# Observations and MHD Simulations of 3D Magnetic Reconnection


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# Outline

- Background
- Observations of **3D magnetic reconnection** in the corona
- **Turbulent reconnection**: dancing downflows and MHD simulations
- **Micro-wave QPPs** at a flare CS: quasi-periodic acceleration
- Summary

# The first guy…

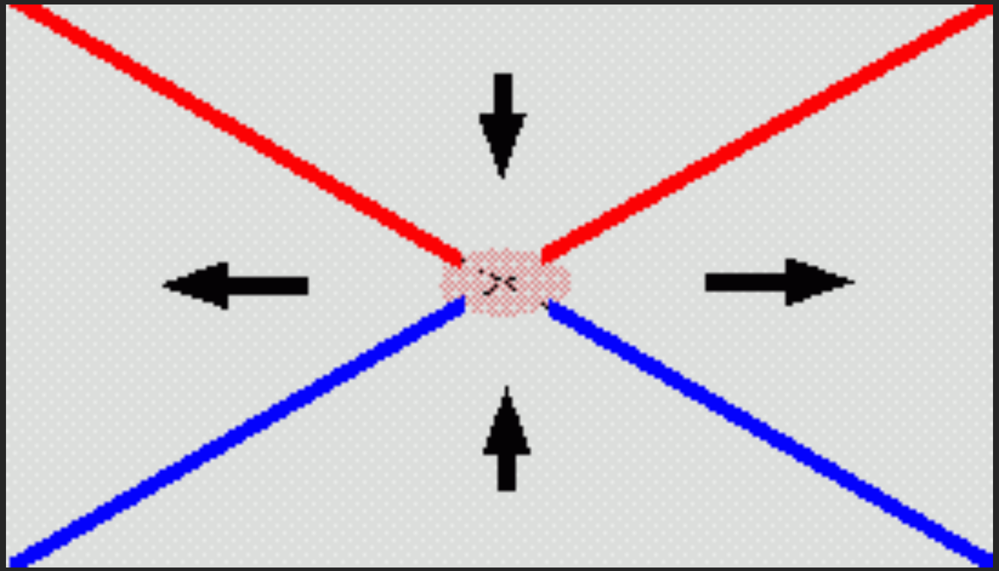
### 6.1.1 Brief History

Dungey (1953) was the first to suggest that *"lines of force can be broken and rejoined"*. Sweet (1958a) then presented a model for the flattening of the magnetic field to form a current sheet when two bipolar regions come together at an X-type neutral point (see Figure 6.6). The magnetic field squeezes out the plasma between them in a process of steady-state reconnection. Parker (1957) developed scaling laws for the model and coined the phrase *"reconnection of field lines"*.

**….From Eric Priest's textbook <MHD of The Sun>, chapter 6, 2014**

# Importance…

## Magnetic Reconnection



- A fundamental physical process in plasmas；

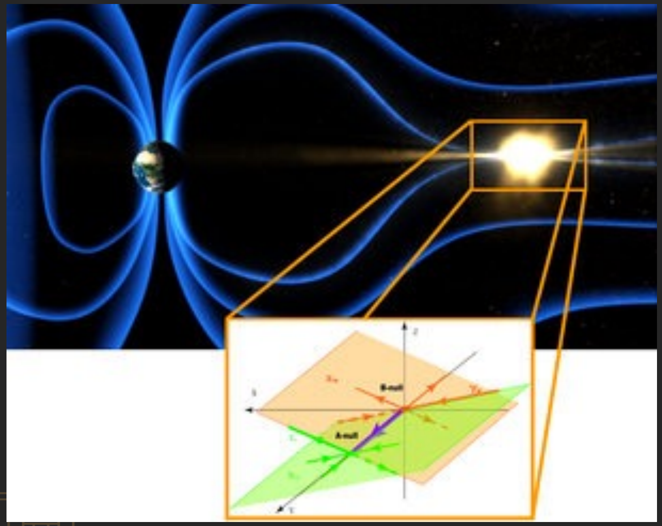
- **Changing magnetic field connectivity, accelerating particles, plasma heating** [Priest 2014 textbook];

- Used for interpreting explosions of different scales.

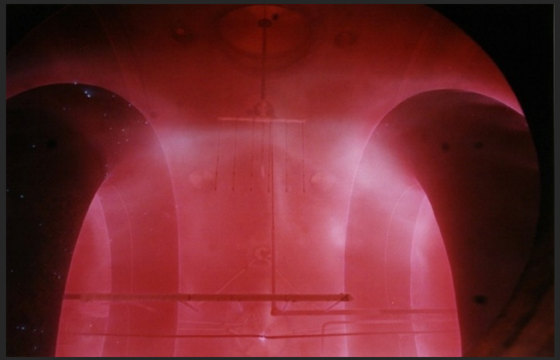
**Open Questions: how does reconnection take place in three dimensions (3D)?** [Ji et al. 2022, **Roadmap** in Nature review physics]

Fast radio bursts

Stellar eruptions

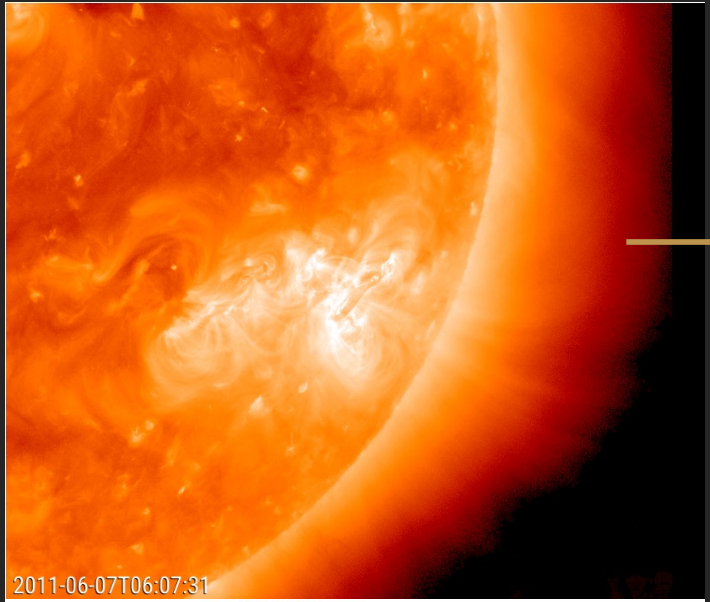


Magnetospheric storms

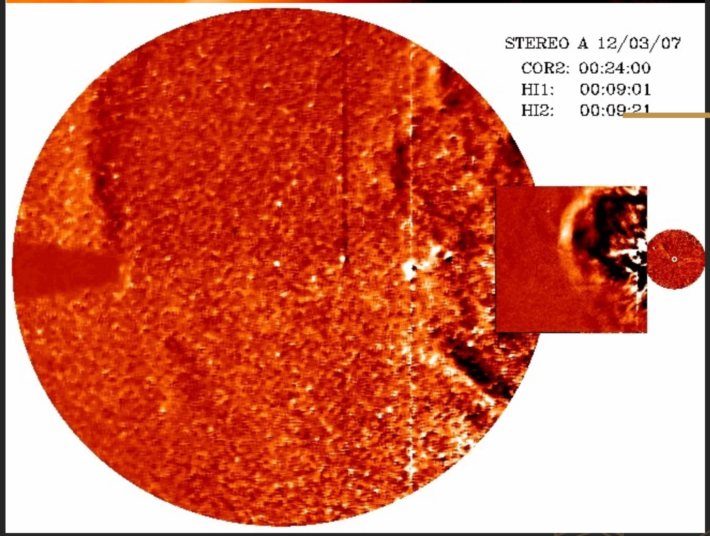


Nuclear fusion

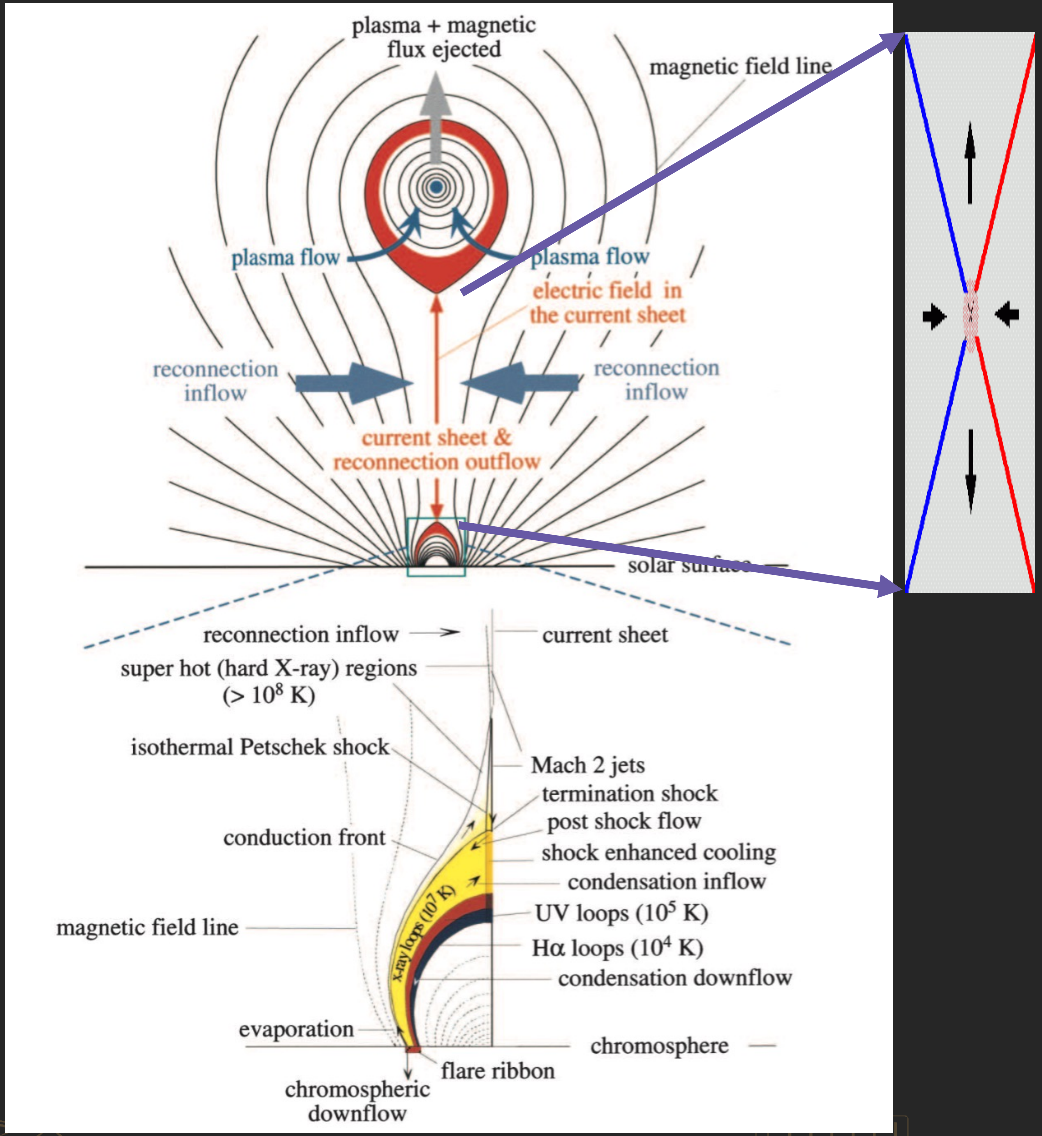
# A key to understand CMEs and flares




- EUV images showing the dynamic corona,
- Expulsion of a large quantity of plasma and magnetic flux from the corona into solar wind…




- White-light images by STEREO/ECCHI
- Interaction of interplanetary CME with the Earth, may give rise to space weather events…



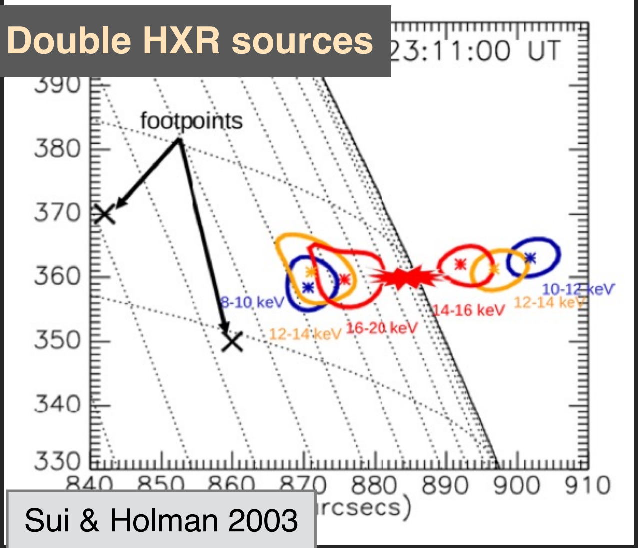

(CSHKP model; Lin & Forbes 2000)

