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

Salvo Guglielmino - INAF Catania

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

Outline

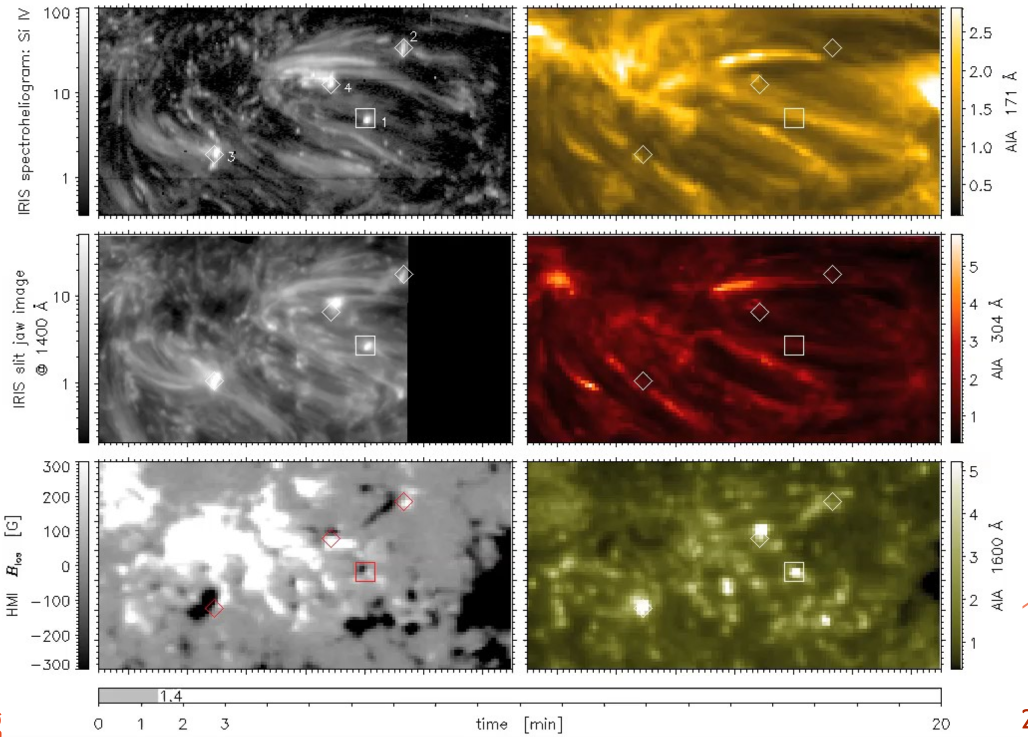
- **Magnetic coupling**
  1. from large scale … to small-scale features
  2. current view of the solar atmospheric structure
- **Interactions**
  - magnetic reconnection
- **Scientific cases**
  1. **Case study:** *Hinode* observations near pores
  2. Coronal heating
- **Interactions in the *IRIS* era**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

Interactions in the *IRIS* era

UV bursts / *IRIS* bombs

Peter et al. (2014)
Science, 346, 1255726

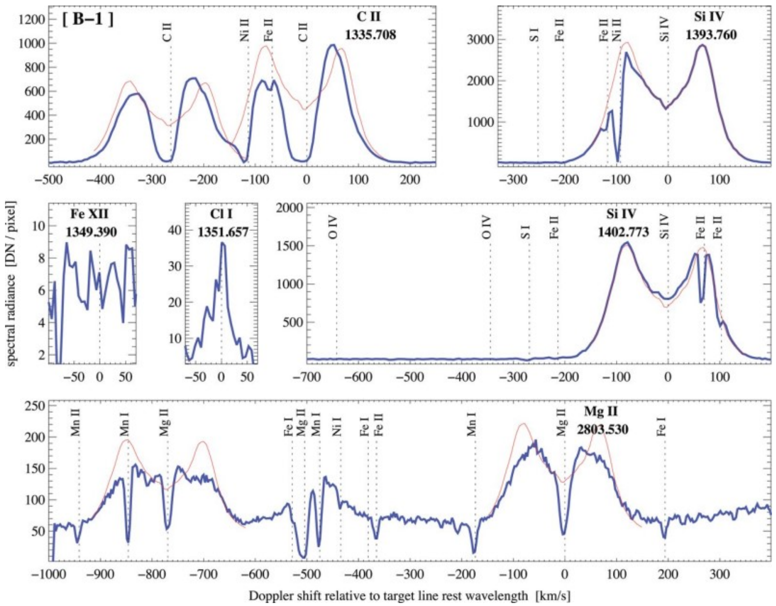
- A new phenomenon whose nature is debated
- **e.g. Vissers et al. (2015); Rouppe van der Voort et al. (2017); … ; review Young et al. (2018)**

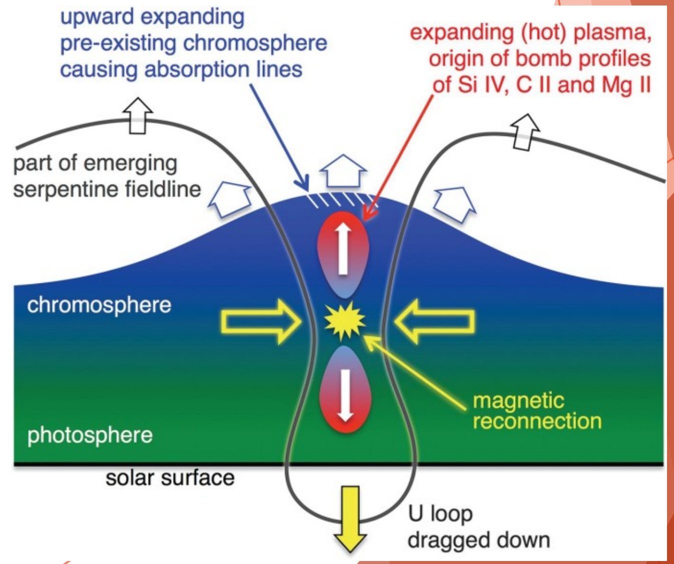


UV bursts / *IRIS* bombs

Peter et al. (2014)
Science, 346, 1255726

- Magnetic energy is converted into internal and kinetic energy by **magnetic reconnection**
  - heating and mass loading of coronal loops
  - small brightening events are visible in Si IV line
  - “pockets” of hot plasma transiently heated up to **10^5 K**



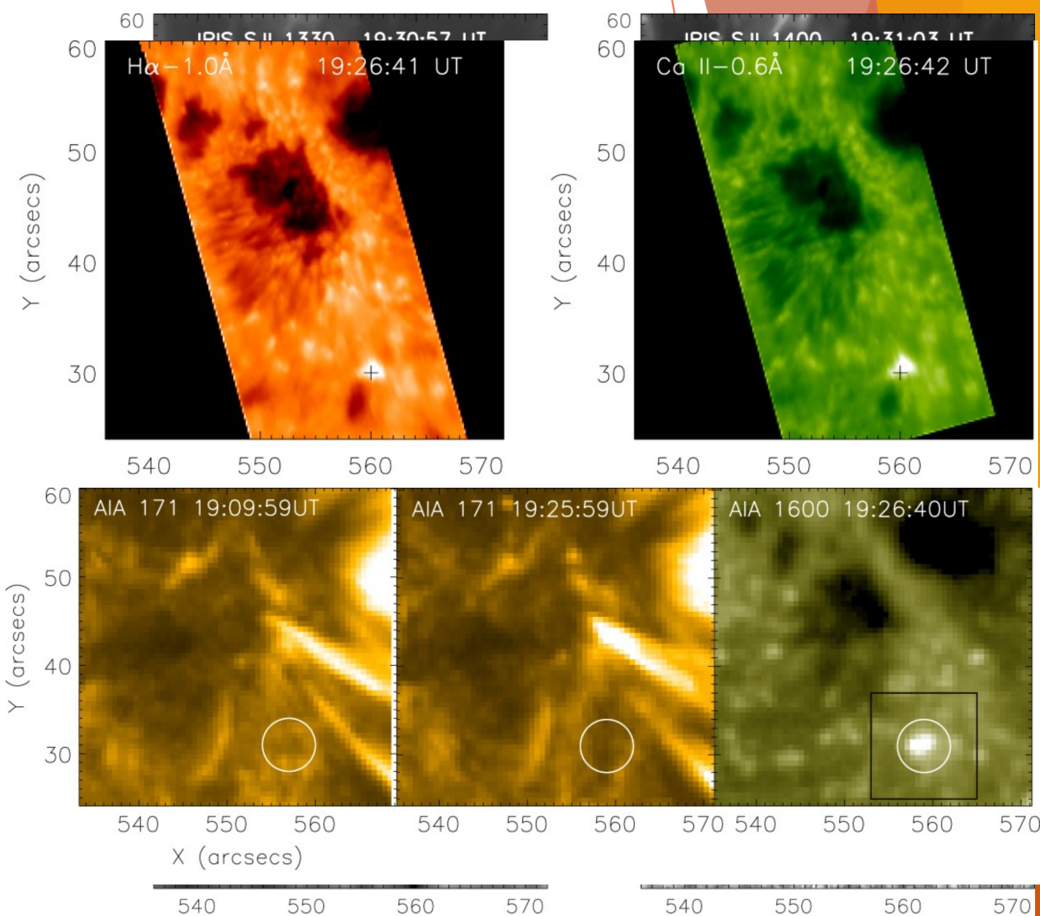


Kim et al. (2015)
ApJ, 810, 38

Small-scale emergence and chromospheric/TR response

NST - IRIS - SDO

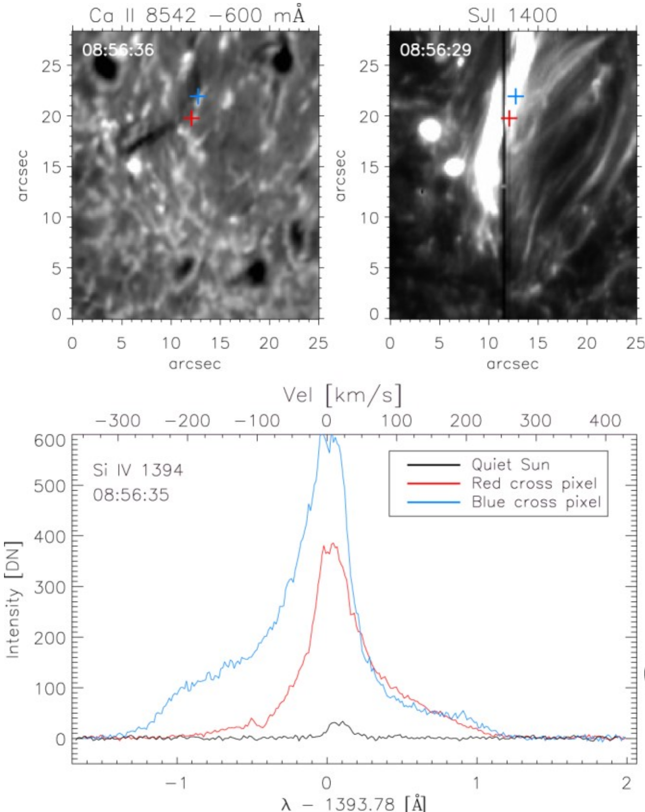
- Simultaneous observations of "hot explosions" in the cool atmosphere
- Emergence of positive flux triggers the explosion
- The Si IV emission profile shows a double-peaked shape with components at -40 km s^{-1} and 80 km s^{-1}
- Only the low atmosphere appears to be involved

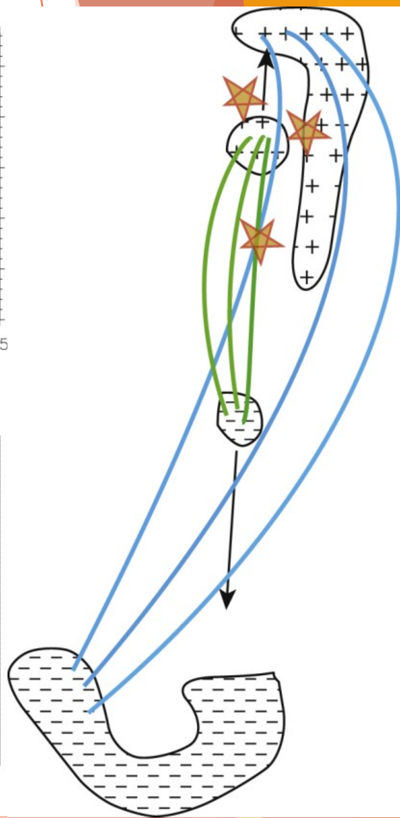


Emergence of magnetic bubbles up to the TR

Ortiz et al. (2016) ApJ, 825, 93

- Delay of ≈10 minutes between the emergence of the horizontal fields and the loop-like connection in the **transition region**
- Evidence of significant amounts of **cool material** above both EFRs
- The new magnetic field pushes the outer magnetic atmosphere **upward**, interacting — and eventually reconnecting — with previously emerged flux

