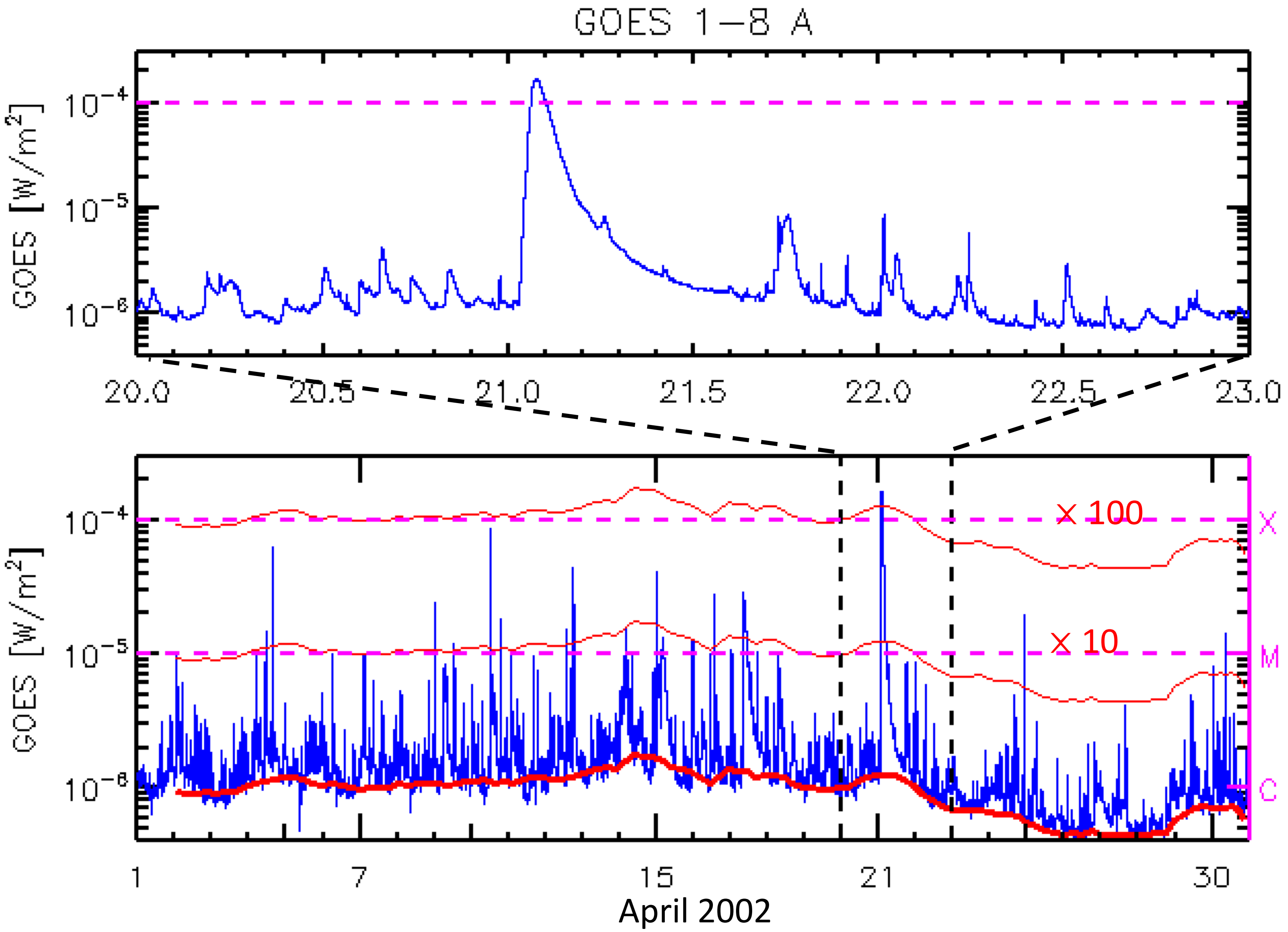
# Solar Flares:
## Everything you need to know*

Dana Longcope

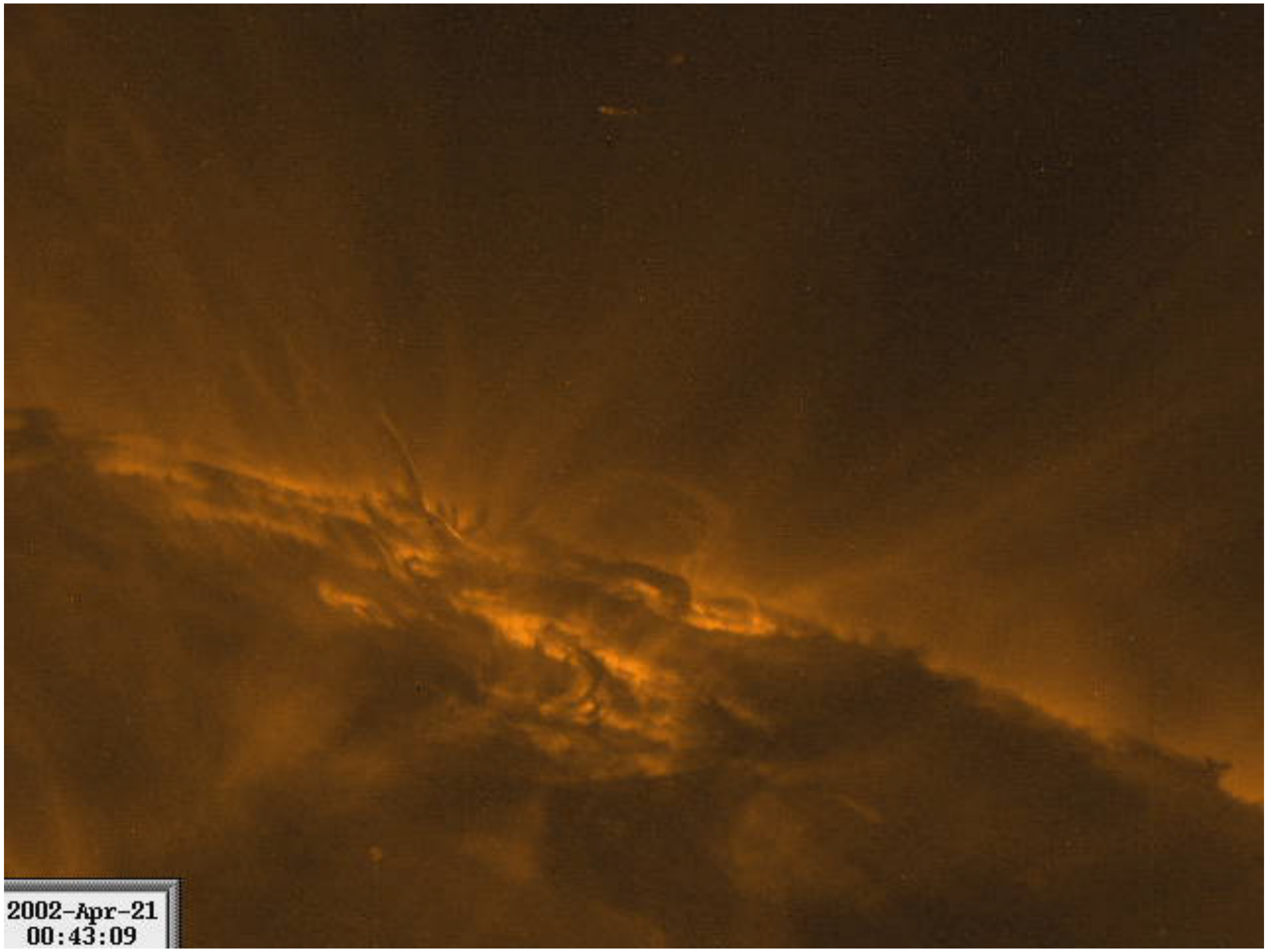
*Montana State University*

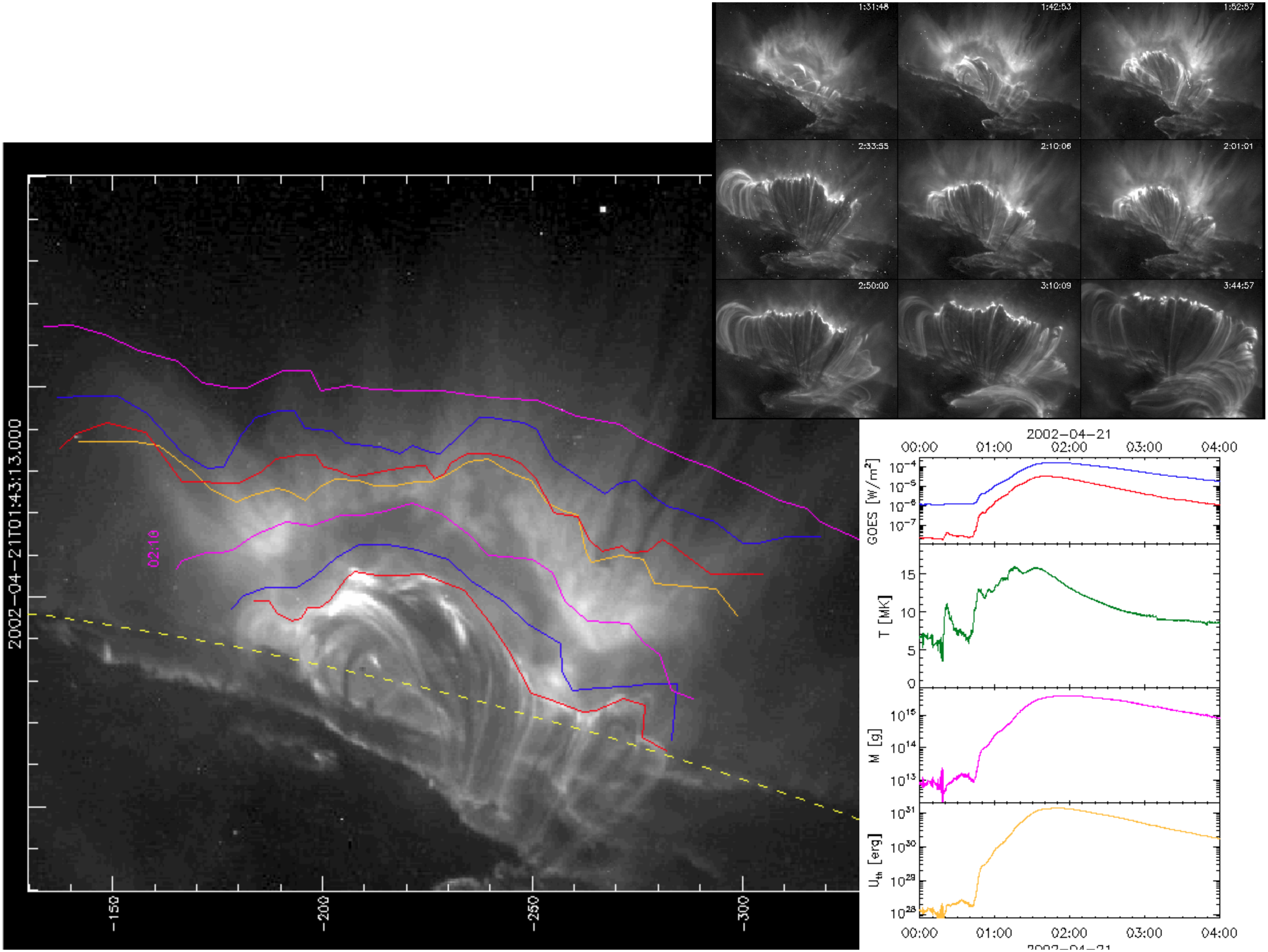
*but were afraid to ask

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

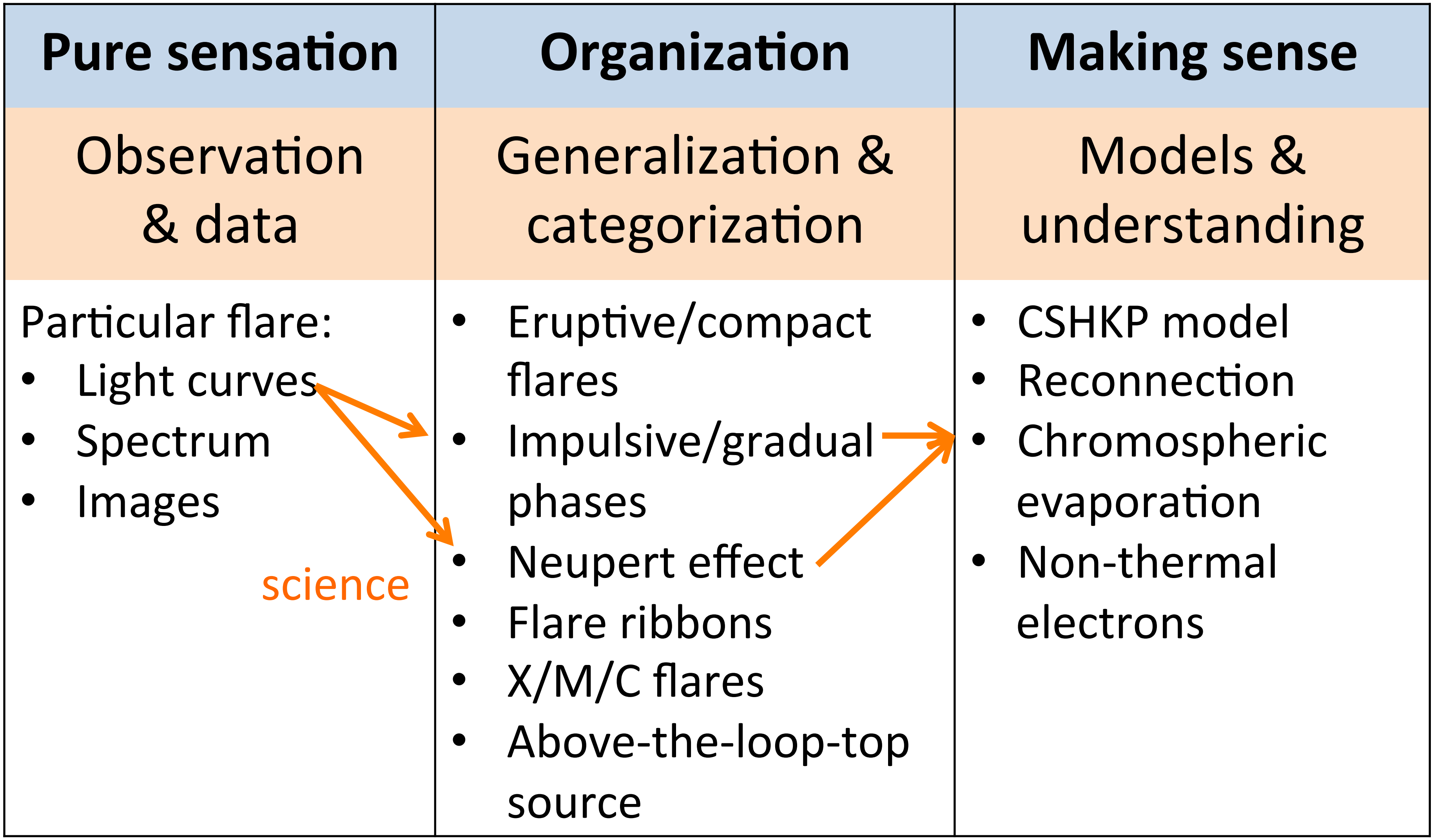


# Close-up of that brightening




2002−04−21T01:43:13.000
02:16
−150
−200
−250
−300
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
2002−04−21
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

