Proton Acceleration in Coronal Shocks

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How are SEPs produced?

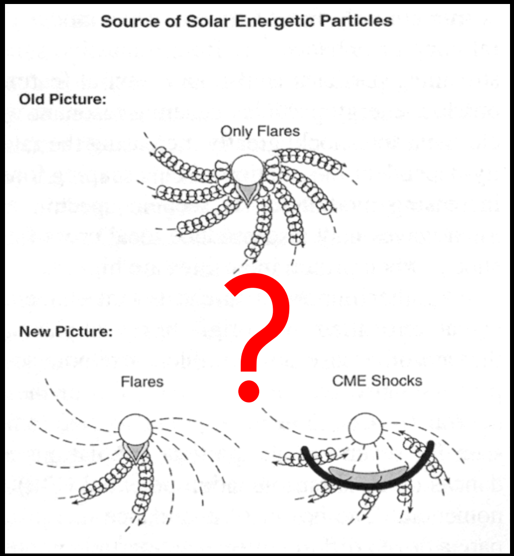
- Solar Energetic Particles (SEP): 1 MeV < E < 500 MeV/nucleon ions;
- Pose significant radiation hazard for astronauts and spacecraft.
- First reported in 1949, initially thought to originate in flares
- Observations in 70s/80s suggested two types:

  impulsive – *small, related to flares, narrow longitudinal ranges*

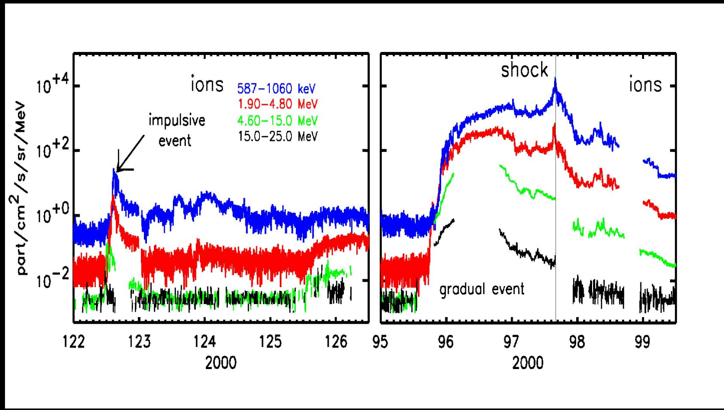
  gradual – *large, related to coronal mass ejection (CME)-driven shocks, wide longitudinal range*

- Newer, better observations suggested two-type picture oversimplified: impulsive signatures seen in gradual events and vice versa
- To add to the confusion:
  1. Shocks can form as low in the corona as 1.2 Rsun (Gopalswamy et al., 2011)
  2. Protons can be accelerated up to 1 GeV in coronal shocks (Kota et al., 2005; Roussev et al., 2004)

  Shocks in corona capable of producing significant SEP fluxes early in events → may masquerade as impulsive events



Reames, 1999



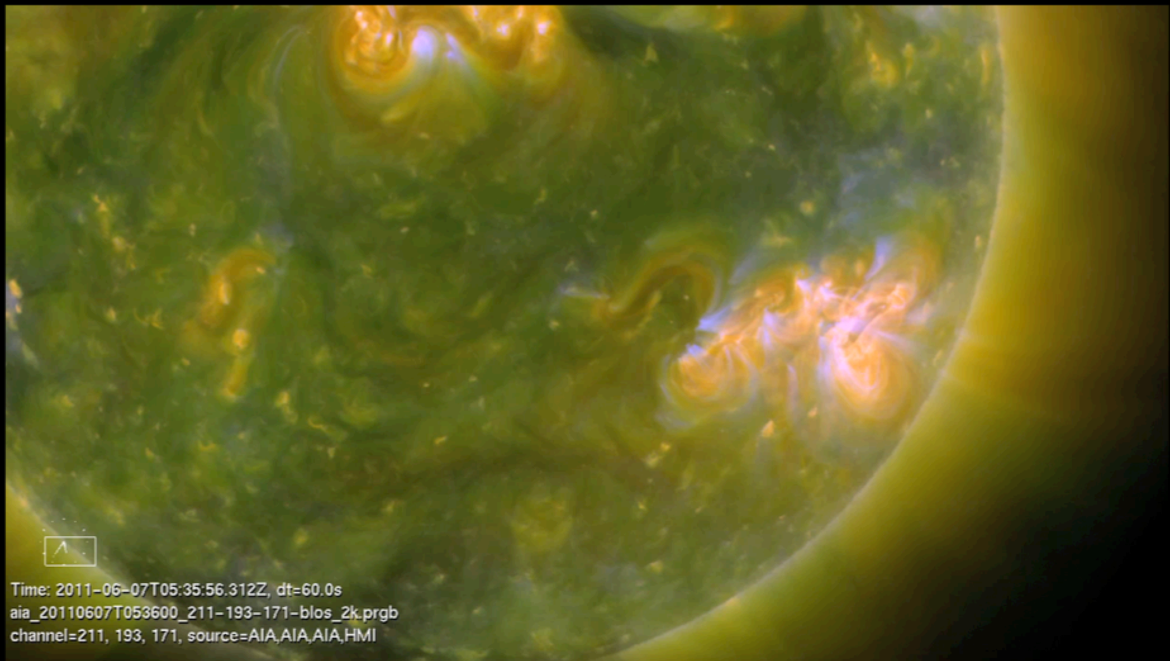
Tylka and Lee, 2006

Questions I am interested in:

1. Can we identify/characterize coronal shocks, estimate acceleration with new, advanced remote observations?

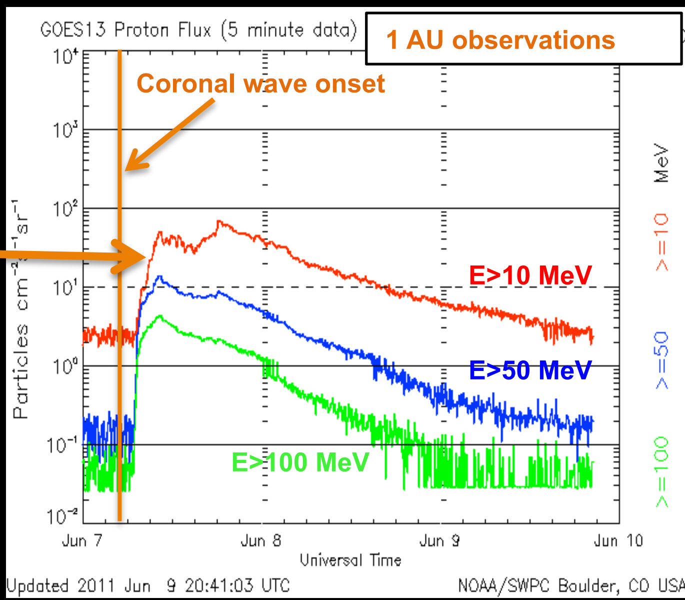
2. Under what conditions do CME-driven coronal shocks accelerate SEPs efficiently?

