The Effects of Uncertainty on Deflection, Rotation, and Bs predictions

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Advocating forward modeling and system studies

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Predicting Impacts

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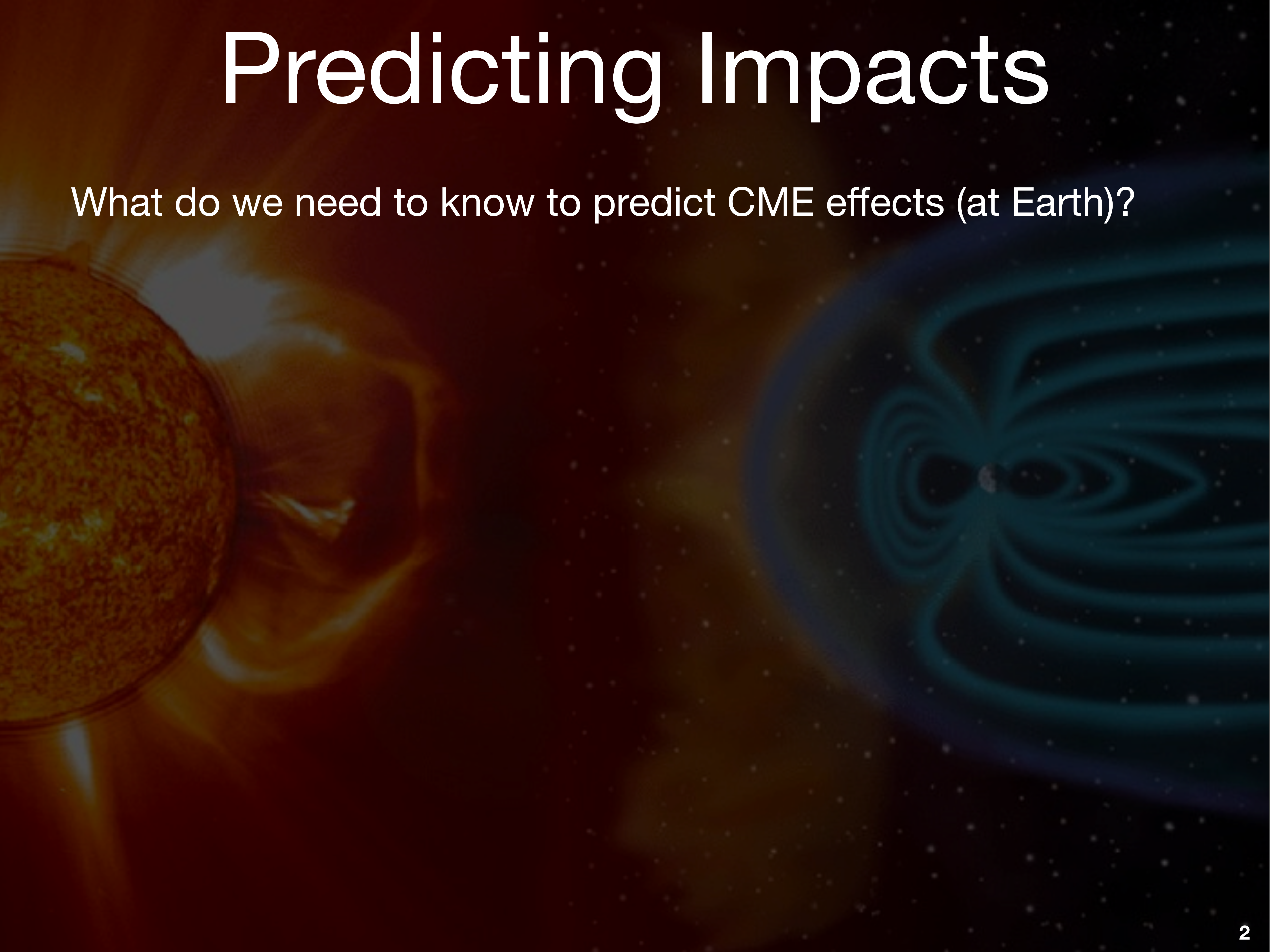

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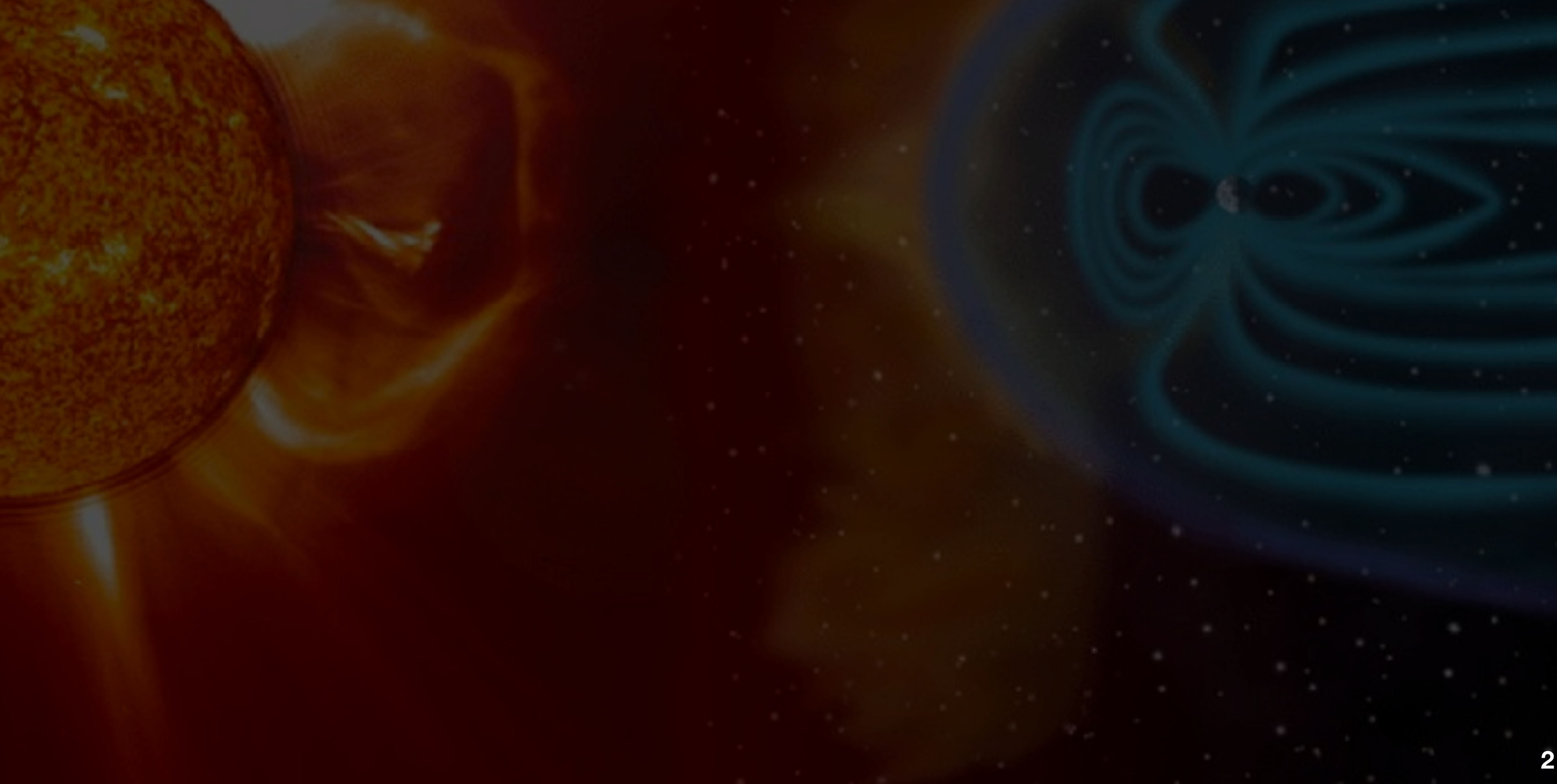

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Southward important for storms, but all components important for understanding actual physics

Forward modeling vs. reconstructing

- Different approaches using the same observations
  - Forward - use what we already ***"know"*** from the corona to ***"predict"*** what we will see in situ
  - Reconstructing - use what we see in situ to compare with what we already knew

 

- See T. Nieves-Chinchilla's talk for different perspective (after break)

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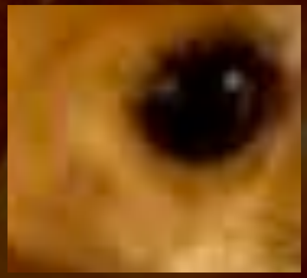
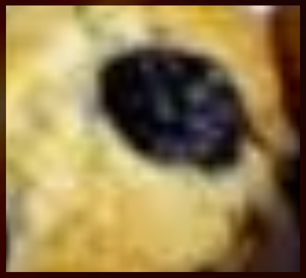

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Reconstructing In Situ

- Approximate locally as cylinder
  - Axis orientation in 3D specified by two angles
- Least-squares fitting of flux rope - change parameters to minimize error

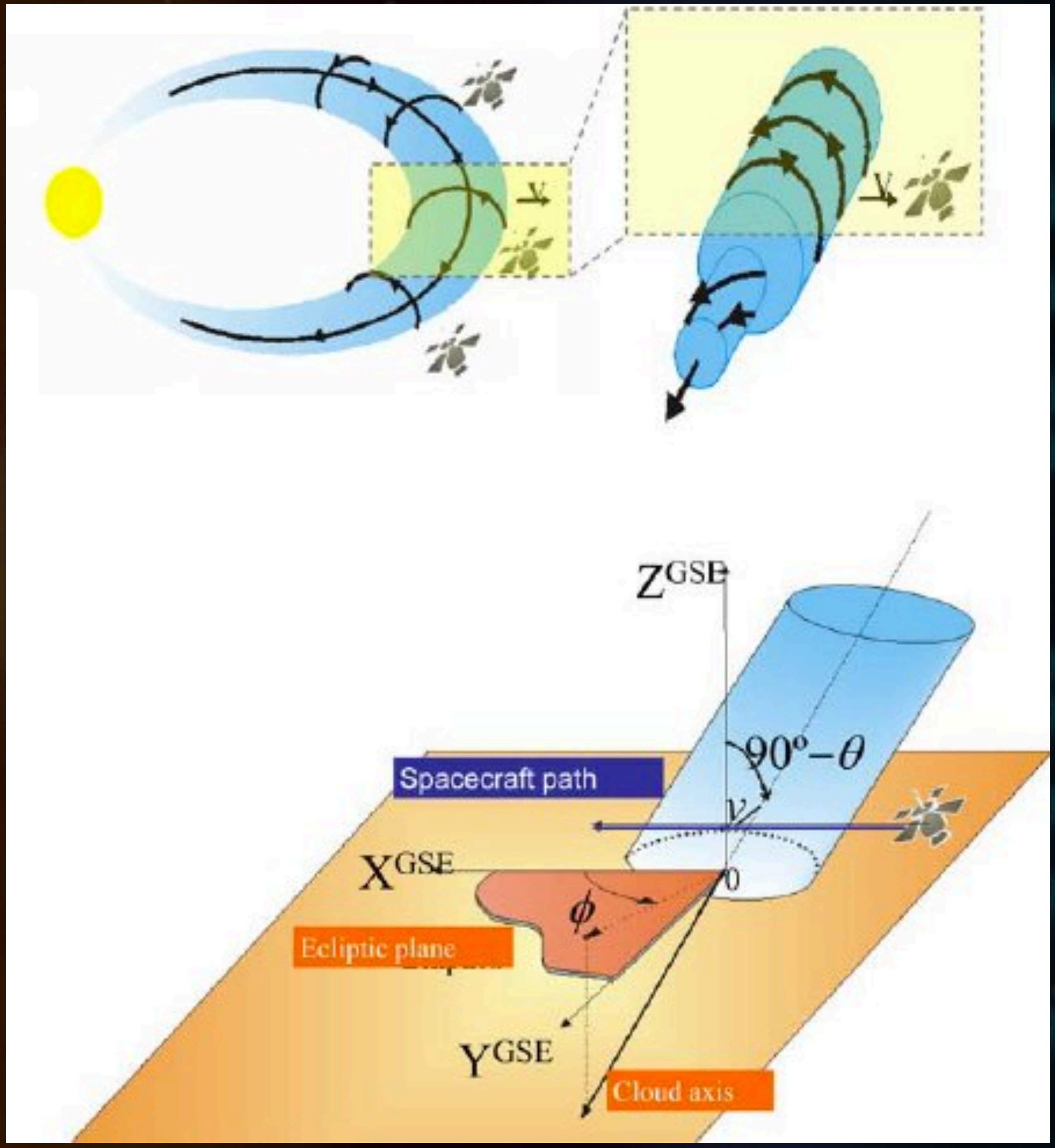


Image from Watermann+ 2009

Comparing In Situ Reconstructions

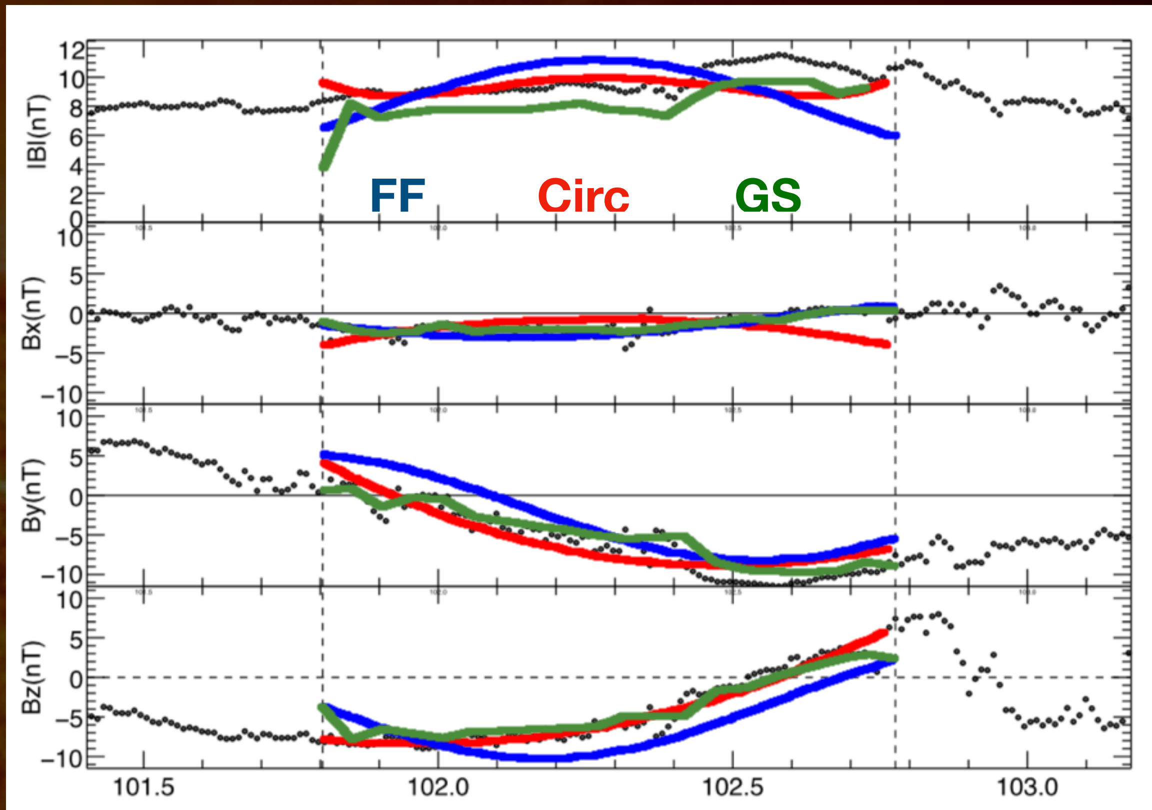


Image from Al-Haddad+ 2018

Event		CCS			GS				FF		
Year	DOY	$\theta(^\circ)$	$\Phi(^\circ)$	χ_{red} (nT)	$\theta(^\circ)$	$\Phi(^\circ)$	χ_{red} (nPa)	b/a	$\theta(^\circ)$	$\Phi(^\circ)$	χ_{red} (nT)
1997	10	232	−21	0.028	214	−16	0.017	0.5	231	−27	0.038
1998	232	264	17	0.044	265	13	0.017	0.6	294	28	0.050
2000	183	359	21	0.045	2	41.5	0.023	0.6	357	48	0.11
2001	111	285	−42	0.025	302	−35	0.017	0.9	272	−48	0.062
2002	273	109	−12	0.035	146	−12	0.015	1	114	18	0.11
2008	143	24	47	0.033	20	12	0.015	0.6	306	68	0.075
2009	273	284	36	0.036	323	14	0.017	0.6	86	−1	0.101
2012	137	7	−1	0.021	105	−13	0.018	0.7	285	10	0.075
2012	318	283	−55	0.023	268	40	0.023	0.6	301	−30	0.050
2013	179	283	−55	0.018	330	−66	0.018	0.8	240	−62	0.050
2013	359	26	−65	0.063	53	−50	0.019	0.5	44	−74	0.043
2014	101	250	−38	0.021	236	−27	0.021	0.9	116	51	0.10
2015	126	133	43	0.041	158	49	0.021	Cx	294	28	0.053

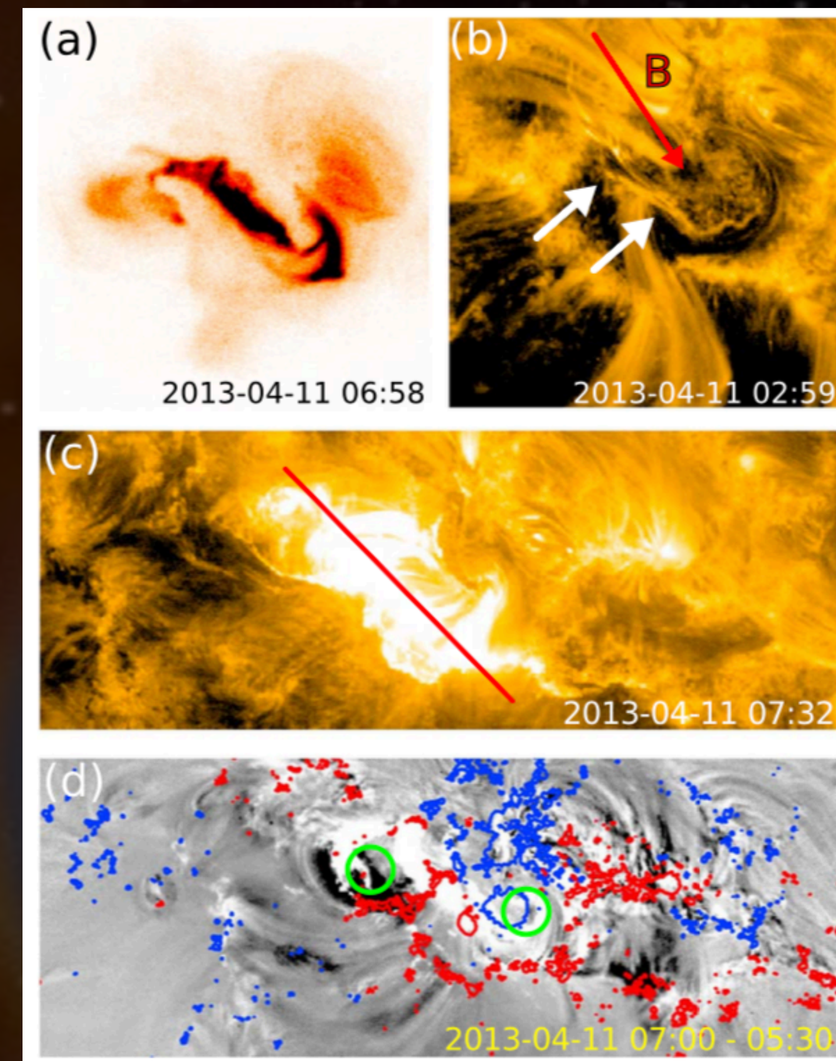
~Half have orientation within 45°

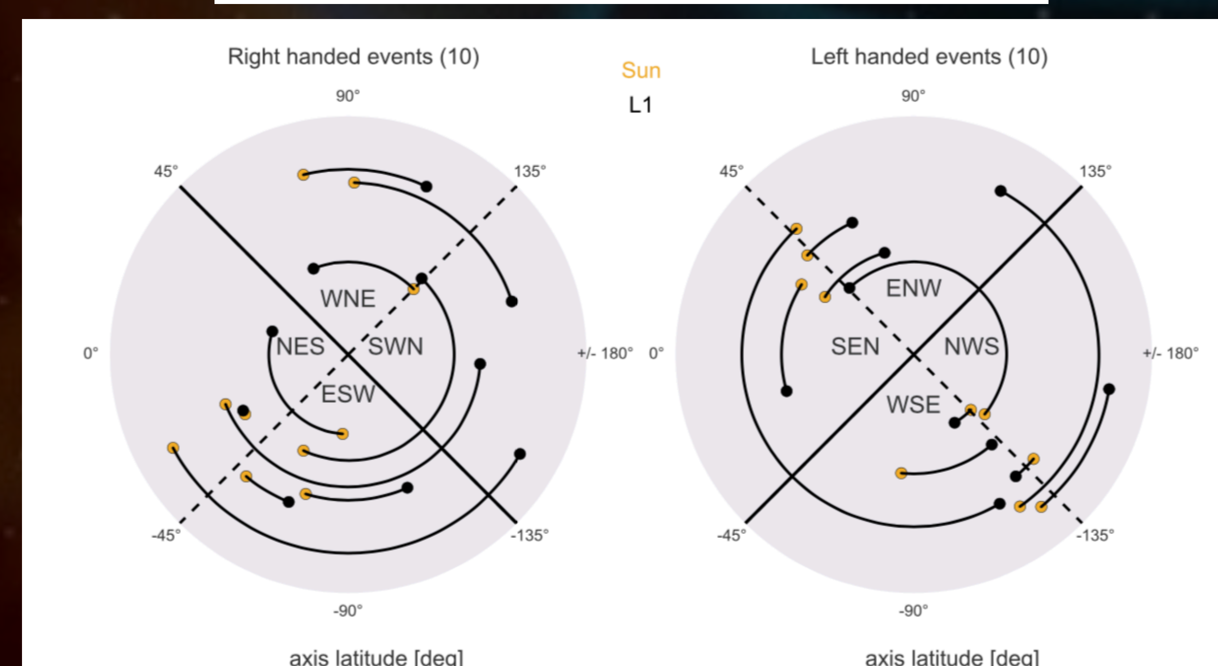
- Reconstructions often disagree (e.g. Al-Haddad 2018)
- Variations between different models
- Variations between different modelers
    - Uncertainty in chosen boundaries
    - Degeneracy in solutions

