Energetic Phenomena on the Sun

Flares and Coronal Mass Ejections

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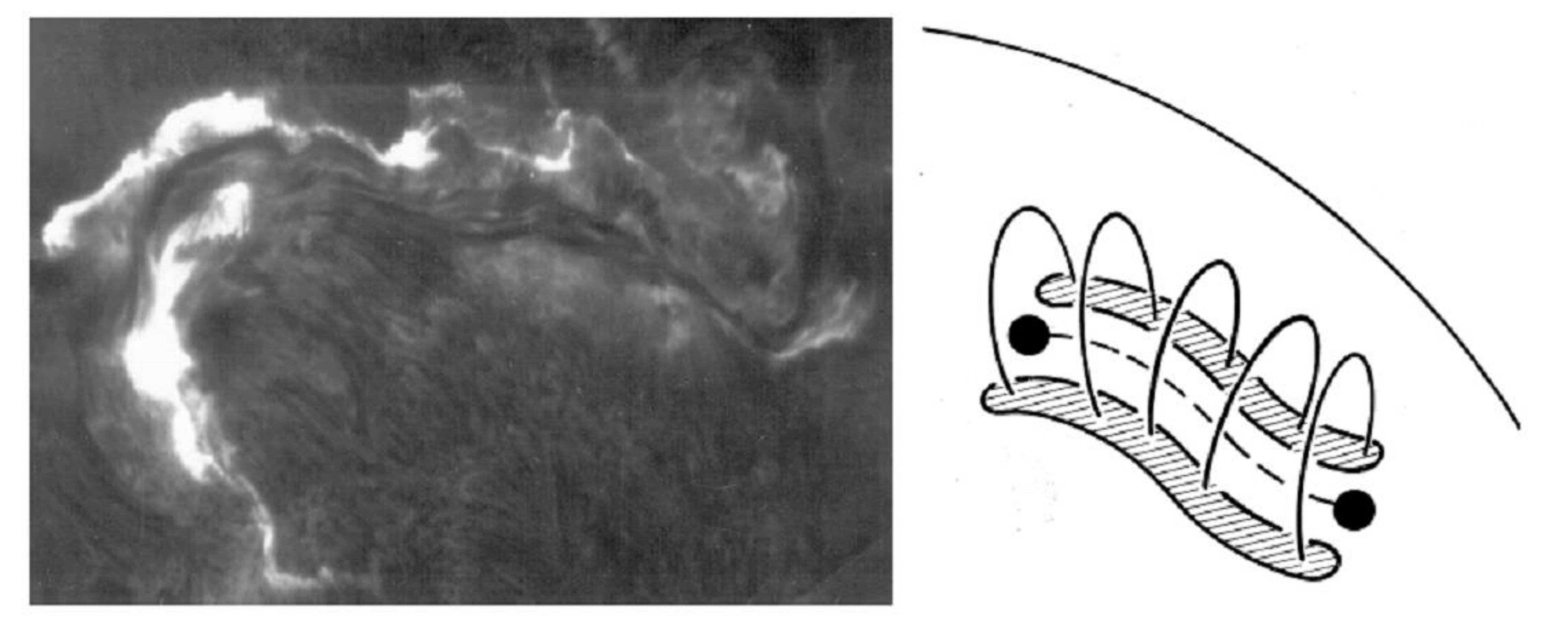
Aim: To describe the theory for the origin of the Flares and Coronal **M**ass **E**jections, to introduce some of the observational and theoretical characteristics of the flares and CMEs and their relationship:

- Understand the magnetic origin of the Flares and the **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model.
- Understand the **standard flare scenario** and corresponding X-Ray and Radio Signatures (Including the ***Neupert effect***).
- Understand the concept of the **Statistical Flare**.
- Understand the "***Standard model***" of **eruptive flares/CMEs**.

Introduction (I)

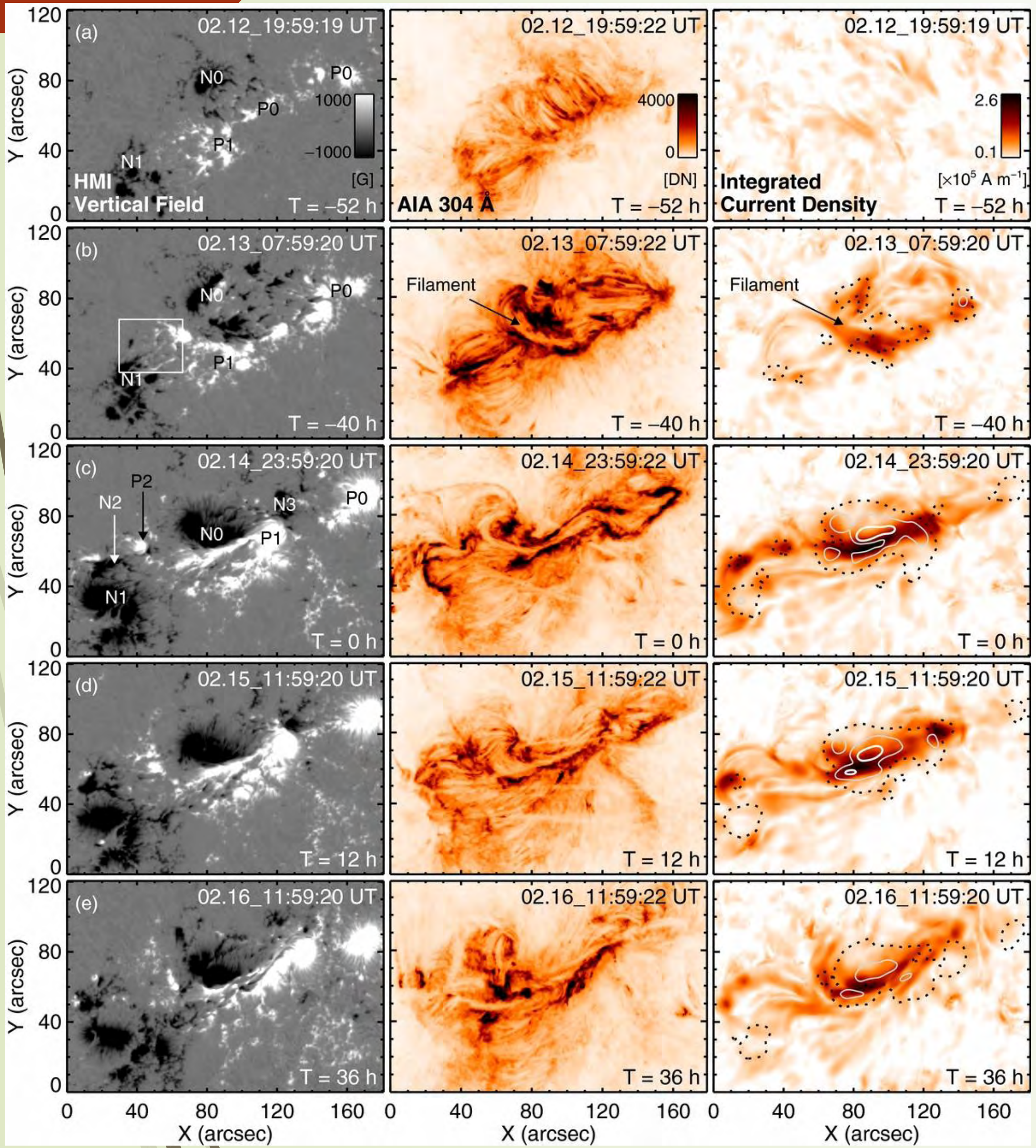
- A **solar flare** is a catastrophic event that is triggered by an instability of the underlying magnetic field configuration and evolves then into a more stable state by changing and reconnecting the magnetic topology. This change provides free magnetic energy that results in plasma heating and particle acceleration. They manifest themselves as enhanced radiation across the whole electromagnetic spectrum due to heating and interaction of high-energetic particles with the solar atmosphere.

A catastrophic event that is triggered by an instability of the **underlying magnetic field configuration**



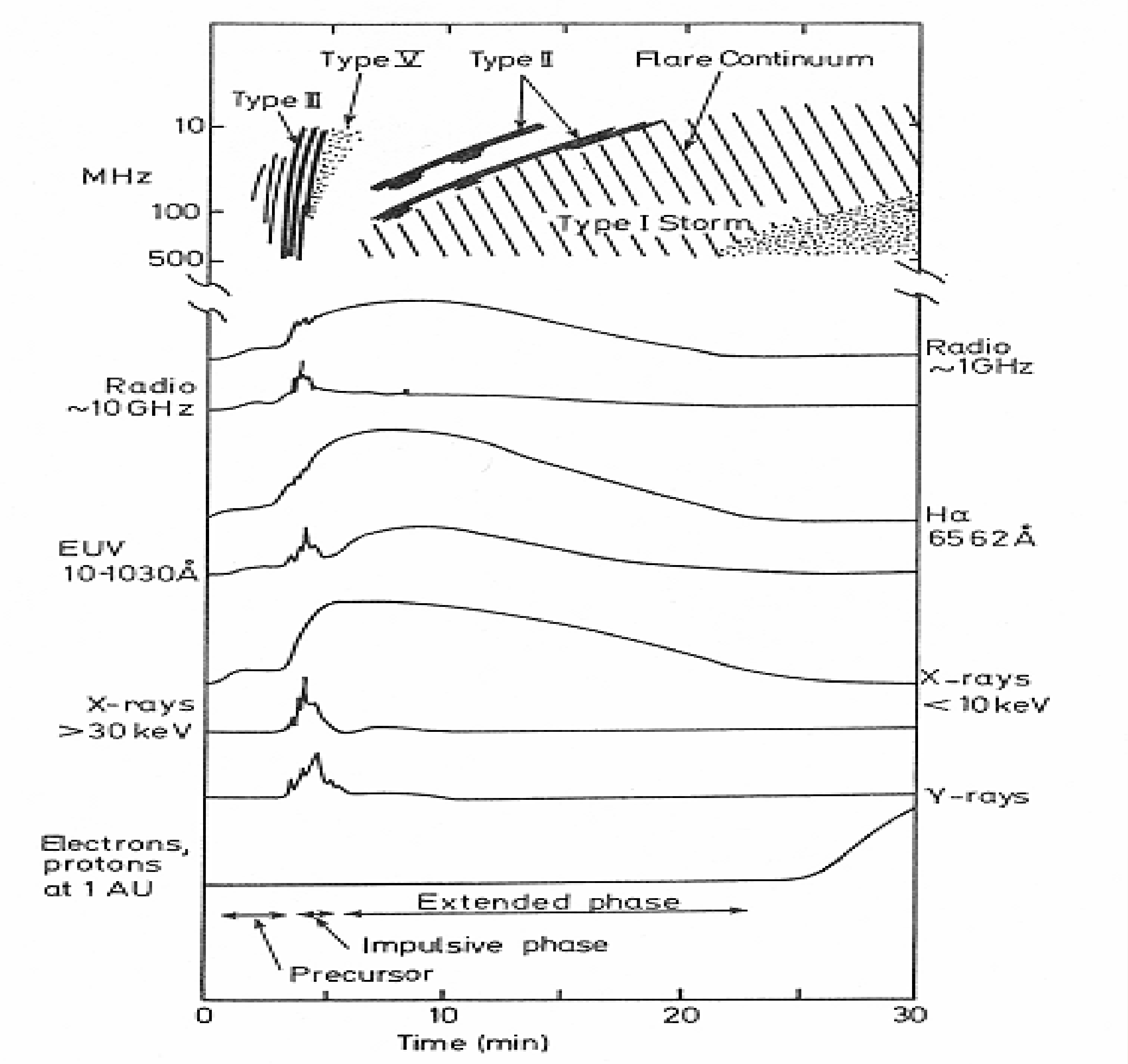
A two ribbon flare recorded in Hα (Pic du Midi). On the right a "cartoon" of the magnetic field configuration.

A catastrophic event that is triggered by an instability of the **underlying magnetic field configuration**



Five snapshots of the evolving AR11158. **Left**: HMI B_z. **Middle**: negative AIA 304 Å image showing chromosphere and transition region structures in which the AR filament is best discernible. **Right** : vertically integrated current density.

Enhanced radiation across the whole electromagnetic spectrum due to heating and interaction of high-energetic particles with the solar atmosphere

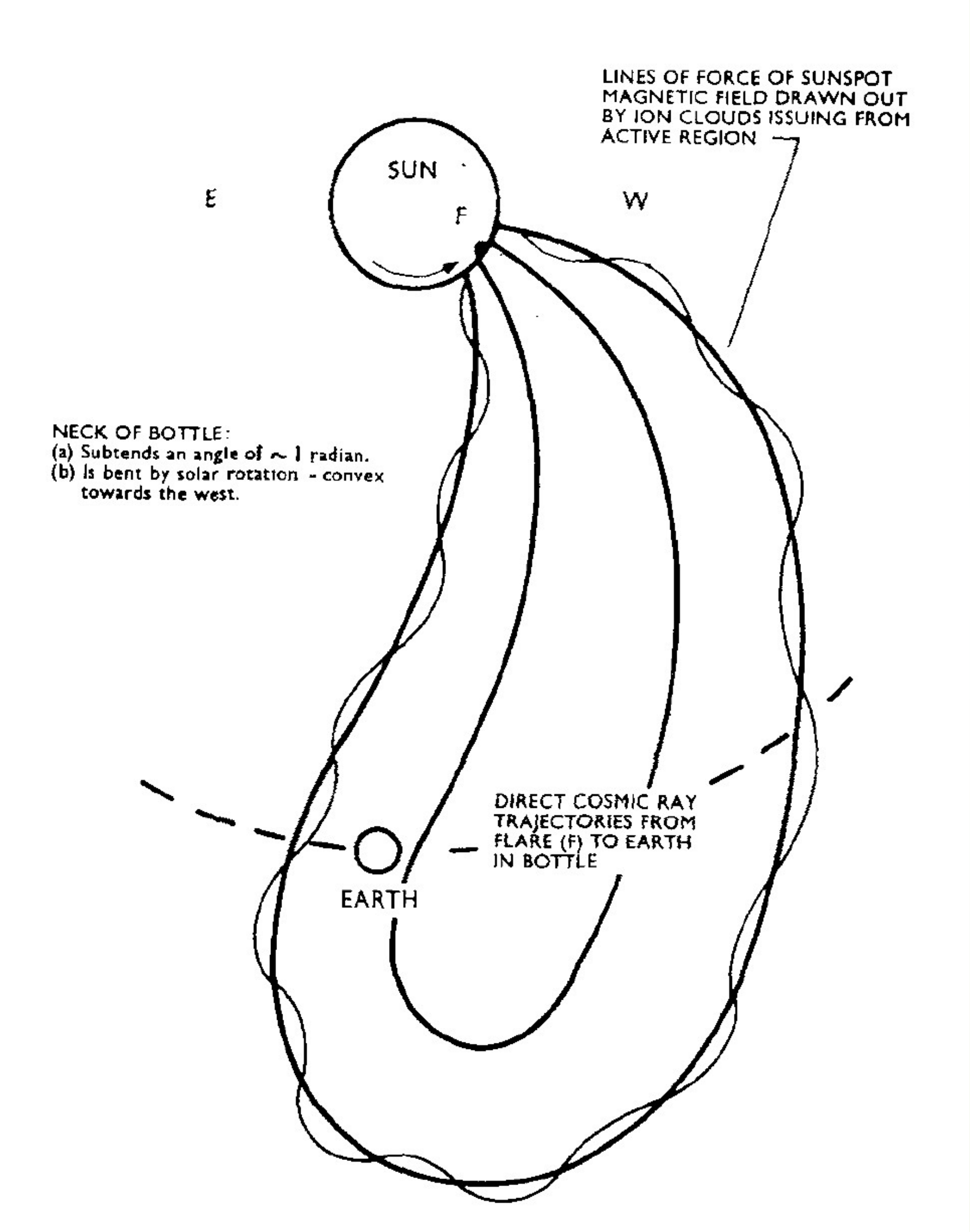


A schematic representation of the different phases of a typical solar flare as observed in electromagnetic and particle radiation.

Introduction (II)

- Coronal mass ejections (**CMEs**) are **huge clouds of magnetized plasma** expelled from the solar corona to interplanetary space with velocities of **~100 km/s** up to **3000 km/s**.
- **Both Flares and CMEs** are powered by a sudden release of magnetic energy in the corona previously stored in **stressed magnetic fields**.

Huge clouds of magnetized plasma expelled from the solar corona to interplanetary space



A very early cartoon. Such a picture in any case **precedes** the neologism "***Coronal Mass Ejection,***" of course.

Nowadays we are pretty sure that **sunspots don't emit massive ion clouds**.

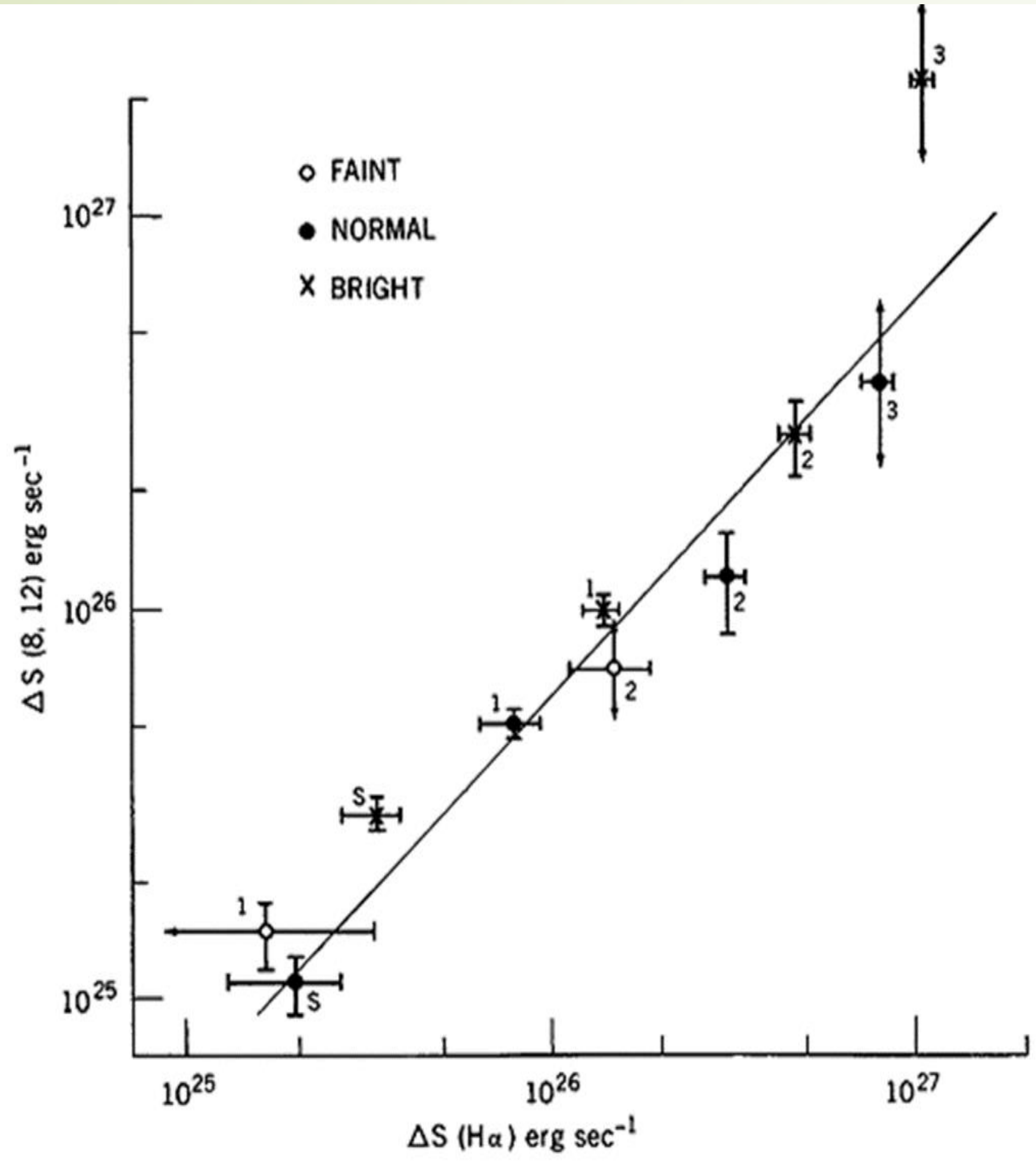
Introduction (III): Summary

- A **solar flare** is a catastrophic event that is triggered by an instability of the underlying magnetic field configuration and evolves then into a more stable state by changing and reconnecting the magnetic topology. This change provides free magnetic energy that results in plasma heating and particle acceleration. They manifest themselves as enhanced radiation across the whole electromagnetic spectrum due to **heating and interaction of high-energetic particles with the solar atmosphere**.
- Coronal mass ejections (**CMEs**) are **huge clouds of magnetized plasma** expelled from the solar corona to interplanetary space with velocities of ~**100 km/s** up to **3000 km/s**.
- **Both Flares and CMEs** are powered by a sudden release of magnetic energy in the corona previously stored in **stressed magnetic fields**.

