



UNIVERSITÀ  
DEGLI STUDI  
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DIPARTIMENTO DI  
FISICA E ASTRONOMIA



1° Conferenza  
Italiana Plasm



# MHD simulations of expanding magnetic clouds in a turbulent interplanetary plasma: virtual spacecraft analysis of magnetic cloud coherence and structure

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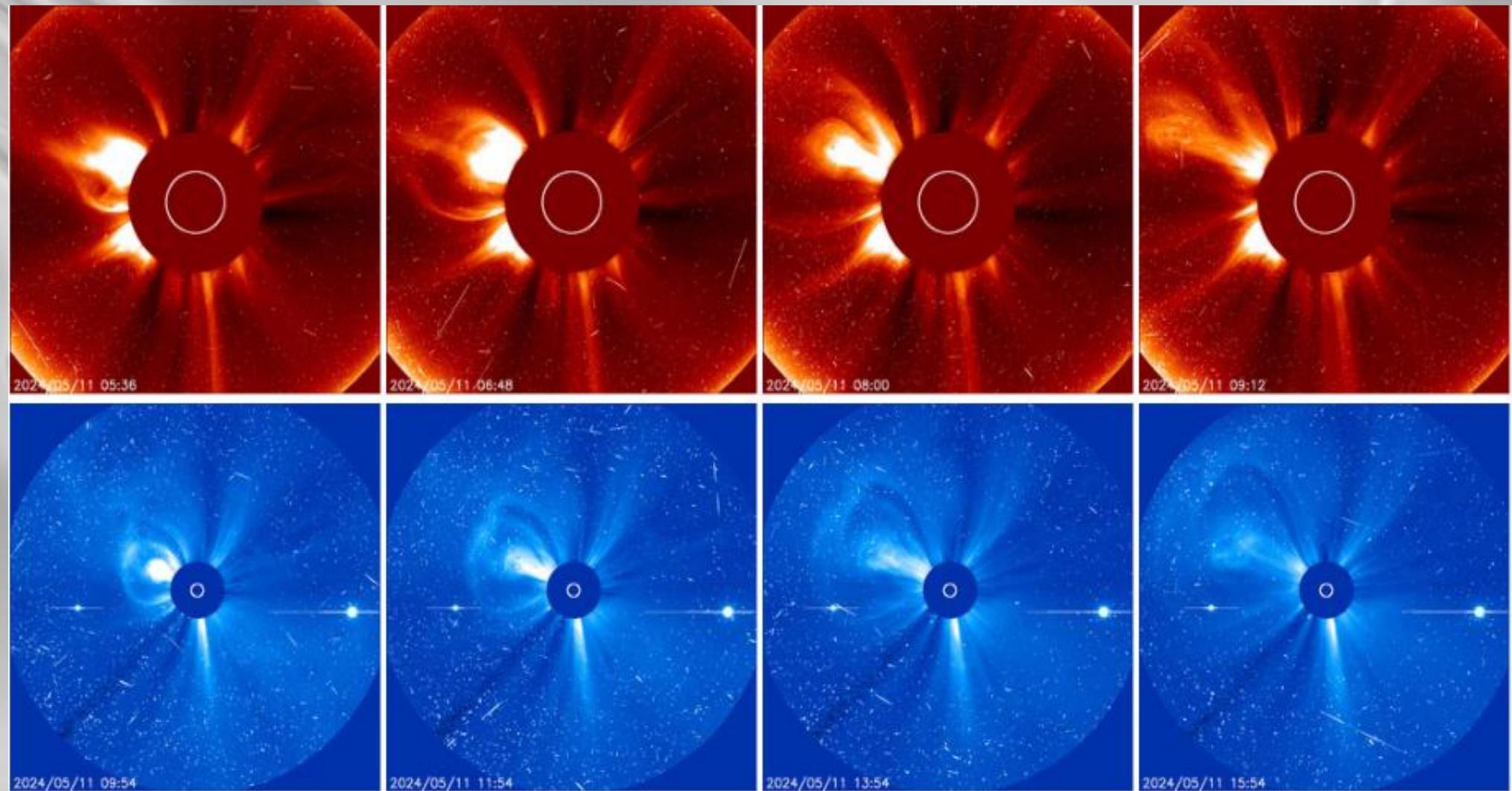
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## CME, ICME, MC and MO: a brief introduction to acronyms

- CMEs (Coronal Mass Ejections) are the most powerful transients driven by the solar atmosphere in the interplanetary medium: they release up to  $10^{13}$  kg of mass with velocities up to about 1000 km/s and associated bulk kinetic energy up to  $10^{33}$  erg
- ICME are the counterpart in the interplanetary medium of the CME

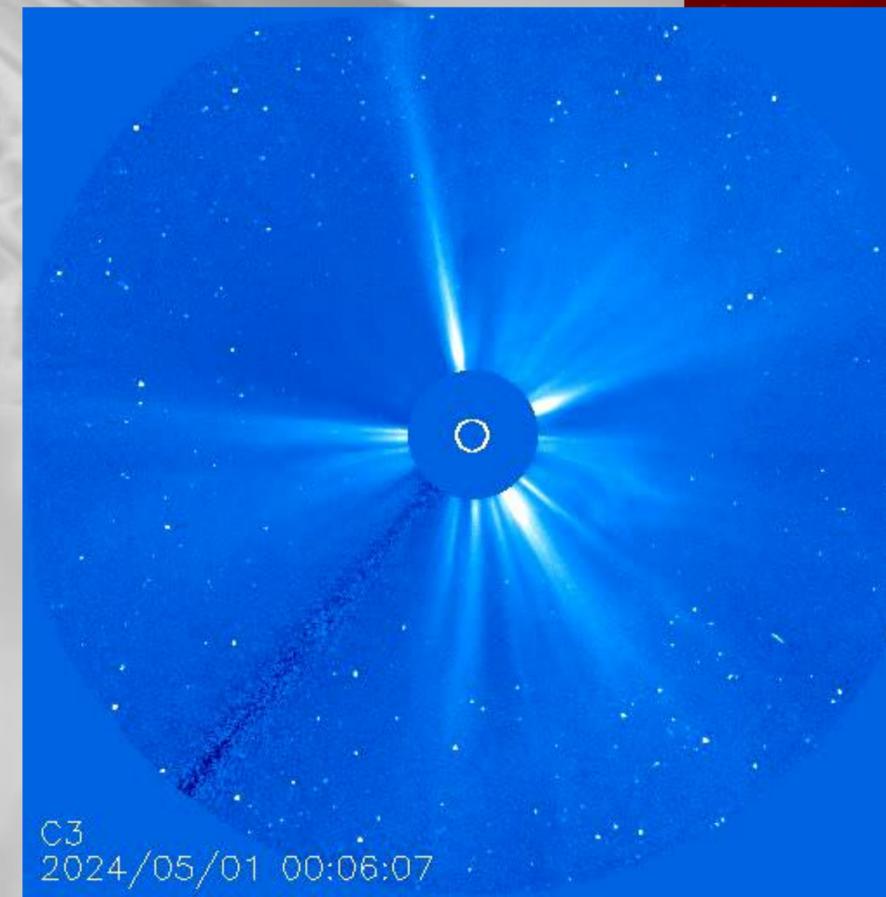
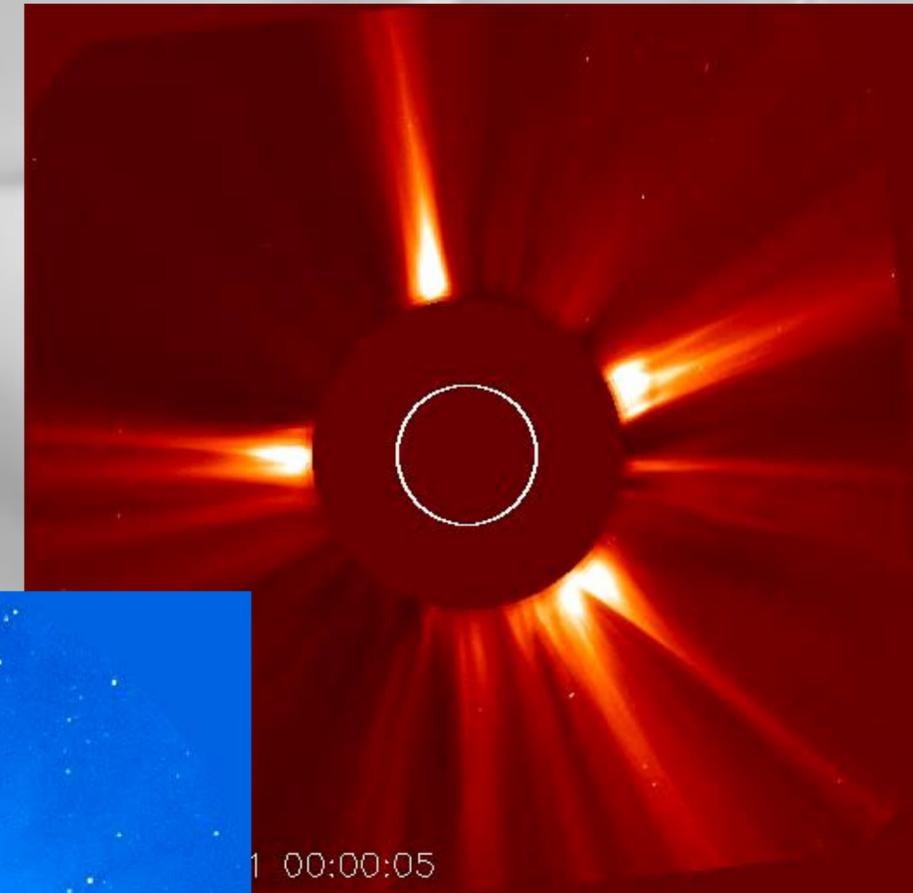




