SOLI INVICTO

Current and Future Challenges in Space Weather Science

A Forecaster's Perspective

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Predicting disturbed conditions of solar and interplanetary weather

- In this presentation, I will address open questions in space weather science that are related to predictions of two major geoeffective phenomena:
  - *geomagnetic storms,*
  - *solar energetic particle (SEP) events.*
- I will concentrate on the modeling efforts rather than on numerous empirical methods.

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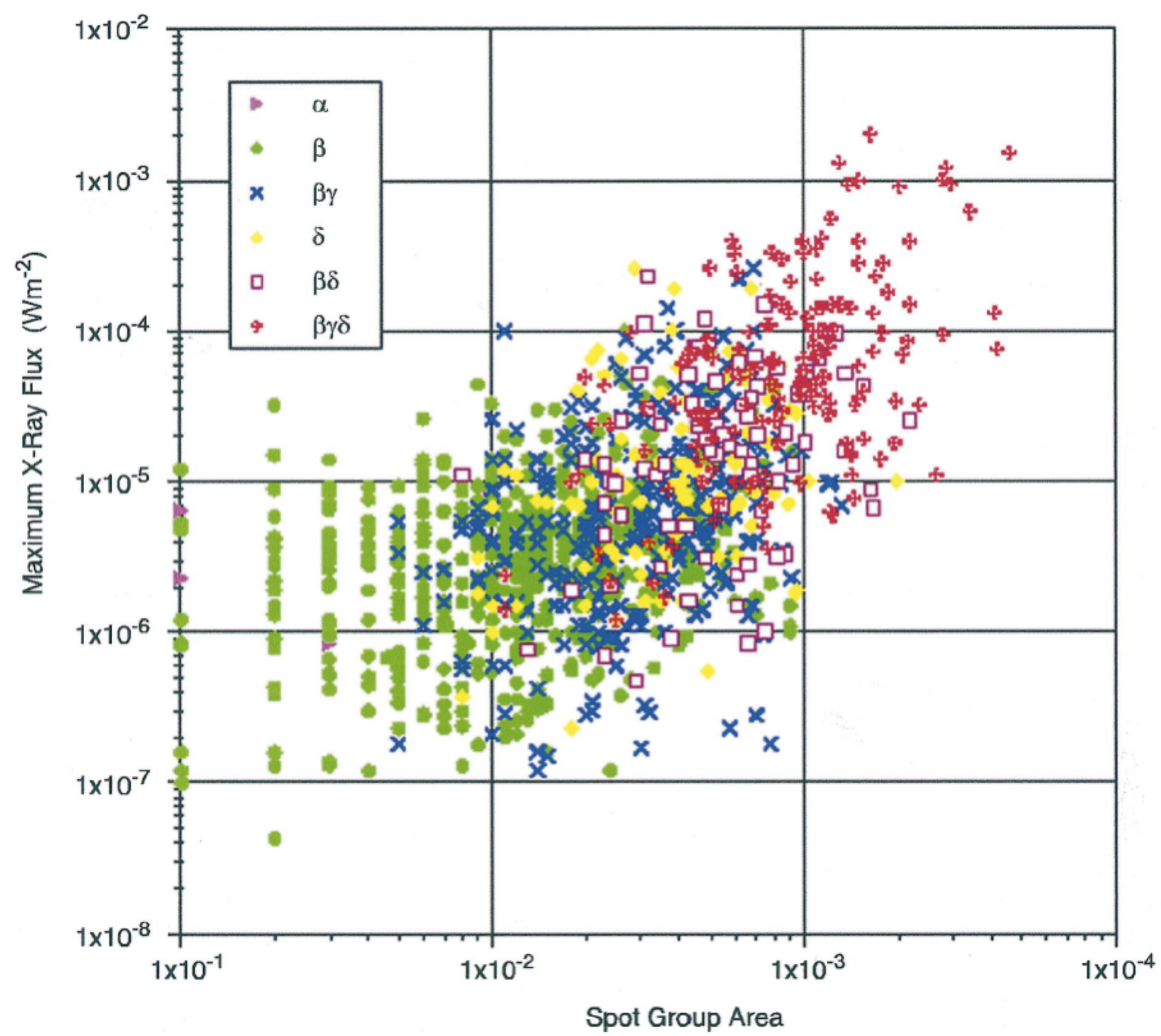
  - What will be the flux, spectrum and composition of SEPs?

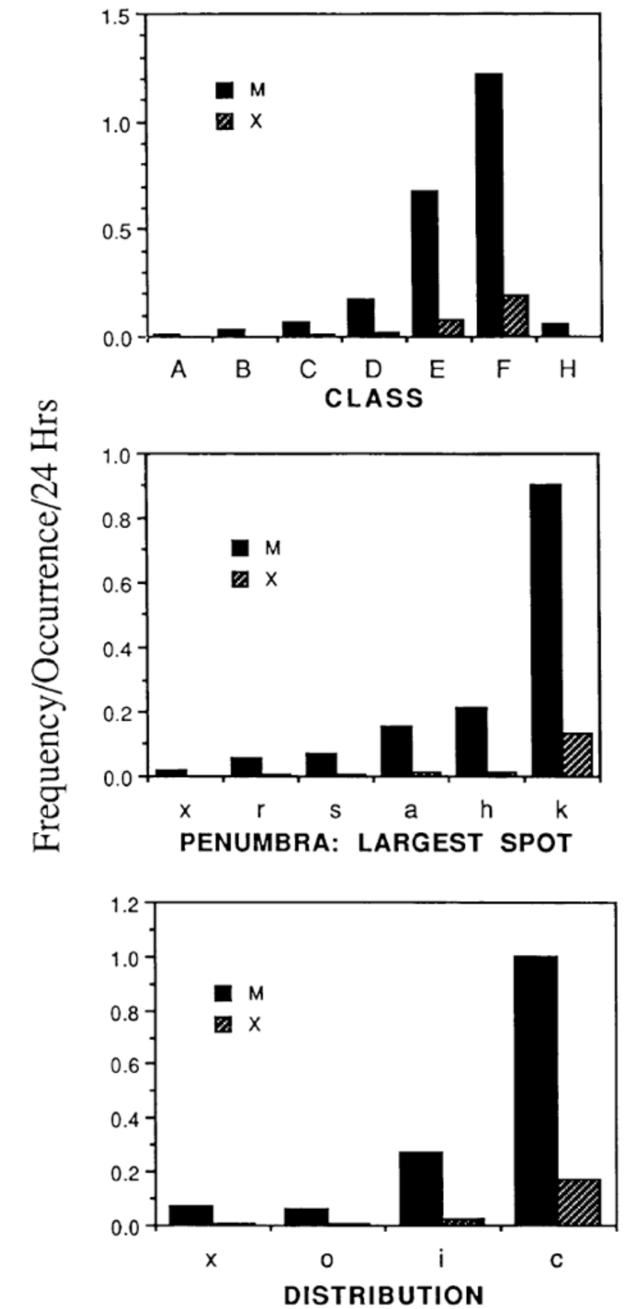
Where and when will an eruption occur?

Prediction of solar eruptions based on active region observations

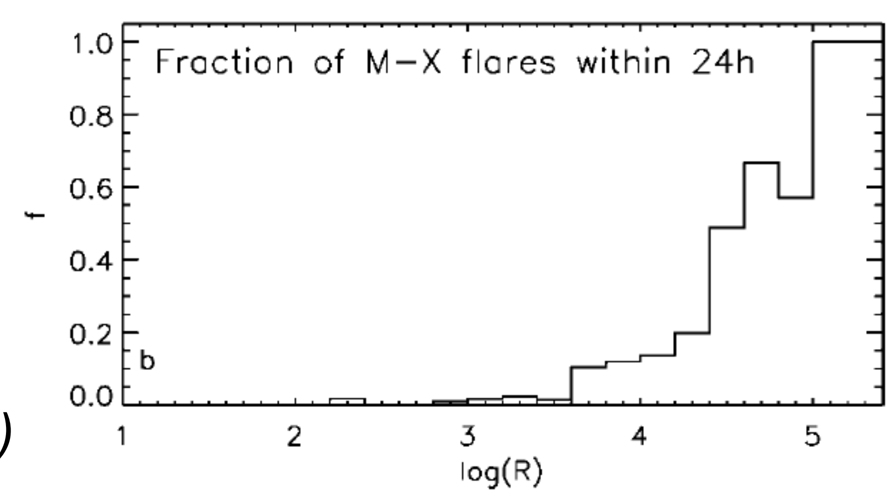
- Prediction of solar eruptive event occurrence is traditionally made in terms of flare probabilities (for the upcoming 24 or 48 hours).
- We can evaluate the flaring probability based on photospheric magnetograms and sunspot group configuration.



(Sammis et al. 2000)



(P. McIntosh 1990)

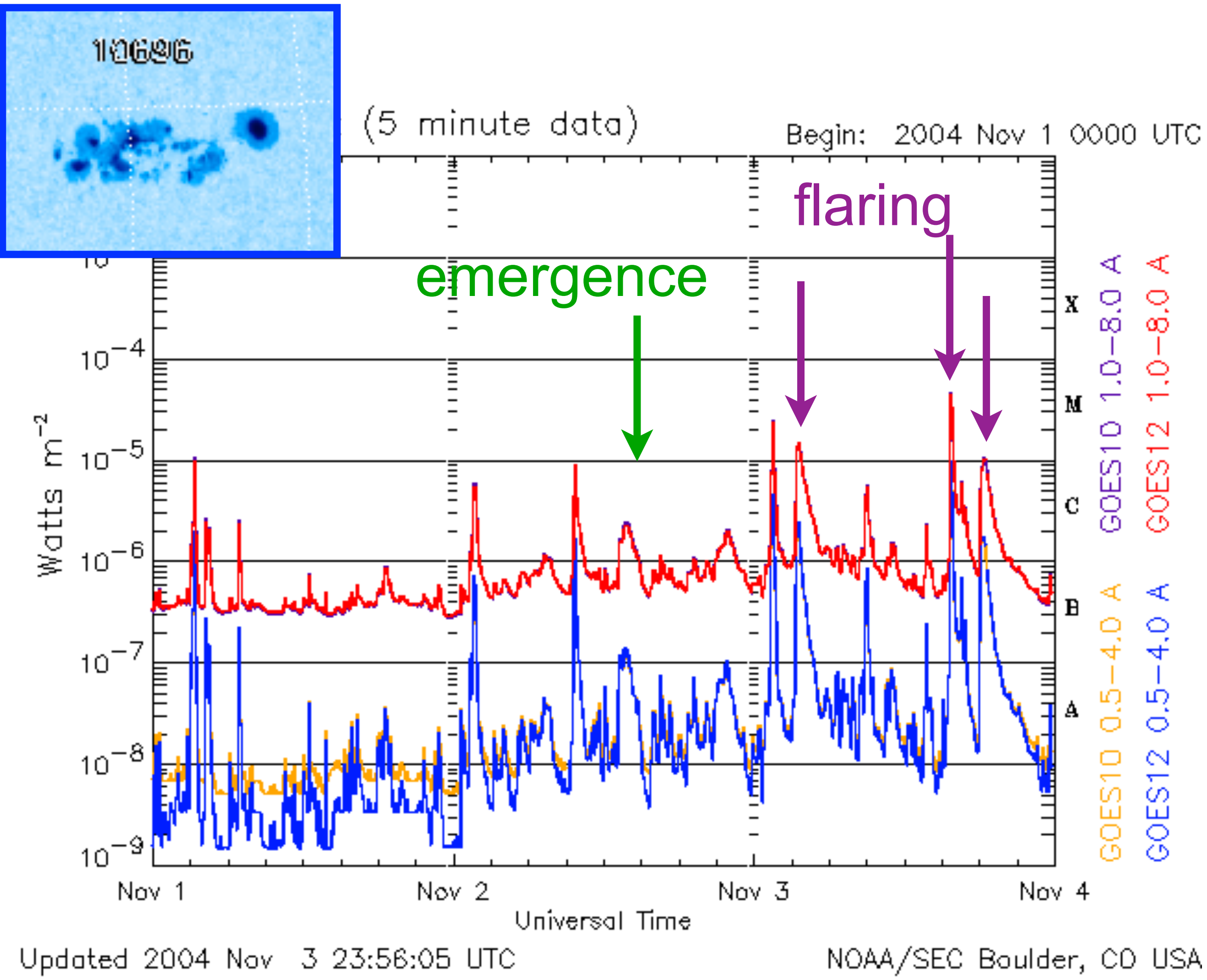


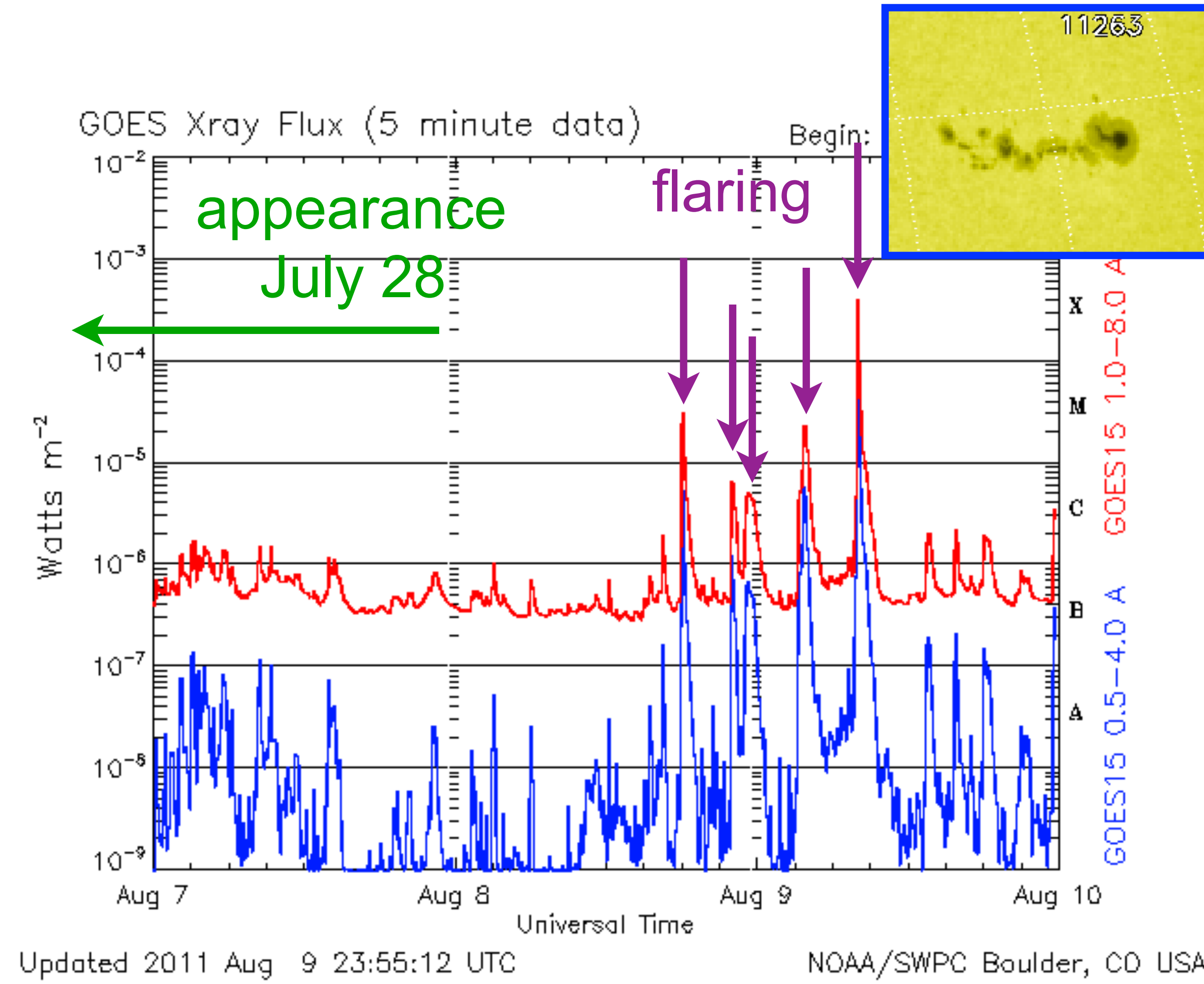
(Schrijver 2007)

+ *many other works*

When will an eruption occur?

Prediction of flare timing is still problematic!





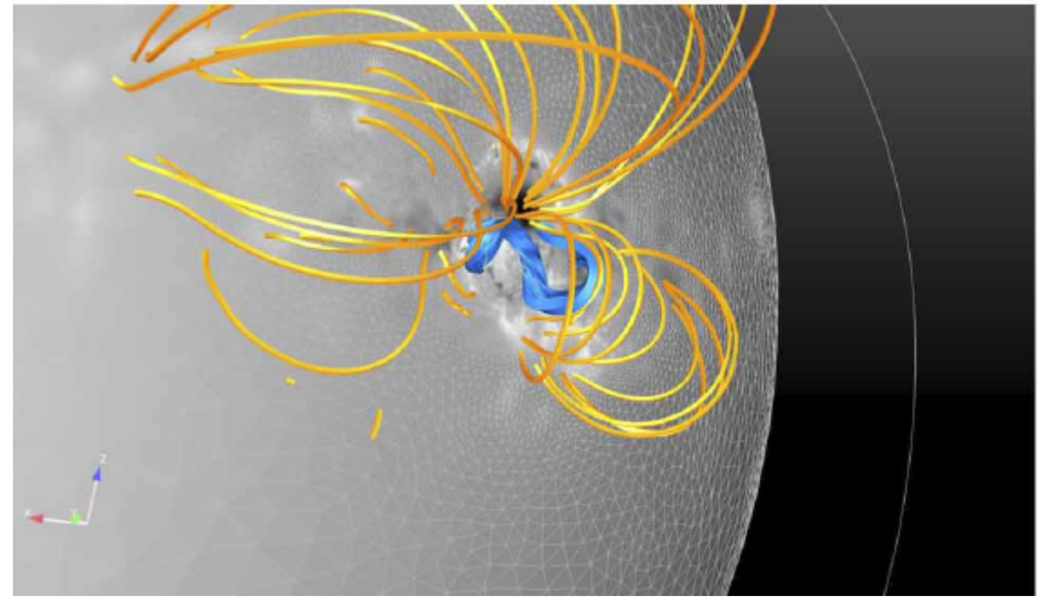
NOAA AR 0696 (November 2004):
strong flaring shortly after its emergence

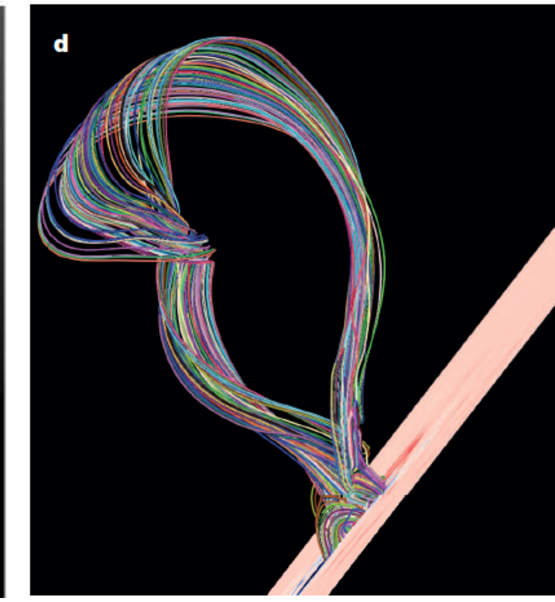
NOAA AR 1263 (August 2011):
strong flaring after a 5-day period of weak (<C3) flaring, and 2 days after the strong magnetic flux emergence

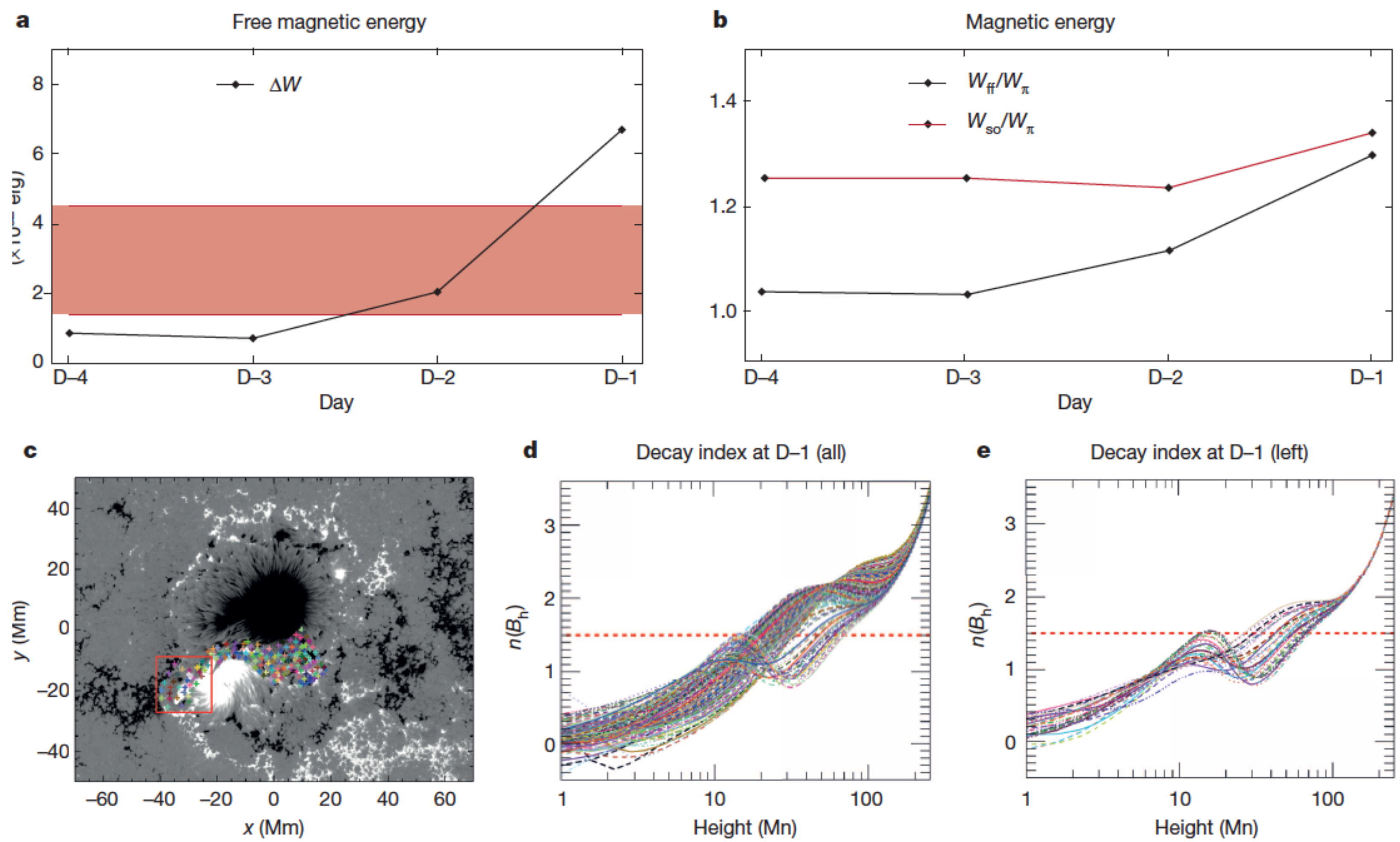
- There is no reliable precursor that would systematically give successful results.

