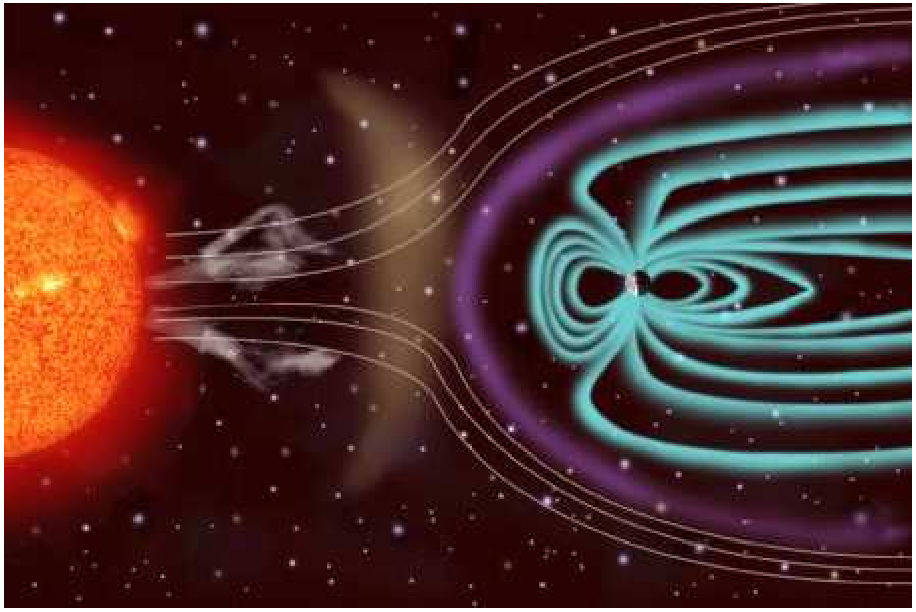
# The shocking Shock Physics: what do we know about the ion acceleration mechanism?



Árpád Kis,

*Research Centre for Astronomy and Space Sciences, Geodetic and Geophysical Institut, Sopron, Hungary*

Short introduction to Shock Physics

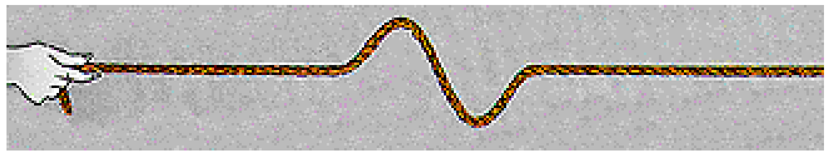
1. The shock wave
    2. The Earth's Bow Shock
    3. Ion populations at the quasi-parallel bow shock

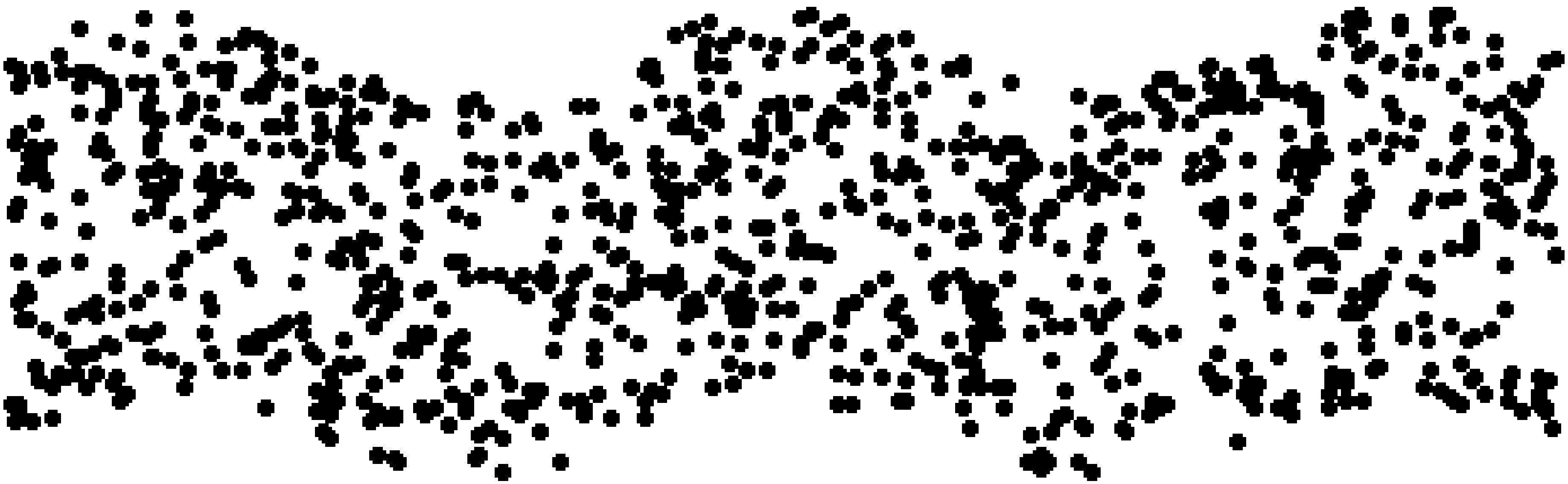
Ion acceleration at the quasi-parallel bow shock