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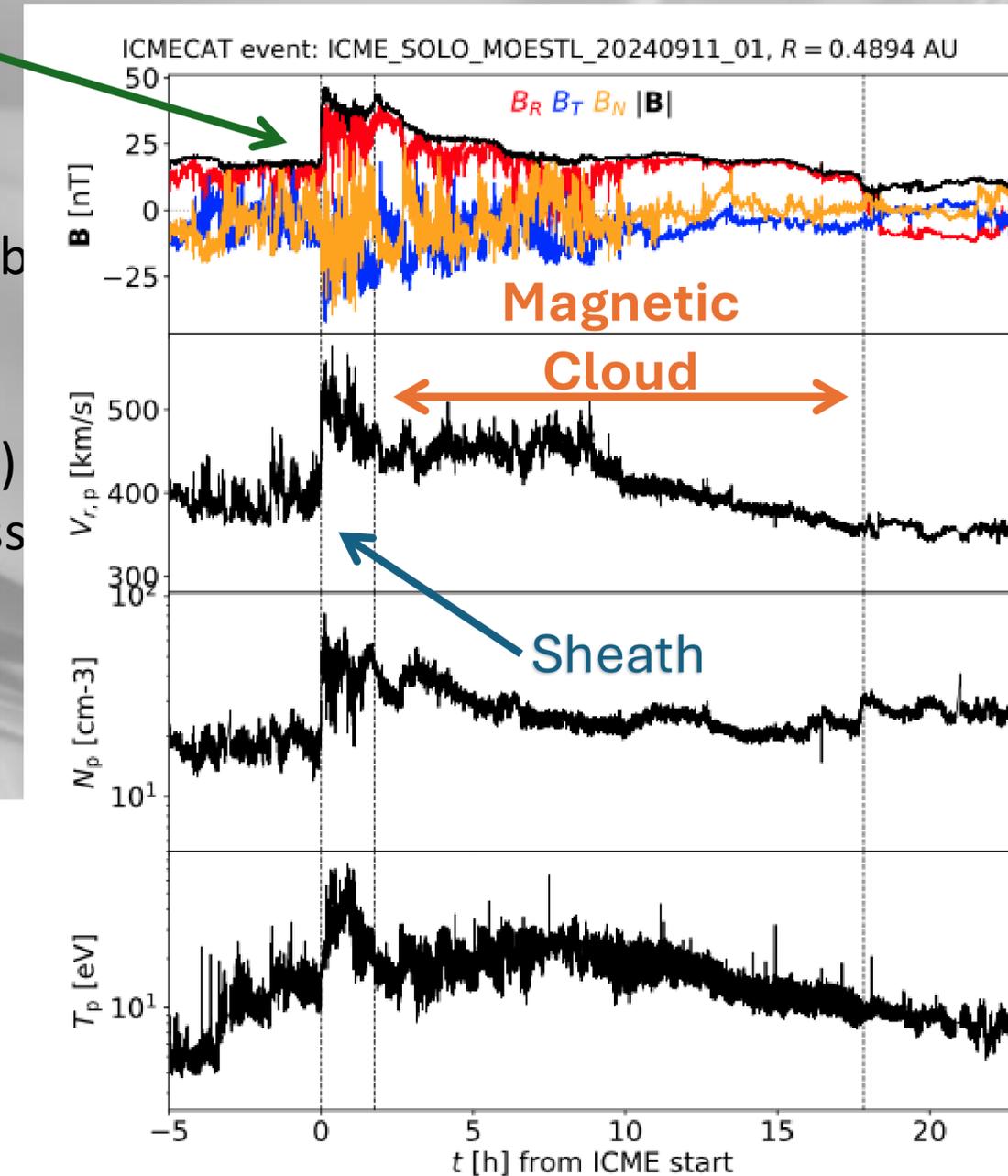
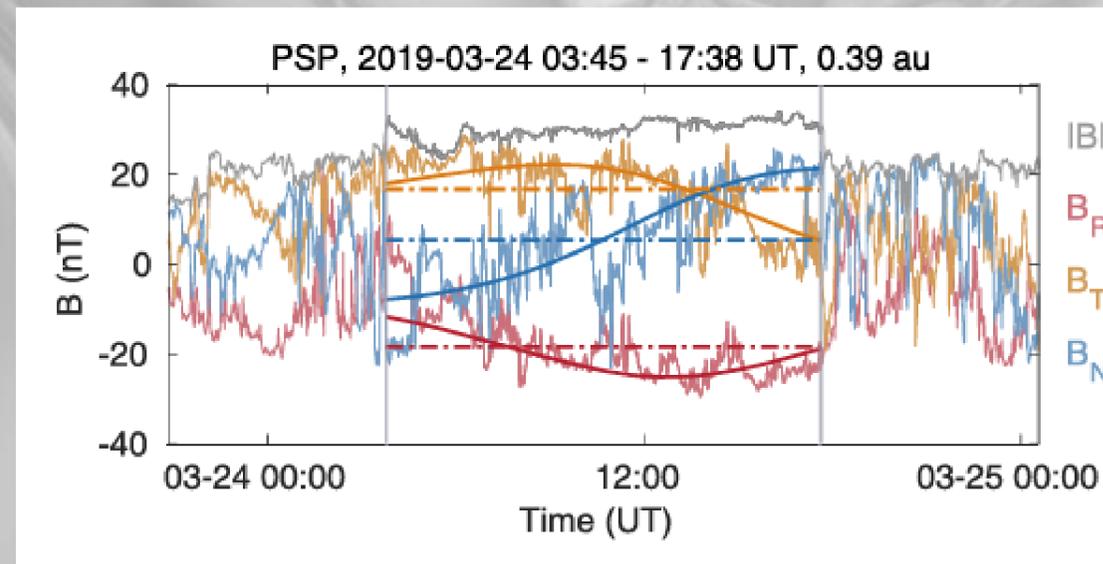




## Forward shock

- The counterparts in the interplanetary medium (ICMEs) are typically identified by the presence of a forward shock, followed by a sheath cloud.
- Behind the sheath a more coherent structure appears, the magnetic cloud (MC) often assuming the shape of a twisted magnetic flux rope. If the structure is less evident is named magnetic ejecta or magnetic obstacles (MO)

