Coherent and large scale structures in the solar wind, their associated driven shocks, and effects on galactic cosmic rays

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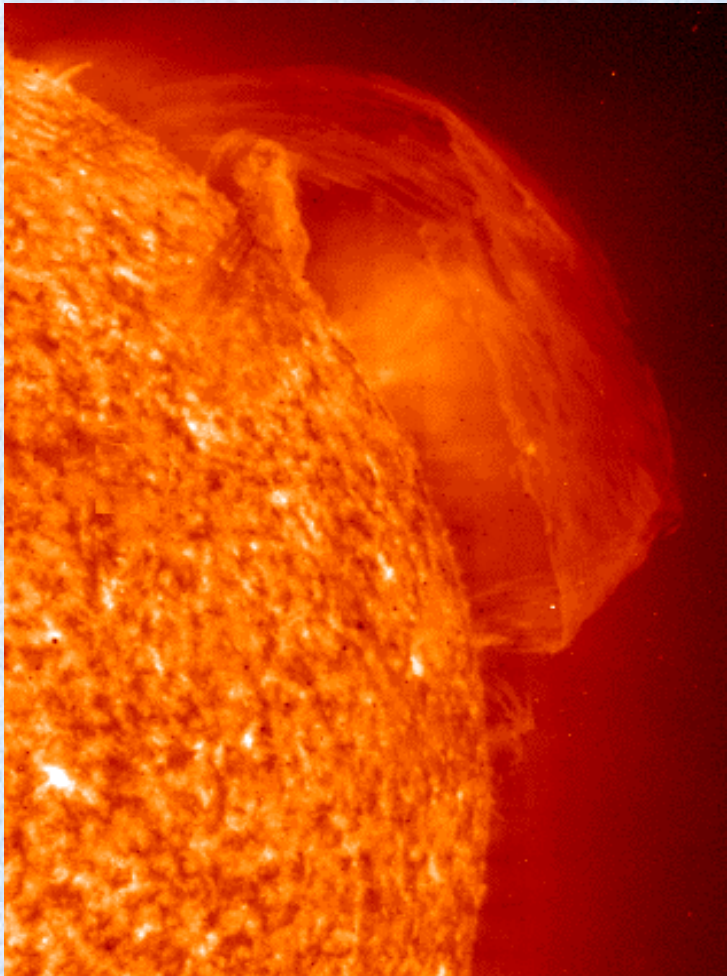

Road Map

- The stationary and the transient heliosphere
- Interplanetary Coronal Mass Ejections (ICMEs)
- In situ observations of ICMEs and Helicity H
- Global 3D structure of ICMEs and global H
- Shocks and transport of galactic cosmic rays
- Auger and LAGO: Space Weather programs
- Summary and Conclusions

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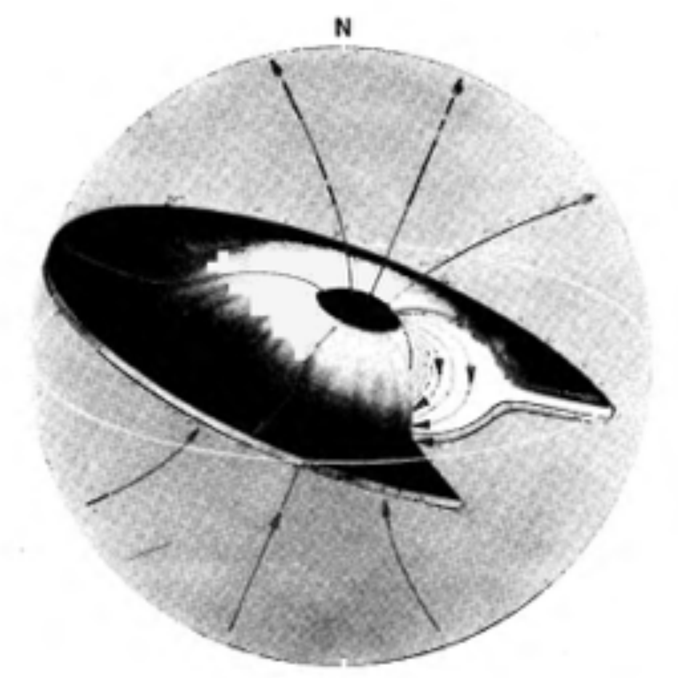
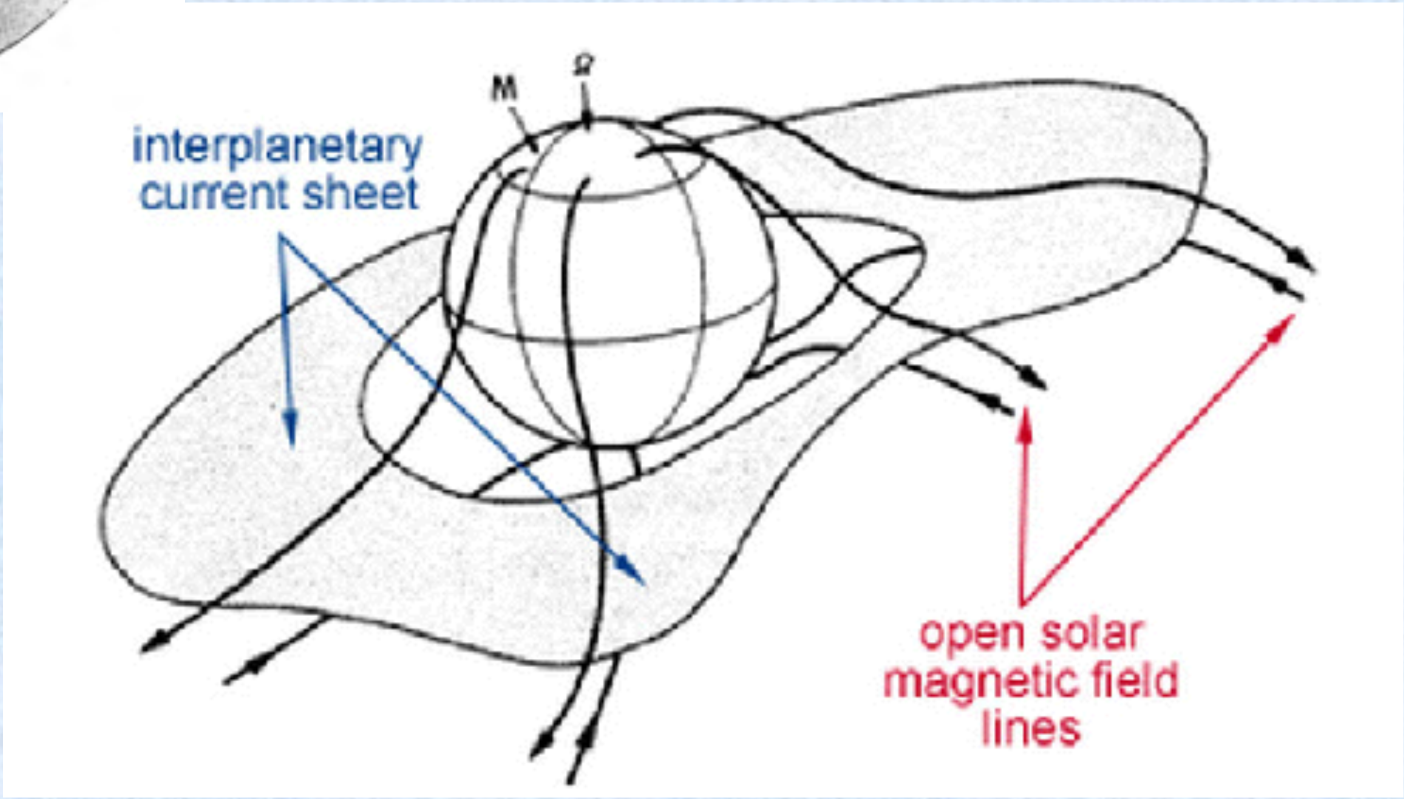
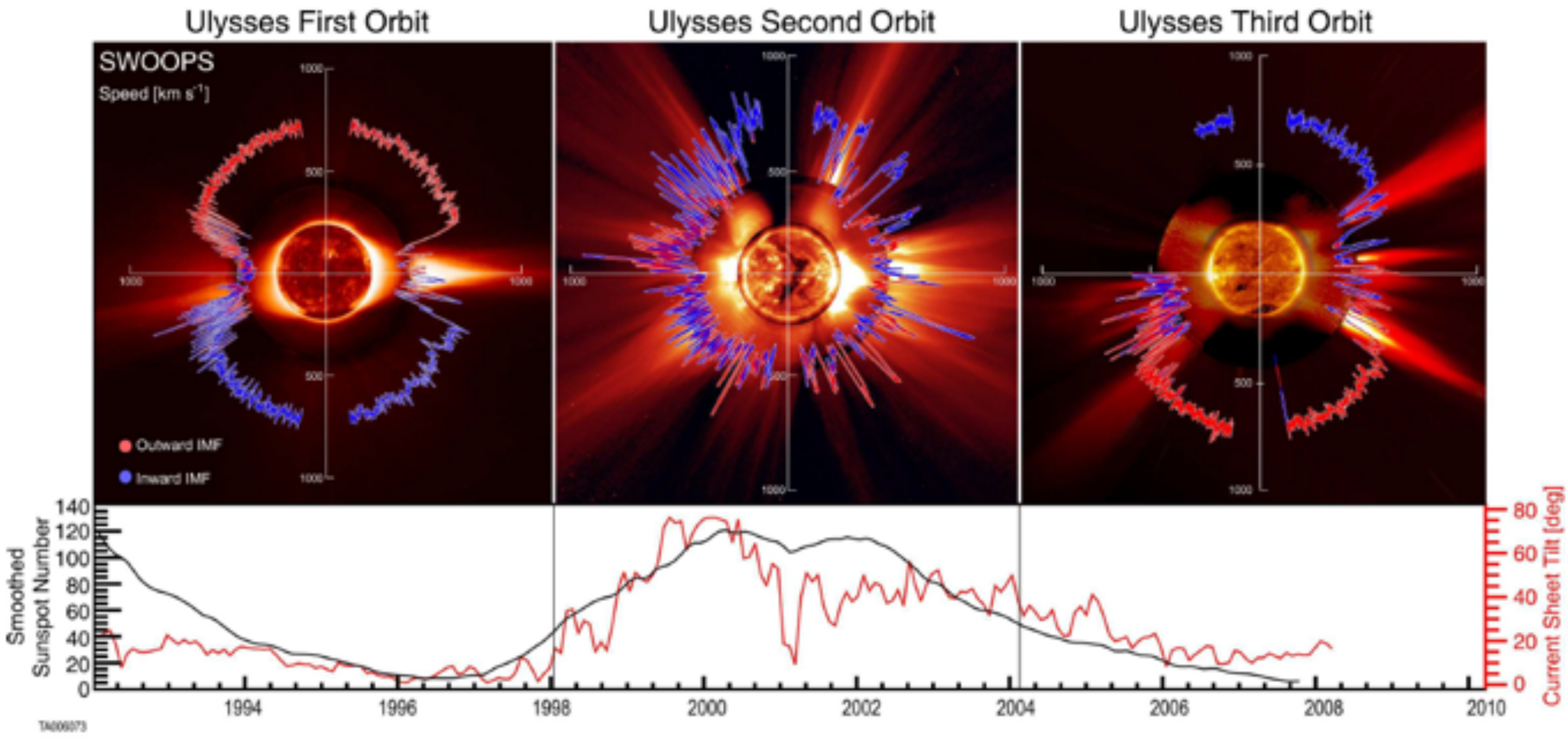


Distorted (advected) dipolar configuration
The Sun rotates and there is a tilt between magnetic dipole and rotation axis

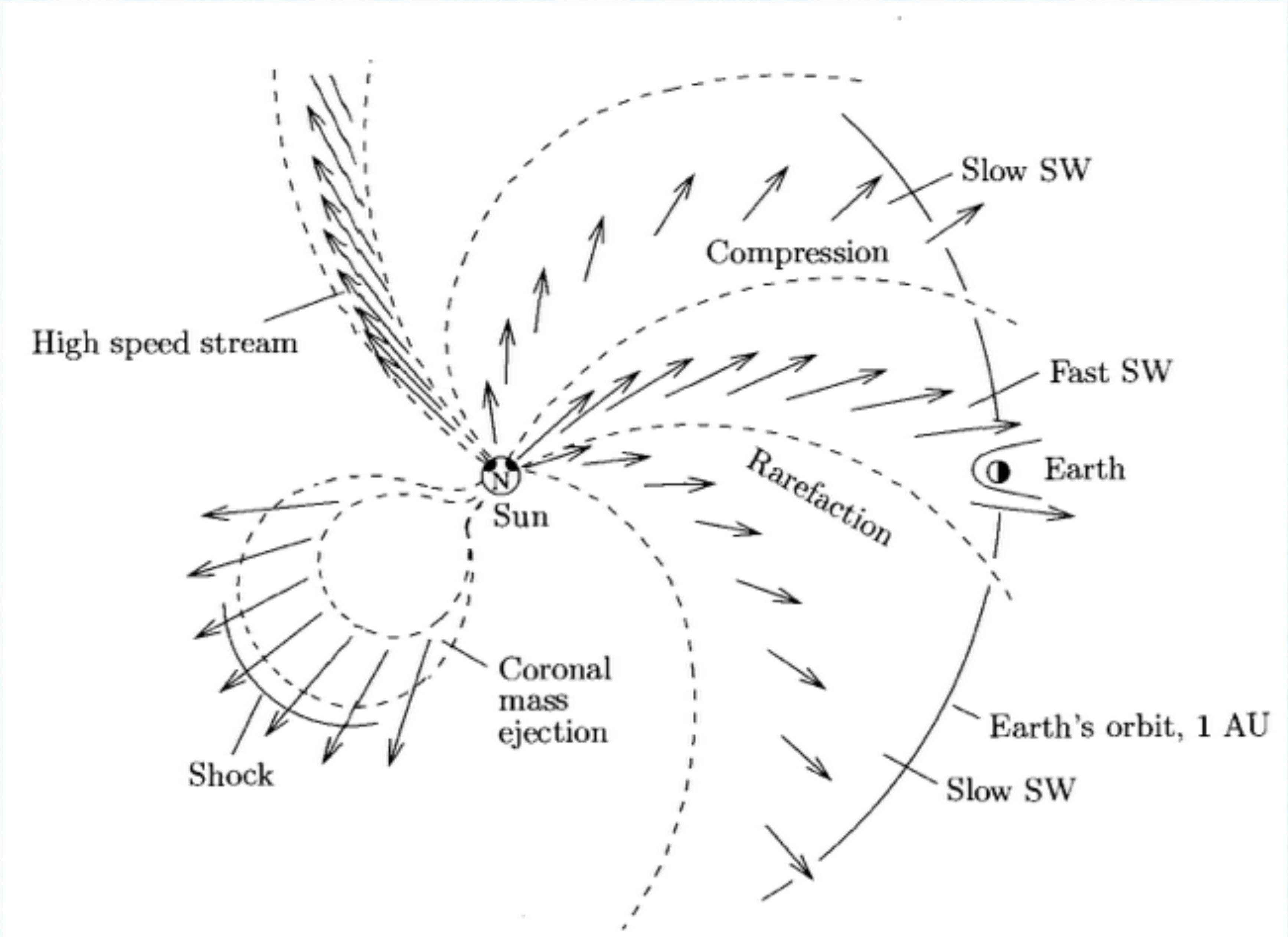


The Solar Wind along the solar cycle



From Gosling, 2010

http://wso.stanford.edu/



Slow SW
Compression
High speed stream
Fast SW
Earth
Rarefaction
N
Sun
Coronal
mass
ejection
Earth's orbit, 1 AU
Shock
Slow SW