# Epistomology



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

Terminology & jargon

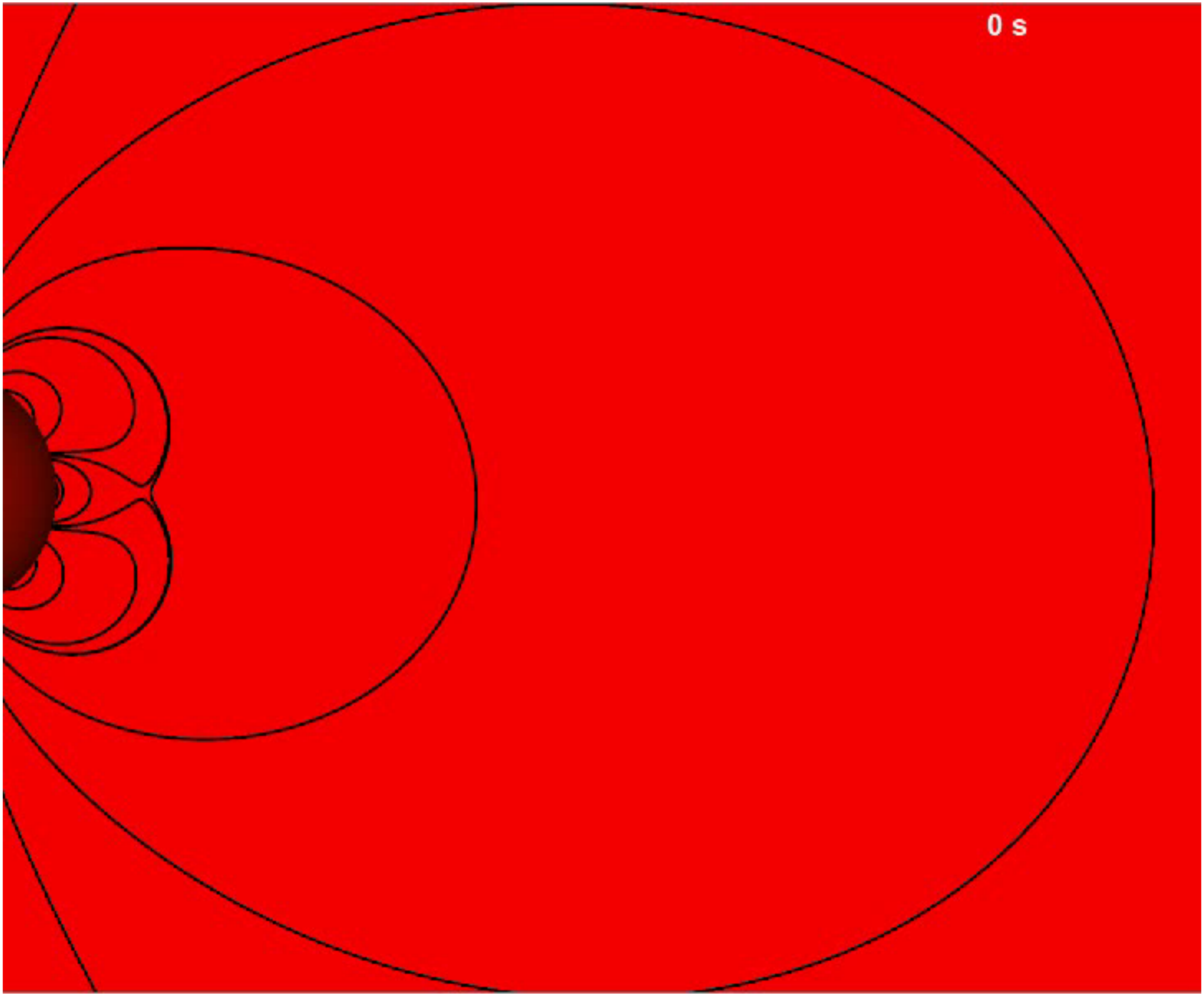
In progress

# Epistomology

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

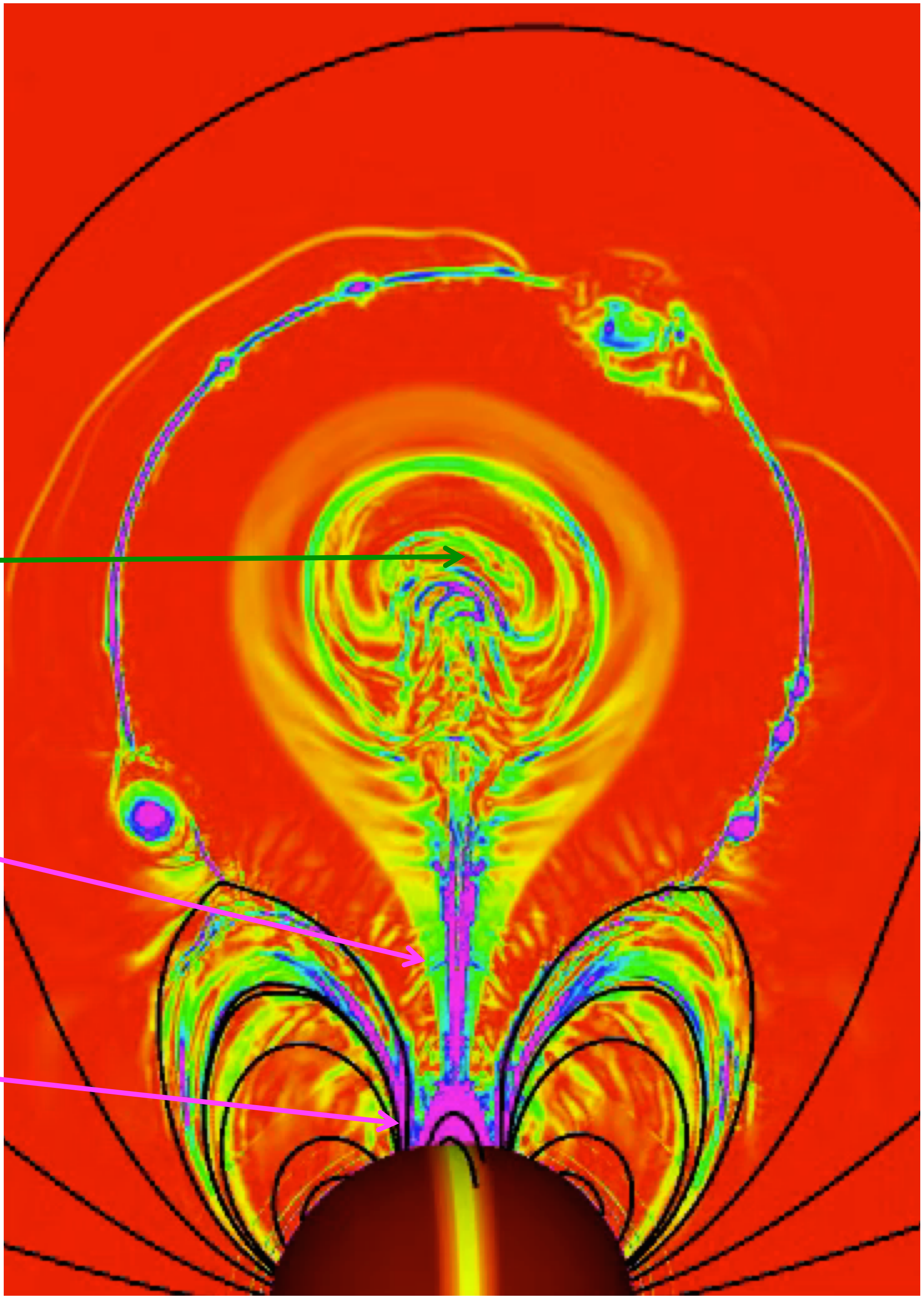
Terminology & jargon

In progress



Model: Karpen et al. 2012

# How they relate…
# the basic picture



CME

Current sheet

flare

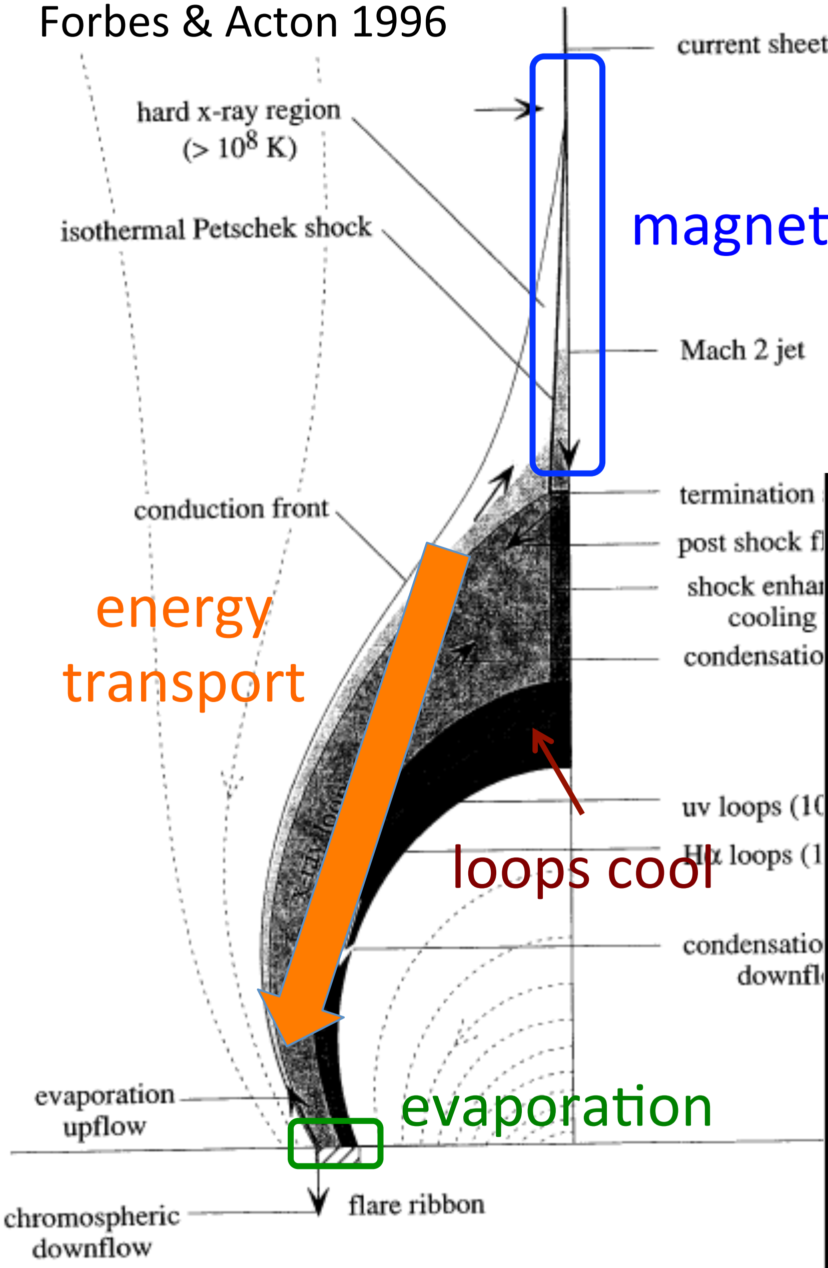
# Progress of a flare

1. Release of magnetic 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

Flare: X-ray brightening

most observations

Forbes & Acton 1996

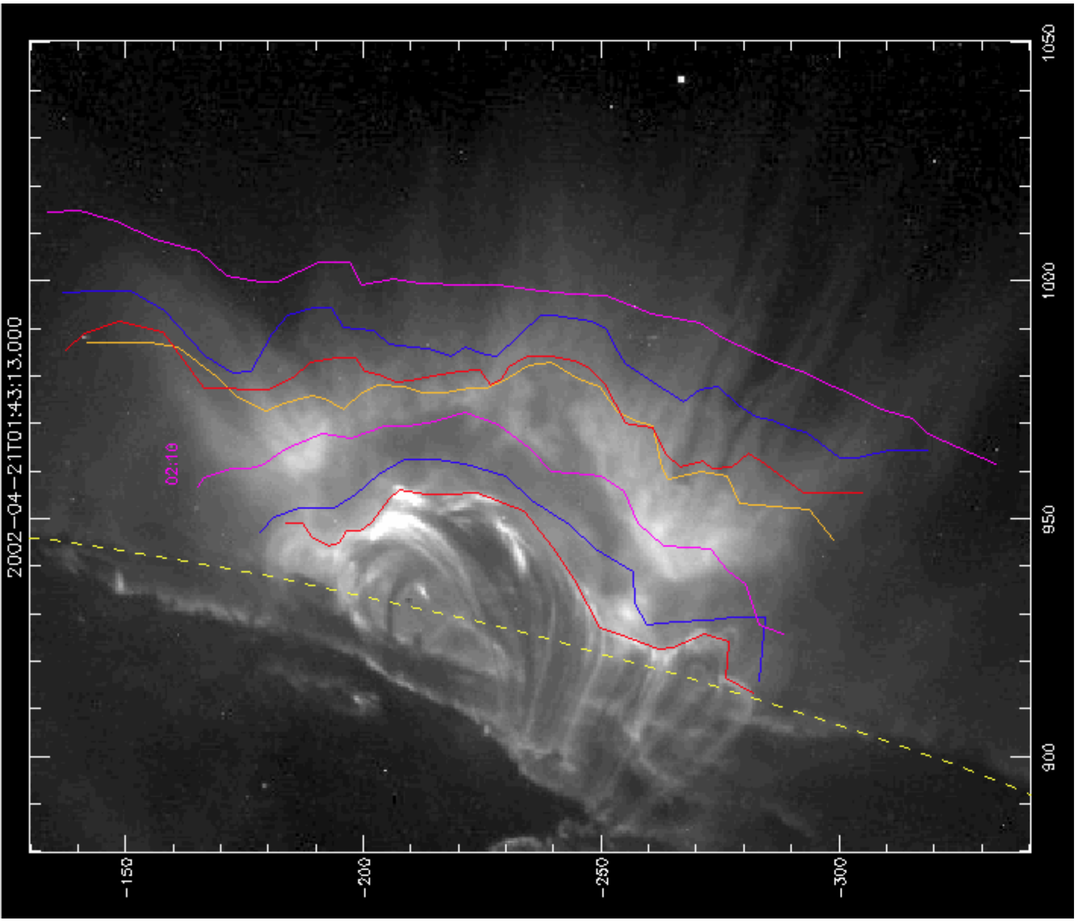


magnetic energy released

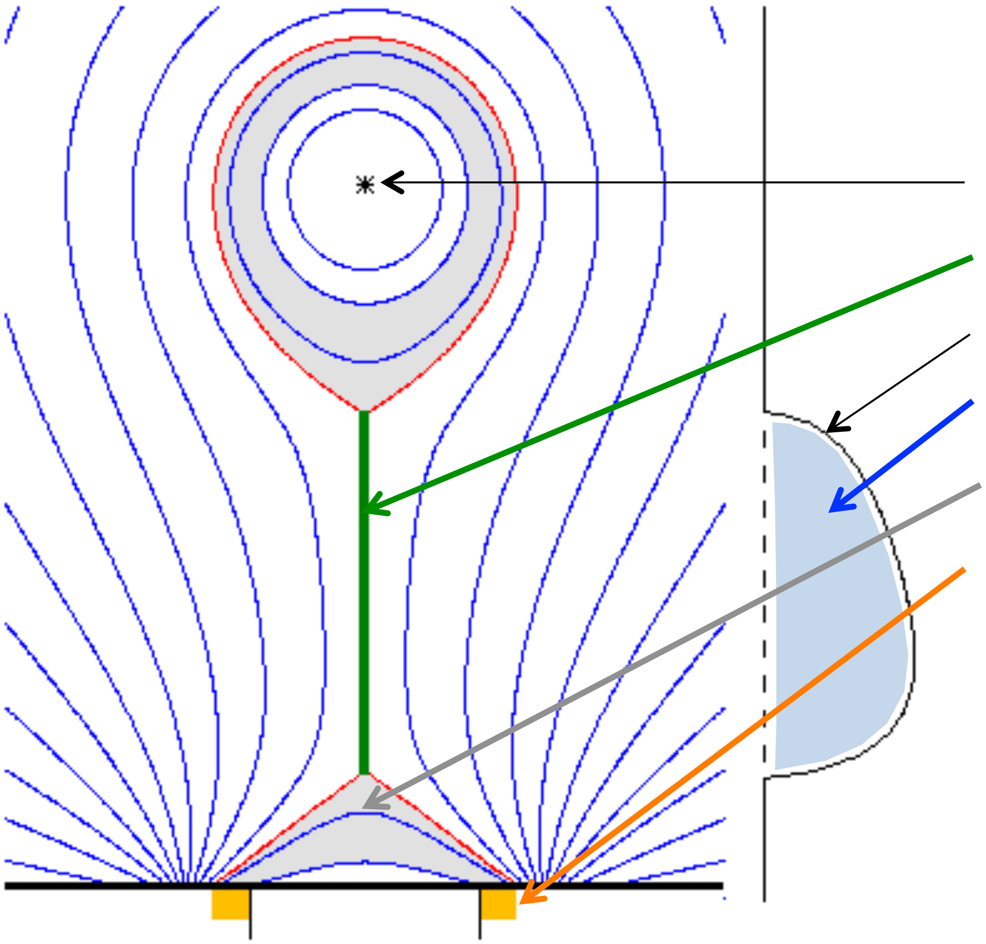
energy transport

loops cool

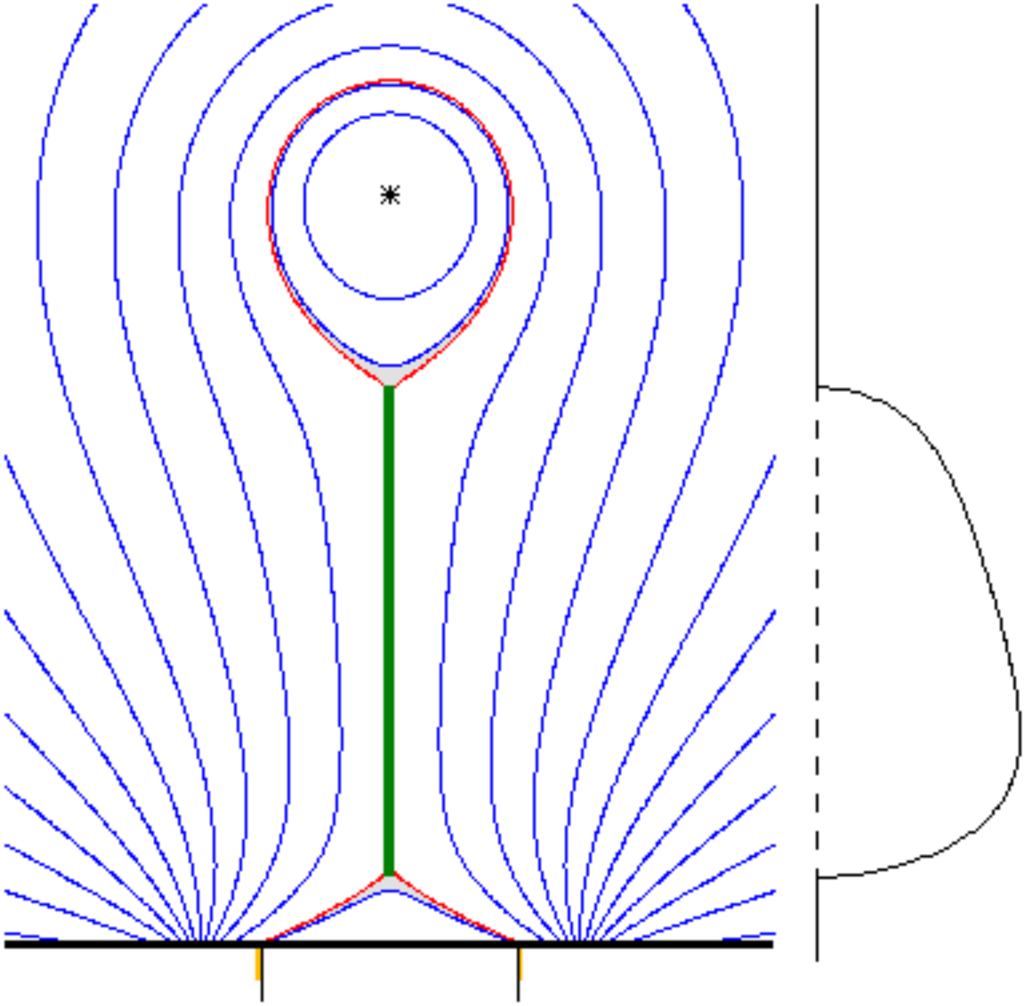
evaporation



# 1. Energy release



- Based on Lin & Forbes 2000
- Fix flux rope (focus on flare)
- CS beneath
- Current density **K**(z)
- Integrates to current $\mathbf{I}$
- reconnected flux in arcade
- Maps to chromospheric ribbons

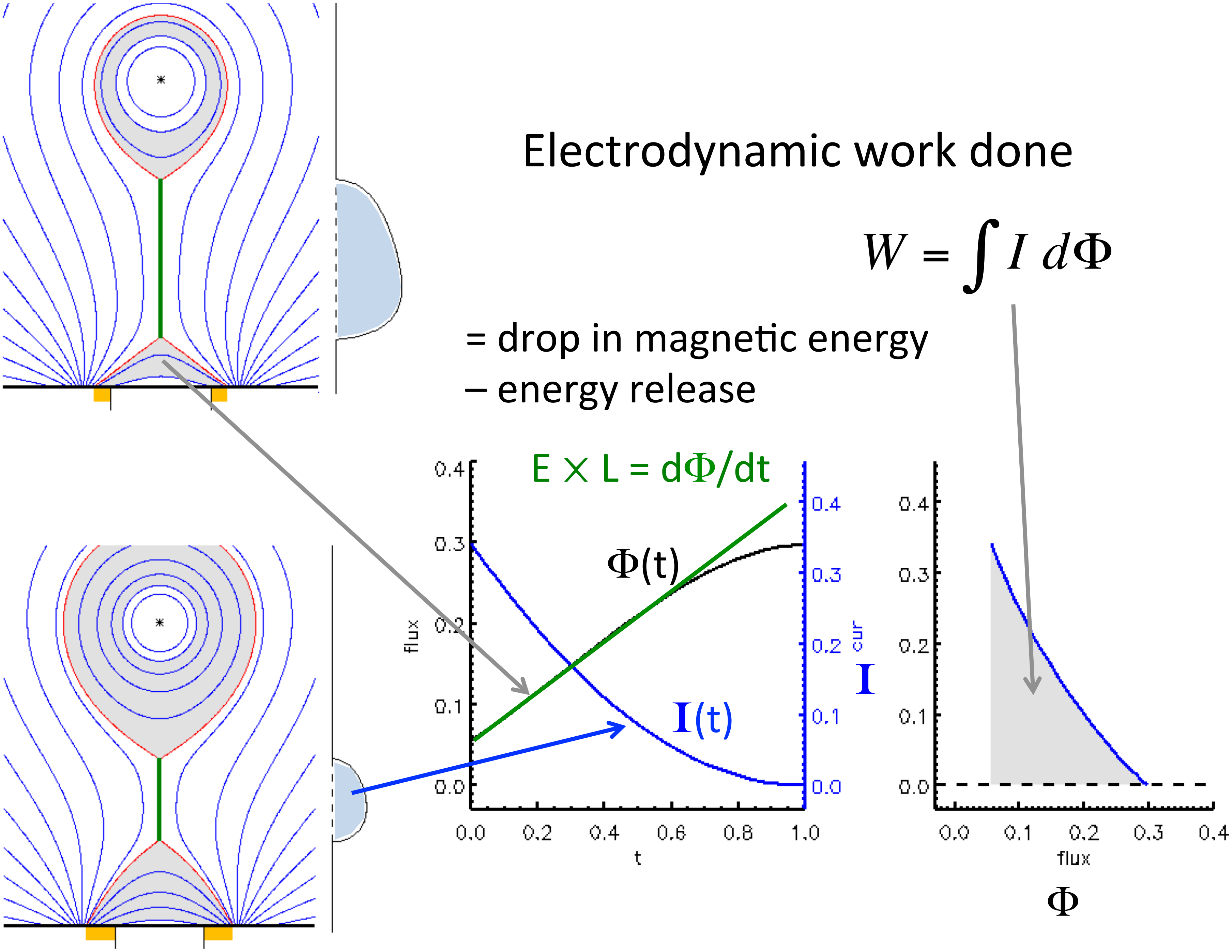


# Electrodynamic work done

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

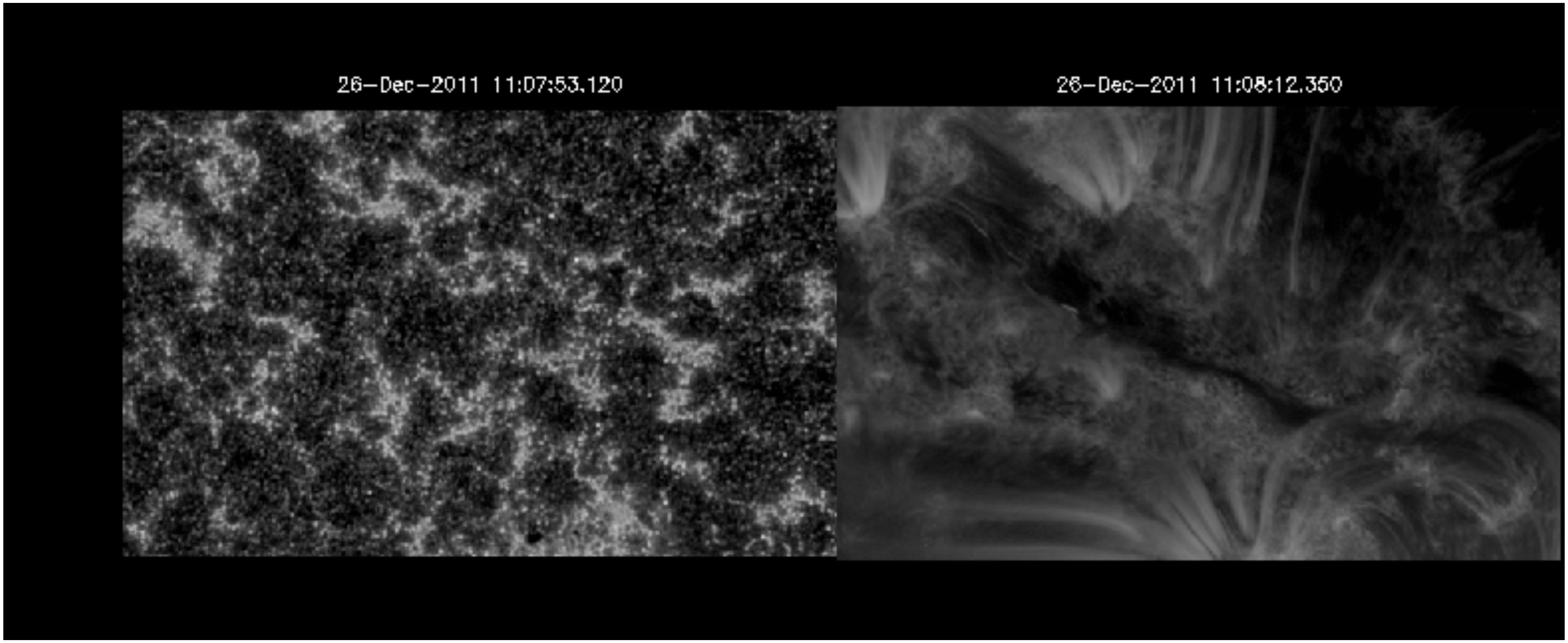
= drop in magnetic energy

– energy release

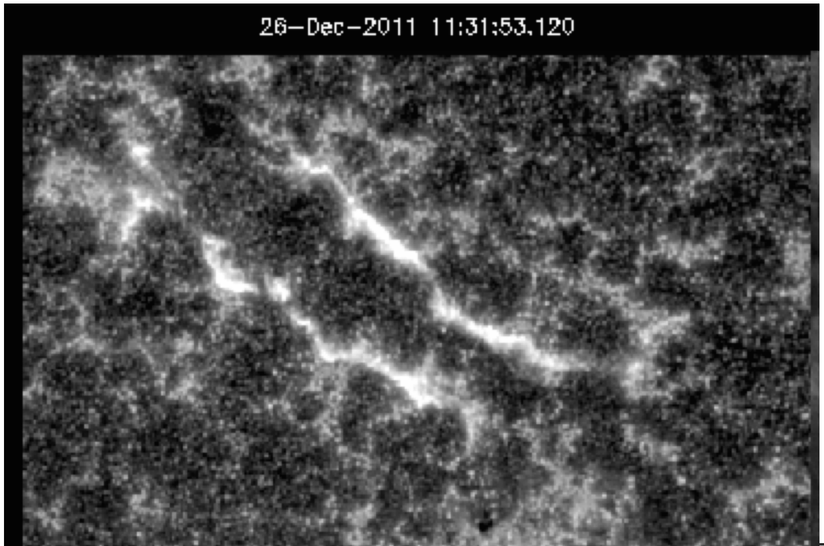


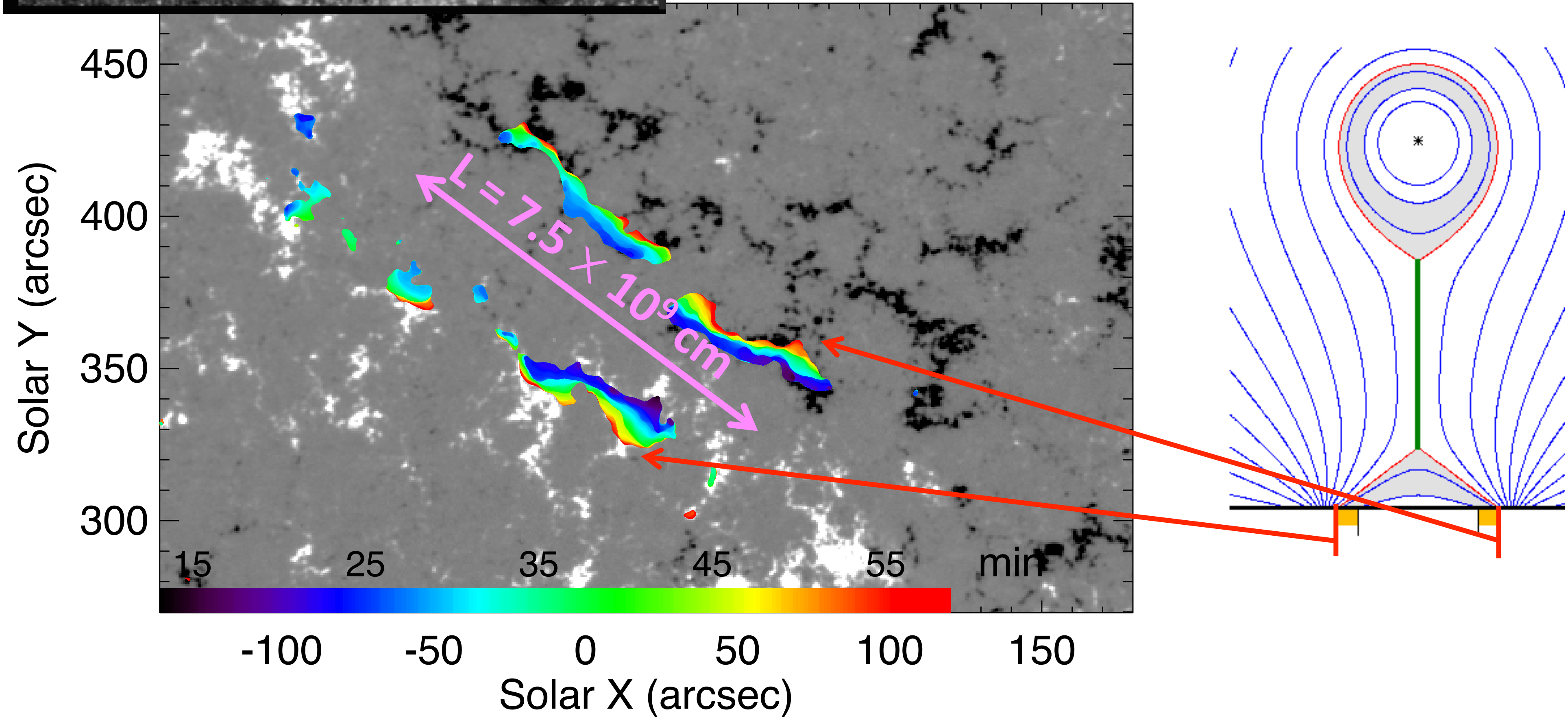
AIA 1600 A:
100,000 K plasma
chromospheric feet

