RoCMI - Svalbard, 28/02/2023

Deciphering the Nanojet Phenomenon

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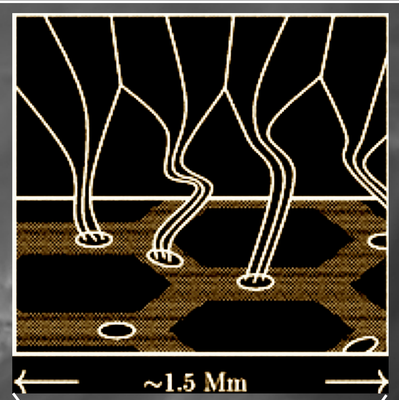
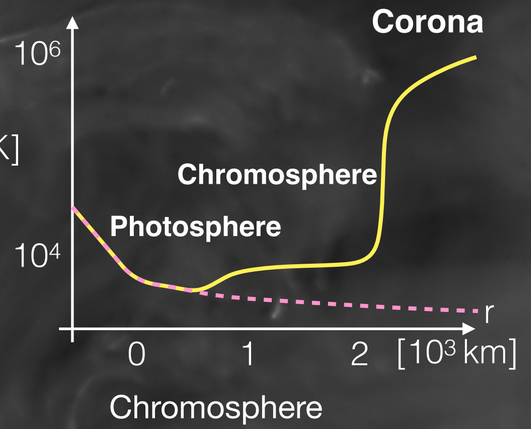
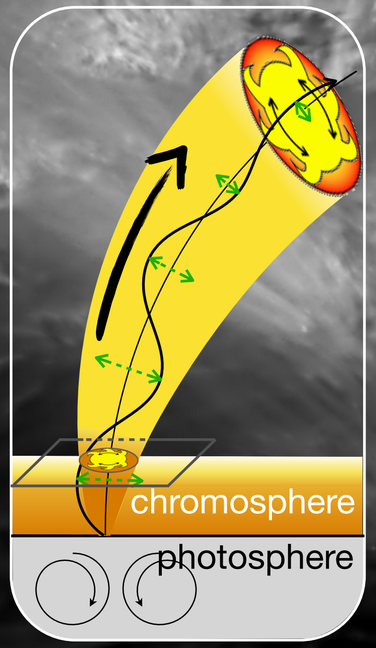
How to differentiate observationally both categories of heating mechanisms?

Large Poynting flux:
10^6 - 10^9 erg cm^{-2} s^{-1}

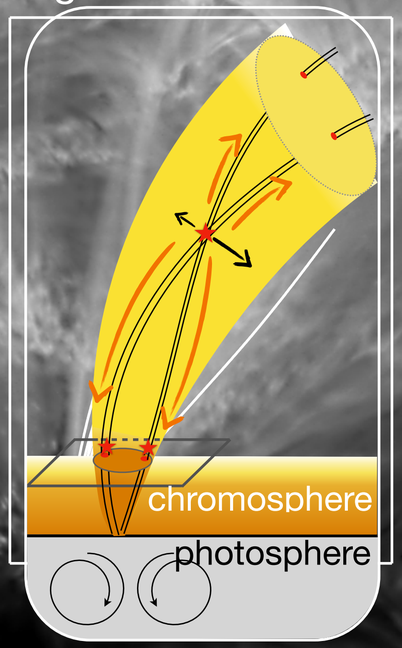


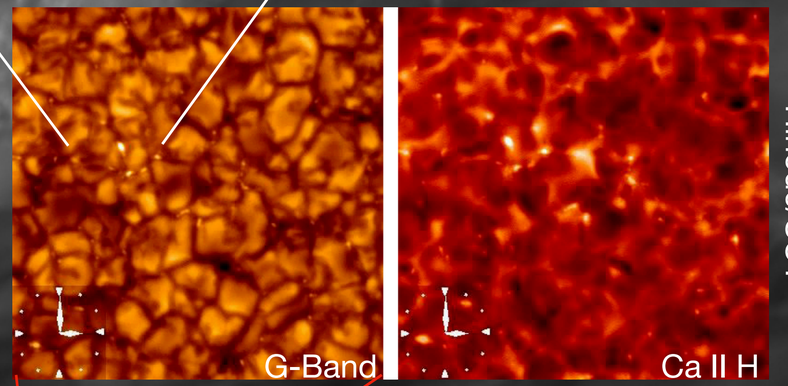


MHD waves



Magnetic reconnection

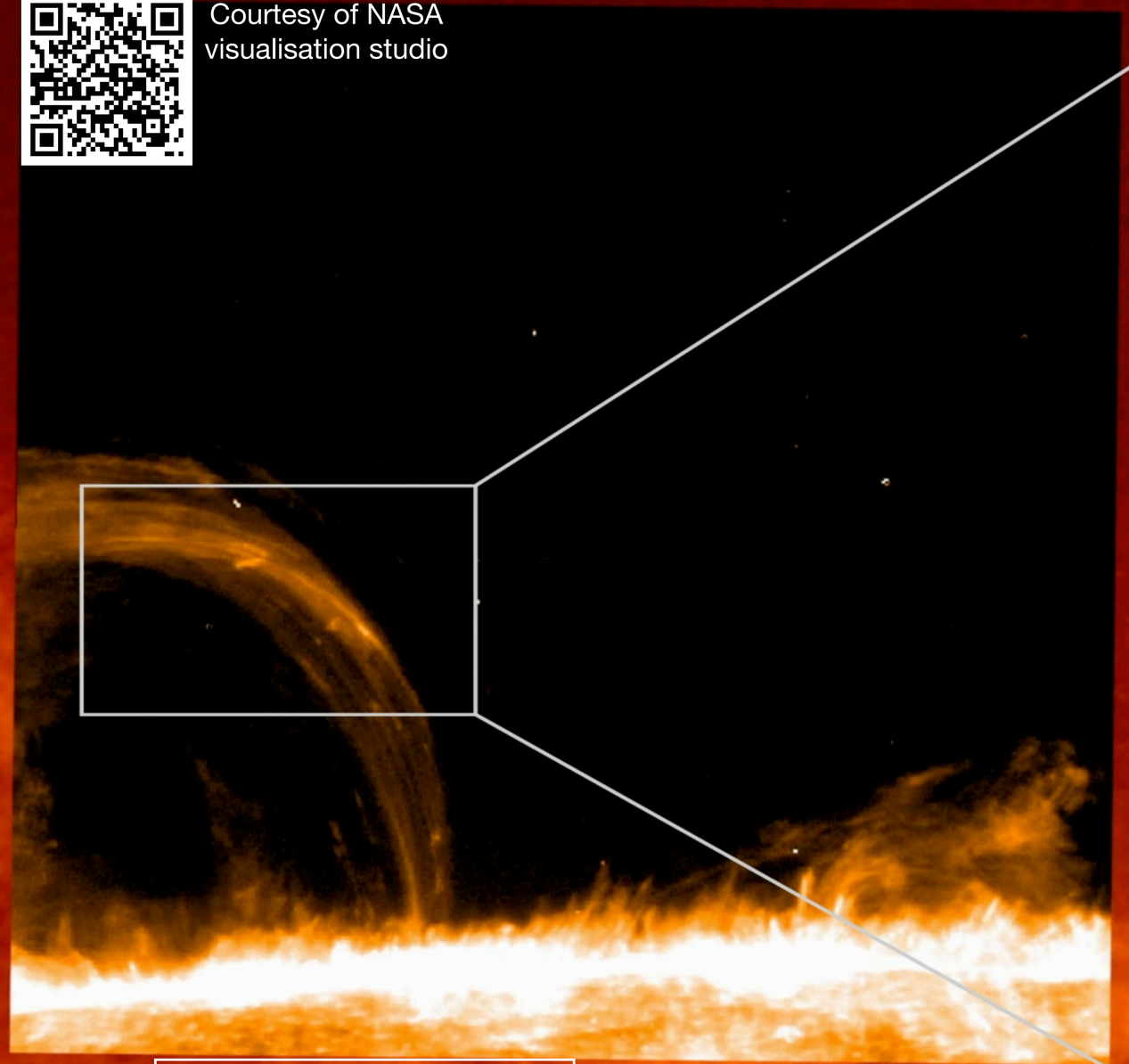




Cranmer & van Ballegooijen (2005)
Parnell & De Moortel (2012)
Matsumoto & Kitai (2010), Chitta et al. (2012)

Solar Orbiter / HRI 174 (Fe X) 10^6 K

Courtesy of NASA visualisation studio



Antolin et al. Nat. Astron. (2021)

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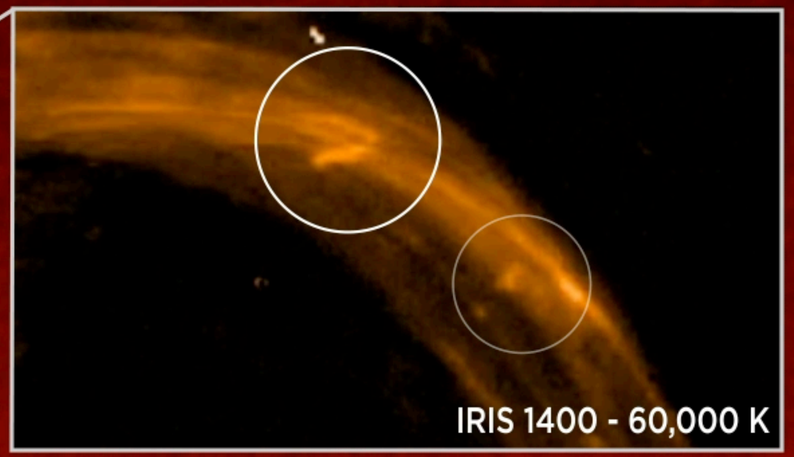
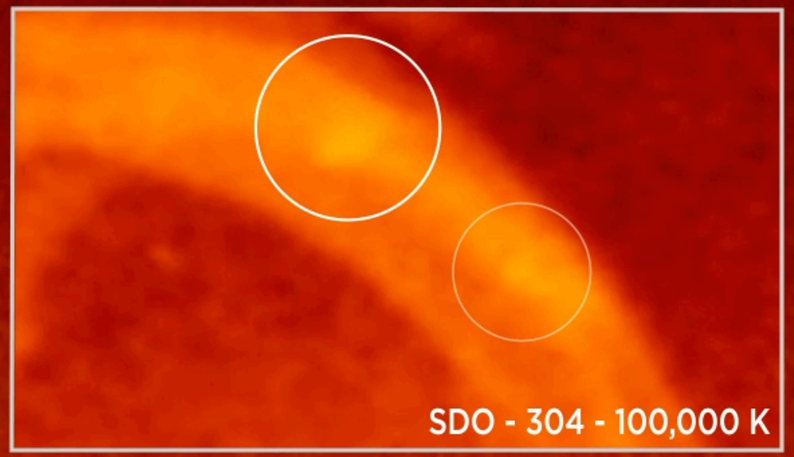