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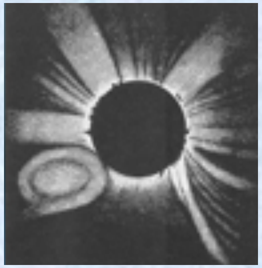
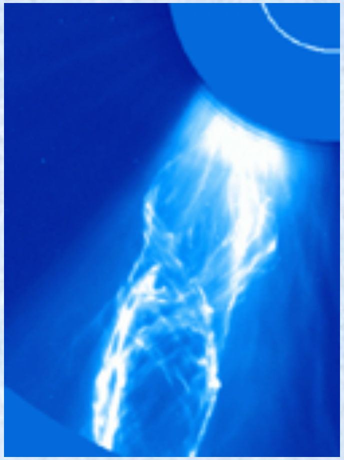
Ejective transient structures: Coronal Mass Ejections

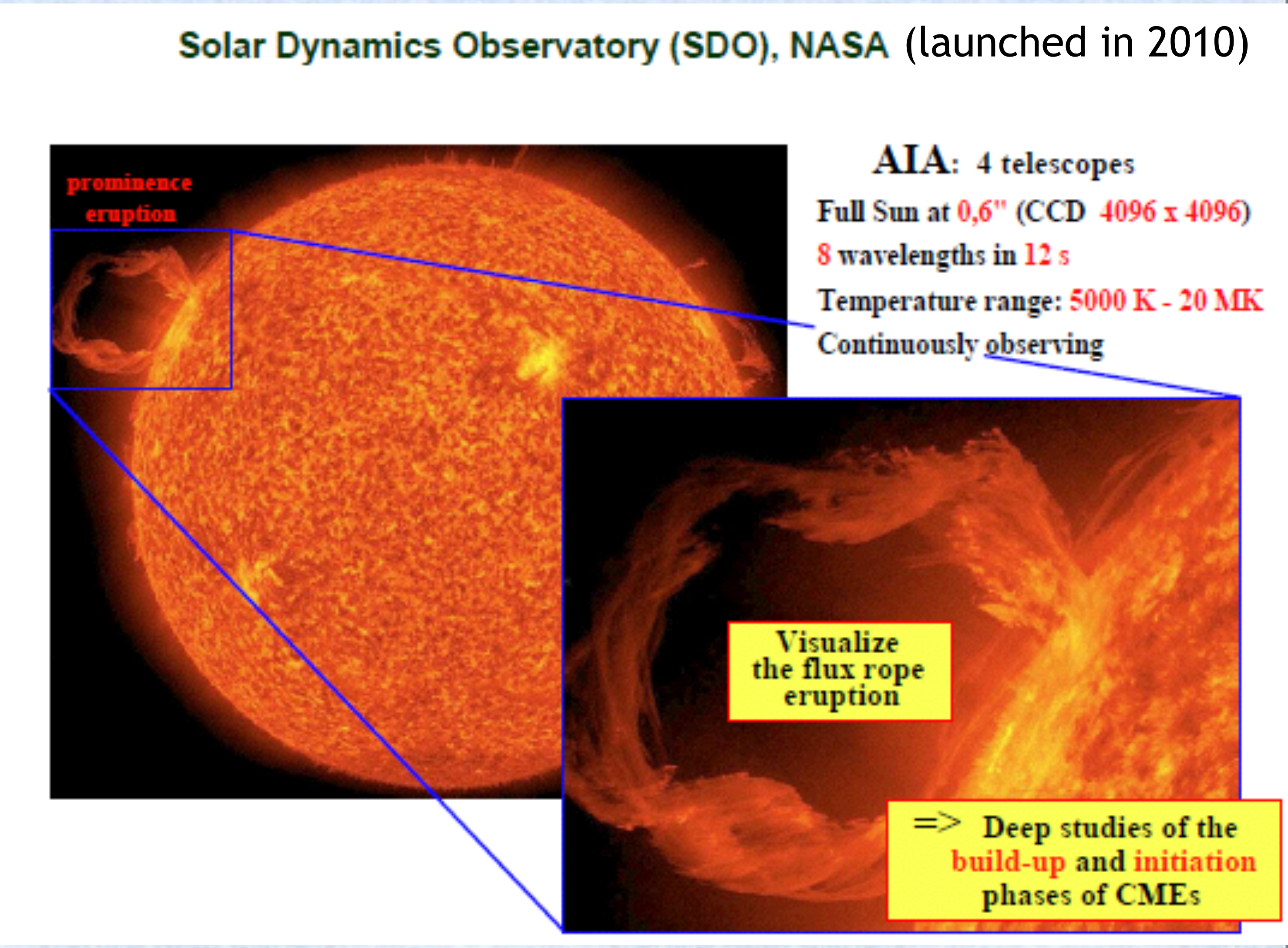


Drawing 1860

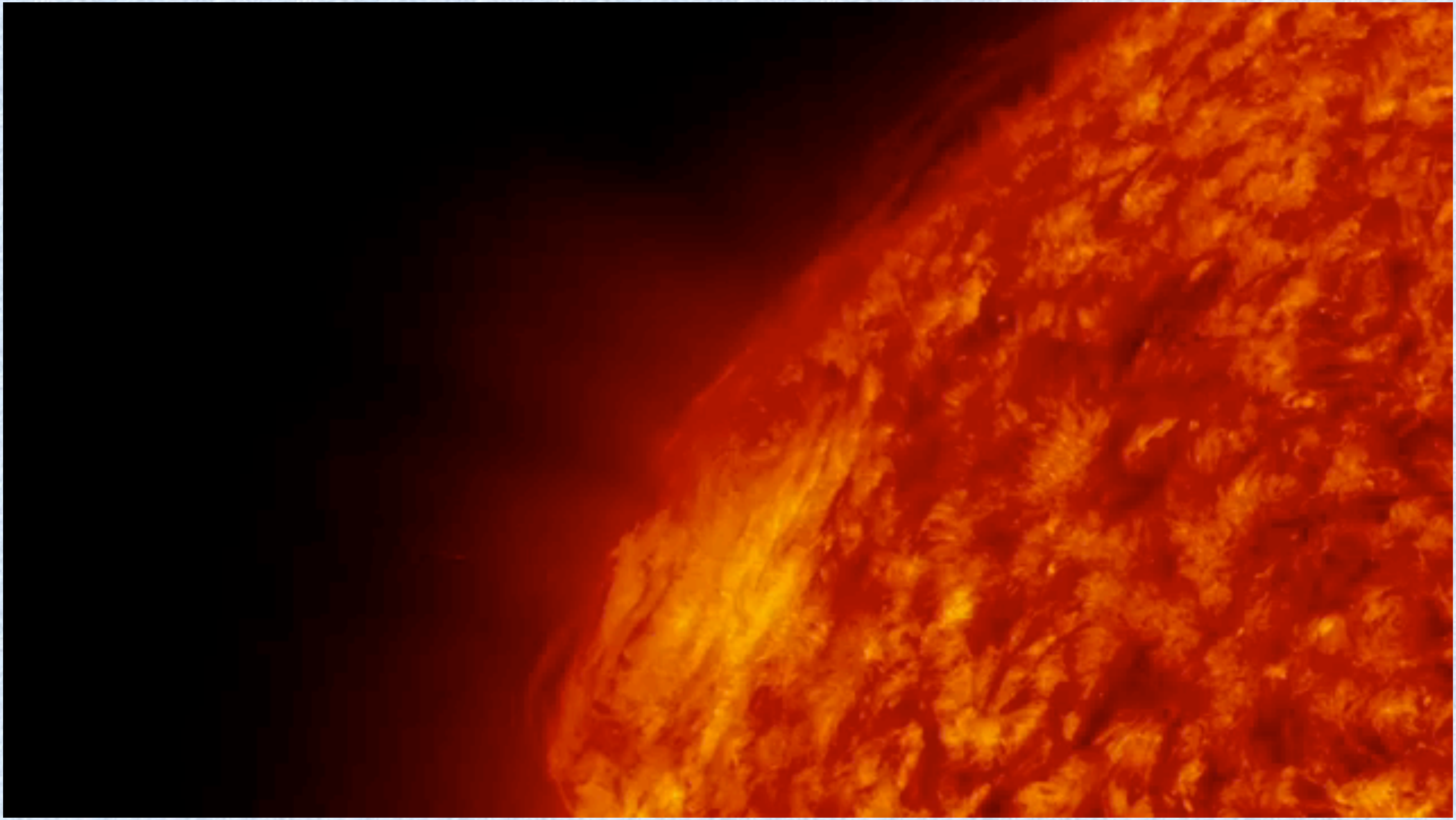


LASCO-SOHO

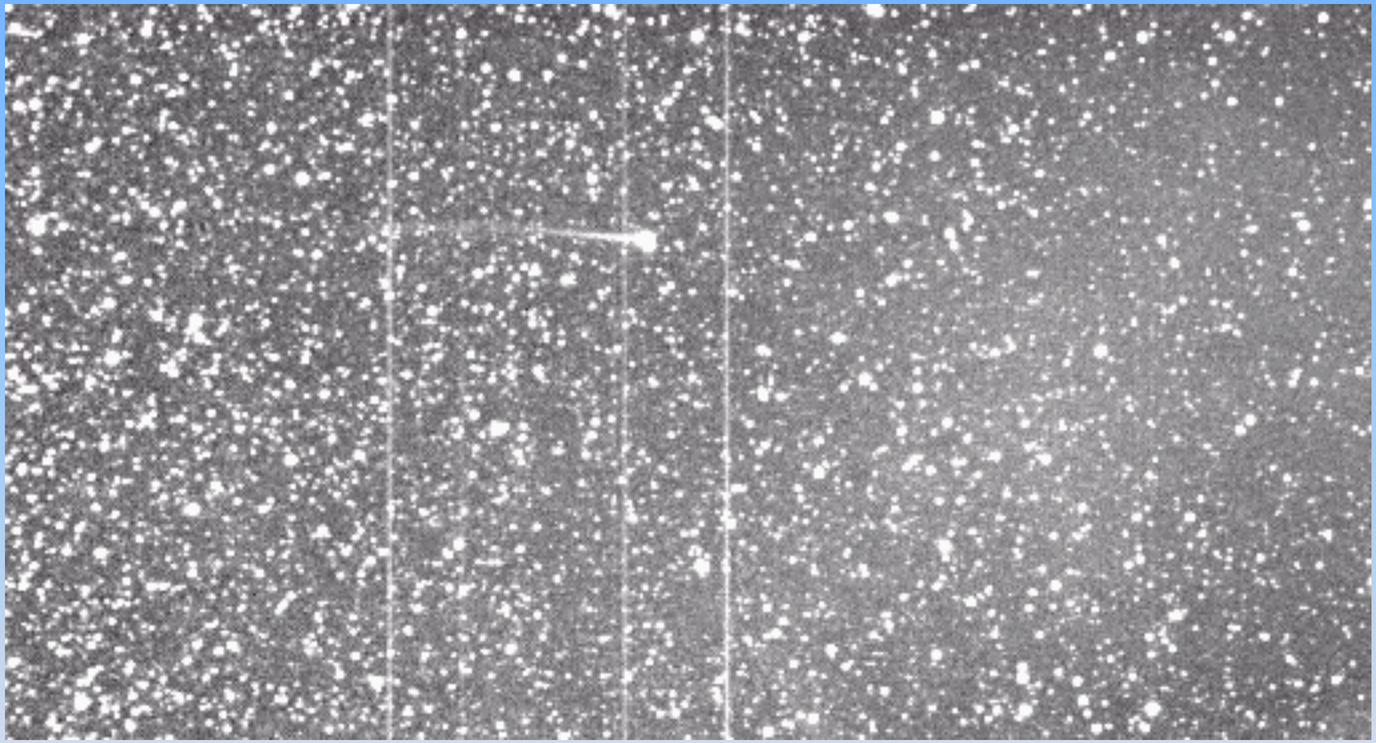
(2000)