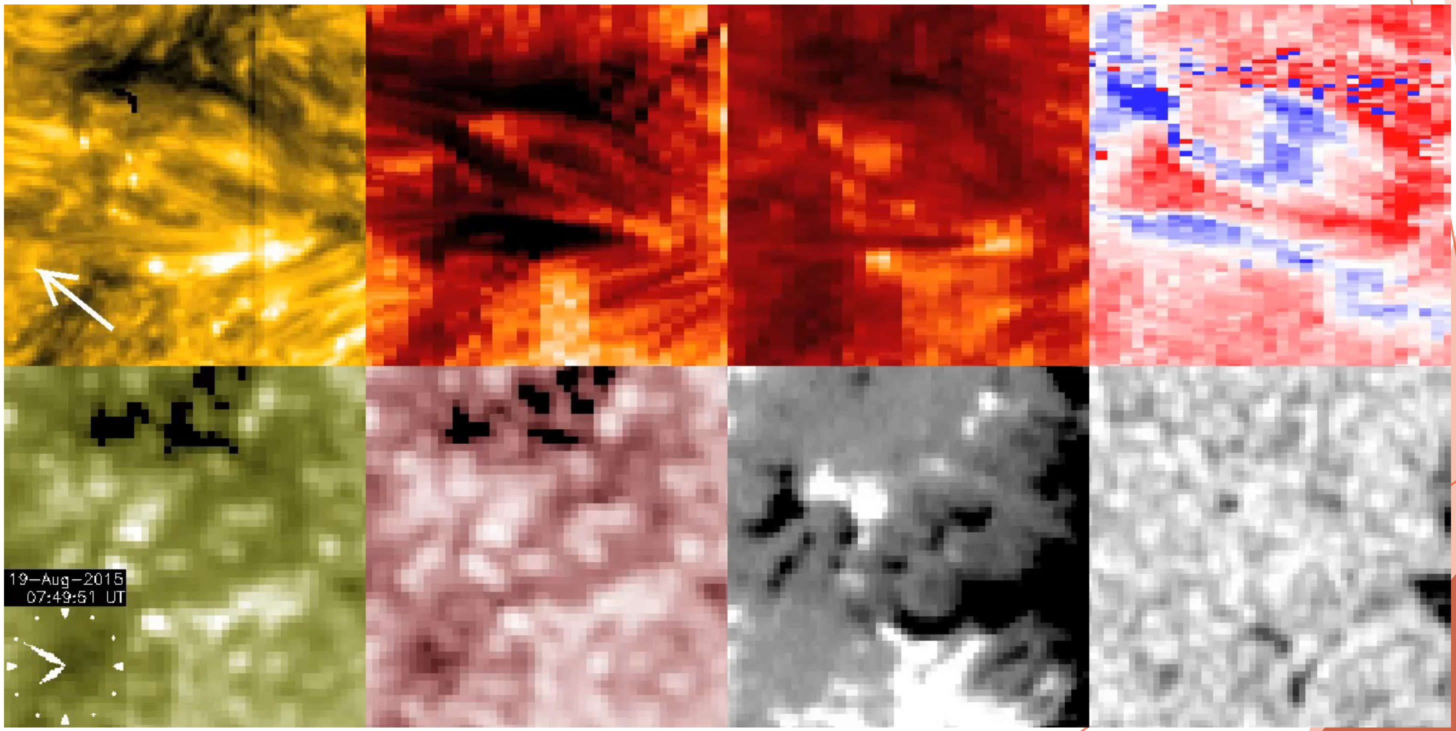




Heating in the earliest phase of emergence

Toriumi et al. (2017)
ApJ, 836, 63

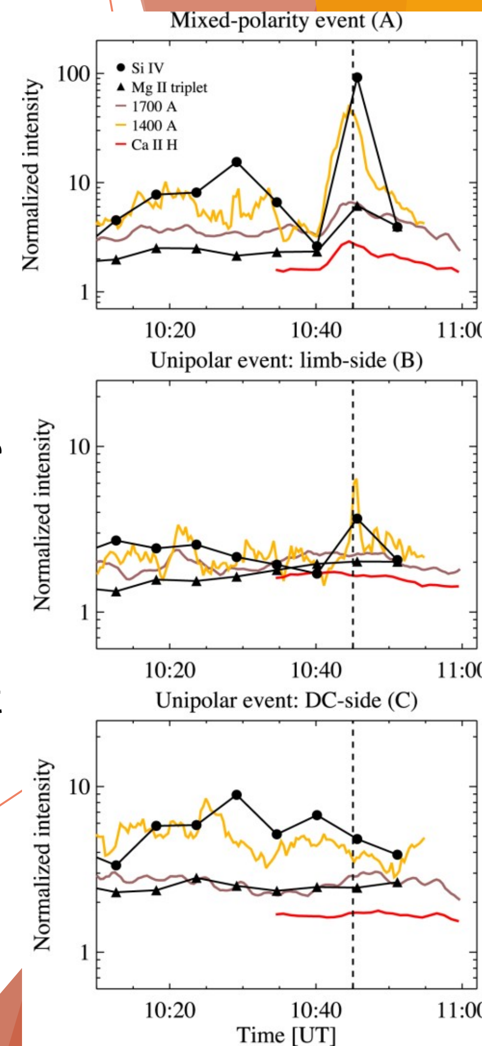
IRIS - *Hinode* - SDO



Heating in the earliest phase of emergence

Toriumi et al. (2017)
ApJ, 836, 63

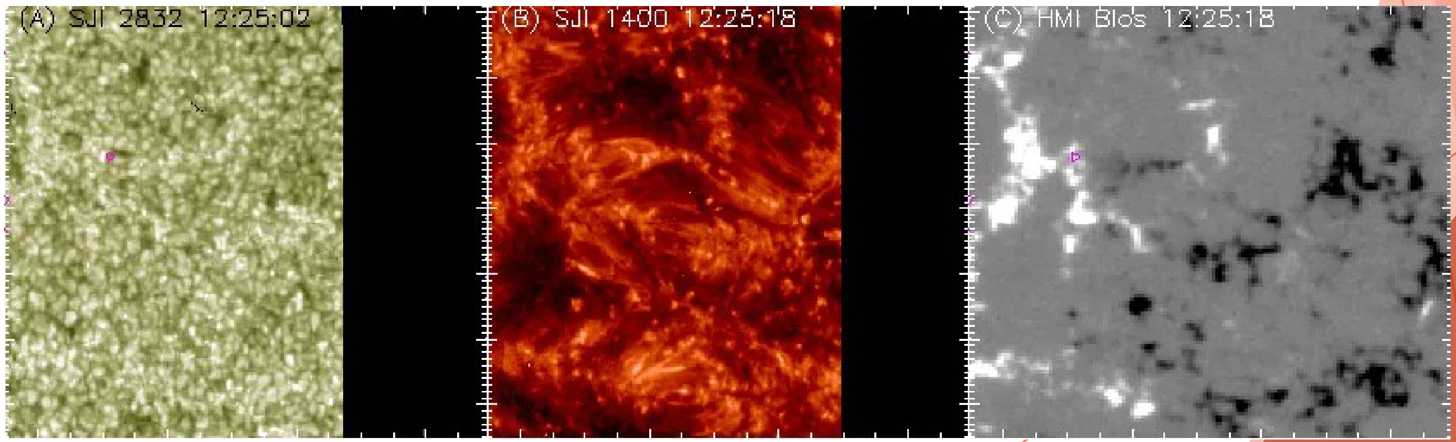
- EFR observed in AR NOAA 12401: **bright points** (BPs) identified in SOT Ca II images, some in an SOT/SP scan
- 7 BPs in the EFR center possess **mixed-polarity** magnetic backgrounds in the photosphere
  - IRIS UV spectra are strongly enhanced and red- or blue-shifted, with tails reaching ±150 km s^{-1}: bi-directional jets?
  - Each brightening lasts for 10-15 minutes, leaving flare-like light curves
  - They show bald patches, i.e. U-shaped magnetic loops
- 10 BPs are found in **unipolar regions** at the EFR edges.
  - They are generally weaker in UV intensities and exhibit systematic redshifts with Doppler speeds up to 40 km s^{-1}
- Both types of BPs show signs of strong **temperature increase** in the low chromosphere: heating events due to **reconnection**



Heating in the earliest phase of emergence

Tian et al. (2018)
ApJ, 854, 174

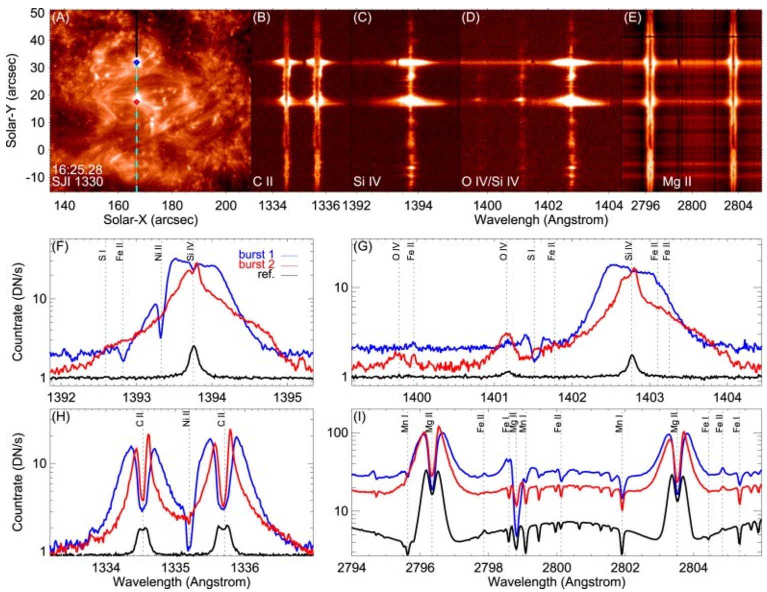
- *SDO*/HMI observed **continuous** emergence of small-scale magnetic bipoles with a rate of ~10^{16} **Mx s^{-1}**
- Flux patches with the same polarity merge and form **pores**
- Interactions between different emerging magnetic fluxes and polarities lead to frequent occurrence of **UV bursts** at 1400 Å

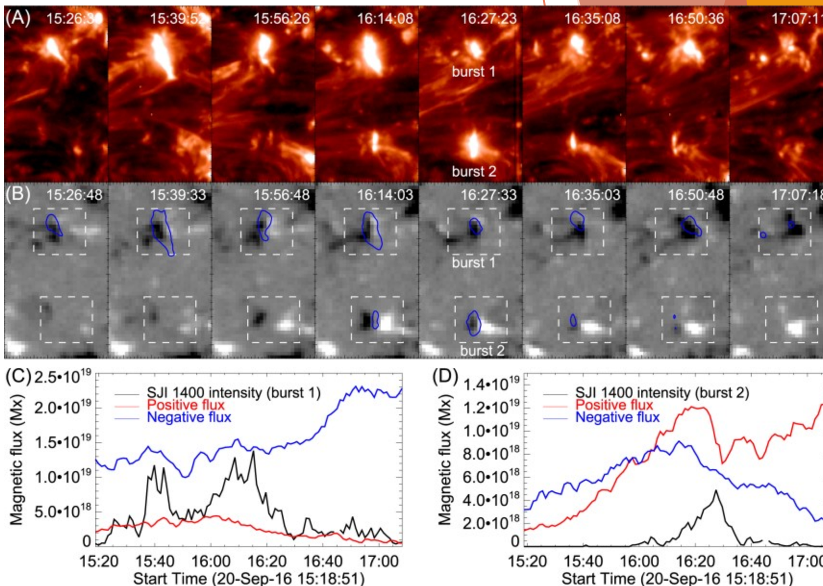


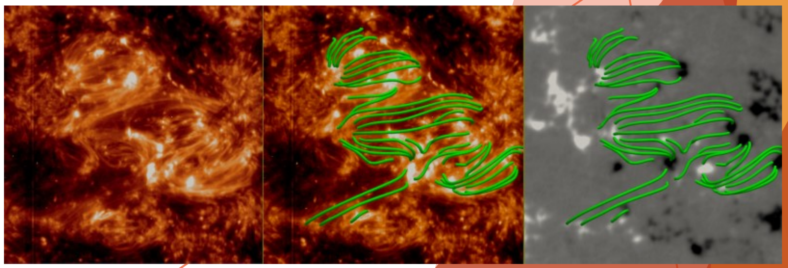
Heating in the earliest phase of emergence

Tian et al. (2018)
ApJ, 854, 174

- The spectra of these UV bursts suggest heating of the local materials up to **T ≈ 10^4 K** in the **lower atmosphere** by magnetic reconnection in magnetic dips





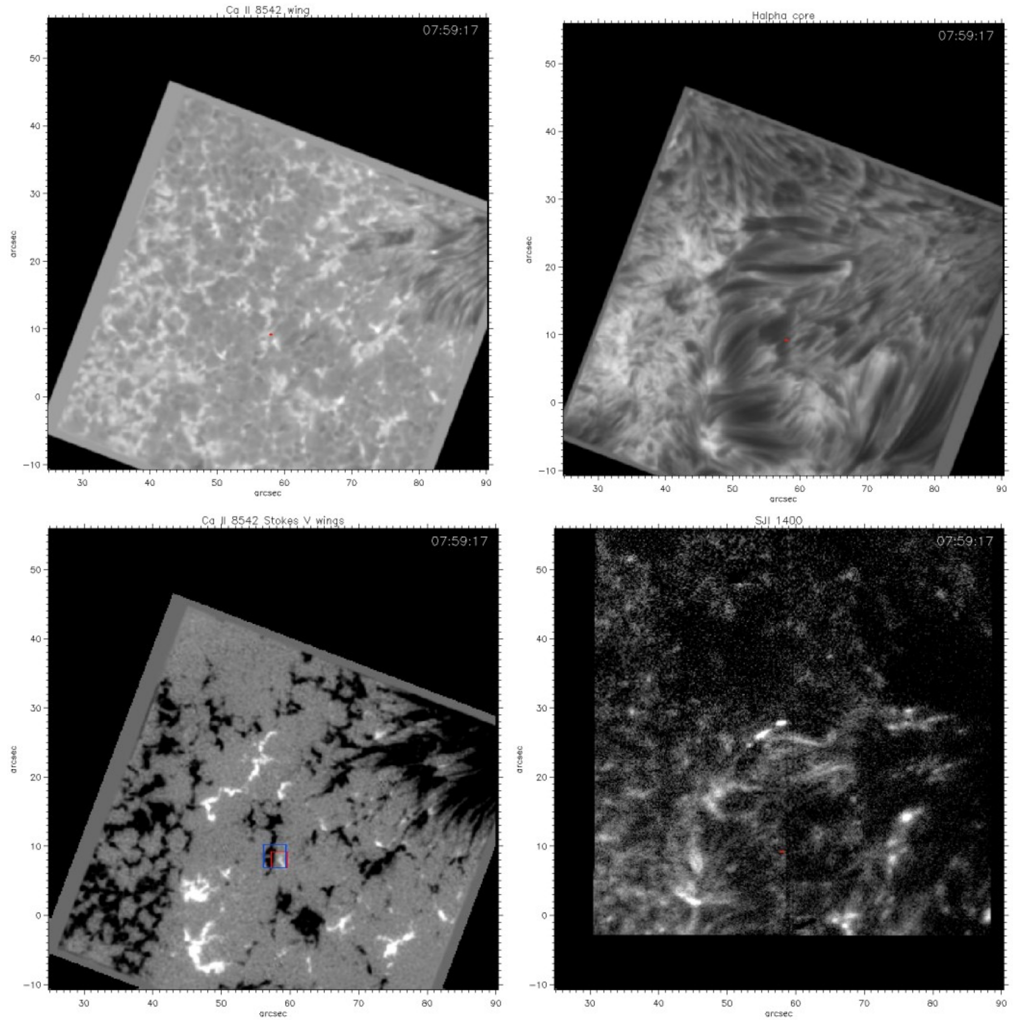


Chen et al. (2019) ApJL, 875, L30

Ortiz et al. (2020) A&A, 633, A58

Relationship between EBs and UBs

- About 20% of the observed **EBs** identified in Hα reveal **UV bursts (UBs)** in *IRIS*
- UBs associated with the upper part of flame-like EBs
- Some UBs and EBs form at different heights during a **common** small-scale reconnection event
  - UBs represent the chromospheric and TR counterpart of EBs
  - UBs are accompanied by ejection of surges
- **Vertical current sheet**



