Simulations of flux emergence events II

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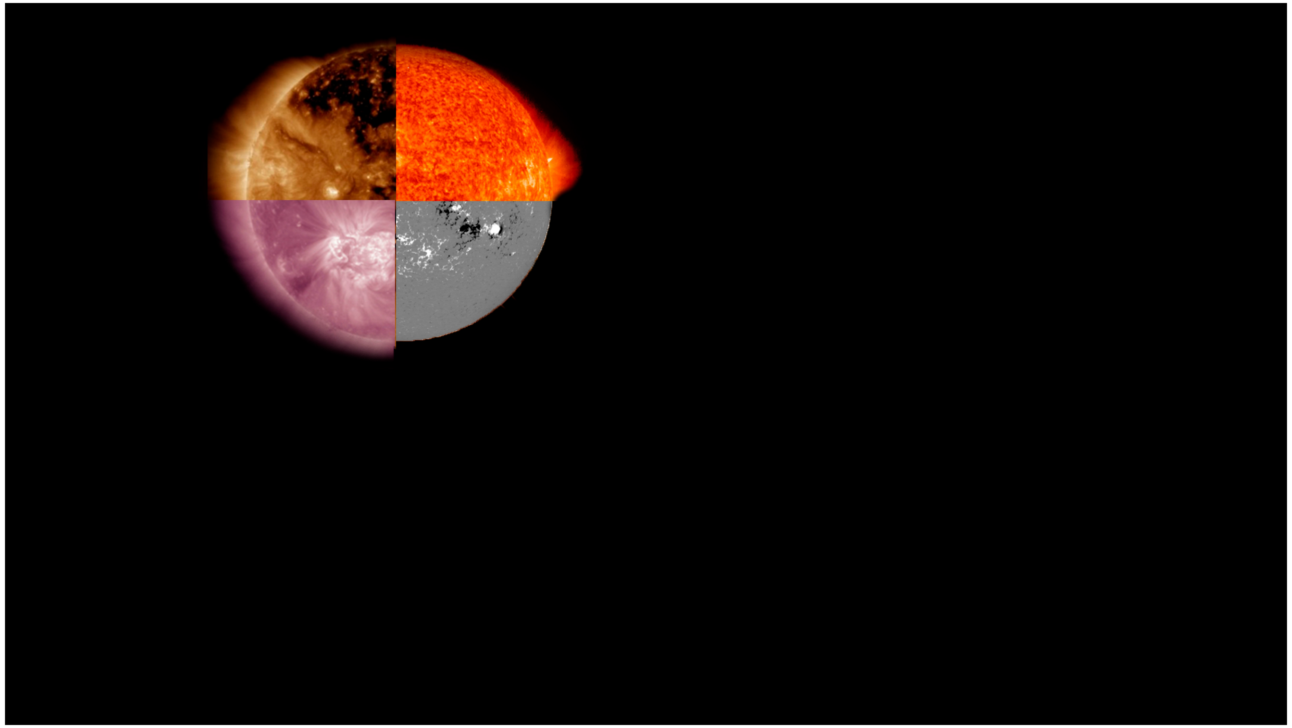
Rosseland Centre for Solar Physics

Introduction

- The Sun shows
a **wide variety of eruptive and ejective phenomena,** that are key to **understanding the solar atmosphere.**



Introduction

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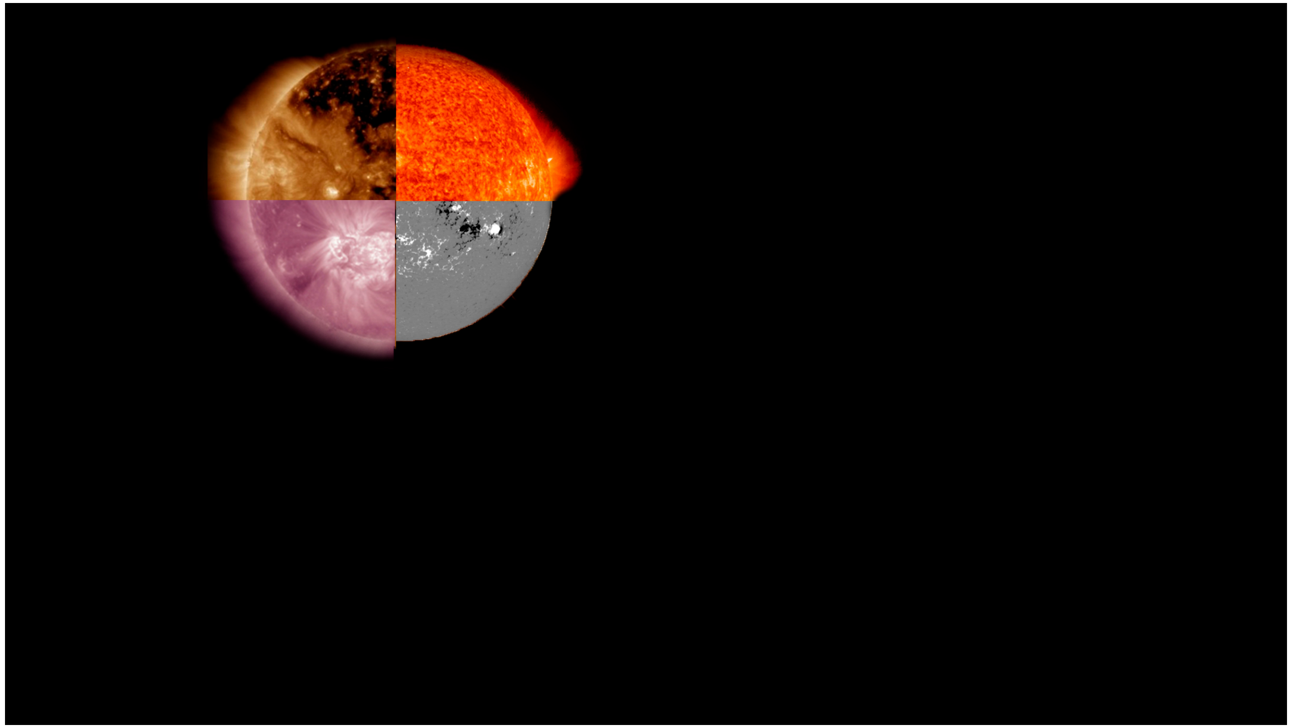

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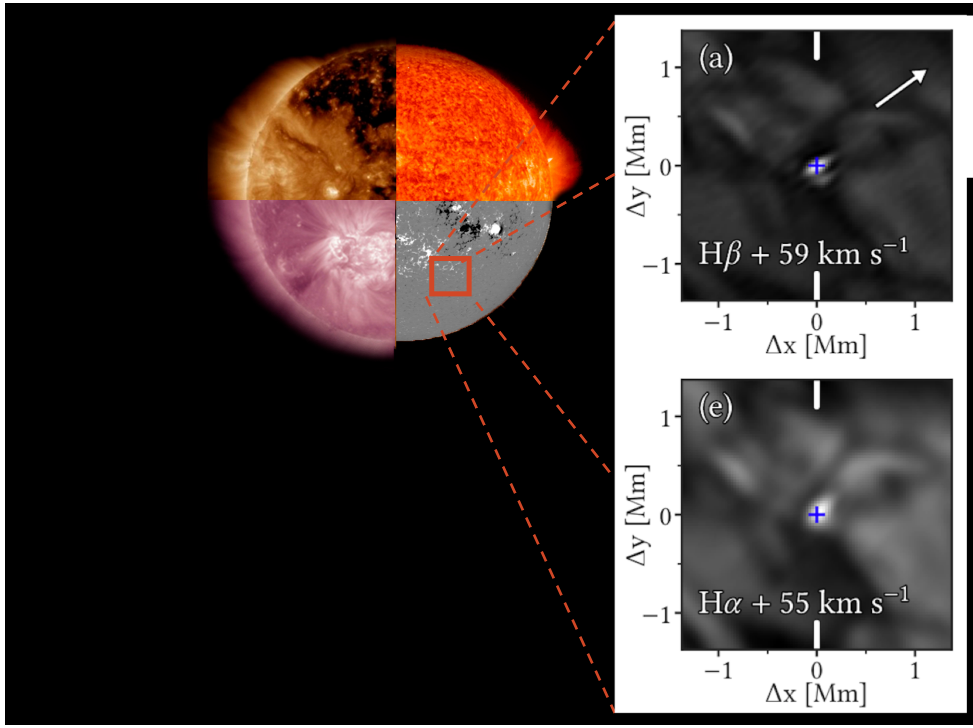

Ellerman Bombs (EBs) (Joshi & Rouppe van der Voort 2020)

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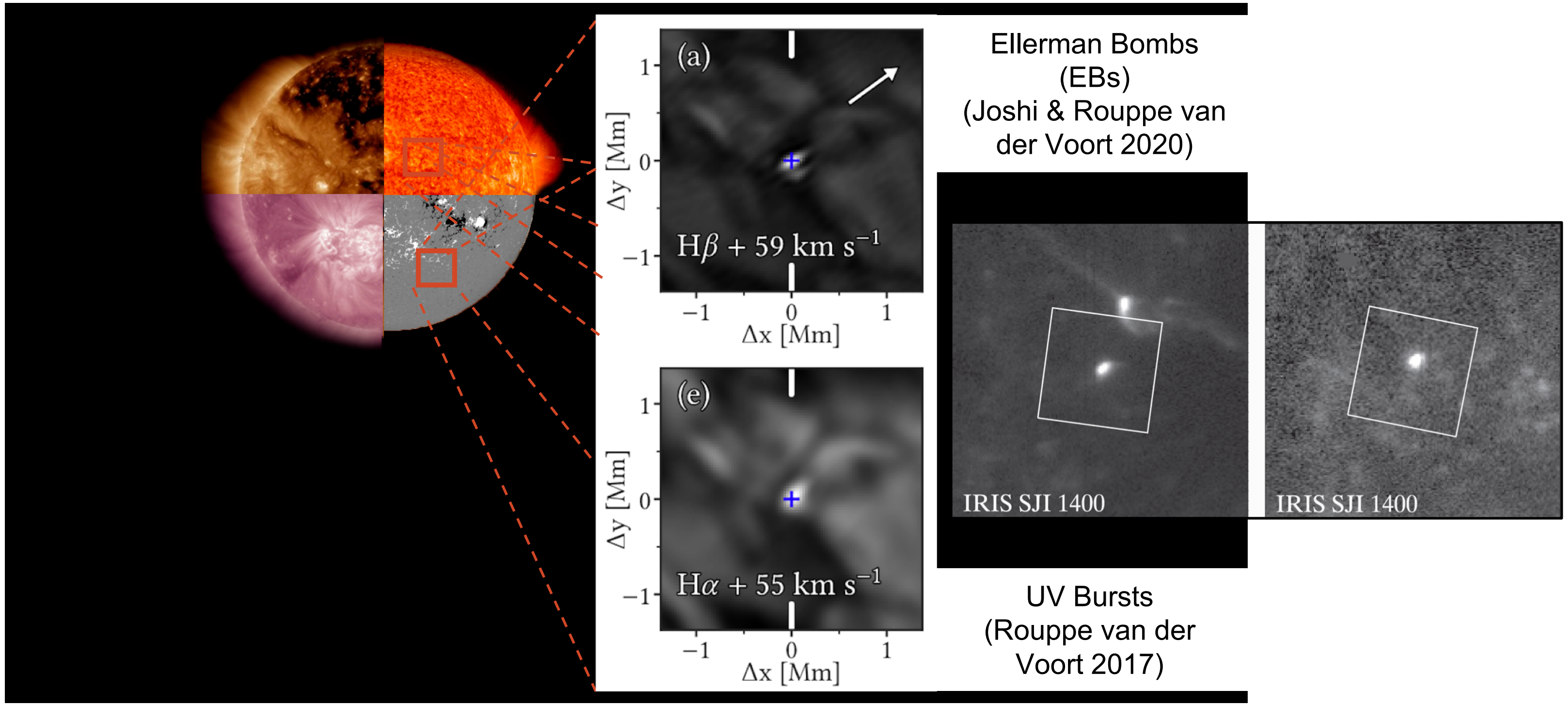

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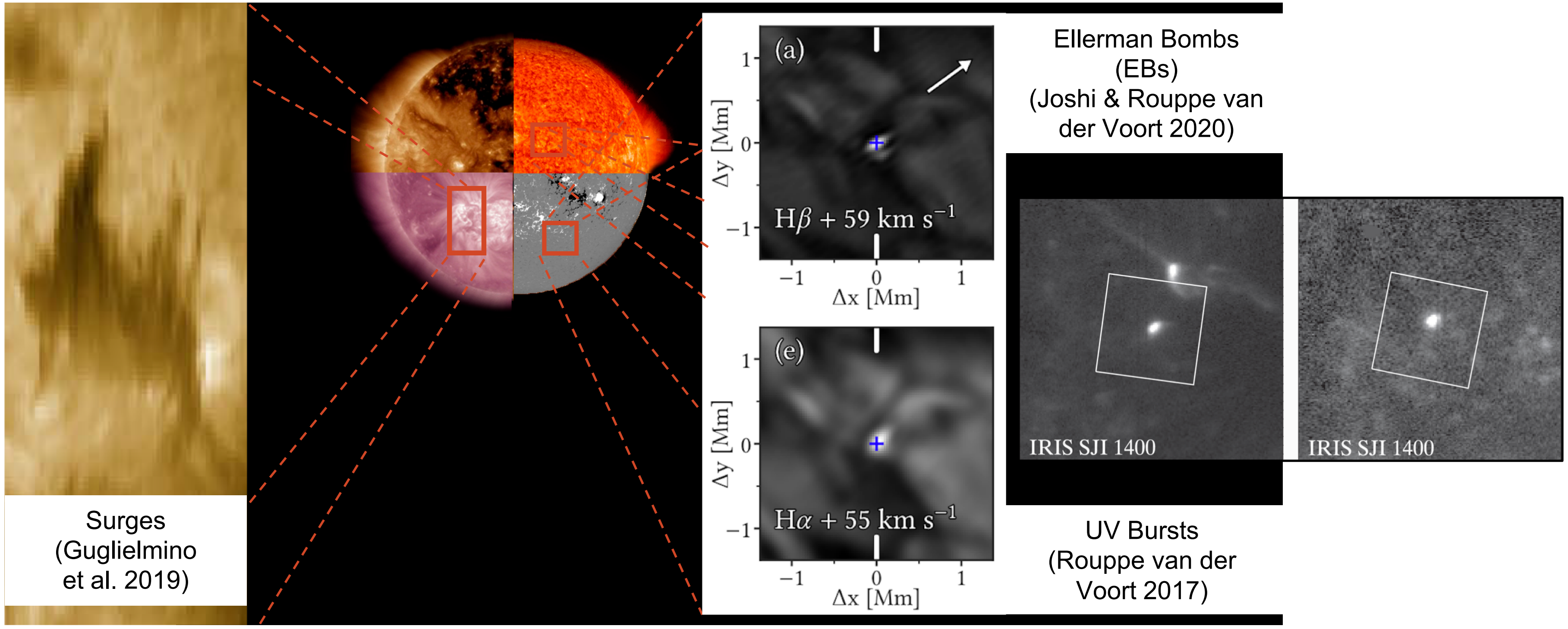

