The Propagation of a CME front in 3D

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CME evolution in the Heliosphere

- Kinematics - acceleration, deceleration
- Morphology - pancaking, complex structure
- Which wins out, CME or solar wind?
- Space weather - how important is drag?
- Other astrophysical problems involving flux tubes/magnetic bubbles in flows.

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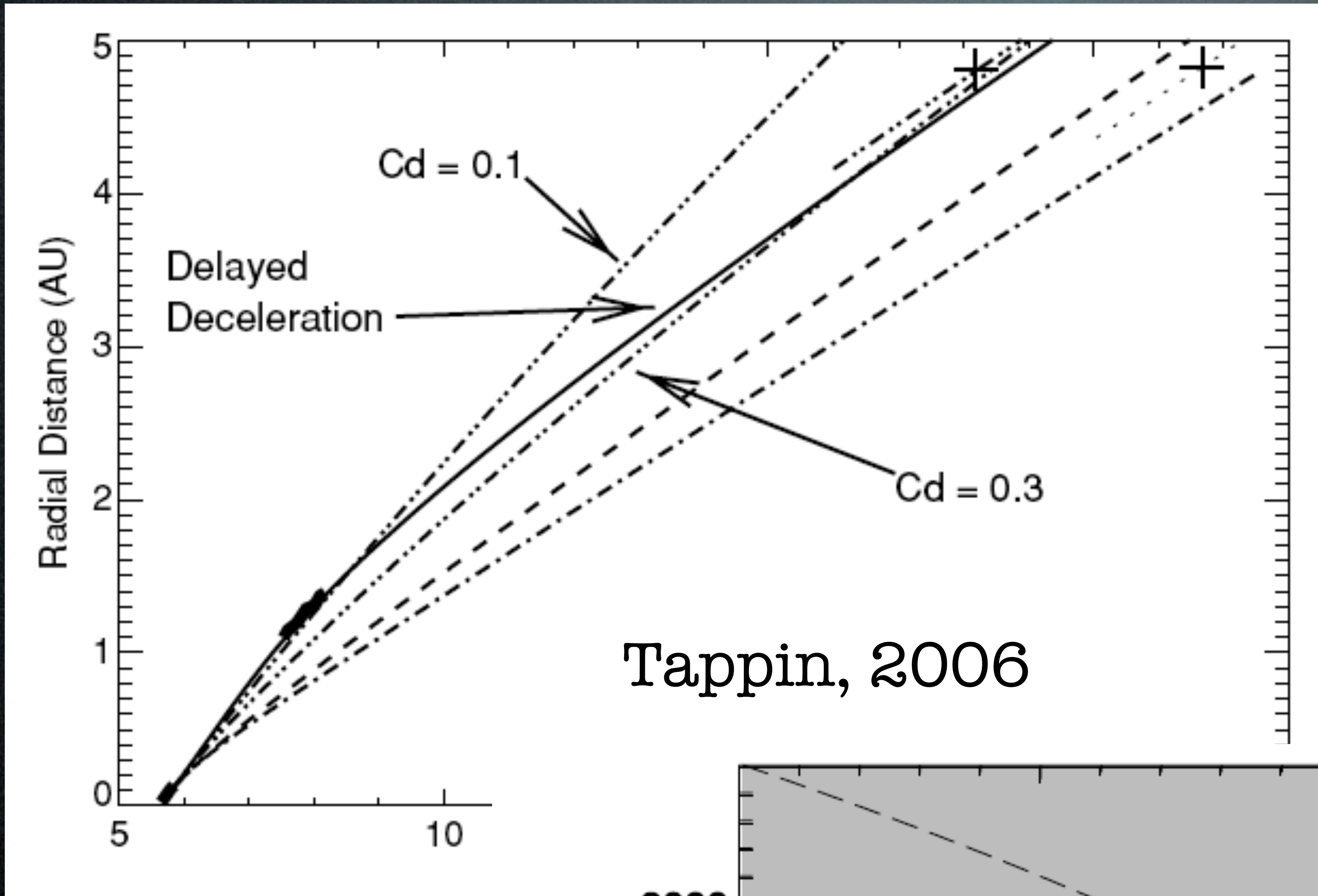

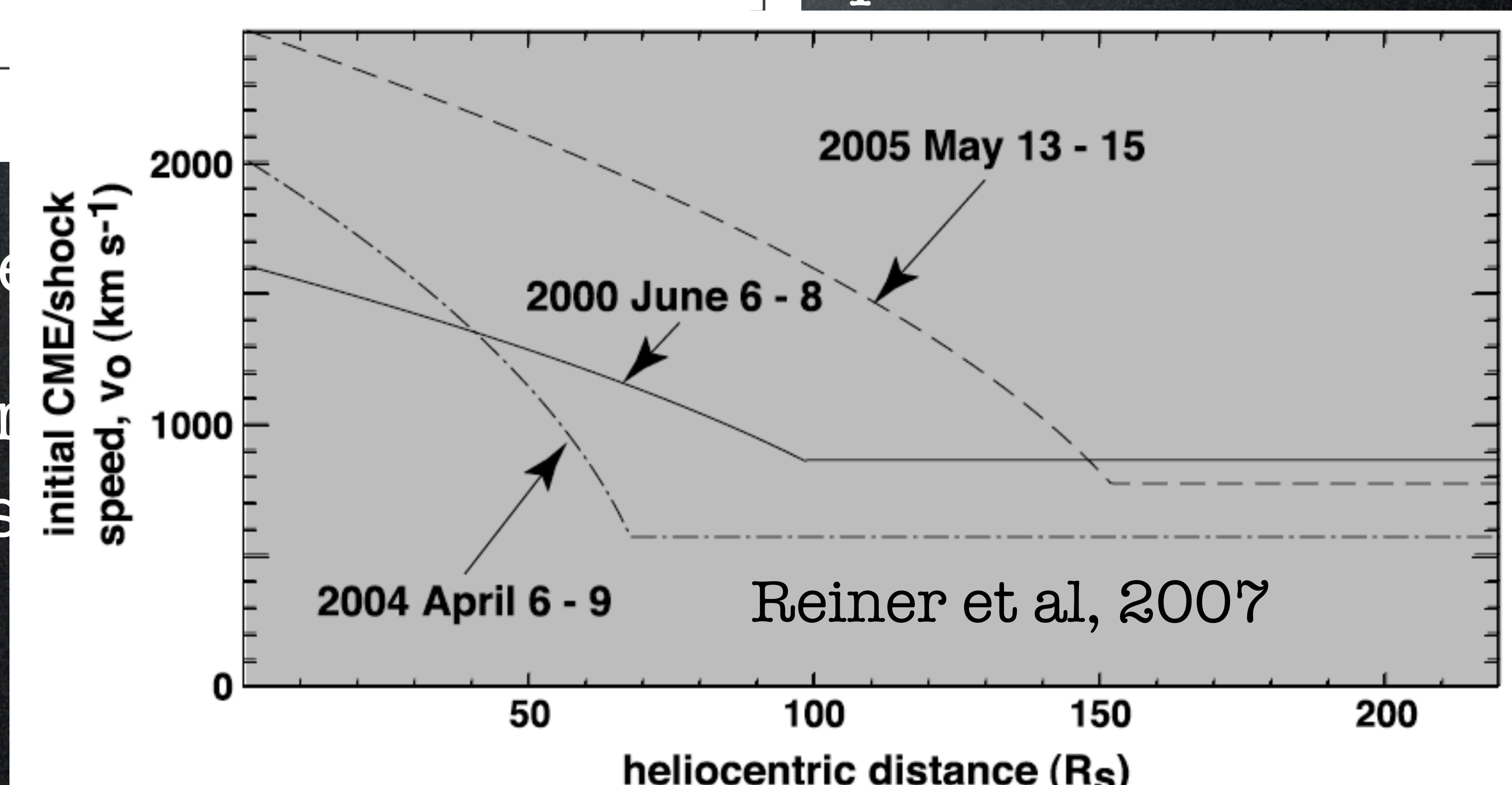

- Space...
- Other... tubes...

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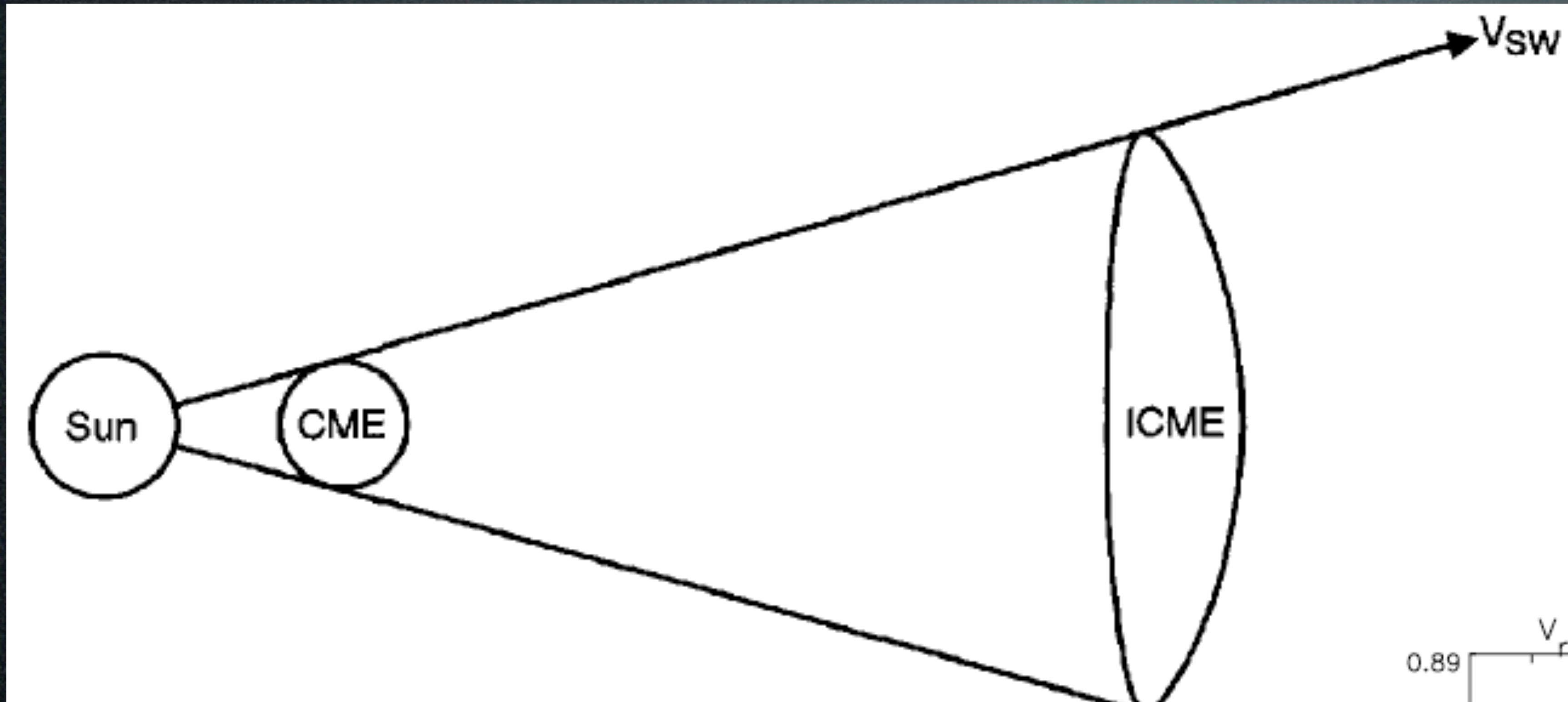
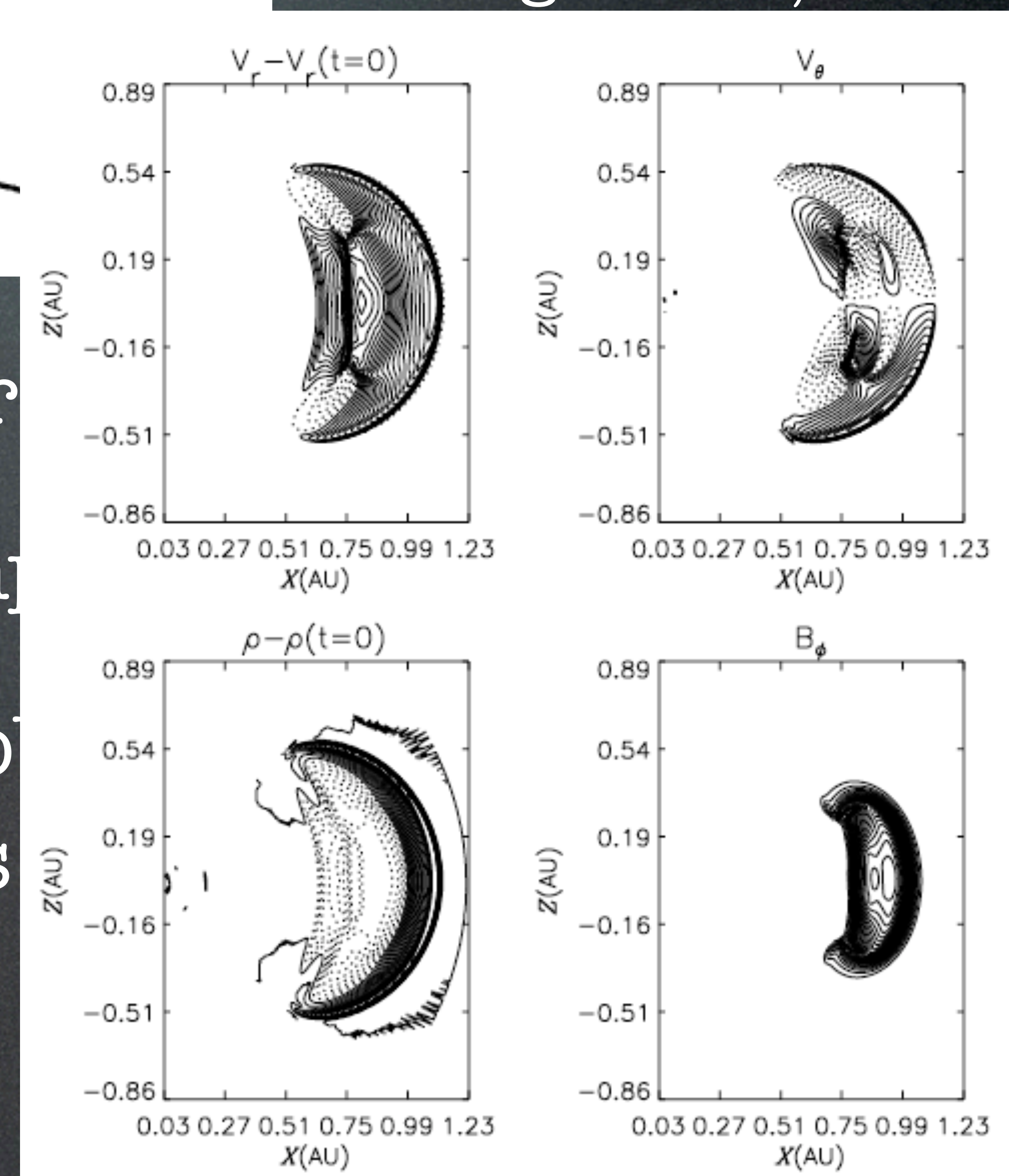