Relationship between EBs and UBs

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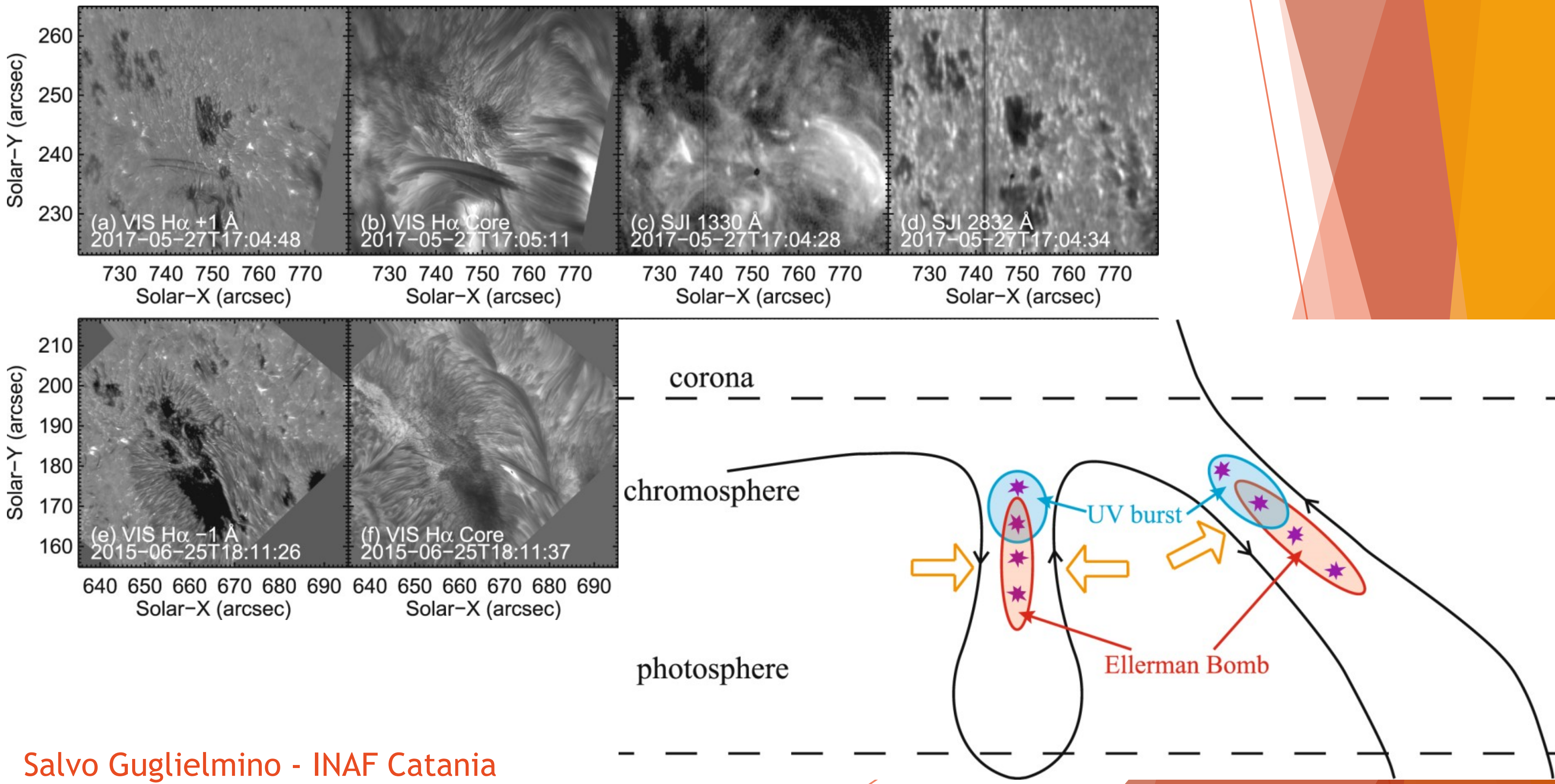
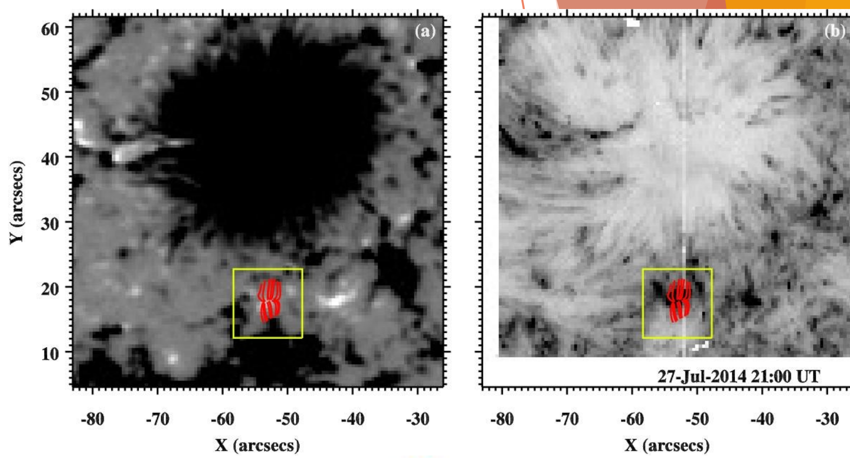
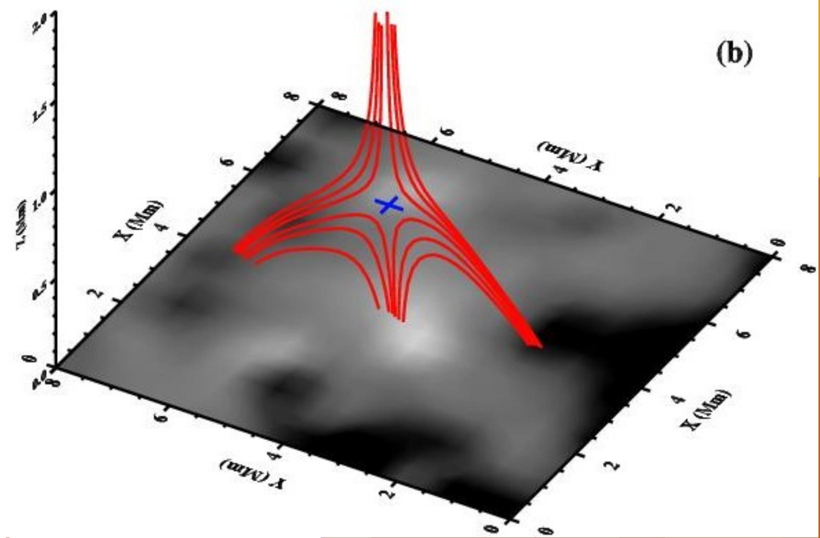


Magnetic topology in UV bursts ang jets

Chitta et al. (2017)
A&A, 605, A49

- A UV burst observed in the **moat** surrounding a sunspot
- UV spectra are **extremely broadened**, indicating ±200 km s^{-1}, with distinct zones of up- and downflows
- Magnetic field extrapolations show a fan-spine topology
    - A **parasitic** magnetic field polarity is underlying the UB
    - A **3D null point** exists at about 500 km, evolving co-spatially with the UB
- The advection of the magnetic feature shears the field lines, triggering reconnection in the **low chromosphere**

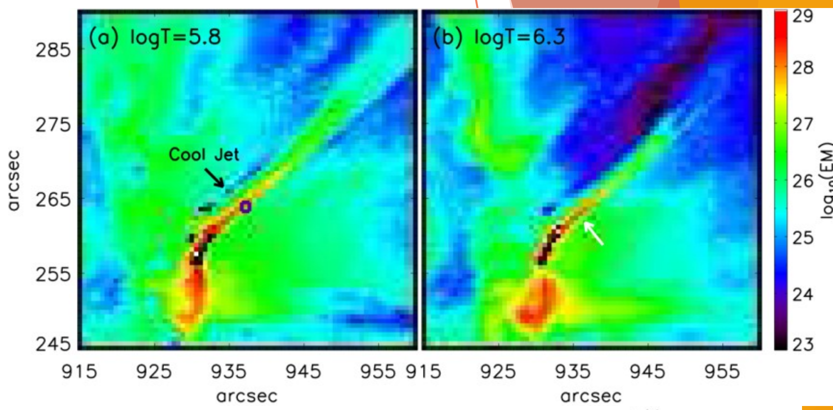


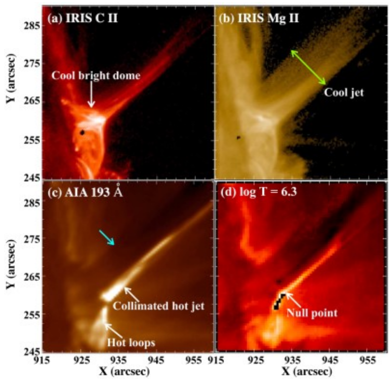


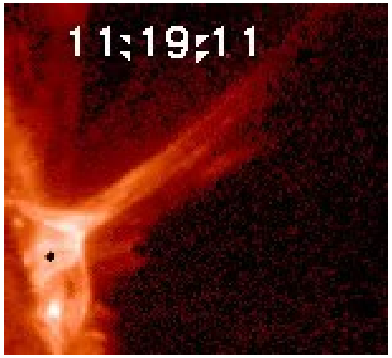
Magnetic topology in UV bursts and jets

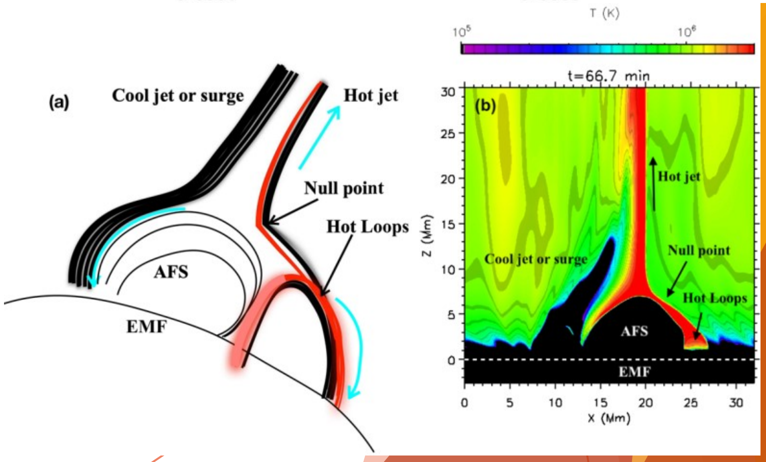
Joshi et al. (2020)
A&A, 639, A22

- Analysis of the **multi-temperature** structure of a series of jets at limb
- Initiation of the jets at the top of a **canopy-like** double-chambered structure with cool and hot emission
- Agreement with 2D and 3D reconnection models









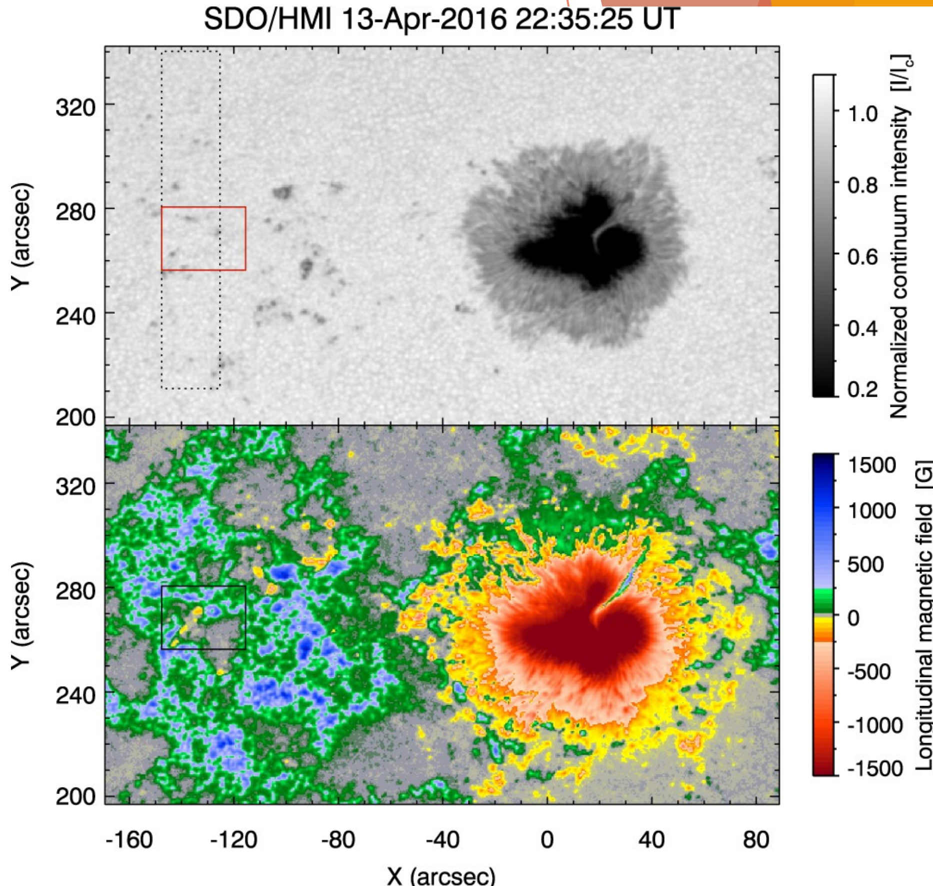
IRIS observations: an EFR within a plage

ACTIVE REGION NOAA 12529 – APRIL 2016

Guglielmino et al. (2018), ApJ, 856, 127
Guglielmino et al. (2019), ApJ, 871, 82
Nóbrega-Siverio, Guglielmino & Sainz Dalda (2021), A&A, 655, A28

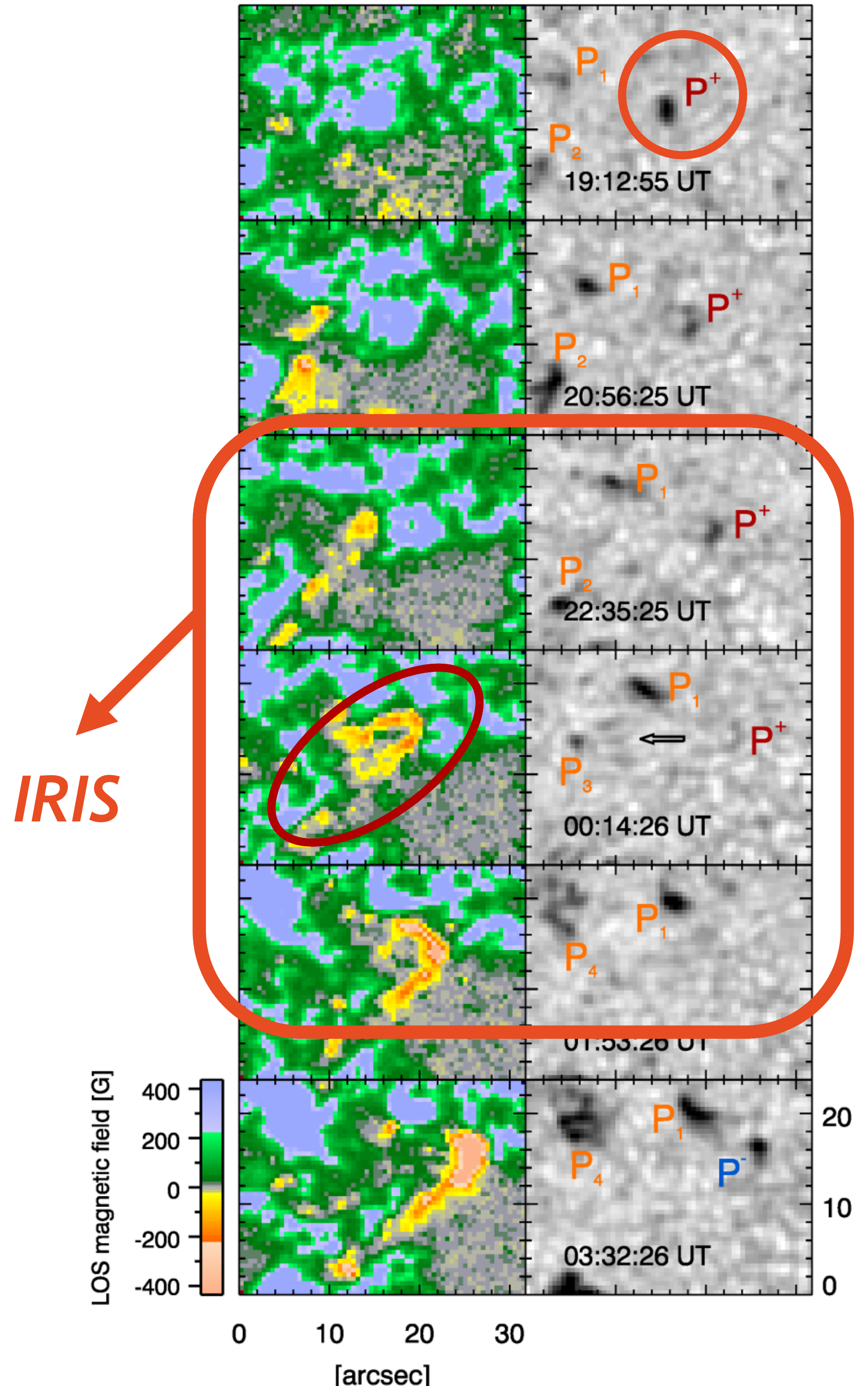
Dataset and context

- Giant AR NOAA 12529 crossed the central meridian on 13-14 April 2016
- An EFR emerged in the f positive polarity of the AR (solid box)
- *IRIS* acquired three data sets during the EFR evolution.
  - The **one** relevant to our study consists of a sequence acquired between 23:34 UT on April 13 and 01:55 UT on April 14, with 6 large dense 64-step rasters and with simultaneous slit-jaw images (SJIs) in the 1400 and 2796 Å passbands
  - The scan sequence has a 0".33 step size, a 31.5 s step cadence, and a 30 s exposure time
  - The raster cadence is about 33 min, with a FOV of 22" x 128" (dashed box)