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

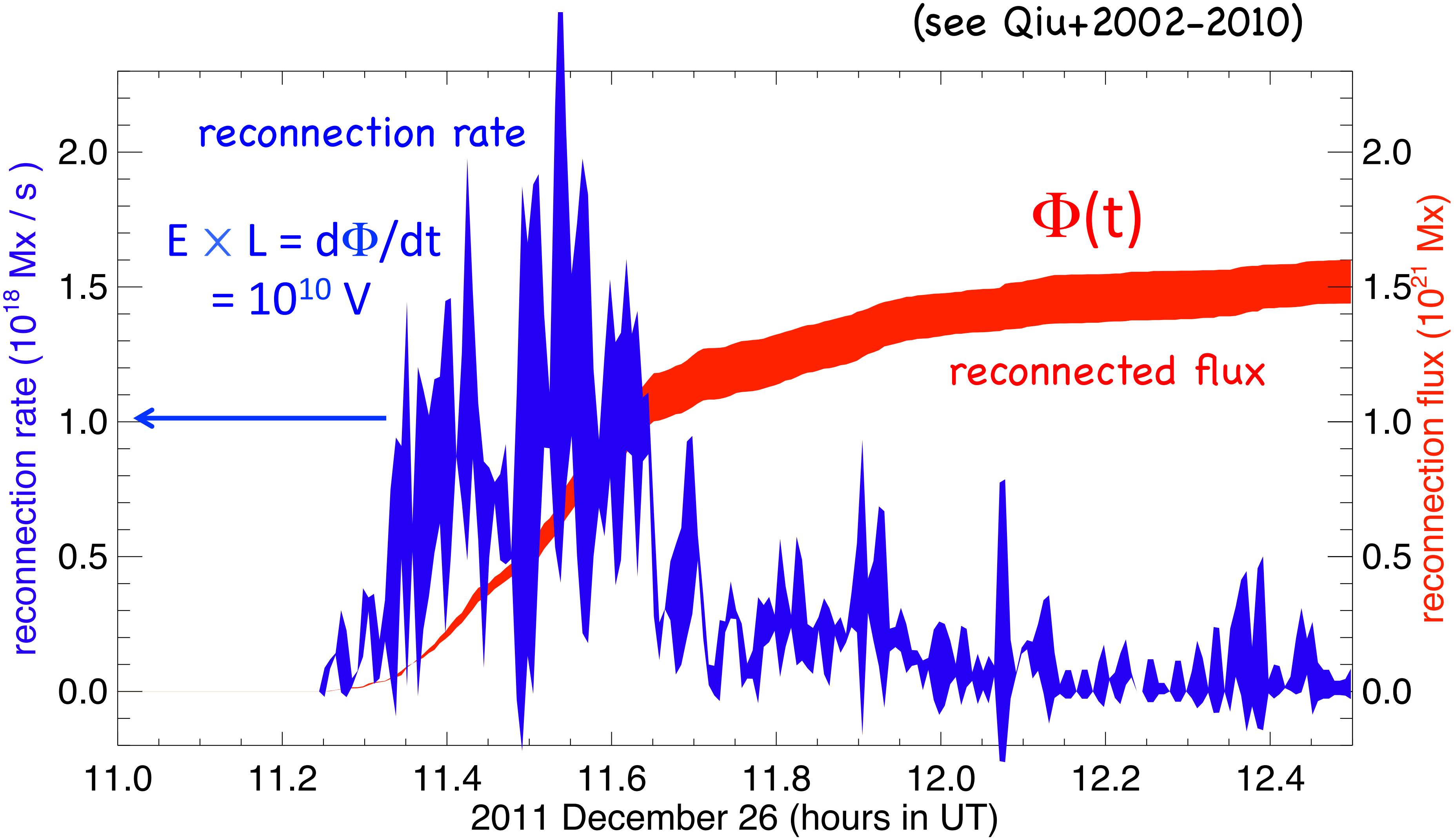


# Flux measured from flare ribbons





(see Qiu+2002-2010)



reconnection rate

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

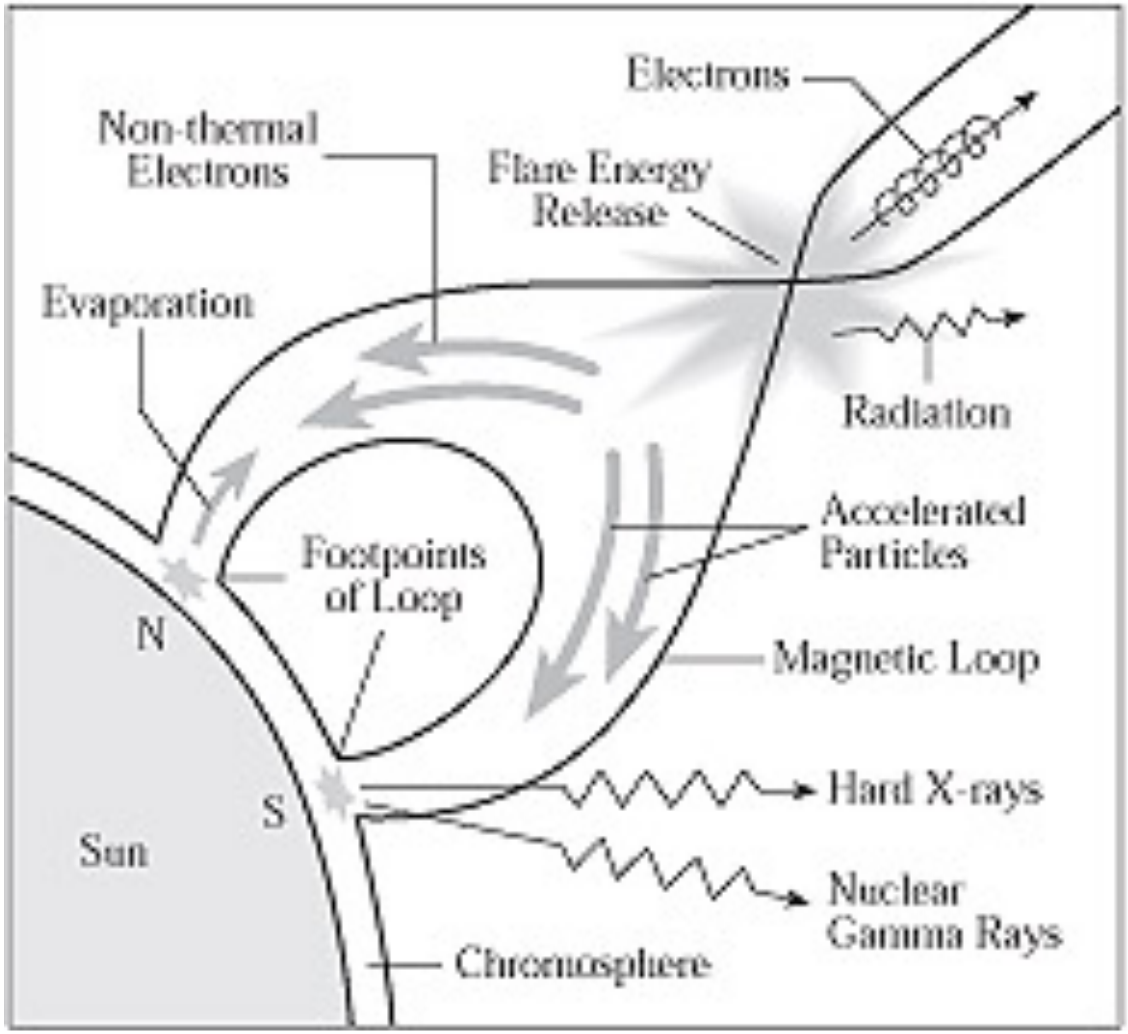
$= 10^{10}$ V

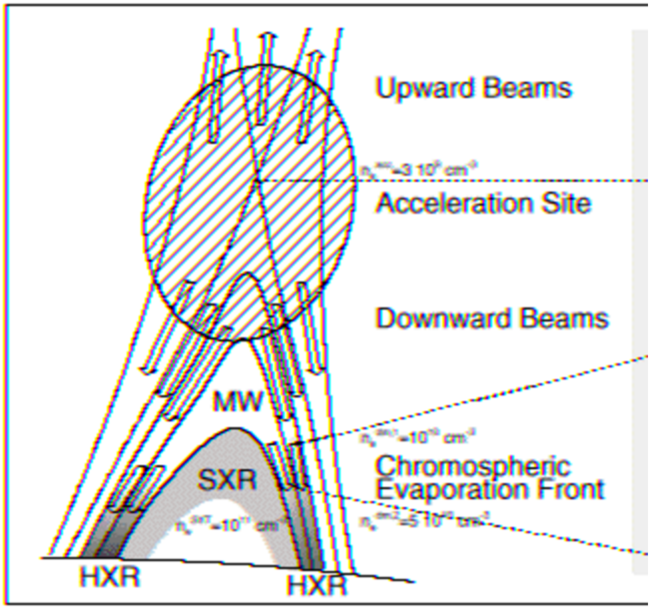
$\Phi(t)$

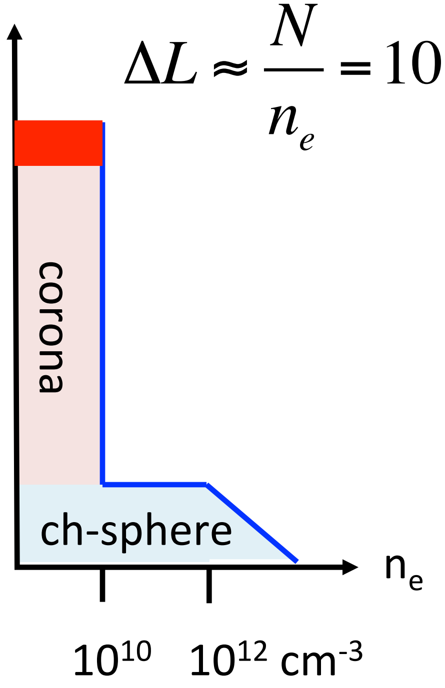
reconnected flux

$$W = \int I\, d\Phi \sim \tfrac{1}{2} I_0 \Delta\Phi \sim \frac{(\Delta\Phi)^2}{8\pi L} = \frac{(1.5\times10^{21})^2}{8\pi\cdot 7.5\times10^{9}} = 1.2\times10^{31}\ \text{erg}$$

# 2. Energy transport



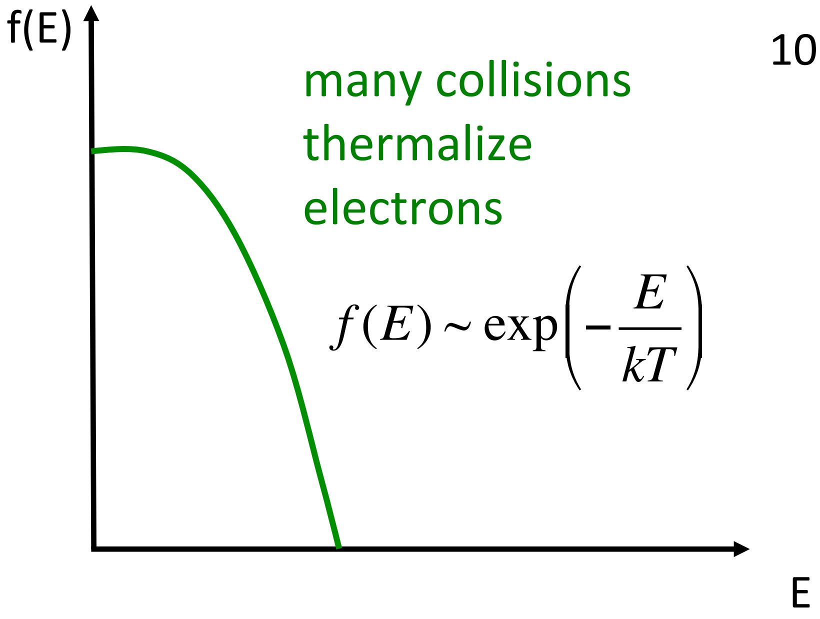




$$\Delta L \approx \frac{N}{n_e} = 10^8 \,\text{cm}$$

Electron collision cross section (Rutherford)

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



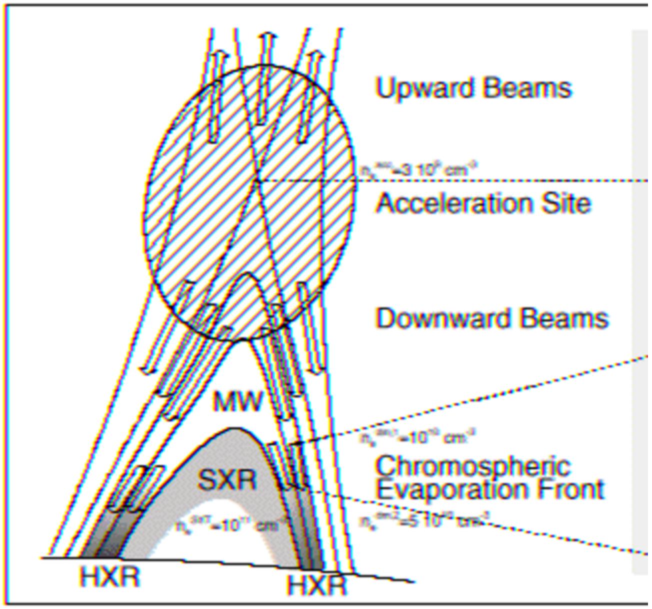
many collisions thermalize electrons

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

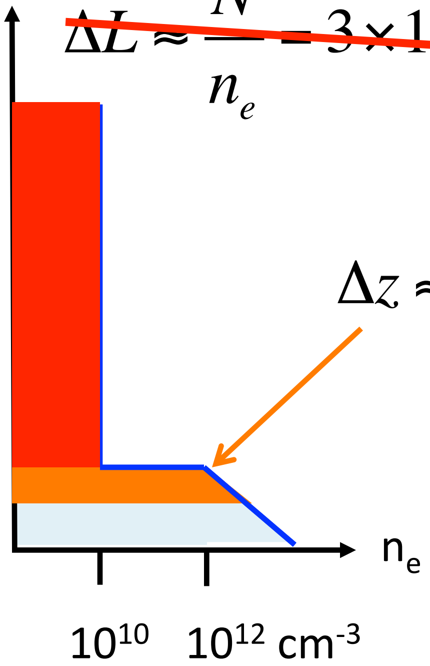
Stopping column

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

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



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



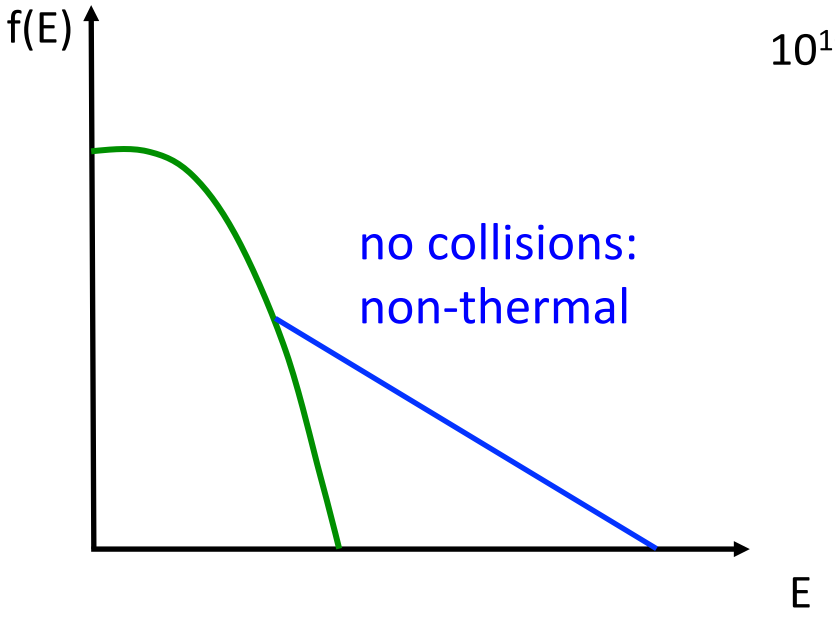
$$\Delta z \approx H_\rho \ln\left(\frac{N}{n_{e,0}H_\rho}\right) = 10^{8}\,\mathrm{cm}$$

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

Stopping column

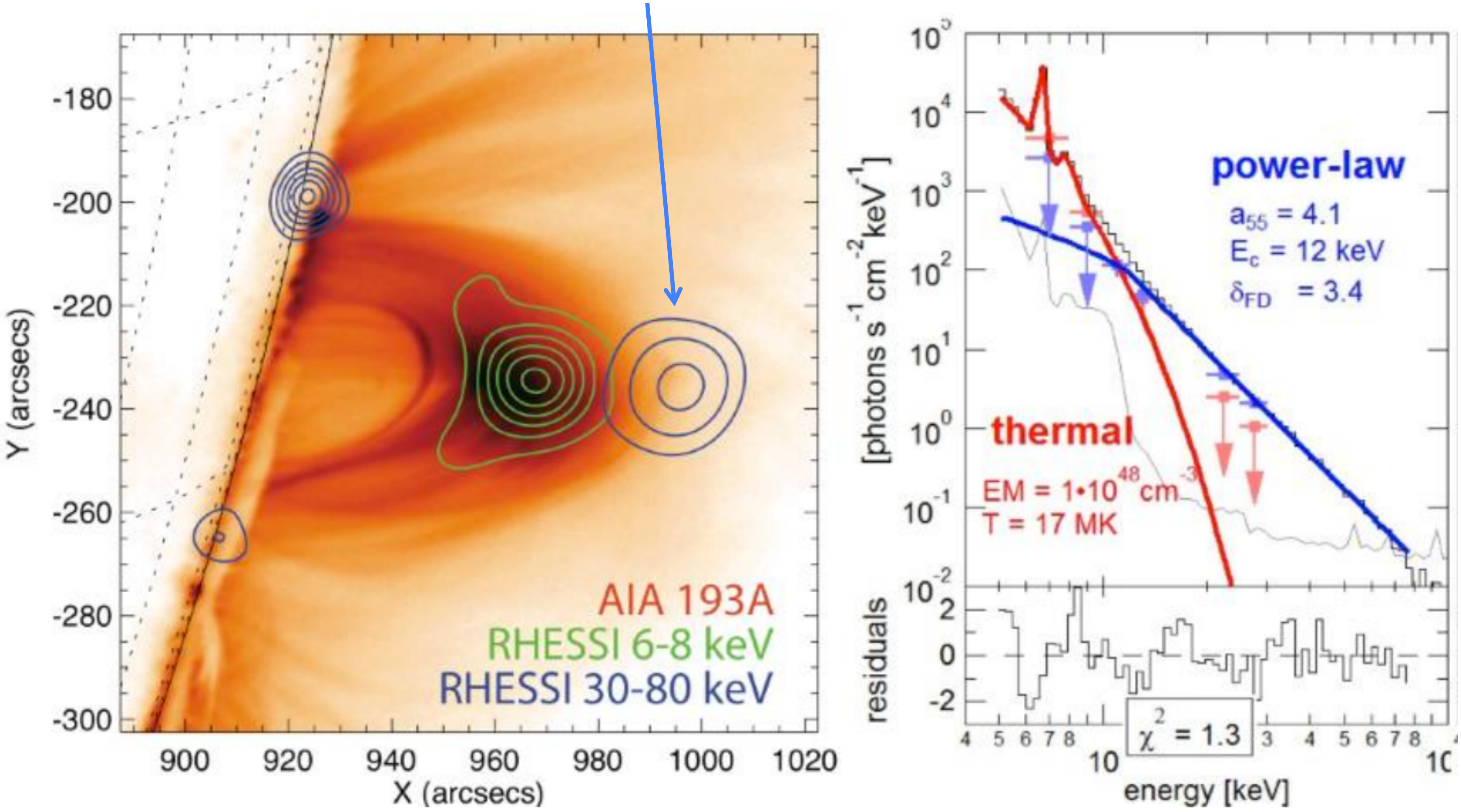
$$N = \int n_e\, d\ell = \frac{1}{\sigma_e} = 10^{17}\ \mathrm{cm}^{-2} \times E_{\mathrm{keV}}^{2}$$

