A Benchmark Community data Set for the Evaluation of Solar Coronal Hole Boundaries

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ISWAT S201 Team

Introduction: Coronal holes and the ambient solar wind

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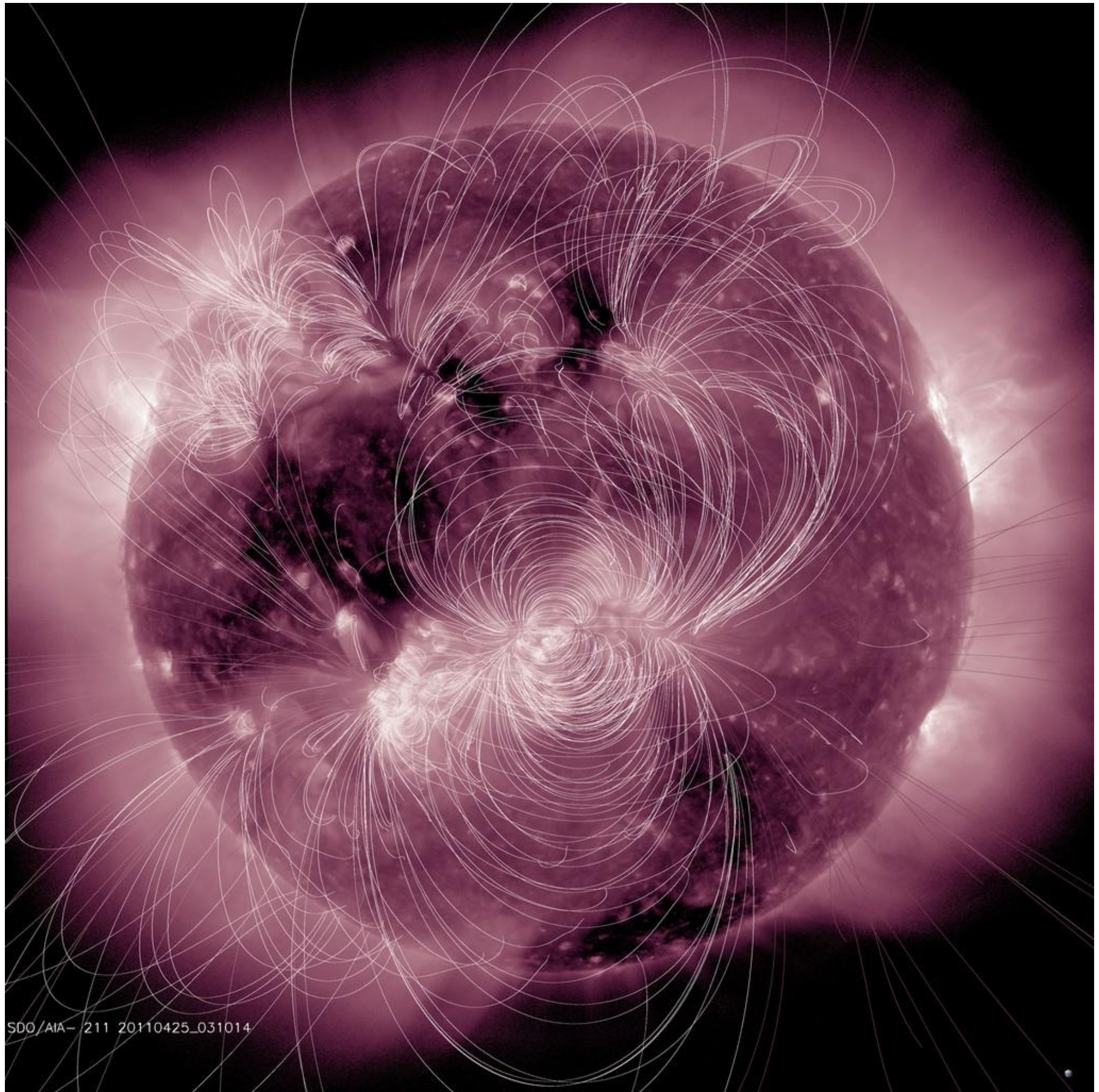
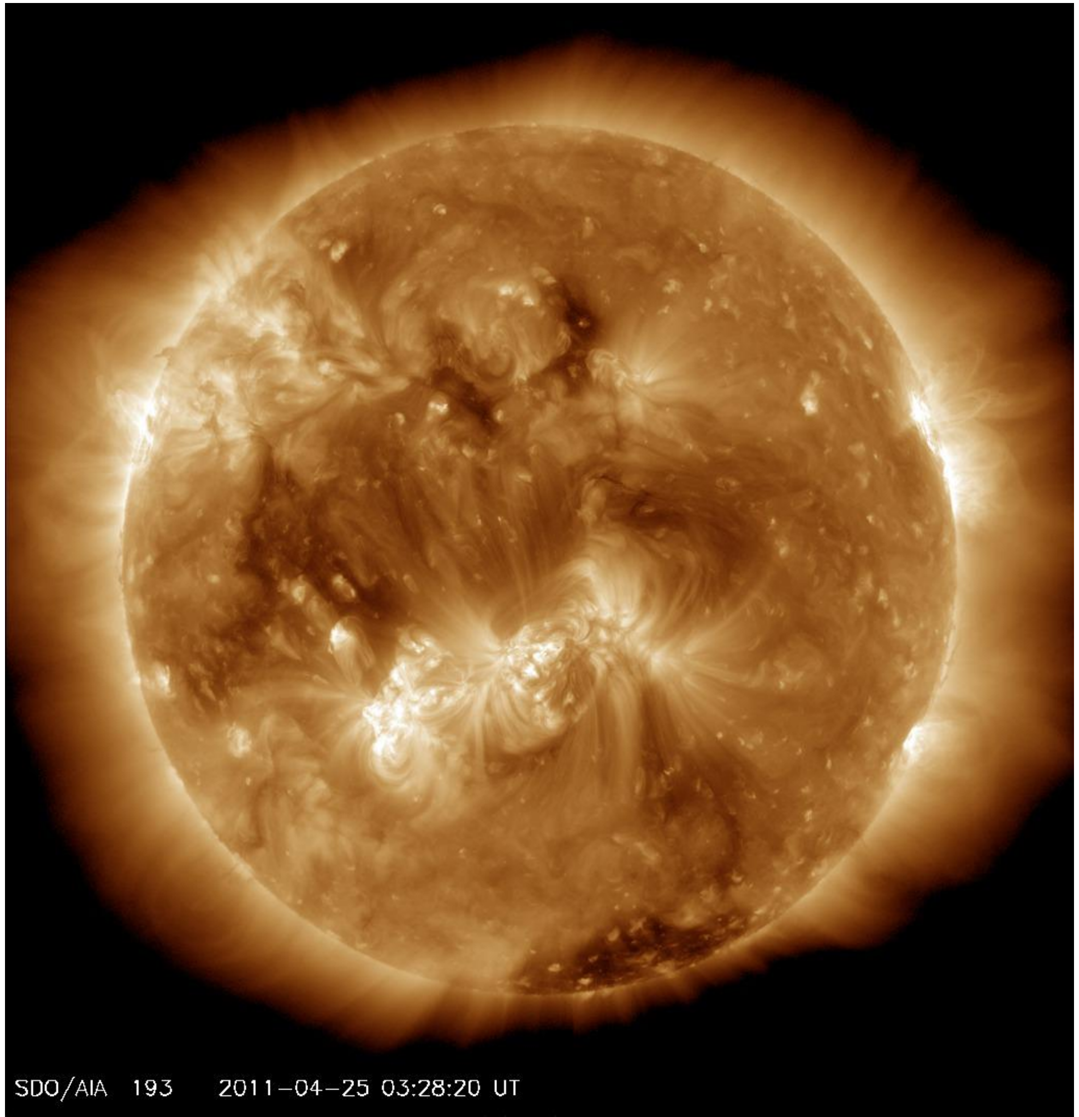
What are coronal holes?

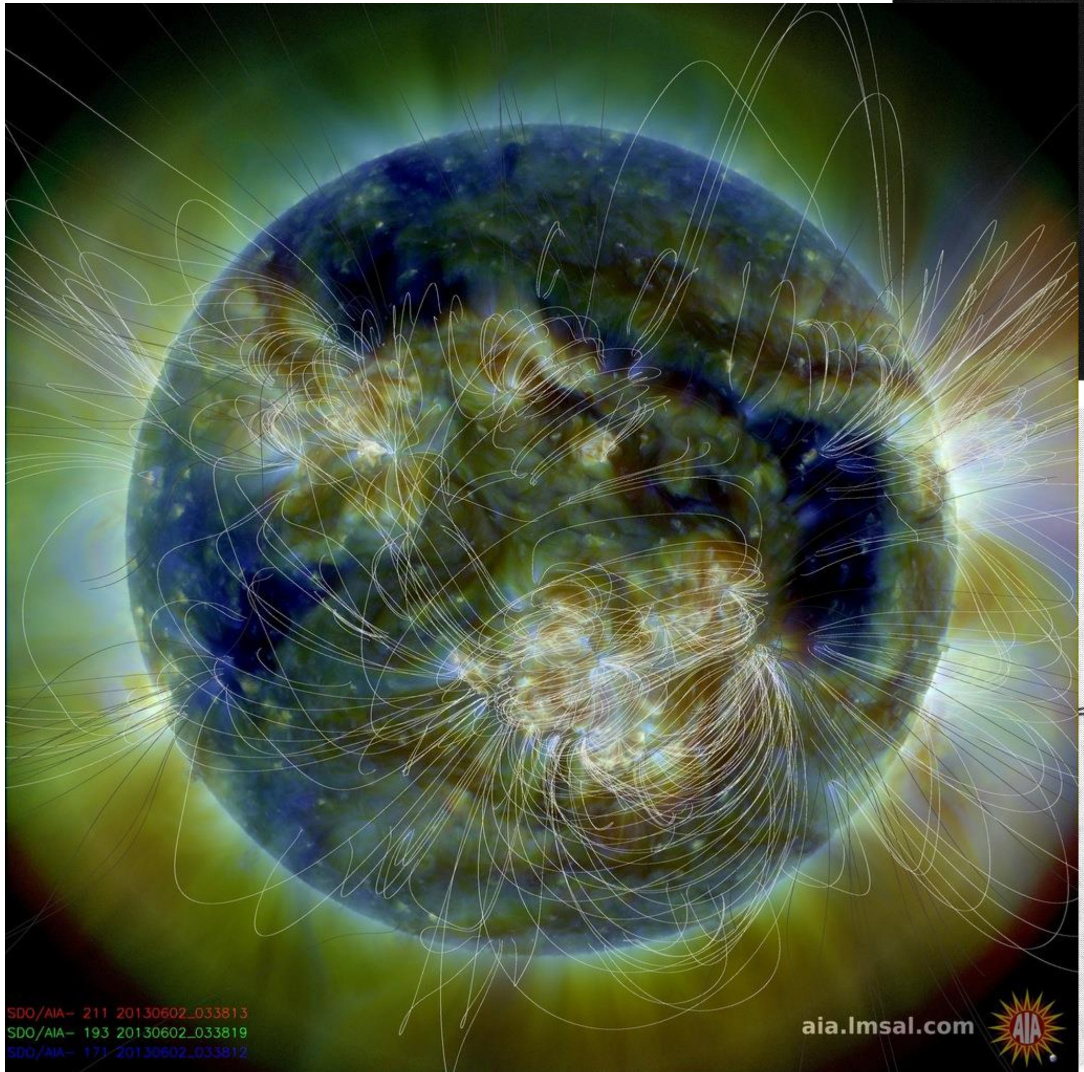
Observational answer: dark regions in solar coronal images

Coronal holes appear as dark areas on the solar surface in the **EUV** (extreme ultraviolet) and **X-ray** radiation. They have a **lower density** and **temperature** compared to the surrounding corona. **Coronal holes** correspond to regions of open magnetic fields. Visible best in lines with temperatures more than 1.5 MK.





Coronal holes correspond to regions of open magnetic fields.