Classifying Solar Flares: The **N**ational **O**ceanic and **A**tmospheric **A**dministration has devised categories for the flares: The biggest flares are known as "**X-class flares**" based on a classification system that divides solar flares according to their strength. The smallest ones are **A-class**, followed by **B**, **C**, **M**, and **X**. Each letter represents a 10-fold increase in flux. Within each class there is a finer scale **from 1 to 9**.

GOES SXR Flux 1-8 A Wm^{-2}		**H_α Class (Surface in degrees squared)**		**Relative Brilliance**
X10	10^{-3}	**4**	24.7	Bright
X	10^{-4}	**3**	12.4	
M	10^{-5}	**2**	5.1	Normal
C	10^{-6}	**1**	2.0	
B	10^{-7}	**S**	<2.0	Faint
A	$<10^{-7}$			

Soft X-rays and Hα Relationship



The tight correlation found between soft X-rays and Hα emission by Thomas and Teske "*Solar soft X-rays and solar activity. II: Soft X-ray emission during solar flares*." Sol. Phys. **16**, 431–453 (1971).

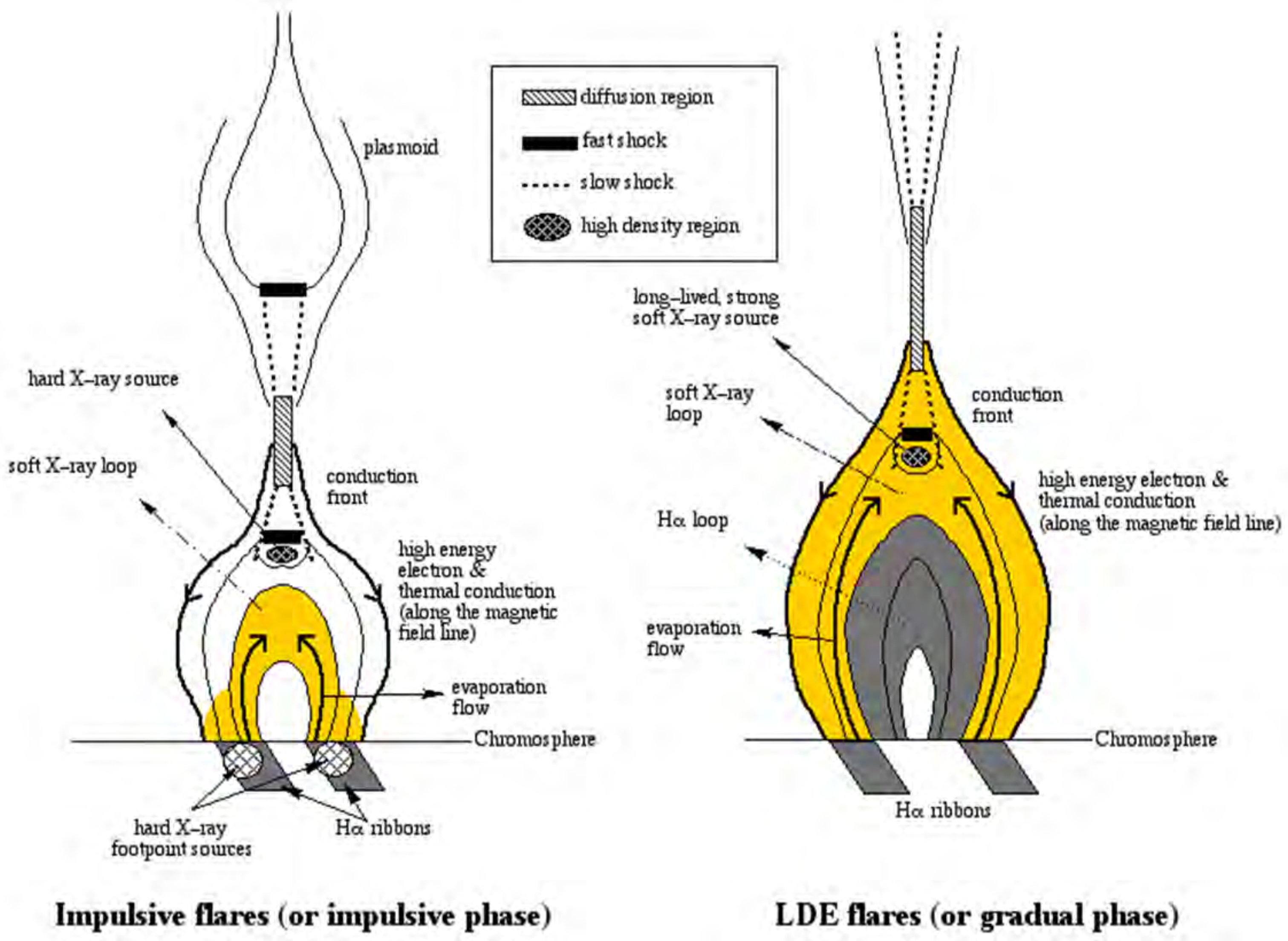
Flare models: What distinguishes the different flare models are mainly the initial magnetic topologies, which are prone to specific instabilities or drivers.

The most widely accepted standard model for flares is the **2D magnetic reconnection** model that evolved from the concepts of Carmichael (1964), Sturrock (1966), Hirayama (1974), Kopp & Pneuman (1976), called the **CSHKP** model according to the initials of these five authors.

The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model

- **C**armichael, H. 1964, in AAS-NASA Symposium on Solar Flares, ed. W. N. Hess (NASA SP-50), 451
- **S**turrock, P. A. 1966, Nature, **211**, 695
- **H**irayama, T. 1974, Sol. Phys., **34**, 323
- **K**opp, R. A., & **P**neuman, G. W. 1976, Sol. Phys., **50**, 85

The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (I)

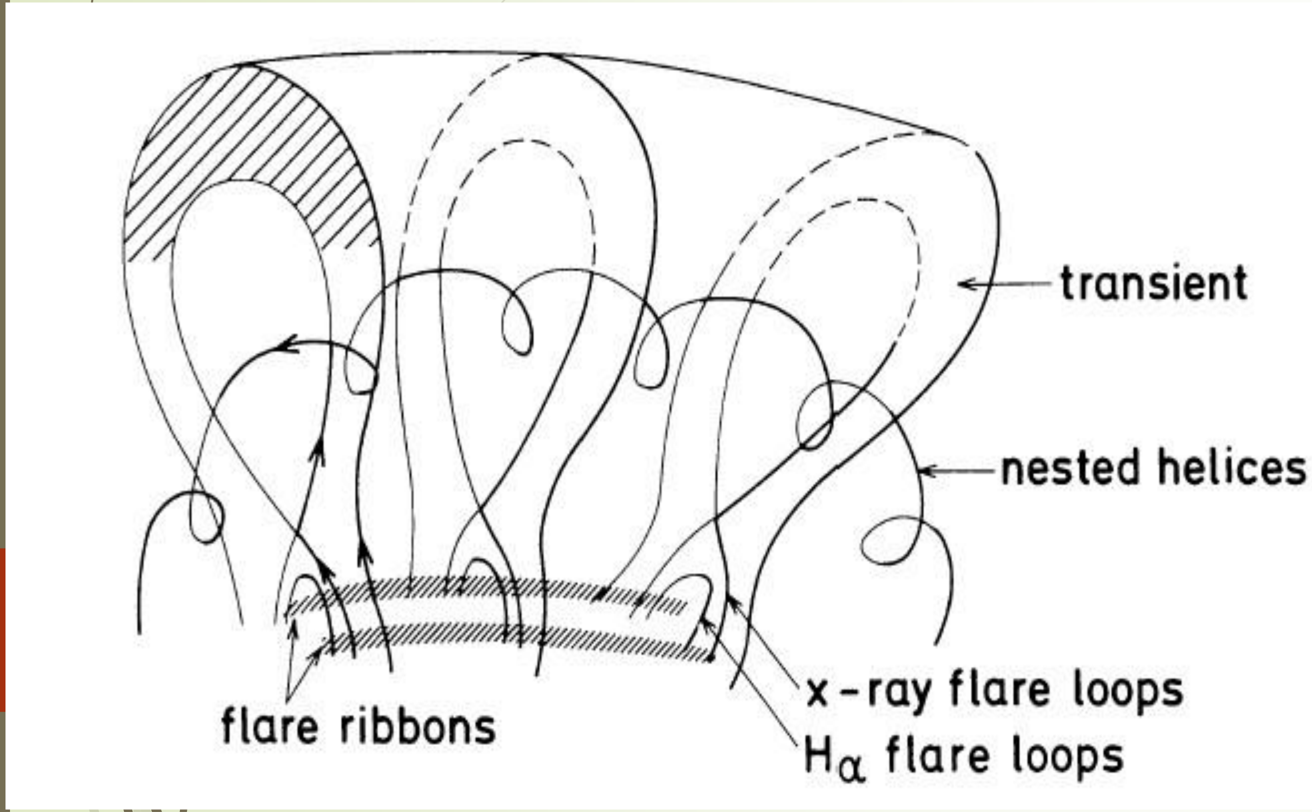


The initial **driver** of the flare process is a **rising prominence** above the neutral line in a flare-prone active region. The rising filament stretches a current sheet above the neutral line, which is **prone to reconnection**.

The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (II)

The **X-type reconnection** region is assumed to be the location of **major magnetic energy dissipation**, which heats the local coronal plasma and accelerates nonthermal particles. These two processes produce **thermal conduction fronts** and **precipitating particles** which both heat the Chromospheric foot points of the newly reconnected field lines. As a result of this impulsive heating, Chromospheric plasma **evaporates** (or **ablates**) and fills the newly reconnected field lines with over dense heated plasma, which produces **soft X-ray-emitting flare loops** with temperatures of $\mathbf{T_e \approx 10-40}$ **MK** and densities of $\mathbf{n_e \approx 10^{10} - 10^{12}}$ cm^{-3} . Once the flare loops cool down by thermal conduction and radiative loss, they also become detectable in EUV ($T_e \approx 1-2$ MK) and H_α ($T_e \approx 10^4 - 10^5$ K). Kopp & Pneuman (1976) refined this scenario further and predicted a continuous rise of the reconnection point, due to the rising prominence.

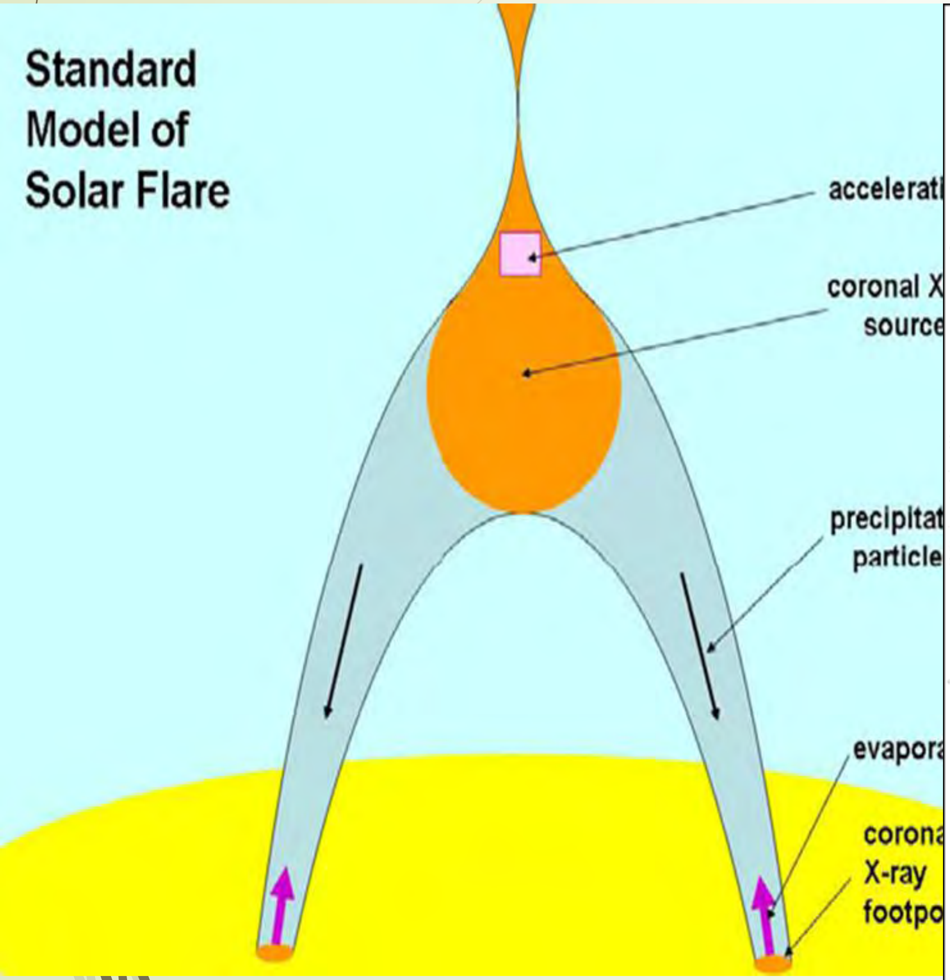
The Carmichael, Sturrock, Hirayama, Kopp, R. A., & Pneuman (CSHKP) flare model (III)

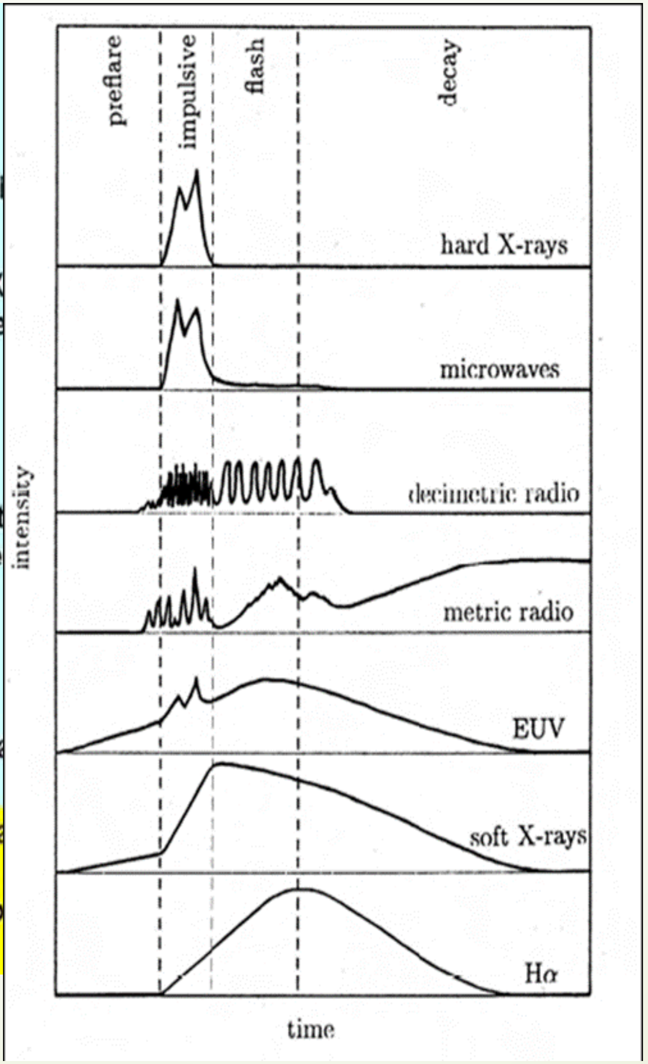


Anzer, U. and G. W. Pneuman, *Magnetic Reconnection and Coronal Transients*, Sol. Phys., **79**, 129-147 (1982)

The **CSHKP** model is essentially a 2D model that describes the evolution in a vertical plane. In the third dimension (along the neutral line) can be independently repeated for multiple flare loops (foot points extend to a **double ribbon**). Probably the extension in the third dimension is not continuous (as a giant 2D current sheet), but highly fragmented into magnetic islands (due to tearing-mode and coalescence instabilities, see the reconnection presentation).