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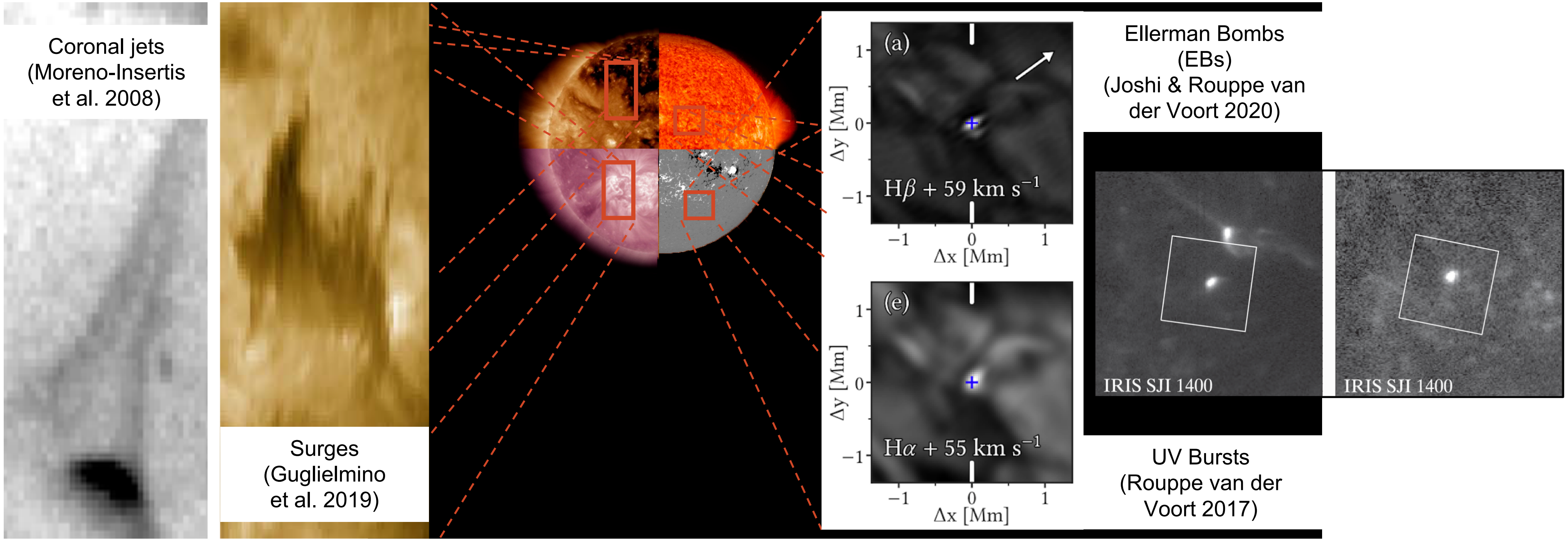

EBs

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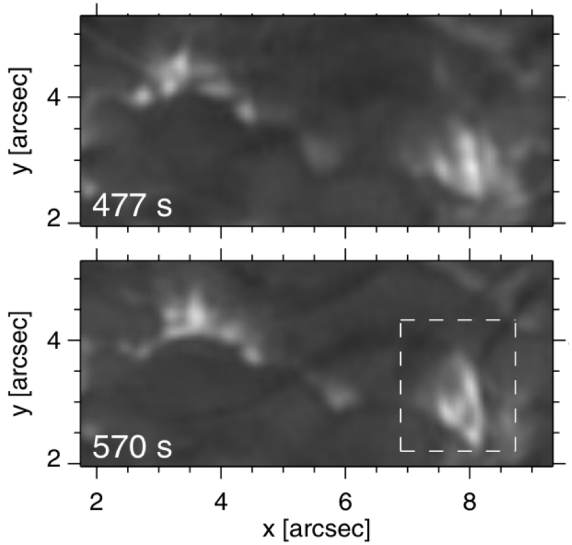
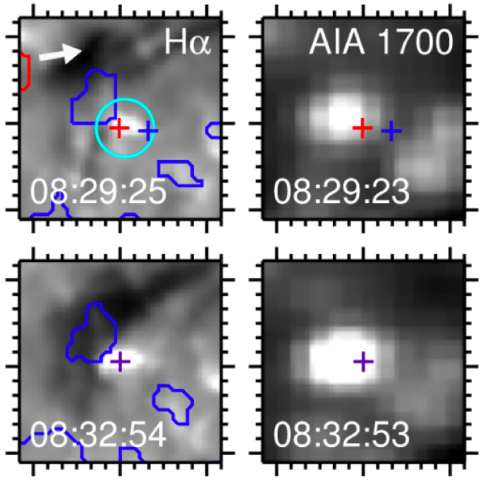
Description:

- Small but intense brightenings of the extended wings of Hα line with the line core unaffected (similar for Hβ, Hγ).
- EBs are also detected as brightenings in Ca II 8542 Å, Ca II H & K, and SDO/AIA 1600 and 1700.
- They last a few minutes and occur repetitively in active regions with much flux emergence, preferentially near and especially between penumbrae.

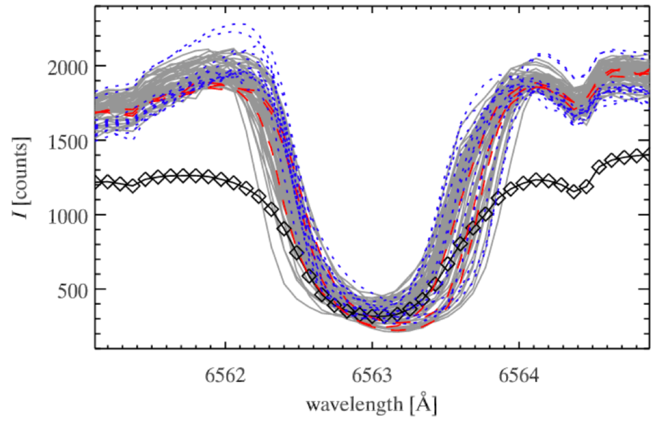
Watanabe et al. 2011



Vissers et al. 2015



Vissers et al. 2013



(e.g., Ellerman 1917, Roy 1973, Georgoulis et al. 2002, Watanabe et al. 2011, Vissers et al. 2013, , Yang et al. 2013, Rutten et al. 2013, Vissers et al. 2015, Rutten et al. 2016, Reid et al. 2017, Hong et al. 2017, Danilovic et al. 2017, Hansteen et al. 2017, Libbrecht et al,. 2017, Vissers et al. 2019, Hansten et al. 2019, Joshi & Rouppe van der Voort 2020, Ortiz et al. 2020, Joshi & Rouppe van der Voort 2022, among others)

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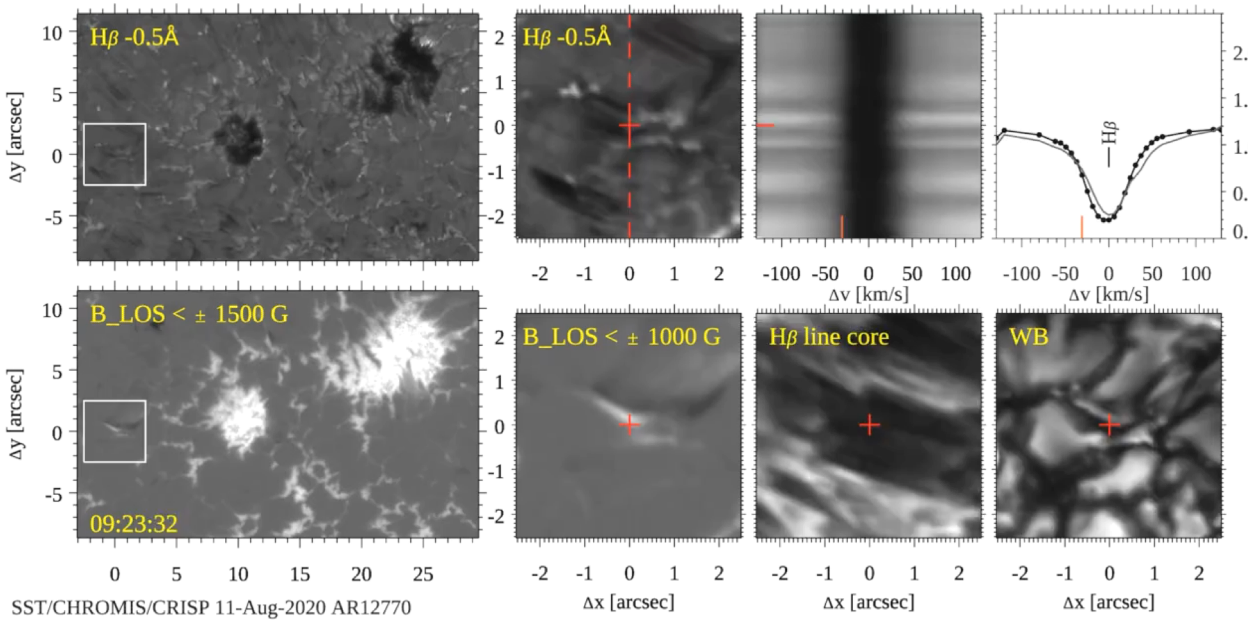
Courtesy of Luc Rouppe van der Voort



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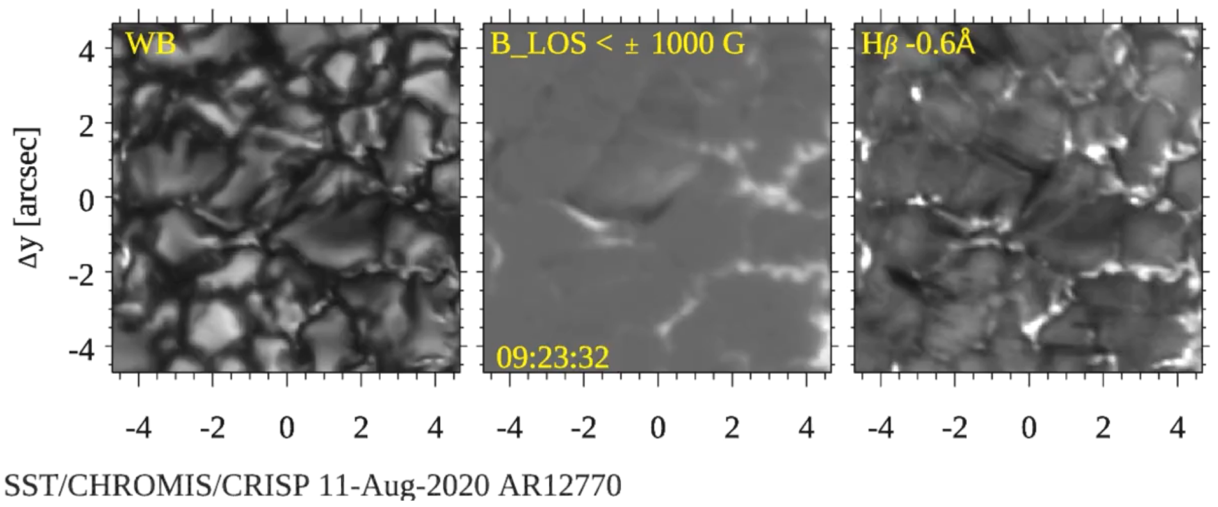

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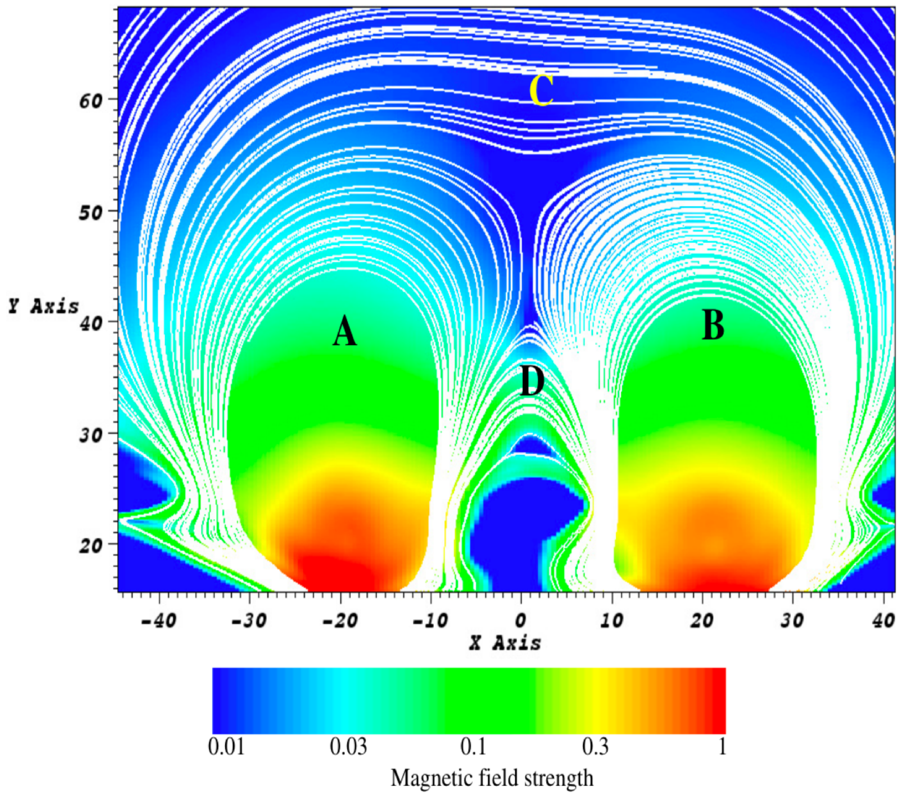
EBs

MHD modeling:

- EBs can be produced converting stored magnetic energy into thermal and kinetic energy through magnetic reconnection.
- Reconnection occurs within dense areas, e.g.,:
  - Between emerging domes.
  - Between a dome and pre-existing ambient field in the low atmosphere.
- Heating per particle is not so efficient.