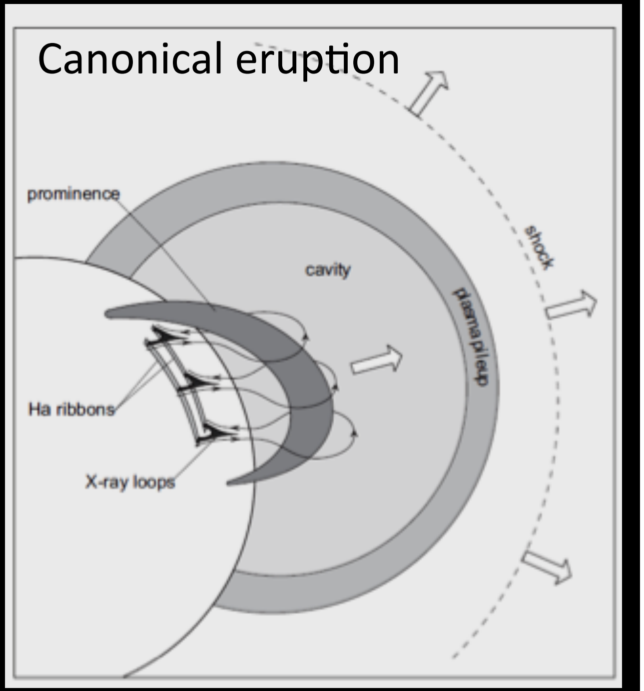
Coronal Mass Ejections and SEPs



Observations:
Atmospheric Imaging Assembly
telescope on
Solar Dynamics Observatory
Spacecraft
Launched in 2010, ultra-high
imaging cadence (12s)
10 UV channels

Shock
or flare?

