Mapping the Sun's Alfvén surface (very soon!) with PUNCH

Steven R. Cranmer, Trestan F. Simon,
Rohit Chhiber, & Chris R. Gilly

Colleagues, students, & co-conspirators: D. Mendoza, G. Strus, K. Kenny, S. Van Kooten, M. Molnar, M. P. Miralles, C. Lopez-Portela, A. Lattimer, A. Schiff, C. DeForest, S. Gibson, R. Morton, M. Shoda, & A. van Ballegooijen
Image credit: M. Druckmüller

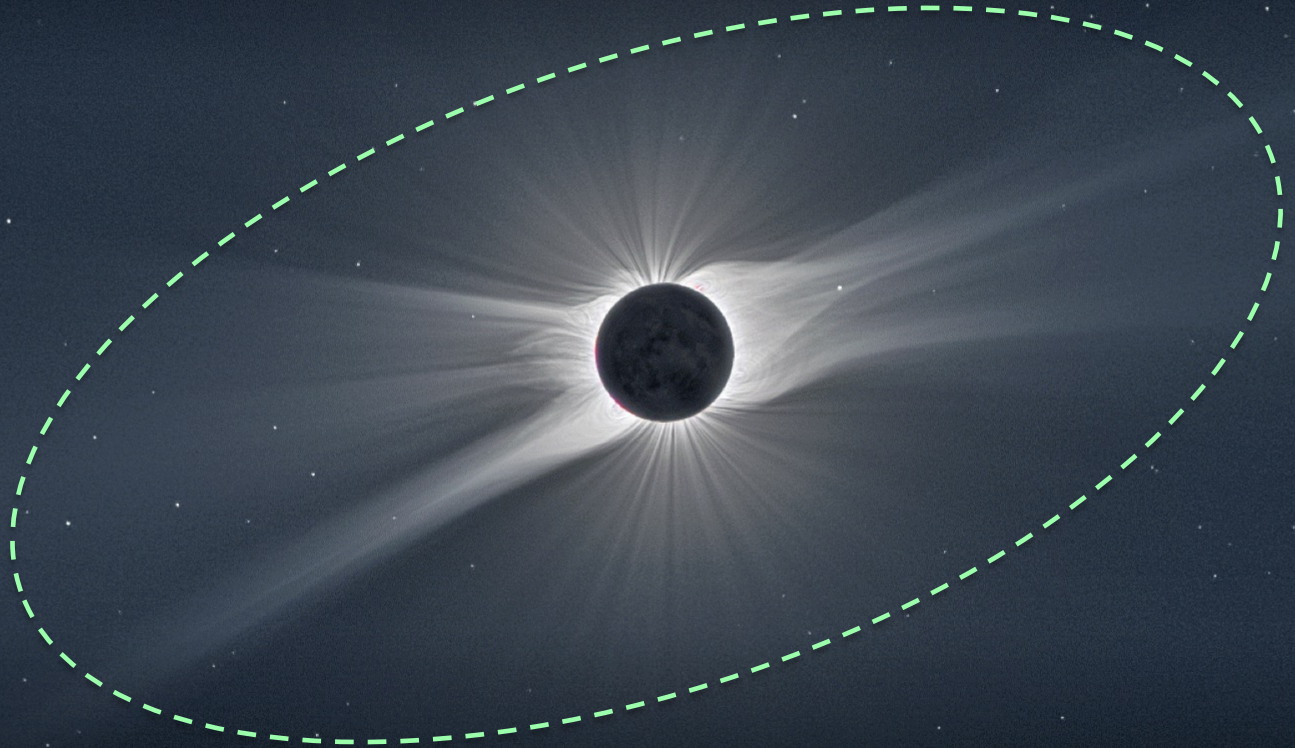
Mapping the Sun's Alfvén surface (very soon!) with PUNCH

PUNCH Working Group 1C: "What are the evolving physical properties of the Alfvén surface?"

Talk Outline:

1. What is it, *where* is it, and what's going on there?
2. How will PUNCH help improve our understanding?
3. Preliminary look at a cool forward-modeling tool...

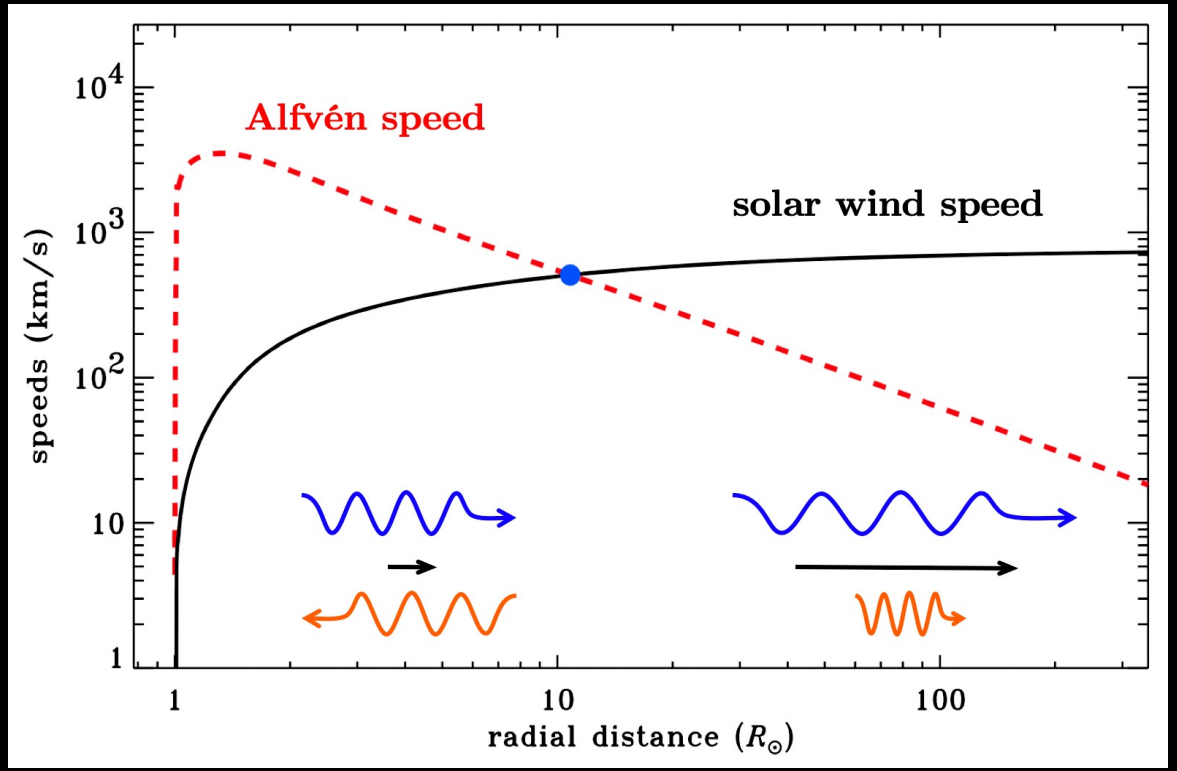
Is there a boundary between the corona and the solar wind?



