Validating Image-Based Methods for Improving Coronal Magnetic Field Models

- **Christopher Rura**

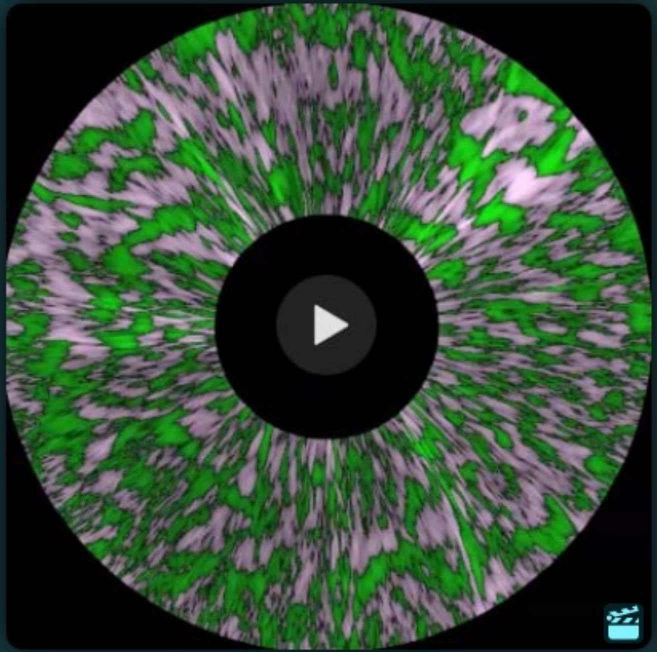
- Acknowledgments: Vadim Uritsky (CUA, NASA GSFC), Shaela Jones (CUA, NASA GSFC) , C. Nick Arge (NASA GSFC) , Nathalia {Naty} Alzate (NASA GSFC)
- PUNCH 5 Science Meeting: June 21, 2024

PUNCH Objective 1A: Global Evolving Solar Wind

Objective 1A: Global solar wind flow

Background Knowledge: What is the solar wind?

DeForest et al. 2018



DeForest et al. 2018

How does the solar wind flow?

- Wind speed can be traced using small features in the corona and heliosphere.
- On global scales, the ambient solar wind is roughly bimodal, with fast and slow streams. This simple description is complicated by shears and complex structure that may dominate the behavior of the solar wind.
- Structures and boundaries in the corona must ultimately give rise to features in the solar wind. Understanding the correspondence requires global measurements of the flow.

Science Working Group 1A Planned Activities

Working group 1A members

- Measure time-dependent solar wind flow from the outer corona to the inner heliosphere.
- Identify the changing flow boundaries between solar wind streams in the corona and heliosphere.
- Determine large-scale flow context necessary to relate coronal structure to in-situ measurements, and to provide ground-truth verification for global simulations.
- Characterize the global solar wind conditions through which transient structures propagate.

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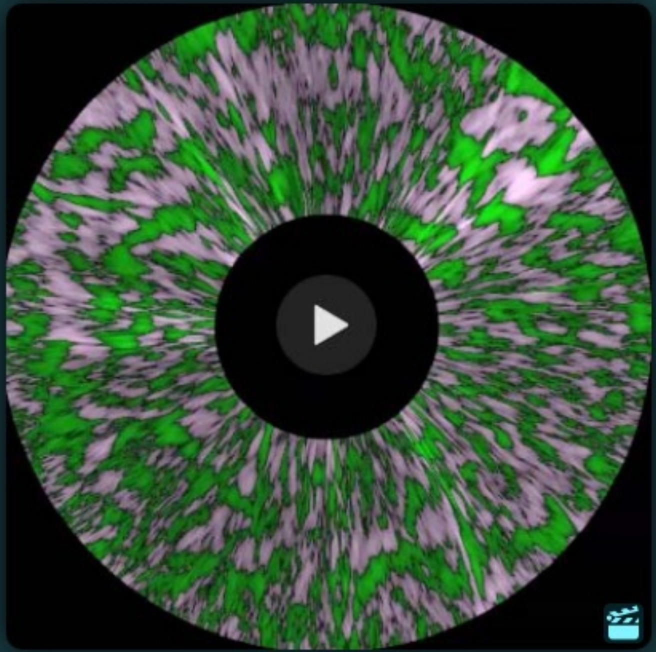

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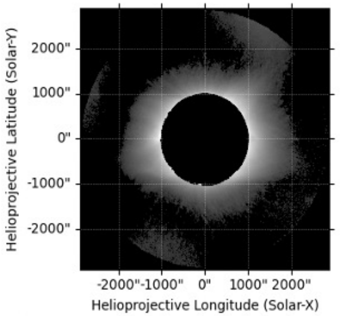
- Determine large-scale flow context necessary to relate coronal structure to in-situ measurements, and to provide ground-truth verification for global simulations.

Validation Framework: Overview

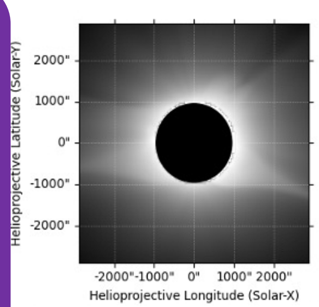


Retrieve Coronagraph Observations

- Retrieve Coronagraph observations around the date of the 2017 solar eclipse, including
- MLSO K-COR white-light pB observations (ground-based)
- STEREO COR-1 white-light pB observations (spaceborne)
- Can extend to include additional sources

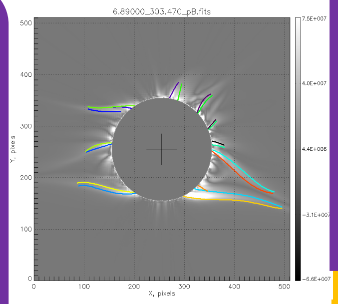
Generate Synthetic pB Images

- Use FORWARD model with PSI output to generate synthetic pB images using plasma density parameters
- Retain Magnetic field parameters generated from PSI model
- Could use other models/synthesis tools



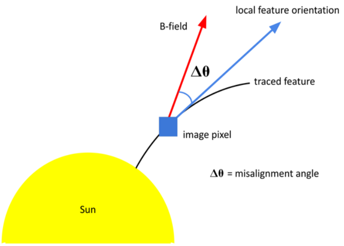
QRaFT

- Trace features in COR-1, K-COR observations and synthetic pB images
- Approximate feature orientations as polynomials and retain orientation angles of each feature
- Could use other feature tracers



Compare to Model

- Calculate angle discrepancy between
  - Features traced in MLSO K-COR observations
  - Features traced in synthetic pB images
  - expected magnetic orientation generated by model



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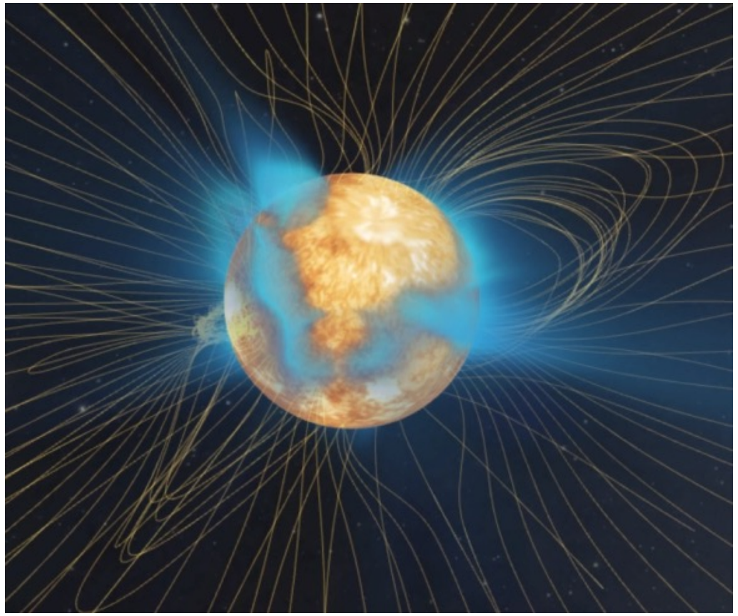
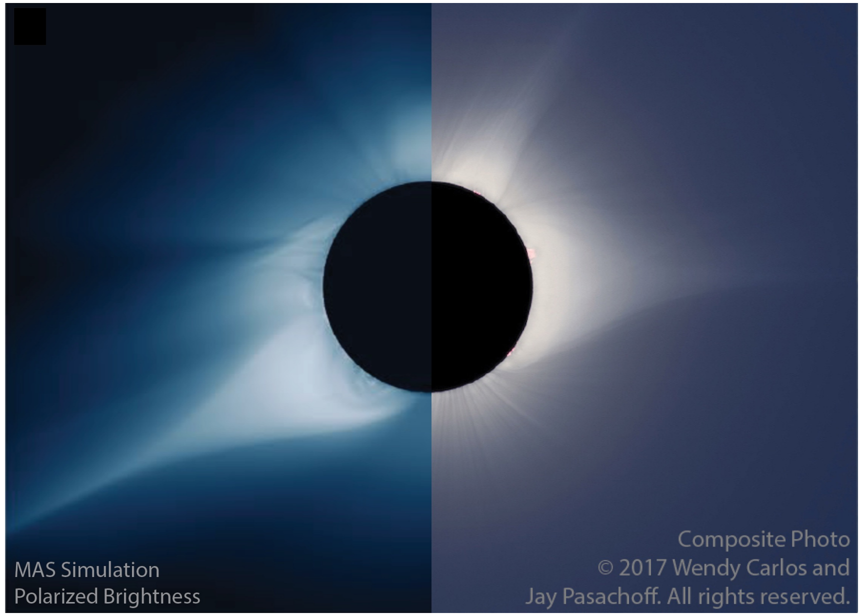
Coronal magnetic field in a global MHD simulation vs observed density structures (Predictive Science Inc. / MAS model)





Mikić, Z., Downs, C., et al. 2018. Predicting the corona for the 21 August 2017 total solar eclipse. Nature Astronomy 2, 913–921. https://doi.org/10.1038/s41550-018-0562-5

Quasi-Radial Field Line Tracing (QRaFT) method of segmenting coronagraph images

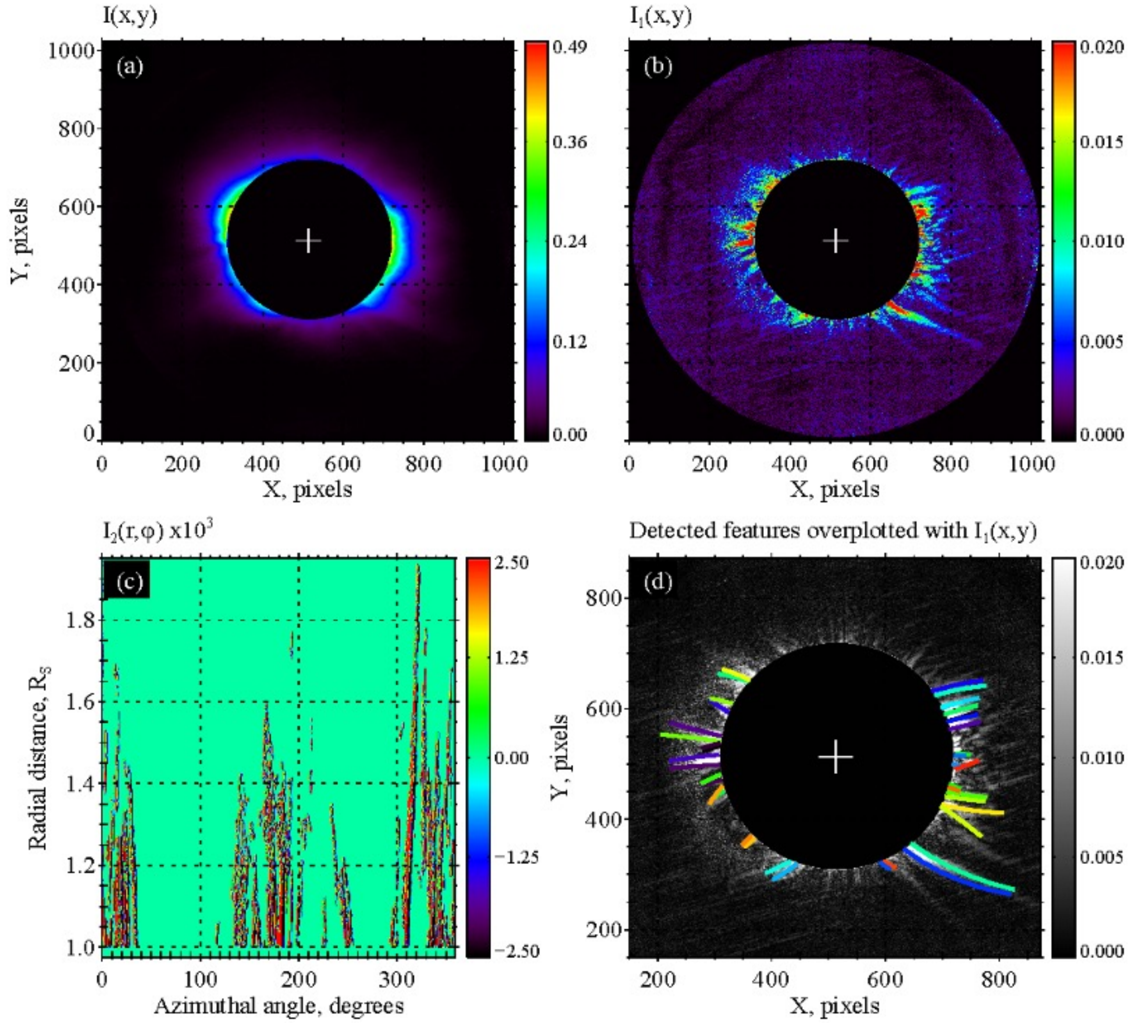


Illustration of the main processing steps of QRaFT.