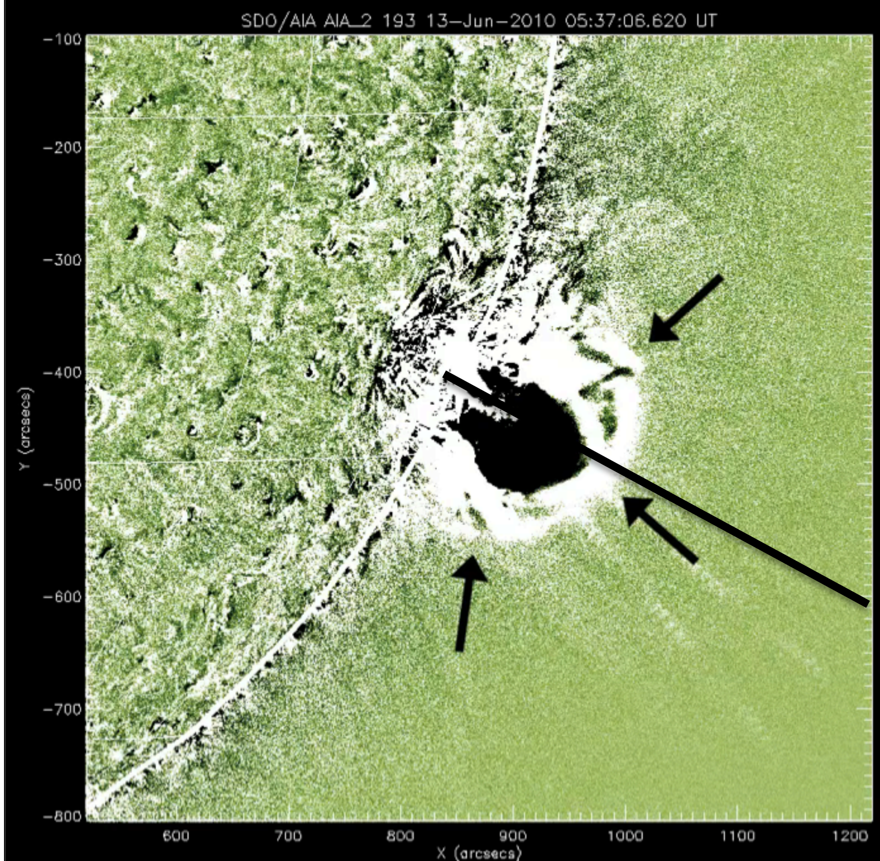




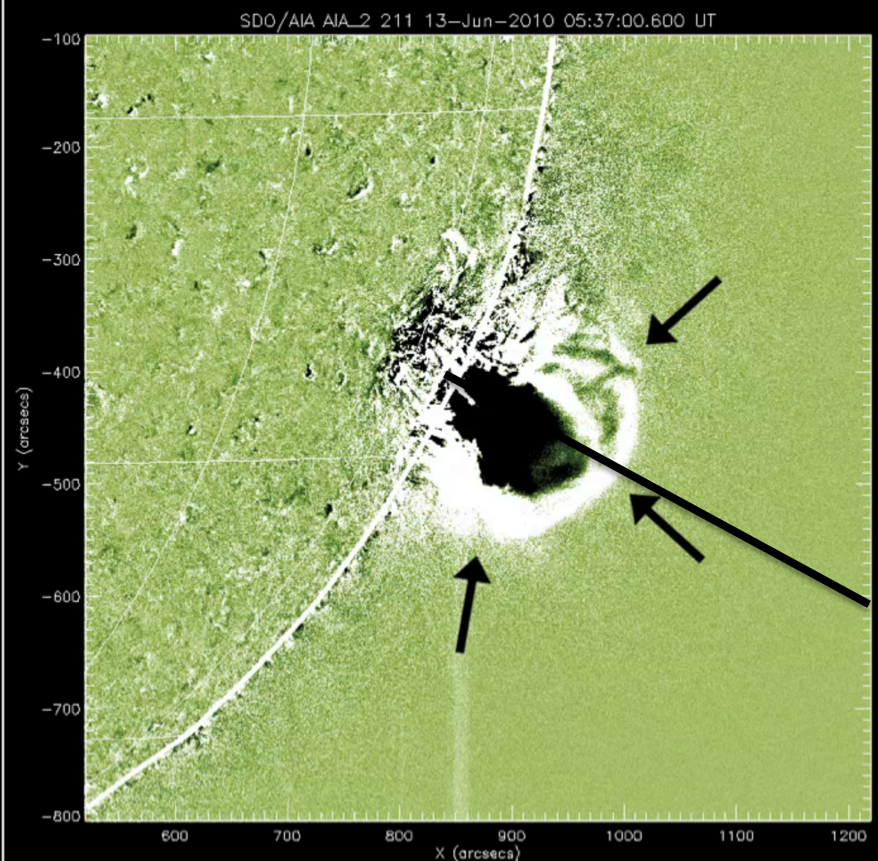
Forbes, 2000

1. Can we use remote coronal observations to identify, characterize shocks and estimate acceleration?

June 13, 2010 event – one of the first AIA events



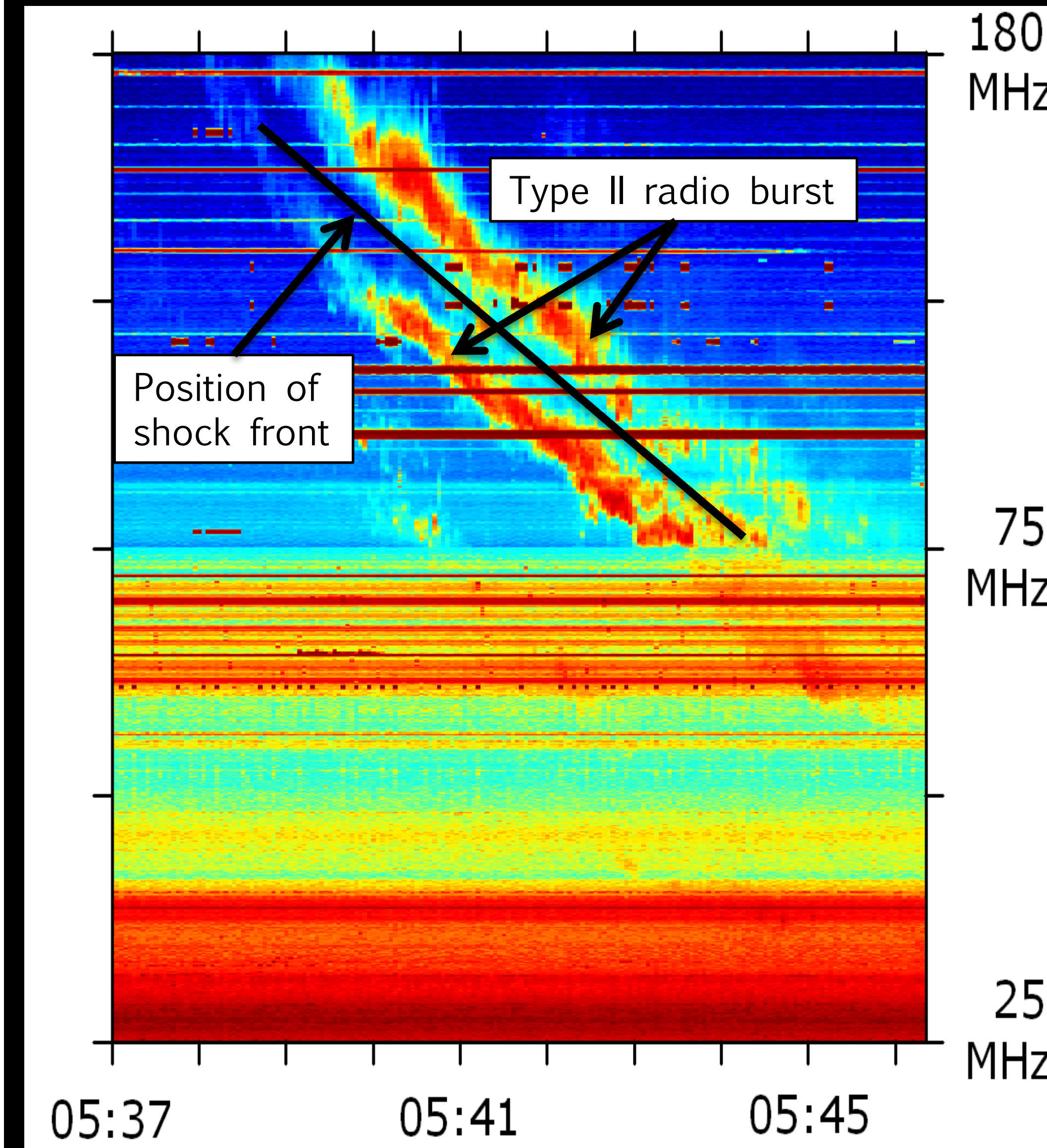
AIA/193 Angstrom



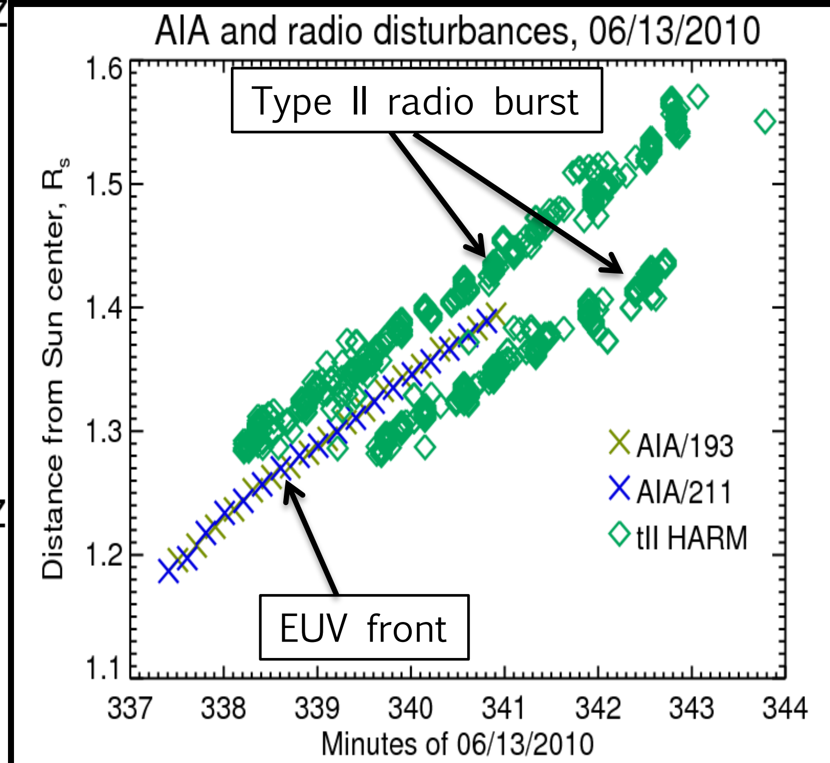
AIA/211 Angstrom

Kozarev et al., 2011

Combining Radio Shock and EUV Wave observations



Kozarev et al., 2011



- Drifting radio bursts signify electron beams accelerated in traveling shocks
- Spatial overlap of observed EUV wave front and radio shock
- Radial speeds of ~650 km/s

Change in density and/or temperature

Estimate plasma density/temperature change in wave sheath from multi-temperature AIA EUV observations!