Archontis et al. 2007

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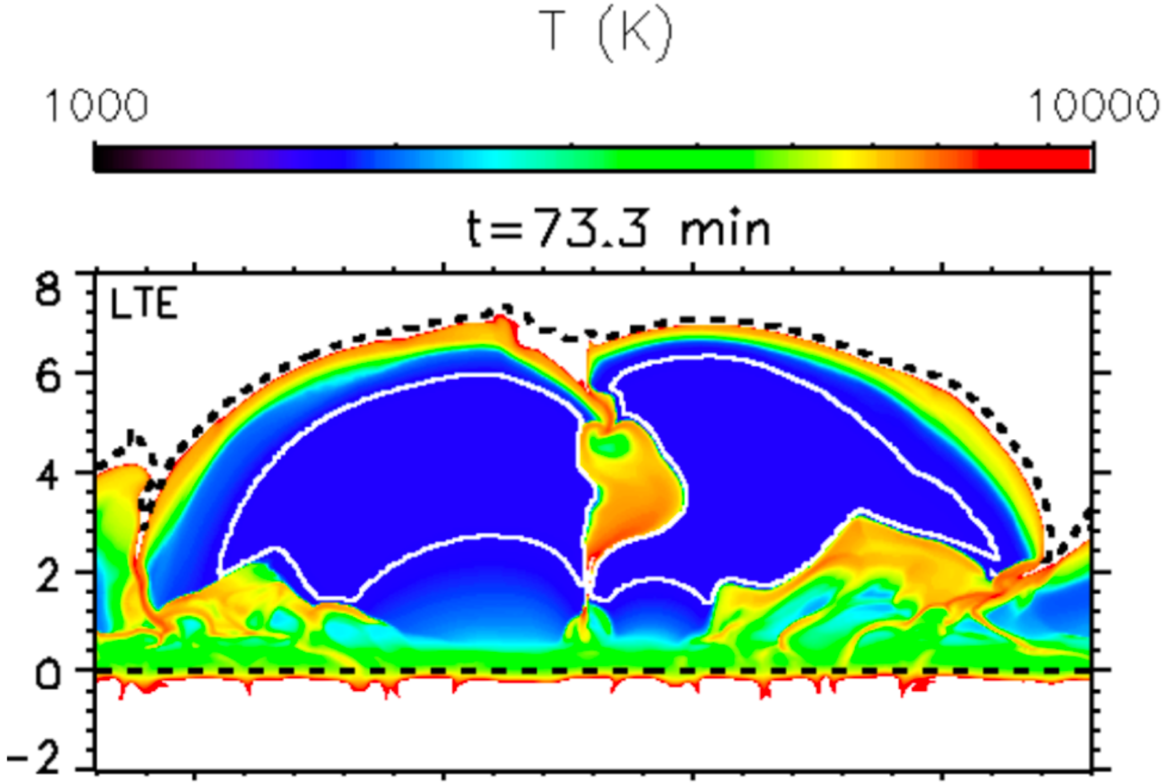

Nóbrega-Siverio et al. 2020

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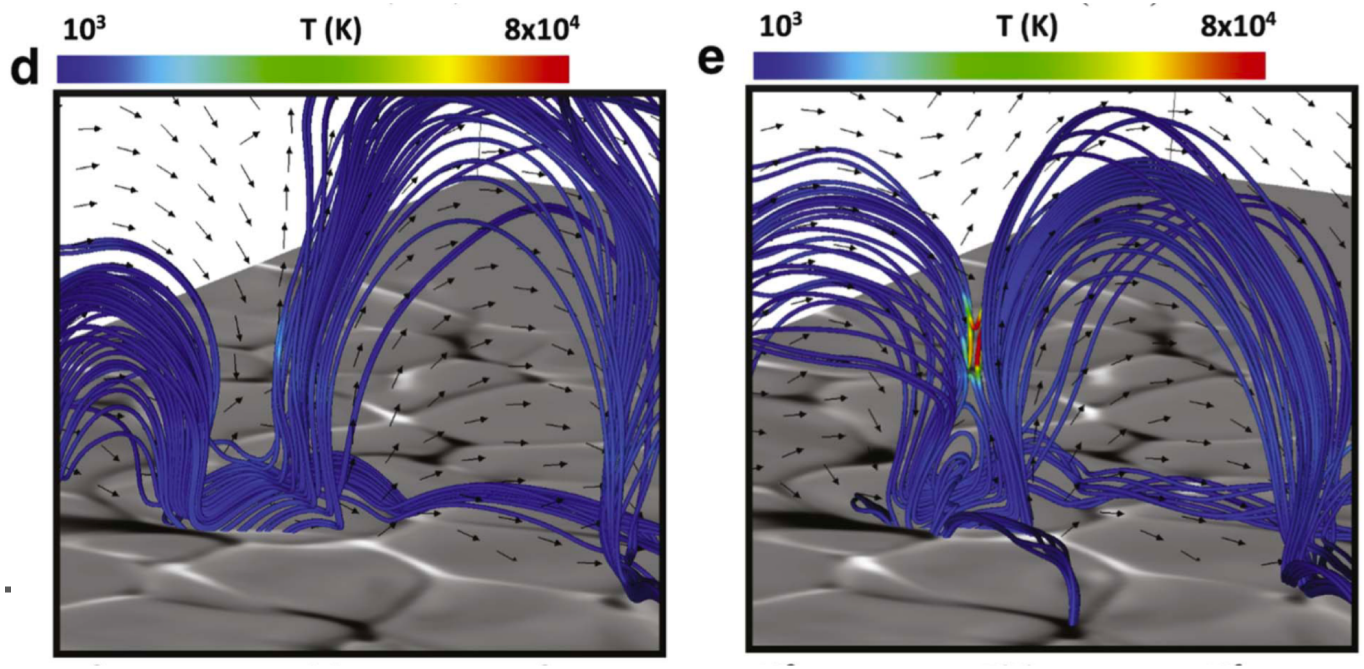

Hansteen et al. 2017

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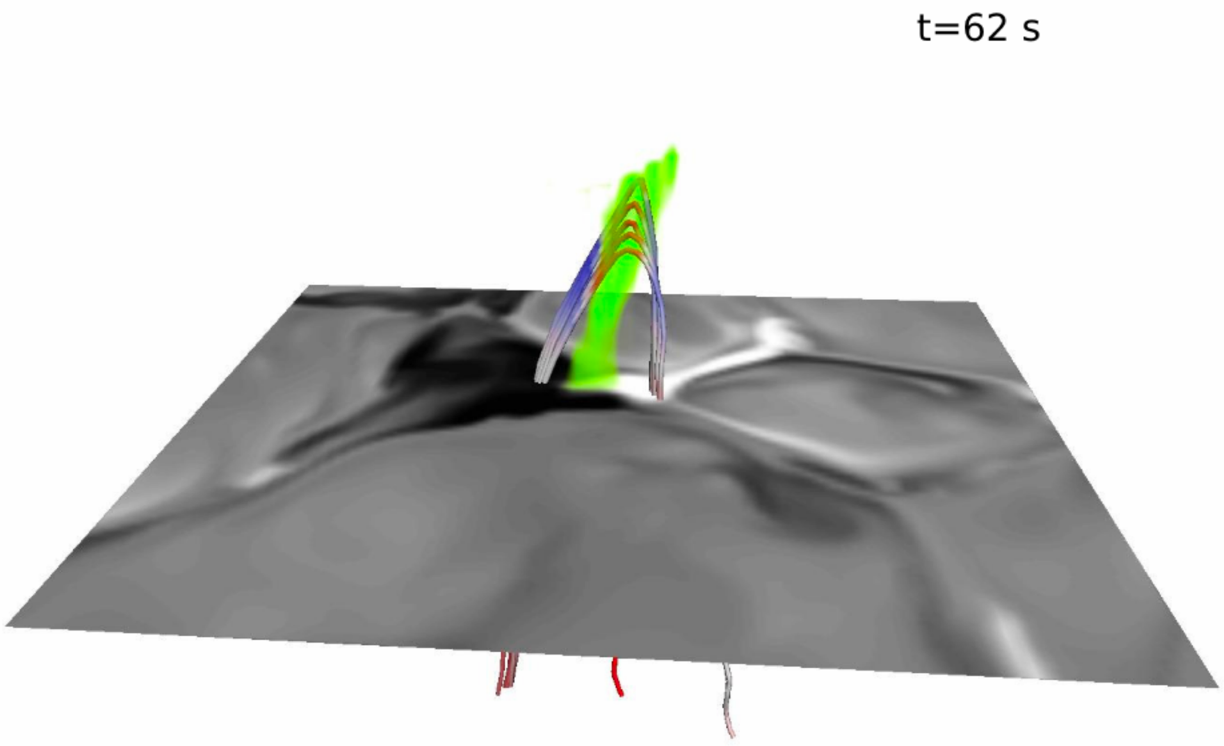


Danilovic et al. 2017

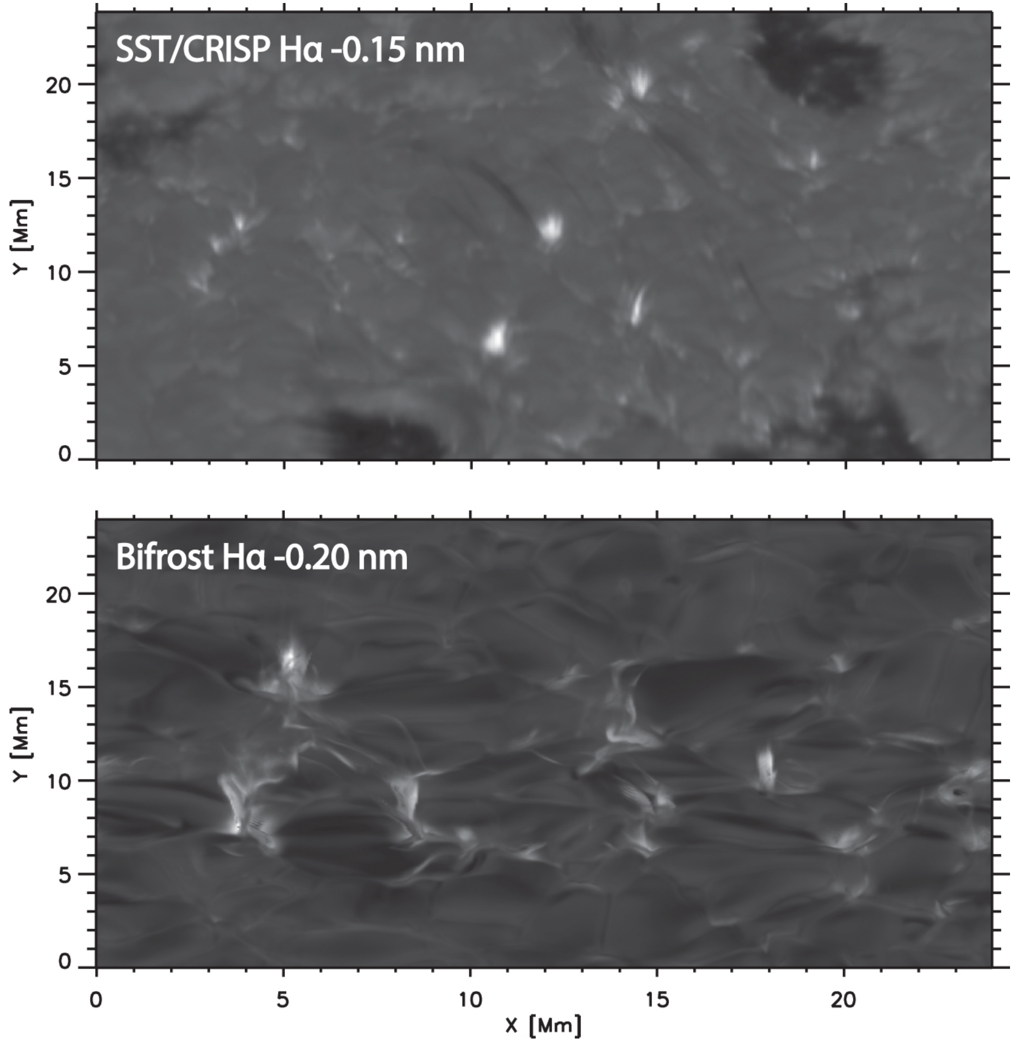
EBs

Comparison with observations:

- Synthetic observables from simulations show striking similarities with observations:

  - Bright compact/Flame-like structures.

  - Extended wings of the Hα profile get significantly enhanced



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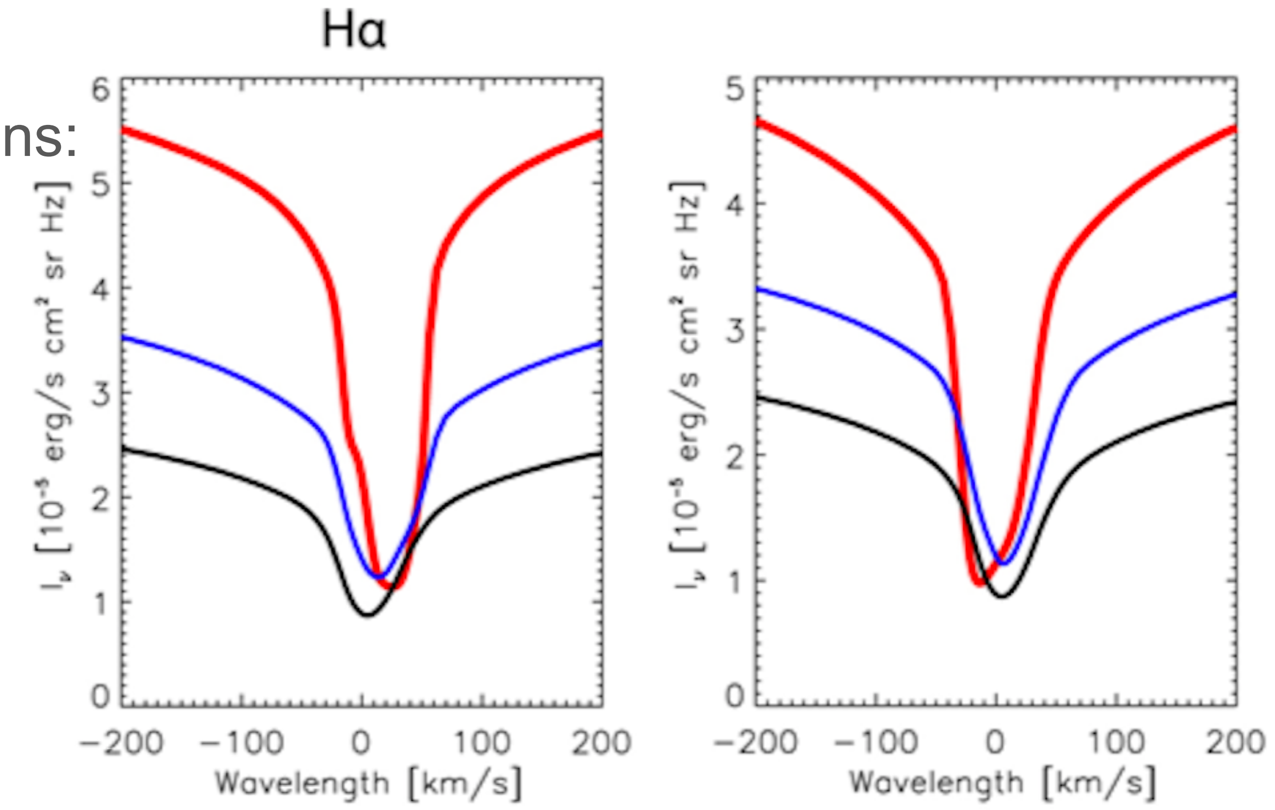
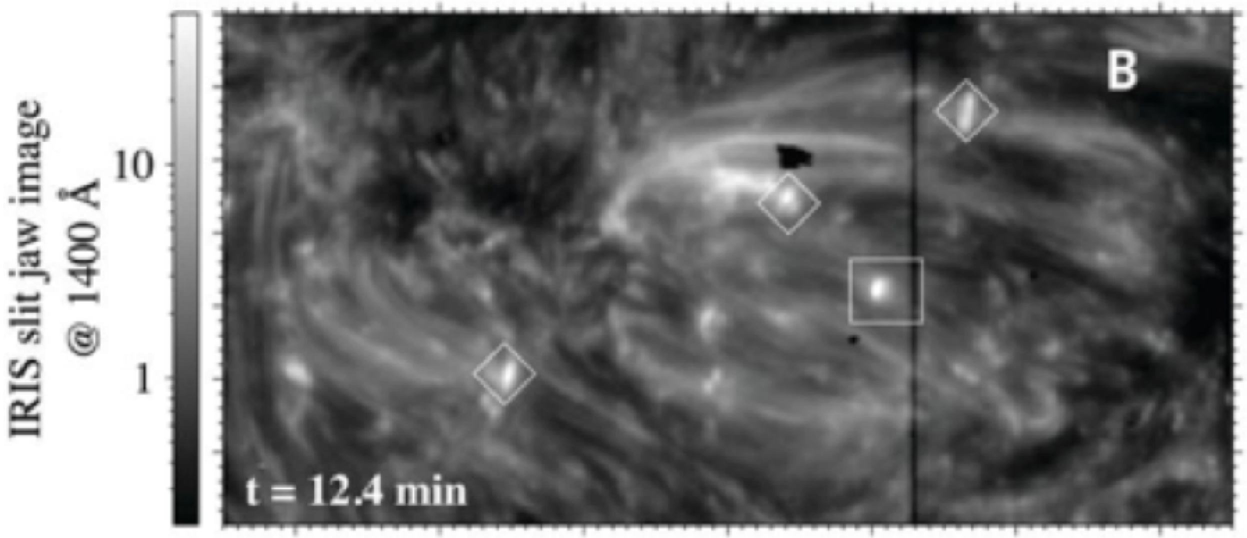


