On the Utility of Flux Rope Models for CME Magnetic Structure Below 30$R_\odot$

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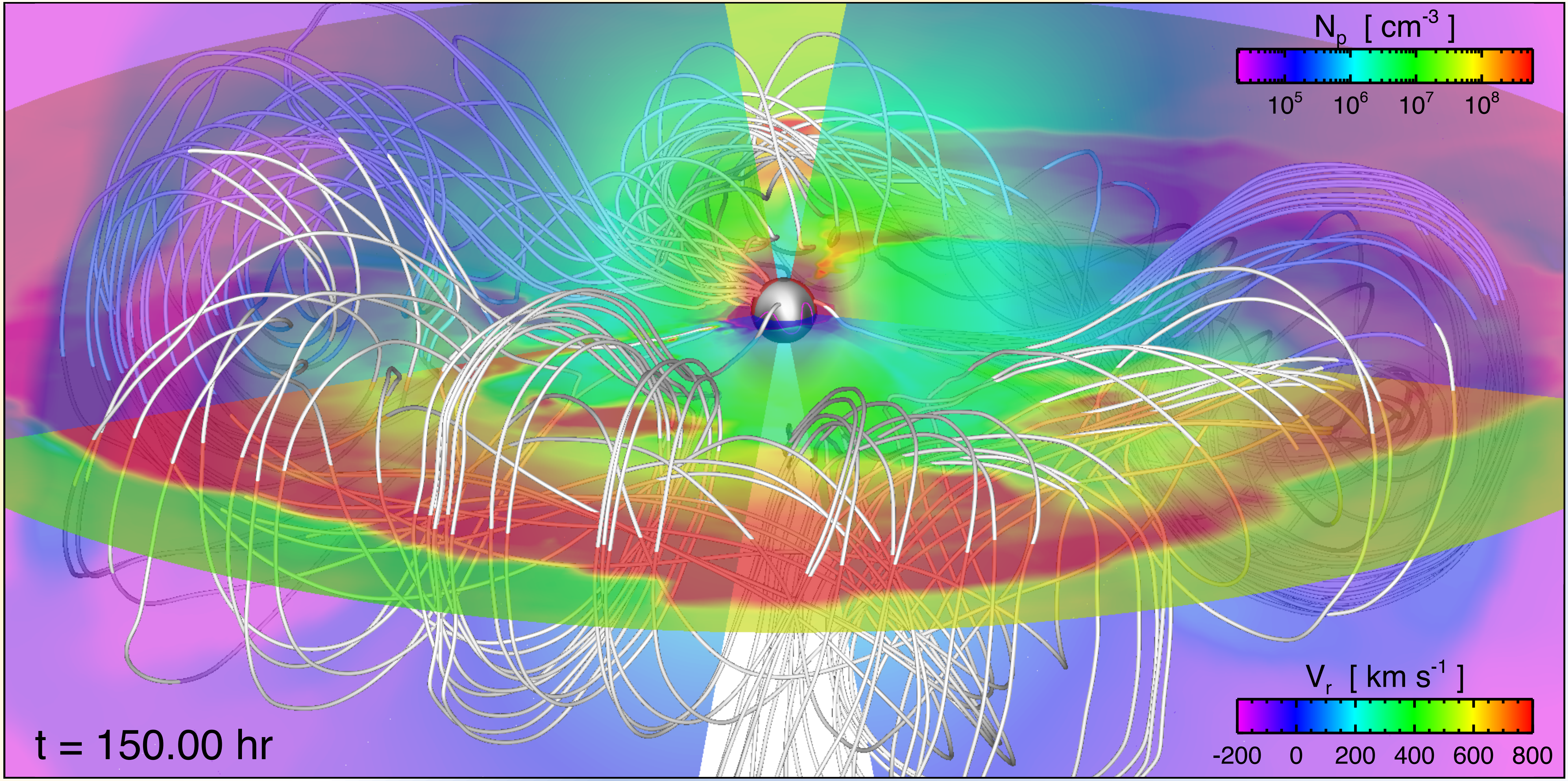
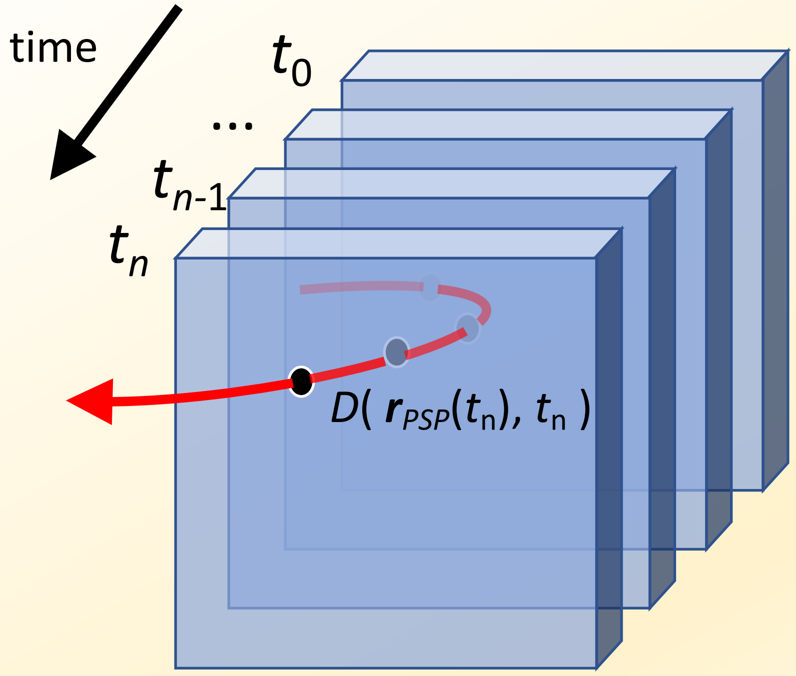
Lynch et al. (2019, ApJ 880:97) Simulation Overview

- Launched 360^o-wide streamer blowout CME (literally entire streamer erupts, simple model for eruptive stellar superflare)
- Moderate-speed CME with V_r > ~800 km/s. Classic magnetic flux rope CME with 3-part density structure/cross-section



