Investigating the structure of magnetised Coronal Mass Ejection models (with Galactic Cosmic Rays)

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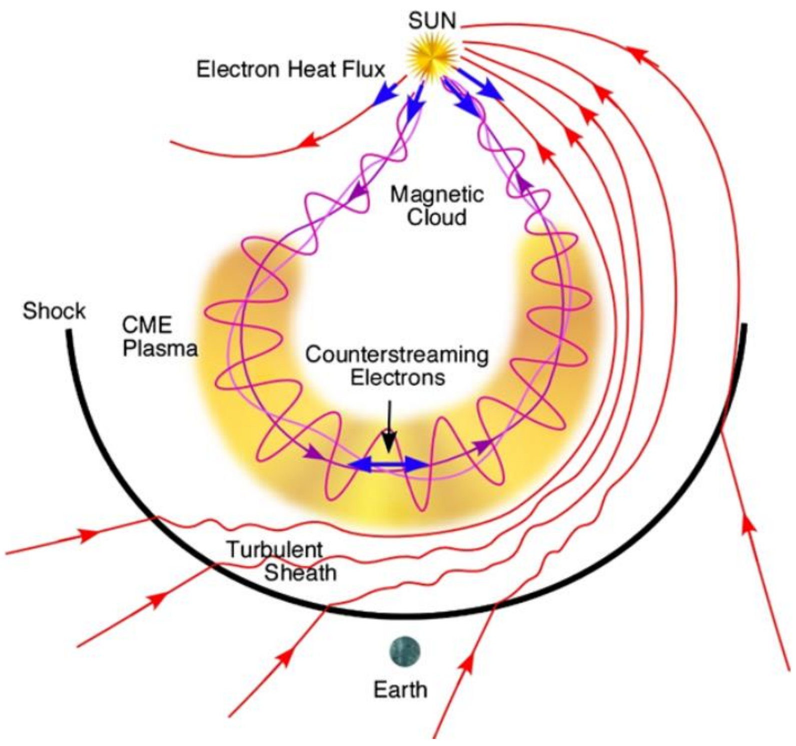
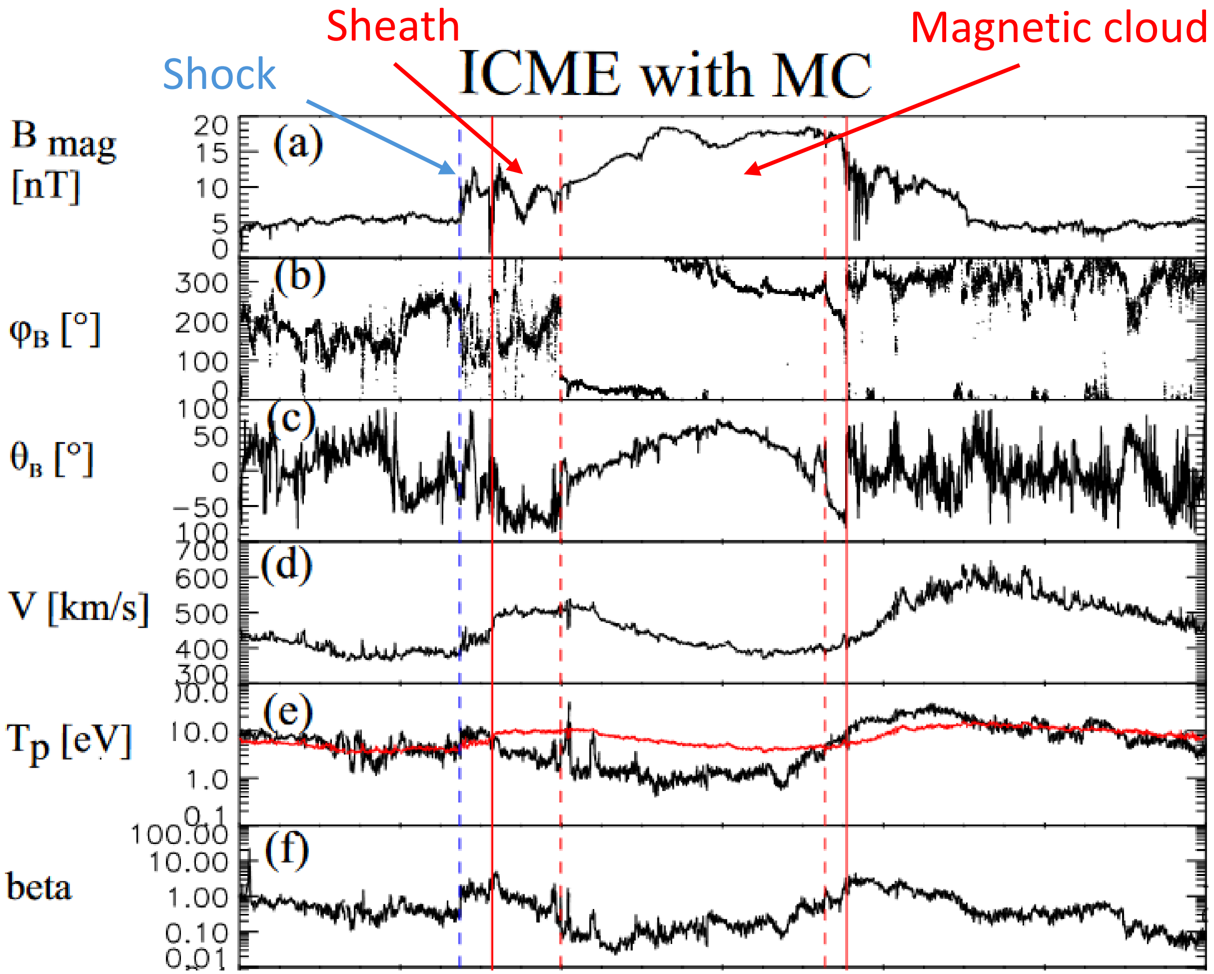
Spring MIST, 9th April 2025

Coronal Mass Ejections

- Main drivers of space weather.
- CME structure: shock, sheath, magnetic cloud (MC).