Sheaths and MCs are highly dynamical with large fluctuations at many scales

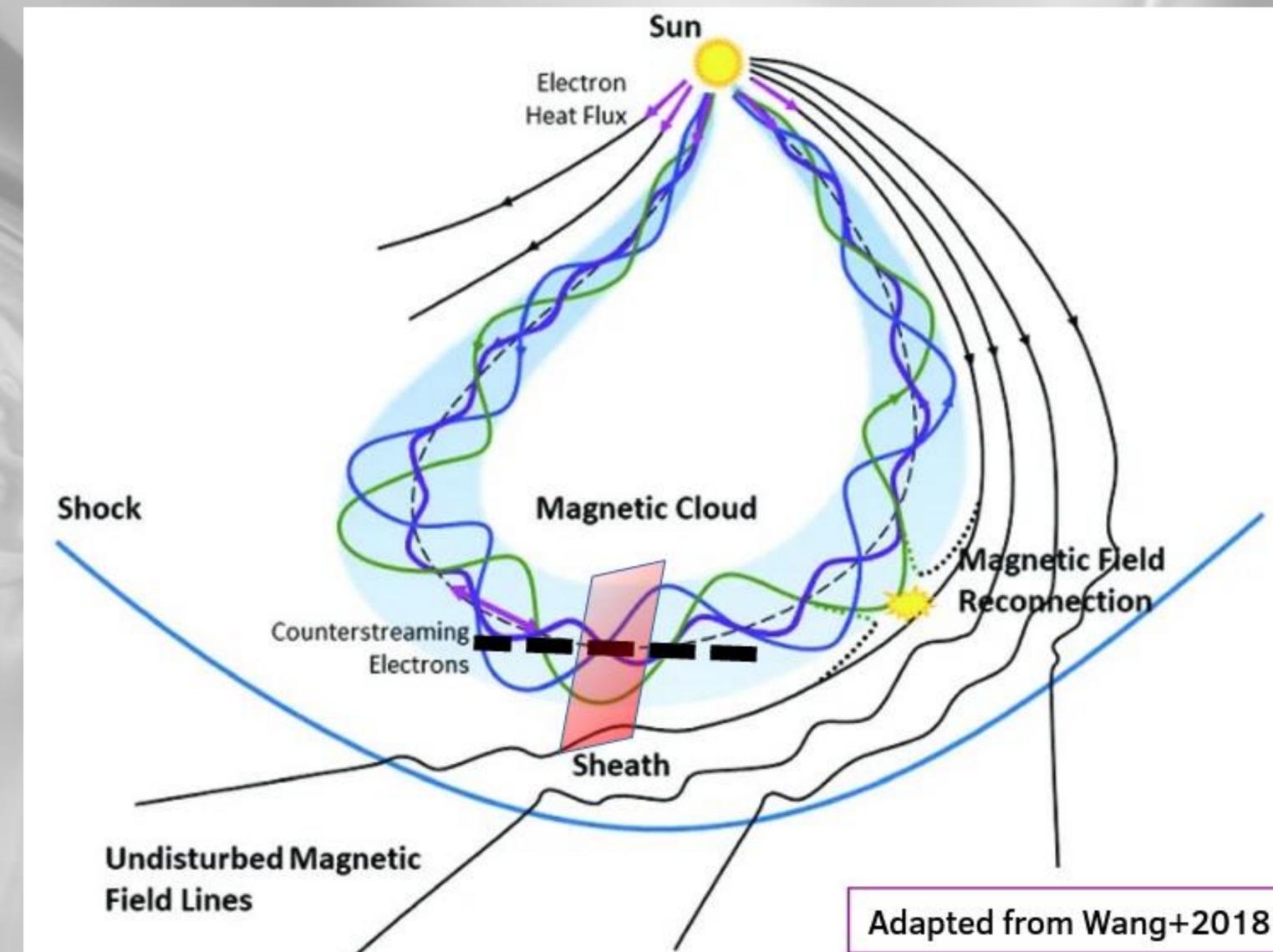


ICME SOLO obs @0.49 AU



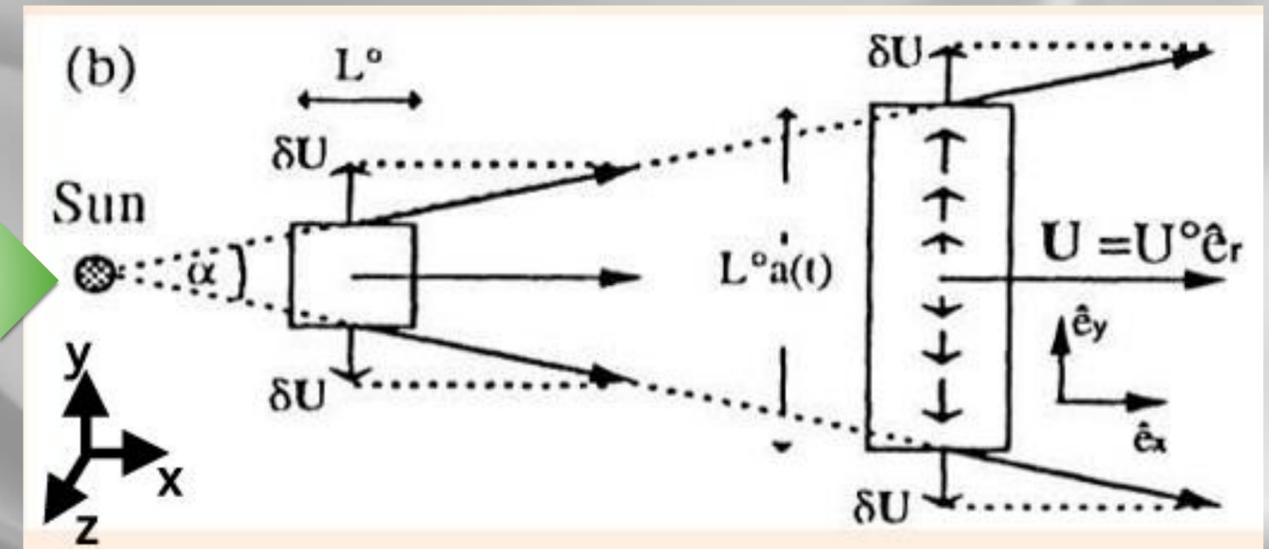
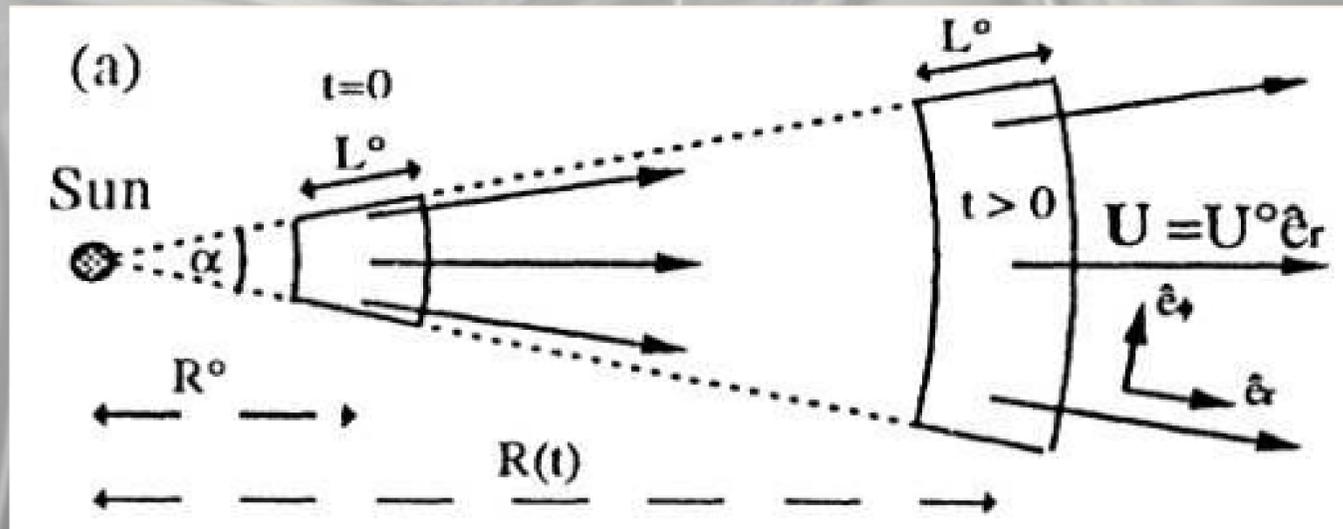
## How to simulate local dynamic driven by global evolution in the heliosphere

- Small scale (Earth-size) dynamic is driven by the local properties of the plasma (mean quantities and fluctuations)
- Moreover the background solar wind fluctuations interact with the ICME at local scales
- At the same time the global expansion of the structure themselves changes its characteristic length and time-scales as well as its coherence
- **Not enough resolution to keep local dynamics in a global simulation**





## The Expanding Box Model strategy



The solar wind is a spherical flow where a parcel of plasma expands

Mass flux, angular momentum magnetic flux and energy flux are conserved as the system, expand spherically

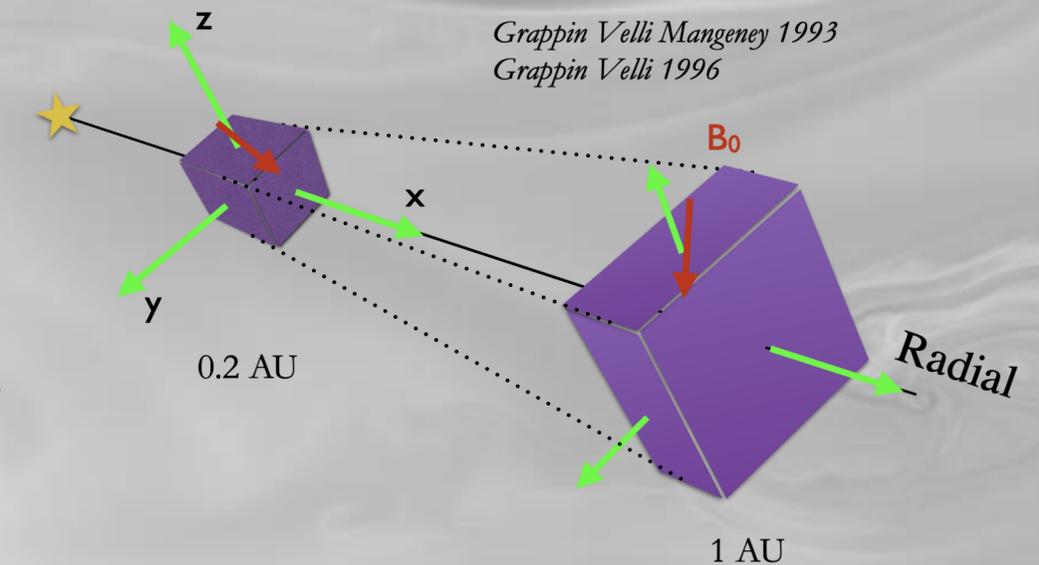
A local approach can be used where apparent forces work on the fluid element stretching its volume and keeping a cartesian geometry (curvature effects neglected)

$$\rho \propto \frac{1}{r^2}$$

$$B_r \propto \frac{1}{r^2} \quad B_t \propto \frac{1}{r}$$

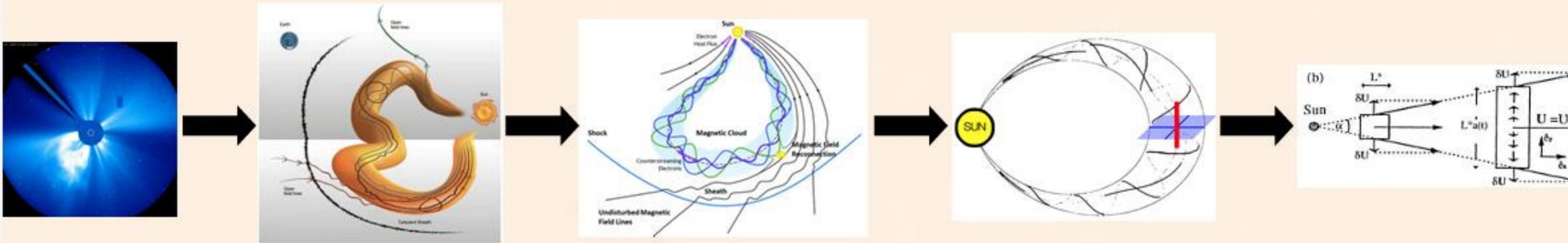
$$U_r = \text{const} \quad U_t \propto \frac{1}{r}$$

$$T \propto \frac{1}{r^{4/3}}$$





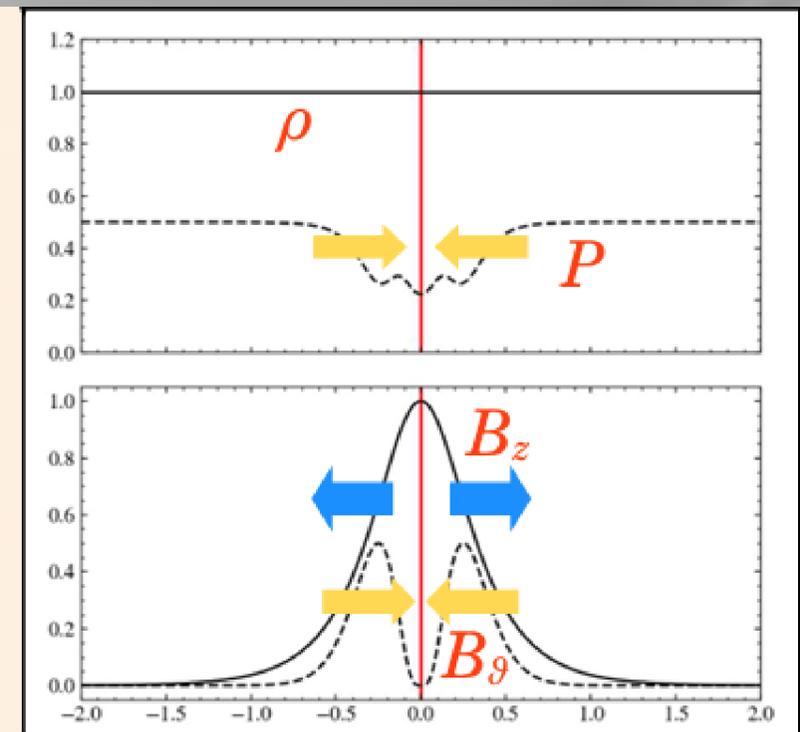
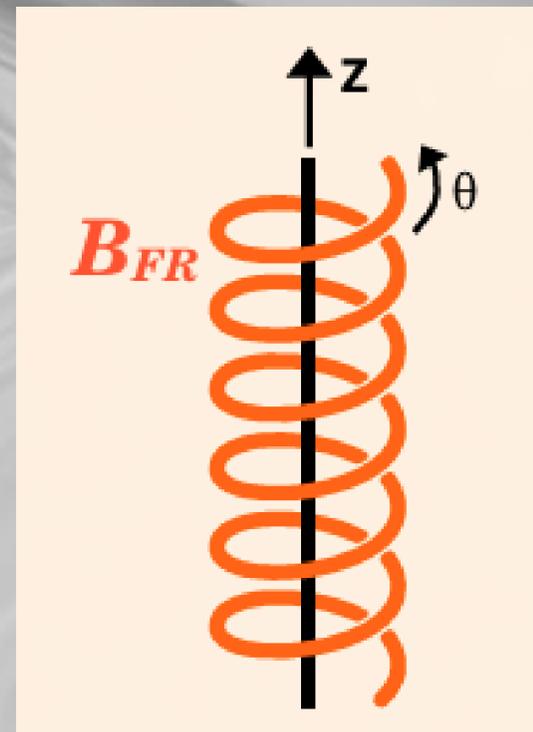
## The ICME in the Expanding Box Model (Sangalli et al, A&A 2025)



