Characterization of Flux-Rope Cross-Section Distortions at Early Stages of Simulated Coronal Mass Ejections

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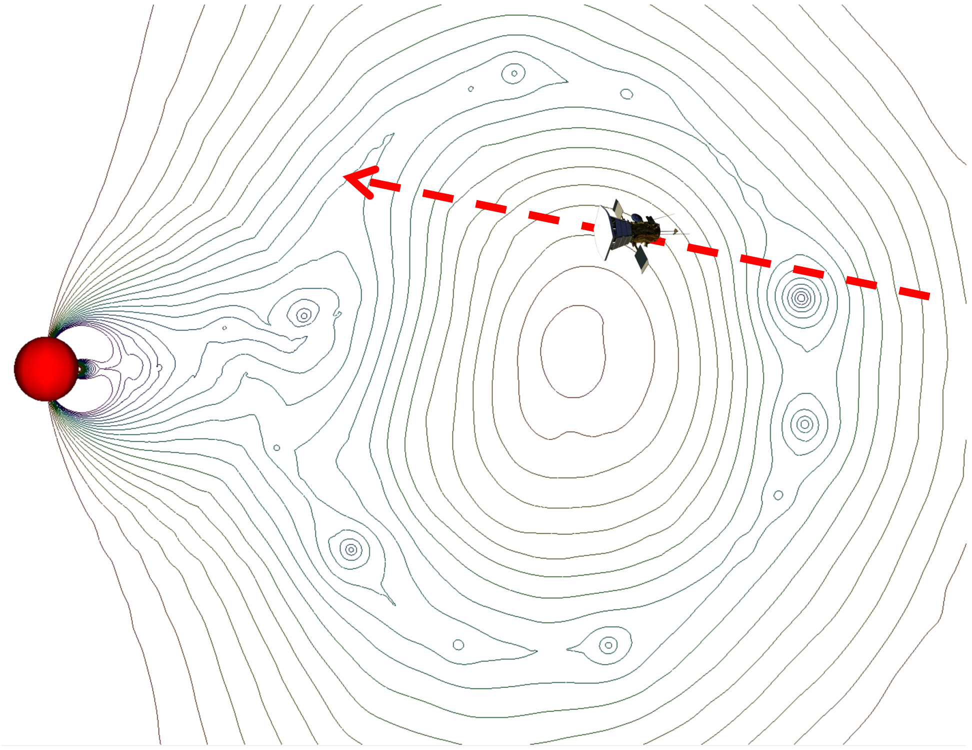
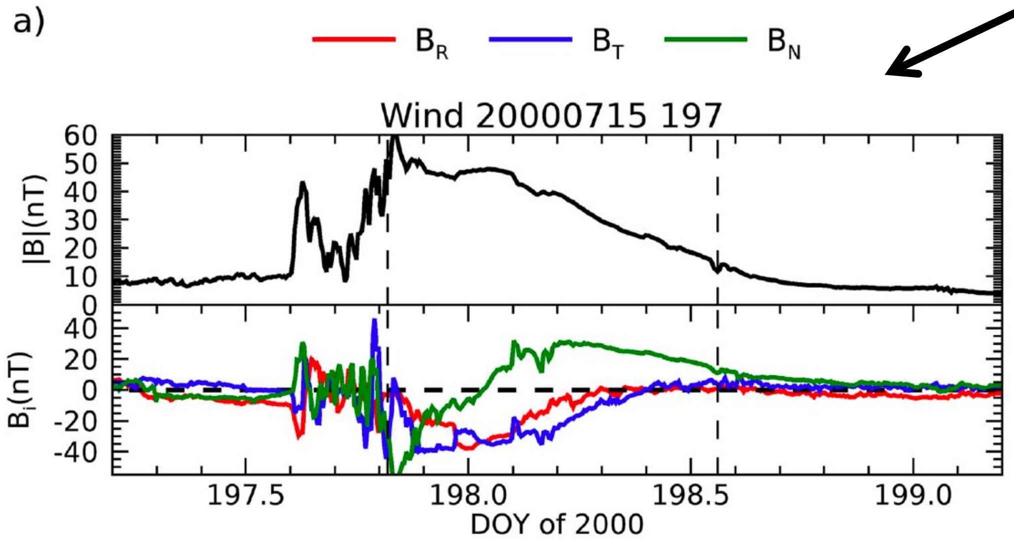
Motivation

- Interpreting in situ observations of coronal mass ejections (CMEs) has been a challenging task for decades.
- Time-series data taken along the path of spacecraft crossing these large-scale and complex structures are usually fitted to models of flux ropes with circular cross section and/or force-free.
- Distortions due to forces exerted by the ambient magnetic field, removal of magnetic flux by reconnection in front of the CME, or pressure from the flare reconnection exhaust at the back of the CME are rarely considered.

Project Goals





From early stages (close to the Sun), compare CME simulations [1] to a recently developed analytical flux rope model [2] to characterize over time:

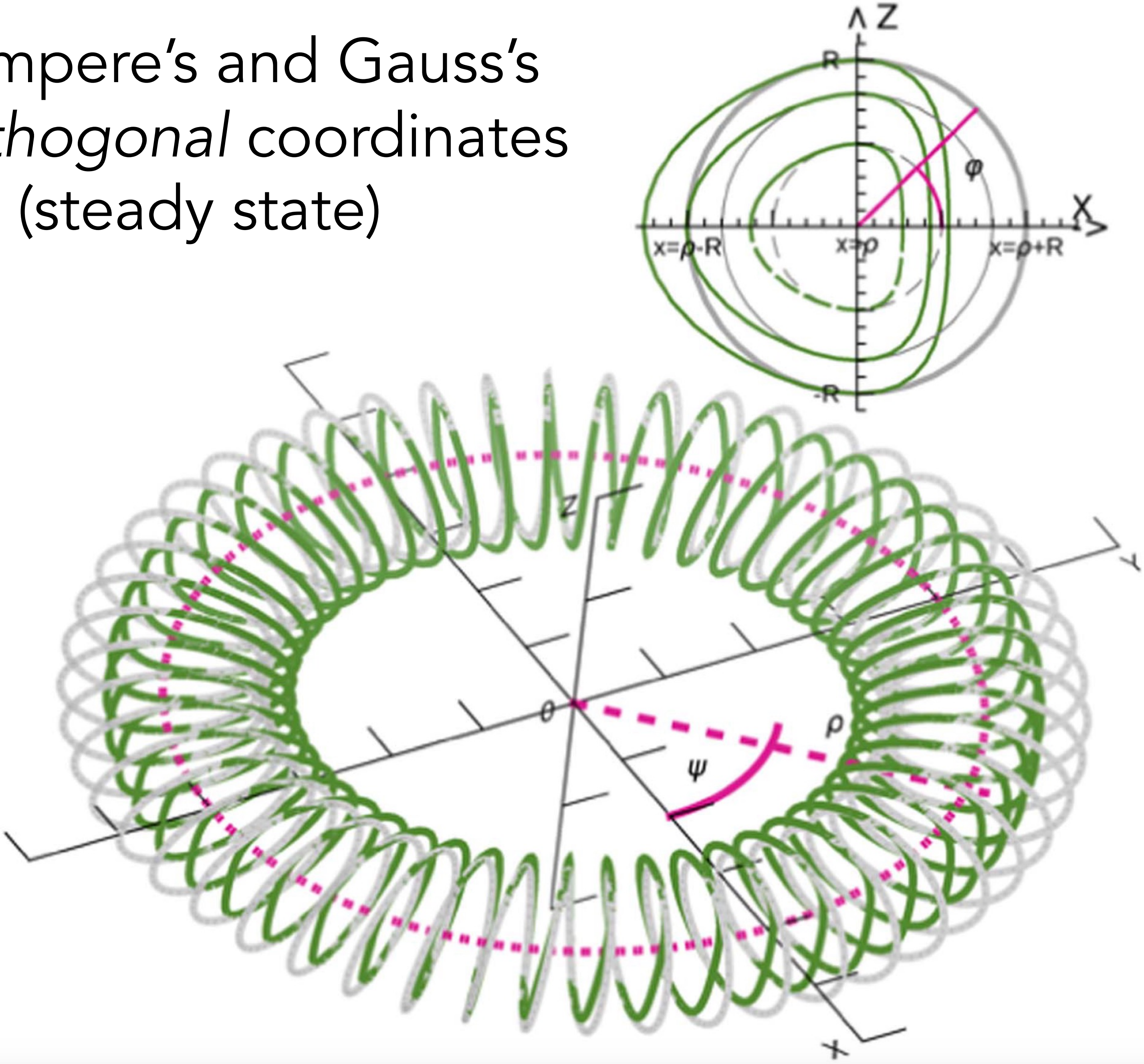
- flux rope's departure from circular cross-section (interpret in situ data of spacecraft crossing a CME, e.g. [2])
- currents and forces (physics of the evolution)

Distorted Toroidal Model [2]

Solution of Ampere's and Gauss's laws in *non-orthogonal* coordinates (r, φ, ψ) (steady state)

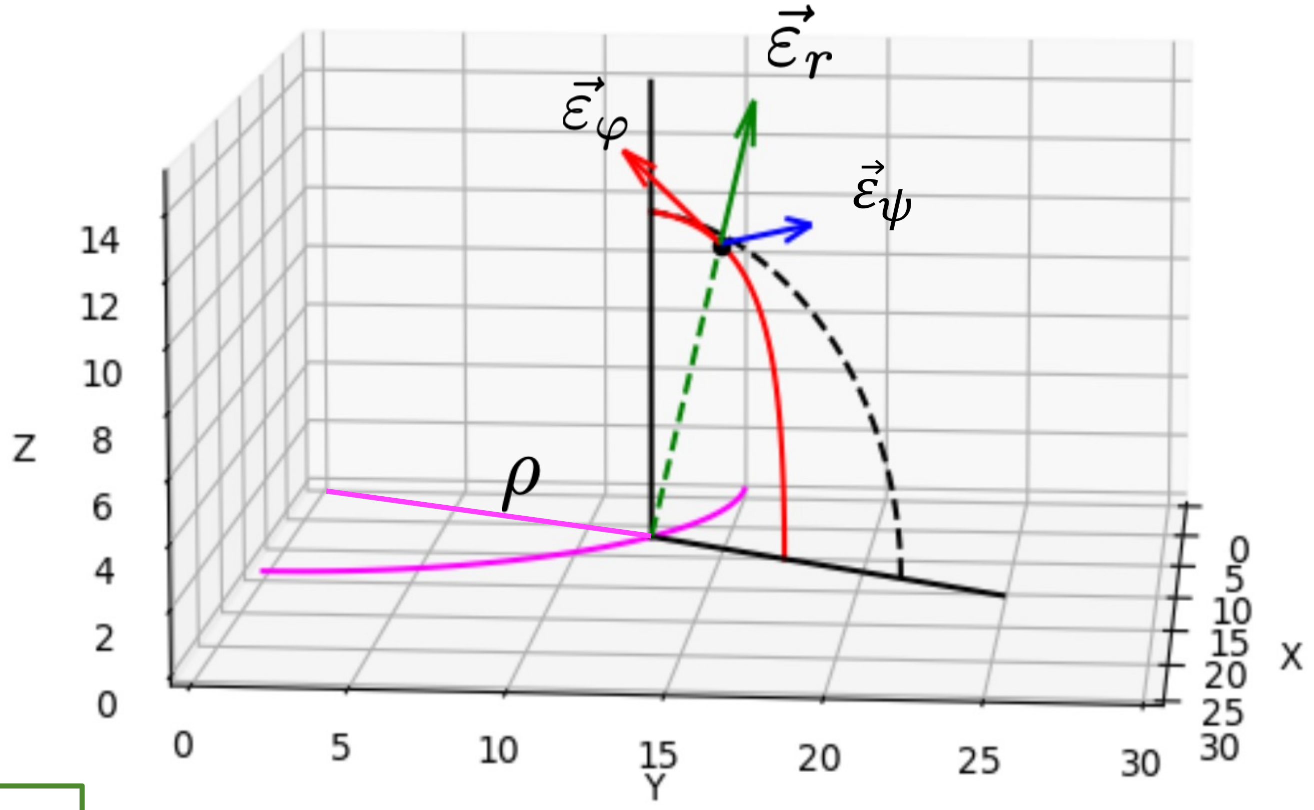
$\frac{d}{d\psi} = 0$ (toroid)

$$B_r = 0$$



Non-orthogonal Coordinate System

(r, φ, ψ)



