Interplanetary magnetic field and relativistic solar particle events

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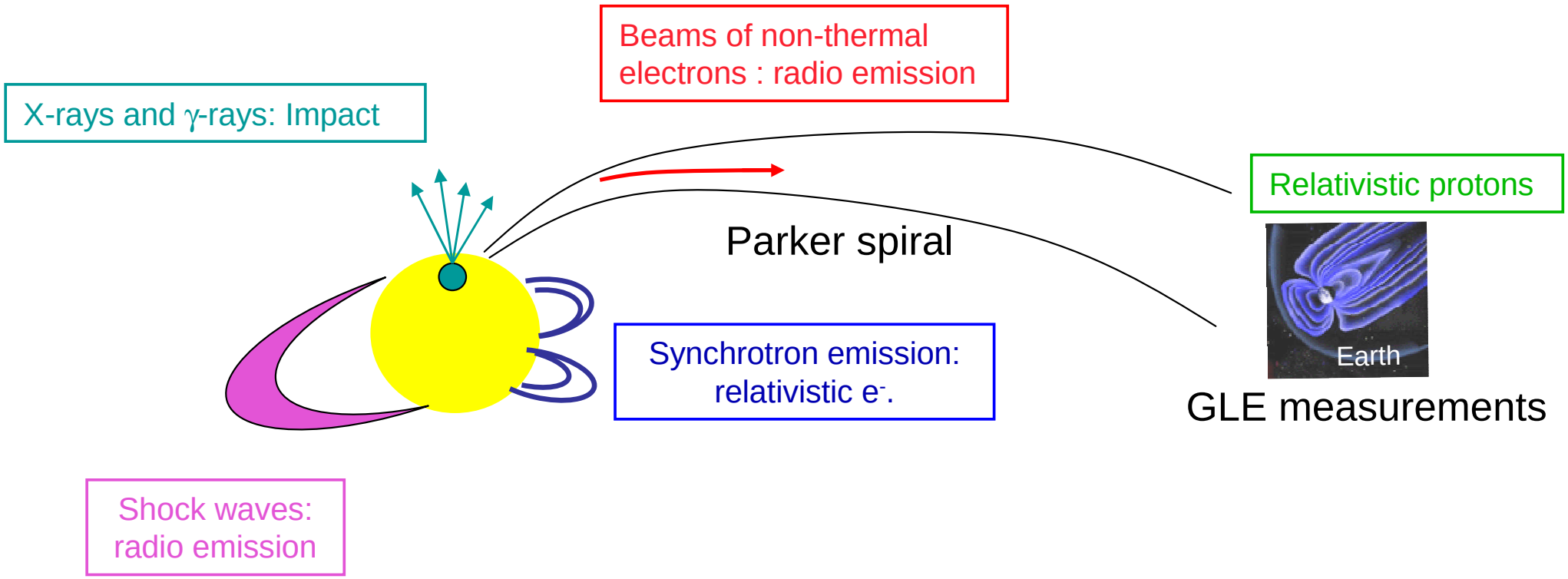
How can we constrain acceleration of relativistic protons ?

- **Multi wavelengths analysis**



- From Earth measurements, go back to Sun across the Parker spiral (1.2 AU)

➔ Constrain the **acceleration regions** of relativistic particles

The timing and connection problem

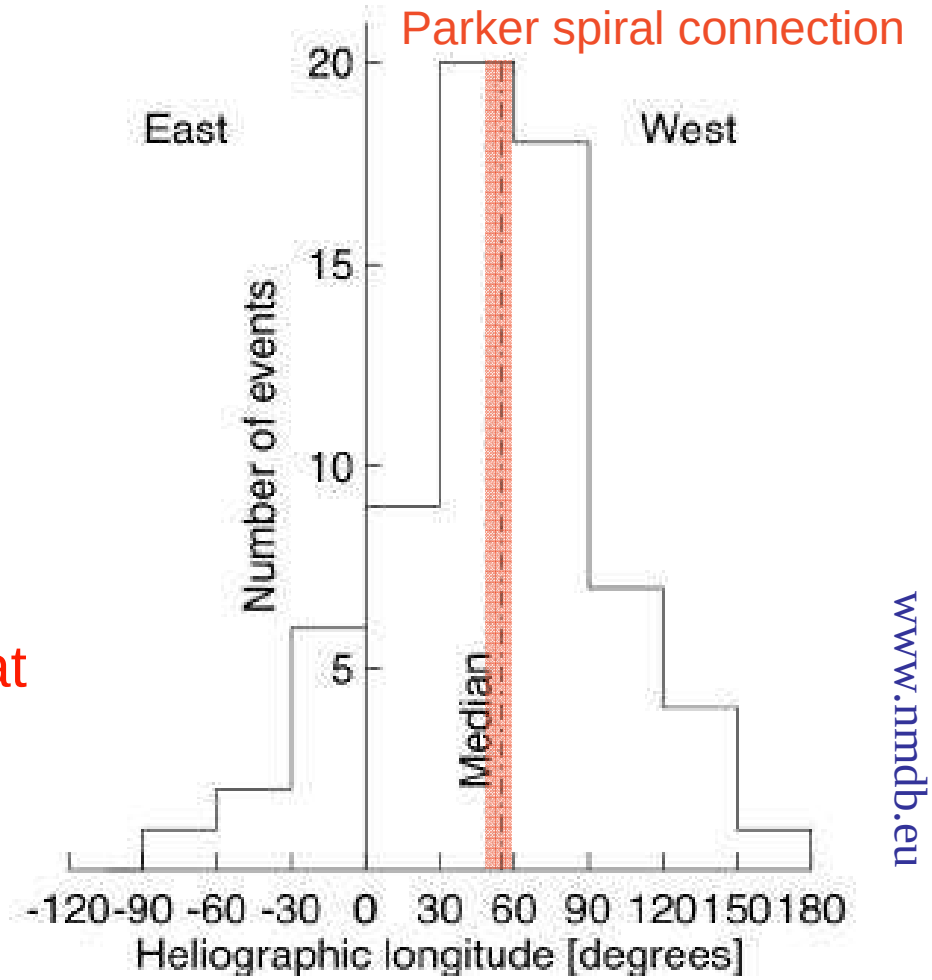
• Delay between the arrival time of the first **relativistic protons at the Earth** (=ground level enhancement or GLE) and various electromagnetic signatures of particle acceleration.

