Validation of 3D CME Trajectories through MHD Simulation for the PUNCH Mission

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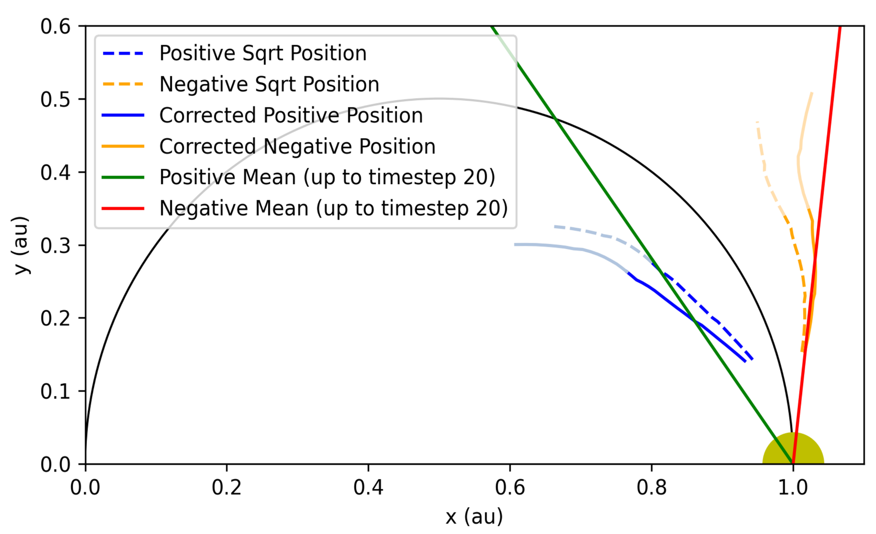
Abstract

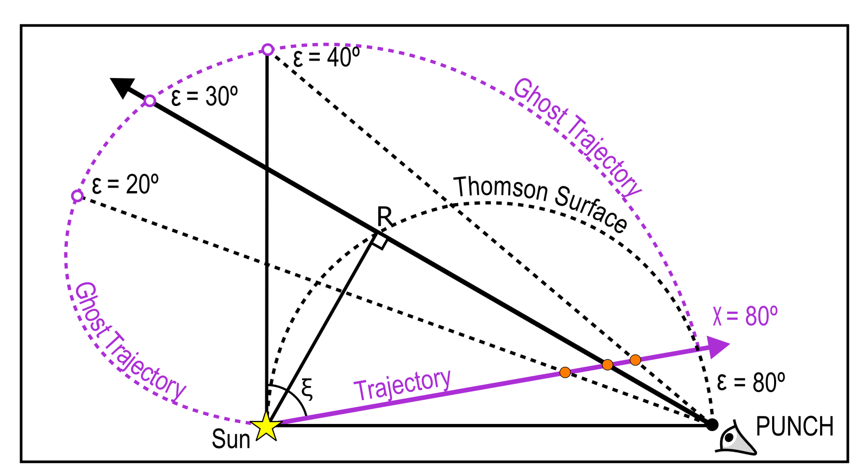
We provide a method for determining the position and trajectory of coronal mass ejections (CMEs) through utilizing polarized and unpolarized (pB and B) images of a simulated inner heliosphere. The simulated data matches the pB and B images to be gathered from the PUNCH Mission. Our analysis involves a custom background subtraction method followed by analytic inversion of the subtracted data to reveal scattering angle. We also implement a simple geometric perspective correction to account for discrepancy between the location of the observed and actual CME front. Finally, we use time-series data to distinguish between "real" and "ghost" CME trajectories.

Analytic Inversion

Along the bright "leading edge" of a CME, multiple sources of scattered light are compacted along the line of sight, allowing us to use the compact inversion equation from DeForest et. al. 2013, displayed below. ξ is the out-of-plane sky angle and ε is elongation angle, labeled in the lower panel to the right. The simulated pB and B images and a hand selected a point located on the CME front yield the necessary pB/B ratio to caclulate the out-of-plane sky/sun exit angle. As the sky angle equation contains a $\pm$, there are two possible exit angles for each sampled point. Separating the two angles requires a time series of observations: the correct trajectory is nearly radial, and the "ghost trajectory" has unphysical lateral motions. The upper panel displays the output of the methods described here, using an MHD simulation with an exit angle parameter of 0^o.

