Translational Tomography with Parker Solar Probe's WISPR

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Outline of the Talk

Background material

- The Sun
- Parker Solar Probe (PSR), Wide-field Imager for Solar Probe (WISPR)
- Inverse problems, tomography

Linear orbital geometry: the simplest case

- Constructing a family of analytic functions, generating basis functions
- Testing the analytic model on a simulated WISPR dataset
- Tomographic results

3D spherical geometry: the next-simplest case

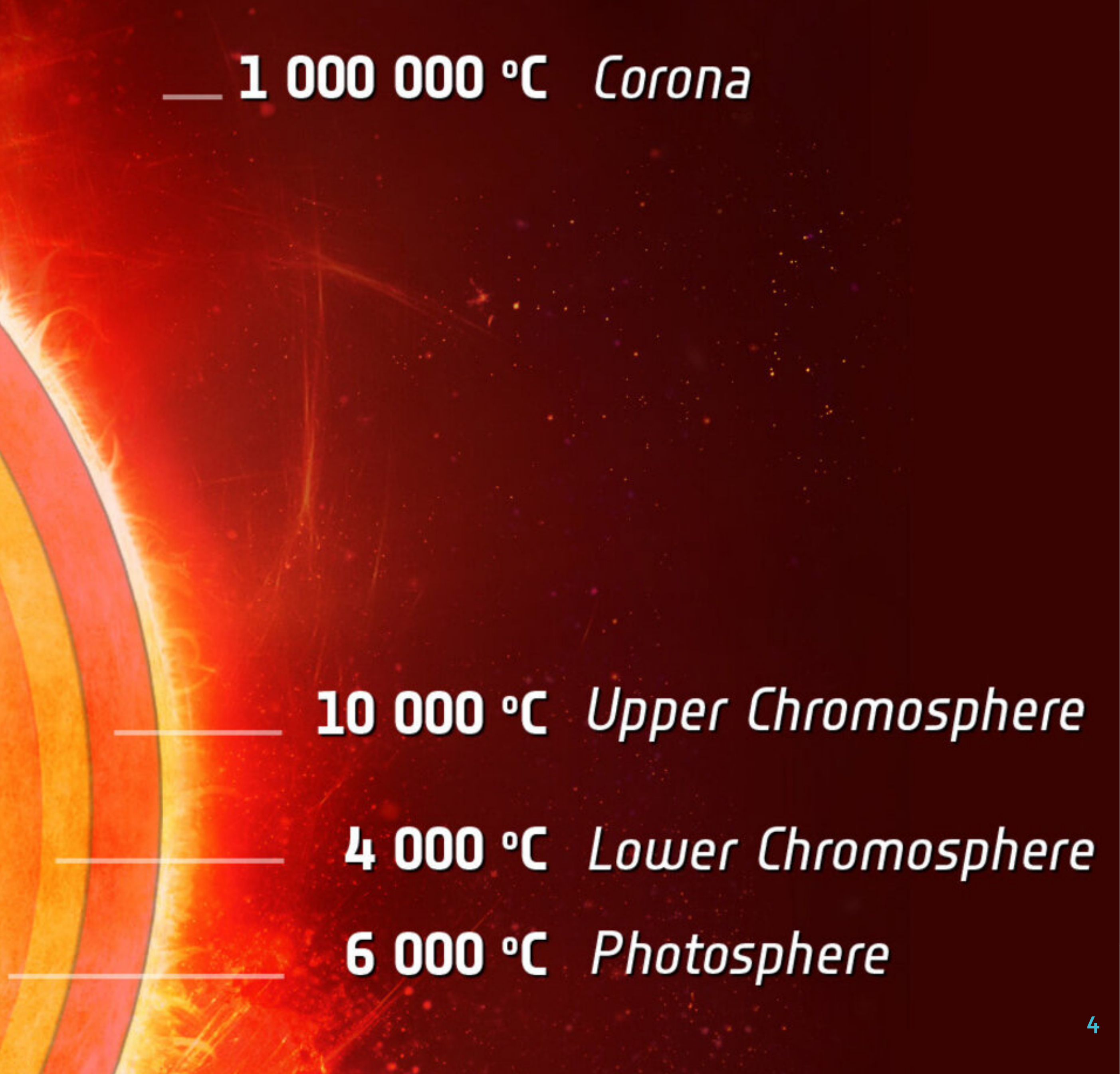
- The need for new basis functions
- Tomographic results

What's next?

I. Background Material

Basics of the Sun

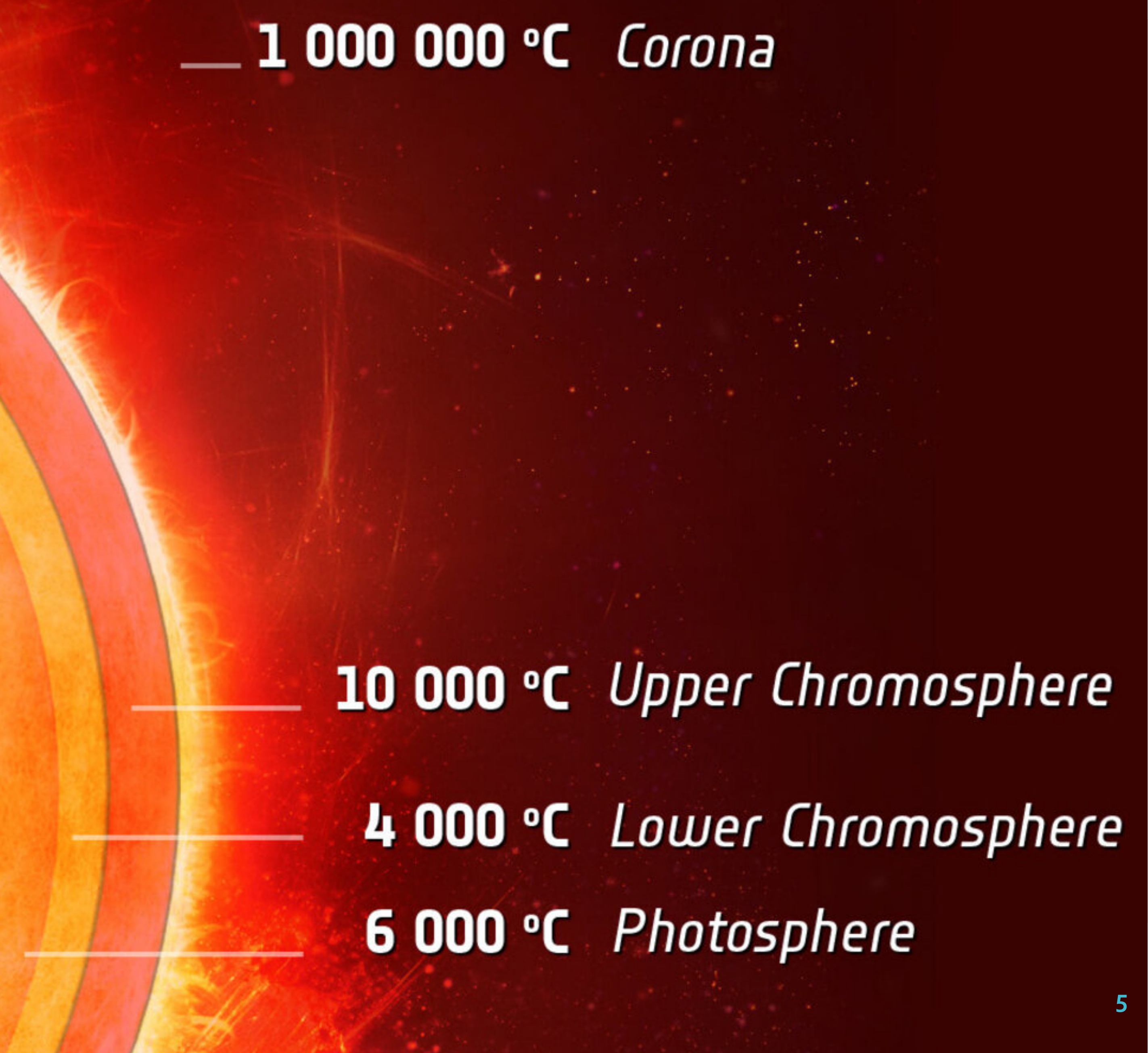
- The Sun is rotating, magnetized ball of plasma (hot, ionized gas!) undergoing nuclear fusion at its core.
- Fusion reactions produce heavier elements and packets of light called **photons.**
- These photons take approximately a million years to escape the “surface” of the Sun.
- The **photosphere** is the visible “surface” of the Sun.
- The **chromosphere** is next layer of the atmosphere (< 1% a solar radius in height).



Credit: ESA

Basics of the Sun

- The **corona**
  - is a low density plasma, composed of charged particles.
  - has two main components:
    - F-Corona: interplanetary dust scatters photospheric radiation
    - K-Corona: electrons scatters photospheric radiation
- **Solar wind** is a continuous outflow of the corona into interplanetary space.
- The **heliosphere** is the region of influence of the Sun – determined by magnetic field and solar wind.



Credit: ESA

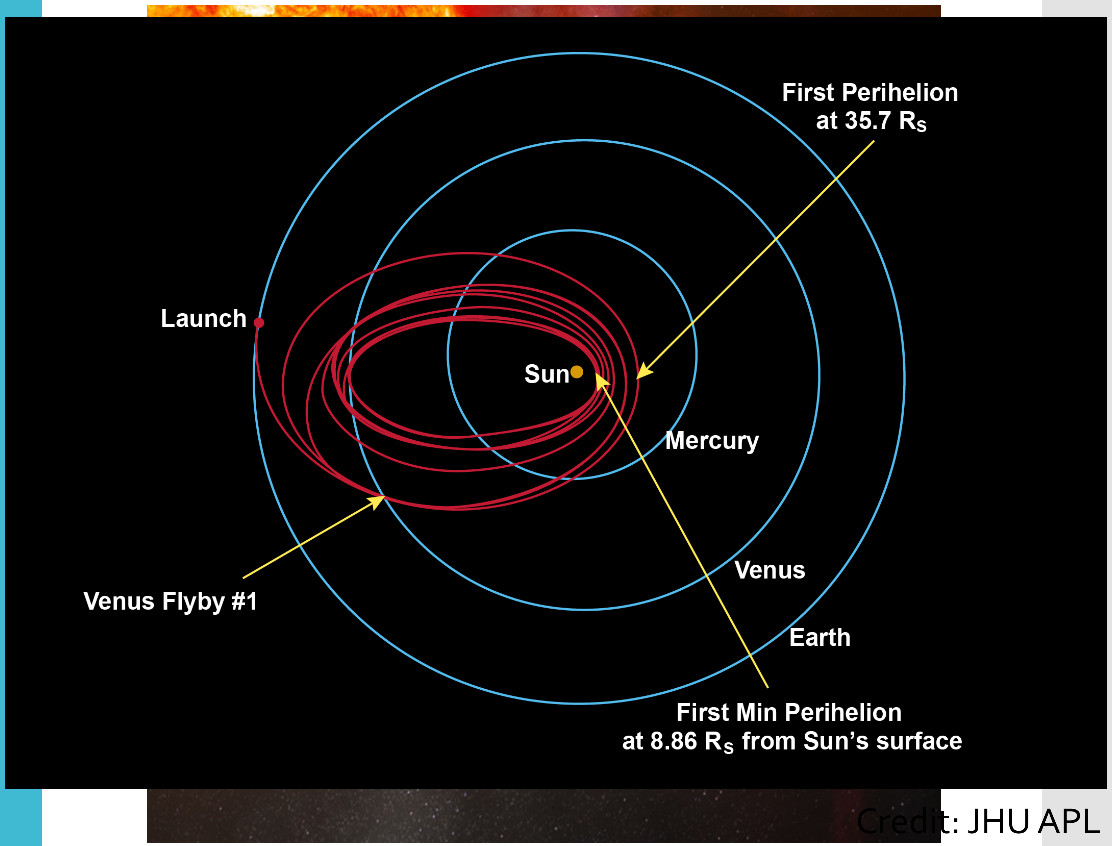
What if we had a spacecraft flying through the inner heliosphere?

We do!!

Parker Solar Probe is a NASA heliophysics "**mission to touch the Sun**", i.e. humanity's first stellar visit (Fox et al., 2016).

