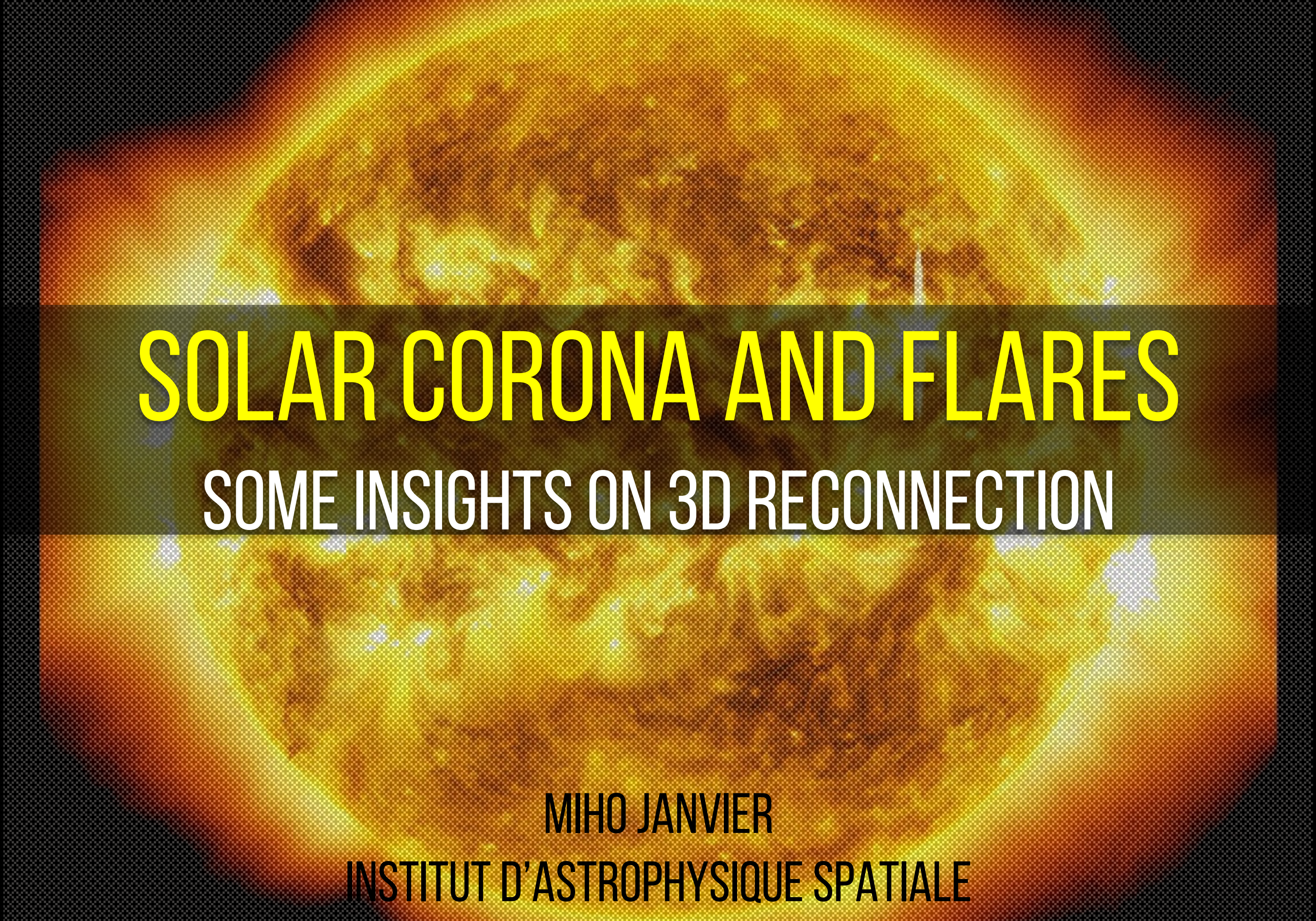
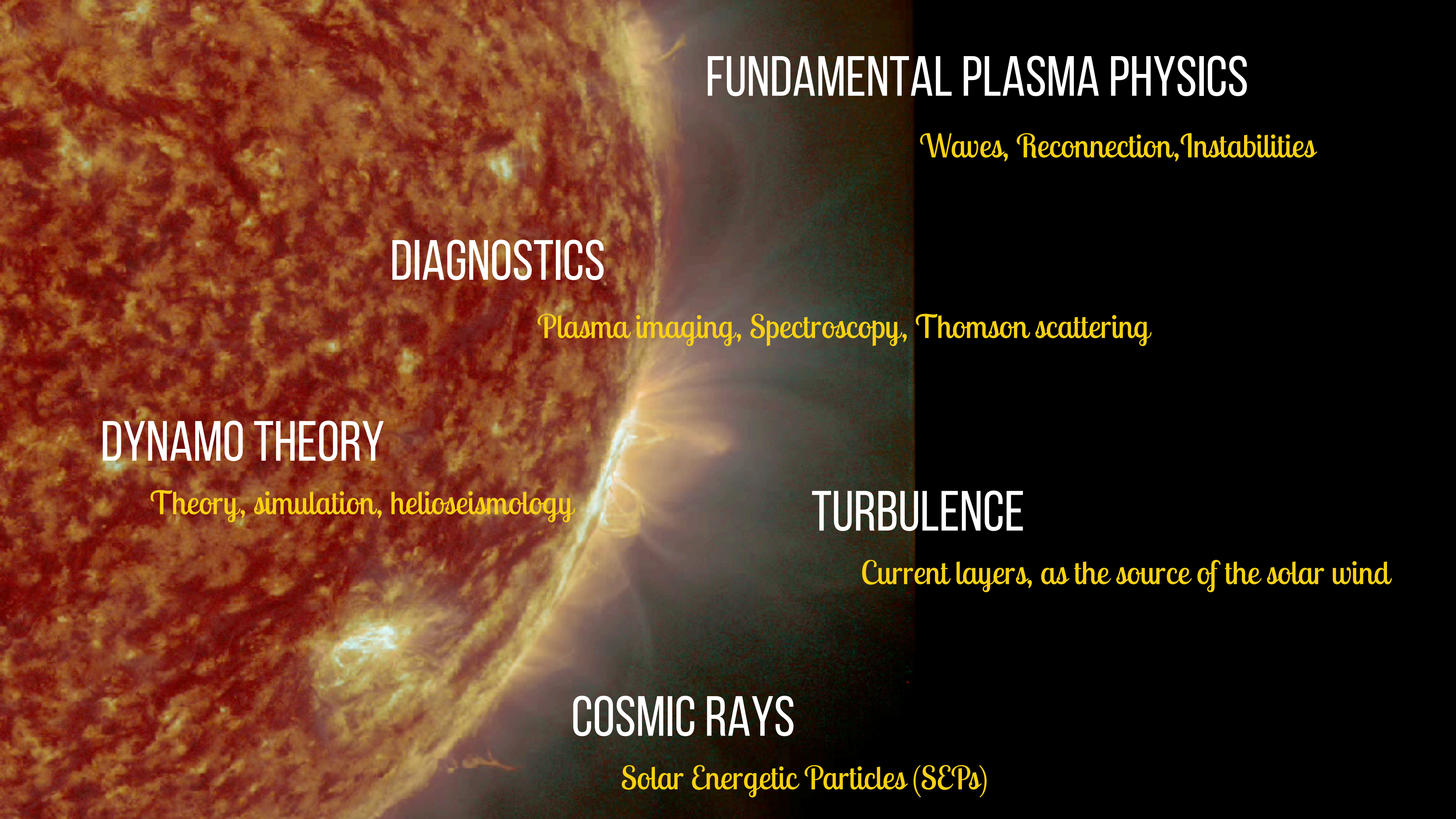


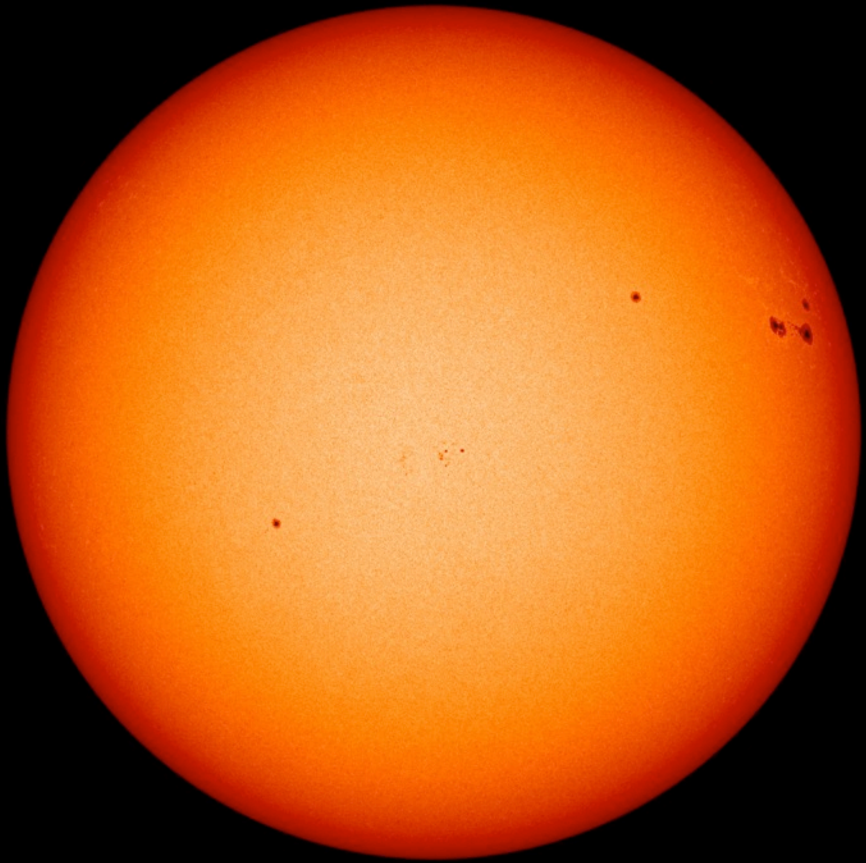
SOLAR CORONA AND FLARES

SOME INSIGHTS ON 3D RECONNECTION

MIHO JANVIER
INSTITUT D'ASTROPHYSIQUE SPATIALE

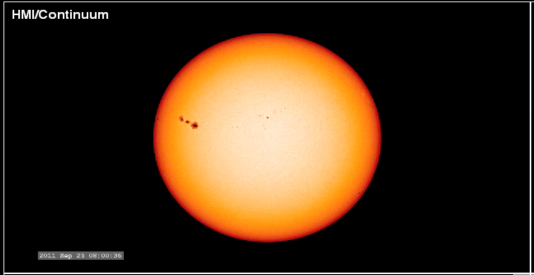

FUNDAMENTAL PLASMA PHYSICS
Waves, Reconnection, Instabilities
DIAGNOSTICS
Plasma imaging, Spectroscopy, Thomson scattering
DYNAMO THEORY
Theory, simulation, helioseismology
TURBULENCE
Current layers, as the source of the solar wind
COSMIC RAYS
Solar Energetic Particles (SEPs)

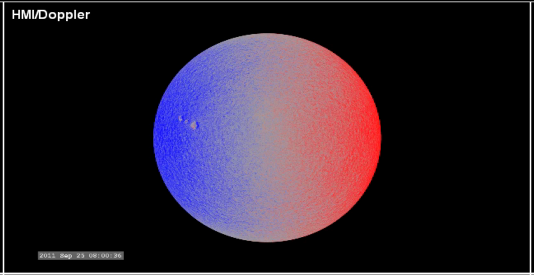
THE SUN IN THE VISIBLE LIGHT

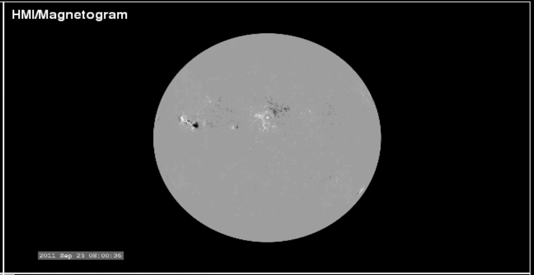


What we see here is the photosphere

THE SUN DURING AN ECLIPSE: THE CORONA







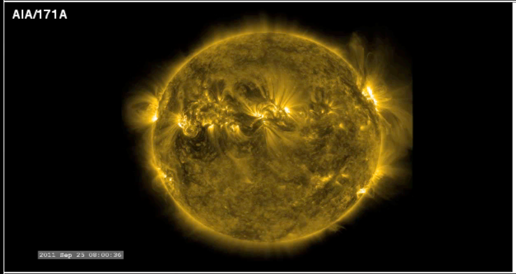
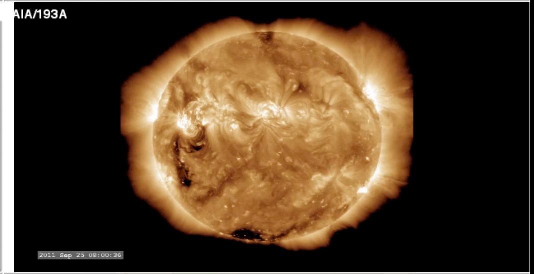
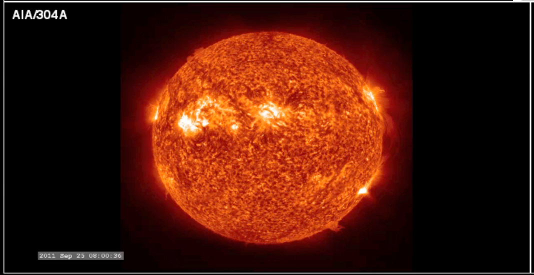
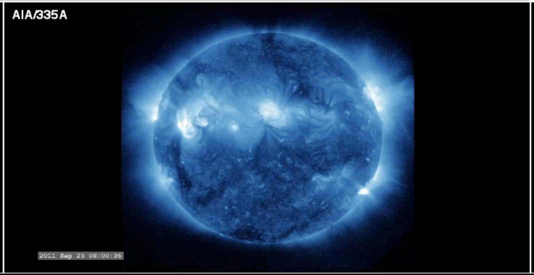


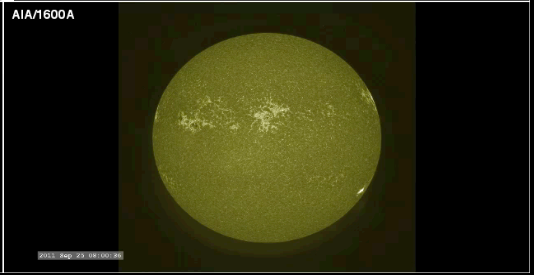
Table A1: AIA wavelength bands.

Channel name	Primary ion(s)	Region of atmosphere*	Char. log(T)
white light	continuum	photosphere	3.7
1700Å	continuum	temperature minimum, photosphere	3.7
304Å**	He II	chromosphere, transition region	4.7
1600Å**	C IV+cont.	transition region + upper photosphere	5.0
171Å**	Fe IX	quiet corona, upper transition region	5.8
193Å**	Fe XII, XXIV	corona and hot flare plasma	6.1, 7.3
211Å**	Fe XIV	active-region corona	6.3
335Å**	Fe XVI	active-region corona	6.4
94Å**	Fe XVIII	flaring regions (partial readout possible)	6.8
131Å**	Fe VIII, XX, XXIII	flaring regions (partial readout possible)	5.6, 7.0, 7.2

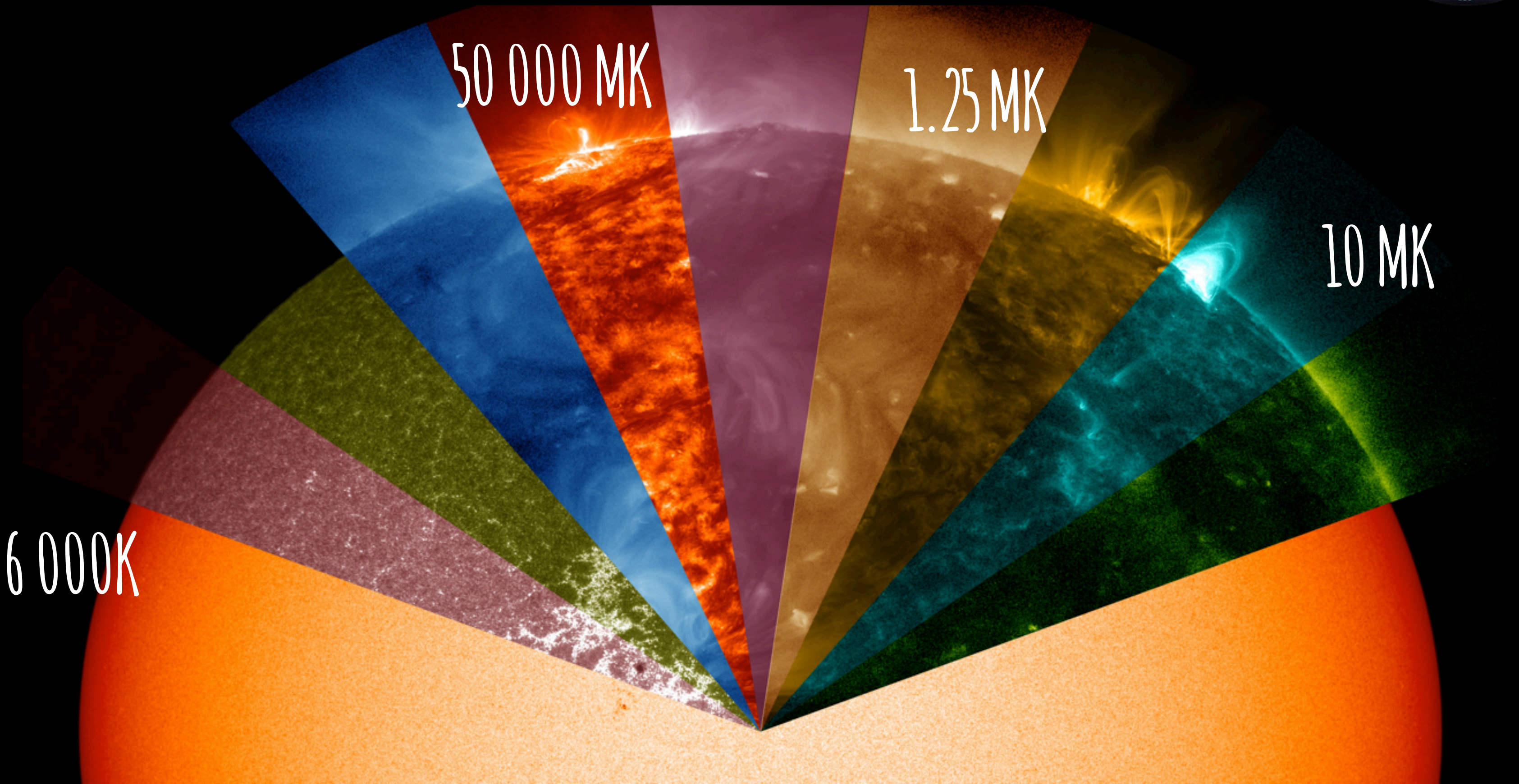




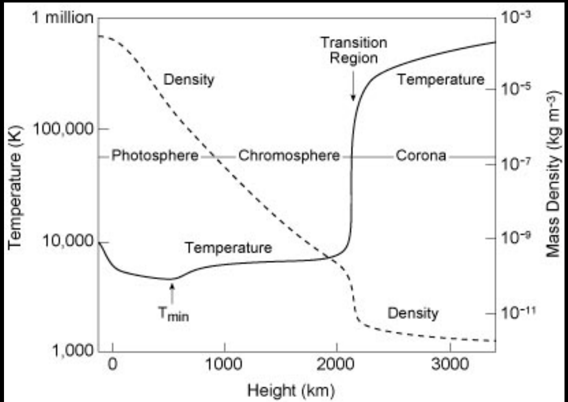


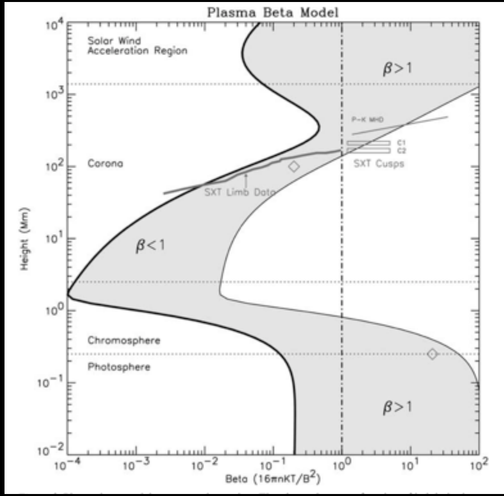


THE TEMPERATURES IN THE SUN'S CORONA



THE CORONA: what conditions?