$$\xi = \varepsilon + \arcsin\left(\pm\sqrt{\frac{1 - pB/B}{1 + pB/B}}\right)$$

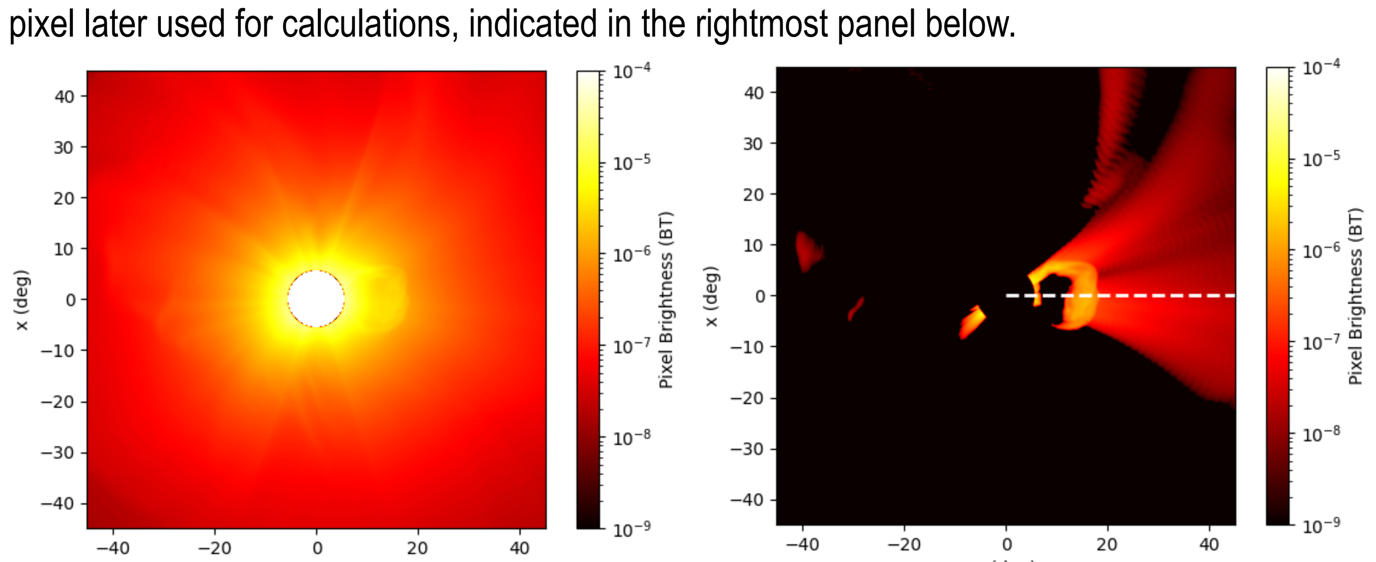




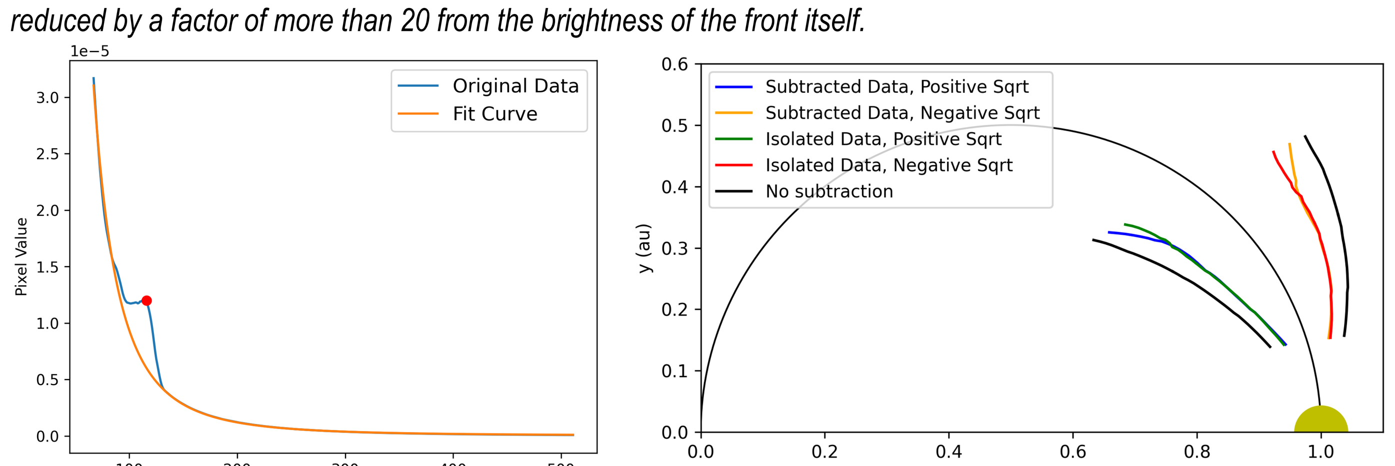
Analytic inversion results from simulated data plotted in space and over time (top) and example "real" vs. "ghost" trajectory ambiguity (bottom). Dashed lines in the upper panel indicate calculation performed before perspective correction. The solution in front of the Thomson Surface in the top panel (blue) is the ghost trajectory in the case, ruled out as it does not lie along a ray passing through the center of the sun. The orange trajectory follows a near-radial trajectory for early time steps. Dashed lines indicate caclulations before perspective correction.

