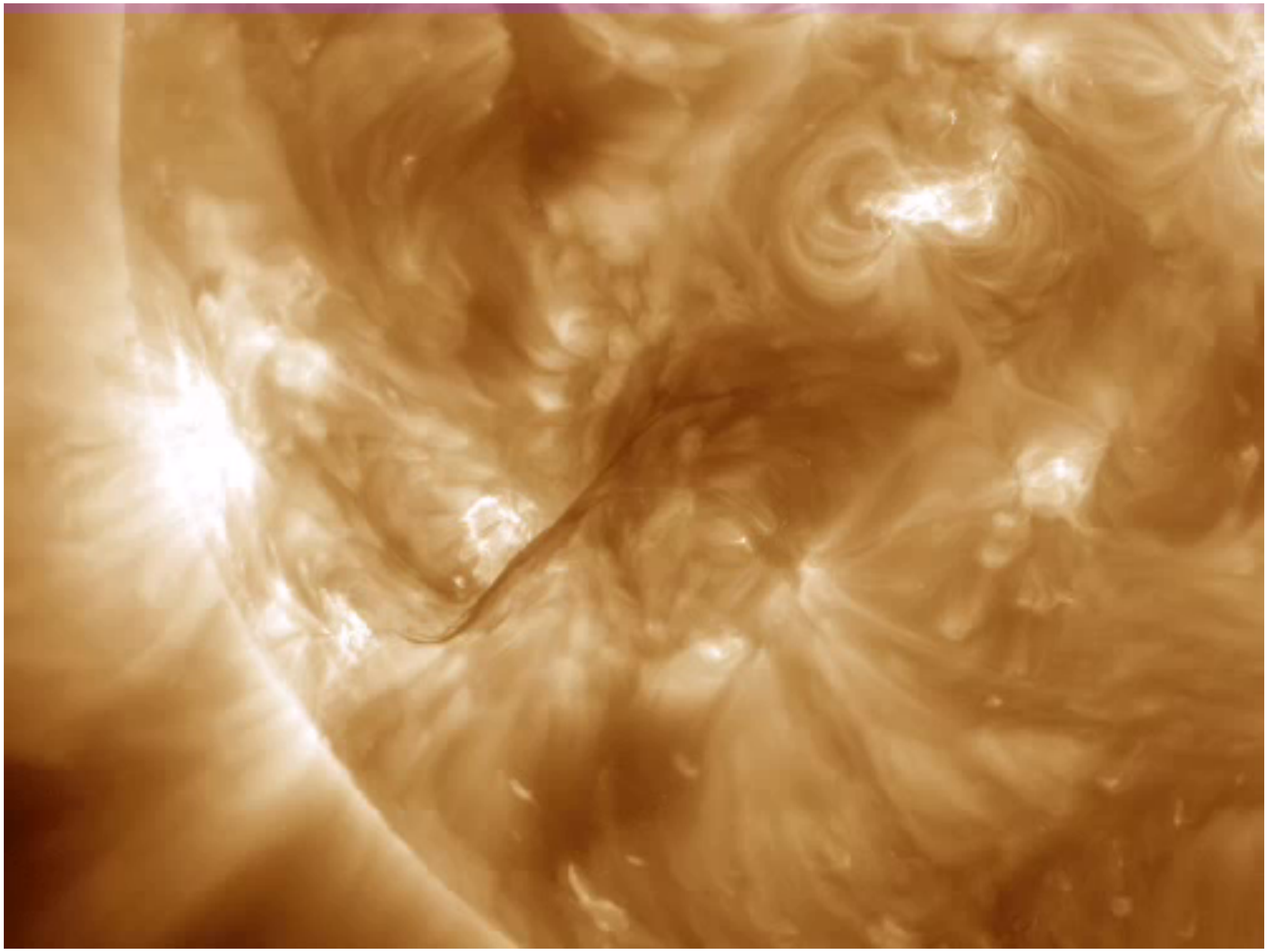
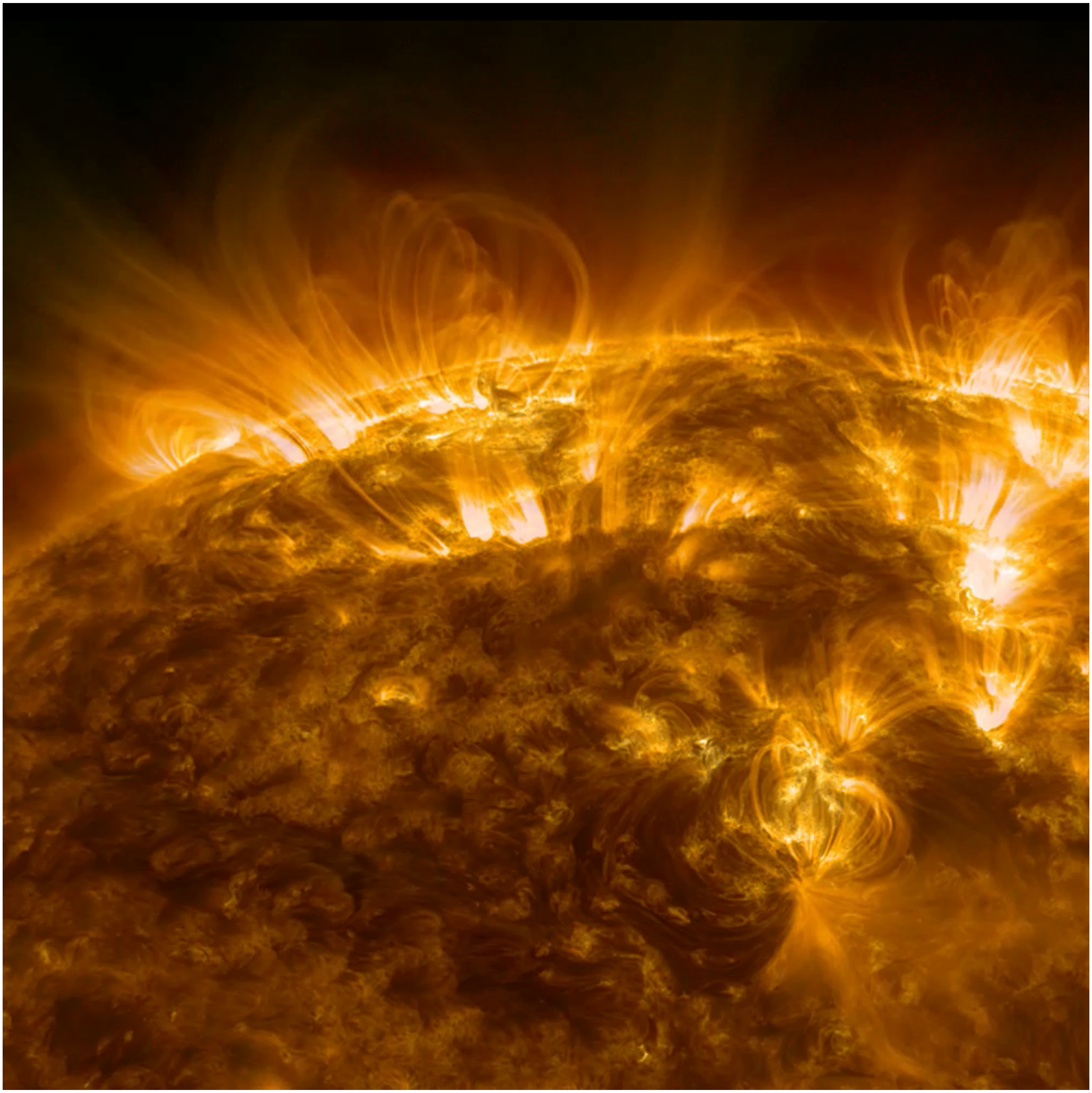
Solar flares and CMEs:

Their physics and their observation

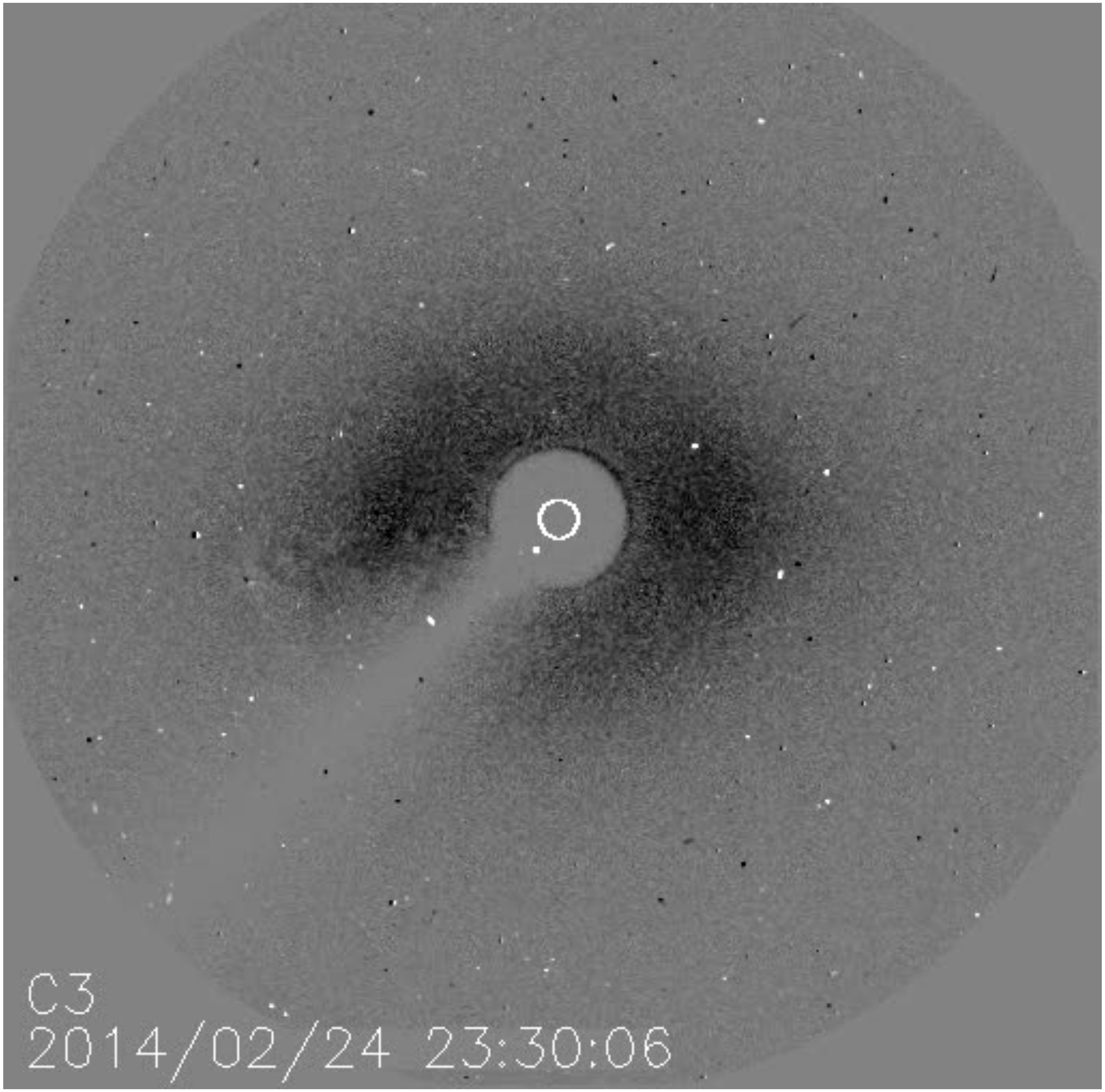
Lecture 1
Jan 18, 2017

What is a solar flare?





Krucker & Hudson, RHESSI nugget #218



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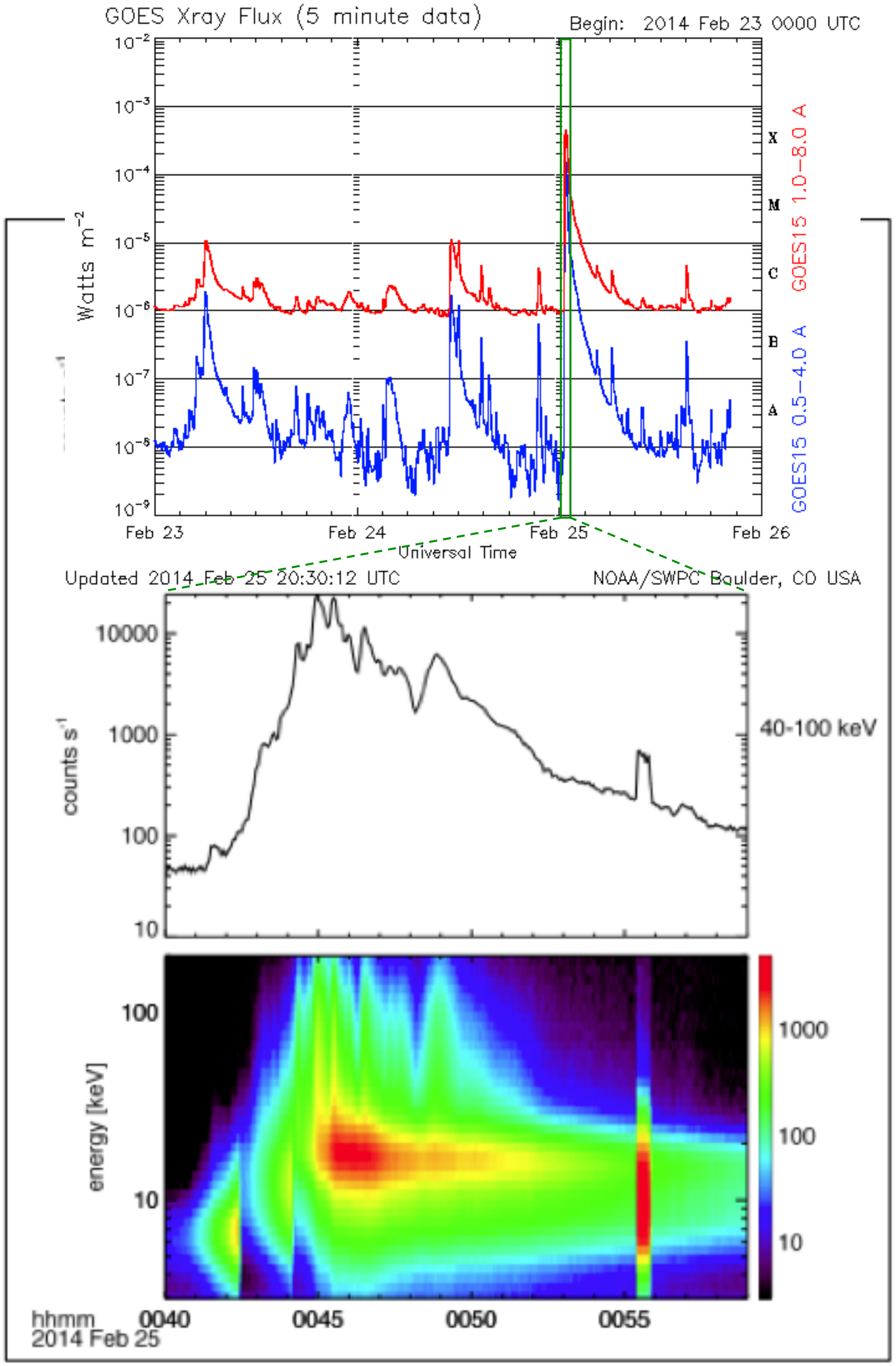
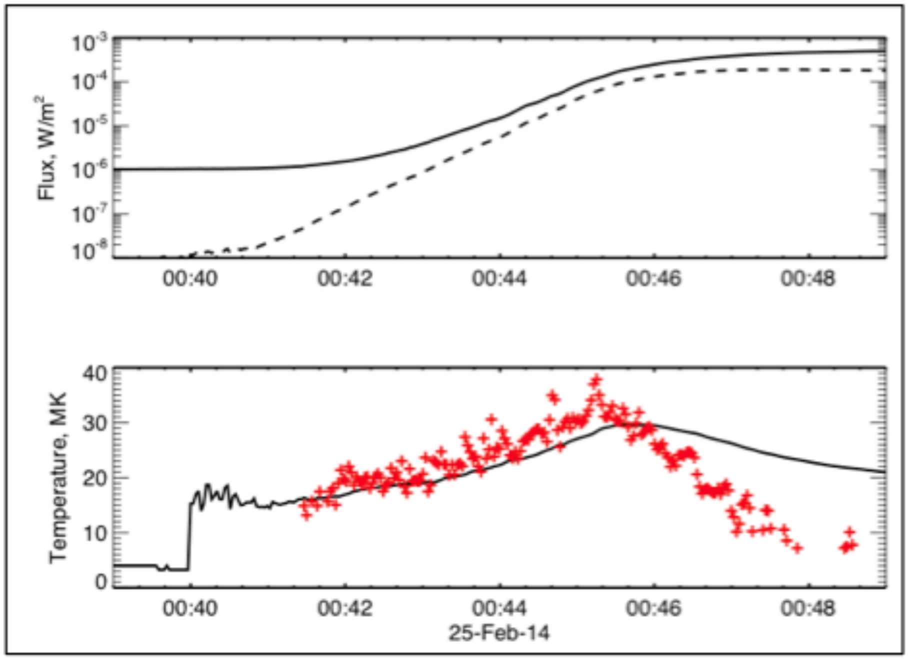
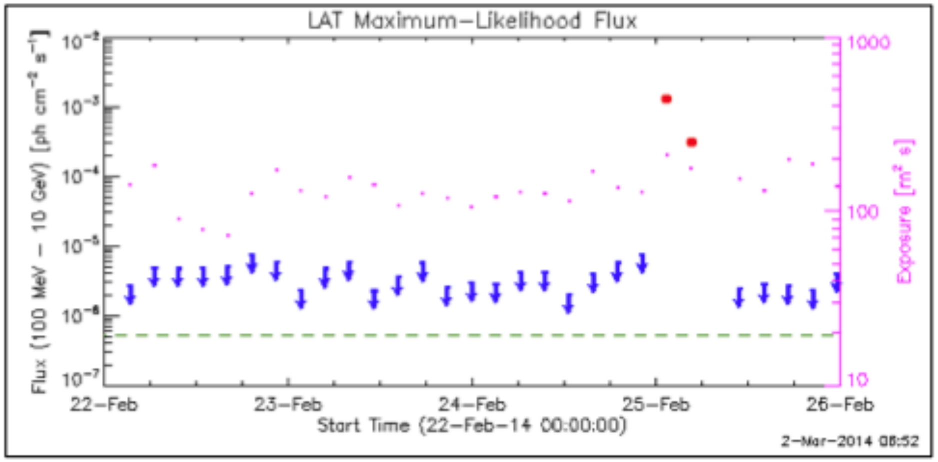
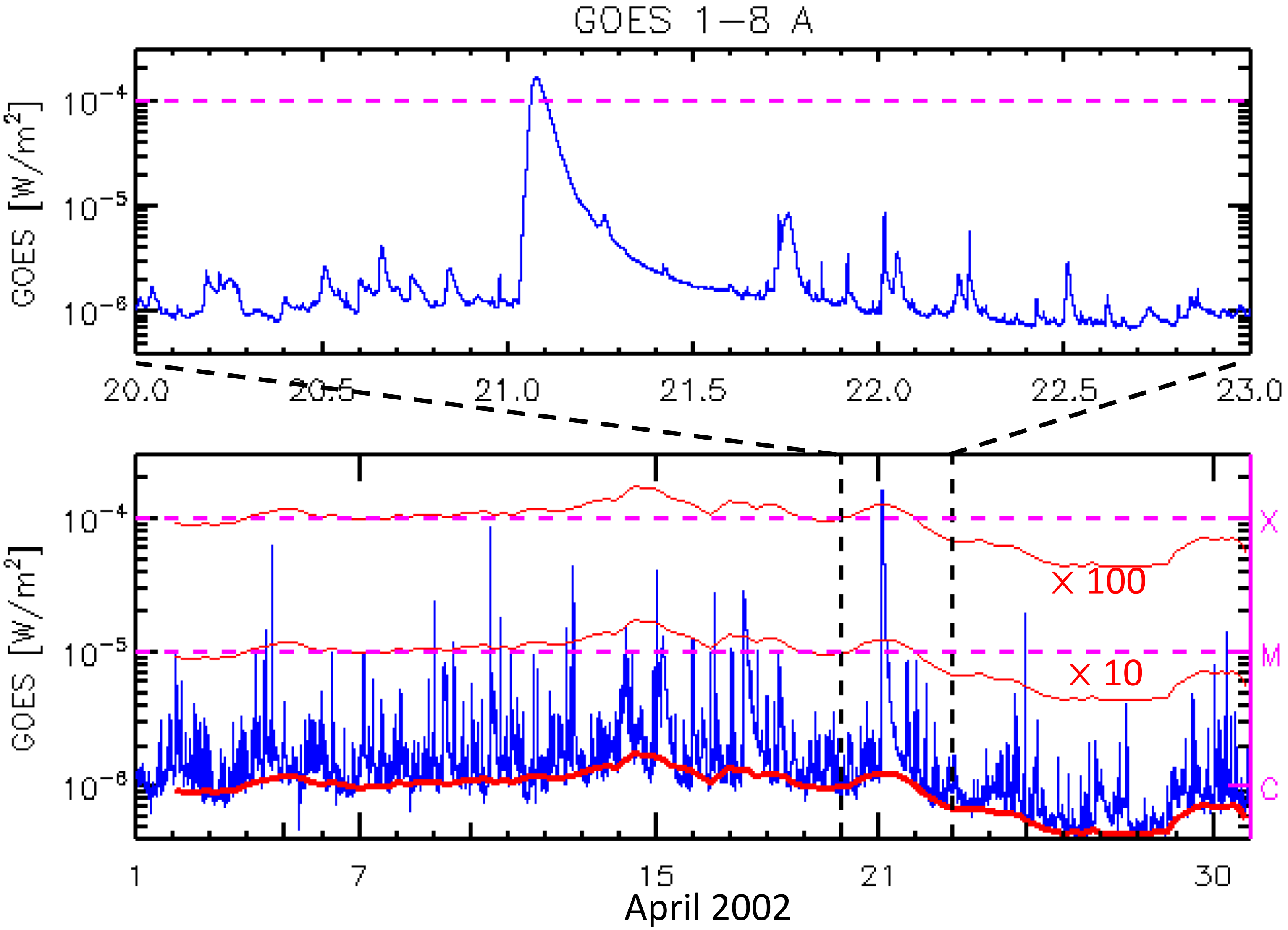


