FRi3D: a novel 3D model of CMEs

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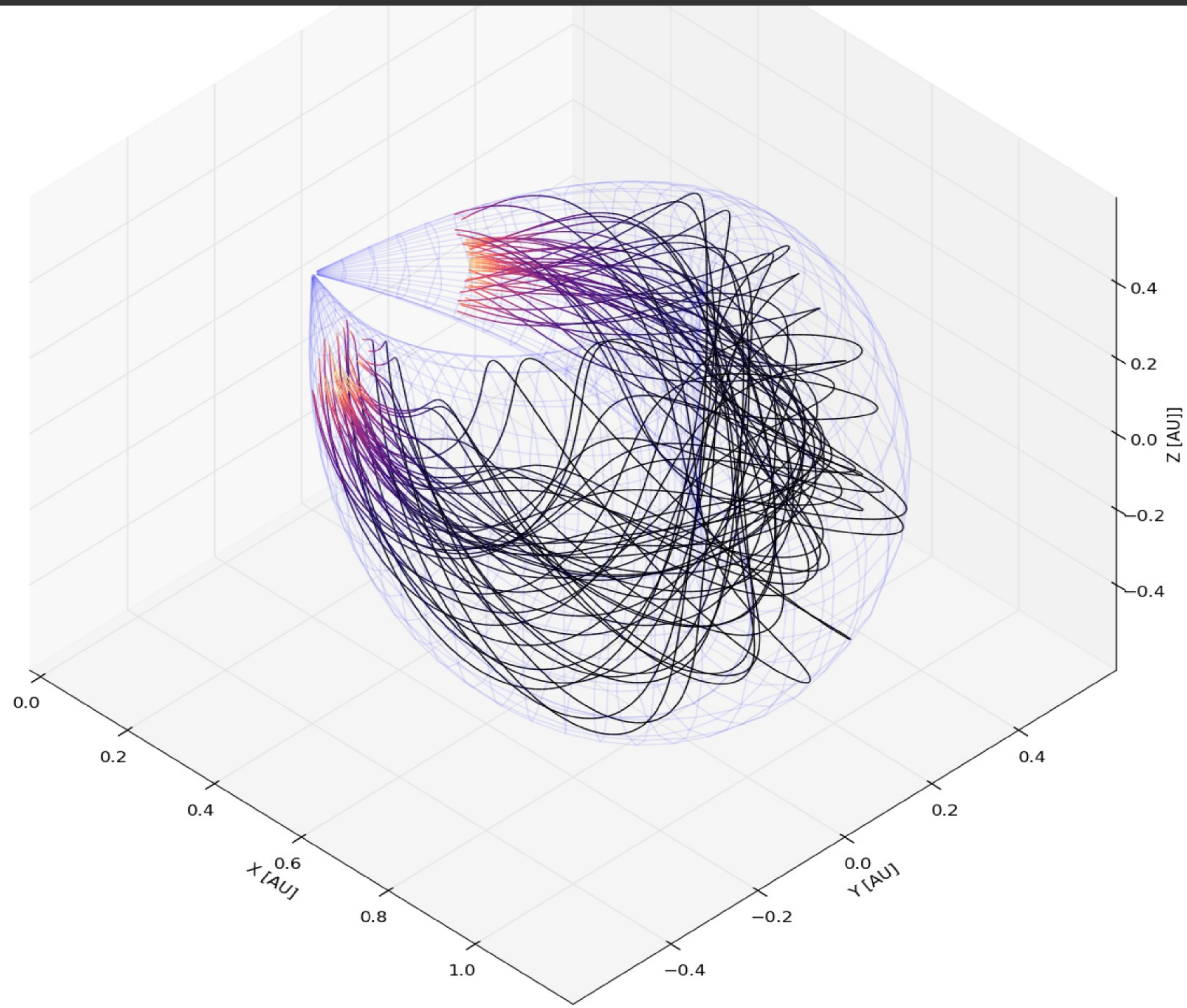


Why model CMEs?

Space weather forecasting in relation to CMEs includes prediction of **both** arrival time and magnetic field.

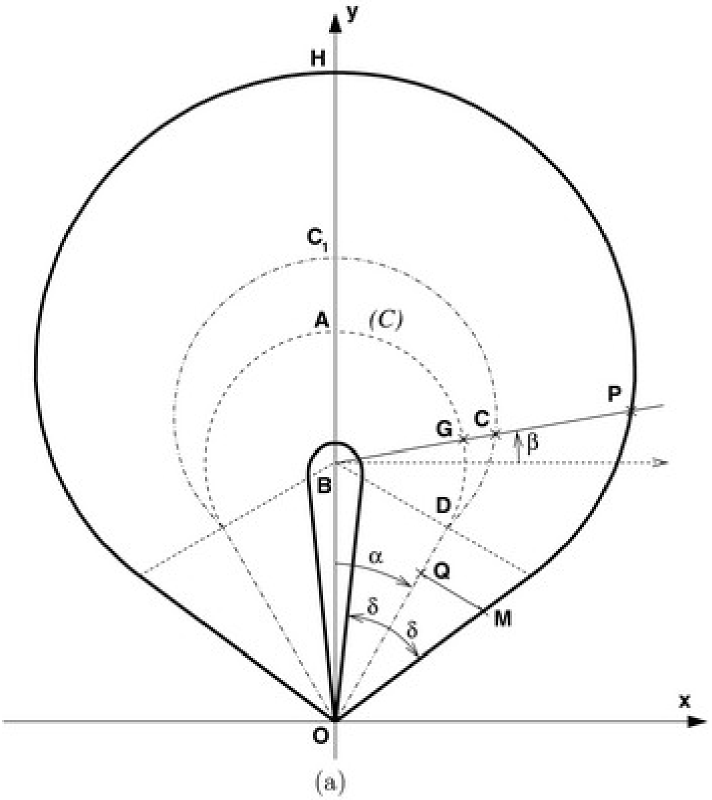
In-situ magnetic field as well as arrival time very much depends on the geometry of the encounter with a CME.

Evolution of a CME in the interplanetary space can make the trajectory of such an encounter even more unpredictable.

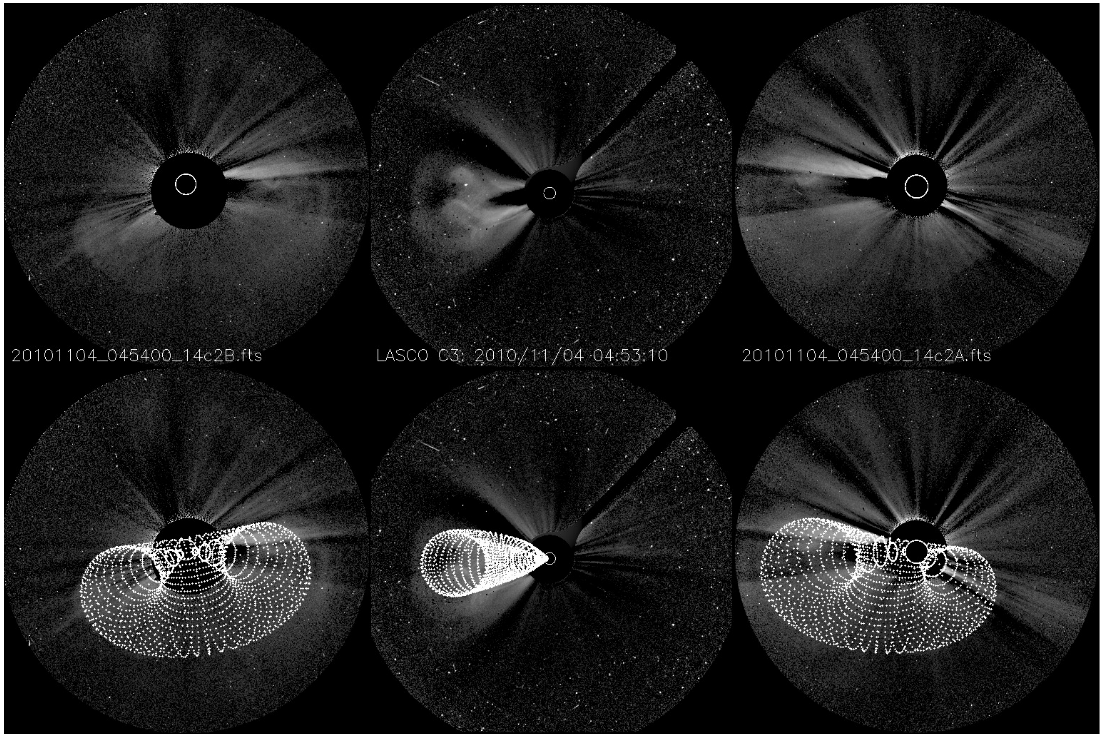
The current approach to CME modelling

White-light fitting techniques, *e.g.*:

- Cone model *[Xie et al., 2004]*
- GCS forward modelling *[Thernisien et al., 2009]*