1. The first-order Fermi acceleration
2. The problem of injection
3. Scattering of energetic ions

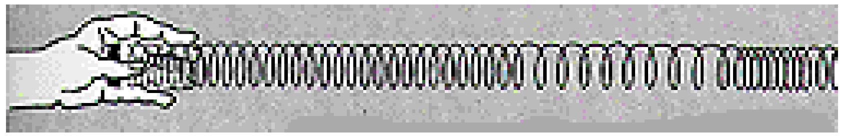
# About waves in general

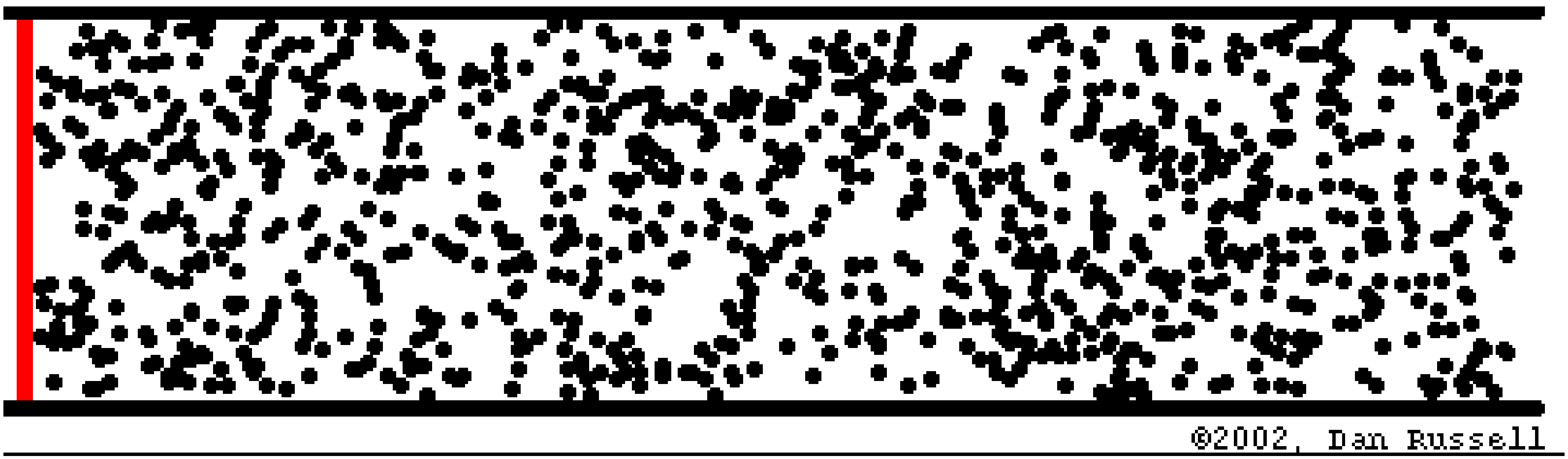
# Transversal wave





# Compressional wave





**Important points to remember:**

- in an ordinary gas the collisions between the gas particles transfer momentum and energy