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

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

Kozarev et al., 2011

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

-Performed DEM calculations (Weber et al., 2005) from six-channel AIA observations

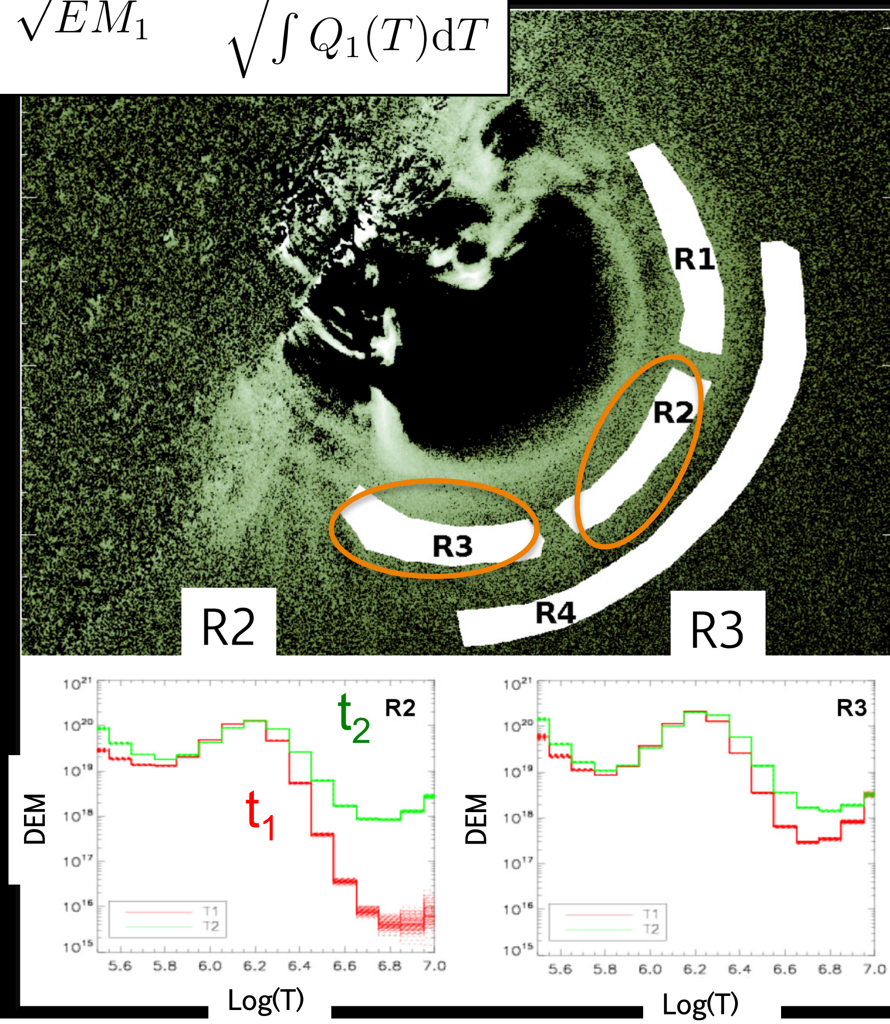
-No significant change in temperature

- Obtained density before/during ratio r (t_1 before event, t_2 during event)

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 behind front suggests wave is a weak shock! Confirms kinematics.



Estimate proton momentum gain from Diffusive Shock Acceleration (DSA) theory

Use:

- Measured shock kinematics and derived shock strength
- Coronal potential magnetic field model
- DSA involves first/second-order Fermi acceleration at shocks
- From DSA, momentum change in time *dt* is (Zank et al., 2006):

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

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

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

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

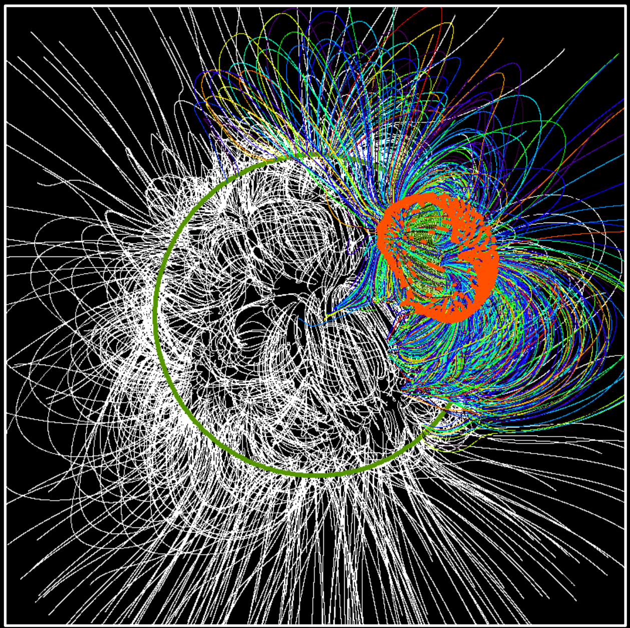
r is density jump
k_{xx} is diffusion coefficient
θ_{BN} is shock-field angle
$\lambda_{||}$ is scattering mean free path
r_g is particle gyroradius

Assume reasonable $\lambda_{||}$
Still need θ_{BN}:
Very important for shock acceleration efficiency

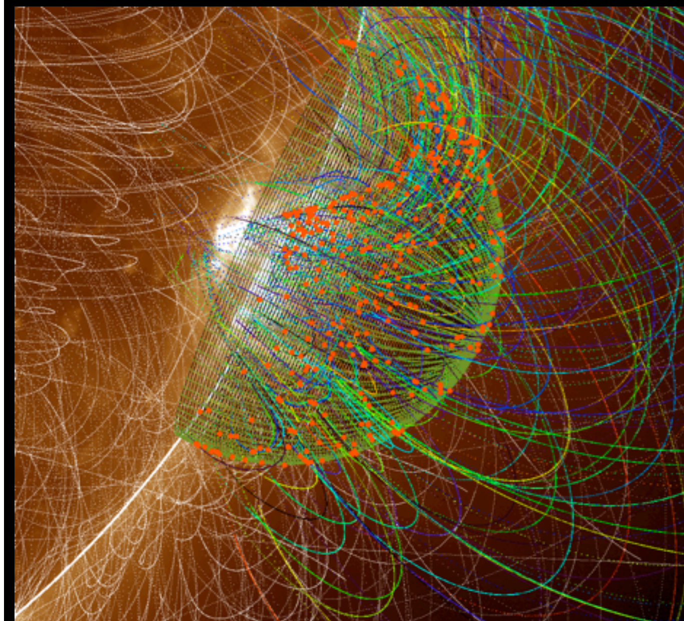
Combine:

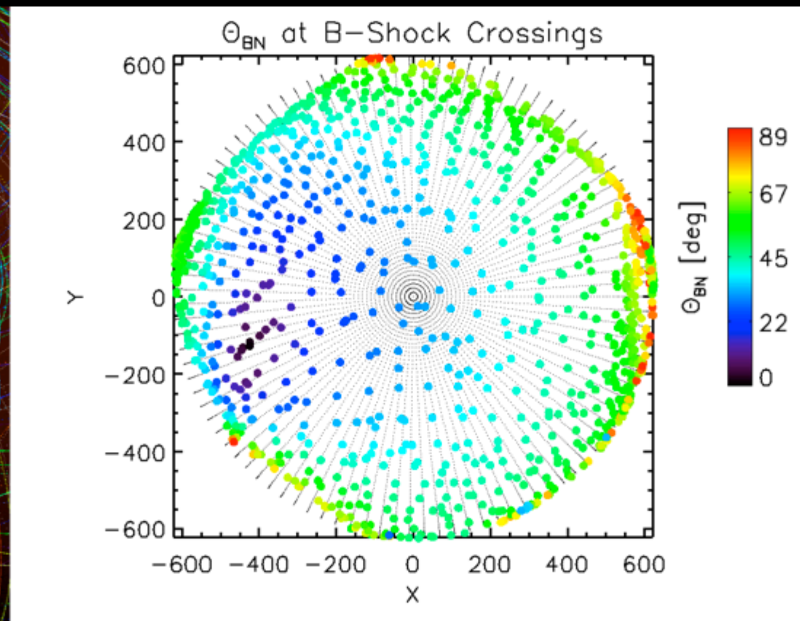
- Coronal potential B-field model from photospheric magnetograms (Schrijver & De Rosa, 2003)

- Geometric spherical shock front model from observed EUV wave kinematics (Kozarev et al., 2012)



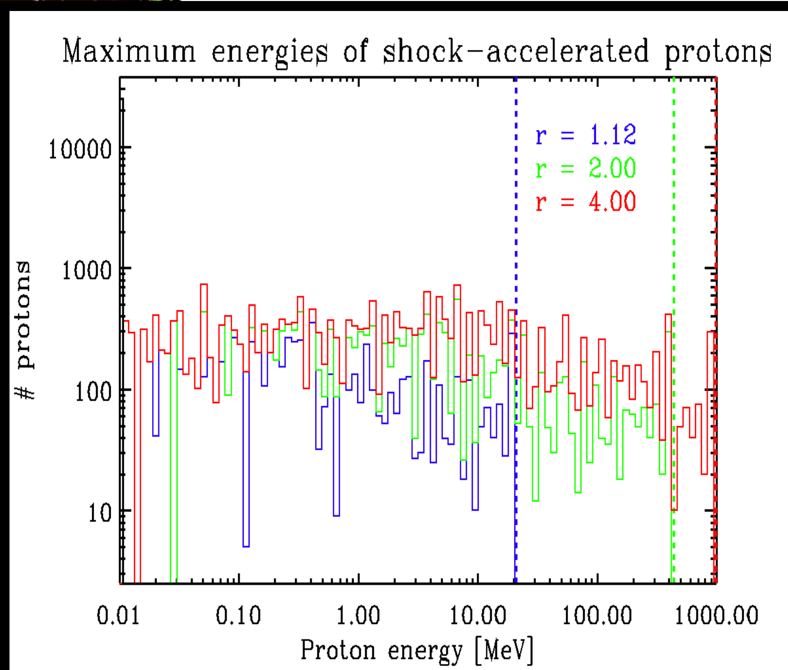
Time-Dependent Shock-Field Crossing Angles





Time-dependent θ_{BN} maps also potentially useful for interpretation of radio observations

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



Kozarev et al., 2012

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

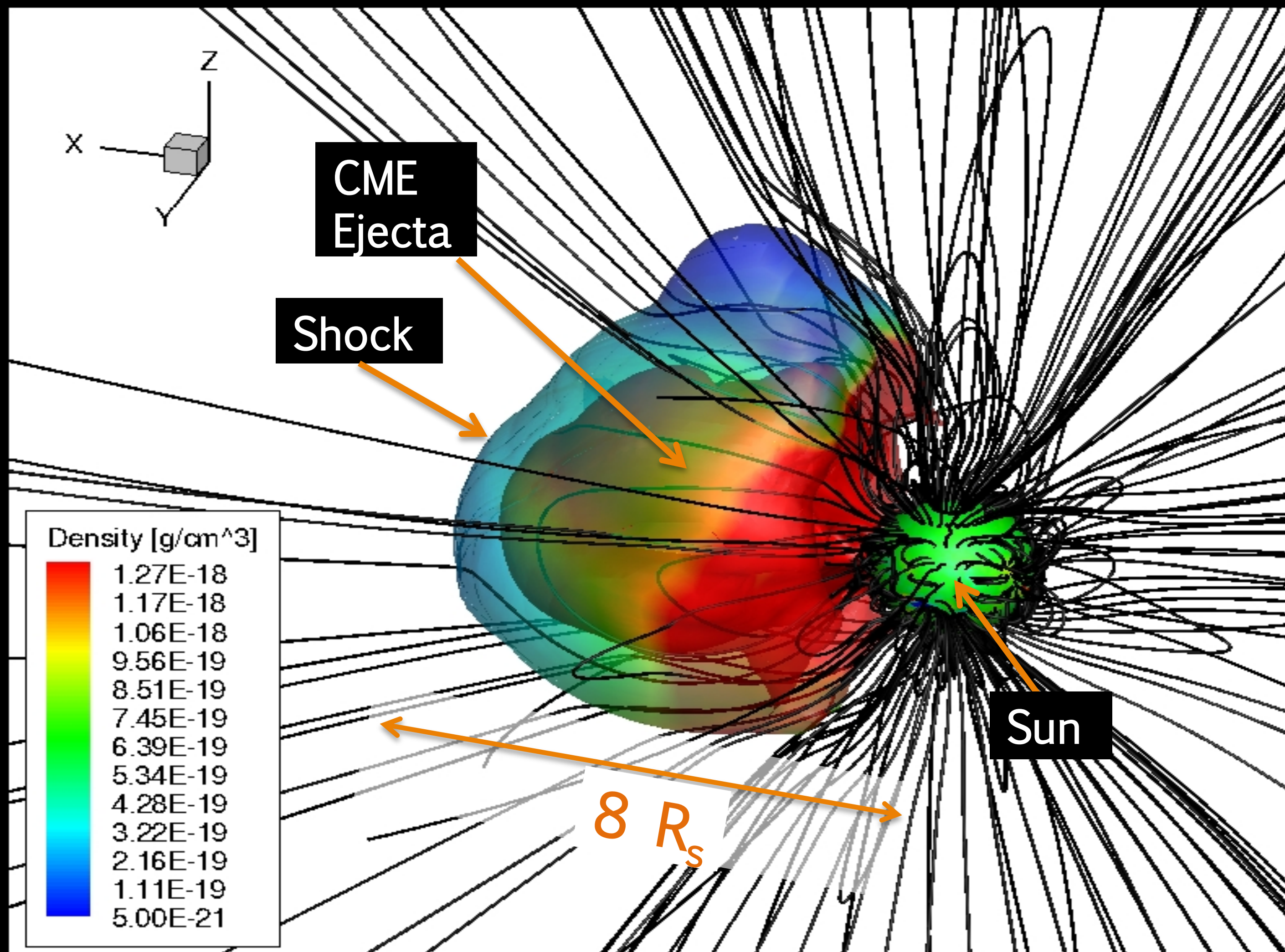
-Faster shocks should accelerate protons to much higher energies

