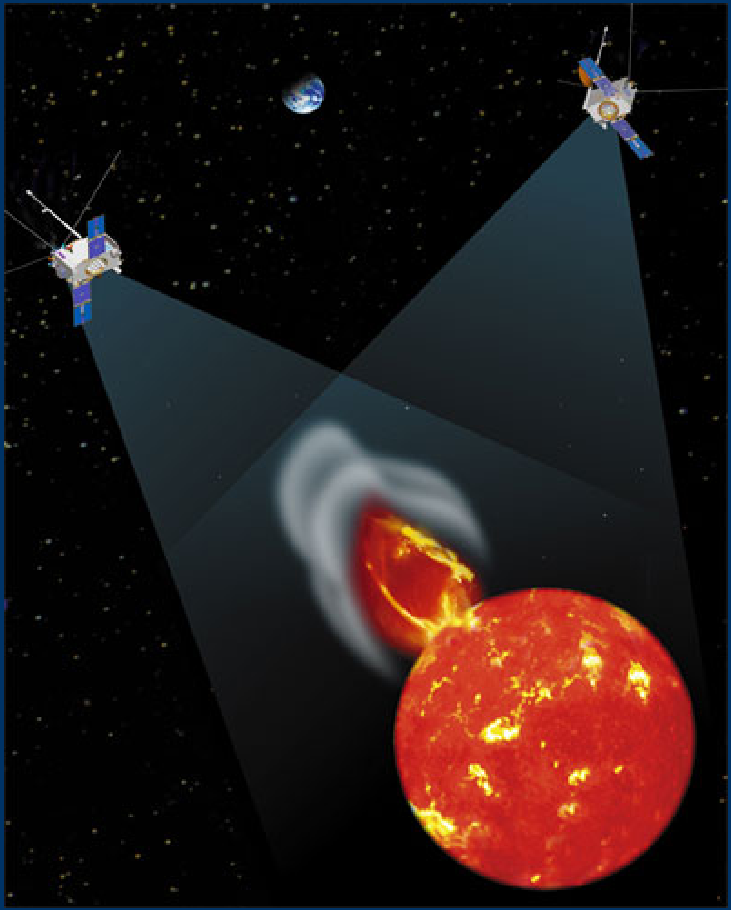
Reconstructing CMEs with Coordinated Imaging and In Situ Observations: Global Structure, Kinematics, and Implications for Space Weather Forecasting



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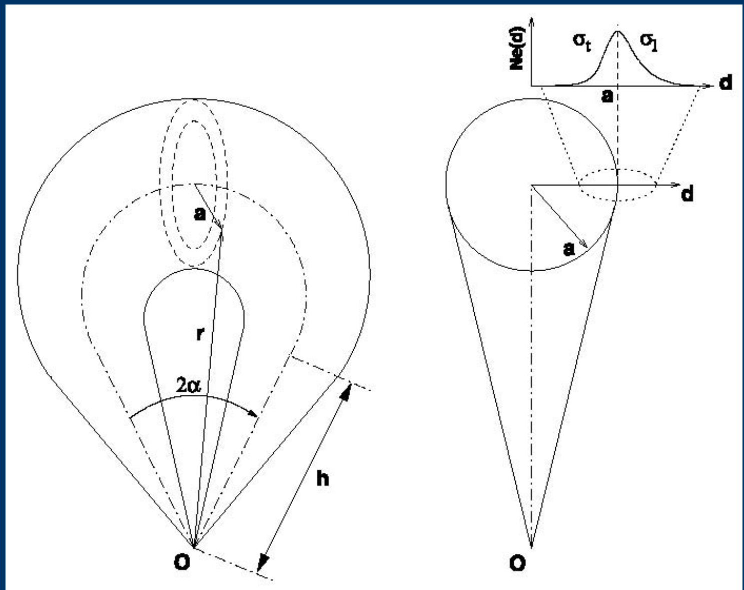
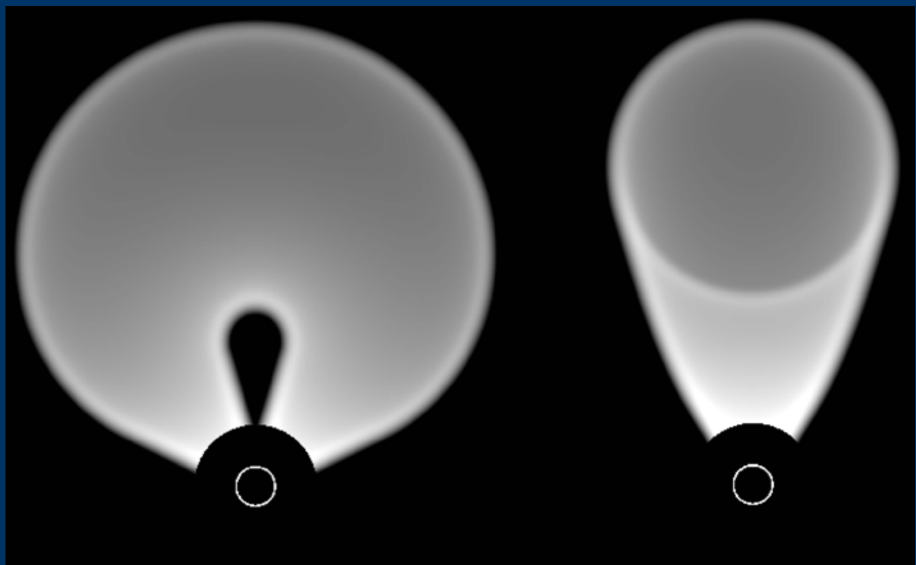
Outline

- What properties can we compare between imaging observations and in situ measurements?
- How do we determine the properties and make the comparison?
- What can we learn from the comparison for CME research and space weather forecasting?

Forward modeling of CME images



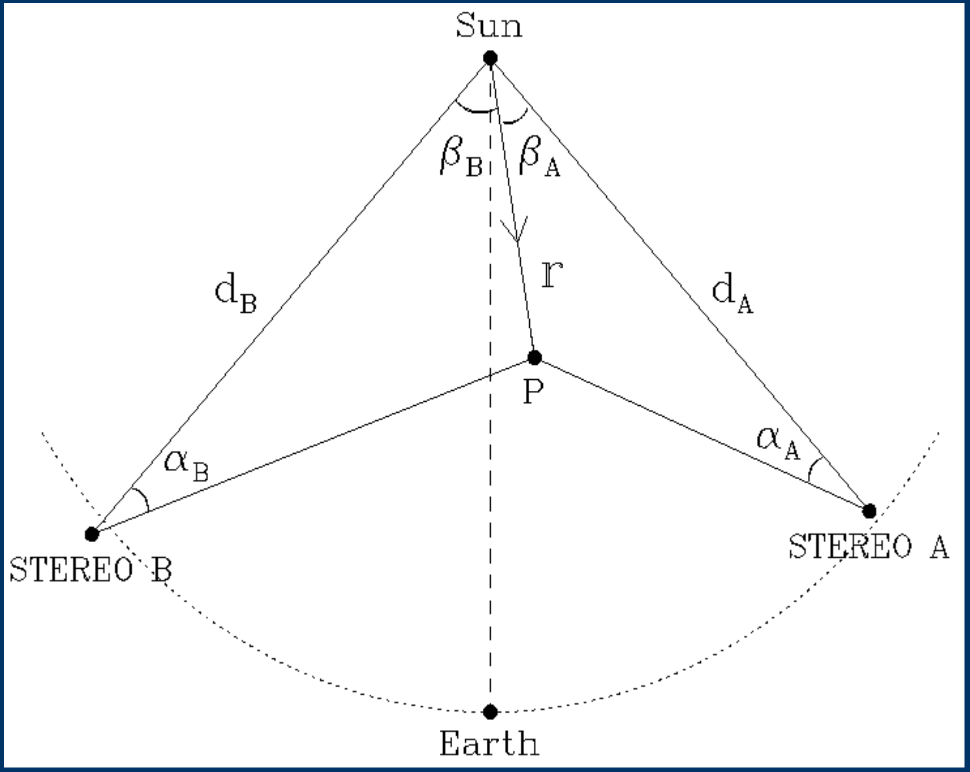


- Geometric model with a rope morphology (density only);
- Calculate Thomson scattering and compare with images observed by STEREO A, B and SOHO;
- Can give the global structure of CMEs including rope orientation and propagation direction, which can then be compared with in situ measurements.

