Prediction & Testing of Bz, Local CME Properties, White Light Images, & Type II Radio Emission from Sun to Earth

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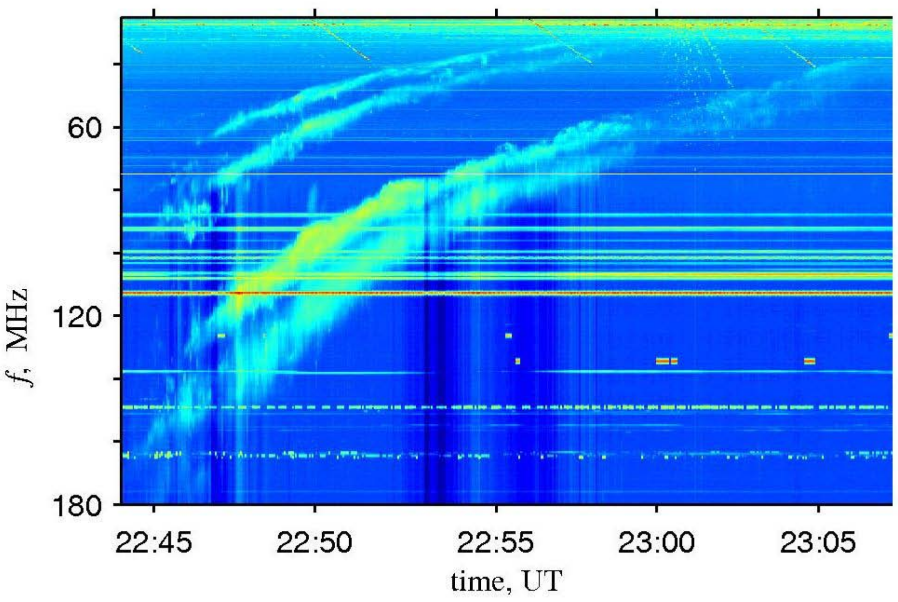
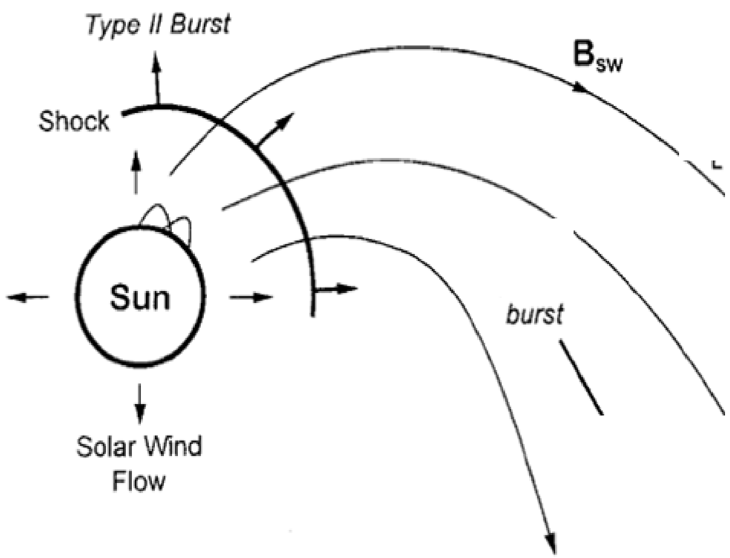




[ISEST, 20/9/2017]

[Schmidt et al., ApJL, 2013; Schmidt & Cairns, JGR, 2014a,b, 2016; Cairns and Schmidt, 2015 ; Schmidt et al., JGR, 2016, 2017]

Outline

1. Type II bursts and CMEs

   ➔Vision: "Predict / measure CMEs & Type IIs to enable better space weather prediction"

2. Plasma physics

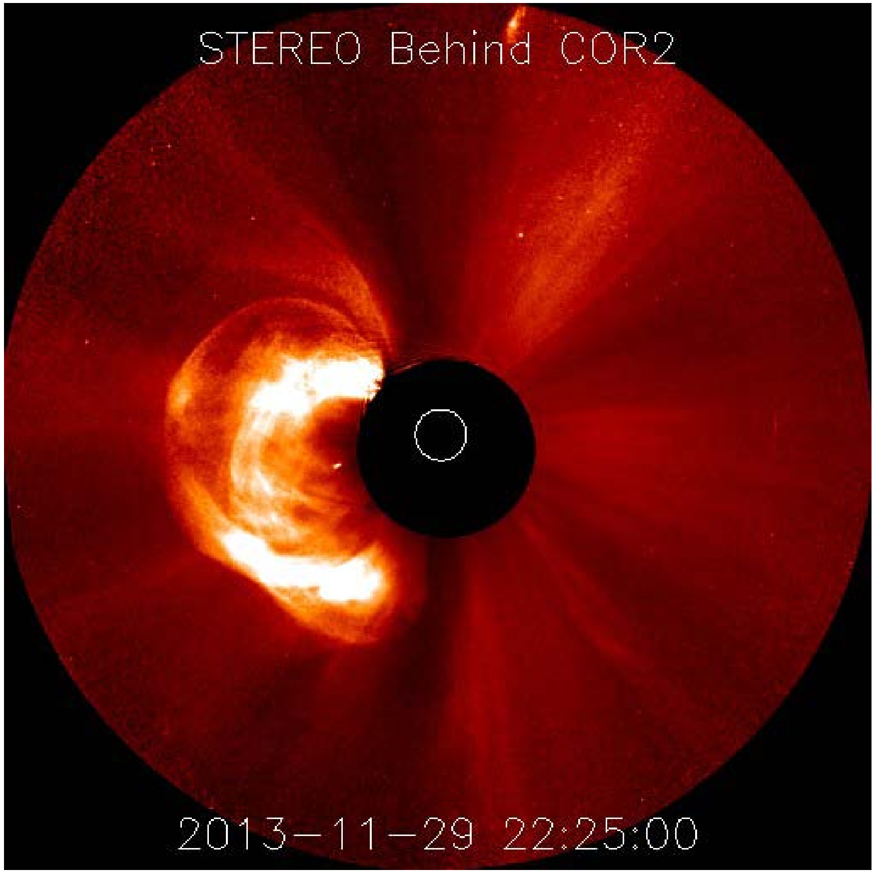
3. Theory & simulation capability

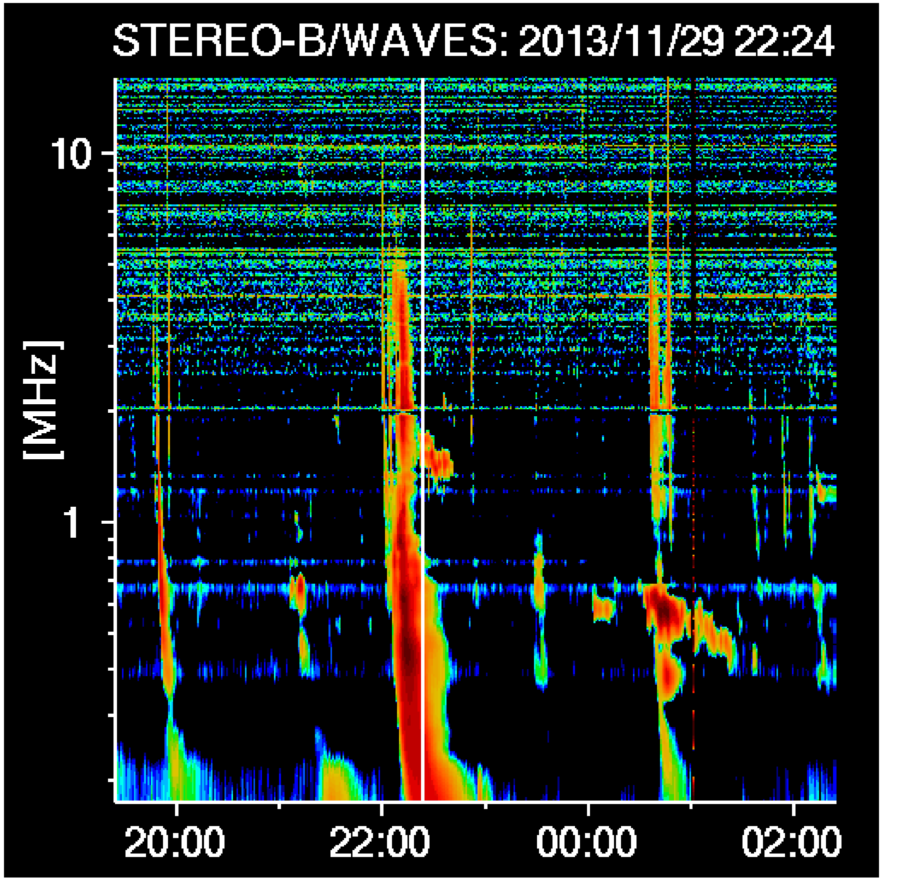
5. Applications
   - 1st interplanetary type II from Sun → 1 AU
     - B_z prediction for space weather
     - White light predictions