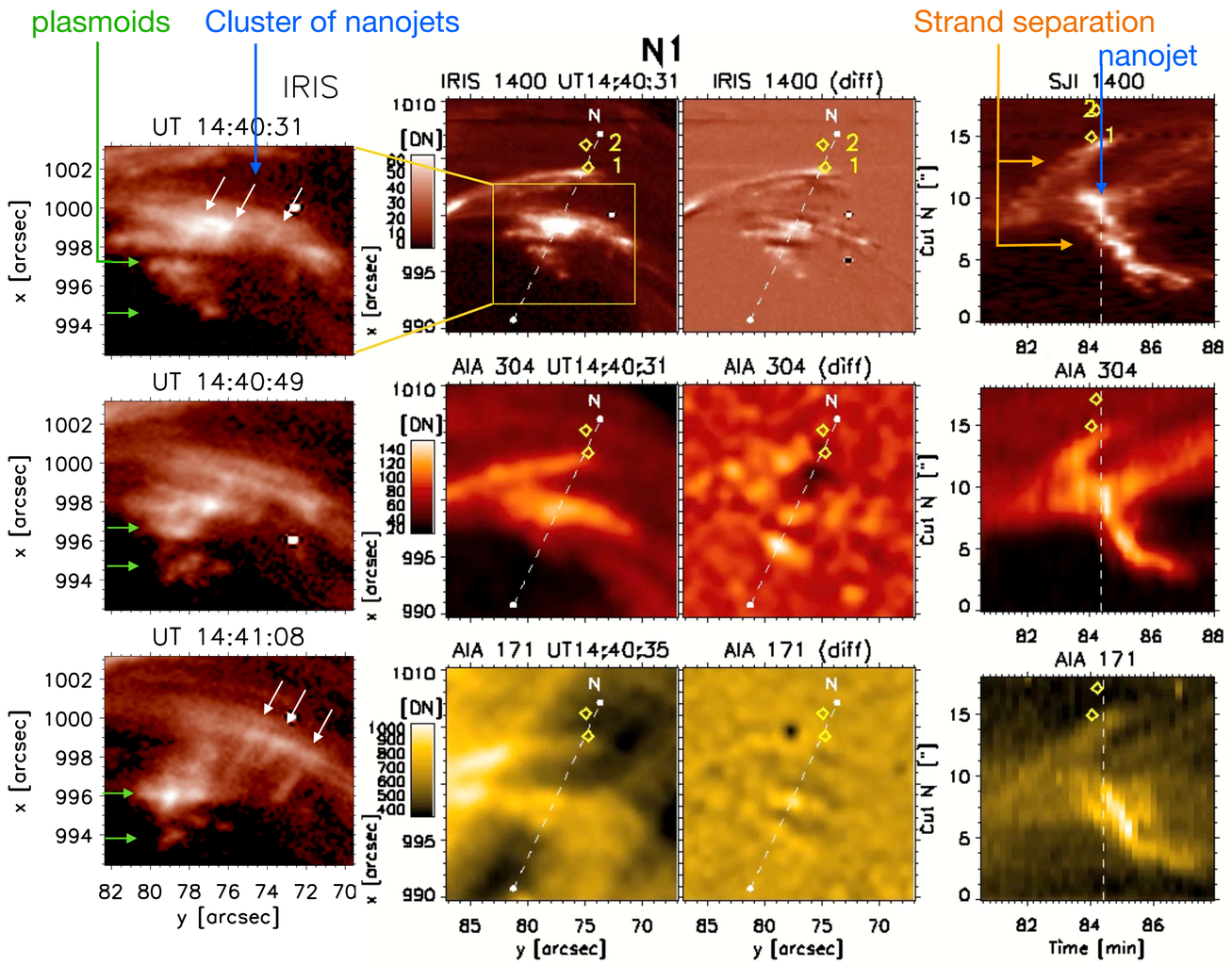


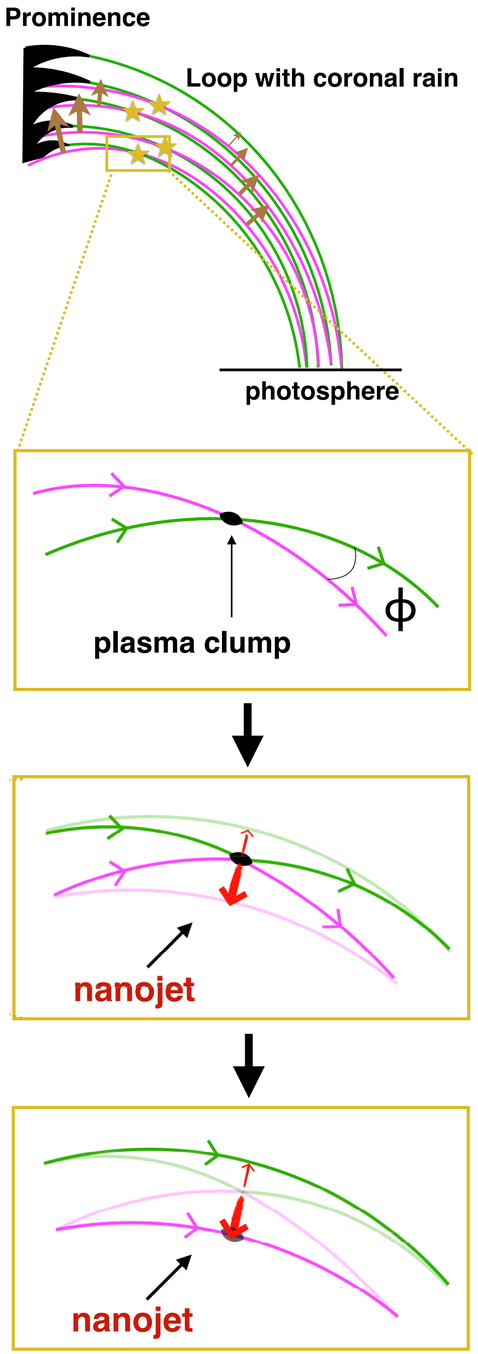
Nanojets

Prominence-coronal rain hybrid eruption

Antolin et al. (2021)

- Intensity bursts ~ nanoflare ≲ 10^{25} erg
- Jet-like, transverse to guide field
- Short lived ~20 s
- v (POS, LOS)>100 km/s
- Lengths: 1000 - 2000 km
- Widths: ~500 km
- Single or clustered occurrence
- Multi-thermal
- Plasmoids for largest
- Uni-directional

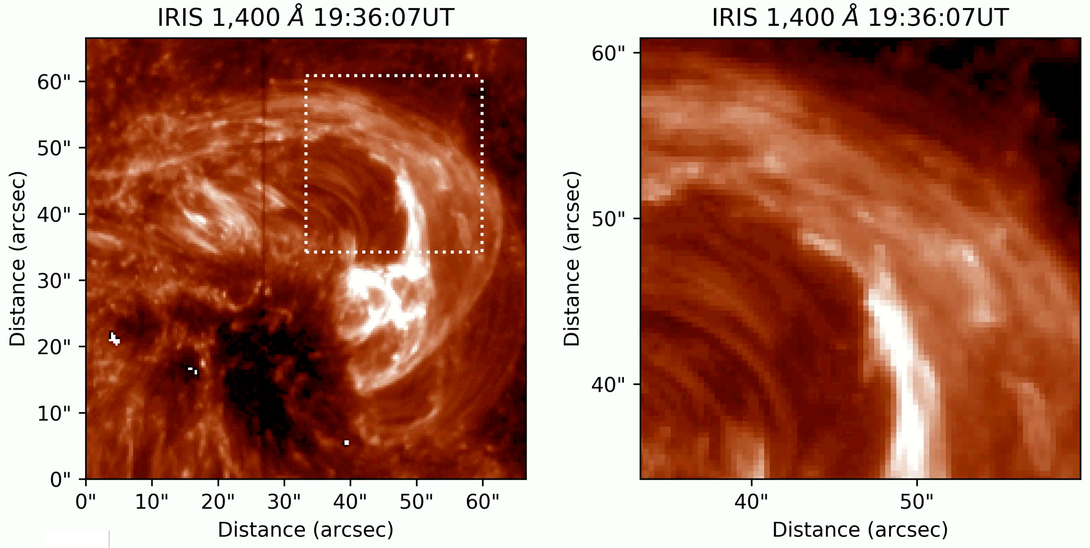


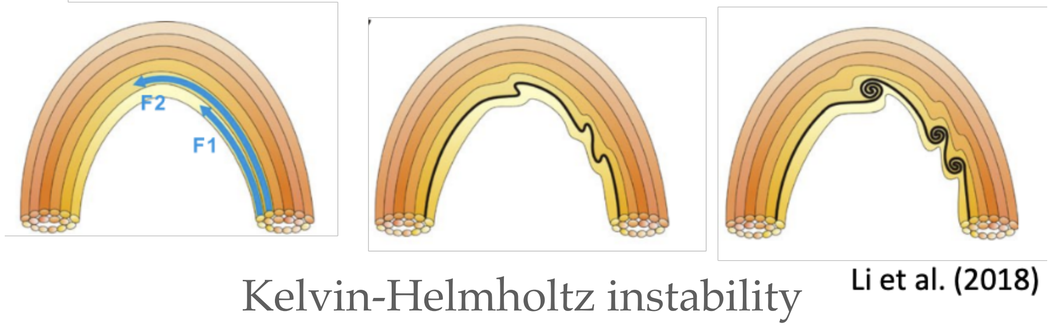


Nanojets

Blowout jet

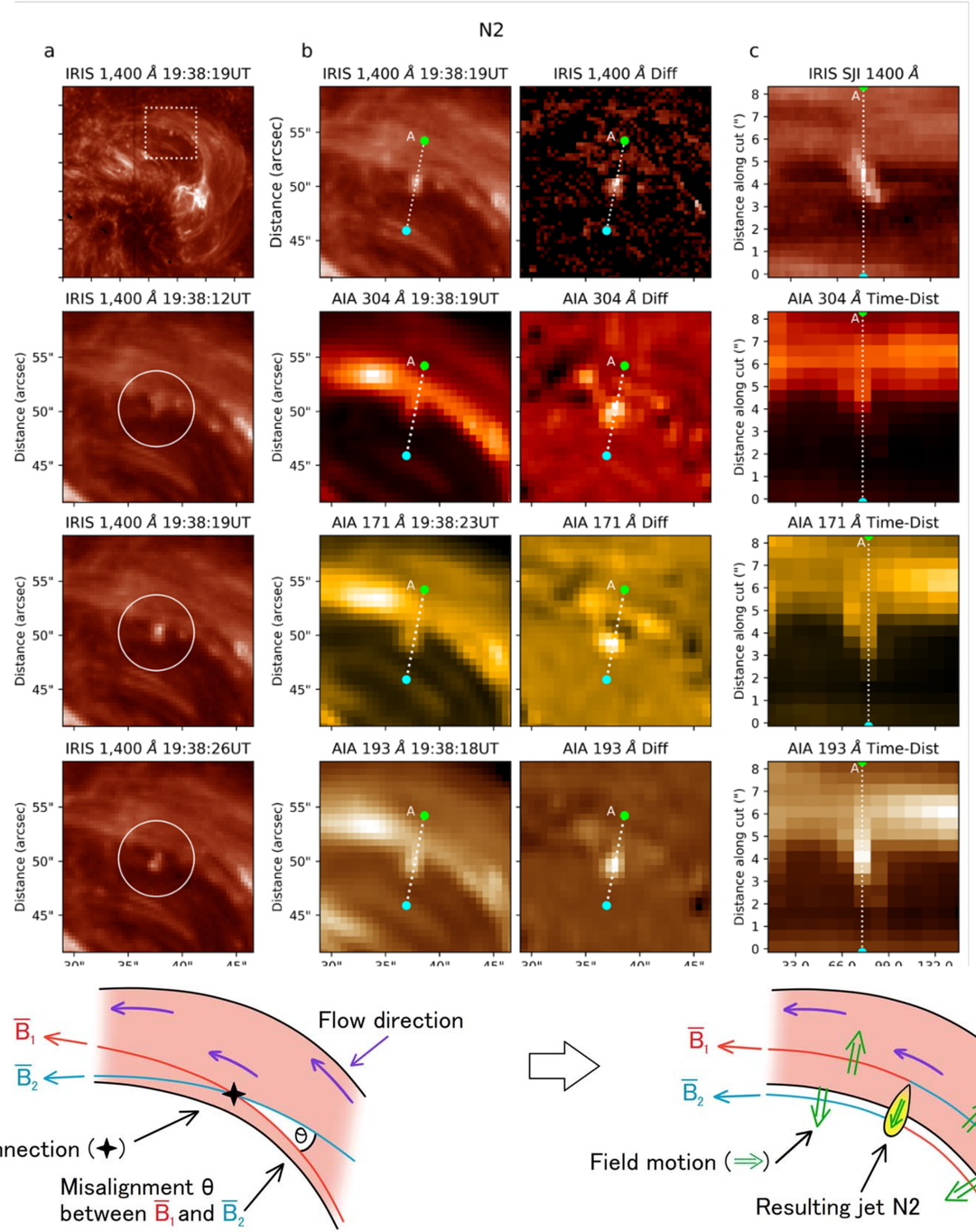
Sukarmadji+ (2022)





Kelvin-Helmholtz instability

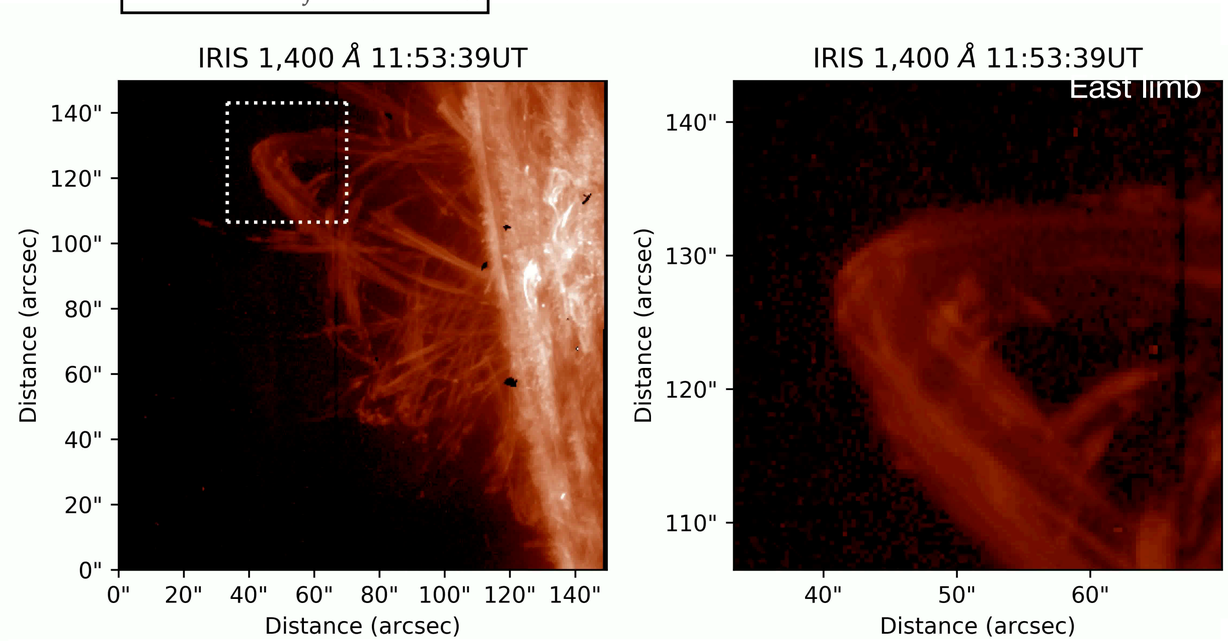
Li et al. (2018)