Carmichael (1972), Kodama et al. (1977), Cliver et al. (1982), Kahler et al. (2003)

• Active regions associated to GLEs not always Earth-connected by the Parker spiral.

Cliver et al. (1982), Stoker (1994), Gopalswamy (2005)

Why is there a systematic delay, and what determines the magnetic connection ?



The timing and connection problem

- **How to explain the delay and the connection problem**

- Acceleration by the CME's shock high in the corona

Kahler (1994), Cliver et al (2004), Reames (2009)

- Delayed acceleration of energetic particles during the flare

Klein et al. (1999), Li et al. (2009)

- Particle diffusion during the interplanetary transport

Wibberenz & Cane (2006), Cane (2003), Richardson et al. (1991)

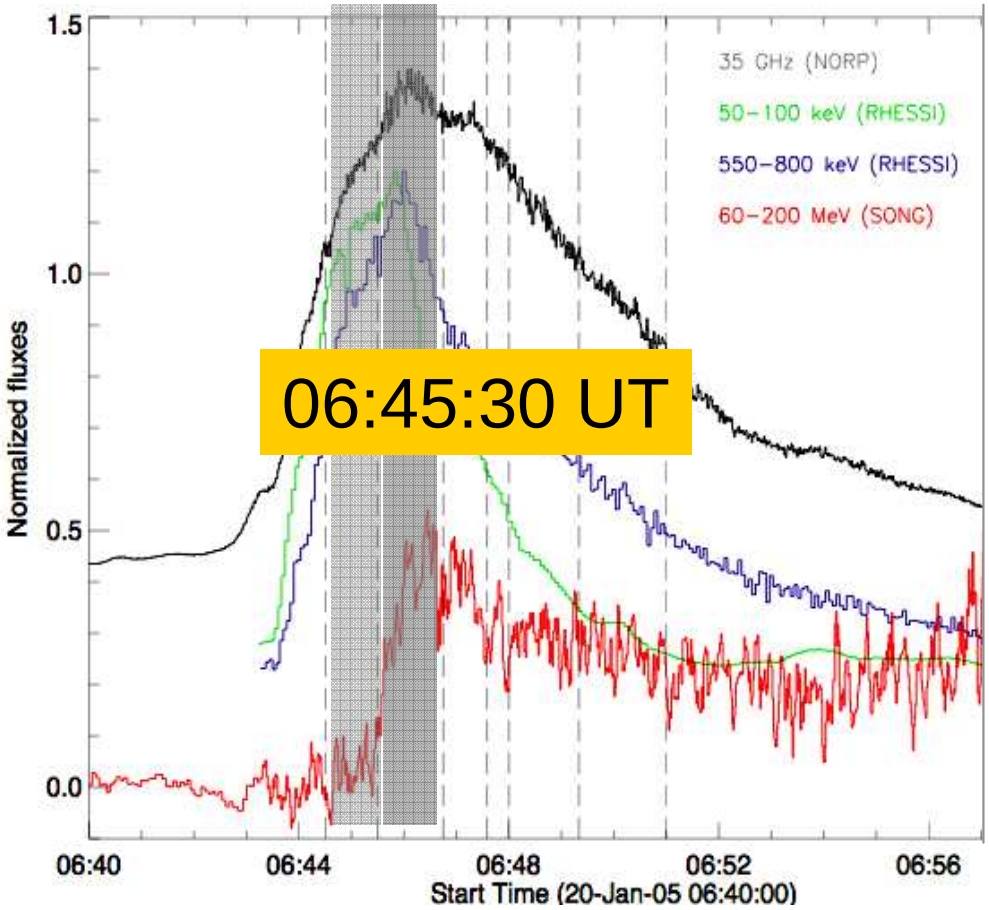
➔ **based on the propagation of particles along the Parker spiral**

Should we always consider the Parker spiral as the real connection between the acceleration site and Earth ?