Remote Observations

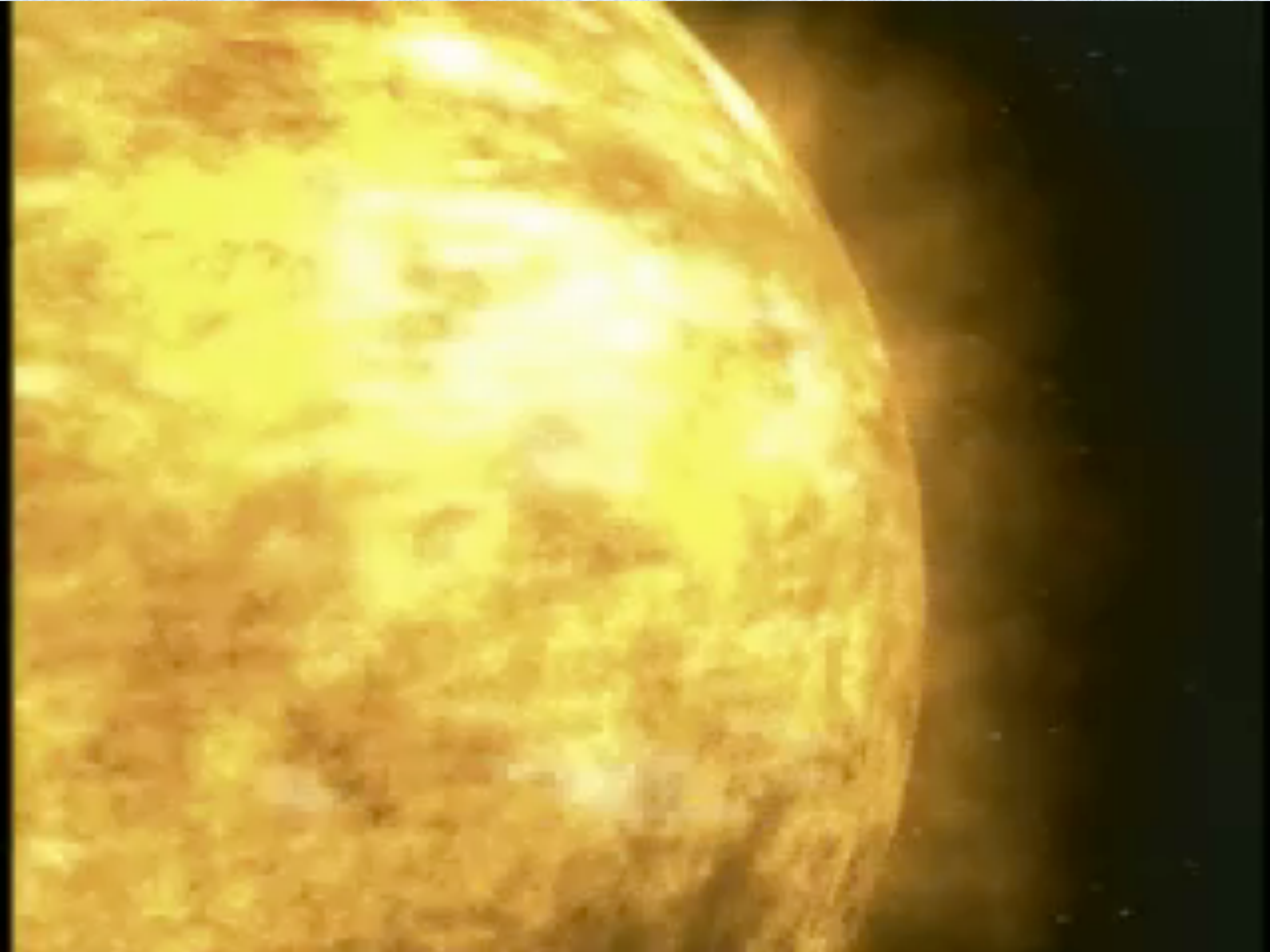


Effect of ICMEs on comets

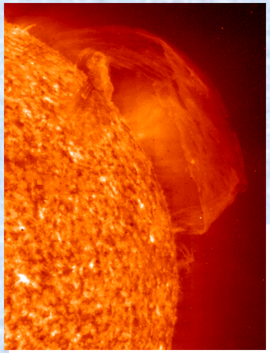


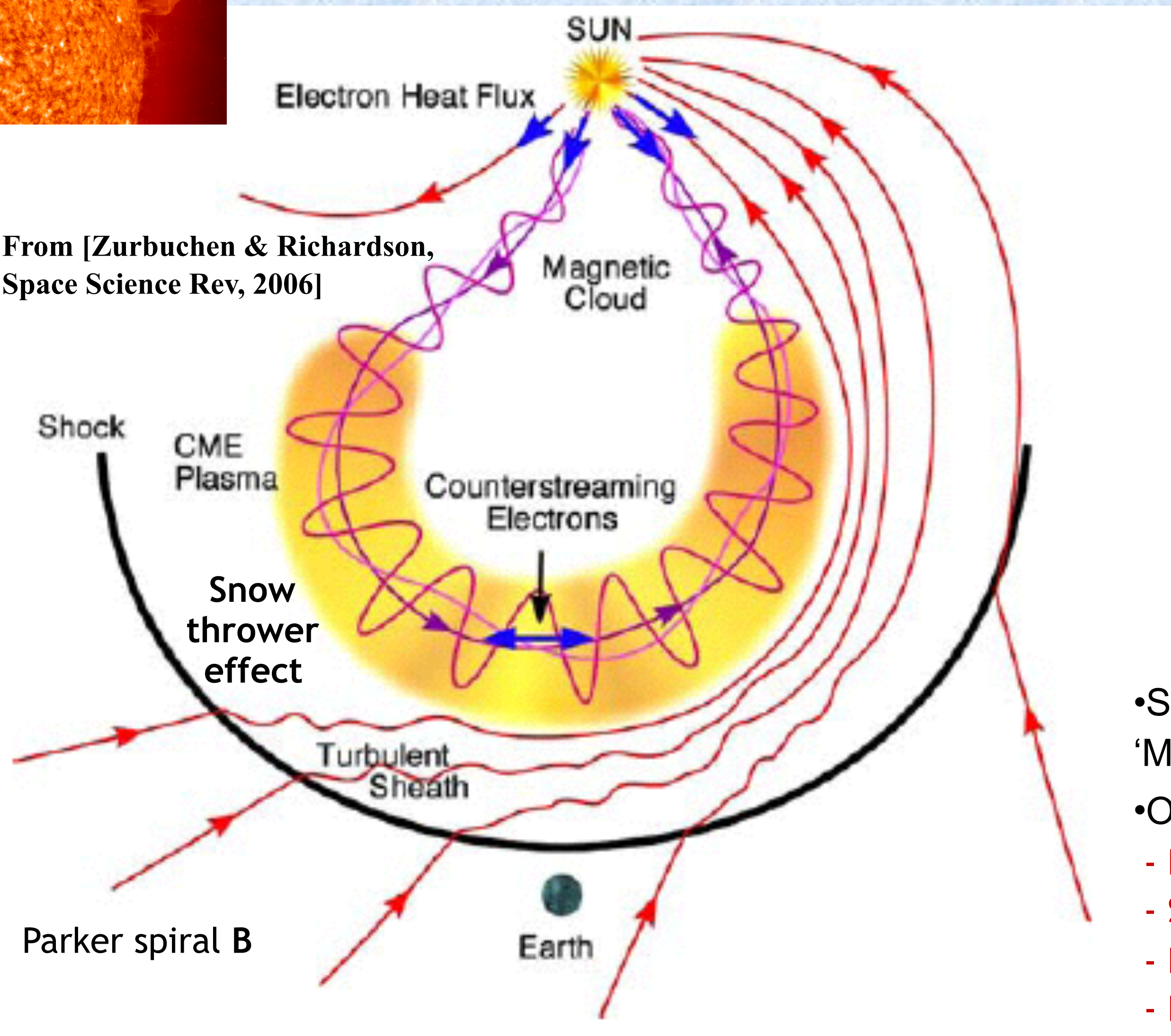
April 20, 2007: An ICME strikes Comet Encke (near Mercury’s orbit)

From NASA's STEREO-A probe



ICMEs and MCs





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

- Strong change of IP plasma and magnetic field (intensity and topology)
- Smooth and large coherent rotation of **B** (helical structures), B increased respect to the SW
- Low plasma beta (β_p) $\Rightarrow$ **Fmag**
- Shock waves driven by fast MCs (presence of turbulent sheath)
- Cold structures (Tp lower than SW at same speed)
- e^-s flows along **B** (>100eVs): proxy of magnetic connectivity

- Subset of ICMEs observed as 'Magnetic Clouds' (MCs) in the SW
- Observed properties at 1AU:
  - Low Tp
  - Smooth and large rotation of **B**
  - Large intensity of **B**
  - Low proton plasma β_p

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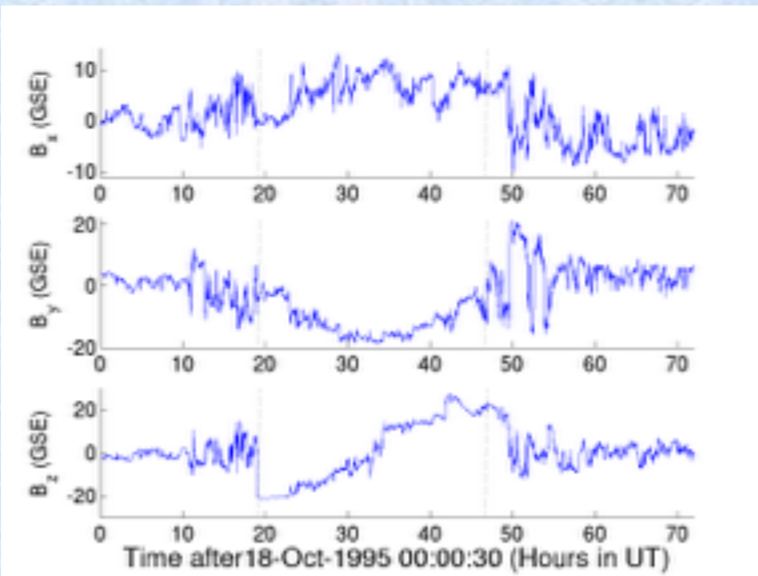
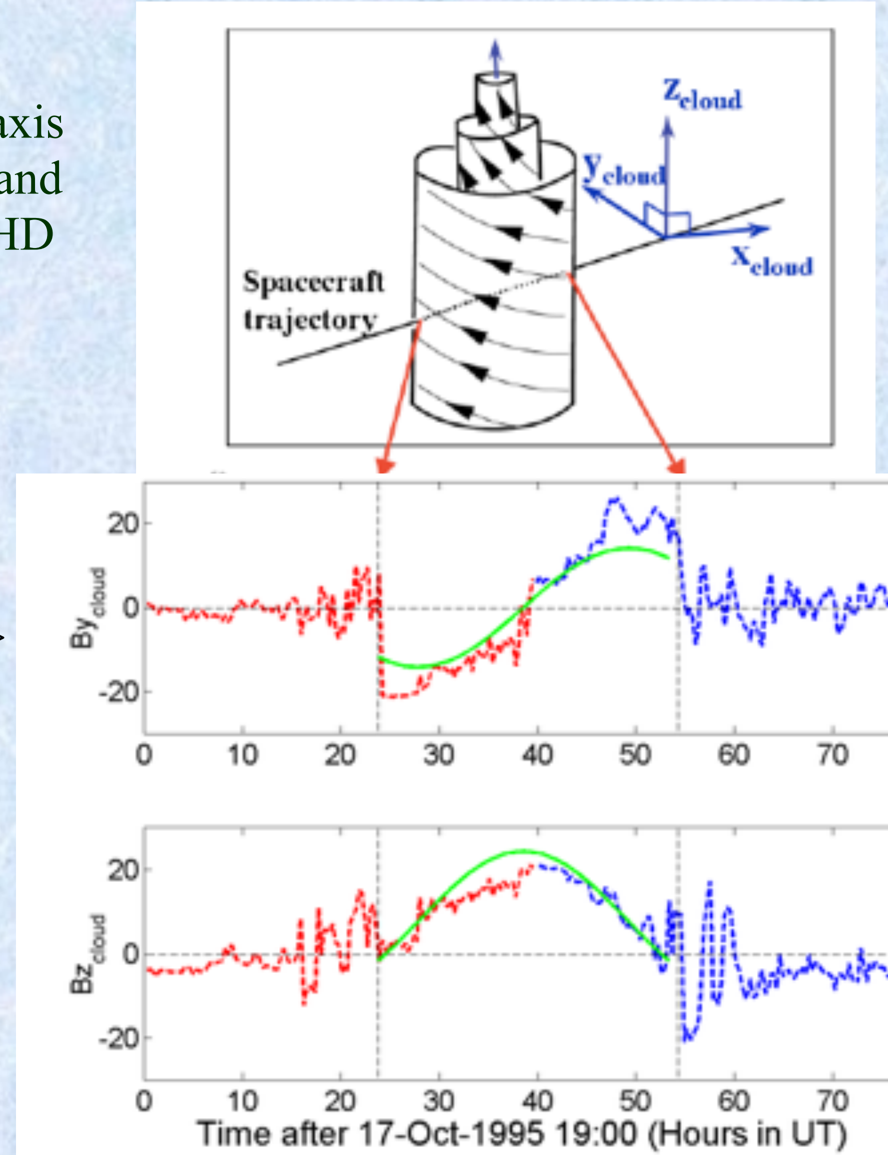
Modeling magnetic clouds

From *in situ* observed **B** → possible to 'orient' the local axis of the flux rope, to model it, and to compute the content of MHD invariants



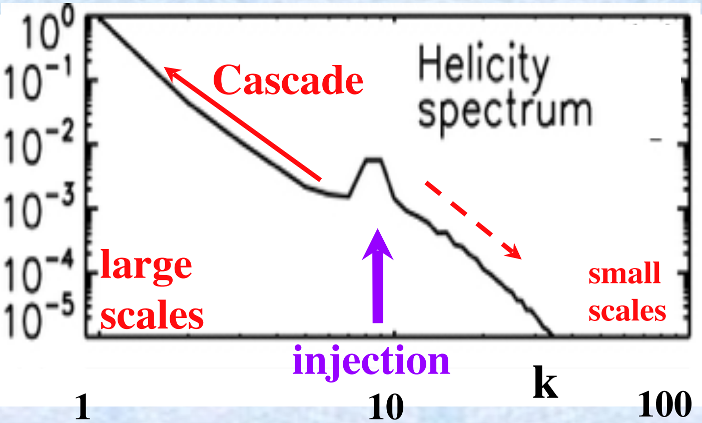


$$\mathbf{B} = B_0[J_0(2\tau_0 r)\mathbf{z} + J_1(2\tau_0 r)\boldsymbol{\varphi}]$$

Possible to fit the free parameters of the model for every analyzed event

[Frisch et al. 1975, Pouquet et al. 1976; Alexakis et al. 2006]

H in Magnetic Clouds: Why?



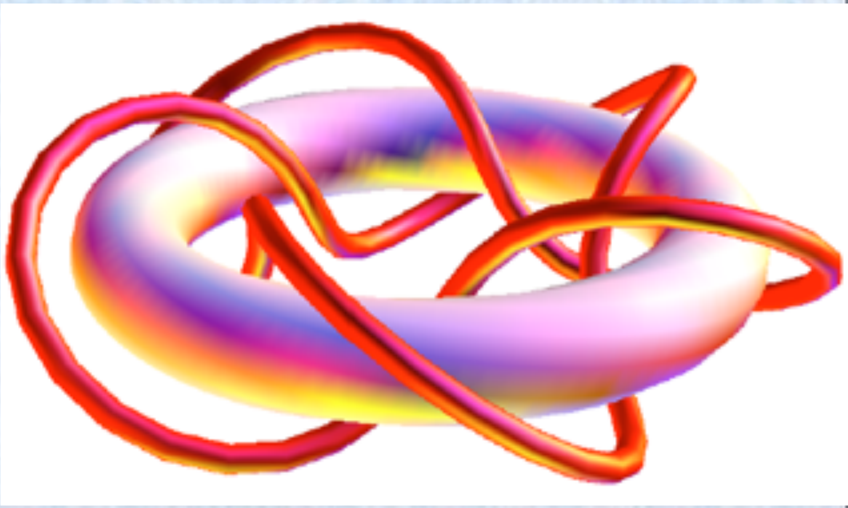
- Inverse cascade in MHD turbulence
-H better conserved than E
(dissipation effective at small *k*: $\nabla^2 \sim k^2$)

- Almost conserved even during transient fast reconnection events [Berger, 1984]

- H to track structures of **B** from (before) its formation to the heliosphere
[Luoni et al. 2005; Mandrini et al. 2005; Dasso et al., 2006, Foullon et al. 2007; Rodriguez et al., 2008]

- CMEs main channel to eliminate H from the Sun: Very important to solar dynamo

- Is the trigger of CMEs a consequence of accumulation of H?:
- controversial results from MHD simul
[e.g., Amari et al., 2003; Phillips et al., 2005]
- observations indicate that flares w/ more H produce CME [Nindos & Andrews, 2004]



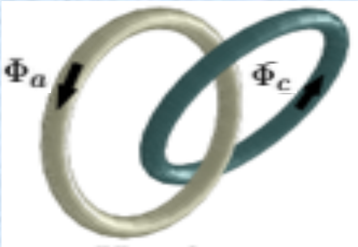
Helicity represents a ‘Gauss linking number’ for field lines

$$H^{\text{closed}} = \int_\Phi \int_\Phi \mathcal{L}^{\text{closed}}_{a,c} \, d\Phi_a \, d\Phi_c$$

Gauss linking number

$$\mathcal{L}^{\text{closed}}_{a,c} = \frac{1}{4\pi} \oint_a \oint_c \hat{t}(\vec{x}_a) \times \hat{t}(\vec{x}_c) \cdot \frac{(\vec{x}_a - \vec{x}_c)}{|\vec{x}_a - \vec{x}_c|^3} \, dl_a \, dl_c$$

<u>Simple example</u>:
Two inter-linked flux tubes



$$H^{\text{closed}} = -2 \, \Phi_a \, \Phi_c$$

Summation over all the field flux tubes pairs

(Elsasser 1956)

$$H^{\text{closed}} = \int_{\mathcal{V}} \vec{A} \cdot \vec{B} \, dV \qquad \vec{B} = \vec{\nabla} \times \vec{A}$$

Well defined only for open **B**:
B_n= **B**•**n**=0 ∀ $S(V)$

(Berger & Fields 1984; Finn & Antonsen 1985)

$$H = \int_{\mathcal{V}} (\vec{A} + \vec{A}_p) \cdot (\vec{B} - \vec{B}_p) \, dV$$

$$\mathbf{B}_p \bullet \mathbf{n}\big|_{S(V)} = \mathbf{B} \bullet \mathbf{n}\big|_{S(V)}$$
$$\nabla \times \mathbf{A}_p = \mathbf{B}_p$$
$$\nabla \times \mathbf{B}_p = 0$$

Fluxes and H from models

Linear Force Free Field
[Lundquist, ArkFys 1950]

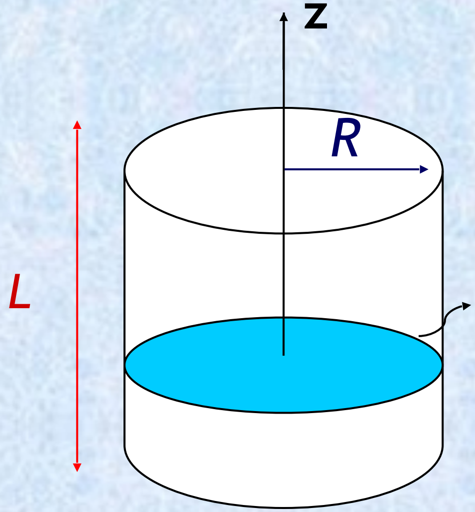
Taylor's state → $\mathbf{B}=B_z(r)\mathbf{z} + B_\phi(r)\boldsymbol{\phi}$

$$\nabla \times \mathbf{B} = 2\tau_0 \mathbf{B} \quad (\tau_0 = cte)$$

$$\mathbf{B} = B_0[J_0(2\tau_0 r)\mathbf{z} + J_1(2\tau_0 r)\boldsymbol{\varphi}]$$

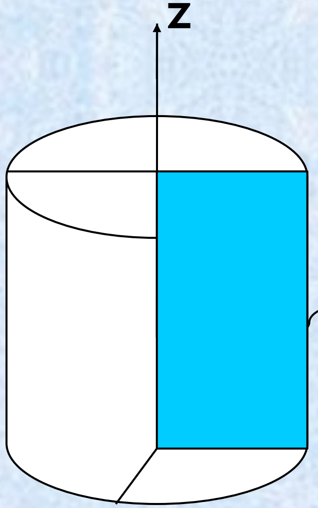
- $\tau(r)=d\varphi/dz=B_\varphi(r)/rB_z(r)$: amount of magnetic field twist
- $\tau_0=\tau(r\sim 0)$
- B_0 is the magnetic field intensity at the cloud axis

$$H = \frac{\pi B_0^2 R^2 L}{\tau_0}\left[J_0^2(2R\tau_0)+J_1^2(2R\tau_0)-\frac{J_0(2R\tau_0)J_1(2R\tau_0)}{2R\tau_0}\right]$$



Surface for F_z

$$F_z = [\pi B_0 R J_1(2R\tau_0)]/\tau_0$$



$$F_\varphi = \frac{B_0 L}{2\tau_0}[1-J_0(2R\tau_0)]$$

Surface for F_φ

$\Delta H_{corona} \sim H_{Magnetic\ Cloud}$?