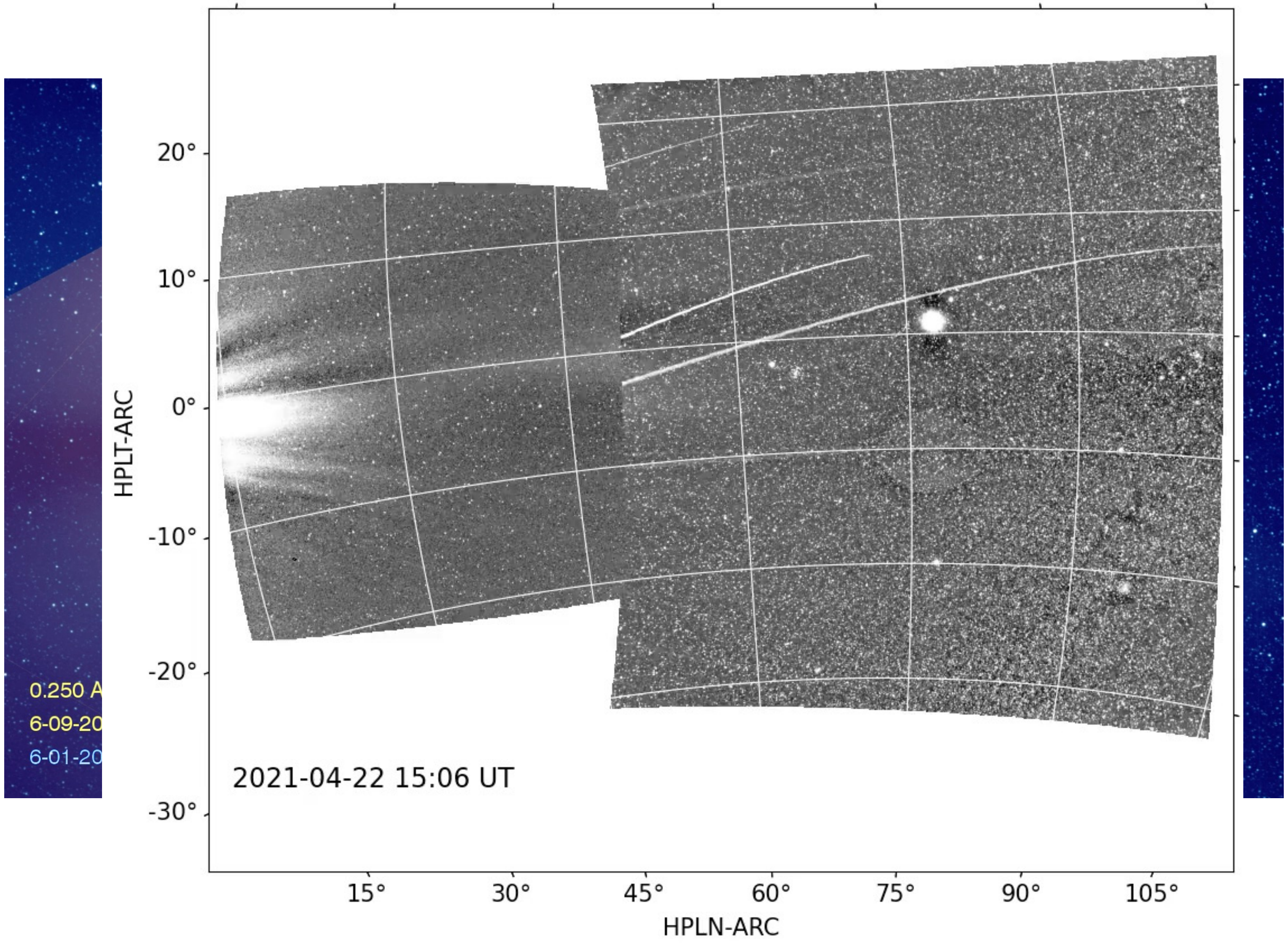
PSP carries **four instrument suites**: FIELDS, SWEAP, ISOIS, and WISPR.

Goal of PSP: "revolutionize our understanding of the corona and expand our knowledge of the origin and evolution of the solar wind" (NASA).



Credit: JHU APL

Credit: NASA



Credit: Stenborg, Gallagher

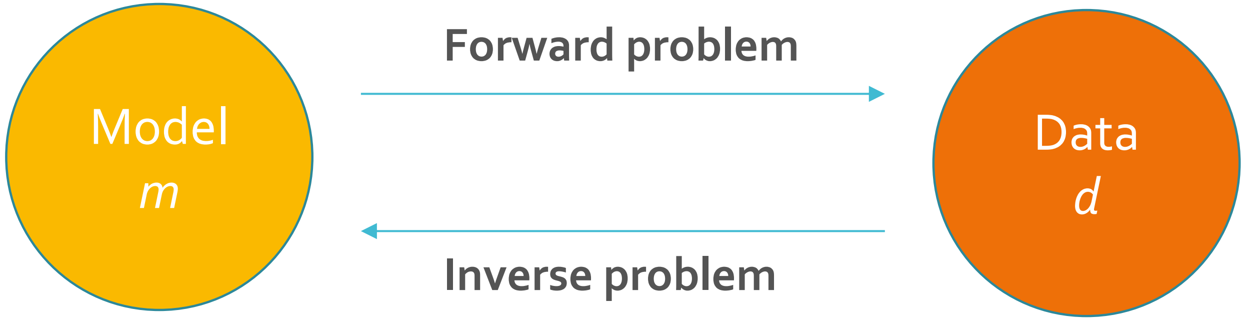
PSP-WISPR

The Wide-field Imager for Solar Probe (WISPR) is the sole imaging suite on-board PSP.

Left: animation of WISPR field-of-view compared to a different imager situated at the Earth

PSP's rapid motion through the solar wind and corona provides novel science opportunities, such as **tomographic reconstruction** with WIPSR!

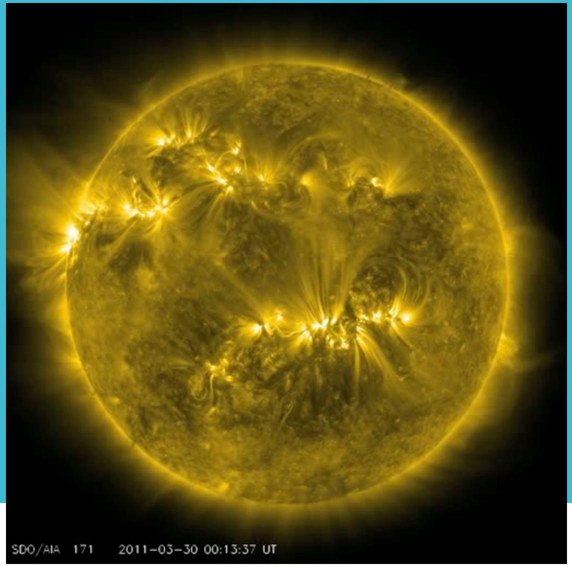
Inverse Problems



- "Inverse theory is an organized set of mathematical techniques for reducing data to obtain knowledge about the physical world on the basis of inferences drawn from observations" (Menke, 2018).

- We **start with a dataset** and a general principle, theory, or model with the **goal of determining the underlying physics**, or the 'model parameters' (Menke 2018).

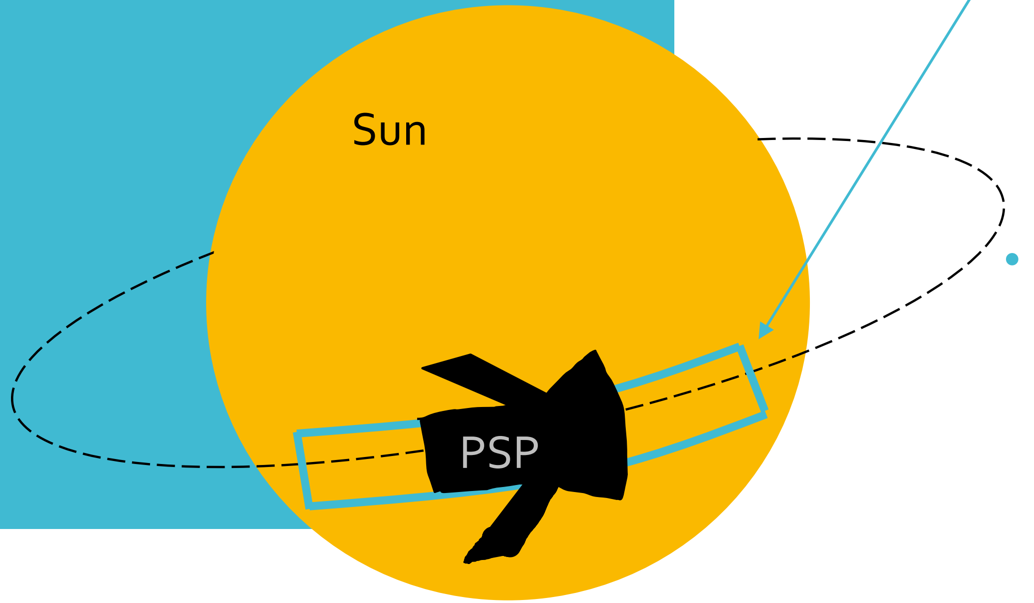
Tomography: One Type of Inverse Problem



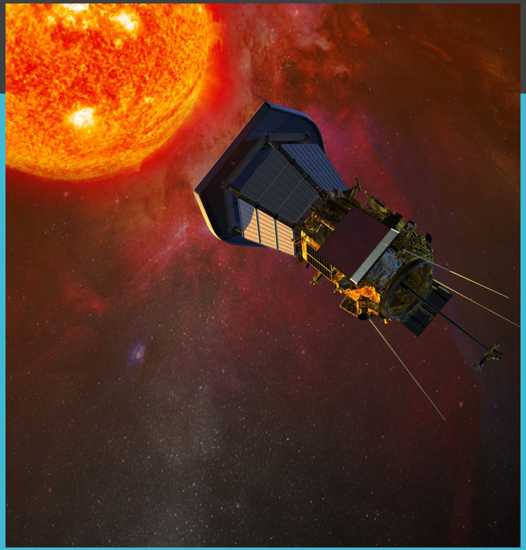
- Tomography is the technique by which one makes measurements in the form of **slices through an object** to form an image of that object (Menke 2018).
- Examples:
  - Computed tomography (CT)
  - Solar rotational tomography

- For this work with PSP-WISPR, our **measurements are made along lines of sight** through the corona.
- Our multiple viewpoints come not from rotational motion but from **PSP's translational motion through the corona.**

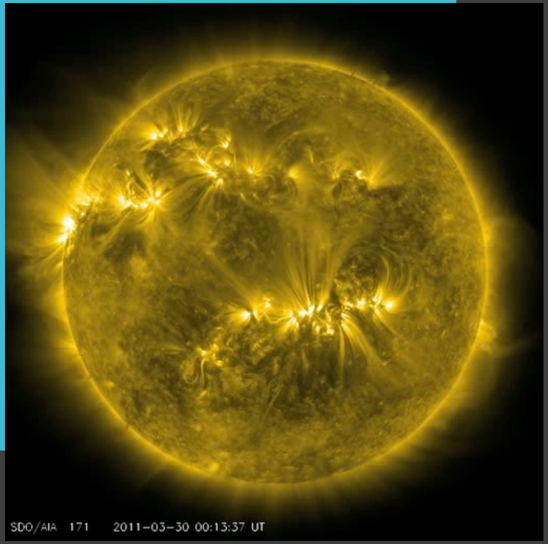
Tomography with WISPR



- We seek to perform *translational* tomography of ambient, stationary radial features using WISPR image sequences near perihelion.
  - **Q:** Why only near perihelion?
- Although we ultimately intend to **reconstruct 3D density structure** in the proximity of PSP, we begin by solving for the **locally horizontal 2D slice,** or "ribbon", of the corona near PSP's linear trajectory.
- This tomography relies on **unique perspective (changes) near perihelion** to invert for structure.
  - We assume that these perspective changes in consecutive WISPR images dominate scene change.
- Tomographic inversion for these particular features removes the background F-corona, which is necessary for:
  - visualizing faint and small-scale structures
  - comparing WISPR images to *in situ* data