The corona has β<1: the magnetic pressure dominates

Magnetic field extrapolations

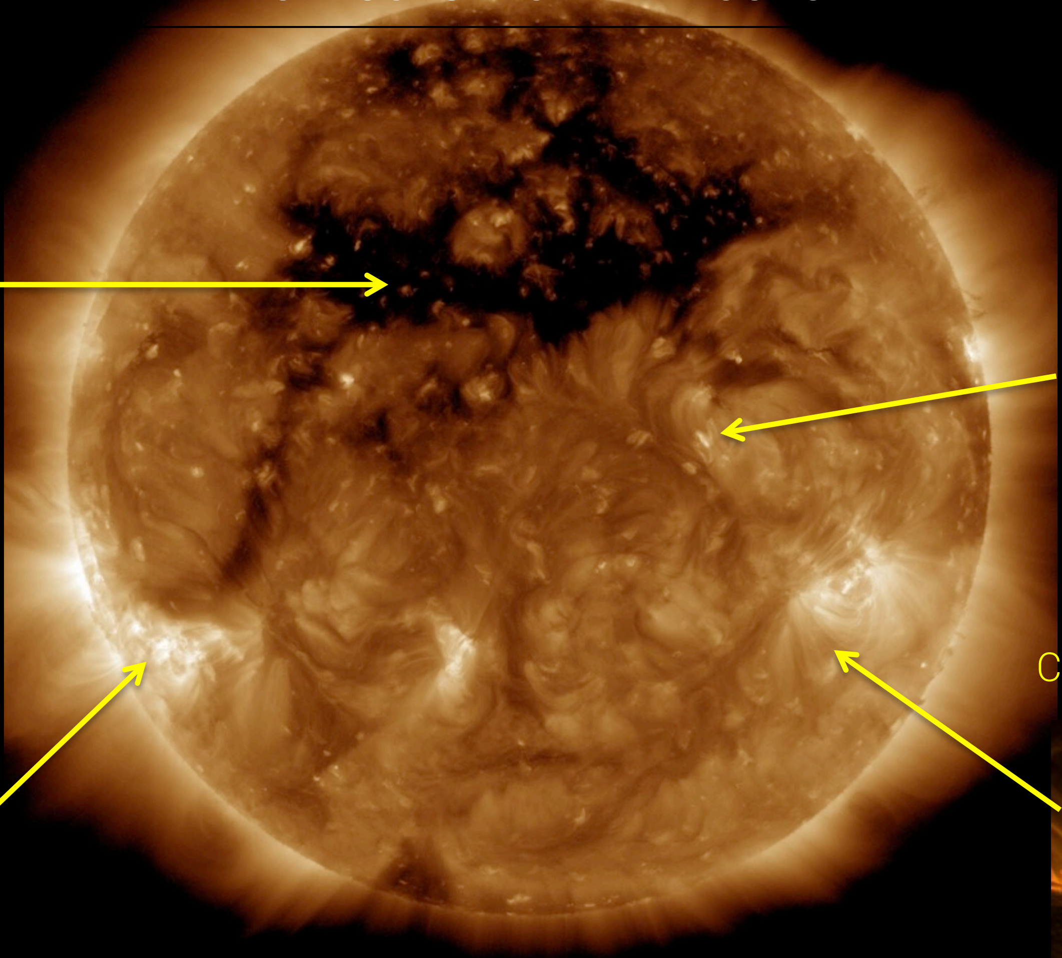
Simulations of the magnetic field behaviors

Problem: it is « sandwiched » between two β>1 regions!

See Gary 2001

THE STRUCTURES IN THE CORONA

Coronal holes
(regions of open
magnetic field lines)



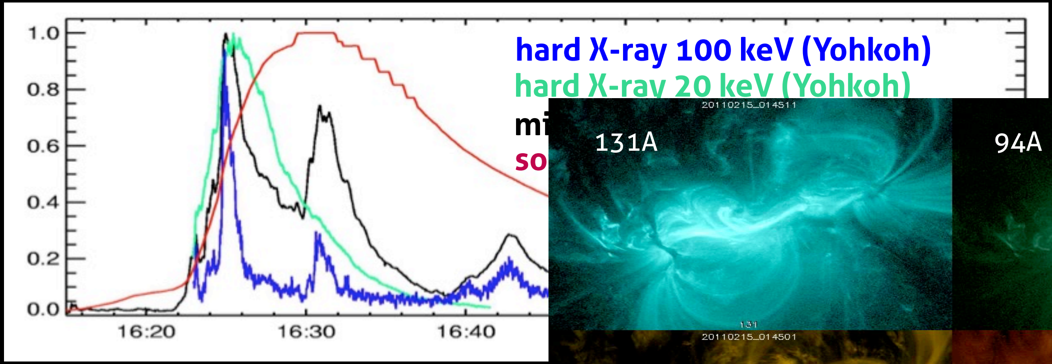
« Quiet » sun regions
(bright points)

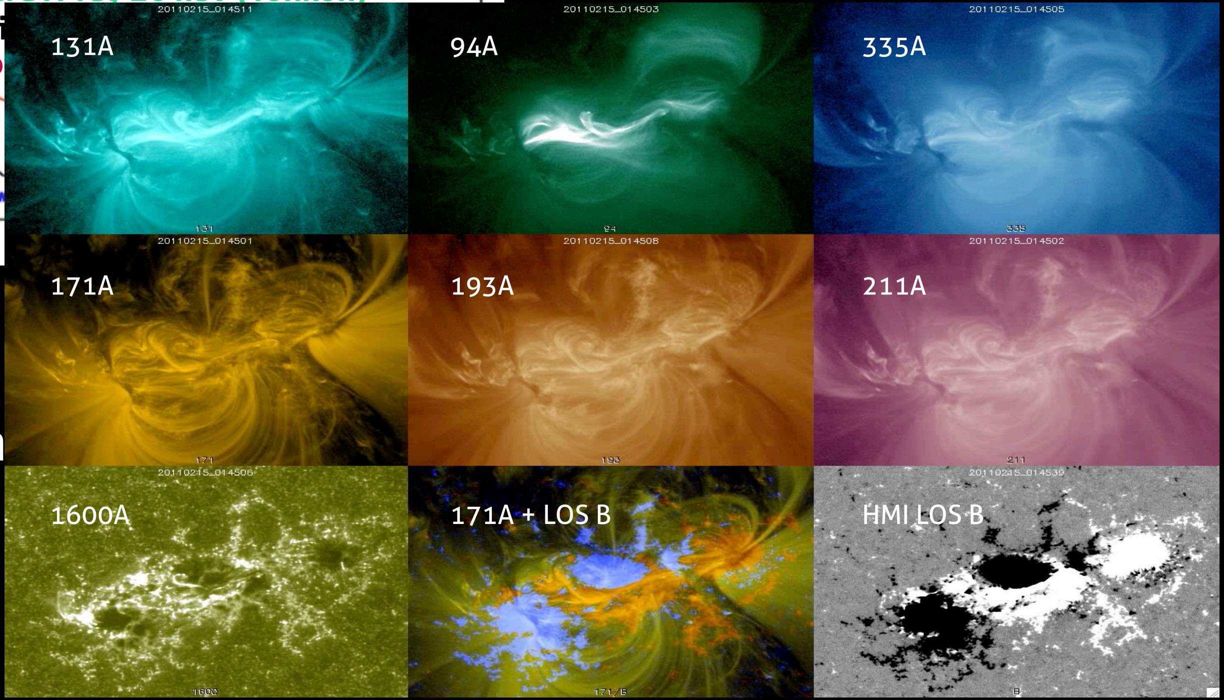
Active regions
(flares)

Coronal loops

WHAT IS A FLARE?

« Flare »: sudden brightening in solar atmosphere



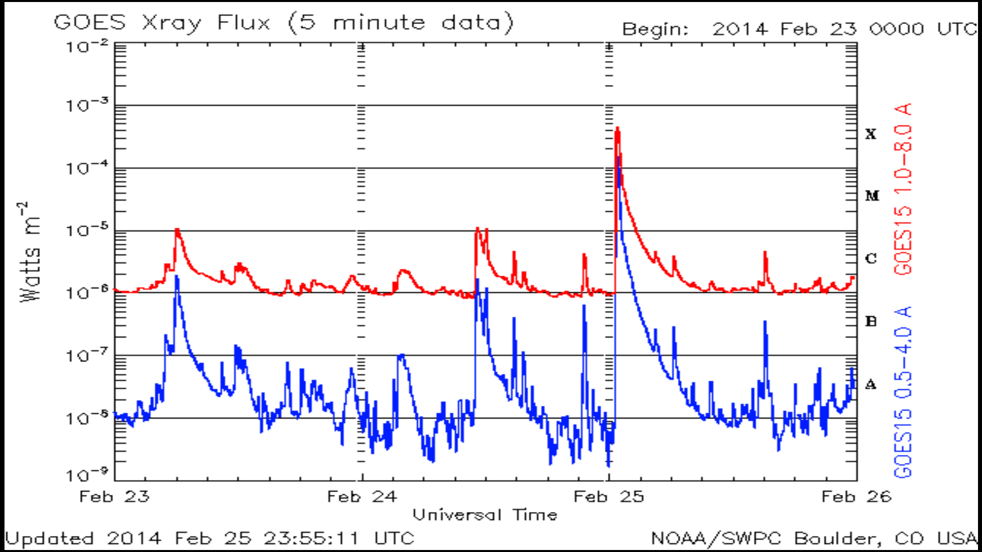


❖ Large number of n
(not detected in the

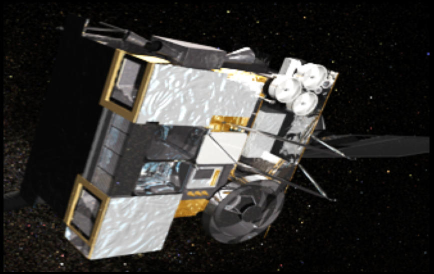
Fev.15, 2011 X-class flare

WHAT IS A FLARE?

Depends on peak of X-ray flux



A GOES soft X-ray time series:
1-8Å and 0.5-4Å passbands



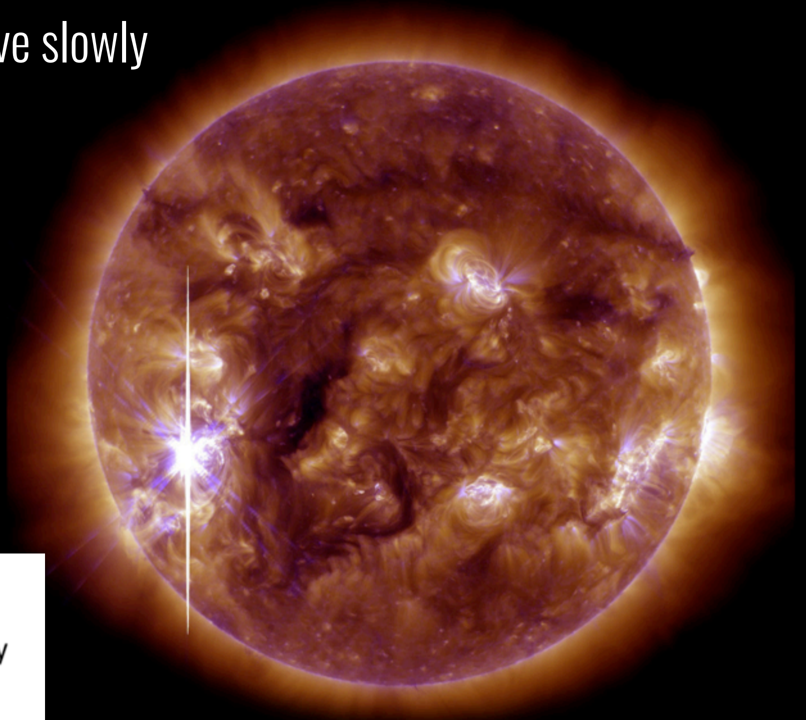
GOES class	1-8Å peak W/m^2
A	$>10^{-8}$
B	$>10^{-7}$
C	$>10^{-6}$
M	$>10^{-5}$
X	$>10^{-4}$
-	$>10^{-3}$

Largest flare:
Halloween flare (Nov 4 2003) 10^{33} erg (10^{26} J) X28
Super flares?
Up to 3.10^{36} erg (10^{29} J)

CORONA HEATING VS FLARES: what's similar/different?

- Coronal heating is quasi-steady, plasma seems to evolve slowly

- Flares are abrupt: plasma heats and evolves rapidly, structural changes, non-thermal electrons not detected in non-flaring hot corona



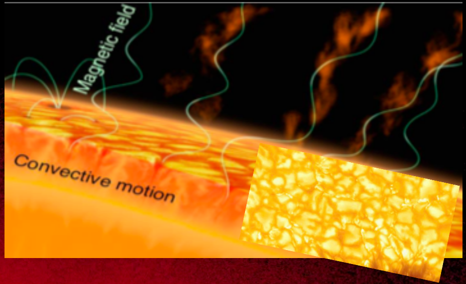
Coronal heating:
- Quasi-steady hot corona means a quasi-continuous dissipation process
- No need for coronal energy storage
- Plasma remains almost Maxwellian

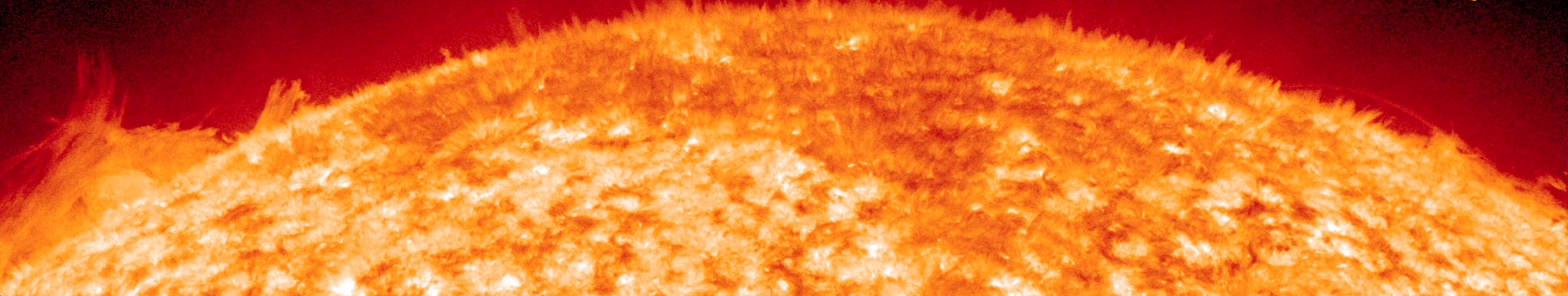
Flares:
- Rapid character of flare means very intermittent energy dissipation
- Need for long-term energy storage.
- Plasma becomes non-Maxwellian

CORONA HEATING VS FLARES: what’s similar/different?

- Coronal heating is quasi-steady, plasma seems to evolve slowly

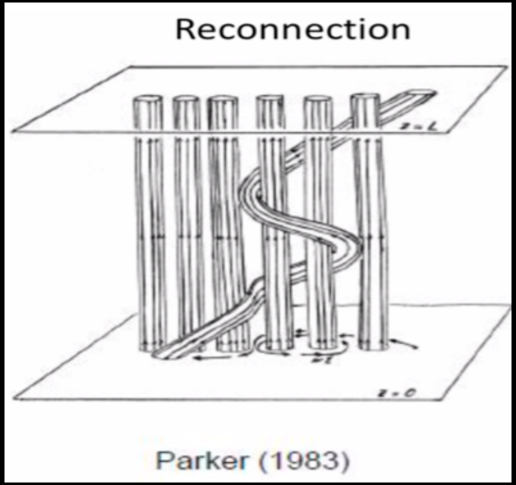
« Spicules », or small « jets » coming from the chromosphere,
Alfvén waves due to motions convective/photospheric layers

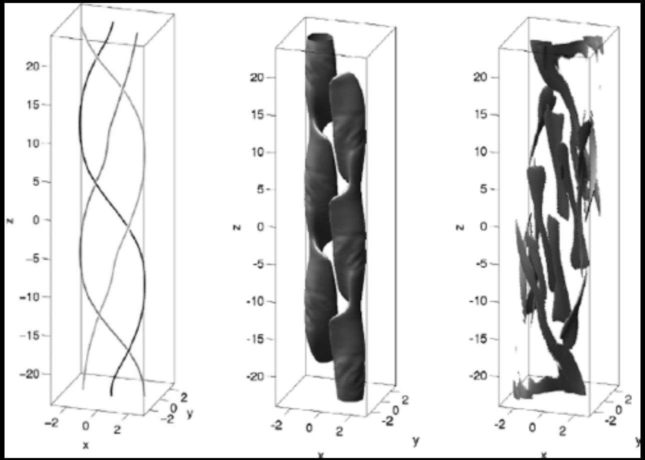




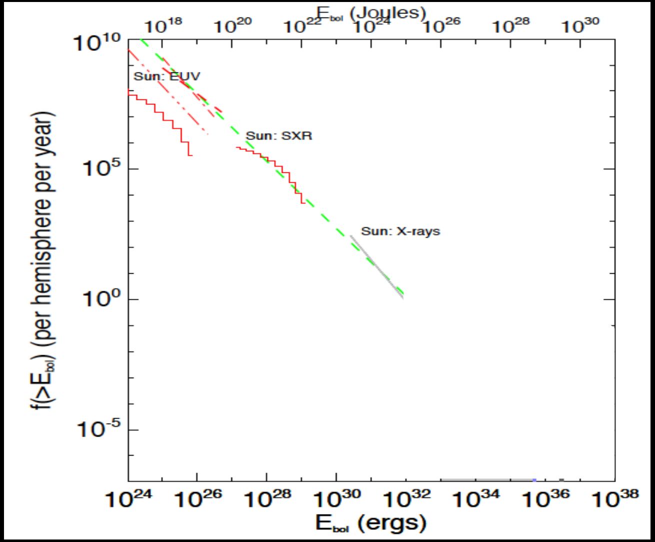
CORONA HEATING VS FLARES: what's similar/different?

- Flares are abrupt: plasma heats and evolves rapidly
  → But if it happens at small scales everywhere, can it work?





Pontin et al. 2011

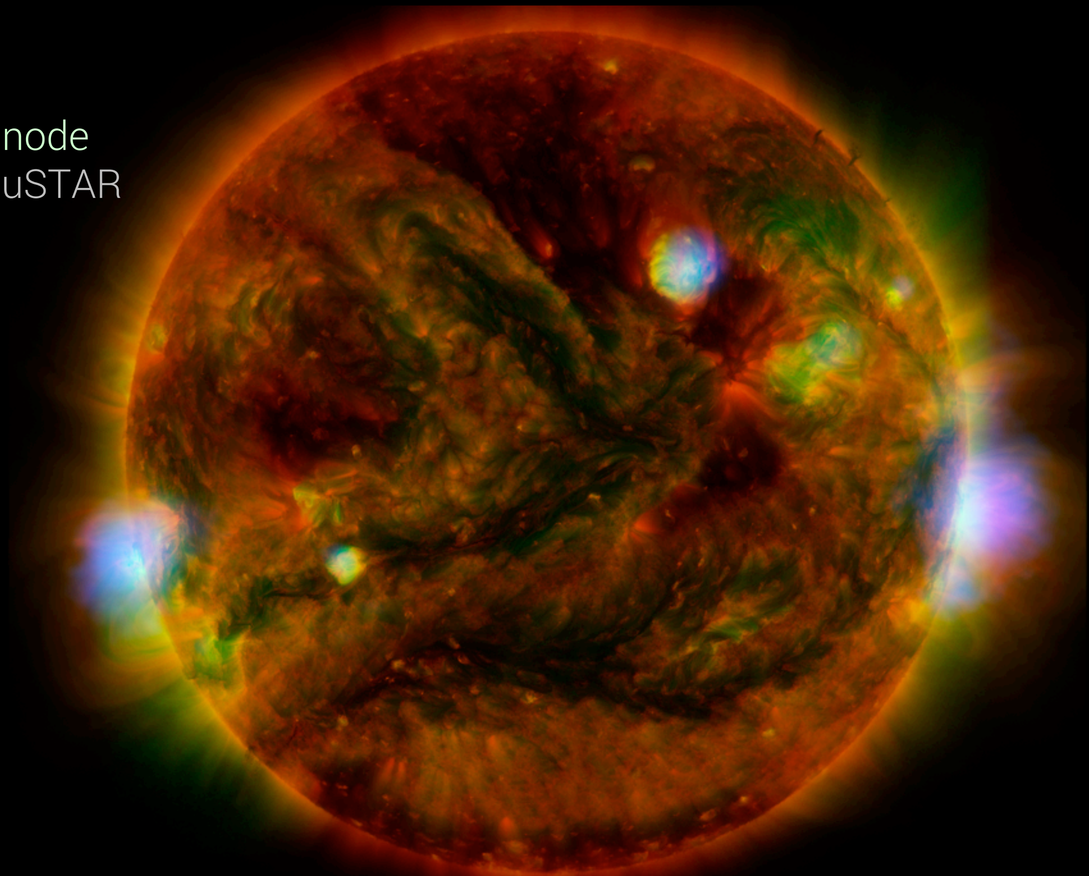


Adapted from Schrijver (2009)

→Coronal heating by reconnection-generated Joule heating and Alfven wave dissipation

