Surges: a fundamental piece in the solar atmosphere puzzle

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Introduction

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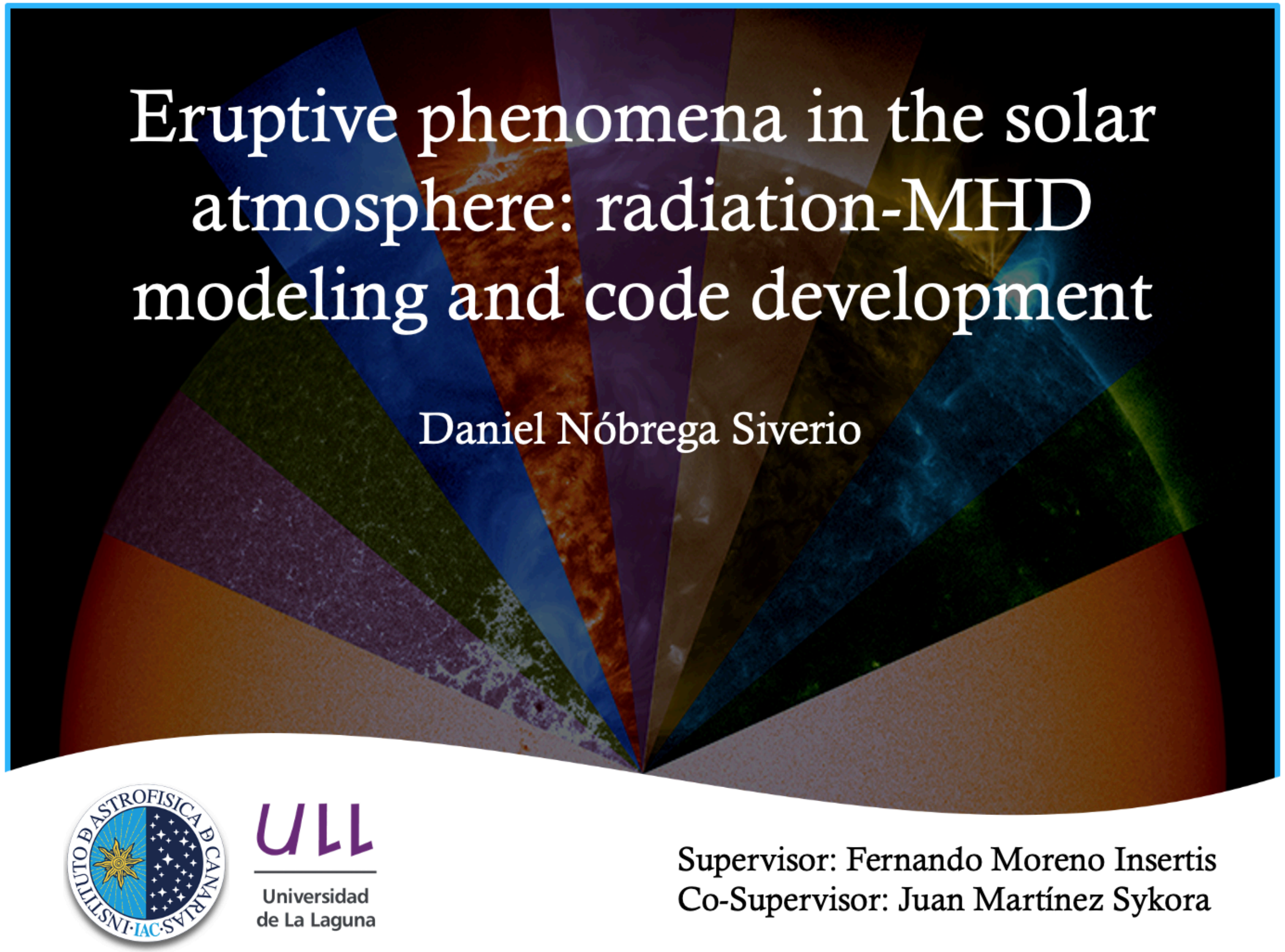
- This talk is a brief summary of the main results of my thesis.

- My thesis was supervised by **Fernando Moreno Insertis** and co-supervised by **Juan Martínez Sykora**



Introduction

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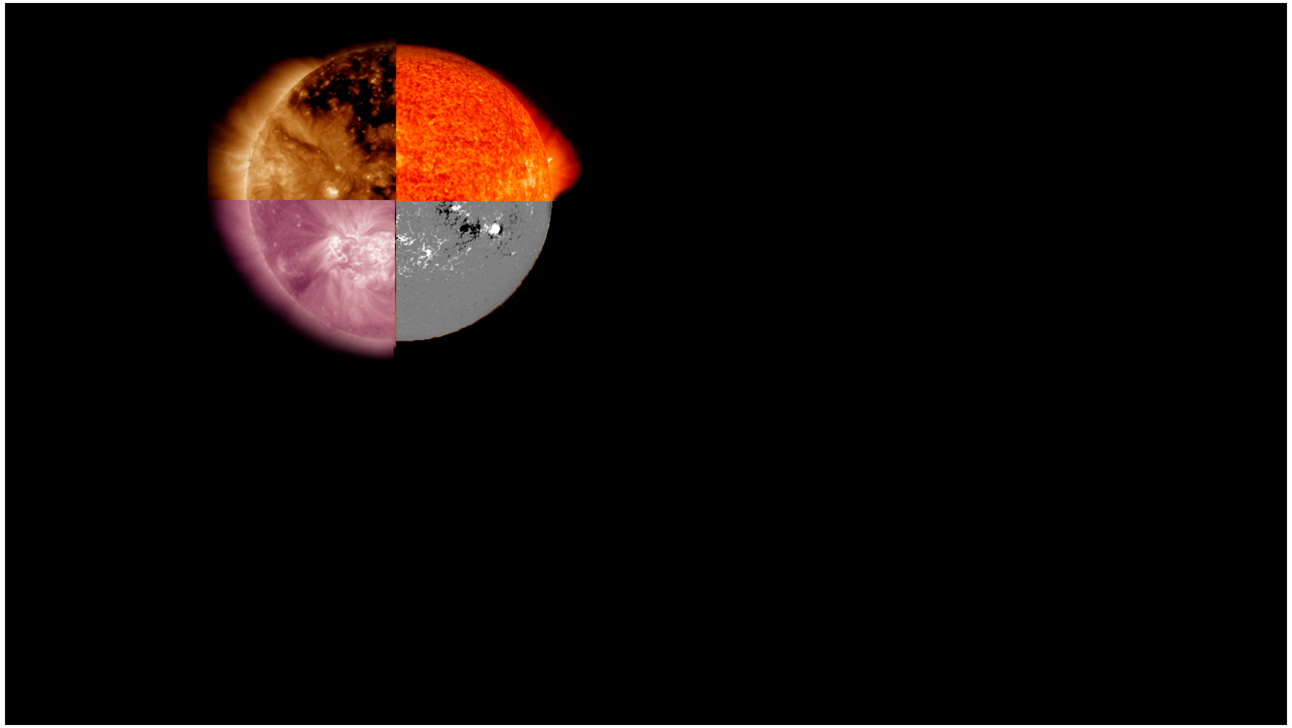
- The Sun shows

a **wide variety of eruptive and ejective phenomena,**

that are key to **understanding the solar atmosphere**



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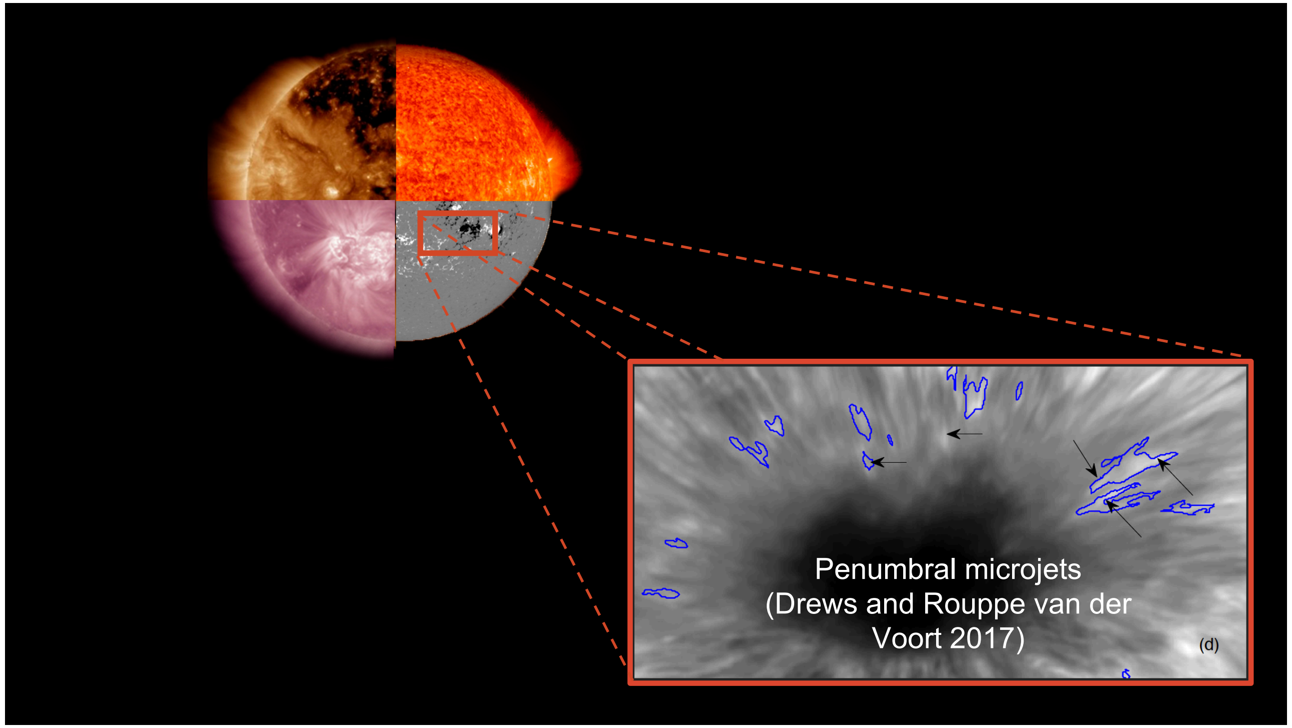

Penumbral microjets (Drews and Rouppe van der Voort 2017)