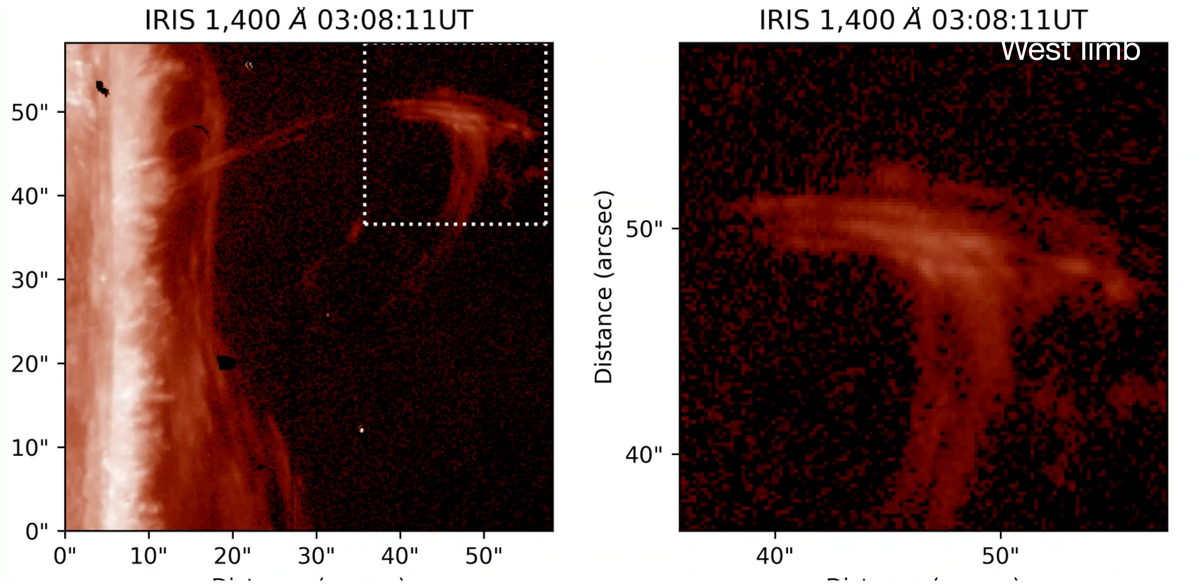


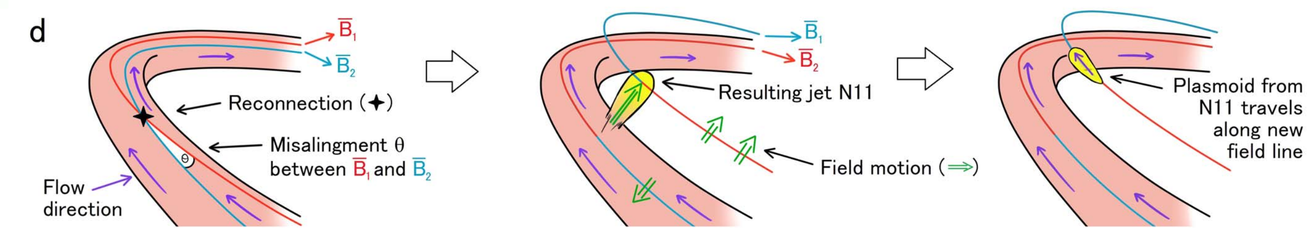
Nanojets

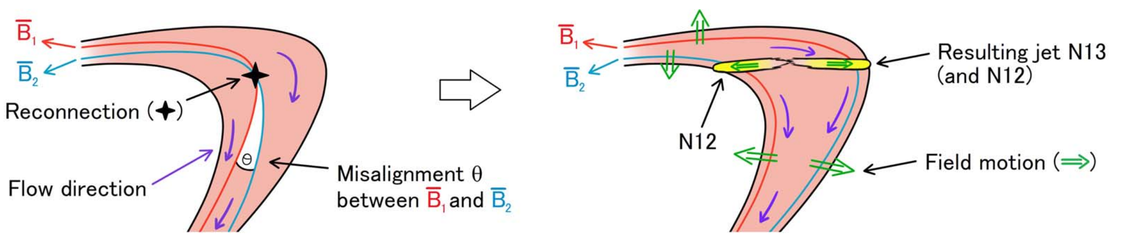
Loops with coronal rain

Sukarmadji+ (2022)







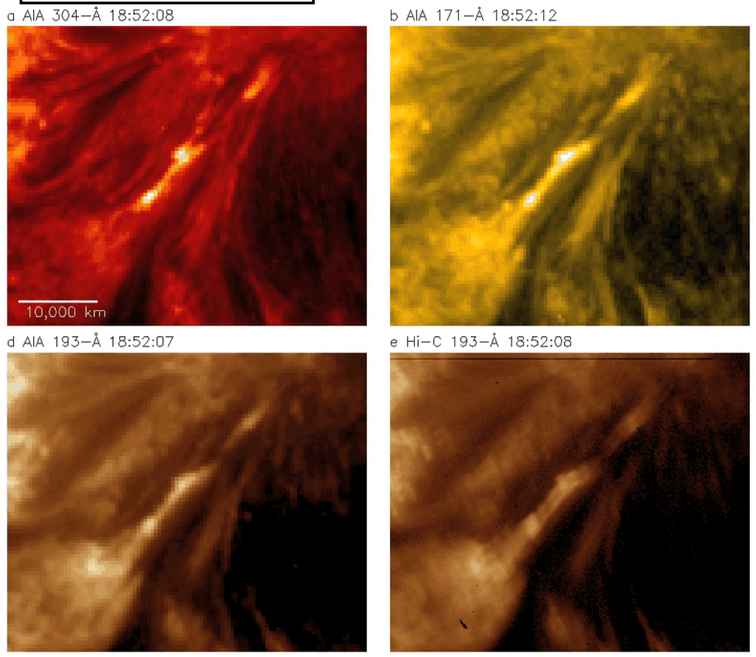


Nanojets

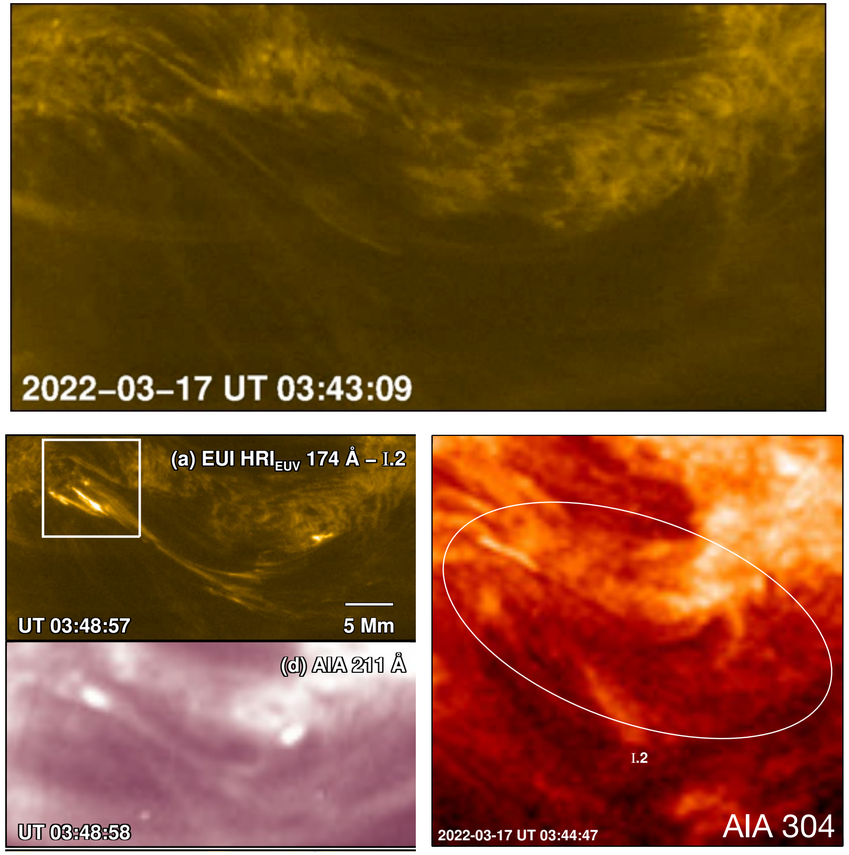
Other events

Coronal / chromospheric structures

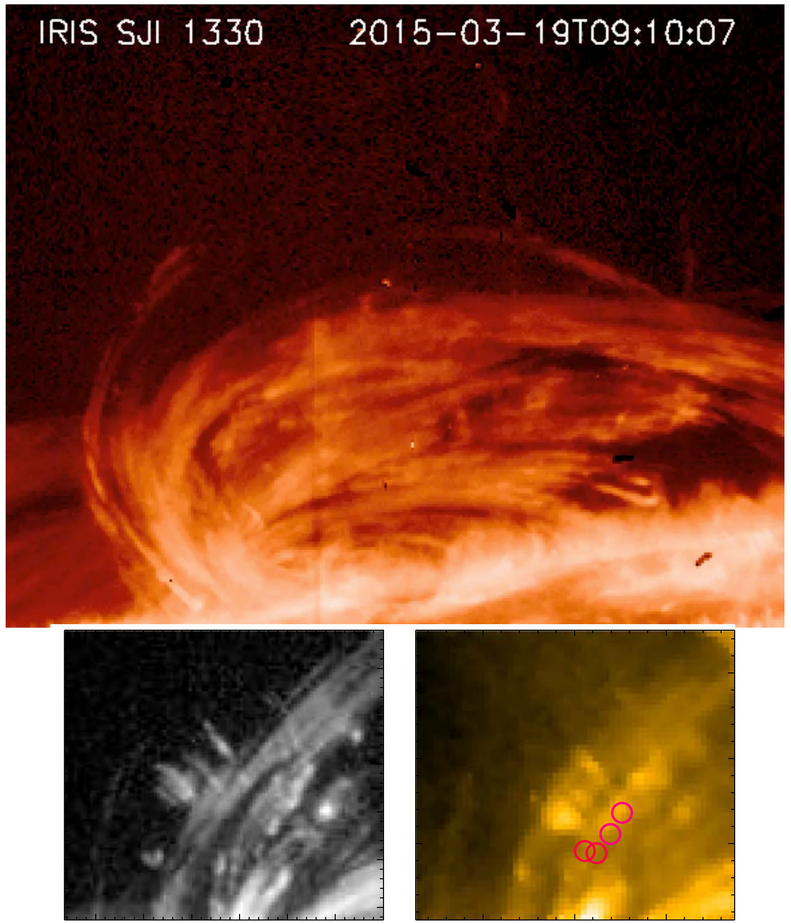
Cirtain+ (2013)



Chitta+ (2022)



Mini-jets in tornadoes *Chen, H.+ (2020)*

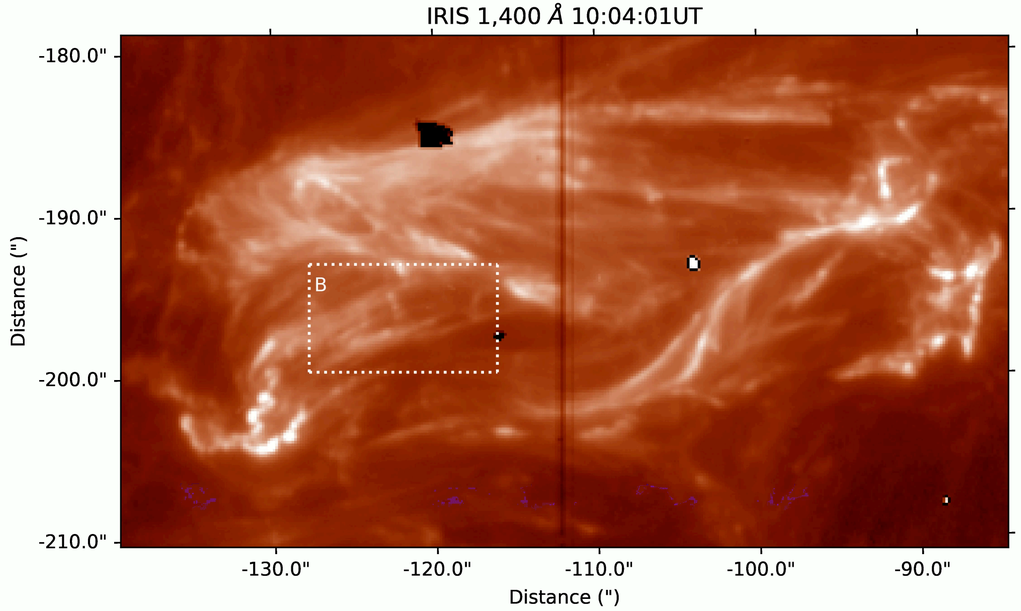


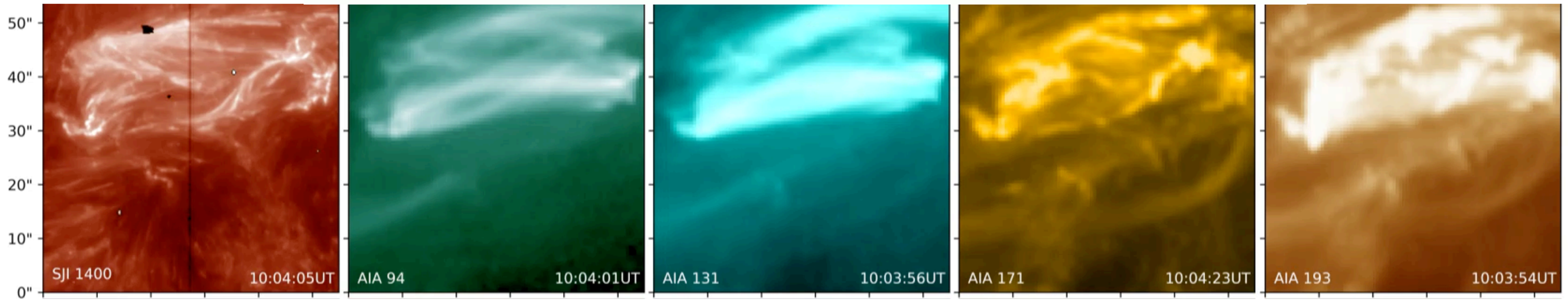
Nanojets

Flaring loops

Sukarmadji et al. (in prep.)