Synthetic Spacecraft Sampling through 4D Simulation Data



- Start with simulation data cube: $D(\,\mathbf{r}, t\,) = D(\,x, y, z, t\,)$
- Want time series $f_{PSP}(\,t\,) = D(\,\mathbf{r}_{PSP}(t), t\,)$
- Have PSP location from ephemeris $\mathbf{r}_{PSP}(t) = [\,x_{PSP}(t), y_{PSP}(t), z_{PSP}(t)\,]$
- Discretized version of everything, doesn't have $D(\,\mathbf{r}_{PSP}(t), t\,)$ exactly, but we do have something that is (reasonably) close in spacetime:

$$\underbrace{t_n < t}_{(1-\delta t)}\underbrace{\leq t_{n+1}}_{\delta t} \quad \text{and} \quad \underbrace{x_i < x_{PSP}}_{\delta x_L}\underbrace{\leq x_{i+1}}_{\delta x_R}, \quad \underbrace{y_j < y_{PSP}}_{\delta y_L}\underbrace{\leq y_{j+1}}_{\delta y_R}, \quad \underbrace{z_k < z_{PSP}}_{\delta z_L}\underbrace{\leq z_{k+1}}_{\delta z_R}$$

- Figure out which data files correspond to $D(\,\mathbf{r}, t_n\,)$ and $D(\,\mathbf{r}, t_{n+1}\,)$

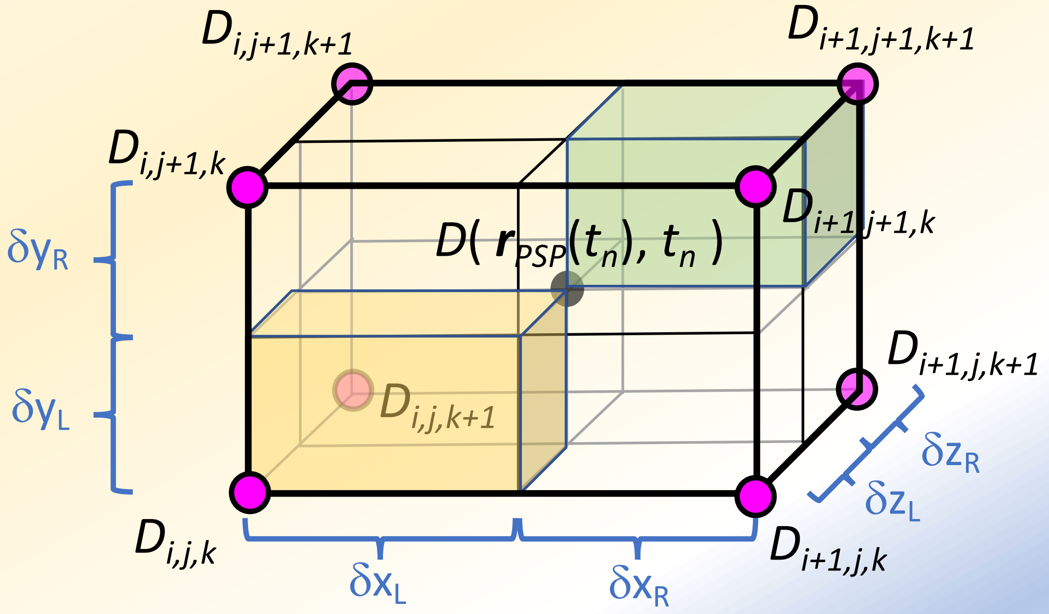
➢ Linear interp in time $D(\,\mathbf{r}, t\,) \sim (1-\delta t)\, D(\,\mathbf{r}(t_n), t_n\,) + \delta t\, D(\,\mathbf{r}(t_{n+1}), t_{n+1}\,)$

1. Need to evaluate $D(\,\mathbf{r}_{PSP}(t_n), t_n\,)$
2. Estimate $D(\,\mathbf{r}_{PSP}(t_n), t_n\,)$ from first-order "volume-weighting"

$$D(\mathbf{r}_{PSP}(tn)) = \frac{1}{V}\sum_{m=1}^{8} w_{9-m} D_m \quad \text{where} \quad \frac{1}{V}\sum_{m=1}^{8} w_m = 1 \;\text{, and}$$

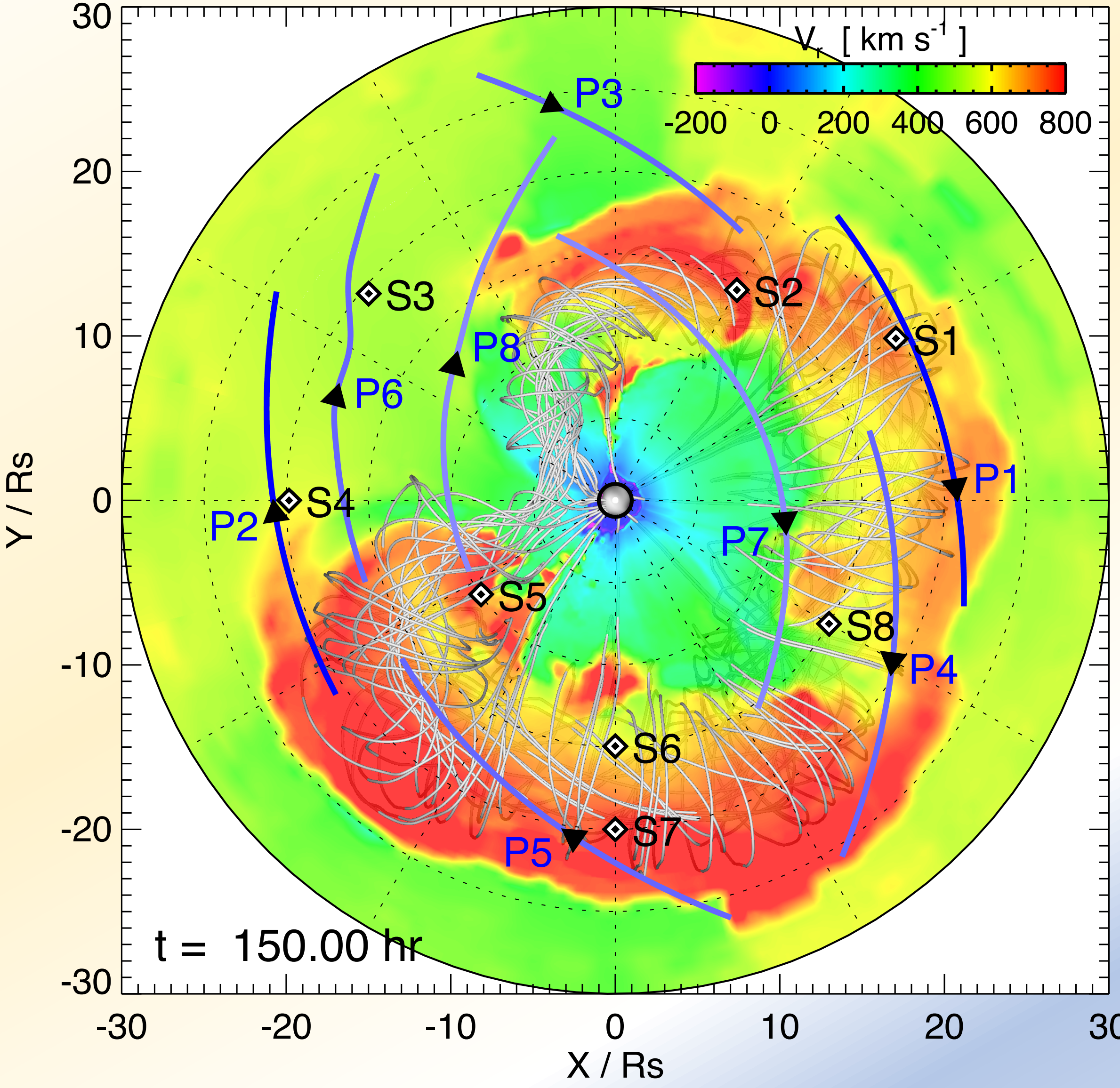
$w_8 D_1 = (\delta x_R \delta y_R \delta z_R)\, D_{i,j,k}$, $w_7 D_2 = (\delta x_L \delta y_R \delta z_R)\, D_{i+1,j,k}$, . . .
$w_2 D_7 = (\delta x_R \delta y_L \delta z_L)\, D_{i,j+1,k+1}$, $w_1 D_8 = (\delta x_L \delta y_L \delta z_L)\, D_{i+1,j+1,k+1}$, with