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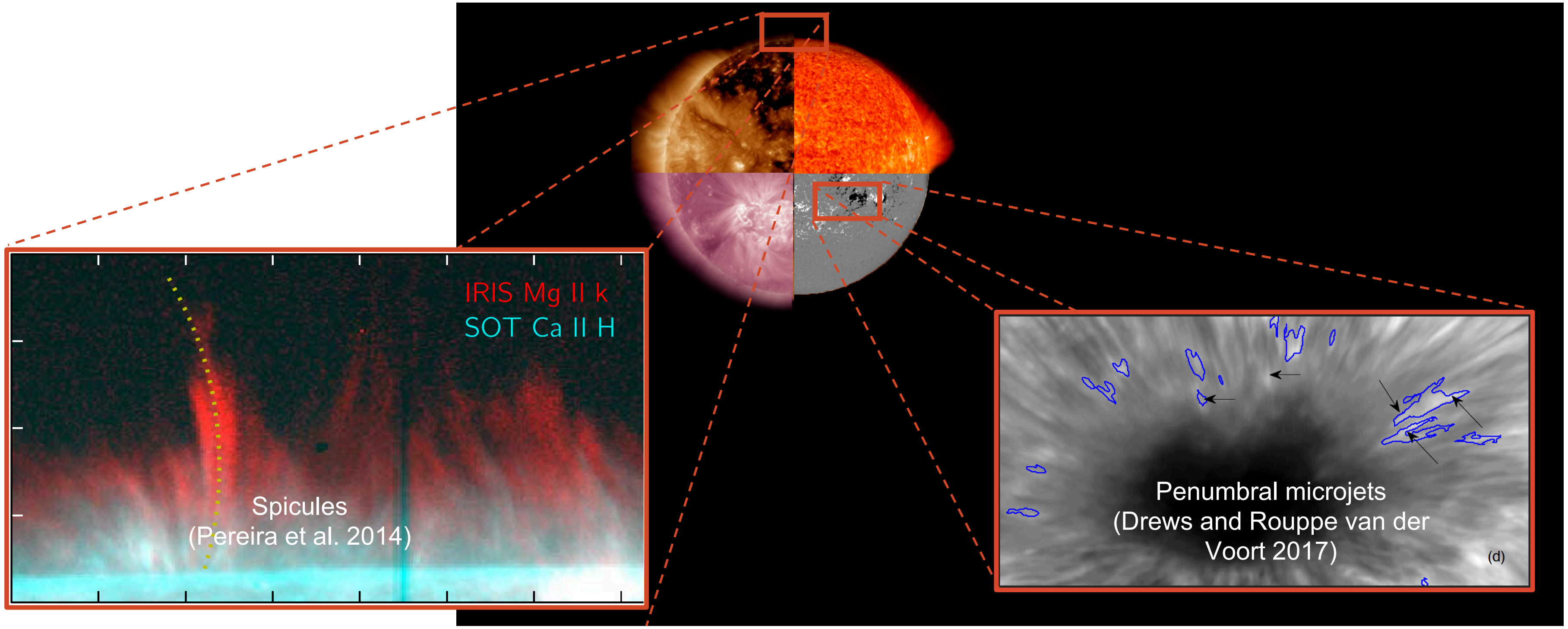

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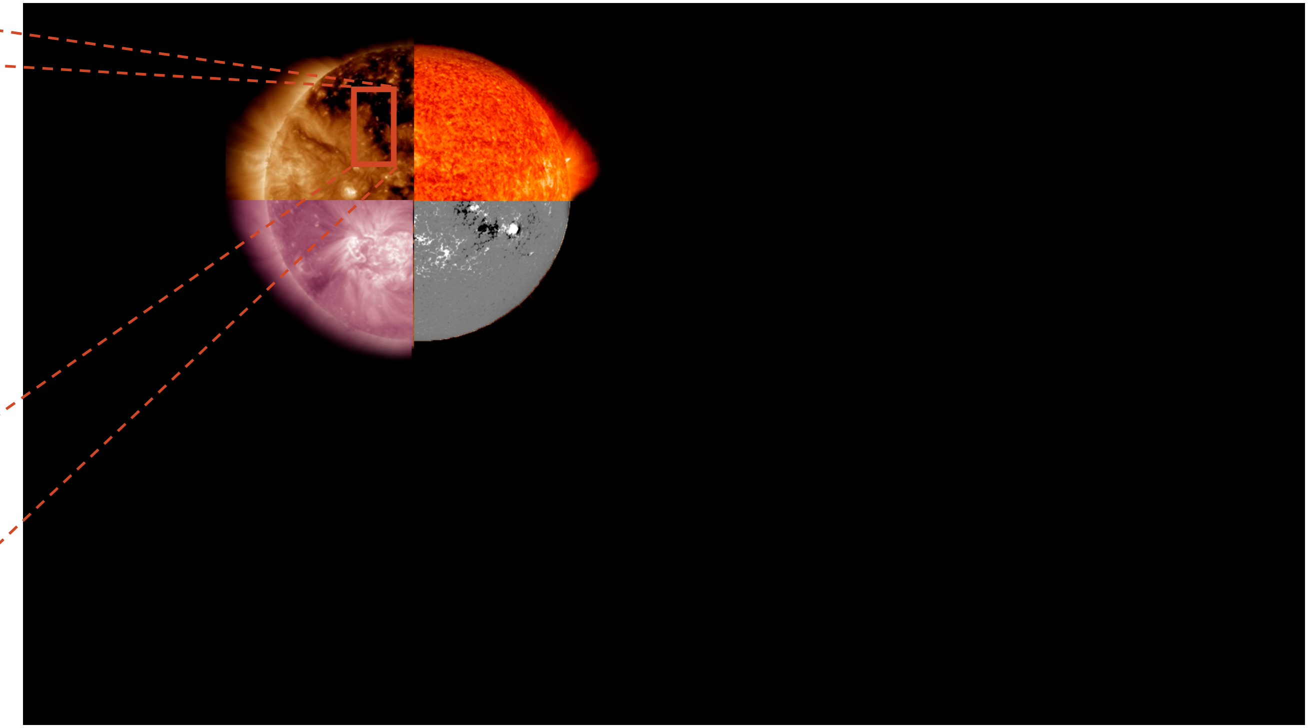

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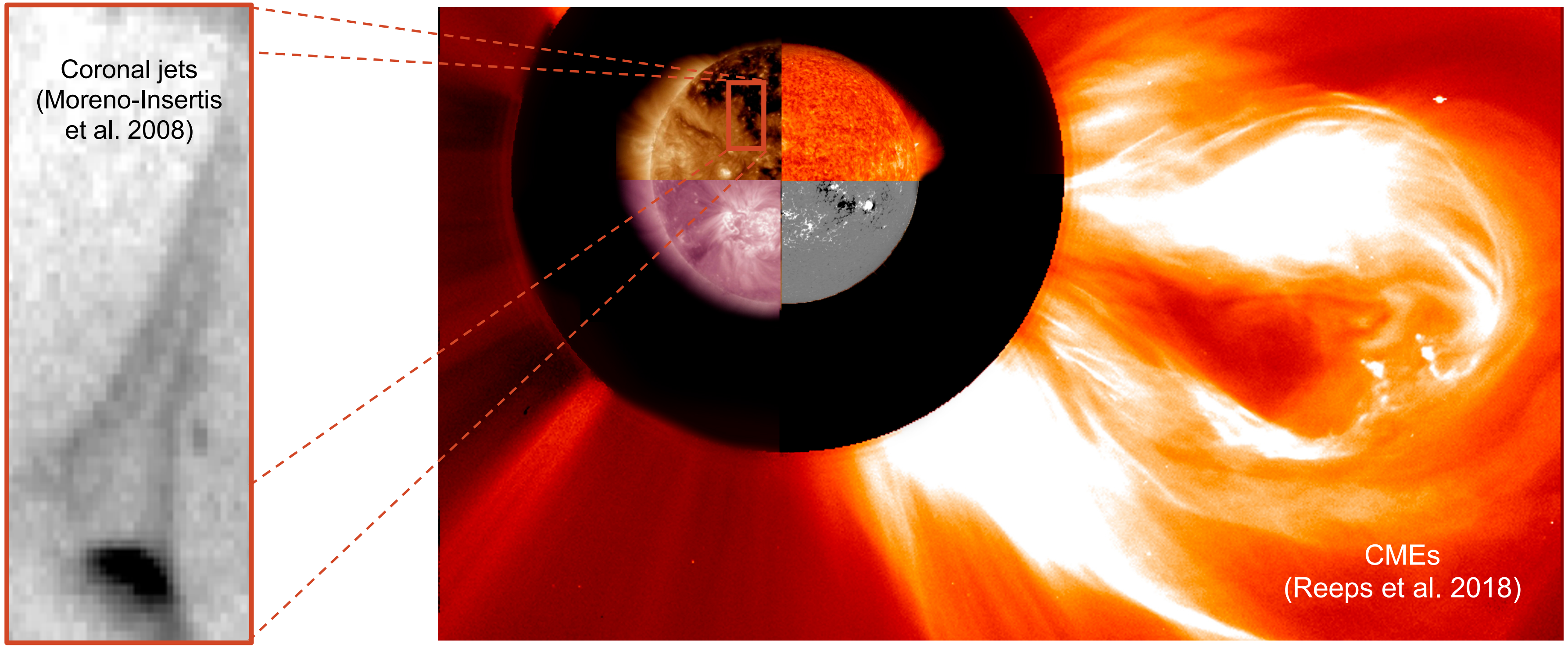

Introduction

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- Within the catalog of eruptive phenomena, there is one that remains poorly understood because of its complexity:

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- Within the catalog of eruptive phenomena, there is one that remains poorly understood because of its complexity:

the surges

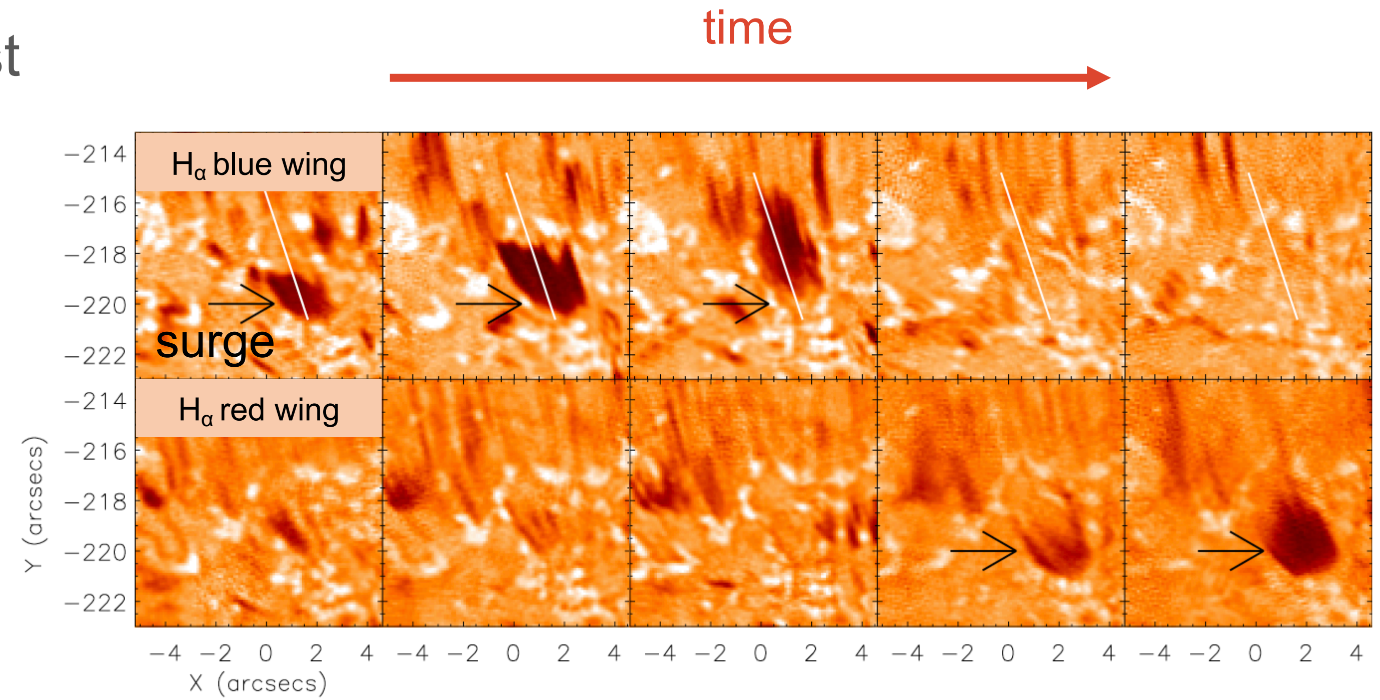
Introduction: Surges

- **What is a surge?**

  \- Plasma **ejections from** the coolest region in the solar atmosphere: **the chromosphere**