Flux rope
major radius

$$
\begin{aligned}
x &= [\rho + r\boxed{F(\varphi)}\cos\varphi]\cos\psi \\
y &= [\rho + r\boxed{F(\varphi)}\cos\varphi]\sin\psi \\
z &= r\sin\varphi
\end{aligned}
$$

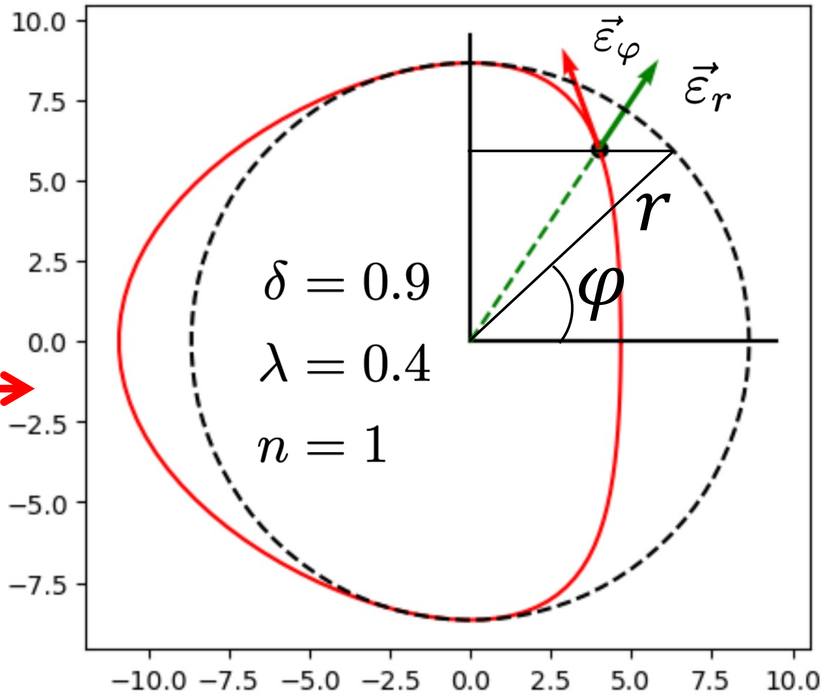
Distortion function

Examples of Distortion Functions

$F(\varphi) = 1$ (circular cross section)

$F(\varphi) = \delta$ (elliptical cross section)

$$F(\varphi) = \delta\,(1 - \lambda \cos^n \varphi)$$



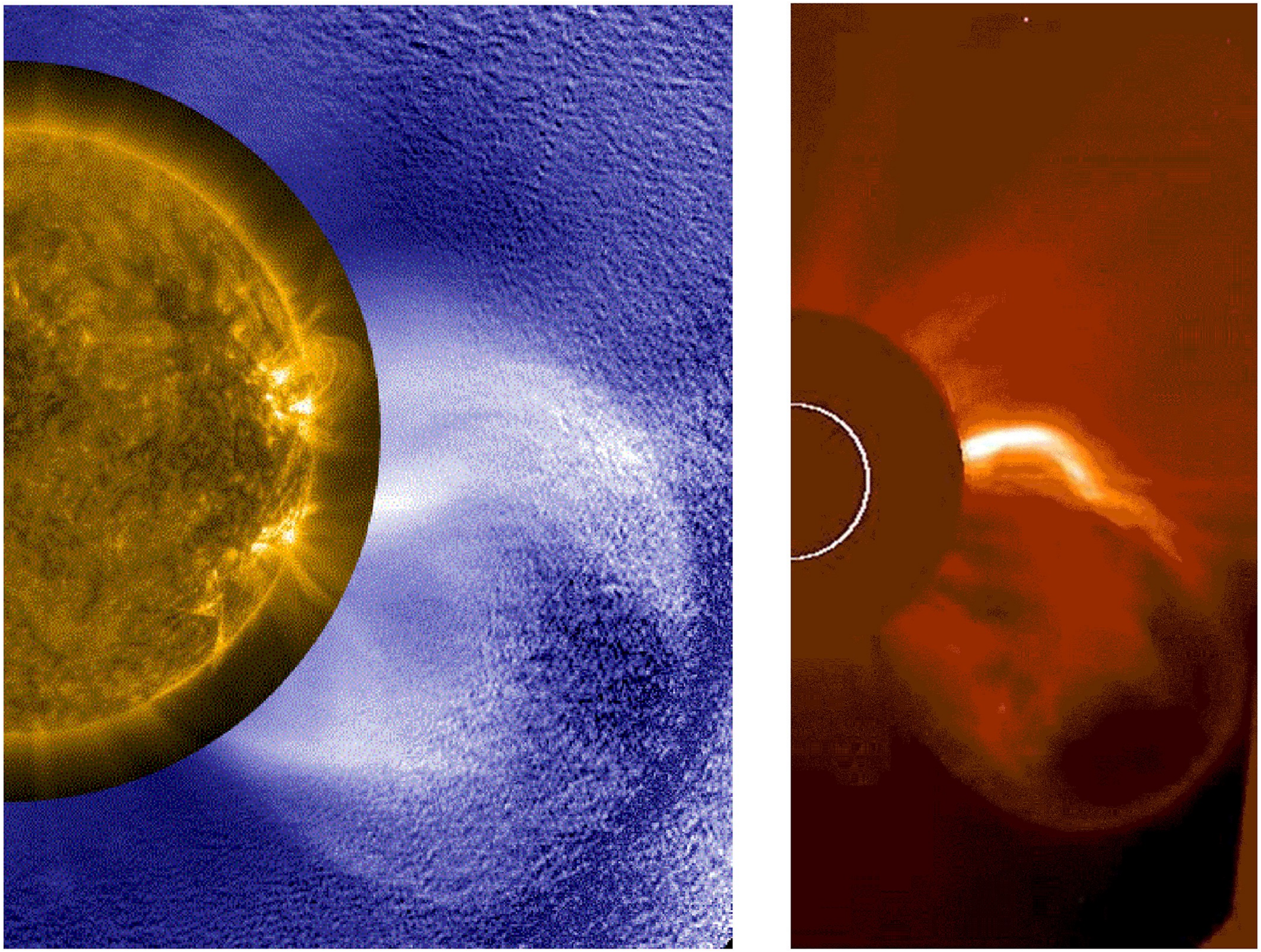
Horizontal /vertical aspect ratio

front-back asymmetry (if n is odd)

