More Than a Star: How Does Solar Activity Impact The Heliosphere?

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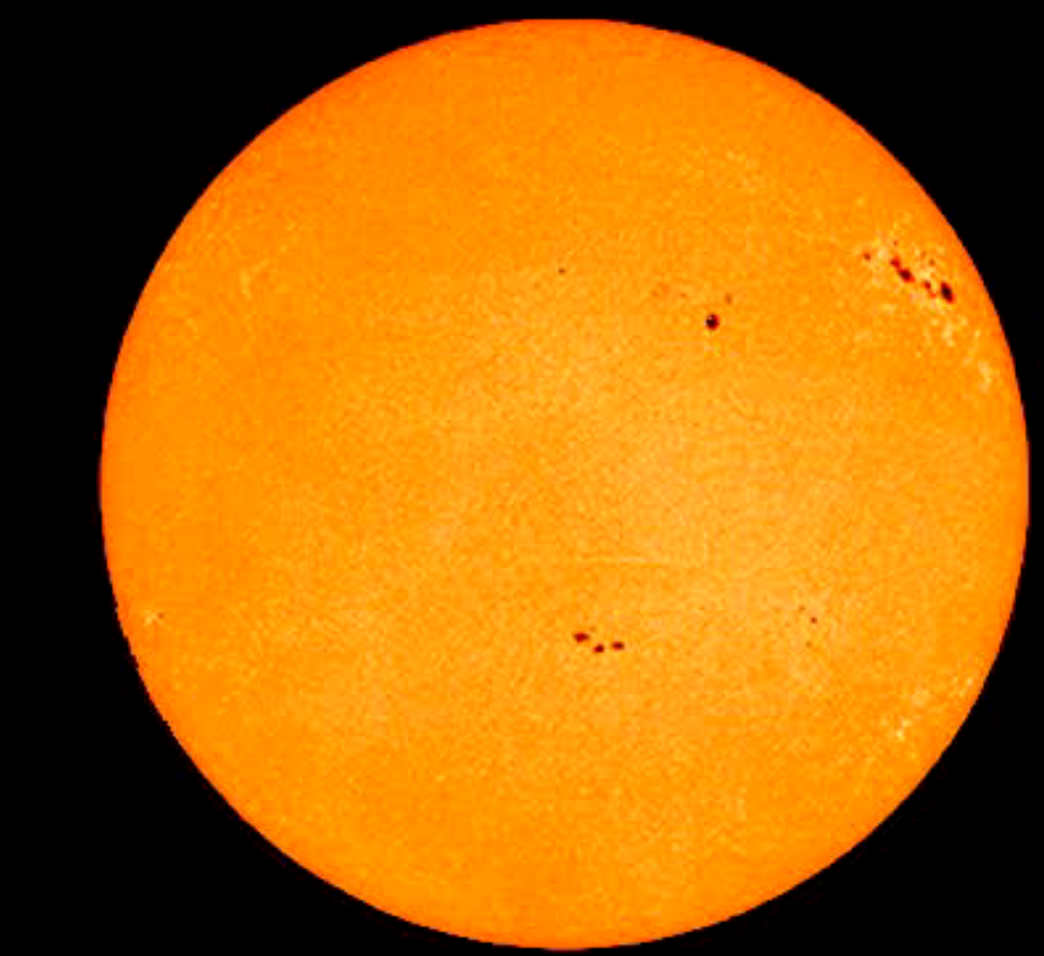
Bashfest 2013 Symposium

Some Interesting Questions

- How is the solar corona heated? How is the solar wind accelerated?
- What are coronal mass ejections? What drives/triggers them?
- Where is the edge of the Heliosphere?
- How/where/when are high energy particles produced during eruptions in the solar corona? Can we use remote observations to characterize this process?

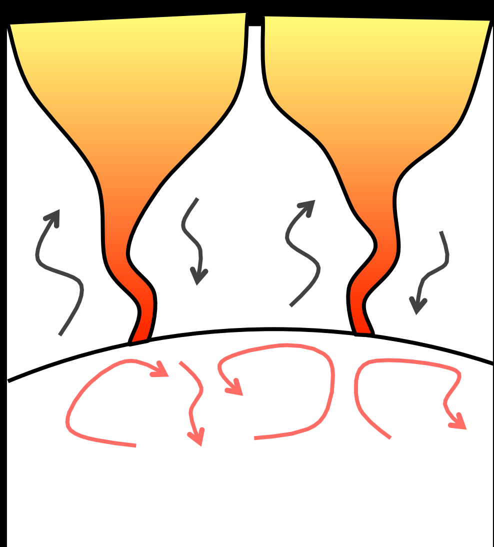
The many faces of the Sun



How is the corona heated?
How is the solar wind accelerated?

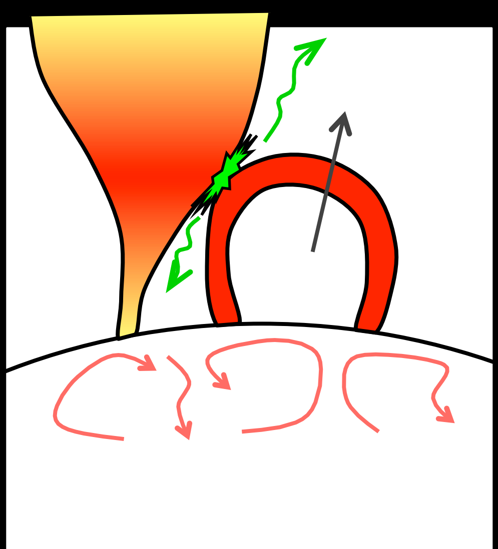
Two general ideas have emerged . . .

- Wave/Turbulence-Driven (**WTD**) models, in which open flux tubes are jostled continuously from below. MHD fluctuations propagate up and damp.
- Reconnection/Loop-Opening (**RLO**) models, in which energy is injected from closed-field regions in the "magnetic carpet."



vs.

Counterpoint:



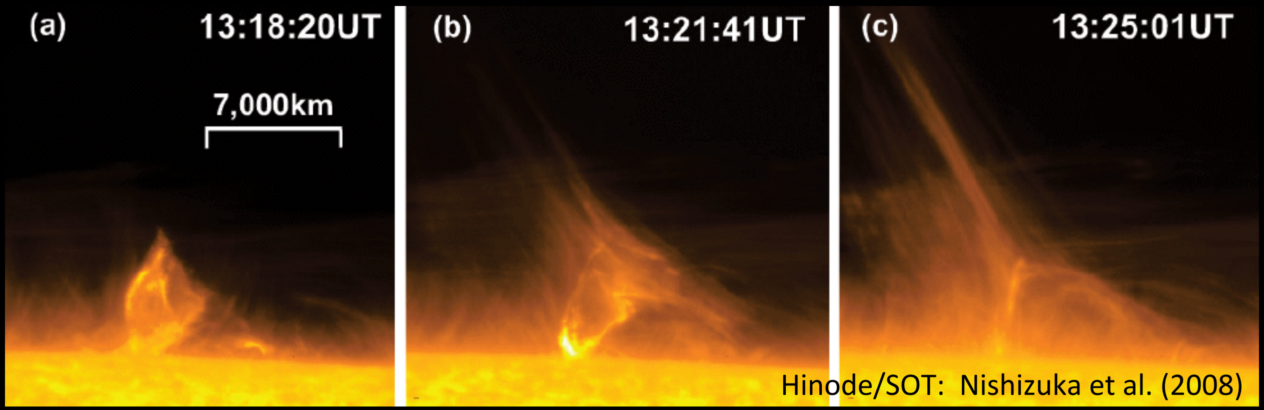
Cranmer & van Ballegooijen (2010)

Roberts (2010)

There's a natural appeal to "RLO"

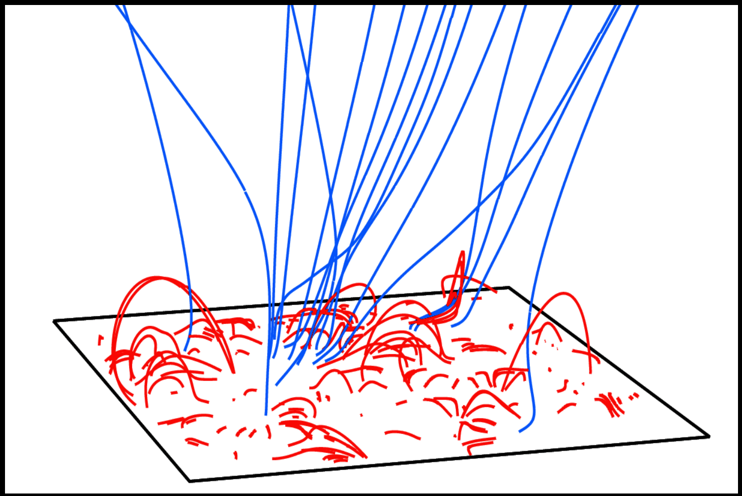
Open-field regions show frequent jet-like events.

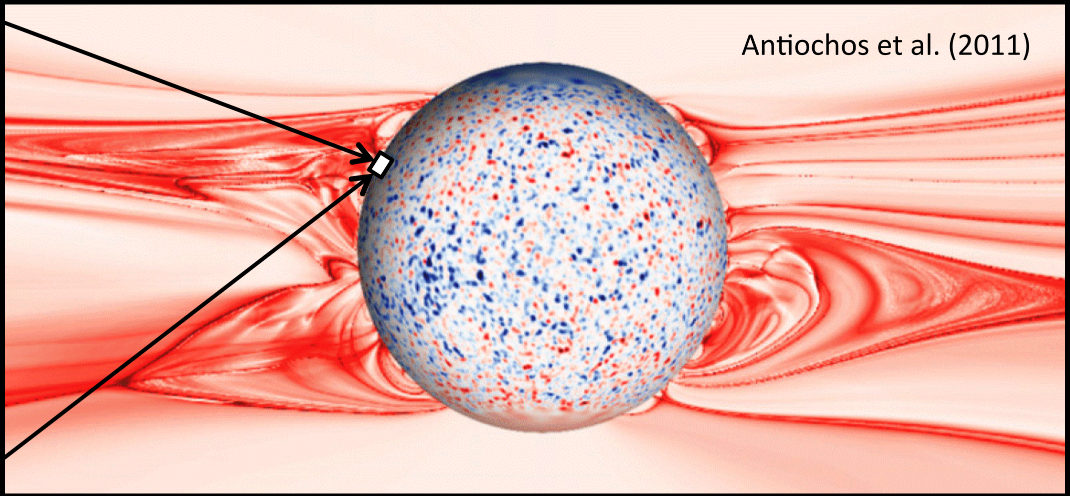
Evidence of **magnetic reconnection** between open and closed fields.



Hinode/SOT: Nishizuka et al. (2008)

But is there enough mass & energy released (in the **subset** of reconnection events that turn closed fields into open fields) to heat/accelerate the entire solar wind?

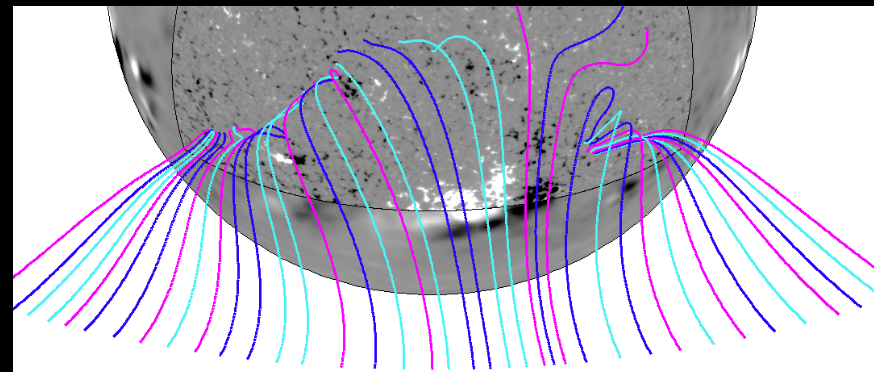




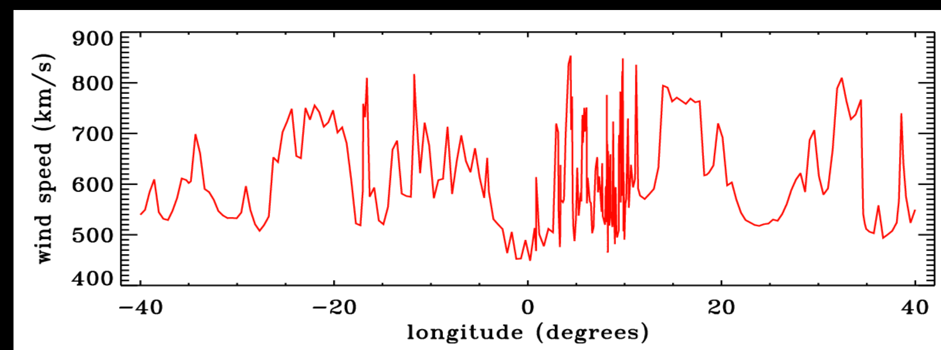
Antiochos et al. (2011)

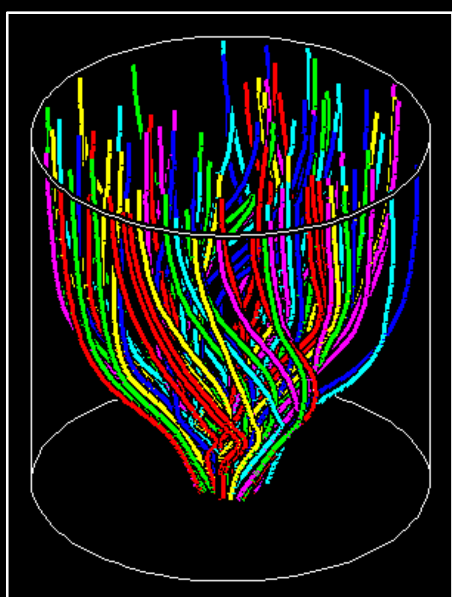
Recent extensions of "WTD" promising

Turbulent solar wind computed along field lines mapped from high-resolution magnetograms, evoking Alfven-wave turbulence dissipation.



Result: Power spectra of field **magnitude** fluctuations at 1 AU may be explained by self-consistent evolution of hi-res collections of flux tubes.



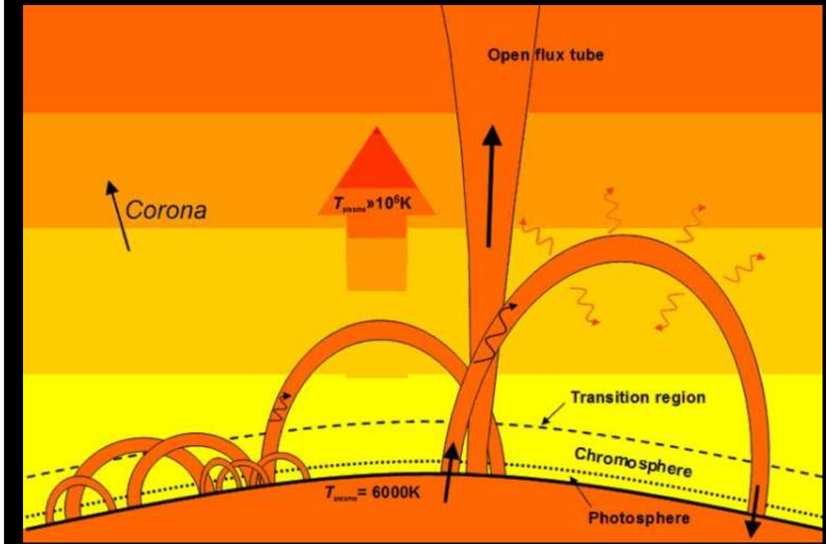


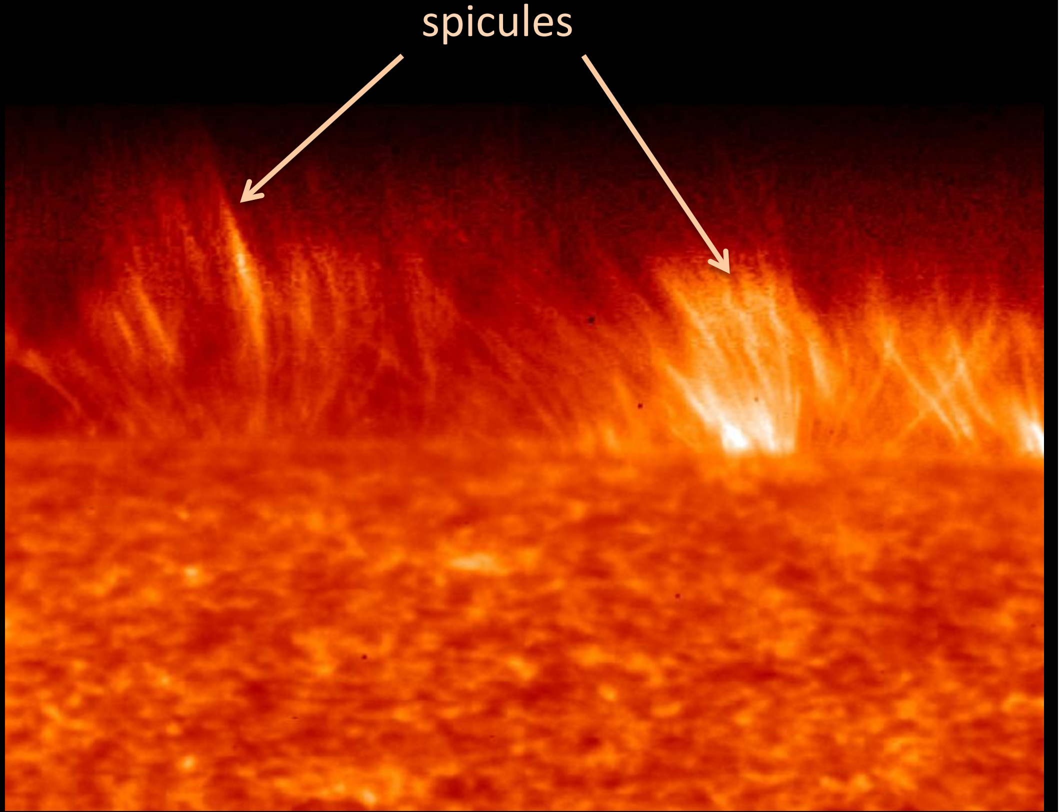
van Ballegooijen et al. (2011) & Asgari-Targhi et al. (2012) simulated incompressible MHD turbulence in expanding flux tubes → coronal loops & open fields.

Result: Basic WTD phenomenology seems to work

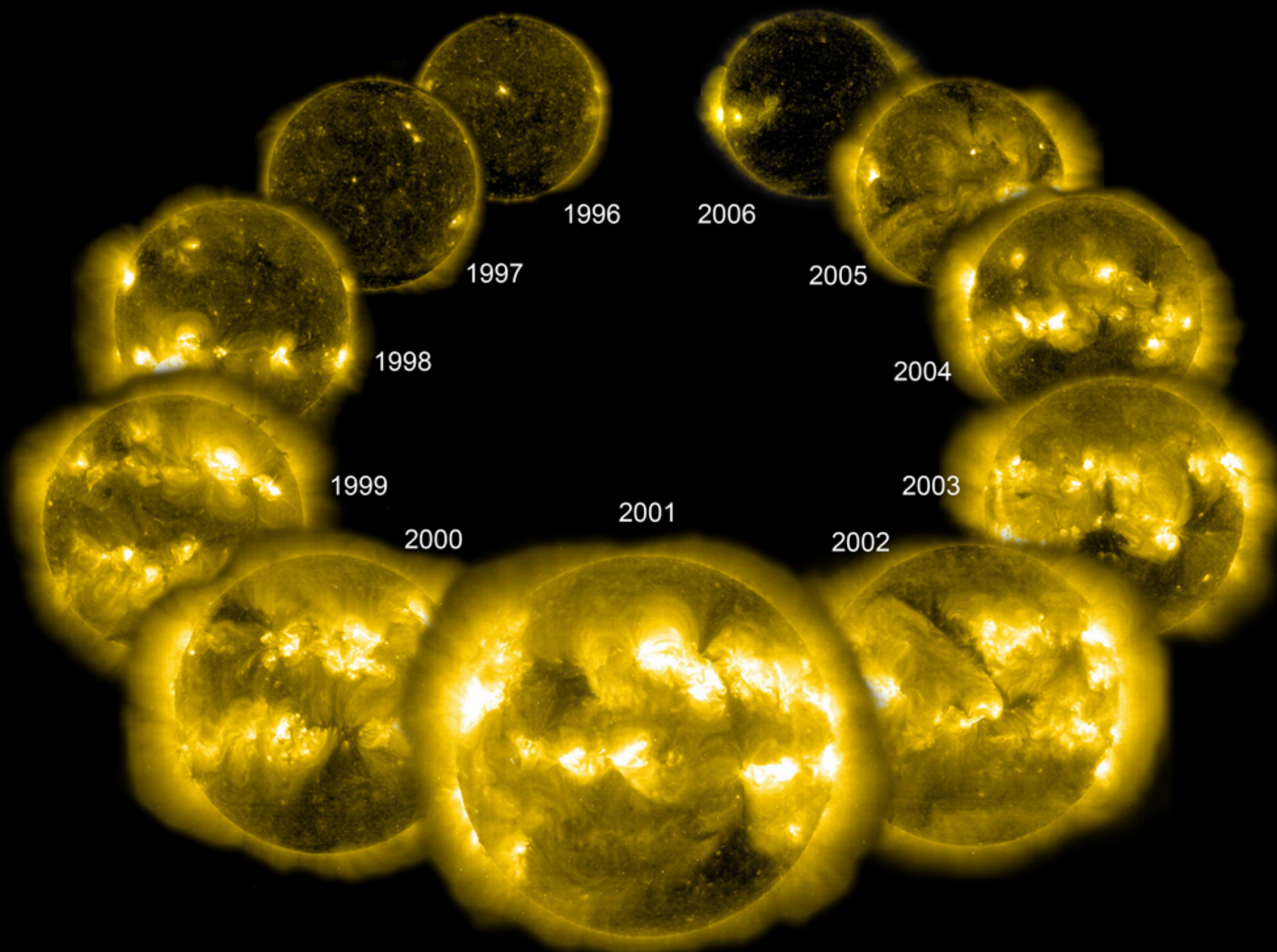
Small-scale feature observations may hold the key to understanding coronal heating

New NASA Interface Region Imaging Spectrograph (IRIS) mission!