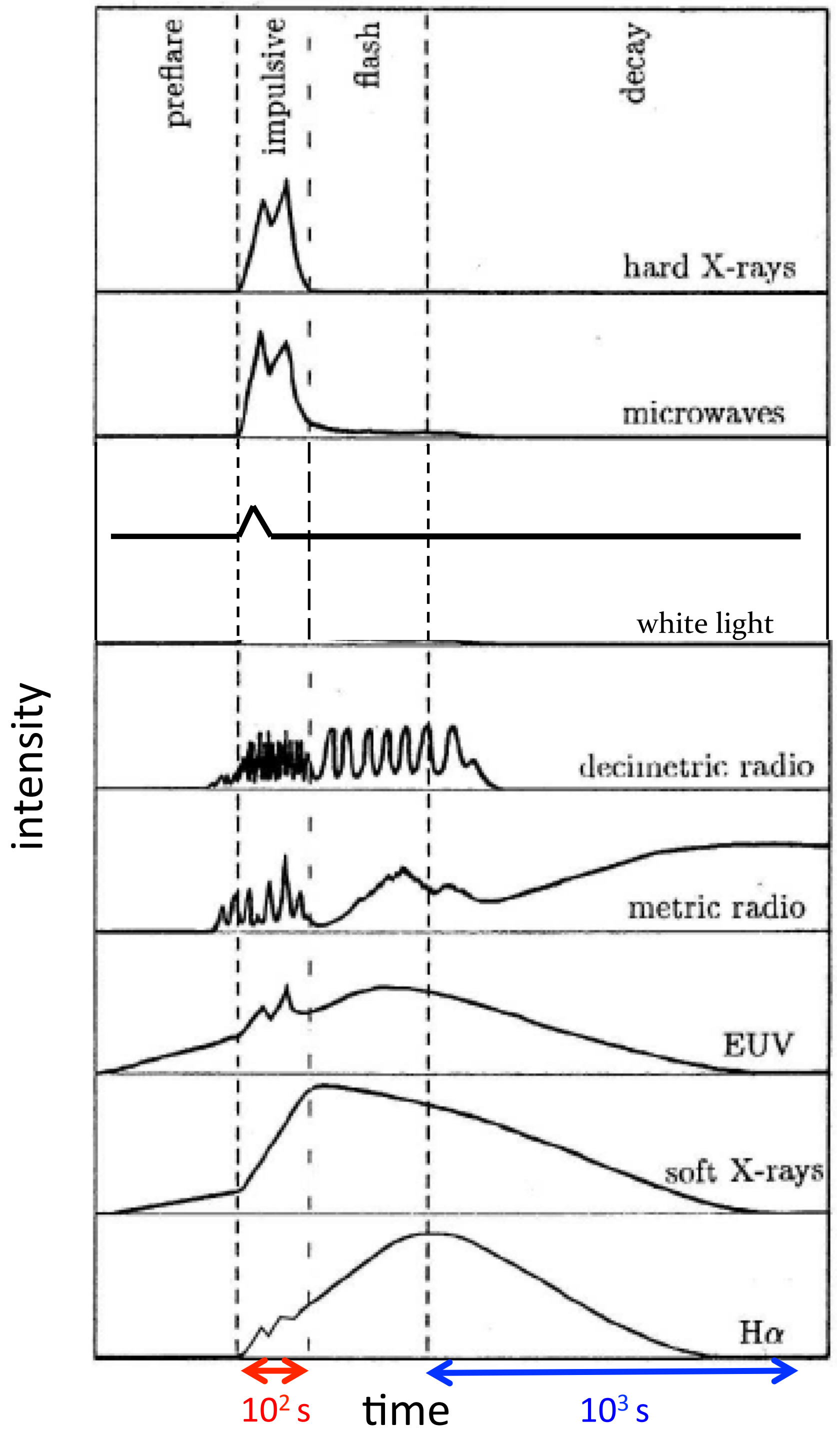




What is a solar flare?

Operational def'n: Flare: sudden brightening in X-rays

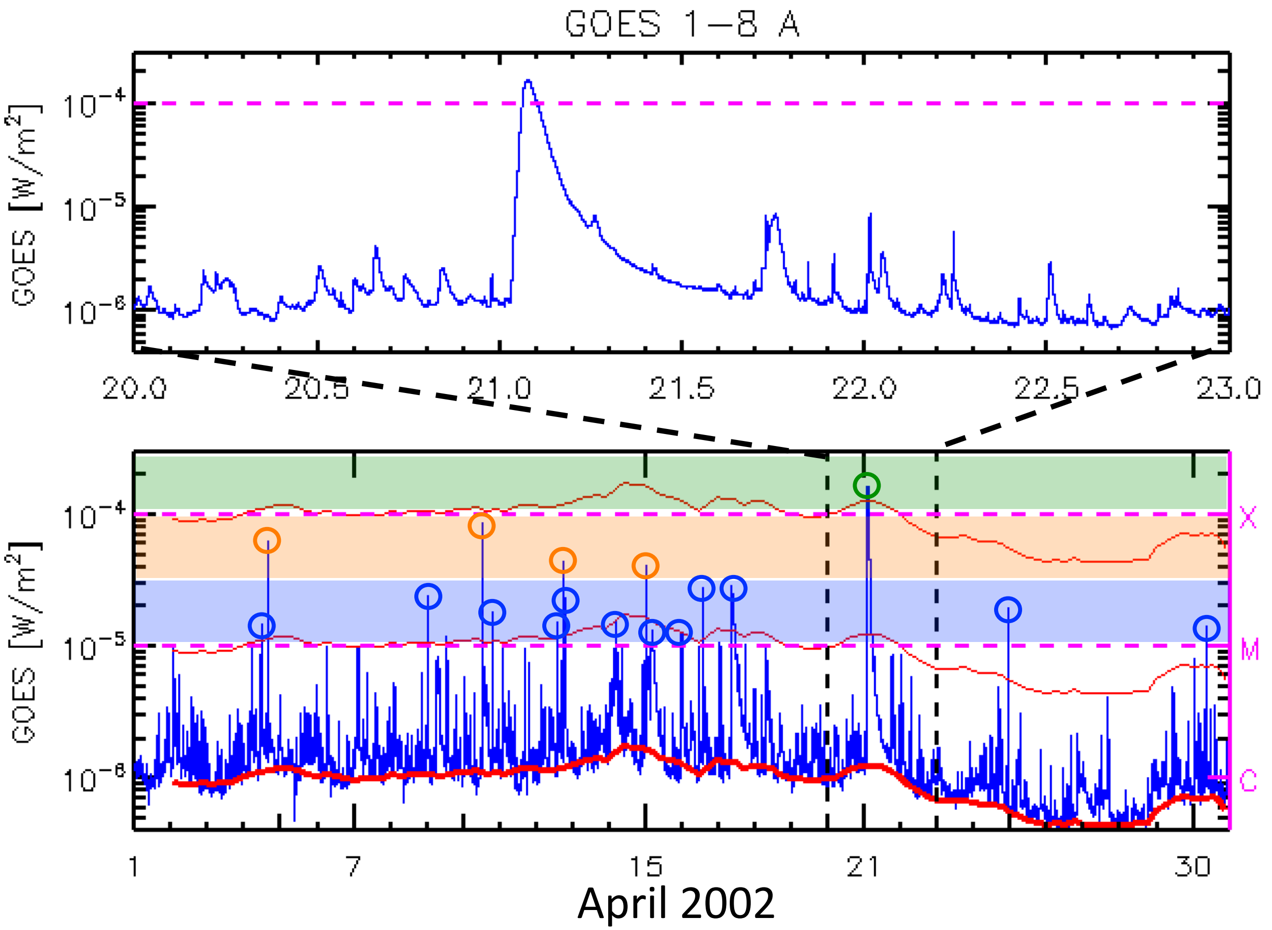




Benz 2002 w/ additions

What is a solar flare?

A member of a population



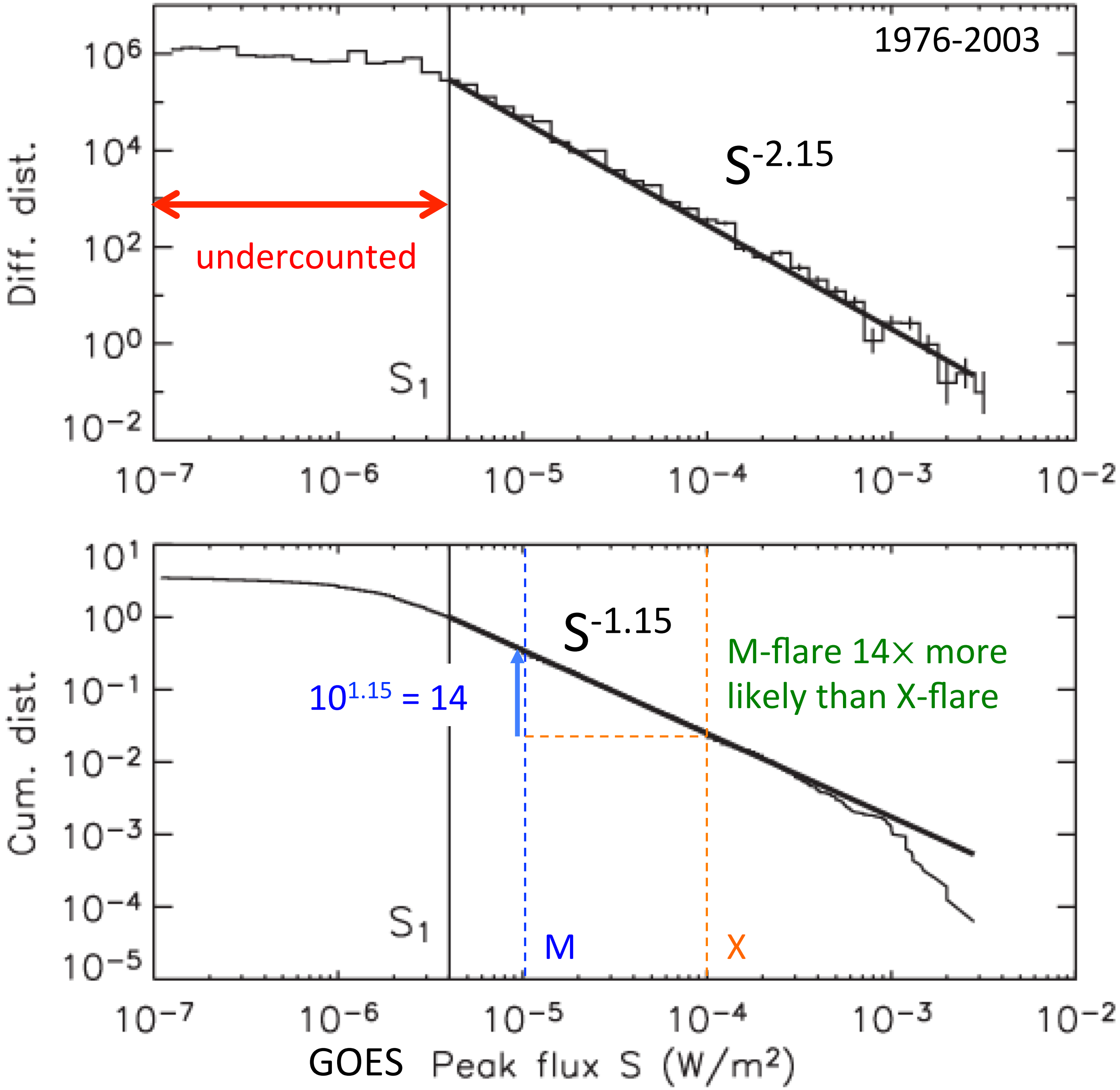
define
amplitude
bins

event
freq.

1 =0.03/day

4 =0.12/day

11 =0.33/day

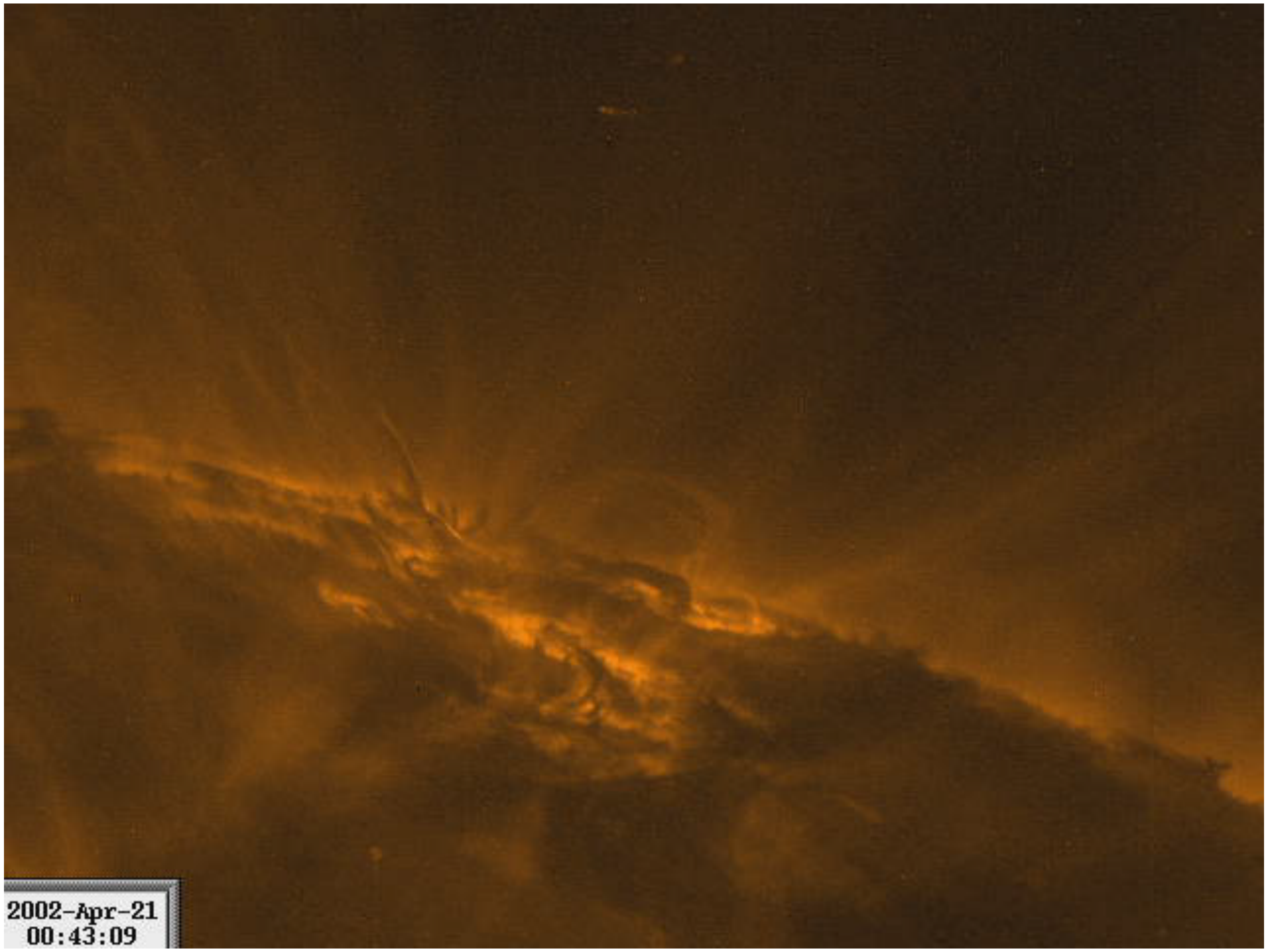


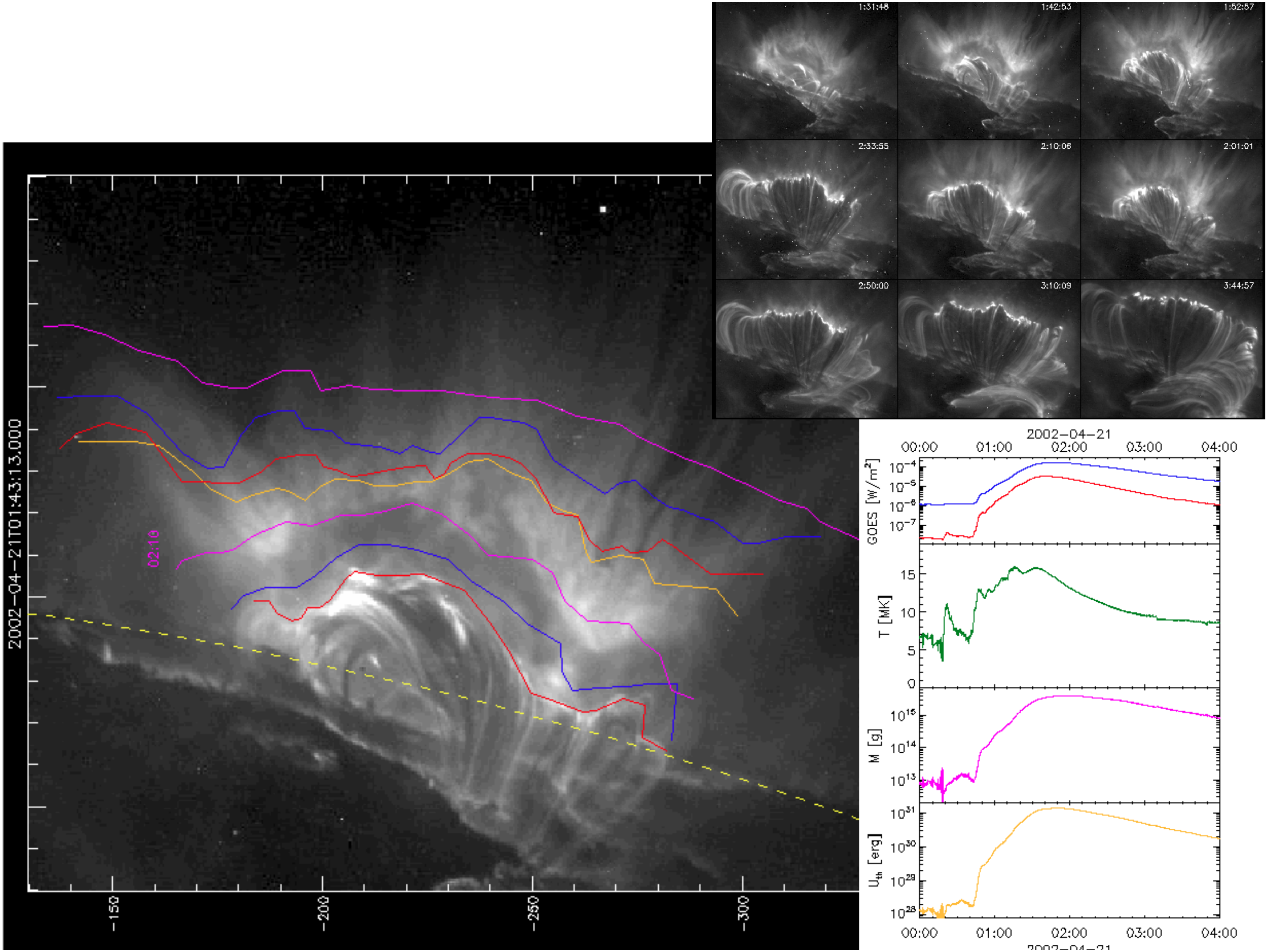
$10^{1.15} = 14$

M-flare 14× more likely than X-flare

Wheatland 2005

What is a solar flare?

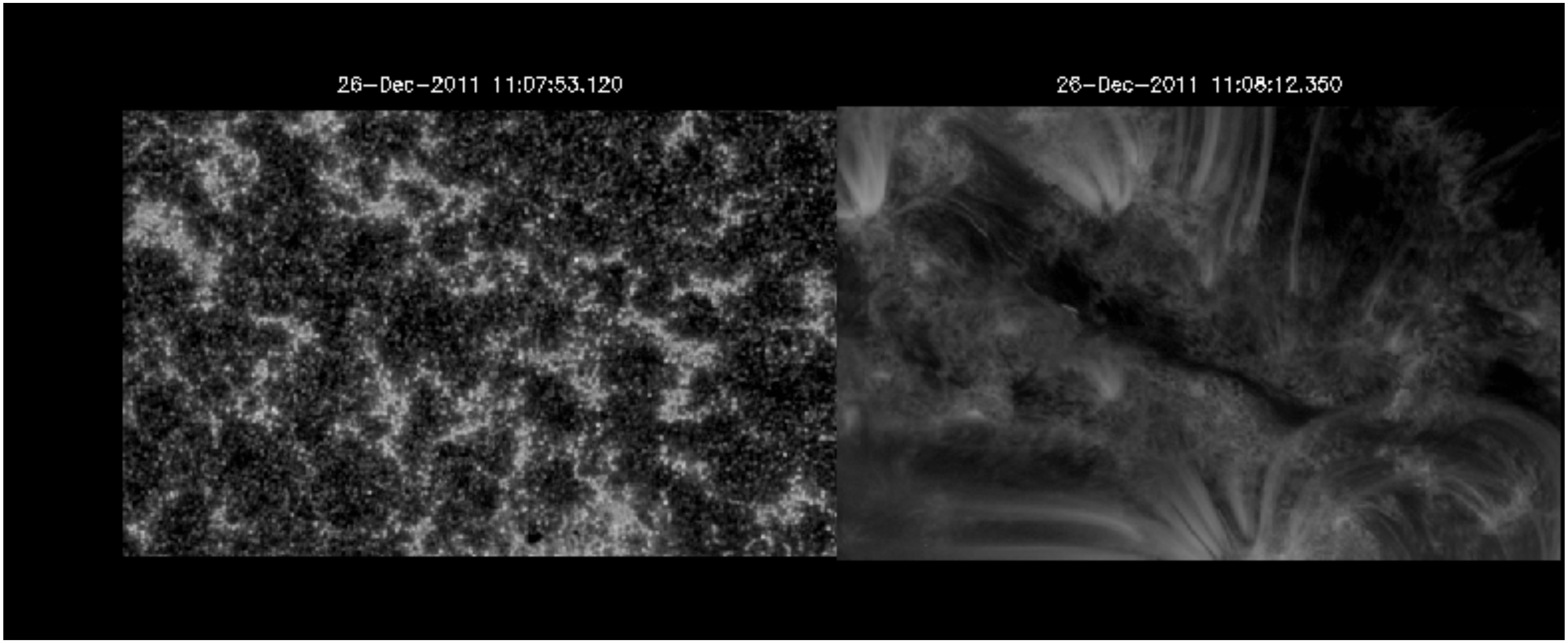



1:31:48
1:42:53
1:52:57
2:33:55
2:10:06
2:01:01
2:50:00
3:10:09
3:44:57
2002−04−21T01:43:13.000
02:16
−150
−200
−250
−300
2002−04−21
00:00
01:00
02:00
03:00
04:00
GOES [W/m^2]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
T [MK]
15
10
5
0
M [g]
10^{15}
10^{14}
10^{13}
U_{th} [erg]
10^{31}
10^{30}
10^{29}
10^{28}
00:00
01:00
02:00
03:00
04:00

What is a solar flare?

