Champ magnétique des régions actives et phénomènes éruptifs

Etienne Pariat
LESIA
Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Univ. Paris Diderot, Sorbonne Paris Cité

Connexions en physique solaire et stellaire
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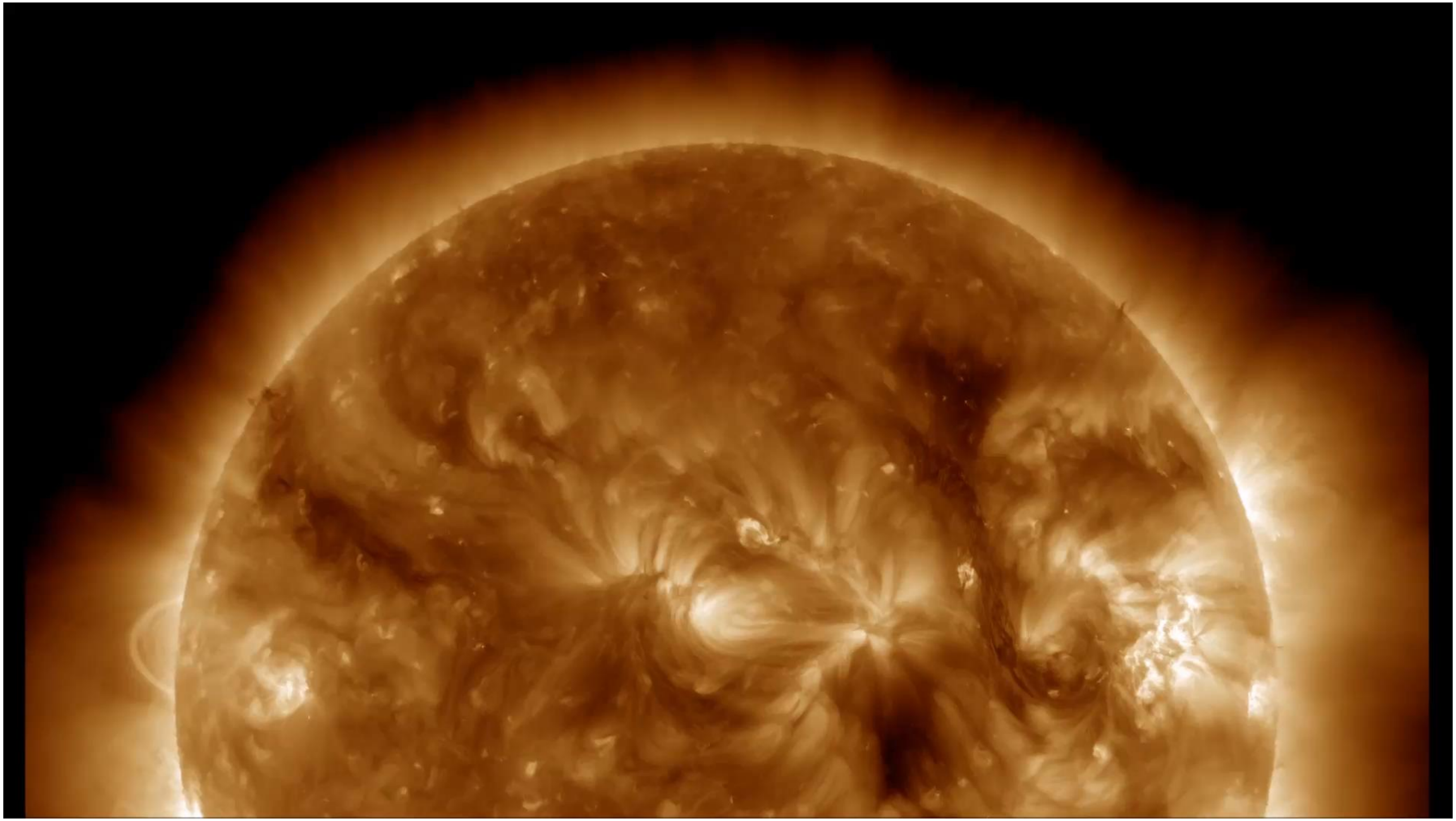
Plan

- Principes de base:
  - Définition et propriétés des éruptions solaires
  - Champ magnétiques des centres éruptifs et leur modélisation
  - Reconnexion magnétique MHD et au-delà
- Résultats principaux: le modèle standard 3D des éruptions
  - Formation des régions actives, structuration des centres éruptifs
  - Production des émissions électromagnétiques
  - Dynamique magnétiques des systèmes éruptifs
- Perspectives/Questions:
  - l'énigme du déclenchement des éruptions
  - la prédiction des éruptions solaires

Solar Eruption



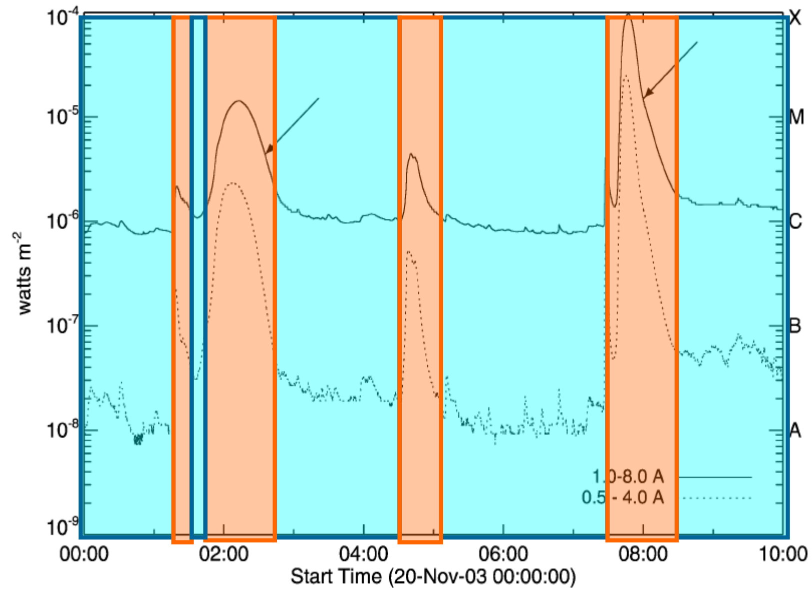
Energy of the largest solar eruption < 10^{27} J

Rotational energy of the Earth 10^{29} J ; Energy emitted by the Sun per second ~10^{26} J

Yearly radiation received by Earth 10^{24} J ; World yearly energy consumption 4×10^{20} J

Solar eruptions: impulsive events

- **Active events are energy storage and release phenomena with**
  - T (E increase) >> T (E decrease)
  - **Long-duration energy storage**
    - a few hours (jets), days (flares) to a few weeks (prominence eruptions)
  - **Sudden energy release :**
    - alfvénic timescales ~ a few minutes
- **➔ impulsive/eruptive events**



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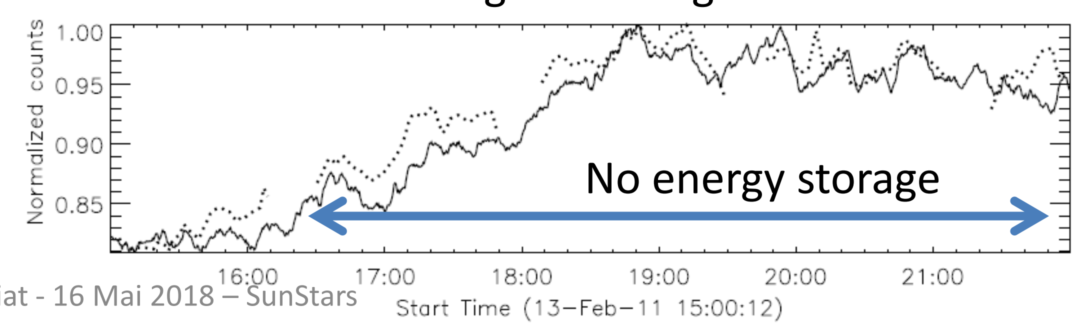
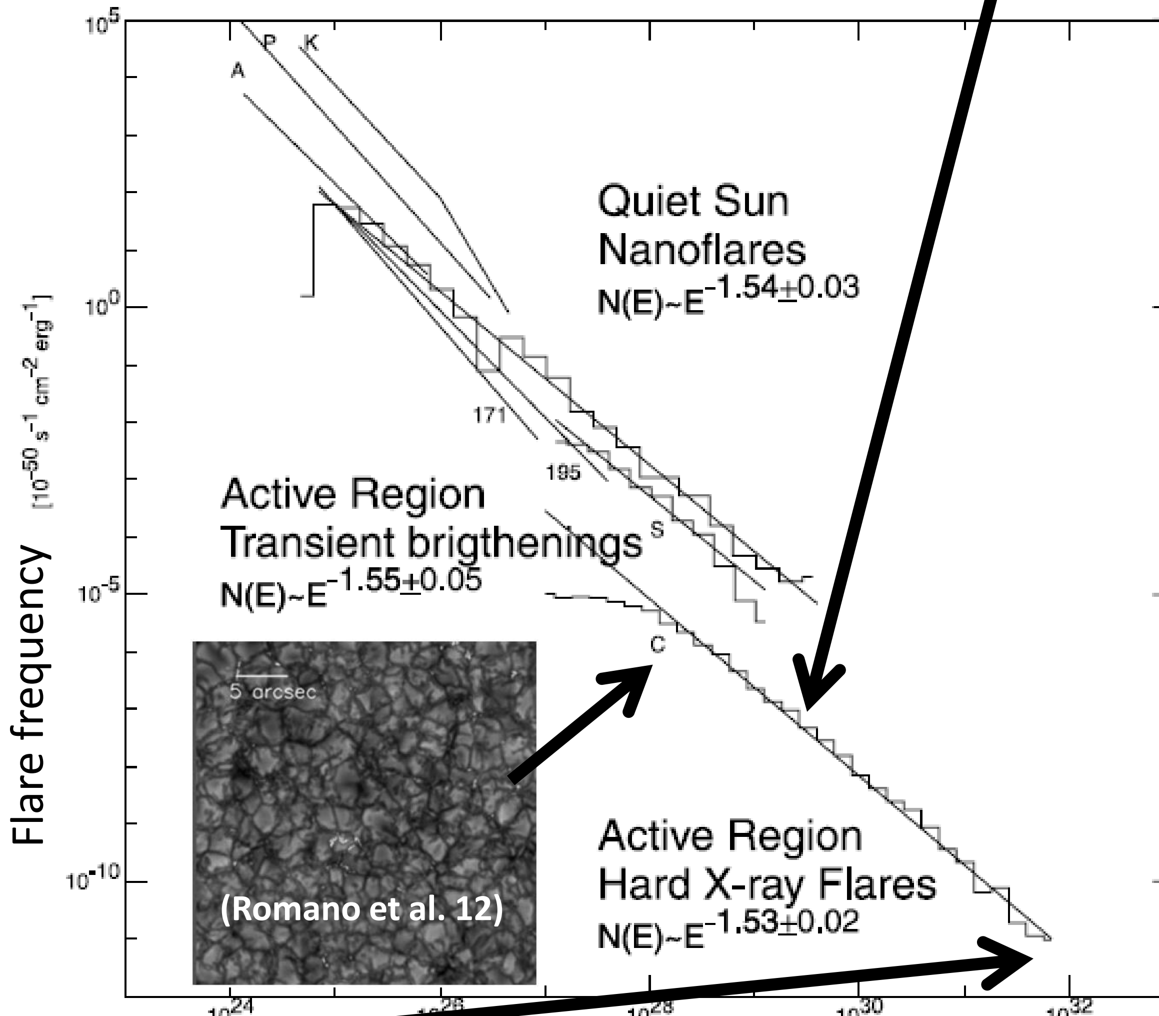
EUV Bright Point light curve

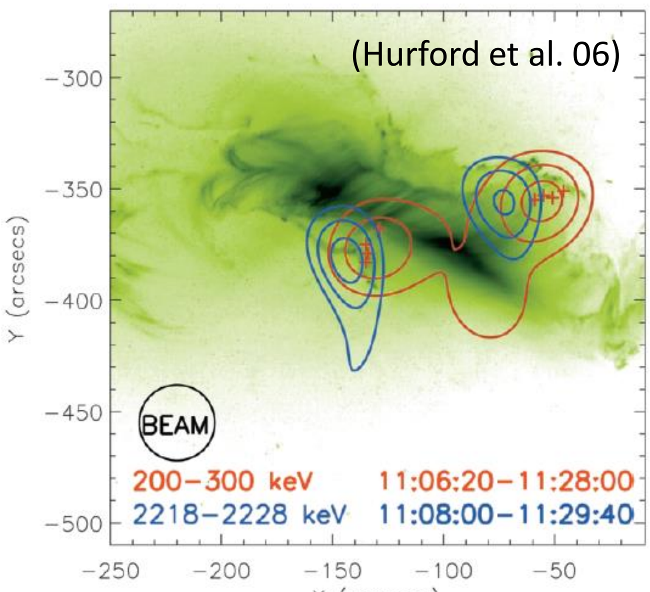


Flare energy distribution

- Brightenings / radiations are present observed over a very wide range of scales



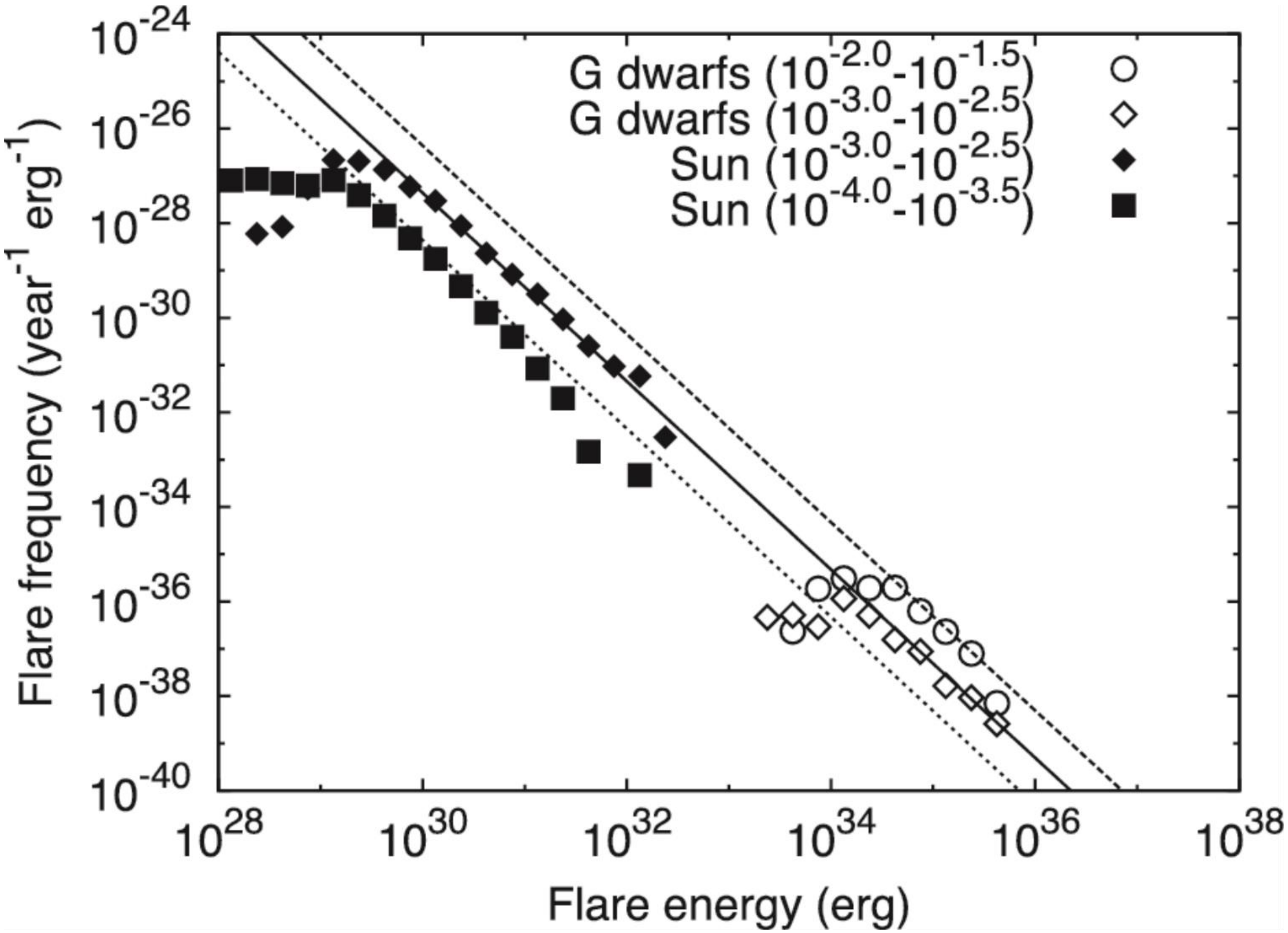
Aschwanden & Parnell (2002)



Flare energy distribution:

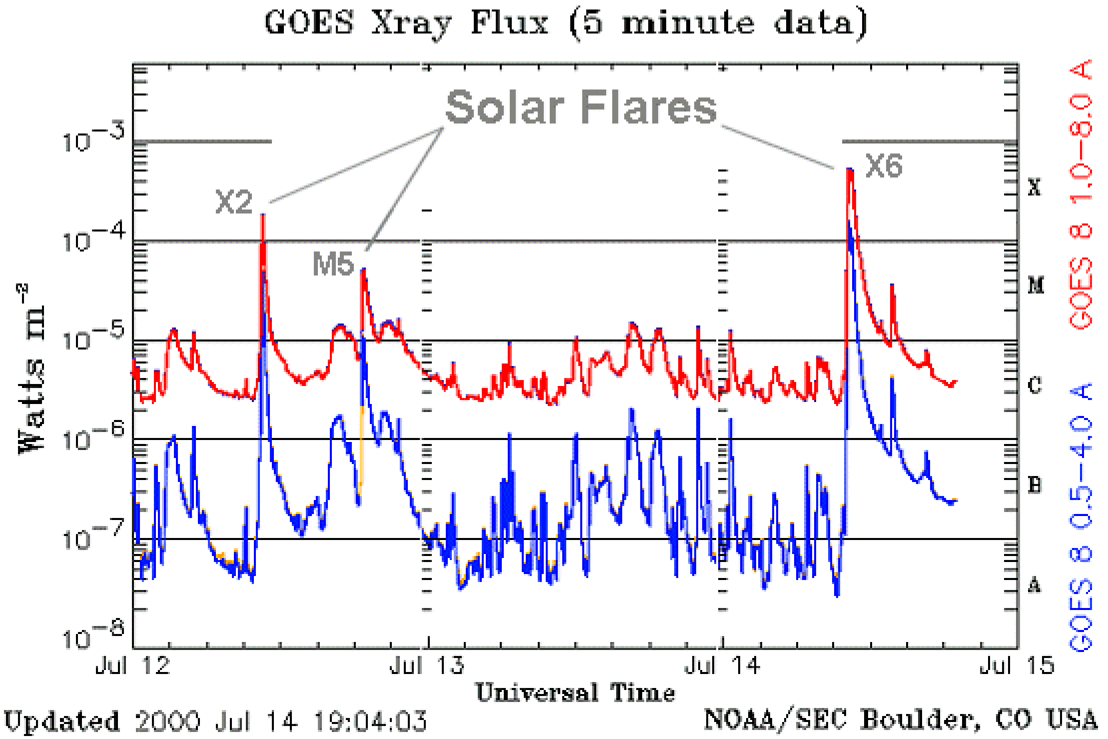
- **Stellar flares detected by Kepler range with the same power law distributions than the solar flares**
  - Same physical mechanism may be activing in both cases.

- However, there is an important energy gap between observed stellar and solar flares



Maehara et al. 2017

Flare classification

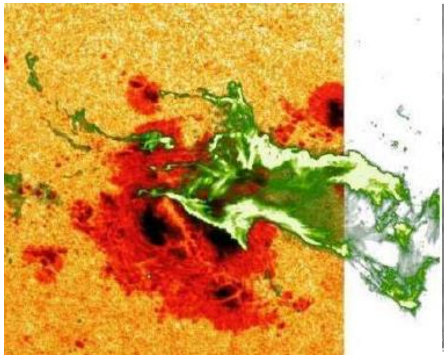


- Flare classification: peak SXR radiation in the 0.1-0.8 nm band
  - Measure by the GOES satellites
  - **Not an energy classification**

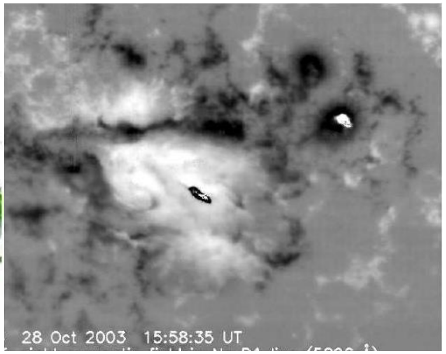
Classes	Flux (peak) 0.1-0.8 nm [W/m^2]
A	10^{-8}-10^{-7}
B	10^{-7}-10^{-6}
C	10^{-6}-10^{-5}
M	10^{-5}-10^{-4}
X	$>10^{-4}$

Where and When?

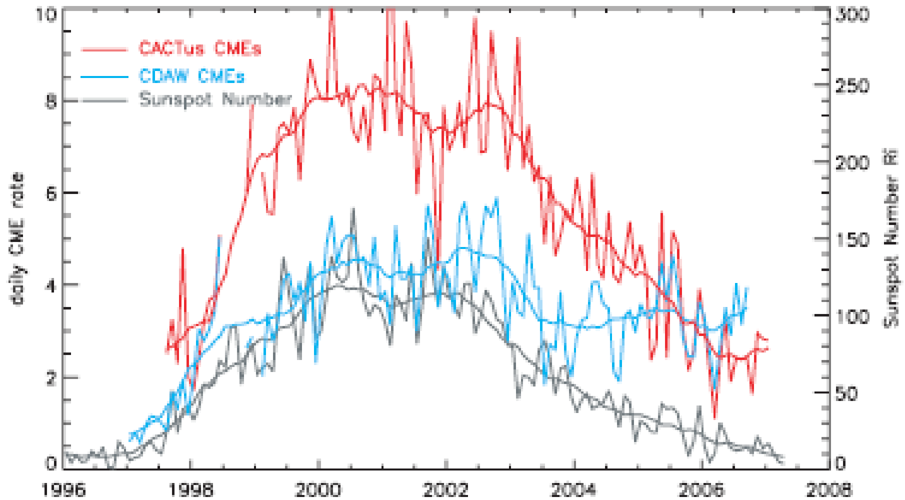
- Active events develops (mostly) in the corona
  - some repercussion on the chromosphere
- **Active events occurs close to magnetic field concentration, e.g: active regions & filaments**
  - **→ cf. talk M. Kretzschmar**
- Occurrence strongly follows the solar cycle
- **Active events are strongly related to the global properties of the solar magnetic field**
  - **Natural consequence of the dynamo**
  - **→ cf. talk S. Brun**

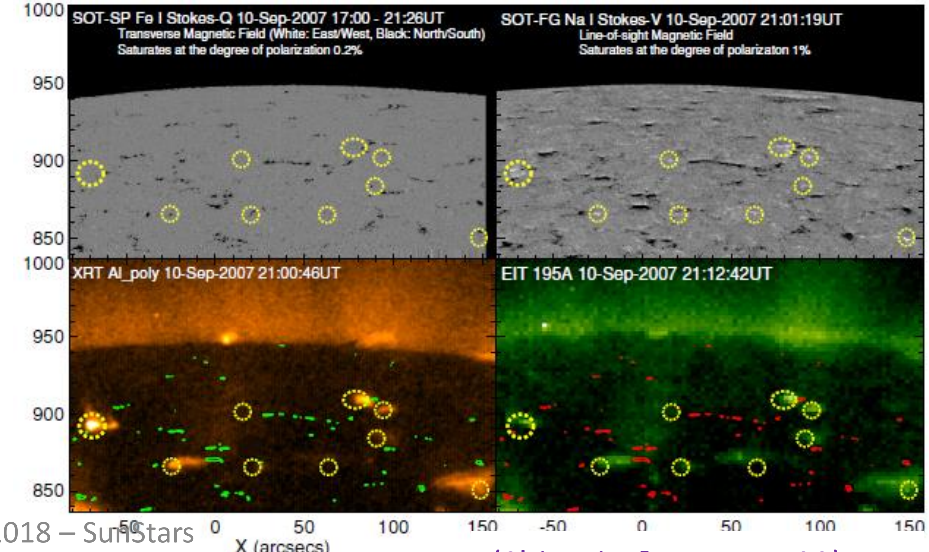


WL + EUV



LoS magnetogram



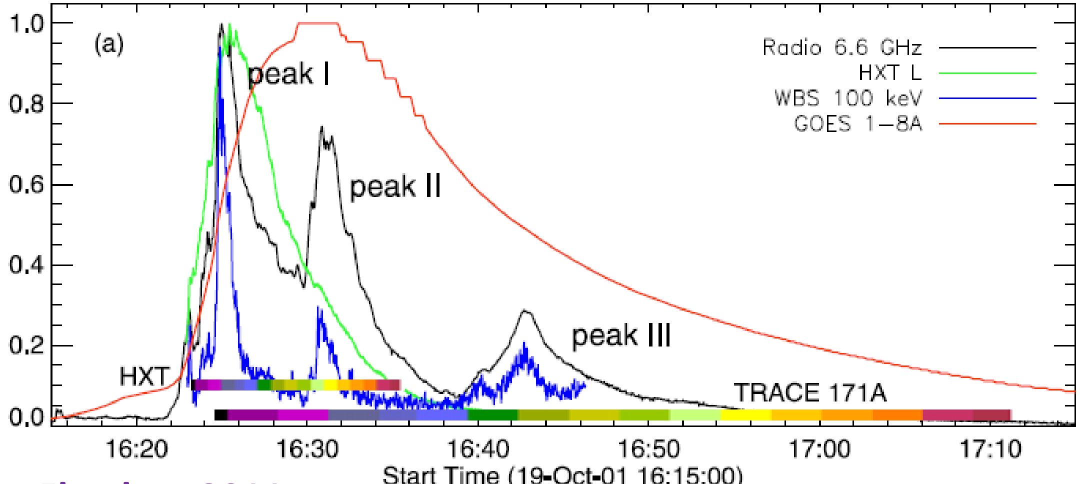


(Shimojo & Tsuneta 09)

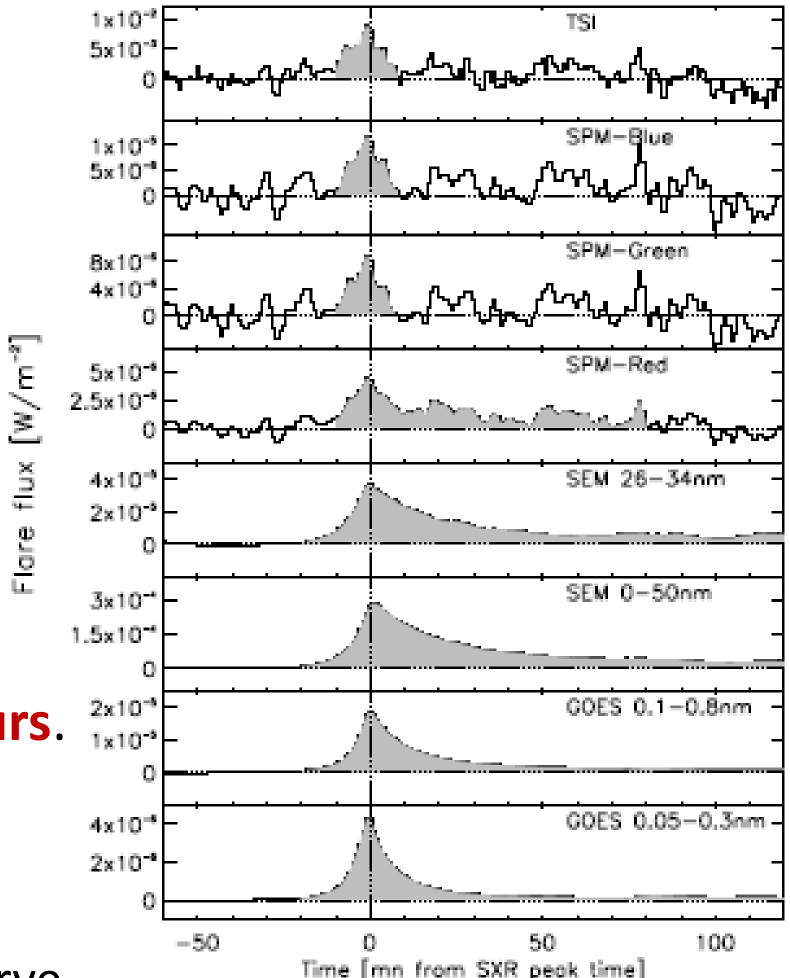
Solar eruptions

- **Eruptions are impulsive & transient events that can present one or several of the following phenomena:**
  - Electromagnetic emission: the “flare”
  - Ejection/bulk flow of solar plasma: e.g. coronal mass ejection (CME)
  - Energetic particle beams
  - Waves

Flare : definition



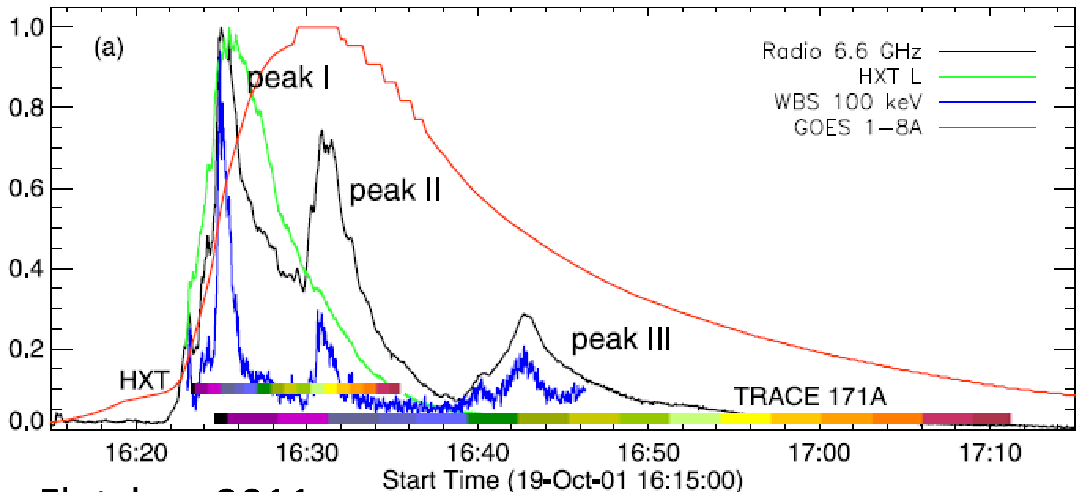
Fletcher, 2011



Kretzschmar, 2011

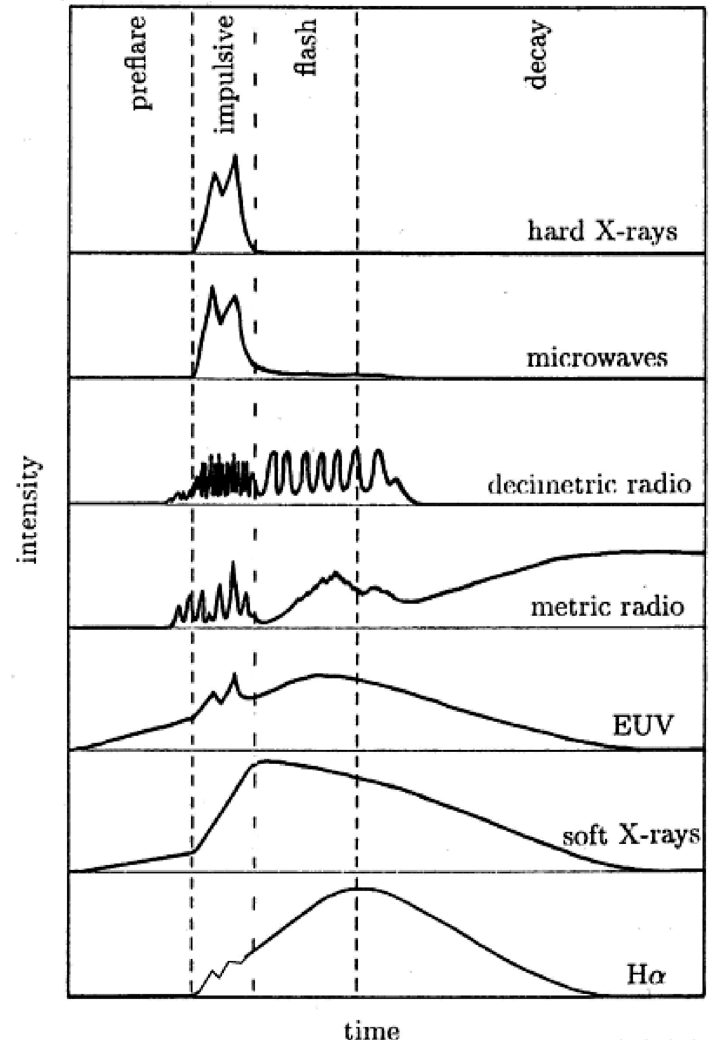
- **Flare: transient and impulsive emission across the electromagnetic spectrum occurring at a time scale of minutes to hours**.
  - Multi-wavelength
- **Most of the energy in white light**
  ➔ black body emission of 9000 K
  - Low contrast in white light: difficult to observe
  - Higher contrast at other wavelengths: used more frequently for flare research.