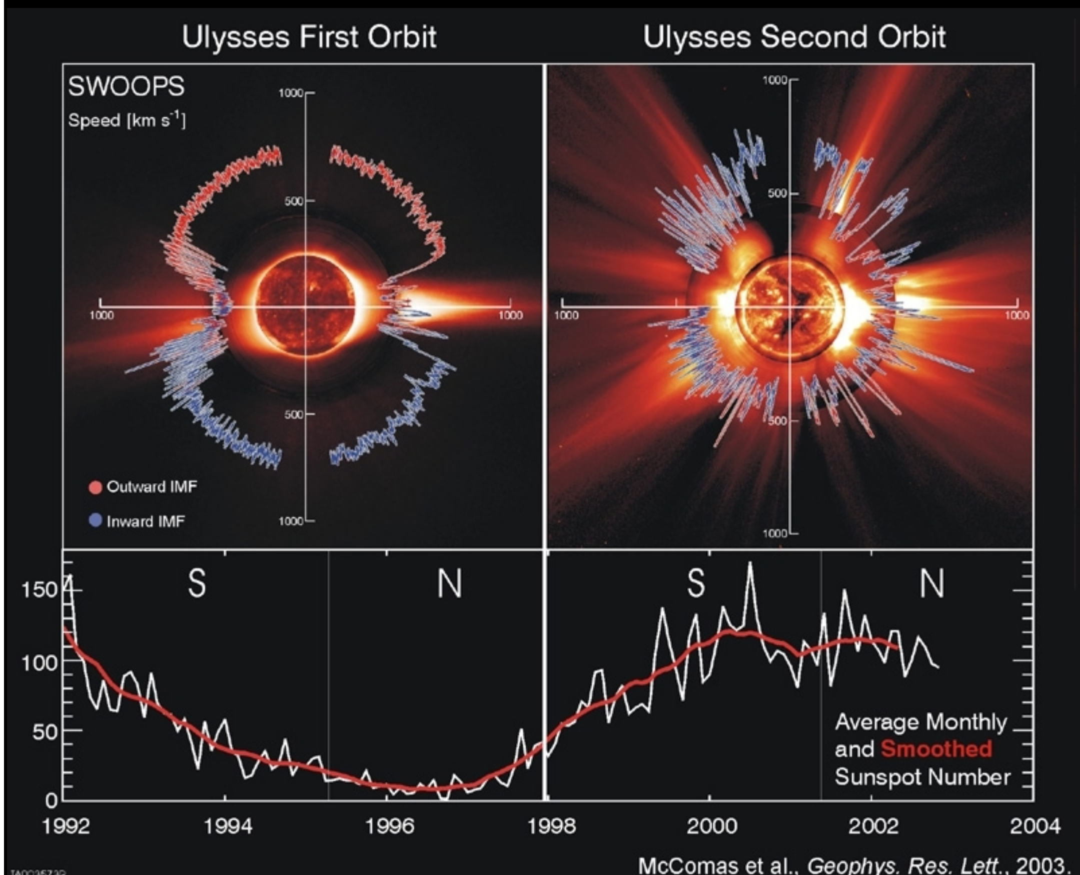


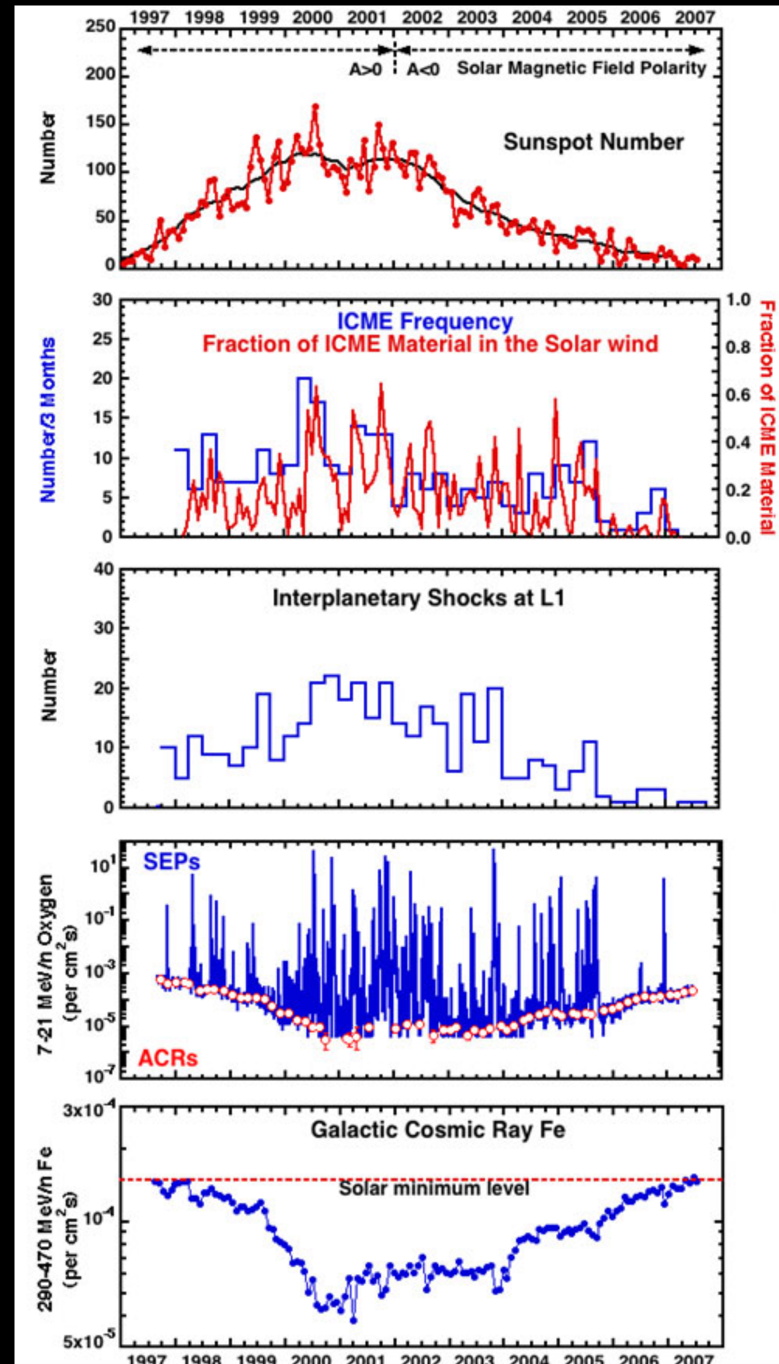
The Solar Cycle



SOHO EIT/NASA

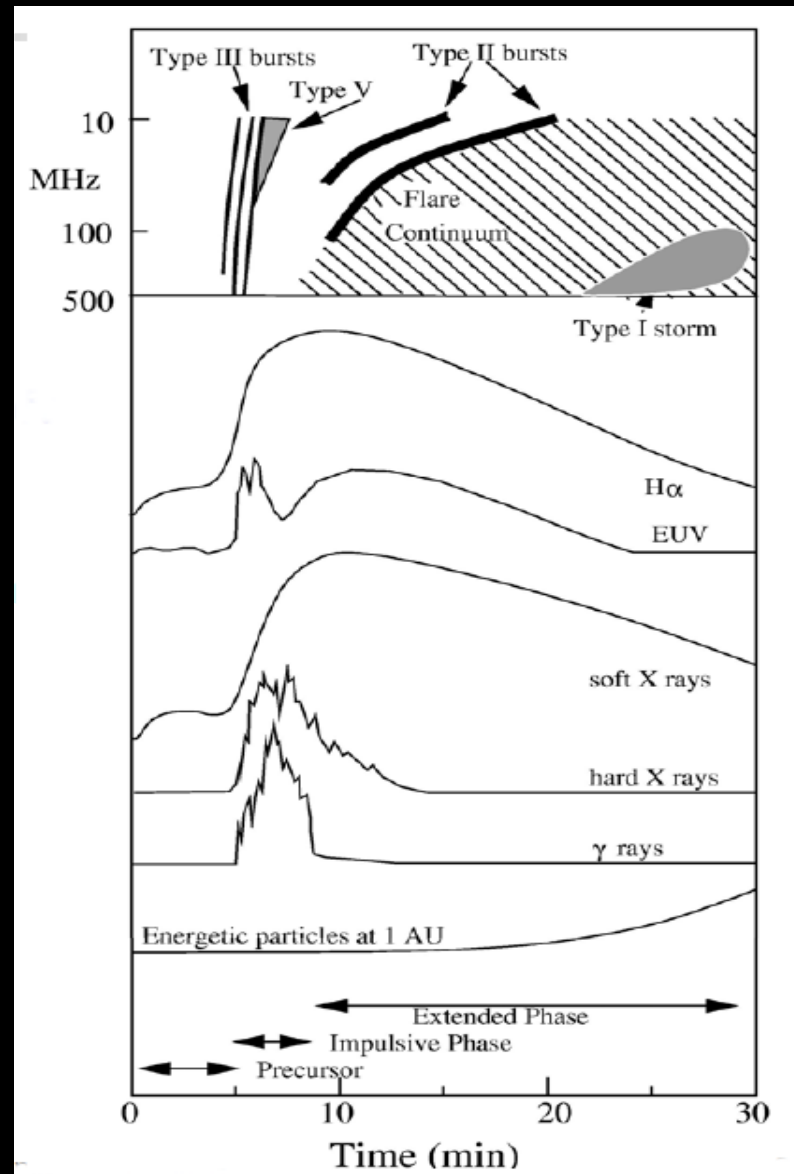
Solar activity cycle manifestation on mid- and long term



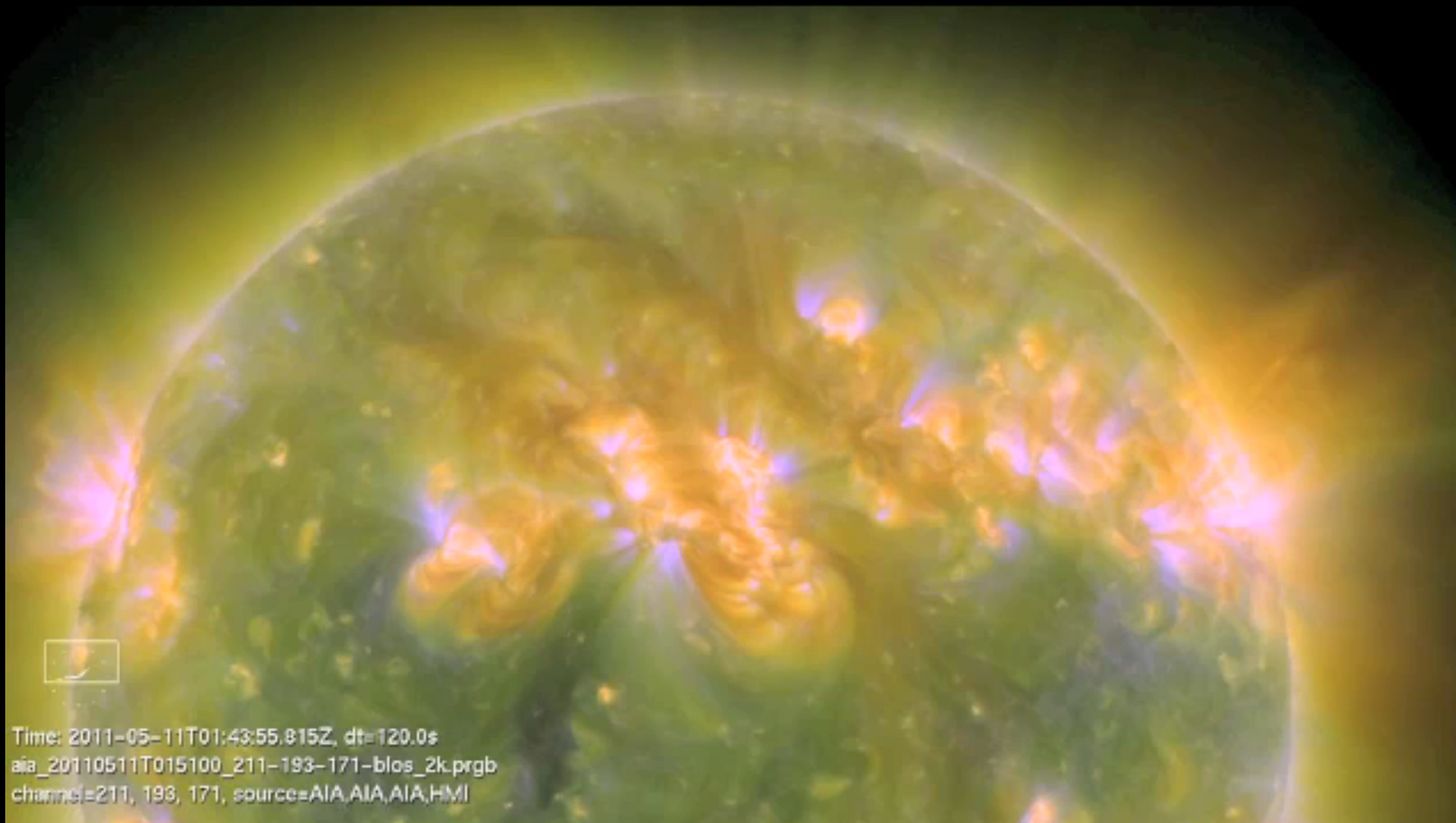


Short-term solar activity: flares and Coronal Mass Ejections (CMEs)

- Flares and CMEs are the most energetic impulsive solar system events – up to 10^{33} ergs released per event
- Usually complementary events
- Occurring throughout the solar cycle, much more common near the peak of solar activity
- Related to highly elevated EUV, X-Ray, microwave, Radio, and particle emissions



Example: the May 11, 2011 event

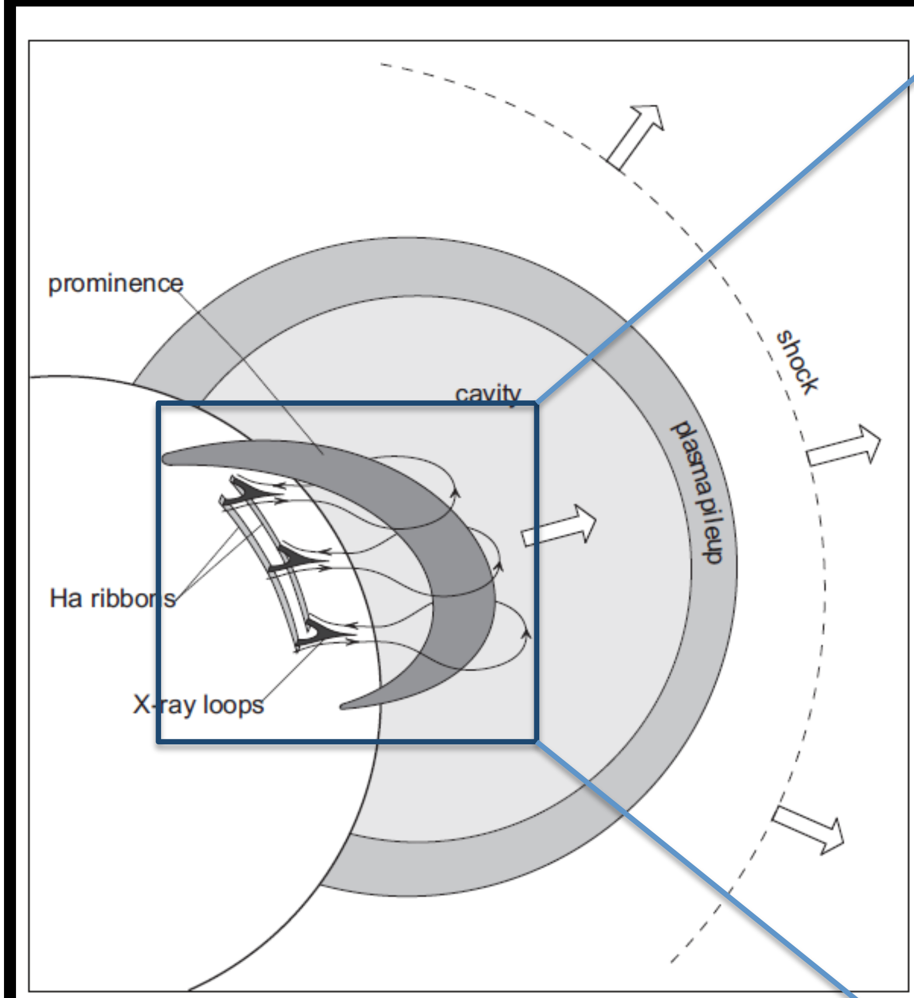


www.lmsal.com/isolsearch

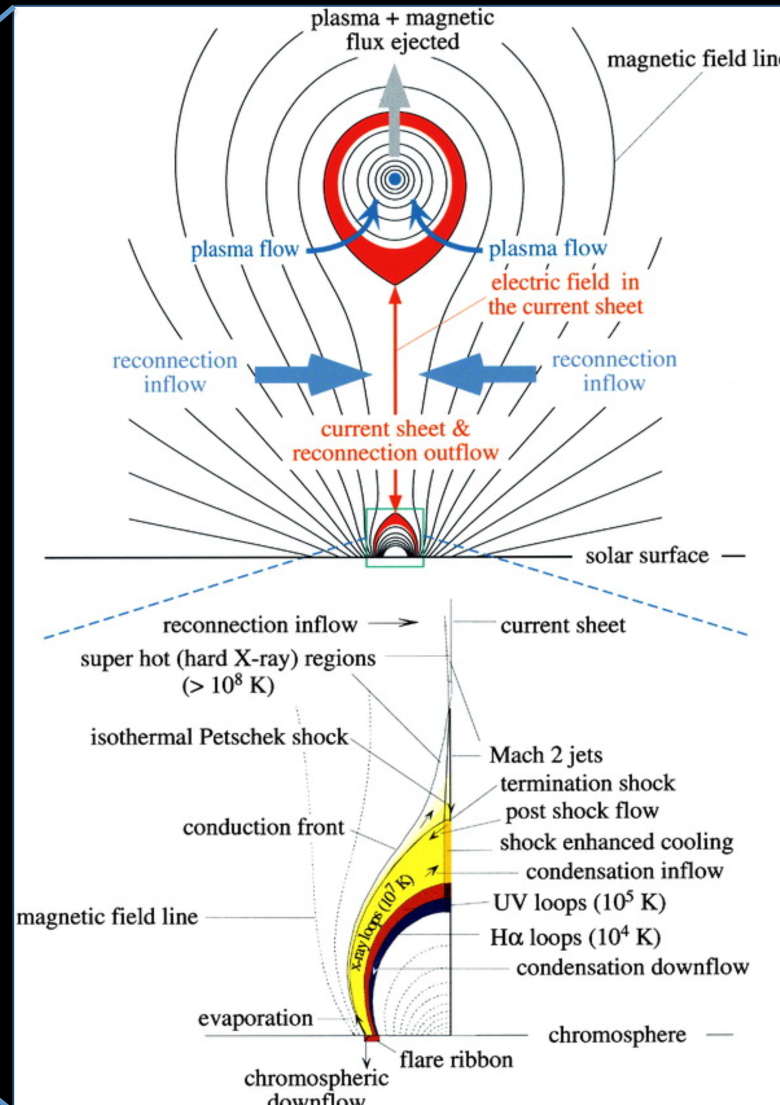
The September 30, 2013 event

www.lmsal.com/isolsearch

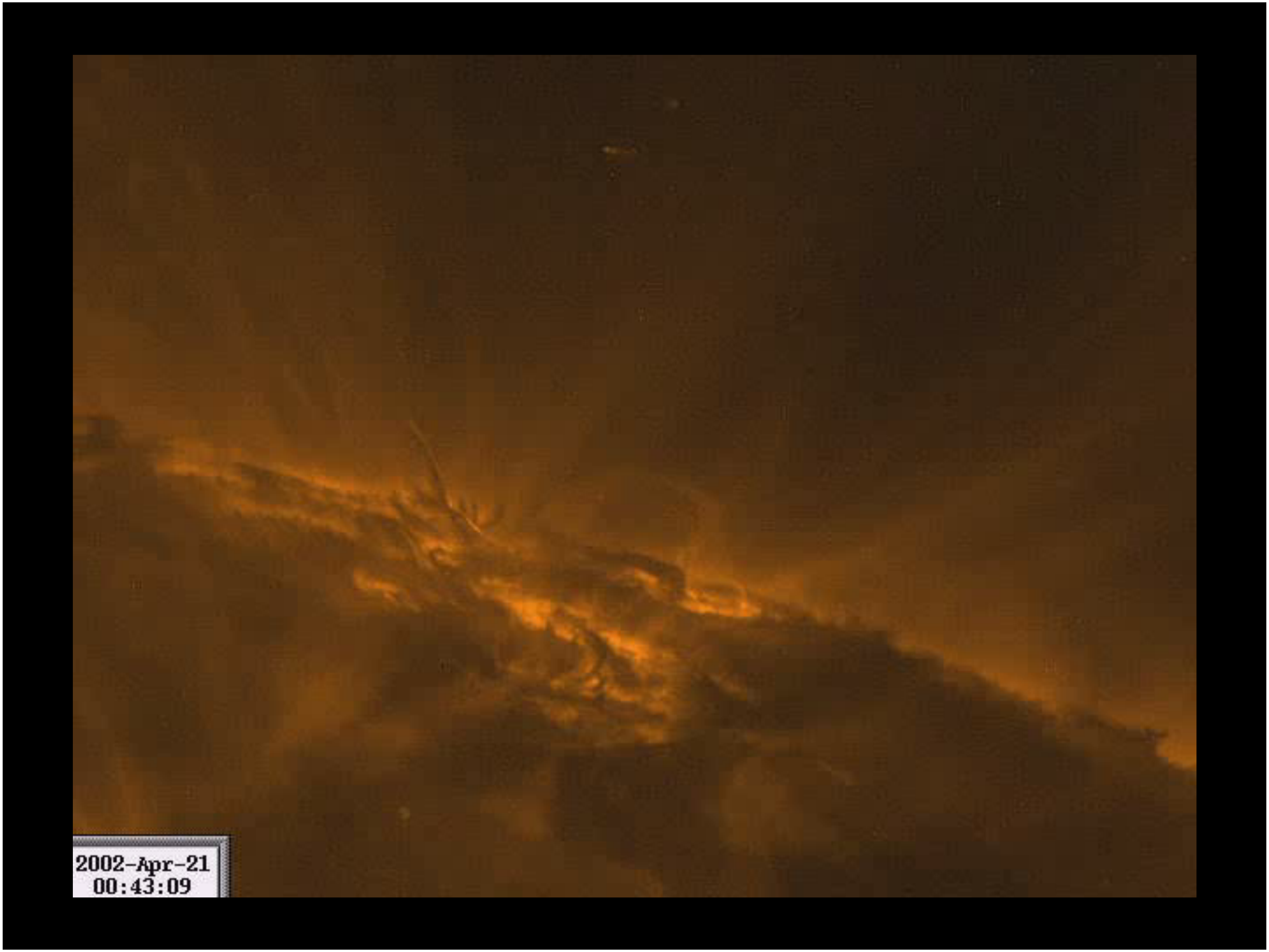
Solar Eruptions: The Standard Picture



Forbes, 2000



Lin, Raymond, and van Ballegooijen, 2003


2002-Apr-21
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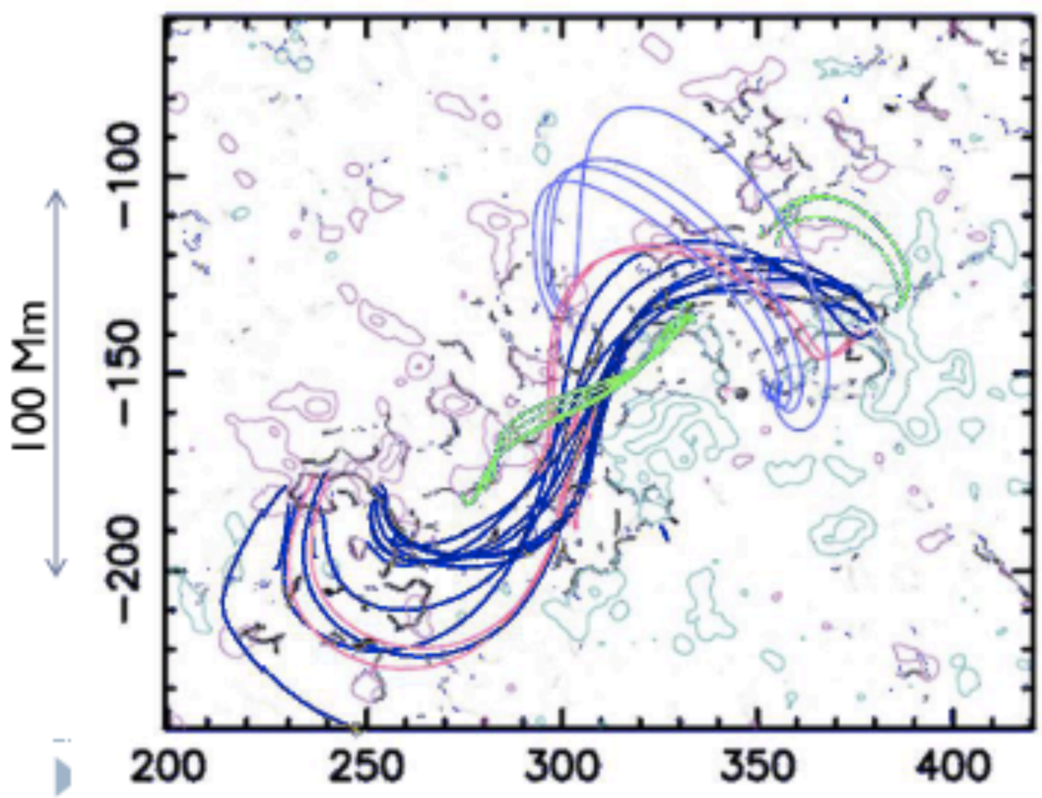
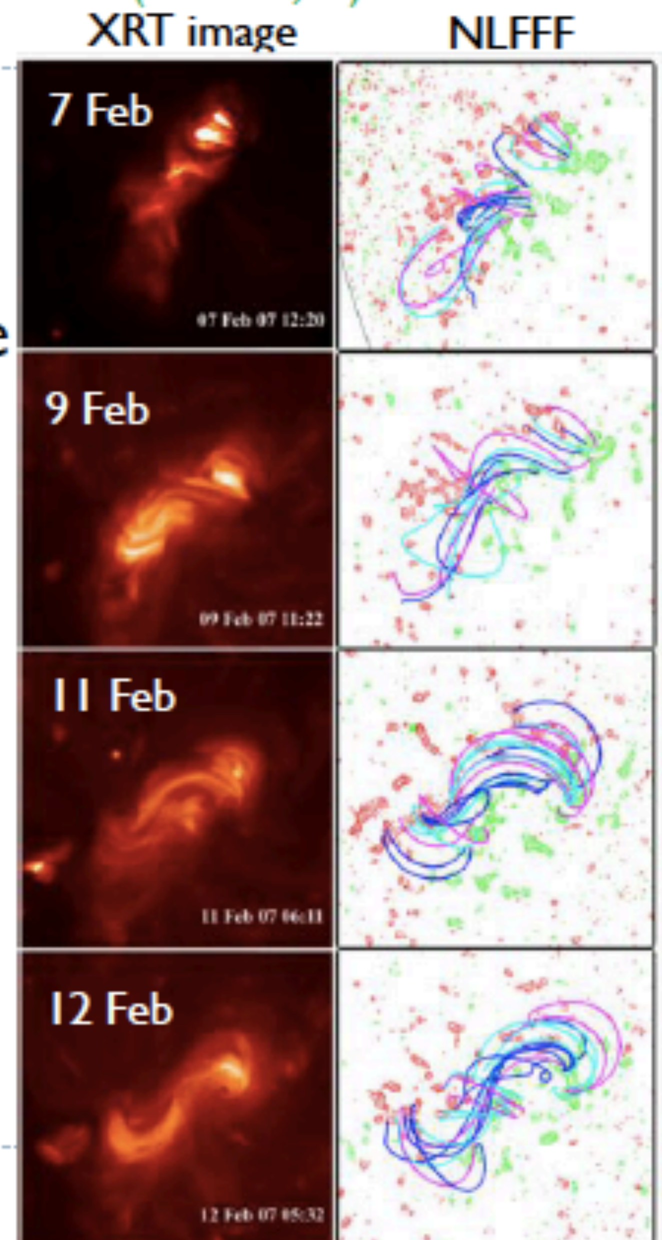
3D magnetic field structure