Russell et al, 2002

Cargill et al, 2002



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CME equation of motion

- Generalised equation of motion for CME $$\rho\frac{Dv}{Dt} = -\vec{j}\times\vec{B} - \nabla P - \rho\vec{g} - F_D$$

Dominates low down (<10 R_{Sun})

Generally neglect

Dominates higher (>10 R_{Sun})

What is the form of F_D and why?

CME Drag

- Number of different forms have been proposed
  - "Snow Plough" (Tappin, 2006)

$$\frac{dv_c}{dt} = \frac{\rho A}{M}(v_c - v_s)(v_c - v_s)$$

  - aerodynamic drag (Cargill, 1996; Vršnak, 2001)

$$\frac{dv_c}{dt} = \frac{\rho A C_D}{M}(v_c - v_s)\left|v_c - v_s\right|$$

$$\frac{dv_c}{dt} = \gamma(v_c - v_s)$$

  - Full MHD modelling
    - drag coefficient (C_D) ~1

Observations to constrain theory

- Need accurate, true kinematics to compare to theory.
- Have to use 3D reconstructions (other effects?)
  - New method and tie-pointing

(Byrne et al in prep; Maloney et al 2008)

- Parametrised drag model

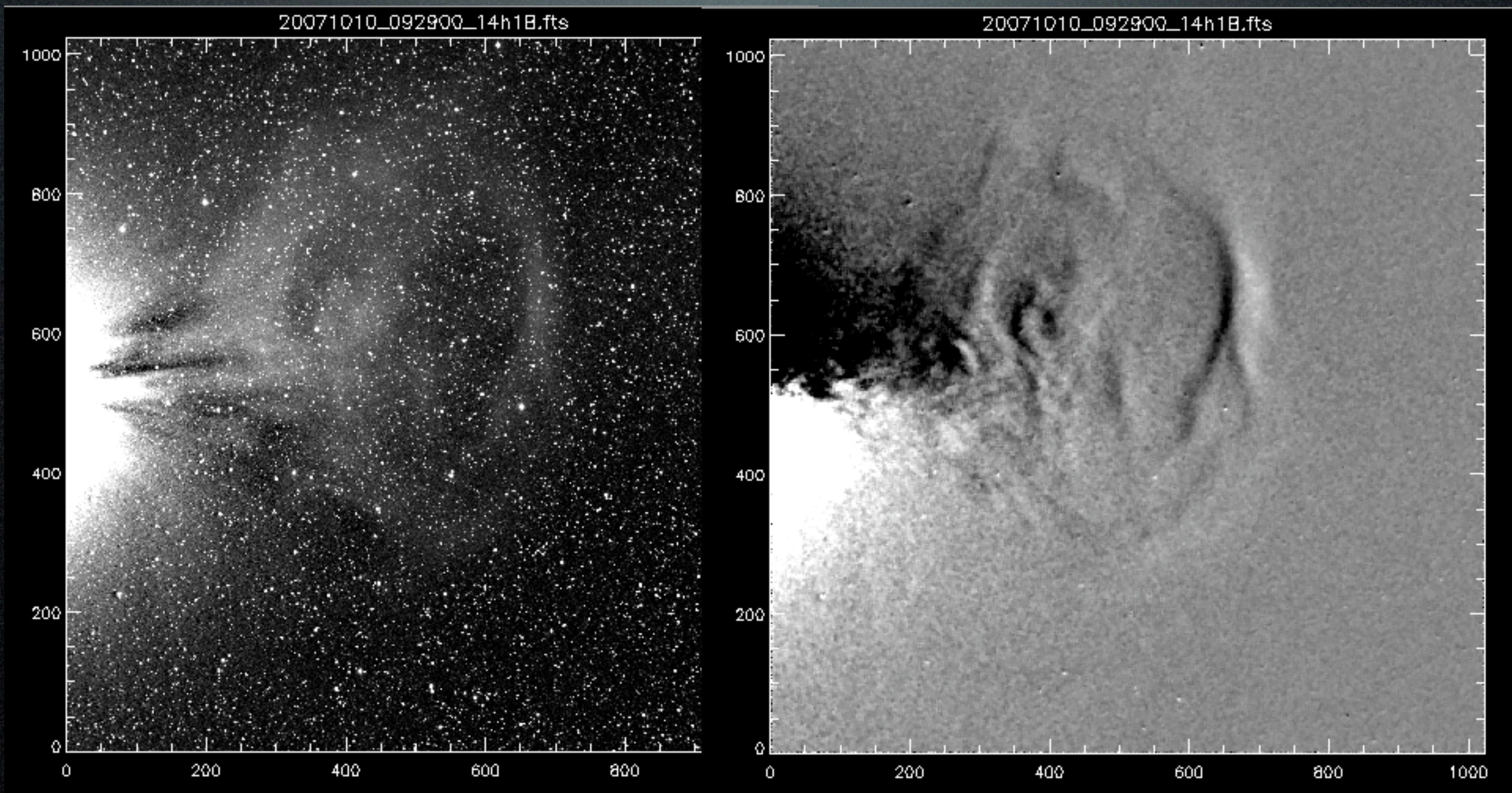
$$\frac{dv_c}{dr} = \alpha R^{-\beta} \left(v_c - v_s\right)^c$$

- Use Bootstrapping to gain estimate of errors, allowing us to say which form of drag fits best.

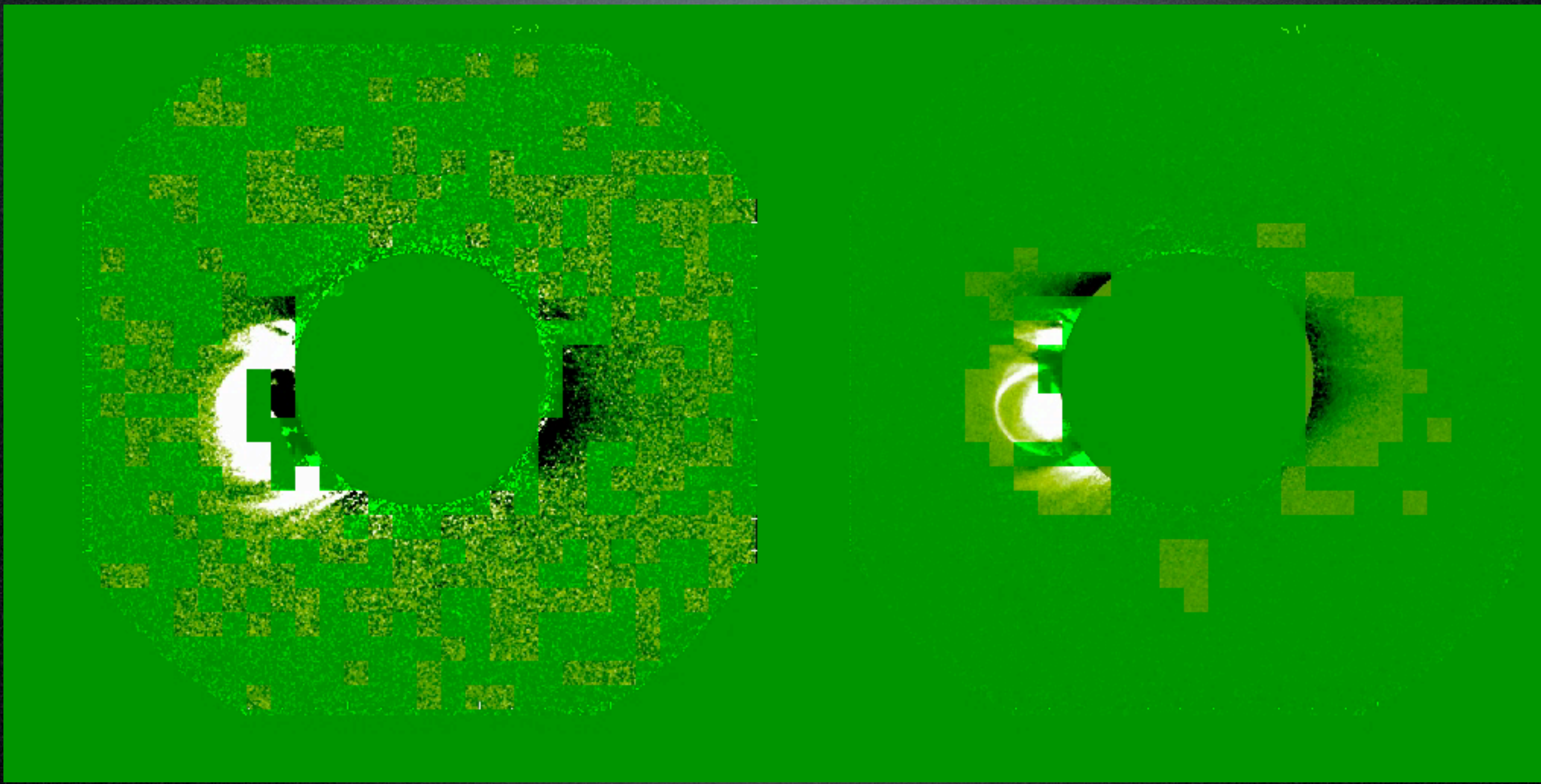
Image Processing

- Modified Running Difference
  - Accounts for stellar motion, suppress signal from stars (cross correlation between images).