Flare lightcurves: phases



Fletcher, 2011

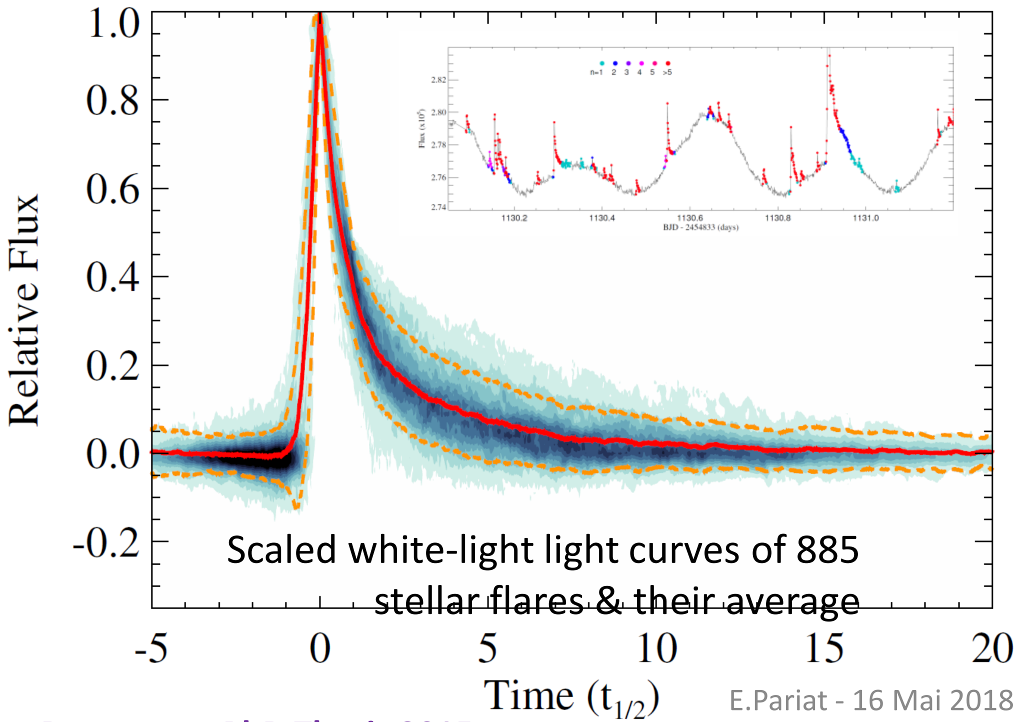
- Impulsive:
  - Hard X rays (HXR), Microwave & White light emission
  - Slow growth of EUV and Soft X rays (SXR)
- Gradual:
  - EUV, SXR, chromospheric lines



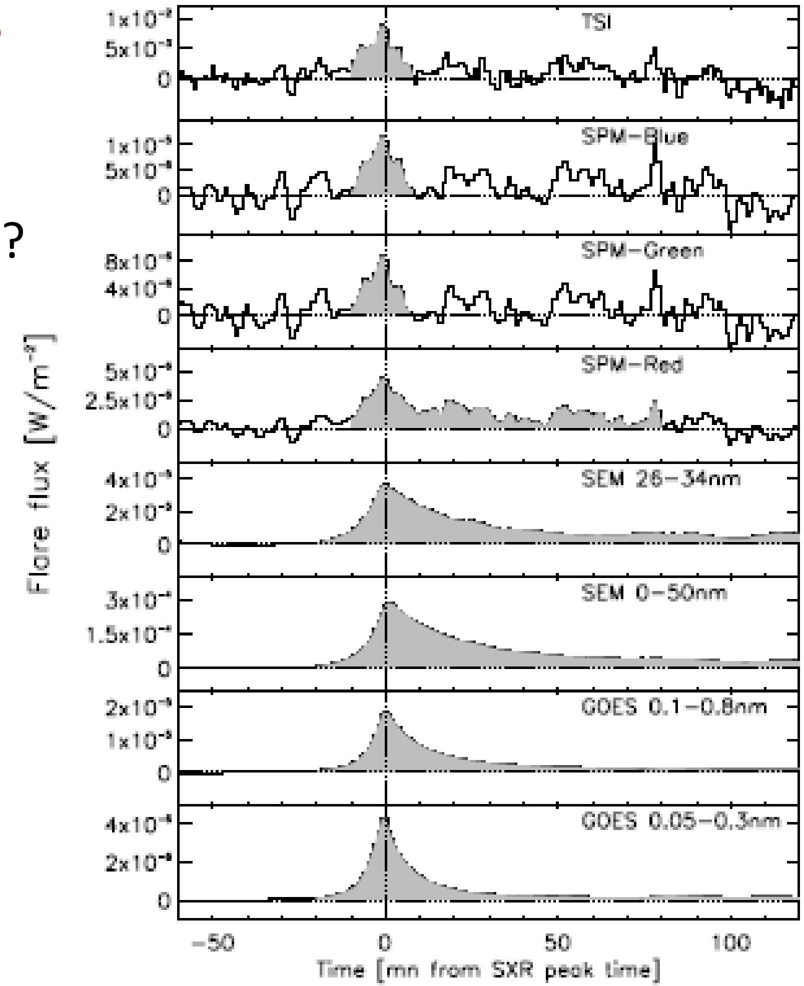
Benz, 2002

Stellar flare lightcurves

- **Stellar flares appears to present similar time profiles to solar flares**
  - **Cf. Talk M. Deleuil**
- → indication for similar physical mechanisms?
  - Not observed in the same waveband



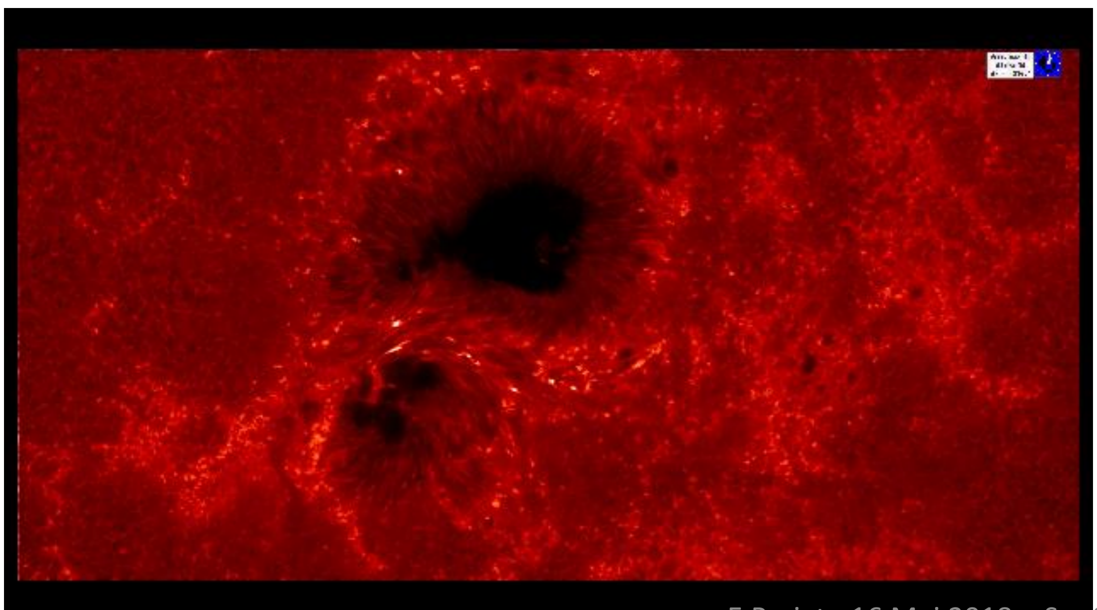
Davenport, PhD Thesis 2015



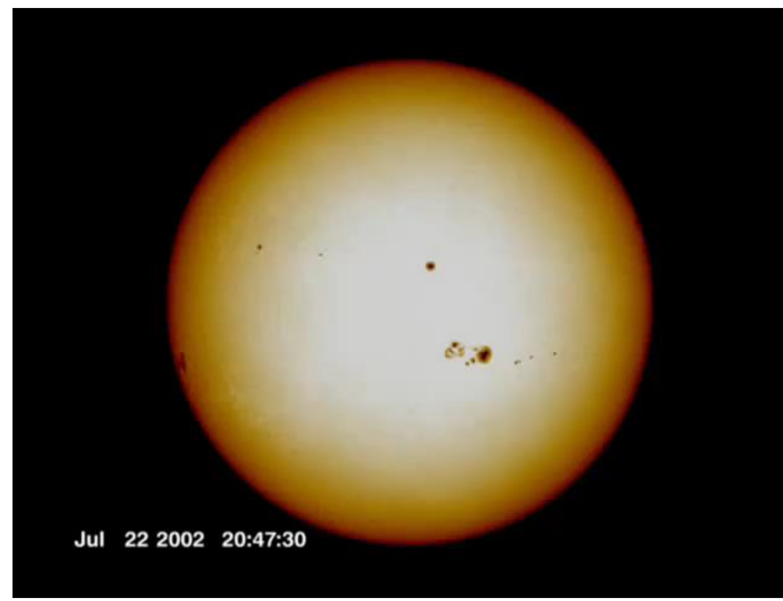
Kretzschmar, 2011

Flares : spatial dynamics

- Solar flares are not just a peak in light curves
- **Flares emissions is highly structured with an important spatial dynamisc:**
  - Flare ribbons (Visible, infrared, EUV)
  - Bright kernels (White light, HXR)
  - Post flare loops (EUV, SXR)
- Huge wealth of information that can be exploited to understand its physical mechanisms

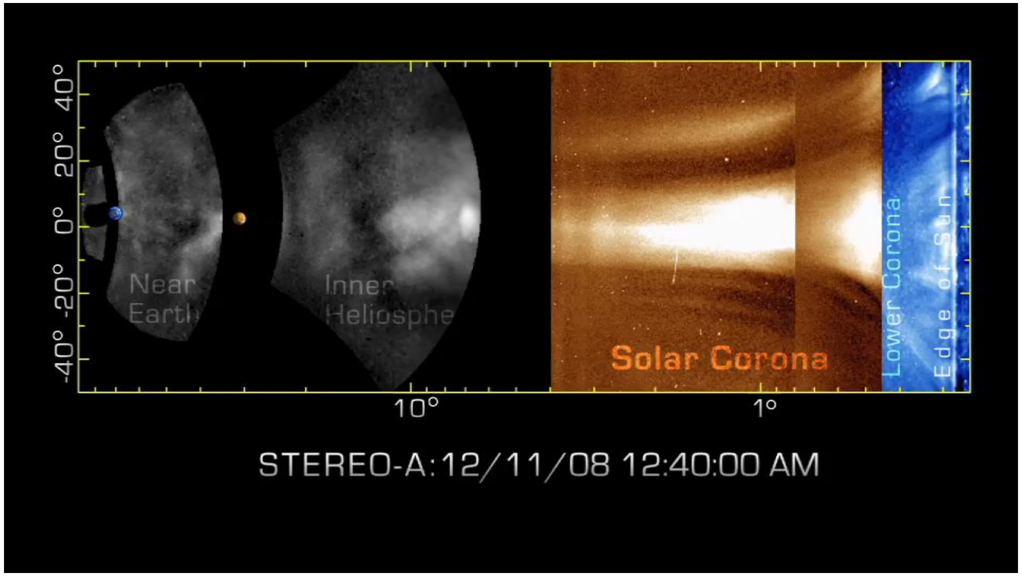


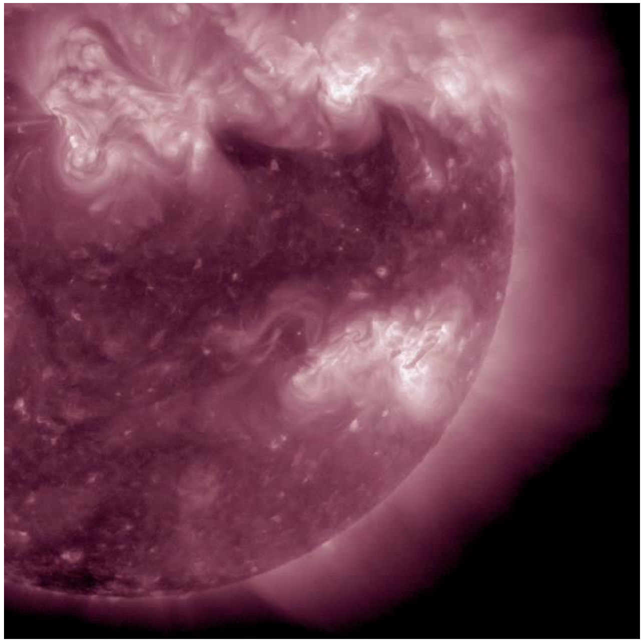
(Hinode/SOT)



(NASA / SVS RHESSI Krucker et al. 03)

Coronal Mass Ejections (CMEs)

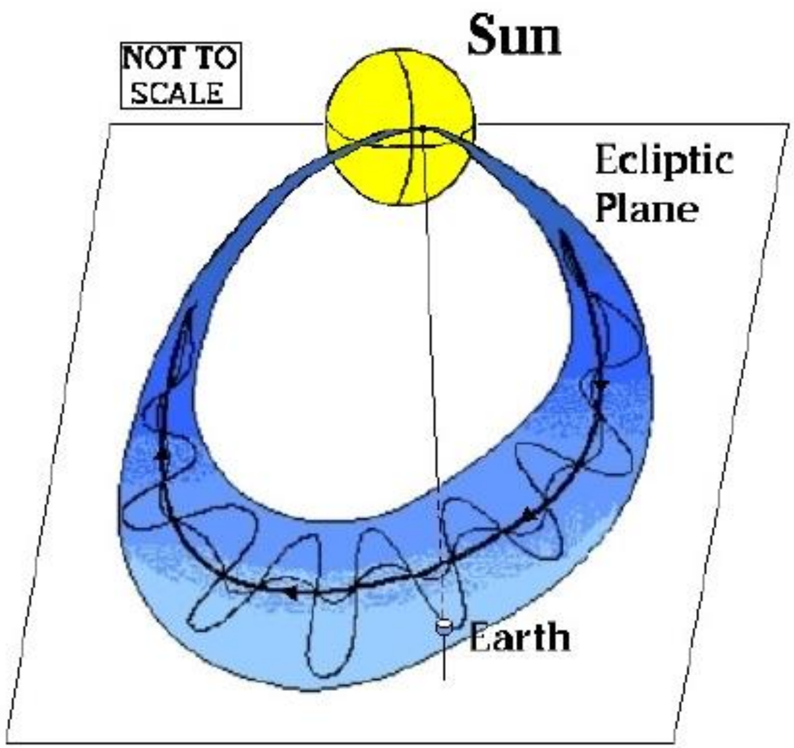


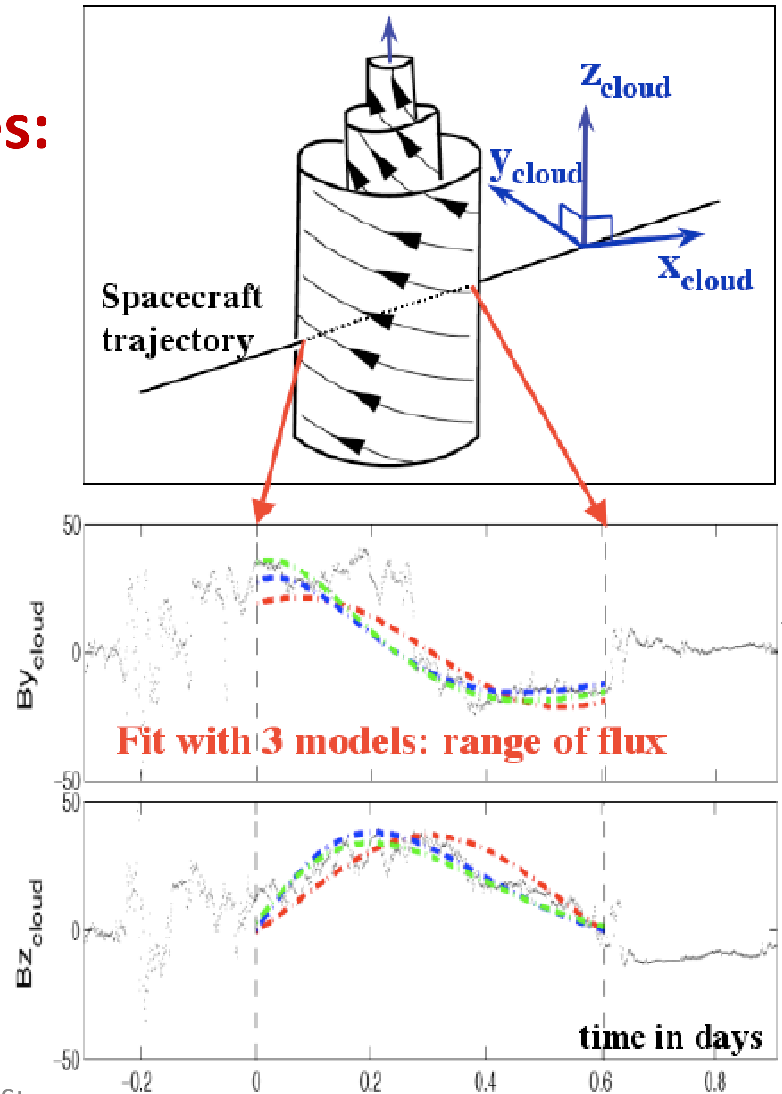


- **CME: large bulb of plasma expelled away from the solar atmosphere**
  - Detected with solar coronograph
  - Velocity: 300-3000 km.s^{-1} ; Mass: 10^{10}-10^{12} kg
- Concomitant phenomena:
  - Waves: “Moreton wave”, “EIT wave”
  - Shock fronts
  - Coronal dimming : darkening around CME source

CMEs in interplanetary medium

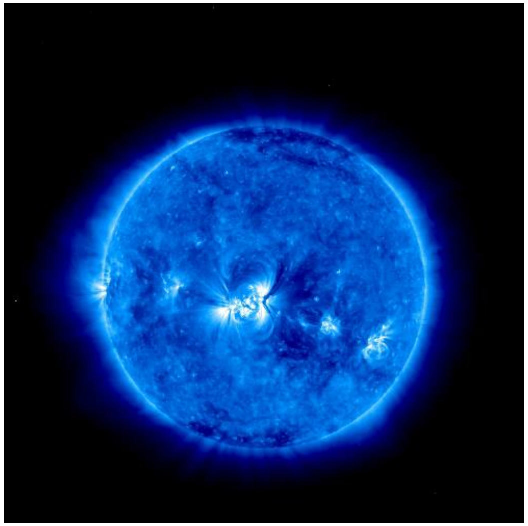
- **CMEs** (ICMEs / magnetic clouds) **are constituted by a magnetic structures: plasma is enclosed in a twisted magnetic flux ropes**



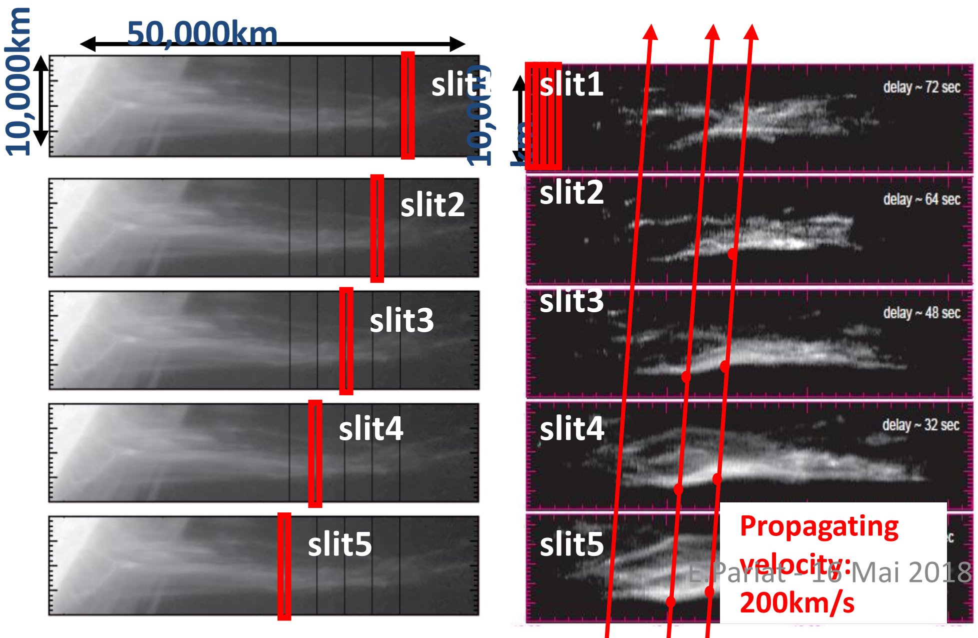


Outflows & waves

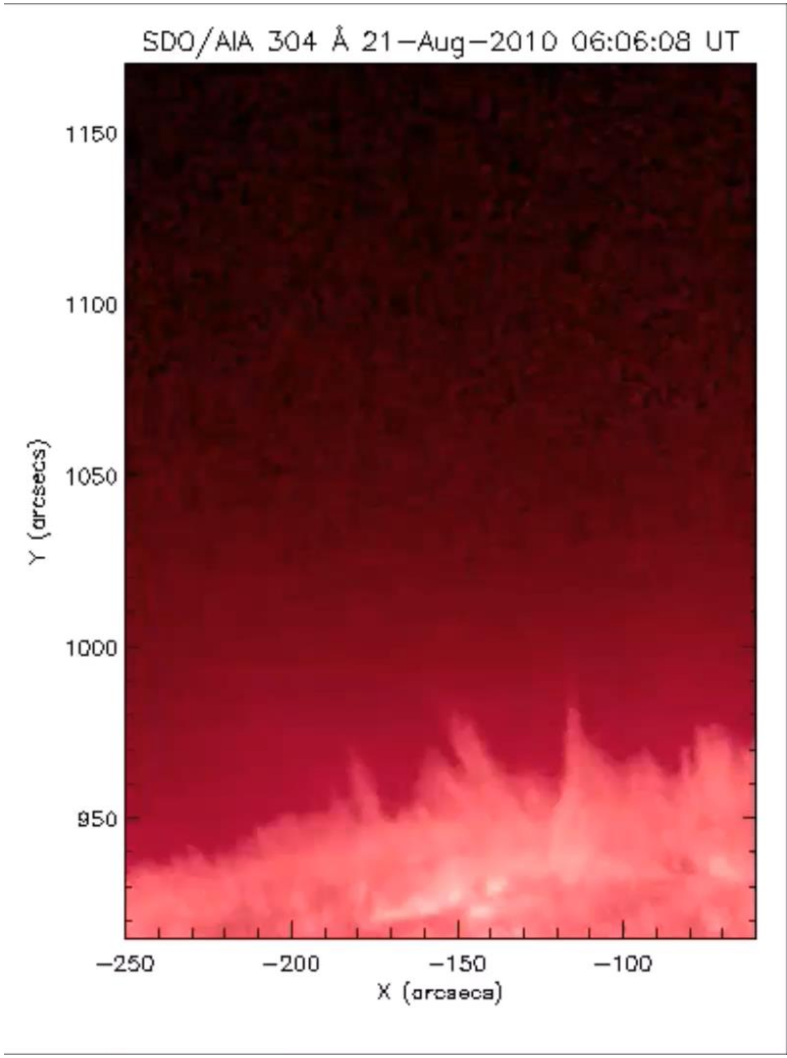
- Jets: collimated brightenings which can be traced up to several solar rad
- Signatures of helical motions and wave patterns along with the jets.