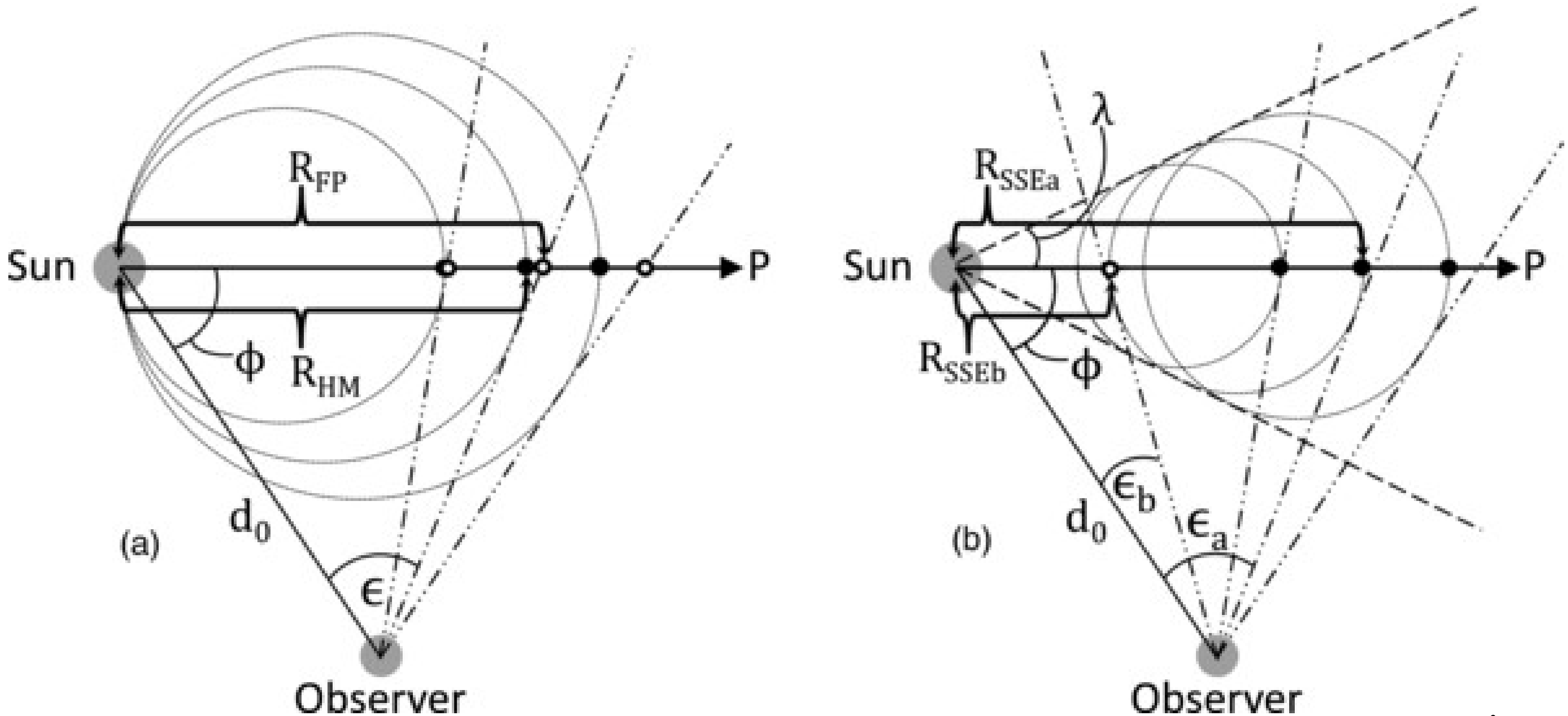
Thernisien et al., 2009



Isavnin et al., 2013

The current approach to CME modelling

J-maps fitting techniques, *e.g.*:
- Fixed-phi model *[Ruillard et al., 2008]*
- Harmonic mean model *[Lugaz, 2009]*
- Self-similar expansion model *[Davies et al., 2012]*
- ElEvoCon technique *[Rollett et al., 2016]*

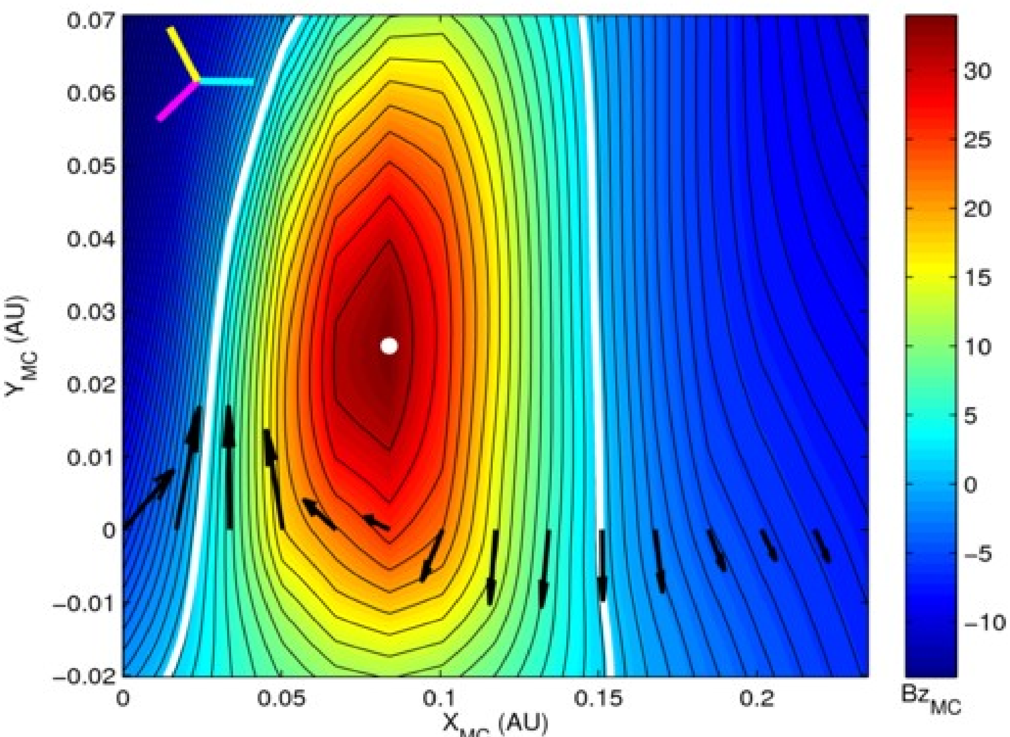


Davies et al., 2012

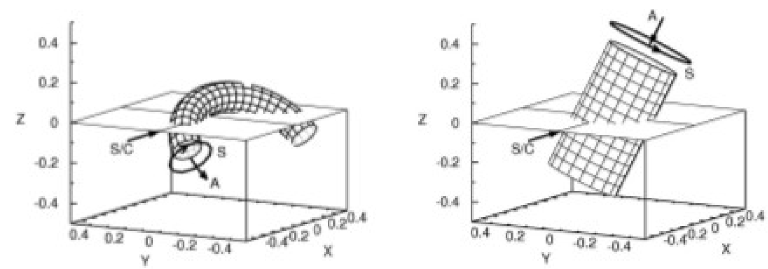
The current approach to CME modelling

Flux-rope fitting and reconstruction techniques, *e.g.*:

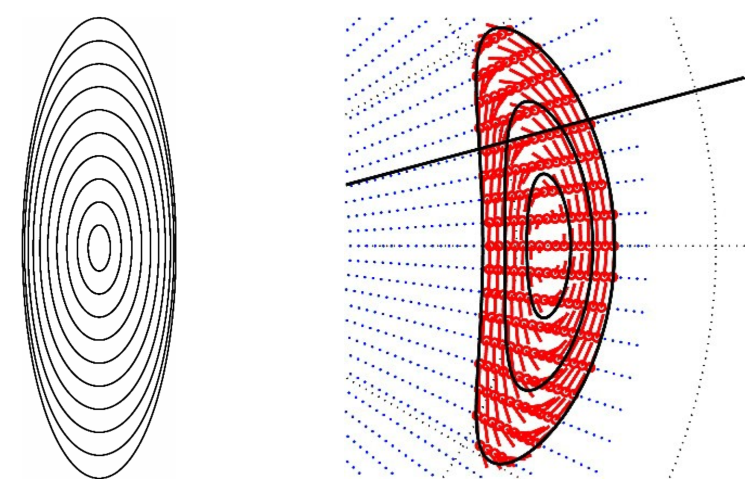
- Cylinder model *[Lepping et al., 1990]*
- Elliptic model *[Hidalgo et al., 2002]*
- Torus and cylinder models *[Marubashi & Lepping, 2007]*
- Kinematically distorted flux-rope model *[Owens, 2006]*
- Grad-Shafranov reconstruction *[Hau et al., 2001]*



Isavnin et al., 2011



Marubashi et al., 2007



Owens, 2006

The current approach to CME modelling

General approach: focus on one or two aspects of CME evolution and neglect all the others.

Consequence: it is really hard to study CME evolution and difficult to link different models and different assumptions consistently.