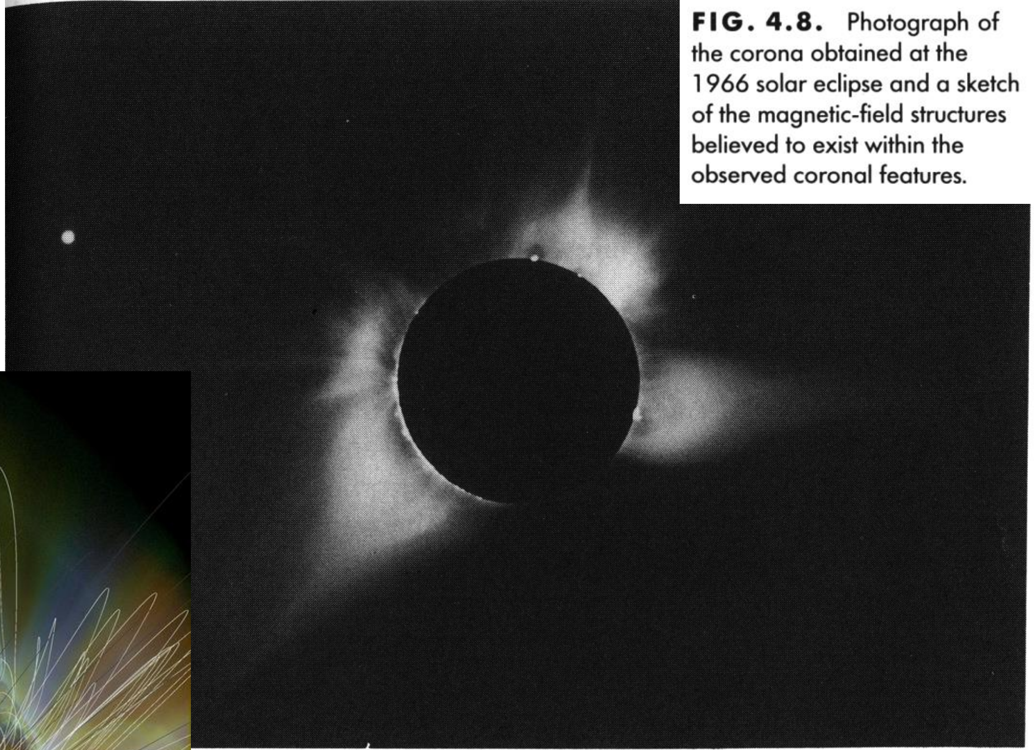
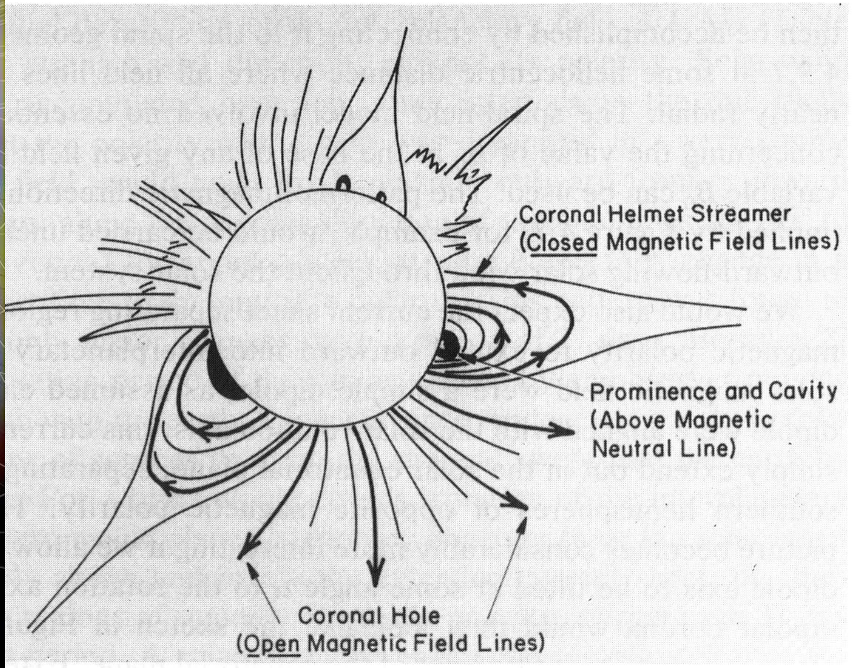


FIG. 4.8. Photograph of the corona obtained at the 1966 solar eclipse and a sketch of the magnetic-field structures believed to exist within the observed coronal features.

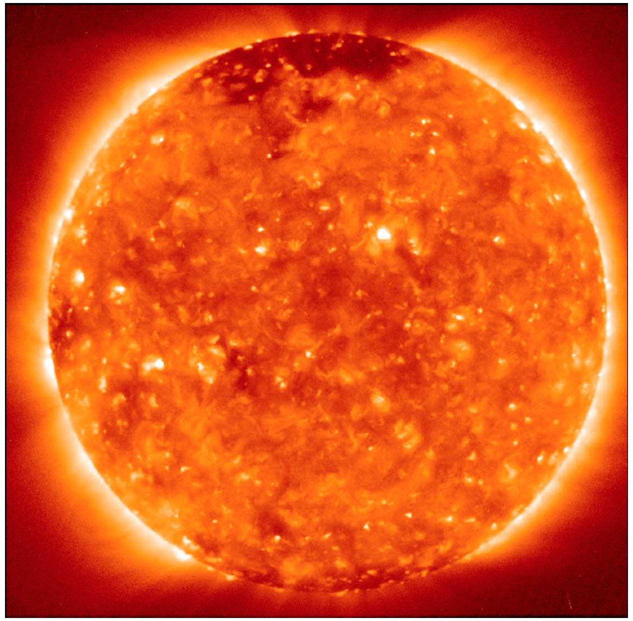


What are coronal holes ?

Observational answer: dark regions in solar coronal images.
- dark due to reduced temperature and density
    - reduced density due to magnetic field lines reaching far into the heliosphere (‘open field lines’)

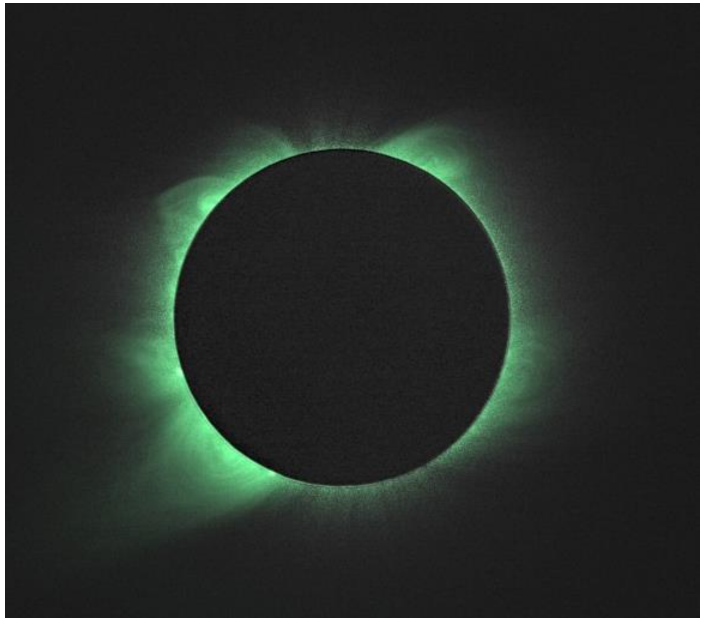
more coronal hole examples:

X-Ray Images



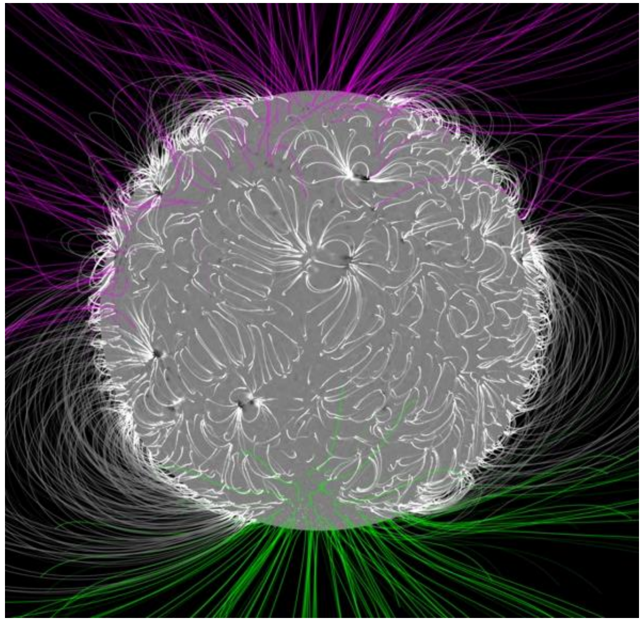
Hinode XRT

Ground-based Observations



Druckmüller, Fe XIV

Theory



PFSS Magnetic Field Model

All of these features are related, yet a one-to-one mapping between features has never been successful.

Coronal Holes are not NOT visible in: Photosphere (including magnetogram)
Chromosphere, e.g. H alpha, Ca II K,H,
EXCEPTION: He I 1083 nm (line formation sensitive to coronal radiation from above)

Slide courtesy M.S. Kirk

What are coronal holes ?

Observational answer: dark regions in solar coronal images.
- dark due to reduced temperature and density
    - reduced density due to magnetic field lines reaching far into the heliosphere ('open field lines')

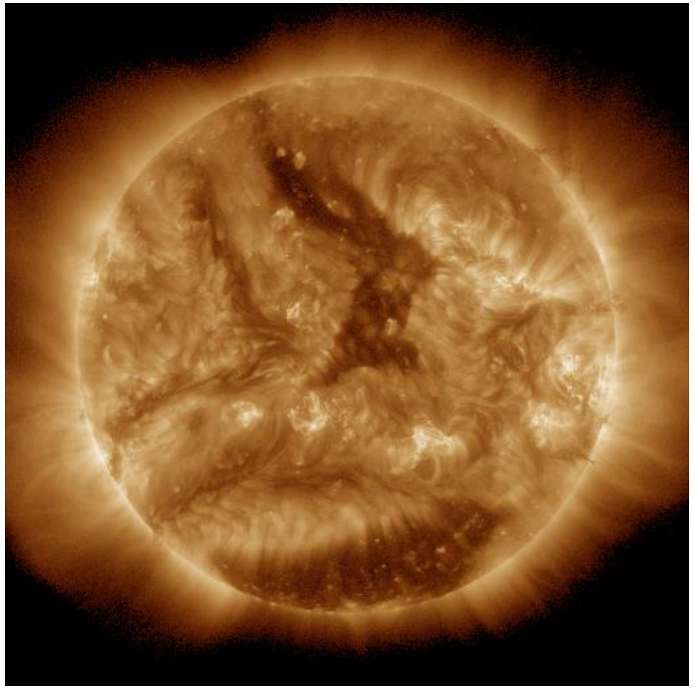
Modelling answer: in a coronal magnetic field extrapolation the CH boundary lies between the surface footpoints of open and closed field lines (where 'open' refers to a field line reaching higher than a certain height above the solar surface, e.g. Potential Field Source Surface Model, R_PFSS=2.5 R_sun)

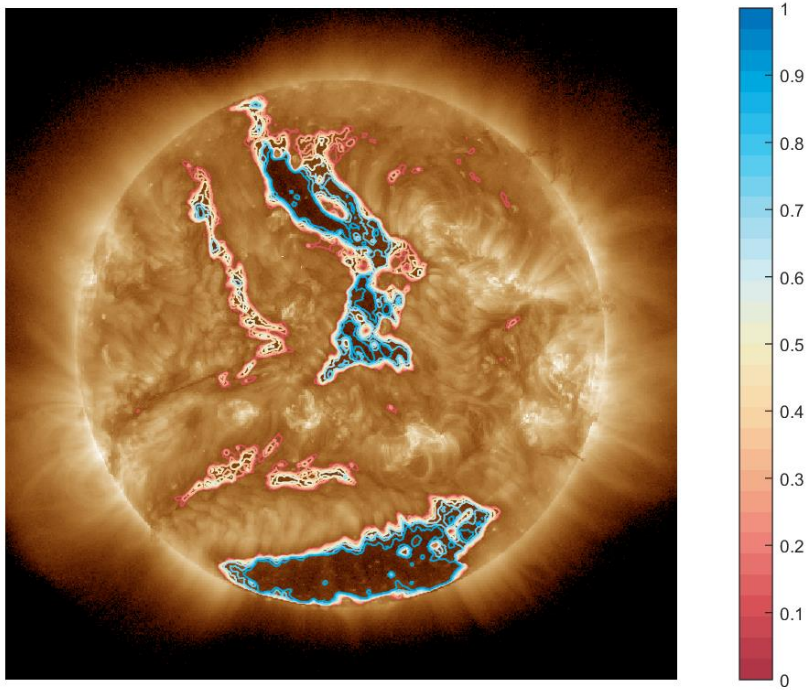
Note: Coronal magnetic field models use photospheric synoptic magnetic field maps to calculate the coronal field, → the CH boundaries from EUV images and from coronal models are different!