6. Conclusions & future work

1. Type II bursts and CMEs (Coronal Mass Ejections)

- CMEs: the most impressive form of solar activity

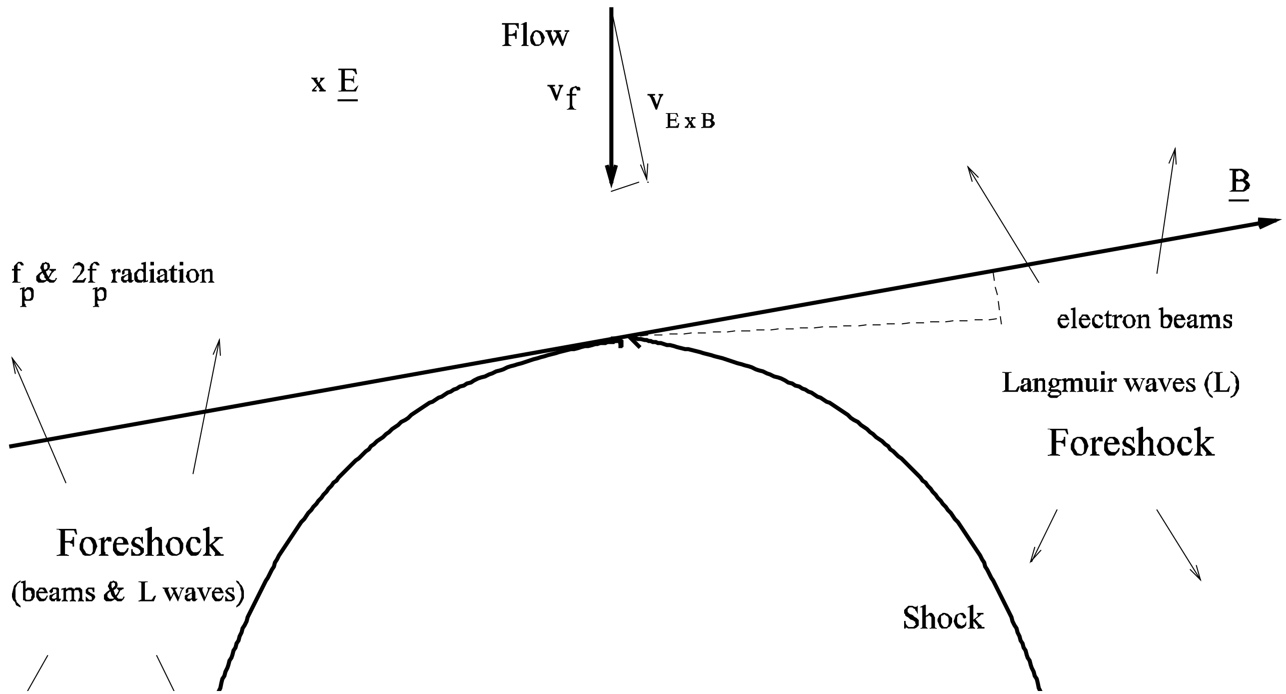




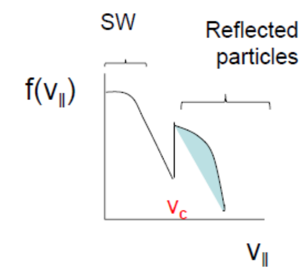
[NASA / CDAW courtesy of N. Gopalswamy]

2. The plasma physics

Detailed Theory: shock + "plasma emission"



$V_c = V_{sh} \sec \theta_{bn}$



[Wild, 1952; Nelson & Melrose, 1985; Cairns, 1986, 1988; …]

- Semi-quantitative, analytic, macroscopic theory exists:

electrons reflected and accelerated at shock → (**Liouville's theorem**) → **unstable beam distributions** → (**SGT**) → **Langmuir waves** → (**nonlinear processes**) → **EM waves at fp, 2fp**

[Knock et al., 2001, 2003a,b; Cairns et al., 2003; Kuncic et al., 2002, Knock & Cairns, 2005; Schmidt & Gopalswamy, 2008; Schmidt & Cairns, 2012a,b]

3. Simulation and Theory Approach

[cf. Schmidt & Gopalswamy, 2008]

- We use the SWMF / BATS-R-US code (3D MHD + radiation)
  1. to model realistic corona for the time period.
  2. simulate CME initiation and propagation.

[Roussev et al. 03, 04, Toth et al., 2012]:

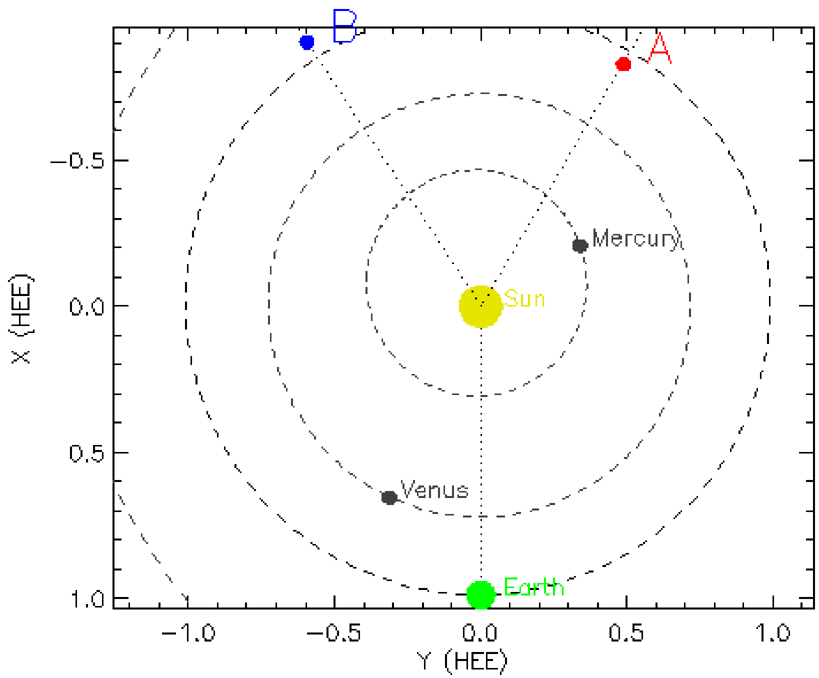
- Kinetic type II theory
  1. Shock & plasma characteristics from BATS-R-US
  2. electron energization at shock
  3. Langmuir waves and radio emission.

[Schmidt & Cairns, JGR, 2012a,b]

- Compare theory and observations.

[Schmidt et al., ApJL, 2013; Schmidt & Cairns, JGR, 2014a,b, 2016,2017 etc.]

4. Sun to Earth: STEREO's 1st in situ Interplanetary Type II Burst



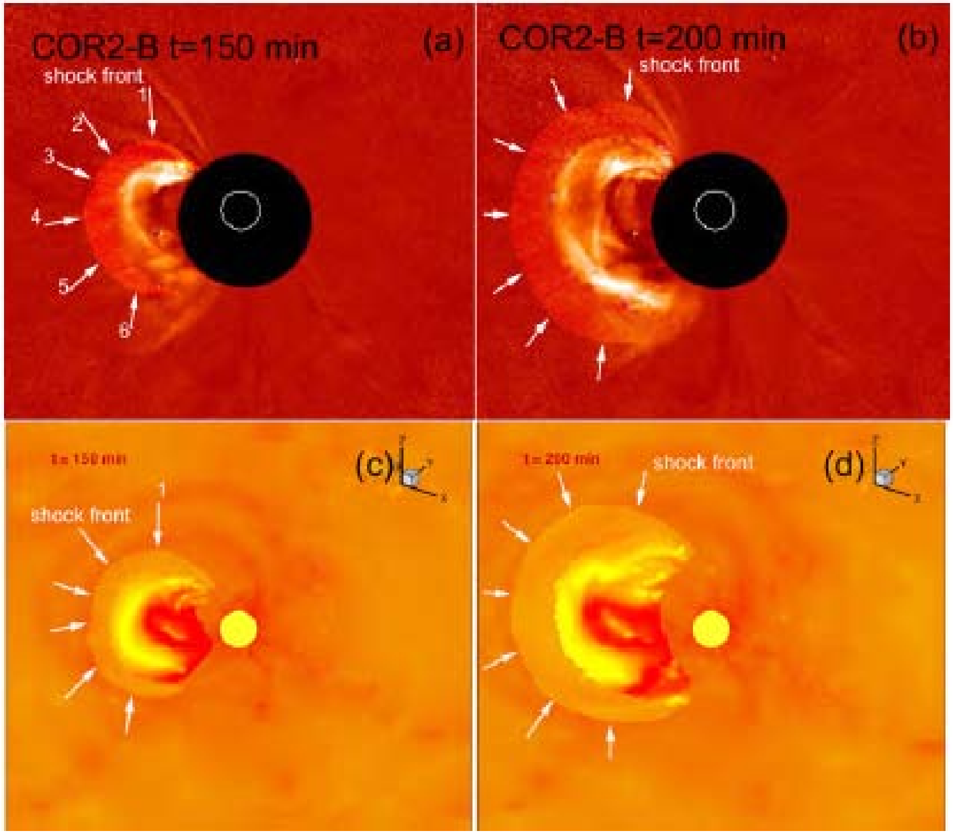
- 29 Nov – 1 Dec 2013
- STEREO A and B (double test since $\Delta r \approx 1$ AU):
  - CME,
  - remote radio,
  - shock crossing at STEREO A only (Langmuir waves, electrons, local radio)
- Excellent agreement from high corona to 1 AU
- B_z prediction .... ➔ space weather prediction