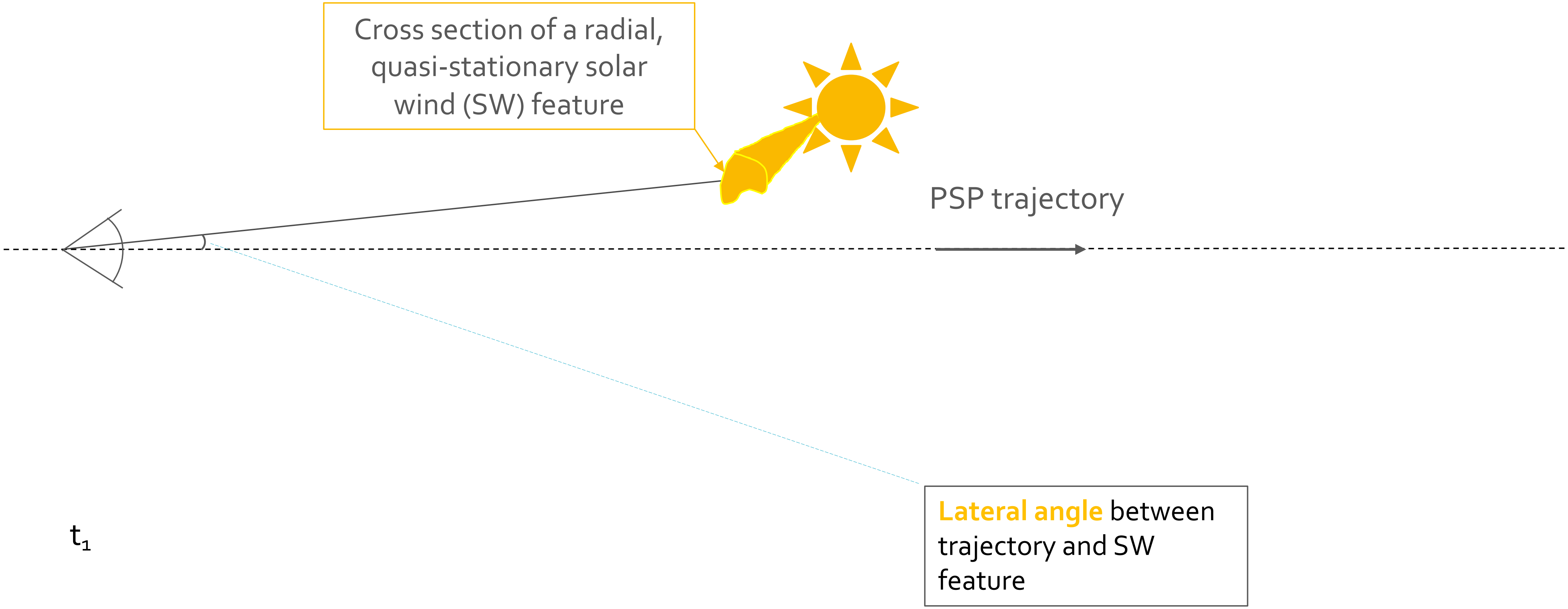
Recap I.



- The Sun is our local star.
- We are close enough to study it in detail!
- As of 2018, we have a spacecraft plunging through the solar wind and corona, which means we can do new science.
- Tomography is a body of techniques used to reconstruct images of an object.
- We want to use PSP’s rapid orbital speeds through coronal structures to reconstruct certain types of coronal features.

II. The Perspective Problem

The Simplest Case: a Straight-line Orbital Trajectory



Linear Approximation of PSP's Near-Perihelion Trajectory

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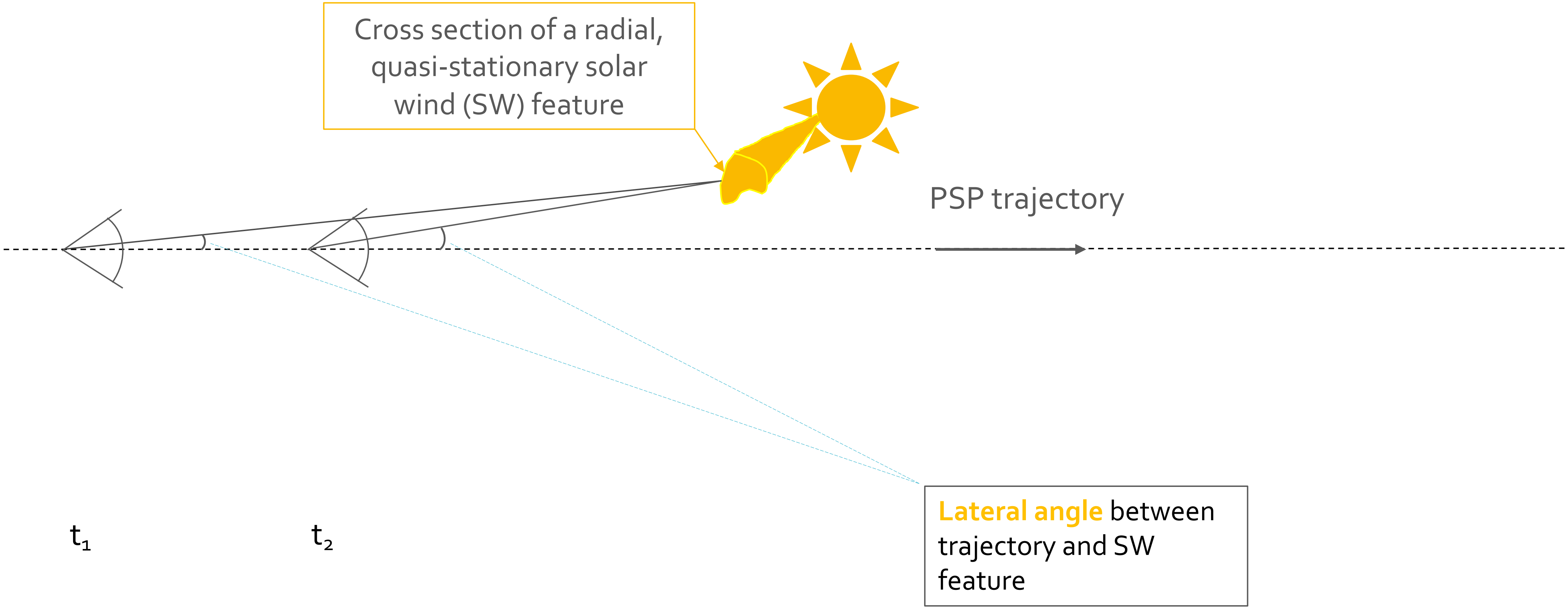
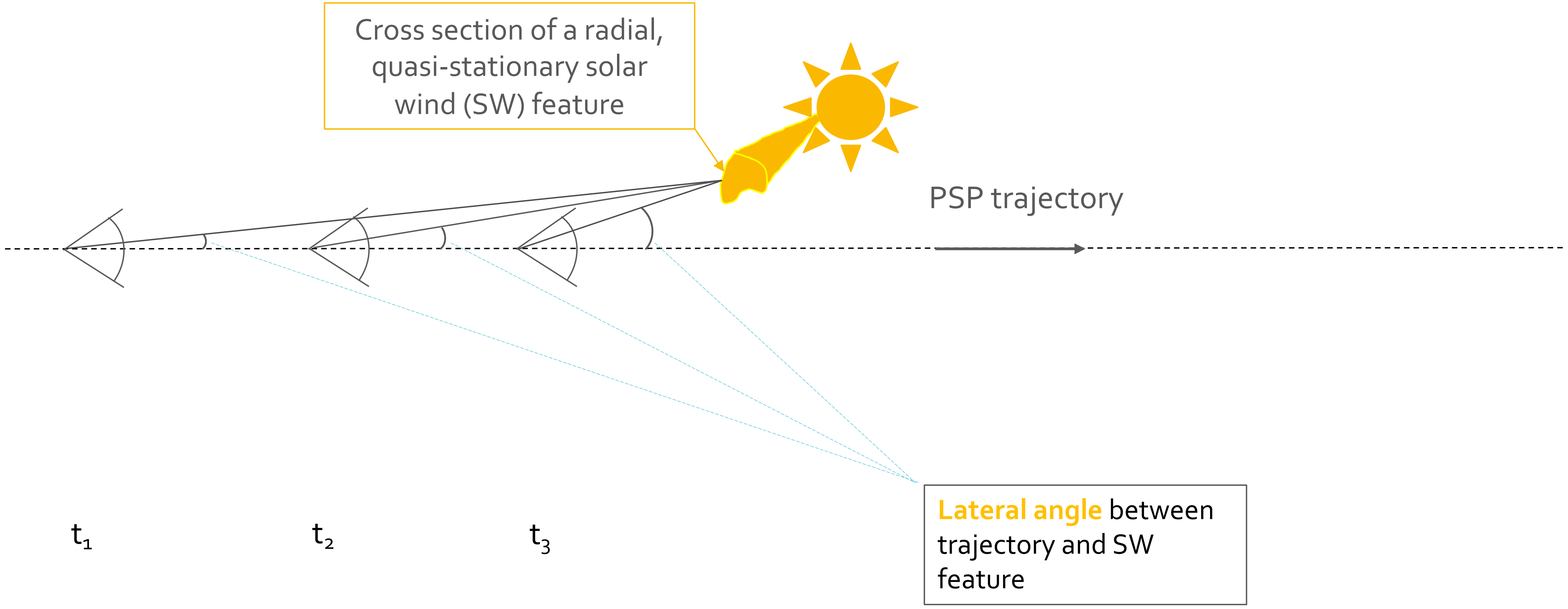
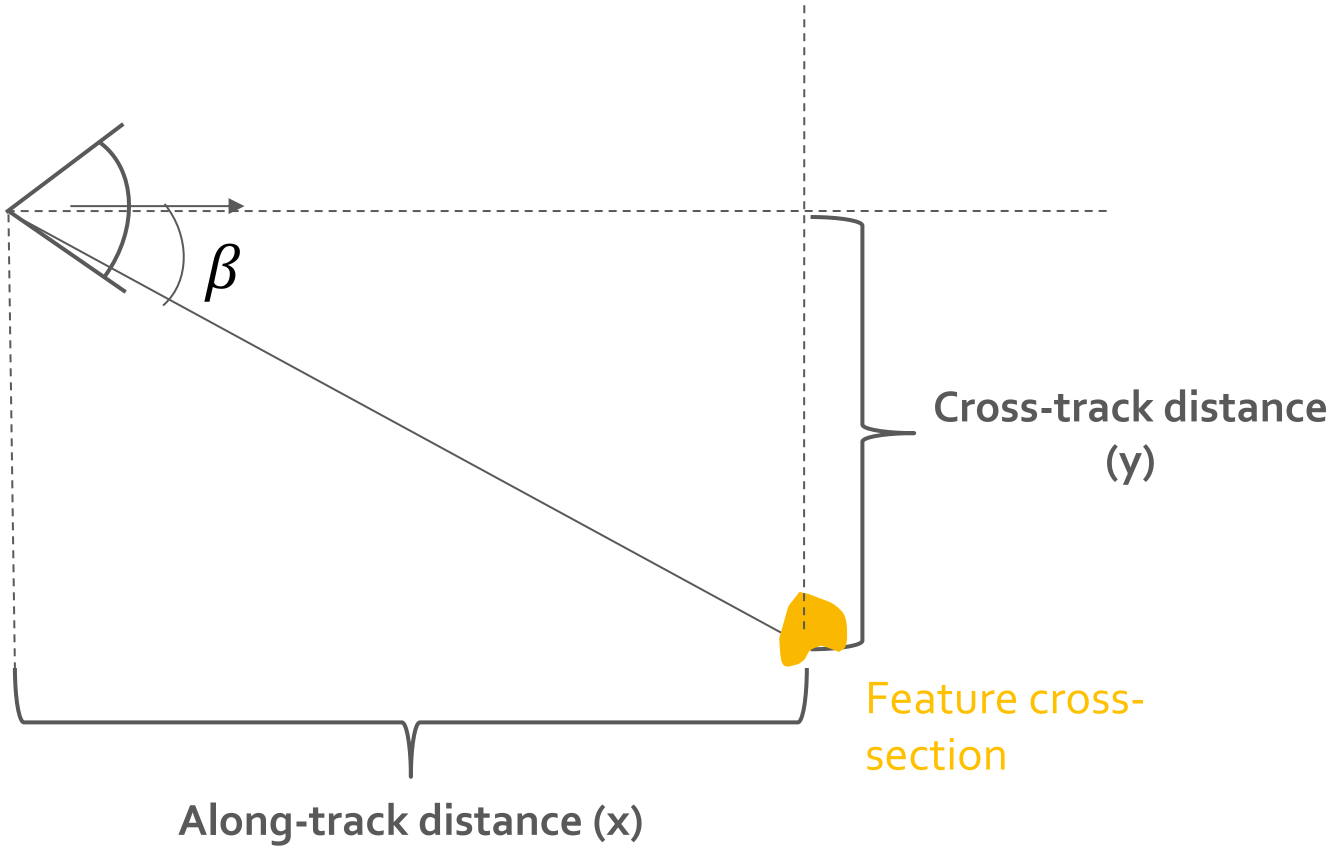