[Richardson and Cane, 2010]



[Kilpua +, 2017]

Galactic Cosmic Rays in the Heliosphere

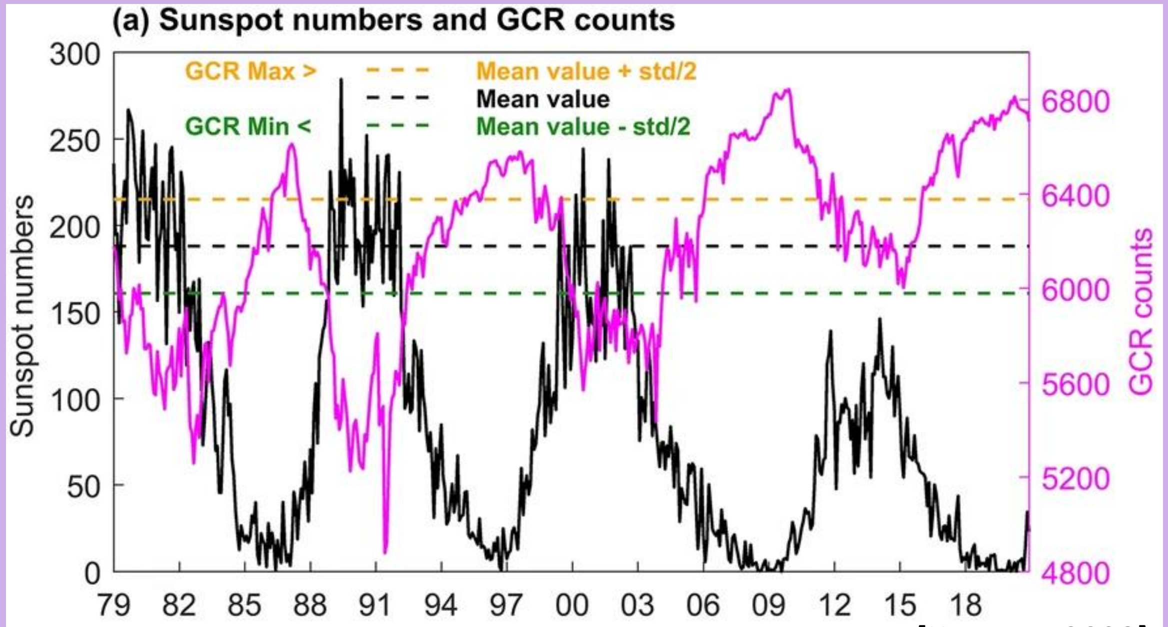
- High energy particles (GeV) – primarily protons, originate outside heliosphere.

- Parker Transport equation:

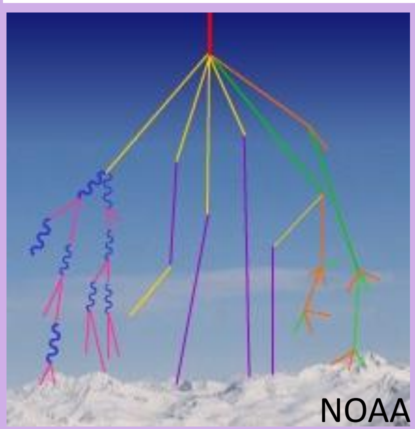
$$\frac{\partial f}{\partial t} + \boldsymbol{V} \cdot \nabla f - \nabla \cdot (\boldsymbol{K} \cdot \nabla f) - \frac{1}{3}(\nabla \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln p} = 0$$

p - momentum $\boldsymbol{V}$ - bulk (Solar wind) velocity $\boldsymbol{K}$ - diffusion coefficient (tensor)

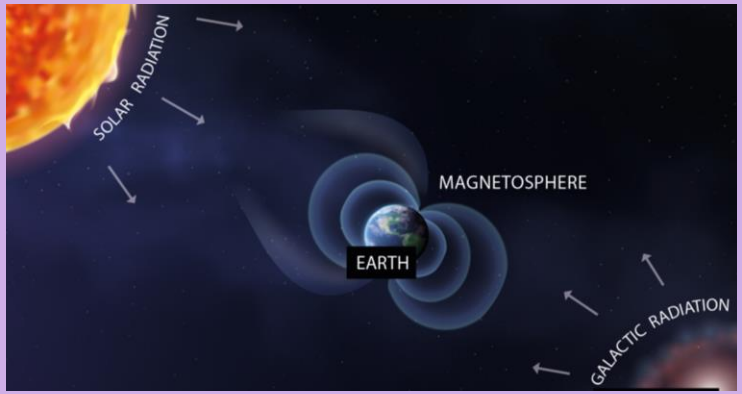
- Observe counts with neutron monitors.



[Kumar +,2023]