Comparing with Coronal Reconstructions

- CME positions and orientations reconstructed in corona typically do not match in situ reconstructions
    - Uncertainty in corona or in situ? (probably both)
    - Evolution between? (probably small beyond outer corona for most cases)

- Marubashi+ (2015) - typically less than 30° (54 CMEs)
- Wood+ (2017) - generally don't match (31 CMEs)
- Palmerio+ (2018) - half vary by less than 45° (20 CMEs)





Images from Palmerio+ 2018

Comparing Spatially Separated

- Reconstructions of same CME from spacecraft separated in longitude and/radial distance often disagree
  - Oversimplifying large scale CME shape?
  - Evolution with distance?
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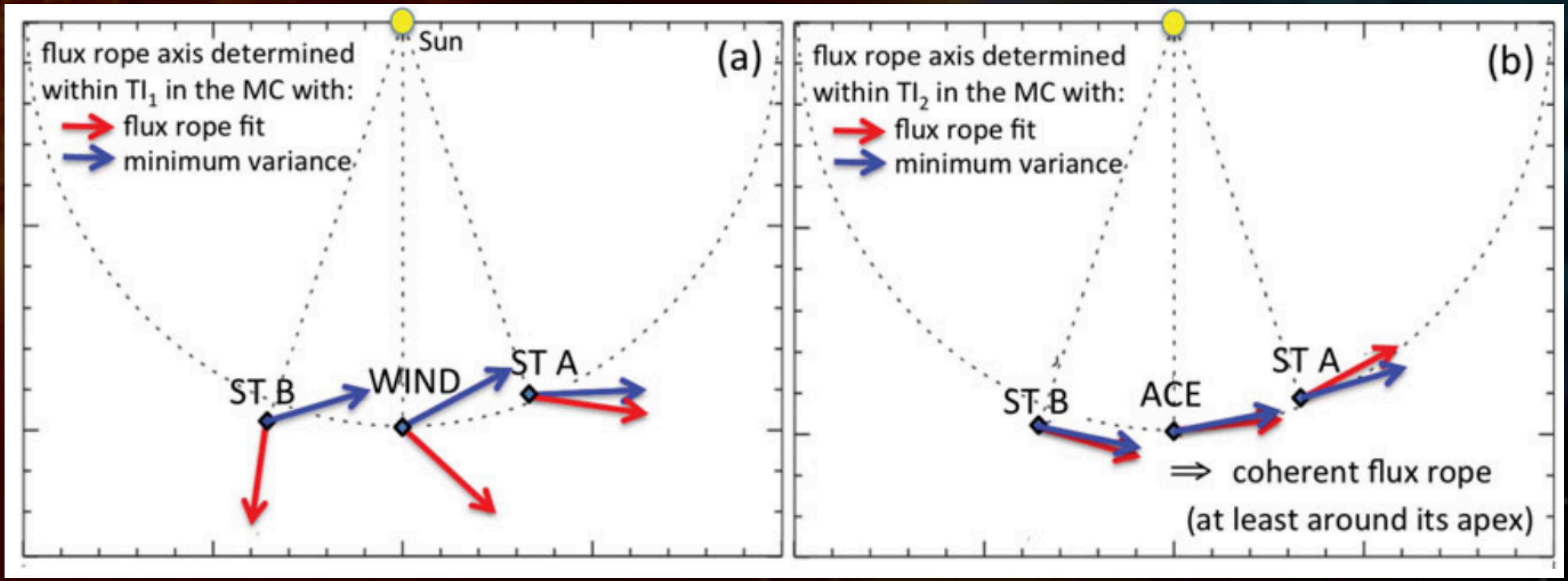

Demoulin+ 2014

Big Picture Studies

- Can develop a more clear and coherent picture by studying the full evolution of a CME from Sun to Earth (e.g. Möstl+ 2015, Patsourakos+ 2016, d'Huys+ 2017, Temmer+ 2017)
  - Use information from earlier in evolution to constrain behavior farther out
  - Abundance of available information

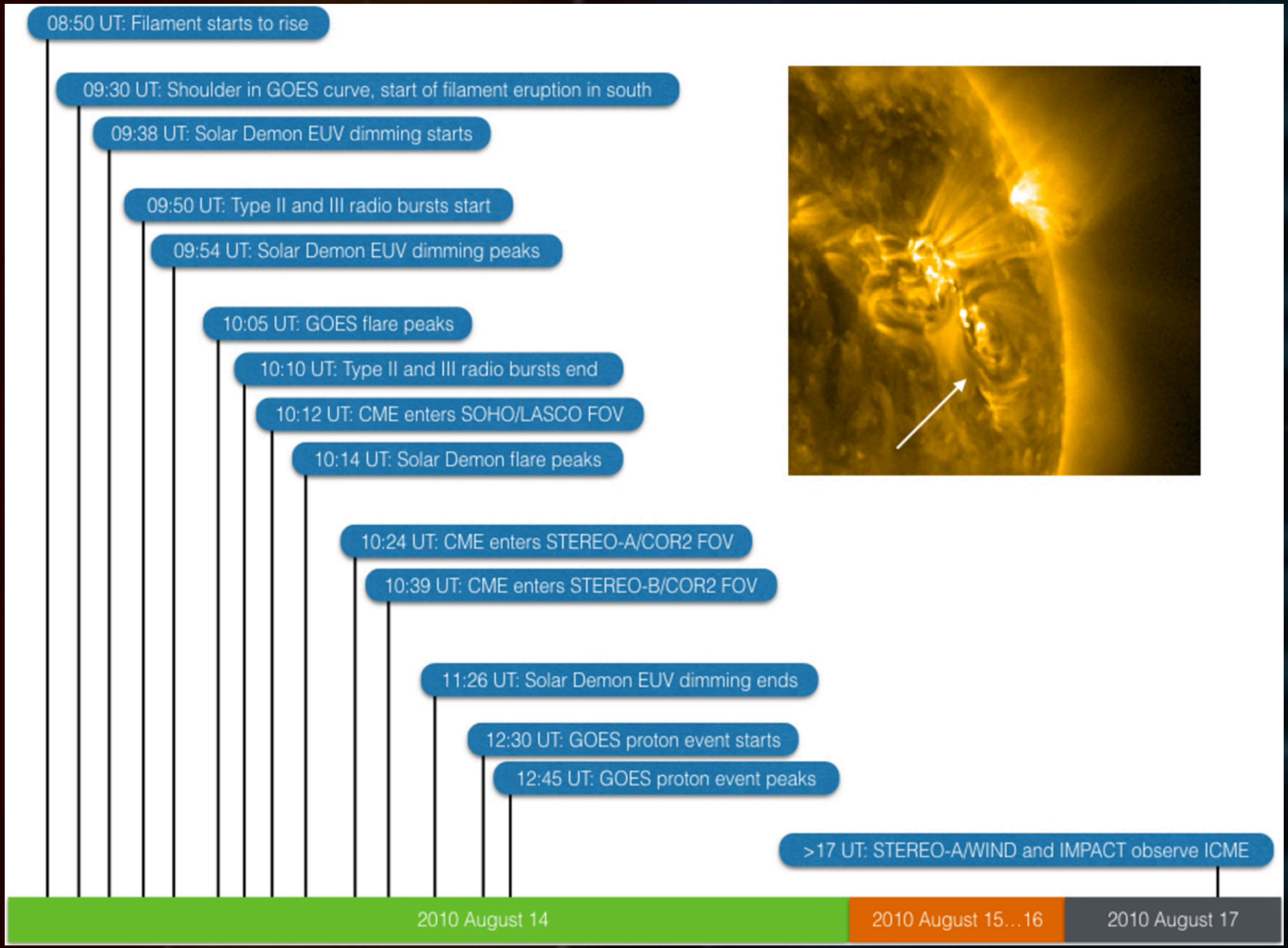

Image from d'Huys+ 2017

Magnetic (?) Big Picture Studies

- Majority of studies stop before rigorous in situ comparison
  - Möstl+ 2015 - glancing blow
  - Patsourakos+ 2016 - complicated case, apply circular flux rope but results vary wildly with chosen boundary
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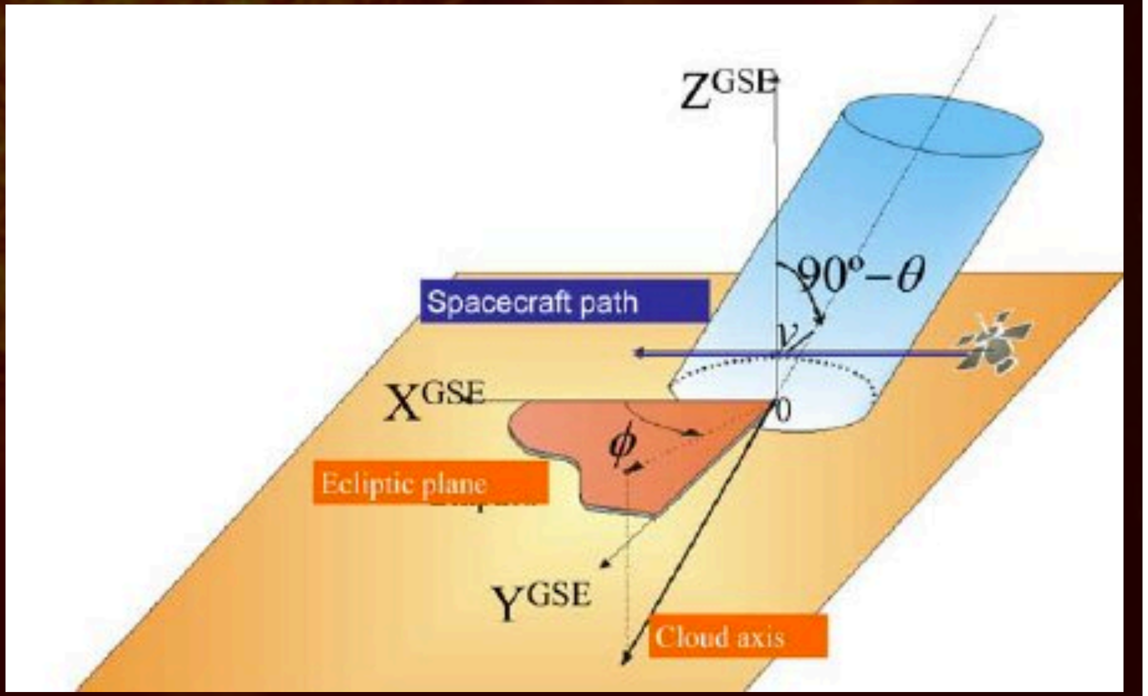

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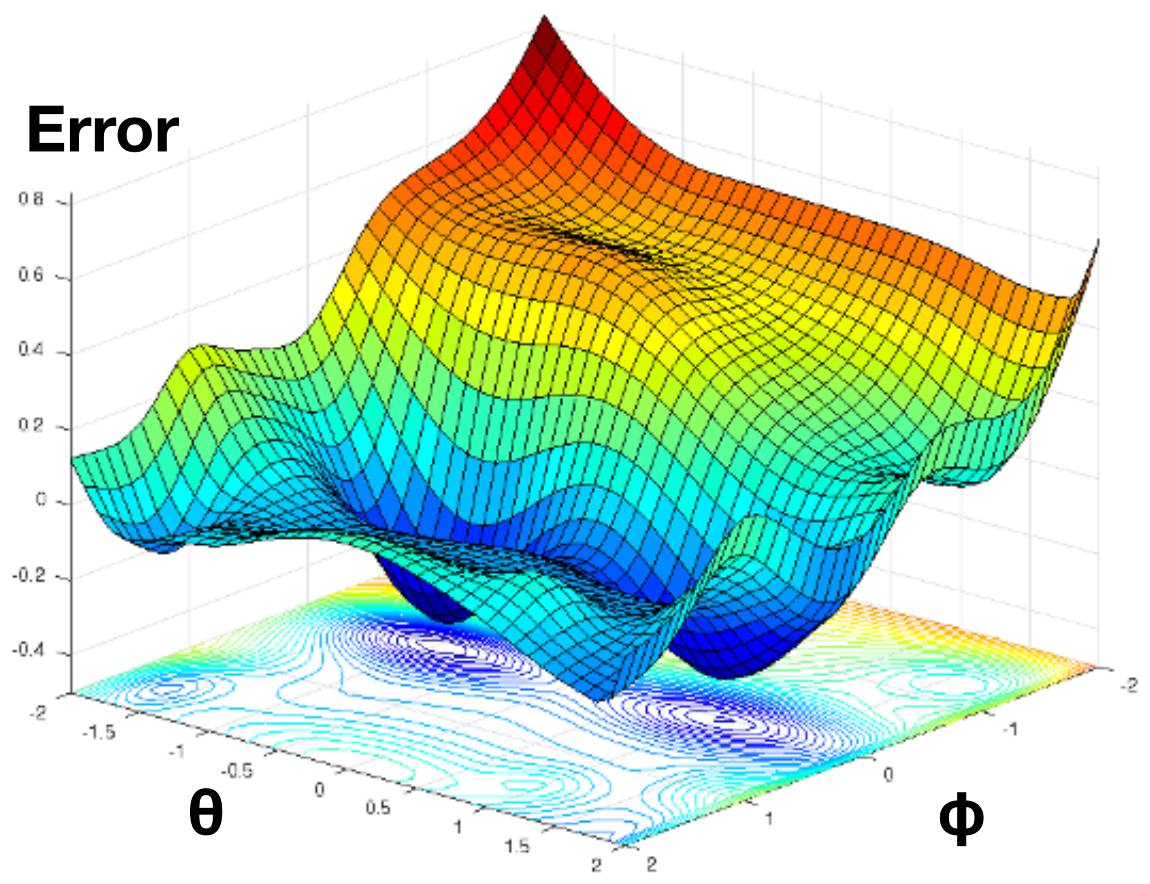

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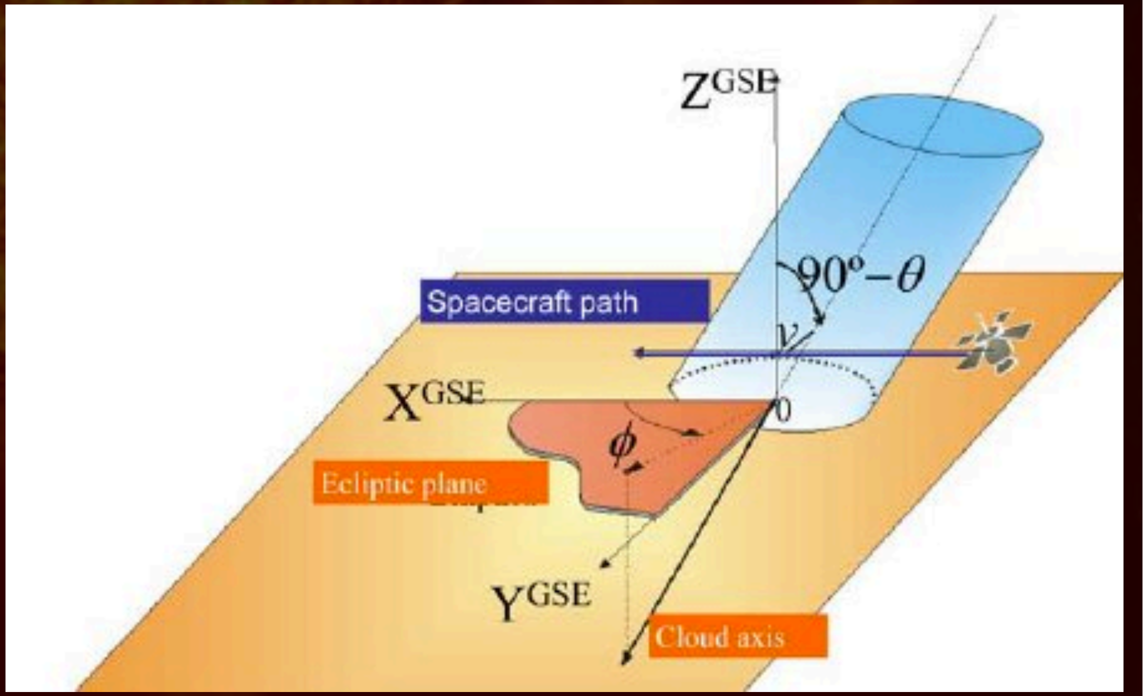

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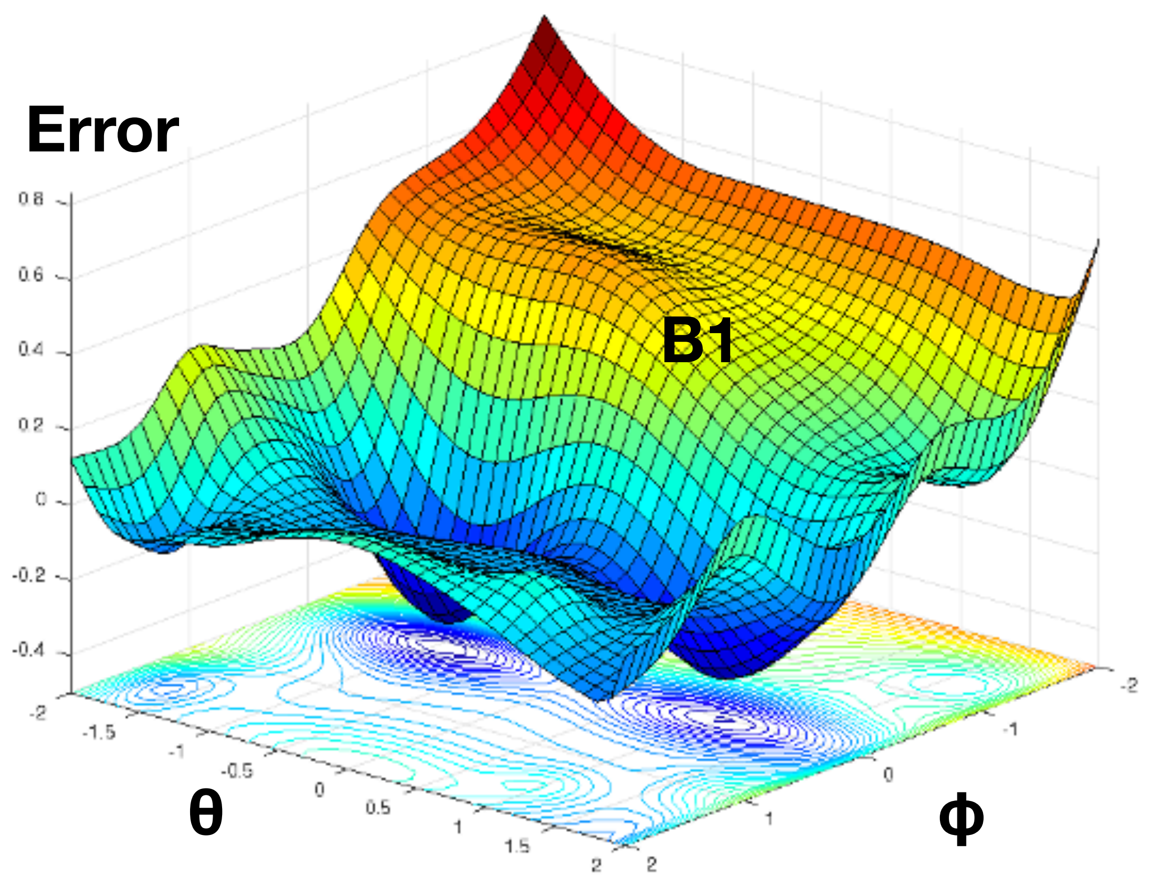