# Evidence for solar magnetic reconnection

X-ray cusp

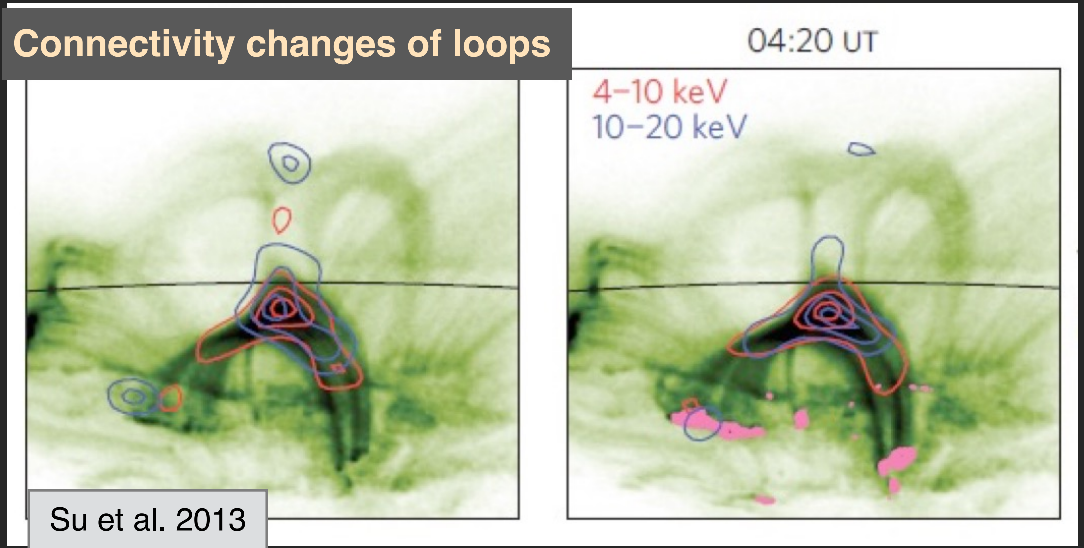
Masuda et al. 1994

Double HXR sources




Sui & Holman 2003

Connectivity changes of loops

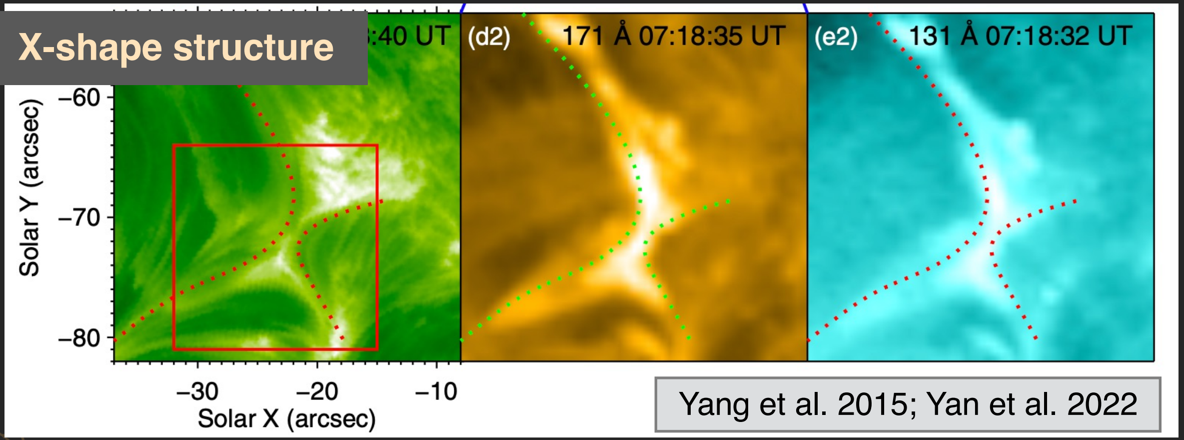



Su et al. 2013

Current sheet caused by a flux rope


Cheng et al. 2011; Seaton et al. 2017; Yan et al. 2018

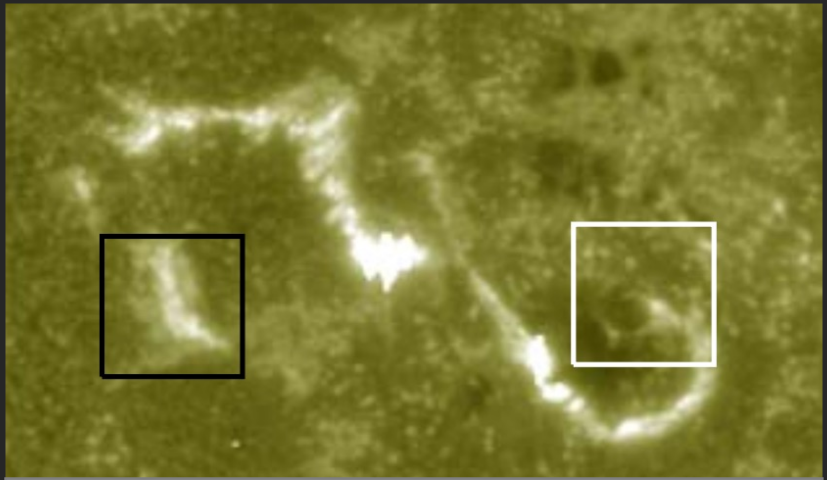
X-shape structure



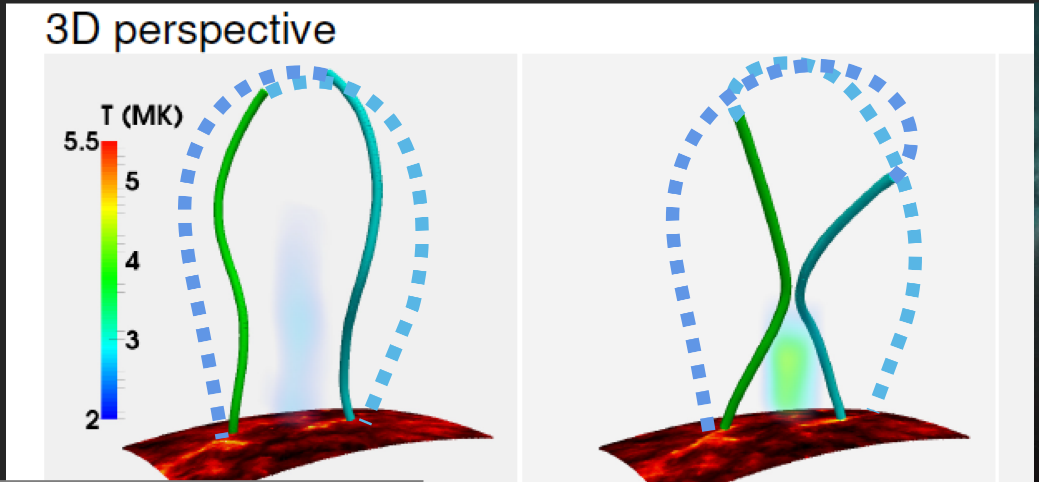

Yang et al. 2015; Yan et al. 2022

More advances: Xue et al. 2015 NC; Li et al. 2016 NP; Chen et al. 2020 NA……

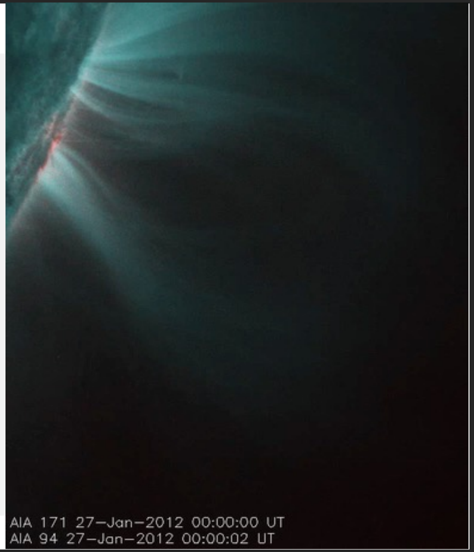
# Dilemma of 2D standard model: hooked imprints



Janvier et al. 2014; Cheng & Ding 2016; Li et al. 2021…



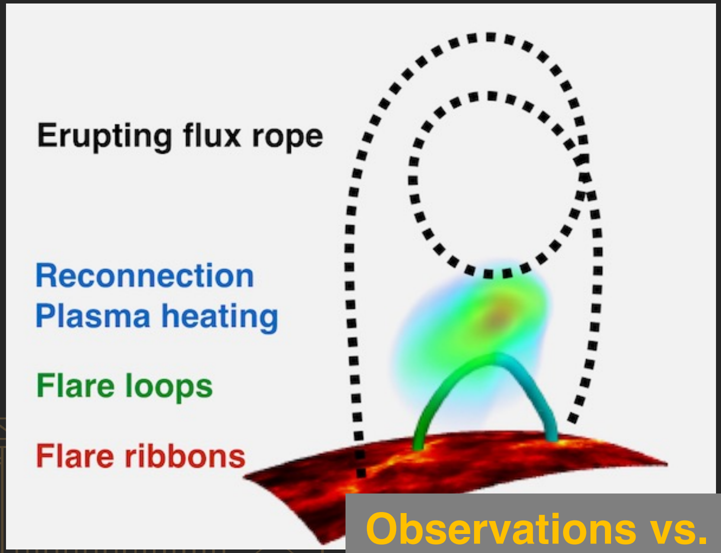

Sun, Cheng et al. 2015, NC

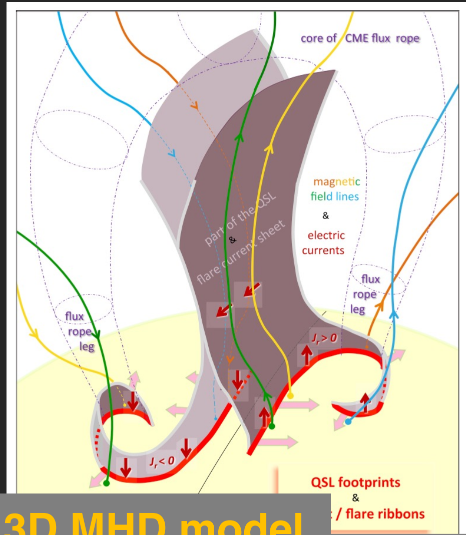



- The imprints of reconnection are not two straight bright ribbons, with **two hooks** at their ends,

- Reconnection taking place between two sheared loops **with a guide field,**

- Forming a twisted rope with **two ends corresponding to hooks and flare loops to straight ribbons.**



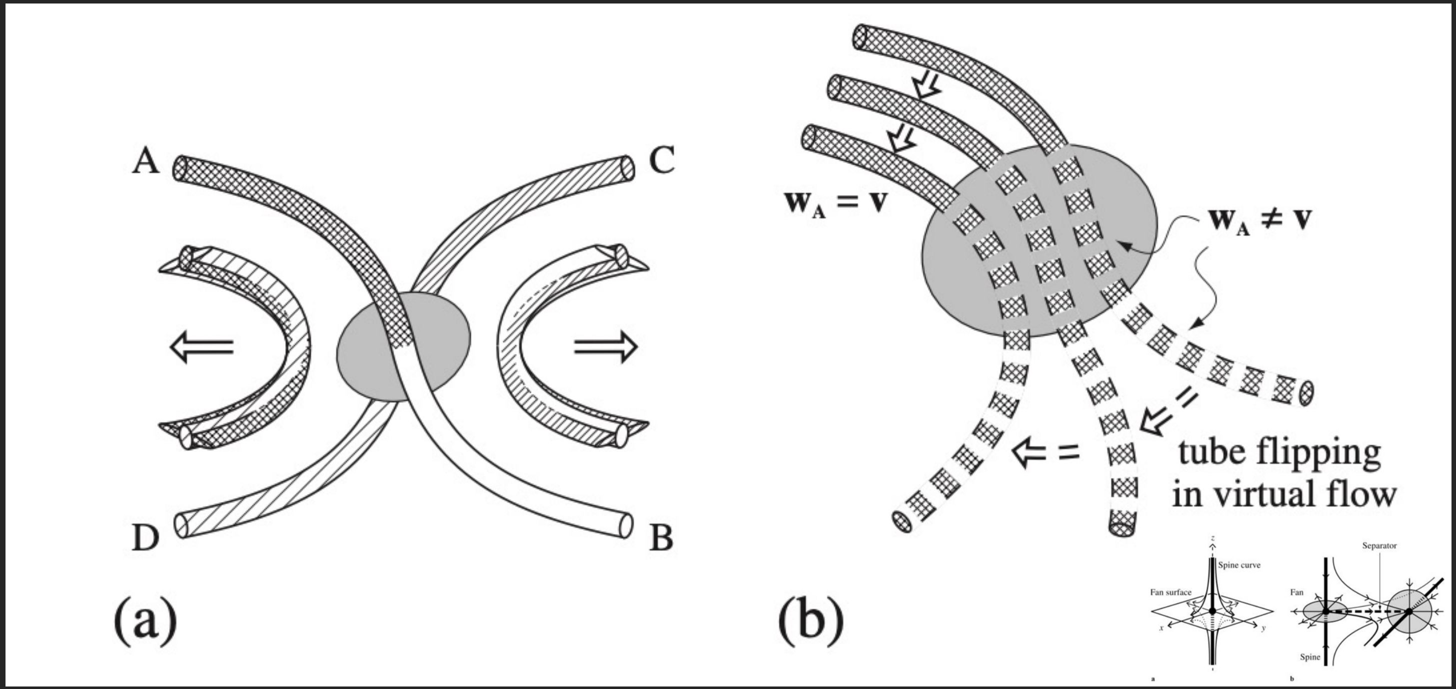




**Observations vs. 3D MHD model**

et al. 2014

# Dilemma of 2D standard model: dancing downflows

## 3D reconnection




*In 3D reconnection (a) two flux tubes break and partly rejoin and (b) the projection of a flux tube slips through the diffusion region and flips in a virtual flow.*

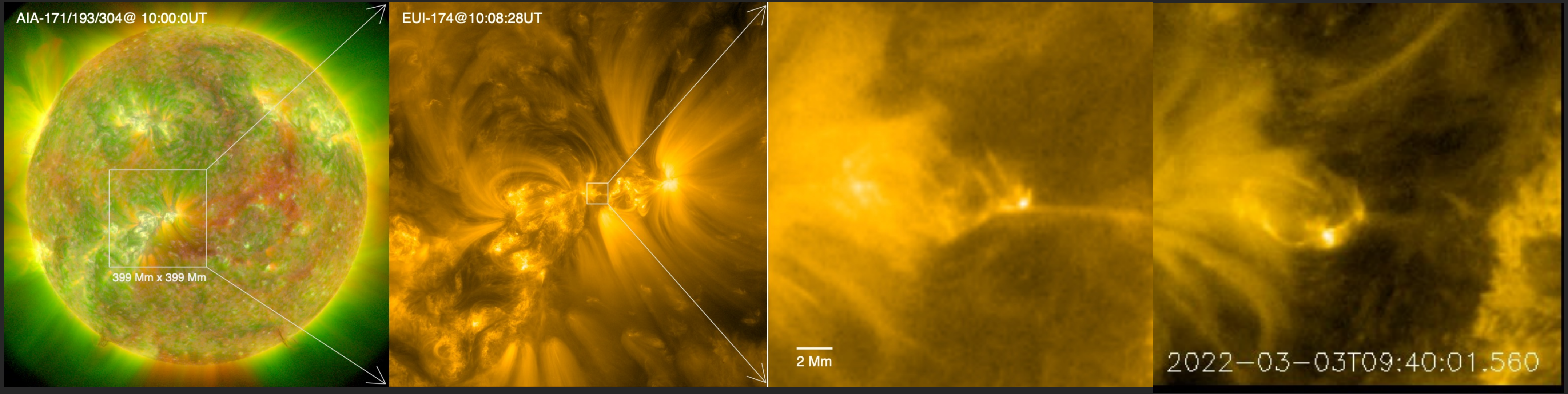
[From Priest et al. 2014, chapter 6, page 244]

## Dancing features


- Mysterious dark downflows and finger-like bright rays
- 50-500 km/s
- Downward moving flux tubes? RTI/RMI?