Detailed temporal analysis

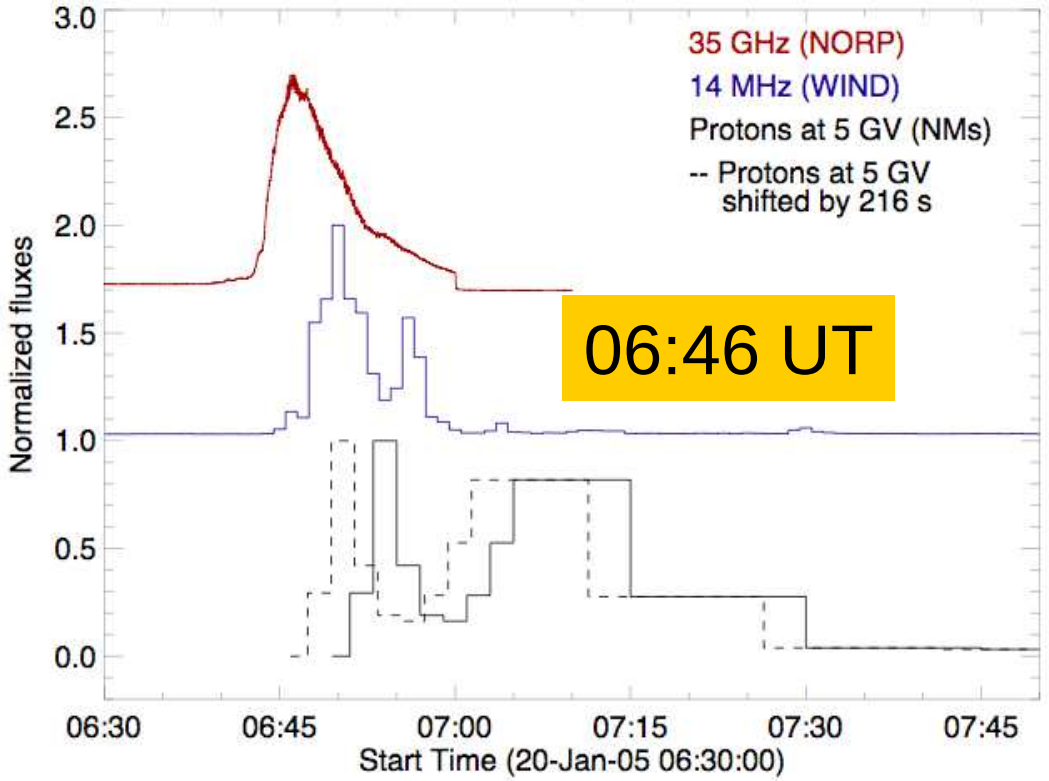
- **GLE on 20 January 2005**

Different episodes of acceleration



Delayed acceleration of the most energetic protons (>300 MeV) and electrons

Common release of radio emitting electron beams and relativistic protons



$$d = 1.4\ AU$$

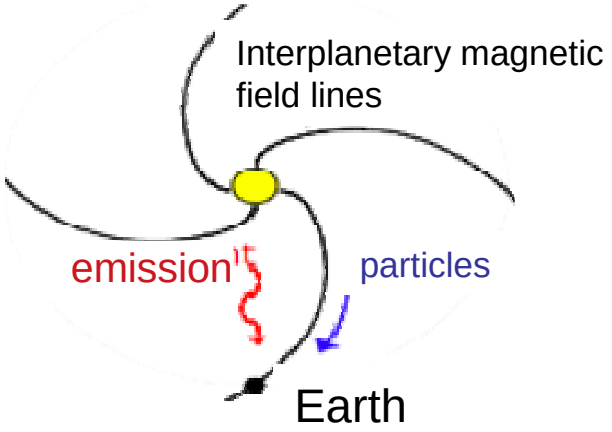
Longer than the nominal Parker spiral …

Masson et al. (2009)

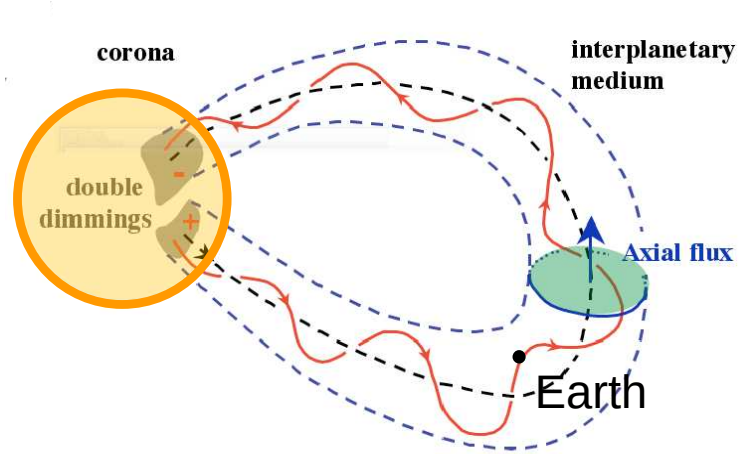
The interplanetary magnetic field (IMF)