Linear Approximation of PSP's Near-Perihelion Trajectory

Parameter Space for Linear Orbit Approximation

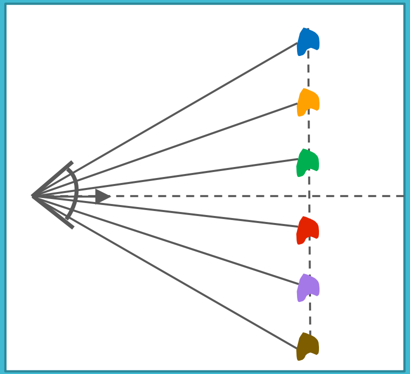


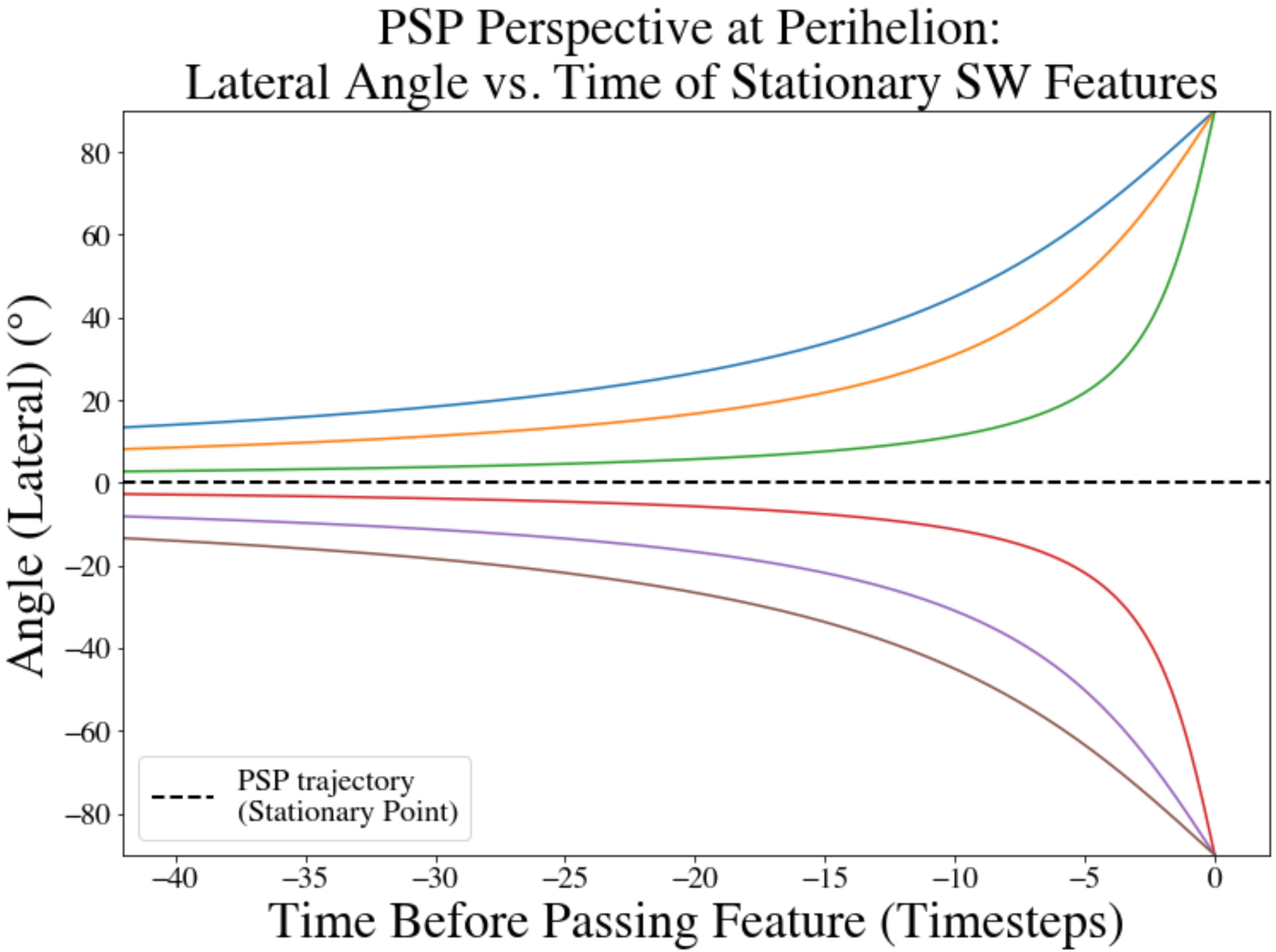
$$\tan(\beta) = \frac{y}{x}$$

$$\beta = \arctan(\frac{y}{x})$$

Family of Arctangent Functions

We can construct families of functions for different values in our parameter space.



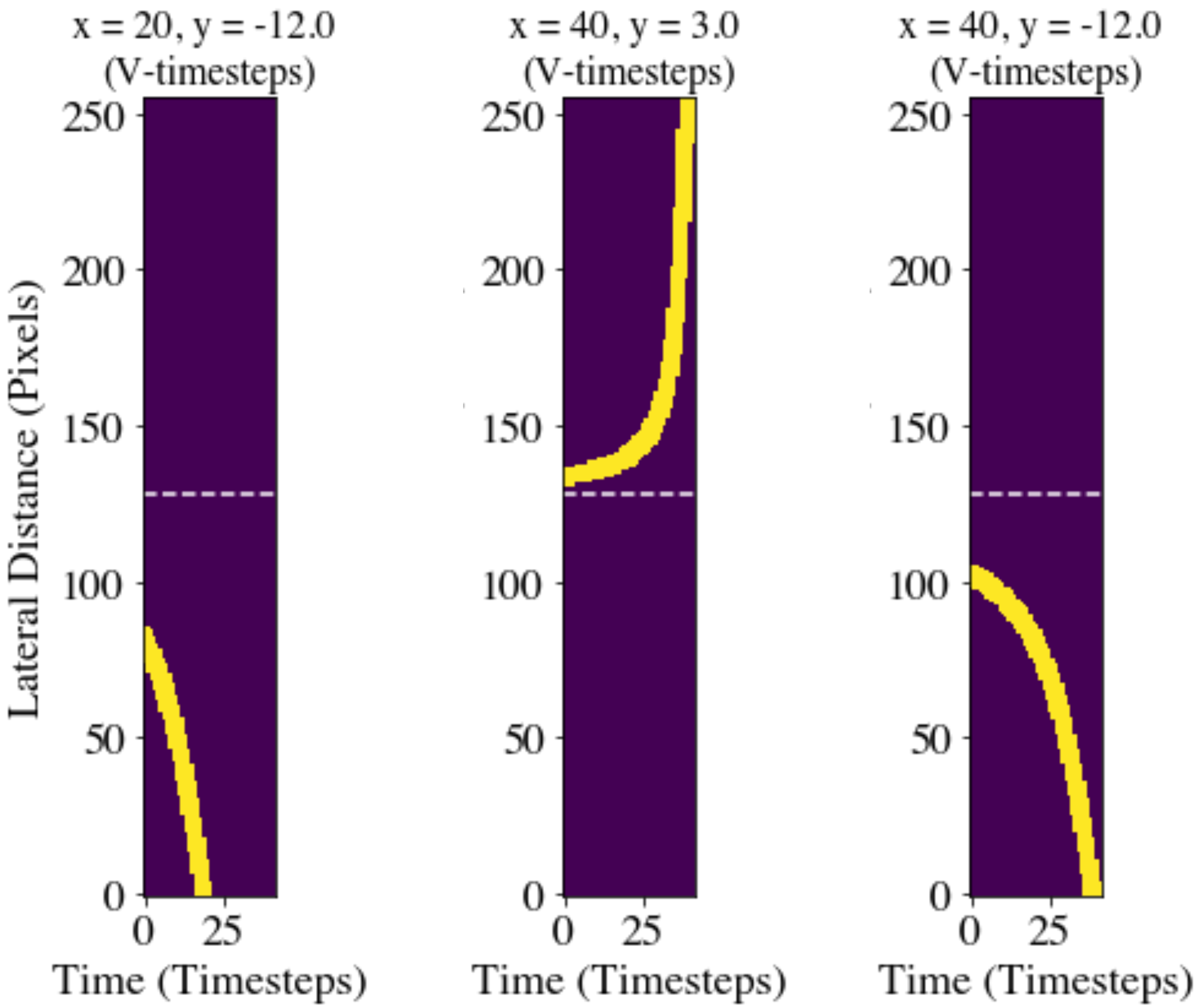


Basis Vectors: Images of Analytic Arctangent Functions

Two parameters characterize the shape and position of each curve.

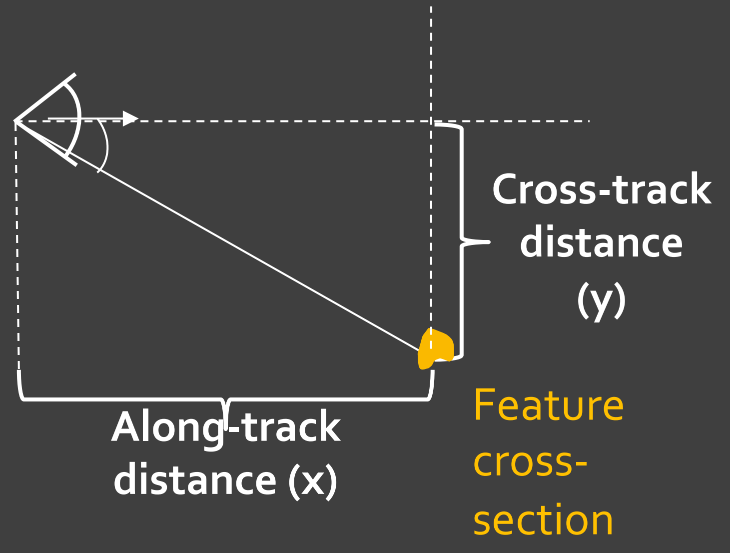
These curves are a few (of many) basis vectors which **partially span the data space:** consecutive WISPR images near perihelion.

We will use these basis functions to change our basis, i.e. **transform a sequence of images** from image coordinates to tomographic coordinates.