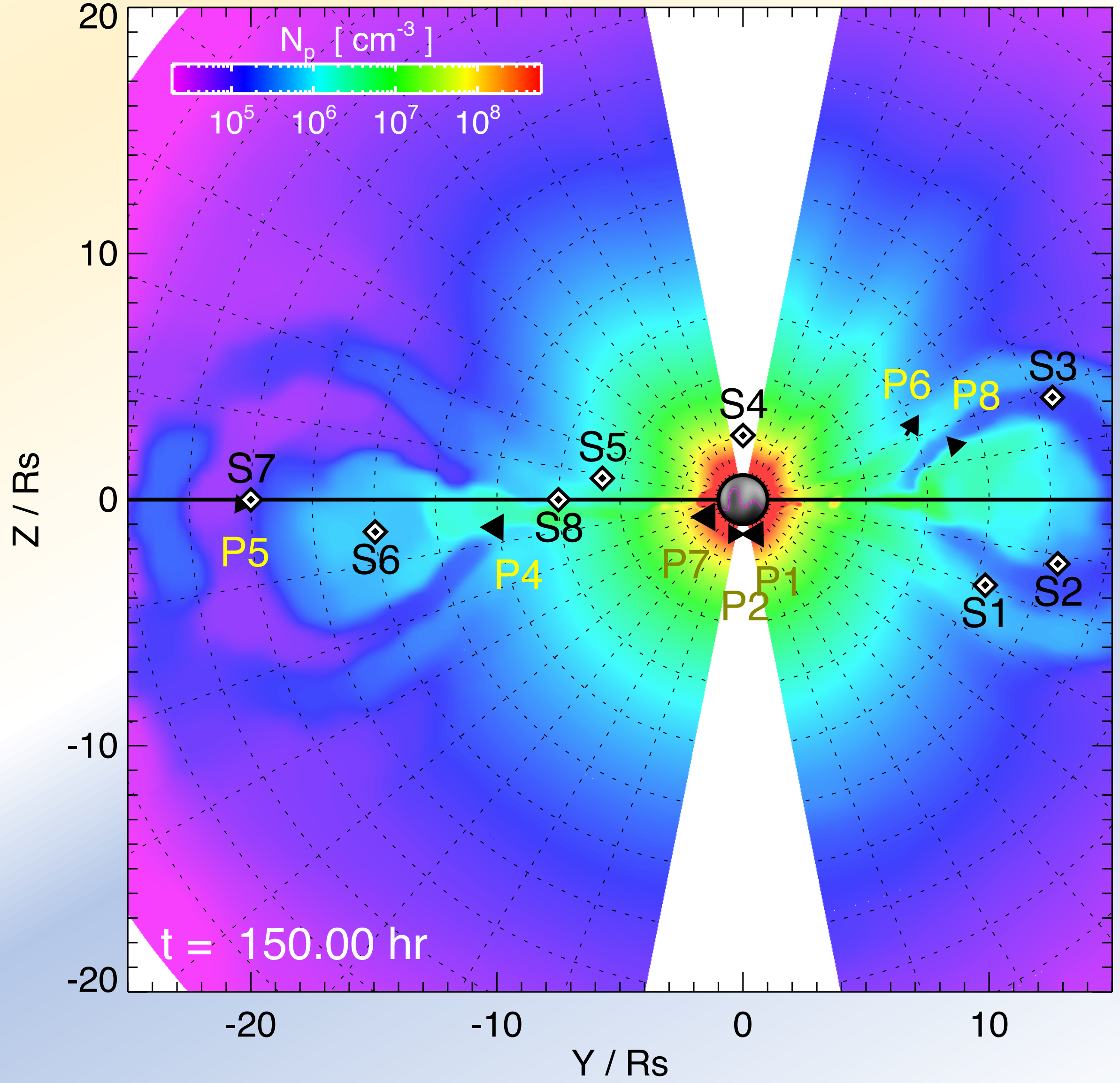
$V = (x_{i+1} - x_i)\,(y_{j+1} - y_j)\,(z_{k+1} - z_k) = (\delta x_L + \delta x_R)\,(\delta y_L + \delta y_R)\,(\delta z_L + \delta z_R)$



