State of the art and gaps on the role of interplanetary structures on Sun-Earth coupling

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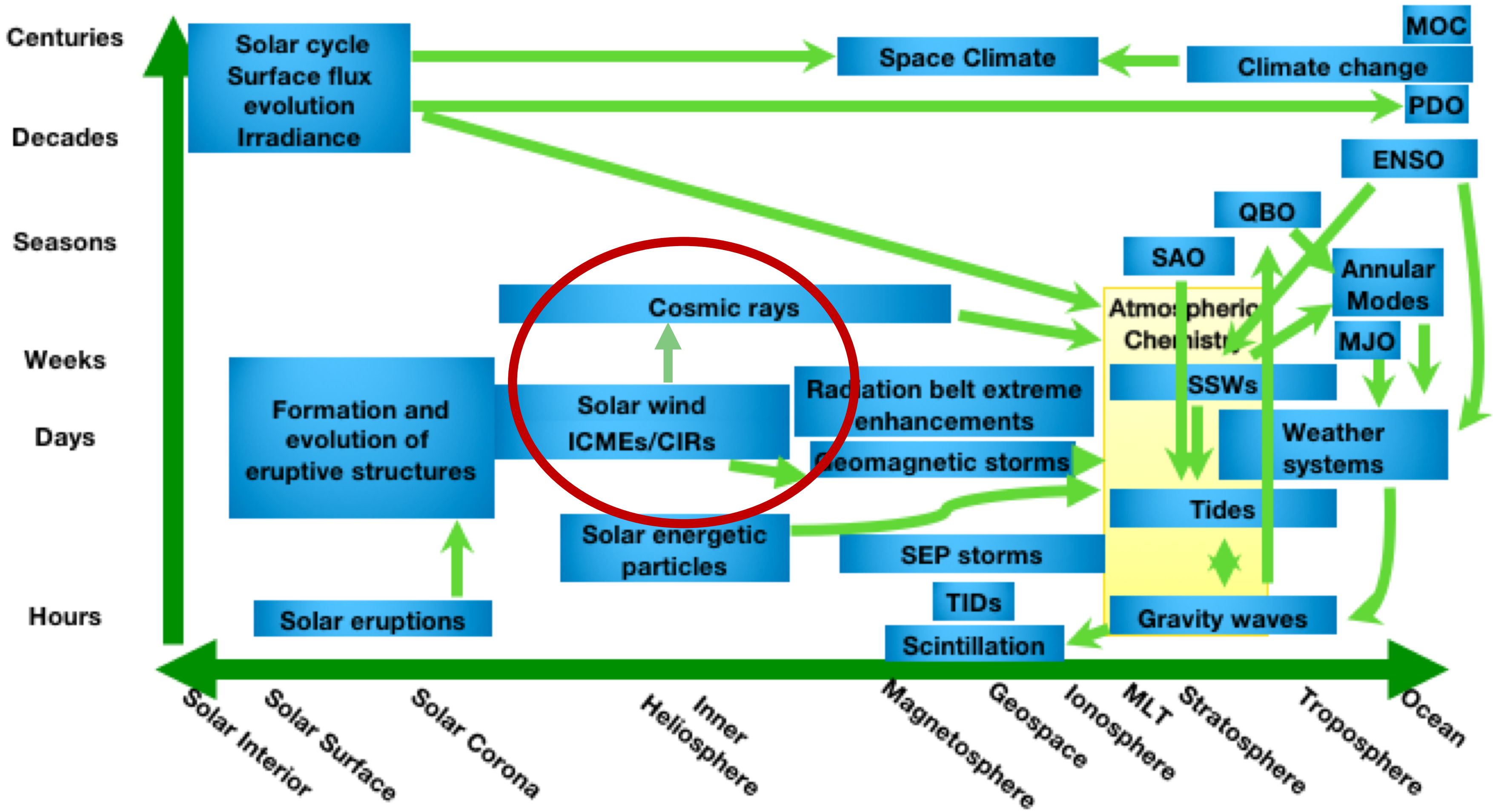
VarSITI completion General Symposium

Session: Predictability of the Variable Solar-Terrestrial Coupling (PreSTo)

An integrated view of solar-terrestrial prediction

Solar-Terrestrial phenomena in various spatial & temporal scales

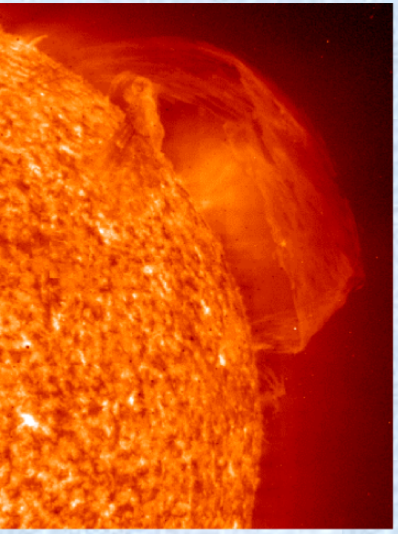


Key solar wind properties for the Sun-Earth coupling and space weather forecasting

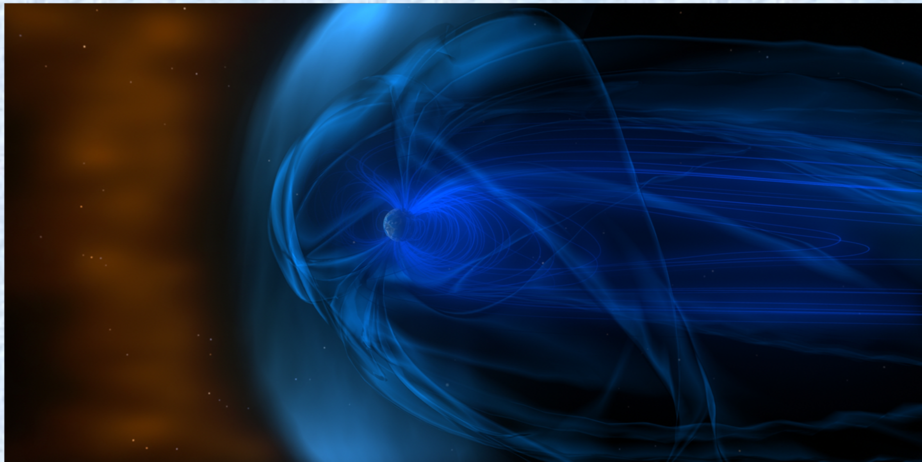
- interplanetary magnetic field
- solar wind speed
- solar wind density
- level of turbulence, etc

interplanetary magnetic field + solar wind speed → dawn-dusk electric field

solar wind speed + solar wind density → dynamic pressure

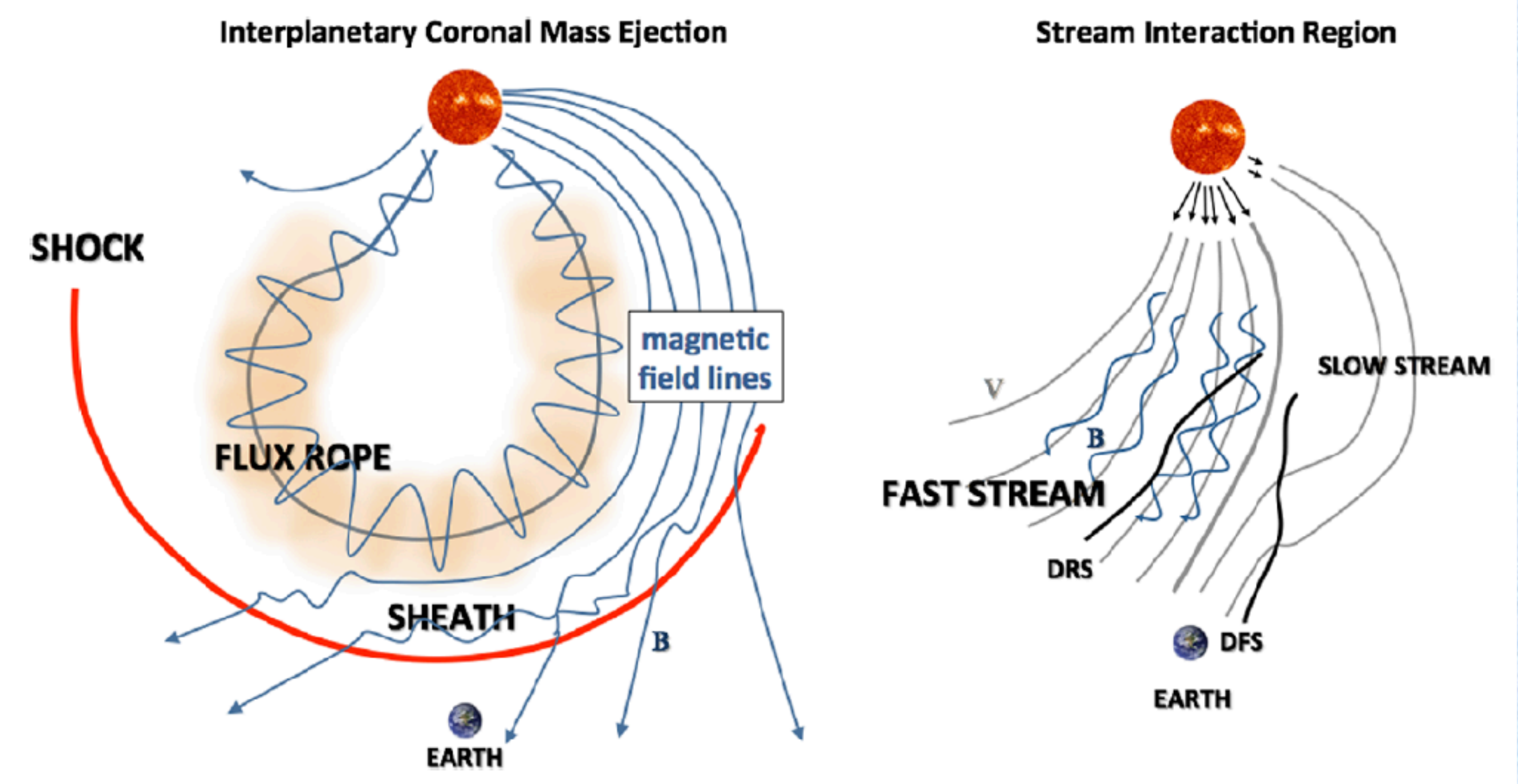


ICMEs are IP transients, that change drastically the interplanetary plasma and magnetic properties near Earth



Main meso-scale structures : ICMEs and CIRs.

Both can produce: acceleration of particles, modulation of GCRs, enhancement of geomagnetic activity



Differences between CIR and CME storms

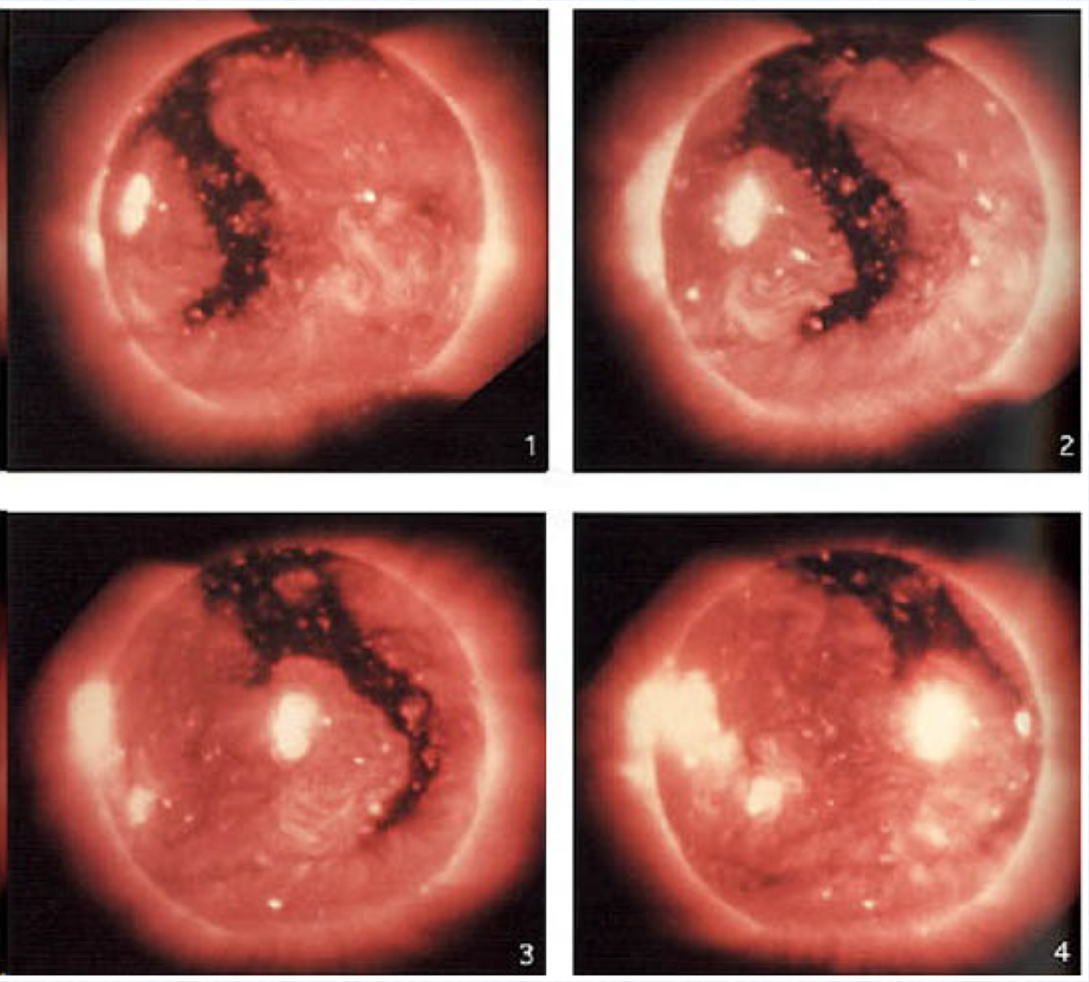
Table 1. A Summary of Some of the Important Differences Between CME-Driven Storms (Shock, Sheath, Ejecta, Cloud) and CIR-Driven Storms (CIR, High-Speed Stream)