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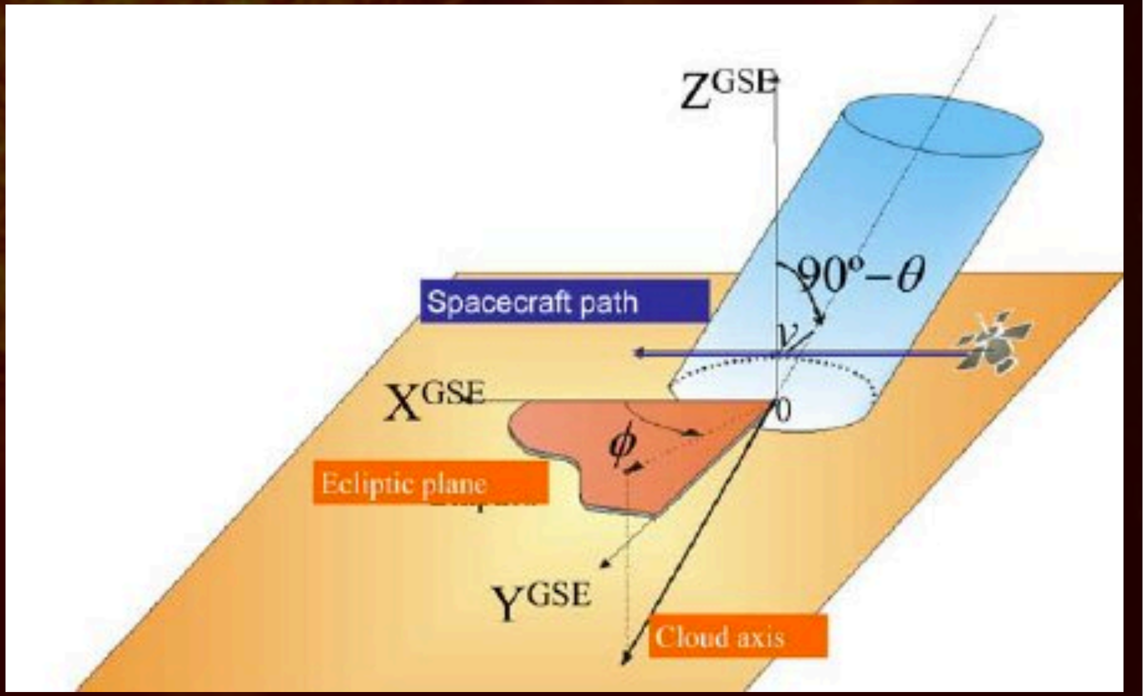

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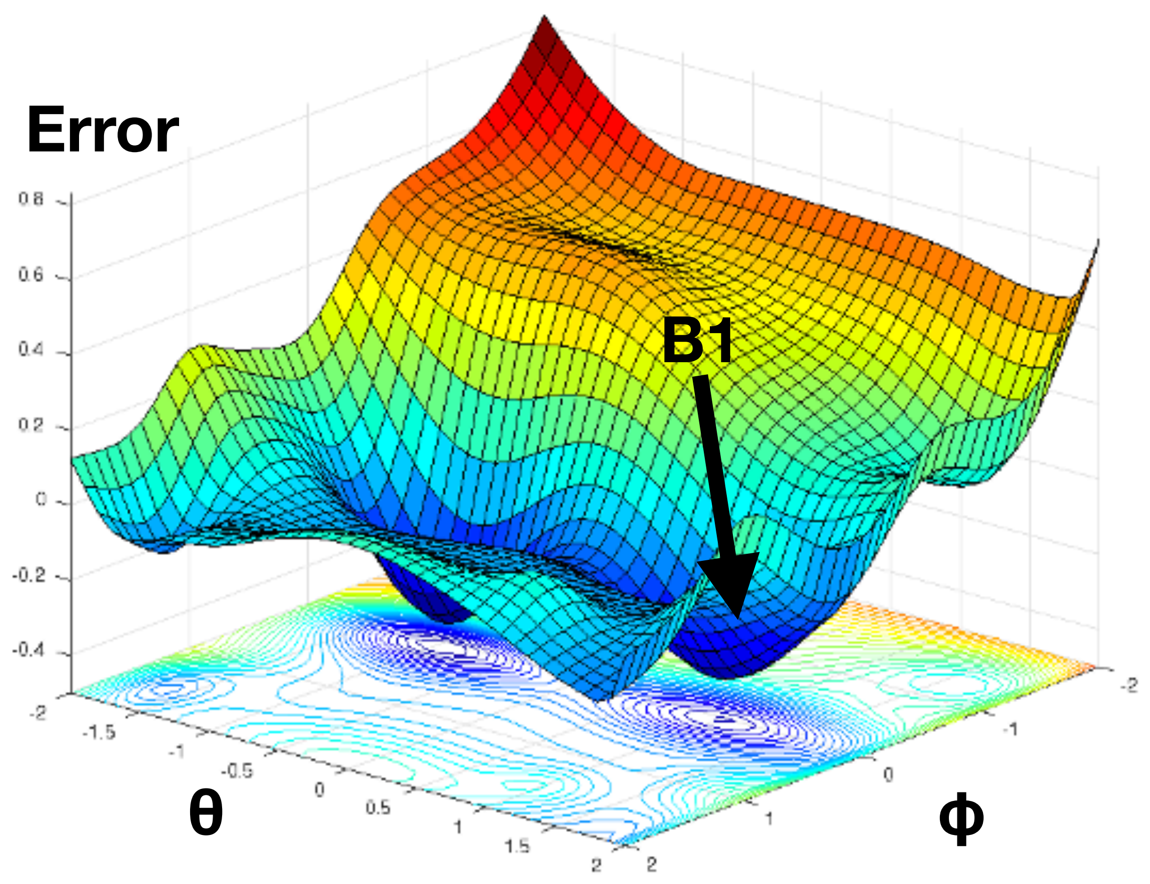

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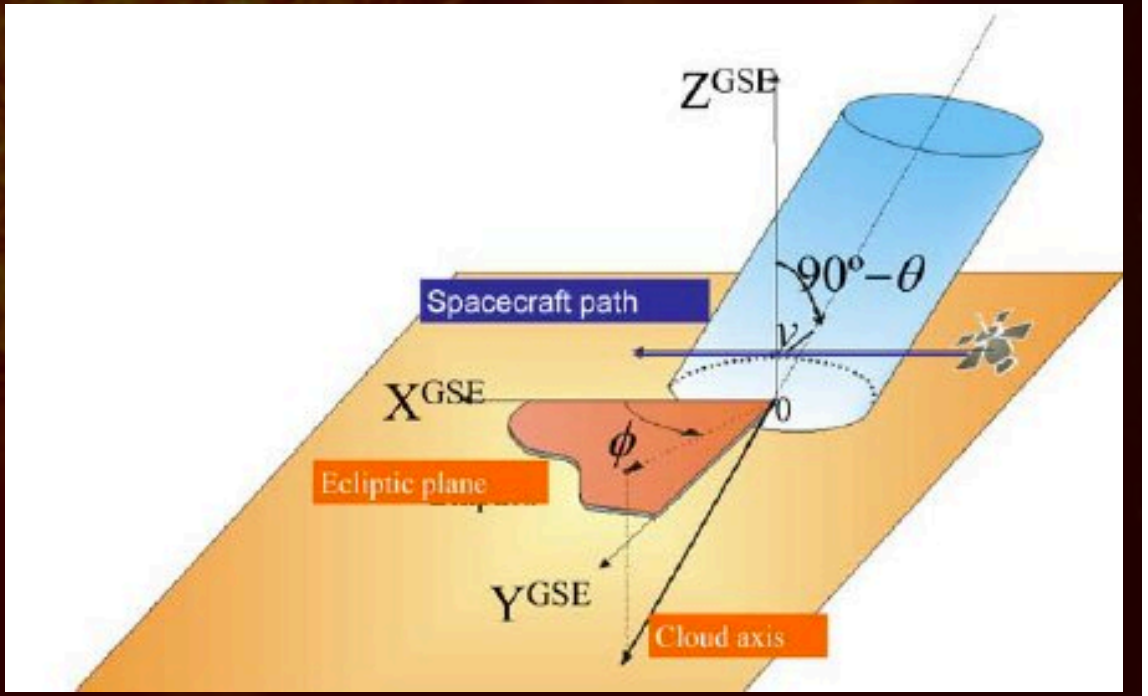

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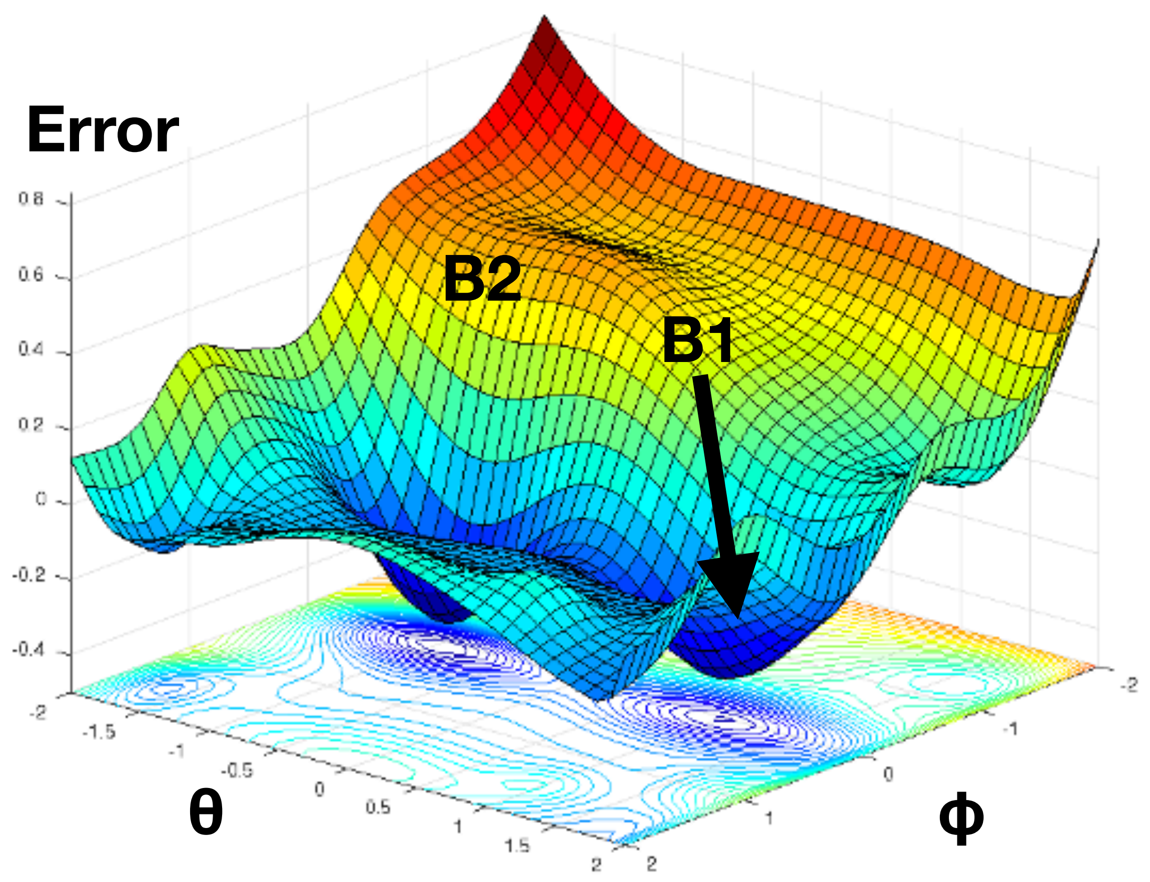

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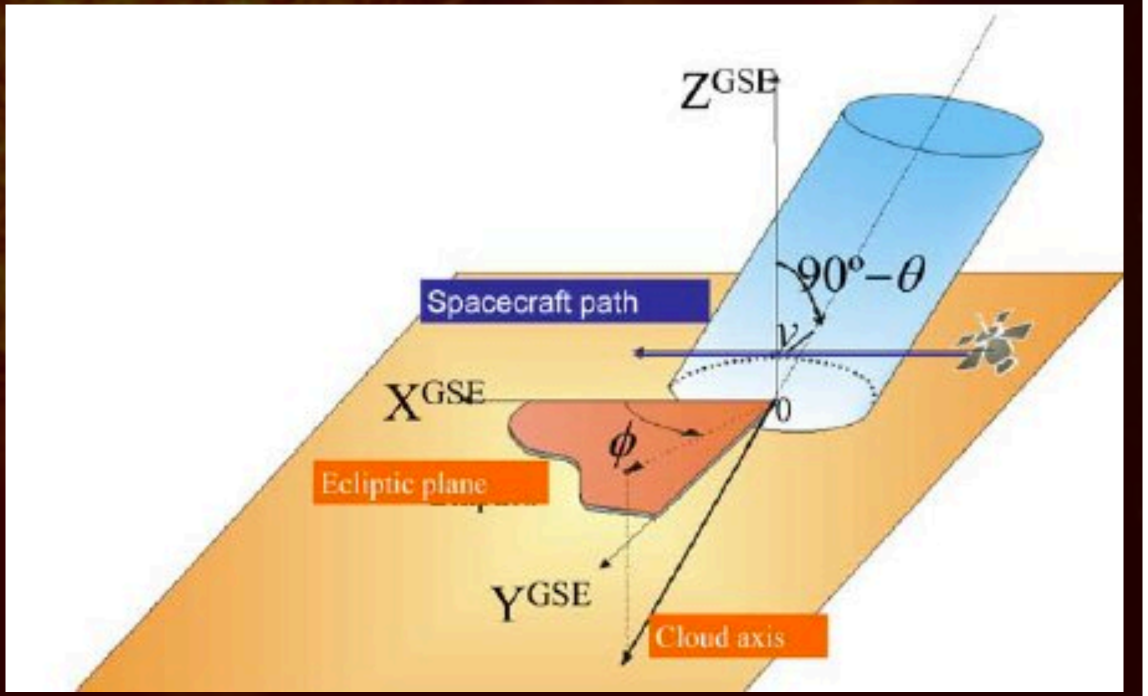

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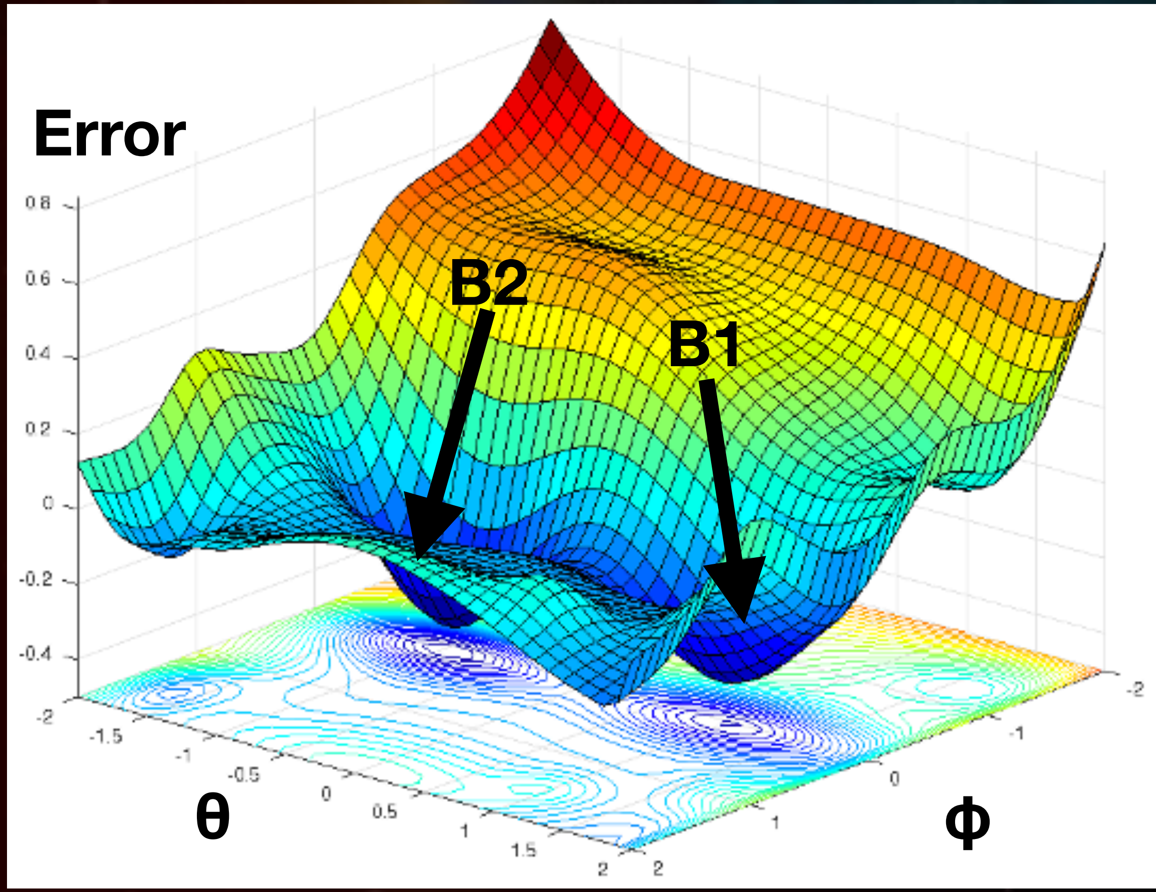

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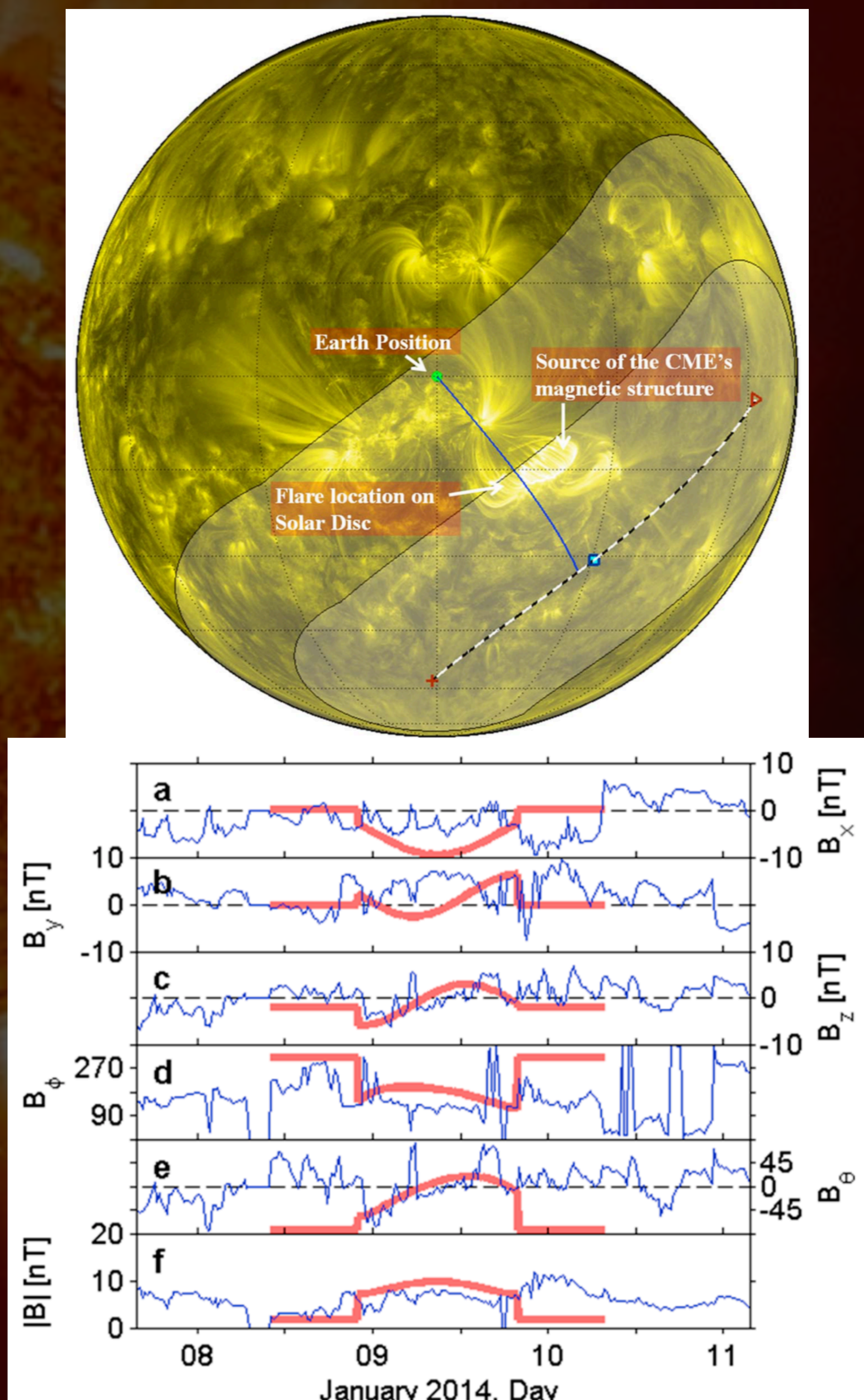
- Can measure most values in corona, with some uncertainty, then propagate to 1 AU
- Highly scalable in level of complexity for each parameter
  - i.e. 2D vs. 3D, constant with distance, self-similar…

BzForecast (Savani+ 2015)