(Patsourakos et al.08)



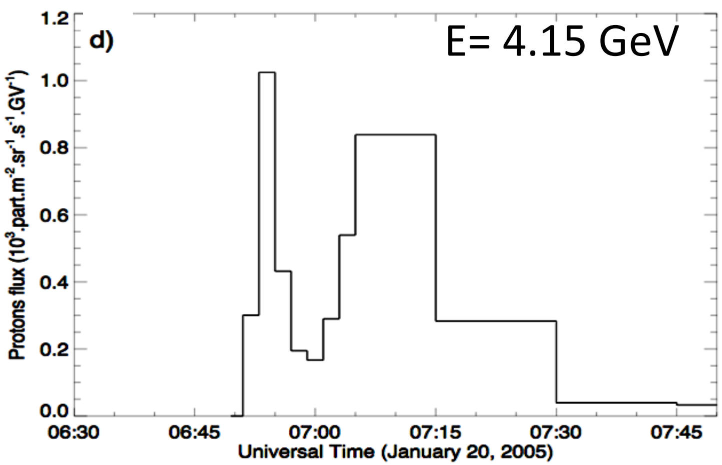
(Nishizuka et al. 09)

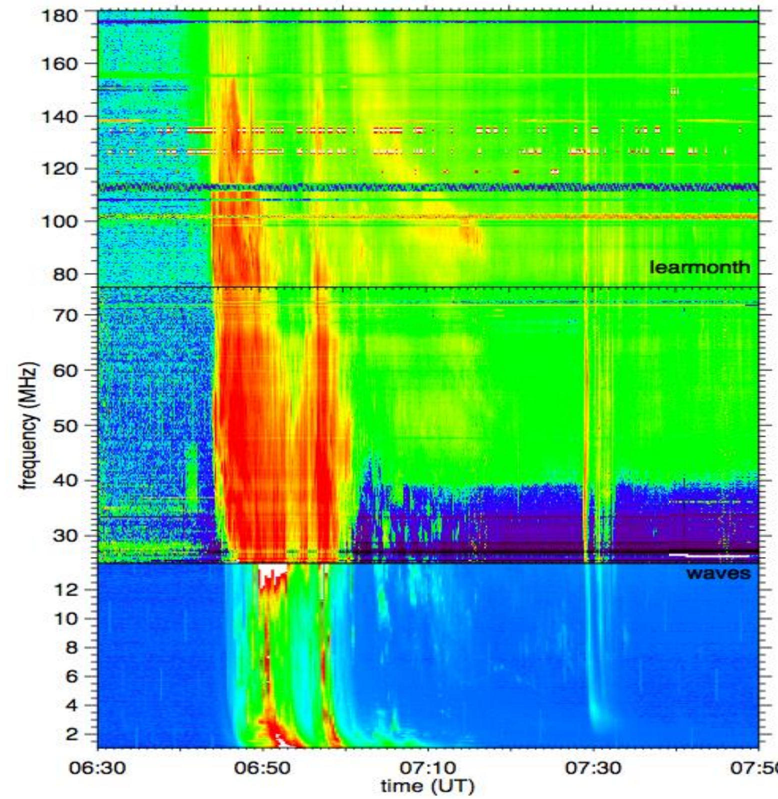


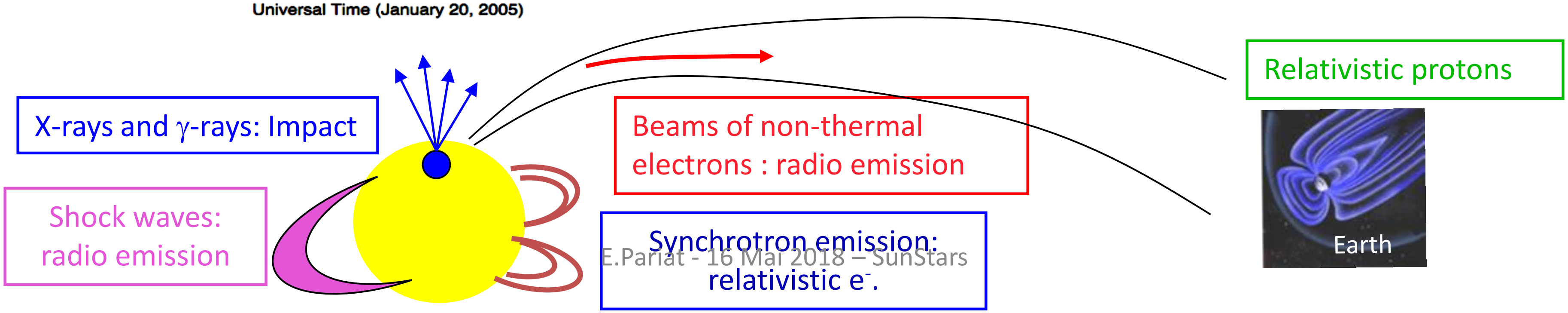
(Shen et al.12)

Energetic particles

- **Solar energetic particle (SEPs):** Particle beams propagating in the heliosphere
- **Ground level enhancement (GLE):** Solar protons accelerated from 100 eV up to GeV
  - relativistic energies
  - detected at Earth by Neutron Monitors







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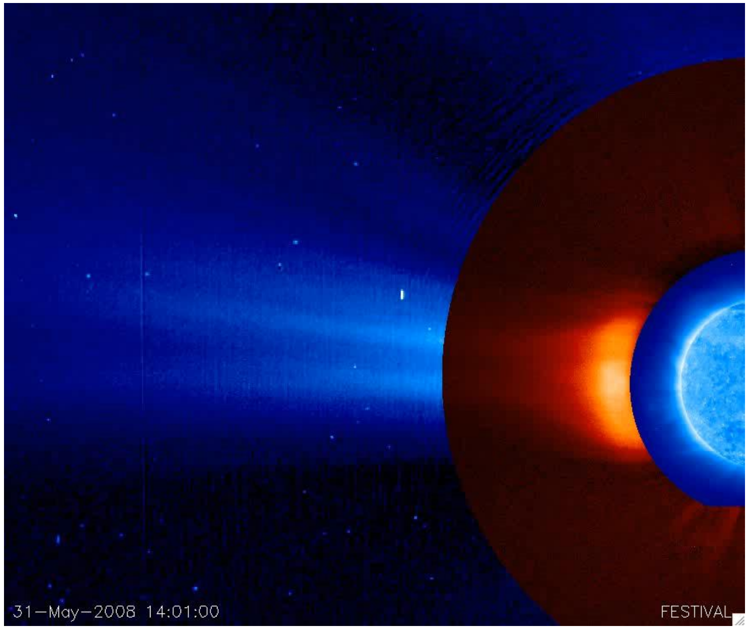
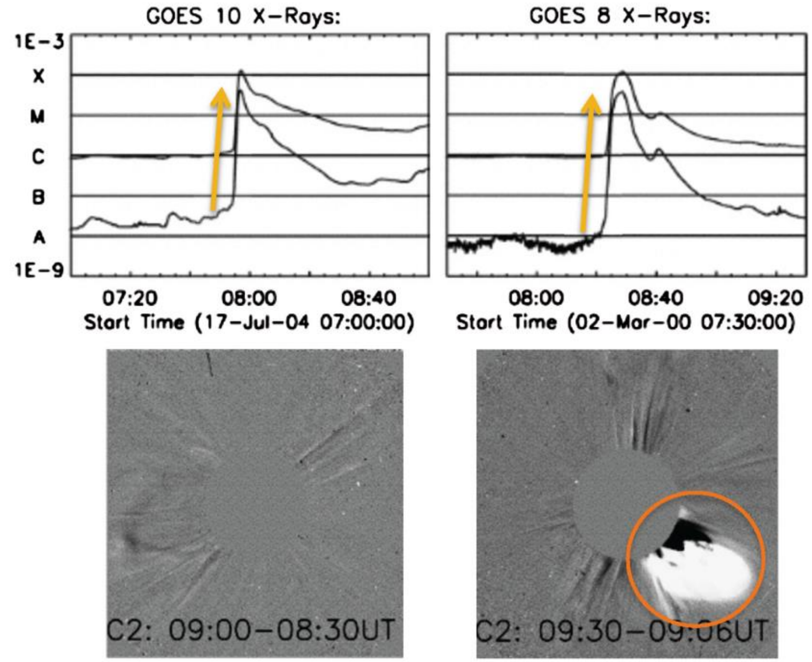
- Nomenclature:
  - Confined flare: flare without ejection
  - Eruptive flare: flare with a CME
  - Failed eruption: flare with an ejection that fails, that does not produce a CME
  - Jet: flare with collimated ejection, no CME/closed magnetic structure
  - Stealth coronal mass ejections: CME with flare emission barely detectable

Solar eruptions: classification





Confined flare

Eruptive flare

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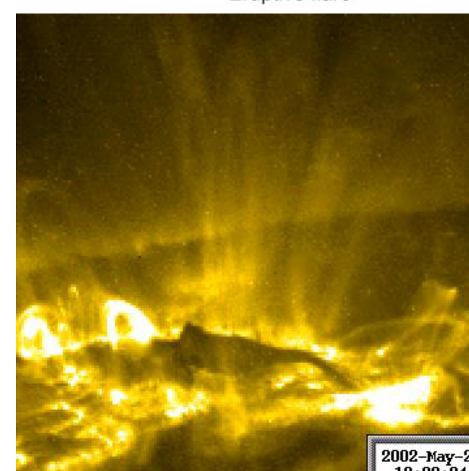

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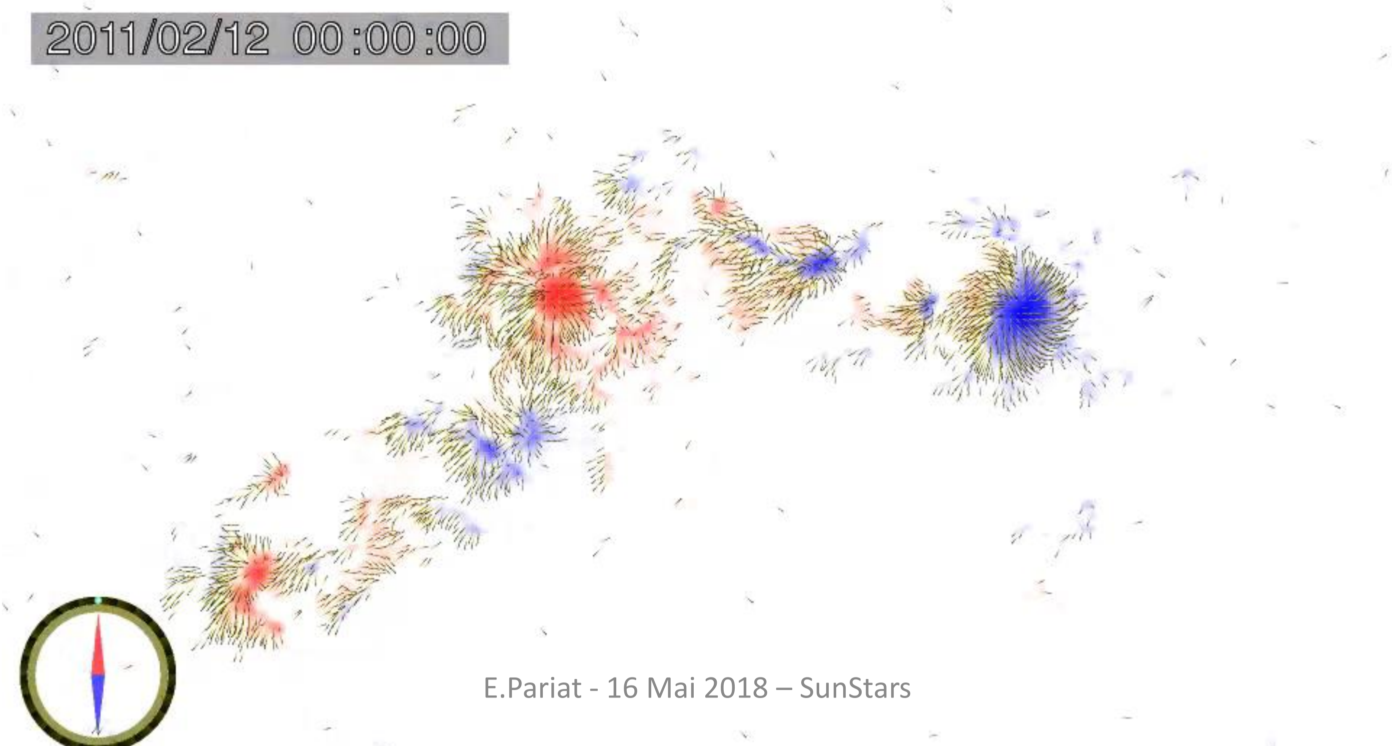
Actives regions magnetic field

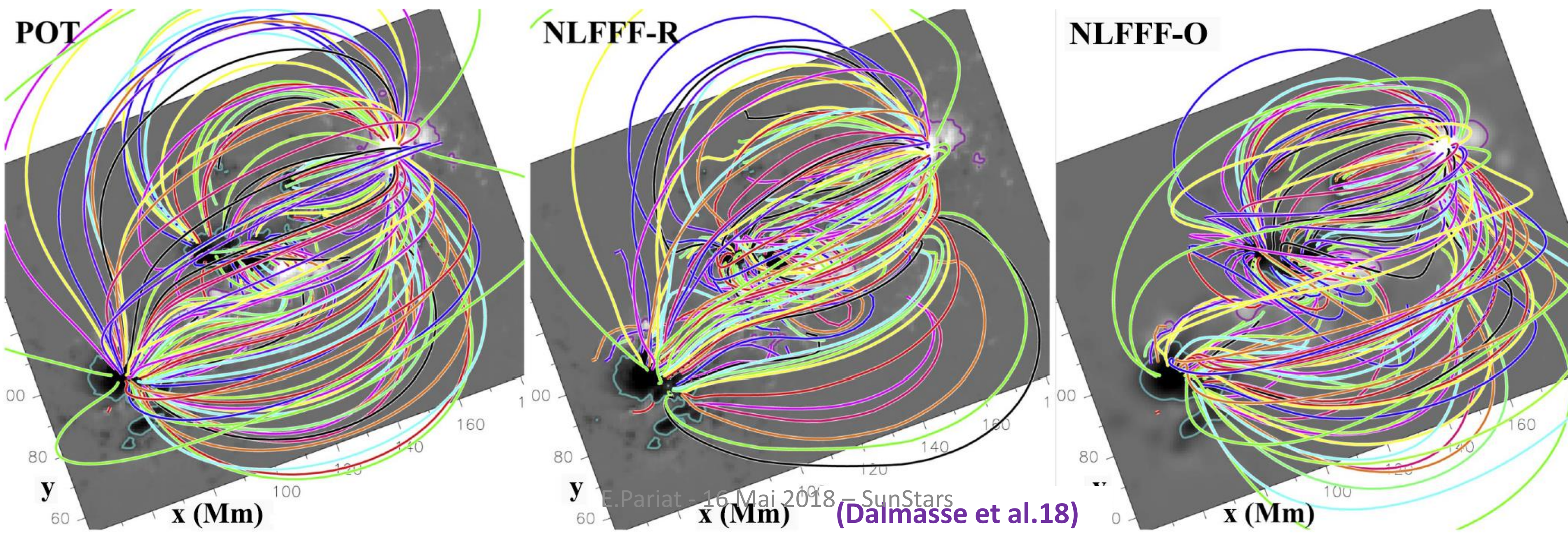
- 2D maps of the photospheric B are routinely measured
  - ➔ cf. talk by A. Lopez Ariste on Magnetic field measurements
  - e.g. with HMI/SDO
    - Full disk line of sight magnetogram (B//) every 45 seconds
    - Full disk full vector magnetograms (B) every 12 minutes



HMI/SDO
AR 11158

3D coronal magnetic field

- **As will be discussed hereafter, the knowledge of the full 3D distribution of the magnetic field in the coronal volume is fundamental to understand eruptivity**
- **From 2D magnetograms one can model the 3D coronal field**
  - → magnetic extrapolation methods
  - Different possible assumptions (not discussed here)
    - Potential field assumption: done routinely but of limited interest
    - More complex assumptions: case by case studies, requires a real "savoir-faire"



(Dalmasse et al.18)

Magnetohydrodynamics (MHD)

- The magneto-hydrodynamics approximation (Alfvén – Nobel 1970) is a physical paradigm of highly conductive fluids (e.g. plasmas and liquid metals), adapted to the **large scale modeling of the solar atmosphere** .

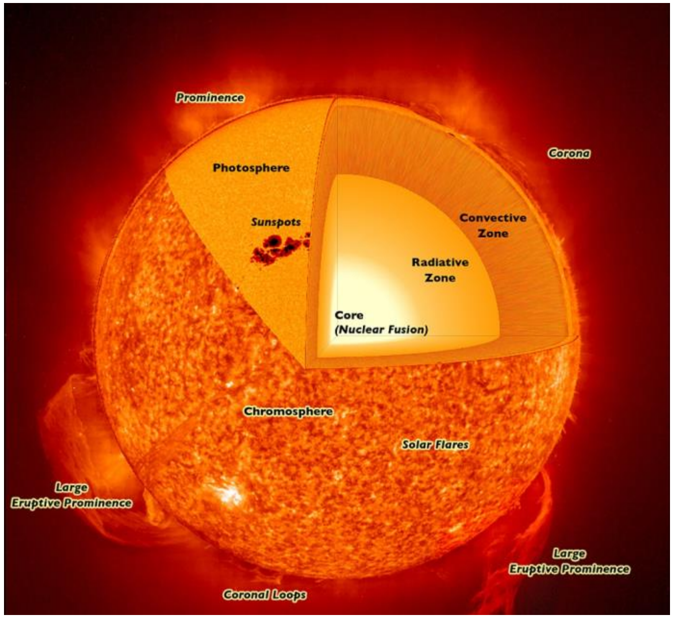
- Hypothesis:
  - Fluid: generally simple fluid but possible extensions toward multi-fluids
  - Quasi-neutral: ions and electrons are coupled
  - Magnetized & conducting: retro-action between plasma & magnetic field
- Limitations:
  - **Limited to large temporal (>1 s) et spatial (>1 m) scales**
  - No effect related to individual particles can be
- **The MHD paradigm allows the self consistent study of solar eruptions**
  - Active regions: $>10^{37}$ particles (L $\sim 10^{8}$ m ; n > 10^{13} m^{-3}): kinetic treatment is simply impossible
  - **Initial and boundary conditions are observed and can be used in the models.**

MHD paradigm in the solar atmosphere

- **Fully ionized** (high T, low dens)
  ➔ atmosphere made of plasma

	T (K)	n (m^{-3})	P (Pa)
Intérieur ($z \approx -10$ Mm)	7×10^4	6×10^{26}	7×10^8
Photosphère ($z = 0$)	5800	9×10^{22}	7×10^3
Chromosphère ($z = 2$ Mm)	10^4	5×10^{16}	2×10^{-2}
Couronne ($z \approx 50$ Mm)	2×10^6	2×10^{14}	2×10^{-3}

- **Fluid approximation** valid for AR dynamics but some particle dynamics at small scales
  - Mean free path: 10^3 -10^5m < length scale of active region: 10^6m - 10^8m
  - Collision time: 10^{-3} s to 1s < typical time scale of ARs: 1 min – 1 day



- **Quasi-neutral**
  - Length scale >> Debye length (~ 1 cm)

- **Non relativistic** scales (v_0 << c)
  - Electric currents are induced by the magnetic field : Ampère Law

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}.$$

Standard MHD Equations

- Mass conservation
- Impulsion conservation
  - Plasma pressure
  - Lorentz force
  - + gravity, viscous stress, …
- Ampère law
  - + relativistic term
- Induction equation & Ohm law
  - + resistivity, Hall term, …
- Closing equations:
  - State law (e.g. perfect gas)
  - Energy conservation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) = 0$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} \quad + \ldots$$

$$\nabla \wedge \mathbf{B} = \mu_0 \mathbf{j} \quad + \ldots$$

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

$$\mathbf{E} + \mathbf{v} \wedge \mathbf{B} = 0 \quad + \ldots$$

$$p = \frac{1}{\tilde{\mu}} \rho \Re T$$

$$\frac{\rho^\gamma}{\gamma - 1} \frac{D}{Dt}\left(\frac{p}{\rho^\gamma}\right) = \nabla.(\kappa \nabla T) - \rho^2 Q(T) + \frac{j^2}{\sigma} \quad + \ldots$$

Lorentz force dominated medium

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\mathbf{J} \times \mathbf{B} + g\mathbf{e}_z + \frac{1}{\rho}\nabla \cdot \tau$$

- Lorentz force: 10^{-6} N.m^{-3}
    - B~0.01 T, L~10^{7}
  - Plasma pressure: 10^{-9} N.m^{-3}
    - P~10^{-2} Pa, L~10^{7}m
  - Viscous stress & Advection: 10^{-10}N.m^{-3}
    - V~10^{5} m.s^{-1}, L~10^{7}m, ρ~10^{-13} kg.m^{-3}
  - Gravity: 10^{-11} N.m^{-3}
    - g~280 m.s^{-2}, ρ~10^{-13} kg.m^{-3}

Energy source

- Energy density in the solar corona: $$E = \frac{1}{2}\rho v^2 + \frac{1}{2\mu}B^2 + U$$
  - $T\sim10^6$; $n_e\sim10^9$ cm^{-3} ; P~1 Dyne cm^{-2} ; $V_0\sim10$ km s^{-1} ; $\gamma=5/3$; g~10^2 m^2 s^{-1} ; $L_0\sim100$ Mm
  - Kinetic energy: E_{kin} ~ 10^3 erg m^{-3}
  - Gravitational potential energy: $\rho g L_0$ ~ 10^5 erg m^{-3}
  - Internal energy: $U=P/(\gamma-1)\sim nK_BT$, U ~ 10^6 erg m^{-3}
  - Magnetic energy:
    - ARs: B=500 G: $E_{mag,\,AR}$ ~ 10^{10} erg m^{-3}
    - Quiet Sun: B=5 G: $E_{mag,QS}$ ~ 10^6 erg m^{-3}
- Energy in a ($L_0\sim100$ Mm)^3 region
  - $E_{kin}\sim10^{25}$ ergs ; $U\sim10^{30}$ ergs ; $E_{mag,AR}\sim10^{34}$ ergs
- **Magnetic energy is the only possible source of main active events**
  - **Typical total energy content of ARs:** $E_{mag,AR}\sim10^{32}$ - 10^{35} ergs

Ideal & non-ideal MHD

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

- For **R**=η**j** ; Magnetic Reynolds number:
  - Rm >> 1: Ideal MHD
  - Rm << 1: Resistive MHD

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

$$\mathcal{R}_m = \frac{V_0 L_0}{\eta}$$

- Solar Corona:
  - $V_0 \sim 10^5$ m s^{-1}, $\eta \sim 1$ m^2 s^{-1}, $L_0 \sim 10^7$ m
  - **Rm > 10^{12} : ideal MHD is a very good approximation of the solar corona, for large scale structure**

- **Exception to the rule: generation of solar eruption**
  - **Non-ideal effect can be LOCALLY (scale < $1^{1\text{-}3}$ m) important**

vs. active regions scale (> 10^7 m)

“Frozen-in” flux in ideal MHD

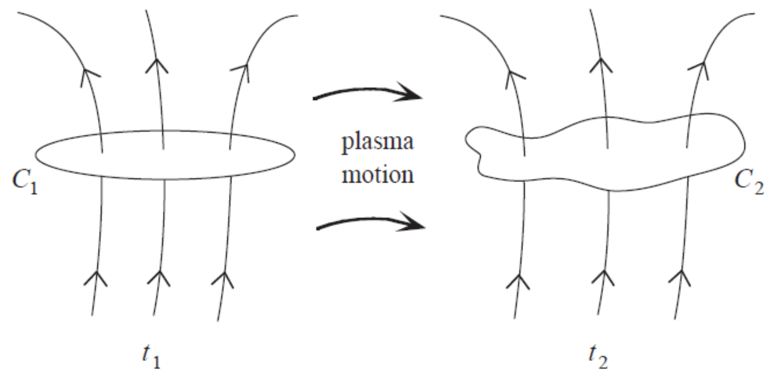
- Ideal MHD induction equation:

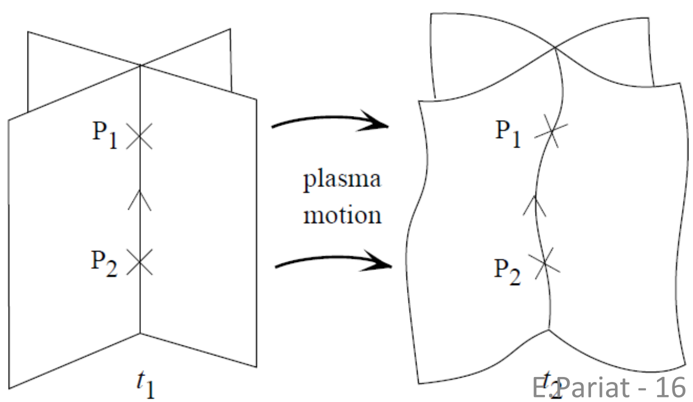
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \cdot$$

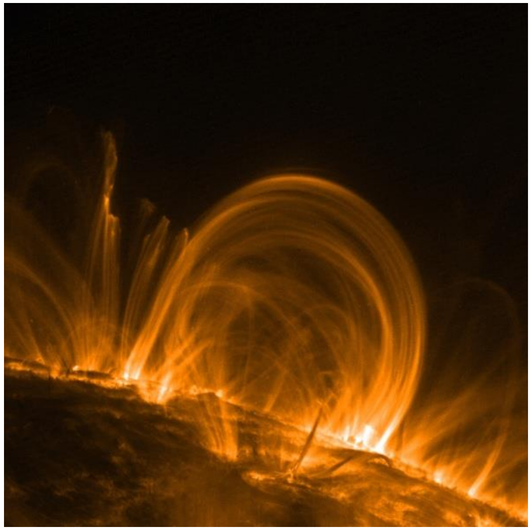
- **Magnetic flux conservation: the flux through any closed co-moving surface is conserved**

$$\frac{d}{dt}\int_S \mathrm{B}\cdot d\mathrm{S} = \int_S \frac{\partial B}{\partial t}\cdot d\mathrm{S} + \int_C \mathrm{B}\cdot \mathrm{v}\times d\mathrm{s}.$$

- **Frozen flux: plasma & magnetic field line are frozen together:**
- ➔ Magnetic field lines are physical objects
- **Connectivity conservation: two plasma elements lying initially on a field line will always do so**
- ➔ field line cannot change its topology / connectivity







Plasma β

- MHD Momentum equation:

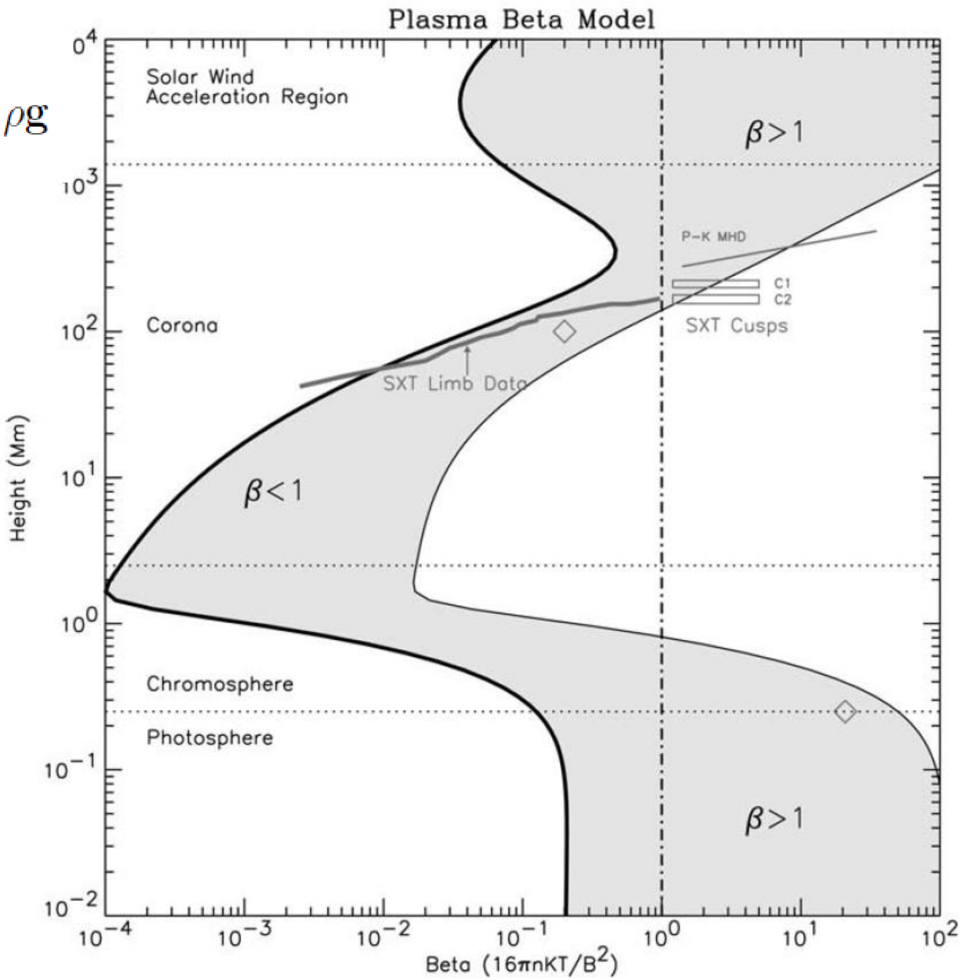
$$\rho\frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v}\cdot\nabla)(\mathbf{v}) = -\nabla P + \frac{1}{\mu}(\nabla\times \mathrm{B})\times \mathrm{B} + \rho \mathbf{g}$$

- Plasma beta:

$$\beta = \frac{2\mu_0 P}{B^2}$$

  - β >> 1: thermodynamic dominates the plasma dynamics
  - β << 1: magnetic field dominates

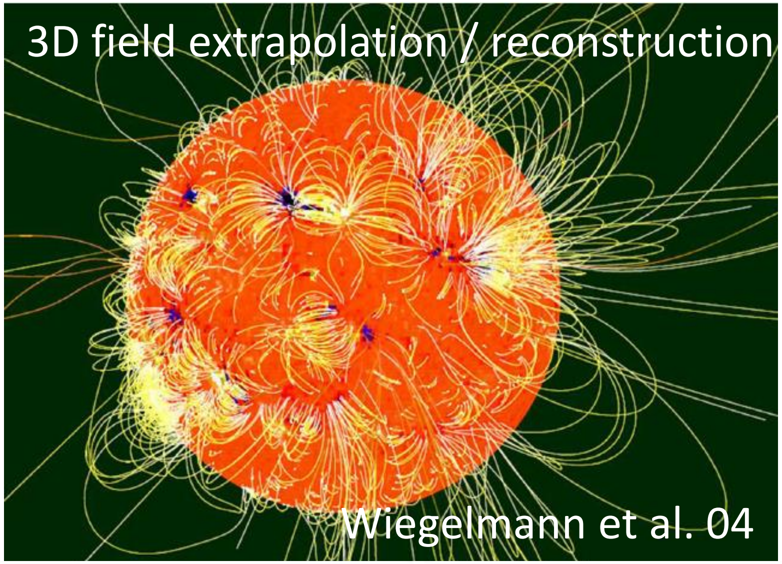
- Corona: β << 1
  - B dominated region: magnetic field fills the whole coronal volume and structure the domain.
- Sub-photosphere: β > 1
  - Plasma dominated: lasma flows advect the magnetic flux tubes