(a) The original image (a Level 1 K-Cor image recorded at 2016/05/27 16:55:33).
(b) The unsigned first-order azimuthal detrended difference in rectangular coordinates.
(c) The second-order difference in polar coordinates.
(d) The image features detected in the 2nd-order differenced image using a percentile-based thresholding. Colors are picked at random to simplify visual comparison.

V. Uritsky. Quasi-Radial Field-line Tracing (QRaFT v2.0): an image analysis package for reconstructing the magnetic field geometry of the open-flux solar corona, GitHub / Zenode, 2022, URL: github.com/uritsky/QRaFT, DOI:10.5281/zenodo.7410948
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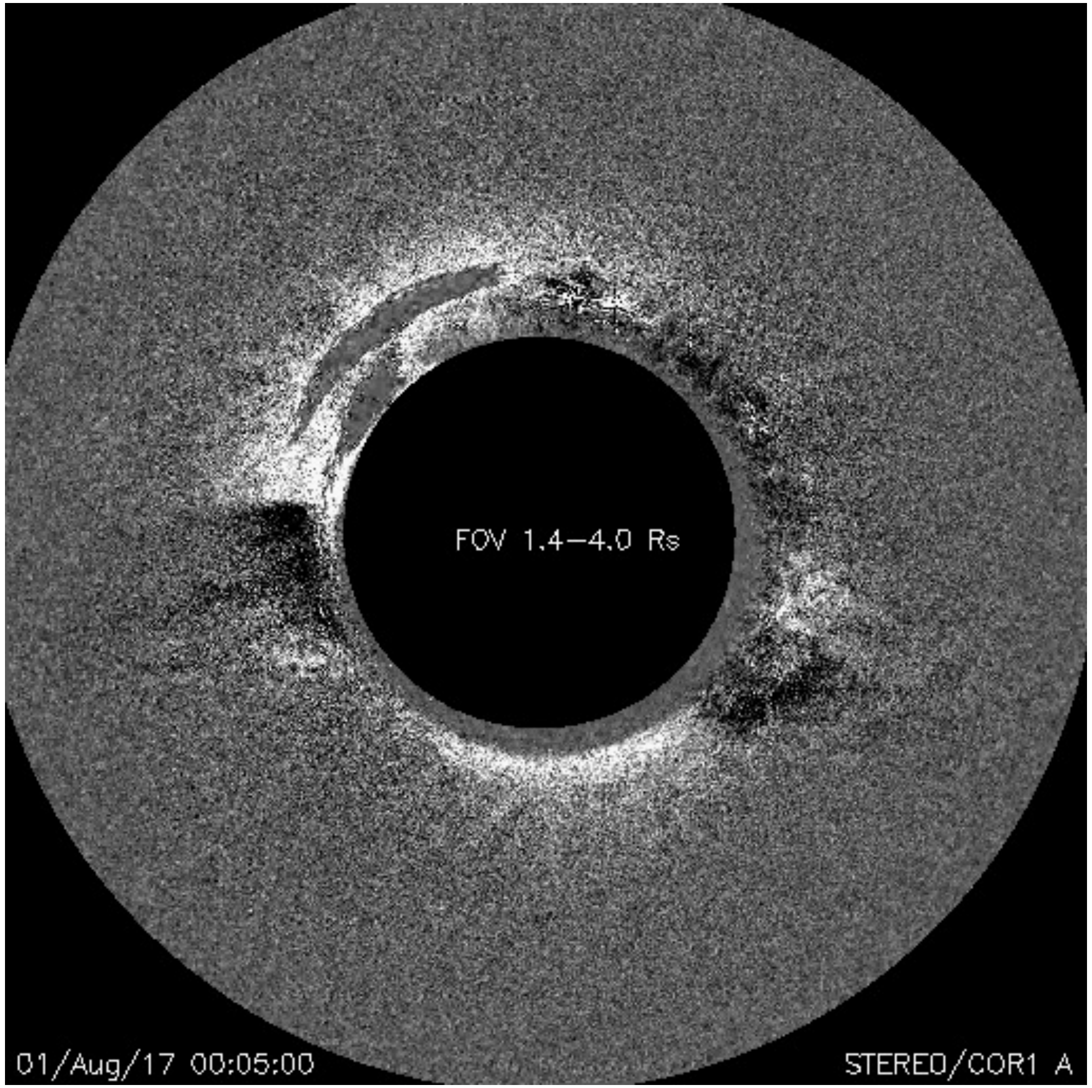
Segmenting Coronal Images

- COR-1
  - White-light coronagraph aboard STEREO A
- Sequential polarized images combined to record polarization brightness
  - Reveals K-Corona
  - Illuminated by Thompson scattering of free coronal electrons
- Able to analyze multiple methods of image processing
  - Image Stacking and Averaged over 30 minutes
  - Bandpass filtering method *(Alzate et al. (2021), ApJ, 919, 98, https://doi.org/10.3847/1538-4357/ac10ca)*
- Quasi-radial features traced and segmented by QRaFT



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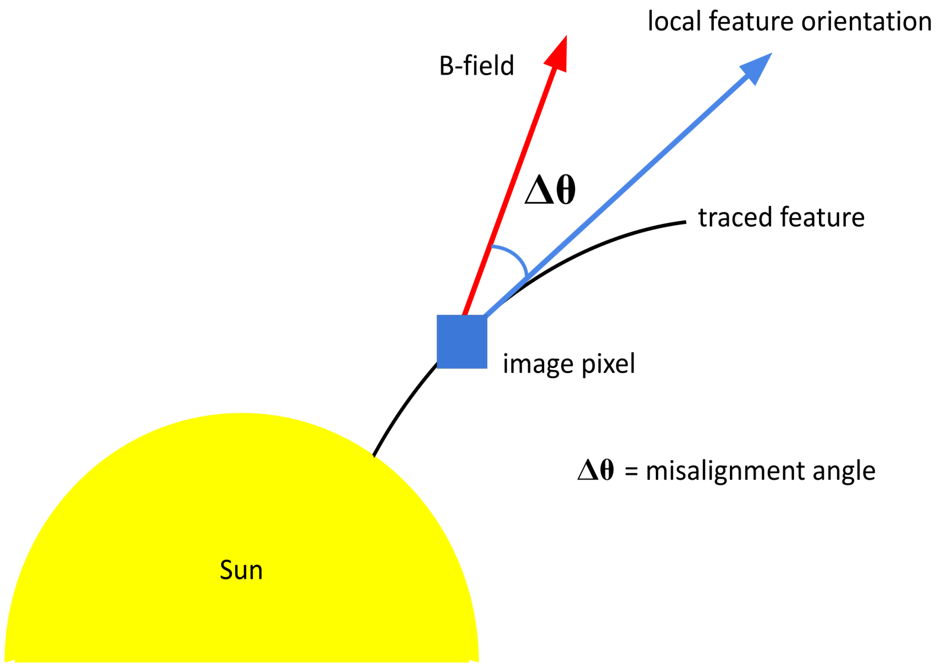

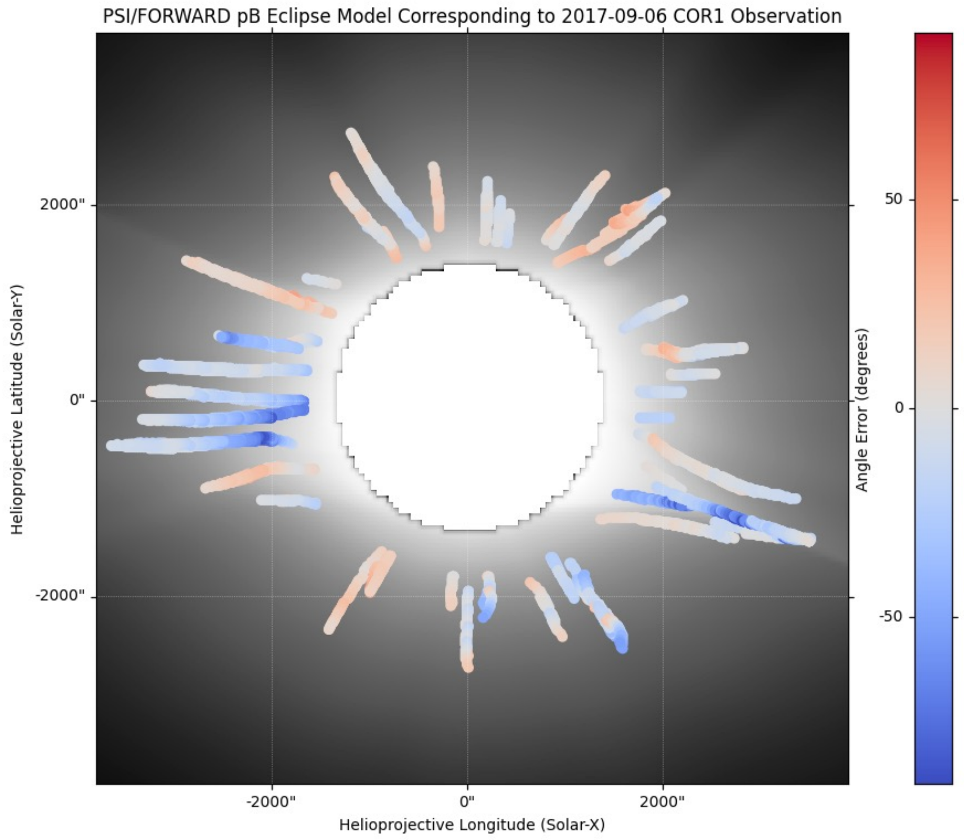

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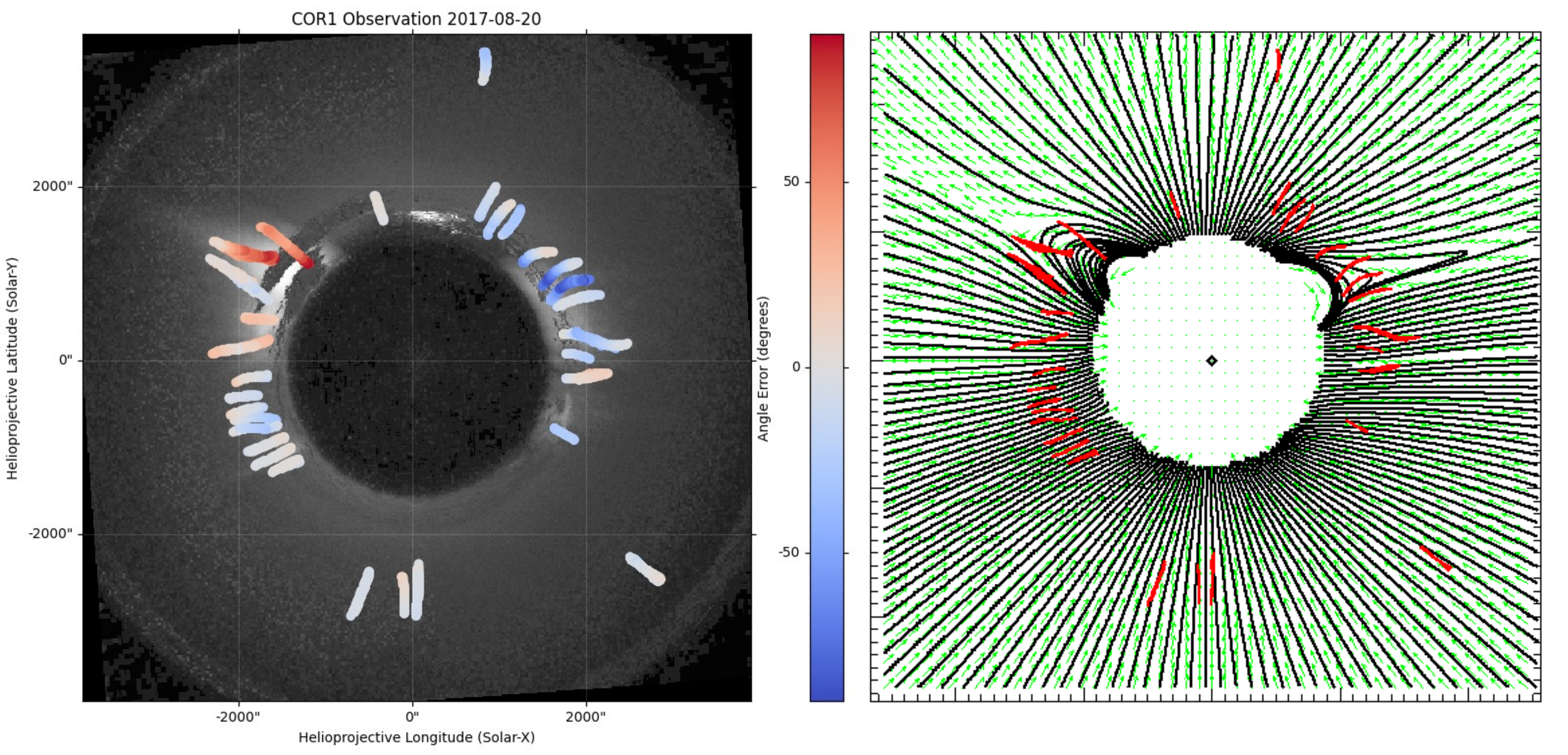
Contributions of Error