- after the wave passes, the medium (the gas) returns to its original state (no increase in temperature and density

- the process is reversible

- and the process is adiabatic

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**What happens if a disturbance travels faster than the speed of the sound?**

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**What happens if a disturbance travels faster than the speed of the sound?**

**→ a shock wave is developed!**

**The shock wave differs significantly from the sound wave:**

**- rises the temperature of the medium**
**- rises the density of the medium**
**- affects the medium irreversebly**

**while the medium is slowed down to subsonic velocity**

Turbulent, “shocked” medium    Shock wave    Undisturbed medium

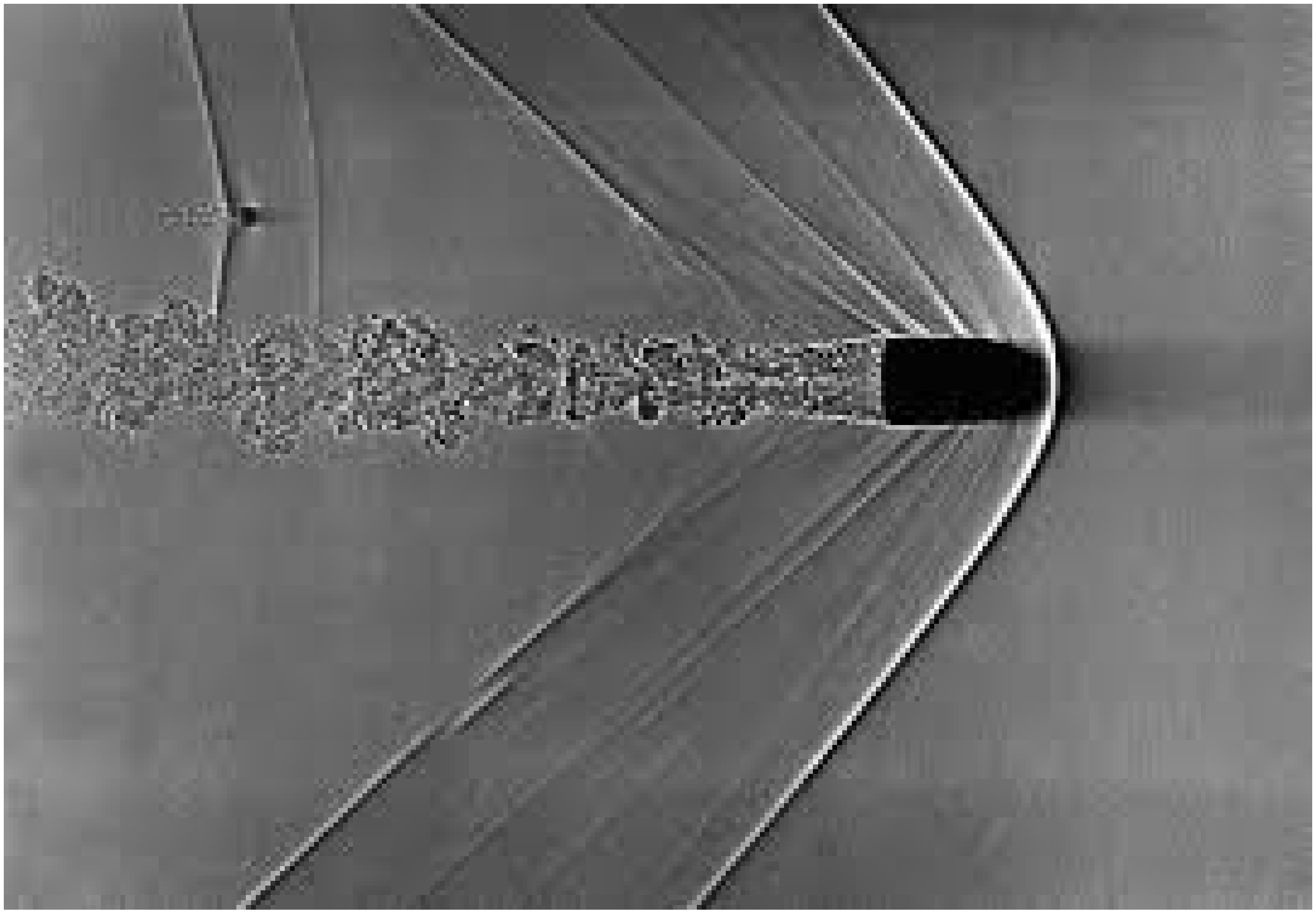
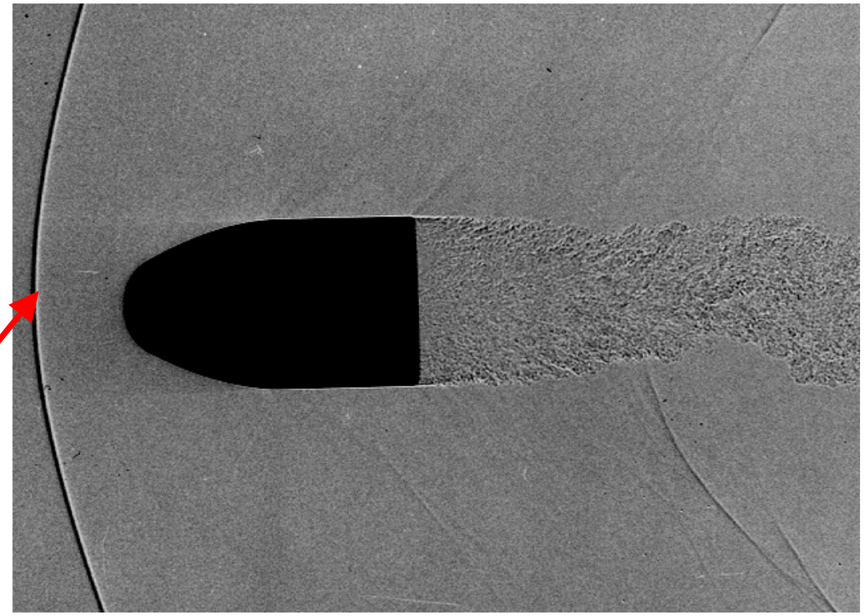
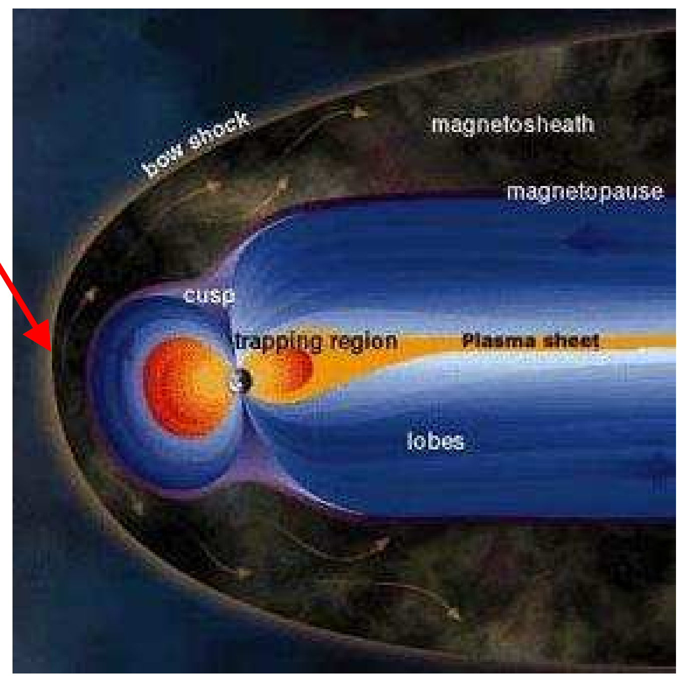