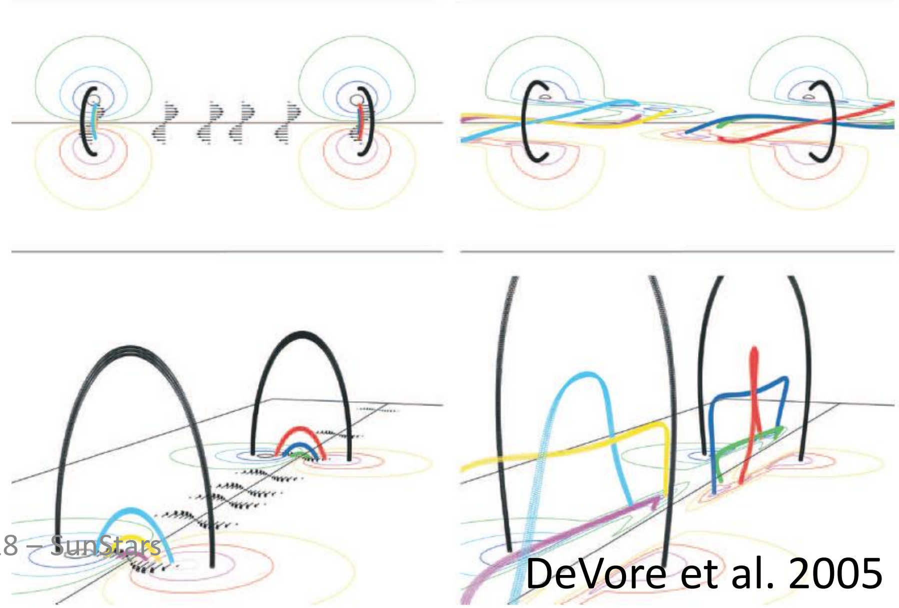


Line-tied approximation

- Coronal field anchored in the lower atmosphere, high-beta region
  - When an Alfvén waves reaches the photosphere
    - Propagation speed drop by a factor 10^4
    - Velocity amplitude drop by a factor 10^8
  - ➔ Quasi-complete reflexion back into the corona

- **Line-tying approximation: from the corona, the low atmosphere is considered as to an infinitively massive and conductive layer**
  - Dynamic of the corona do not affect the lower atmosphere
  - Coronal field is driven, by motion at the Photosphere/Chromosphere





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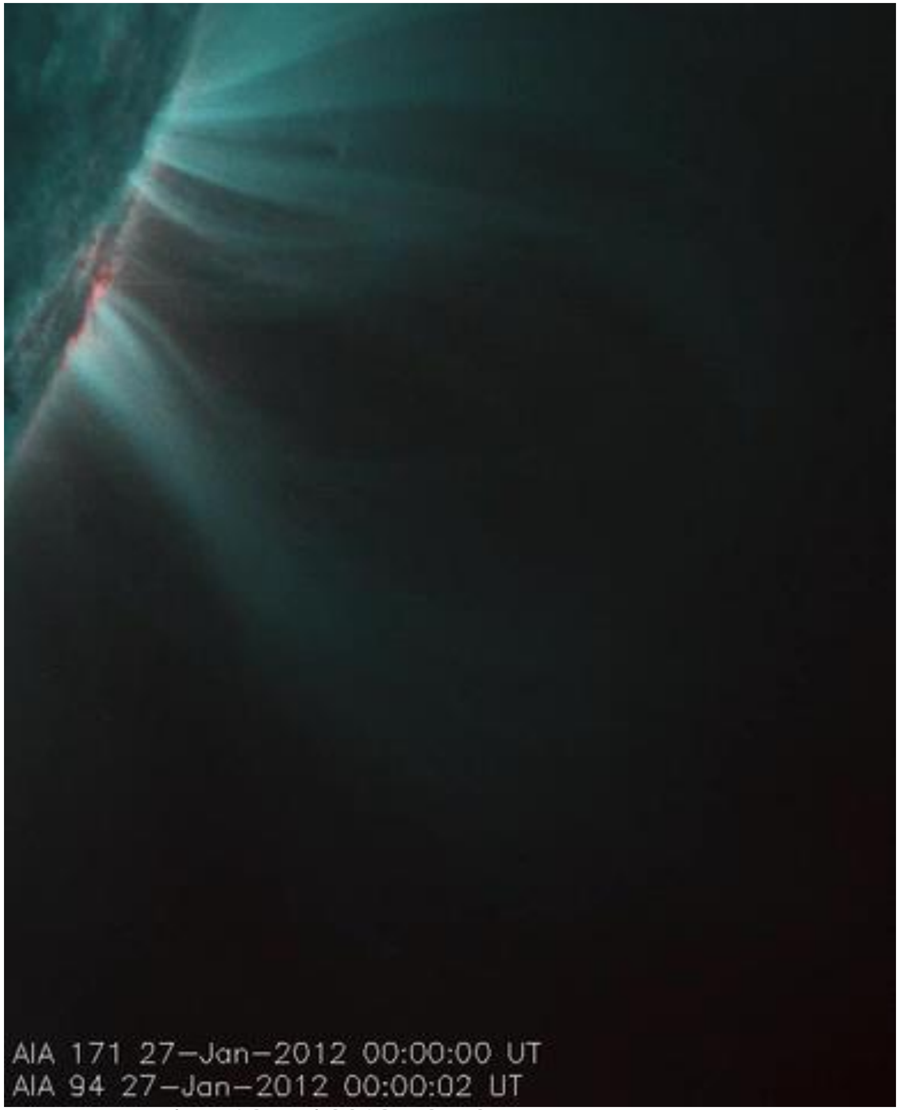
Energy release mechanism

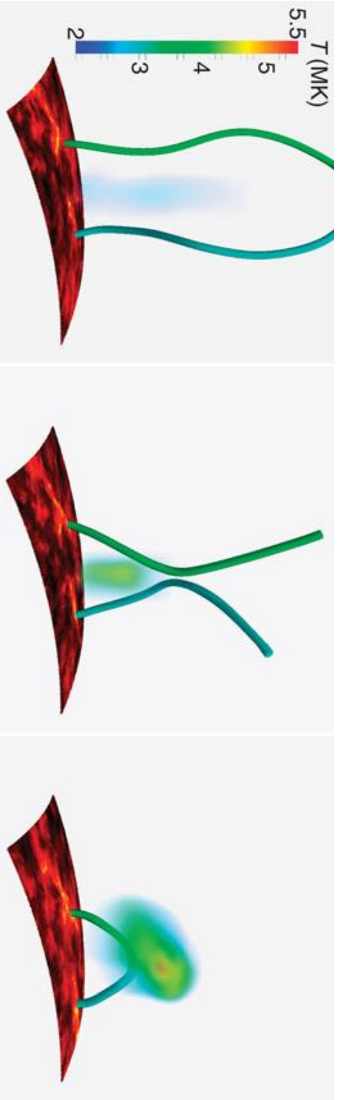
- The energy release mecanism(s) must:
  - Develop in a magnetically dominated environement
  - Extract the free magnetic energy
  - Allow the acceleration of particles to very high energy
  - Allow the ejection of plasma
  - Allow some disconnection of the magnetic field
  - Be impulsive, i.e. existence of a switch-on effect

At the heart of solar eruptions: magnetic reconnection

- **Solar eruptions are related to the brutal reconfiguration of its magnetic field**

- Magnetic reconnection is the physical mechanism that enables this reconfiguration and is thus central to eruptions





Li et al. 2015

Magnetic reconnection

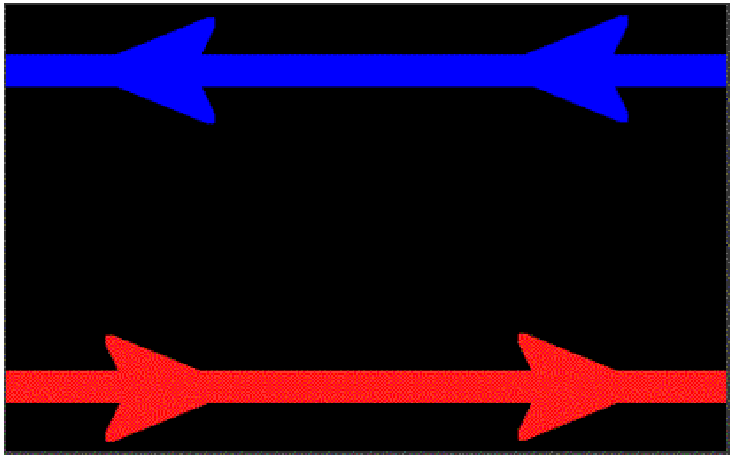
- **Magnetic reconnection is the mechanism that correspond to the local violation of the ideal MHD conditions**

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

- Magnetic Reynolds number:
  - $R_m >> 1$: Ideal MHD ; $R_m << 1$: Resistive MHD

$$\mathcal{R}_m = \frac{V_0 L_0}{\eta}$$

- Solar Corona: V_0~1 km s-1, η~ 10^{-3} m^2 s^{-1} :
  - R_m ~1 for L_0~1 m: recon. is a VERY localized process relatively to solar scales

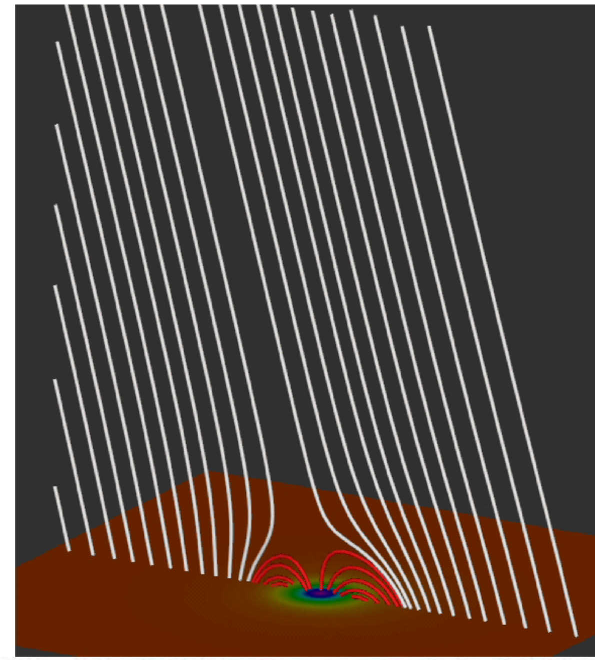


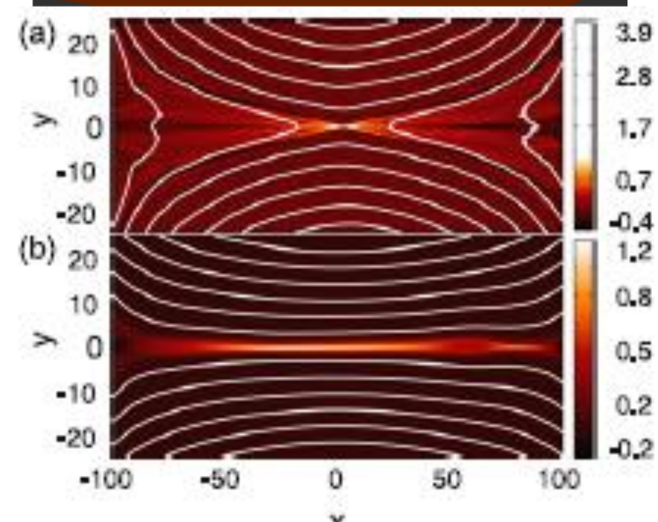
- **Magnetic reconnection locally diffuse the plasma and allows a change of connectivity of the field lines**

The do and do not of reconnection

- **Magnetic reconnection does change the connectivity of the magnetic field**

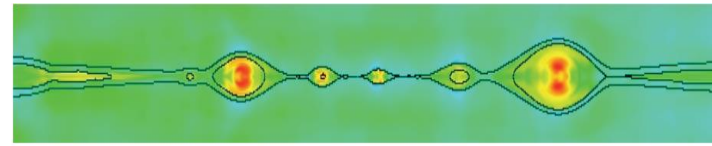
- Strictly speaking, **reconnection does not:**
  - **Dissipate magnetic energy:** dissipation is due to reconnected field line slingshot and shocks.
  - **Heat the plasma**: post reconnection compression and joule heating by the current sheets
  - **Accelerate particles**: particle are likely accelerated by the electric currents of the current sheet
  - Dissipate magnetic helicity

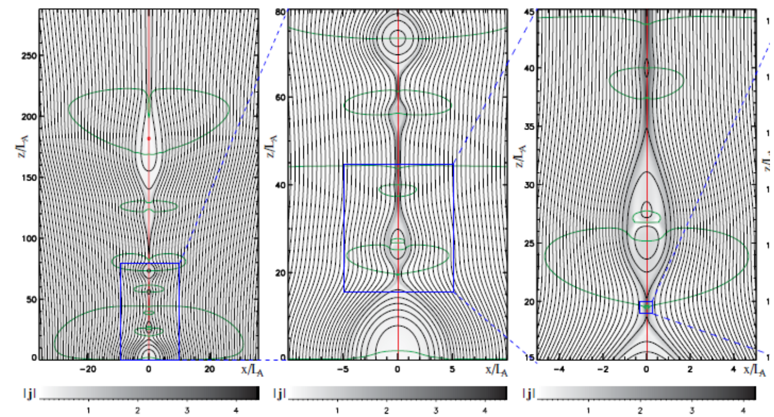




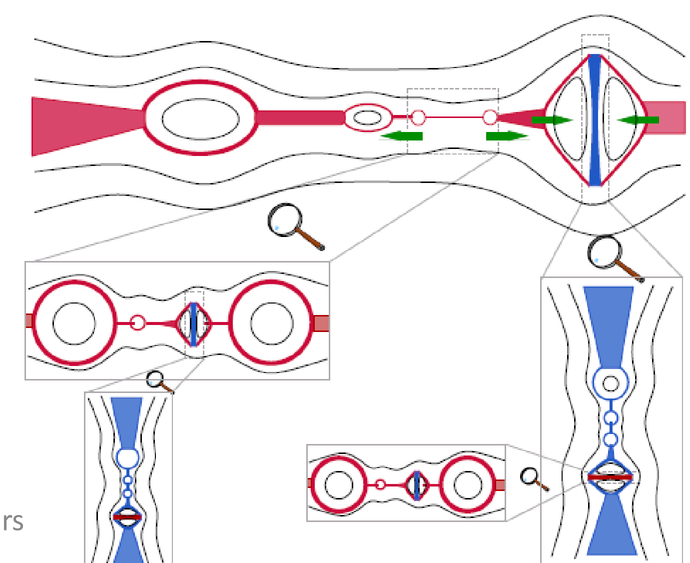
The do and do not of reconnection

- **Magnetic reconnection does**
  - **creates plasmoids which fragment the electric current sheets,**
  - ➔ induce strong non-linear effect that can enhance electric current intensity





- While magnetic reconnection has been mostly studied in 2D, its 3D dynamics offers a much wider range of dynamics: still an extremely lively domain of plasma physics



- **Reconnection is a schizophrenic mechanism**
  - **Magnetic reconnection is an MHD concept, and the condition of its trigger are organized at the large MHD scales.**
  - **HOWEVER, its precise descriptions requires a full kinetic description, outside of the validity of the MHD paradigm.**

Evidences of reconnection

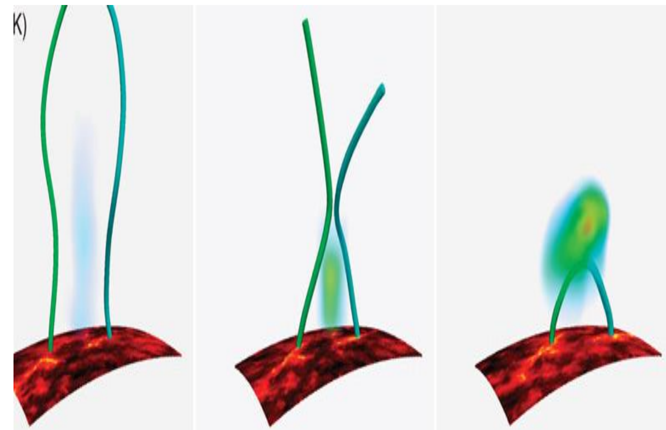
- **No direct observation of reconnection but numerous consistent evidence**

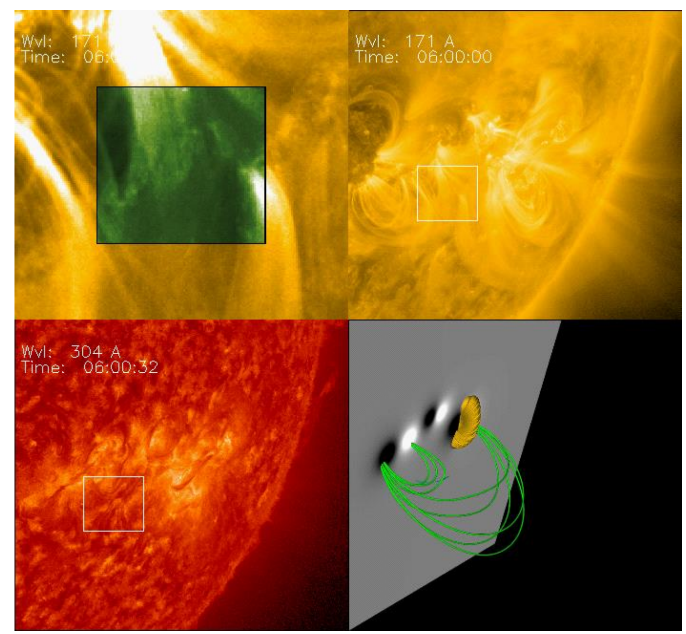
- Reconnection is fully consistent with
  - Energetic events (10^{20}-10^{25}J).
  - Violent energy release (cf. trigger mechanism)
  - **Non-thermal particles can be accelerated at the current sheets involved in reconnection**
    - Though details of the mechanism poorly understood

- Change of the coronal loops connectivity during active events

- Observed structures consistent with reconnection scenarios
  - Cusp shaped loops
  - Supra-arcades downflows
  - CME current sheet

- Reconnection models (analytical and numerical) can reproduce a large variety of active phenomena





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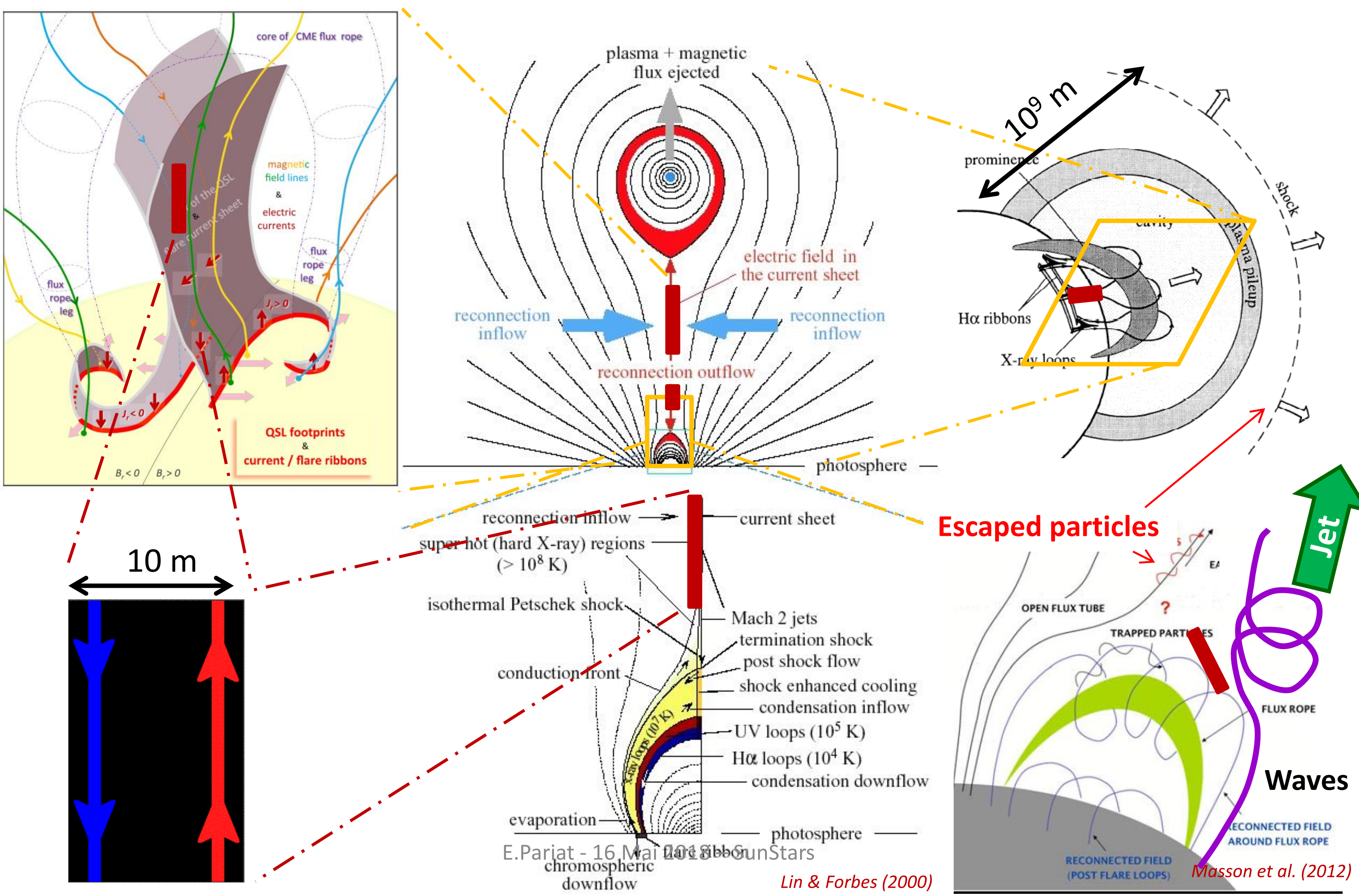
The standard model

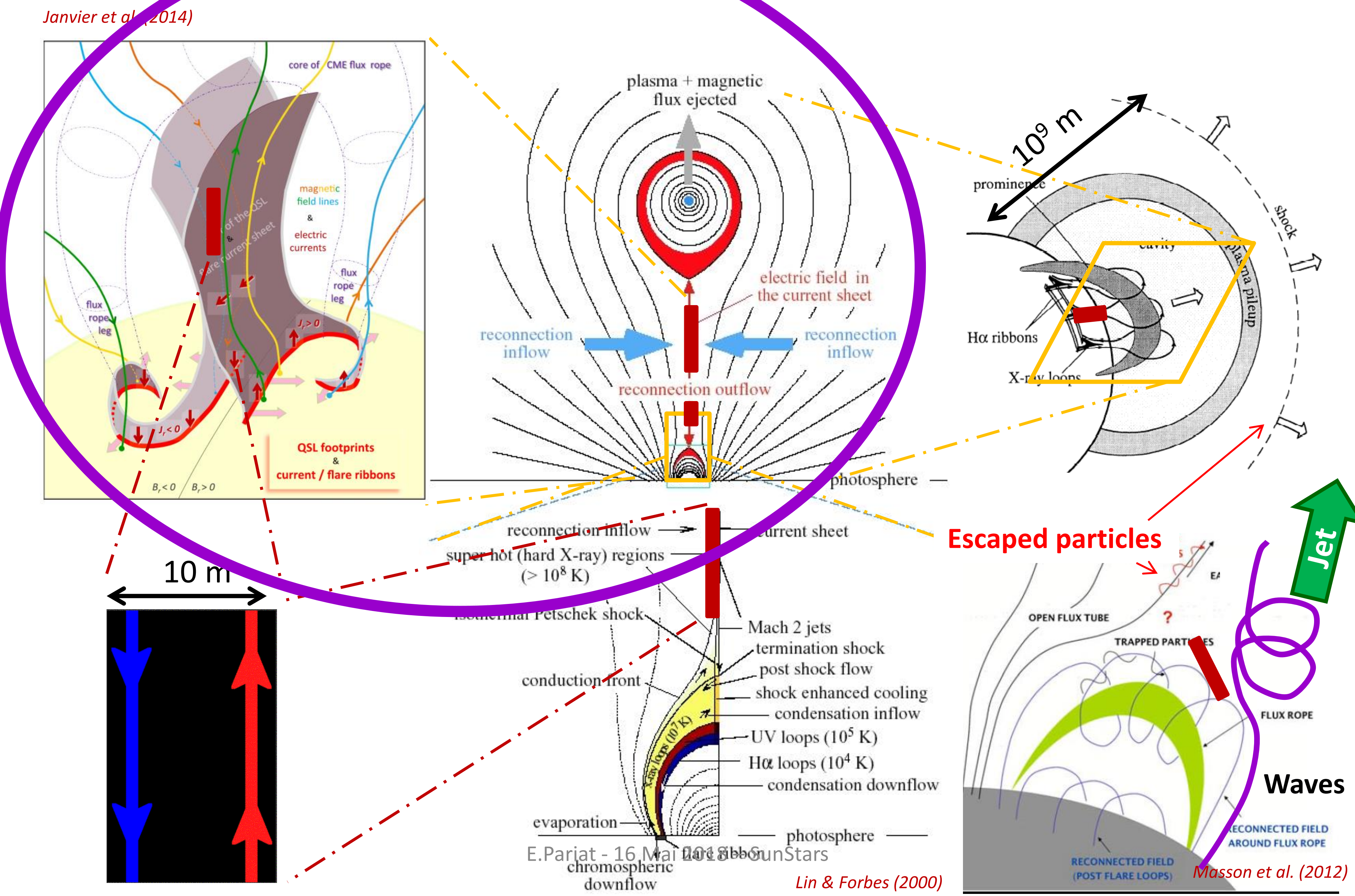
Janvier et al. (2014)



Lin & Forbes (2000)

Masson et al. (2012)

The standard model



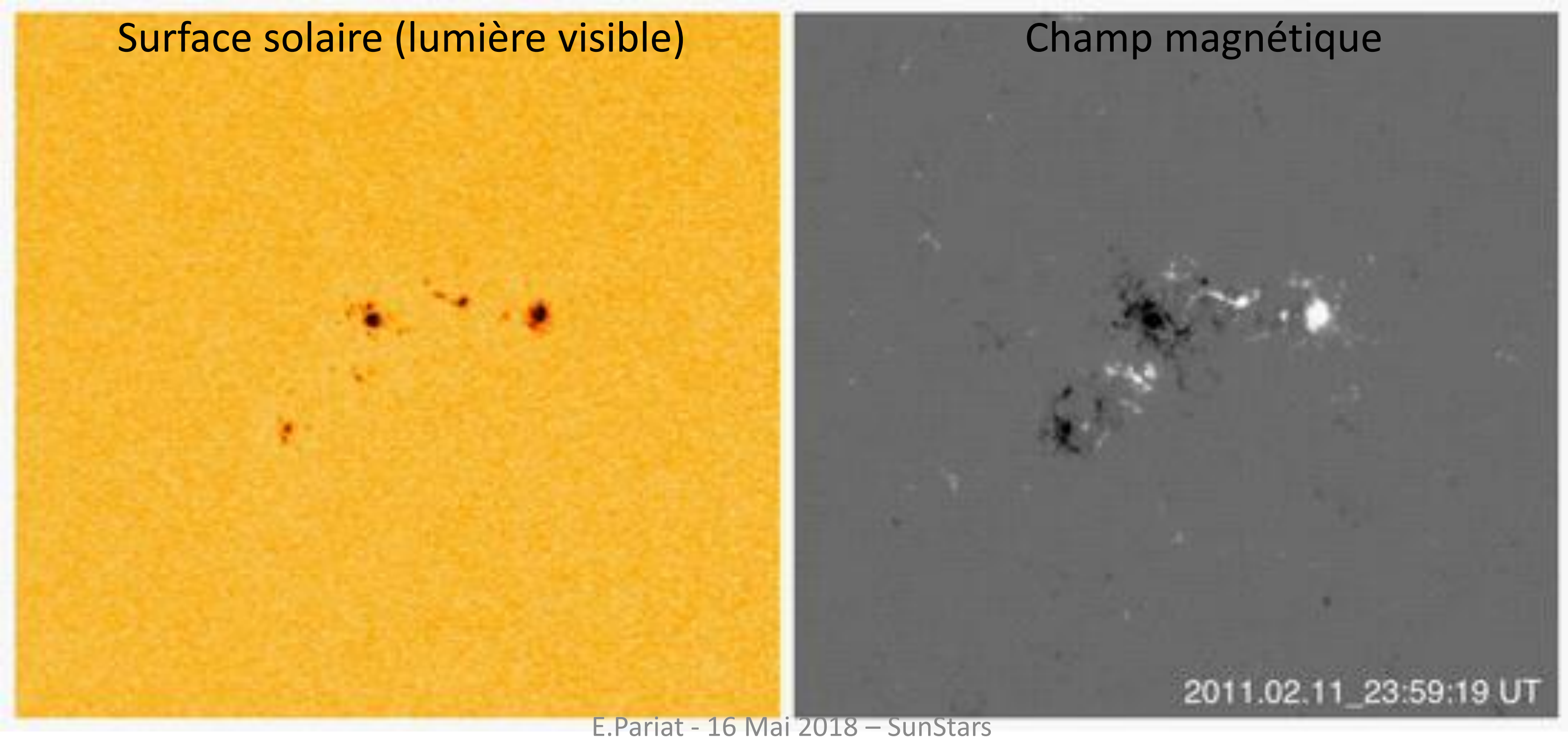
Flux emergence

- The solar atmosphere is a magnetically dominated environment
  → no dynamo effect & no field intensification
- **➔ coronal magnetic field and magnetic energy are generated and transported from the solar interior thanks to "magnetic flux emergence" processes.**