Background Subtraction

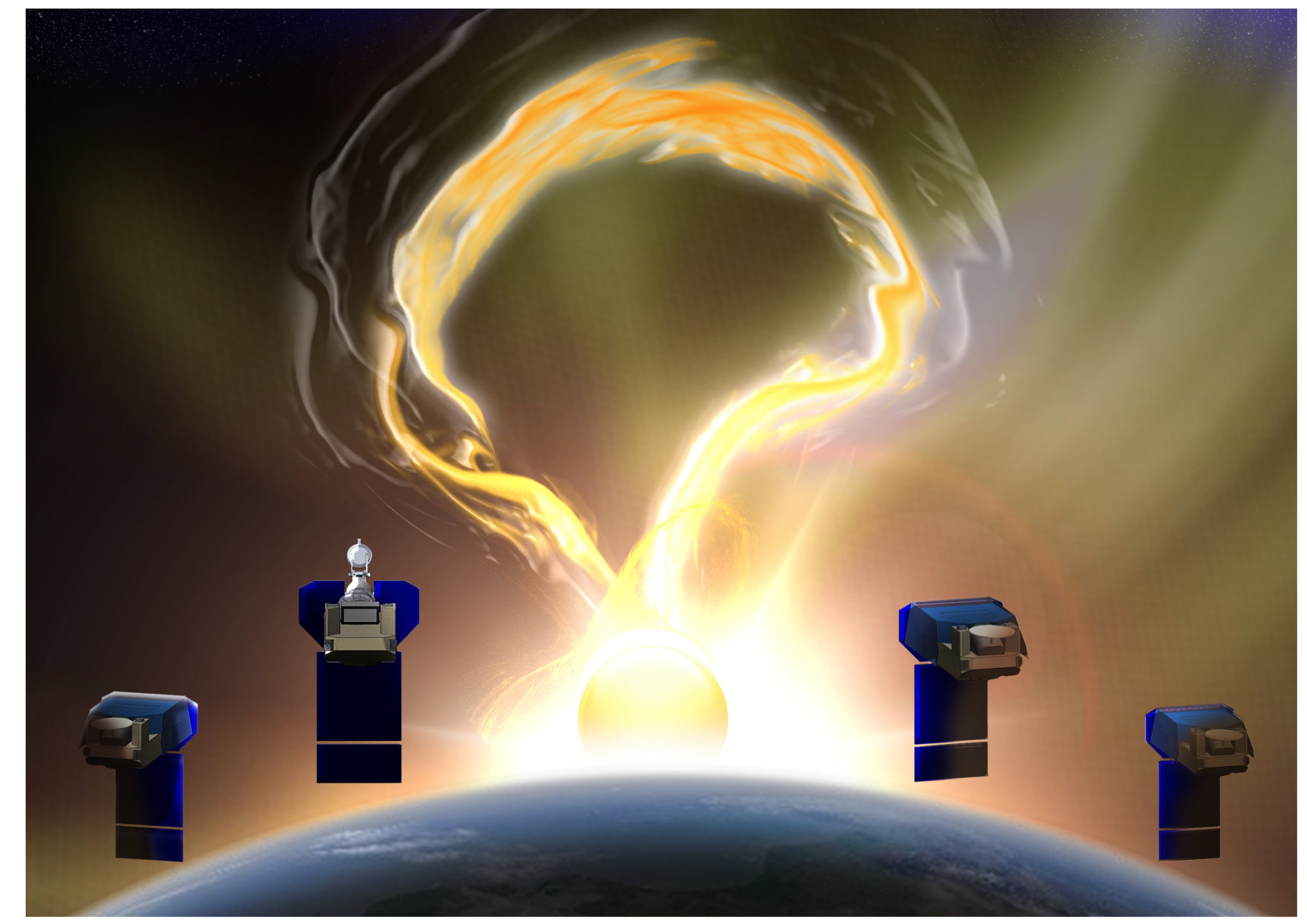
Background subtraction is necessary both to isolate the K corona from the F corona and (in real instrument data) other sources of light, and to separate the K brightness of a particular feature (e.g., the CME bright front) from the K brightness of the rest of the corona along a given line of sight. pB and B data is first coverted to the tangentially-aligned and radially-aligned virtual-polarizer brightnesses, B_T, and B_R. We fit an analytic function to each image along a radial line containing the pixel later used for calculations, indicated in the rightmost panel below.