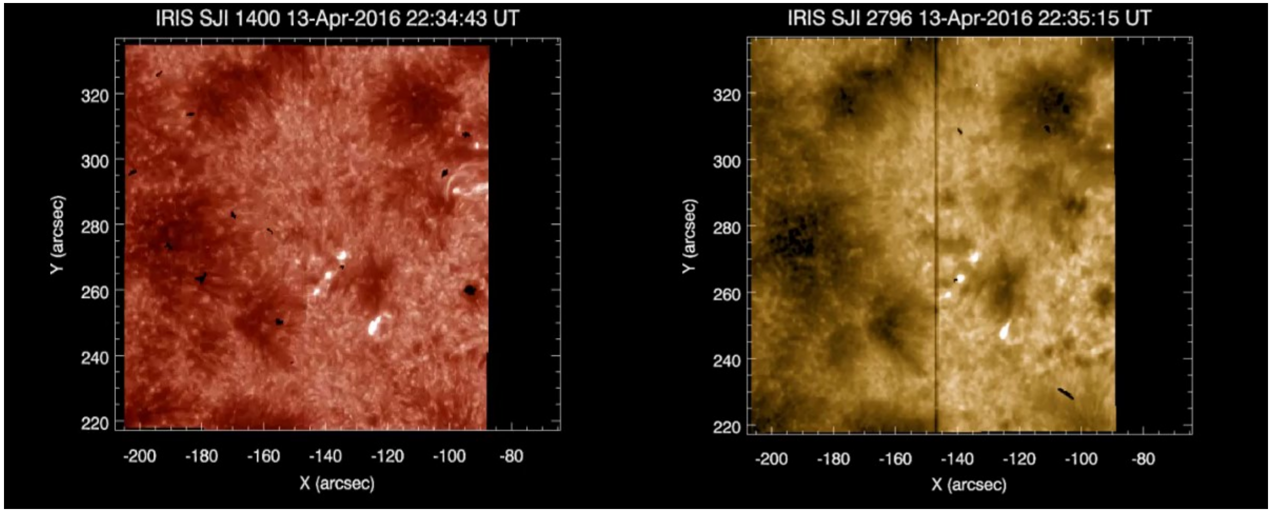


Photosphere: *SDO/HMI* sequence

- The EFR emerged in a unipolar plage
- P⁺ became smaller and disappeared
  - The positive polarity pore, initially located at the center of the EFR subFOV, shrank and finally disappeared as flux from the negative polarity of the EFR approached it
  - Dark aligned features in the continuum were observed in the emergence zone and traced the B_h fields of the EFR
- New flux formed P⁻
  - The flux concentration formed by the accumulation of the negative polarity flux of the EFR forms a new pore

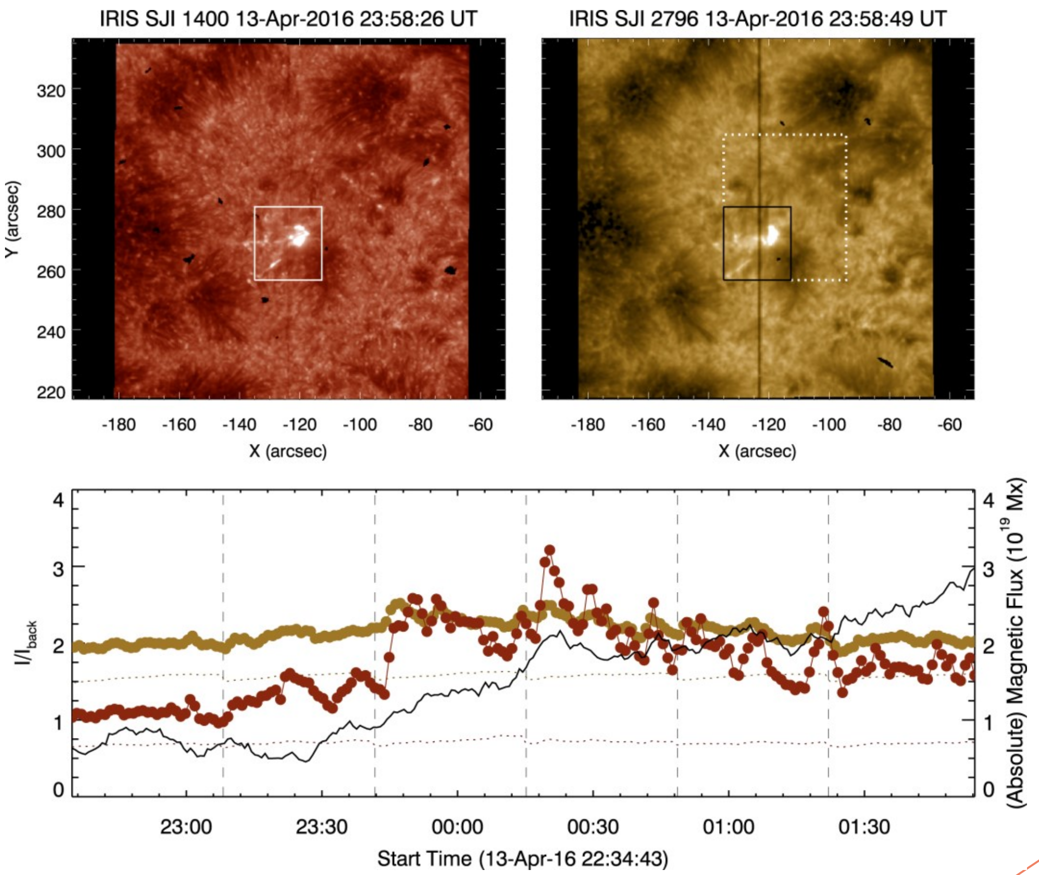


Response to flux emergence of the upper atmospheric layers

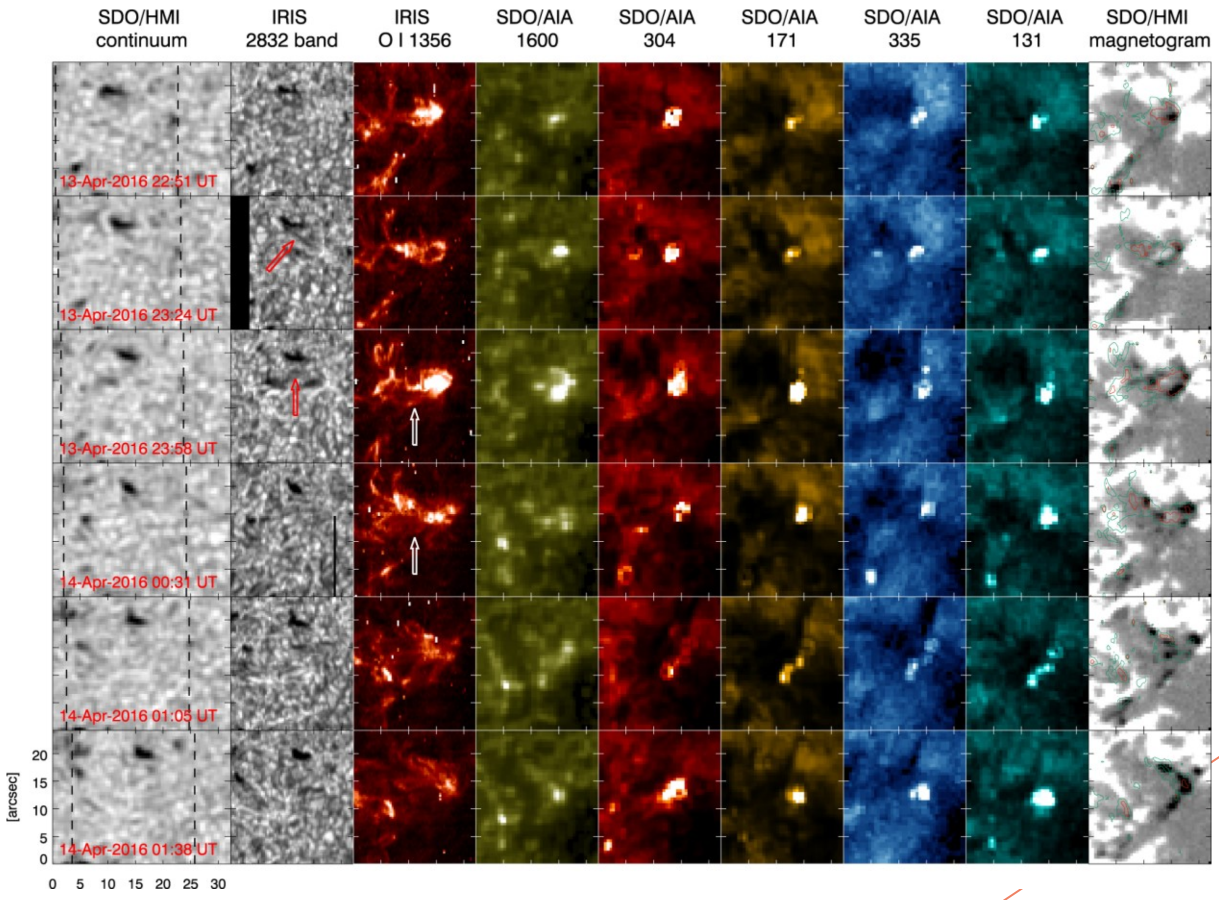


- *IRIS* sequence shows UV **brightenings** and **plasma ejections** in the EFR site

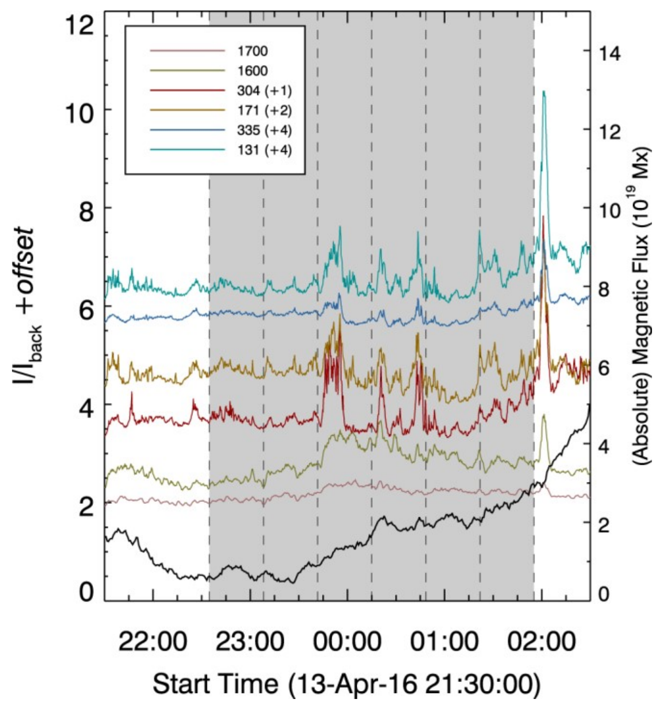
Response to flux emergence of the upper atmospheric layers



Response to flux emergence in coronal layers

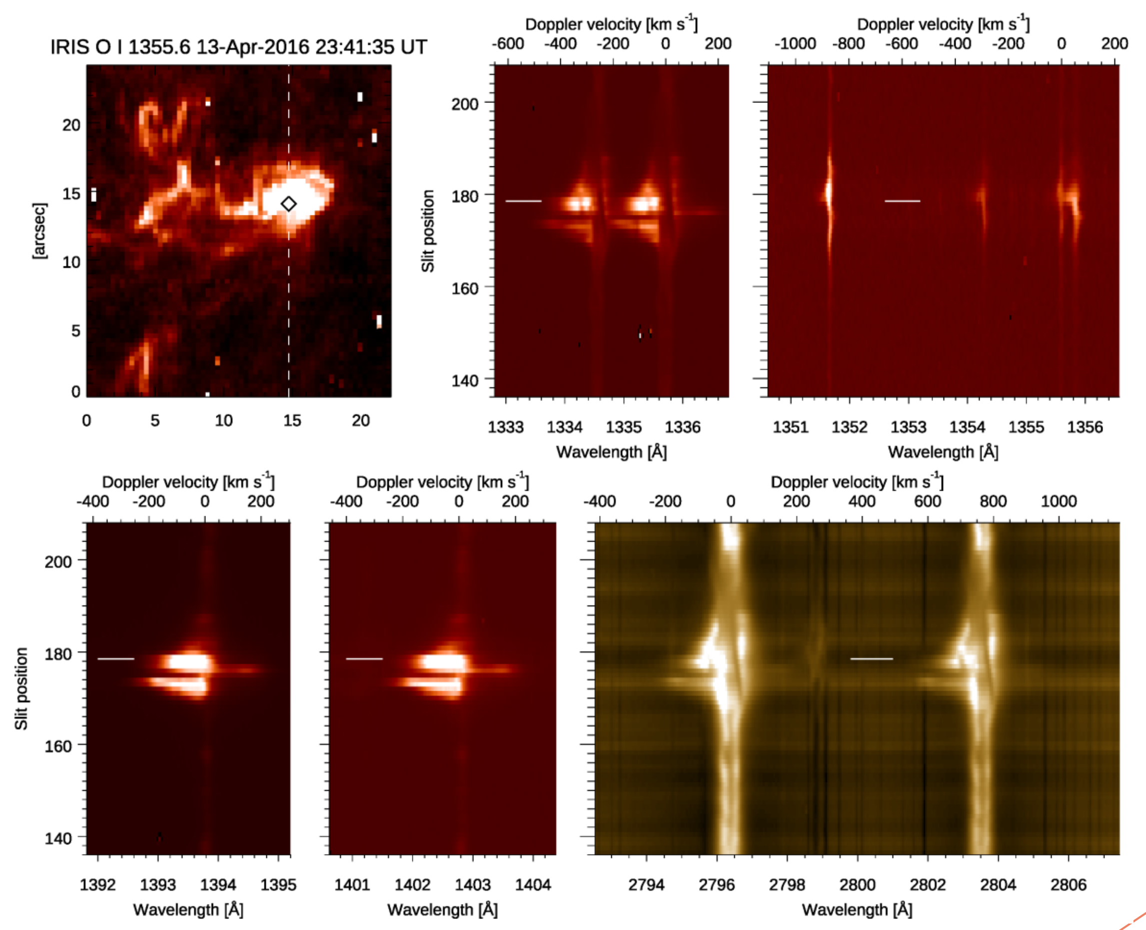


Response to flux emergence in coronal layers



- **ALL** SDO/AIA channels exhibit a counterpart of the event
- Contrasting trend between 1600/1700 Å and higher temperature filters, showing a **bursty** behavior
- Brightness enhancements were observed throughout the **whole sequence**
- The **UV burst** consists of **repeated episodes** lasting for **hours**