Is there a boundary between the corona and the solar wind?

- The Alfvén surface (or Alfvén radius, or Alfvén zone) is a useful place to draw this distinction.

- Below r_A, information (waves) can propagate both in & out. Above r_A, the solar wind drags out both inward & outward modes, and information doesn't propagate back down to the Sun.



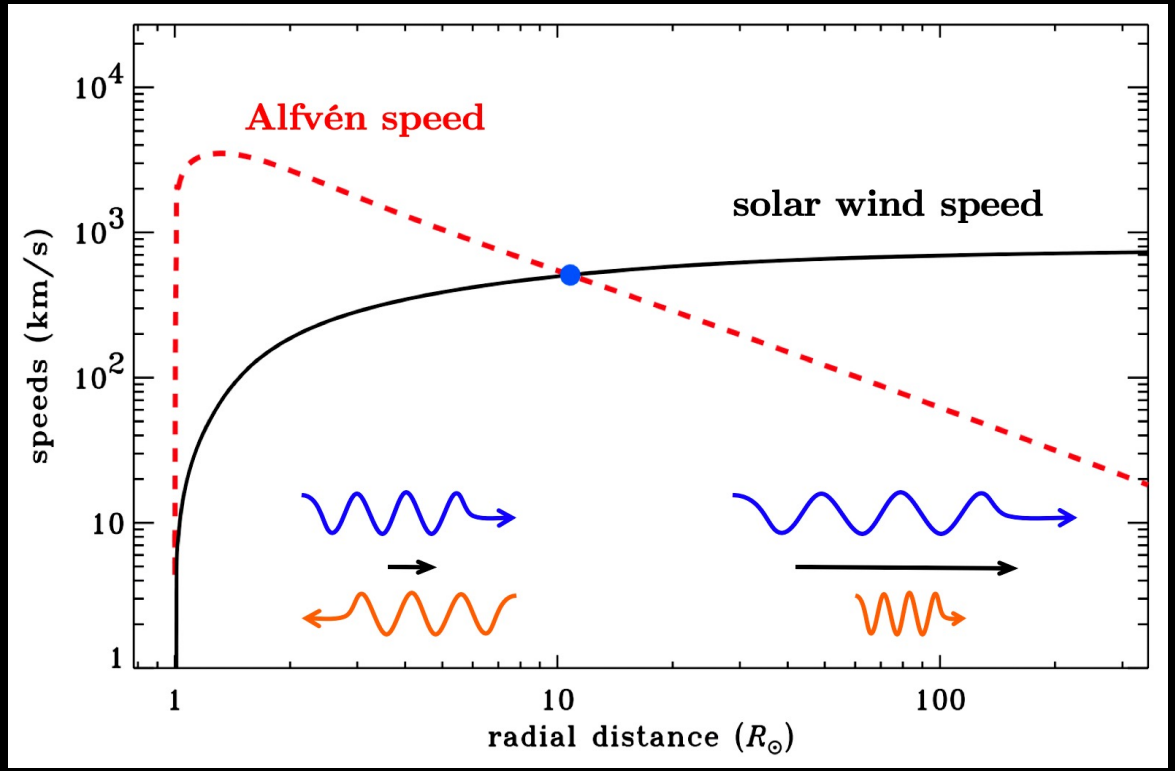
Is there a boundary between the corona and the solar wind?

- The Alfvén surface (or Alfvén radius, or Alfvén zone) is a useful place to draw this distinction.

- Below r_A, information (waves) can propagate both in & out. Above r_A, the solar wind drags out both inward & outward modes, and information doesn't propagate back down to the Sun.

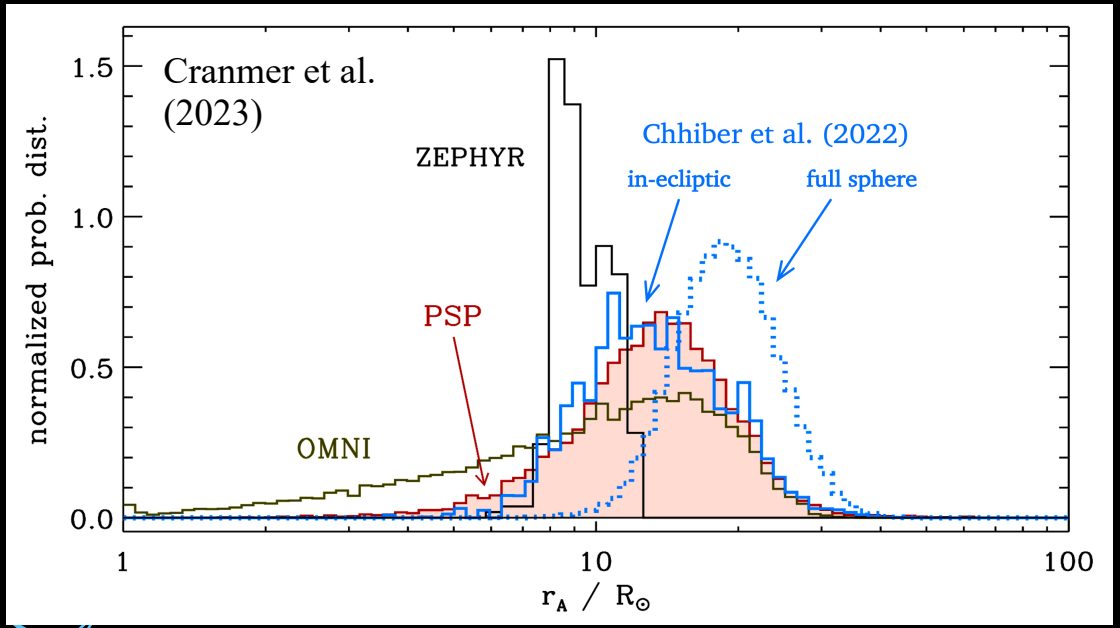
- It's the angular momentum "lever-arm" of the corona (Weber & Davis 1967).