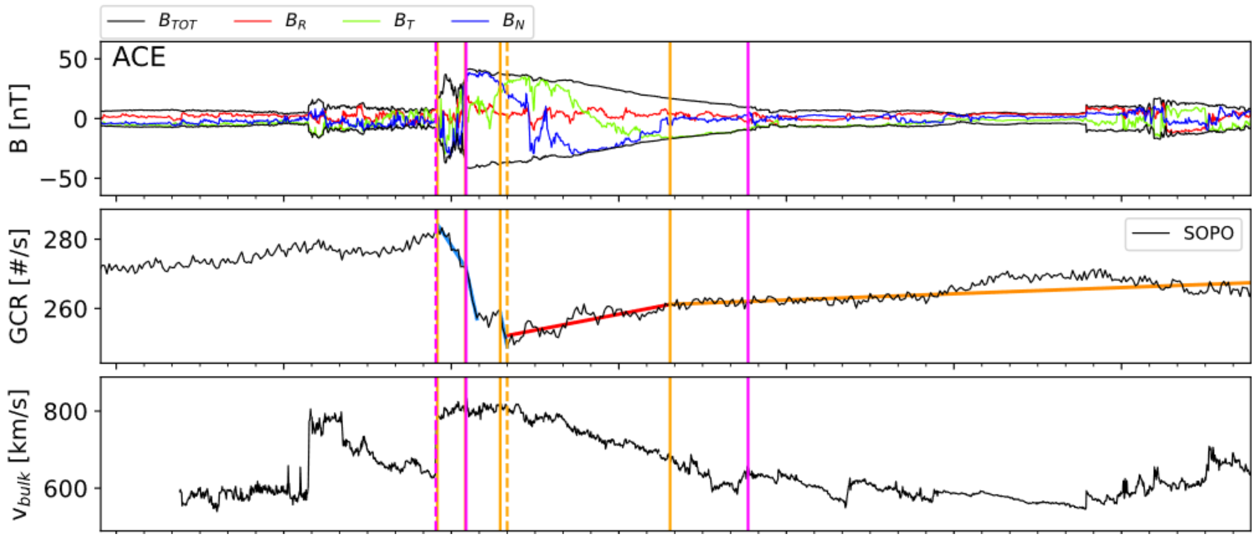


NOAA

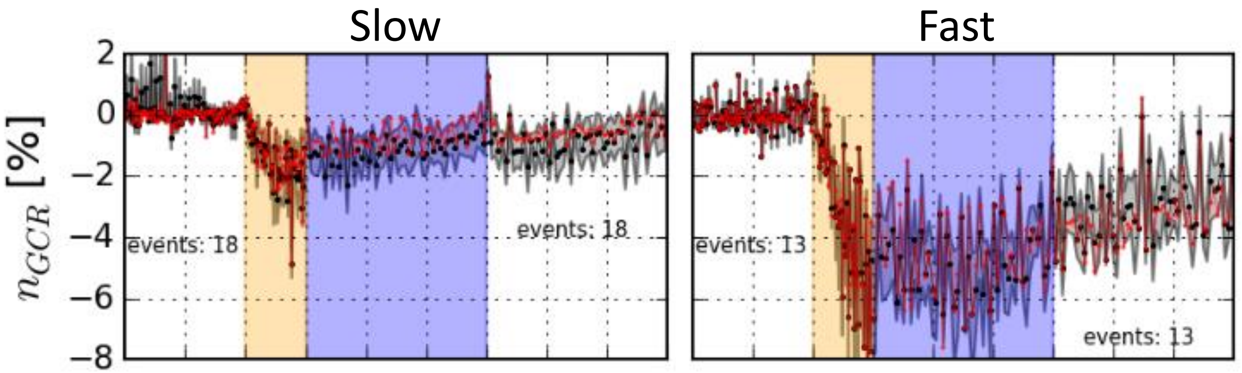


CME-GCR Interaction

- Forbush (1937) decrease (Fd).
- 2-step.
- Greater magnitude of Fds generally correlated with faster CMEs (Masías-Meza+, 2016), and greater magnetic field strength (Janvier +, 2021).
- Slow recovery.



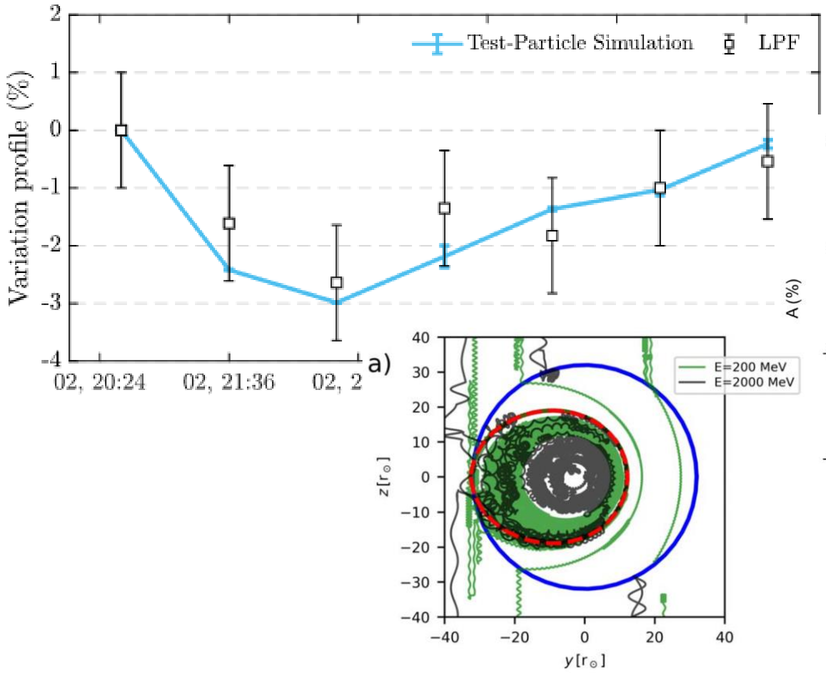
[Davies+,2023]

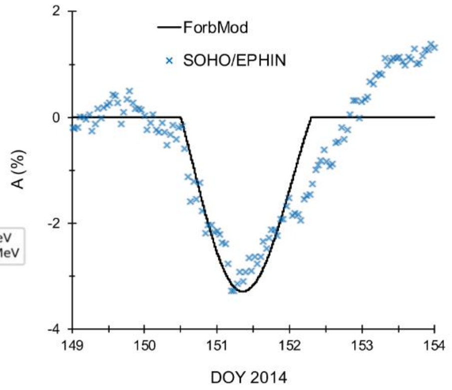


Modelling

Previous efforts:

FORBMOD (Dumbovic+, 2018)





Other Studies (Luo+, 2017, Benella+,2020, Laitinen and Dalla, 2020)

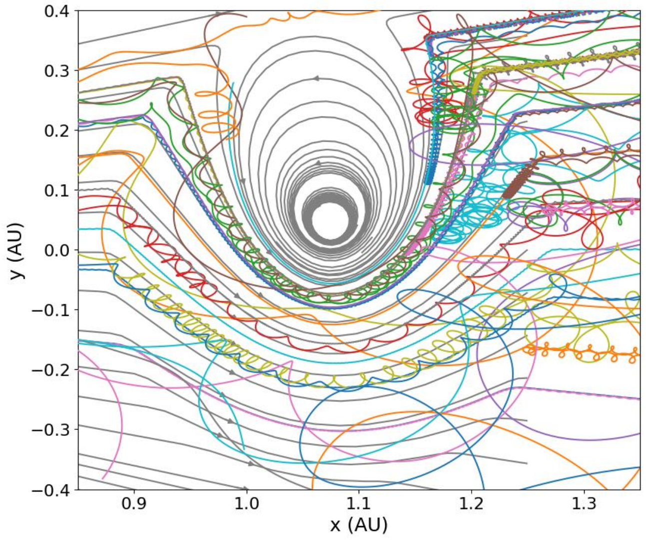
Aims:

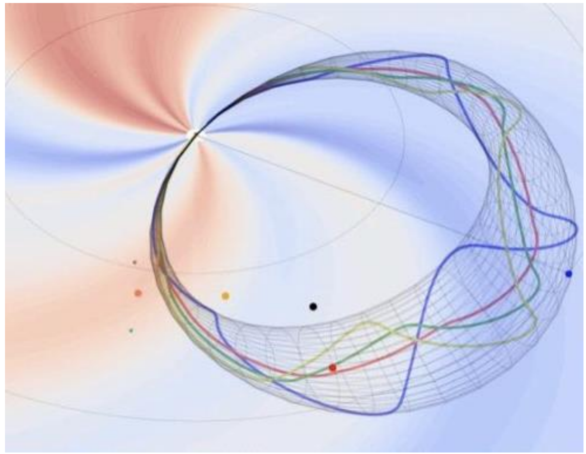
- Use test particles to model Forbush decreases (Fds) with complex, 3D fields and solar wind interaction.
- Compare CME models to observe differences in GCR interaction and structure.
- Probe CME structure from in situ GCR measurements?