Can modern models predict an eruption?

- Amari et al. (2014) used a state-of-the-art model of the corona and the CME eruption.
- They simulated the increase of the free magnetic energy in the days before the eruption in response to photospheric motions.
- Once the free magnetic energy became close to the energy of a partially open field, a CME occurred.
- It is however, not clear why e.g. a smaller eruption could not occur earlier.



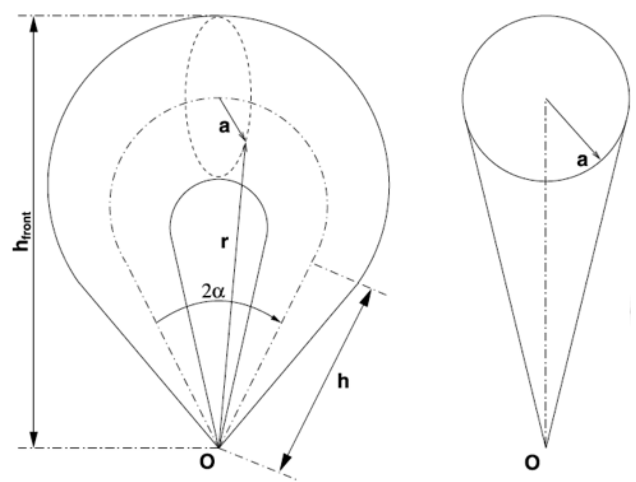


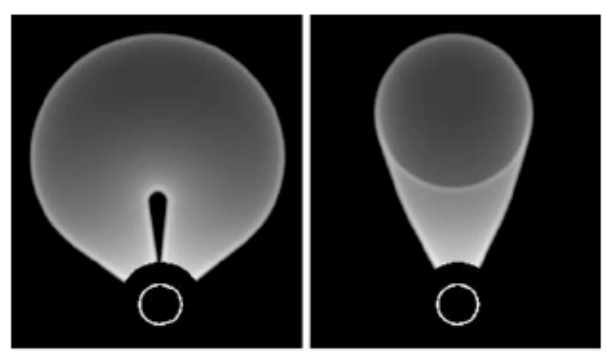


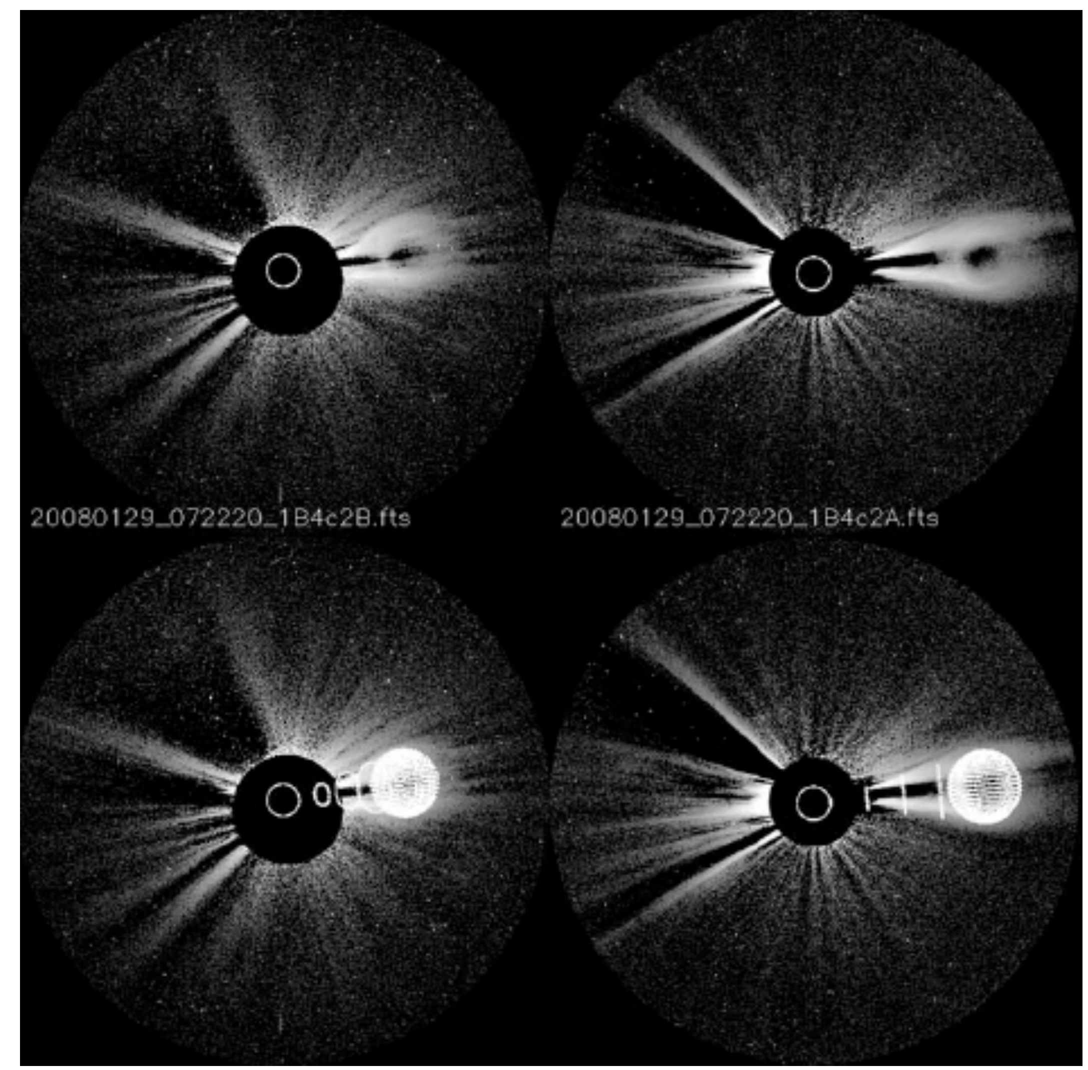
What will be the characteristics of the eruption?

Will a coronal mass ejection (CME) occur?

- We cannot yet predict if a flare (magnetic energy release) will be accompanied by a CME (magnetic energy release and helicity release?).
- We can evaluate the direction of the CME propagation in 3D and estimate its true radial speed on the base of coronagraphic observations (e.g. forward modeling of flux rope CMEs based on the data taken by several coronagraphs).

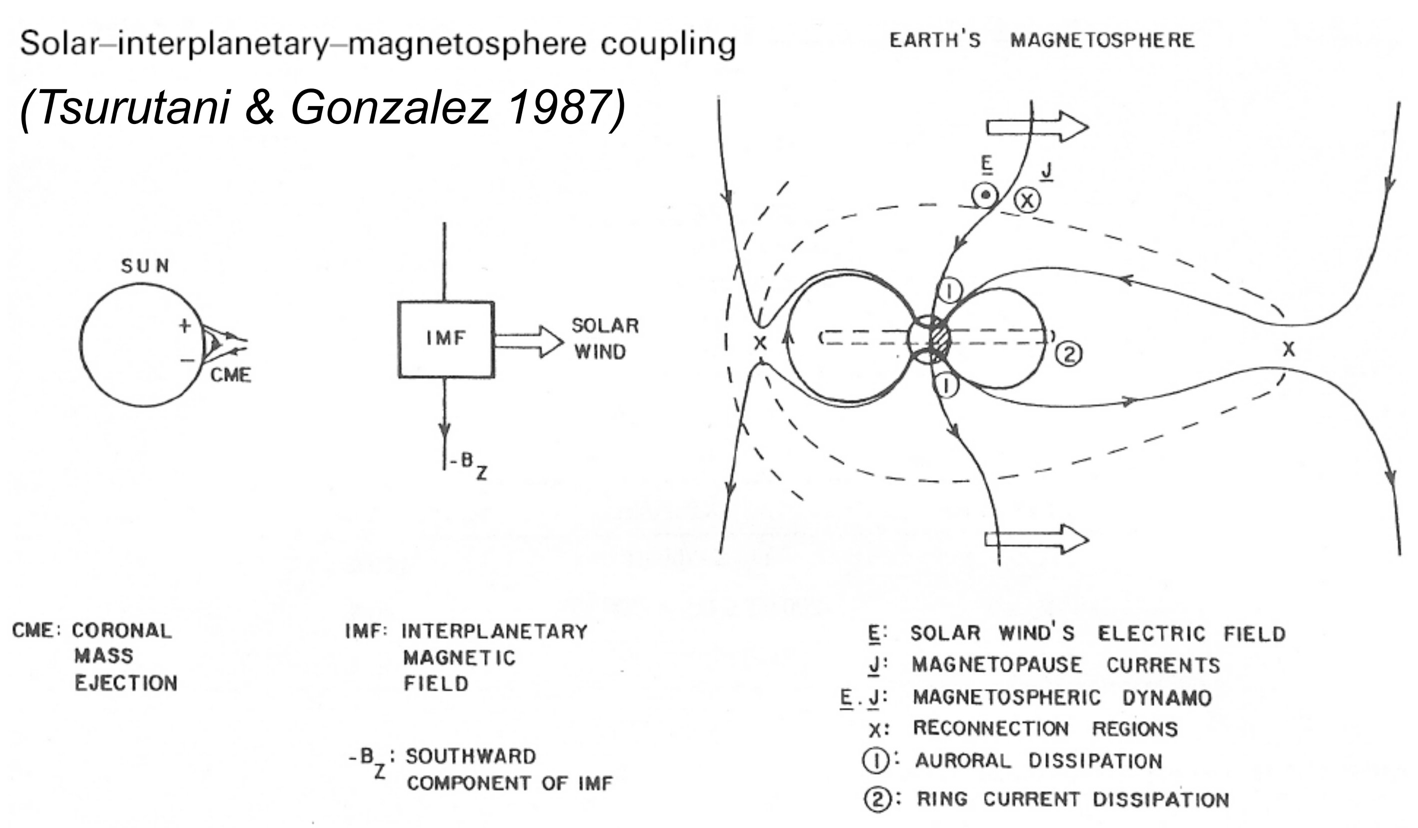






(See e.g. J. Chen et al. 1997, Thernisien et al. 2006, 2008, and review by Mierla et al. 2008)

Geomagnetic storms: what we know

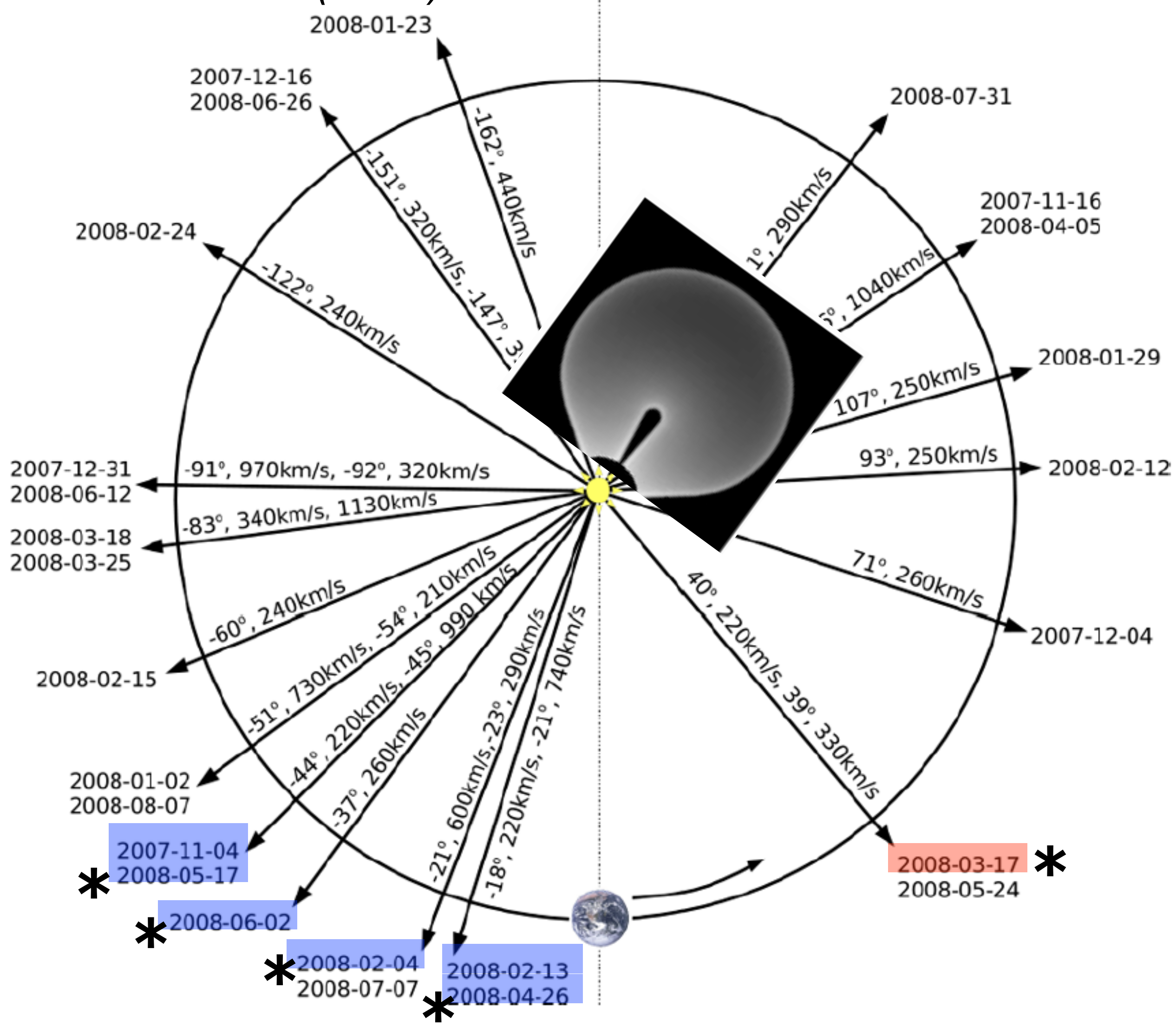


The chain of solar-terrestrial connections at work for the geomagnetic storm generation

- All the strongest geomagnetic storms are produced by CMEs!
- The solar wind – magnetosphere coupling is governed by the duskward electric field $E_y \sim vB_z$.
- However, v varies only by a factor of 2 (maybe 5 in extreme events). B_z varies by a factor of 10 and is thus a more important parameter.
- To be geoeffective, the CME-associated disturbance should:
  - arrive to the Earth;
  - have a suitable magnetic field configuration: the interplanetary magnetic field (IMF) B_z component should be negative (southward), strong enough and long-lasting.

Where will the ICME arrive?

Figure adapted from
Thernisien et al. (2008).



- On the base of the data from two STEREO coronagraphs, 15 flux rope CMEs were estimated to arrive to one of the in situ detection points (STEREO A, STEREO B, or ACE),
- Within the error bars, 14 events arrived at the expected location.
- For one event, a third viewpoint (SOHO) was necessary to determine the geometry correctly.
- Flux rope model (Chen et al. 1997, Thernisien et l. 2006) is good enough to predict if a flux rope CME will arrive (or not) at a given location at 1 AU.

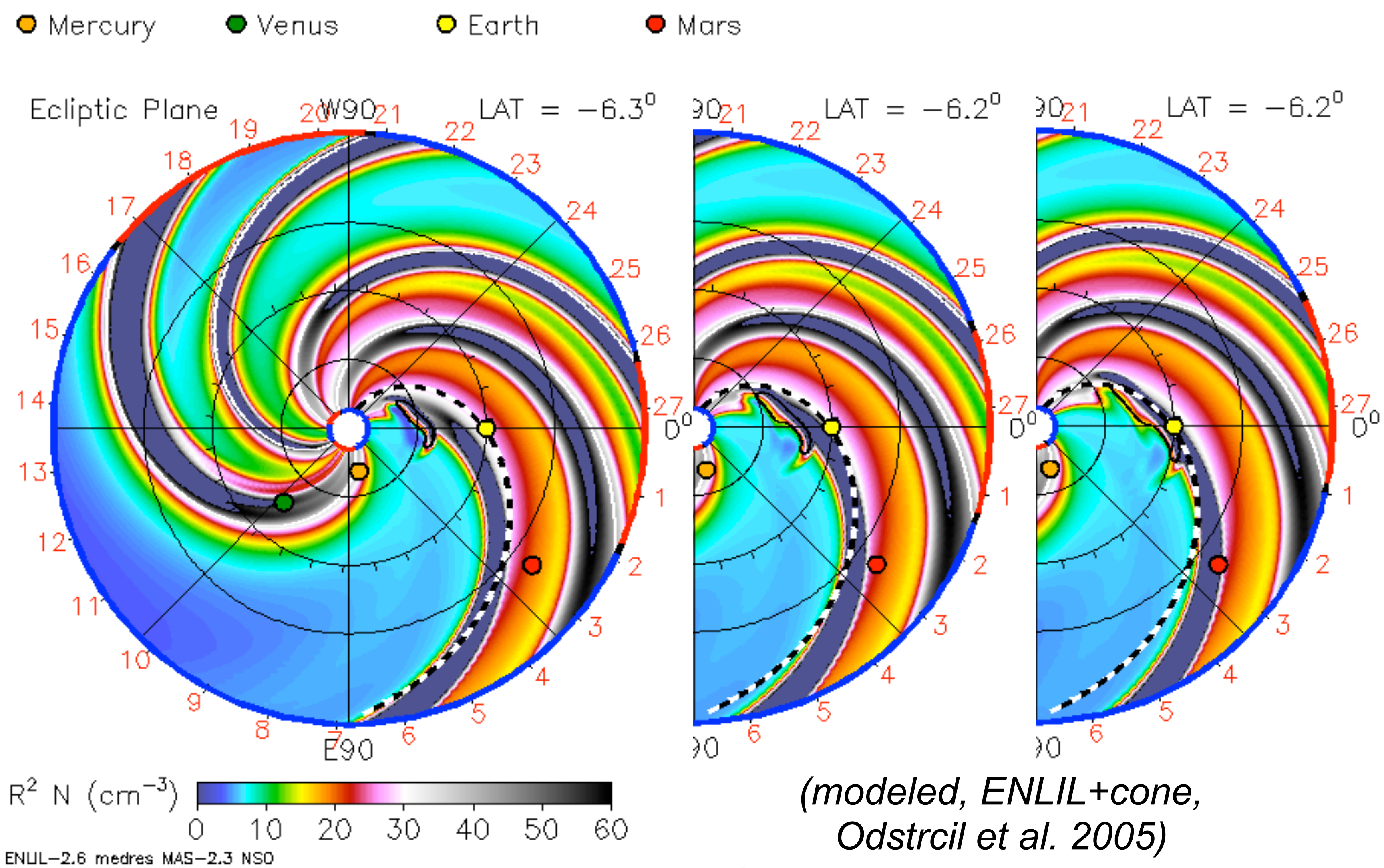
(Rodriguez et al. 2011)

In blue: ICMEs that should arrive at STEREO B

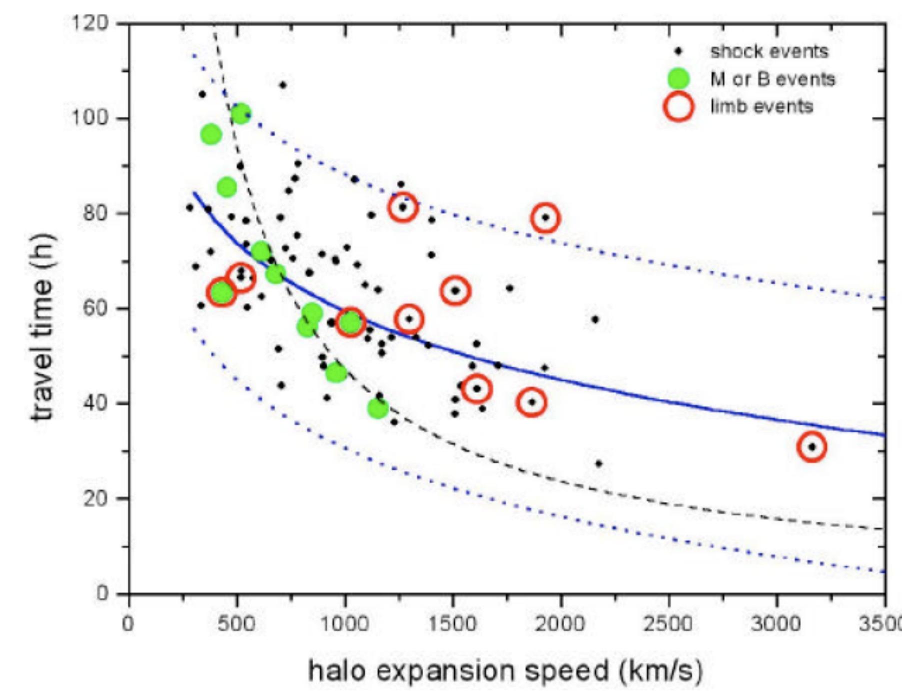
In red: ICMEs that should arrive at STEREO A

Where and when will the ICME arrive?