- **Sun-Earth connections and IP path length**

Parker spiral
D ~ 1.2 AU



Interplanetary coronal mass ejection or magnetic cloud
D > 1.2 UA



- **Which IMF for particle propagation ?**

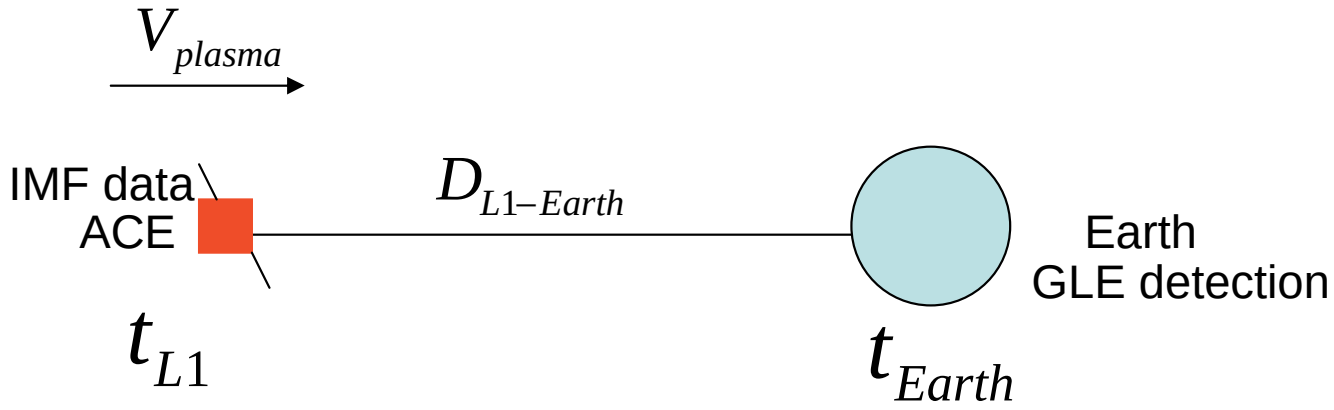
Measurements of the magnetic field and plasma parameters ➡ Magnetic structure of the IP space

In-situ particles measurements (Velocity dispersion analysis) ➡ { Length travelled by energetic particles ; Injection time of energetic particles

Magnetic structure of IMF during the GLE

Study of the magnetic structure for 10 GLEs of the 23rd solar cycle

- **Magnetic structure at L1 ➔ Earth:**



- **The time correction for magnetic and plasma data**

Plasma speed of the magnetic structure (PS or ICME)

$$\Delta t = \frac{D_{L1-Earth}}{V_{plasma}} \qquad t_{Earth} = t_{L1} + \Delta t$$

We shifted in time the magnetic and plasma data for each GLE

Magnetic structure of IMF during GLE

- **Magnetic field and plasma measurements (ACE / MAG and SWEPAM)**

Parker spiral (quiet IMF)

B non coherent, $B_{mag} \sim 5$ nT + $\beta_p \sim 1$ + $T_{exp} \sim T_{obs} \sim 2.10^5$ K

(Lopez & Freeman, JGR 1986; Elliot et al., JGR, 2005)

Interplanetary coronal mass ejection

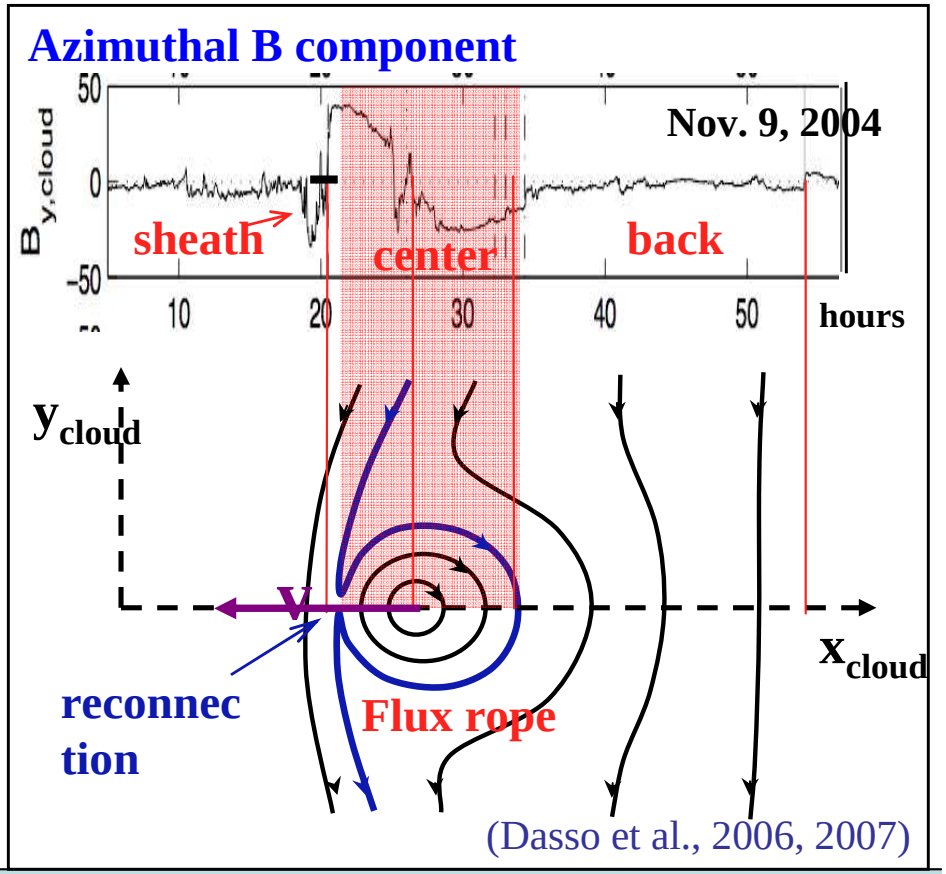
- Increase of B_{mag} , high coherent B_{mag}

