Tracing an Interplanetary Magnetic Cloud from Mercury to Venus, Earth and beyond

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ISEST Workshop, Jeju   2017.09.20

Motivation

How does the twist distribute in the cross-section of a magnetic flux rope?

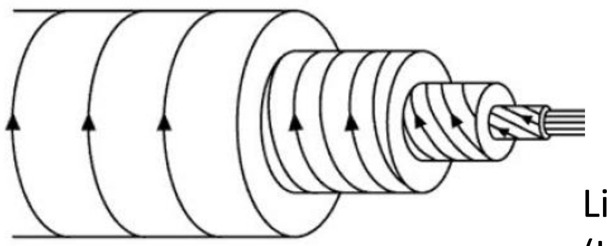
Twist: $T = \frac{B_\varphi}{rB_z}$, Total twist angle: $\Phi_T = \int_0^l T dz$, Number of turns: $\tau = \frac{T}{2\pi}$, or $n = \frac{\Phi_T}{2\pi}$

Two competing scenarios:

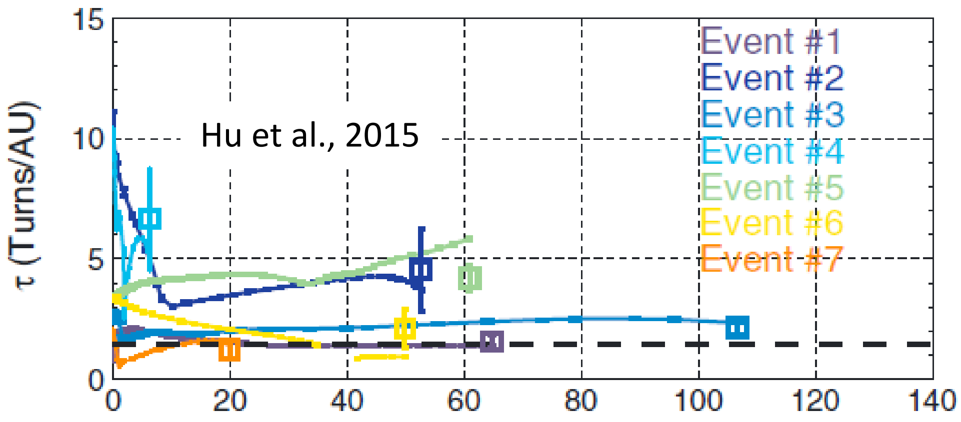
1. Less-twist at the axis and increasing to periphery:

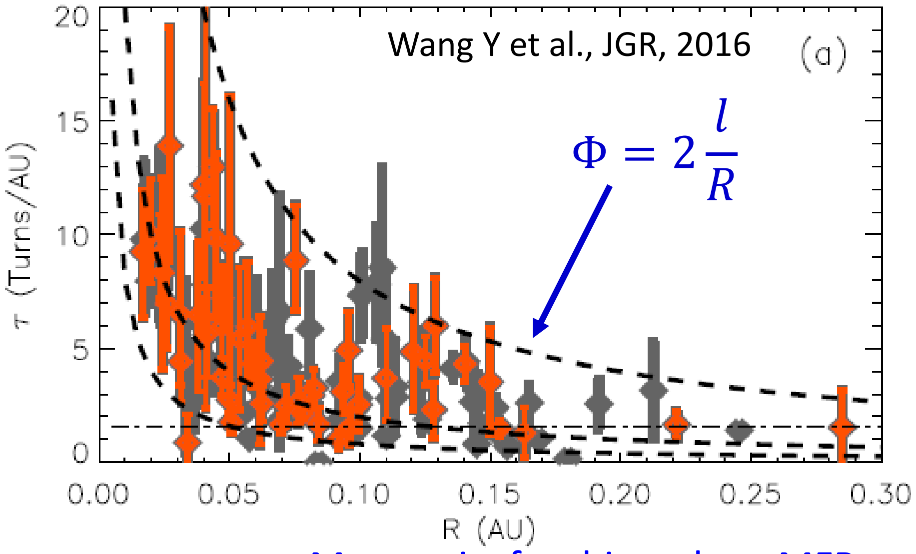
   → Linear force-free field has minimum magnetic energy (Lundquist solution), MCs have sufficient time to relax

2. High-twist core enveloped with a weak-twist shell



Linear force-free (Lundquist, 1950)



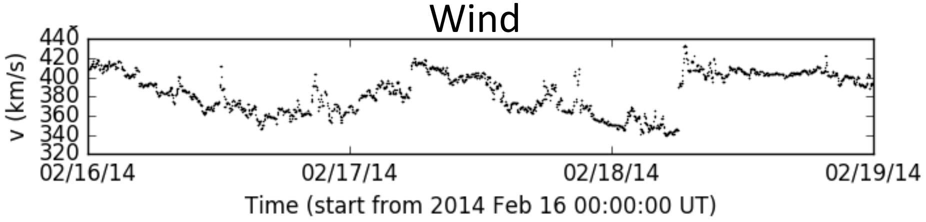


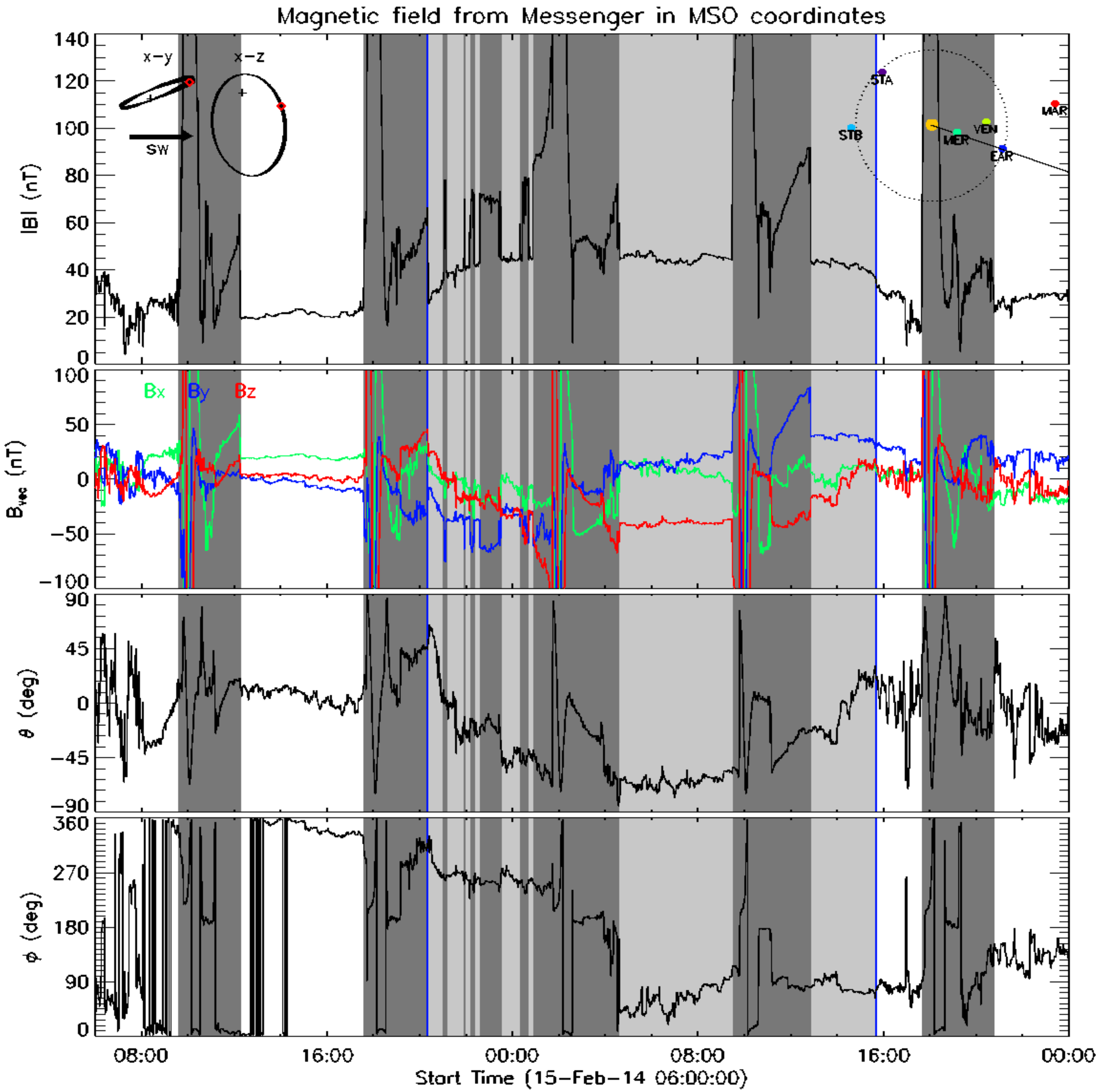
More twist for thin or long MFRs

A clear MC at Mercury during Feb. 15 – 16

- Arrived before 20:20 UT on Feb.15
- Ended around 15:40 UT on the next day
- Lasted for more than 19 hours
- Magnetic field was about 40 nT on average with a peak of nearly 50 nT
- No driven-shock