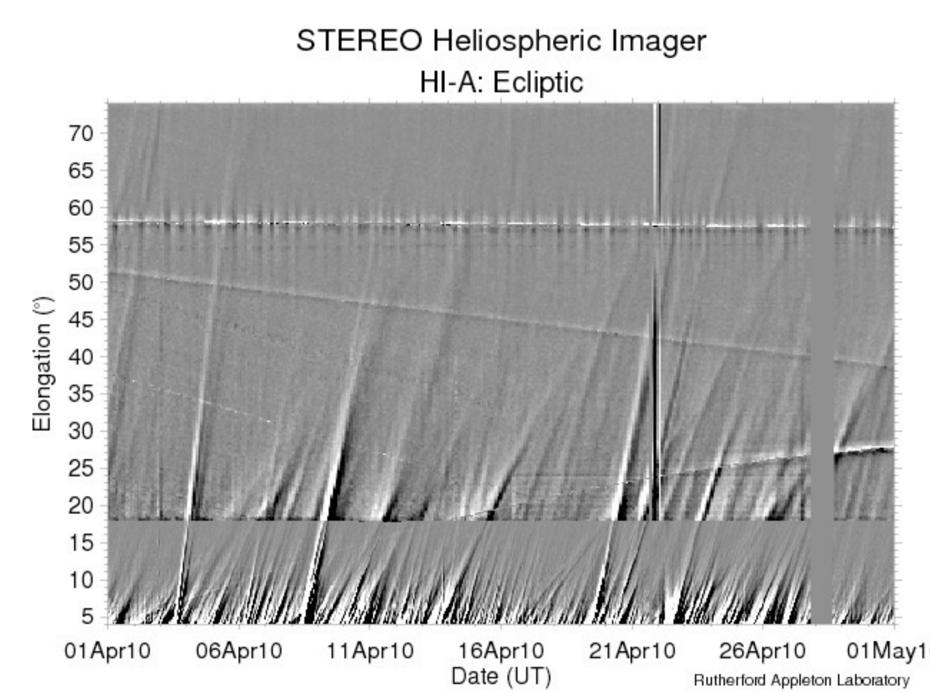
ICME propagation in the heliosphere



(modeled, ENLIL+cone, Odstrcil et al. 2005)



(empirical, Schwenn et al. 2005)

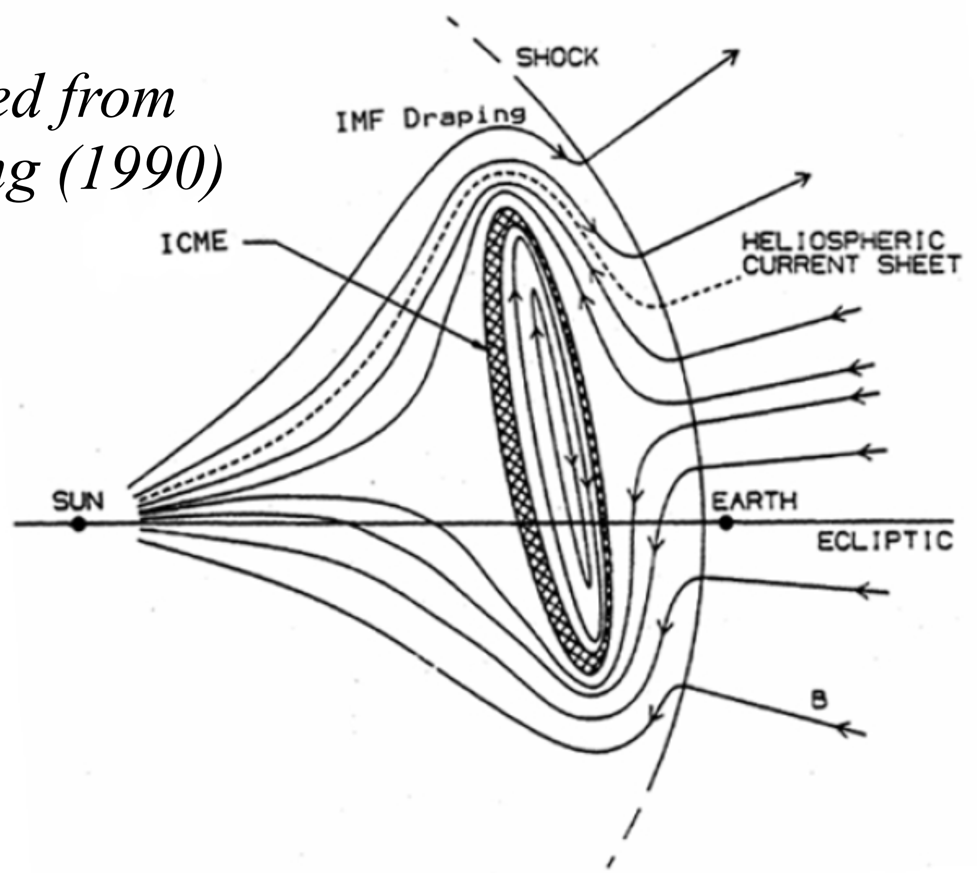


(observed, STEREO SECCHI/HI J-map)

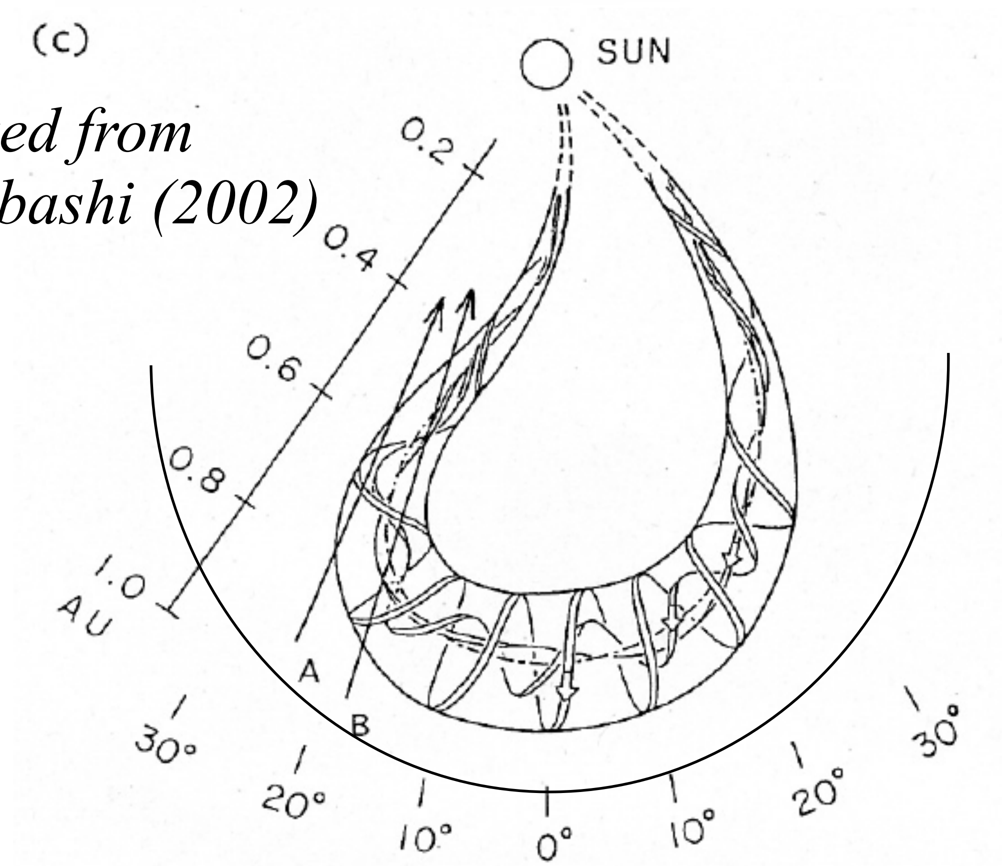
- For a limited amount of CME-ICME data collected since 2011, the accuracy of the ICME arrival time prediction is reported to reach ±7 hours (*Millward et al. 2013*).
- This is a significant improvement in comparison with the accuracy of empirical methods (around ±12 hours).
- Unfortunately, ENLIL does now allow to distinguish between the shock and the ICME.

What part of the ICME will arrive at the Earth?

adapted from Gosling (1990)



adapted from Marubashi (2002)



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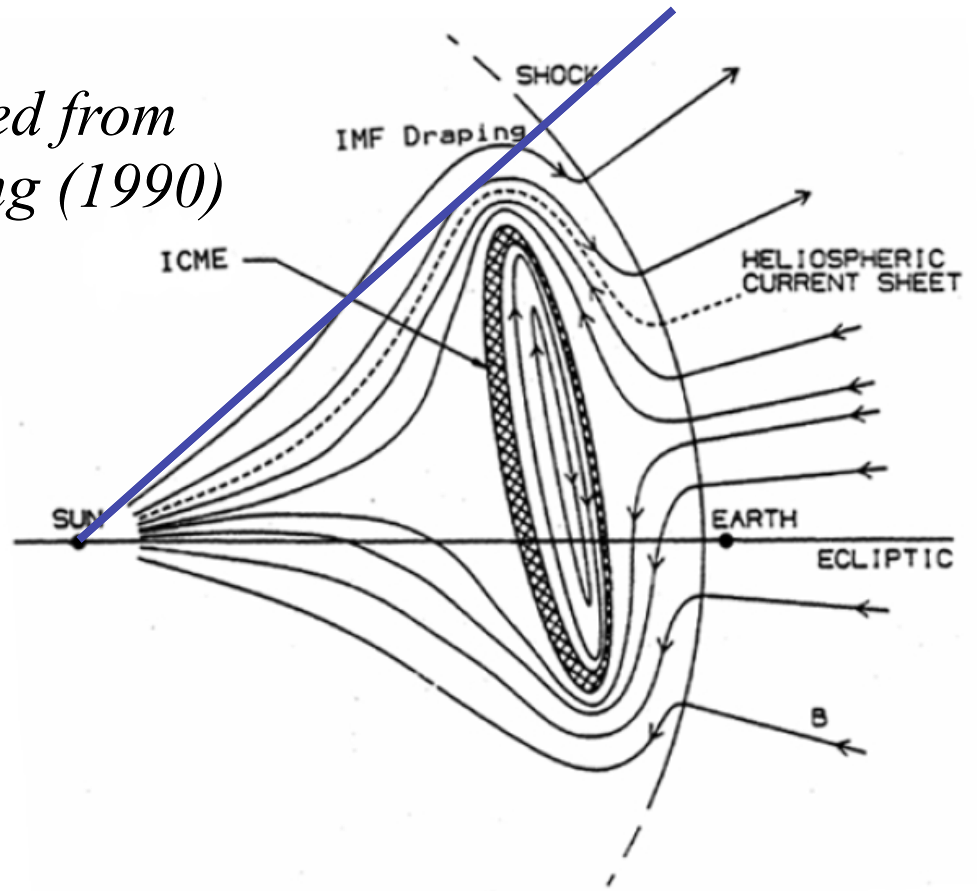

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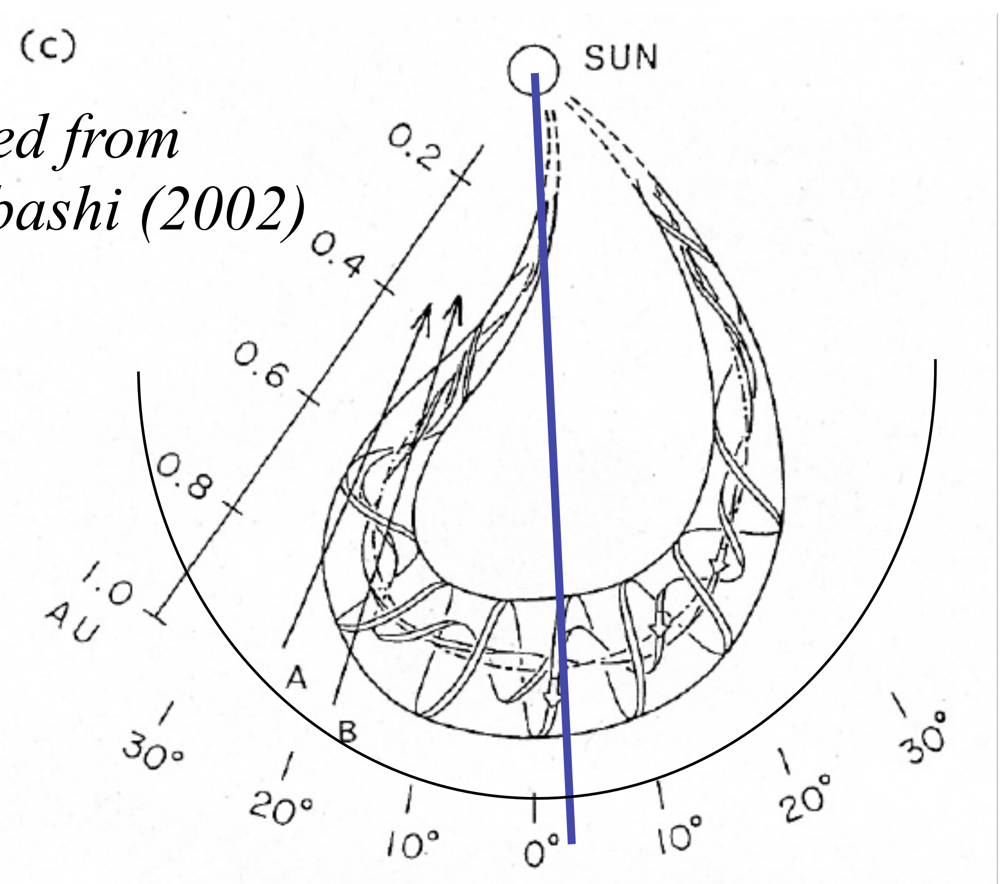

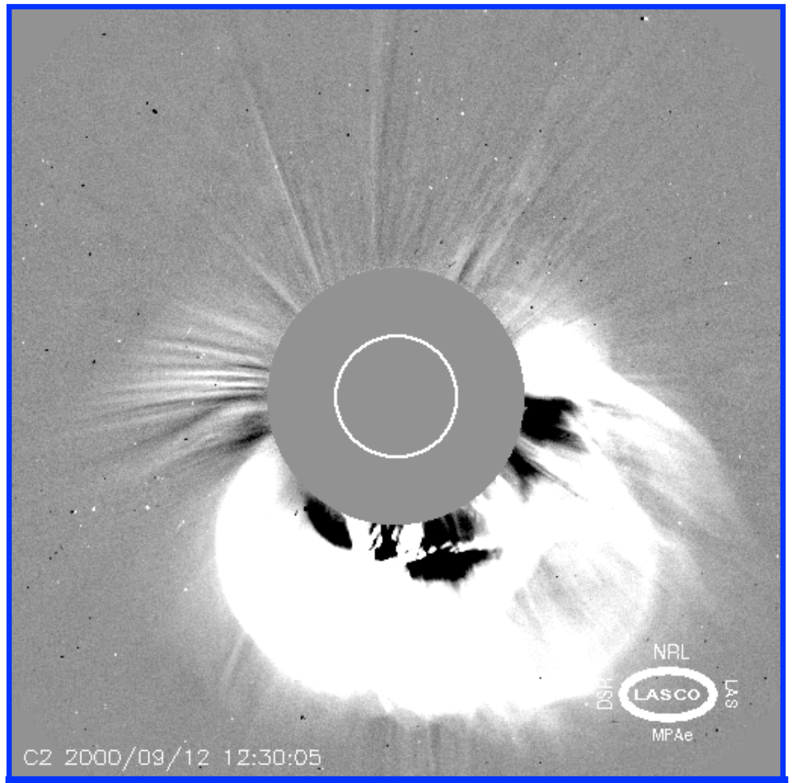

NS asymmetric halo

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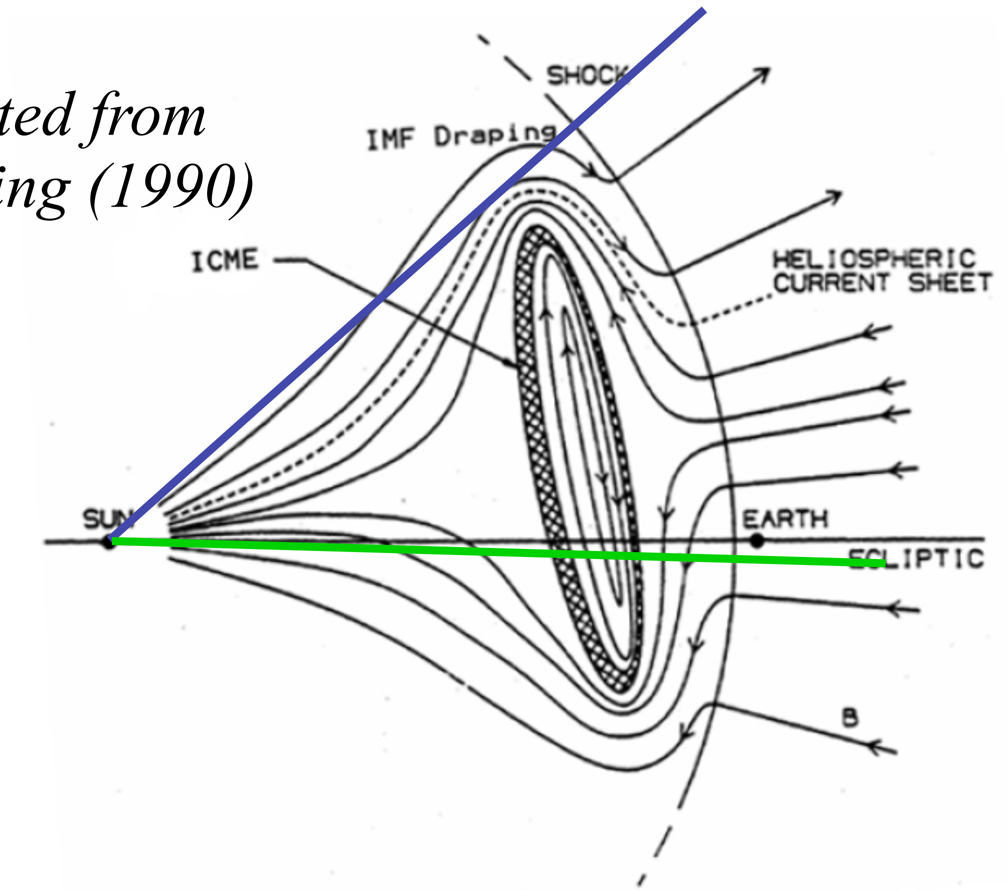

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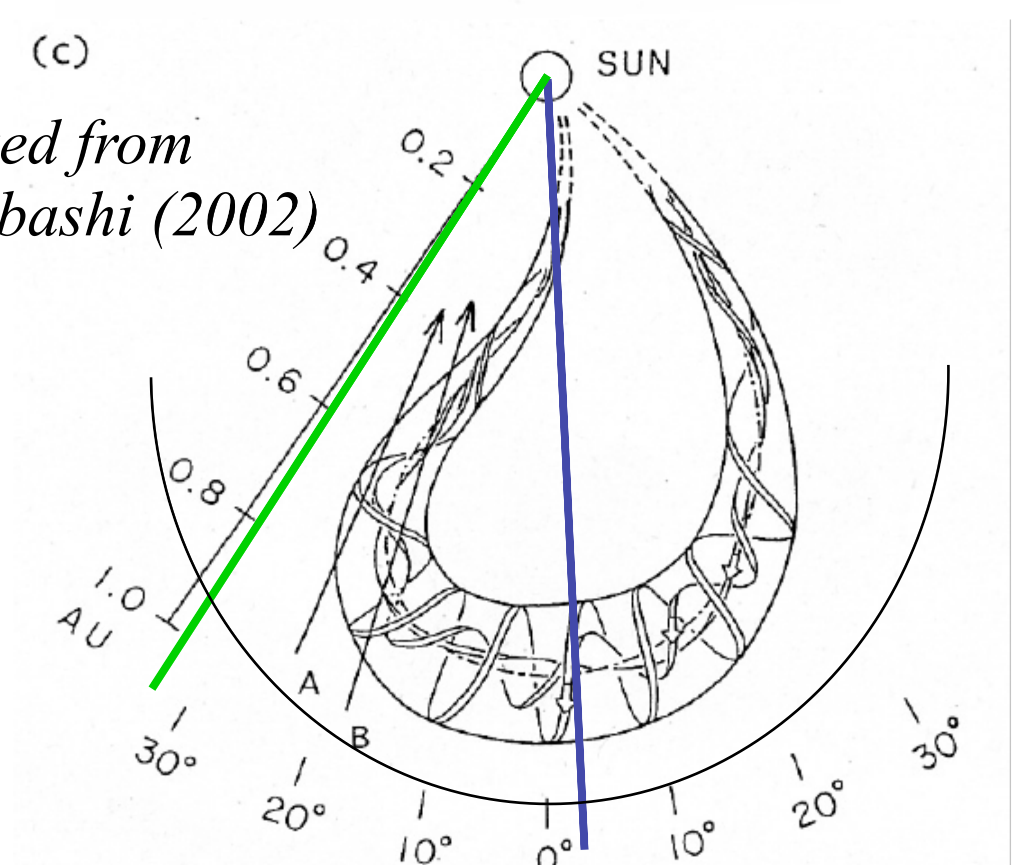