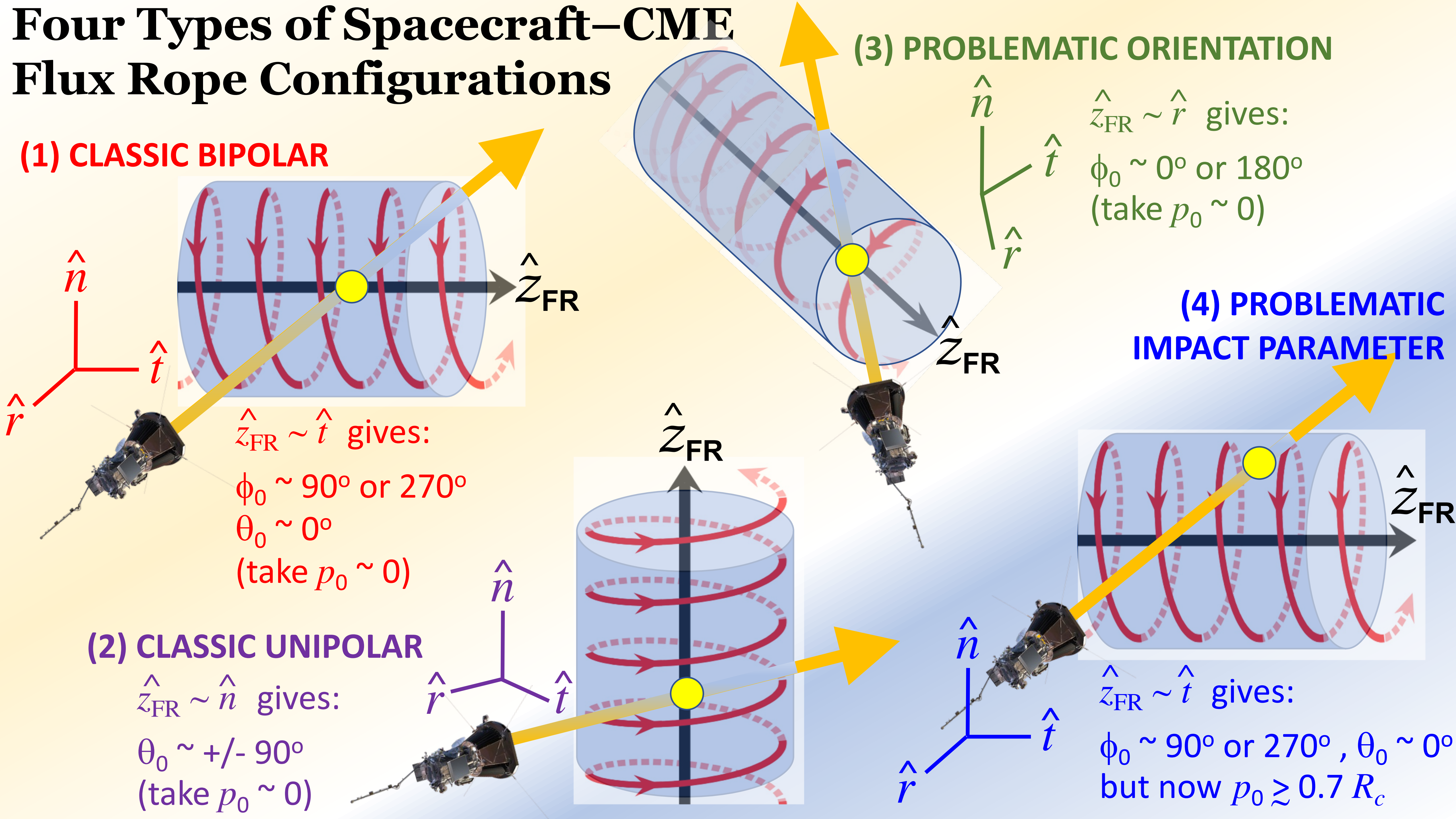
Synthetic Spacecraft Sampling through 4D Simulation Data

- Eight STATIONARY Observers (**S1—S8**) and eight PSP-like MOVING Observers (**P1—P8**)
- PSP-like Observer trajectories derived from PSP Encounters 7, 9, and future Encounter 23 (e.g. $9.8R_\odot < r_{PSP} < 20.4R_\odot$)