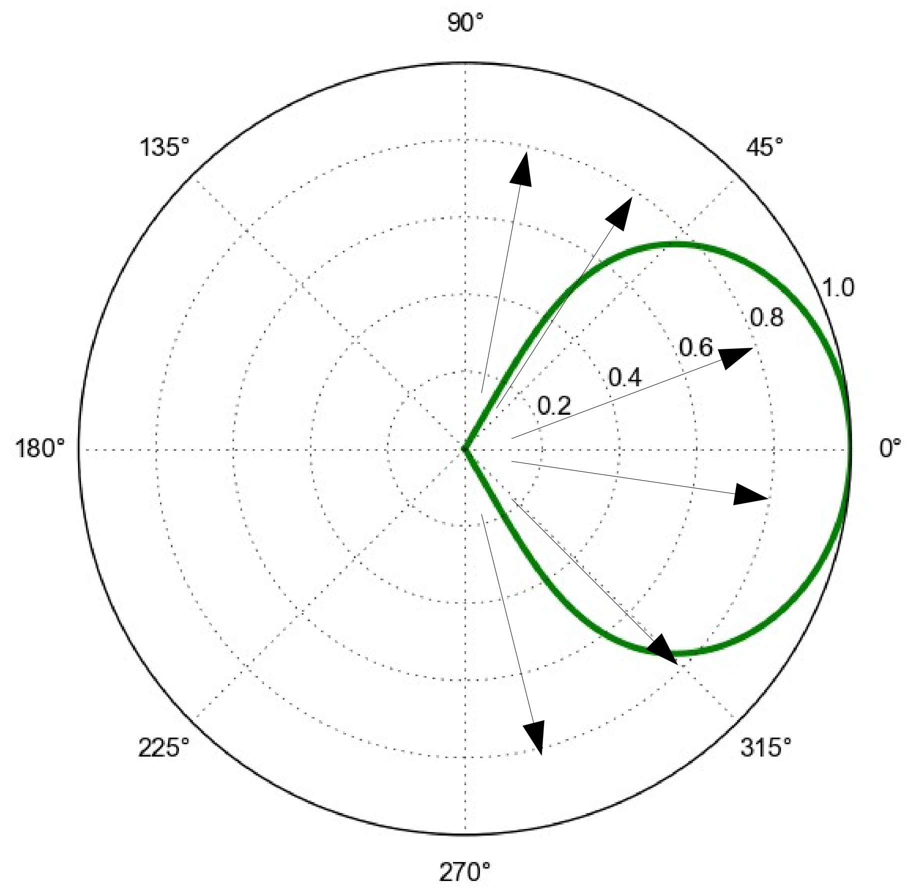
Solution: let's try to merge all the major aspects of 3D geometry and magnetic structure of CMEs into a single model: **F**lux **R**ope **i**n **3D** or **FRi3D**.

What a CME model should be capable of?

- Reasonable 3D geometry
- Support for typical deformations
  - Expansion
  - Deflection
  - Rotation
  - ”Pancaking” due to radial expansion
  - Skew due to solar rotation
  - Front flattening (fast CMEs)
- 3D magnetic field configuration
- Reasonable magnetic field configuration in 2D cuts

Figuring out the shape of CME

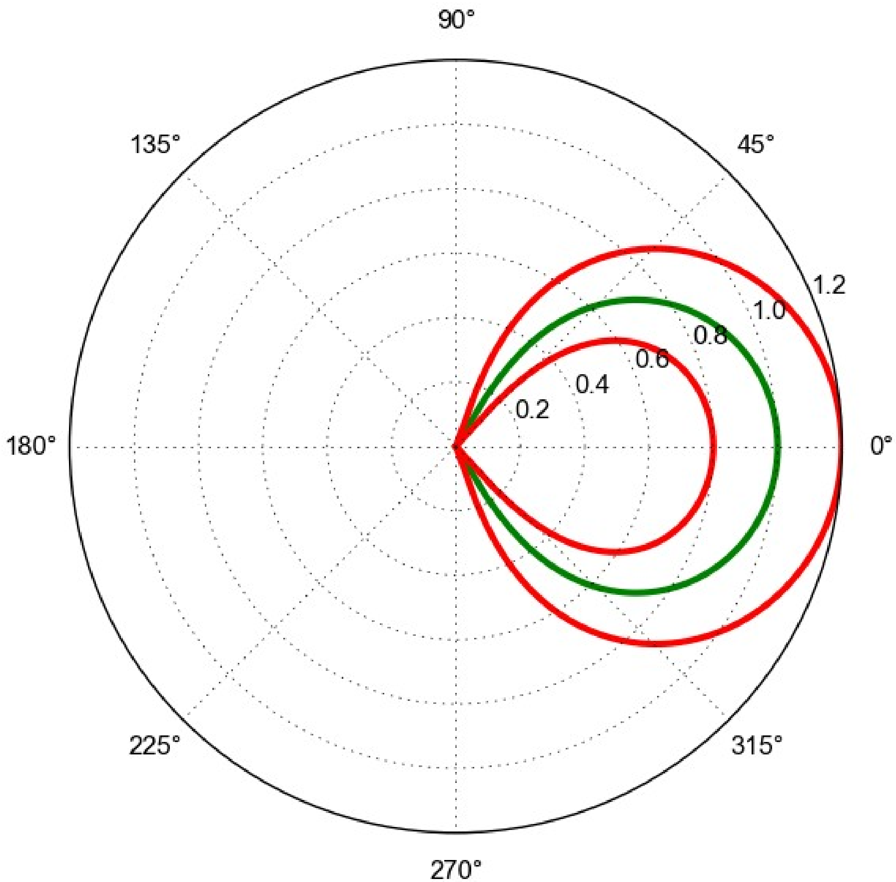
Starting with simplified hydrodynamic description: magnetic slingshot in a radial outflow.

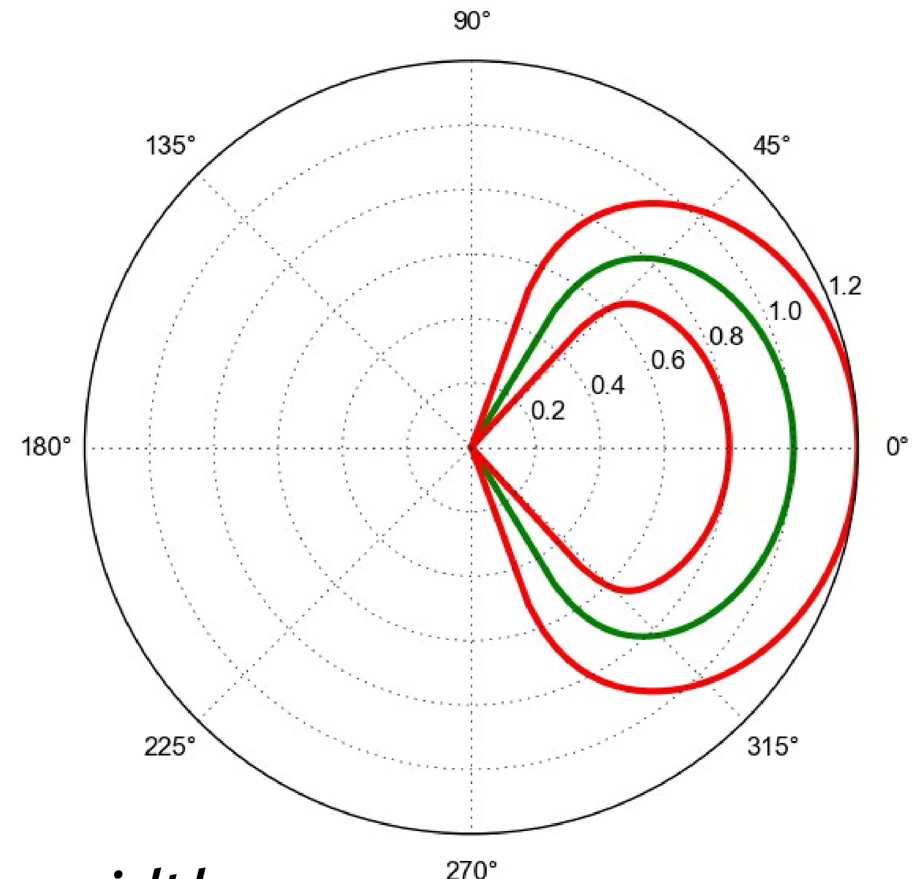


Balance of HD forces and magnetic tension provides an estimate for the shape of CME.

Front flattening

The constants from HD solution (outflow speed, viscosity, etc.) regulate the front flattening.