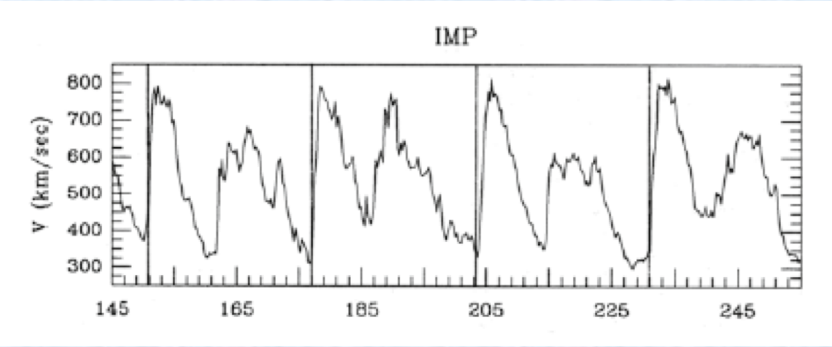
Phenomenon	CME-Driven Storms	CIR-Driven Storms
Phase of the solar cycle when dominant	solar maximum	declining phase
Occurrence pattern	irregular	27-day repeating
Calm before the storm	sometimes	usually
Solar energetic particles (SEP)	sometimes	none
Storm sudden commencement (SSC)	common	infrequent
Mach number of the bow shock	moderate	high
β of magnetosheath flow	low	high
Plasma-sheet density	very superdense	superdense
Plasma-sheet temperature	hot	hotter
Plasma-sheet O^+/H^+ ratio	extremely high	elevated
Spacecraft surface charging	less severe	more severe
Ring current (Dst)	stronger	weaker
Global sawtooth oscillations	sometimes	no
ULF pulsations	shorter duration	longer duration
Dipole distortion	very strong	strong
Saturation of polar-cap potential	sometimes	no
Fluxes of relativistic electrons	less severe	more severe
Formation of new radiation belts	sometimes	no
Convection interval	shorter	longer
Great aurora	sometimes	rare
Geomagnetically induced current (GIC)	sometimes	no

from *Borovsky and Denton*, 2006

Coronal Holes: source regions of high-speed solar wind streams

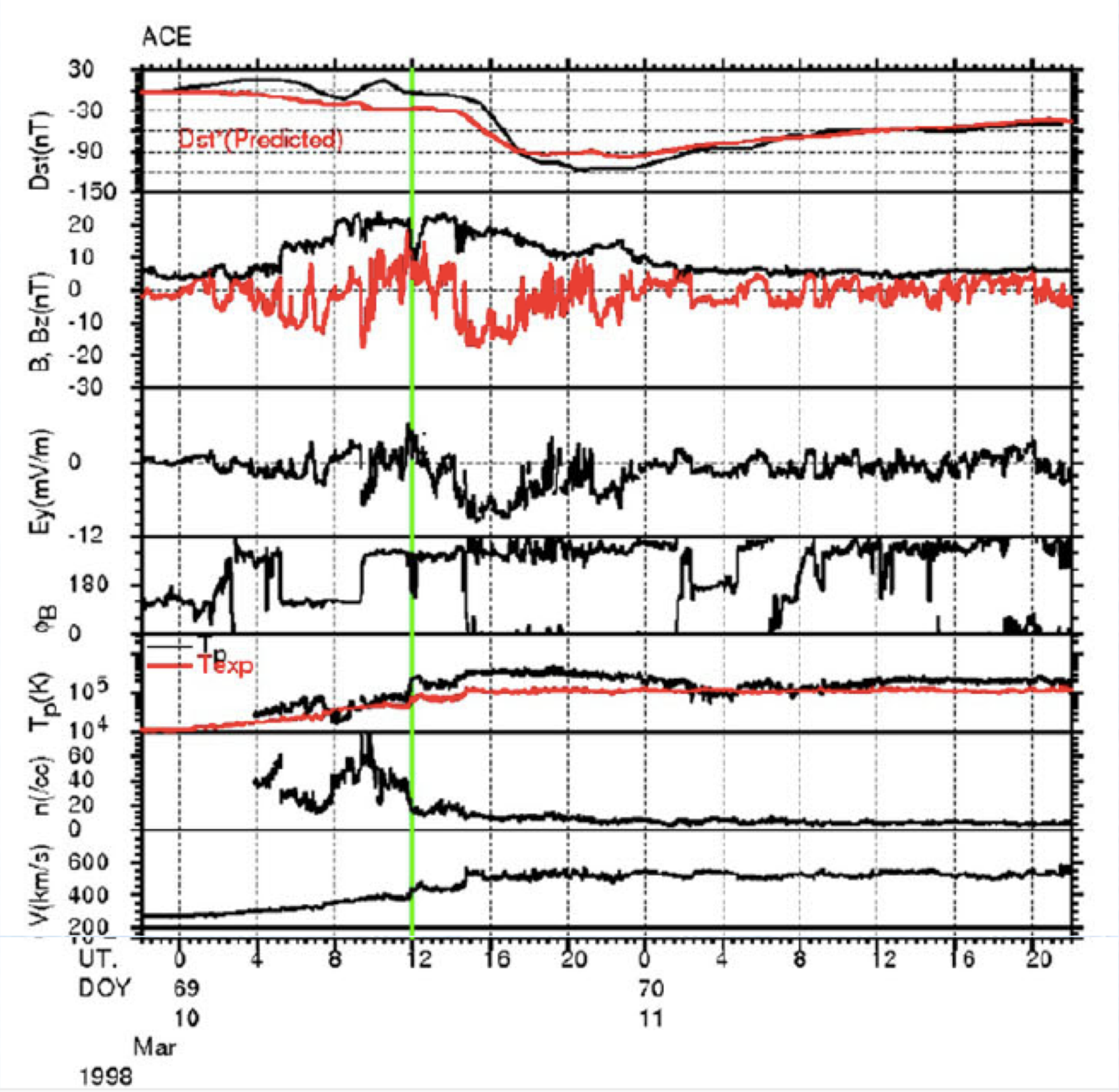
Skylab Soft-X observations of CH (dark region).





Due to the solar rotation, when CH are present during long periods of time, it is possible to see the repetition of CIRs

CIRs producing Geomagnetic Storms

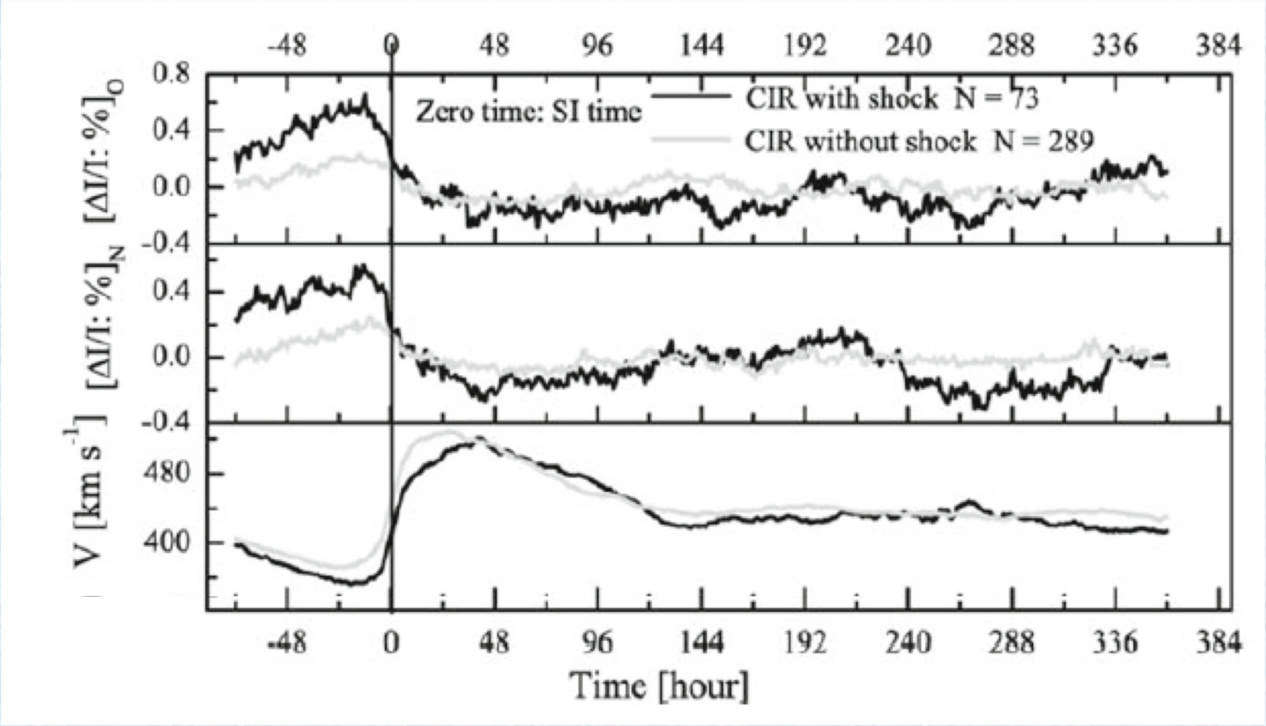


Adapted from Richardson [2018]

CIRs producing Forbush Decreaes

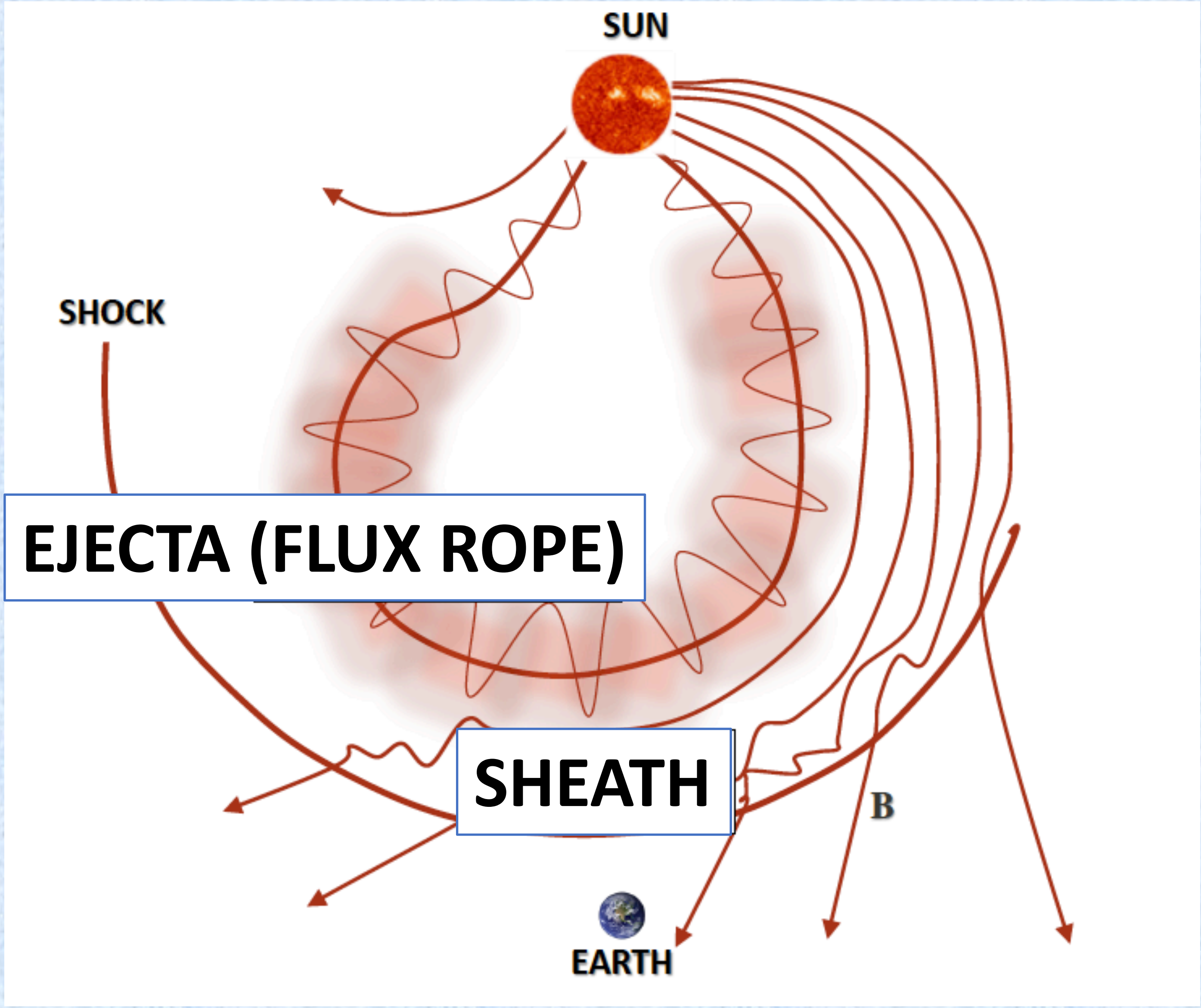
Superposed epoch:

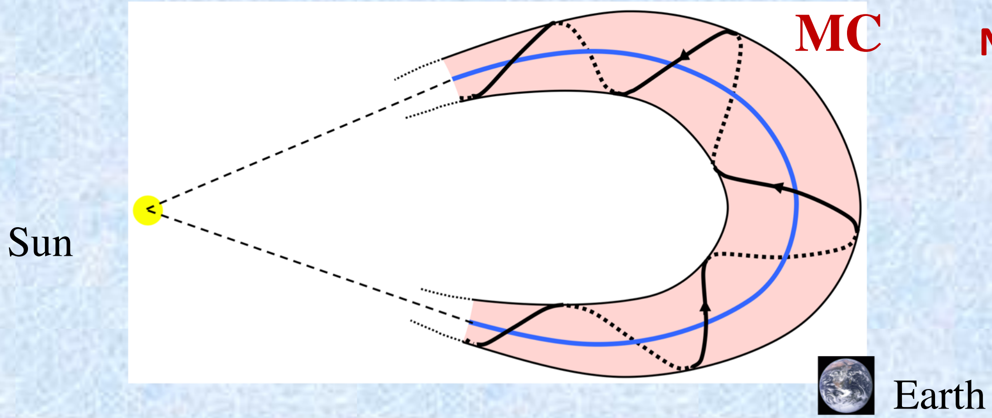
- Fixing the slow-fast interface position
- Oulu and Newark NMs stations



Adapted from Badruddin & Kumar [2016]