Photo by NASA

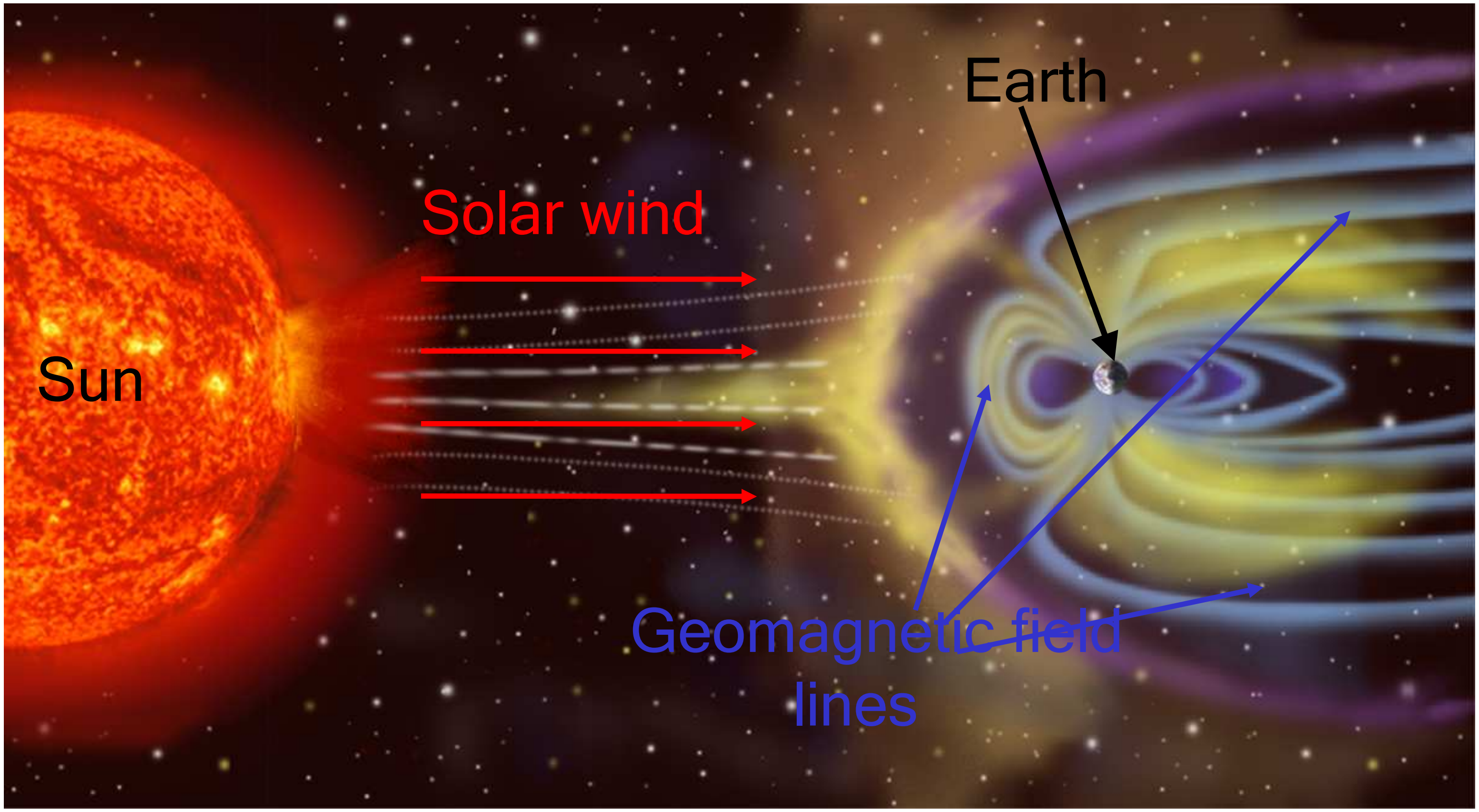
You are familiar with the shock wave since you know **Thor**!