4.1 White light predictions from simulations

Data

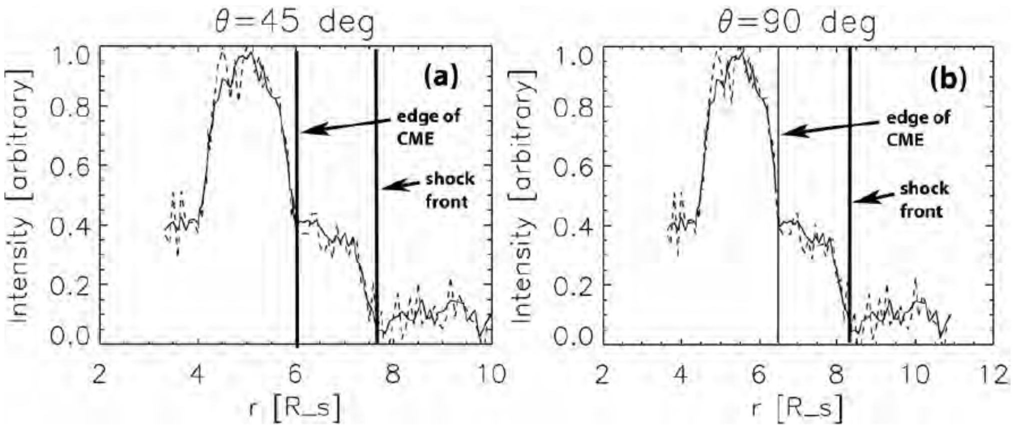
29 Nov 2013
CME near 20 UT

Prediction with BATS-R-US



- Predict observable shock
- White light observations &
- predictions agree well.

Intensity along rays
➔ Clearly abrupt shocks

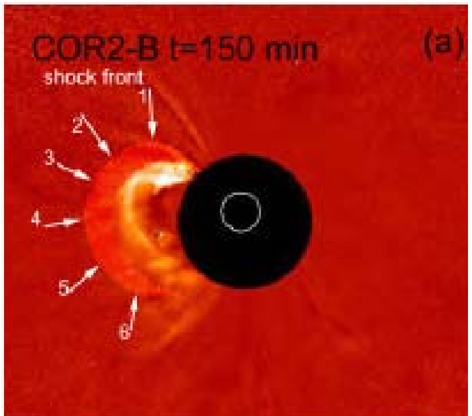


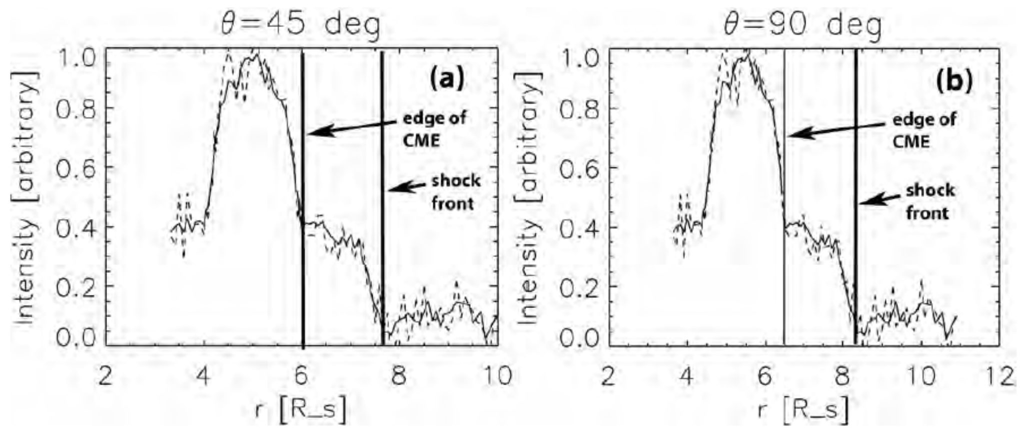
[Schmidt et al., JGR, 2016]

[Schmidt et al., JGR, 2016]

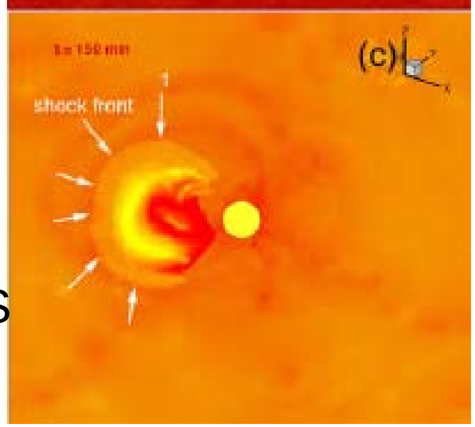
White light: very well-modelled ➔ shocks