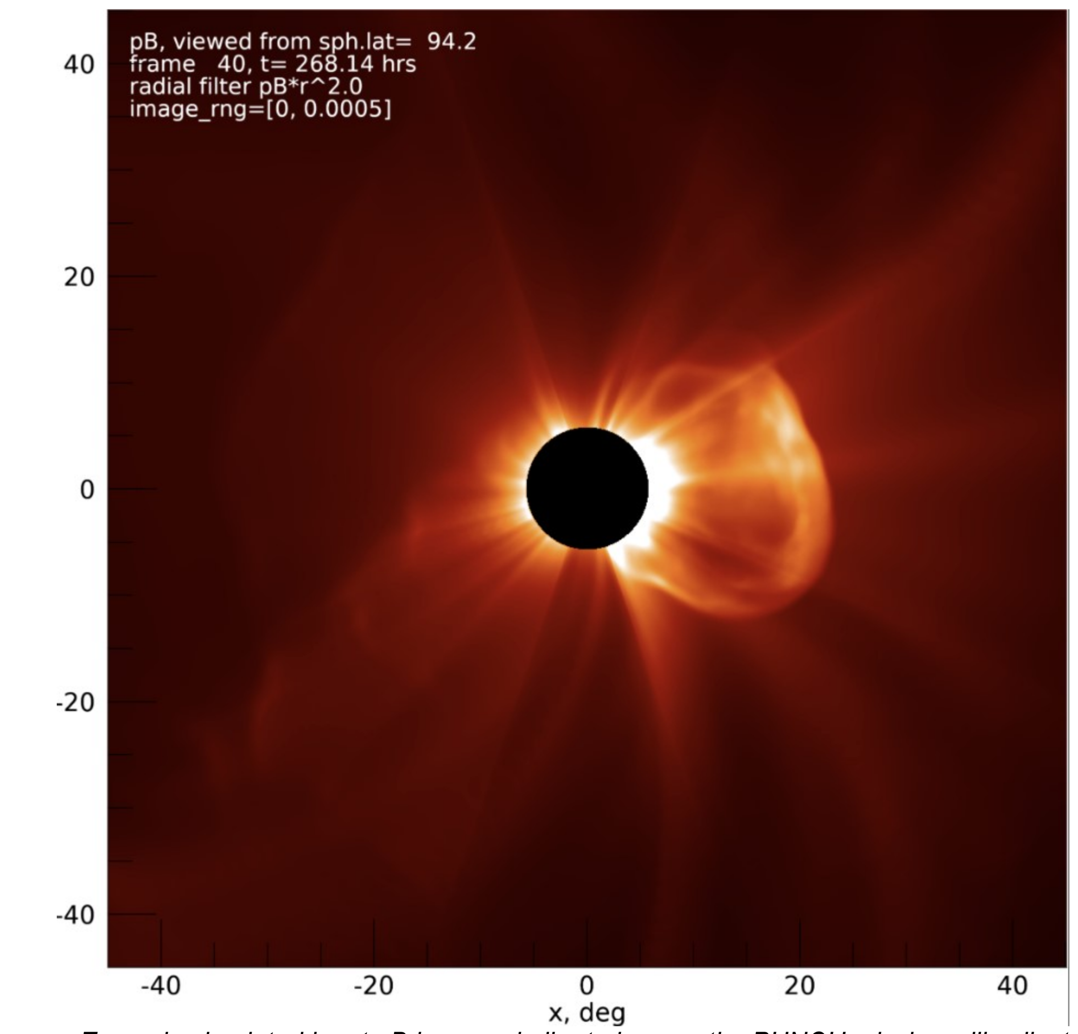
Images of MHD simulation before (left) and after (right) background subtraction show the effectiveness of the fit method described. The dashed line indicates the ray along which data was sampled to fit the background (the same ray containing the sampled locations on the CME front). In the background subtracted frame, the CME is effectively isolated from the steady background K corona. Note the logarithmic brightness scale: even the bright fan features in front of the CME are reduced by a factor of more than 20 from the brightness of the front itself.