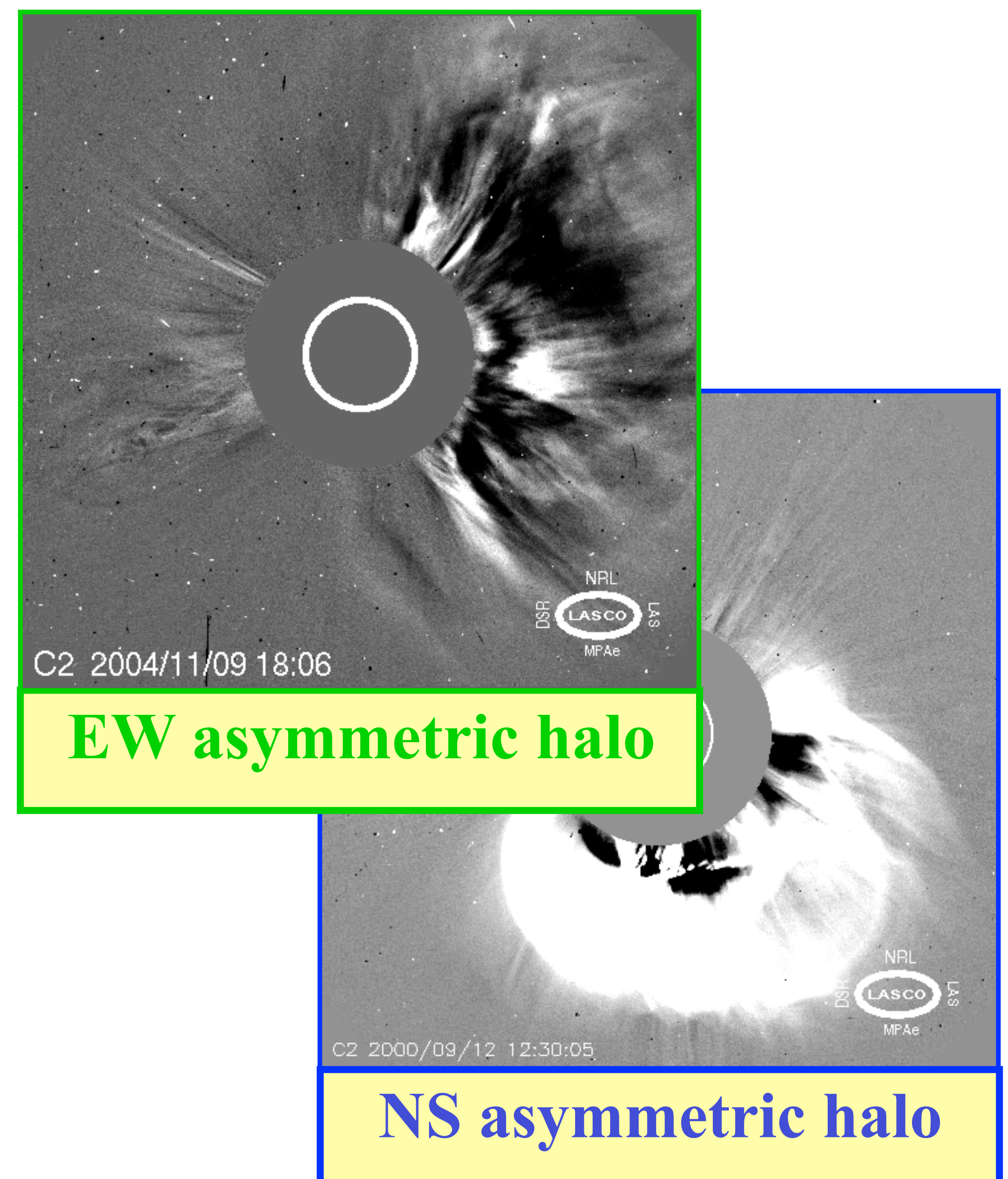

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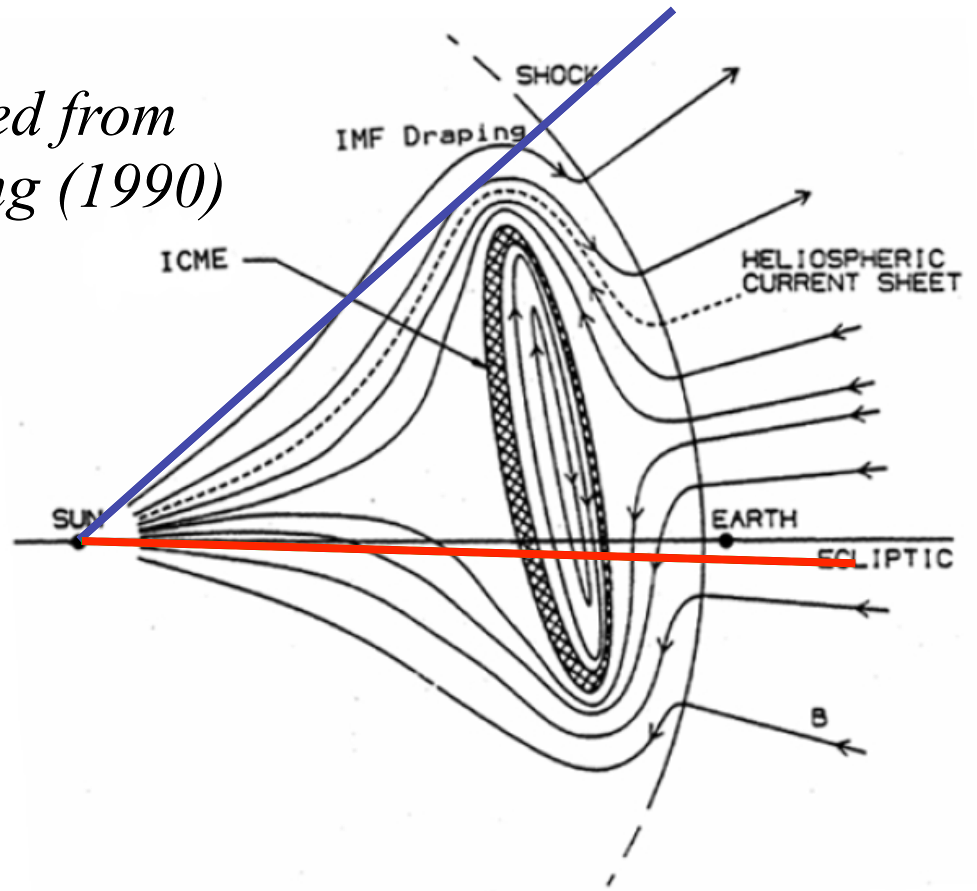

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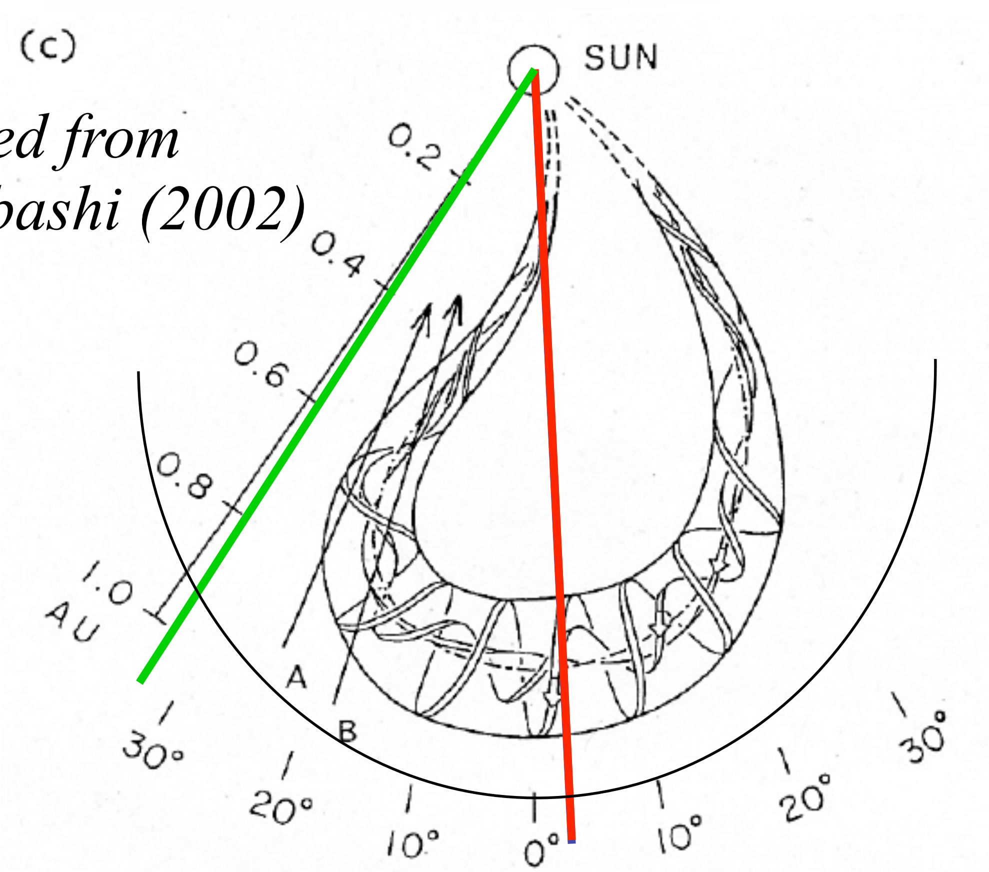
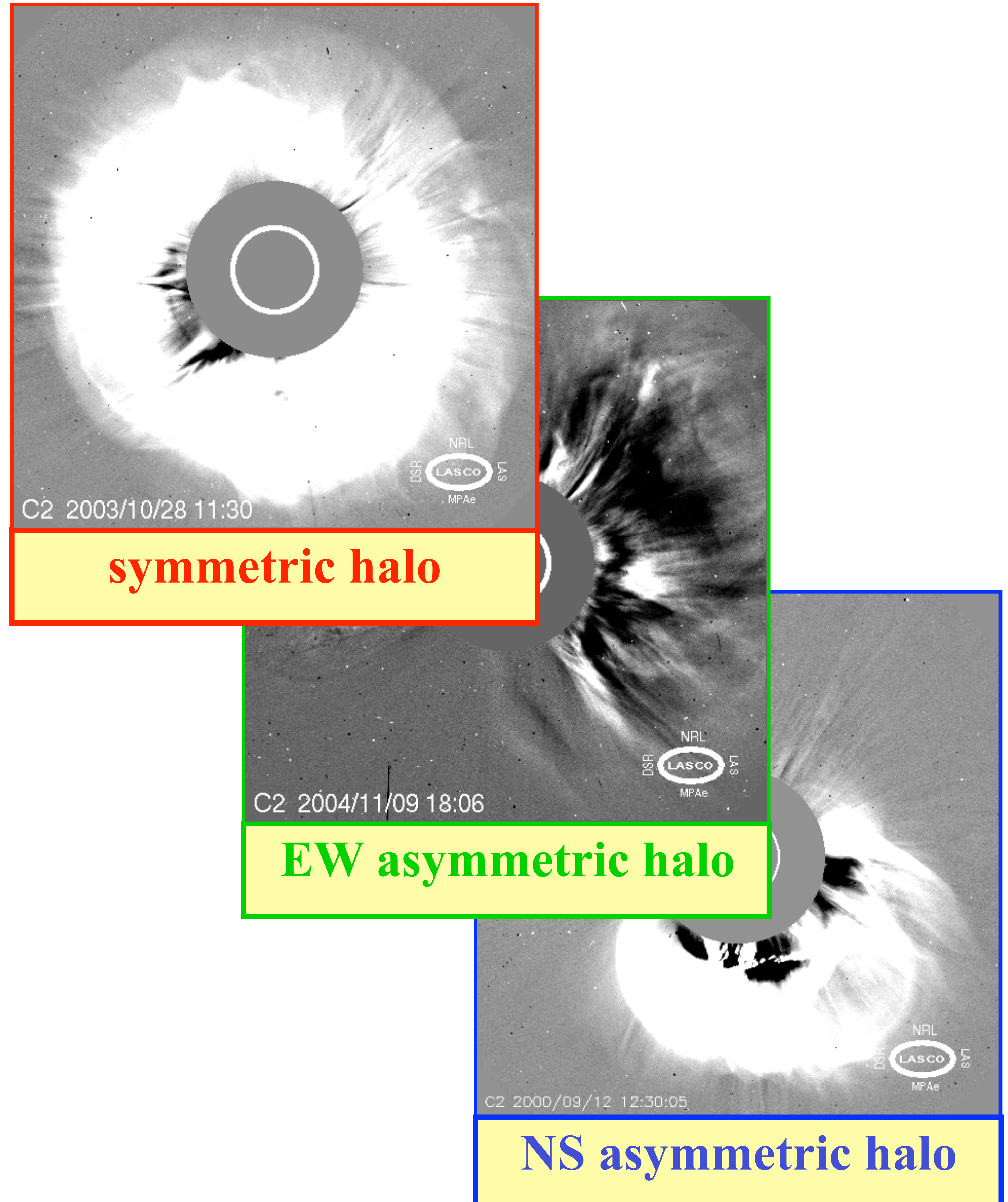
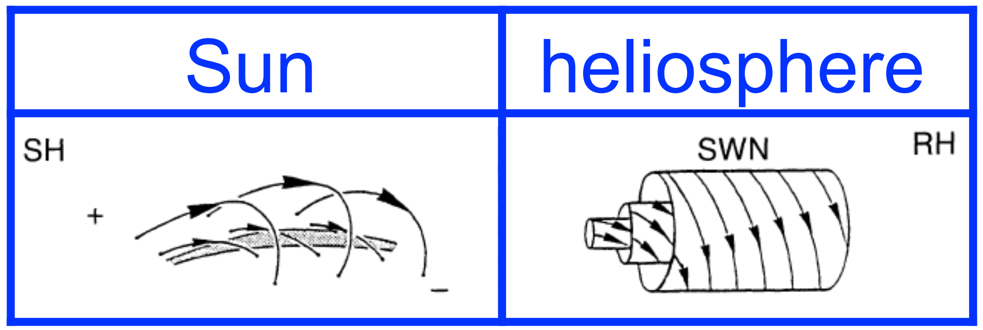




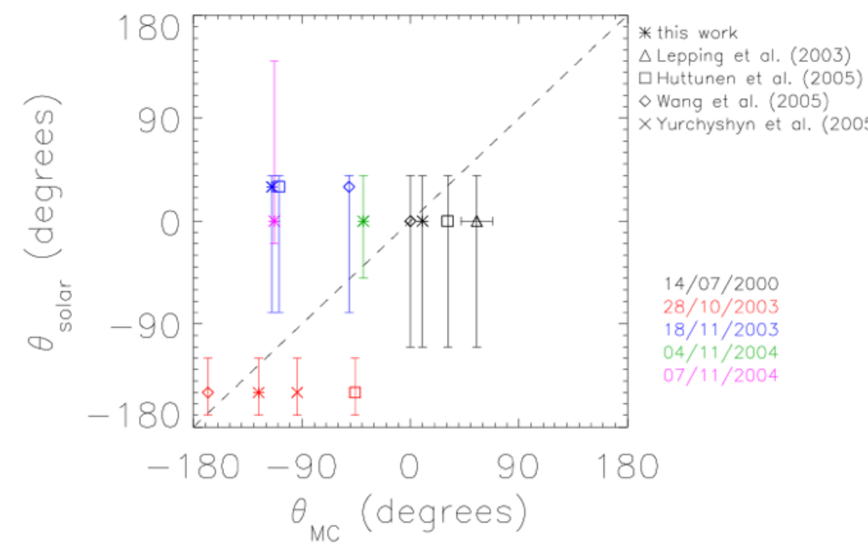
What will be the ICME structure?

Inferring the magnetic cloud orientation from solar observations

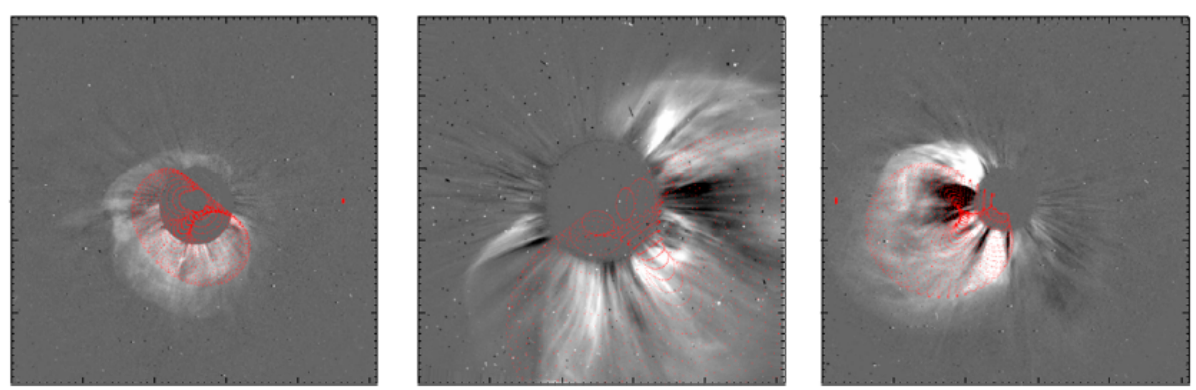
- Attempts to derive the magnetic cloud orientation from solar observations (filament/arcade orientation) have mixed success.
- In addition, it is not clear if the resulting ICME will have the configuration of a magnetic cloud!

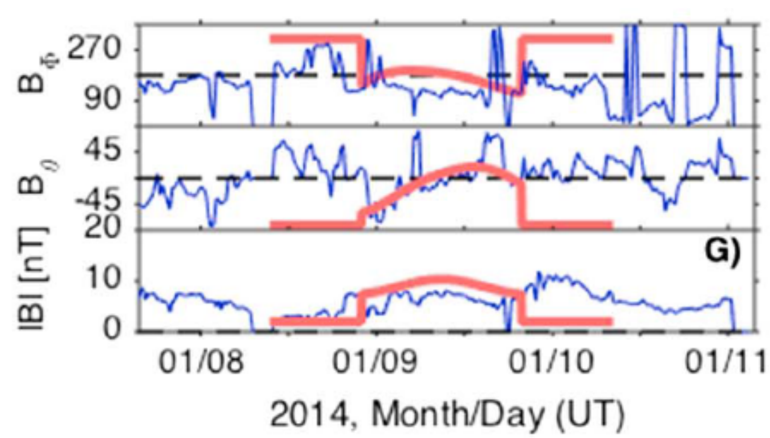


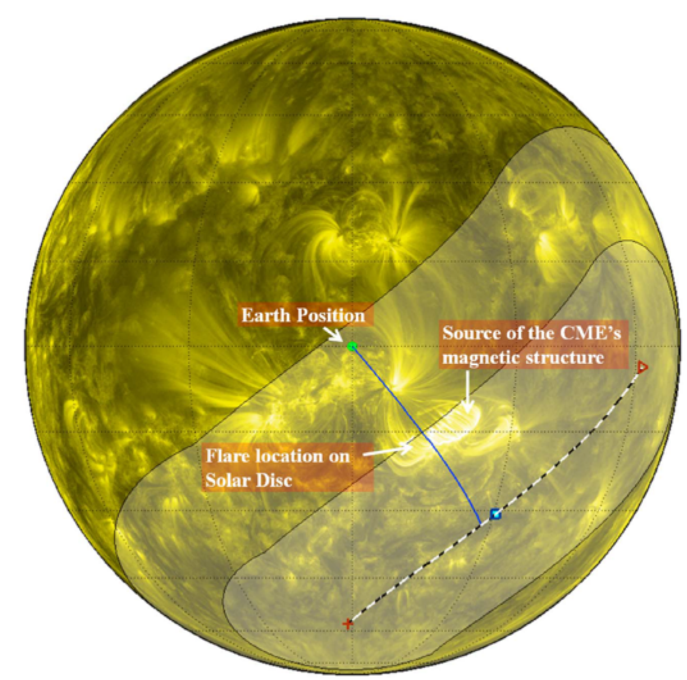
(Marubashi 1986; Bothmer & Schwenn 1994; Rust 1994; Bothmer & Schwenn 1998 Yurchyshyn et al. 2001; McAllister et al. 2001)



(Zhukov et al. 2005)