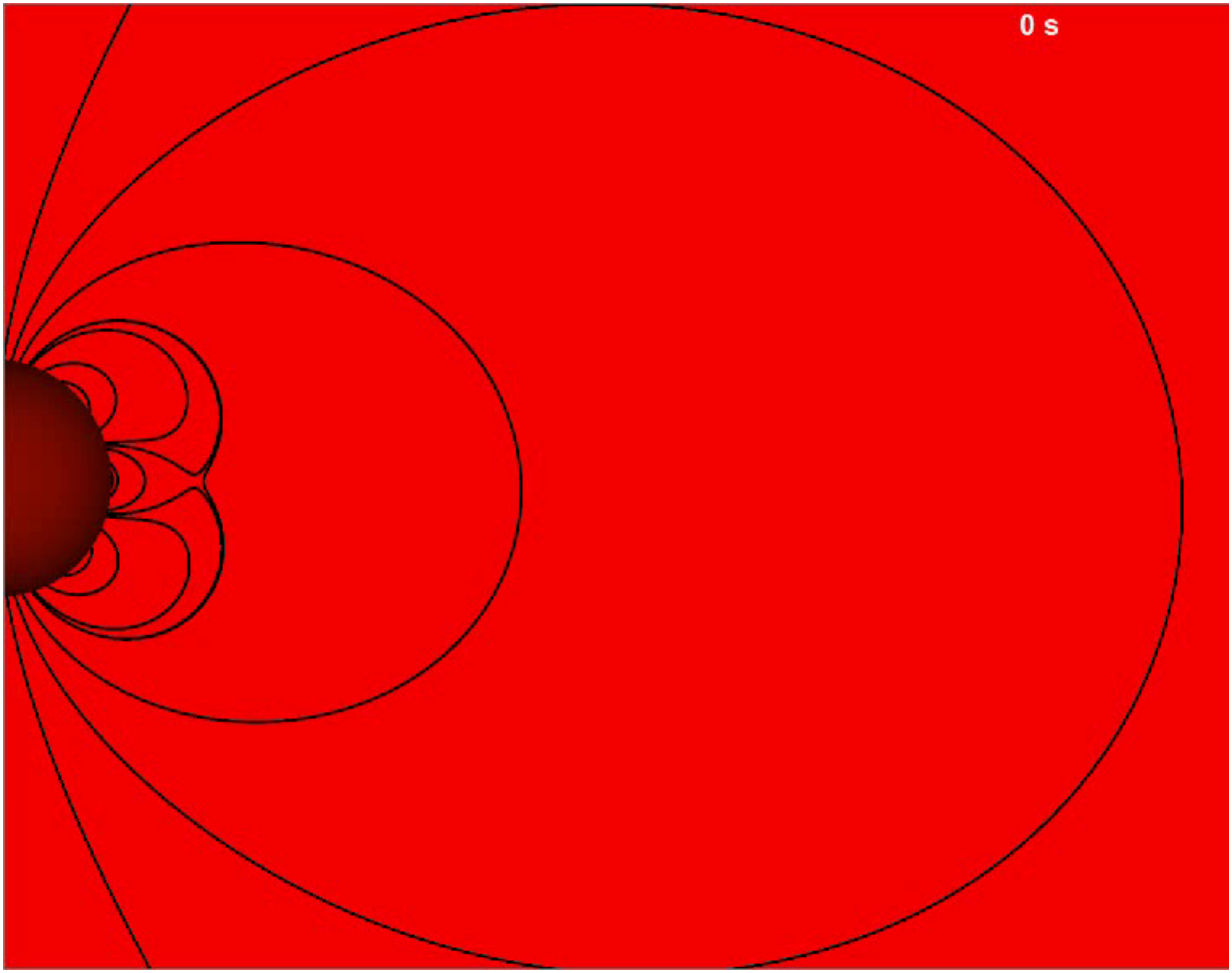
AIA 1600 A:
100,000 K plasma
Chromospheric/TR feet

AIA 171 A:
1,00,000 K plasma
coronal loops



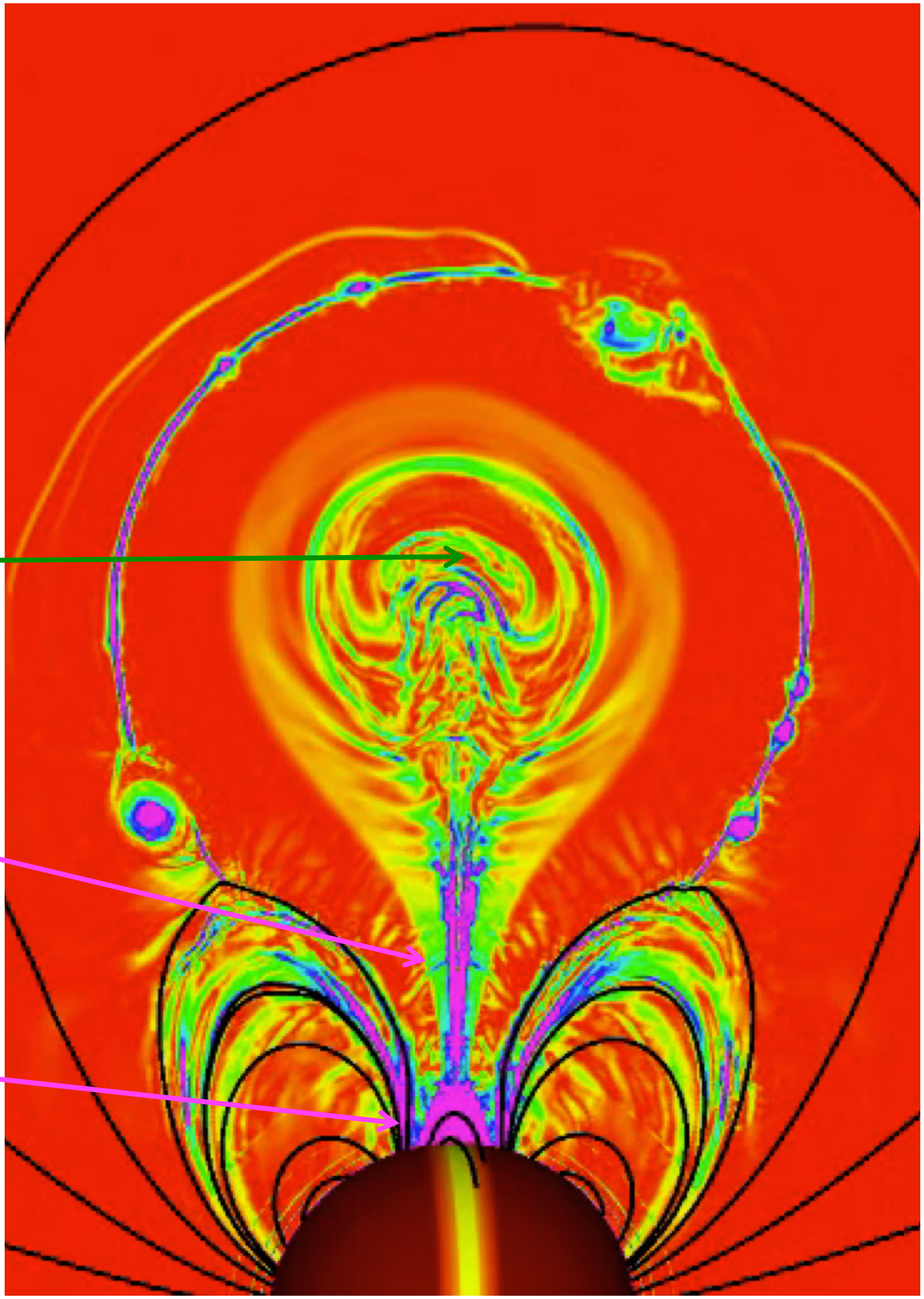
What is a solar flare?

|J|



Model: Karpen et al. 2012

How they relate… the basic picture



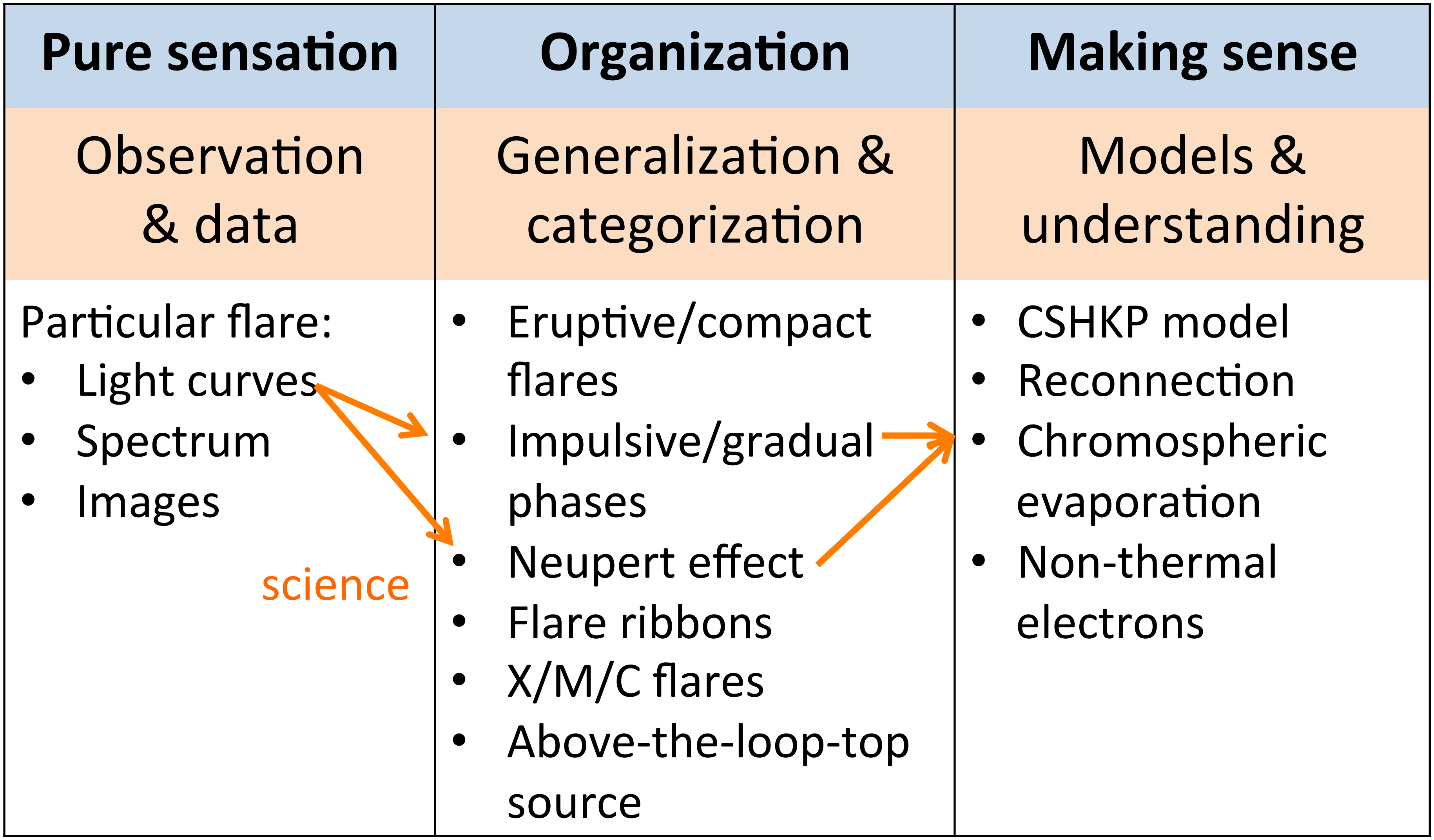
|J|

CME

Current sheet

flare

Epistemology

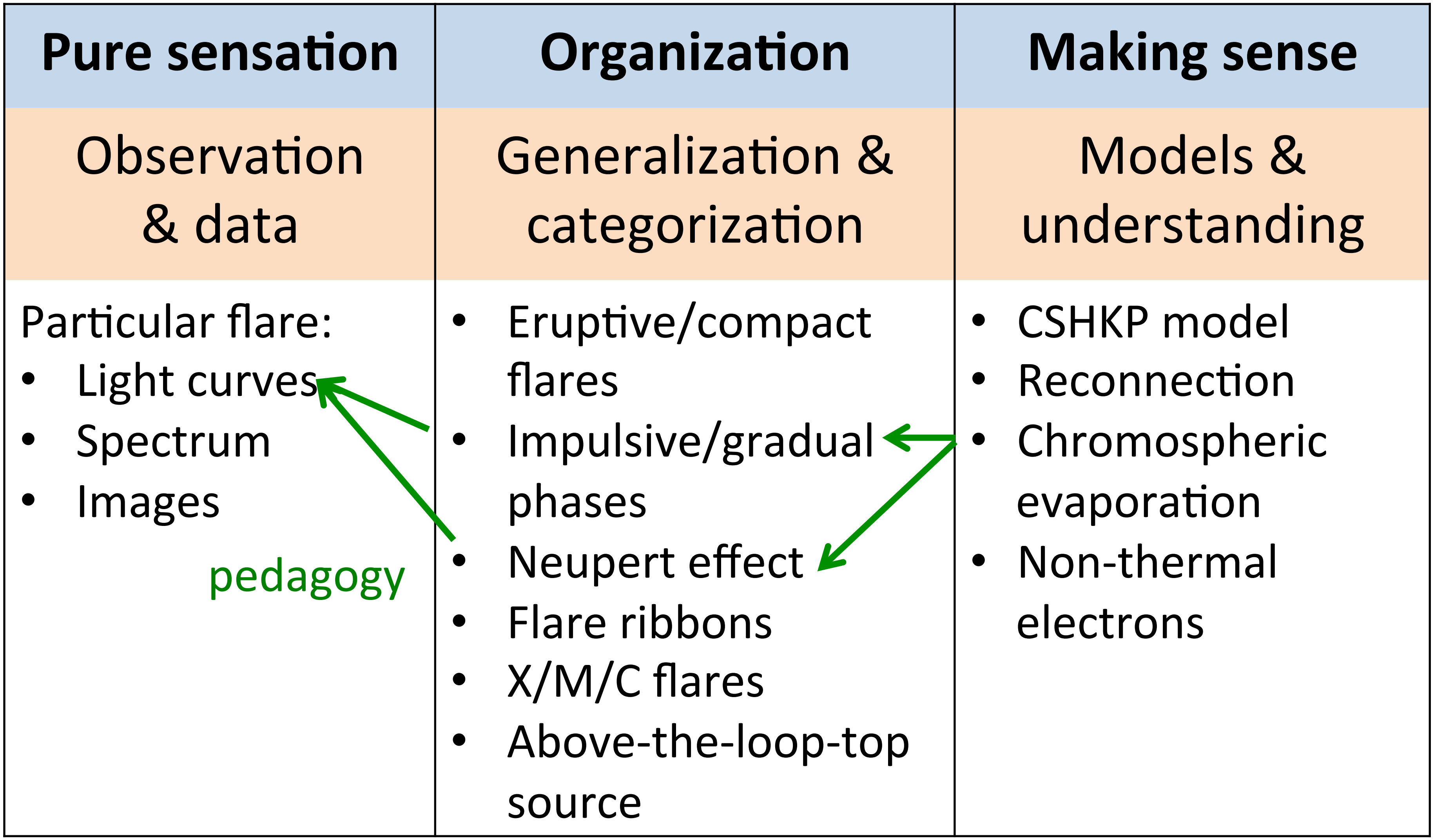


Pure sensation	**Organization**	**Making sense**
Observation & data	Generalization & categorization	Models & understanding
Particular flare: - Light curves - Spectrum - Images	- Eruptive/compact flares - Impulsive/gradual phases - Neupert effect - Flare ribbons - X/M/C flares - Above-the-loop-top source	- CSHKP model - Reconnection - Chromospheric evaporation - Non-thermal electrons

Terminology & jargon

In progress

Epistemology



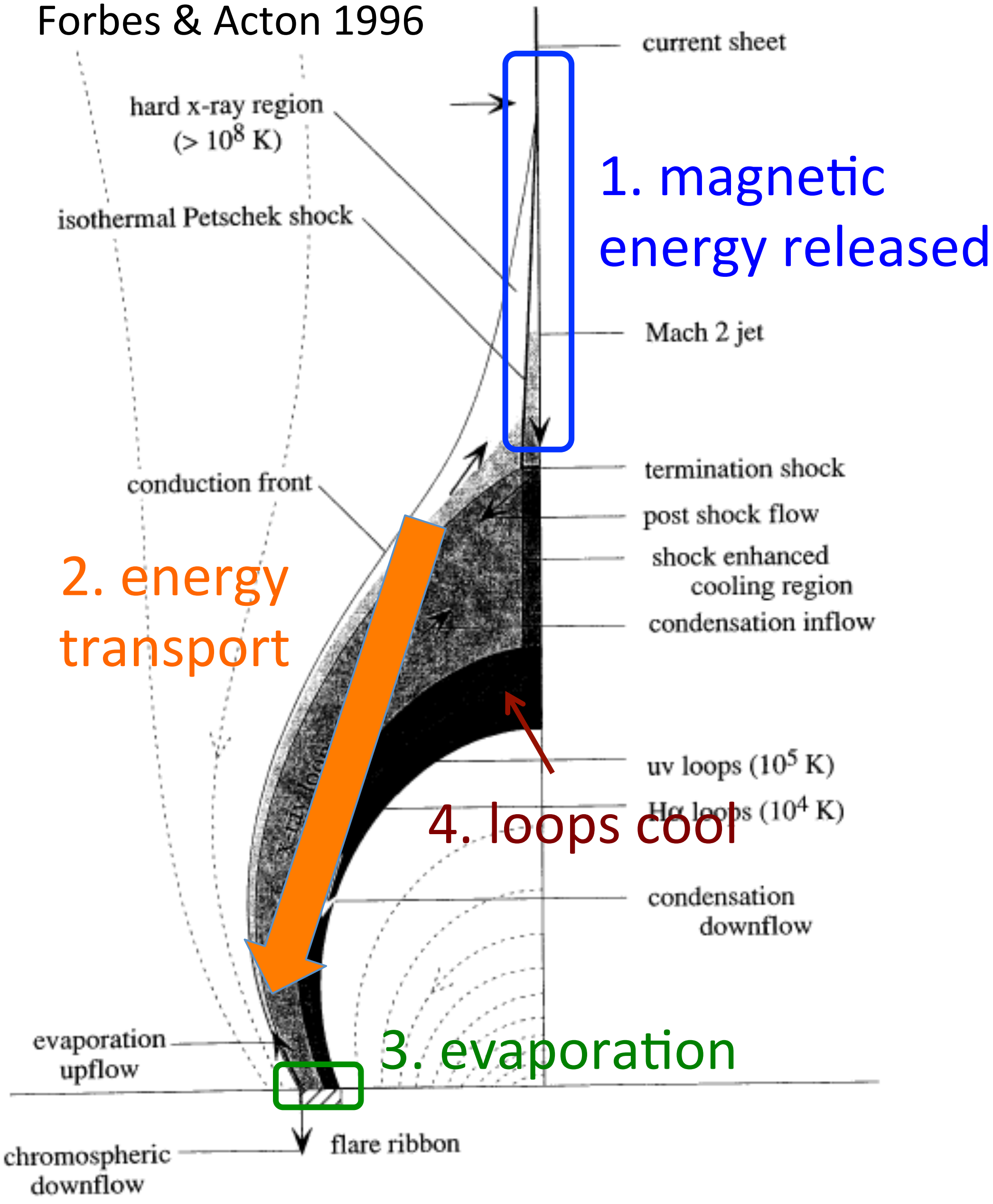
Pure sensation	Organization	Making sense
Observation & data	Generalization & categorization	Models & understanding
Particular flare: • Light curves • Spectrum • Images	• Eruptive/compact flares • Impulsive/gradual phases • Neupert effect • Flare ribbons • X/M/C flares • Above-the-loop-top source	• CSHKP model • Reconnection • Chromospheric evaporation • Non-thermal electrons

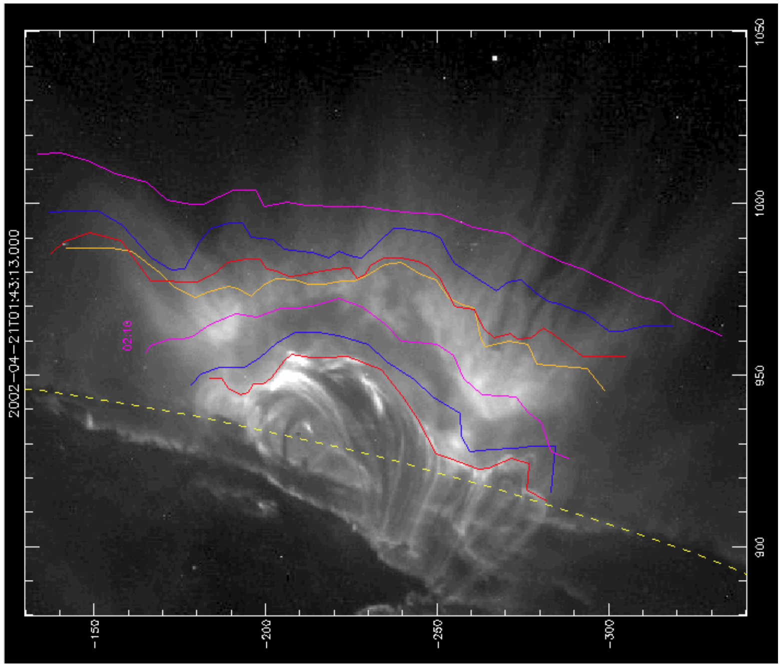
pedagogy

Terminology & jargon

In progress

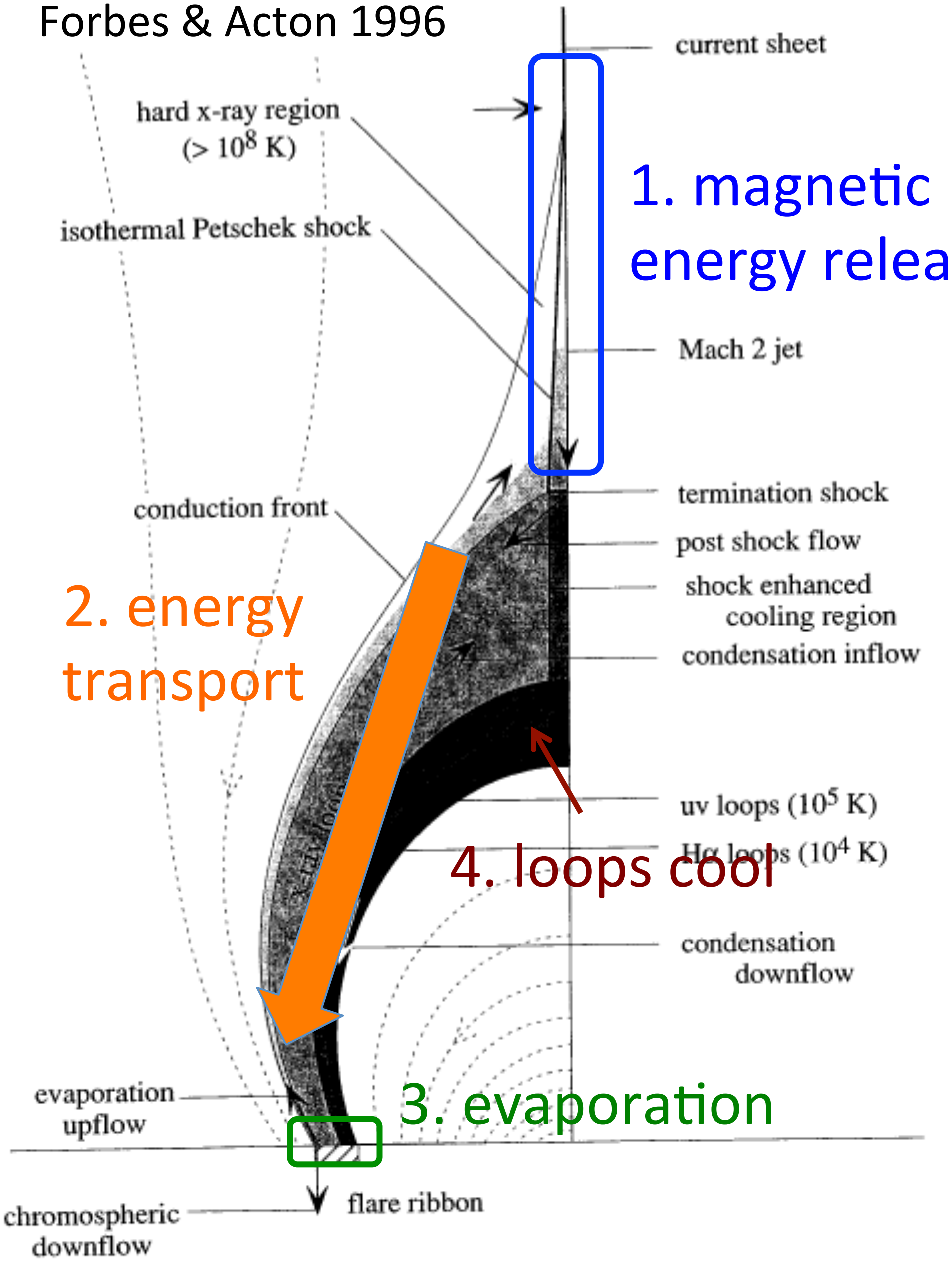
CSHKP*: the standard model
(of big eruptive flares)