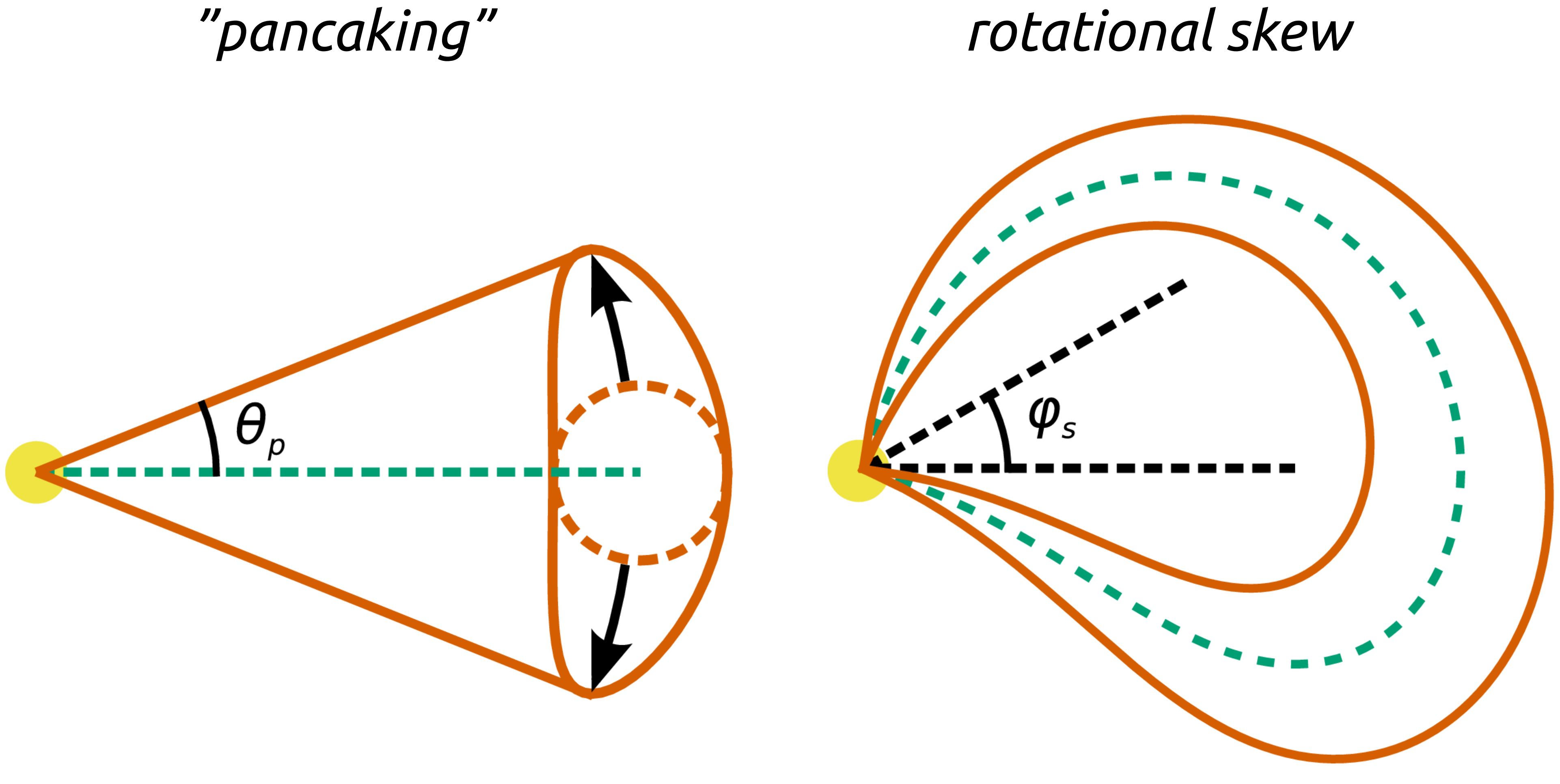


same angular width

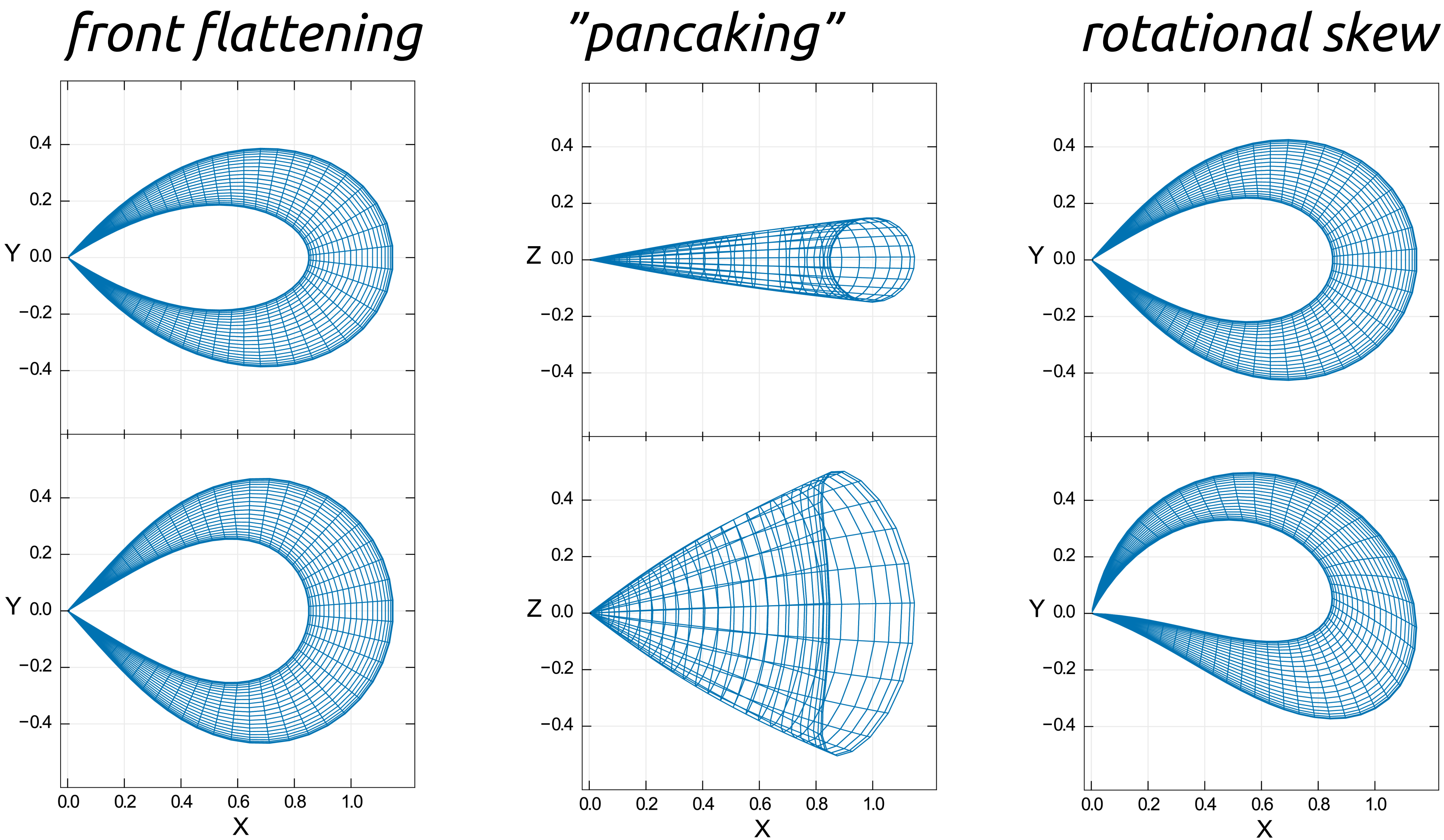
slow outflow (=slow CME) *fast outflow (=fast CME)*

”Pancaking” and rotational skew

”Pancaking” and rotational skew can be easily introduced via geometric transformations.



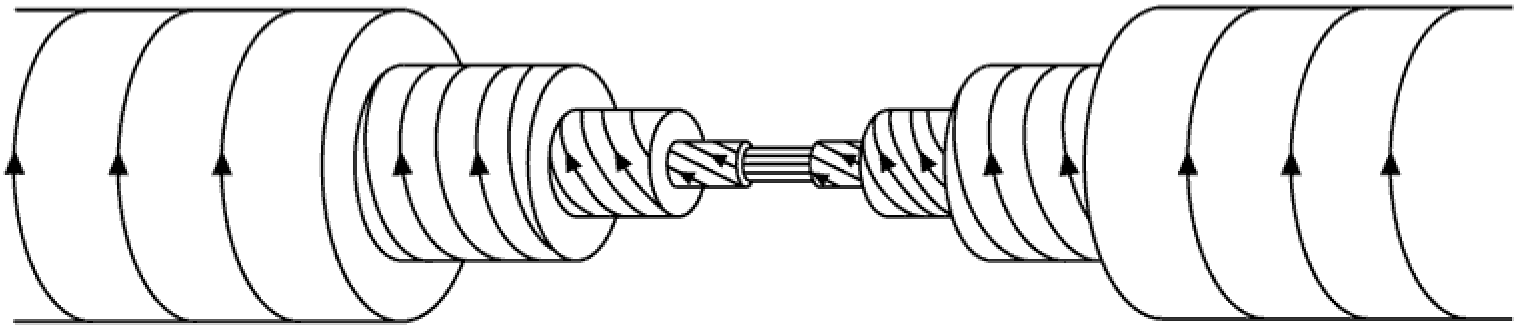
3D shell of the FRi3D model



Similar to GCS model but fully (and continuously) analytic and includes flattening, "pancaking" and rotational skew.