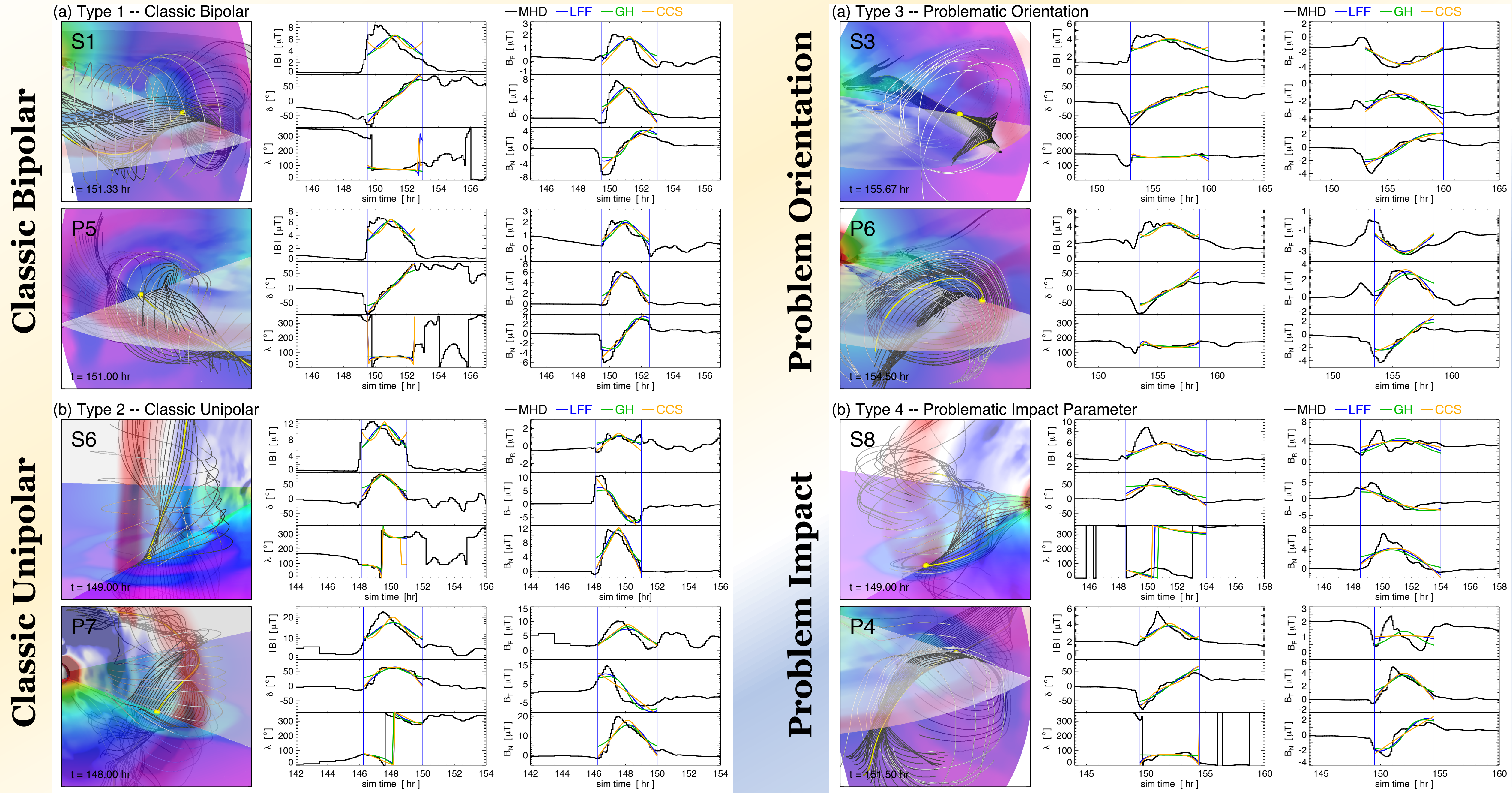




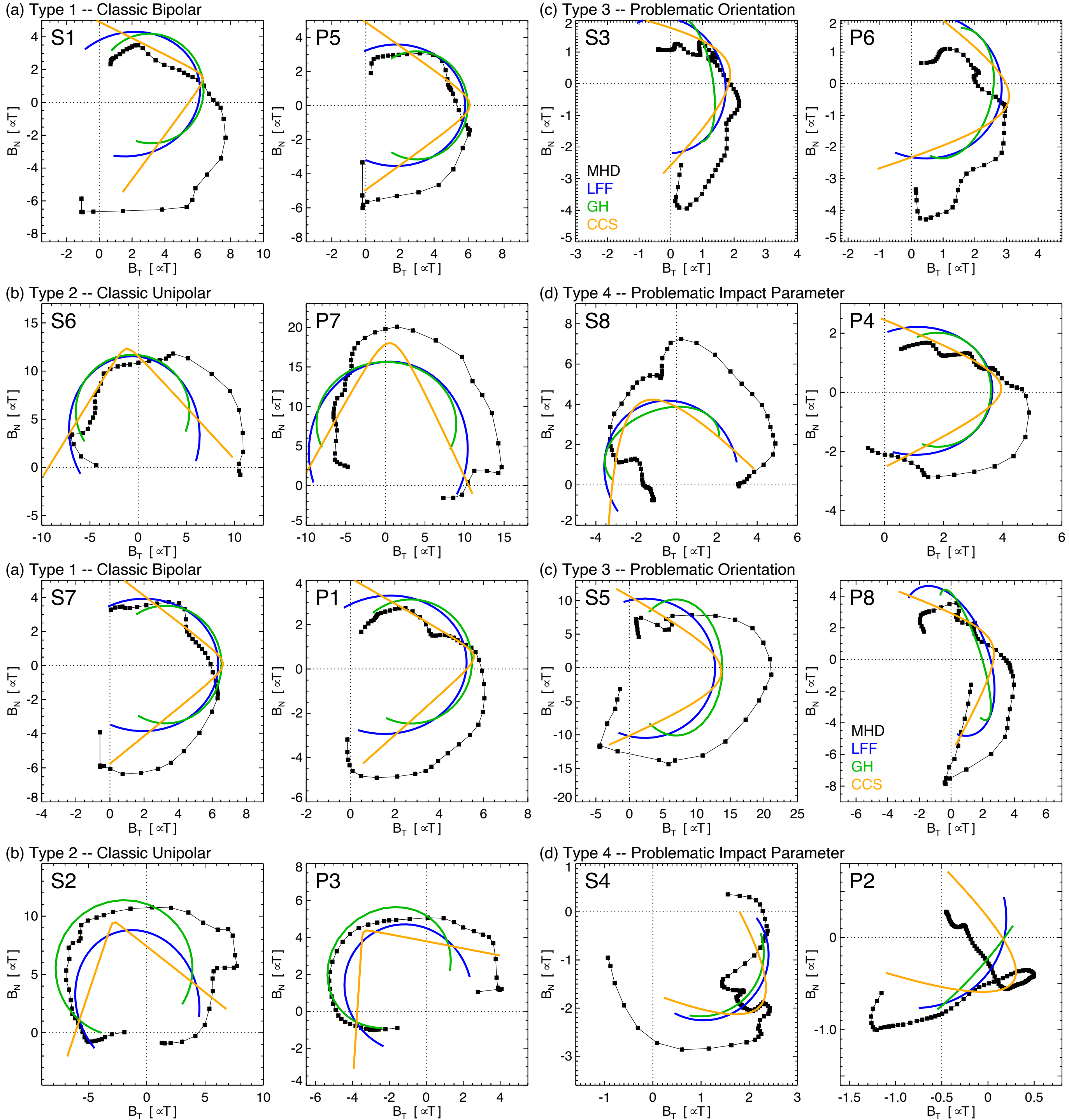
Four Types of Spacecraft–CME Flux Rope Configurations



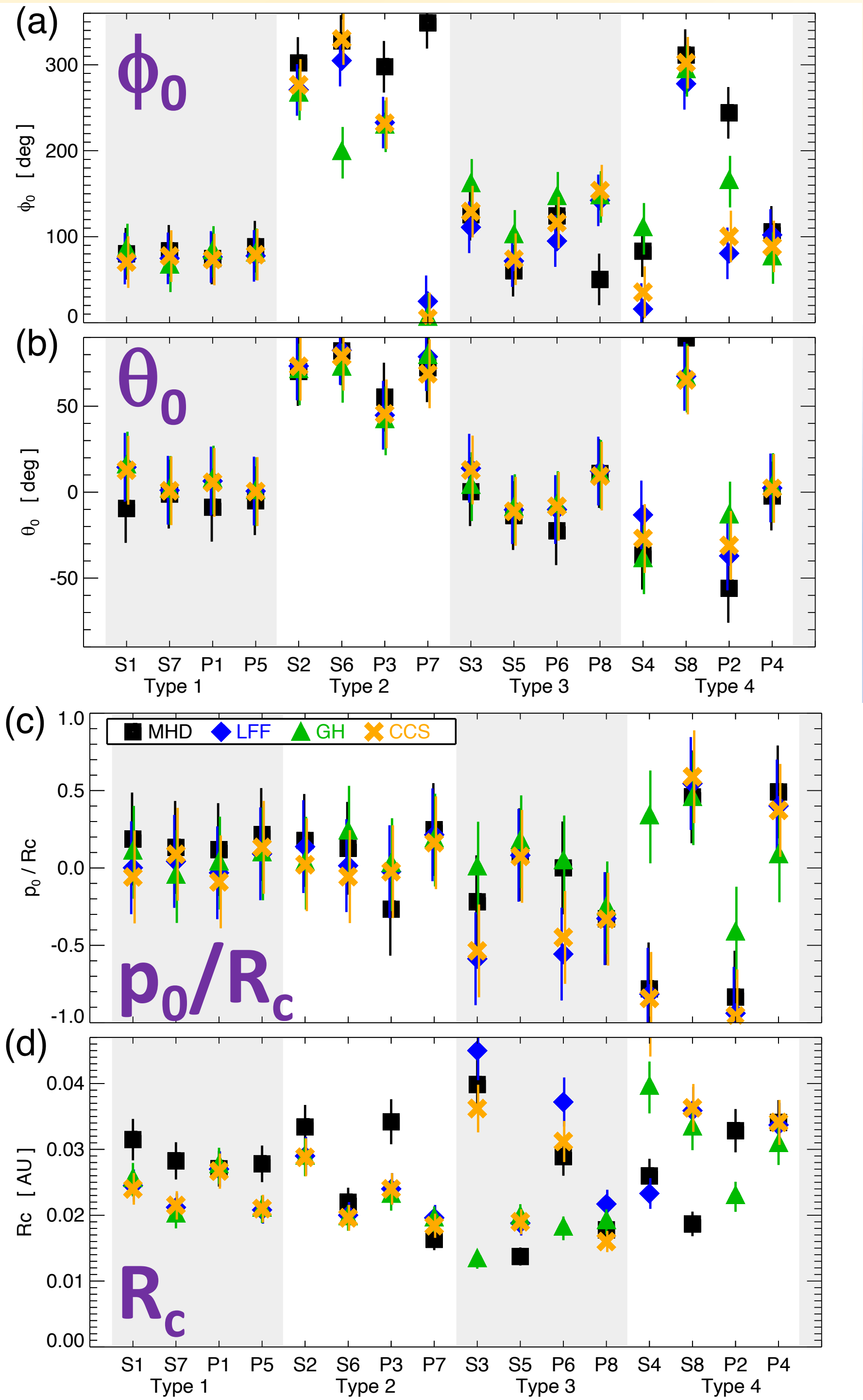
In-situ Flux Rope Model Fitting (LFF,GH,CCS) to MHD Data