[McKenzie & Savage 2009; Guo et al. 2014; Reeves et al. 2017; Samanta et al. 2021; Shen et al. 2022……]

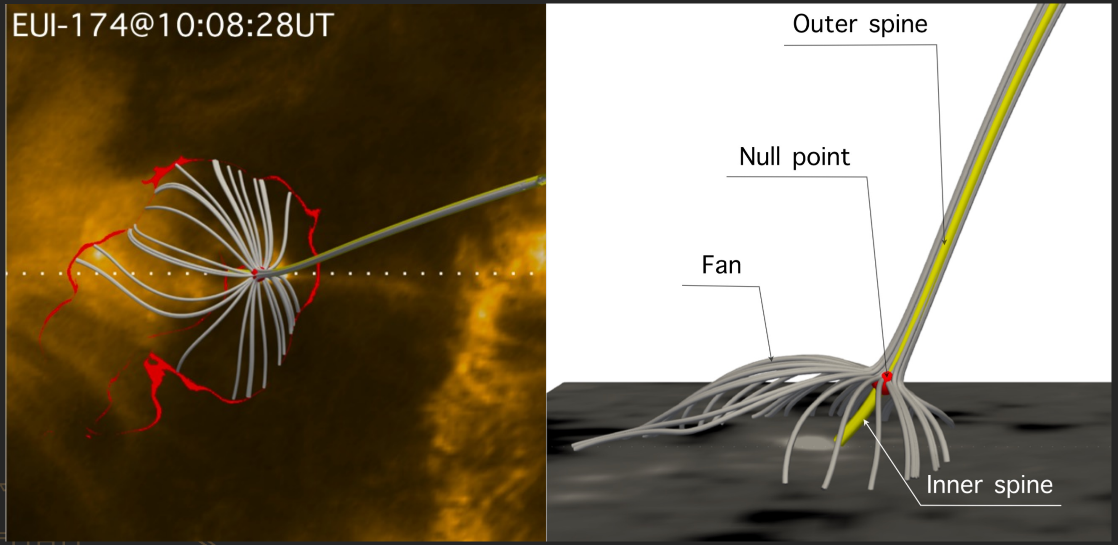
# Tiny 3D null-point reconnection in the corona




- **A point-like brightening with a spatial scale of ~390 km** has been visible at the EUI 174 A,
- Less visible and details at the AIA bands,
- Blobs continuously out of the bright point
- **The temperature close to 10 MK**

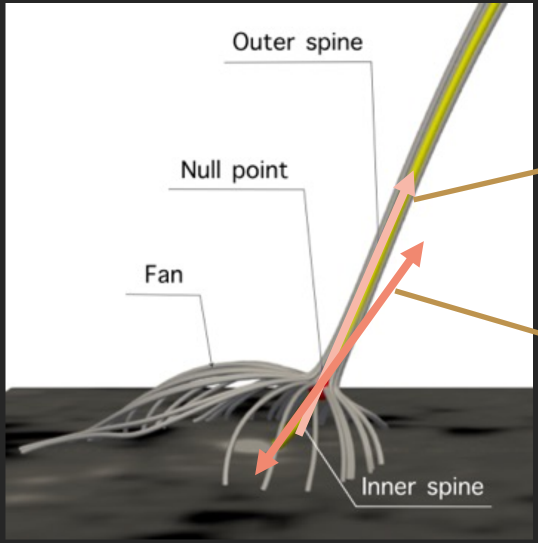
-The null-point is **co-spatial** with the bright point, the bottom of the fan surface corresponds to the basement.

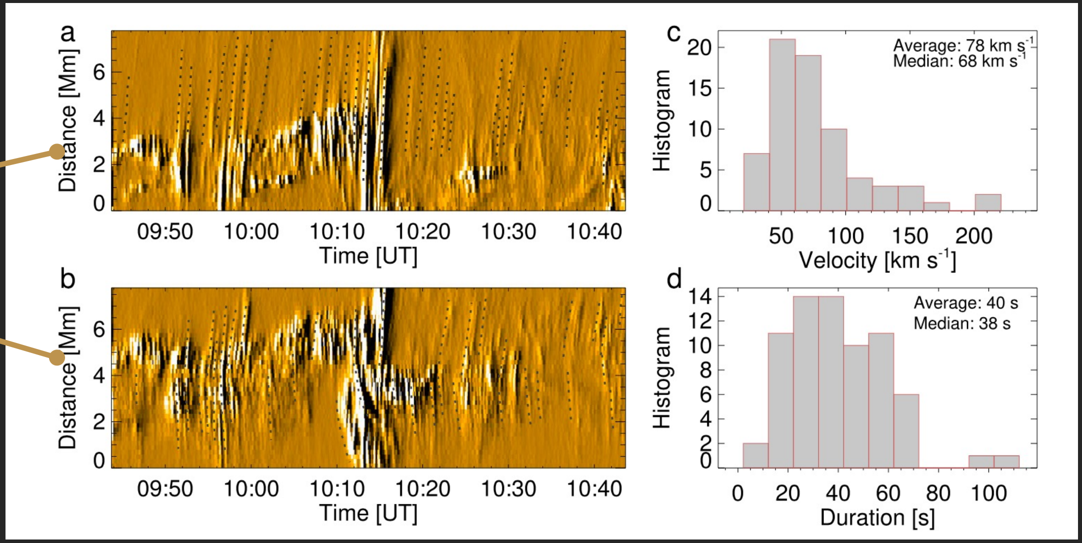
- Continuous dynamics show **persistent null-point reconnection.**




(Cheng, et al. 2023 NC)

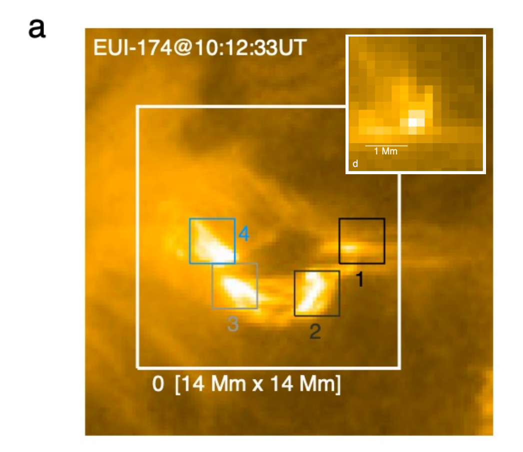
# Persistent outflows and heating showing persistent reconnection

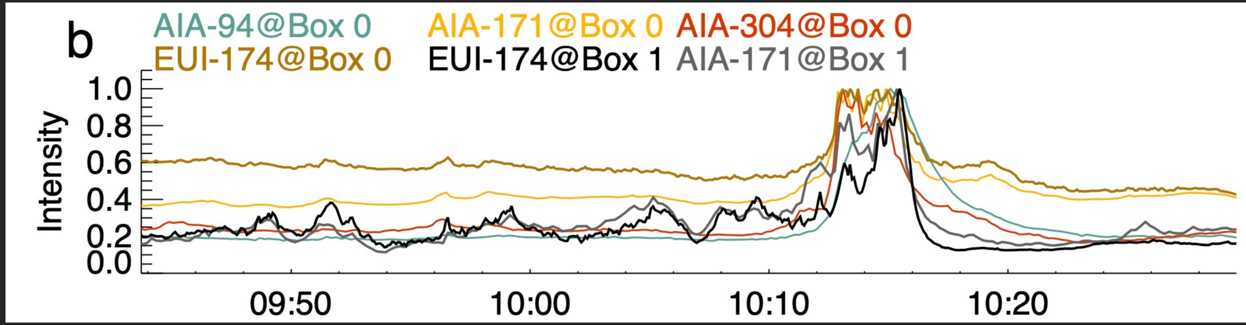



-**Multi-directional blobs,** moving outward along the spine and toward along the fan surface

-The velocity ranges from 30 km/s to 210 km/s with an average (median) value of 78 (68) km/s




- A number of spikes with different amplitudes in the time profile of the EUI 174 Å integrated intensity of the point-like brightening, only big ones detectable in the AIA 171 Å curve,
- Only a few large spikes are seen for all light curves over the whole box,

(Cheng, et al. 2023 NC)

**Also see Duan, Tian, et al. 2024**

**High-resolution (<1”) and high-cadence (<10 s) are necessary to disclose the persistent reconnection in the corona at a tiny scale**

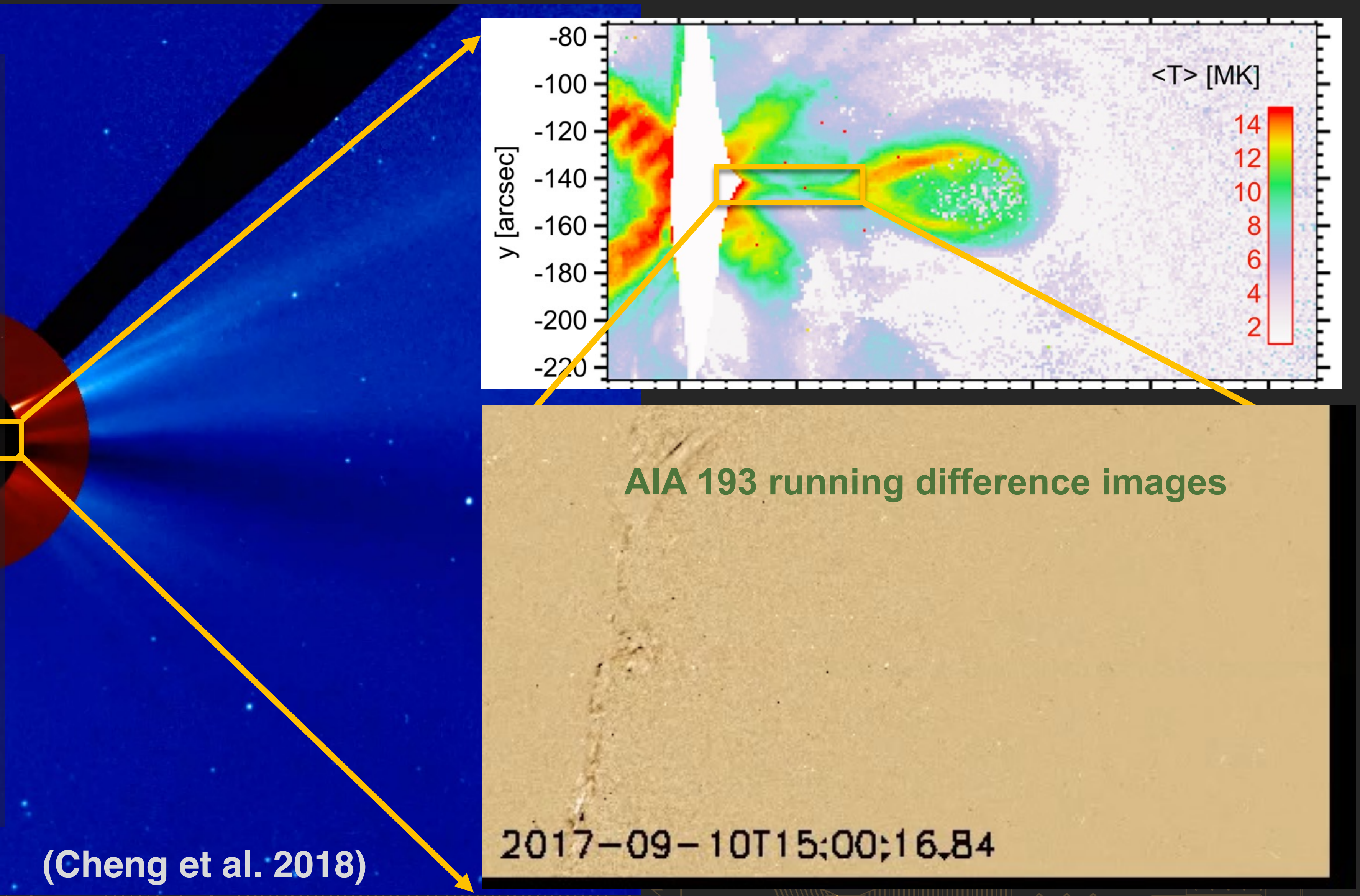
# A flux rope eruption with a long current sheet

- Very fast CME with a speed of 3000 km/s and the second largest flare in the past ten years,

- The linear structure connecting the CME bottom and flare top is clearly observed

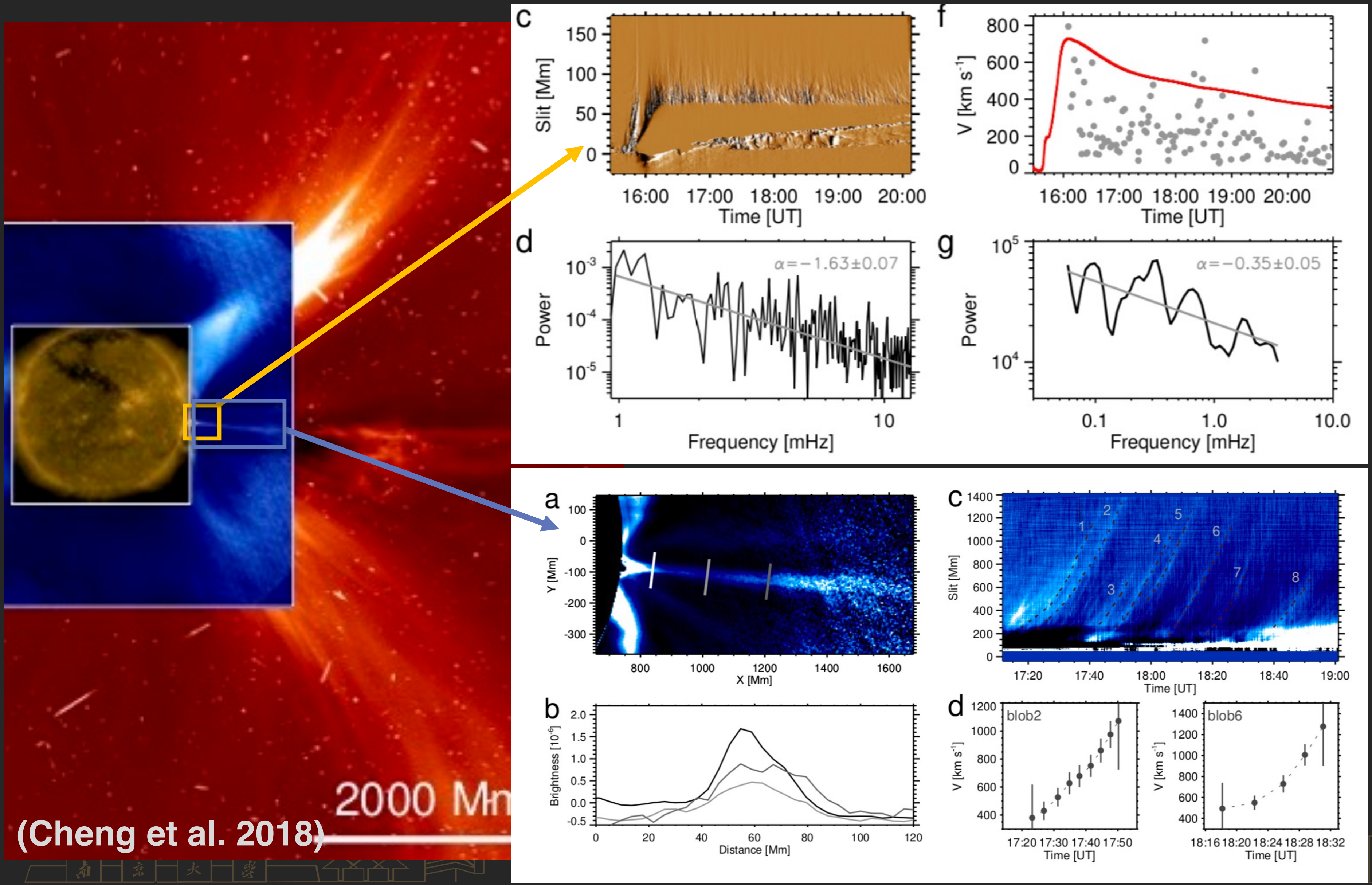
- Similar to 2D picture of solar eruption by Lin & Forbes (2000)

- **Outflow jets appears to be very dynamic.**




(Cheng et al. 2018)