Flux-rope cross-section and non-orthogonal coordinates (origin: axis of the flux rope)

$F(\varphi) = ?$ (simulations)

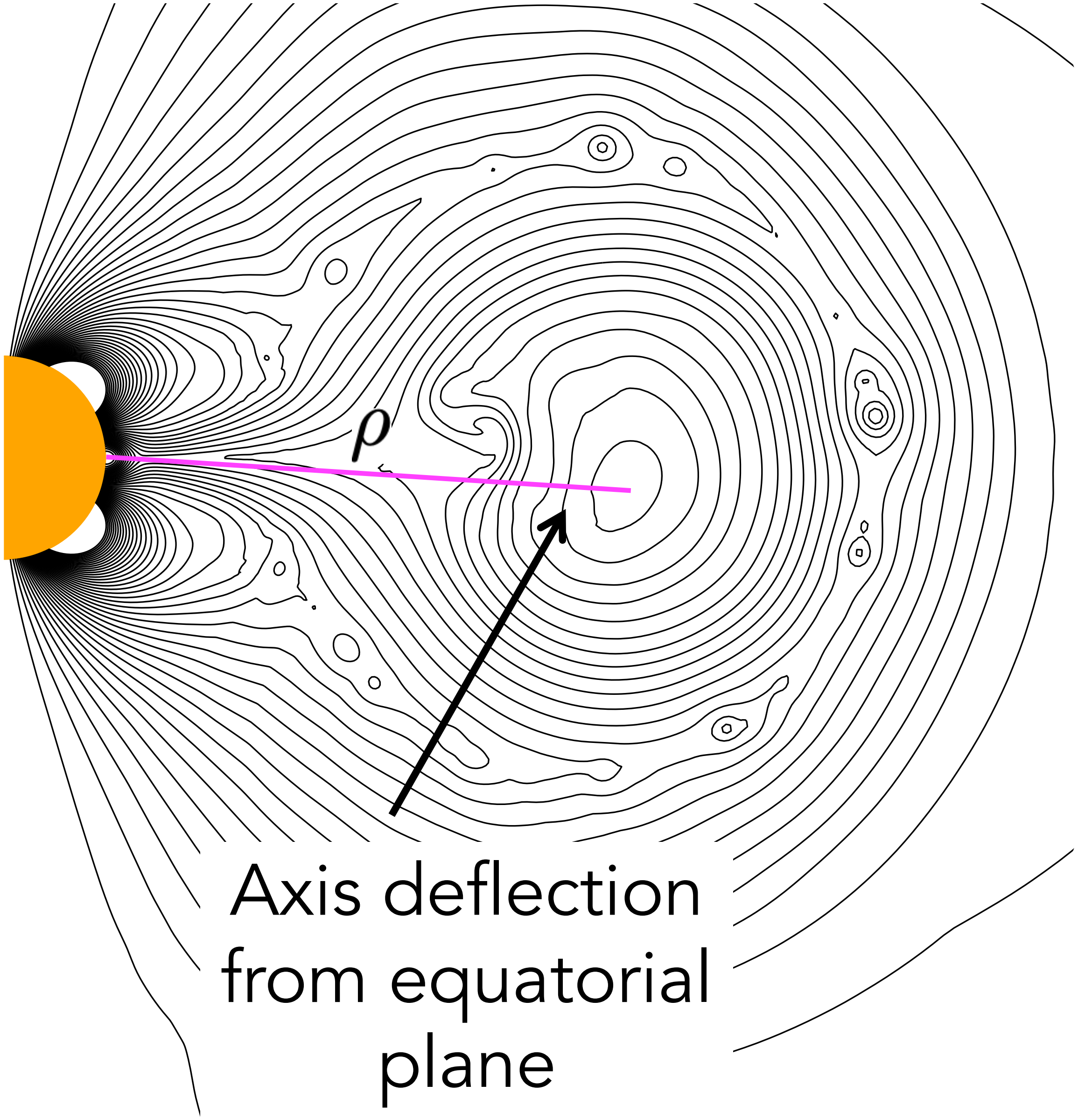
Coronal Mass Ejection Observation [3]



2.5D (Toroidal) MHD CME Simulation (ARMS code) [2]