Left: Radiance vs. radial distance in pixels from center of sun on B_T image. Data is gathered along a ray passing through a selected point on the front of the CME. Hand-selected point on CME front is displayed in red. Orange fit curve is used for image subtraction displayed in the figure above.
Right: Subtracted output calculations plotted over calculations with the background entirely removed from the simulation images, isolating the CME. Original data without subtraction is plotted as reference.



PUNCH is a mission to image the outer reaches of the solar corona and the inner portion of the solar wind as a single, unified system. While the mission is suitable for studying the zodiacal light, the primary observing requirements are to image and track "K corona" plasma structures in 3-D using their polarization characteristics.



Example simulated input pB image, similar to images the PUNCH mission will collect. Each pB (polarized brightness) image is paired with a B (total brightness) image. The pB/B ratio allows us to determine scattering angle, and thus, 3D location.

Perspective Correction

As a final step, we apply a perspective correction to deduce the true exit angle of the CME from the observed exit angle of the CME front. Indicated in the panel to the right, the observed exit angle (ξ) does not align with the true exit angle (ξ'), since the 2-D projected leading edge of the CME, is not the same as the 3-D leading point of the CME. To find the angle offset with respect to the center of the CME sphere, θ, requires modeling the shape of the CME. A simple model is a sphere, with projected outline matching the observed curvature of the CME leading edge. The equation relating key geometry parameters to offset angle θ is below.

$$\theta = \arccos\left(\frac{r}{\ell}\right) + \arccos\left(\frac{d^2 + \ell^2 - R^2}{2d\ell}\right) - \pi$$