[Mandrini et al. A&A 2005]

tiny event
11 May 1998
L_{cloud} = 0.5 AU

$2.3 \leq |\Delta H_{corona}| \leq 3.1$
$1.5 \leq |H_{cloud}| \leq 3.0$ ~

Units : 10^{39} Mx²

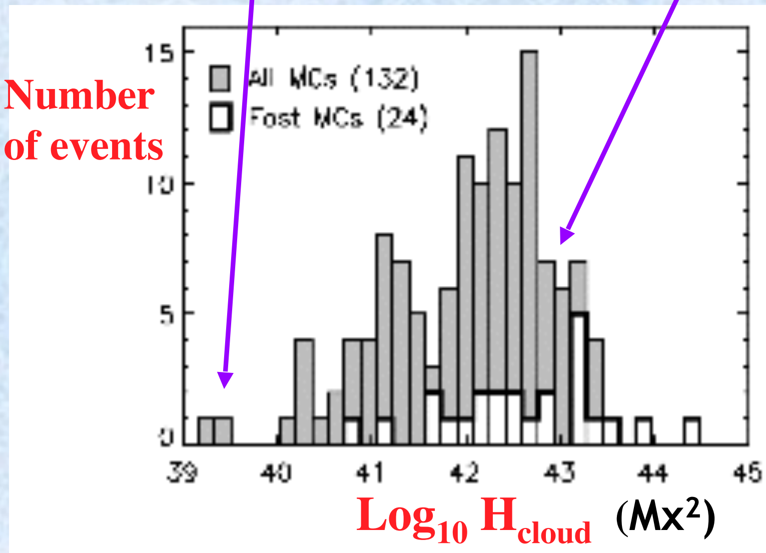
[Luoni et al. JASTP 2005; Dasso et al., A&A 2006]

large event
14 Oct. 1995
L_{cloud} = 2 AU

$3 \leq \Delta H_{corona} \leq 6$
$7 \leq H_{cloud} \leq 12$

factor ~ 2

Units : 10^{42} Mx²



Comparison of H_{cor} with H_{MC}
(including emerged H)
have been also used to analyze Sun-MC linking
[e.g., Longcope et al., SolPhys 2007;
Foullon et al., SolPhys 2007;
Rodriguez et al., Annales Geophys 2008]

Large range of H_{cloud} : 5 orders of magnitude !

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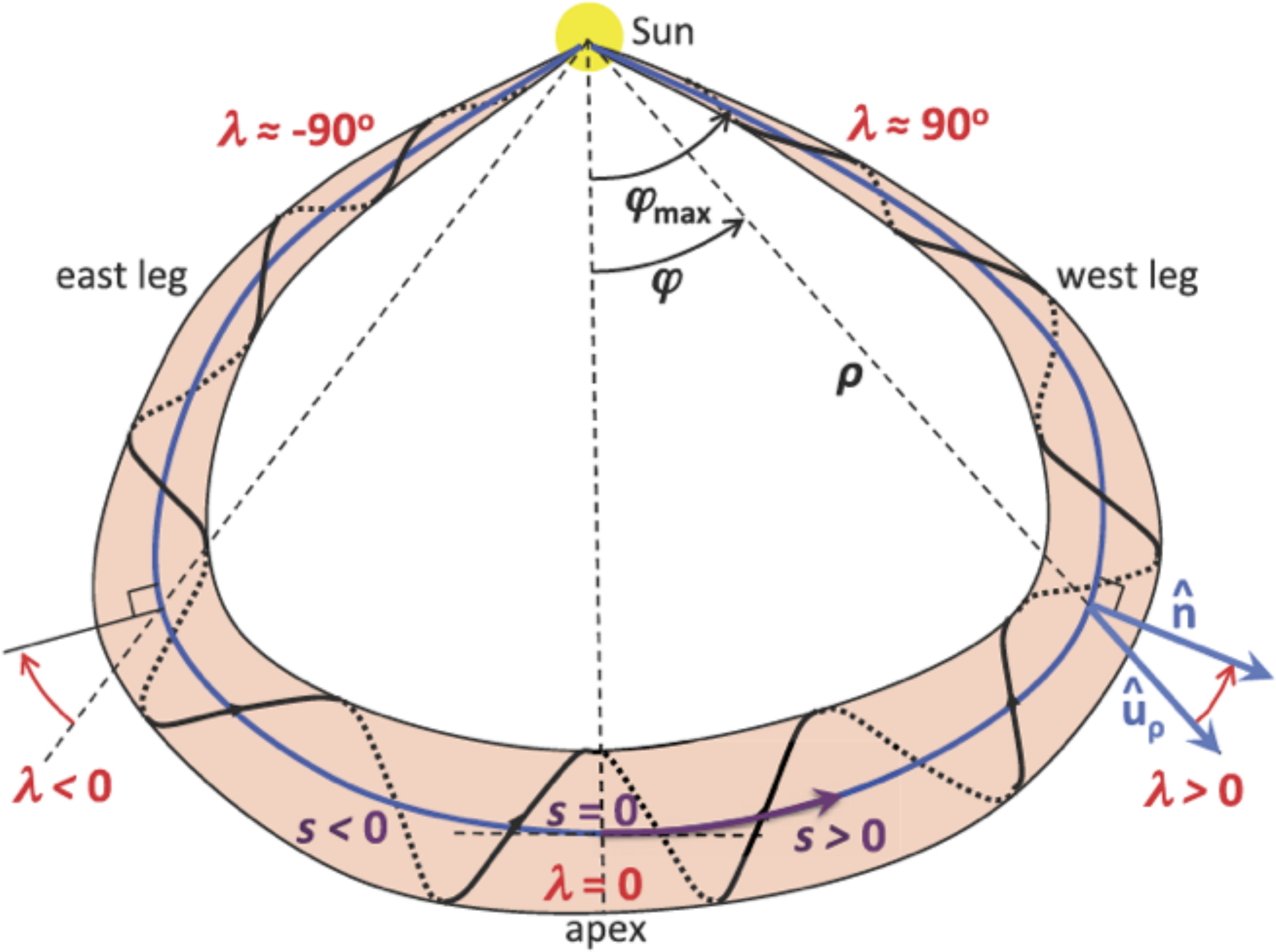
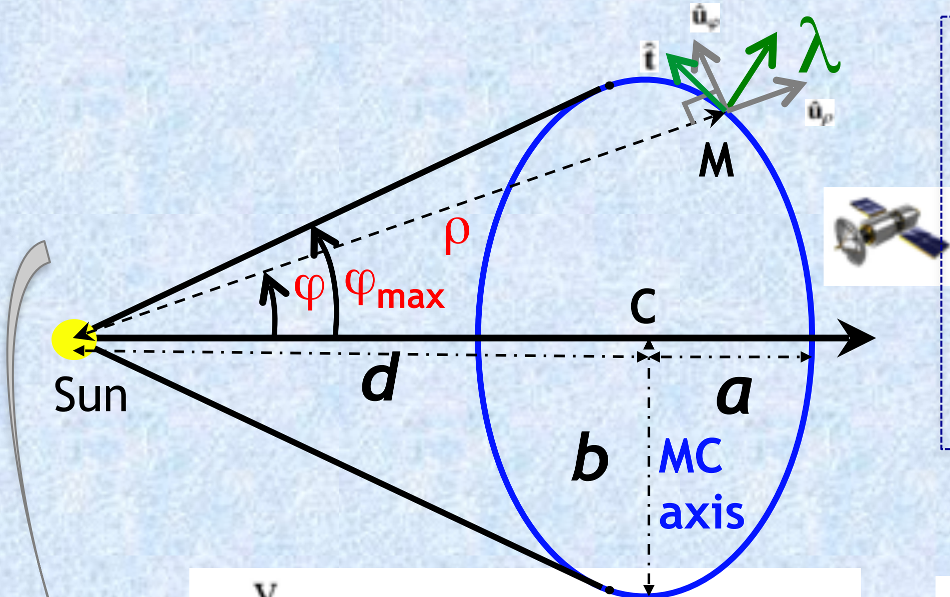

Sun
λ ≈ -90°
λ ≈ 90°
φmax
φ
east leg
west leg
ρ
n̂
ûρ
λ < 0
λ > 0
s = 0
s < 0
s > 0
λ = 0
apex

Janvier et al. [2013]



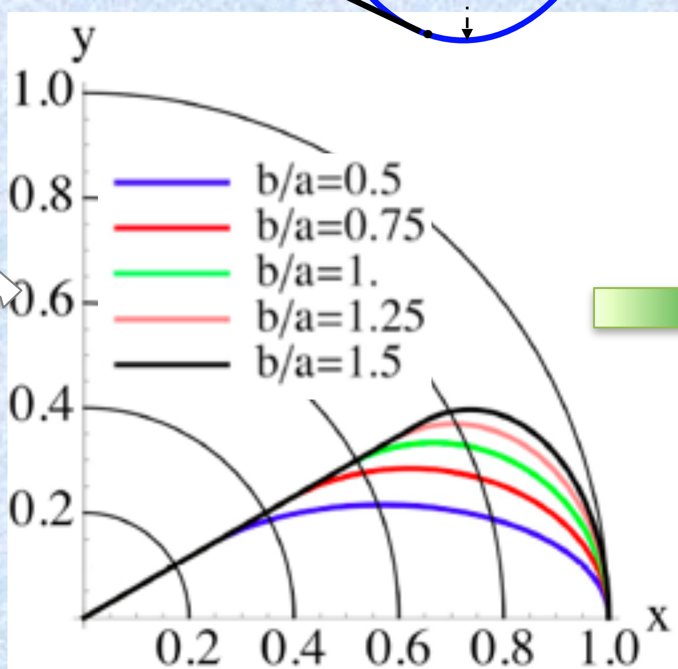
Distribution for the synthetic model:

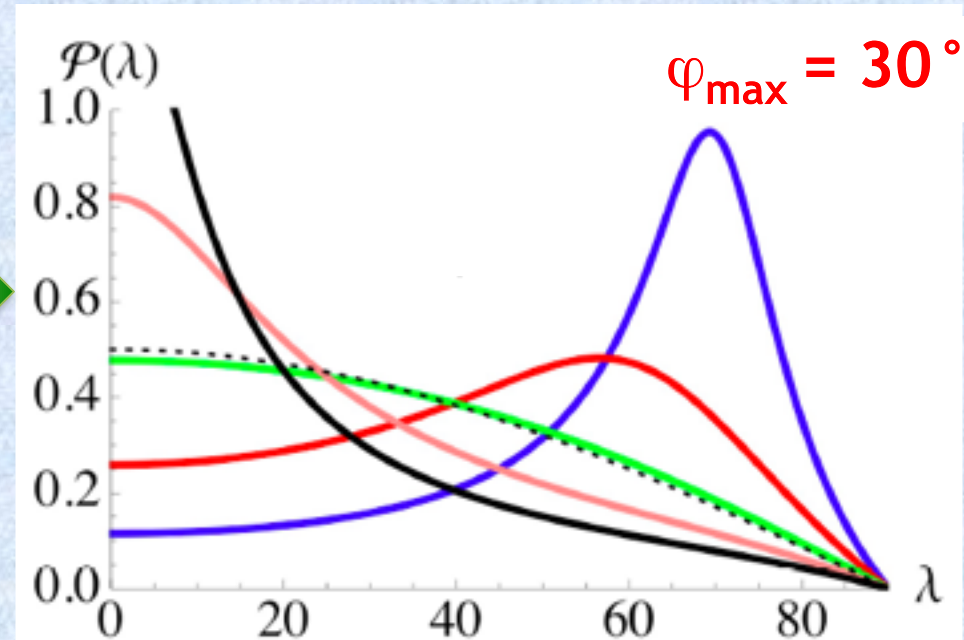
$$\mathcal{P}(\lambda) = \mathcal{P}_\varphi \, |d\varphi/d\lambda|$$

$1/(2\,\varphi_{max})$

Equiprobable in φ

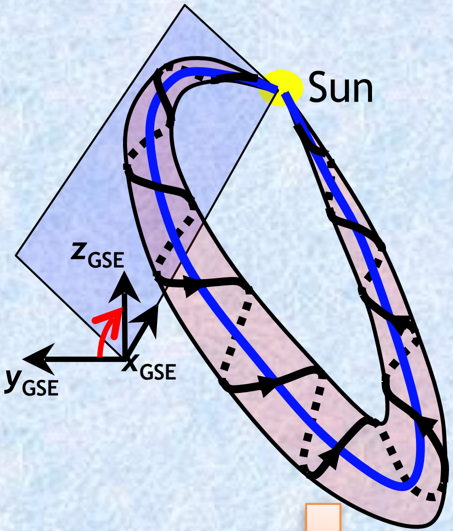
Computed from the model geometry

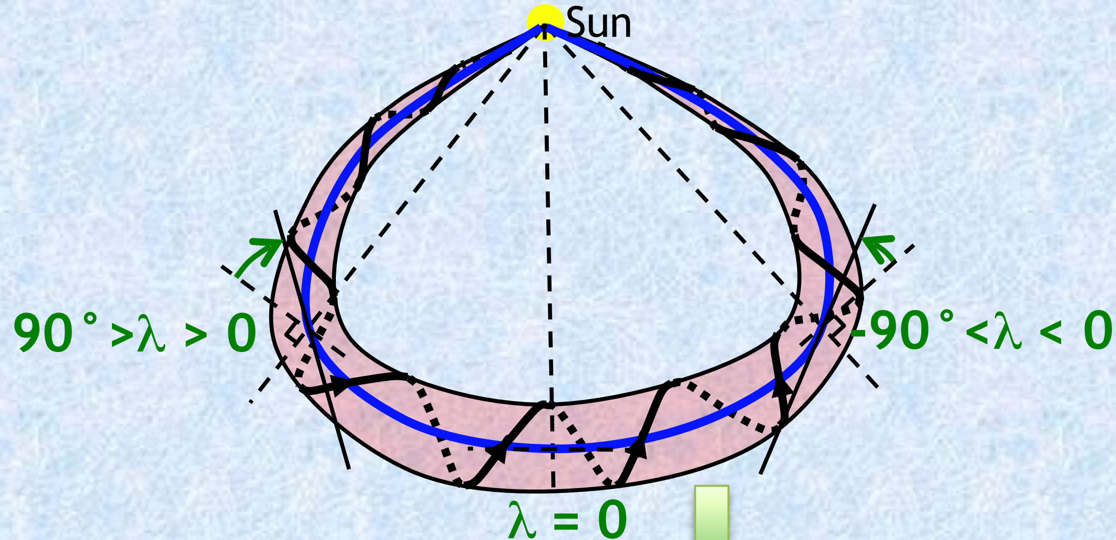




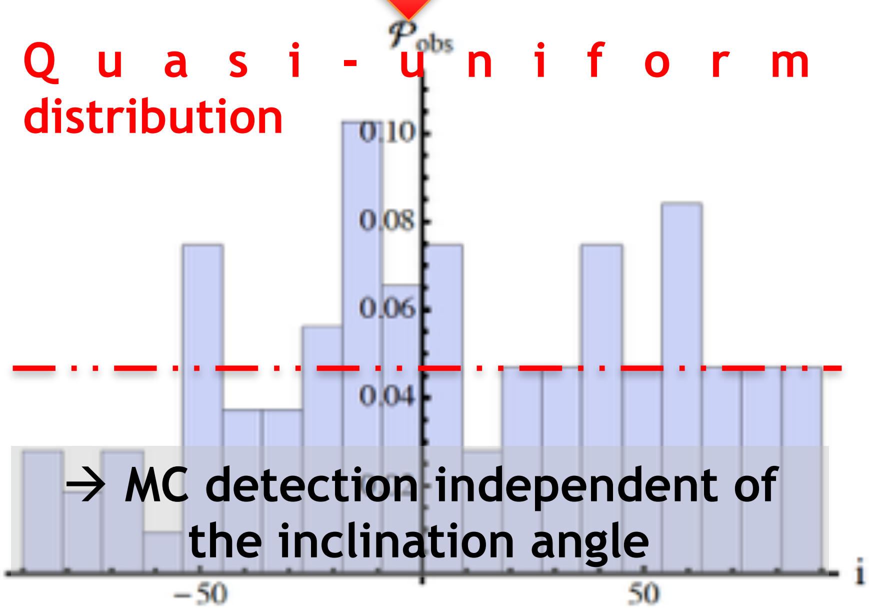
◇ WIND Spacecraft data (107 MCs observed at 1AU)