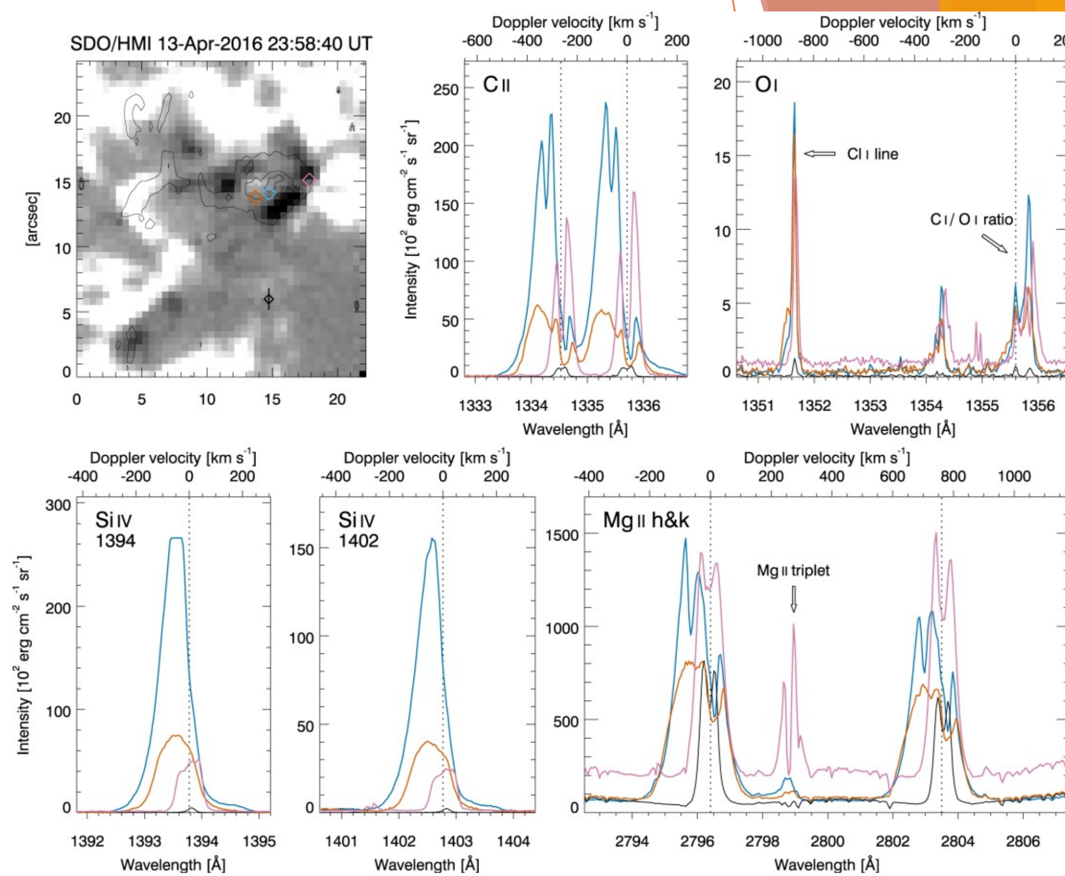
IRIS spectral features



IRIS spectral features

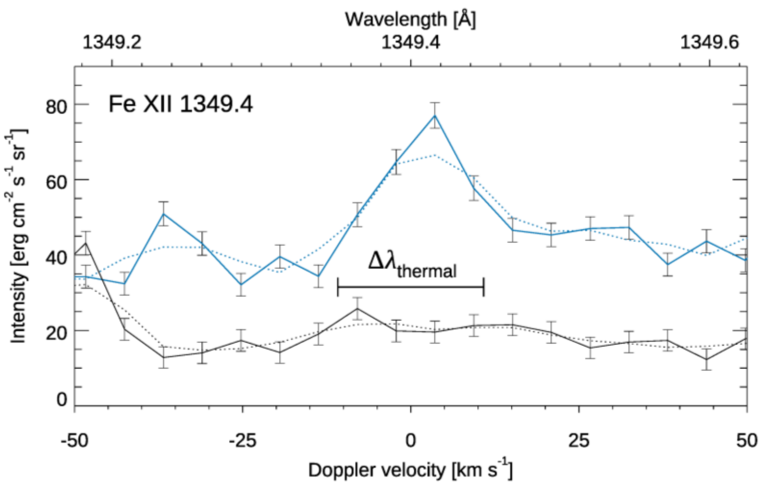
- UV burst core
  - blueshifts
  - components with different velocity
  - spectral features
    - “absence” of O IV line
    - Mg II triplet emission
    - inverted C I / O I ratio
    - detection of Fe XII line

- Contact region
  - plasma at rest
  - strong Mg II triplet



Orange, **blue**, **pink** profiles:
random positions over the UV burst
Black profile: average over 6 quiet-Sun pixels

Detection of the coronal Fe XII 1349.4 Å line



log *T* [K] ≈ 6.1

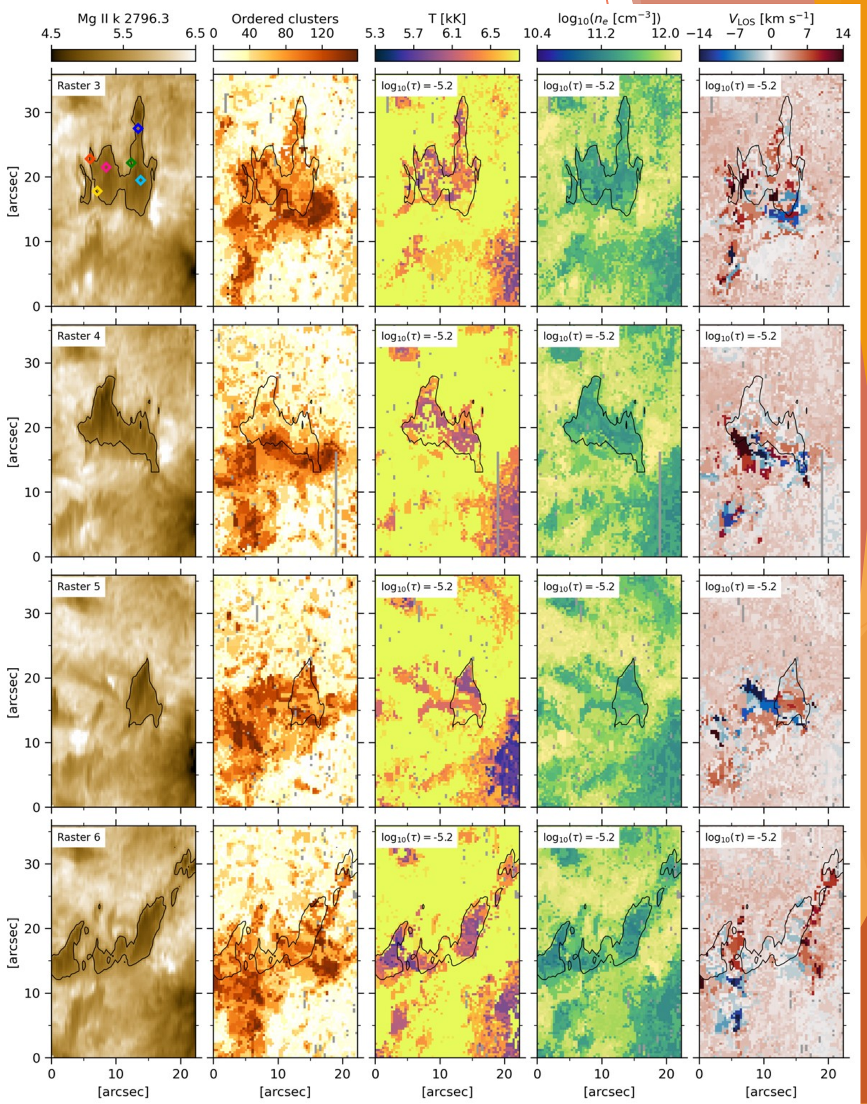
- Spectrum around the Fe XII coronal line, obtained by **summing the signal** in the 3x5 pixels region around the **UV burst core**
- The **black line** represents the background

Characterization of surges

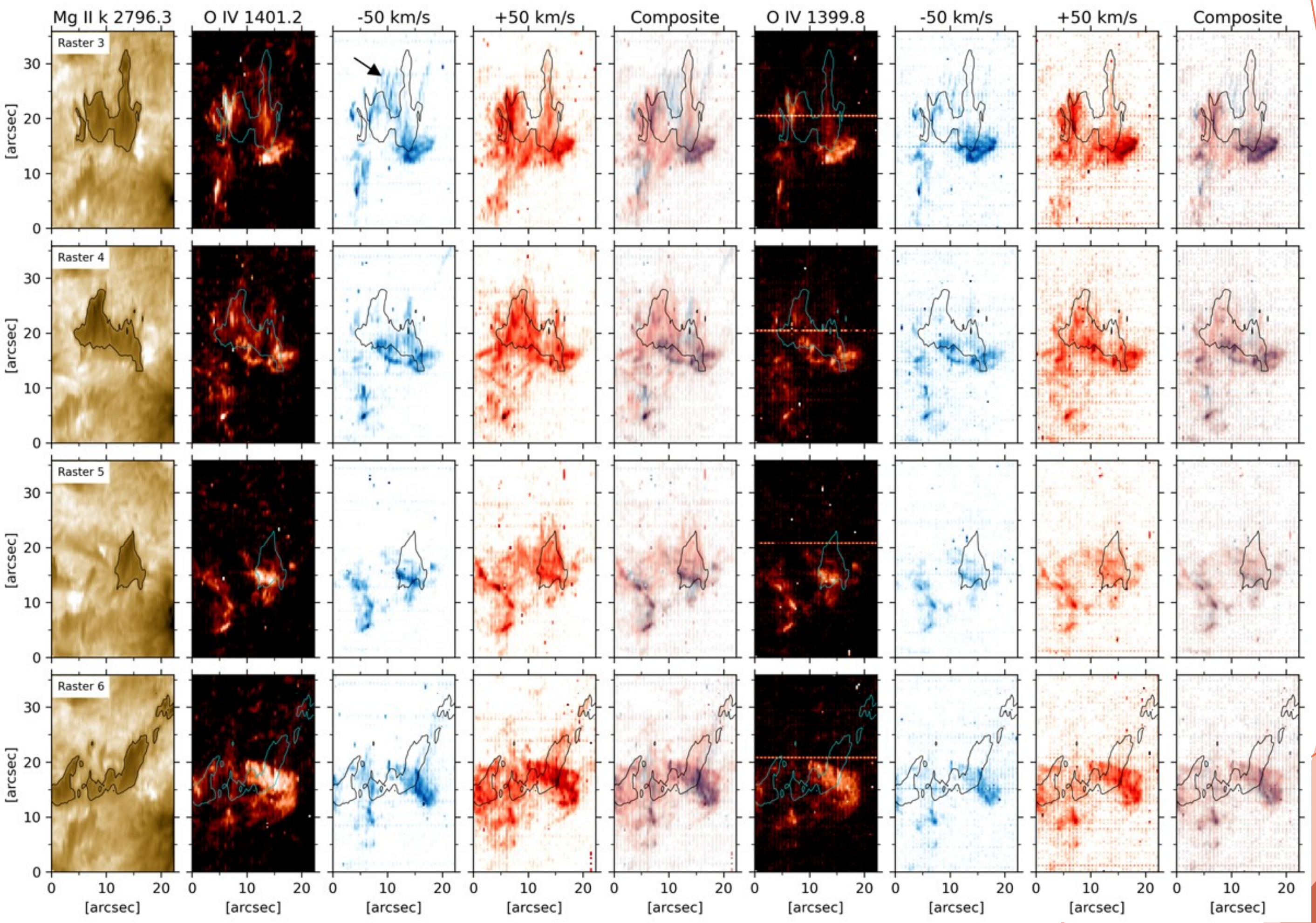
- Considering the representative Mg II h&k line profiles of surges, we have examined their low- and mid-chromosphere:
  - using the **k-means algorithm**
  - performing inversions with the **STiC code**

Chromosphere

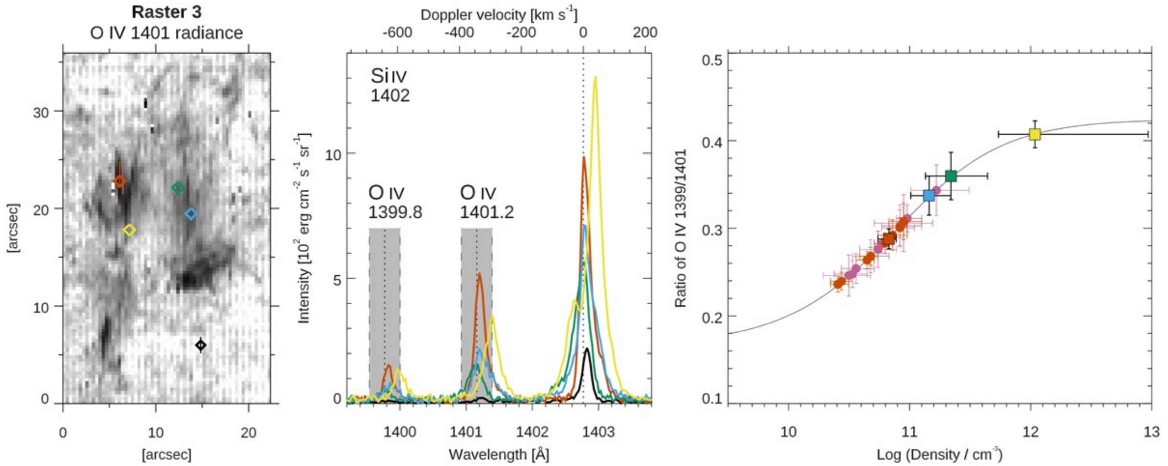
- T = 6 kK
  at $-6.0 \leq \log_{10}(\tau) \leq -3.2$
- $n_e \sim 1.6 \times 10^{11}$ cm^{-3}
  up to 10^{12} cm^{-3}
- v_{LOS} of a few km s^{-1}
  at $-6.0 \leq \log10(\tau) \leq -4.8$