  \- They are observed as **blue and redshifted absorptions** mainly in **H_α 6563 Å**

  \- Surges have velocities of **20-50 km/s**, lengths of **10-50 Mm** and lifetimes between **10 to 60 min**



Nelson and Doyle (2013)

Introduction: Surges

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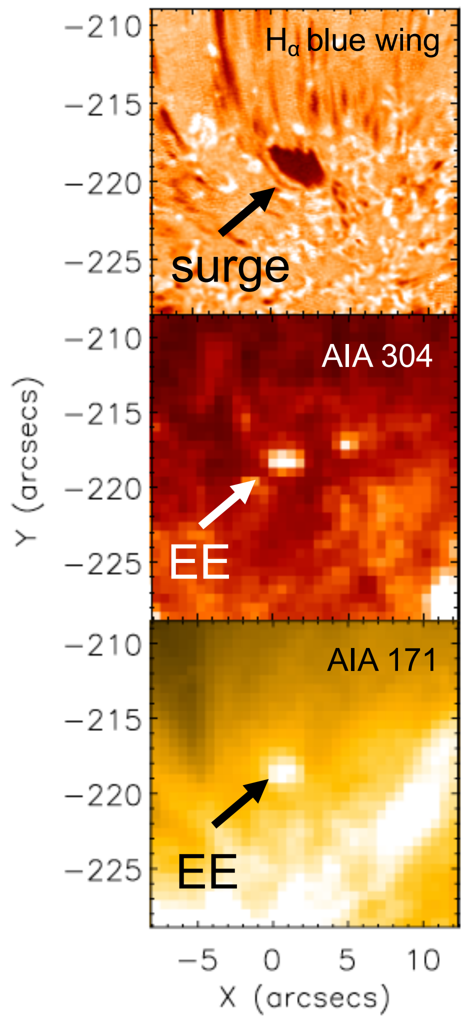
- **Surges** are closely **related to**

  - fundamental mechanisms like **magnetic flux emergence**
  (e.g., Kurokawa and Kawai 1993, Chae et al. 1999, Jiang et al. 2007, Kurokawa etal.2007, Brooks et al. 2007, Wang et al. 2014, Vargas Domínguez et al. 2014, Kim et al. 2015, Guglielmino et al. 2018, among others)

  - **other phenomena** in the solar atmosphere:

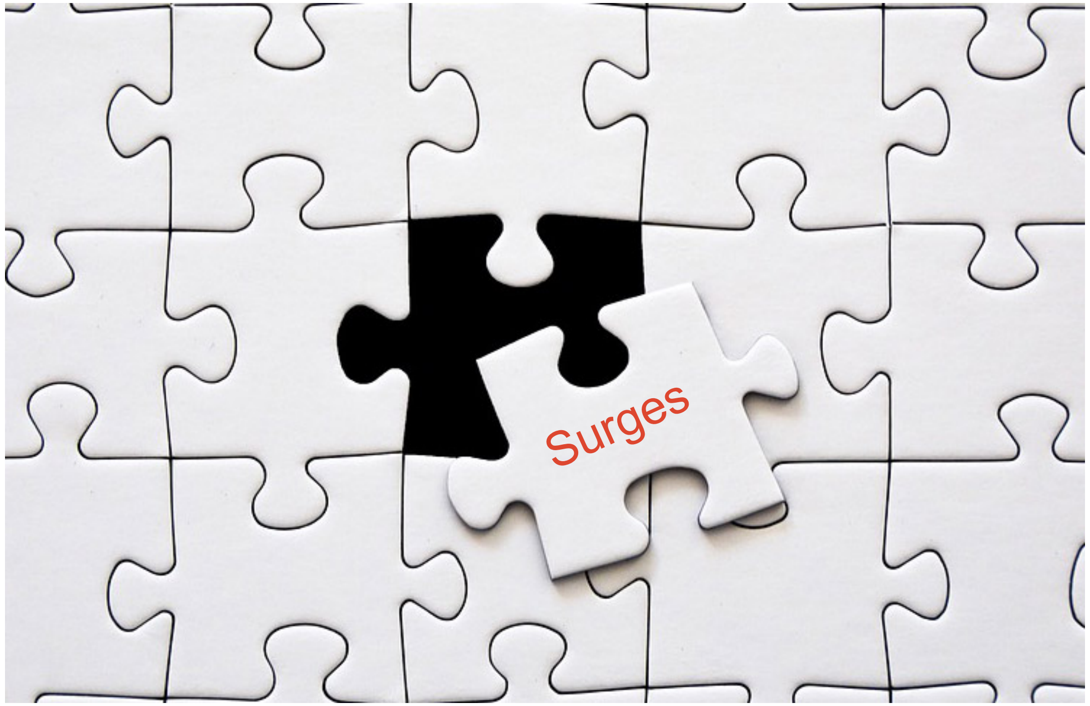
    - Explosive events (EEs)
    (e.g., Madjarska et al. 2009, Nelson and Doyle 2013, Huang et al. 2017)
    - Ellerman Bombs, UV Bursts
    (e.g., Watanabe et al. 2011, Vissers et al. 2013, Kim et al. 2015, Ortiz et al. 2020)
    - UV, EUV, X-ray jets
    (e.g., Schmieder et al. 1995, Canfield et al. 1996, Chen et al. 2008, Zhang and Ji 2014)
    - Flares
    (e.g., Wang and Liu 2012, Huang et al. 2014, Schrijver and Higgings 2015)

Nelson and Doyle (2013)



Introduction: Surges

- **Surges are an essential** piece **in the solar atmosphere** puzzle



Introduction: Surges

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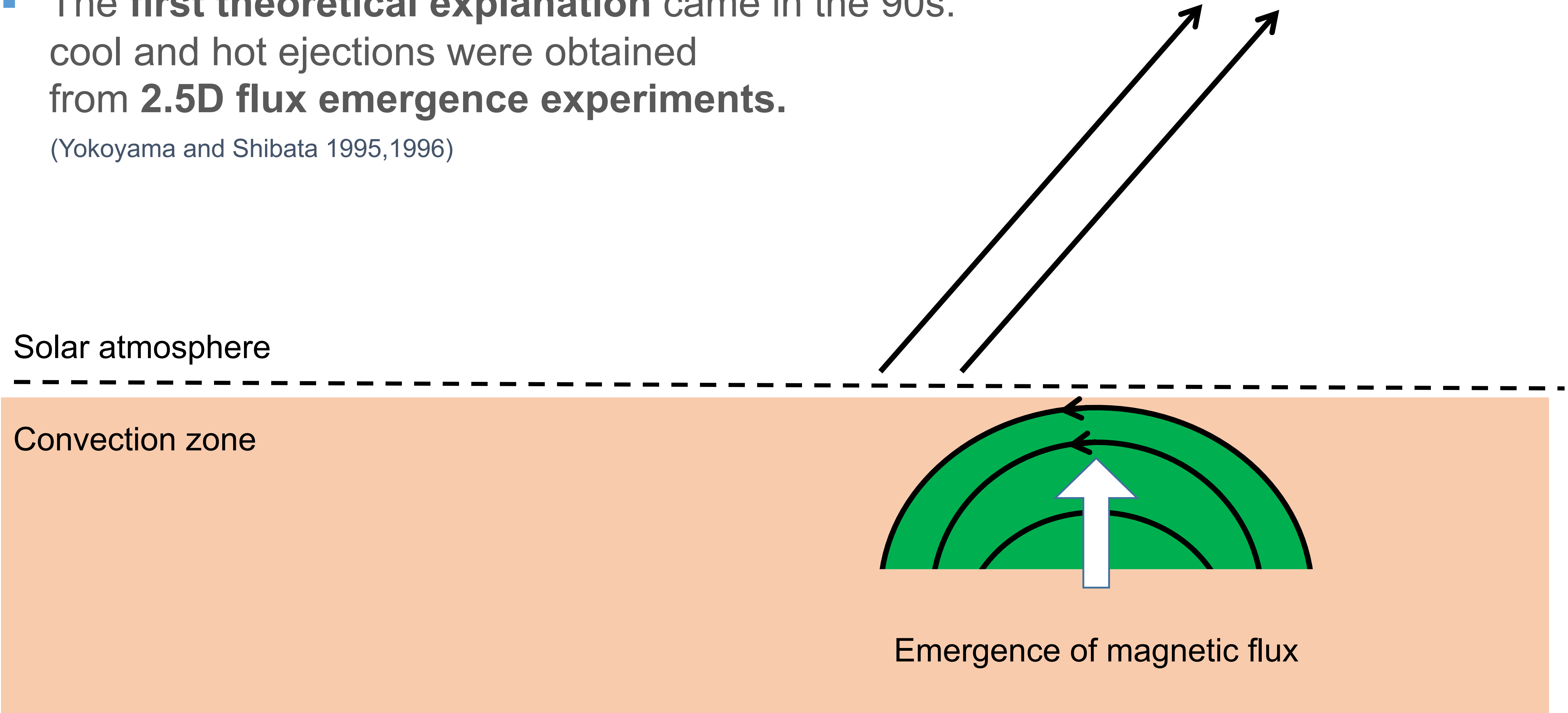
- The **first theoretical explanation** came in the 90s: cool and hot ejections were obtained from **2.5D flux emergence experiments.**
  (Yokoyama and Shibata 1995,1996)