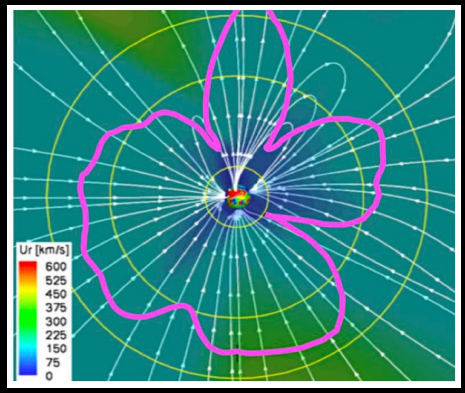
- Measuring the wind speed at r_A gives $V_A \rightarrow B$ there, too.



Where is it?

- We have 3D simulations, extrapolations from 1 AU data, and some fascinating crossings with *Parker Solar Probe!*
- Bold (?) prediction: nearly always in the PUNCH **NFI** field of view!

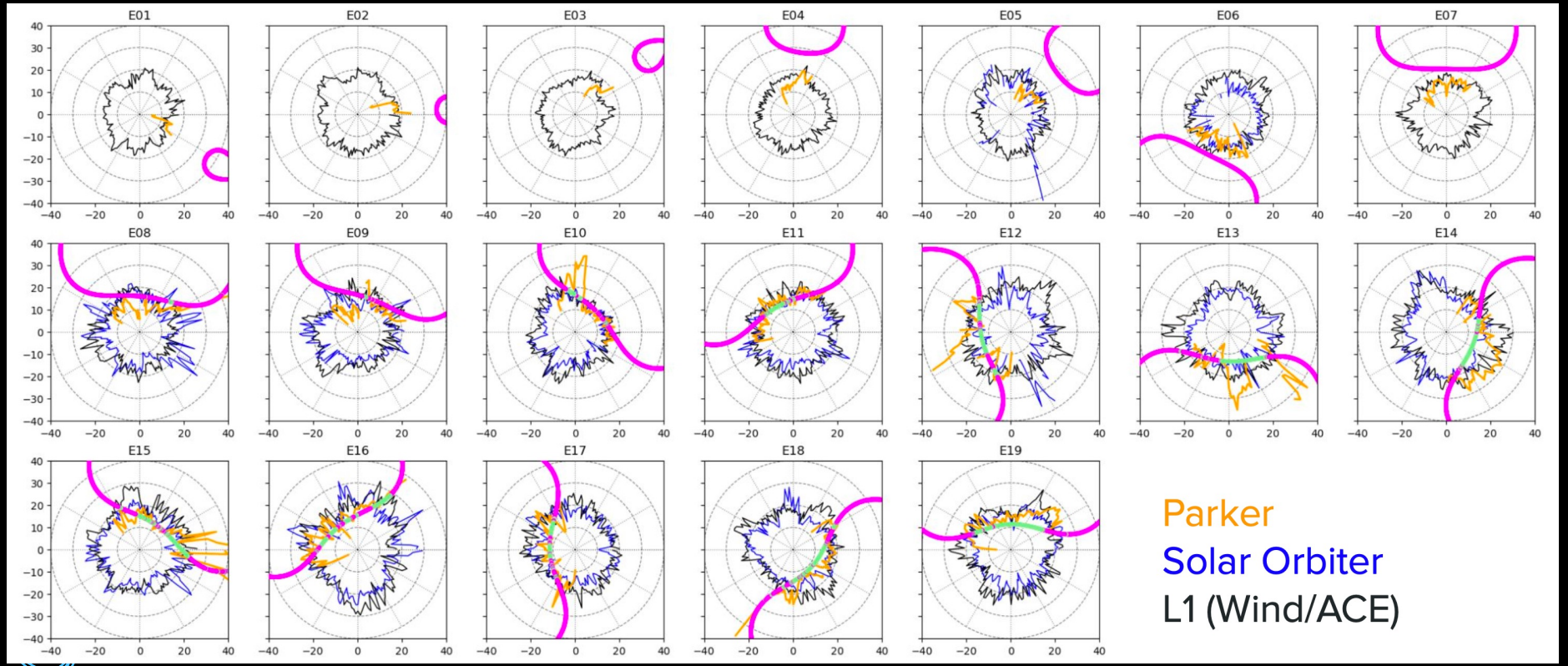




Cohen (2015)

Where is it?

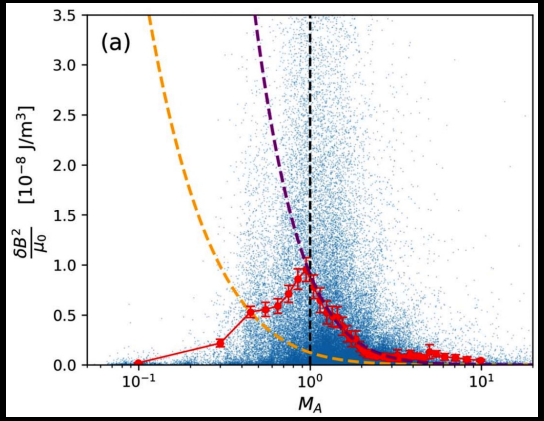
- Badman et al. (2024, Fall AGU) mapped it from 2018 to 2024 . . .