+ $\beta_p < 1$ + $T_{exp} > 2\ T_{obs}$

(Liu et al., 2005; Ebert et al., 2009)

- Magnetic Cloud = rotation of B + low T_p

- **Back** of ICME or MC : discontinuity of **B** components



(Dasso et al., 2006, 2007)

Example 1: Parker spiral

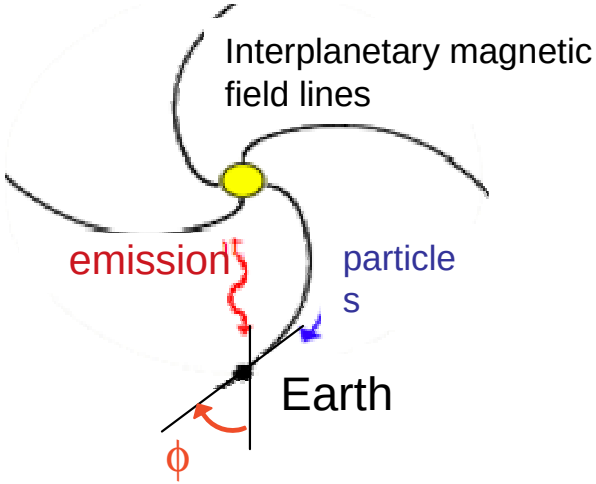
Magnetic field : non coherent and low B_{mag}

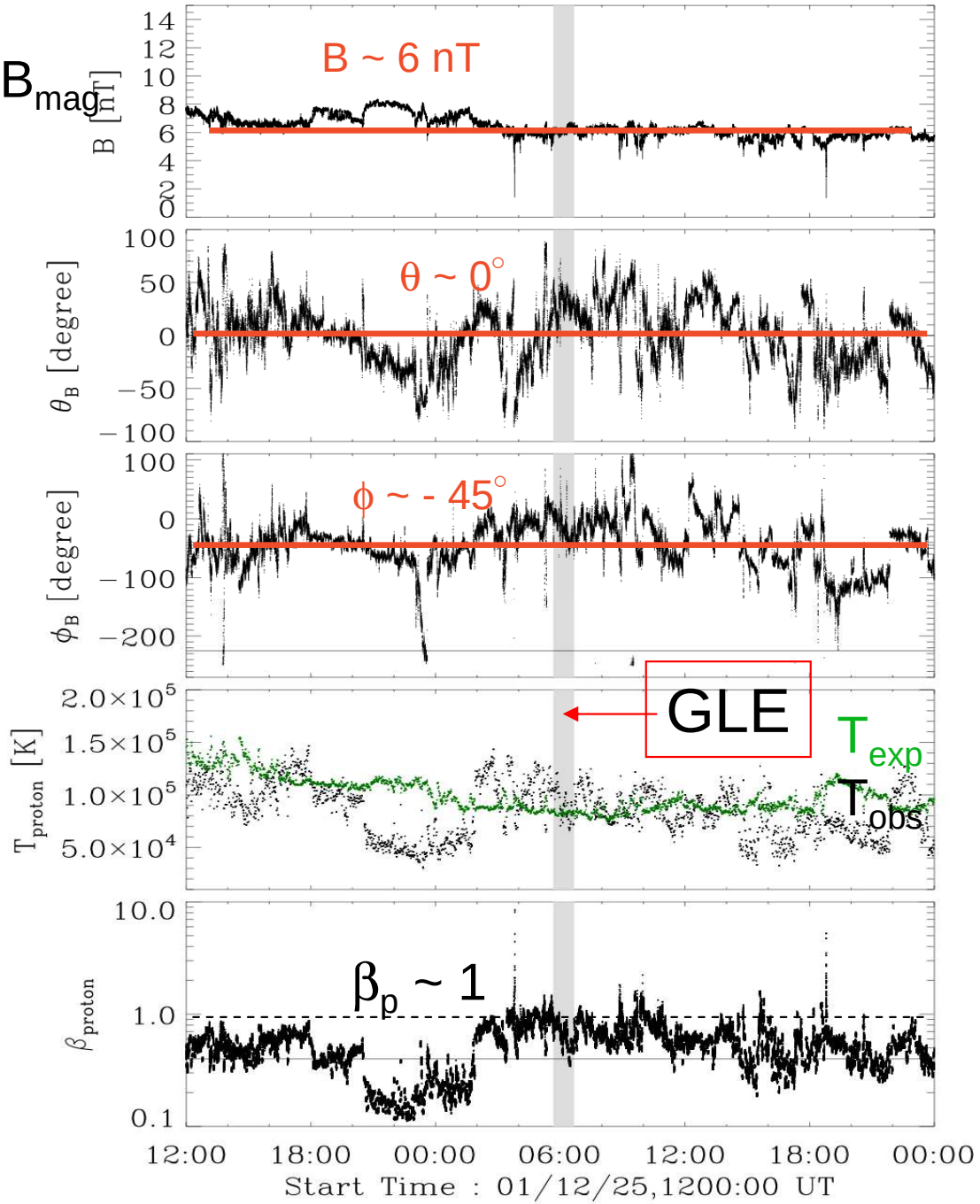
+

Plasma parameter :