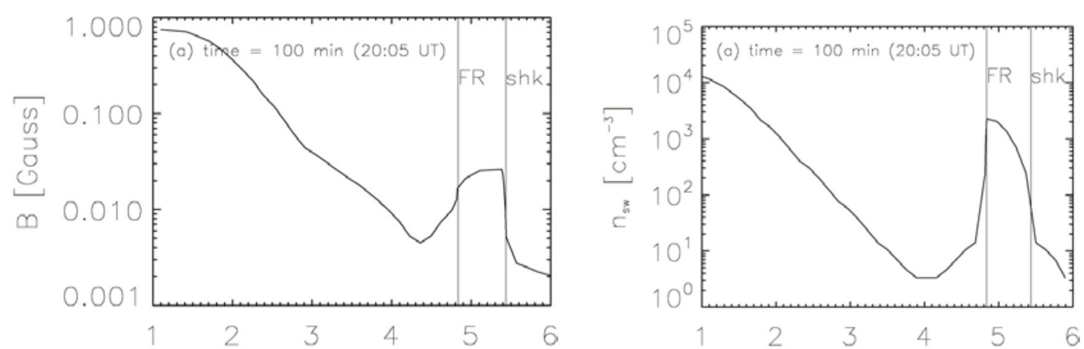
Data





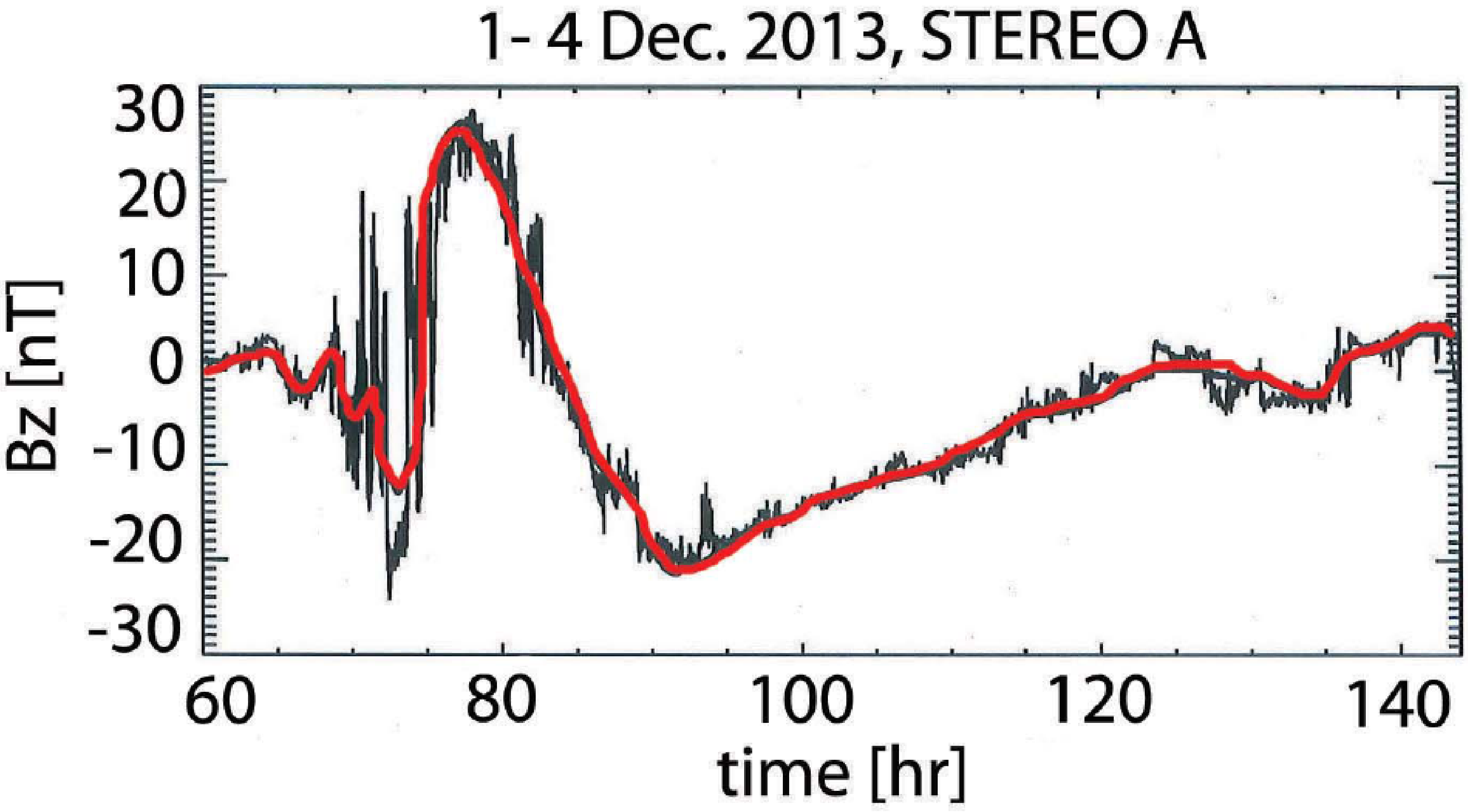
Prediction with BATS-R-US





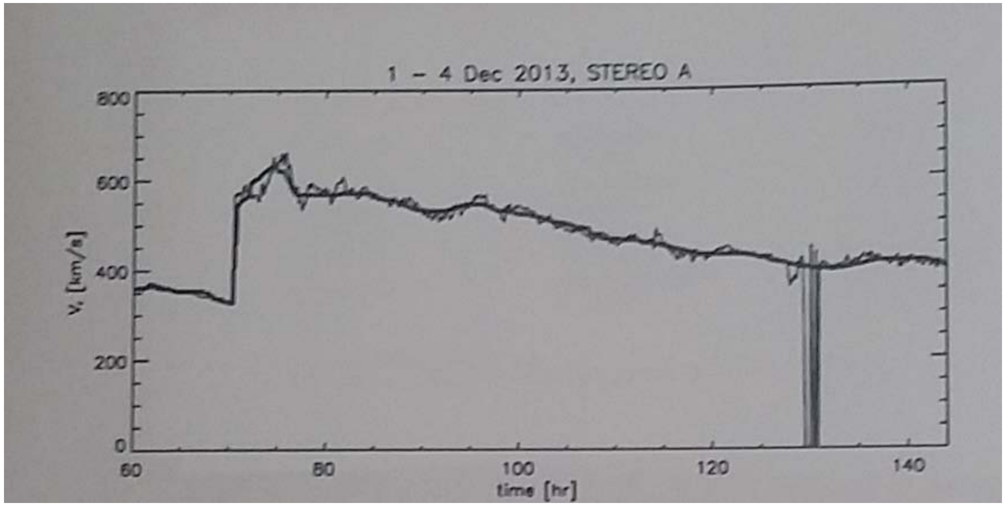
- Very good quantitative agreement along rays (obs = dashed)
- Simulation data show shocks ➔ Observed features are shocks.

4.2 Very good B_z and CME predictions at STEREO A

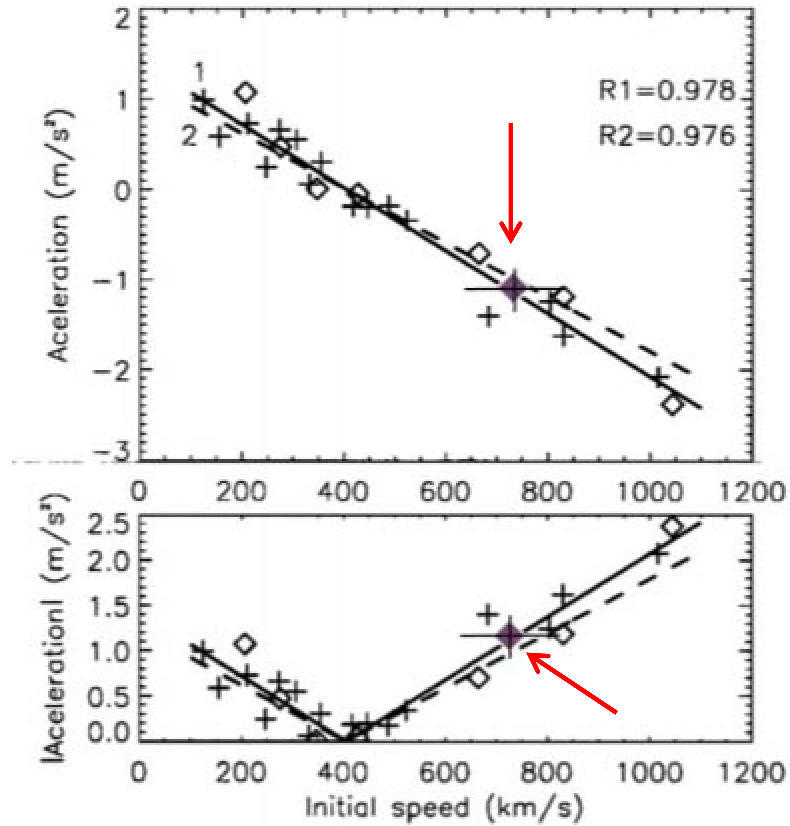


- STEREO A data (black) and prediction (red)
- ➔ very good prediction of B_z before shock → into CME

Shock - CME motion & arrival predicted well



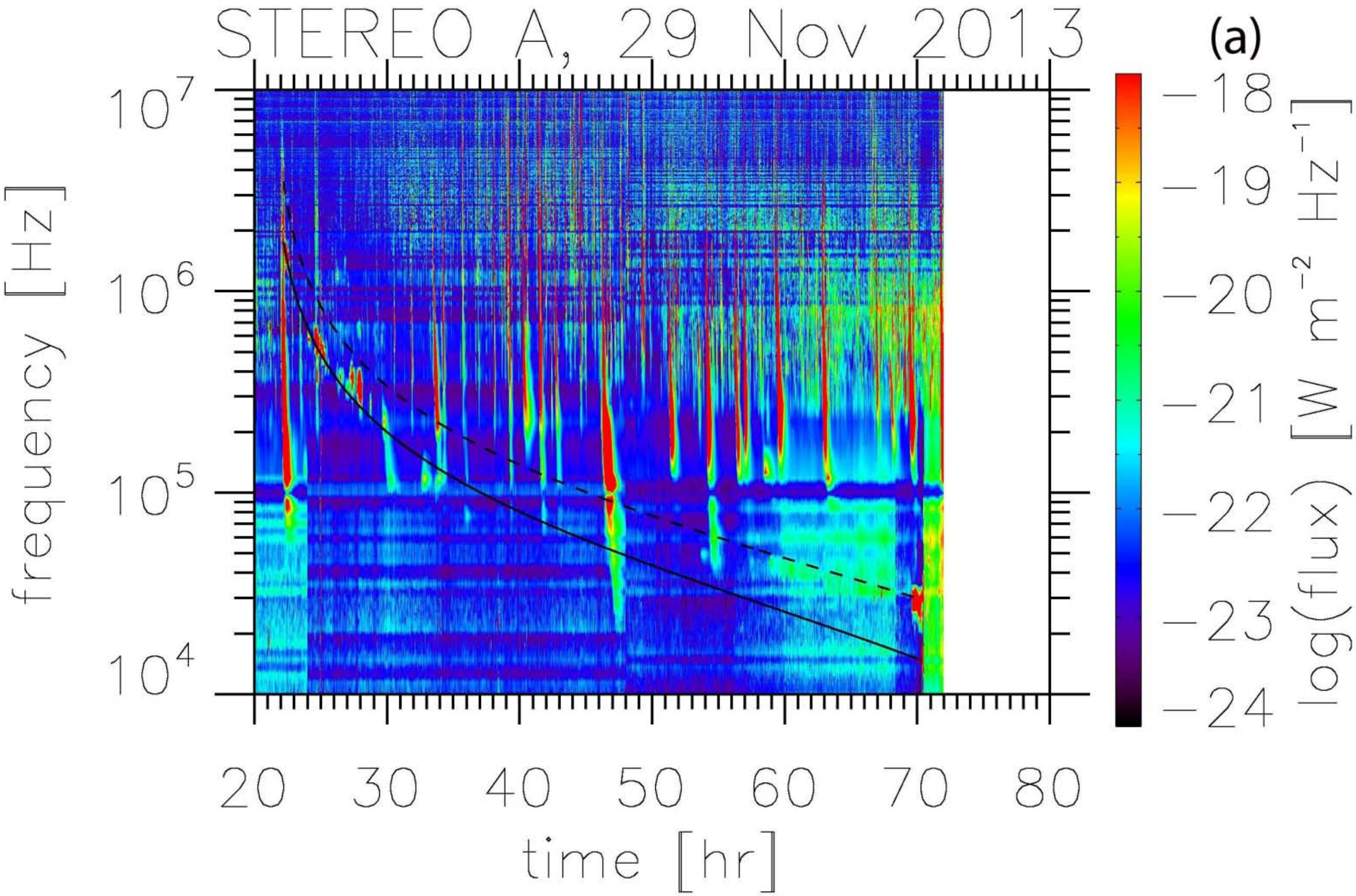
- STEREO A data (thin black) and prediction (thick black)



[M. Astore,2016]

- Find V_x and shock arrival predicted very well.
- Simulated shock decelerates as predicted by Gopalswamy et al. [2000] data & model for CMEs