# Intermittent outflows implying fragmented CS



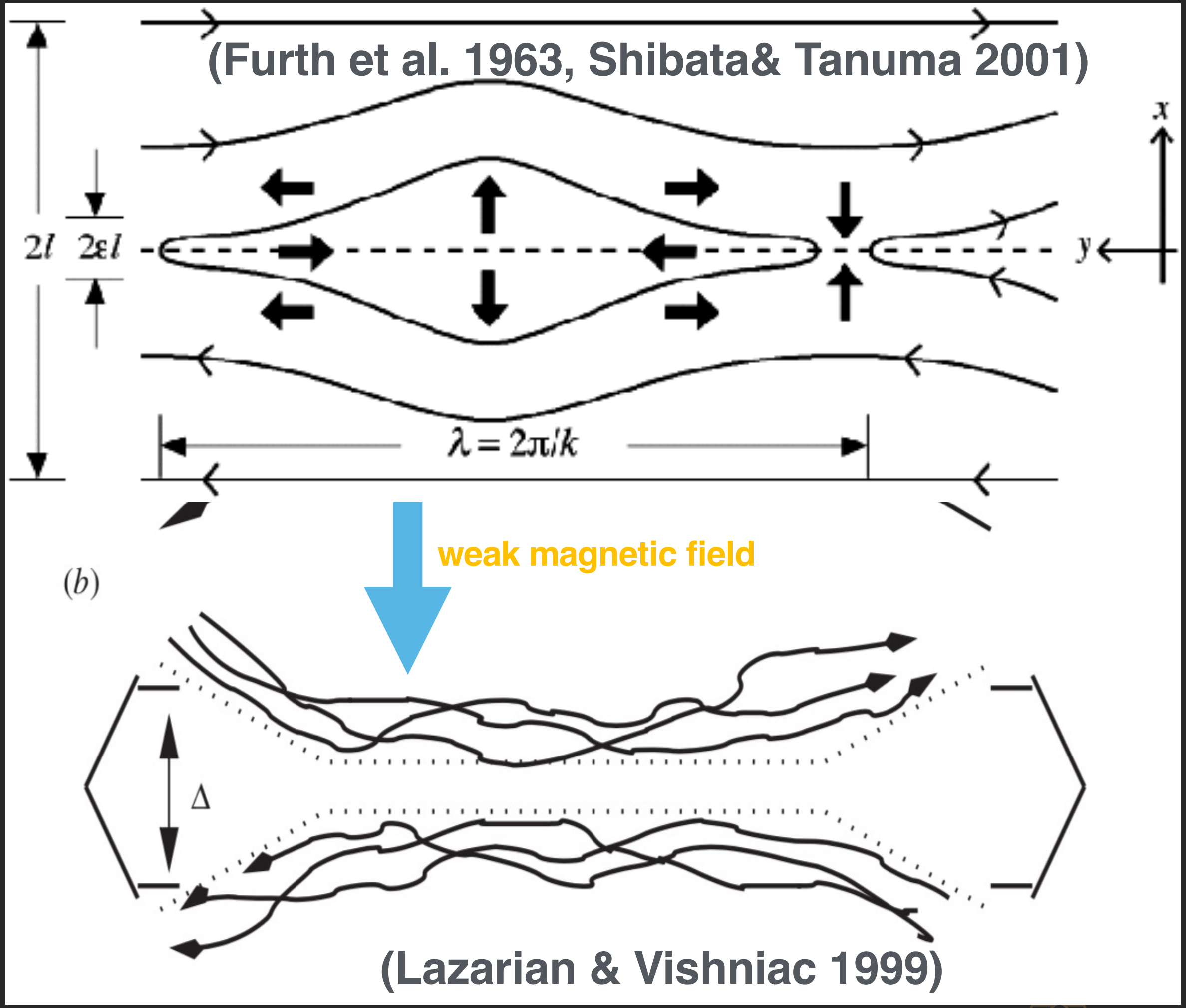

- Velocities of the outflow jets have a wide distribution even though their average decreases,

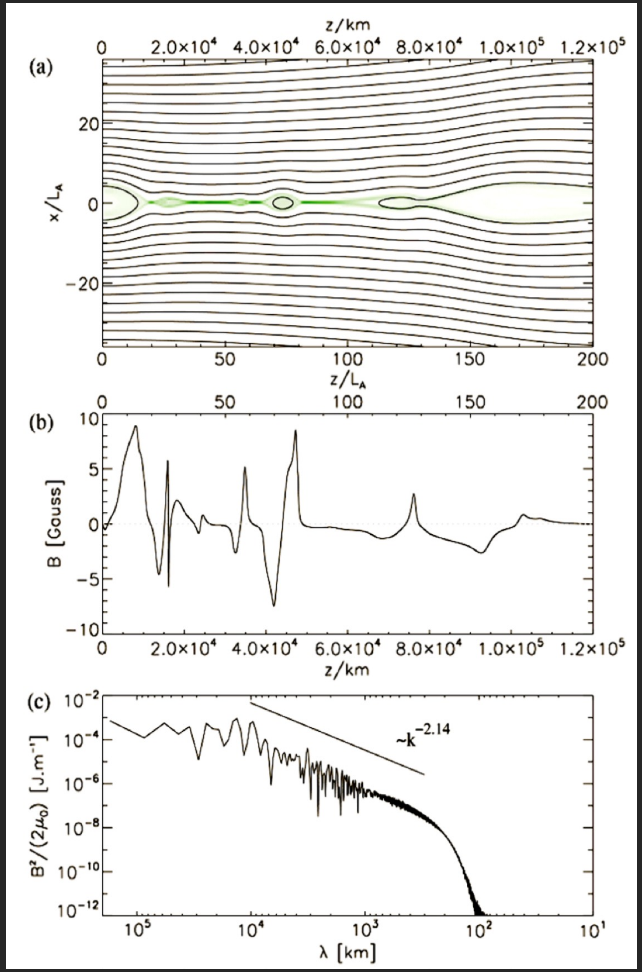
- Intensity at the outflow region fluctuates in time with a power law spectrum,

- Anti-sunward blobs are intermittently formed in the current sheet with different sizes and velocities

**Reconnection within CS is modulated by turbulence!**

# Turbulent magnetic reconnection

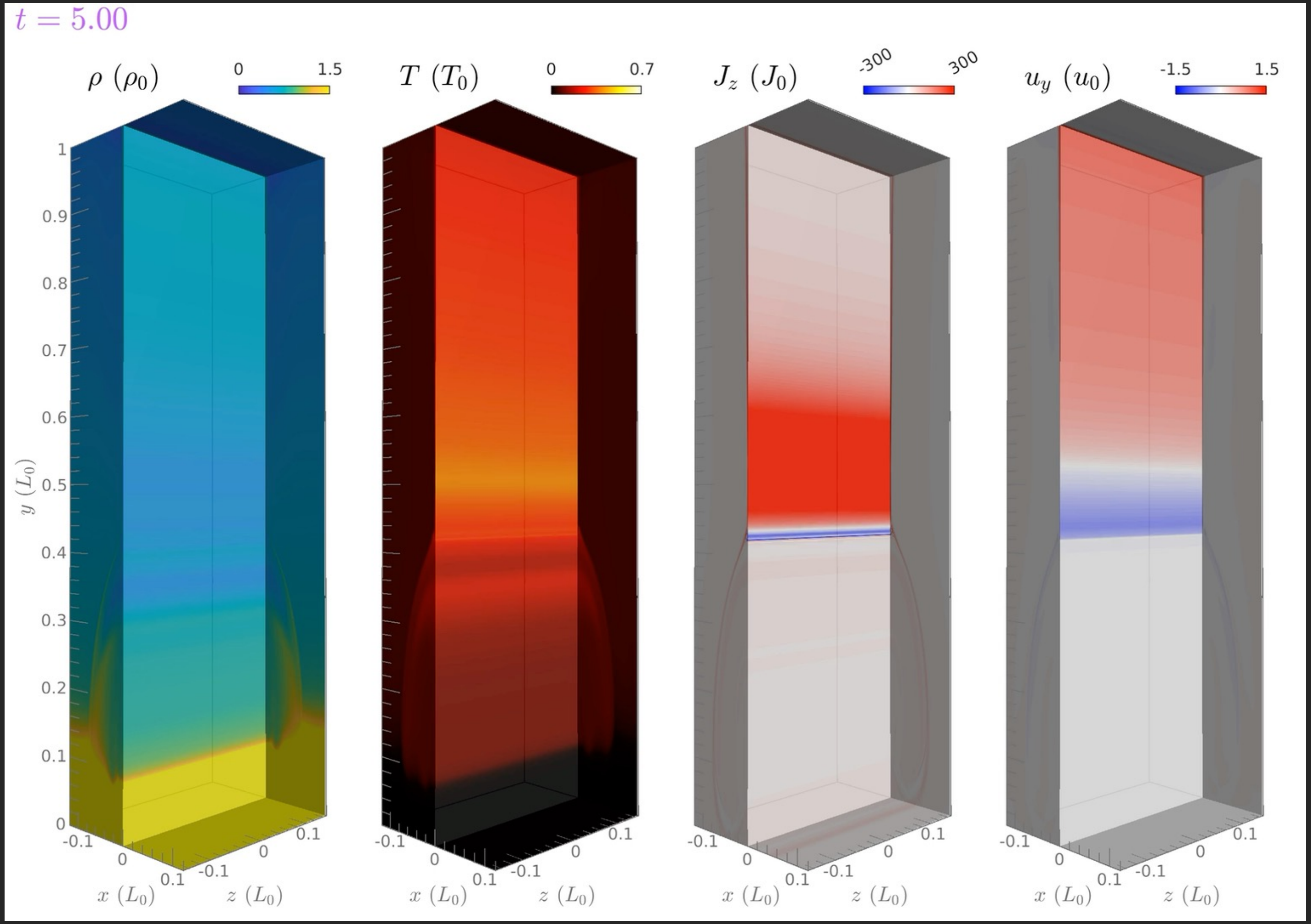



(Barta et al. 2011a, 2011b; Mei et al. 2012, Ni et al. 2015, Huang et al. 2017…)

- Due to tearing mode instability, the long CS is fragmented, forming many magnetic islands
- Giving rise to turbulence that enhances reconnection in turn

# MHD simulations of 3D reconnection in flare current sheet



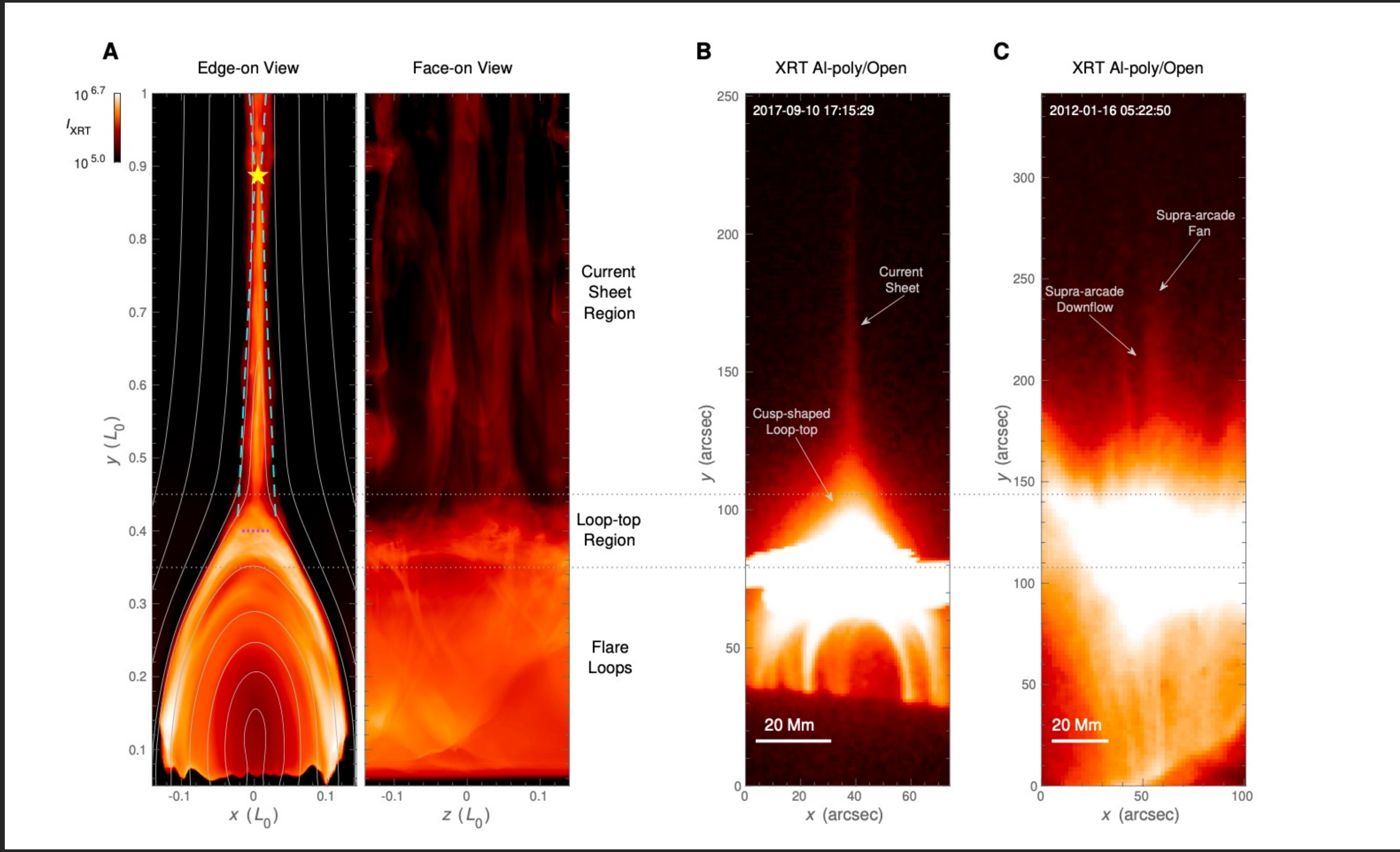

| Symbol | Units (SI) |
|---|---|
| $\rho_0$ | $1.67\times10^{-11}$ kg/m$^3$ |
| $L_0$ | 50 Mm |
| $B_0$ | 20 Gauss |
| $V_A, u_0$ | 436.26 km/s |
| $P_0$ | 3.18 Pa |
| $T_0$ | 11.52 MK |
| $t_0$ | 114.61 s |

Level 0: 480*960*144
Level 1:
$x \in [-0.3, 0.3]$
$y \in [0, 2]$
$z \in [-0.15, 0.15]$
Level 2
$x \in [-0.1, 0.1]$
$y \in [0, 2]$
$z \in [-0.15, 0.15]$
Minimum grid: 26 km
Total grids $10^9$
>4M core-hour

Density | Temperature | z-direction Current | y-direction velocity

(Wang, Cheng et al. 2023, ApJL)

