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Nanoflares, avalanches & coronal heating.

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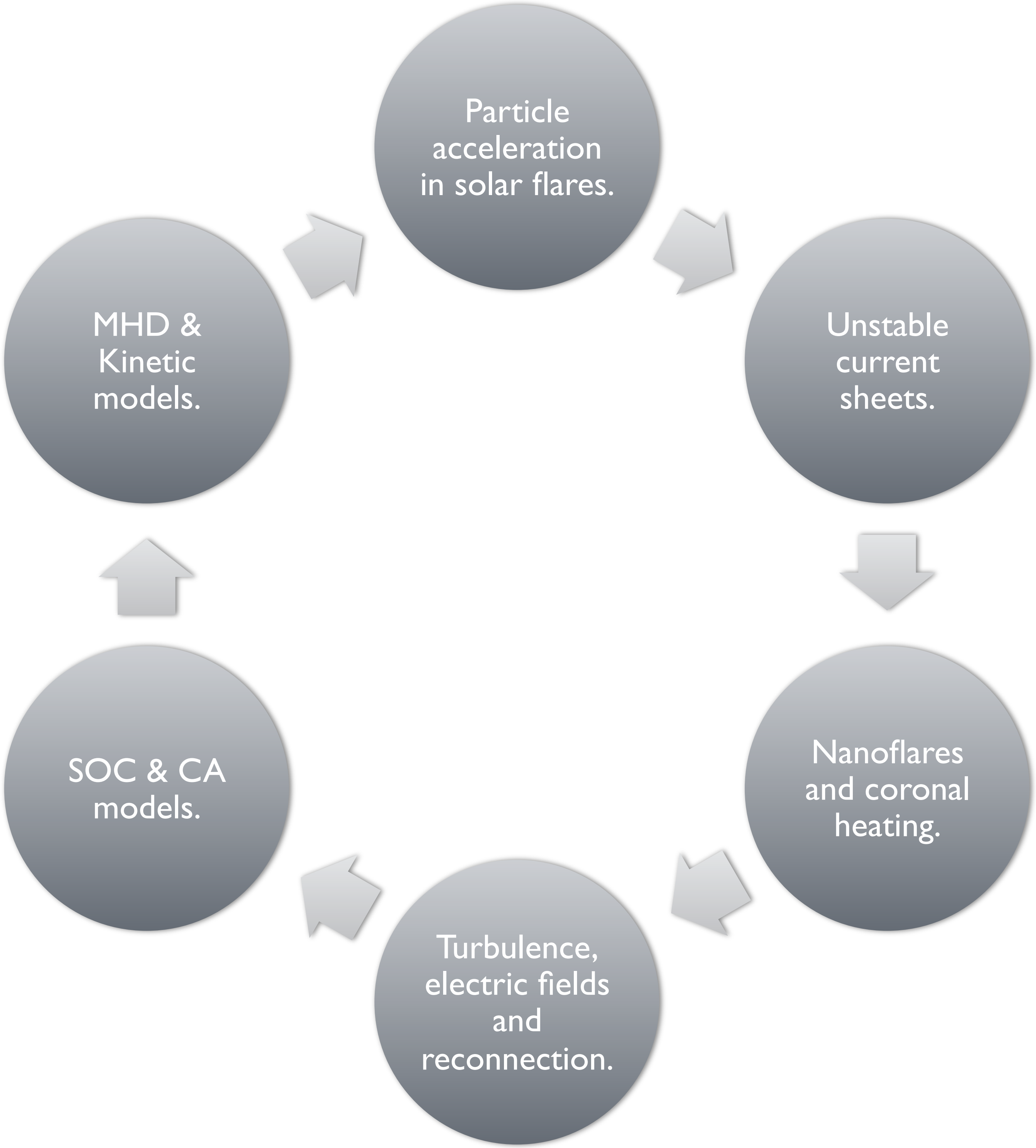
Overview

- Numerical experiment: MHD & initial conditions.
- Flux emergence at / above the photosphere.
- Fragmentation of current layers / intermittent heating.
- Patchy reconnection.
- Onset and clustering of small flares (nano/micro-flares).
- Heating of the solar atmosphere.

Relevant work from Hel.A.S members.



- Anastasiadis, A.
- Georgoulis, M.
- Gontikakis, C.
- Isliker, H.
- Nindos, A.
- Patsourakos, S.
- Tsinganos, K.
- Vlahos, L.

Bifrost simulations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{u}) + p\nabla \cdot \mathbf{u} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c + \eta j^2 + Q_{visc}$$

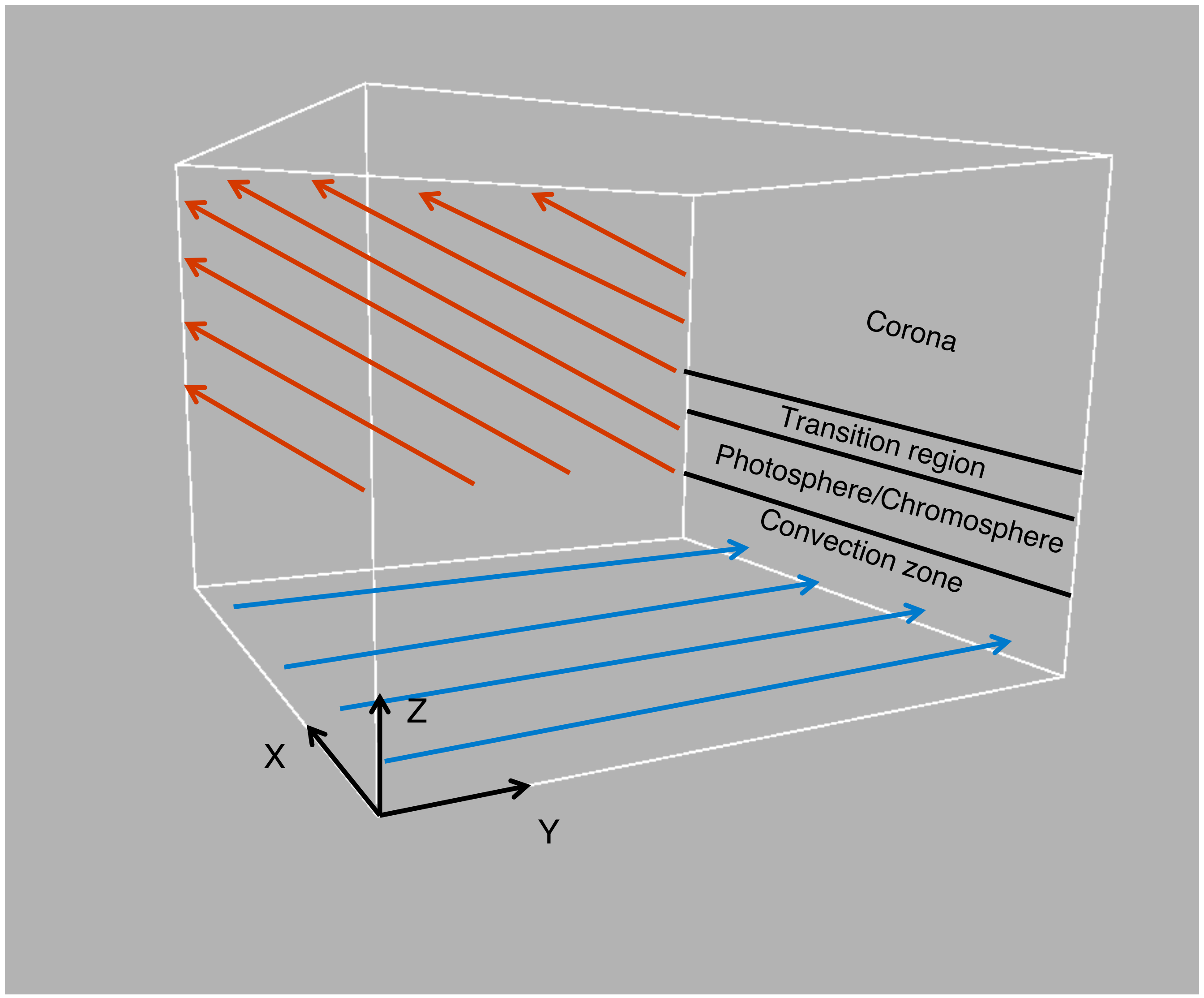
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + \tau) = -\nabla p + \mathbf{j} \times \mathbf{B} - g\rho$$

Hansteen 2004, Hansteen, Carlsson, Gudiksen 2007,
Martínez Sykora, Hansteen, Carlsson 2008, Gudiksen et al 2011

Numerical set-up

Stratification & magnetic field



Emerging field (flux sheet).

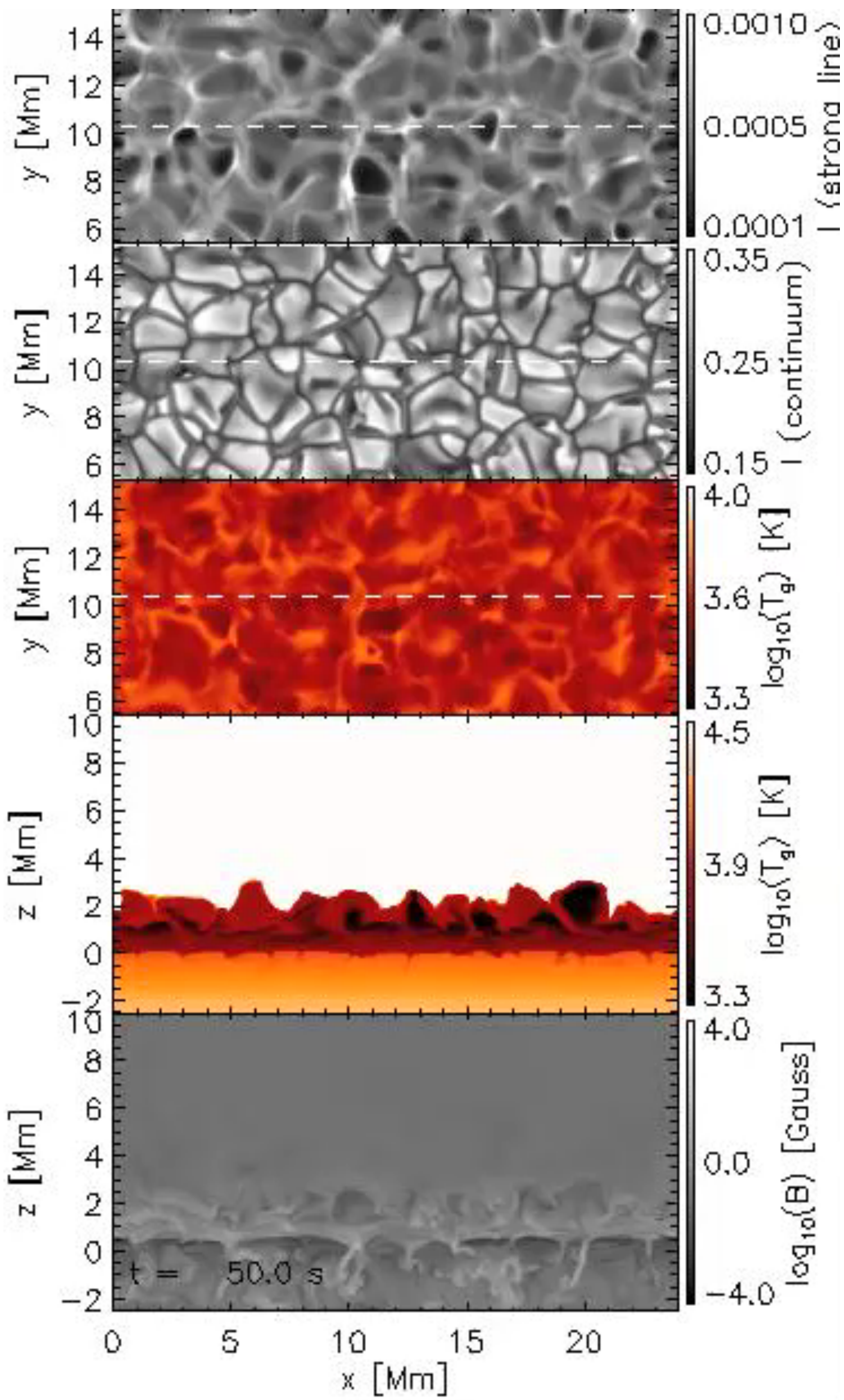
Ambient magnetic field (oblique, space filling).

Archontis & Hansteen, ApJ (2014)

- CZ (z=-2.5 Mm).
- PHOT./CHR. (z=0-2.5 Mm). T~ $6\times10^3 - O(10^4)$ K.
- TR (z~2.5-4 Mm).
- COR. (z~4 Mm). T > 6×10^5 K.
- 24x24x17 Mm, 504x504x496 grid.

- Convection is driven by optically thick radiative transfer from the photosphere.
- Radiative losses in the chrom. include scattering, optically thin in the corona.
- Field-aligned thermal conduction is included.
- Hyper-diffusion is included.

- Initial ambient field of B~0.1 G with inclination of 45° with respect to z axis.
- Flux sheet (B_y=3300 G at bottom boundary) within [x,y]=[0-24,3-16 Mm] for 105 min.



1st phase: emergence to the photosphere

- Vertical slices at y~10 Mm.
- Horizontal slices at z~700 km above phot.
- Intensity: continuum, 630 nm & CaII 854.2 nm.

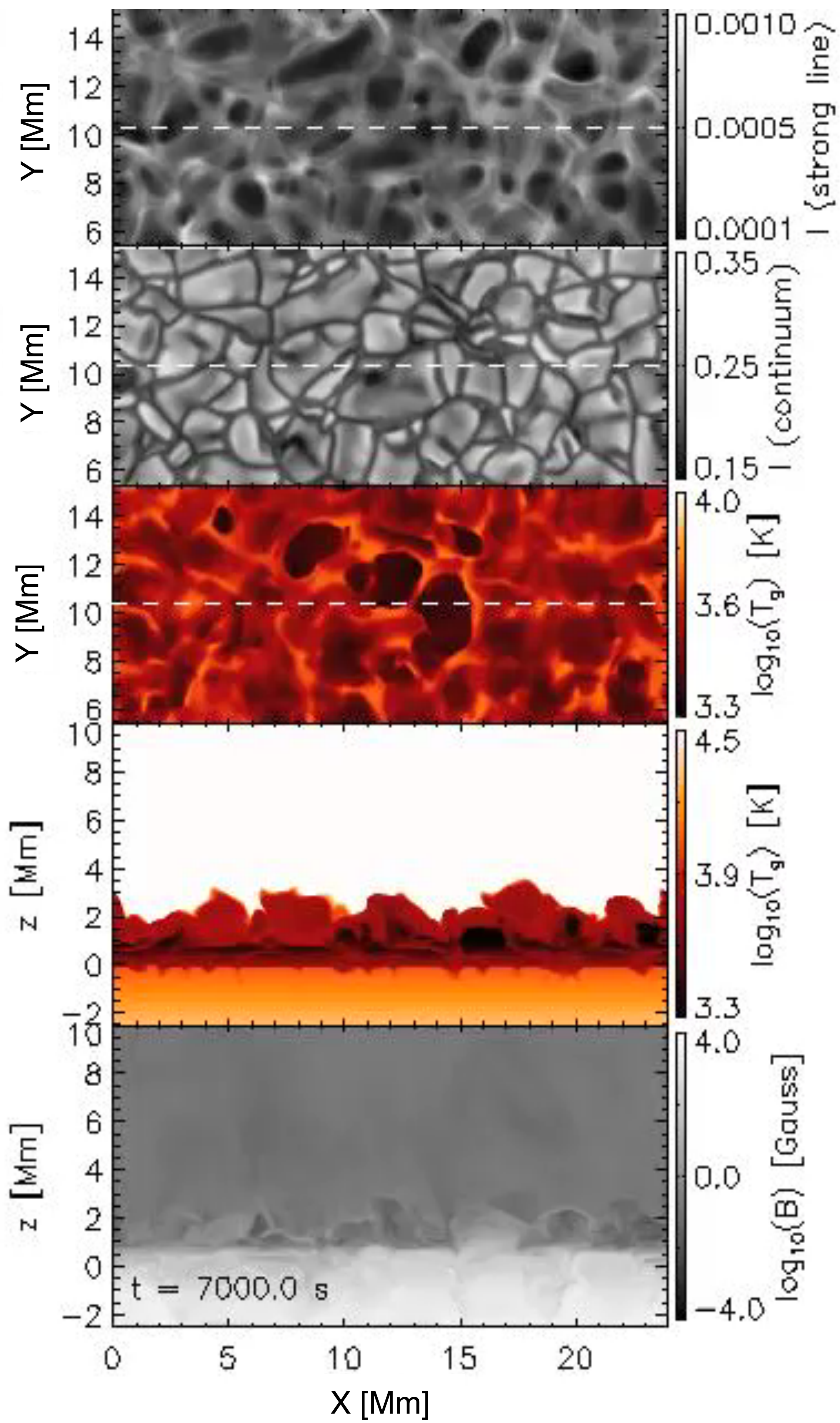
- B-flux elements pile up (surface) for ~15 min.
- $B_{hor\_ph} \approx 500$ G $(B_{z\_max}=1.8$ kG).
- B-field emerges above the surface after ~2hrs.

- Chromospheric temperature structure set by acoustic shocks, oscillations etc. until magnetic field emerges into outer atmosphere.

- Photospheric and chromospheric intensity little changed by flux emergence during 1st phase.

- Larger granules appear at the beginning of 2nd phase.

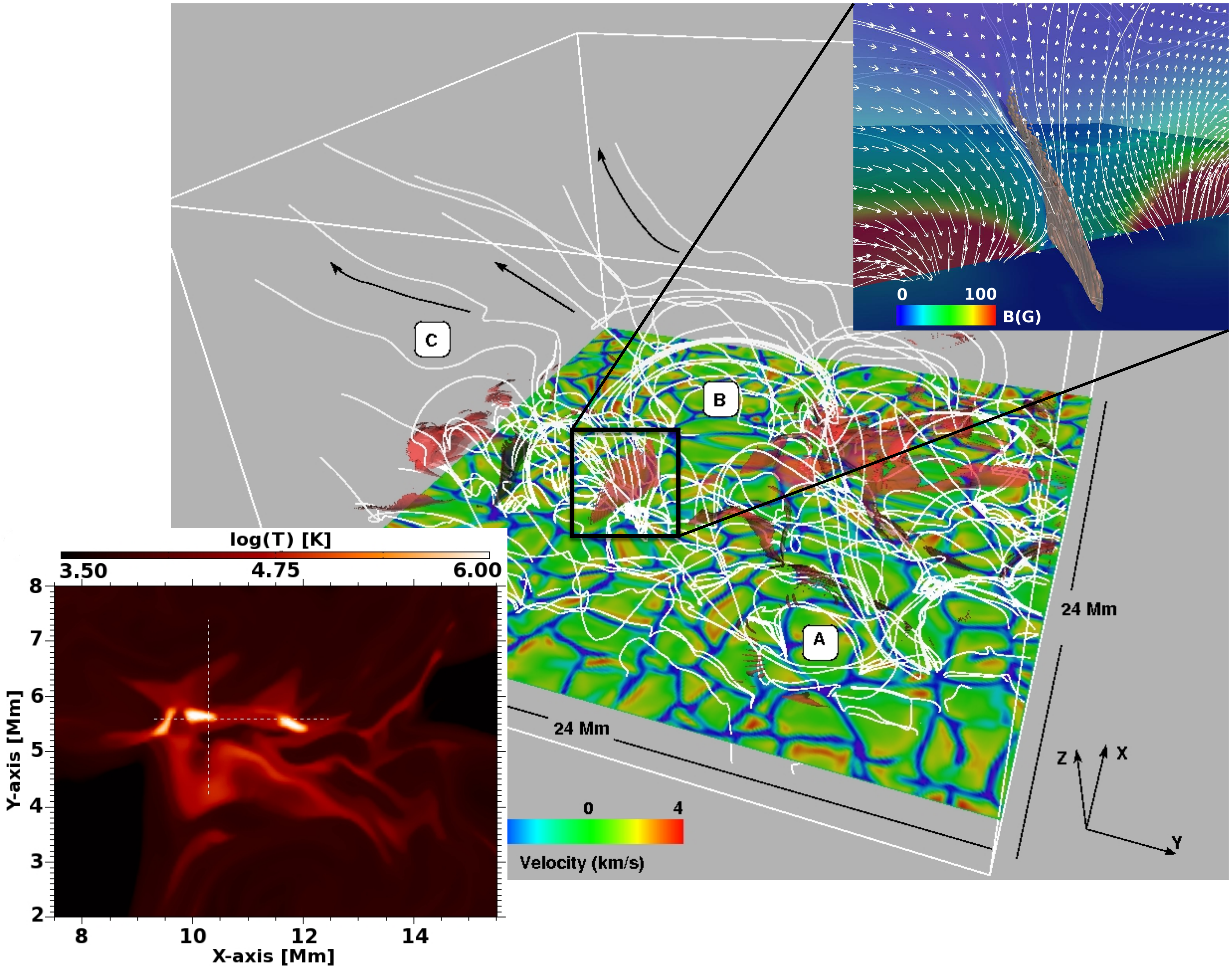
2^{nd} phase: emergence above the photosphere



- The emerging field enters the corona.
- Emerging loops: dense and cool (adiabatic expansion).
- Photosphere: granule size change, bright points.
- Chrom/corona: local temperature increase.
- (Low) chromosphere intensity and contrast increase.
- Magnetic loops interact (e.g. reconnect).

See Ortiz et al. 2014, ApJ 781, 126 for this phase.

Multi-scale emergence of magnetic flux



Nanoflares and Microflares

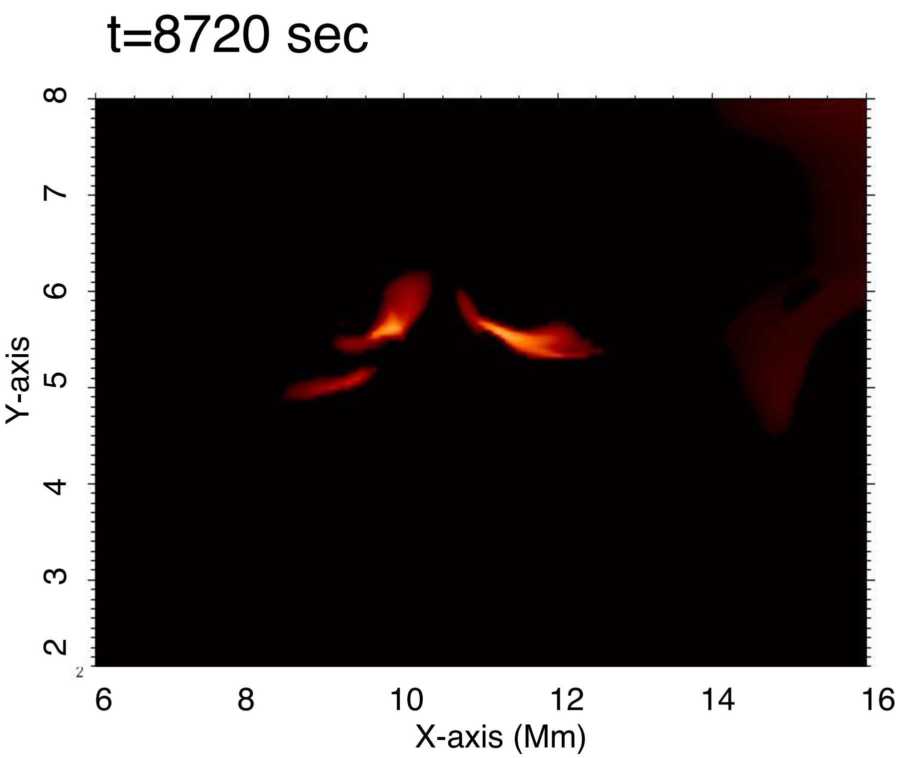
Nanoflare: impulsive energy release on small spatial scales (Parker, E. 1957).

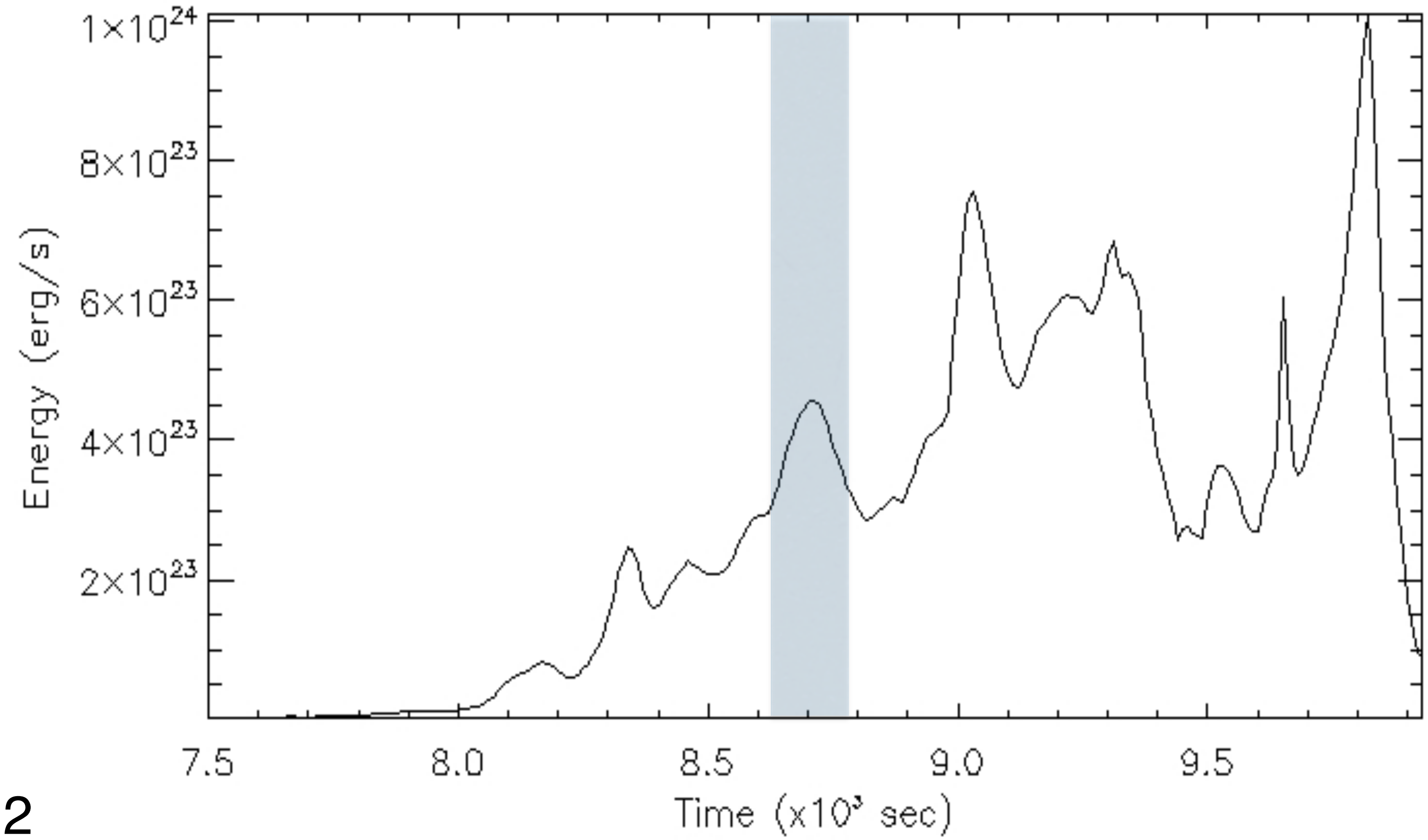
Motivation: Observations of localized brightenings estimated to contain 10^{24} erg.