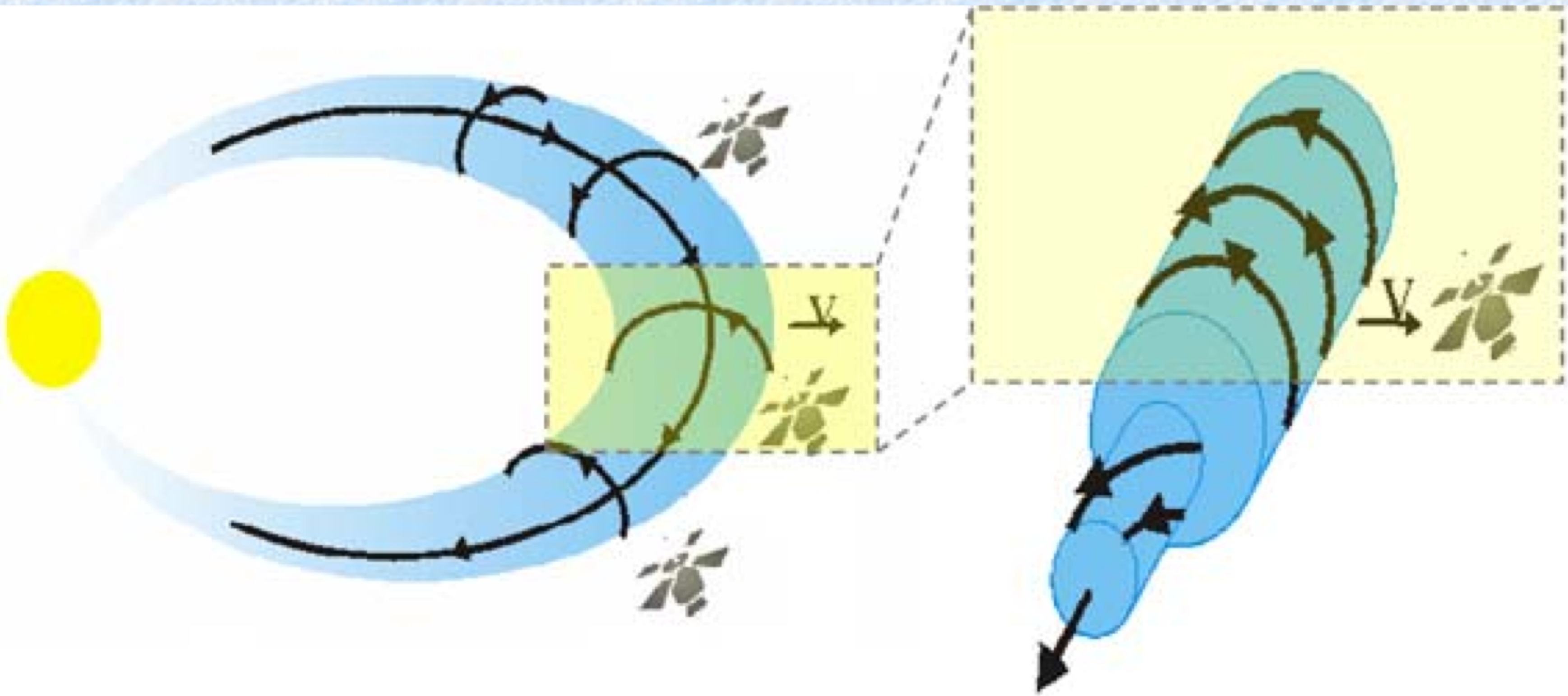
Two major key structures: ejecta & sheath



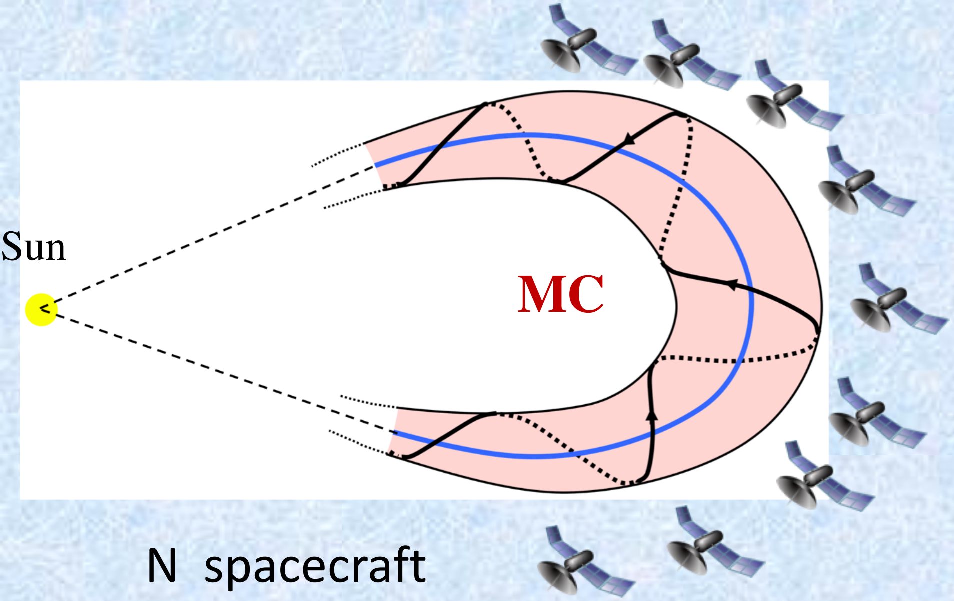


Note that the Earth/MC relative size is not real !
Thus, knowledge of details of the MC structure are importante to determine how geoeffective will be

Cylindrical good approximation for local slide



It is possible to get the global 3D shape from a model, compared with statistical observations of a single MC crossed by multiple spacecrafts

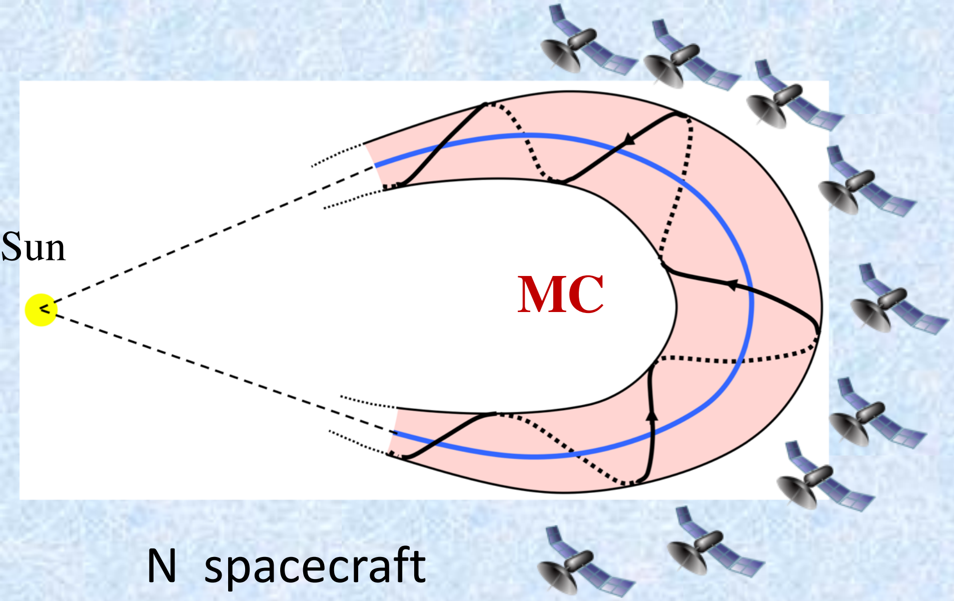


N spacecraft

N ×

May be interplanetary cubesats in the near future?

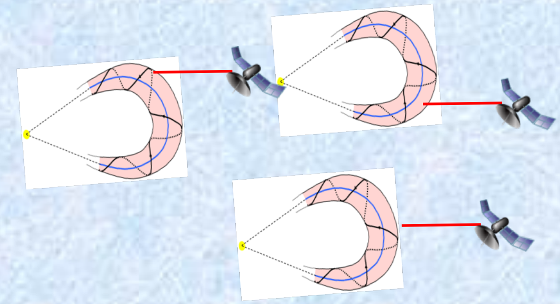
It is possible to get the global 3D shape from a model, compared with statistical observations of a single MC crossed by multiple spacecrafts



N × 

May be interplanetary cubesats in the near future?

At the moment, one single spacecraft, but for many events observed at different places



Crossing a statistically significant # of events =>

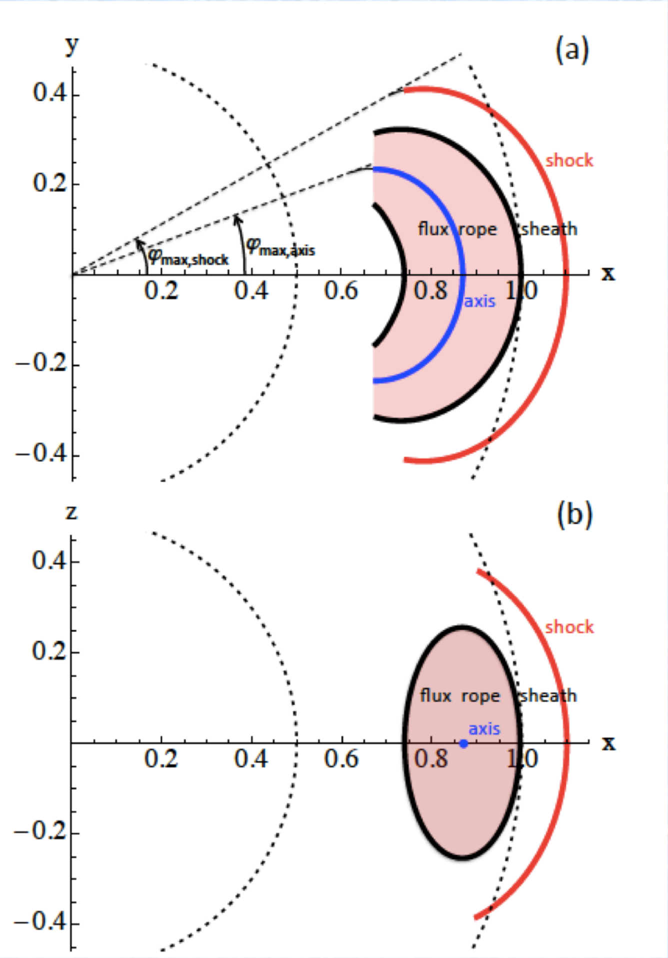
large variety of crossing at different locations (along the flux rope). For similar sample of MCs, equivalent to the scenario of the left

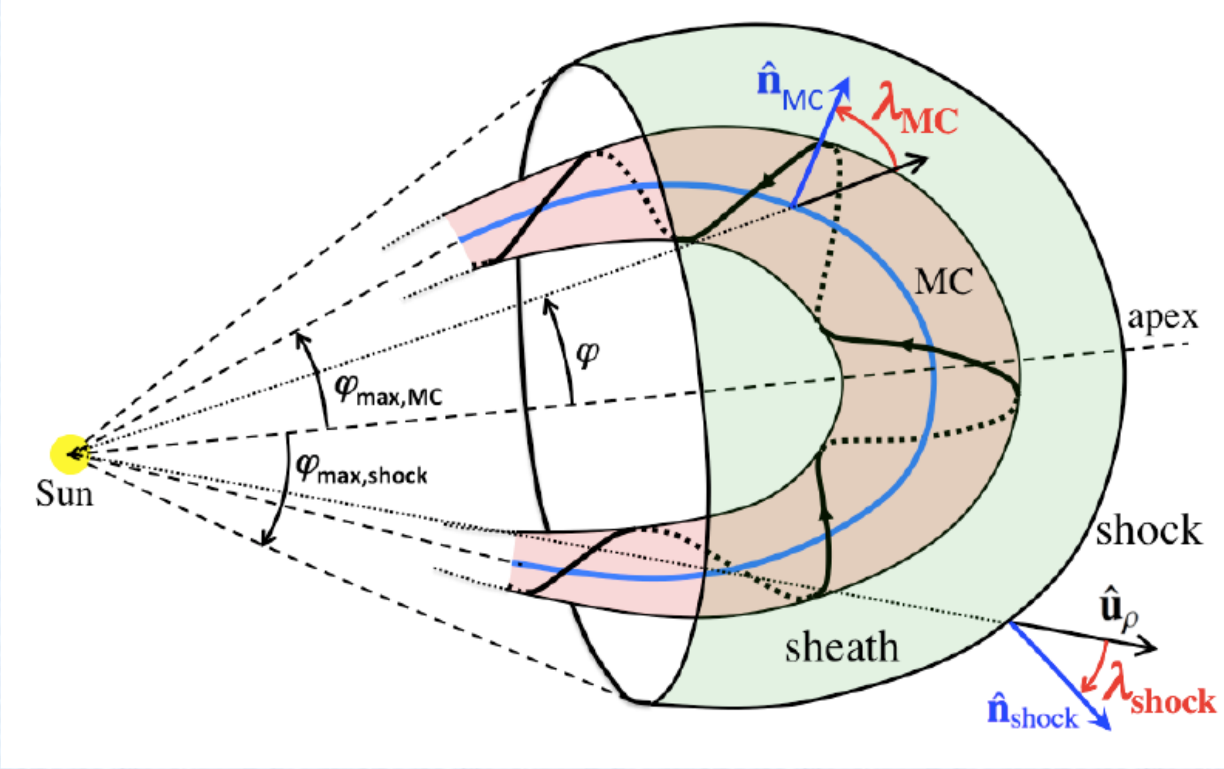
[Janvier+ 2013, 2014]

Then, from assuming a free geometrical model, and comparison with observations => a typical shape can be deduced

First quantitative cartoon for typical flux rope and driven shock, based on statistical analysis

Same procedure for the shape of the 3D surface of the shock wave: elliptical shape (symmetry axis along Sun-apex) [Janvier+ 2015]

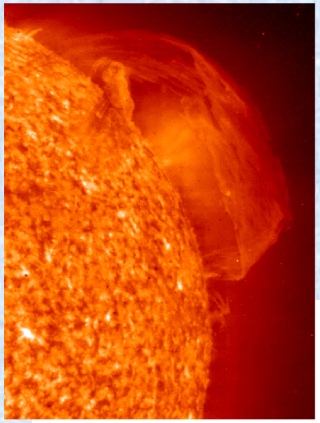


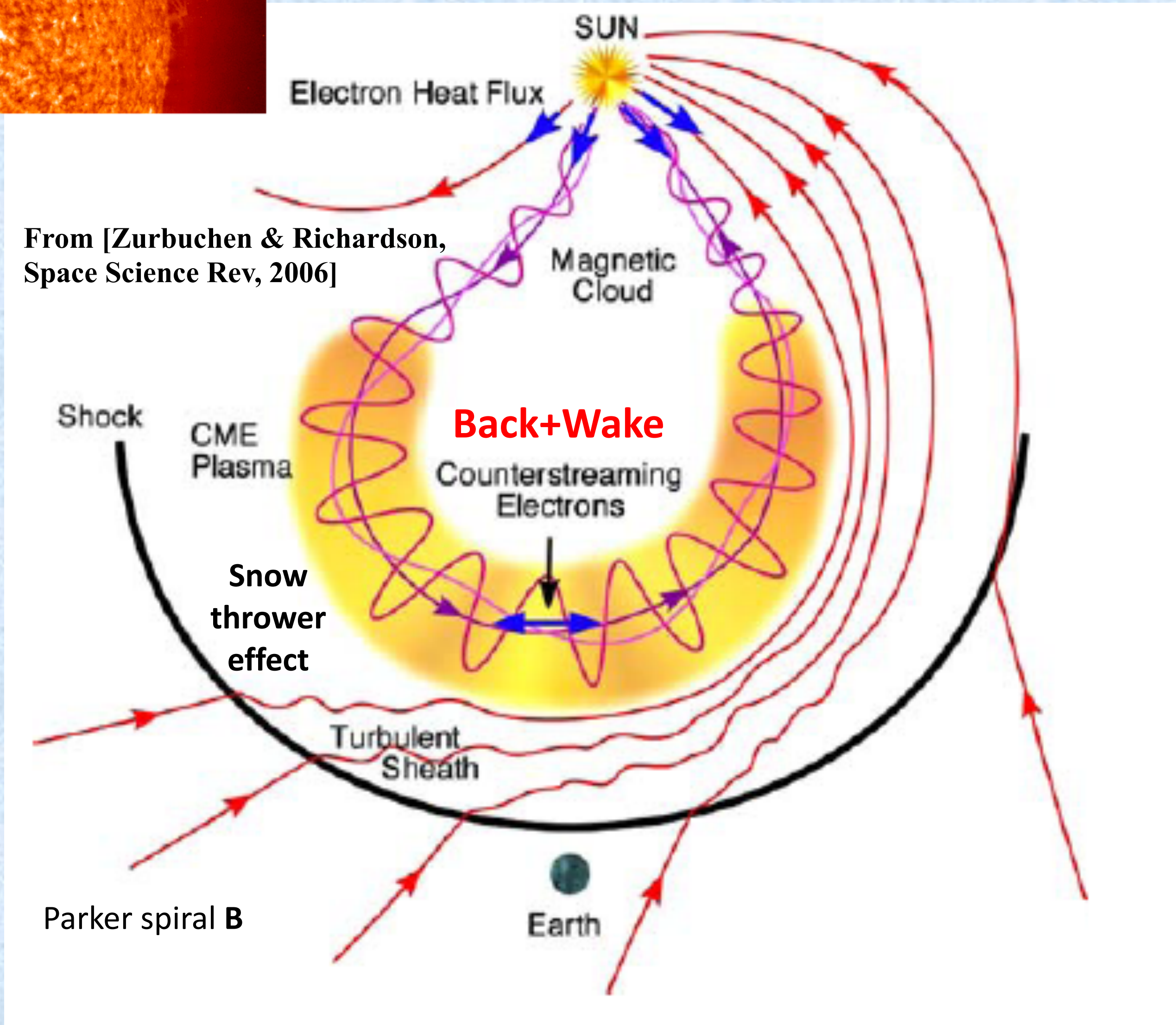


[Demoulin+, A&A, 2016]