Forbes & Acton 1996



*Carmichael 1964, Sturrock 1968,
Hirayama 1974,
Kopp & Pneuman 1976

Forbes & Acton 1996

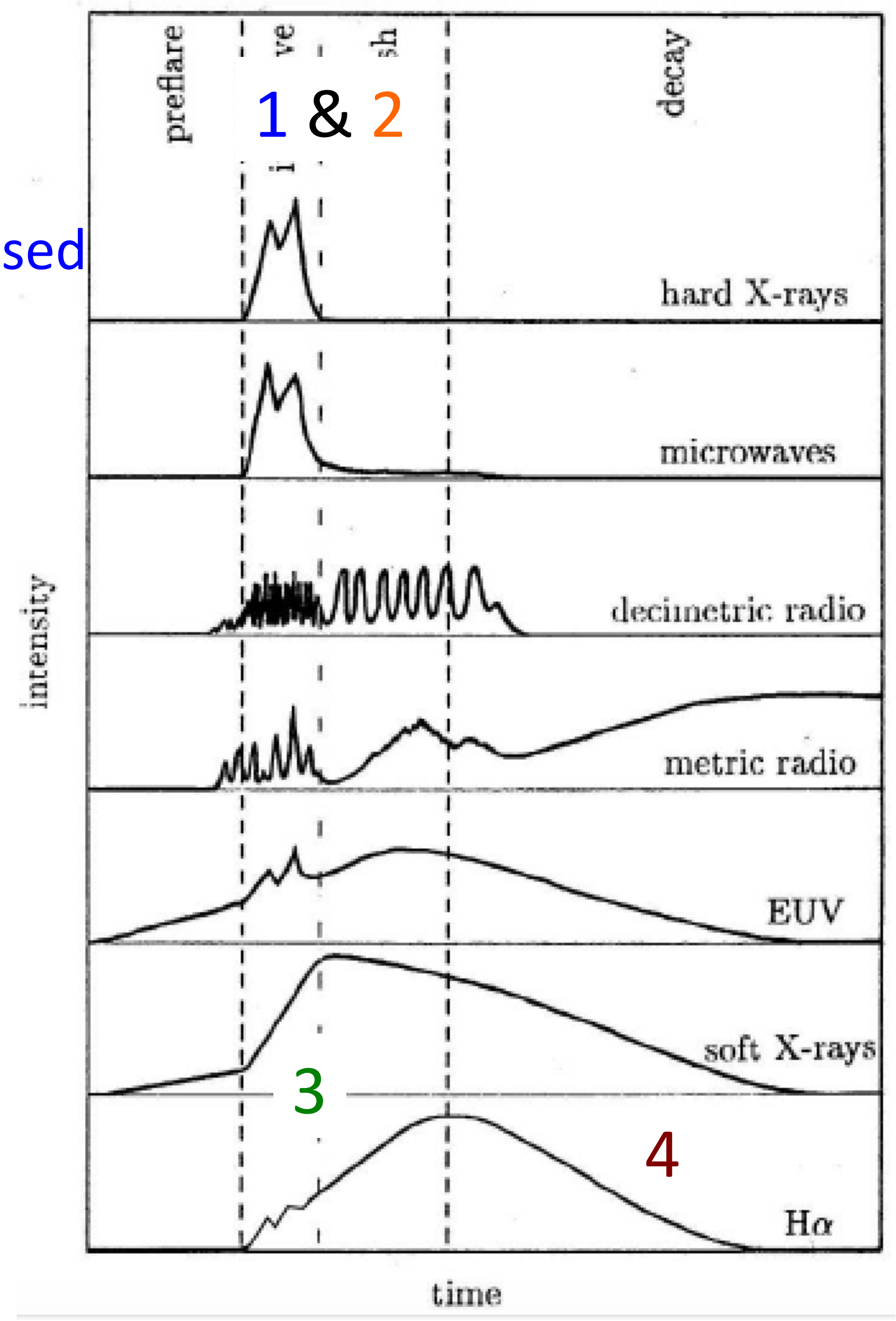


1. magnetic energy released

2. energy transport

3. evaporation

4. loops cool



1 & 2

3

4

Progress of a flare

0. Storage of magnetic energy
1. Release of stored energy
2. Downward energy transport
    a. Thermal conduction (fluid)
    b. Non-thermal electrons (beyond fluid)
3. Evaporation: Loops fill
4. Loops Cool
    a. Thermal conduction
    b. Radiative cooling

Progress of this course

0. Storage of magnetic energy
1. Release of stored energy
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I. Energy release & eruption (CMEs)

III. Impulsive phase

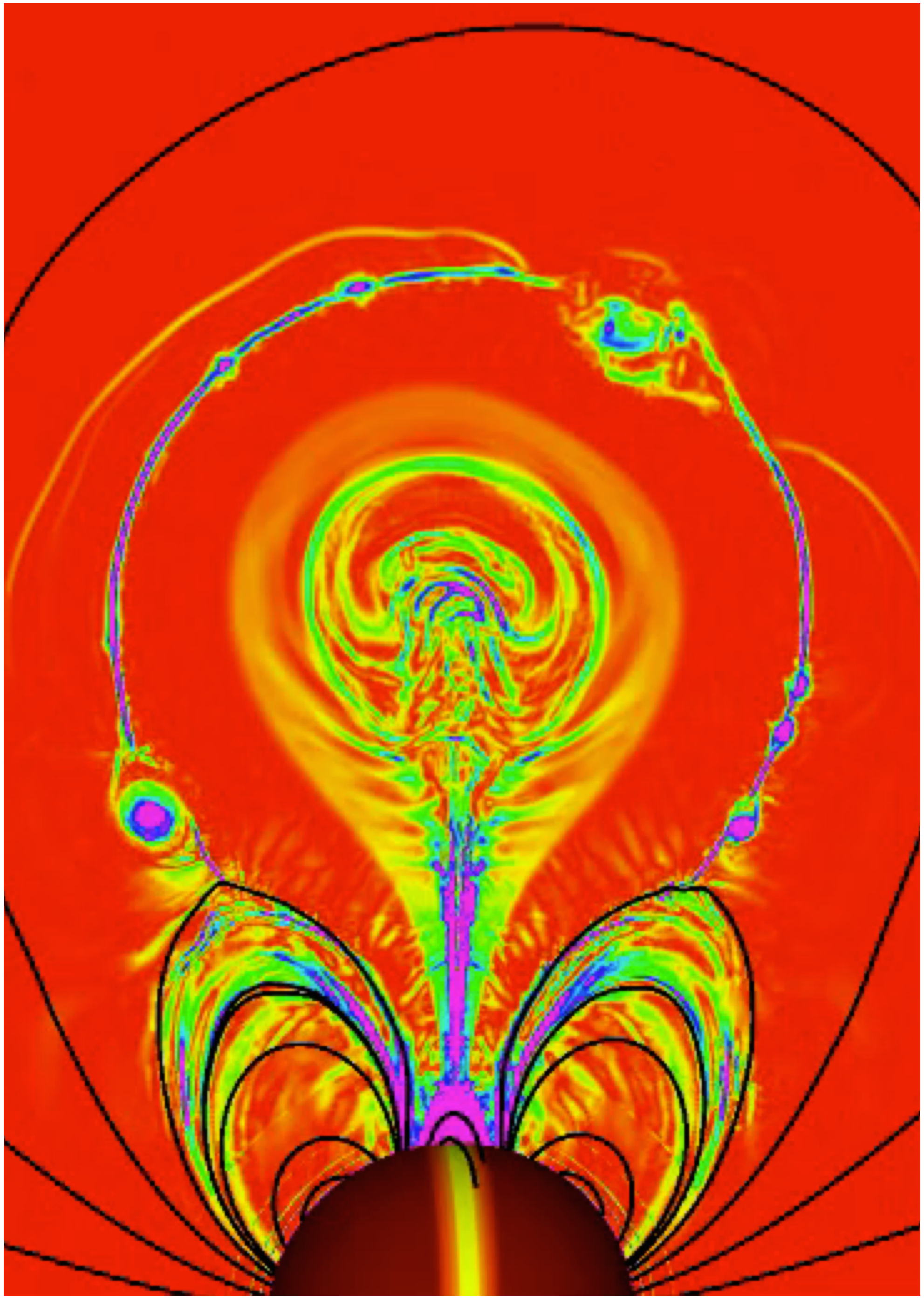
II. Flare loops

1. Energy release

- MHD – large scale, slow evolution (> msec)
- Instability
- Reconnection

$\beta \ll 1$

➔ focus on magnetic field



MHD equations

Dynamical evolution of fluid densities & **B**

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

mass continuity

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)\mathbf{u} = -\nabla p + \tfrac{1}{4\pi}\mathbf{J} \times \mathbf{B} + \rho \mathbf{g}$$

momentum

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\tfrac{5}{3} p \nabla \cdot \mathbf{u} + \tfrac{\eta}{6\pi}\left|\mathbf{J}\right|^2 + \cdots$$

energy

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\eta \mathbf{J} - \mathbf{u} \times \mathbf{B})$$

induction
(Faraday+Ohm)

$$\mathbf{J} = \nabla \times \mathbf{B}$$

Ampere

MHD equations

Dynamical evolution of fluid densities & **B**

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

$\beta << 1$

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$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{u} = -\cancel{\nabla p} + \tfrac{1}{4\pi}\mathbf{J}\times\mathbf{B} + \cancel{\rho \mathbf{g}}$$

momentum

$$\frac{\partial p}{\partial t} + \mathbf{u}\cdot\nabla p = -\tfrac{5}{3}\,p\nabla\cdot\mathbf{u} + \tfrac{\eta}{6\pi}|\mathbf{J}|^2 + \cdots$$

energy

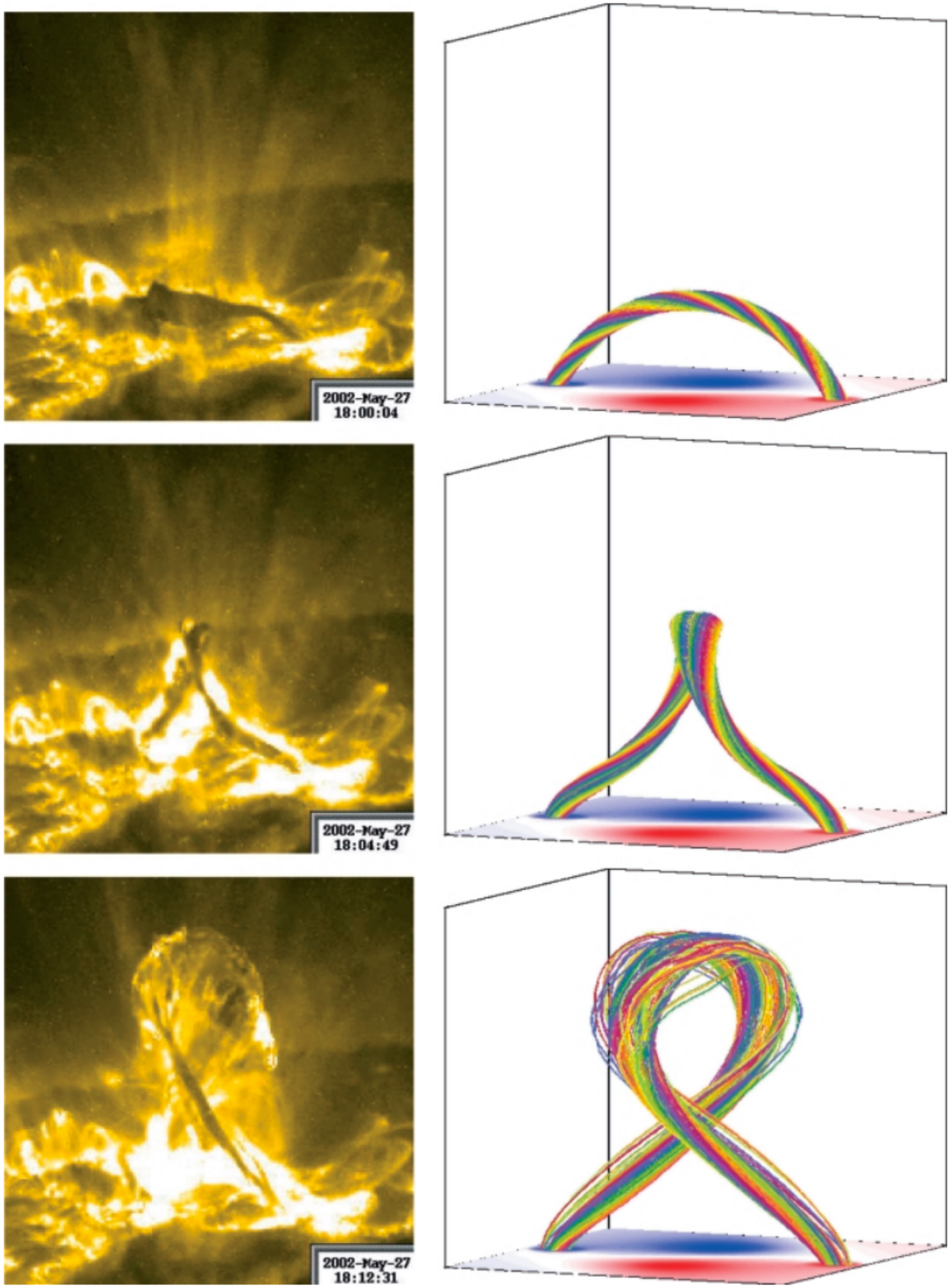
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times(\eta\mathbf{J} - \mathbf{u}\times\mathbf{B})$$

induction
(Faraday+Ohm)

$$\mathbf{J} = \nabla\times\mathbf{B}$$

Ampere

A CME is an MHD instability

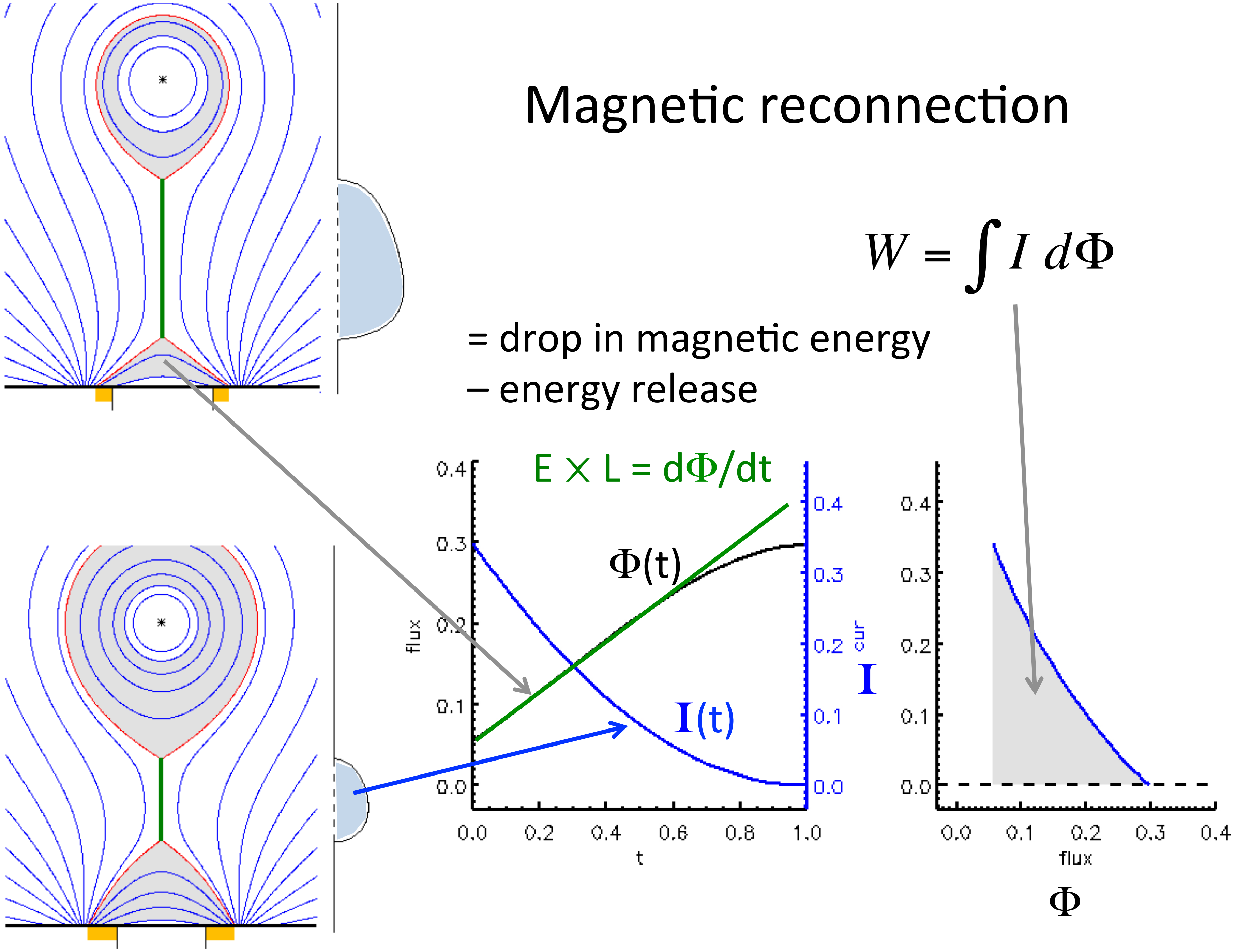


Torok & Kliem 2005

Questions to address

- What is the nature of the MHD instability driving a CME?
- How does magnetic energy get released?
  - What triggers the release?
  - What roles is played by magnetic reconnection?
- Into which other forms is the magnetic energy converted? How?