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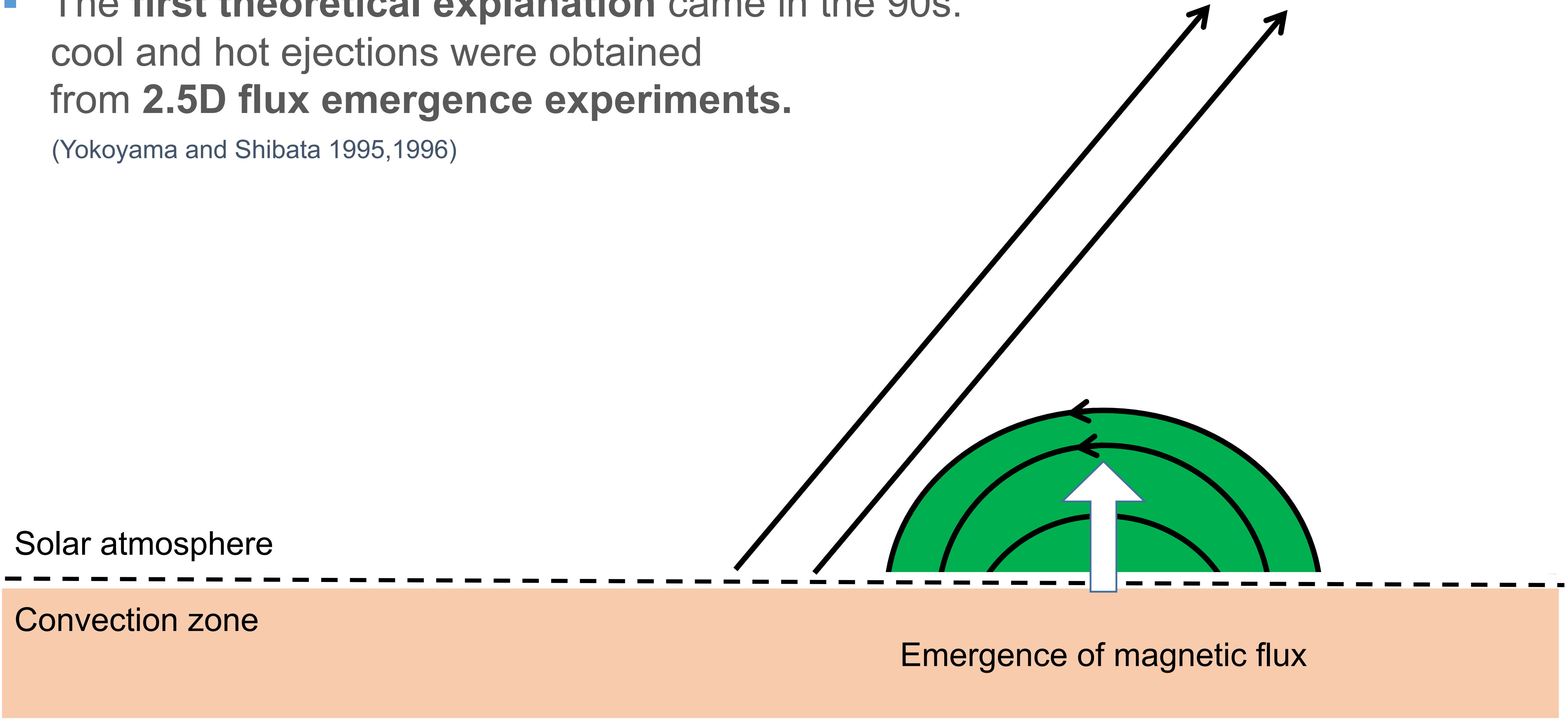

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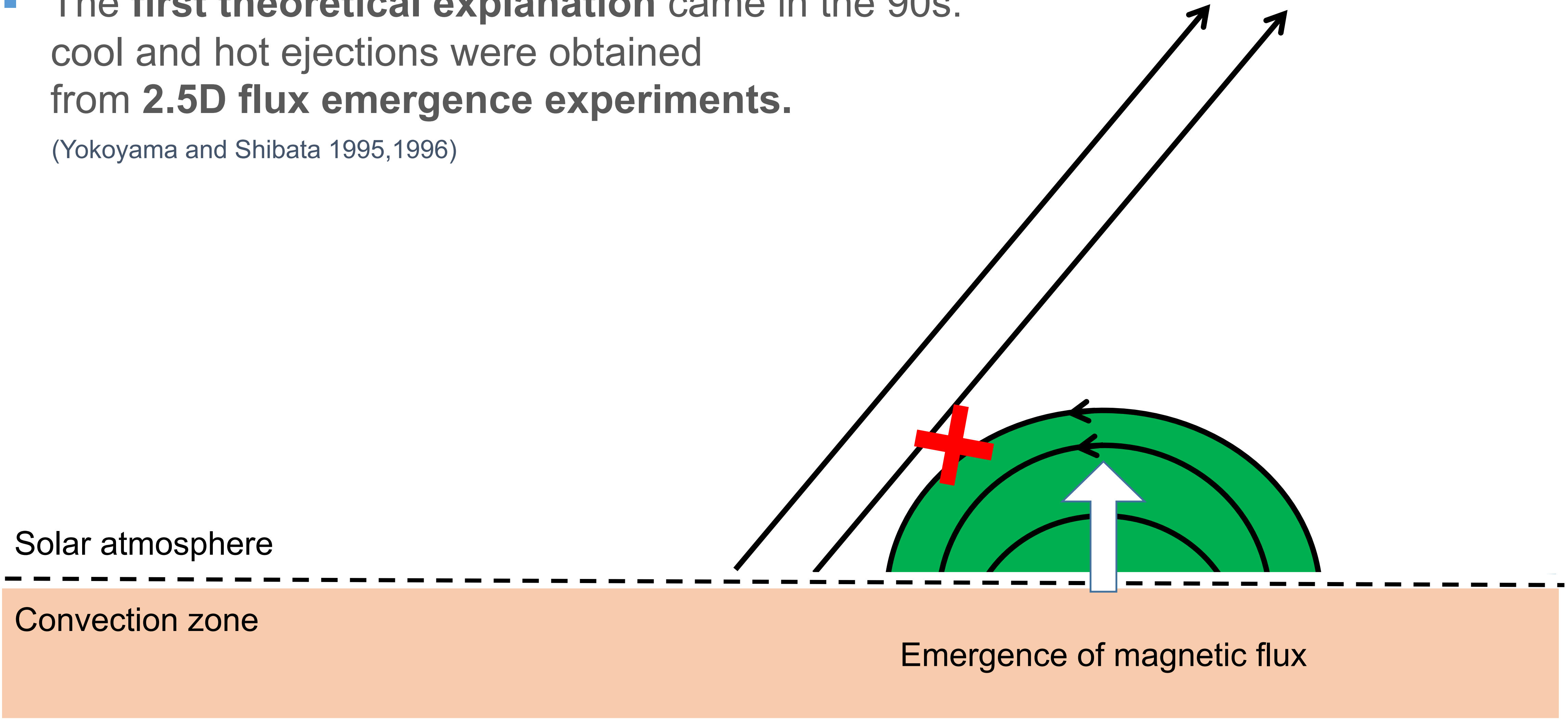

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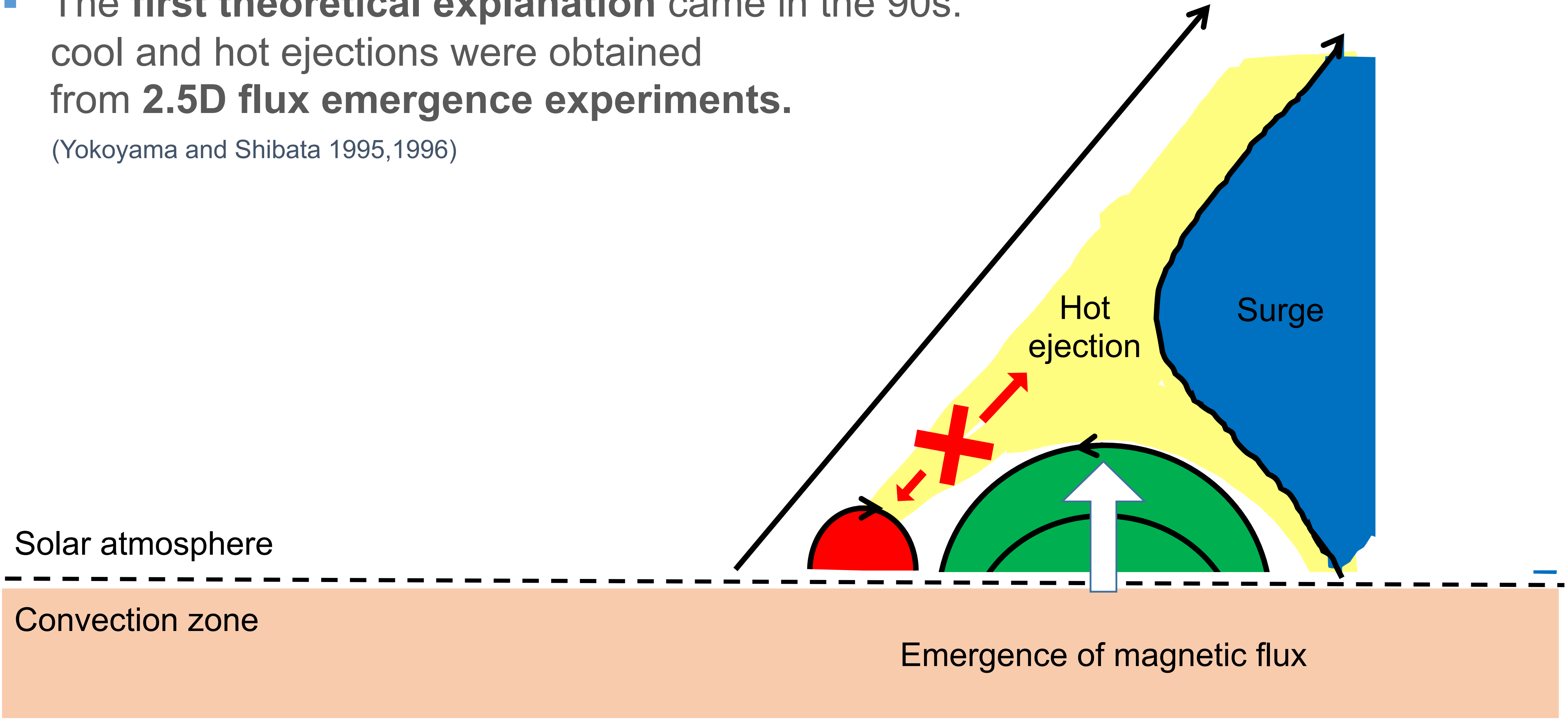
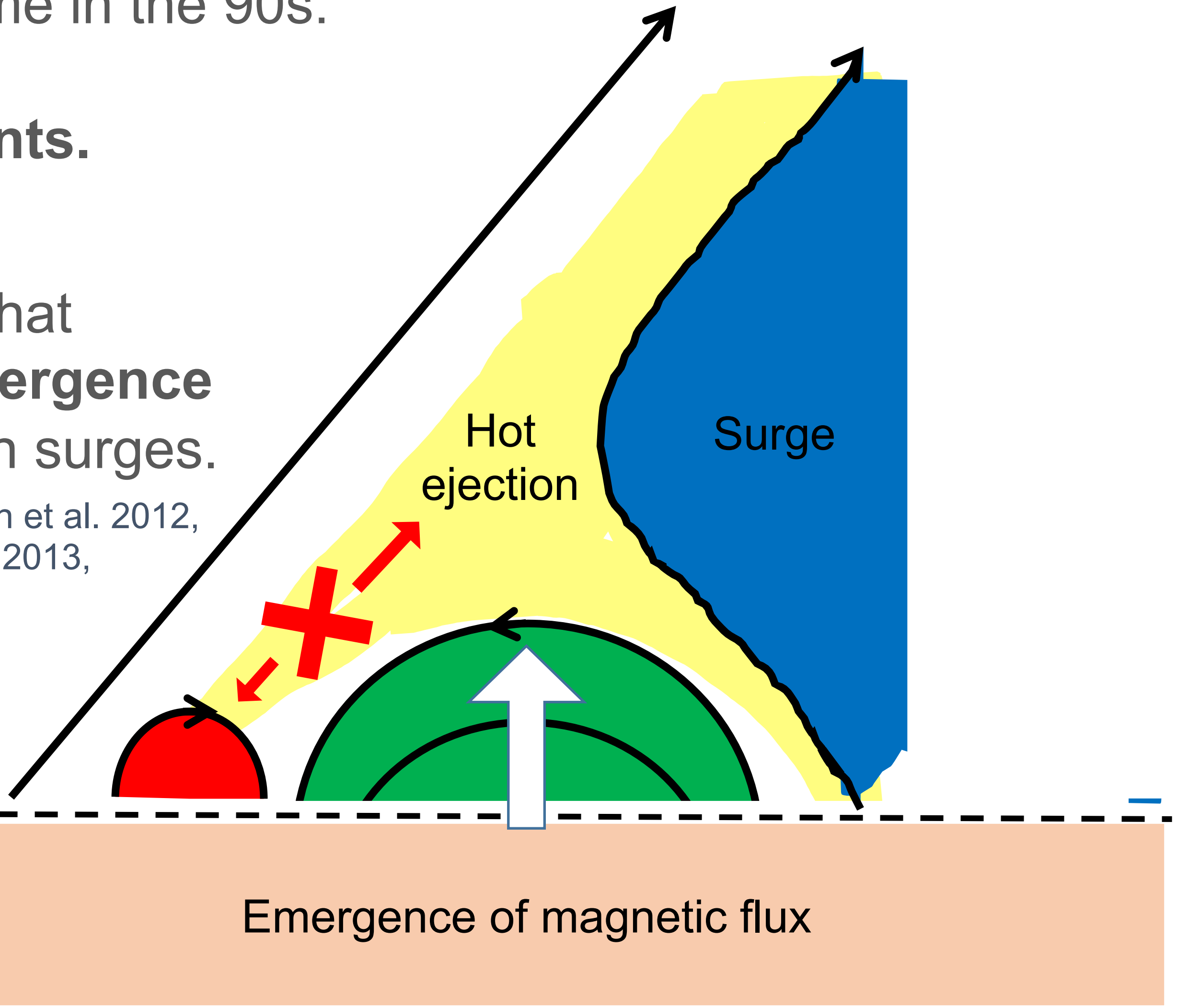