What are NOT coronal holes ?

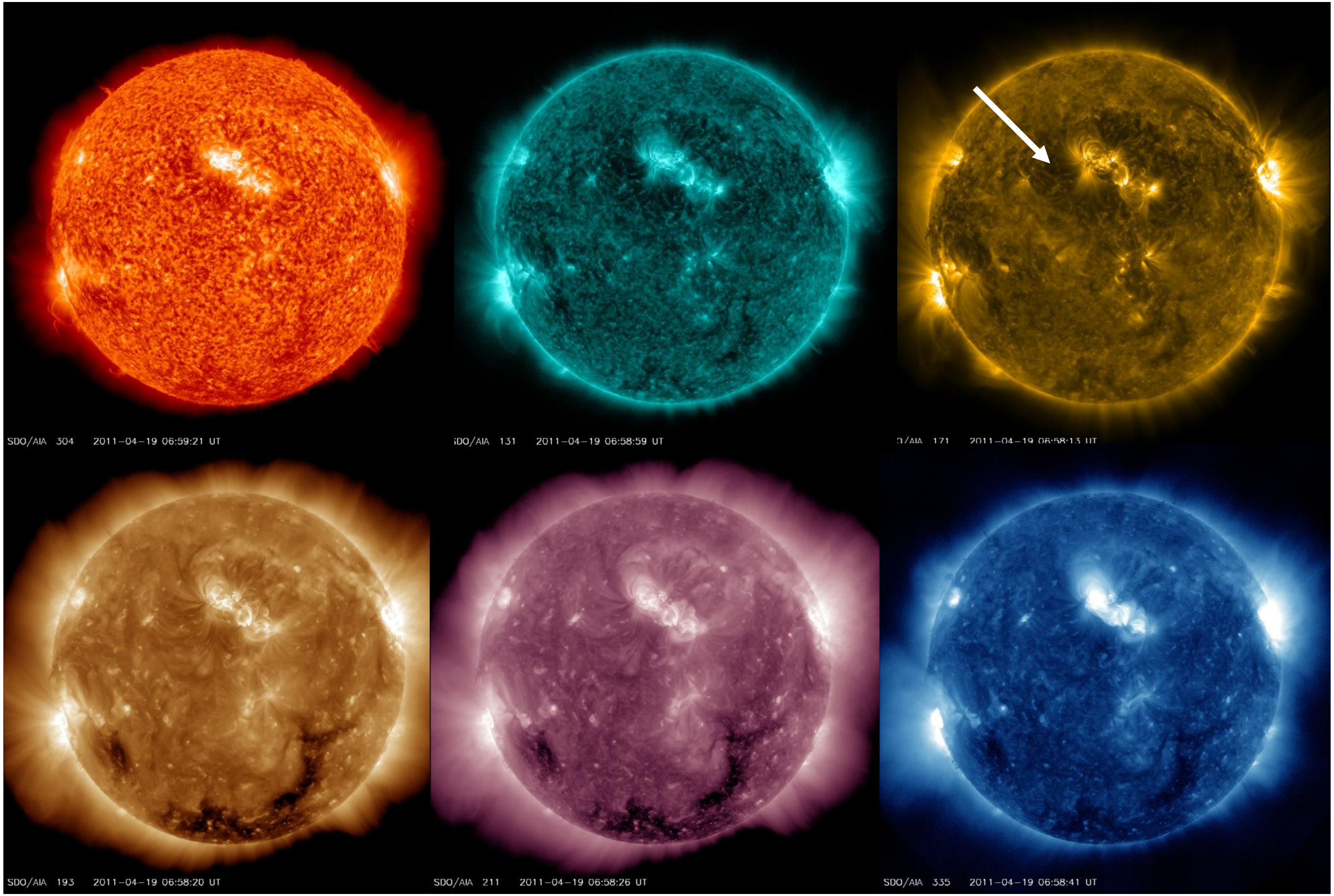
To identify coronal holes is not straightforward, there are many methods!

And there are pitfalls:





Solar Filaments are sometimes as dark as coronal holes – can be misidentified!
Filaments are closed field structures!



Active Region Canopies, dark regions around active regions, seen in cool AIA channels (below 1.5MK)
(for more information see: Wang, Robbrecht, Muglach, ApJ, 2011)

In-situ Solar Wind

Range of speed of the ambient solar wind: 300 - 800 km/s

Slow solar wind: 300 - 400 km/s
Fast solar wind: 600 - 800 km/s (‘high speed stream’, HSS)

400 - 600 km/s – fast or slow?

Solar origin of solar wind:
Fast: coronal holes, deep in CH
Slow: also coronal holes, but boundary of CH

Why study coronal holes and coronal hole boundaries?

Large CHs and their HSSs have space weather impact at Earth:
Geomagnetic storms and increase of electron density in the radiation belts (can lead to spacecraft anomalies), HSS can change CME propagation

CH boundaries are used in semi-empirical solar wind models (e.g. WSA)

Identify the source of the slow solar wind

Note: CH boundaries can not be validated as we do not know the ground truth!
Solar wind models can be validated via in-situ solar wind measurements.

Assessment of Solar Coronal Hole Boundary Locations By Comparing Different Coronal Hole Detection Methods

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K. Muglach (NASA/GSFC, CUA)
M.A. Reiss (NASA/GSFC, CCMC)

and Coronal Hole Boundary Working Team

Context:

This activity is part of the COSPAR initiative:

International Space Weather Action Teams (ISWAT)

which is a global hub for collaborations addressing challenges across the field of space weather

https://iswat-cospar.org/

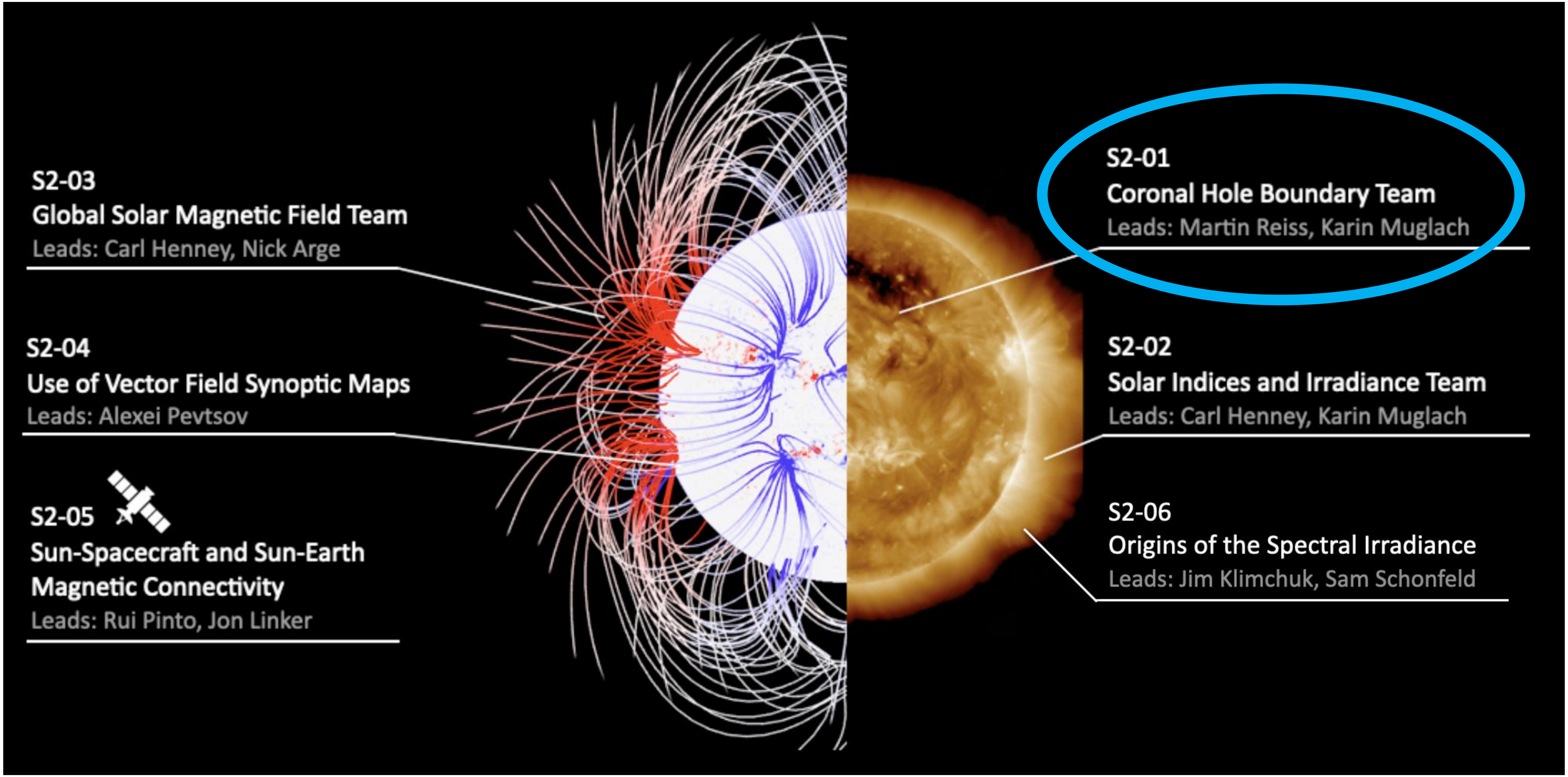
ISWAT overview:

S: Space weather origins at the Sun	H: Heliosphere variability	G: Coupled geospace system	Impacts
S1: Long-term solar variability	H1: Heliospheric magnetic field and solar wind	G1: Geomagnetic environment	Climate
S2: Ambient solar magnetic field, heating and spectral irradiance	H2: CME structure, evolution and propagation through heliosphere	G2a: Atmosphere variability	Electric power systems/GICs
S3: Solar eruptions	H3: Radiation environment in heliosphere	G2b: Ionosphere variability	Satellite/debris drag
	H4: Space weather at other planets/planetary bodies	G3: Near-Earth radiation and plasma environment	Navigation/ Communications
			(Aero)space assets functions
			Human Exploration

Overarching Activities:

- Assessment
- Innovative Solutions
- Information Architecture & Data Utilization
- Education & Outreach

ISWAT S2 overview:



Participants:

Team leads:

M. A. Reiss NASA/GSFC/CCMC, Greenbelt, MD USA
K. Muglach, NASA/GSFC, Greenbelt, MD, USA

Aug. 2019: 6 participants, from 2 institutions
Jan. 2021: 22 participants, from 12 institutions
Jun. 2021: 31 participants from 17 institutions

update: Jun. 2024: 48 participants from 28 institutions

General objectives of project:

- Study and compare different automated coronal hole detection methods provided by the space weather community
- Develop strategies to quantitatively assess the spatial and temporal uncertainty of coronal hole boundary locations
- Use this information to further improve the predictive capabilities of ambient solar wind models.