Image Processing

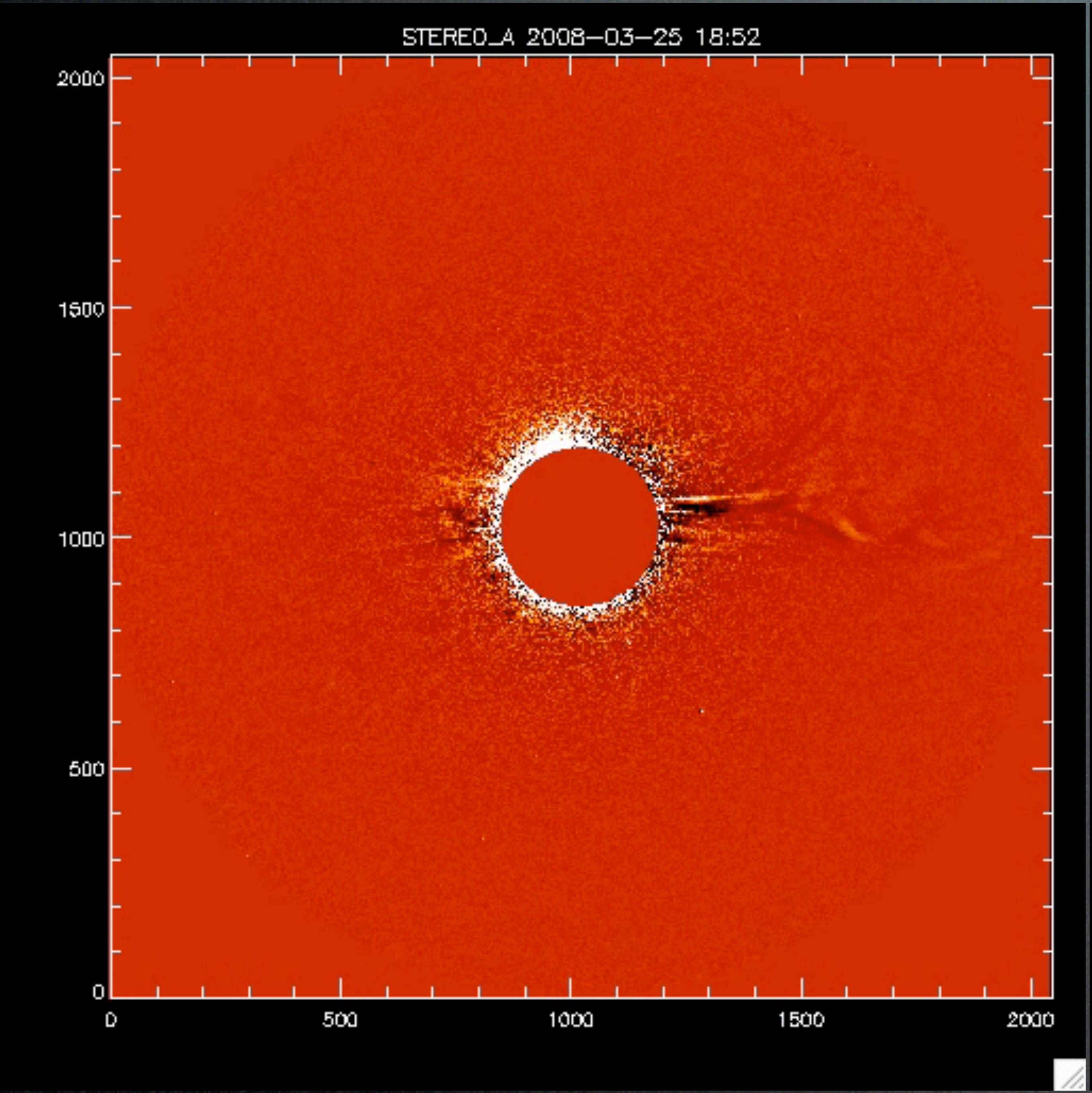


Observations

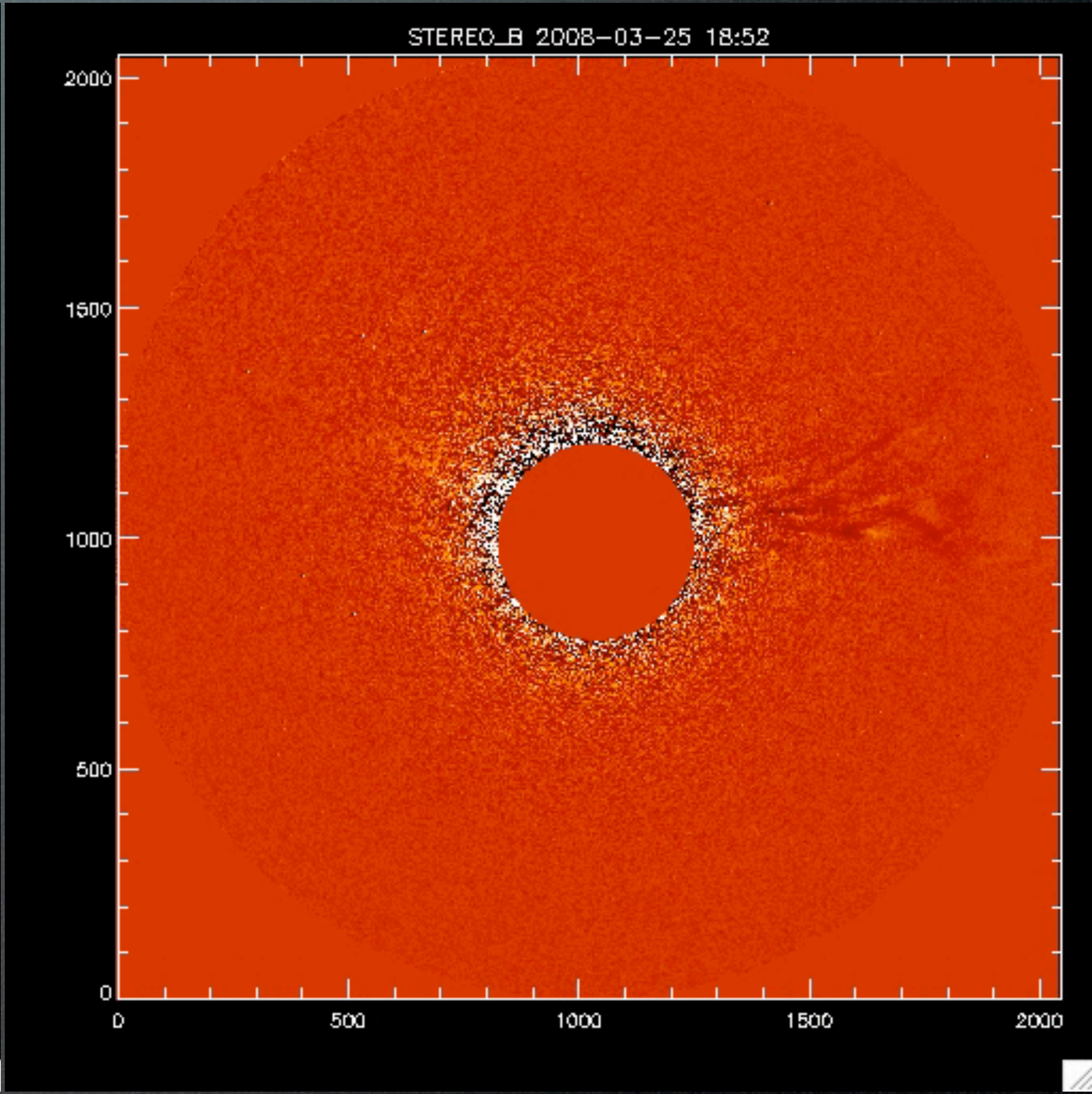


Ahead Behind

Observations

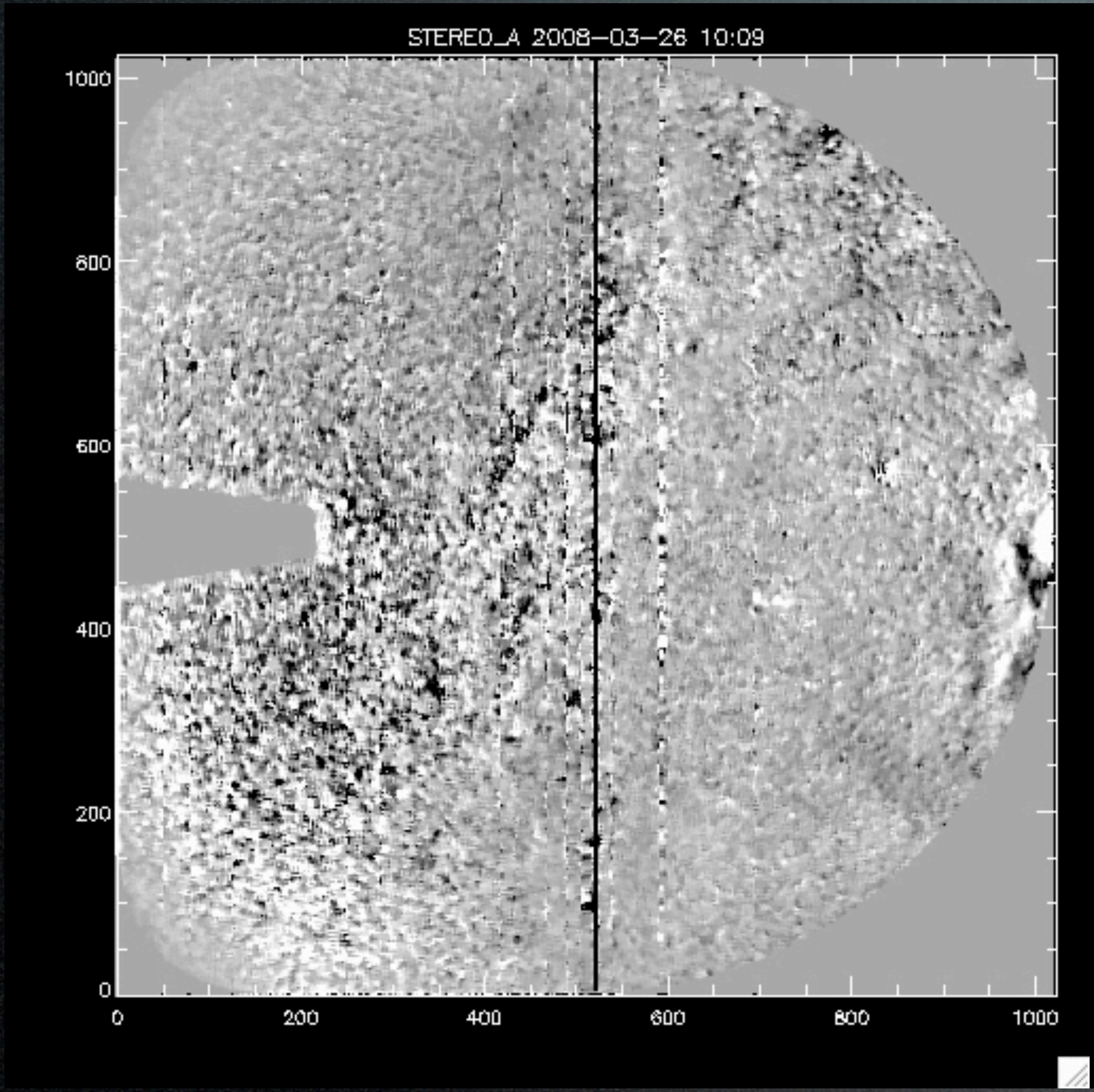


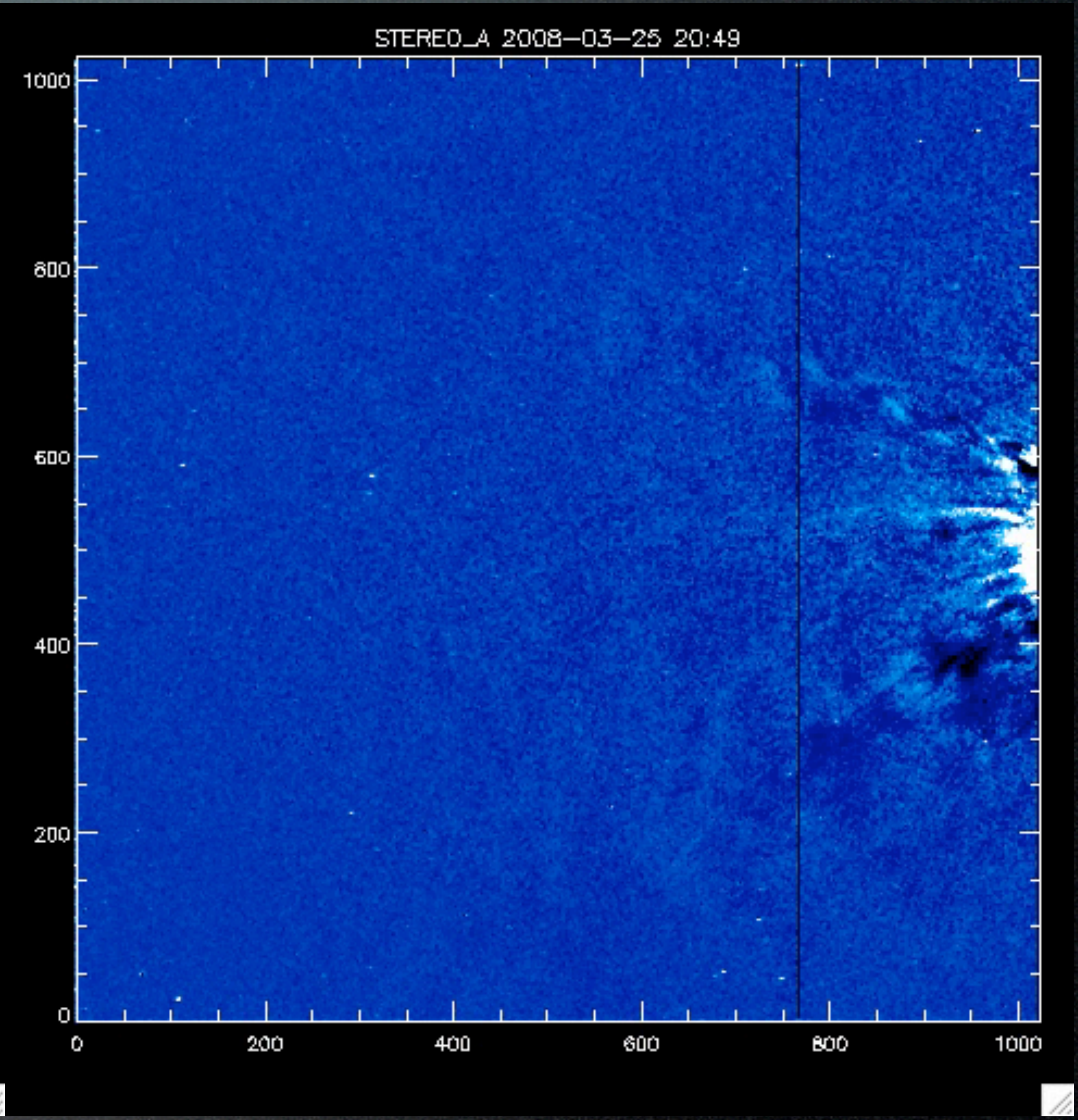
Ahead



Behind

Observations

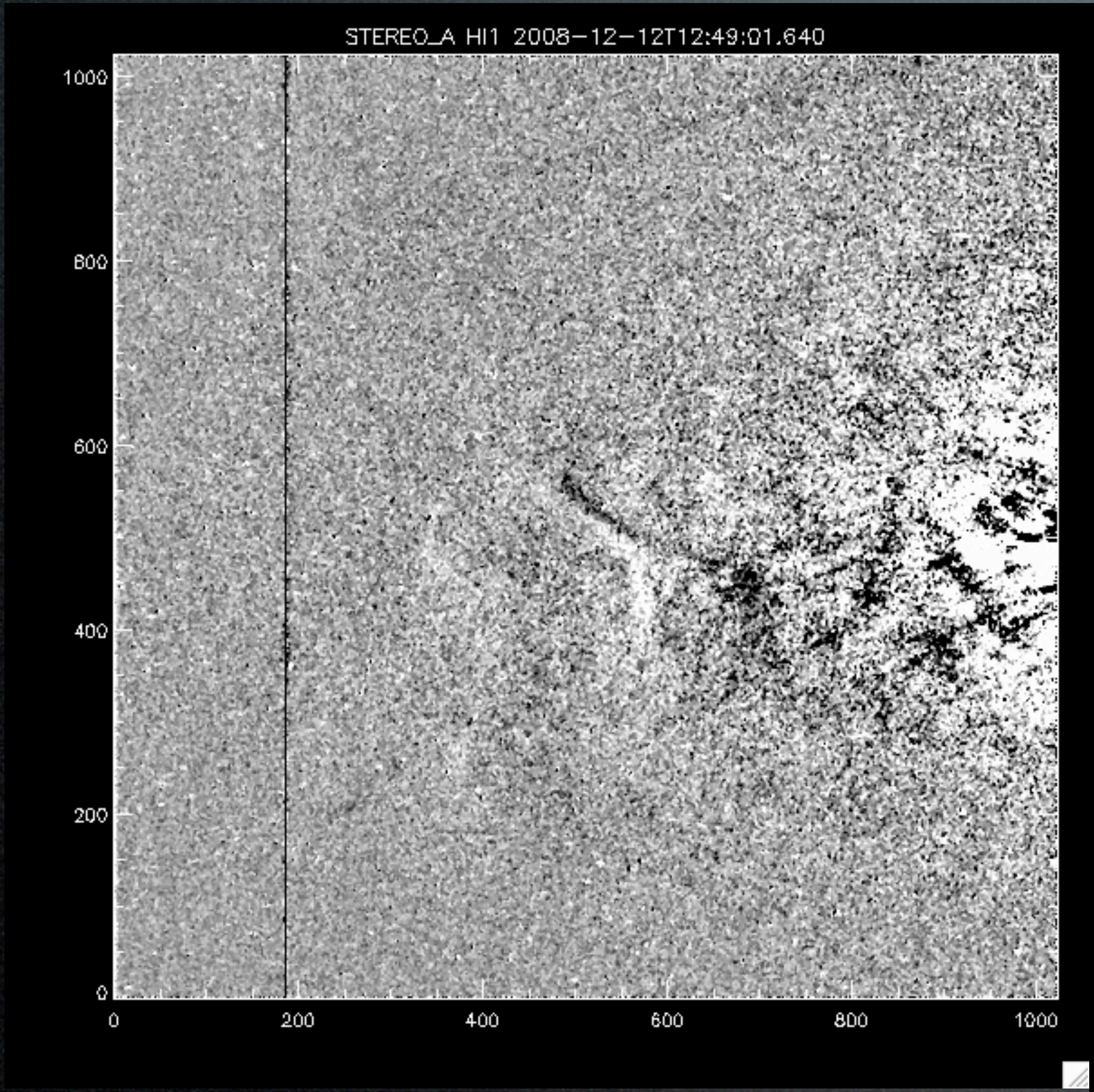