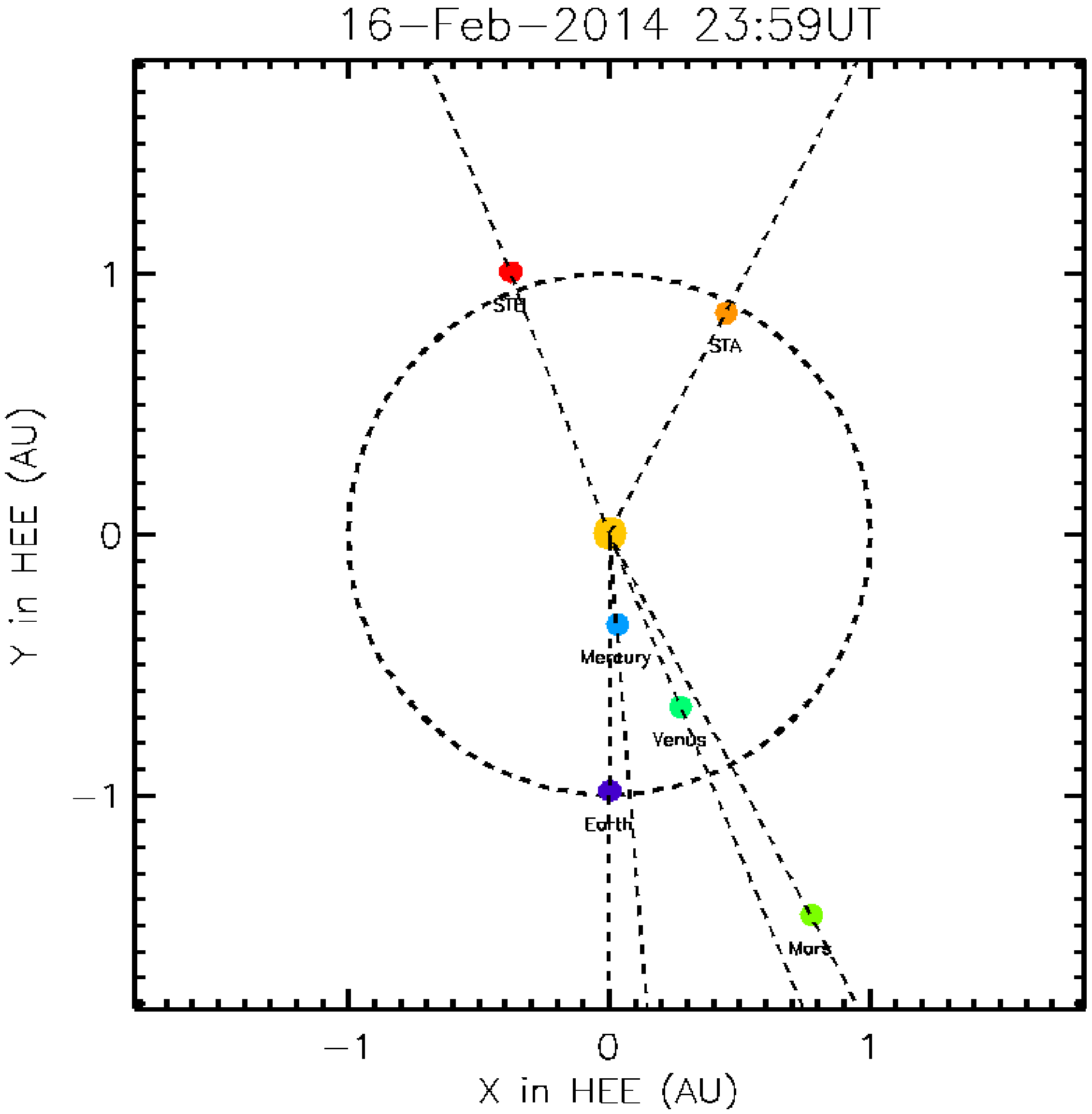
  → Front < 400 km/s, a slow CME?