Magnetic reconnection



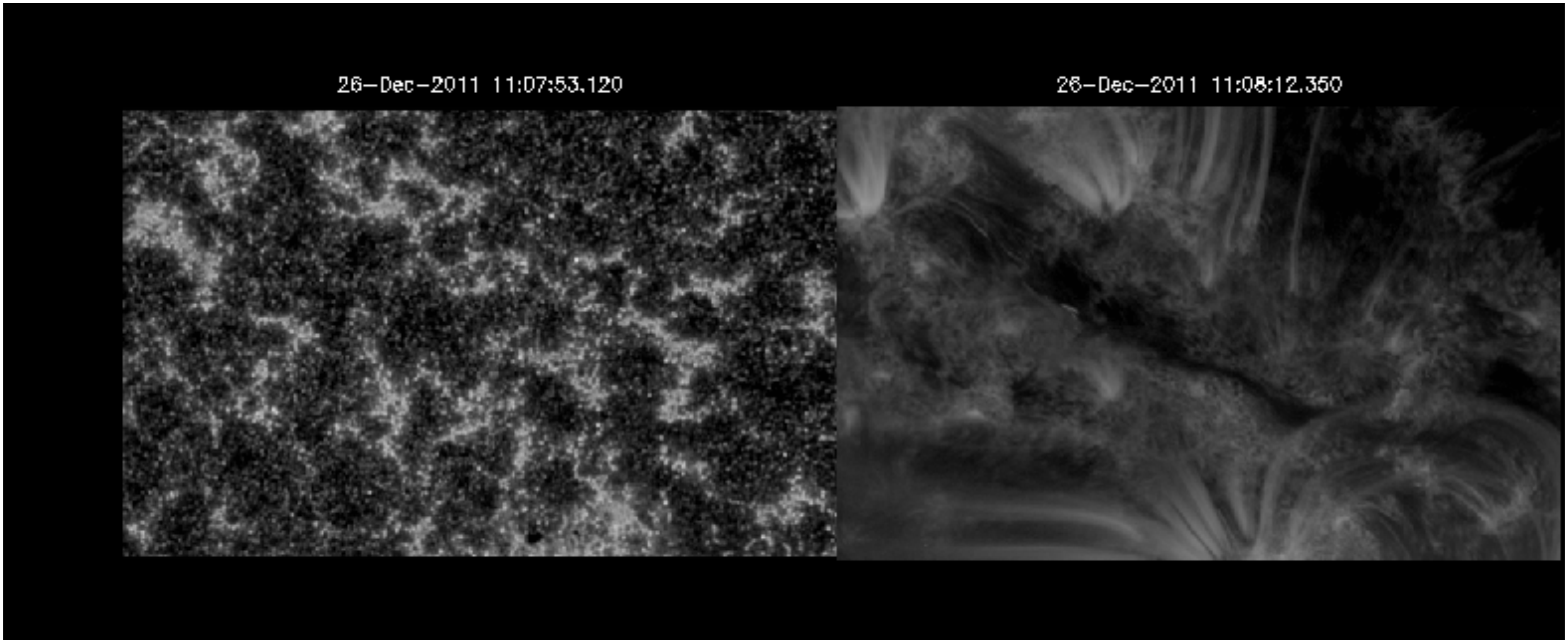
$$W = \int I \, d\Phi$$

= drop in magnetic energy
– energy release

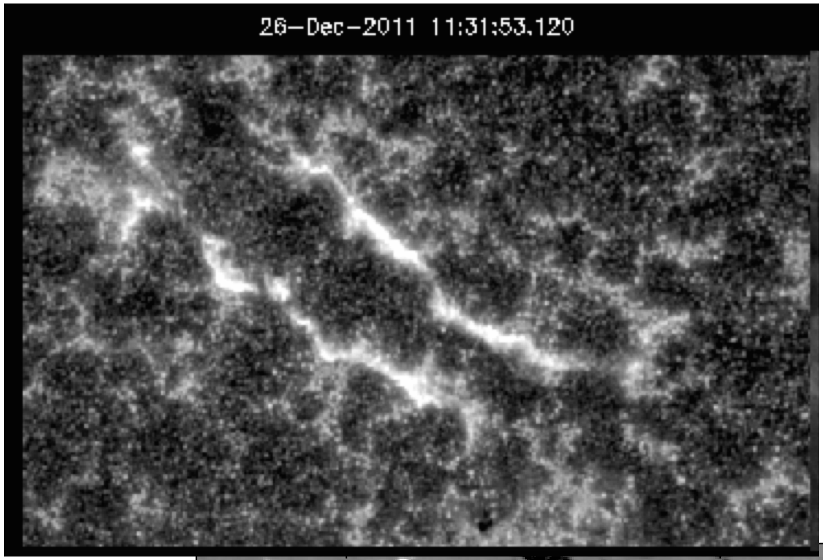
$E \times L = d\Phi/dt$

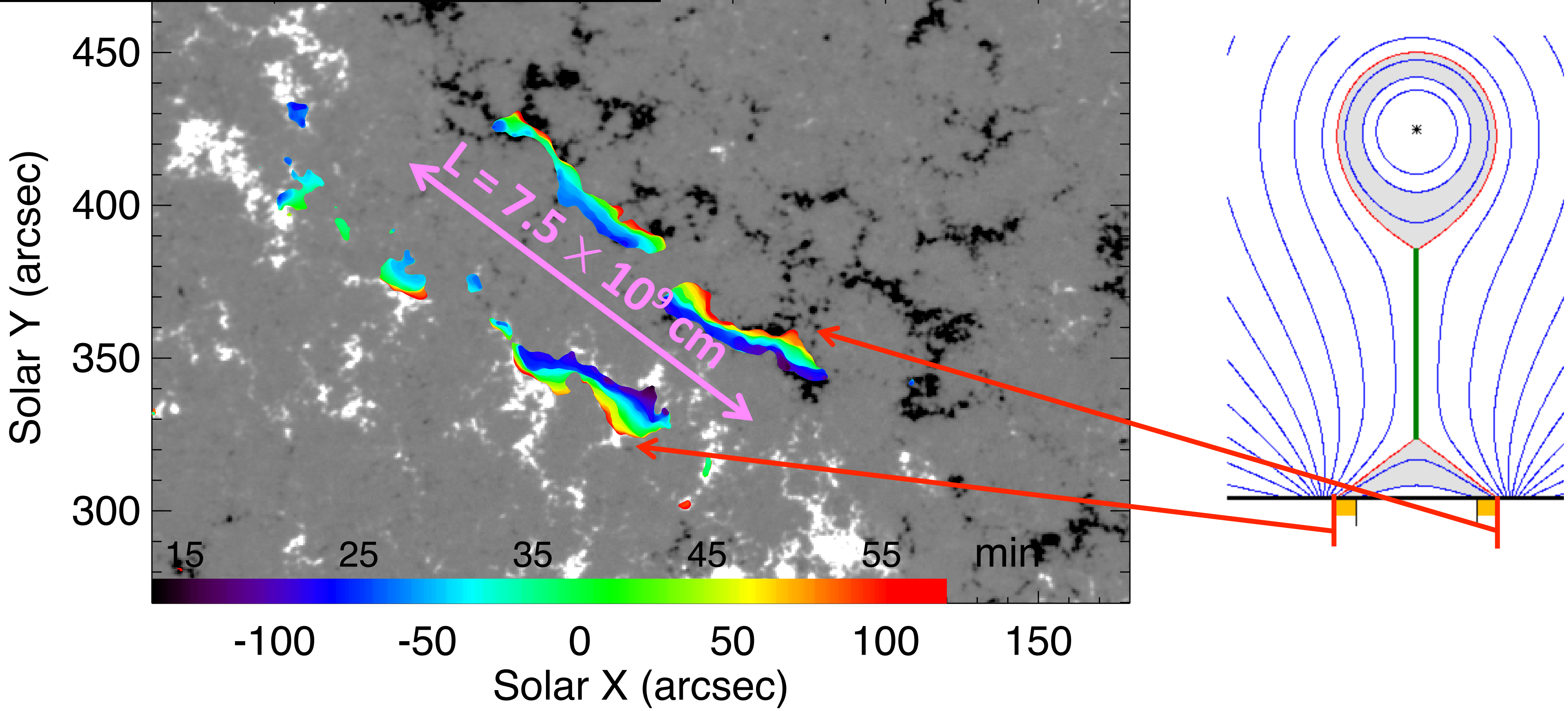
AIA 1600 A:
100,000 K plasma
Chromospheric/TR feet

AIA 171 A:
1,00,000 K plasma
coronal loops

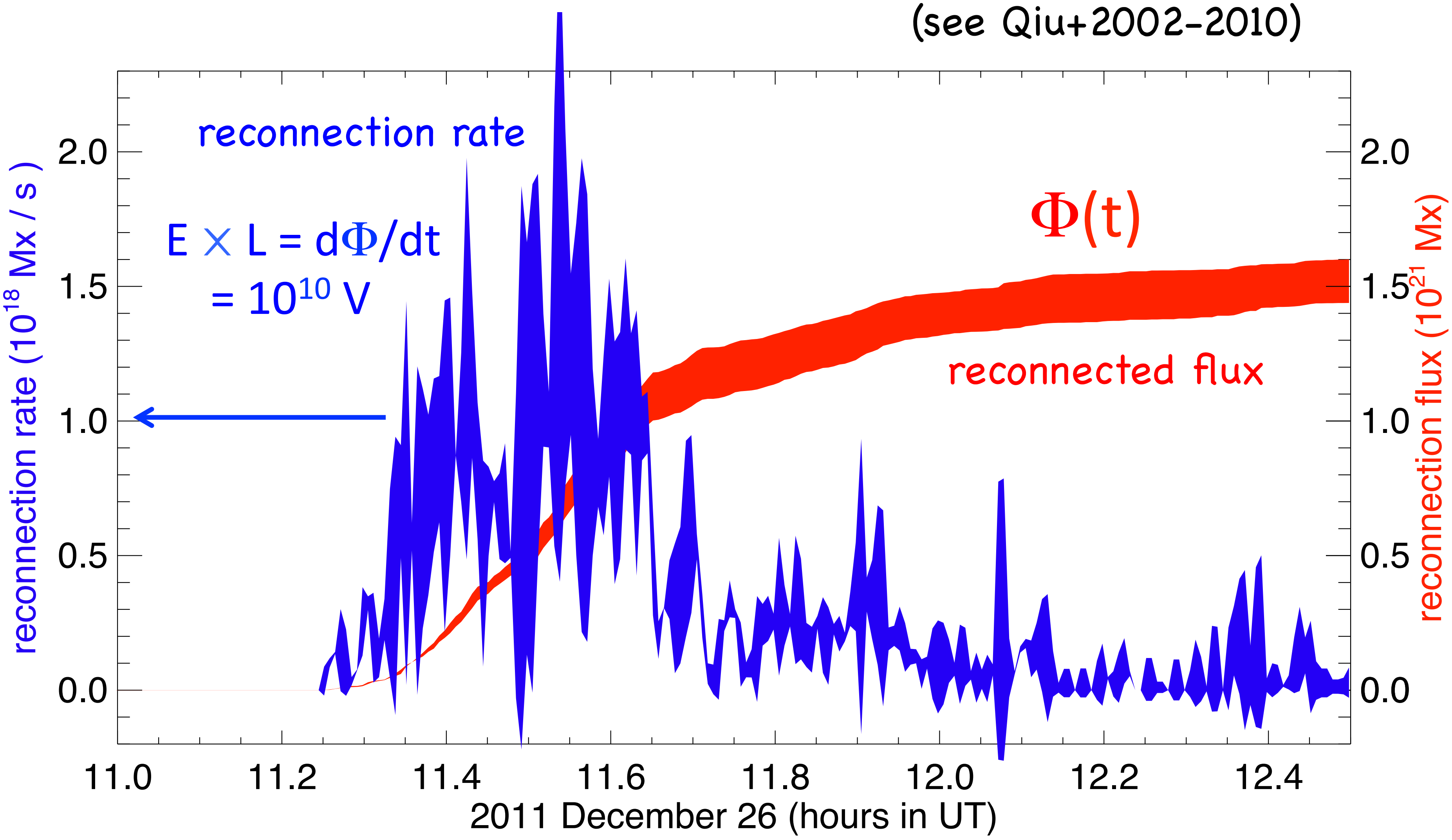


Flux measured from flare ribbons





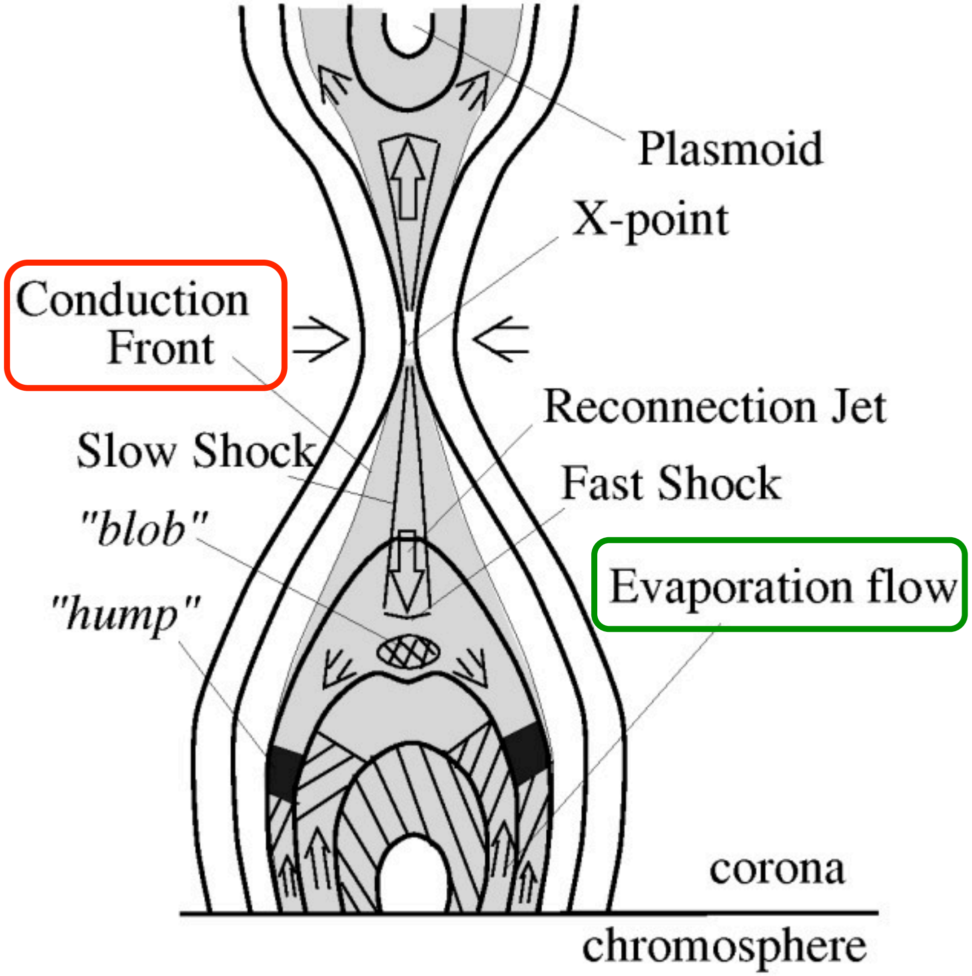
(see Qiu+2002-2010)



$E \times L = d\Phi/dt$
$= 10^{10}$ V

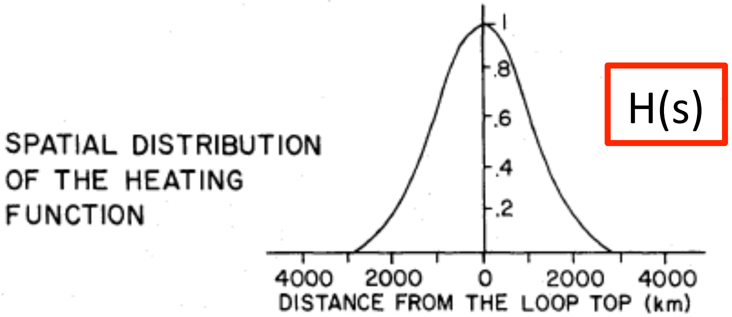
$$W = \int I \, d\Phi \sim \tfrac{1}{2} I_0 \Delta\Phi \sim \frac{(\Delta\Phi)^2}{8\pi L} = \frac{(1.5\times10^{21})^2}{8\pi\cdot7.5\times10^{9}} = 1.2 \times 10^{31} \text{ erg}$$

3. Evaporation



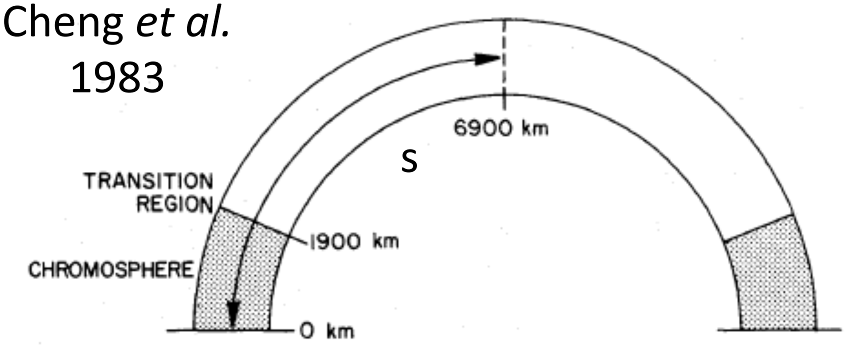
From Yokoyama & Shibata 1998

Modeling loops



H(s)

Cheng *et al.* 1983



1d gas-dynamics

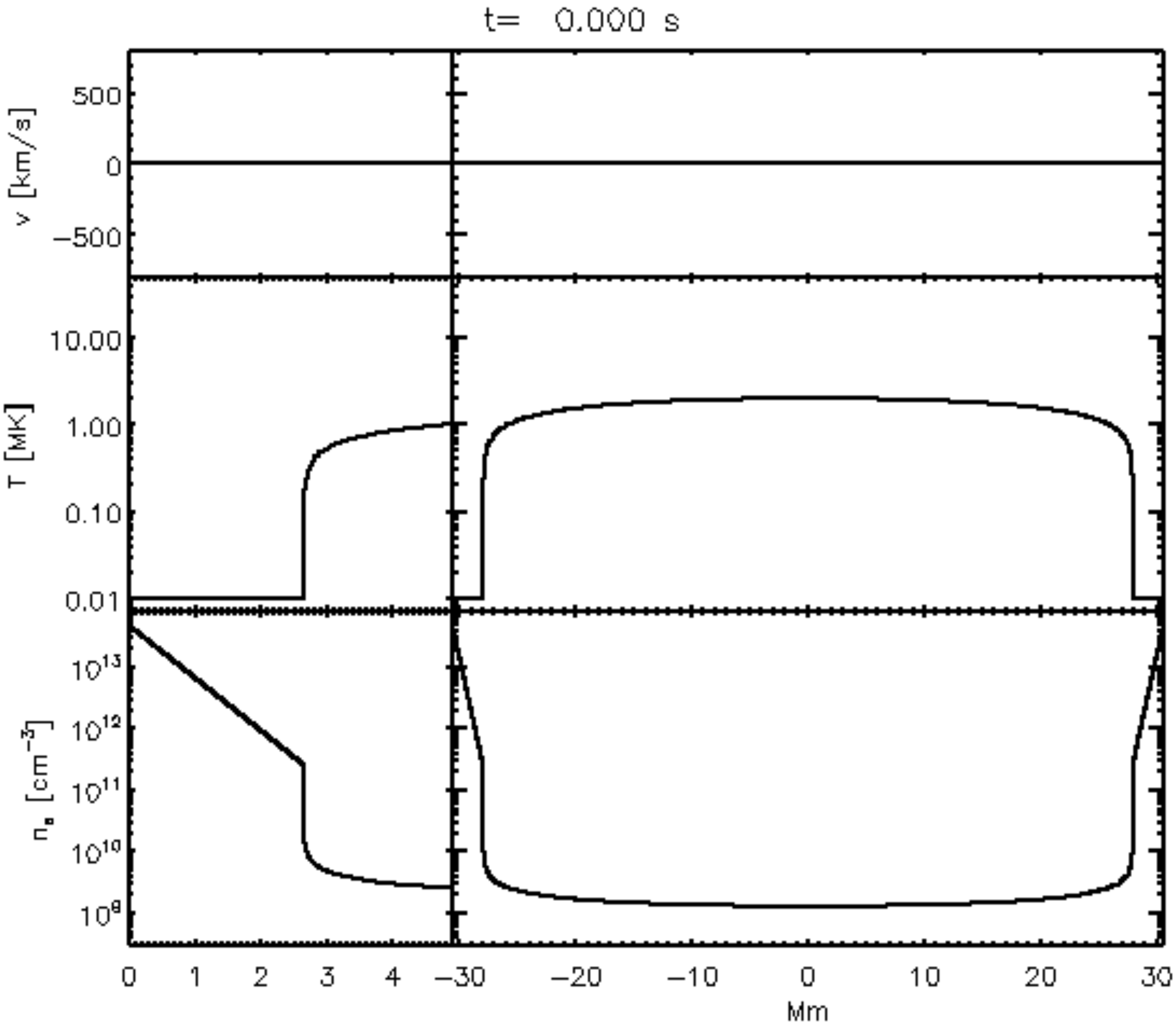
Krall & Antiochos 1980

$$\frac{\partial n}{\partial t} + \frac{1}{A(s)} \frac{\partial}{\partial s}(Anv) = 0, \tag{1}$$

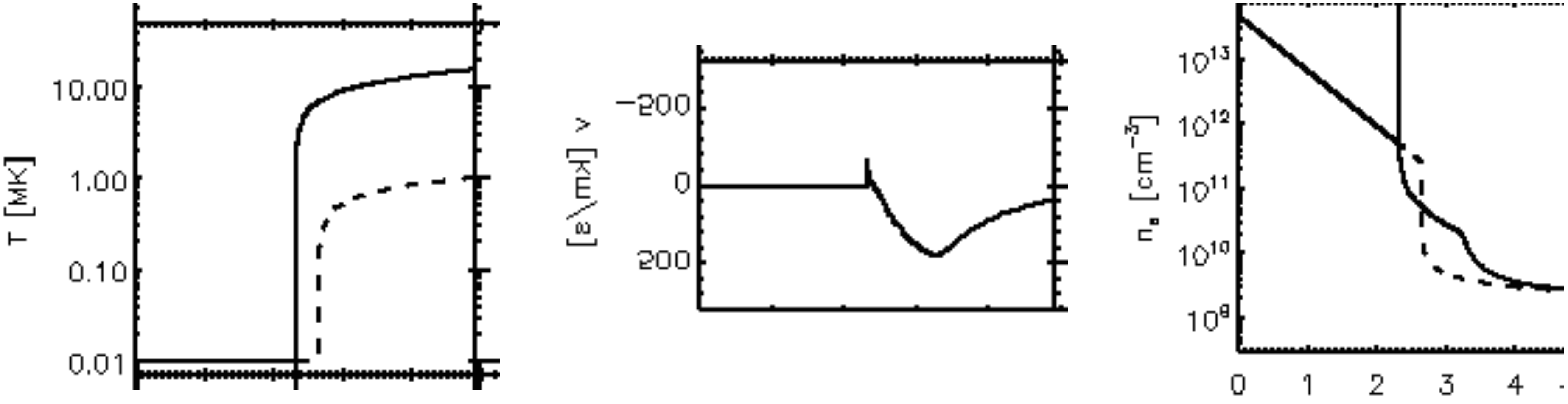
$$n\left(\frac{\partial}{\partial t} + v\frac{\partial}{\partial s}\right)v + \frac{1}{m}\frac{\partial p}{\partial s} = ng_{\parallel}(s), \tag{2}$$