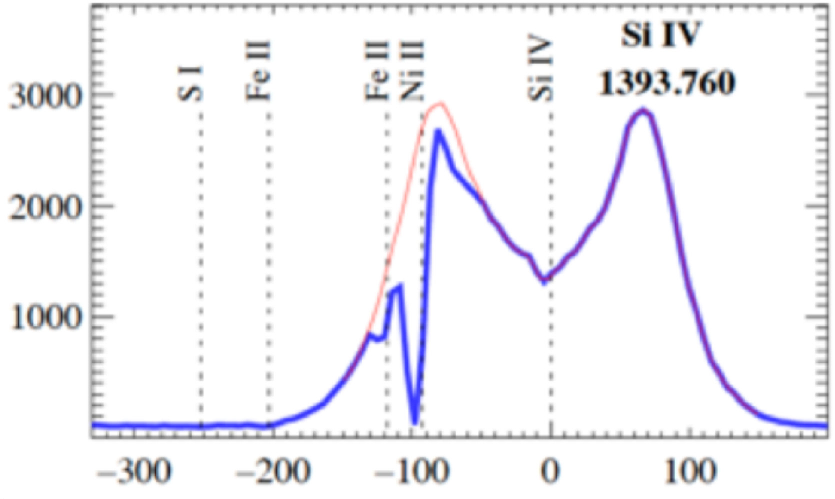
Hansteen et al. 2017

UV bursts

Description:

- Roundish compact structures: $L \leq 1''$.
- Bright structures: ~100-1000 brighter than their surroundings.
- Visible in the ultraviolet (UV) spectra.
- Duration between tens of seconds to ~1 hour.
- UV bursts can be found in emerging flux regions (EFRs), associated to Moving Magnetic Features (MMFs), and in Light Bridges (LBs).
- Association with EBs, surges, jets.





Peter et al. 2014

Check the recent review by
Young et al. 2018

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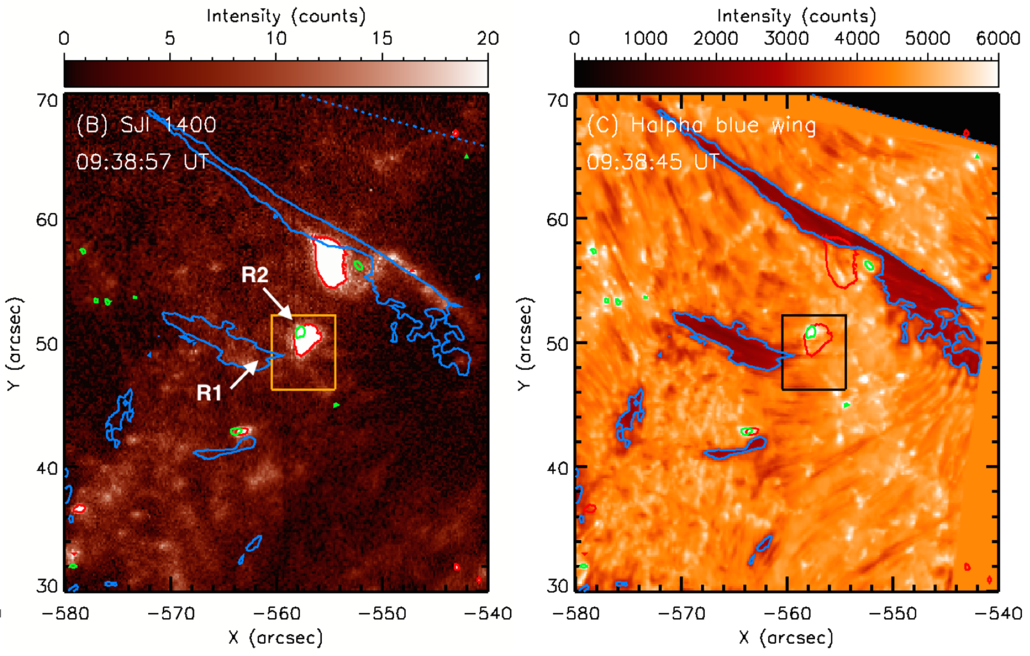

Nóbrega-Siverio et al. 2017

Check the recent review by
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UV bursts

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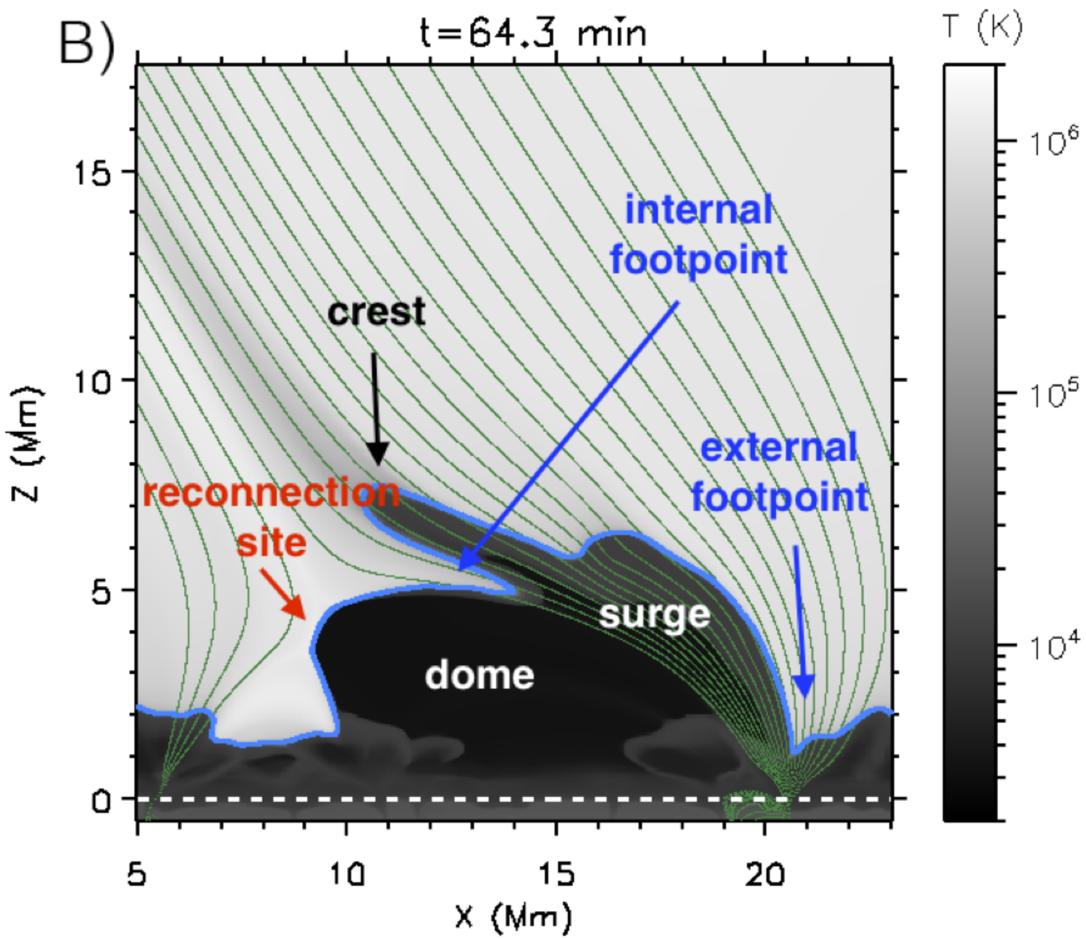
MHD modeling:

- Magnetic reconnection between emerging fields and/or with the pre-existing field.
- Reconnection occurs higher up in the atmosphere than for the EBs.
- Because of the stratification and/or dome rarefaction, Joule heating is more efficient to heat plasma up to 1e5 K.

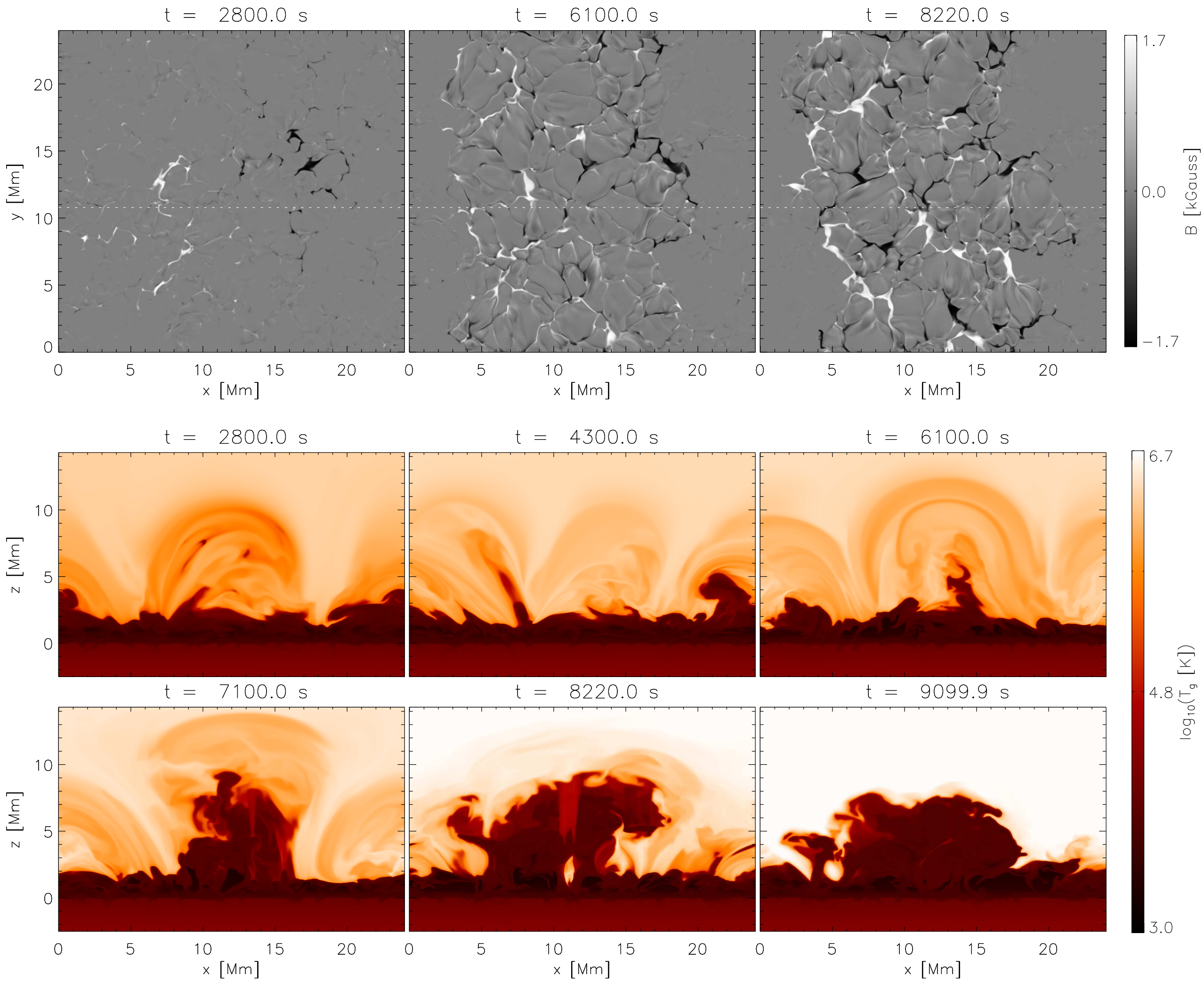


Nóbrega-Siverio et al. 2017, 2018

UV bursts

MHD modeling:

- No compelling reasons to assume that UV bursts occur in the photosphere.
- EBs and UV bursts can be co-located as result of reconnection in a long current sheet that extends through the chromosphere.
- UV bursts can be found after an EB, due to the expansion and rarefaction of the dome.

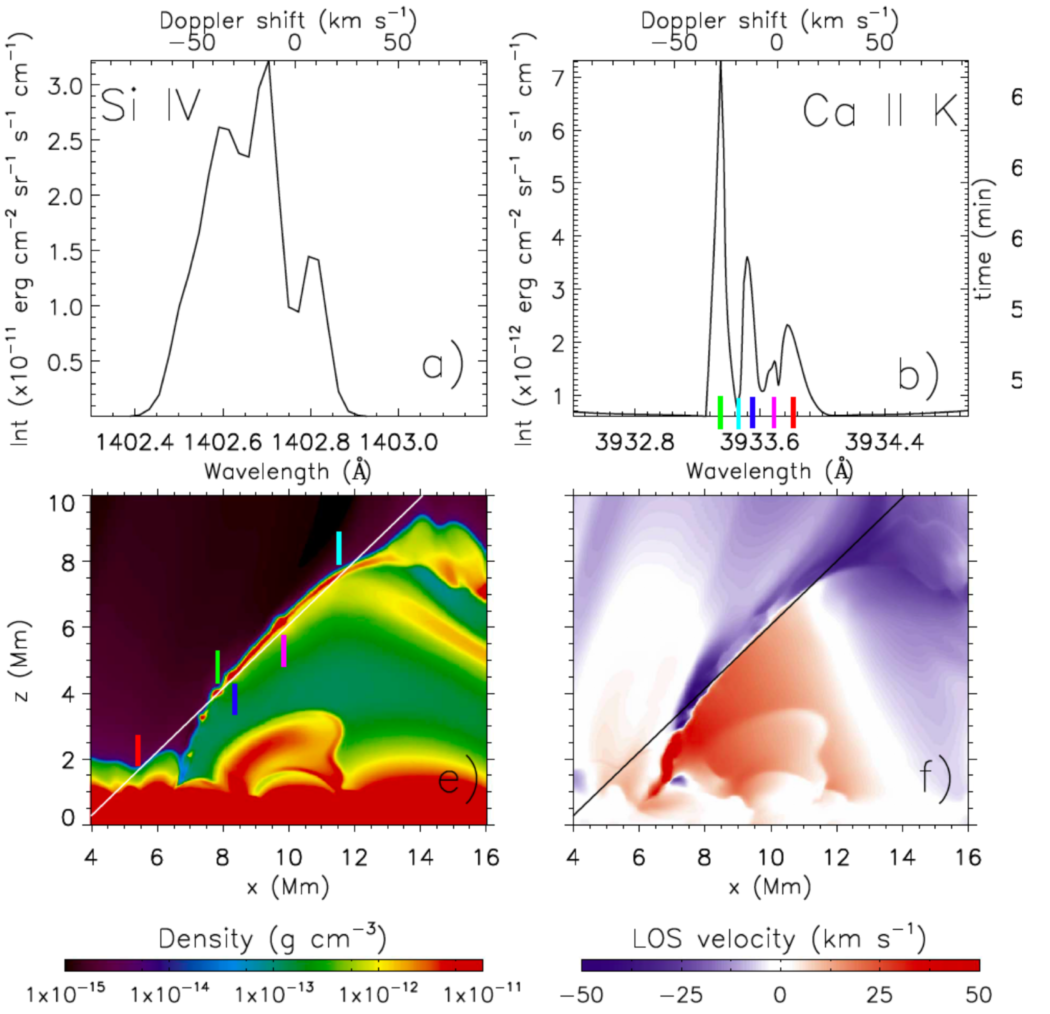


Hansteen et al. 2019

UV bursts

Comparison with observations:

- Numerical experiments can explain highly broadened, non-Gaussian Si IV profiles observed with IRIS.
- Numerical experiments can explain triangular-shaped Ca II K profiles observed with SST.
- Non-Gaussian/triangular-shaped spectral line profiles are good proxies for plasmoid-mediated reconnection.