Type of flare	Thermal energy release (erg)	Size (Mm)
Average nanoflare	$\leq 10^{24}$	O(1)
Largest nanoflare	$\sim 10^{27}$	O(1)
Microflares	10^{27}-10^{30}	1-10
Large flares	$\sim (10^{30} - 10^{33})$	≥ 10

Parker, E. (1957), Aschwanden, M. J. (2005), Shibata & Magara (2011).

Small-scale brightenings in the nanoflare energy regime.



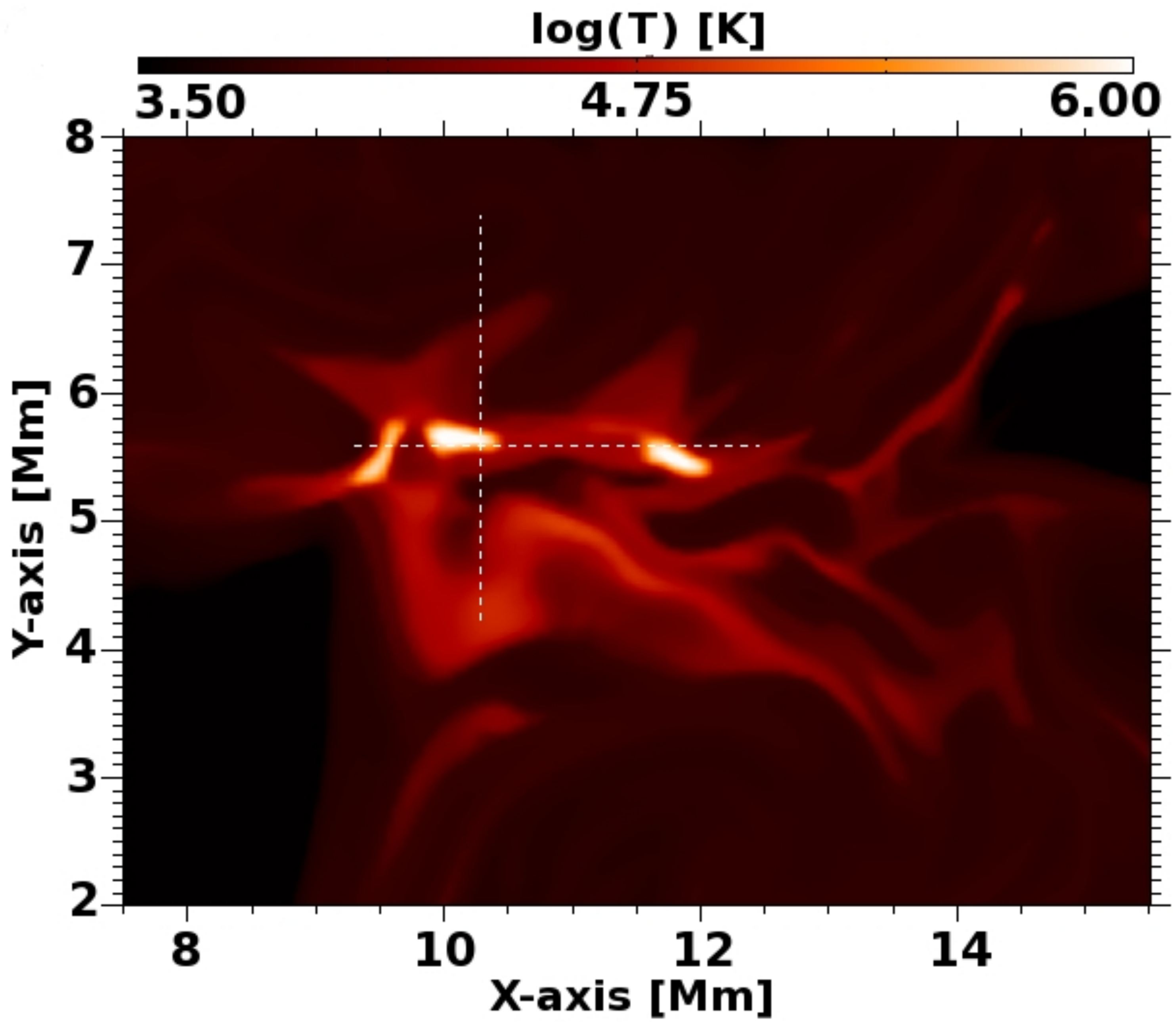


Fe XII 19.5 nm: Log(T_{max}(k)) ~ 6.2

Thermal energy (corona): impulsive energy release – bursts.

Cluster of three small (nano)-flares : ~ 4 x 10^{23} erg/s.

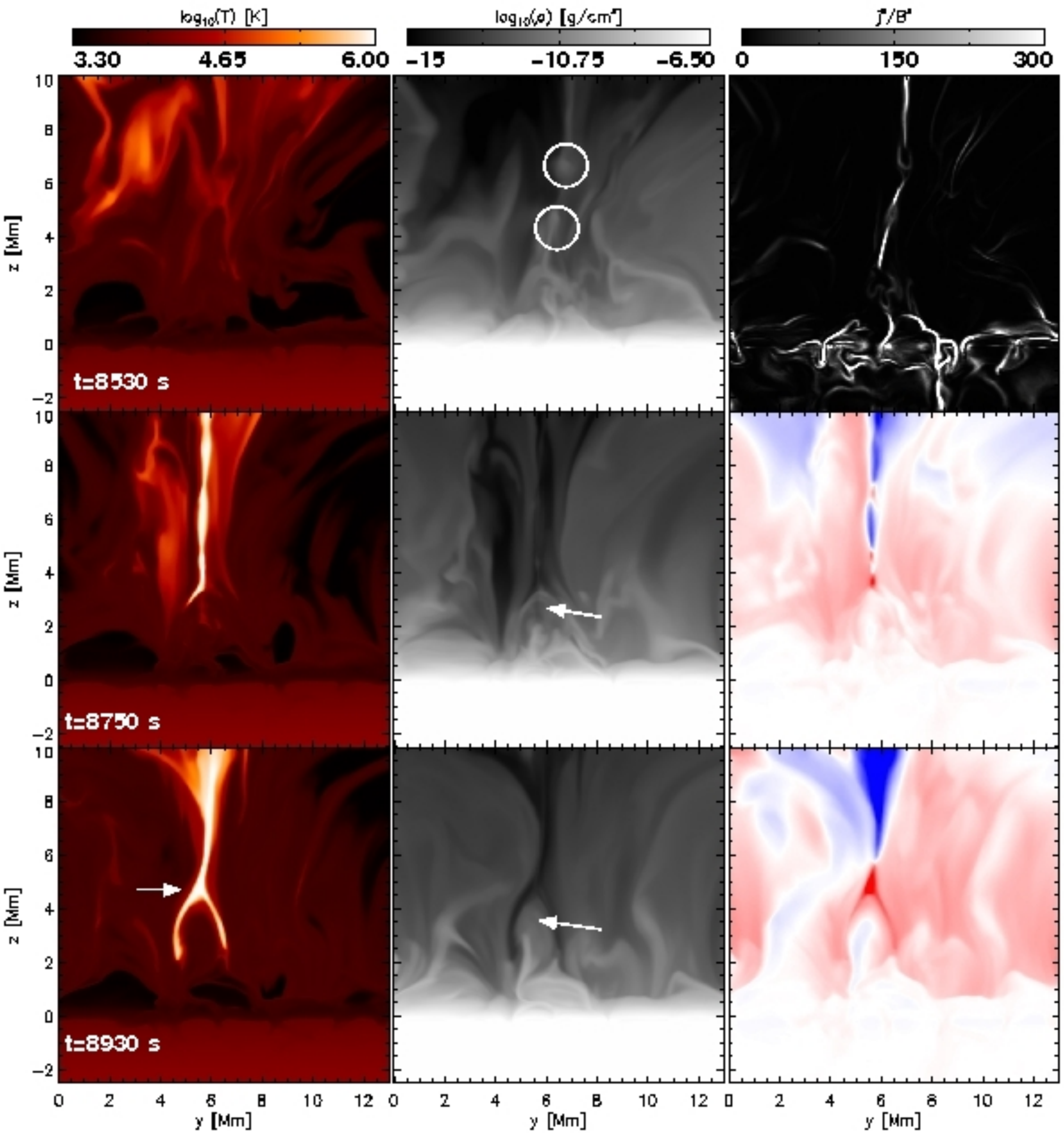
How do these flares form?



Do these flares occur independently of each other?

Do these flares cluster together to produce another flare?

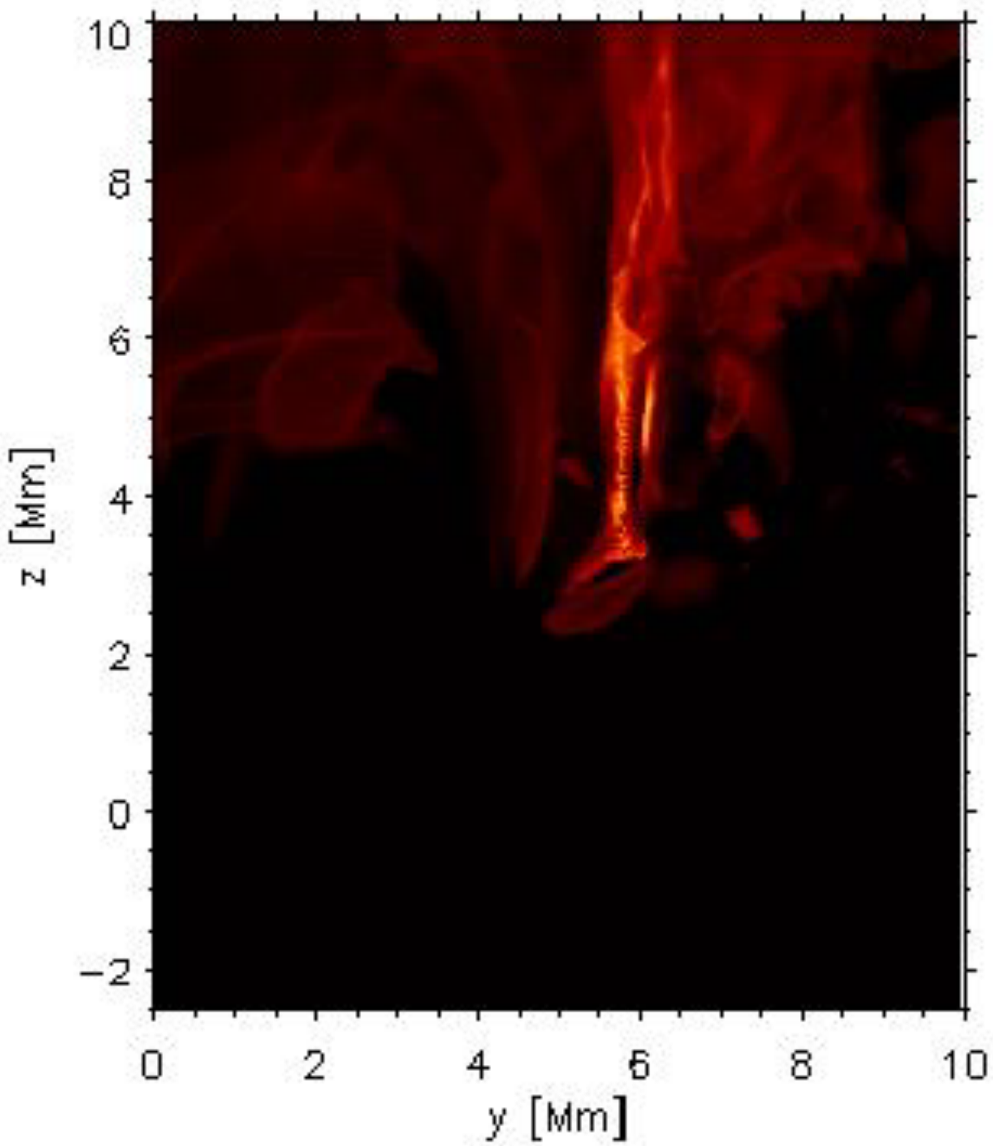
Evolution across the current sheet



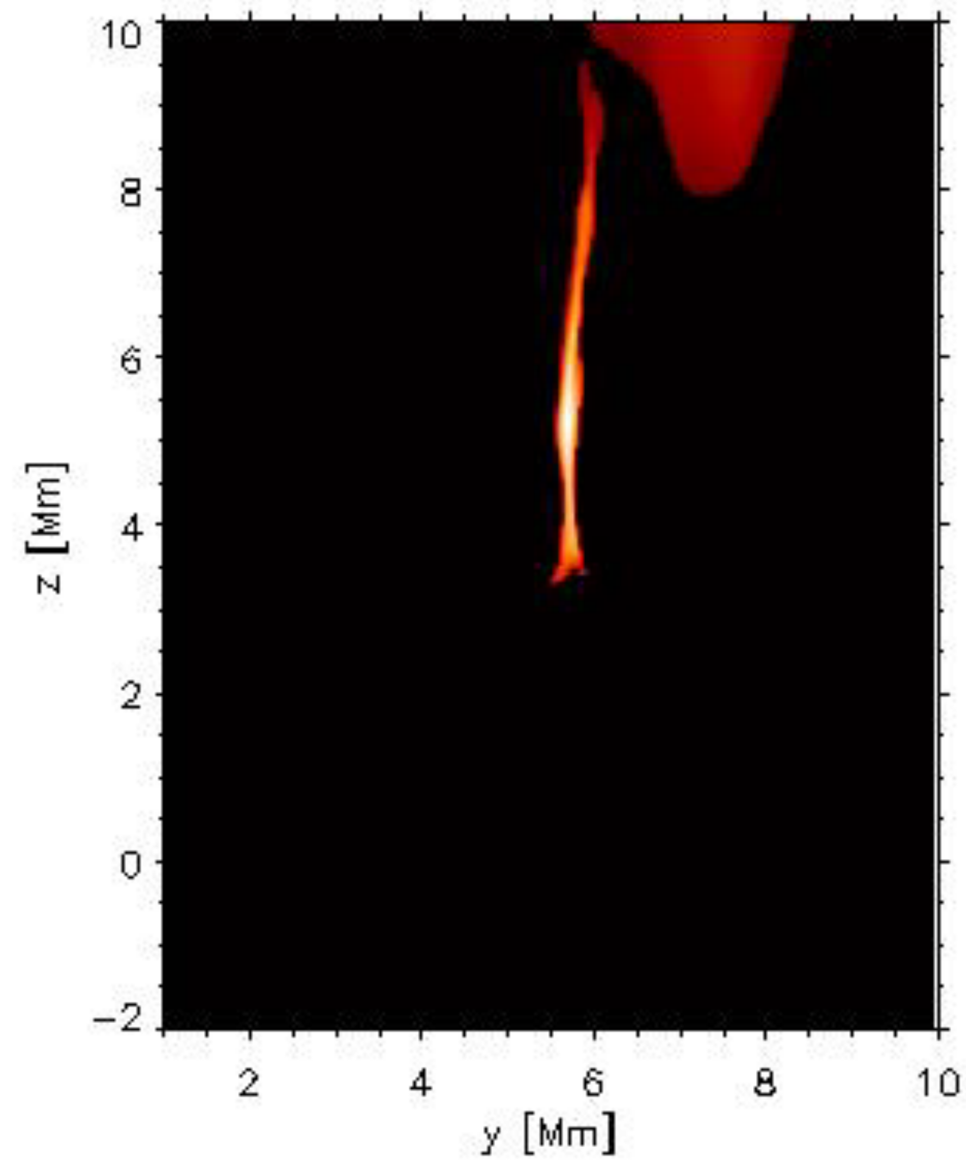
- Long, thin current layer.
- Tearing instability – plasmoids.
- Ejection of plasmoids – reconnection – X-ray temperatures.
- Jets (V~200-400 km/s, T~2.5 mK).
- Small (post)-flare loops (L~ 1 Mm, T~ 2 mK).
- TR and chromospheric heating (footpoints, 10^5-10^6 K).
- Average lifetime : 1-2 min.
- Energy release: 10^{23}-10^{24} erg/s.

Plasma heating at the current interface

Si IV 139.3 nm



Fe XII 19.5 nm

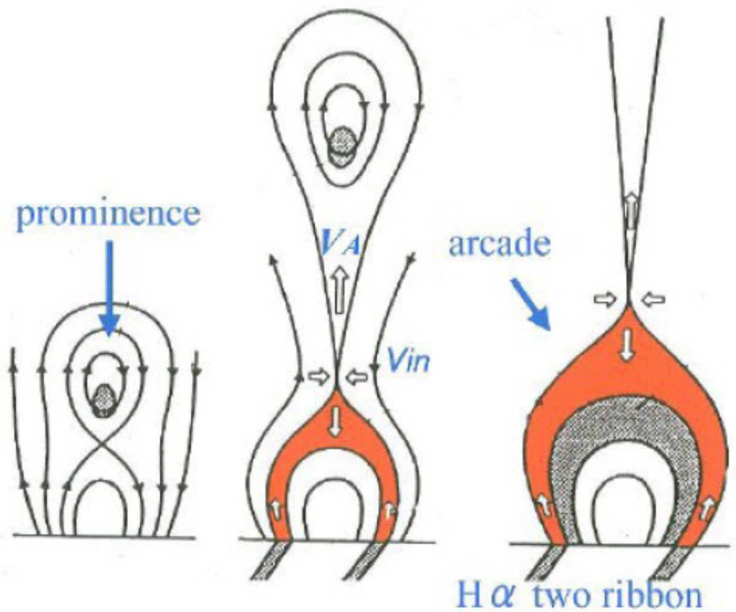


Si IV 139.3nm : Log(T_{max}(k)) ~ 4.8

Fe XII 19.5 nm: Log(T_{max}(k)) ~ 6.2

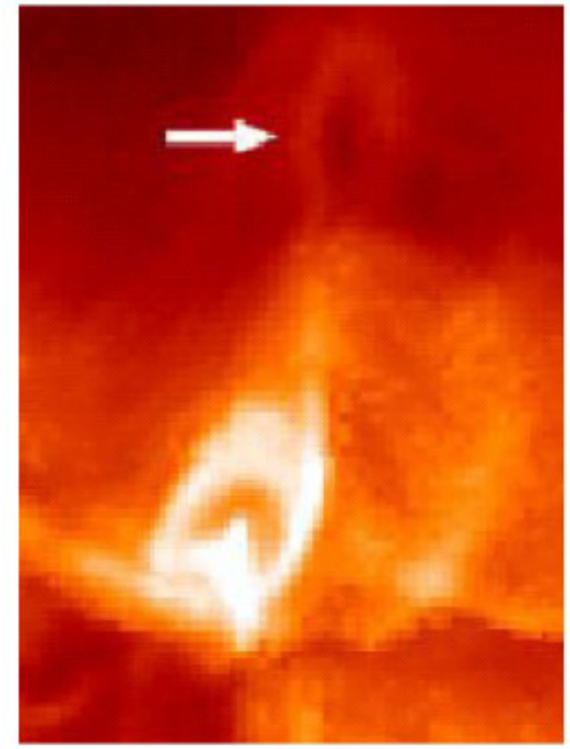
‘Standard’ reconnection flare model(s)

CSHKP (2D view)

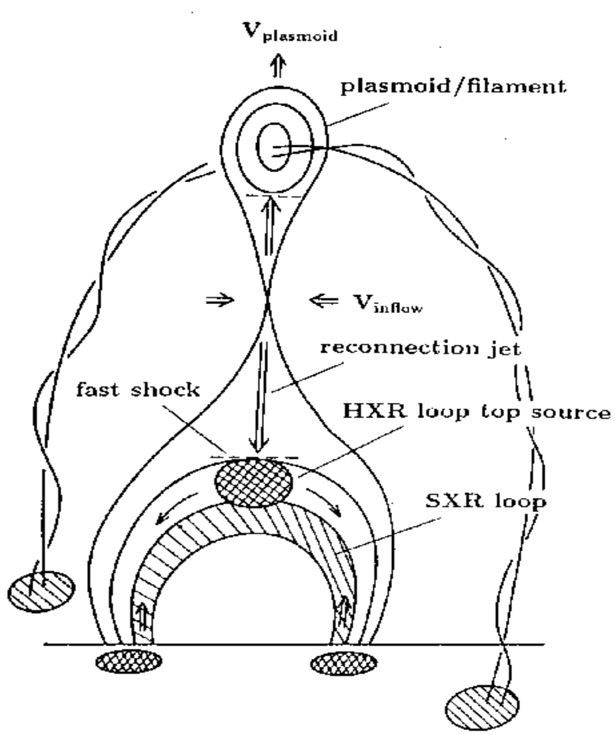


⇒should be observed in Soft-Xrays

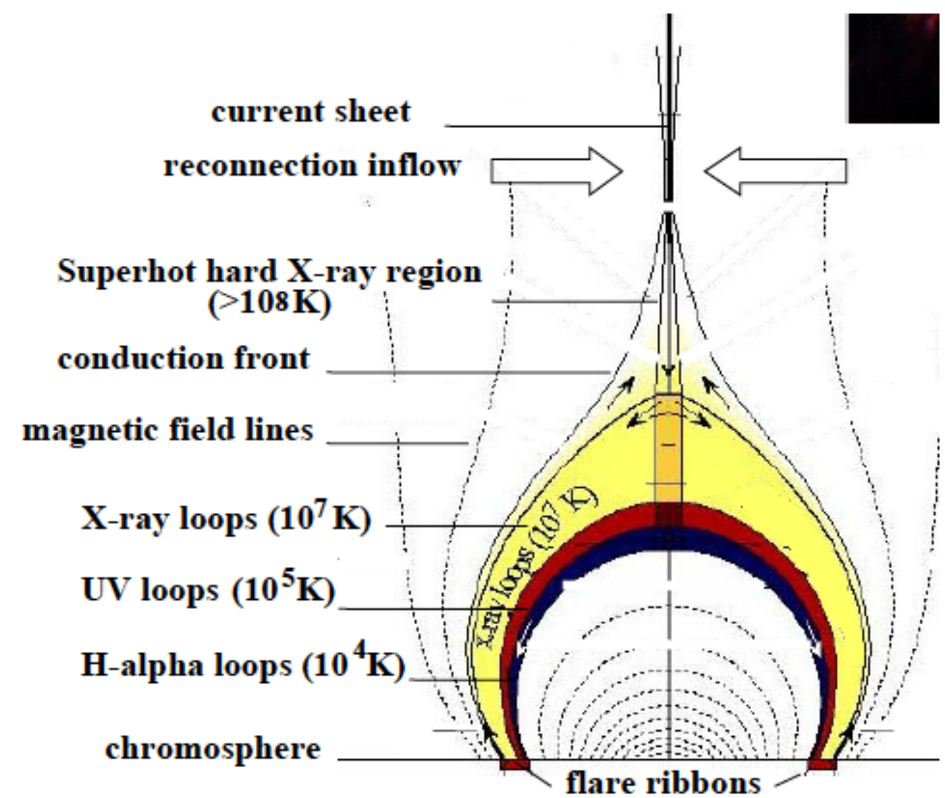
Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp-Pneuman 1976



Plasmoid ejection associated with LDE flare (Yohkoh/SXT)



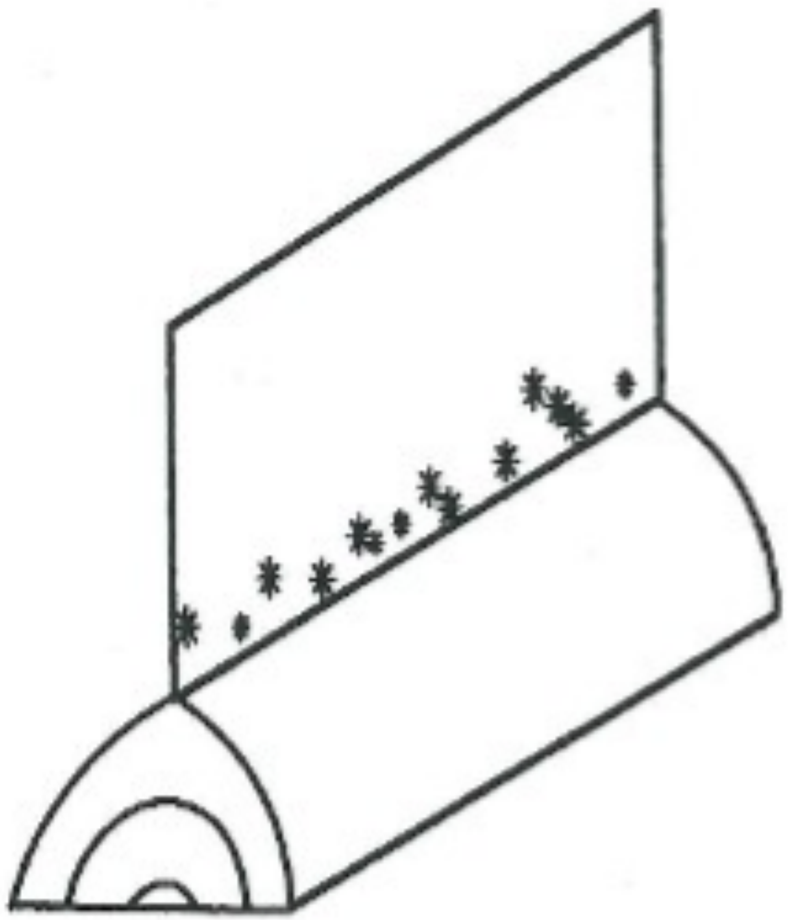
Shibata, et.al. ApJ 451, L83, 1995.