The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (IV)

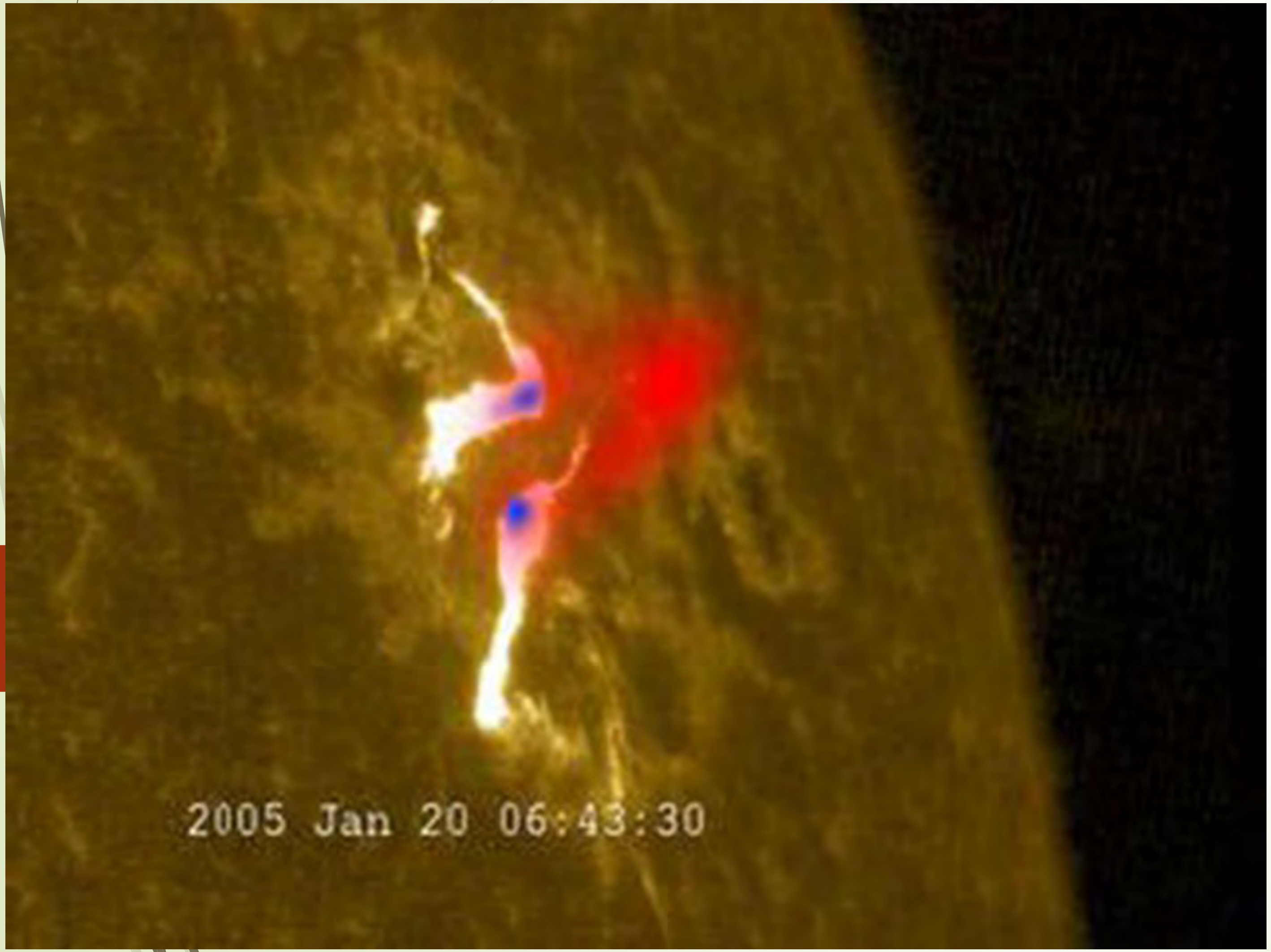




Standard flare scenario of Energy release at high altitudes. In a large event, the **pre flare phase** typically lasts **a few minutes**, the **impulsive phase 3 -10 minutes**, the **flash phase 5 - 20 minutes**, and the **decay one to several hours.**

Arnold O. Benz, "*Flare Observations*", Living Rev. Solar Phys., **5**, (2008), 1.

The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (V)



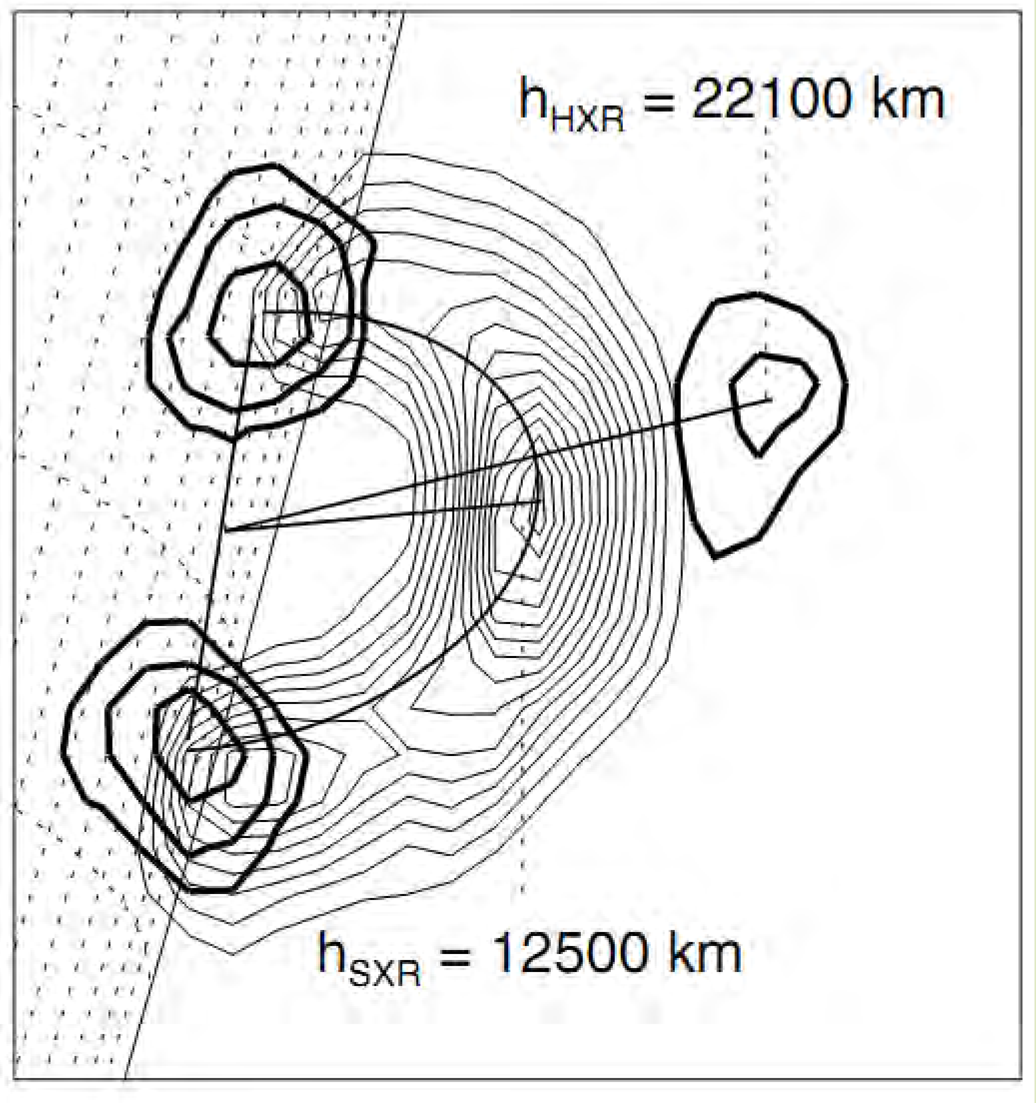
RHESSI flare observations of **soft X-rays** (red, **8-12 keV**) and **hard X-rays** (blue, **20-50 keV**) overlaid **on** an **H_α background**.

Arnold O. Benz, "*Flare Observations*", Living Rev. Solar Phys., **5**, (2008), 1.

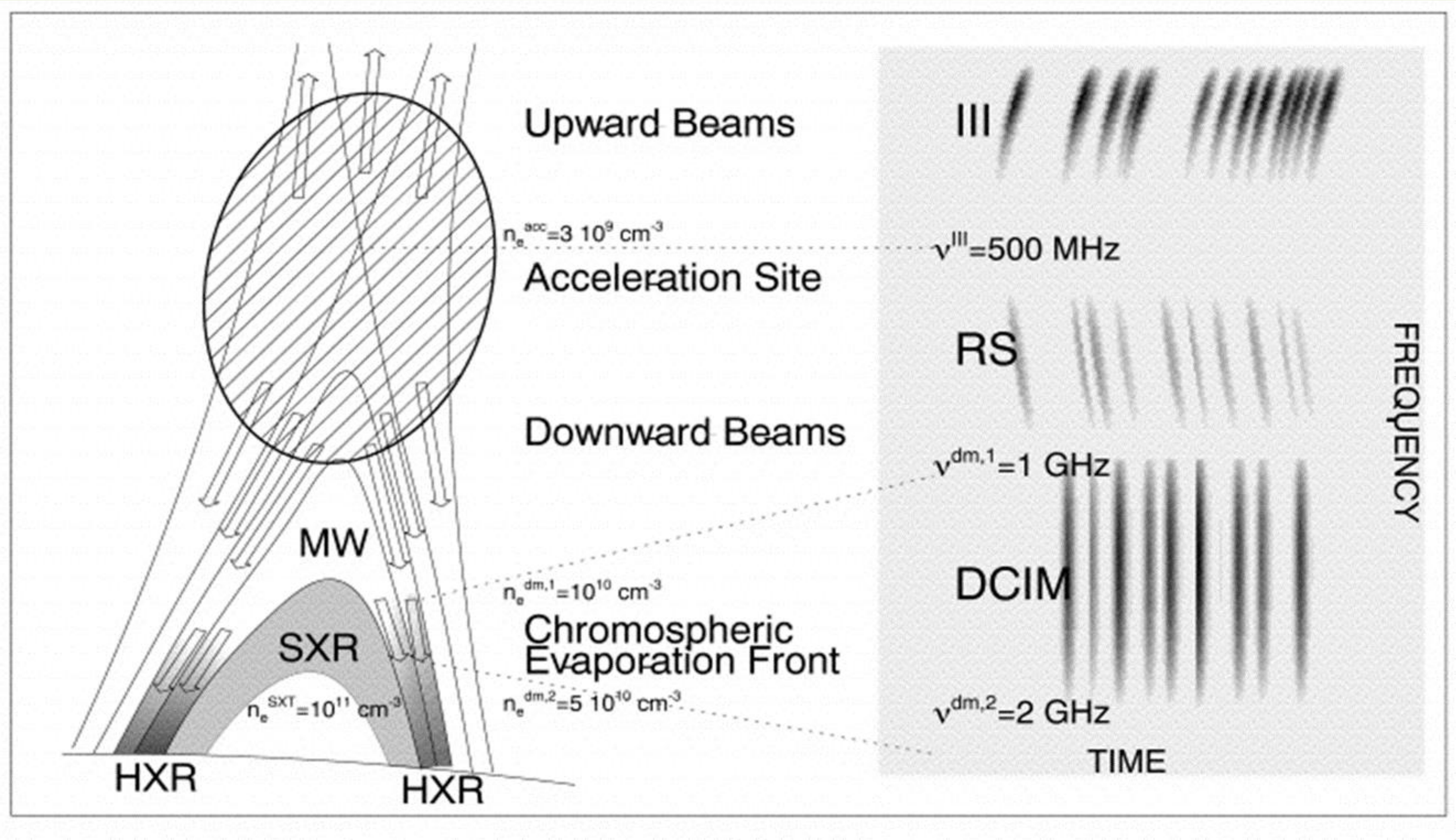
The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (VI)

A Yohkoh/HXT 23-33 keV image (thick contours) and Be119 SXT image (thin contours) of the 92-Jan-13, 17:28 UT flare.

Temporary trapping in a cusp region below the reconnection point can explain the coronal HXR emission

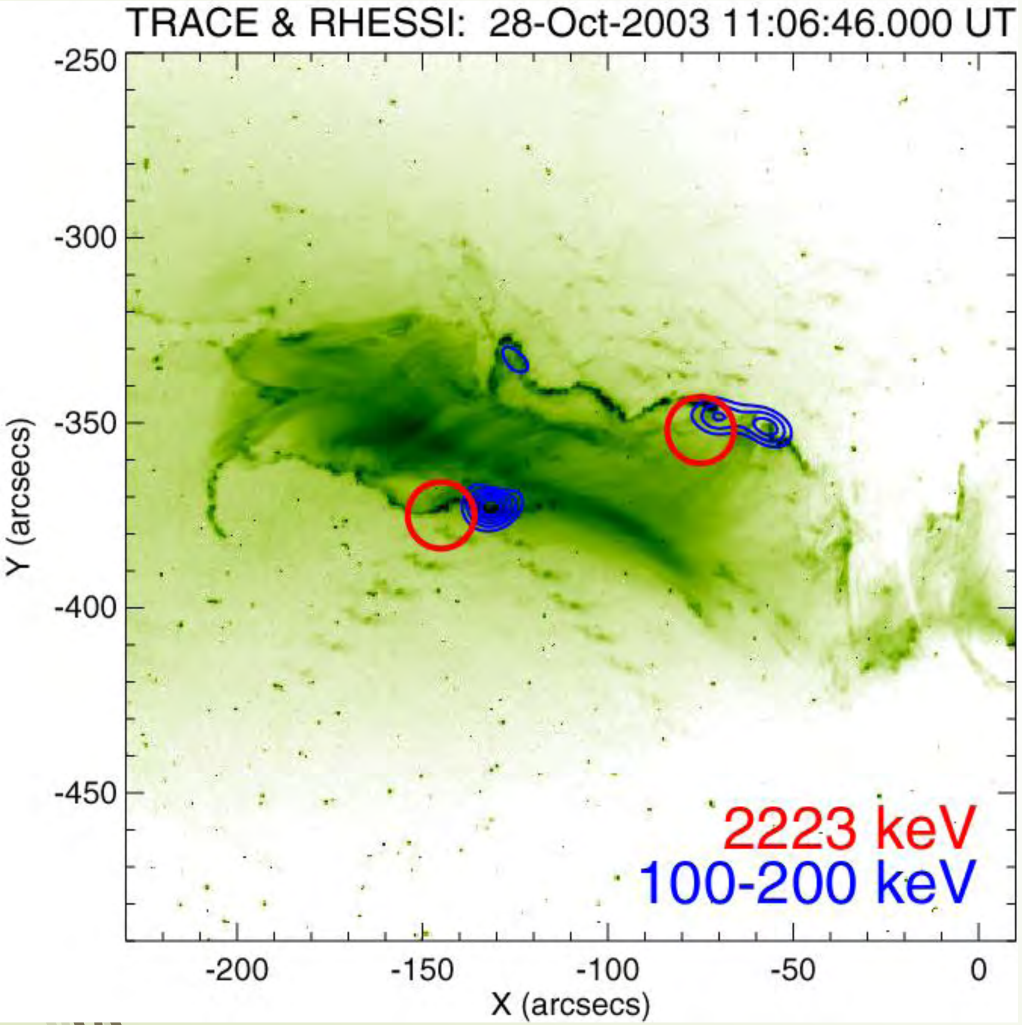


The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (VII): Location of particle acceleration



"Electron Densities in Solar Flare Loops, Chromospheric Evaporation Up flows, and Acceleration Sites," Aschwanden M. J., and Benz, A. O., Ap. J. **480**, 825 (1997)

The **C**armichael, **S**turrock, **H**irayama, **K**opp, R. A., & **P**neuman (**CSHKP**) flare model (VIII): Location of particle acceleration



HXR image (electrons) is snapshot at 11:06:46 UT

HXR ribbons are moving 2.2 MeV is produced ~100 s delayed
2.2 MeV image (protons) is averaged over 15 minutes different spatial resolution Electrons ~2″, 2223 keV: ~30″

CONCLUSIONS:
1) Electrons and protons both close to ribbons
2) difference <15″ (~10^4 km)
3) e and p are accelerated in loops of similar size

The Neupert effect: Neupert, noted that in the rise phase of the **soft X-rays their flux** corresponds to the **time integral** of the **centimeter radio flux** since the start of the flare (t_o). As the centimeter flare emission is emitted by relativistic electrons, it is not surprising that the **same correlation** was later also found between the **soft X-ray flux** (F_{SXR}) and the cumulative **time integral of the hard X-ray flux** (F_{SXR}) :

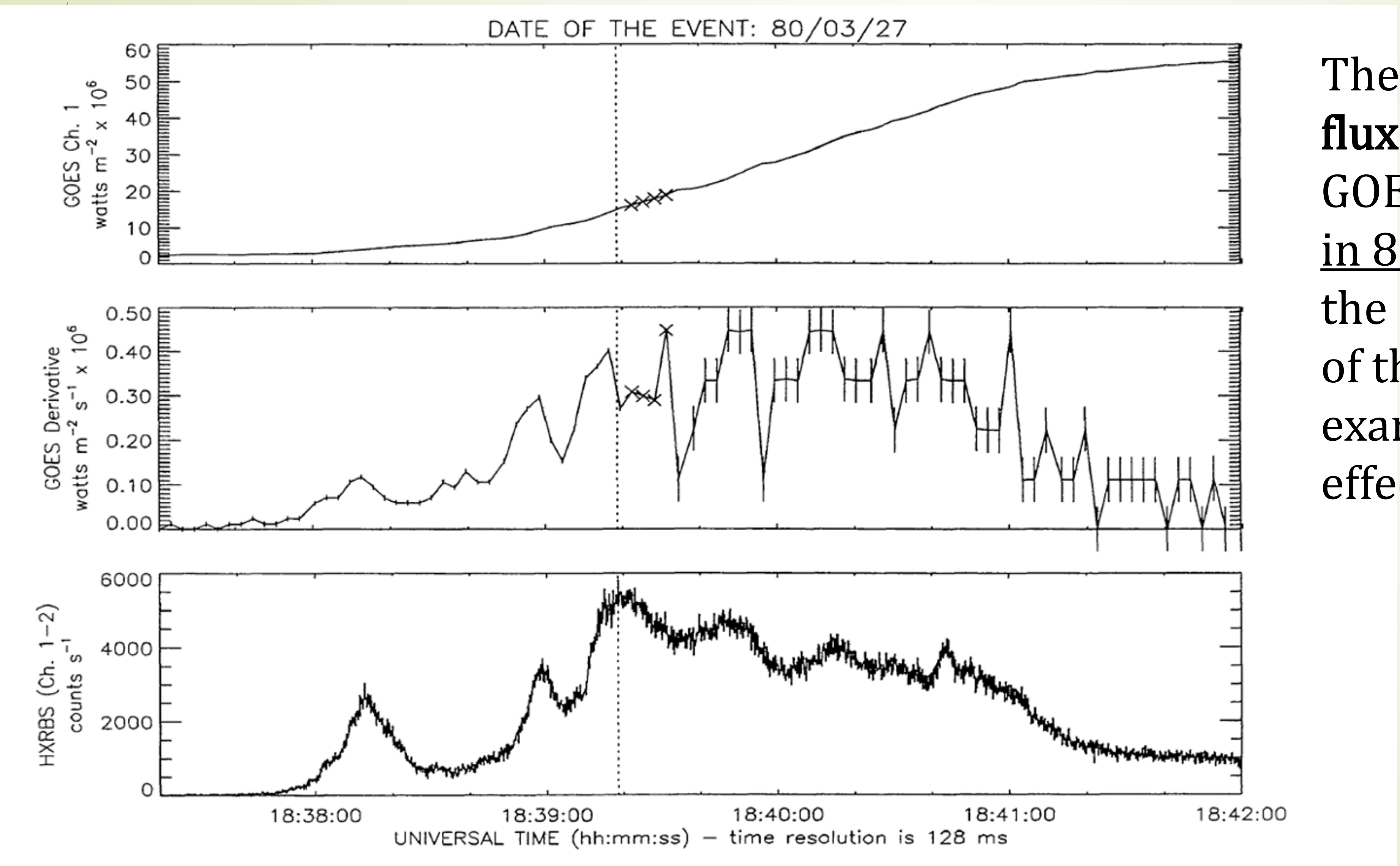
$$F_{SXR}(t) \propto \int_{t_o}^{t} F_{HXR}(t)dt \Leftrightarrow \frac{d}{dt}F_{SXR}(t) \propto F_{HXR}(t)$$

This empirical relationship is called the "***Neupert effect***". Examples are presented in the following Slides.