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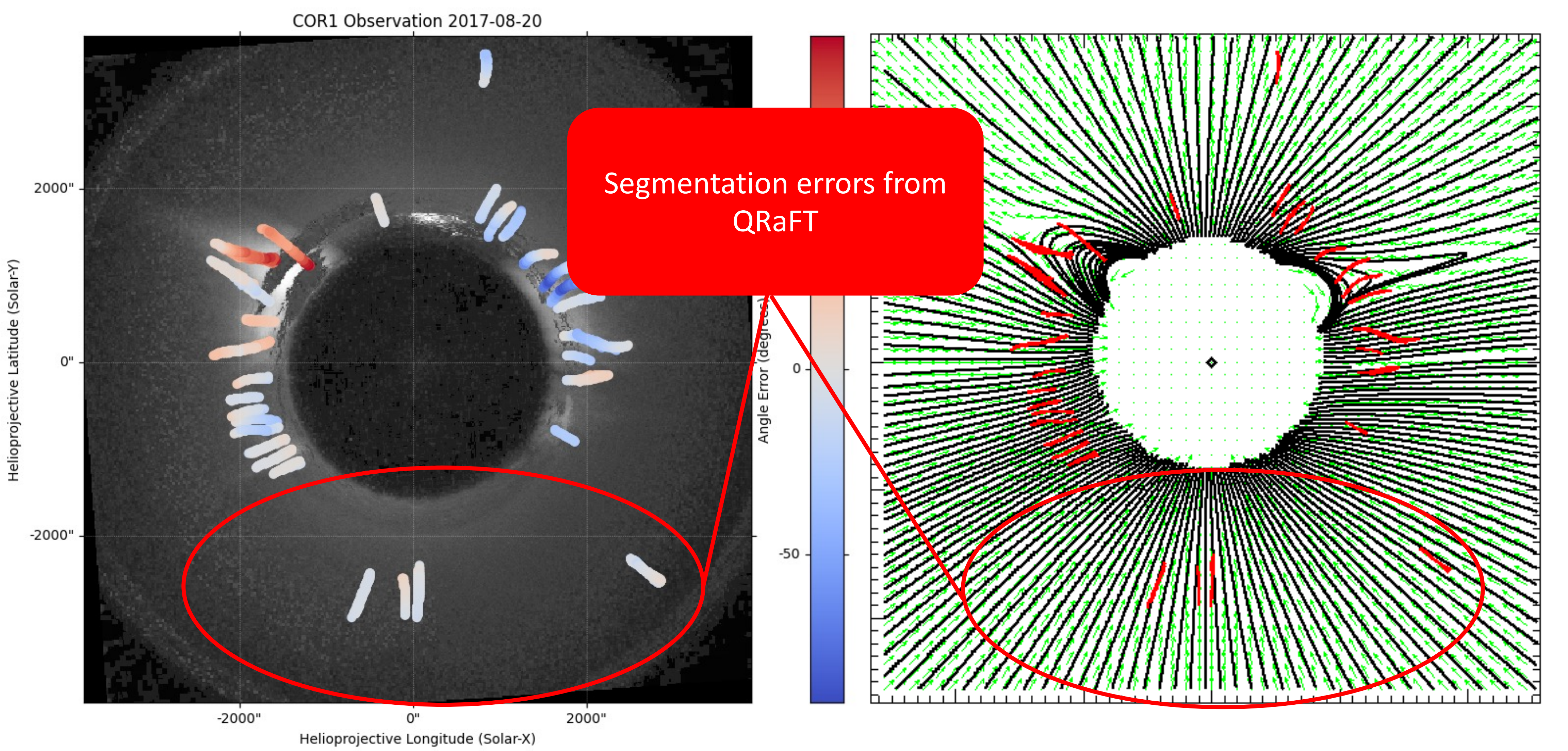

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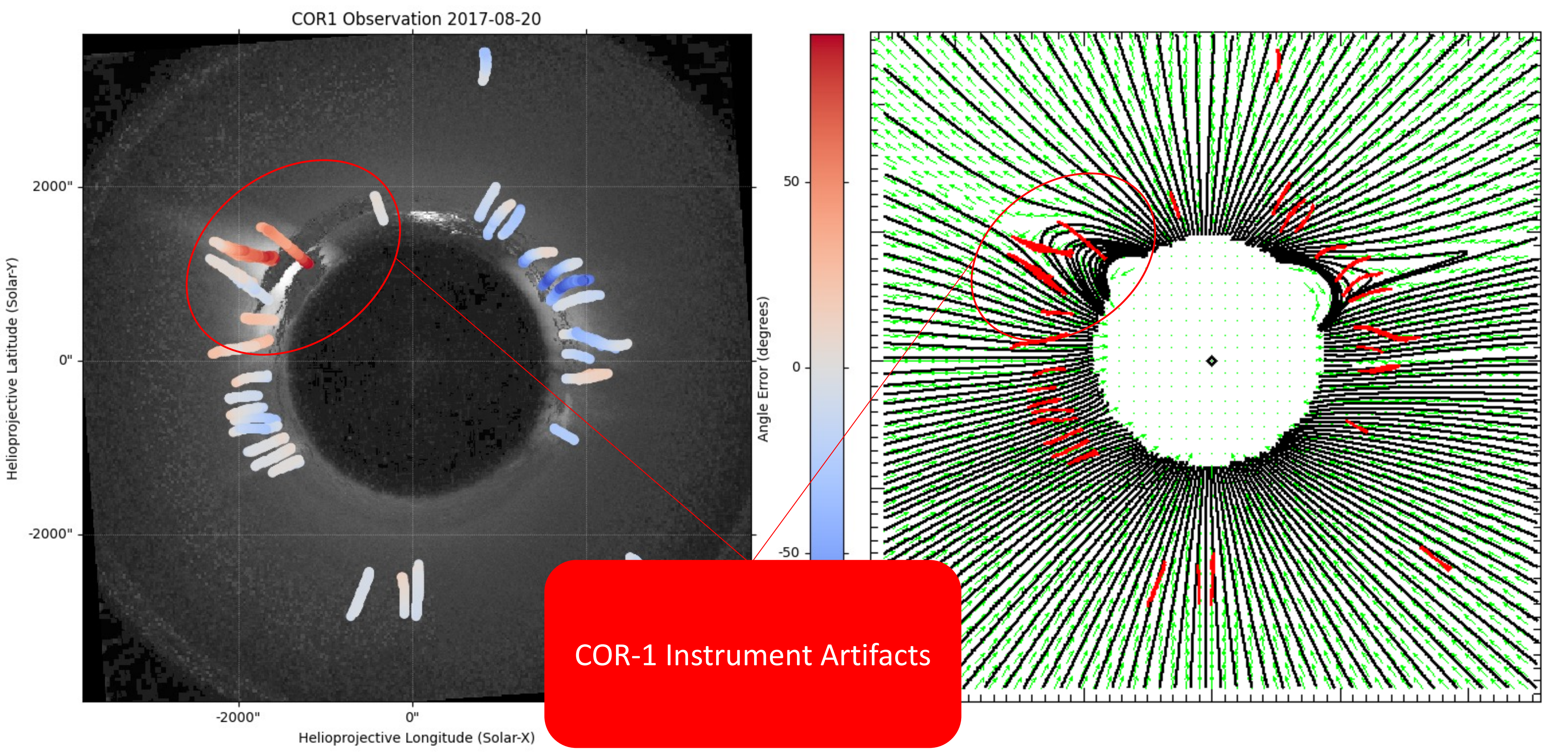

COR-1 Instrument Artifacts

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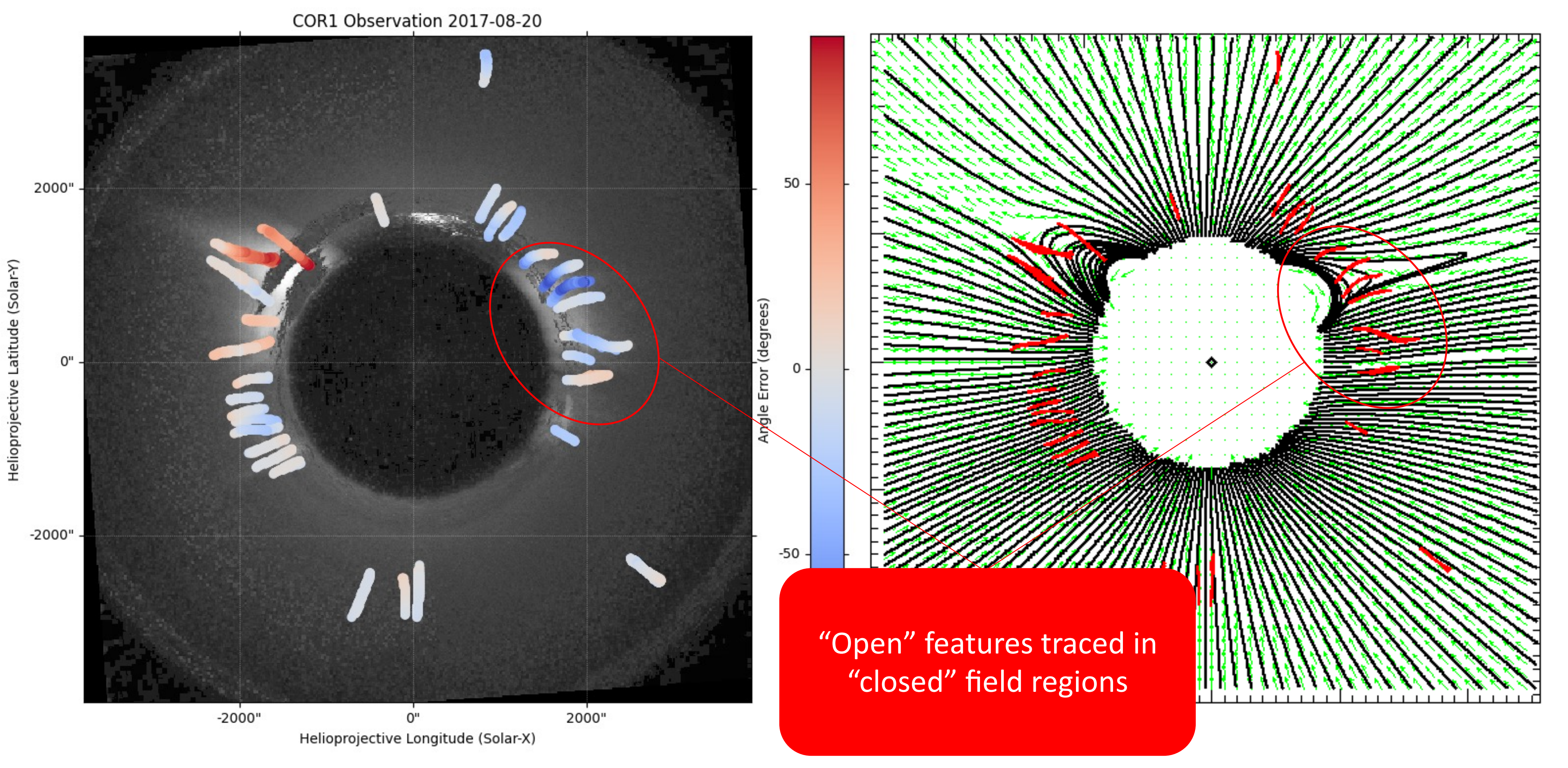
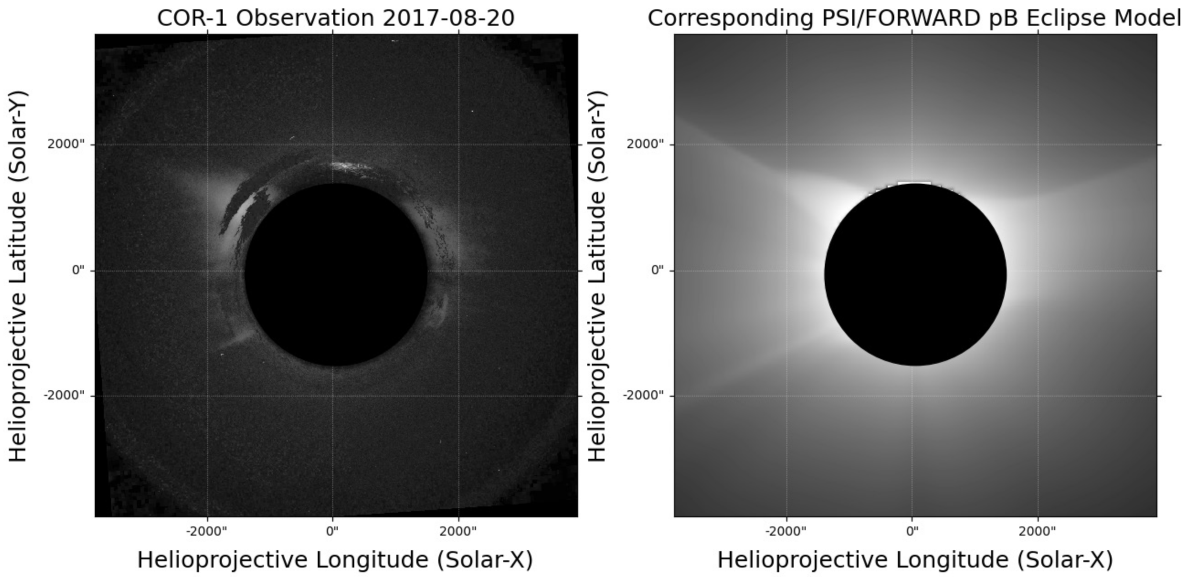
Contributions of Error