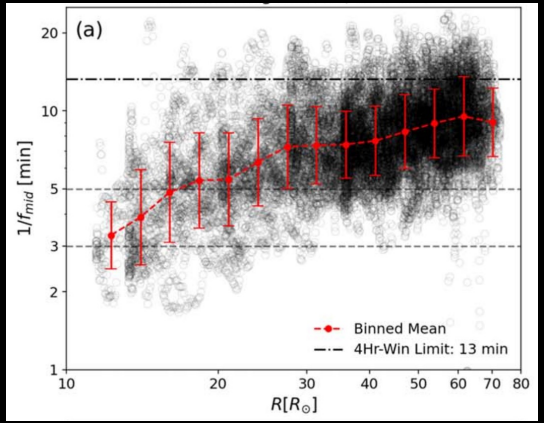


What has PSP learned about this region?

In the vicinity of r_A,

- the radial evolution of Alfvén waves departs strongly from unidirectional WKB theory (Ruffolo et al. 2024).
- alpha particles get preferentially heated and accelerated with respect to protons (Amaro & Vaivads 2024; Ran et al. 2024).
- there are bursts of 2-minute period (8 mHz) waves, and the typical frequencies get shorter as PSP gets closer to the Sun (Huang et al. 2024).



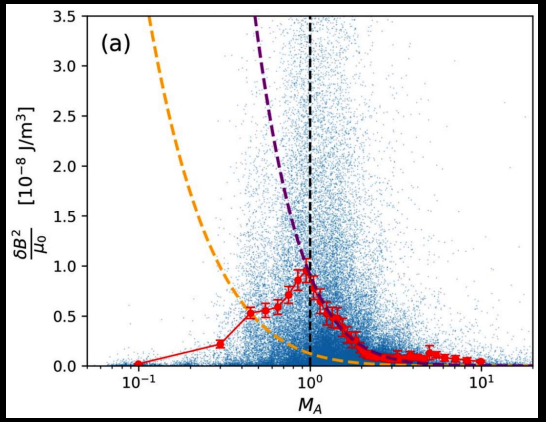


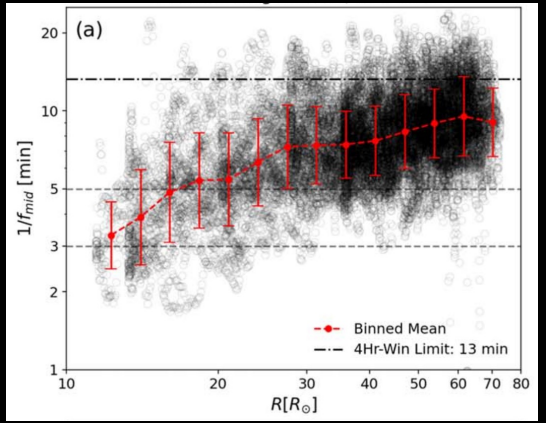
What has PSP learned about this region?

In the vicinity of r_A,

- the radial evolution of Alfvén waves departs strongly from unidirectional WKB theory (Ruffolo et al. 2024).
- alpha particles get preferentially heated and accelerated with respect to protons (Amaro & Vaivads 2024; Ran et al. 2024).
- there are bursts of 2-minute period (8 mHz) waves, and the typical frequencies get shorter as PSP gets closer to the Sun (Huang et al. 2024).

"Who ordered that?"





Outline:

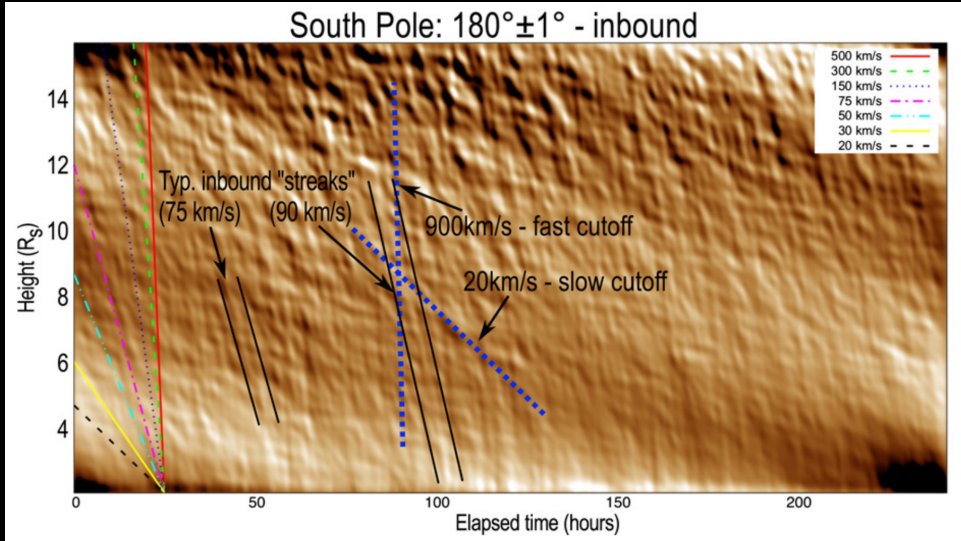
1. What is it, *where* is it, and what's going on there?
2. How will PUNCH help improve our understanding?
3. Preliminary look at a cool forward-modeling tool...