Characterization of surges



Characterization of surges



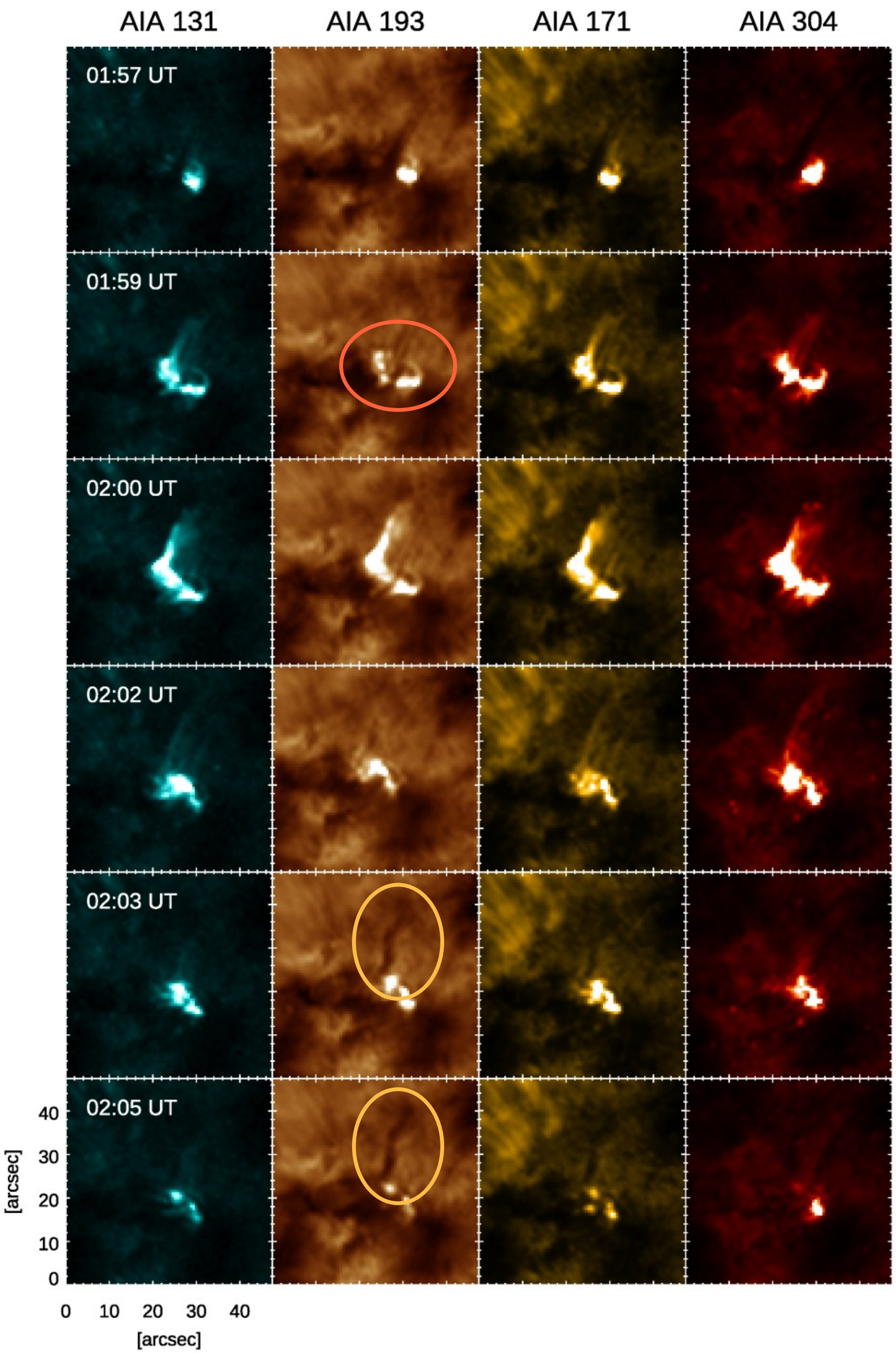
- The **transition region** properties have been investigated by analyzing the far-UV spectra:
  - emission in weak lines
  - density diagnostics based on **O IV 1399.8 / 1401.2 Å** lines

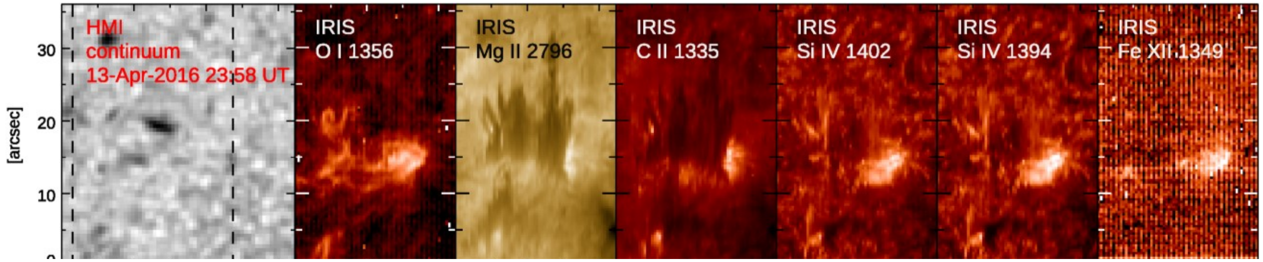
Transition region

- $n_e \sim 2.5 \times 10^{10}$ cm^{-3} up to 10^{12} cm^{-3}

Eruption at late stages

- Just after the end of *IRIS* observations, a sudden intensity peak occurred
- *SDO*/AIA filtergrams show the formation of a **circular ribbon**, typically found in fan-spine configurations with parasitic polarities
- **Eruptions** were observed, being followed by **catastrophic cooling**





- Observations of a small-scale magnetic flux emergence event show a **fundamental impact** in the upper atmospheric layers
  - Cancellation of pre-existing flux with an EFR: **P^+** -> **P^-**
  - Recurrent **UV bursts**, with counterparts in the corona
  - **Surge/jet** activity at chromospheric and coronal levels
  - Eruption and **flaring** during the late emergence phase

Penumbral brightenings linked to EFRs

Active Region NOAA 12546 – MAY 2016

Murabito et al. (2020), ApJ, 890, 96

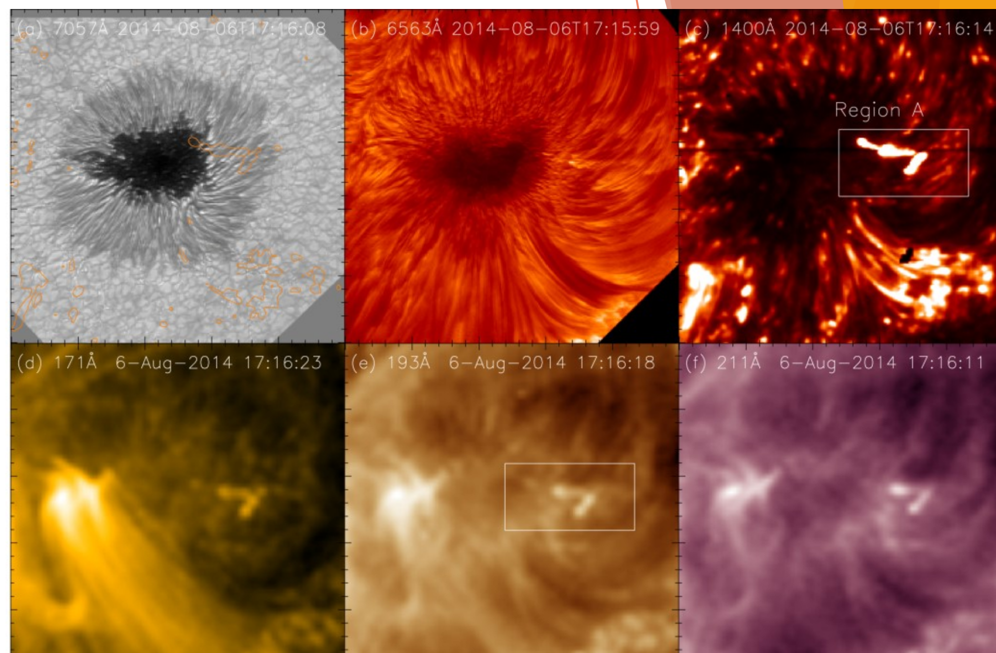
Previous observations

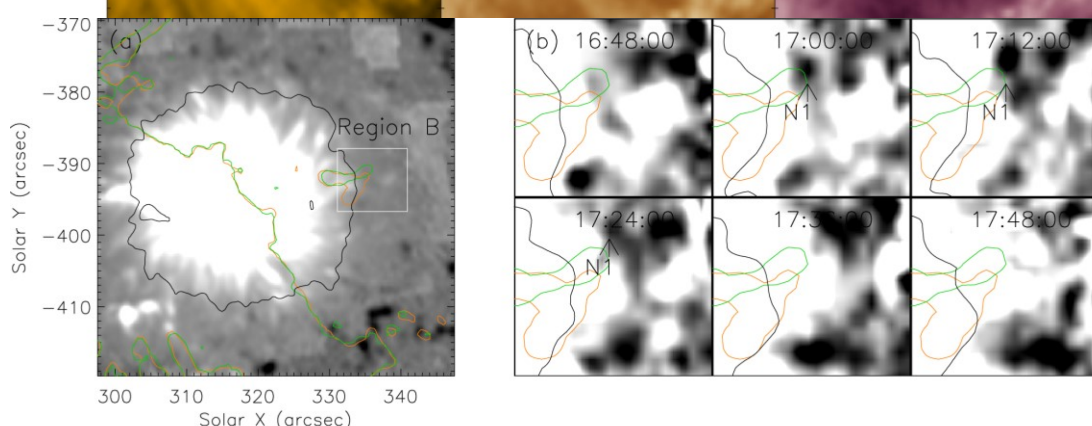
Bai et al. (2016)
ApJ, 823, 60

- Sub-arcsecond nanoflare events (10^{22} - 10^{25} erg) with signatures from the chromosphere to corona

Magnetic topology

- An MMF appeared close to the penumbral boundary at the same location of one footpoint
- It seems to be associated with magnetic reconnection between EFR and pre-existing magnetic field





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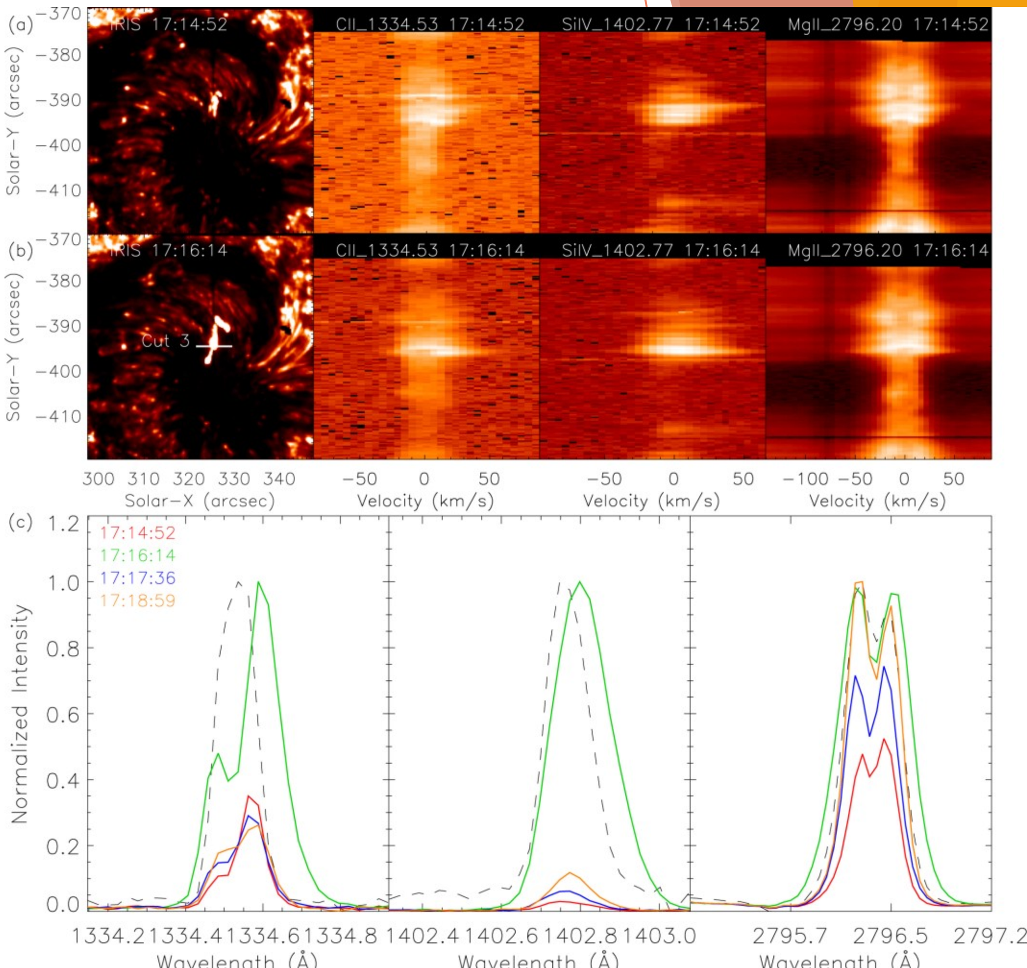
Previous observations

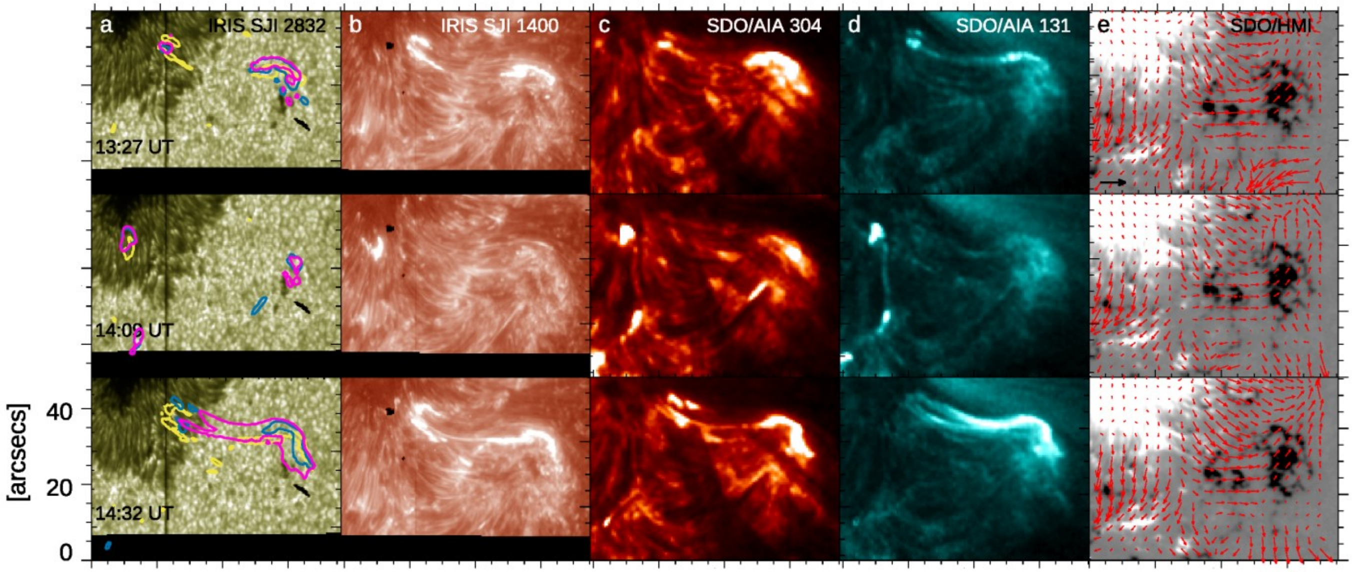
- *IRIS* spectra:
  Si IV, C II and Mg II lines are **enhanced** and **broadened up**
  - no evidence for chromospheric evaporation
  - redshift in the Si IV 1402.77 Å line: downflow in the TR
- DEM analysis:
  6.6 ≤ log *T* [K] ≤ 7.2