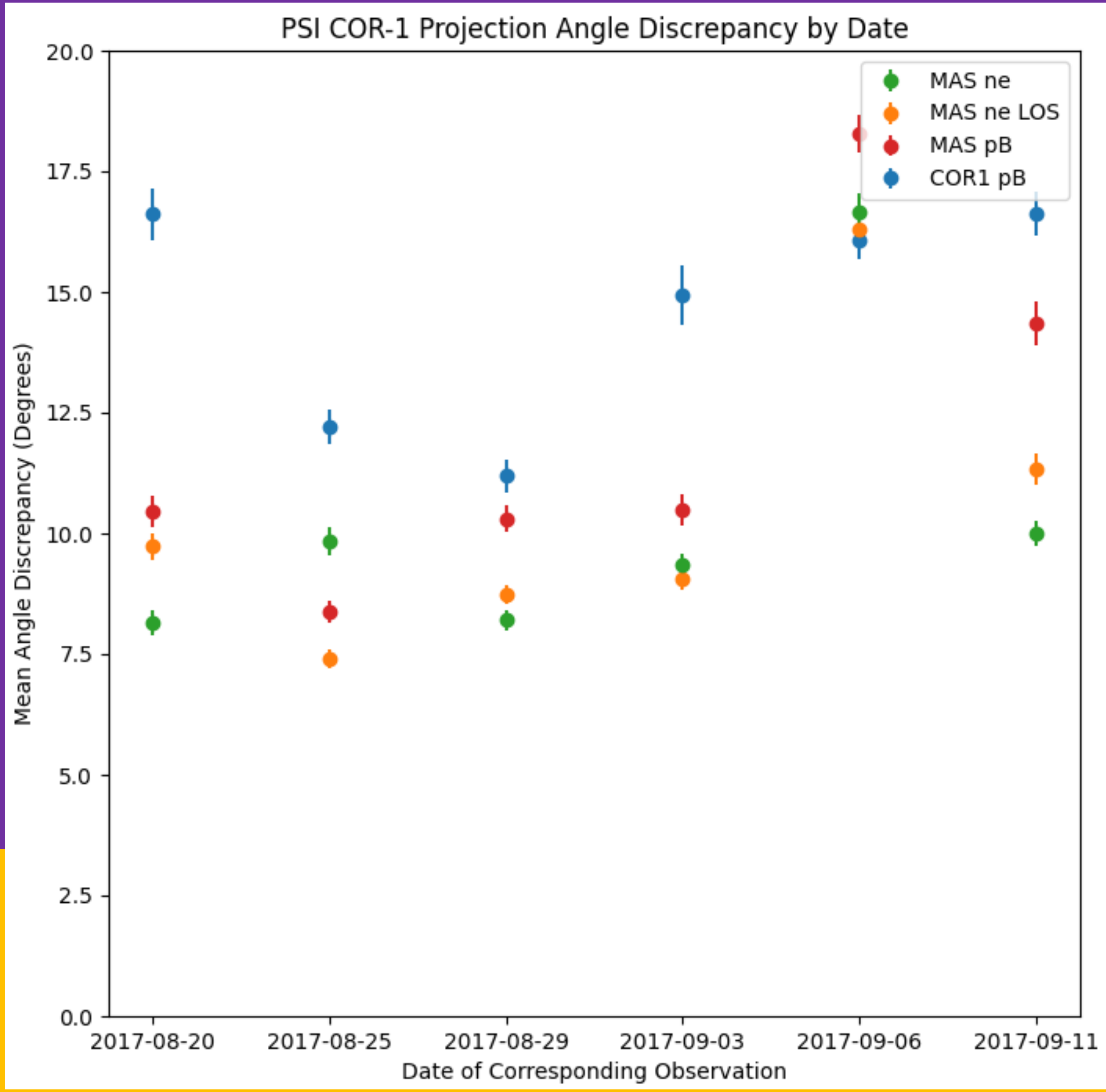


"Open" features traced in "closed" field regions

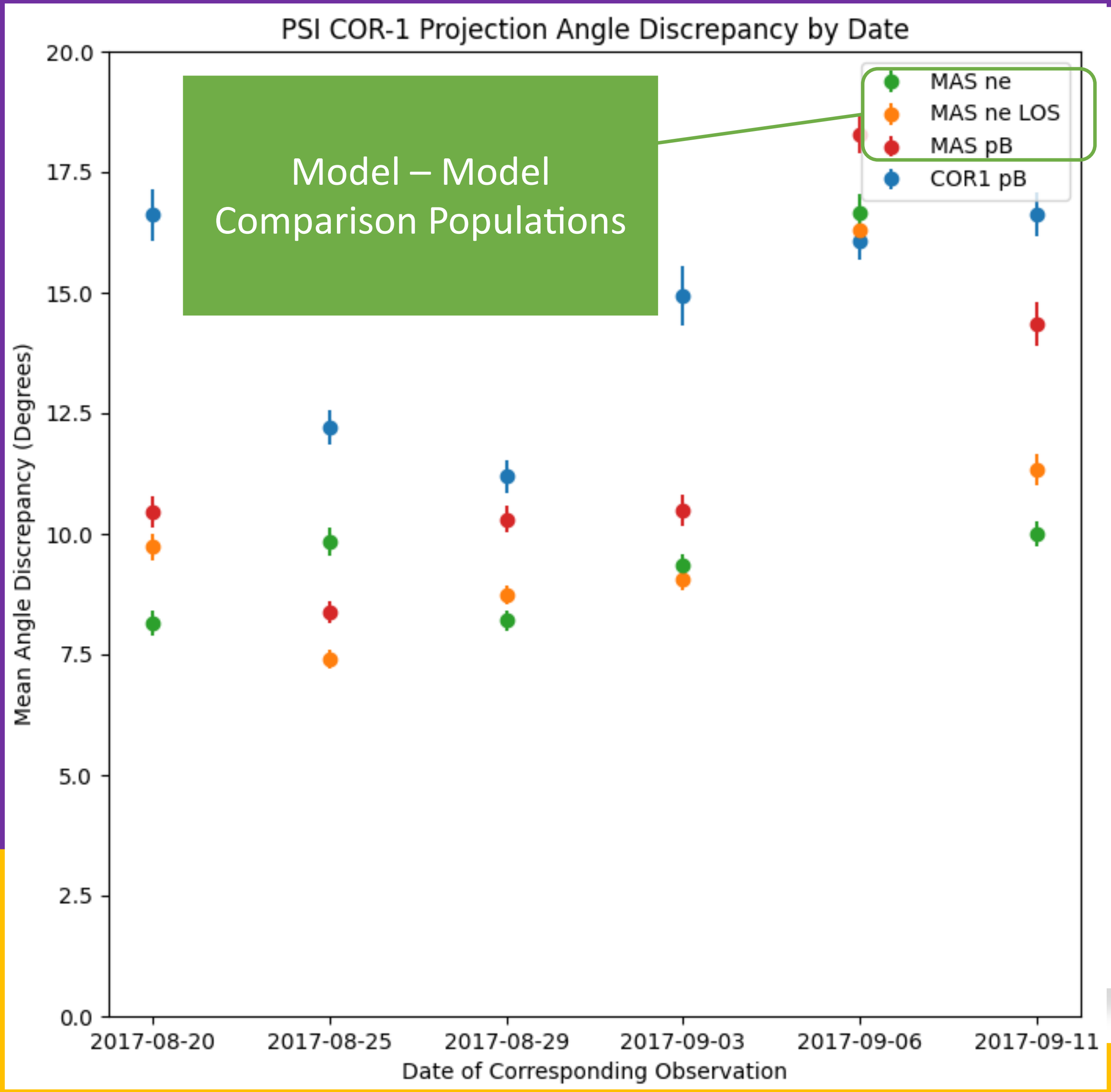
Comparison Populations

- MAS Central POS Electron Density
  - Ideal 1-1 comparison with Central POS B field
- MAS Line-of-Sight Integrated Electron Density
  - Electron density integrated along the line of sight (LOS) of observer
- FORWARD pB
  - Line-of-sight integrated electron density with artificial scattering
- COR-1 pB
  - White-light coronagraph aboard STEREO A that records polarized brightness (pB)