50 keV → N=3 × $10^{20}$ cm$^{-2}$

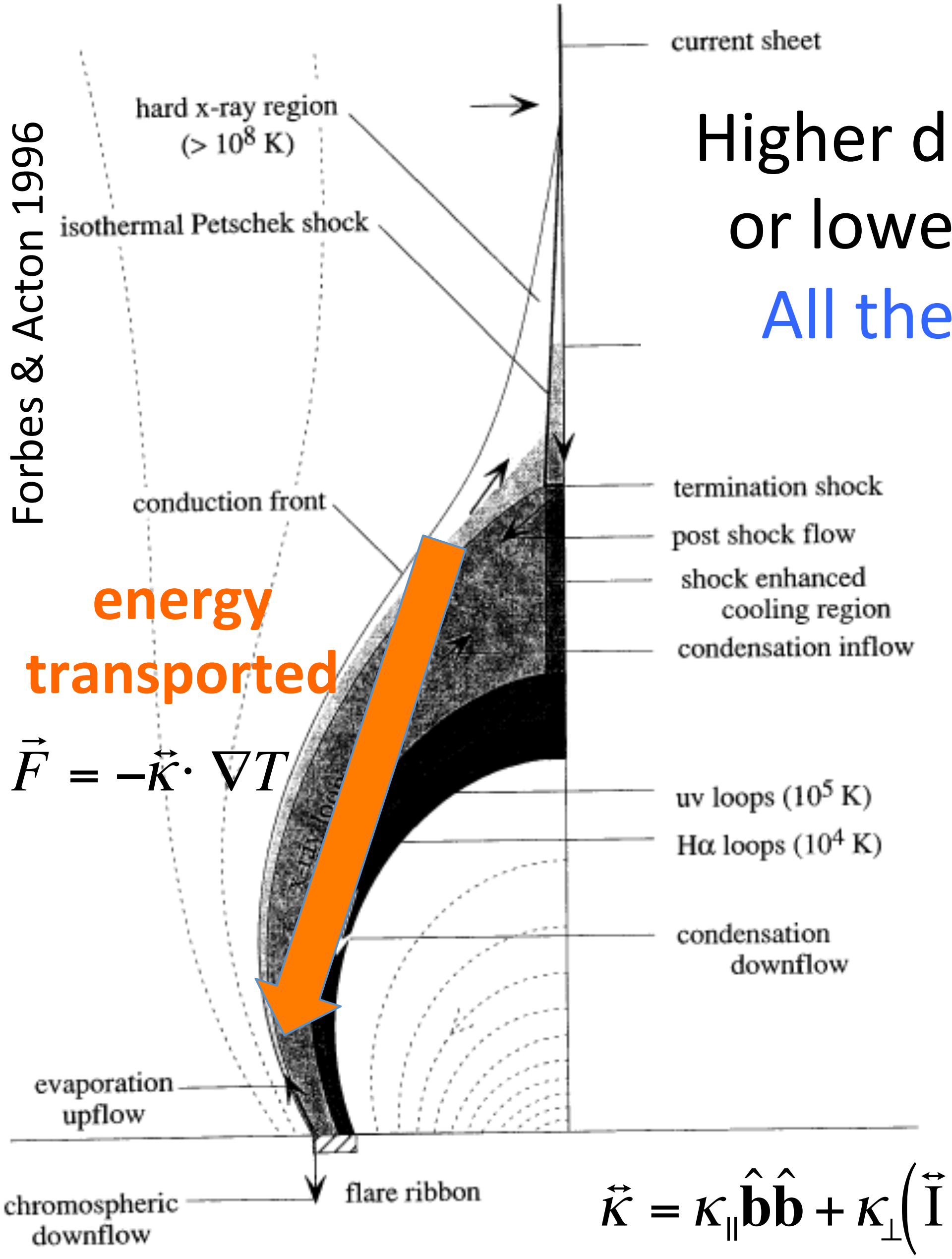


# Observed by RHESSI (Lin *et al.*)

e$^-$s trapped in CS?



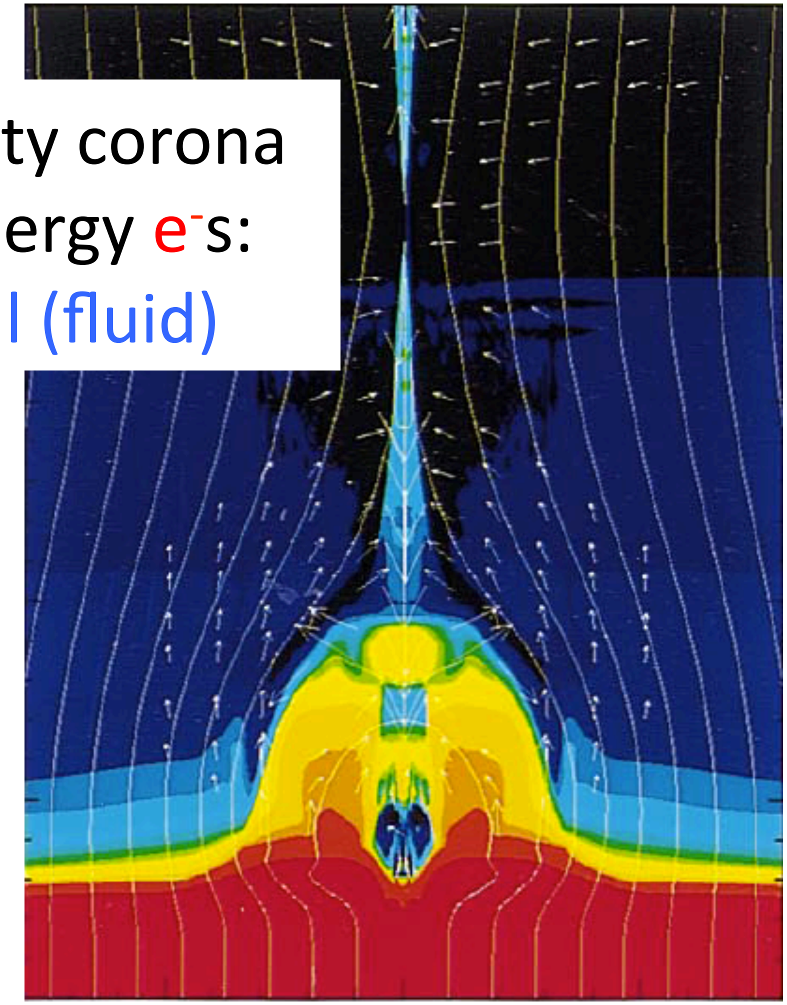
## Higher density corona
## or lower energy $e^-$s:
## All thermal (fluid)



Forbes & Acton 1996

**energy transported**

$$\vec{F} = -\overleftrightarrow{\kappa}\cdot\nabla T$$

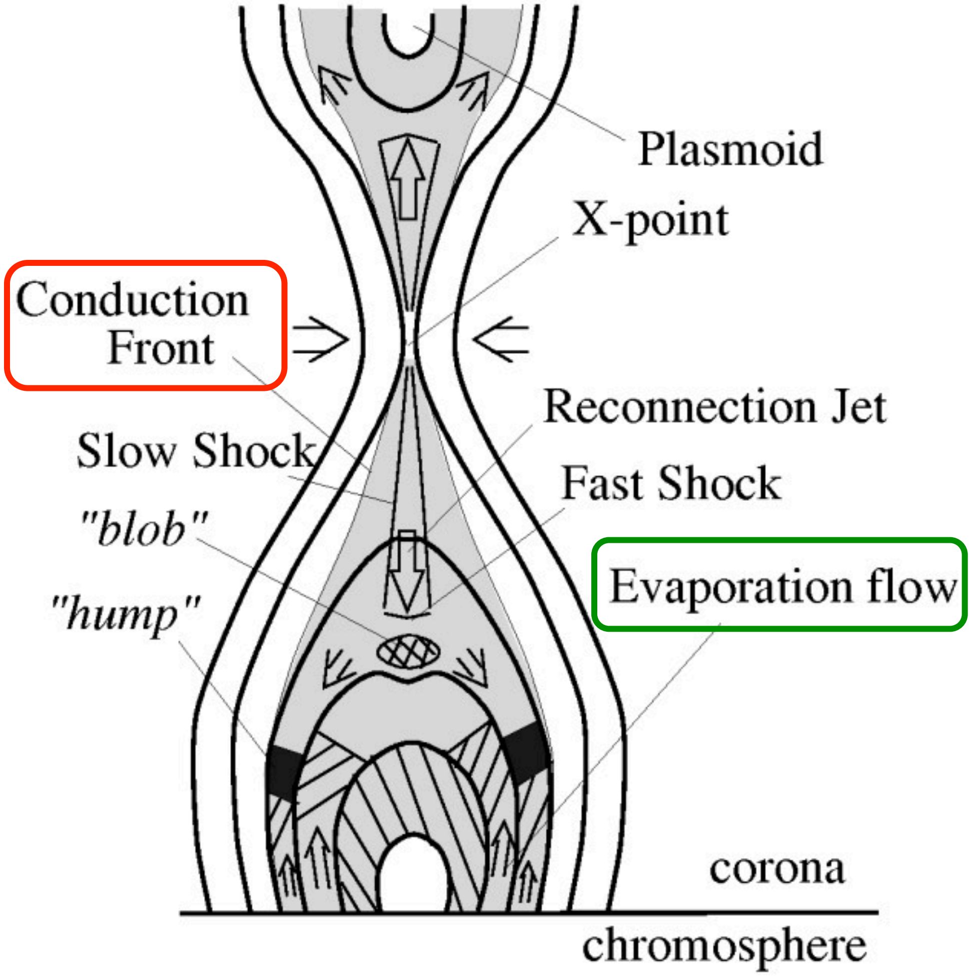


Yokoyama & Shibata 2001

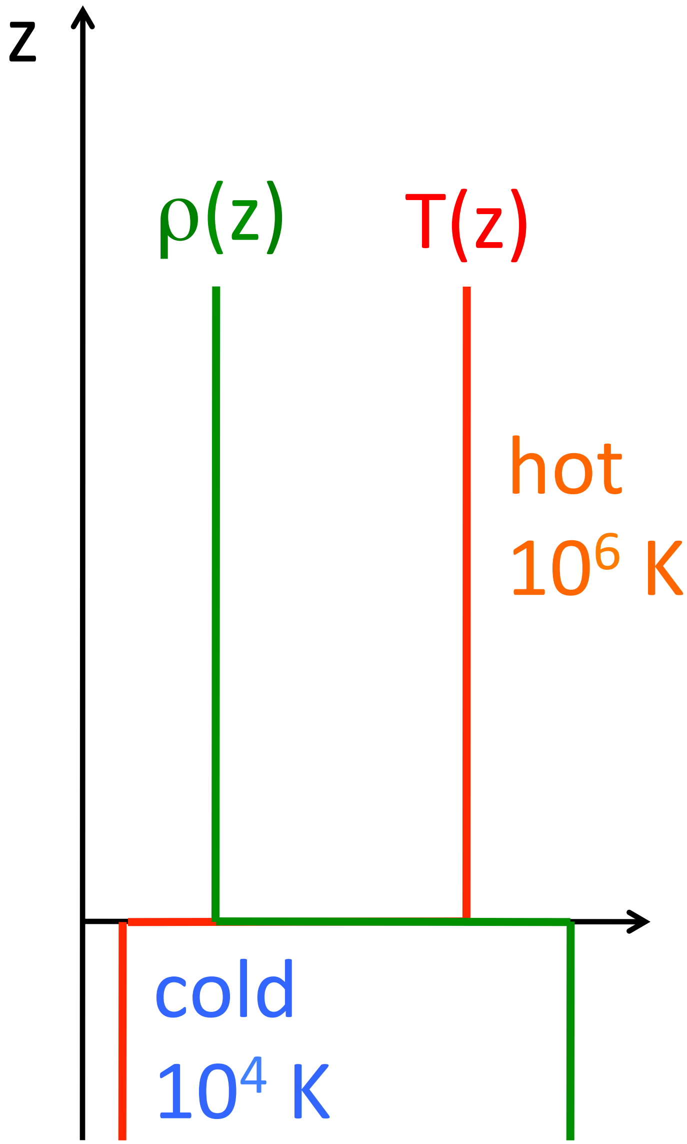
$$\overleftrightarrow{\kappa} = \kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}} + \kappa_{\perp}\left(\overleftrightarrow{\mathrm{I}} - \hat{\mathbf{b}}\hat{\mathbf{b}}\right)$$

$$\frac{\kappa_{\parallel}}{\kappa_{\perp}} \sim (\Omega_e\tau_{ee})^2 \sim 10^{14}$$

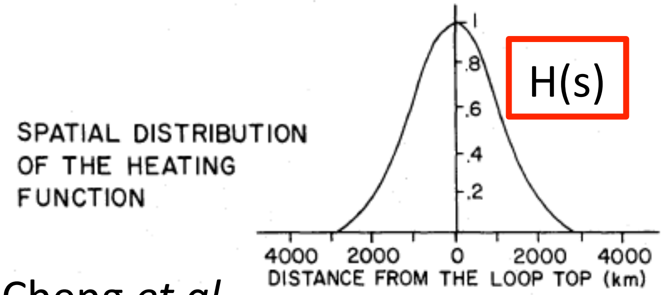
# 3. Evaporation



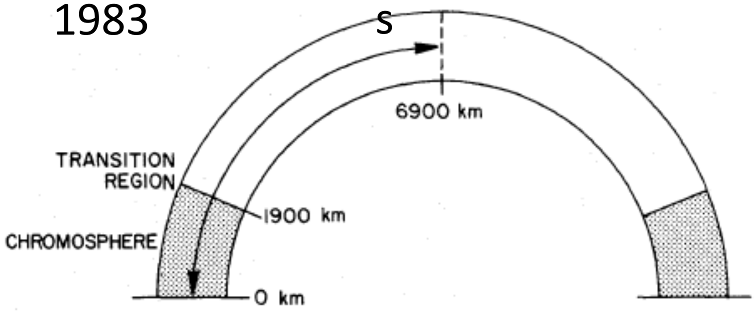
From Yokoyama & Shibata 1998



# Modeling evaporation



Cheng *et al.*
1983



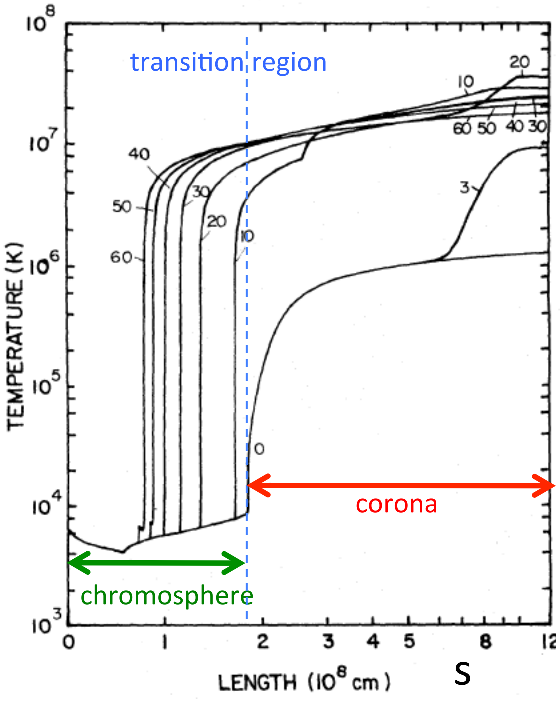
Krall &
Antiochos
1980

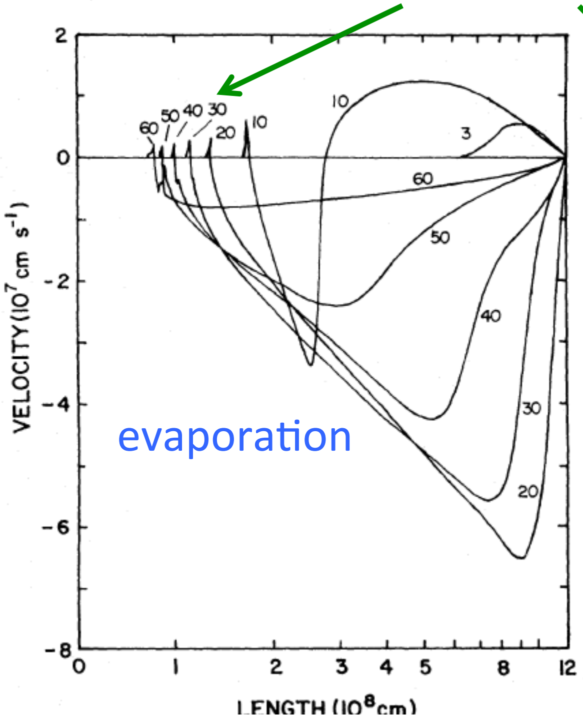
$$\frac{\partial n}{\partial t}+\frac{1}{A(s)}\frac{\partial}{\partial s}(Anv)=0, \qquad (1)$$

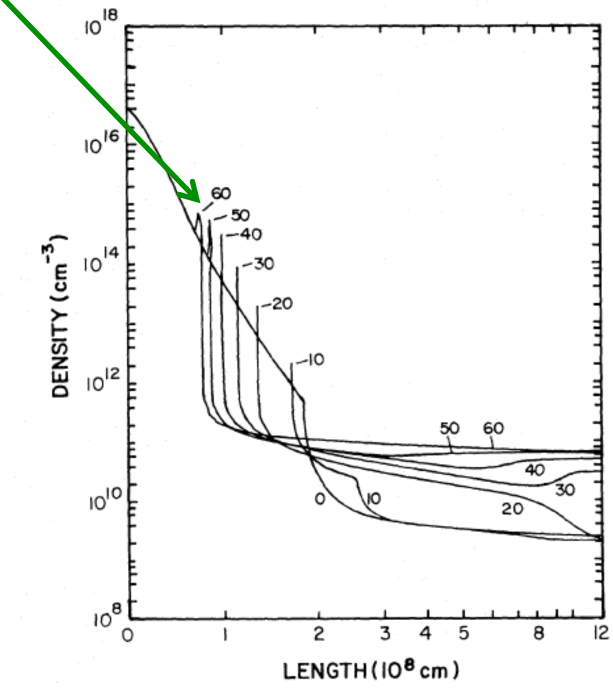
$$n\left(\frac{\partial}{\partial t}+v\frac{\partial}{\partial s}\right)v+\frac{1}{m}\frac{\partial p}{\partial s}=ng_{\parallel}(s), \qquad (2)$$

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

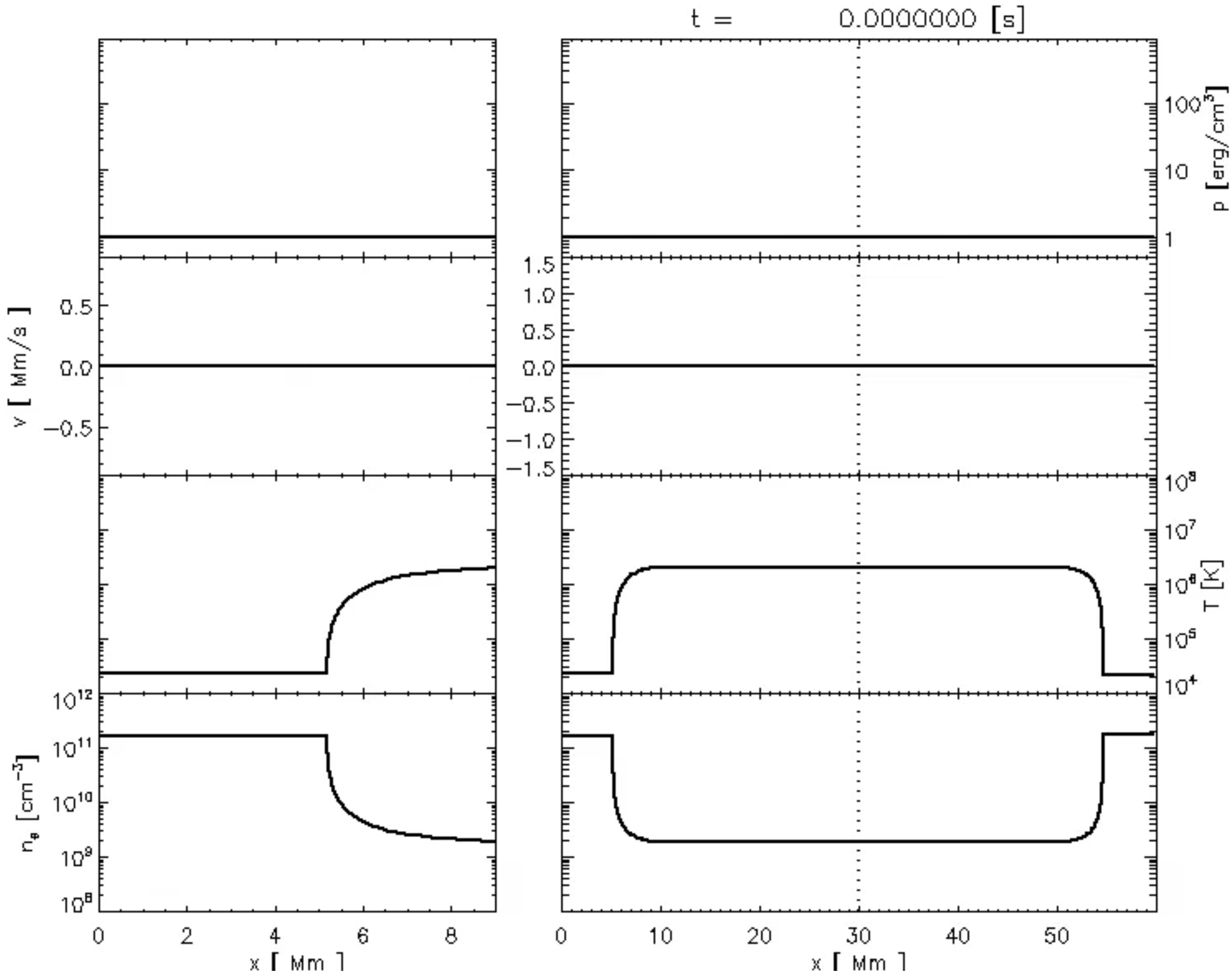
"condensation"