Thernisien et al., ApJ, 2006

Geometric triangulation of imaging observations

Liu et al., ApJ, 2010a, 2010b

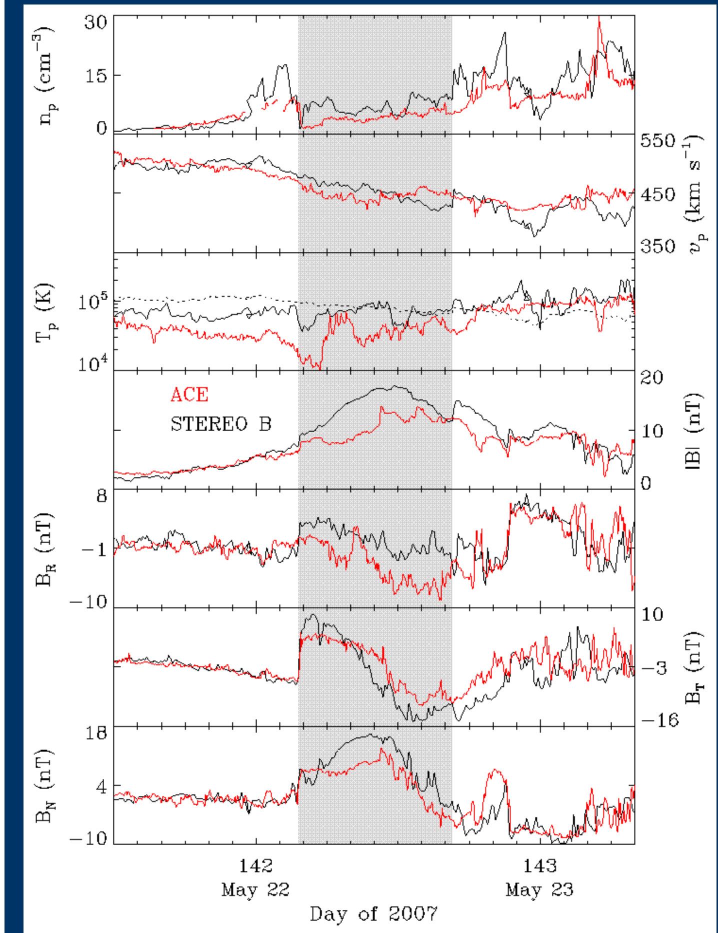


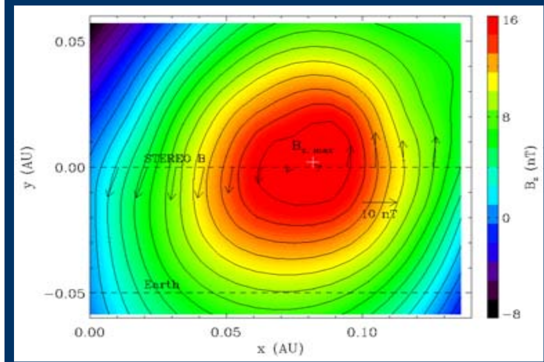
$$\begin{cases} \dfrac{r\sin(\alpha_A+\beta_A)}{\sin\alpha_A} = d_A \\ \dfrac{r\sin(\alpha_B+\beta_B)}{\sin\alpha_B} = d_B \\ \beta_A+\beta_B=\gamma \end{cases} \Rightarrow$$

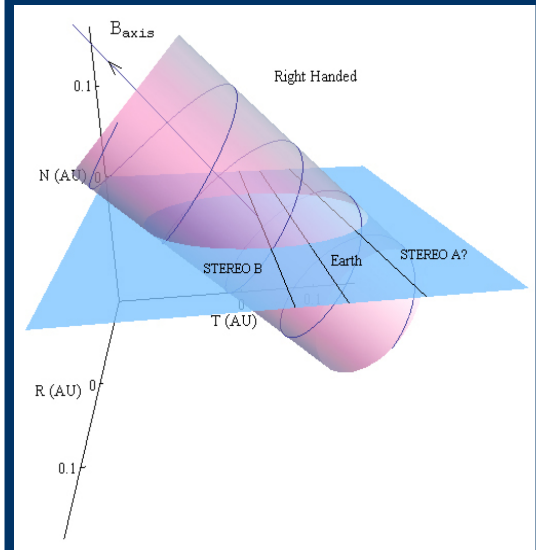
$$\tan\beta_A = \frac{\sin\alpha_A\sin(\alpha_B+\gamma) - f\sin\alpha_A\sin\alpha_B}{\sin\alpha_A\cos(\alpha_B+\gamma)+f\cos\alpha_A\sin\alpha_B}$$

- Can determine the propagation direction, radial distance and velocity continuously out to 1 AU;
- The predicted arrival time and velocity at 1 AU can then be compared with in situ data.

In situ measurements and reconstruction





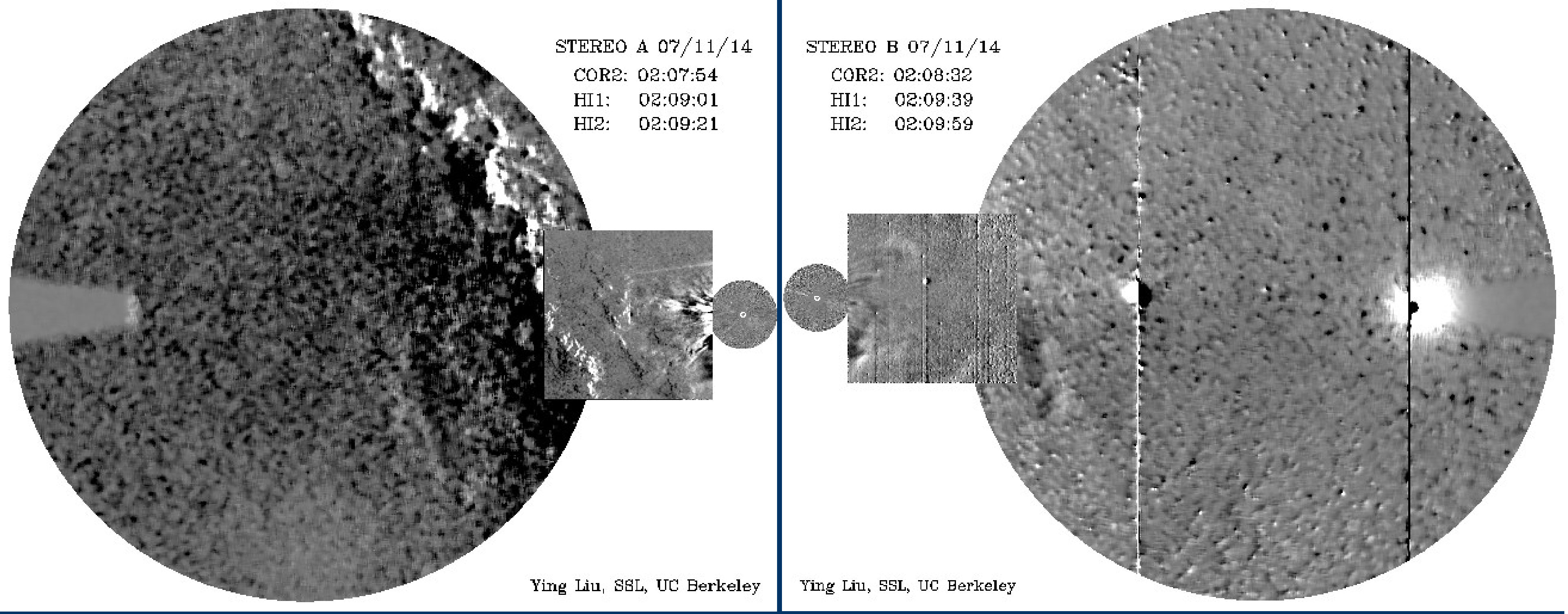


- Reconstruction with in situ data can give the flux rope orientation and cross section;
- A rough knowledge of propagation direction relative to the ecliptic plane may also be obtained;
- The in situ arrival time, velocity, propagation direction and flux-rope orientation can then be compared with those determined from imaging data.