(adapted from Forbes & Acton, 1996)

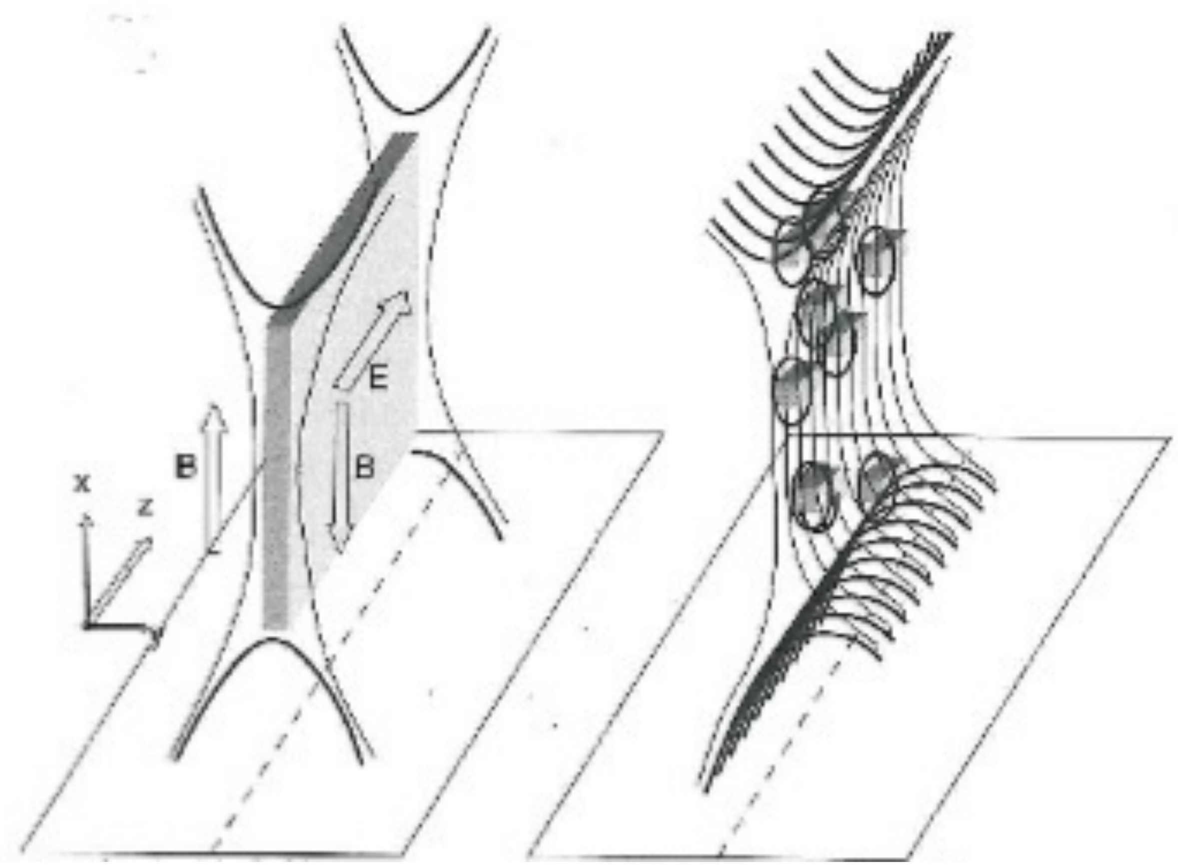
Does the ‘standard’ model hold in 3D?

In 3D, *patchy* reconnection



Klimchuck, J. (1996), Forbes & Aston (1996)

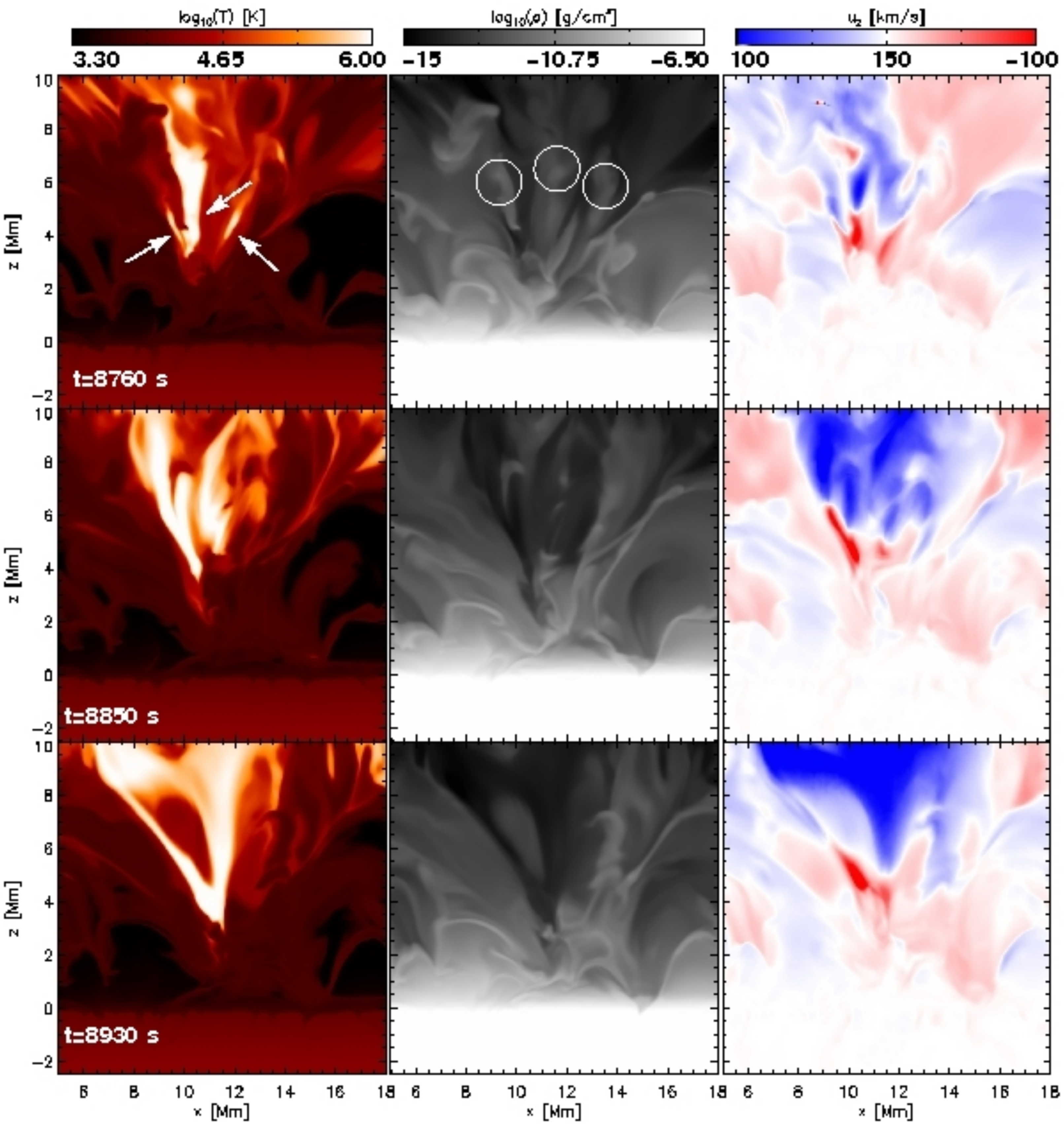
In 3D, *fragmentation* of currents



Aschwanden, M. J. (2002)

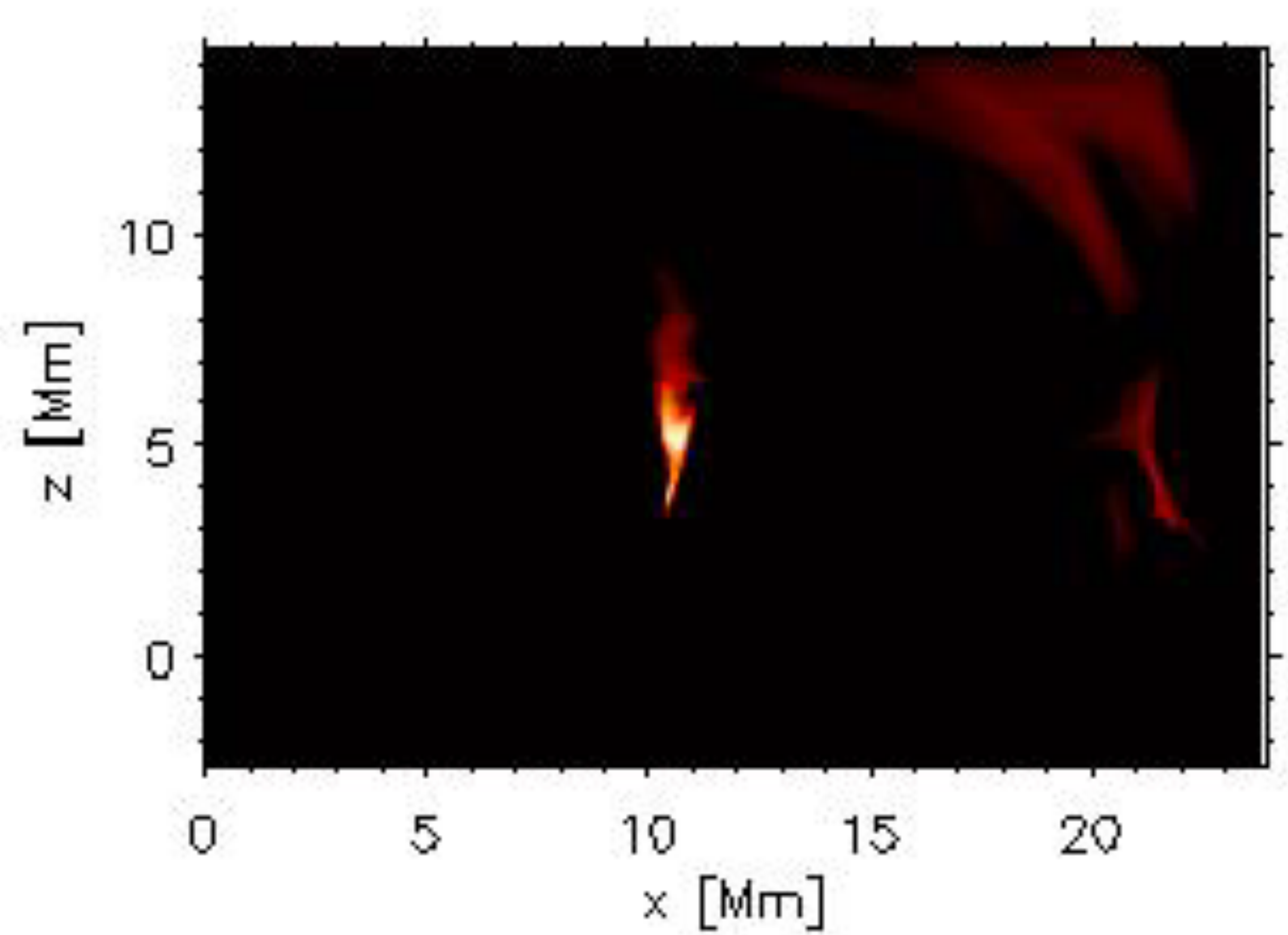
VERY IMPORTANT !! FOR PARTICLE ACCELERATION AND PLASMA HEATING.

Evolution along the current sheet

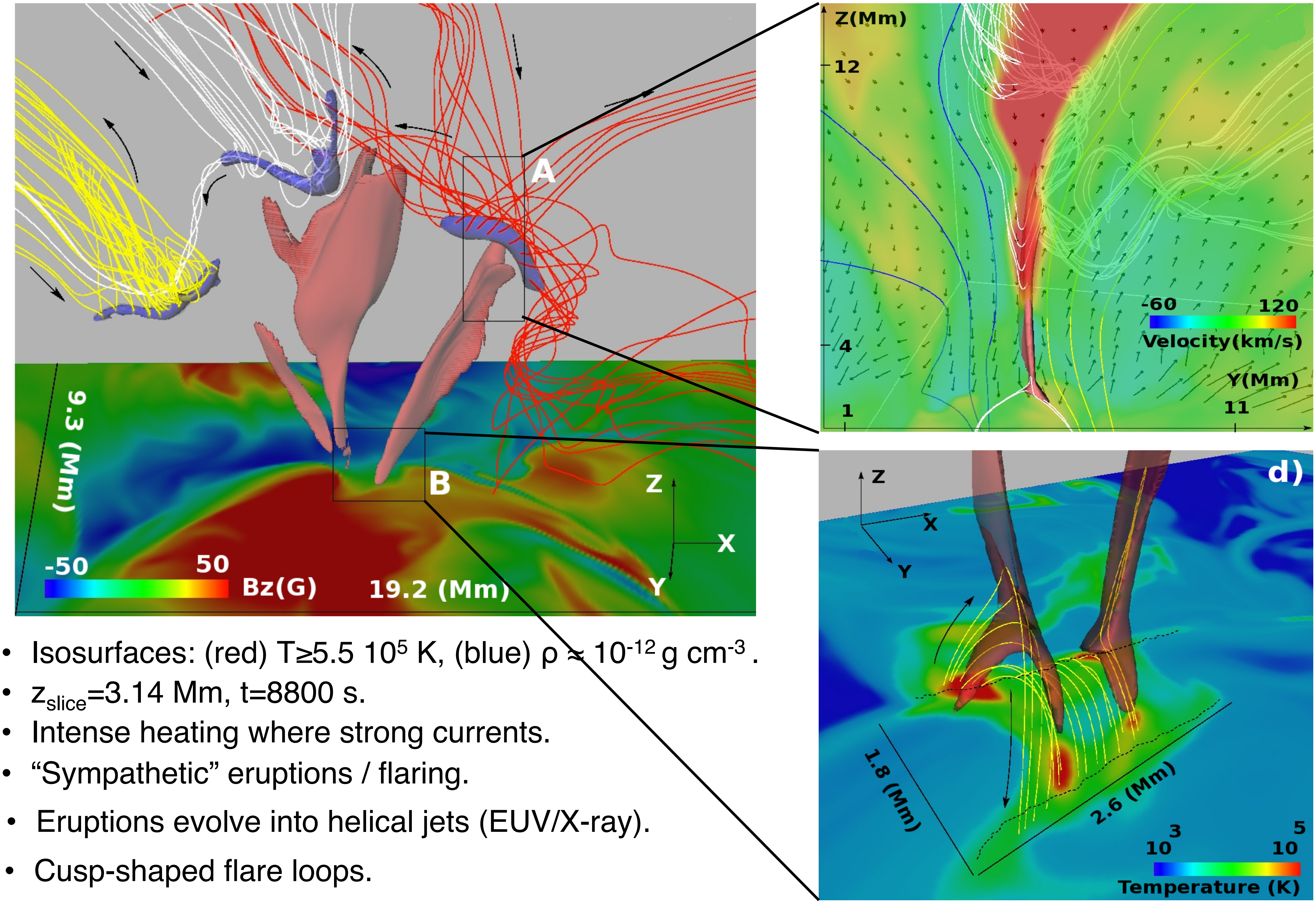


- Not one but several plasmoids.
- Patchy reconnection – spatially intermittent heating.
- Cluster of small flares.
- Fragmentation of current.
- Many sites of acceleration.
- One flare stimulates(?) the other. “Sympathetic” flaring?
- Larger energy release: the composite effect of the adjacent small flares.
- ‘Composite’ flare: 10^{24} – 10^{25} erg/s.

The composite effect (avalanche) of the adjacent nanoflares: FE XII 19.5 nm

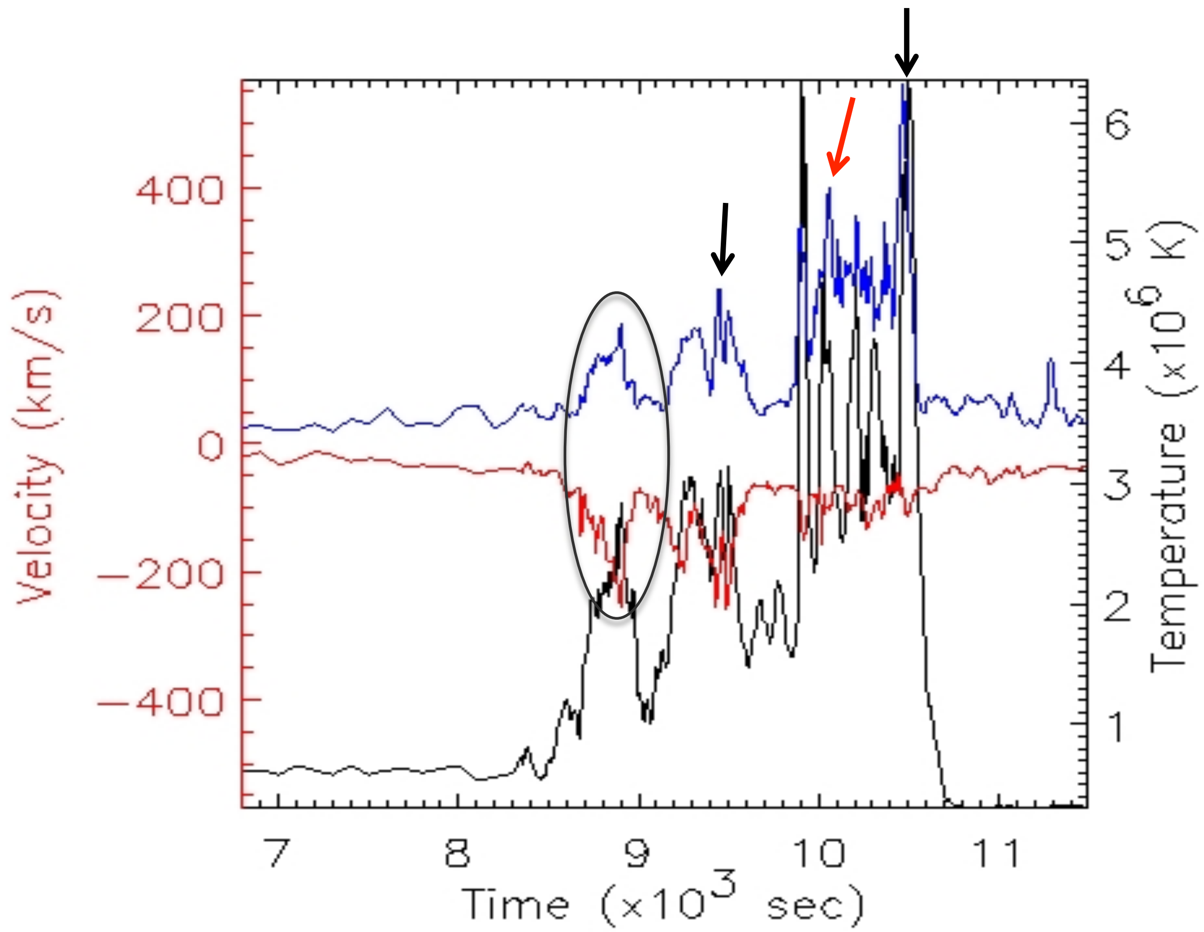


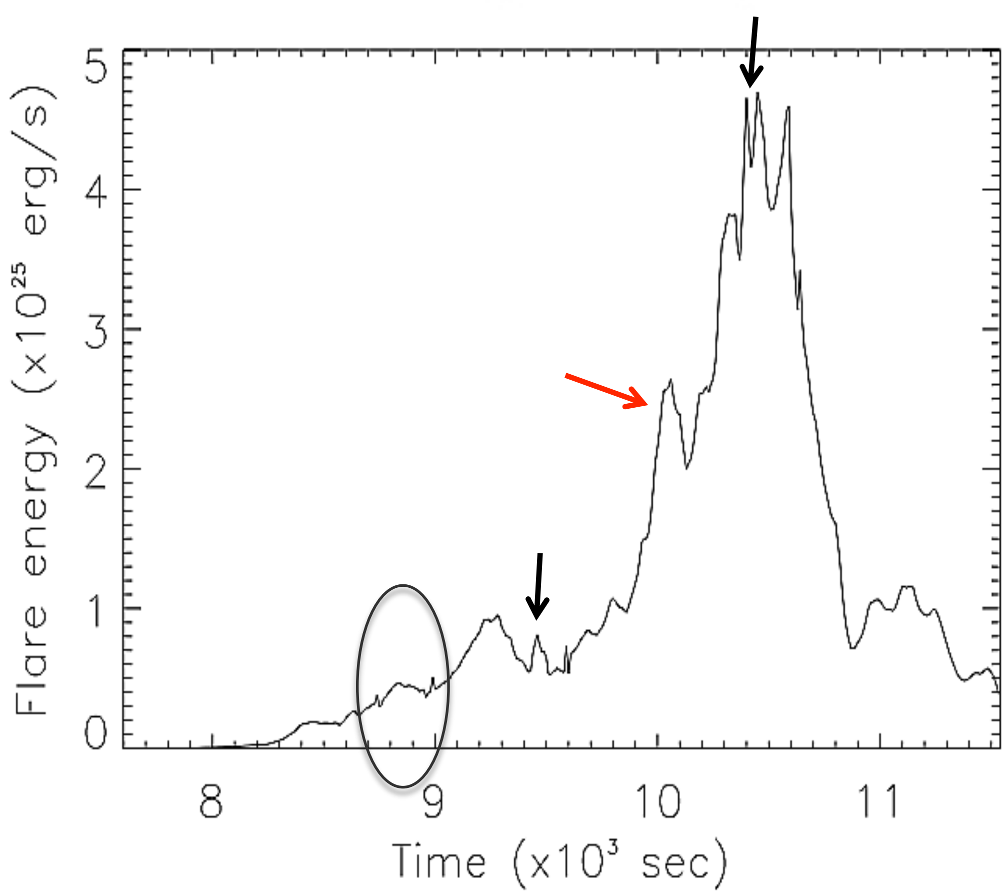
3D view: plasmoids, heating, jets, flares.



- Isosurfaces: (red) T≥5.5 10^5 K, (blue) ρ ≈ 10^{-12} g cm^{-3}.
- z_{slice}=3.14 Mm, t=8800 s.
- Intense heating where strong currents.
- “Sympathetic” eruptions / flaring.
- Eruptions evolve into helical jets (EUV/X-ray).
- Cusp-shaped flare loops.

Temperature, vertical velocity (V_Z) and energy.



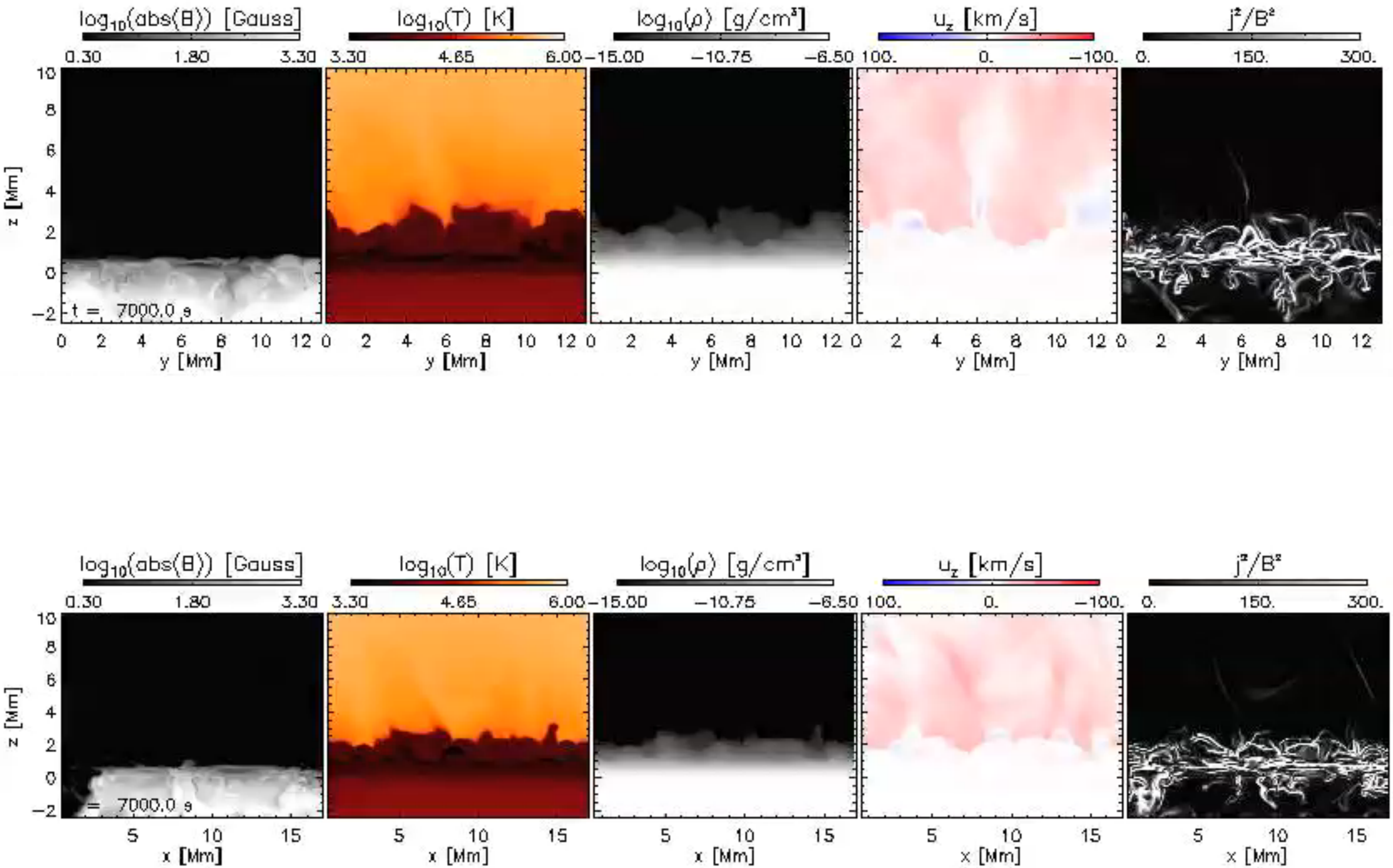


- Plasma heating (1-6 MK) by small flares.
- Reconnection-driven acceleration.
- Heating-Energy: good correlation.
- Short-lived bursts of energy.
- ↑ "Individual' energy emissions.
- ↑ Superposition of small flares.
- Lifetime of small flares: 30 s – 3 min.
- Flares at all atmospheric heights.
- High occurrence rate: ~ 4 x 10^{-20} s^{-1} cm^{-2}.
- Average energy flux: $1.2x10^6$ - $7x10^7$ erg s^{-1} cm^{-2} .