Twist of magnetic field-lines in a flux rope

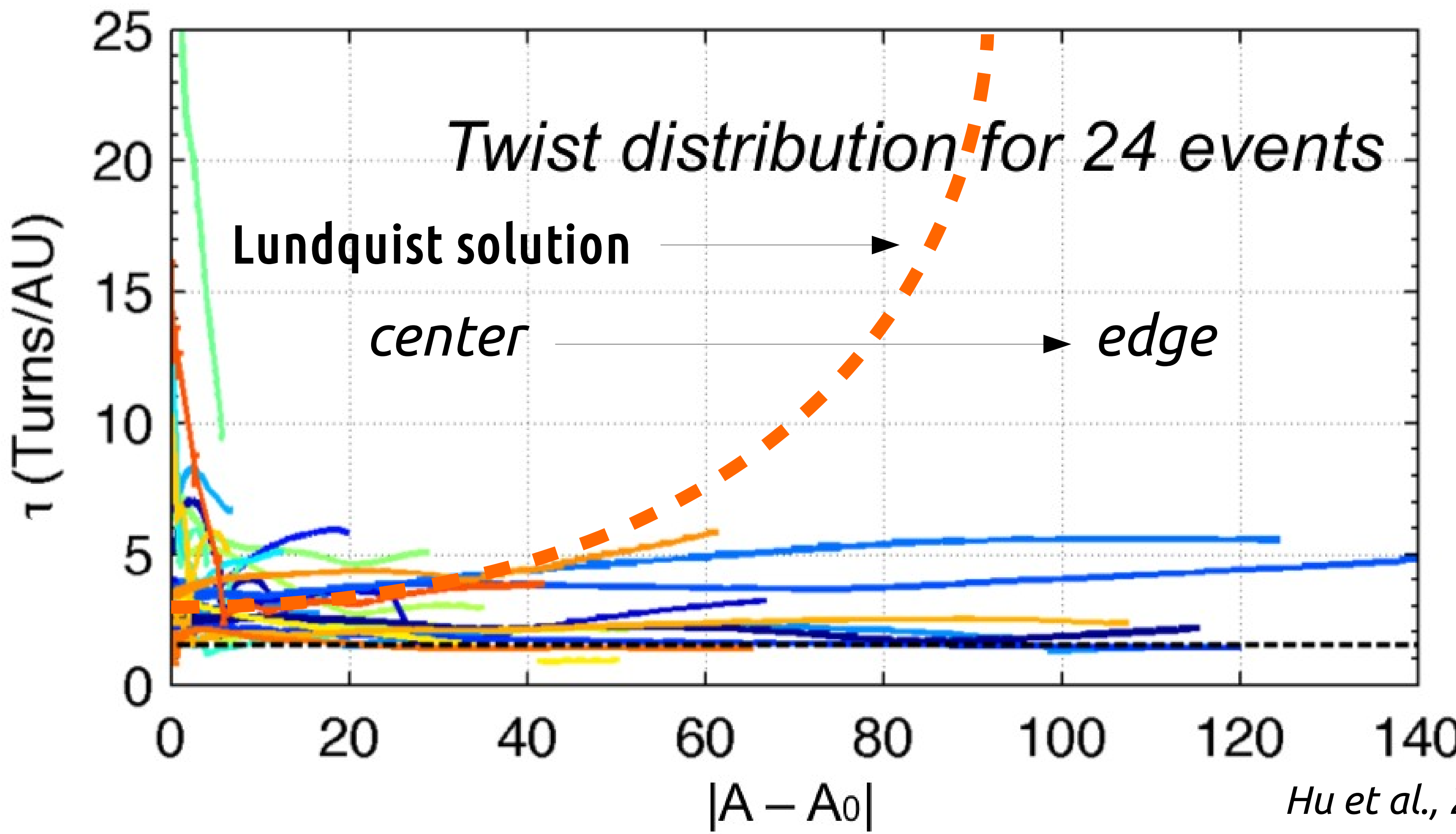
Classical Lundquist representation: twist increases towards the edge of a flux rope going to infinity.



Interior Structure of Flux Rope

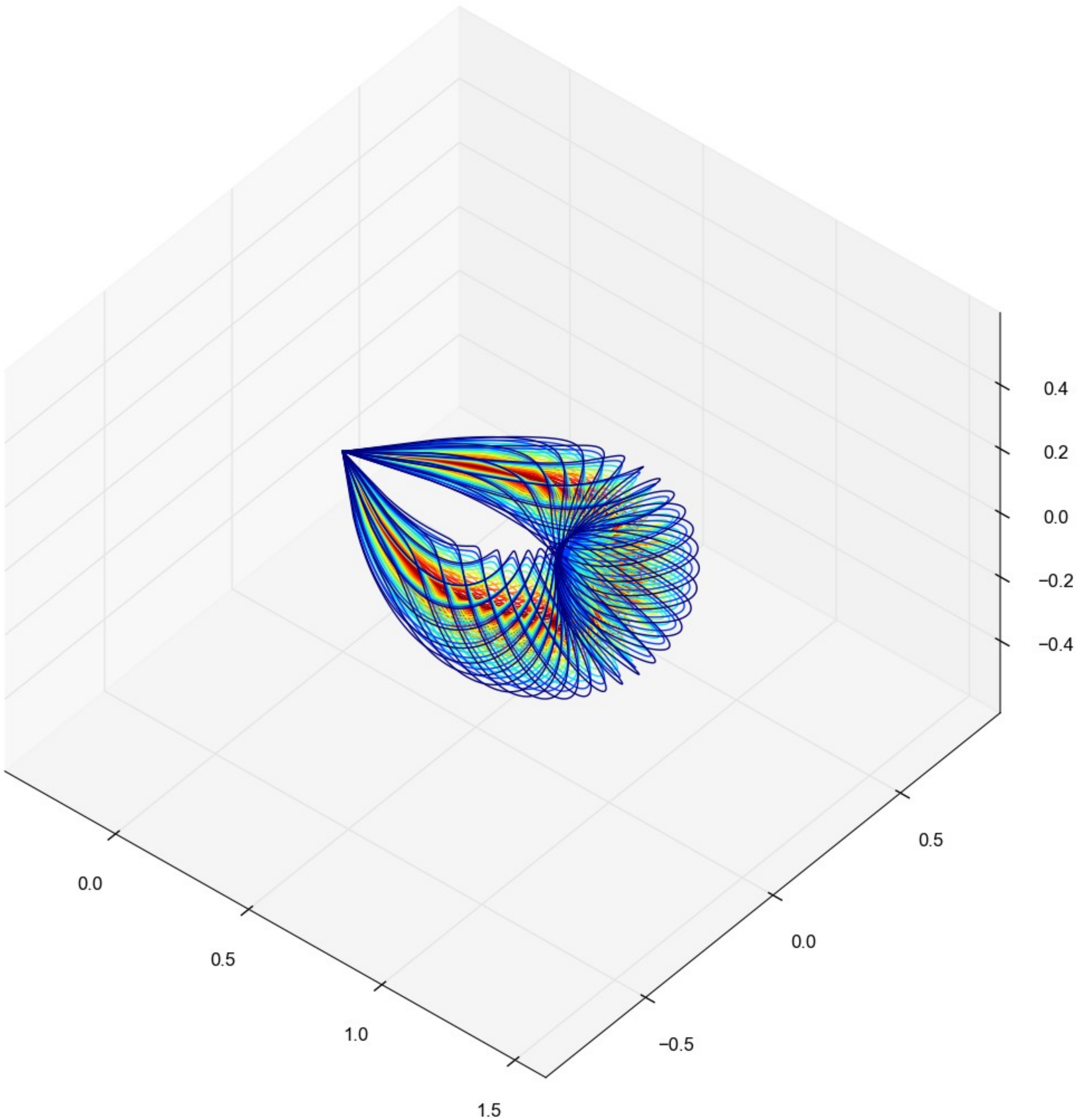
Twist of magnetic field-lines in a flux rope

The twist in flux-rope CMEs is **low** and **constant** contradictory to the Lundquist solution *[Hu et al., 2015]*