Savcheva & van Ballegooijen (2009), Savcheva et al. (2012a, b)

- February 2007
- Builds up S-shape over time
- Different types of loops prior to flare

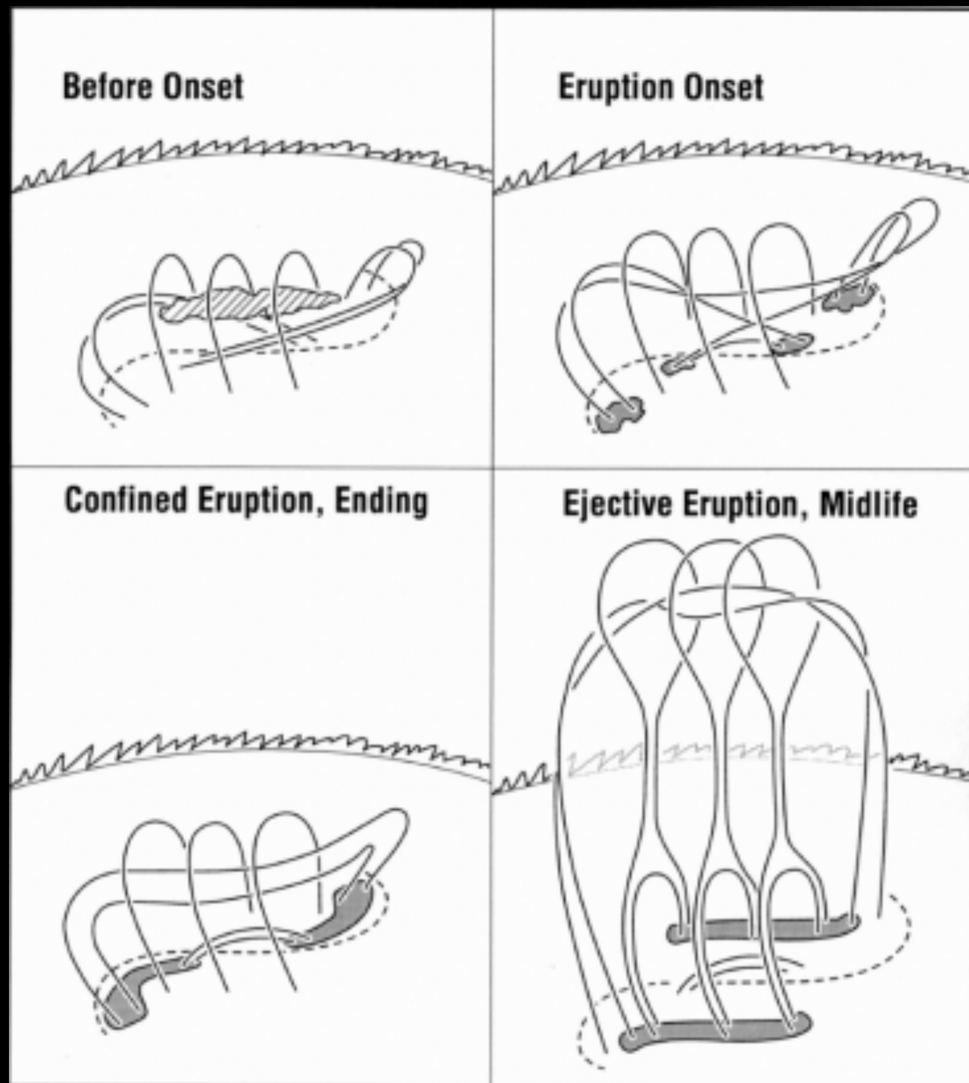




Likely triggers/drivers of CME eruption:

- Tether cutting reconnection
- Loss of equilibrium (through kink and/or torus instability)

Tether cutting reconnection

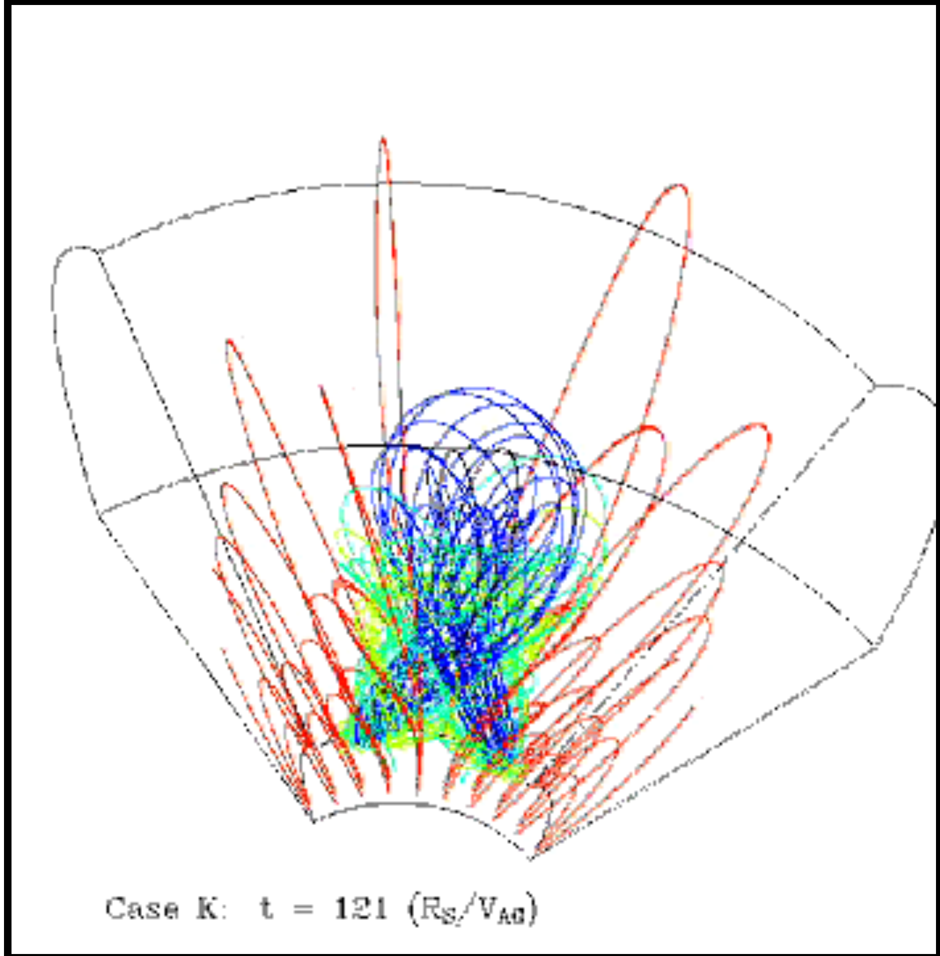


Moore et al., 2001

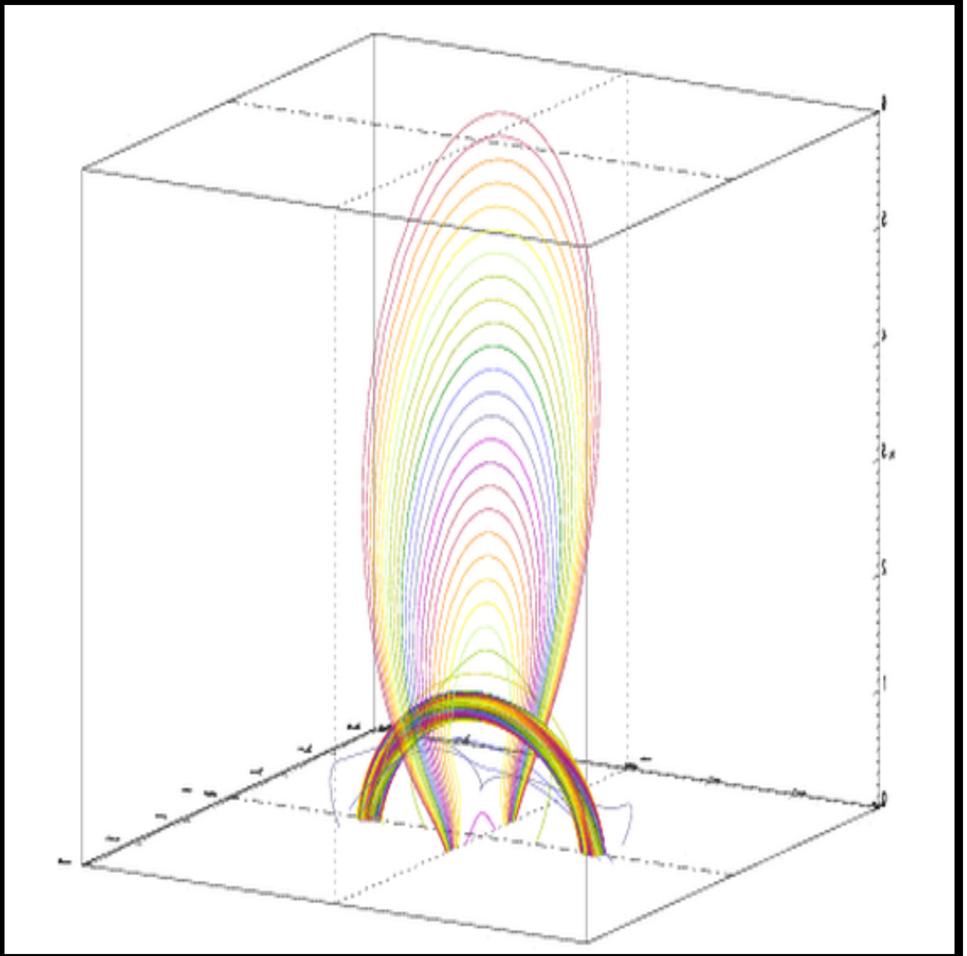
Loss of Equilibrium – ideal MHD instabilities

Fan, 2010

Kliem & Torok, 2011

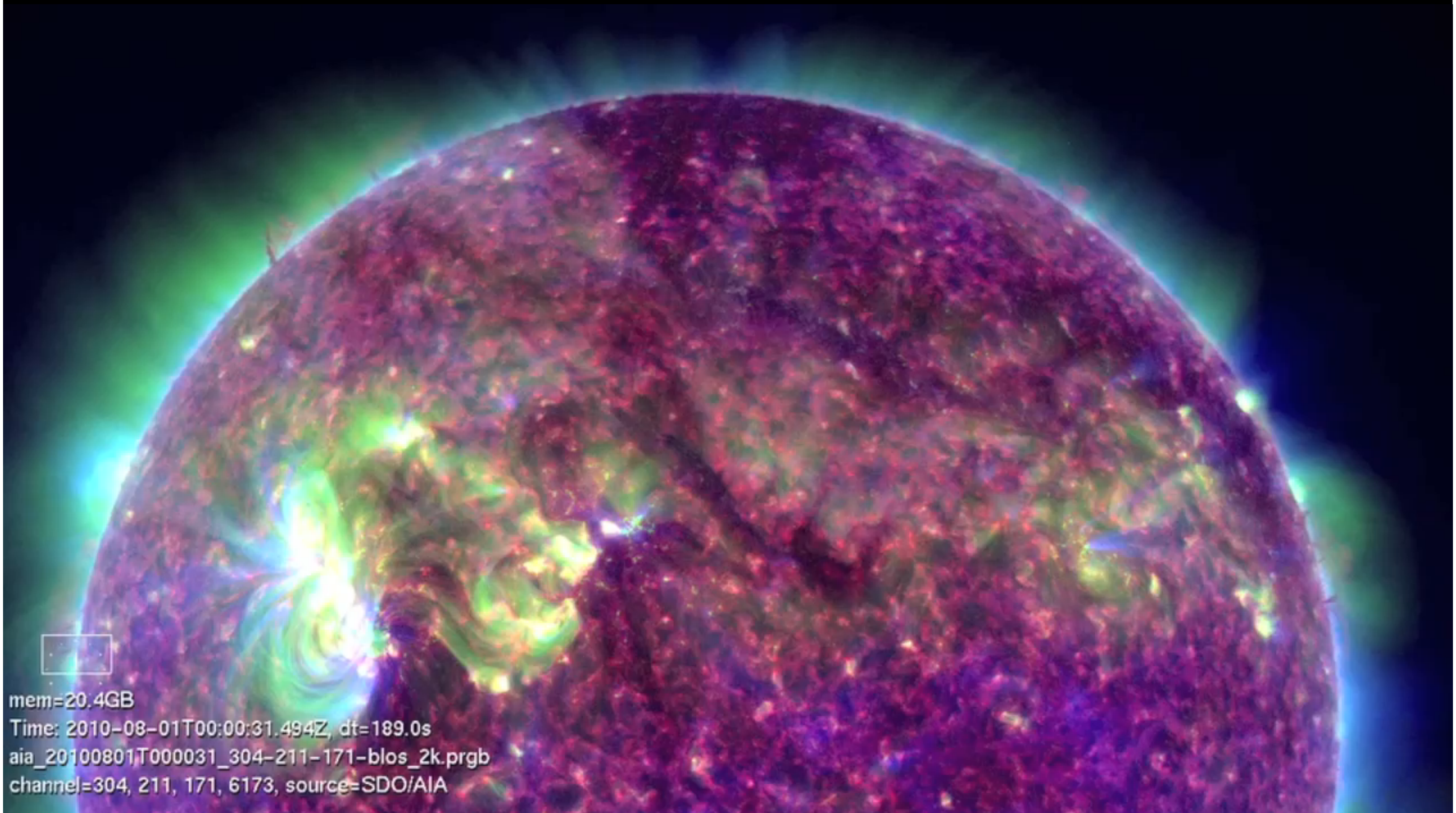


Kink instability



Torus instability

Sympathetic Eruptions - August 1, 2010



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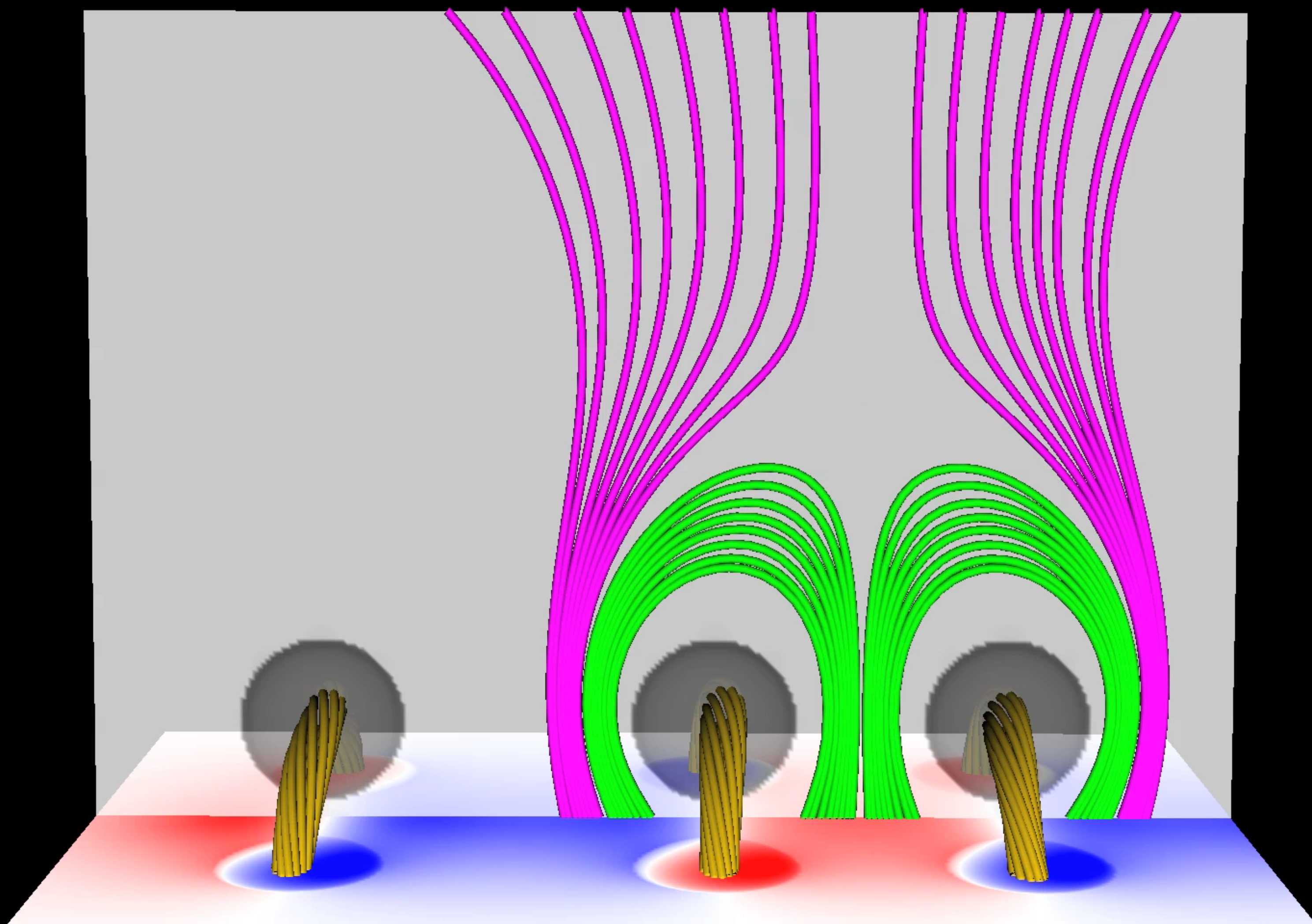
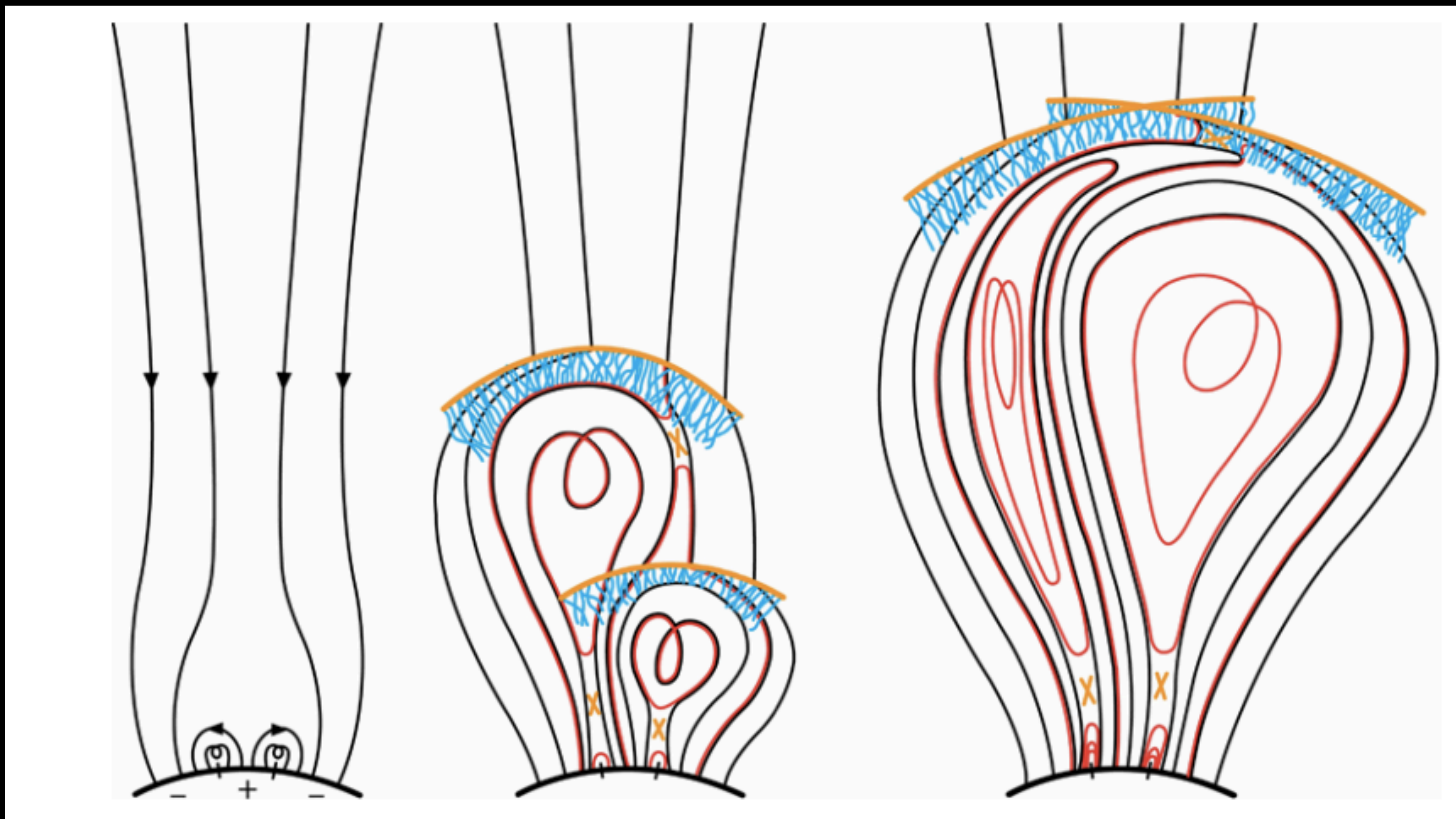
Can sympathetic eruptions be triggered?