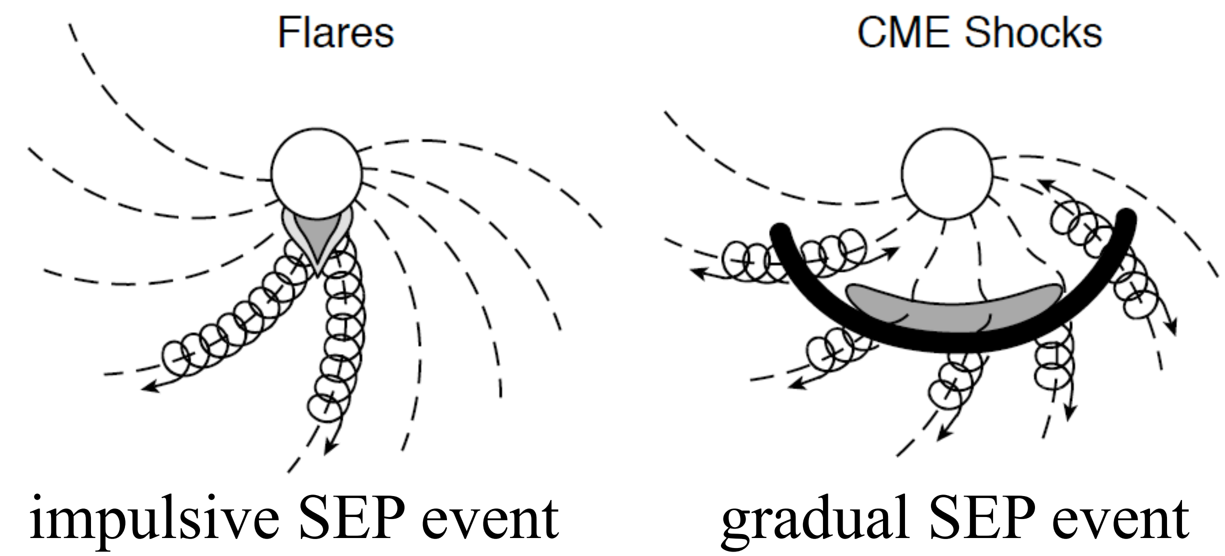




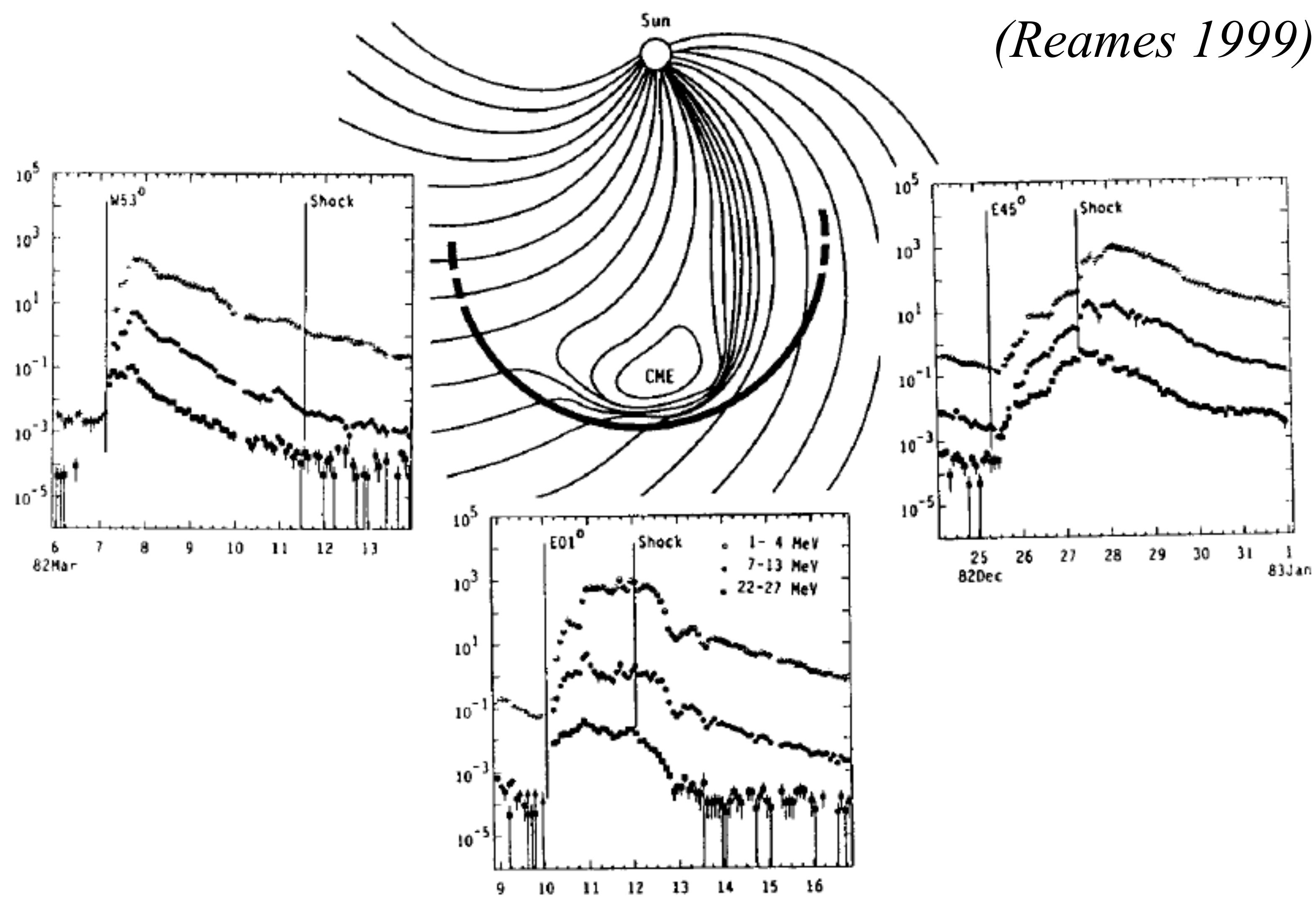
(Savani et al. 2015)

SEP events: what we know

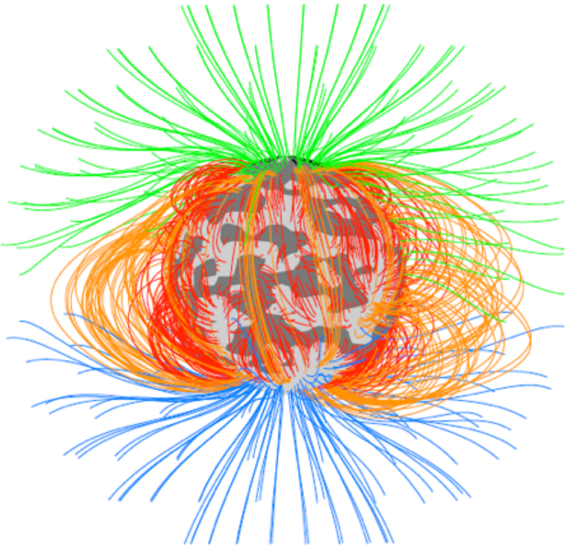
- SEP events can generally be classified as impulsive (produced by flares) and gradual (accelerated at the CME-driven shocks).
- Western events produce a quick rise of the SEP flux.
- Eastern events produce a slow rise.
- To predict the time profile of the particle flux, we need to know the configuration of the interplanetary magnetic field (IMF).

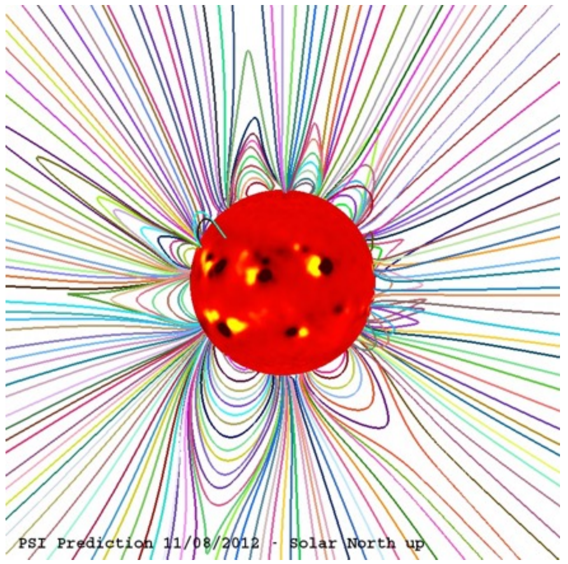


(Reames 1999)



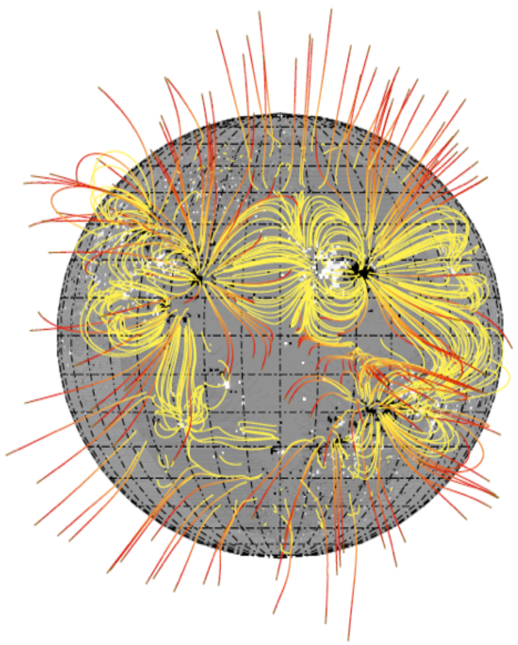
Global models of the corona and heliosphere

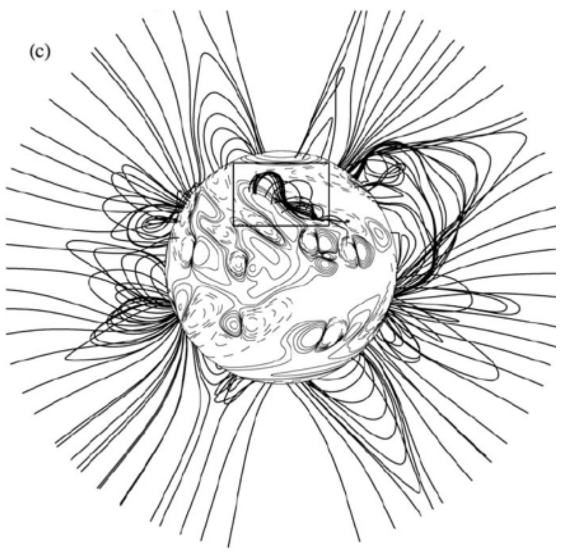




- Coronal models

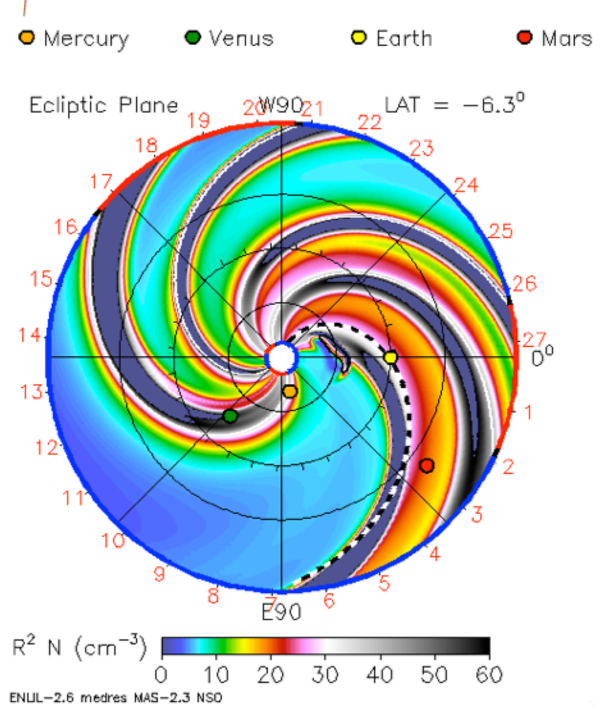
  - Potential field source surface (PFSS) model (e.g. Wang & Sheeley; DeRosa & Schrijver,..)
  - CORHEL/MAS model (Linker et al.)
  - Nonlinear force-free field (NLFFF) models (Yeates & MacKay; Tadesse, Wiegelmann, et al.)





- Solar wind models (taking a coronal model as a lower boundary condition)

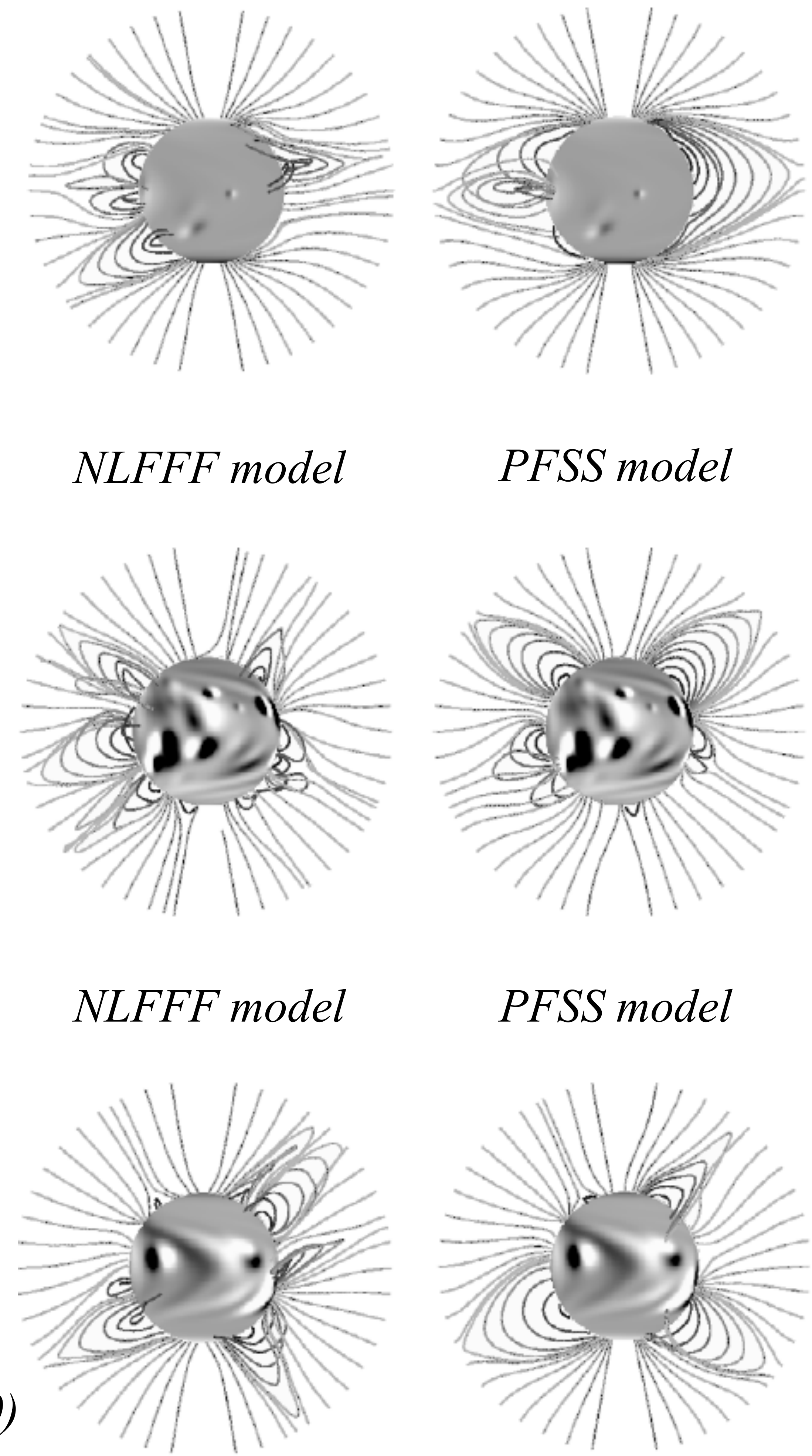
  - Wang-Sheeley-Arge (WSA) model
  - ENLIL model (Odstrcil et al.)
  - SWMF model (Gombosi et al.)
  - Euhforia model (Pomoell et al.)
  - ...



- Further on I will talk mostly about the PFSS model (or WSA model when applied to the solar wind) as it is much more extensively tested and validated than other models.

Problems of models to derive coronal magnetic fields

- The extrapolated field is strongly model-dependent.
- The extrapolated field is static.
- Realistic extrapolations also require difficult horizontal photospheric field measurements and strong assumptions about critical but unobserved quantities (e.g. magnetic field at the low-β coronal base is assumed to be the same as in the high-β photosphere).
- The extrapolated field cannot always reproduce accurately complex magnetic configuration of the solar corona.

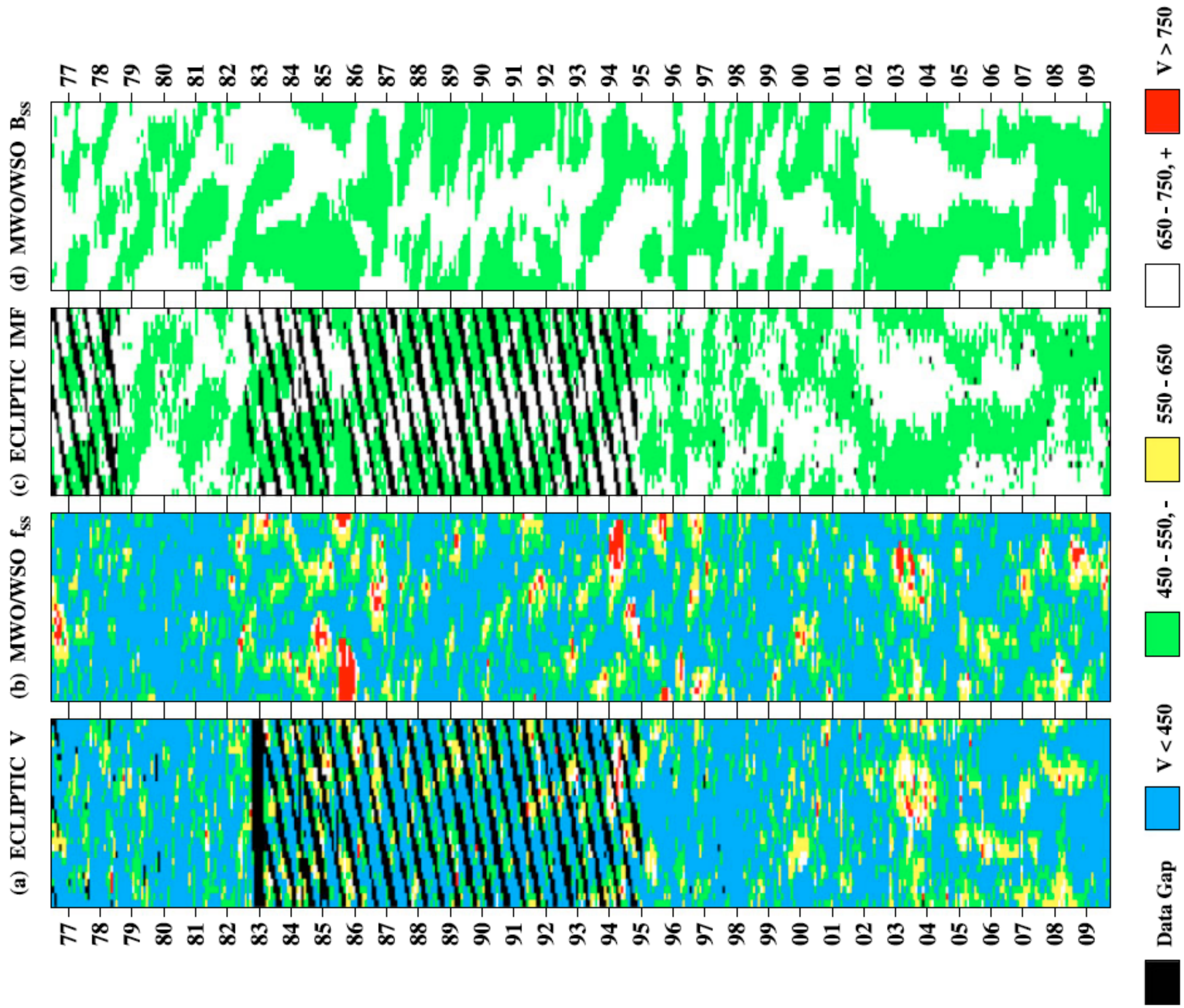


(Yeates et al. 2010)

PFSS/WSA model: a successful description of the solar wind?