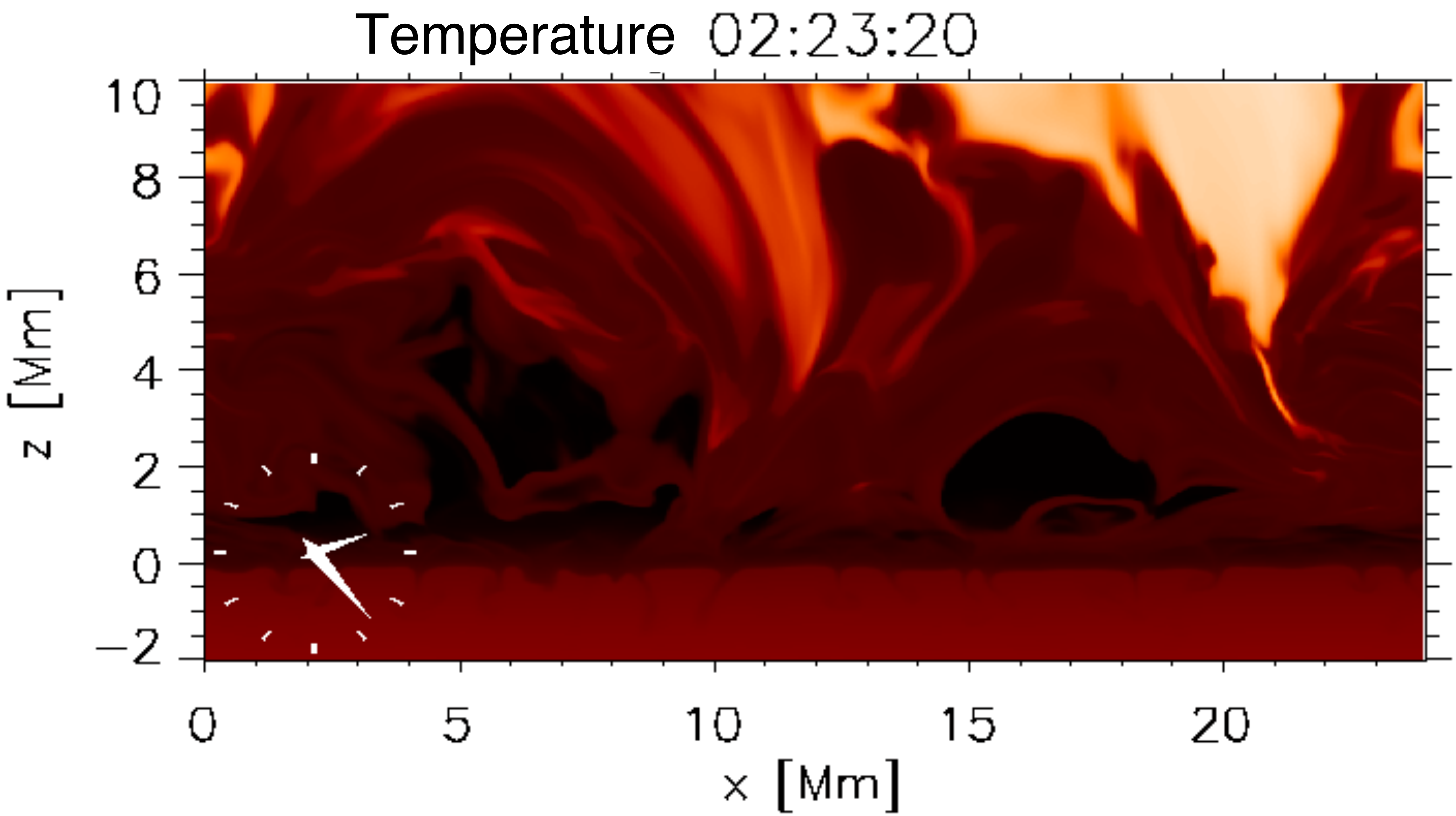
Summary

- Ejection of plasmoids leads to ‘patchy’ reconnection and, thus, spatially intermittent heating.
- Plasmoids share field lines, thus the eruption of one plasmoid initiates the "sympathetic" eruption of others.
- Eruption of plasmoids evolves into helical jets. Velocities comparable to local Alfvén speed.
- Average lifetime of individual small flares is of order 30 s - 3 minutes. Plasma heated to 1-6 MK.
- Some larger flares have energies of $O(10^{25})$ erg/s, but many events are superpositions of several small flares with 10^{23}-10^{24} erg/s.
- Average energy flux in the corona: $O(10^{6}-10^{7})$ ergs s^{-1} cm^{-2}.
- Considerable contribution of heating in the corona from small flares.

Evolution along and across the interface



The composite effect of the adjacent nanoflares



Time: 8600 – 9000 sec.

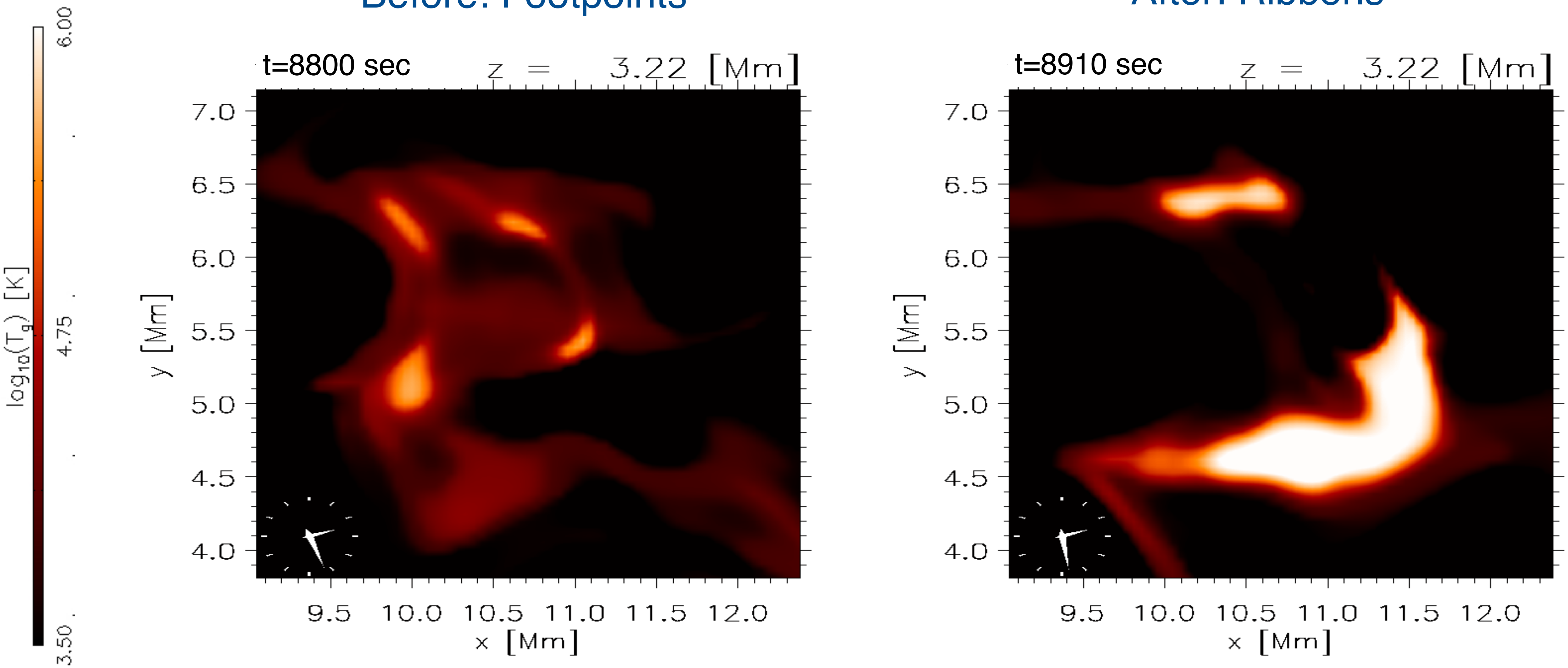
Log(T (K))=[3.3-6].

Nano/micro flares cluster together to produce another flare. Avalanche?

Before and after the clustering of flares.

Before: Footpoints

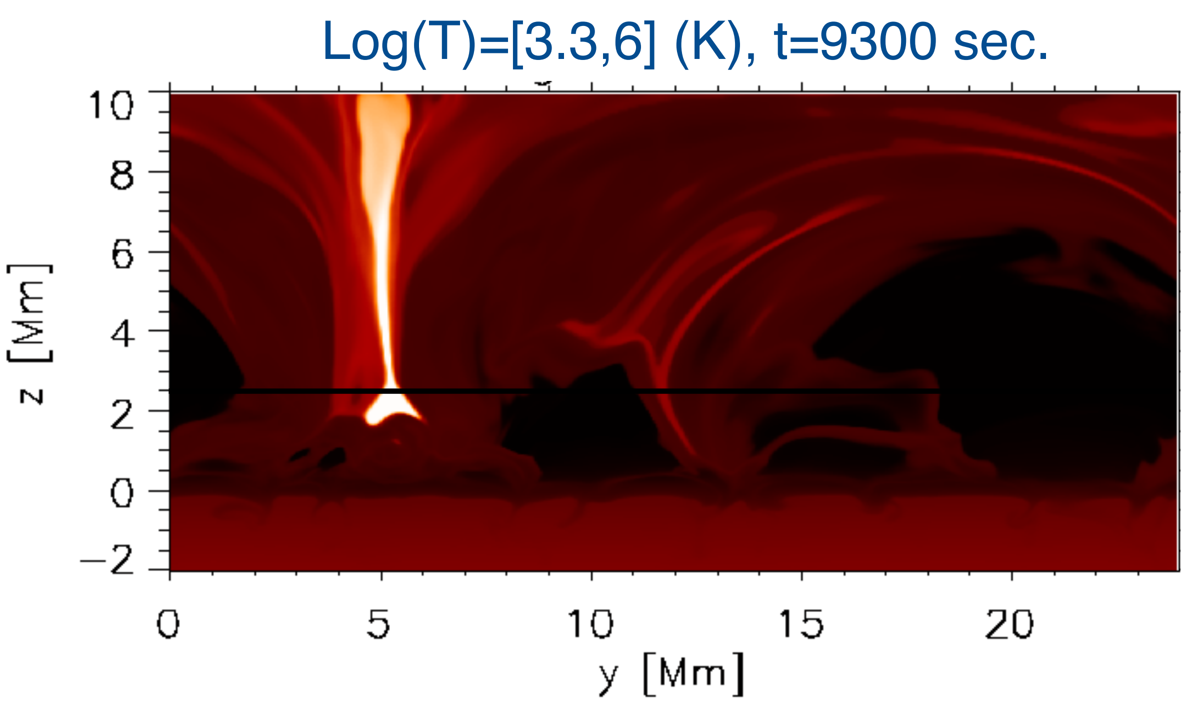
After: Ribbons

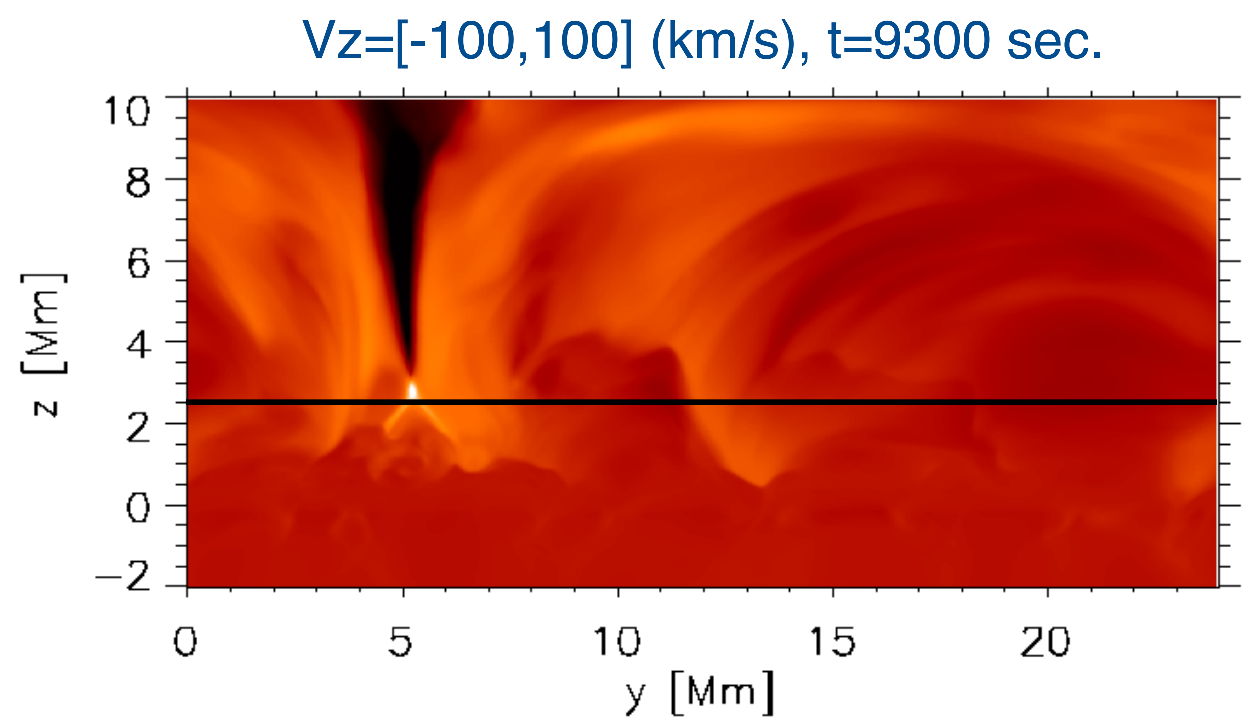


Heating at the footpoints: 3.5-5 x 10^5 K. Density: ~10^{-13} gr/cm^3 . Downflows: 20-30 km/s.

Heating at the ribbons: 1-1.7 MK. Density: ~ 10^{-13} gr/cm^3 . Downflows: 50-70 km/s.

Interface: Onset in the Transition Region.





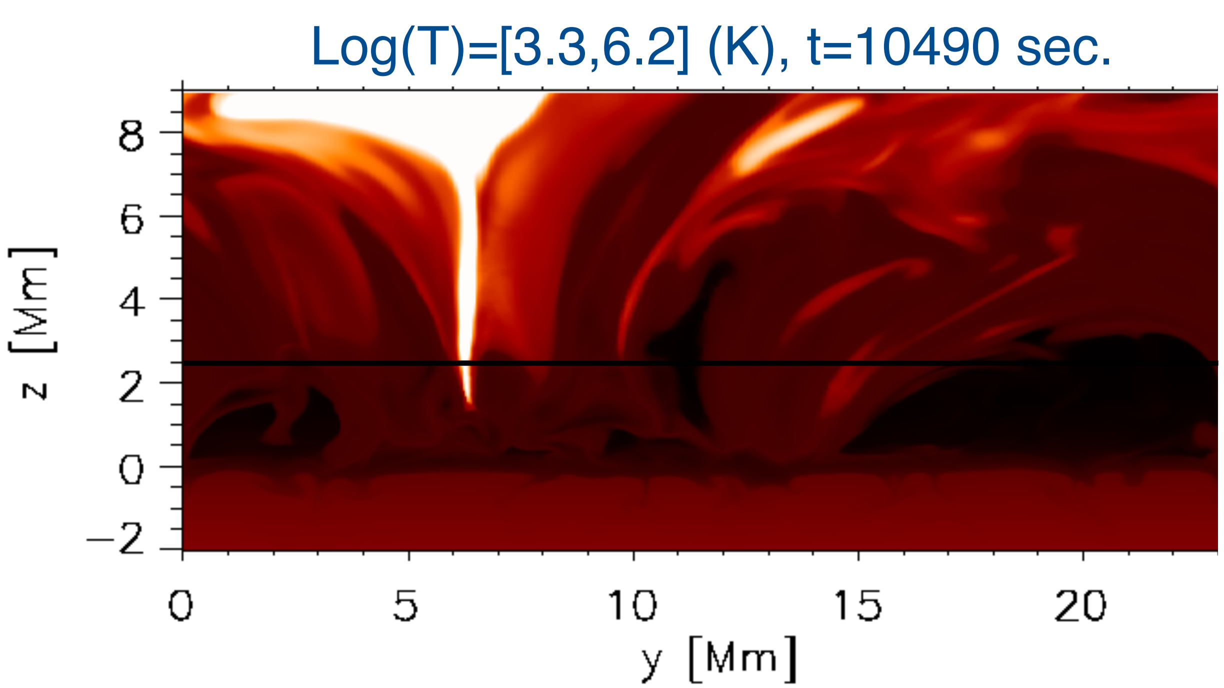
Deposition of energy in the Transition Region.

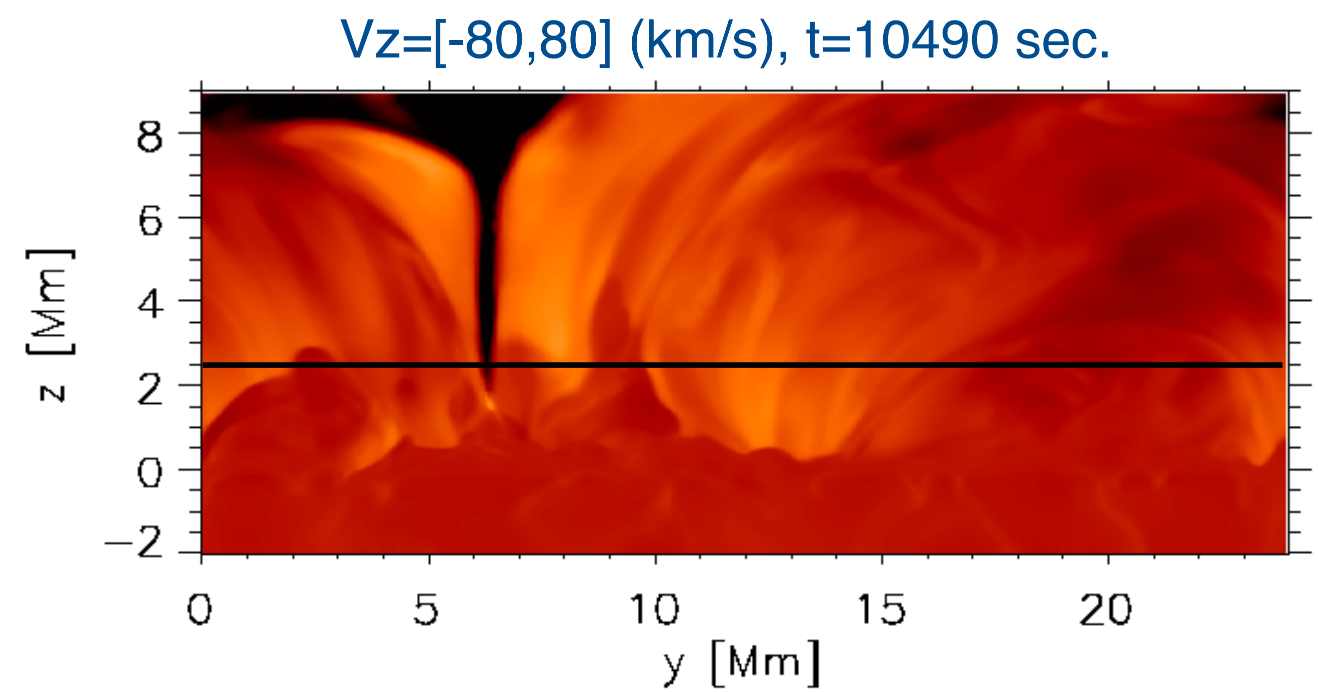
Onset of nanoflare(s) (~10^{23} erg/s).

Jets up to 150 km/s.

Heating (max): Transition Region (2.5 MK), Upper Chromosphere (1.9 MK).

Interface: Onset in the Chromosphere.





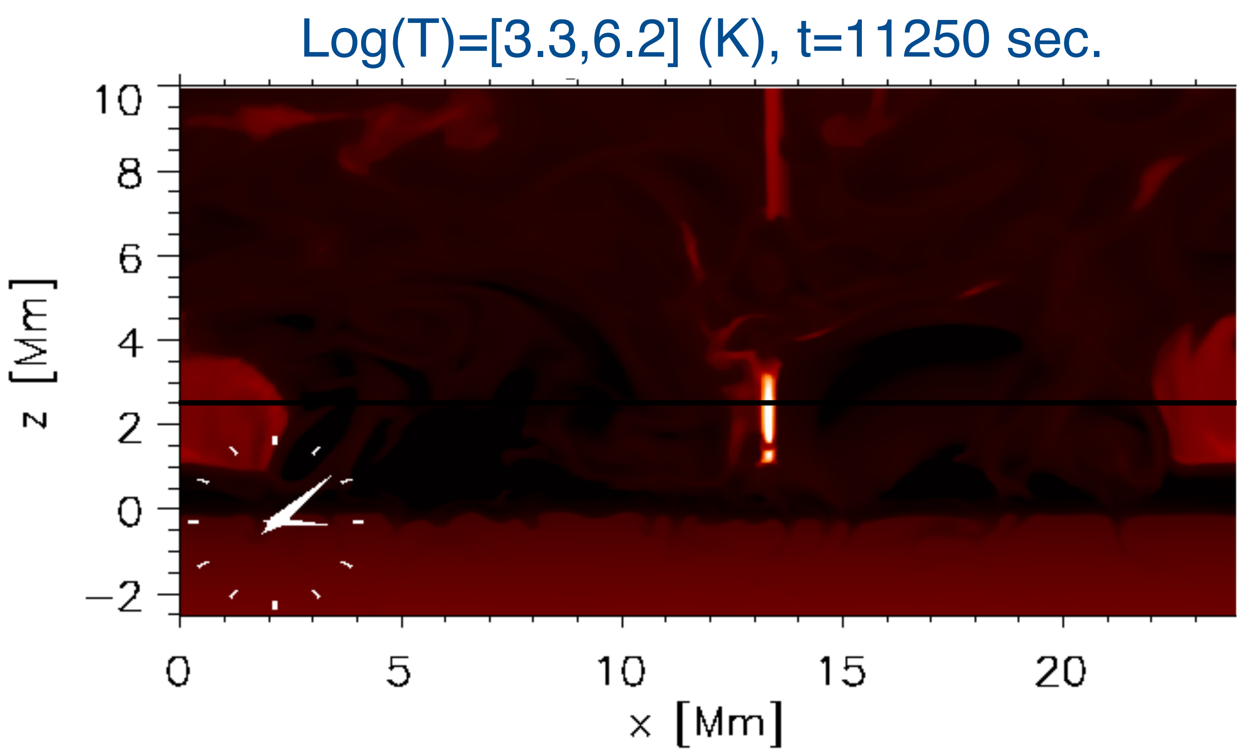
Deposition of energy in the Chromosphere.

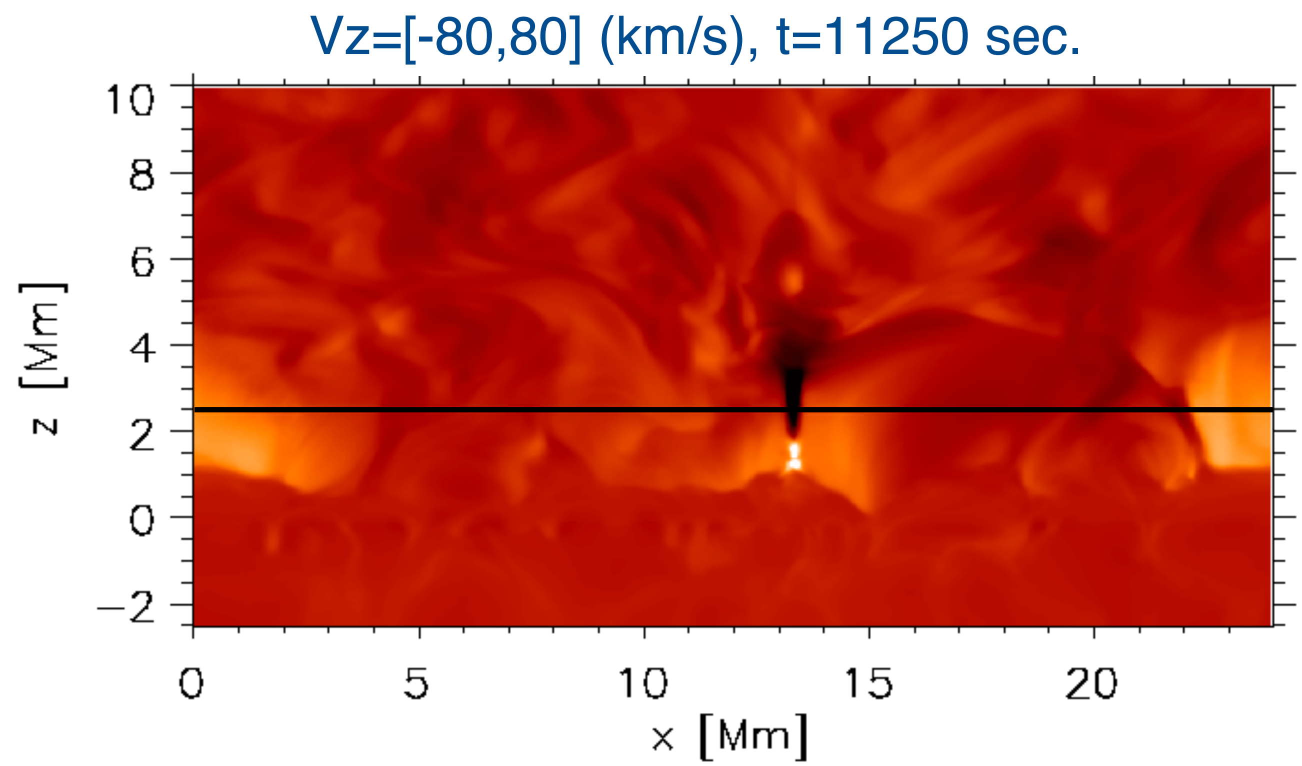
Onset of nano/micro-flare(s) (10^{24} - 10^{25} erg/s).

Upflows ~ 50-60 km/s (chromosphere), > 300 km/s (corona).

Heating (max): Transition Region/Corona (5-6 MK), Upper Chromosphere (2 MK).

Domain: Onset in the Chromosphere.