Rouppe van der Voort et al. 2017

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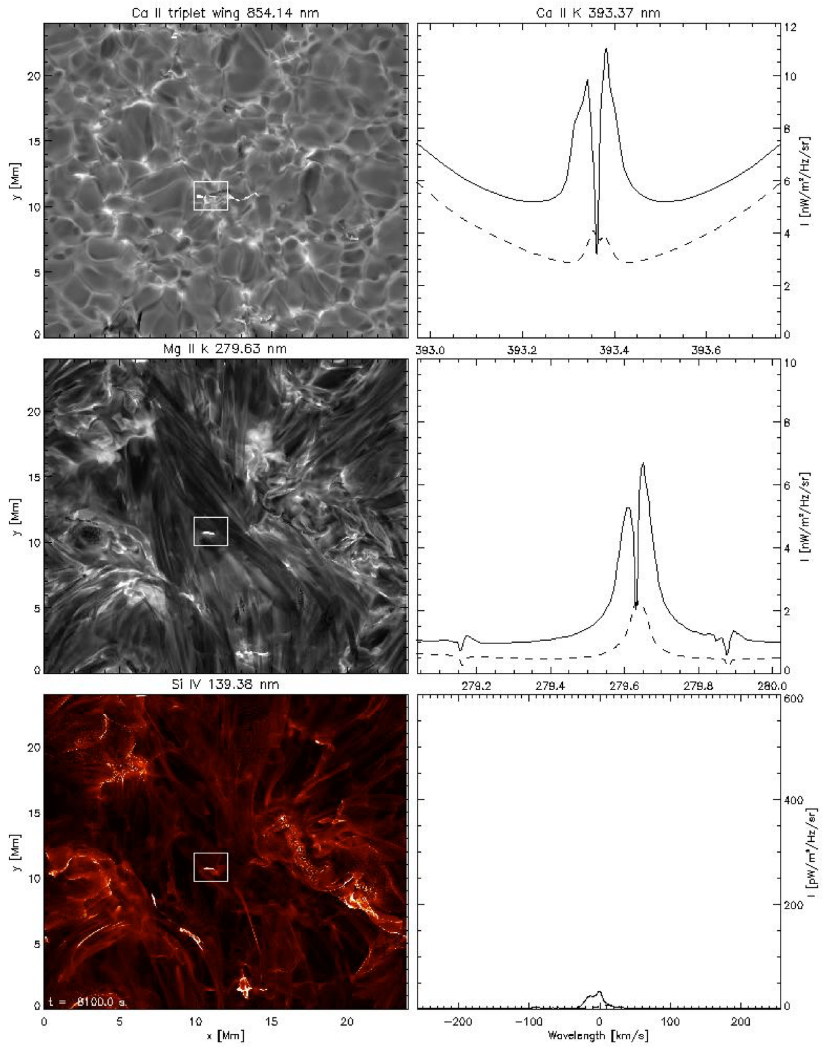


Hansteen et al. 2019

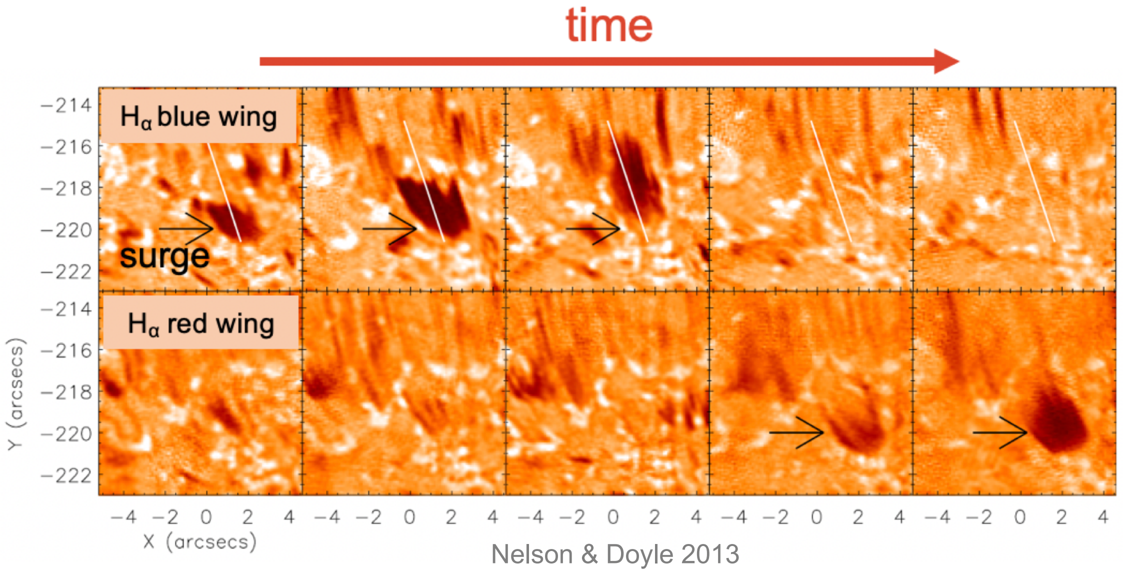
Surges

Description:

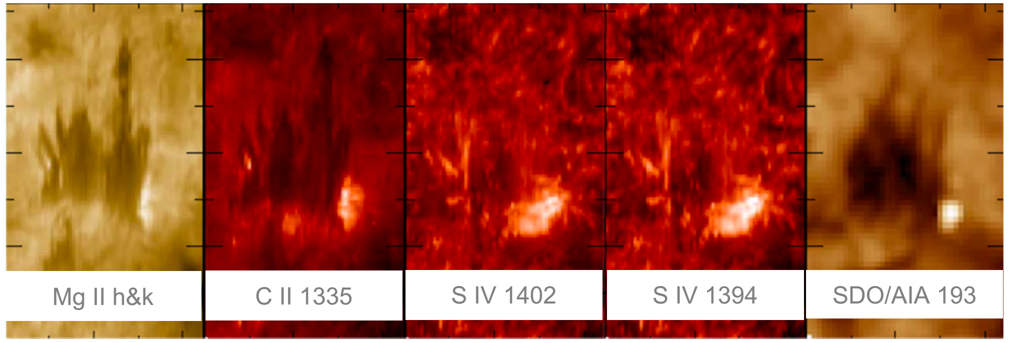
- Chromospheric ejections traditionally observed in H_α as blue-redshifted absorption (also observed in other lines like Ca II H&K, Ca II 8542Å, Mg II h&k).
- They consist of thread-like structures and can be recurrent and have rotational motions.

Velocities	20-50 km/s
Length	10-50 Mm
Lifetime	~10-60 min

- Related to EBs, UV bursts, light bridges, jets, and flares.



Nelson & Doyle 2013



Guglielmino et al. 2019

(e.g., McMath and Petit 1937, Roy 1973, Kurokawa and Kawai 1993, Schmieder et al. 1995, Canfield et al. 1996, Chae et al. 1999, Yoshimura et al. 2003, Liu and Kurokawa 2004, Brooks et al. 2007, Jiang et al. 2007, Nishizuka et al. 2008, Liu et al. 2009, Guglielmino et al. 2010, Yang et al. 2013 , Nelson and Doyle 2013, Bong et al. 2014, Vargas Domínguez et al. 2014, Wang et al. 2014, Kim et al. 2015, Li et al. 2016, Cho et al. 2019, Guglielmino et al. 2018, 2019, Joshi et al. 2020, Verma et al. 2020, Ortiz et al. 2020, Nóbrega-Siverio et al. 2021, Panesar et al. 2021, among others)

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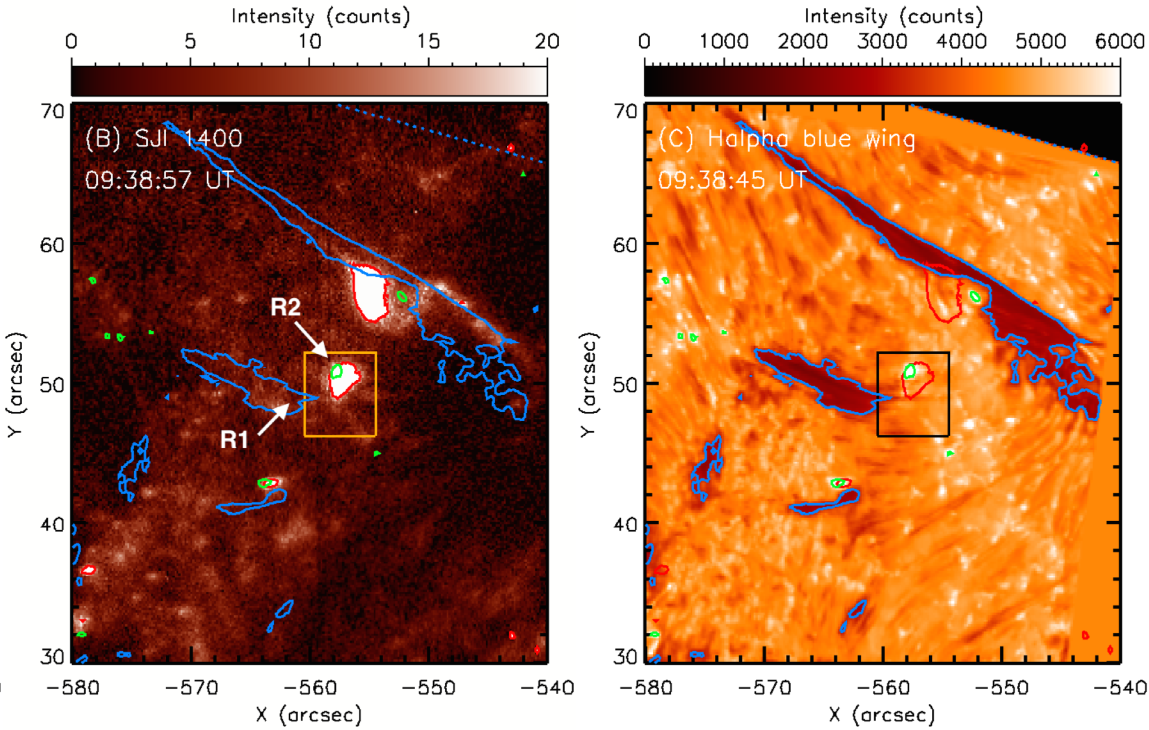

Nóbrega-Siverio et al. 2017

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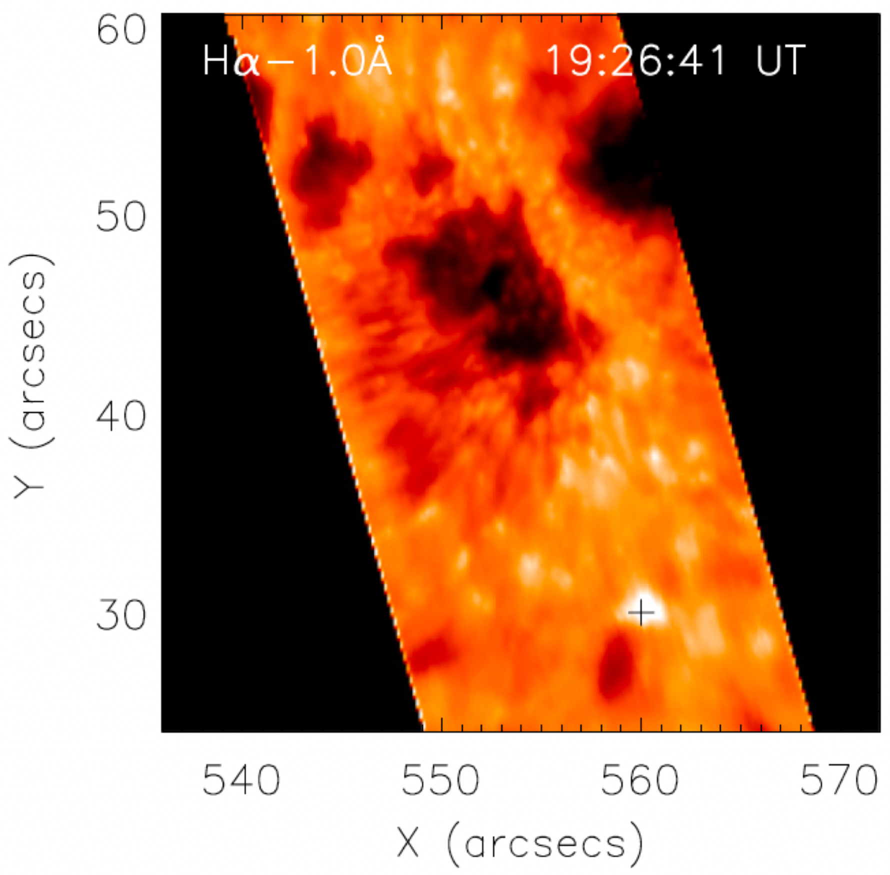


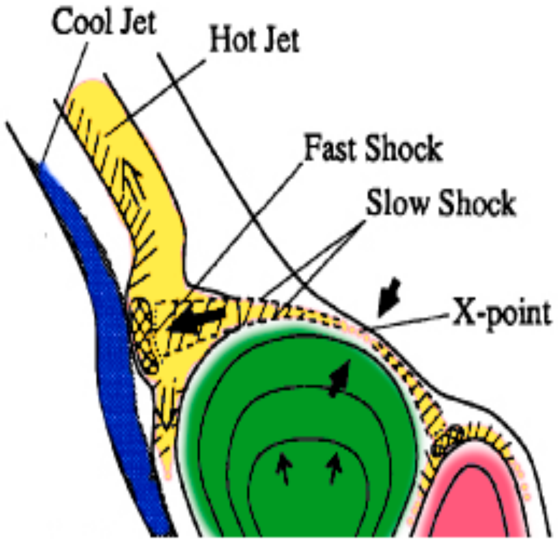
Kim et al. 2015

(e.g., McMath and Petit 1937, Roy 1973, Kurokawa and Kawai 1993, Schmieder et al. 1995, Canfield et al. 1996, Chae et al. 1999, Yoshimura et al. 2003, Liu and Kurokawa 2004, Brooks et al. 2007, Jiang et al. 2007, Nishizuka et al. 2008, Liu et al. 2009, Guglielmino et al. 2010, Yang et al. 2013 , Nelson and Doyle 2013, Bong et al. 2014, Vargas Domínguez et al. 2014, Wang et al. 2014, Kim et al. 2015, Li et al. 2016, Cho et al. 2019, Guglielmino et al. 2018, 2019, Joshi et al. 2020, Verma et al. 2020, Ortiz et al. 2020, Nóbrega-Siverio et al. 2021, Panesar et al. 2021, among others)