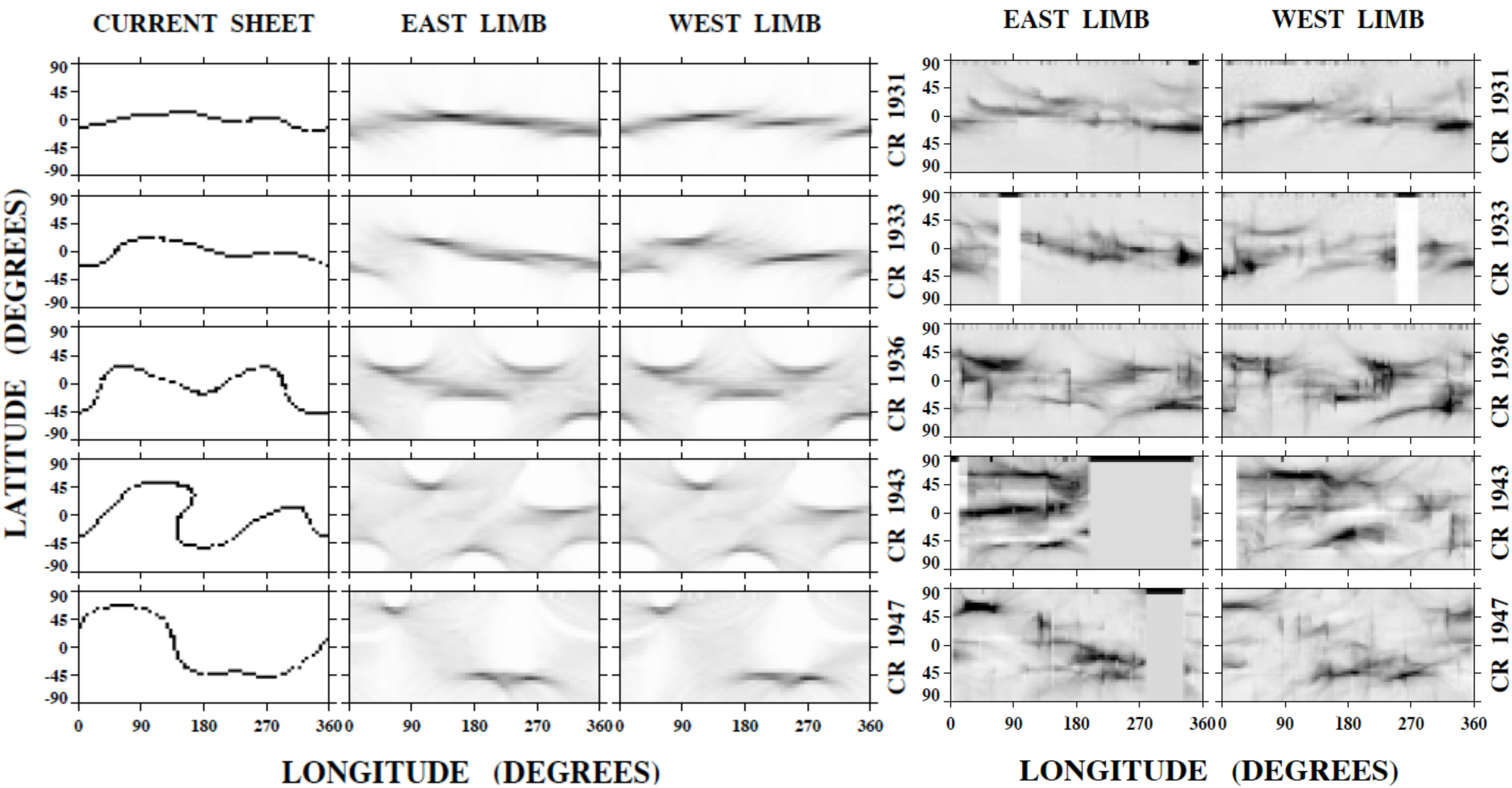
- The PFSS/WSA model was found successful to describe the sector structure of the interplanetary magnetic field and the general configuration of the fast/slow solar wind in the heliosphere.

- The agreement holds both for low and high solar activity.



(Y.-M. Wang 2011)

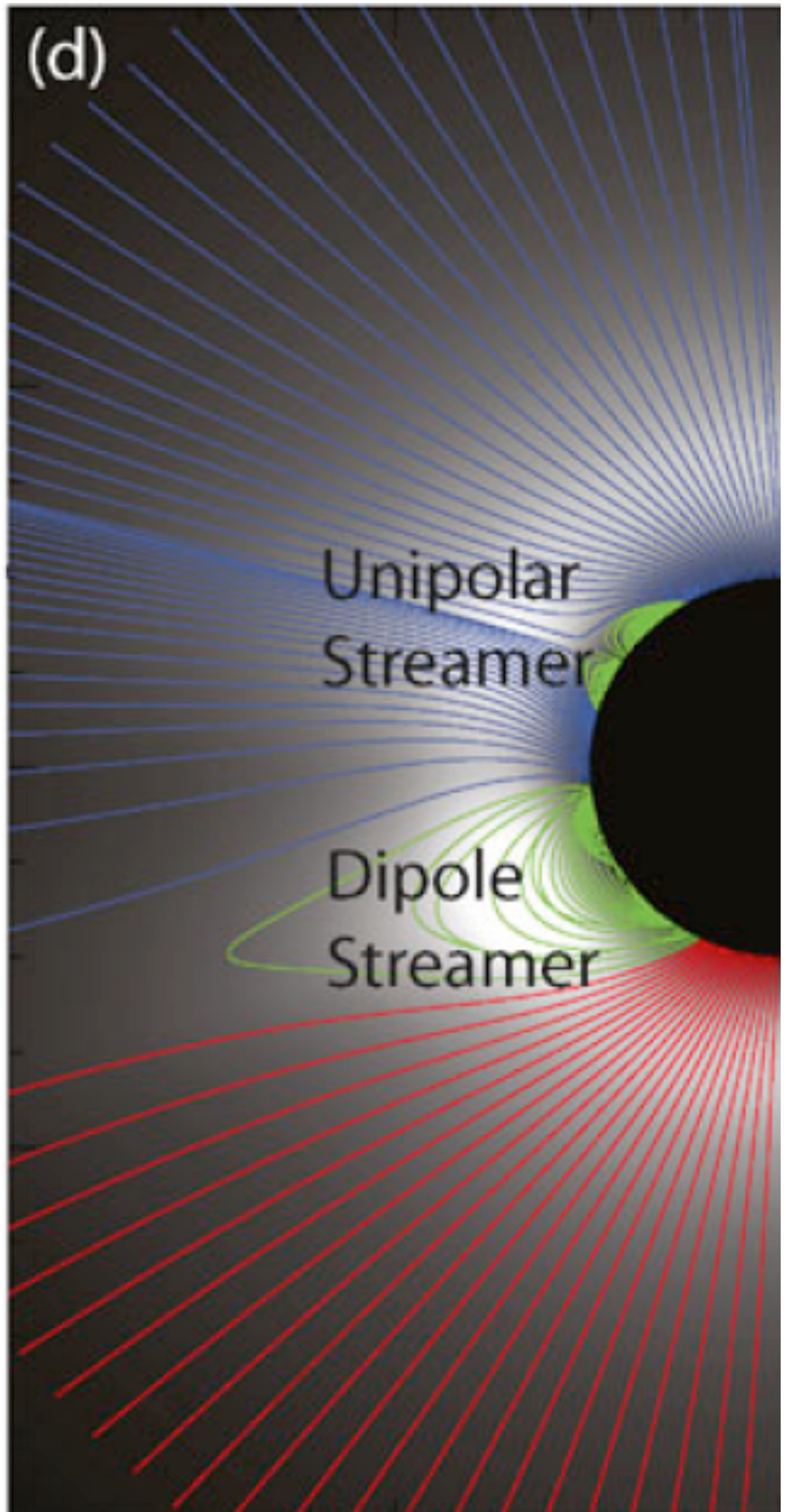
Coronal streamer belt



The configuration of the coronal streamer belt can be described by the coronal neutral line in the PFSS model, but only approximately and only during the low activity epoch.

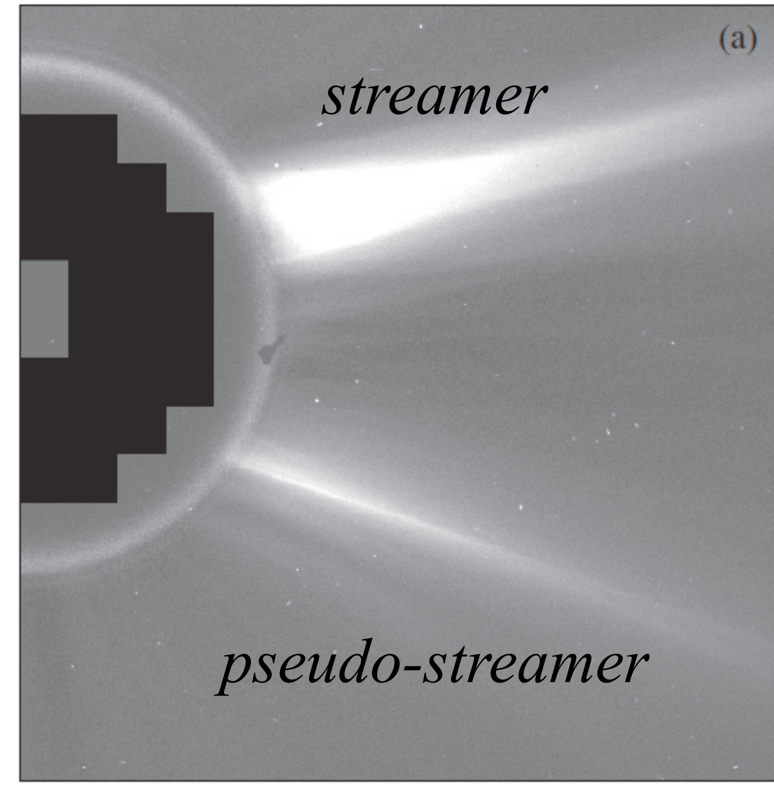
(Y.-M. Wang et al. 2000)

Coronal pseudo-streamers

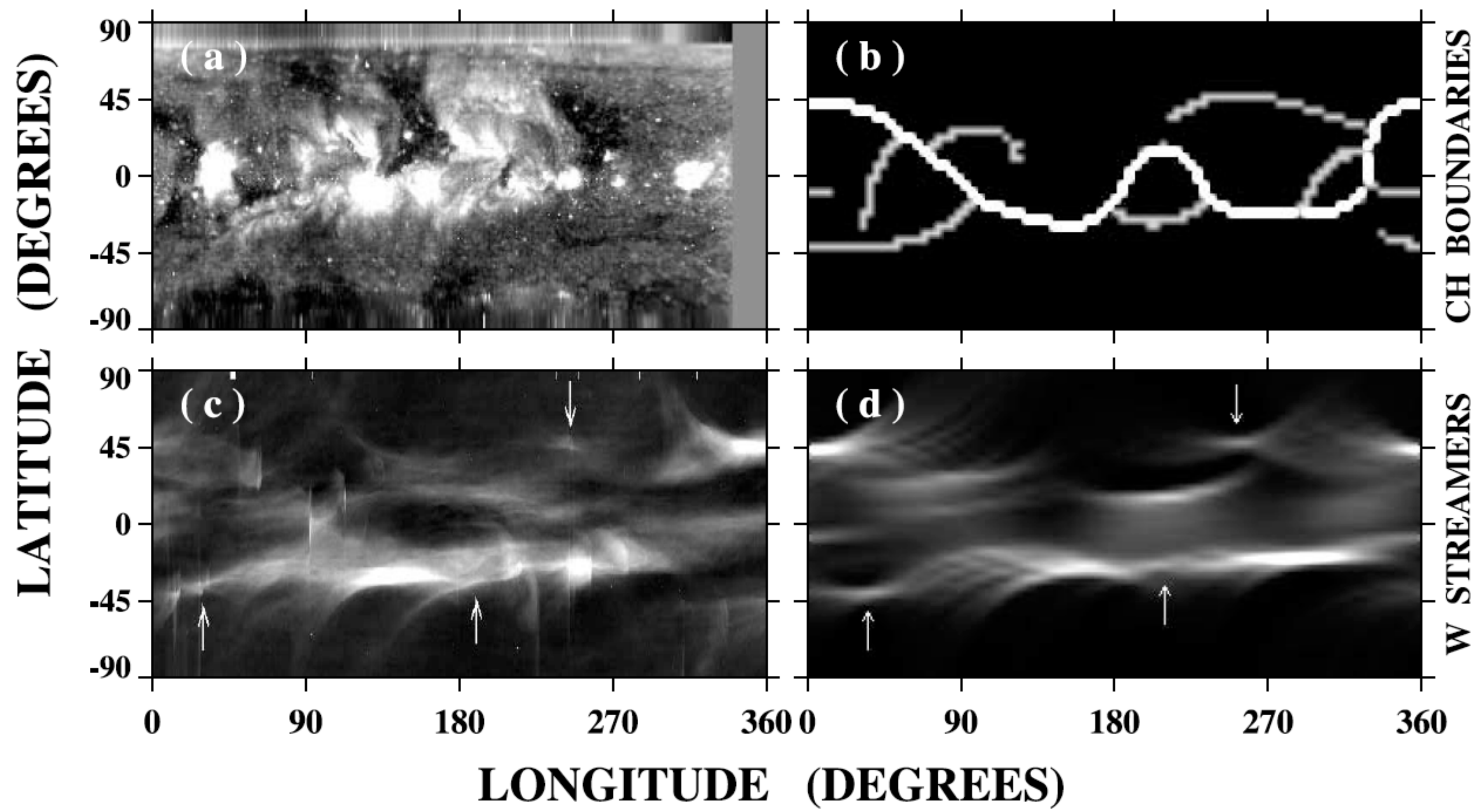


(Riley & Luhmann 2012)

PFSS model describes the streamer belt structure better if pseudo-streamers are taken into account *(Wang et al. 2007)*

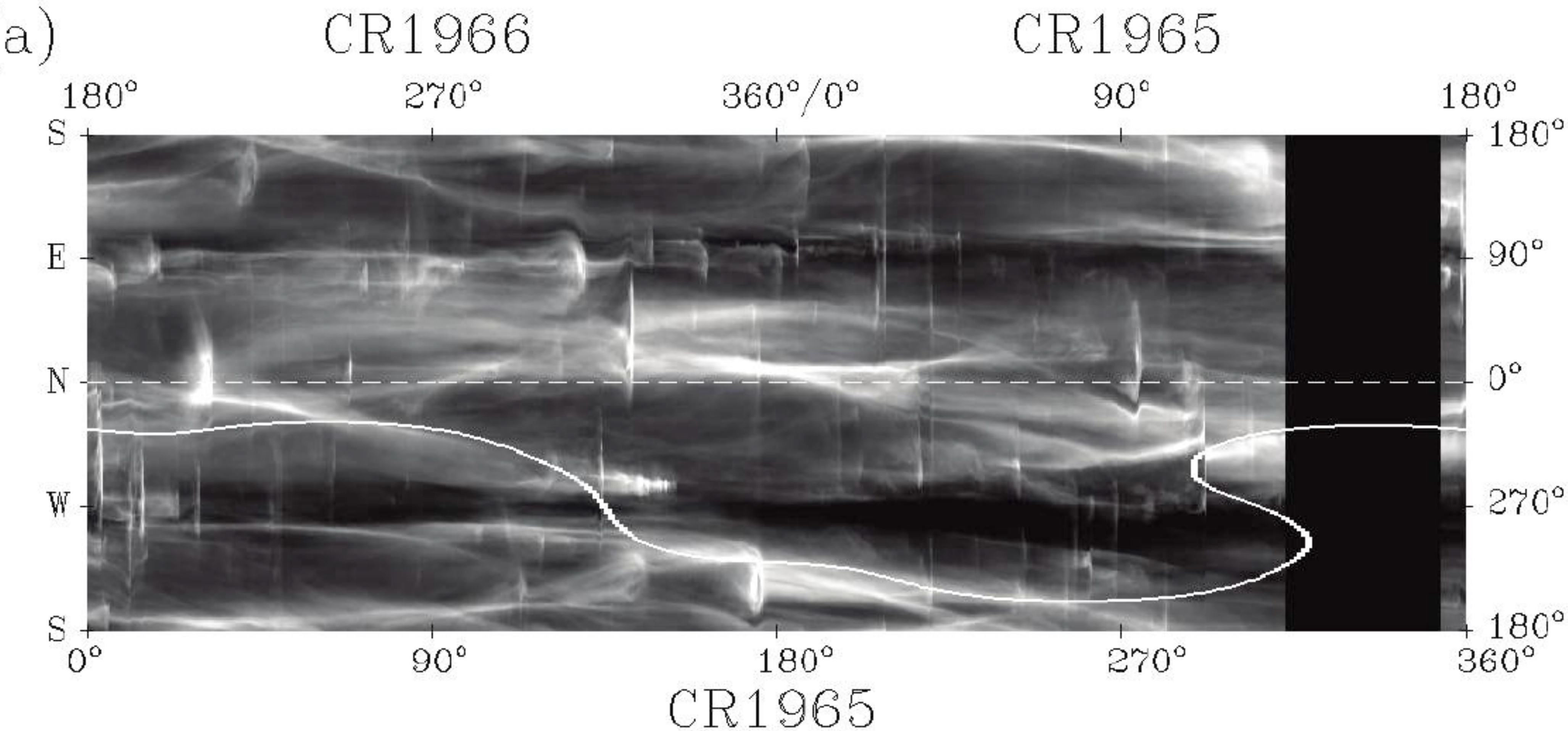


(Y.-M. Wang et al. 2012)

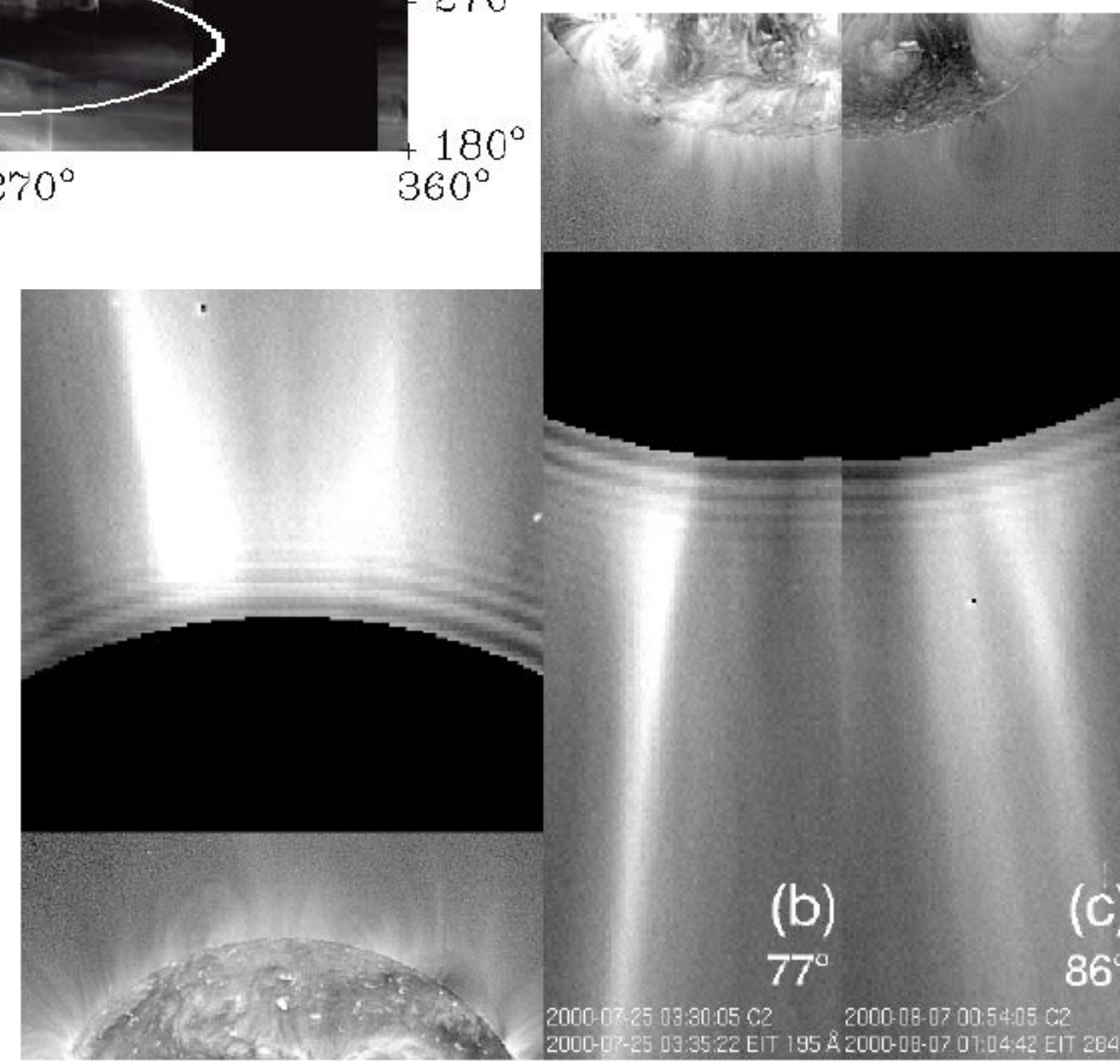


(Y.-M. Wang et al. 2007)

Polar coronal streamers

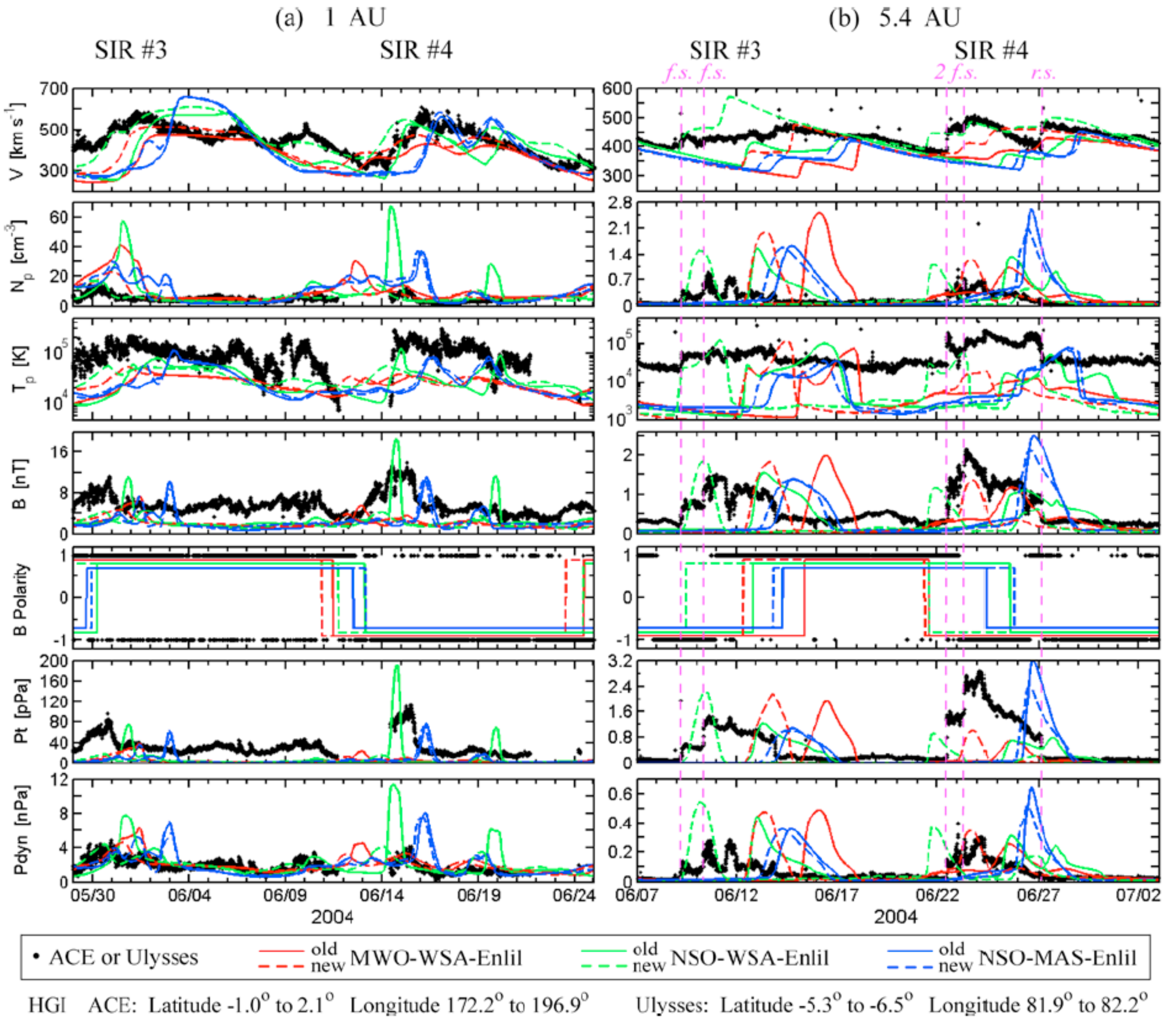


- Polar coronal streamers often cannot be described by the PFSS model *(Zhukov et al. 2008)*.
- Note that polar streamers are NOT pseudo-streamers *(Zhukov et al. 2008)*!
- Bad agreement between models and observations in this case can perhaps be expected as solar polar magnetic field is difficult to observe.