↓

close collaboration with ISWAT H1-01:

Ambient Solar Wind Validation Working Team

Specific objectives of project:

- Study and compare different automated coronal hole detection methods provided by the space weather community
- Evaluate CH boundaries derived from these methods:

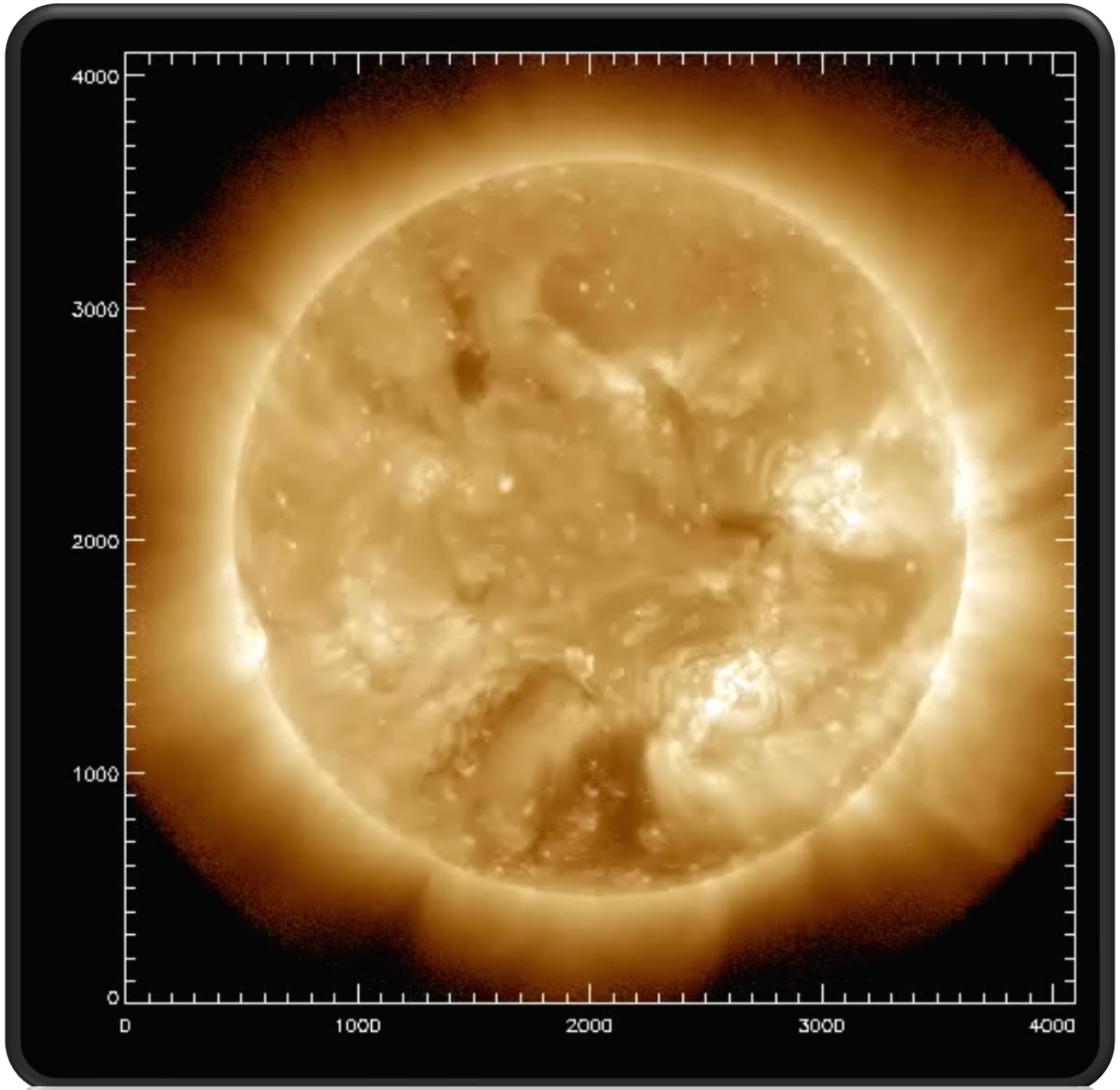
  - compare location of boundary (gives observed uncertainties of CH boundaries)

  - compare parameters derived from these boundaries:

    e.g. average coronal intensity inside the CH, average photospheric signed magnetic flux in CH, average unsigned flux in CH

Data to be used:

SDO/AIA and SDO/HMI



29 full disk images were selected (2014-2019)

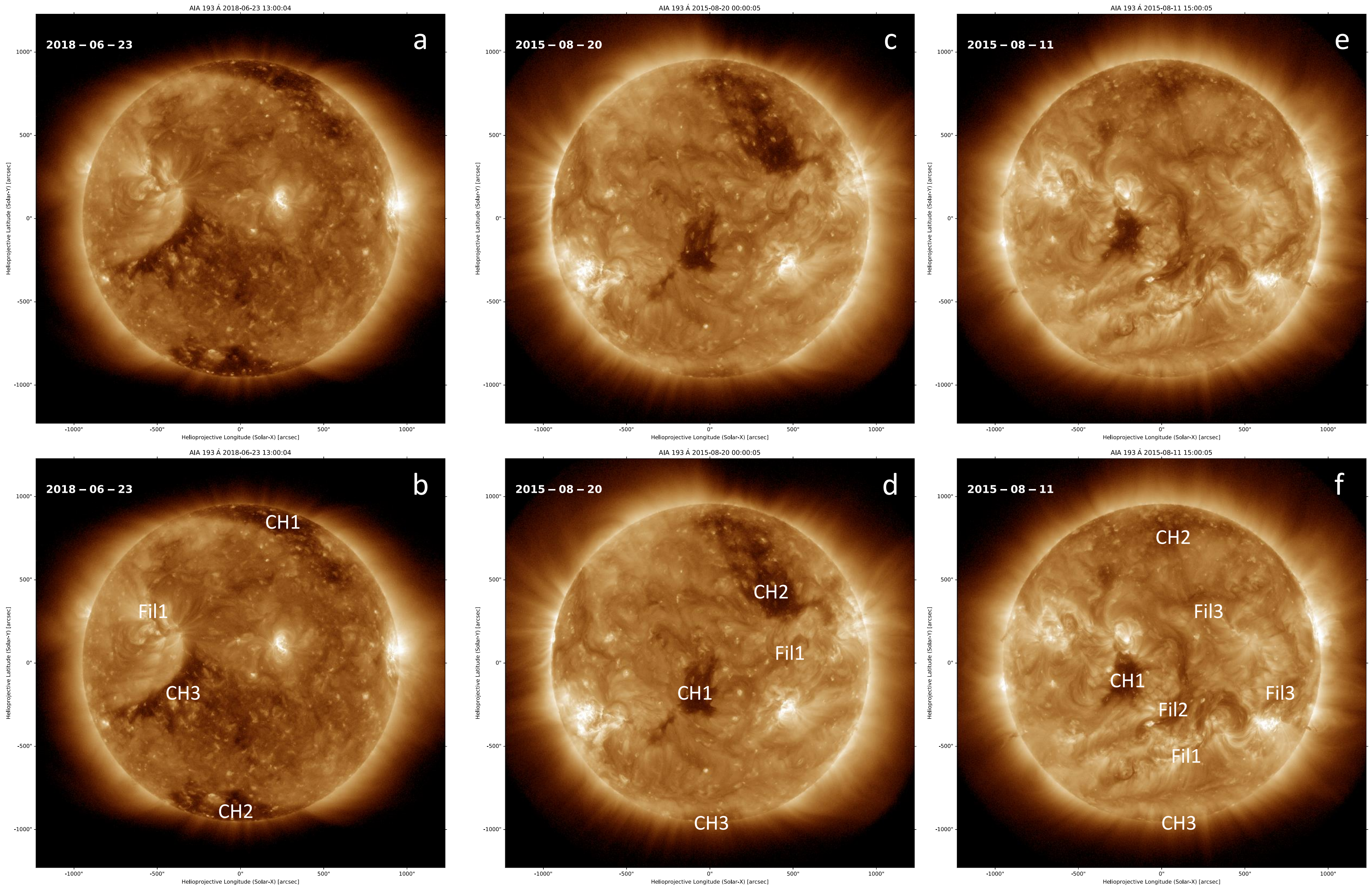
all AIA EUV channels and HMI LOS magnetograms can be used

AIA 193 A shown here as example

Participating methods:

ACWE	New Mexico State University	Boucheron et al. (2016)
CATCH	University of Graz	Heinemann et al. (2019)
CHARM	University of Colorado	Krista & Gallagher (2009)
CHIMERA	Trinity College Dublin	Garton et al. (2018)
CHIPS	Virginia Tech	Reiss et al. (2023)
CHMAP	Predictive Science Inc.	Caplan et al.2016)
CHORTLE	Southwest Research Institute	Lowder et al. (2014)
CHRONNOS	University of Graz	Jarolim et al. (2021)
CNN193	Moscow State University	Illarionov & Tlatov (2018)
SPoCA	Royal Observatory of Belgium	Delouille et al. (2018)
SPoCA-HEK	Royal Observatory of Belgium	Verbeeck et al. (2014)
SYNCH	University of Oulu	Hamada et al. (2018)
WWWBCS	University of Warwick	Reiss et al. (2023)
TH35		

Uncertainties in Coronal Hole Boundaries



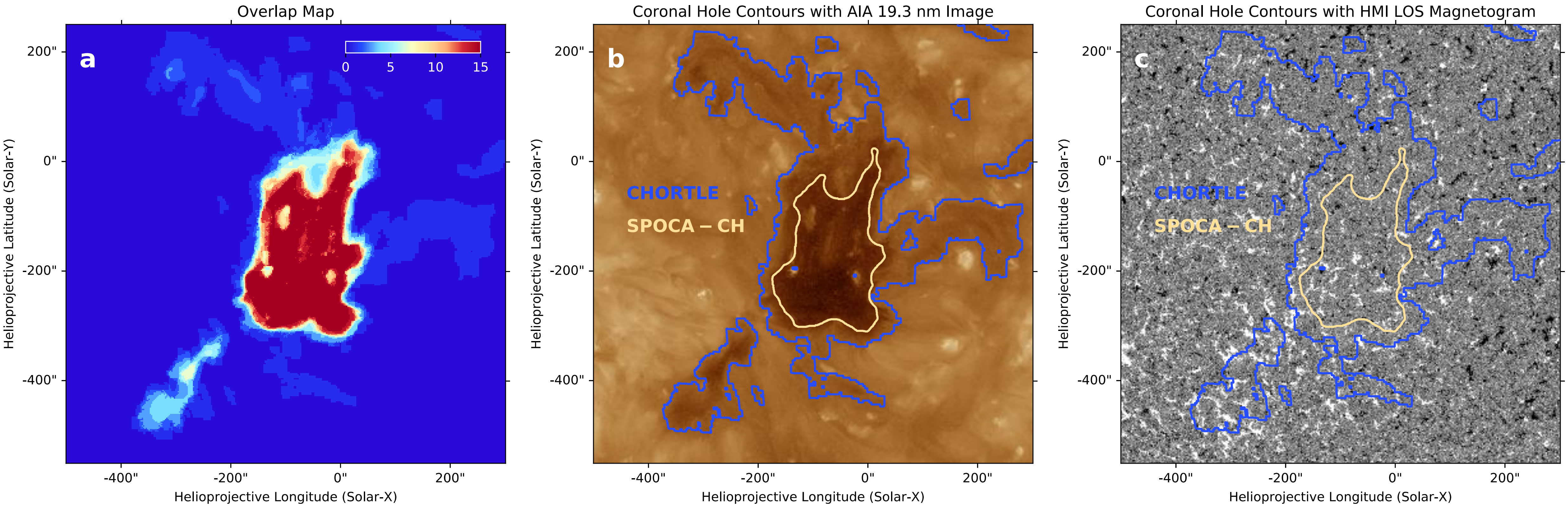
3 examples:

top row:

AIA 193A

bottom row:

manually annotated labels for coronal holes and filaments



Comparison of 15 methods with contour overlays (2015-08-20):

a) Probability map, b) largest and smallest contour on AIA 193 A, c) largest and smallest contour on HMI magnetogram

Reasonable agreement of CH boundary

Uncertainties in Coronal Hole Boundaries

Final result: comparison of 15 methods, CH parameters and min/max ratio (2015-08-20):

a) CH area (4.21)