Bai et al. (2016)
ApJ, 823, 60



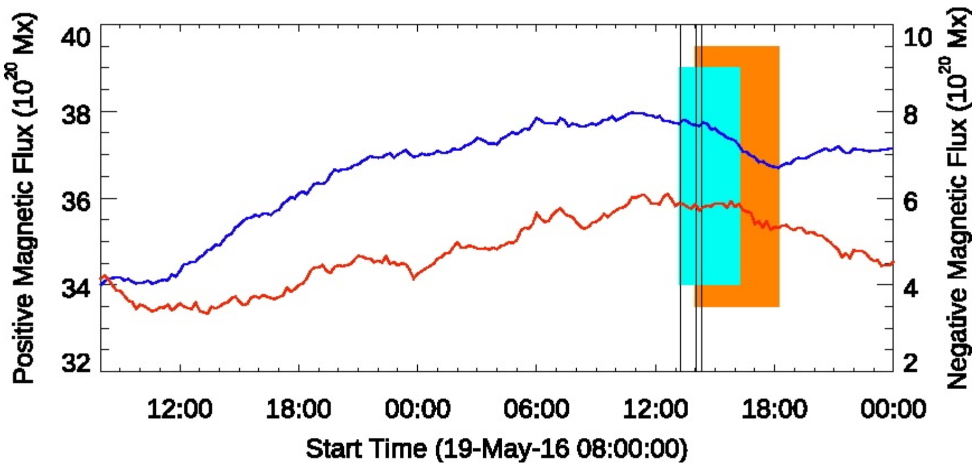
Our multiwavelength observations

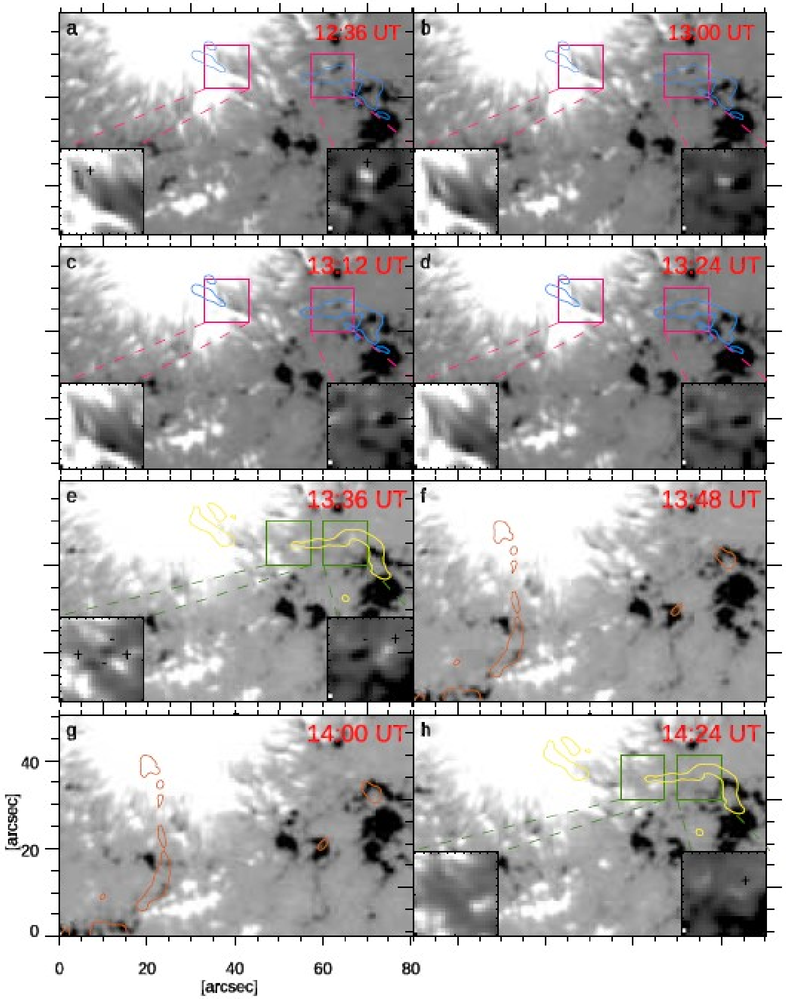
- Homologous brightening events
- Two of these events correspond to **B-class flares**
- One footpoint is always embedded in the **penumbra**



SDO/HMI observations

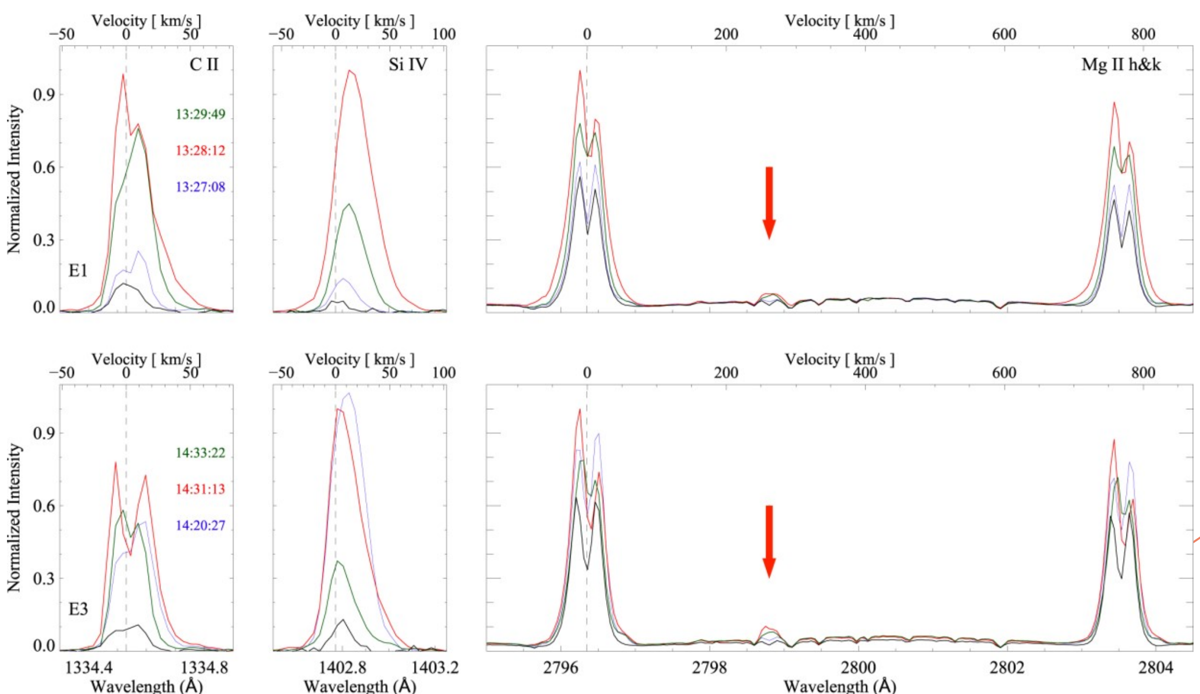
- Interplay between **EFRs** and moving magnetic features (**MMFs**)
  - Two EFRs (3×10^{20} Mx and 5×10^{19} Mx) emerged close to the **penumbral fields**, modifying their configuration
  - The interaction with some MMFs lead to partial **cancellation events**





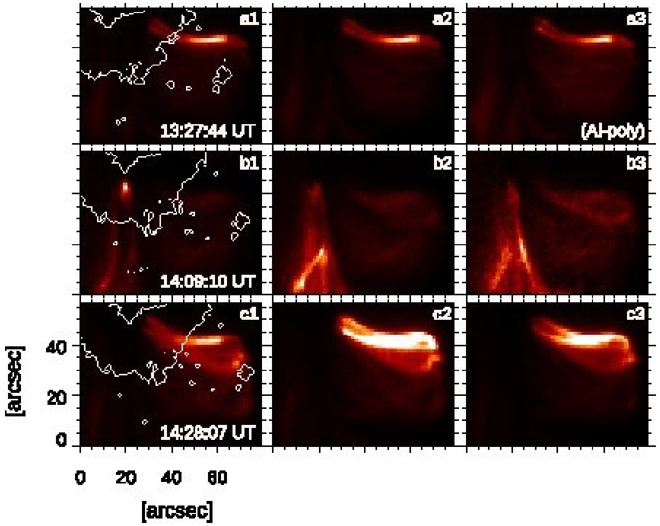
IRIS observations

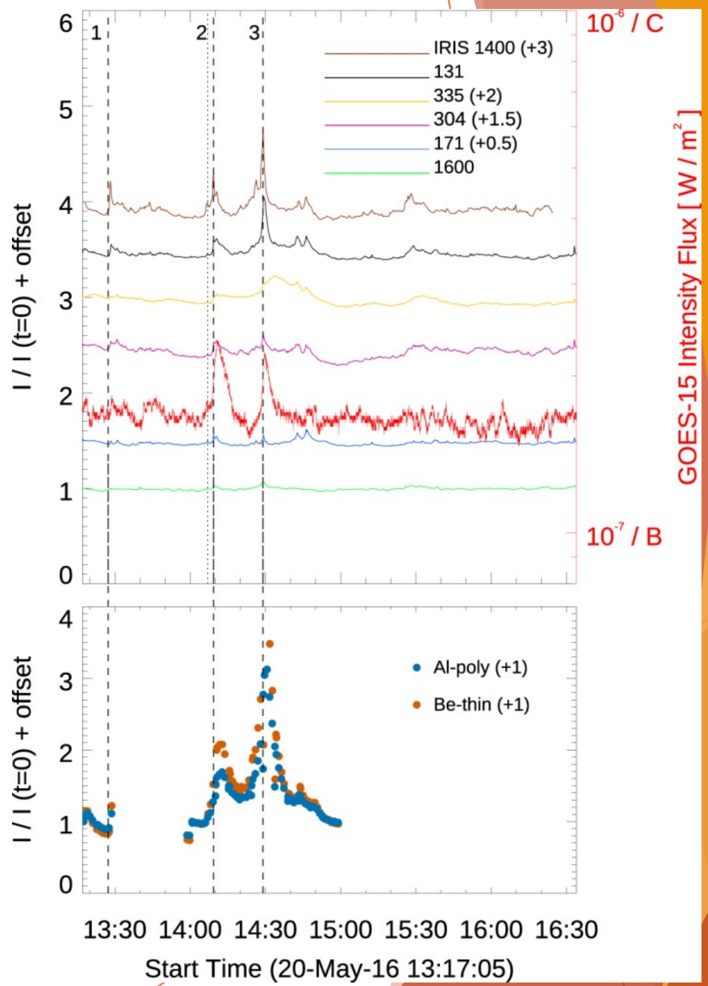
- C II and Si IV profiles enhanced by a factor of ≈10
- C II and Mg II h&k double-peaked profiles exhibited **blue lobes** **stronger** than the **red lobes** at the peak
- Emission in the Mg II 2798.8 triplet



XRT observations

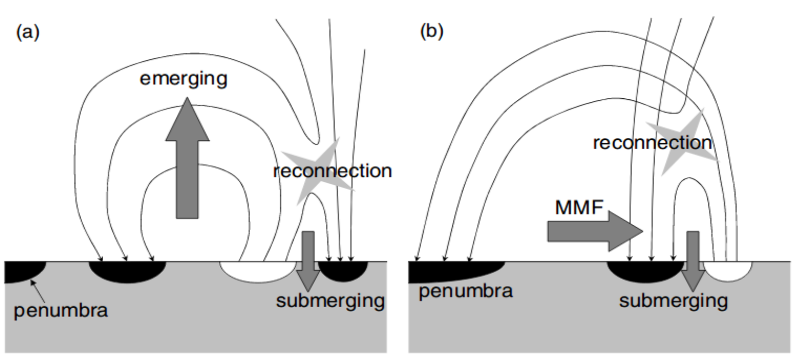
- Same plasma behavior as in AIA 131
- Possible connection between opposite polarity patches of the diffuse field and MMF in E2
- The strongest coronal brightening is observed during E3





Reconnection scenario

- Two of the brightening events result from reconnection at different heights, activated by interaction of **pre-existing fields** and either **EFR or MMFs**
- Our observations could be explained with the model for microflares proposed by Kano et al. (2010)



- Clear signatures of the **chromospheric evaporation** (profile asymmetries), missed in the observations by Bai et al. (2016), are revealed

Perspectives

The future:
Solar Orbiter contributions

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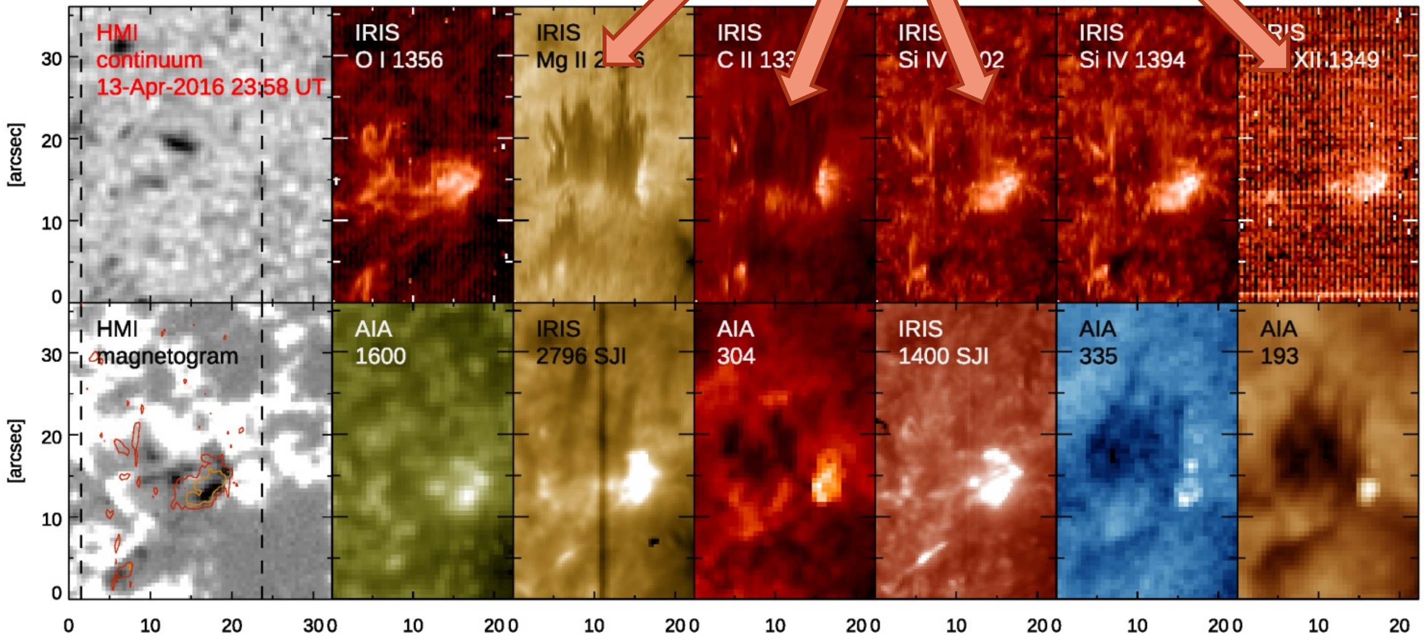