PSI COR-1 Projection Angle Discrepancy by Date
MAS ne
MAS ne LOS
MAS pB
COR1 pB
Mean Angle Discrepancy (Degrees)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
2017-08-20
2017-08-25
2017-08-29
2017-09-03
2017-09-06
2017-09-11
Date of Corresponding Observation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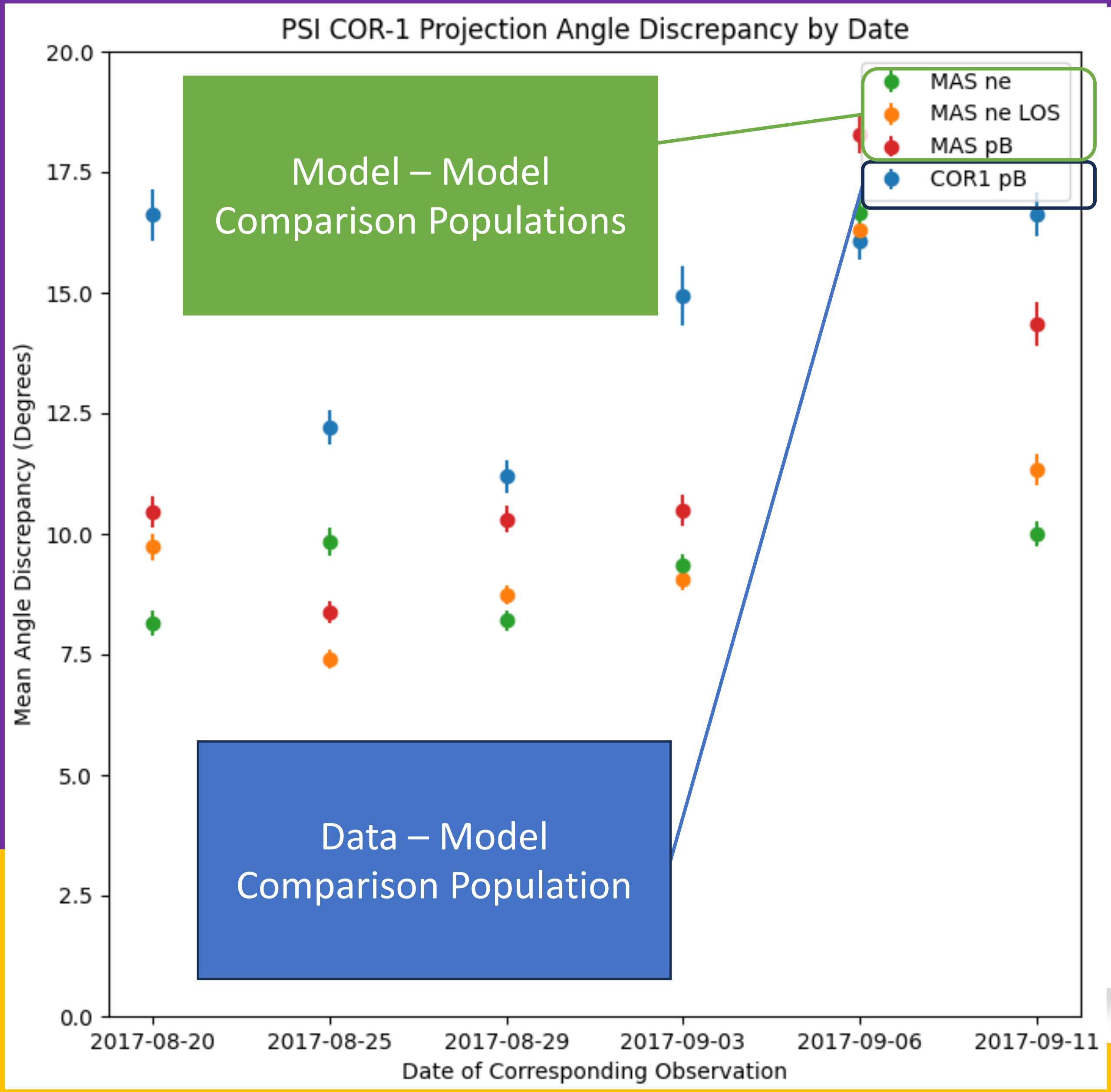
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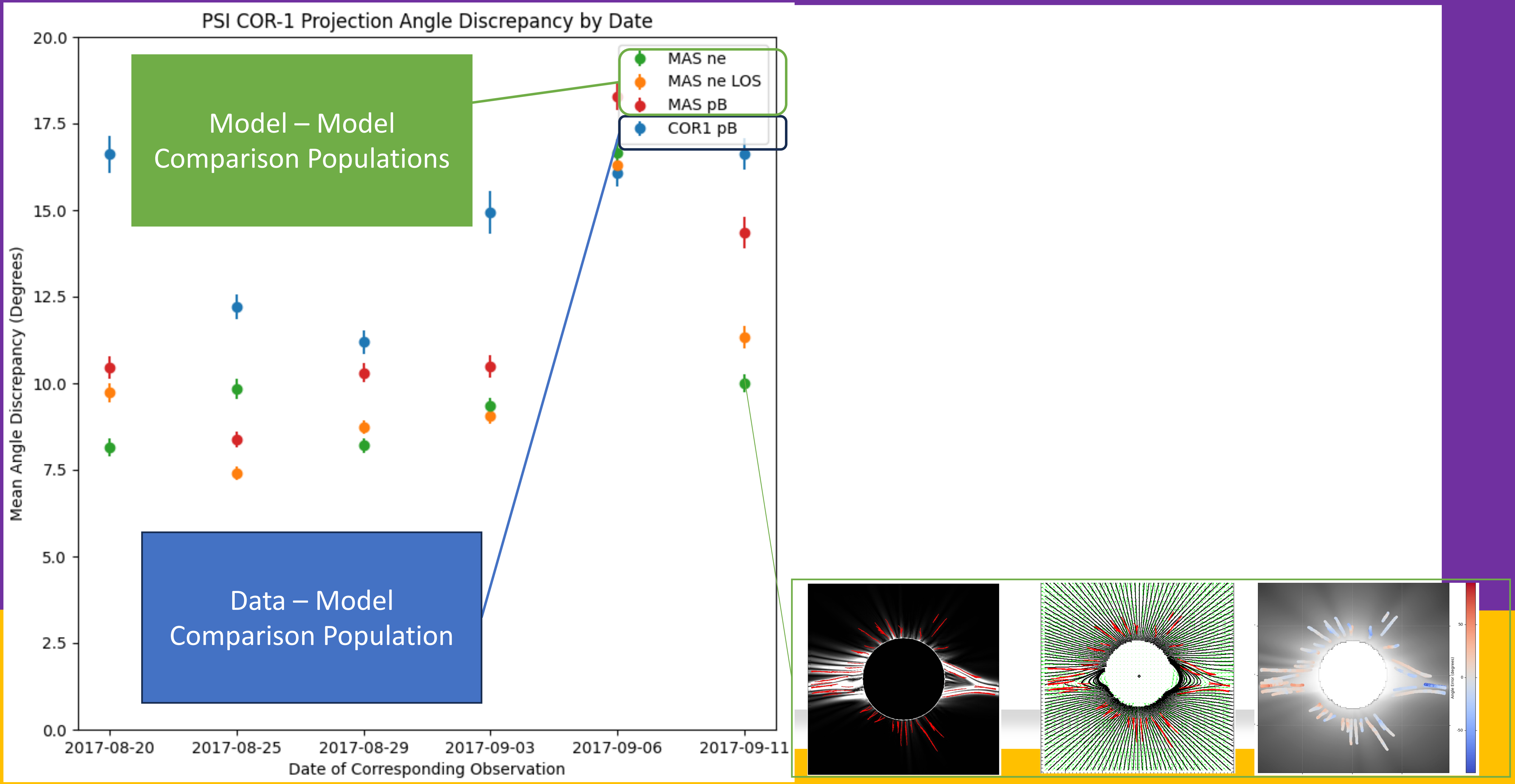
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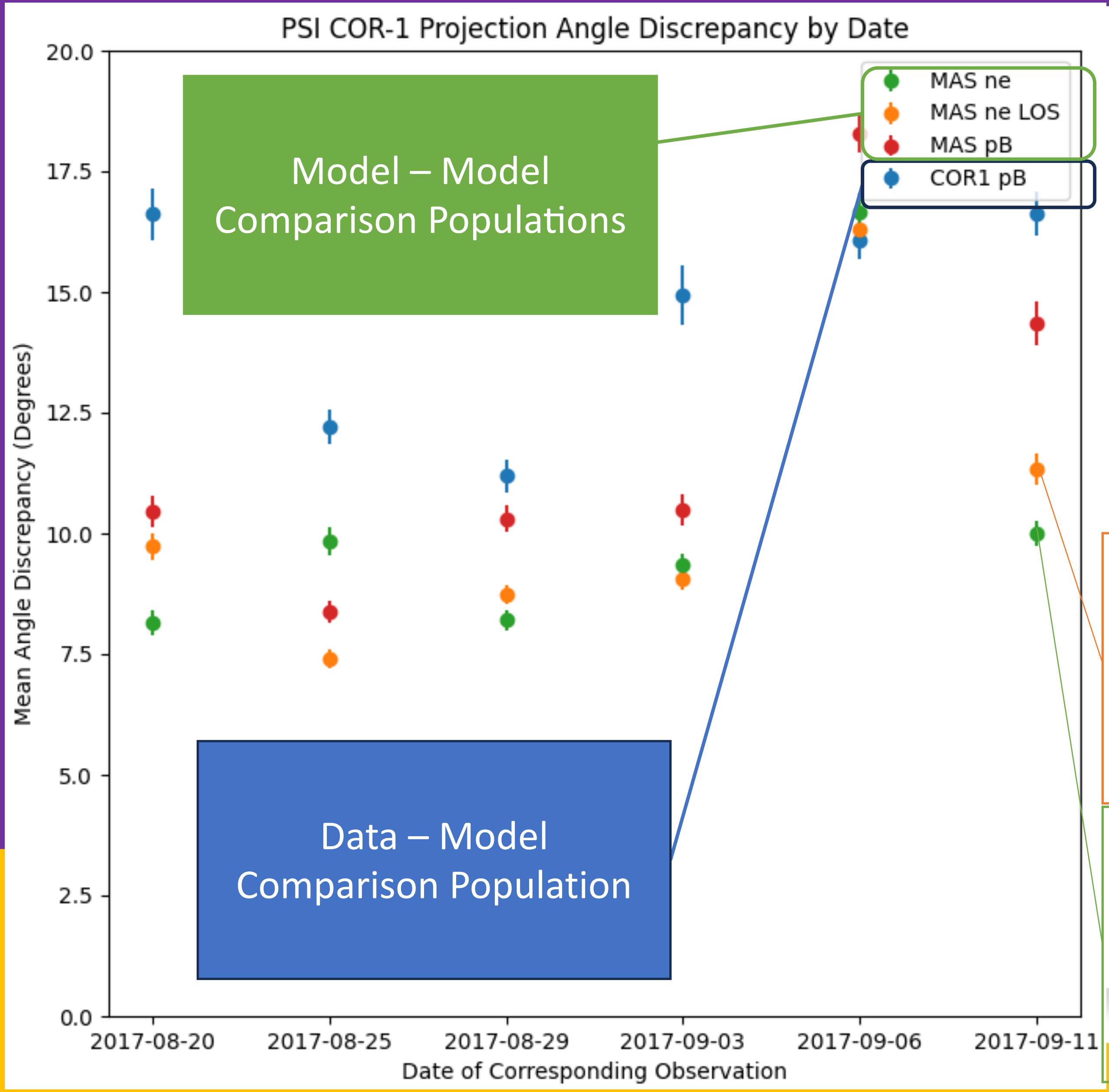
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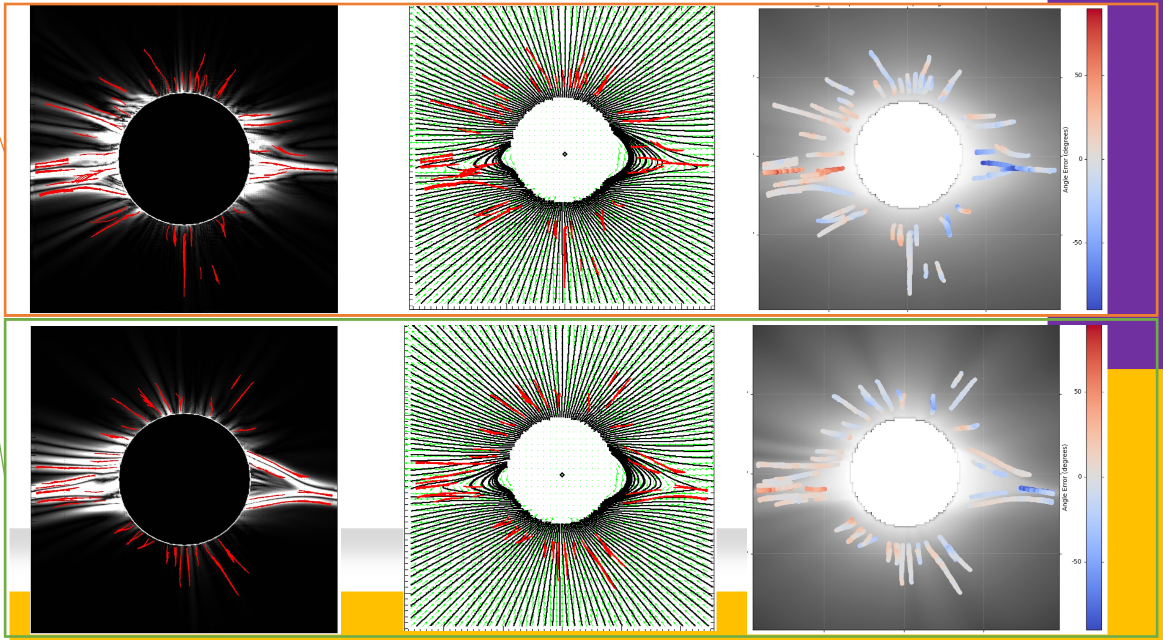