2. Under what conditions do CME-driven coronal shocks accelerate SEPs efficiently?

Numerical simulations: CME evolution and SEP acceleration

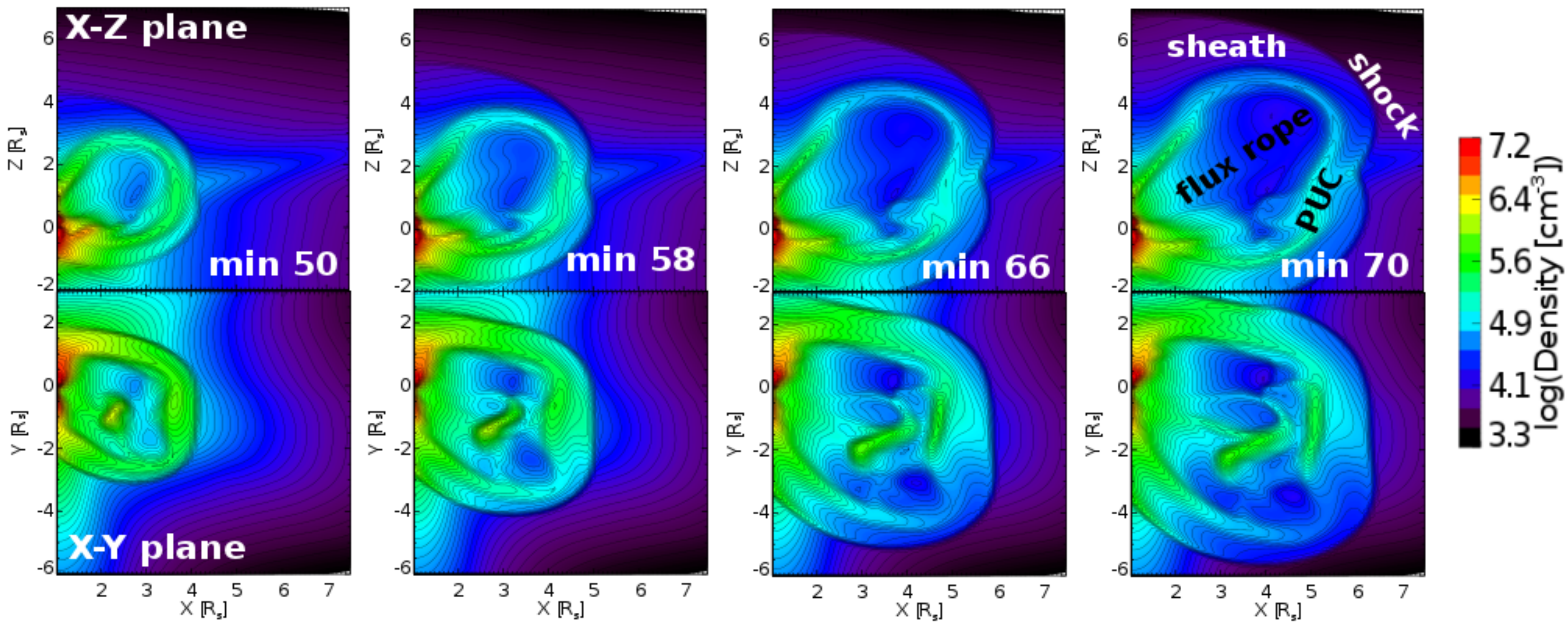
MHD simulation of May 13, 2005 CME

(provided by Rebekah Evans)