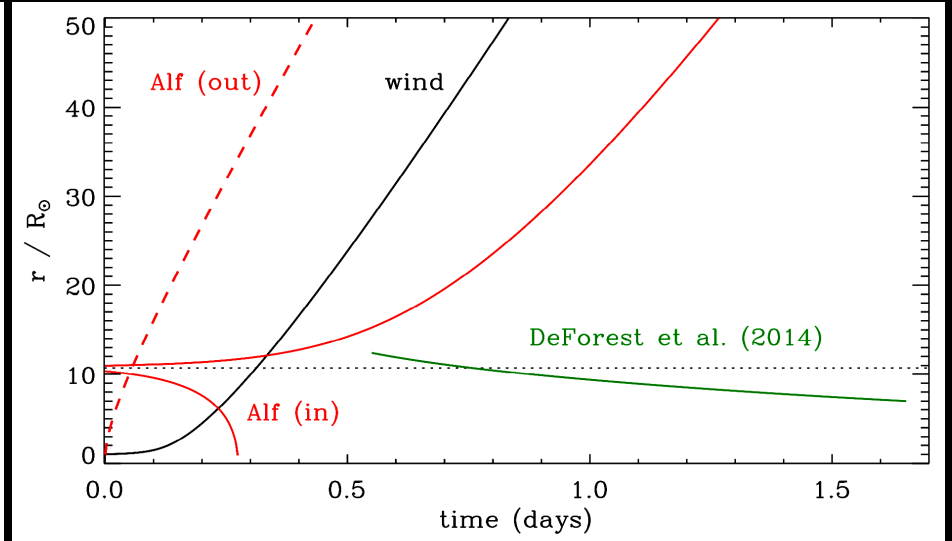
Coronagraph imaging can see inflows, too

- The corona is full of small density inhomogeneities (“blobs”) that flow in & out.
- Tracking outflowing blobs with off-limb imaging has helped probe solar-wind dynamics.

Coronagraph imaging can see inflows, too

- The corona is full of small density inhomogeneities ("blobs") that flow in & out.
- Tracking outflowing blobs with off-limb imaging has helped probe solar-wind dynamics.
- DeForest et al. (2014) used COR2 to find a few examples of **inflow** (12 to 7 R_{sun}), but the kinematics didn't match expectations from how MHD waves behave!

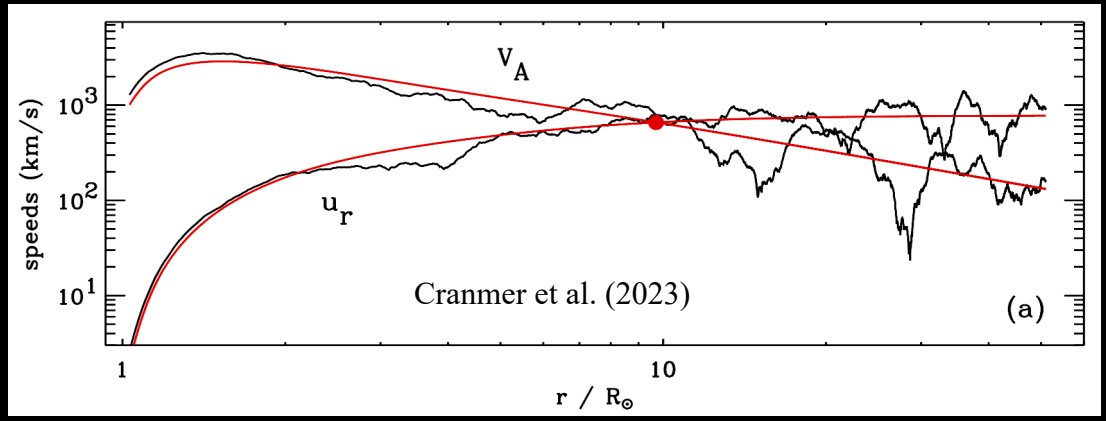


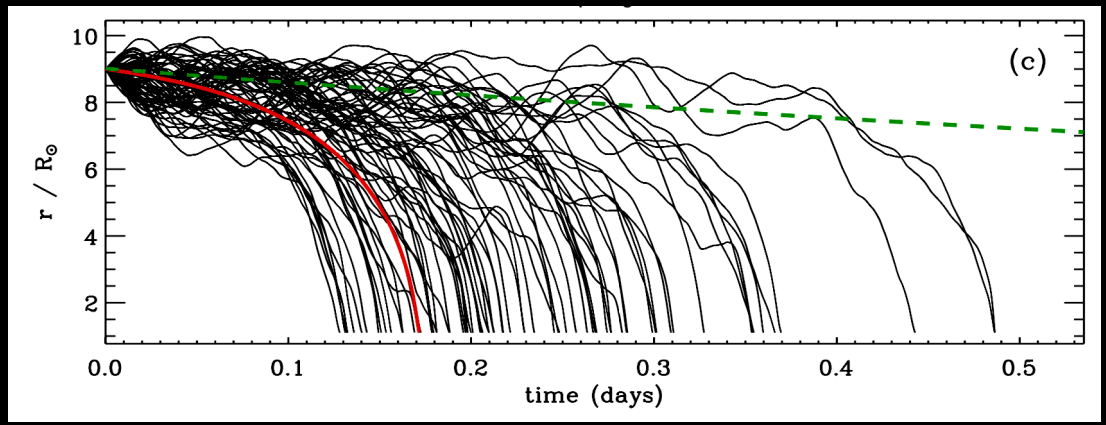


Coronagraph imaging can see inflows, too

- Theoretical models abound (see Tenerani et al. 2016; Cranmer et al. 2021), and they hint that the blobs may be gaining mass by **"snowplowing"** plasma in front of them. Are they reconnection exhausts? Kelvin-Helmholtz vortices? Supra-Alfvénic shocks?

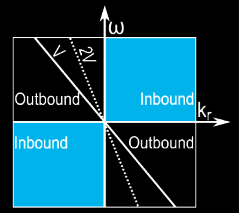
- On the other hand, including **turbulence** produces time-varying "froth" such that r_A bobs up & down and there can be multiple places where $u=V_A$. Can this explain the decelerated inflow?