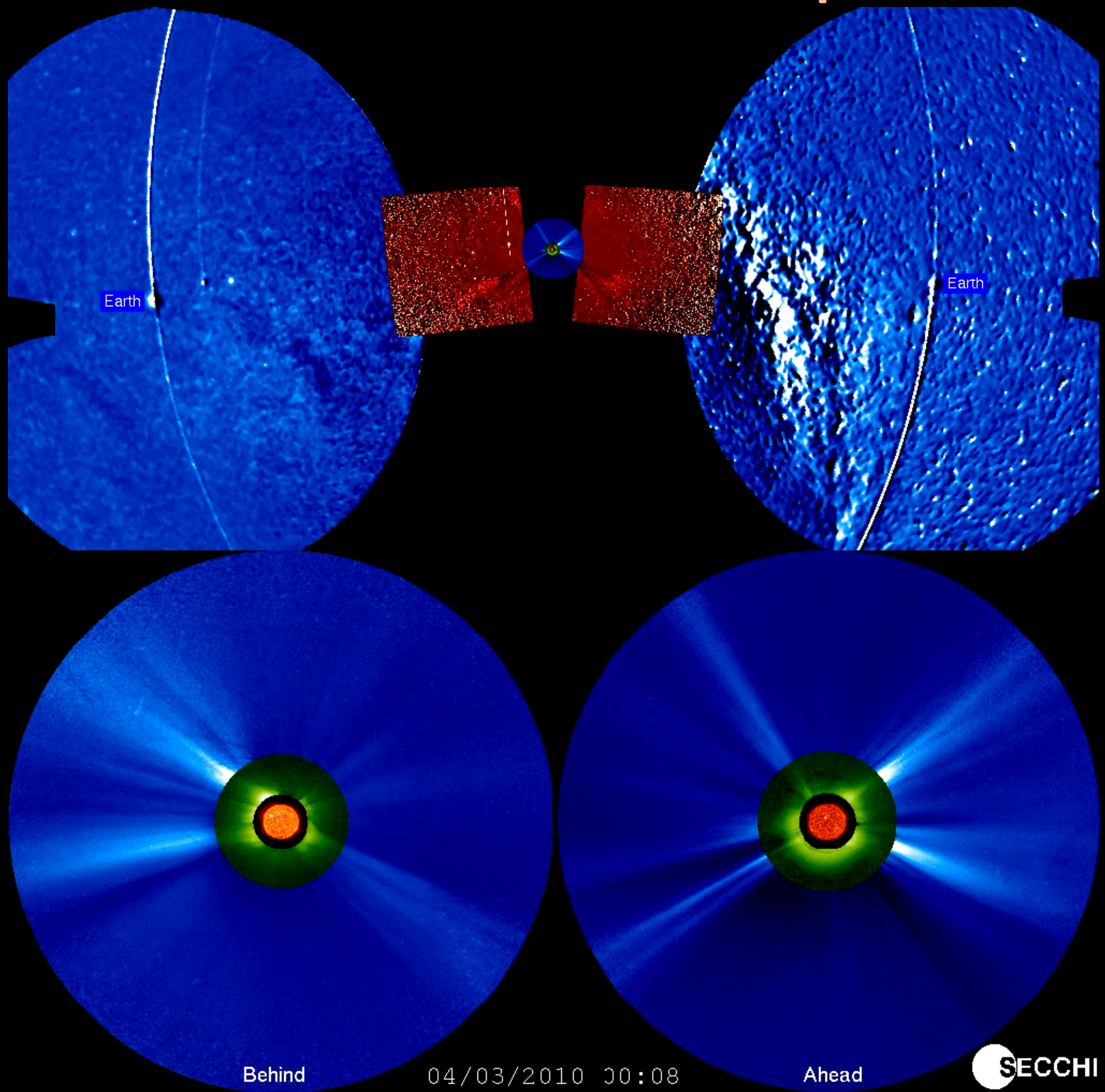
Torok et al., 2011

CME-CME interactions - enhanced shocks



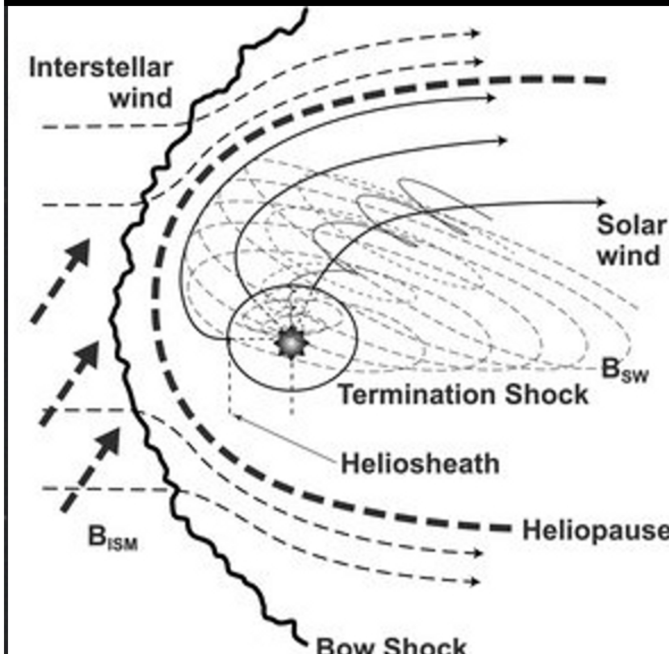
Li et al., 2012

CMEs in the heliosphere



http://secchi.nrl.navy.mil/index.php?p=movies

Voyagers and the edge of the heliosphere



Opher, 2010

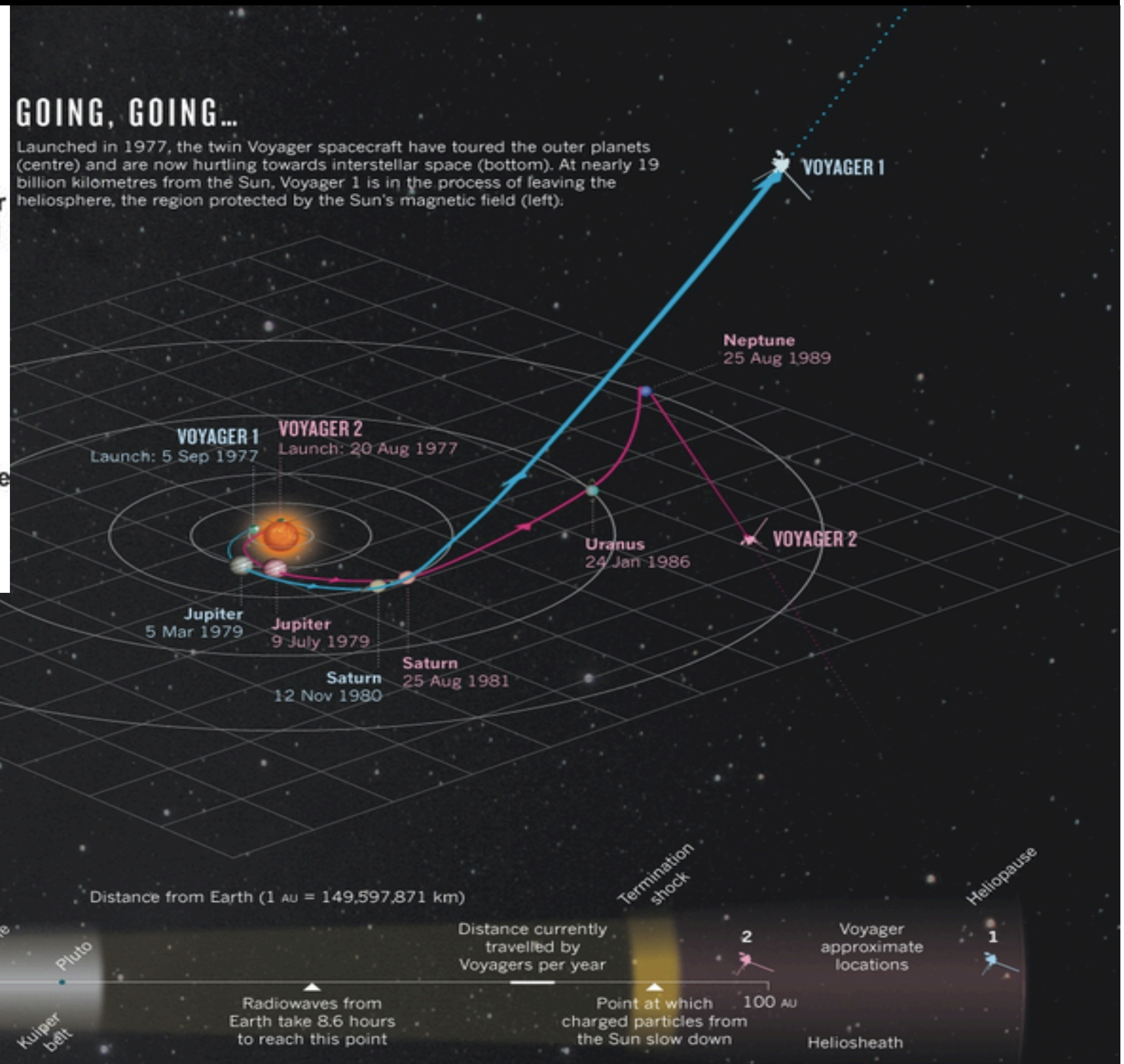
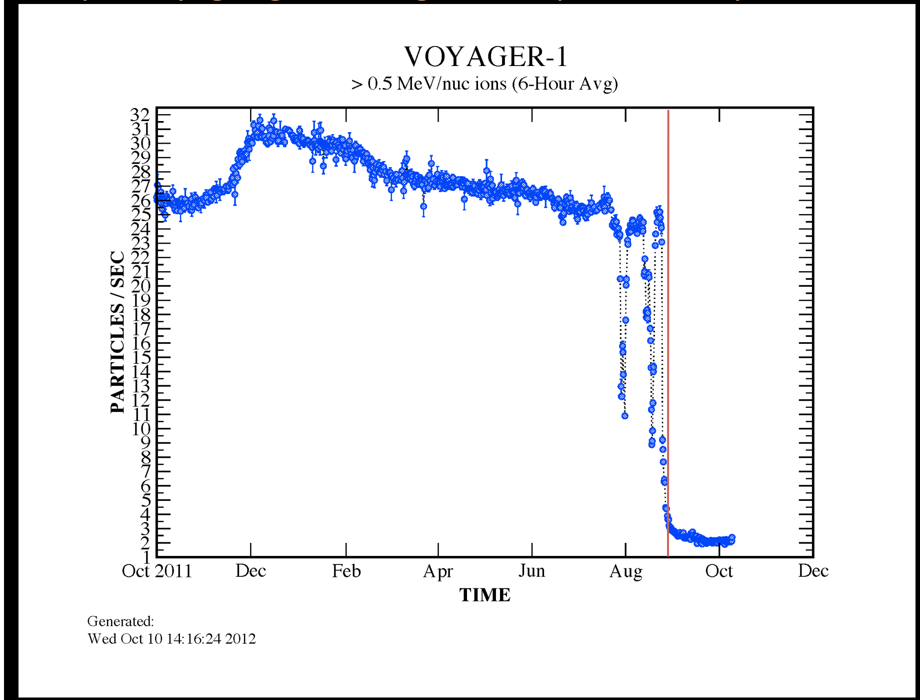
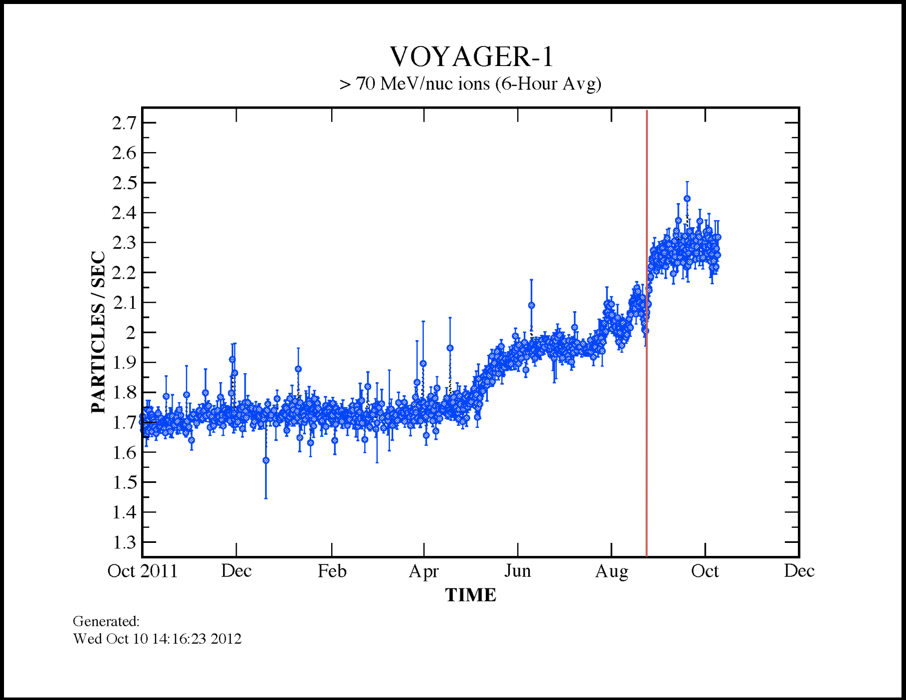


IMAGE: NIK SPENCER/NATURE

V1 crossed the heliopause on August 25, 2012: Why was it announced only a month ago?

http://voyager.gsfc.nasa.gov/heliopause/heliopause/v1la1.html

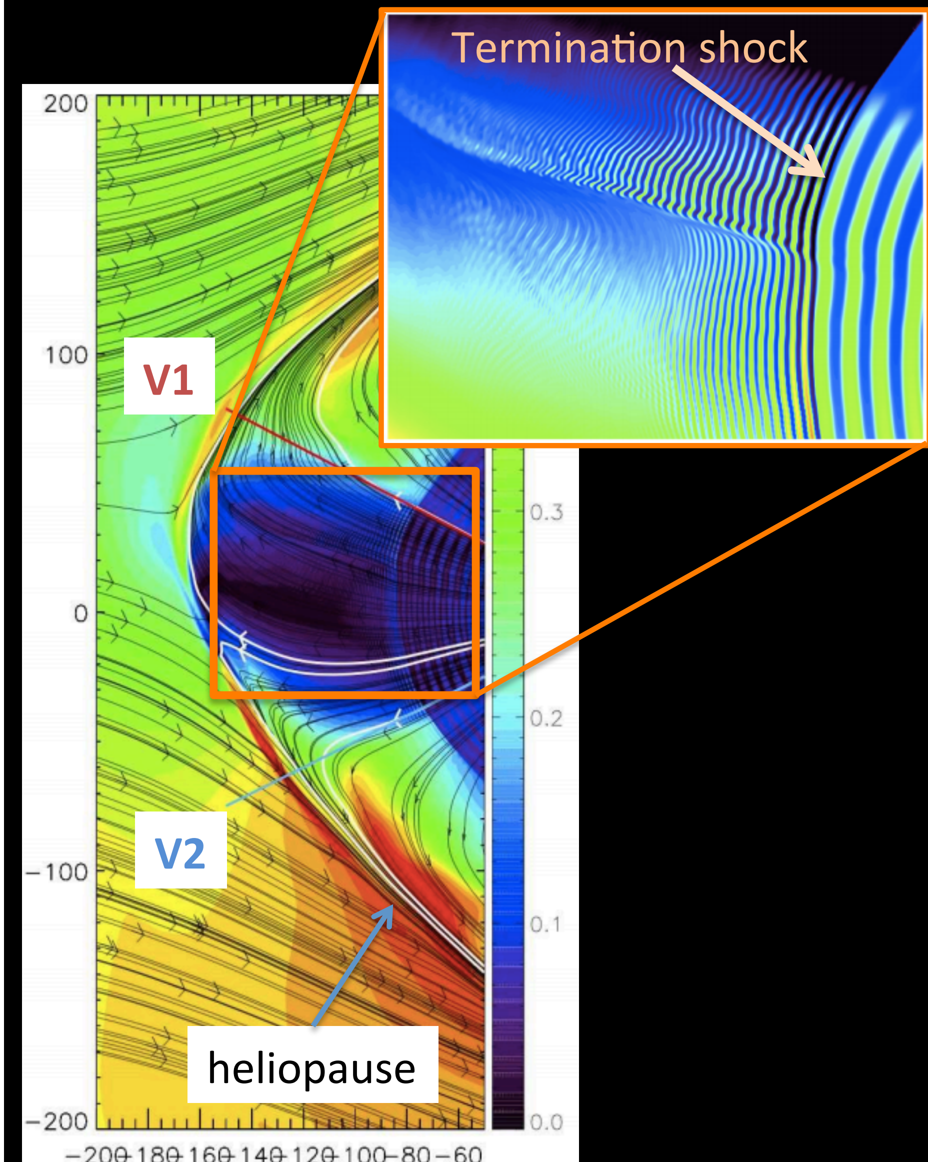




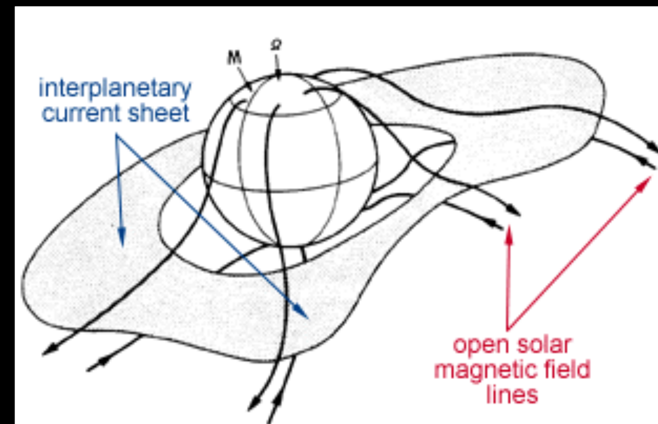
3 tell-tale signs expected:

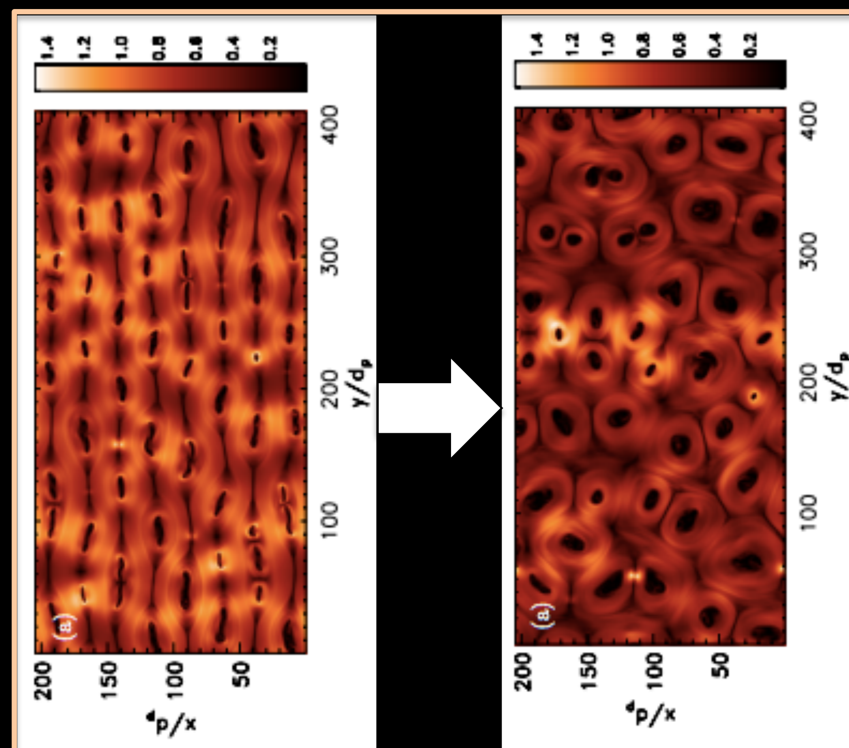
- Sharp decrease in solar wind density and speed
- Sharp increase in GCR fluxes
- Sharp change in B-field direction – Not seen! Why?

The porous heliosheath



Opher et al., 2011





A porous, open heliosheath

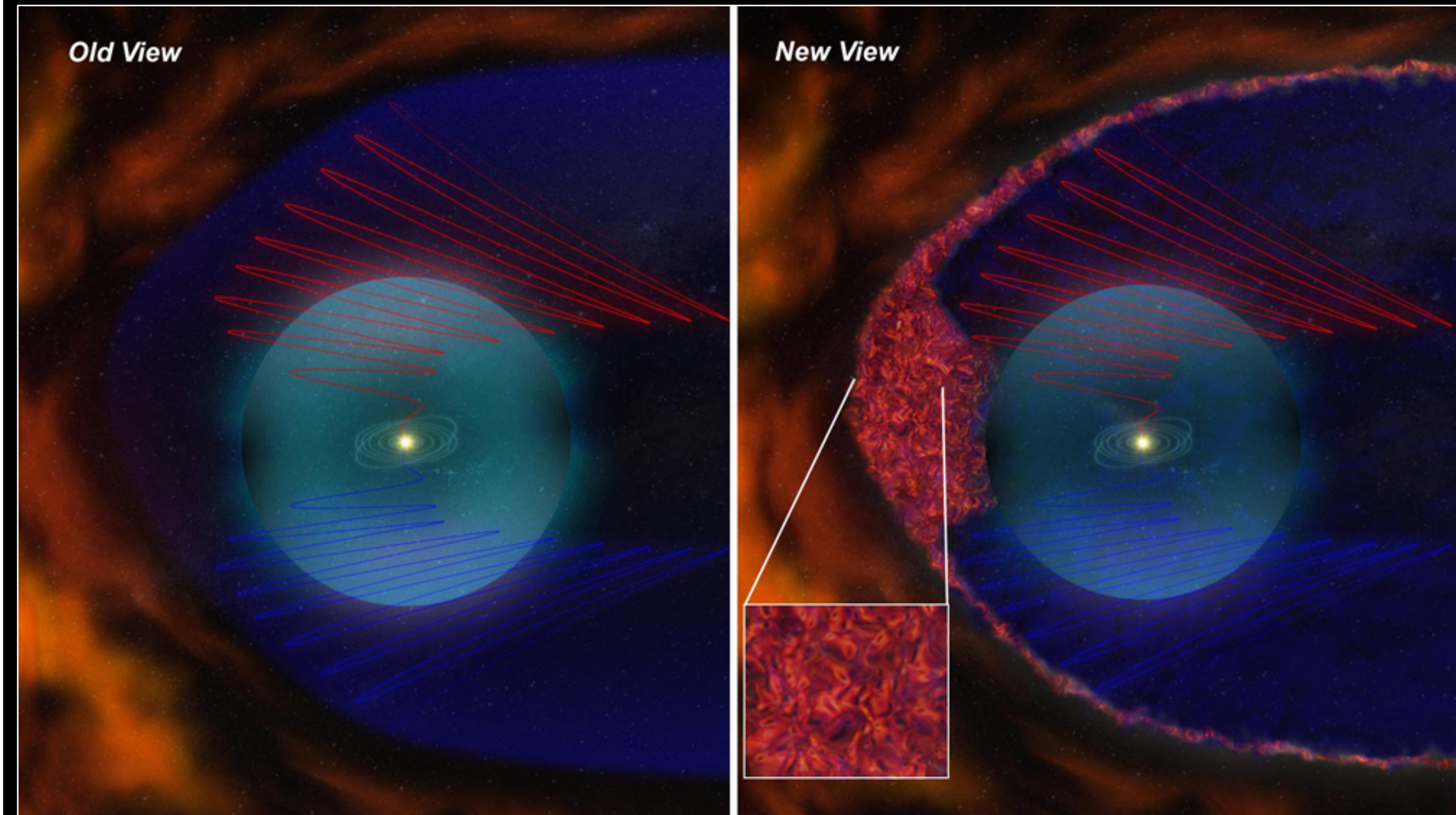
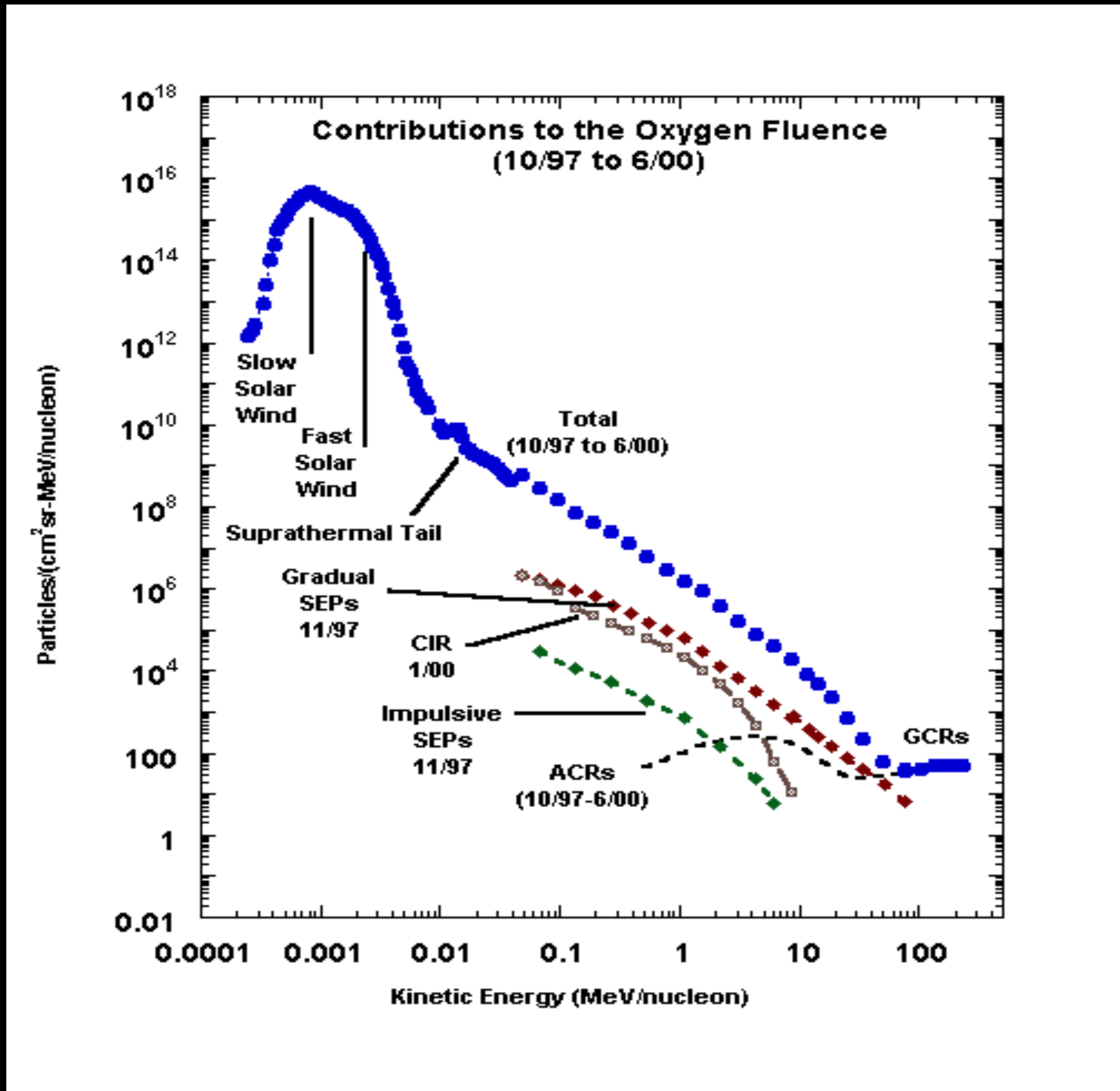