We assume the ICME as a flux-rope expanding in the solar wind (2.5D invariant along the main axis of the FR)

Two main ingredients:

- local equilibrium between gas pressure, magnetic pressure and magnetic tension
- Spherical expansion





## The ICME in the Expanding Box Model (Sangalli et al, A&A 2025)

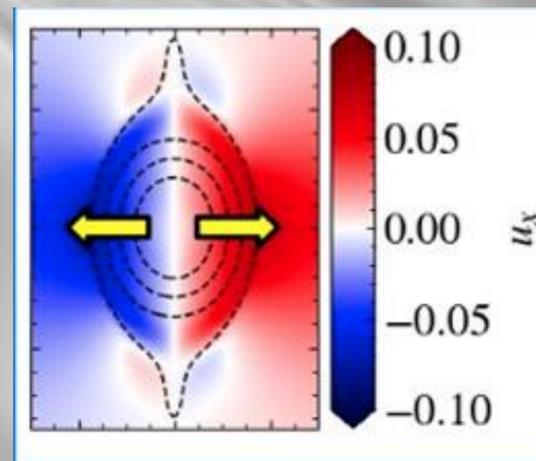
Laminar case

Effect of the expansion (kinematic) and local dynamics (distortion)

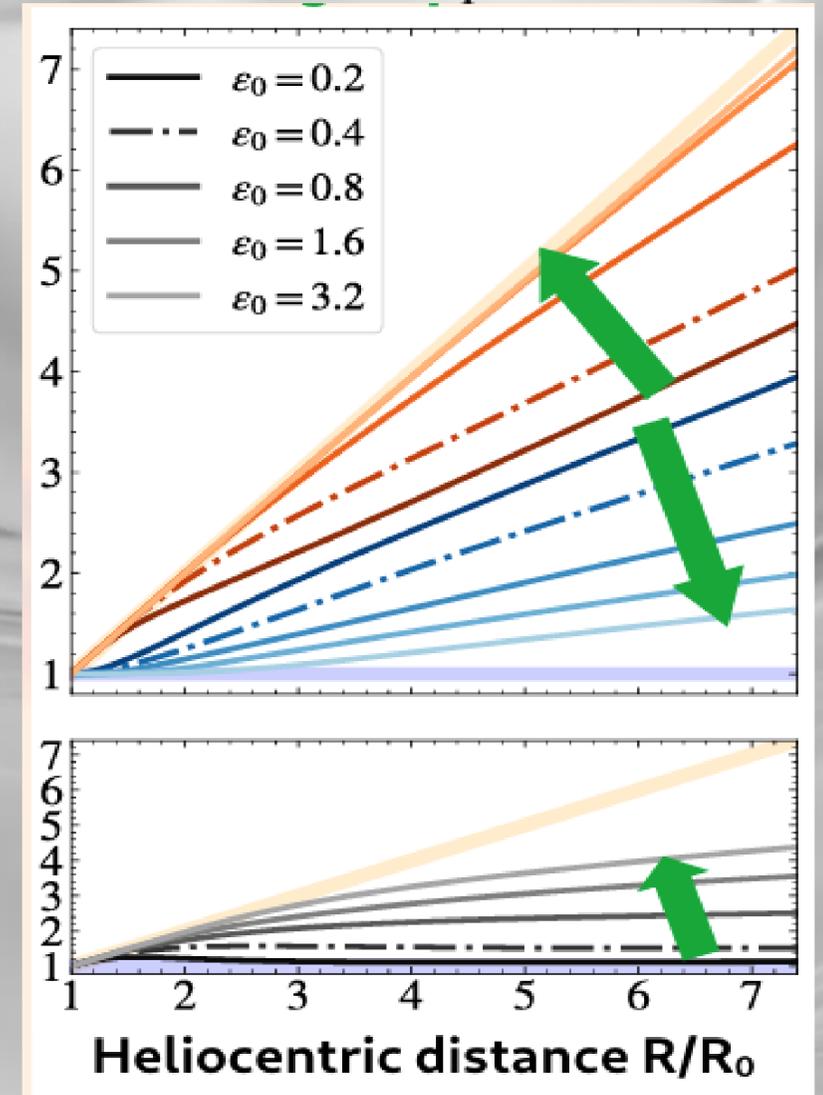
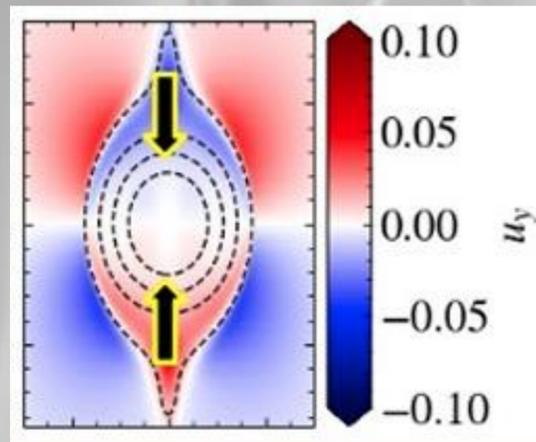
$$\epsilon_0 = \frac{\tau_A}{\tau_{\text{exp}}}$$

The spherical flow perturbs the internal balance of forces

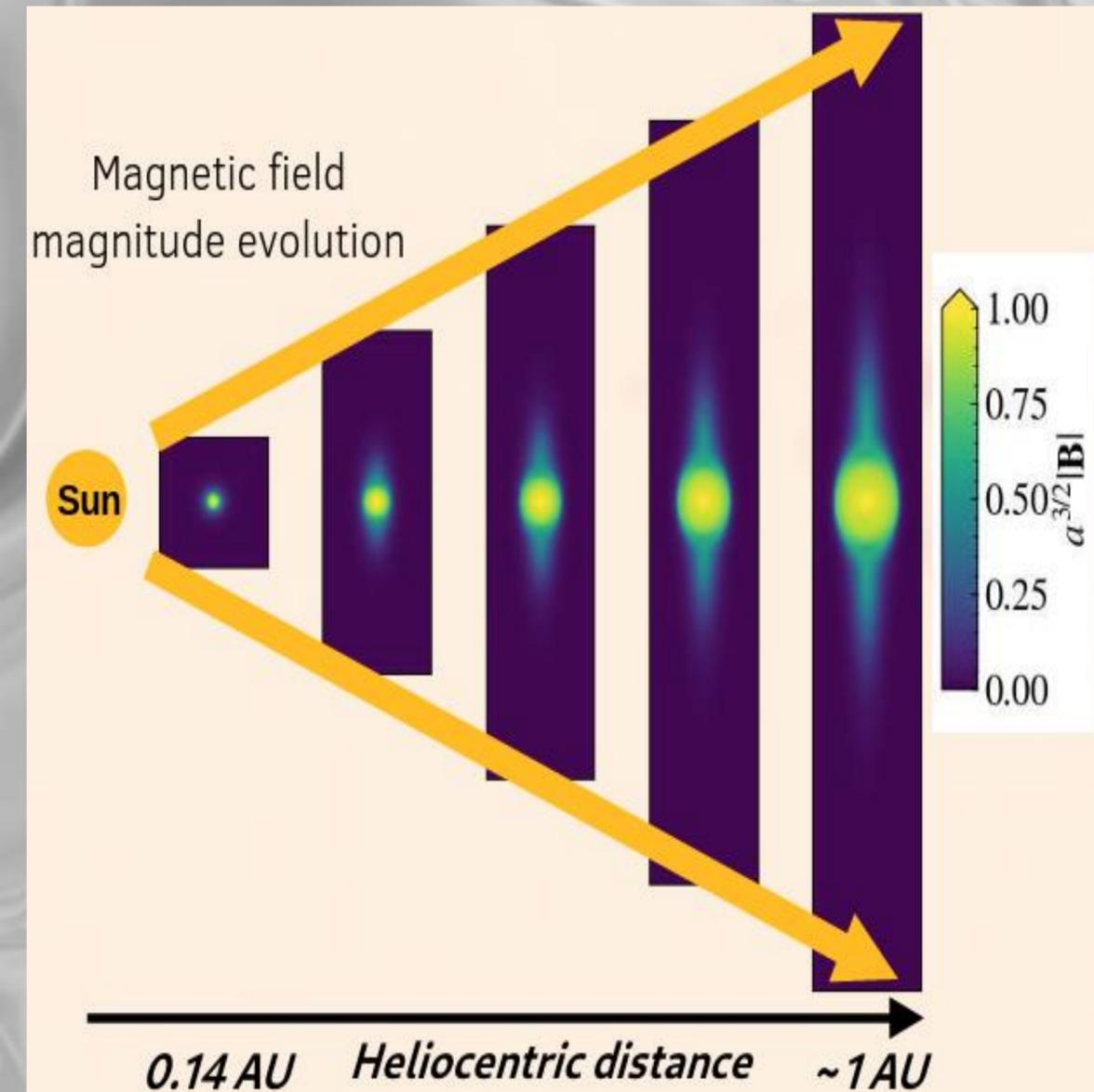
- Over-pressure in the radial (stretching)



Over-tension in the transverse (compression)