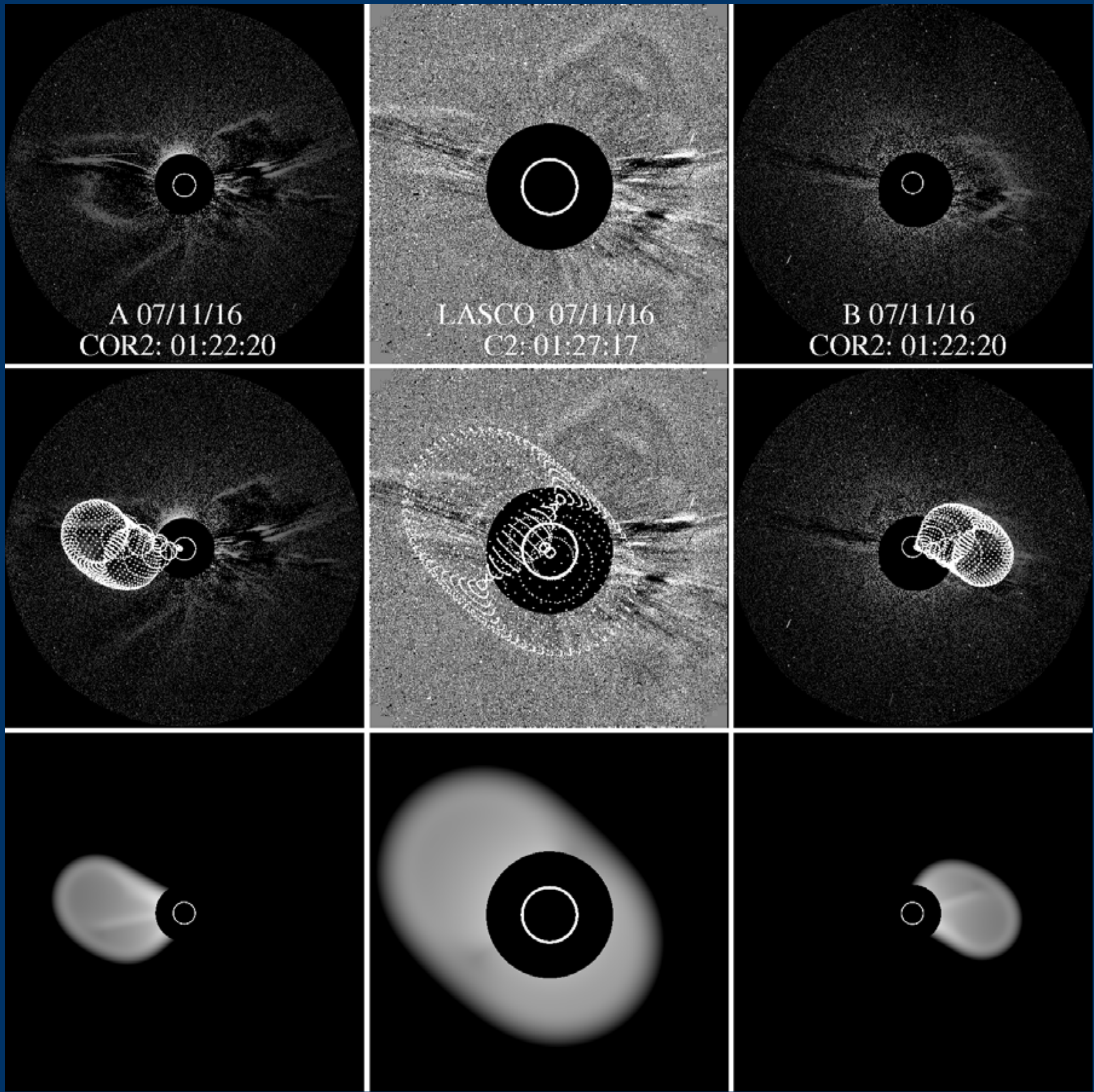
Hu & Sonnerup, 2002;
Liu et al., ApJL, 2008

The 2007 Nov 15 – 19 CME / ICME

Two views of the CME: Separation between STEREO A and B is about 40 deg.



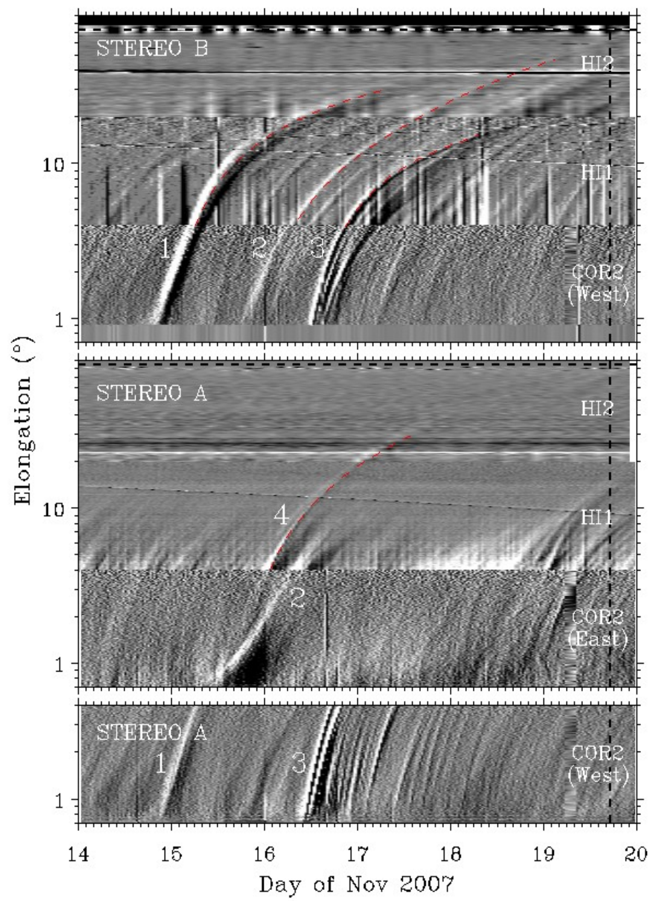
The 2007 Nov 15 – 19 CME / ICME

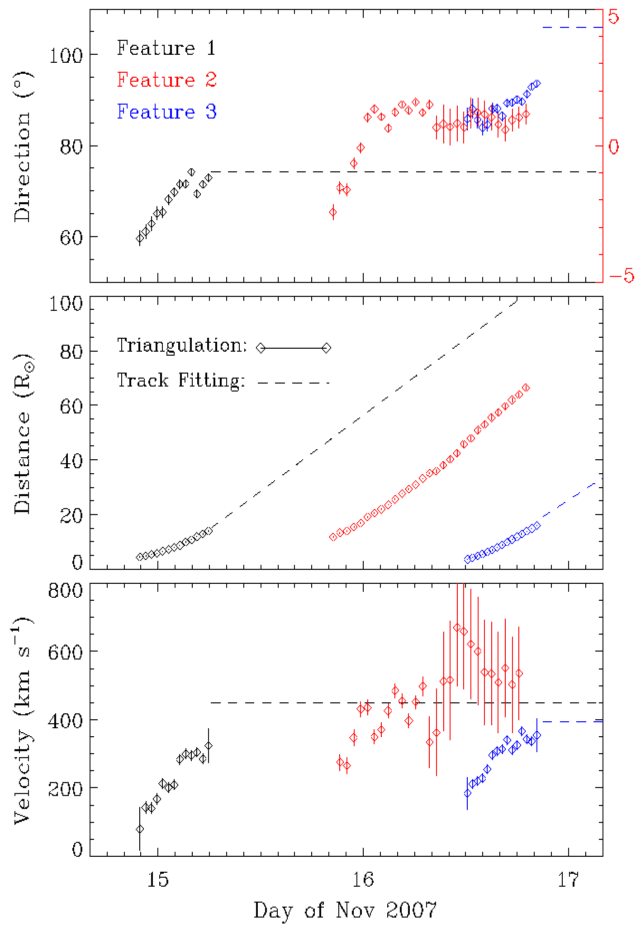


CME image forward modeling:

- Propagation direction: 2 deg east of the Sun-Earth line, and ±1 deg with respect to the ecliptic plane;
- Flux-rope tilt angle: 36 deg clockwise from the ecliptic.