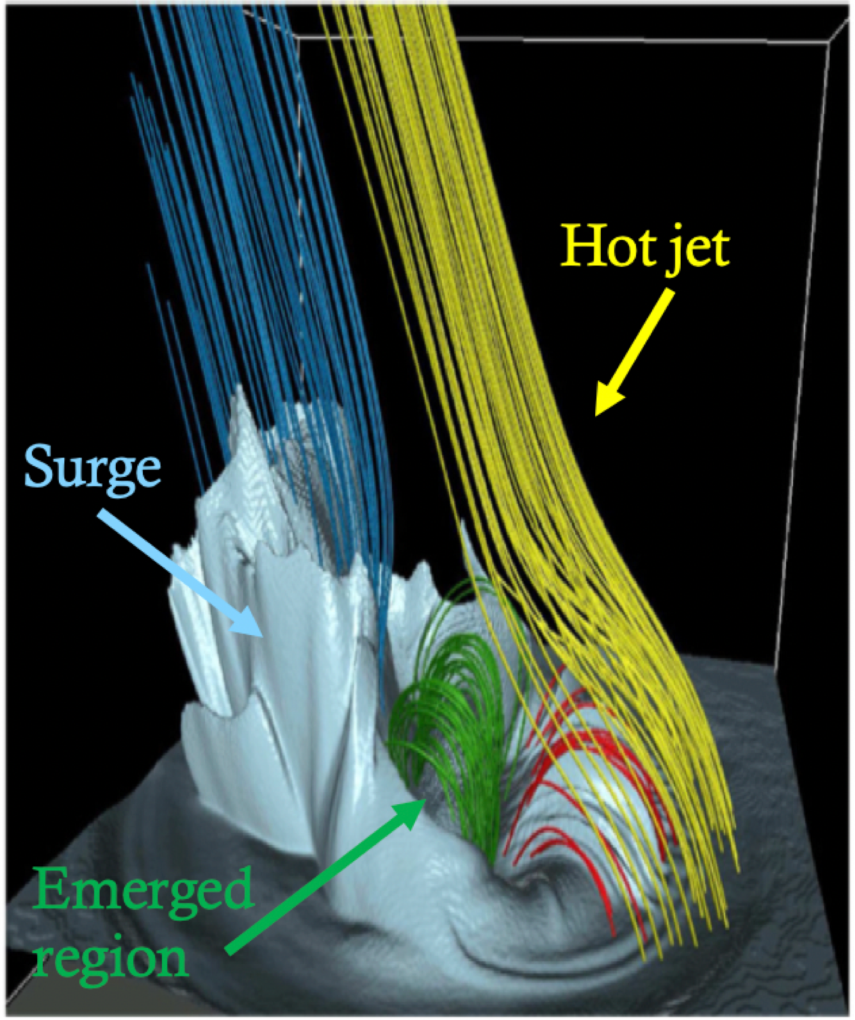
Surges

MHD modeling:

- Peeling-like mechanism
  that drags cool and dense material
  to greater heights in the atmosphere:
  slingshot effect and whip-like motion.



Yokoyama & Shibata 1995,1996



Moreno-Insertis & Galsgaard 2013

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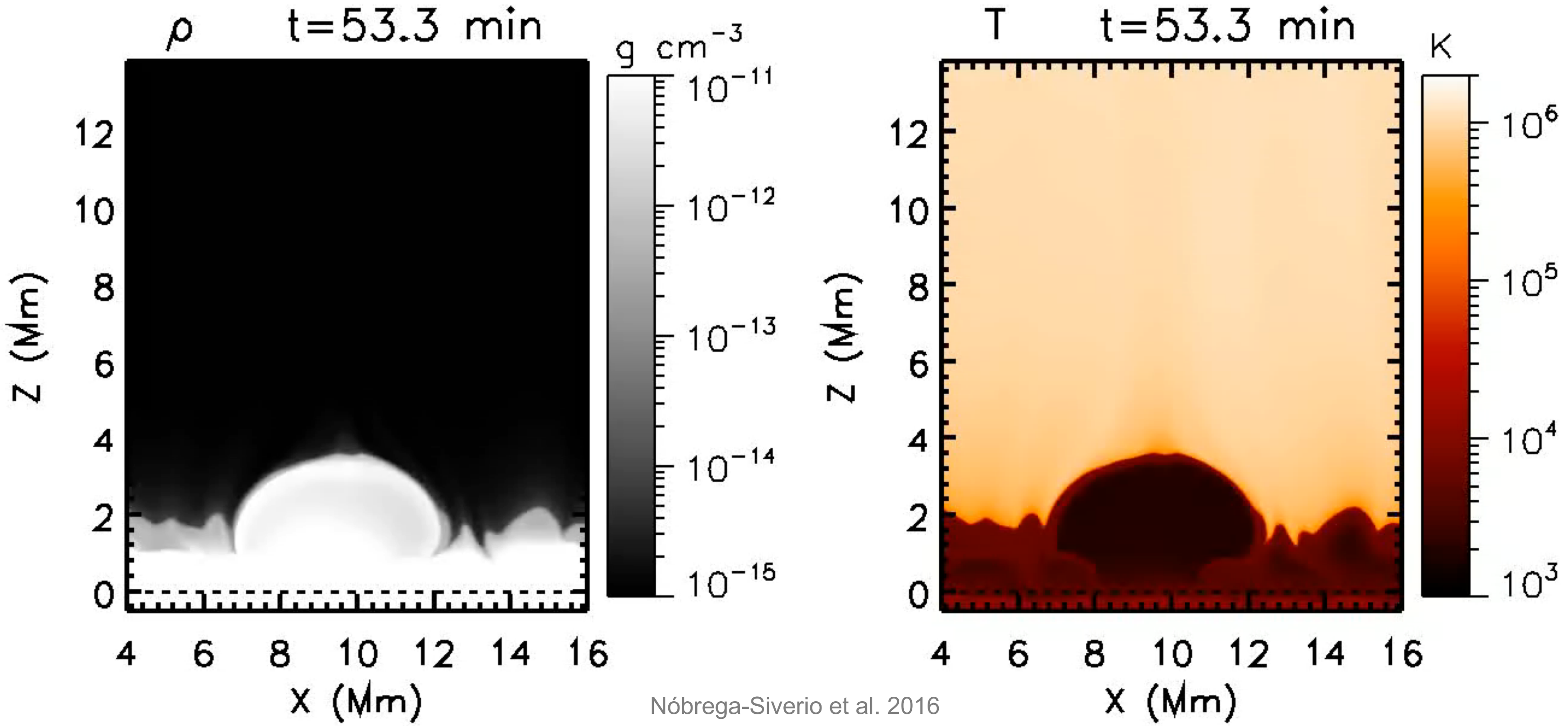


Nóbrega-Siverio et al. 2016

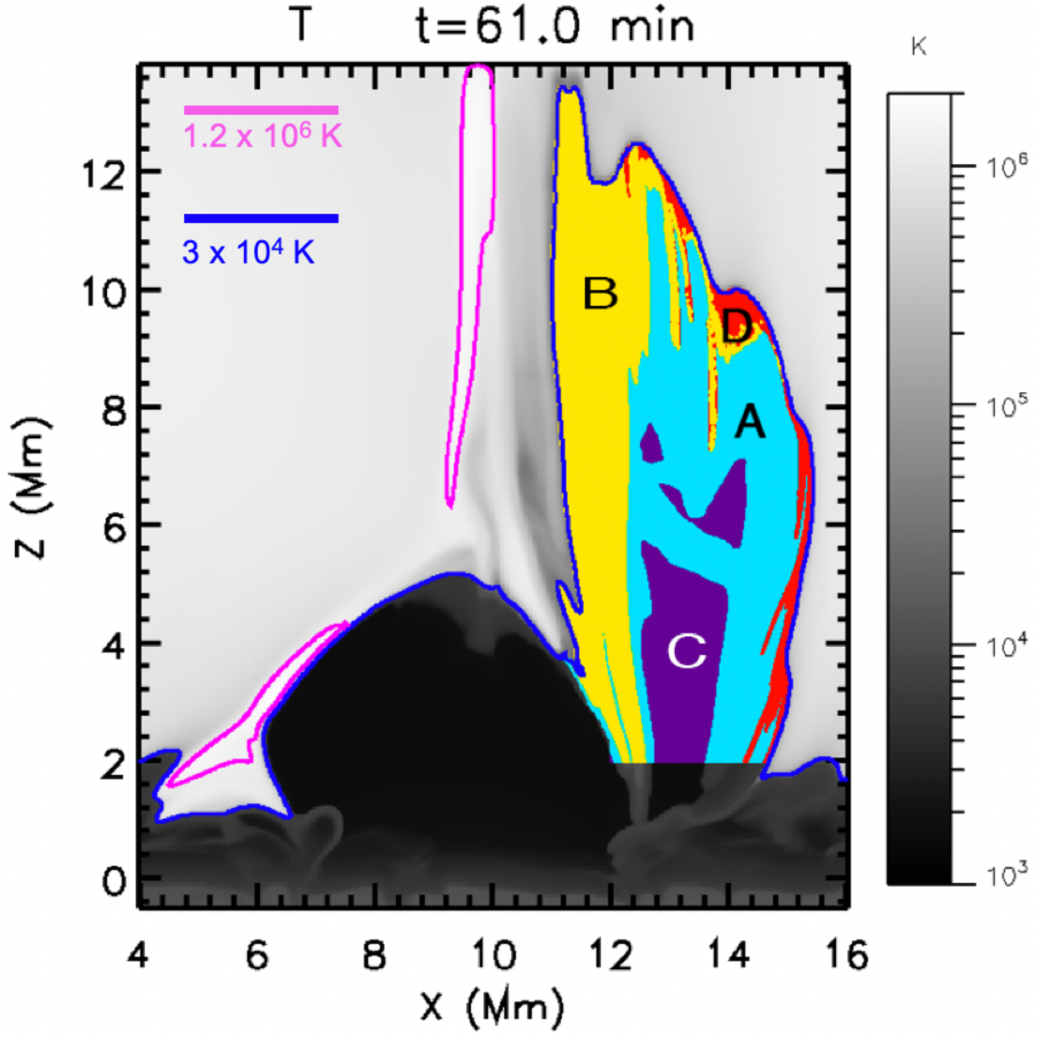
Surges

MHD modeling:

- Peeling-like mechanism
  that drags cool and dense material
  to greater heights in the atmosphere:
  slingshot effect and whip-like motion.

- Entropy sources are essential:
  a significant fraction of the surges is missed
  when not including thermal conduction
  and optically thin losses.

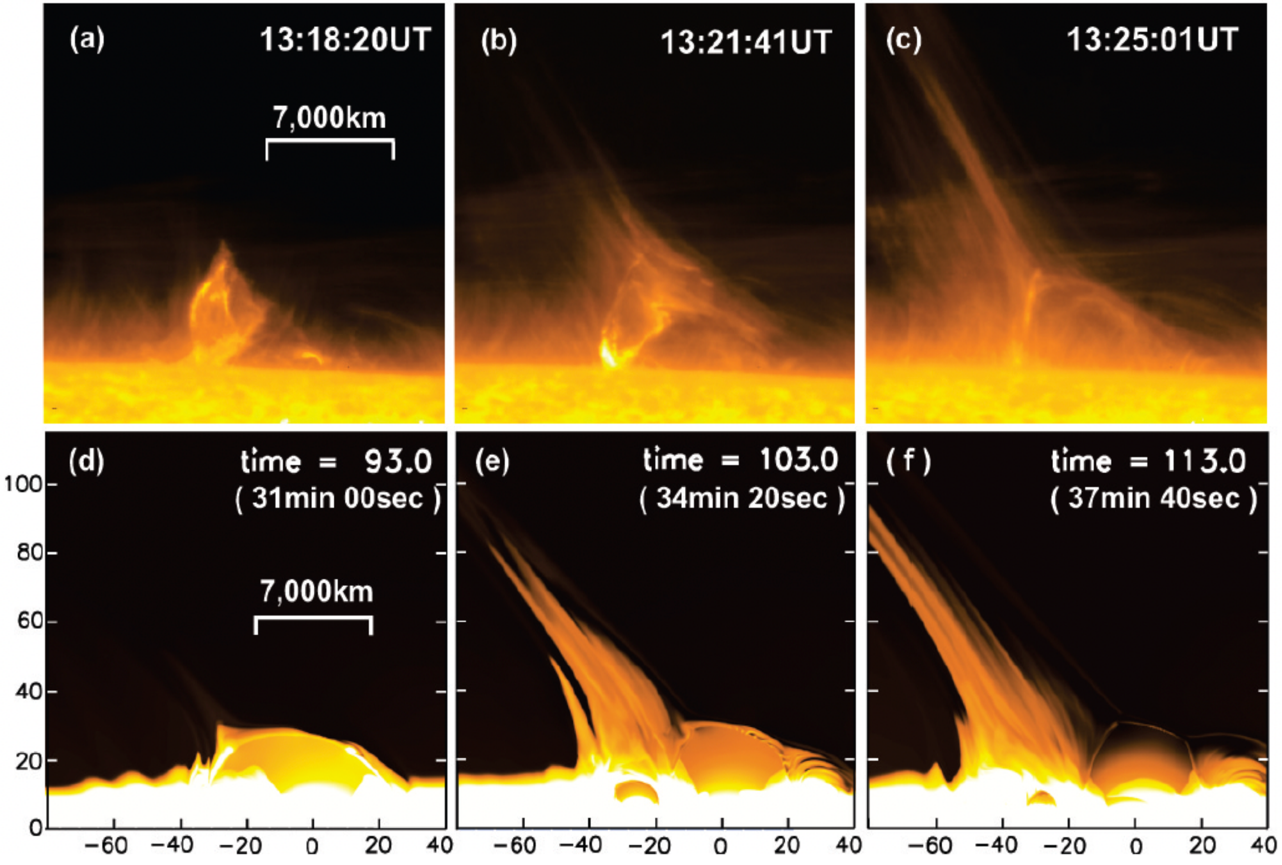
(Yokoyama & Shibata 1995, 1996, Nishizuka et al. 2008, Jian et al. 2012, Takasao et al. 2013, Yang et al. 2013, Moreno-Insertis et al. 2013, MacTaggart et al. 2015, Nóbrega-Siverio et al. 2016, 2017, 2018)



Nóbrega-Siverio et al. 2016

Comparison with observations:

- Morphological comparisons show agreement with observational features.