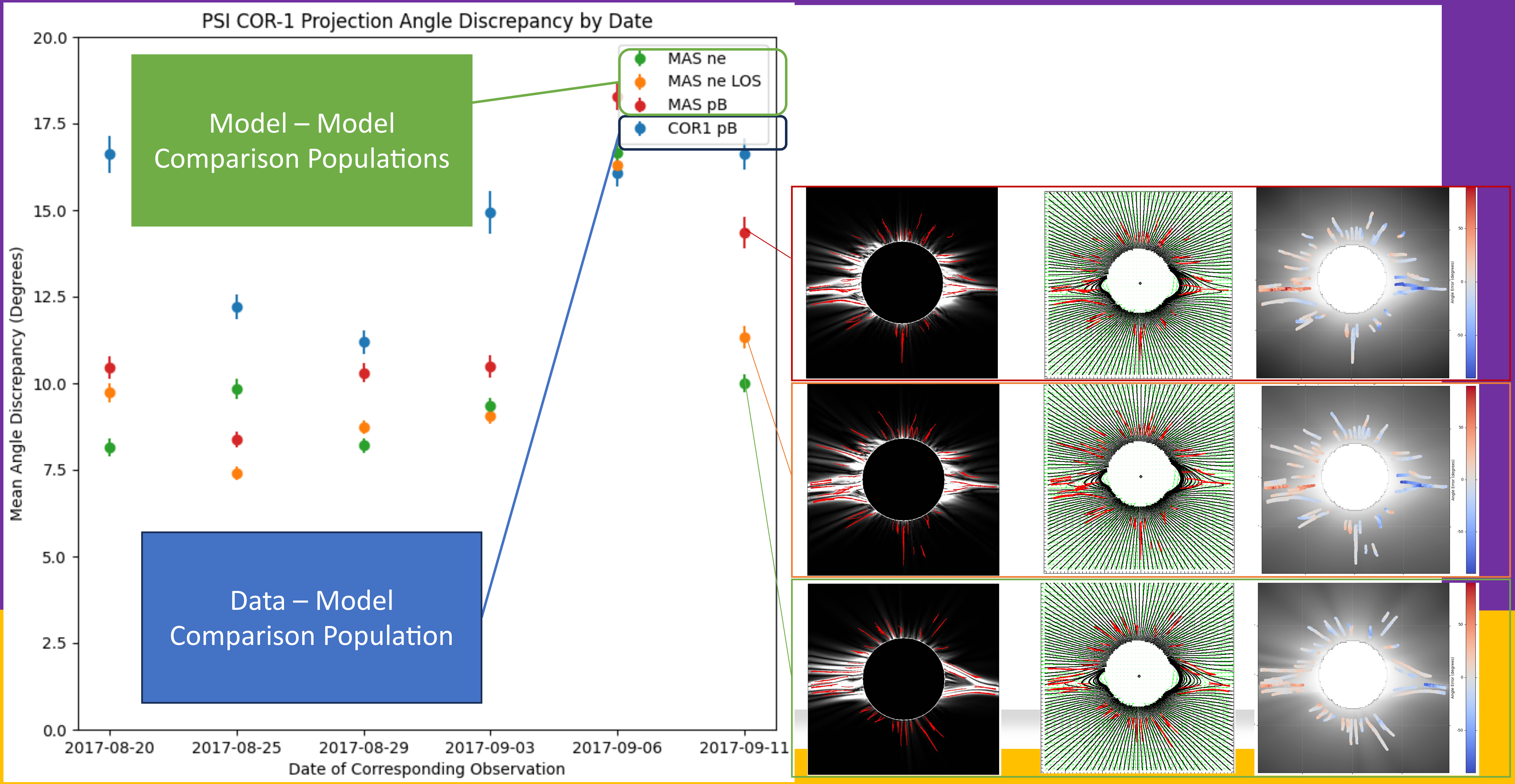
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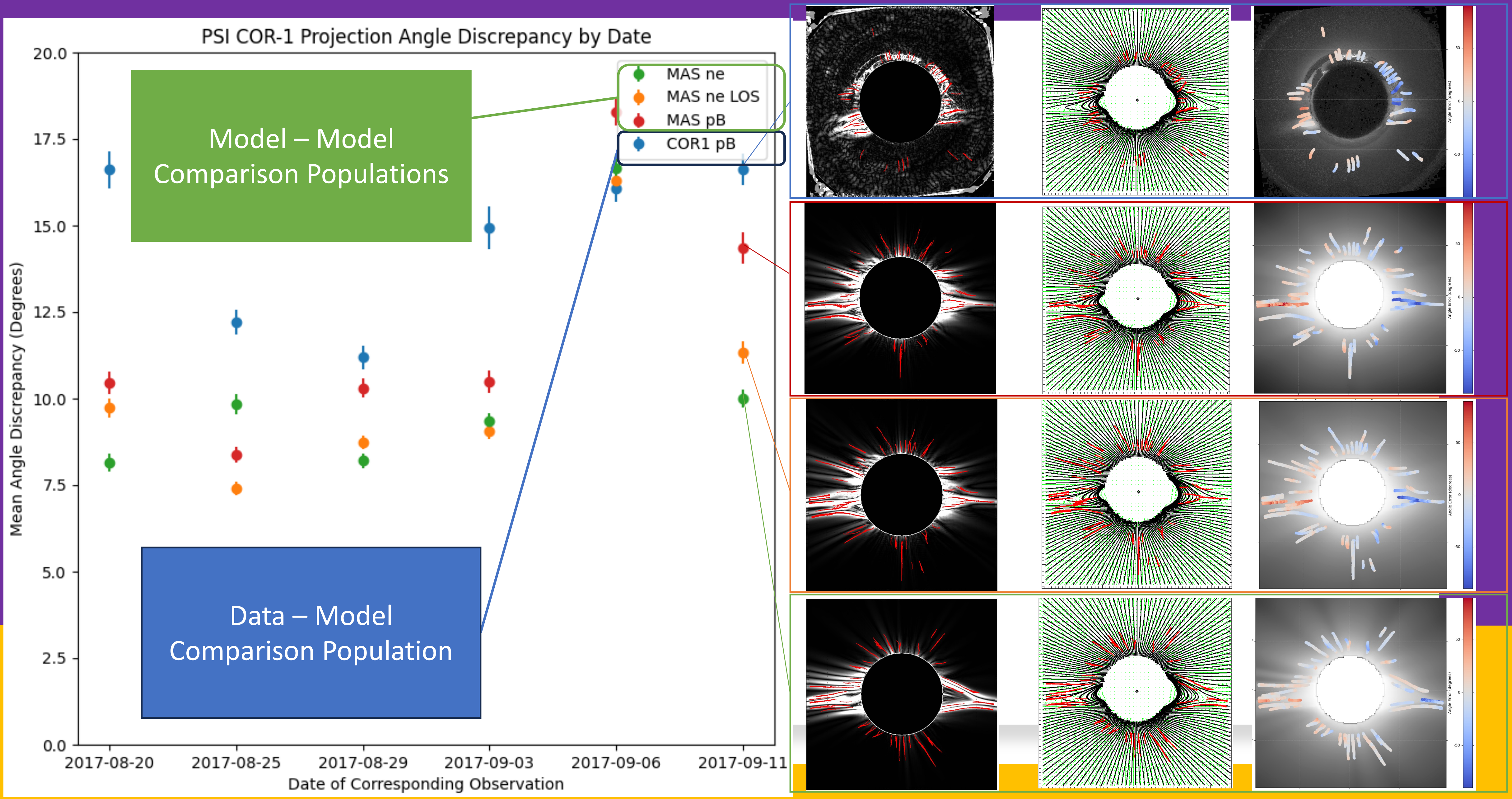
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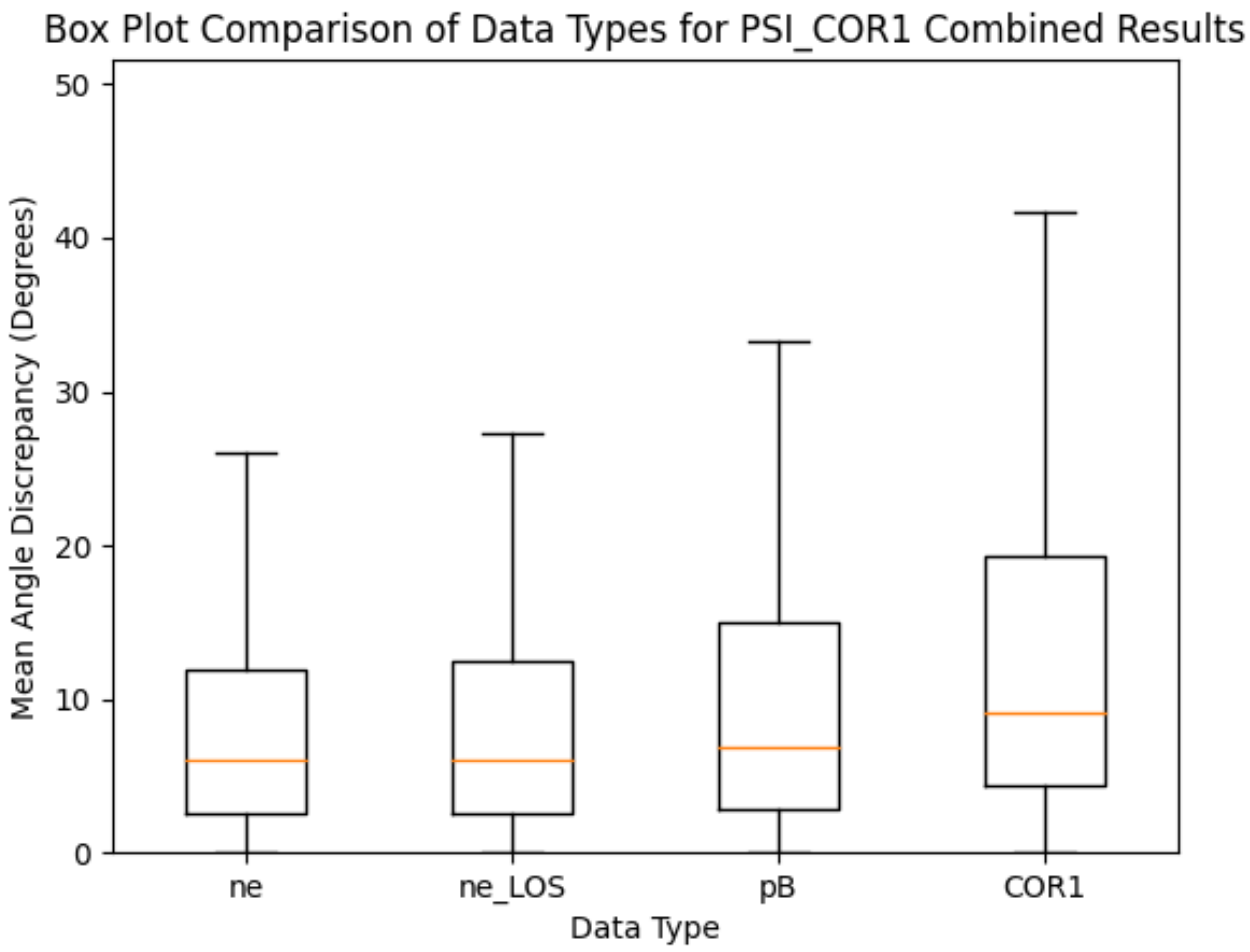
Using Global Statistics to Diagnose Error Contributions