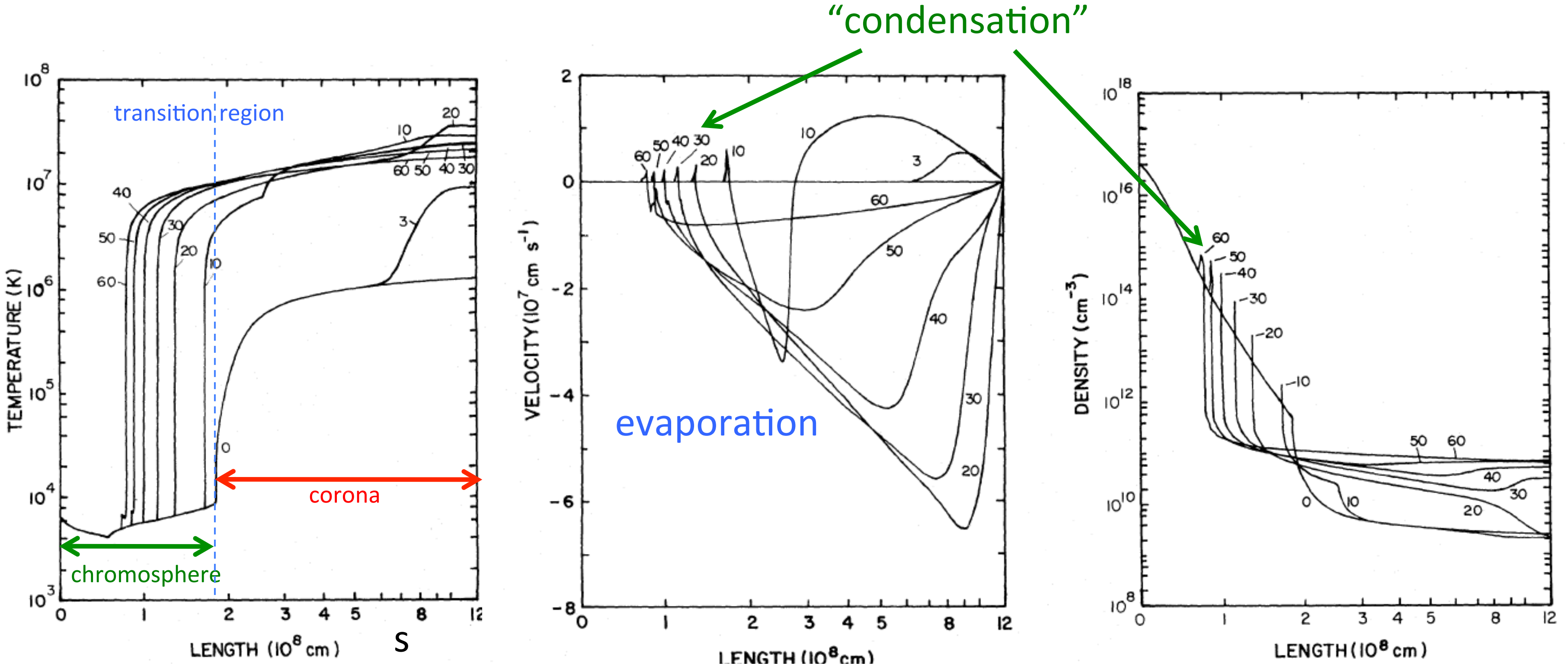
$$3kn\left(\frac{\partial}{\partial t} + v\frac{\partial}{\partial s}\right)T + \frac{p}{A(s)}\frac{\partial}{\partial s}(Av) - \frac{1}{A}\frac{\partial}{\partial s}\left(AK\frac{\partial T}{\partial s}\right) + n^2\Lambda(T) = \boxed{H(s)} \tag{3}$$

energy input (i.e. 1 & 2)


t= 0.000 s
v [km/s]
500
0
−500
T [MK]
10.00
1.00
0.10
0.01
n_e [cm^{-3}]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
0
1
2
3
4
−30
−20
−10
0
10
20
30
Mm