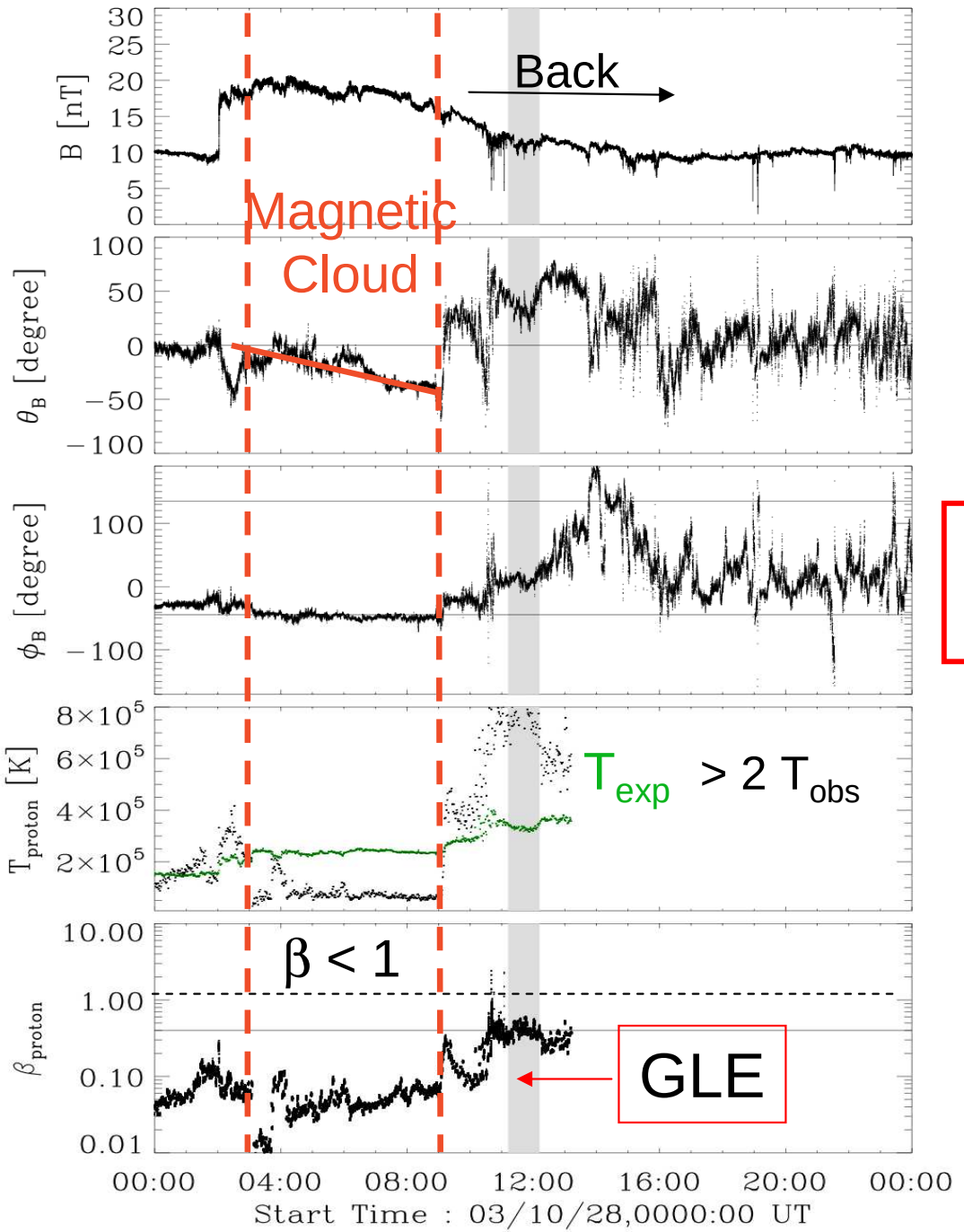
$\beta_p \sim 1$ and $T_{exp} \sim T_{obs} \sim 2.10^5$ K

Propagation along the Parker spiral in a quiescent solar wind





Example 2: Back of a Magnetic cloud



Propagation of particles in the back

An ICME presents the same characteristics but it is not a flux rope = no B rotation

Interplanetary length and solar release time

- **Velocity dispersion analysis**

  - Starting time of relativistic proton flux at Earth (Neutron monitors)

    (Moraal et al., ICRC, 2009)

  - Proton fluxes measured by the 5 lowest energy channels: 12- 40 MeV (SoHO / ERNE) ➔ starting time http://www.srl.utu.fi/erne_data/