Introduction: Surges

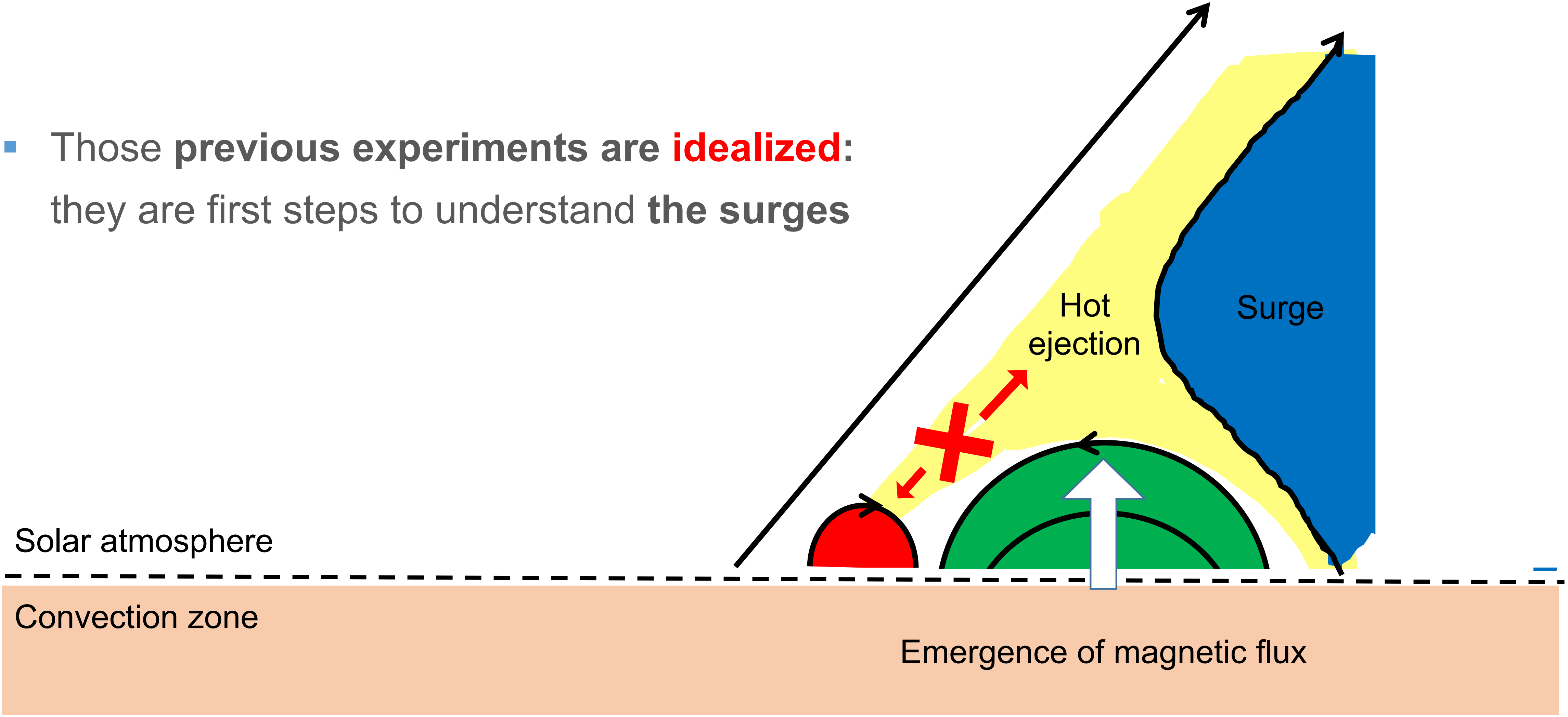
- The **first theoretical explanation** came in the 90s: cool and hot ejections were obtained from **2.5D flux emergence experiments.**
  (Yokoyama and Shibata 1995,1996)

- Further numerical experiments show that **magnetic reconnection and flux emergence** are key physical mechanisms to obtain surges.
  (e.g., Nishizuka et al. 2008, Moreno-Insertis et al. 2008, Jian et al. 2012, Takasao et al. 2013, Yang et al. 2013, Moreno-Insertis et al. 2013, MacTaggart et al. 2015)



Introduction: Surges

- Those **previous experiments are** **idealized**: they are first steps to understand **the surges**



Aim of the thesis

1. Getting a **better understanding of the surges**, including processes not taken into account in the past:

Thermal conduction	Optically thin cooling	Realistic equation of state (EOS)
Detailed radiative transfer	Scattering	Nonequilibrium (NEQ) ionization

2. Studying **ground and space observations**

3. Comparing numerical experiments and observations through **forward modeling**

Results (Nóbrega-Siverio et al. 2016)

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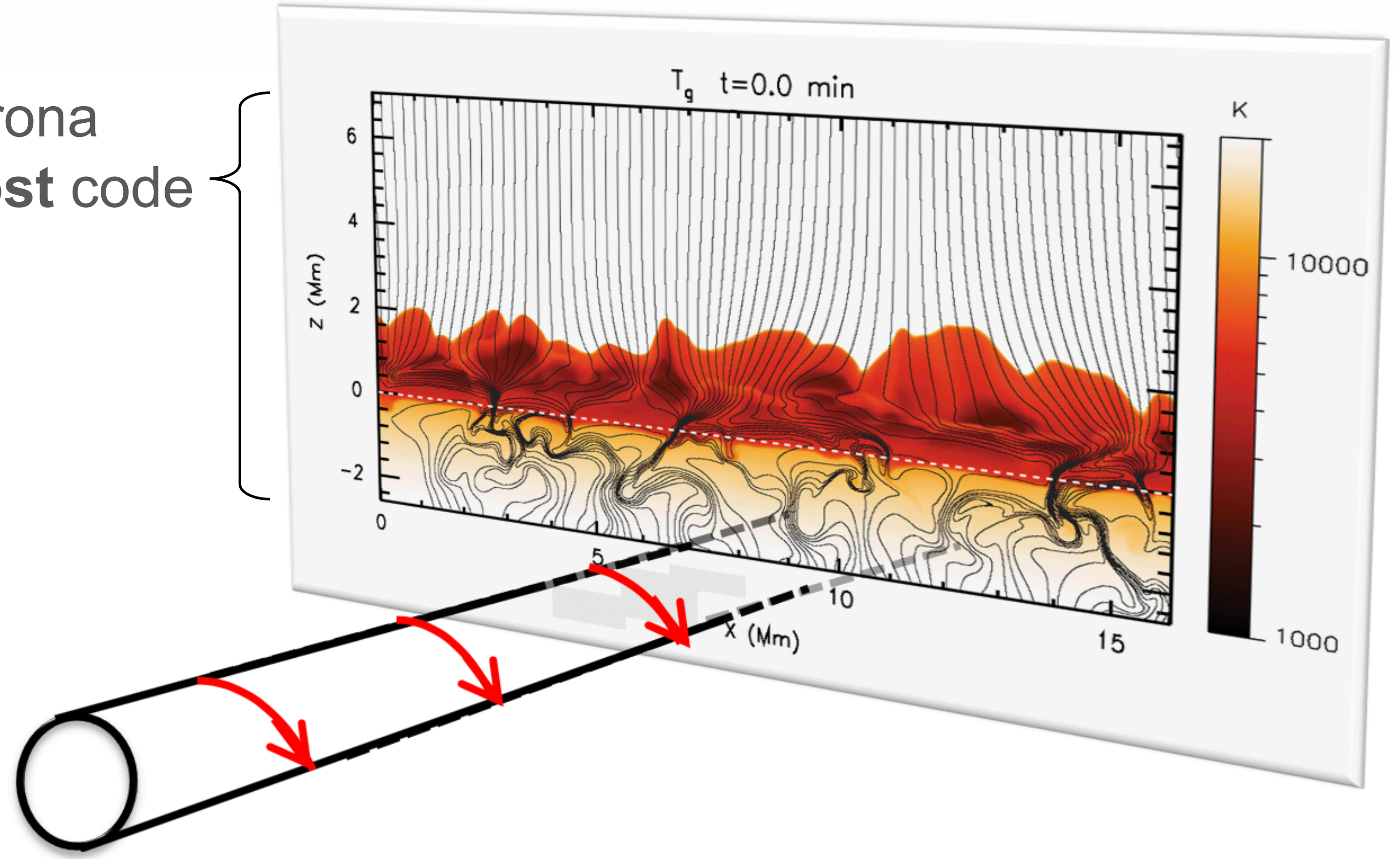
- We performed a flux emergence experiment:

  - **2.5D experiment** spans from the convection zone to the corona using the radiative-MHD **Bifrost** code (Gudiksen et al. 2011)