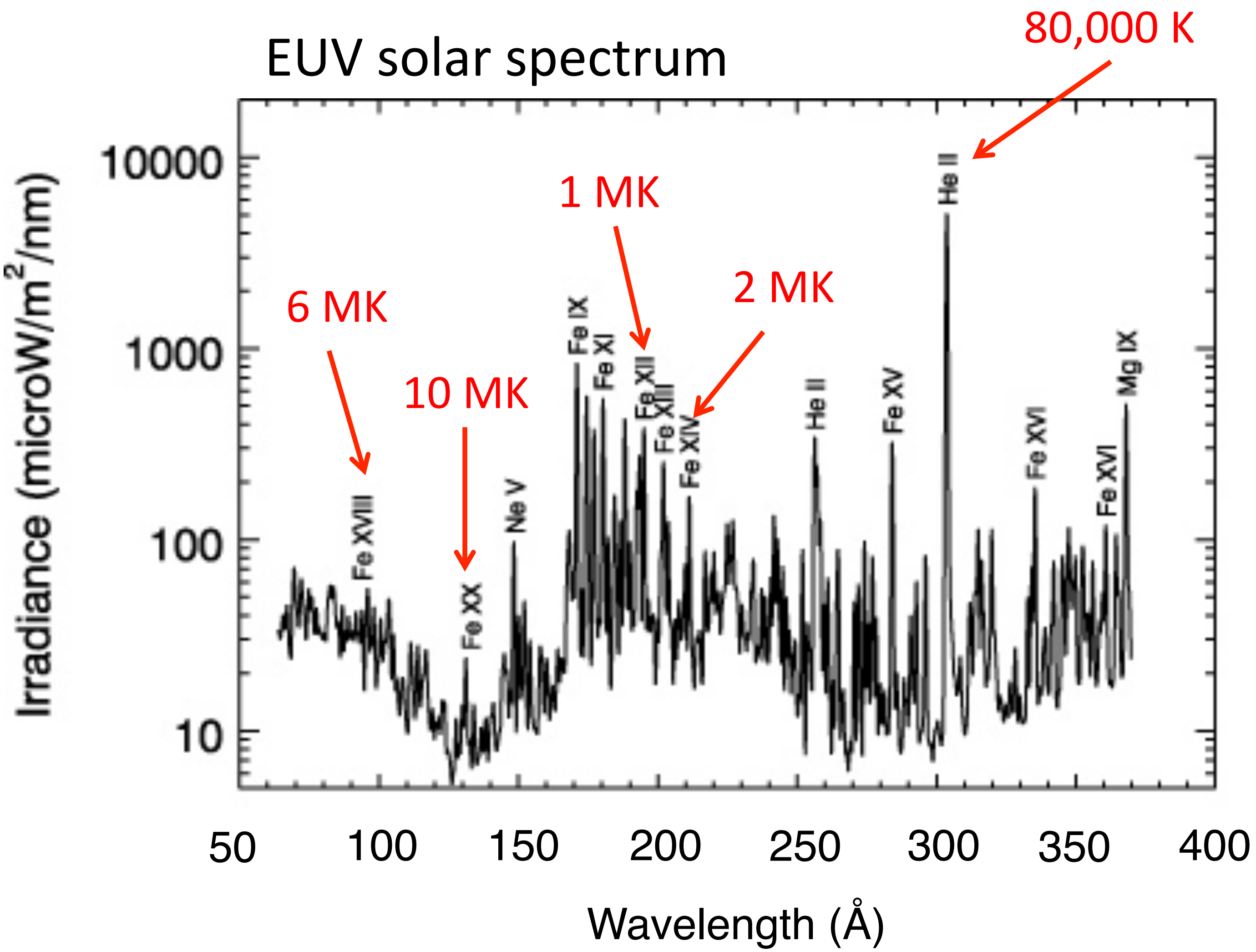
Modeling evaporation



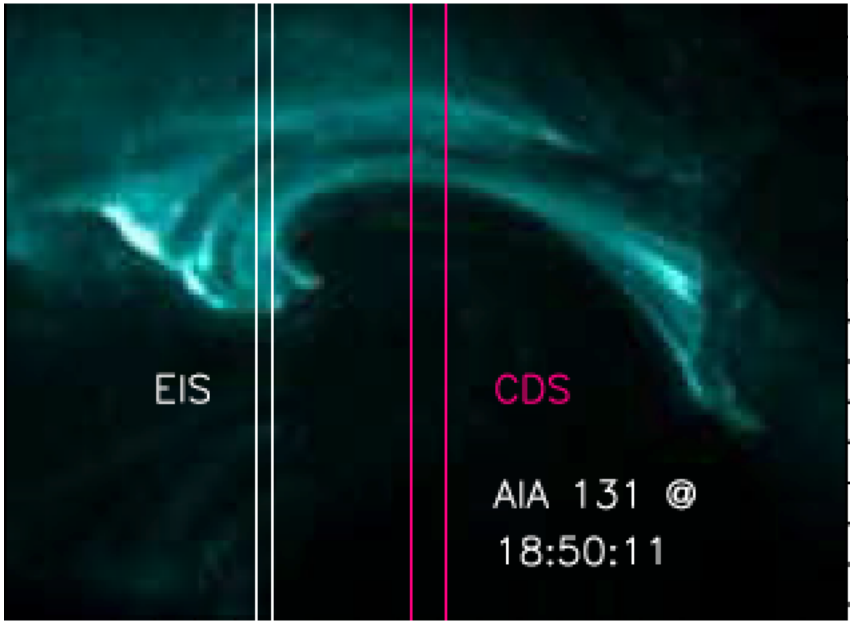


Emslie & Nagai 1985

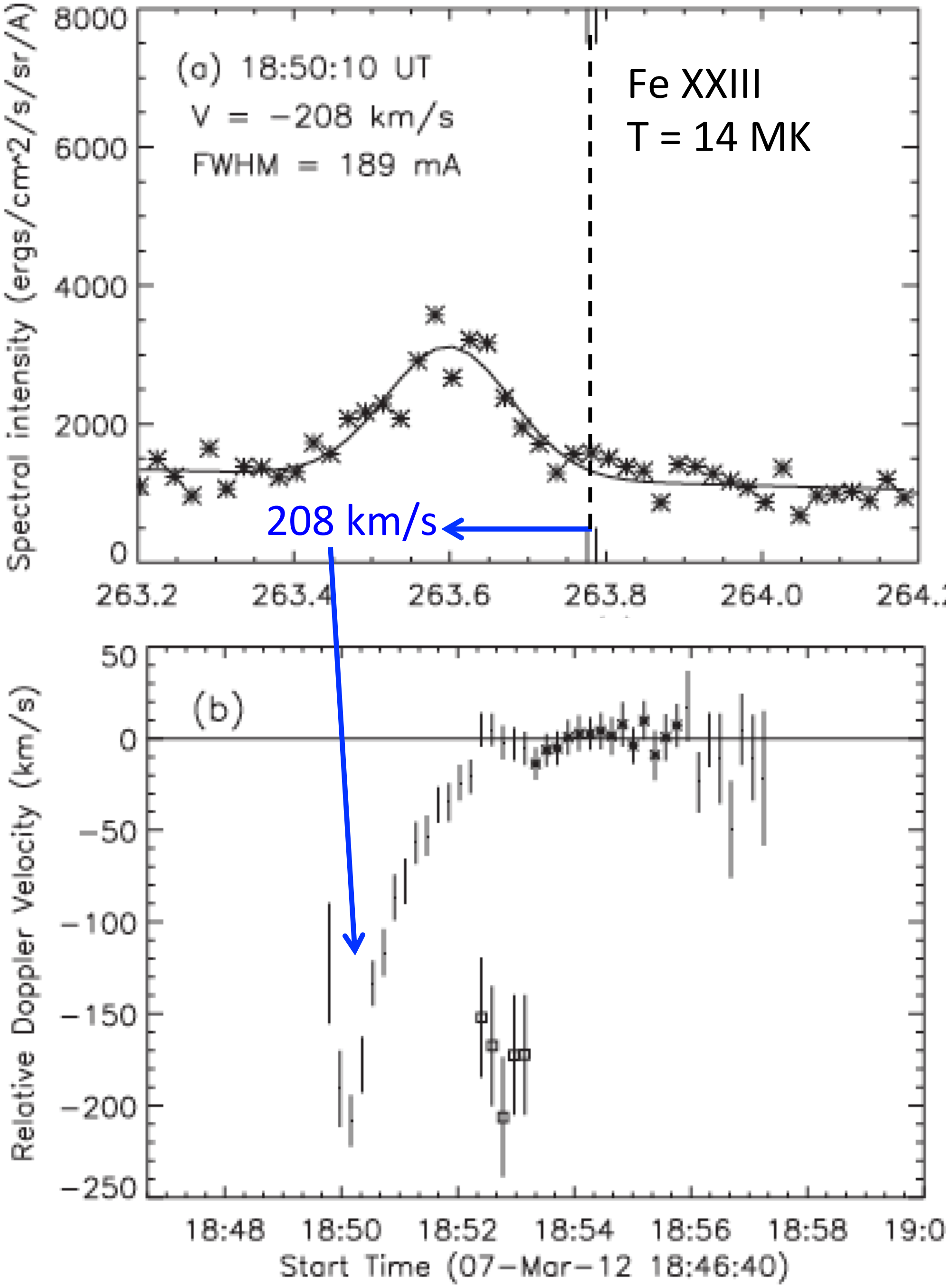
Observing loops


EUV solar spectrum

NASA SDO/EVE

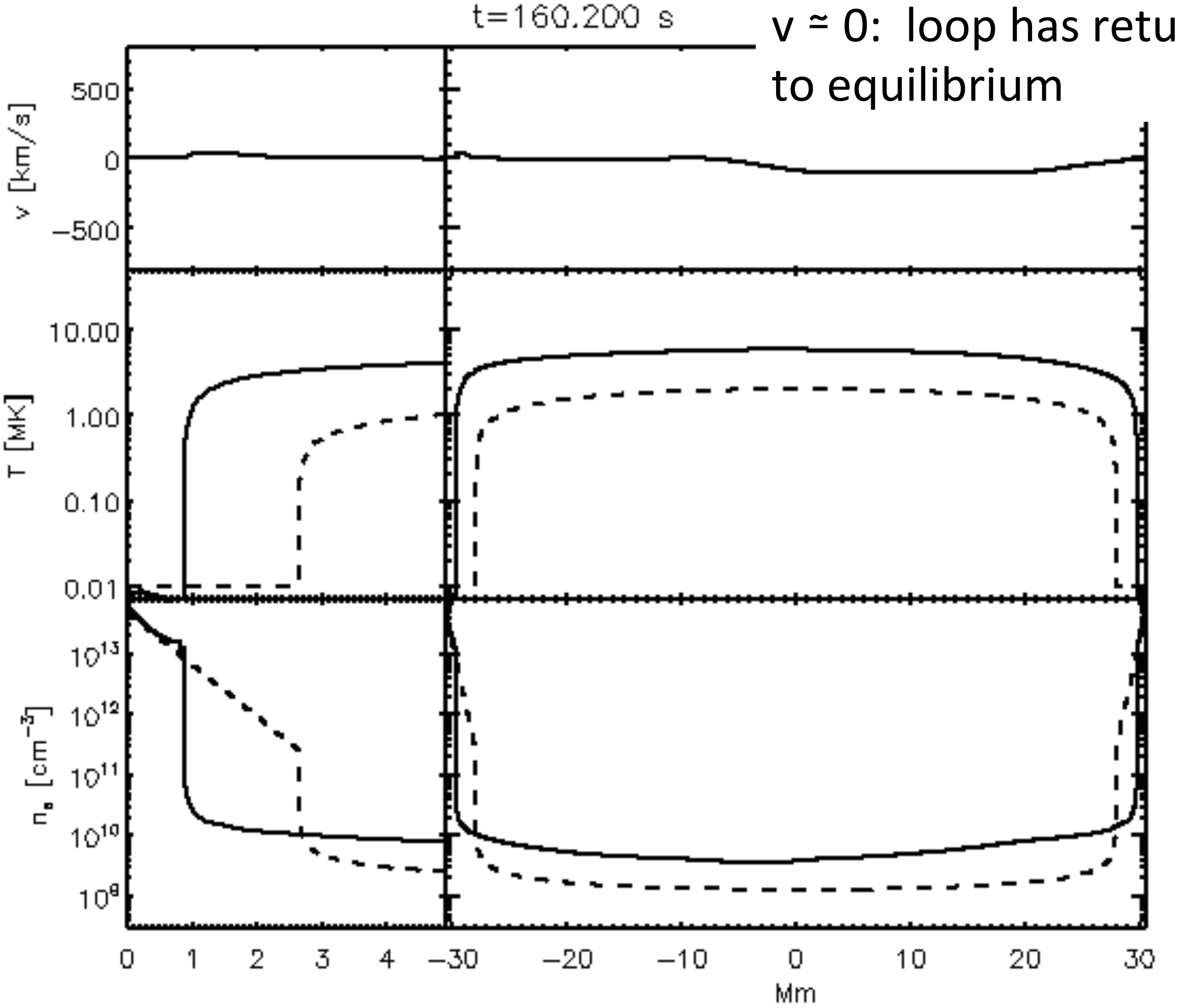


Brosius 2013



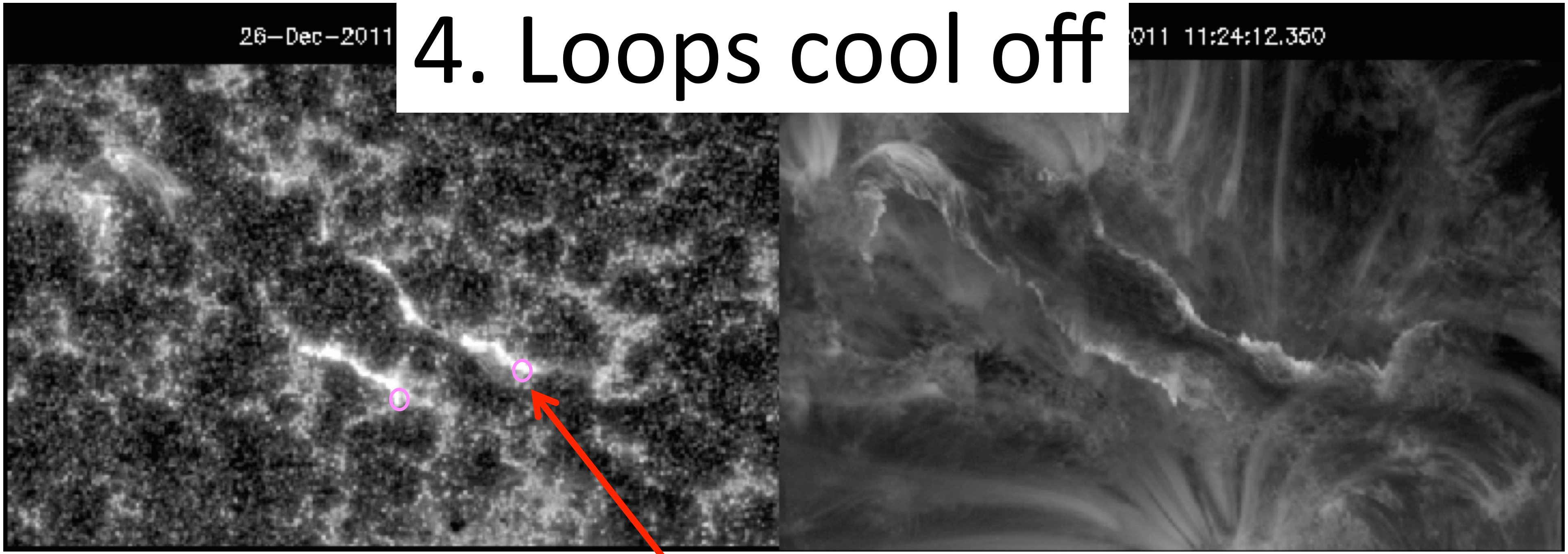
Fe XXIII
T = 14 MK

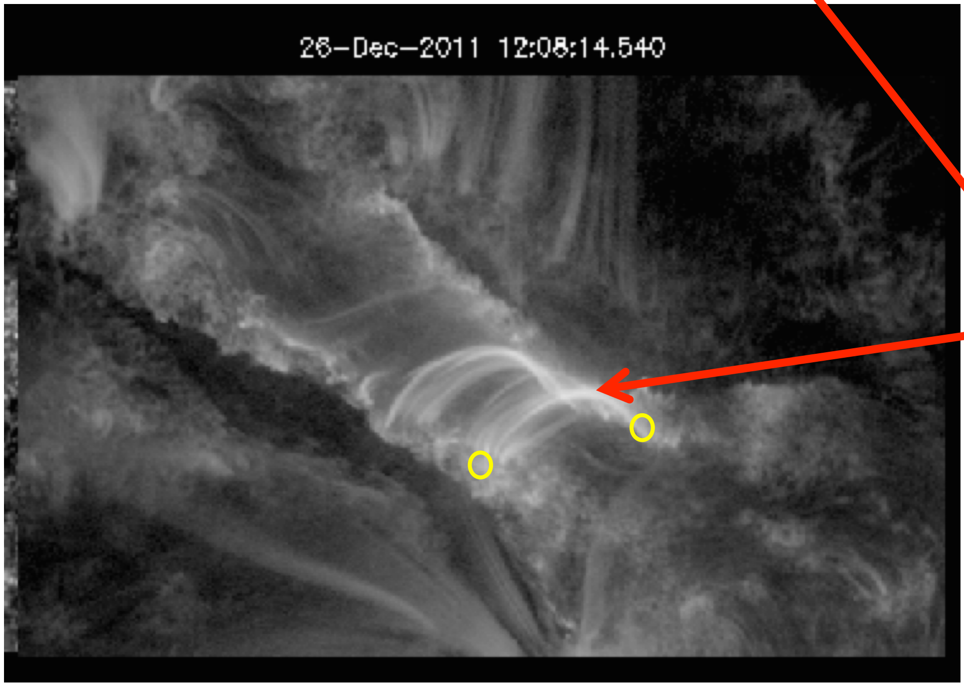
v ≃ 0: loop has returned to equilibrium



Hotter & denser than it started

4. Loops cool off

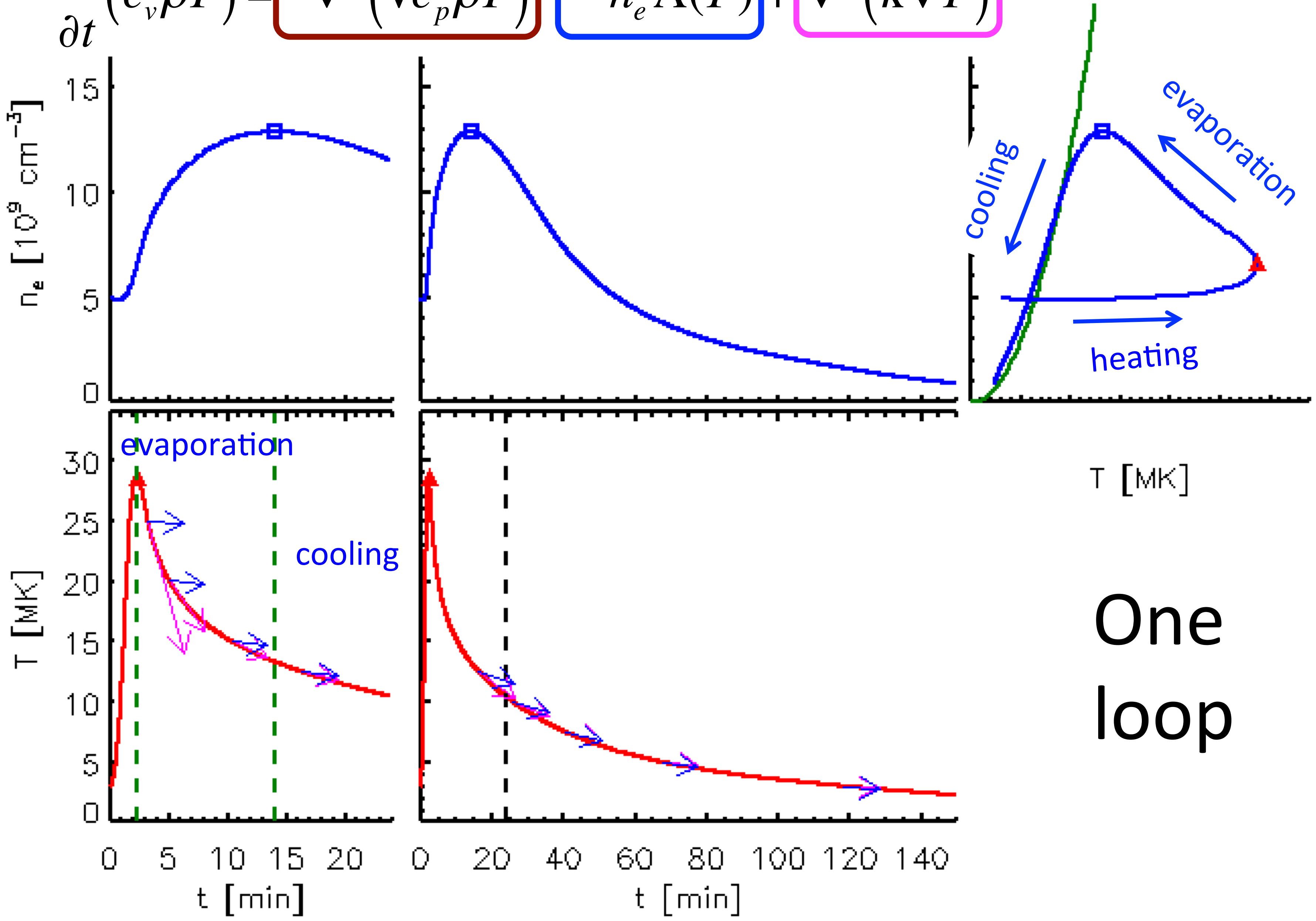




- Energy released
- Feet brighten
- Loop appears @ 10^6 K
  - 44 min. later

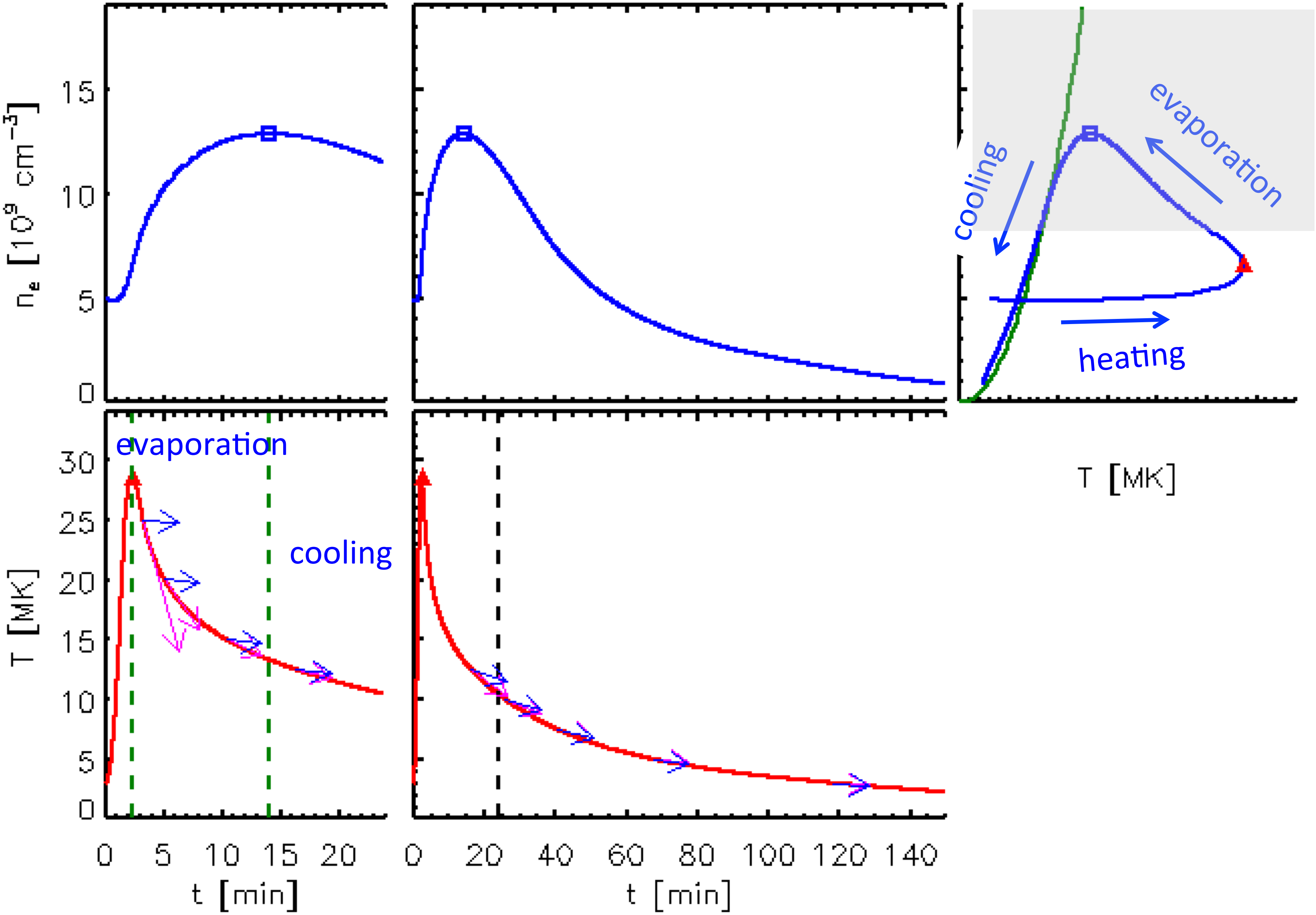
enthalpy flux radiation conduction

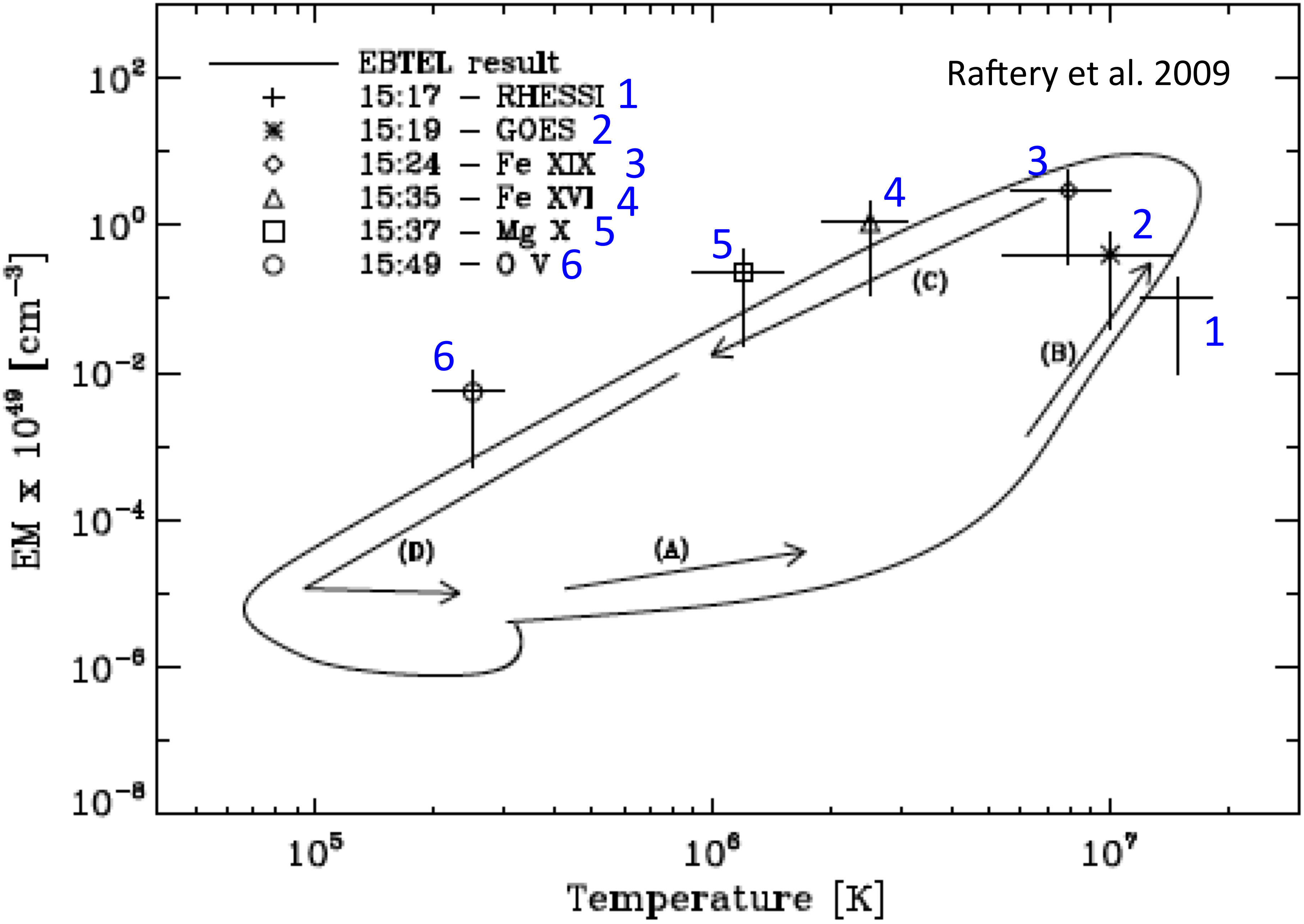
$$\frac{\partial}{\partial t}\left(c_v \rho T\right) = \boxed{-\nabla\cdot\left(\mathbf{v} c_p \rho T\right)} \boxed{-n_e^2\Lambda(T)} + \boxed{\nabla\cdot\left(\kappa\nabla T\right)}$$



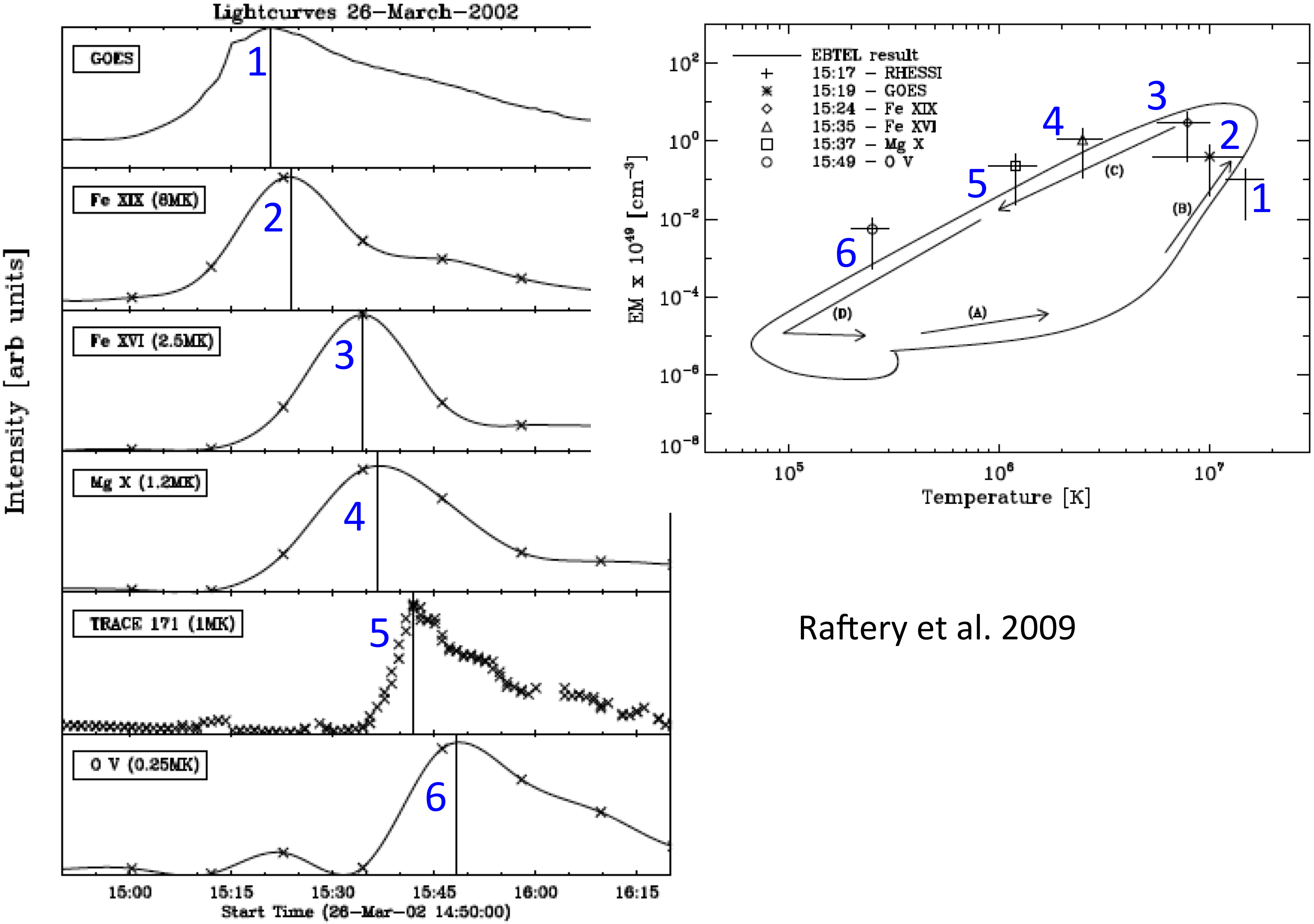
One
loop

More dense = more visible



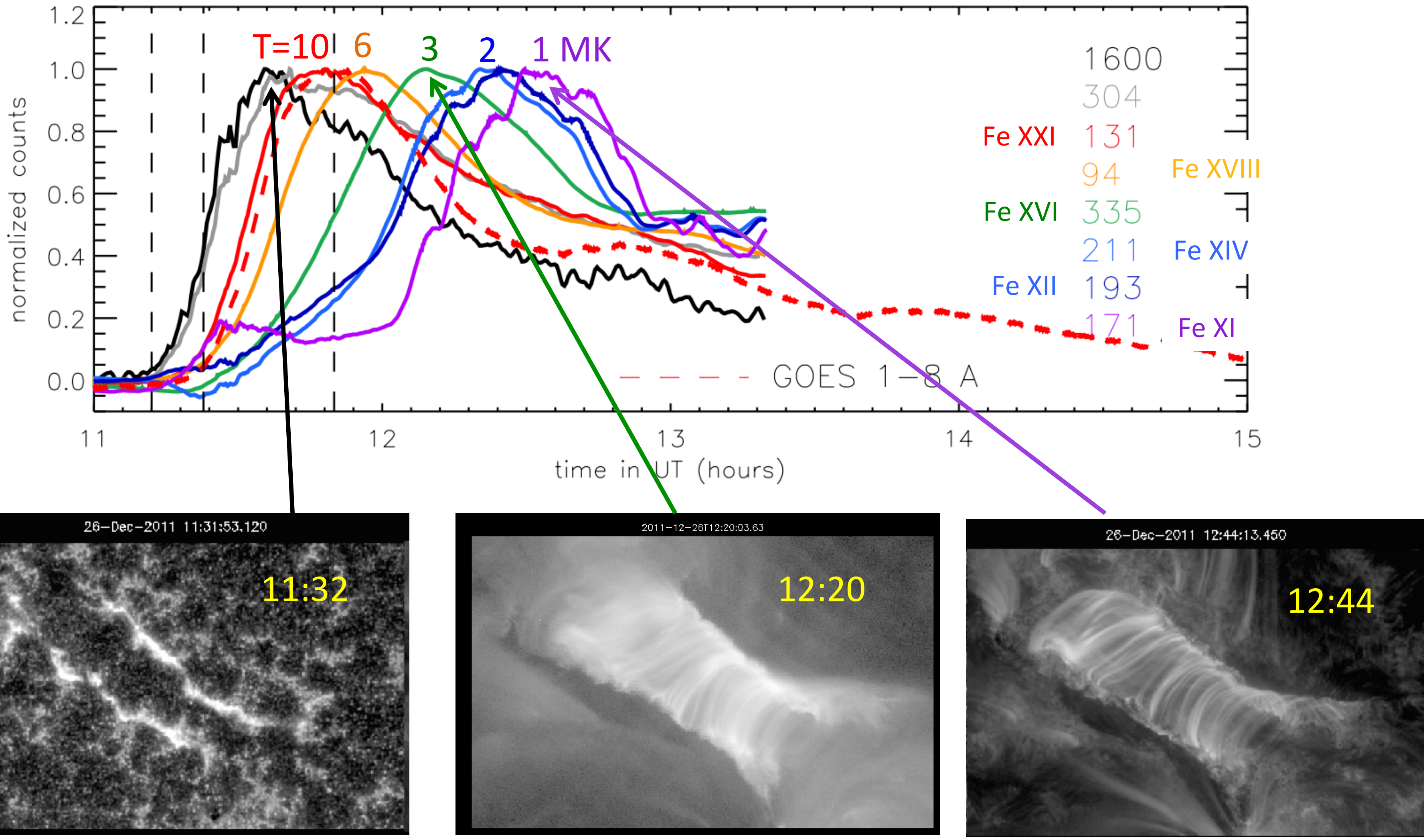


Raftery et al. 2009

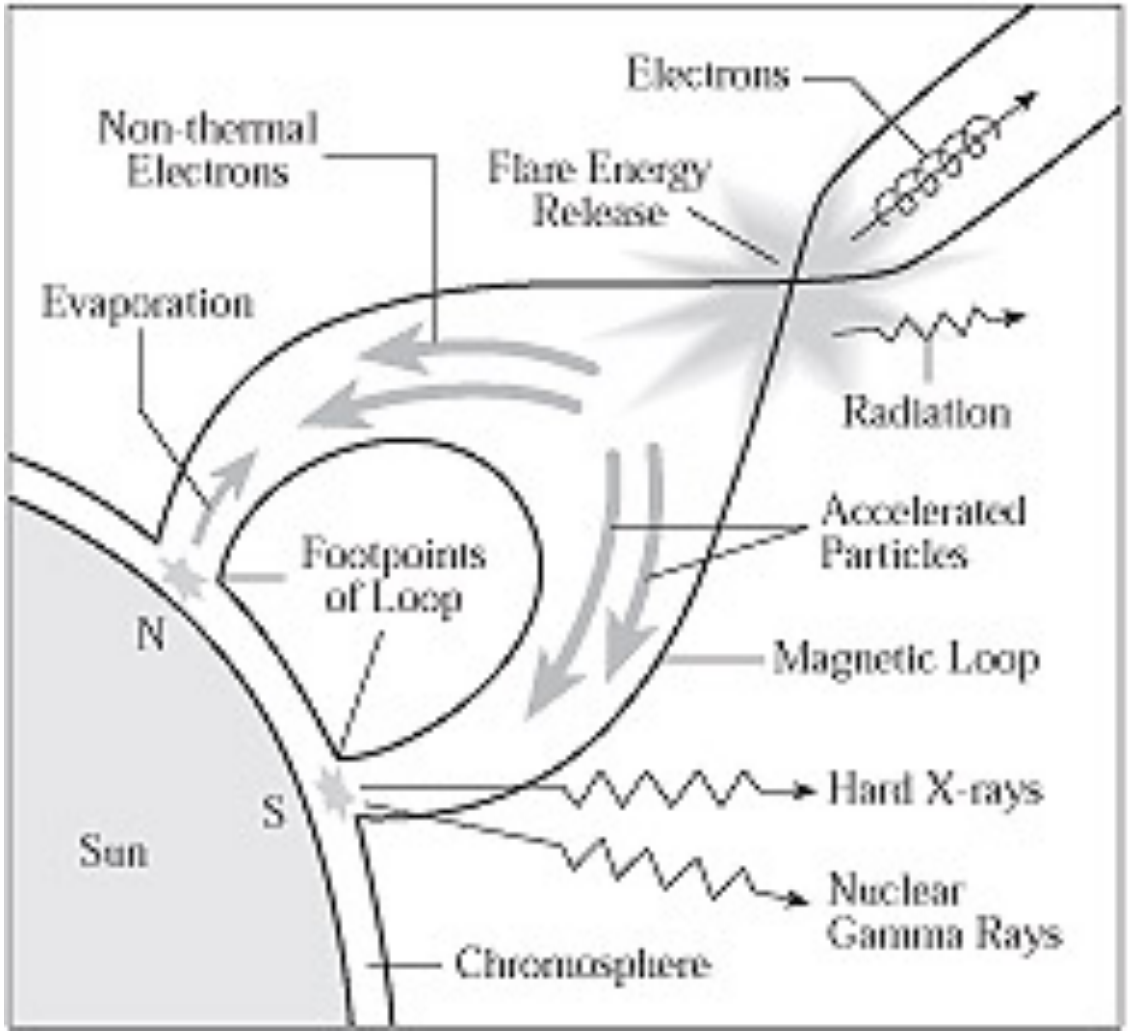


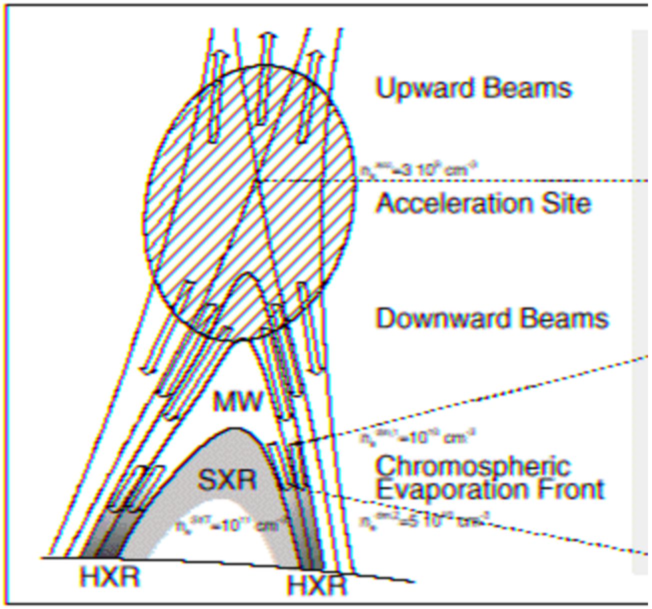
Raftery et al. 2009

Cooling observed

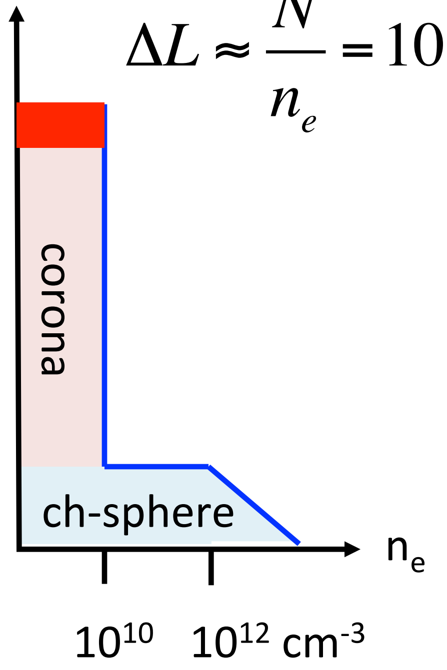


2. Energy transport





$$\Delta L \approx \frac{N}{n_e} = 10^8\,\mathrm{cm}$$



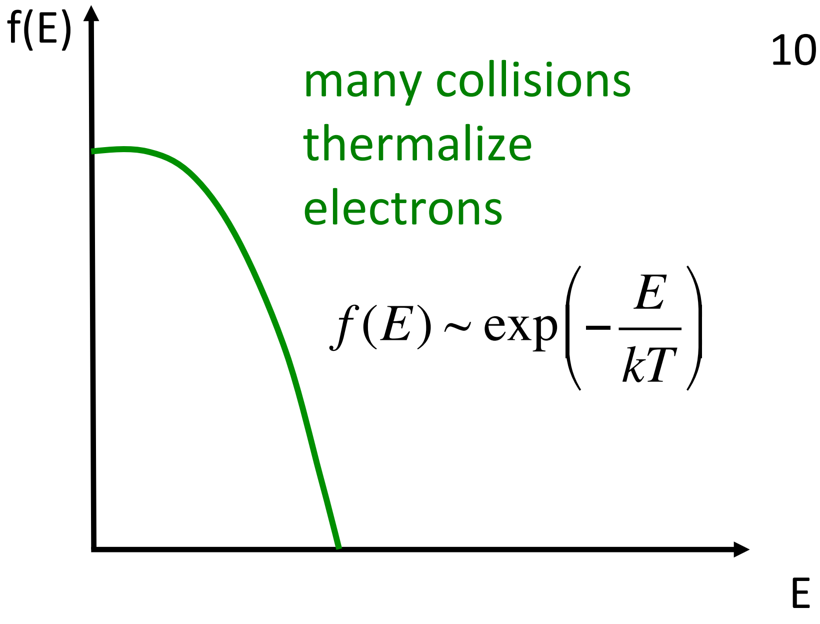
Electron collision cross section (Rutherford)