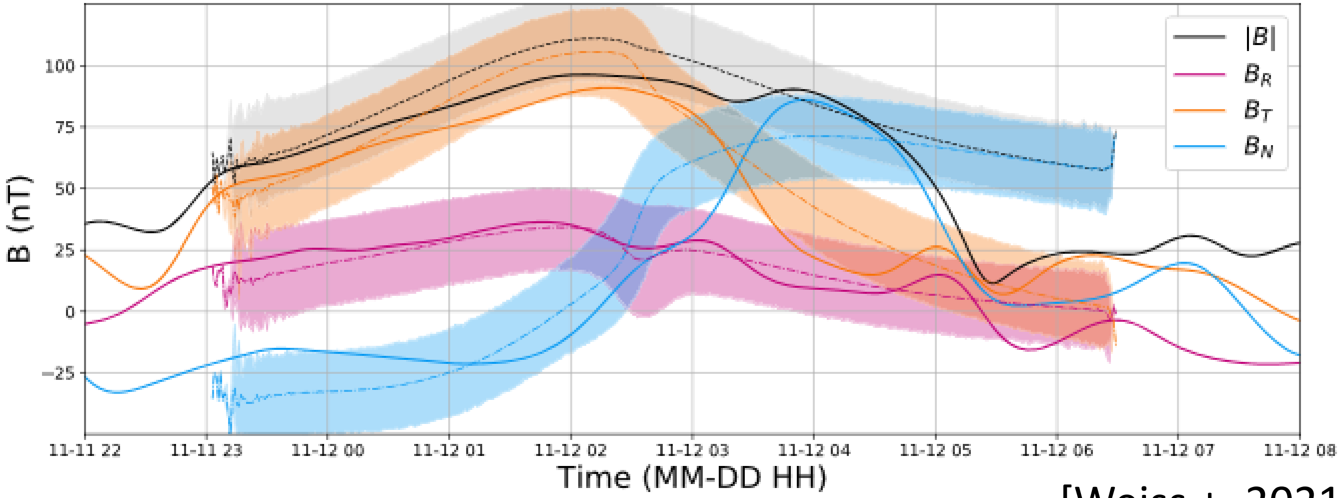
Coronal mass ejection models

3DCORE Flux Rope [Möstl +, 2018]

- Analytic FR model (Gold-Hoyle).
- Self-similar expansion and drag model propagation
- Can fit to real events.





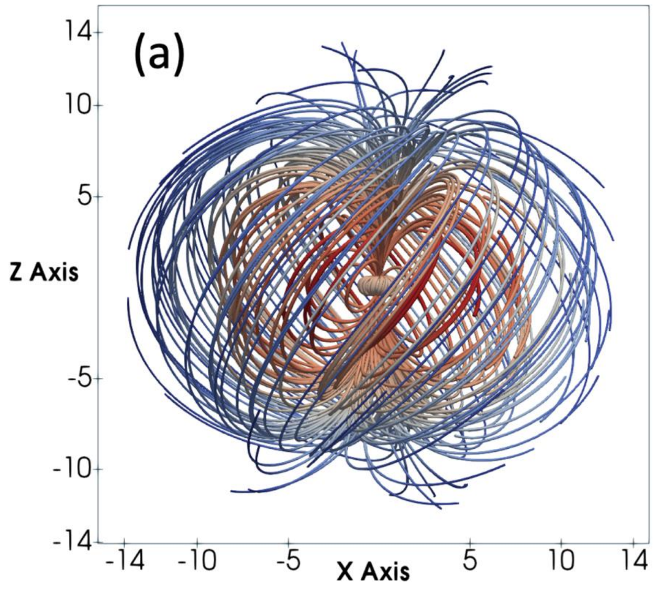


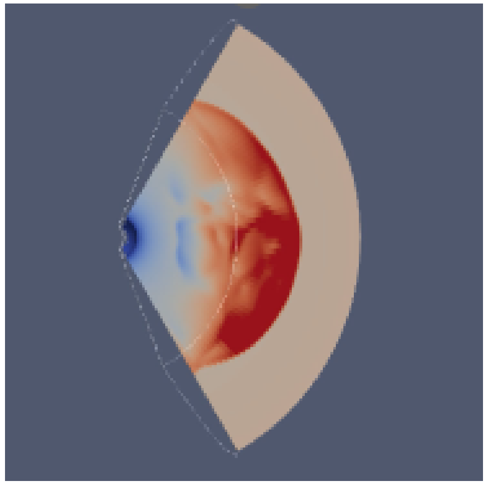
[Weiss +, 2021]

Coronal mass ejection models

MHD Spheromak

- Spherical MHD with shock, sheath and SW.
- Magnetic field rotation similar to flux rope.

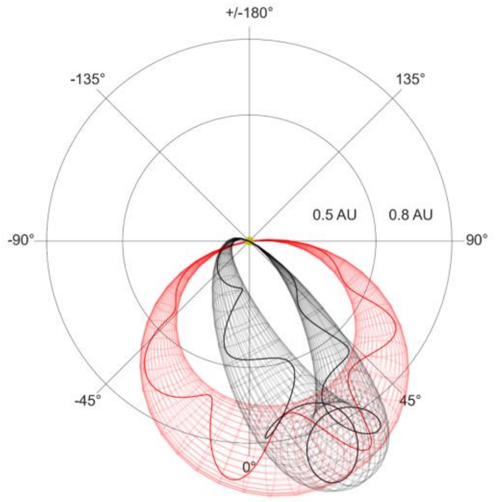


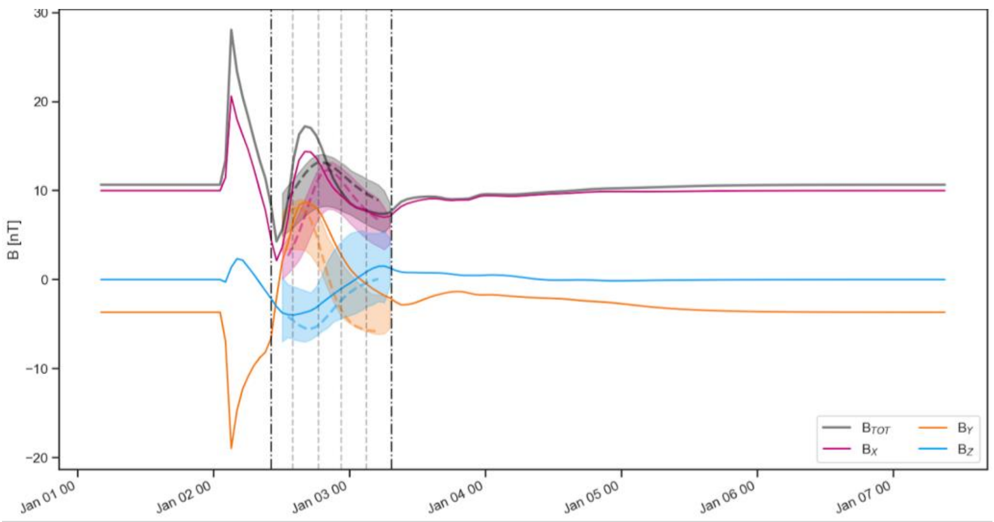


[Koehn +, 2022]

Fitting flux rope model to Spheromak:

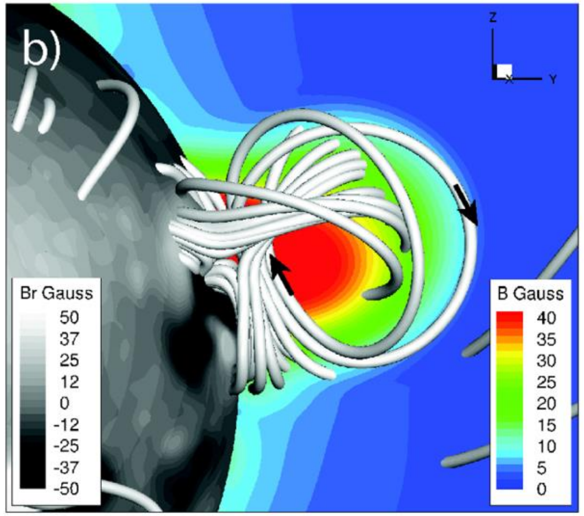
Attempt to compare parameters



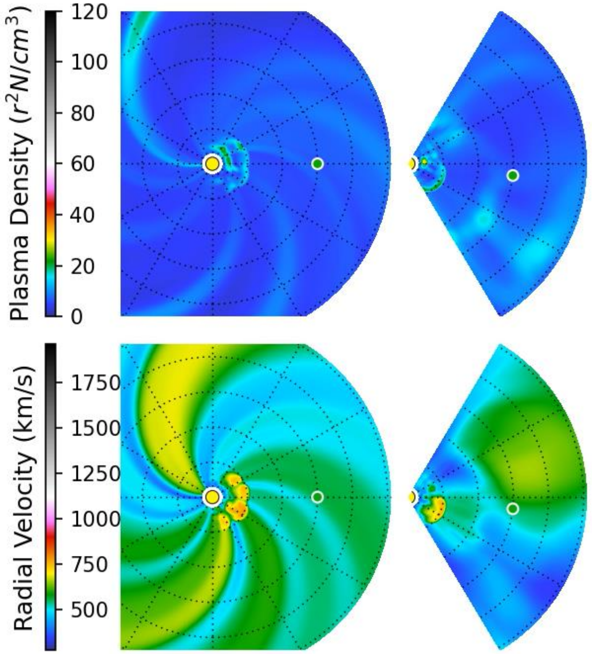


Coronal mass ejection models

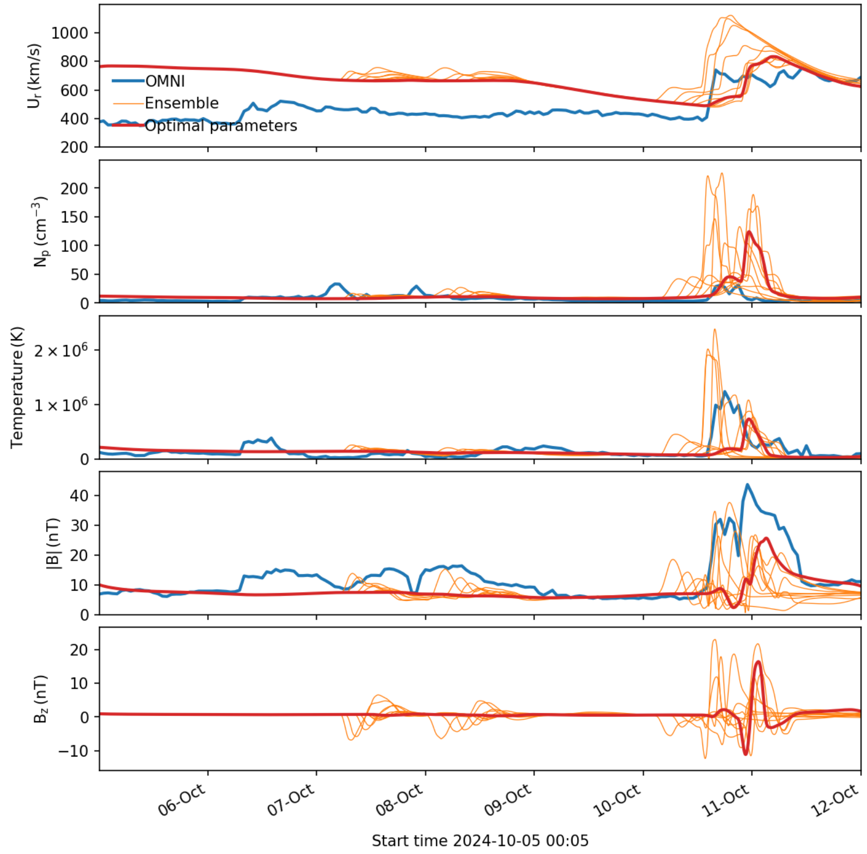
Gibson-Low MHD Flux Rope



[Manchester+, 2014]



[Arber+, https://www.spacepager.eu/]

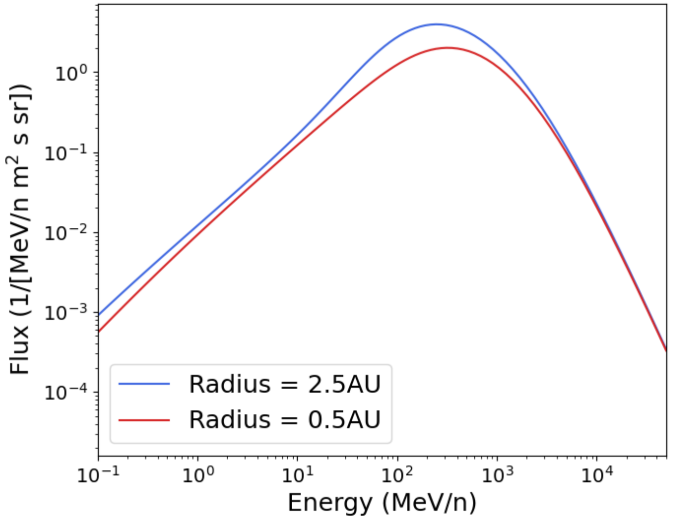


- Coronal simulation coupled with inner heliosphere.
- Magnetised CME ensemble forecasts with realistic solar wind background.
- High-resolution ‘science’ runs also available

Test Particle Simulation

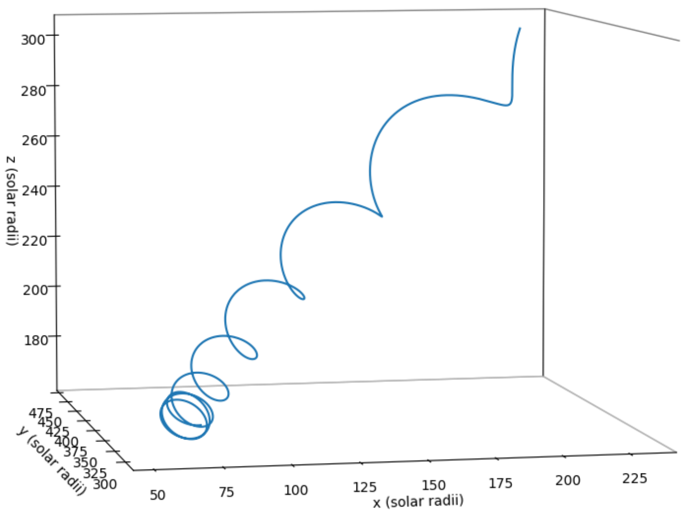
Inputs:

- Spawn particles with weight given by BON2020 (Slaba and Whitman, 2020).
- CME models provide inner heliosphere fields.
- Currently no turbulence incorporated.