Image: NASA

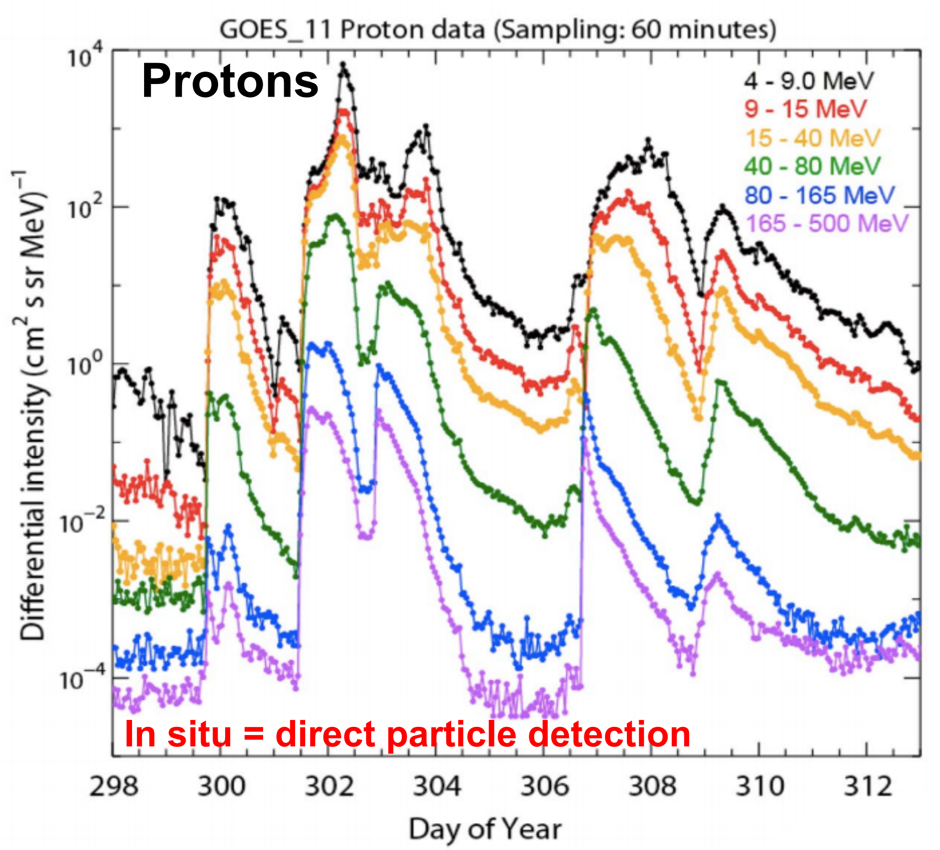
Particle populations in the heliosphere

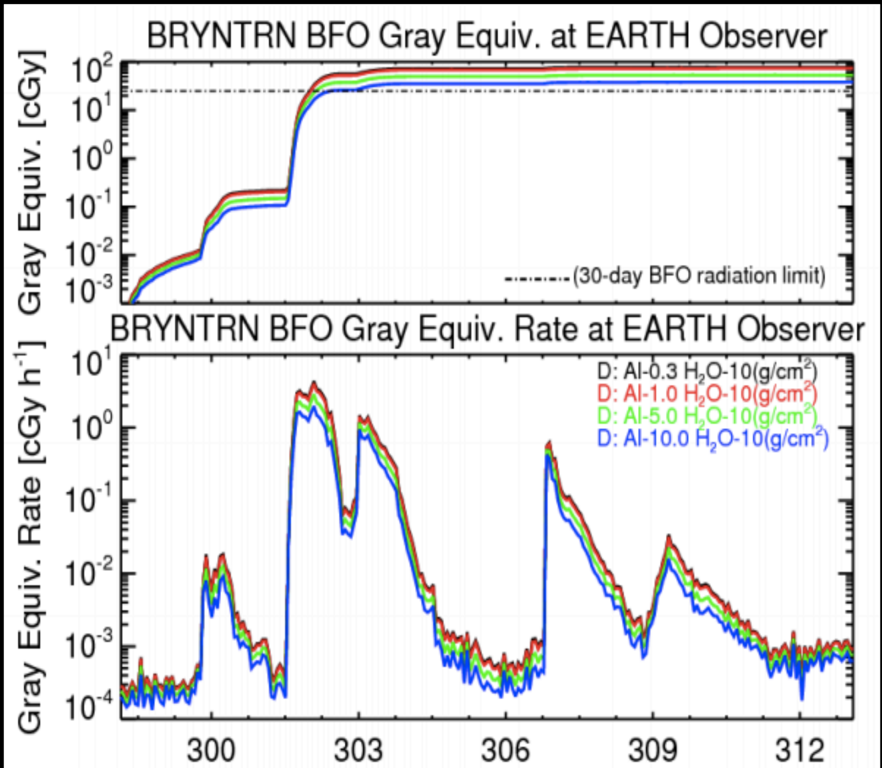


http://www.srl.caltech.edu/ACE/ASC/DATA/level3/fluences/ContribsToOxygenFluence.gif

Solar Energetic Particles (SEPs)

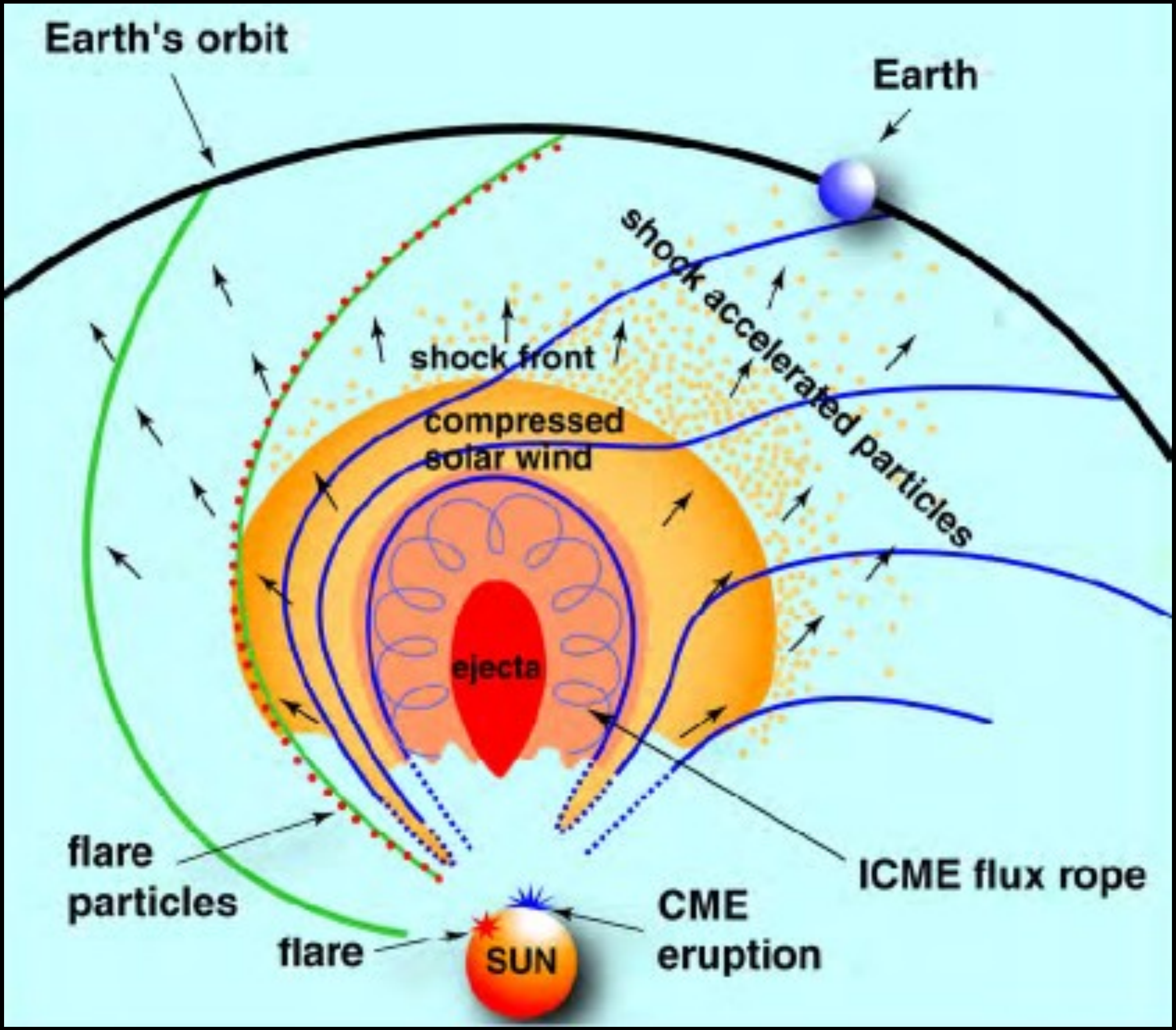
- propagate along interplanetary magnetic field (IMF) lines
- impact planetary environments
- can cause serious damage to satellite electronics
- can cause acute or long-term radiation disease to astronauts





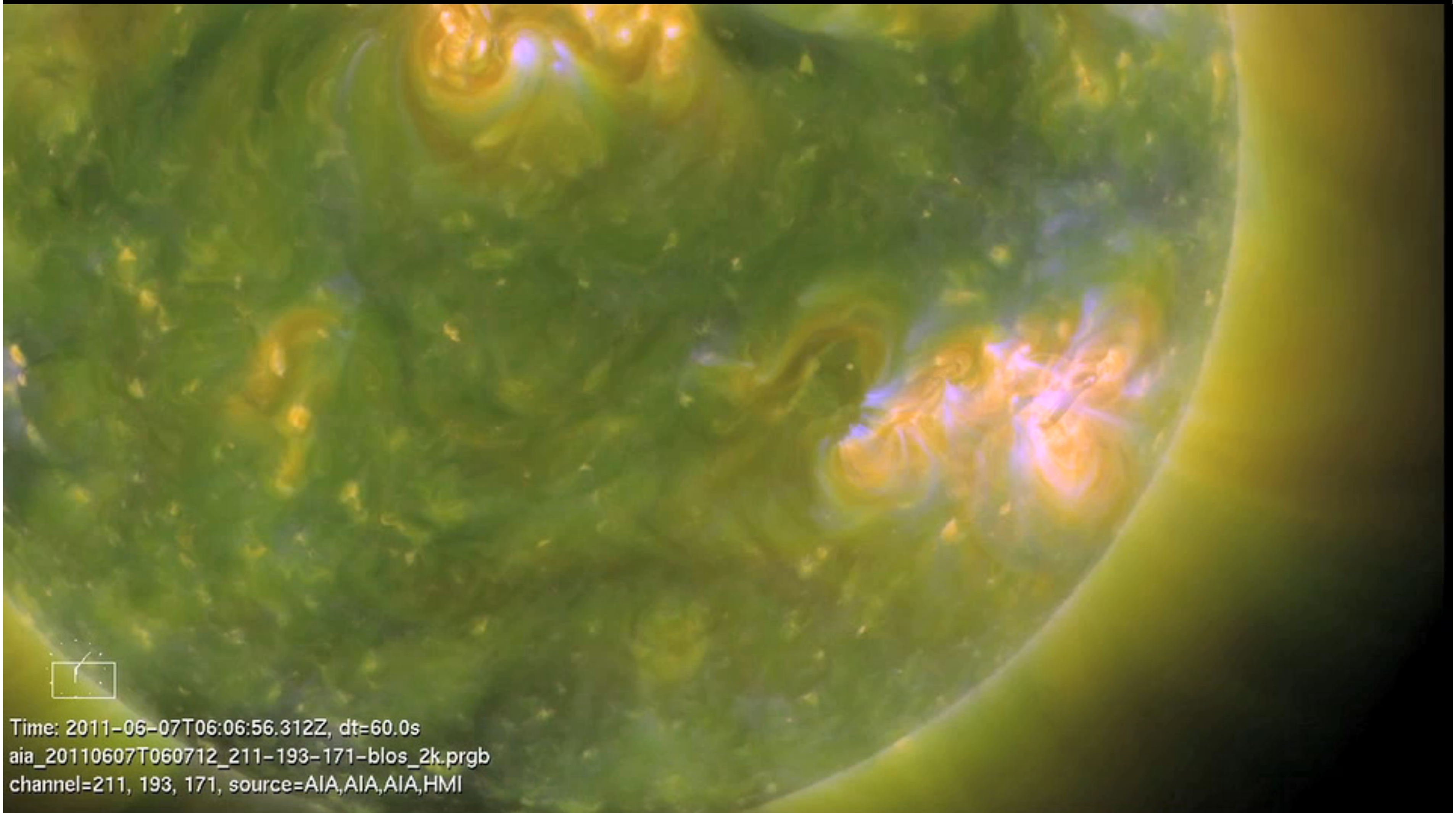
Pourarsalan et al., 2010

How SEPs are made: Flares and CMEs



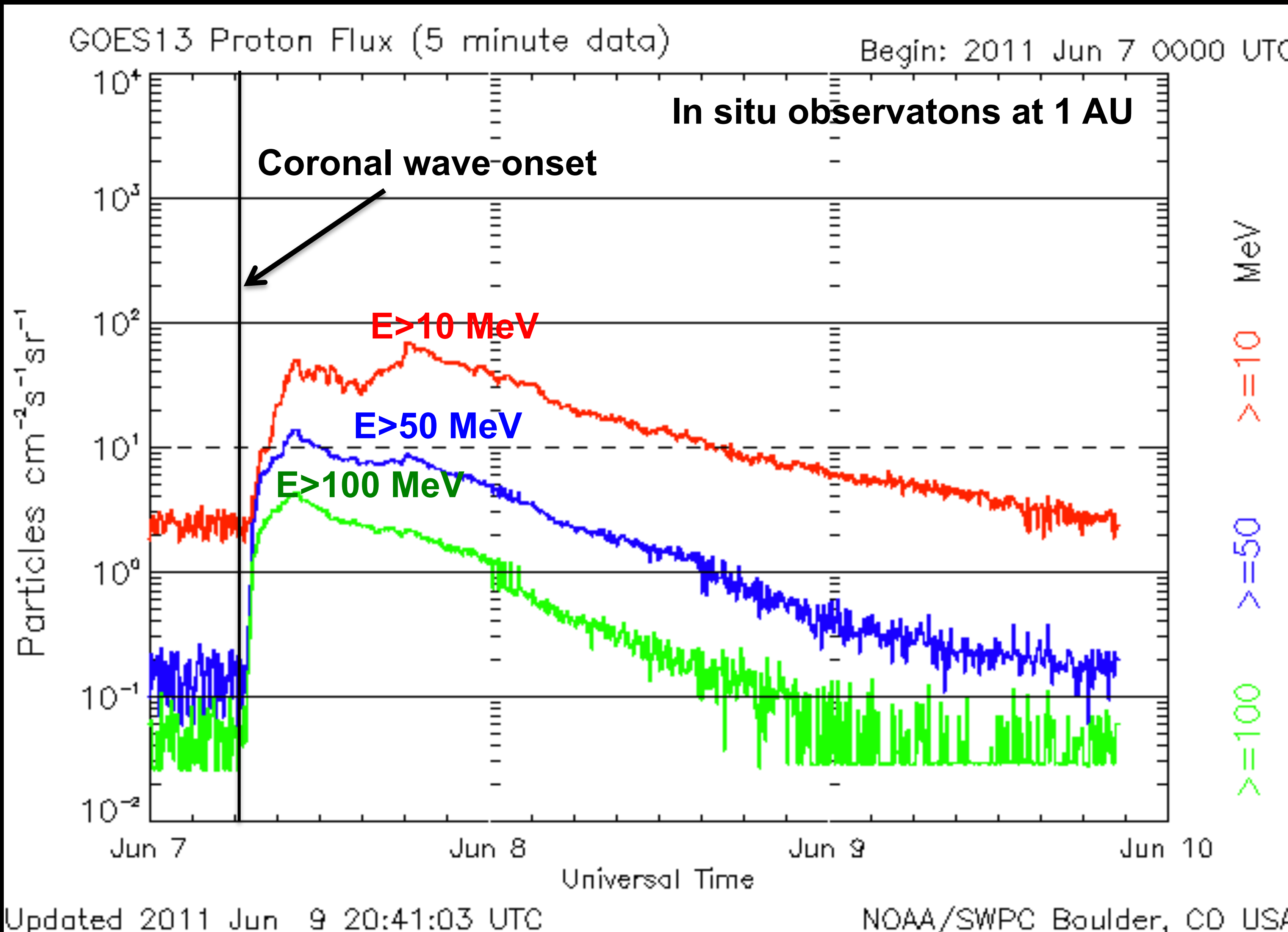
A look at the inner solar system from above

JUNE 7, 2011 CME



www.lmsal.com/isolsearch

Particles are accelerated (and leave) very quickly!



Flare vs. CME particle acceleration

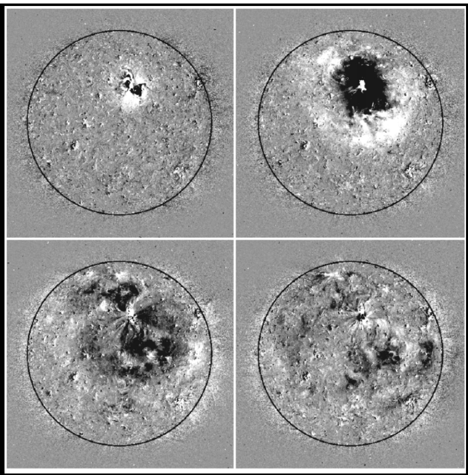
- Flares can accelerate particles to high energies (especially electrons), e.g., Kahler et al. (2007)
- However, flares occur very low in corona, so access to open field lines uncertain
- Flare protons not usually observed to high energies in situ
- Fast CMEs drive shock waves (metric radio observations) very close to the Sun
- Simulations show shock waves can accelerate particles to very high energies (esp. protons) – e.g., Manchester et al. (2005), Roussev et al. (2004), Sokolov et al. (2009)
- Can CME-driven shocks in the corona accelerate SEPs?
- Can we use remote coronal observations to characterize acceleration?

Coronal EUV waves

- Magnetosonic waves?
- Pseudo-waves (due to reconnection)?
- Both?