Neupert suggested that there may be a **direct causal relation** between the **energetic electrons** and the **thermal plasma**: the soft X-rays may originate from a plasma heated by the accumulated energy deposited through flare accelerated electrons. It should be remarked here that the Equation is only an approximation and that the correspondence with theory **works only if cooling** (by conduction or radiation) **is negligible**.

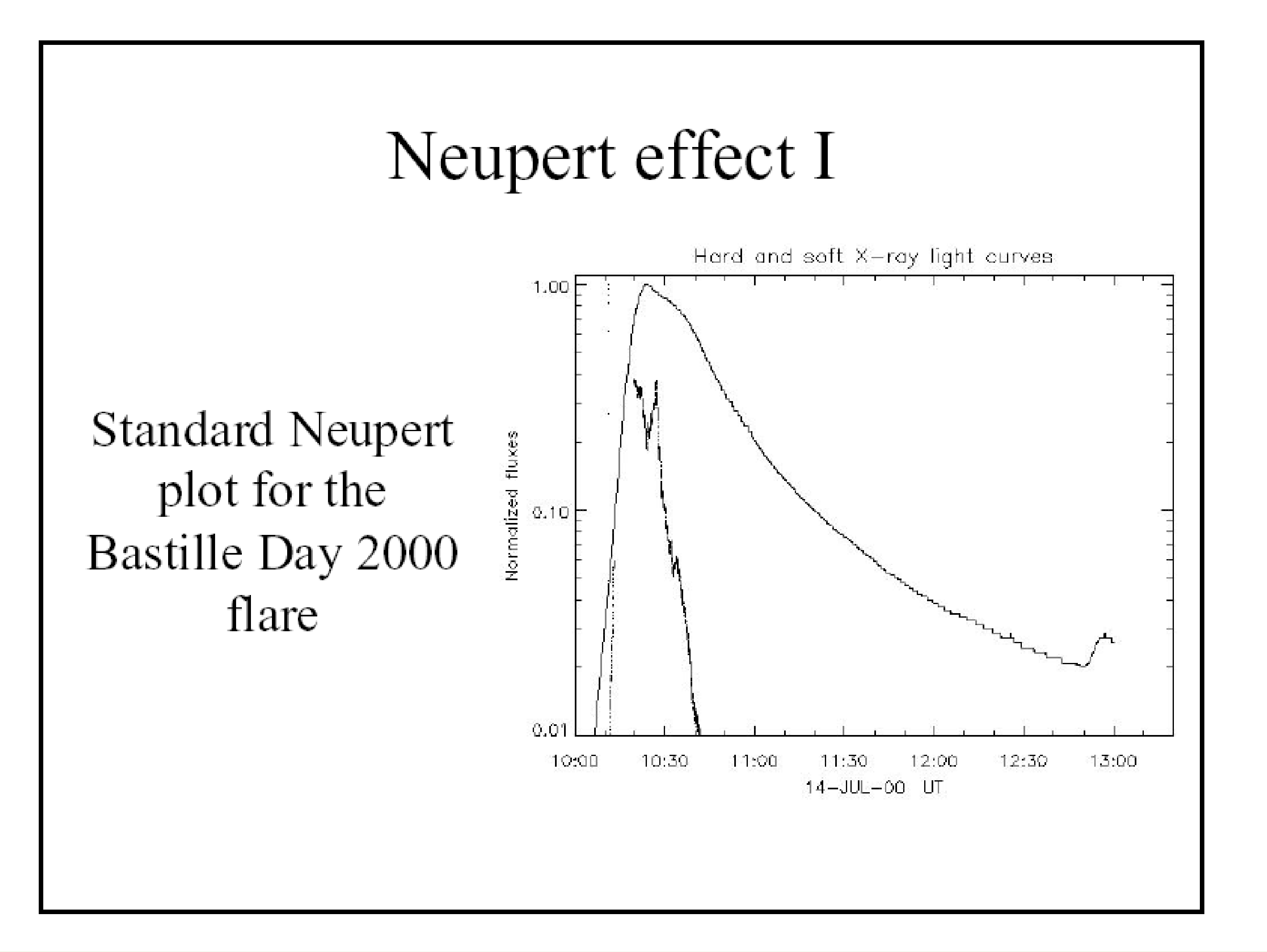
Neupert, W.M., 1968, "*Comparison of Solar X-Ray Line Emission with Microwave Emission during Flares*", Astrophys. J. Lett., L59 also Benz (2008).

Neupert effect: $\frac{d}{dt} F_{SXR} \propto F_{HXR}$

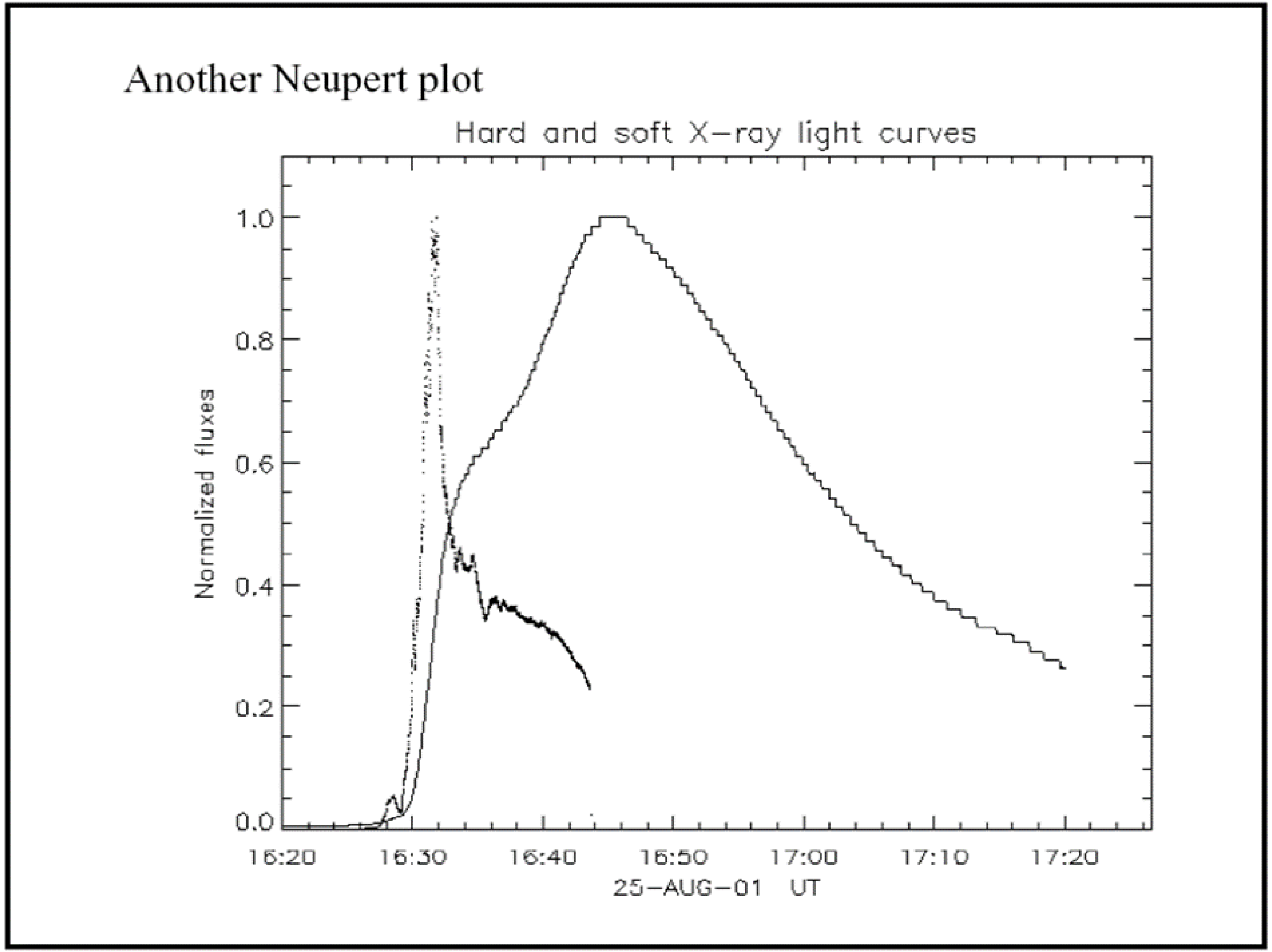


The **derivative** of the **SXR flux** (observation by the GOES satellite) correlates in 80% of the flares with the **HXR flux** (observation of the RHESSI). This is an example of the Neupert effect

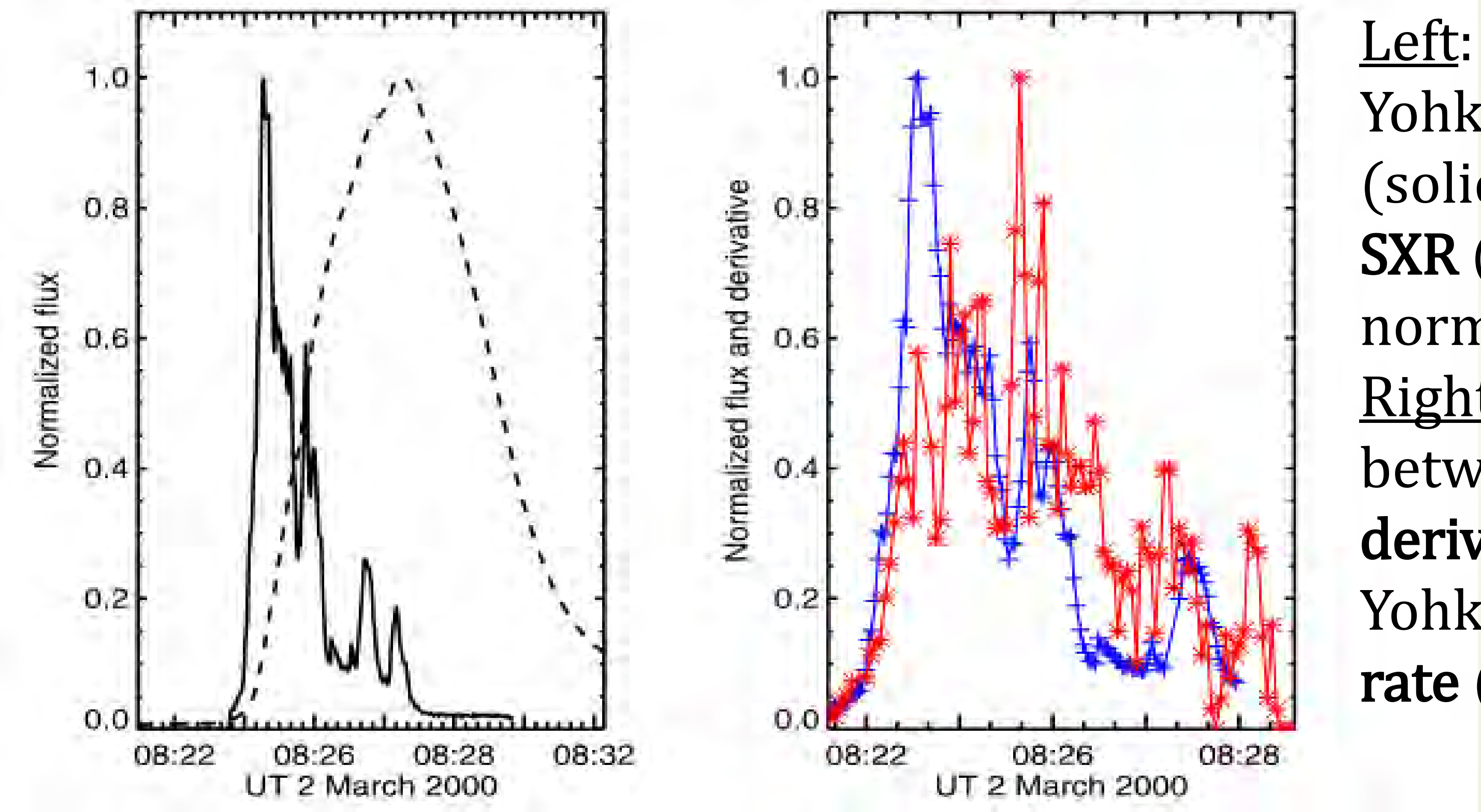
Neupert effect: $\frac{d}{dt} F_{SXR} \propto F_{HXR}$



Neupert effect: $\frac{d}{dt} F_{SXR} \propto F_{HXR}$



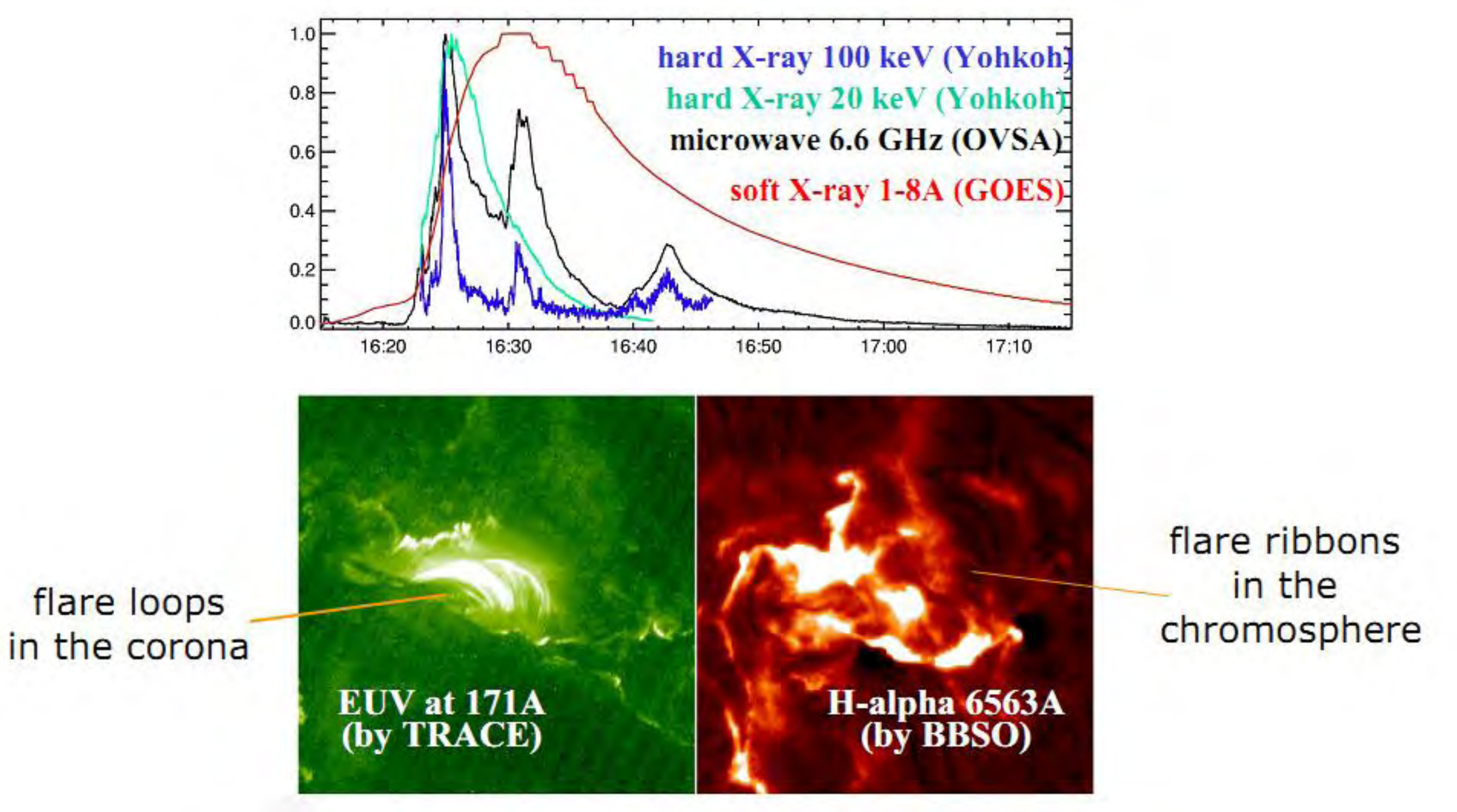
Neupert effect: $\frac{d}{dt} F_{SXR} \propto F_{HXR}$



Left: **HXR flux**, as observed Yohkoh/HXT in 33–53 keV (solid) and GOES 1–8 Å **SXR** (dashed), both normalized to peak values. Right: **Comparison** between the **GOES derivative** (red) and the Yohkoh/HXT **HXR count rate** (blue)

Hugh S. Hudson «Global Properties of Solar Flares» Space Sci Rev (2011) **158**: 5-41

A large flare observed in different wavelengths



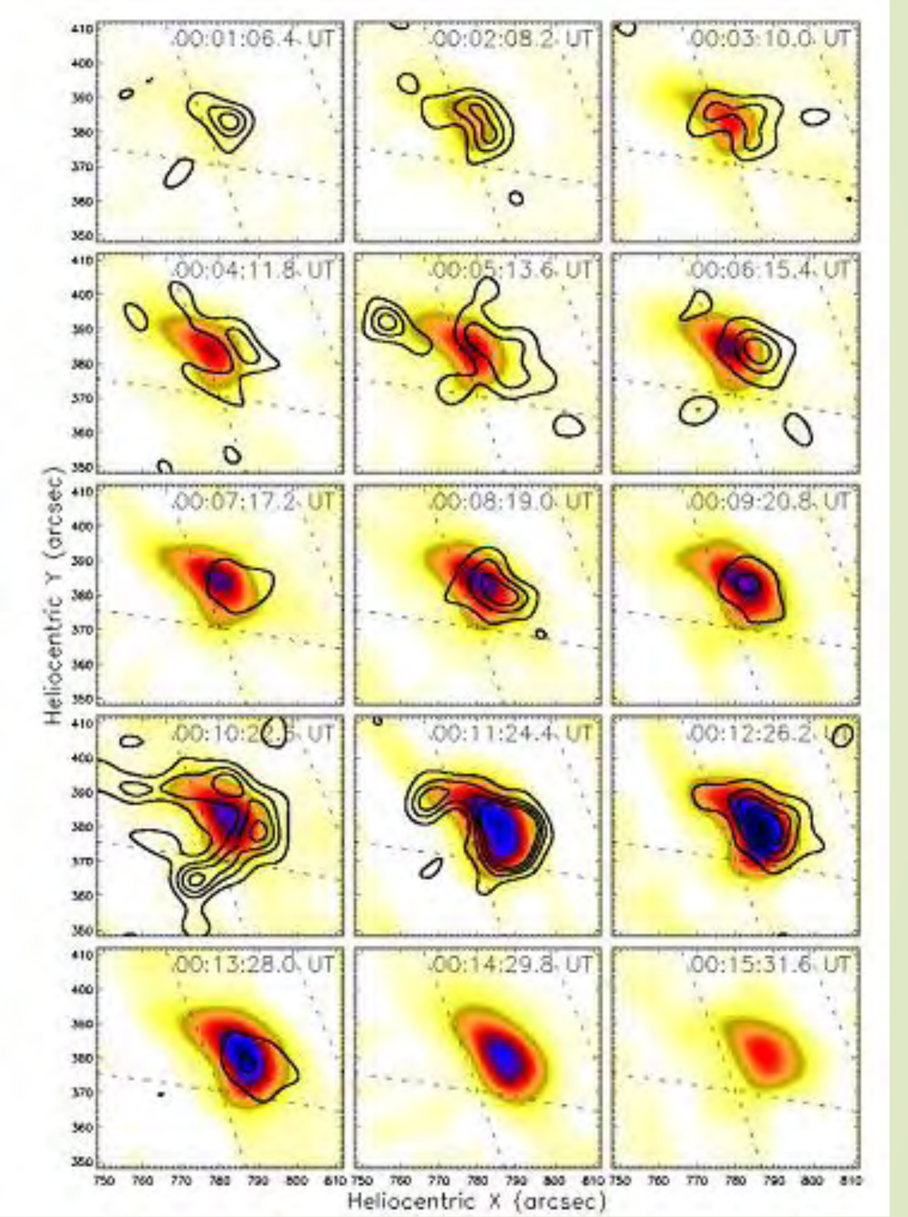
Standard flare model

(see Arnold O. Benz, "*Flare Observations*", Living Rev. Solar Phys., **5**, (2008), 1.)