Field Rotation Visualized w/ B_N–B_T Hodogram



Cf. FR Model Parameters & MHD Estimates



How Non-Force Free are the CCS FR Model and MHD Simulation Profiles?

Look at ratio of $J_\perp/J_{\text{total}}$ (as in Nieves-Chinchilla et al. 2016)

$$J_{\text{total}} = J_\parallel + J_\perp \text{ (with respect to } \boldsymbol{B}\text{)}$$

$$J_\parallel = \frac{(J \cdot B)B}{|B|^2}, \quad J_\perp = \frac{J \times B}{|B|}$$

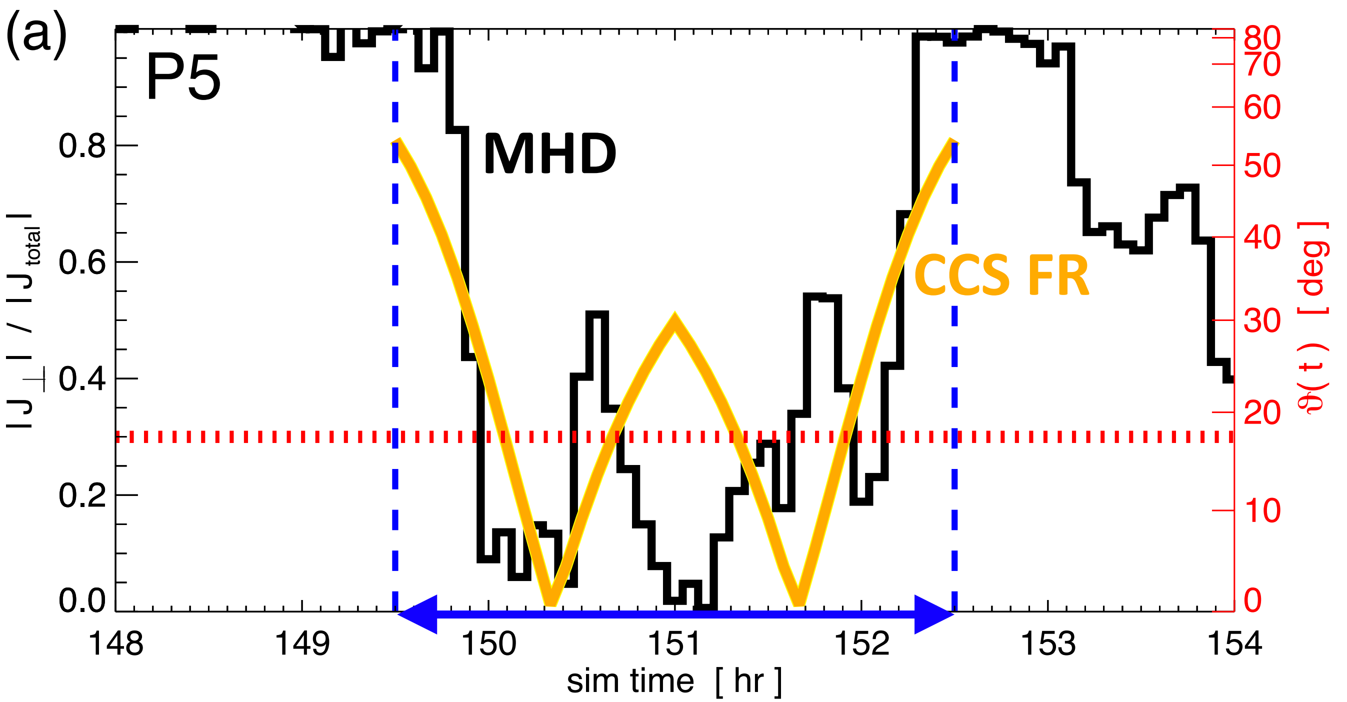
Can write this in terms of misalignment angle ϑ between ***J*** and ***B*** :