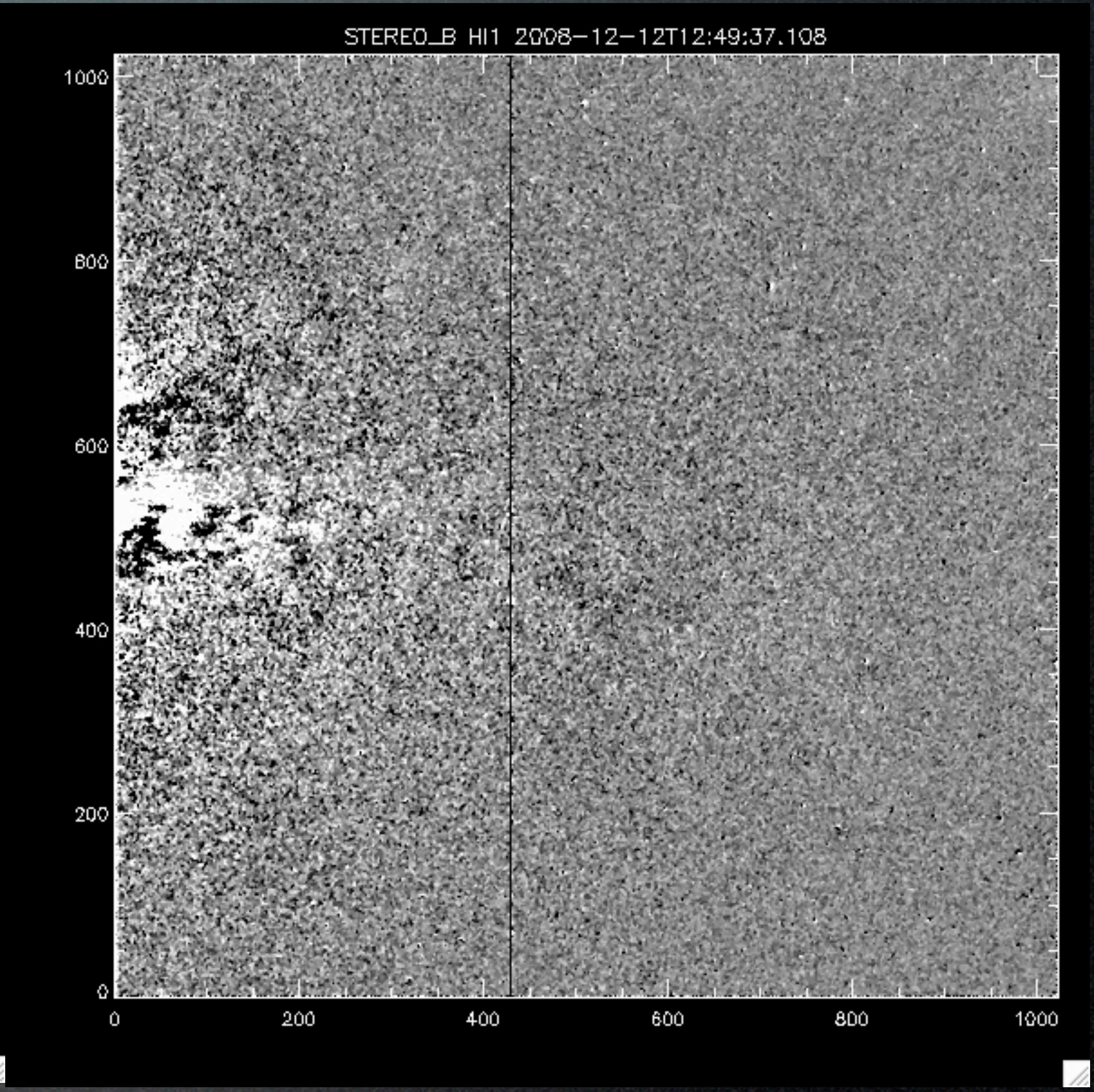


HI2 Ahead

HI1 Ahead

Observations

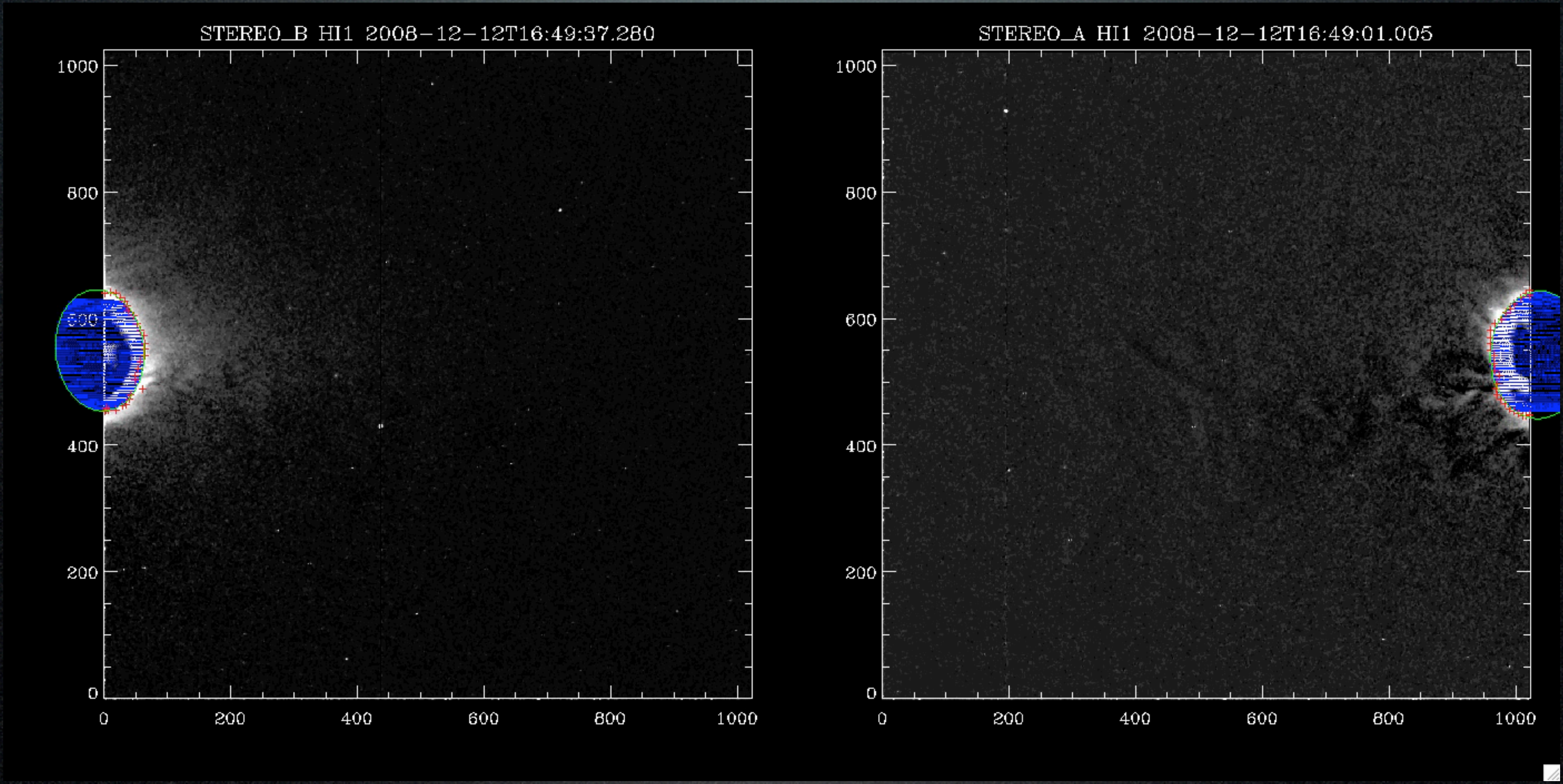




Ahead

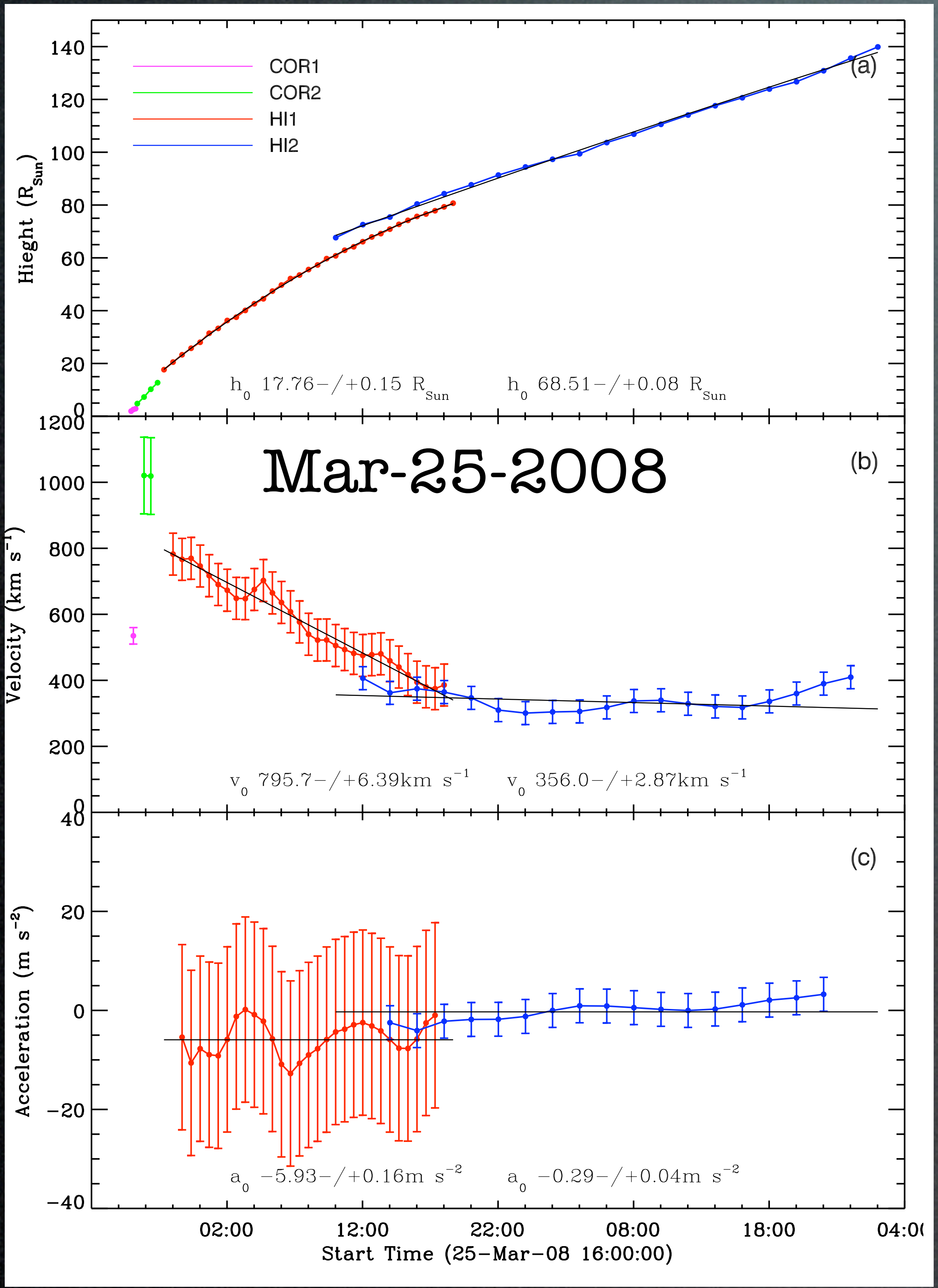
Behind

Observations

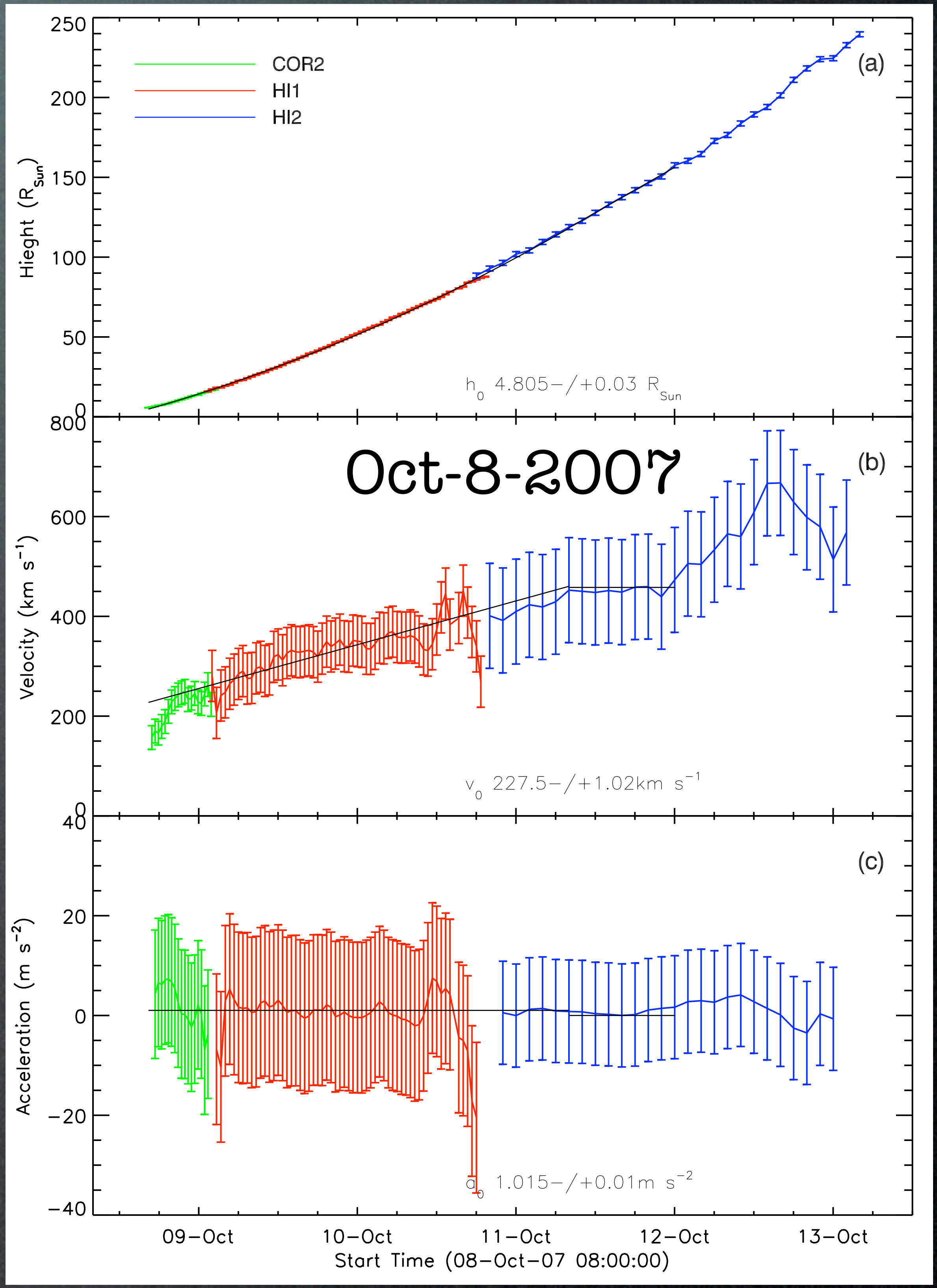


HI1 Behind HI1 Ahead

Kinematics

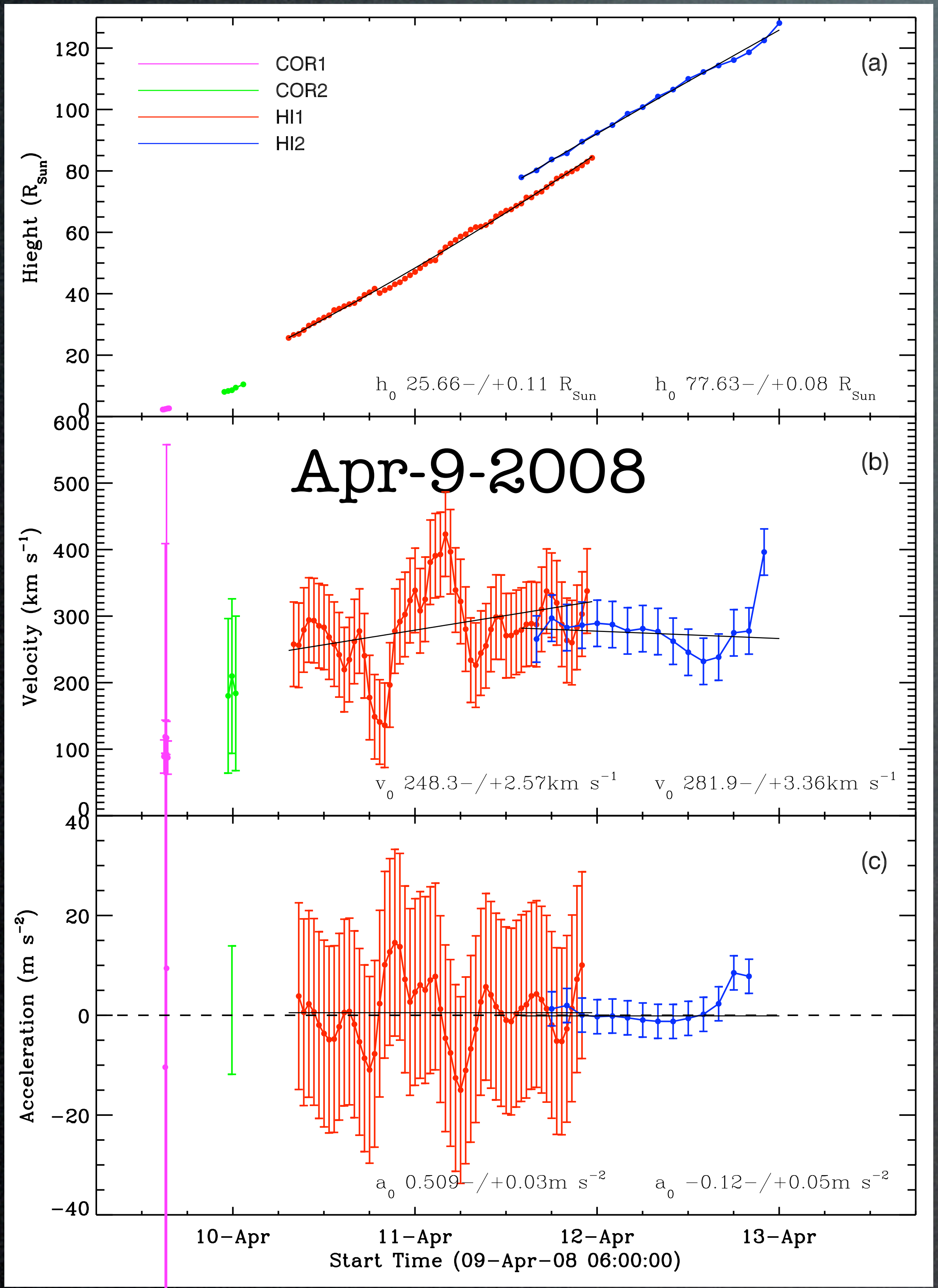


COR1
COR2
HI1
HI2
(a)
Hieght (R_{Sun})
h_0 17.76−/+0.15 R_{Sun}
h_0 68.51−/+0.08 R_{Sun}
Mar-25-2008
(b)
Velocity (km s^{-1})
v_0 795.7−/+6.39km s^{-1}
v_0 356.0−/+2.87km s^{-1}
(c)
Acceleration (m s^{-2})
a_0 −5.93−/+0.16m s^{-2}
a_0 −0.29−/+0.04m s^{-2}
02:00
12:00
22:00
08:00
18:00
04:00
Start Time (25−Mar−08 16:00:00)