- C class flare
- >100 nanojets

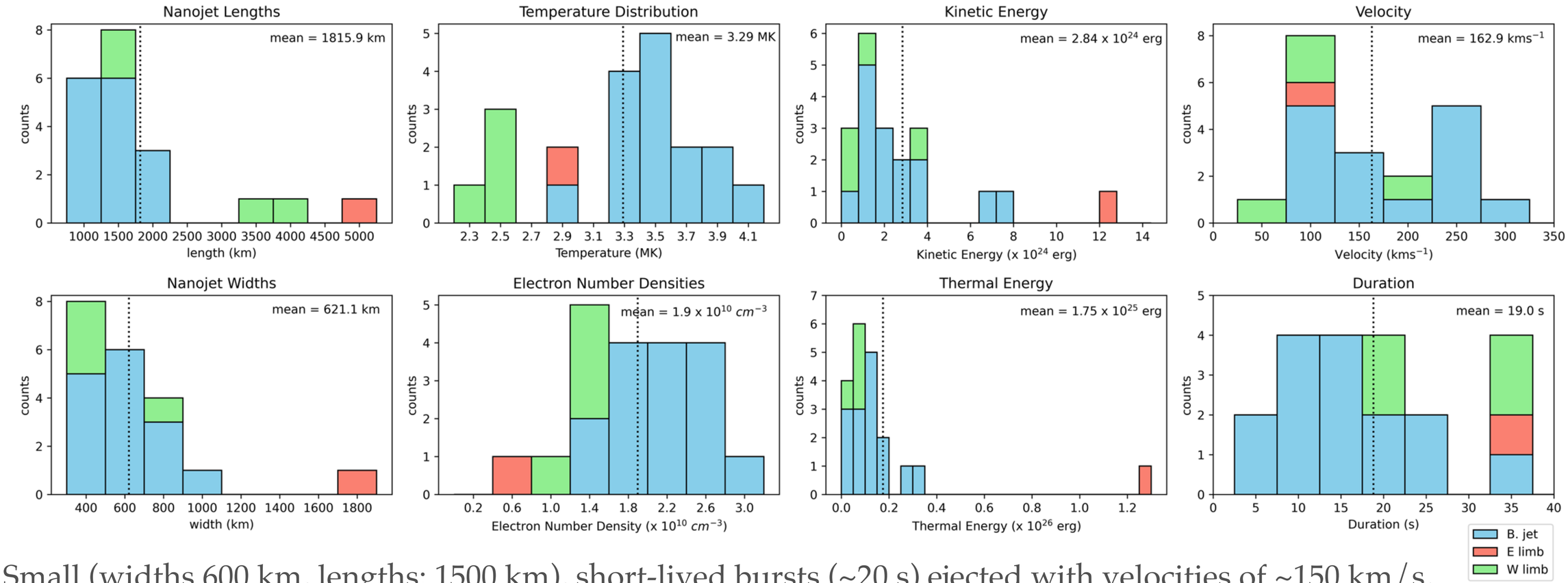




Nanojets

Statistics

Sukarmadji+ (2022)



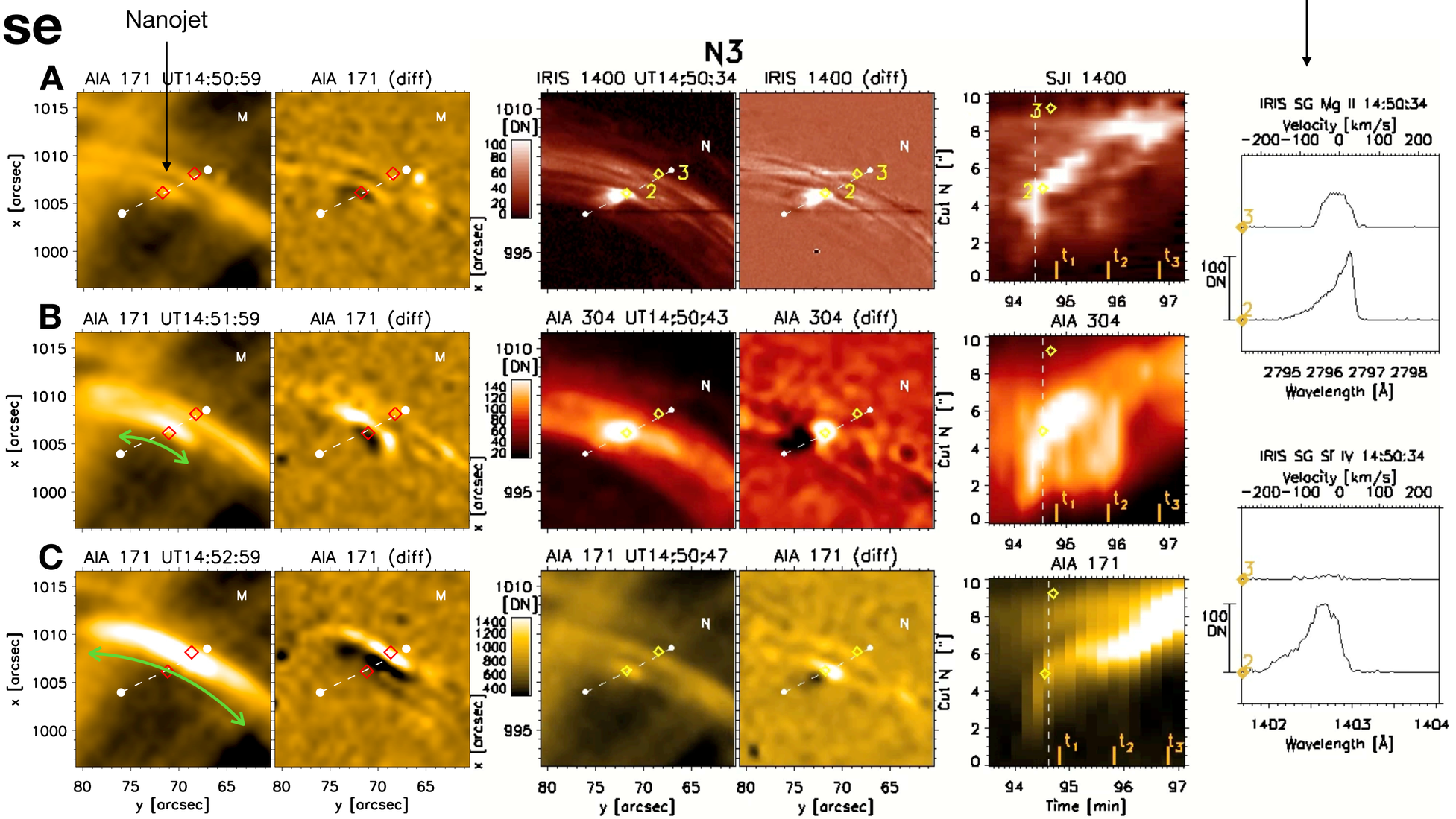
- Small (widths 600 km, lengths: 1500 km), short-lived bursts (~20 s) ejected with velocities of ~150 km/s, in nanoflare energy range

Nanojets

Global response

Antolin et al. (2021)

- Transverse separation of rain strands
- Spread along & across the loop, numbers increase with time
- Precede formation of coronal strands
- Multi-thermal
- Heating to coronal temperatures (<5 MK)

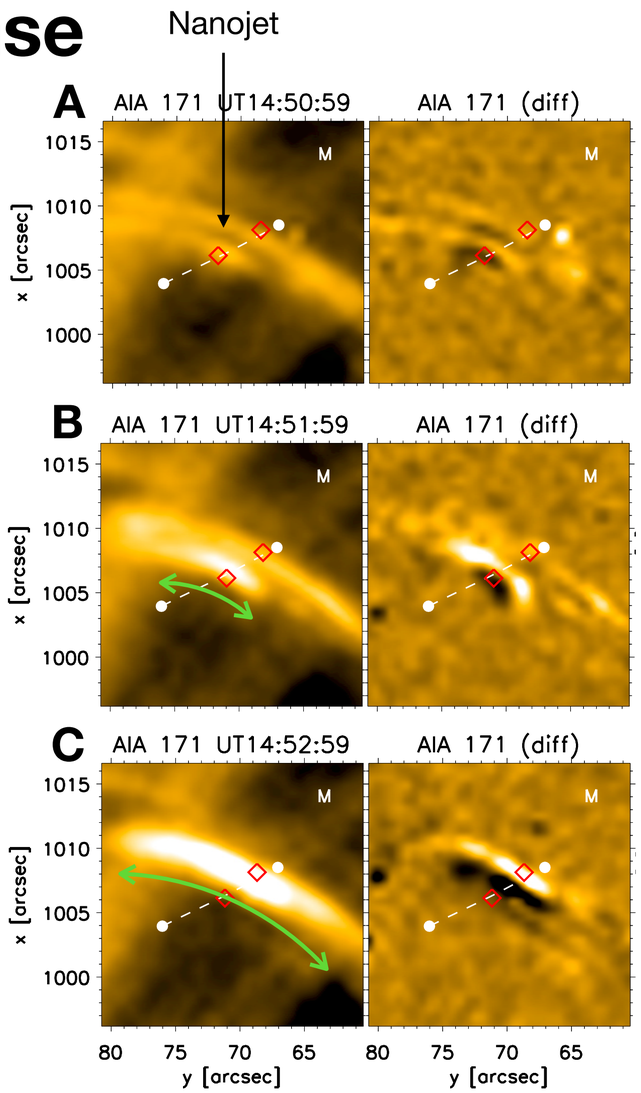


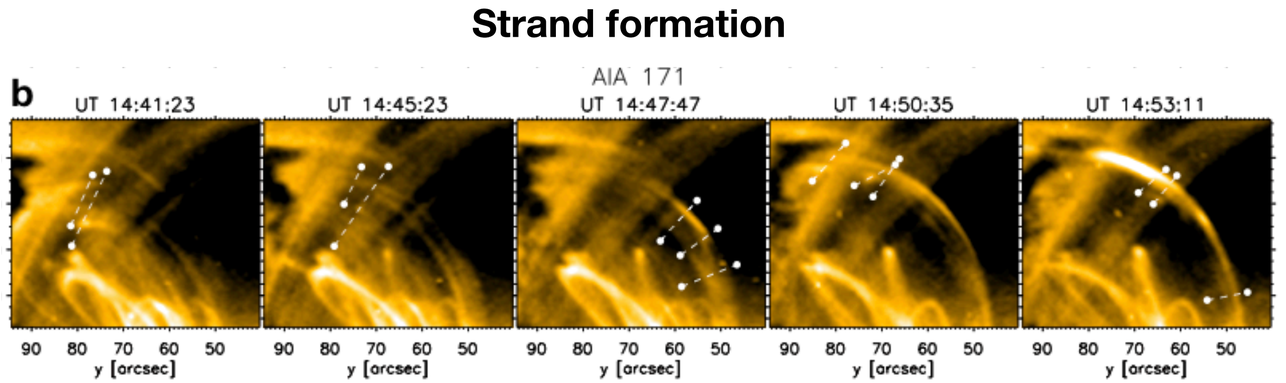
Nanojets

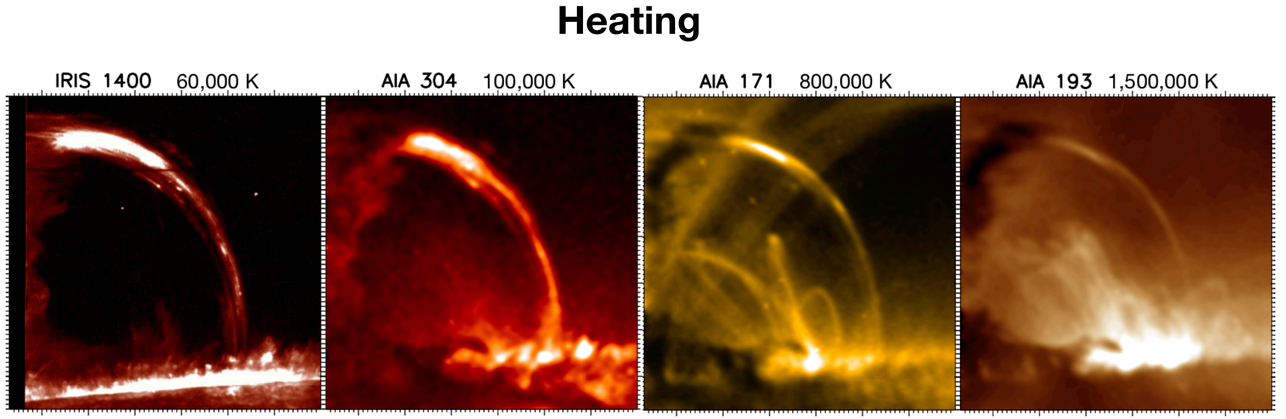
Global response

Antolin et al. (2021)

- Formation of coronal strands
- Coronal heating of loop
- Transverse MHD oscillations (see Ramada Sukarmadji's talk)







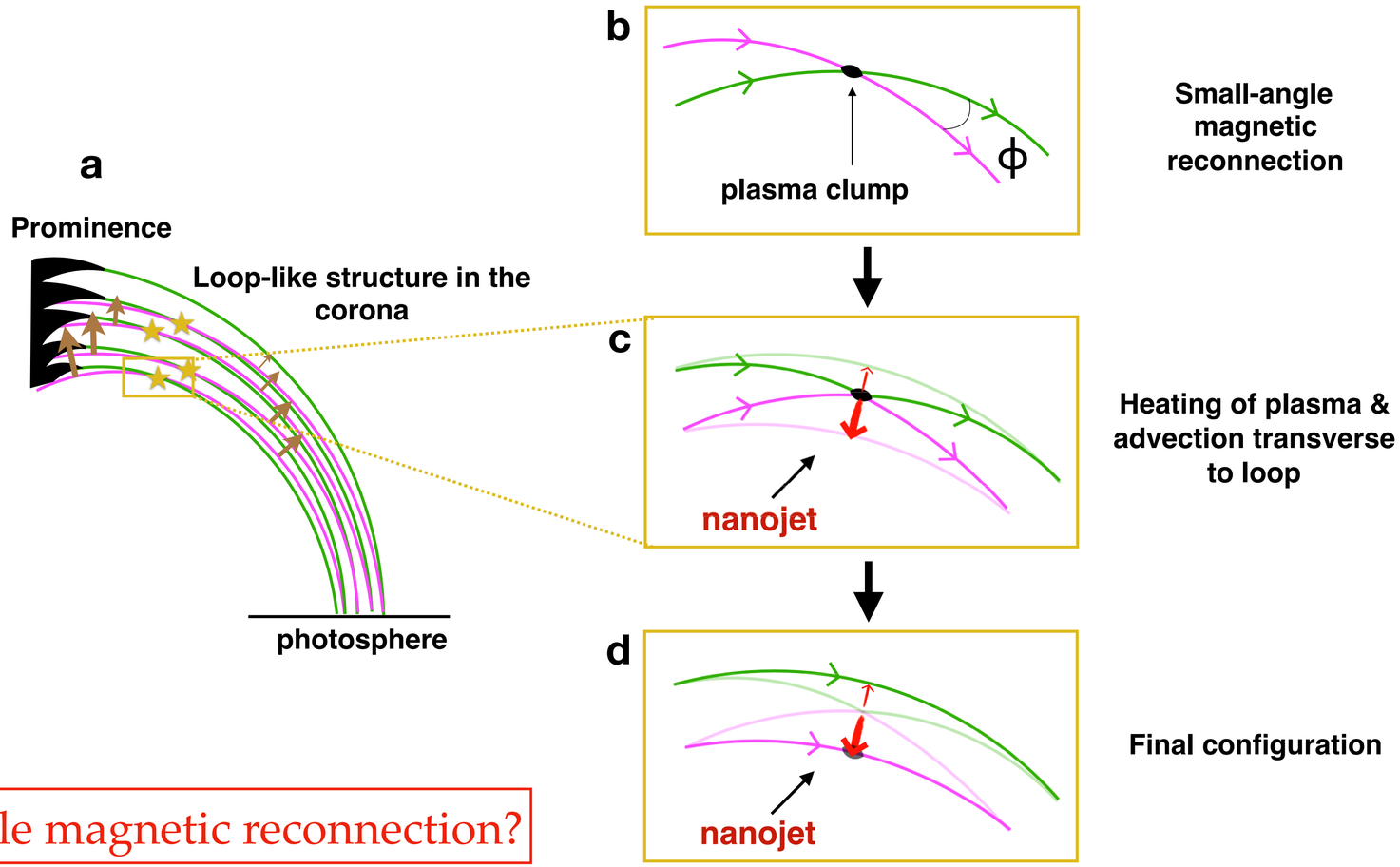
Discussion

What is the nanojet?