Coronal and CME density evolution

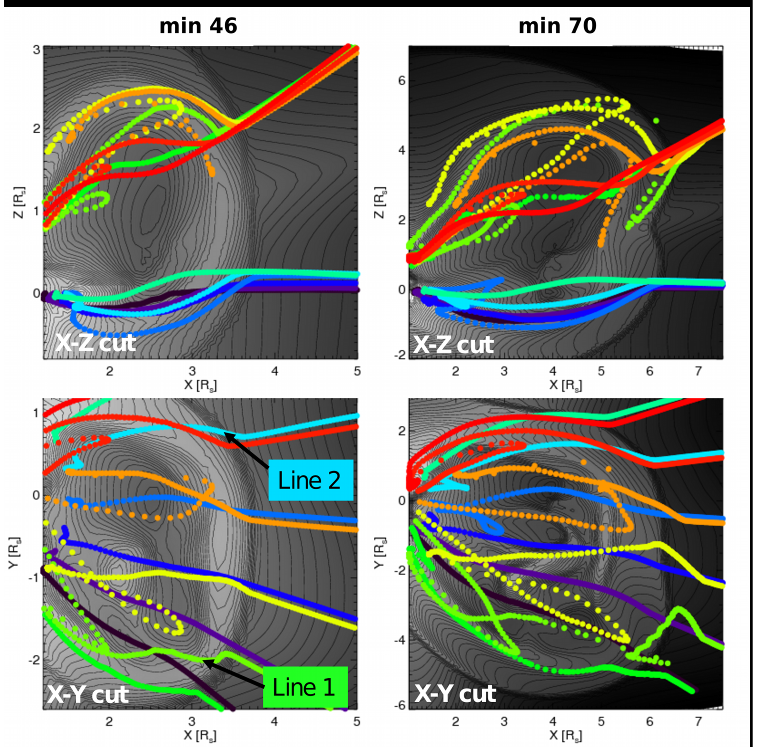
Kozarev et al., 2013



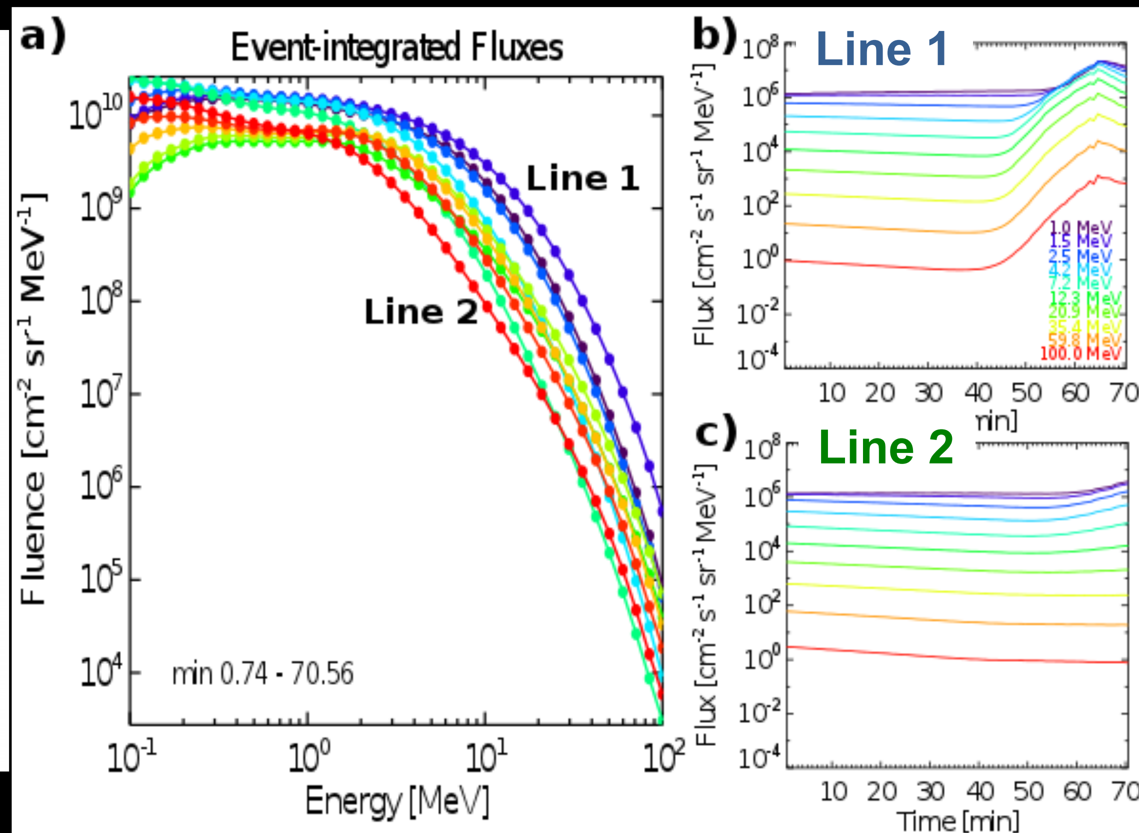
- X-Z and X-Y slices of density evolution over 20 minutes
- Expansion preferentially in +Z and –Y directions
- Sheath and Pile-Up Compression (PUC)
- PUC wrapped closely around flux rope.
- A dimple develops where part of the shock is still inside the streamer

Acceleration along field lines distorted by CME

Kozarev et al., 2013



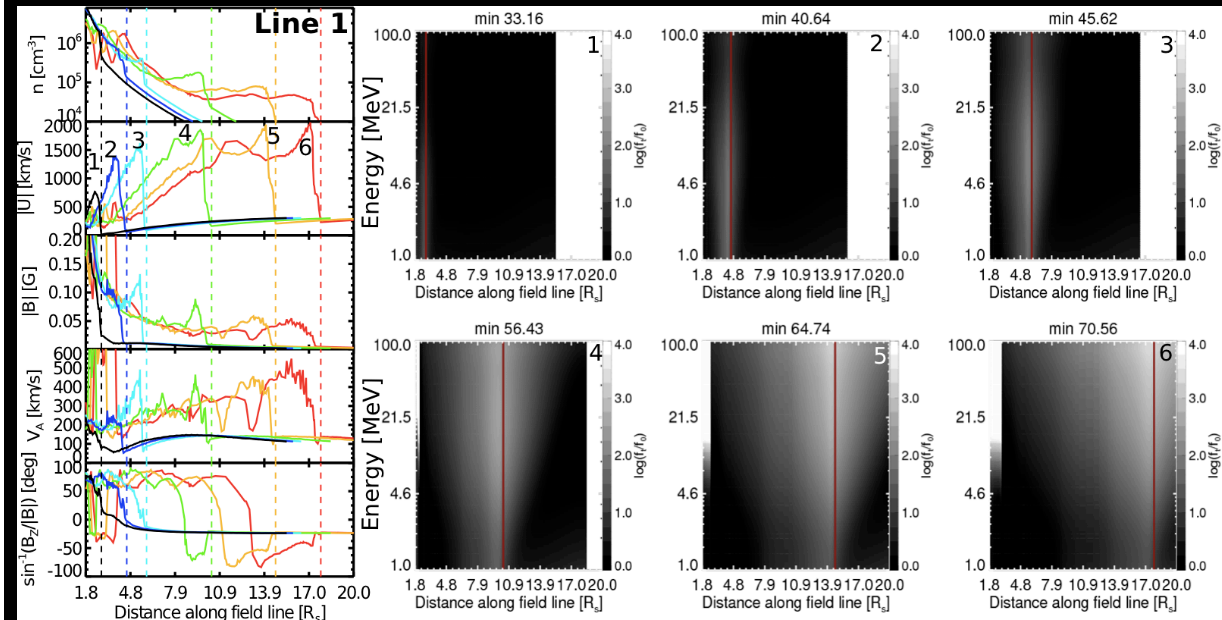
Density contours + Field lines



•Look at two lines: one with most acceleration (Line 1), one with least (Line 2)