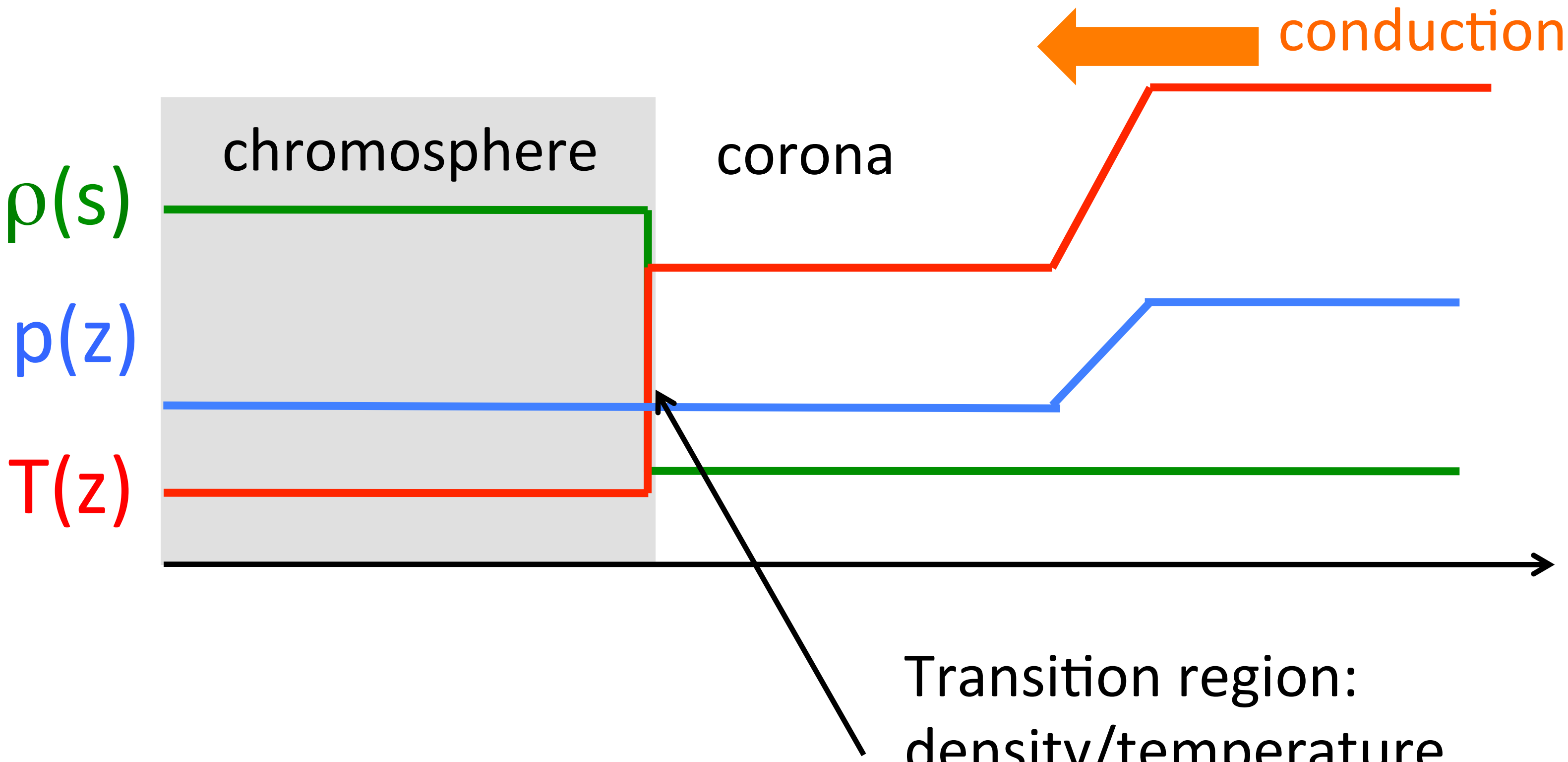




Emslie & Nagai 1985


t = 0.0000000 [s]
p [erg/cm$^3$]
100
10
1
v [ Mm/s ]
0.5
0.0
−0.5
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
10$^8$
10$^7$
10$^6$
10$^5$
10$^4$
T [K]
n$_e$ [cm$^{-3}$]
10$^{12}$
10$^{11}$
10$^{10}$
10$^9$
10$^8$
0
2
4
6
8
x [ Mm ]
0
10
20
30
40
50
x [ Mm ]

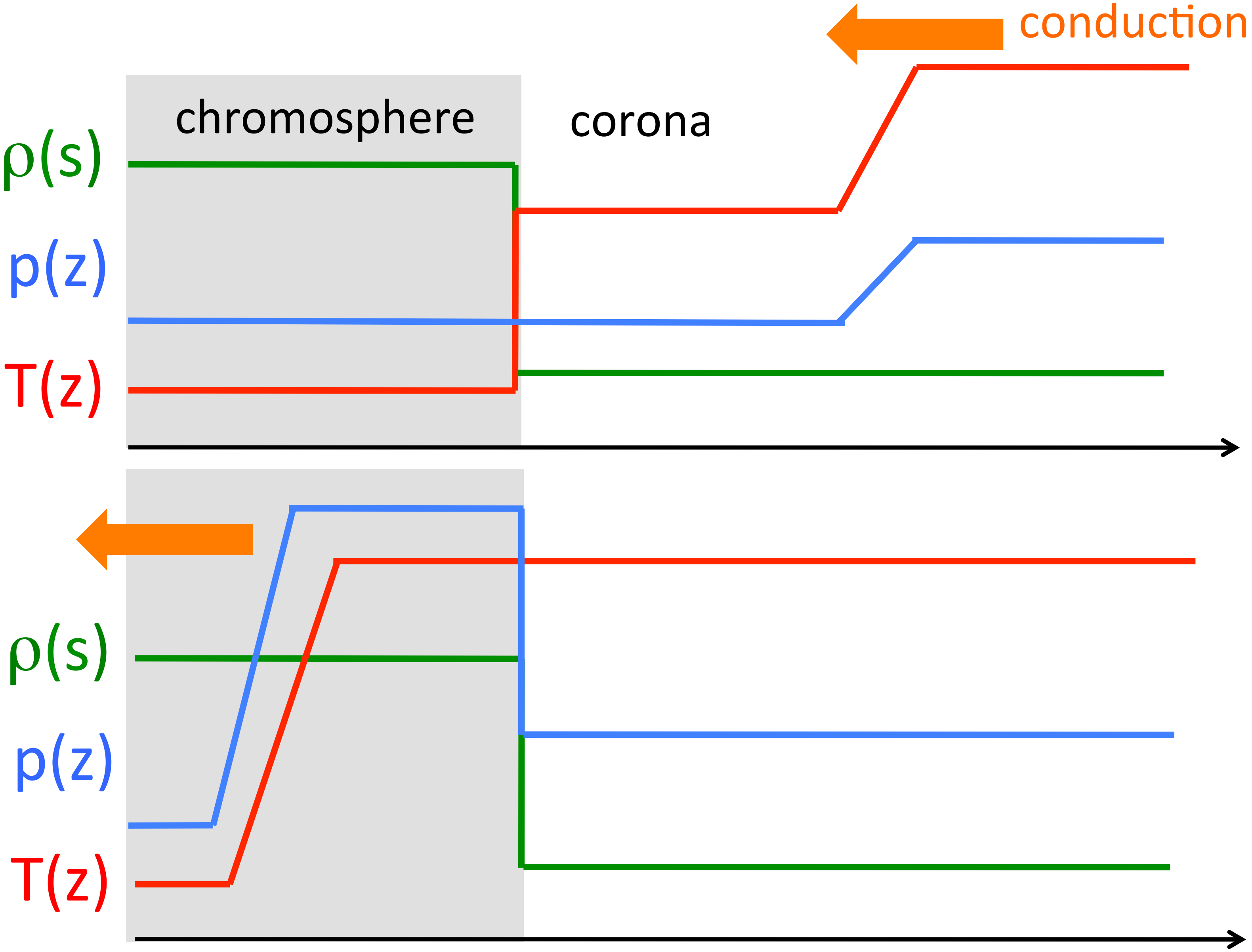
# The Basic Picture



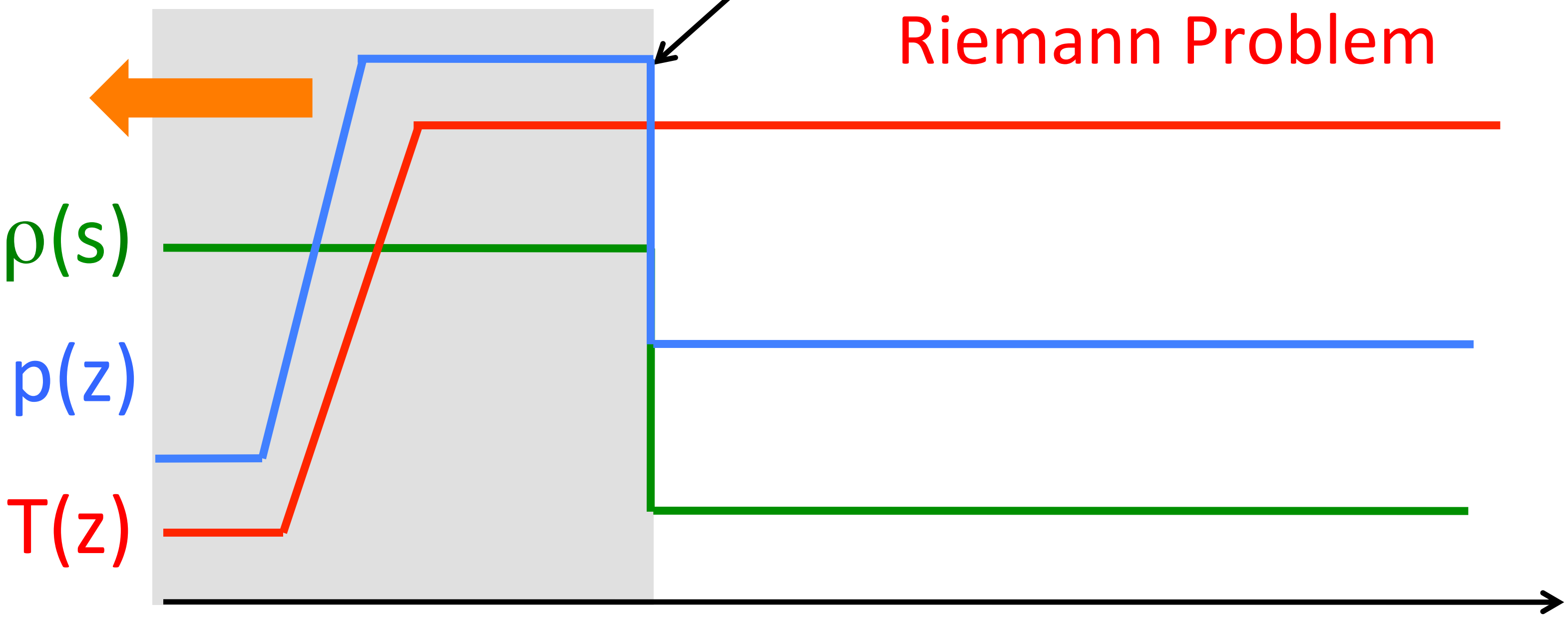
Transition region:
density/temperature
jump @ constant
pressure

$$\frac{\rho_{\mathrm{ch},0}}{\rho_{\mathrm{co},0}} = \frac{T_{\mathrm{co},0}}{T_{\mathrm{ch},0}} = R_{\mathrm{tr}}.$$

# The Basic Picture



# The Basic Picture



Transition region: pressure jump @ constant temperature

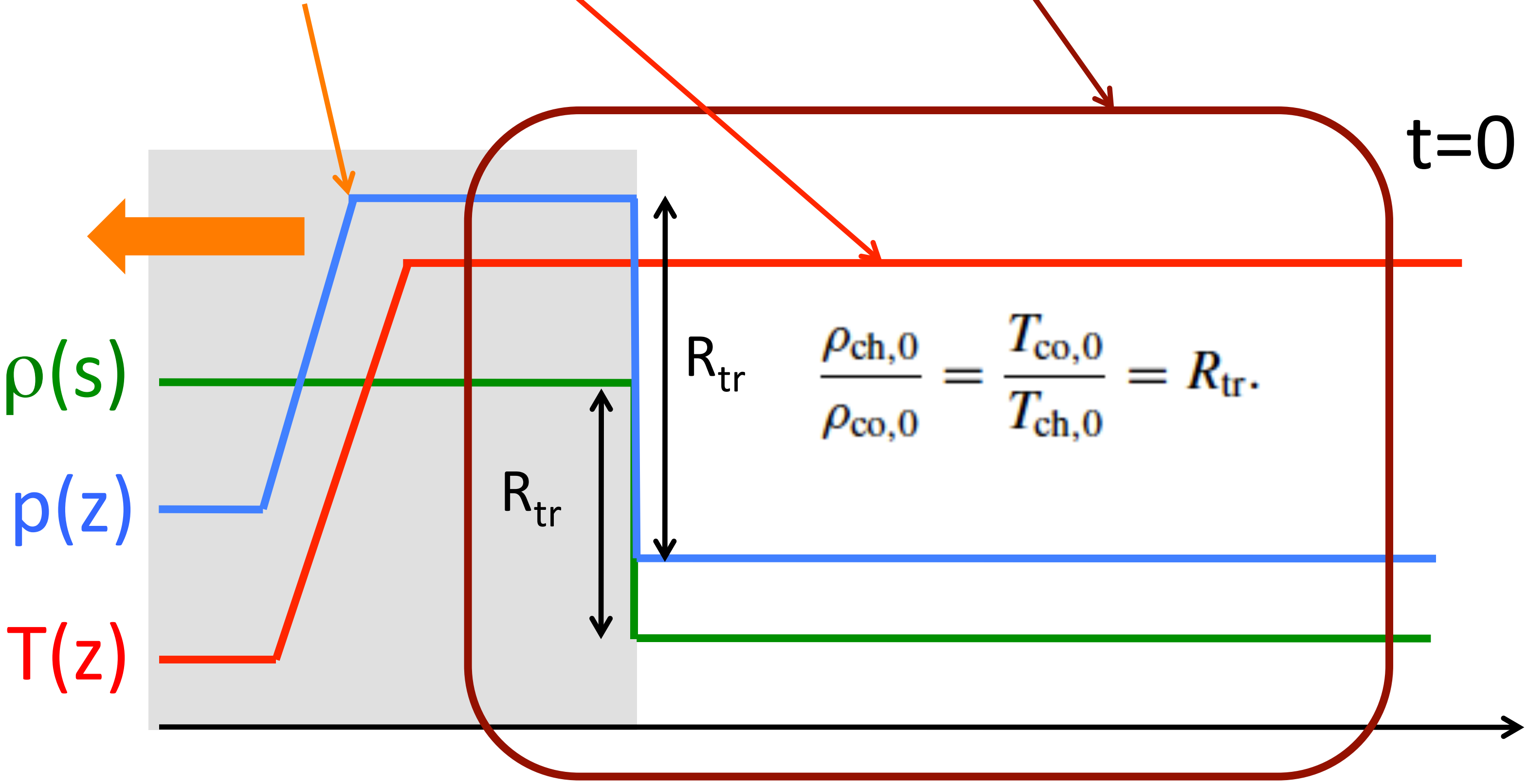
Riemann Problem

# Evaporation as Riemann Problem

- conduction creates uniform high temp. around TR
- evaporation occurs @ constant T for t>0

  **Isothermal Riemann problem**

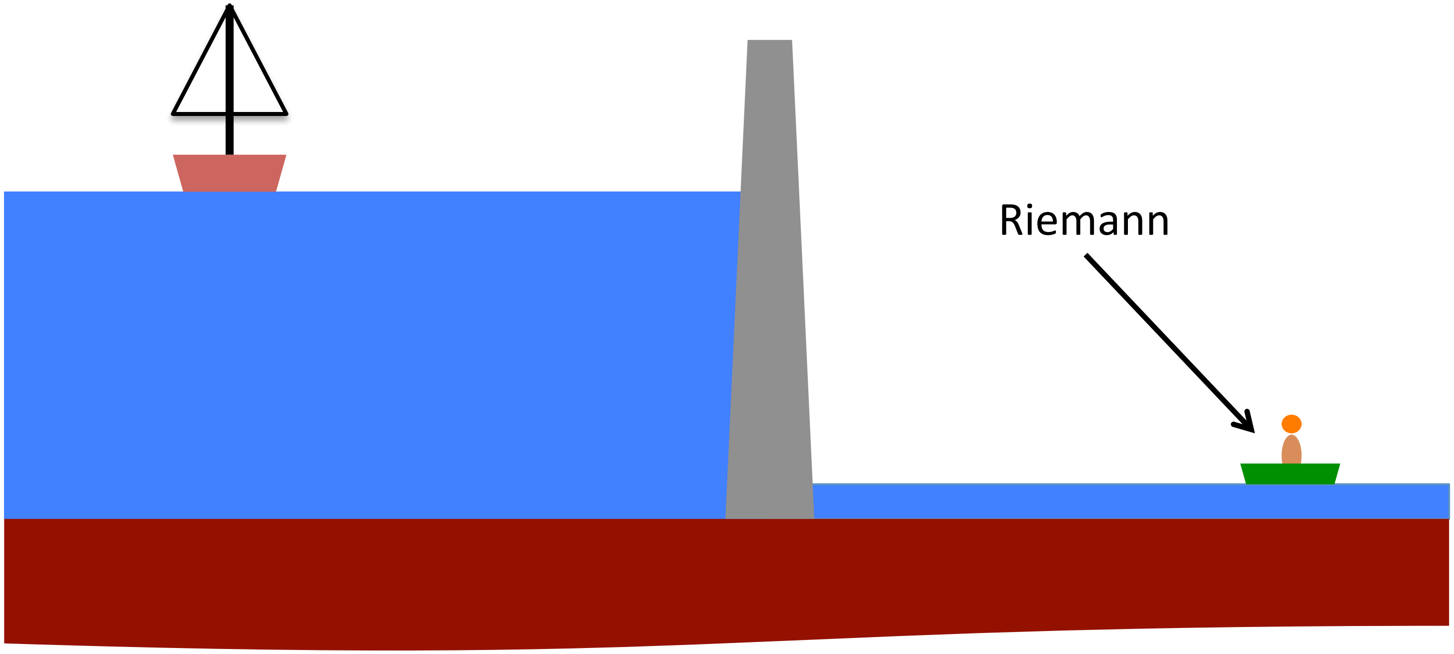
- isothermal – sound speed $a$; iso-T Mach #: $v/a = M^{(it)}$
- condensation shock (hypersonic) propagates down



$$\frac{\rho_{\mathrm{ch},0}}{\rho_{\mathrm{co},0}} = \frac{T_{\mathrm{co},0}}{T_{\mathrm{ch},0}} = R_{\mathrm{tr}}.$$

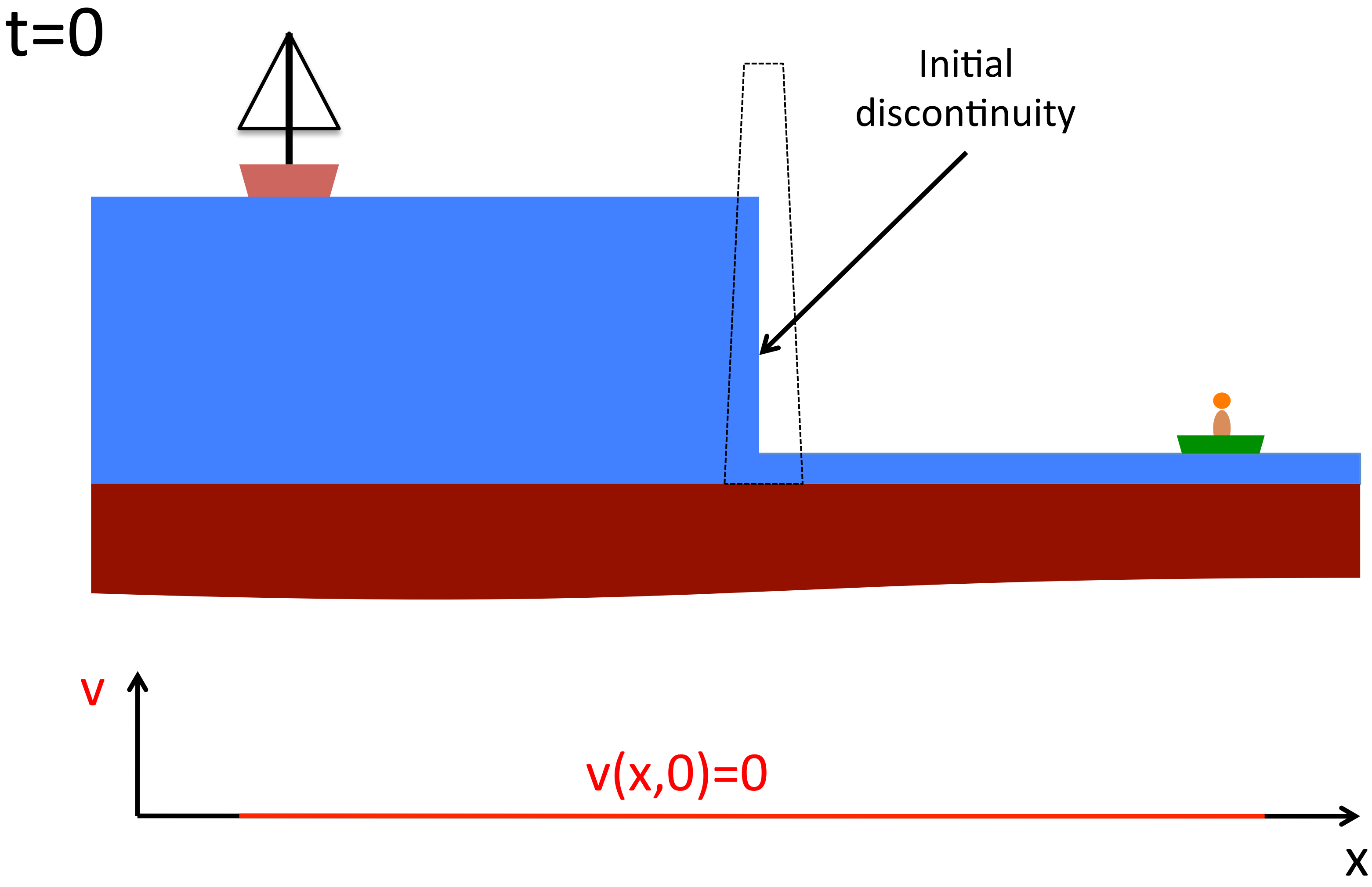
# Riemann’s Problem:

## what happens when the dam breaks?



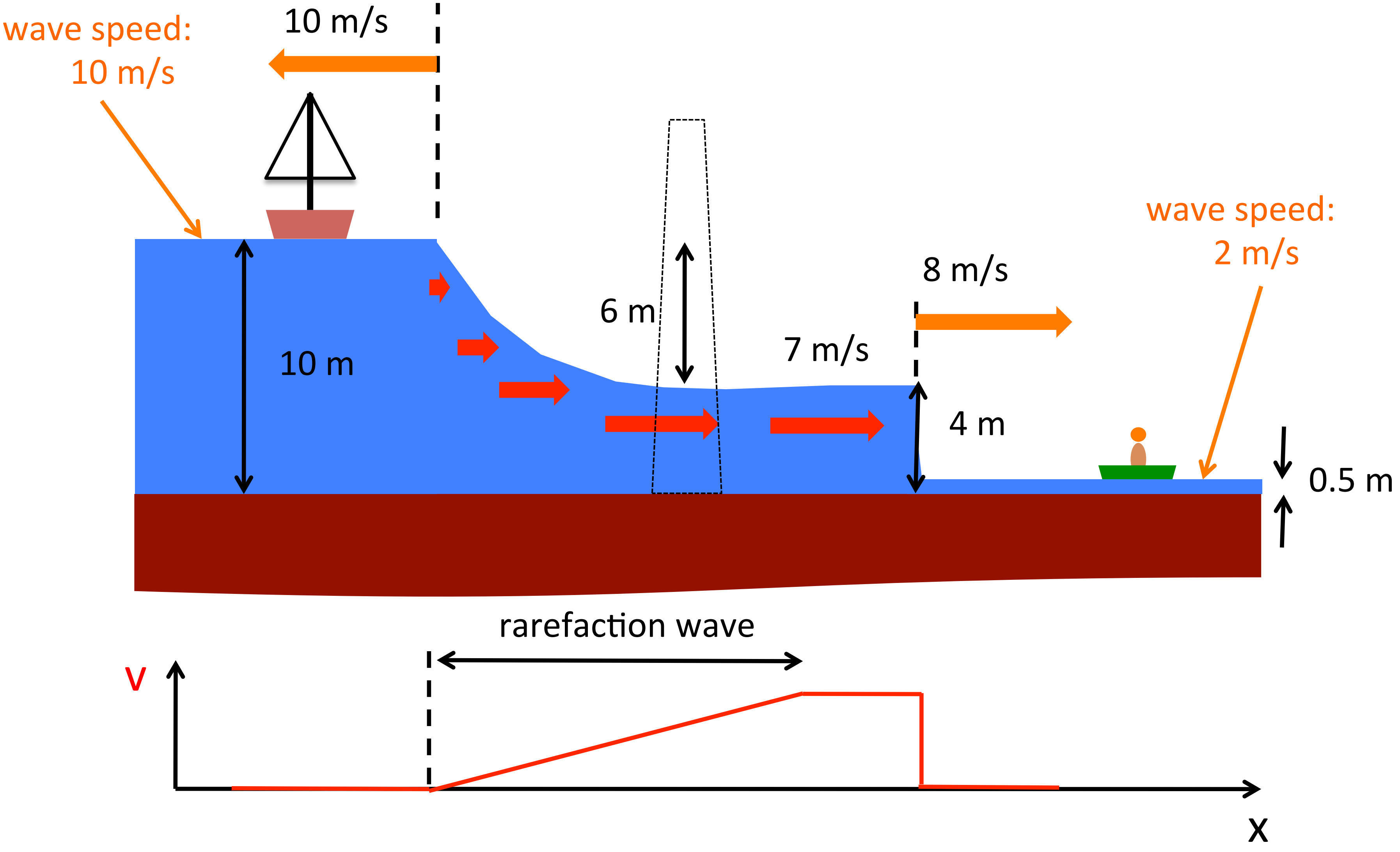
# Riemann's Problem:

## what happens when the dam breaks?



# Riemann's Problem:

## what happens when the dam breaks?



$$\boxed{\left[M_{\mathrm{es}}^{(it)}\right]^2 = 4R_{\mathrm{tr}}\,\exp\left(-\sqrt{3} - M_{\mathrm{es}}^{(it)} + \frac{1}{M_{\mathrm{es}}^{(it)}}\right),}$$

ES:

$$\frac{v_e}{a} = M_{\mathrm{es}}^{(it)} - \frac{1}{M_{\mathrm{es}}^{(it)}}.$$

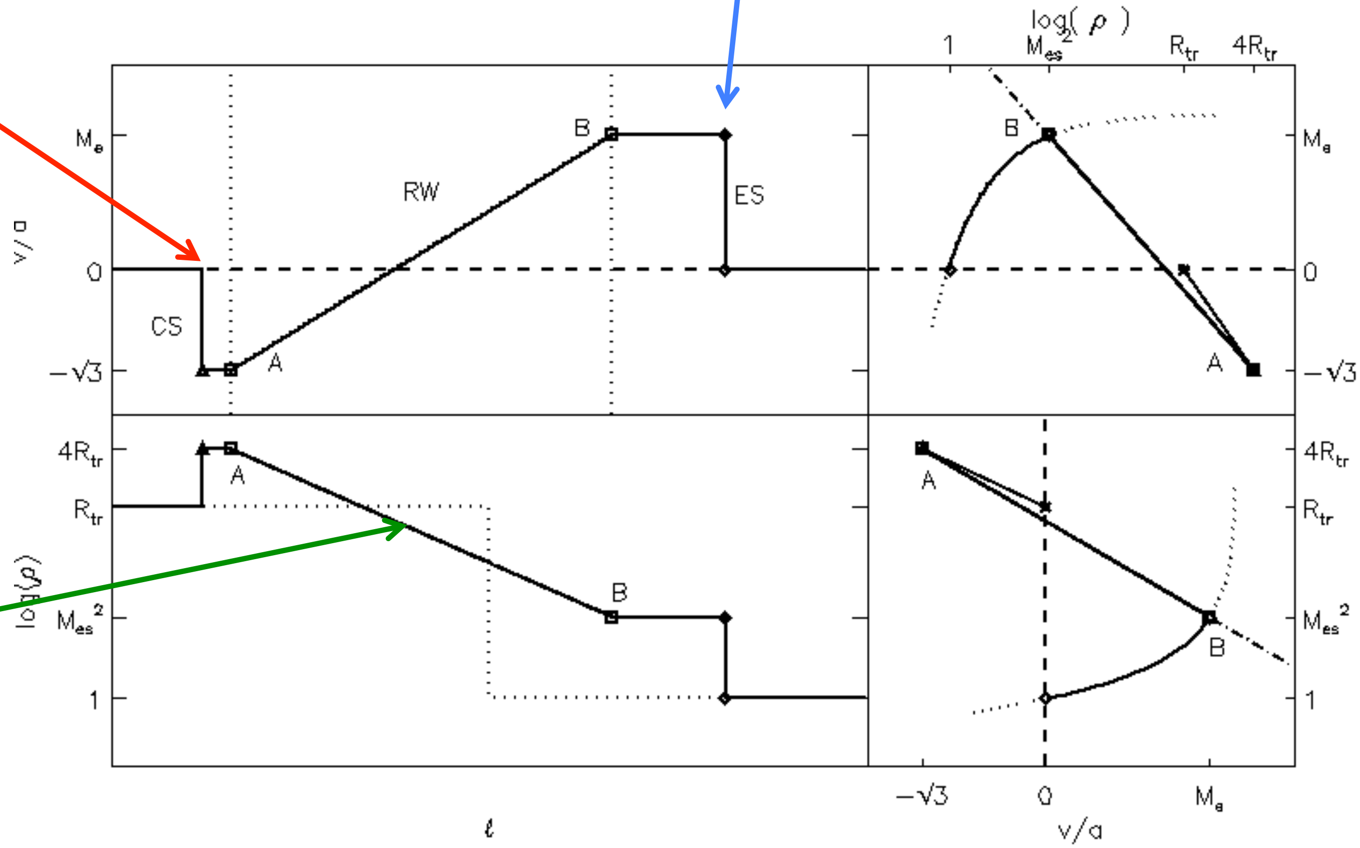
$$\frac{\rho_e}{\rho_{co,0}} = \left[M_{es}^{(it)}\right]^2$$

Condensation shock (CS): (hypersonic)

$$v_c = -\sqrt{3}\,a$$

$$\rho_c = 4\rho_{ch,0}$$

$$= 4R_{tr}\,\rho_{co,0}$$



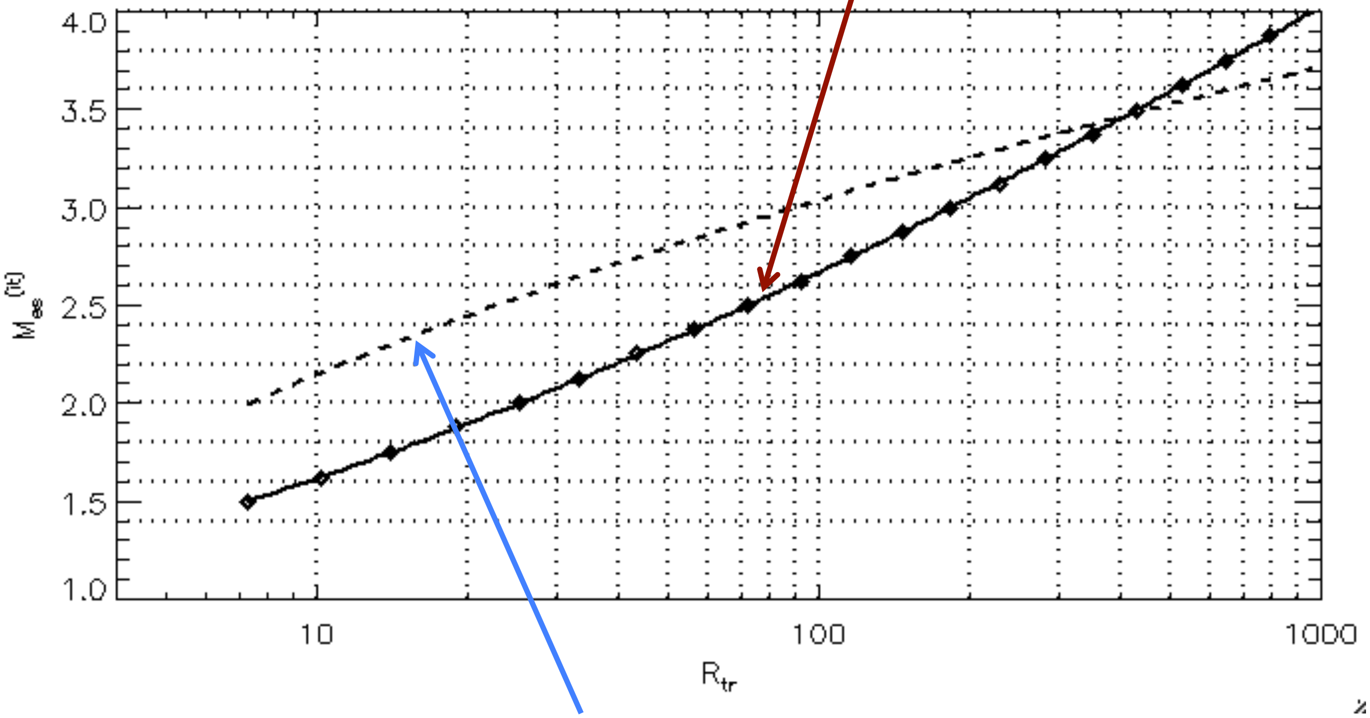
Rarefaction Wave (RW):

$$v(\ell, t) = \frac{\ell}{t} + a,$$

$$\rho(\ell, t) = \rho_0\,\exp\left(-\frac{\ell}{at}\right) = \rho_0\,\exp\left(1 - \frac{v}{a}\right) = 4R_{\mathrm{tr}}\,\exp\left(-\sqrt{3} - \frac{v}{a}\right)\,\rho_{\mathrm{co},0}$$

$$\boxed{\left[M_{\mathrm{es}}^{(it)}\right]^2 = 4R_{\mathrm{tr}}\, \exp\left(-\sqrt{3} - M_{\mathrm{es}}^{(it)} + \frac{1}{M_{\mathrm{es}}^{(it)}}\right),}$$

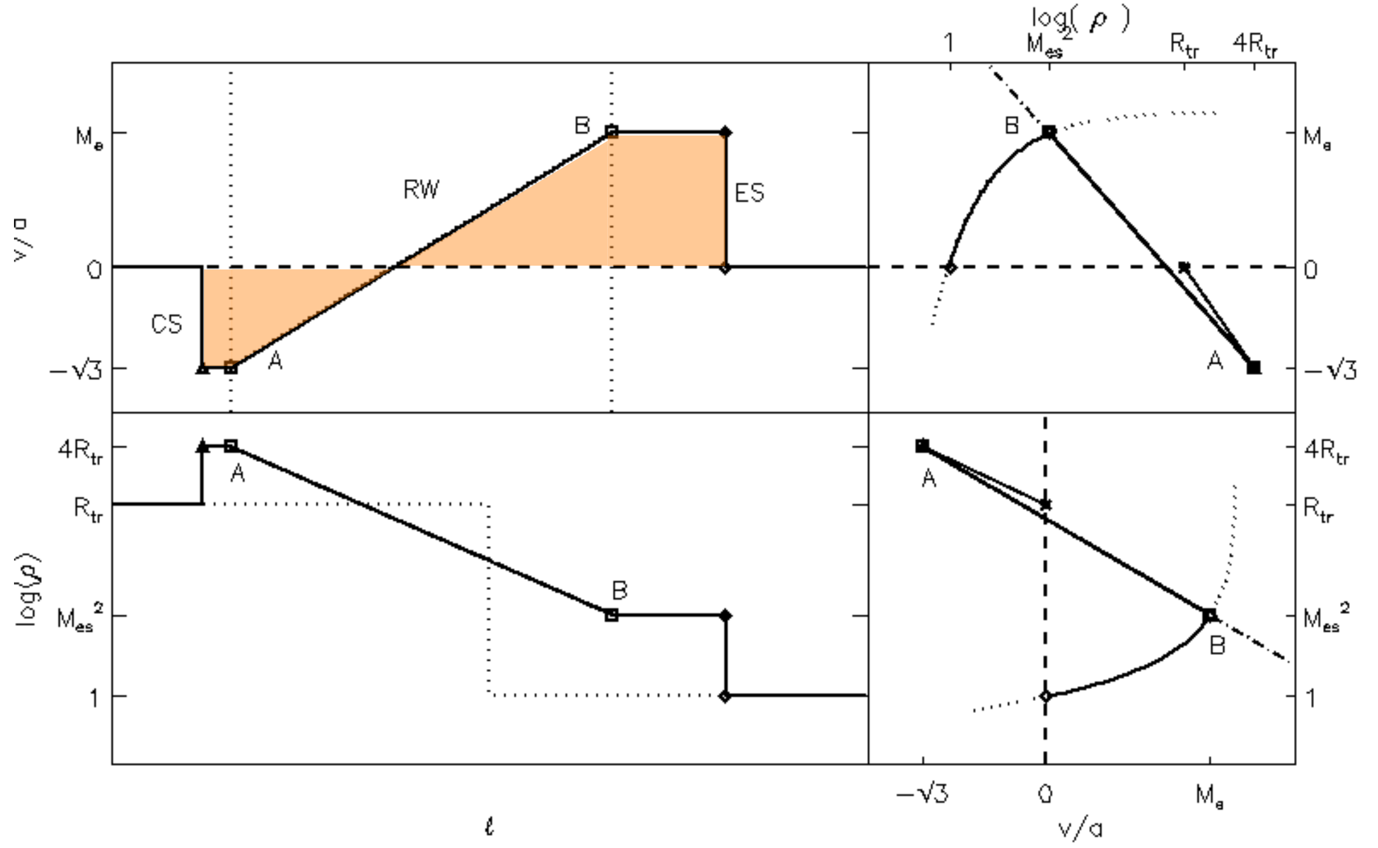
$$M_{\mathrm{es}}^{(it)} \simeq 2.670 + 1.209\, \log(R_{\mathrm{tr}}/100)\, [1 + 0.126\, \log(R_{\mathrm{tr}}/100)].$$



$$v_{\mathrm{FCM}} = \sqrt{(6/5)\, \ln R_{\mathrm{tr}}}\, c_{s,*} = \sqrt{2 \ln R_{\mathrm{tr}}}\, a.$$

Fisher, Canfield &
McClymont 1984

Longcope 2014

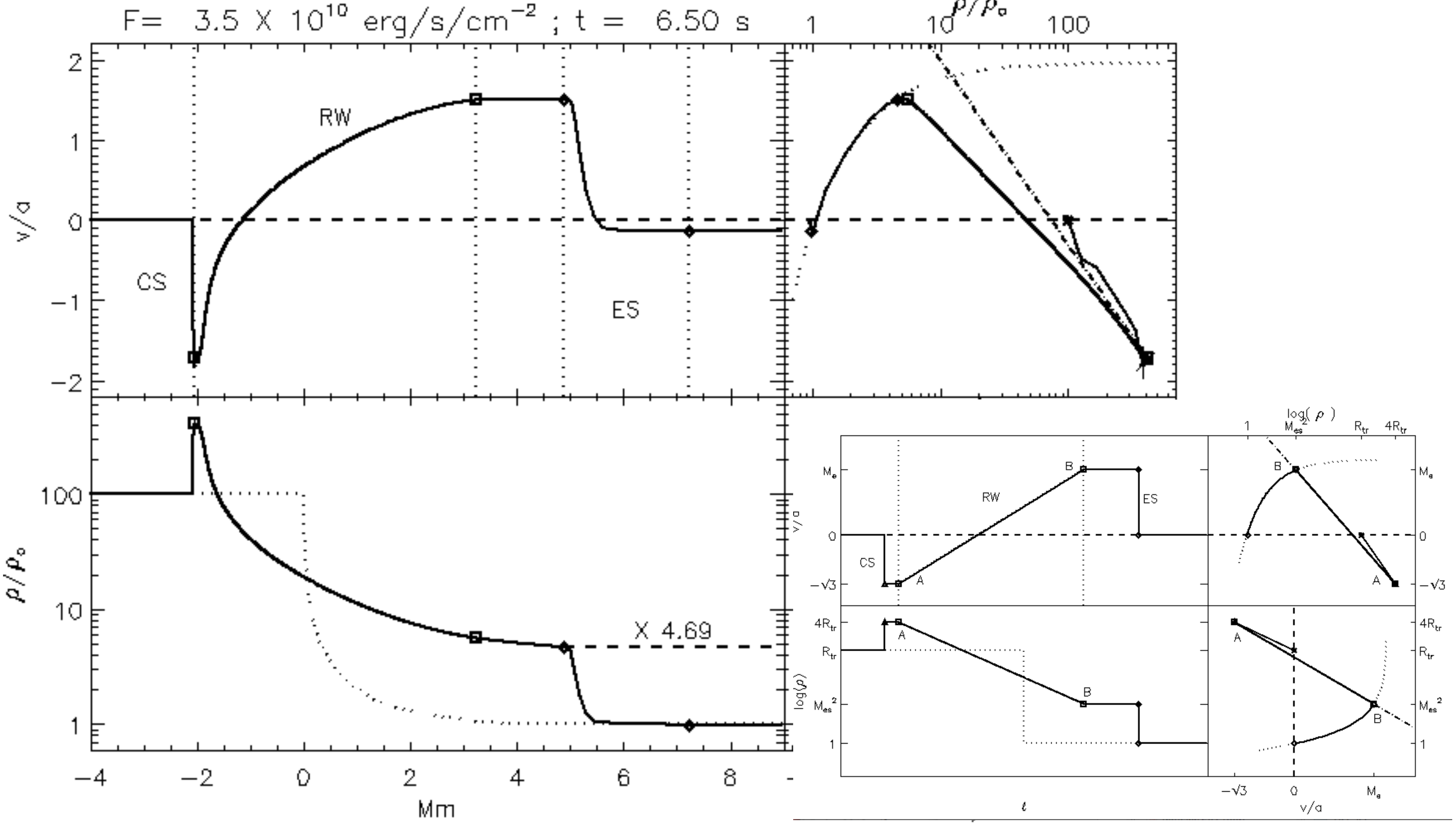


$$E_K = \int \frac{1}{2}\rho v^2\, d\ell = \frac{1}{2}\rho_{\rm co,0}\, a^3\, t \int \frac{\rho(\tilde{\ell})}{\rho_{\rm co,0}}[M^{(it)}(\tilde{\ell})]^2 d\tilde{\ell},$$