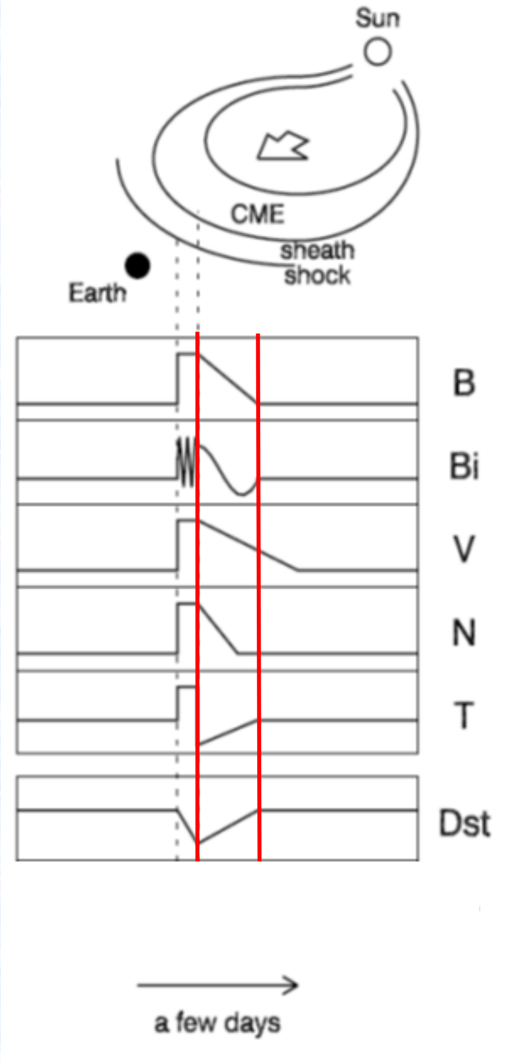
When an ICME strongly interacts with non-stationary solar wind or for ICME-ICME interaction, the evolution is not smooth and strong deviations are expected on the 3D shape and on the geo-effectiveness [Dasso+ JGR 2009]

Four key substructures inside an ICME: shock, sheath, ejecta and back-wake





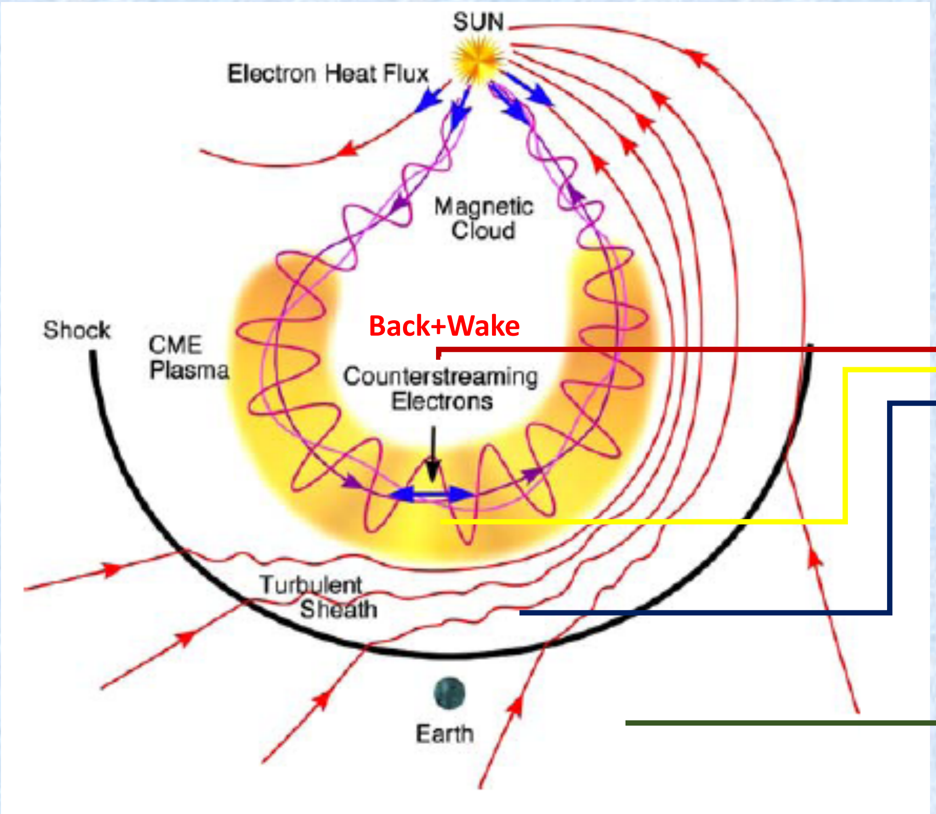
From [Zurbuchen & Richardson, Space Science Rev, 2006]

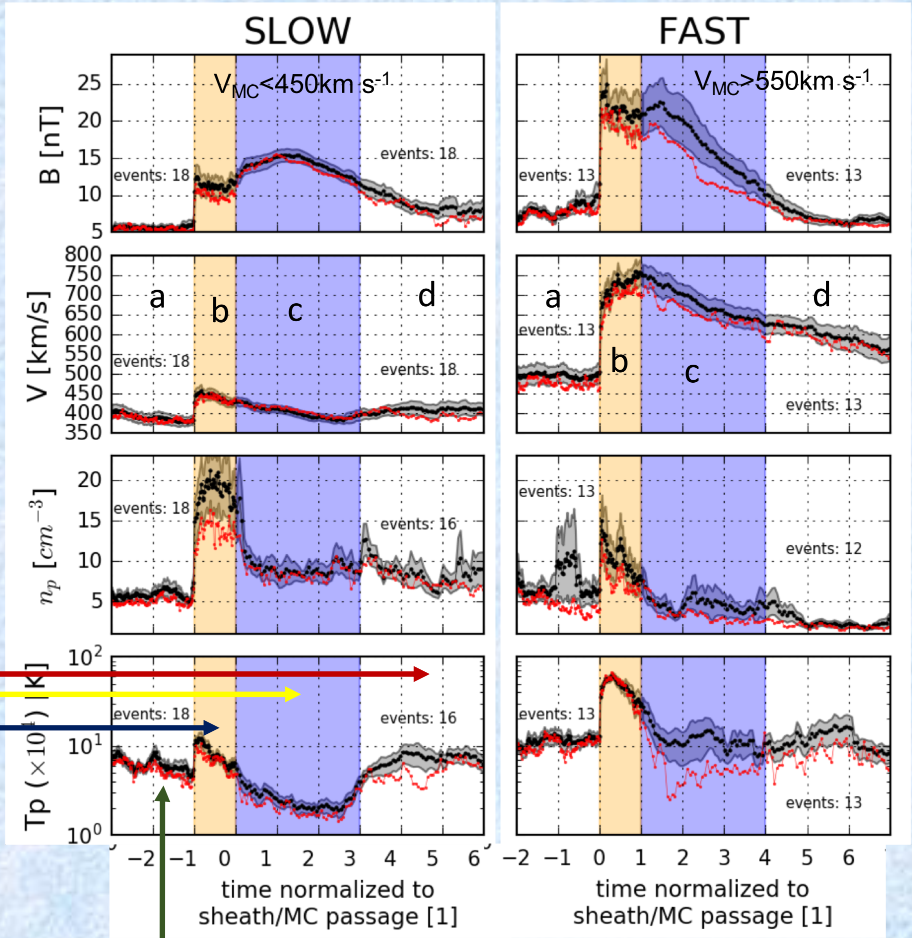


Kataoka and Miyoshi, 2006

Superposed Epoch Analysis: Splitting samples by velocity (best ‘order-parameter’)

-ACE: MAG and SWEPAM, Range: 1998-2006, MCs having sheath & shock





Masías-Meza+, 2016

$V_x(t)$ & $B_s(t)$ near Earth are determined
by (i) solar initial condition and (ii) **IP evolution**

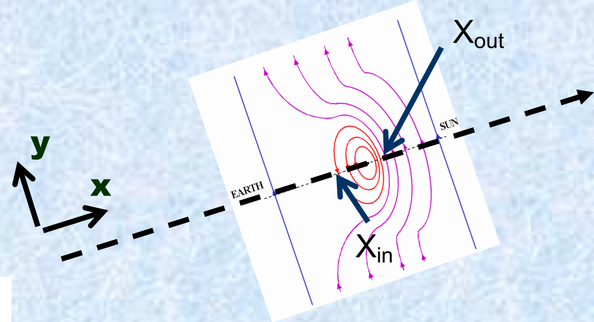
Then, two ICME/MC with same initial conditions can arrive Earth with **different $V_x(t)$ & $B_s(t)$** profiles

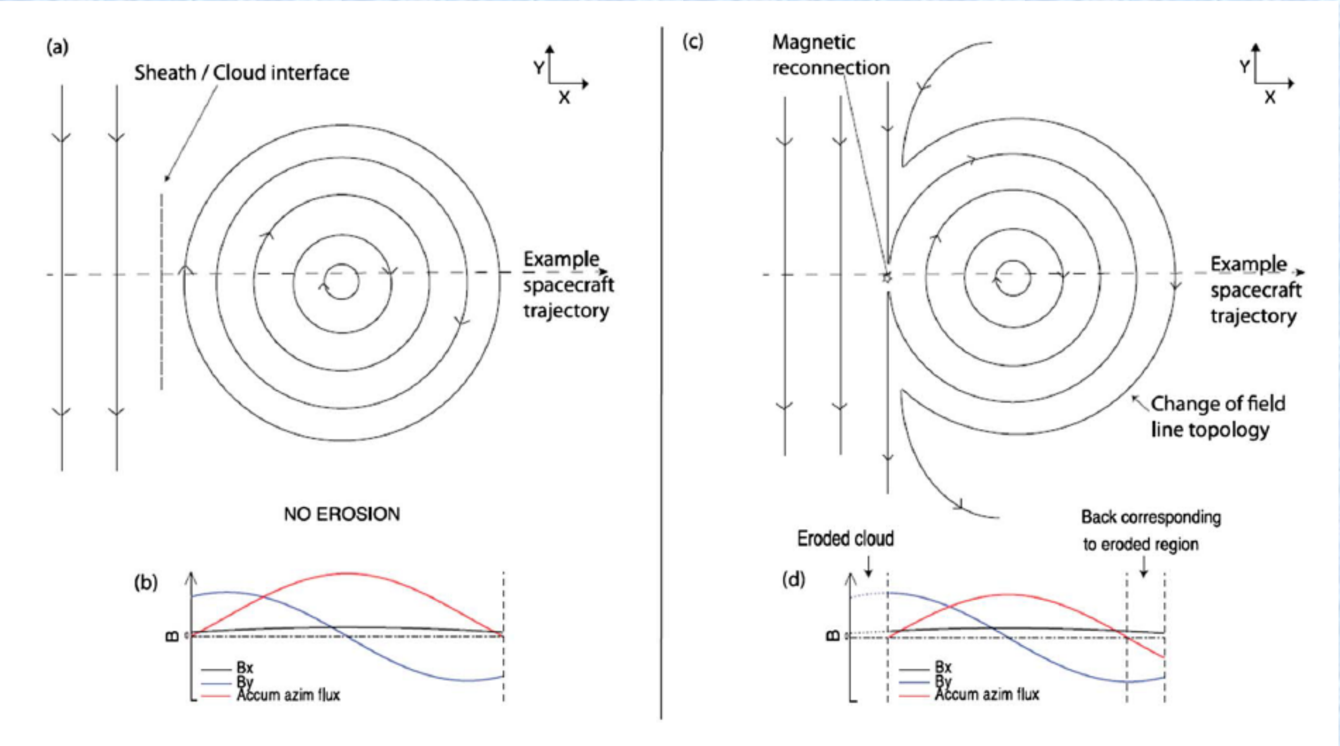
What are the most relevant physical mechanisms in the IP evolution?
(expansion, interaction w ambient, ICME-ICME interaction, erosion, …)
How much affect each one?