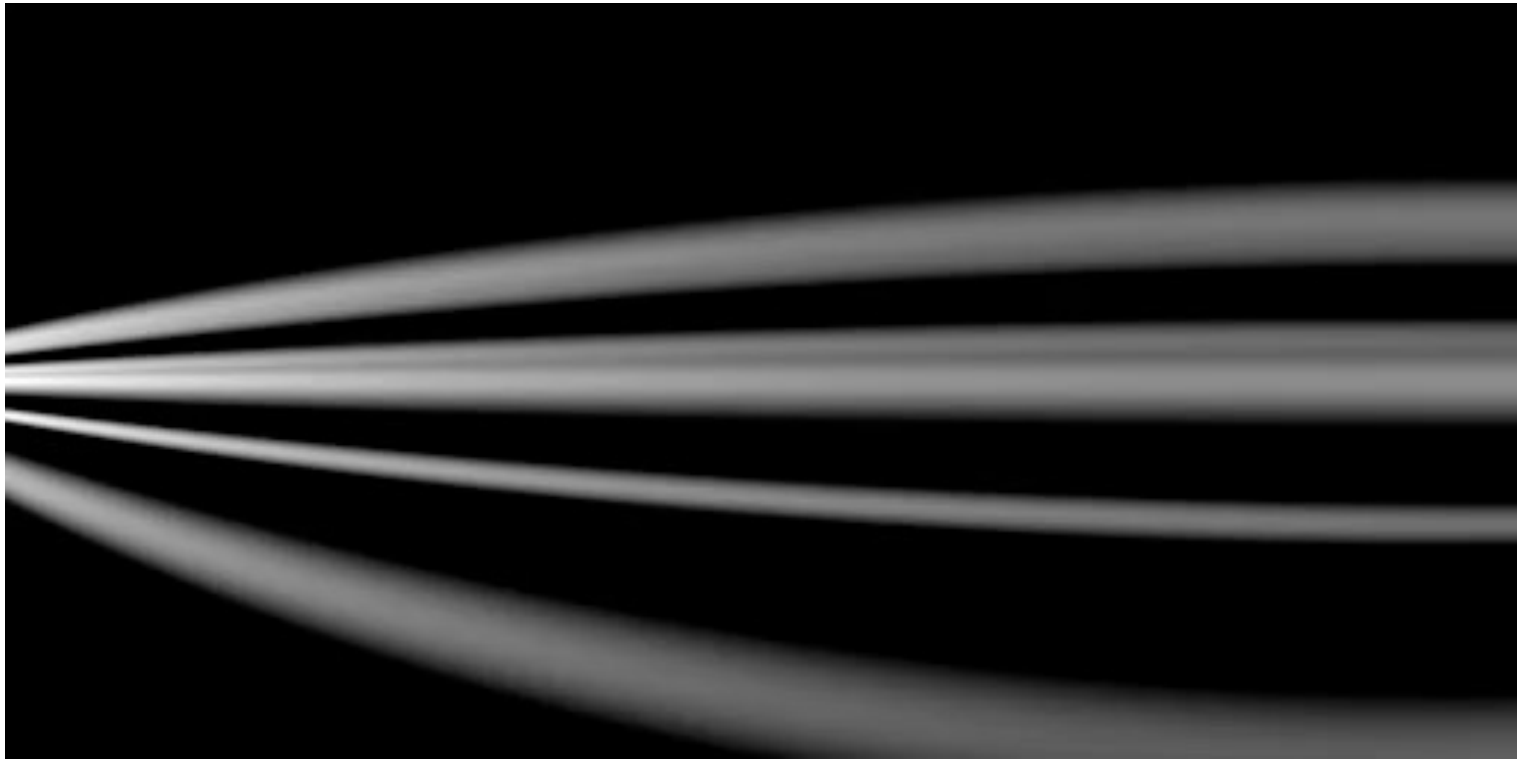
Recap II.

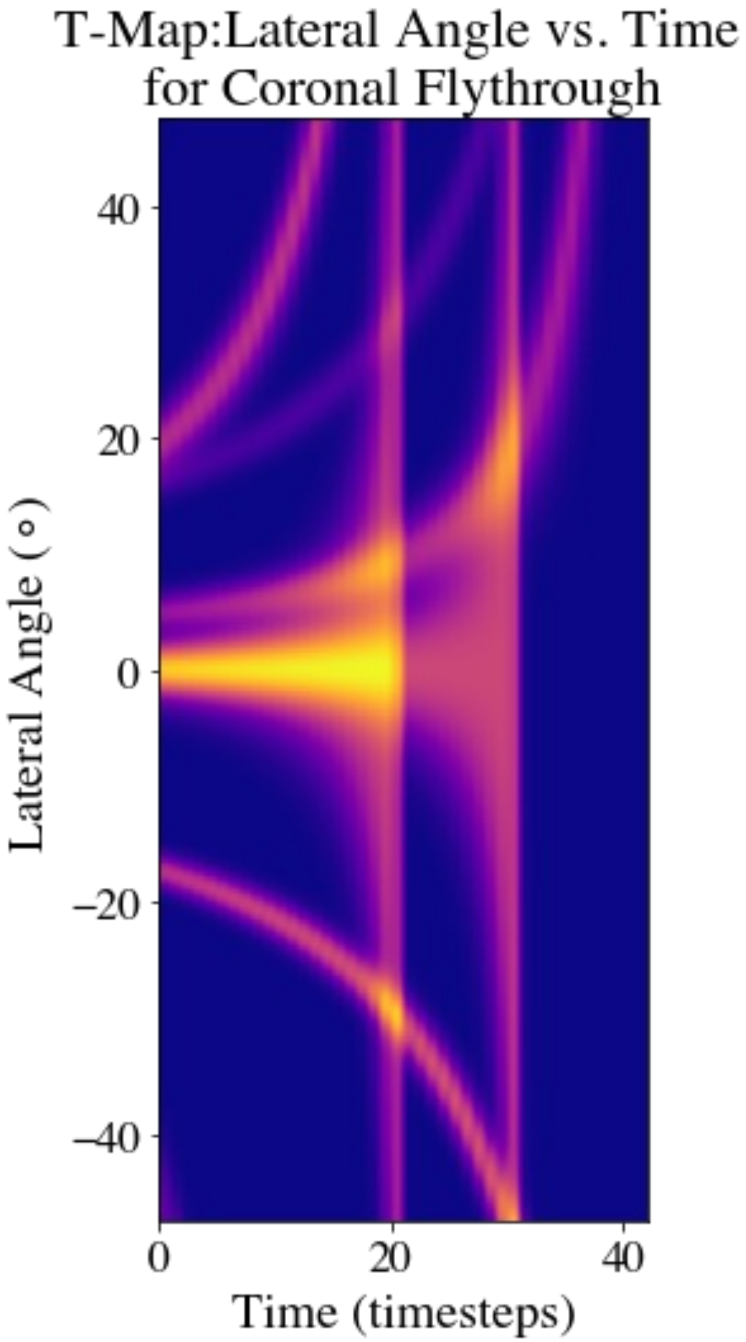
- We explored the simplest approximation of the spacecraft's orbital motion and how features appear to be moving through the field of view under this approximation.
- We parameterized the features with two distances with respect to the spacecraft and trajectory.
- We generated 'image curves' that we can compare to a real or synthetic WISPR dataset.



III. Testing the Method on a Model Dataset

Here we see a movie comprised of **42 synthetic WISPR images** during a simulated **12hr PSP perihelion pass**, with **15min cadence**.



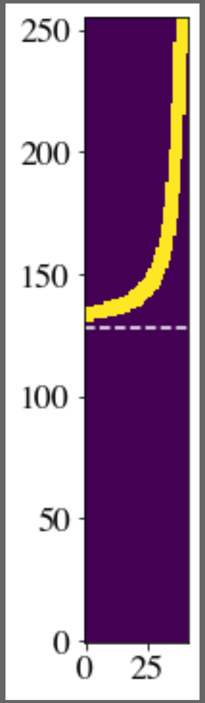


Making a 'T-Map' from the Synthetic Flythrough Dataset

The T-Map is a composite image we constructed from the sequence of images.

We select the **same column of pixels** per image (i.e. time step), where the streamer strands stop expanding (straight ahead).

It shows **where the streamer strands leave the FoV** and **indicates their perpendicular distance from orbital track.**



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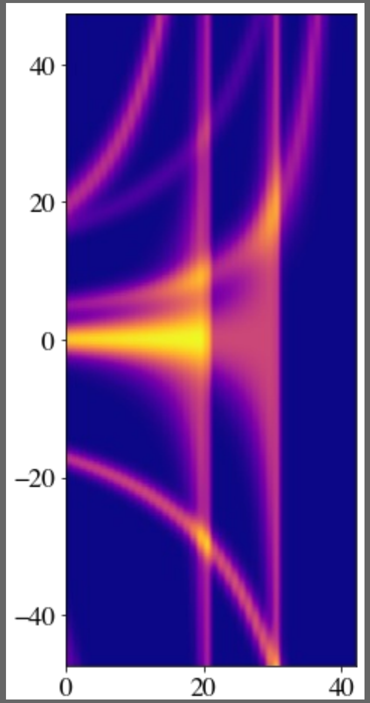

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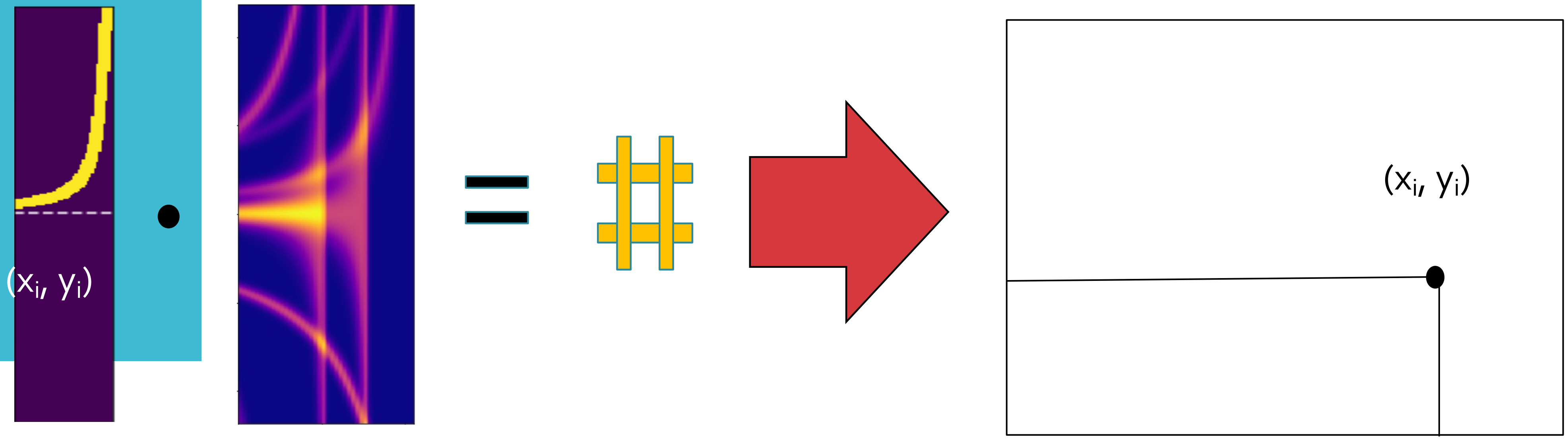
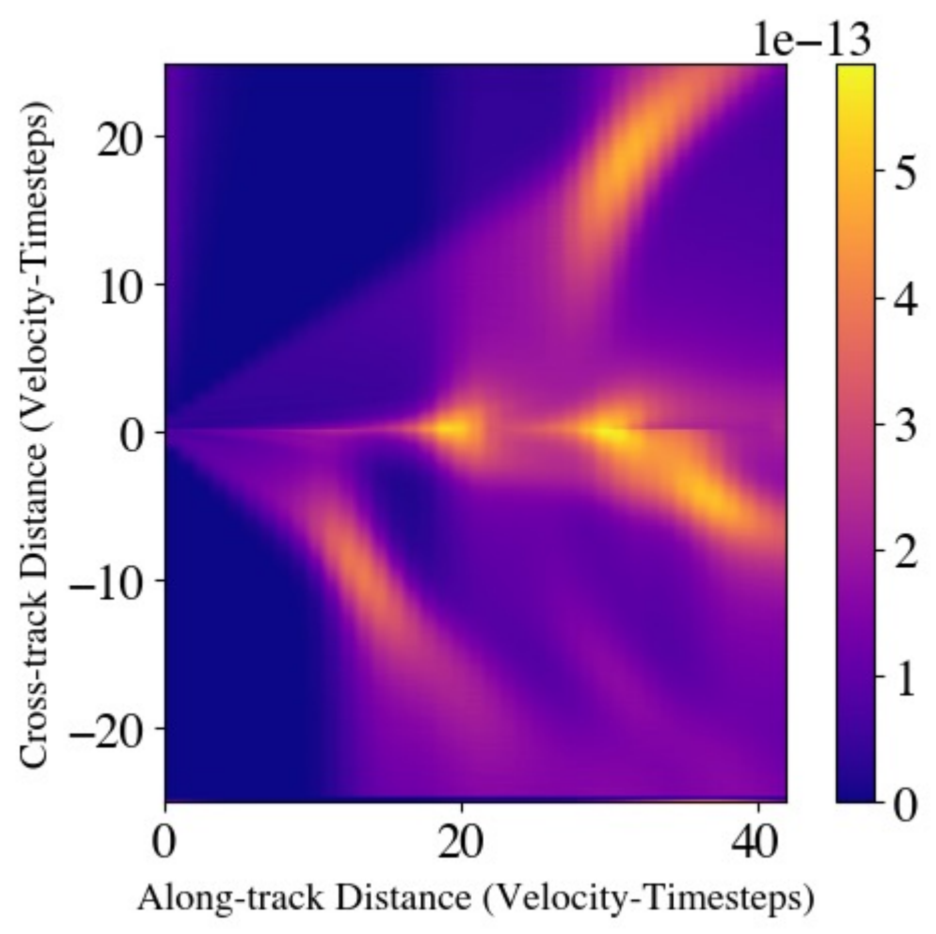
Taking the Dot Product of Each Basis Function with the T-Map

Populating the Tomogram with Dot Products

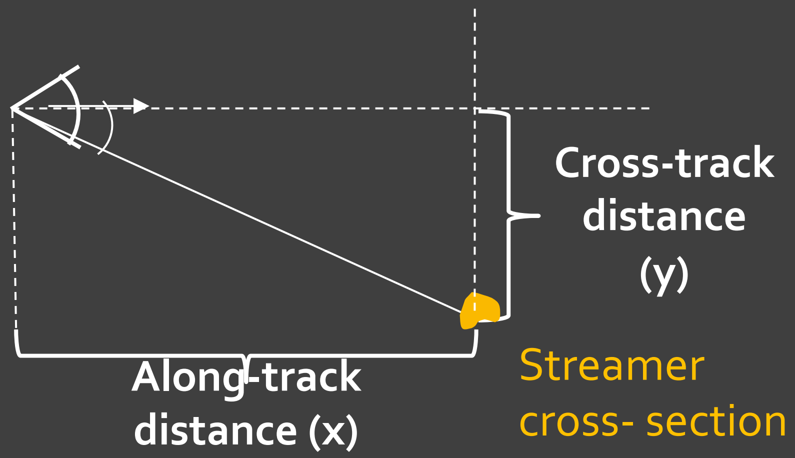
- The tomogram is an **output image** whose **every pixel coordinate corresponds to a unique basis function parameter pair**.
- Our units are 'velocity timesteps' where we have set the PSP speed to 1 km/s.
- Bright spots on the tomogram ought to tell us where the best agreement between the basis elements and the T-Map lie.