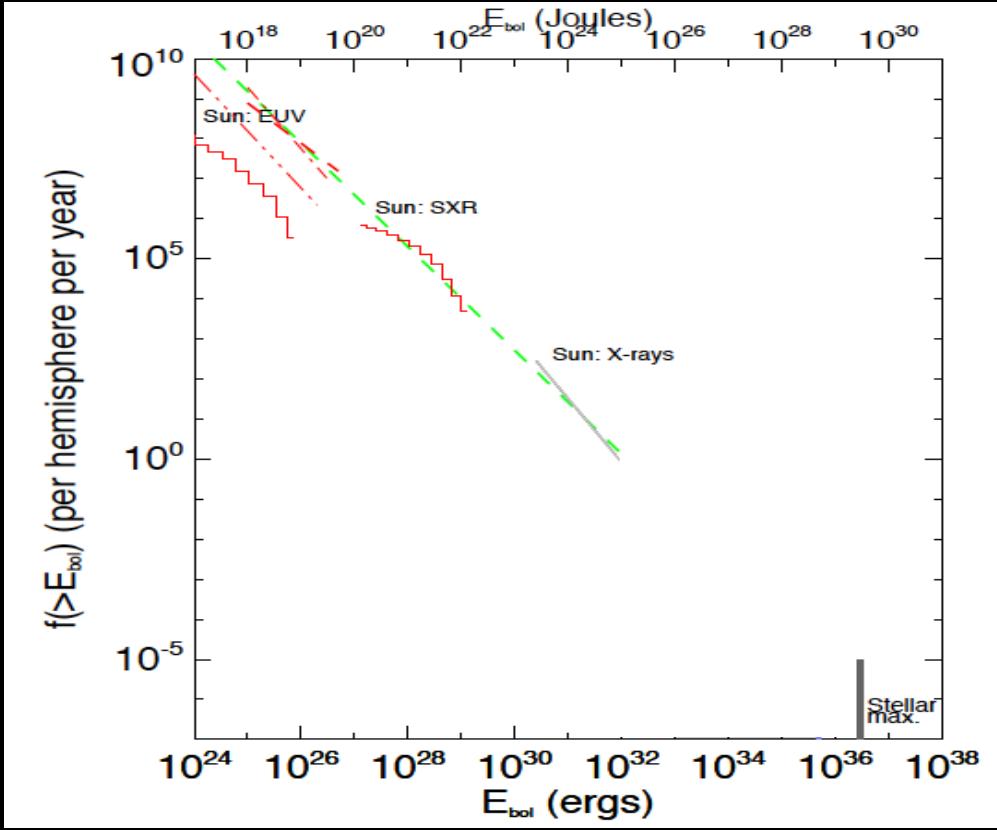
NUSTAR: SHOWING MICRO-FLARES IN QUIET SUN REGIONS

- EUV from SDO
- Low X-rays from Hinode
- High X-rays from NuSTAR



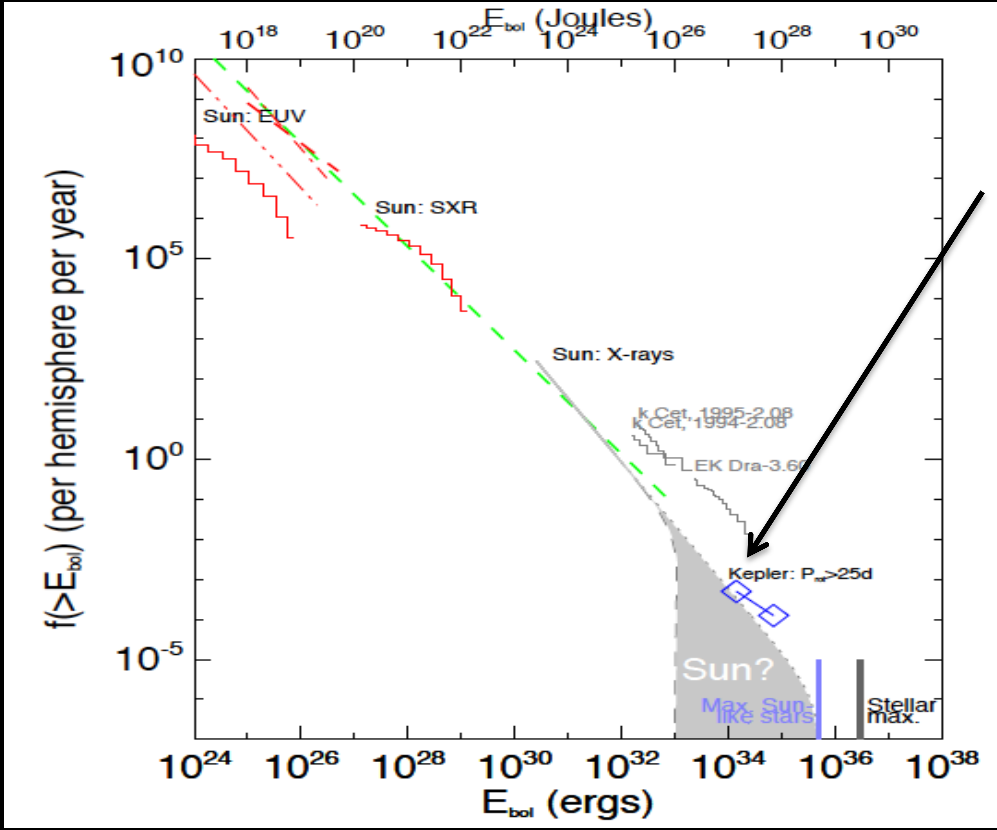
Coronal heating?
Probably a combination of all mechanisms…

FROM SOLAR FLARES TO STELLAR FLARES



Adapted from Schrijver (2009)

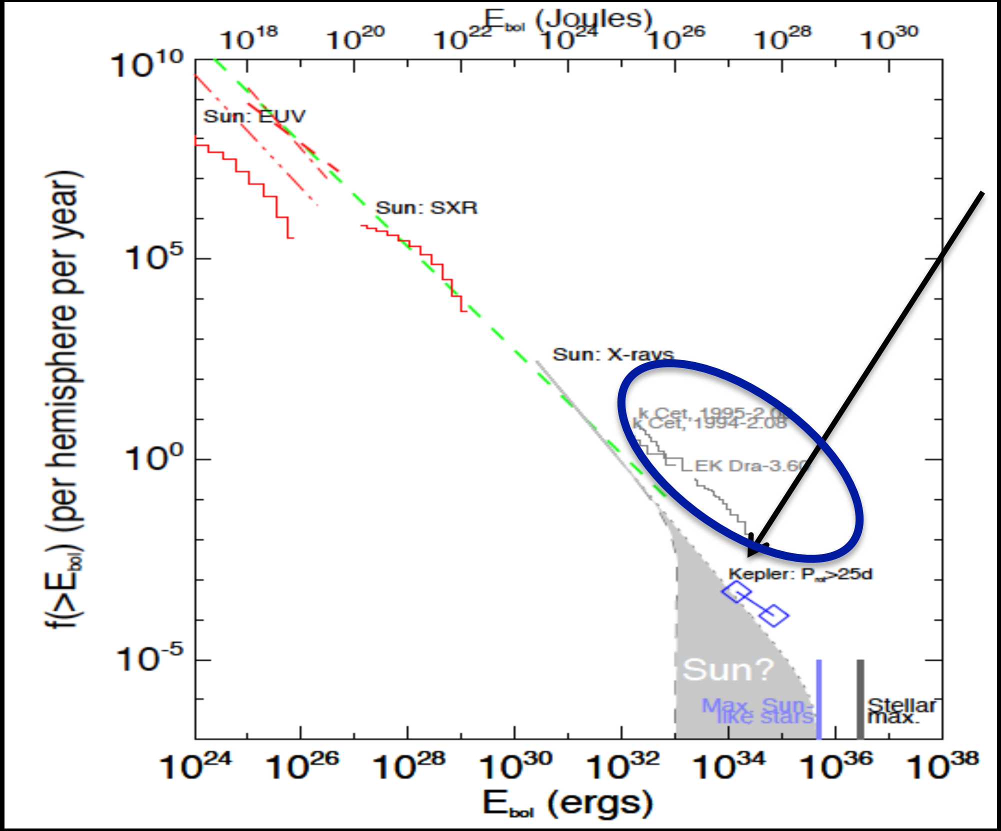
FROM SOLAR FLARES TO STELLAR FLARES



Adapted from Schrijver (2009)

Kepler data suggests continuation up to 5.10^{35} erg

FROM SOLAR FLARES TO STELLAR FLARES

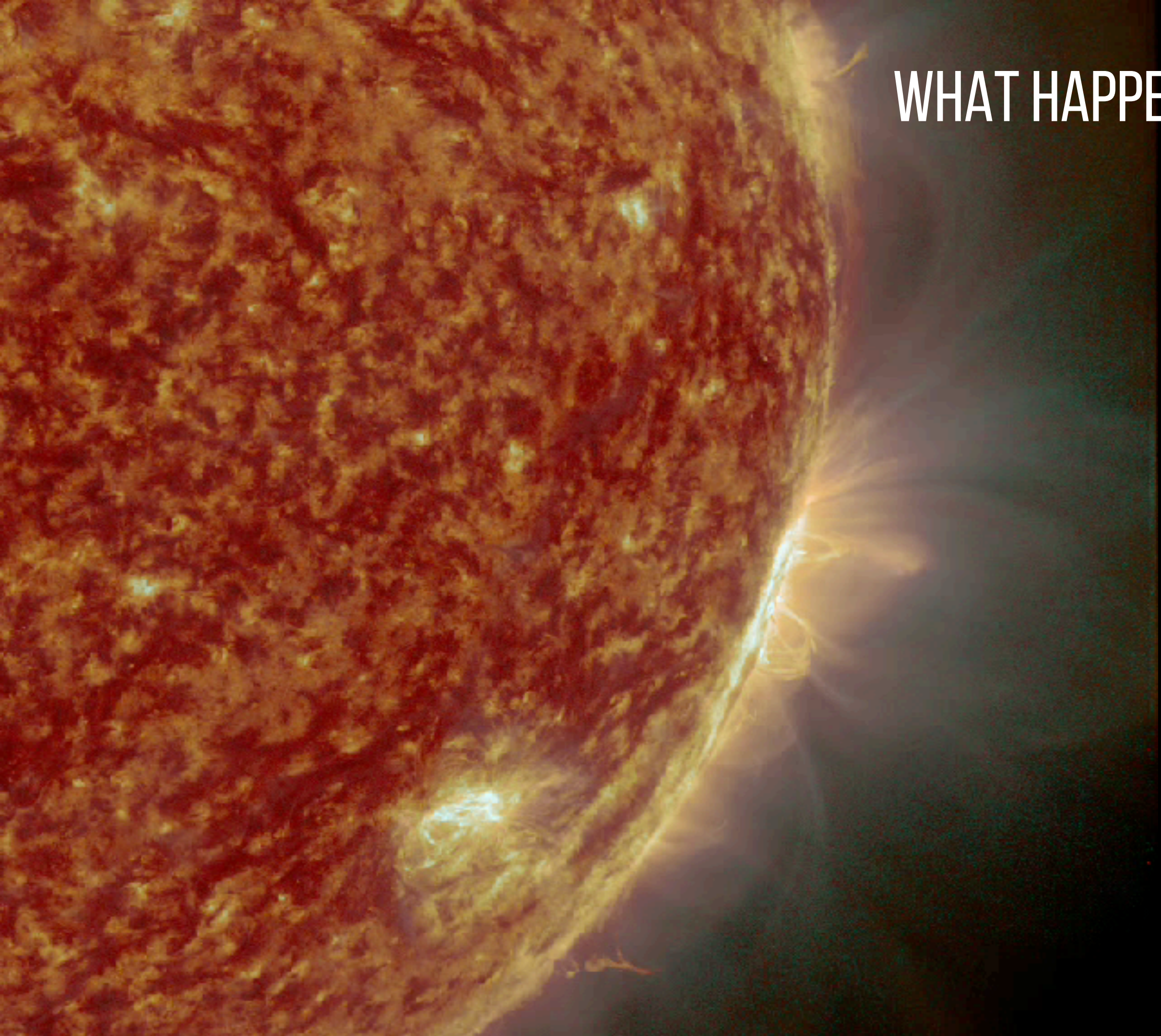


Adapted from Schrijver (2009)

Kepler data suggests continuation up to 5.10^{35} erg

But frequency scaling with more active stars fails...

Understanding of solar flares may (or may not!) help us understand flaring activity on other stars....

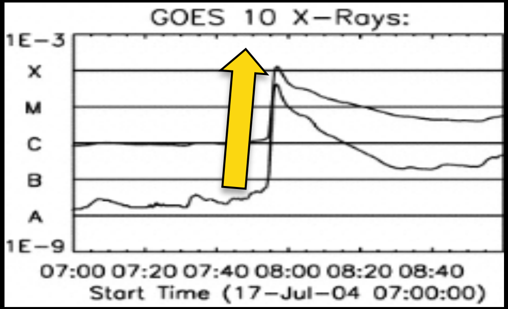


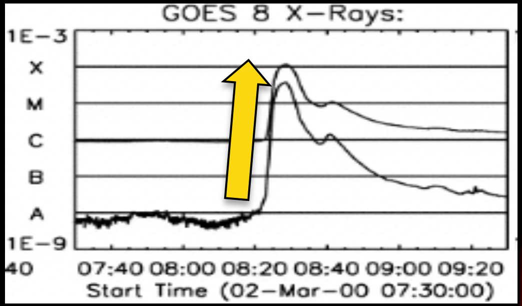
WHAT HAPPENS DURING A SOLAR FLARE?

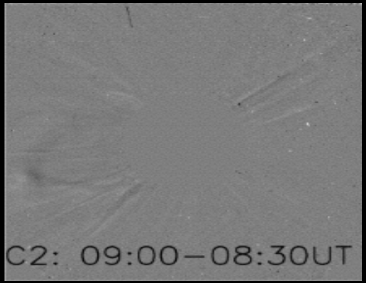
From observational aspects to models

CHARACTERISTICS OF SOLAR FLARES: observations

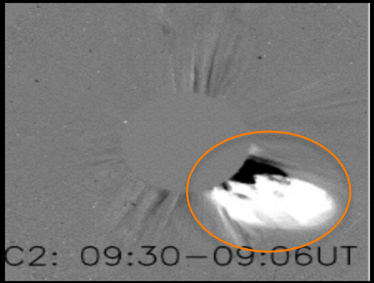
Flares can be **eruptive** or **confined**



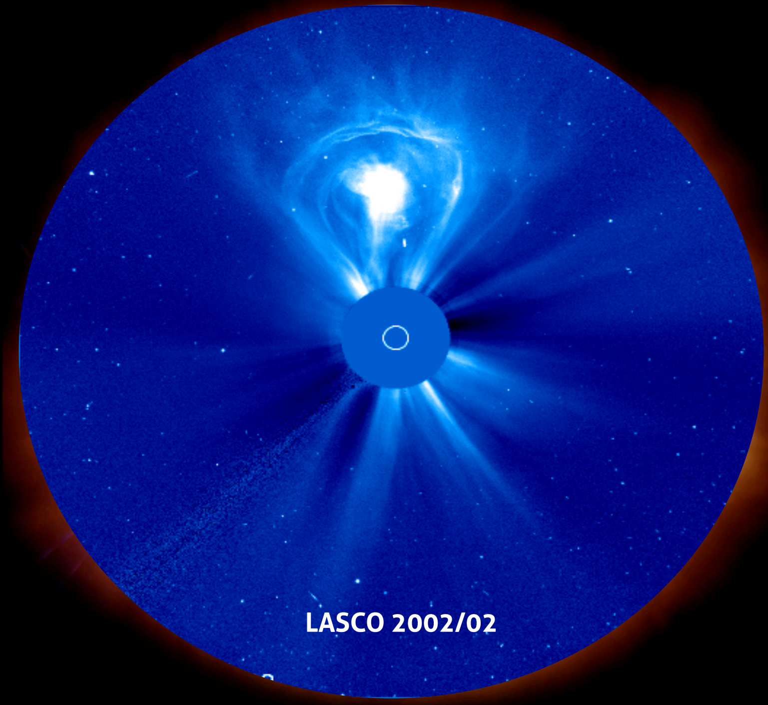




Confined flares



Eruptive flares

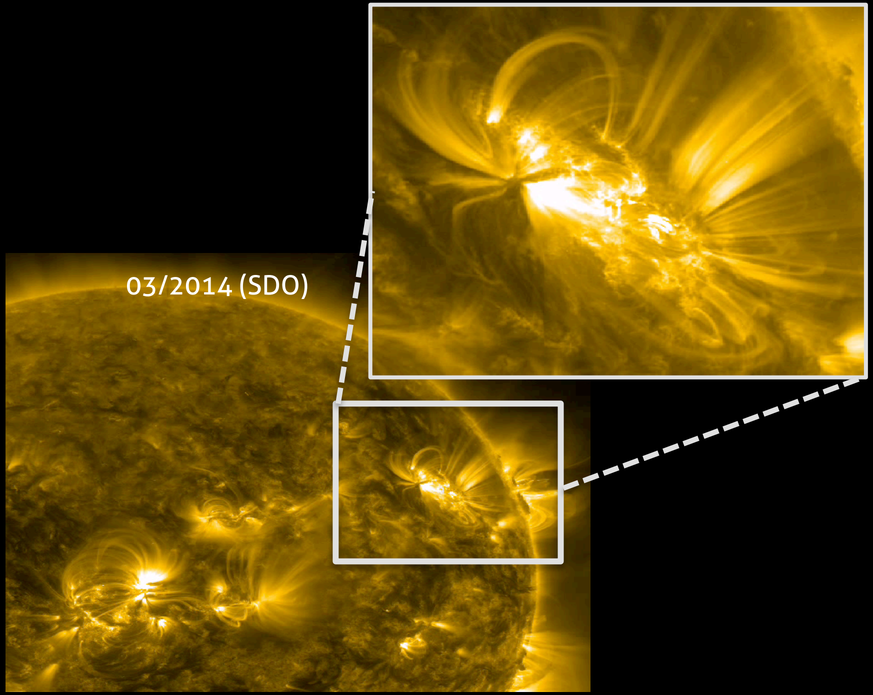


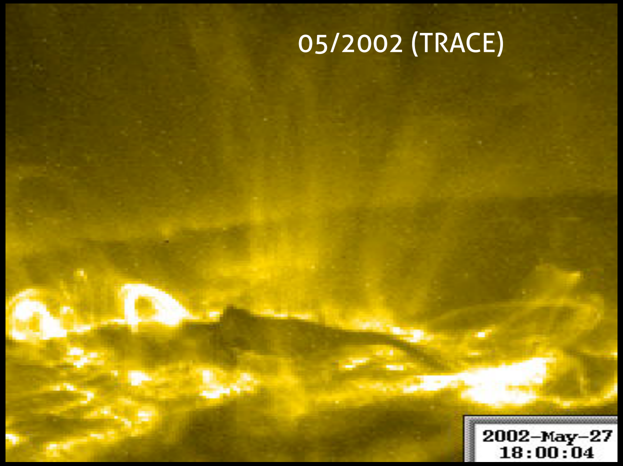
Eruptive flares:

associated with a CME

CHARACTERISTICS OF SOLAR FLARES: confined flares

Flare – Emission & Loops

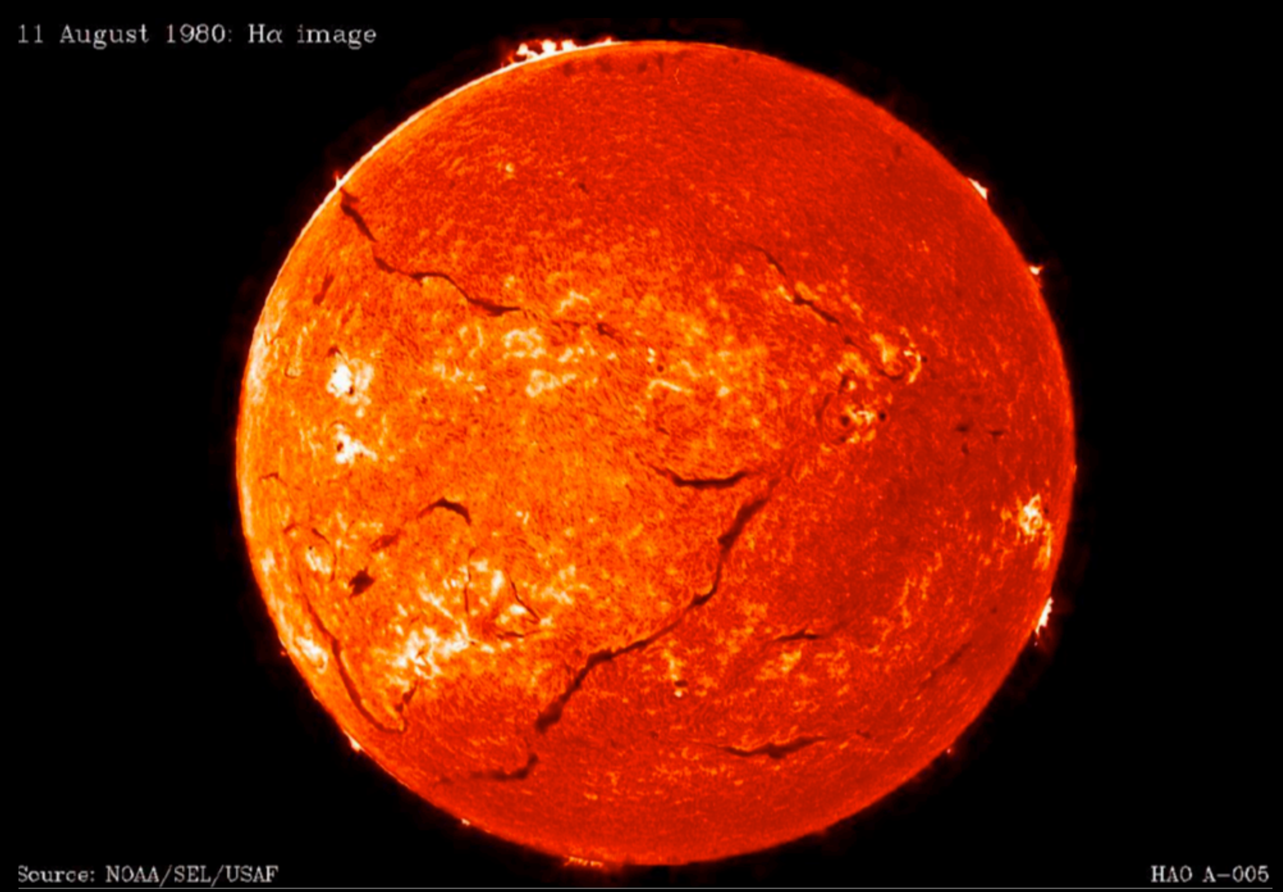




Failed filament eruption

Ji et al. (2003)