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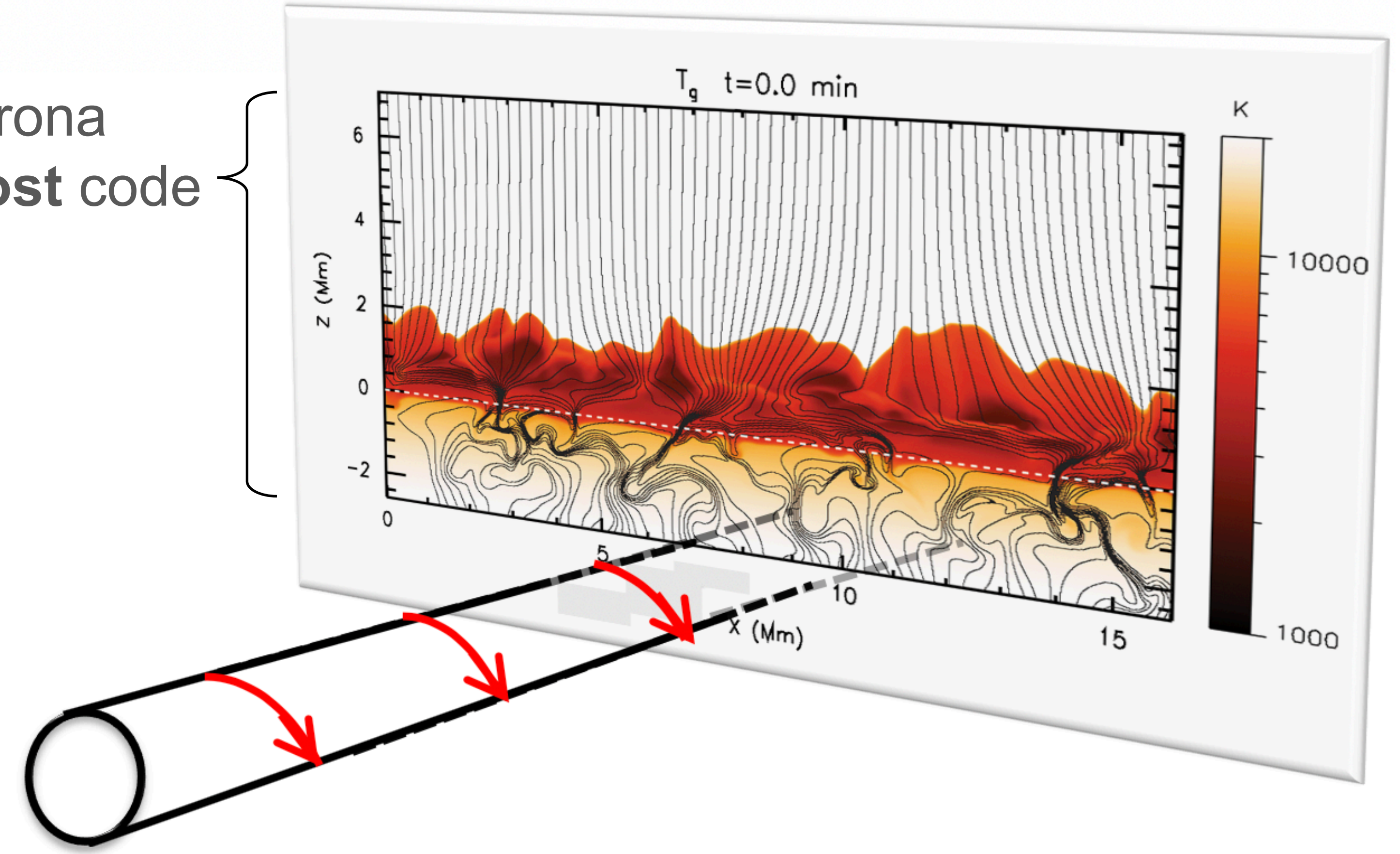
  - **Magnetic flux emergence** through the injection of a twisted magnetic tube

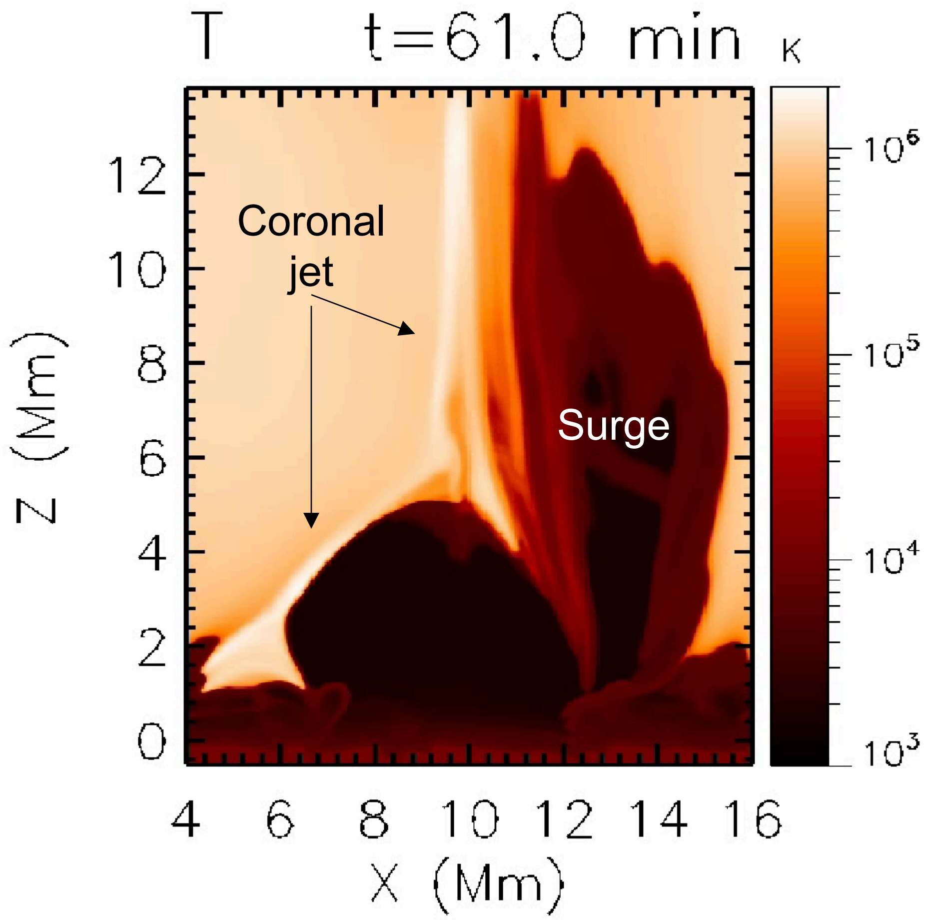


Results (Nóbrega-Siverio et al. 2016)

- After roughly one hour of solar time:

  - We can distinguish **the surge** as an **elongated cool and dense structure**

  - The surge appears next to a **hot and fast coronal jet**



Results (Nóbrega-Siverio et al. 2016)

- We studied the role of the **entropy sources:**

  heating by viscous and Joule terms,

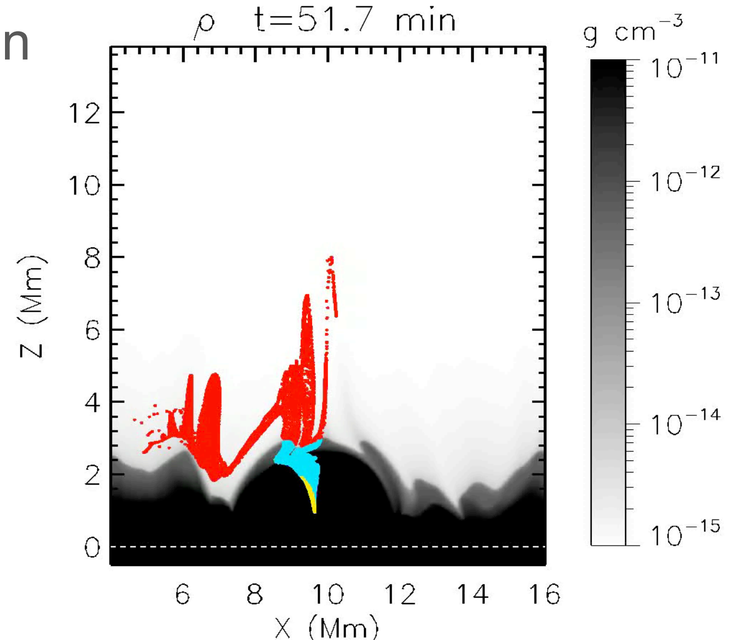
  cooling by thermal conduction, optically thin losses,…

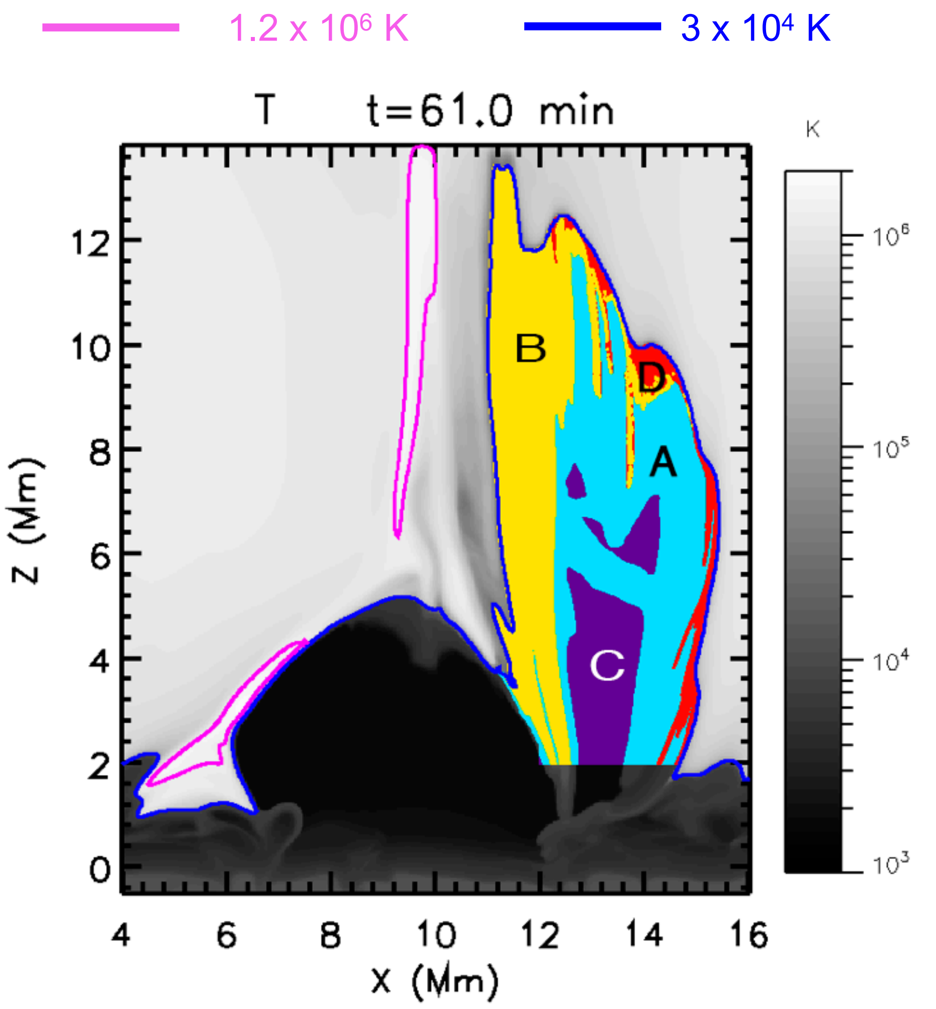
- We found **4 different populations**

  with respect to the evolution

  of the thermal properties

  of the plasma





Results (Nóbrega-Siverio et al. 2016)