The 2007 Nov 15 – 19 CME / ICME





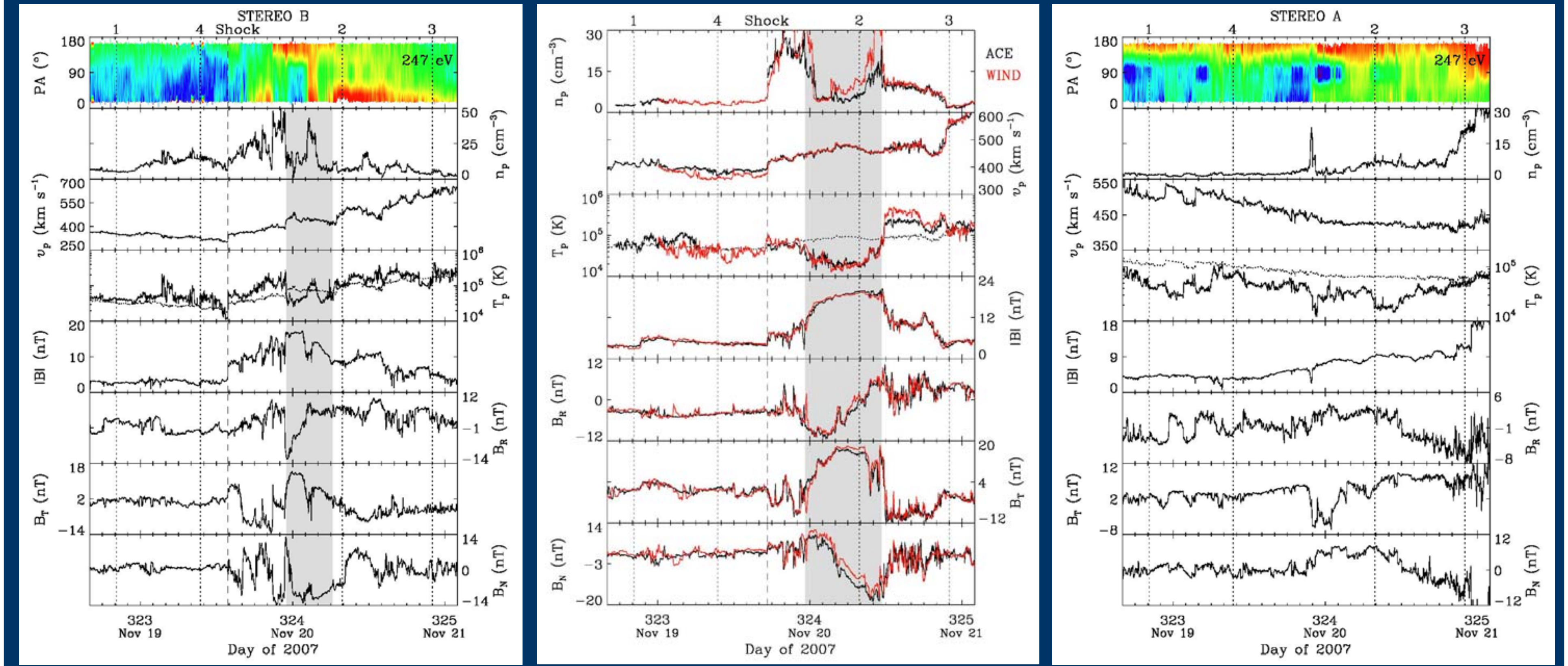
Geometric triangulation:

- The Nov 15 CME (2nd feature) has a propagation direction changing from eastward to westward and then staying at 1 deg west of the Sun-Earth line;
- Its speed first increases and then decreases;
- The other two CMEs may be too west to reach the Earth;
- Track fitting is also performed and compared to triangulation.

The 2007 Nov 15 – 19 CME / ICME

In situ measurements:

- An ICME was observed at the Earth and STEREO B but missed A;
- Only the Nov 15 CME shows the right arrival time and propagation direction.

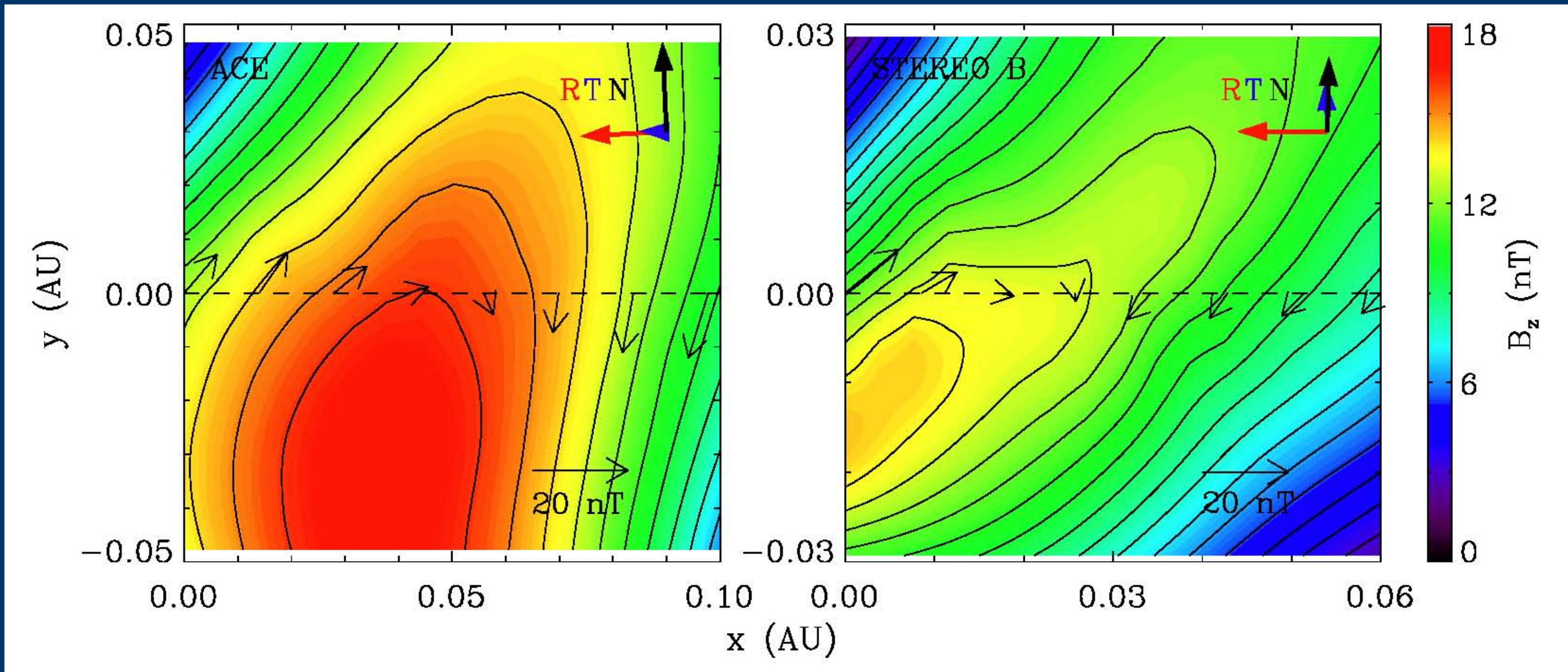


The 2007 Nov 15 – 19 CME / ICME

In situ reconstruction:

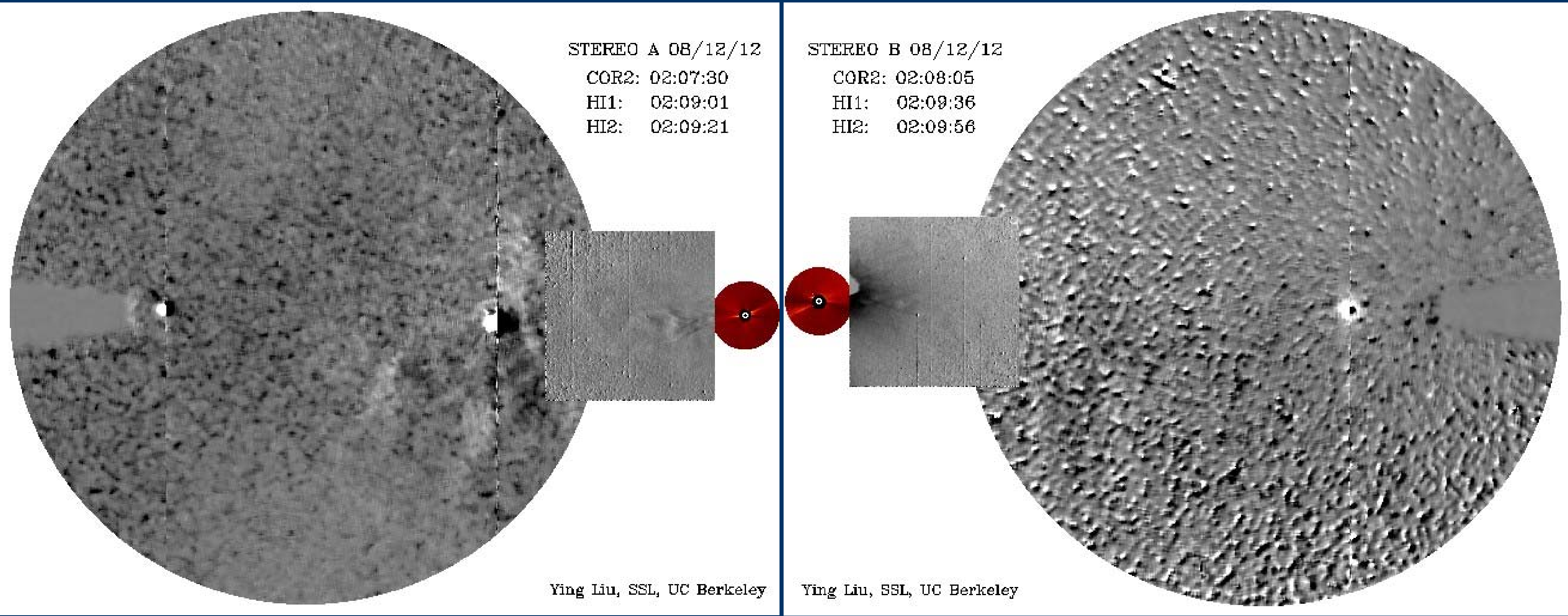
• The reconstruction gives an axis tilt angle of about -1.4 deg (RTN) at Earth and -33.8 deg at B (recall the tilt angle given by image modeling is -36 deg);

• The maximum axial field is below the ecliptic, so the overall propagation direction is likely to be southward at 1 AU (recall ±1 deg from image modeling).