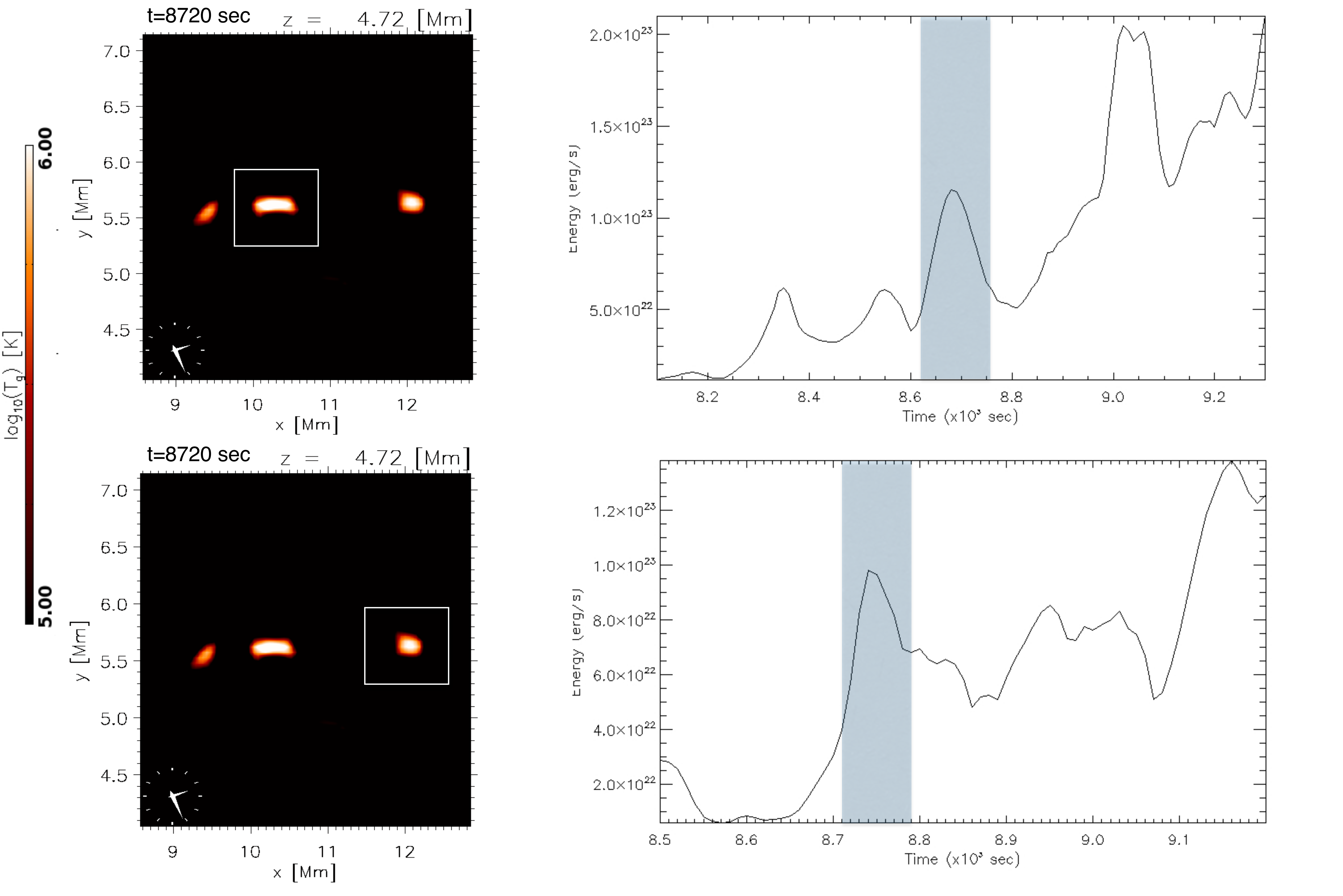
Deposition of energy in the chromosphere.

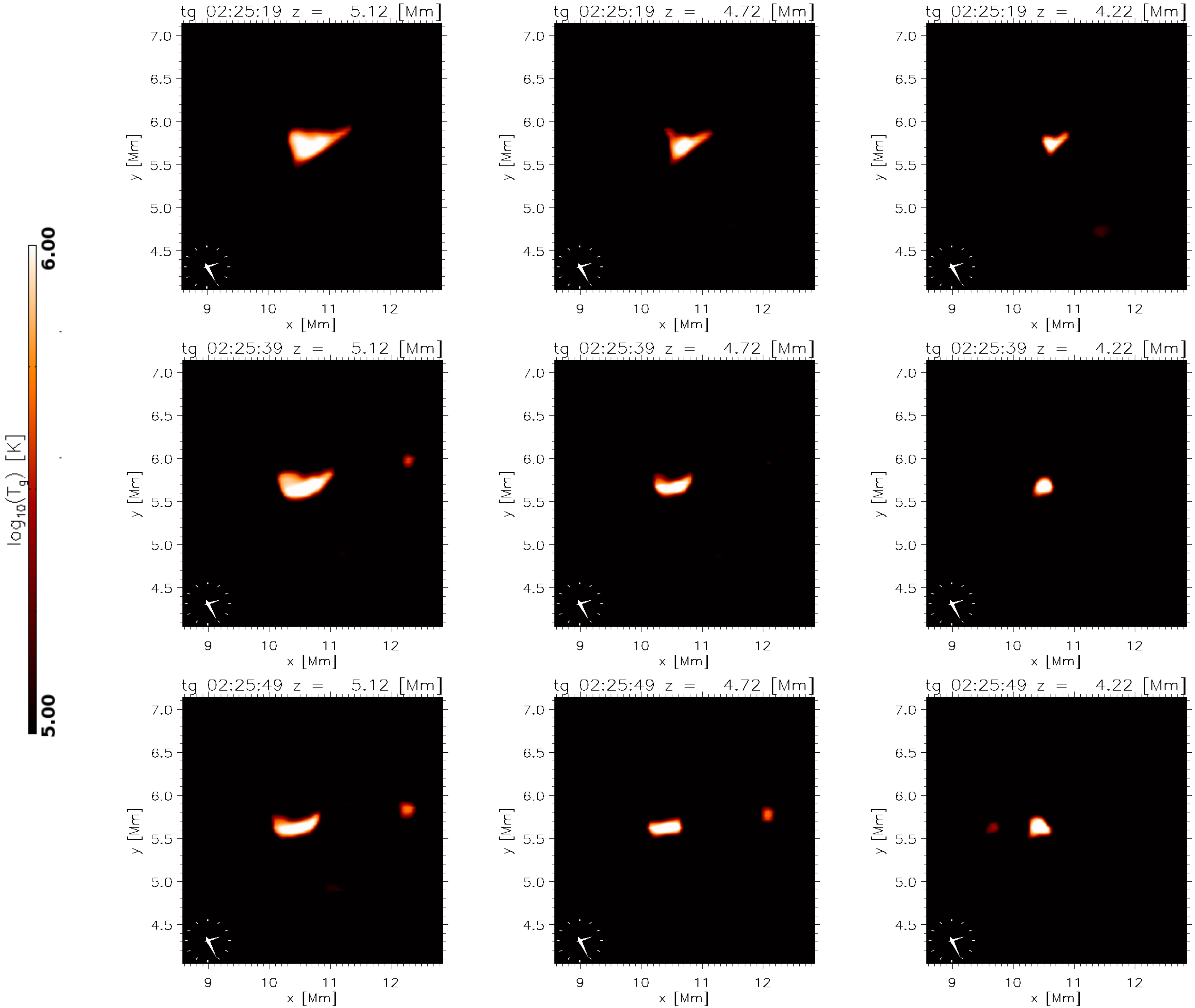
Onset of nano/micro-flare(s) (10^{24} - 10^{25} erg/s).

Upflows ~ 86 km/s (chromosphere), > 100 km/s (transition region).

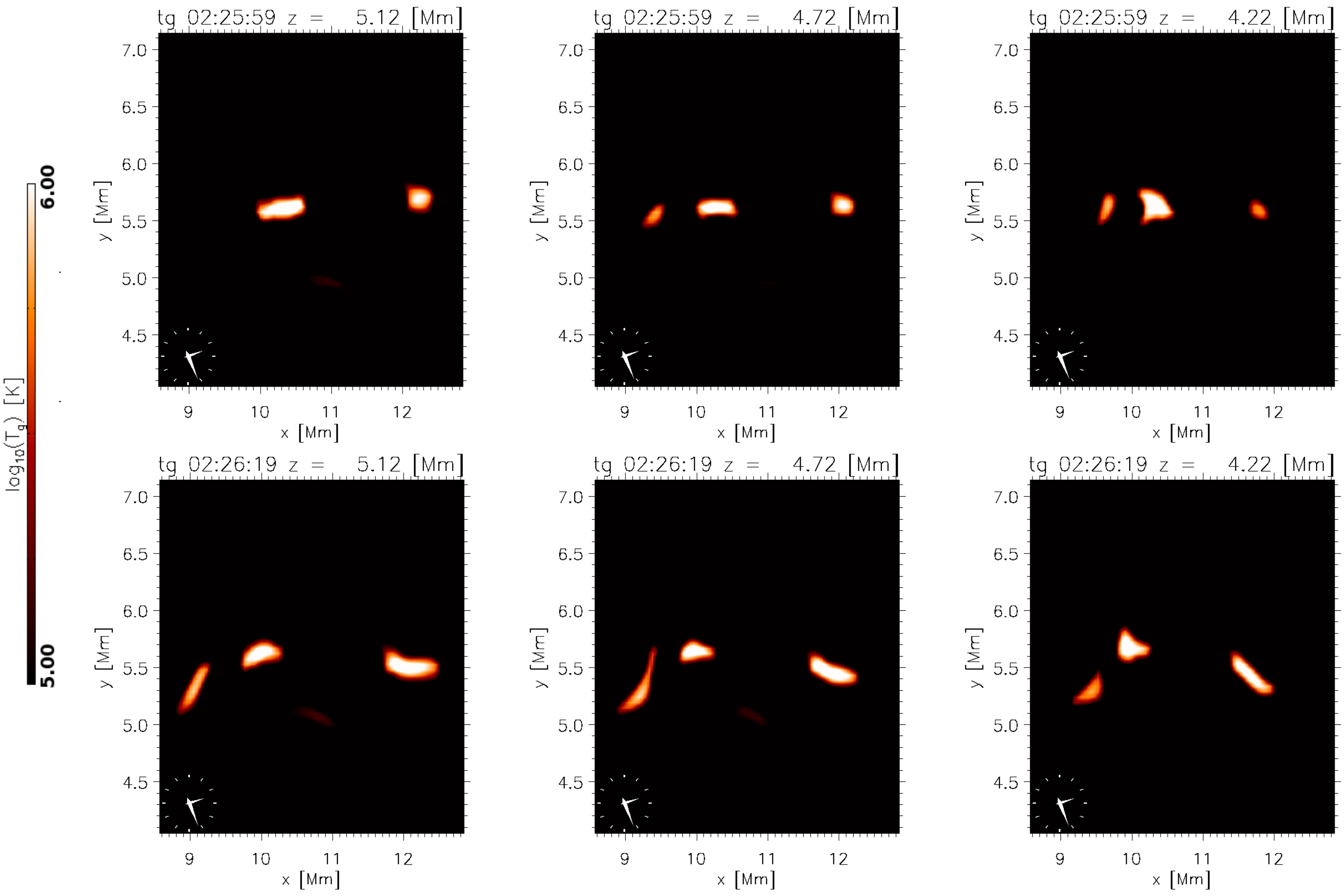
Heating (max): mid Chromosphere (8×10^4 K).

Energy of the ‘individual’ small flares



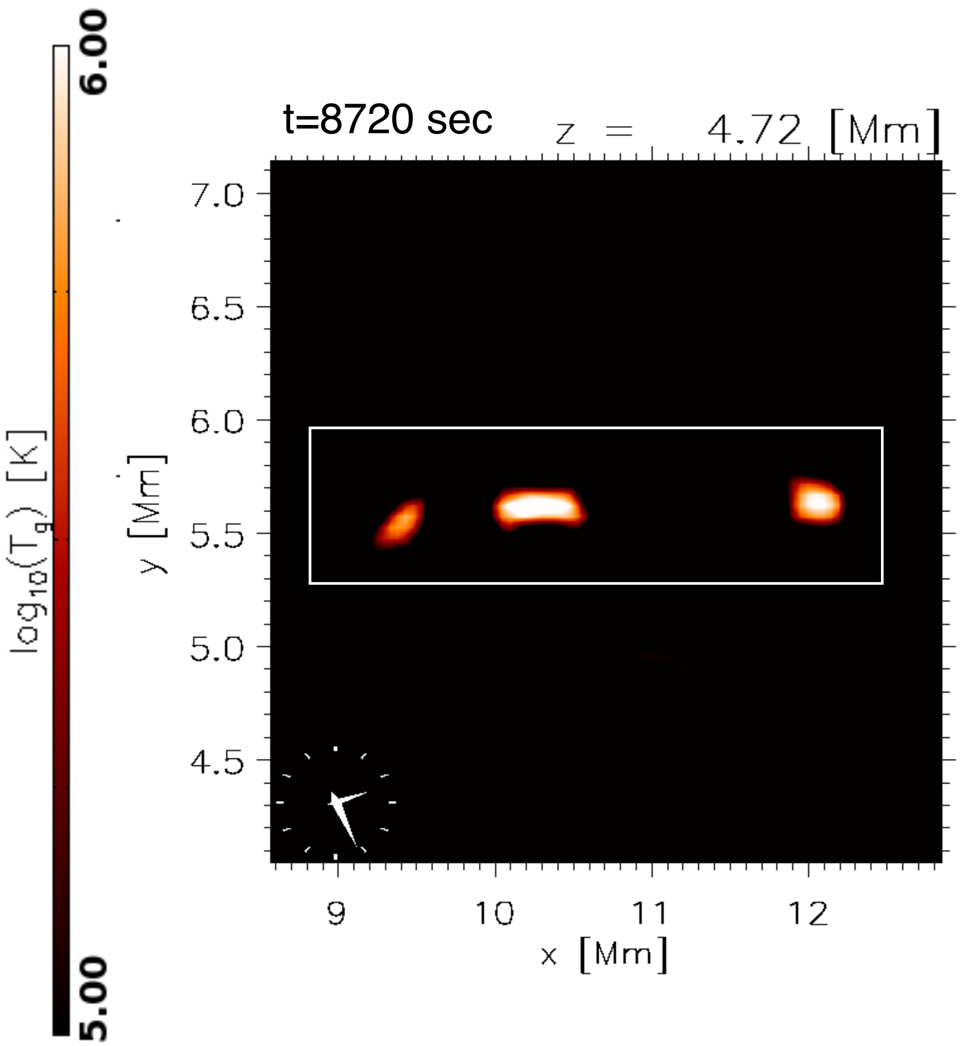


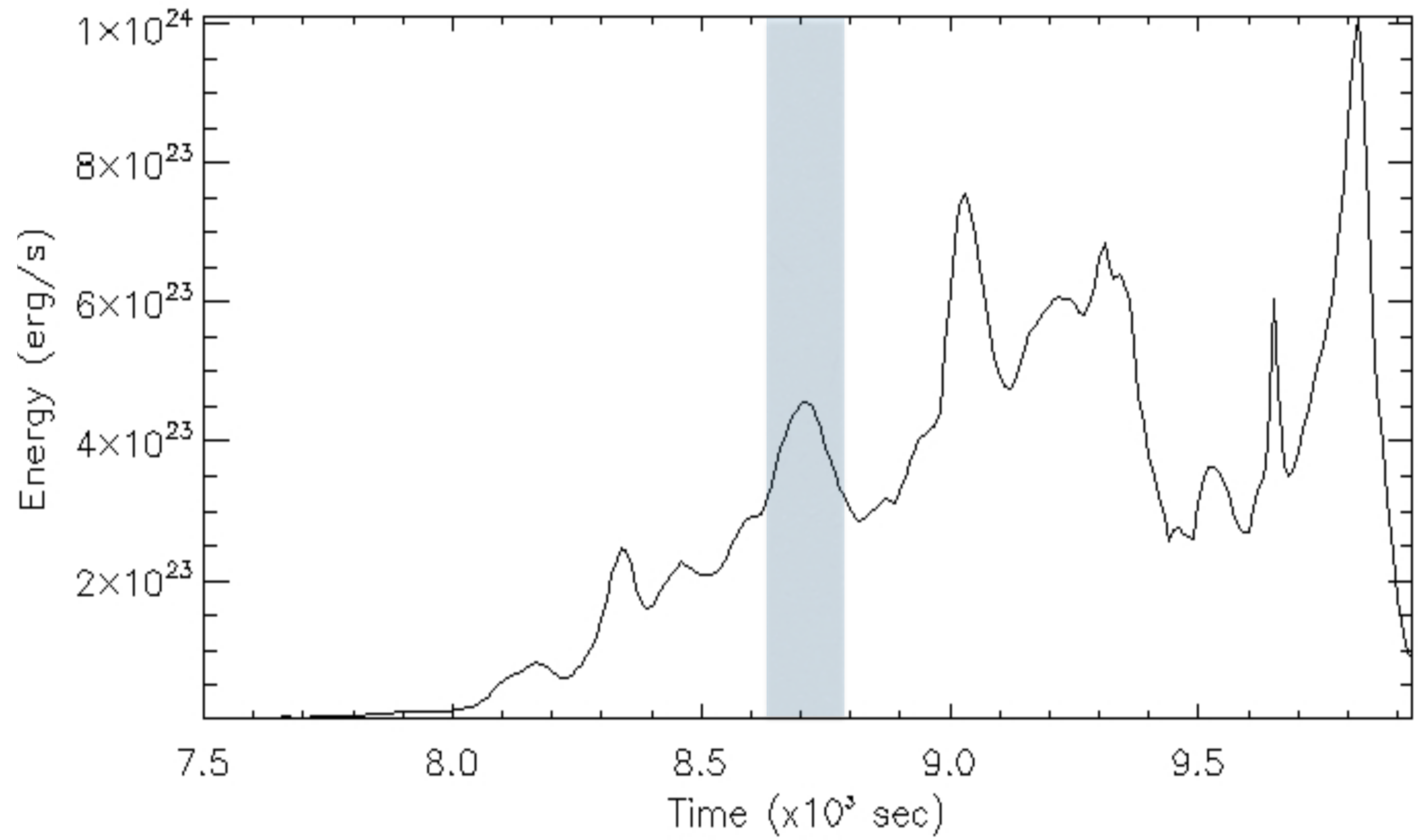
tg 02:25:19 z = 5.12 [Mm]
tg 02:25:19 z = 4.72 [Mm]
tg 02:25:19 z = 4.22 [Mm]
tg 02:25:39 z = 5.12 [Mm]
tg 02:25:39 z = 4.72 [Mm]
tg 02:25:39 z = 4.22 [Mm]
tg 02:25:49 z = 5.12 [Mm]
tg 02:25:49 z = 4.72 [Mm]
tg 02:25:49 z = 4.22 [Mm]
y [Mm]
x [Mm]
log10(Tg) [K]
6.00
5.00



tg 02:25:59 z = 5.12 [Mm]
tg 02:25:59 z = 4.72 [Mm]
tg 02:25:59 z = 4.22 [Mm]
tg 02:26:19 z = 5.12 [Mm]
tg 02:26:19 z = 4.72 [Mm]
tg 02:26:19 z = 4.22 [Mm]
y [Mm]
x [Mm]
7.0
6.5
6.0
5.5
5.0
4.5
9
10
11
12
$\log_{10}(T_g)$ [K]
6.00
5.00

Small-scale brightenings in the nanoflare energy regime.

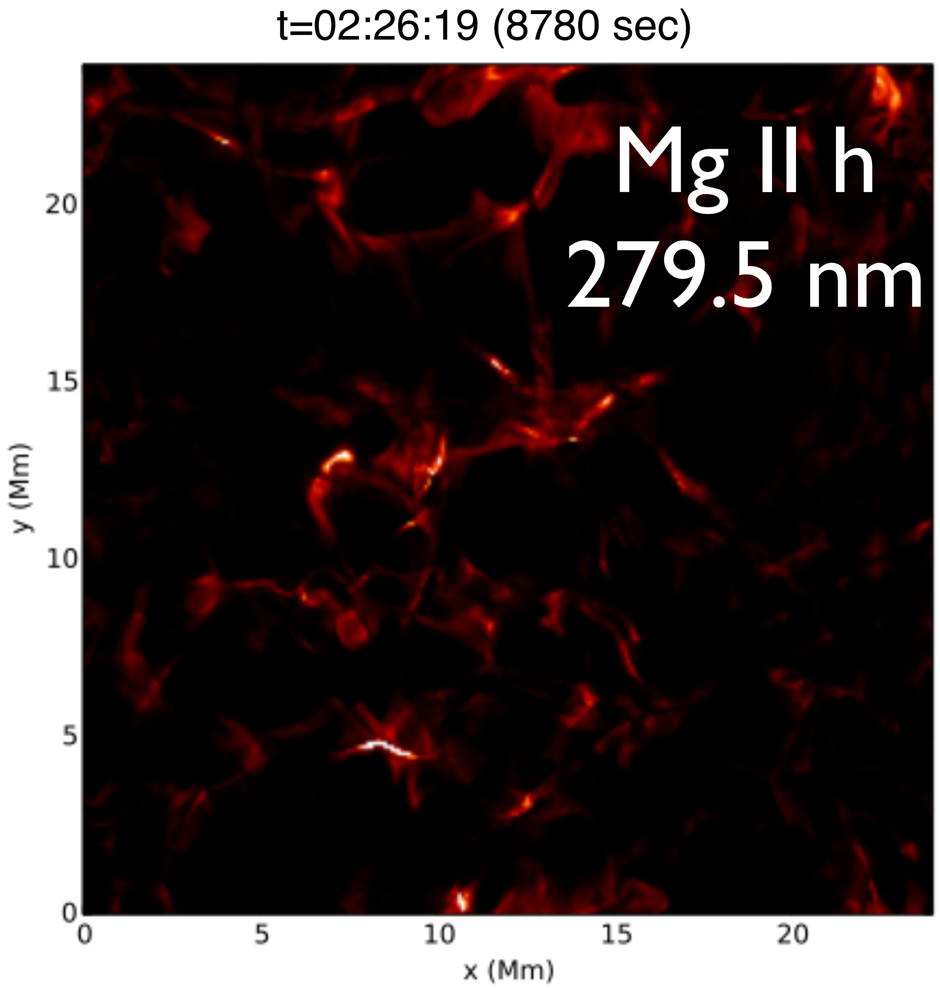


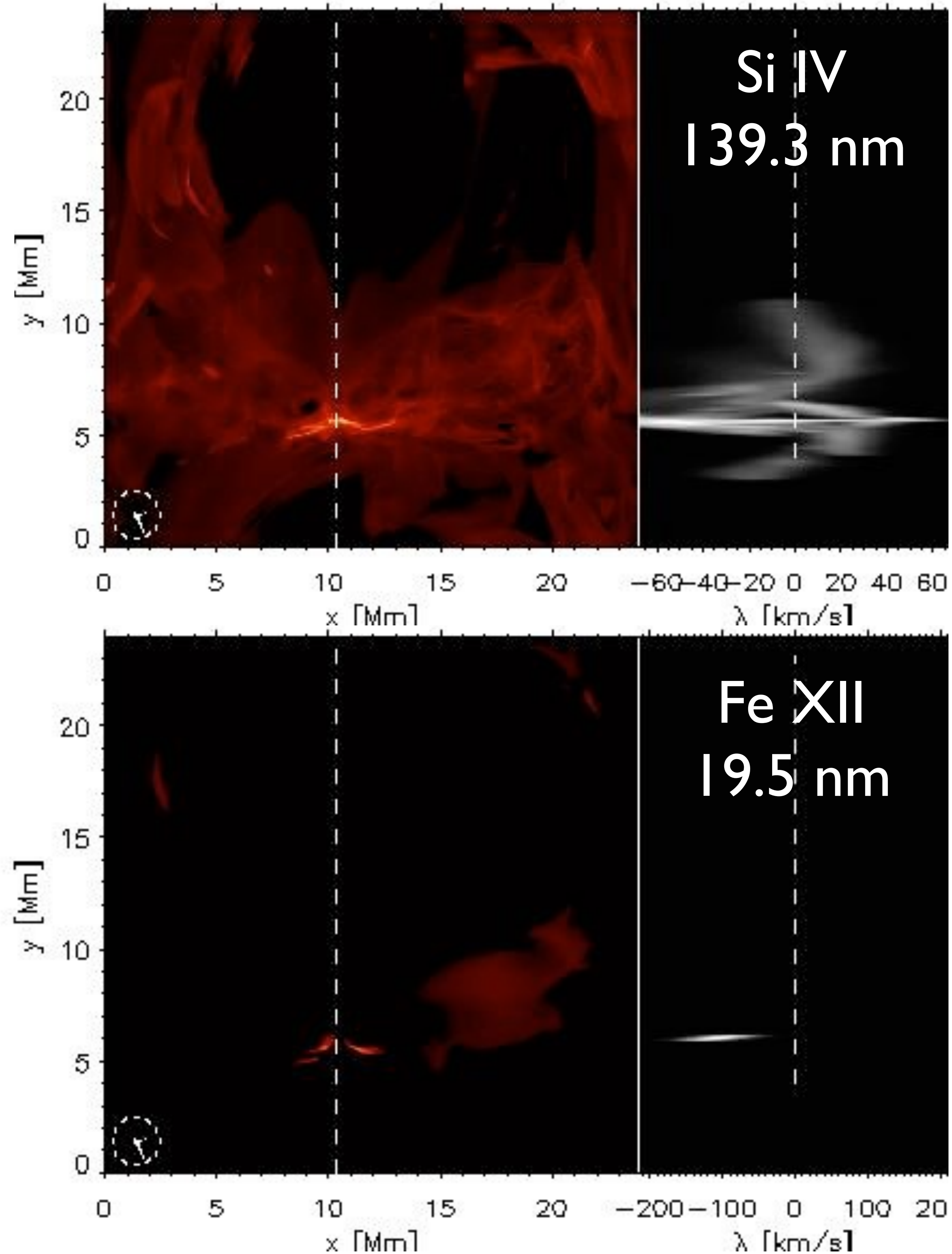


Temperatures: 7×10^5 K (left), 1.5×10^6 K (central), 1×10^6 K (right).

Thermal energy (corona): impulsive energy release – many bursts.

Cluster of three small (nano)-flares : ~ 4 x 10^{23} erg/s.