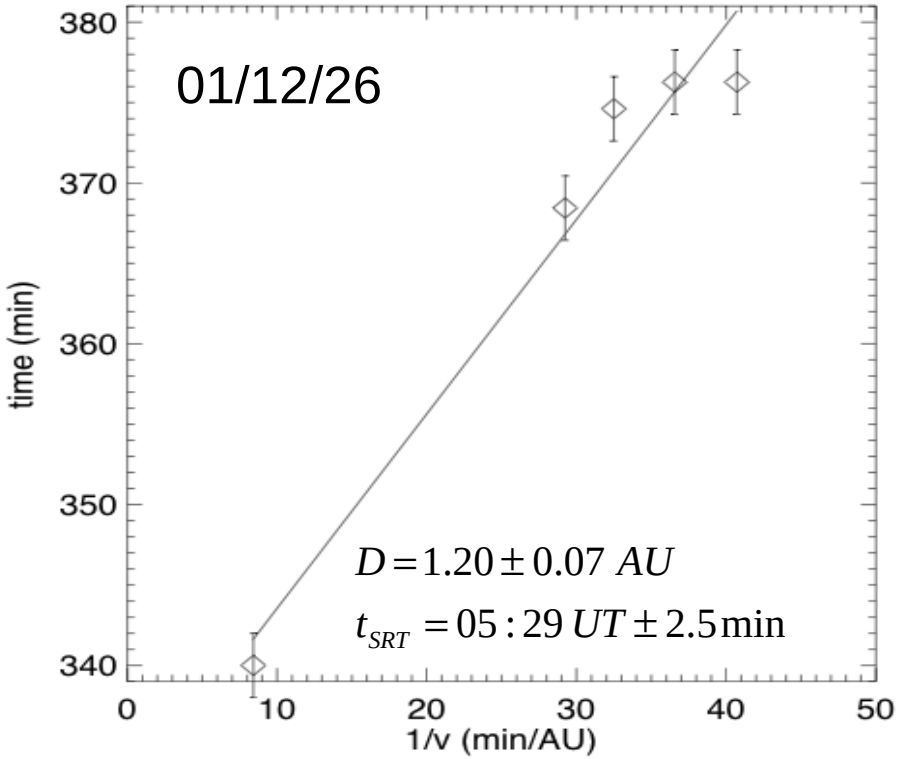
    (t_{onset} : crossing between flux and background + 3σ)

➔ **Assuming that all particles are injected simultaneously**

Interplanetary length

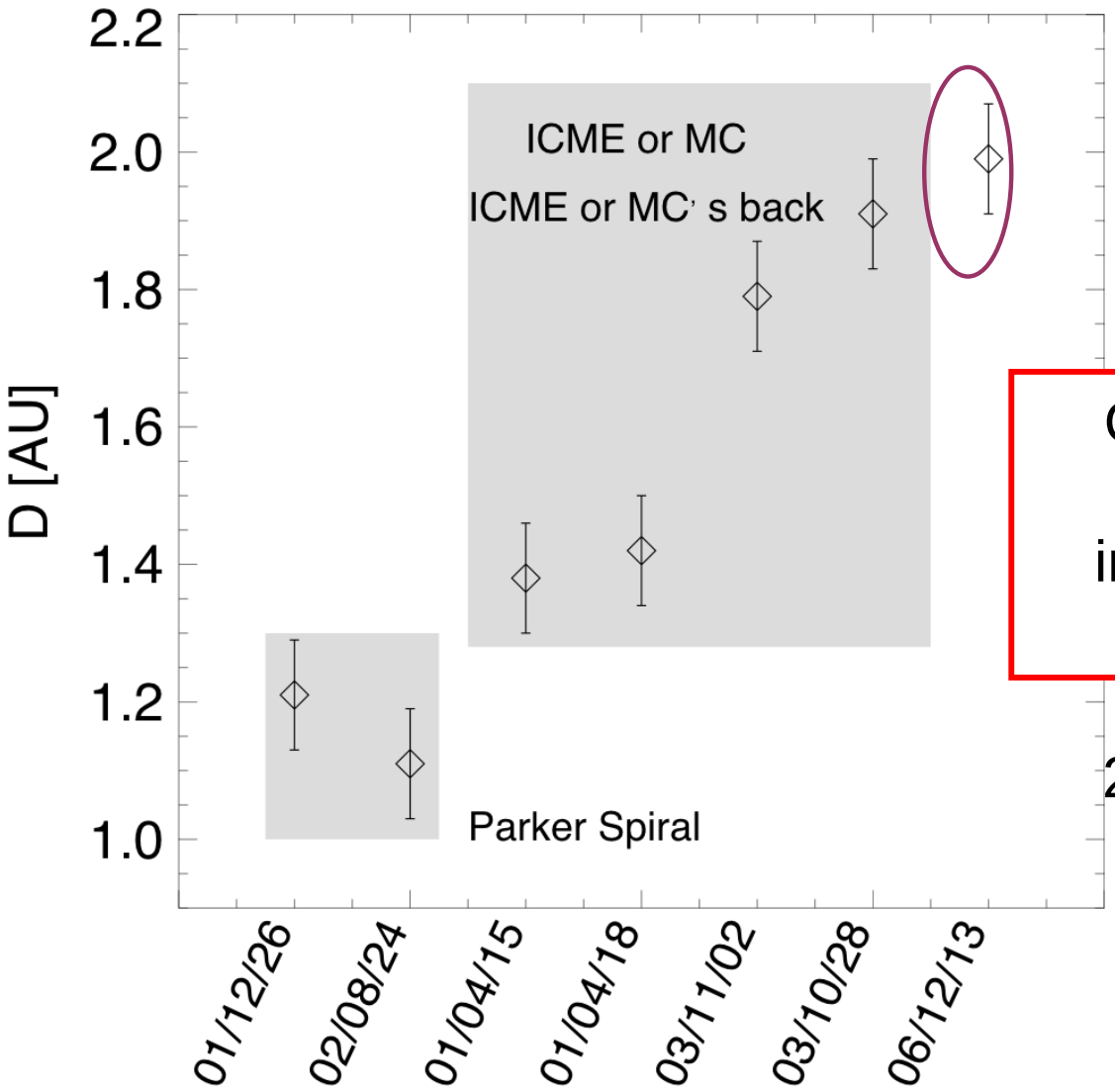
Solar release time

$$t_{onset} = \frac{L}{V_p} + t_{SRT}$$



Performing on 7 events (missing data)