Antolin et al. (2021)

- Nanojet = heating + advection of reconnected field lines transverse to the loop
- Different from usual jets: no major field-aligned flow involved

➡ signature of small-angle magnetic reconnection



Are nanojets a general feature of small-angle magnetic reconnection?

Discussion

How common are nanojets and in what scenarios can we find them?

1. Loops with coronal rain
2. Blowout jets
3. Eruptions and flaring

Is the cool material (rain) playing an important role?

- Observational bias?
- Thermal instability can facilitate reconnection (e.g. *Sen & Keppens 2022*)

Discussion

Nanojet number vs Total energy release

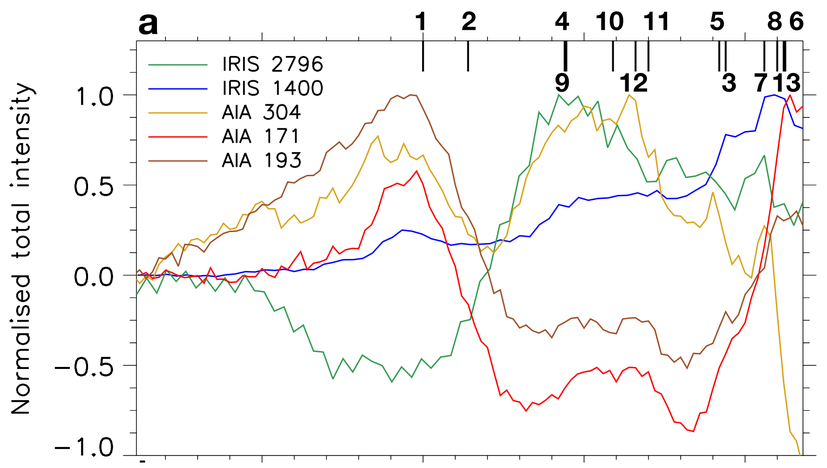
- West Limb Case (<T> ~ 10^5 K): 1 nanojets
- East Limb Case (<T> ~ 10^5 K): 4 nanojets
- Blowout Jet (<T> ~ $10^{6.5}$ K): 15 nanojets
- Prominence/Coronal Rain structure (<T> ~ $10^{6.7}$ K): ~ 150 nanojets
- C Class flare: ~ hundreds

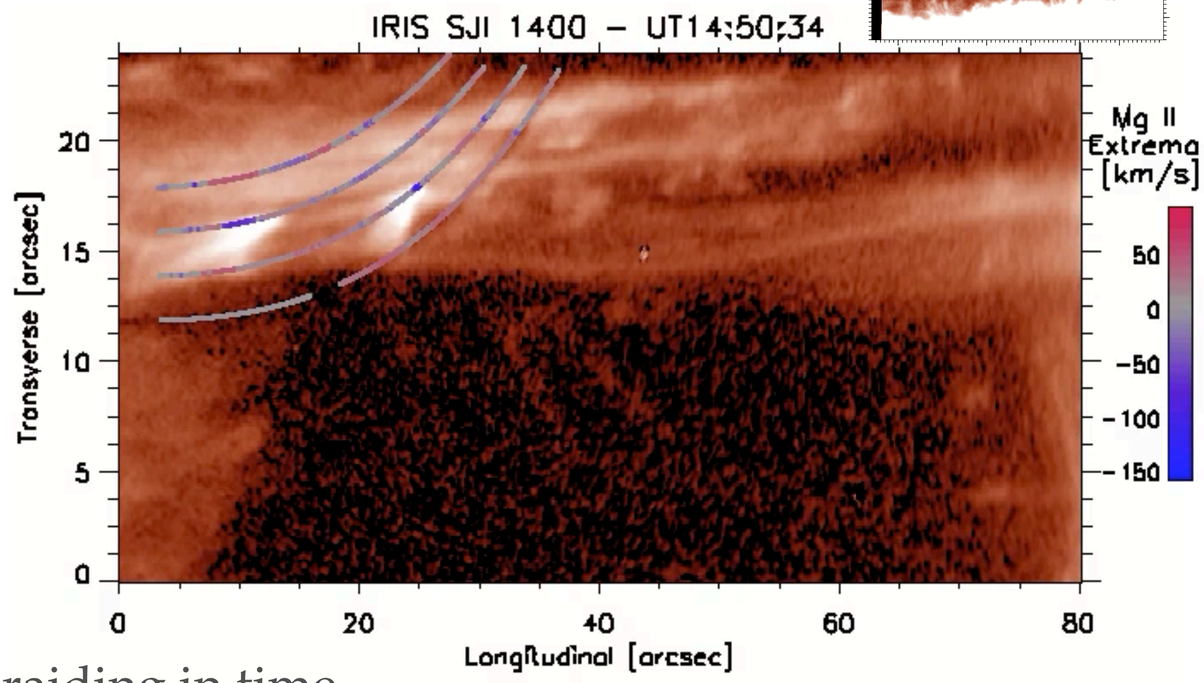
Is there a correlation between the number of nanojets with the total energy released?

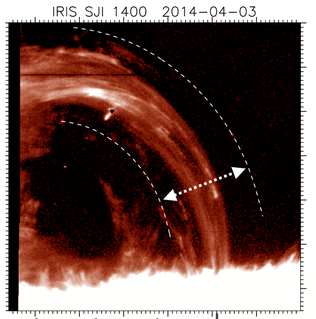
Drivers of the reconnection

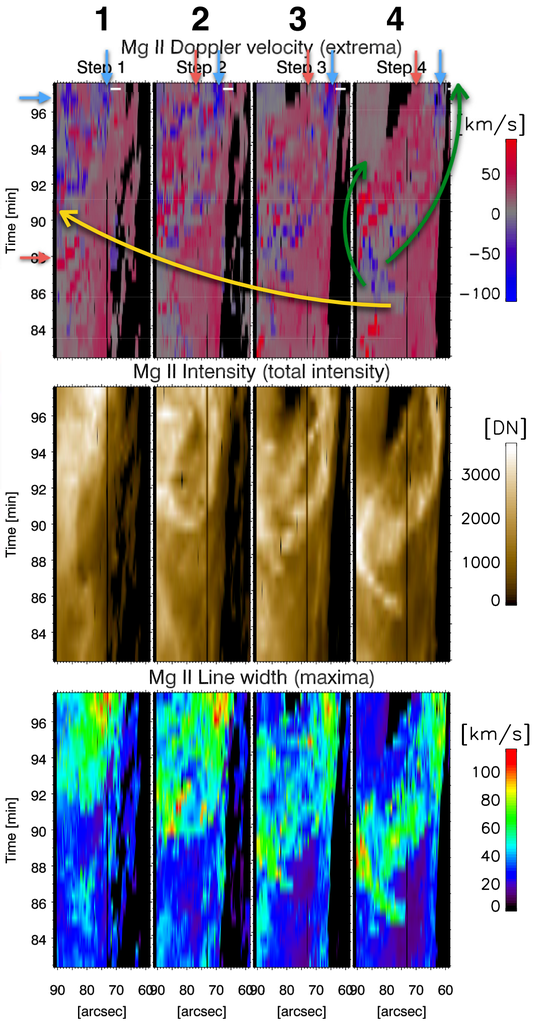
Braiding and shear flows

Antolin et al. (2021)









MHD avalanche?

- Reduction of braiding in time
- complex internal rotation patterns
- ∑ ~ 150 nanojets in 13 min, spread across & along loop
- First clusters are the most energetic
- Numbers and clustering associated with energy release

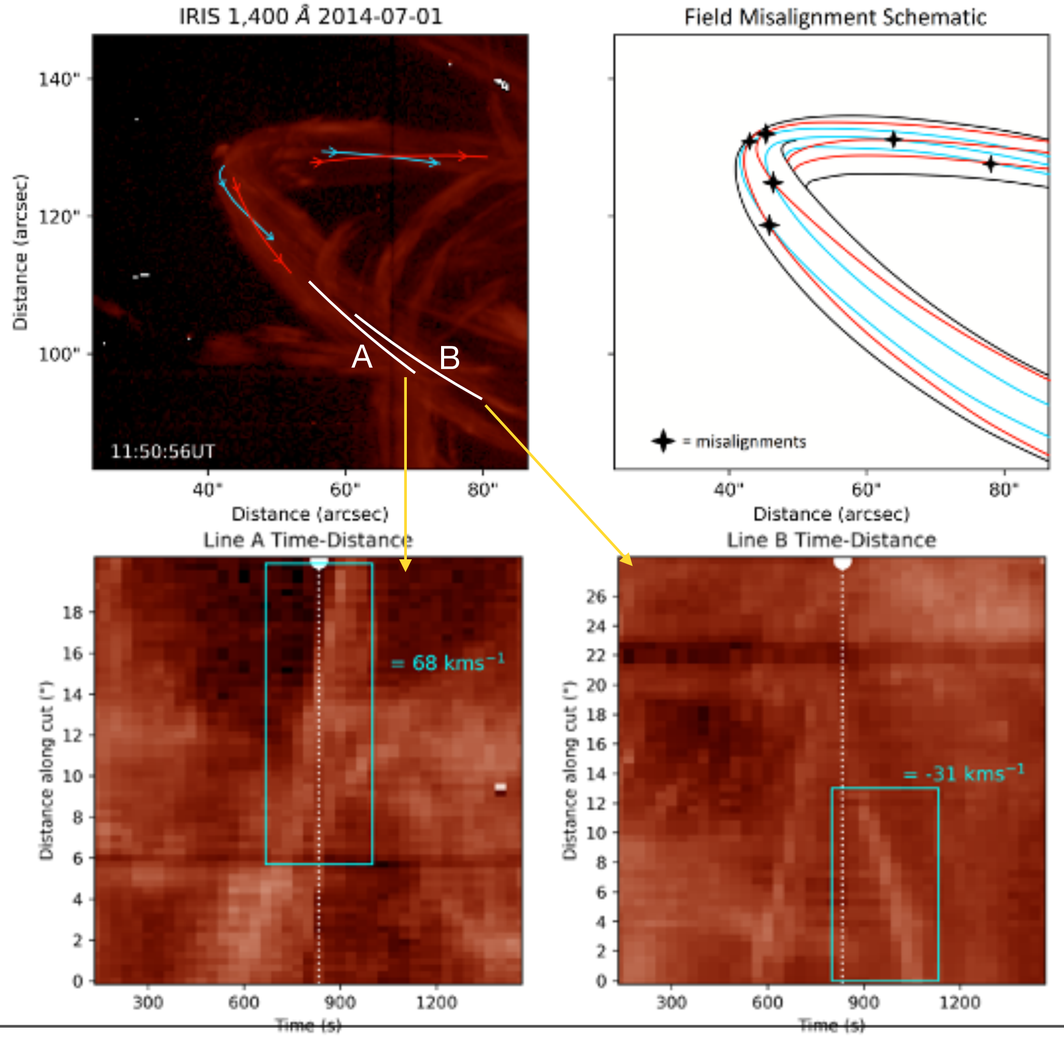
Drivers of the reconnection

Braiding and shear flows

Sukarmadji+ (2022)

- Blowout jet:
  - 45-60°
  - Velocity shear of 294 km s^{-1}
  - KHI reported by *Li et al. 2018*
- East and west limb rain events:
  - 5-15°
  - Velocity shear: 147 km s^{-1} and 68 km s^{-1}
  - Dynamic instabilities?