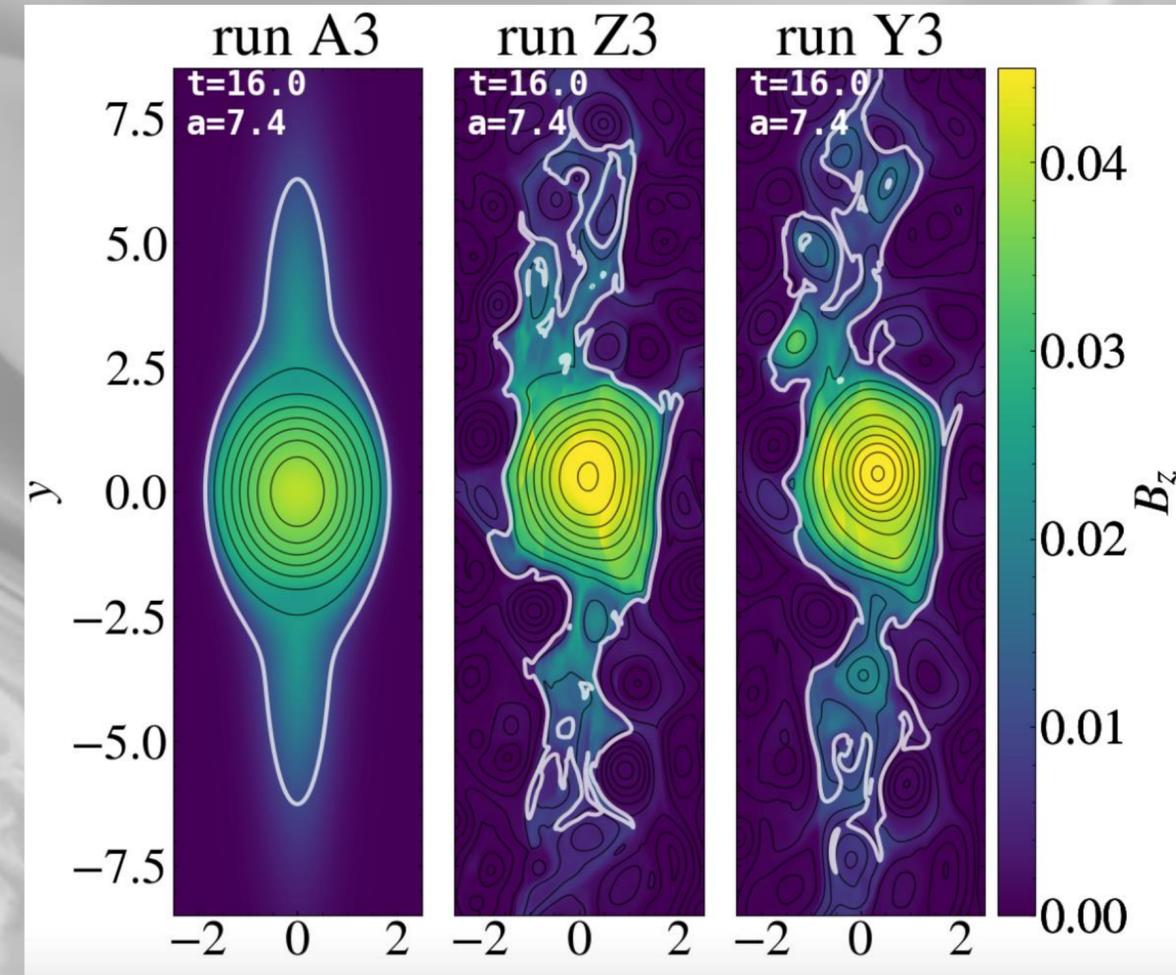
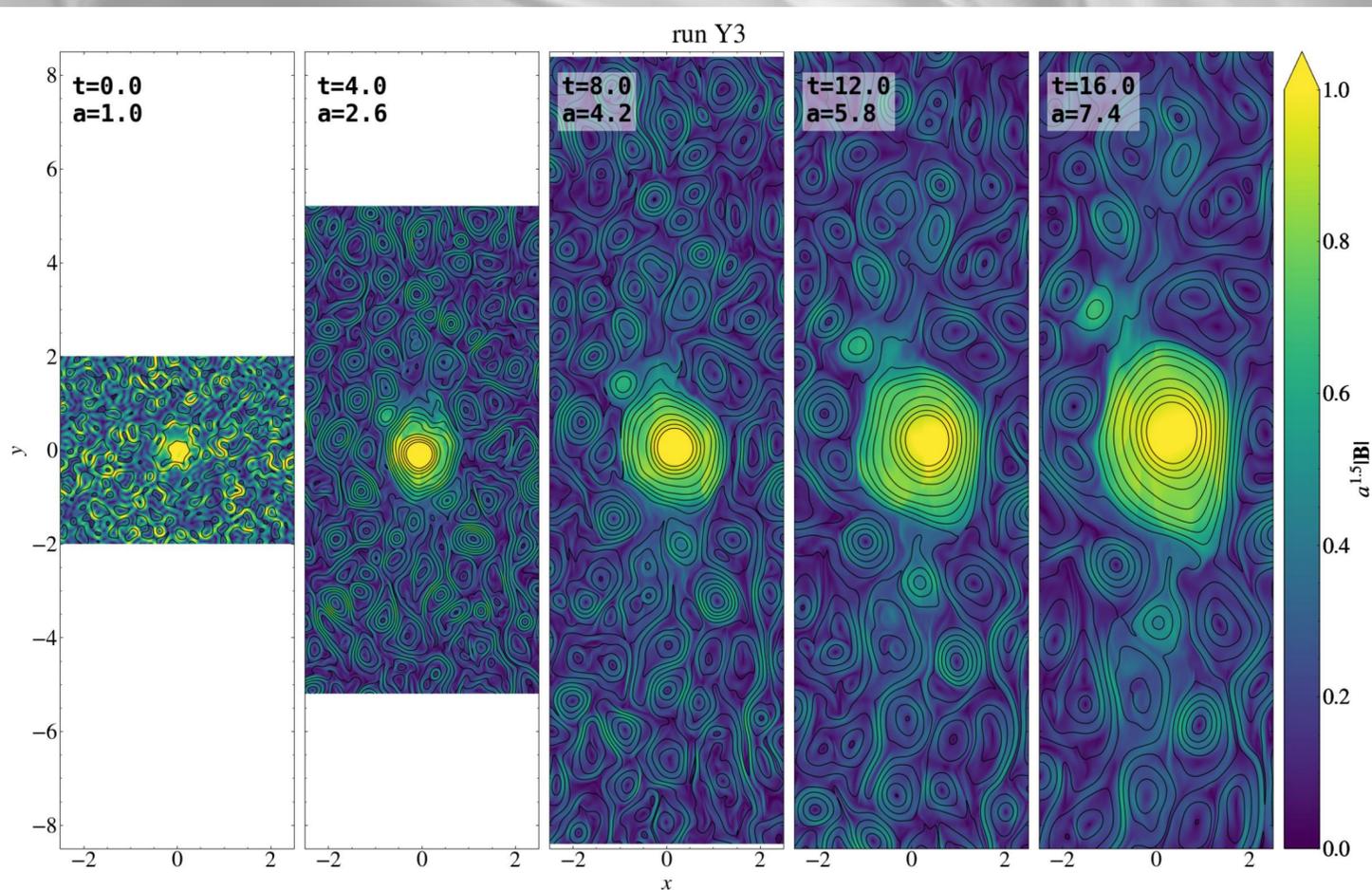
- Faster expansion -> more kinematic





# The ICME in the Expanding Box Model (Sangalli et al, A&A 2025)

## Turbulent case



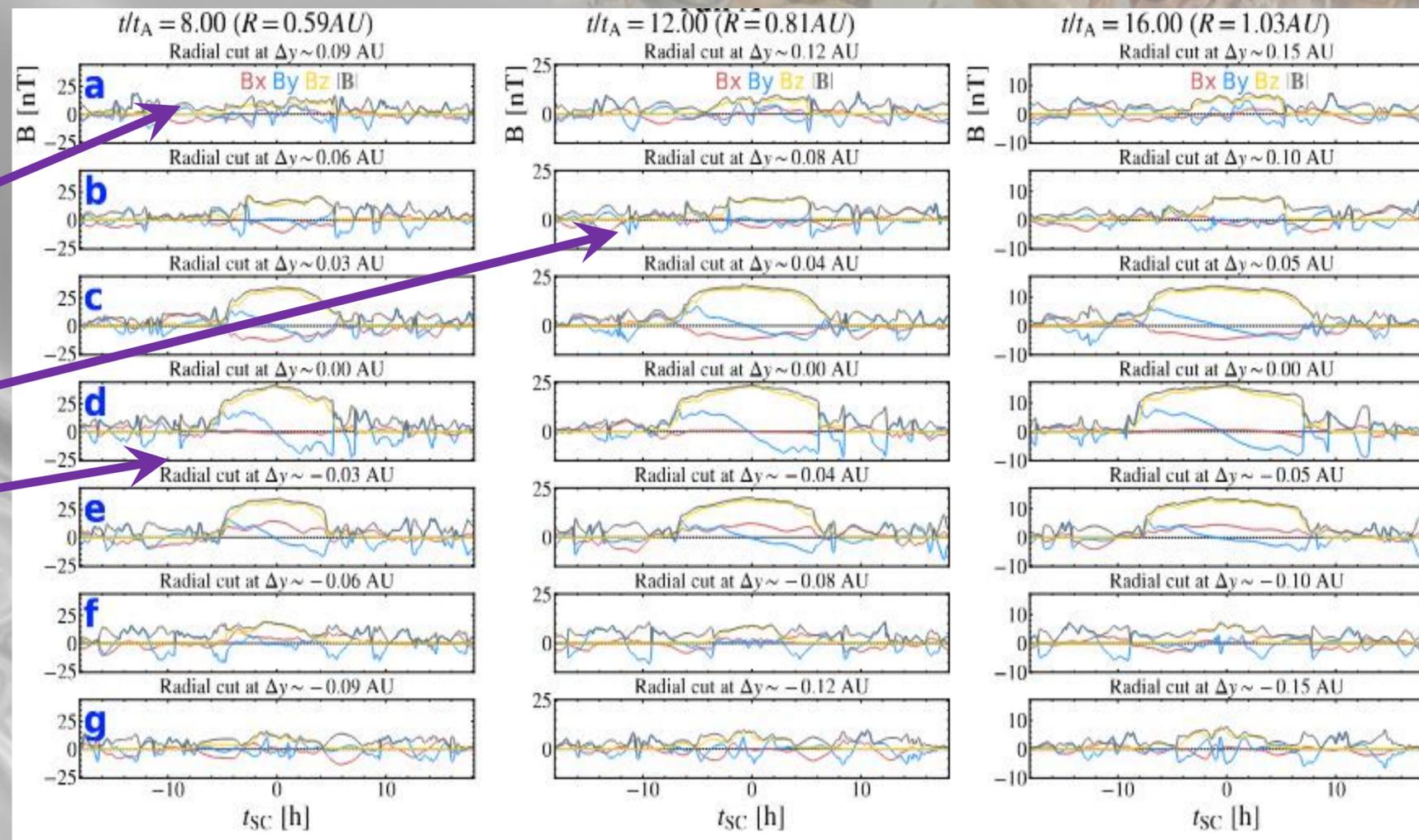
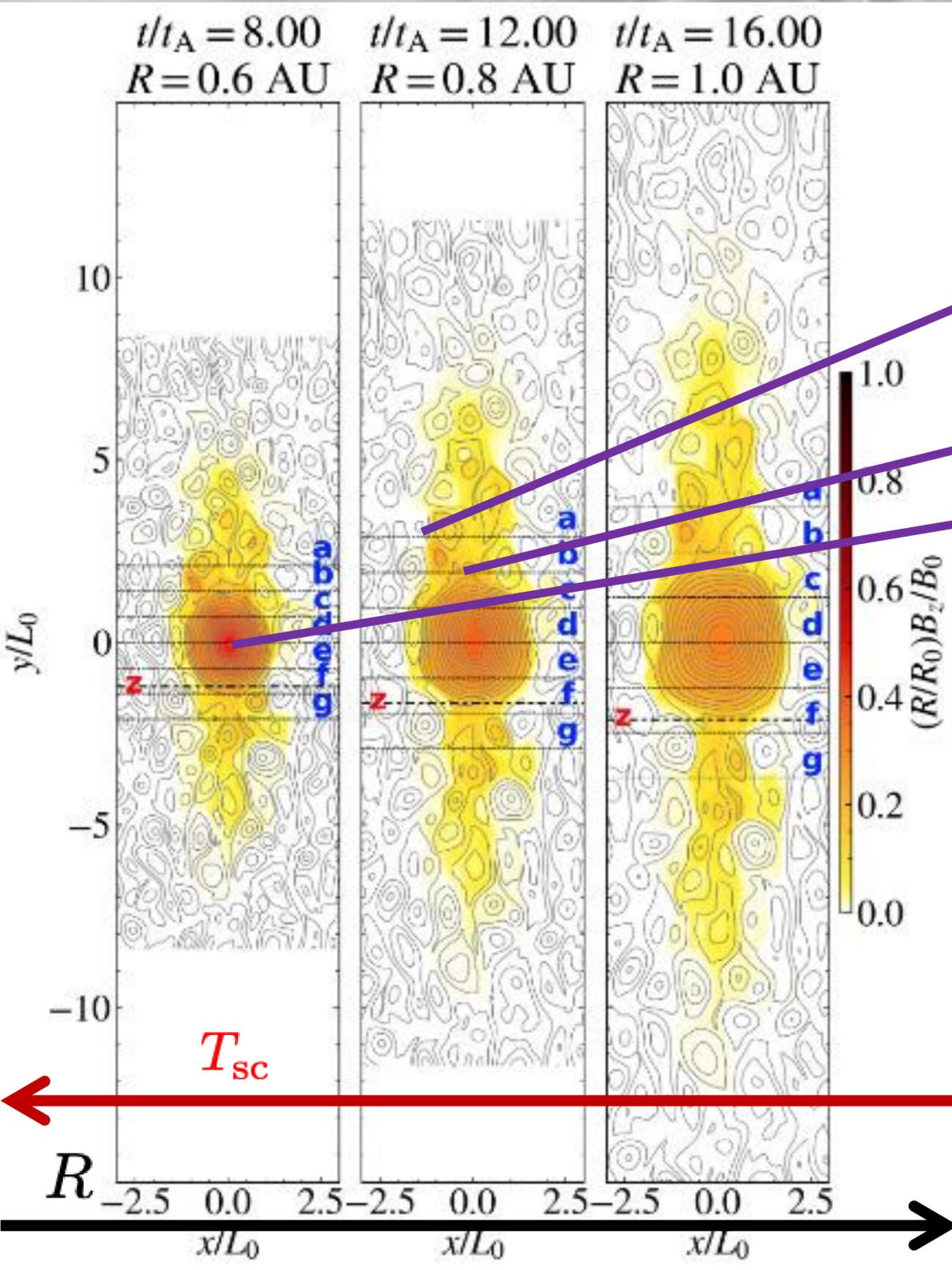
0.14 AU