- **Correlation** of **soft X-ray** flux with **cumulative hard X-ray** flux (*Neupert effect*)
- **Hard X-rays** (> 25 keV) often **originate** from sources **at the foot points** of the loop emitting soft X-rays.
- The **coronal hard X-ray** source, where reconnection releases energy, is occasionally observed to be **above the soft X-ray loop**, into which energy was release before and which is still emitting soft X-rays
- The **energy in accelerated electrons** tends to be **larger than** the **thermal energy** contained in the soft X-ray source.
- The **hard X-ray** spectrum of non-thermal electrons in the **coronal source** is considerably **softer than in the foot points**, suggesting that the latter is a thick target.
- The **emission measure of the soft X-ray** source greatly **increases** during the impulsive phase, indicating that Chromospheric **material is evaporating** during this period.

Deviations from standard flare scenario (I)

A variant of the standard model has been proposed for flares without foot points . The flare loop has been found so dense that accelerated electrons have collisions already in the corona and lose a large fraction of their energy to the flare loop. A preceding flare at the same location may have produced the high density of the loop.



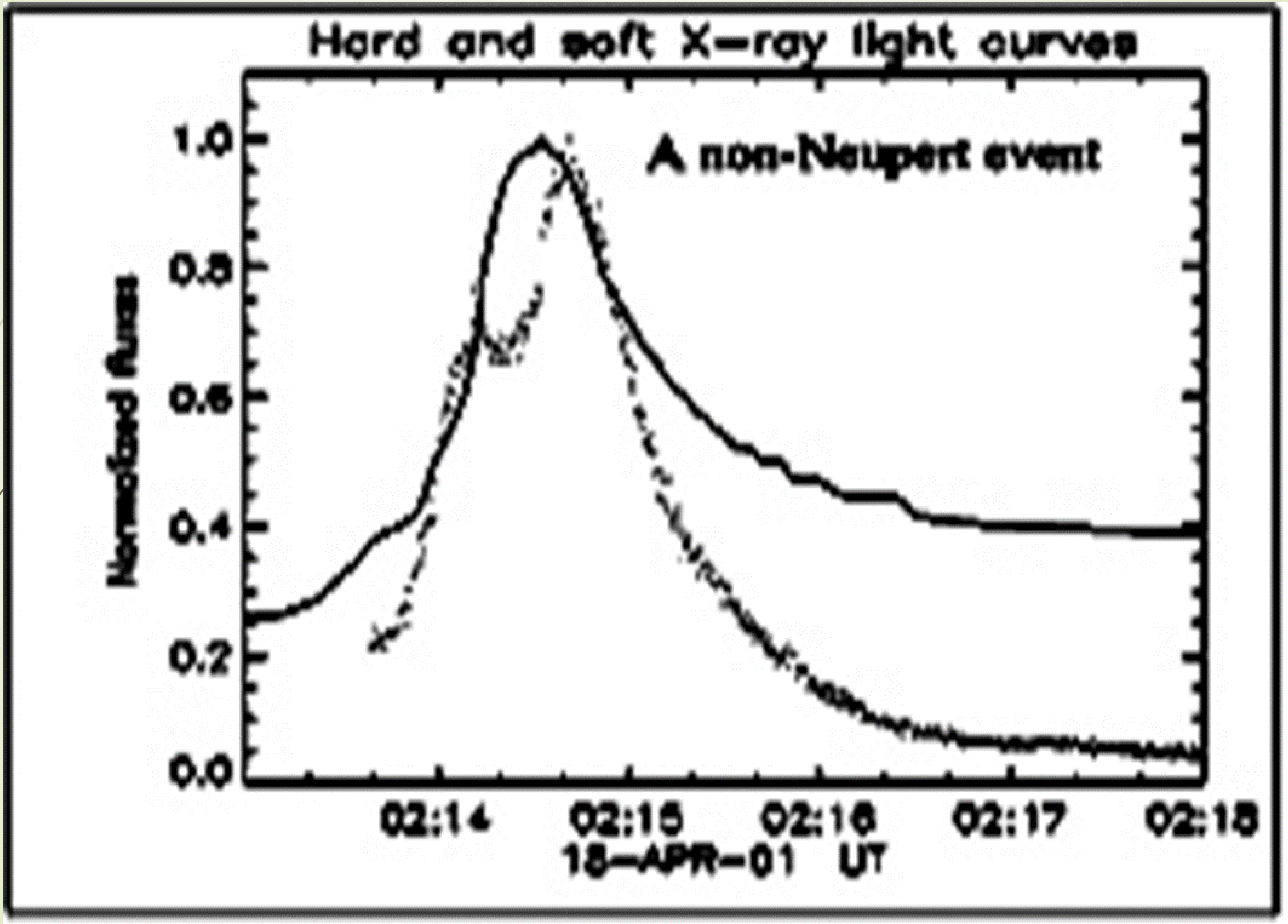
RHESSI observations at 6–12 keV (colors) and 25–50 keV (contours) of a coronal flare. The high-energy photons have a non-thermal origin and originate near the loop-top without pronounced foot points.

Deviations from standard flare scenario (II)

In about half of the HXR events, the Neupert behavior is violated in terms of relative timing between soft and hard X-ray. This is quite obvious in flares with SXR preceding the HXR emission.

An alternative to the standard scenario is that the soft X-ray emitting plasma is not heated exclusively by high-energy electrons; some coronal particles get so little energy during flare energy release that they have frequent enough collisions to approximately retain their Maxwellian velocity distribution. Thus their energization corresponds to heating. In a pre flare, the heat of the coronal source may reach the chromosphere by thermal conduction.

Arnold O. Benz, "*Flare Observations*", Living Rev. Solar Phys., **5**, (2008), 1.
Veronig, A.M., Brown, J.C., 2004, "*A Coronal Thick-Target Interpretation of Two Hard X-Ray Loop Events*", Ap. J. Lett., **603**, L117–L120.
Veronig, A., Vrsnak, B., Dennis, B.R., Temmer, M., Hanslmeier, A., Magdalenic, J., 2002, "*Investigation of the Neupert effect in solar flares. I. Statistical properties and the evaporation model*", A&A., **392**, 699–712.



Hard and soft X-ray light curves
A non-Neupert event
Normalized flux
1.0
0.8
0.6
0.4
0.2
0.0
02:14
02:15
02:16
02:17
02:18
18-APR-01 UT

The Emerging Flux Model (I)

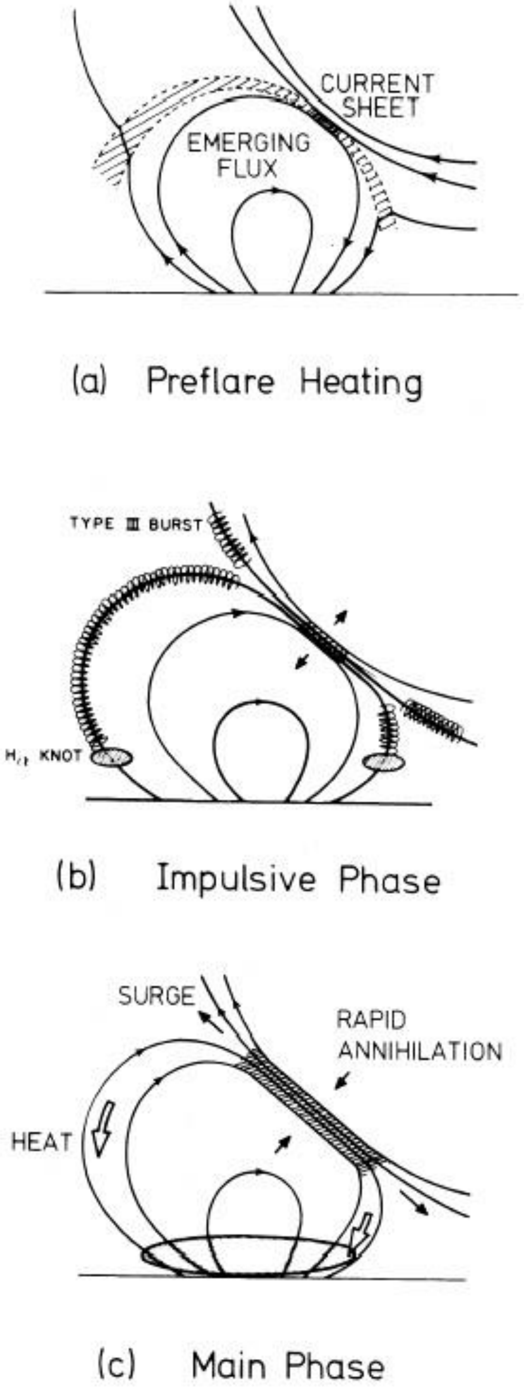
While the driver is a rising filament/prominence in the CSHKP model, the process of flux emergence has been considered as a driver too. This model consists of three phases:

(1) a **pre-flare heating** phase where a new magnetic flux emerges beneath the flare filament and continuously reconnects and heats the current sheet between the old and new flux.

(2) The **impulsive phase** starts when the heated current sheet loses equilibrium at a critical height and turbulent electrical resistivity causes the current sheet rapidly to expand, accelerating particles and triggering Chromospheric evaporation.

(3) The **main phase** where the current sheet reaches a new steady state with marginal reconnection.

However, numerical simulations indicate that the current sheets reconnect almost as quickly as they are formed; it is therefore believed that this model can only apply to small flares.

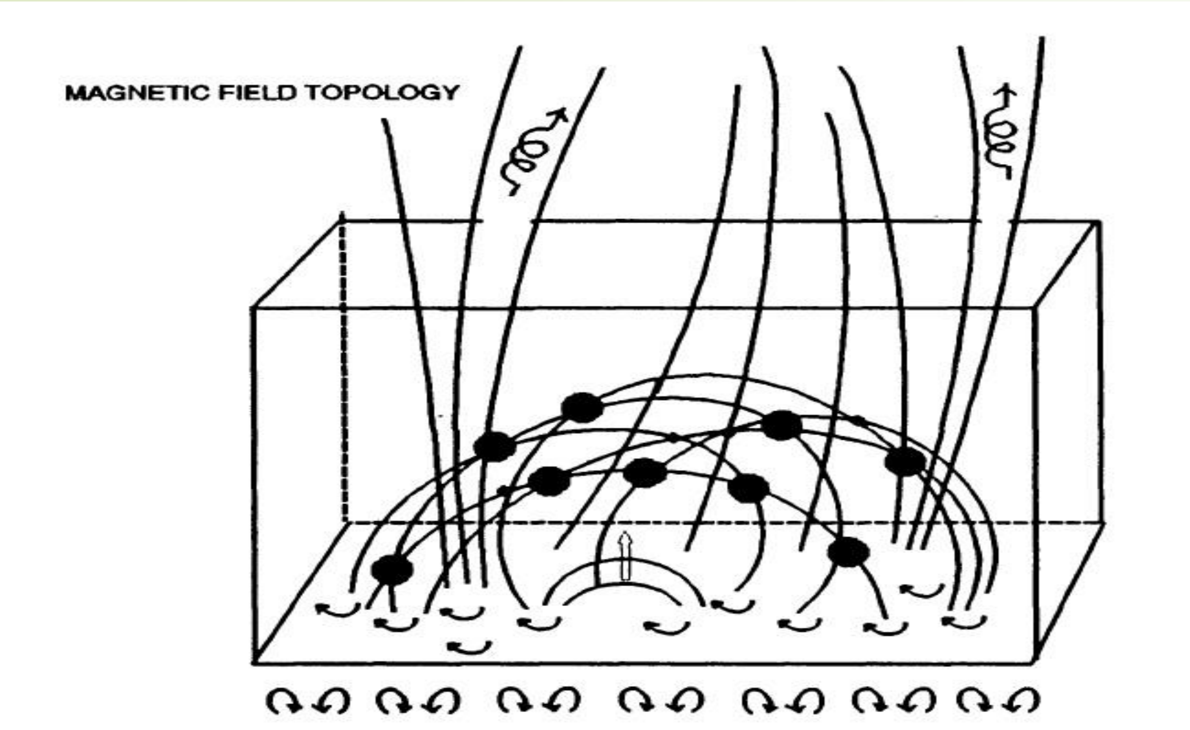


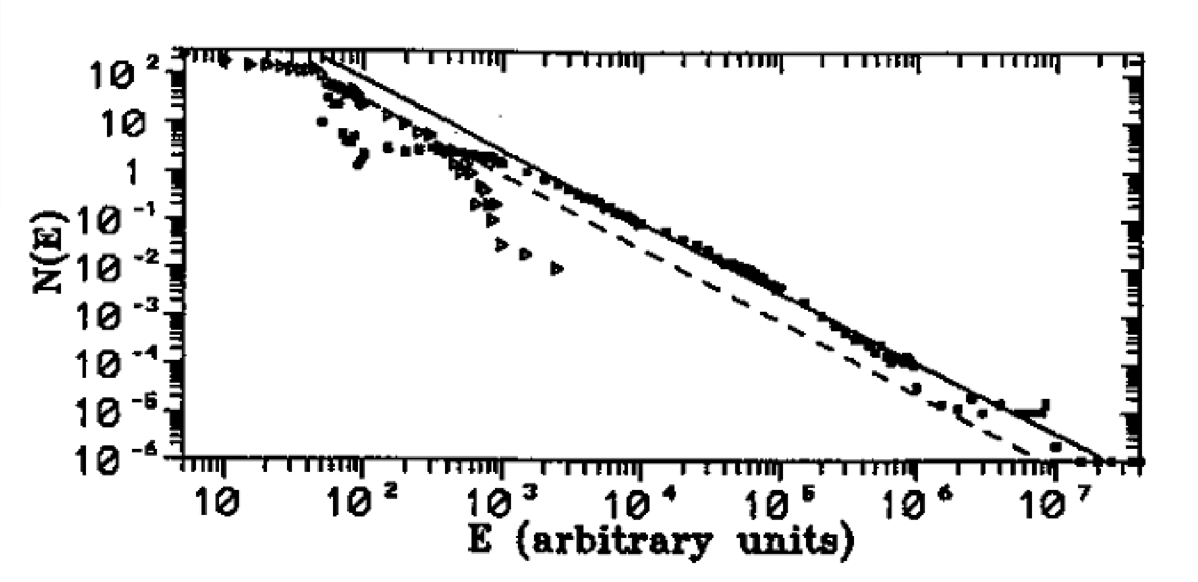
The Emerging Flux Model (II)

The **emerging flux mechanism** for a simple loop flare: (a) **Preflare phase**. The emerging flux reconnects with the overlying field; shock waves (dashed) radiate from a small current sheet and heat the plasma as it passes through them into the shaded region. (b), **Impulsive phase**. The onset of turbulence in the current sheet causes a rapid expansion. The resulting electric field accelerates particles, which escape along field lines and produce an **impulsive microwave burst** as they spiral. Those that move downward give rise to **HXR**, while those that escape upward on to open field lines produce **type Ill radio bursts**. (c), **Main phase**. The current sheet reaches *a* new steady state, with reconnection based on a marginally turbulent resistivity. It is much bigger than before, and both **heat** and **particles** are conducted down to the lower chromosphere where they **produce the Ha flare**.

Heyvaerts, J., E. R. Priest, and D. M. Rust. "*An emerging flux model for the solar flare phenomenon*." Ap. J **216** (1977): 123-137.