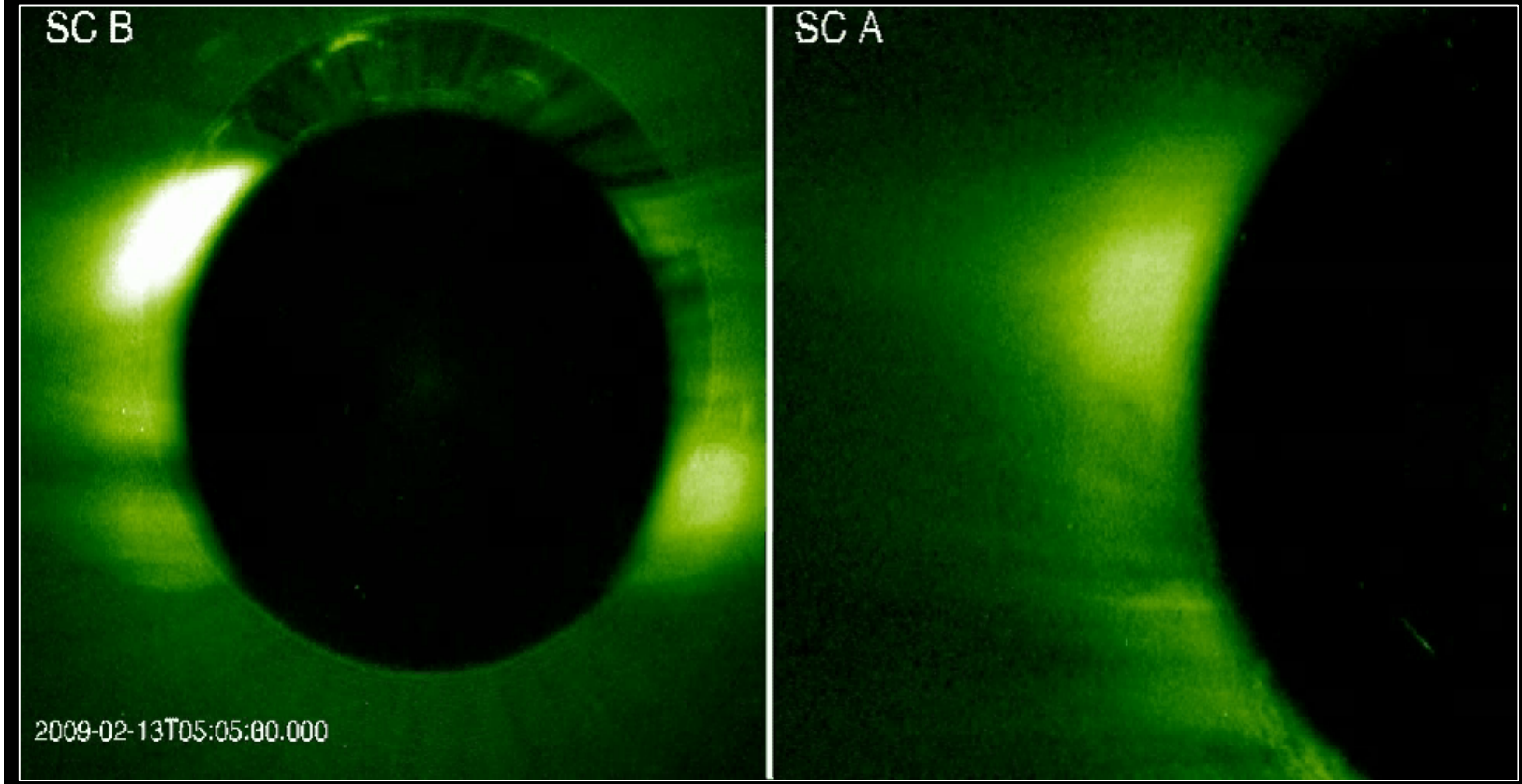
Likely waves

SoHO/EIT



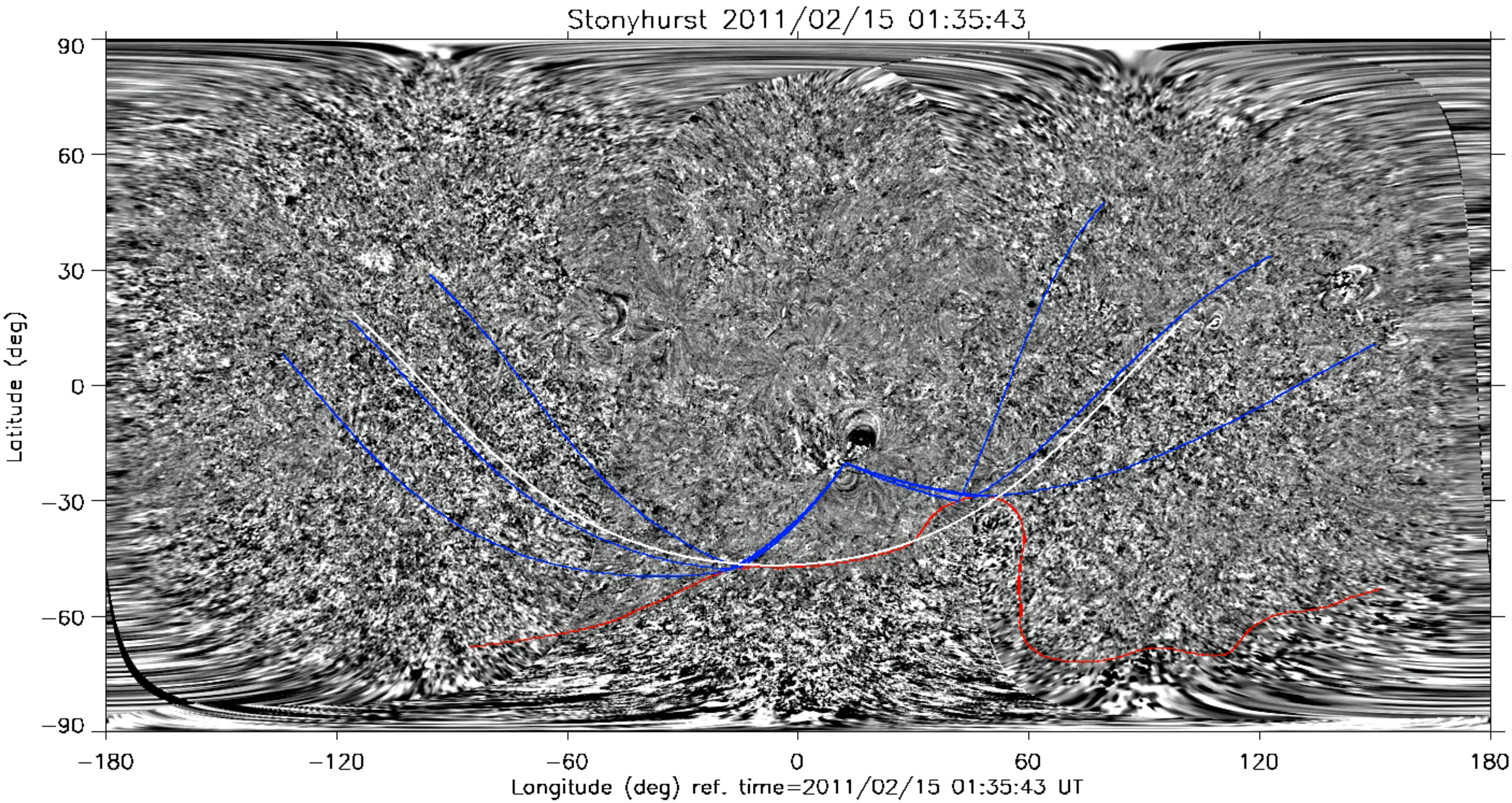
Thompson et al., 1998

SECCHI/EUVI-COR1



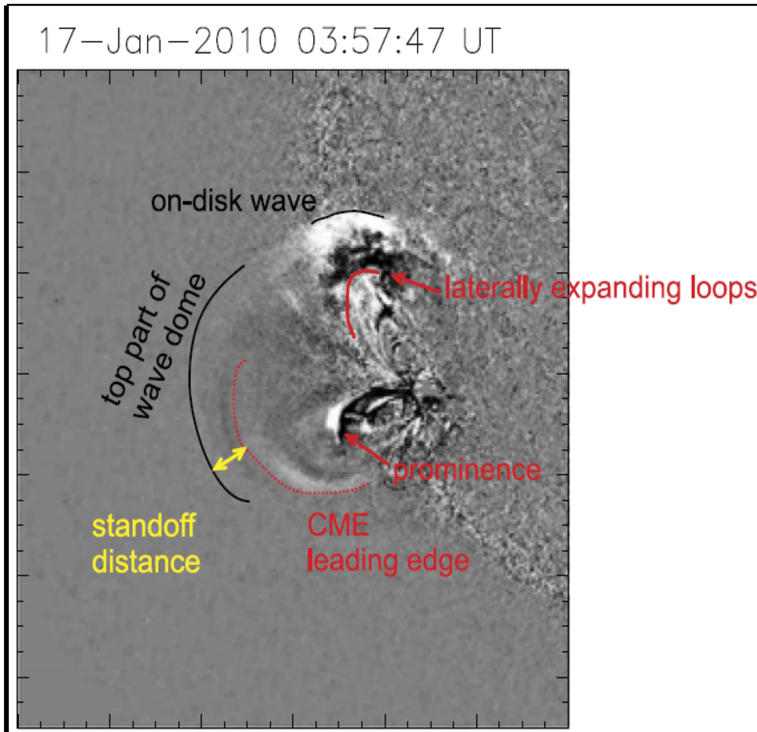
Patsourakos et al., 2009

Reflections/Refractions

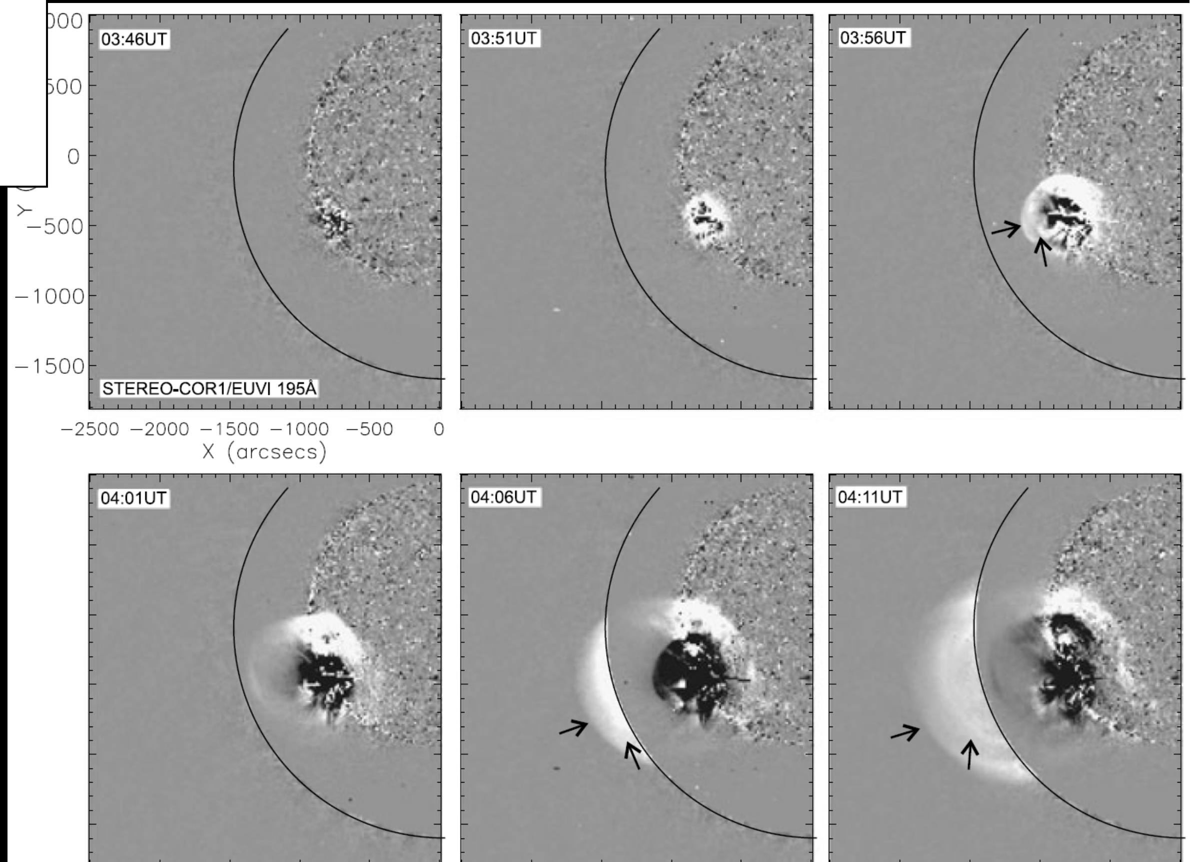


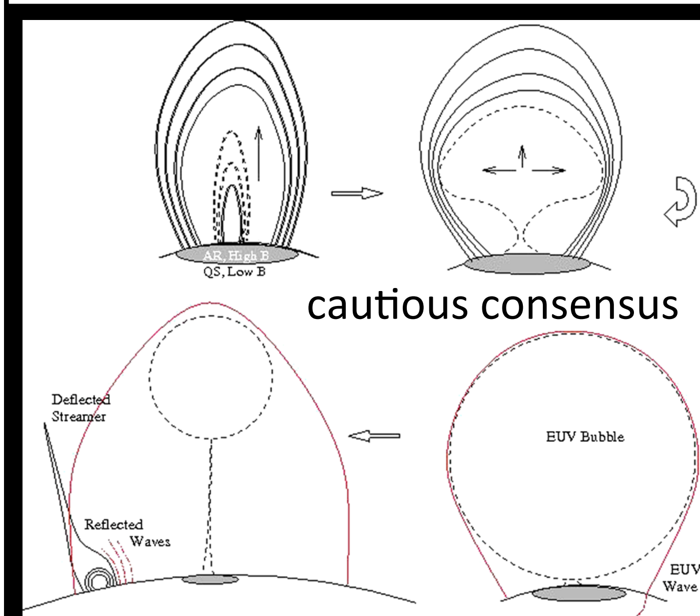
Olmedo et al., 2012

Dome-like coronal waves



Temmer et al., 2012

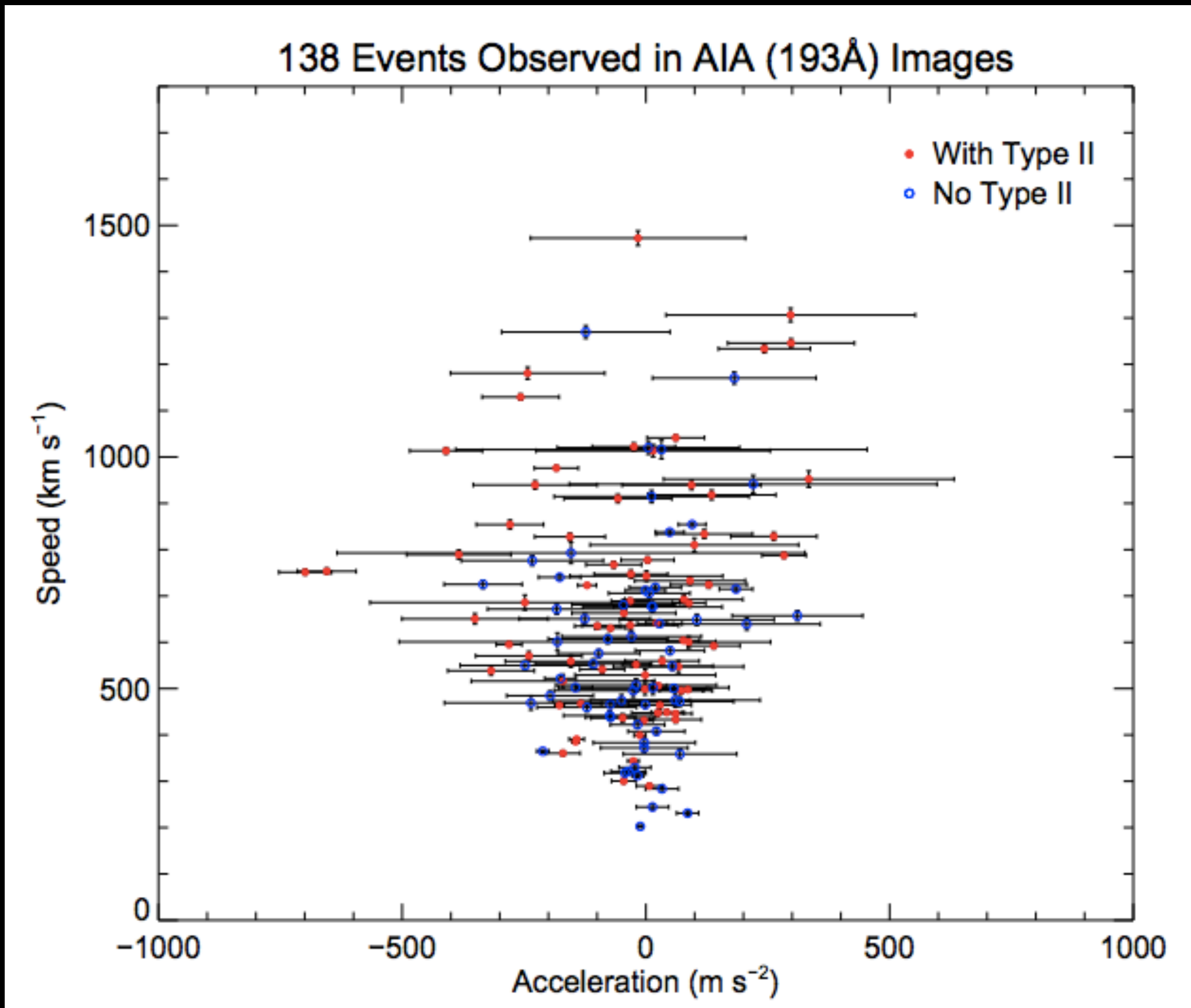




cautious consensus

Patsourakos and Vourlidas, 2012

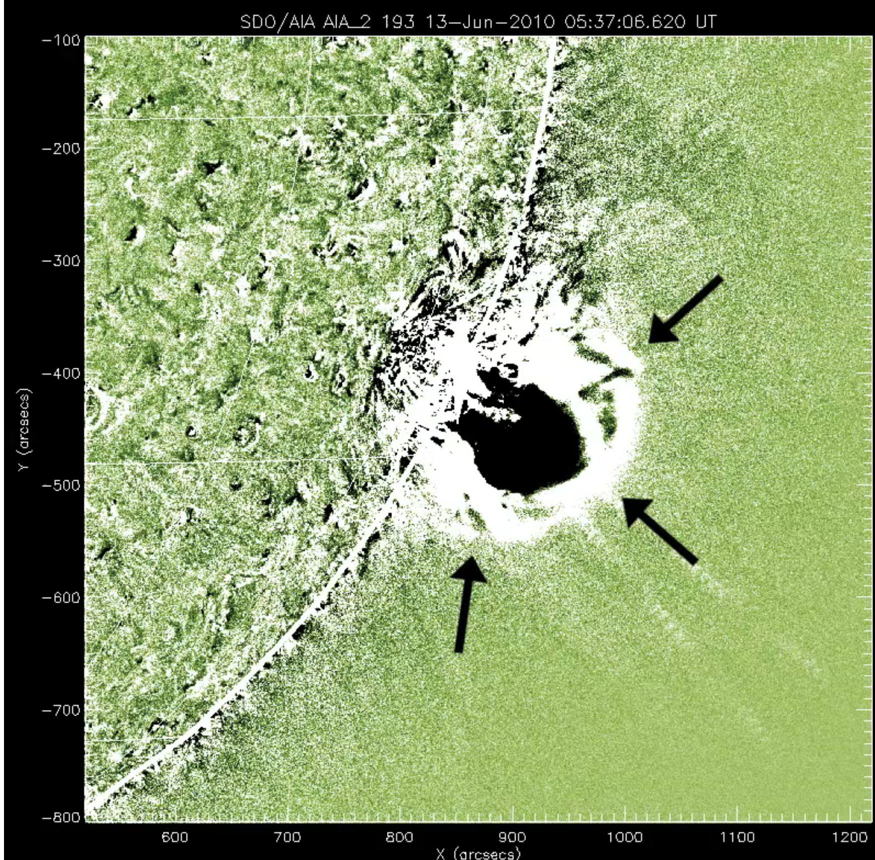
Preliminary wave statistics



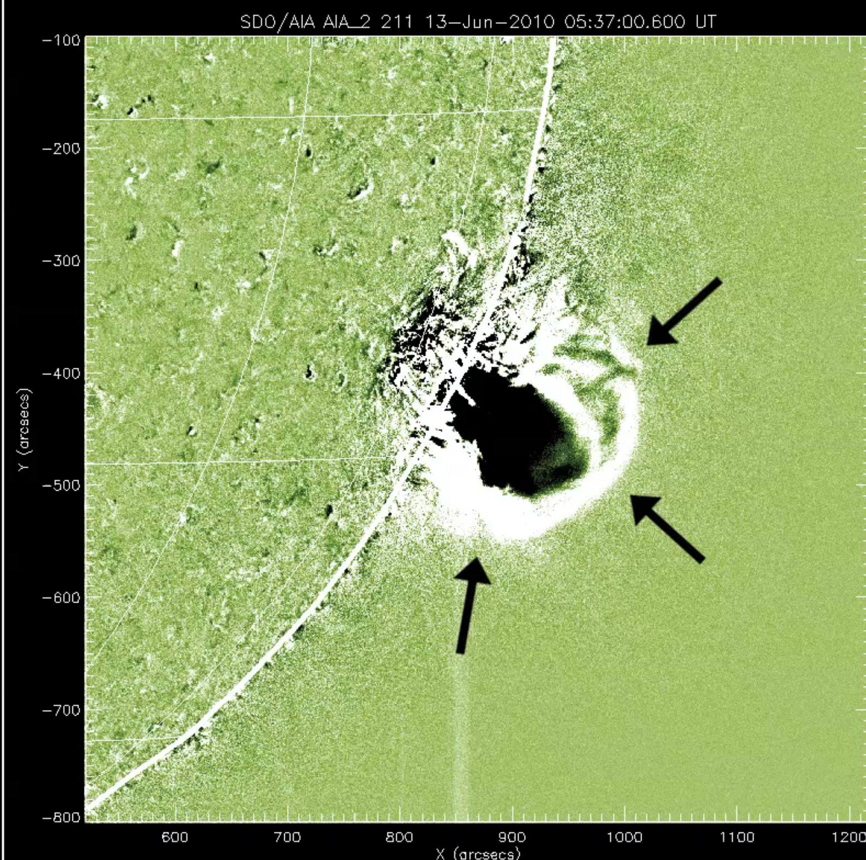
Nitta et al., 2013

Can we use remote observations of coronal waves/ shocks to learn about particle acceleration?

June 13, 2010 event – 12-sec cadence, 5 min-propagation



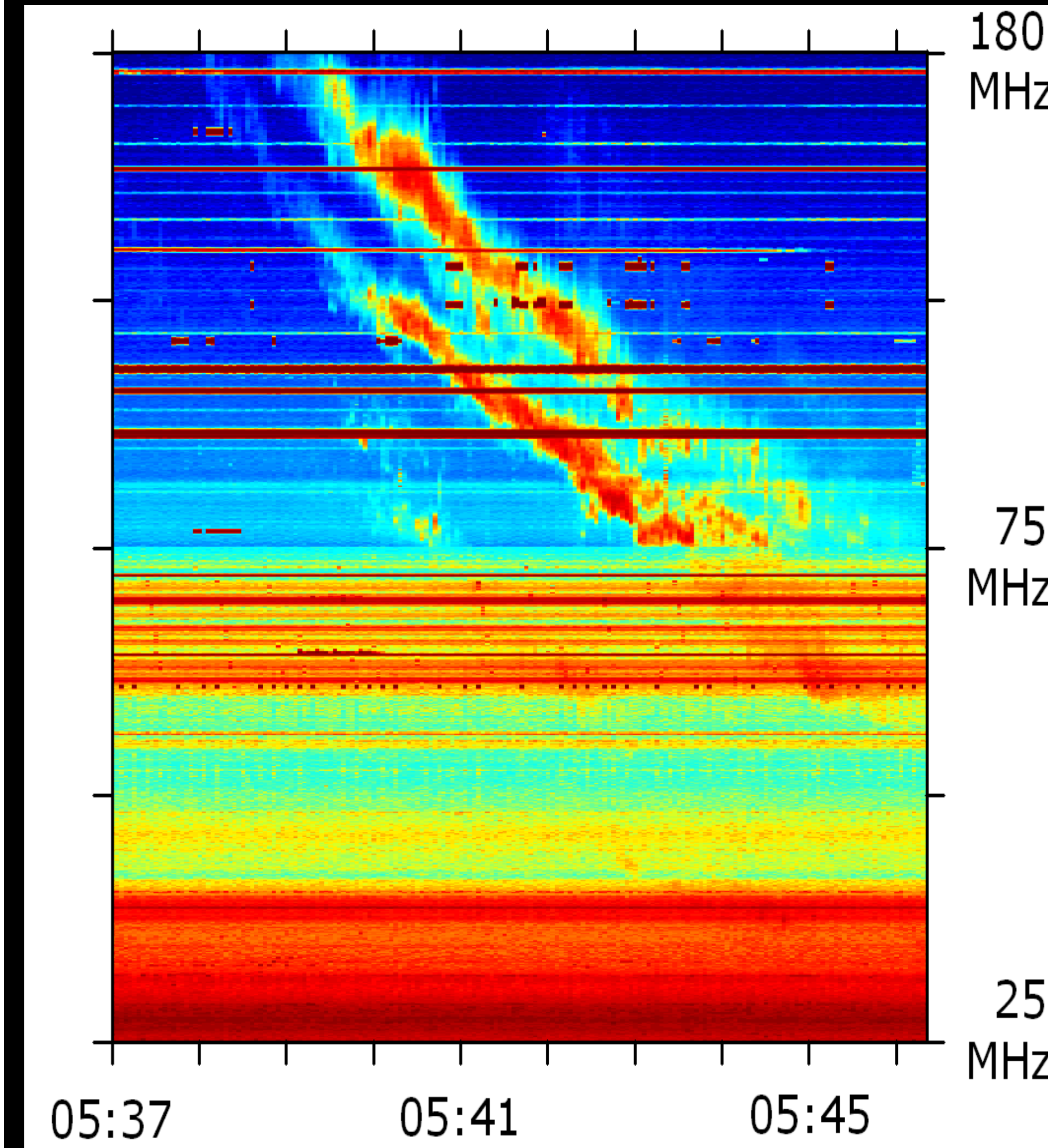
AIA/193 Angstrom



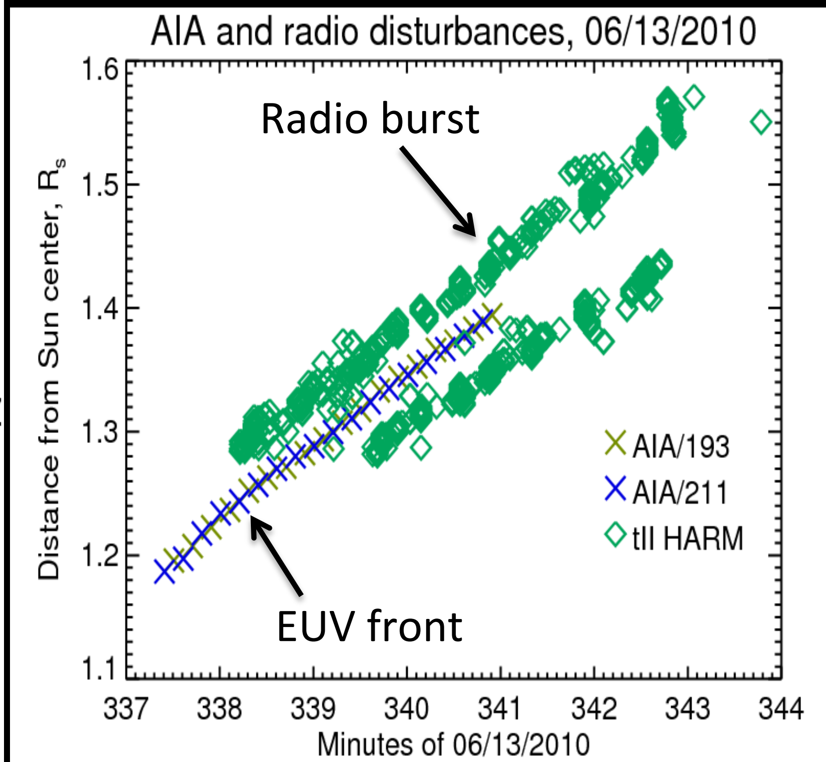
AIA/211 Angstrom

Kozarev et al., 2011a

Radio and EUV observations



Kozarev et al., 2011a



- Coincidence of EUV wave and radio shock
- Radial speeds of 650 km/s

Change in density and/or temperature

Estimate wave density change from multi-channel EUV observations!

$$n_e^2 dV = Q(T)dT$$

$$r = \frac{n_{e2}}{n_{e1}} \sim \frac{\sqrt{EM_2}}{\sqrt{EM_1}} \sim \frac{\sqrt{\int Q_2(T)\mathrm{d}T}}{\sqrt{\int Q_1(T)\mathrm{d}T}}$$

•Differential Emission Measure (DEM, Q(T)) – amount of emitting material in a volume dV in temperature interval dT

•Don't know dV, but can take ratios

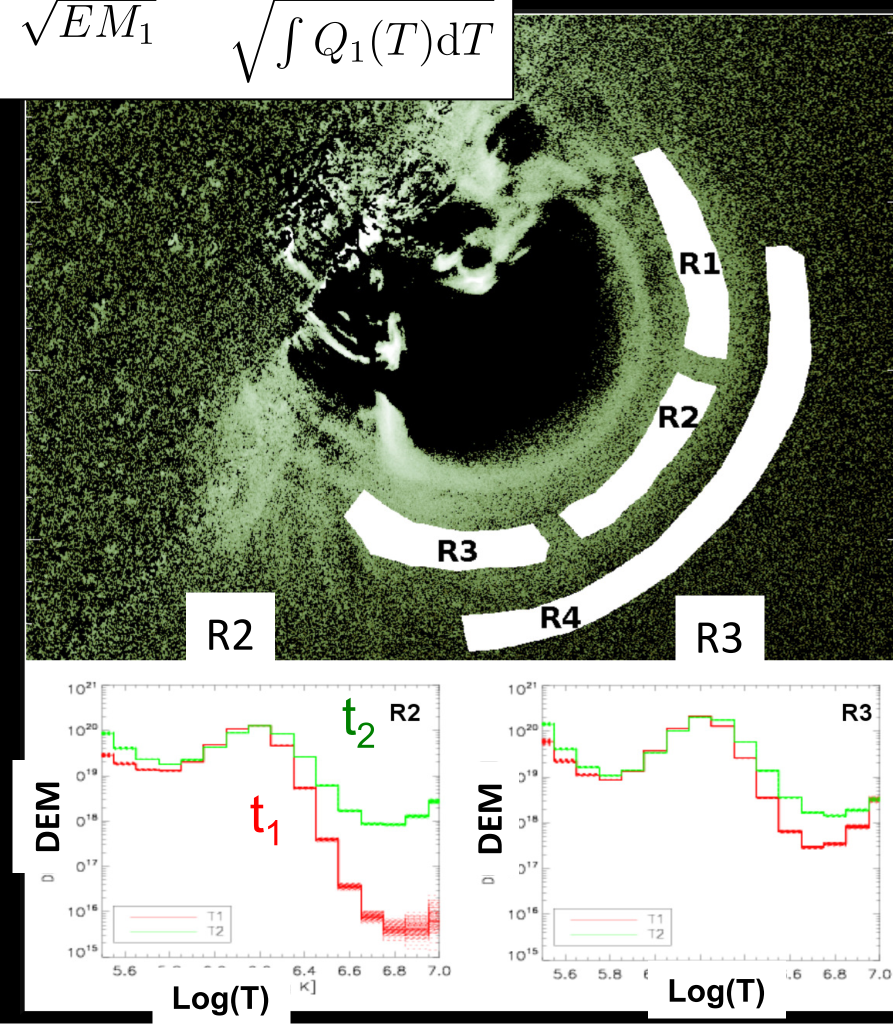
•t1 before event, t2 during

For R2, r~1.18

•For R3, r~1.12

•Slightly lower than estimates from radio observations – r~1.56 (Ma et al., 2011)

•Density jump suggests wave is signature of a weak shock!