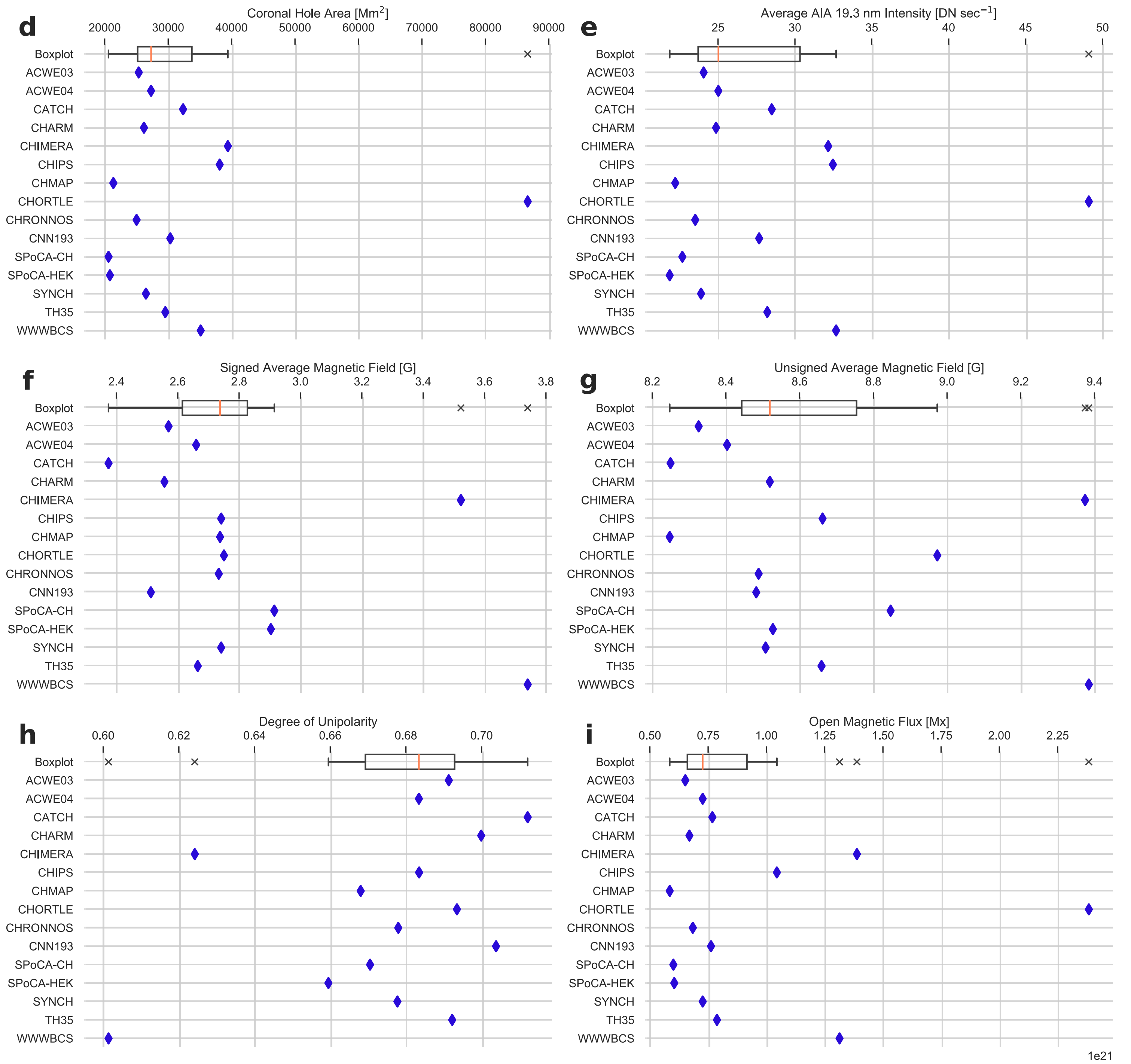
b) AIA 193 av. Brightness (2.25)

c) av. signed magnetic flux (1.58)

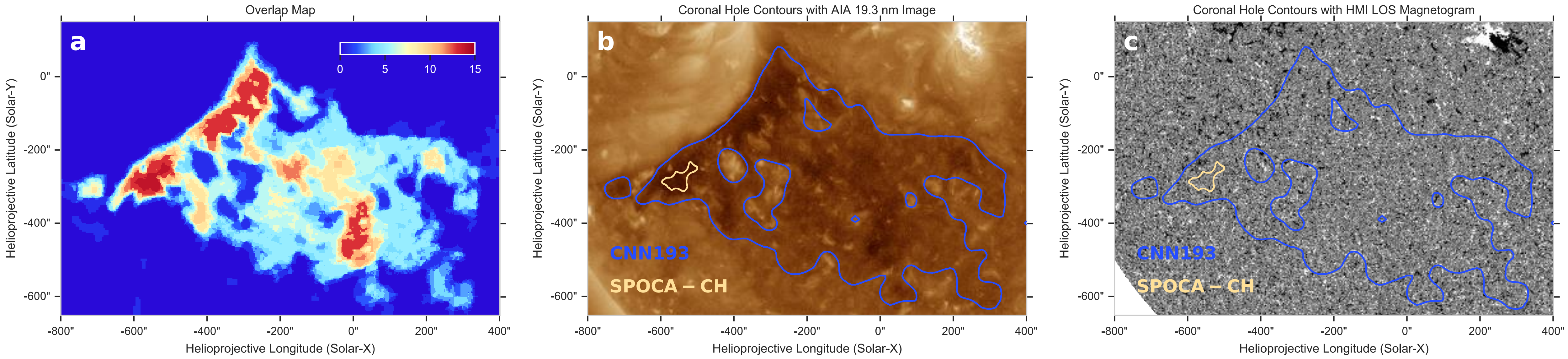
d) av. unsigned magn. Flux (1.14)

e) Unipolarity (1.18)

f) open flux estimate (4.08)



Coronal Hole Boundaries: Results from a Community wide Assessment Project



Comparison of 15 methods with contour overlays (2018-06-23):

a) Probability map, b) largest and smallest contour on AIA 193 A, c) largest and smallest contour on HMI magnetogram

Considerable disagreement of CH boundary!

(CH caused HSS and enhanced geomagnetic activity (Kp(max)=5)

Coronal Hole Boundaries: Results from a Community wide Assessment Project

Final result: comparison of 15 methods CH parameters and min/max ratio (2018-06-23):

a) CH area (107.16)

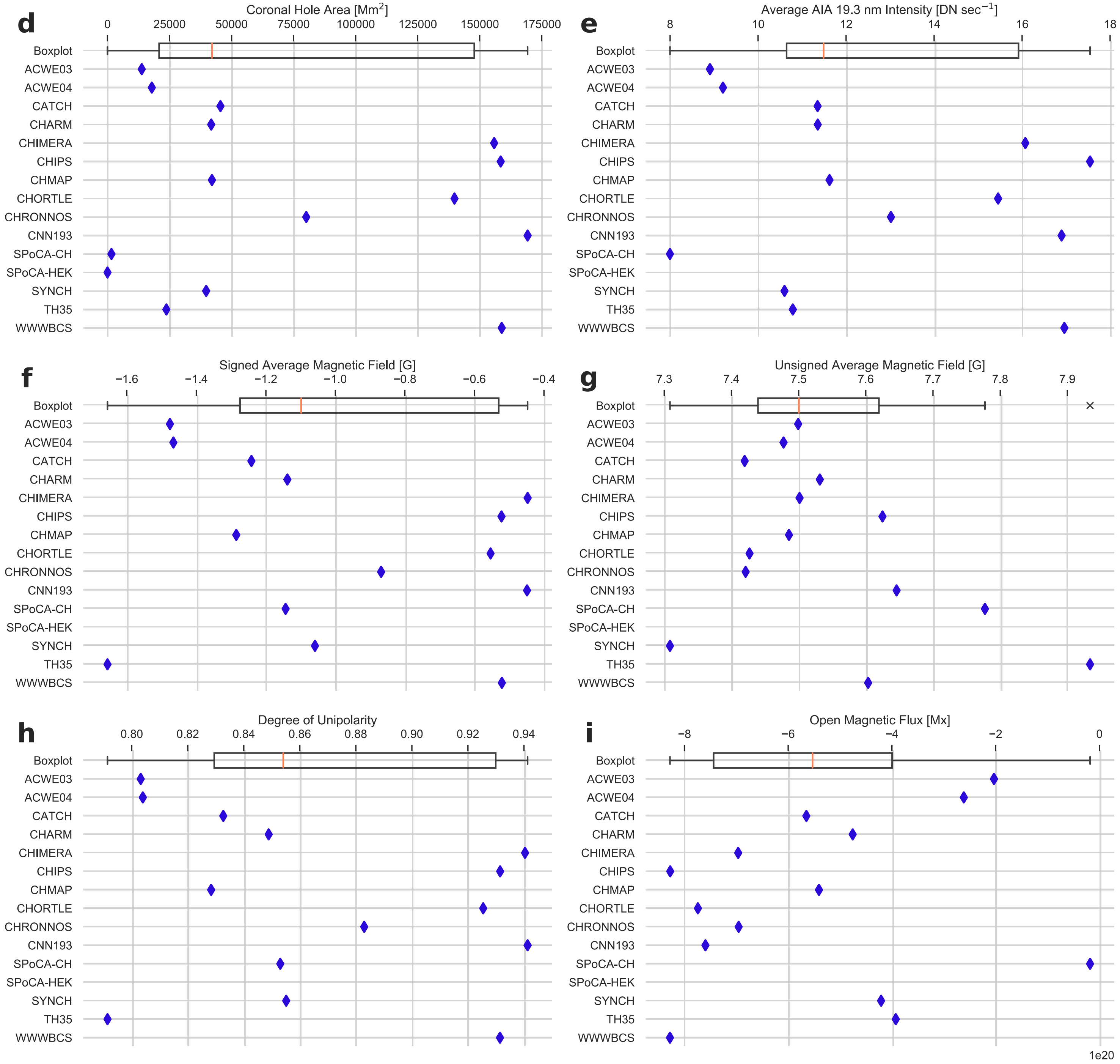
b) AIA 193 av. intensity (2.19)

c) av. signed magnetic flux (0.27)

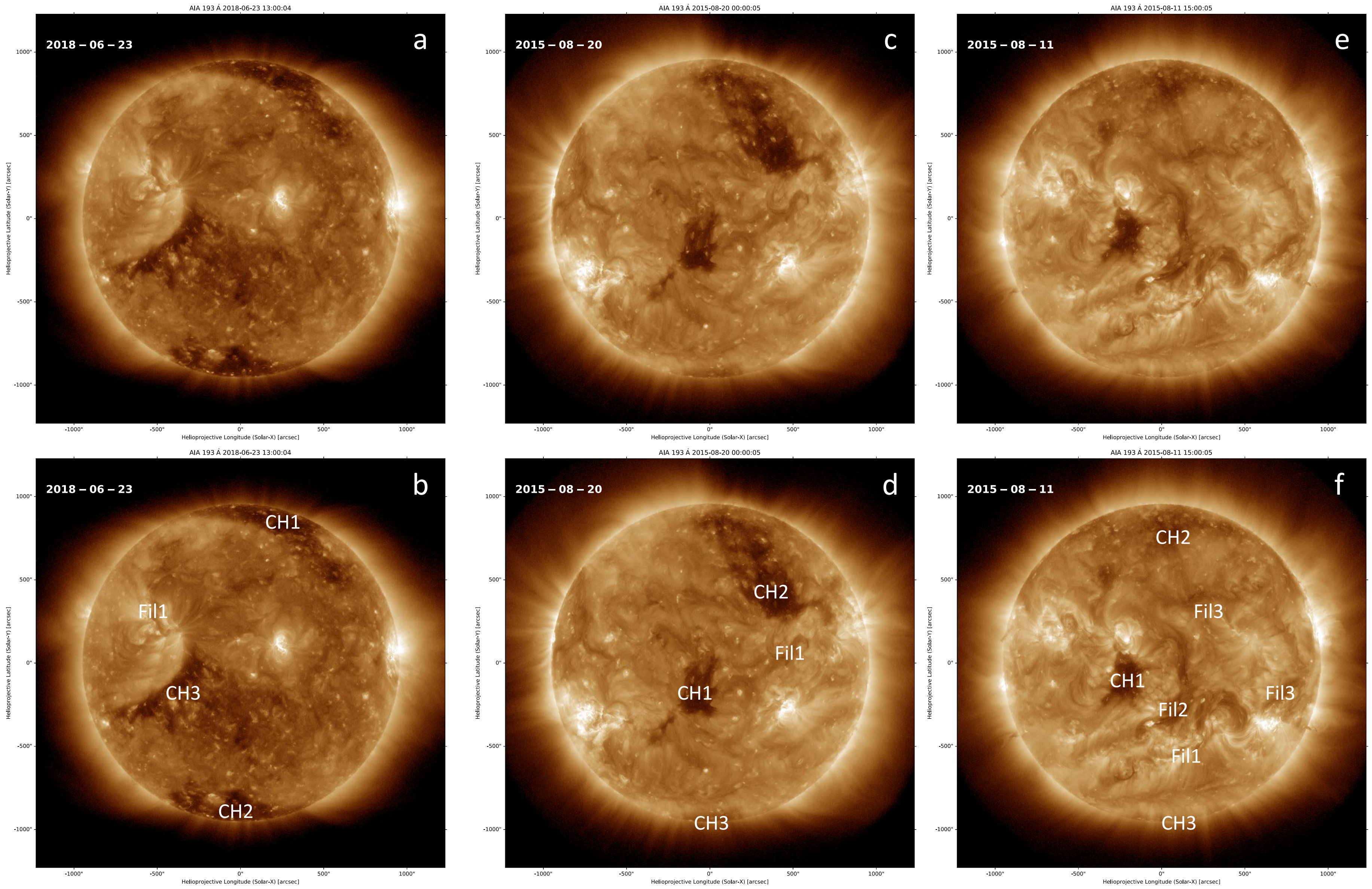
d) av. unsigned magn. flux (1.09)

e) unipolarity (1.19)

f) open flux estimate (0.02)