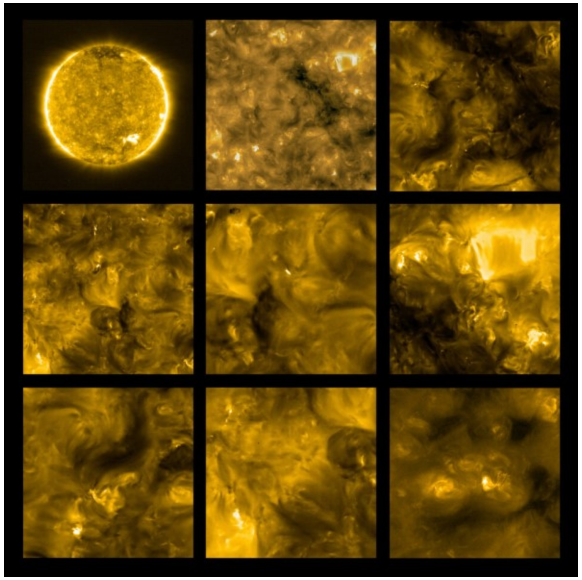
PHI

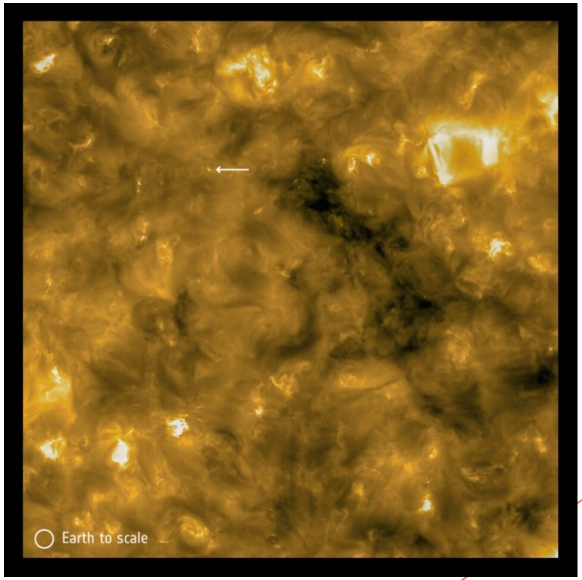
EUI

Campfires on the Sun

First observations from Solar Orbiter

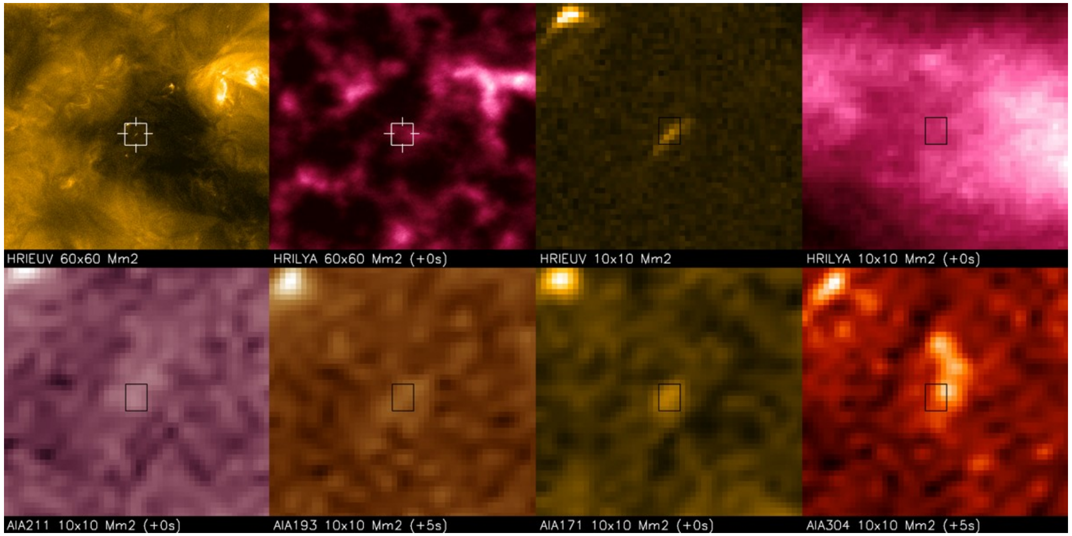
- Revealed by SolO/EUI at 174 Å
- Tiny brightenings with a size of 400 km
- Connected to coronal heating **???**





Campfires on the Sun

Berghmans et al. (2021)
A&A, 656, L4

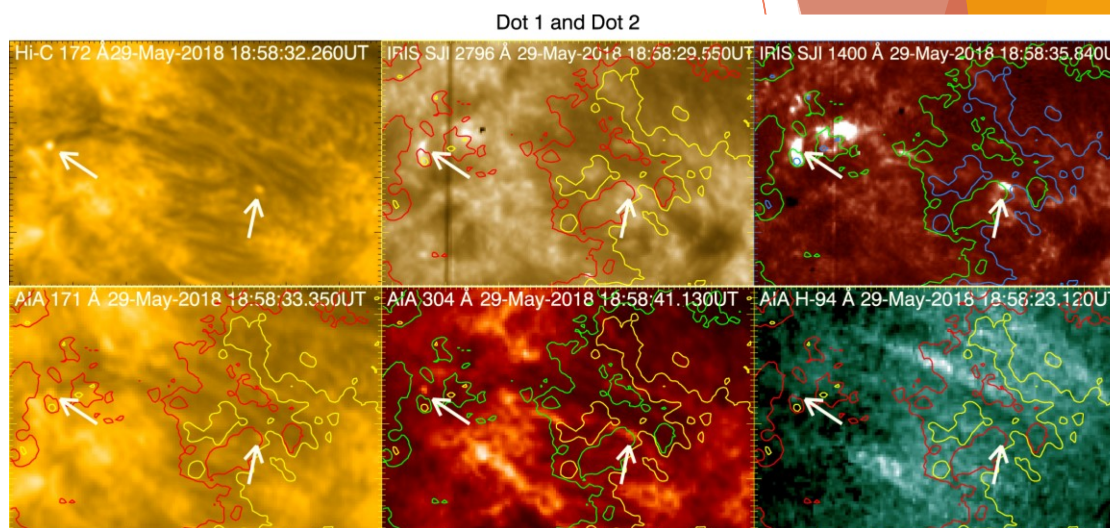


- Small-scale brightening events visible in SolO/EUI **HRI_{EUV} (17.4 nm)** but not in **$HRI_{Ly\alpha}$ (121.6 nm)**
- Weaker and fuzzier in AIA 17.1 – 19.3 – 21.1 – 30.4 nm
- Emission measure: **log *T* [K] ≈ 6.1**

Tiwari et al. (2019)
ApJ, 887, 56

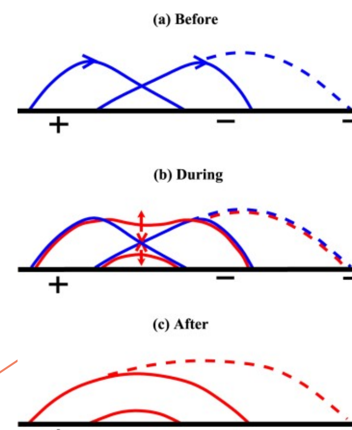
Relationship between campfires and Hi-C brightenings

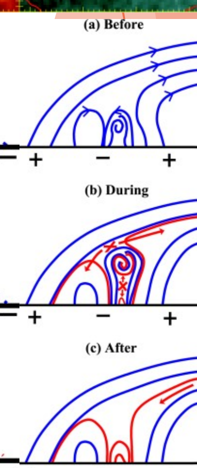
- The 2nd flight of the Hi-C rocket revealed similar small-scale coronal events
  - seated at neutral lines
  - flux cancellation
  - chromospheric/TR origin
  - no cooling sequence



- Morphological differences: three types of brightenings
  I. dot-like
  II. loop-like
  III. surge/jet-like

magnetic configuration

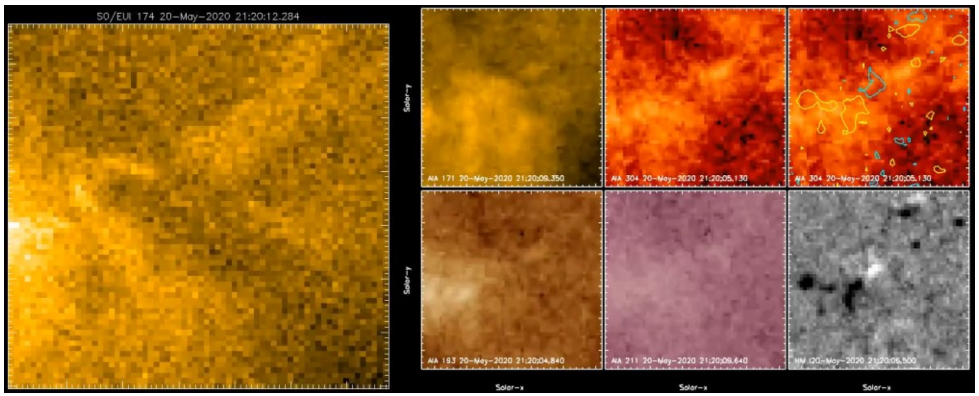




Campfires on the Sun: first analyses

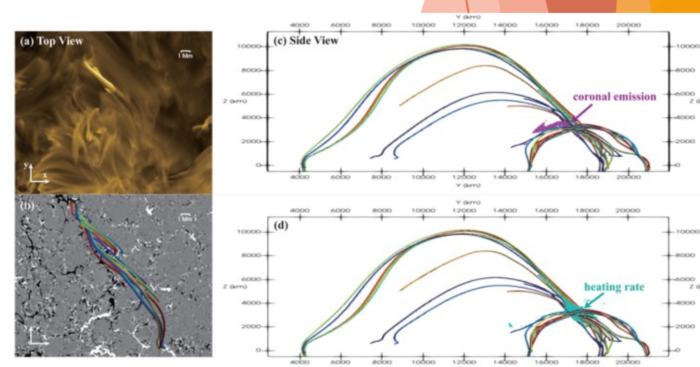
Panesar et al. (2021)
ApJL, 921, L20

Chen et al. (2021)
A&A, 656, L7



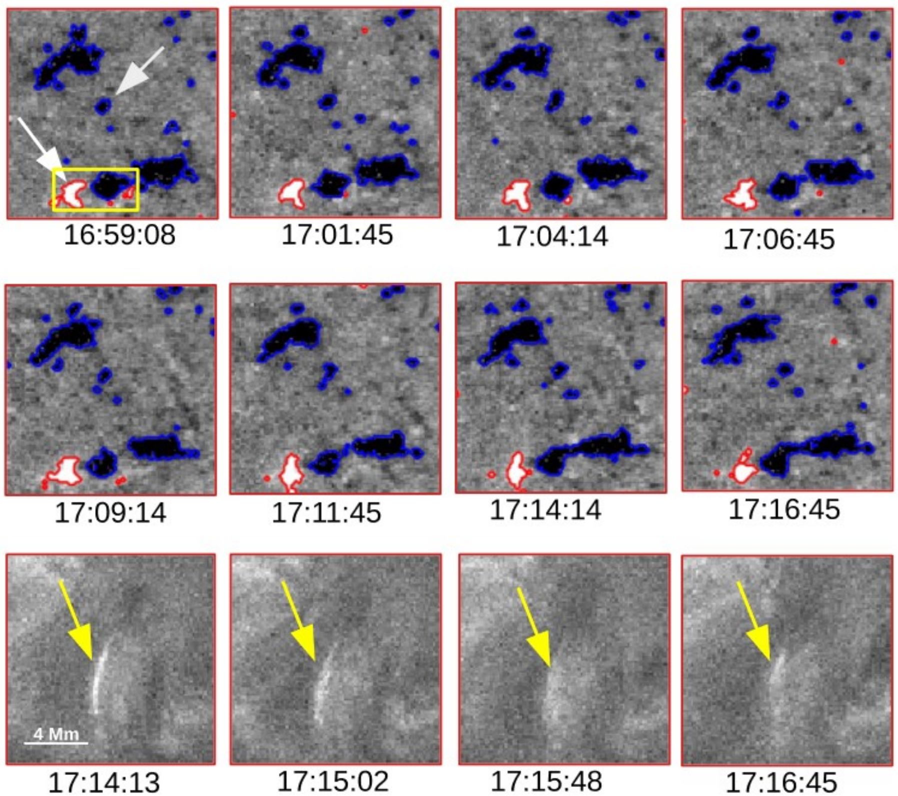
- Investigation of the magnetic origin of campfires in the quiet solar corona
  - campfires are rooted at the edges of photospheric **magnetic network** lanes
  - most of them reside above the **neutral line** between majority-polarity magnetic flux patch and a merging minority-polarity flux patch, as a result of **flux cancelation**

- 3D MHD models support the reconnection scenario
  - loop-like features
  - height: 2 – 5 Mm
  - temperature > 1 MK
  - untwisting of a flux rope



Campfires on the Sun: magnetic driver

Kahil et al. (2022)
A&A, in press



- First SolO/PHI observations cospatial to SolO/EUI
  - ≈70% campfires are confined between bipolar magnetic features, exhibiting signatures of flux cancelation
  - **magnetic reconnection** triggered at the footpoints
  - **HOWEVER**, about 25% campfires are not associated to such magnetic activity in the photosphere, which implies that other heating mechanisms power these energy release events in EUV

Conclusions

- Flux emergence continuously reshapes the solar atmosphere and has a **fundamental impact** in the upper layers
- The **interplay** between emerging fields and other flux systems appears as the trigger for **energy release phenomena** through small-scale reconnection episodes
- The timing of the phenomena suggests a bottom-top process, often beginning in the lower atmosphere and later, but not always, involving the overlying layers
- MEMENTO: solar resistivity values are far from those required in simulations to trigger magnetic reconnection !!!
- A **synergetic approach**, available in the upcoming era of Solar Orbiter and DKIST/EST observations, is expected to give new insights for a **complete picture** of flux emergence from the photosphere to the corona