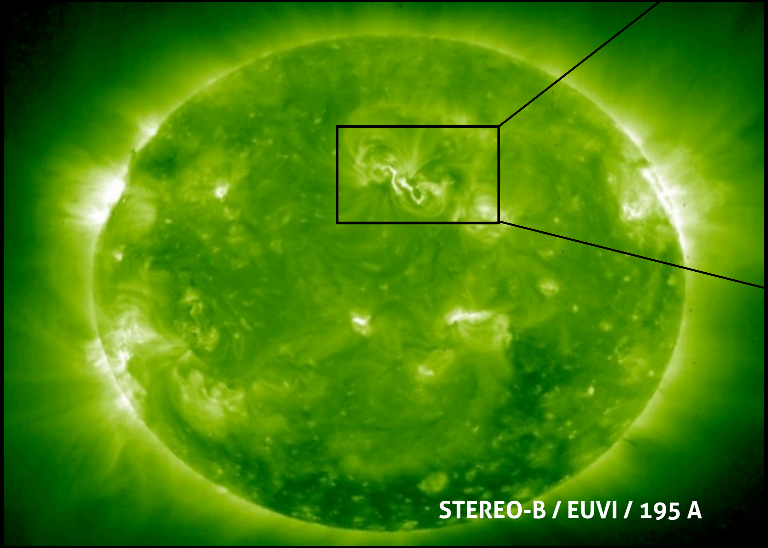
CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: prominences/filaments

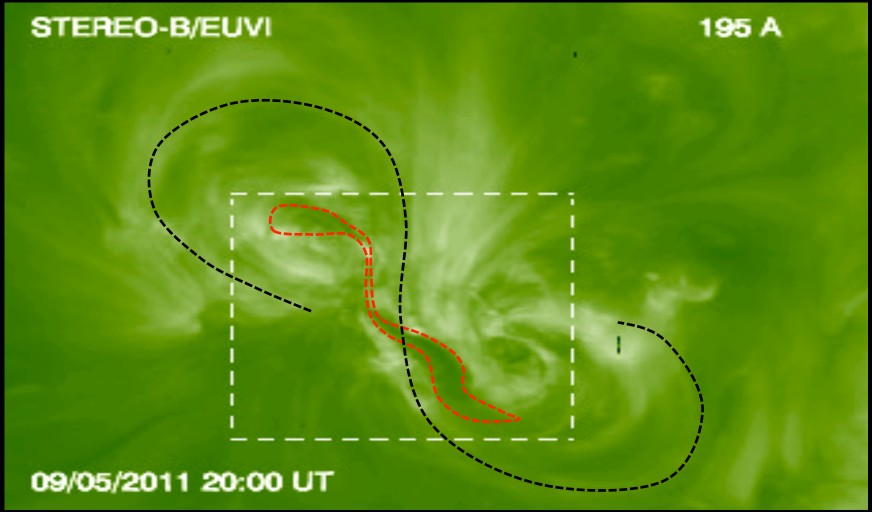


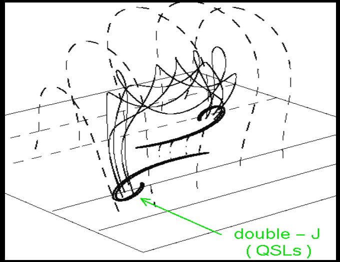
CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: prominences/filaments

Pre-eruptive sigmoid & filament
(not always)

Rust & Kumar (1996),Green & Kliem (2009), Schmieder (2013), Aulanier et al. (2012)

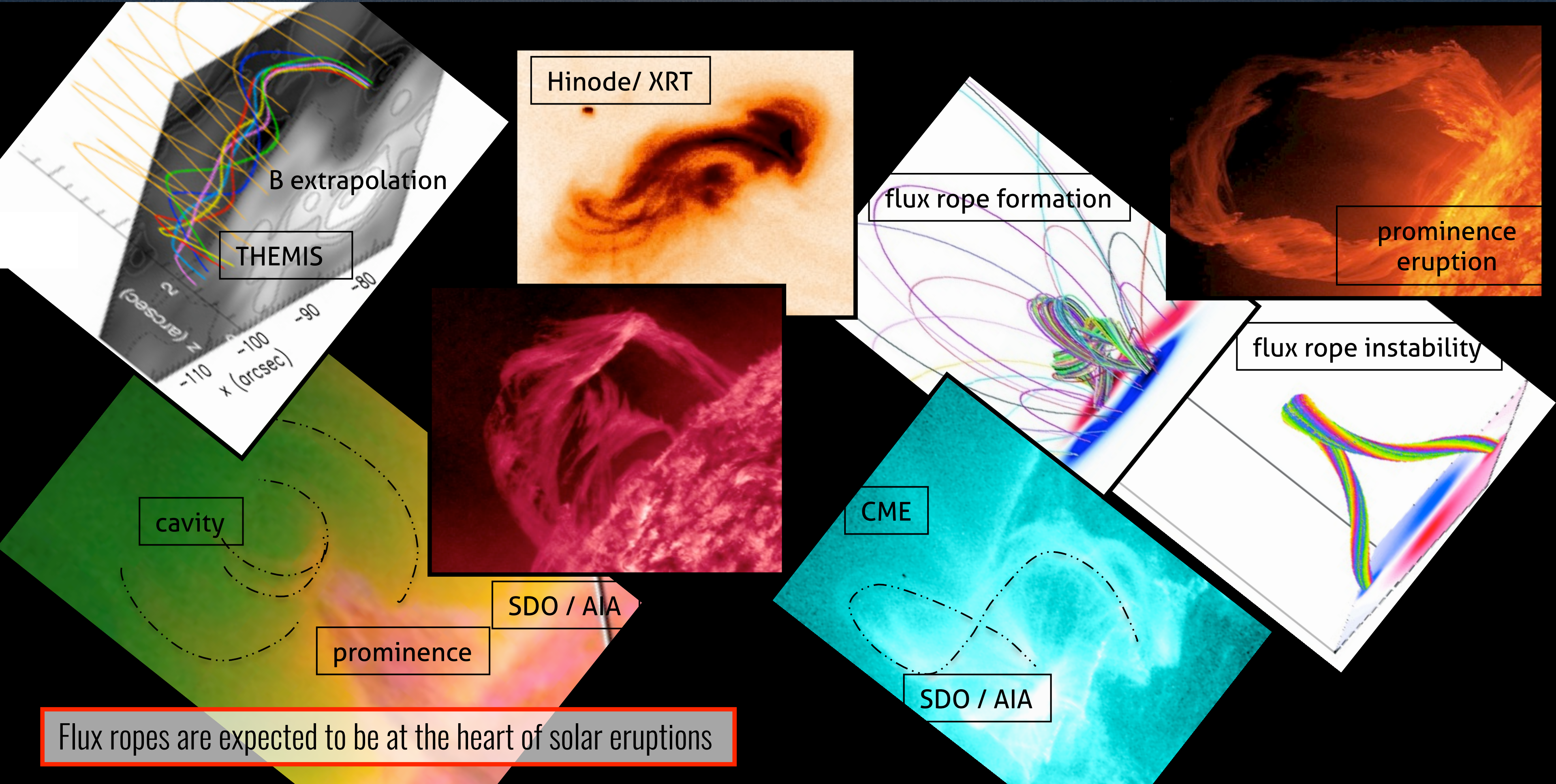






We think they are indicative of the presence of a FLUX ROPE

FLUX ROPES ARE FOUND EVERYWHERE

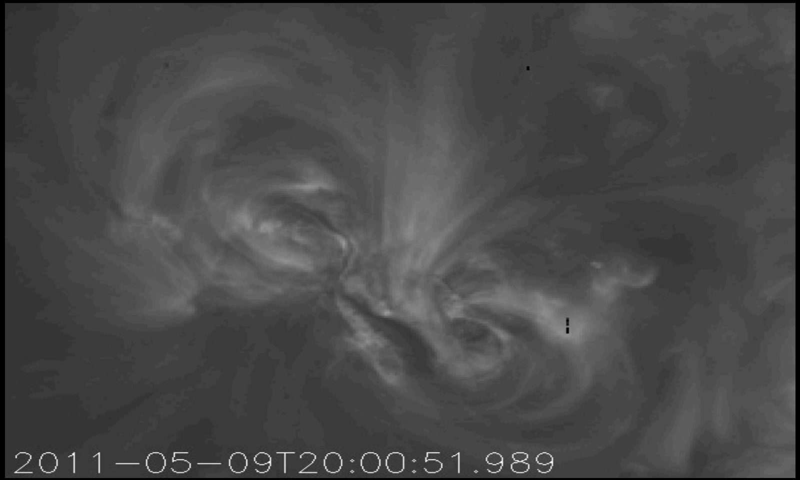


Flux ropes are expected to be at the heart of solar erruptions

CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: flare loops

Flare loops

⟹Low-to-high altitude loop brightening
⟹Strong-to-weak shear transition



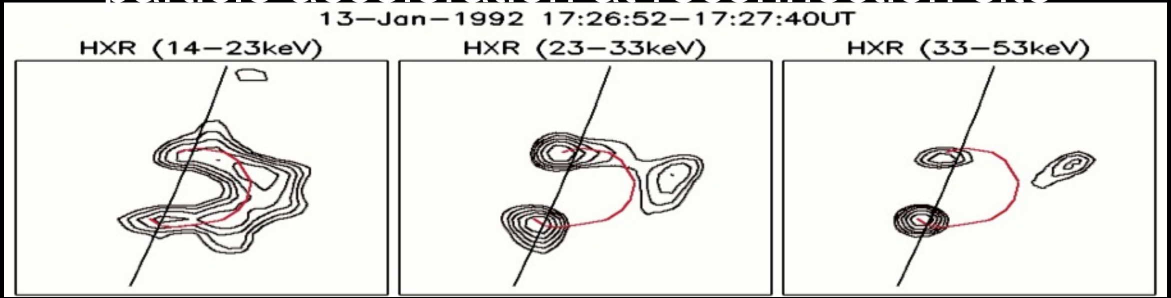
STEREO-B / EUVI / 195 A

CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: flare loops

Hard X-ray source above the loop top:

particle acceleration at reconnection site

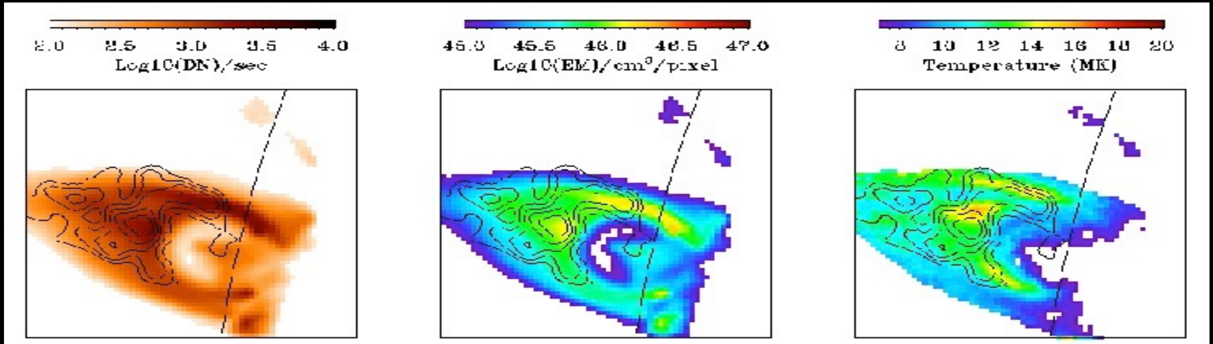
Masuda et al. (1994), Hudson et al. (2001), Sui et al. (2003)



SXR high temperature ridges along outer or newly formed loops:

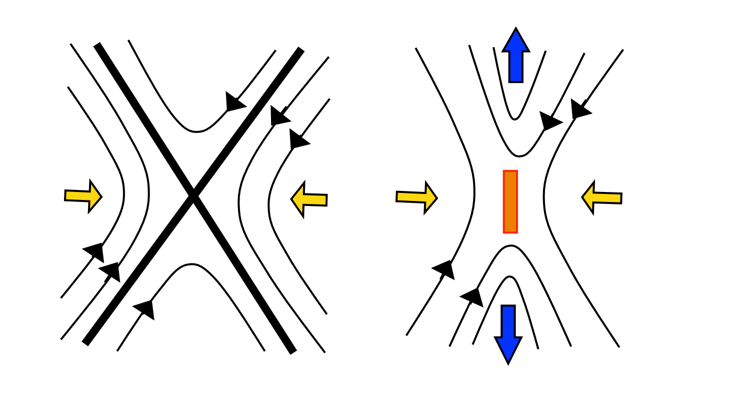
heating takes place

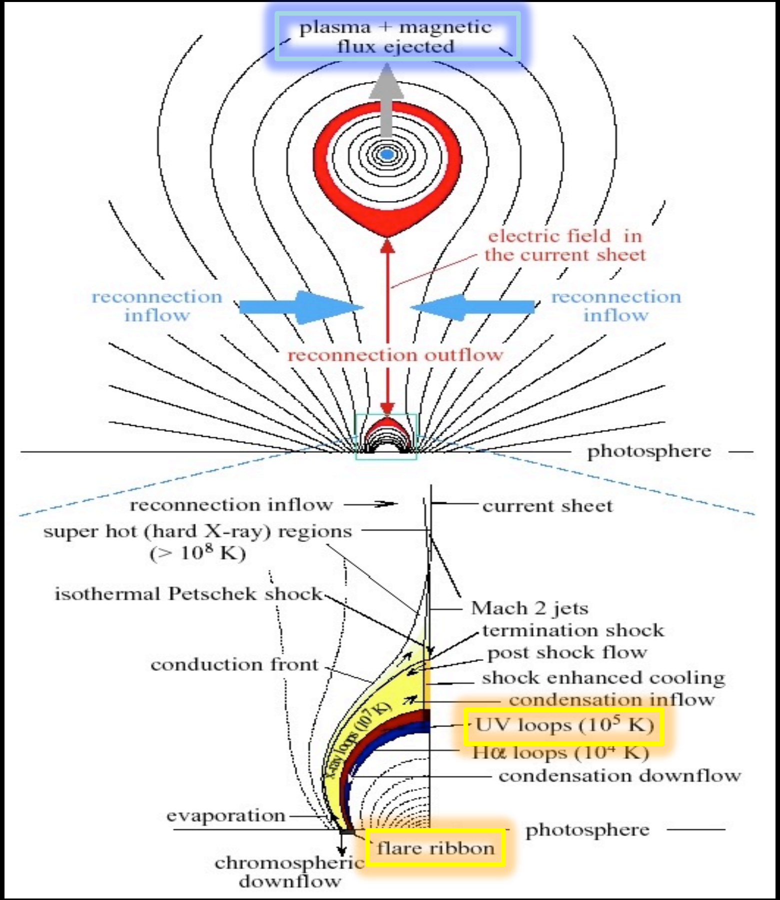
Tsuneta et al. (1996)



*

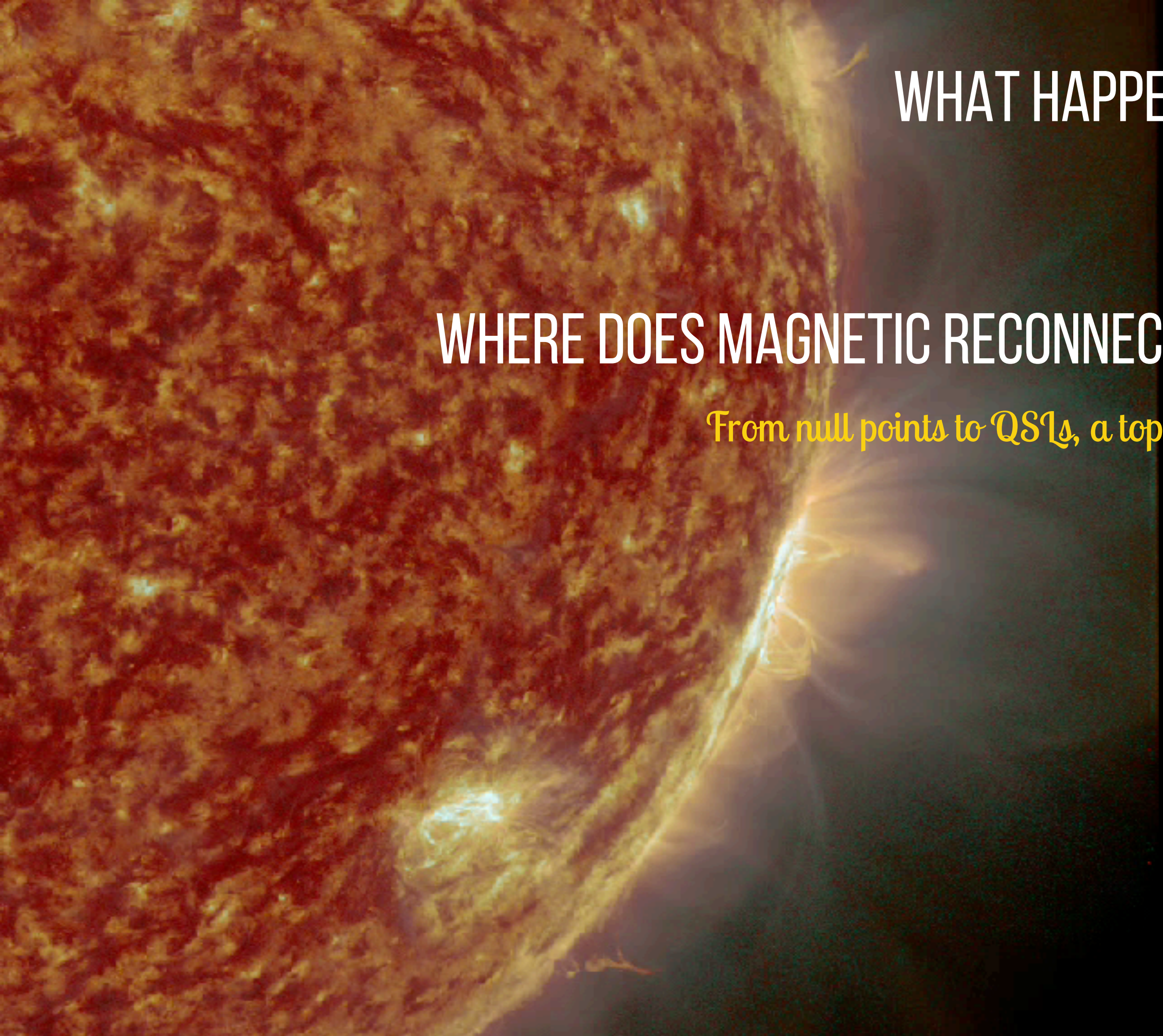
CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: the CSHKP model





Carmichael (1964)
Sturrock (1966)
Hirayama (1974)
Kopp & Pneumann (1976)
.
Forbes & Malherbe (1986)

STANDARD FLARE MODEL IS DEVELOPED



WHAT HAPPENS DURING A SOLAR FLARE?

From observational aspects to models

WHERE DOES MAGNETIC RECONNECTION OCCUR?