We focus now on the main IP aspects of ICMEs-MCs which affect their geoeffectiveness during propagation from Sun to Earth:

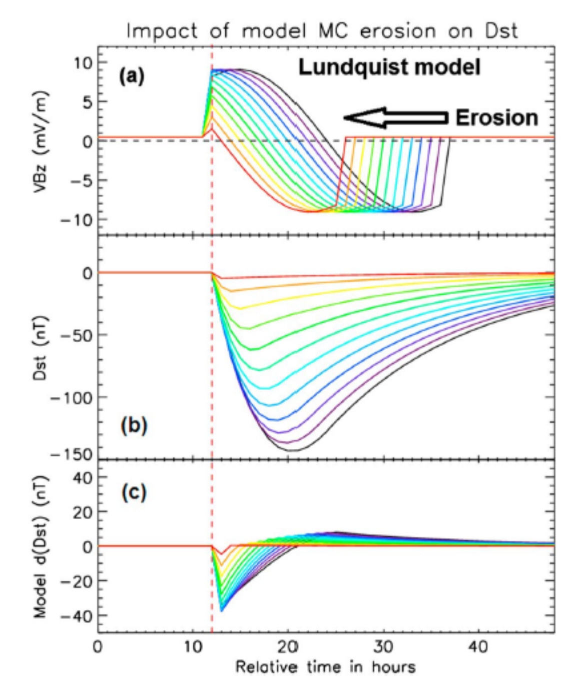
- Erosion
- Expansion
- ICME-ICME interaction

How much erosion from Sun to 1 AU can affect the geoeffectiveness





[Dasso+ 2006,
Lavraud+ 2014
Ruffenach+ 2015]



Numerical estimations for one eroded case provide a reduction of the Dst peak around 30%

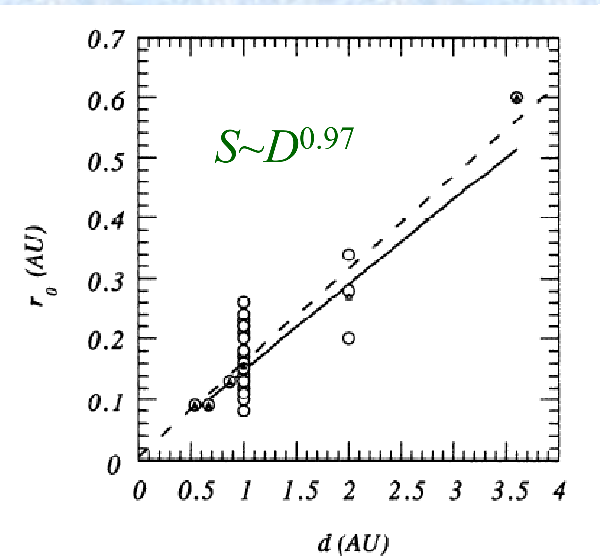
Eroded case 30% weaker than if no erosion had occurred

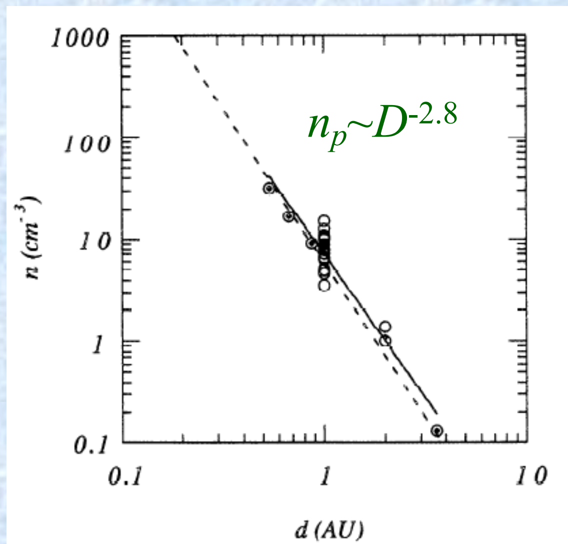
Modeling evolution of MCs from assuming:
(i) conservation of mass, magnetic fluxes
(ii) isotropic self-similar expansion
(iii) $S \sim D$

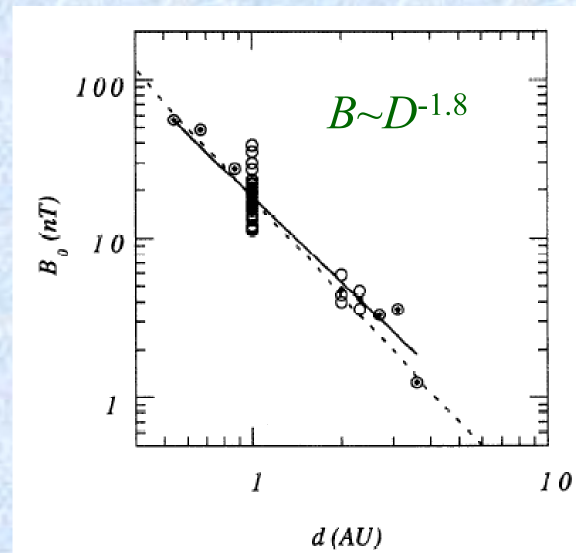
Then: $n_p \sim D^{-3}$ & $B \sim D^{-2}$

Different MCs observed at different solar distances *D* are consistent with these expectations for global expansion

[From Kumar & Rust, JGR 1996]







Large uncertainties (only a few & different observed events)

Other studies provided refined expansion rates

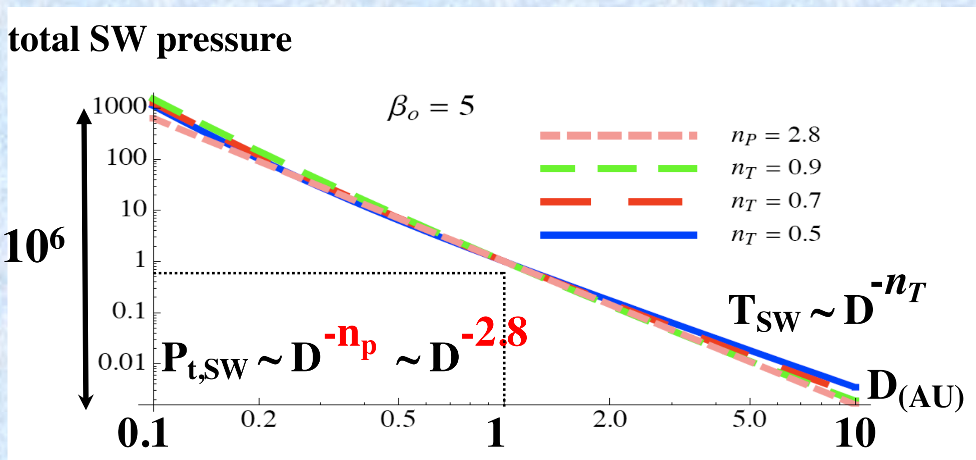
[e.g., Bothmer & Schwenn‘98; Leitner et al.’07; Gulisano et al.’10; Gulisano et al.’12]

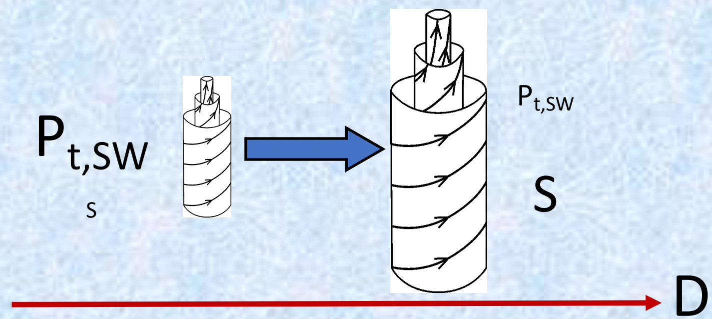
THE SW TOTAL PRESSURE DEFINES THE CROSS-SECTION EXPANSION RATE

Simple estimation of the pressure balance ($\beta_{MC} << 1$):

$$P_{B,MC} \sim P_{t,MC} \sim \underset{\substack{\uparrow \\ \text{few units}}}{c} \; P_{t,SW}$$

$P_{t,SW}$ is the main source of MC size evolution

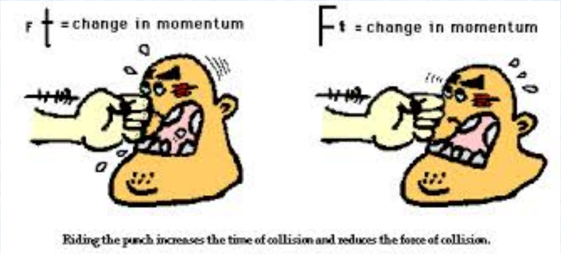




(Démoulin & Dasso 2009)

=> self-similar expansion : $S = S_0 \, D^{n_p/4} \sim S_0 \, D^{0.7}$

Changes on the level of geo-effectiveness associated with ICME-ICME interaction



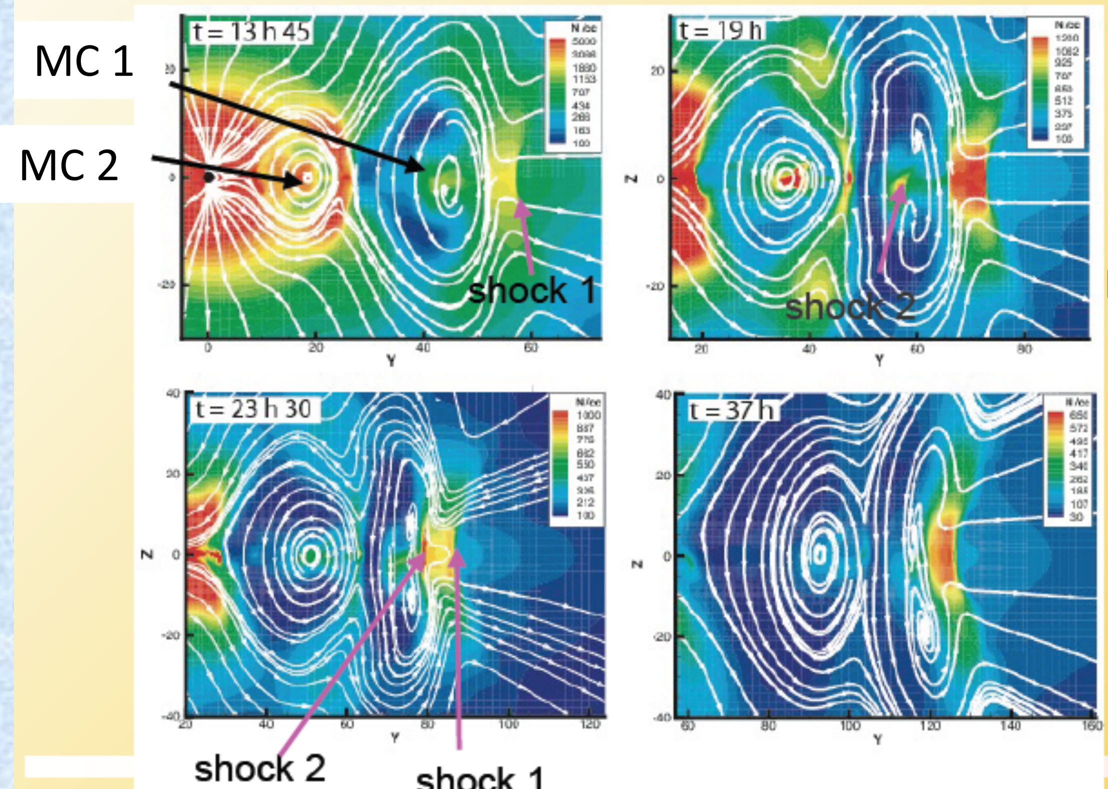
Not only forces at the moment of observations.
Time profile of interaction (story) is very important !!!

- **Arrival**: deflection, changes on speed & size
- **Magnetic structure shape**: Compression/expansion, reconnection, passage of shock through ICME-1, deformation
- **Double kick**: pre-kick to the magnetosphere by the ICME1, and knockout by the ICME2 (2-steps)

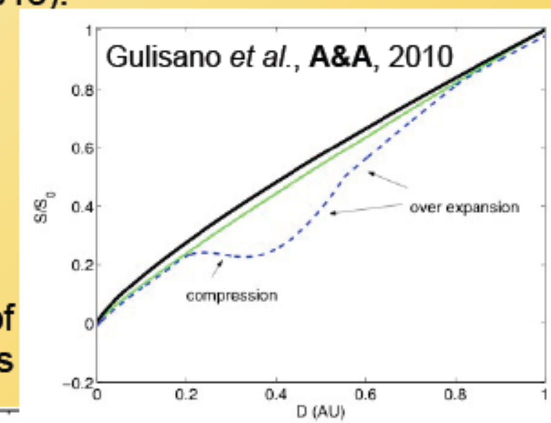
3D MHD simulation

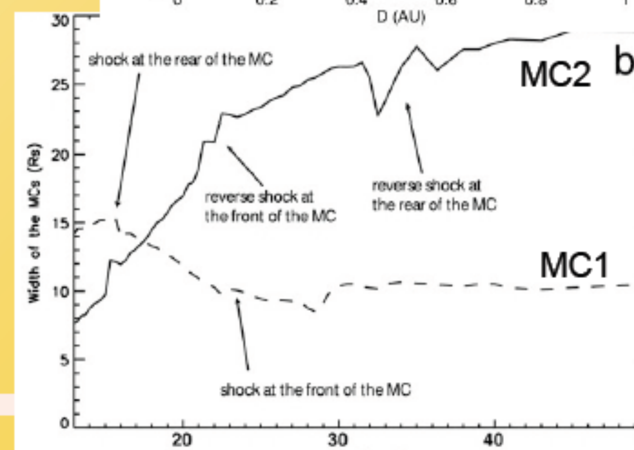
Compression of the first MC

- MC1 is compressed by the 2nd shock and it cannot over-expand due to the presence of MC2 at its back (Lugaz *et al.*, **ApJ**, 2005; Xiong *et al.*, **JGR**, 2006-2009).
- Influence of reconnection and relative orientations (Lugaz et al., 2013).



Radial sizes of the 2 MCs





Cortesy from Noe Lugaz

In general (because ICME-1 is slower) ICME-1 is weaker (good correlation between V,B,R from single events)

Then, ICME-1 is more affected by ICME-2 than the inverse (more similar to a car-truck collision than to a car-car collision)

Interactions between magnetized fluid structures (as ICMEs) are different than interactions between solid objects!