4.3 Interplanetary type II of 29 No – 1 Dec 2013

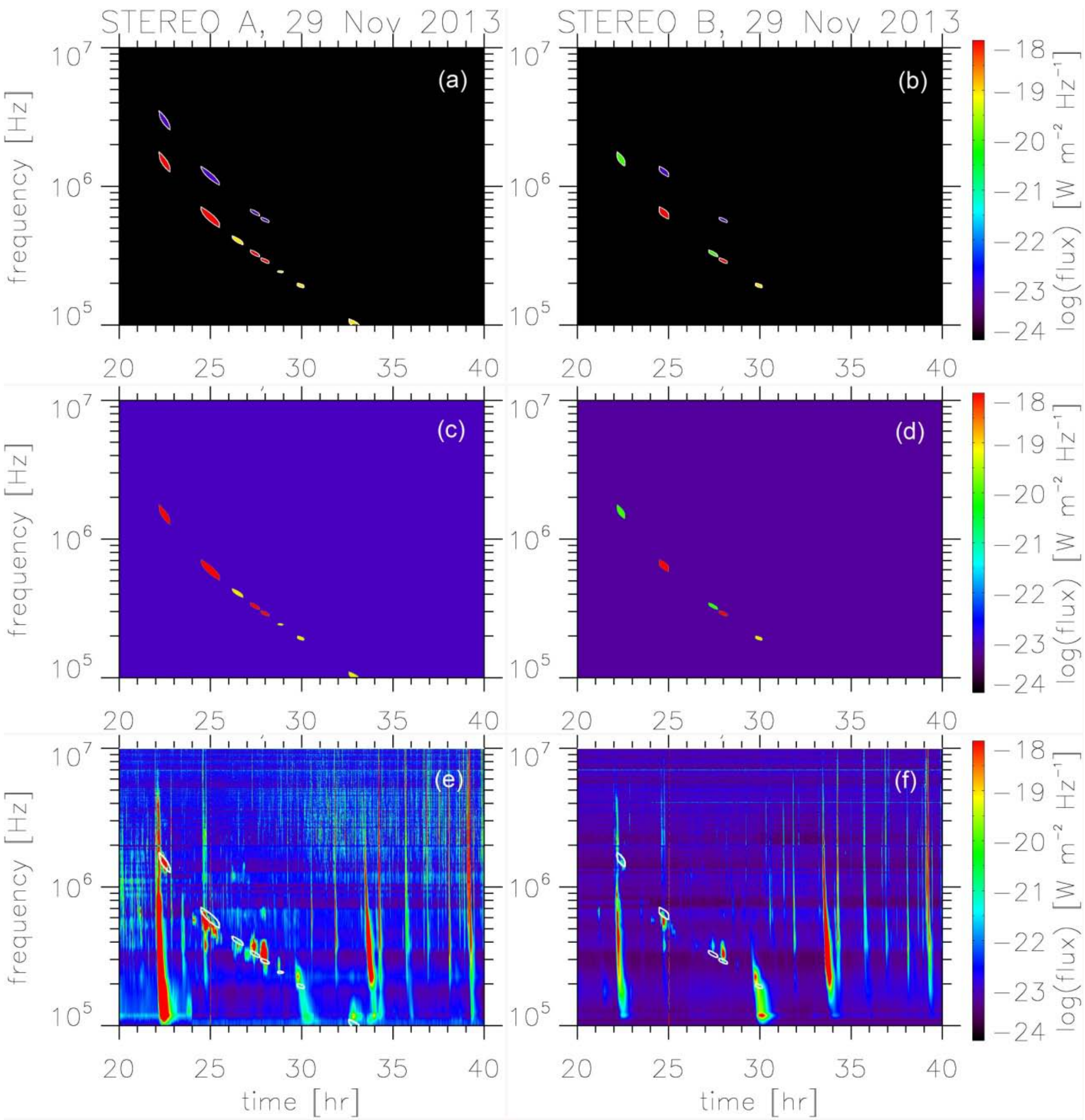


10^{-26} Wm^{-2} Hz^{-1}
= 1 Jy
= 10^{-4} sfu

[S.D. Bale, personal comm., 2013; Graham & Cairns, 2015; Schmidt & Cairns, 2016]

- f_p & $2f_p$ from high corona to 1 AU - huge variability
- local shock crossing and both local & remote emission
- > 4 orders of magnitude in flux , 3 in f, and 2 in R

Comparisons for high corona (5 - 0.1MHz)



Predictions, no background

(also predict no metric type II)

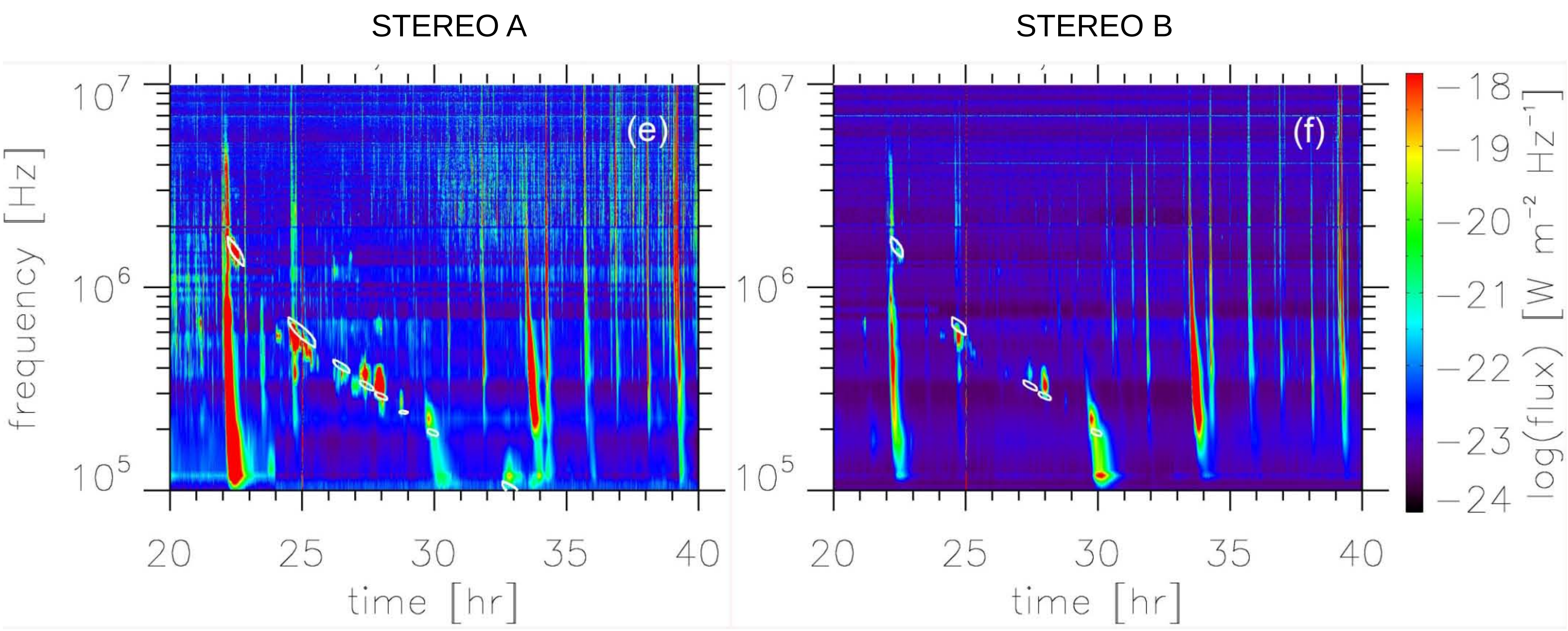
Predictions with background
➔ only f_p observable

Overplot theory on data ➔ excellent agreement for STEREO A and B ($\Delta \approx 1$ AU):

- within factor 10 in flux, 20% in f, 1 hour in time

- 10^4 in flux, 10^2 in f, 20 in t

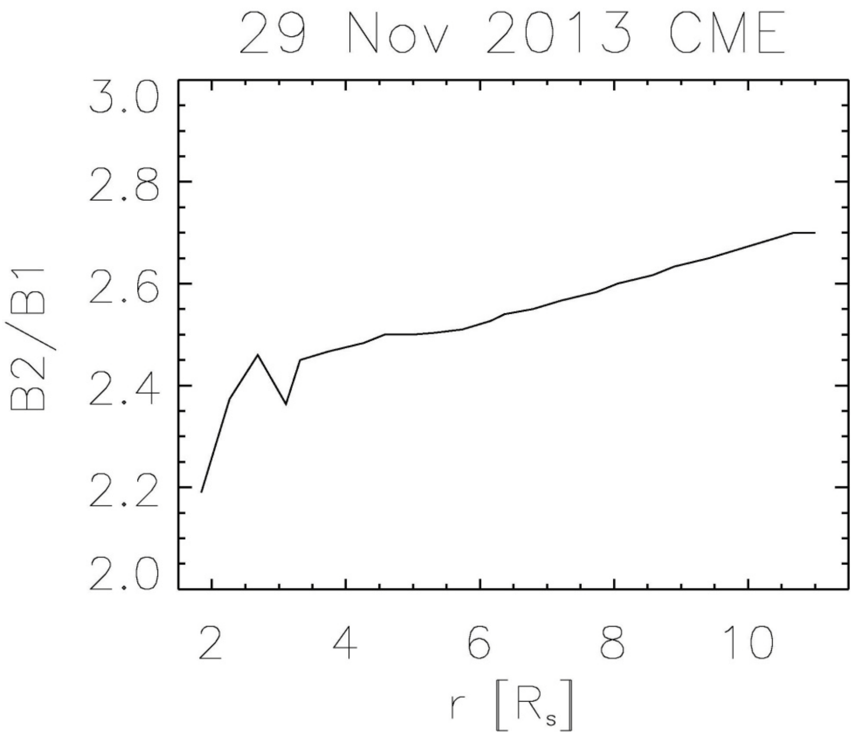
Excellent agreement for high corona (5 - 0.1MHz)