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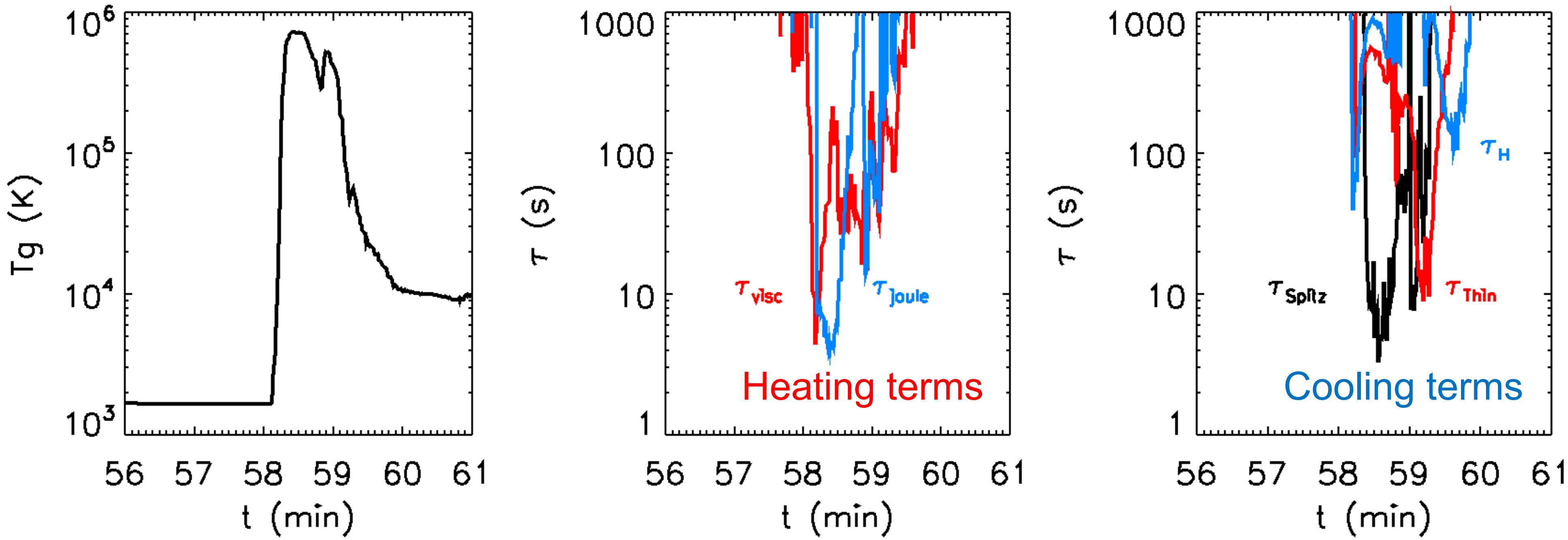
- Representative evolution of the plasma in **Population B**



$$\tau = \frac{e}{|Q|}$$

e: internal energy per unit volume

Q: entropy source term

- Would be possible to observationally detect a hint of this behavior?

Results (Nóbrega-Siverio et al. 2017)

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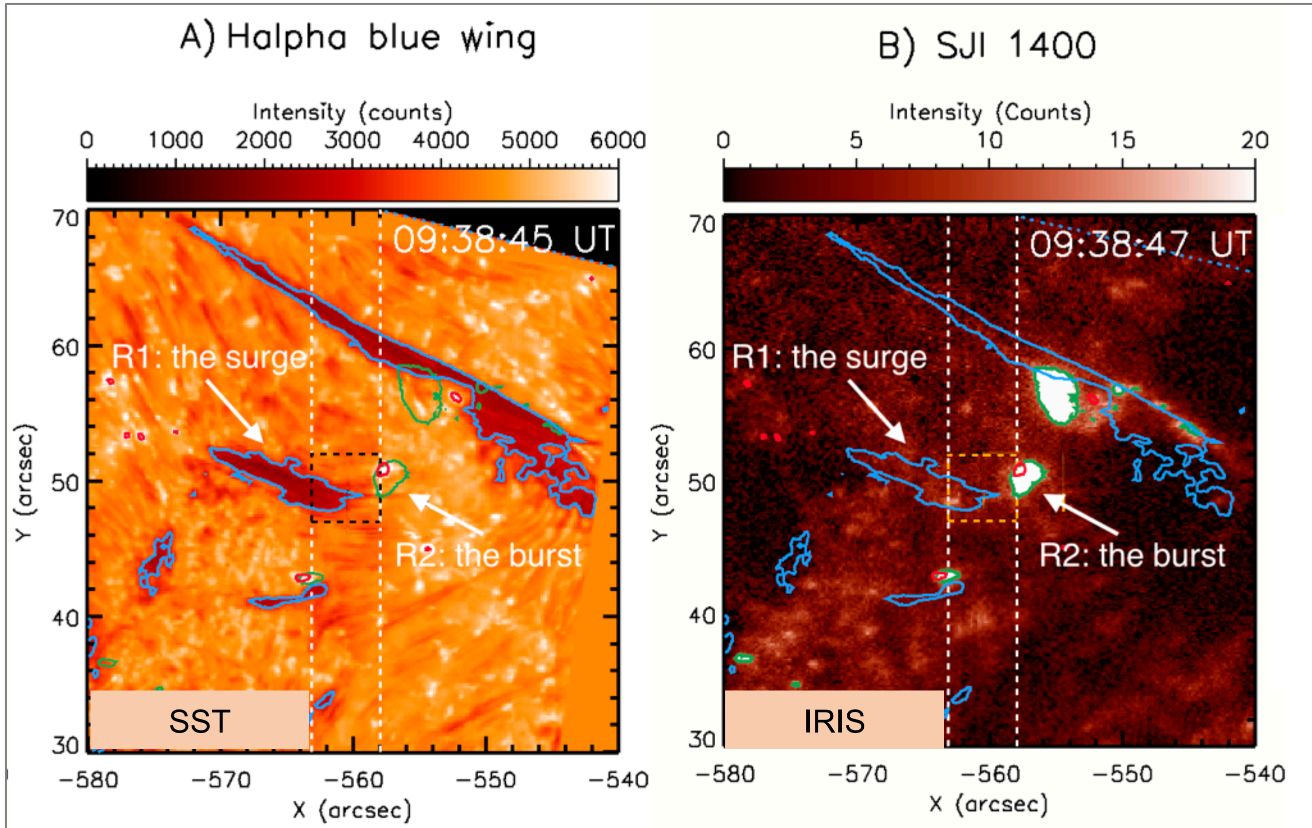
- We studied a simultaneous episode of an Hα surge and UV burst
  - We use **coordinated observations:**
    - IRIS (de Pontieu et al. 2014)
    - SST (Scharmer et al. 2003)

IRIS + SST (2016 September 03, 07:49:21 to 10:03:37 UT).
AR12585 at (-561'',44'') $\mu = 0.8$



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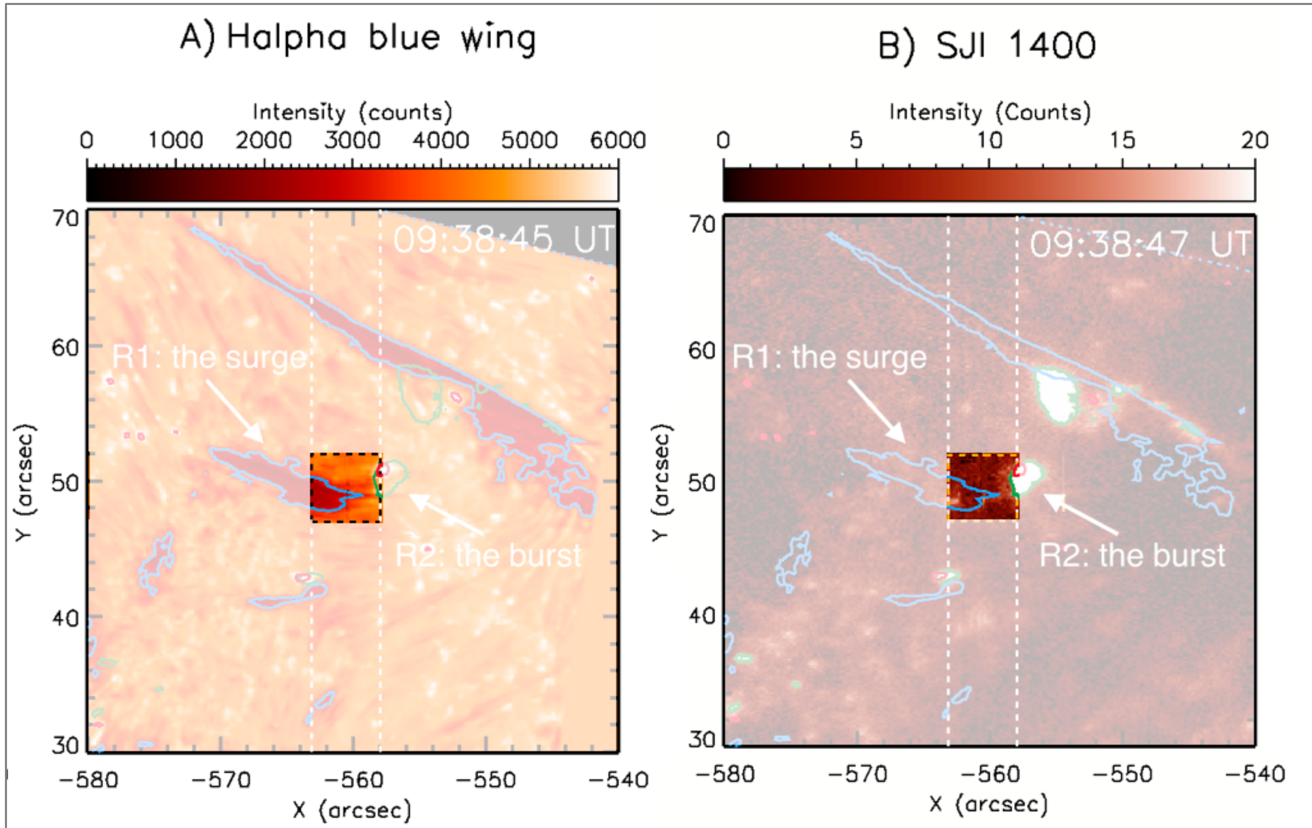