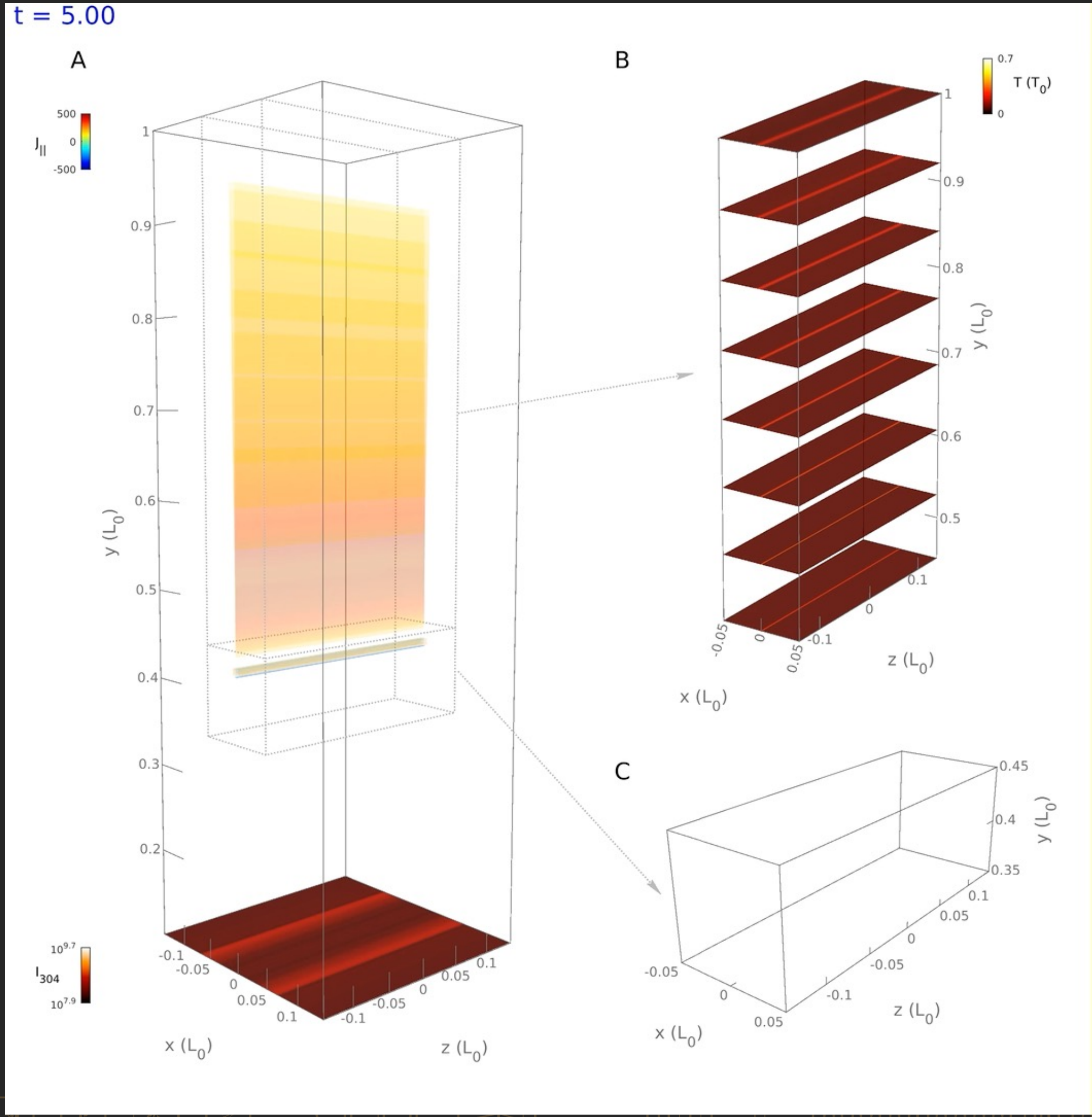
# Comparison with observations

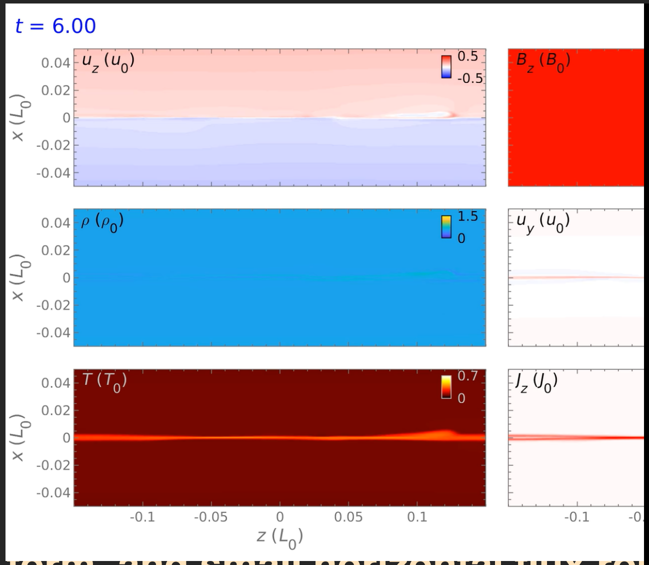



- The flare current sheet appears as a Petscheck-type 2D standard configuration seen from edge-on view
- Presenting finger-like bright-dark structures above the loop top seen from face-on view, similar to observations

(Wang, Cheng et al. 2023, ApJL)

# Coupling of tearing-mode and Kelvin-Helmholtz causing turbulence in current sheet

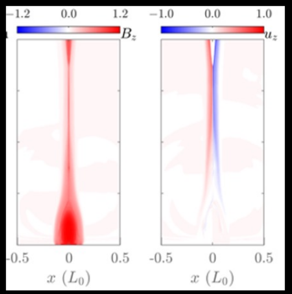



在 $\partial_z$~0近似下，z方向 $\boldsymbol{J}\times\boldsymbol{B}$~

$$\rho\frac{du_z}{dt}\sim \boxed{B_y}\boxed{\frac{\partial B_z}{\partial y}}+\boxed{B_x}\boxed{\frac{\partial B_z}{\partial x}}$$

关于电流片中心反对称，从而触发剪切流



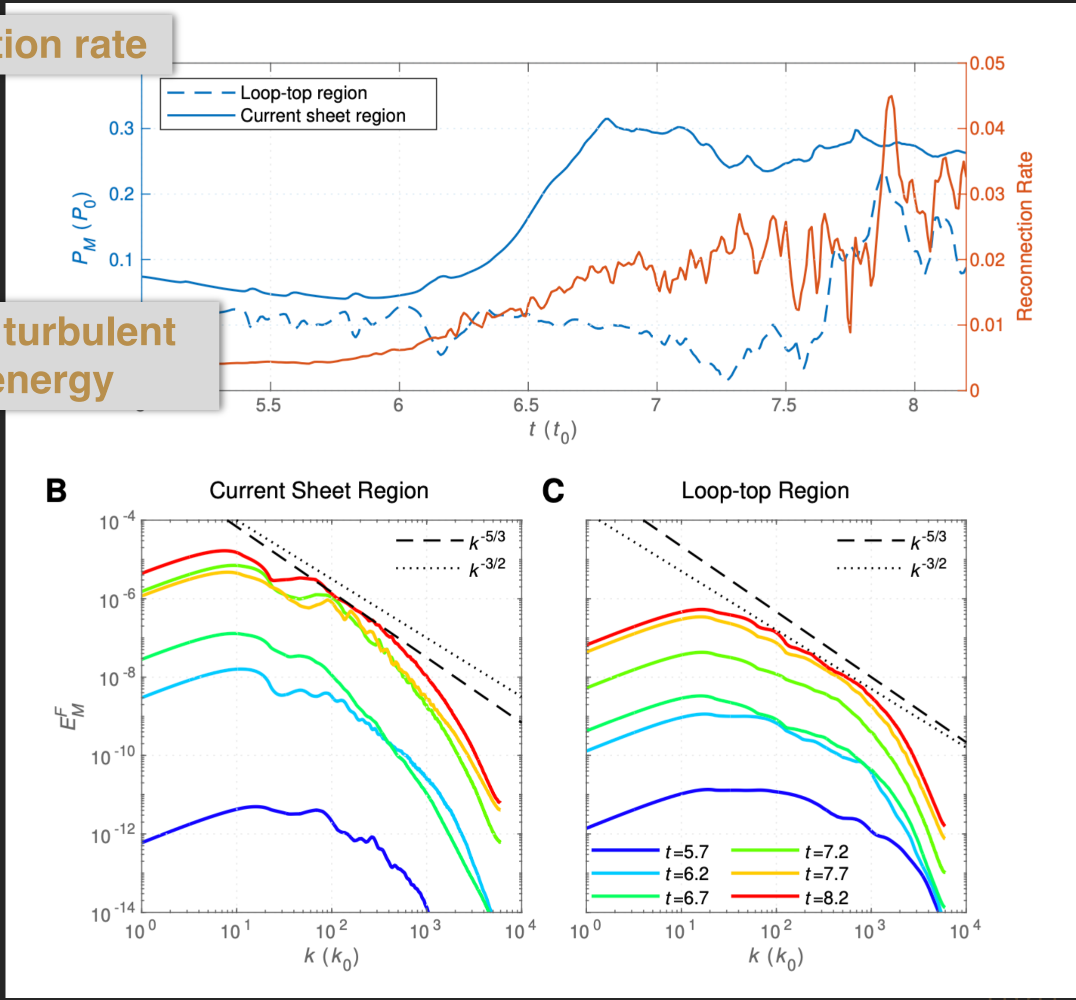

- form, and small horizontal flux ro... generated by the TMI.
- In the impulsive stage, the reconnection rate increases dramatically as kink instability starts and then dominates the break of the CS with the coupling of 3D KHI, giving rise to magnetic flux ropes of various scales.
- In the end, the evolution enters a fully turbulent stage, during which small-scale current structures keep emerging.

(Wang, Cheng et al. 2023, ApJL)

# Turbulent reconnection in flare current sheet

Reconnection rate

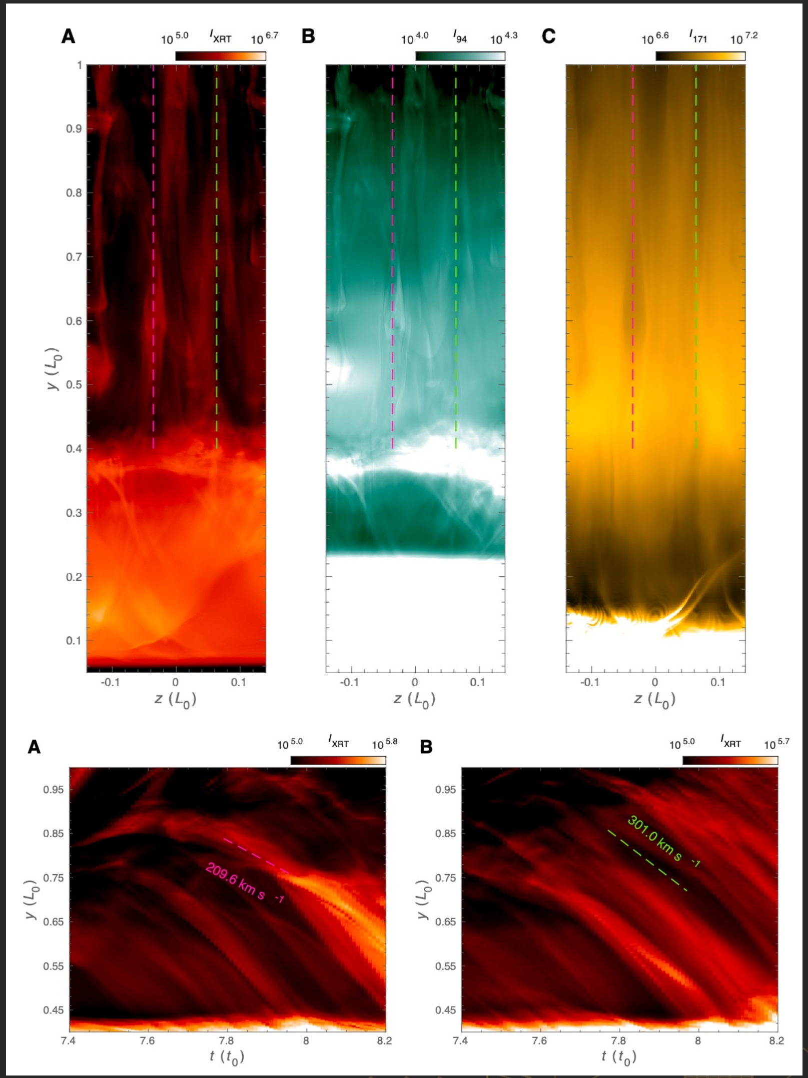
Spectra of turbulent magnetic energy



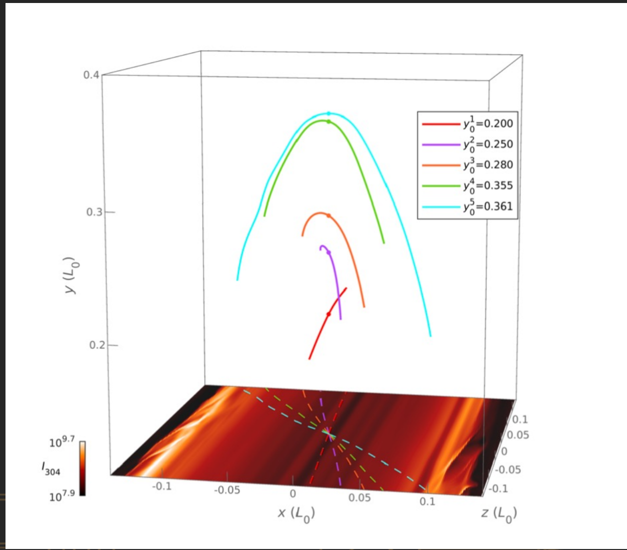

- The magnetic energy release rate at the CS dominates the reconnection rate, at the later stage, the second reconnection also takes place at the flare loop top, even comparable with that at the CS.
- After t~7ta, the spectral index for turbulent magnetic energy at current sheet close to -5/3, consistent with Kolmogorov spectral index, showing the CS is fully turbulent.
- it tends to -3/2 at the flare loop top region, close to the Boldyrev value, showing a strong anisotropic turbulence.