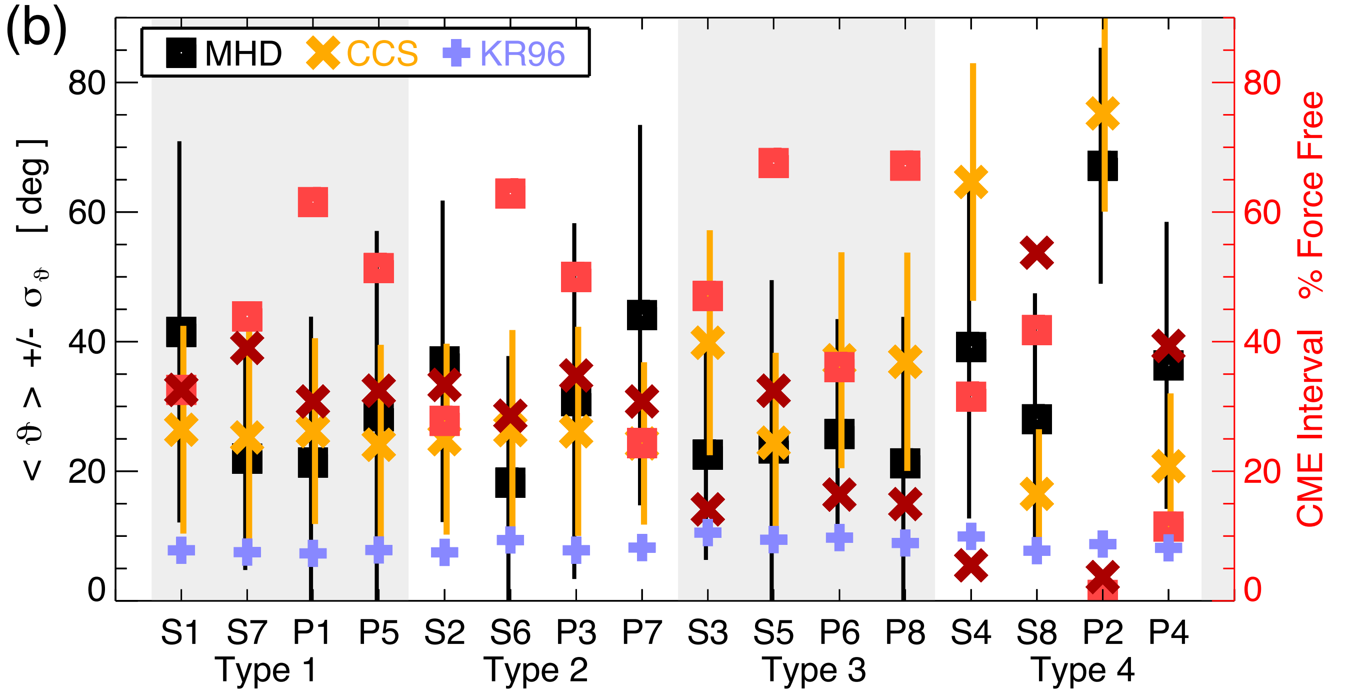
$$\frac{|J_\perp|}{|J|} = \frac{|J \times B|}{|J||B|} = |\sin\vartheta|$$

Möstl et al. (2009) "approximately force-free" threshold of $|\sin\vartheta| \lesssim 0.30 \rightarrow |\vartheta| \lesssim 17^o$

PSP-like P5 MHD flux rope is 51% FF

CCS FR model for P5 FR is 32% FF





Cf. In-situ FR Model Flux Content & MHD Estimates

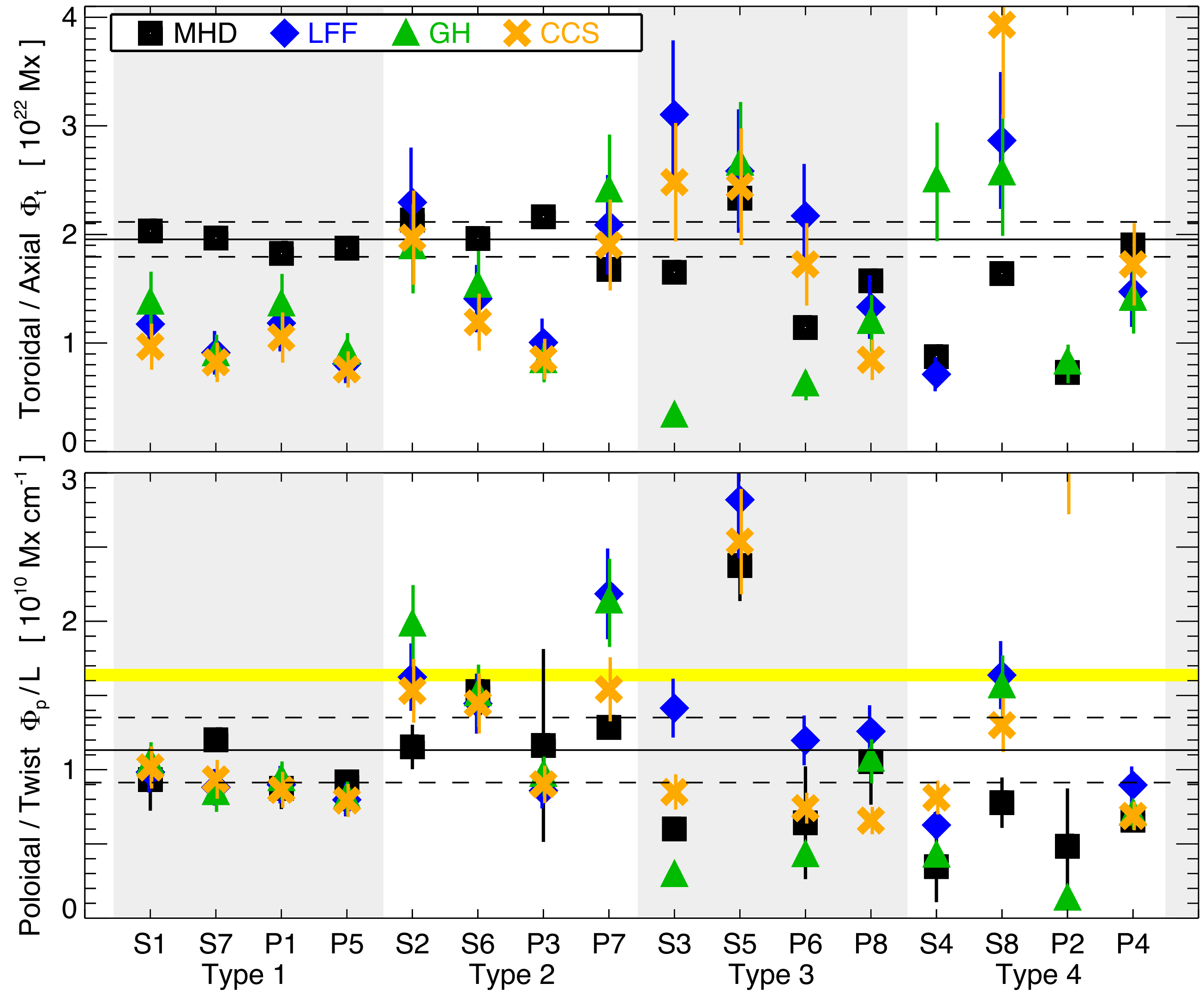
In-situ models have analytic expressions for toroidal/axial flux (Φ_t) and poloidal/twist flux per unit length (Φ_p/L) based on fit parameters. How close are these to MHD values?