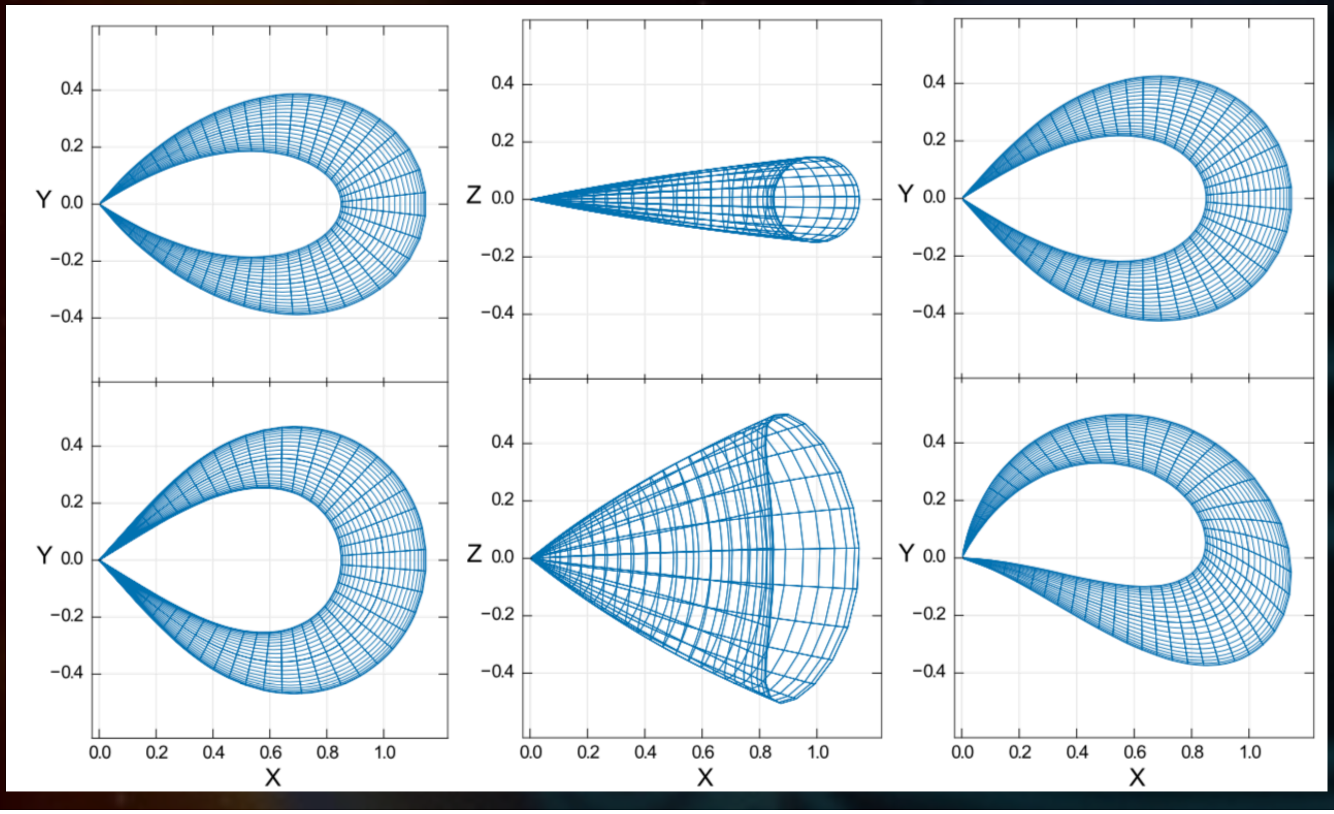
Measure a CME's location, determine a satellite's relative location, apply simple flux rope model

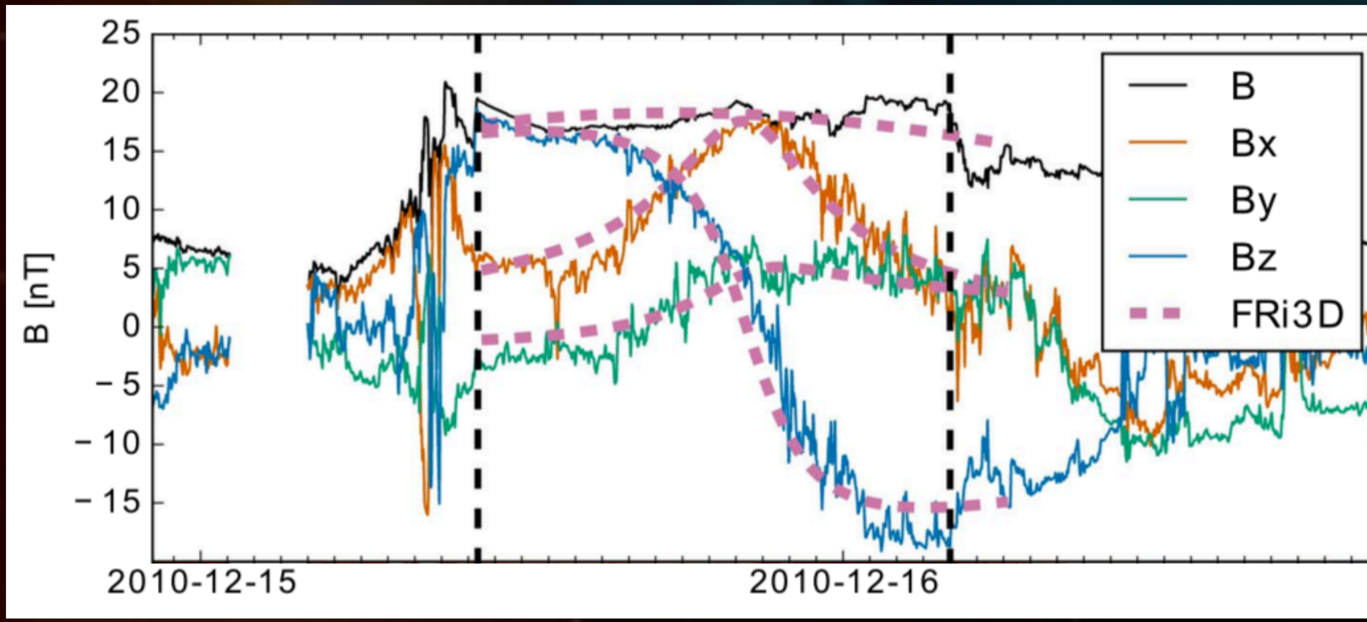


- GCS fits to get position/orientation, angular width
- Cross-sectional width determined by statistical properties of CMEs
- Speed from observations/1 AU predictions
- Lundquist force-free flux rope model
  - Bothmer-Schwenn orientation
  - Strength from WSA-ENLIL+Cone
- Calculate Kp as well

FRi3D (Isavnin+ 2016)

- GCS fits to start/for comparison
- Much more flexible shape than BzForecast
  - Can add flattening, pancaking, and skewing
- Speed from avg. observed
- Lundquist flux rope
- Perform independent ***fits*** to coronal and in situ
  - Hint at future forward modeling using early fits (coronal, HI, in situ) to drive later predictions





Accuracy v. Usability

As models become more complex they can better reproduce the observations but it becomes harder to accurately determine all their free parameters

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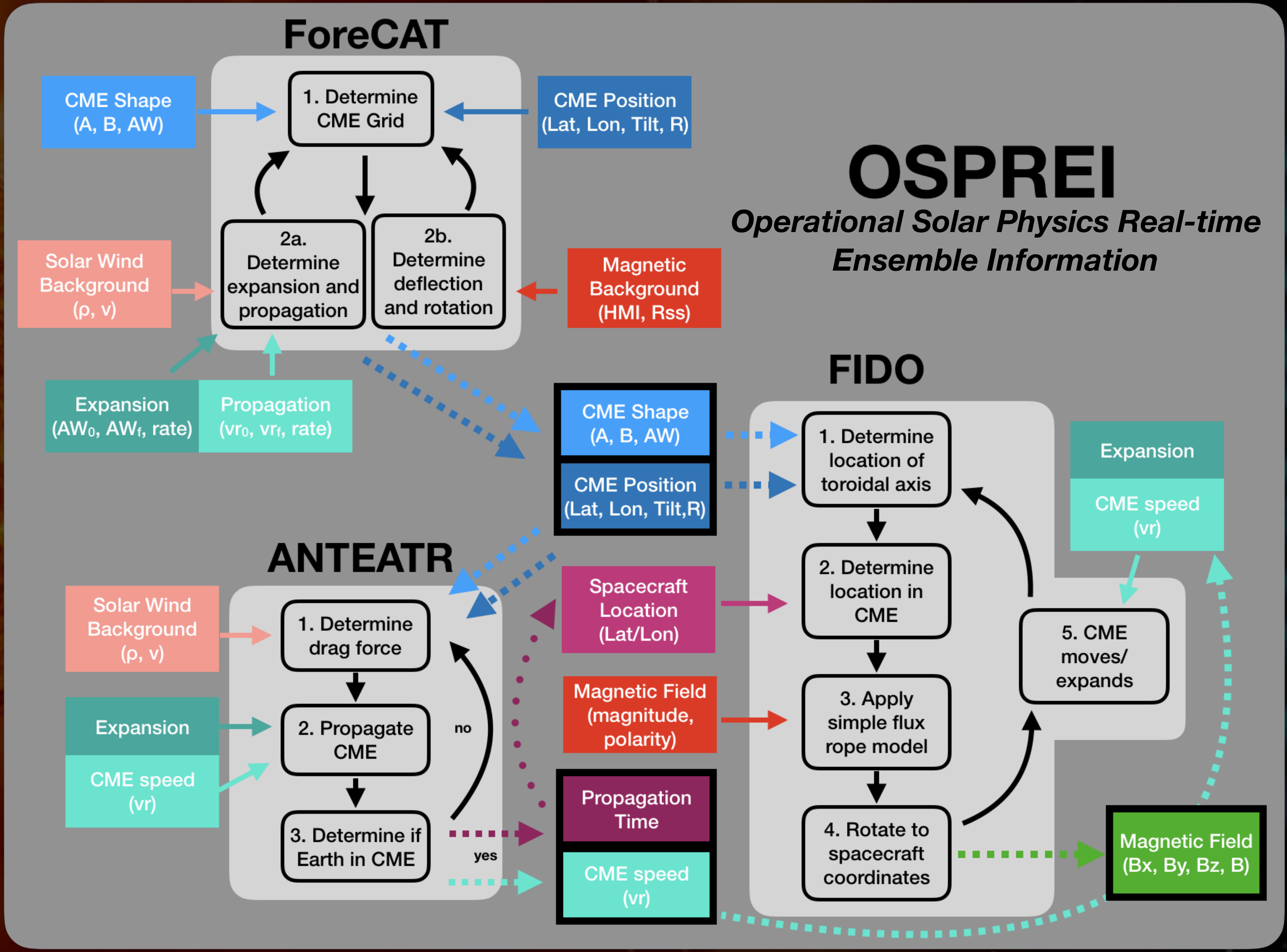
FIDO is part of a suite of models designed to answer **IF**, **WHEN**, and **HOW** and use the uncertainty in input parameters to determine the likelihood of predictions

Combined (Simplified) Modeling



*Just for flux rope!!! Shock/sheath would be additional components

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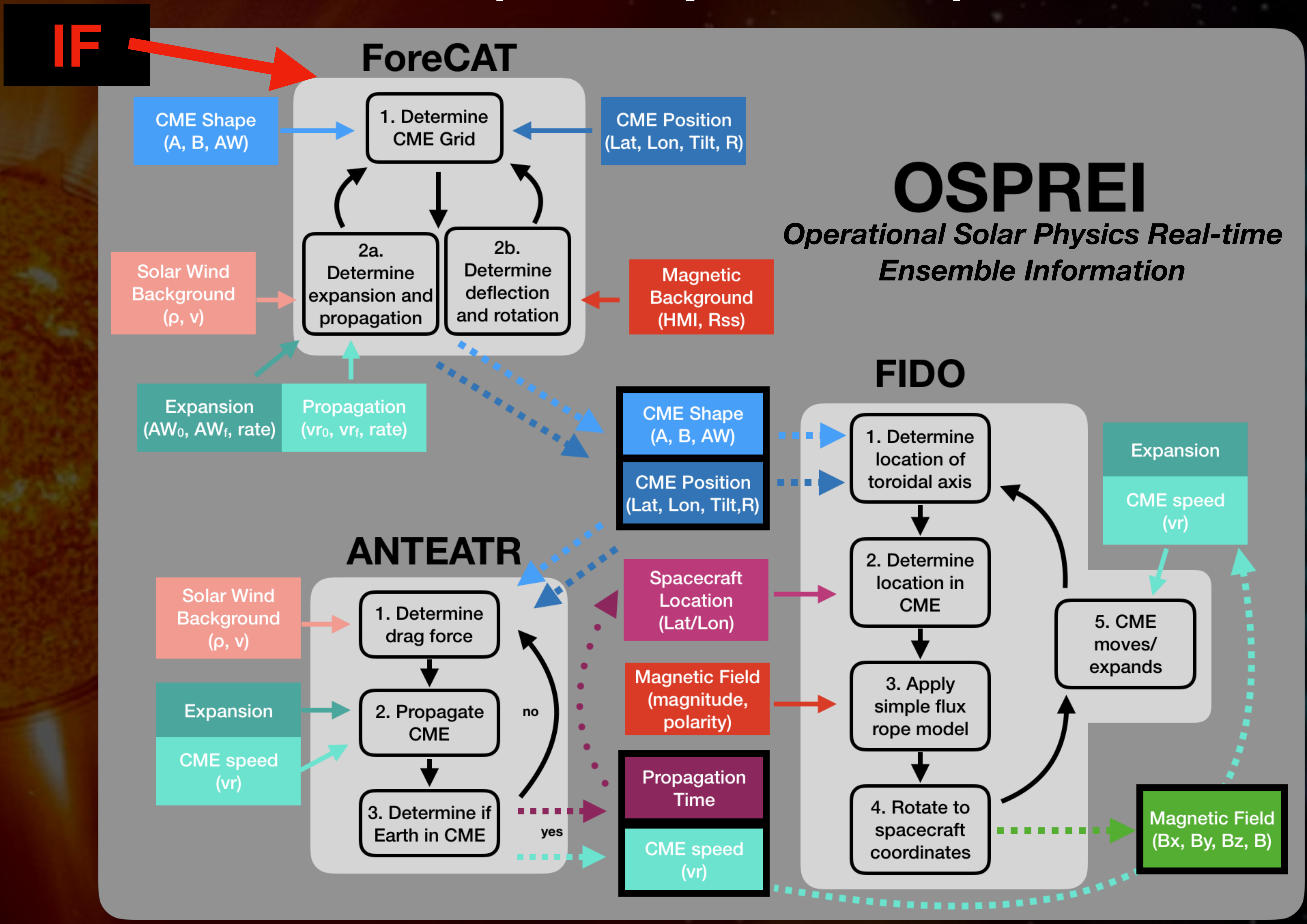

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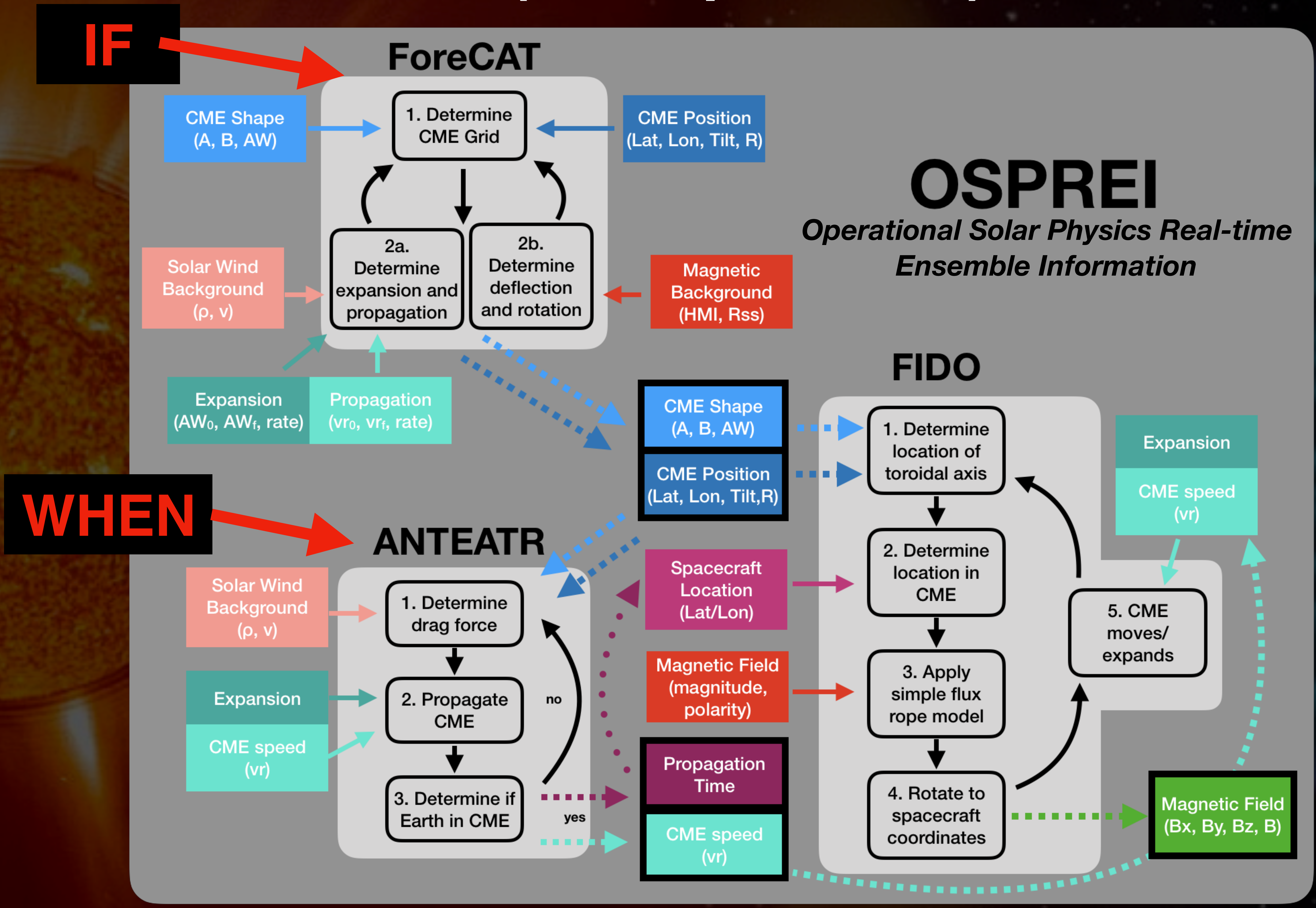

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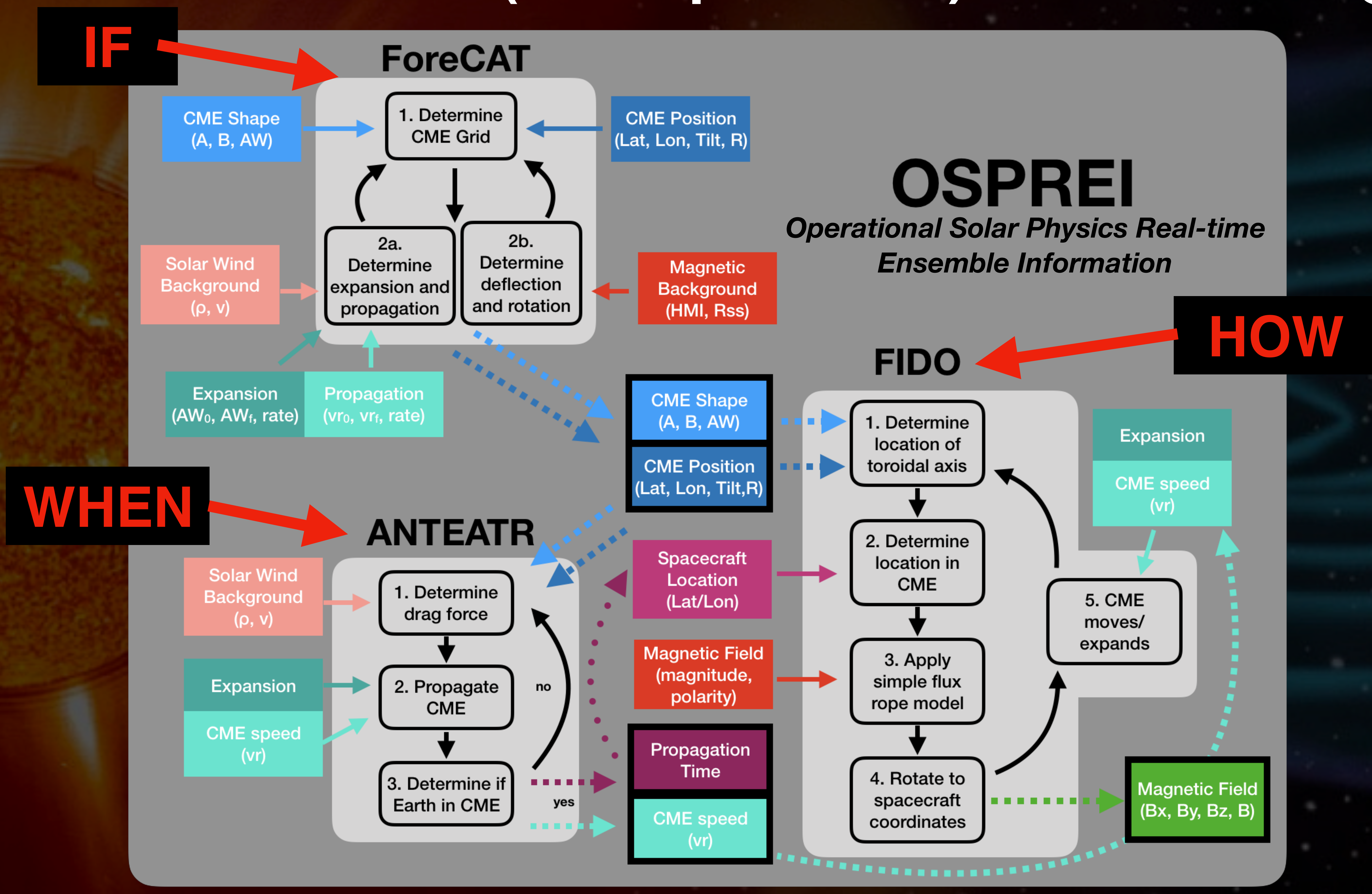