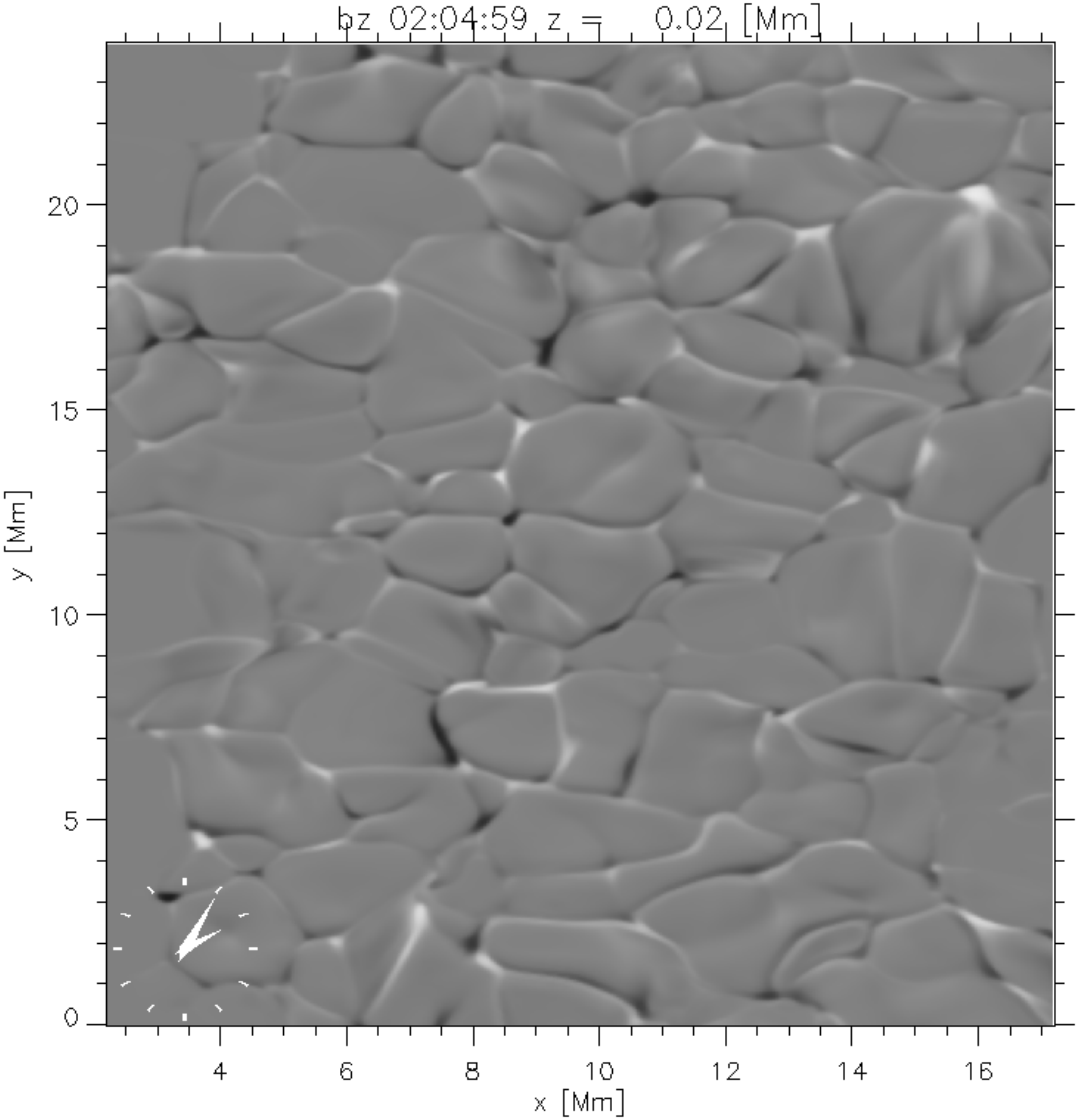


Mg II h 279.5 nm: $Log(T_{max}(k)) \sim 4.0$

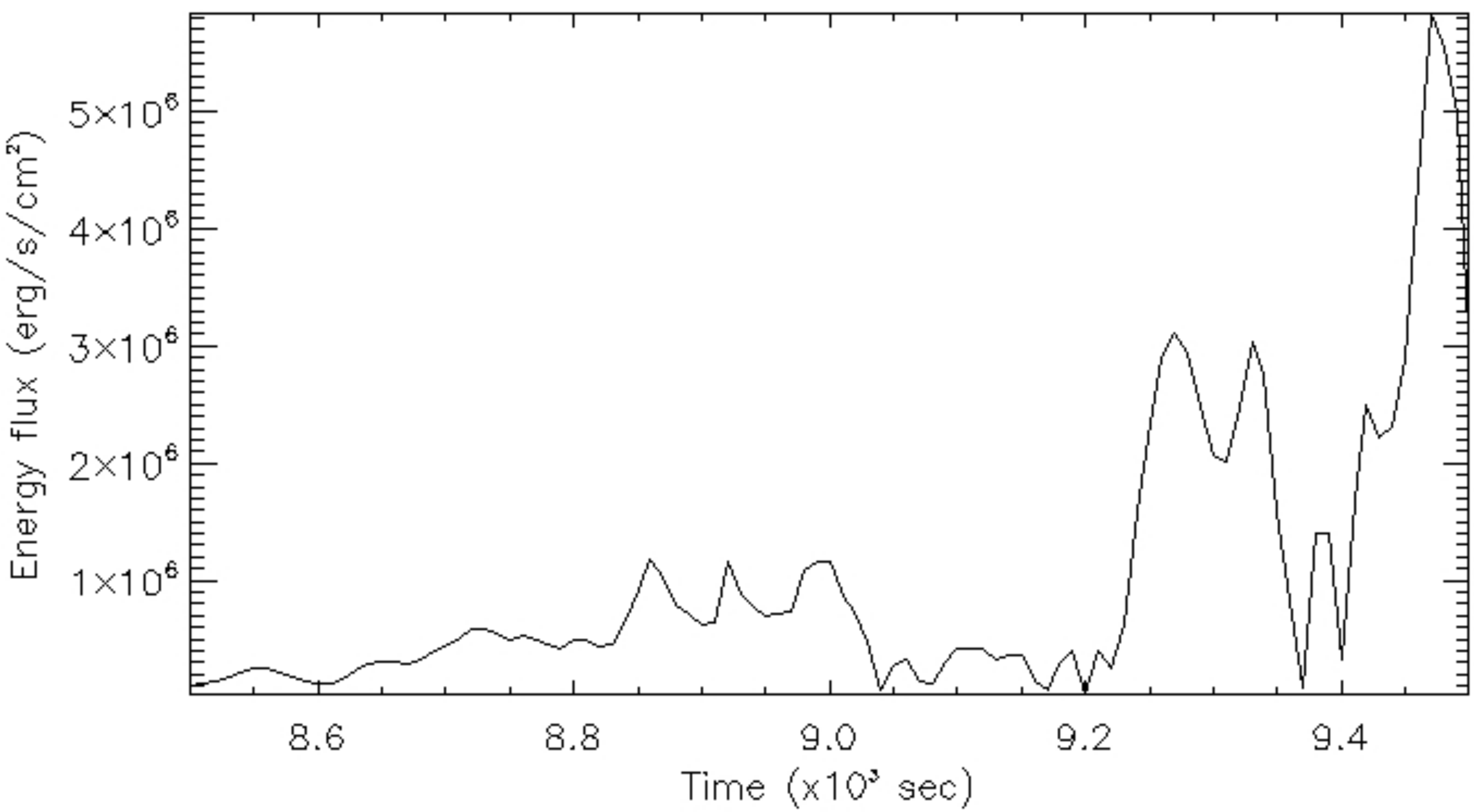
Si IV 139.3nm : $Log(T_{max}(k)) \sim 4.8$

Fe XII 19.5 nm: $Log(T_{max}(k)) \sim 6.2$

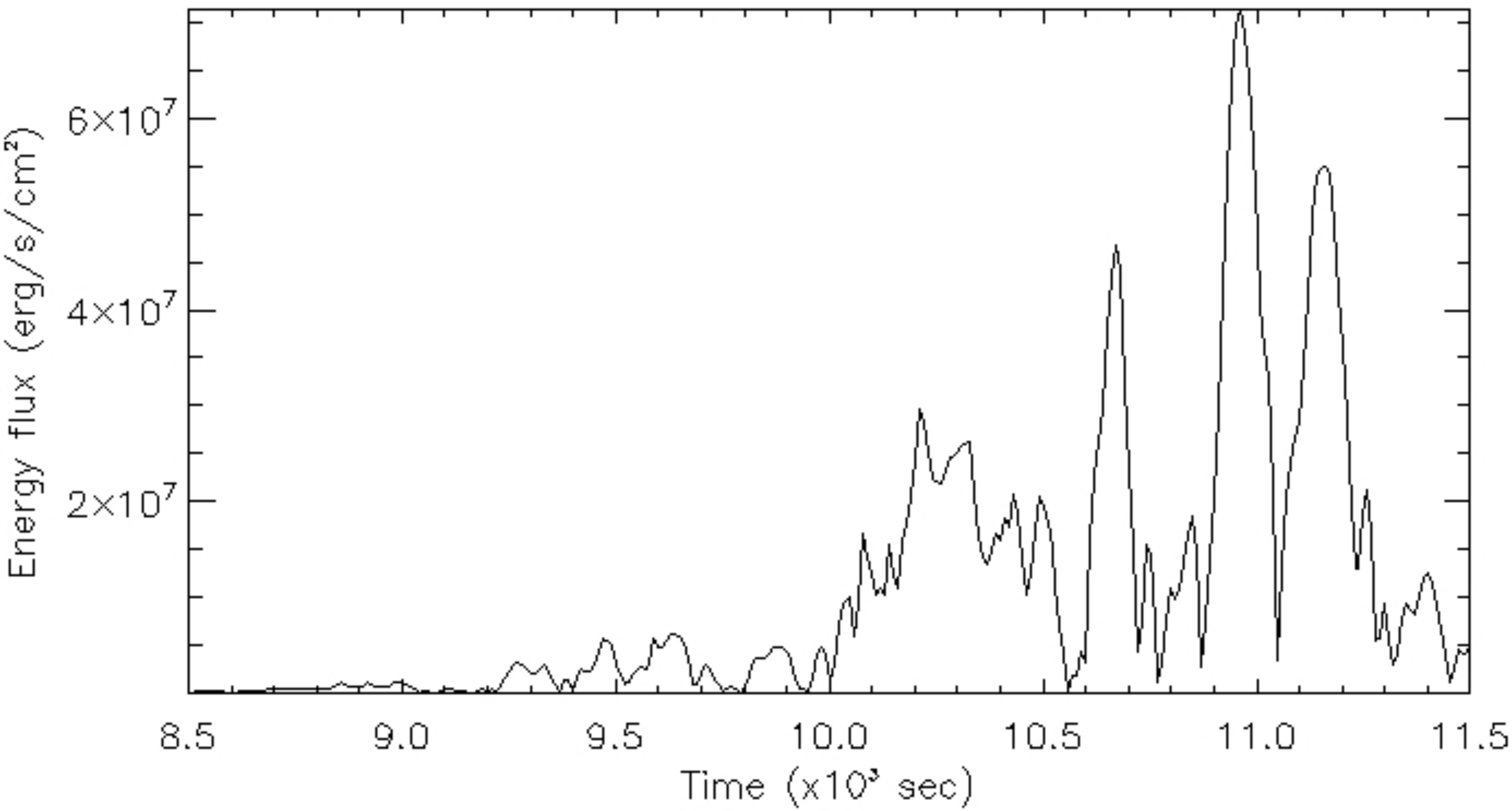
Emergence at the photosphere



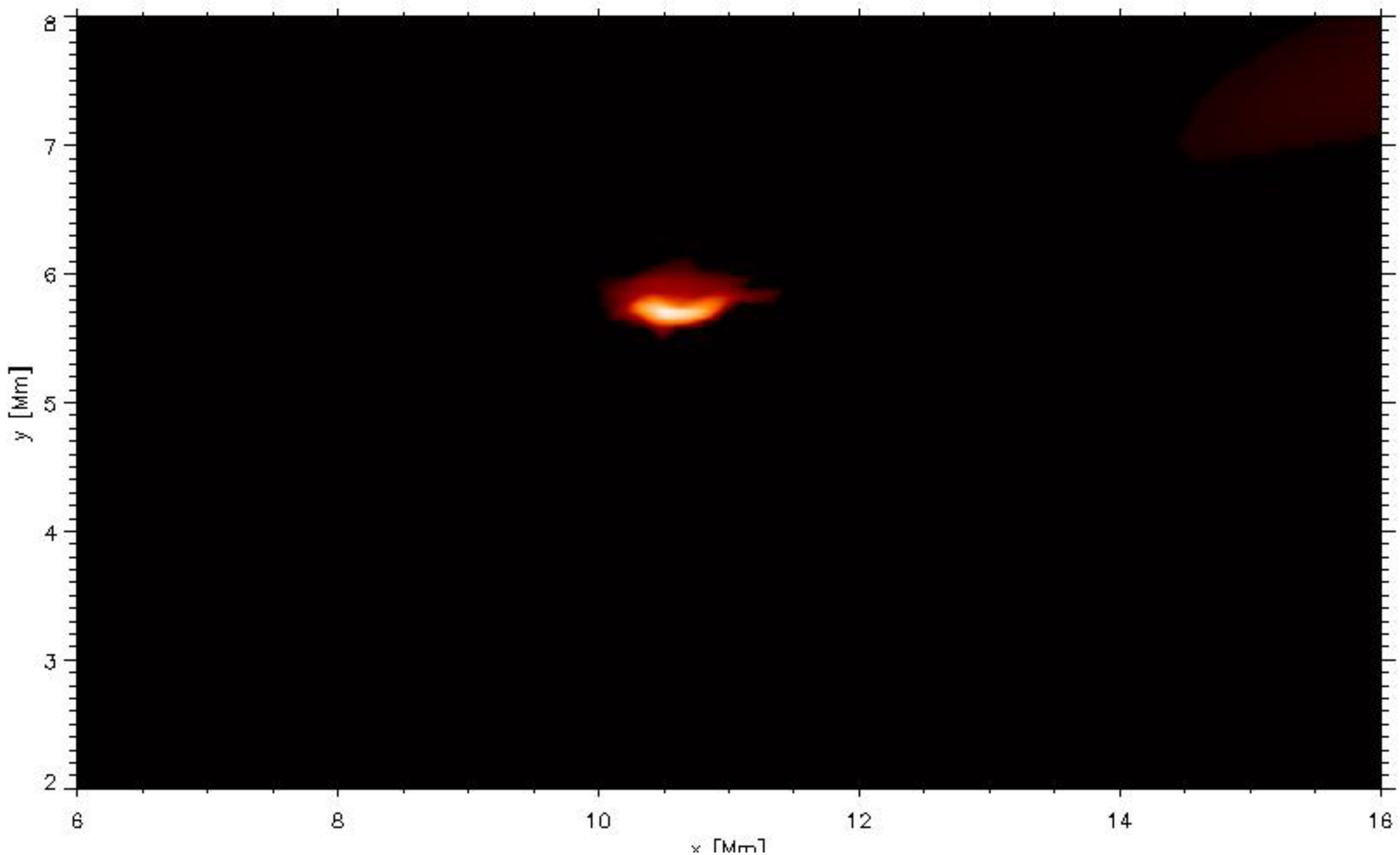
Energy flux carried by small flares



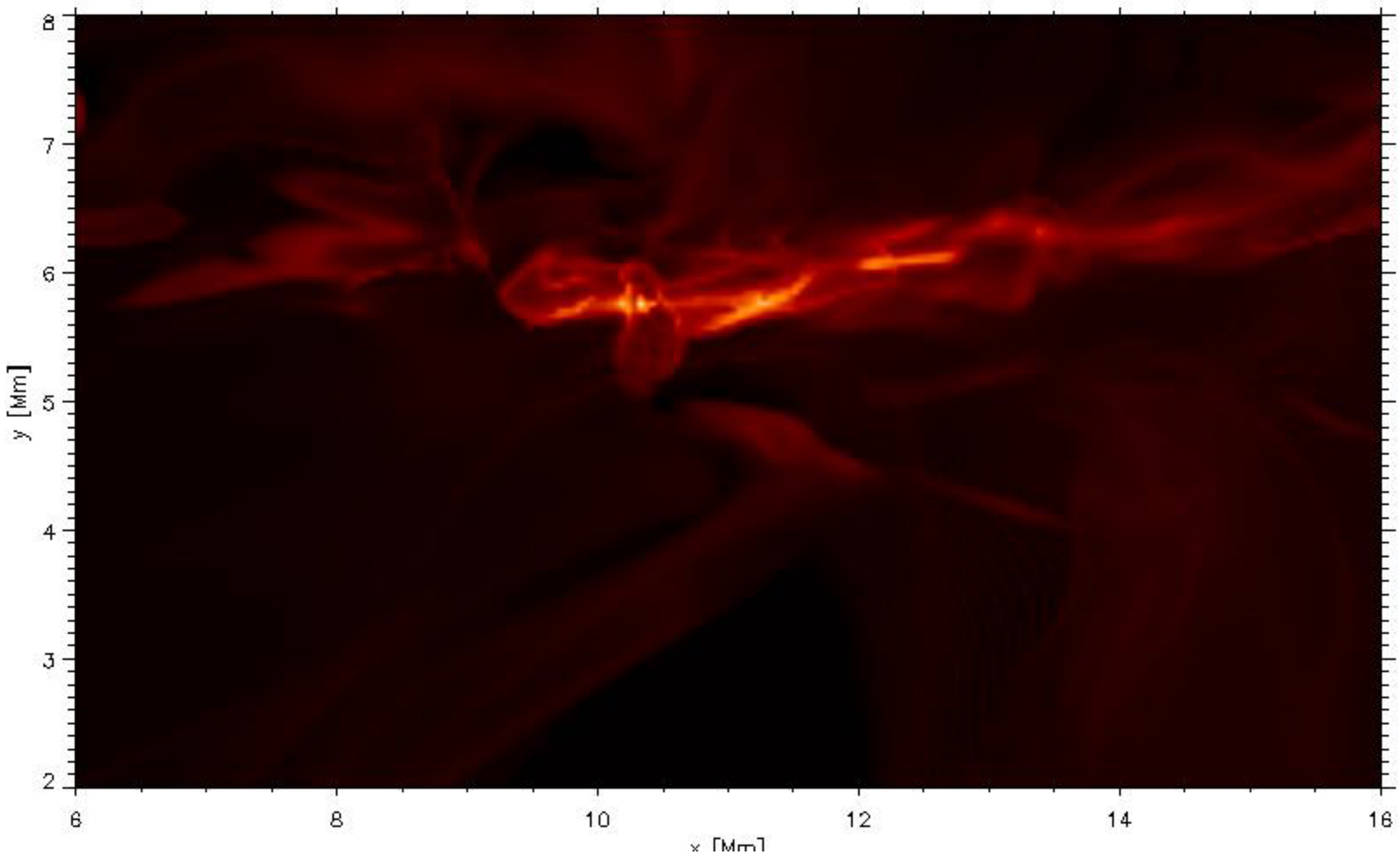
Energy flux carried by 'small' flares



FE XII 19.5 nm (top view)

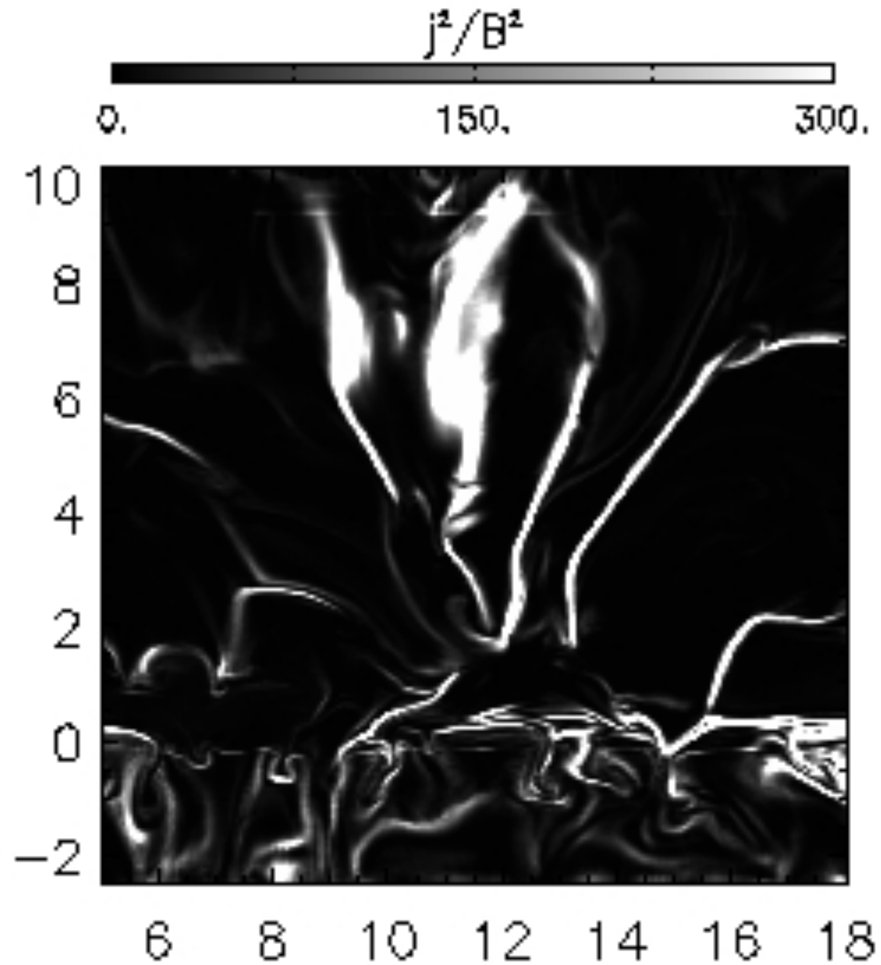


Si IV 139.3 (top view)



Current layer

- Size: height ~ 10 Mm, width (x) < 0.5 M, length ~ 4 Mm.
- Resolution at photosphere/chromosphere ~ 25-40 km.
- 10-20 grid points across the current layer.
- Max temperature distribution within the current layer .



Flares

- Occurrence rate: minimum 10 flares in 38 min in one current sheet + area of integration 4.3Mm x 4.7 Mm, gives 2.1×10^{-20} s^{-1} cm^{-2} .
- Average energy flux: typical energies in small flares $O(10^{26})$-$O(10^{27})$ erg, gives 2.1×10^{6} erg s^{-1} cm^{-2} or 2.1×10^{7} erg s^{-1} cm^{-2}.
- Poynting flux in the corona, over the whole domain: 1-60 kW m^{-2}.

EOS

** Ideal gas law

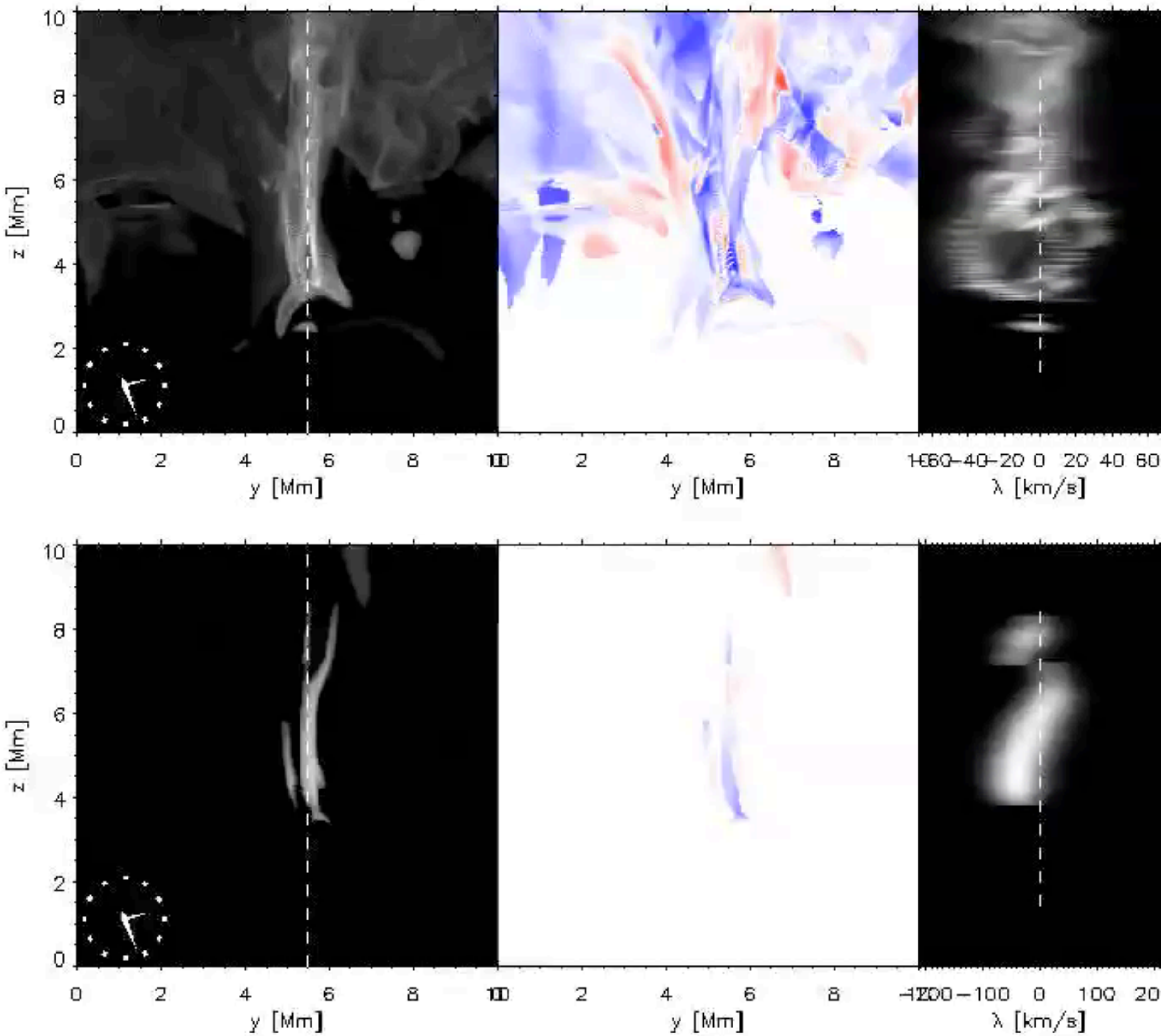
** The second module implements an EOS based on tables generated with the Uppsala Opacity Package (Gustafsson et al. 1975). It assumes local thermodynamic equilibrium (LTE) for atomic level populations and instantaneous molecular dissociation equilibria. This package is required when running with full radiative transfer (see Sect. 8.3), as it also provides the opacity, thermal emission and scattering probability for the radiation bins. The tables are generated with a separate program; different tables can be generated to account for different stellar spectral type, chemical composition and number of radiation bins.