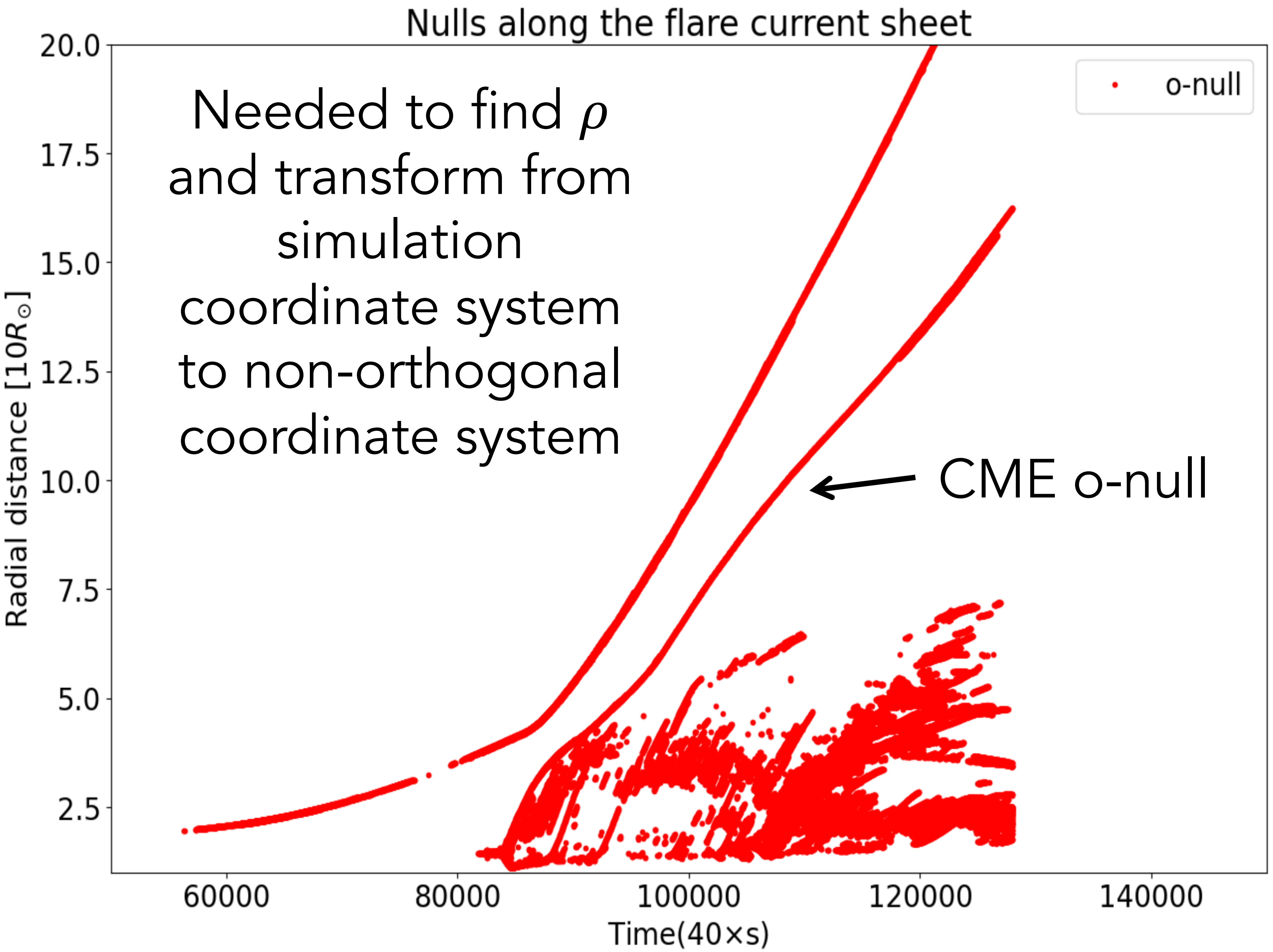
Cross section of simulated CME flux rope

See previous work by Lynch et al. [4] that compared similar simulations to a *force-free* model



Axis deflection from equatorial plane

O-null Tracking in Simulation

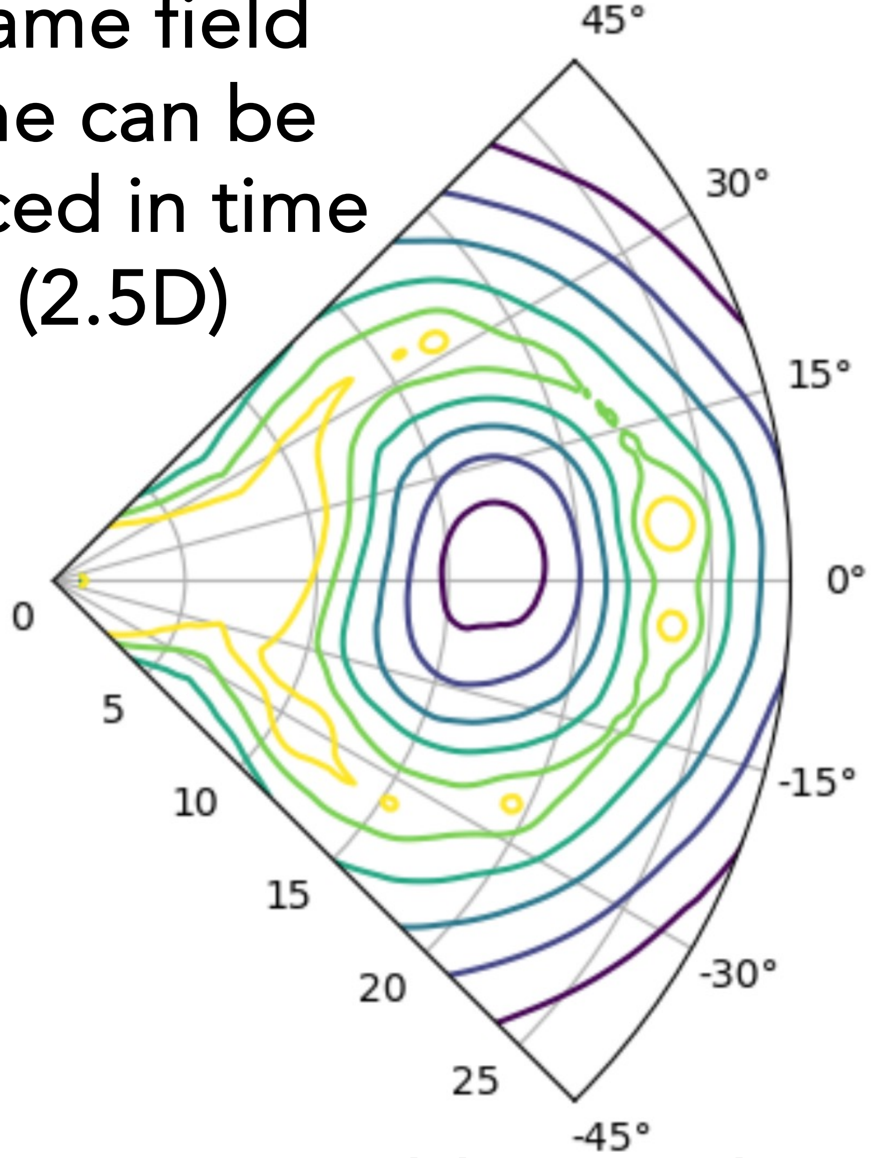


Needed to find ρ and transform from simulation coordinate system to non-orthogonal coordinate system