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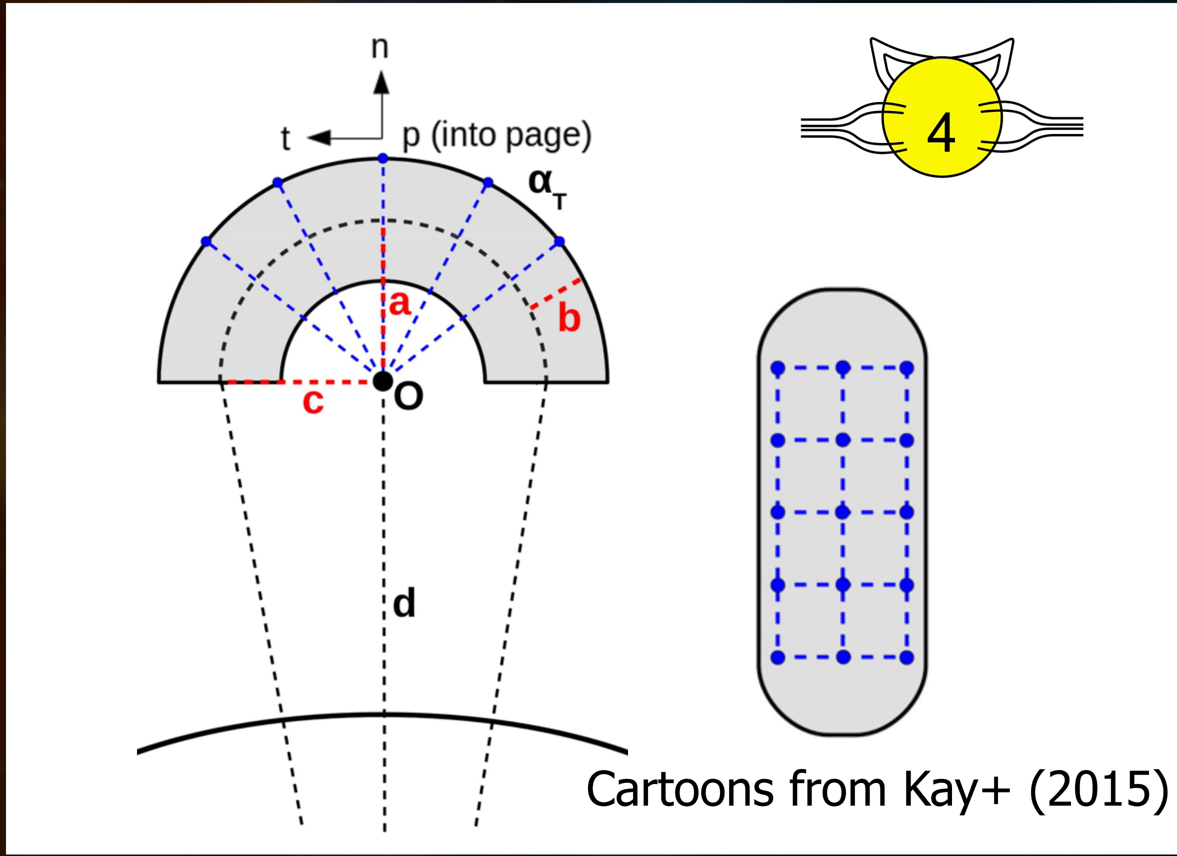
ForeCAT Model

Forecasting a CME's Altered Trajectory

- Simple analytic model for CME deflection and rotation from JxB of external solar background (Kay+2015 - 3D version)
  - Rigid torus shape
  - Only external forces
  - Highly computationally efficient

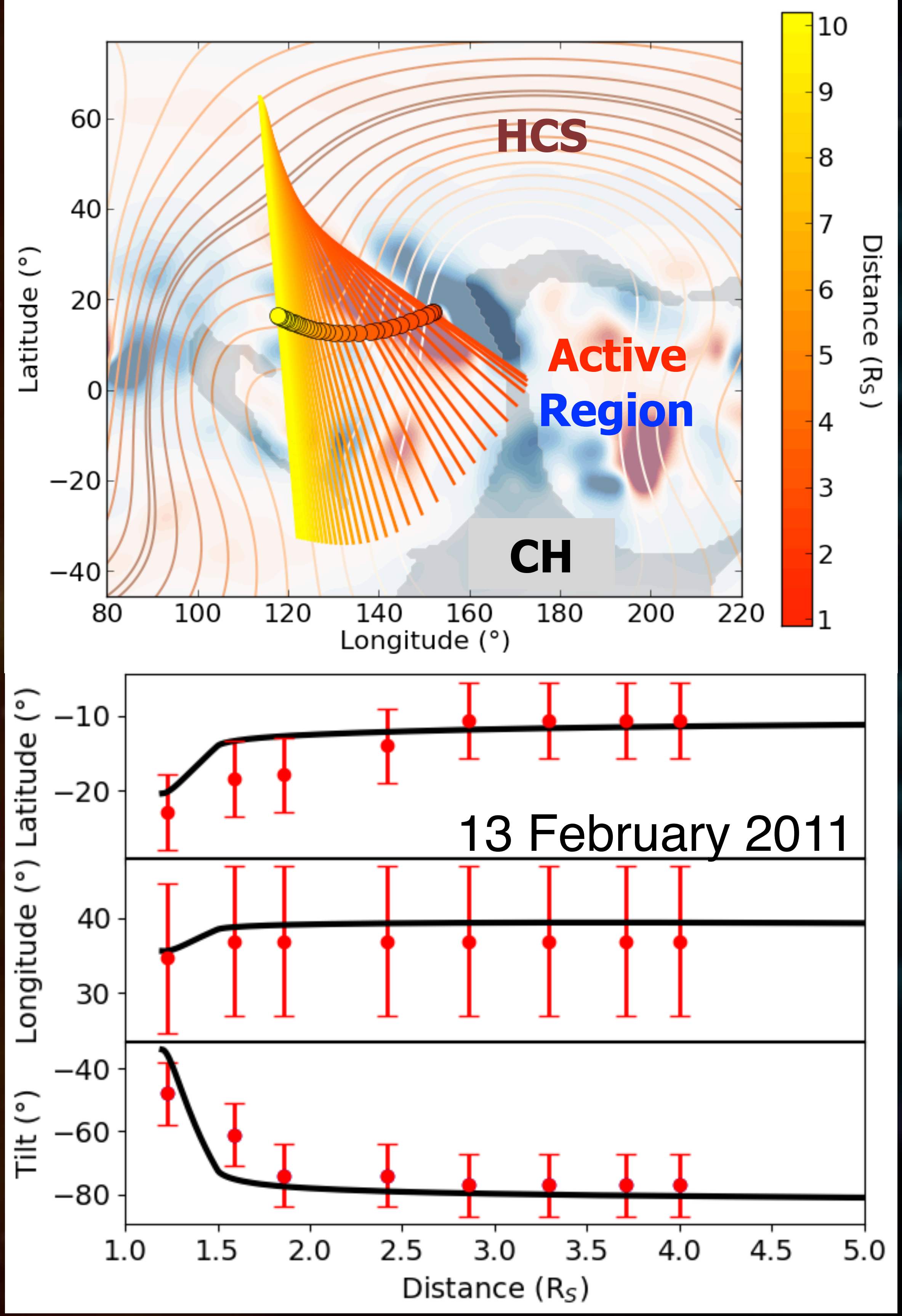


Cartoons from Kay+ (2015)

- CME expansion and radial propagation from empirical models constrained by observations

ForeCAT Results

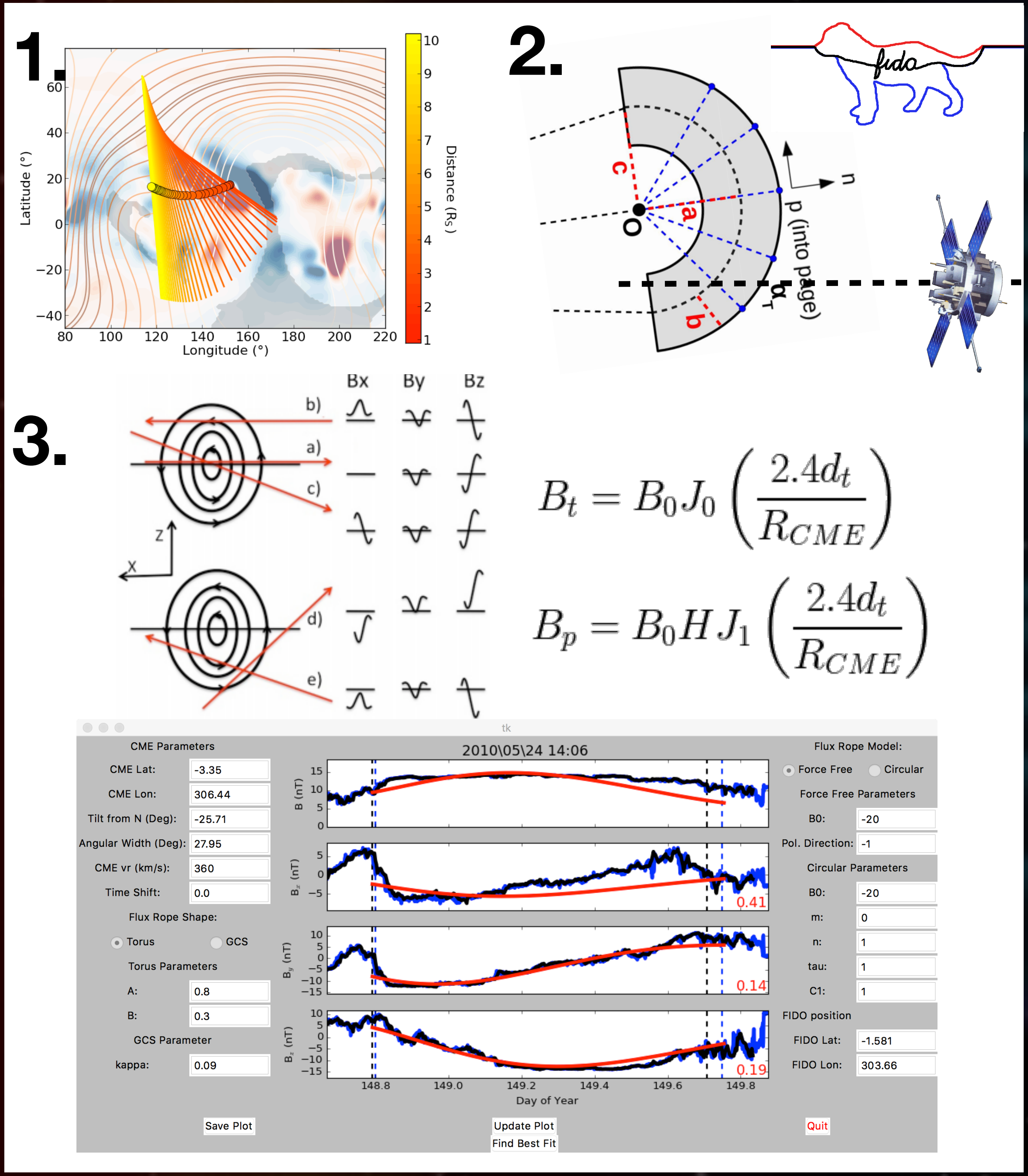
- Reproduces global trends in CME deflection/rotation
  - Deflection away from CH toward HCS
  - More massive/faster deflect less
- Reproduce specific observed cases (e.g. Kay+2017a, Capannolo+2017)
  - Compare **GCS reconstructions** with **ForeCAT results**



FIDO Model

ForeCAT In situ Data Observer

1. Take ForeCAT results for latitude, longitude, and tilt
2. Pass torus over spacecraft to get distance from torus axis
3. Apply simple flux rope model



- Aiming for ~hourly averages
- Total magnitude B_0 free parameter/automatically scaled

code available github.com/ckay314/FIDO

FIDO Results

- ForeCAT yields 7° latitudinal deflection, 2° longitudinal deflection, and 18° rotation
- Compare **ACE data** with FIDO using **ForeCAT** and **undeflected results (initial position)**
  - Undeflected does not impact!
- Simulate **150 random cases** with lat/lon/tilt that differ from the deflected ForeCAT result by less than ±5°/10°/10°

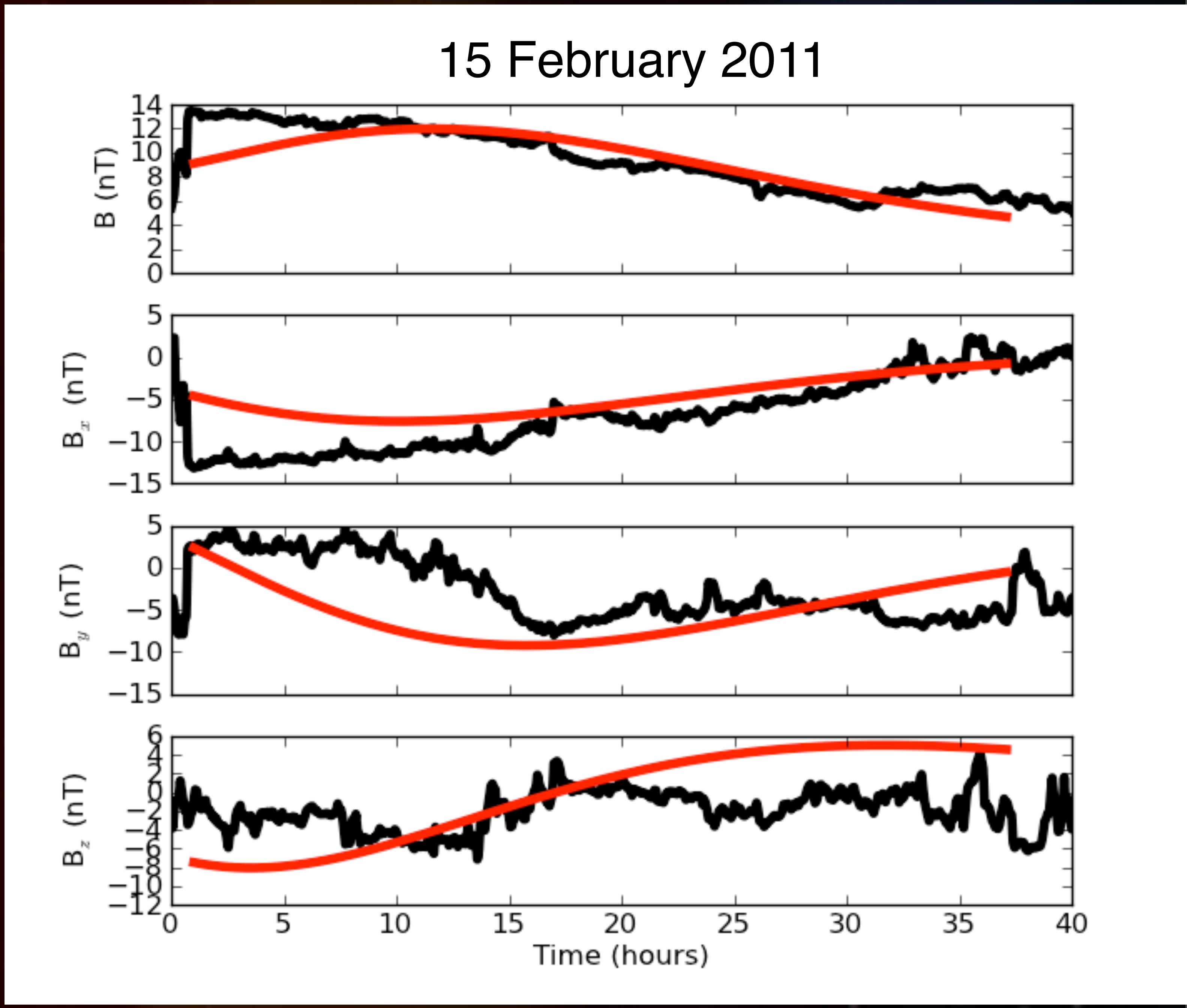


Figure from *Kay+ (2017b)*

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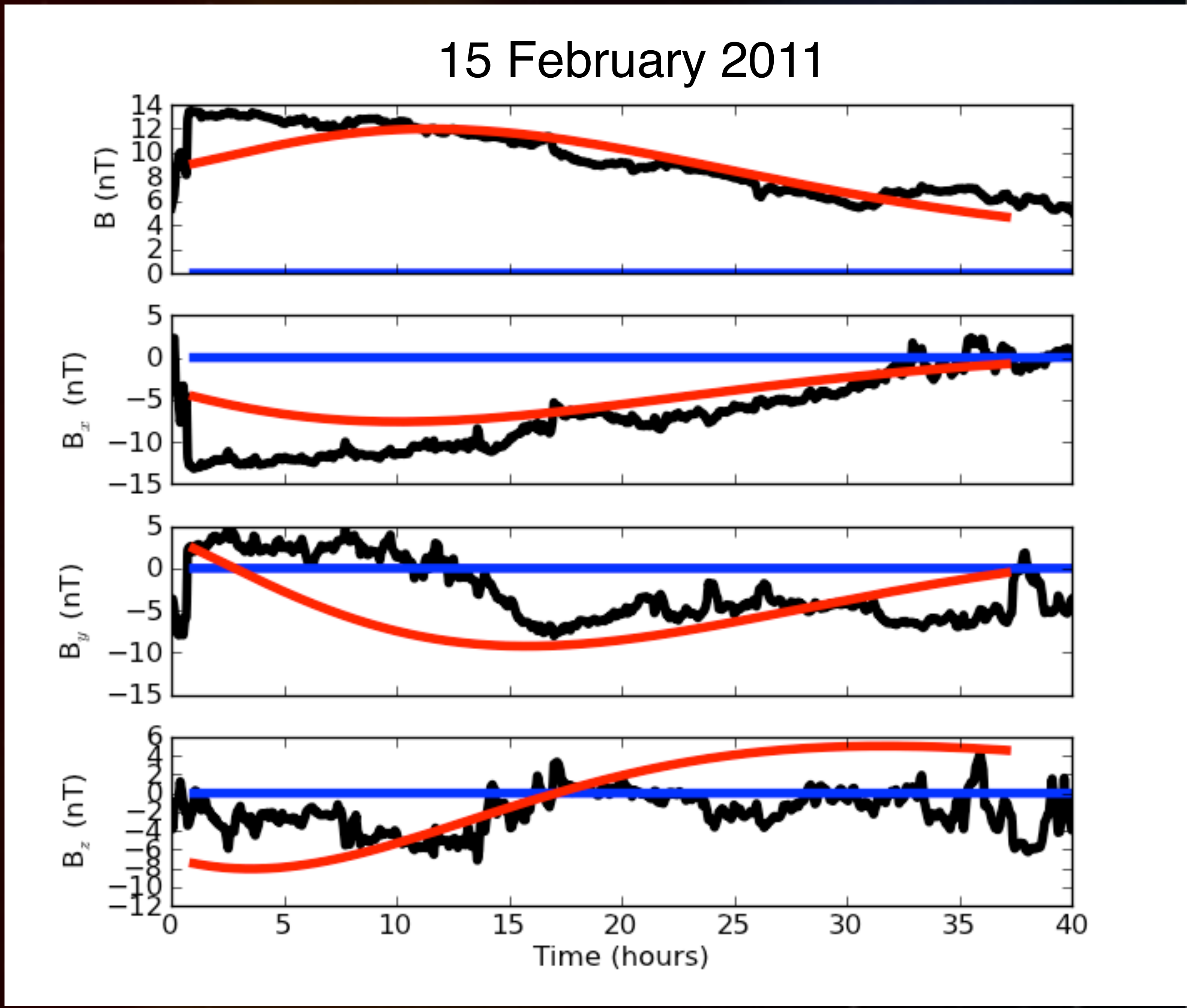