1.0 AU

- CME evolution in an expanding and turbulent wind

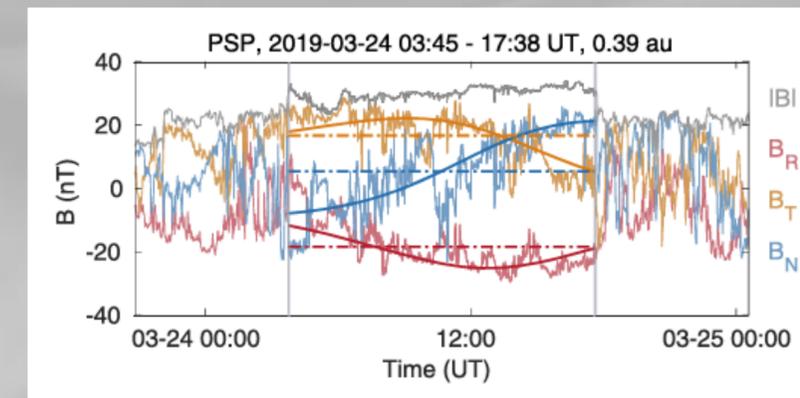
- Turbulence changes the internal dynamics
- Even in presence of strong turbulence the FR keeps its large scale coherency
- **Strong turbulence may favour detachment of secondary magnetic enhancements.**

# Virtual s/c analysis (Sangalli et al, in prep.)



A s/c could cross the MC radially (x) at different impact parameters wrt main axis of the FR measuring:

- A FR
- A Magnetic enhancement with no FR
- Almost none

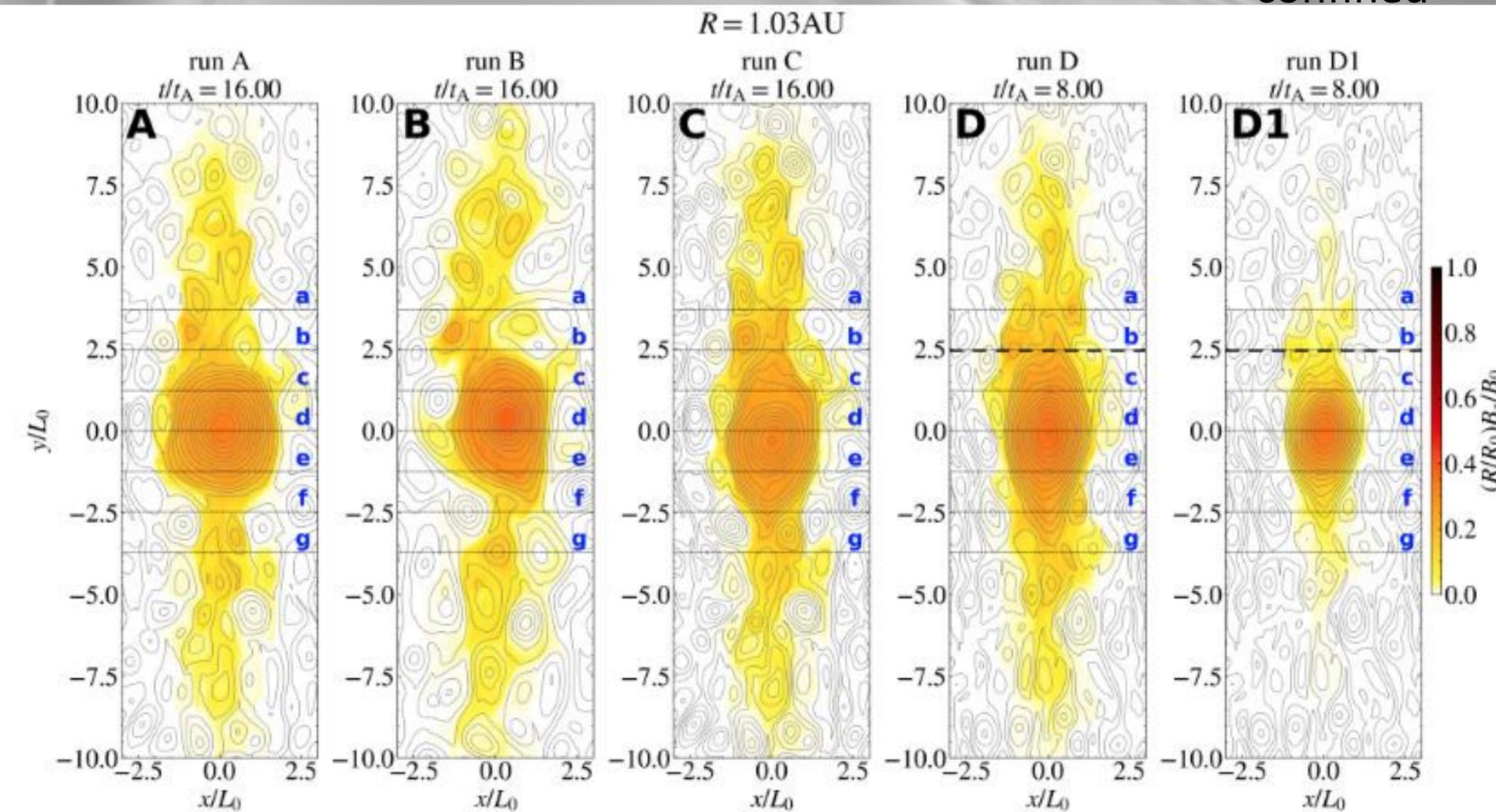




## Virtual s/c analysis (Sangalli et al, in prep.)

- Different values of turbulence, magnetic tension, MC velocity and confinement of the initial axial MF inside the FR can modify the distortion properties of the MC in the interplanetary medium