Fragmentation of energy release-Statistical Flare (I)

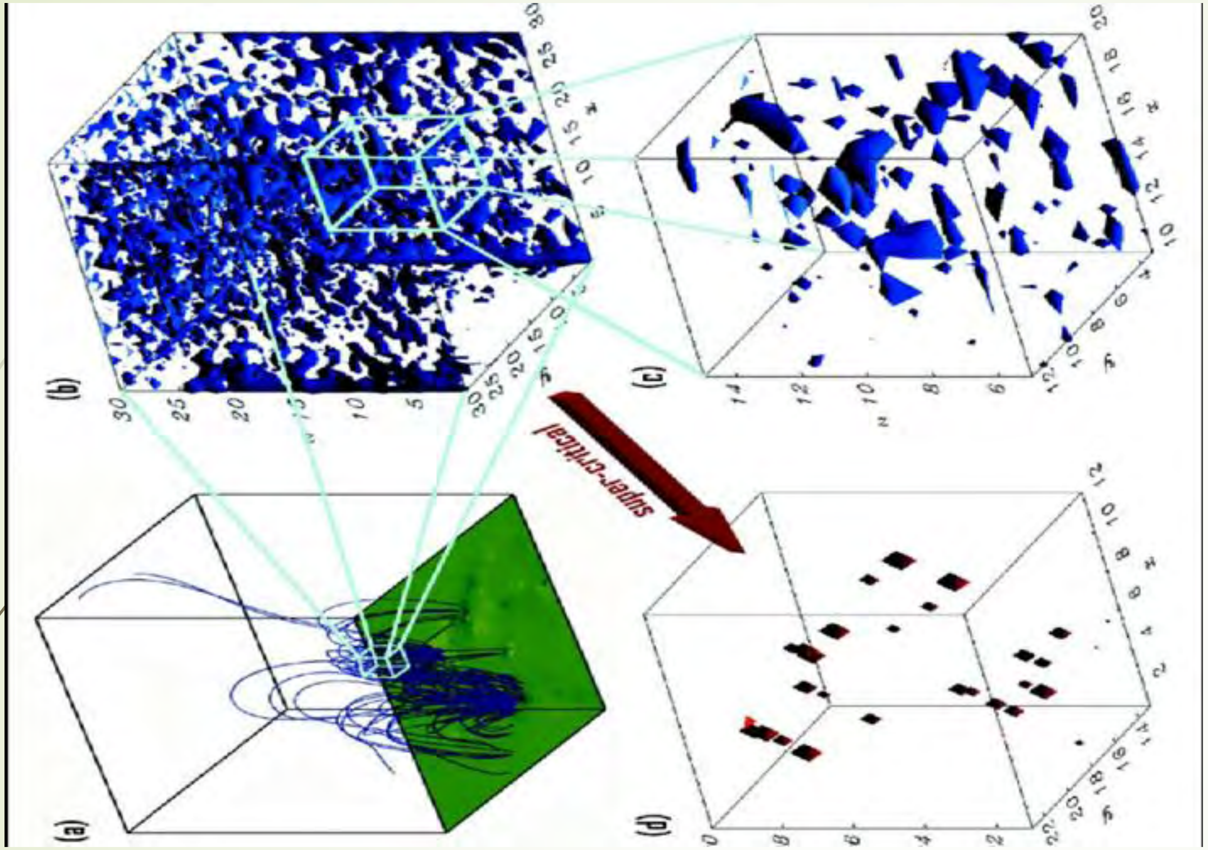


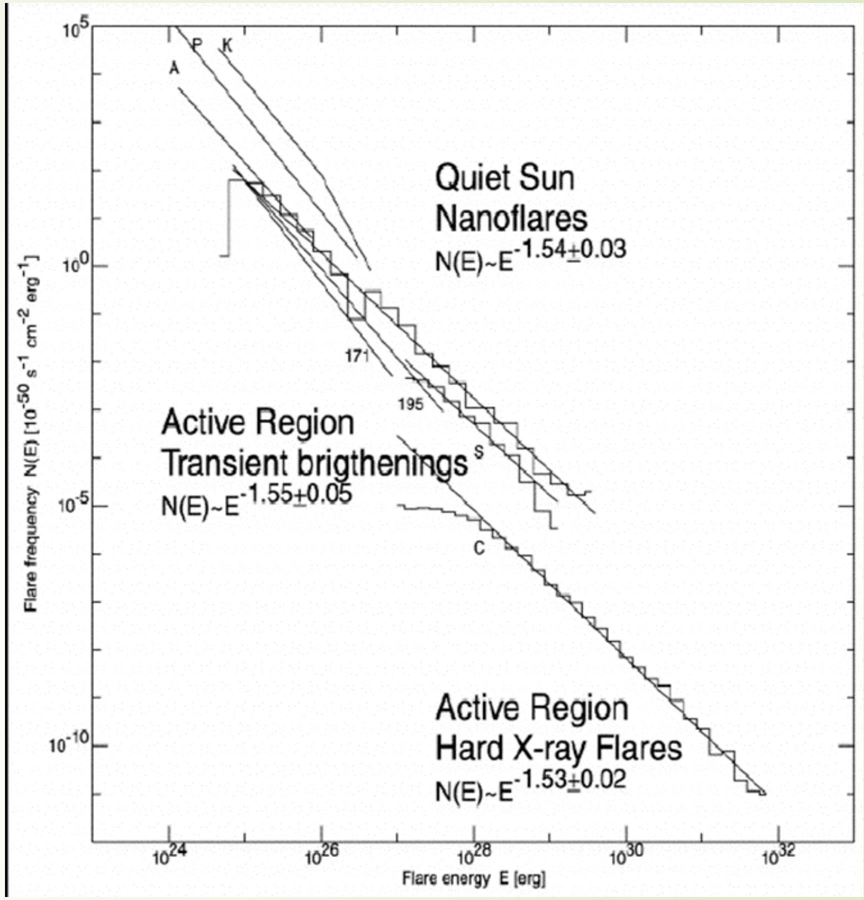


Left: **Magnetic topology** of the "***Statistical Flare***" of numerous interacting magnetic structures prone to **small scale reconnection** resulting in "**Flaring Elements**"; these **trigger neighbours** and "***cluster***" to a flare. Right: Distribution (*power law*) of released **energy of each flare** (as a "cluster" of "Flaring Elements").

Vlahos, L., "*Theory of fragmented energy release on the Sun,*" Space Sci. Rev. **68**, 39 (1994).

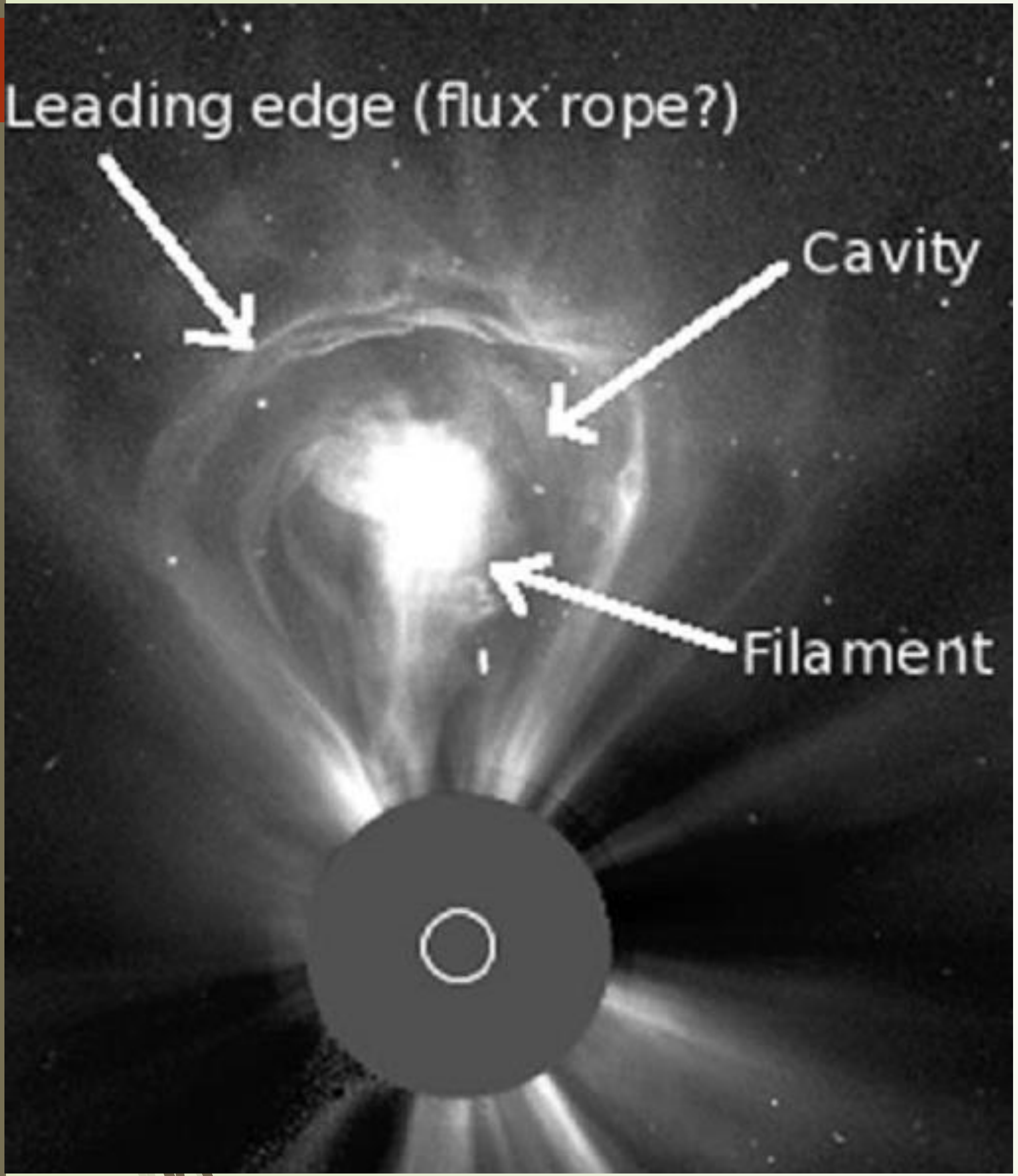
Fragmentation of energy release-Statistical Flare (II)





Left: Simulation of "**Flaring Elements**" which <u>**trigger neighbours**</u>. Right: <u>Energy distribution</u> (*power law*) of **Nano flares**, **transient brightenings**, **flares**. (Compare with the energy distribution from the Statistical Flare distribution in the previous slide).

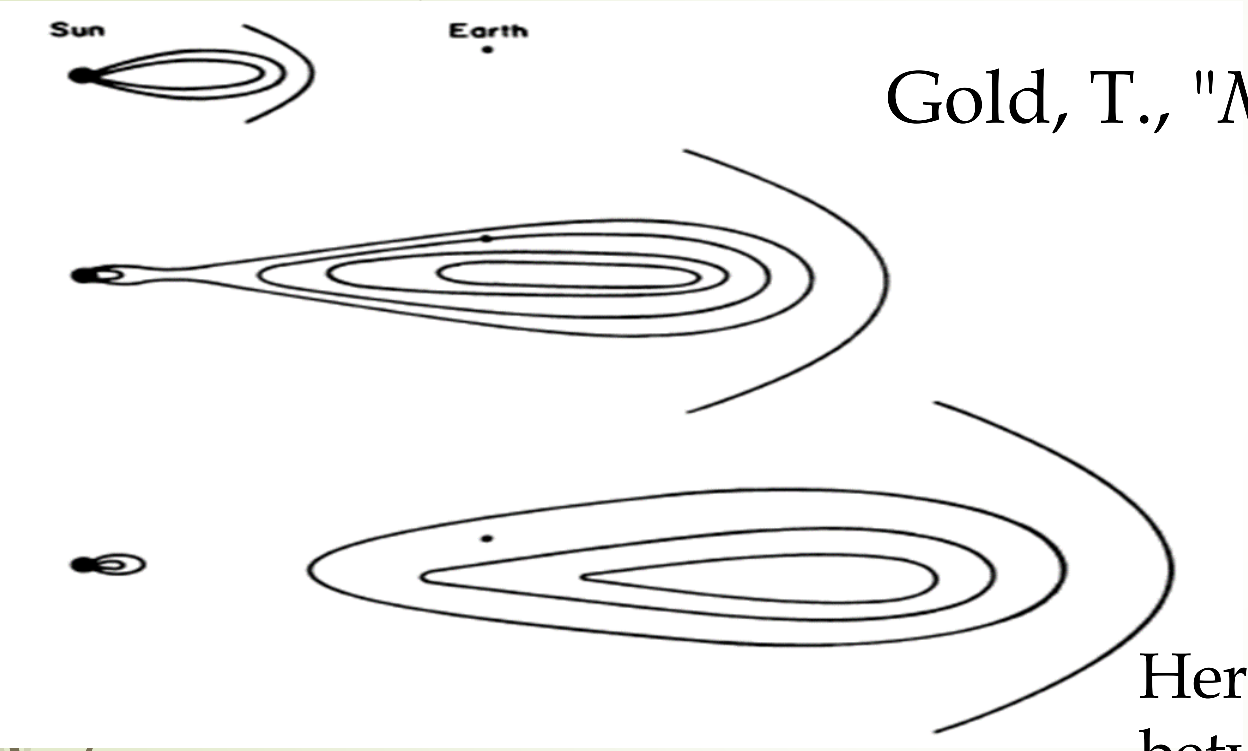
Coronal Mass Ejection (I)



A CME, or coronal mass ejection, is a large **eruption of plasma and magnetic field** from the Sun. It can contain a mass larger than 10^{13} kg and may achieve a speed of several thousand kilometres per second. A typical CME has a mass of ~ 10^{14}–10^{16} g and a speed ≈ 200-2,000 km/s. It typically spans several tens of degrees of heliographic latitude (and probably longitude).

Image of a "***classic***" three-part CME observed by the SOHO/LASCO coronagraph. The white circle represents the surface of the Sun while the grey disk is the occulter of the coronagraph.

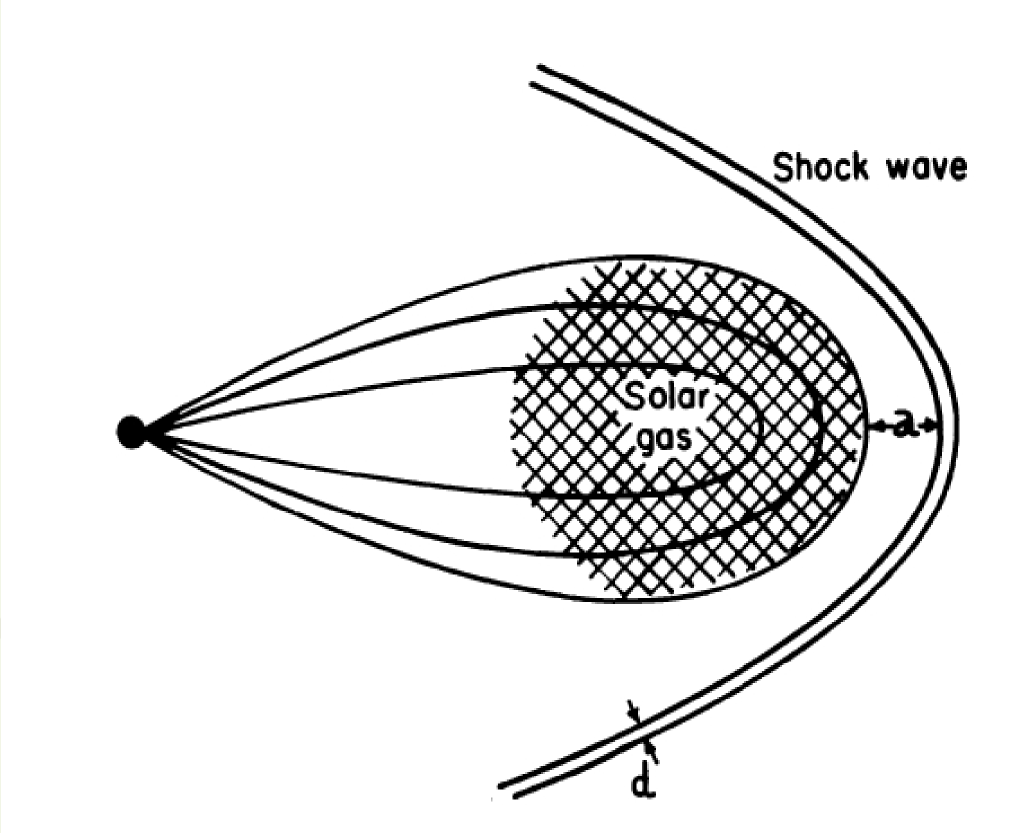
Coronal Mass Ejection (II)



Gold, T., "*Magnetic Storms*," SSR **1**, 100 (1962).

Here Gold pointed out the contradiction between the repeated occurrence of what we now call CMEs, and the then-known rough invariability of the interplanetary magnetic field.

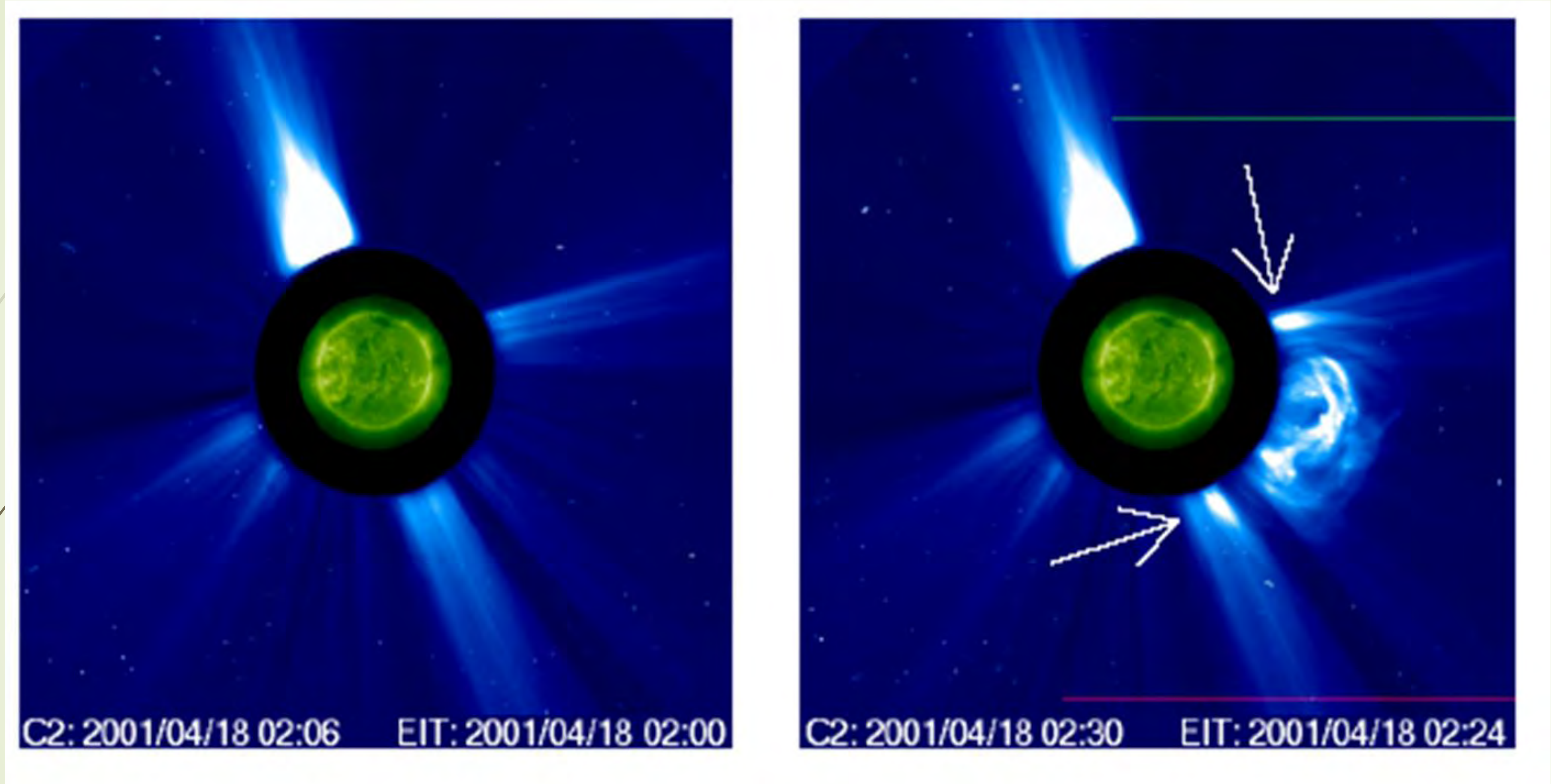
Coronal **M**ass **E**jection (III)