Courtesy
NASA SVS

Emergence and eruptivity

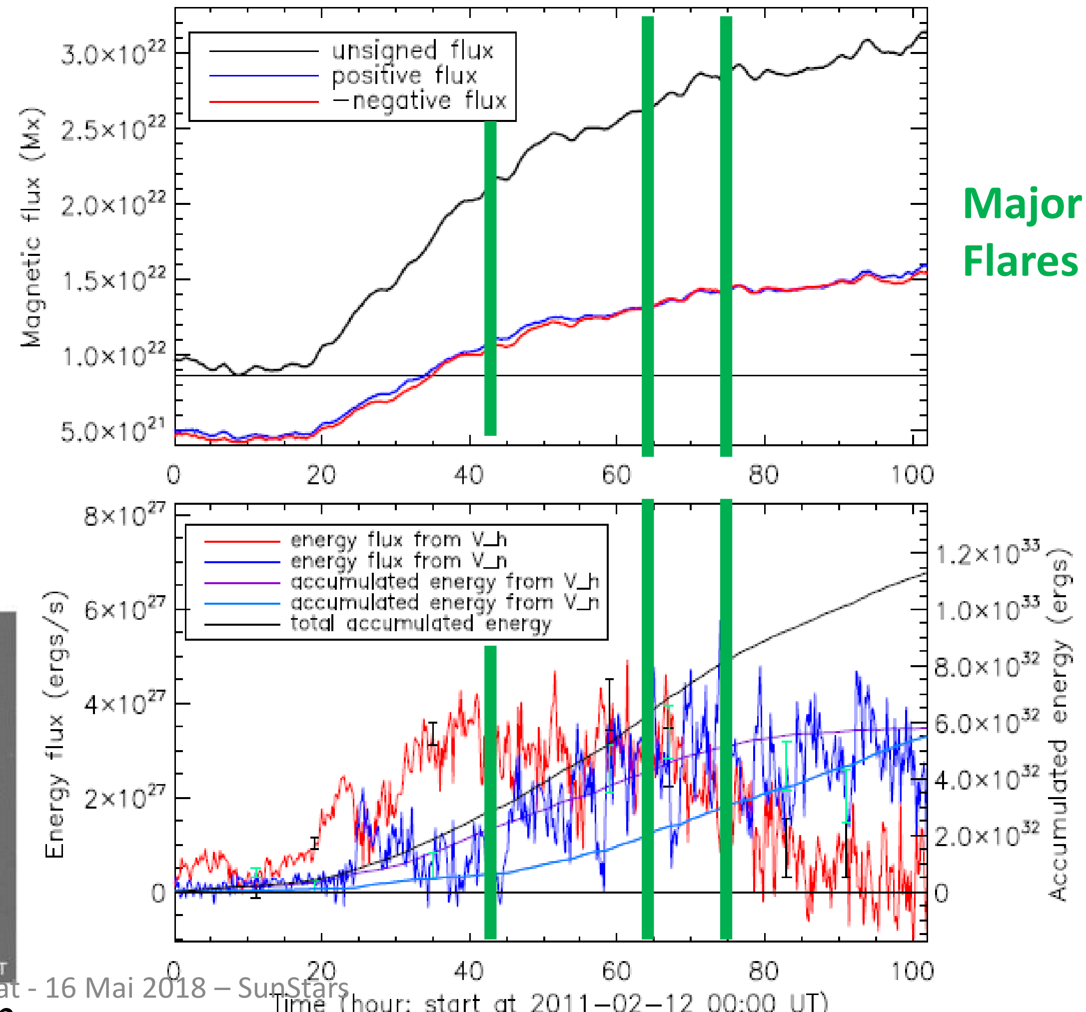
- Before and during a solar flare there is no brutal variations at the solar surface: flux emergence is a relatively smooth process relatively to eruptivity.
- **As with volcanism, there is no easily-observed known precursor sign to solar eruptions.**

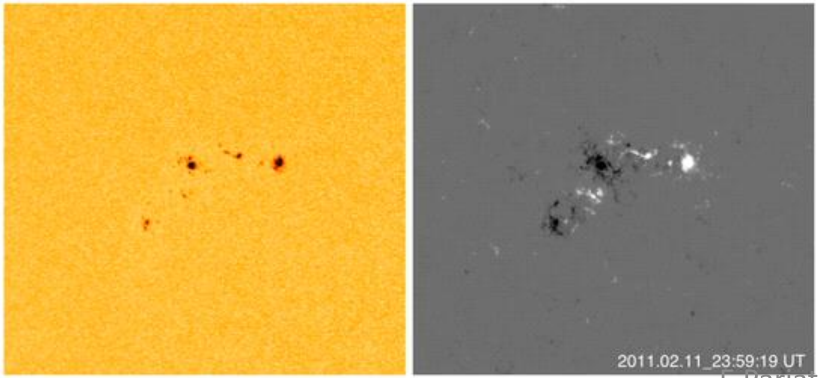


(Liu & Schuk 12)

Energy build-up

- Smooth changes of the magnetic flux and of the magnetic energy prior to a flare
- ➔ **Energy release trigger is not primarily correlated with the driving mechanism of the energy injection.**
- During active events the photospheric field distribution is almost unchanged

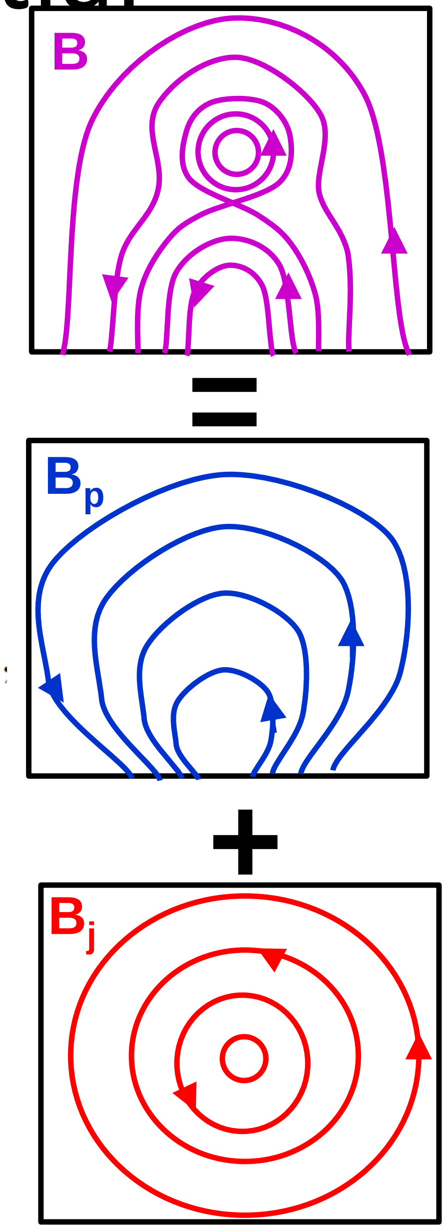




White light (SDO/HMI) B_{los} magnetogram

Potential & Non-Potential

- **Not all magnetic energy are equals!**
- **For a given distribution of a magnetic field on the boundary of a domain, there is an unique decomposition of the magnetic field in potential and non-potential field.**

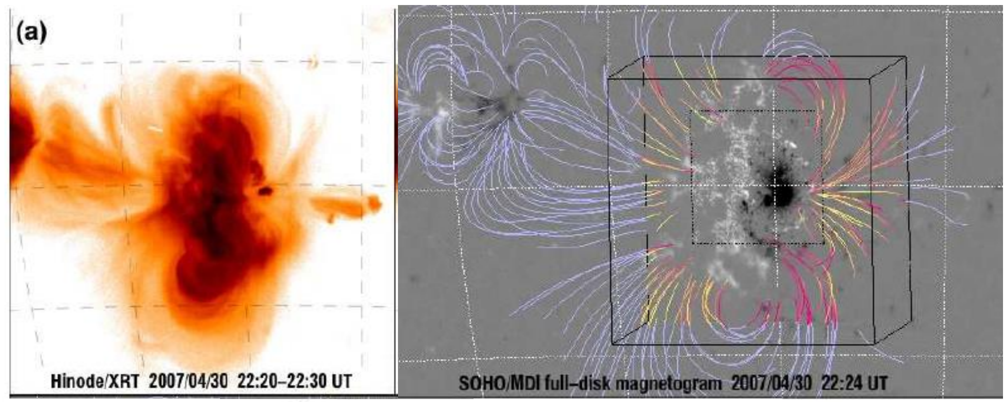


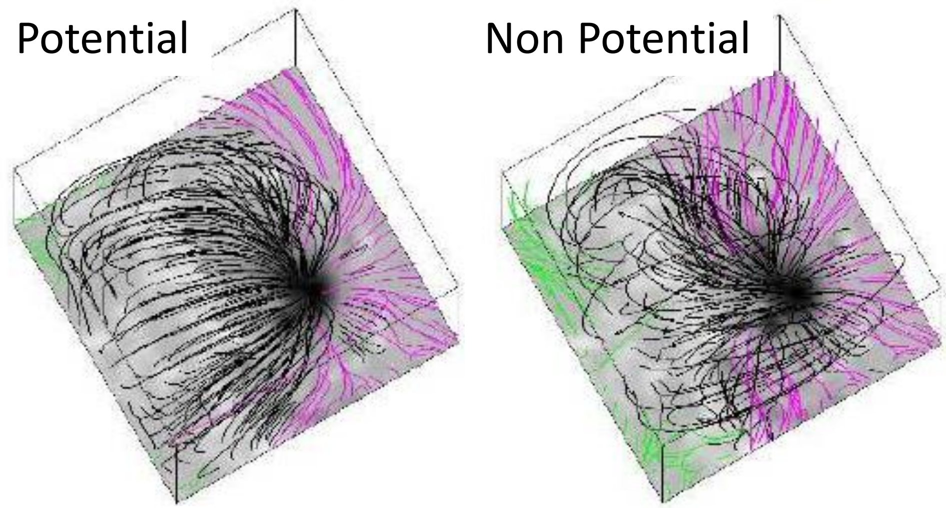
- **Potential field:** $\boldsymbol{B}_{\mathrm{p}} = \nabla\phi, \qquad \hat{\boldsymbol{n}}\cdot(\boldsymbol{B}-\boldsymbol{B}_{\mathrm{p}})|_{\partial\mathcal{V}} = 0$
  - the potential field has the same normal distribution than the studied field on the whole boundary
- **Non-potential field:**
  - The non potential field "carry" electric currents of the studied field. $\nabla\times\boldsymbol{B}_j = \nabla\times\boldsymbol{B} = \mu_0\boldsymbol{j}$
- **Thomson theorem:** $E_{mag} = E_{pot} + E_{free}$
  - Total magnetic energy is the sum of the mag. energy of the potential field and the "free" magnetic energy (mag. energy of the non-potential field)

Free magnetic energy

$$E_{mag} = E_{pot} + E_{free}$$

- Observationally based fact: during an eruption, **B** distribution barely changes
  ➔ Bp and Epot do not change
  ➔ the energy source of an eruption is the free magnetic energy
- **To erupt, to flare, the magnetic system prior to an active events must be**
  - **non-potential**
  - **have free magnetic energy**
  - **must carry electric currents.**
- **Free magnetic is a necessary condition for eruptivity but it is not a sufficient condition.**
  - Magnetic structures with large free energy are more likely to flare.
  - Free energy does not inform on when that region will flare



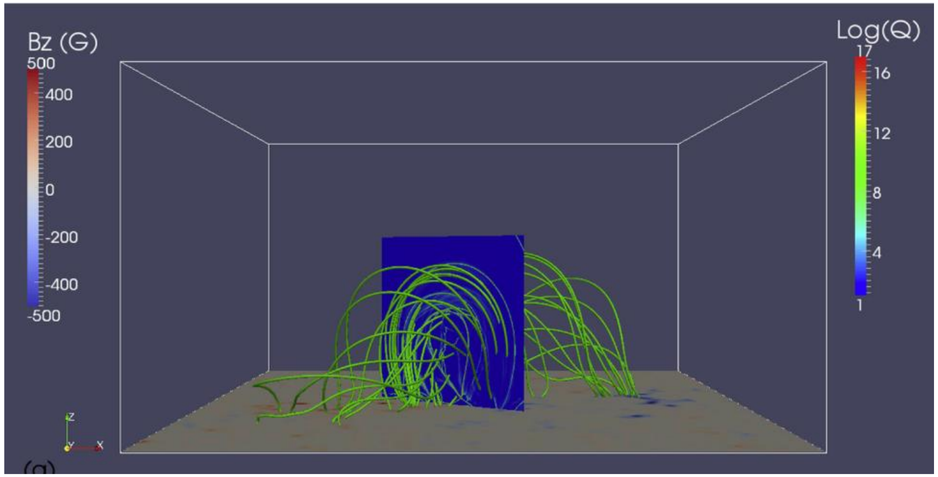


Active-Region Coronae Classification Percentages

Poteniality (1)	Actual (2)	Nonflaring (3)	Flaring (4)	<f (5)	>f (6)
Near	51%	22%	28%	49%	2%
Non	49%	7%	42%	9%	40%

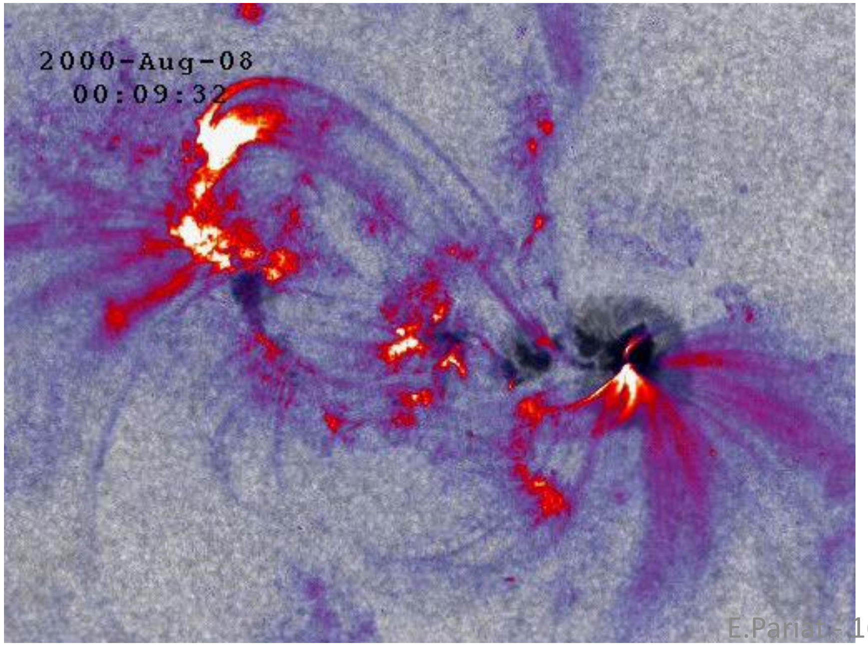
Forms of non-potentiality

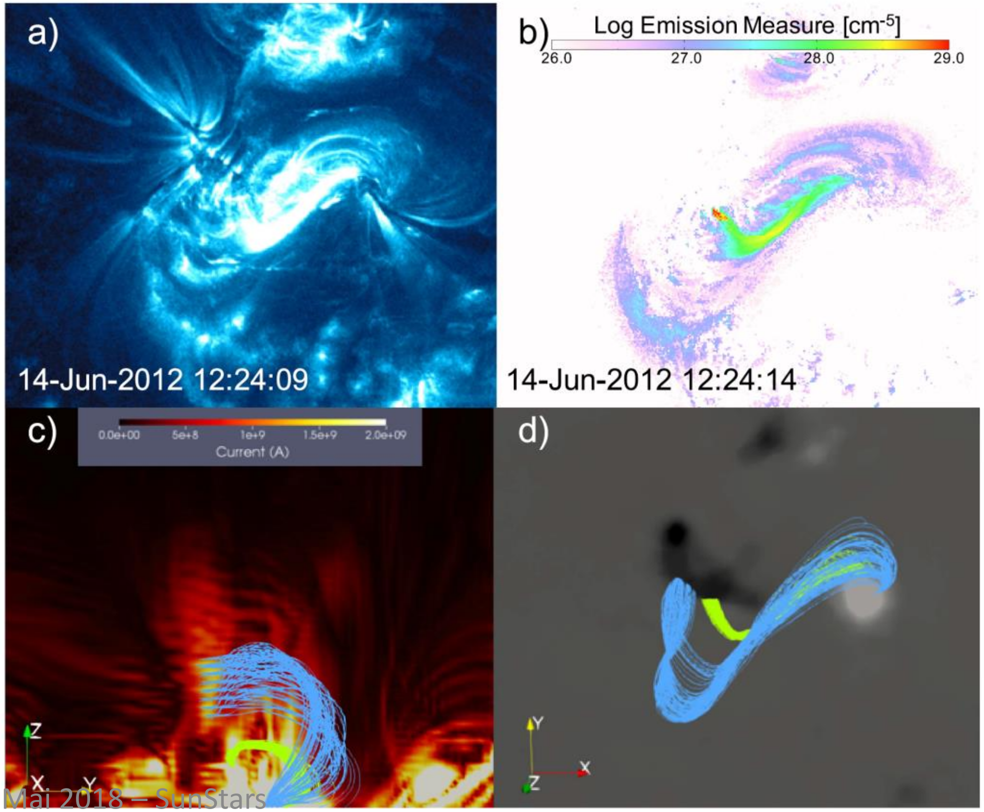
Non-potential fields
= volume electric-current carrying fields
= sheared or twisted magnetic field
= important magnetic helicity content



Guo et al. 17

Rotation of an AR

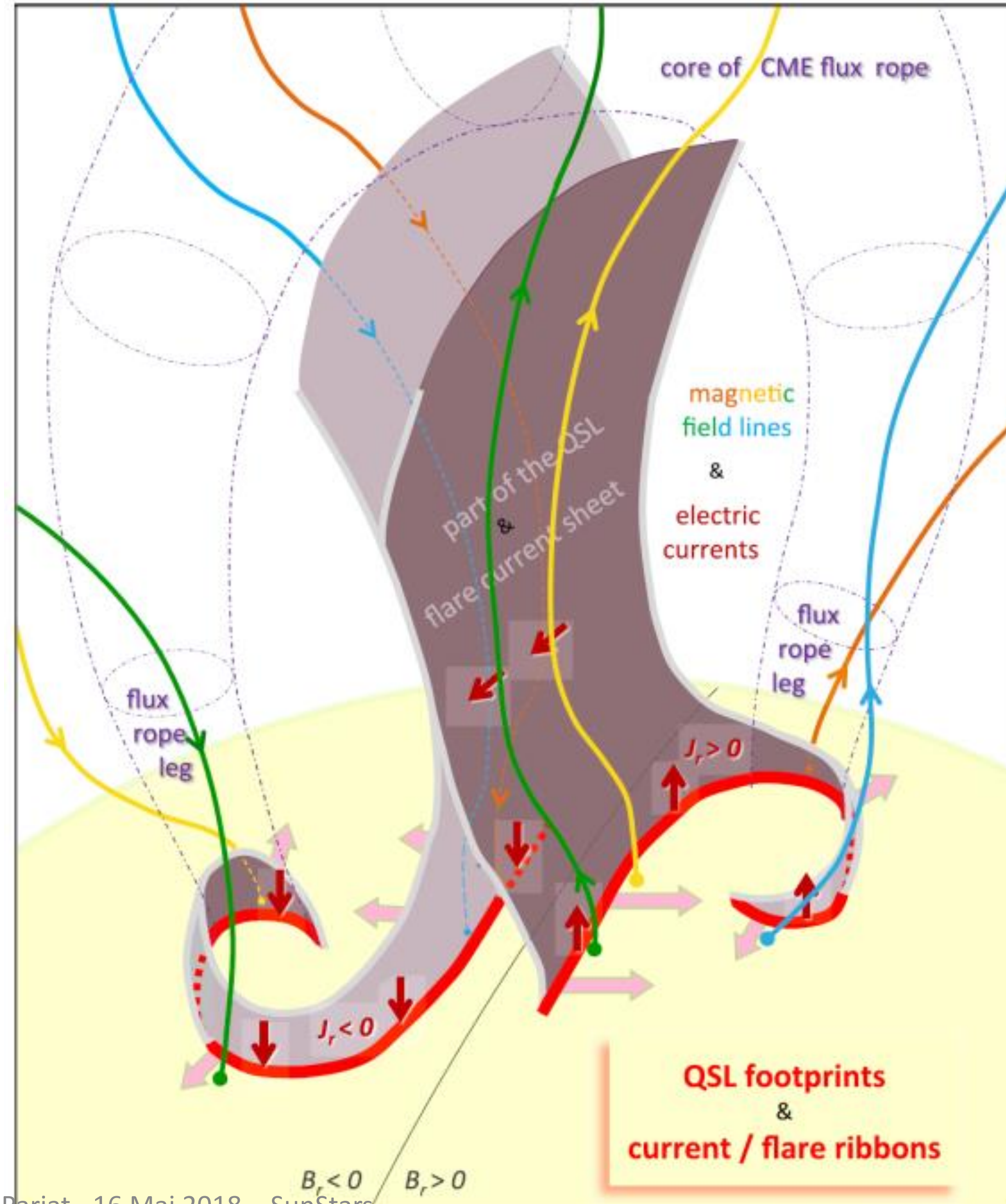




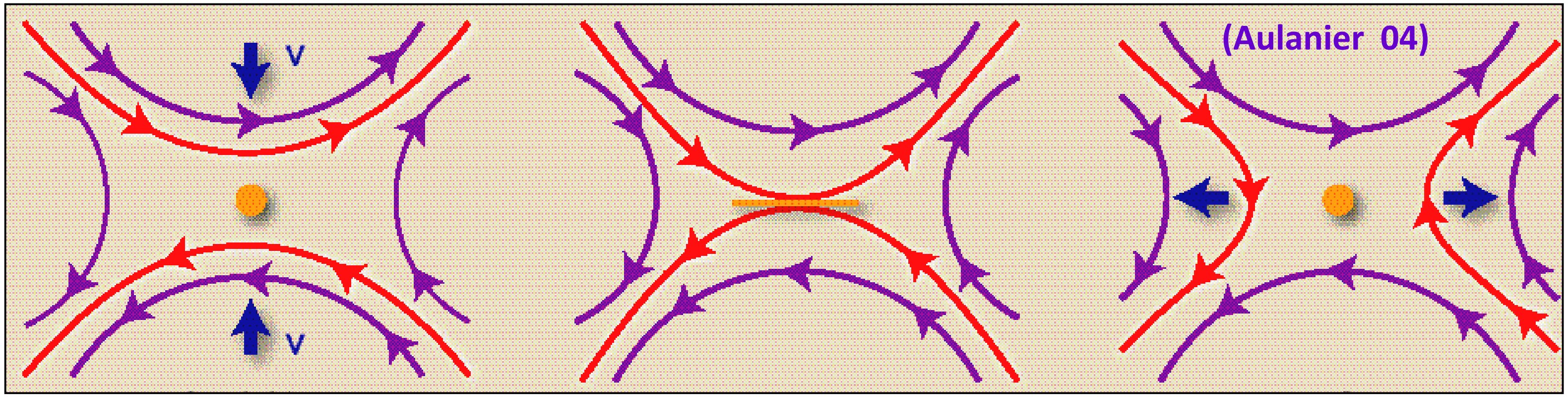
James et al. 18

Where can reconnection takes place?

- Eruptions are untypical events.
- They do not occurs everywhere
- They do not occur all the time
- ➔ reconnection only occurs in specific places and conditions!



Magnetic reconnection



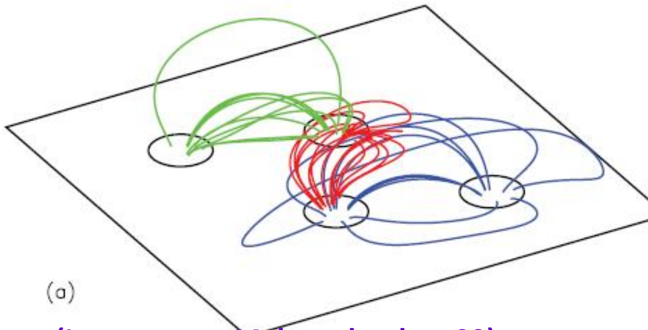
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B})$$

- Reconnection occurs where/when **the resistive term** is high:
  - Possibly depends on local plasma condition: η can increases with temperature, depending on type of collisions, ….
  - Depends on the geometry of the magnetic field: the field must present strong rotational of the electric current density, i.e **localized thin current sheet** $\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$.

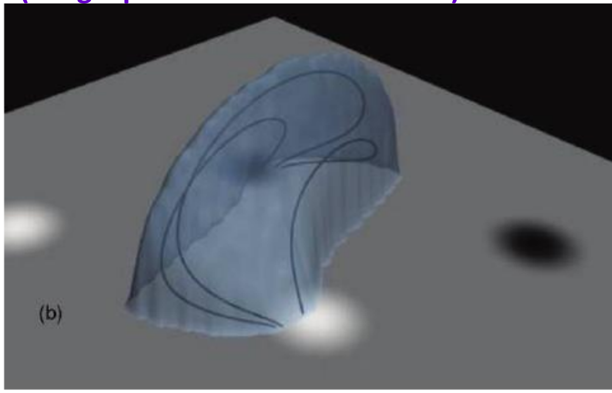
- Magnetic reconnection is a challenging process to understand because it couples strongly local and global scales

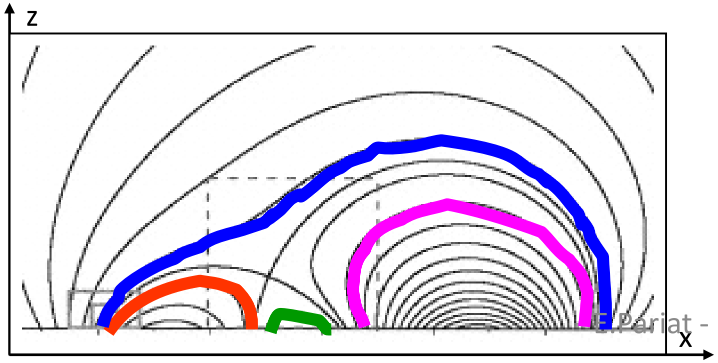
How are current sheet formed ?

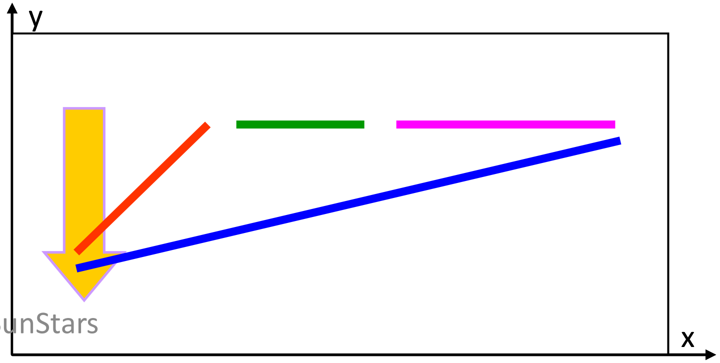
- 3D coronal field is formed by several connectivity domains
  - F.l.s of a same connectivity domain can be continuously deformed from one to another
- **Separatrix surface**:
  - boundary between 2 connectivity domains
  - **surface of discontinuity of the connectivity**
  - **Separatrice**: particular field line of a separatrix
- **Quasi-spontaneous current sheet formation along separatrix surface**
  - Displacement around the separatrix
  - ➔ Jump in B_y
  - ➔ **Non null localized current density** $\mu_0 \mathbf{J} = \nabla \times \mathbf{B}.$



(Longcope et Malanushenkoa 09)







Volume currents & current sheets

- In MHD, electric currents are induced by the field

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}.$$

  - Lorentz Force

$$\mathbf{F}_L = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{\mu_0}$$

- **Force free volume currents**

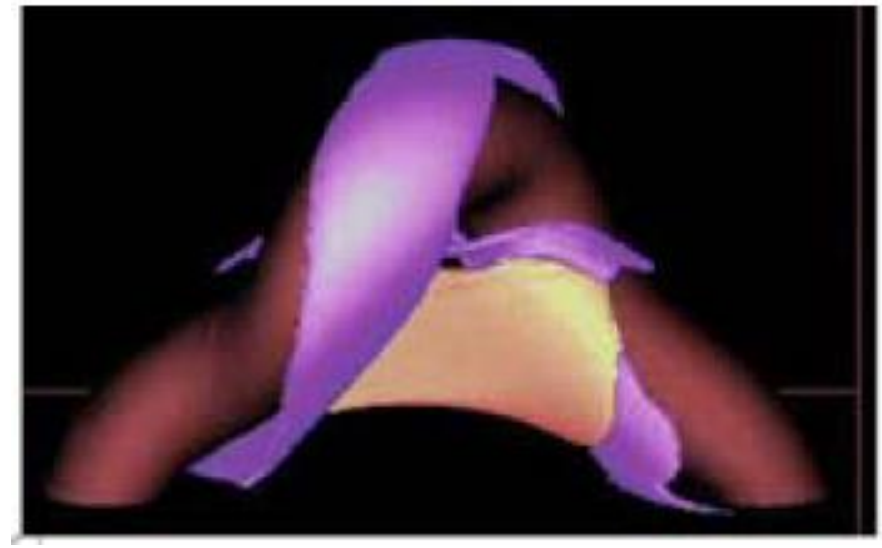
$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0,$$

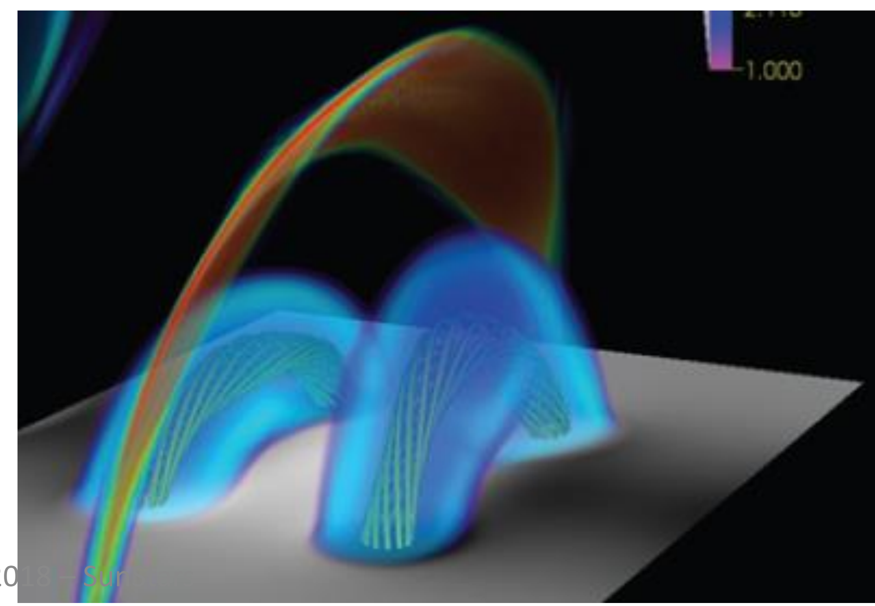
  - Field aligned

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}.$$

  - Important for free energy accumulation
  - Stable structure in general

- **Non-force free current sheets**.
  - Non field aligned
  - Lorentz force present
  - Important for reconnection