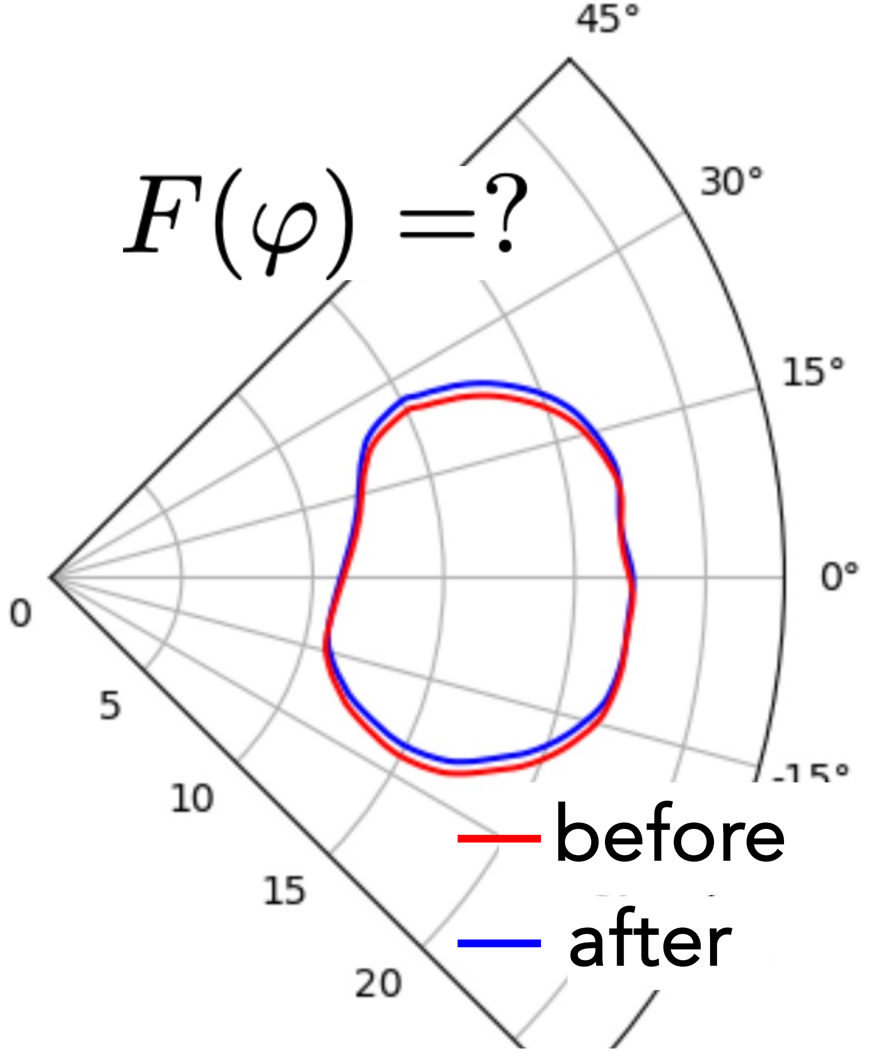
CME o-null

CME Cross Section: Contours of Poloidal Flux Function

Same field line can be traced in time (2.5D)



Not unique (adds complexity for automatization)