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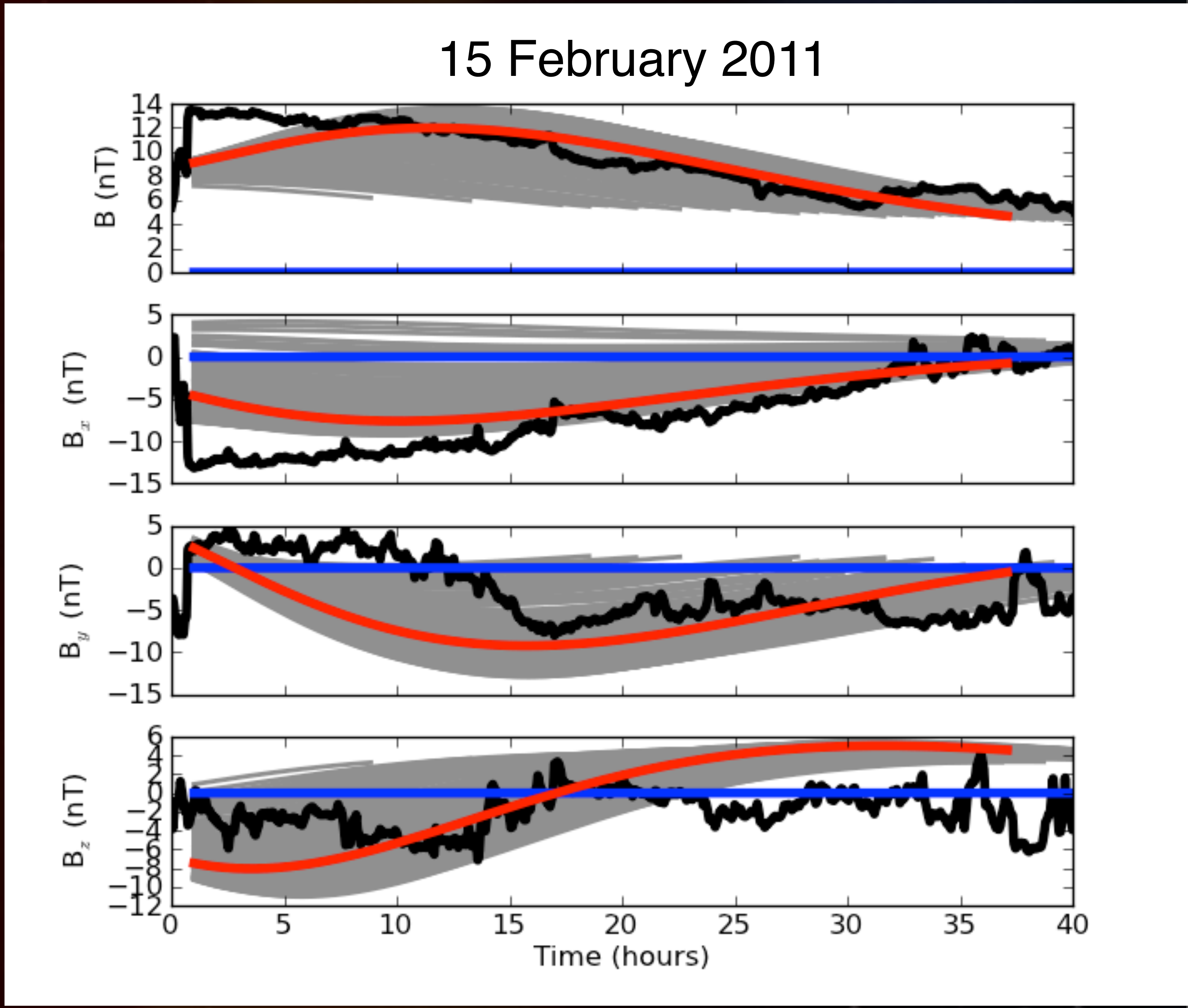


Figure from *Kay+ (2017b)*

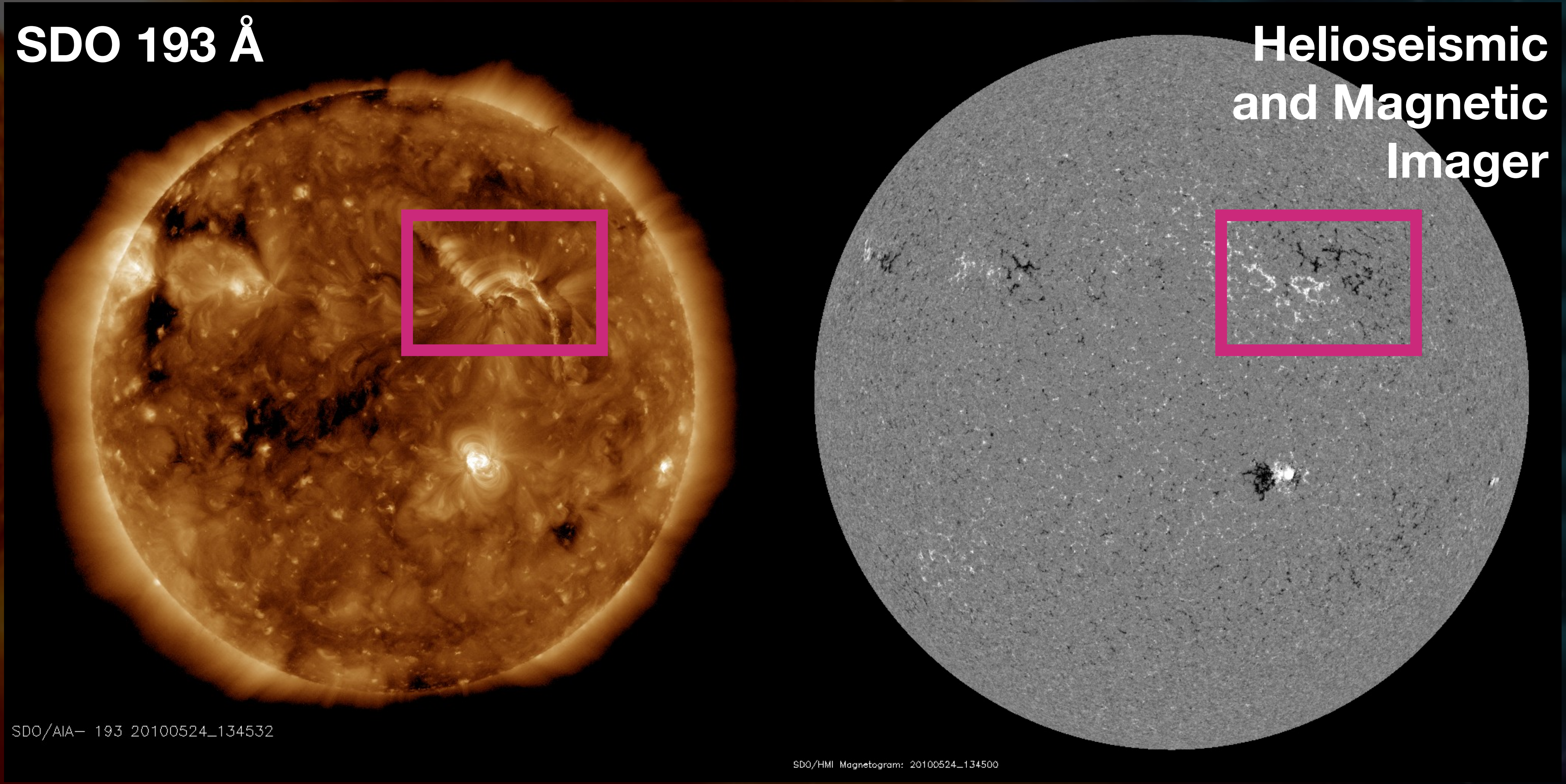
45 CMEs Study

- Set of 45 CMEs with STEREO observations and identified ICME counterparts (Richardson+Cane ICME list)

1. Identify precise source location using SDO and HMI magnetogram
2. Fit GCS to observations from both STEREO coronagraphs
3. Simulate the coronal behavior with ForeCAT
4. Compare the FIDO results with ACE and Wind data
    - FIDO driven by both ForeCAT and GCS position/orientation
    - FIDO best fits to in situ observations → difference between our ability to determine FIDO inputs vs. limitations of a simple model

Example Case

- 24 May 2010 CME



Magnetic field derived from difference between Doppler velocities in observations in two different circular polarizations

Images from Kay et al. (2017c)

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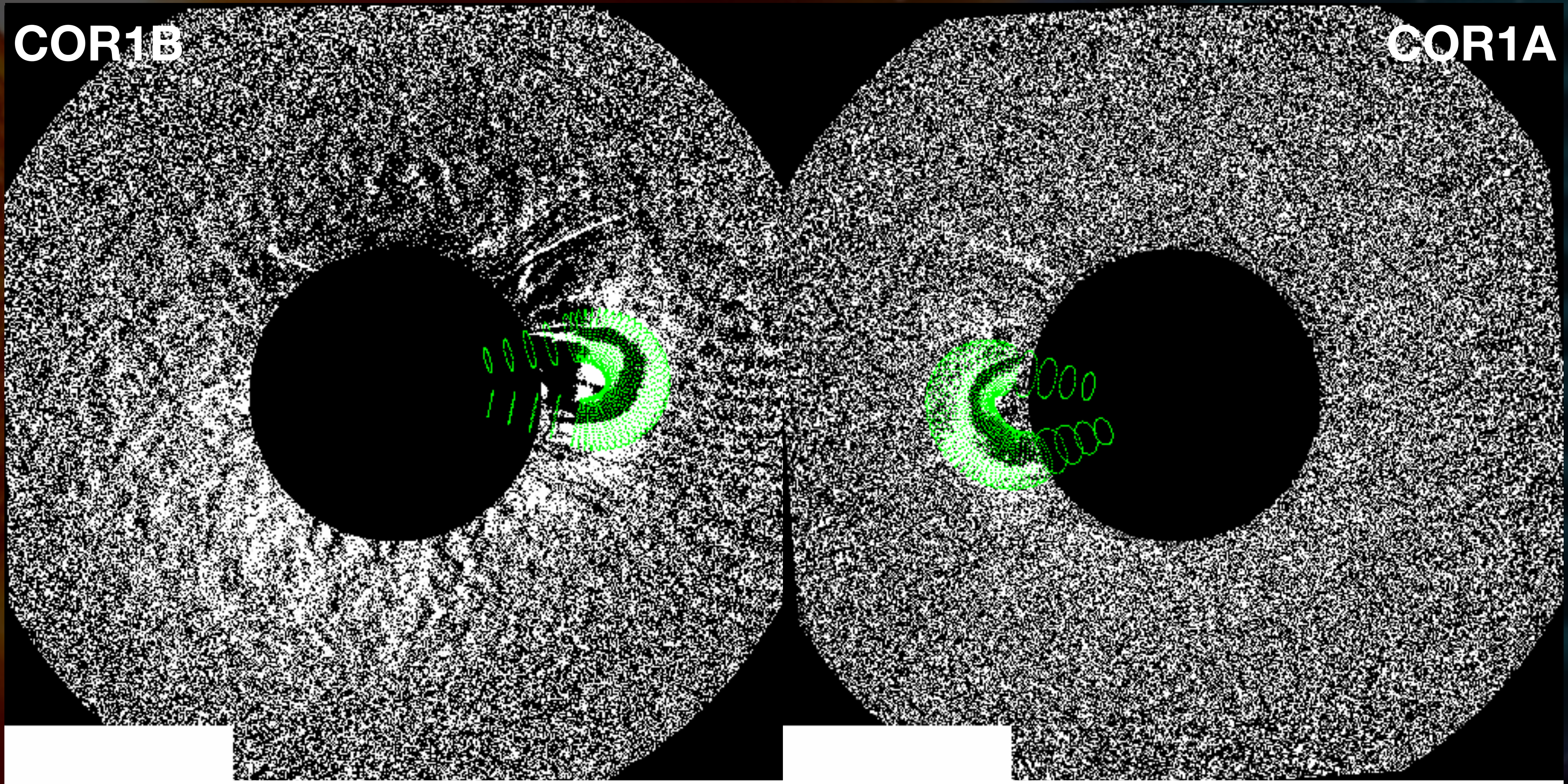

Running difference of white-light/visual observations
1.3-4 solar radii

Images from Kay et al. (2017c)

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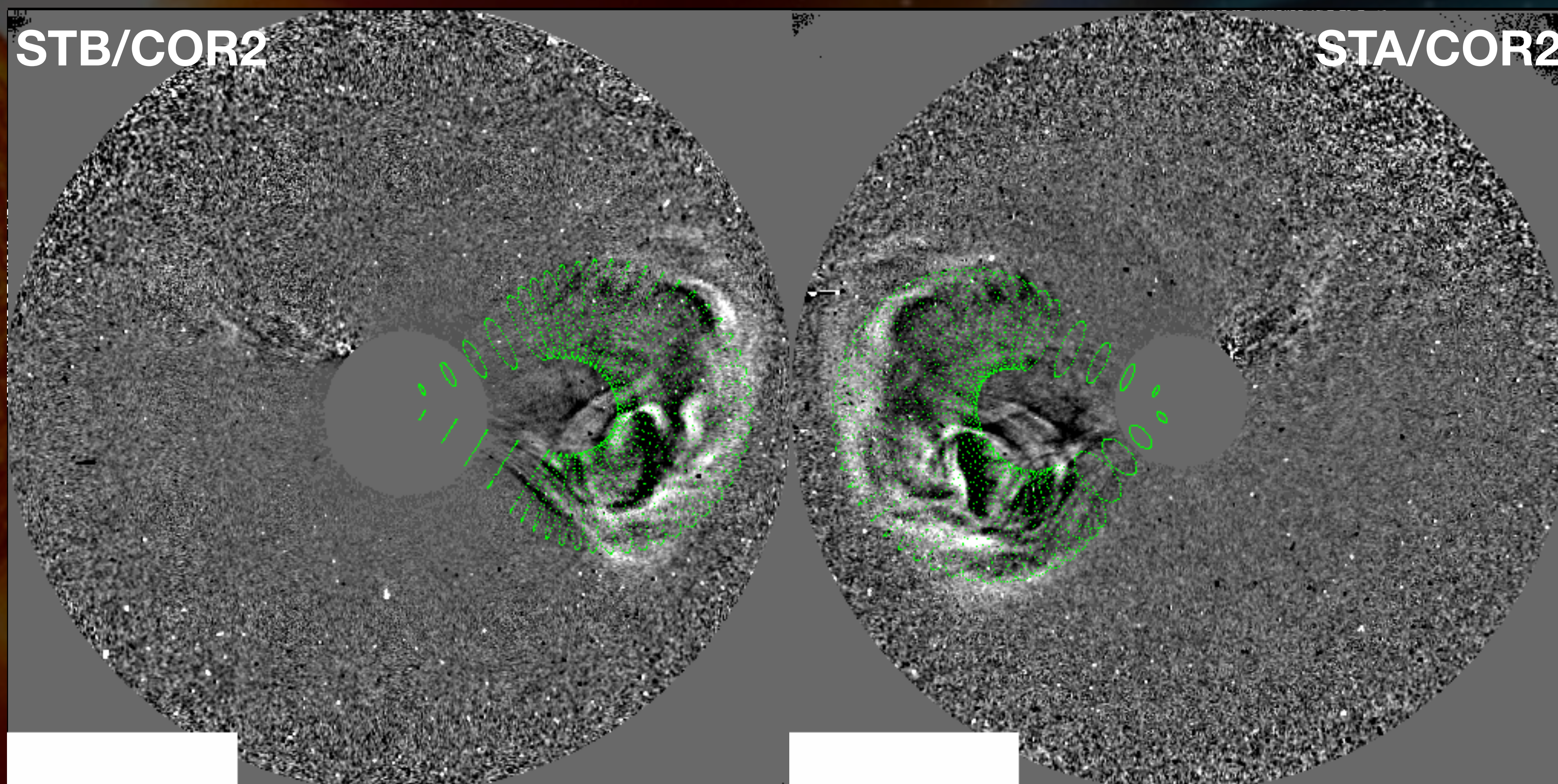

Running difference of white-light/visual observations
2-15 solar radii

Images from Kay et al. (2017c)

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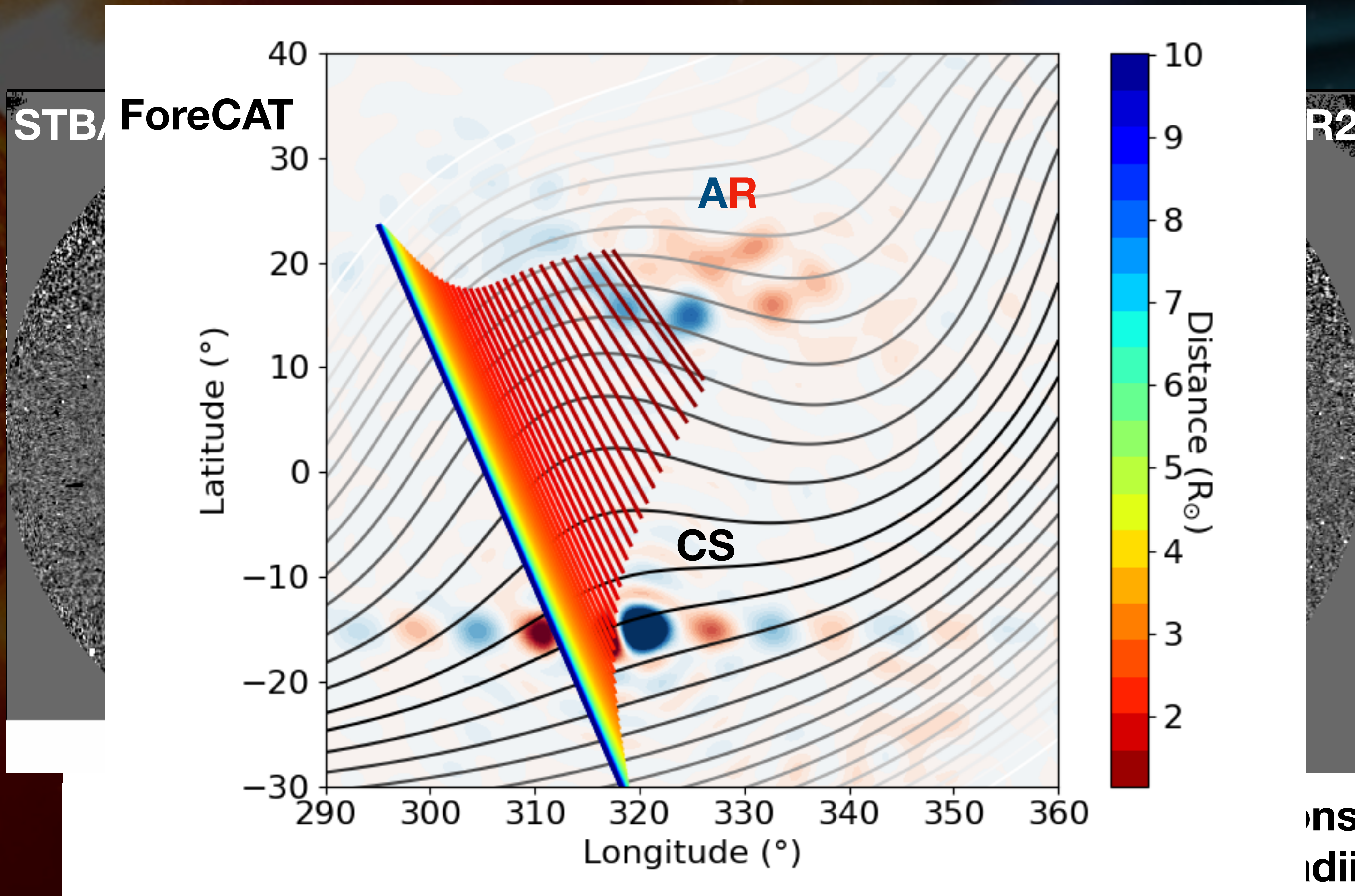