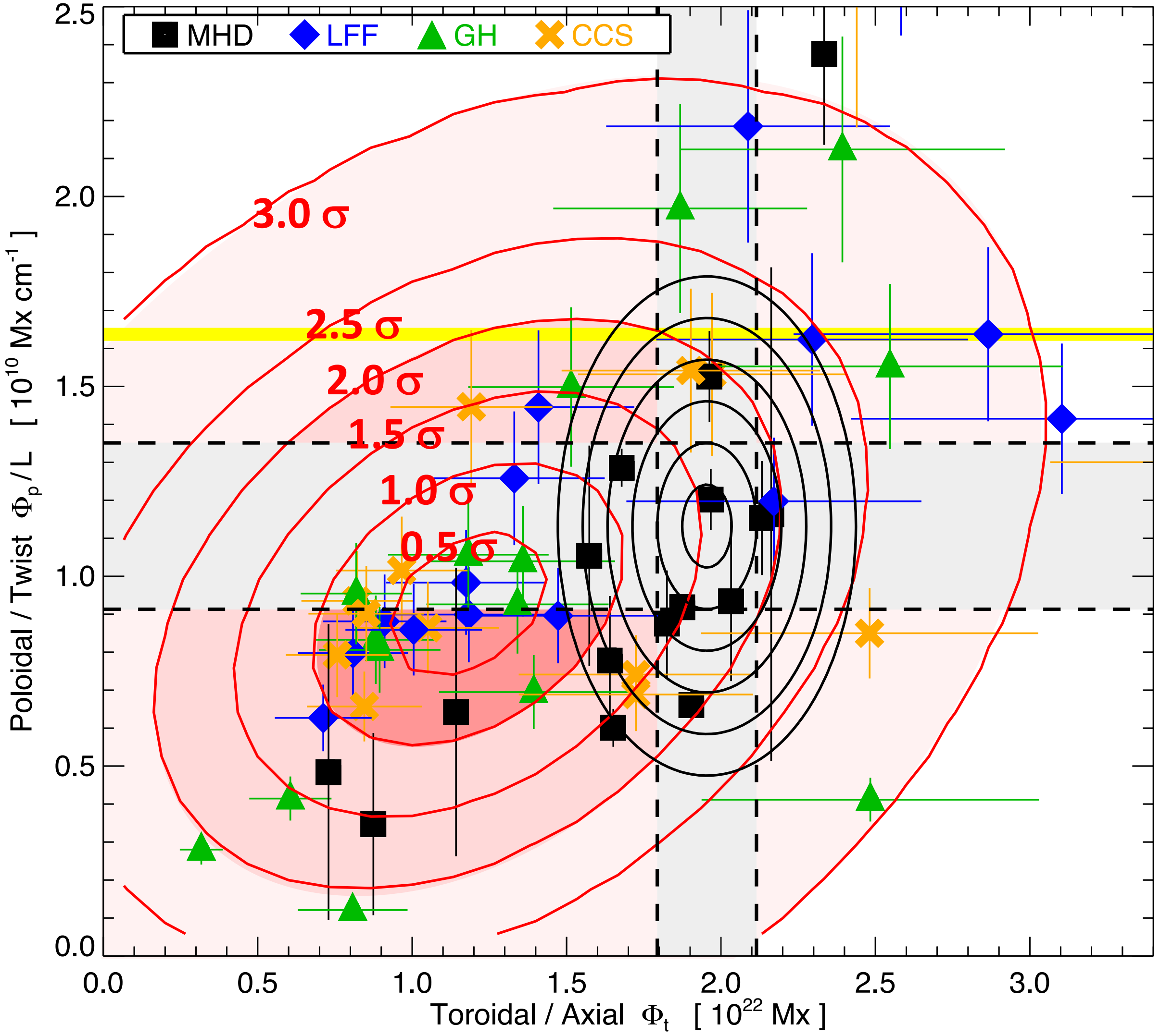
- Classic Type 1&2 cfg better fit than Problematic Type 3&4…

$$\Phi_t^{\mathrm{LFF}} = (2J_1(x_{01})/x_{01})B_0\,\pi R_c^2, \qquad (\Phi_p/L)^{\mathrm{LFF}} = (1/x_{01})B_0\,R_c,$$

$$\Phi_t^{\mathrm{GH}} = \ln\left[1+\tau^2R_c^2\right]B_0\,\pi(1/\tau)^2, \qquad (\Phi_p/L)^{\mathrm{GH}} = \ln\left[1+\tau^2R_c^2\right]B_0(1/2\tau),$$

$$\Phi_t^{\mathrm{CCS}} = (1/3)B_0\,\pi R_c^2. \qquad (\Phi_p/L)^{\mathrm{CCS}} = (1/4)\left(\mu_0 j_z^0 R_c\right)R_c.$$





Summary & Conclusions

- Created 16 synthetic in-situ profiles of CME flux rope encounters at $r < 30R_\odot$ through different parts of the Lynch et al. (2019) global-scale, 360^o-wide streamer blowout MHD simulation. Examined performance of 3 simplest in-situ flux rope models: (1) the Lundquist Bessel function (LFF), (2) Gold-Hoyle uniform twist (GH), and (3) the non-force free Circular Cross-Section (CCS) model.

- The "classic" bipolar and unipolar CME–spacecraft configurations were generally well-fit by every FR model. The "problematic" orientation and impact parameter CME–spacecraft configurations were generally less successful.
  * The $B_N - B_T$ hodograms show that in-situ FR fits that appear okay for $\boldsymbol{B}_{\mathrm{RTN}}$ time series can look much worse in this visualization format.
  * Compared in-situ model parameters and their MHD estimates [ϕ_0 , θ_0 , p_0/R_c , R_c]. Surprisingly, there was a systematic underestimation of FR size R_c . Otherwise, Type 1&2 better fit than 3&4.

- Examined $\boldsymbol{J} \times \boldsymbol{B}$ misalignment angle ($\sin \vartheta$) in MHD profiles and CCS FR model fits:
  * MHD profiles *more* force-free than CCS FR fits, but *less* force-free than Kumar & Rust (1996) assumption of "small departure from Lundquist solution." Using $\vartheta \lesssim 17^o$ threshold, MHD profiles ranged between 30–60% "force-free" at $r < 30R_\odot$, lending support to Lynch et al. (2004) hypothesis that magnetic energy dissipation in FR interior could result in CME plasma heating.

- MHD toroidal & poloidal flux content apparently systematically underestimated by in-situ FR models:
  * $< \Phi_t^{\mathrm{MHD}} > \sim 1.63 < \Phi_t^{\mathrm{FR}} >$ and $< (\Phi_p/L)^{\mathrm{MHD}} > \sim 1.26 < (\Phi_p/L)^{\mathrm{FR}} >$

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