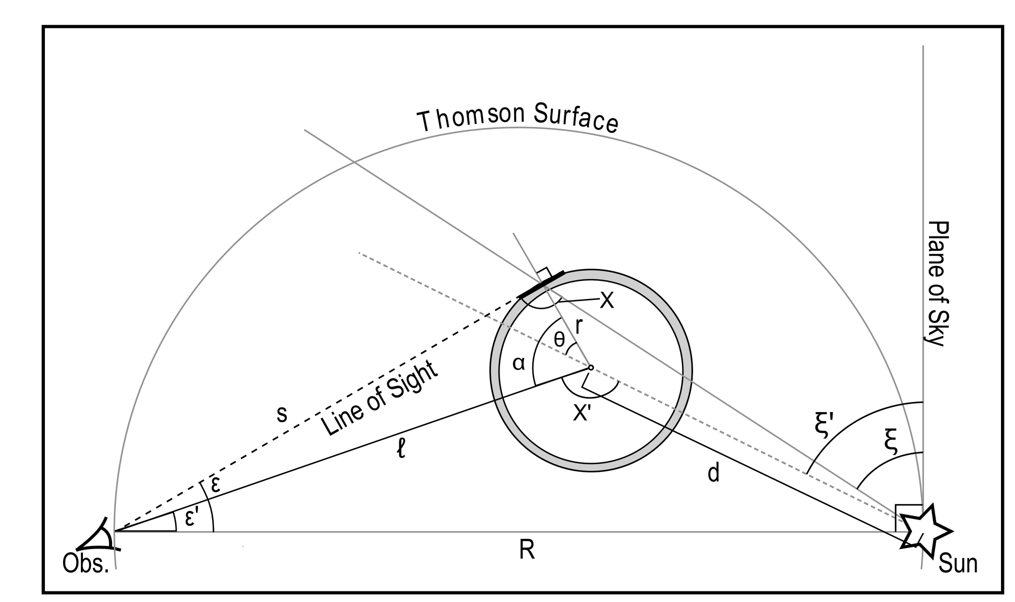
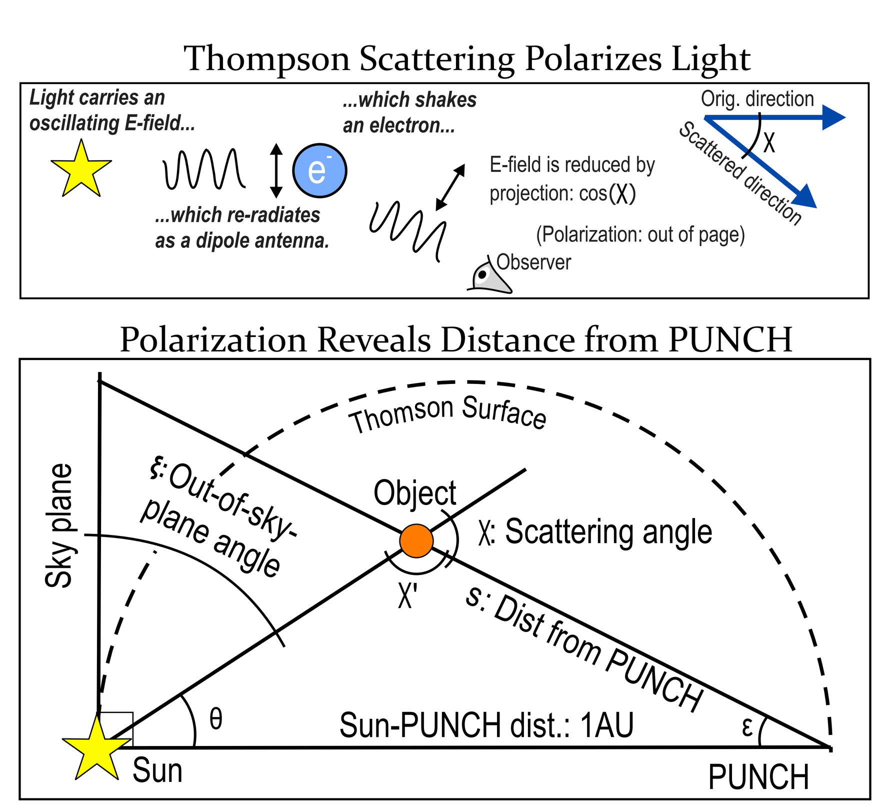


Illustration of error in calculated exit angle ξ as a result of the geometry of the CME. The CME can be modeled as a bounding sphere, where the front lies on the tangent line, labeled "Line of Sight." Derived quantity, ξ', represents the true exit angle of the 3D leading point.

How Polarization Reveals 3D Structure



Thomson scattering polarizes light perpendicular to the plane formed by the Sun, the Observer, and the scattering electron (Minnaert, 1930). The brightness (**B**) - which depends on the square of the E-field - has two components: radially polarized (**B_R**) and tangentially polarized (**B_T**). The polarization ratio is **PR = $B_R/B_T \approx \cos^2 X$**, so **X≈acos√(PR)**. This is exact if we assume the Sun is a point source - appropriate for heights > 2-3R⊙. **PR** can also be written in terms of the observed degree of polarization: **PR = (1-p)/(1+p)**, where p is the degree of polarization and **p = pB/B** .
We locate objects in 3D by measuring the polarization ratio PR, and inferring the angle **X = acos(±√PR)**. The two solutions - front vs. back - can be distinguished. The complement **X'** and known elongation angle **ε** then reveal the out-of-sky angle **ξ**; for the front-side case shown here, **ξ = 90° - θ = -90° + ε + X'** and distance **s = (1 AU)(sin θ / sin X')**.

Conclusion

- *We have demonstrated 3D tracking of a realistic CME event using the polarization signal from a simulated PUNCH instrument observing an MHD model.*
- *Performing time-series observations of the polarization ratio on the CME front, we can distinguish between "ghost" and "real" CME trajectories, providing an estimate out-of-plane sky angle for a given CME.*
- *Fitting an analytic function to the background of a CME image allows us to effectively isolate the CME, increasing the accuracy of 3D trajectory calculations.*
- *By modeling the surface of a CME as a sphere, we can analytically correct for perspective effects, yielding the true exit angle of the CME.*