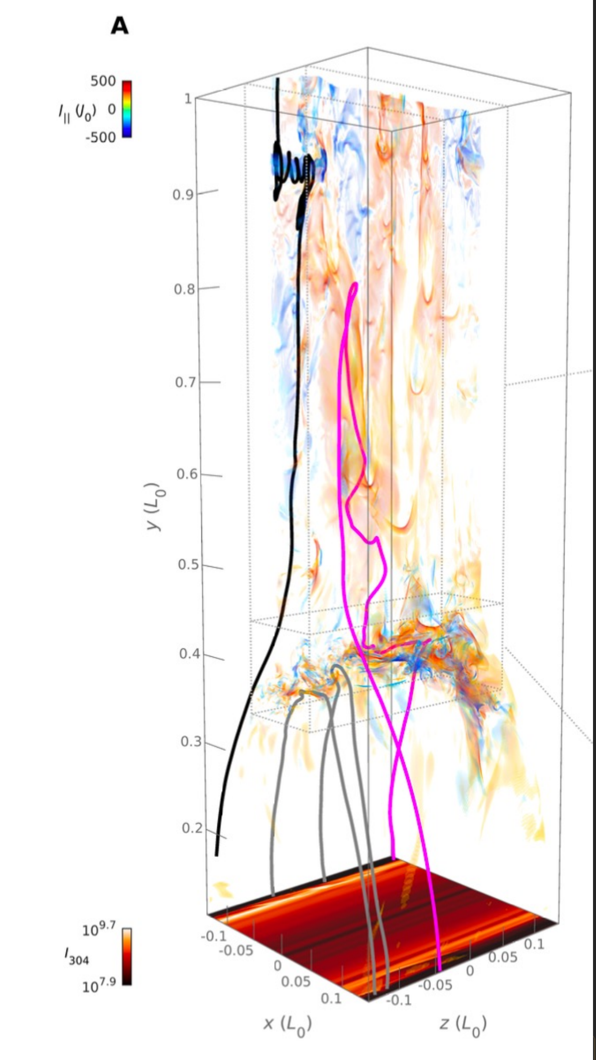
(Wang, Cheng et al. 2023, ApJL)

# SADs and strong-to-weak shear in flare loops



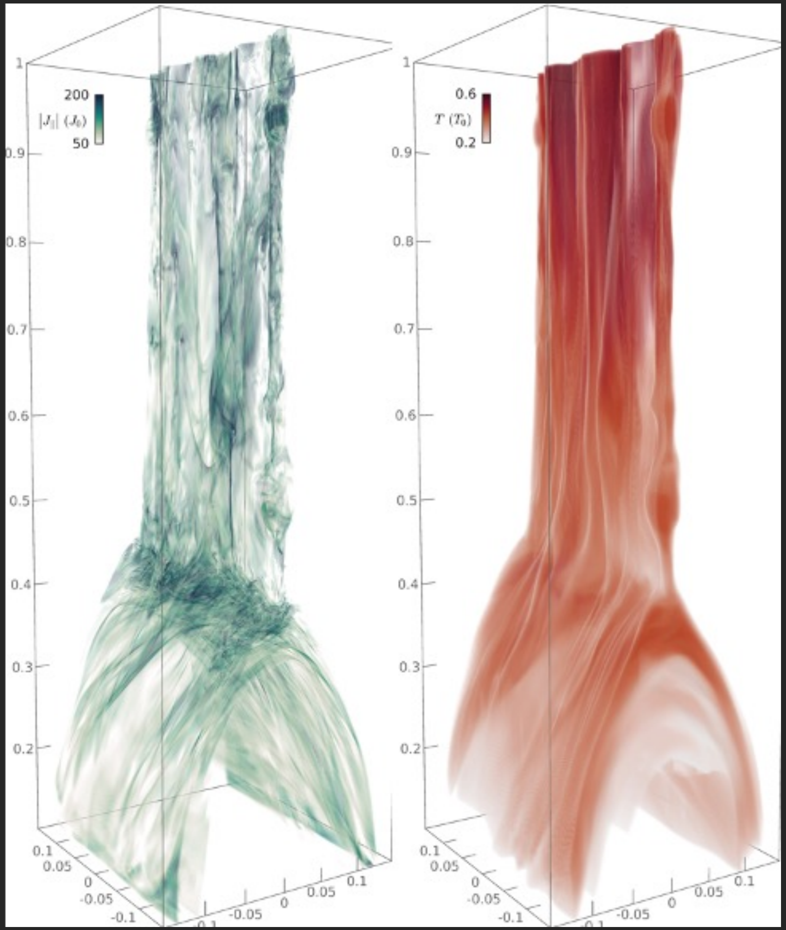

- SADs appear to be bright in XRT and AIA 94 A but dark in 171 A with initial speed being sub-Alfvenic but decreasing as approaching the loop top.
- Highly fluctuated magnetic fields in the CS have different footpoints with those at the loop top to flare ribbons.



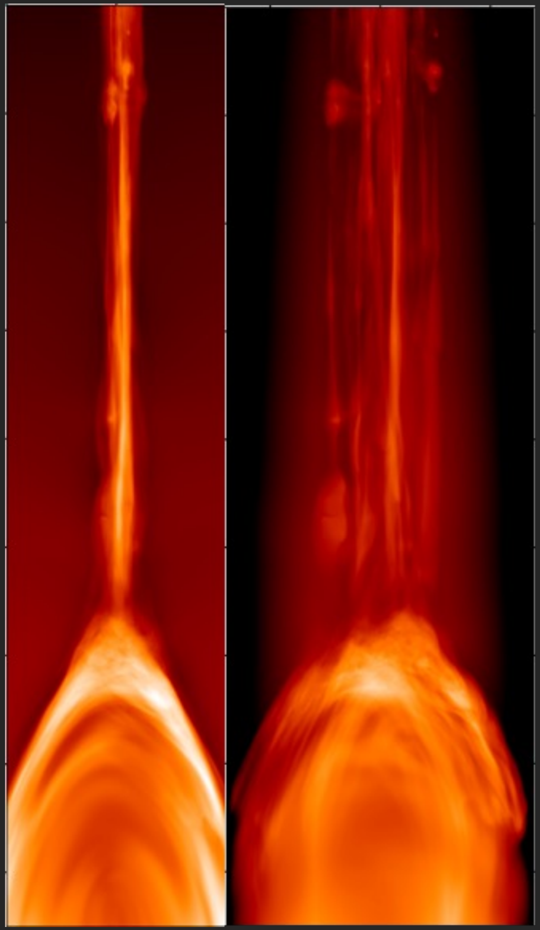



(Wang, Cheng et al. 2023, ApJL)

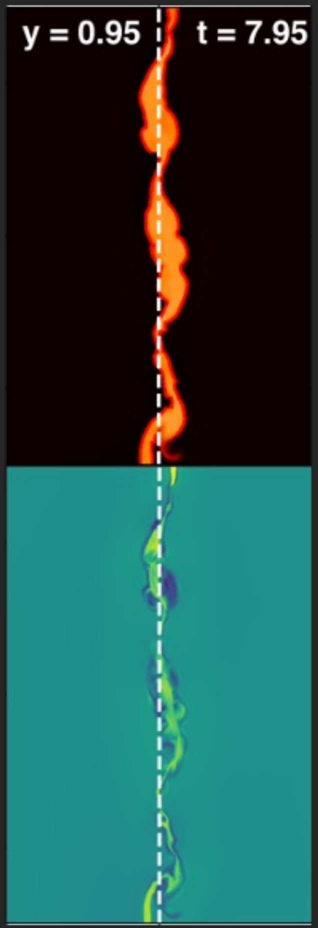
# Why is the current sheet so rare?



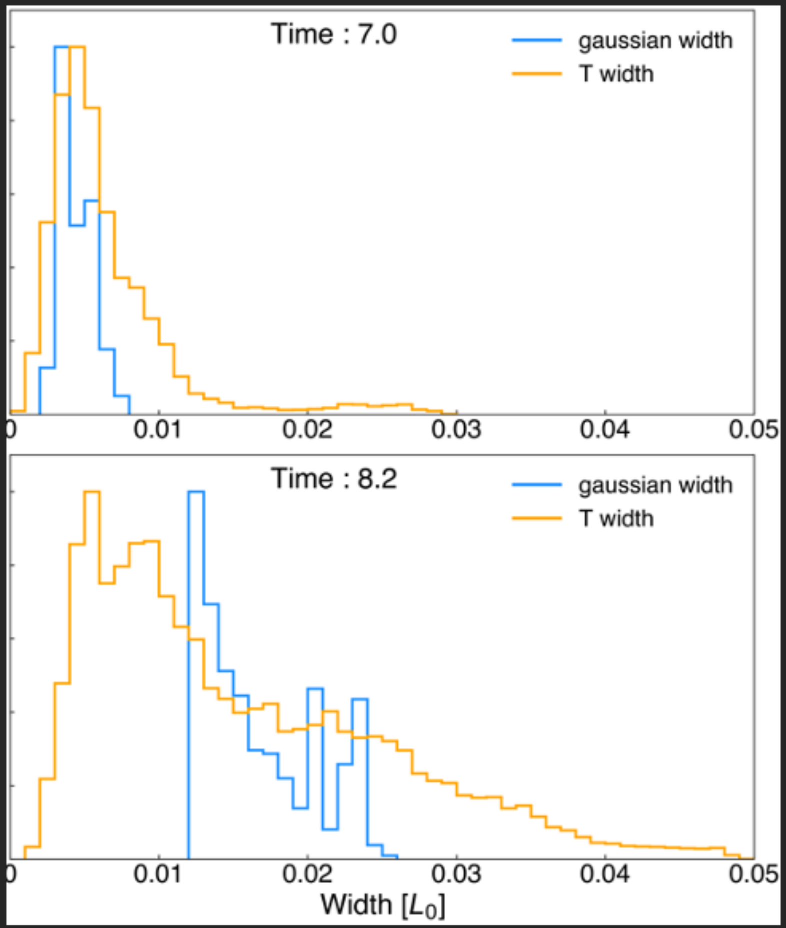

Density | Temperature



edge-on | from 20°




x-z plane




Observed vs. T

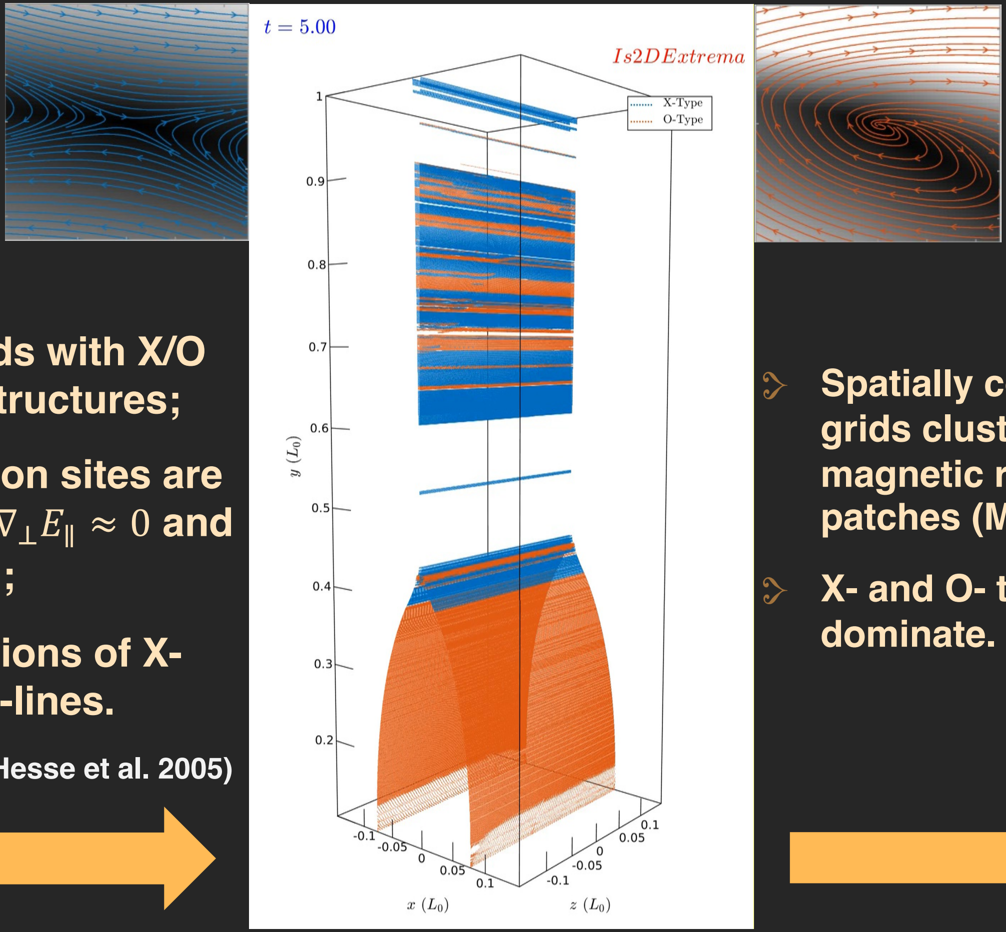
(Ren, Wang, Cheng et al. 2024, in preparation)

- Turbulence in the current sheet makes its observables to be interpreted complicatedly.

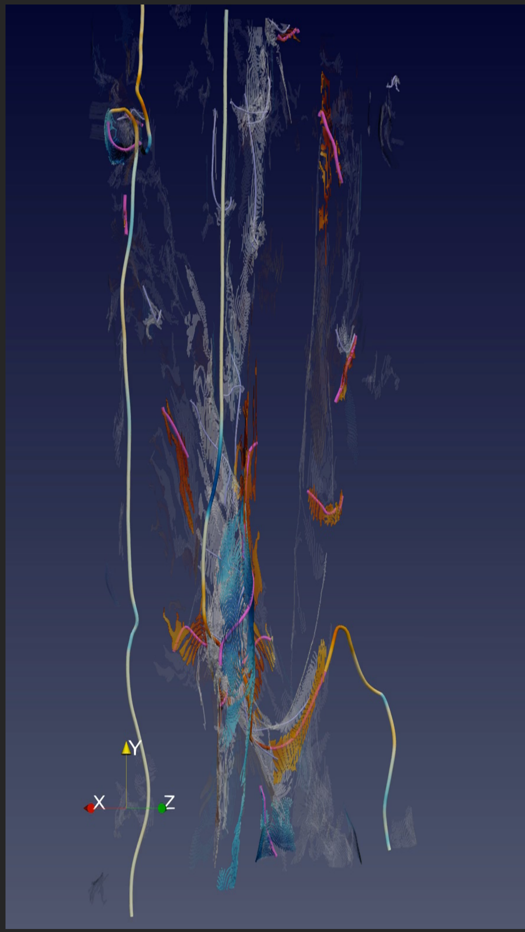
# Determining reconnection locations and topologies


- Identify grids with X/O magnetic structures;
- Reconnection sites are located by $\nabla_\perp E_\parallel \approx 0$ and $|E_\parallel| > E_{thres}$;
- Generalizations of X-lines and O-lines.

(see GMR theory: Hesse et al. 2005)



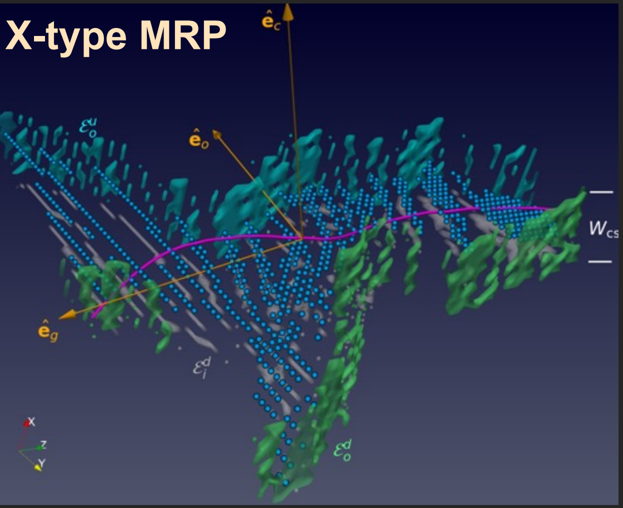

- Spatially connected grids cluster to form magnetic reconnection patches (MRPs);
- X- and O- type MRPs dominate.