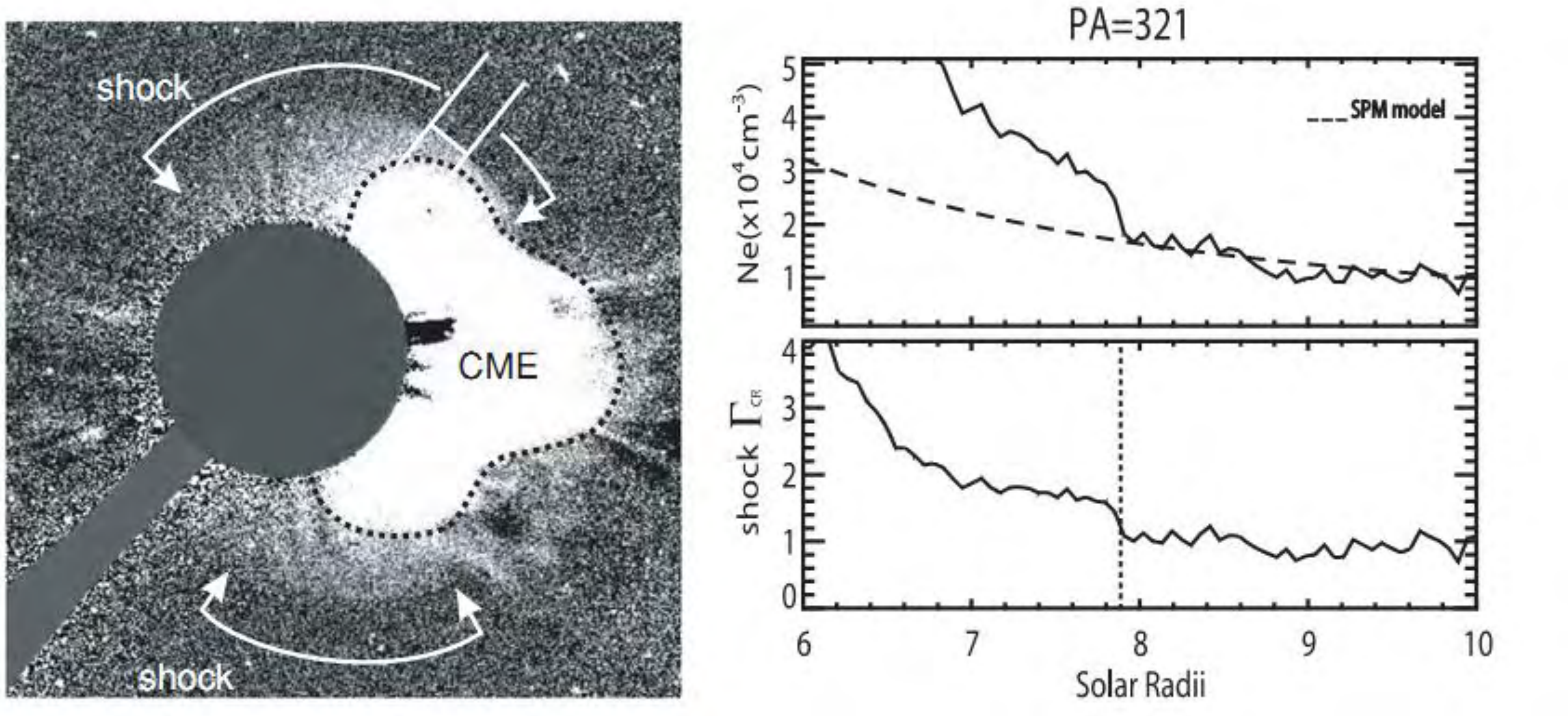
In this classic but little-cited paper, Gold described the basic physics of a plasma **cloud ejected** from the Sun and **interacting with the solar wind** on its way out, forming a **shock**. Nowadays we'd call "**Solar gas**" a **CME**.

Gold, T., "*Magnetic Storms*," SSR **1**, 100 (1962).

Coronal Mass Ejection (III)



SOHO/LASCO C2 & EIT CME Recording

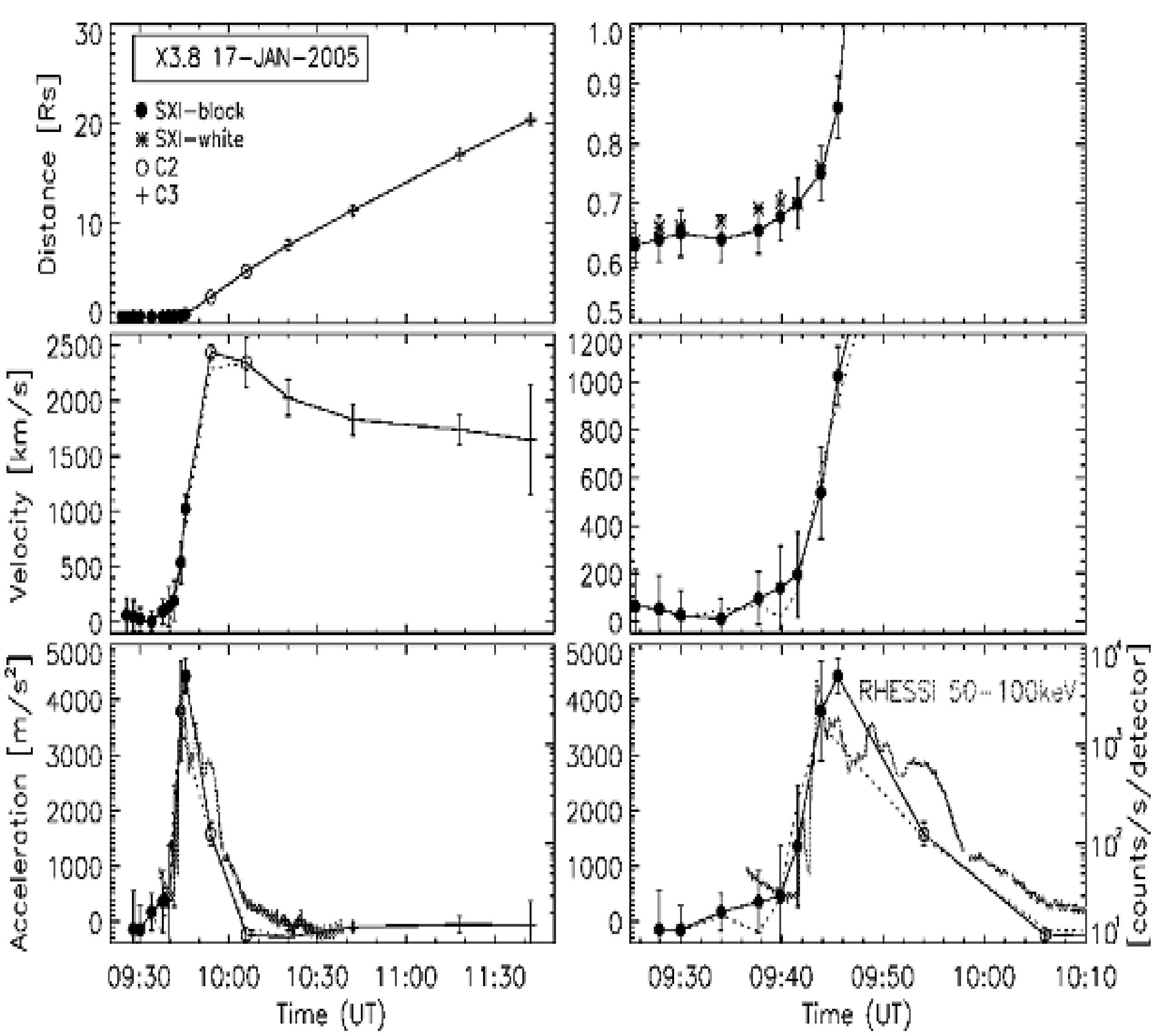


Left panel: selected image for the 1997 November 6 CME. A clear **shock signature** can be seen at the **flanks of the CME**. The parallel lines over the shock front show the profile with the strongest shock signature.

Right panel: the top plot shows the estimated upstream and down stream density profile at (position angle) **P.A. = 321º** (solid) and the background corona density from the Saito model (dashed). The bottom plot shows the density ratio, $\mathbf{\Gamma_{CR}}$ = 1.6, at 7.9 $R_\odot$ which we use as a proxy to the shock strength.

Coronal **M**ass **E**jection (IV)

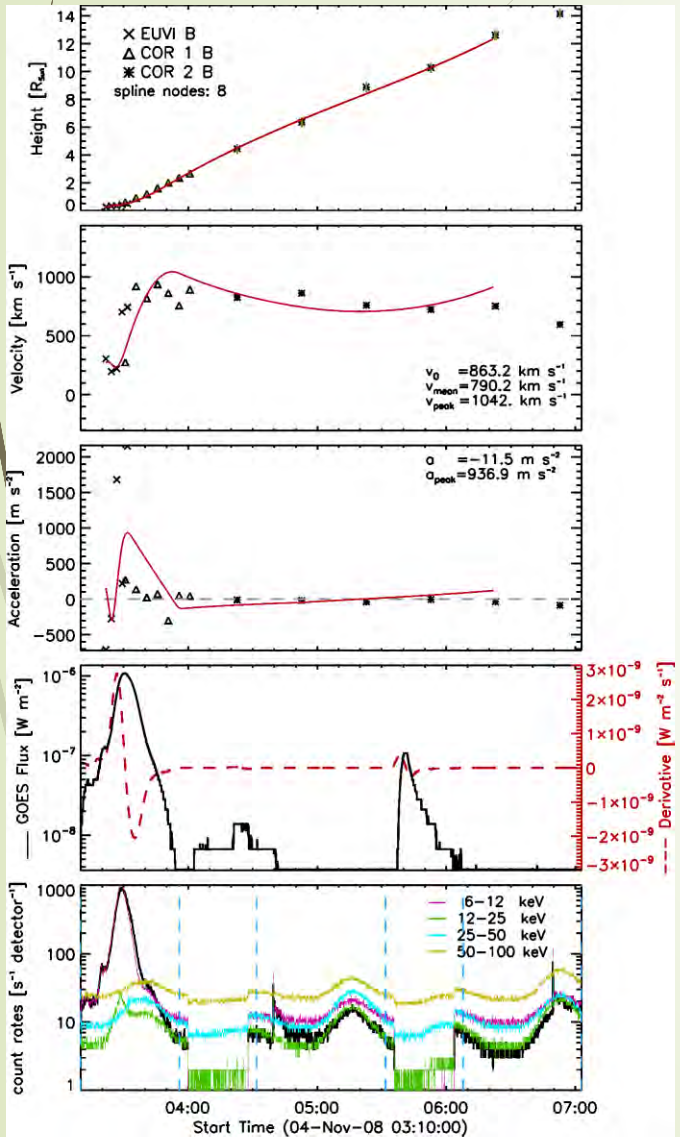
Relation between **CME dynamics** and **flare evolution**

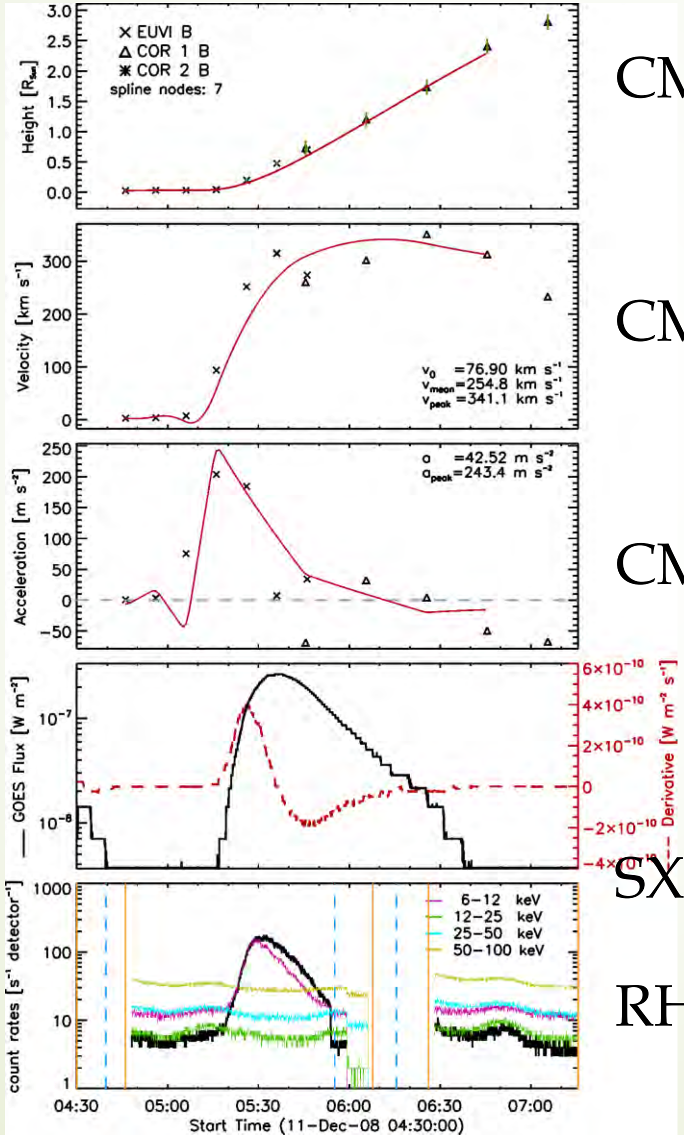


Event of 2005 January 17. Top to Bottom: distance-time profile **d(t)**, velocity **v(t)**, and acceleration **a(t)** of the **CME** as observed by different instruments. In the bottom panel, we plot also the **RHESSI 50–100 keV HXR** flux of the associated **flare**. The left panels show the full CME height range, up to $30R_{\odot}$. The right panels zoom into the **early acceleration phase**, of the **CME** as observed in **SXI**.

Coronal Mass Ejection (V)

Relation between CME dynamics and flare evolution





CME height vs time

CME velocity

CME acceleration

GOES flare SXRs & derivative

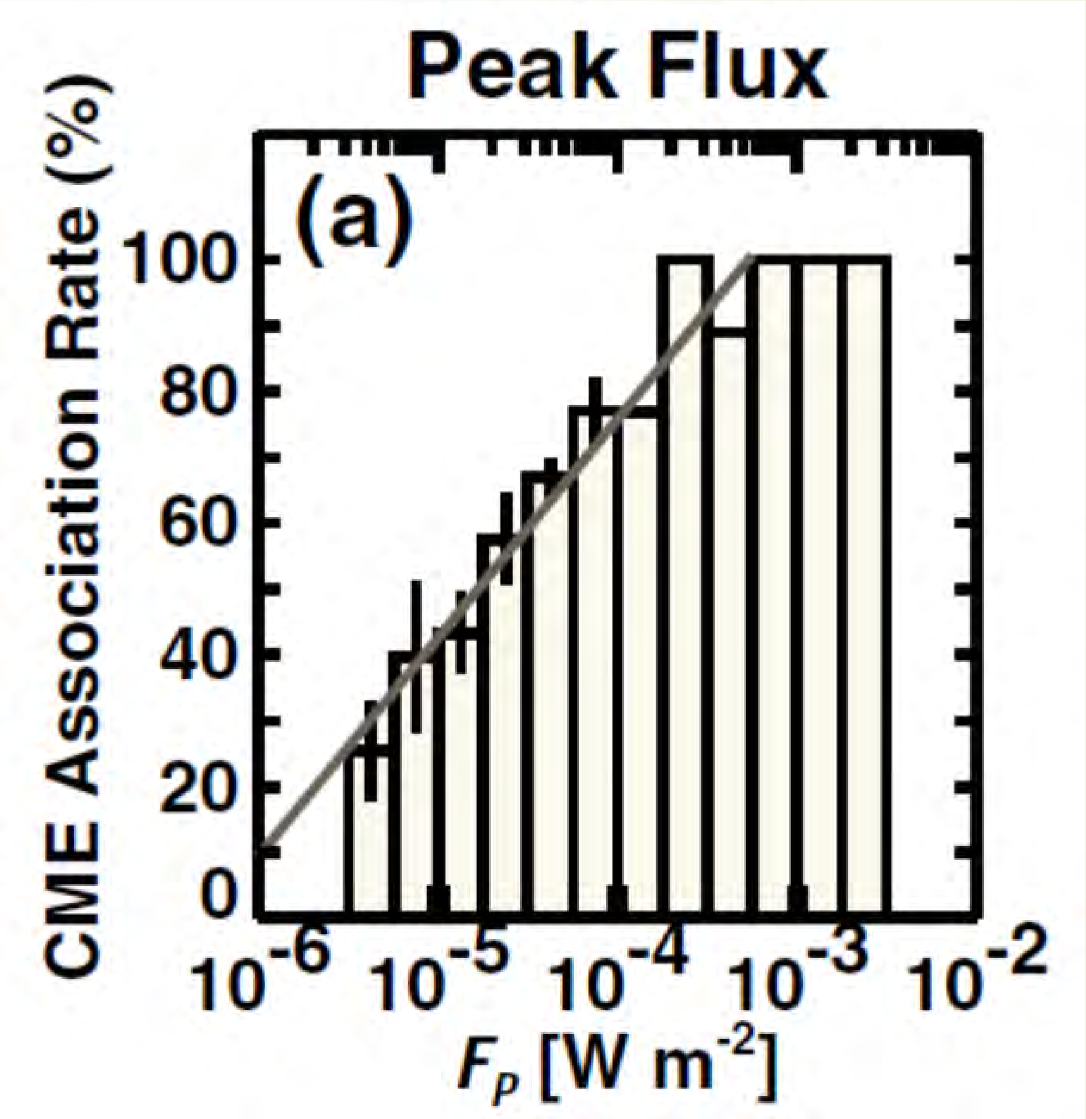
RHESSI flare HXRs

Seminar talk Academy of Athens, 2010 June 29

Coronal Mass Ejection (VI)