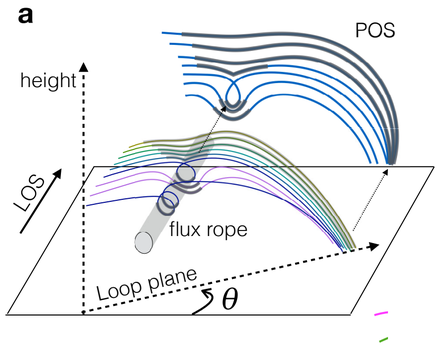
Kelvin-Helmholtz Rayleigh-Taylor

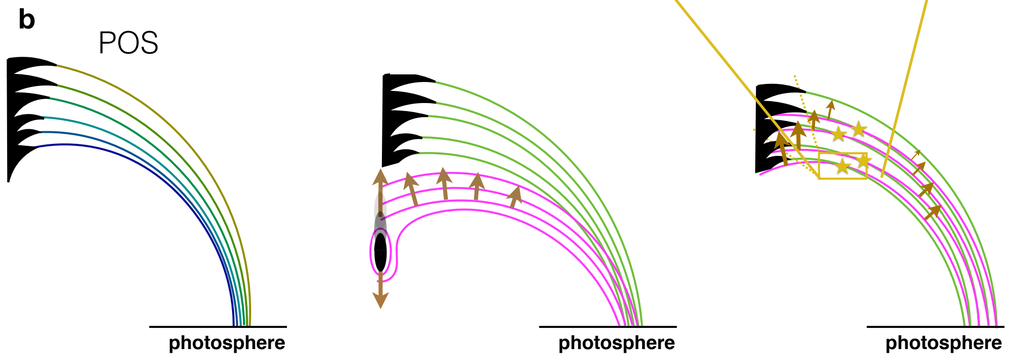


Drivers of the reconnection

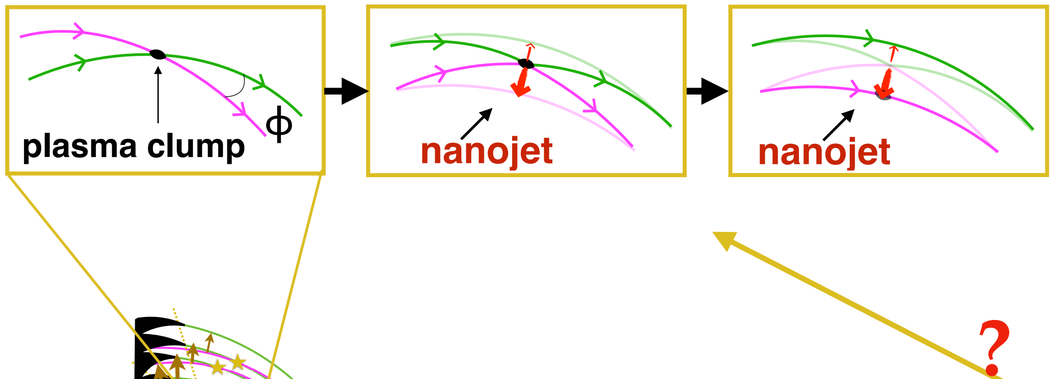
Prominence stability loss & dynamic instabilities

Antolin+ (2021)

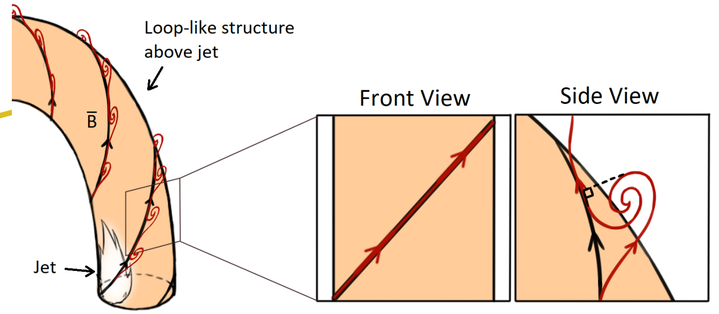




General feature of reconnection at small angle, independent of reconnection driver?



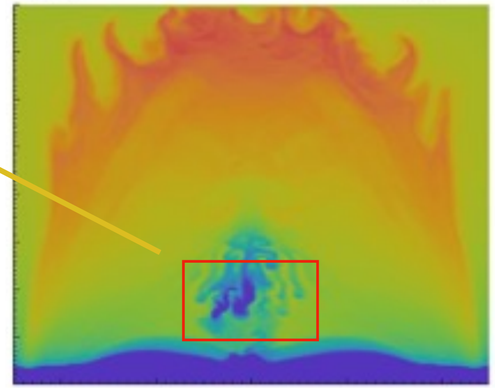
Kelvin-Helmholtz instability ✔



Sukarmadji+ (2022)

Rayleigh-Taylor instability ?

?

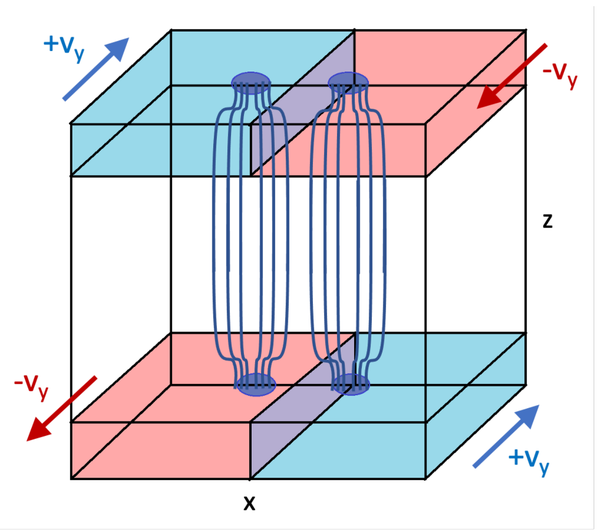


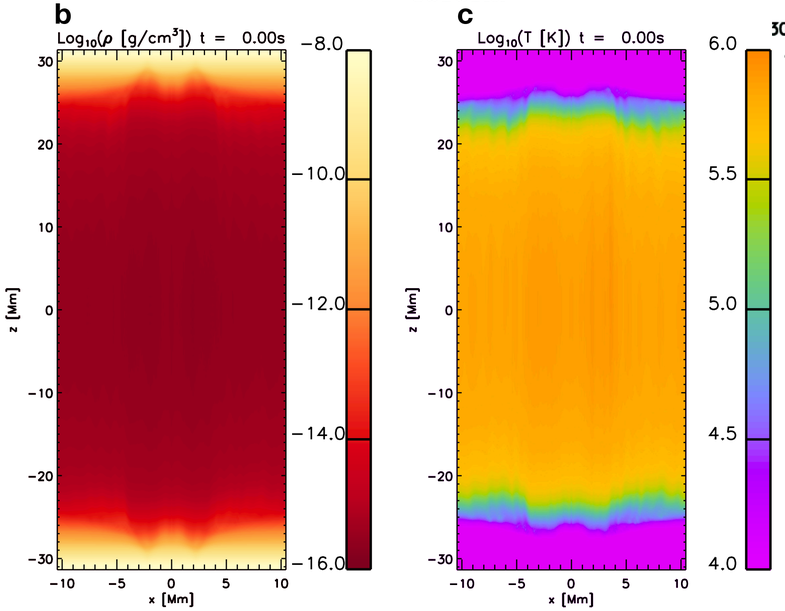
Numerical simulations of nanojets

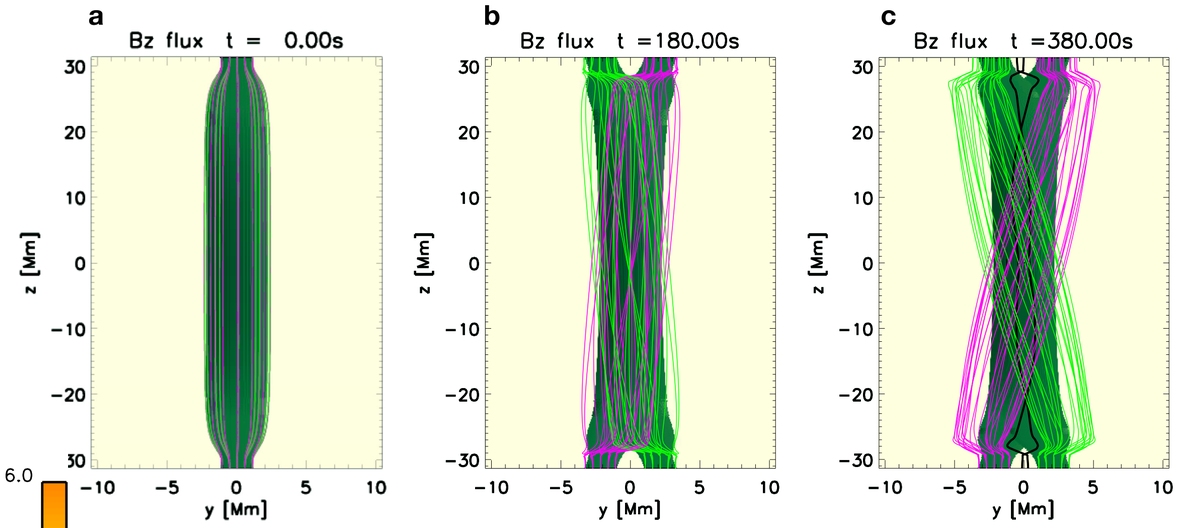
PLUTO code

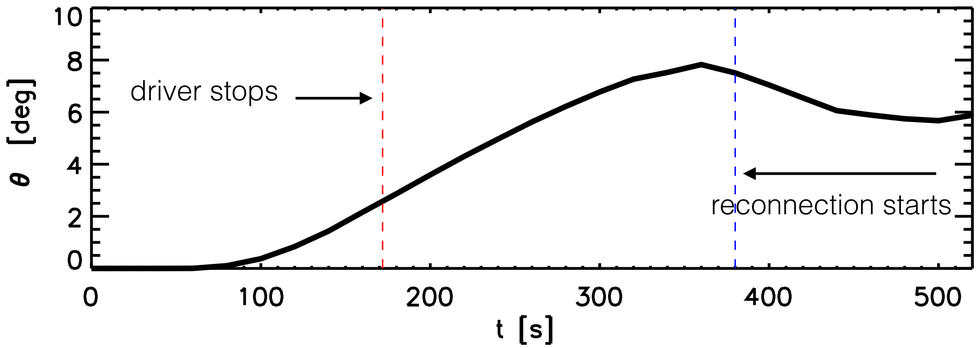
- 2 flux tubes in stratified atmosphere chromosphere+corona+artificially broadened TR (Lionello+ 2009)
- MHD + thermal conduction & radiation + anomalous resistivity
- Relaxation prior to driving

$B_{corona} = 15$ G



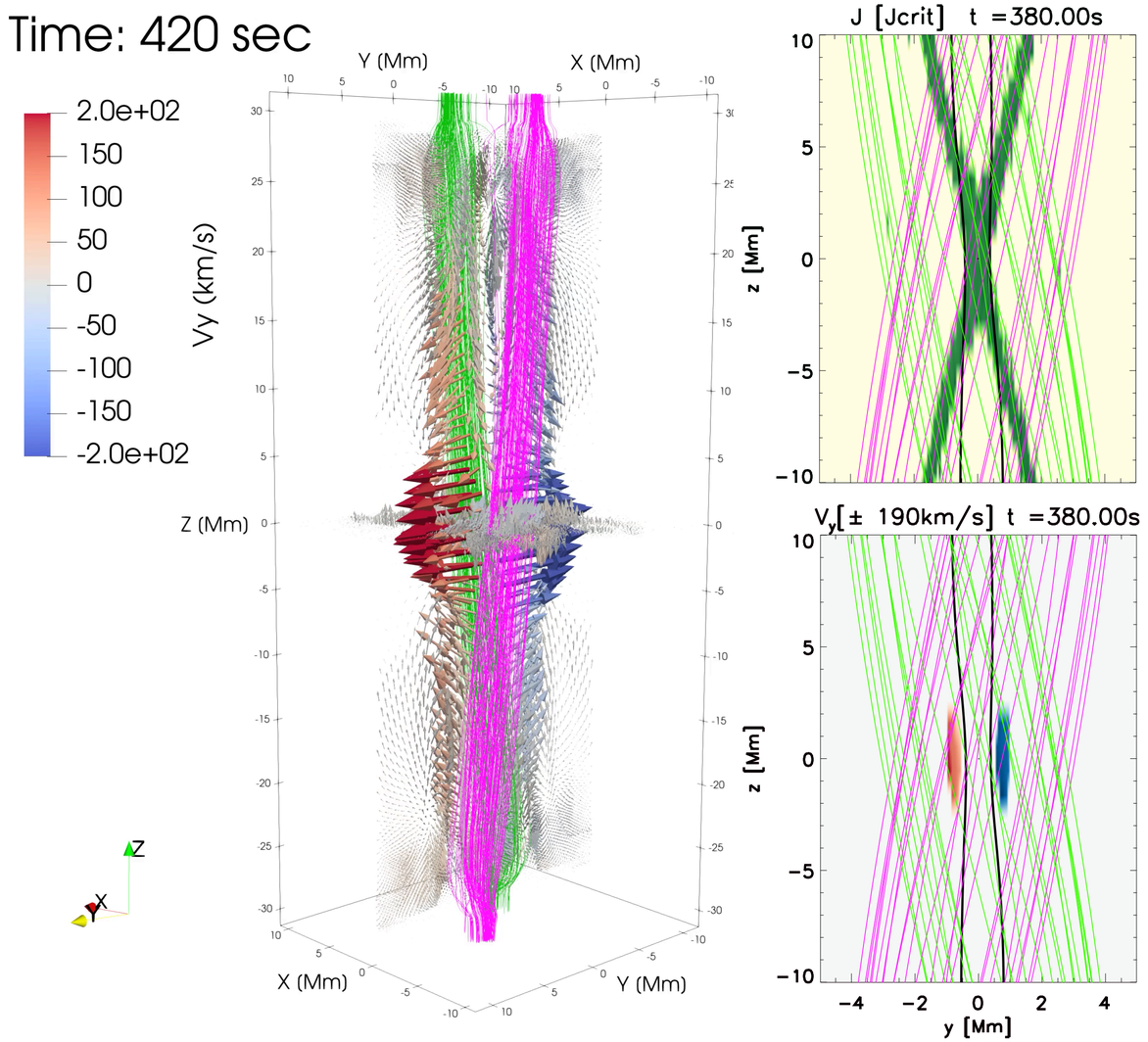




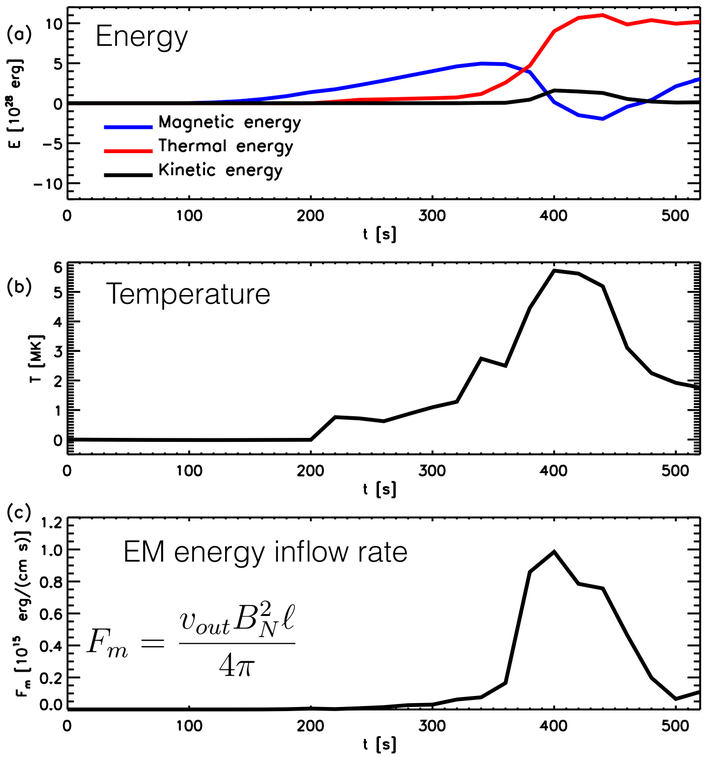


Antolin et al. (2021)