Interplanetary length versus magnetic structure



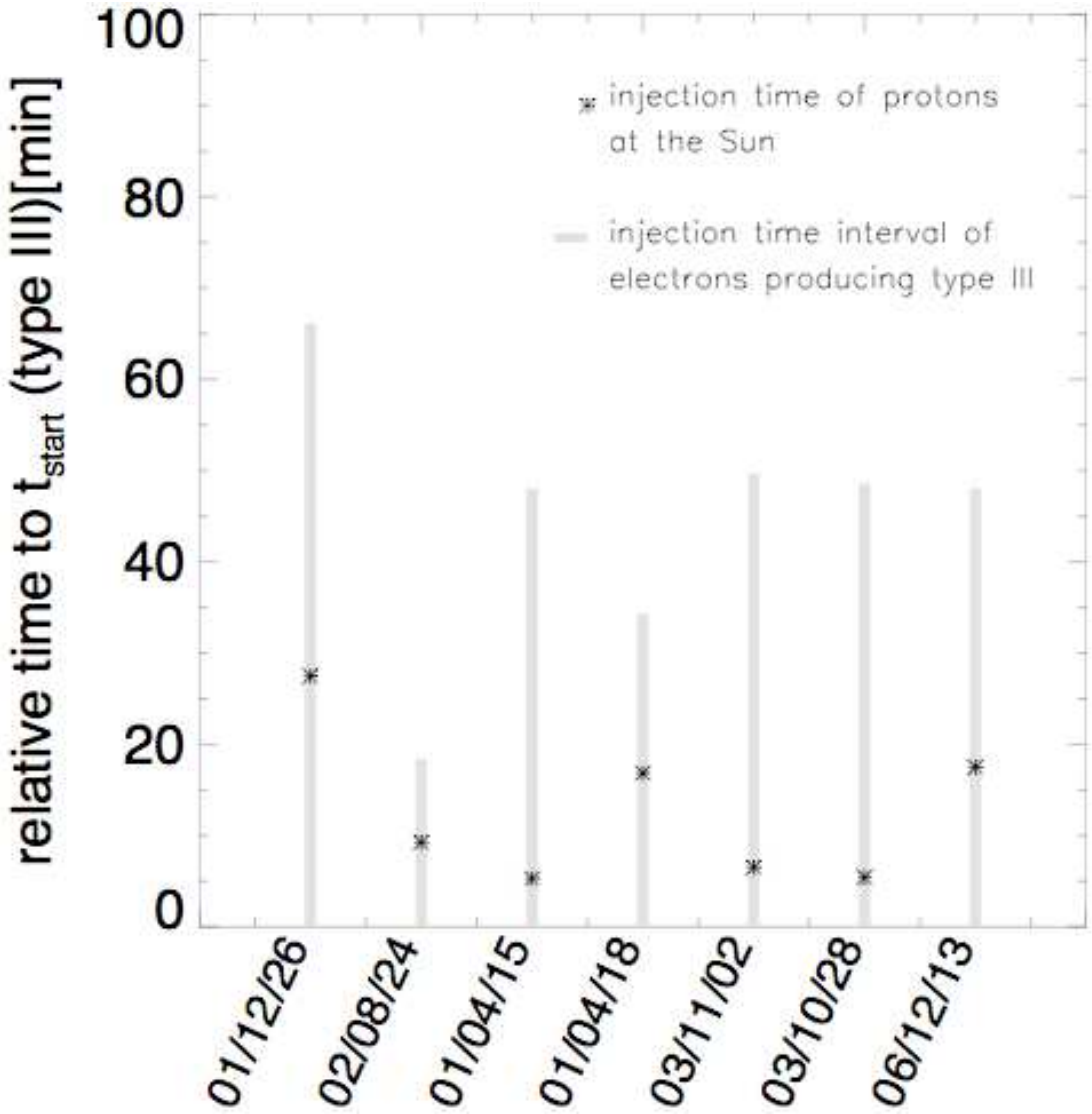
Consistent results between path length and interplanetary magnetic structure (7 GLEs)

28 /10 /03: relativistic particles travel 2 AU

(Miroshnichenko et al., 2005)

2006 December 13: Interplanetary structure like Parker spiral and a travelled length of 2 AU ➔ Shock acceleration or delayed injection ???

Solar release time versus electron type III injection



Timing comparison of the injection time of protons at the Sun and the interval during which electrons are injected and produce type III burst.

Time interval of the main group of type III bursts:

$\Delta t_{typeIII}$ ➔ background + 3σ

Protons are injected during electron injection

Conclusion

- **Results**

From two independent studies: - magnetic structure of the IMF
- velocity dispersion analysis (travelled length)

➔ consistent results for interplanetary length and the injection time

- **What is new for the understanding of solar relativistic particles?**

➔ Interplanetary geometry plays a crucial role in the timing problem.

Delay can be explained not only by the interplanetary magnetic field structure, and not only by IP diffusion or by (a priori delayed) shock acceleration.

➔ An essential constraint to associate the solar phenomena to particles acceleration

Could affect the conclusion on the solar mechanism at the origin of the acceleration