[An example in Dasso+, JGR, 2009]

After the collision, ICME-1 (car ahead truck) can be observed as
smaller and stronger (B) than expected !
[the truck does not permit the typical expected expansion]

Effects of IP conditions on transport of GCRs, on short and large time scales (i.e., Forbush and solar cycle modulation)

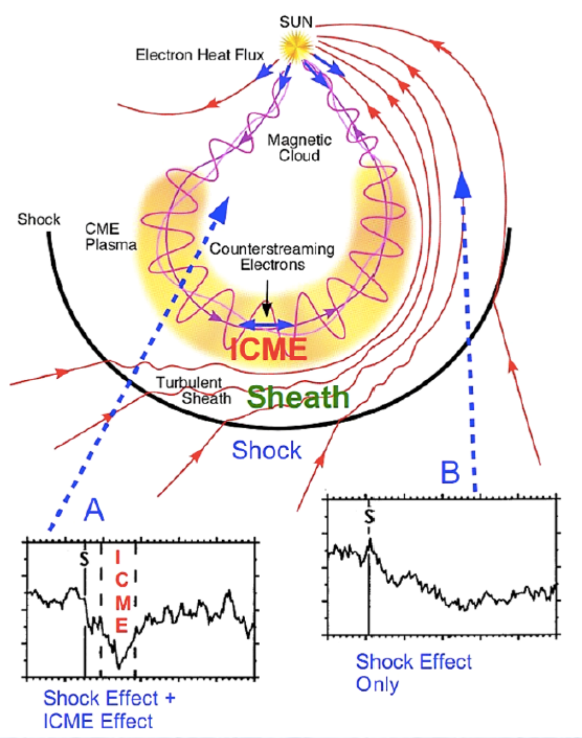
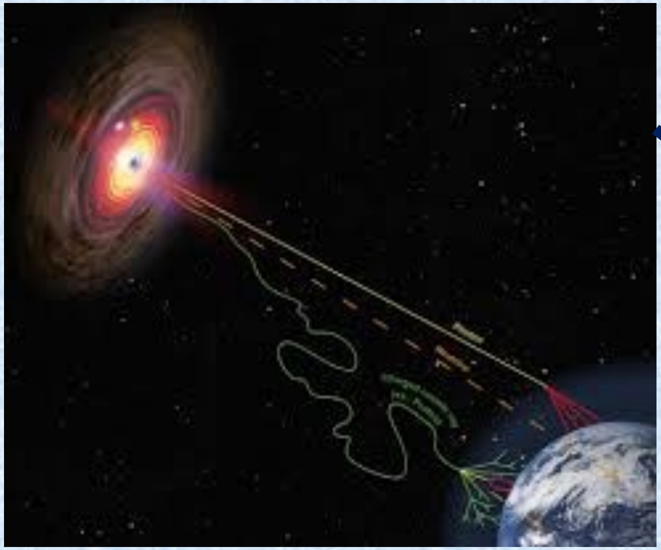
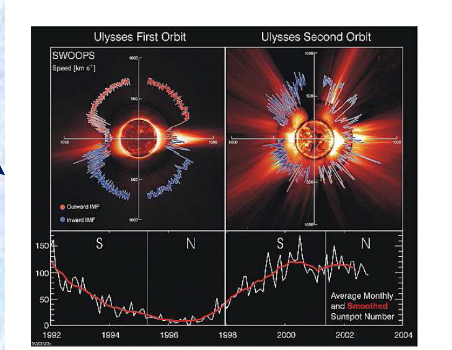
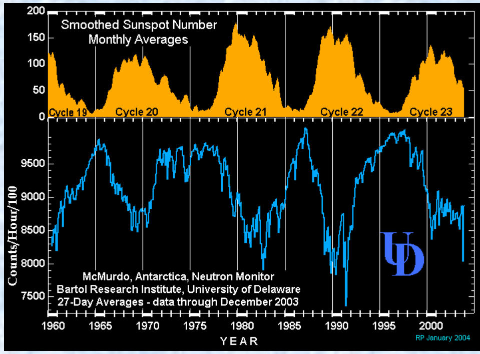


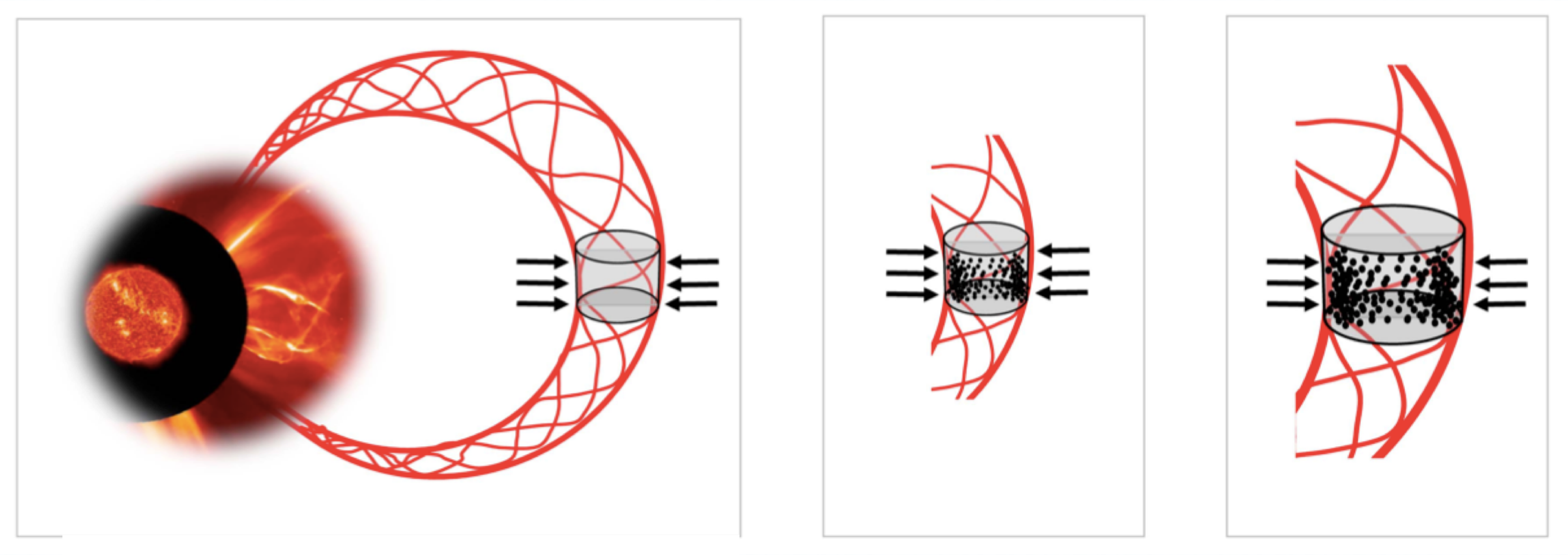
Figure from Richardson & Cane [2011]

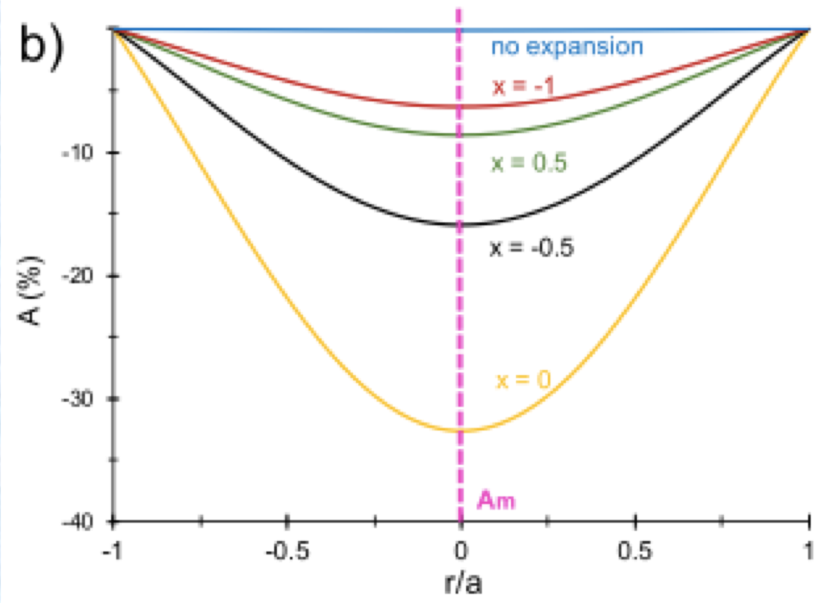




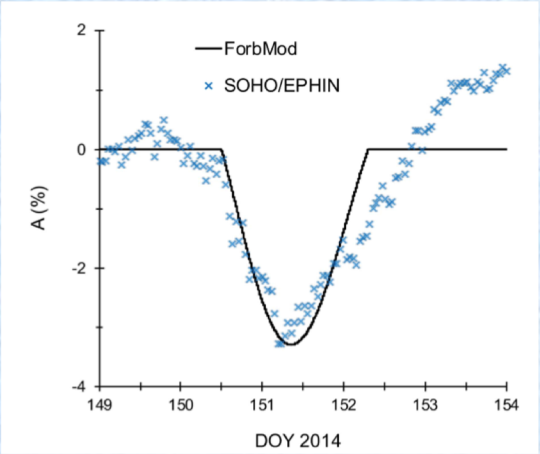


Importance of the expansion effects on Forbush decreases

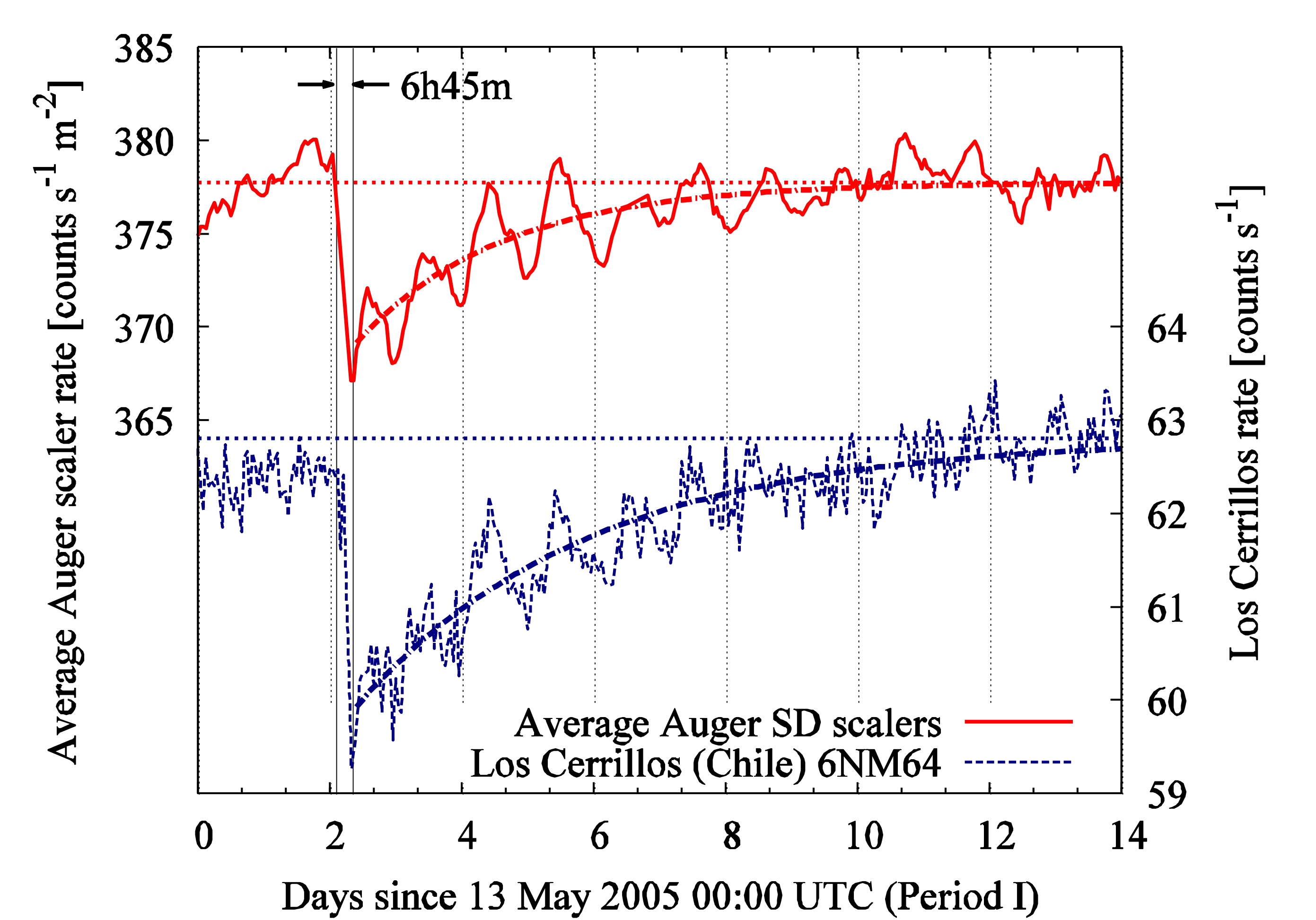




[Dumbovic+, 2018]



- Comparison of a Forbush Decrease observed with a typical Neutron Monitor (NM, blue dashed) and with a Water Cherenkov radiation Detector (WCD, red solid).
- Forbush event: May 15th, 2005, NM is from Los Cerrillos (Chile). WCD is from the Pierre Auger Observatory.
- FD-NM peak was ~ 7% & FD-WCD peak was ~ 3%
- Similar daily variations in the flux are seen at both observatories.
- **WCDs can discriminate different energy channels in secondaries.**



From Pierre Auger Collaboration [Jinst, 2011]

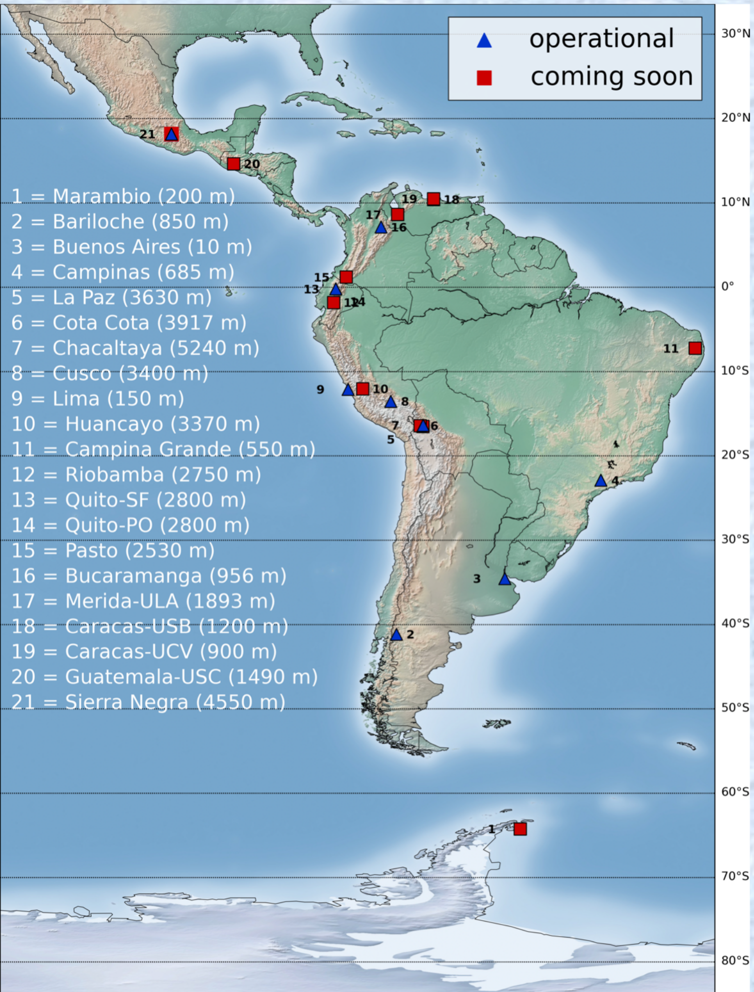
WCDs from the LAGO Collab have also observed FDs [e.g., Asorey+ICRC, 2016]

A LAGO node at Antarctic [Dasso+,ICRC, 2016]

LATIN AMERICAN GIANT OBSERVATORY (LAGO):

WWW.LAGOPROJECT.ORG

A LATIN AMERICAN ASTROPARTICLE NETWORK



Operative LAGO detectors will cover a geographical gap.