Results:
The Tomogram



- The tomogram
  - is a **cross-section** of the placement of all the features in the model,
  - gives the **physical distance** of the parameters in the vicinity of the spacecraft, and
  - will allow us to compare WISPR images and *in situ* data.



Analysis of the Tomogram

Comparing the centroids on our tomogram to the ground-truth streamer footpoint locations (bottom plot), they **don't match up.**

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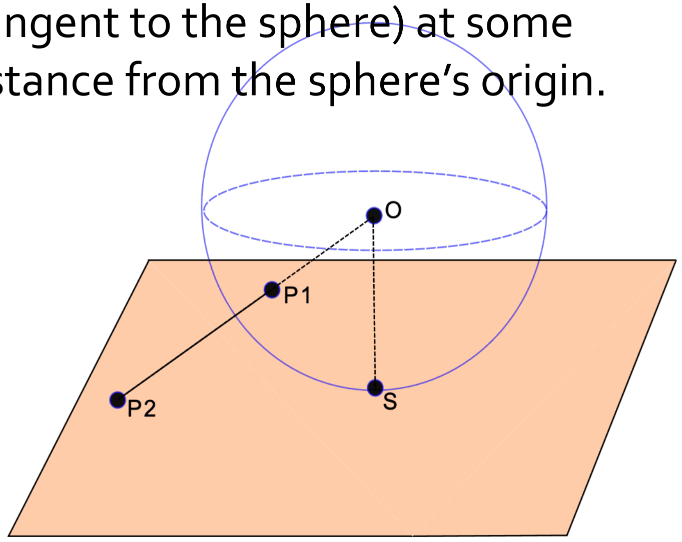
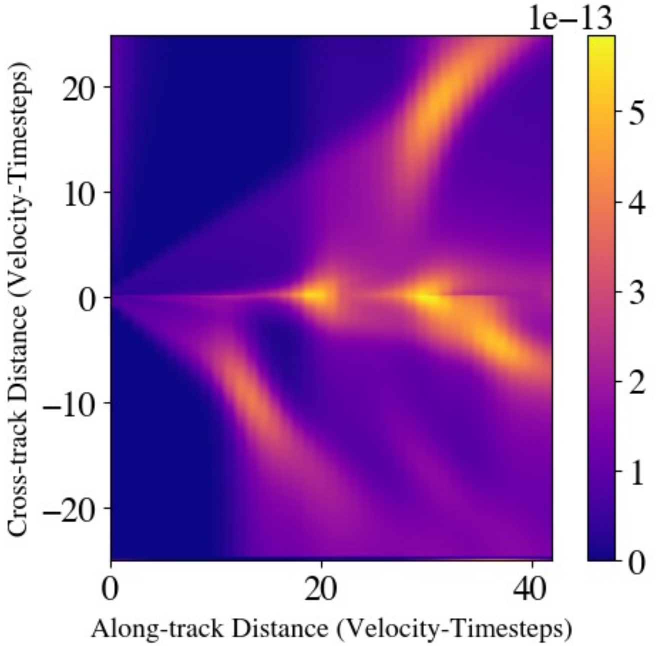
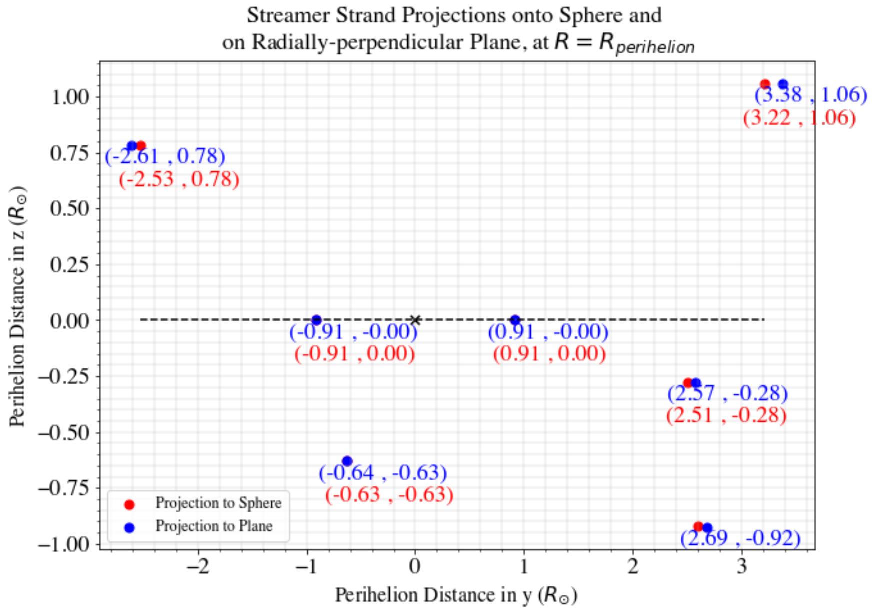
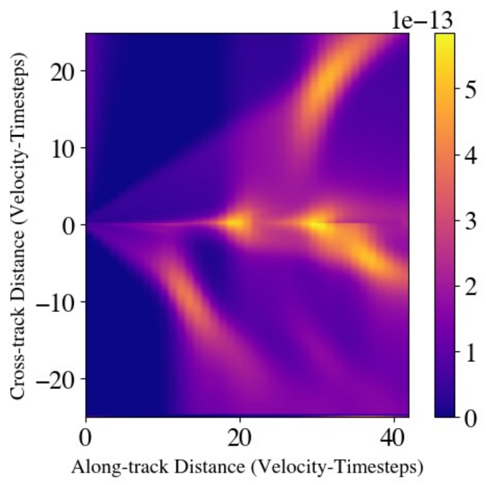
A Gnomonic projection tells us where a point on a sphere lies on a plane (tangent to the sphere) at some distance from the sphere's origin.







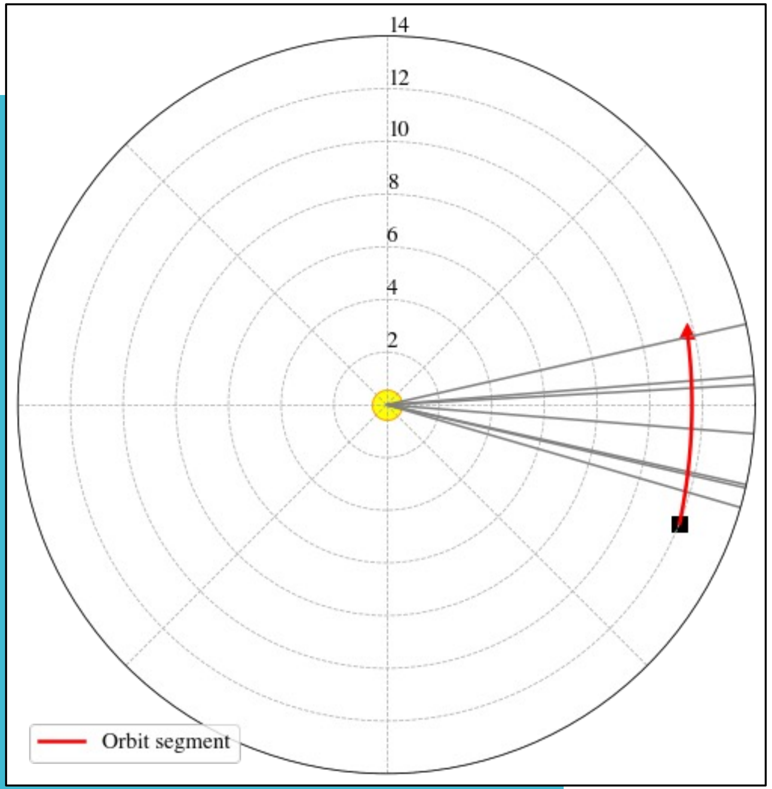
Recap III.

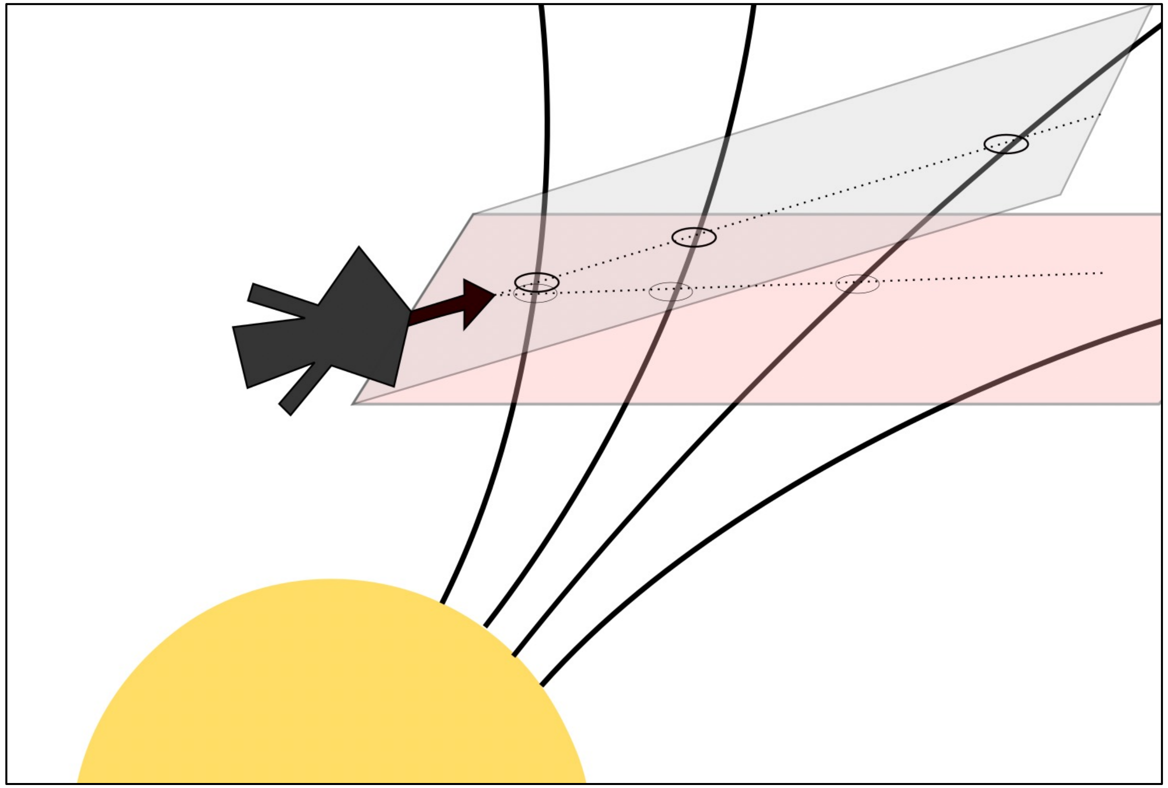


- With a model dataset, we created a T-Map against which we could compare the image curves.
- To compare, we took the dot product of each basis element with the T-Map and filled in a tomogram.
- The tomogram – a cross-section of the corona near PSP's trajectory – indicates the positions of the streamer strands on a plane that runs along and perpendicular to the track.
- Our tomogram results (i.e. extracted positions) did not match up with the known locations of the stria in the model, telling us that something in our simple method is flawed.

