic reconnection in the **low atmosphere** release energy that lights up the overlying AFS and **heats** the surrounding chromosphere





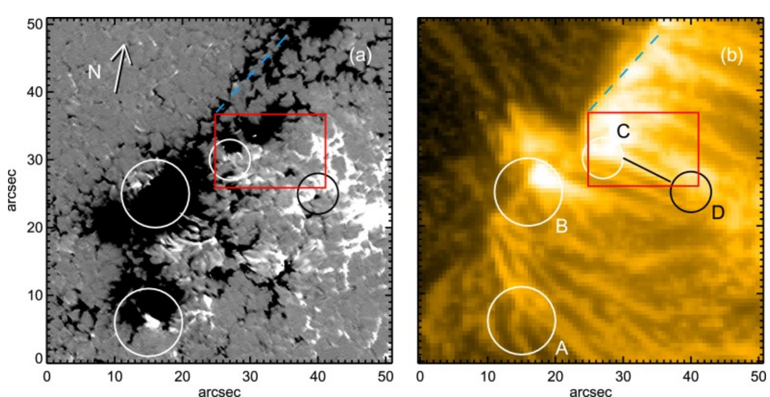


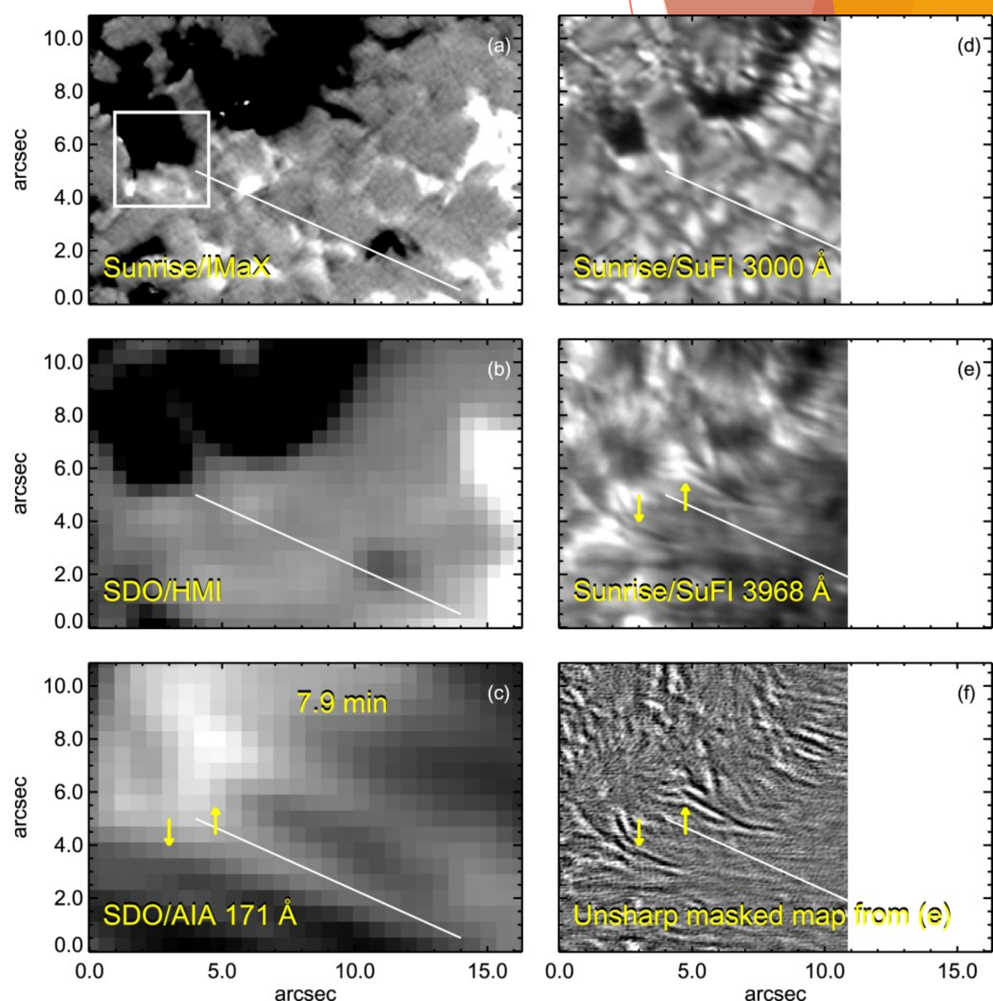


Chromospheric and coronal heating

Chitta et al. (2017) ApJSS, 229, 4

- SUNRISE hi-res observations detected **mixed polarities** at the footpoints of bright coronal loops
  - IMaX revealed cancellation of photospheric magnetic flux at a rate of ≈10^{15} Mx s^{-1}
  - SuFI observed small-scale chromospheric jets, with inverse-Y shape