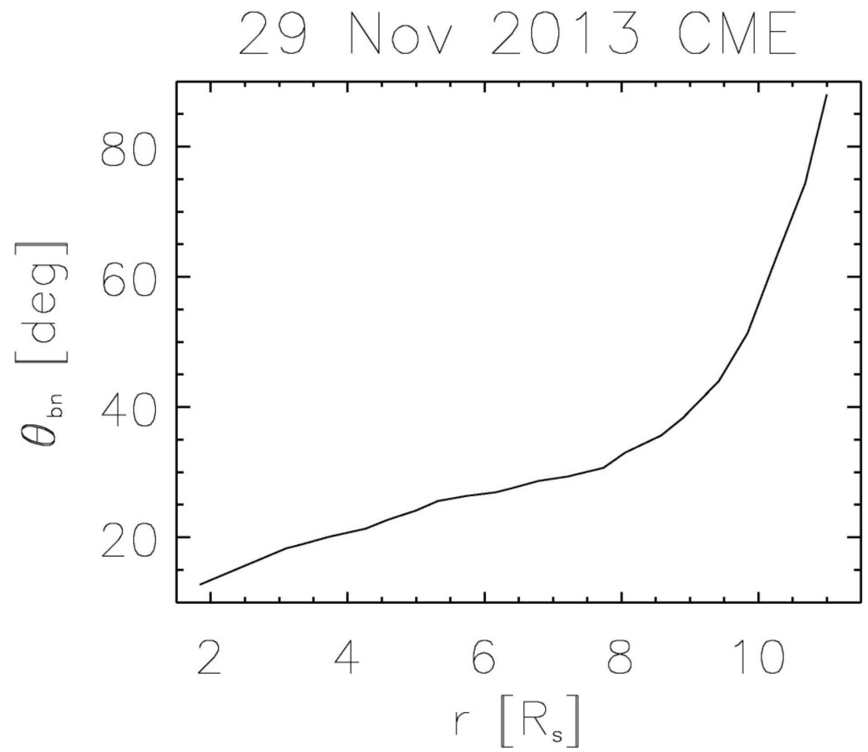


- Excellent agreement for both STEREO A and B (separated by $\Delta r \approx 1$ AU):
  - agree within factor 10 in flux, 20% in f, 1 hour in time
  - variations of > 10^4 in flux, 10^2 in f, 20 in t
- Comparisons of source locations with simulations / theory still TBD.

Radio onset and explanation of flux (f,t) & blobs ..

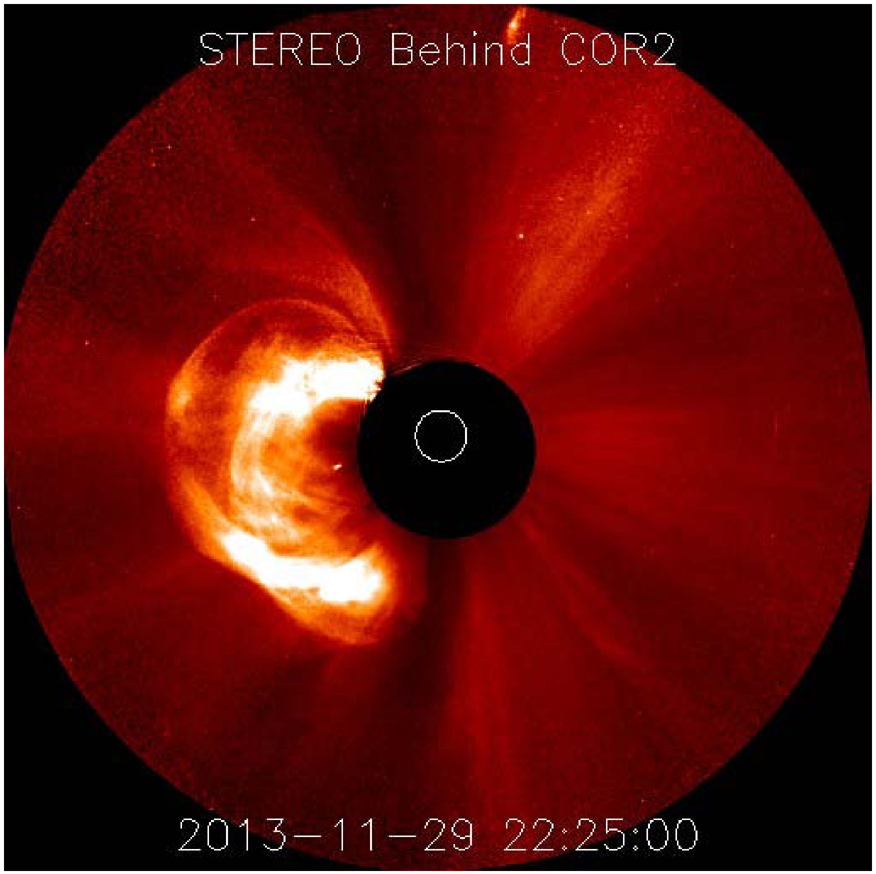
- Electron reflection & acceleration (and so Langmuir & radio emission) depends on local θ_{bn}, shock speed / mirror, T_e etc.

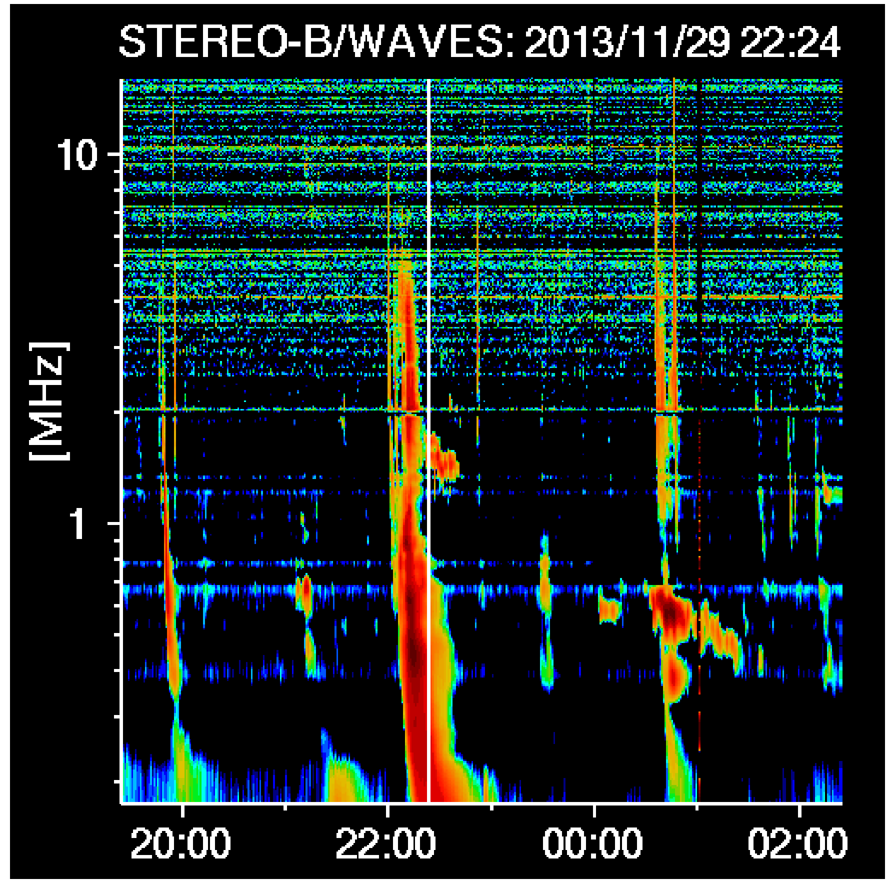




- Here shock develops before 2 R_S but $\theta_{bn} << 85^o$ at shock nose until ~ 11 R_S ➔ radio onset at time and frequency observed.