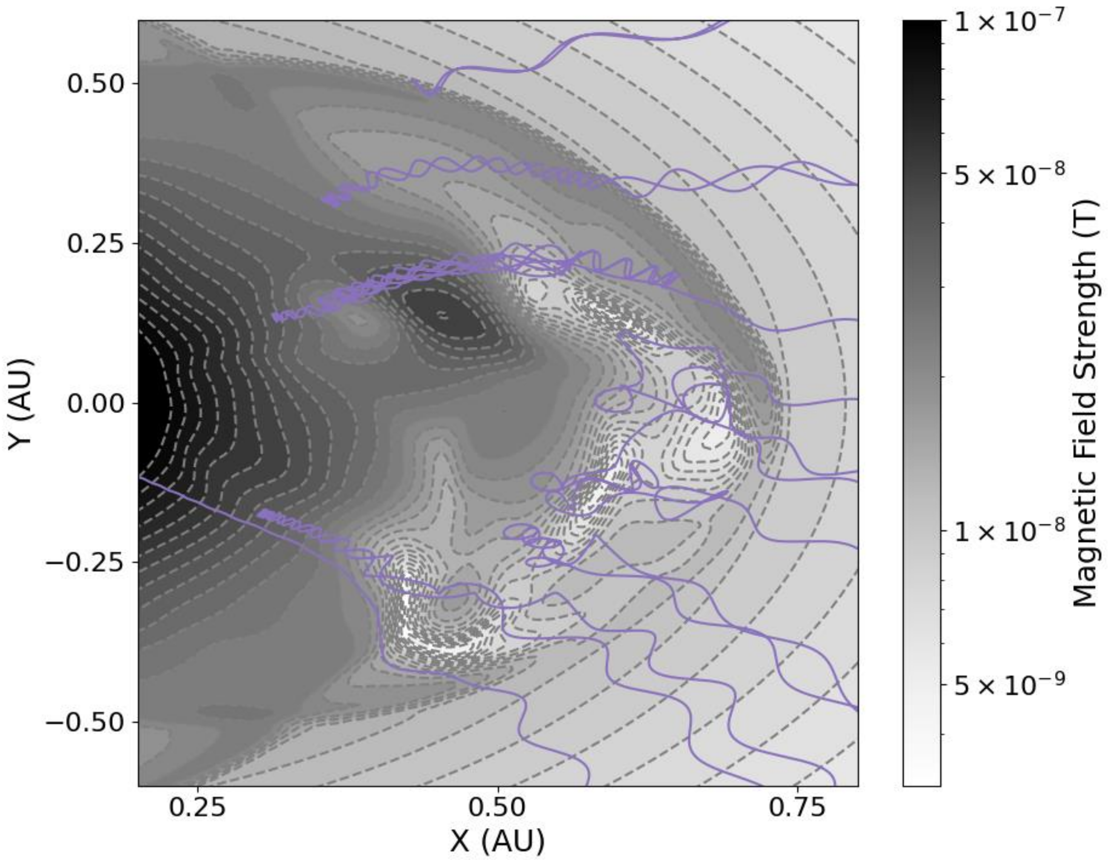


Method:

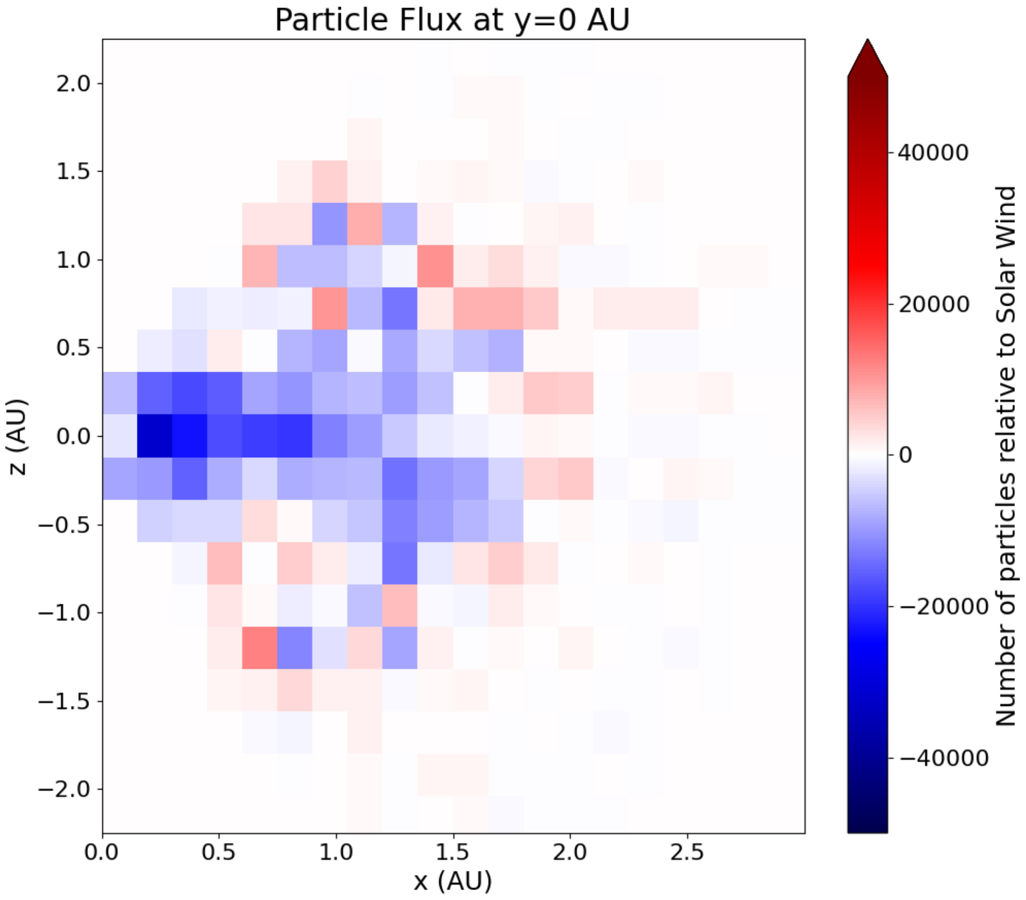
- Boris (1970) integrator: full orbit test-particles.
- Magnetic and electric field stationary, particles are evolved for each timestep.