Relation between **CME dynamics** and **flare evolution**

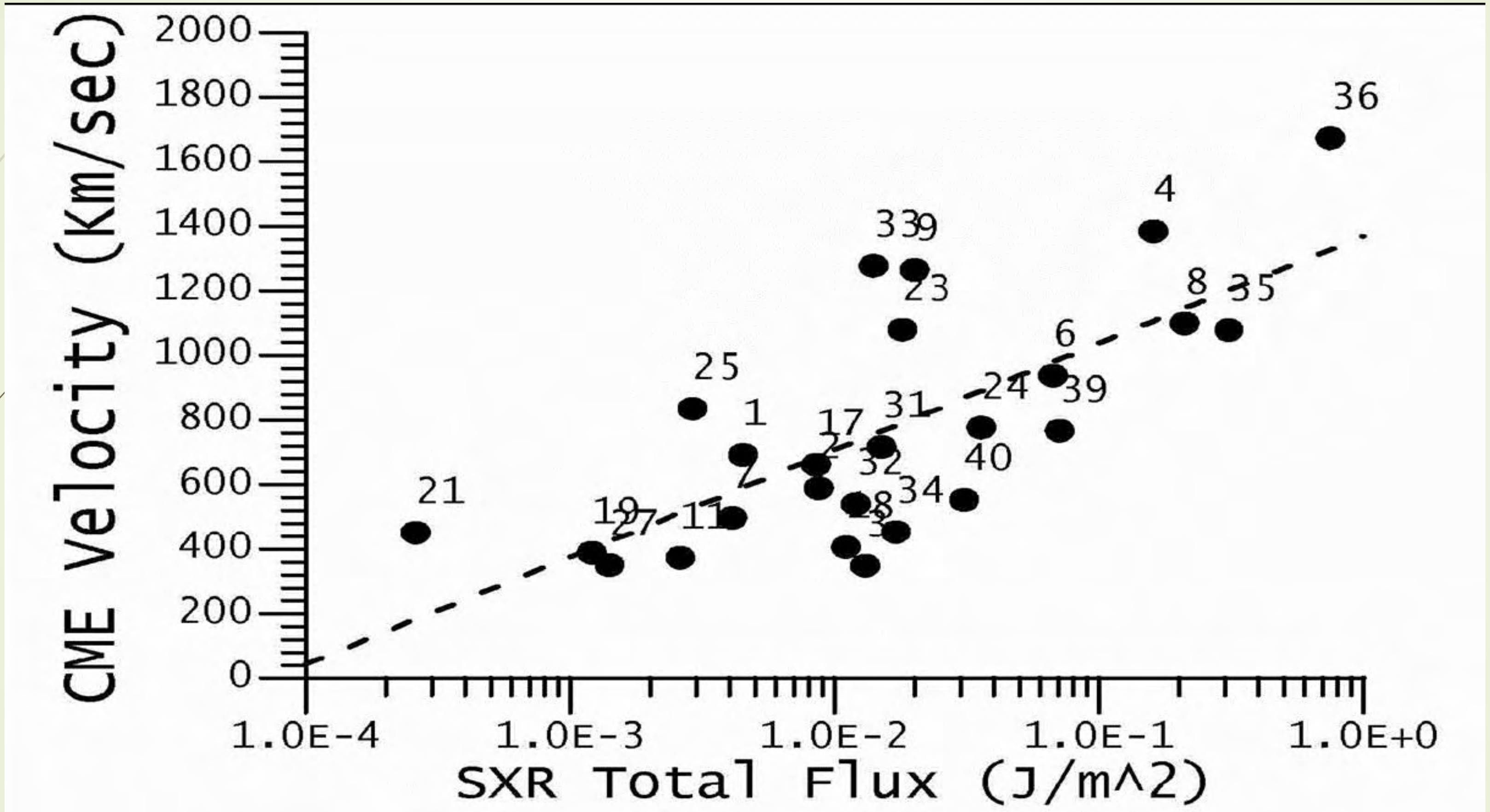
- Not all flares are accompanied by CMEs and vice versa
- Association rate of flares and CMEs, after accounting for biasing effects strongly increasing function with flare importance approaching 100% for strongest events



Yashiro et al. (2006) Ap. J., 650, L143, 2006

Coronal Mass Ejection (VII)

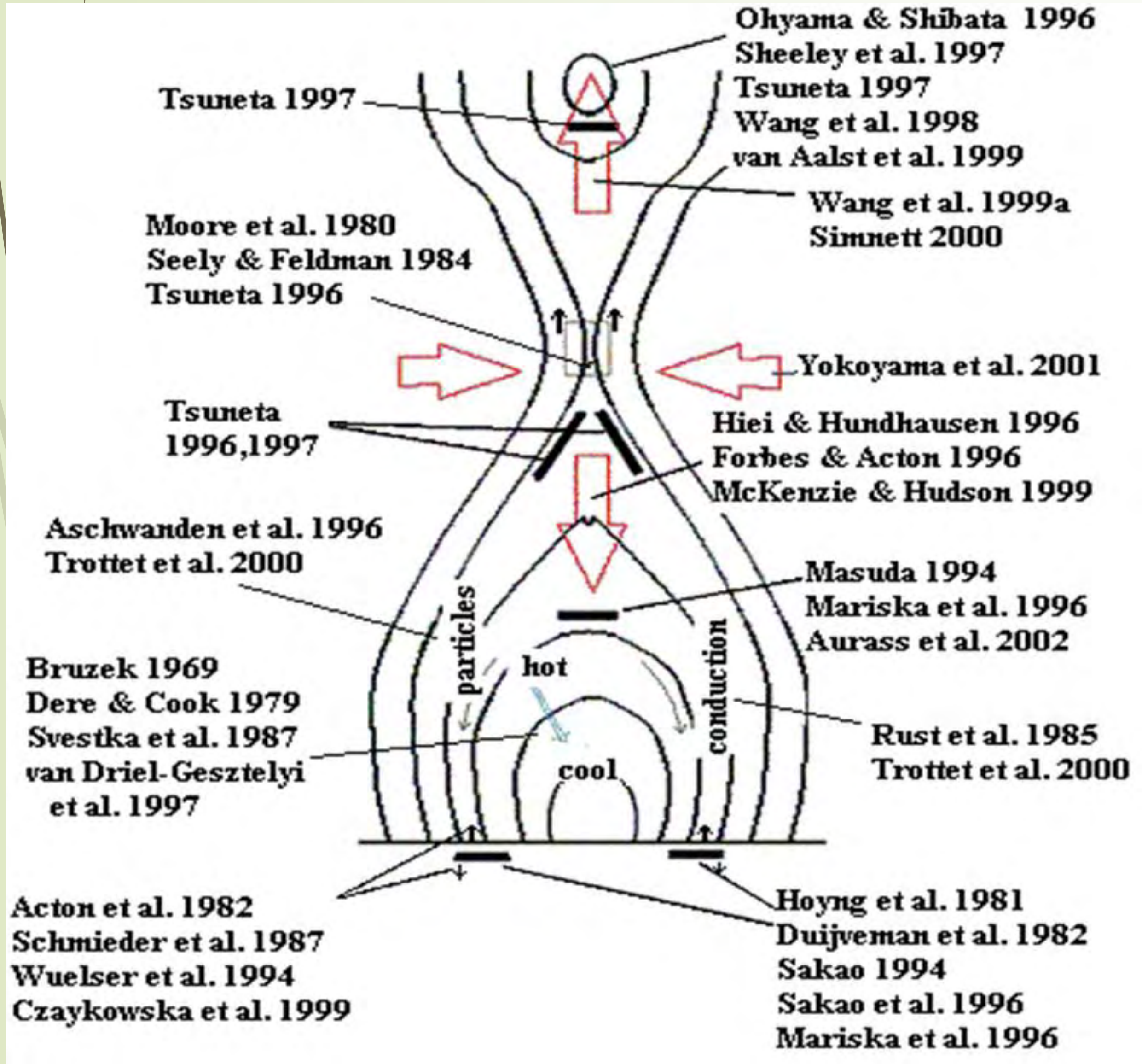
Relation between **CME dynamics** and **flare evolution**



Velocities of CMEs vs. integrated flux (FSXR) of associated SXR flares. The data are fitted with $\mathbf{V_{CME} = 150 \ln(F_{SXR}) + 1384}$. Caroubalos & al.: A&A **413**, p.1125-1133 (2004)

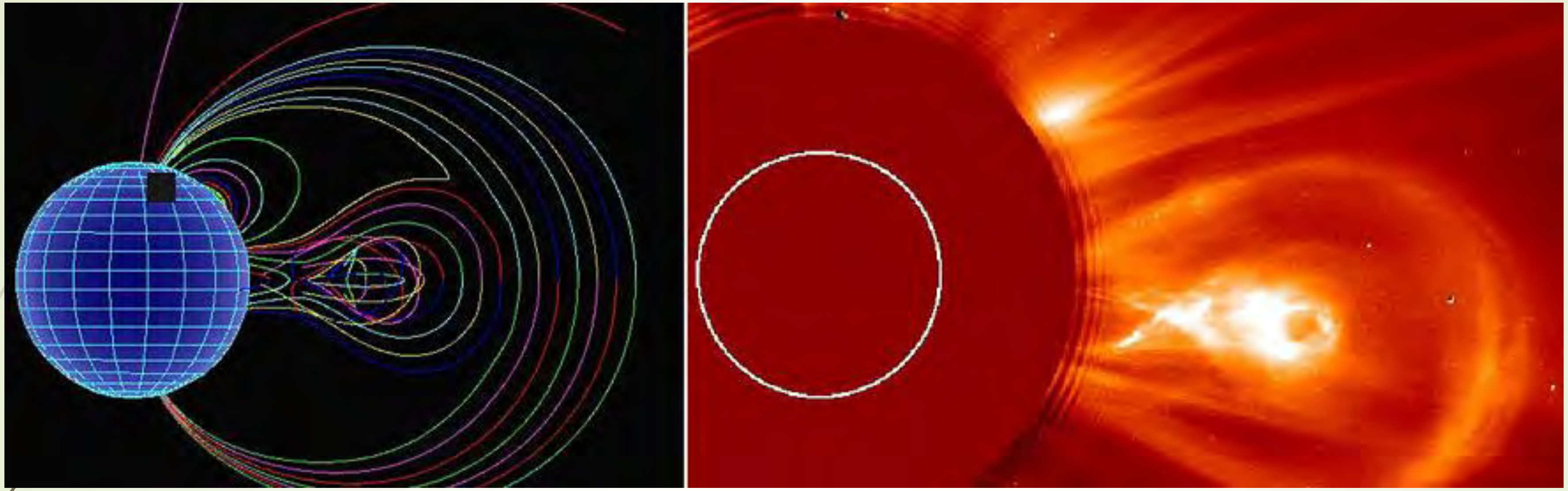
Coronal **M**ass **E**jection (VI)

Relation between **CME dynamics** and **flare evolution**



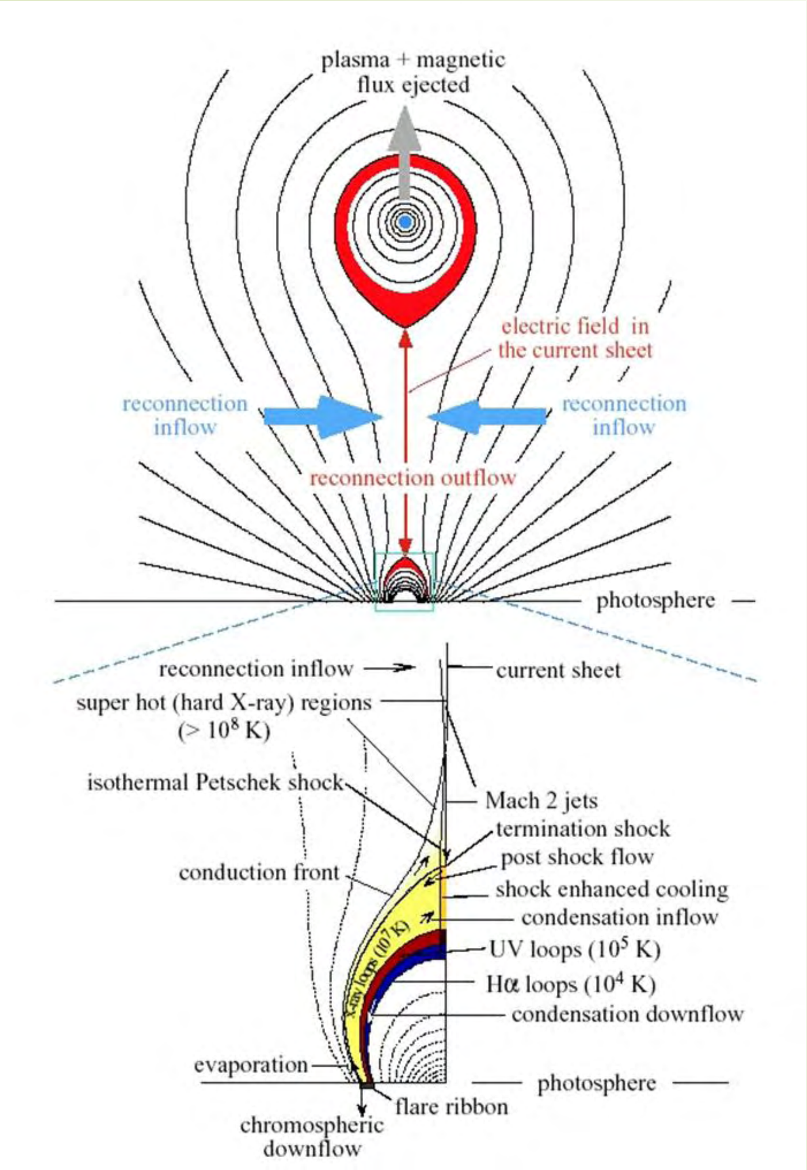
A memorable cartoon not because it adds any new wrinkles to **CSHKP** model, but because it labels the parts of the cartoon with some of names from the enormous literature swirling around this **basic idea** - **observations** -**theory** and **modeling**.

McKenzie, D. E., "*Signatures of reconnection in eruptive flares,*" *Yohkoh 10th anniversary meeting*, COSPAR Colloquia Series, p. 155 (2002).
http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/thepages/McKenzie_CSHKP.html



Left: A schematic drawing of the one-loop flare model.
Right: Observation of an apparent X-point behind a Coronal Mass Ejection observed by LASCO/SOHO in white light.

Coronal Mass Ejection (VII)
Relation between **CME dynamics** and **flare evolution**

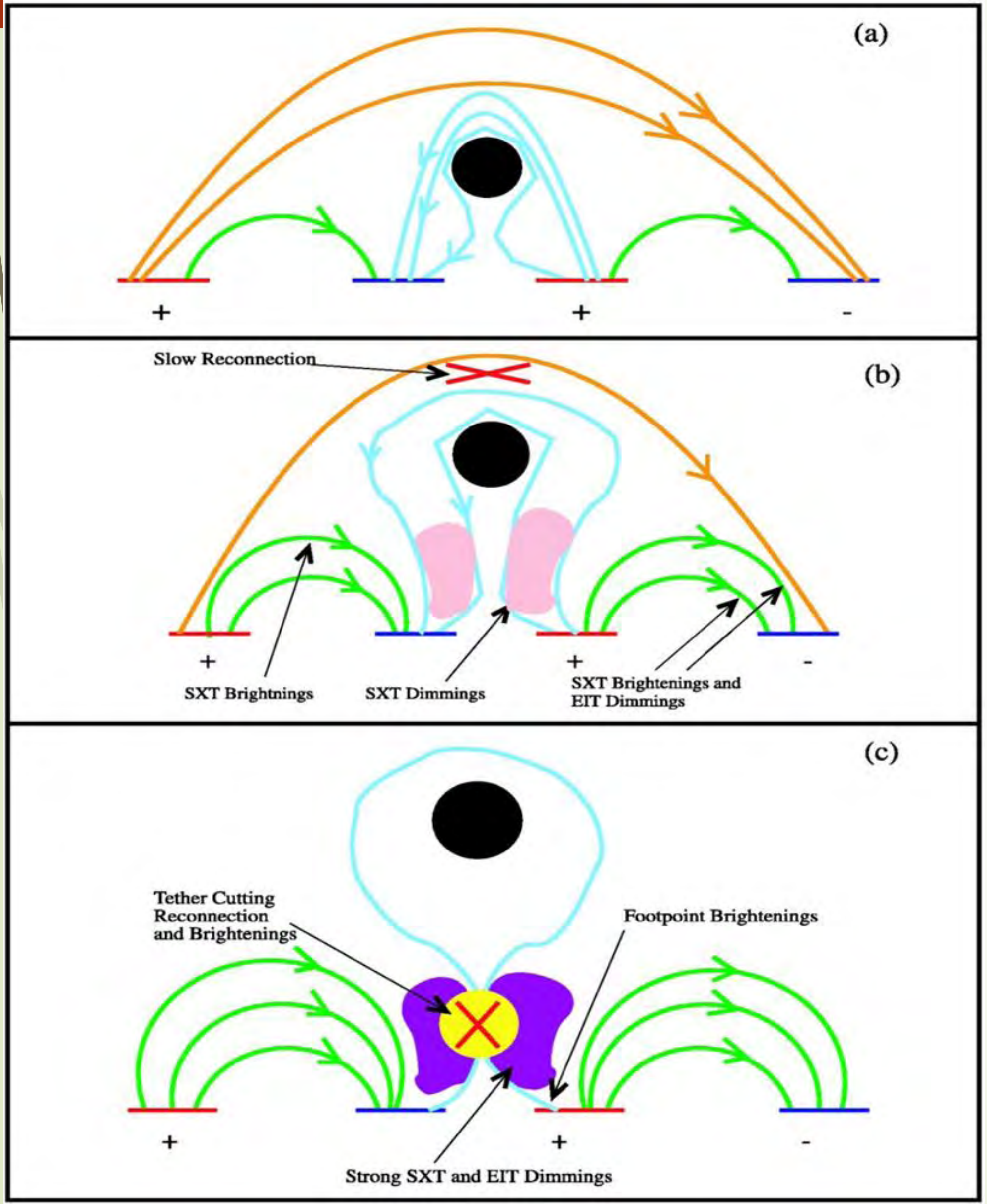


Unified CME-flare model

- CME: flux rope
- Flare
- Coronal loop arcade
- Hα flare ribbon
- Magnetic reconnection
  - Underneath the flux rope
  - Above the loop arcade
- Current sheet
- Reconnection inflow

Lin & Forbes, T.G., "*Effects of reconnection on the coronal mass ejection process*," JGR **105**, 2375 (2002).

Coronal Mass Ejection (VIII)
Relation between **CME dynamics** and **flare evolution**



The "***break-out***" model, of S. Antiochos.

Antiochos, S. K., "*The Magnetic Topology of Solar Eruptions,*" ApJ **502**, 181L (1999).

Sterling, A. C., and Moore, R. L., "*Evidence for gradual external reconnection before explosive eruption of a solar filament,*" ApJ **602**, 1024, 2004.