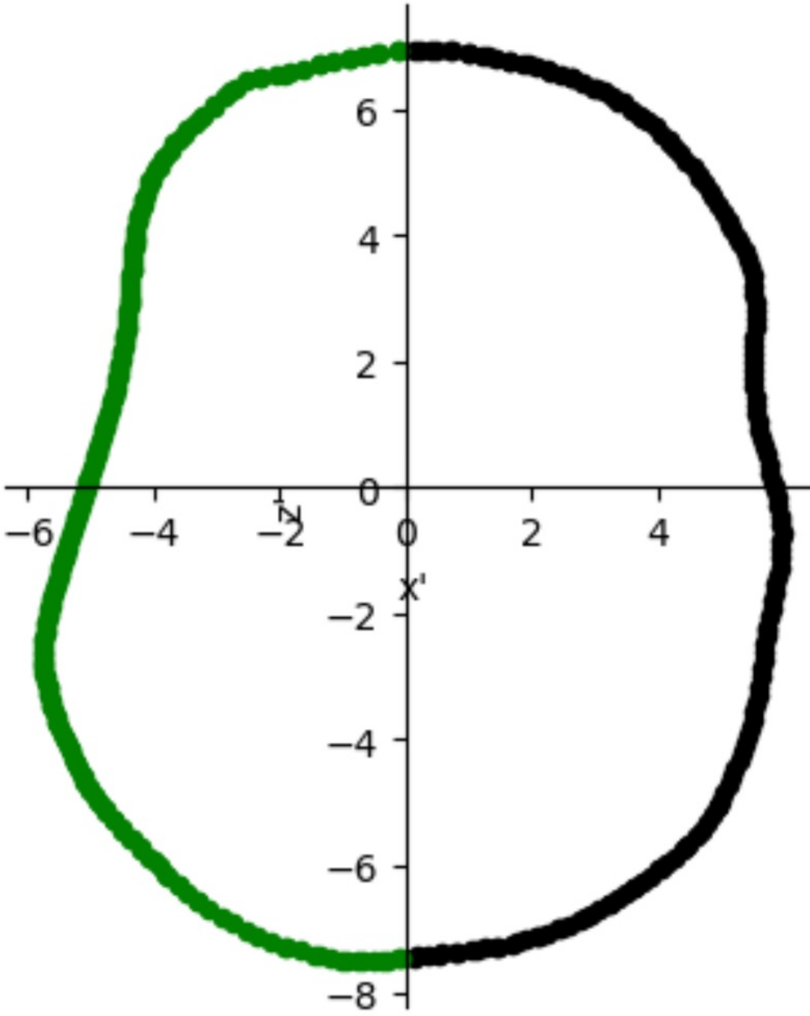


$F(\varphi) = ?$

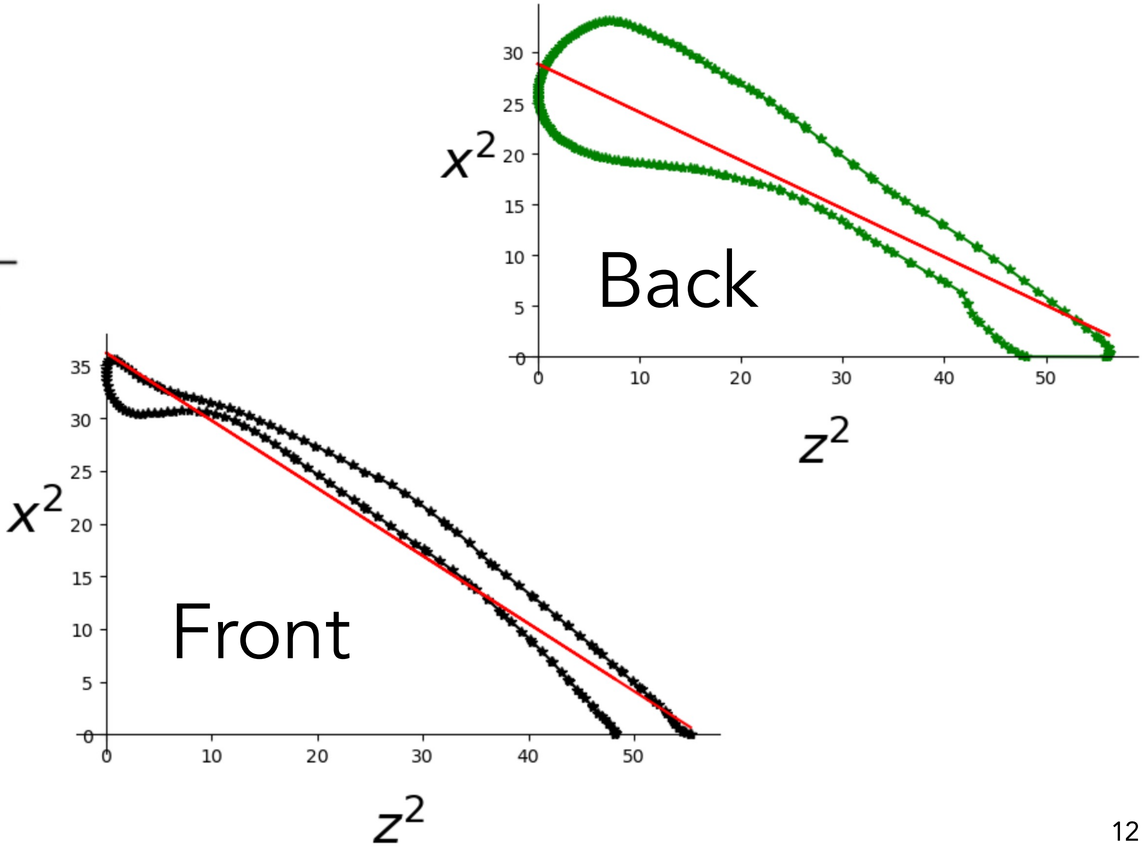
Rotate coordinate system to account for deflection

Simplest Case: Assume Elliptical Cross Section ($F(\varphi) = \delta$)

$$x^2 = \delta^2 r^2 - \delta^2 z^2$$

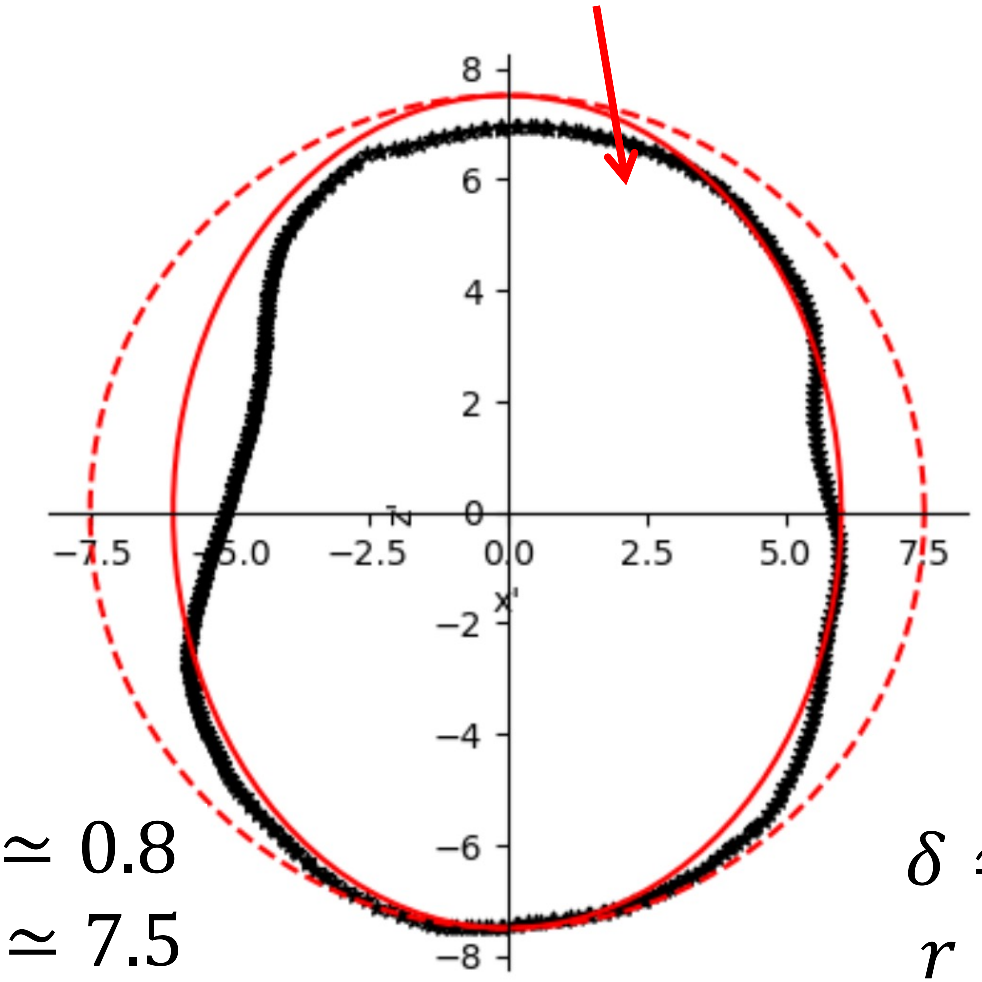


Simple machine learning linear regression with python (scikit-learn) to estimate δ and r