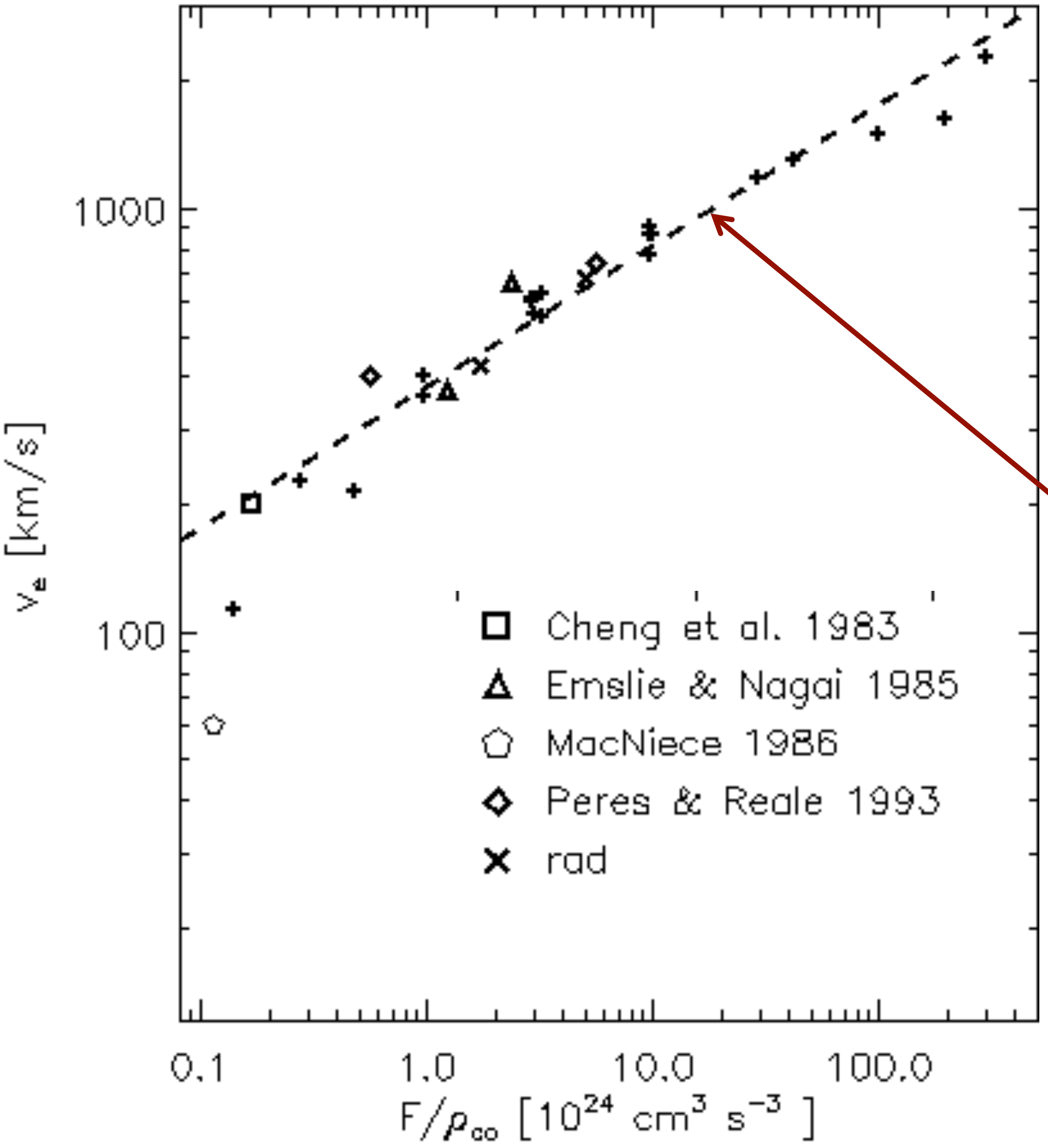
Flare
energy
flux

$$F = \frac{dE_K}{dt} \sim \rho_{co,0}\; a^3$$

$$\boxed{v_e = aM_e^{(it)} \approx C_e\left(\frac{F}{\rho_{co,0}}\right)^{1/3}}$$



F= 3.5 X 10$^{10}$ erg/s/cm$^{-2}$ ; t = 6.50 s
$\rho/\rho_o$
1
10
100
v/a
2
1
0
−1
−2
RW
CS
ES
$\rho/\rho_o$
100
10
1
X 4.69
−4
−2
0
2
4
6
8
Mm
log( $\rho$ )
1
$M_{es}^2$
$R_{tr}$
$4R_{tr}$
$M_e$
0
$-\sqrt{3}$
v/a
B
RW
ES
CS
A
B
A
$4R_{tr}$
$R_{tr}$
log($\rho$)
$M_{es}^2$
1
A
B
A
B
$\ell$
$-\sqrt{3}$
0
$M_e$
v/a



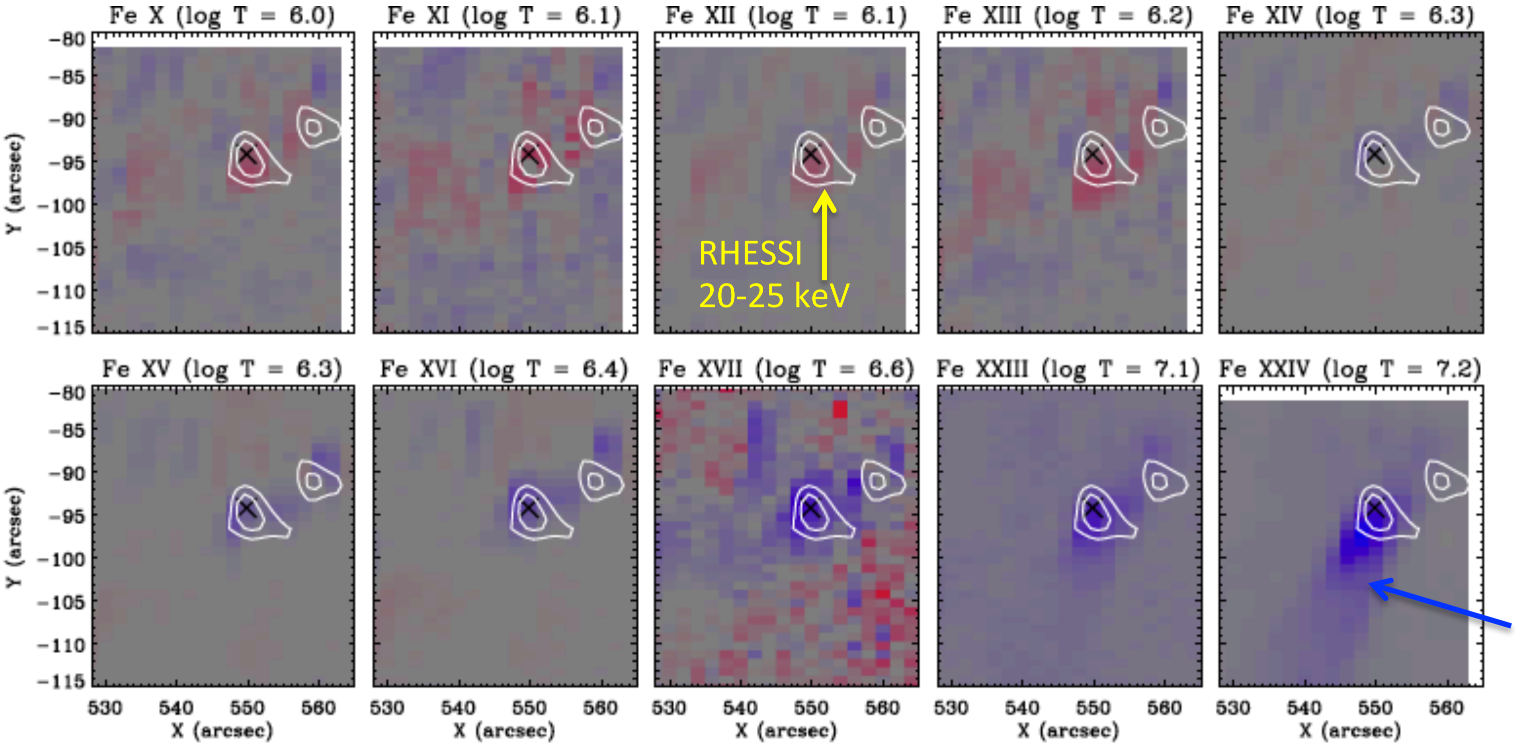
Simulations from the past

$$v_e = C_e \left( \frac{F}{\rho_{co,0}} \right)^{1/3}$$

$C_e = 0.38$

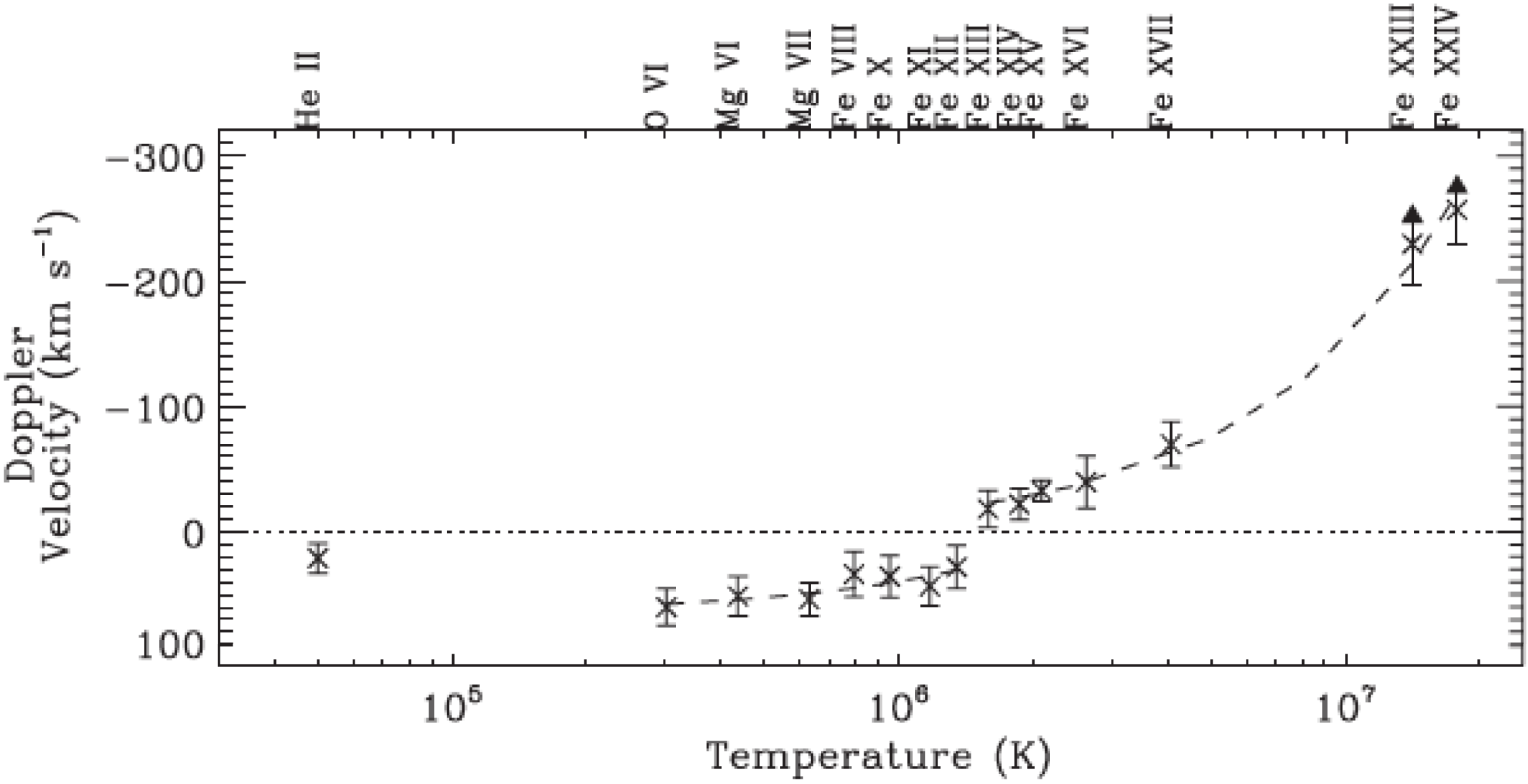
# Evaporation observed

Milligan & Dennis 2009



RHESSI 20-25 keV

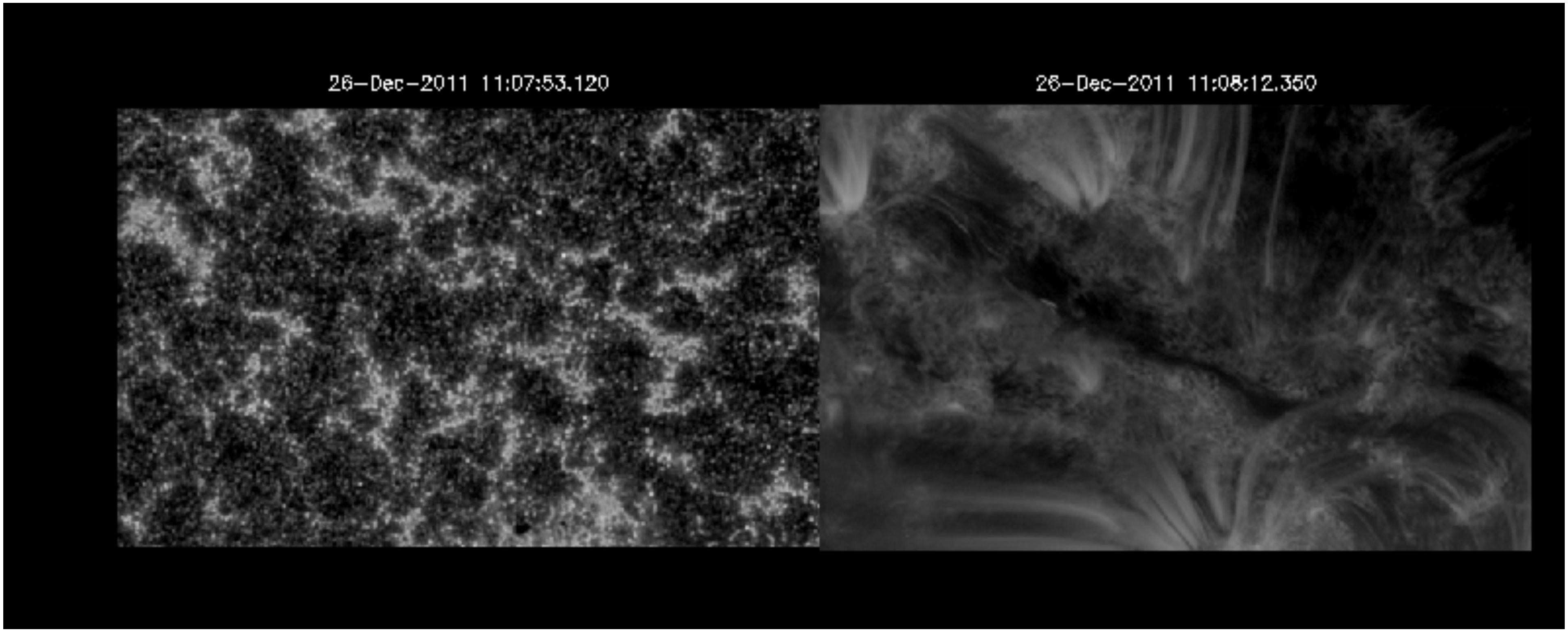
Hinode EIS

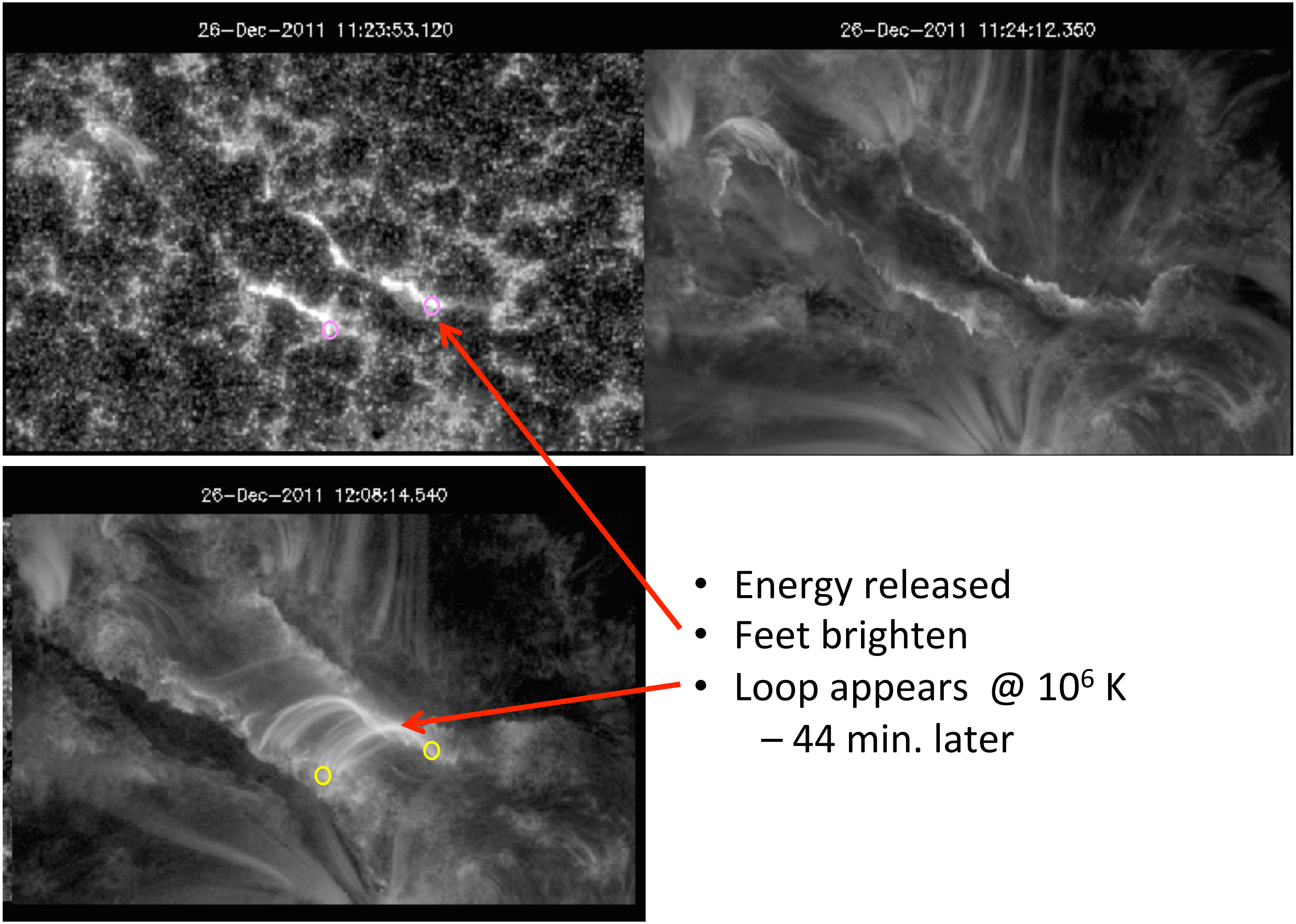

He II
O VI
Mg VI
Mg VII
Fe VIII
Fe X
Fe XI
Fe XII
Fe XIII
Fe XIV
Fe XV
Fe XVI
Fe XVII
Fe XXIII
Fe XXIV
−300
−200
−100
0
100
Doppler Velocity (km s$^{-1}$)
$10^5$
$10^6$
$10^7$
Temperature (K)

# 4. Loops cool off

AIA 1600 A:
100,000 K plasma
chromospheric feet

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



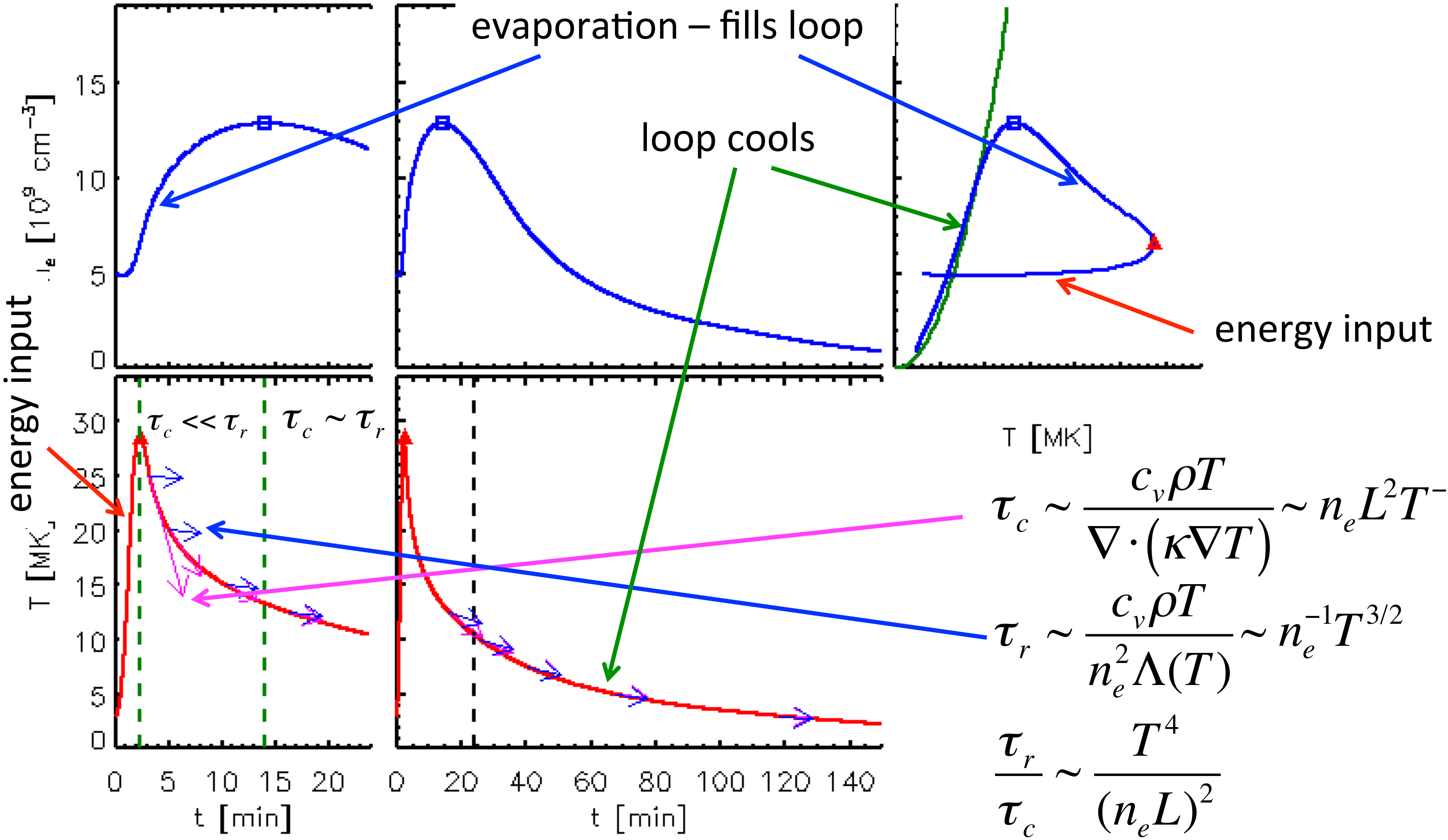


- Energy released
- Feet brighten
- Loop appears @ $10^6$ K
  - – 44 min. later

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 coo



Conduction drives evaporation – fills loop

loop cools

energy input

energy input

$$\tau_c \sim \frac{c_v\rho T}{\nabla\cdot\left(\kappa\nabla T\right)} \sim n_e L^2 T^{-5/2}$$