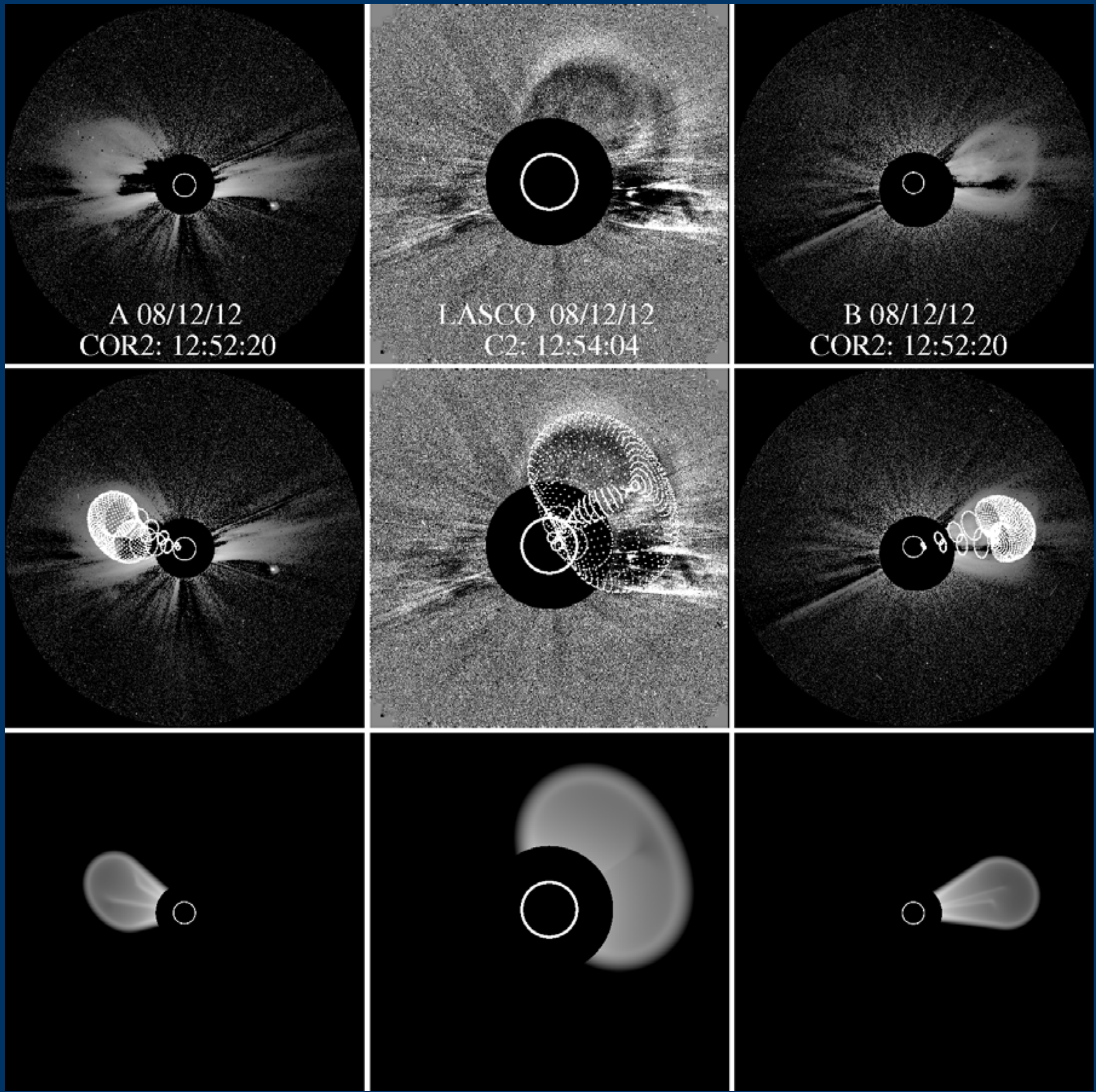


The 2008 Dec 12 – 17 CME / ICME

Two views of the CME: Separation between STEREO A and B is about 86.3 deg.



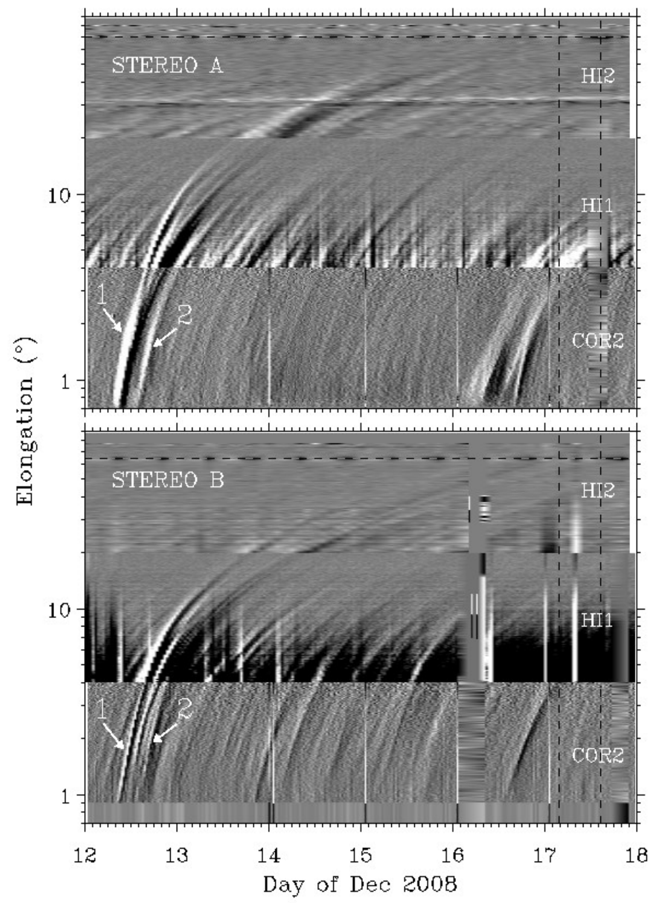
The 2008 Dec 12 – 17 CME / ICME

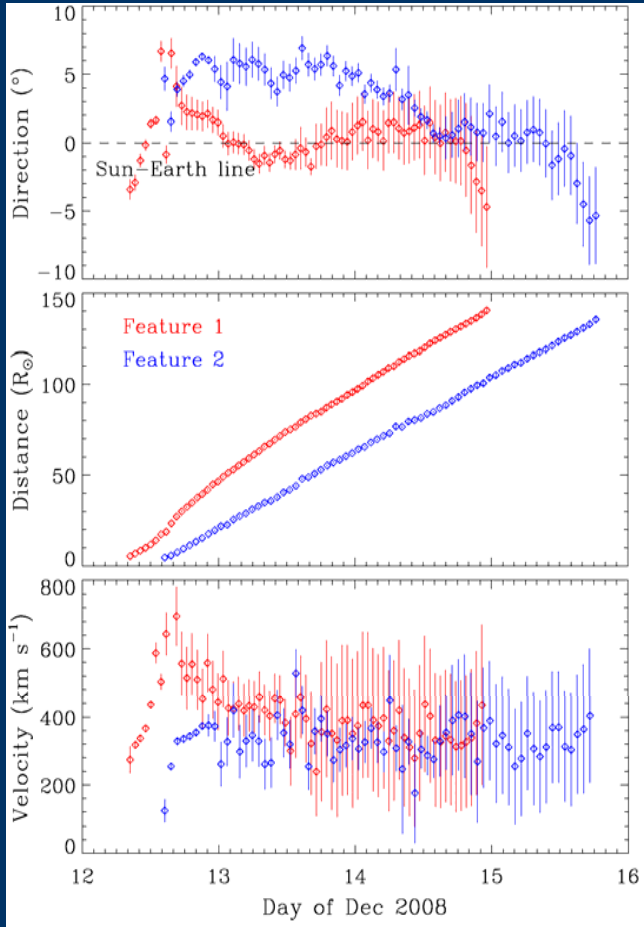


CME image forward modeling:

- Propagation direction: 10 deg west of the Sun-Earth line, and 8 deg with respect to the ecliptic plane;
- Flux-rope tilt angle: 53 deg clockwise from the ecliptic.

The 2008 Dec 12 – 17 CME / ICME





Geometric triangulation:

- Two tracks associated with the CME can be identified up to 50 deg;
- The propagation direction first changes from eastward to westward and then is roughly within 10 deg of the Sun-Earth line;
- The features can be continuously tracked up to 0.7 AU (without projection);
- Its speed first increases and then decreases.