Janvier et al. [2013]





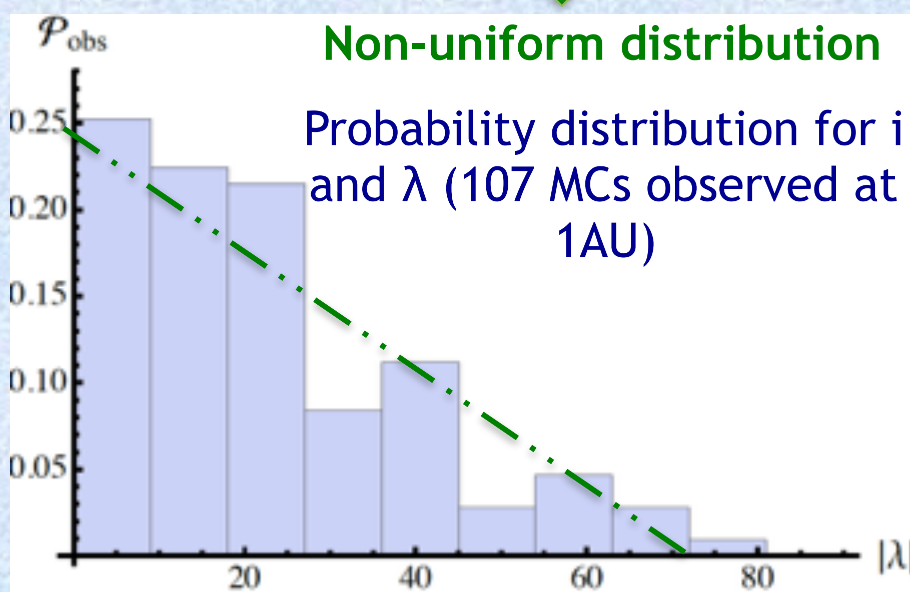
Quasi-uniform distribution



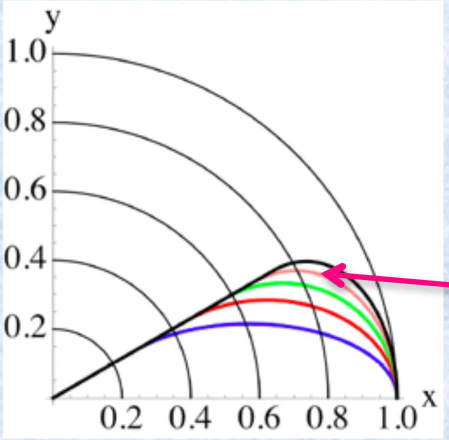
→ MC detection independent of the inclination angle

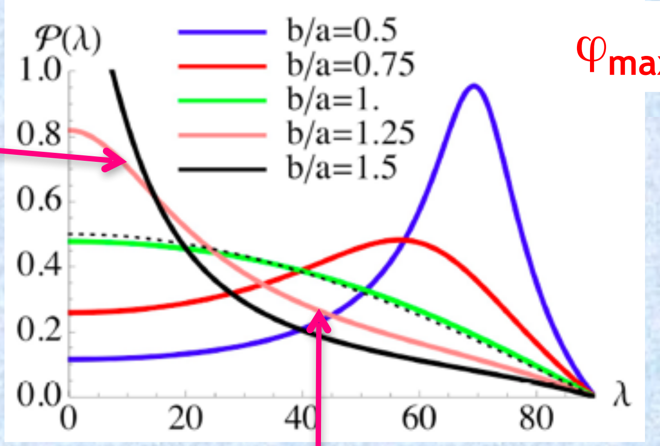
Non-uniform distribution

Probability distribution for i and λ (107 MCs observed at 1AU)



Janvier et al. [2013]





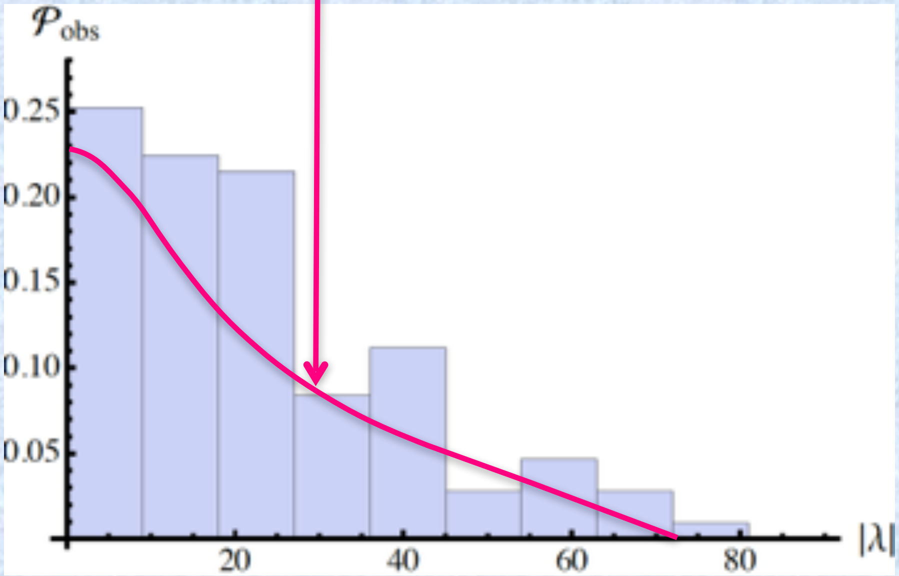
φ_{max} = 30 °

Satisfying cases for aspect ratio:

1<b/a≤1.3

(not too round, not too flat)

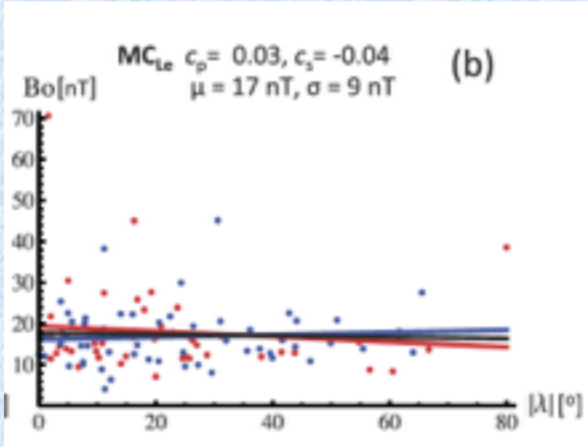
<u>Found the most probable shape for the axis!</u>

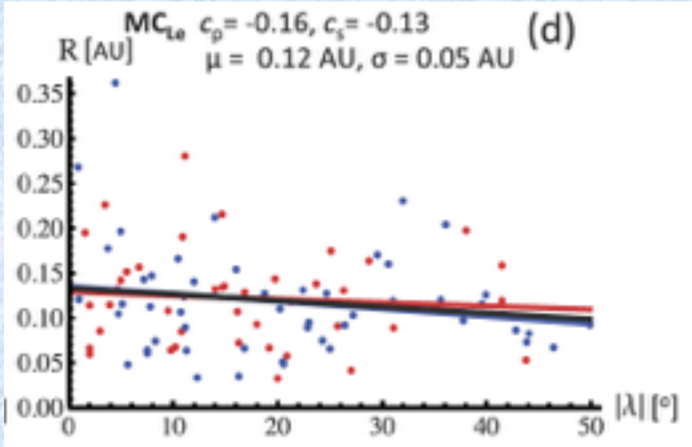


$$H = L \int_0^R 2A_a(r)B_a(r)2\pi r \, dr = \frac{2\pi J_1^2(c)}{c} B_0^2 R^3 L$$

Demoulin et al., 2016

From the analysis of ~100 events in situ observed:





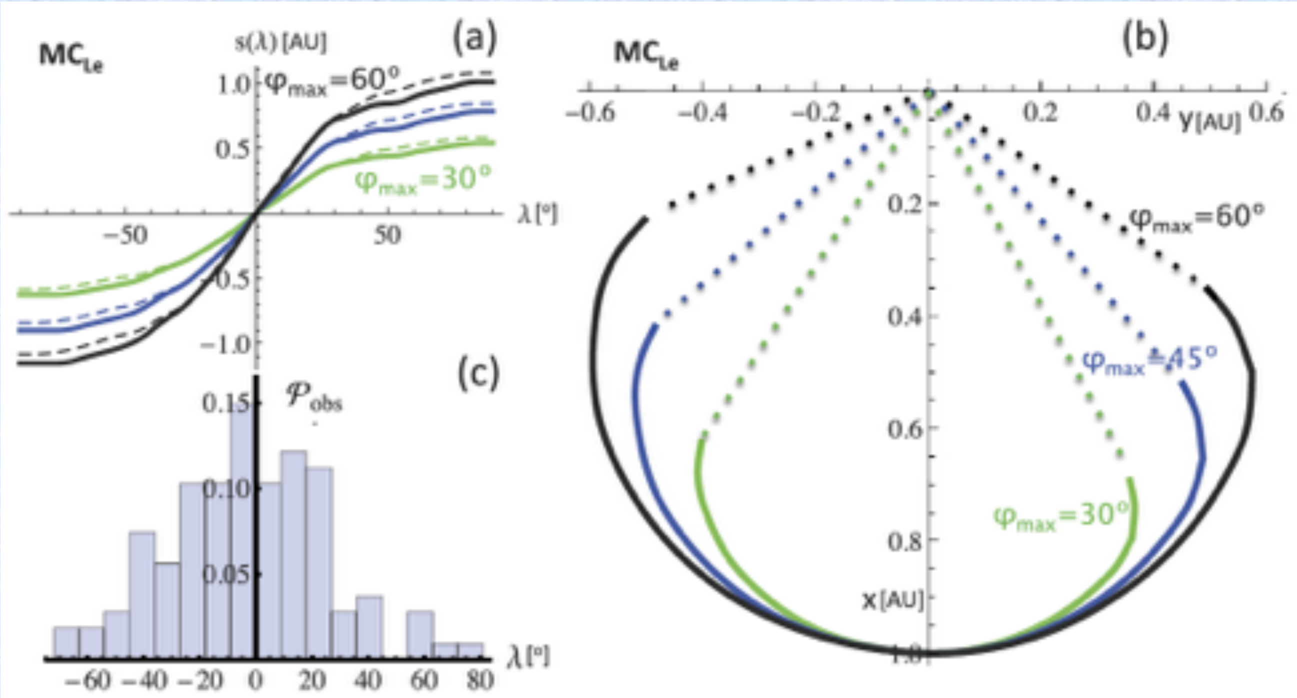
* Fit 3D model
(determination of global shape)

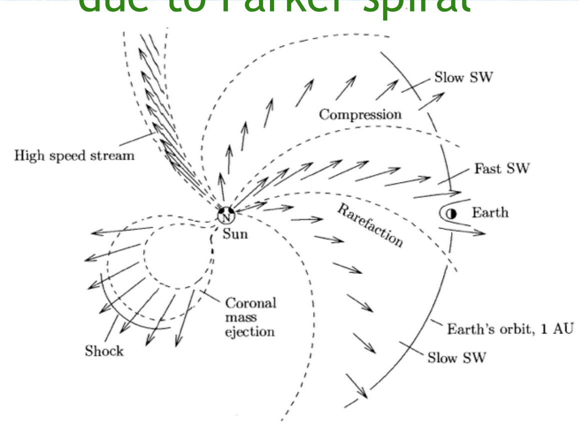
* Uniform B_0,R
along the axis

* Compute total released H
(constraints for the
solar dynamo models)
$H_{MC,cycle}$ ~ 2.5×10^{46} Mx^2

(similar to H from 2k large ARs)

* Low level of asymmetry
due to Parker spiral





Friends of Friends 2016

Cross diffusion of GCRs, to enter into de Flux Rope during the MC expansion

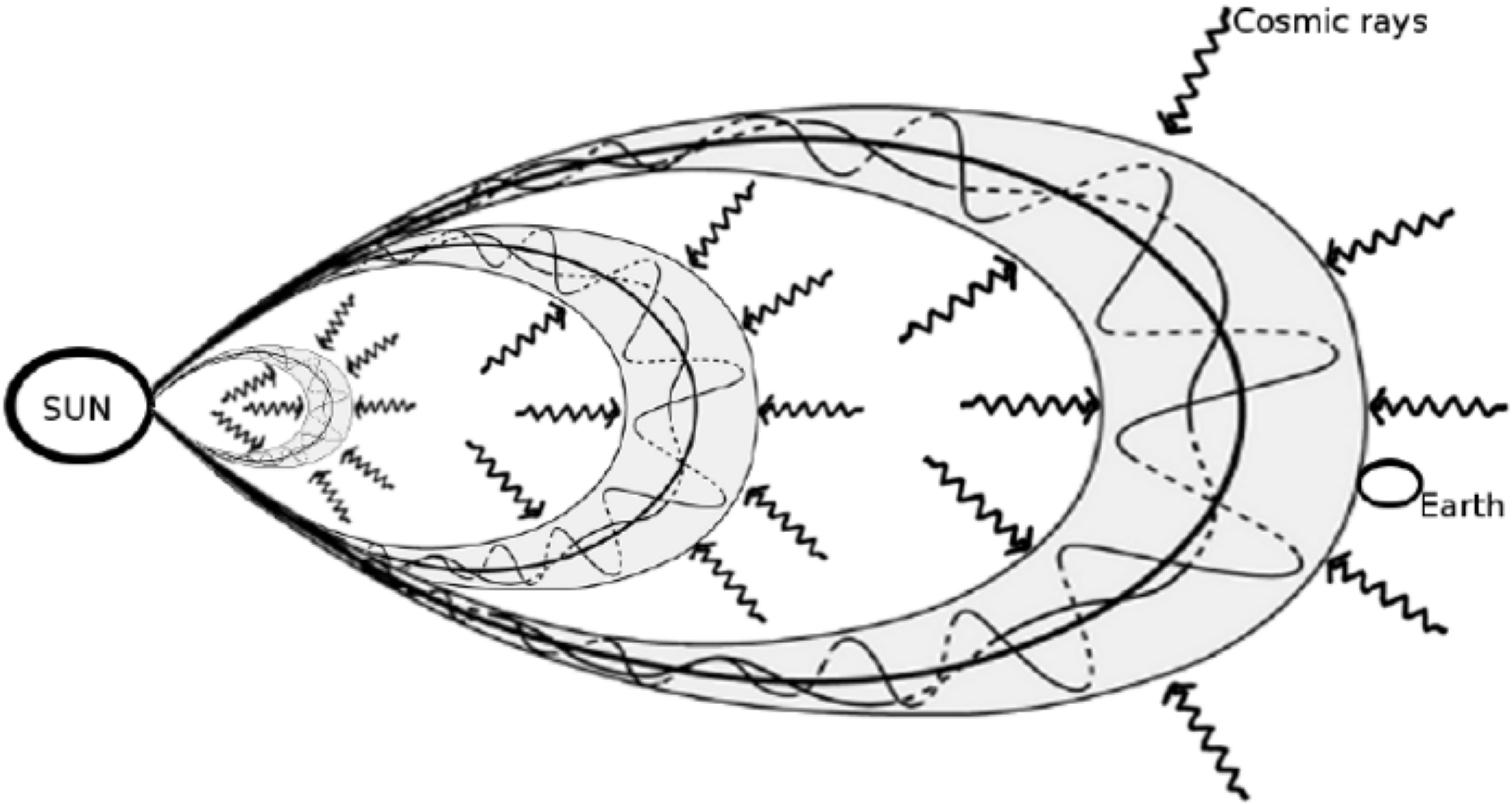


Figure from [Arunbabu, A&A, 2013]