From null points to QSLs, a topology story

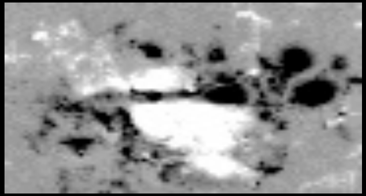
MAGNETIC TOPOLOGY: UNDERSTANDING LOCATIONS OF ENERGY RELEASE

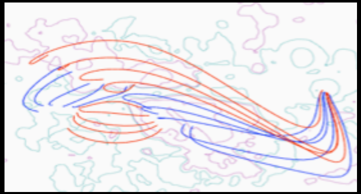
Method:

Input the photospheric magnetogram

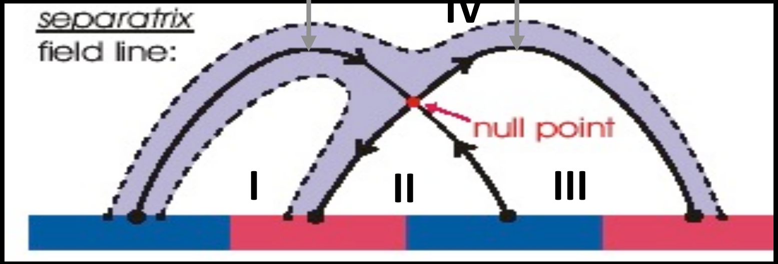
Compute the coronal field

Compute magnetic null points & separatrices



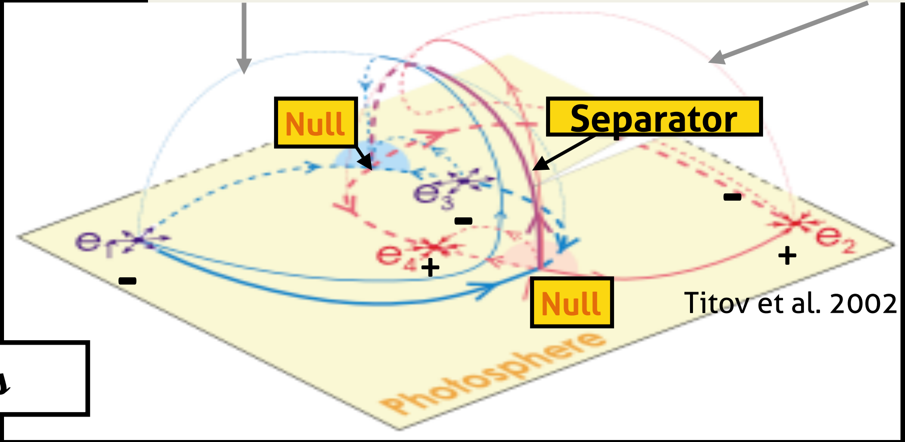


2D separatrices

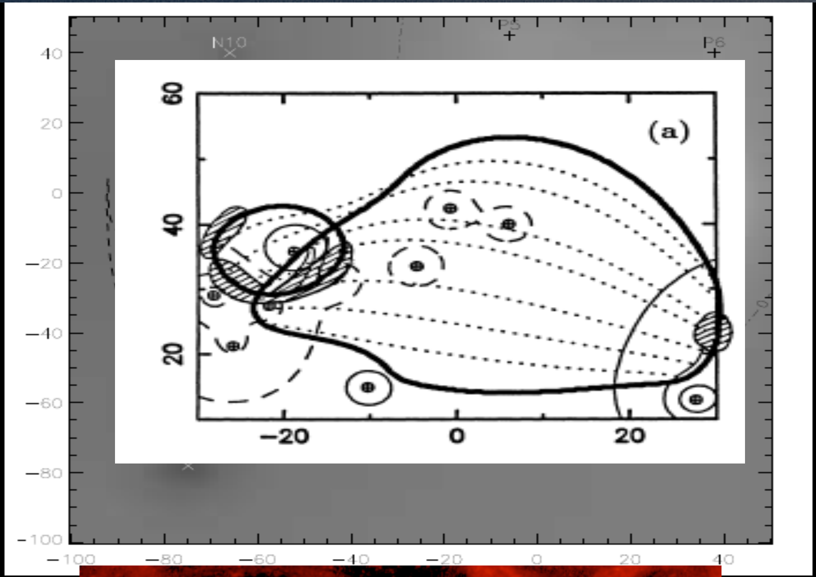


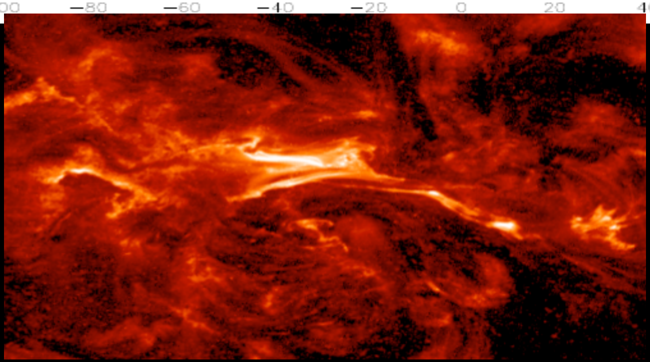
4 connectivity domains

3D separatrices: 2 intersecting cupola



TOPOLOGY OF SOLAR FLARES: 3D extensions





Magnetic Charge Topology Models:

From 4 point charges...
Baum & Brathenal 1980, Gorbachev & Somov 1988, Lau 1993

...to multiple ones:
Mandrini et al. 1993, Démoulin et al. 1994a, Longcope 1996, Aulanier 1998

Démoulin et al. **1994b:**
Photospheric mapping of the magnetic field:
Flares occur in regions where no null points are found

If no null points: mapping functions of field line footpoints from one boundary to another are continuous

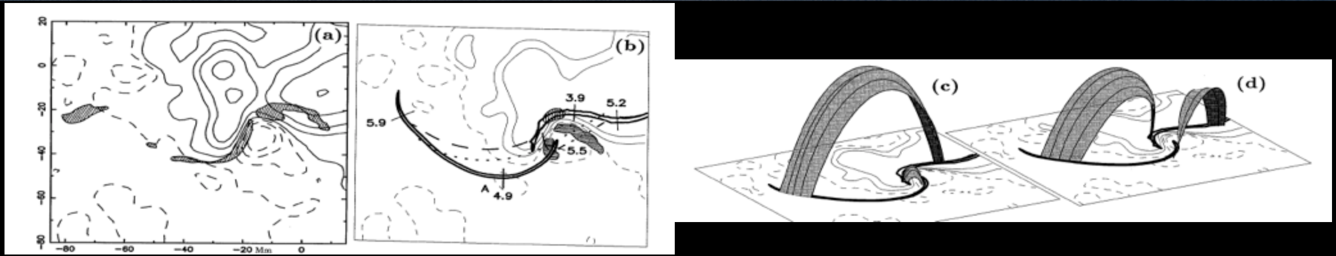
Schindler et al. **1988**
Hesse & Schindler **1988**

→ Separatrices/Separators do not need to exist
→ « Reconnection » takes place where $E_{||}$ is important (« non-idealness »)

Also: Priest & Forbes 1989, 1992

FLARES IN 3D: no null point configuration

Priest & Démoulin **1995**
Démoulin et al. **1996-1997**



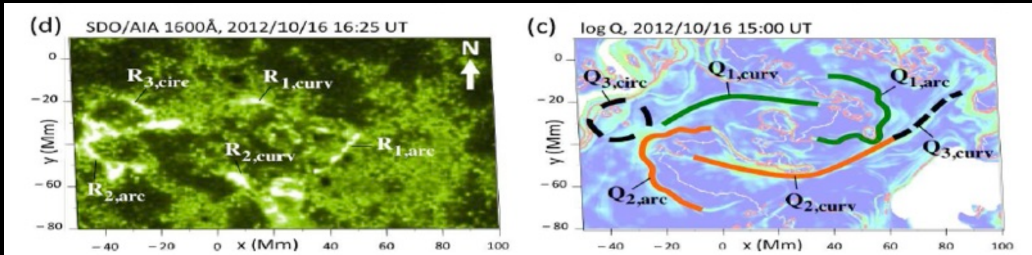
Idea of reconnection happening in regions of strong magnetic field distortion:

« Quasi » separatrix layers

Reconnection can occur (and does) **physically** in regions where ideal MHD breaks down

Since then: numerous evidences of flaring activity associated with quasi-separatrix layers:

Schmieder et al. 97, Démoulin et al. 97, Mandrini et al. 97, Bagala et al. 00, Wang et al. 00, Fletcher et al. 01, Mandrini et al. 06, Masson et al. 09, Chandra et al. 11, Savcheva et al. 12, Inoue et al. 13, Zhao et al. 14, Savcheva et al. 14, Dudik et al. 14



e.g. to explain « non-standard » flare: Dalmasse et al. (2015), Joshi et al. (2019)

INTRODUCING QUASI-SEPARATRIX LAYERS

In 3D:
Strong distortion of magnetic field ⇛ Current layer
Ideal MHD can still break down in those finite-J regions.

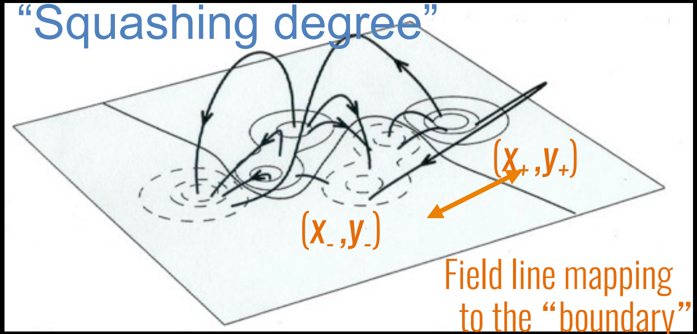
Localized, drastic change of magnetic connectivity (but continuous without null points)

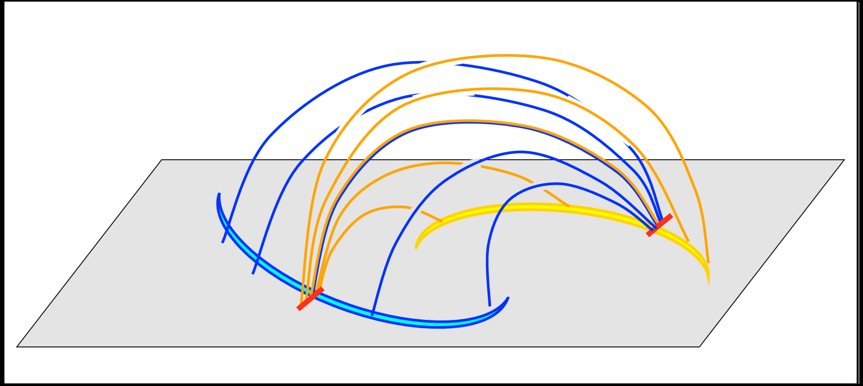
QSL definition: regions where

$$Q \equiv \frac{\| F \|^2}{B_{n,+} / B_{n,-}} >> 1$$

$$F = \begin{pmatrix} \partial x_- / \partial x_+ & \partial x_- / \partial y_+ \\ \partial y_- / \partial x_+ & \partial y_- / \partial y_+ \end{pmatrix}$$

Démoulin et al. (1996), Titov et al. (2002), Pariat et al. (2012)



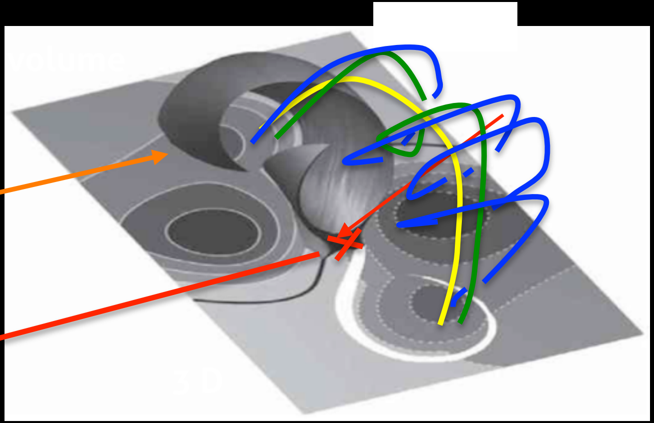


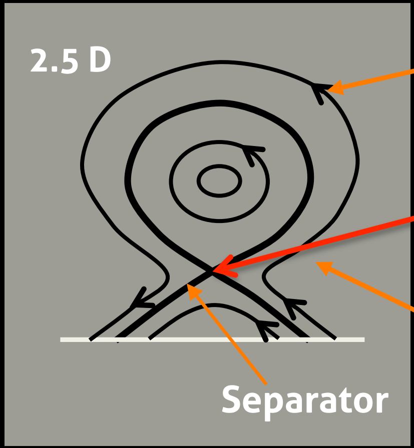
FLUX ROPE QSLS

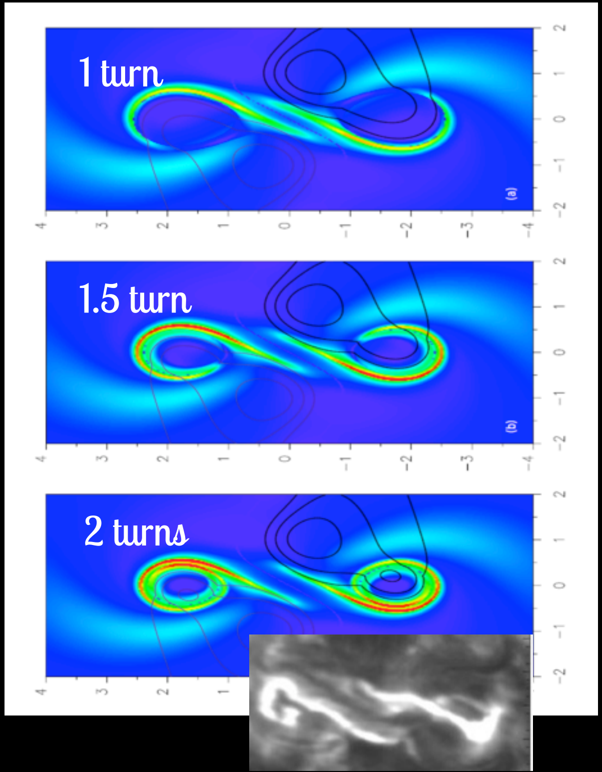
QSLS IN TWISTED CONFIGURATION

Hyperbolic Flux Tube:
X-shape in a 2D plane
(largest *Q* region)

half QSL



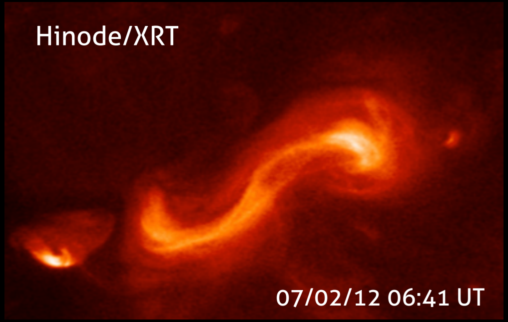


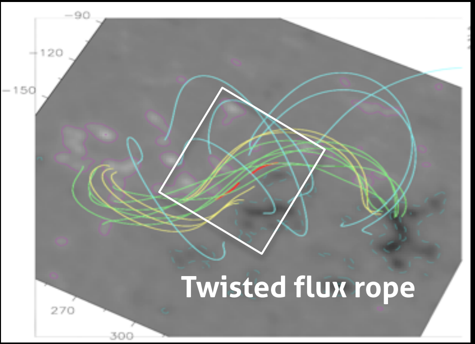


Q large
→ thin volume

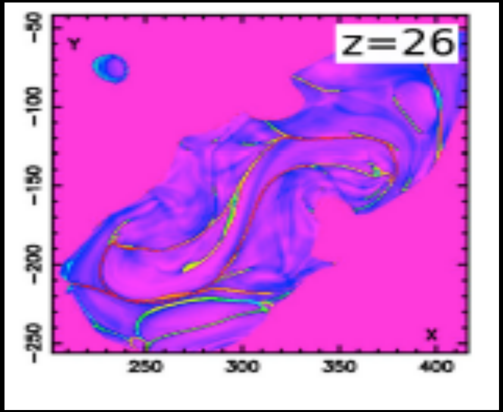
VALIDATION FROM OBSERVATIONS

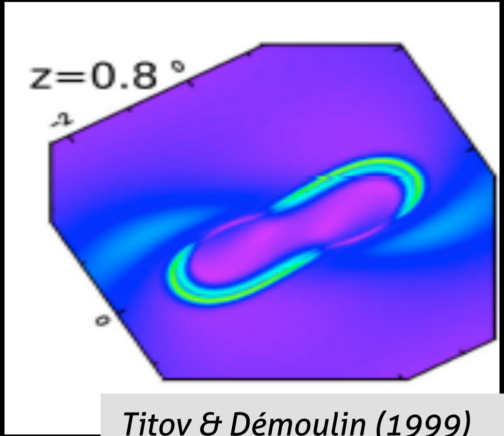
TOPOLOGY ANALYSIS WITH MAGNETIC FIELD EXTRAPOLATIONS





- 1st QSLs from a data-constrained model
- More complex than previous analytical model but similarities in shape

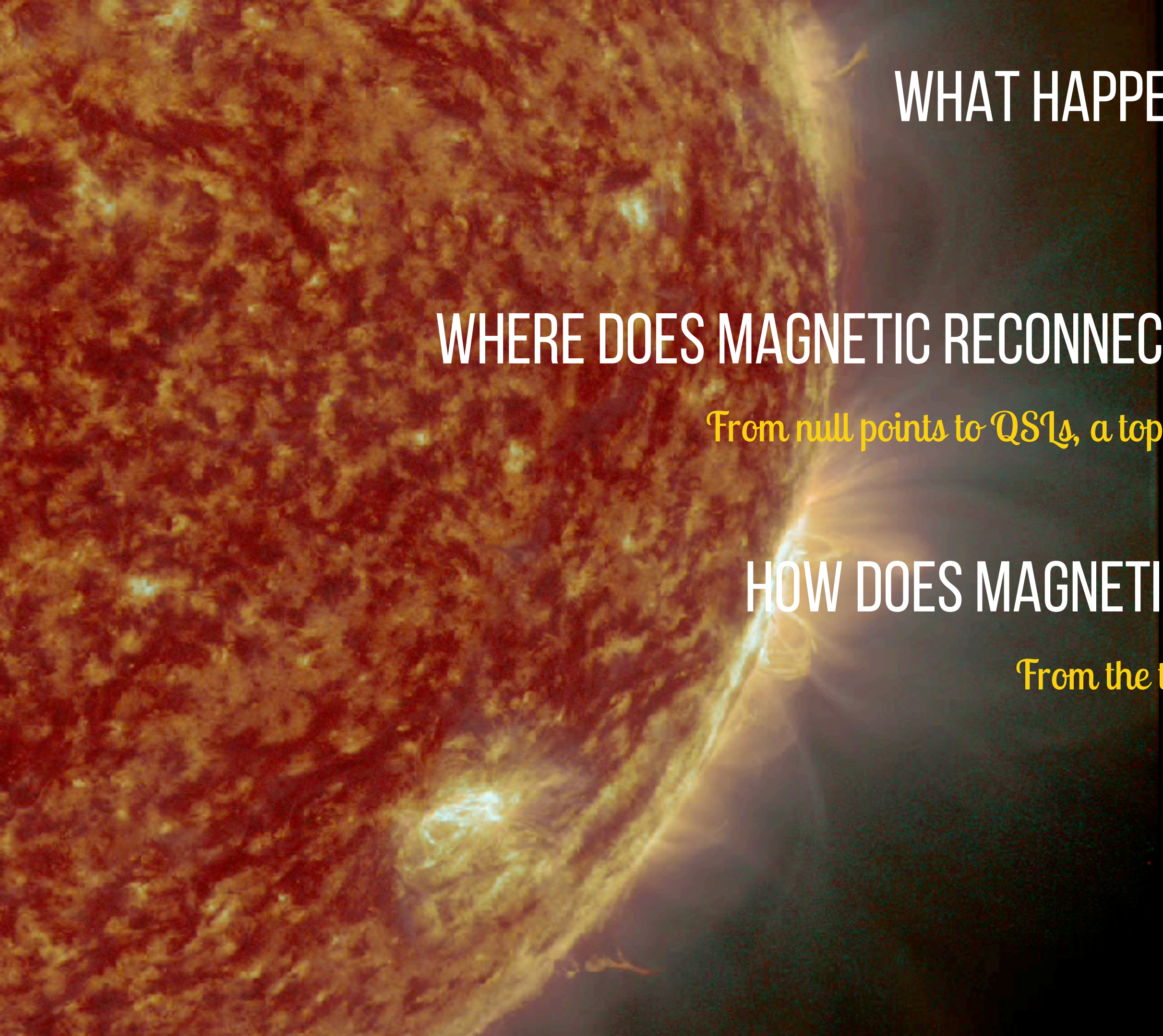




Titov & Démoulin (1999)

⟾Similar shape as for an analytical model (so-called Titov-Démoulin model)

Savcheva et al. (2012a,b)



WHAT HAPPENS DURING A SOLAR FLARE?

From observational aspects to models

WHERE DOES MAGNETIC RECONNECTION OCCUR?

From null points to QSLs, a topology story

HOW DOES MAGNETIC RECONNECTION OCCUR?