The 2008 Dec 12 – 17 CME / ICME

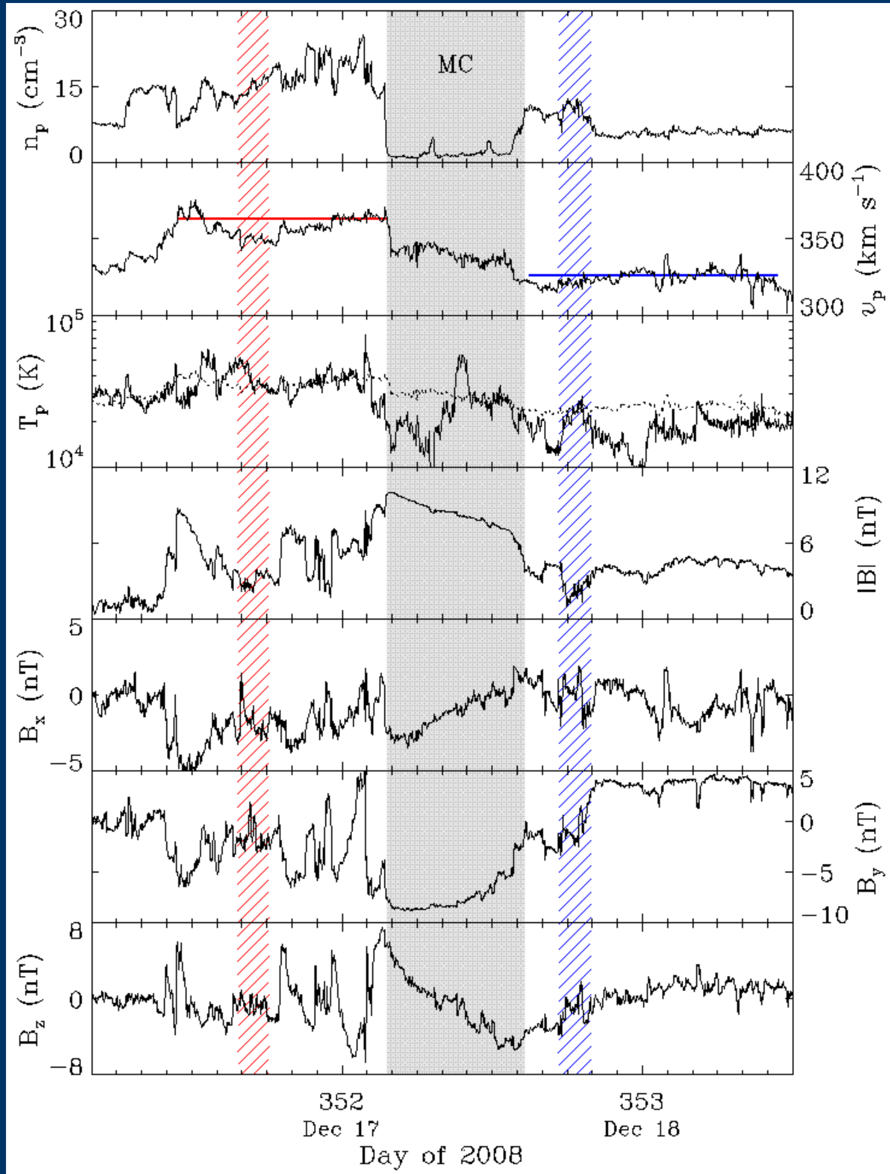
In situ measurements:

• A magnetic cloud was observed at the Earth but likely missed STEREO A and B;

• Predicted arrival times (hatched area) of CME leading and trailing edges bracket the cloud and are coincident with enhanced density regions;

• Predicted radial velocities are also well confirmed by the in situ measurements;

• The flux rope cannot be imaged due to its low density.

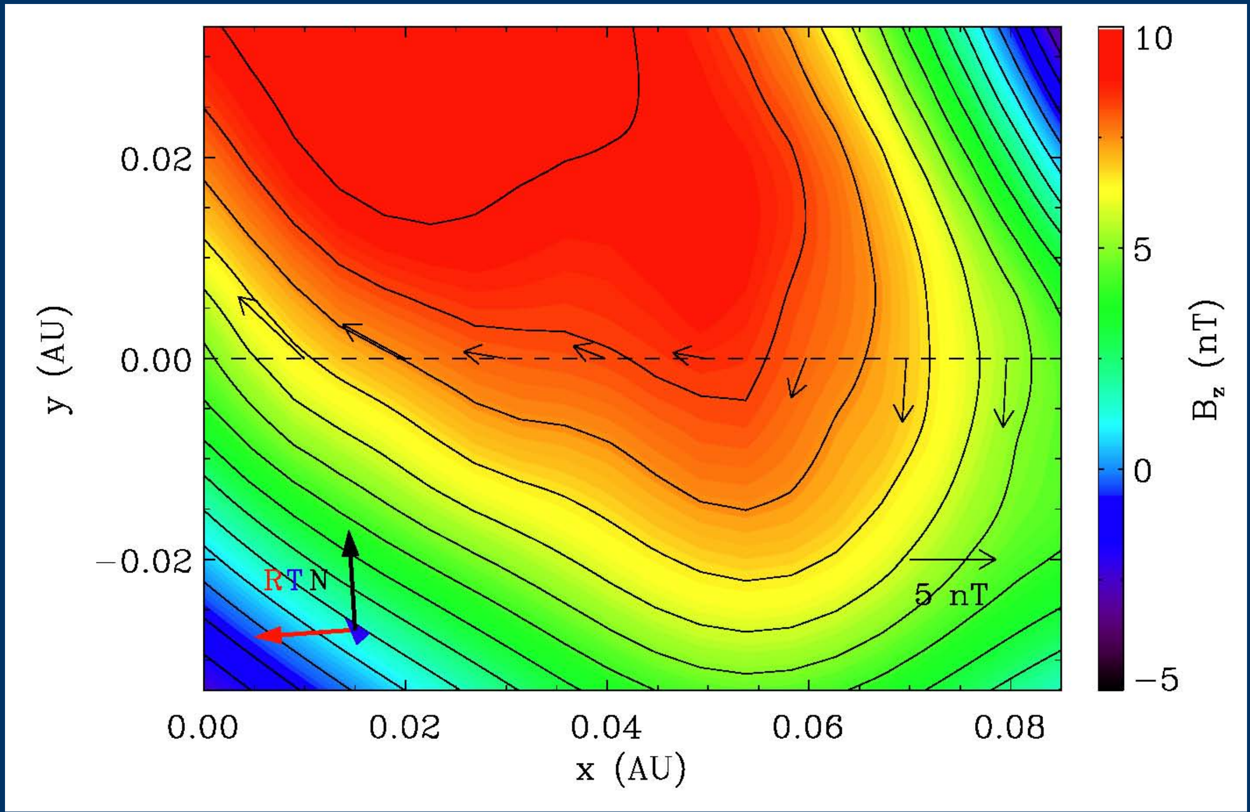


The 2008 Dec 12 – 17 CME / ICME

In situ reconstruction:

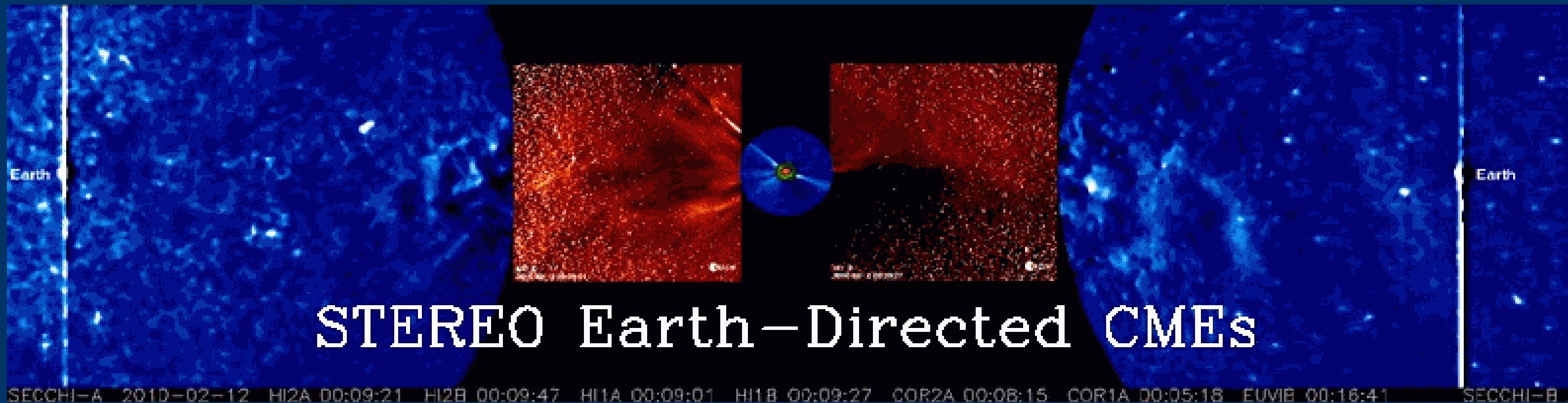
• The reconstruction gives an axis tilt angle of about -6.4 deg (RTN) at Earth (recall -53 deg from image modeling);

• The maximum axial field is above the ecliptic, so the overall propagation direction is likely to be northward at 1 AU (recall 8 deg from image modeling).