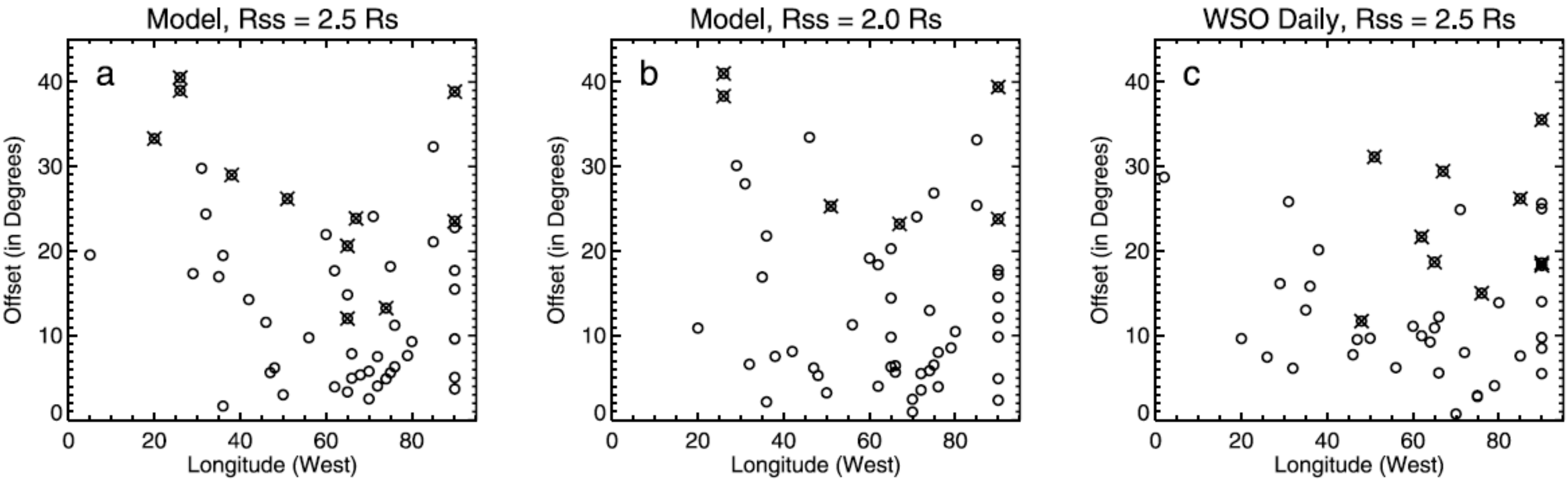


Solar wind prediction by the ENLIL model has its limitations!

- The predicted arrival times of the background solar wind (in particular, stream interaction regions) can be offset from reality by up to 2 days at 1 AU and up to 4 days at 5.4 AU *(Jian et al. 2011)*.



Impulsive SEP events demonstrate a limited precision of the PFSS model



Only in 40% of the cases one can find magnetic field lines that are close (within ±7.5° in longitude and ±5° in latitude) both to the impulsive SEP event source region and to the Earth-connected field line at the source surface *(Nitta et al. 2006).*

Modern IMF models are not better than the Archimedean spiral model

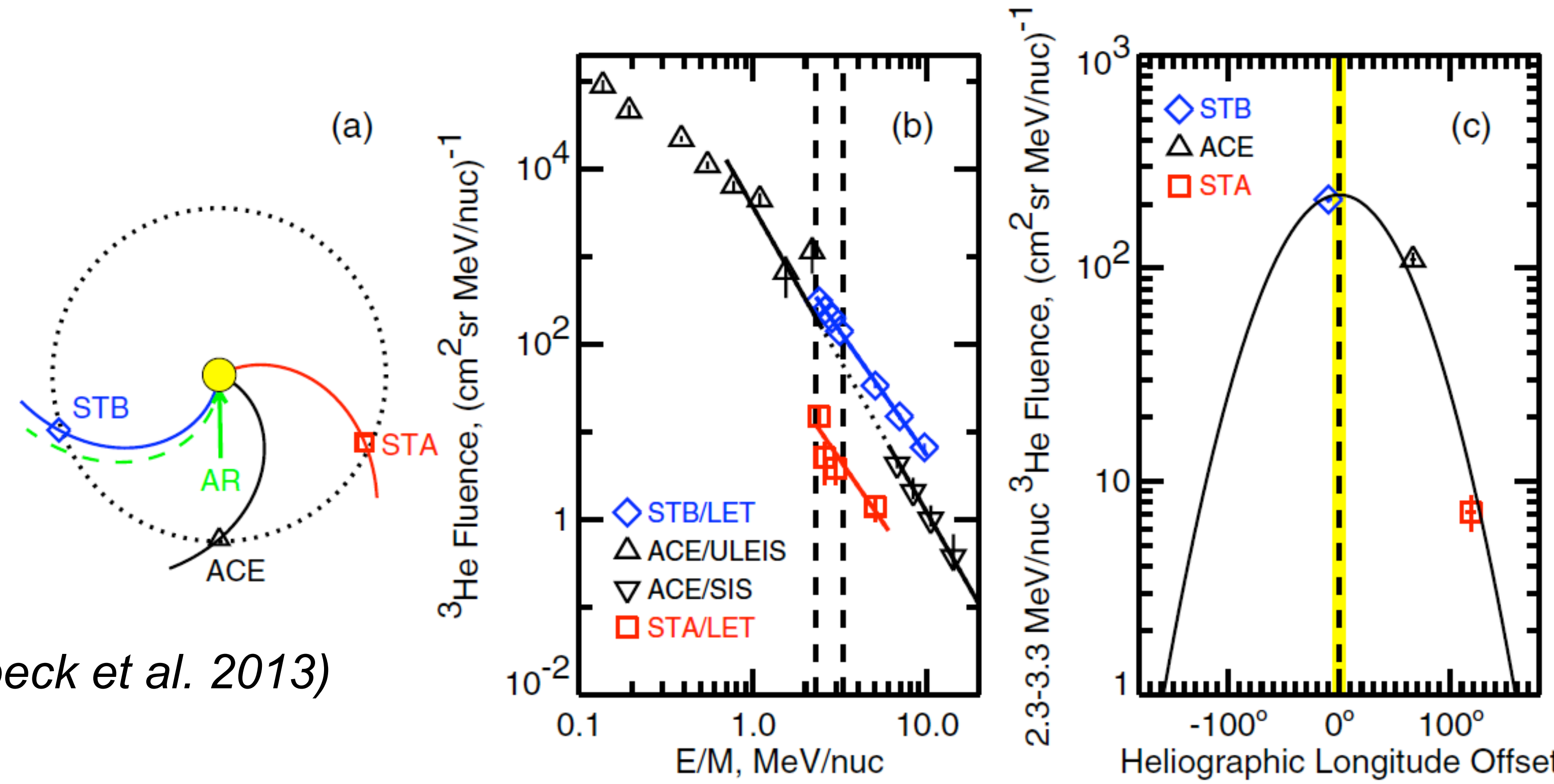
Table 6. Difference in Longitude and Latitude Between the Models' Foot Point Forecasts and the Identified SEP Source Locations[a]

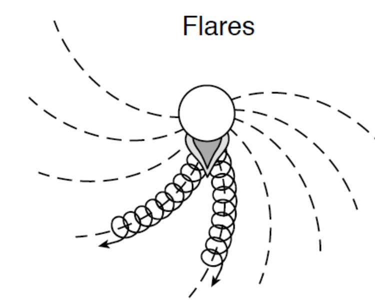
SEP Event Number	Longitude Offset				Latitude Offset			
	ASM	PFSS + Spiral	WSA	WSA/ENLIL	ASM	PFSS + Spiral	WSA	WSA/ENLIL
1	2°E	20°E	1°E/10°E	20°E	30°N	38°N	93°N/91°N	29°N
2	44°W	56°W	56°W/57°W	56°W	22°N	6°N	6°N	8°N
3	10°E	13°W	7°W	5°W	11°N	32°N	38°N	46°N
4	12°E	9°E	22°W/19°W	8°E	11°N	8°S	6°S	1°S
5	29°E	37°E	13°W/14°W	2°W	24°S	52°S	56°S	58°S
6	30°W	32°W	35°W	47°W	26°S	11°S	11°S	12°N
7	15°E	12°E	9°E	7°E	8°N	17°N	29°N	42°N
8	10°E	2°W	34W°/32W	20°W	10°N	2°S	0°S	0°S
9	6°E	1°W	5°E/34°E	34°E	23°S	3°S	1°N/7°S	16°N
10	10°E	0°	9°W/13°W	5°W	10°S	8°S	8°S	16°N
11	95°W	88°W	93°W/78°W	88°W	10°N	25°N	27°N/40°N	27°N
11*	46°W	39°W	44°W/29°W	39°W	16°N	31°N	33°N/46°N	33°N
12	24°W	26°W	32°W/31°W	26°W	15°S	24°S	26°S/25°S	23°S
13	28°E	13°E	38°W	20°W	16°N	1°S	13°S	41°S
14	10°E	50°E	68°E/66°E	56°E	26°S	30°S	29°S	22°S
15	27°W	3°E	16°E	16°E	16°S	27°S	24°S	24°S
Average	23	25	27/32	24	17	19	27/24	25
Average Excl. 2, 11, 14	17	14	18/22	18	17	19	29/25	26

[a]Event 11* is our proposed alternative source location (at 31°W, 18°S) for event 11.

- The performance of modern models is not better than that of the simplest Archimedean spiral model (ASM in the table), according to recent validation studies *(MacNeice et al. 2011)*.
- The main source of error seems to be the models' inability to reproduce low-latitude open flux.

Detection of impulsive SEP events over a wide range of longitudes





(Wiedenbeck et al. 2013)

- Contrary to what one can expect from the classical picture, detections of impulsive SEP events (i.e. those accelerated by flares) by widely separated spacecraft are not uncommon, even with longitudinal separations above 60° *(Wiedenbeck et al. 2013, Dresing et al. 2012)*.

- This can be explained - a posteriori - by a sufficiently strong diffusion of particles perpendicularly to the interplanetary magnetic field *(Giacalone and Jokipii 2012)*, or by particle propagation along meandering field lines *(Laitinen et al. 2013)*.

- However, at present there is no independent way to infer the amount of the cross-field diffusion and use it in a predictive model.

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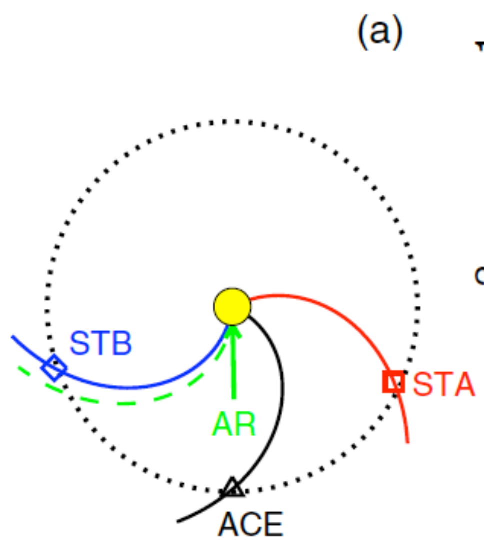

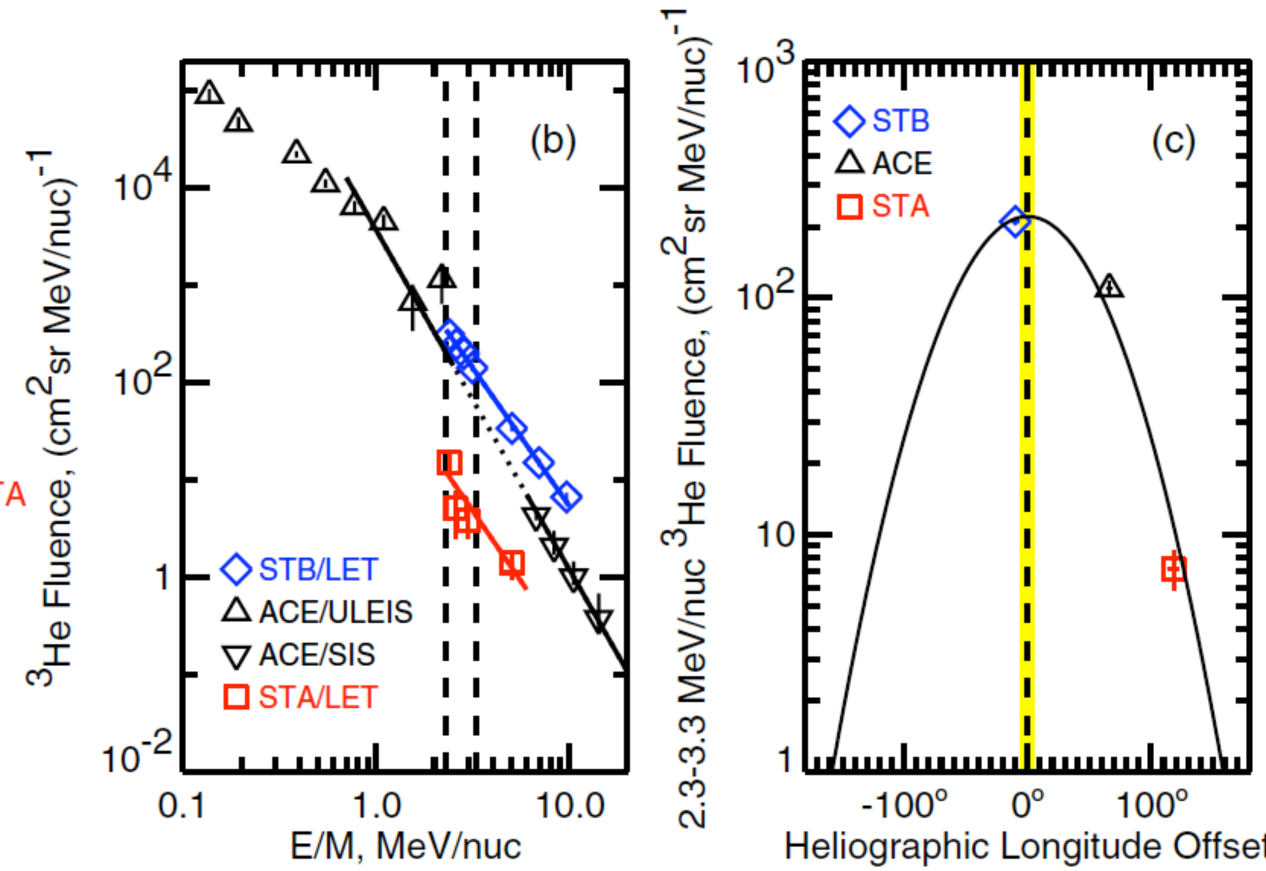

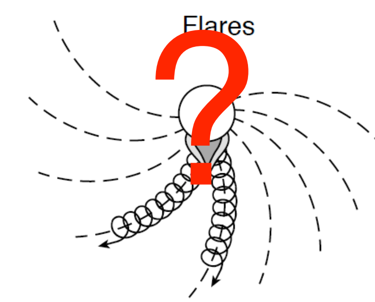

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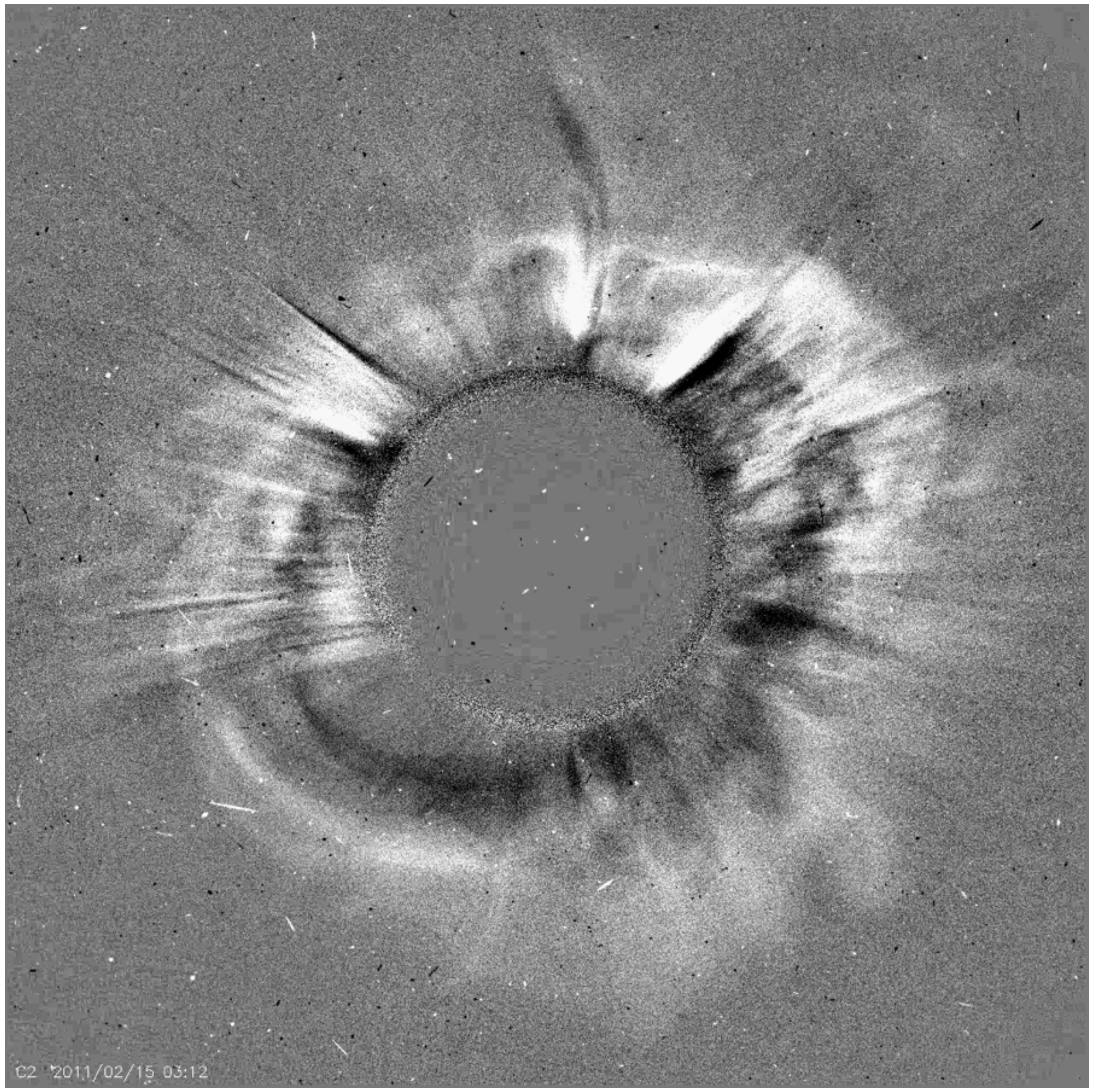
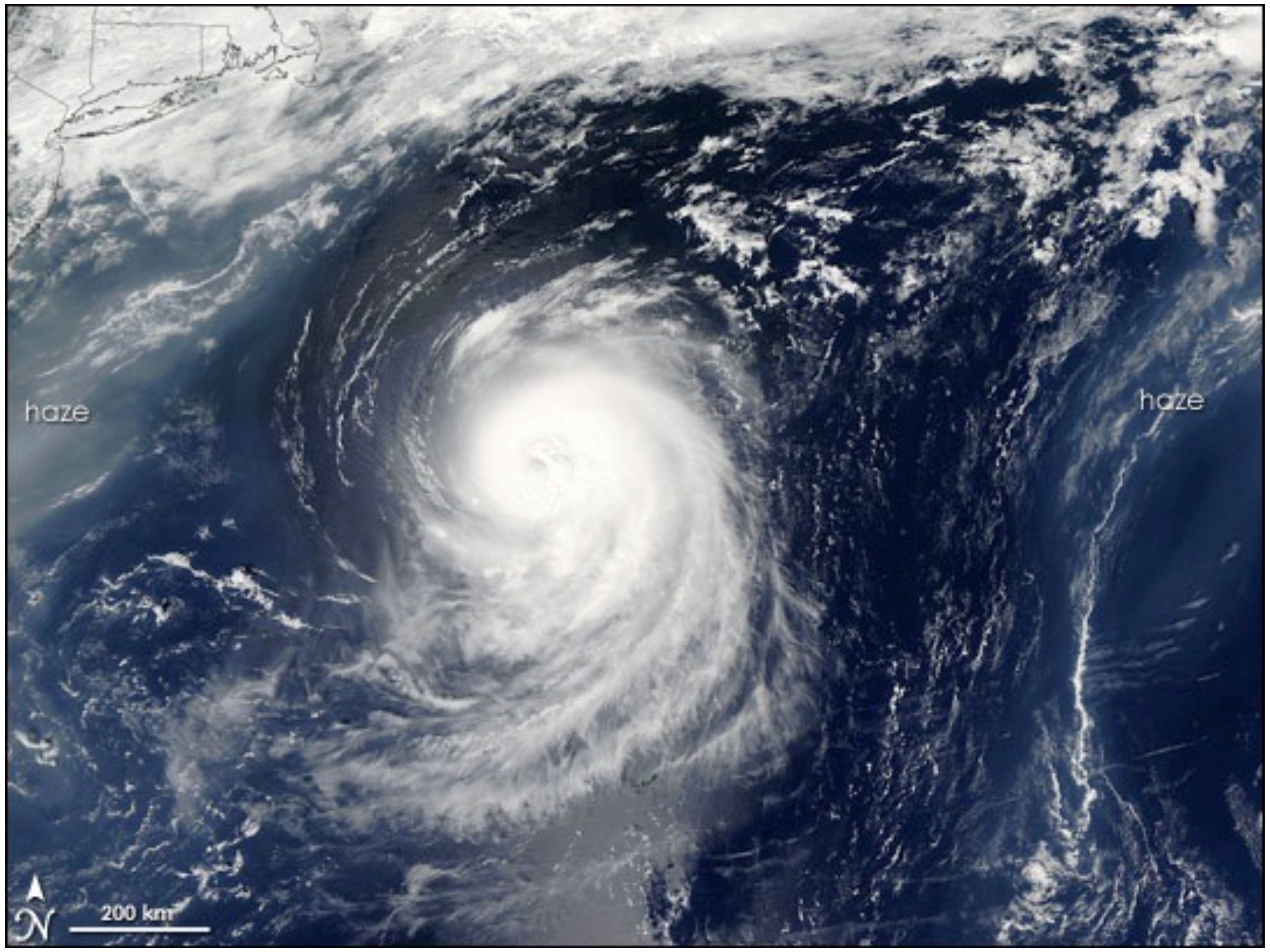
Predicting weather on Earth vs predicting weather in space?