Reference      Turb ↑      Tension ↓      Faster      Faster and more confined

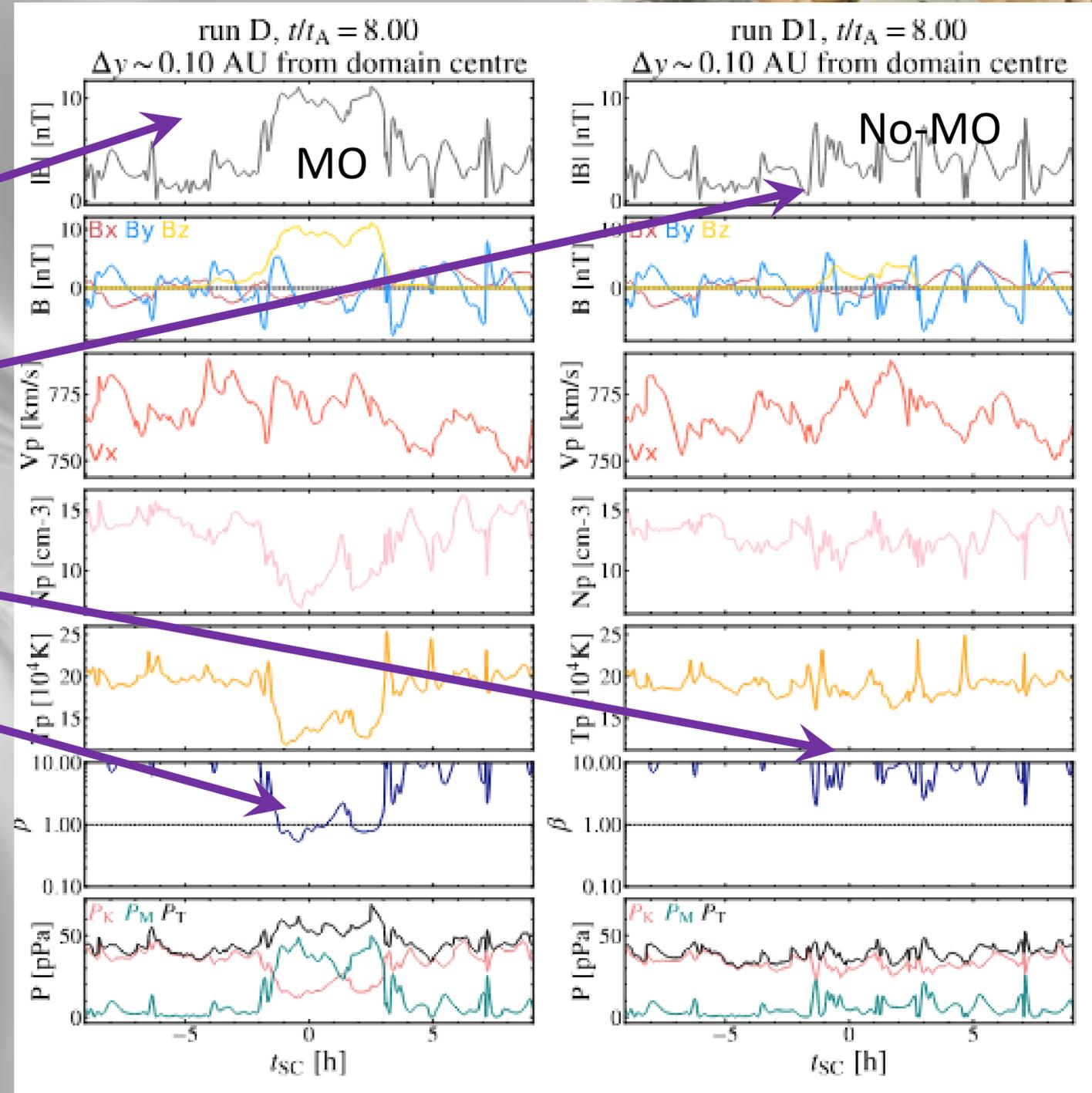
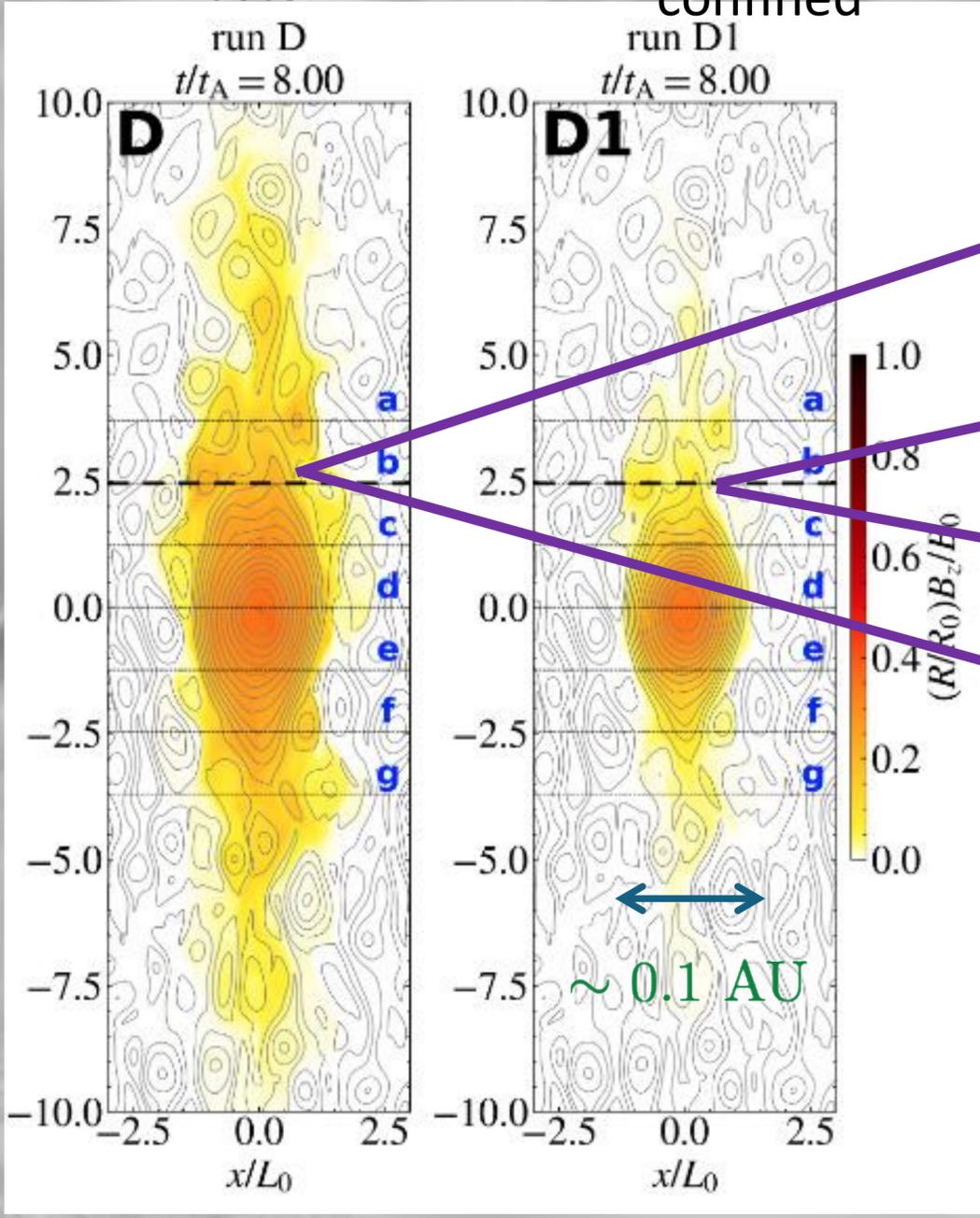


Stronger turbulence, less tension and faster expansions introduce larger deformations allowing the presence of signatures at larger distances from the center



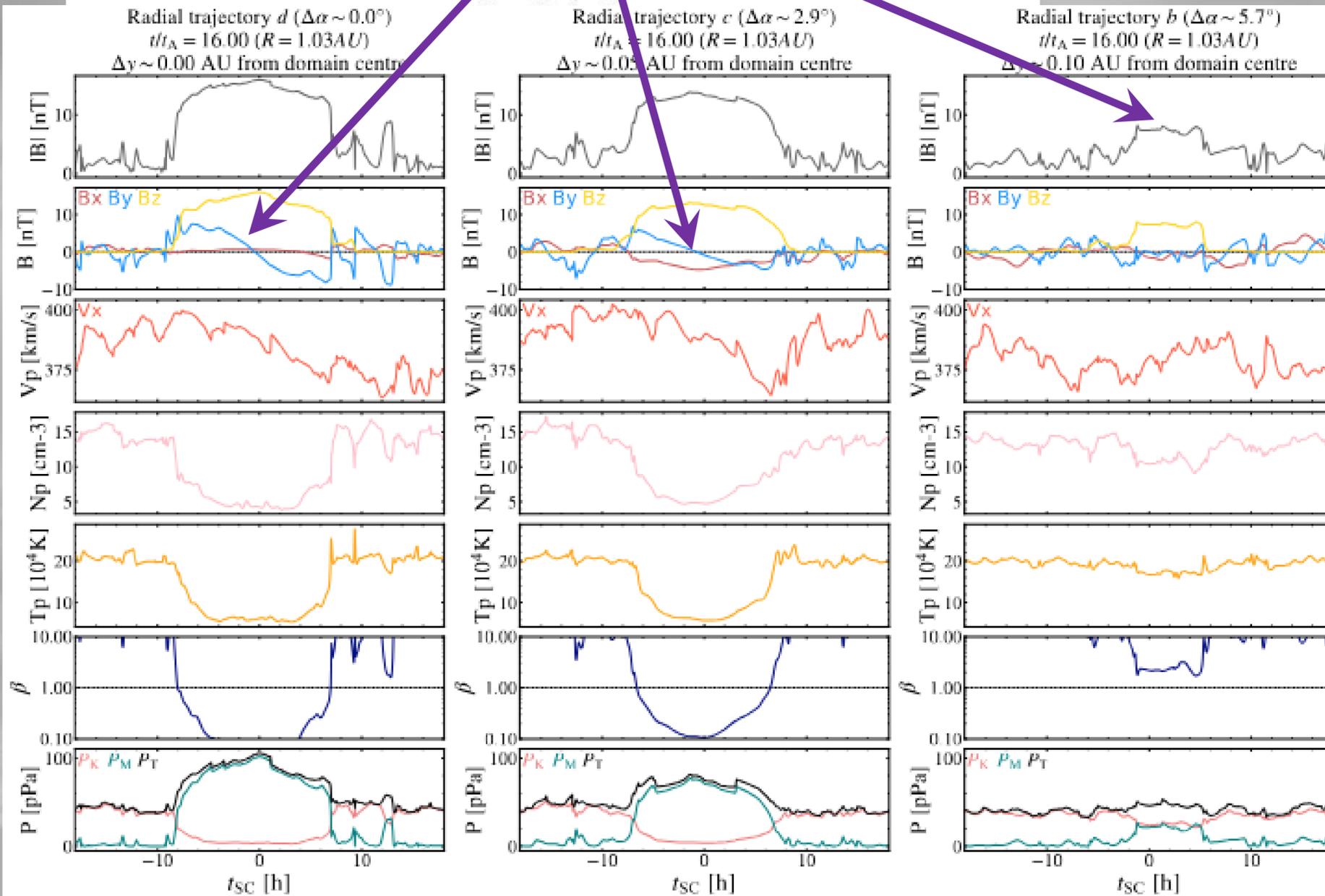
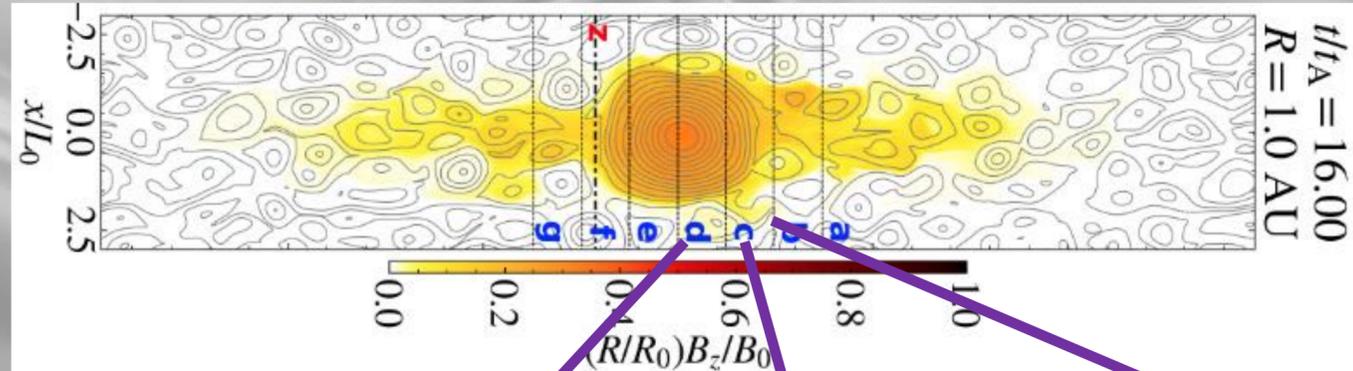
Faster and more confined