From the trigger to slipping reconnection

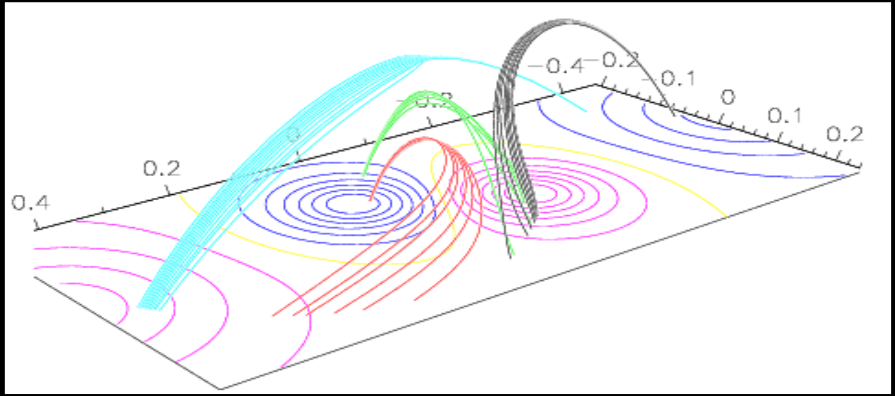
RECONNECTION IN 3D: SLIPPING RECONNECTION

In 3D:
Strong distortion of magnetic field ⇛ Current layer
Ideal MHD can still break down in those finite-J regions.

⟹Slipping reconnection

successive reconnection due to the continuous change of connectivity

Démoulin et al. (1996), Titov et al. (2002), Pariat et al. (2012)



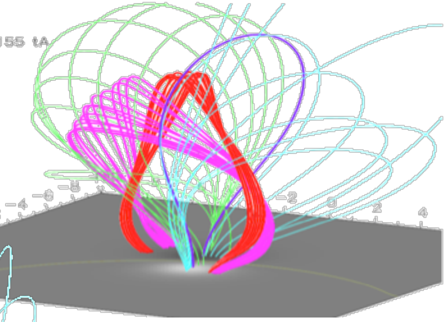
❖ Current layers: Similar location as QSLs

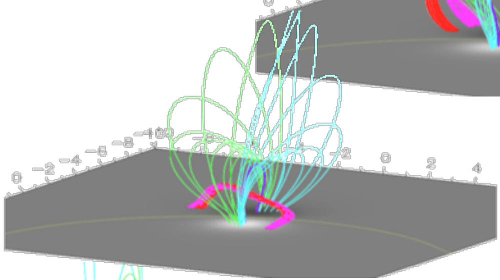
See also: (Galsgaard et al. 00, 03, Pontin et al. 05, Aulanier et al. 05, 06, Pariat et al. 06, Büchner 06, Dreher et al. 08, …)

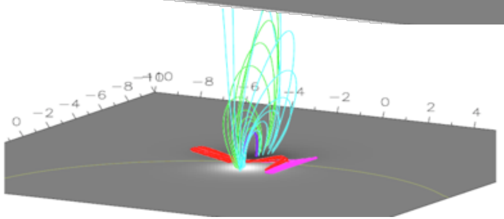
RECONNECTION IN 3D: SLIPPING RECONNECTION

THRESHOLD FOR ERUPTIONS?

OHM code $\beta = g = 0$

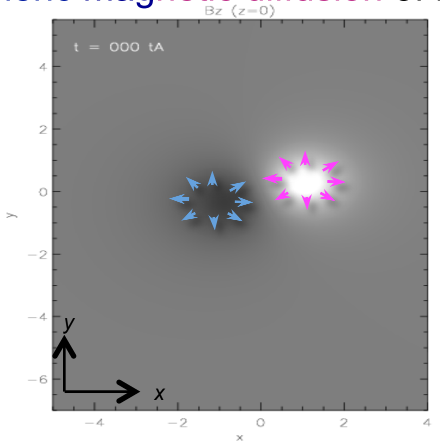






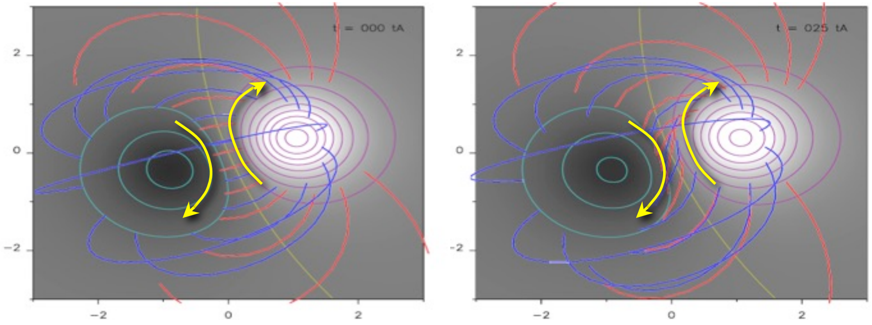
Aulanier, Török, Démoulin & DeLuca (2010)

❖ Photospheric magnetic diffusion of $B_{x,y,z}$



Aulanier, Török, Démoulin & DeLuca (2010)

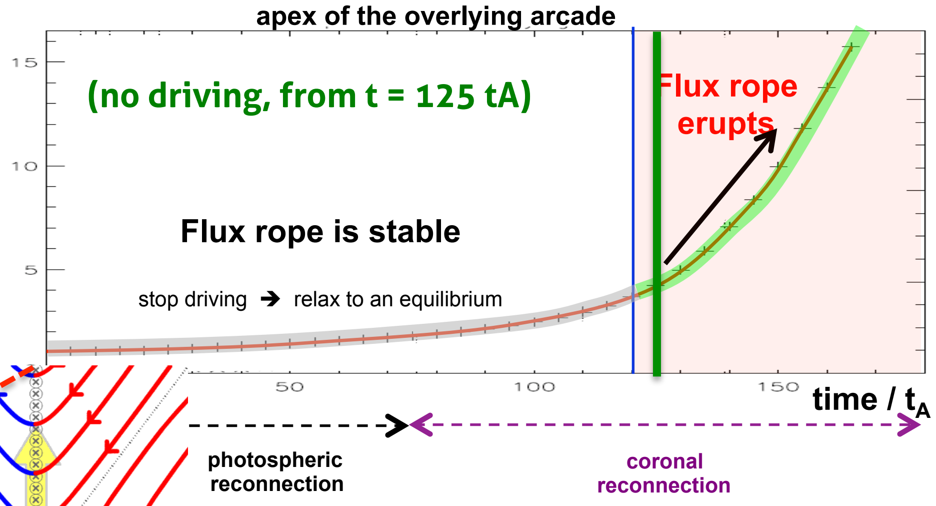
❖ Photospheric shearing motions $u_{x,y}$

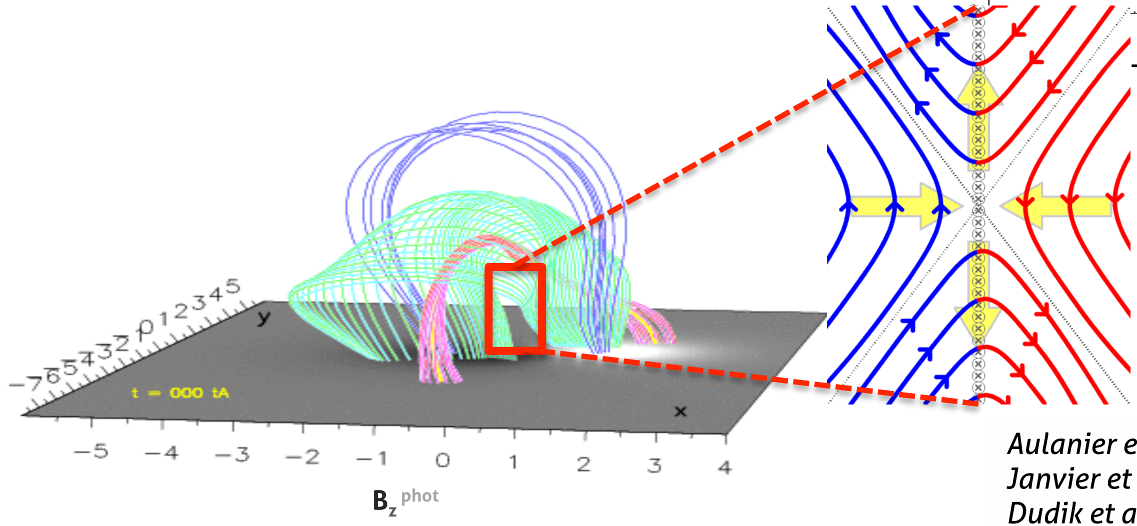


RECONNECTION IN 3D: SLIPPING RECONNECTION

THRESHOLD FOR ERUPTIONS?

Coronal arcades
Erupting flux rope





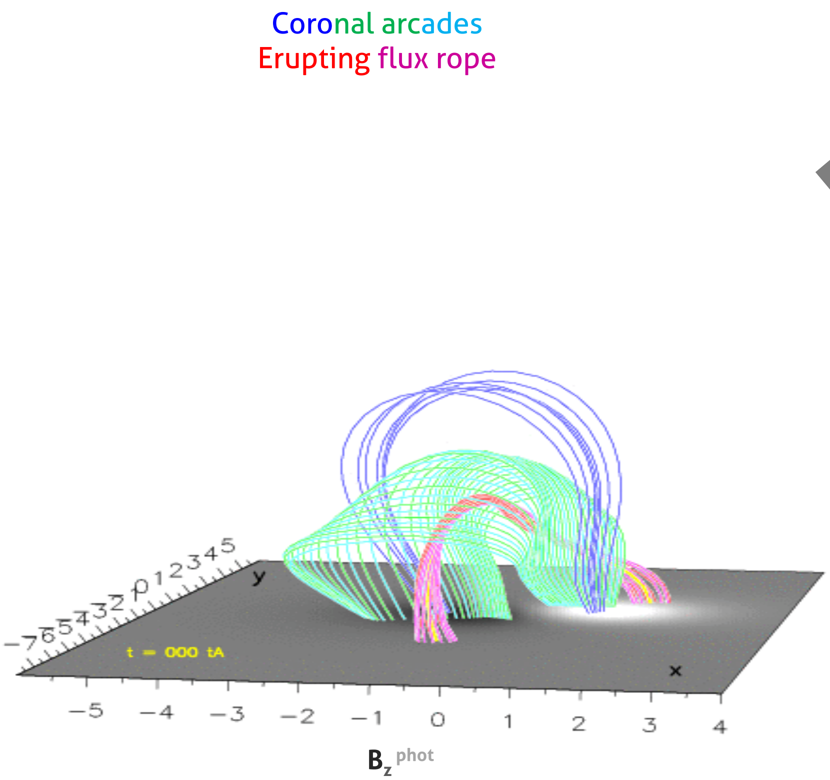
⟾ TORUS INSTABILITY

Démoulin & Aulanier (2010)

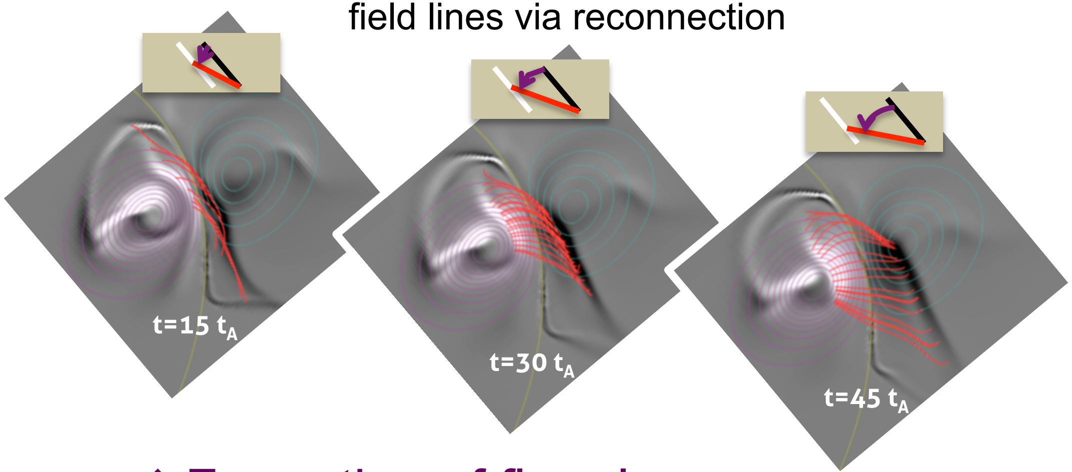
Aulanier et al. (2012)
Janvier et al, (2013)
Dudik et al. (2014)

RECONNECTION IN 3D: SLIPPING RECONNECTION

THRESHOLD FOR ERUPTIONS?



❖ Shear transferred from pre-eruptive field lines via reconnection

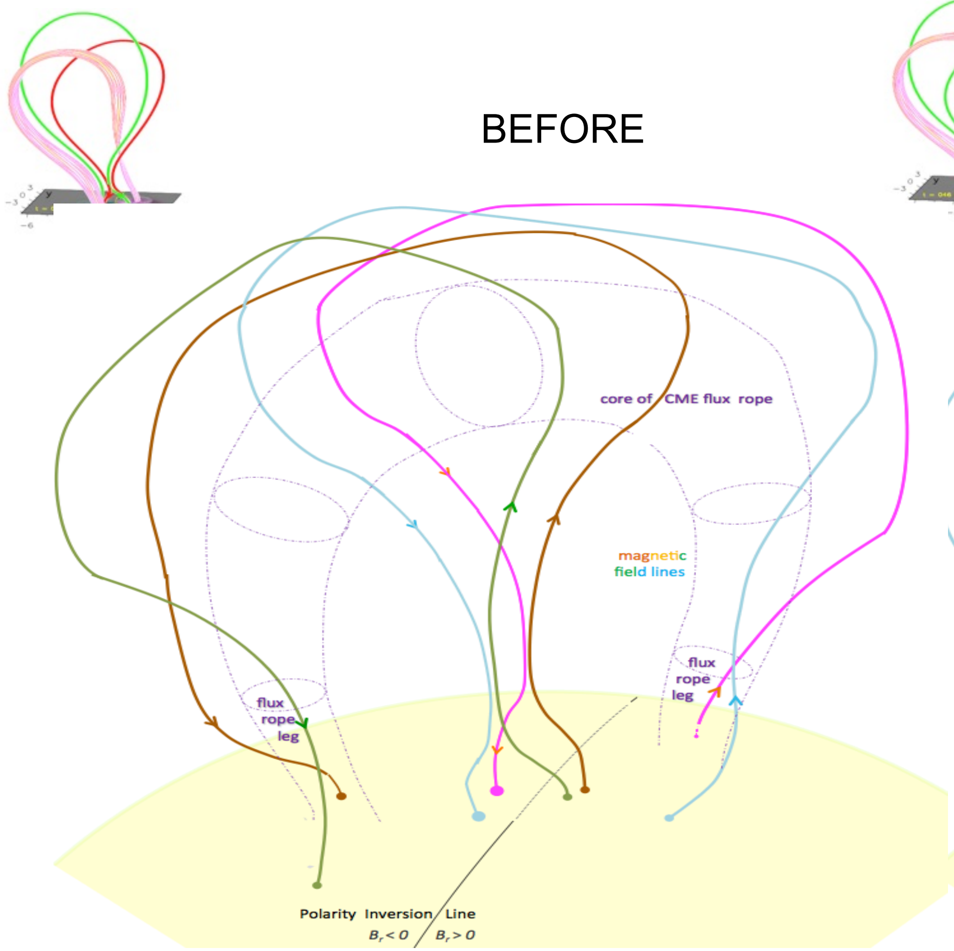


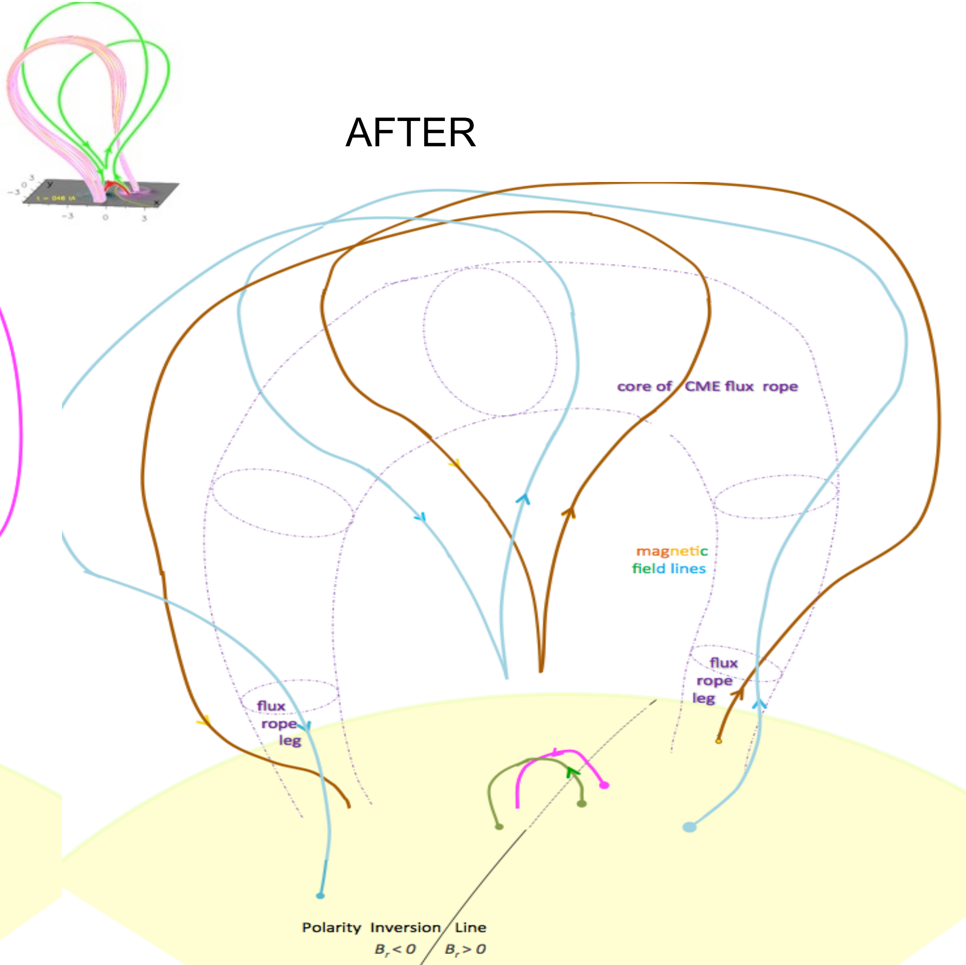
❖ Formation of flare loops:

- strong-to-weak shear transition
- Low to high altitude formation

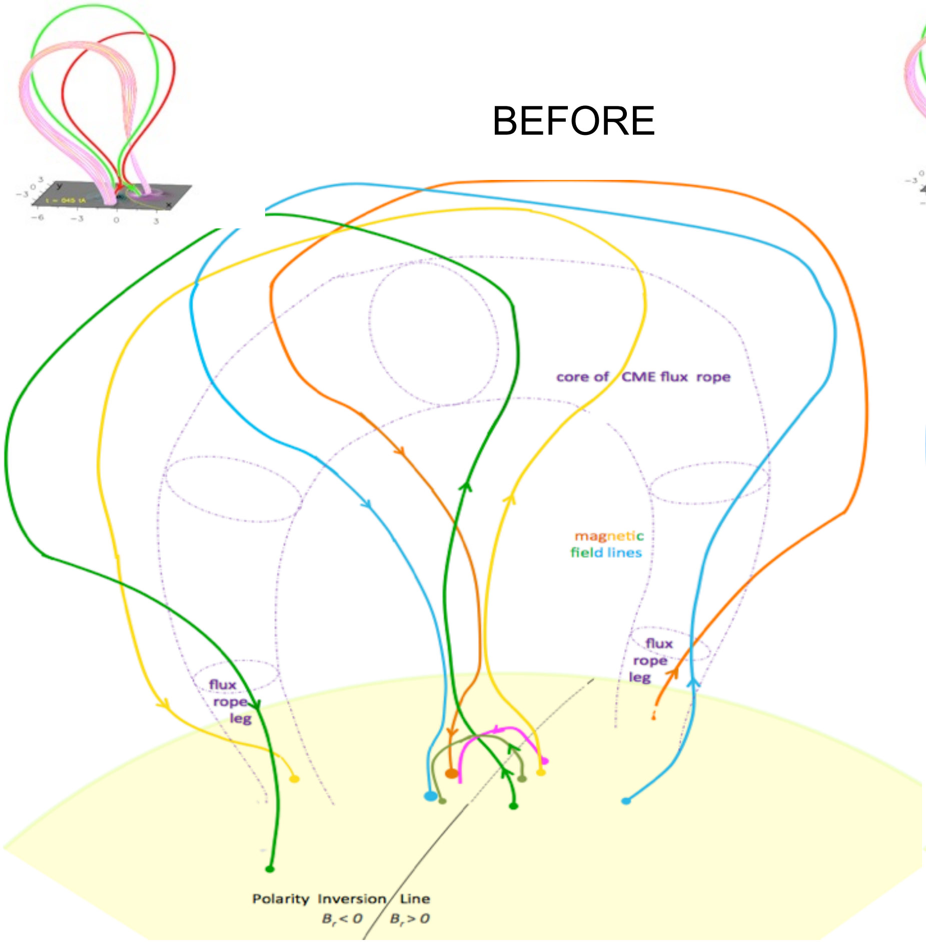
❖ Envelope formation of the flux rope

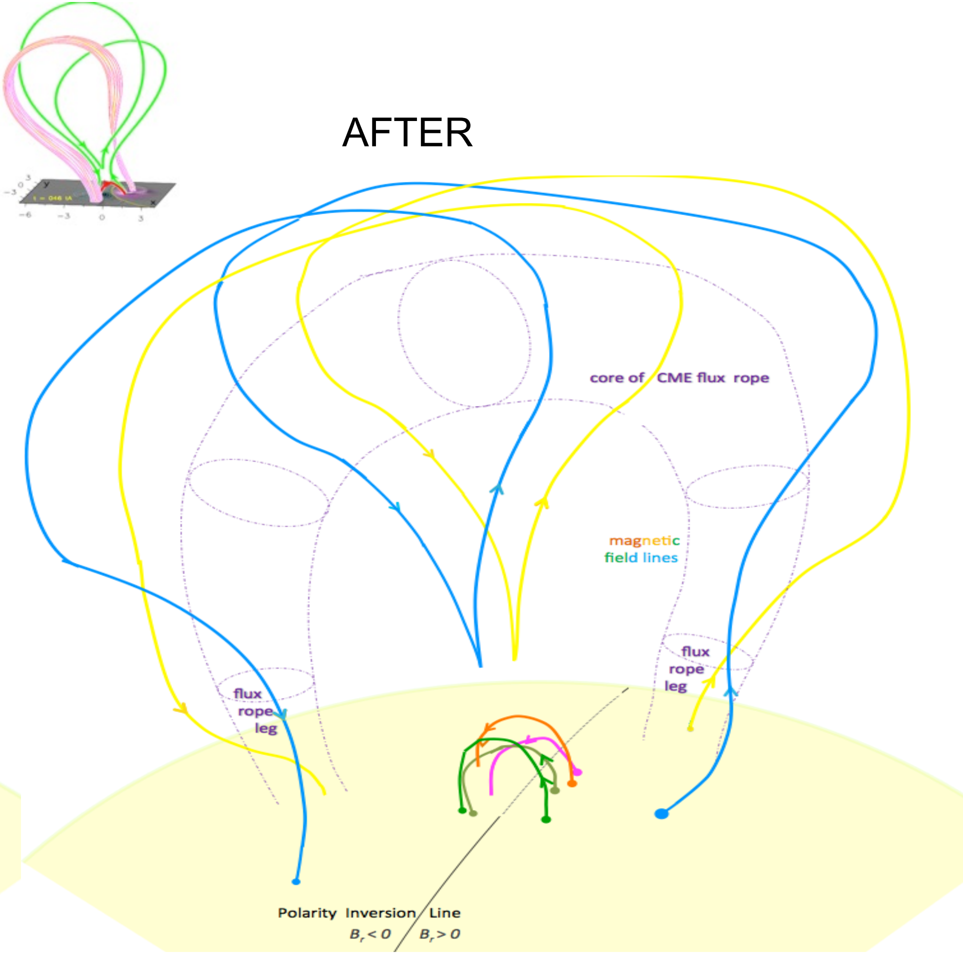
FLUX ROPE: A FULLY 3D STRUCTURE





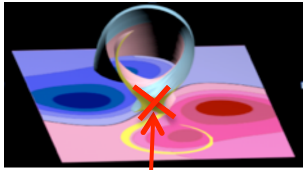
FLUX ROPE: A FULLY 3D STRUCTURE





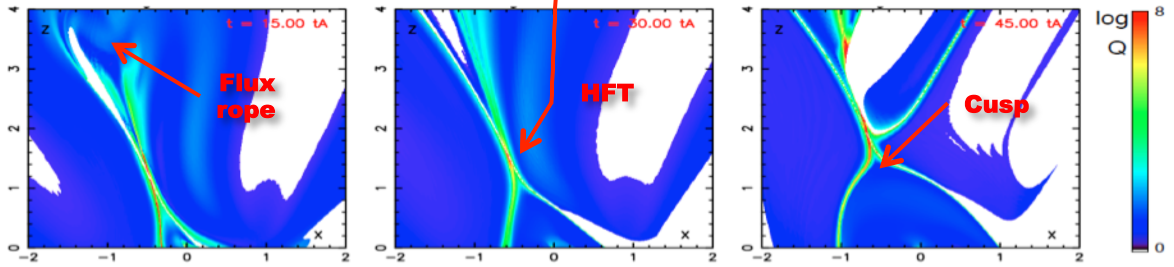
WHERE DOES RECONNECTION TAKE PLACE IN THE SIMULATION?

Vertical cuts



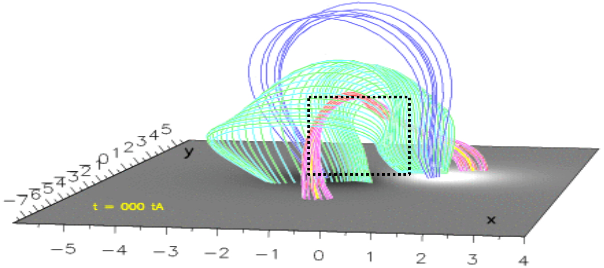
Q = *squashing factor*

«gradient of field line connectivity»



time

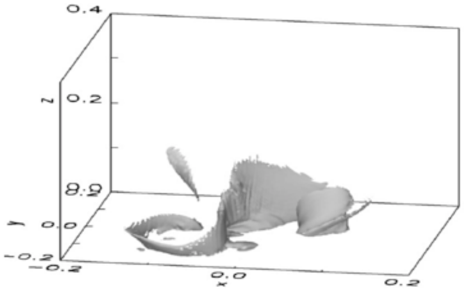
Coronal arcades
Erupting flux rope



B_z phot

Janvier, Aulanier, Pariat & Démoulin (2013)

WHERE DOES RECONNECTION TAKE PLACE IN THE SIMULATION?

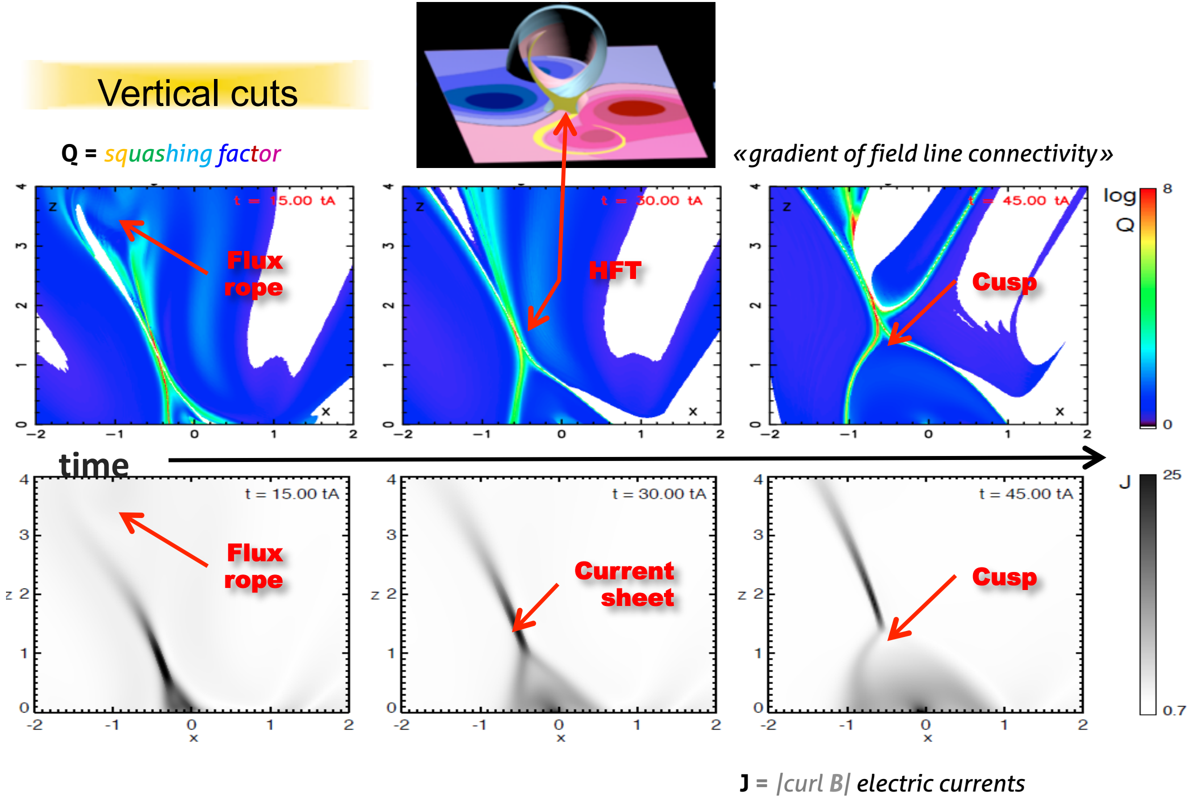


- ❖ Current layers: Similar location as QSLs

See also: (Galsgaard et al. 00, 03, Pontin et al. 05, Aulanier et al. 05, 06, Pariat et al. 06, Büchner 06, Dreher et al. 08, ...)

- ❖ Collapse of the coronal current layer (=thinning)

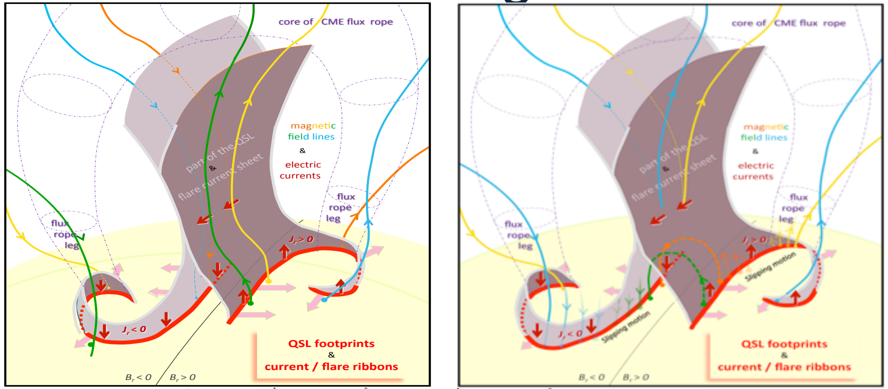
Prediction from the model (not yet observable)

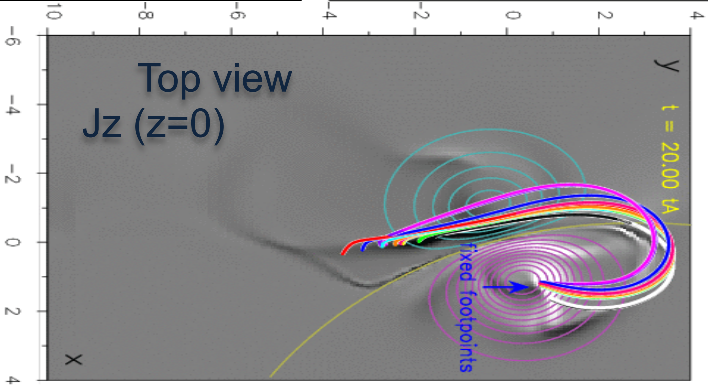


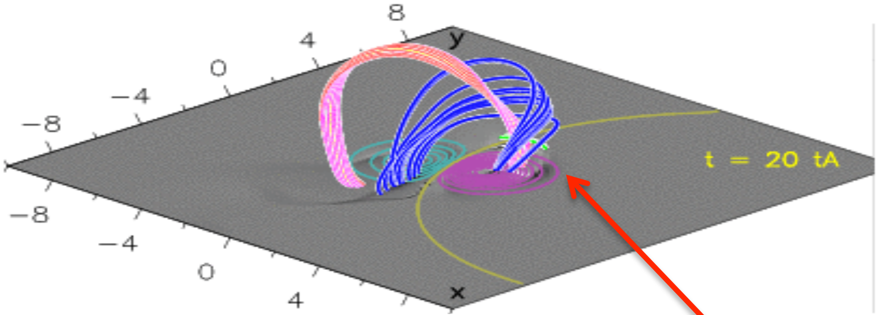
Janvier, Aulanier, Pariat & Démoulin (2013)

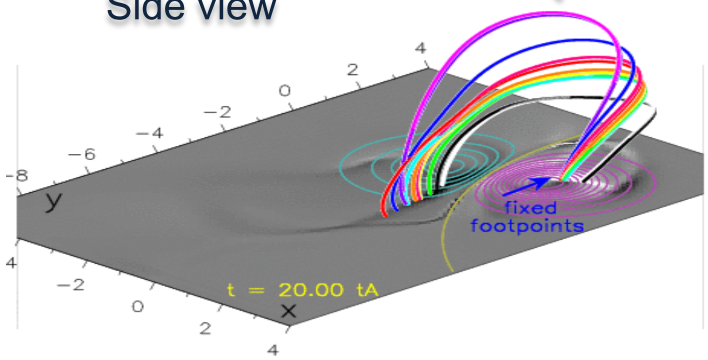
Slipping reconnection (reconnection in 3D)

Creation of new magnetic structures (here, the flux rope):

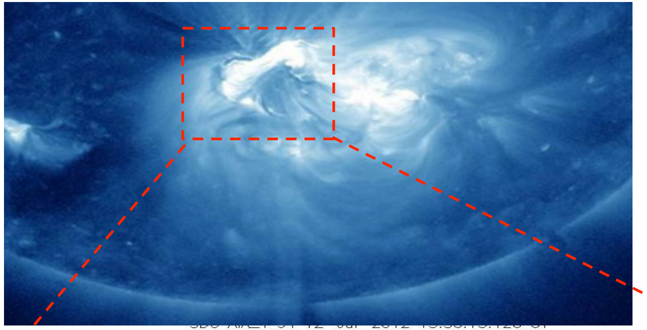






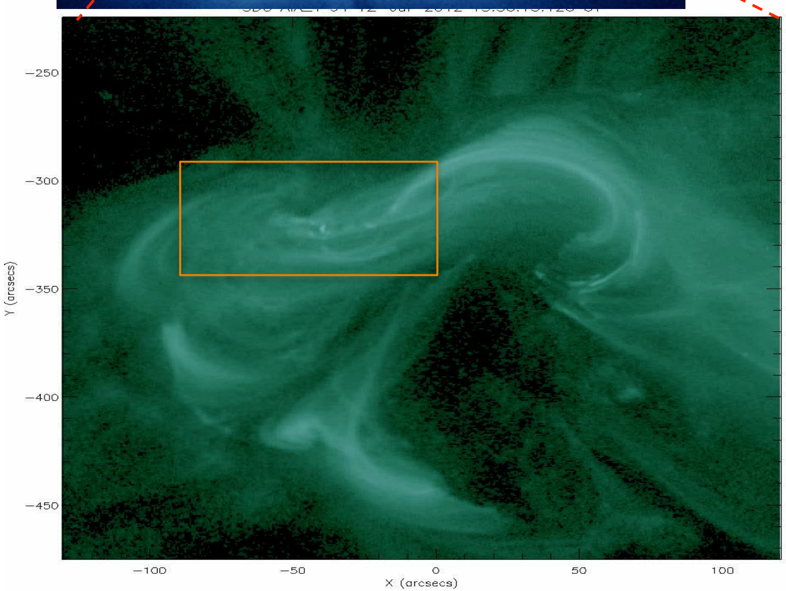


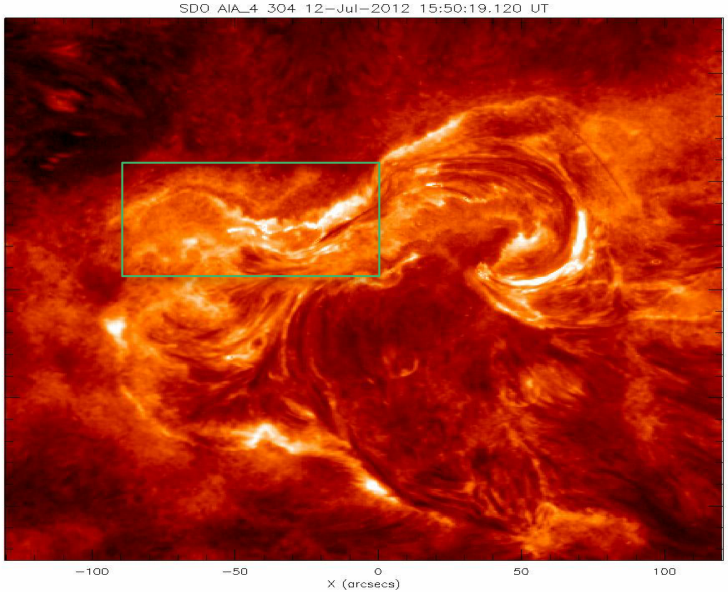
So... Does it really exist?



X-class flare of July 2012

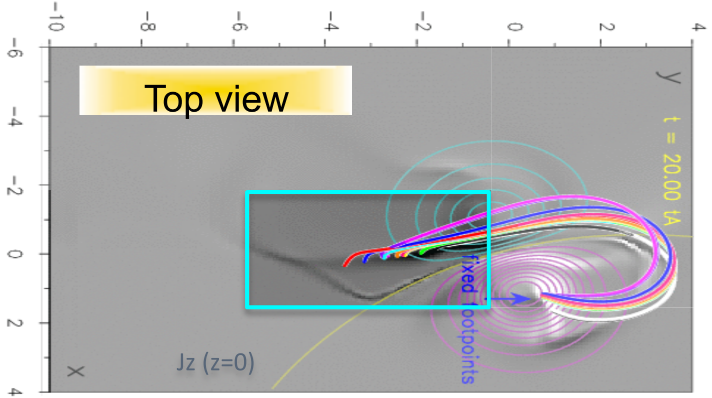
Dudik et al (2014)





Slipping in a flare

Slipping reconnection with QSLs:
successive change of magnetic connectivity



Janvier, Aulanier, Pariat & Démoulin (2013)

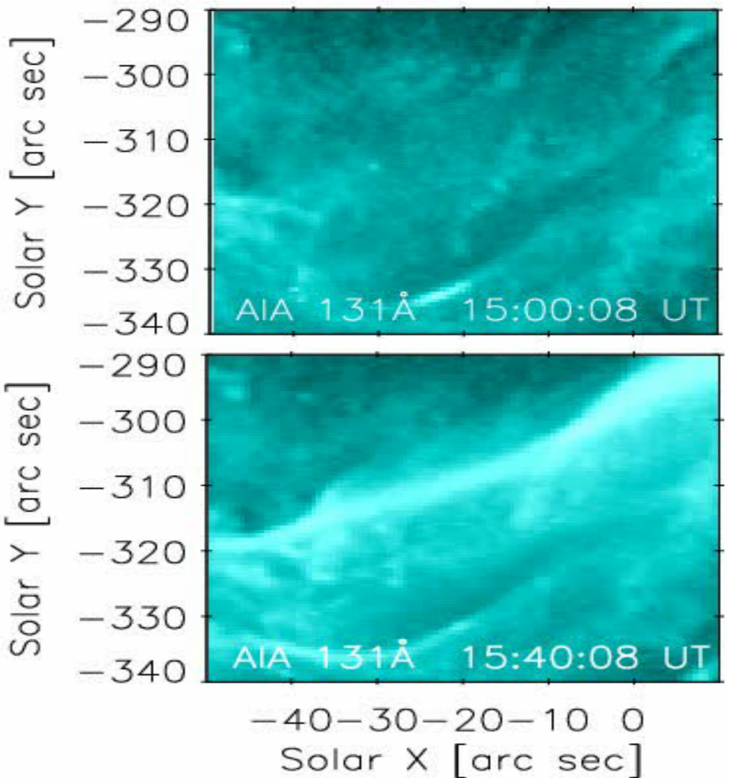
Leads to:

- ❖ Apparent field line motion
  See also: Aulanier et al. (2007)

- ❖ Kernel motion
  See also: Young et al. (2013)

X-class flare of July 2012

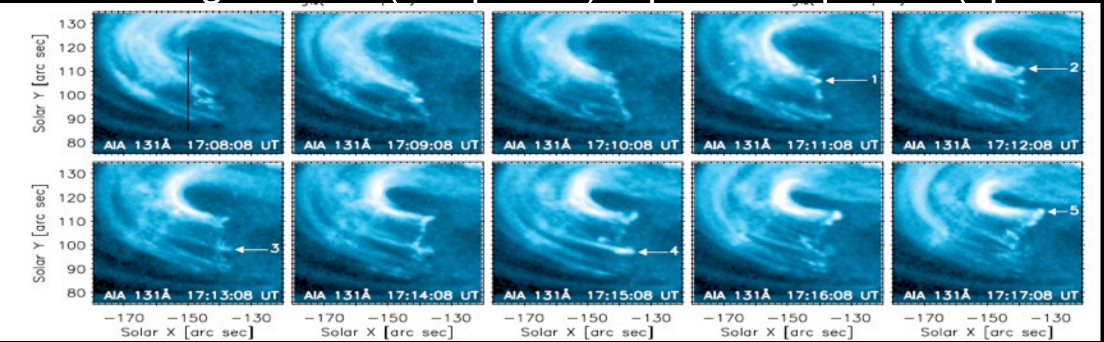
Dudik, et al (2014)