Numerical simulations of nanojets



Case $v_{max} = 20$ km s^{-1}

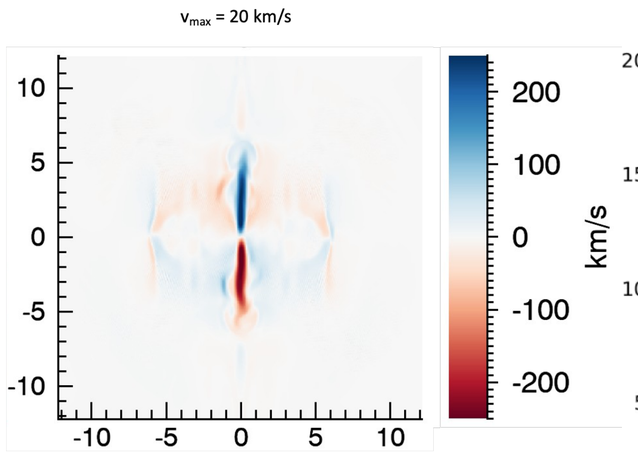


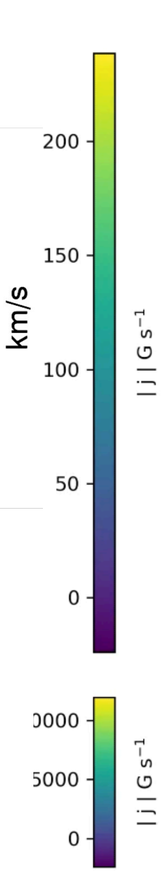
$$F_m = \frac{v_{out} B_N^2 \ell}{4\pi}$$

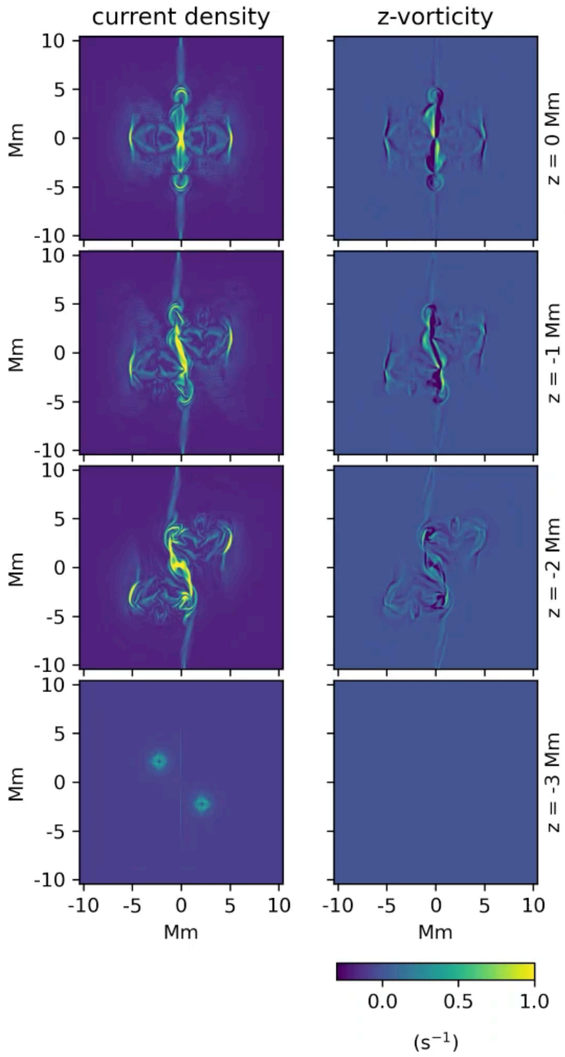
- Highly localised reconnection event
- High speed jet-like structure perpendicular to field
- Magnetic tension main driver of jet
- field-aligned flow~20km/s
- Local T increase
- Large-scale perpendicular displacement of field lines

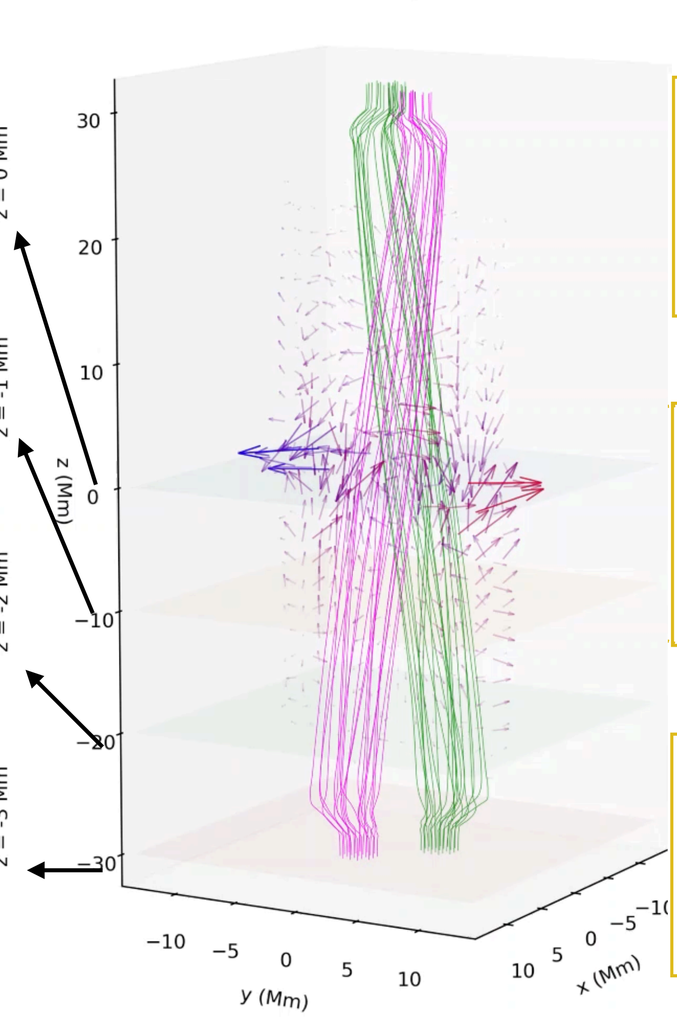
Numerical simulations of nanojets

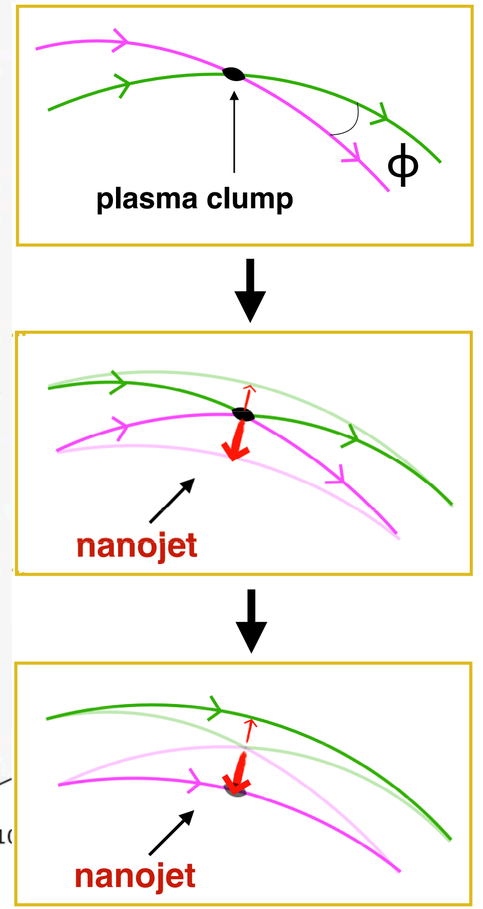
Sukarmadji et al. (in prep.)











- Similar dynamics and morphology to observed nanojets
- Lifetime ~< 1min
- Similar to largest nanojets observed

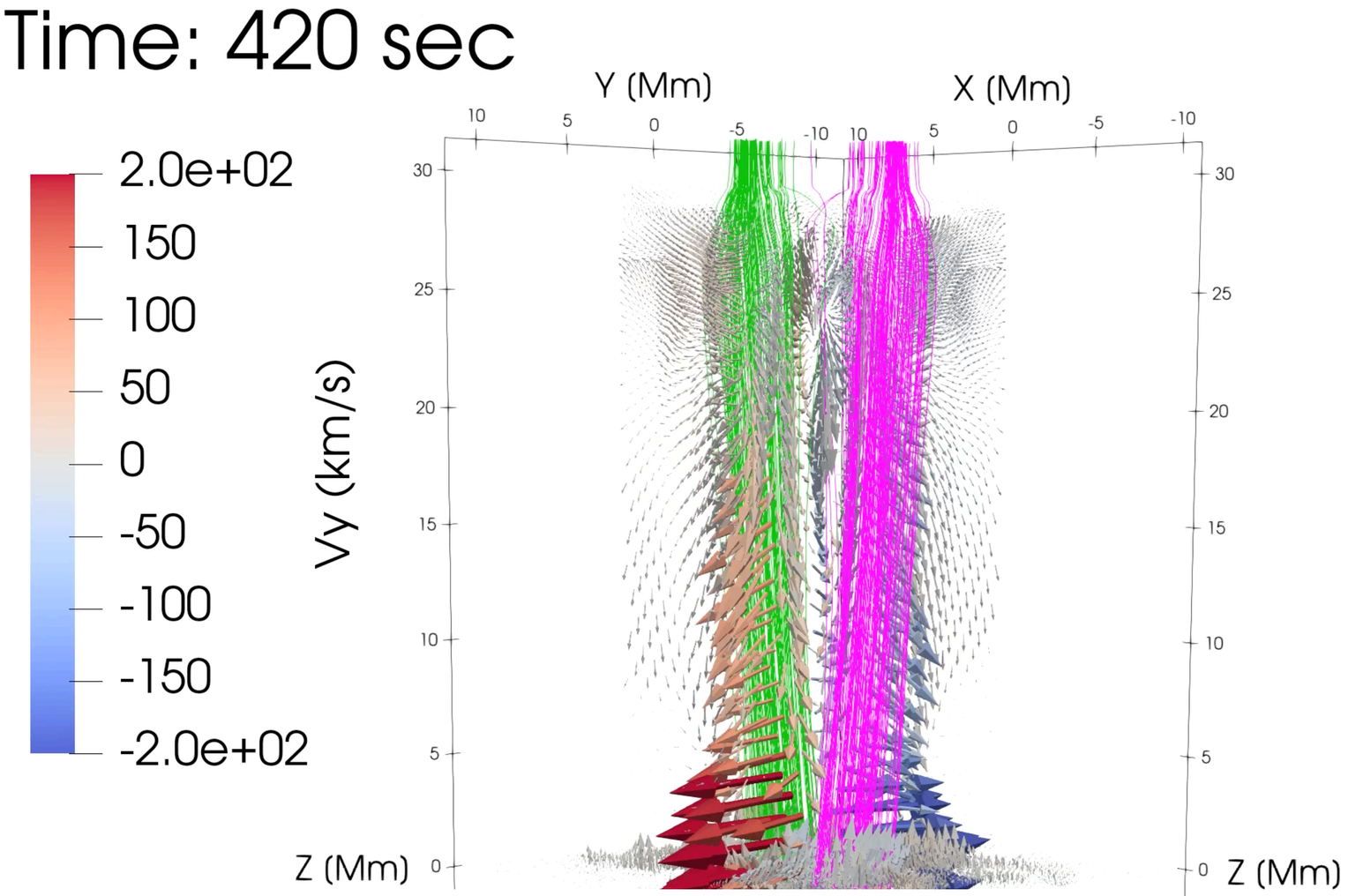
- Nanojets match with small-angle **magnetic reconnection**

Numerical simulations of nanojets

Origin of the reconnection

Sukarmadji et al. (in prep.)

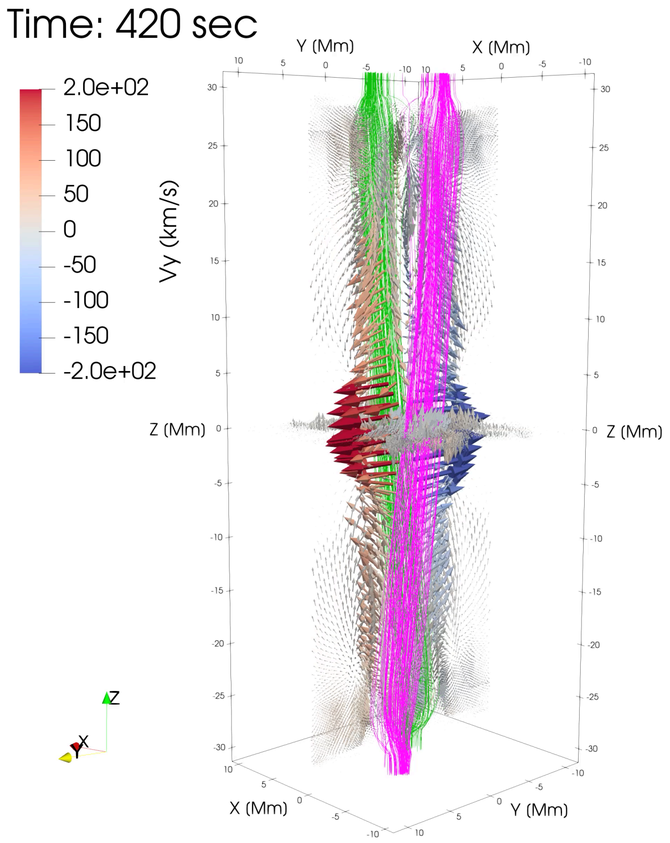
- Alfvén wave at the origin of the reconnection?