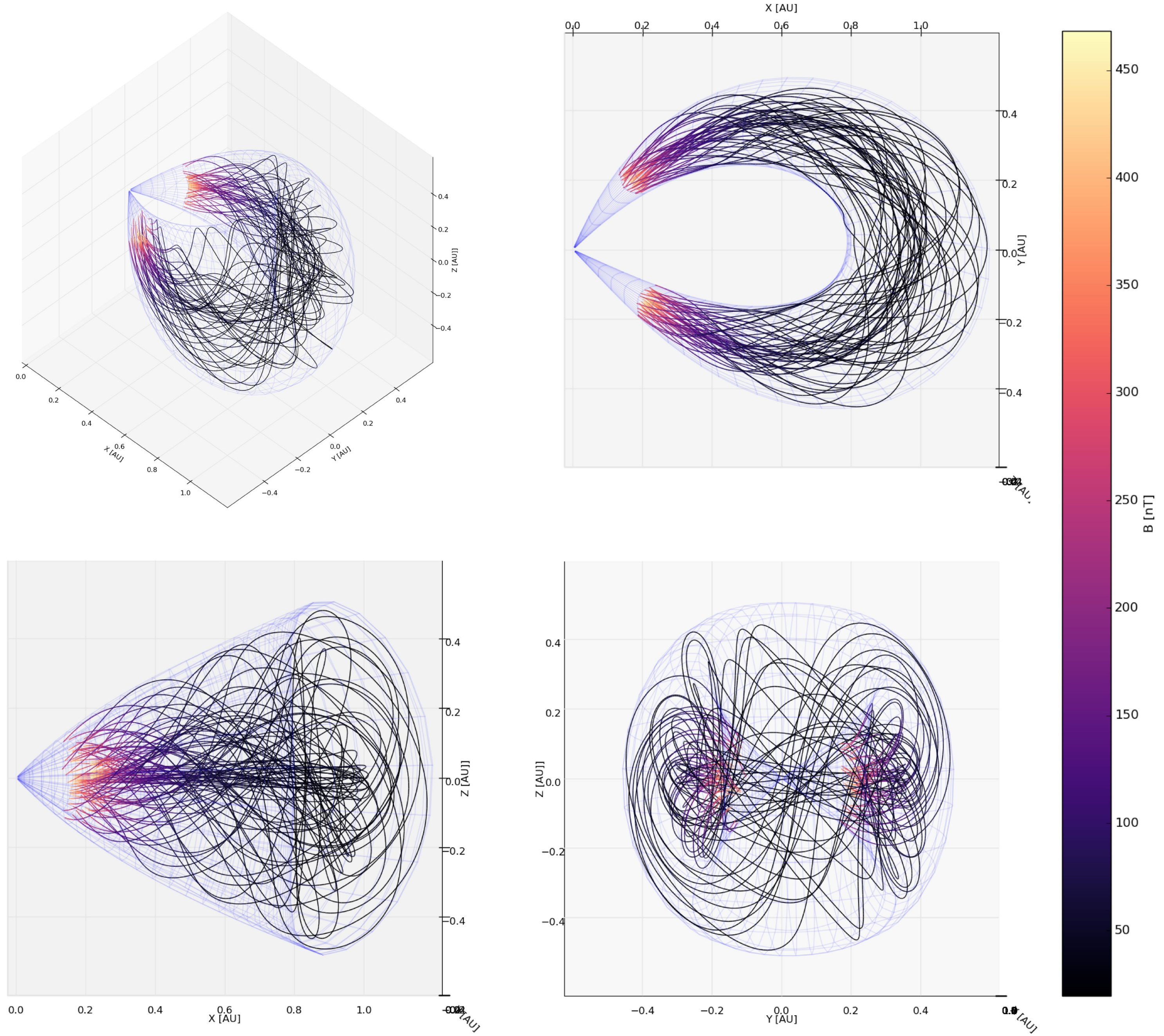


Hu et al., 2015

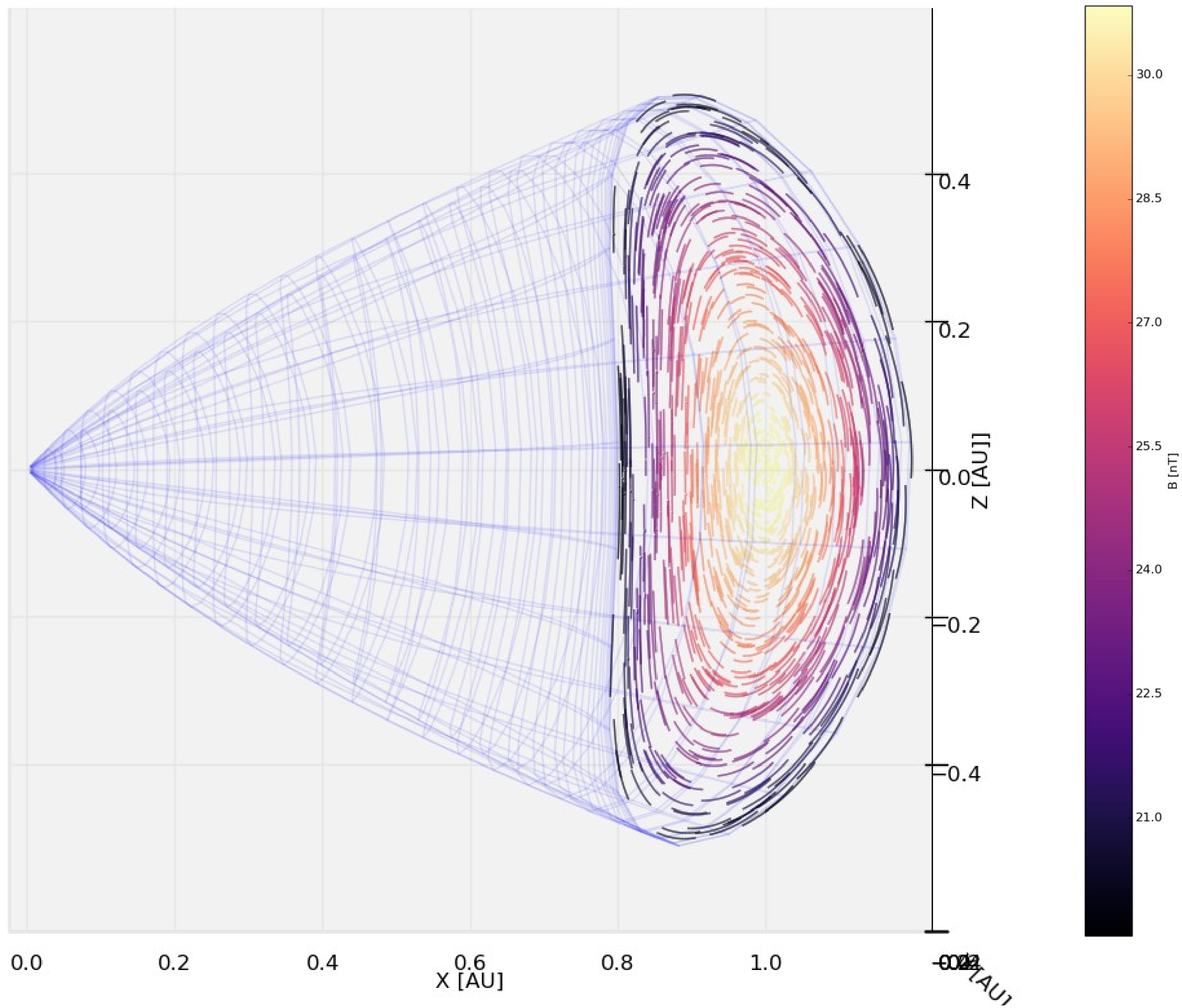
3D magnetic field structure with constant twist