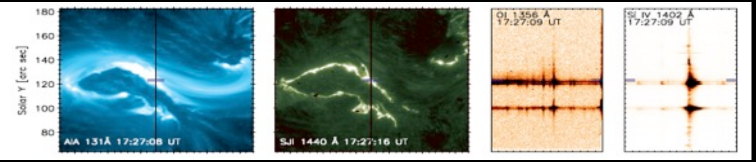


Further evidences…

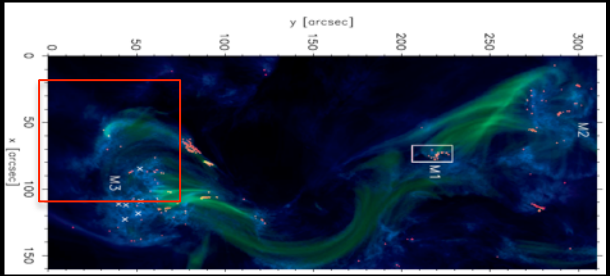
Now further evidences pointed out + detailed analysis

❖ Moving kernels (footpoints) + plasma upflows (spectroscopy diagnostics)



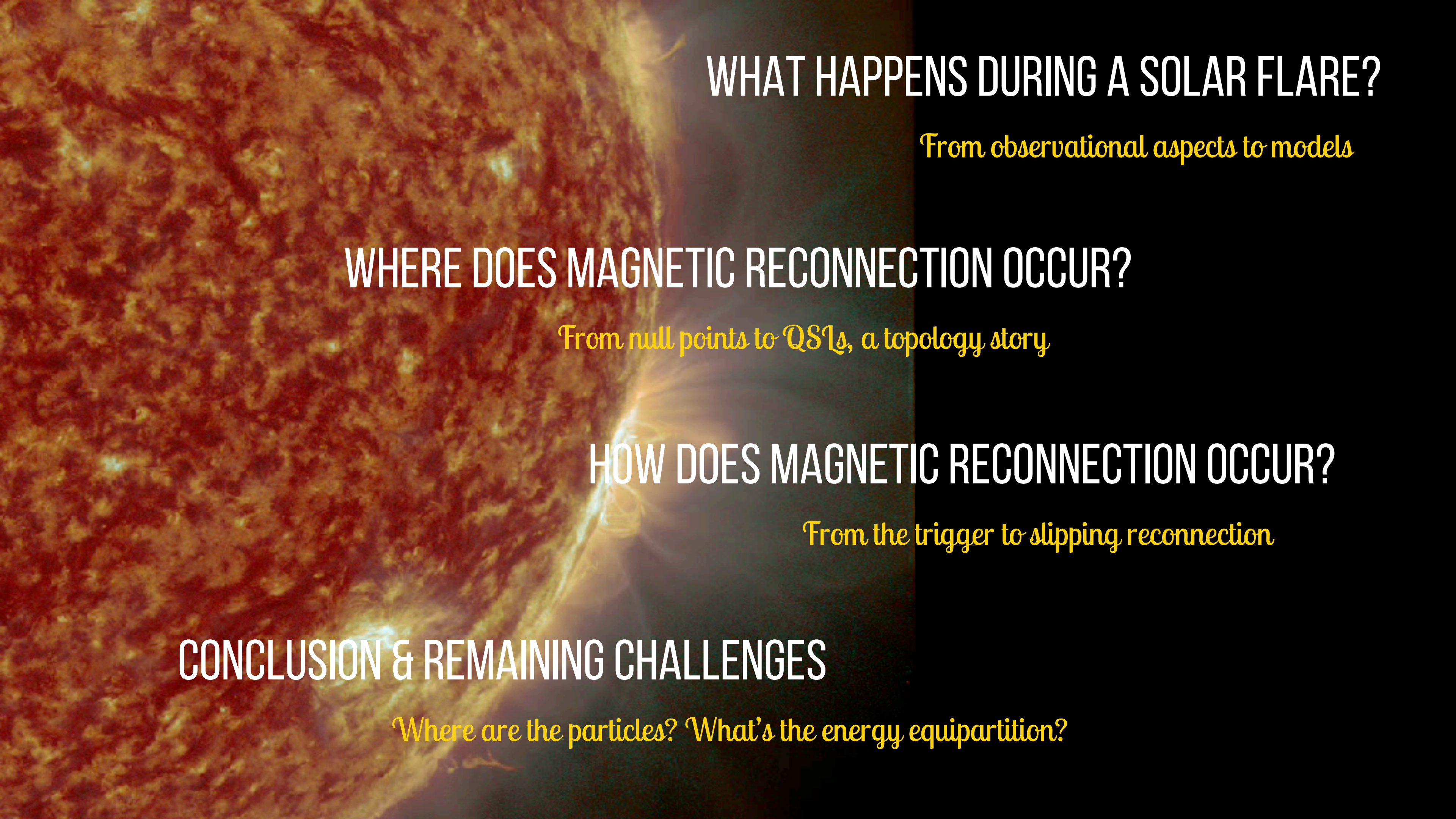


Testa et al. (2013)



❖ To explain flickering at the end points of some coronal loops

Direct observations:
2007: 1st observation (Hinode) Aulanier et al. 2007
Dudik et al. 2014 (1st observation for flares)
Li & Zhang 2014, Li & Zhang 2015, Dudik et al. 2016, Polito et al. 2016


WHAT HAPPENS DURING A SOLAR FLARE?
From observational aspects to models
WHERE DOES MAGNETIC RECONNECTION OCCUR?
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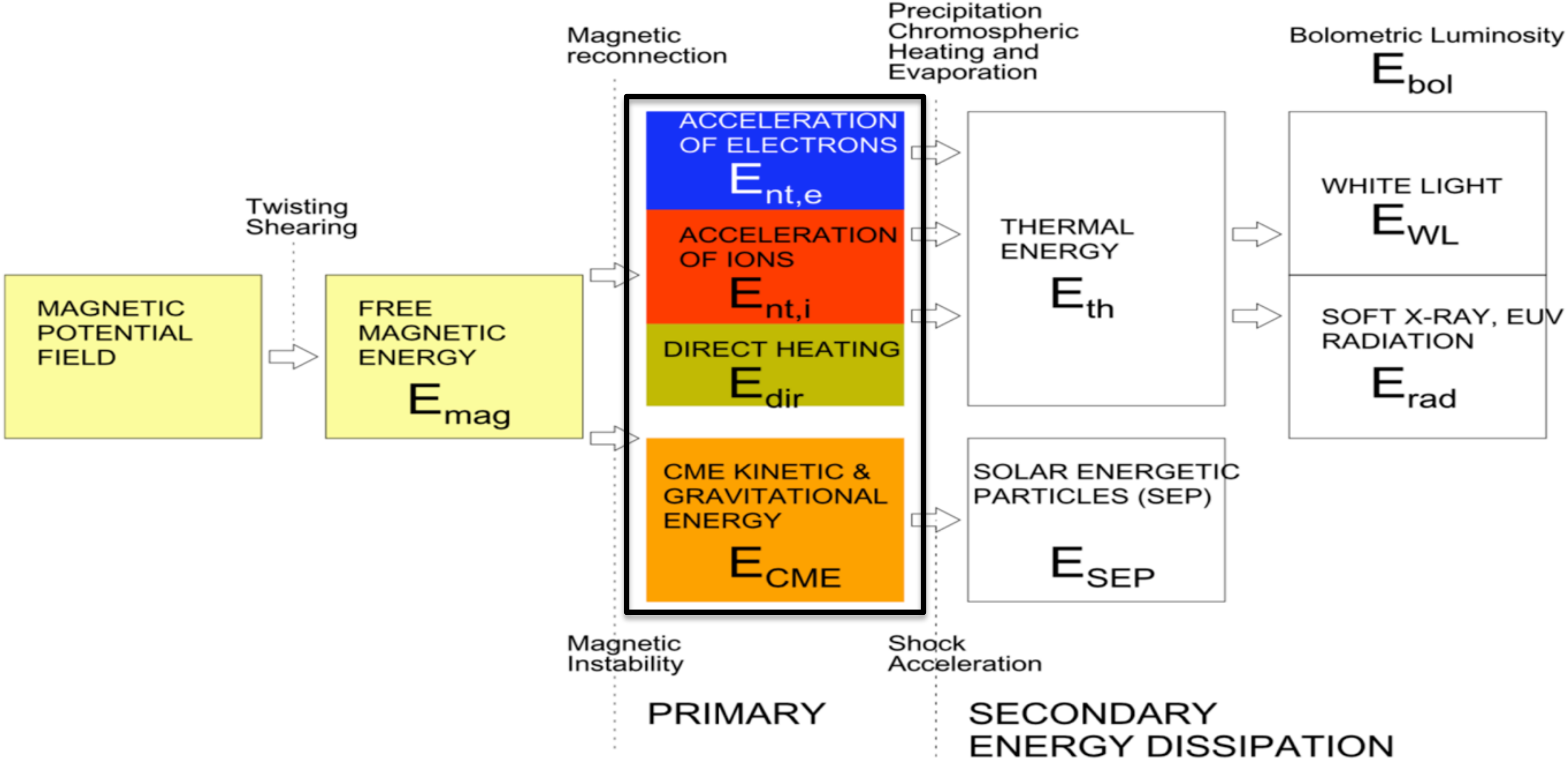
HOW DOES MAGNETIC RECONNECTION OCCUR?
From the trigger to slipping reconnection
CONCLUSION & REMAINING CHALLENGES
Where are the particles? What's the energy equipartition?

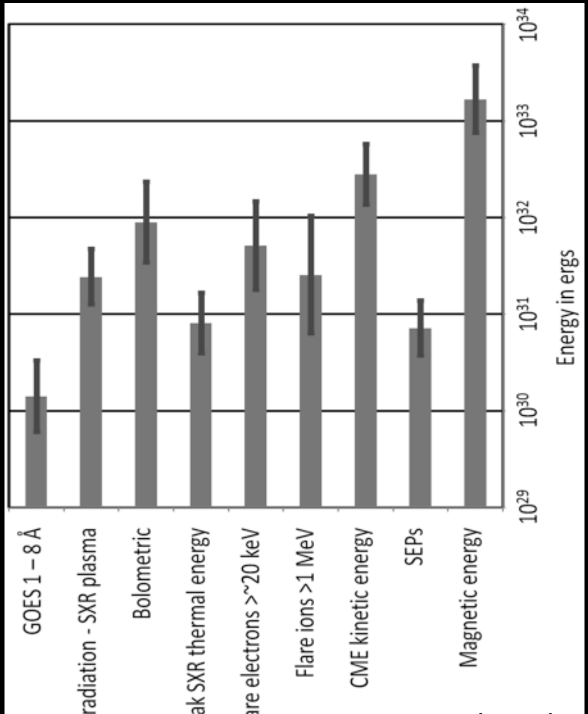
FROM MHD TO PARTICLE MODELS? (ENERGETIC PERSPECTIVES)



Aschwanden et al. 2014-2017 (series of 5 papers treating flare energy, update from Emslie et al. 2012

REMAINING CHALLENGES

Energetics of flares (CME kinetic energy)



Emslie et al. (2012)

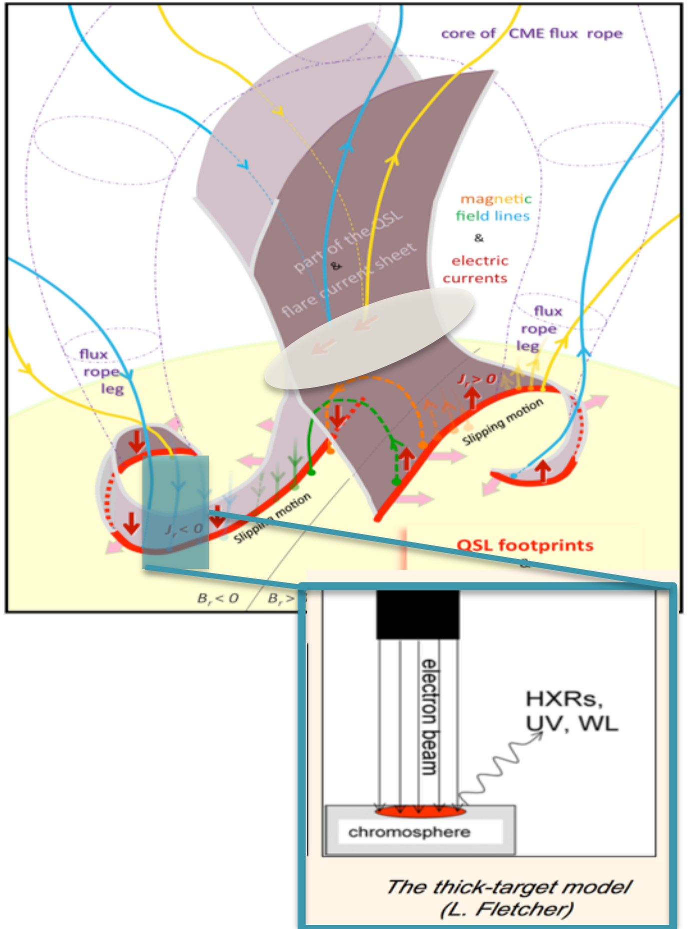
- Emslie: kinetic energy ~ same or 3x bolometric energy
- Model prediction: kinetic enercy ~ 5-10% of flare energy

Amari et al. (2003), also: Jacobs et al. 2006; Lynch et al. 2008; Reeves et al. 2010, Aulanier et al. 2012

Why such discrepancies?
- Observational biases?
- Numerical problems in ALL codes?

WHAT'S THE ENERGY PARTITION DURING SOLAR FLARES?

FROM MHD TO PARTICLE MODELS?



Macroscopic dynamics of magnetic fields

flux ropes, field distortion, current layers

+

instabilities, forcing (e.g. photospheric motions)

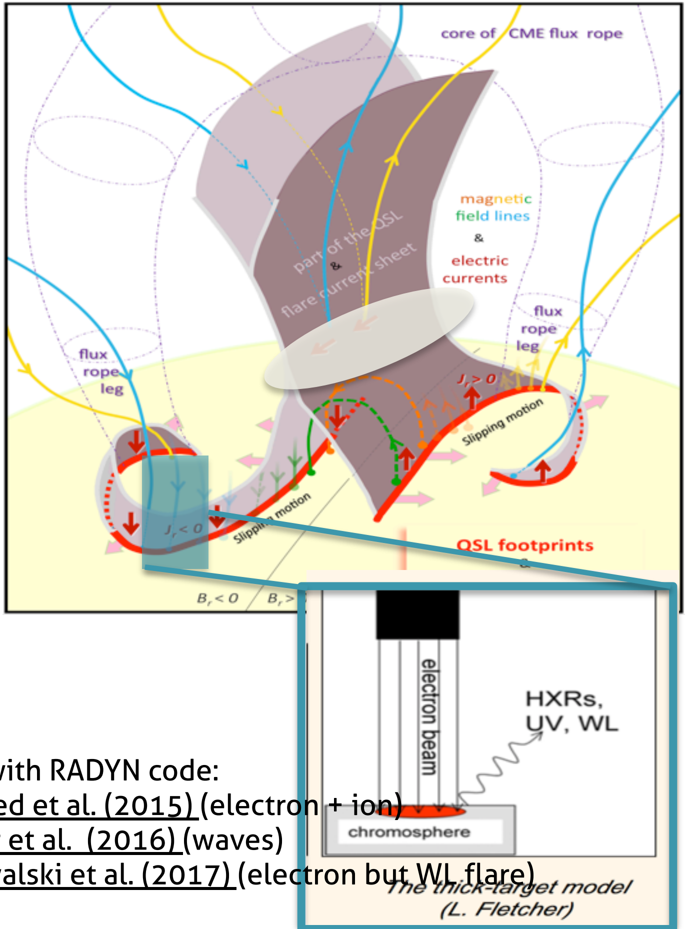
Current layer collapse, reconnection, large-scale morphology changes

Transport of Energy

Particles acceleration, Waves

Chromospheric/Photospheric reaction (e.g. White-light flares),

FROM MHD TO PARTICLE MODELS?



Macroscopic dynamics of magnetic fields

flux ropes, field distortion, current layers

+

instabilities, forcing (e.g. photospheric motions)

Current layer collapse, reconnection, large-scale morphology changes

How is magnetic energy converted during reconnection?
Energetic partition between particles and waves?

Transport of Energy

Particles acceleration, Waves

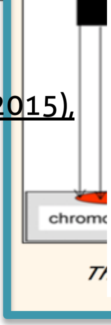
Chromospheric/Photospheric reaction (e.g. White-light flares),

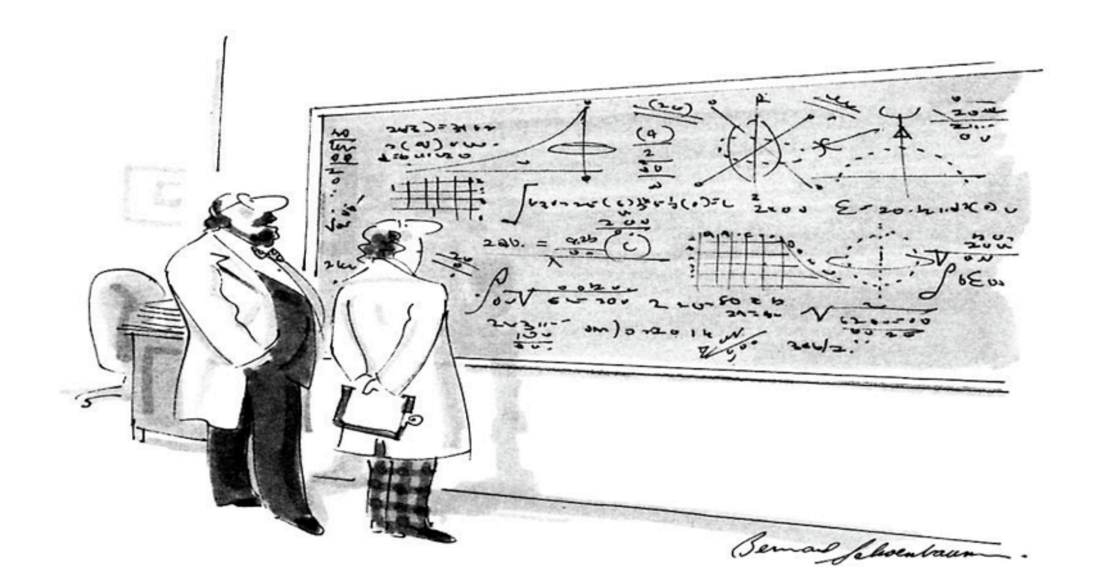
Ex with RADYN code:
Allred et al. (2015) (electron + ion)
Kerr et al. (2016) (waves)
Kowalski et al. (2017) (electron but WL flare)

FROM MHD TO PARTICLE MODELS?

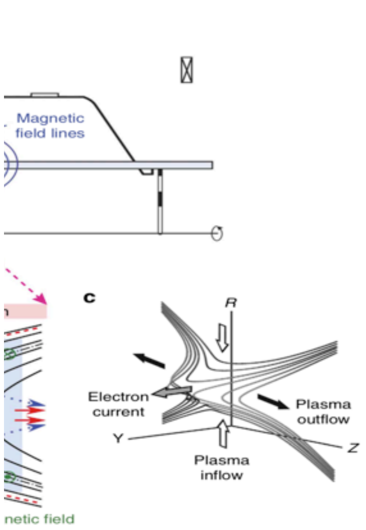
Magnetic islands, turbulence, shocks, Alfvèn waves…

Allred et al. (2015),





“Oh, if only it were so simple.”



nt for ions and electrons

« >50% of the magnetic energy is converted to particle energy, 2/3 of which transferred to ions and 1/3 to electrons. » → Also confirmed in MMS mission (see Toledo-Redondo et al. 2017)

WHY I NEEDED MORE TIME

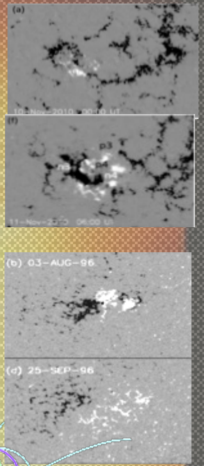
Types/class of flares

- ❖ Confined flare (localised)
- ❖ Eruptive flare (with CME)

Driver of eruptive flares:

Large flux dispersal

- ❖ Coronal tension ➘ + Flux rope formation
- ❖ Torus unstable flux rope



Storage

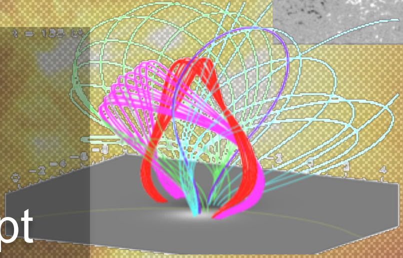
Emergence/boundary motions

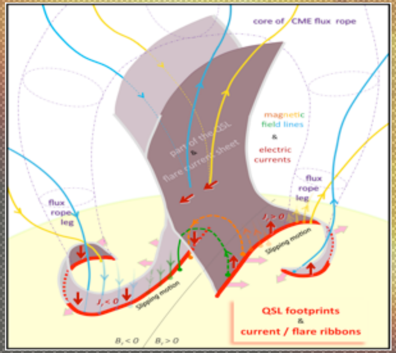
- ❖ Currents are important!

Topology of flares

Null points and QSLs

- ❖ QSLs extend the concept of separatrices





Reconnection

Observations, models