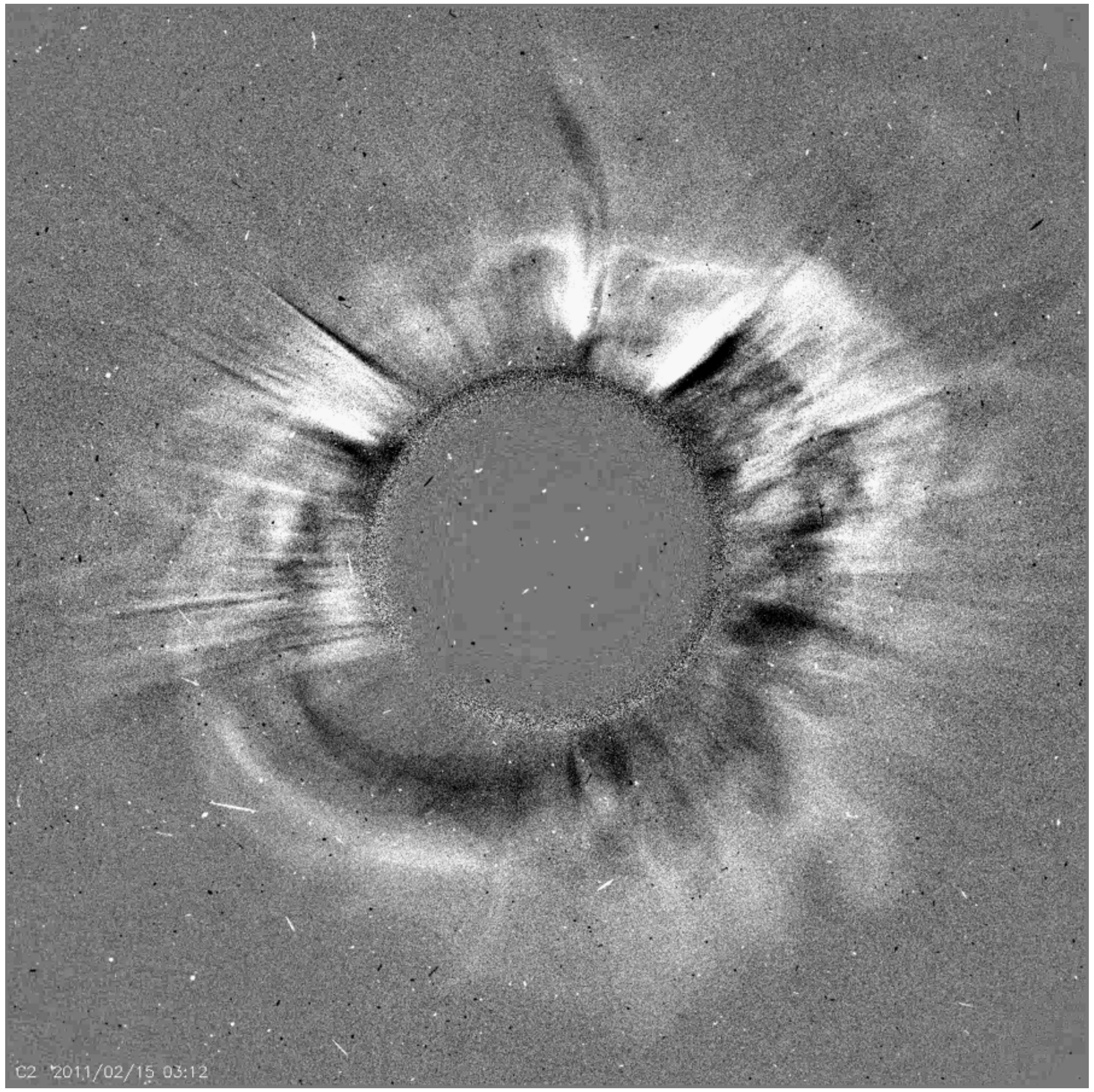


halo CME,
February 15, 2011



hurricane Irene,
August 15, 2011

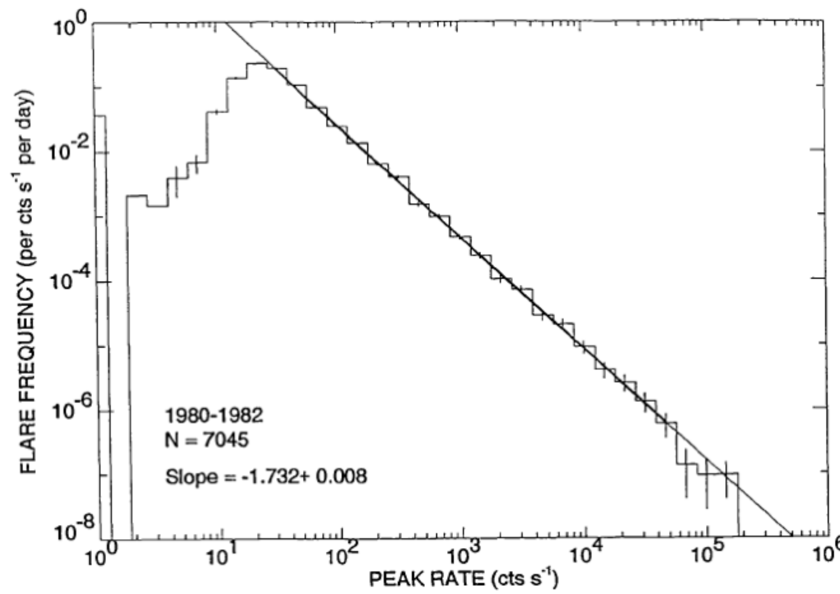
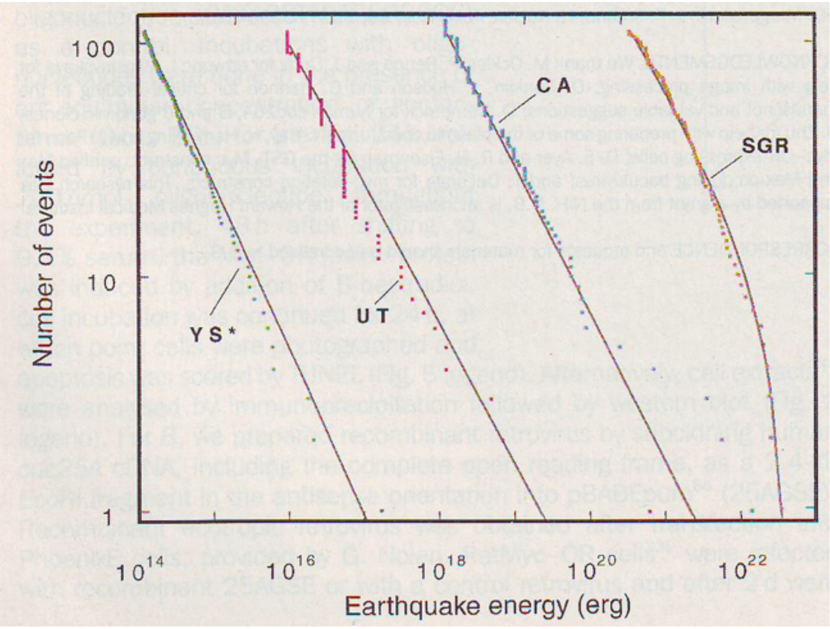
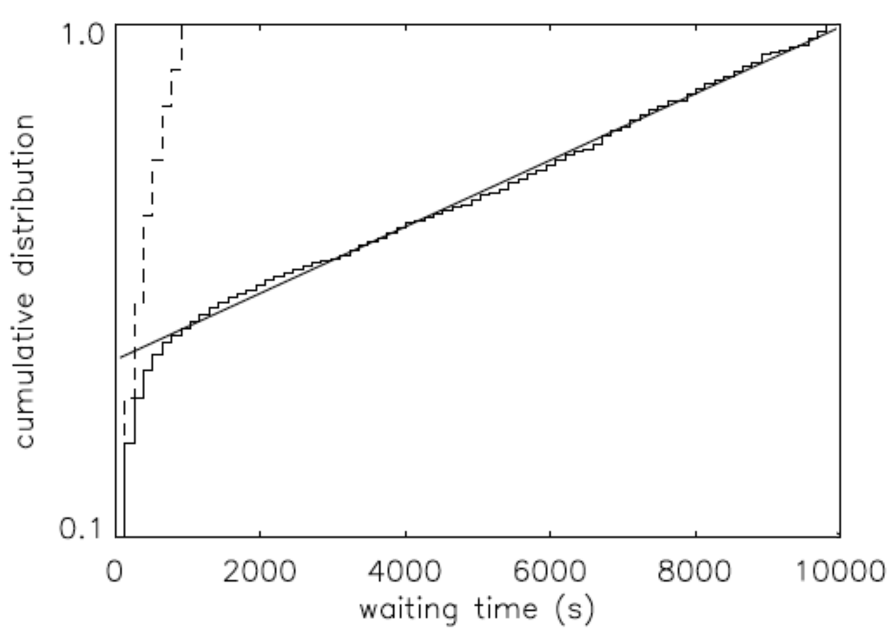
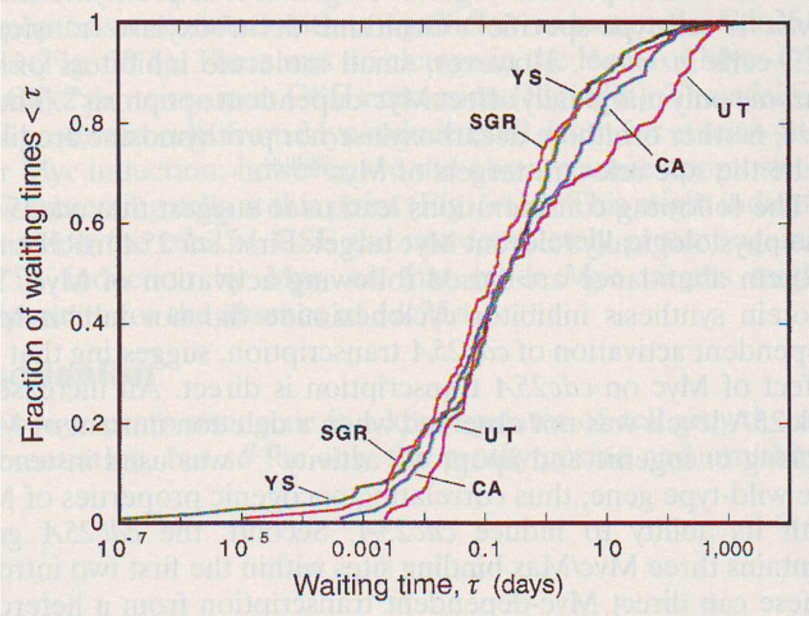
Predicting solar eruptions vs predicting earthquakes!



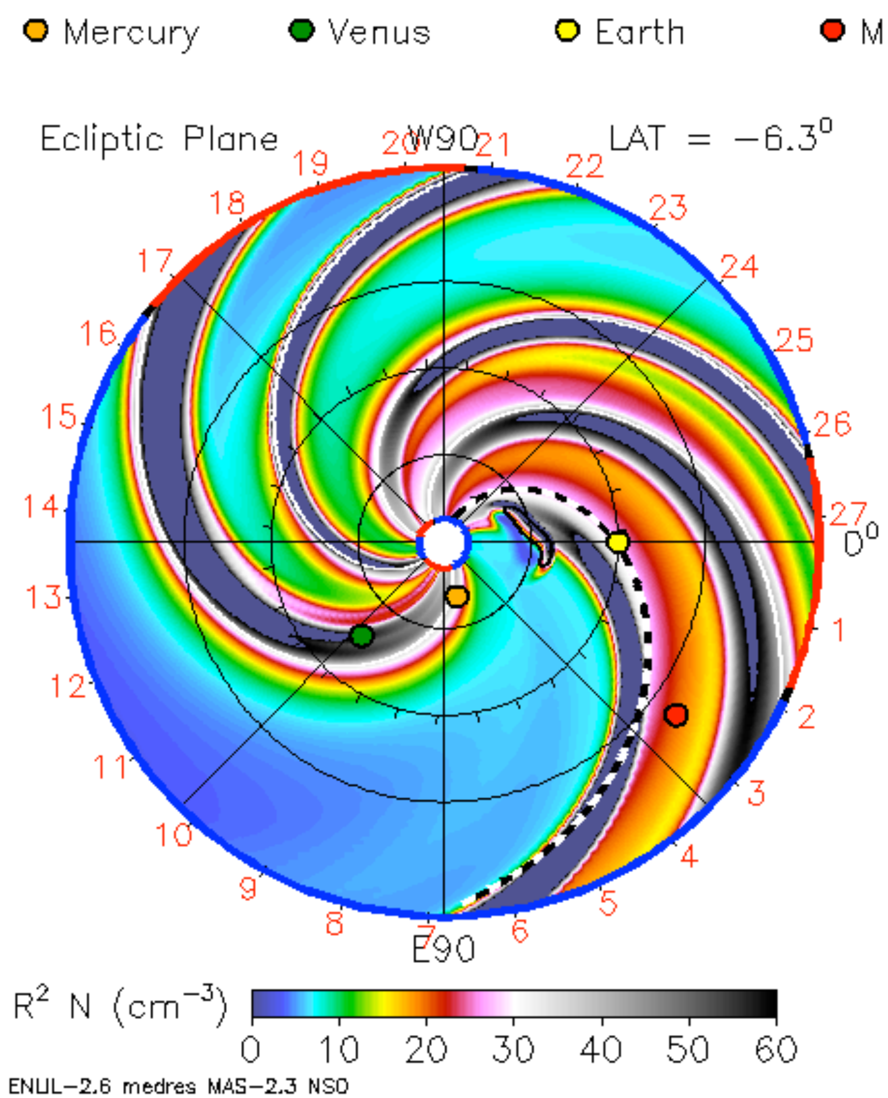
halo CME,
February 15, 2011

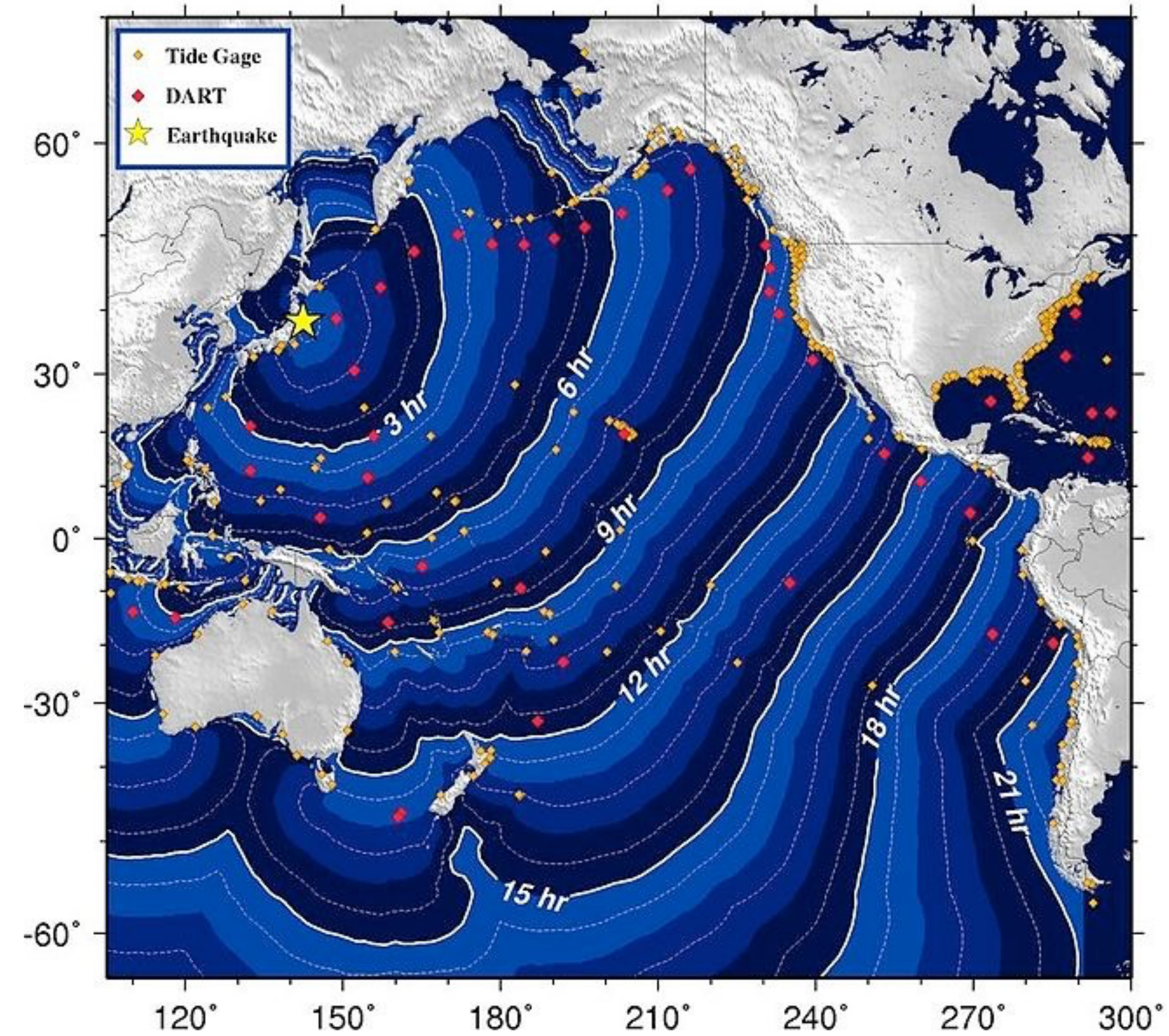
Tohoku earthquake,
March 11, 2011

Predicting solar eruptions vs predicting earthquakes!

	flares	earthquakes
Power-law energy distributions		
	(Crosby et al. 1993)	(Cheng et al. 1996)
Similar waiting-time distributions (lognormal or Weibull distribution?)		
	(adapted from Wheatland et al. 1998)	(Cheng et al. 1996)

ICME propagation vs tsunami propagation





- Predictive models exist both for tsunami propagation and ICME propagation.
- Tsunami is a surface wave and its speed depends on the square root of the water depth.
- ICME is a convective disturbance and its propagation speed strongly depends on the source CME dynamics.

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- Regarding the IMF configuration, quantitative validation studies of many model predictions (e.g. positions and shapes of coronal holes, streamers) are currently scarce.

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  - This is valid along all the three pathways mentioned in the white paper!