Results – Spheromak CME



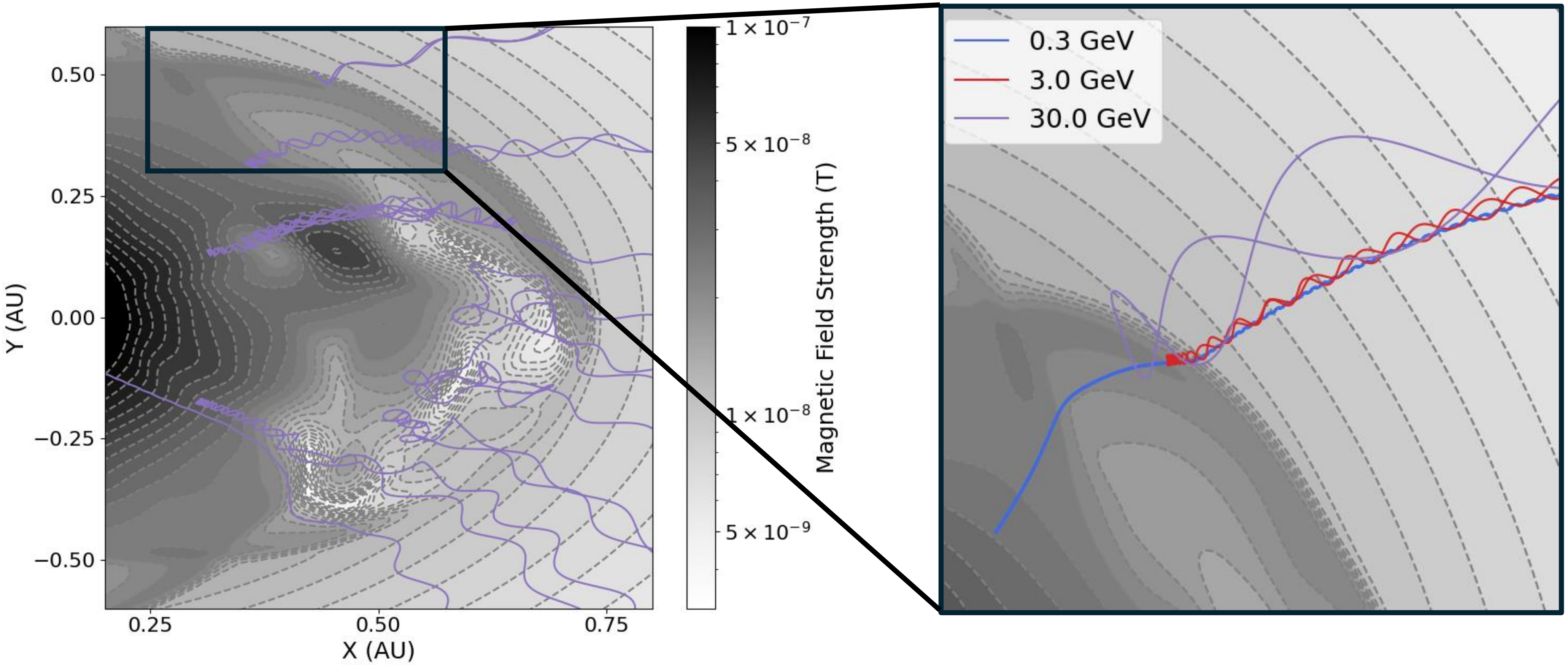
Particles interacting with CME.



Forbush decrease in space.

*Low resolution, preliminary results

Results – Spheromak CME



Particles interacting with CME.

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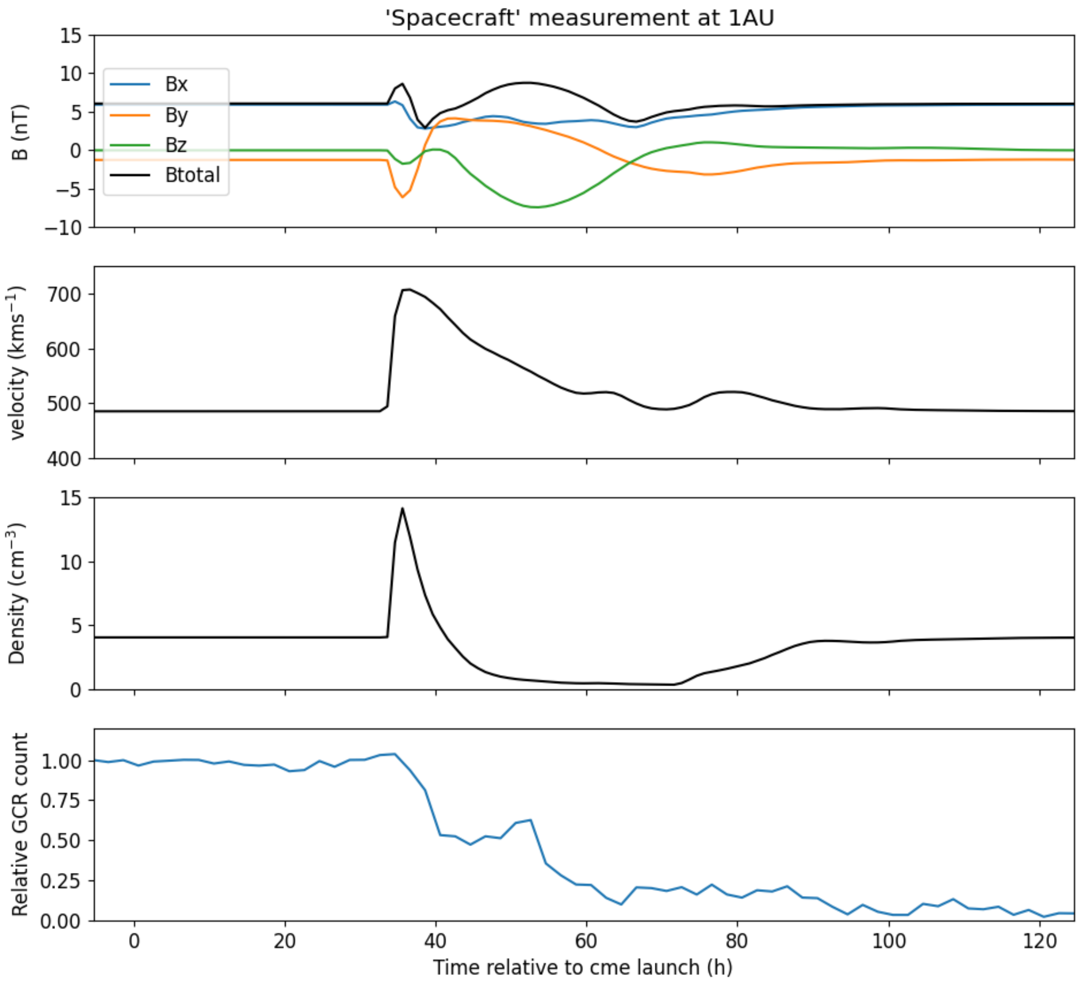
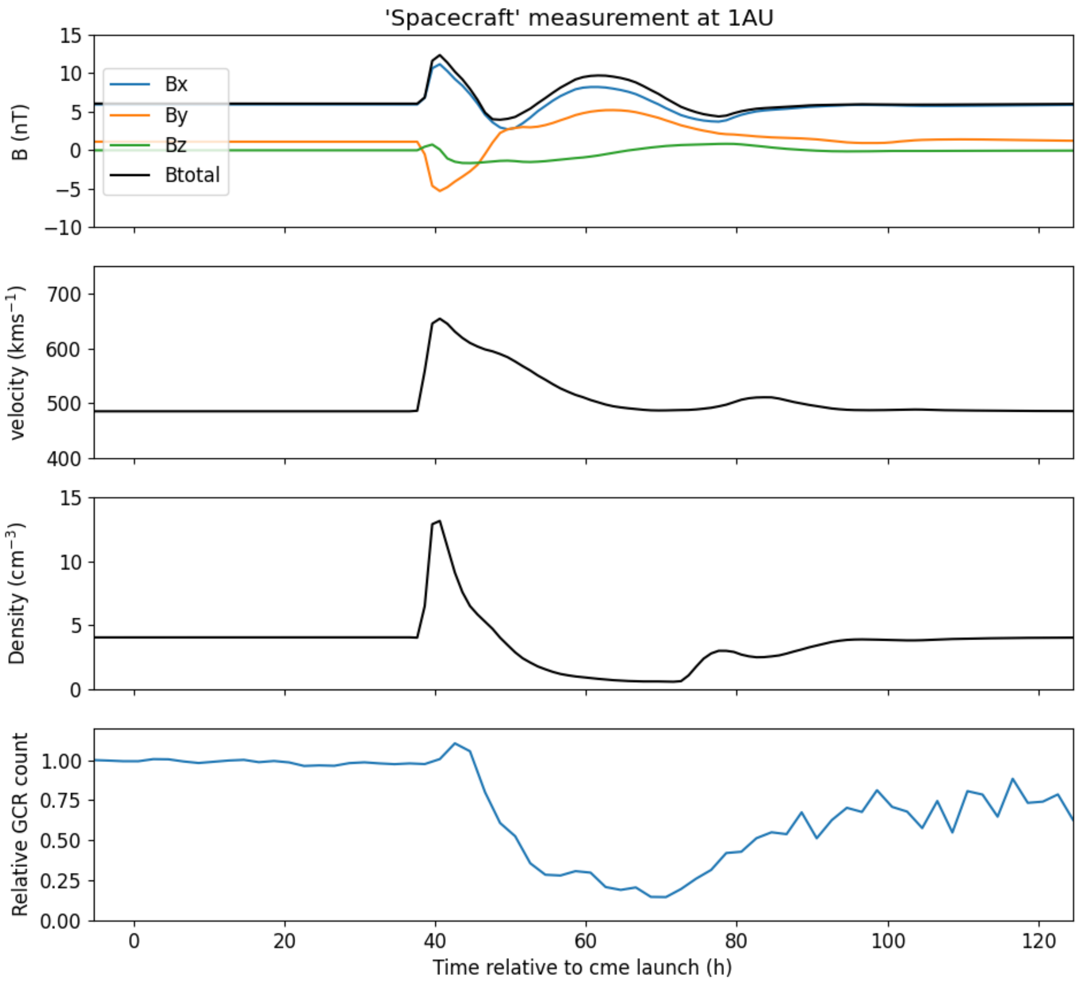
Results – Spheromak CME