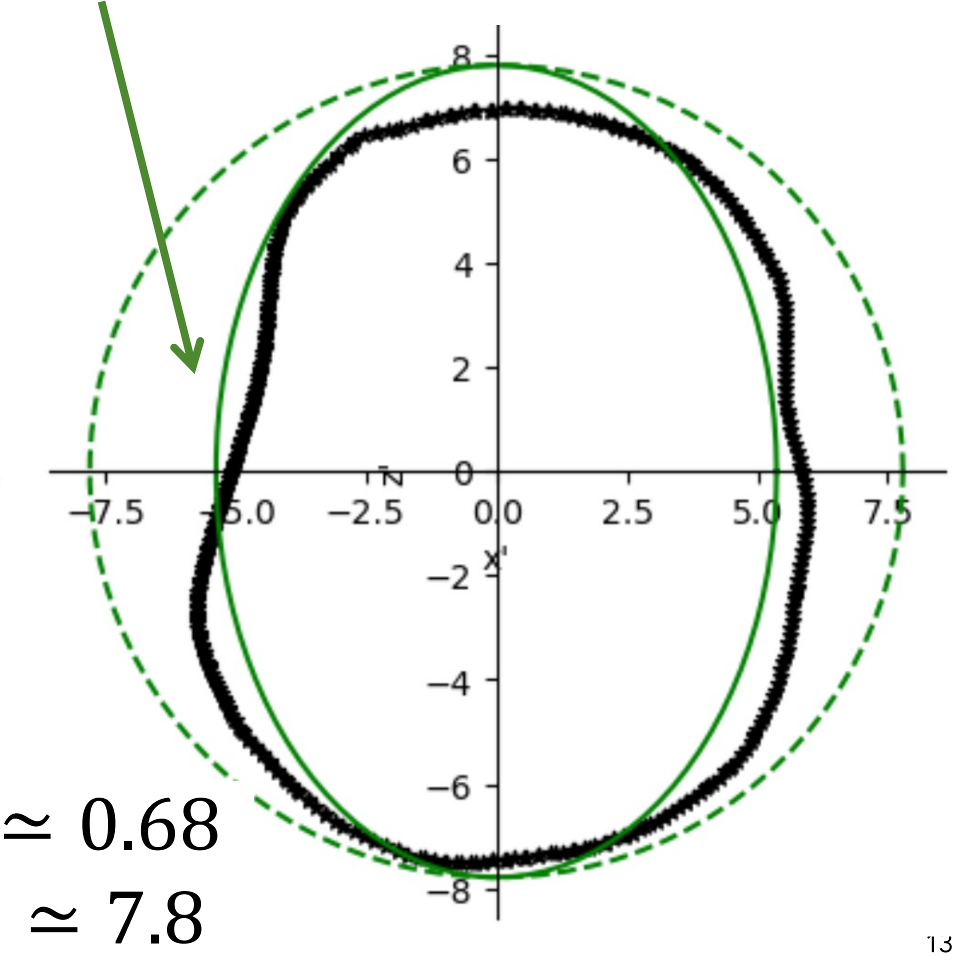
Elliptical Cross Section

Front fit: strapping field compression maintains vertical symmetry relatively well



$\delta \simeq 0.8$
$r \simeq 7.5$

Back fit: top/bottom asymmetric flare reconnection outflow deforms back of the CME (not captured by the analytical model)

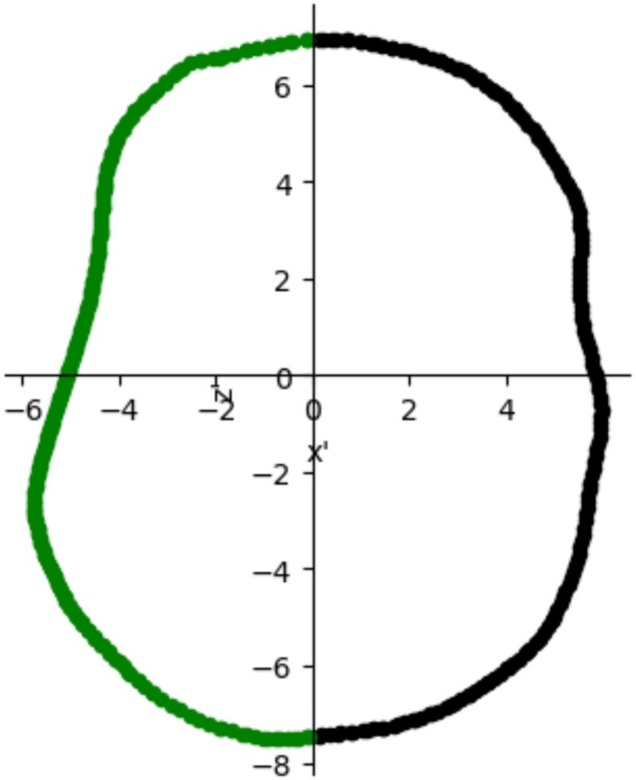


$\delta \simeq 0.68$
$r \simeq 7.8$

Case: $F(\varphi) = \delta\left(1 - \lambda \cos^{n} \varphi\right)$

Fit δ, r, λ, and n

$$x^2 = r^2\delta^2 \left(1 - \lambda(\pm 1)^n \left(1 - \frac{z^2}{r^2}\right)^{n/2}\right)^2 \left(1 - \frac{z^2}{r^2}\right)$$



If n is odd (horizontal asymmetry), the equation to fit is non-separable, therefore we cannot used standard non-linear machine learning gradient descent algorithms.

We developed a customized machine learning non-separable gradient descent algorithm (still tweaking it)

Conclusions

- This work is cross-disciplinary, combining models of flux ropes in the lower corona and in the heliosphere (lots to learn from each area).
- The bases of the method are in place.
- Currently working on method to quantify front/back asymmetry with a customized non-separable, nonlinear, gradient descent algorithm (testing convergence, local-vs.-global minimum issues, etc.)
- Top/bottom asymmetries due to flare reconnection and deflections from the equatorial plane are not captured by the analytical model. Strategies to address these issues are needed.

Future work

- Automatization to fit many contours and follow each one over time.
- Characterize currents as function of the analytical model variables.
- Study magnetic field to identify in situ signatures related to distortion and compression.
- Change magnetic field strapping field to study frontal compression.

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