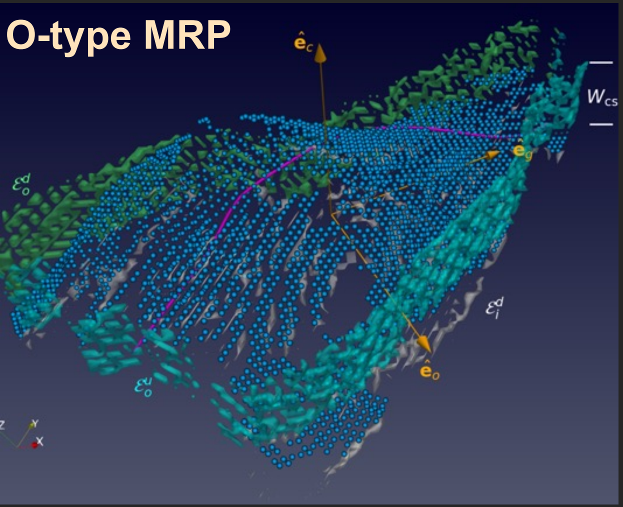



(Wang, Cheng et al. 2024, A&A)
**LoRD** Toolkit: open source

(Wang, Cheng et al. 2024 in preparation)

# Statistical Laws of Turbulent Reconnection

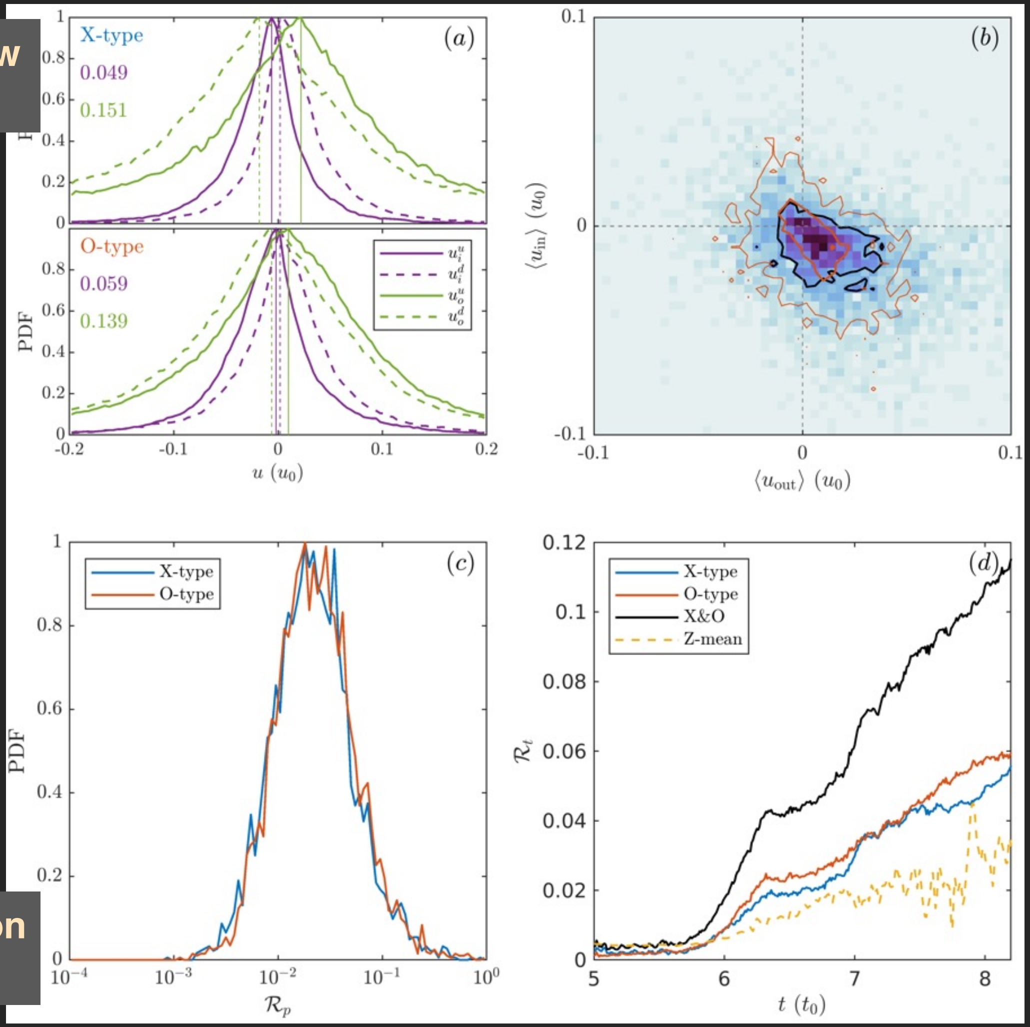


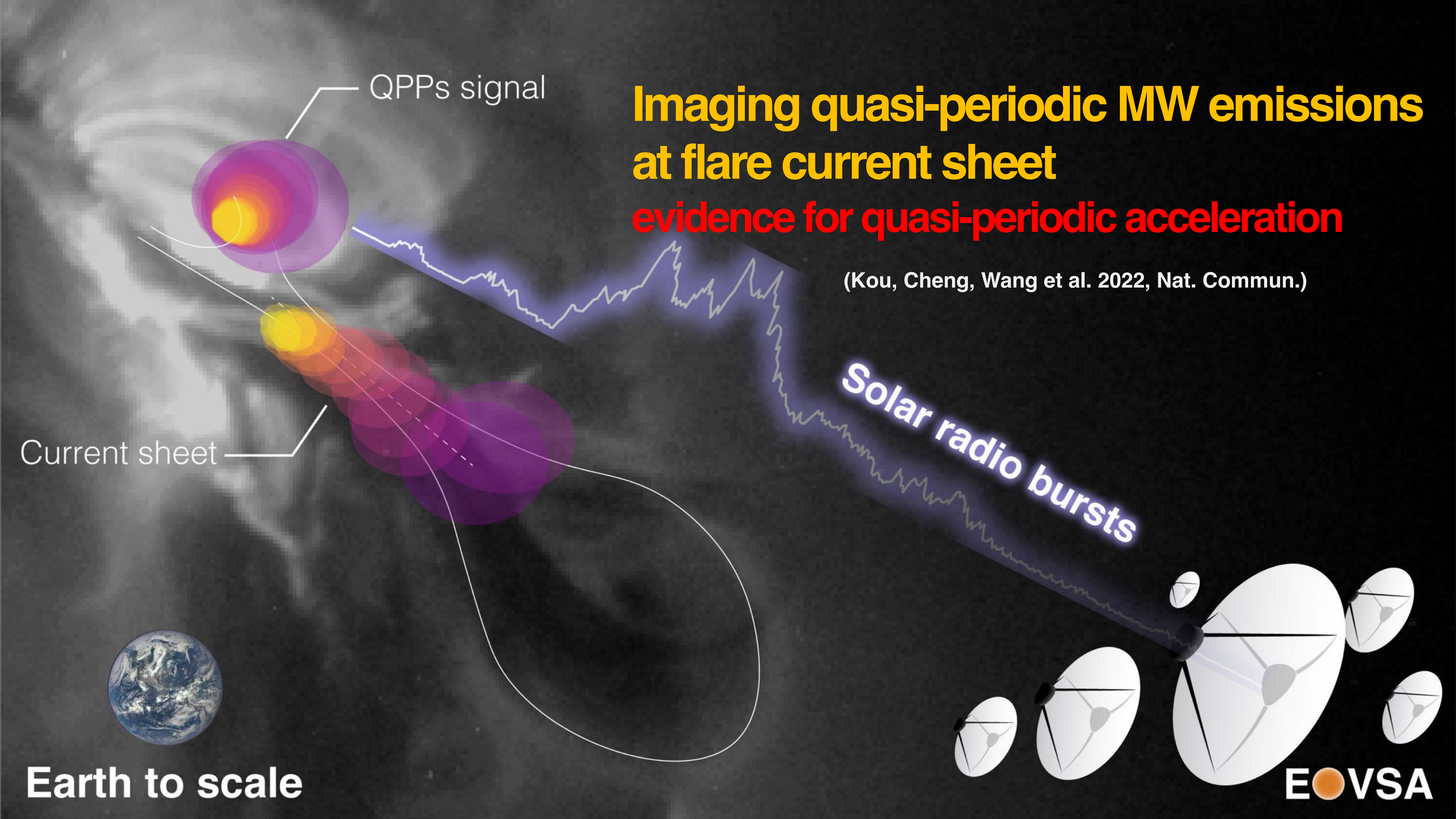

- Besides the classical X-type magnetic reconnection patches (MRPs), O-type MRPs also have significant contributions to the global reconnection rate.
- X- and O-type MRPs exhibit similar statistical laws in velocity configuration and reconnection rate.
- Our results for the first time presents the basic reconnection pattern and magnetic topology of 3D turbulent reconnection.

Inflow/outflow Velocity

Reconnection rate



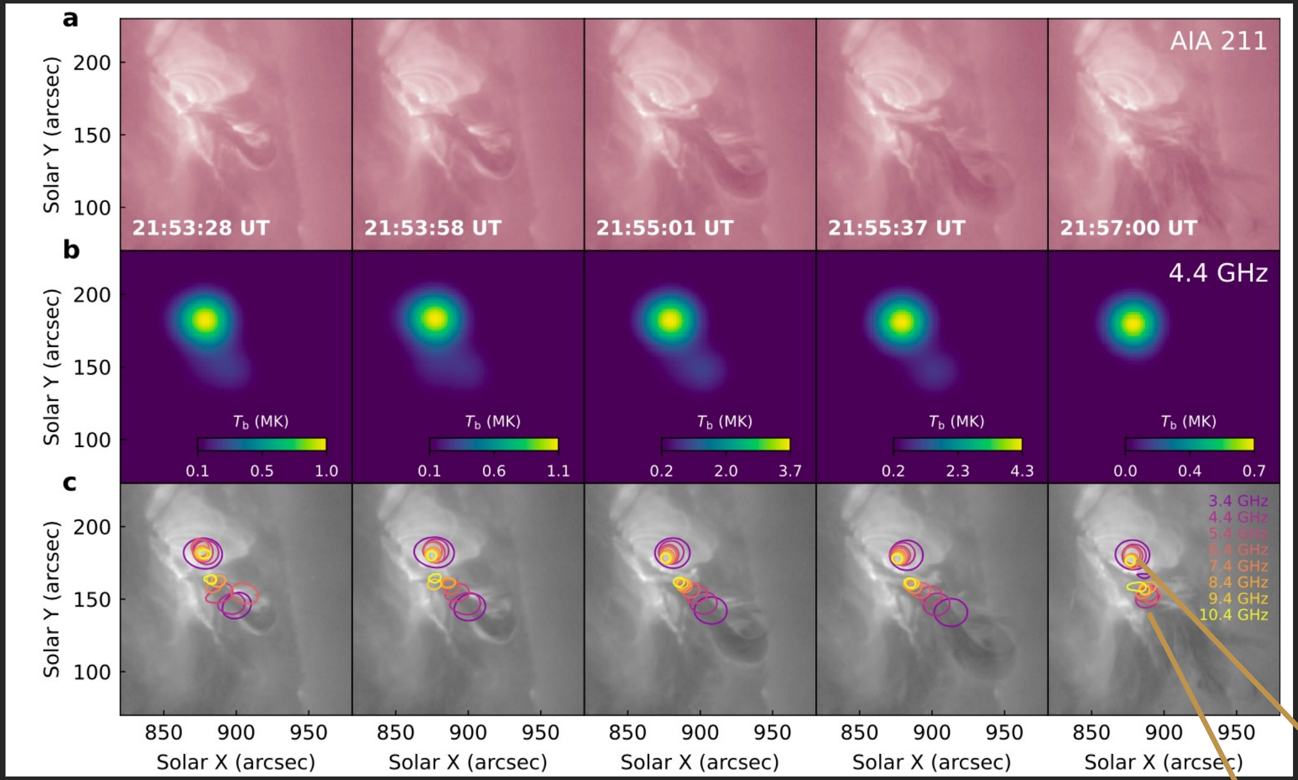

(Wang, Cheng et al. 2024 in preparation)

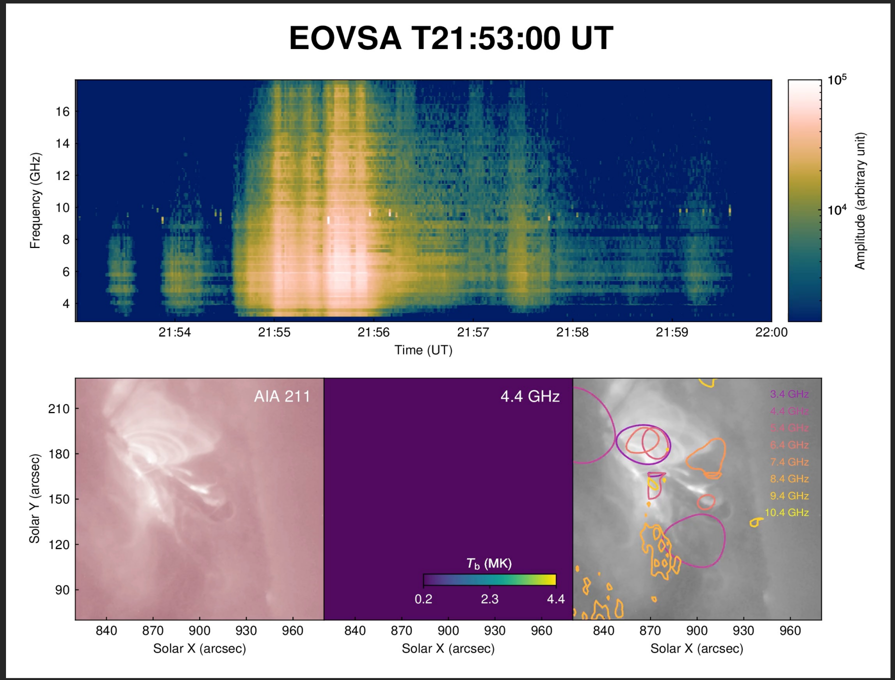


Imaging quasi-periodic MW emissions at flare current sheet
evidence for quasi-periodic acceleration
(Kou, Cheng, Wang et al. 2022, Nat. Commun.)
QPPs signal
Current sheet
Solar radio bursts
Earth to scale
EOVSA

# Quasi-periodic microwave imaging of flare current sheet

EOVSA (microwave, 3-18 GHz) and AIA (EUV, 211 A)