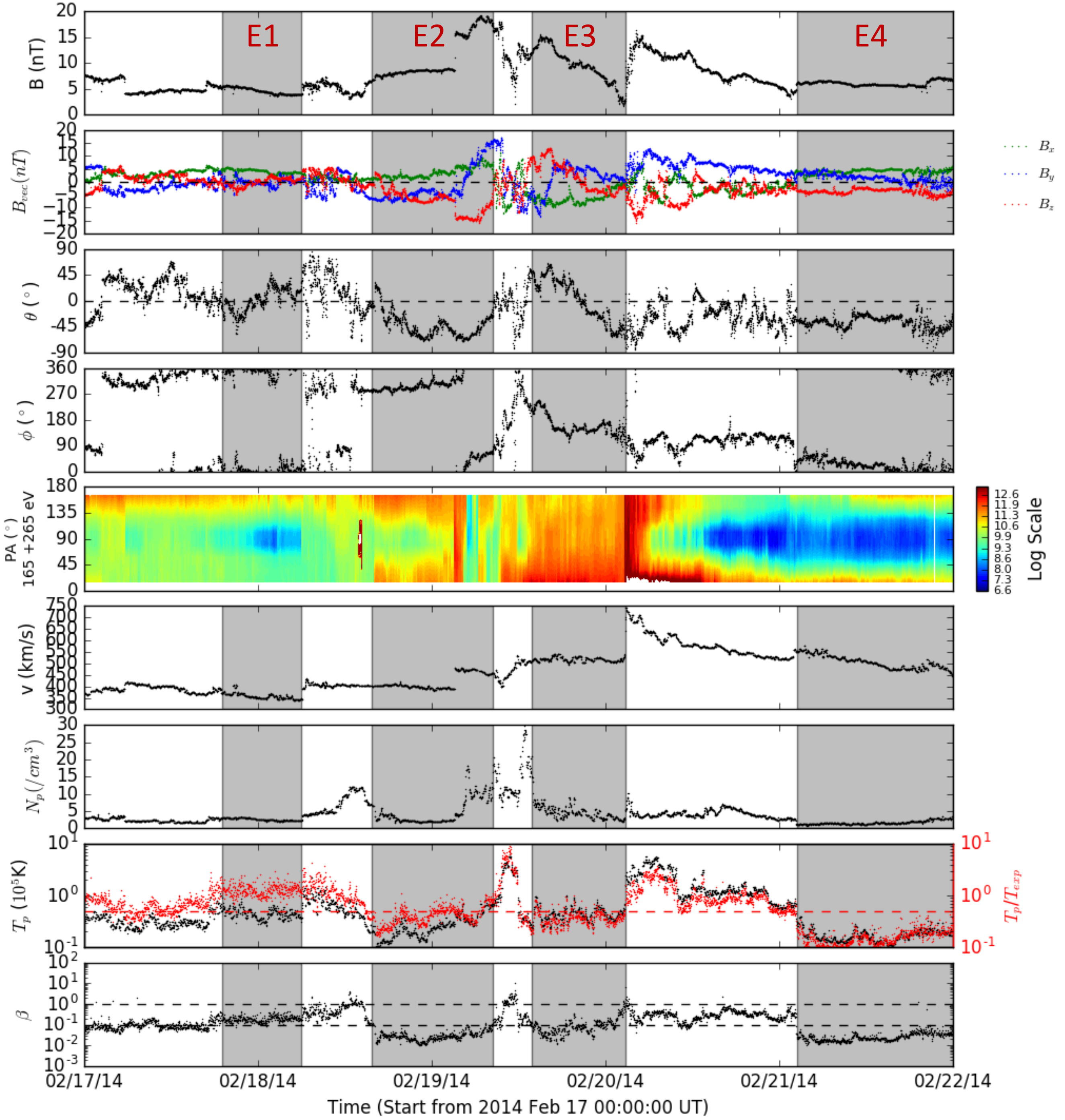




Its counterpart at the Earth

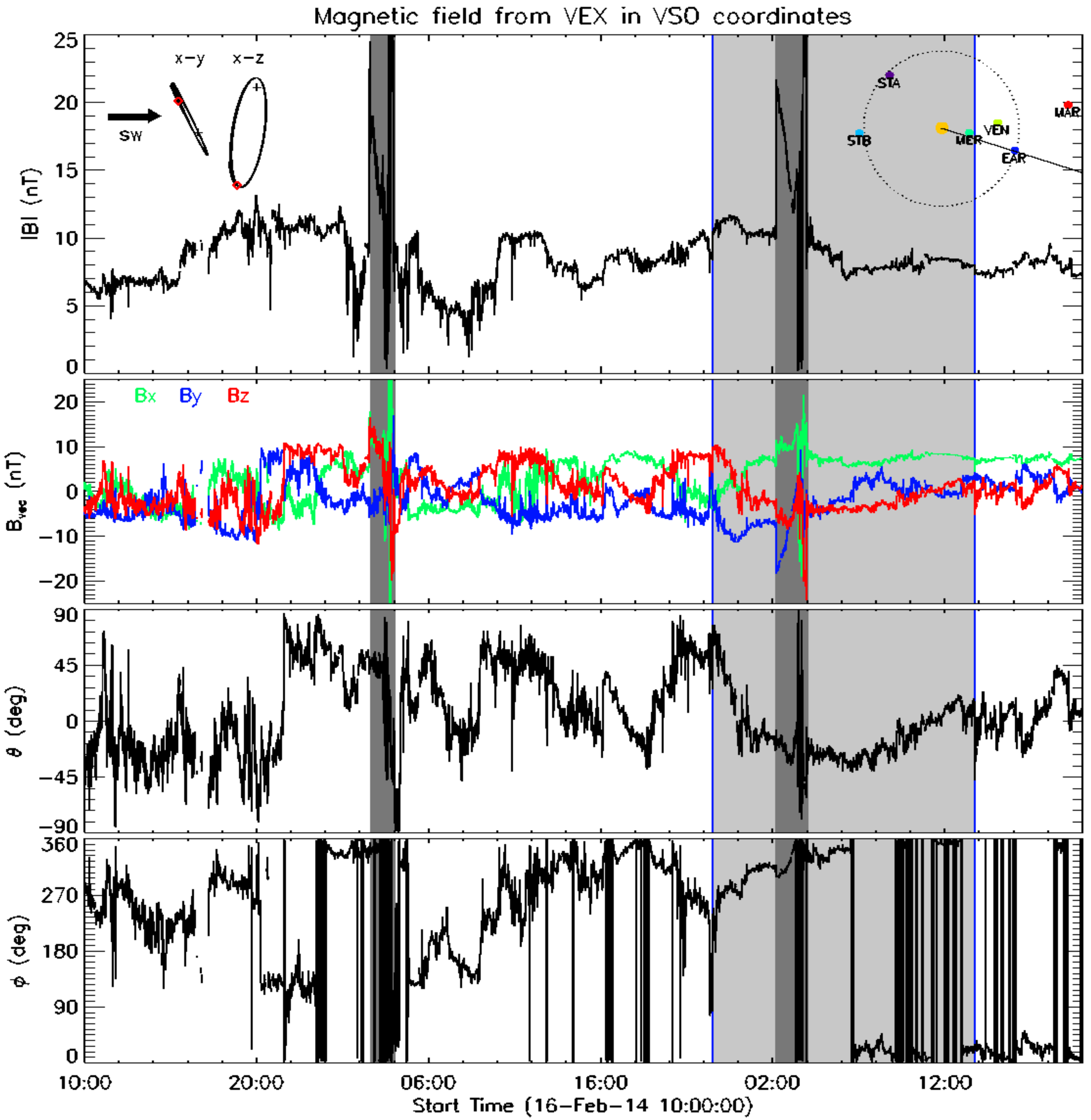
- 2.15 20:20 UT Arrived at Mercury @ 0.35AU





A MC-like structure at Venus during Feb. 16 -18

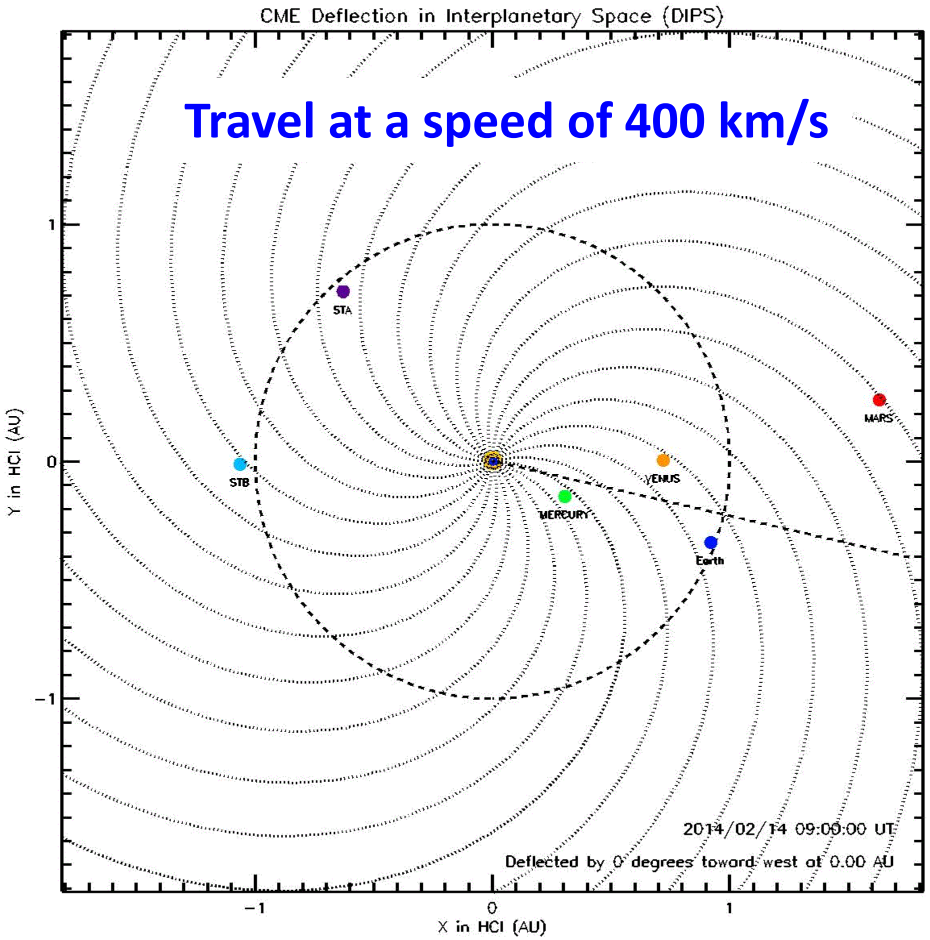
- Arrived at 22:40 UT on Feb.17
- Ended at 13:00 UT on the next day
- A similar pattern in angles
- Profile of the total B is different
- No shock ahead
- **Question: why the MC spent about 50 hrs from Mercury to Venus (~0.37 AU), but less than 18 hrs from Venus to Earth (~0.28 AU)?**
- **Is it the counterpart of the CME?**