IV. Spherical Geometry for PSP Trajectory

Continuing with our iterative approach, let's try the next-simplest geometric approximation for the orbital path: a circle.



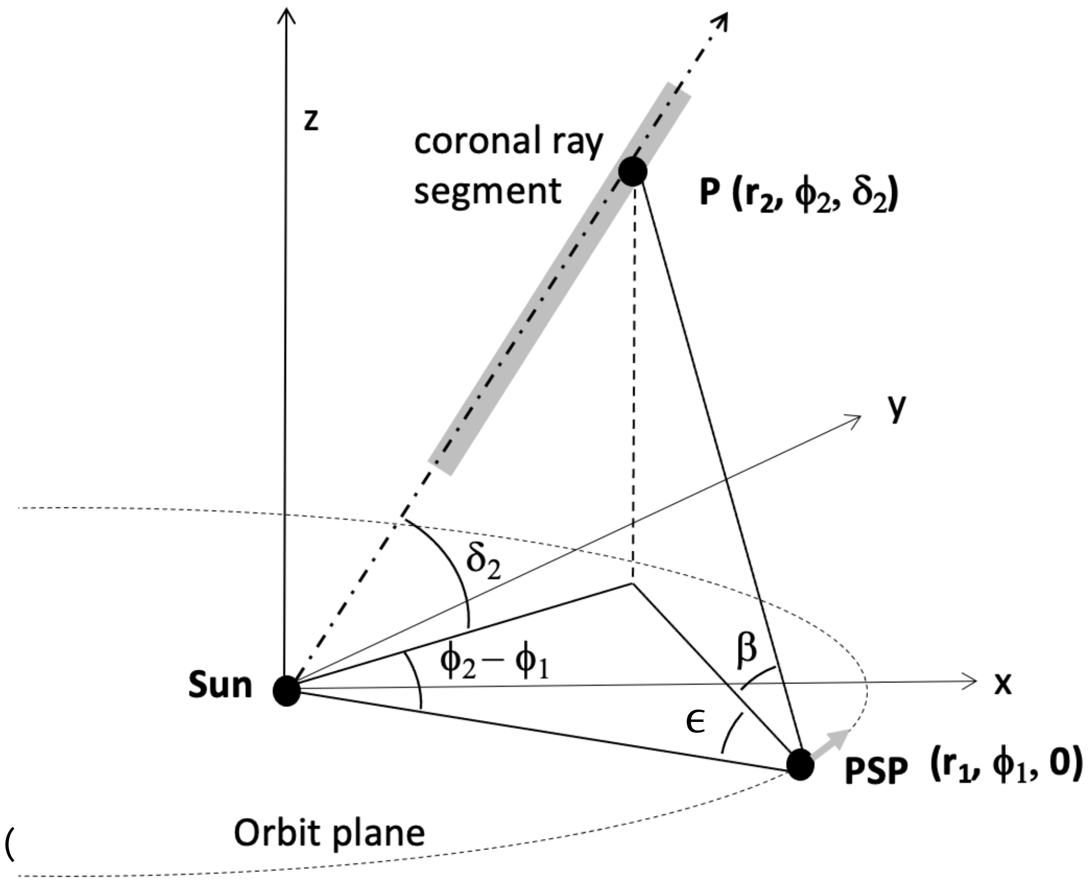


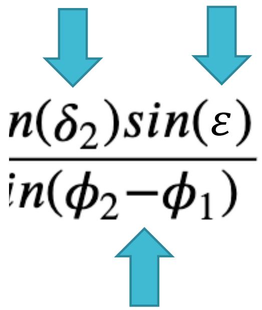
Spherical Orbital Geometry

- Both the **gray** plane and pink plane intersect the features at different locations along the rays.
- It is critical that our model captures the plane corresponding to the WISPR direction of motion.
- The linear approximation may not be capturing the right dihedral plane!

A New Family of Arctangent Functions

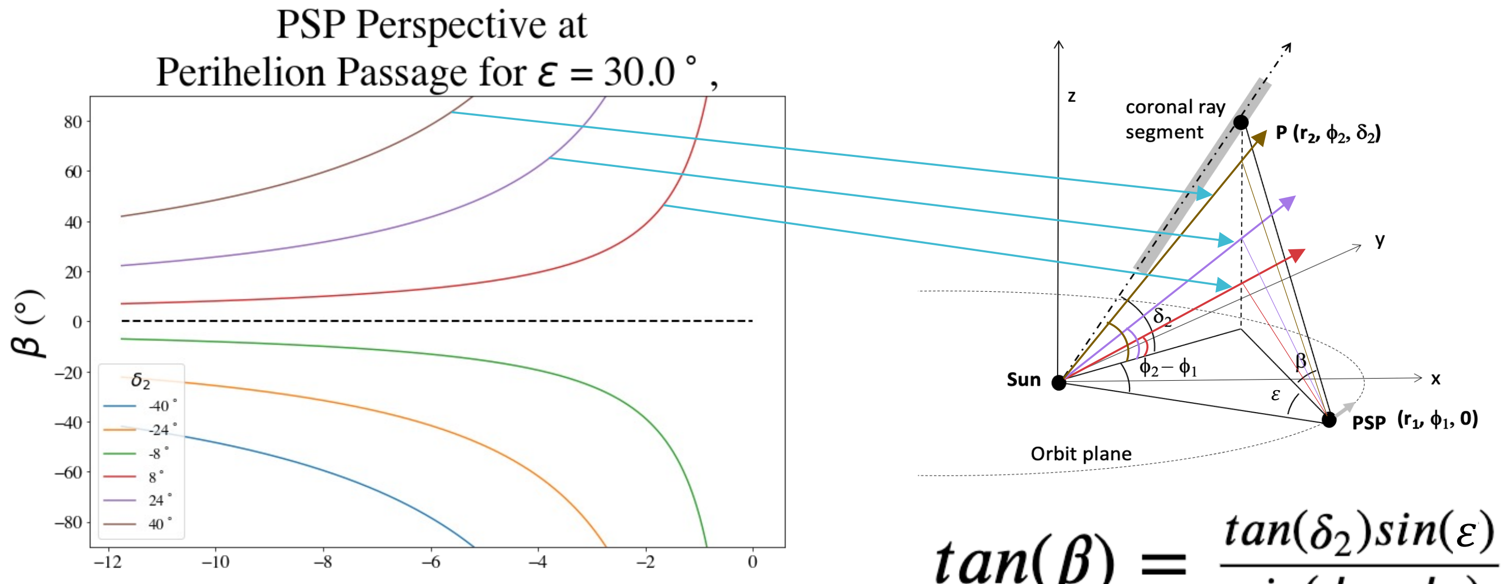
- We derived a new closed-form analytic expression to model the apparent kinematics of stationary solar wind features, in **3D spherical geometry**.
- Note: There are **five angles** relating the (moving) spacecraft to the (stationary) feature.