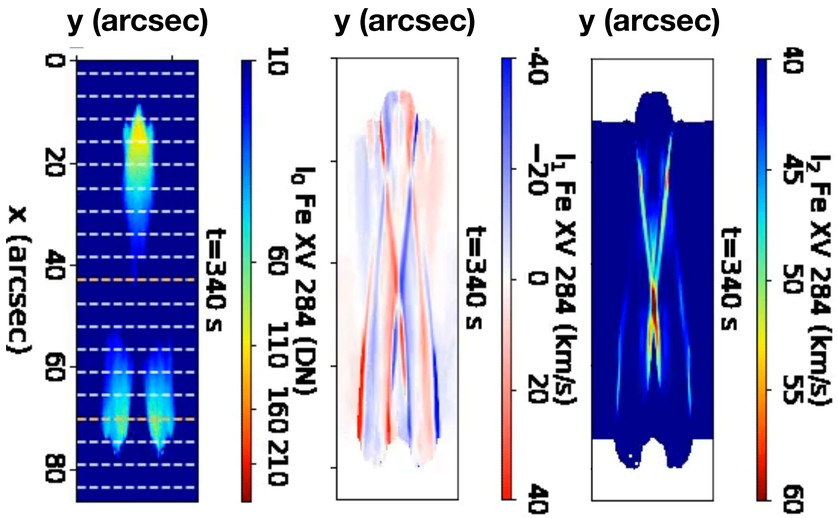
Sukarmadji et al. (in prep.)

Numerical simulations of nanojets

Forward modelling for MUSE



De Pontieu et al. ApJ (2022)



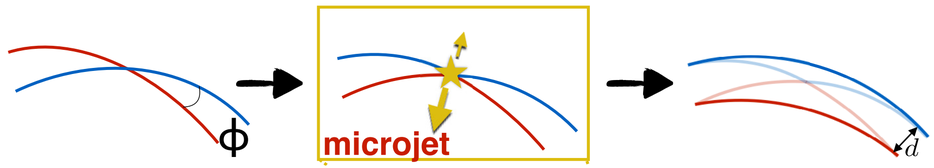
By P. Pagano

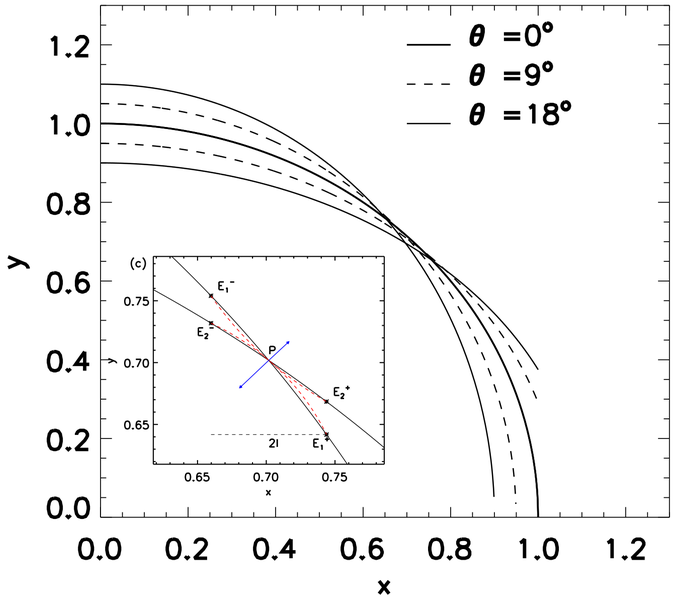
- Nanojet features can be clearly identified at 0.3″ and 10 s cadence in the Fe XV 284 line of MUSE
  - Increase in intensity all along strands
  - Transverse separation of strands (in imaging & Doppler)
  - Enhanced non-thermal line broadening at reconnection location

Discussion

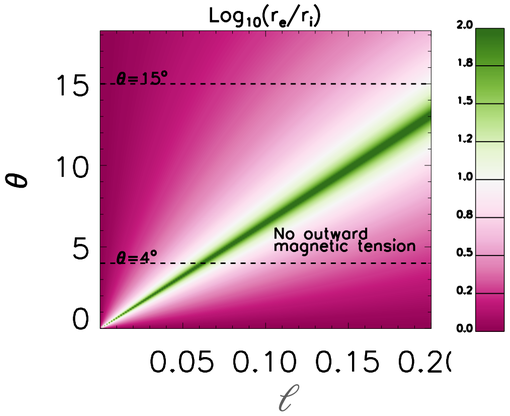
Why unidirectional nanojets? Curvature & braiding?

Pagano, Antolin & Petralia (2021)





re/ri = inward/outward magnetic tension



ℓ~retracting length of reconnected field lines from reconnection site

- Inward / Outward ~ 100

➡ The curvature (& braiding) of the loop is important!

Inward directed magnetic tension >> outward directed magnetic tension

Conclusions

Nanojet properties

- Small (lengths~1500 km), dynamic (>100 km/s), short-lived (~<20 s), multi-thermal, nanoflare energies
- Unidirectional nature (no clear bidirectional jet)
- Global response suggestive of MHD avalanche
- Accompanied by transverse displacement of strands
- Reconnection driver:
  - Linked to prominence eruptions & flares
  - Braiding (incl. roles of Alfvén waves)
  - Dynamic instabilities (KHI, RTI)

3D MHD numerical modelling

- Nanojets: **small-angle magnetic reconnection: transverse advection of field lines accelerated by magnetic tension**

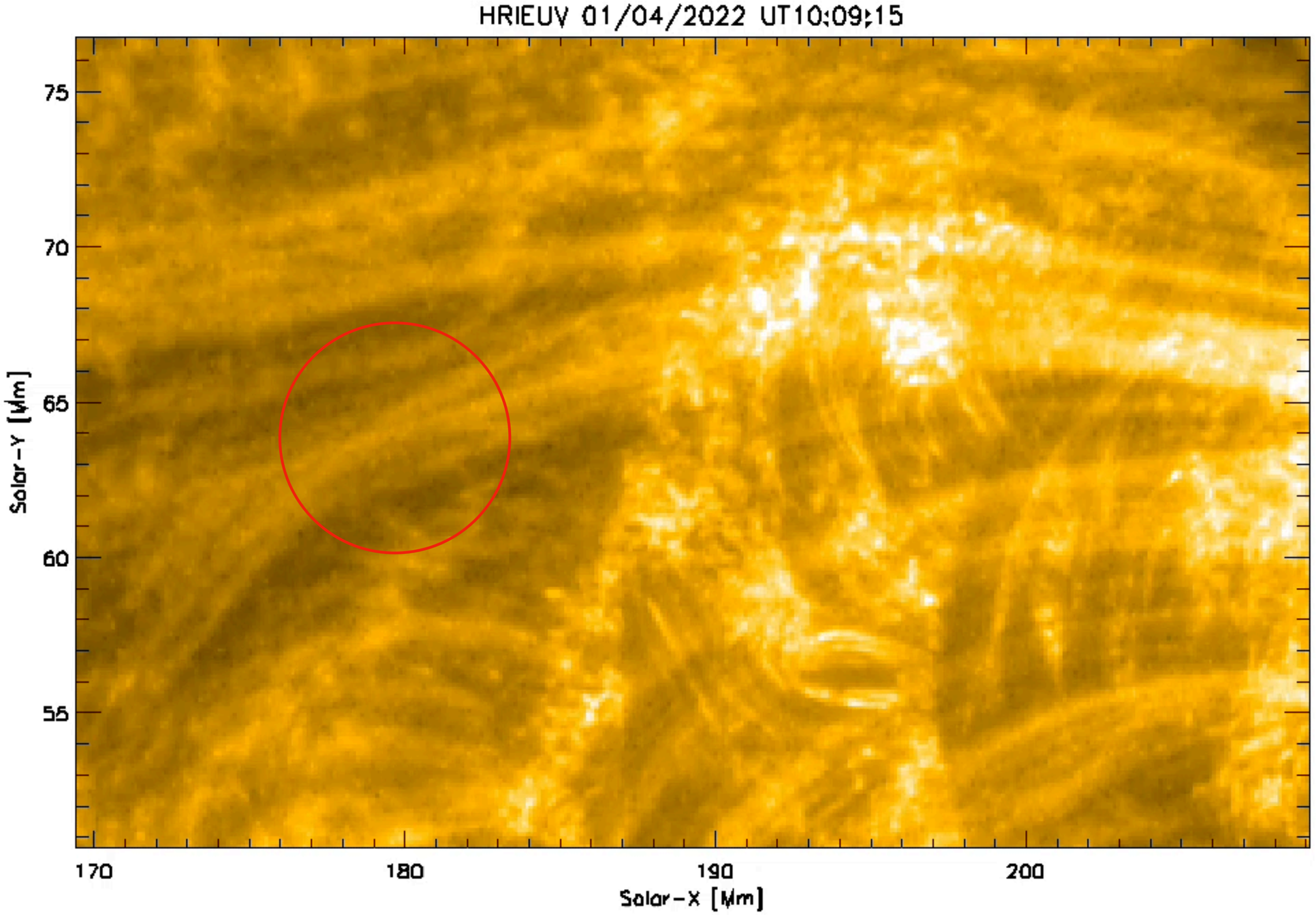
Effects

- Heating to coronal temperatures
- Correlation between energy release and nanojet numbers?
- Transverse MHD oscillations can be a signature of braiding-induced reconnection -> see talk by Ramada Sukarmadji

Still unknown:

- How much do nanojets contribute to coronal heating?
- How common are nanojets?

  ➡ Solar Orbiter/EUI, DKIST, EUVST, MUSE
- What is the dominant driver for small-angle reconnection?
- What is the role of cool plasma?
- What is the role of waves in reconnection?
- Why unidirectional?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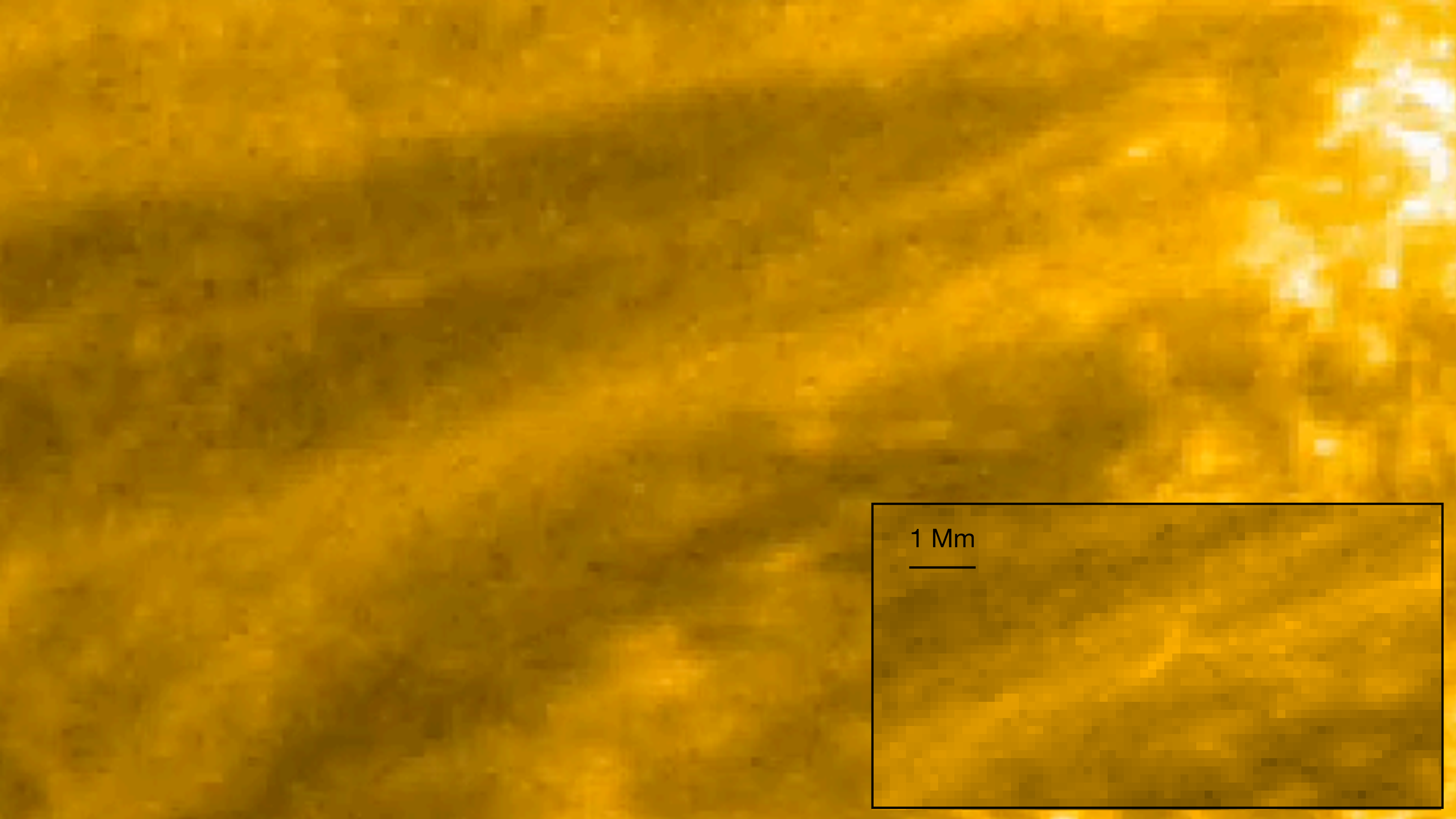
1 Mm