COR2
HI1
HI2
(a)
Hieght (R_{Sun})
h_0 4.805−/+0.03 R_{Sun}
Oct-8-2007
(b)
Velocity (km s^{-1})
v_0 227.5−/+1.02km s^{-1}
(c)
Acceleration (m s^{-2})
a_0 1.015−/+0.01m s^{-2}
09−Oct
10−Oct
11−Oct
12−Oct
13−Oct
Start Time (08−Oct−07 08:00:00)

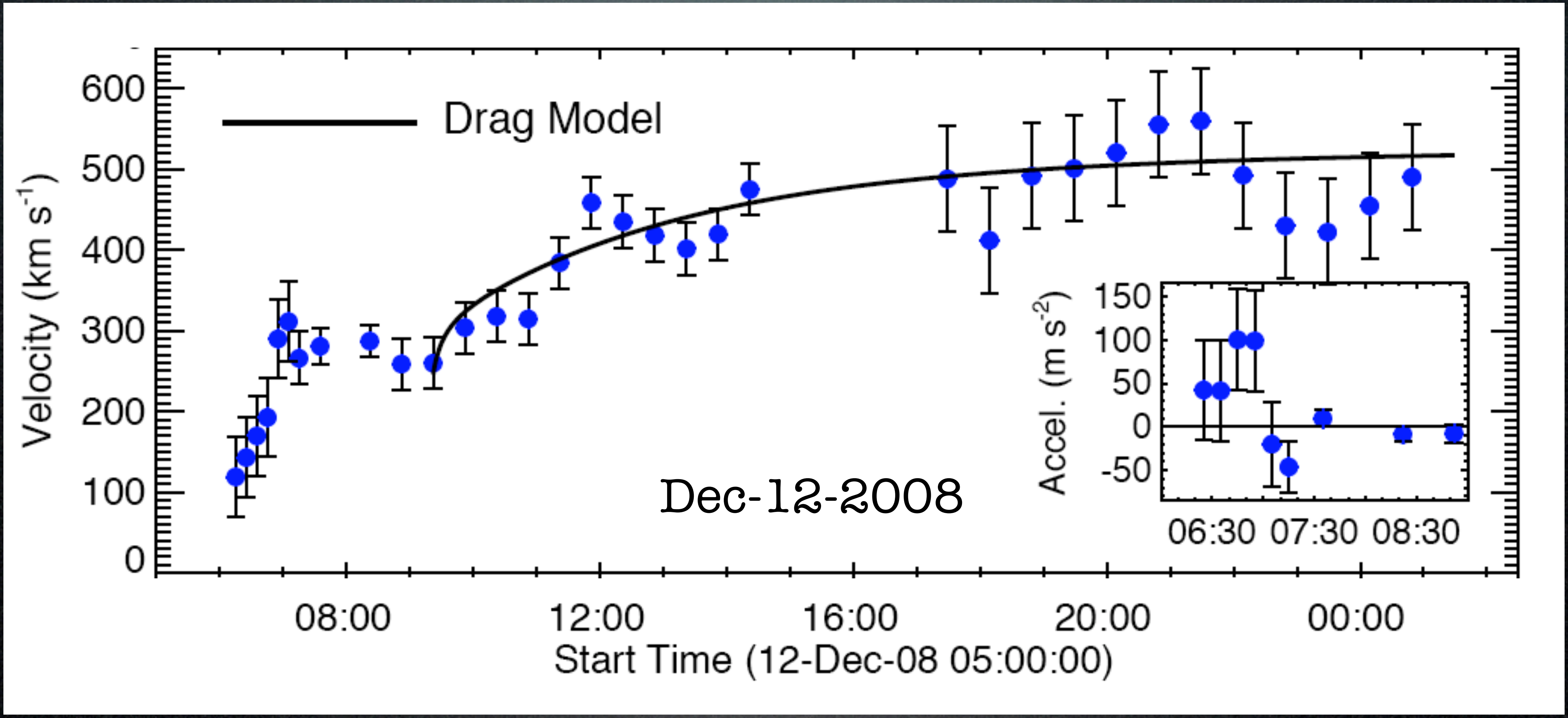
Kinematics



- Can derive true CME kinematics.
- They show some CMEs undergo significant acceleration in the Heliosphere.
- Acceleration is consistent with drag.

Maloney et al 2010 in prep

Kinematics



Byrne et al in prep 2010

Bootstrapping

- Bootstapping is part of a broader class of resampling methods (Efron, 1982).

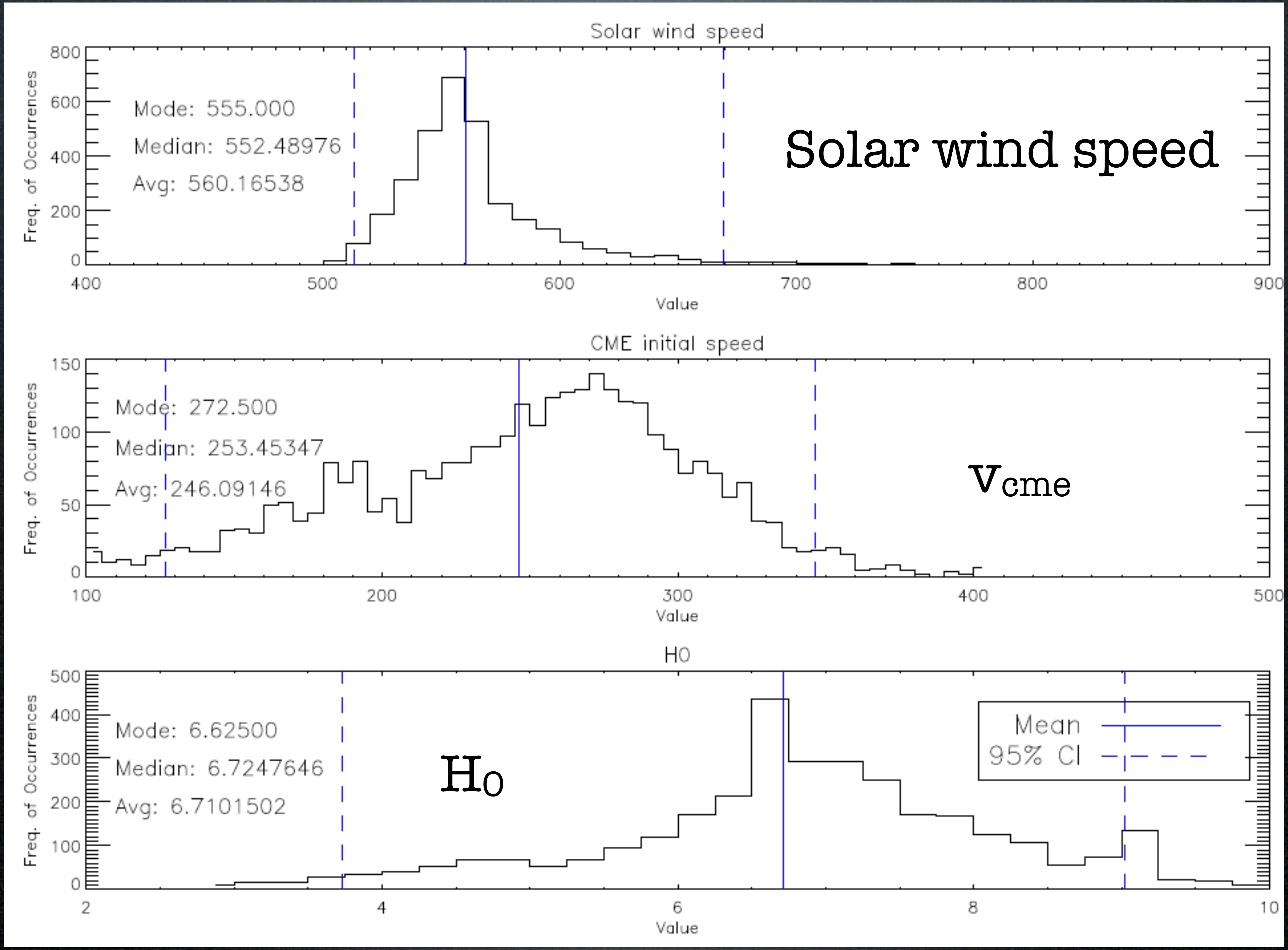
- Statistical method to estimate a property of an approximately sampled distribution.

- Method

  1. Fit model and calculate residuals
  $$\widehat{\epsilon_i} = y_i - \widehat{y_i}$$
  3. Add randomly resampled residuals
  $$y_i^* = y_i + \widehat{\epsilon_j}$$
  5. Refit the boostrap response y_i^*
  6. Repeat 2 and 3 many times (~10,000)

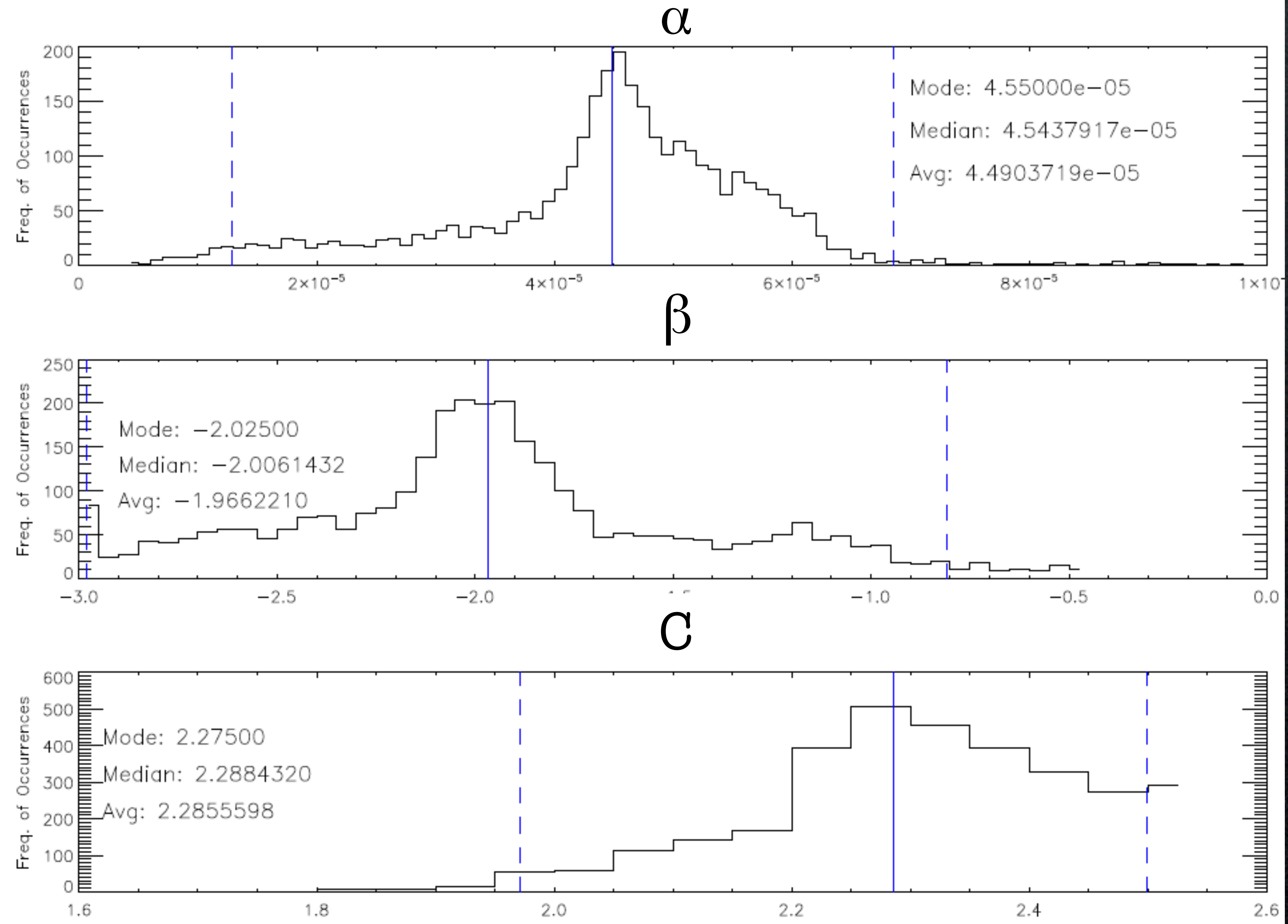
- Extract distributions for free parameters