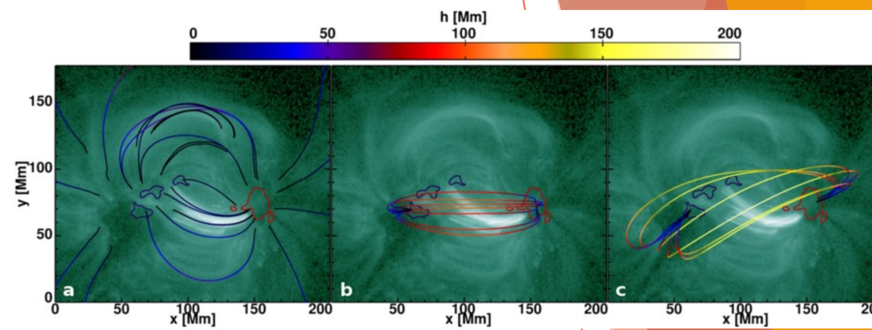


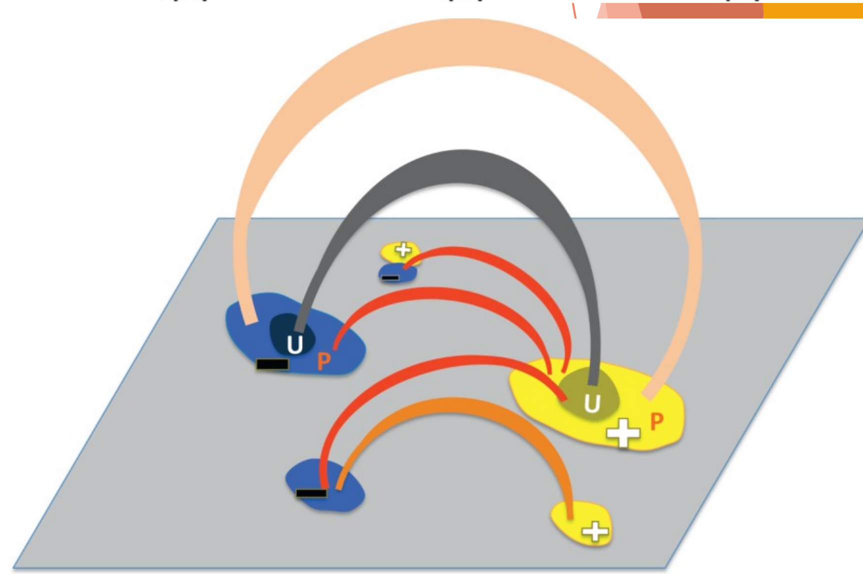


Chromospheric and coronal heating: other evidence

Tiwari et al. (2017) ApJL, 843, L20

- Brightest loops have one root in the regions of **mixed-polarity flux** and the other in kG regions (umbra/penumbra)
- Loops connecting unipolar plages are less bright
- "umbra-to-umbra" loops **invisible**
  - higher Poynting flux via magnetoconvection
  - higher dissipation rate through reconnection
  - fields braided by convective motions
- Heating depends on the **footpoint field configuration**



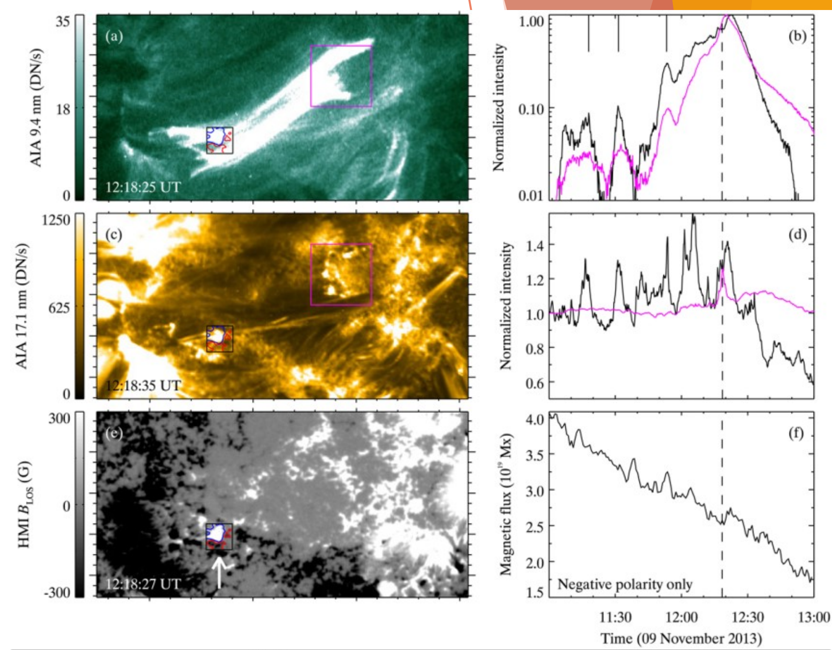


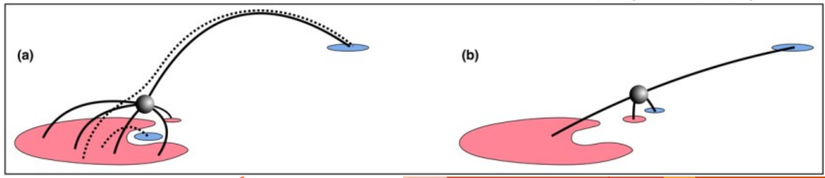
Chromospheric and coronal heating: nanoflares

Chitta et al. (2018) A&A, 615, L9

Chitta et al. (2020) A&A, 644, A130

- Support by observationally motivated **analytic models** of flux cancellation **(Priest et al. 2018; Syntelis et al. 2019; Syntelis & Priest 2020)**
- Complex **mixed polarity** field distribution is associated to flux cancellation and energy release heating the corona in **AR and plages** **(Chitta et al. 2018, 2019, 2020)**
- Photospheric HMI and multiband UV/EUV AIA observations may confirm the scenario also in the **quiet Sun** **(Park 2020; Chitta et al. 2021)**





To be continued…