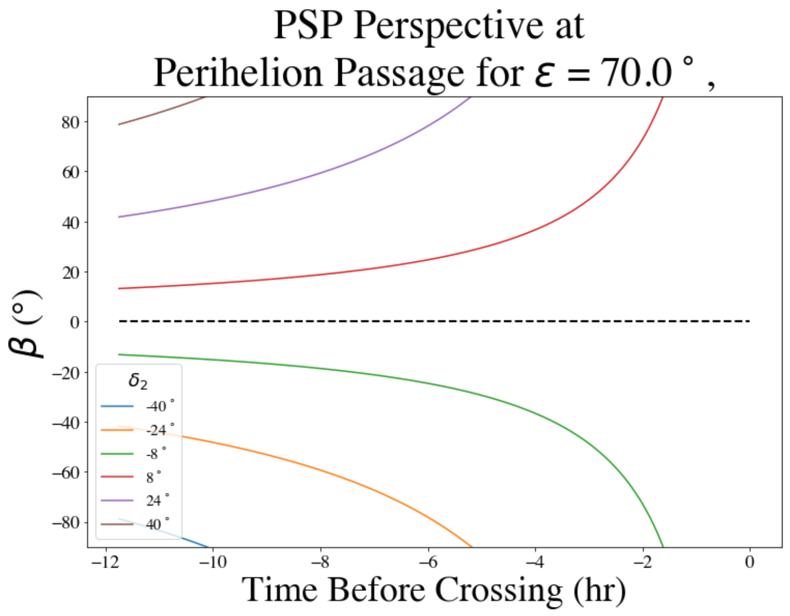


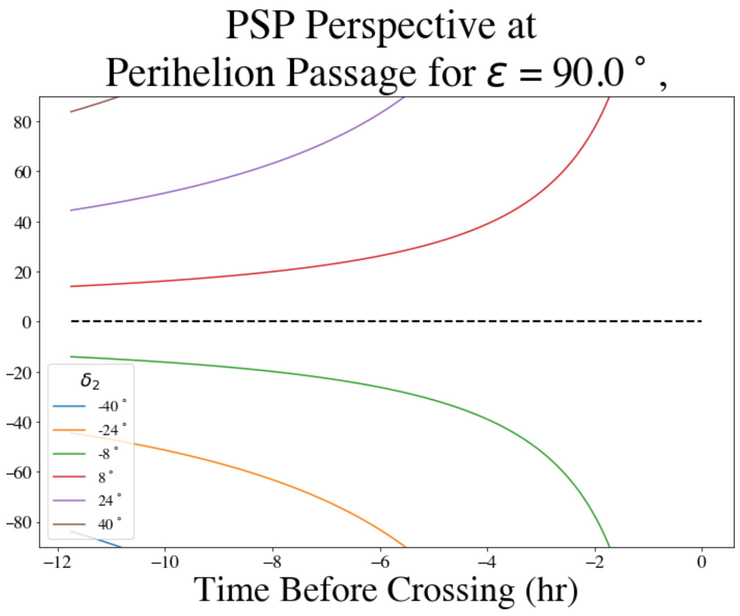
Credit: Liewer et al. (

The New Analytic Arctangent Functions

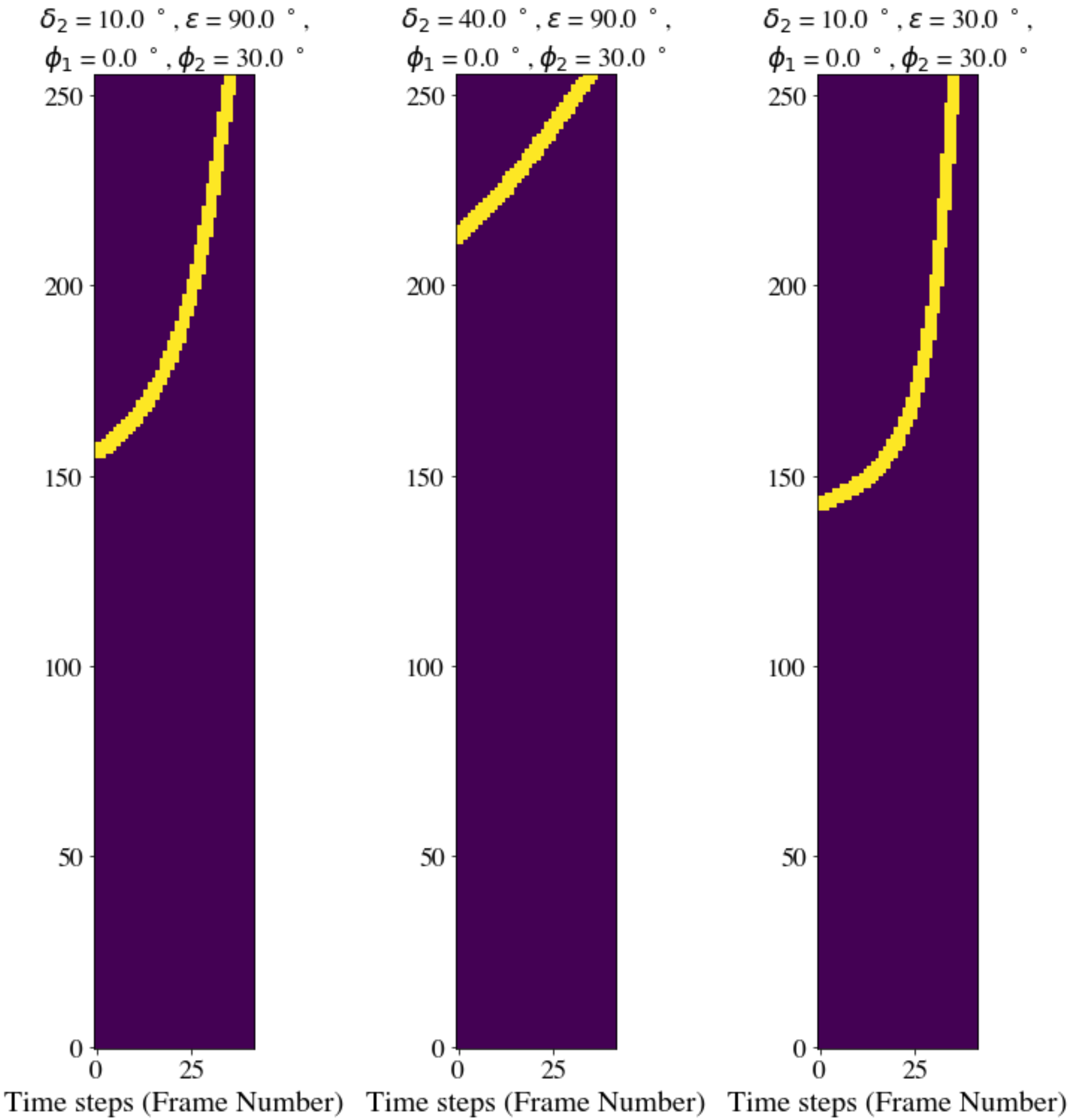


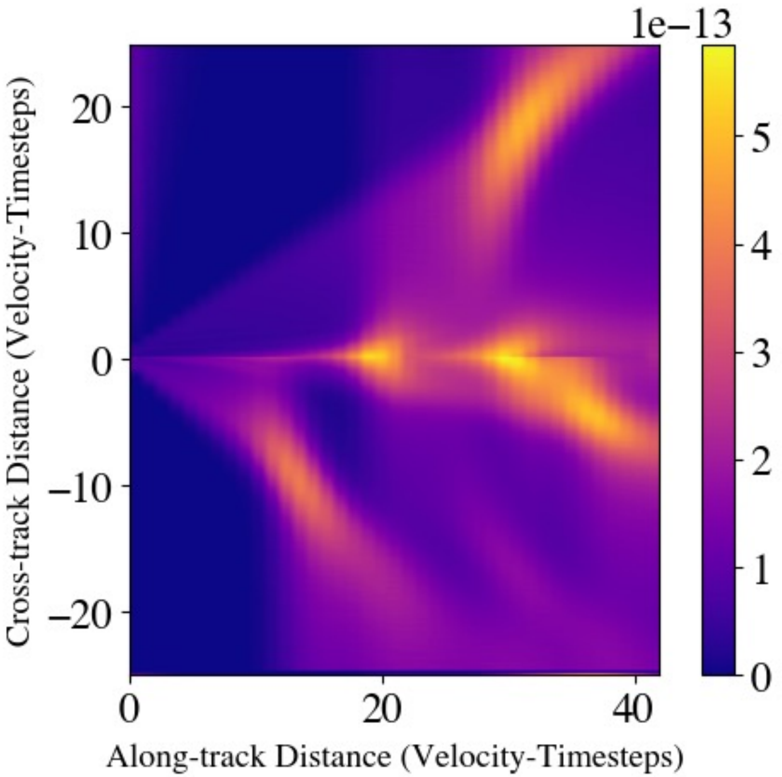
$$\tan(\beta) = \frac{\tan(\delta_2)\sin(\varepsilon)}{\sin(\phi_2 - \phi_1)}$$

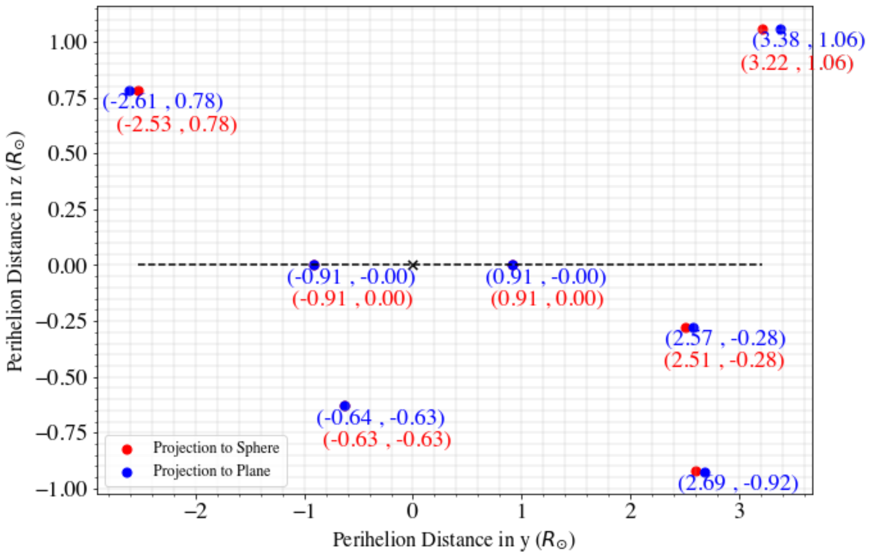


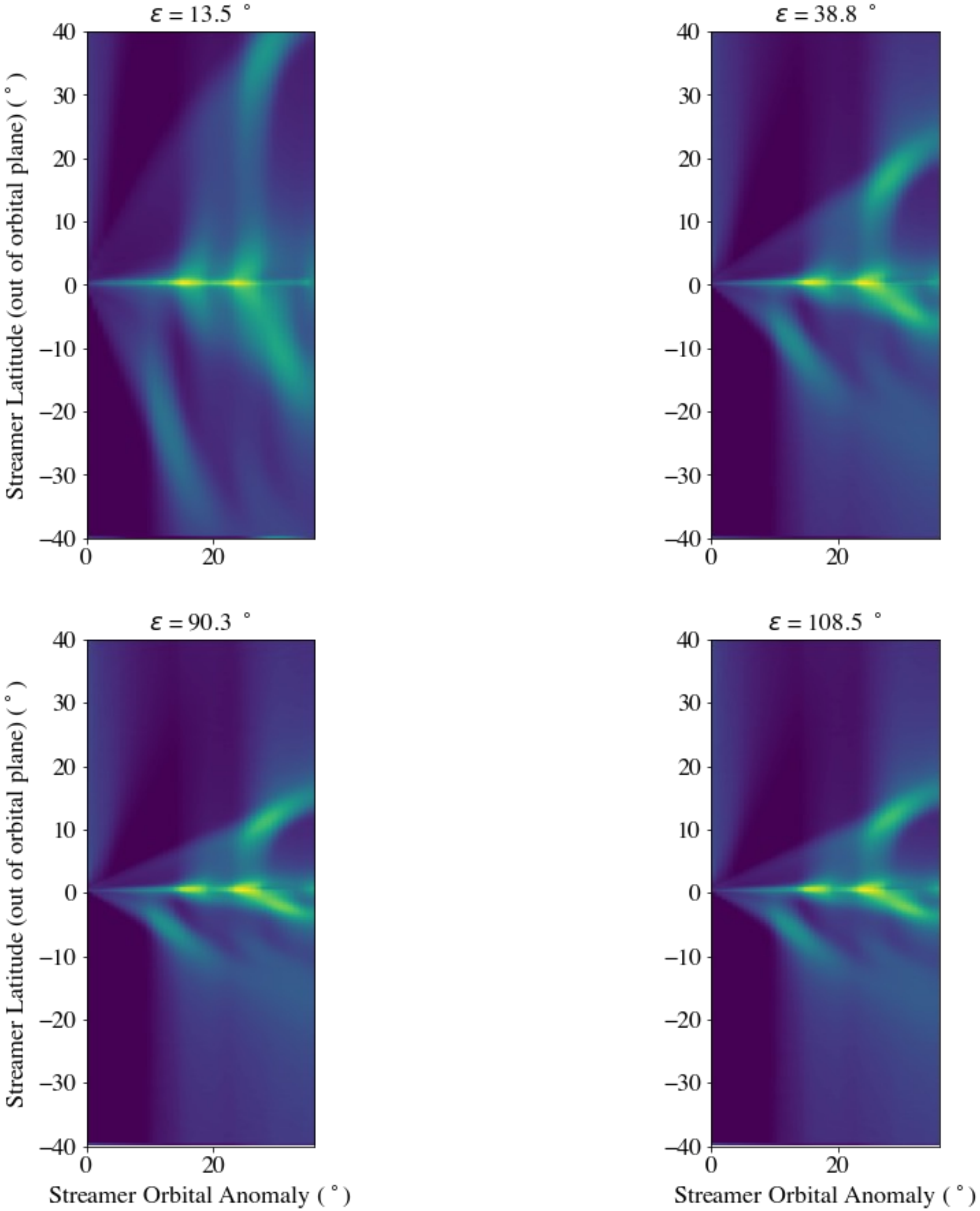


New Basis Elements (i.e. Image Curves)

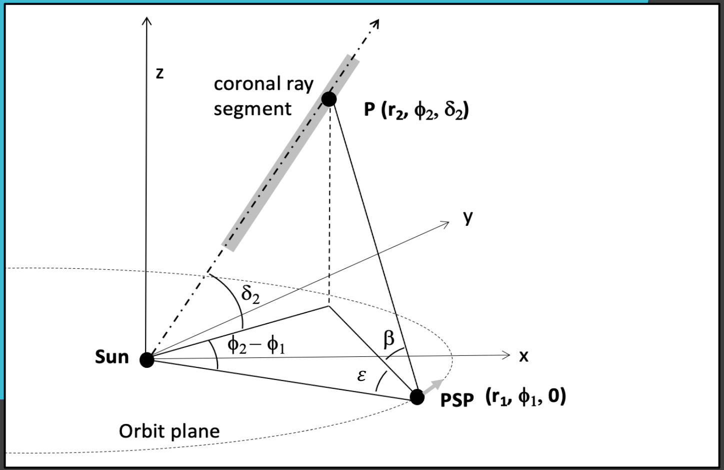



1e−13
Cross-track Distance (Velocity-Timesteps)
Along-track Distance (Velocity-Timesteps)


(-2.61 , 0.78)
(-2.53 , 0.78)
(3.38 , 1.06)
(3.22 , 1.06)
(-0.91 , -0.00)
(-0.91 , 0.00)
(0.91 , -0.00)
(0.91 , 0.00)
(2.57 , -0.28)
(2.51 , -0.28)
(-0.64 , -0.63)
(-0.63 , -0.63)
(2.69 , -0.92)
Projection to Sphere
Projection to Plane
Perihelion Distance in z ($R_\odot$)
Perihelion Distance in y ($R_\odot$)


$\varepsilon = 13.5$ °
$\varepsilon = 38.8$ °
$\varepsilon = 90.3$ °
$\varepsilon = 108.5$ °
Streamer Latitude (out of orbital plane) (°)
Streamer Orbital Anomaly (°)
Streamer Orbital Anomaly (°)

Recap IV.



- We tried another approximation of the orbital path: spherical geometry.
- Following the same steps as for the linear orbit approximation, we produced but several tomograms – for every value of ε.
- We again found that our results didn't match the known stria locations and thus have more work to do!
- It's critical that we 'get it right' with the model data before working with real WISPR image sequences.

V. What's Next?

Next Steps

Resolving issues with synthetic flythrough data

- Projection we aren't accounting for?
- What other effects, features in the Thernisien & Liewer model don't we understand?

→ **Performing line-of-sight integration myself or budling my own synthetic flythrough model**

Dealing with non-orthogonality

- We can explore and employ regularization techniques to reduce 'overlap' between basis elements.

Inverting real WISPR data

- We will **reproject** images near perihelion (within ~a day) and invert for radial features using the same method applied to the synthetic data.
- Eventually we would love to compare these reconstructions with *in situ* data for streamer belt/ plasma sheet crossings.

Thanks, everyone, for your ear!

What questions, ideas, and feedback have you for me?