Results



Solar wind speed
Mode: 555.000
Median: 552.48976
Avg: 560.16538
Solar wind speed
Freq. of Occurrences
Value
CME initial speed
Mode: 272.500
Median: 253.45347
Avg: 246.09146
v_{cme}
H0
Mode: 6.62500
Median: 6.7247646
Avg: 6.7101502
H_0
Mean
95% CI

Results


α
Freq. of Occurrences
Mode: 4.55000e-05
Median: 4.5437917e-05
Avg: 4.4903719e-05
β
Freq. of Occurrences
Mode: −2.02500
Median: −2.0061432
Avg: −1.9662210
C
Freq. of Occurrences
Mode: 2.27500
Median: 2.2884320
Avg: 2.2855598

Results

Parameter	Bootstrap	Observation	Other studies
Solar wind velocity (km/s)	560^{+109}_{-47}	530	
CME initial velocity (km/s)	246^{+100}_{-119}	260	
CME initial height (R_{Sun})	$6.7^{+2.3}_{-3.0}$	6.6	
α	$4.49^{+2.37}_{-3.21} \times 10^{-05}$		$1.16 \pm 0.12 \times 10^{-3}$ $22.5 \pm 2.5 \times 10^{-6}$
β	$-1.97^{+1.16}_{-1.01}$		1.35 ± 0.4 2.24 ± 0.5
C	$2.28^{+0.21}_{-0.31}$		1 or 2

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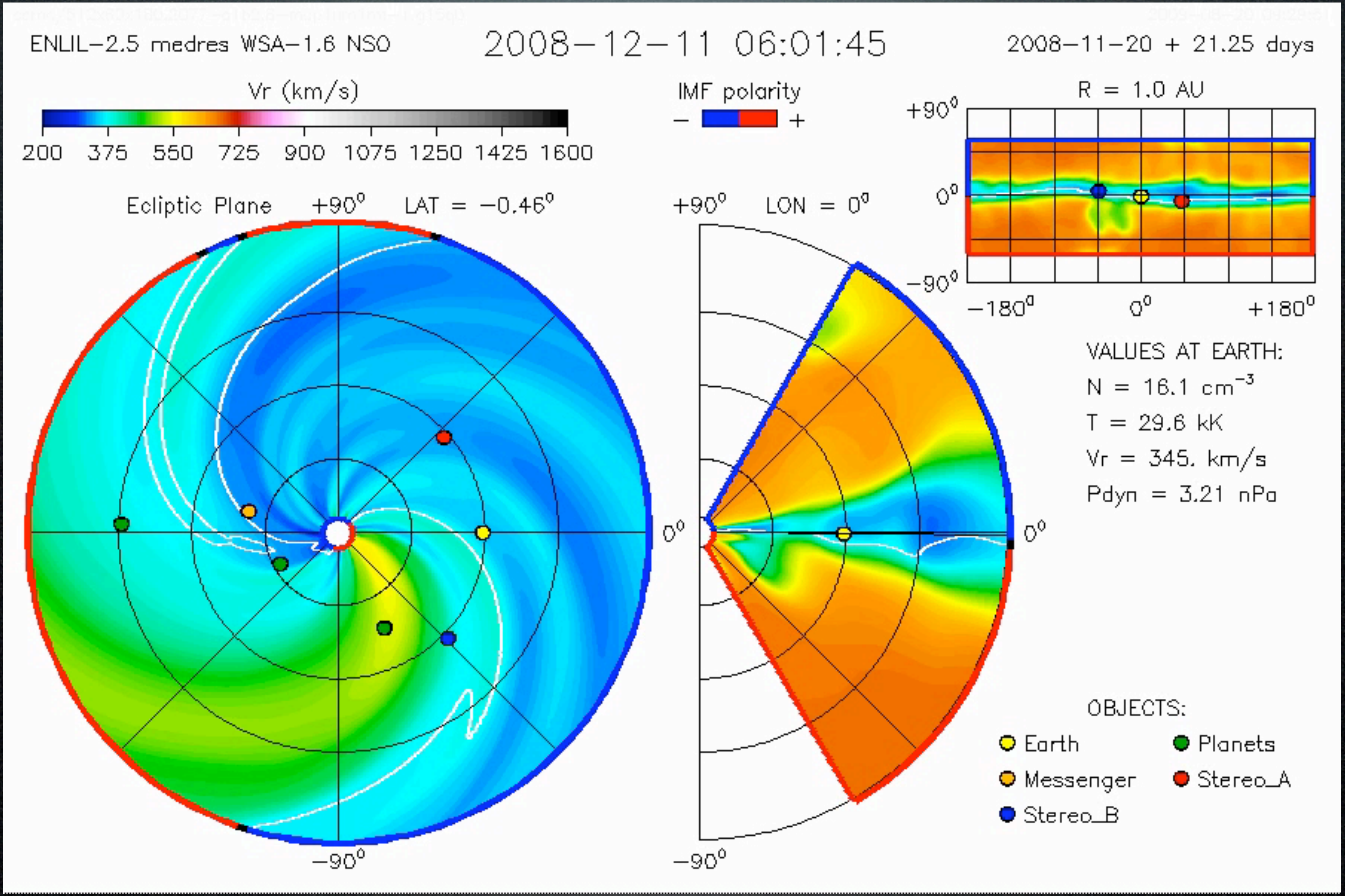
CME arrival time

- Based on 3D reconstruction to ~50 R_{Sun} we predicted an arrival time (at L1) of ~15-Dec-2008 13:10 (const velocity)
- In-situ data show arrival time of ~16-Dec-2008 09:00
- Used 3D reconstruction to tightly constrain ENIL+cone inputs
  - Results from ENIL gives the arrival time ~16-Dec-2008 08:09
  - CME interacts with slow-speed solar wind ahead of it and slows down

Community Coordinated Modeling Center

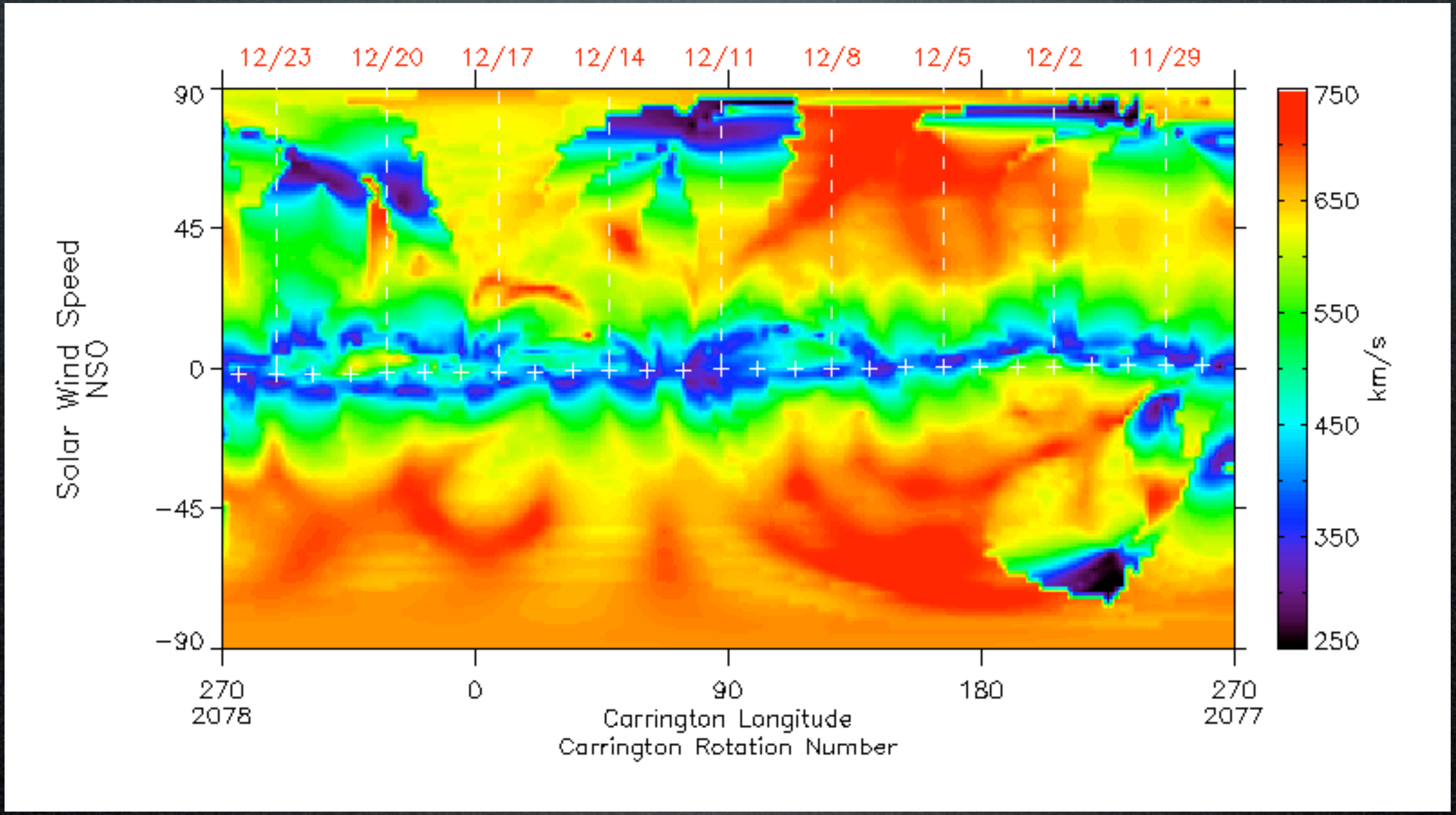
CME arrival time



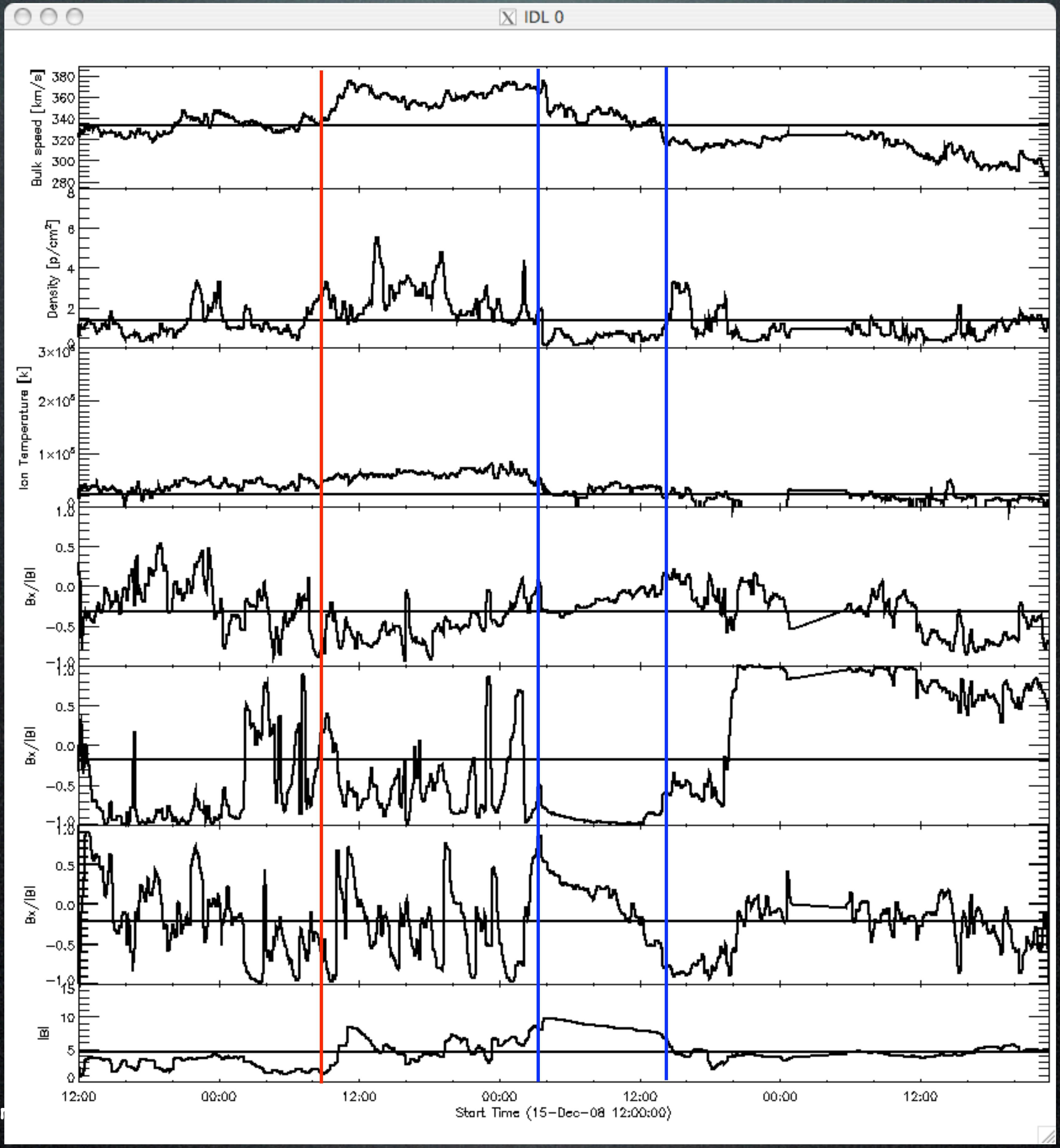
Conclusions

- CME are accelerated in Heliosphere
  - Can be close to the Sun < 50 R_{Sun}
- Complex, dynamic interaction between CME and solar wind effecting both kinematics and morphology
- As a result of complex interaction arrival time prediction hard.
- For 2008-Dec-12 CME aerodynamic drag is acting on the CME, accelerating it from 350 to 450 km/s

Fast solar wind source



In-situ data



Shane Maloney, '

Image Processing

- Image segmentation:
    - **Intensity Based**
    - Multi-scale (Wavelets, Curvelets)
    - Morphological Operations
- Modified Running Difference
    - Accounts for stellar motion, suppress signal from stars (cross correlation between images).