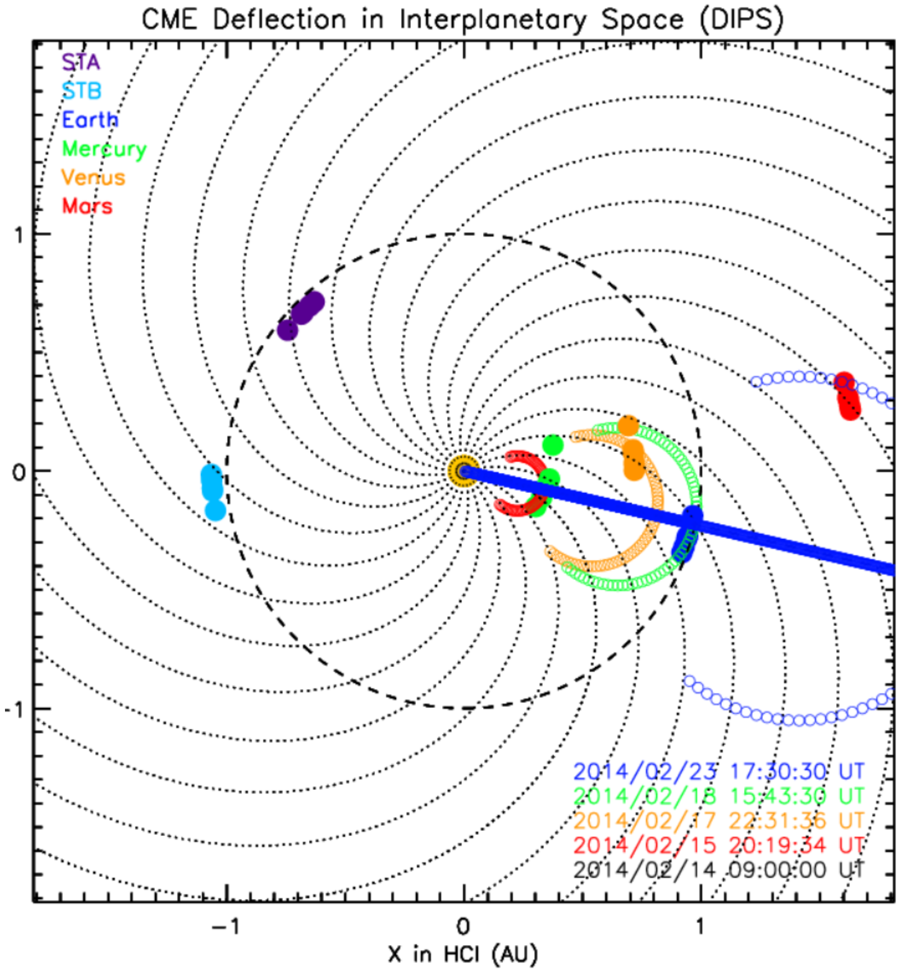


Model the arrivals of the CME at different distances

0.35 AU, 75 Rs, 35 hrs → 0.37 AU, 80 Rs, 50 hrs → 0.28 AU, 60 Rs, 17 hrs → 0.65 AU, 140 Rs, 122 hrs

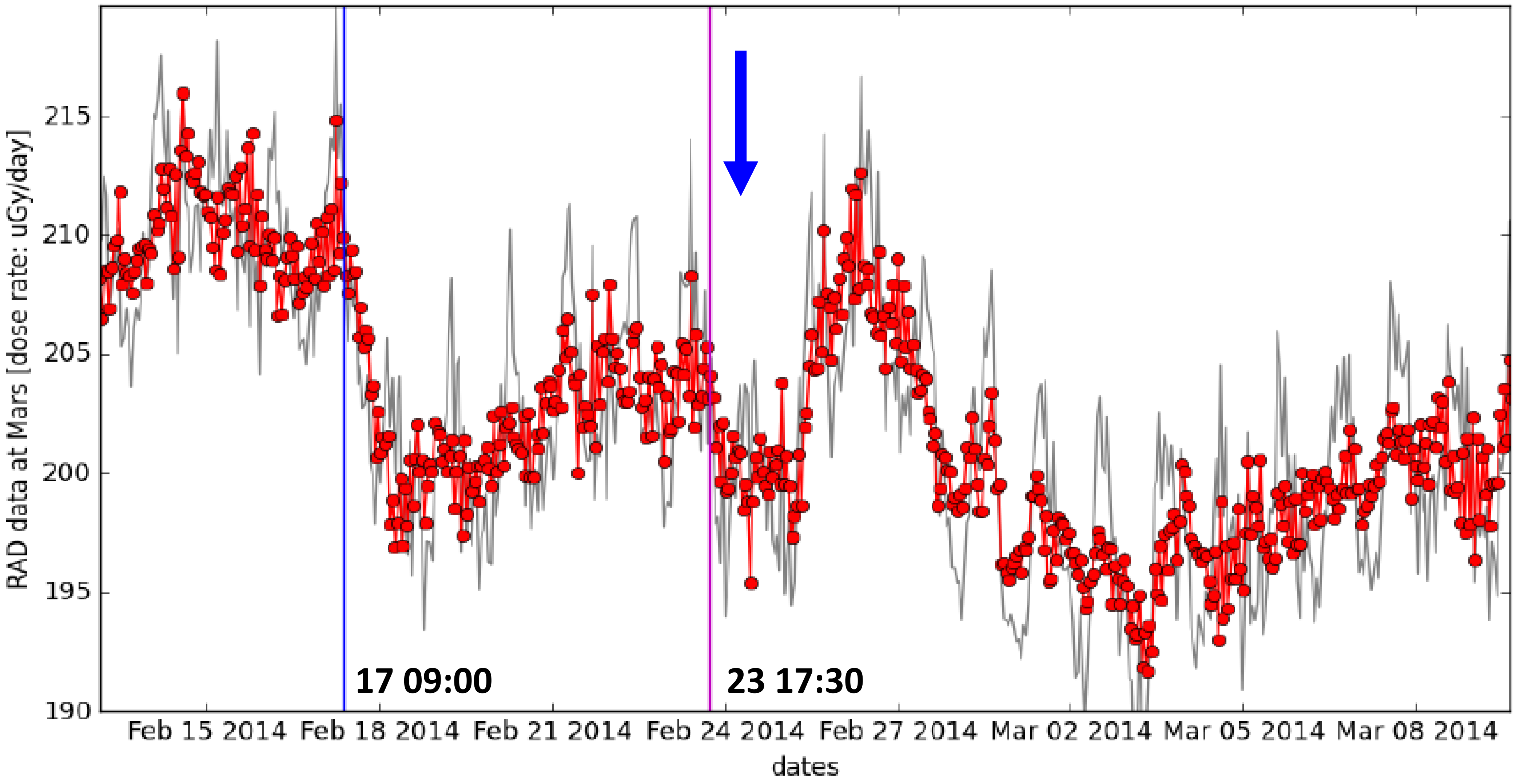
Sun	Mercury	Venus	Earth	Mars
2.14 09:00?	2.15 20:20	2.17 22:30	2.18 15:45	2.23 17:30?





- DIPS model (Wang Y. et al., JGR, 2014; Zhuang B. et al., ApJ, 2017)
- Match the obs.
- Expanded and then compressed
- Predict:
  - → Launched before 09:00 UT on Feb.14
  - → Arrived at Mars before 17:30 UT on Feb.23