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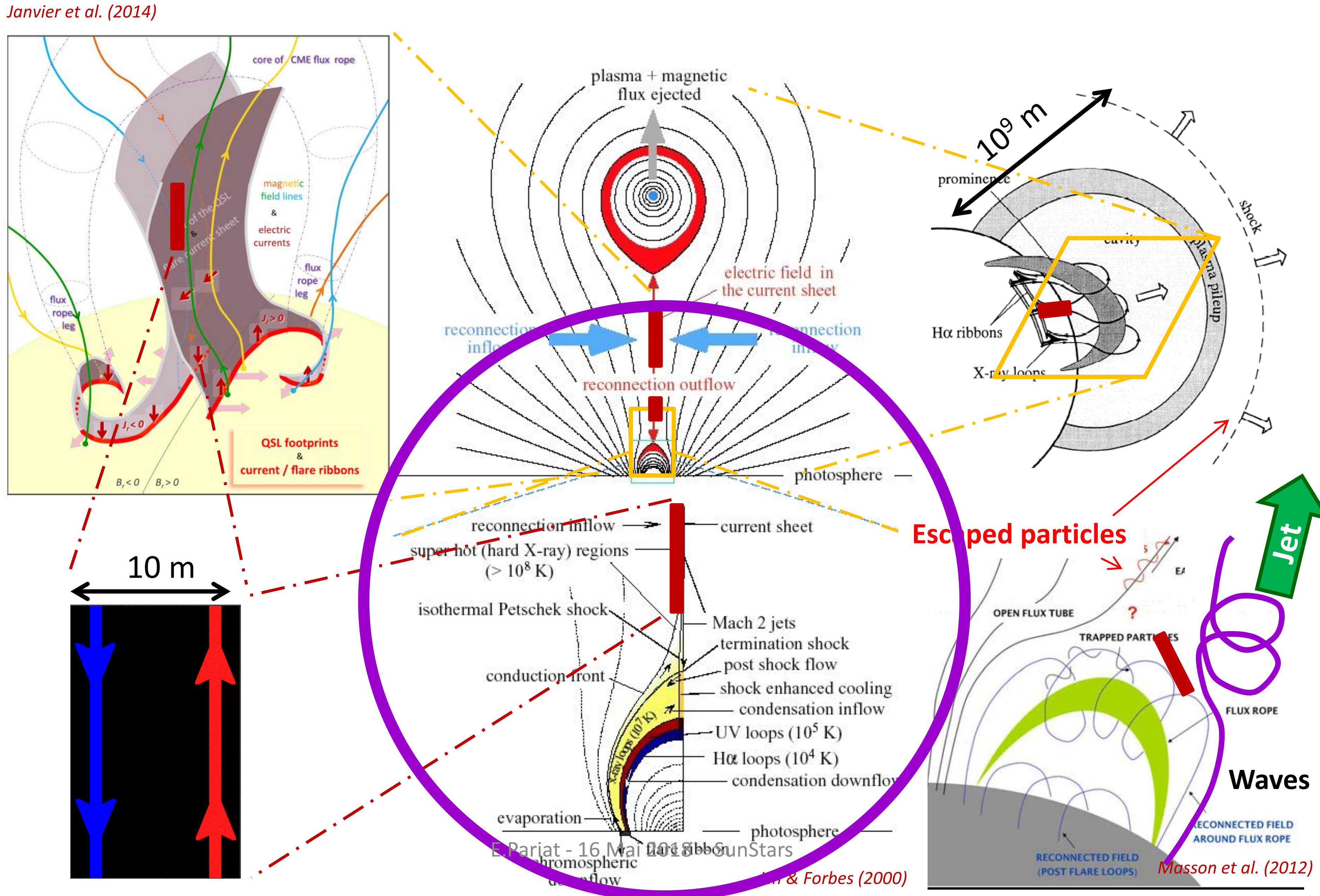
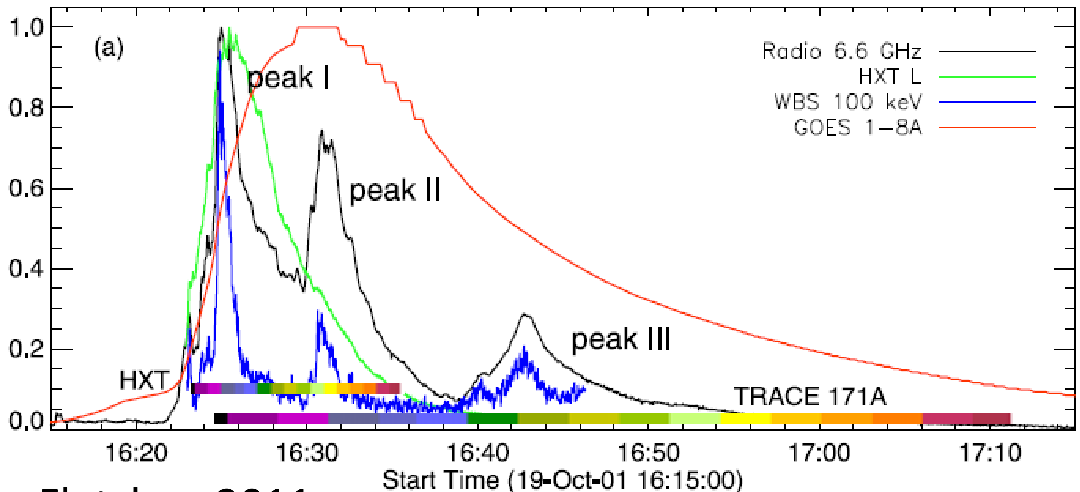
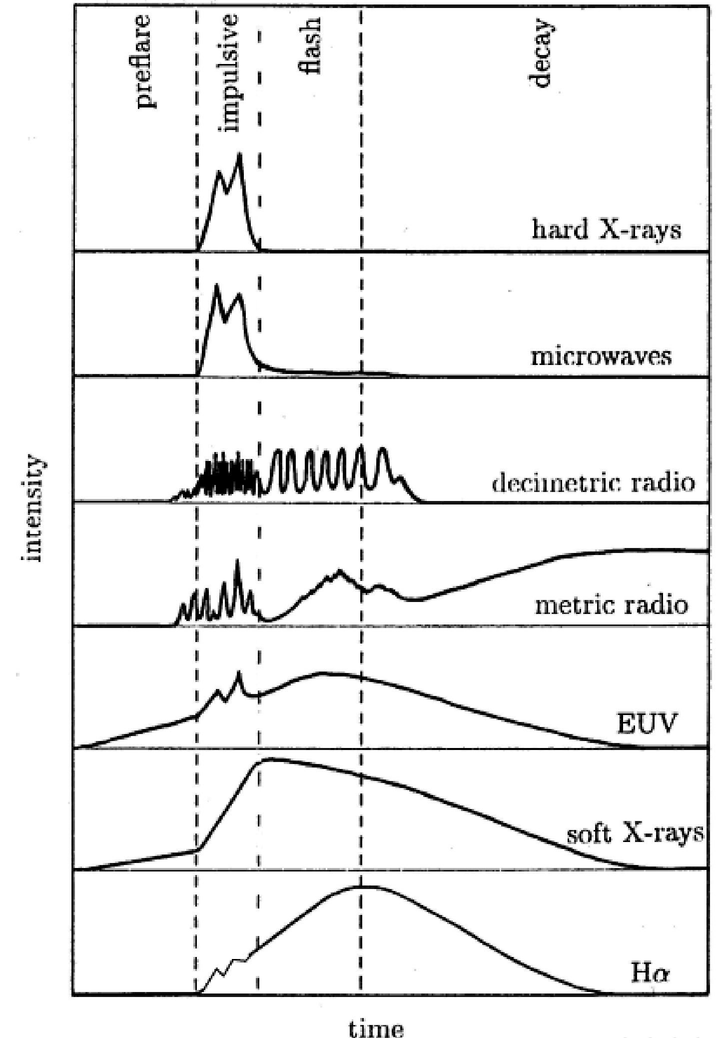
The standard model



Reminder: flare phases



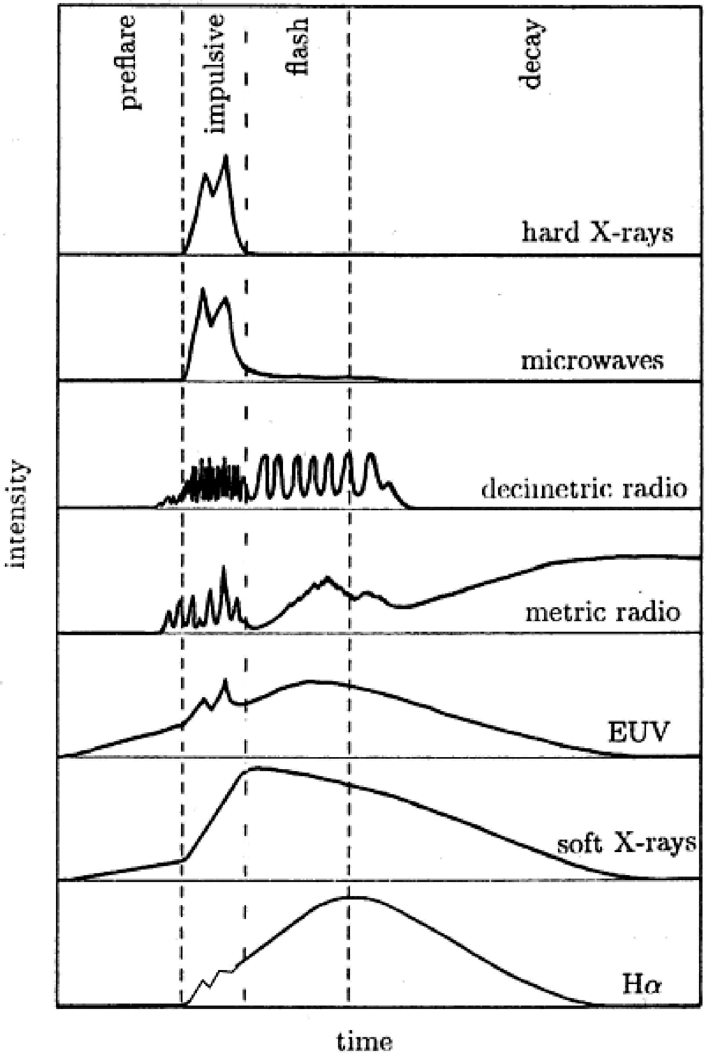
Fletcher, 2011



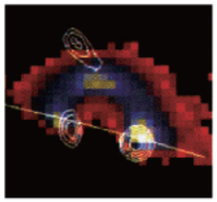
Benz, 2002

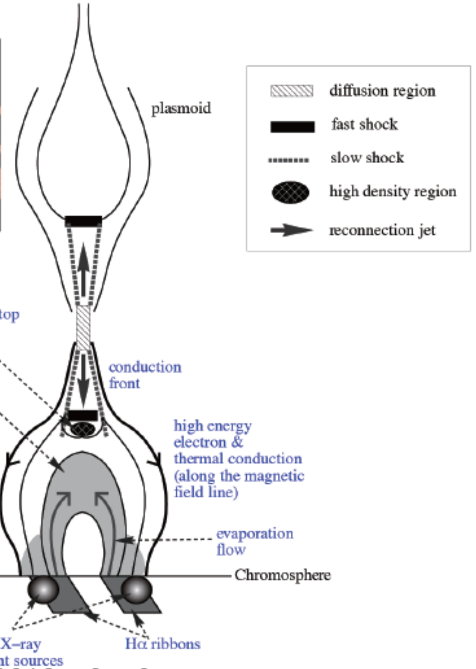
- Impulsive:
  - Hard X rays (HXR), Microwave & White light emission
  - Slow growth of EUV and Soft X rays (SXR)
- Gradual:
  - EUV, SXR, chromospheric lines

Flare Emission : Impulsive Phase



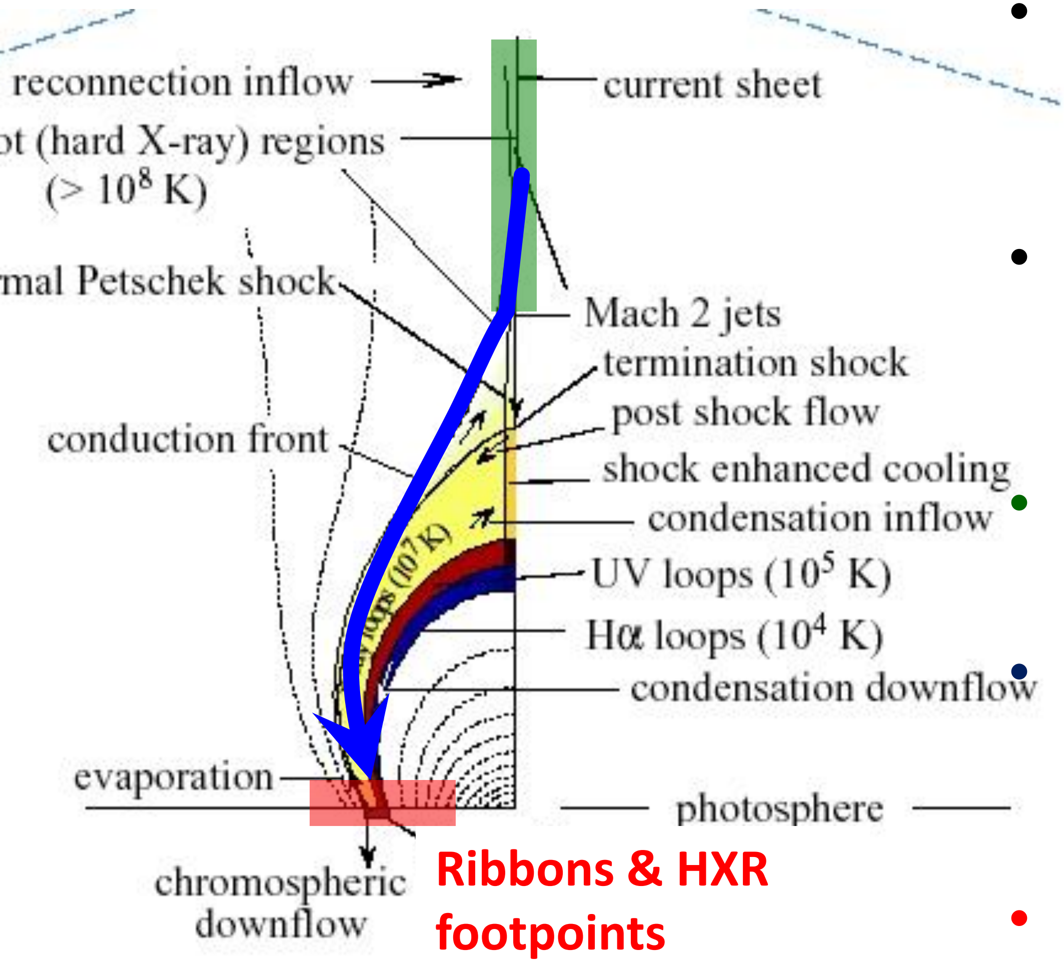
- **The thick target model: Injection from a (coronal) accelerator into a (chromospheric) passive target**
- Accelerated e- beam flowing along field lines → gyrosynchrotron emission observed in microwave
- e- beams interacting with dense plasma: **Bremstrahlung**
  - **Hard X ray foot point emission**
  - Coronal emission (If corona dense enough:)
- Accelerated ions interacting with dense plasma: γ rays





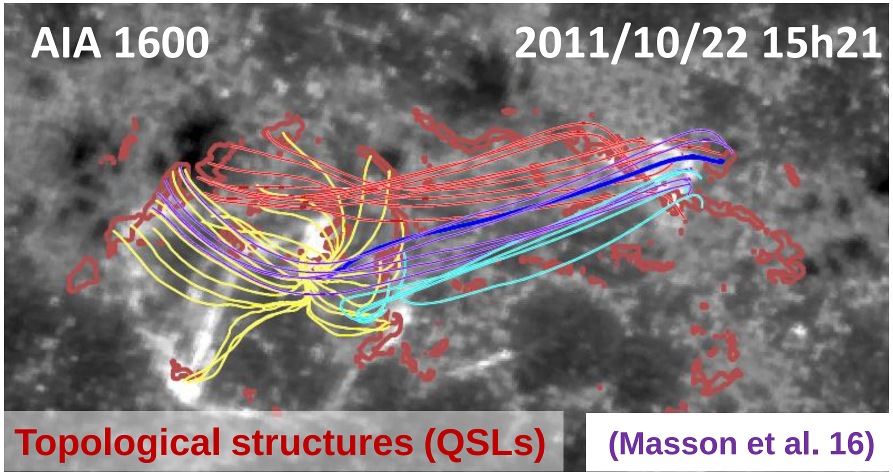
Impulsive phase (or impulsive flare)

Ribbons & HXR link with magnetic field

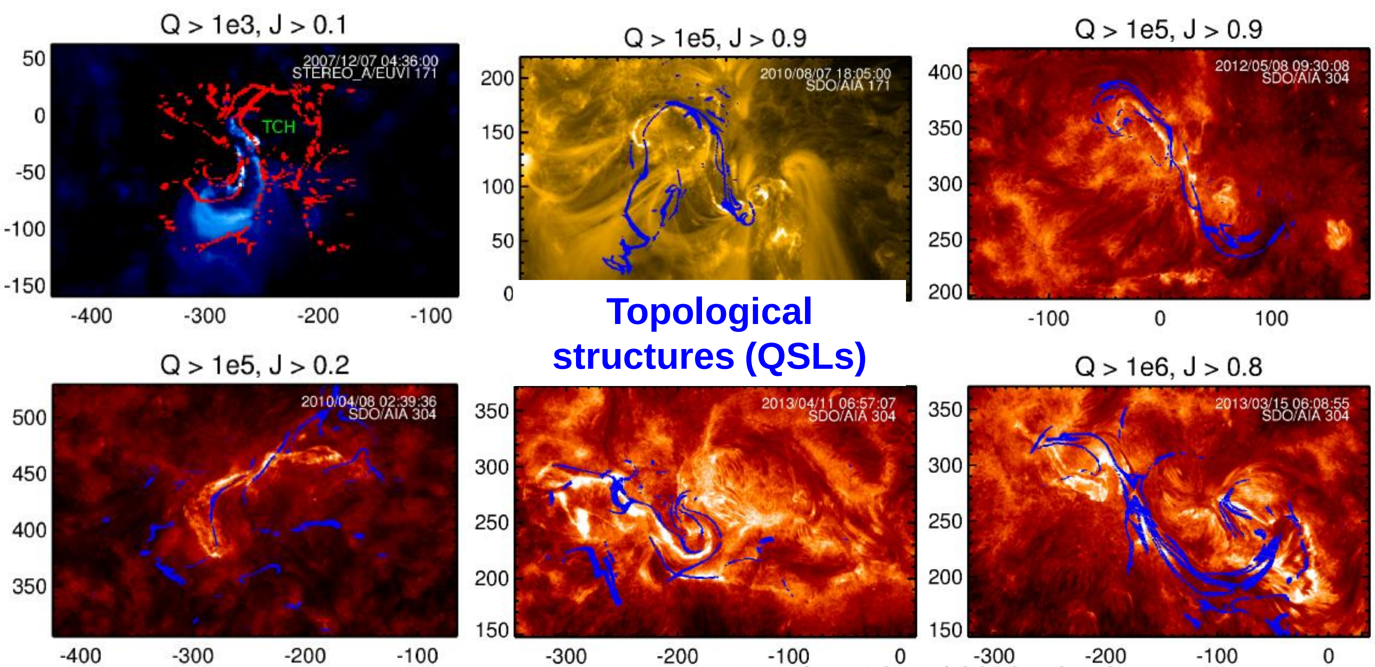


- Standard model: **accelerated particles/energy** flowing from the **reconnection site**
- interacts with lower denser layers ➔ formation of **Ribbons and HXR footpoint**
- **Reconnection** occurs where current sheets are located
- **Separatrices** defines preferential sites for current build-up hence **reconnection**
- ➔ **Ribbons** are located at the footpoint of **separatrices**

Ribbons and topological structures



- Topological analysis allows to deduce the positions & shapes of the ribbons
- Long record of excellent match between ribbons & topological structures **(e.g. Gorbachev 88, Gorbachev & Somov 89, Mandrini et al. 91,14, Démoulin et al. 93, 94, Van Driel-Gesztelyi et al. 94, …, Savcheva et al 12a-b, 14, Inoue et al. 13, Dudik et al. 14, Liu et al. 14, Zhao et al. 14, , Masson et al. 09,16)**



(Savcheva et al. 15a)

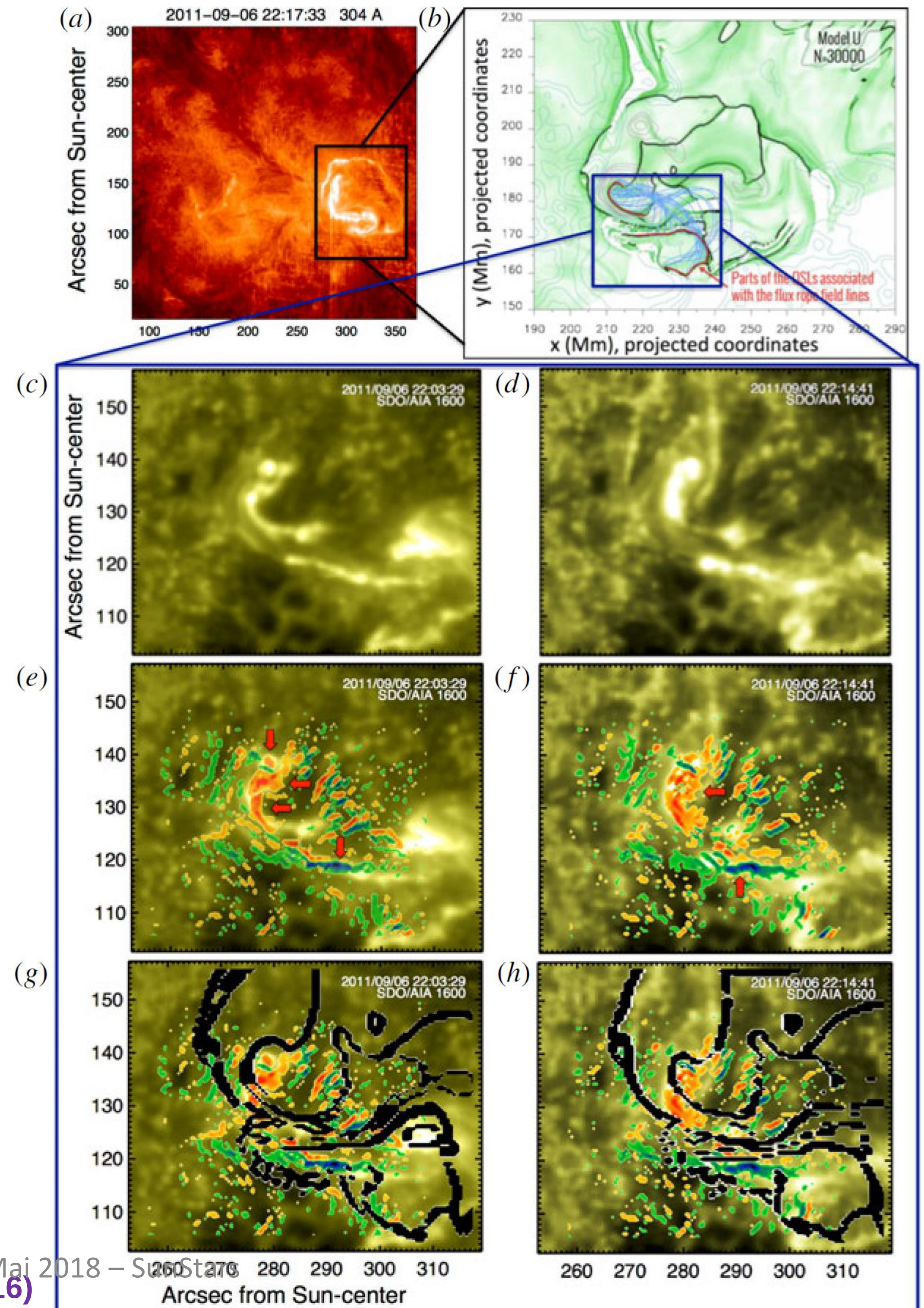
- Particular topological structures correspond to specific ribbons shape:
- Double J-shaped ribbons ⇔ Flux rope
- Circular ribbons ⇔ 3D null points

Ribbons, topology & electric currents

- Recent improvement in magnetic field measurements enable the determination of the normal component of photospheric electric currents (Jz)

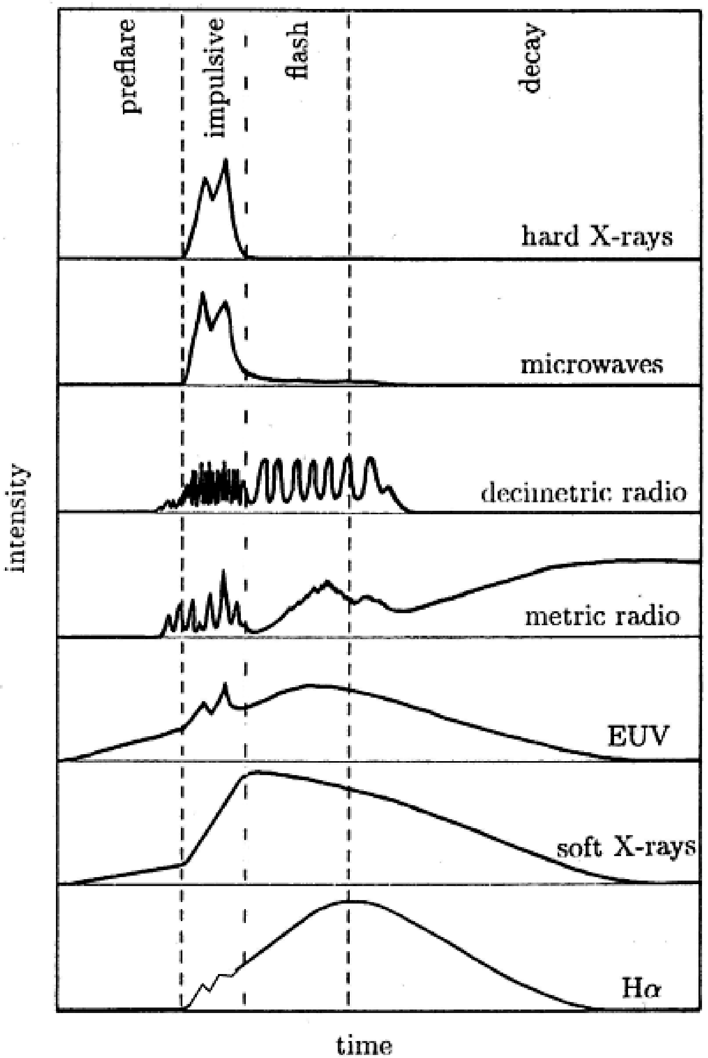
- As predicted, electric current sheets are found to be co-spatial with
  - EUV ribbons
  - Reconstruction topological structures

- ➔ Further confirmation of the standard model for eruptions

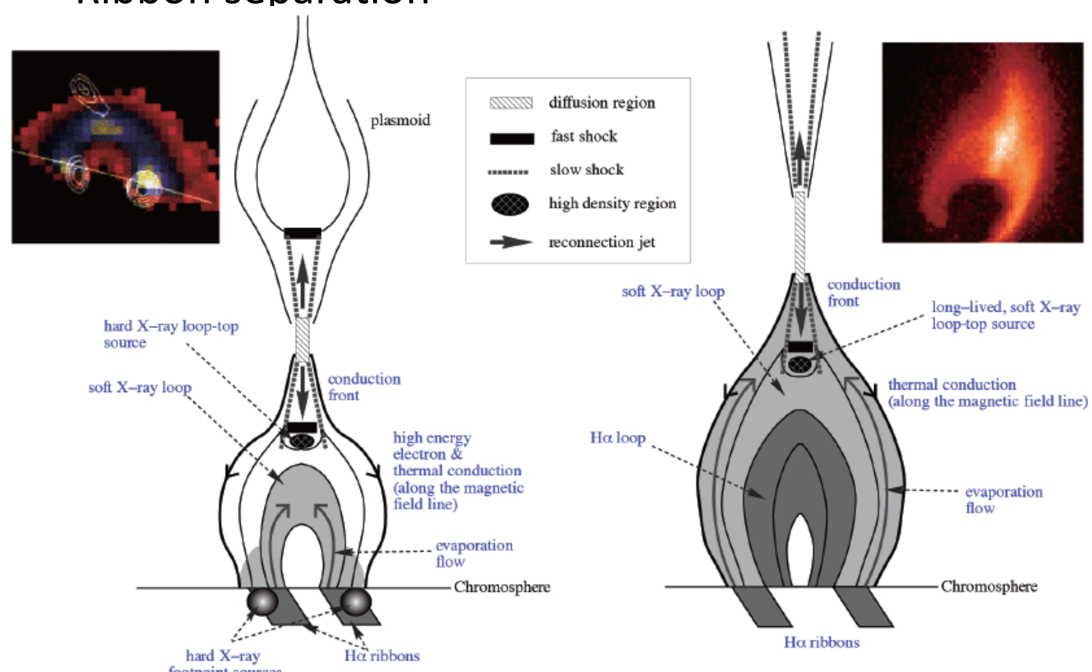


(Janvier et al. 16)