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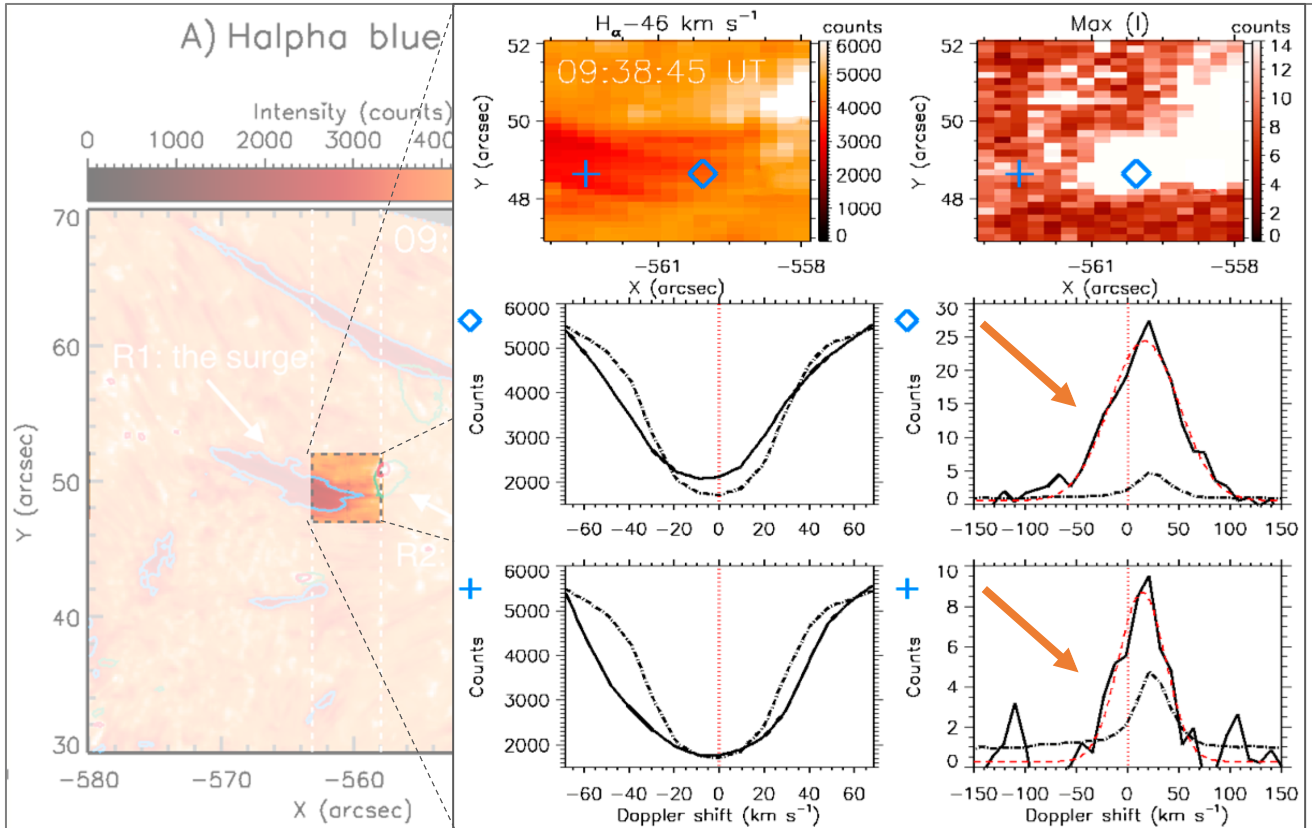
- We studied a simultaneous episode of an Hα surge and UV burst
  - We use **coordinated observations:**
    - IRIS (de Pontieu et al. 2014)
    - **SST** (Scharmer et al. 2003)
  - Surges can show **enhanced emission in temperatures ~10⁵ K.**
  - Si IV surge profiles are **brighter and broader** than an average transition region
  - Can we explain that **enhanced emission** of the surge using numerical experiments?

IRIS + SST (2016 September 03, 07:49:21 to 10:03:37 UT).
AR12585 at (-561'',44'') $\mu = 0.8$



Results (Nóbrega-Siverio et al. 2018)

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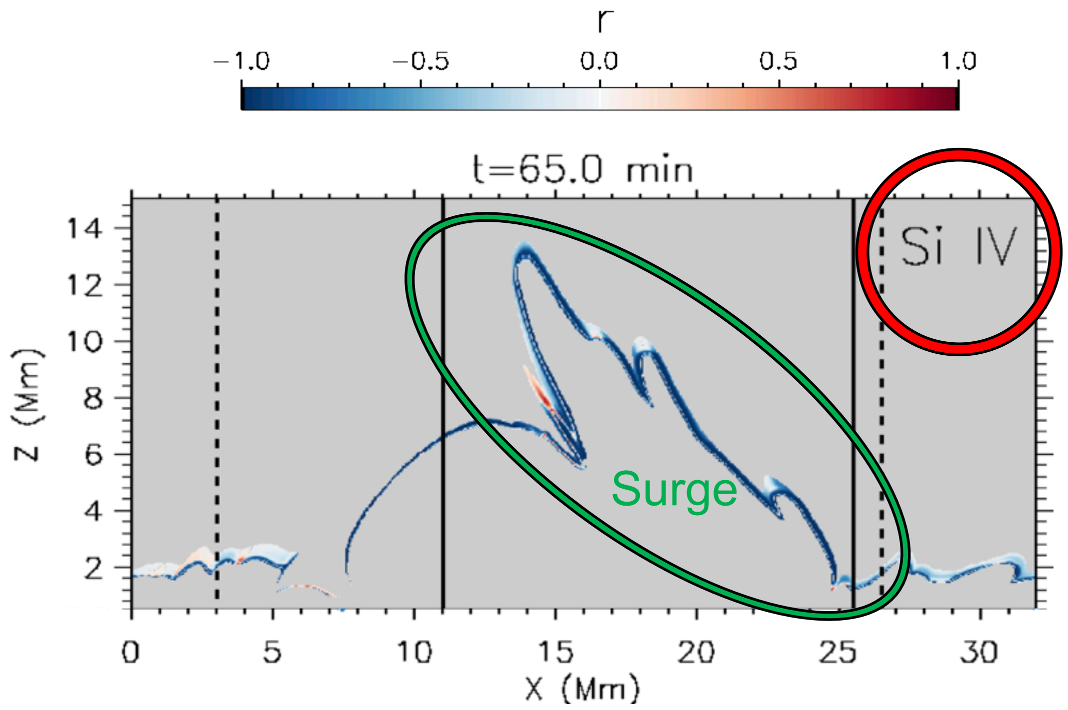
- We performed a new experiment **including now NEQ ionization effects**



$$r = \frac{n_{SE}-n_{NEQ}}{n_{SE}+n_{NEQ}}, \quad r \in [-1,1]$$

n: number density (Si IV)
SE: Statistical Equilibrium
NEQ: Non-Equilibrium

- The **NEQ** ionization has a **massive impact** on the **surge** and **emerged region**
- The **SE** seriously **underestimates** the number density values and, therefore, the emissivity

Results (Nóbrega-Siverio et al. 2018)

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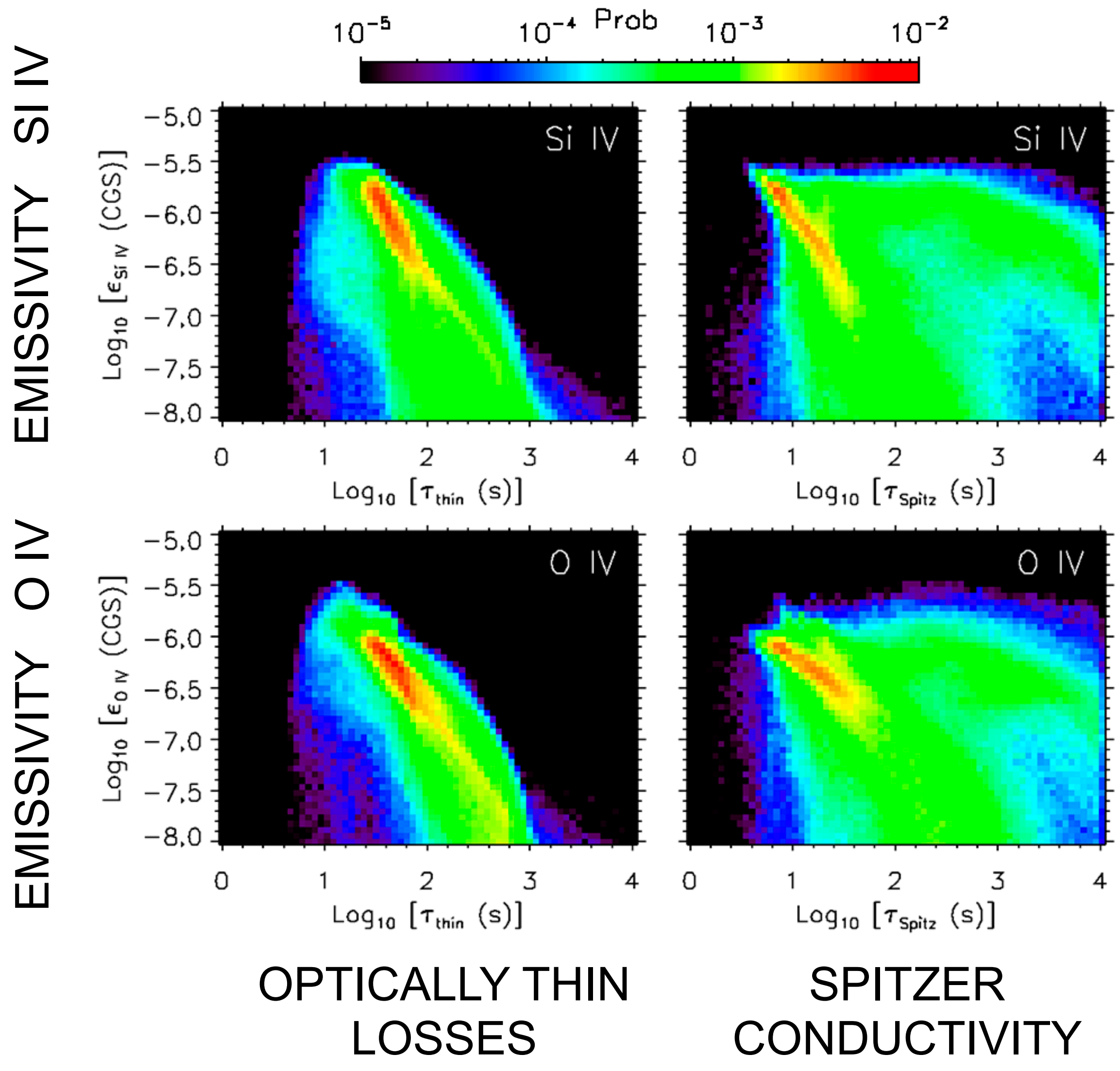

$$\tau = \frac{e}{|Q|}$$

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Q: entropy source term

- **Clear correlation** between large values of the **emissivity** and **short characteristic times** of the **entropy sources:**
  - Optically thin losses: 20 – 100 s
  - Thermal conduction: 4 – 40 s
- **Fast characteristic times** are likely to produce **departures** from the **ionization equilibrium**

Conclusions

- The **entropy sources are essential** for the surge evolution:
  - Previous experiments miss important aspects of the surge

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- Surges can show **enhanced emission** in transition region **(TR) temperatures** ($\sim 10^5$ K):
  - We have found evidences in Si IV and recently in O IV

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- The **entropy sources are essential** for the surge evolution:
  - Previous experiments miss important aspects of the surge

- Surges can show **enhanced emission** in transition region **(TR) temperatures** (~10^5 K):
  - We have found evidences in Si IV and recently in O IV

- The **nonequilibrium ionization** is key for the **TR diagnostics of surges:**
  - The entropy sources are responsible for the departure from the statistical equilibrium ionization.