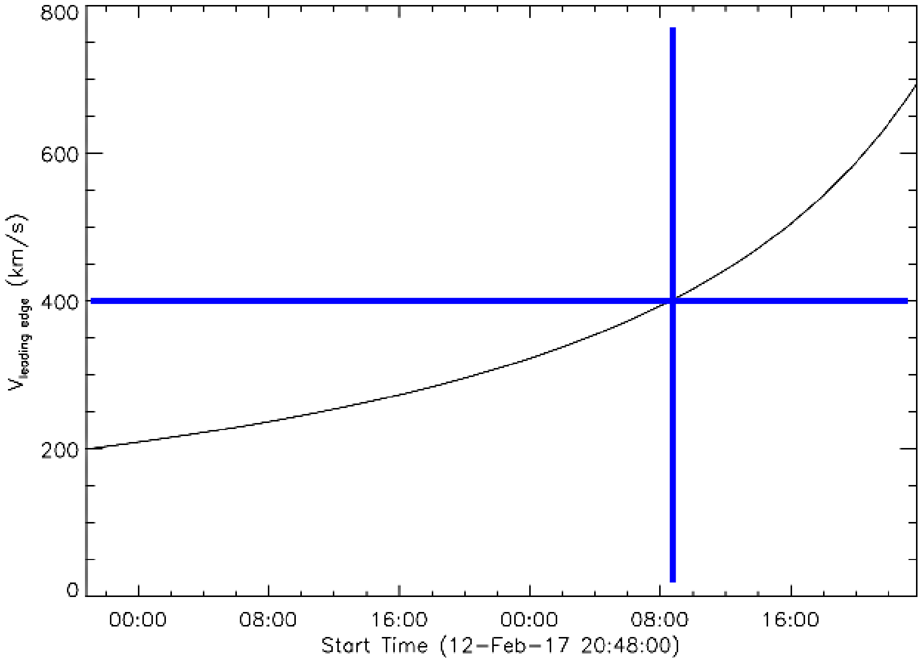
A clear Forbush decrease (FD) observed at Mars



An unclear source CME

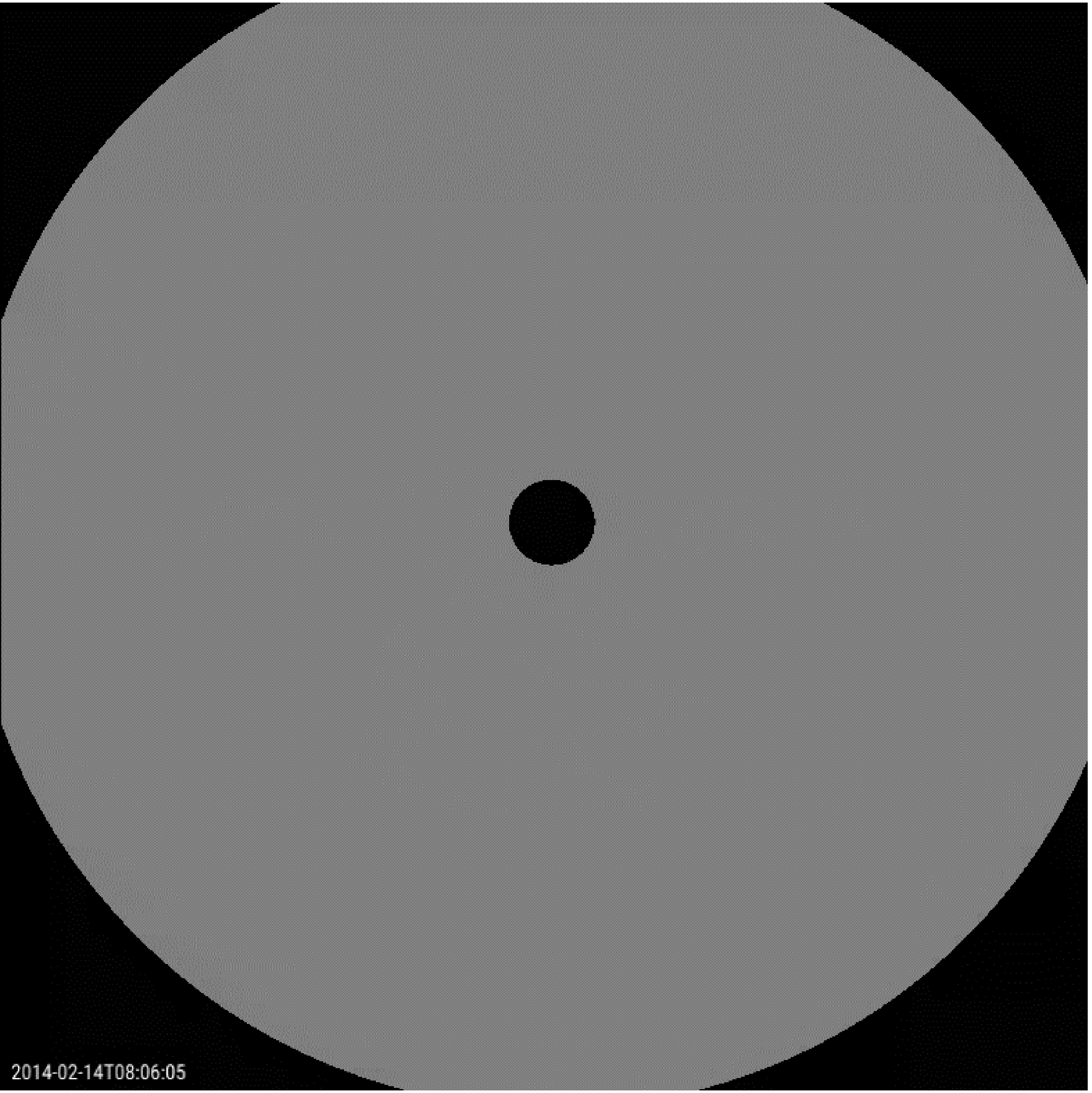
	CDAW			GCS Fitting	Comment
Date	**First App**	**App Width**	**Speed**	**Direction**	
2014.2.12	23:06	360	872		Too fast
2014.2.13	16:36	104	502		To STA+,S
2014.2.14	8:48	360	1165	W145S02	To STA; Too fast
	11:42				**Contaminated by the previous one**
	16:00	145	345		To STB+,N
	17:24	64	283		Too slow
2014.2.15	2:24	138	362	W46S05	To Earth+; Too slow