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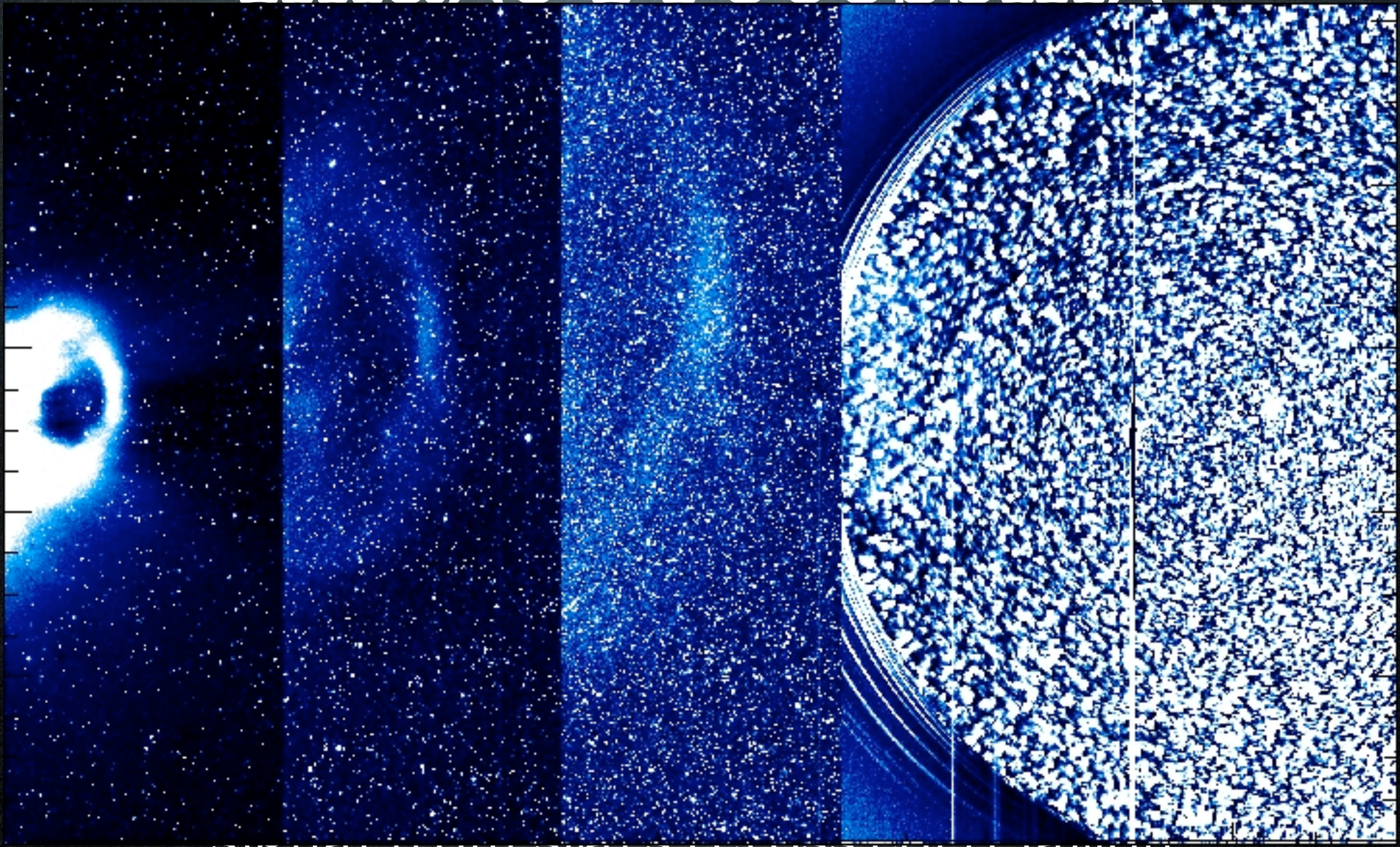

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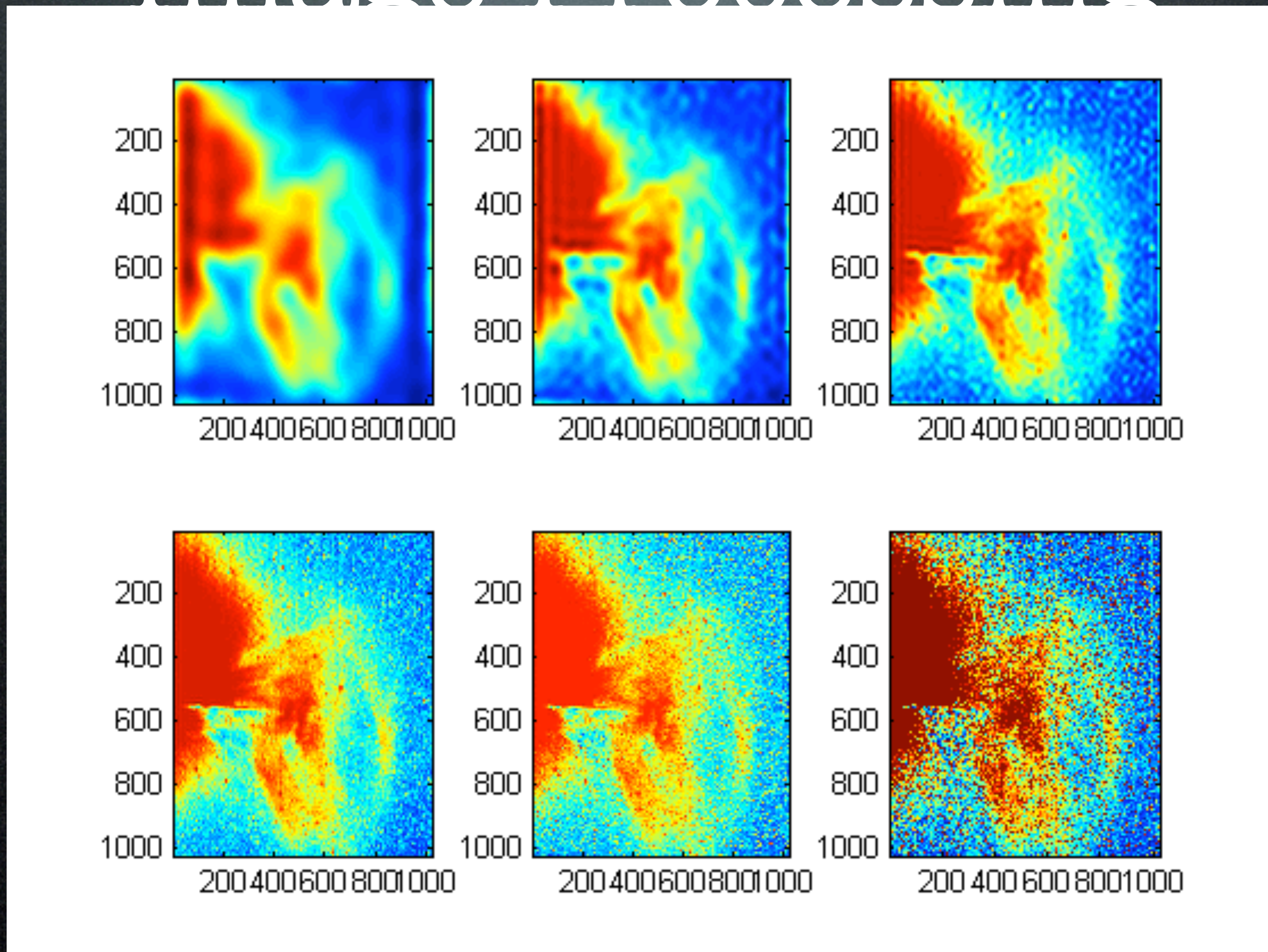

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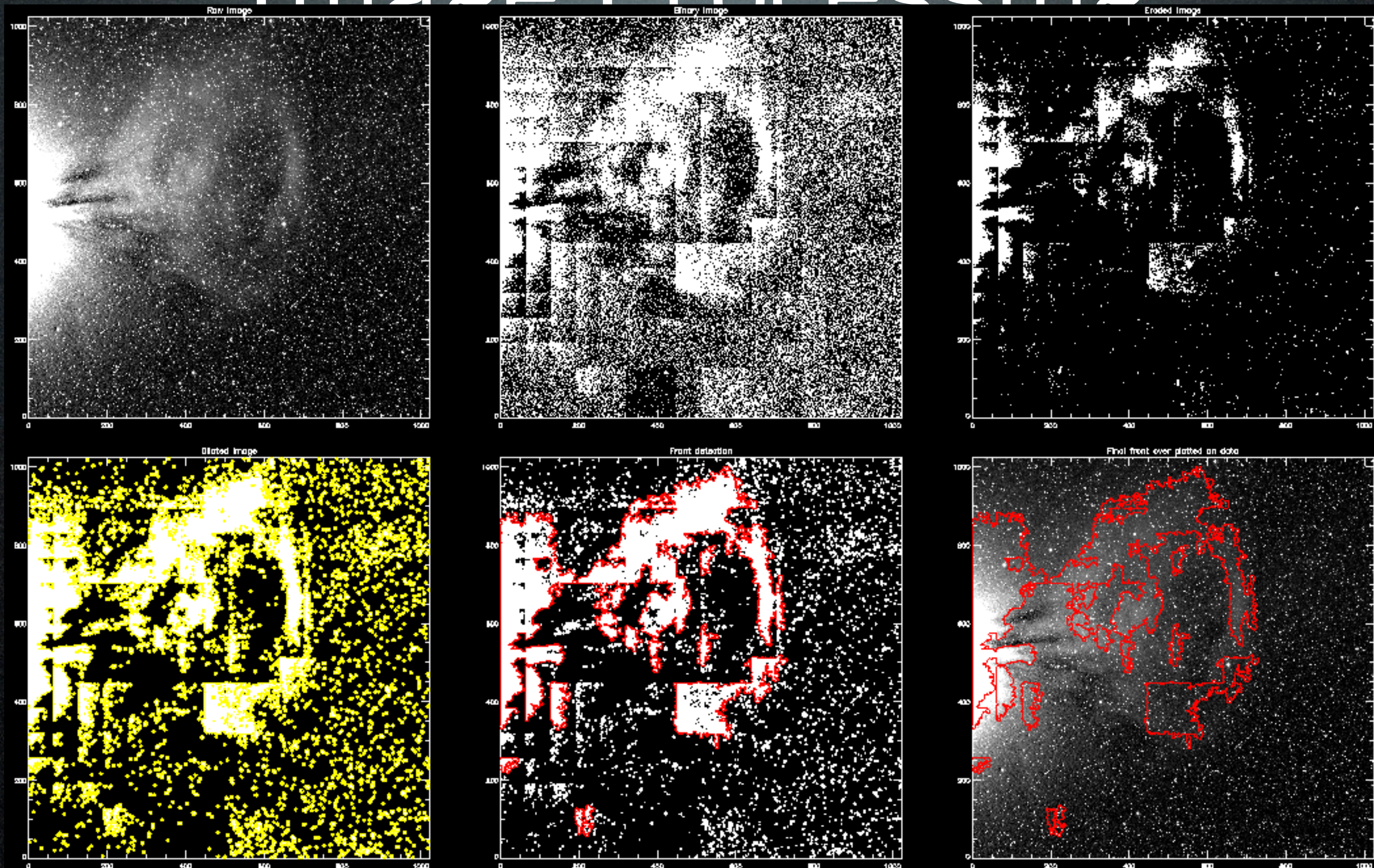

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