Further examine acceleration along two field lines

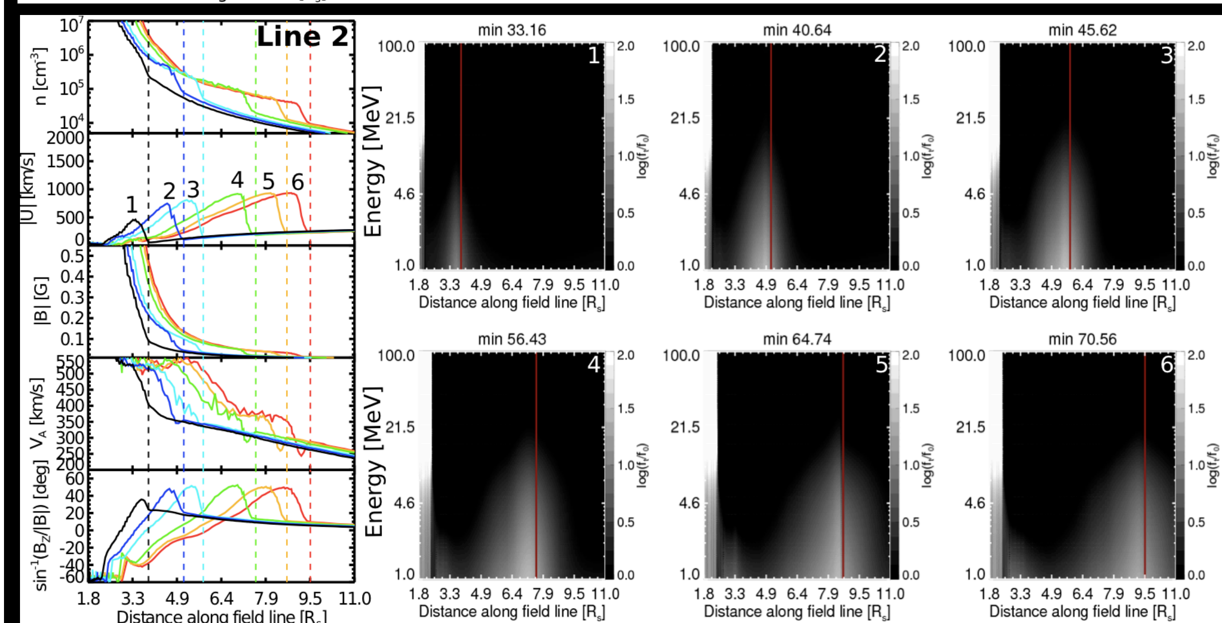
Kozarev et al., 2013



Line 1

-Acceleration mostly near shock

-Some of it could be due to pile-up compression region behind shock



Line 2

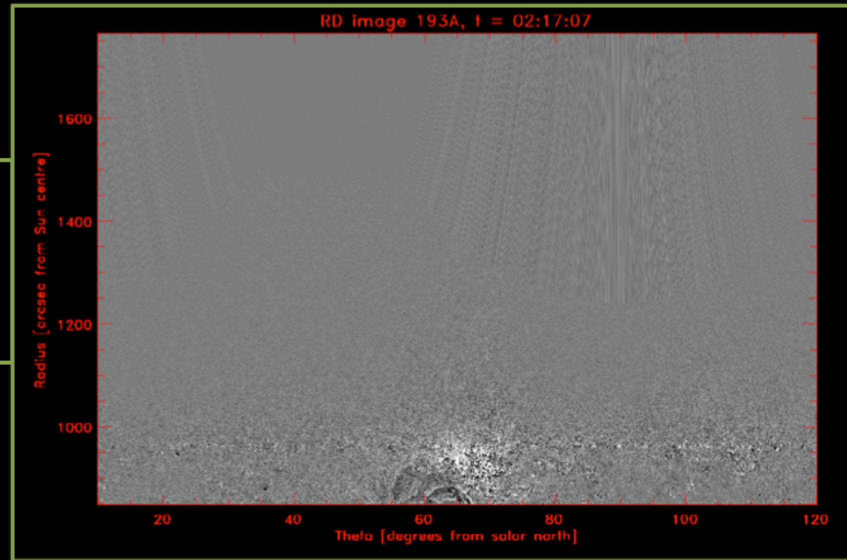
-Efficient acceleration along line in fast-expanding CME region

-Much less acceleration in region of slower expansion

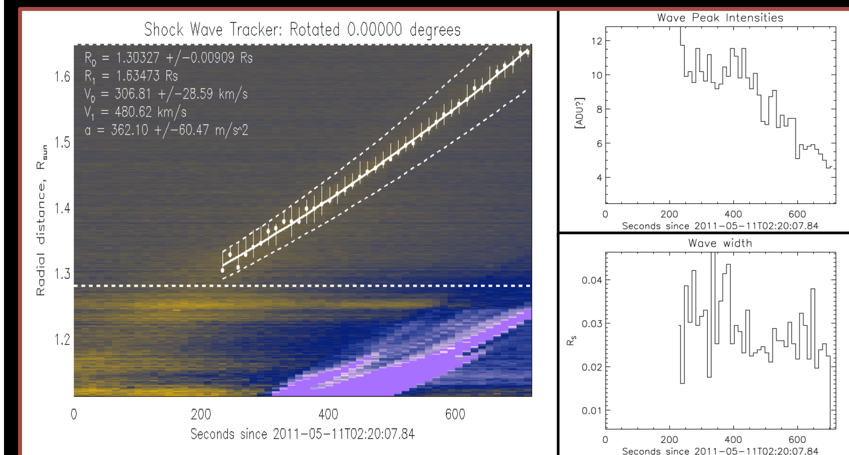
-Detailed shock dynamics crucial to modeling acceleration properly!

Current Efforts:

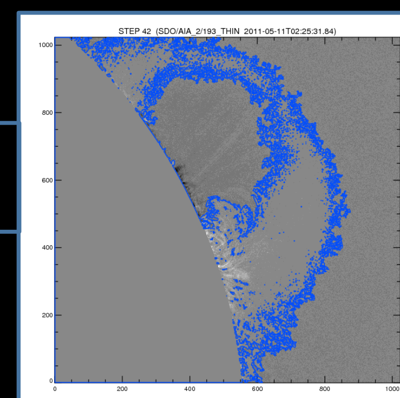
Develop and combine tools for better EUV wave characterization → better acceleration estimation



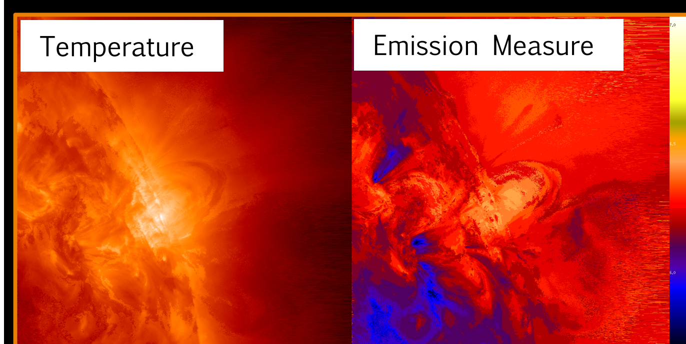
Use deprojected AIA data to study lateral speeds, relation between overexpansion of erupting filaments/loops and wave morphology (width intensity) related to plasma pile-up



Use improved radial kinematic measurements to study wave evolution and characteristics



Develop and improve algorithms for automatic detection and tracking of waves, in order to improve the geometric shock front model and θ_{BN} estimation



Calculate and use time-dependent DEM maps to study change in temperature and density → shock evolution and strength