Type II starts ~11 R_S ←→ consistent with predictions

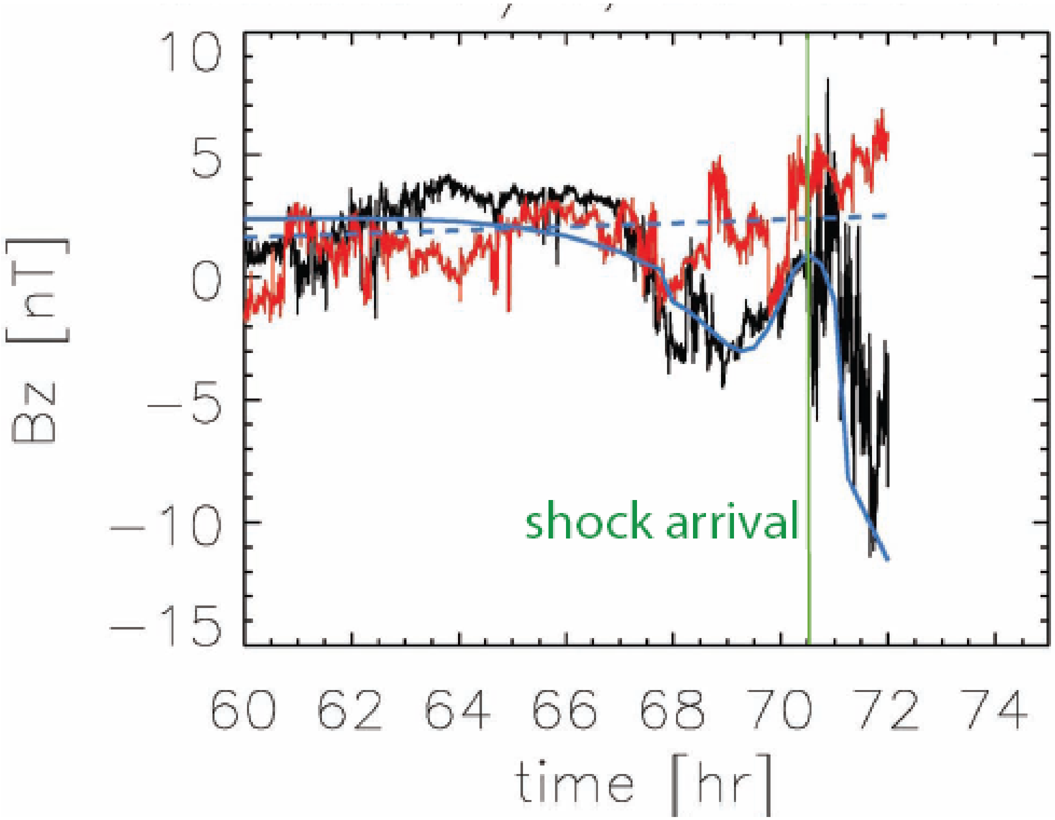




5. Conclusions

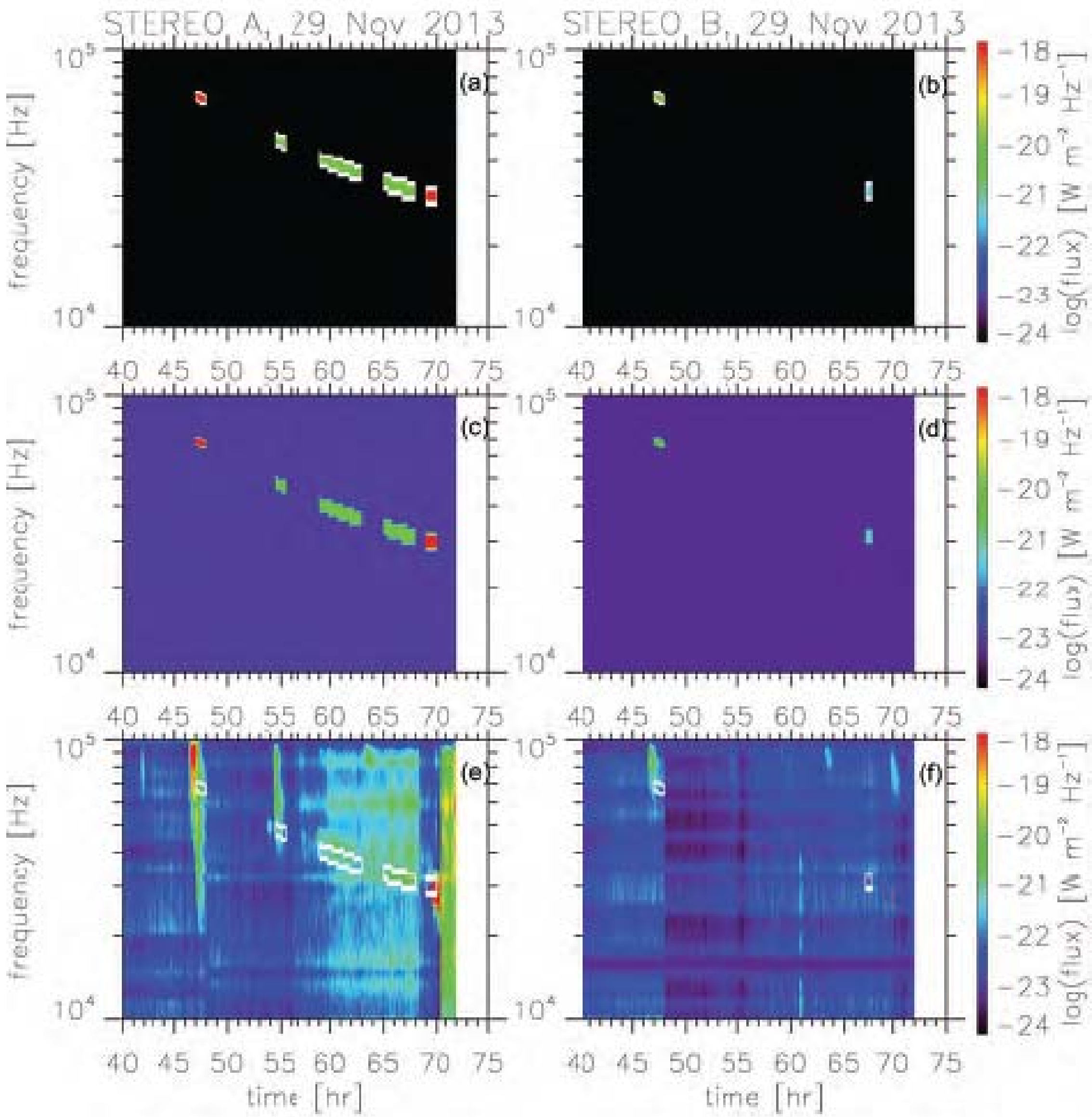
- Arguably close to accurately simulating CMEs & “solving the type II problem”:
  - White light images accurately predicted (CME and shock).
  - CME plasma & field variables predicted well, including B_z.
  - CME arrival, speed & deceleration agree well with data.
  - 1^{st} interplanetary (IP) type II accurately simulated from Sun to 1 AU: f_p and $2f_p$ emission, local onset, lack of metric, CME arrival, … B_z
  - Agreement over factors of 10^6 in flux, 10^3 in f, and 10^2 in r and t
- Type IIs involve fundamental plasma physics that is widely relevant in plasma / space / astro-physics.
- Agreement ➔ strong support that BATS-R-US code (3D MHD) can accurately model 3D corona/wind & CME.
- Space weather relevance: ➔ use type II & white light data-theory iterations to confidently predict CME arrival and B_z.

5.2 Good B_z and CME predictions at STEREO A



- STEREO A data (black) and prediction (blue solid curve)
- ➔ good prediction of B_z and shock / CME arrival
- ➔ vision intact to predict space weather using type IIs ...
- STEREO B less good: data (red) and prediction (- - -)

Excellent agreement for solar wind (10 – 100 kHz)



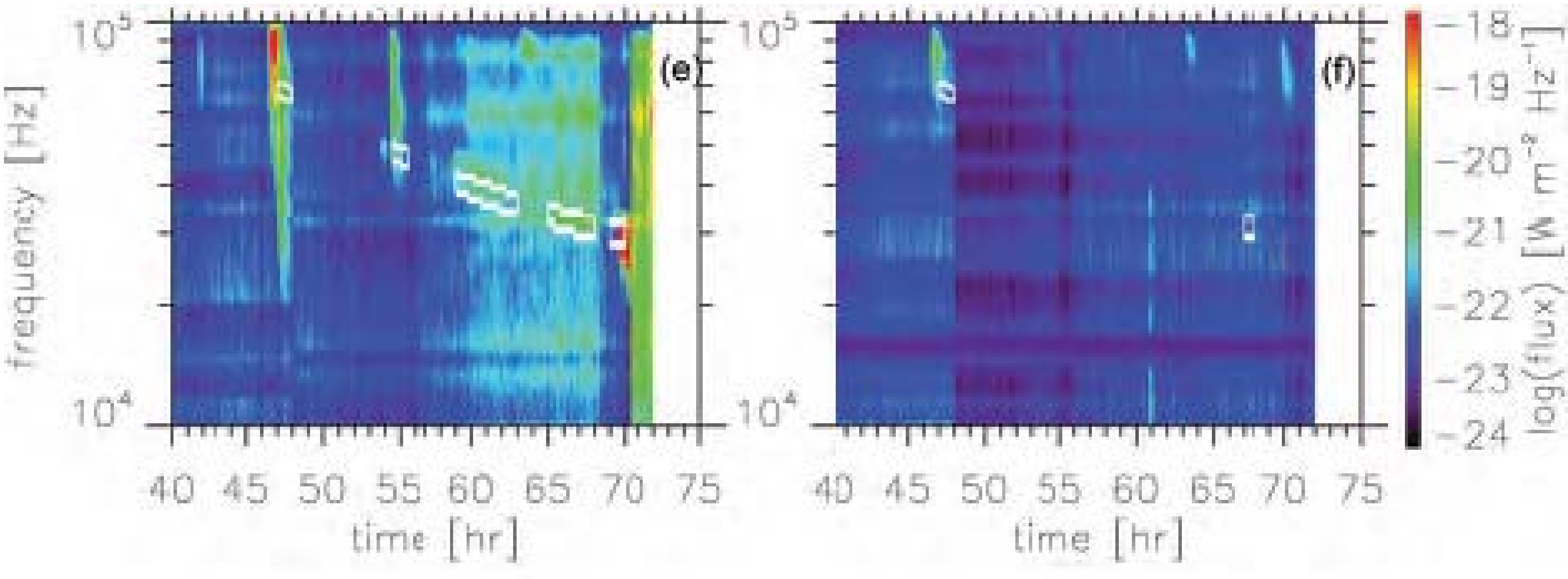
Predictions, no background

Predictions with background
➔ only $2f_p$ observable

Overplot theory on data ➔ excellent agreement for STEREO A and B (Δ≈1 AU):