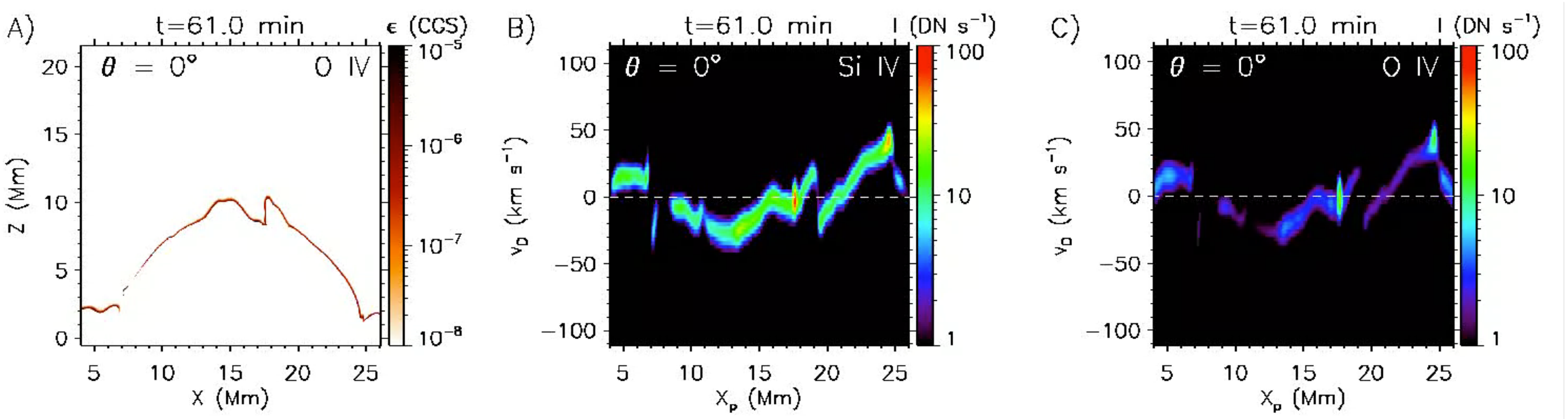
Nishizuka et al. 2008

Surges

Comparison with observations:

- Morphological comparisons show agreement with observational features.
- The boundaries of the surge can show enhanced emission in TR lines like Si IV 1402Å, O IV 1401Å.

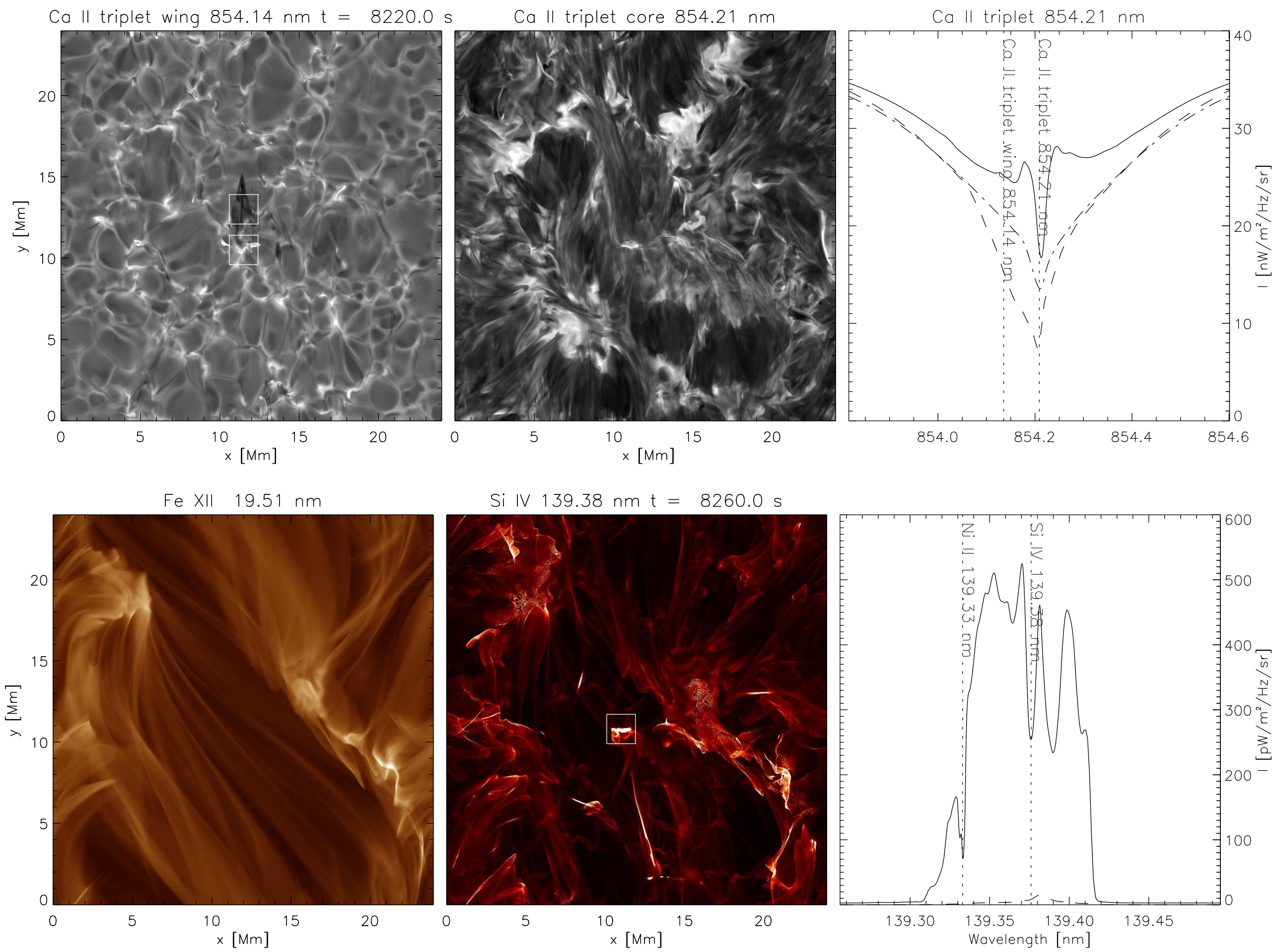
Nóbrega-Siverio et al. 2017



Surges

Comparison with observations:

- Morphological comparisons show agreement with observational features.
- The boundaries of the surge can show enhanced emission in TR lines like Si IV 1402Å, O IV 1401Å.
- Numerical experiments explain the relationship between, e.g., UV bursts and surges.



Hansteen et al. 2019

Coronal jets

Description:

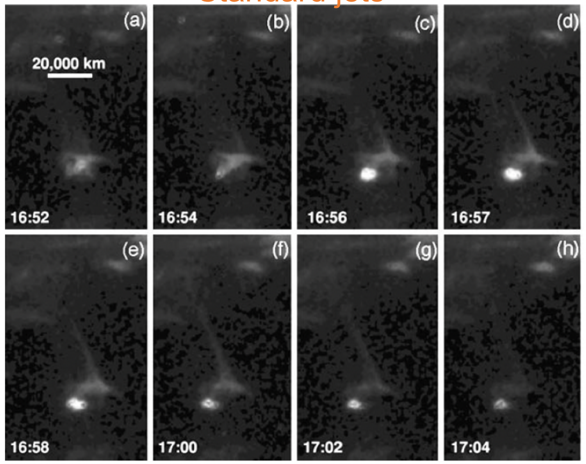
- High-velocity collimated plasma ejections with coronal temperatures observed in X-rays and EUV (Yohkoh, SOHO, RHESSI, Hinode, STEREO, SDO).
- Jets show an inverted-Y, Eiffel tower, or λ shape. There are two types:
  - **standard jets**: narrow spine, point-like brightening at the base.
  - **blow-out jets**: broad spine, substantial cool emission, helical and transverse motions.
- Related to surges and minifilament eruptions.

(see more details in the review by Raouafi et al. 2016)

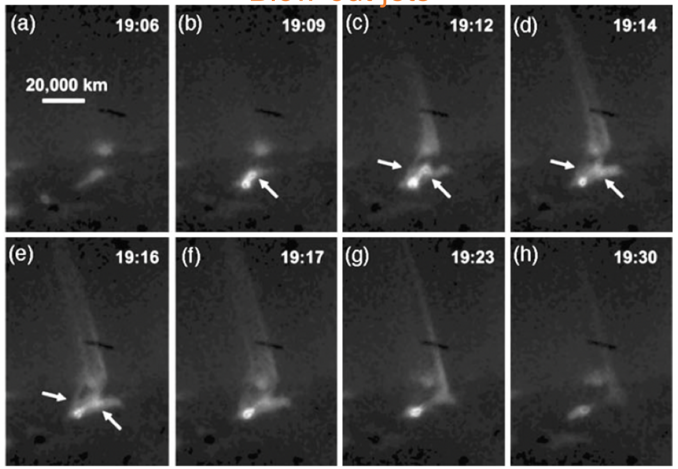
Velocity	70-400 km s^{-1}
Temperature	[1.6-2.5] x 10^{6} K
Density	[1-5]x10^{-15} g cm^{-3}
Length	10-120 Mm
Width	6-10 Mm
Lifetime	1-100 min

Savcheva et al. 2007, Nitiscò et al. 2009, Madjarska et al. 2012

Standard jets



Blow-out jets



Moore et al. 2010

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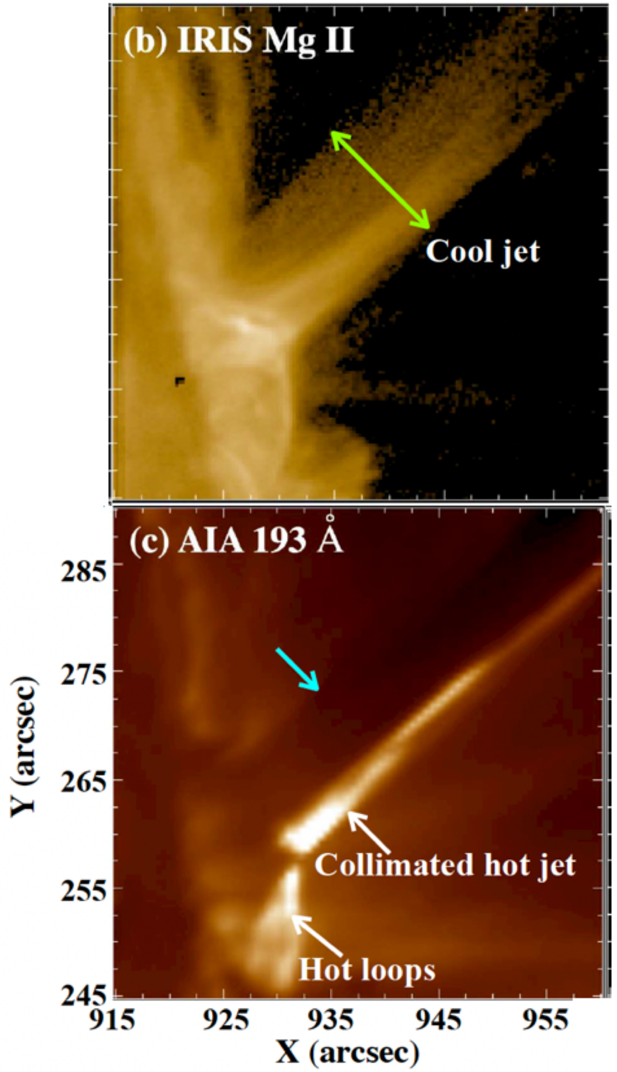
- Jets show an inverted-Y, Eiffel tower, or λ shape. There are two types:
  - **standard jets**: narrow spine, point-like brightening at the base.
  - **blow-out jets**: broad spine, substantial cool emission, helical and transverse motions.
- Related to surges and minifilament eruptions.

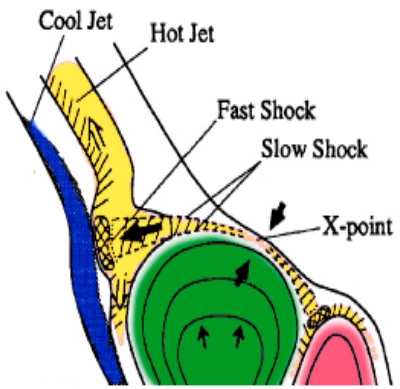
Joshi et al. 2020



Coronal jets

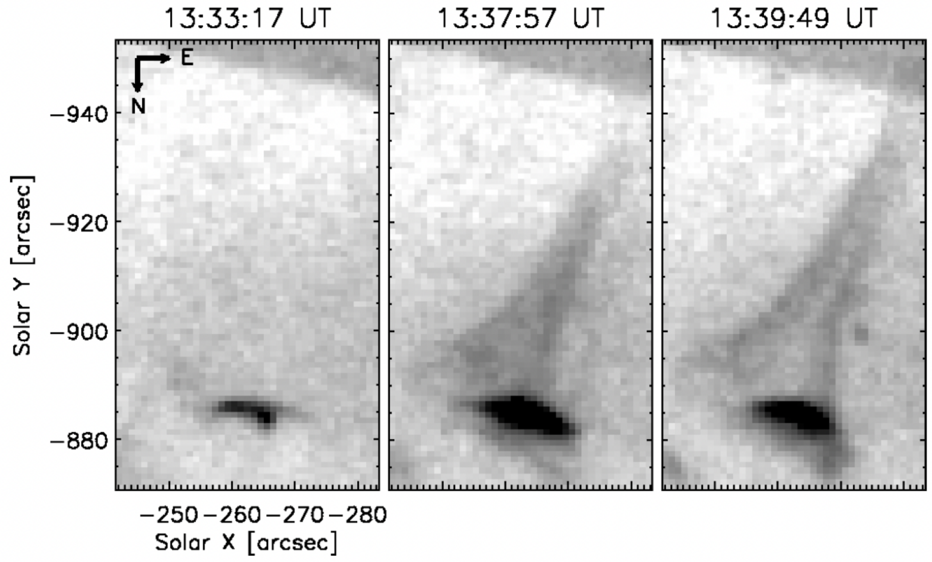
MHD modeling (standard jets):

- Hot ejections are produced converting stored magnetic energy into thermal and kinetic energy through magnetic reconnection.
- The plasma is accelerated to Alfven velocities due to the high curvature of the new reconnected lines (slingshot mechanism).
- Fast shocks are generated when the ejected plasma collides against the ambient field. The reconnection outflow is not only diverted, but additionally accelerated by pressure gradients.