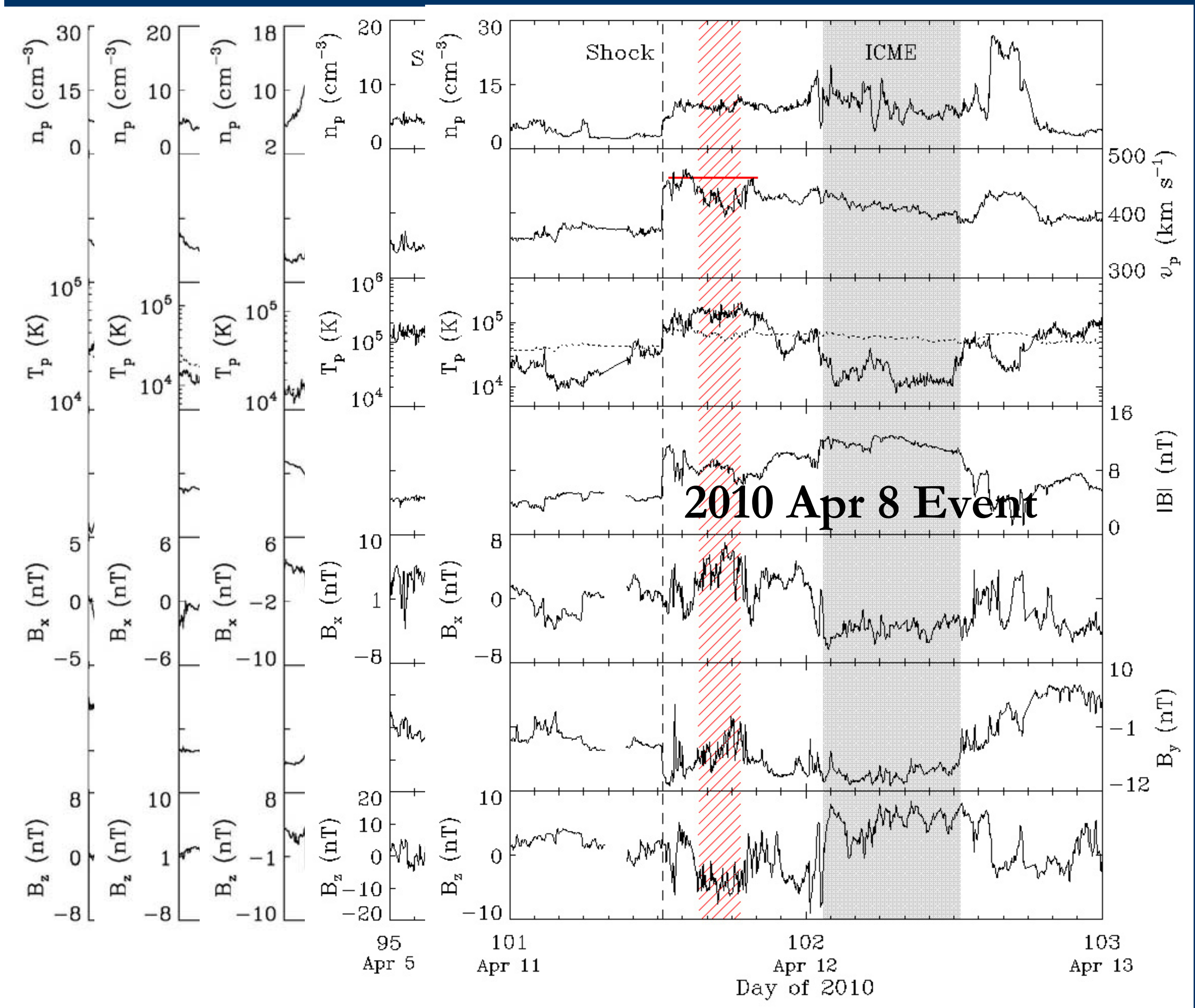
More events: CME catalog

http://sprg.ssl.berkeley.edu/~liuxying/CME_catalog.htm



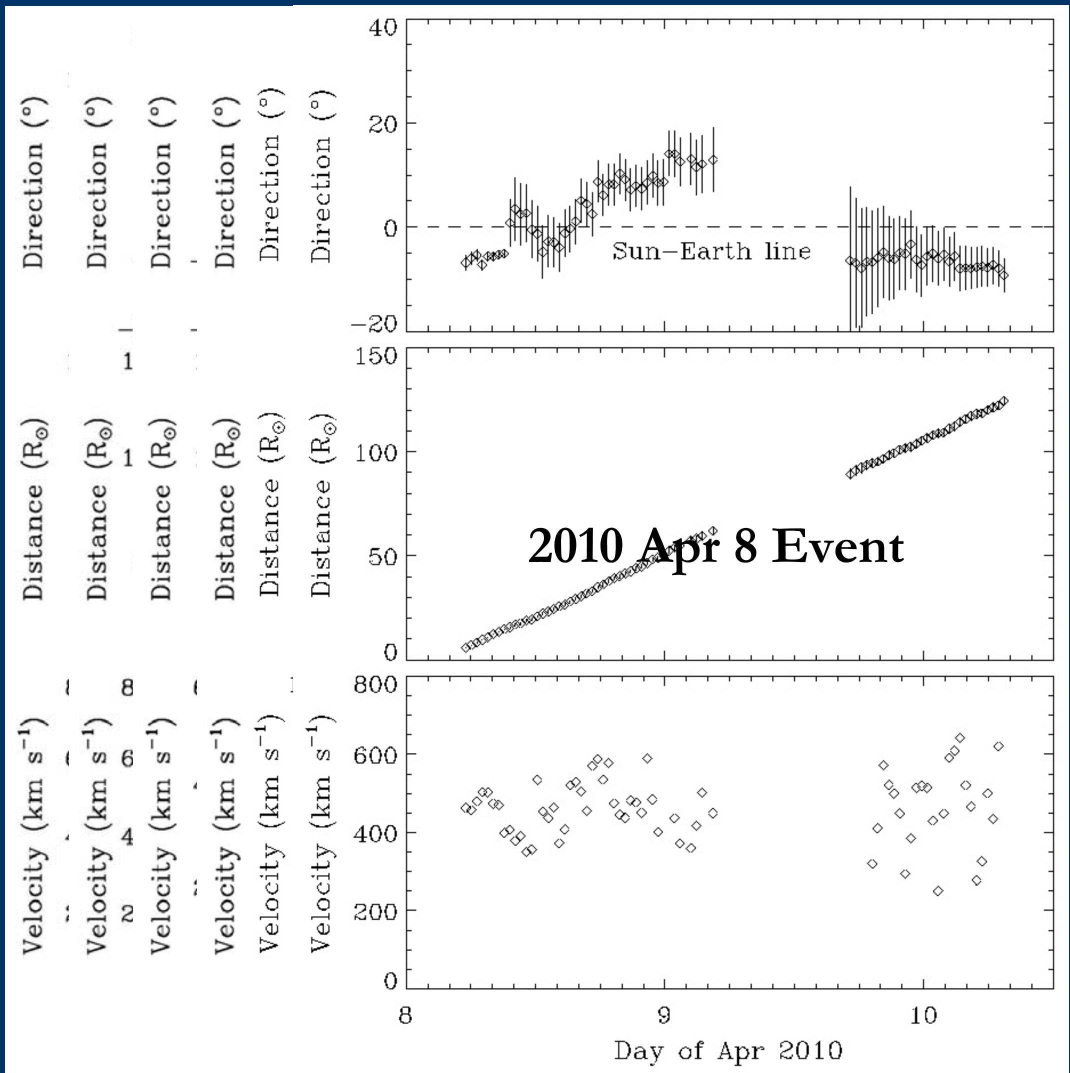
- Movies made of composite images from SECCHI with FOVs to scale, which show CME evolution in virtually the entire Sun-Earth space;
- Time-elongation maps (J maps) along the ecliptic plane showing tracks associated with the CMEs;
- CME kinematics in the ecliptic plane (propagation direction, radial distance and velocity) derived from triangulation analysis (continuously from the Sun all the way out to 1 AU);
- Plots showing ICMEs/magnetic clouds (and shocks if any) observed in situ at 1 AU and comparison with triangulation analysis (on predicted arrival time and radial velocity);
- In situ reconstruction results (flux-rope cross section and orientation) from the Grad-Shafranov method.