* CME candidates > 50 degrees

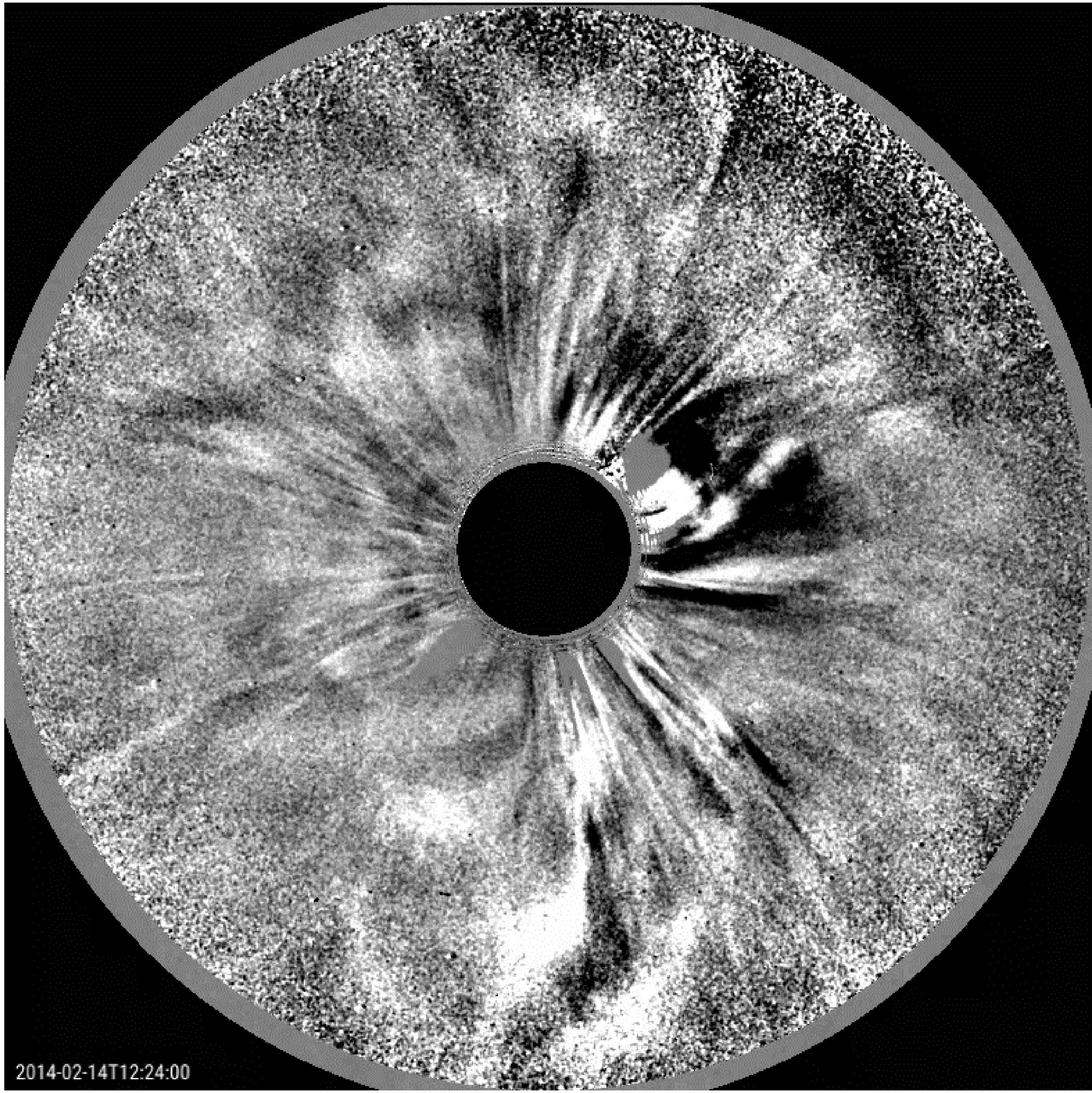


- A weak CME with ambiguous surface signature

SOHO/LASCO



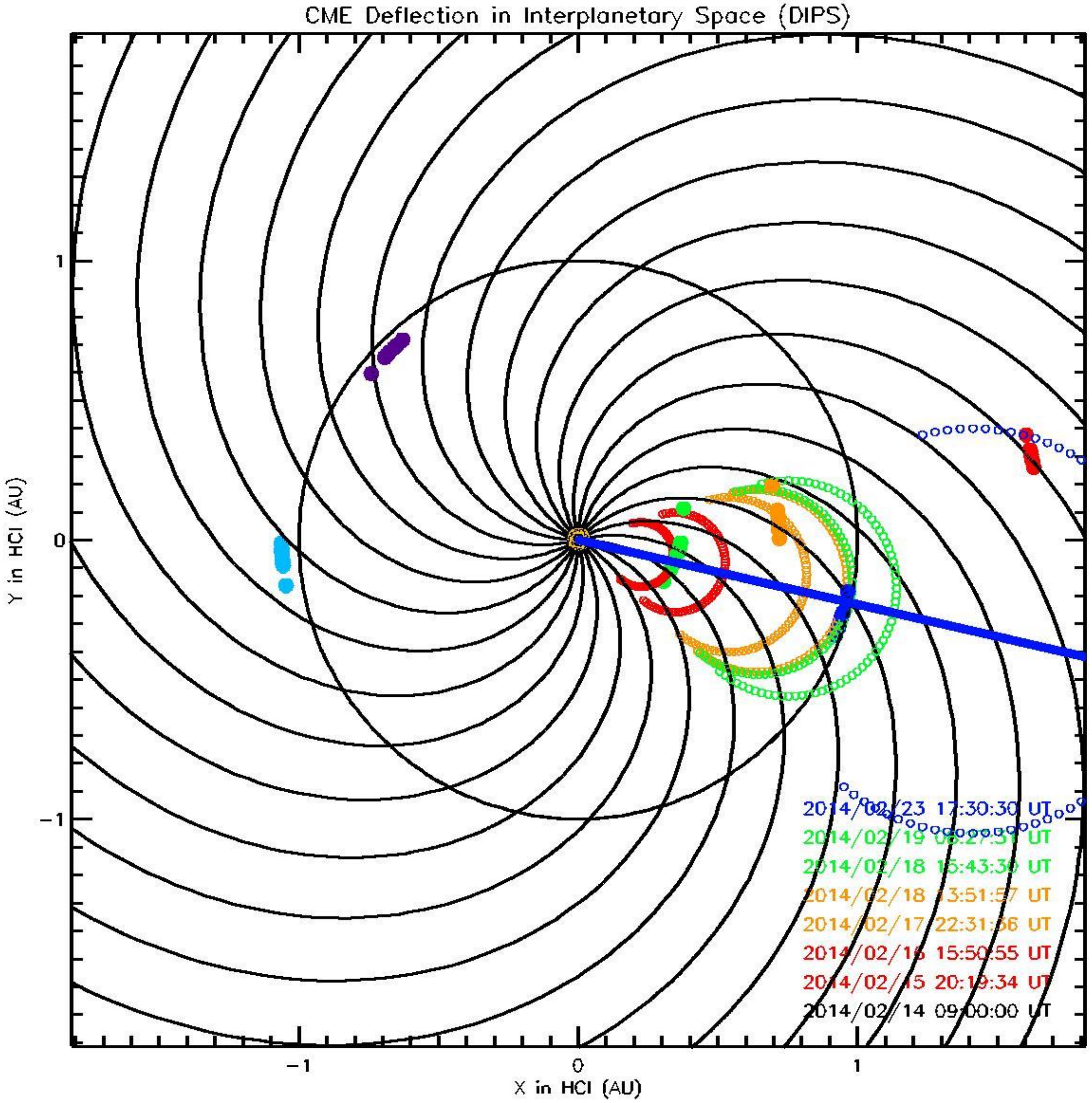
STEREO-A/COR2



First appearance in LASCO around 11:42 UT

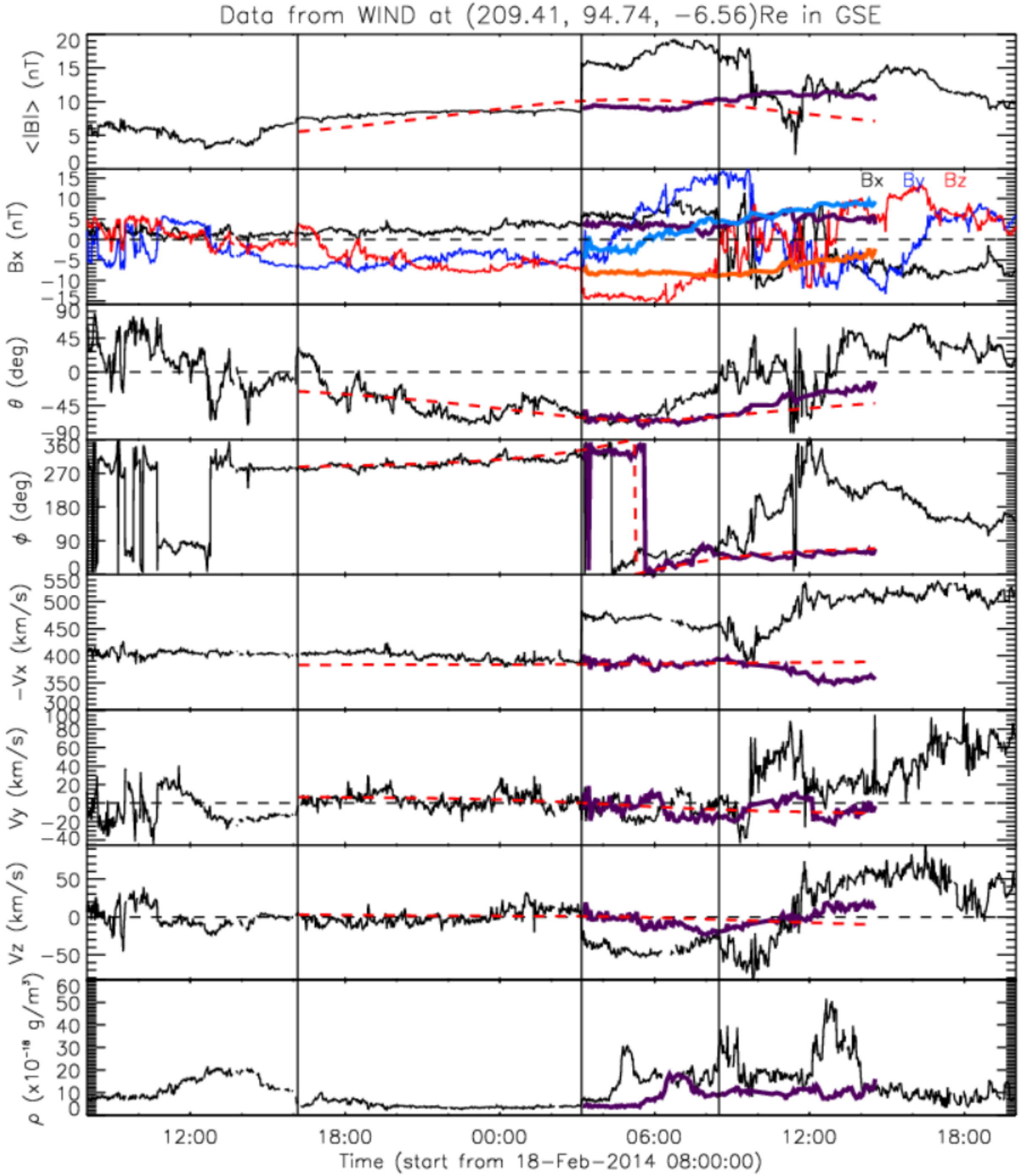
Evolution of the magnetic properties of the CME flux rope

- Kinematic evolution has been shown
- How about the magnetic properties?
  - → Axial magnetic flux, F_z
  - → Twist of magnetic field lines, τ
- Fitting the observed MCs with a uniform-twist force-free flux rope model (Wang Y. et al., JGR, 2016)