And also will provide energy resolution for:
- direct observations for secondary CRs
- modeled primary CRs

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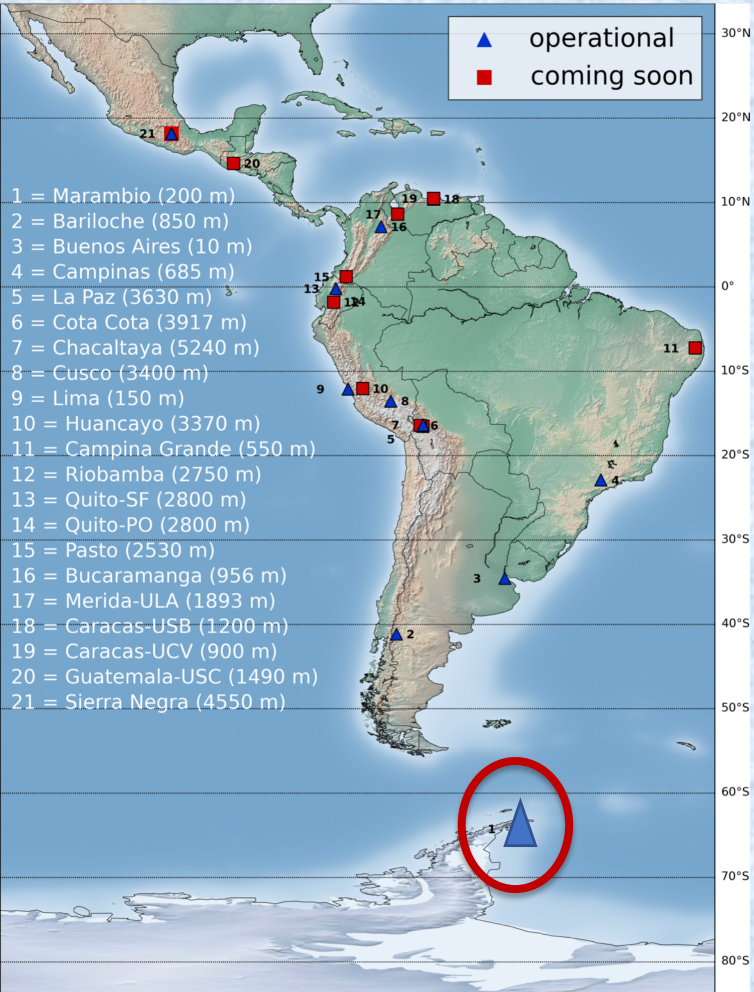

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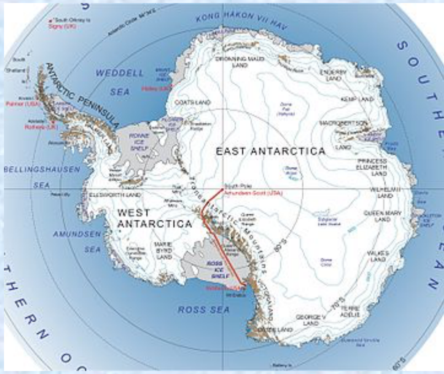
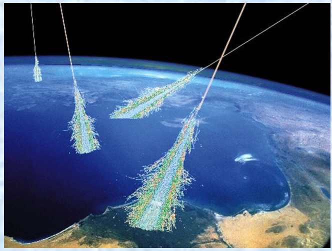
NEWRUS (NEW antarctic cosmic Rays detector to Use in Space weather)

An Space Weather laboratory was recently set up (Jan-March, 2019) in the Argentine Antarctic Marambio base. Different instruments were installed: particle detector (NEWRUS), meteorological station, magnetometer, etc. NEWRUS forms part of a LAGO node (Water Cherenkov detector).
[More details in the poster session]





Comparison of Newrus during its first month of observations at Antarctic

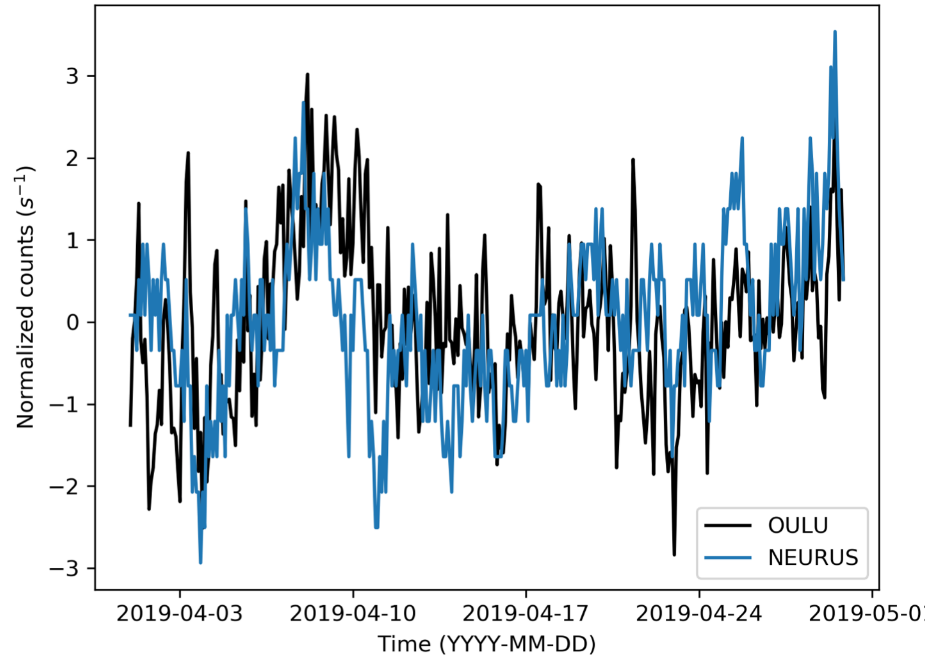
OULU	65.05587, 25.46792
APTY	67.5704, 33.3935
NEURUS	-64.23934, -56.62491

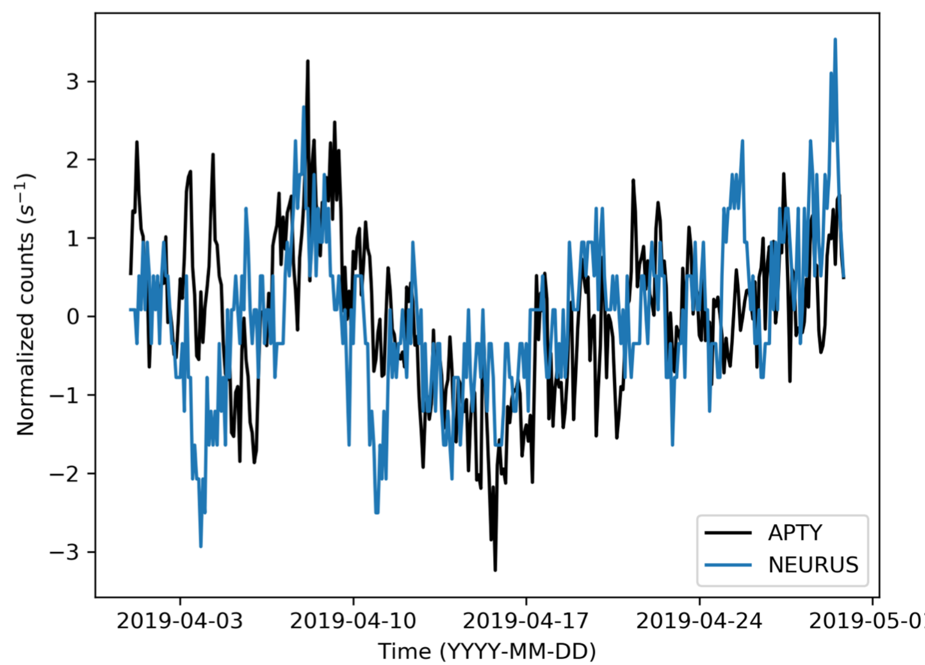
Rc_{OULU} ~ 1 GV

Rc_{APTY} ~ 1 GV

Rc_{Neurus} ~ 2 GV

Data will be publicly available in internet for science and operative aims





Identified main gaps on CIRs and ICMEs (1)

- **HSS**: Improve high speed streams prediction from coronal hole observations.Even more important now considering weakening overall solar activity. Importance for radiation belts (linked w/ RB losses via precipitation to the atmospheric effects).
- **Relevant instability for eruption**: empirical parameter to determine the eruption.
- **Injected FR**: Improve prediction of Flux Rope orientation and intensity from solar observations of arcade (combined with another obs, such as reconnected flux). For instance to improve the input of FRs in models.
- **Arrival time:** Improve the uncertainty on forecast ICME arrival time.
- **Bz**: To determine the magnetic configuration of Flux Ropes inside ICMEs and their global shape (global axis and shock surface). To improve techniques to determine the FR orientation from in-situ observations. Use of multi-S/C and models.
- **Ambient solar wind**: To determine solar wind conditions where transients are propagating (essential to predict ICME evolution). To improve observations from multi-S/C, for instance at L4/L5.
- **Heliospheric Models**: To improve them from adapting relevant physical processes using numerical patches. To implement data-assimilation (e.g. from radio observations: scintillation, radio type, heliospheric imagers) & S/C.

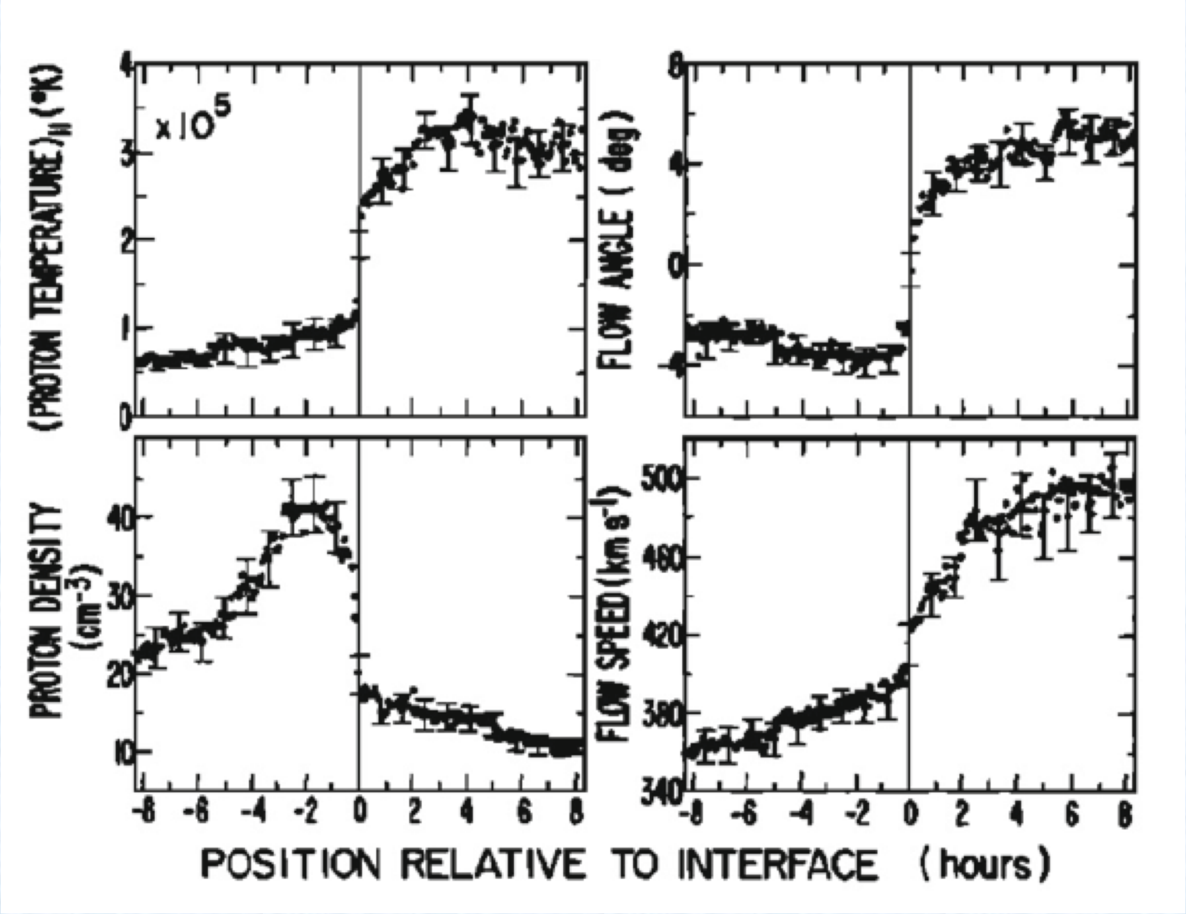
Identified main gaps on CIRs and ICMEs (2)

- **Reconnection**: Comparison of reconnection processes in solar wind and magnetosphere (e.g., using MSS).
- **Impact:** sub-structures of CIRs/ICMEs Are ICMEs bi-modal (fast/slow)? To quantify the relative importance of different physical mechanisms (e.g., erosion, expansion, deviation, drag, expansion) occurring in the interaction with ambient solar wind during the travel of ICMEs from the Sun to 1 AU. Also when CME-CME interaction is present.
- **Forbush decrease**: To quantify GCRs shielding due to ICMEs and CIRs. To improve physical understanding and instruments for GCRs observations at different energies.
- **How to balance correctly between different drivers of space weather** (SIRs, HSSs, CMEs, flares, direct interactions and energetic particle acceleration)?
- **Future mission potential** (Solar Orbiter, Parker Solar Probe).

Many Thanks for your attention !!!