$$\sigma_e = 10^{-17}\ \mathrm{cm}^2 \times E_{\mathrm{keV}}^{-2}$$

"stop": $\int \sigma_e n_e \, d\ell = 1$

Stopping column

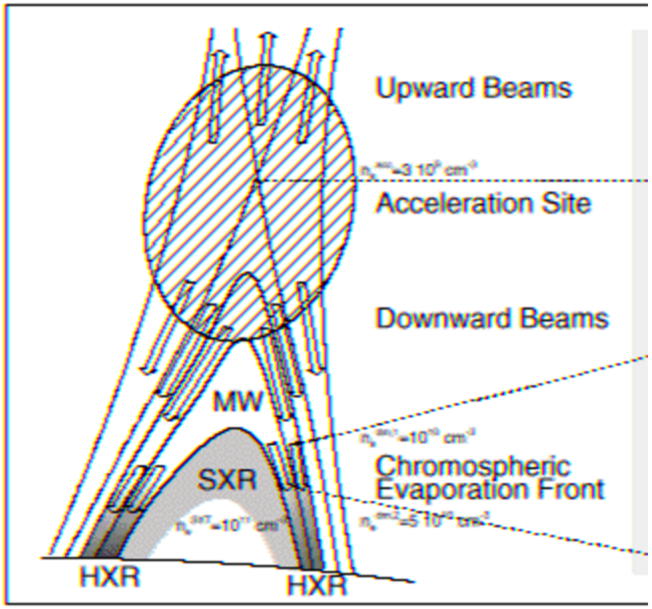
$$N = \int n_e \, d\ell = \frac{1}{\sigma_e} = 10^{17}\ \mathrm{cm}^{-2} \times E_{\mathrm{keV}}^{2}$$



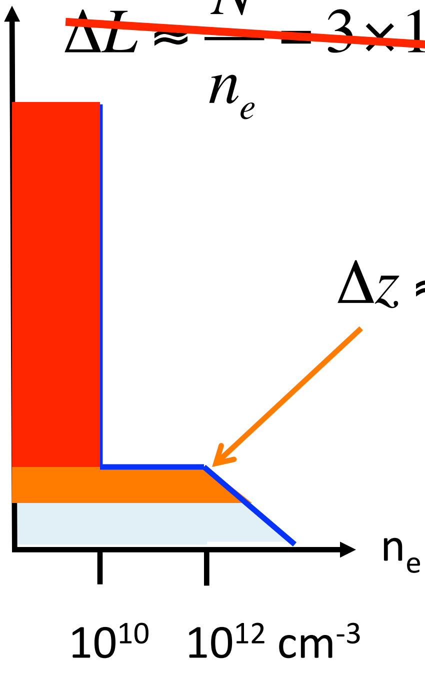
many collisions thermalize electrons

$$f(E) \sim \exp\left(-\frac{E}{kT}\right)$$

3 keV (T=30 MK) → $N = 10^{18}\ \mathrm{cm}^{-2}$

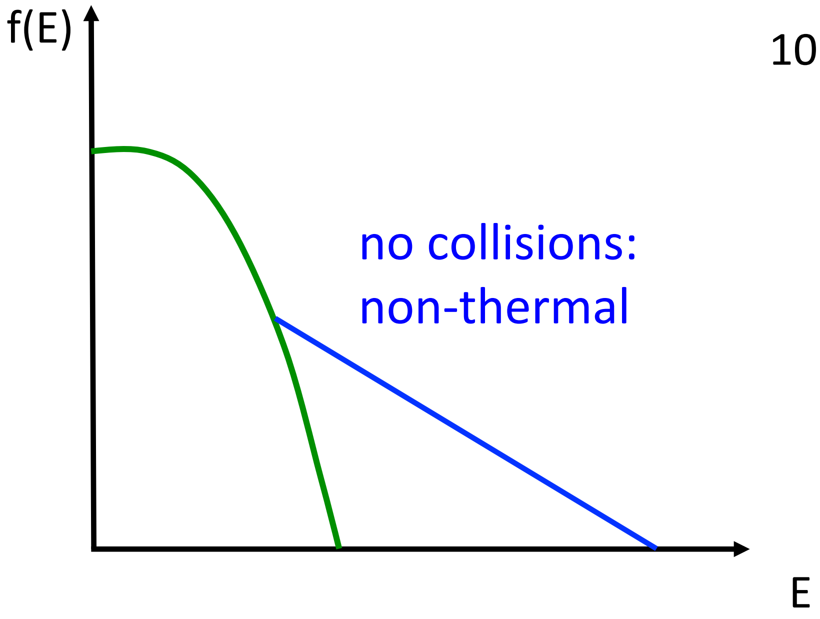


$$\cancel{\Delta L \approx \frac{N}{n_e} = 3\times 10^{10}\,\mathrm{cm}}$$



$$\Delta z \approx H_\rho \ln\left(\frac{N}{n_{e,0}H_\rho}\right) = 10^{8}\,\mathrm{cm}$$

$$\sigma_e = 10^{-17}\ \mathrm{cm}^2 \times E_{\mathrm{keV}}^{-2}$$



Stopping column

$$N = \int n_e\, d\ell = \frac{1}{\sigma_e} = 10^{17}\ \mathrm{cm}^{-2} \times E_{\mathrm{keV}}^{2}$$

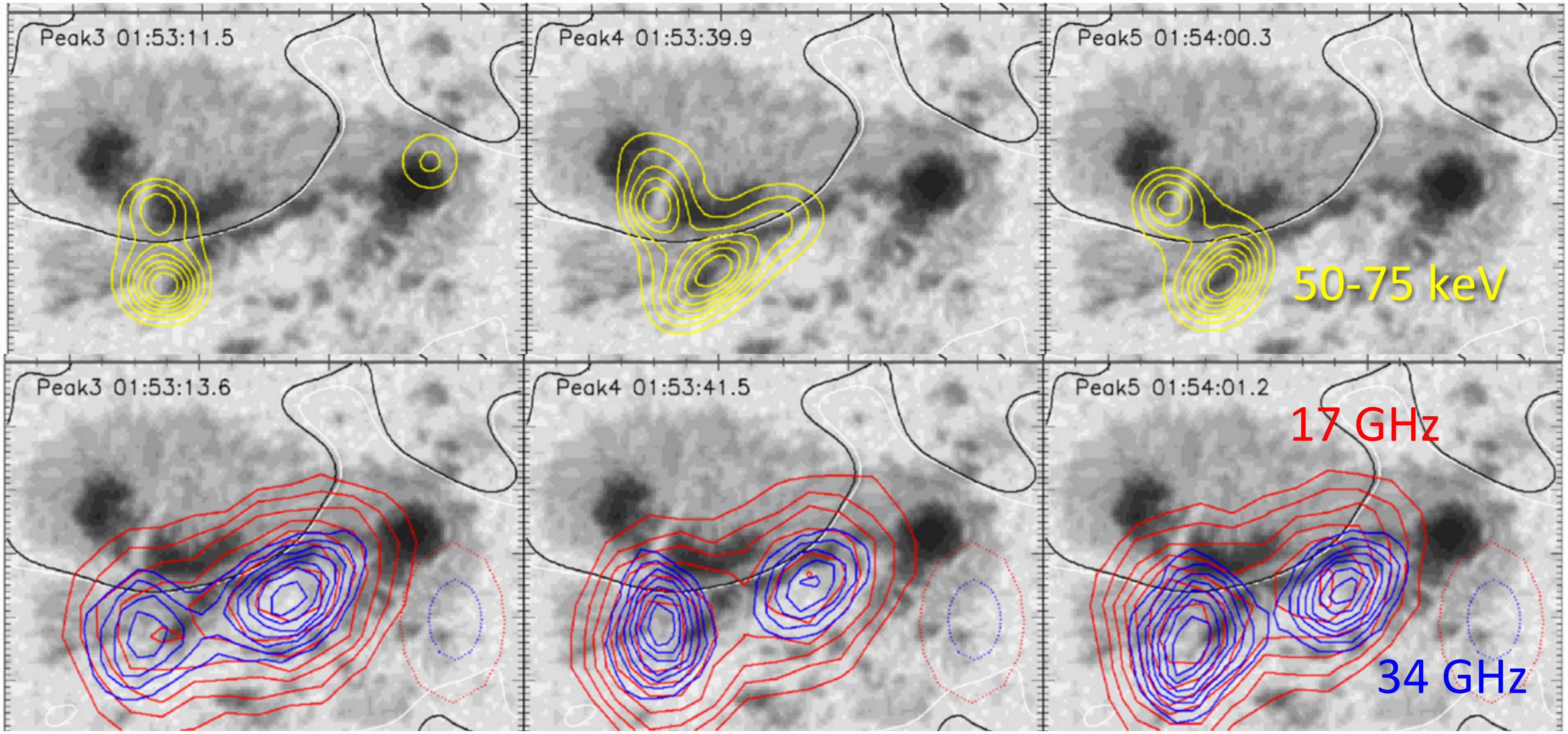
50 keV → N=3 × 10^{20} cm^{-2}

How do we "see" 50 keV e^-s?

1. From ~ 50 keV photons they emit: hard X-rays

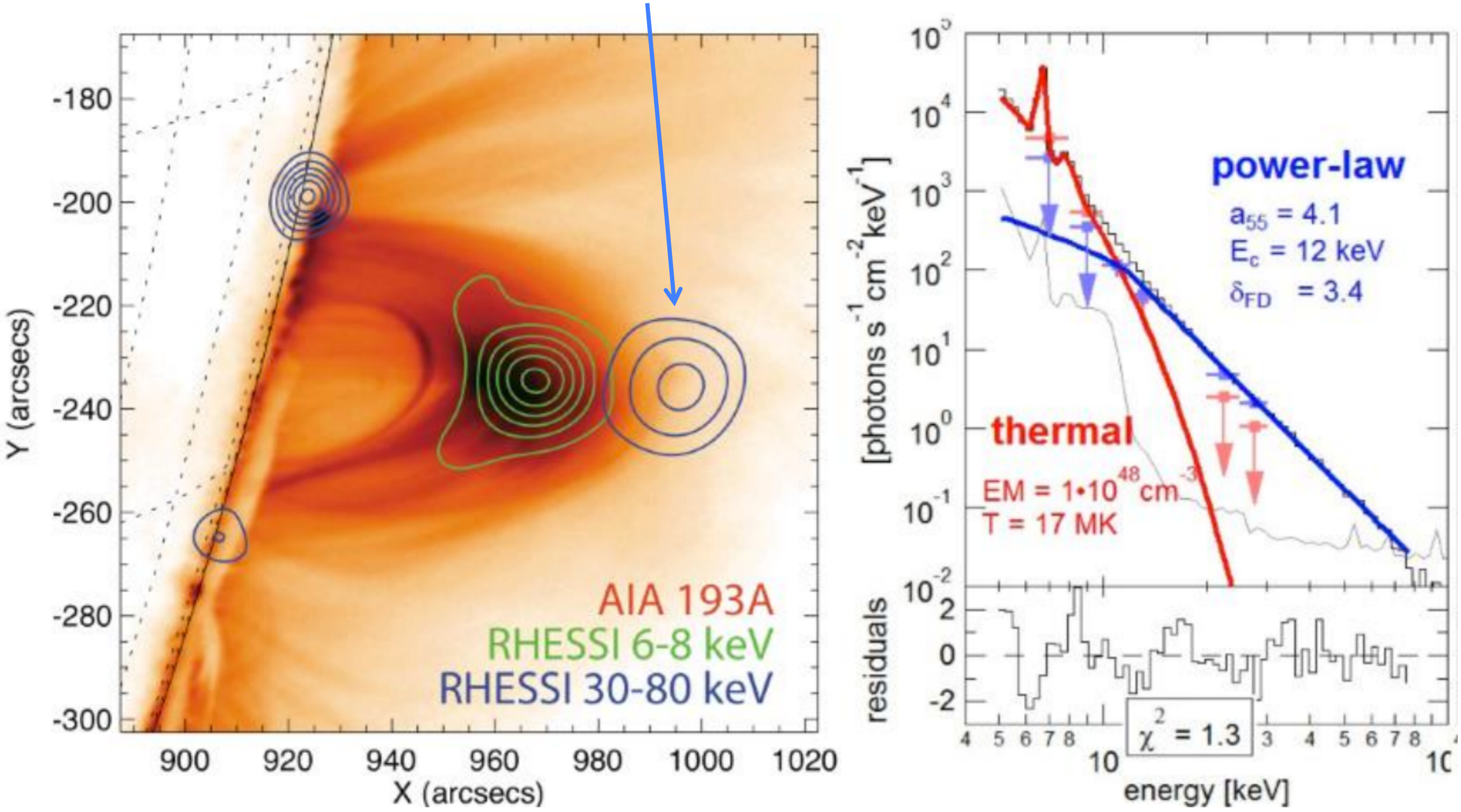
2. From plasma waves they create:
μ-waves and radio waves

Kuroda et al. 2015

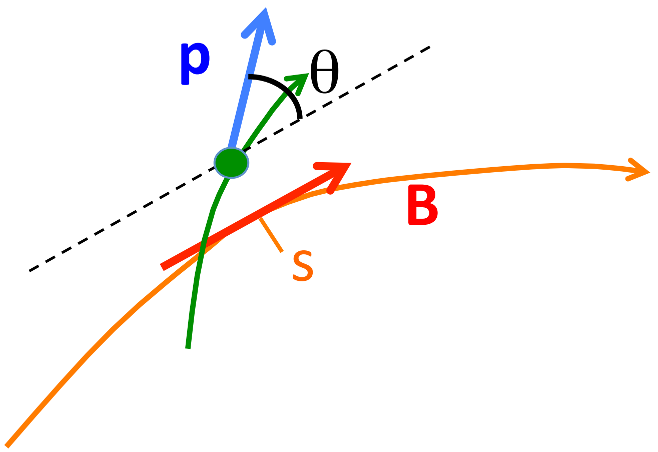


Observed by RHESSI (Lin *et al.*)

e^-s trapped in CS?



Modeling the *e*⁻ population



$$\mu = \cos\theta$$

$$f(s,\mu,p,t)\,ds\,d\mu\,dp$$

= # *e*⁻s in volume of (s,μ,p) space

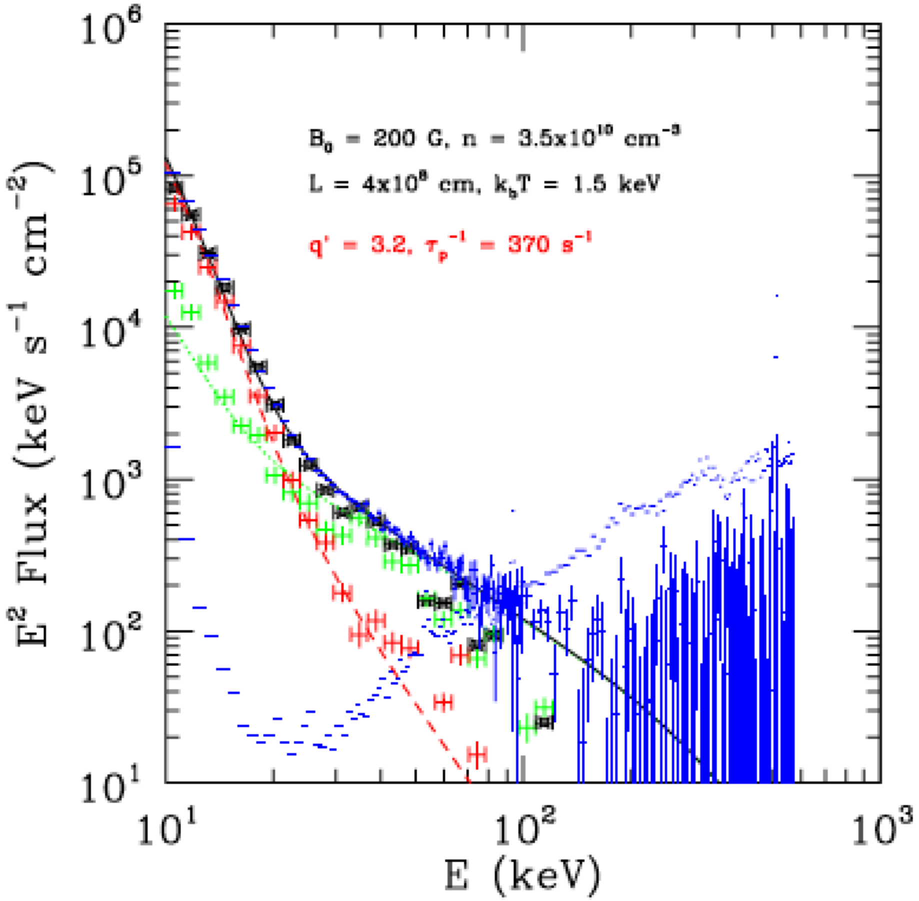
NB: Maxwellian

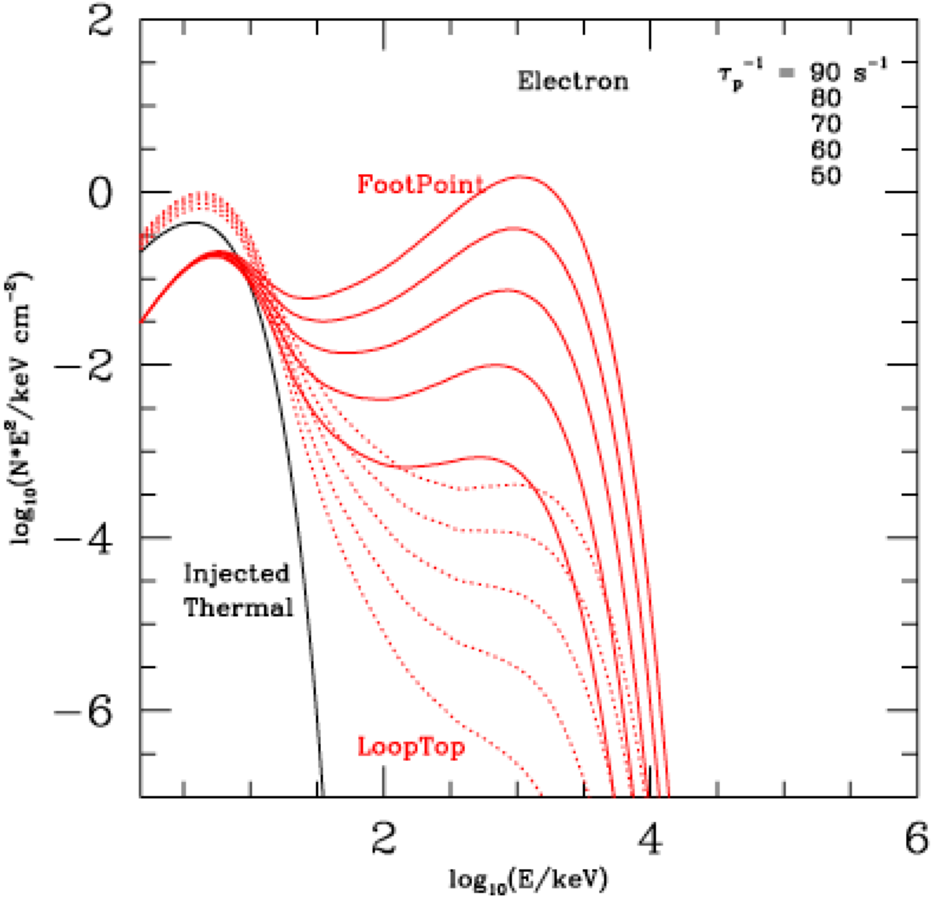
$$f(\mu,p) \sim e^{-p^2/2mkT}$$

Fokker-Planck equation:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial s} = \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left(D_{pp}\frac{\partial f}{\partial p} + D_{p\mu}\frac{\partial f}{\partial \mu}\right) + \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu} + D_{\mu p}\frac{\partial f}{\partial p}\right) - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\dot{p}_L f\right) + S,$$

Petrosian 2012





$$\frac{\partial f}{\partial t}+v\frac{\partial f}{\partial s}=\frac{1}{p^2}\frac{\partial}{\partial p}p^2\left(D_{pp}\frac{\partial f}{\partial p}+D_{p\mu}\frac{\partial f}{\partial \mu}\right)$$

$$+\frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}+D_{\mu p}\frac{\partial f}{\partial p}\right)-\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\dot{p}_L f\right)+S,$$

Summary

- CME/Flare consists of 4 things:

  erg. release, erg. Xport, evaporation, loop cooling
- Involve different elements of Physics:

  Fluids (MHD), radiation, kinetic theory
- Will cover all 4 in this course – out of order

Next

Physics of eruption: MHD instabilities