Uncertainties in Coronal Hole Boundaries



Identification statistics:

86 CHs, 71 filaments

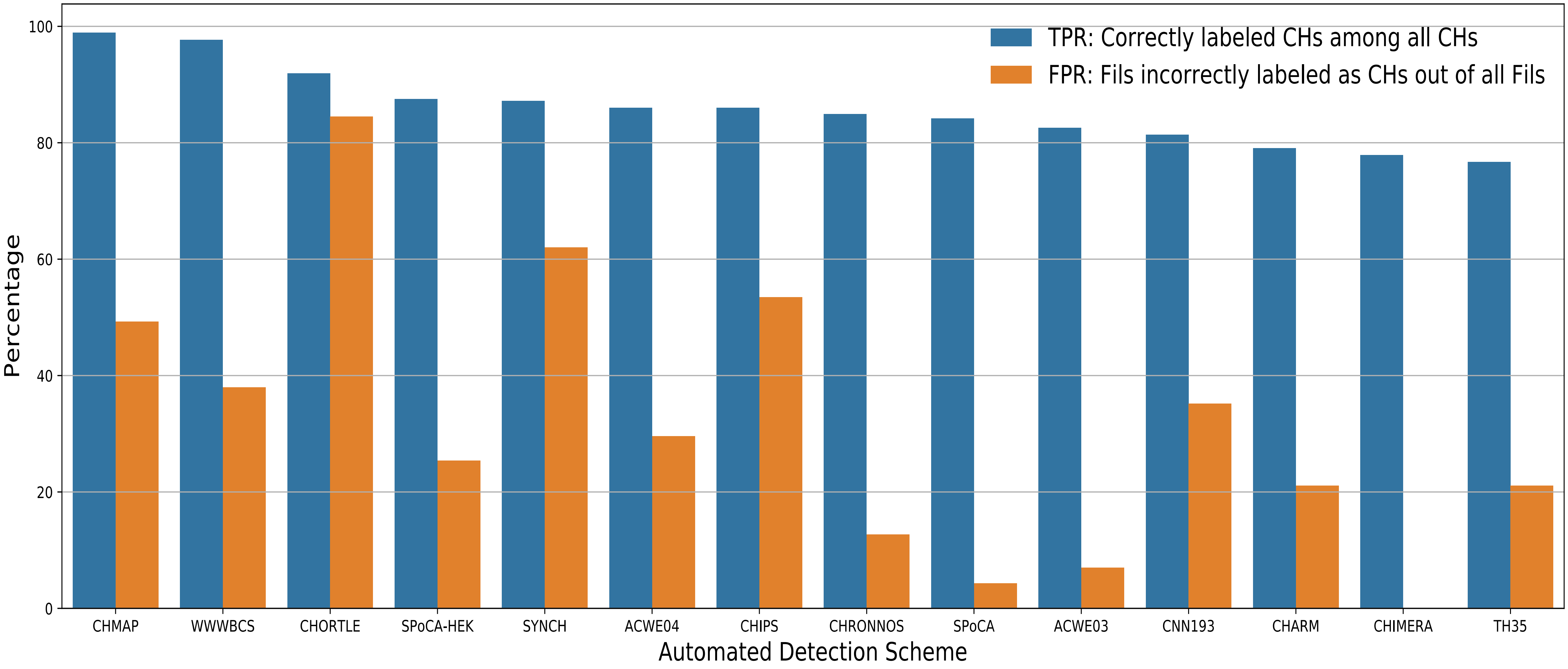
True positive TP (id CH)

False Positives FP (id Fil)

True Negatives TN (not id Fil)

False Negatives FN (not id CH)

Uncertainties in Coronal Hole Boundaries



First results published: Reiss, Muglach et al. 2021, ApJ 913, #28

Follow-up paper: Reiss, Muglach et al. 2024, ApJL, 271:6

Community benchmark data set is publicly available!

AIA and HMI images, ID masks, labelled images, complete identification statistics

Intended as comparison data set for future CH detection schemes!

Want to join the ISWAT team?

https://iswat-cospar.org/S2-01

Other Activities of the S201 Team

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Additional Team Activity:

Additional focus CH studies:

Forming smaller sub teams, any CH research topic possible

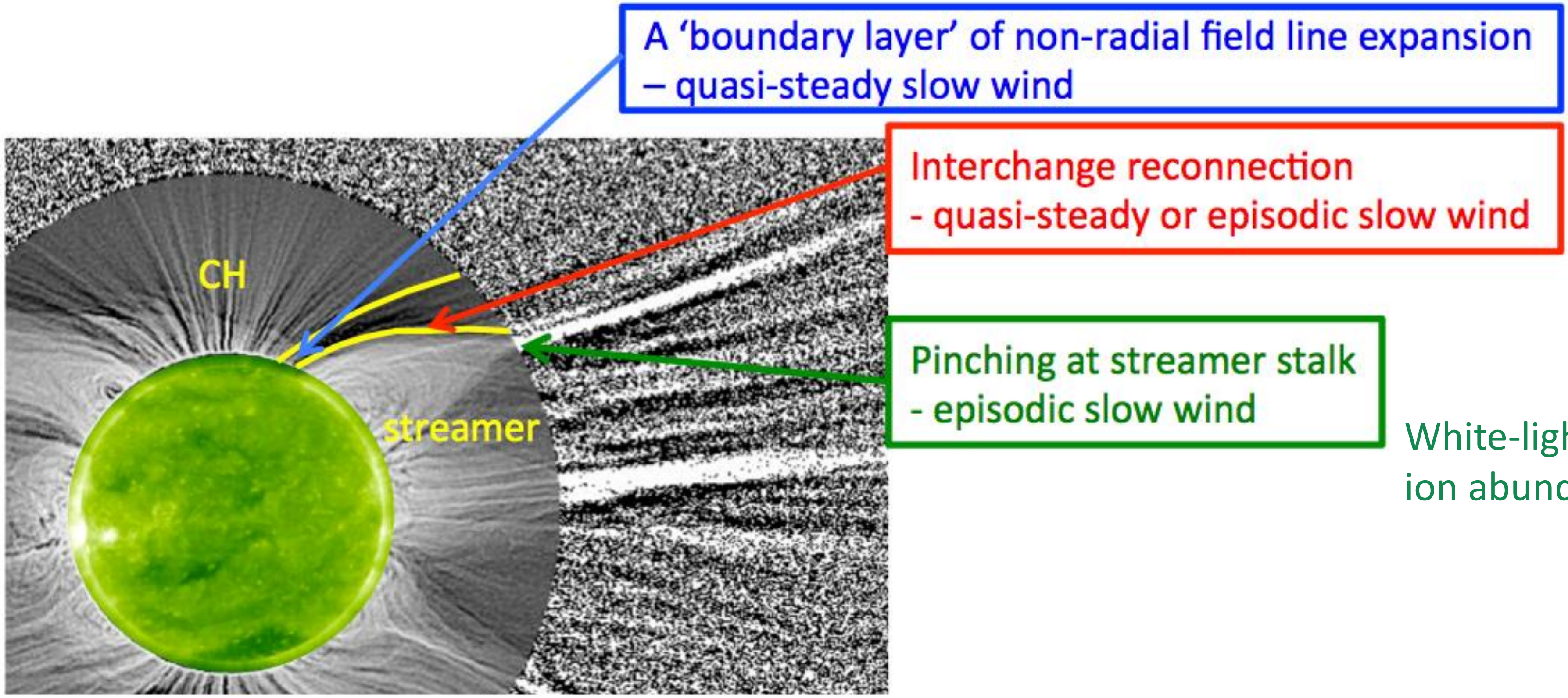
- Physics of CH Boundaries: Y.-K. Ko (NRL), K. Muglach (GSFC)
- How Streamers and Other Structures Affect CH Boundaries: E. Mason (GSFC)
  Paper published: Mason, E., Uritsky, V.M., 2022, ApJL, 937, L19, doi:10.3847/2041-8213/ac9124
- Automated CH Detection Schemes: S. Chakraborty (Virginia Tech)
- Interaction of MHD Waves with CH Boundaries: I. Piantschitsch
  new action team S2-07 (Propagating coronal waves and magnetic field interaction)

CH Boundary Identification in association with the slow solar wind formation

Yuan-Kuen Ko, Karin Muglach, Pete Riley, Yi-Ming Wang

Supported by the NASA HGI Program

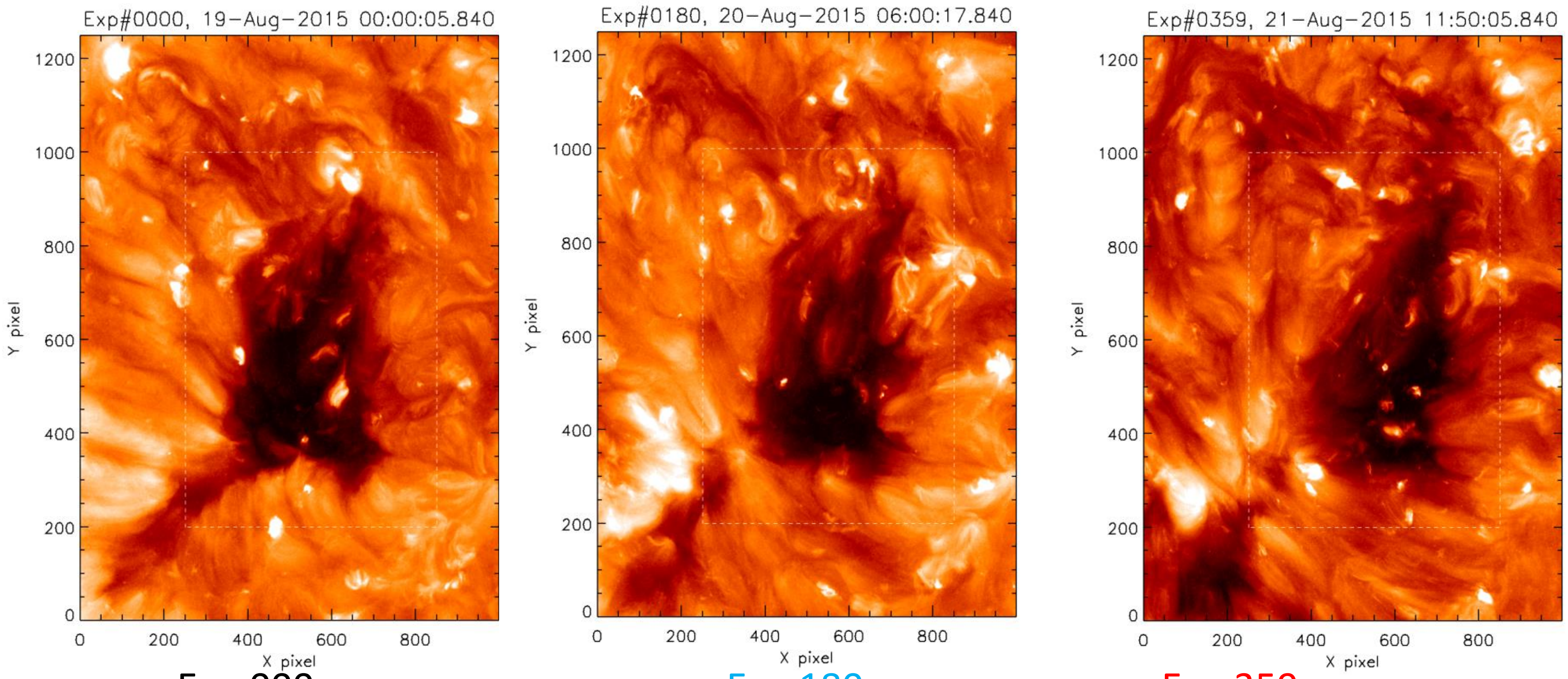
Coronal Boundary is the source region of the slow solar wind
Three scenarios



Larger low coronal heating and density with diverging field, low FIP bias

Enhanced heating and density, source of white-light blobs, high FIP bias, folded IMF (associated with “switchbacks”?)