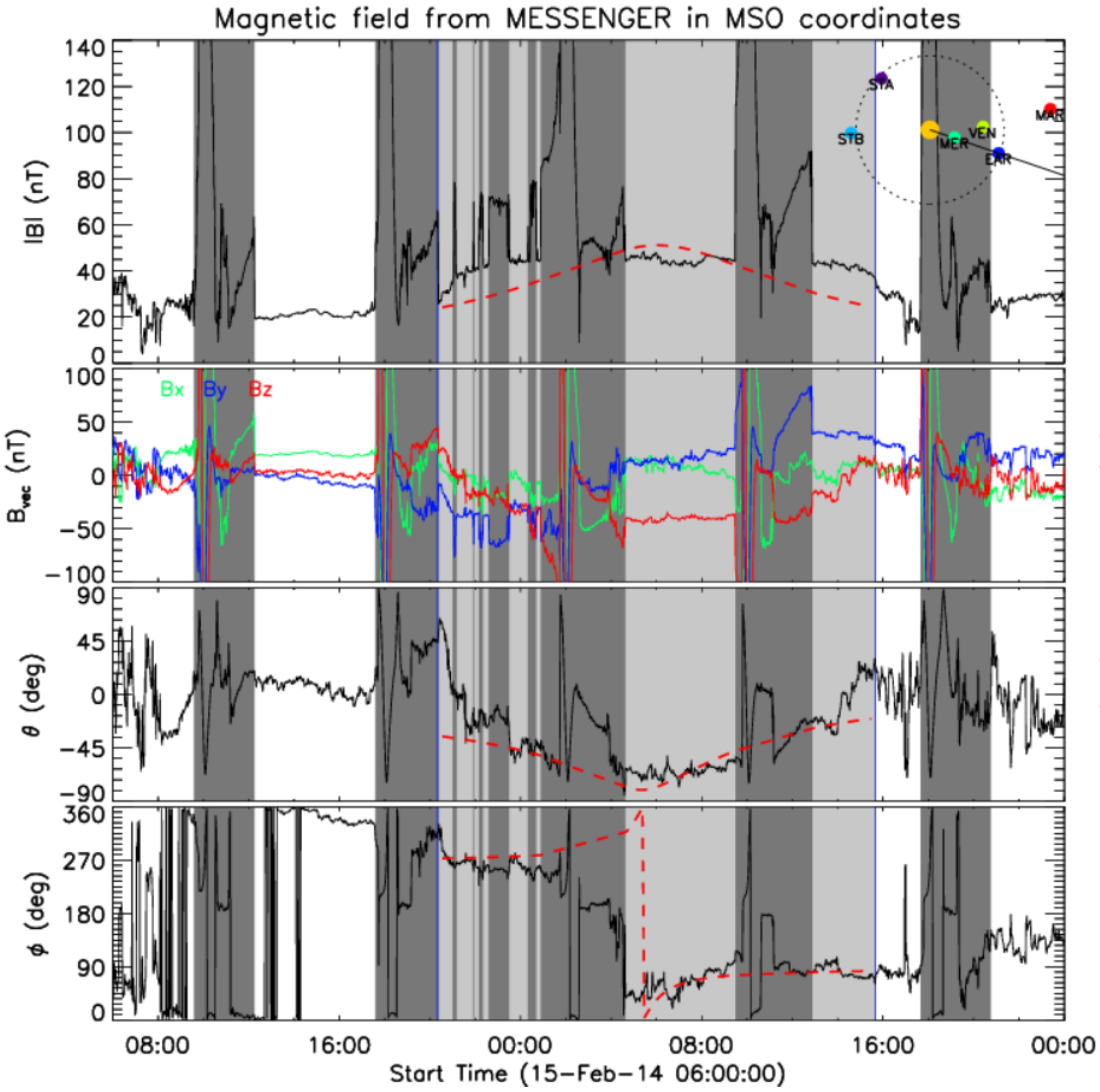


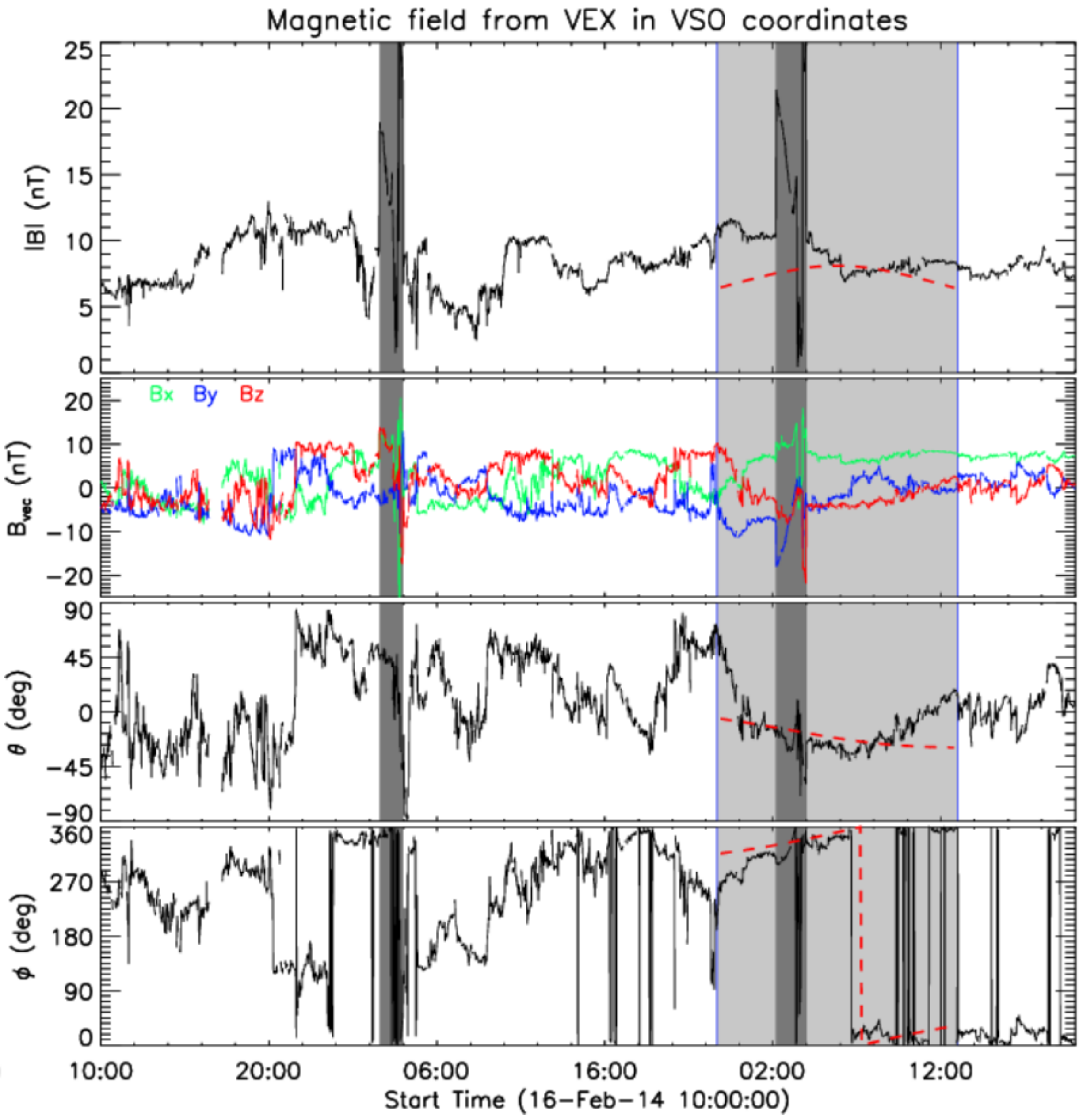
Recover the shocked structure

- Based on shock relations, calculate
  - → shock normal: (-0.93, -0.01, -0.37), θ_{Bn}=87 deg
  - → shock speed: 585 km/s
  - → compression ratio: 1.69
- convert the shocked (downstream) ***B*** and ***v*** to un-shocked (upstream) ***B*** and v, with assumptions:
  - → the sheath plasma follows the shock relation and
  - → the same compression and normal direction in the sheath region



Fitting the MC at Mercury and Venus





Results

- Helicity per AU, h_m, and turns per AU, τ, have been normalized to the distance at 1 AU, $h_{m,AU}$ and τ_{AU}
- Axial flux, F_z, and $-h_{m,AU}$ decreased significantly from Mercury to Earth

  F_z: 19% - 54% at Venus

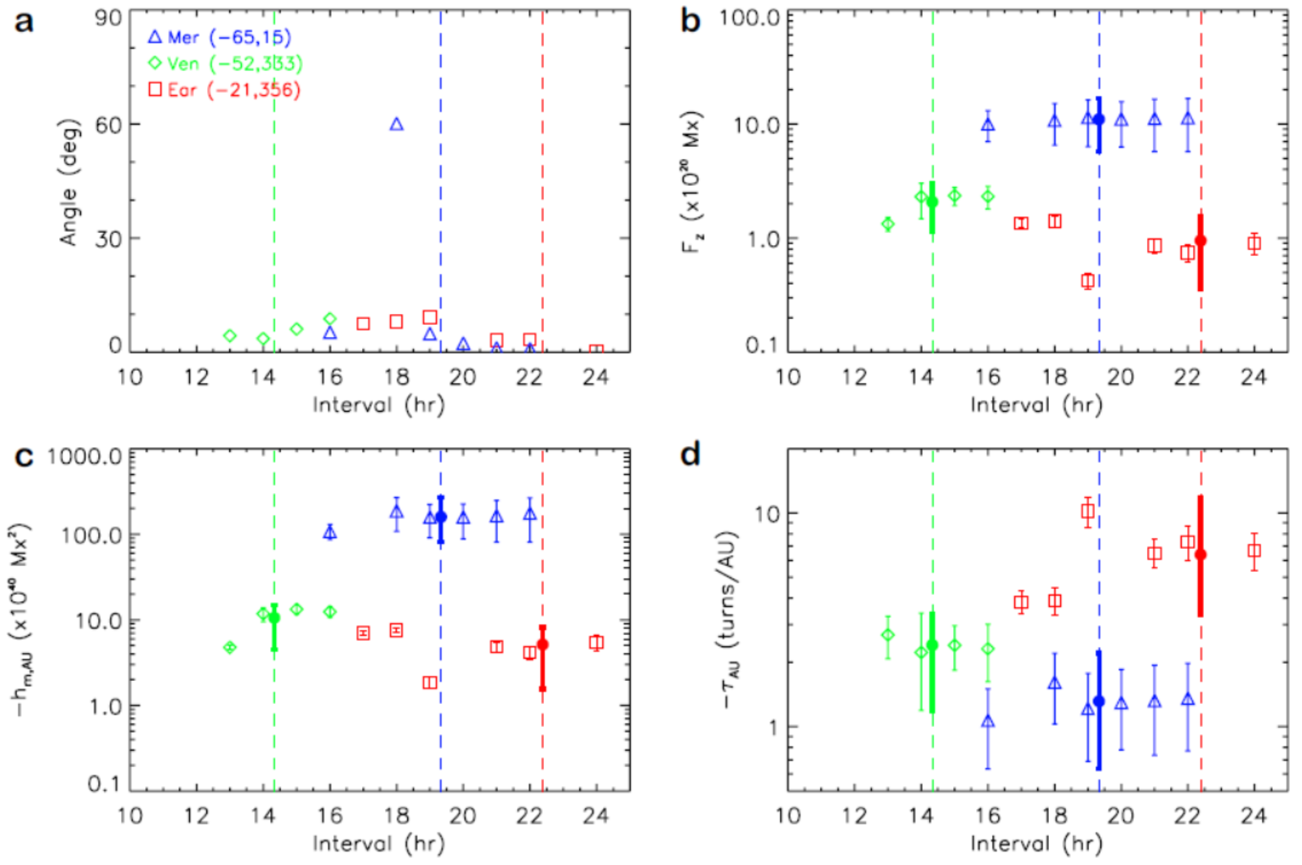
  9% - 28% at Earth

  $-h_{m,AU}$: 7% - 19% at Venus

  3% - 10% at Earth

  → Eroded greatly, expose inner core in sw at 1 AU
- $-\tau_{AU}$ increased from Mercury to Earth