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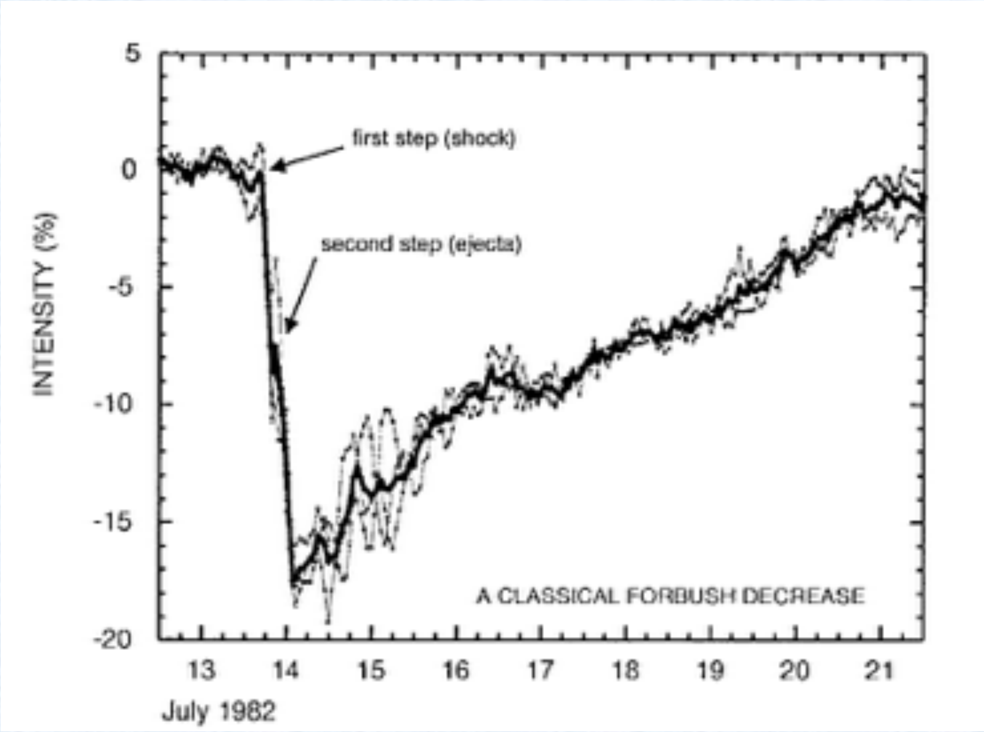
Observations of a two step Forbush Decrease produced by an ICME and its driven shock, observed from ground Neutron Monitors



[Cane, SSR, 2000]

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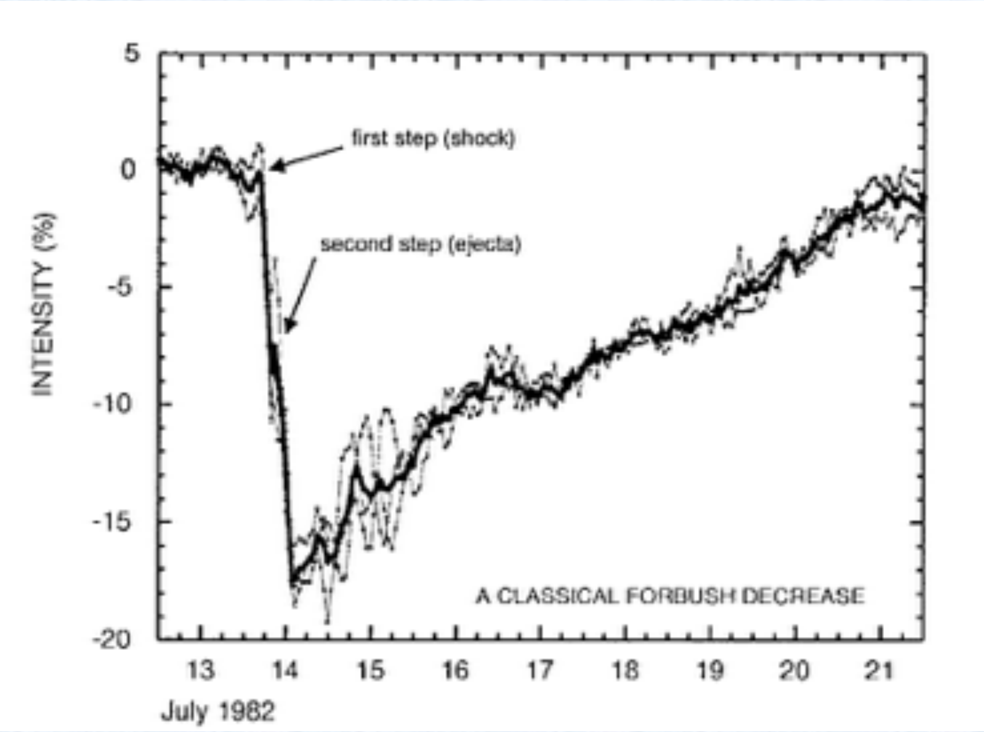

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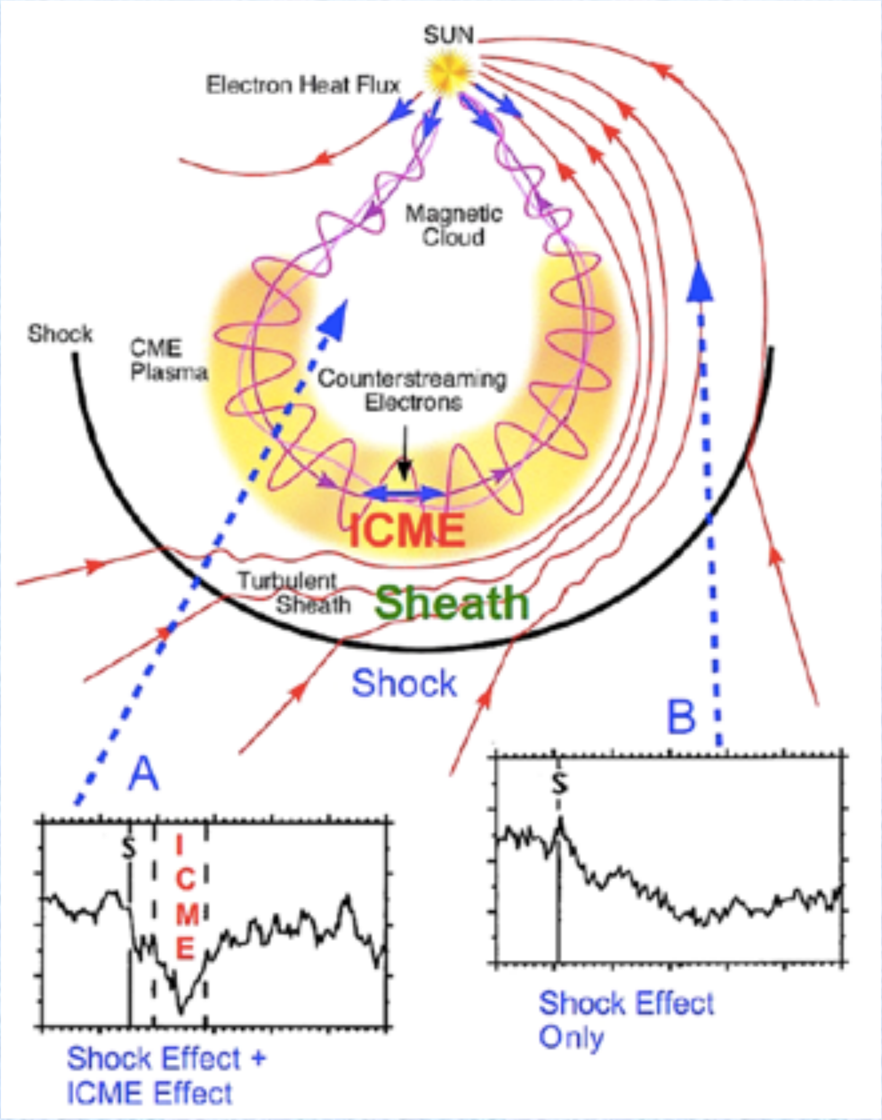
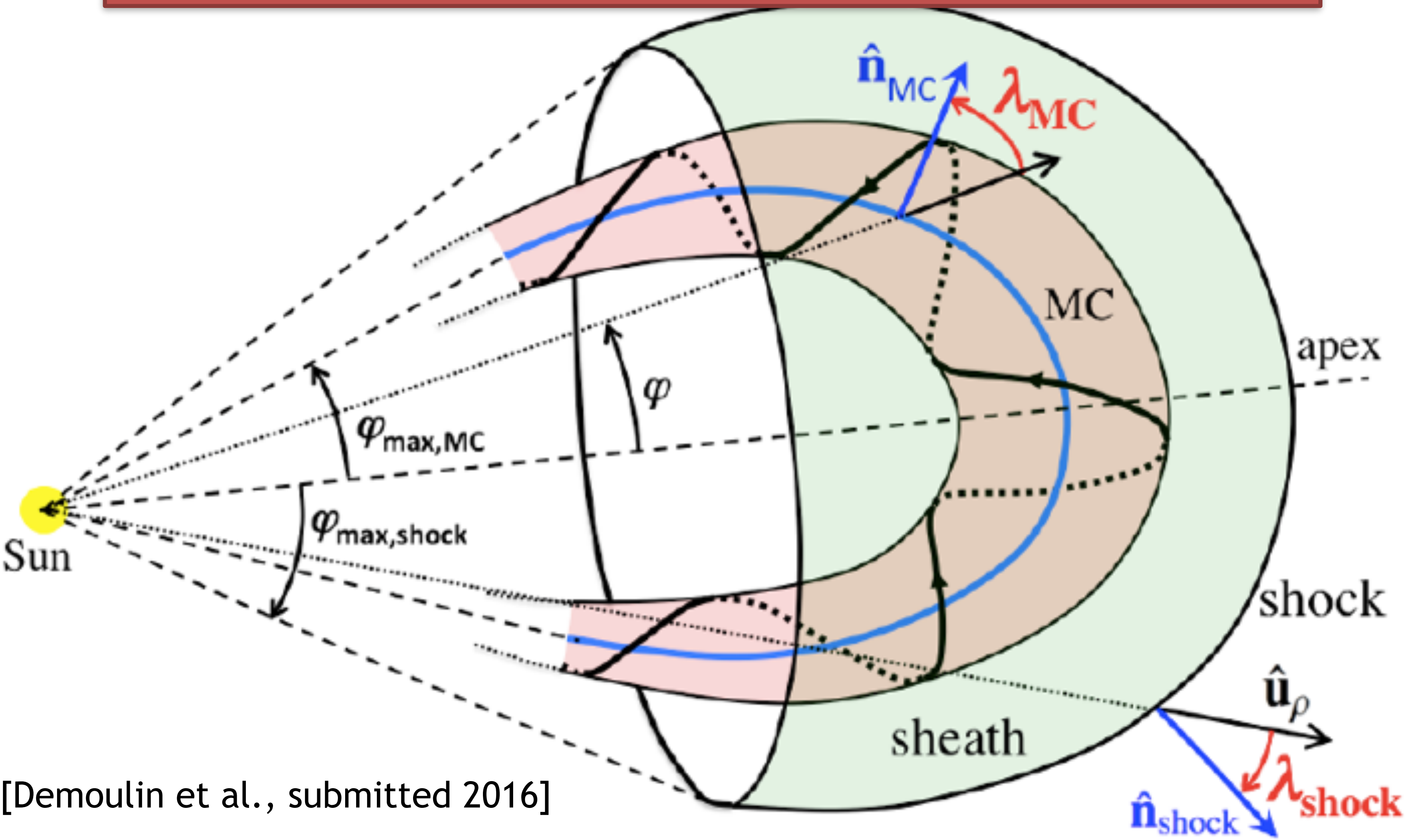


Figure from Richardson & Cane [2011]

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



[Demoulin et al., submitted 2016]

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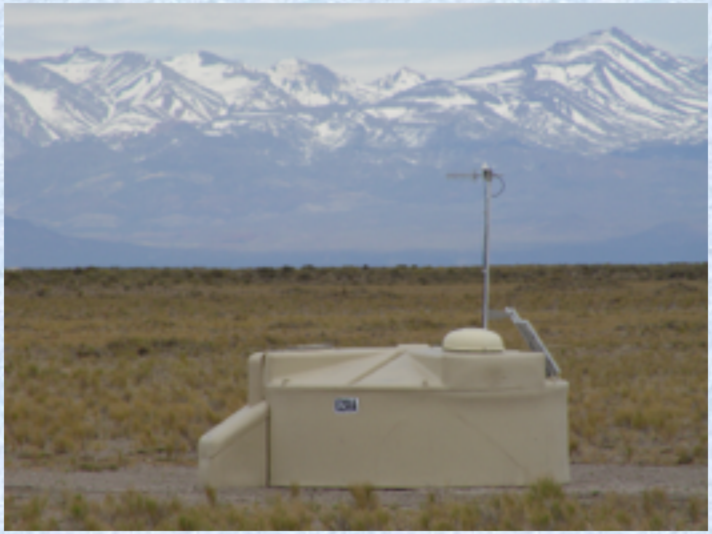
Pierre Auger Observatory: Water-Cherenkov Detectors

20 countries

1600 detectors covering 3000 km^2



- Polyethylene tank with 10 m^2 of detection area
- 12 m^3 of high purity water in a reflective liner bag
- Cherenkov radiation produced by the passage of charged particles in the detector is collected by three 9" photomultipliers
- Sensitive to high energy photons
- Signals processed by a FADC with a sampling rate of 40 MHz

- Radio communications system
- Timing provided by GPS system
- Stations powered by solar panels and batteries

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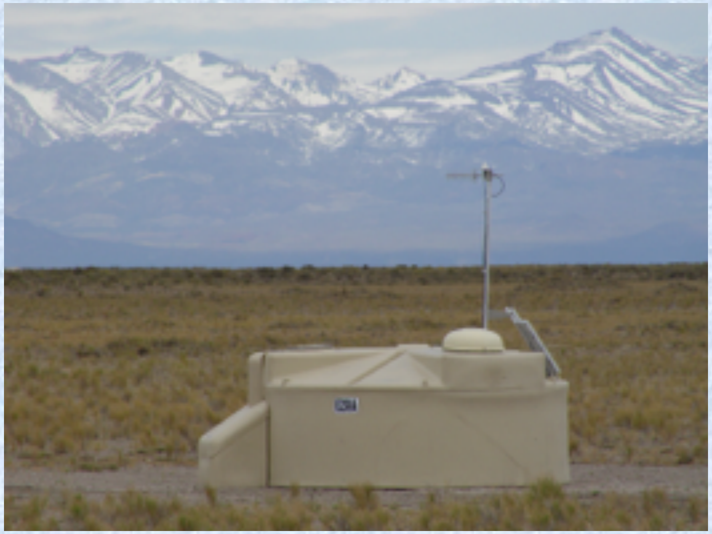