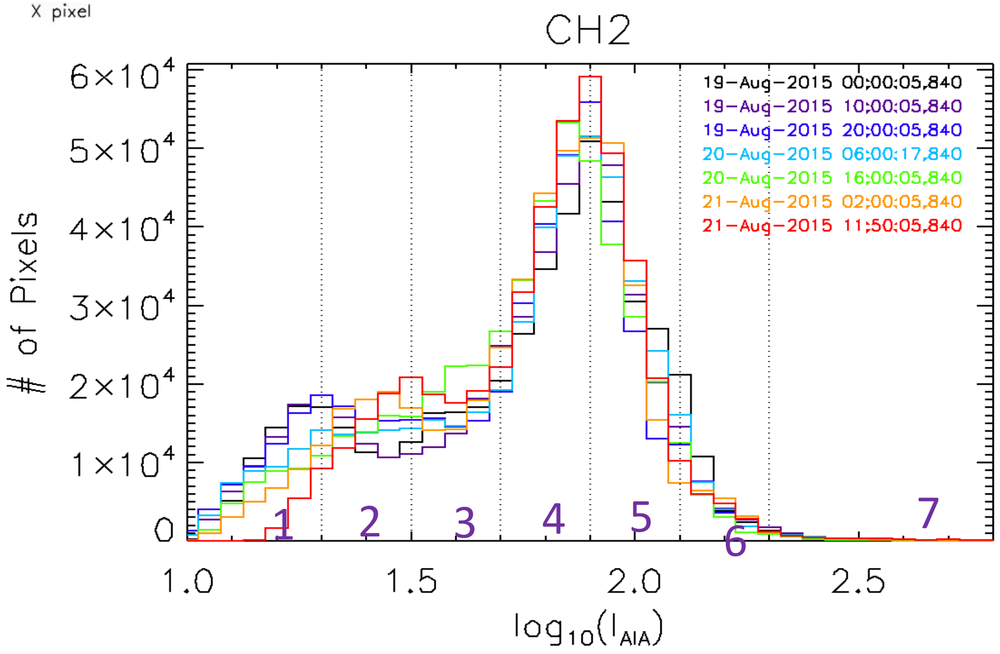
White-light blobs, depleted heavy ion abundance, small flux ropes

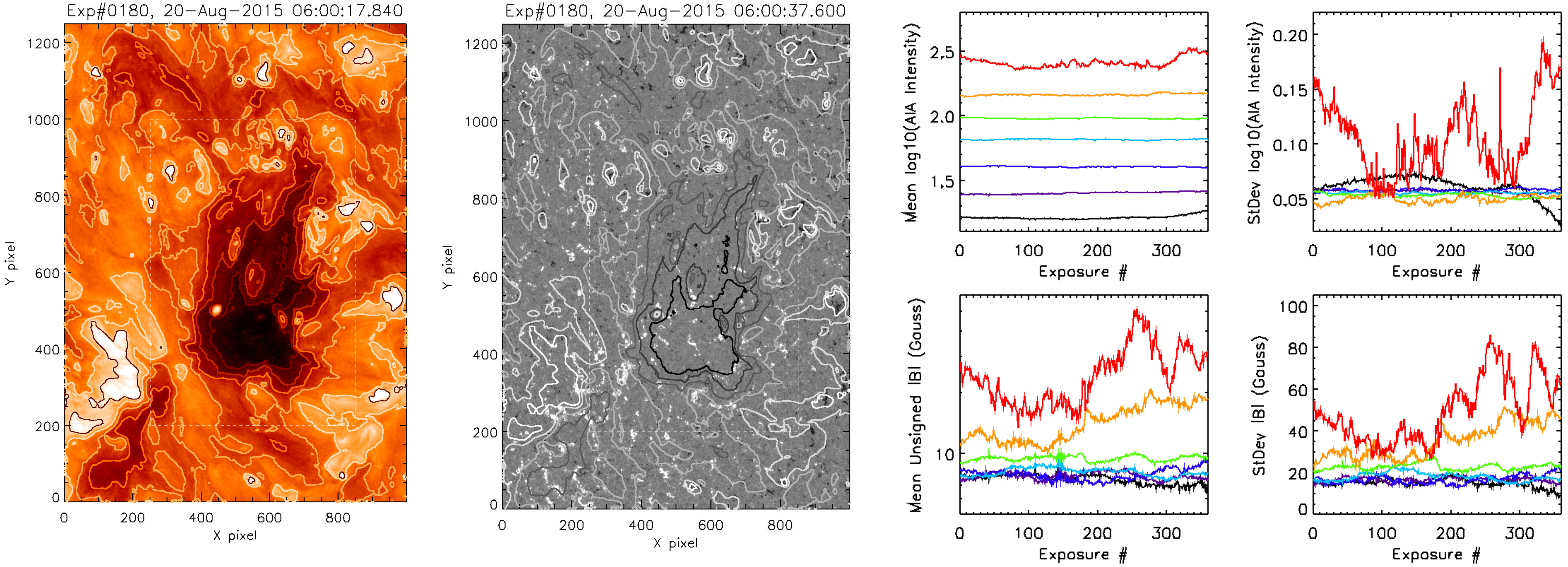


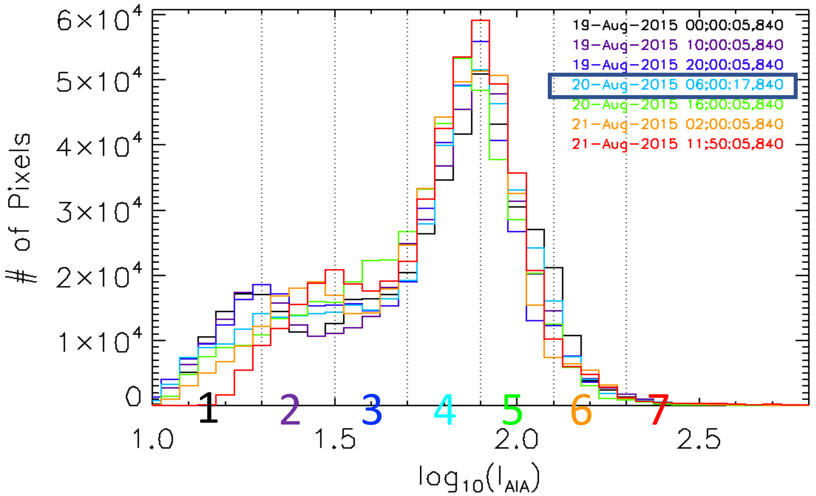
Exp.000 Exp.180 Exp.359

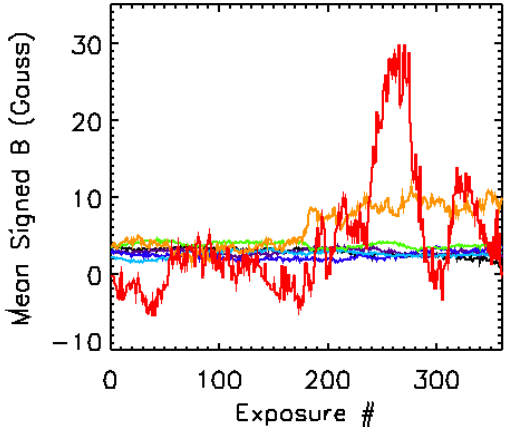
Equatorial CH on disk center on 2015 Aug.20

- Concurrent AIA 193 images and HMI magnetograms were selected every 10 minutes from 19-Aug-2015 00:00:05 UT to 21-Aug-2015 11:50:05 UT when this CH past the central meridian (360 images total)
- Subfield in each image maps with the solar rotation
- AIA 193 intensity distributions do not change significantly during this 2.5 days period.
- 7 intensity intervals were selected to obtain the mean coronal emission intensity and photospheric magnetic field properties in each intensity level within the selected box in each image







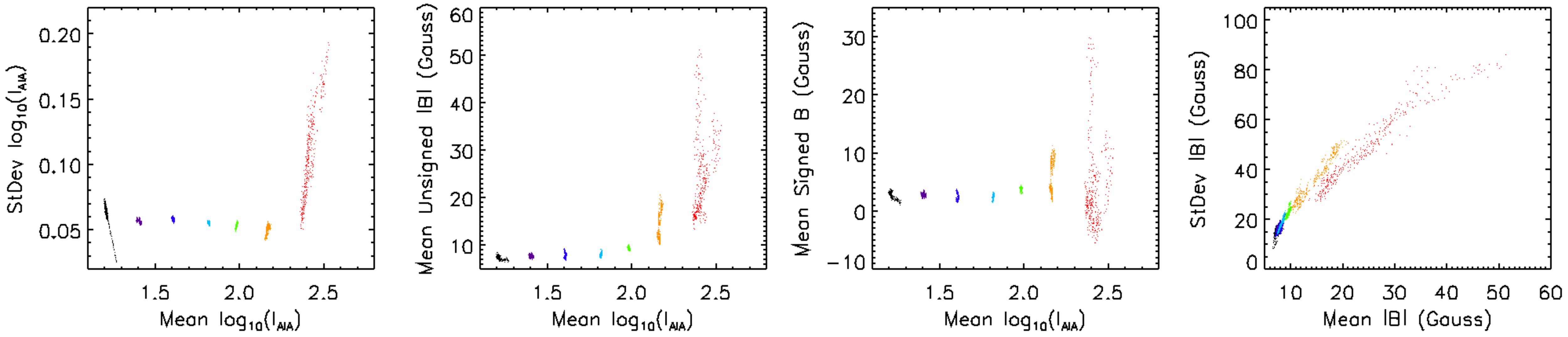


The intensity fluctuation in the two highest AIA 193 intensity levels (red and orange curves) are distinct from the lower intensity ones