Flare Emission : gradual Phase



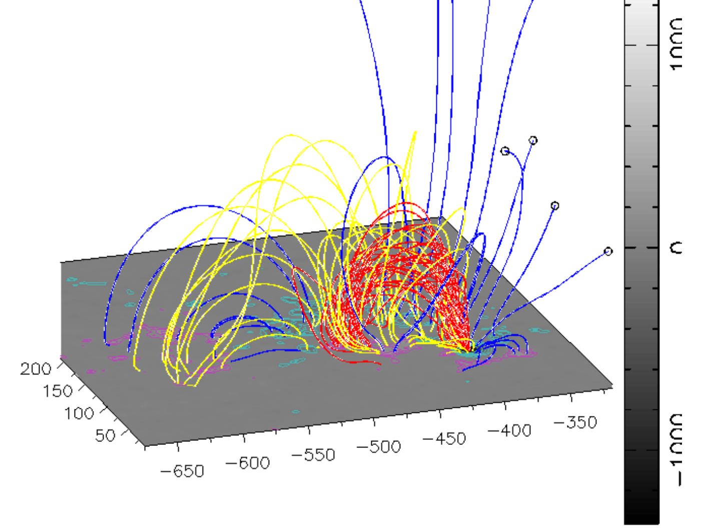
- **Heating of the plasma from accelerated particles & thermal conduction from corona:**
- ➔ Thermal emission in EUV and Soft X-ray
  - – Neupert effect: time integrated HXR flux % SXR flux
- **Chromospheric evaporation**: chromospheric pressure increases ➔ upflows from chromospheric to corona
  - – Denser coronal loops ➔ radiation in EUV
- Ribbon separation



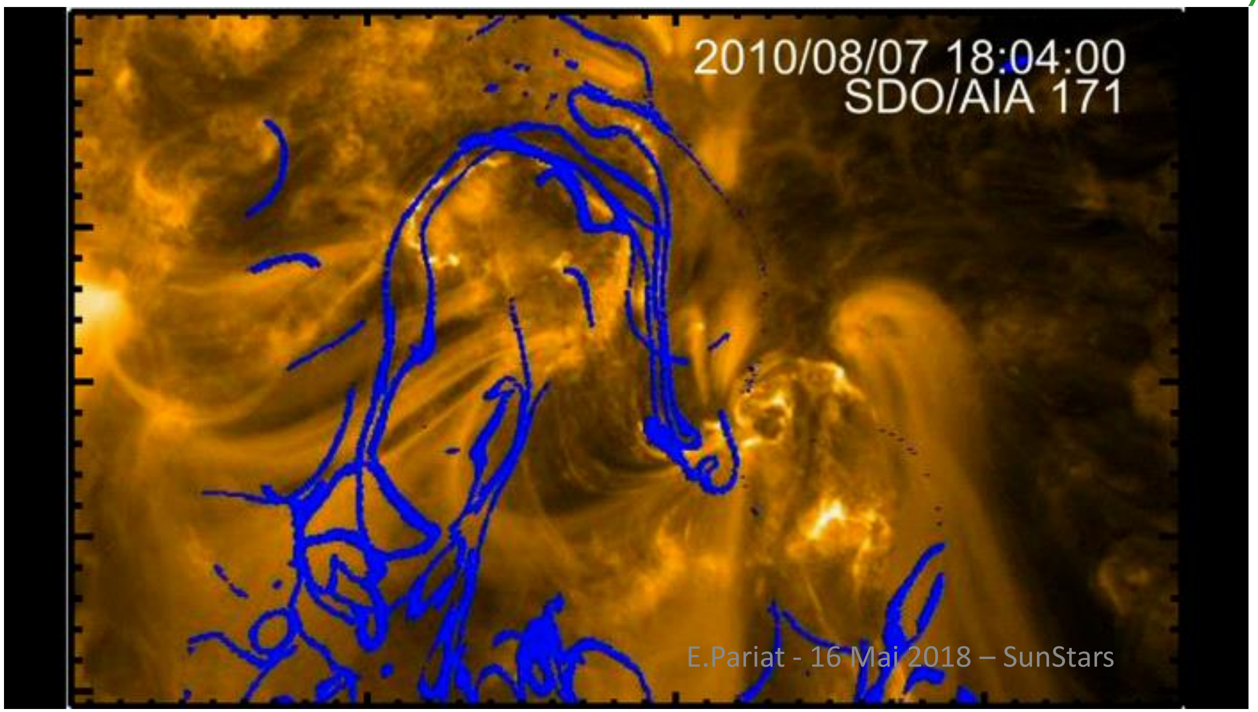
Impulsive phase (or impulsive flare) **Gradual phase (or LDE flare)**

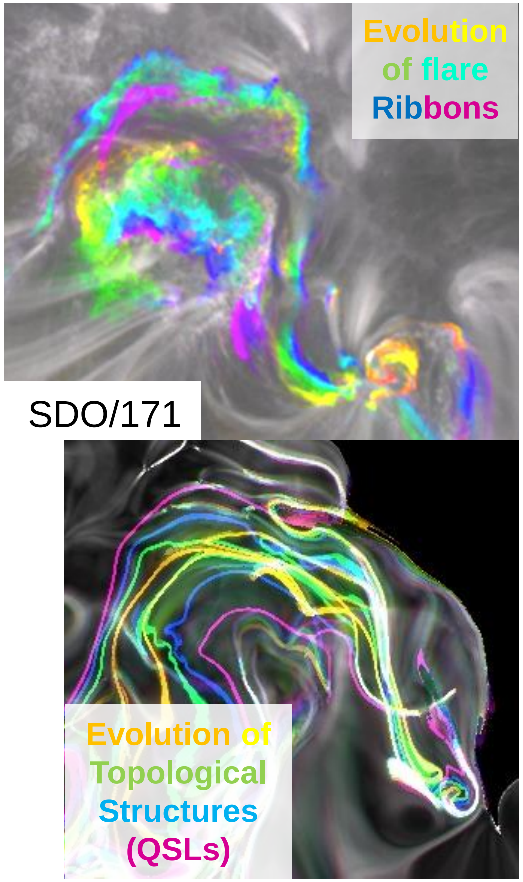
Ribbons evolution

- **Thanks to simulations initiated with observed magnetic field data it is possible to predict the evolution of the EUV emission!**
- Predicted ribbons matches very well the shape and dynamic of the observed ones
  - Comparison of uncorrelated datasets
    - Pré-eruption magnetic field measurements
    - Post eruption EUV emission



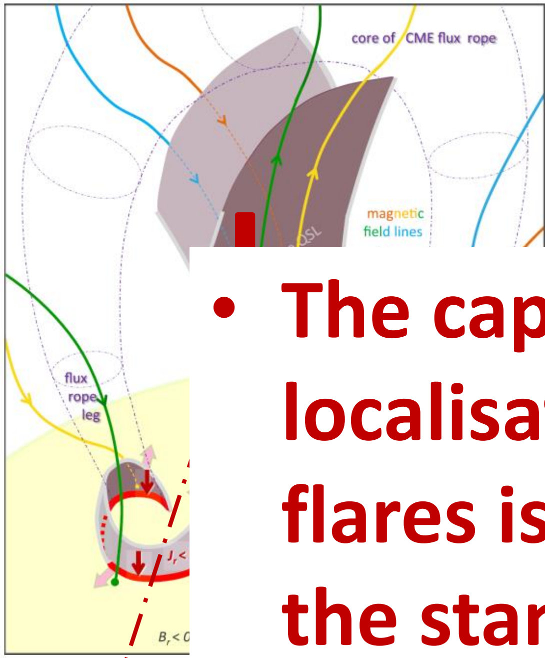
(Savcheva et al. 15b)

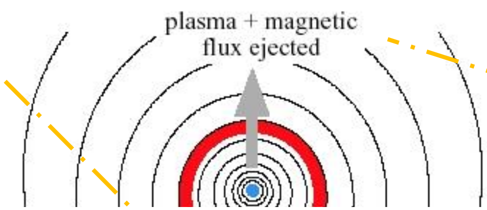


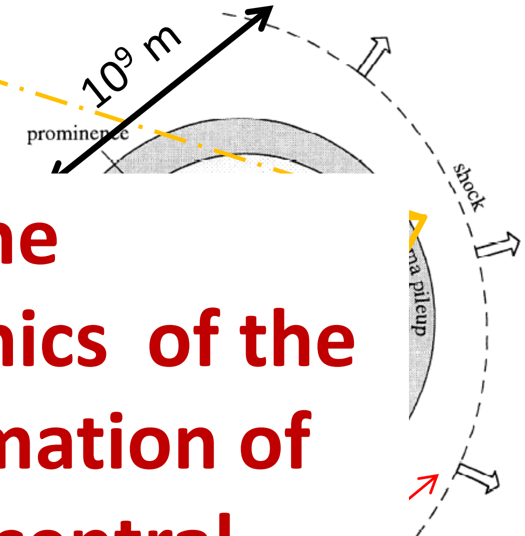


The standard model

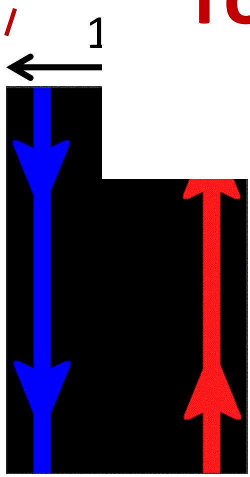
Janvier et al. (2014)

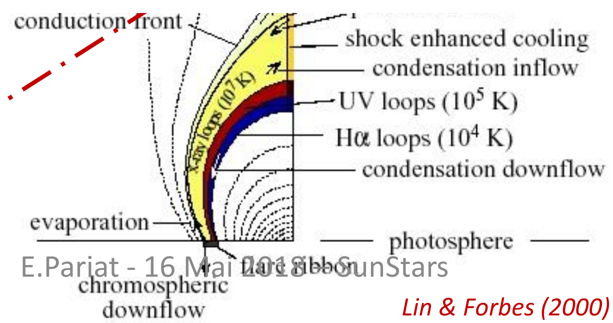




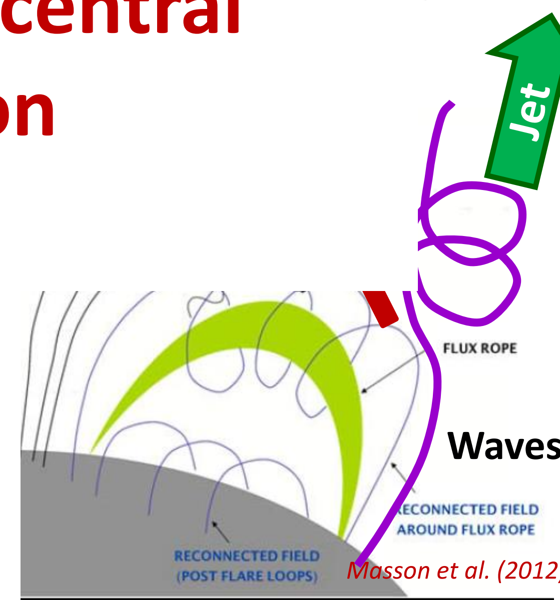


- **The capacity to « predict » the localisation, shapes & dynamics of the flares is an important confirmation of the standard model and the central role of magnetic reconnection**





Lin & Forbes (2000)

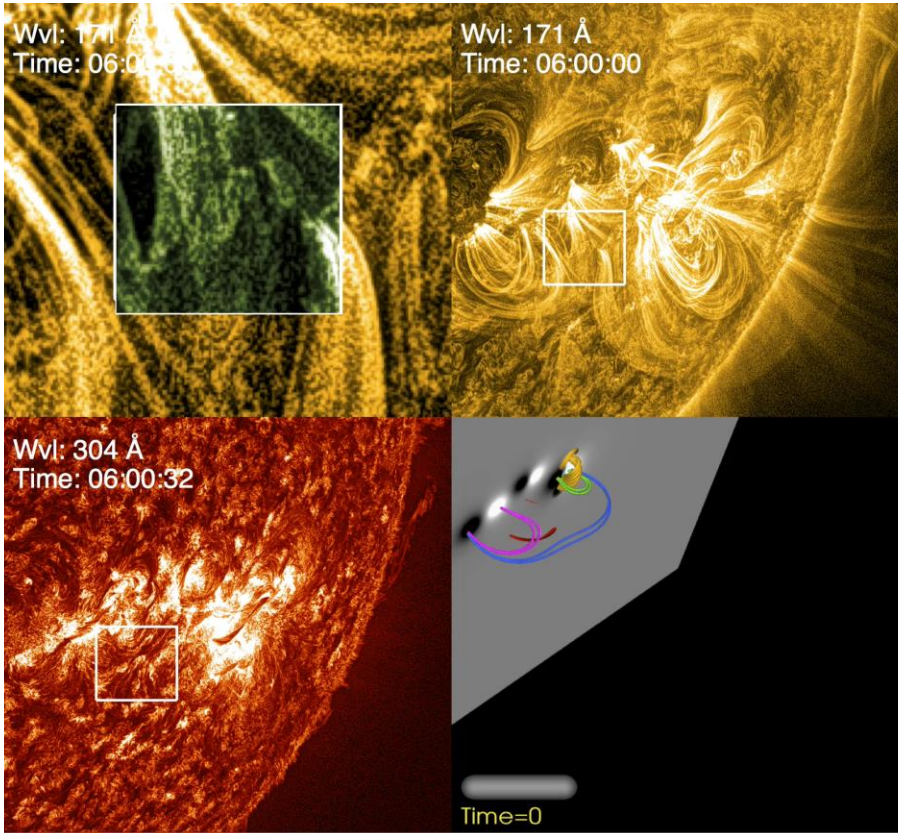


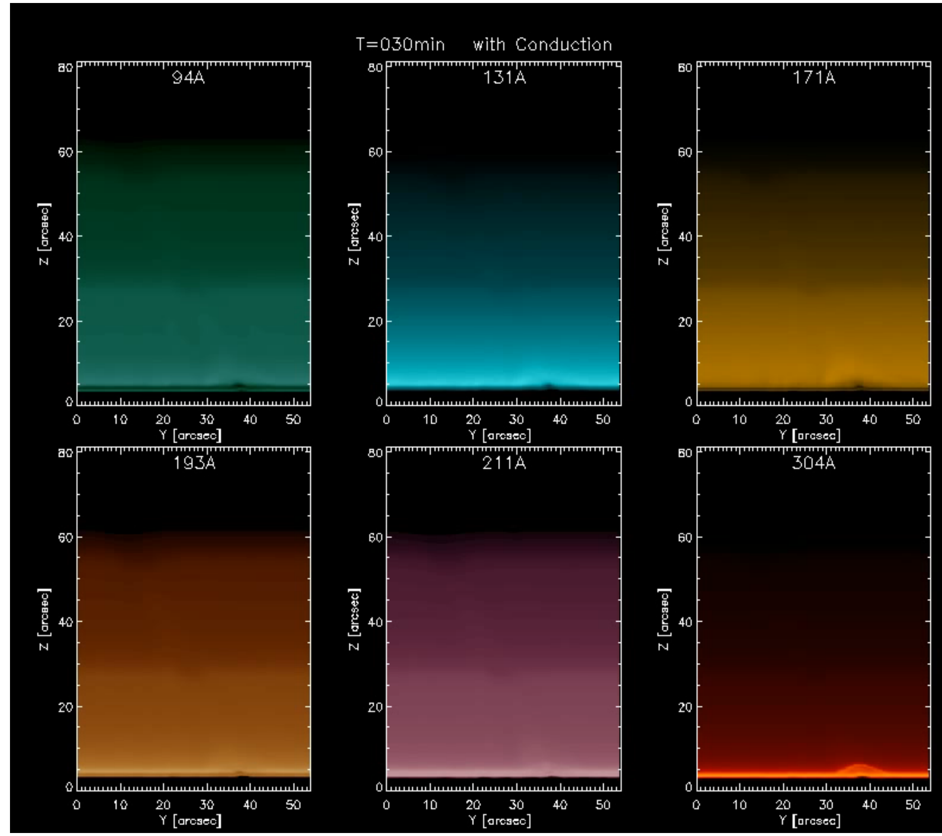
Masson et al. (2012)

Plan

- Principes de base:
  - Définition et propriétés des éruptions solaires
  - Champ magnétiques des centres éruptifs et leur modélisation
  - Reconnexion magnétique MHD et au-delà
- Résultats principaux: le modèle standard 3D des éruptions
  - Formation des régions actives, structuration des centres éruptifs
  - Production des émissions électromagnétiques
  - Dynamique magnétiques des systèmes éruptifs
- Perspectives/Questions:
  - l'énigme du déclenchement des éruptions
  - la prédiction des éruptions solaires

Dynamics of erupting system





- Numerical simulations allows an excellent understanding of the dynamics of eruptive magnetic structures, from the Sun to the Earth, with good capabilities to reproduce specific events thanks to data-tuned, data-initiated or data-driven models

Plan

- Principes de base:
  - Définition et propriétés des éruptions solaires
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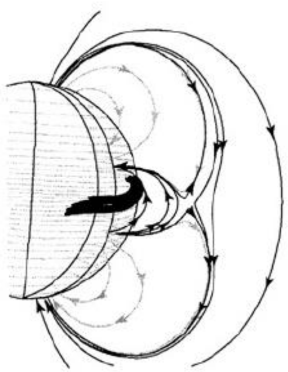
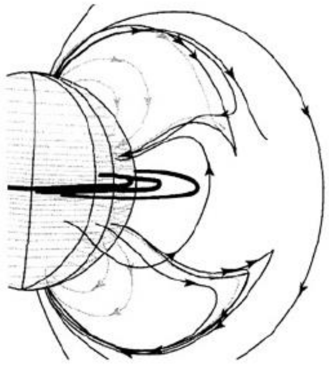
  - la prédiction des éruptions solaires

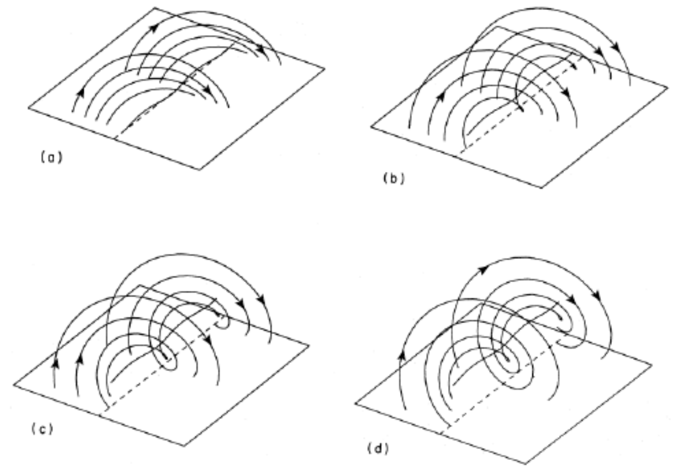
Opens questions

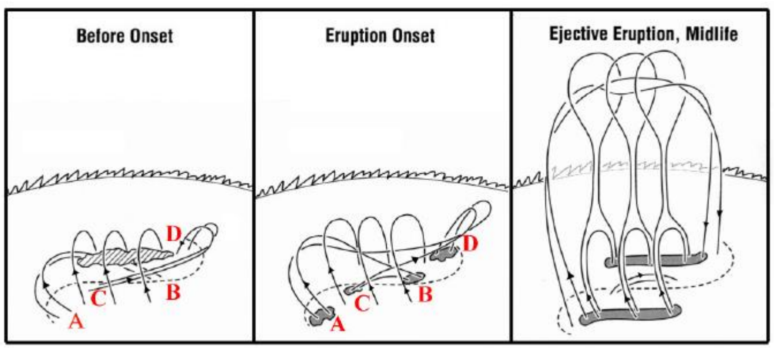
- While the 3D standard model allows a vast understanding of the eruptions phenomena two key issues remains:
  - How are particles accelerated during eruptions
    - Related to the properties of the physical mechanisms developing around the reconnection site.
    - not treated here
  - How are eruptions triggered? What makes the magnetic system suddenly unstable? Why are eruptions "eruptive"?

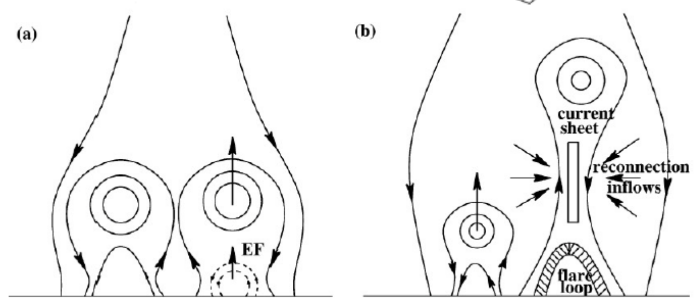
A jungle of models

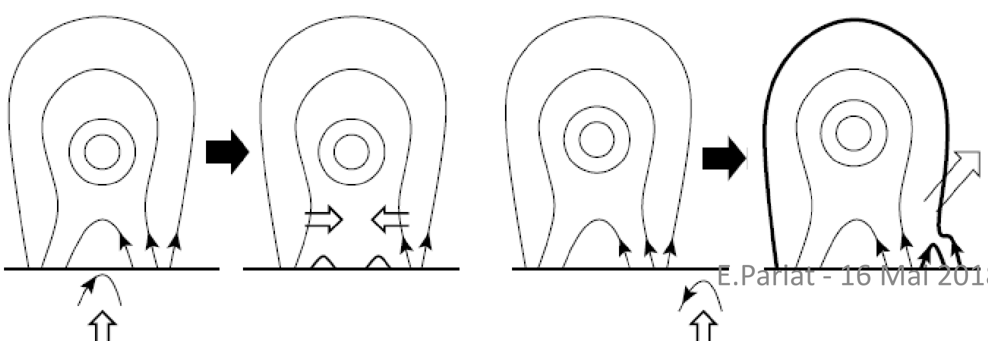


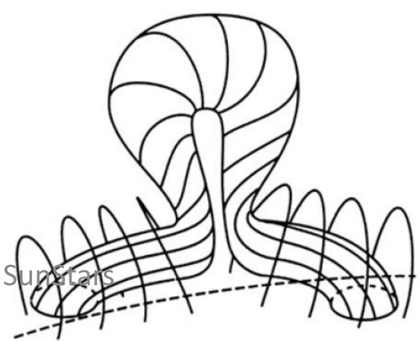


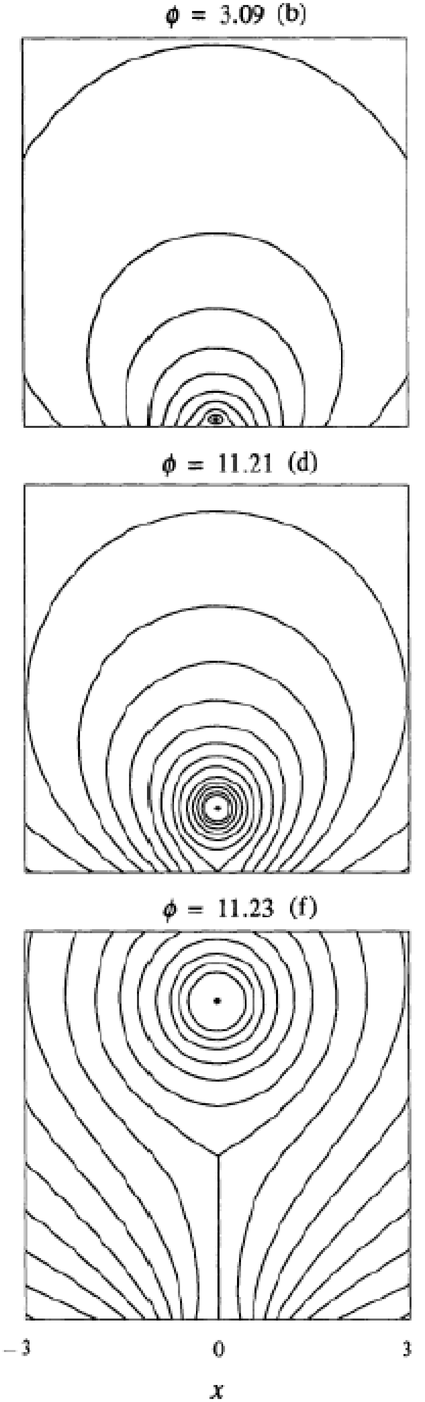






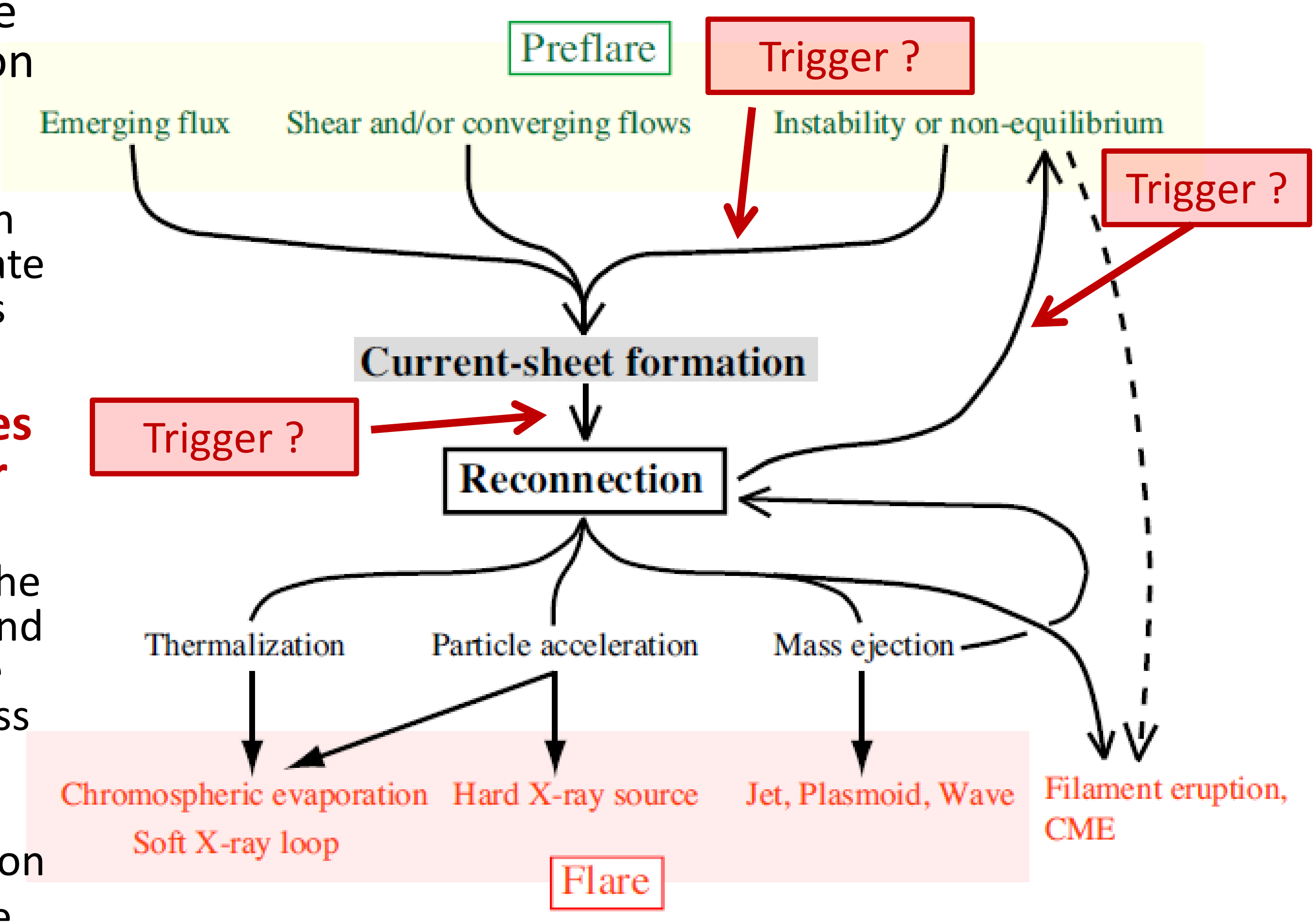






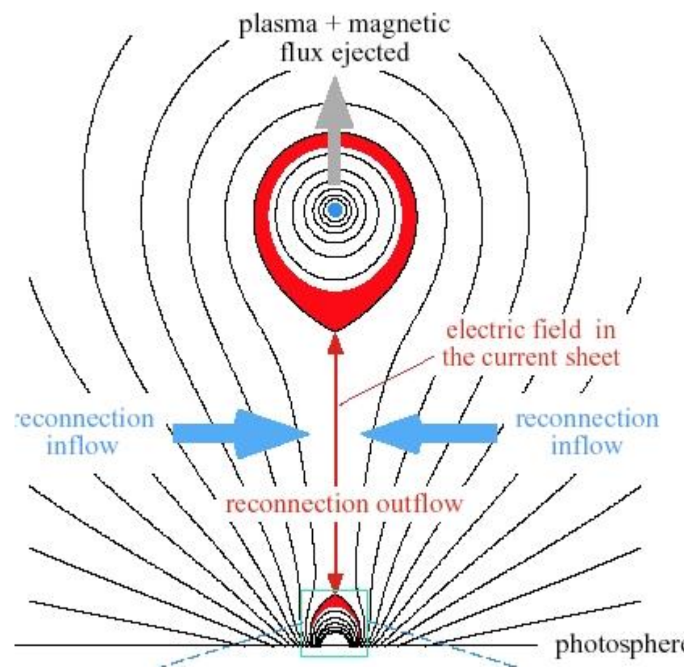
Active event trigger

- Motions, flux emergence lead to the spontaneous formation of currents sheets at separatrices
  - "Slow" reconnection continuously dissipate the formed currents
- **Impulsiveness of flares must involve a trigger mechanism:**
  - allows to enhance the reconnection rate and the efficiency of the reconnection process
  - Trigger can be an instability or a catastrophic evolution
  - Mechanisms may be non exclusive