$$\tau_r \sim \frac{c_v\rho T}{n_e^2\Lambda(T)} \sim n_e^{-1} T^{3/2}$$

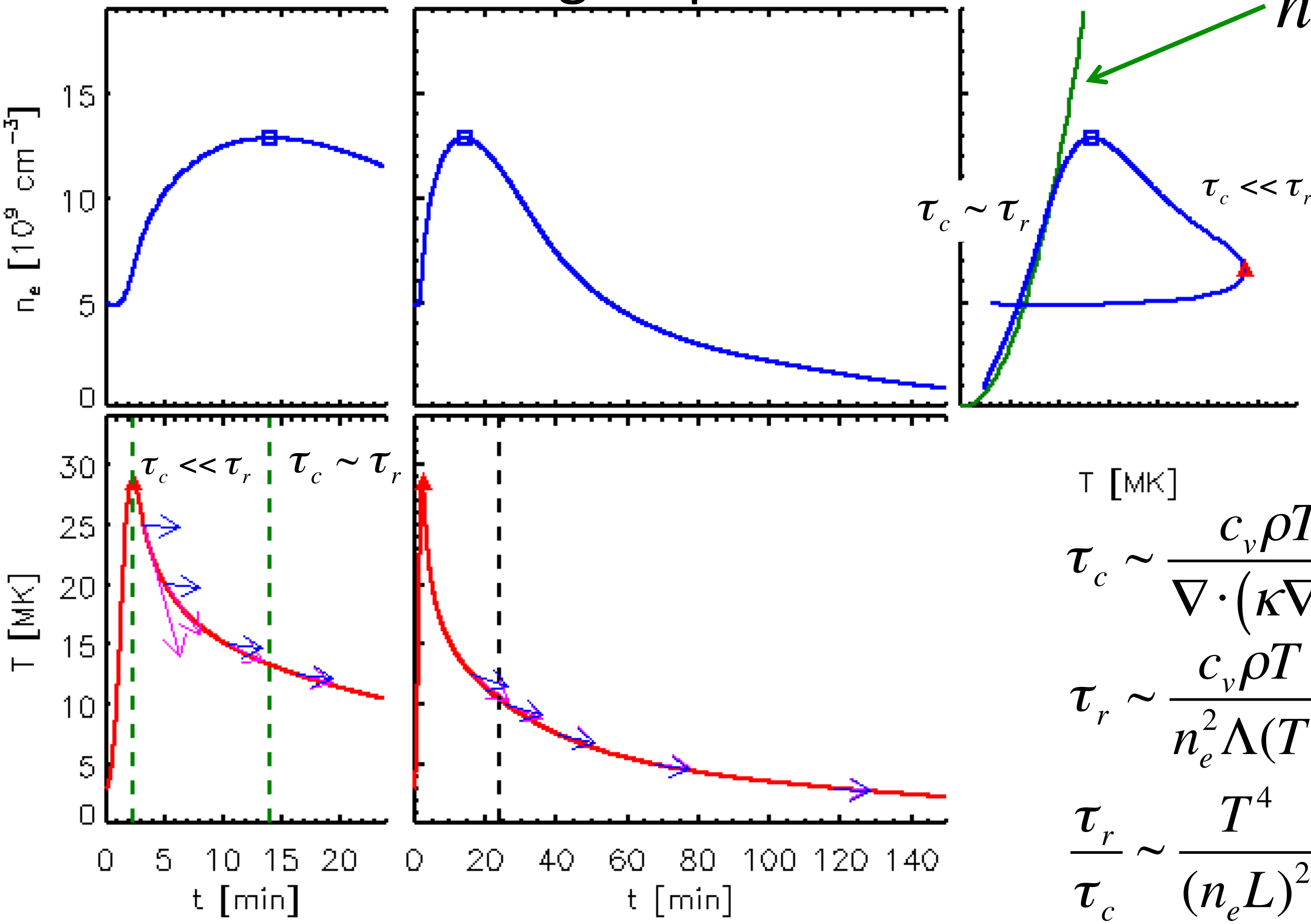
$$\frac{\tau_r}{\tau_c} \sim \frac{T^4}{(n_e L)^2}$$

slow draining & $\nabla p = 0$ $\frac{\partial}{\partial t}\left(\frac{3}{2}p\right) \rightarrow -H(t)$

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

Same as
equilibrium
(RTV)

## One cooling loop



$$n_e \sim L^{-1}T^2$$

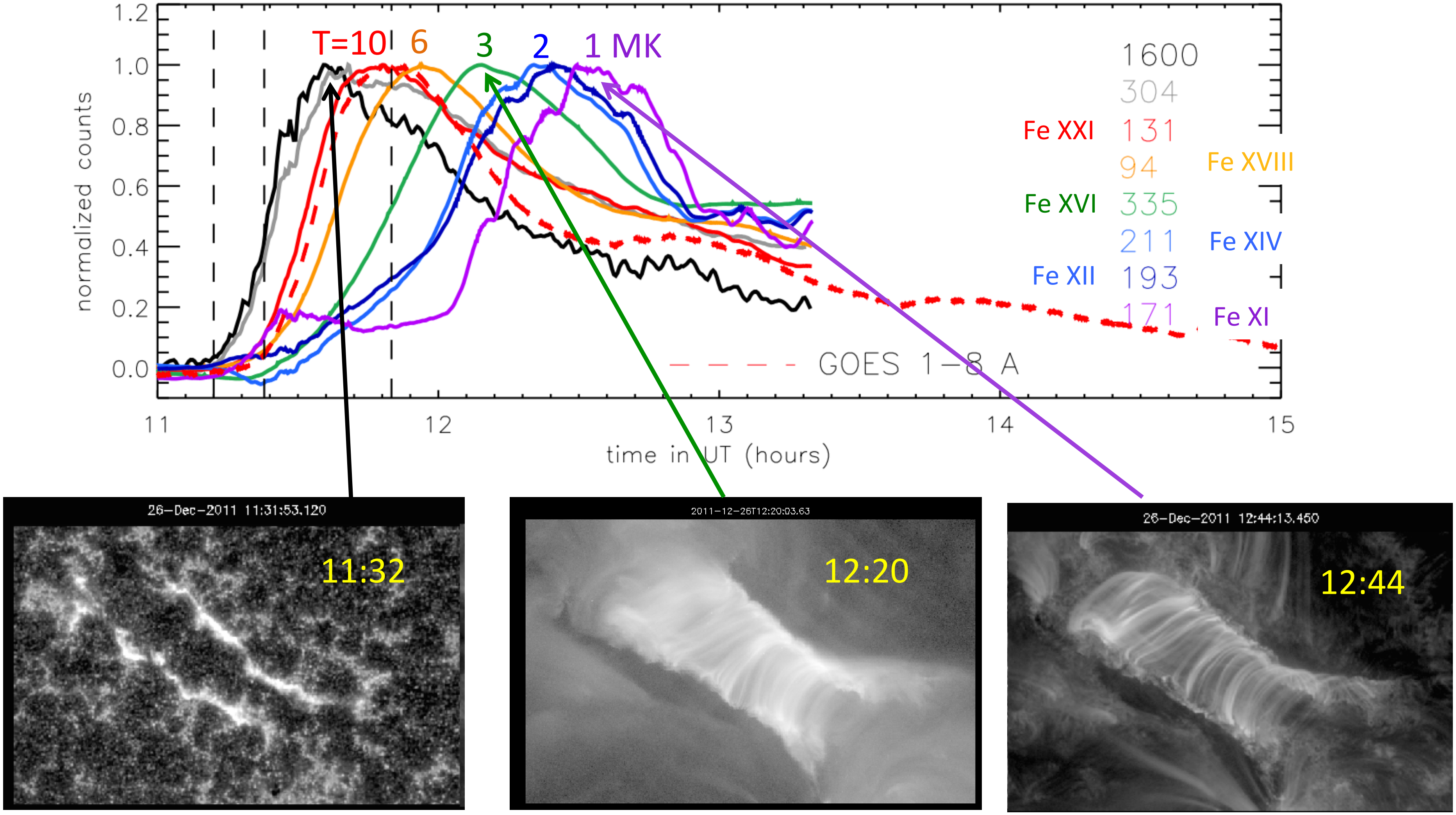
$$\tau_c \sim \tau_r$$

$$\tau_c \sim \frac{c_v\rho T}{\nabla\cdot\left(\kappa\nabla T\right)} \sim n_e L^2 T^{-5/2}$$

$$\tau_r \sim \frac{c_v\rho T}{n_e^2\Lambda(T)} \sim n_e^{-1}T^{3/2}$$

$$\frac{\tau_r}{\tau_c} \sim \frac{T^4}{(n_e L)^2}$$

# Cooling observed

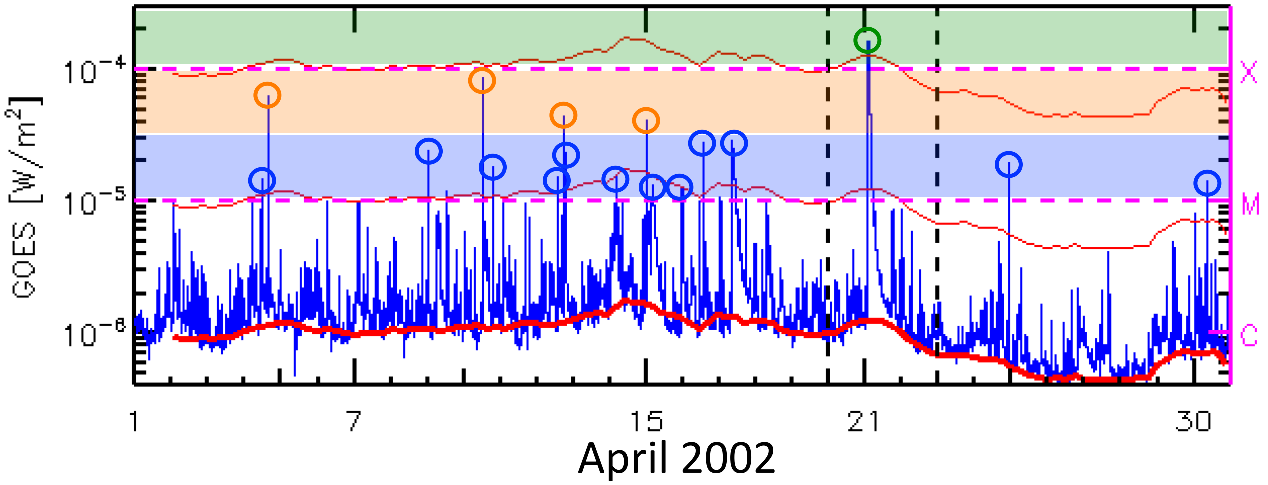


# **The population:** flare statistics

Ignore details of events:
focus on statistics

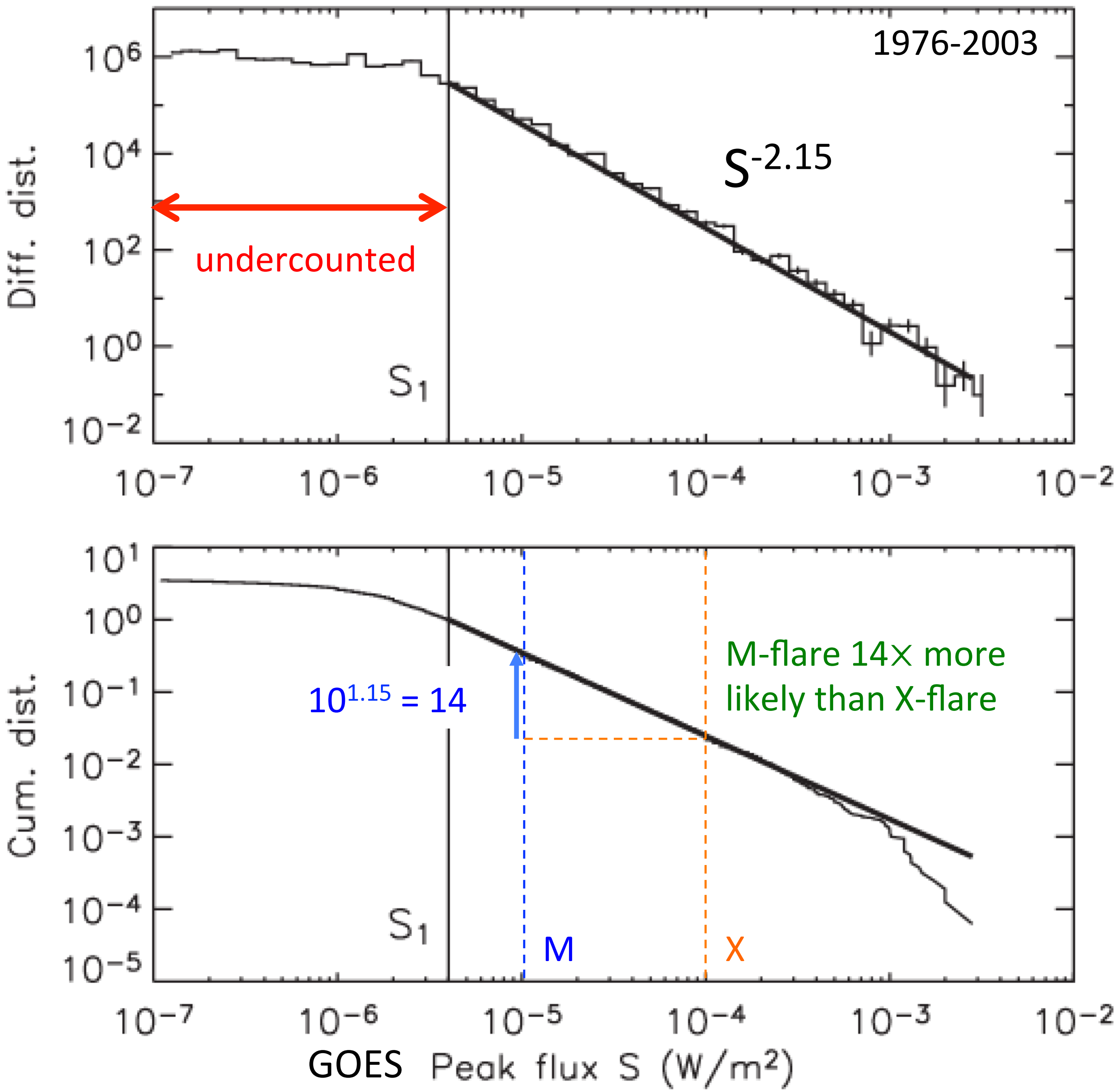
Count events in each bin

define
amplitude
bins



Convert
to freq.

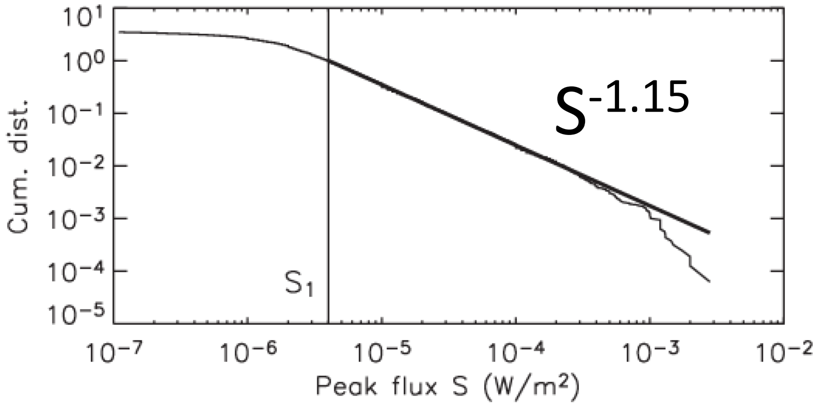
| | |
|---|---|
| 1 | =0.03/day |
| 4 | =0.12/day |
| 11 | =0.33/day |



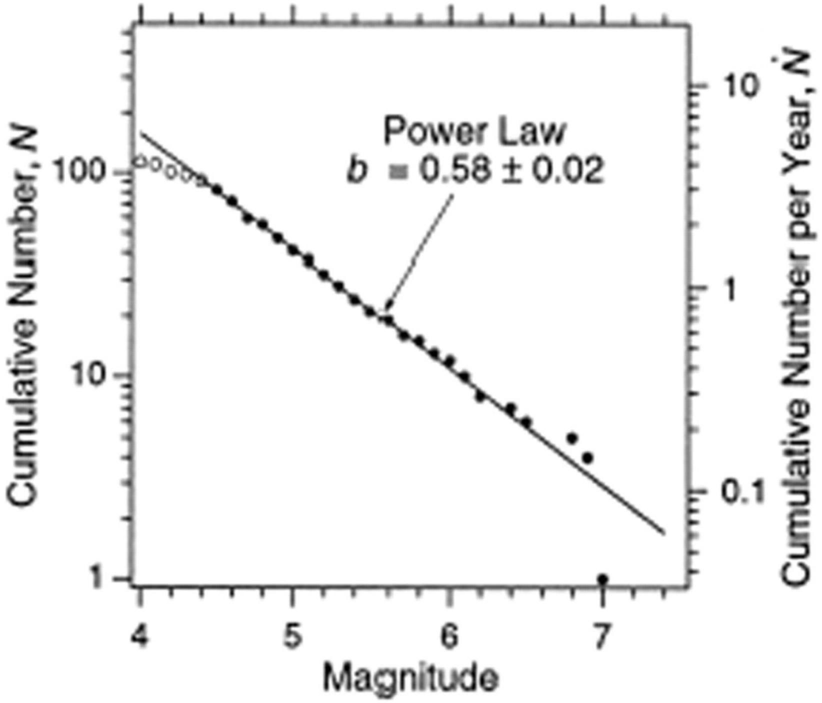
M-flare 14× more likely than X-flare

Wheatland 2005

# What could it mean?

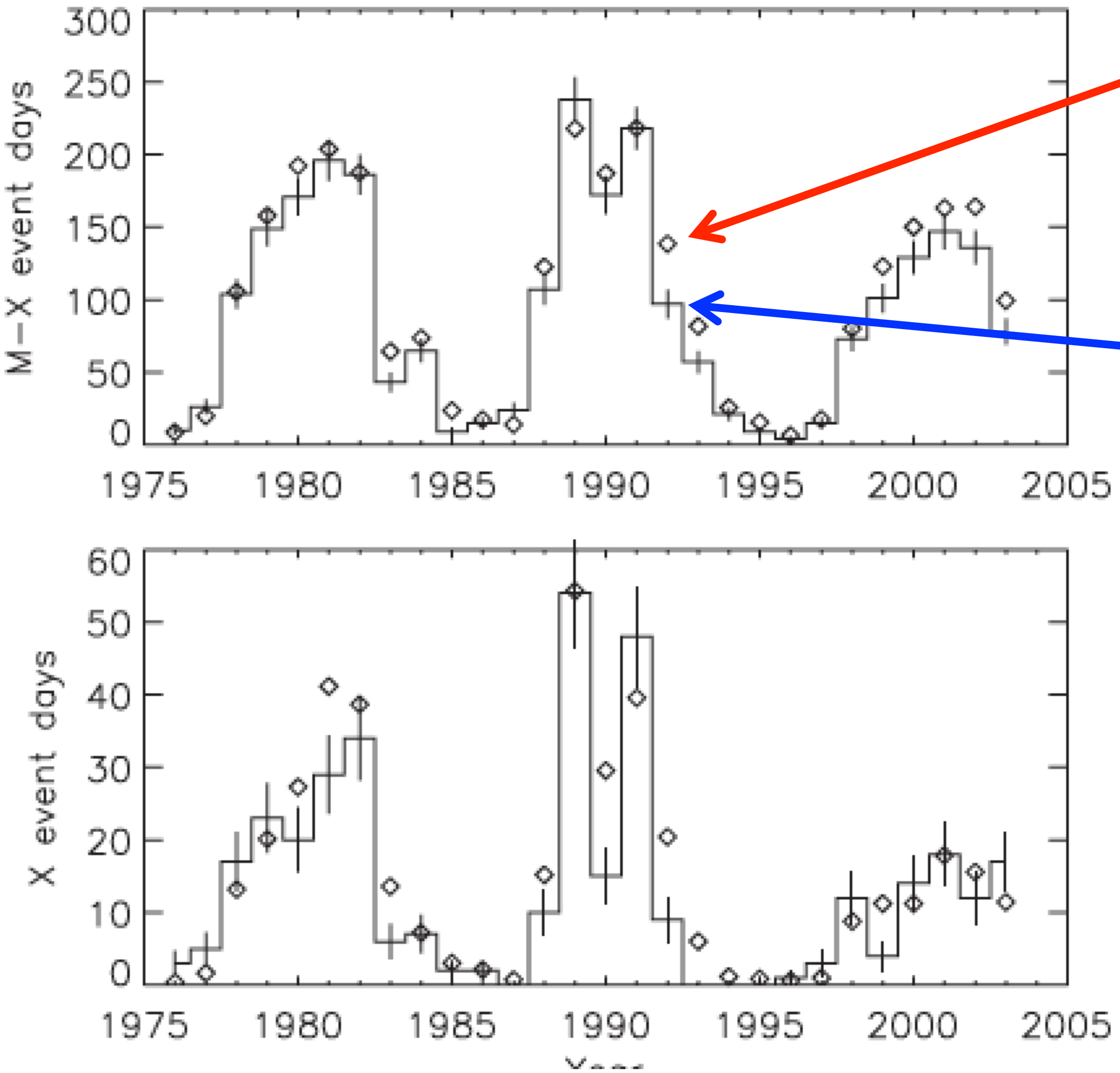


Solar Flares



Earthquakes

# Distributions as a forecasting tool



Predicted based on prior power law

observed

Wheatland 2005b

# Summary

- A **Flare** is a sudden brightening of the entire star (the Sun) in X-rays
- Energy is released from the coronal magnetic field
- Non-magnetic energy is transported downward to drive chromospheric evaporation
  - **the actual ``flare''**
- Loops cool and then appear in various EUV images
- Flares of various amplitudes appear at different frequencies: larger flares less frequently