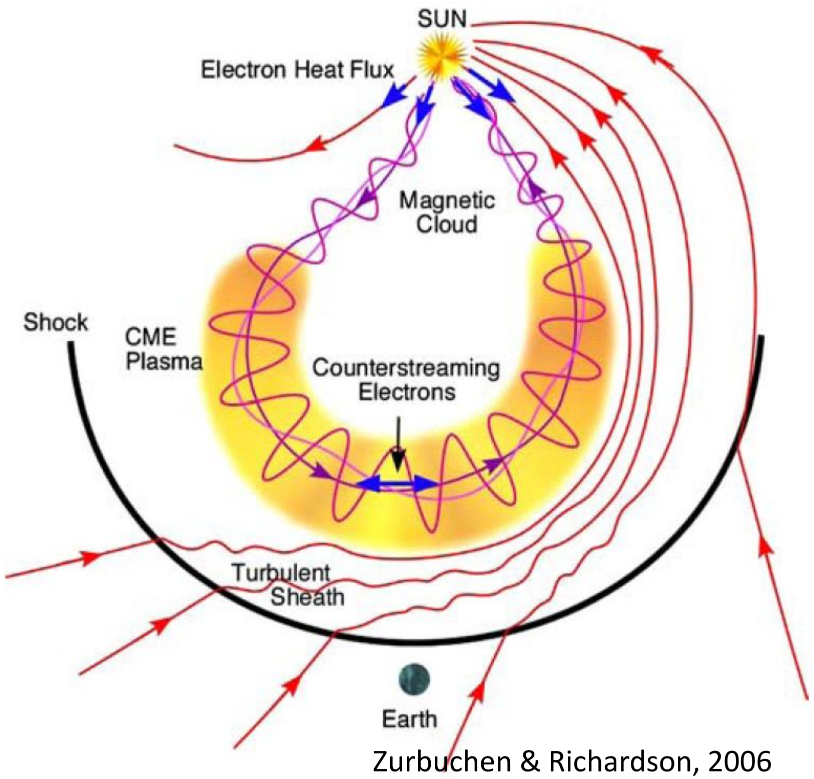
  → High-twist core



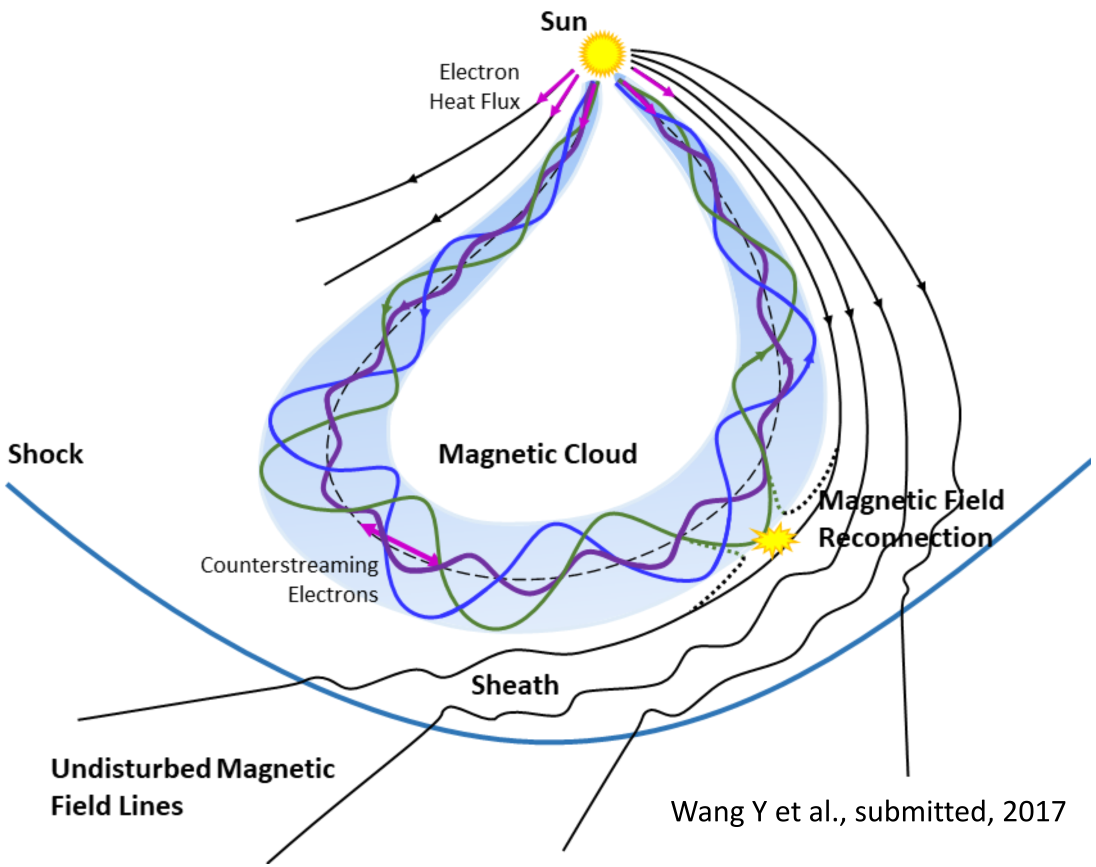
	r	(θ, ϕ)	F_z	τ	τ_{AU}	$h_{m,AU}$
	AU	deg	$\times 10^{20}$ Mx	turns/AU	turns/AU	$\times 10^{40}$ Mx^2
Mercury	0.35	(−65, 15)	$11.0^{+5.8}_{-5.3}$	$-3.8^{+1.9}_{-2.5}$	$-1.3^{+0.7}_{-0.9}$	-160^{+79}_{-108}
Venus	0.72(0.84)	(−52, 333)	$2.1^{+1.0}_{-0.9}$	$-6.9^{+3.5}_{-2.8}$	$-2.4^{+1.2}_{-1.0}$	$-10.6^{+6.1}_{-4.4}$
Earth	1.0	(−21, 356)	$1.0^{+0.6}_{-0.6}$	$-6.4^{+3.1}_{-5.4}$	$-6.4^{+3.1}_{-5.4}$	$-5.1^{+3.6}_{-3.0}$

Conclusions

- A stage-like distribution of twist for a post-eruption magnetic flux rope, consisting of a high-twist core and weak-twist outer shell
- Fine structures may exist because we have only three points



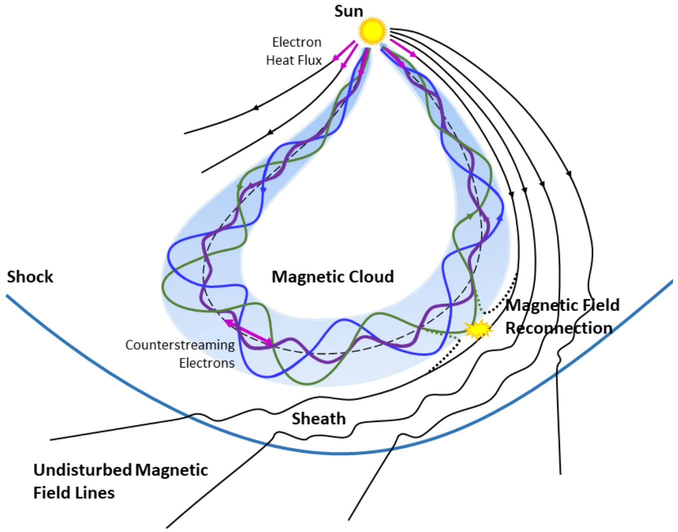
Zurbuchen & Richardson, 2006



Wang Y et al., submitted, 2017

Discussion

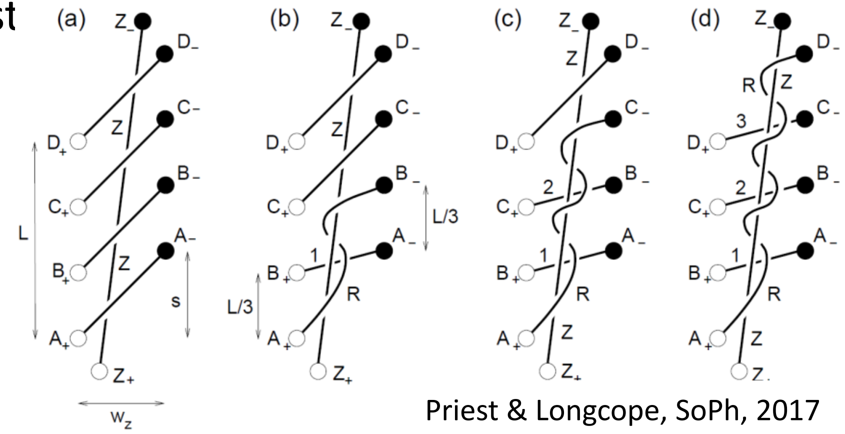
- Challenge to the current understanding of solar eruptions as well as the formation and instability of MFRs



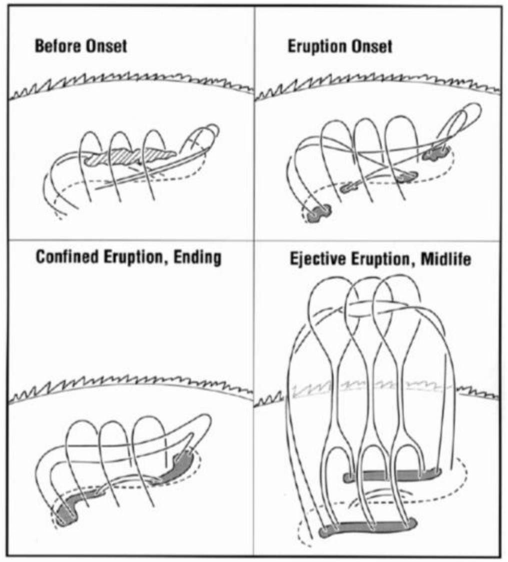
➢ No pre-existing MFR prior to a CME, magnetic reconnection produces higher twisted field lines than core

VS.

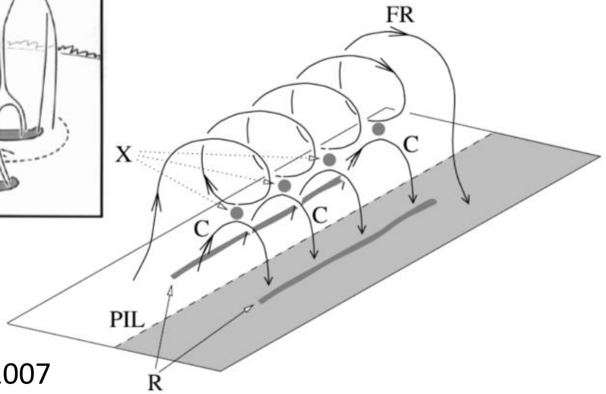
➢ Need a pre-existing MFR; magnetic reconnection produces a different twist from the core



Priest & Longcope, SoPh, 2017



Moore et al., ApJ, 2001



Longcope & Beveridge, ApJ, 2007

Thanks for your attention!