** The third package computes the gas temperature, gas pressure and electron density explicitly based on the non-equilibrium ionization of hydrogen in the solar atmosphere. This package can only be used for simulations of the solar atmosphere.

Side view

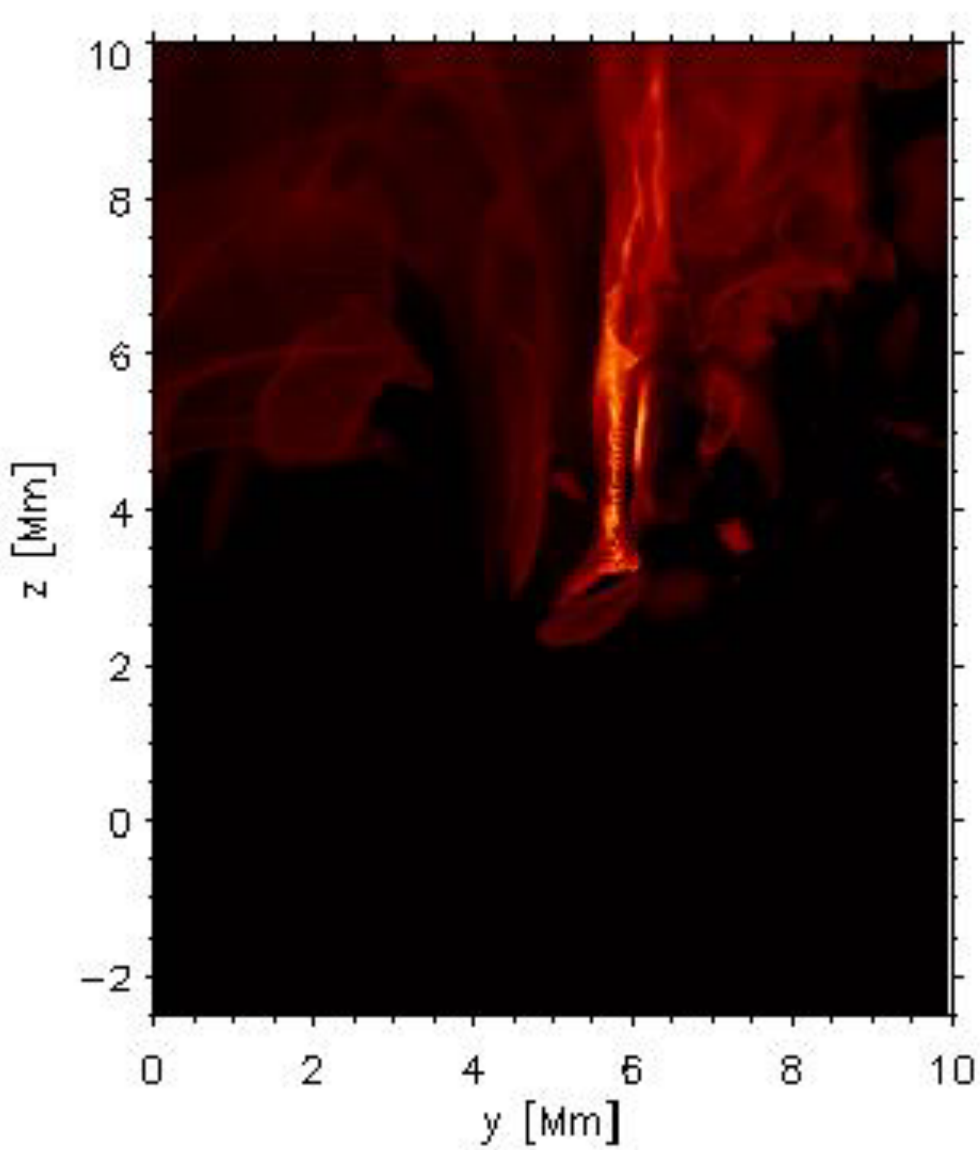
Si IV
139.3 nm

Fe XII
19.5 nm

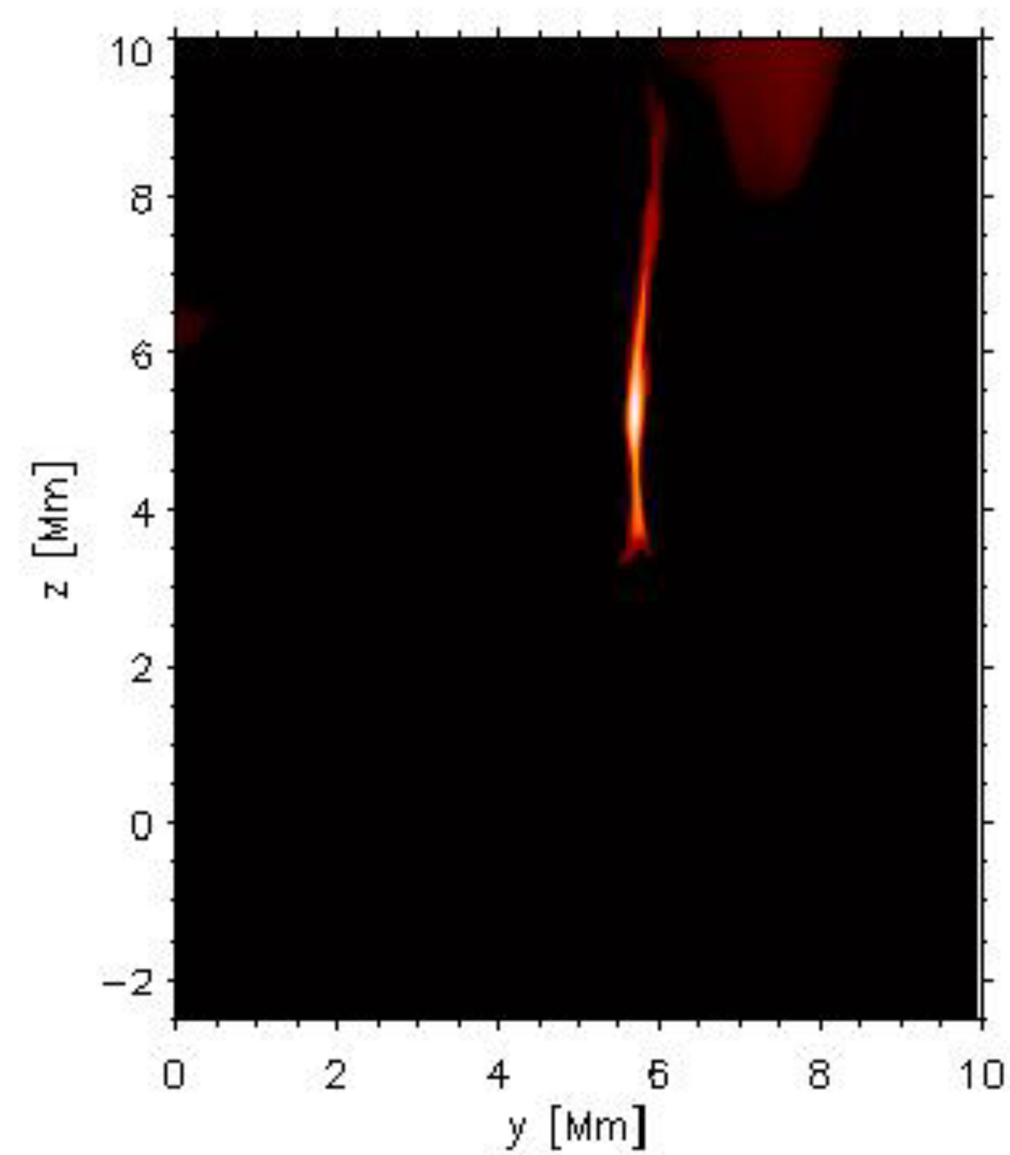


Side view

Si IV 139.3 nm



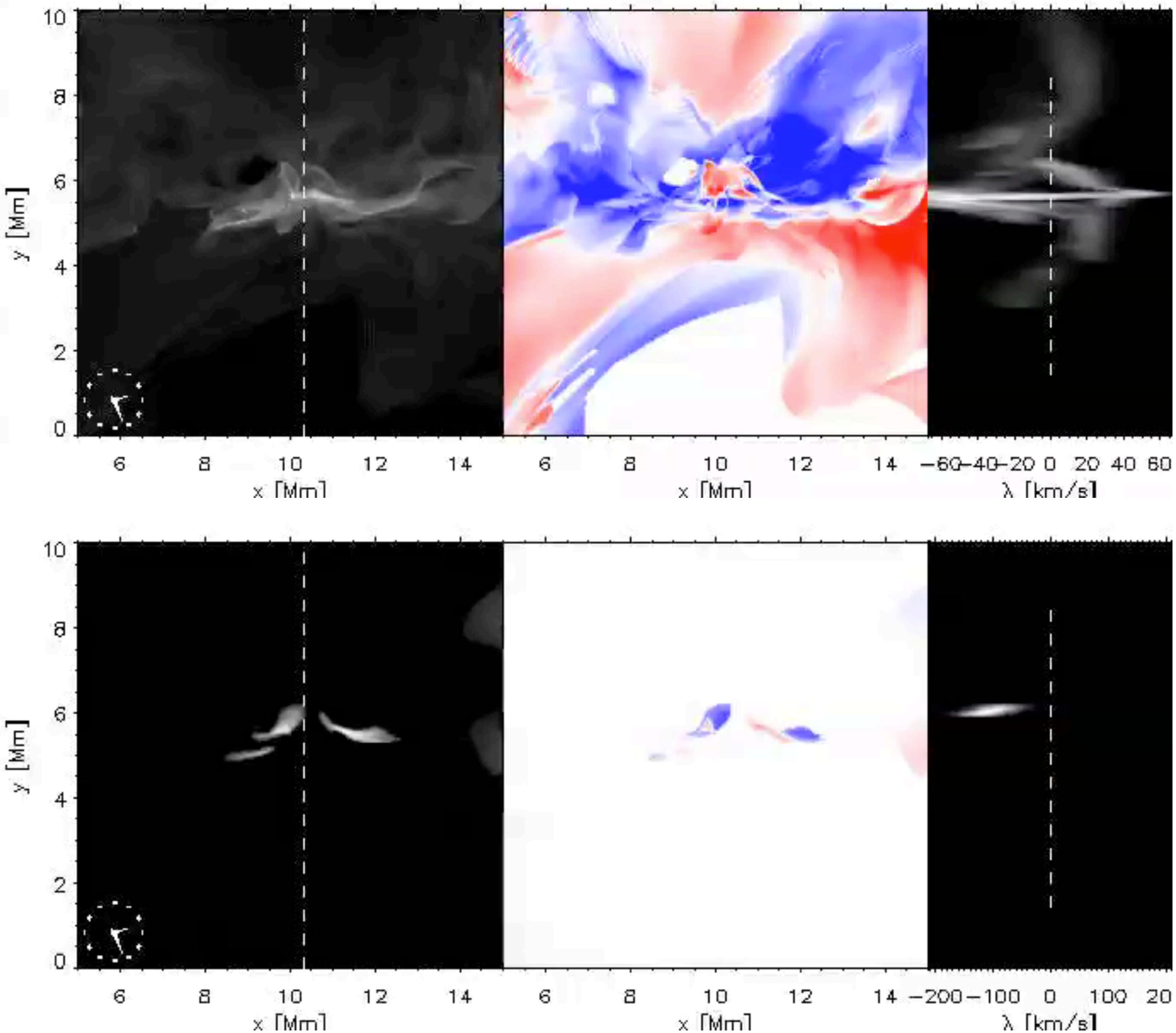
Fe XII 19.5 nm

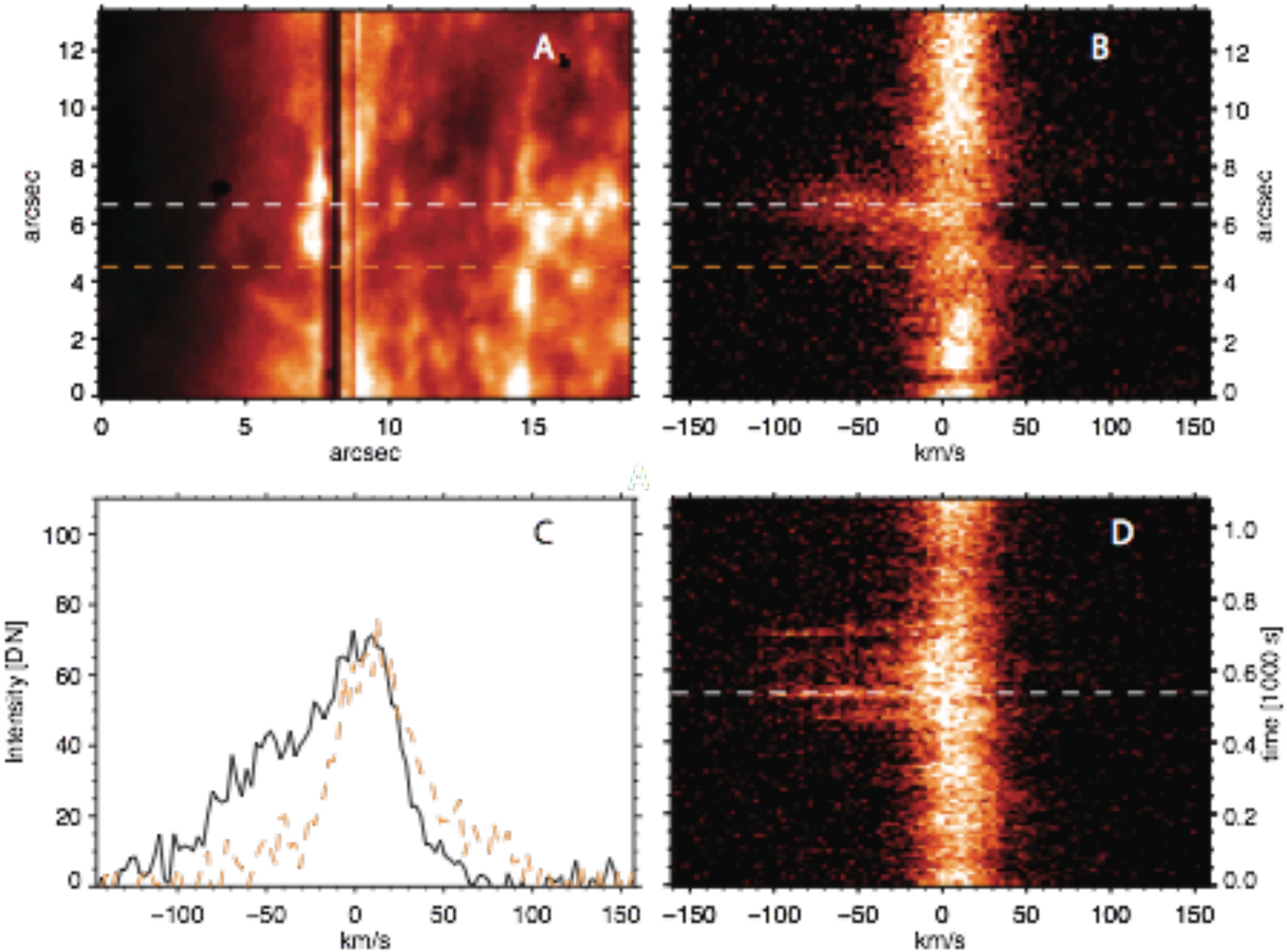


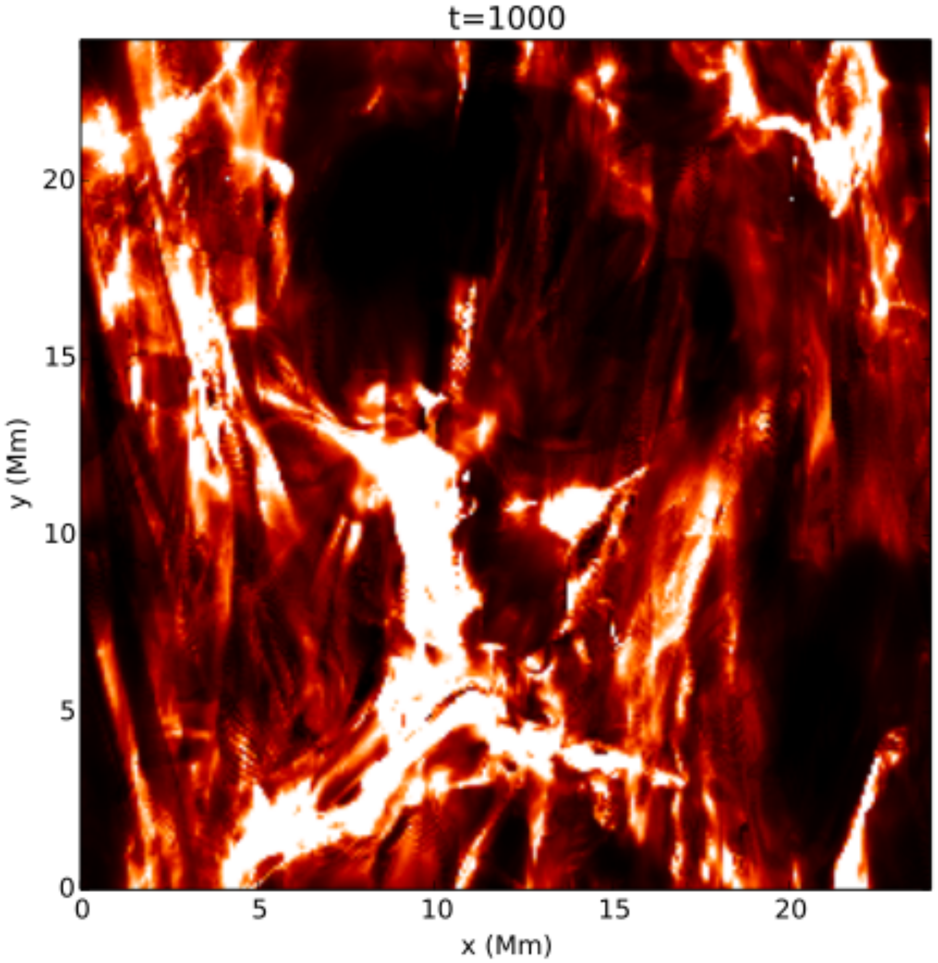
Top view

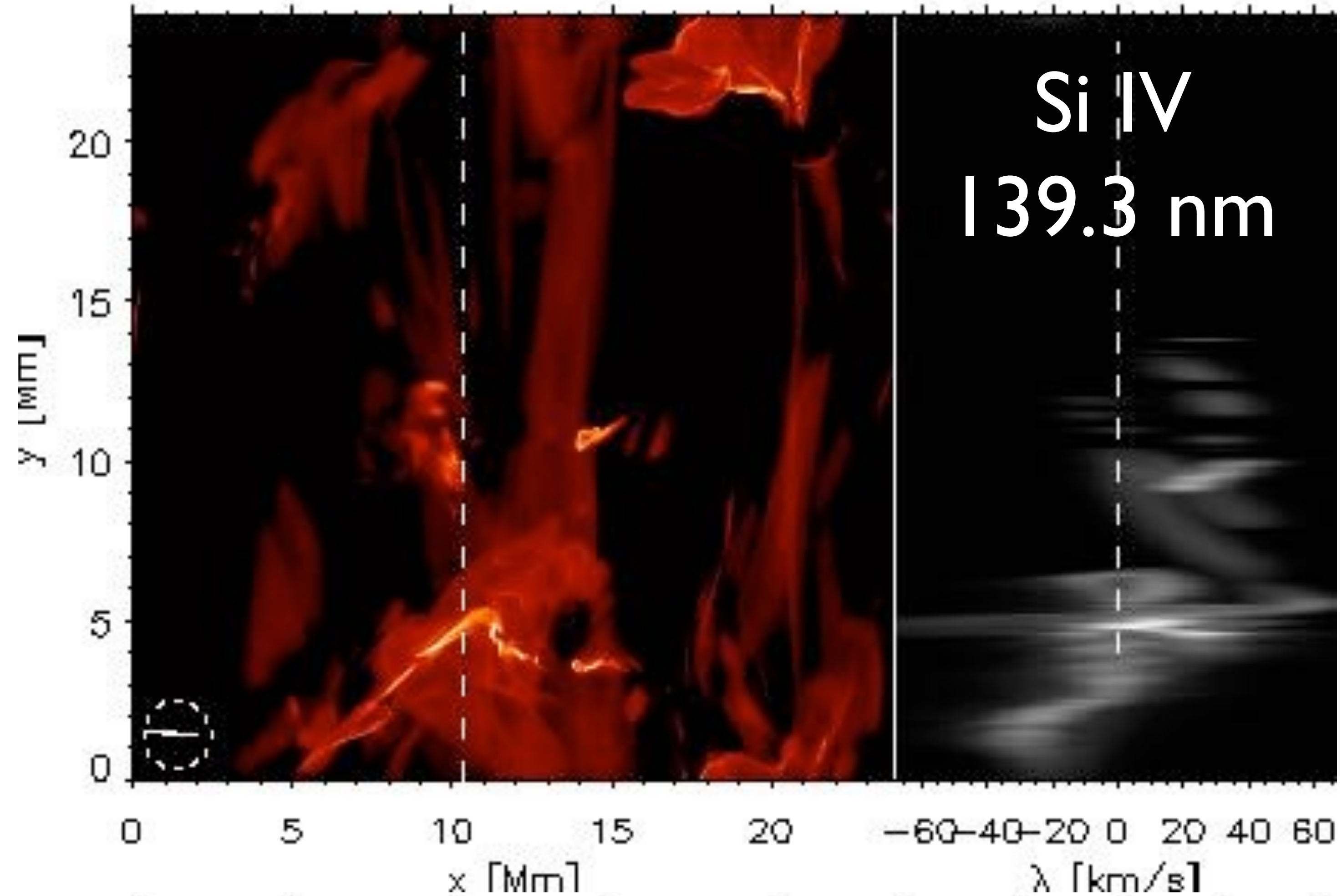
Si IV
139.3 nm

Fe XII
19.5 nm

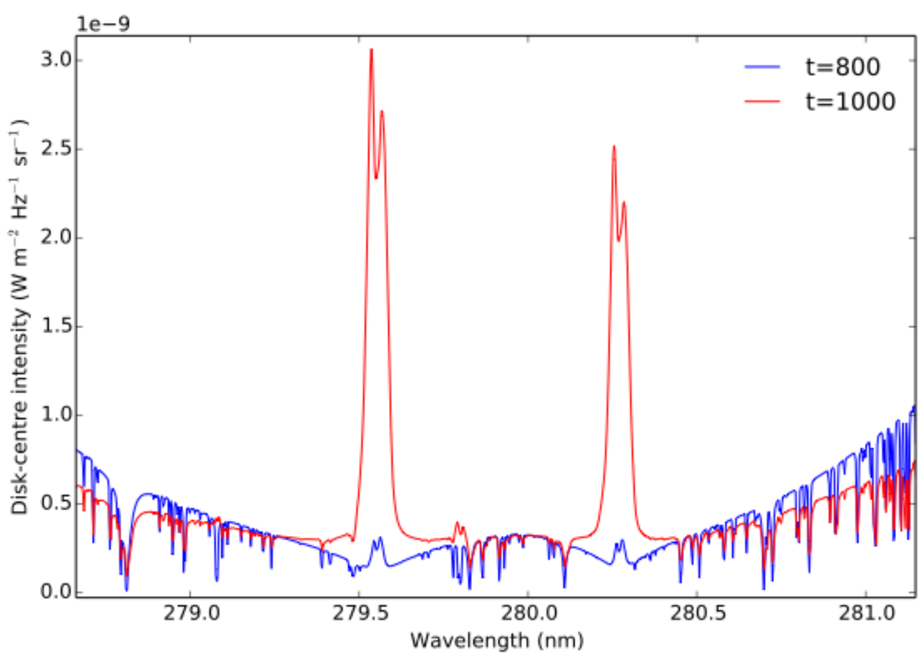


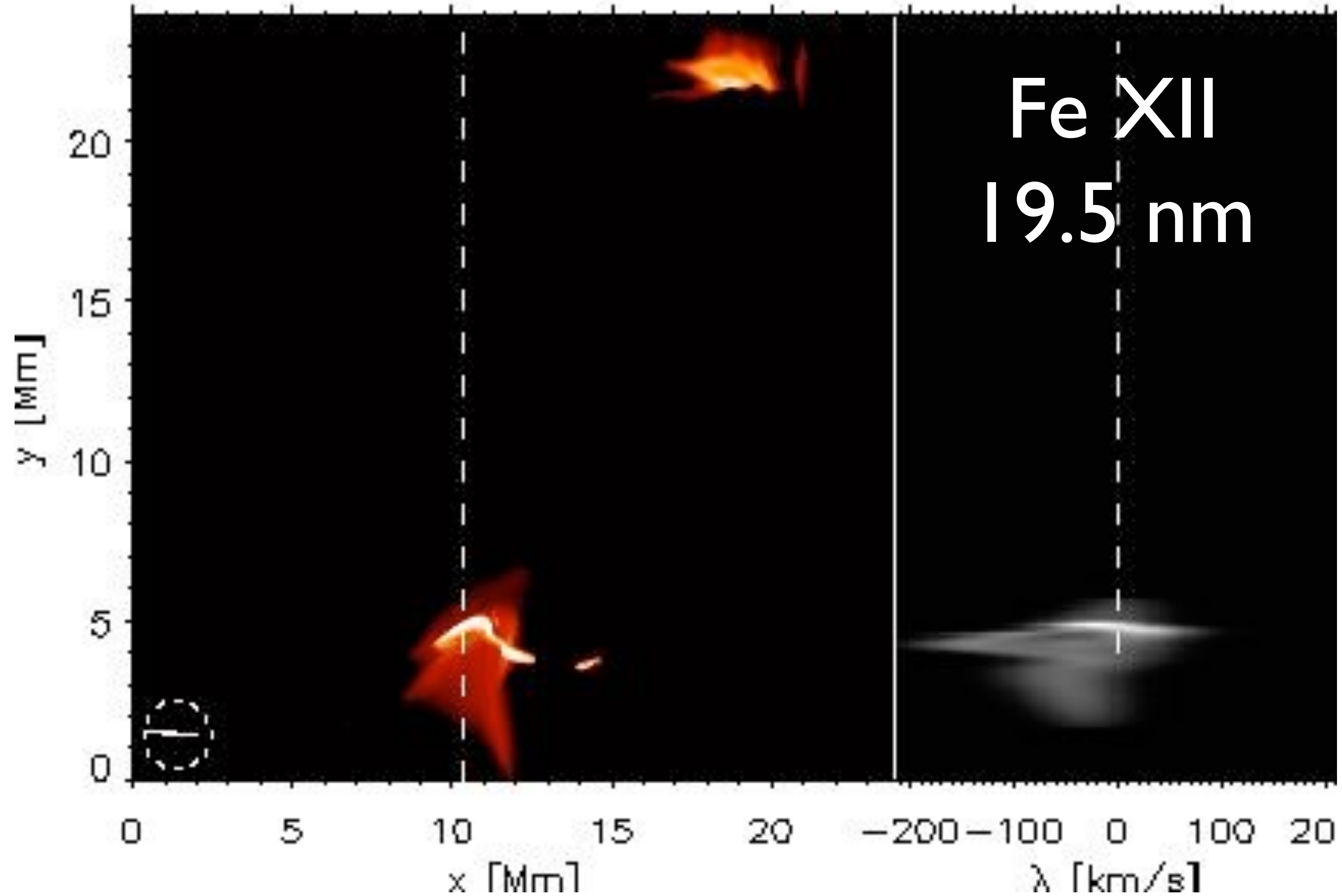

A
B
C
D
arcsec
km/s
Intensity [DN]
time [1000 s]