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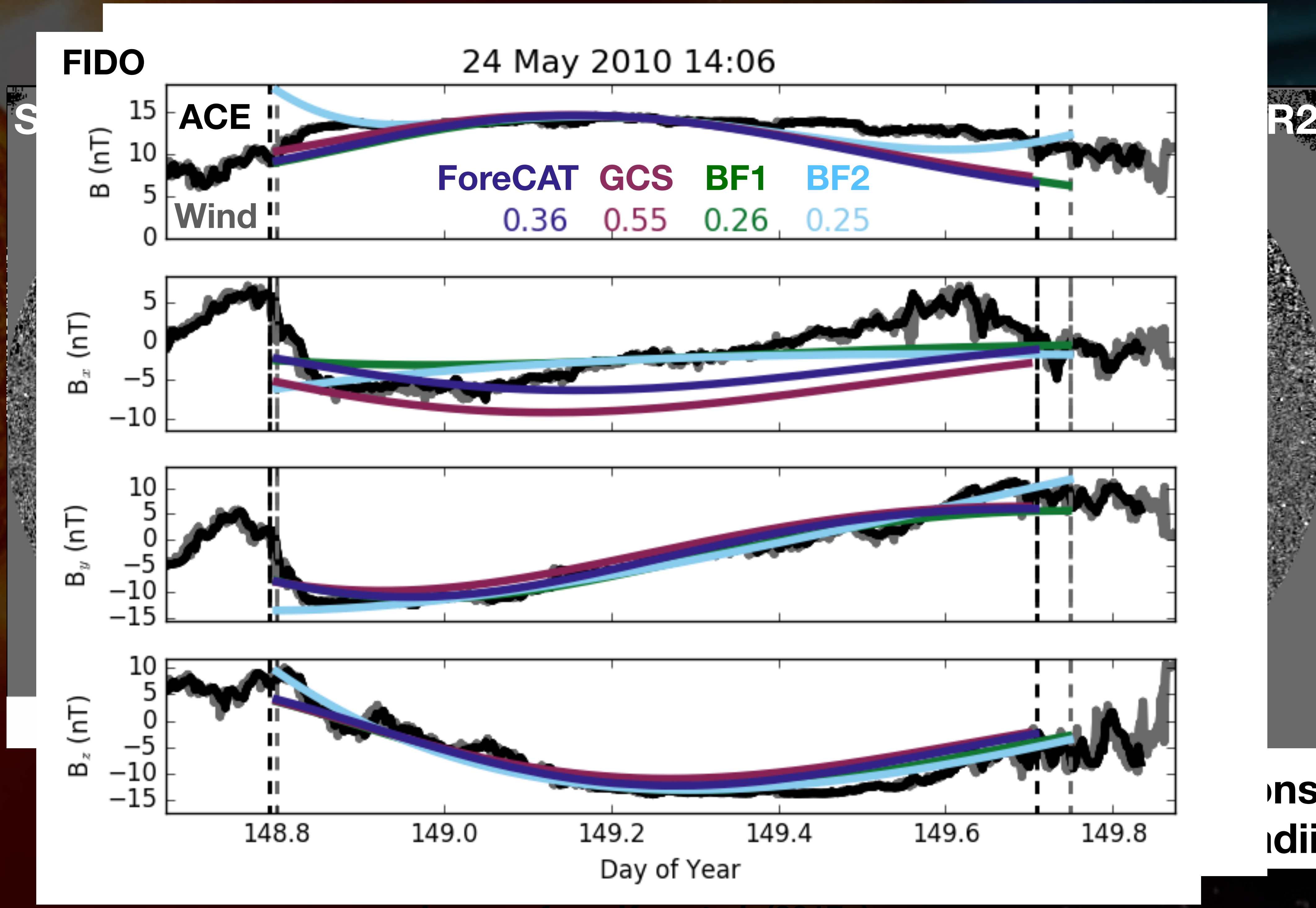
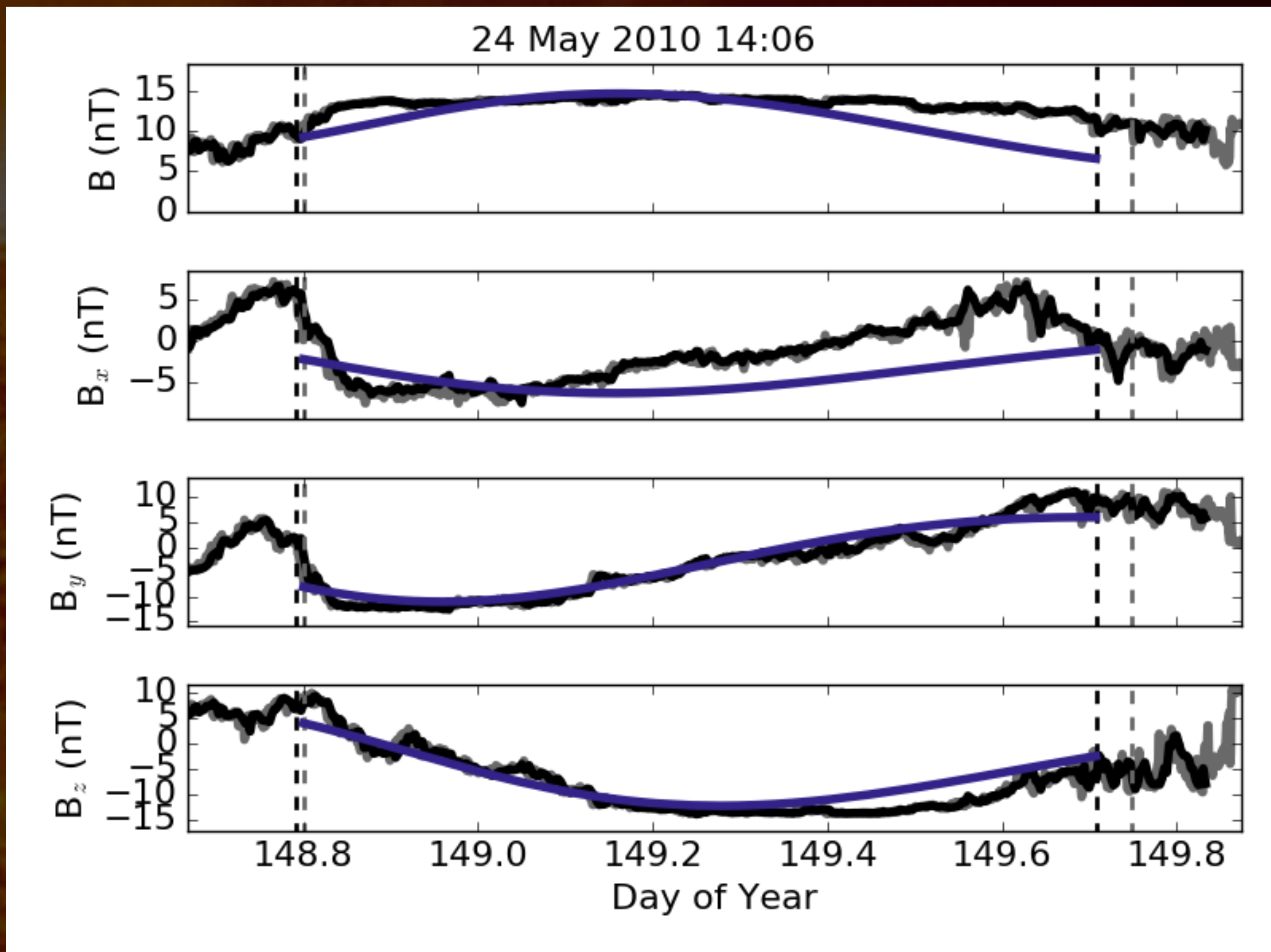
Example Case

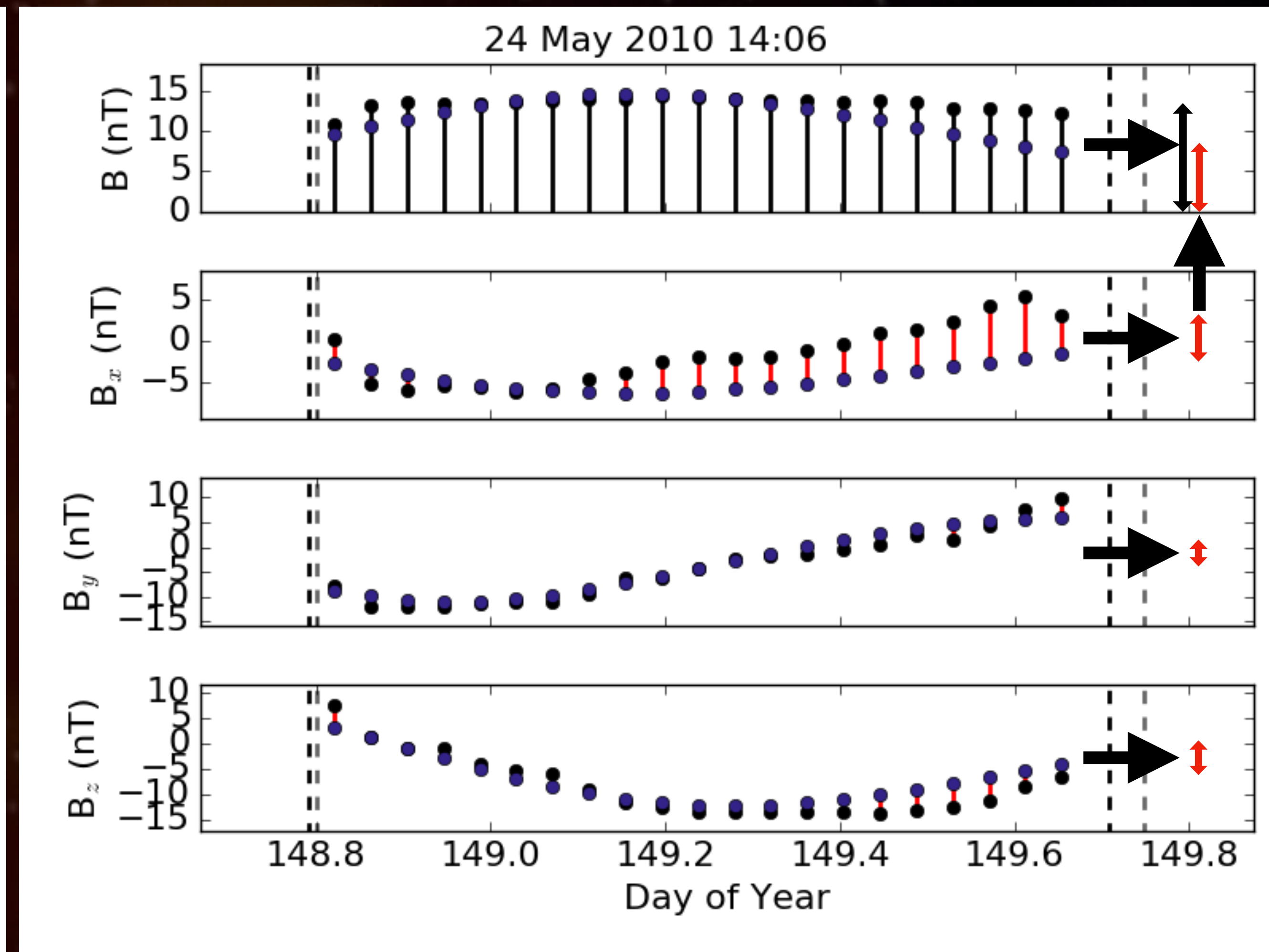
- 24 May 2010 CME



Images from Kay et al. (2017c)

In Situ Quality of Fit





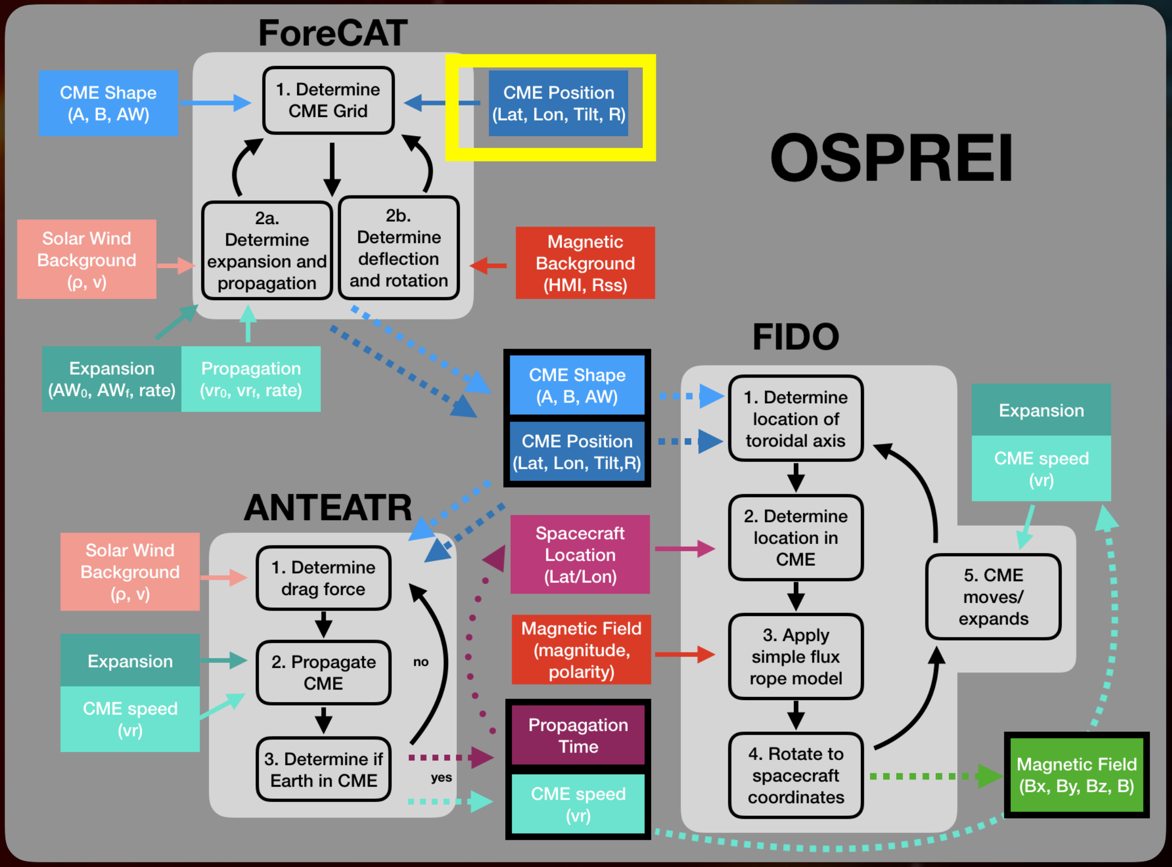
- First rigorous metric defining the quality of fit to in situ observations
- Comparison of vector magnitude of average hourly error in each component with total magnetic field strength
- Scores range between 0 (best) and 2 (worst)
    - 1 ~ correct sign and magnitude within factor of two

In Situ Score Summary

- ForeCAT driven results tend to outperform GCS by ~0.1
  - Average score 0.7 for ForeCAT-driven results
  - Ranges between 0.2 and 1.05
  - Do have few cases where GCS is better
- Best fits tend to outperform ForeCAT-driven by ~0.1
  - Some room for improvement in input parameters, but fundamental limit based on physics include in model

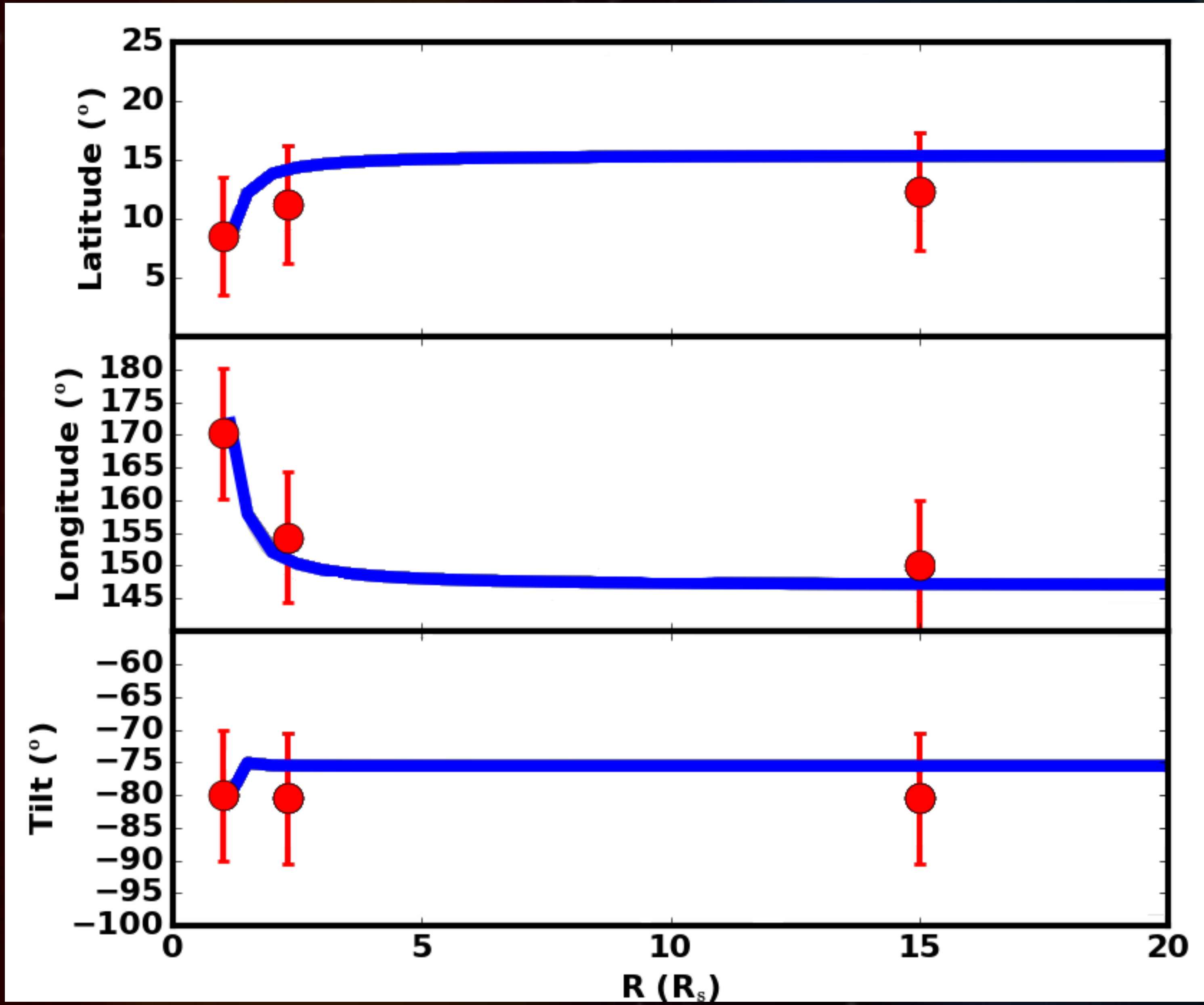
Ensemble Project

- Six CMEs selected from previous study
  - Range of deflections and rotations
- Simulate 100 CMEs with small range in initial latitude, longitude, and tilt in ForeCAT (2°/2°/10°)
  - All other parameters held constant
- Use ForeCAT results to drive FIDO and ANTEATR



Example Case - Coronal Behavior

- 28 September 2012 CME
- Compare **observations** with **"seed" case**
  - Deflects 7° N and 24° E
  - Rotates 1.5°

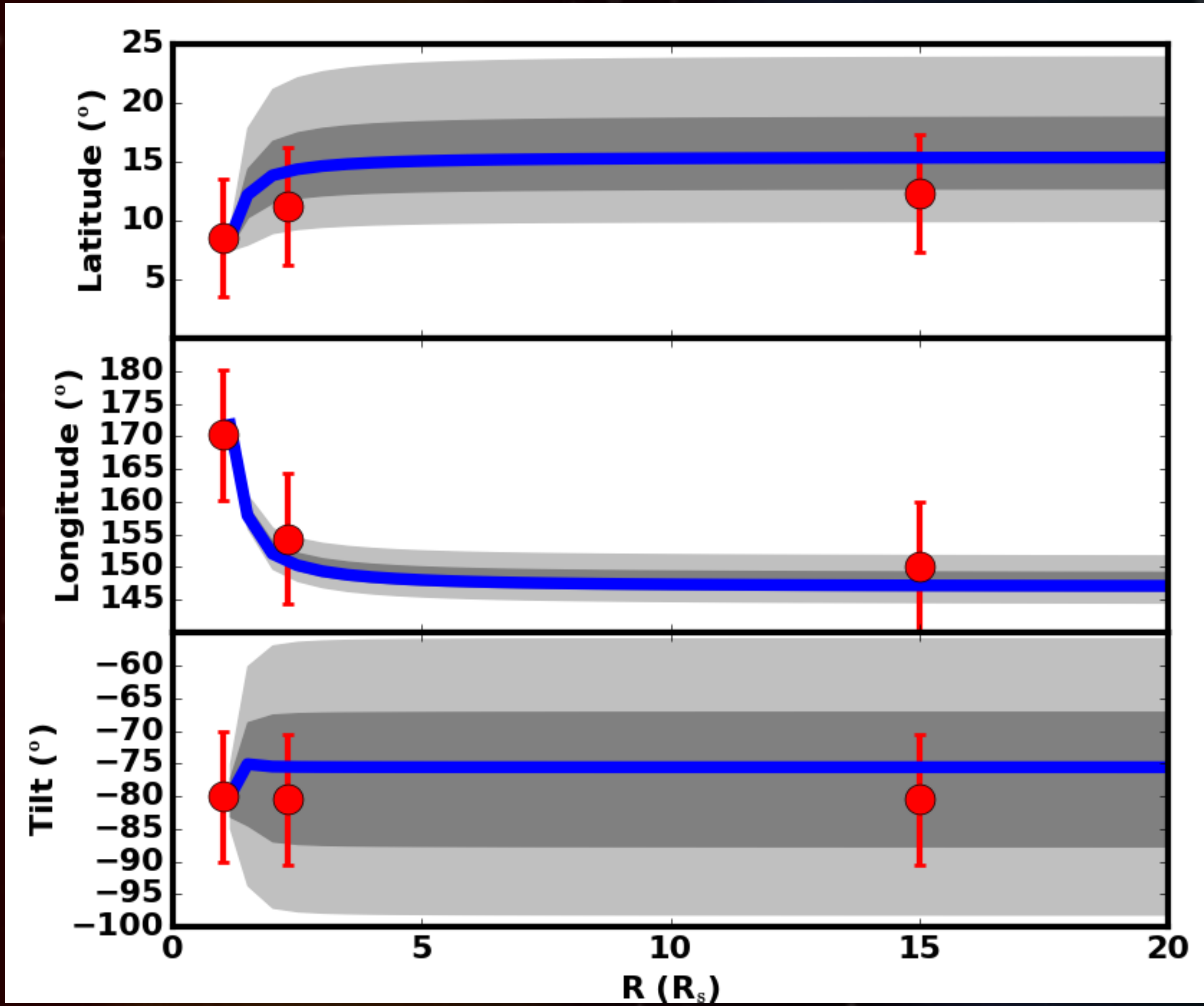


GCS reconstructions
Ensemble Seed

Core
Full Range

Example Case - Coronal Behavior

- 28 September 2012 CME
- Compare **observations** with **"seed" case**
  - Deflects 7° N and 24° E
  - Rotates 1.5°
- Range of **core** and **full ensemble**
  - Lat def variation ~half of total motion
  - Lon def variation small
  - Ensemble consistent with no rotation