Finally, can estimate particle momentum gain from Diffusive Shock Acceleration (DSA) theory. Use:

-Measured shock kinematics and derived shock strength

-A model for the coronal magnetic field

Zank et al., 2006

Change in momentum in time dt due to DSA acceleration is

$$dp = \frac{V_{sh}^2 p(r-1)dt}{3r\kappa_{xx}}$$

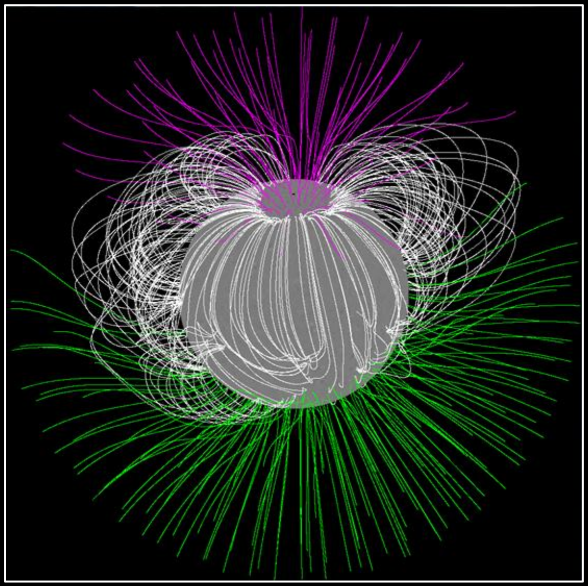
$$\kappa_{xx} = \kappa_{\|} \cos^2(\theta_{BN}) + \kappa_{\perp} \sin^2(\theta_{BN})$$

$$\kappa_{\|} = v\lambda_{\|}/3$$

$$\kappa_{\perp} = \kappa_{\|}/[1+(\lambda_{\|}/r_g)^2]$$

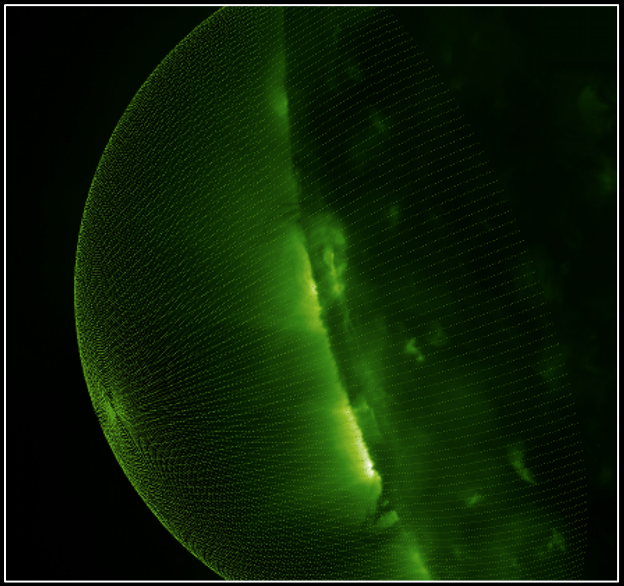
r is density jump, k_{xx} is diffusion coefficient, dependent on θ_{BN} (shock normal-field angle)

Need θ_{BN} ->



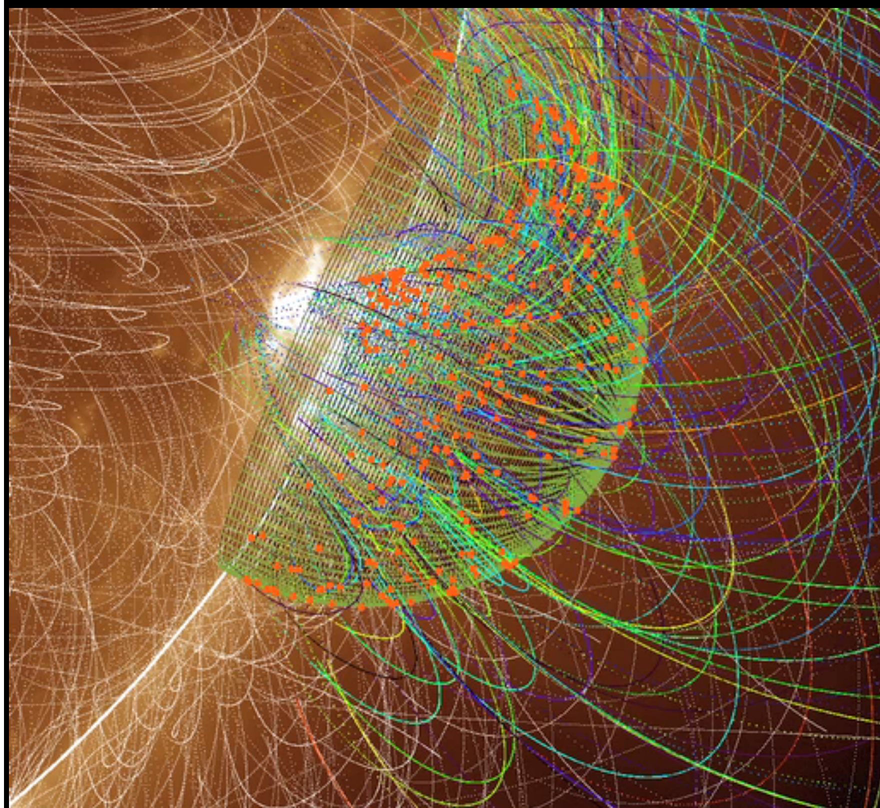
Coronal potential field model
(Schrijver & De Rosa, 2003)

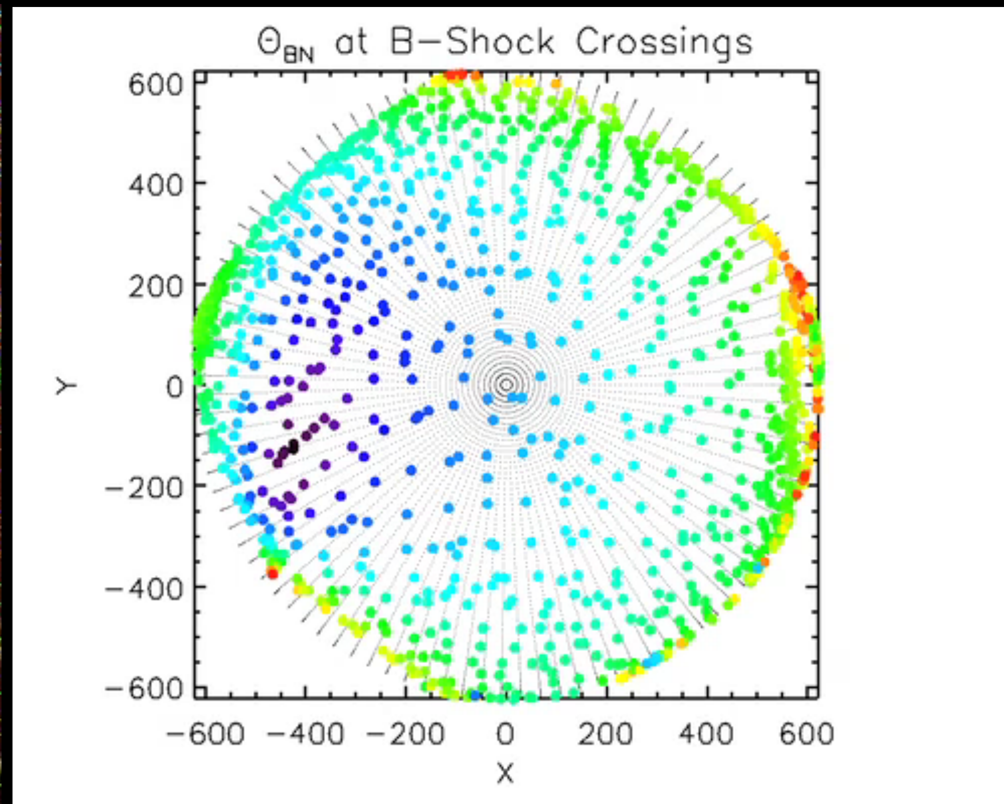
+



Shock front model
(Kozarev et al., 2011b)

Time-dependent Shock-Field crossing angles





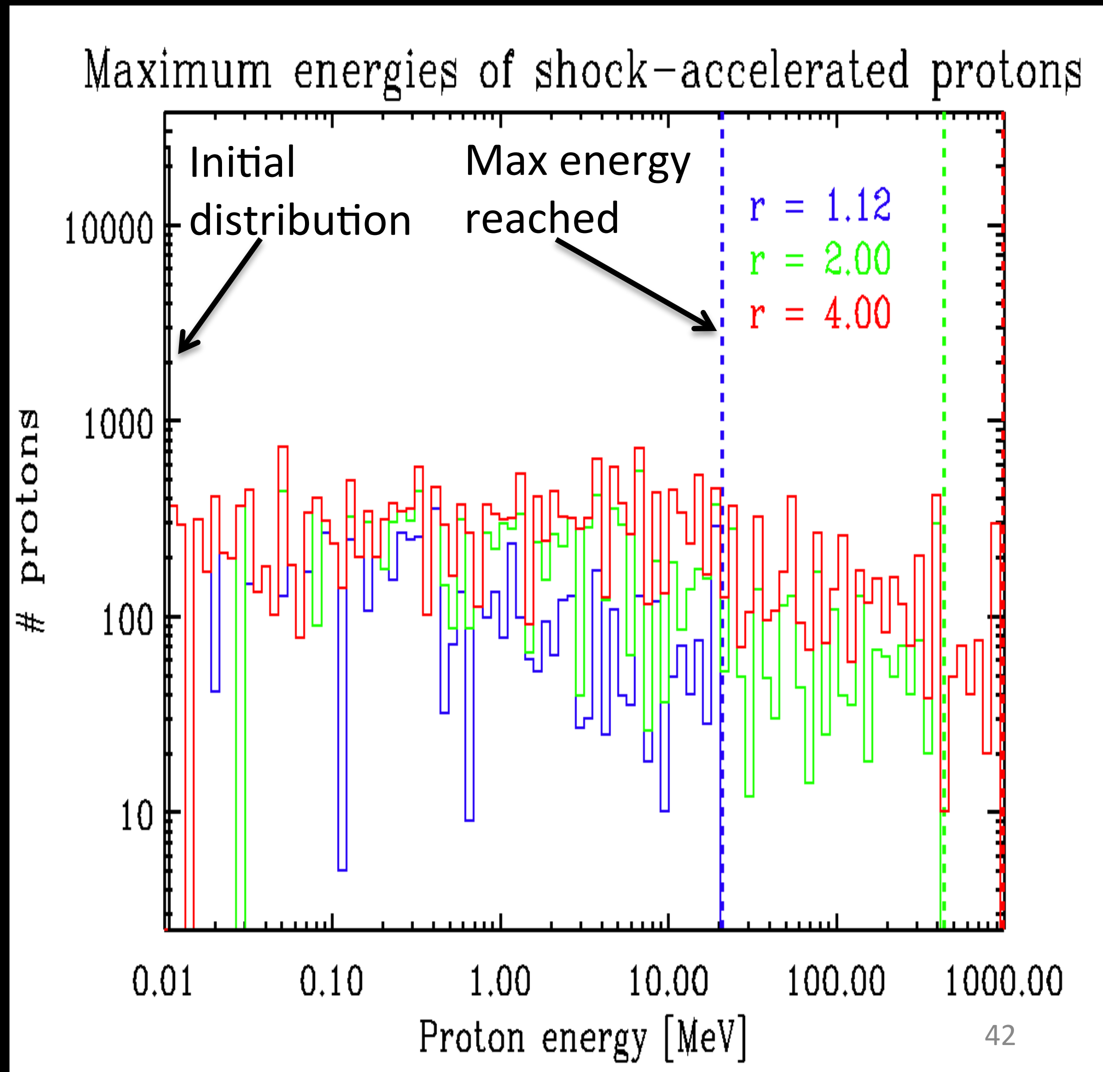
Proton energy gain modeled

Model:
- One 10 keV proton per field line
- Update energy only if shock crosses line
- Ignore solar wind speed – small in low corona

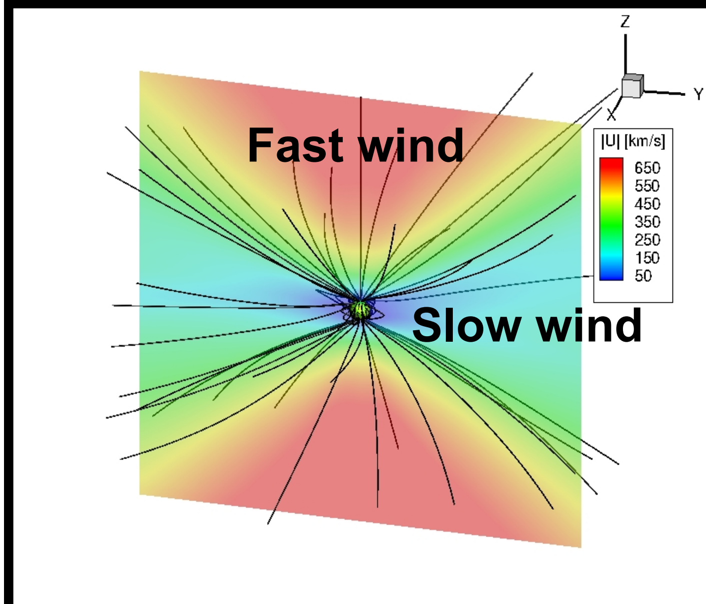
Results:
-Weak shock able to accelerate protons to ~20 MeV in ~5 min.

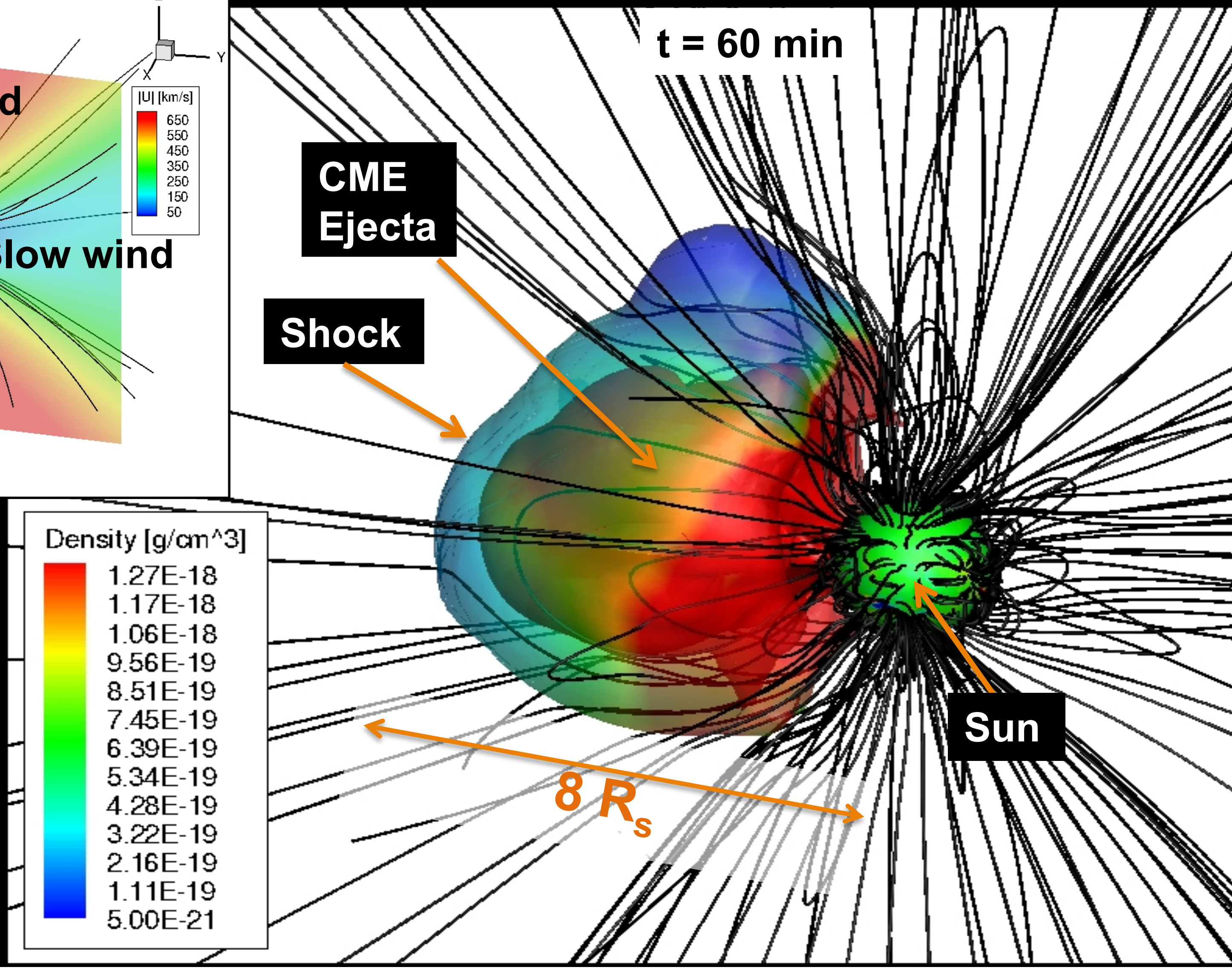
-Consistent with no significant increase of proton fluxes at 1 AU on June 13, 2010

-Stronger shocks should accelerate protons to much higher energies



Coupled simulations of CME and SEP acceleration:
- MHD simulation of CME + kinetic proton simulation

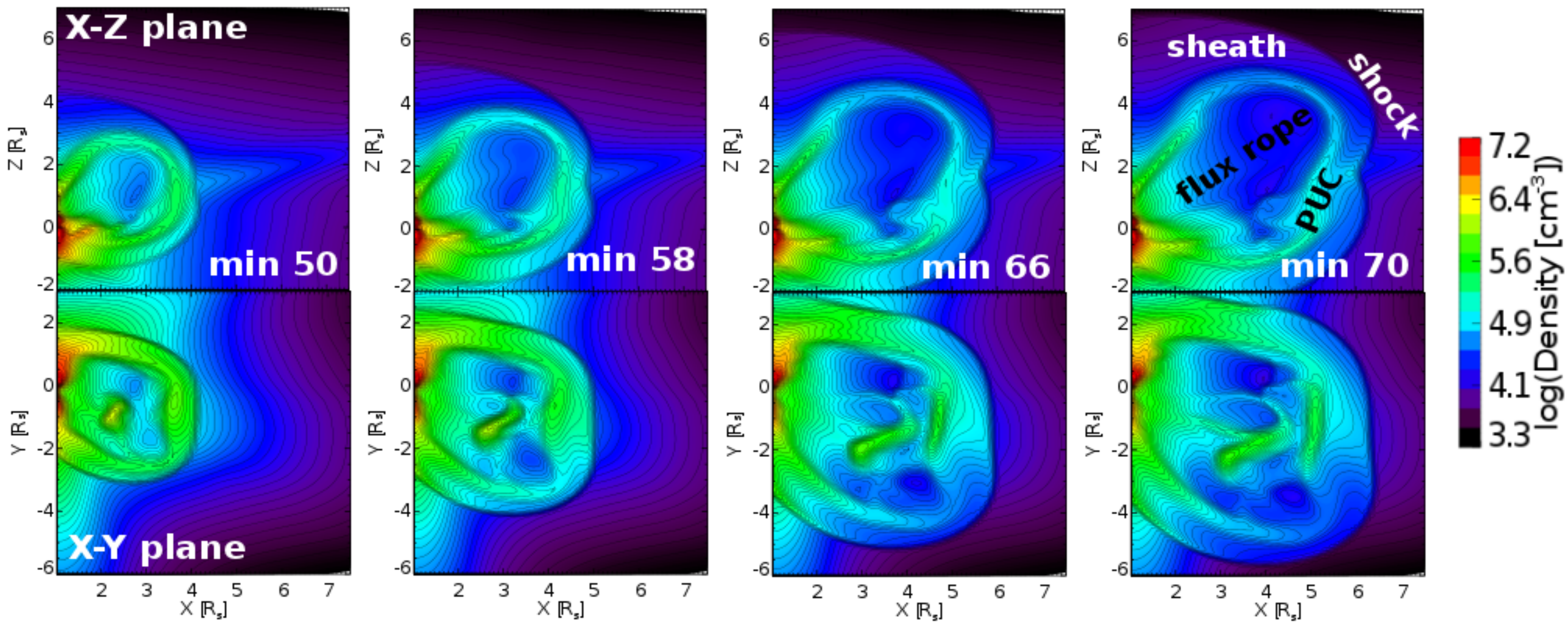




Used results from an MHD simulation of May 13, 2005 CME (provided by Rebekah Evans)

Coronal and CME density evolution

Kozarev et al., 2013

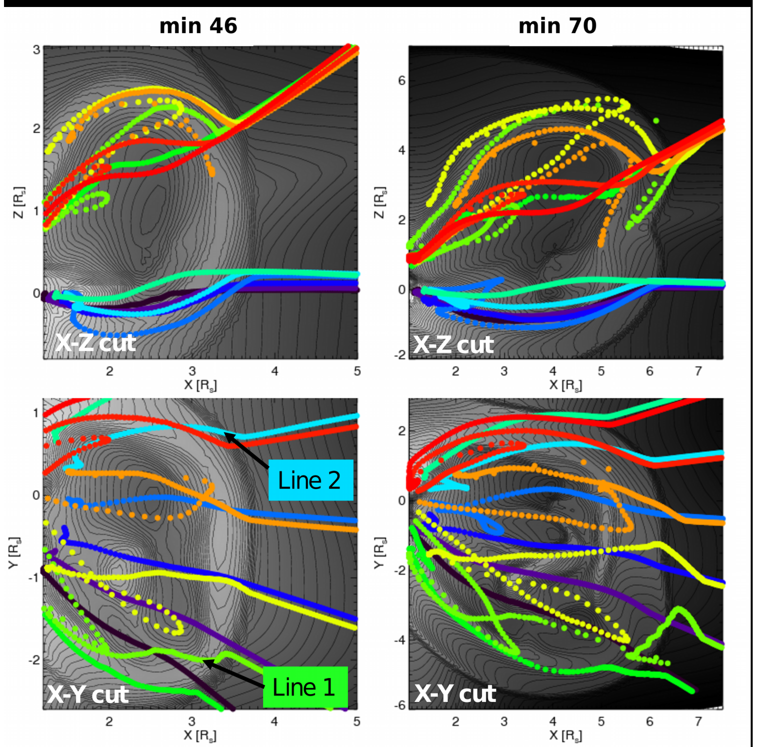


- X-Z and X-Y slices of density evolution over 20 minutes
- Expansion continues preferentially in +Z and –Y directions

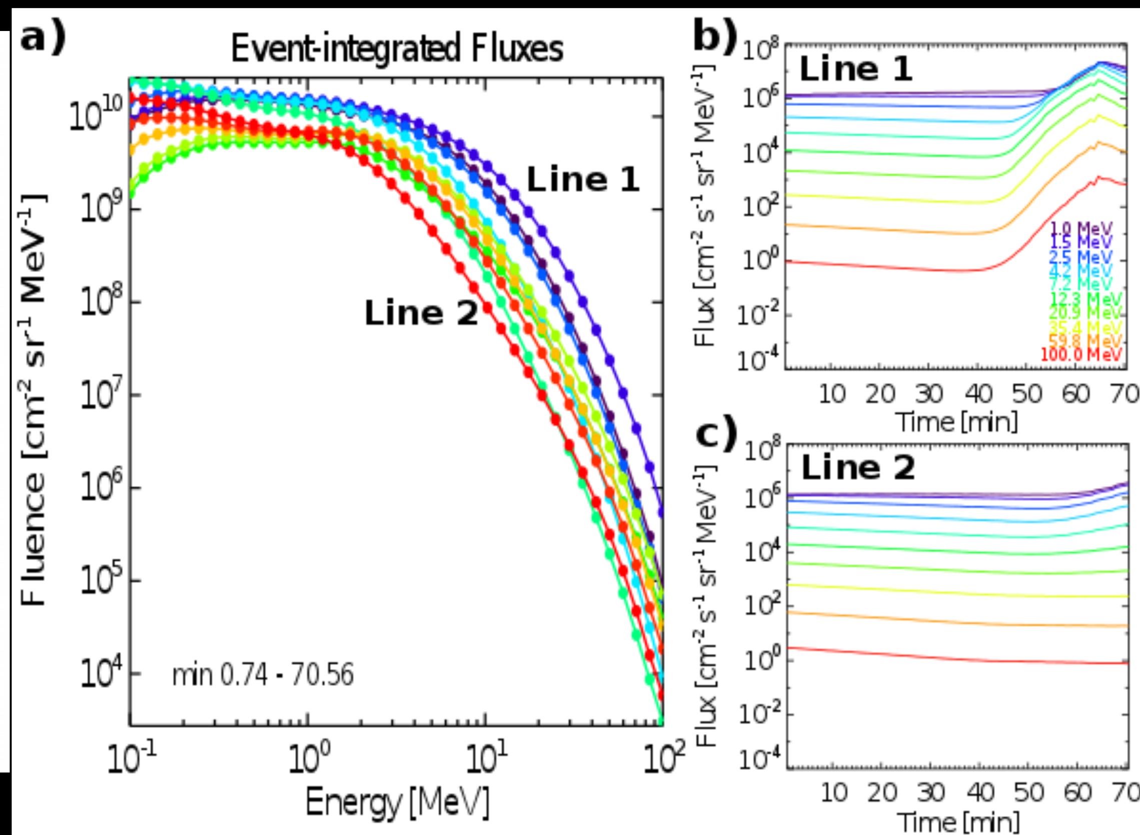
- Sheath and Pile-Up Compression (PUC)
- PUC wrapped closely around flux rope.
- A dimple develops where part of the shock is still inside the streamer