Accuracy of geometric triangulation predictions



- The arrival time prediction is good to a few hours;
- The predicted velocity also agrees with in situ measurements at 1 AU;
- Check out the catalog for details!

Westward motion of CMEs at acceleration phase



- All these CMEs undergo a westward motion with respect to the Sun-Earth at their acceleration phase;
- We suggest this as a universal feature produced by the magnetic field connecting the Sun and CMEs and rotation of the Sun;
- The westward motion would mainly occur within the Alfven radius r_A when

$$\rho v^2 / 2 \le B^2 / 2\mu_0$$

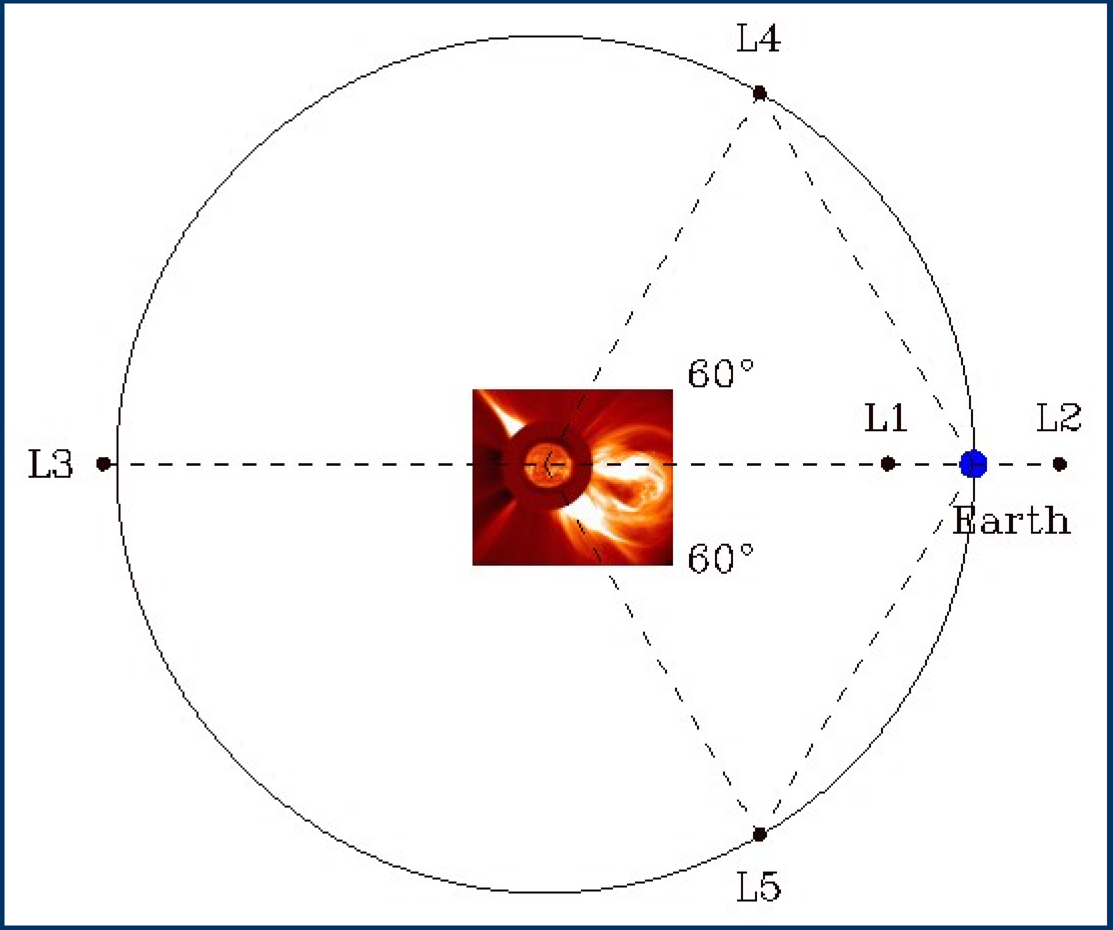
- For the present CMEs

$$r_A \sim 10 - 20 r_s$$

Recap of the main points

- CME propagation directions can be determined to a relatively good precision as shown by the consistency between different methods;
- The geometric triangulation technique shows a promising capability to link solar observations with corresponding in situ signatures at 1 AU and to predict CME arrival at the Earth;
- The flux-rope orientation derived from imaging observations may have a large uncertainty as indicated by the comparison with in situ reconstruction;
- The flux rope within CMEs, which has the most hazardous southward magnetic field, cannot be imaged at large distances due to expansion;
- We find that CMEs undergo a westward migration with respect to the Sun-Earth line at their acceleration phase, which we suggest as a universal feature produced by the magnetic field connecting the Sun and ejecta.

Concept for future missions at L4 and L5

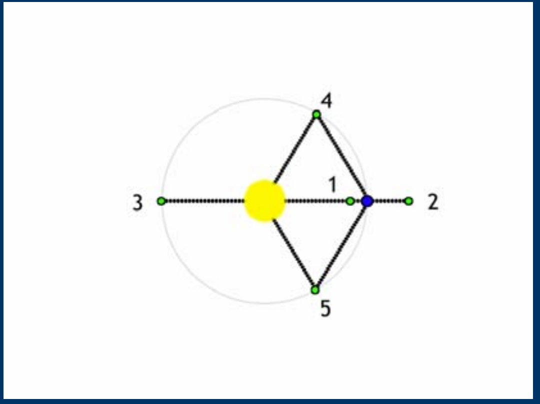


Five Lagrangian points of the Sun-Earth system:

• L4 and L5 have the same orbit as the Earth but lie at 60 degrees ahead and behind;

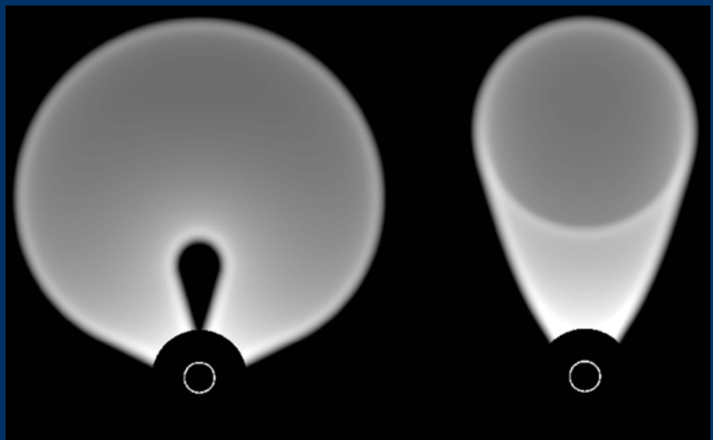
• L4 and L5 are resistant to gravitational perturbations;

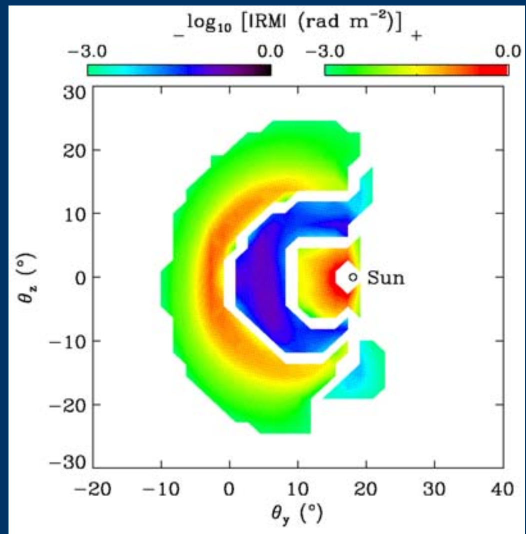
• Apply the same triangulation concept to future missions at L4 and L5.

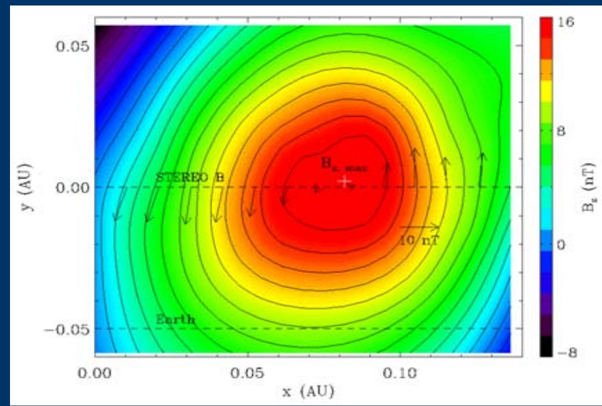


Future work

CME studies with coordinated imaging, Faraday rotation and in situ observations:







White-light images give density structure

Faraday rotation gives magnetic field structure (Liu et al., ApJ, 2007)

In situ data give constraints