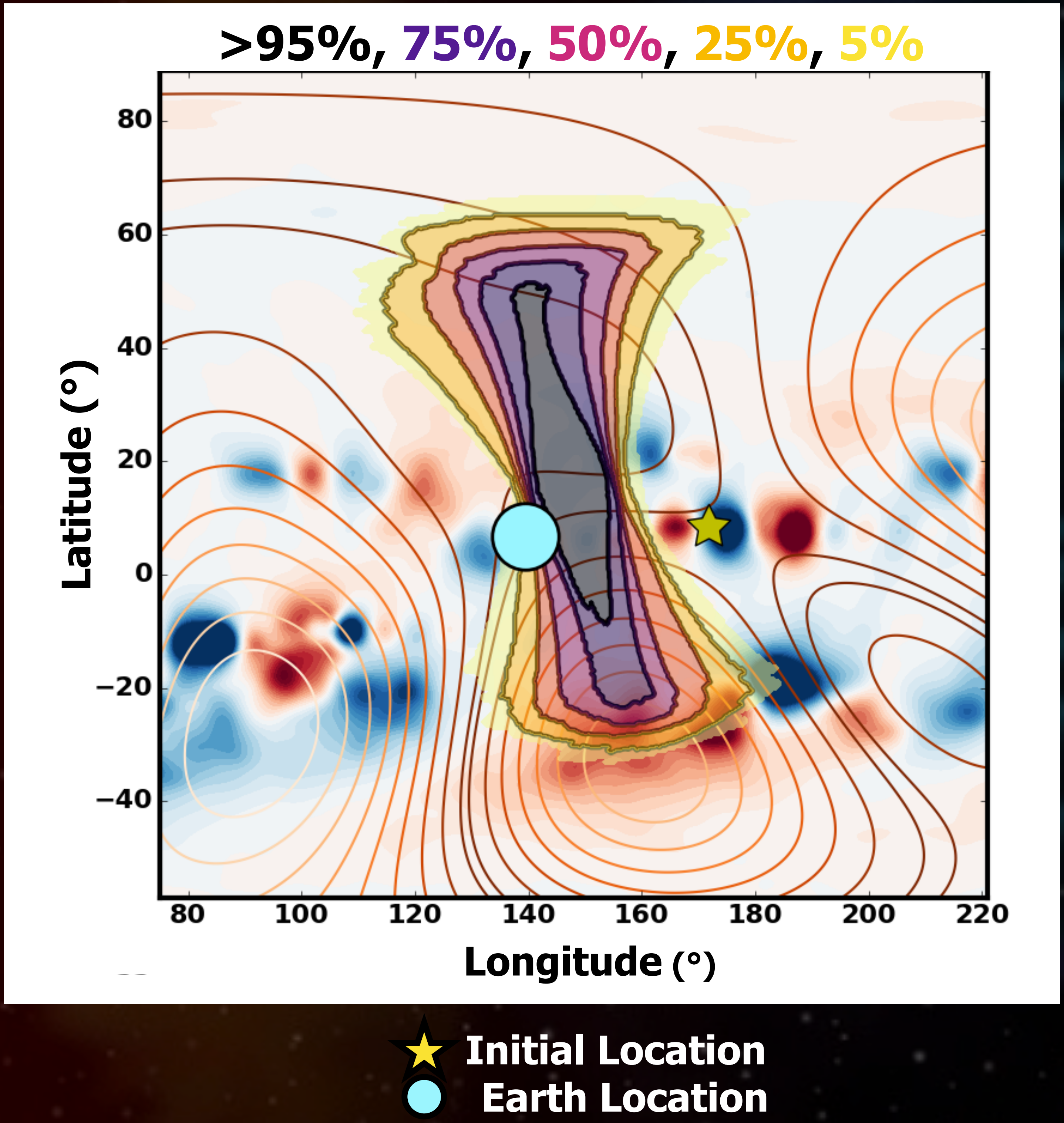
GCS reconstructions
Ensemble Seed

Core
Full Range

Example Case - Impact Percentage

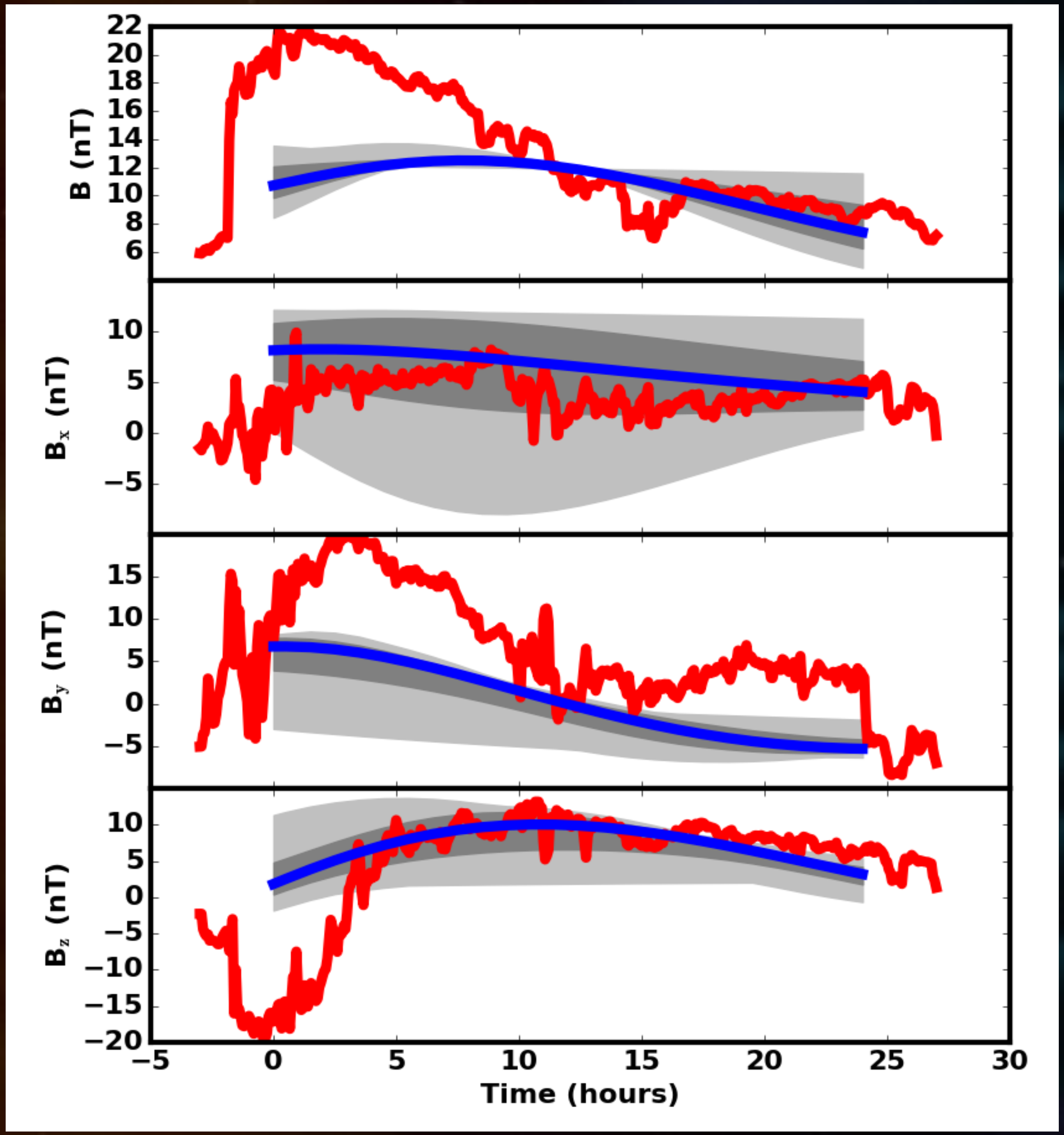
- Projection of CME torus shape onto solar surface
- Determine percentage of ensemble members that would impact based on latitude and longitude

- **Earth** impact skims along cross-sectional edge near CME nose
  - 86/100 expect to impact
  - Sensitive to width



Example Case - In Situ Profiles

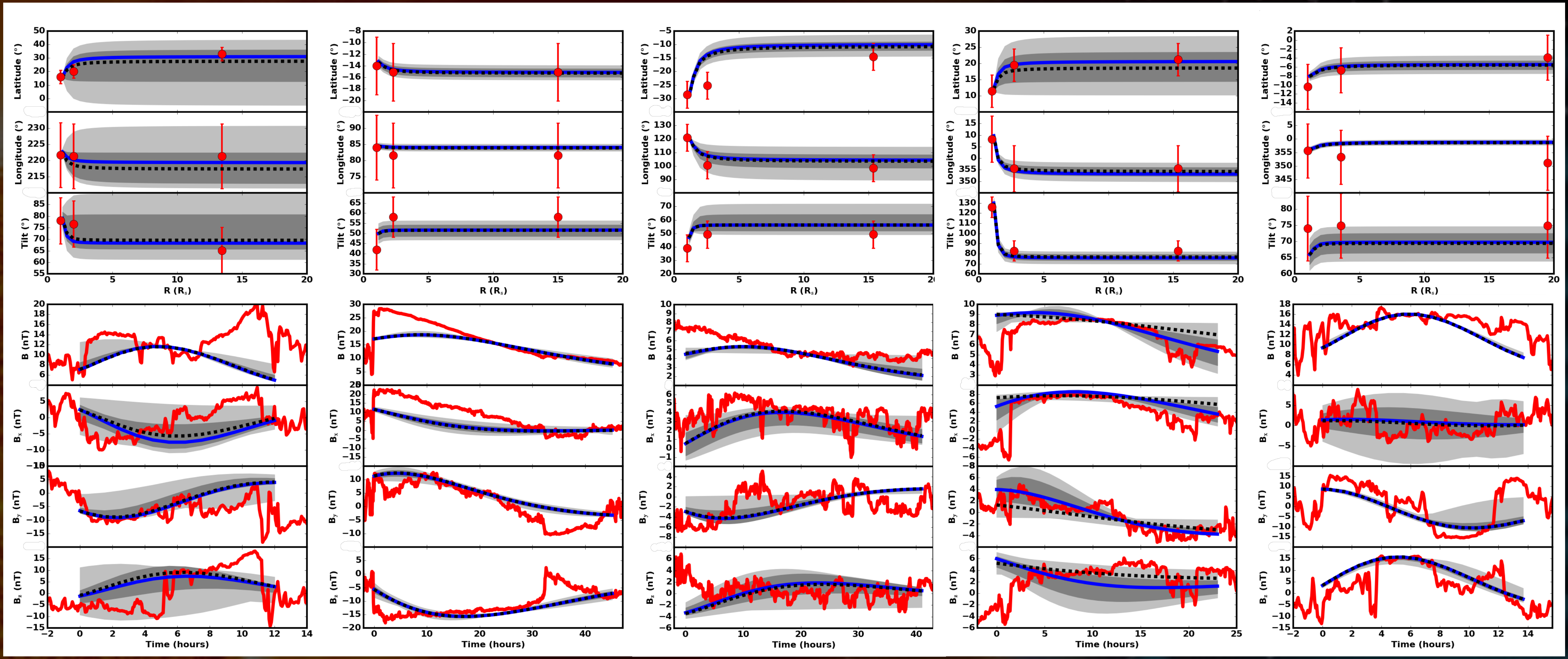
- Use final lat/lon/tilt from each ensemble member
  - Scale to match observed average magnitude and duration → focus on change in profile



ACE observations
Ensemble Seed
Core
Full Range

- "Core" typically matches obs.
- Small variations in B_y and B_z
- Full range of B_x shows profiles with both polarities

Other Cases



- Same magnitude of uncertainty in initial parameter leads to variety of coronal behavior
- Uncertainty not uniform between lat/lon/tilt or B_x/B_y/B_z
- Larger coronal uncertainty → larger in situ uncertainty

ANTEATR Model

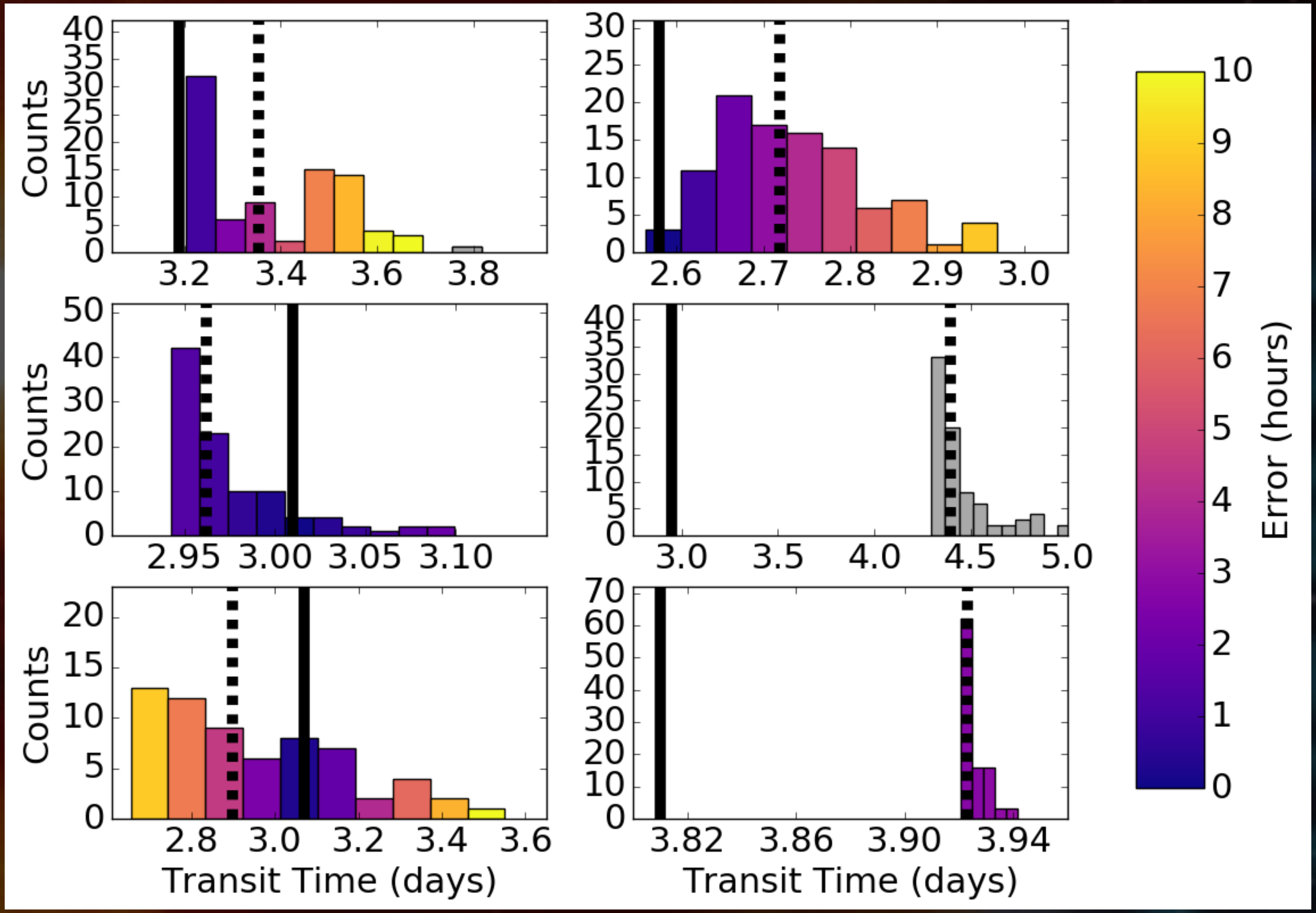
Another Type of Ensemble Arrival Time Results

- Radially propagate ForeCAT CME from ~20 Rs to near 1 AU
- Drag from background solar wind

$$F_D = -C_D\, A\, \rho_{SW}\, (v_{CME} - v_{SW})\, |v_{CME} - v_{SW}|$$

- Simple solar wind model
    - v constant, ρ falls as R^2
- Add “in CME” check from FIDO once near 1 AU
    - Determine both transit time and velocity at contact
- CME shape/location more complex (3D) than most other models but drag/background less complex (1D)

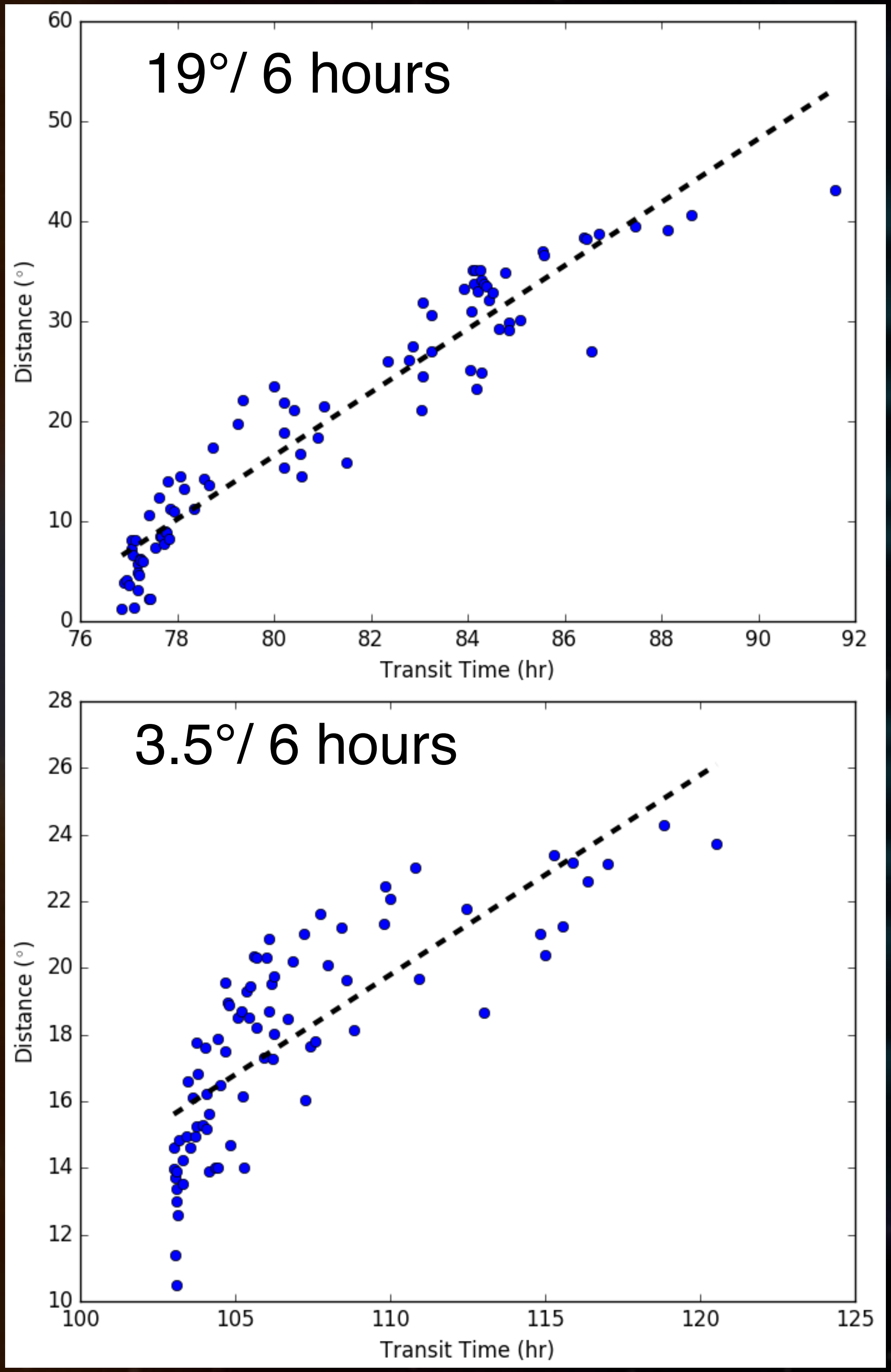
Arrival Time Results



- **One CME** has obs. coronal v (CDAW) < transit time v
- Average error in median predicted value only 3 hours
- Average range of 11.3 hours
- Average error in velocity of 15 km/s

Deriving Sensitivity

- Want to quantify *how accurately* CME position must be known for accurate arrival times
  - Determine change in CME position that corresponds to change of six hours (~average best-case error in field)
- Rate varies from case to case (0.5° to 19°)
  - Less sensitive near CME nose
- On average, 6 hours corresponds to about 8°
  - Very limited sample, not entirely linear, → order of magnitude estimate!



Summary

- Big picture studies can provide more insight than simply considering a small portion of a CME's evolution
  - Combination of distances and observations + modeling
- Forward modeling can yield useful information about in situ magnetic field and arrival time
- Uncertainty in initial parameters can have large effects on results
  - Shown for model-driven forward modeling, certainly holds for (GCS) reconstruction-driven results
- In the future, using distribution of ensemble results will allow for assigning probability to predictions