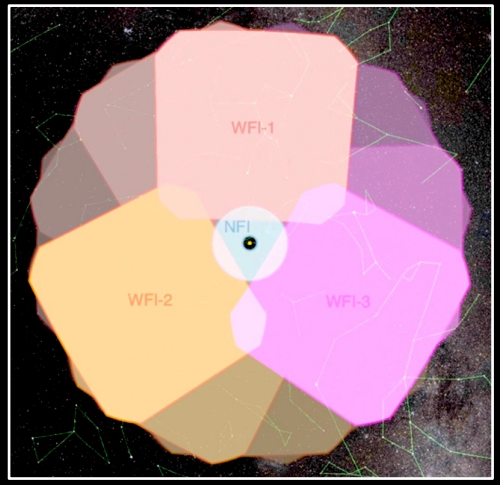




PUNCH flow tracking

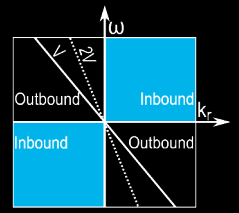
- PUNCH will produce visible-light images between 6 and 32 R_s with 4 minute cadence in the NFI field of view.
- To measure flow speeds of inflowing & outflowing features, we use:
  - well-tested flow-tracking algorithms
  - spatio-temporal Fourier filtering
  - (some) 3D localization via polarization

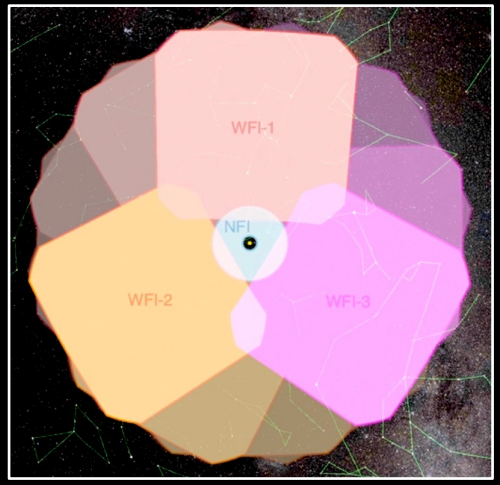




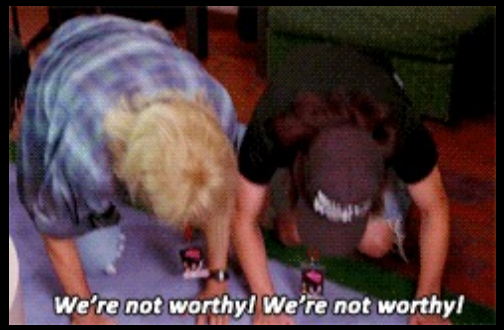
PUNCH flow tracking

- PUNCH will produce visible-light images between 6 and 32 R_s with 4 minute cadence in the NFI field of view.
- To measure flow speeds of inflowing & outflowing features, we use:
  - well-tested flow-tracking algorithms
  - spatio-temporal Fourier filtering
  - (some) 3D localization via polarization





- Working Group 1C is thankful for all the work being done by Working Group 1A !
- Will the decelerating inbound features seen by DeForest et al (2014) be just the "tip of the iceberg?" Will lower-contrast features not undergo so much snowplowing? What will the **lifetimes** of these features tell us about the solar wind & turbulence?



Outline:

1. What is it, *where* is it, and what's going on there?
2. How will PUNCH help improve our understanding?
3. Preliminary look at a cool forward-modeling tool...

A new forward-modeling tool

- To really know that we're interpreting PUNCH data properly, it's nice to have model 3D data that we can process into simulated PUNCH images, then evaluate whether our interpretation lines up with the known **"ground truth."**

  (see also Nisticò et al. 2020, who did comprehensive benchmarking with a code like this for WISPR/PSP)

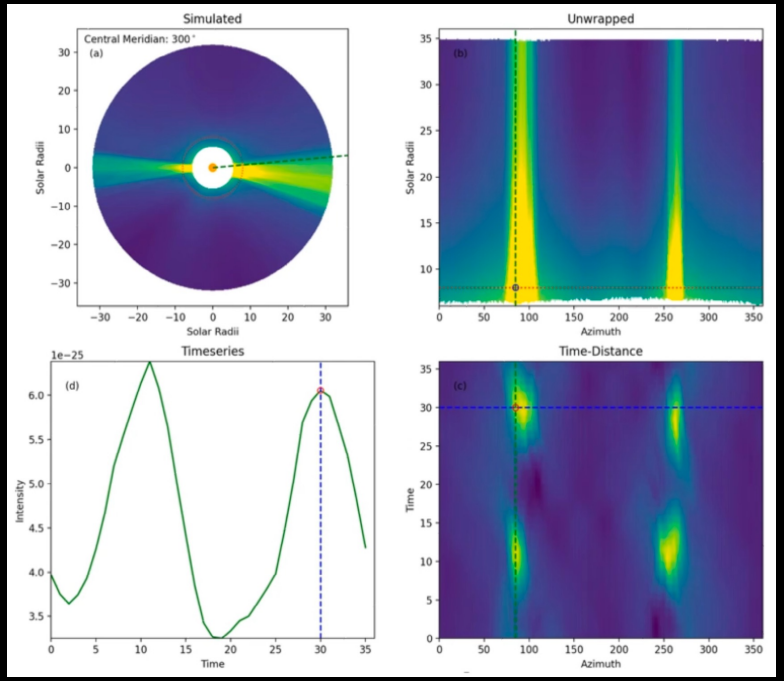
A new forward-modeling tool

- To really know that we're interpreting PUNCH data properly, it's nice to have model 3D data that we can process into simulated PUNCH images, then evaluate whether our interpretation lines up with the known **"ground truth."**