… and after implementing flux conservation

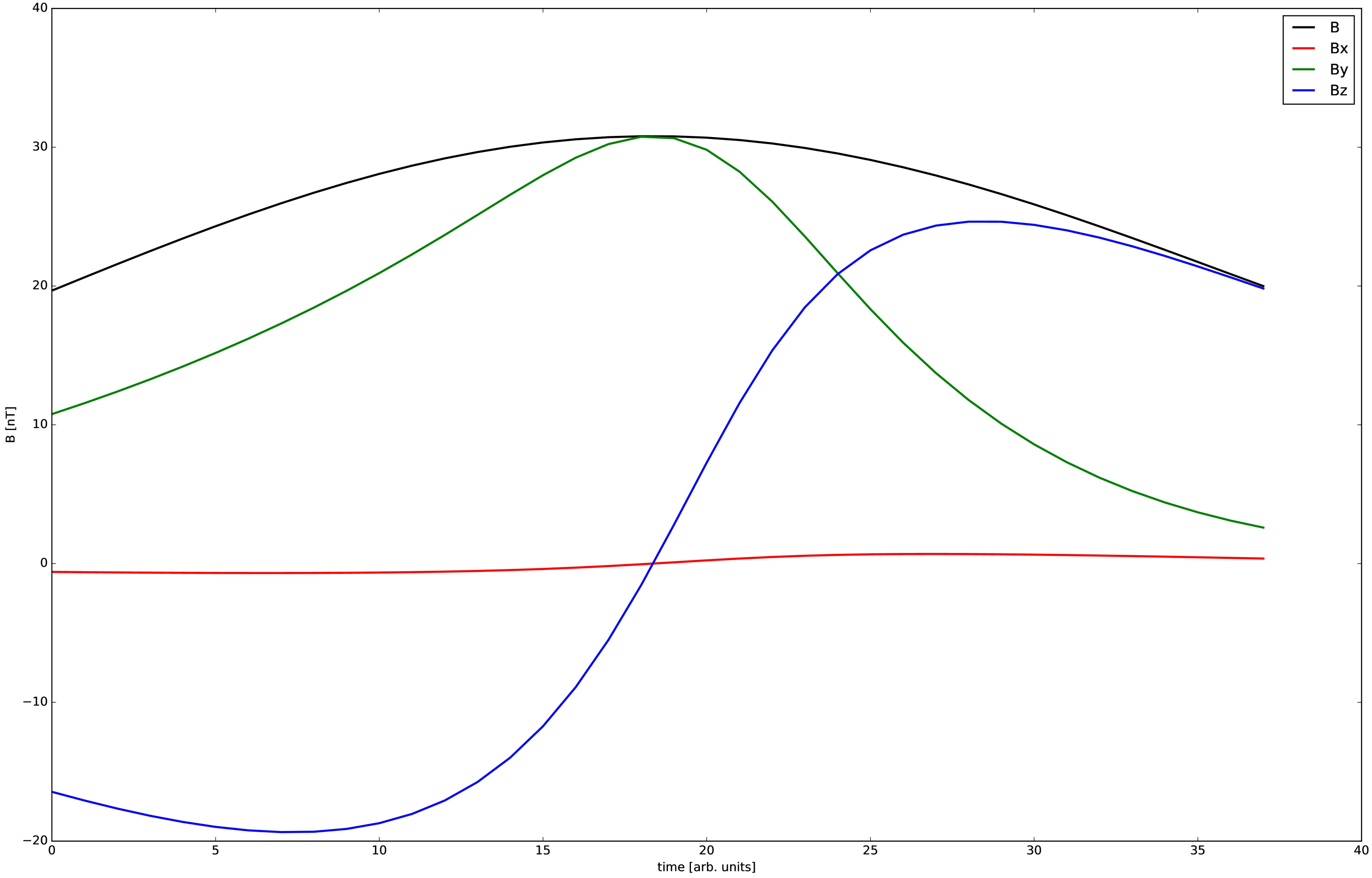


Cross-section of the FRi3D model



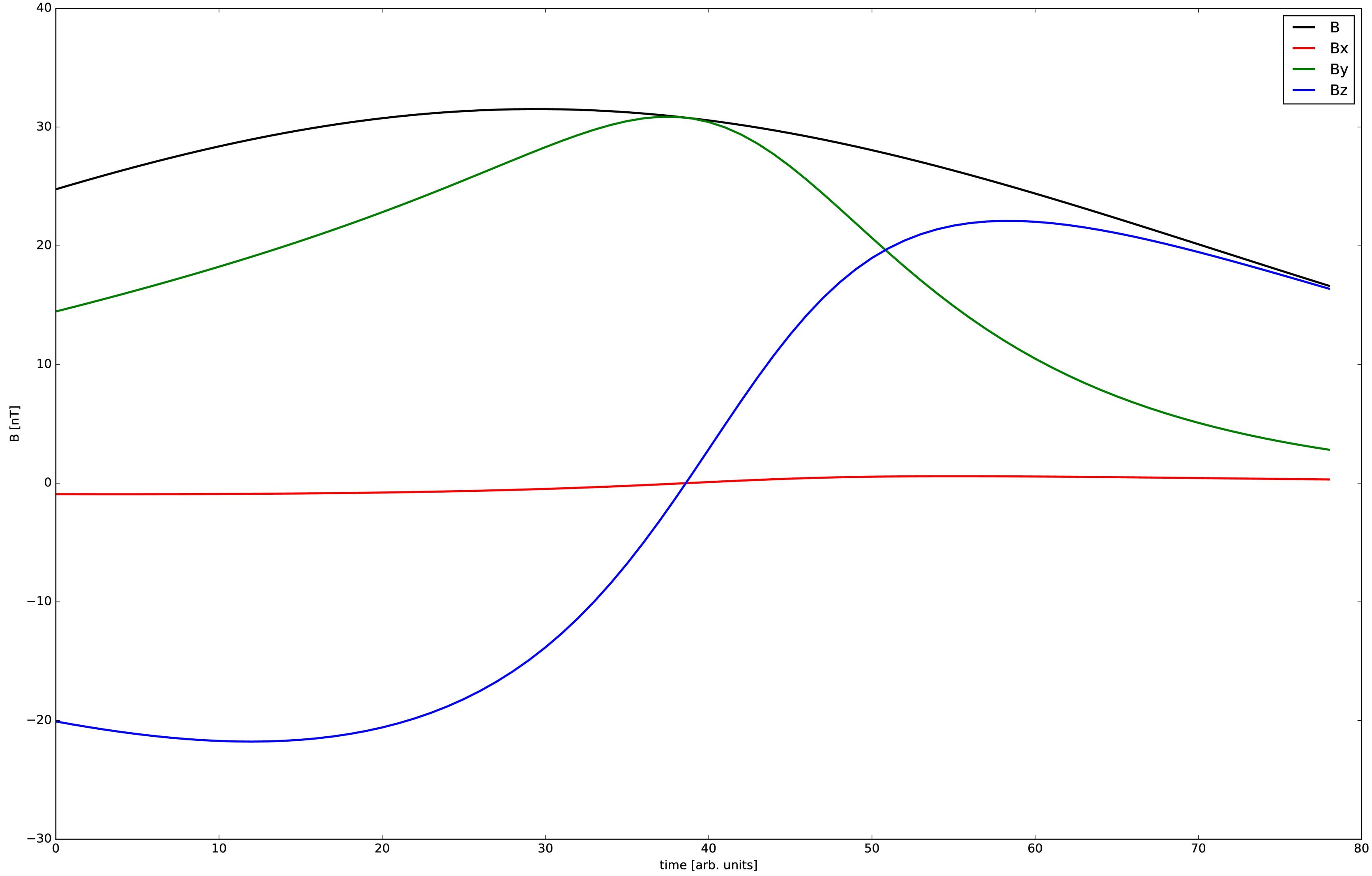
Synthetic in-situ measurements of magnetic field

no evolution



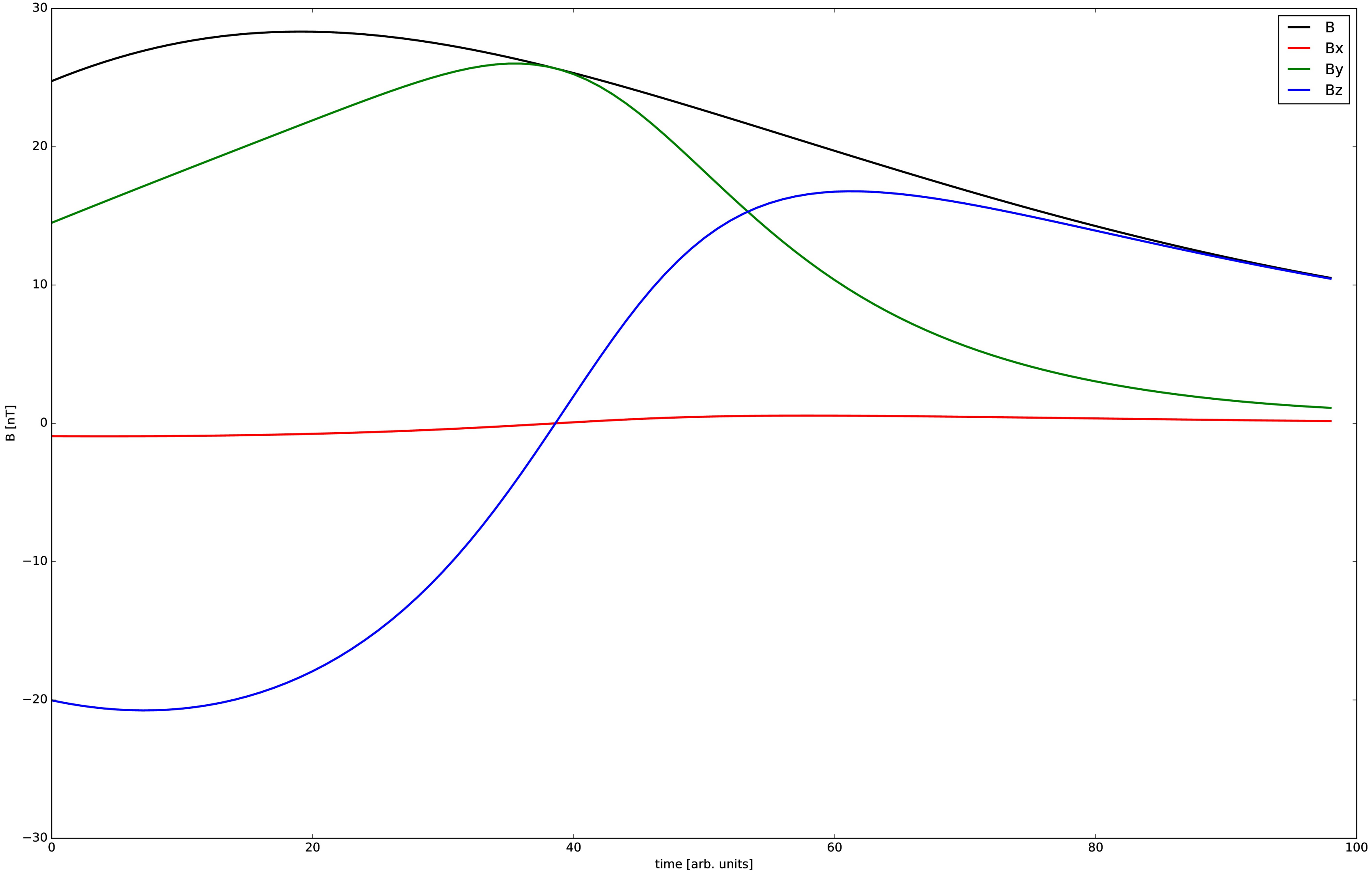
Synthetic in-situ measurements of magnetic field