Faster



The presence of MO can be linked to the magnetic properties of the ejecta near the Sun. If the axial field is more confined at the beginning the MO are no more observed

# Virtual s/c analysis (Sangalli et al, in prep.)



At say 1 AU a FR or a MO can be observed depending on the impact parameter with respect to the central axis of the FR

**A MO measurements can be the signature of a nearby stronger FR of an expanding ICME**



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# HENON

HEliospheric pioNeer for sOlar and interplanetary threats defeNce



**HENON** is a **pathfinder** mission (**ASI-ESA**) that will explore for the first time ever the *DRO orbits* bringing a payload tailored for Space Weather operations and science. ITALY: INAF, UNIFI, UNICAL, ARGOTEC, SPACEDYS

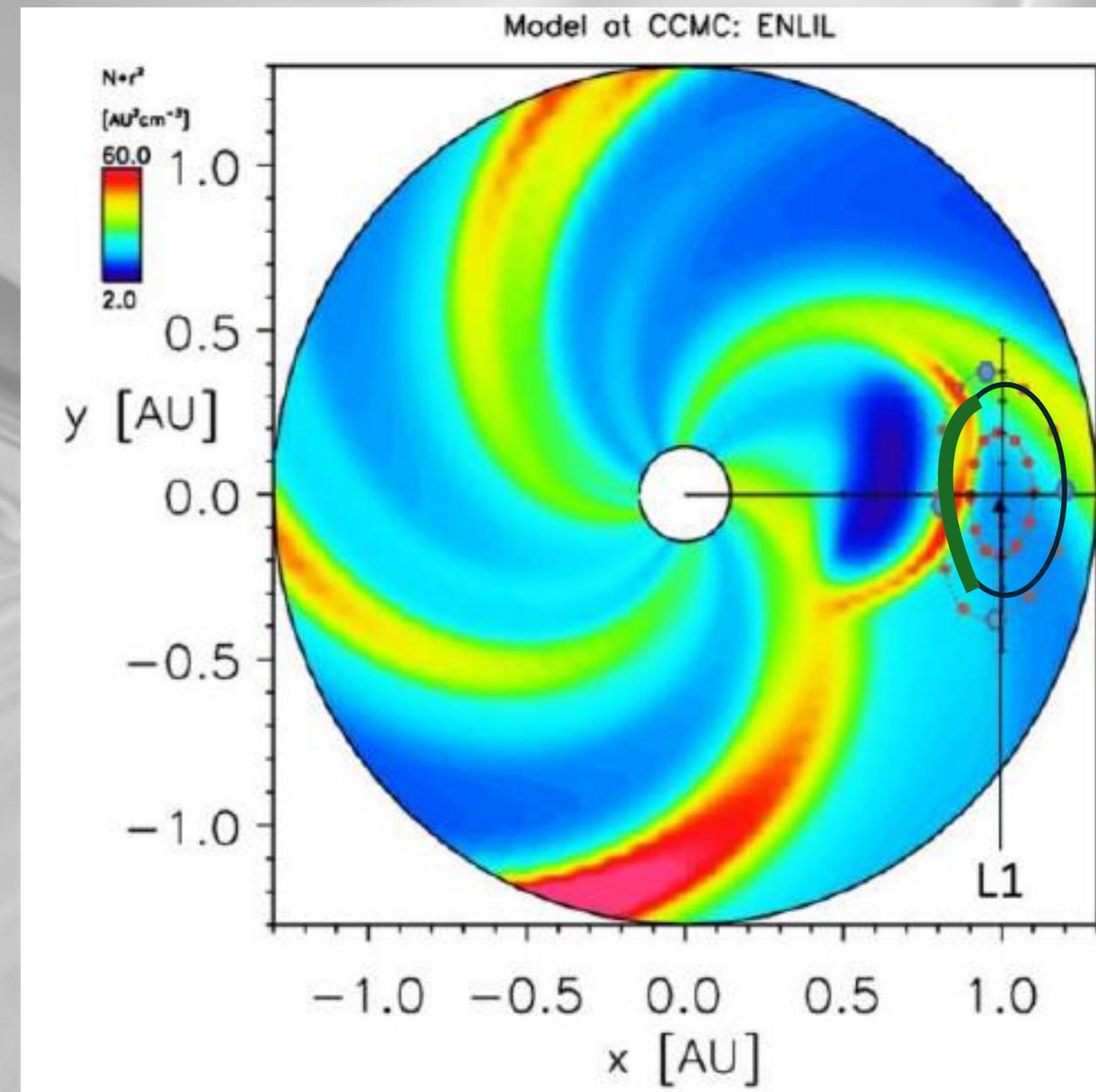
1 cubesat 12U that embarks a radiation monitor (REPE) together with magnetic field (MAGIC) and plasma instruments (FARADY CUP)

Using DRO orbits will remain **long time upstream of the Earth at a distance much larger than L1** → alerts much earlier (~5 h)

**Lunched as Piggybag toward L2 with ESA-PLATO mission (early 2027)**

**Final orbit at 0.085 AU after about 1 year from the lunch**

Depending on HENON results a multiple CubeSat mission can be taken into consideration.

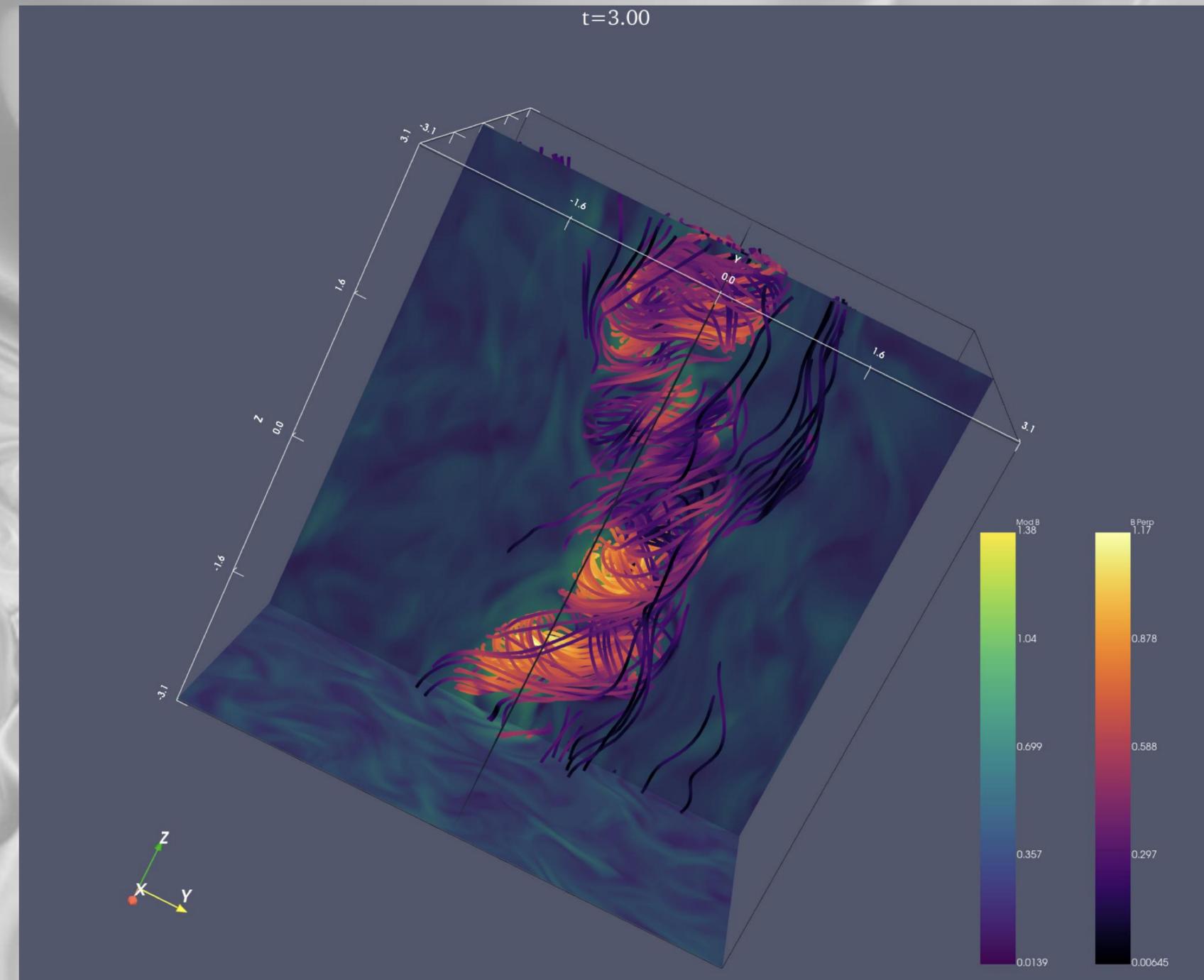




## Work in progress 3D analysis

Full 3D simulations could introduce

- Finite coherence length along the main axis of the ICME
- Deformations due to different interactions with the background turbulence
- Deformations due to the self-destabilization (kink-sausage instabilities)
- Wind shears driven deformations





## Conclusions

- A magnetic flux rope embedded in a spherical flow develops an internal dynamics, which provide a radial expansion as observed in MC
- Strong and relatively long-lived turbulence alters the flux-rope dynamics but it keeps its coherence
- Fluctuations may produce the detachment of secondary flux ropes
- Virtual S/C crossing shows that the observation of MC or MO could be related to the impact parameter of the s/c with respect the main axis of the MC flux-rope → better interpretation of the data & forecast predictions for future missions (e. g. HENON)
- The presence of MO can be related to the initial (launch) condition of the CME in the interplanetary medium