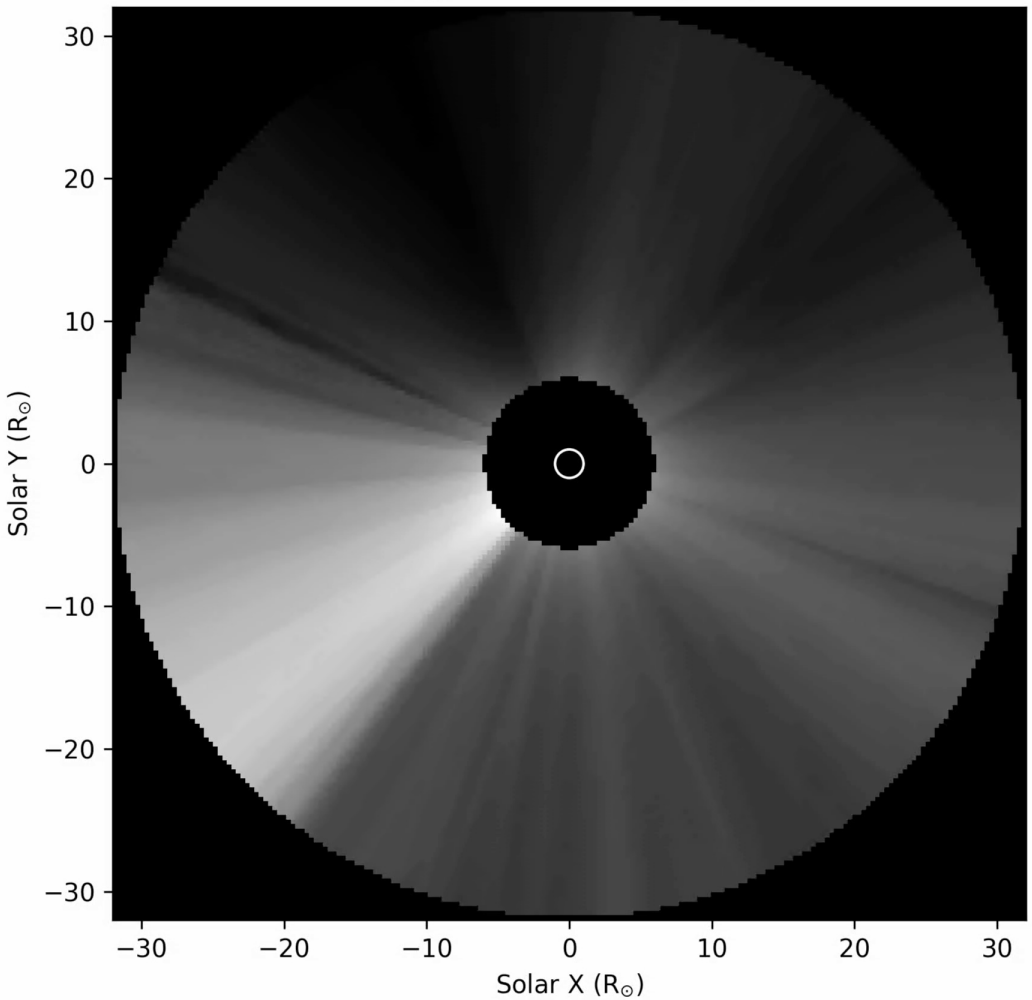
  (see also Nisticò et al. 2020, who did comprehensive benchmarking with a code like this for WISPR/PSP)

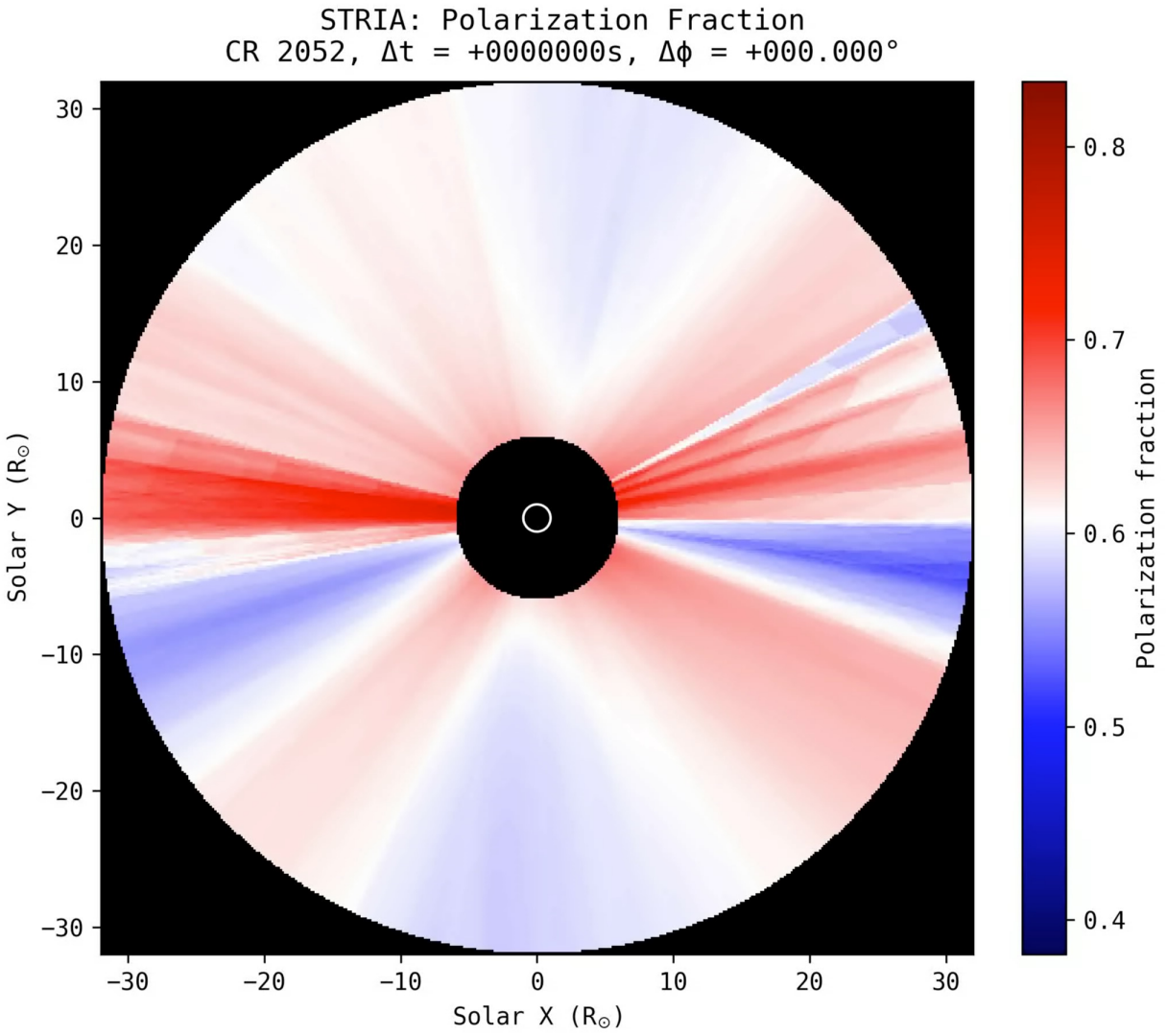
- Initial ideas for a code called STRIA were explored by C. Gilly (2022), with S. Gibson (FORWARD).