Acceleration along field lines distorted by CME

Kozarev et al., 2013



Density contours + Field lines

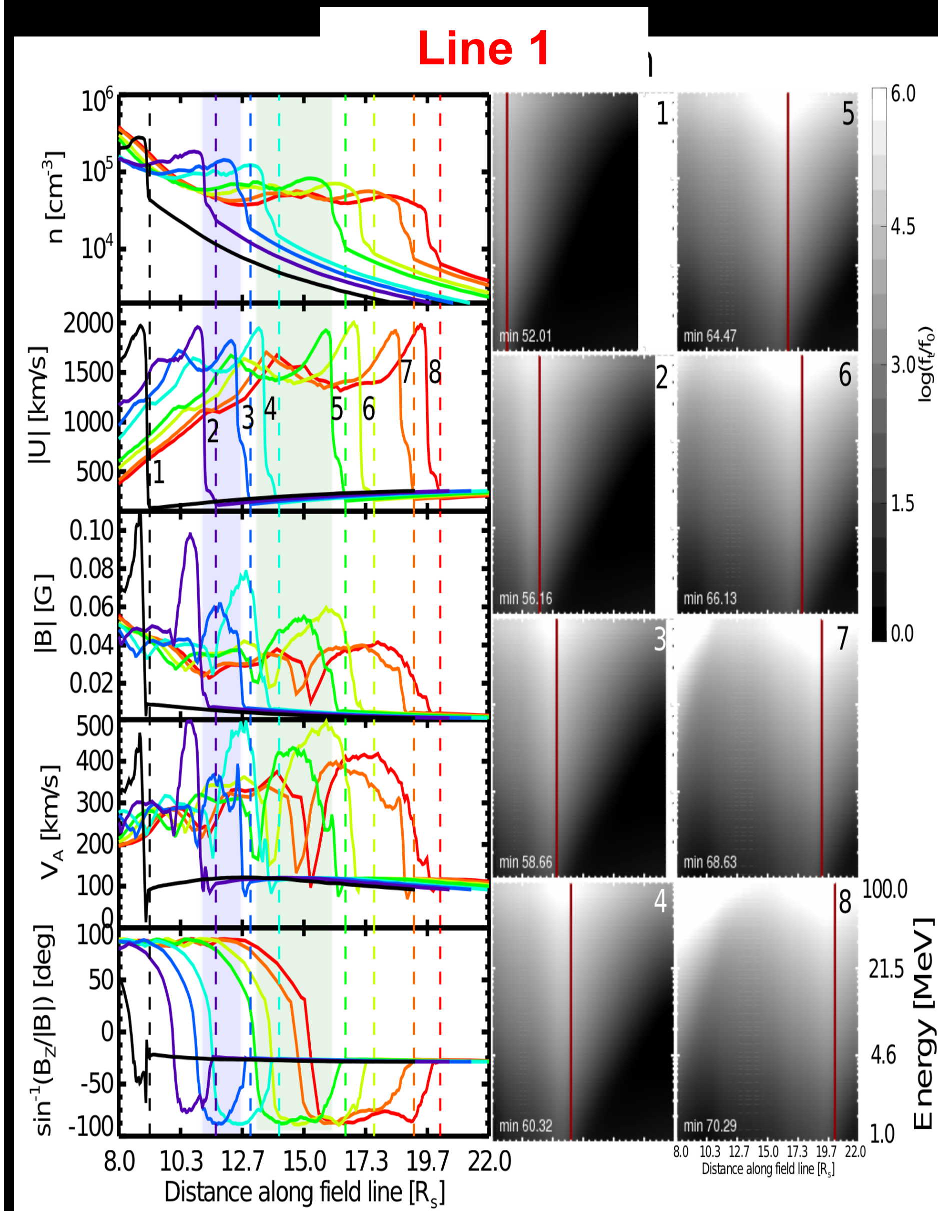


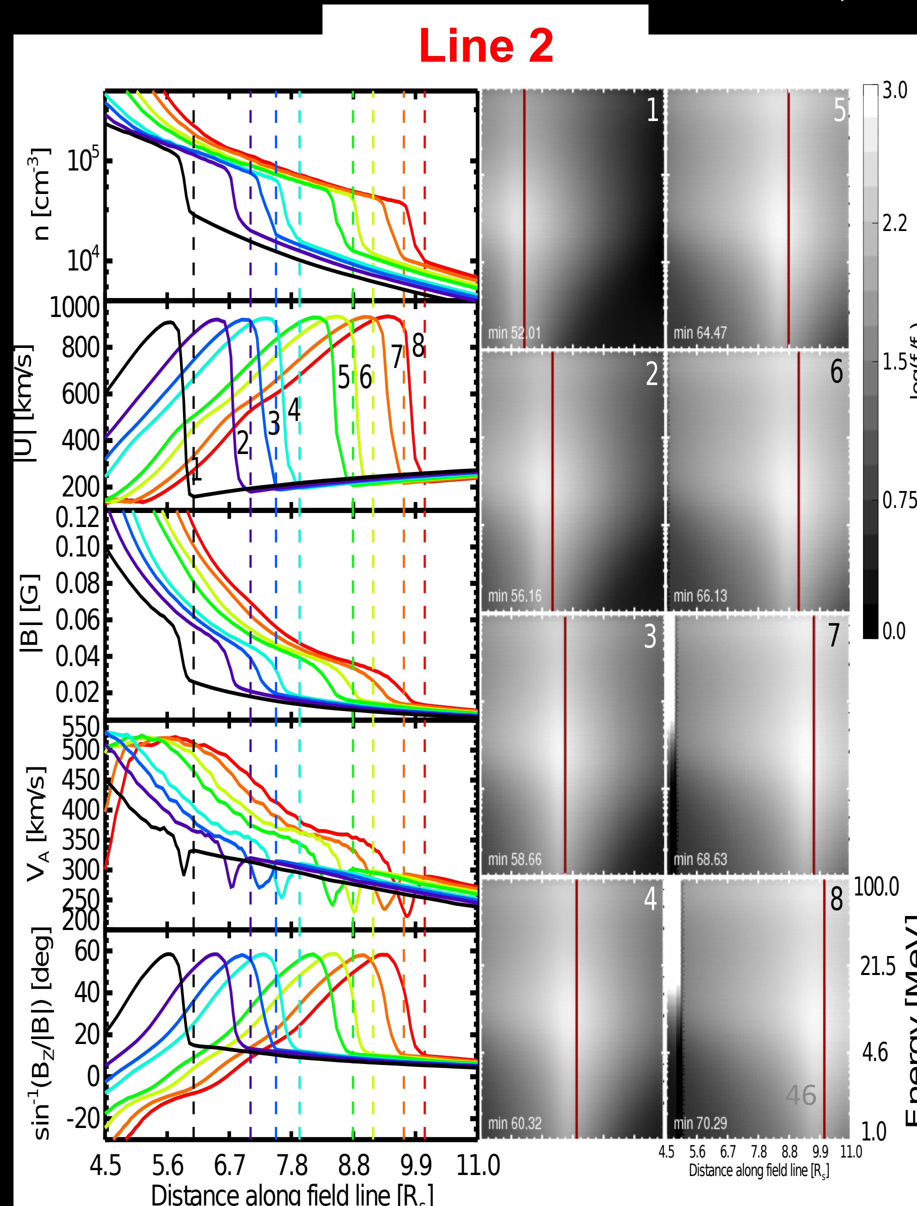
•Look at two lines: one with most acceleration, one with least

• Call them **Line 1** and **Line 2**

Further examine acceleration along two field lines

Kozarev et al., 2013



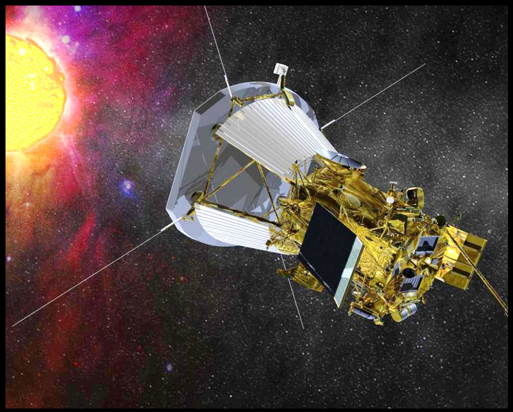


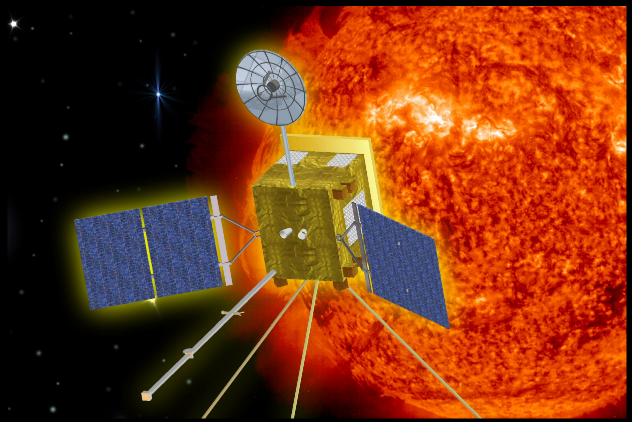
CME-SEP modeling conclusions

- Shape and dynamics of CME governed by coronal conditions
- CME dynamics dictated shock shape and strength
- Varying enhancement of SEP fluxes along the shock front
- Significant acceleration due to pile-up compression region!
- Strong and weak acceleration both present!

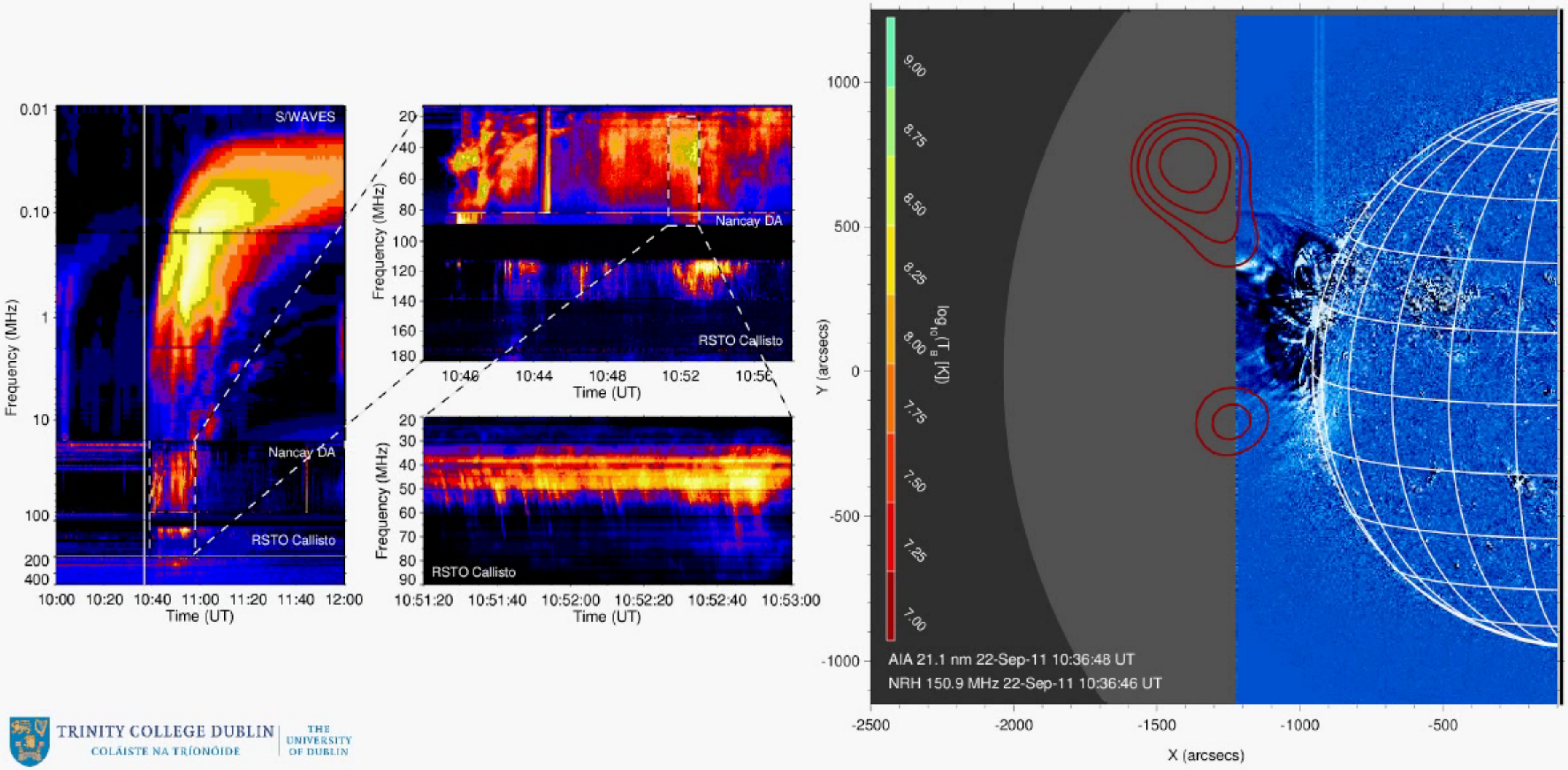
Summary

- The Sun is very dynamic on multiple time scales
- Magnetic field reorganization plays a central role in solar activity
- Shocks, turbulence, and reconnection are important universal phenomena in heliophysics
- Heliophysics is just beginning to study how magnetic field dynamics influences the manifestations of activity
- Future missions such as Solar Probe Plus and Solar Orbiter, will allow for even more insight into solar activity!





Instead of a "Thank You" slide: high-cadence imaging of coronal shocks

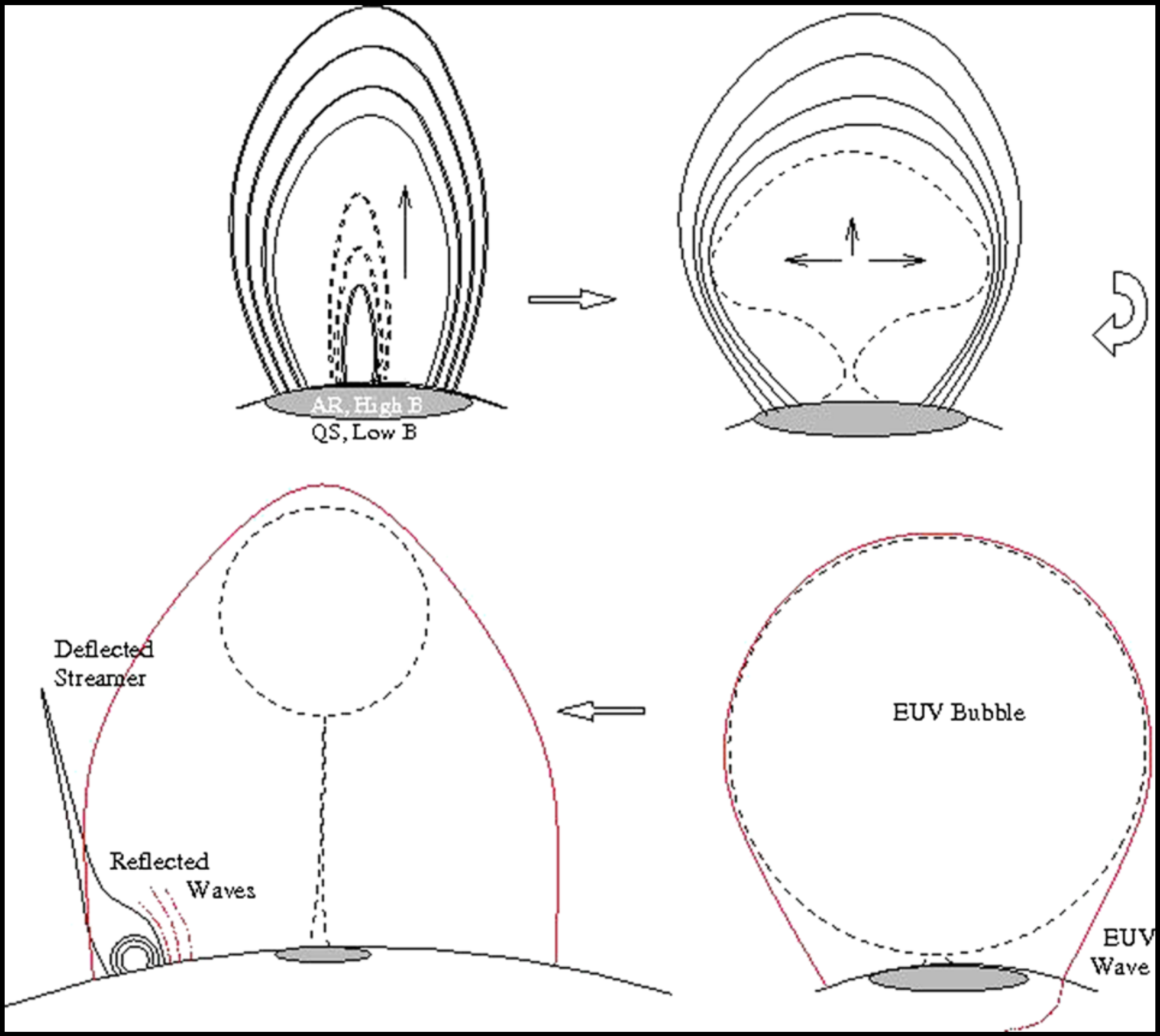


TRINITY COLLEGE DUBLIN COLÁISTE NA TRÍONÓIDE THE UNIVERSITY OF DUBLIN

Carley et al., 2013

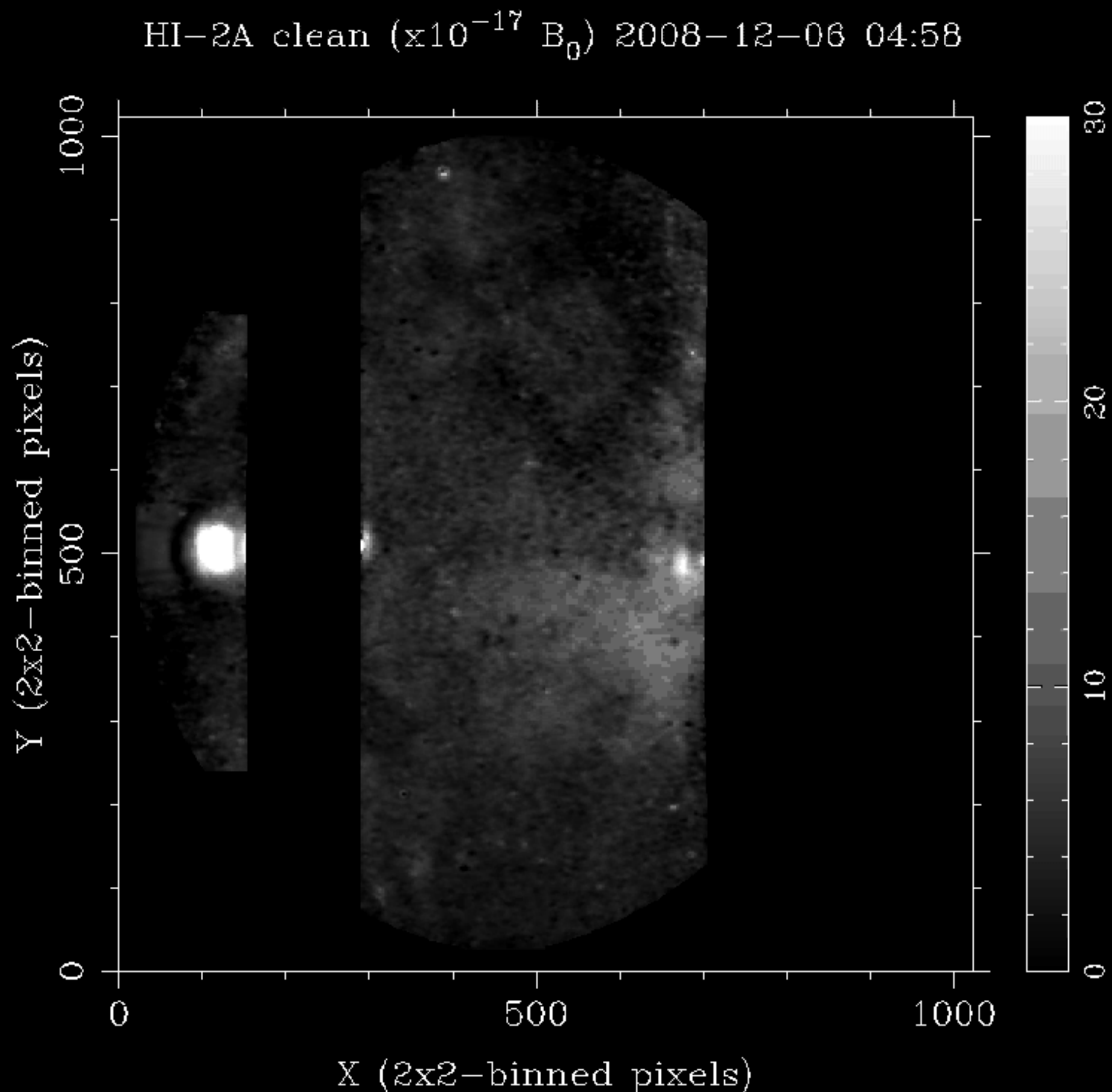
Thank You!

One big picture



Patsourakos & Vourlidas 2012

The Solar Wind



Coronal Waves

Finally, can estimate amount of shock acceleration, using:
-Diffusive Shock Acceleration (DSA) theory
-Measured shock kinematics and derived shock strength
-A model for the coronal magnetic field

Change in momentum in time dt due to DSA acceleration is

$$dp = \frac{V_{sh}^2 p(r-1)dt}{3r\kappa_{xx}}$$

Particle acceleration timescale (Zank et al., 2006)

$$\tau_{acc} = \left(\frac{1}{p}\frac{dp}{dt}\right)^{-1} = \frac{3r\kappa_{xx}}{V_{sh}^2(r-1)}$$

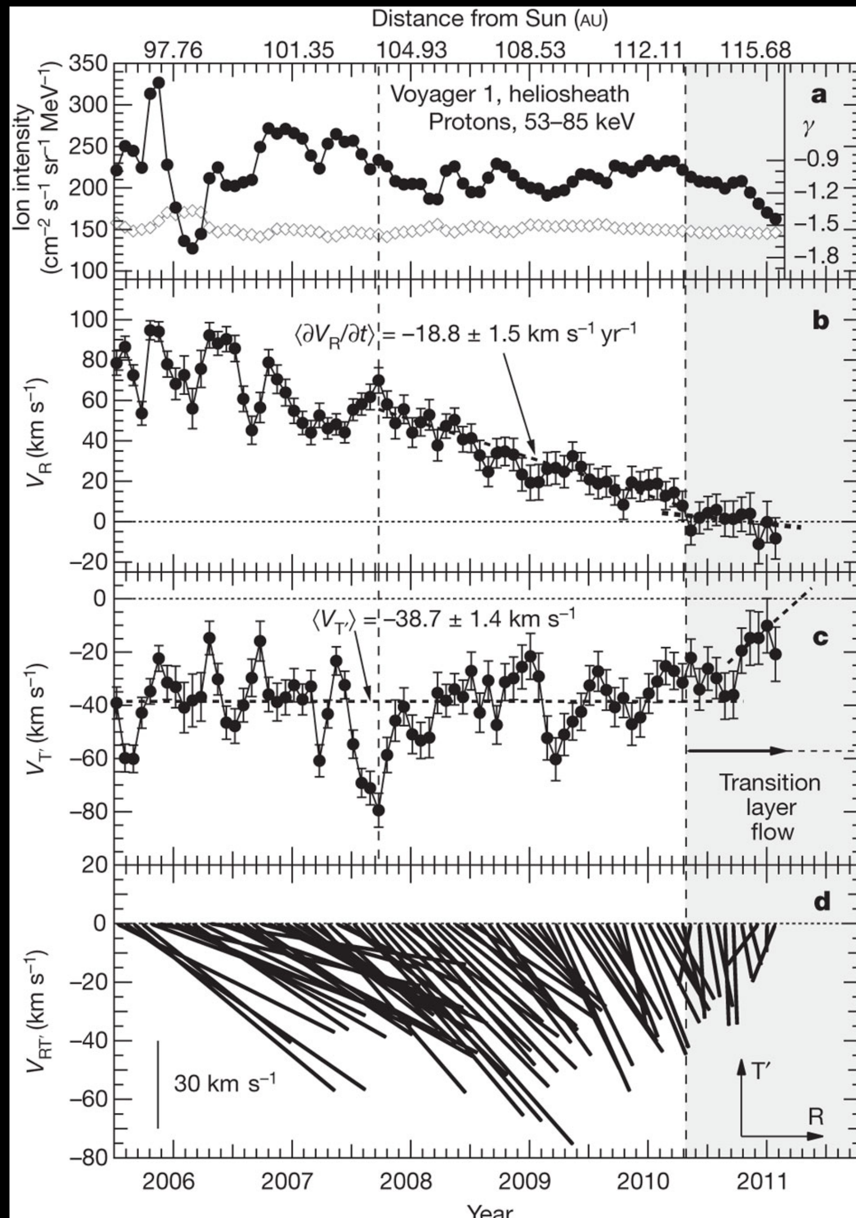
Diffusion coefficient

$$\kappa_{xx} = \kappa_{\|}\cos^2(\theta_{BN}) + \kappa_{\perp}\sin^2(\theta_{BN})$$

$$\kappa_{\|} = v\lambda_{\|}/3 \qquad \kappa_{\perp} = \kappa_{\|}/[1+(\lambda_{\|}/r_g)^2]$$

θ_{BN} is shock normal-field angle, $\lambda_{\|}$ is scattering mean free path, r is density jump

Directional velocity measurements from Voyager 1



SM Krimigis *et al.* *Nature* **474**, 359-361 (2011) doi:10.1038/nature10115

The heliosphere and its boundaries in the general direction of Voyager 1.