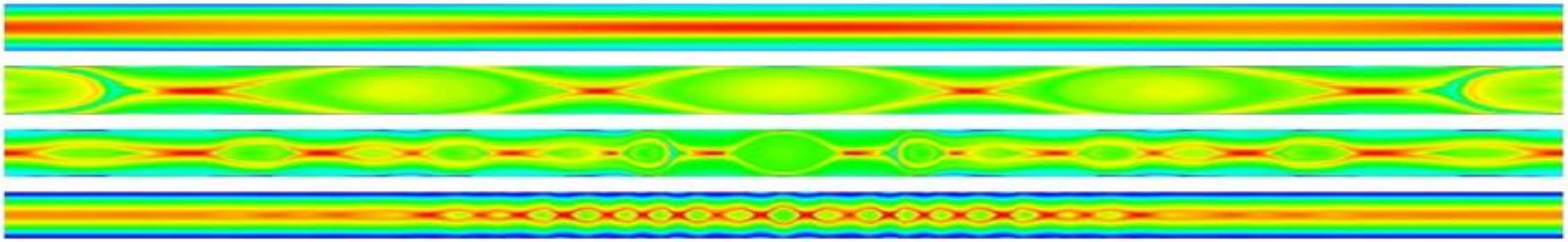


High reconnection rate trigger

- **Driven reconnection: catastrophic enhancement of the reconnection rate**
  - current sheet thinning, extension, and/or intensification
  - **Large scale driver: e.g. flows, ~~flux emergence~~, magnetic forcing (CME)**
- But not a trigger/instability scenario
  - Does not explain why the system is unstable

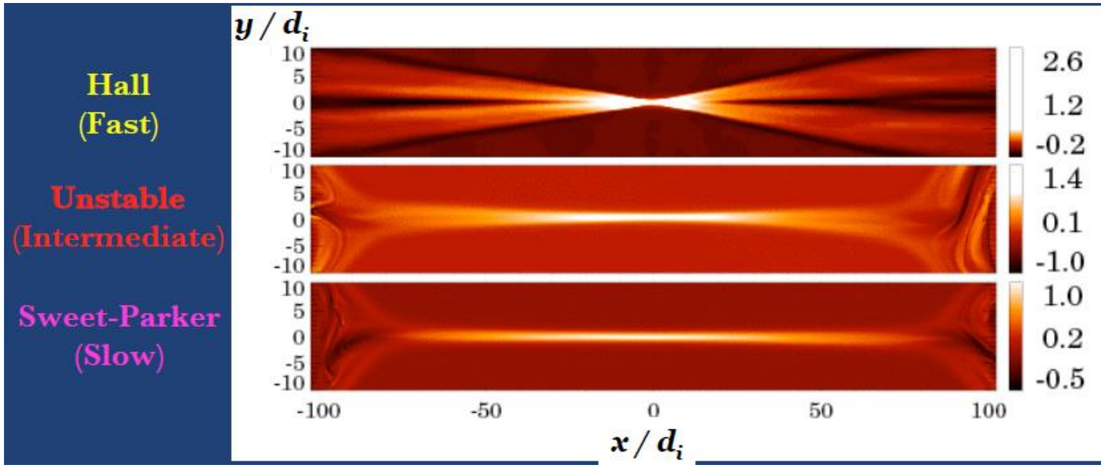


Spontaneous reconnection



(Samtaney et al. 2009)

- **Modification of the property of the current sheet**, e.g. fractal structure
  - Local instability: e.g tearing
  - Catastrophic formation plasmoids
- **Modification of the reconnection regime**
  - Modification of local plasma property ➔ Locally enhanced resitivity



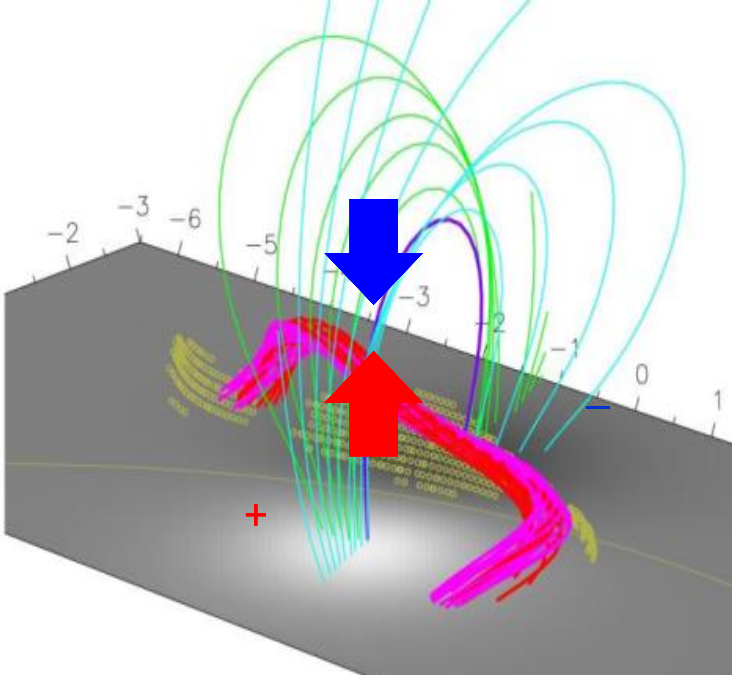
Cassak et al. 06

- **These trigger scenario are:**
  - **Local (<10 m scale)**
  - **Related to the physics of reconnection,**
  - **Not in the MHD paradigm, but rather requires full particle plasma physics**

ideal MHD instability: torus instability

- **Magnetic structure of CMEs progenitors has:**
  - **A current carrying structure: flux rope or sheared arcade: a structure with volume electric currents**
  - **An external confining magnetic field**

- Two opposite directed magnetic forces are acting on the current carrying structure (gravity neglected)
- **Repulsive: magnetic pressure, $\nabla B^2/2\mu$**, due to the confined expansion of the sheared B fields on their photospheric side
- **Constraining: Magnetic Tension, $(B.\nabla)B/\mu$**, due to the curvature of the coronal B field lines

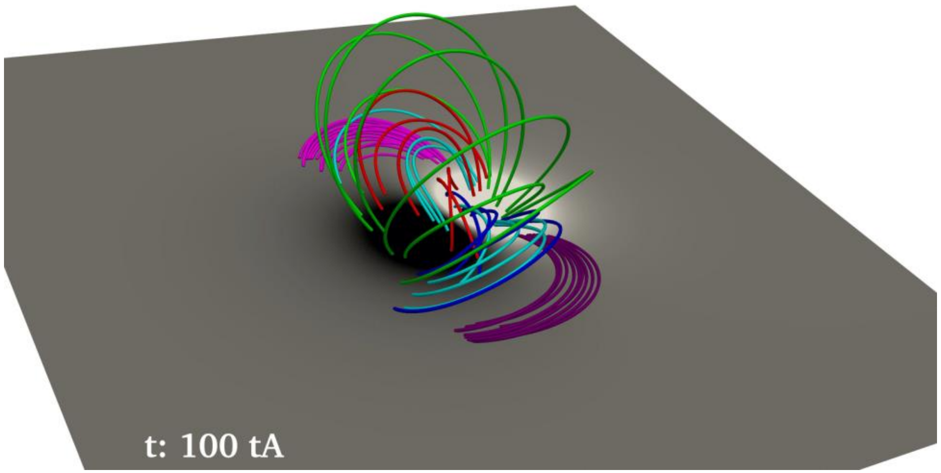


Aulanier et al. (2010)

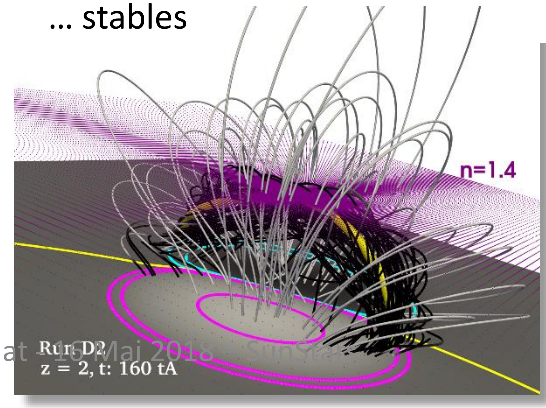
An ideal MHD instability scenario: torus instability

- Two opposite directed forces
  - **Repulsive: magnetic pressure,** of the current carrying structure
  - **Constraining: magnetic Tension, (B.∇)B/μ**, of the external field
- The system remains stable as long as the confining field is « sufficiently » strong.
  - Theory working well (analytical criteria) for electric current wires
- Not generalized for 3D magnetic configuration in MHD
  - However parametric simulations give consistent results

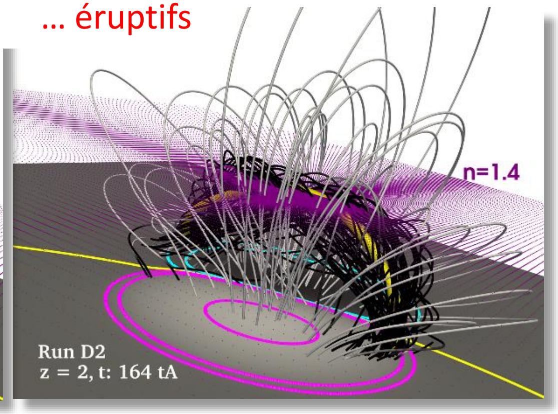
Zuccarello et al. 2015



… stables



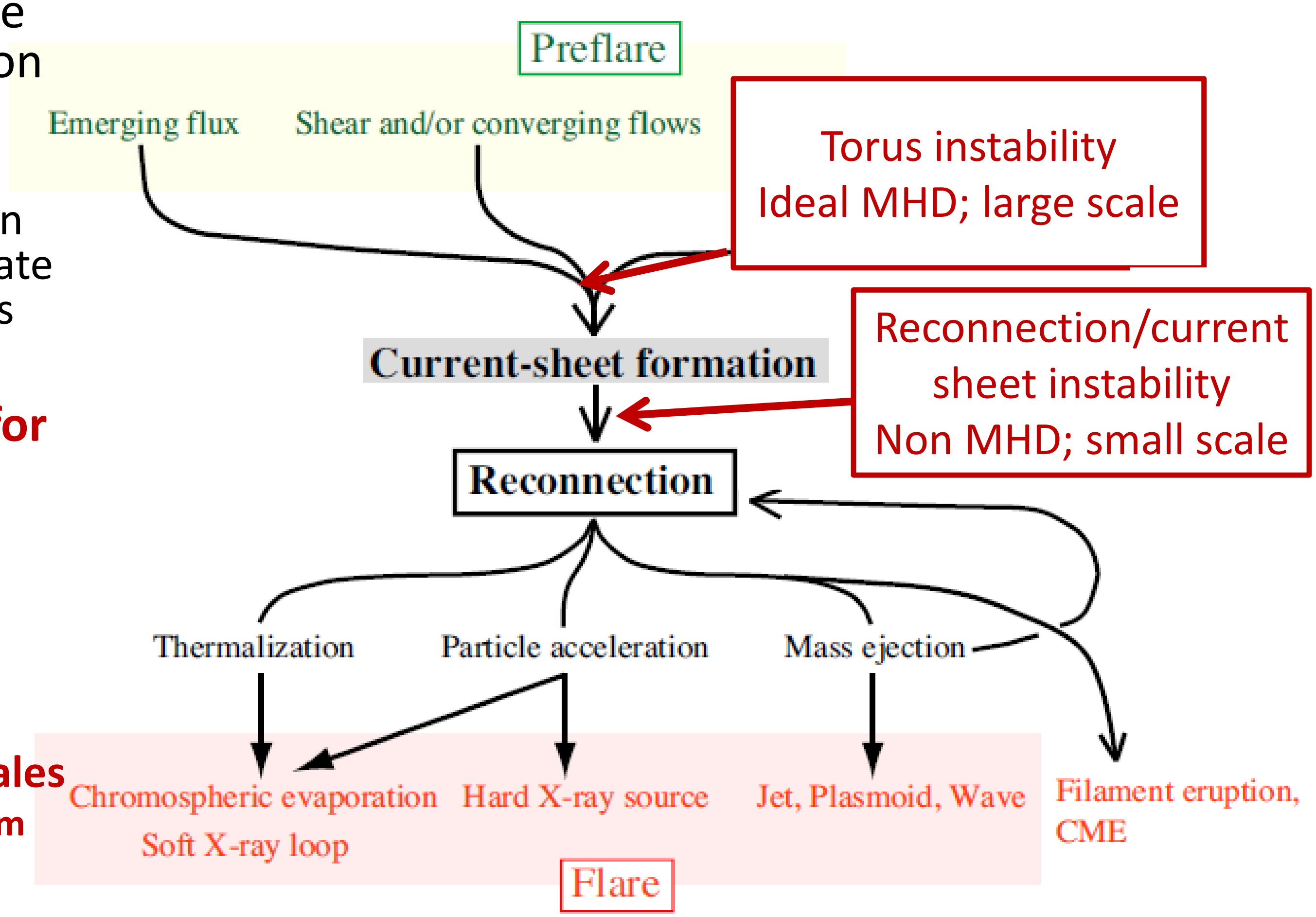
… éruptifs



Active event trigger

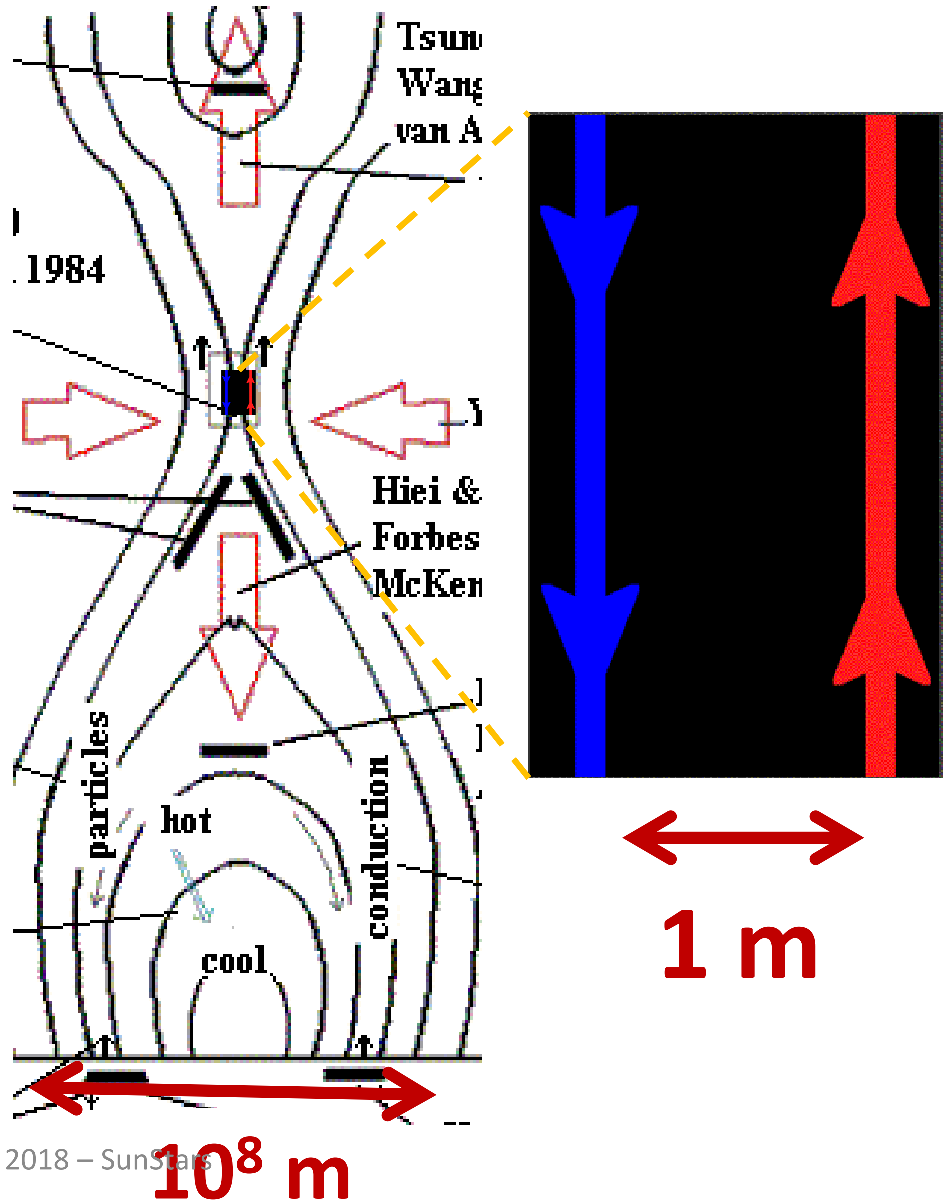
- Motions, flux emergence lead to the spontaneous formation of currents sheets at separatrices
  - "Slow" reconnection continuously dissipate the formed currents

- **Two main scenarios for eruption trigger**
  - **Involving different physical paradigm**
    - **MHD**
    - **Full particle**
  - **Developing at different spatial scales**
    - **Ideal MHD: > 10^6 m**
    - **Non MHD: < 10 m**



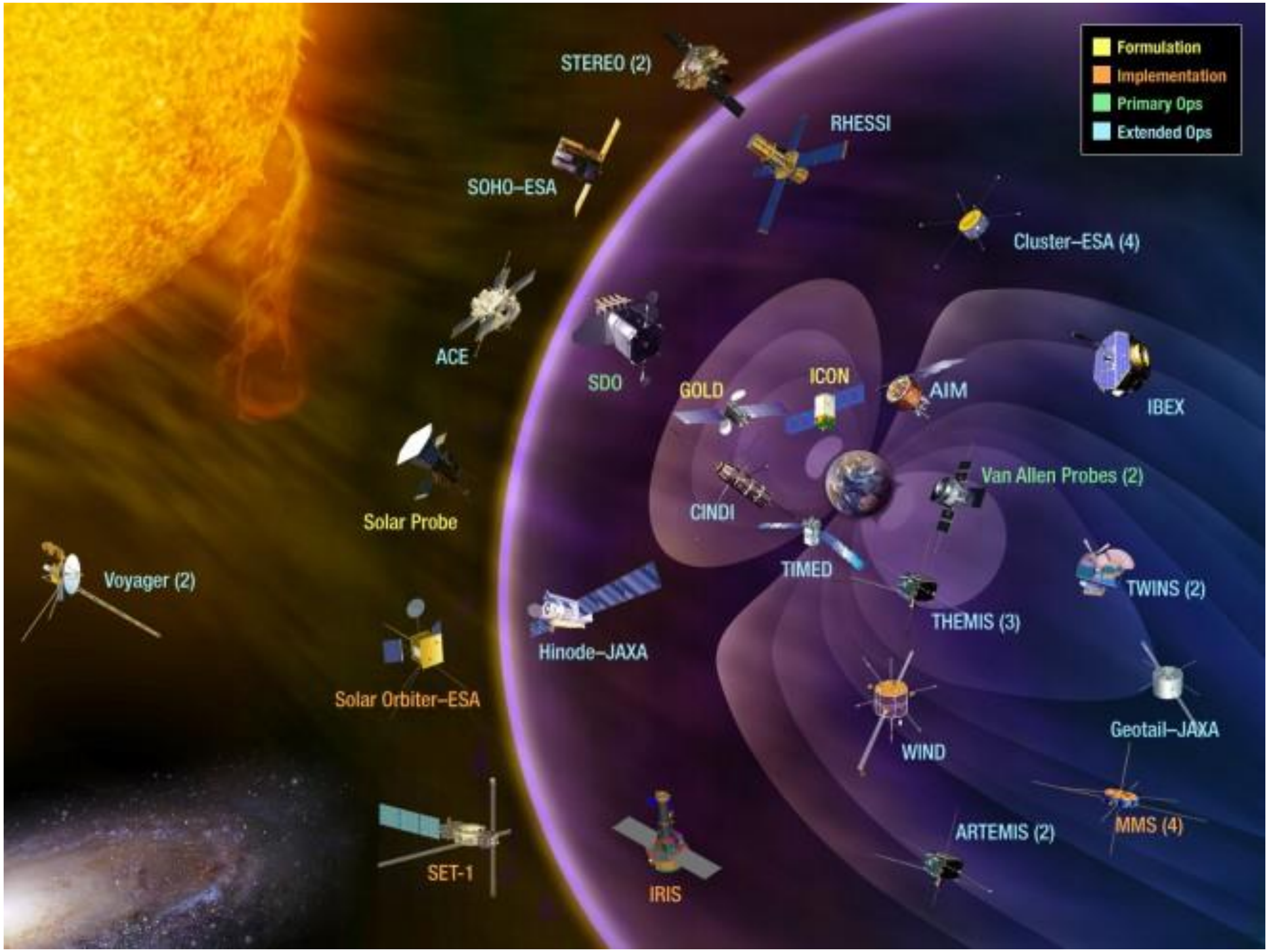
The trigger issue

- **The two main trigger scenario candidates are developing on different physical paradigm at vastly different scales**
  - Large scale 10^7-10^9 m: active regions, magnetic structuration & energy storage
  - Small scale, 0.1-10 m: reconnection
- Today one cannot directly compare, model & simulate these scenarios altogether.
  - Observations: highest resolution: ~50 km
  - Laboratory experiment: physical condition too different, scaling limited
  - Numerical simulations
    - Necessary power:~10^{30-38} units to simulate simultaneously
    - Actual capacity:~10^{12} treated units
- **➔ No direct determination of the relative role of this process is possible (and for some time)!**

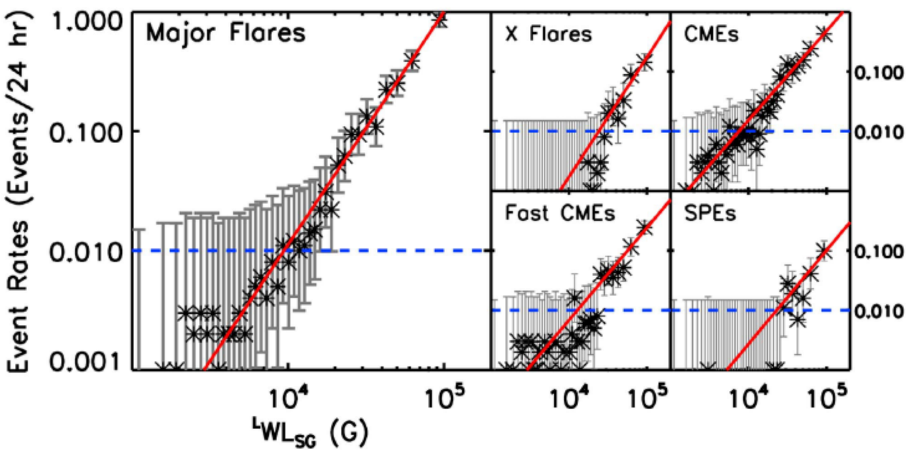


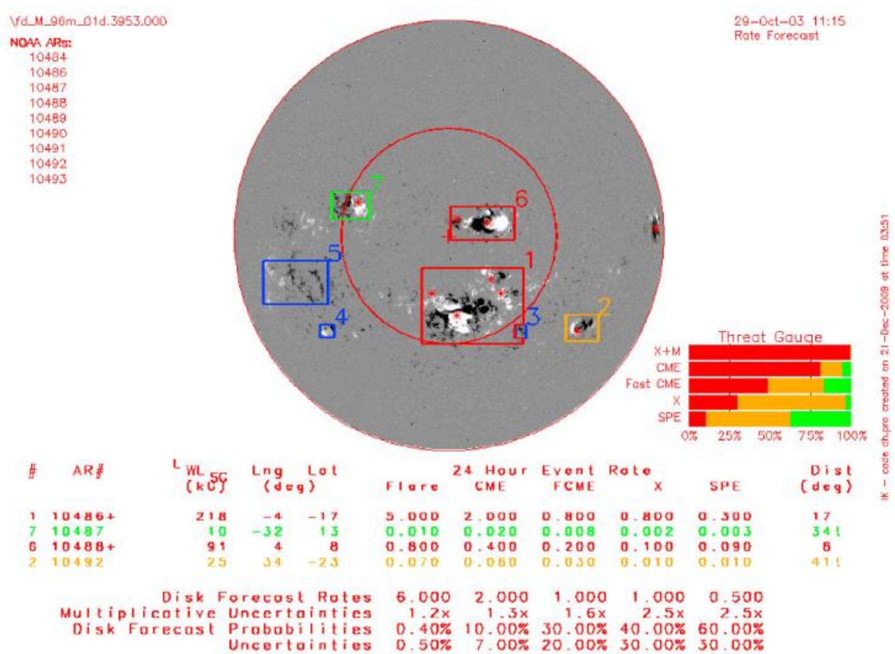
Solar activity surveillance

- Development of a new applied discipline: space weather
- Alert capacity is limited to the impact of CMEs
- No capacity for advance (<a few minutes) prediction of flares and energetic particles



Eruption predictions





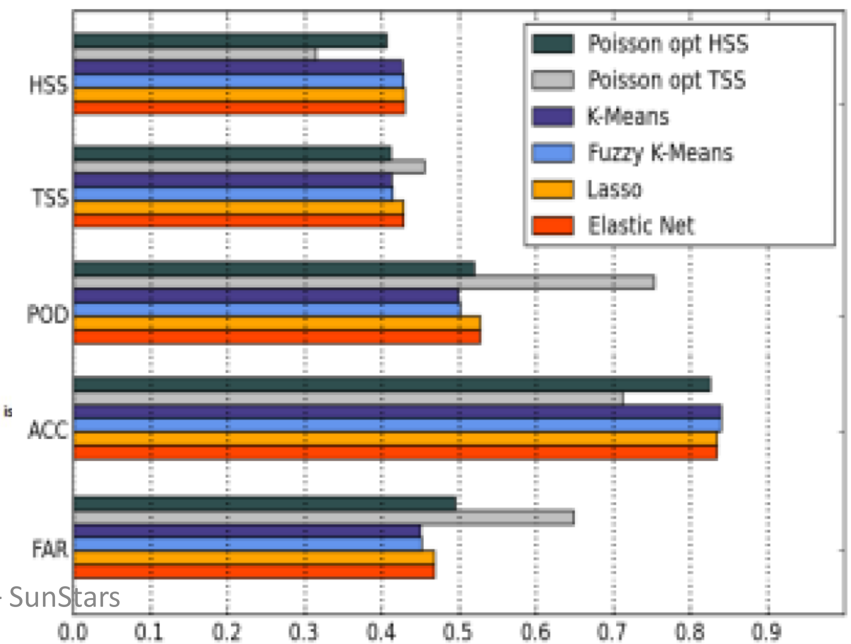
(Falconer et al. 11)

- Predictions are based on empirical model
  - Comparison with past activity
  - Only working with large time window (> 24h)
- **Probability of detection of an X-class flare: ~40%**
- No quantitative estimation of eruptivity
- ➔ Mainly surveillance

FLARECAST

- FLARECAST: new generation automatic prediction system: prediction in the big data era.
- Automatic extraction of active regions properties: > 170 quantities measured at each instant for each active center
- Use of ~20 data mining and artificial intelligence algorithm
  - Supervised machine learning, Unsupervised learning techniques, regression, hybrid methods, multi-tasks
- But… only a marginal improvement in detection probability
  - Most of the criteria are based on 2D magnetograms, hence on the energization process (necessary condition) and not on the trigger mechanism (sufficient condition)

	HLA	HLO	SVC	RF	average
flare_index_past	7,33	7,16	1,89	1,63	4,50
sharp_kw/usiz/total	9,47	11,81	6,95	17,94	11,54
decay_index_br/tot_l_over_hmin	21,65	9,67	23,9	31,29	21,63
wlsg_br/value_int	17,11	41,7	21,15	7,72	21,92
r_value_blos_logr	15,91	3,08	63,05	11,61	23,41
sharp_kw/ushz/max	35,58	28,51	15,77	18,46	24,58
r_value_br_logr	5,12	9,79	77,43	7,99	25,08
sharp_kw/usiz/max	4,95	31,65	49,53	16,44	25,64
mpil_br/max_length	24,31	14,94	33,56	36,6	27,35
flare_past	3,1	5,34	19,59	88,02	29,01
alpha_exp_fft_br/alpha	52,09	9,22	17,09	42,3	30,18
sharp_kw/usiz/ave	14,81	31,05	53,15	31,55	32,64
helicity_br/tot_uns_dhdt_s	42,66	27,98	45,59	17,2	33,36
wlsg_blos/value_int	30,18	46,23	79,5	2,59	39,63
flow_field_bvec/diver_max	21,31	27,28	36,37	74,85	39,95
ising_energy_part_blos/ising_energy_part	66,04	43,73	38,12	16,01	40,98
sharp_kw/hz/max	71,48	23,01	39,93	30,91	41,33
sharp_kw/snetjzpp/total	46,46	57,71	30,57	31,04	41,45
flow_field_bvec/v_median	30,36	26,88	47,11	62,38	41,68
sharp_kw/twistp/max	44,59	18,44	41,41	63,81	42,06
helicity_br/tot_uns_dhdt	55,48	34,97	36,54	41,96	42,24
sharp_kw/ushz/ave	45,19	34,87	46,69	42,3	42,26
sharp_kw/ushz/total	55,53	50,66	50,48	13,77	42,61



Conclusions

- While understanding of solar eruptions has hugely progress, key questions remains regarding
  - the trigger process
  - the energy budget & particle acceleration induced by magnetic reconnection

- Needs for understanding solar eruptions
  - go beyond the simple quest for knowledge
  - becomes more and more highly driven by the need for quantitative prediction of the impact of solar activity on human assets.

- ➔ challenging push for a new generation of tools, instrumental and numerical, that will support the applied bourgeoning discipline of space weather. This tools shall be
  - Sufficiently fast
  - Precise and quantitative
  - Standardized and reliable