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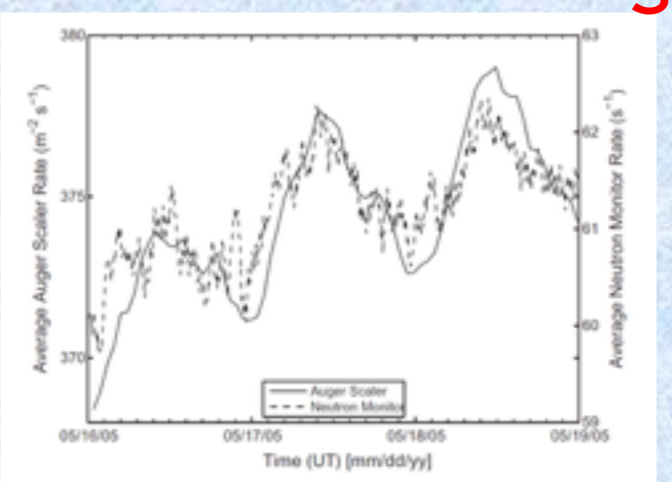
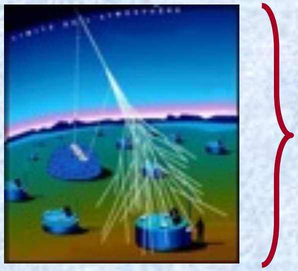
Scalers:

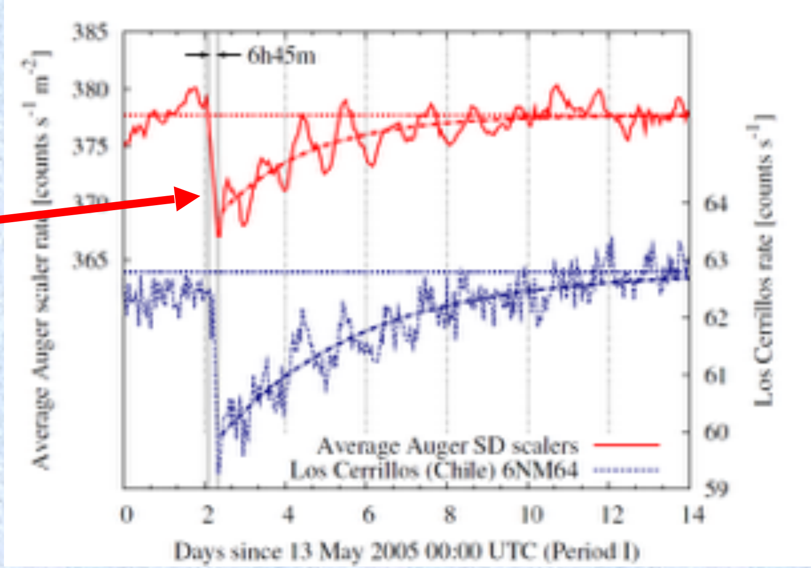
- Counters of signals above a very low threshold
- Installed in all detectors of the Surface Array
- At the origin intended for long term stability and monitoring studies, now for Space Physics studies

Daily modulation and Forbush observed with Auger scaler (Space Weather)

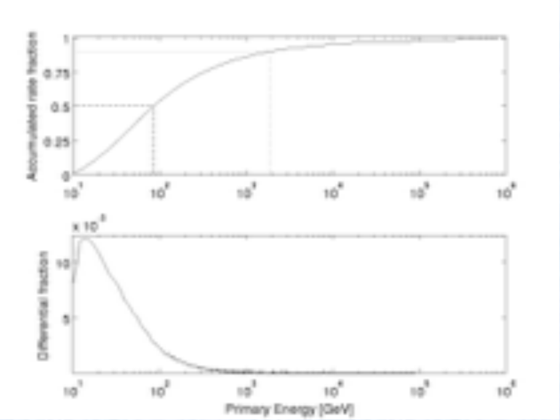


Dasso, Asorey, Auger [ASR, 2012]



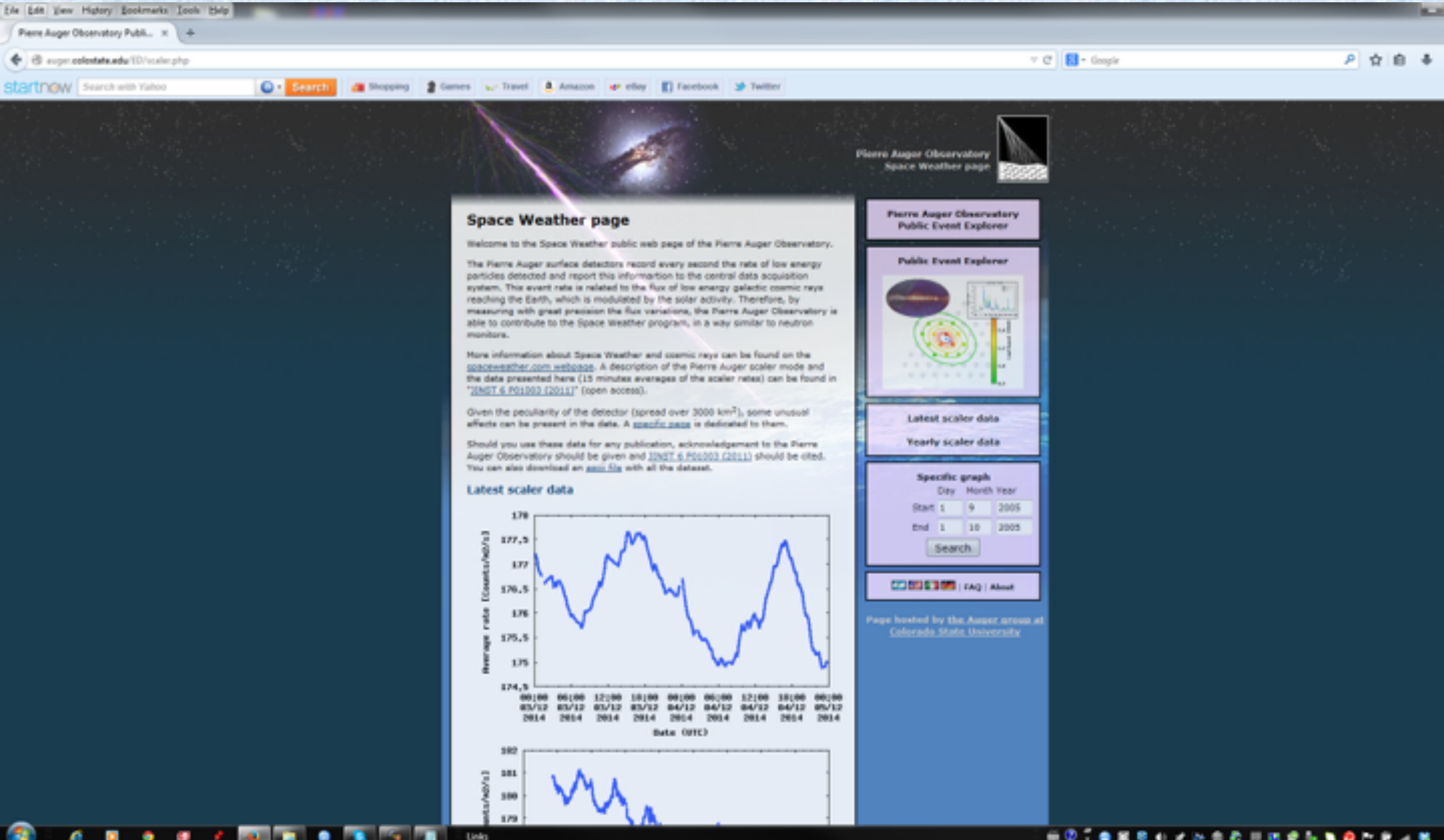


(The Pierre Auger Collaboration, 2011)



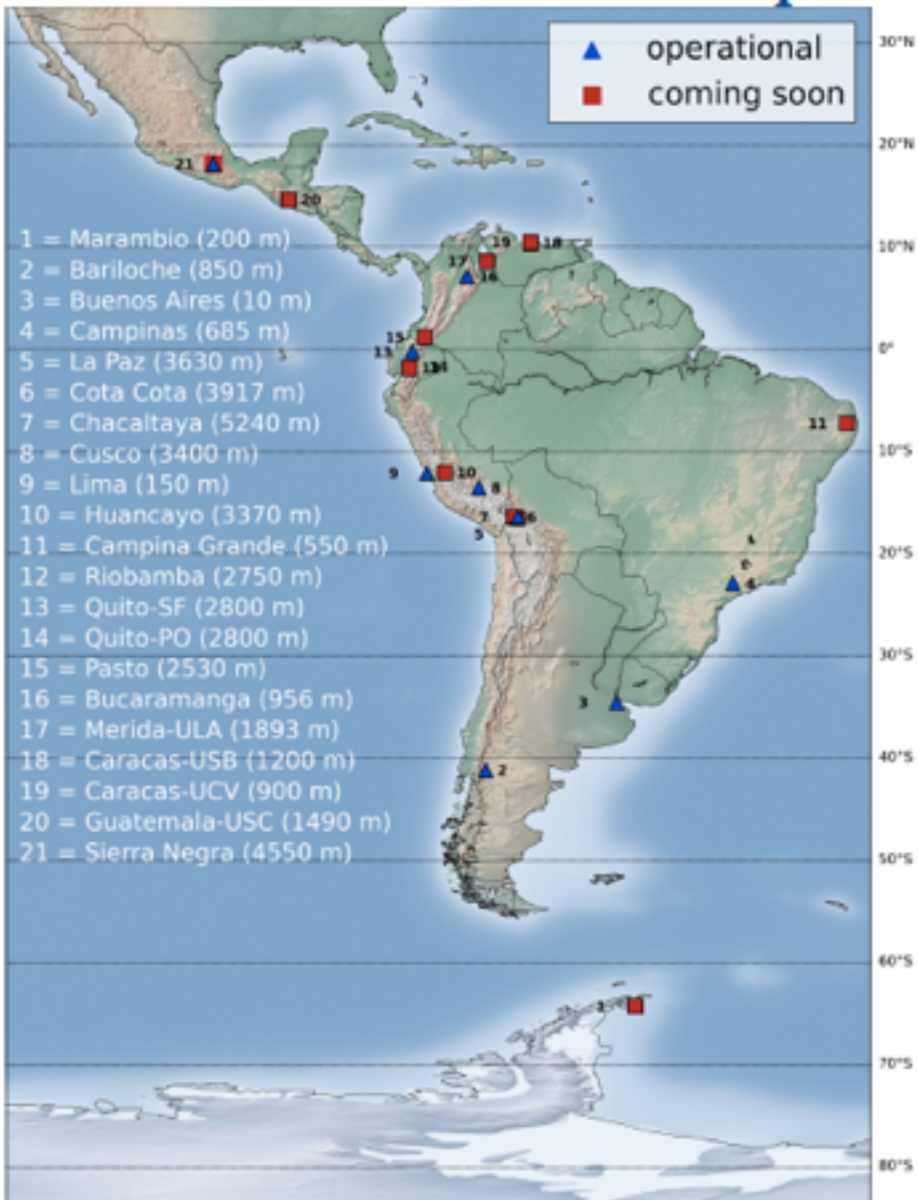
The typical energy of primary CRs observed are of the order of 100 GeVs
[Dasso, Asorey, Auger, ASR, 2012]

Auger scalers (15’) public access



Latin American Giant Observatory (LAGO): www.lagoproject.org

The *Latin American* astroparticle network



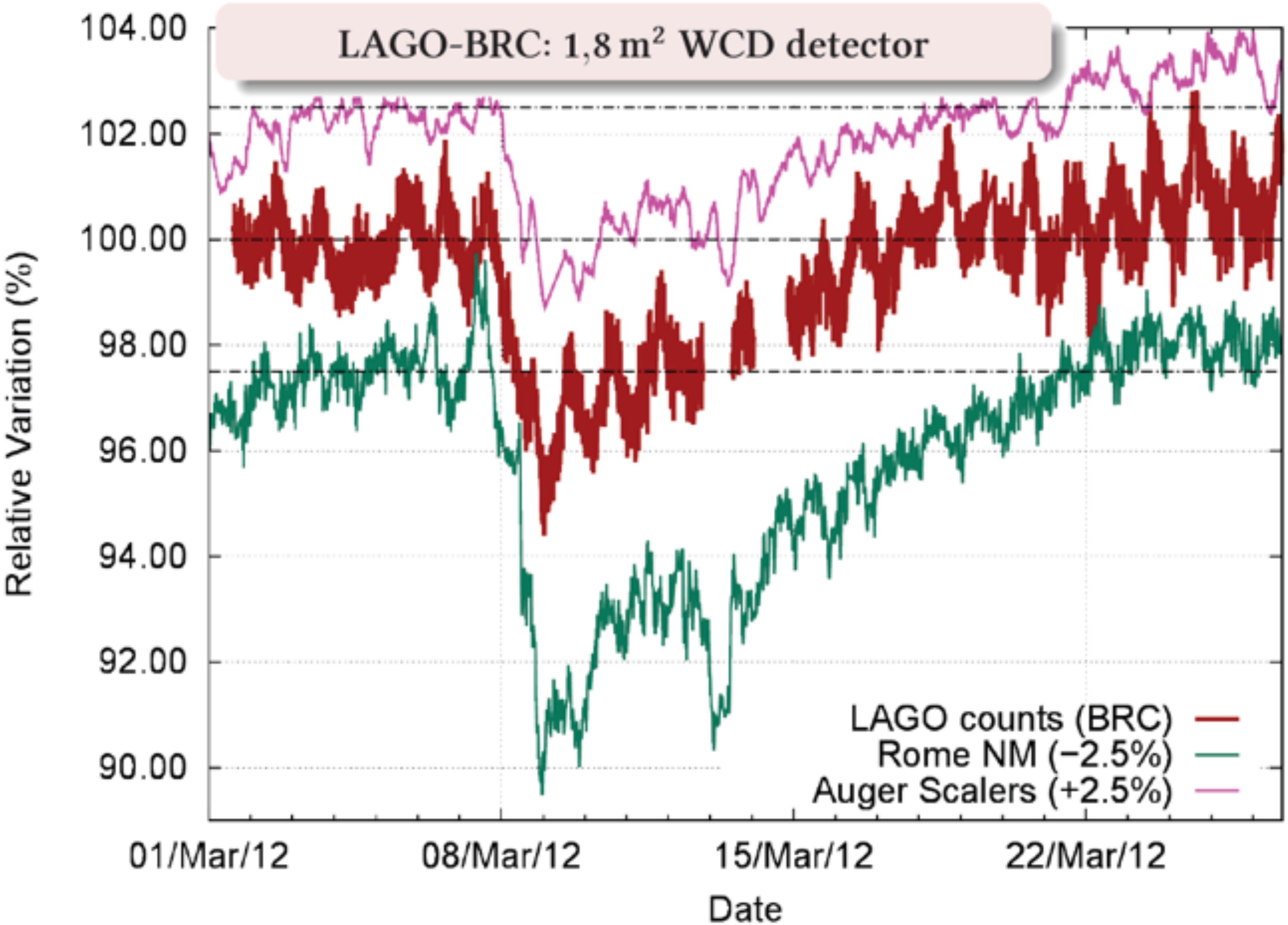
Network status

30 LA sites: 10 operational + 11 starting in 2015-2016 + 9 planned

How it works?