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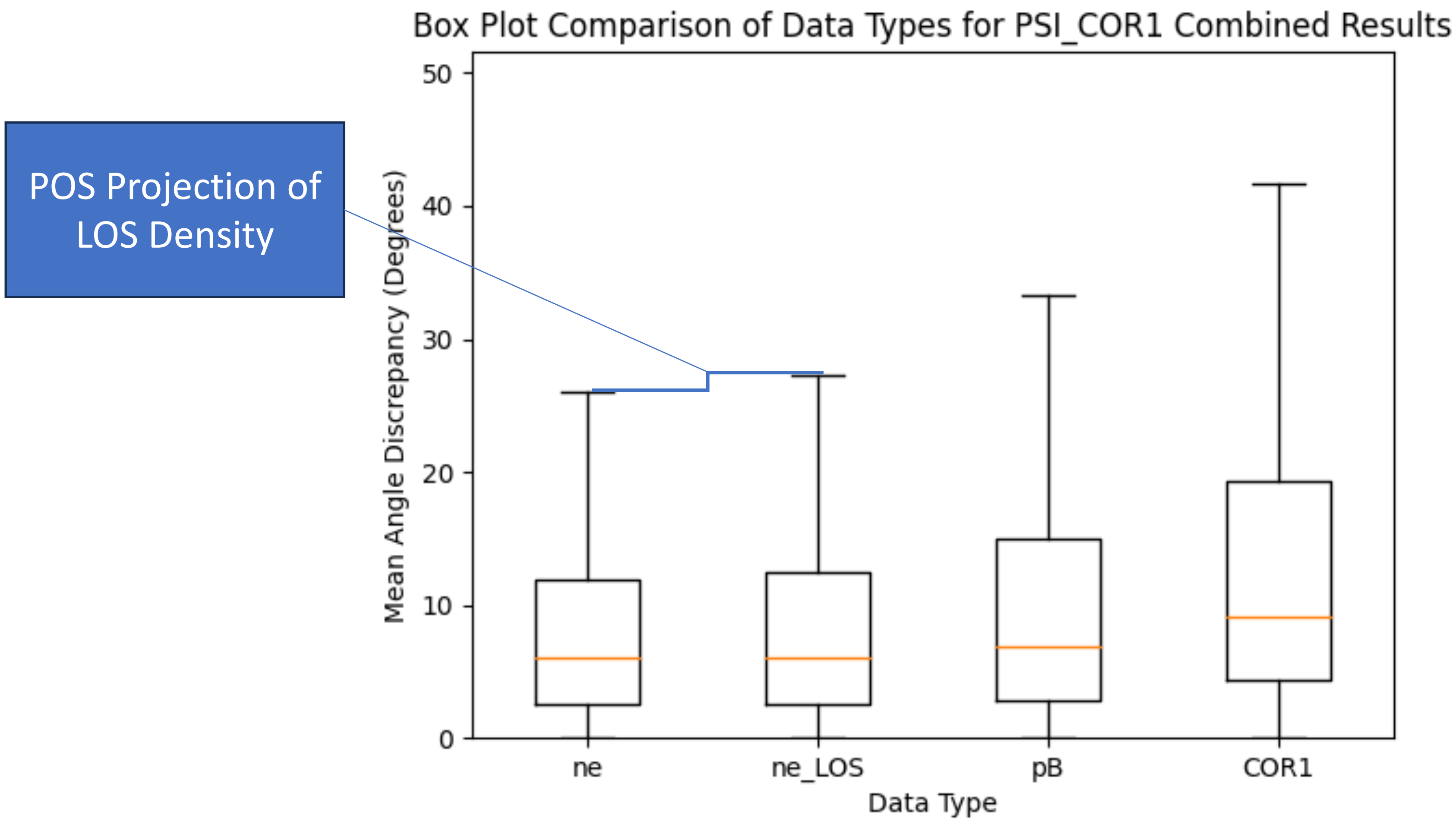

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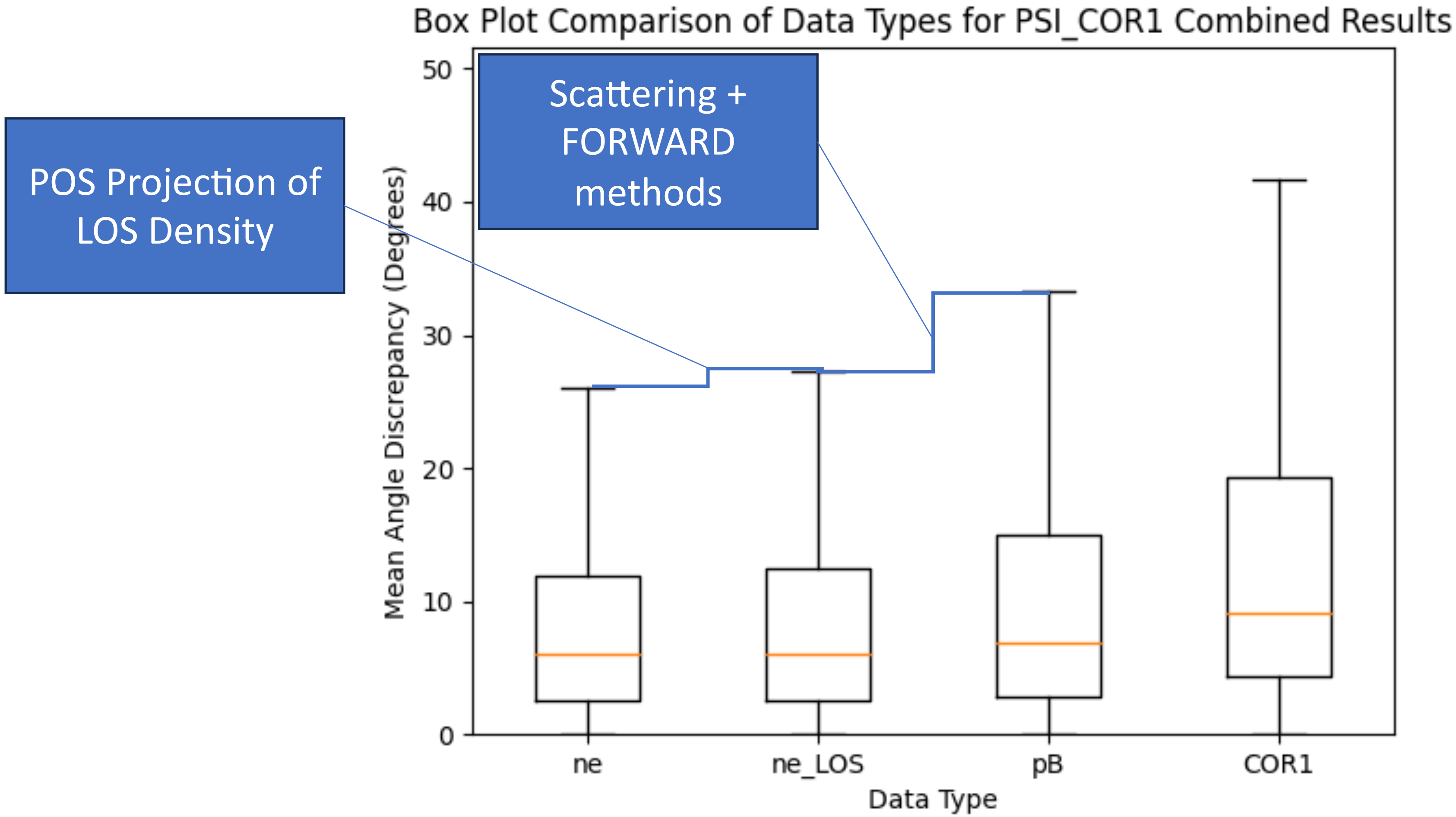

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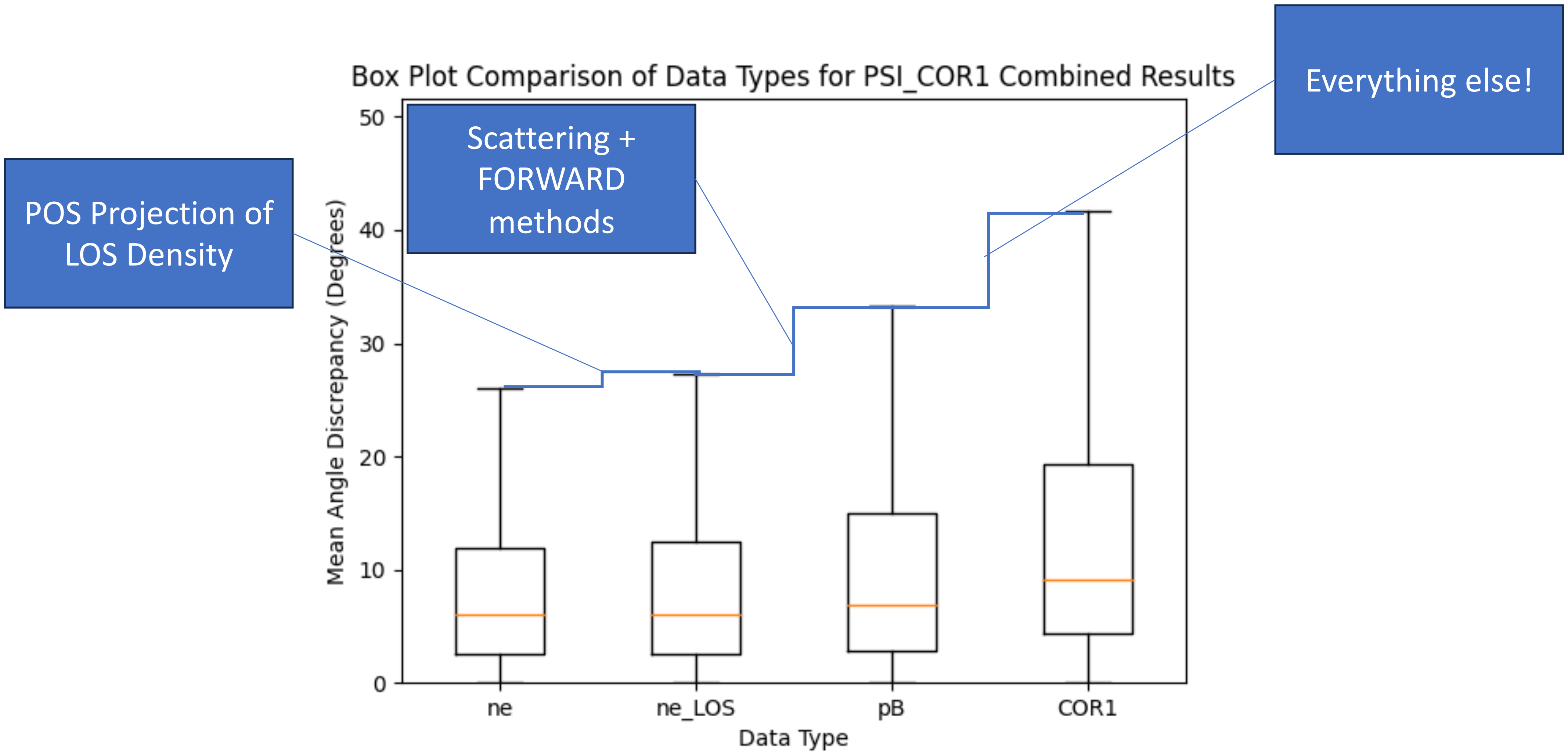

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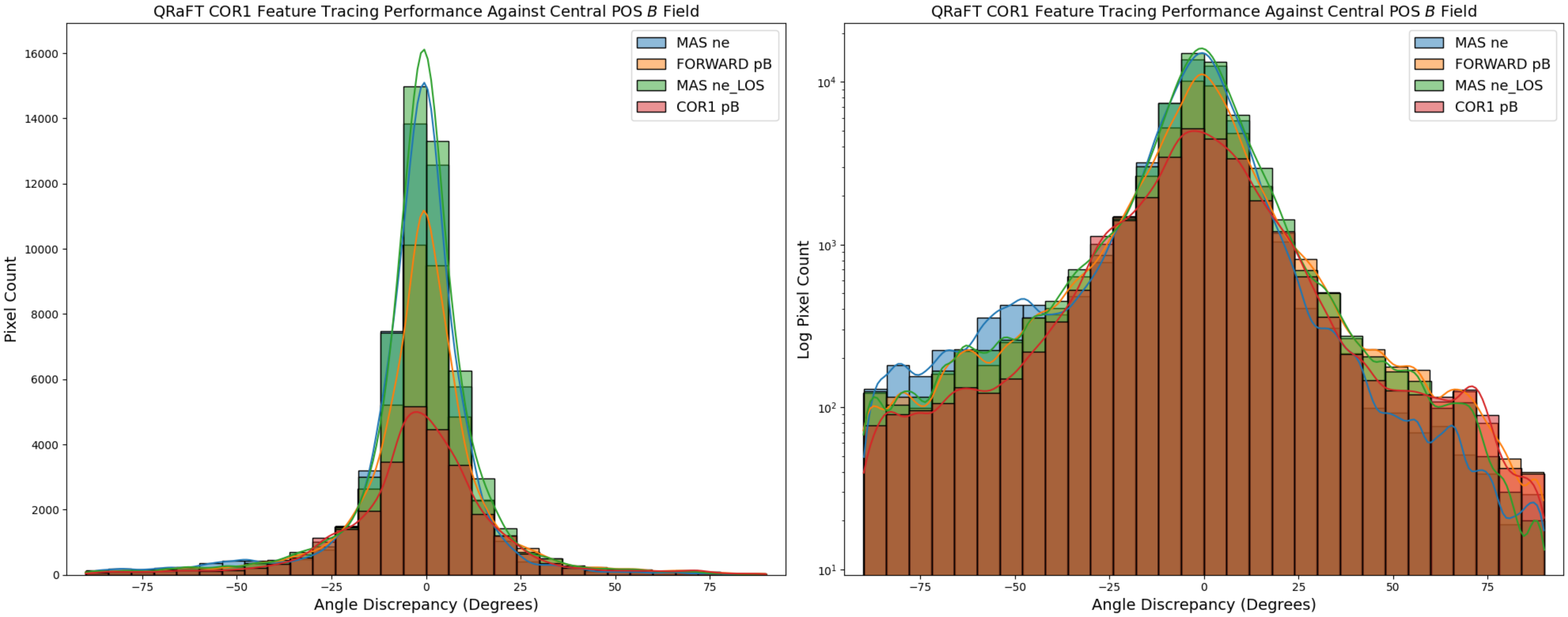
Using Global Statistics to Analyze Similarity