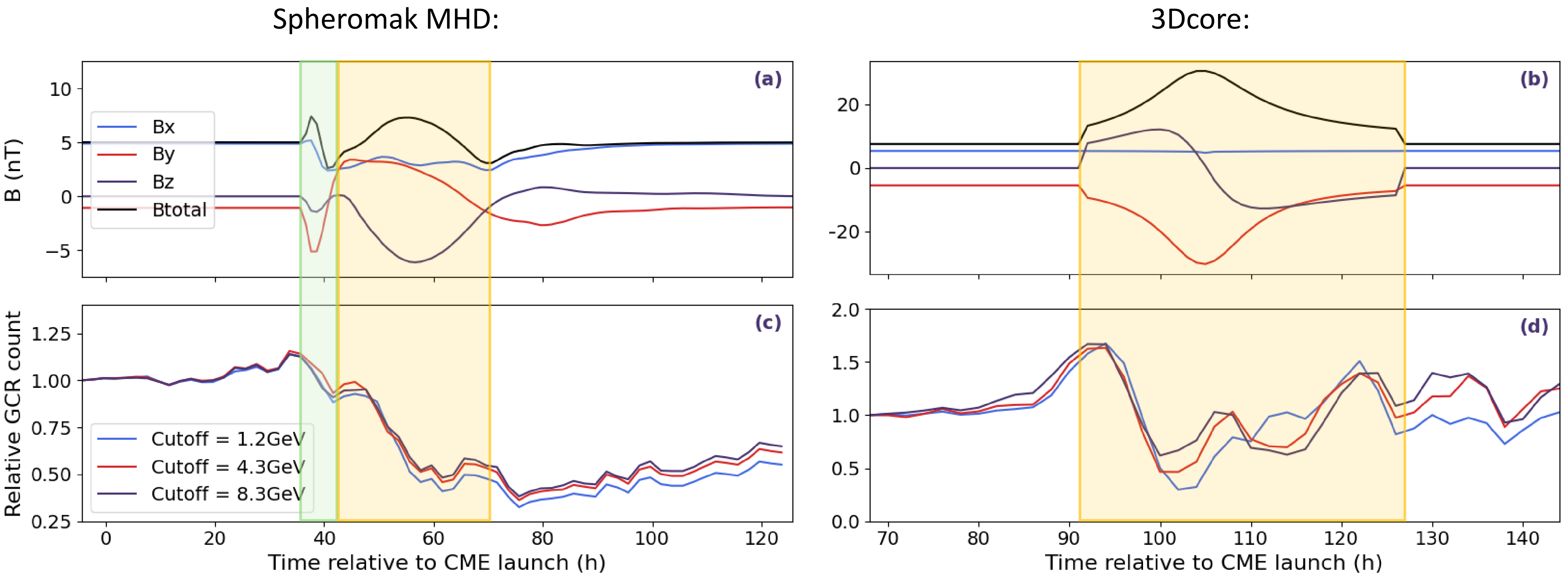
Centre of CME:



Right side of CME:



Results – Comparing Models



1-step and 2-step decreases are reproduced as expected.

Conclusions and Future Work

- We are comparing 3 different CME field models
- We also compare Fd from 3 different models
  - Able to reproduce 2 step decrease.
  - Model without shock only has 1 step decrease.

Reproduce recovery phase and decrease magnitude:

- Does this require simulating turbulence?

Compare with observed events: multipoint observations to see if we can reproduce evolution correctly.

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