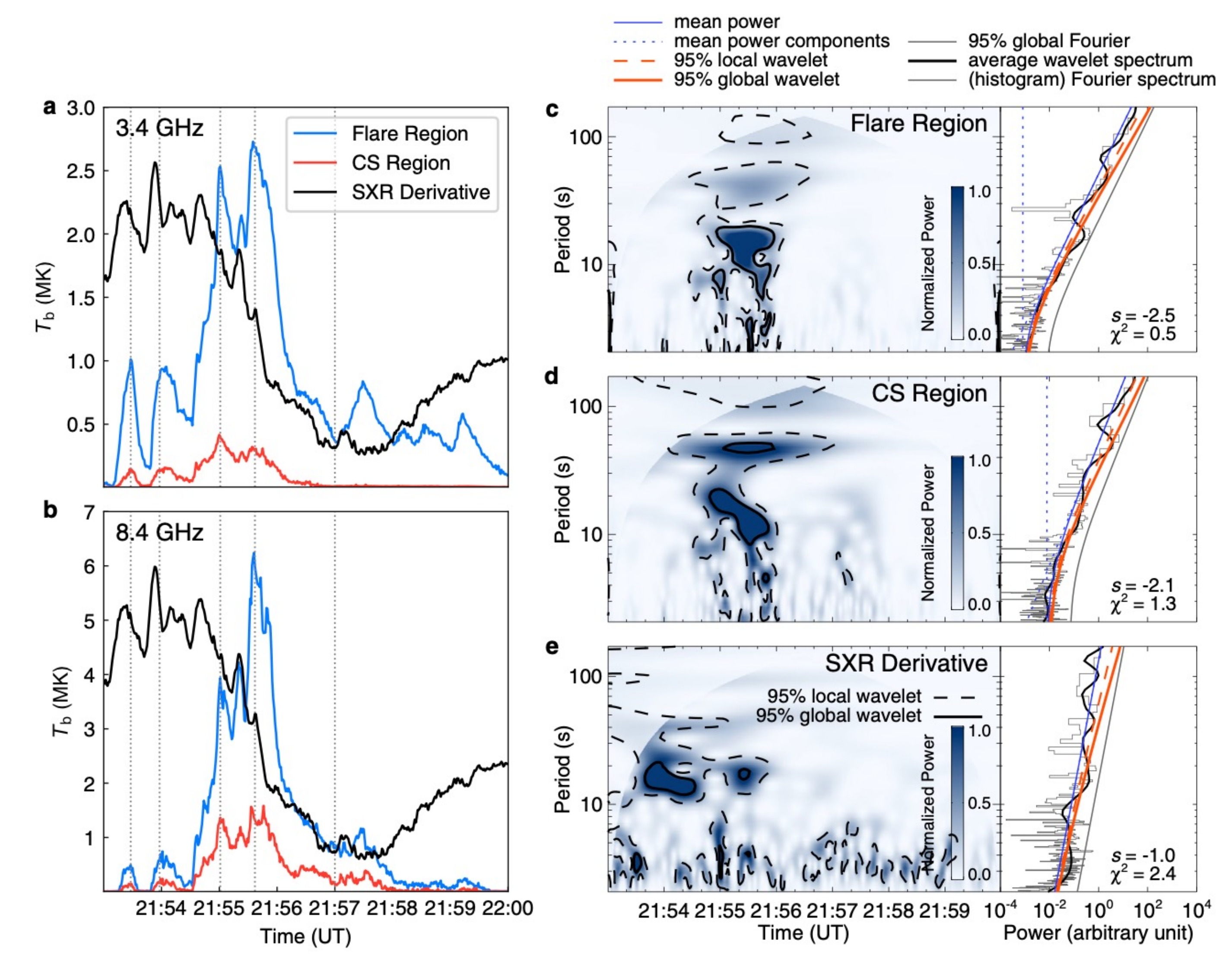

**Main sources located at the flare loops** with their centroids almost unchanged at different frequencies

**Secondary sources along the CS** with their centroids ascending with decreasing frequencies

**Microwave sources seem to be emitted by non-thermal electrons accelerated in the close vicinity of the flare current sheet**

(Kou, Cheng, Wang et al. 2022 NC)

# Quasi-periodicity of spatially resolved MW emissions




- $T_b$ for the two sources vary synchronously and present an obvious quasi-periodicity

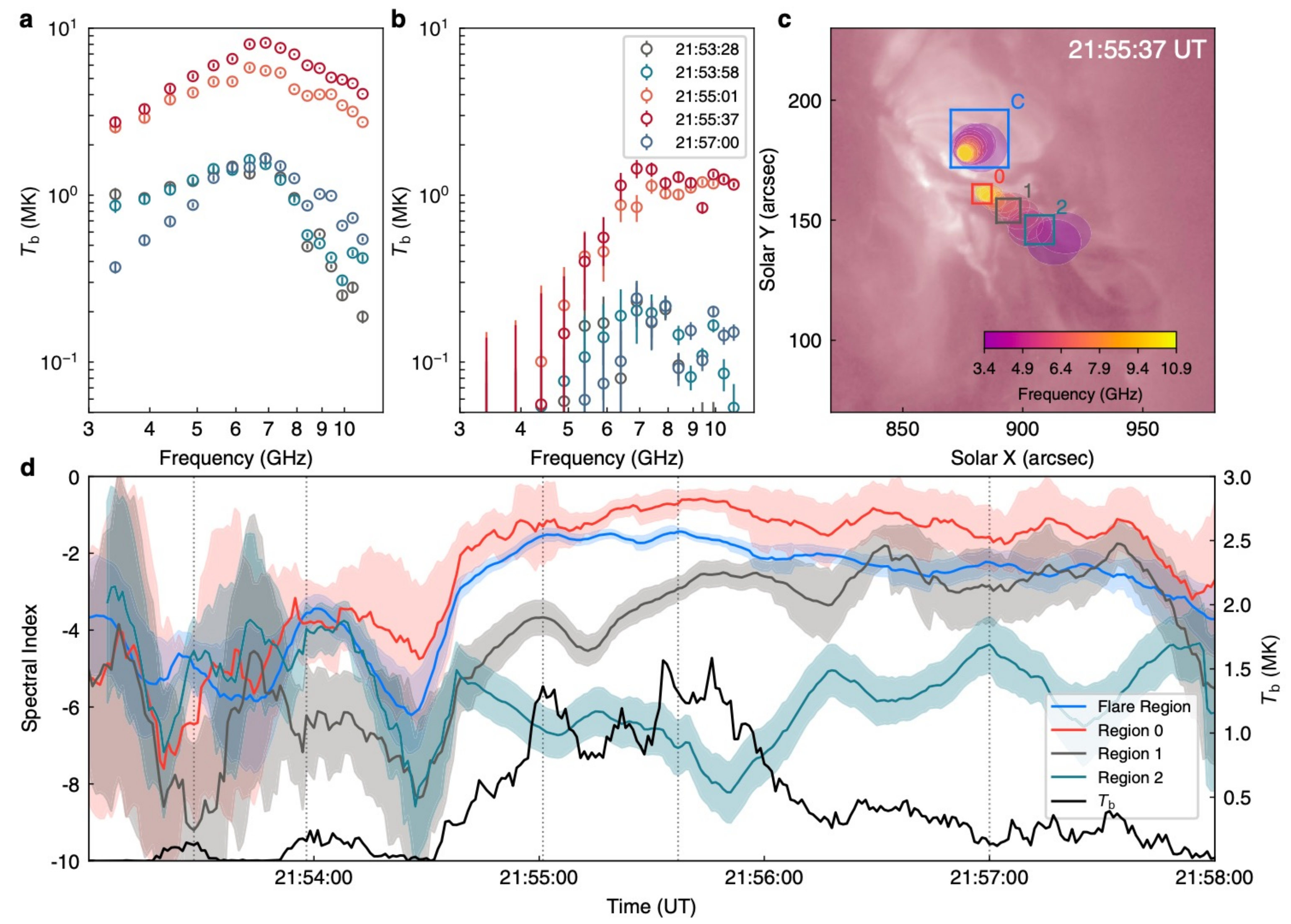
- The main period is in the range of about 10-20 s and the second one is around 30-60 s.

- Such a periodicity is also observed in the time derivative of the spatially integrated SXR emission.

**Non-thermal electrons generate the flare hot plasma and excite MW emissions**

(Kou, Cheng, Wang et al. 2022 NC)

# Spectra of spatially resolved MW emissions



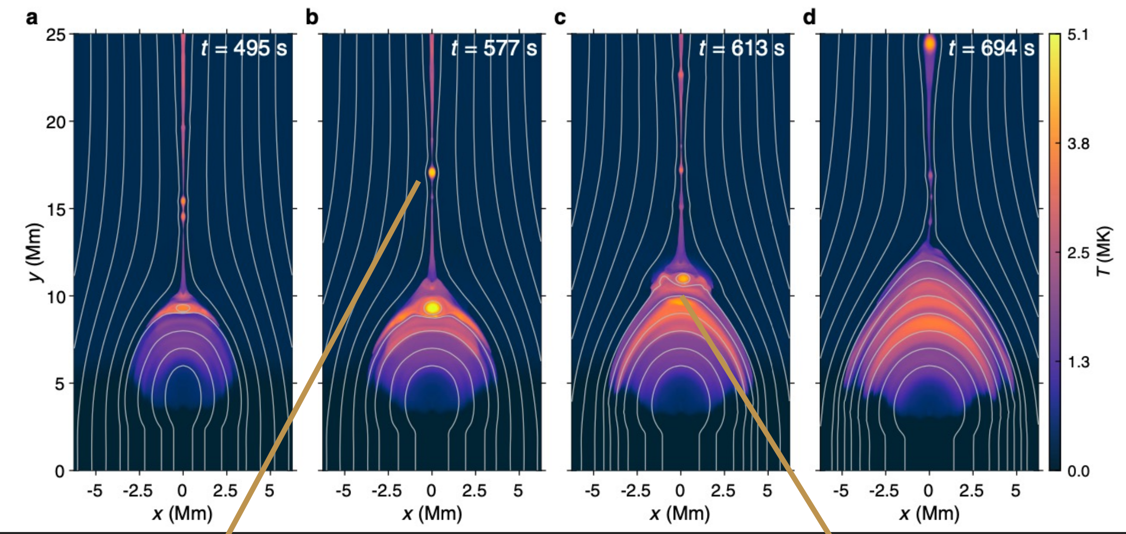

- Temporal evolution of spectral index is synchronized with that of brightness temperature

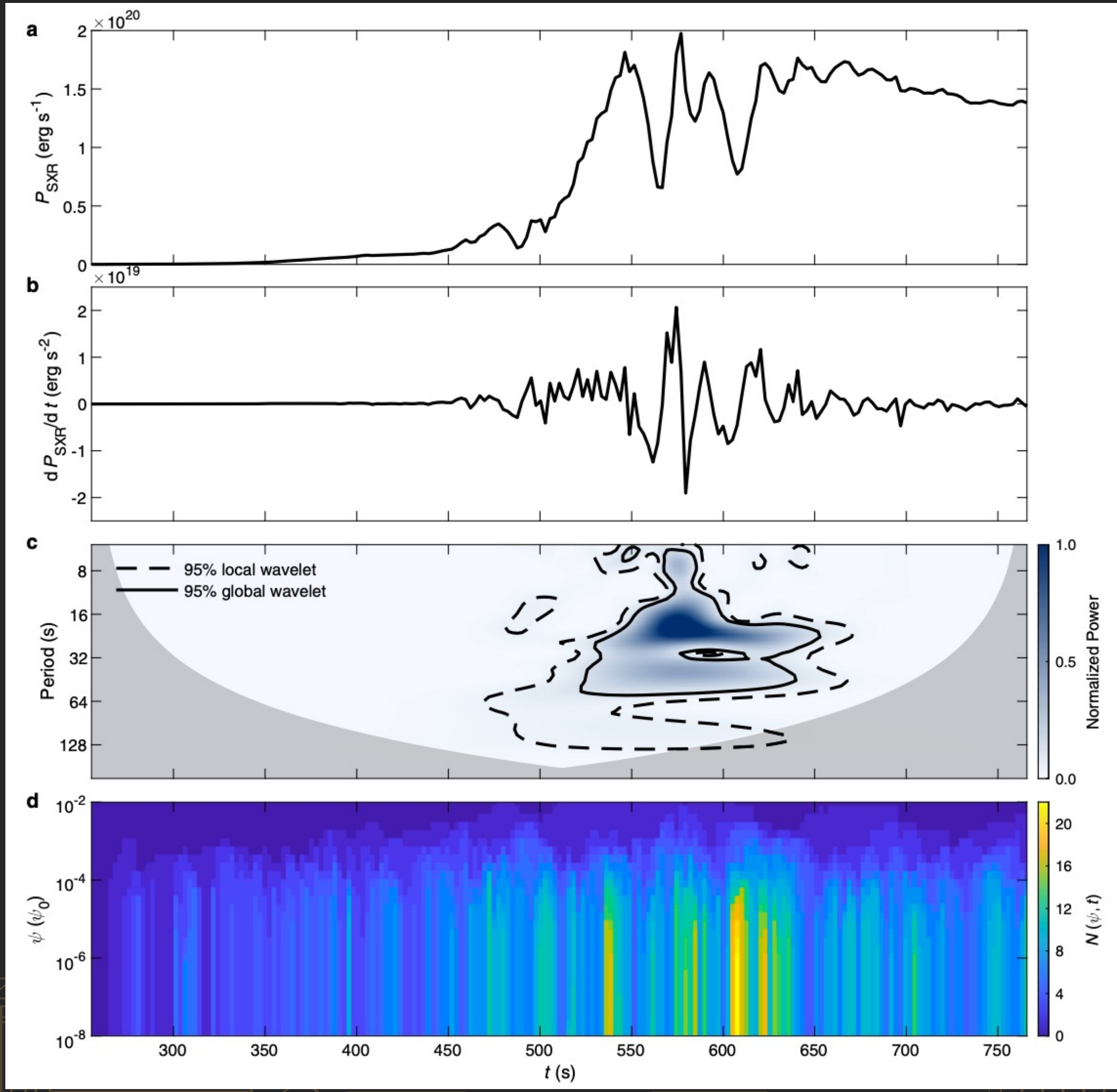
- Spectra are the hardest at Region 0 and become soft toward Region 1 and 2, but slightly soft at the flare loops

**Quasi-periodic acceleration of non-thermal electrons producing quasi-periodic microwave emissions**

(Kou, Cheng, Wang et al. 2022 NC; Chen et al. 2020 NA)

# Quasi-periodical MW emissions caused by magnetic islands




Magnetic islands appearing in the CS

magnetic islands move downwards and interact with flare loops

**The quasi-periodicity of magnetic reconnection is caused by magnetic islands within the long-stretched CS**

(Kou, Cheng, Wang et al. 2022 NC)

# Summary

1. 2D reconnection is easy to understand but not realistic, we determined **3D structure of reconnection** either for the large-scale eruption or for the tiny-scale bright point;
2. We provided **evidence for turbulent reconnection** in the long CME-flare CS; through **high-resolution 3D MHD simulations with realistic flare environment, we determined its origin and** reproduced flare dynamics of different scales comparable with observations;
3. **We located MW QPPs at the flare current sheet**, suggesting electrons are accelerated by quasi-periodical reconnection, likely due to the modulation of plasmoids.

**Thanks!**

***References:***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2. *Cheng X., Li Y., Wan L.F., et al., 2018, ApJ, 866, 64*
3. *Kou Y.K., Cheng X., Wang Y.L., et al., 2022, NatCo, 13, 7680*
4. *Cheng X., Priest E., Li H.T., et al., 2023, NatCo, 14, 2107*
5. *Wang Y.L., Cheng X., Ding M.D., et al., 2023, ApJL, 954, L36*