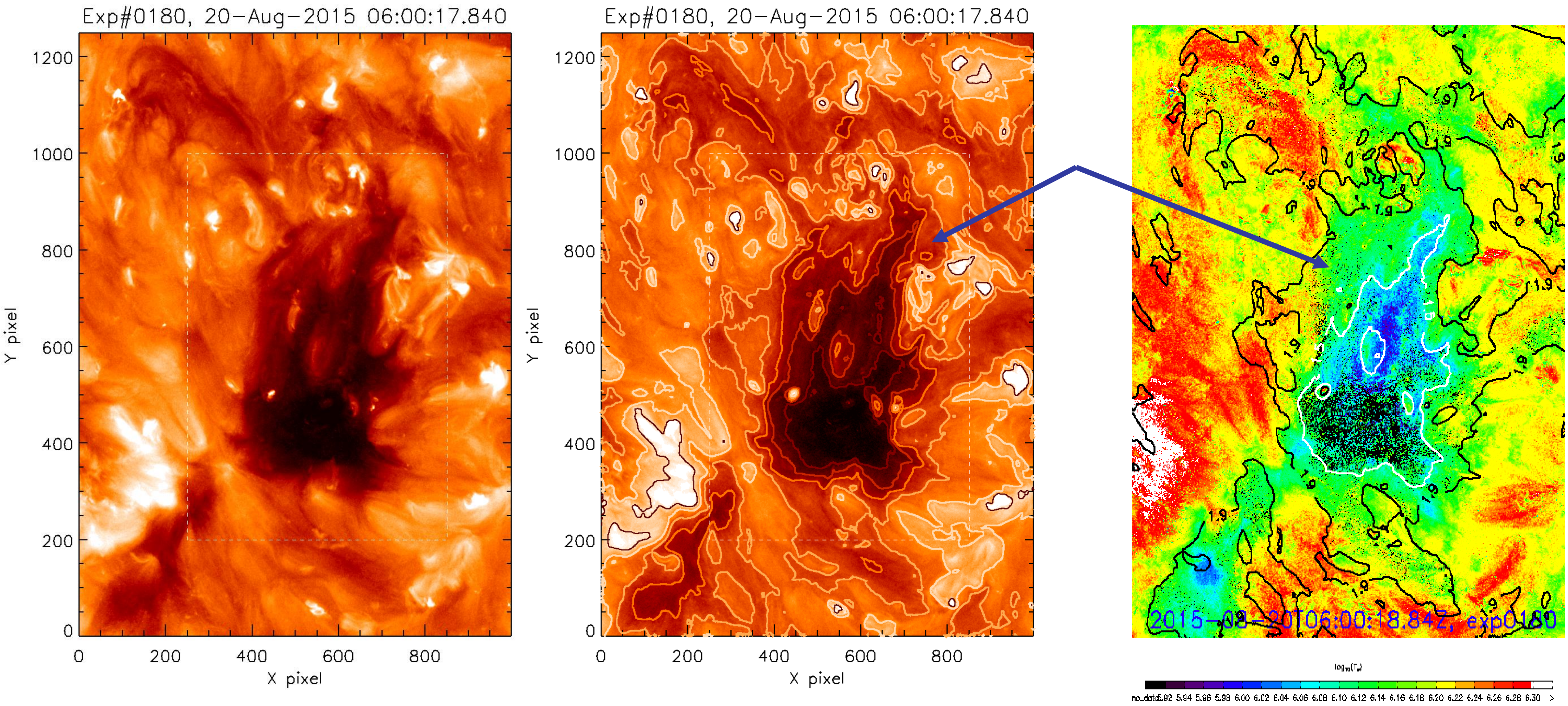
Correlation between coronal emission and magnetic field properties

- The range of variation of both the EUV intensity and photospheric magnetic field strength in the two highest AIA 193 intensity levels is distinct from that in the lower intensity ones

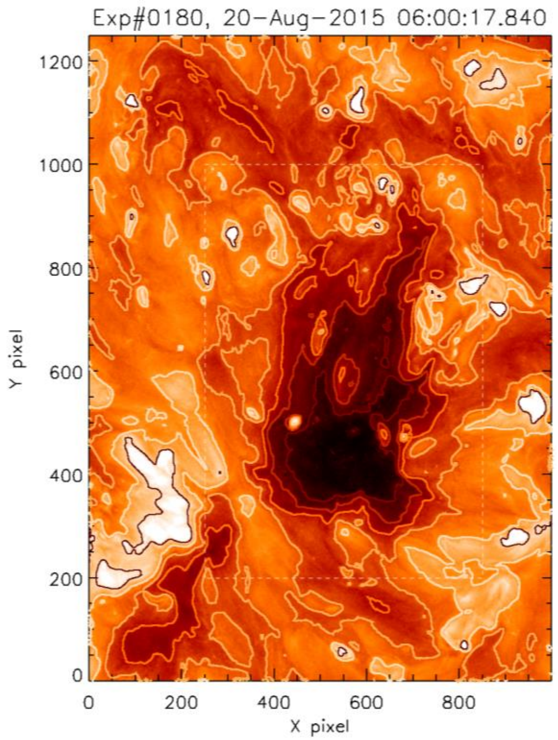
- Fluctuation in δB positively correlates with $|B|$

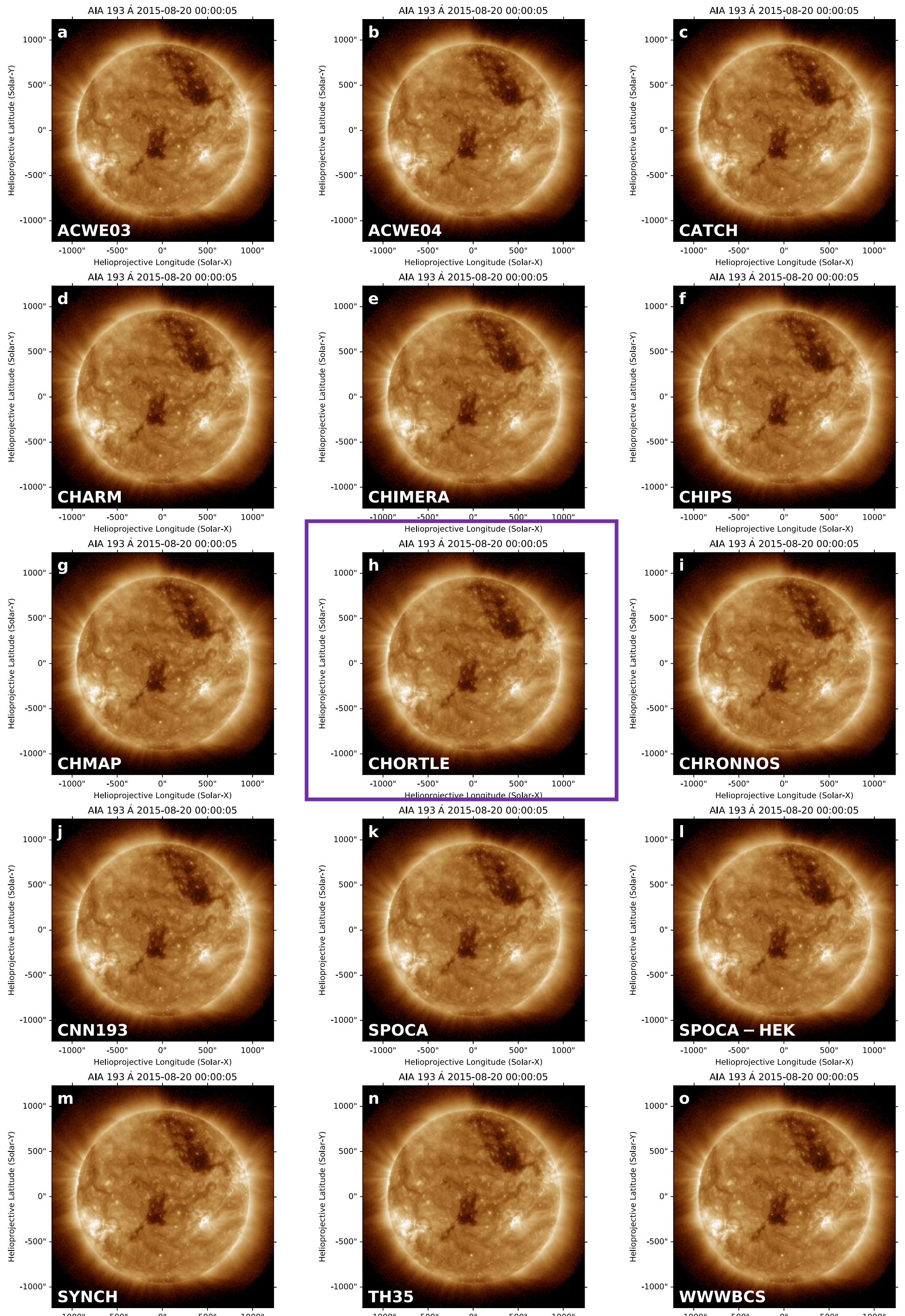


The spatial distribution of the "effective electron temperature" (right panel) from the differential emission measure (DEM) calculated with the 6 AIA EUV channels (Cheung et al. 2015) also indicates that the CH boundary is likely around the 5th intensity level, NOT at the 'dip' (between level 2 and 3) as often used in the threshold CHB identification scheme.



Compare with other CH Boundary Detection Schemes (Reiss et al. 2024)





Main Findings

This study indicates that the CH/open field area is significantly larger than the visually dark area in the EUV/X-ray images. The bold implications are:

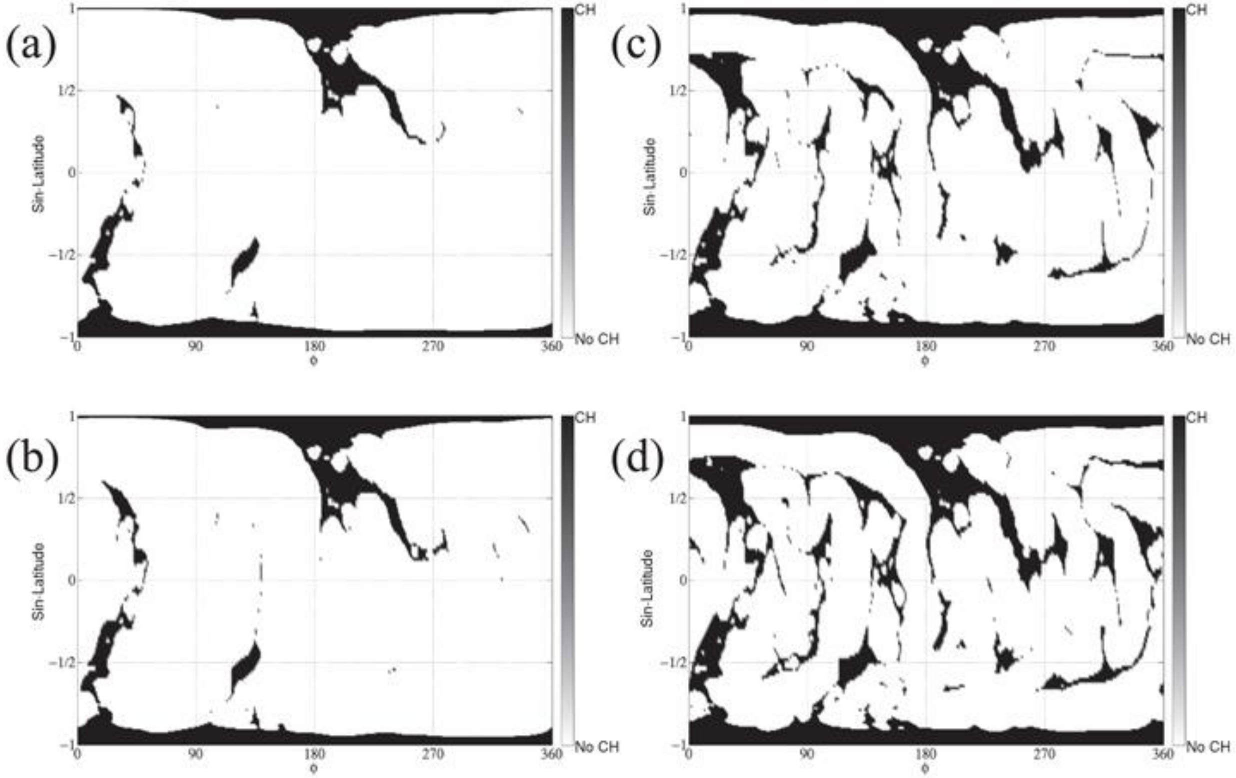
- The “quasi-steady” slow solar wind would emerge from a large area in between the ‘dark center’ of the CH and the ‘bright quiet Sun/active region loops’. Diverging field lines in this area play a role in setting the slow solar wind properties.

- The “open field problem” could be explained.

Linker et al. (2017) found that, in order to match the IMF field (1.7-2.2 nT) , the location of the source surface for the PFSS model needs to be much lower. Correspondingly, the CH area is larger.

Rss=2.5 Ro
Open flux = 0.79 nT

Rss=1.4 Ro
Open flux = 1.60 nT



Rss=2.0 Ro
Open flux = 0.92 nT

Rss=1.3 Ro
Open flux = 1.91 nT