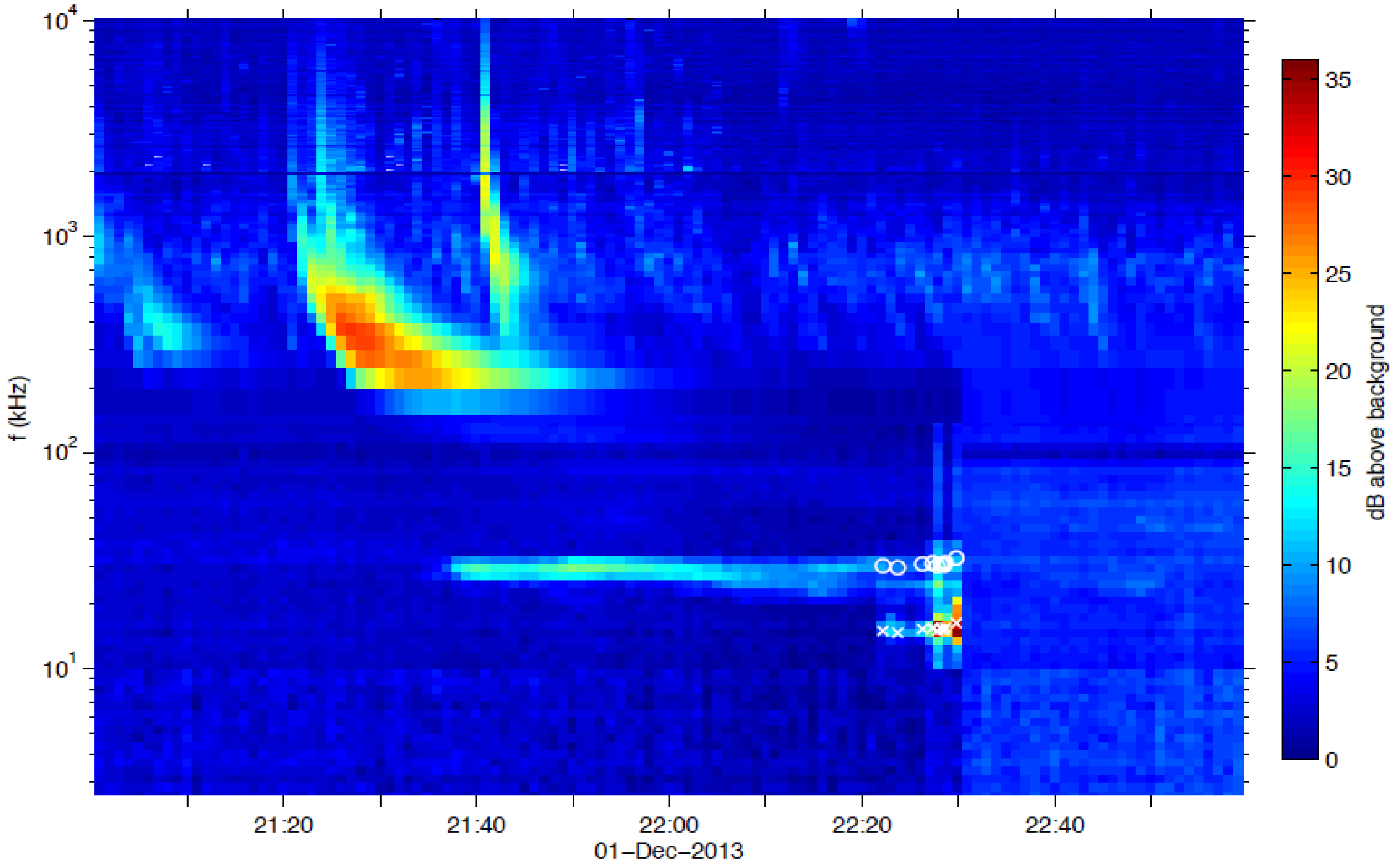
- within factor 10 in flux, 10% in f, 1 hour in time
- 10^4 in flux, 10^2 in f, 20 in t

Excellent agreement for solar wind (10- 100 kHz)



- Excellent agreement for both STEREO A and B (separated by $\Delta r \approx 1$ AU):
  - agree within factor 10 in flux, 10% in f, 1 hour in time
  - variations of > 10^4 in flux, 3 in f, 20 in t
  - Comparisons of source locations with simulations / theory still TBD.

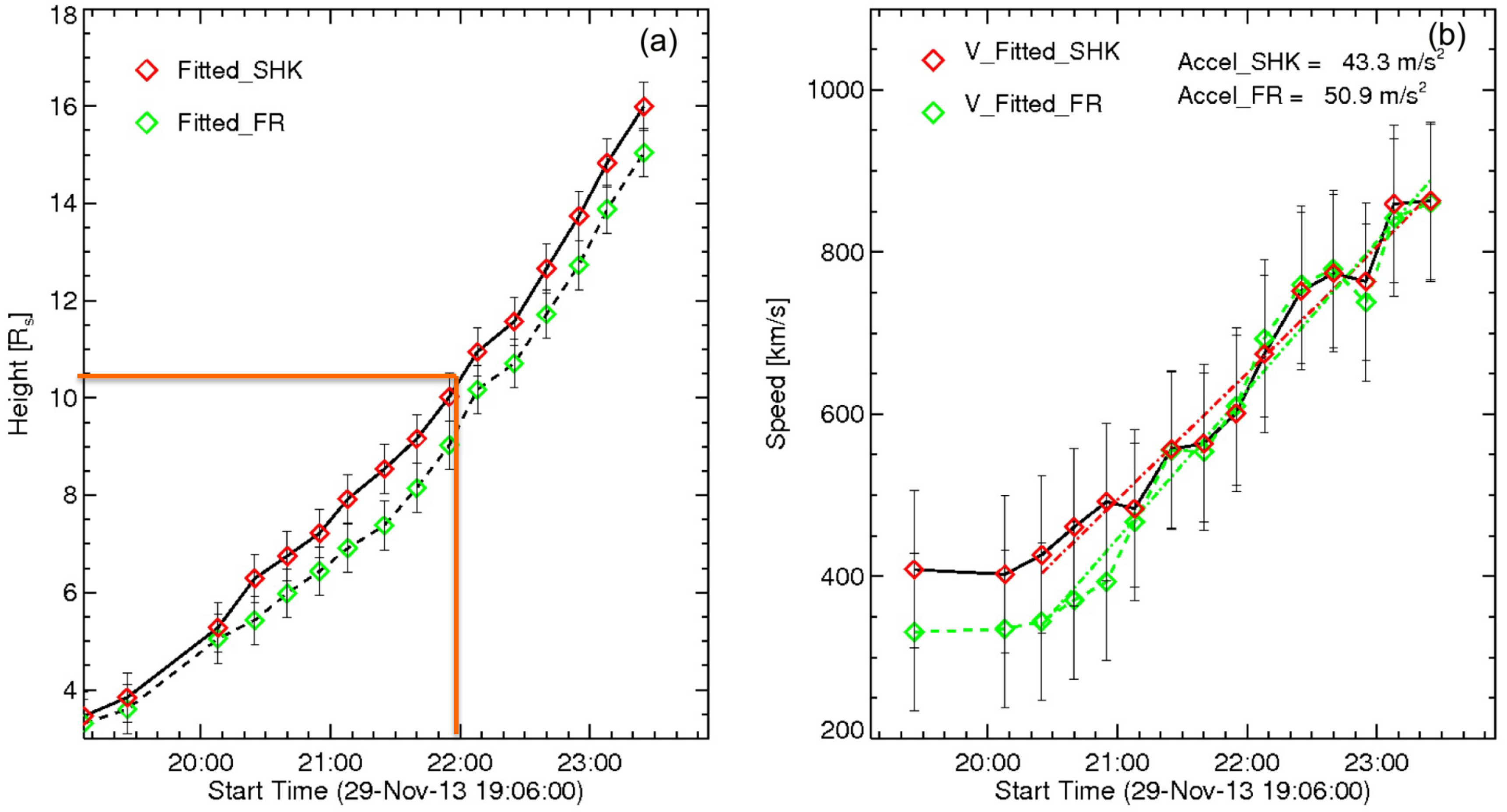
STEREO A: local 2fp emission



[Graham & Cairns, JGR, 2015]

CME observations III

CME initiation ≡ 18:25 UT



- Height-time and velocity-time diagrams for shock (SHK, red) and flux rope (FR, green) from wire frame analysis
- The shock height at the onset of the radio burst (≈ 22:00) is ≈10.5 Rs.

  Question: Why is this so late?