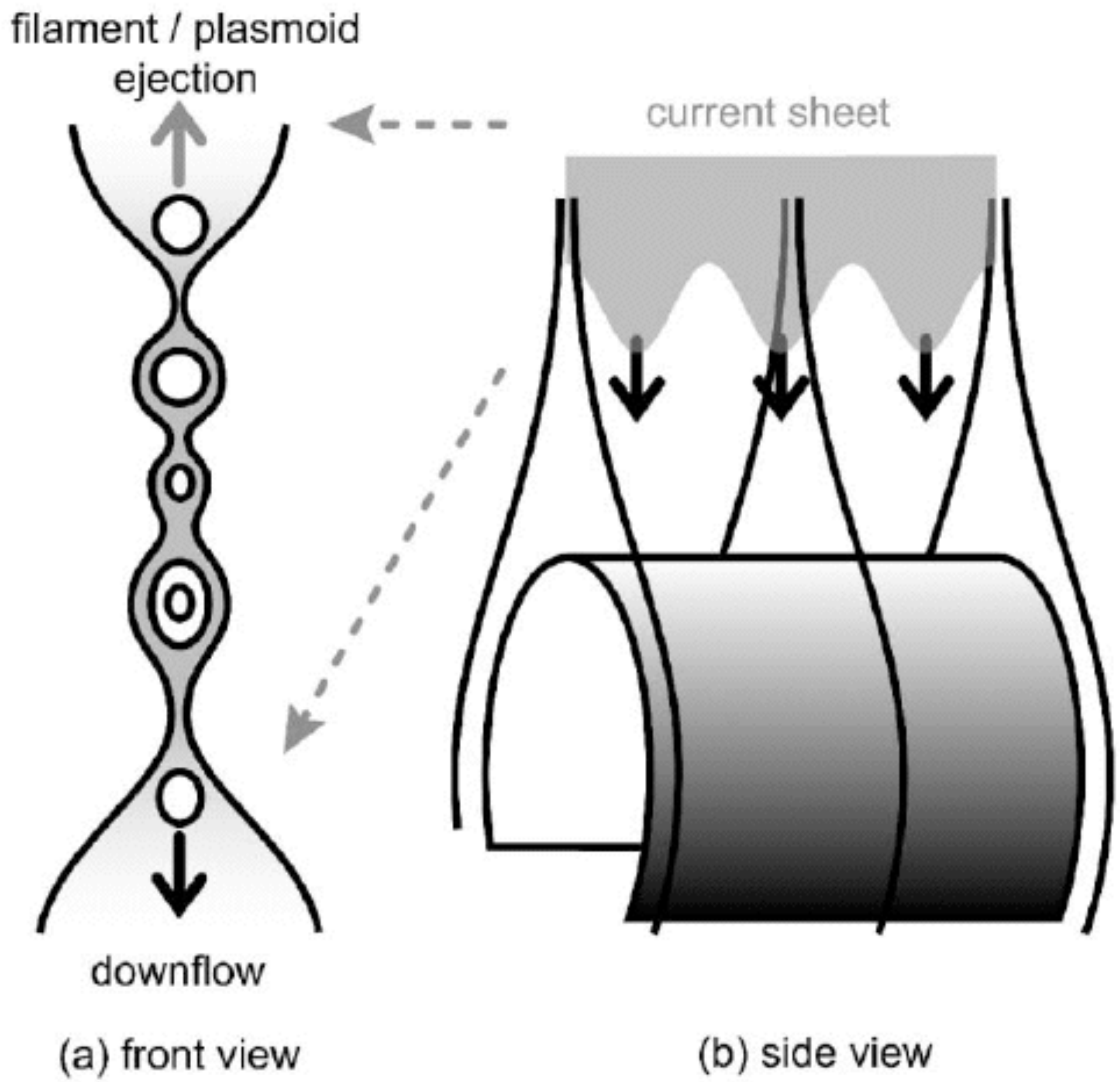




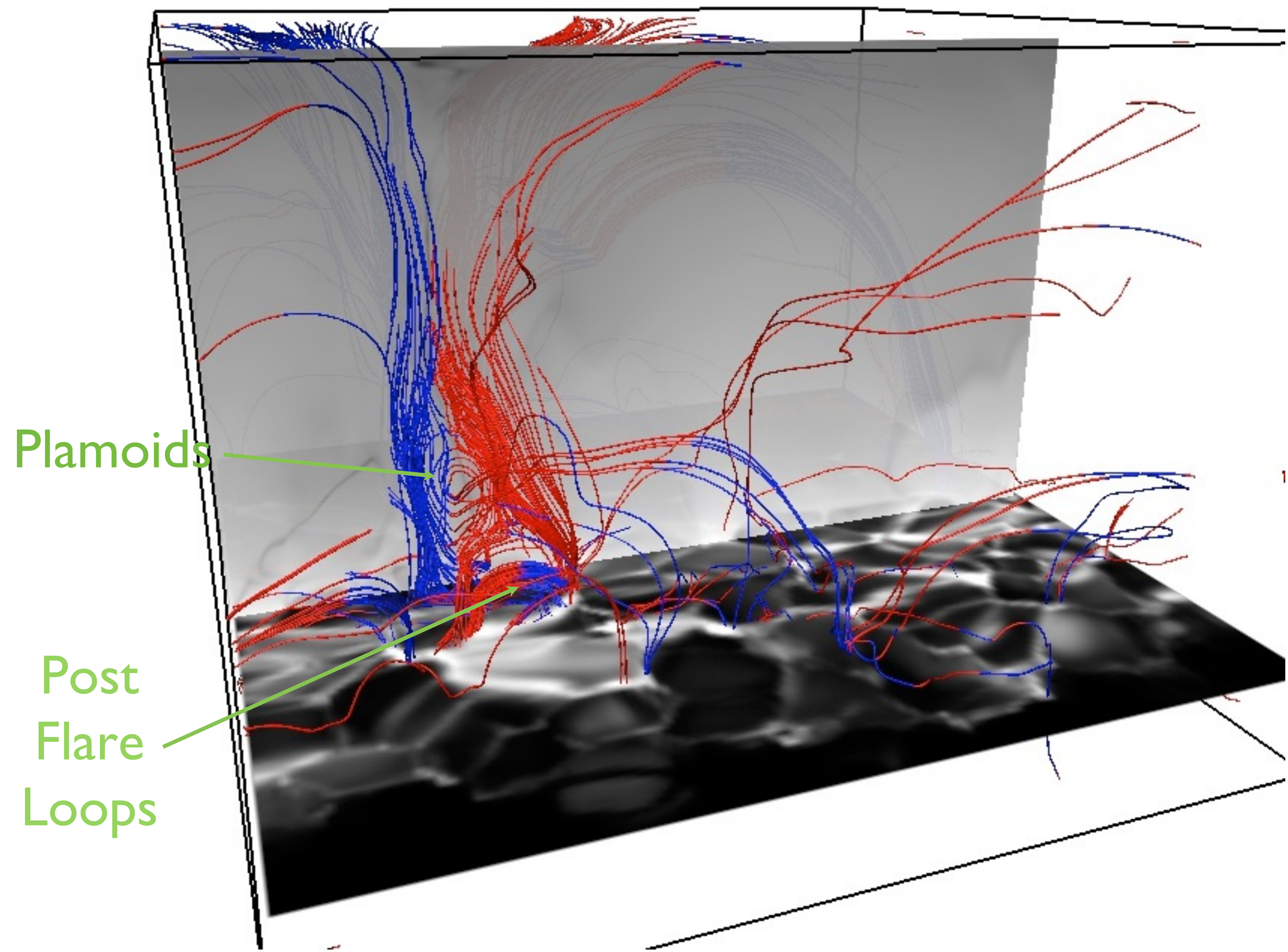
Mg II h
279.5 nm

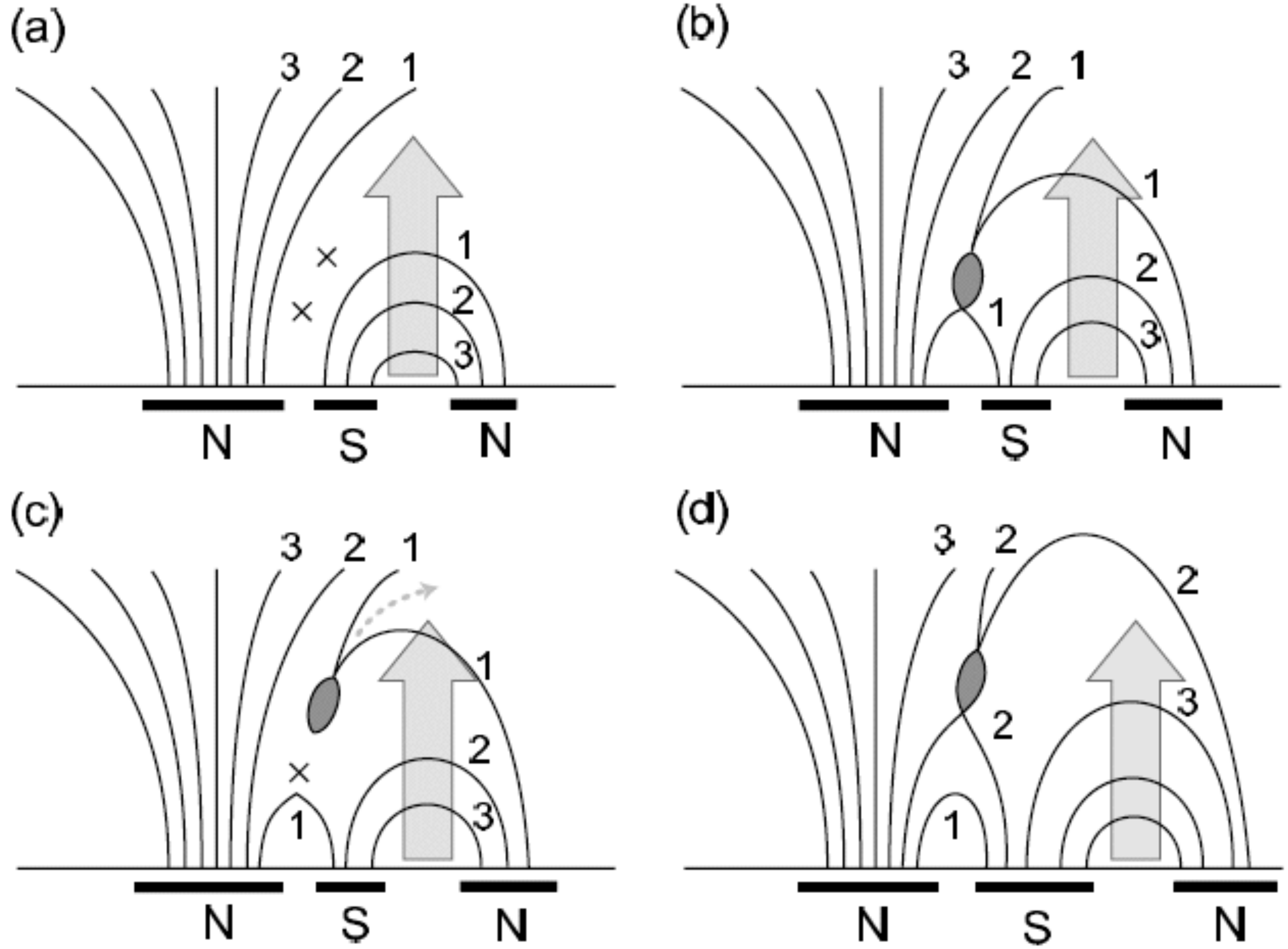




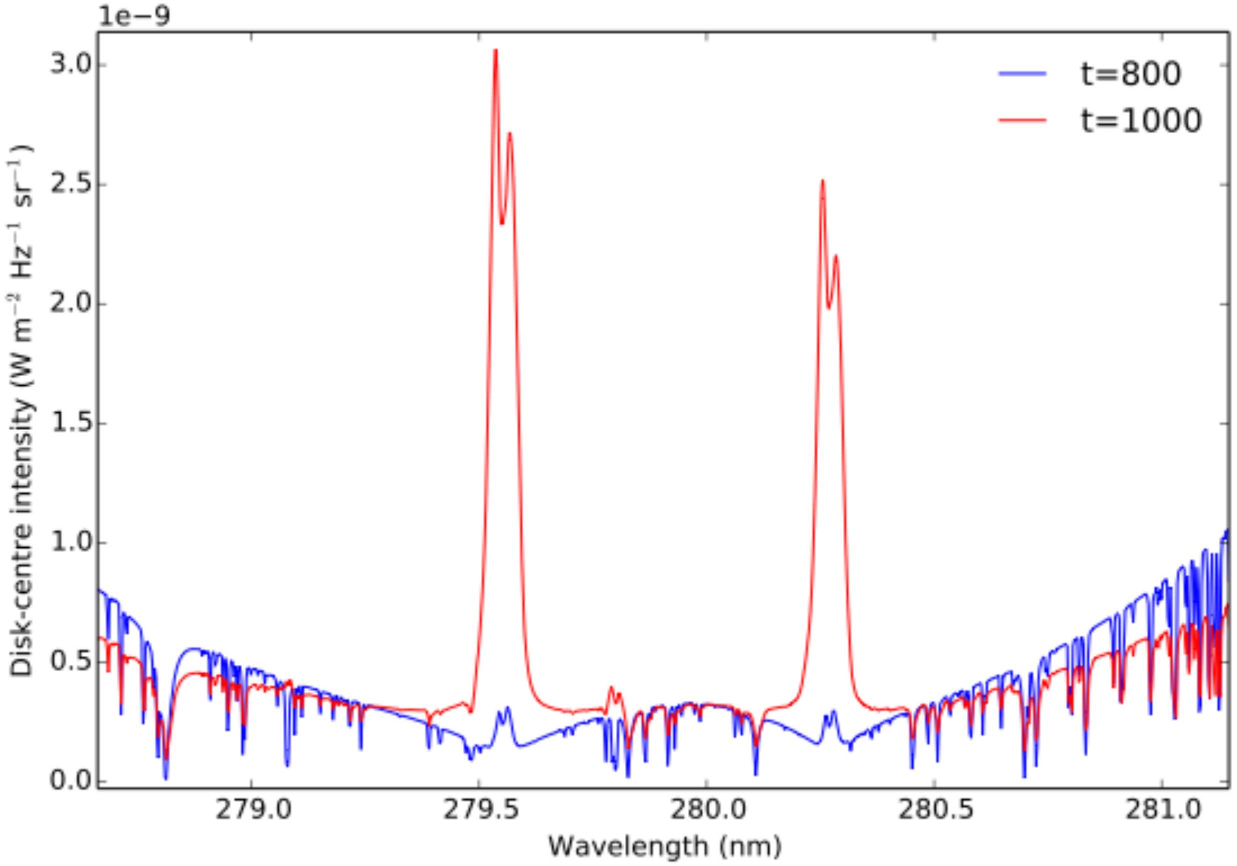


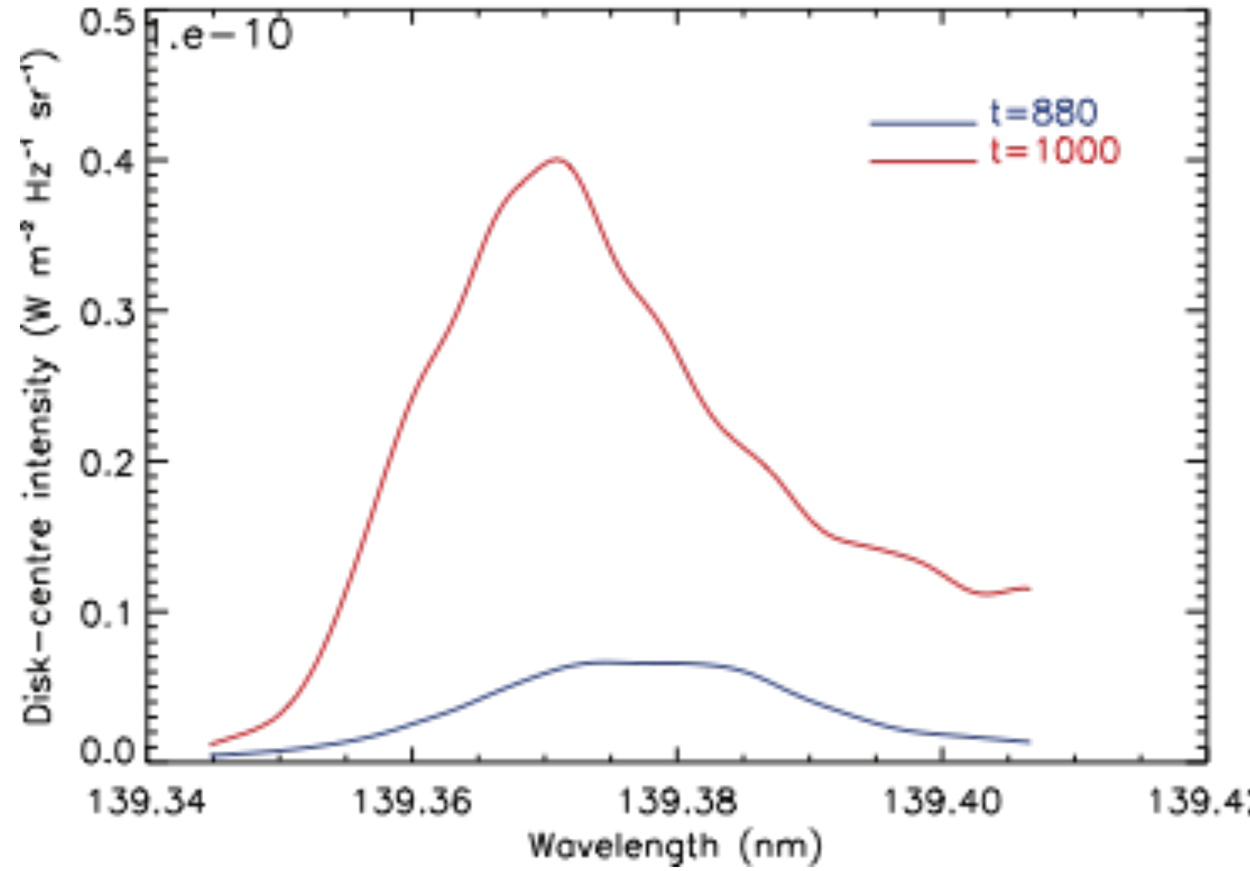
Asai, A, Yokoyama, T., Shimojo, M., and Shibata, K., "Downflow motions associated with impulsive non-thermal emission in the 2002 July 23 solar flare," ApJ 605, L77 (2004)

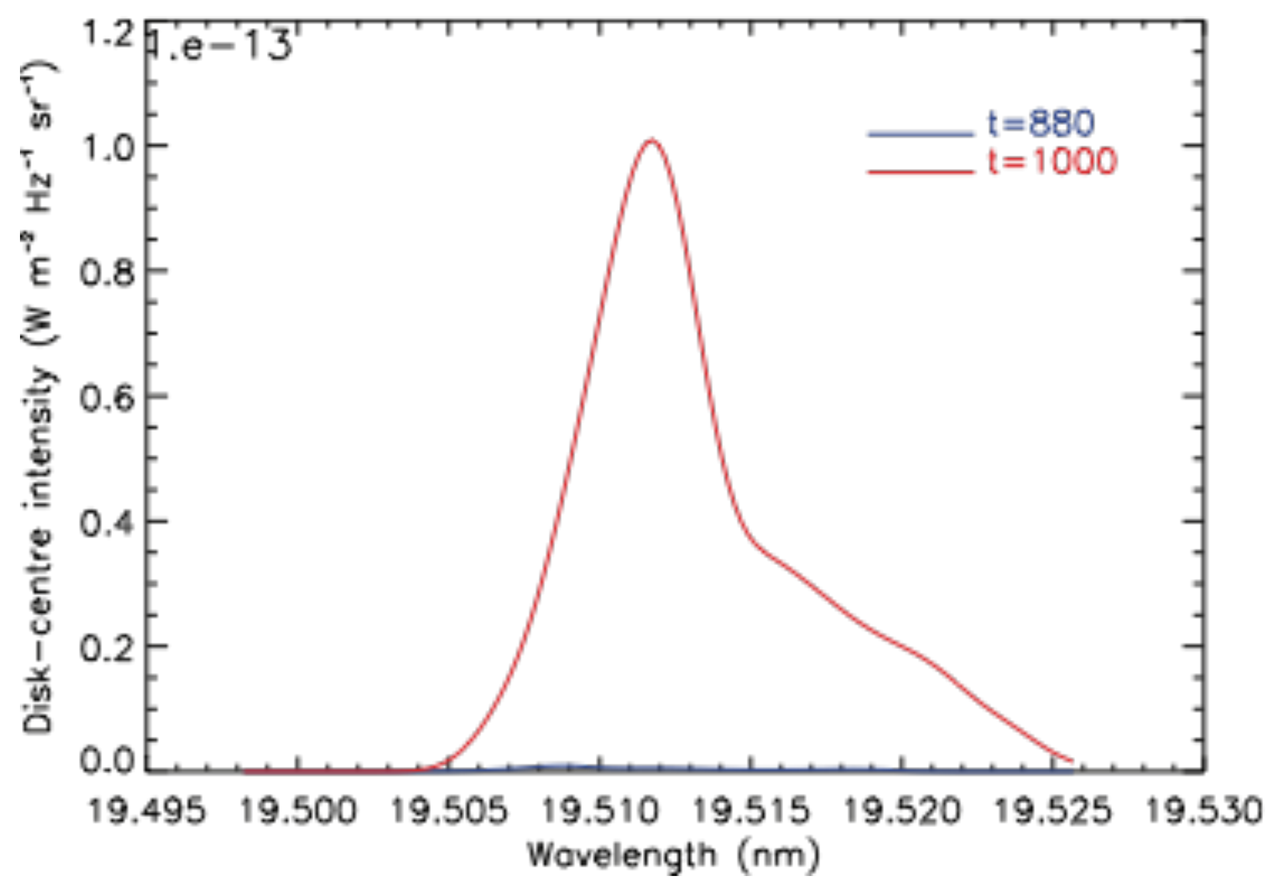

Plamoids
Post
Flare
Loops



Takasaki, H., Asai, A., Kiyohara, J., Shimojo, M., Terasawa, T., Takei, Y., and Shibata, K., ApJ 613, 592 (2004).


1e−9
t=800
t=1000
Disk-centre intensity (W m^{-2} Hz^{-1} sr^{-1})
3.0
2.5
2.0
1.5
1.0
0.5
0.0
279.0
279.5
280.0
280.5
281.0
Wavelength (nm)


1.e−10
t=880
t=1000
Disk−centre intensity (W m^{-2} Hz^{-1} sr^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
139.34
139.36
139.38
139.40
139.42
Wavelength (nm)


1.e−13
t=880
t=1000
Disk−centre intensity (W m^{-2} Hz^{-1} sr^{-1})
1.2
1.0
0.8
0.6
0.4
0.2
0.0
19.495
19.500
19.505
19.510
19.515
19.520
19.525
19.530
Wavelength (nm)

BIFROST: Basic assumptions

Hansteen 2004, Hansteen, Carlsson, Gudiksen 2007,
Martínez Sykora, Hansteen, Carlsson 2008, Gudiksen et al 2011

- 6th order scheme, with "artificial viscosity/diffusion"
- Open vertical boundaries, horizontally periodic
- Possible to introduce field through bottom boundary

- "Realistic" EOS
- Detailed radiative transfer along 48 rays
  - Multi group opacities (4 bins) with scattering
- NLTE radiative losses in the chromosphere, optically thin in corona

- Conduction along field lines
  - Operator split and solved by using multi grid method

- Time dependent Hydrogen ionization
- Generalized Ohm's Law

Injection of field at the bottom boundary

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$$

set electric field at boundary to strive for desired field:

$$E_x^n = E_x + \frac{\Delta(B_y)}{\tau} \Delta z \qquad [\Delta(B_y) = B_y^n - B_y]$$

For example flux tube with twist

$$\mathbf{B}_{long} = B_o \exp\left(-\frac{r^2}{R^2}\right) \mathbf{e}_z$$

$$\mathbf{B}_{trans} = B_{long}\, r\, q\, \mathbf{e}_\phi,$$

$$r = \sqrt{(x - x_o)^2 + (z - z_o)^2} \qquad \lambda = q\, R.$$

Properties	Left	Center	Right	Joint
T_cor. (K)	9.7×10^5 (upflow)	≥ 2MK (upflow)	> 1MK (upflow)	≥ 2MK (upflow)
T_tr. (K)	$8\text{-}9 \times 10^5$ (downflow)	≈ 1MK (cusp)	≈ 1MK (downflow)	≈ 1.5 MK (cusp)
T_chrom. (K)	$O(10^5)$ (footpoints)	$O(10^5)$ (footpoints)	$O(10^5)$ (footpoints)	1-1.2 MK (ribbons)
Energy (erg/s)	$1\text{-}2 \times 10^{23}$	$3\text{-}4 \times 10^{23}$	$2\text{-}3 \times 10^{23}$	