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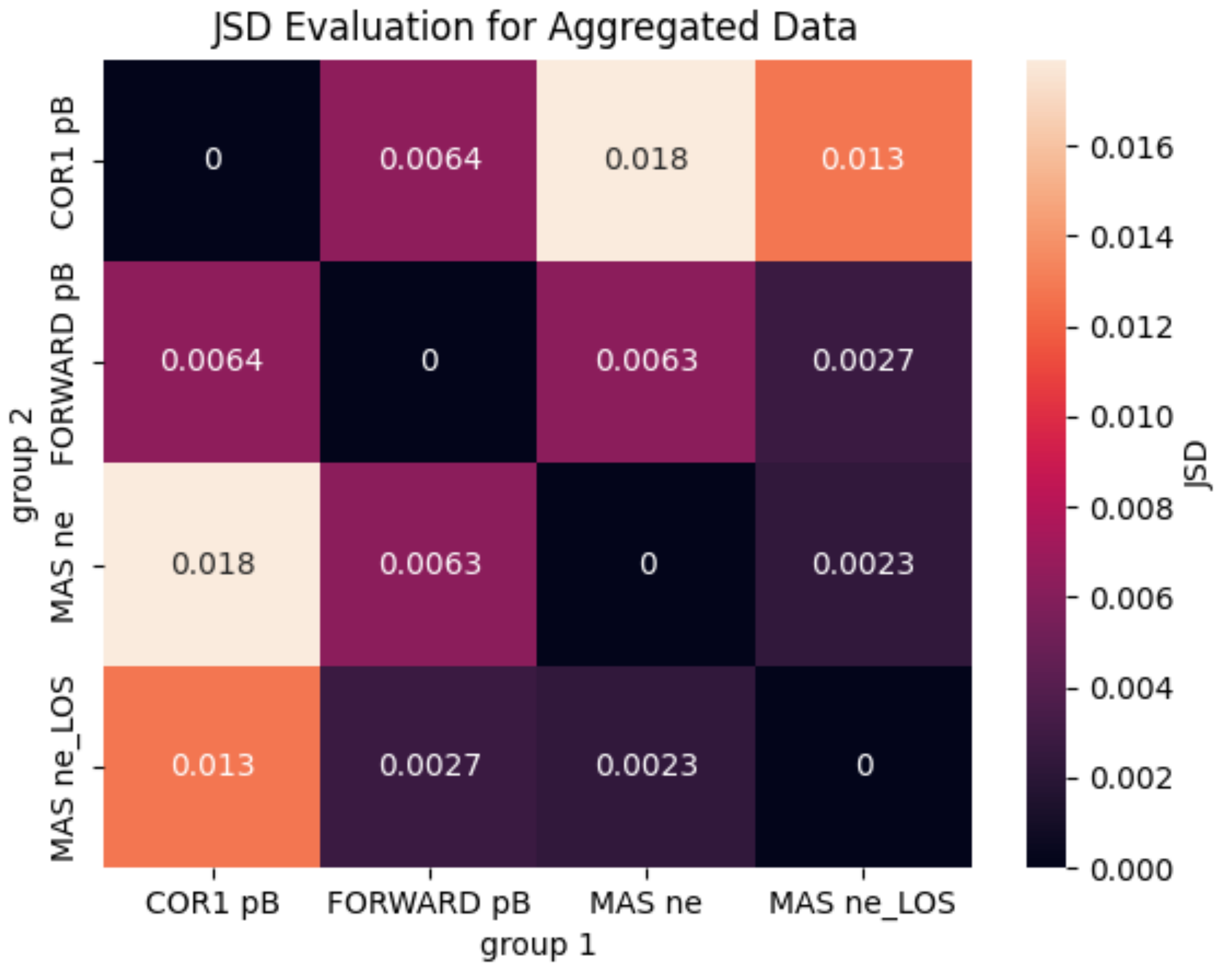
Using Global Statistics to Analyze Similarity

$$JSD(P||Q) = \frac{1}{2} D_{KL}(P||M) + \frac{1}{2} D_{KL}(Q||M)$$

$$*M = \frac{1}{2}(P + Q)$$

$$D_{KL}(P||Q) = \sum_{x} P(x) \log \frac{P(x)}{Q(x)}$$



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Validation Framework: Preliminary Statistics

data type	date	mean	median	std	95% CI	n
MAS n_e POS	combined	10.4786	5.996	13.8553	0.11815	52833
MAS n_e LOS	combined	10.5036	6.0348	13.3483	0.10975	56828
FORWARD pB	combined	12.1194	6.88286	14.9605	0.14097	43265
COR-1 pB	combined	14.5542	9.15746	15.6939	0.18417	27897
random	combined	44.698	44.5507	26.0692	0.24032	45205

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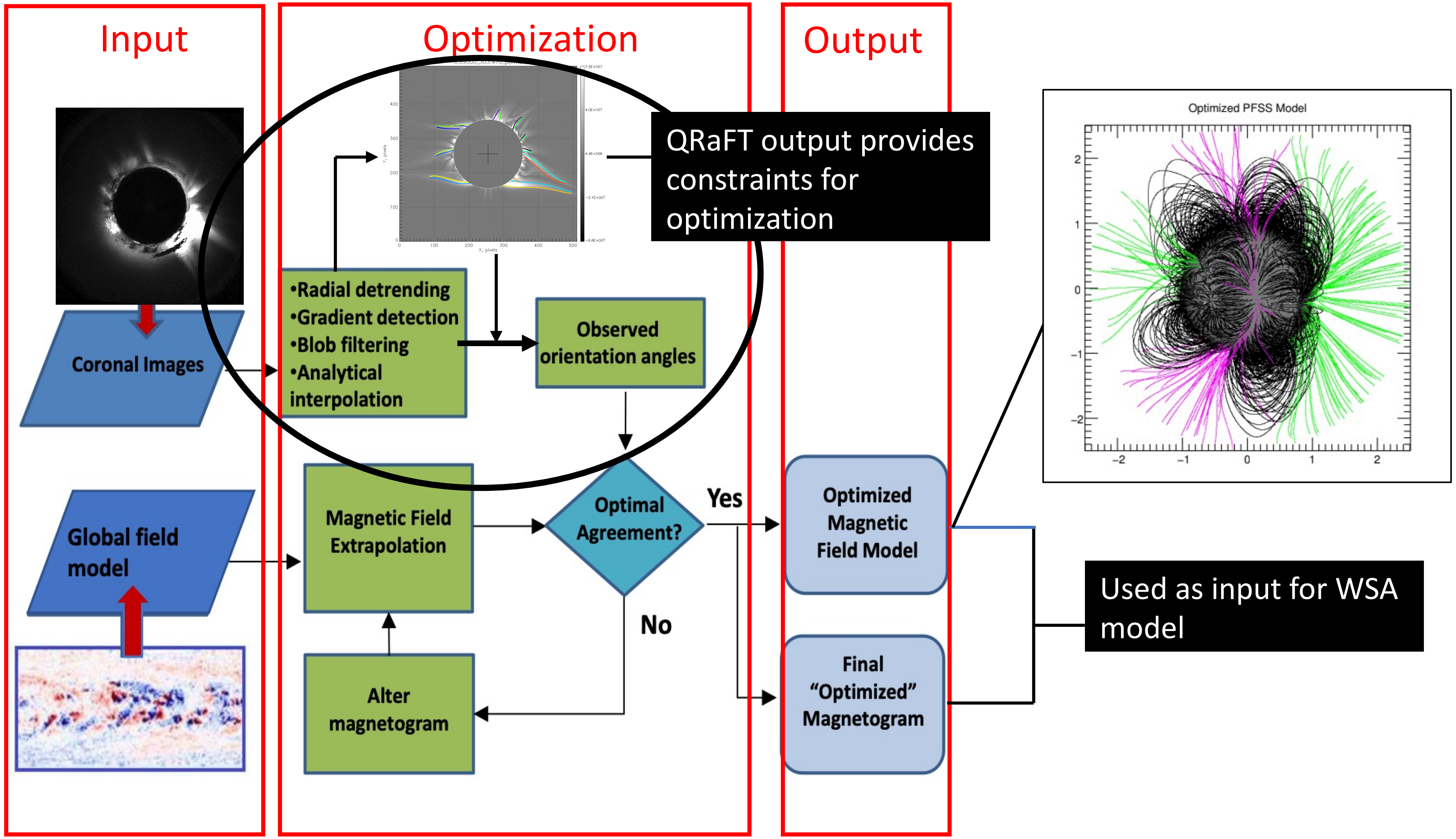
Validation Framework: Conclusions

- Provides quantifiable ground-truth validation against MAS model
- Created metrics to correlate white-light pB feature segmentations to model B field
- Diagnose/quantify error between several model populations and coronal segmentations
  - MAS Central POS electron density vs central B field orientation
  - MAS LOS integrated electron density vs central B field orientation
  - FORWARD pB vs central B field orientation
  - COR-1 pB vs central B field orientation
- Can adapt framework to use for
  - PUNCH and other data sources
  - Other MHD simulations
  - Other coronal feature tracers
- Verified coronal segmentations is representative of simulated magnetic structure

Thank You!

NASA



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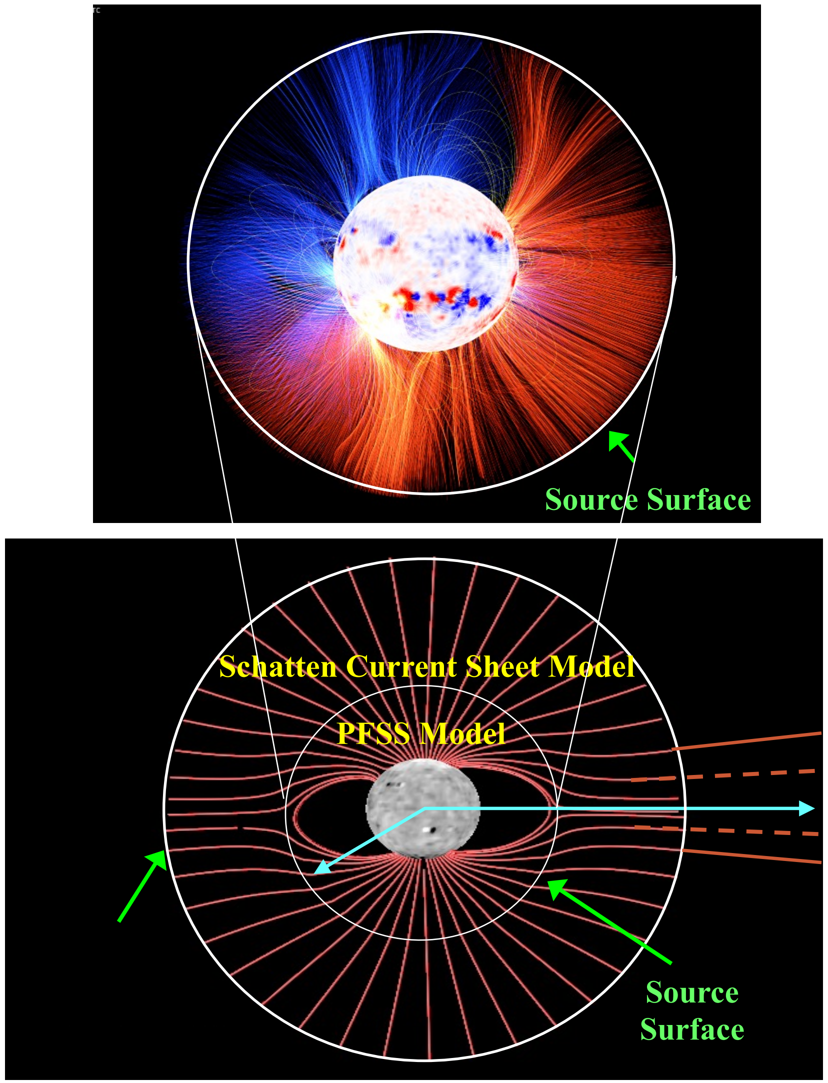
Wang-Sheeley-Arge (WSA) Model: Overview

- Combined empirical and physics-based model of the corona and solar wind.
- Input: ground/space based magnetic field maps
- Output: Simple WSA model provides:
  - Coronal magnetic field
  - Solar wind (SW) speed & interplanetary magnetic field (IMF) polarity
  - Sun-spacecraft magnetic field connectivity
  - Inner B.C. for advanced MHD SW models
- Research Applications
  - Coronal and solar wind studies
- Supports NASA mission & community research objectives and needs
- Supports operational forecasting
  - NOAA/SWPC, USAF-557th Weather Wing, USSF, UK Met office, & Korean Space Weather Center (KSWC)



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