Yokoyama & Shibata et al. 1996

Observations



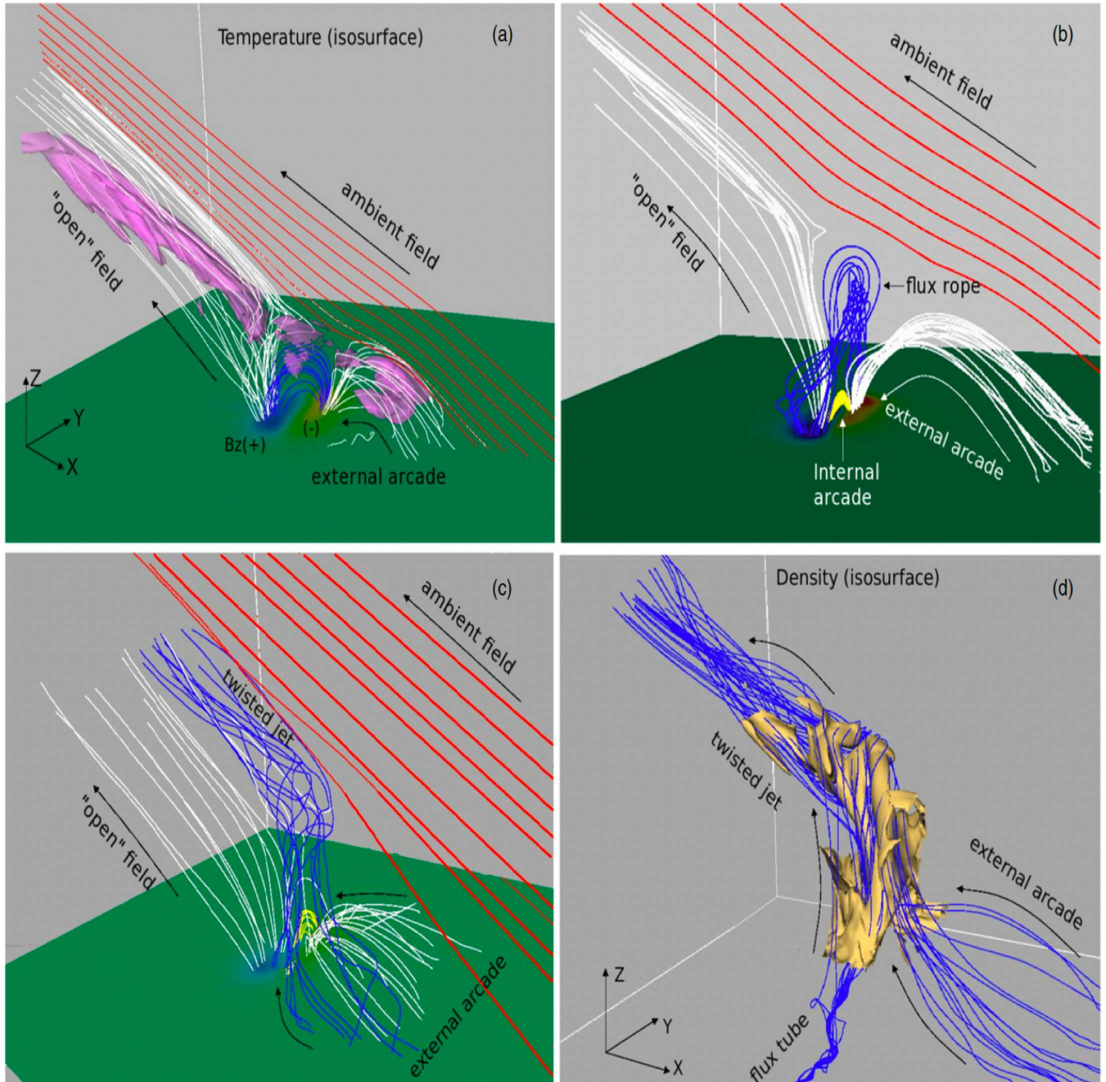
Moreno-Insertis et al. 2008

Coronal jets

MHD modeling (blow-out jets):

- They can be generated through an ideal kink-like instability, explosively releasing the free energy.
- Shearing can create a minifilament that is later ejected via magnetic breakout.
- Significant untwisting is released during this process leading to a rotating spine.
- Nonlinear torsional Alfven waves propagate along newly reconnected field lines, carrying away a large fraction of the stored energy.

Archontis et al. 2013

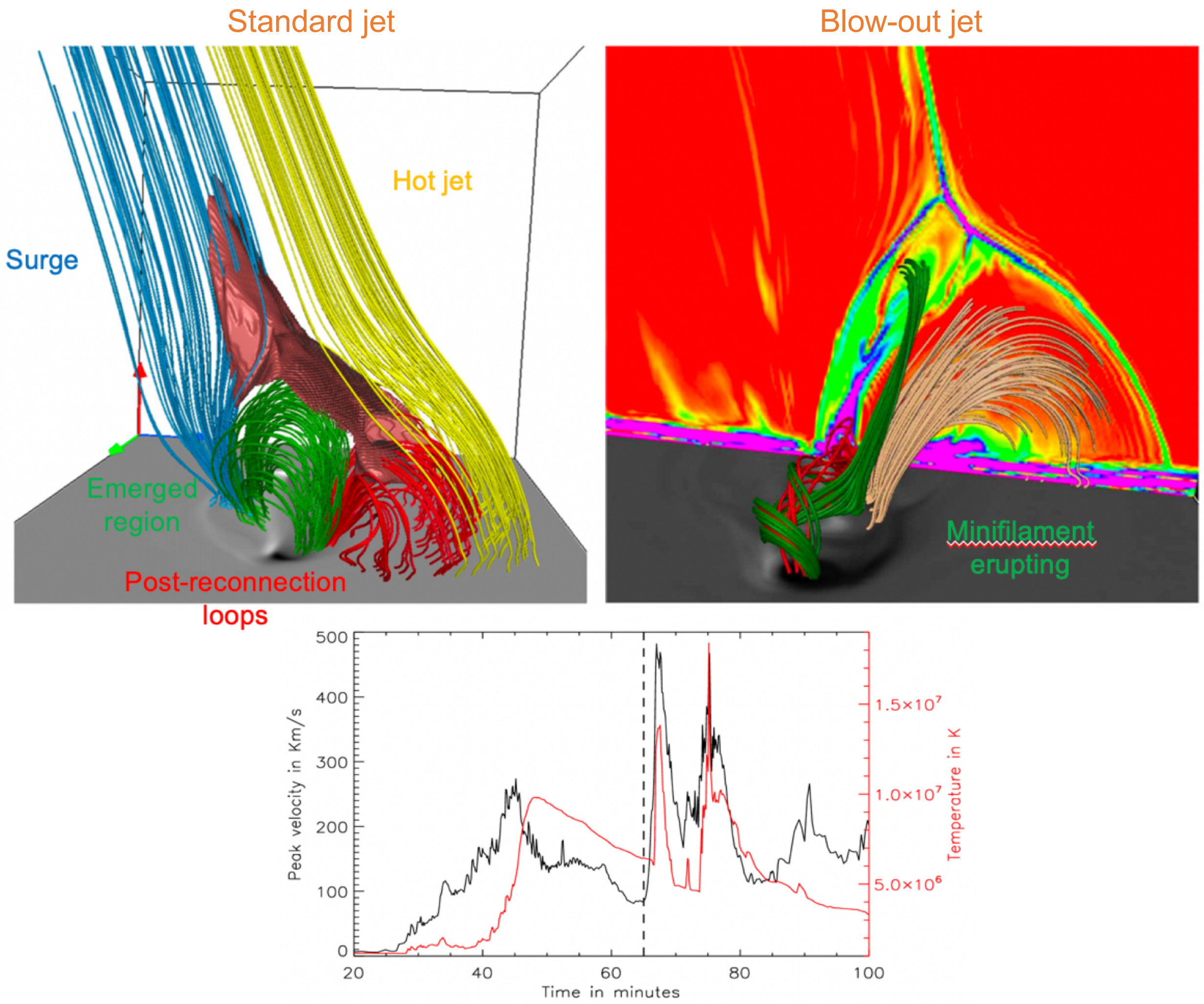


Coronal jets

MHD modeling:

- Depending on the configuration, standard jets may precede blow-out jets.
- The reconnection may be so slow that a straight jet is not unambiguously noted before the blow-out jet.
- Standard jet may inhibit the blow-out jet because it drains away free energy.
- The decay of the standard jet can be followed by recurrent violent phases with different eruptions.

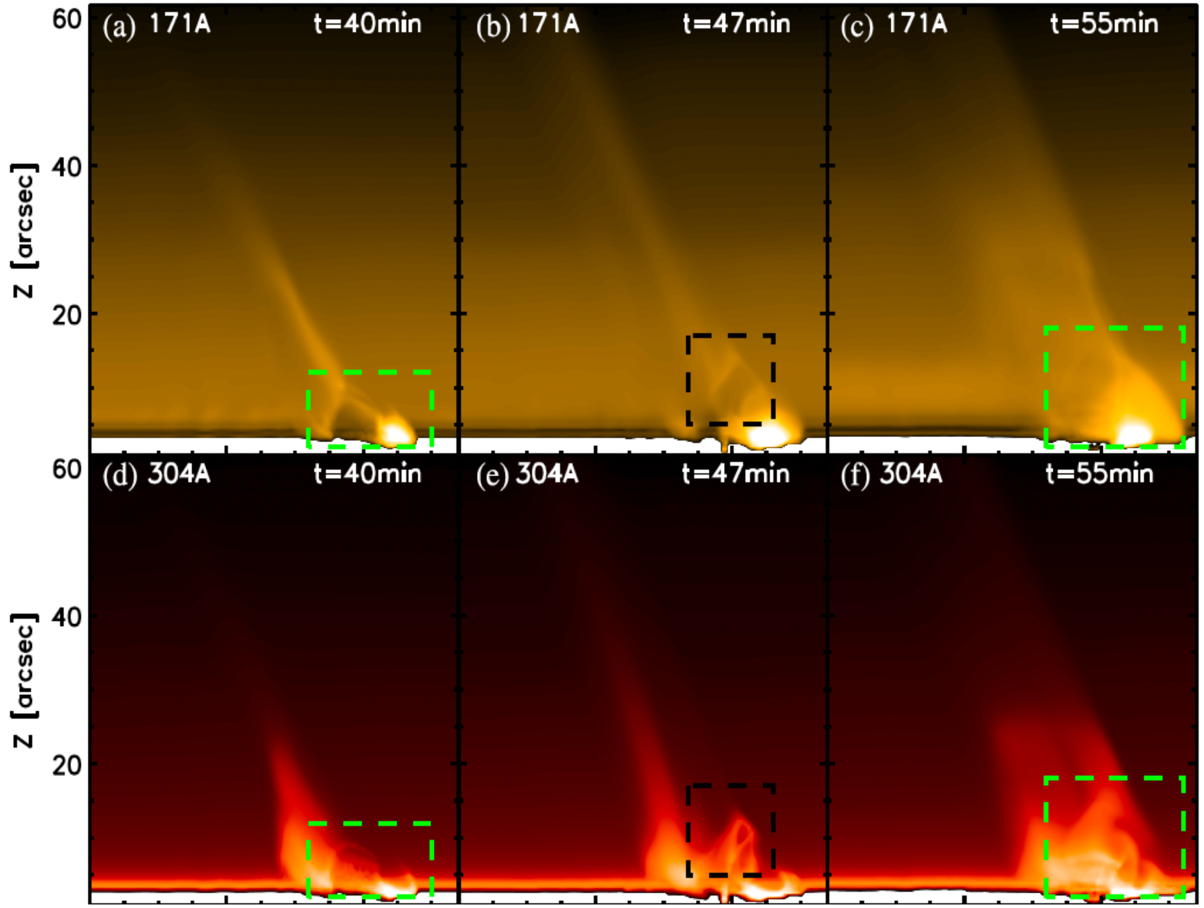
Moreno-Insertis & Galgsaard et al. 2013



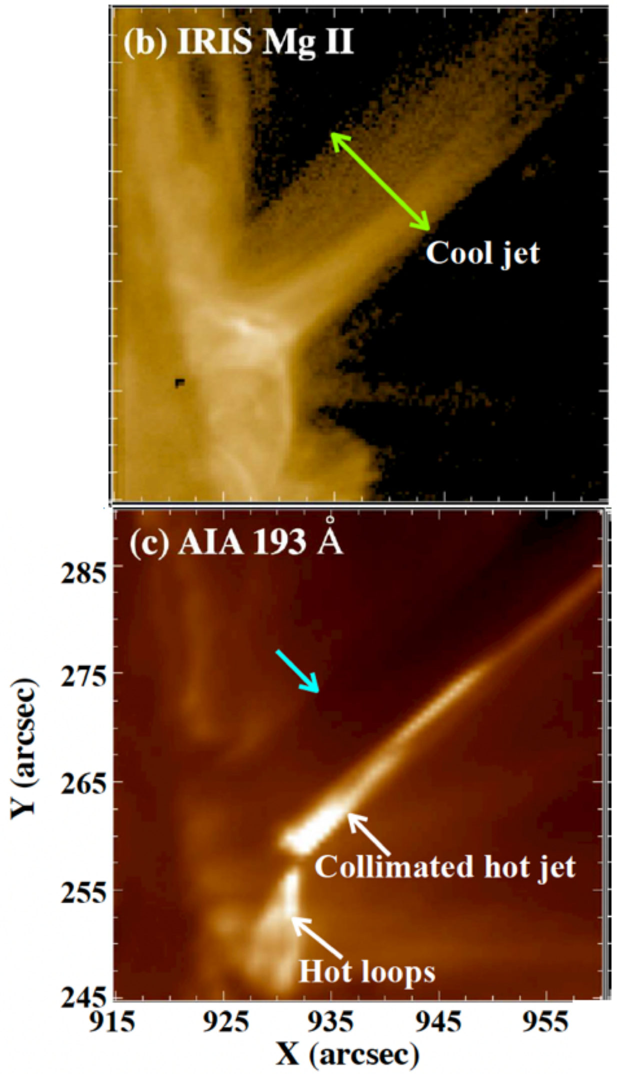
Coronal jets

Comparison with observations:

Standard jet Fang et al. 2014 Blow-out jet



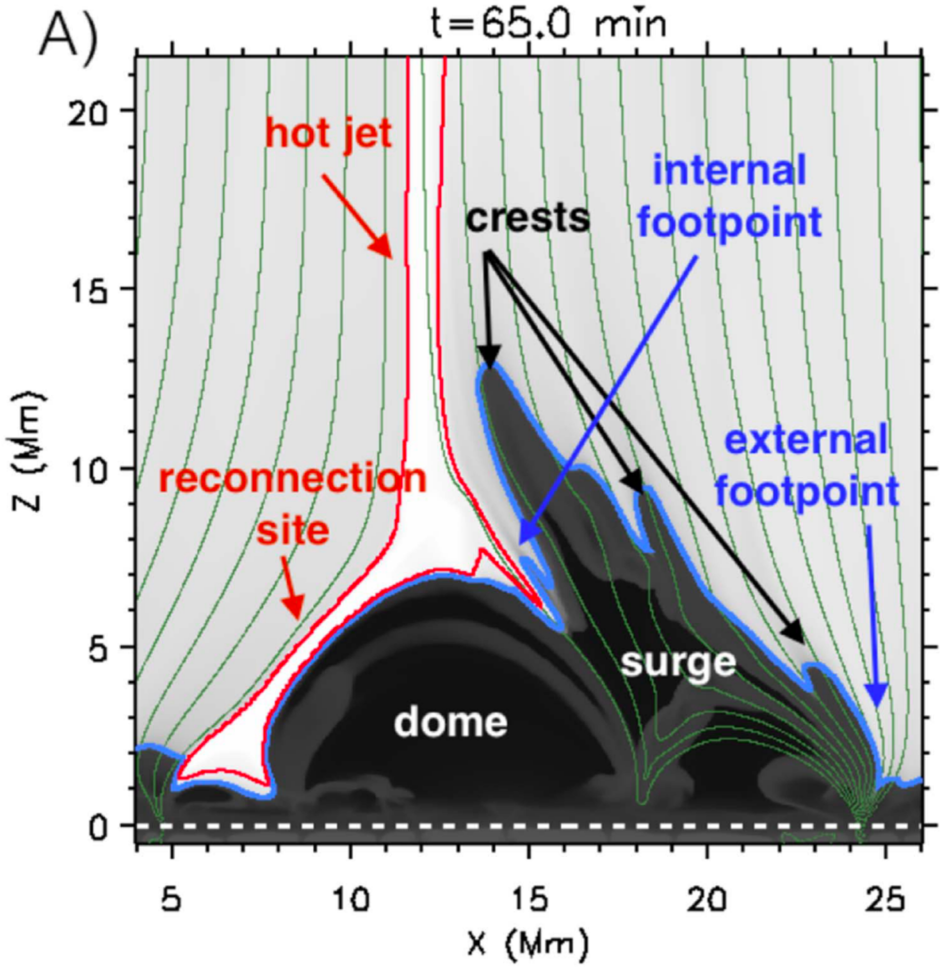
Joshi et al. 2020



Take away messages

Eruptive/ejective phenomena:

- Magnetic reconnection between emerging and/or pre-existing field can lead to different eruptive/ejective phenomena in the solar atmosphere.
- Numerical experiments can explain both the individual appearance and the relationship between them.
- Synthetic observables show striking similarities with photospheric, chromospheric, transition region and coronal observations.



Nóbrega-Siverio et al. 2017