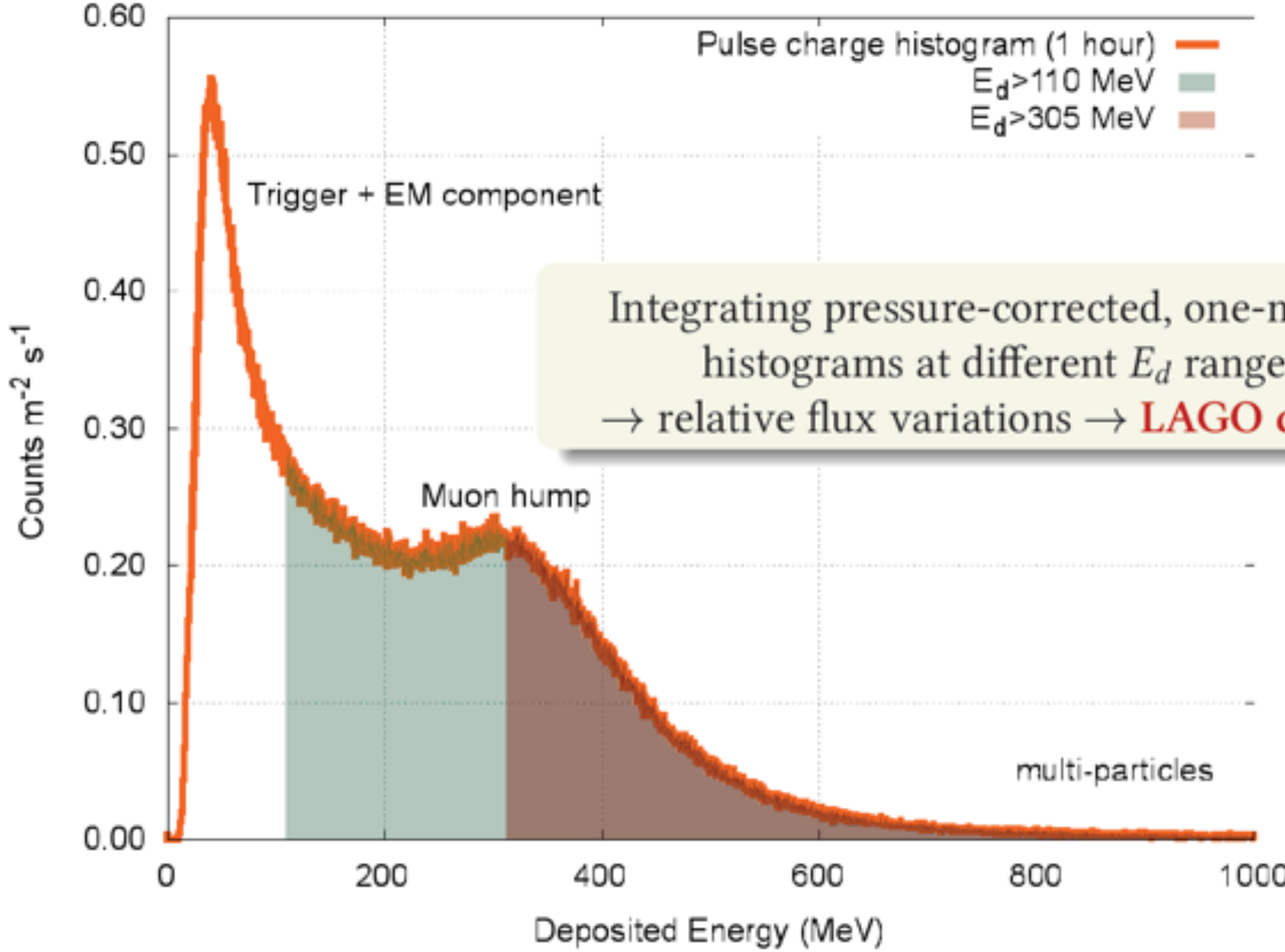
- Non-centralized, collaborative network of institutions
- 3 working groups, 10+1 members coordination committee, 1 P.I.
- Developments, expertize and data are shared across the network
- Primary objectives conducted by specific LAGO programs

08/March/2012: Forbush event ← single LAGO detector



Data

$$\text{Charge integrated pulse histogram} \xrightarrow[\text{simulations}]{\text{Detector response}} \text{deposited energy } E_d$$



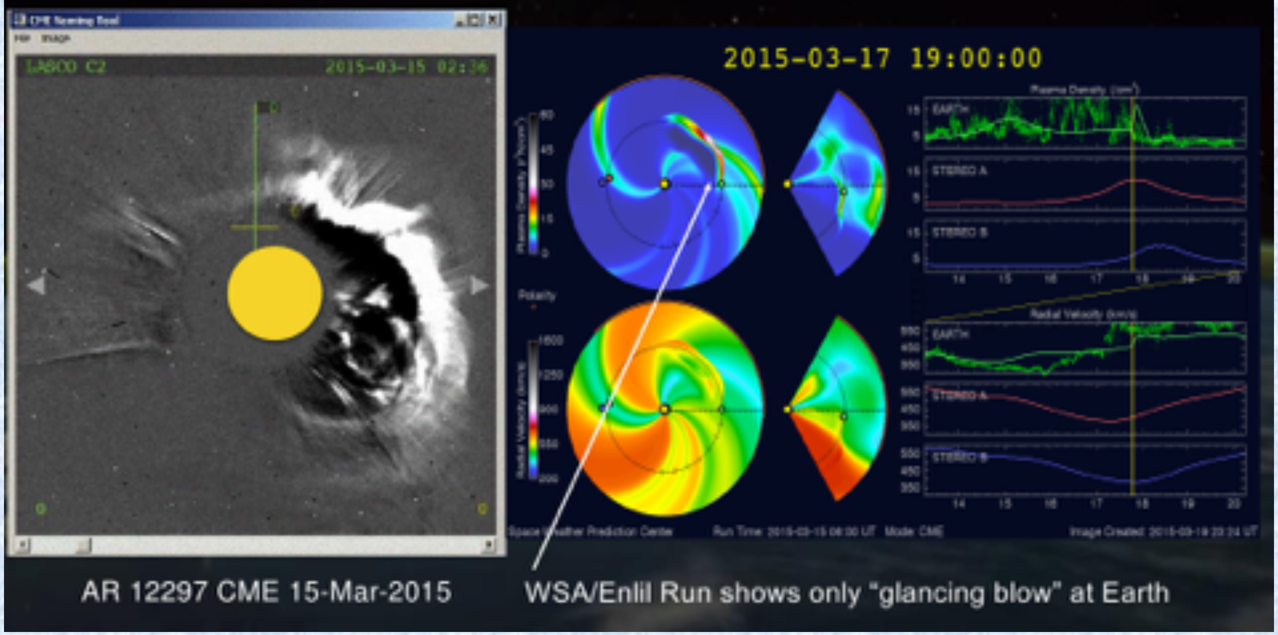
Integrating pressure-corrected, one-minute histograms at different E_d ranges $\rightarrow$ relative flux variations $\rightarrow$ **LAGO counts**

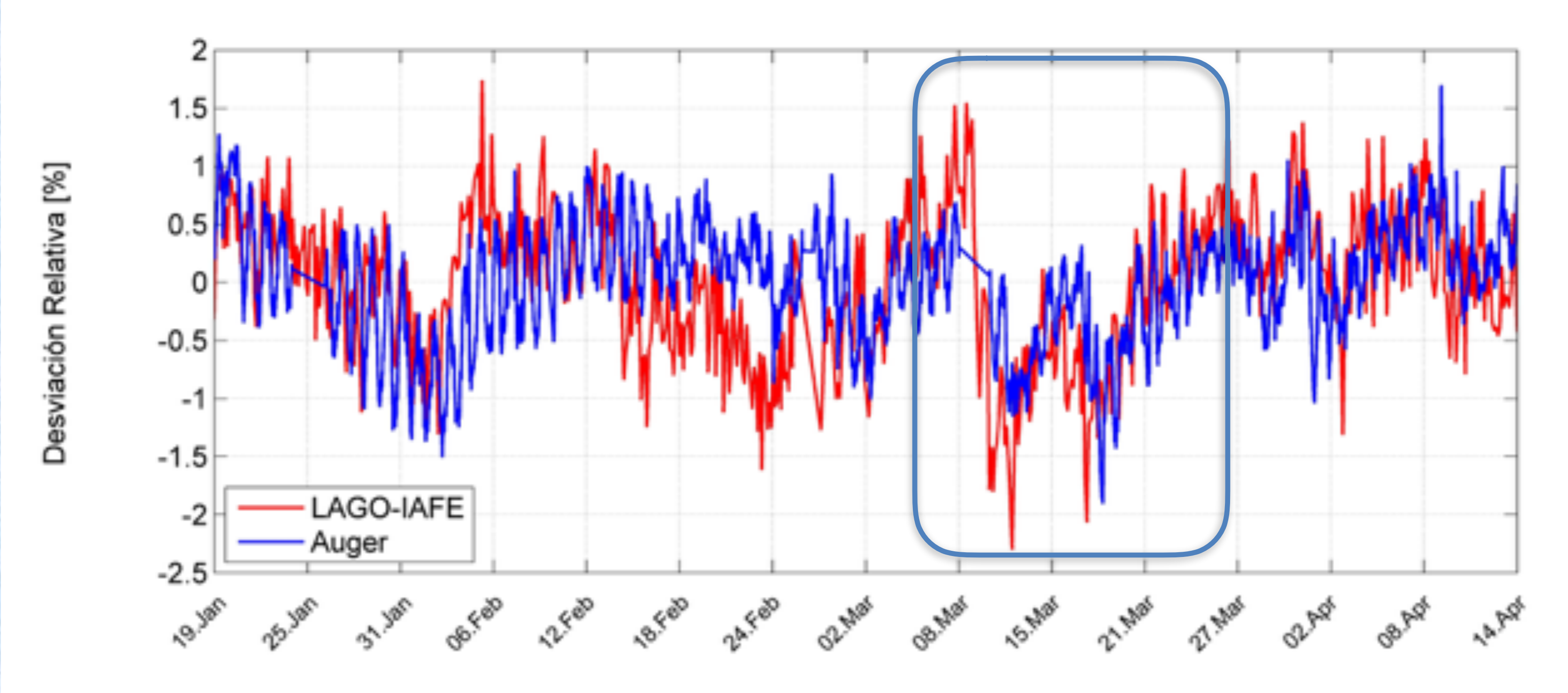
LAGO detectors at Marambio argentine base, Antarctic

Institutional project of the
Instituto Antartico
Argentina
(INST-20-2012/13)
Argentine Antarctic plan.
PICT-2013-1462
PIP-11220130100439CO
PIDDEF-2014-8

Thermal room for 3 autonomous Cherenkov detectors, weather station for permanent monitoring and calibration, and communication (on-line public data for permanent monitoring Space Weather conditions)

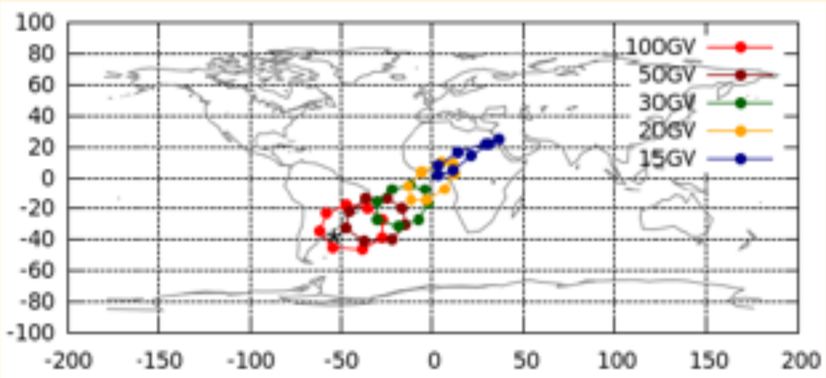
CR detector at IAFE ready to be deployed at Antarctic



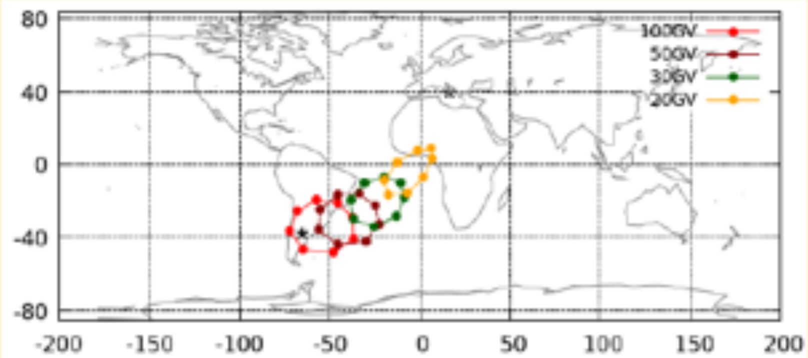


Asymptotic Directions for zenith=15° (projected on Earth surface):
Obs: These directions do not change along the day.

Buenos Aires (Rc=8.42 GV)

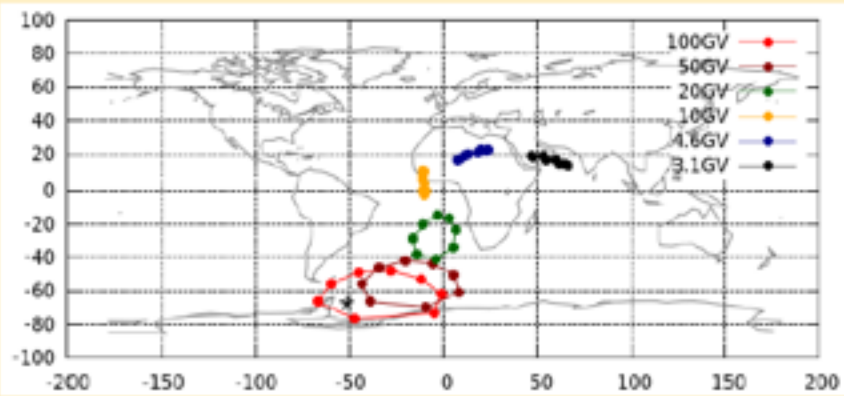


Malargue (Rc=9.60 GV)

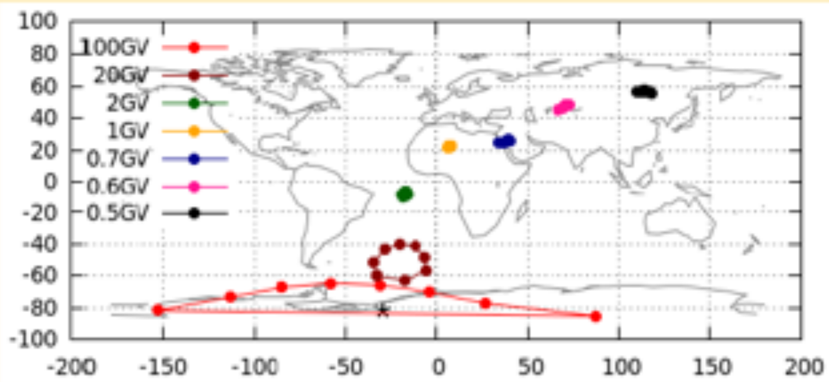


Masias-Meza et al. (IAU Proceedings, 2012)

Marambio (Rc=2.22 GV)



Belgrano II (Rc=0.33 GV)



[Masías-Meza & Dasso, 2014]

Summary and Conclusions

•Interplanetary Coronal Mass Ejections (ICMEs) are the most geoeffective transients in the IP medium. Magnetic Clouds (MCs) are a subset (helical) of ICMEs, containing large amount of magnetic helicity (H).

• We presented a summary of the MCs main properties, as well the state of the art on the quantification of the content of H and their 3D shape in the heliosphere.

• These huge magnetic structures have severe influence on the propagation of galactic cosmic rays (GCRs). Thus, improving the knowledge of them will help to understand better the GCR modulation in the solar wind.

• We presented the Space Weather programs of two international collaborations (Pierre Auger and LAGO). In particular, they started to study the link between the transport of GCRs and MCs.

• We presented the Antarctic LAGO node, which will also operate as a permanent space radiation monitor, complementing other Space Weather observatories in Argentina

Thank you very much for your attention !