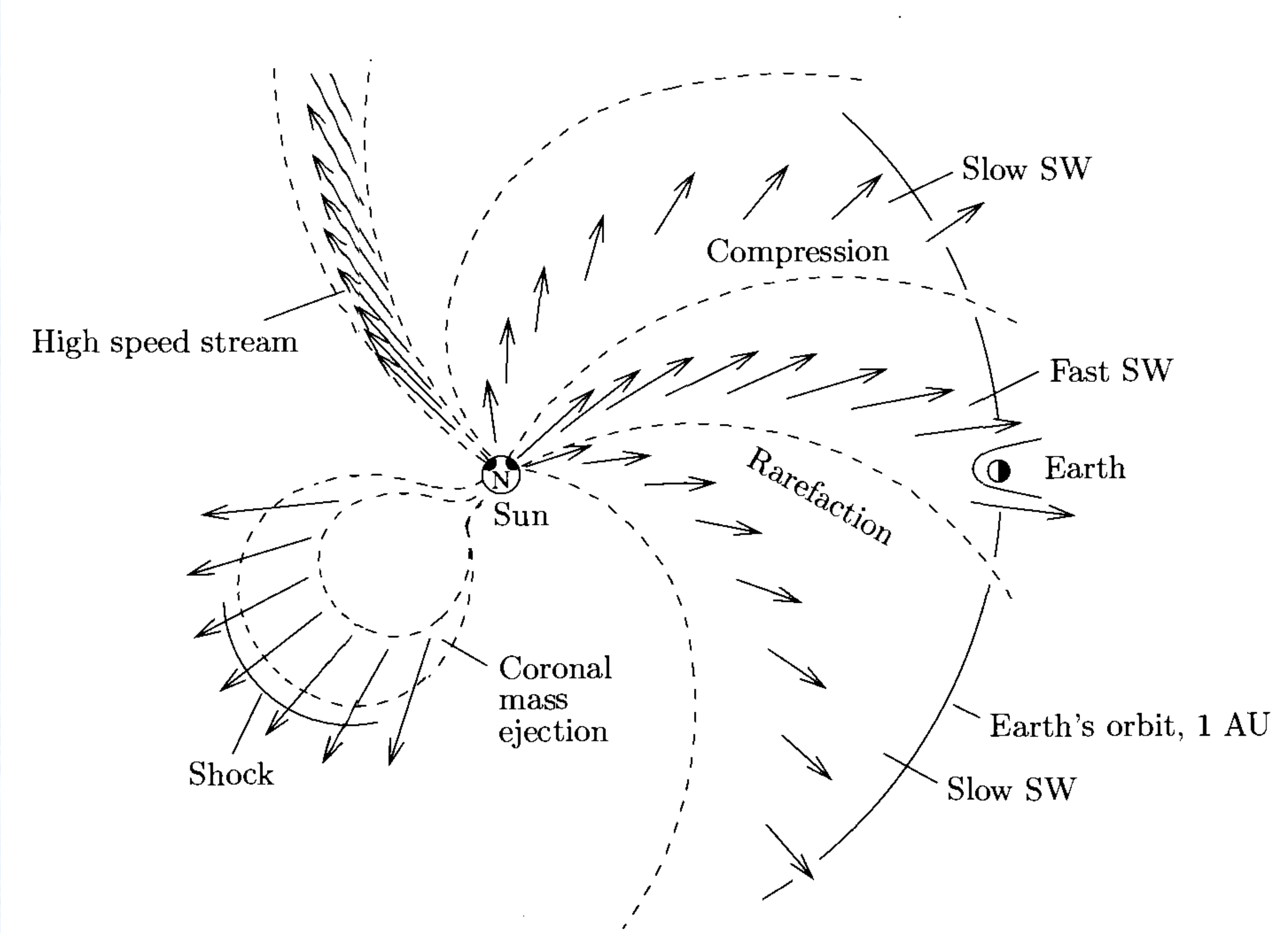
End

Superposed epoch analysis of CIRs

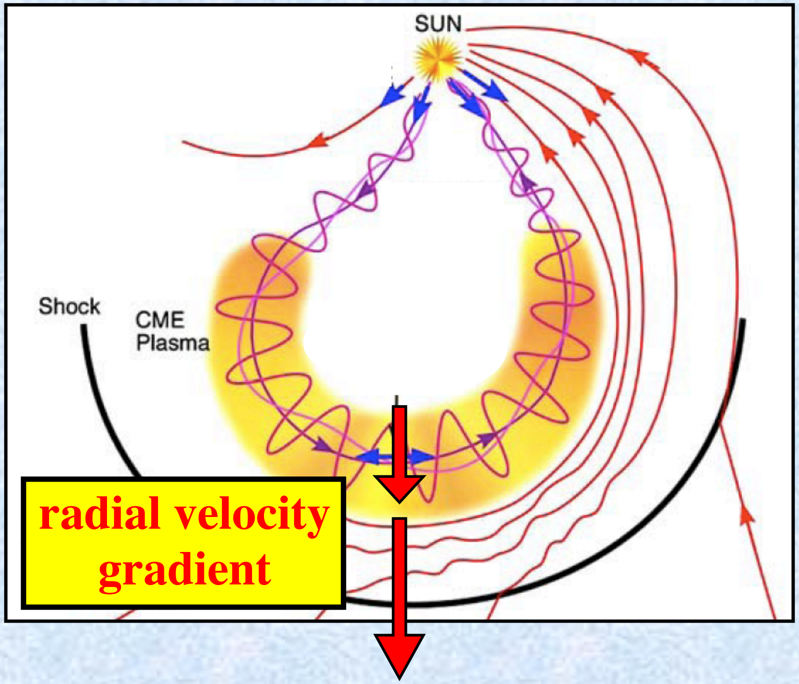


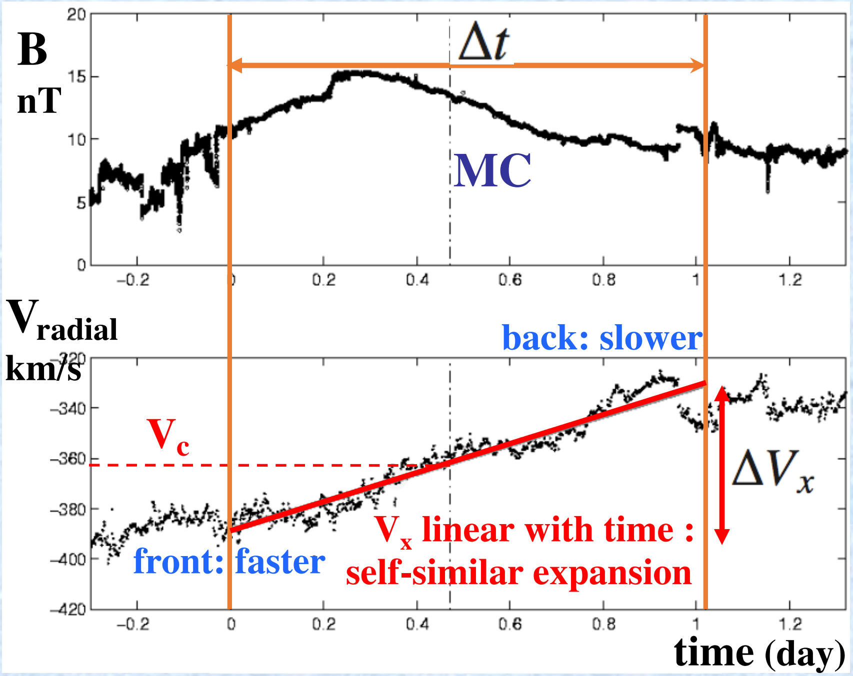
- 23 events
- Taking the interface as the common reference
- Figure from review of Richardson [2018]

Large-scale heliospheric structures driving Sun-Earth coupling



Expansion rate from local velocity profile





observed in situ in each ICME

Non dimensional expansion rate :

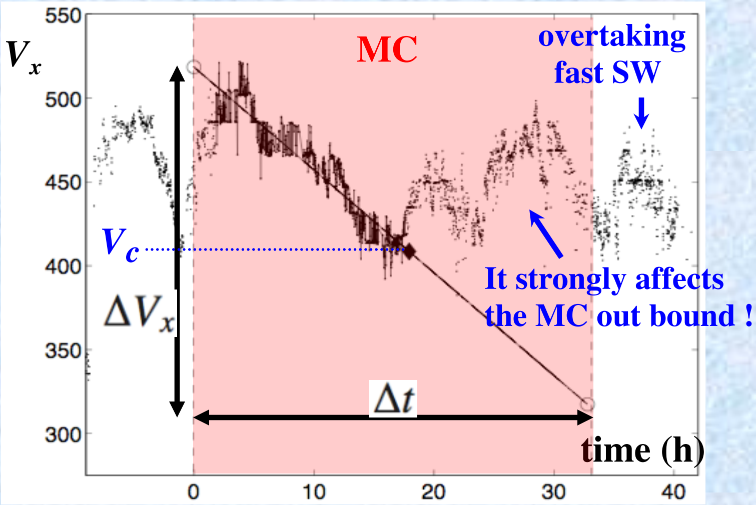
$$\boxed{\zeta = \frac{\Delta V_x}{\Delta t} \frac{D}{V_c^2}}$$

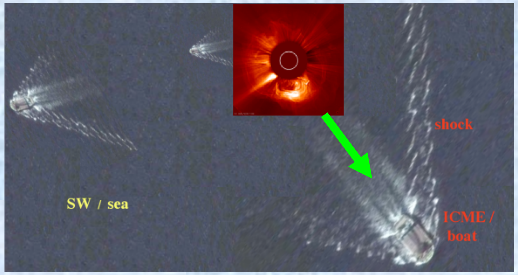
(Démoulin et al. 2008
Gulisano et al. 2010)

If $\mathrm{d}S/\mathrm{d}t = \Delta V$
(local ~ global)

$$\boxed{S(D) = S_0 (D/D_0)^{\zeta}}$$

MC overtaken by a fast SW stream

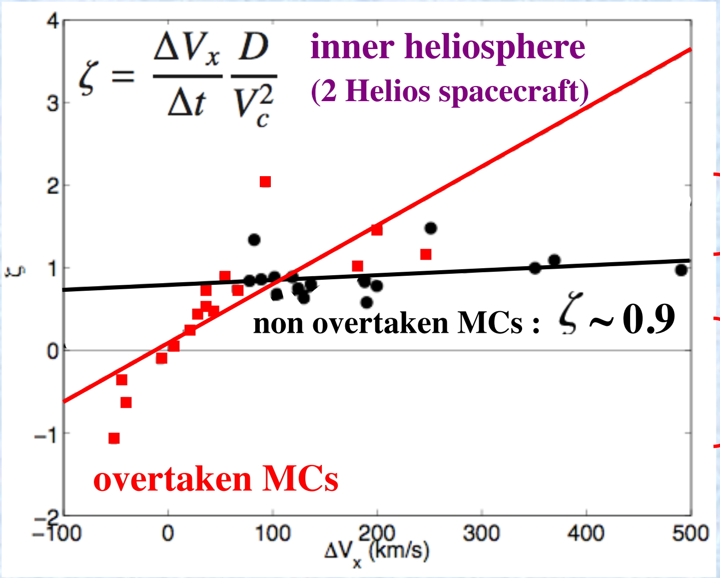


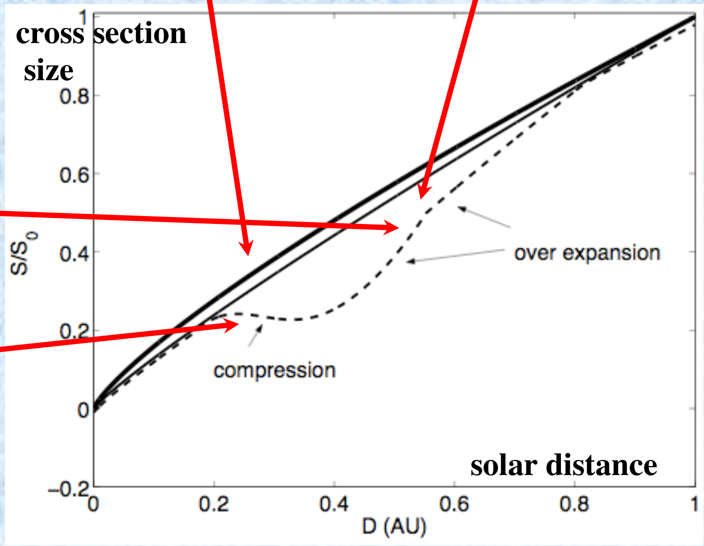


Interpretation :

temporal evolution of the interaction

beginning	later on
compression	**over expansion**
	(because over pressure / SW)





(Gulisano et al. 2010)

Forbush decrease

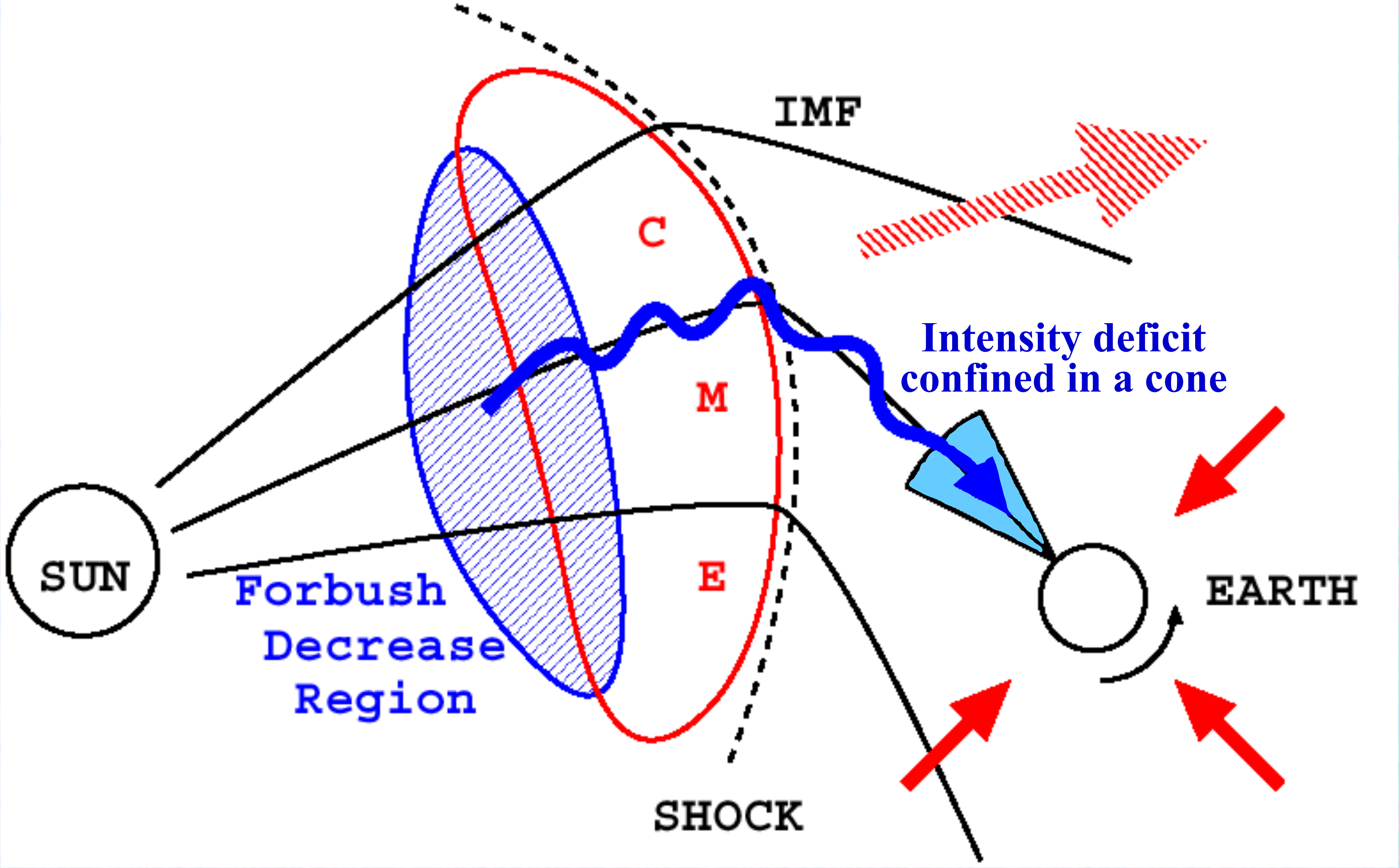


Figure credit: K. Munakata