propagation without expansion

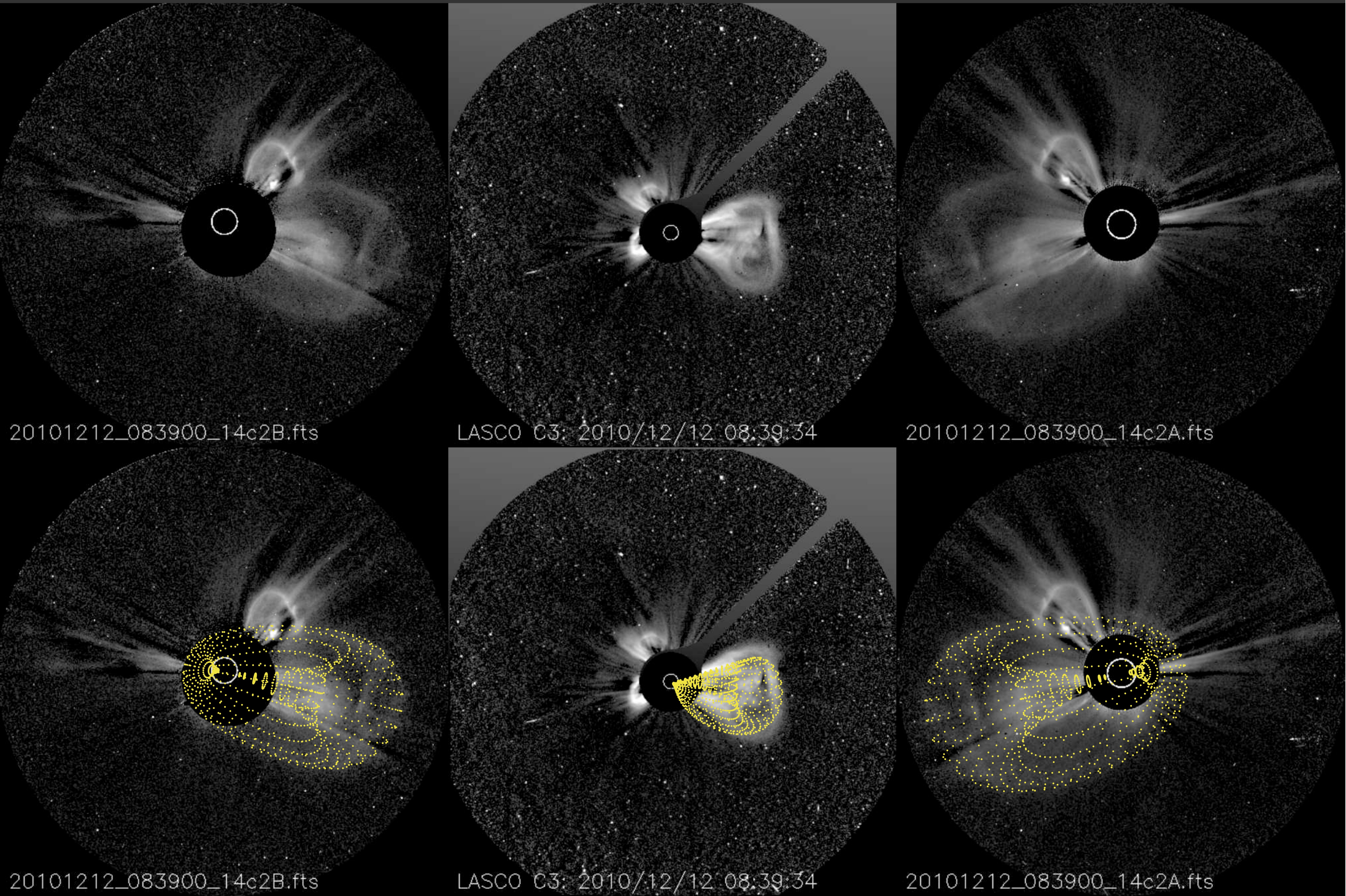


Synthetic in-situ measurements of magnetic field

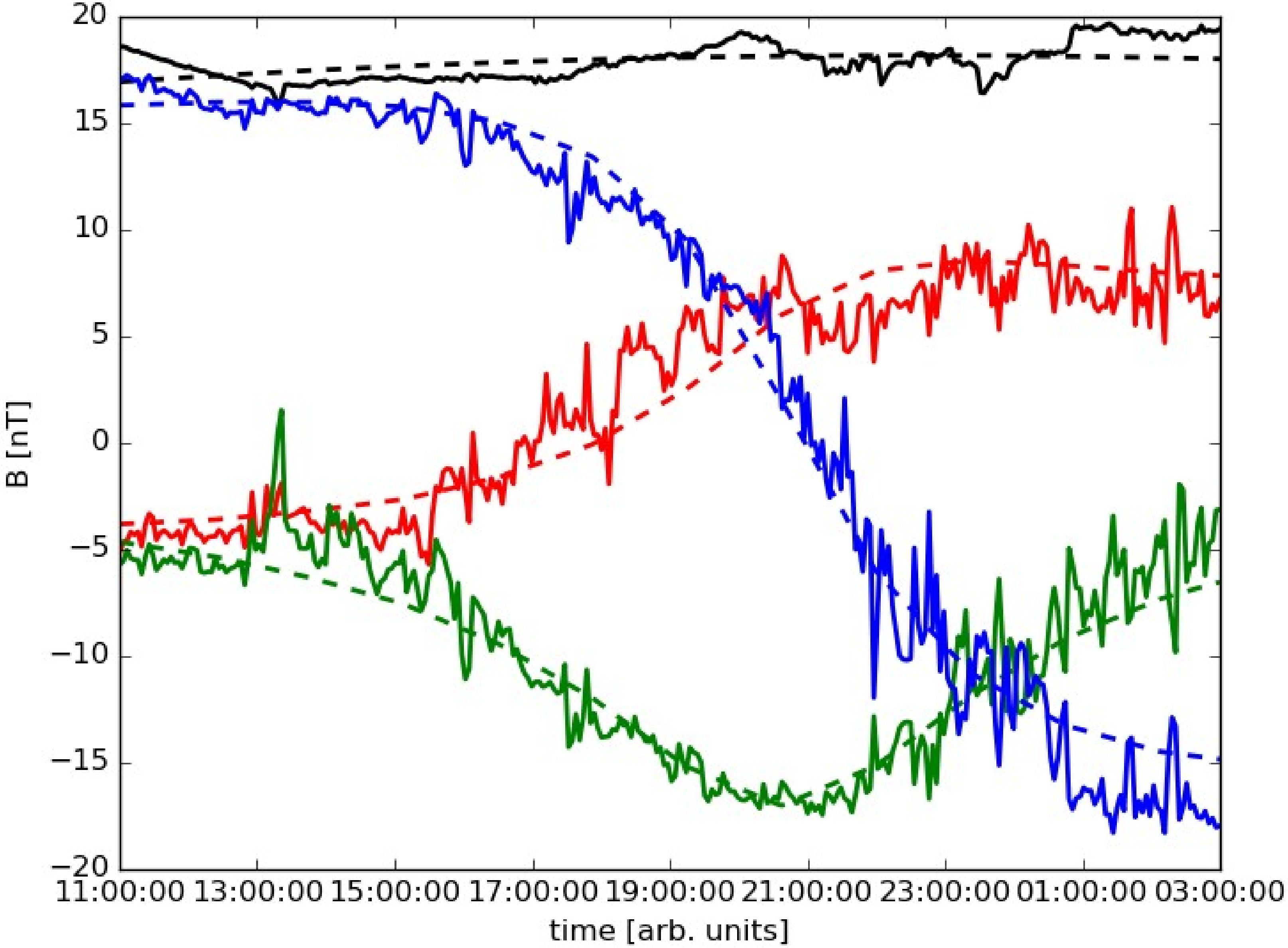
propagation with expansion



Fitting FRi3D to a real CME: white-light



Fitting FRi3D to a real CME: *in-situ*



Outlook

FRi3D can be applied to any white-light and *in-situ* observations, which gives numerous possibilities for future studies, *e.g.*,

- non-trivial geometries of spacecraft-CME encounters, *e.g.*, through the leg of a CME
- multi-spacecraft and spacecraft line-up events → *CME evolution, space weather forecasting*
- 3D fits to heliospheric imager data → *space weather forecasting, for L5 missions especially*
- input to MHD simulations → *CME evolution, CME-CME interaction*

Thank you!