- Unlike output from MHD sims, STRIA constructs the 3D plasma state with a **building-block** approach.

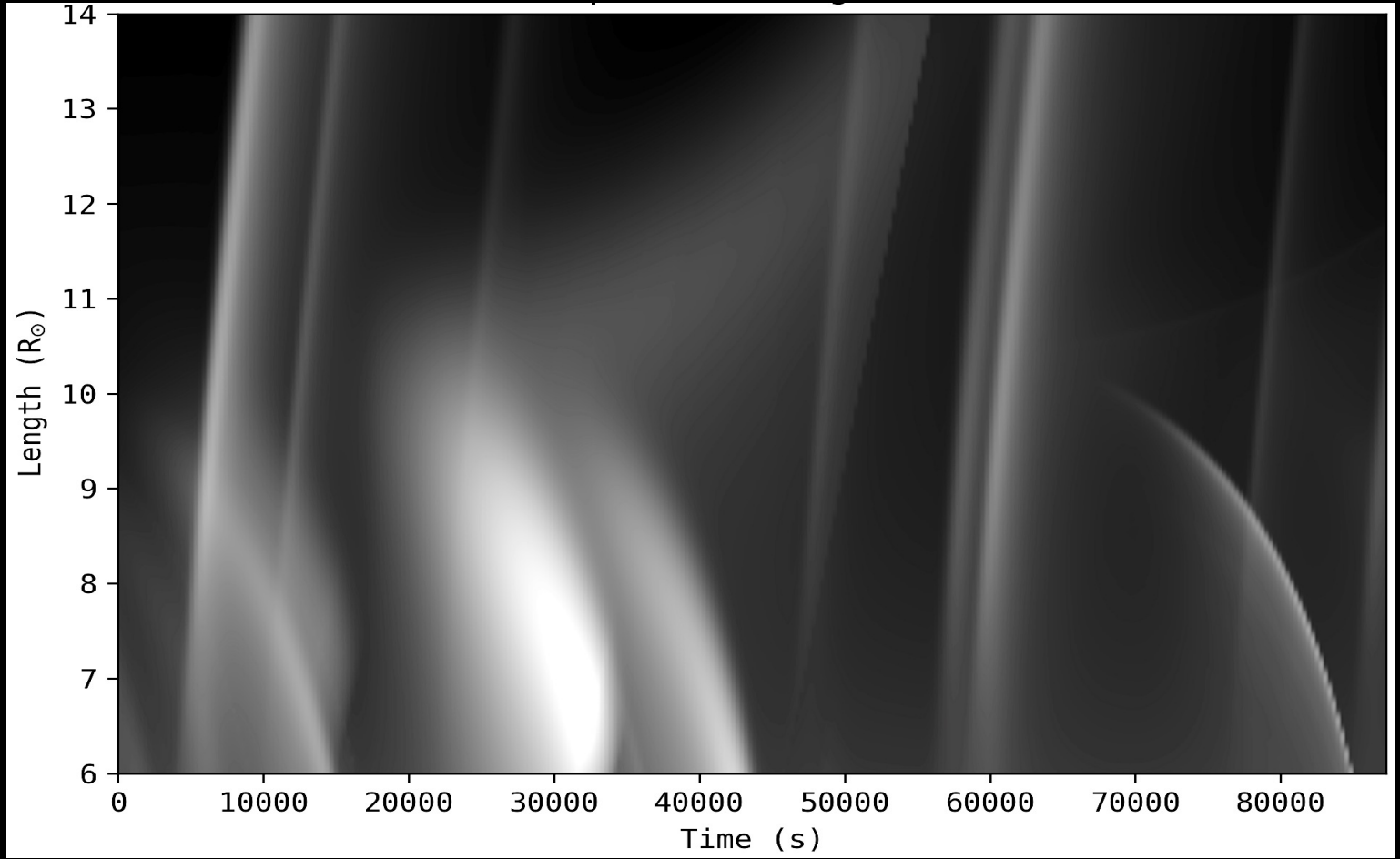


- In 2024, this wheel was re-invented (with 50x speedup in python) by undergrad Trestan Simon.


STRIA plot B_k: CR2105.000
(x, y, z) = (200, 401, 200)
30
20
10
0
−10
−20
−30
Solar Y ($R_\odot$)
−30
−20
−10
0
10
20
30
Solar X ($R_\odot$)


STRIA: Polarization Fraction
CR 2052, Δt = +0000000s, Δϕ = +000.000°
Solar Y (R⊙)
Solar X (R⊙)
Polarization fraction
30
20
10
0
−10
−20
−30
0.8
0.7
0.6
0.5
0.4

An example "J-plot" with both outward & inward blobs



Conclusions

- Using PUNCH to locate the Alfvén surface --- and to probe the dynamics of turbulent parcels in its vicinity --- is expected to improve our understanding of coronal heating & solar wind acceleration.

- Coordination with other instruments/missions/telescopes could be the "secret sauce" that provides even more multi-scale context & insight . . .