Bow Shock


bow shock
magnetosheath
magnetopause
cusp
trapping region
Plasma sheet
lobes

# Sun-Earth connection: the outer boundary




When spacecraft were developed, it was discovered that the interplanetary space is dominated by a rare, magnetised, high-velocity plasma flow, consisting of a neutral mixture of electrons and nucleii: the solar wind.

When the supersonic solar wind reaches the Earth's magnetosphere, a shock wave, the bow shock is formed. The solar wind is slowed down to subsonic speed, while the plasma is heated and its density and the magnetic field magnitude increases.

**Important points to remember:**

- the solar wind is a **collisionless plasma**, where practically there are no collisions between the particles

- the mean free path for Coulomb collisions is larger than the size of the system

- The discovery of the Earth's bow shock (Ness et. al., 1964) demonstrated that shock waves can exist in collisionless plasmas.

- Since the solar wind flow is continious, the Earth's bow shock is “standing” shock regarded from our planet

- the main challenge posed by the existence of a collisionless bow shock is to understand how the dissipation takes place in a collisionless medium

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- the main challenge posed by the existence of a collisionless bow shock is to understand how the dissipation takes place in a collisionless medium.

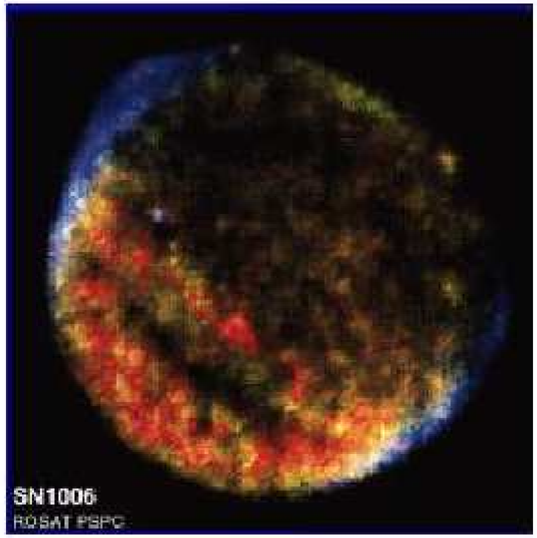
**Now why do we study the Earth's bow shock?**

1. Collisionless shocks have their scientific importance in their own right

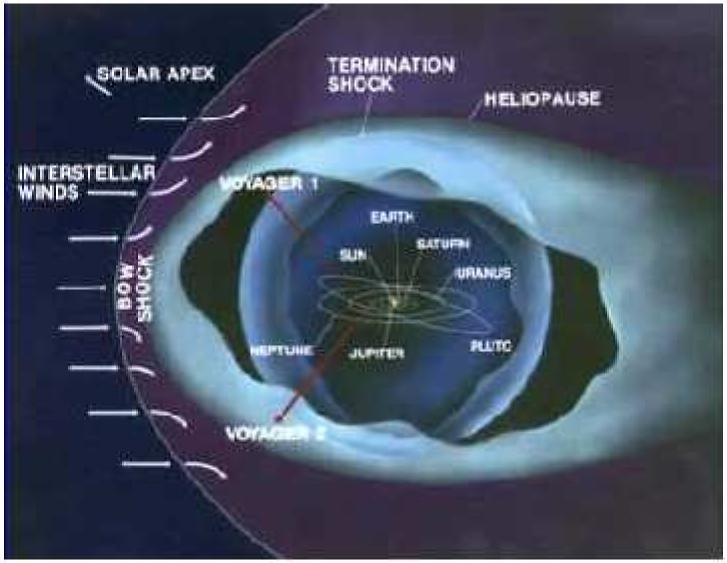
2. They are involved in a very wide range of phenomena

3. They are known to accelerate ions to high energies: they are very efficient particle accelerators!

# The Universal Shock Wave

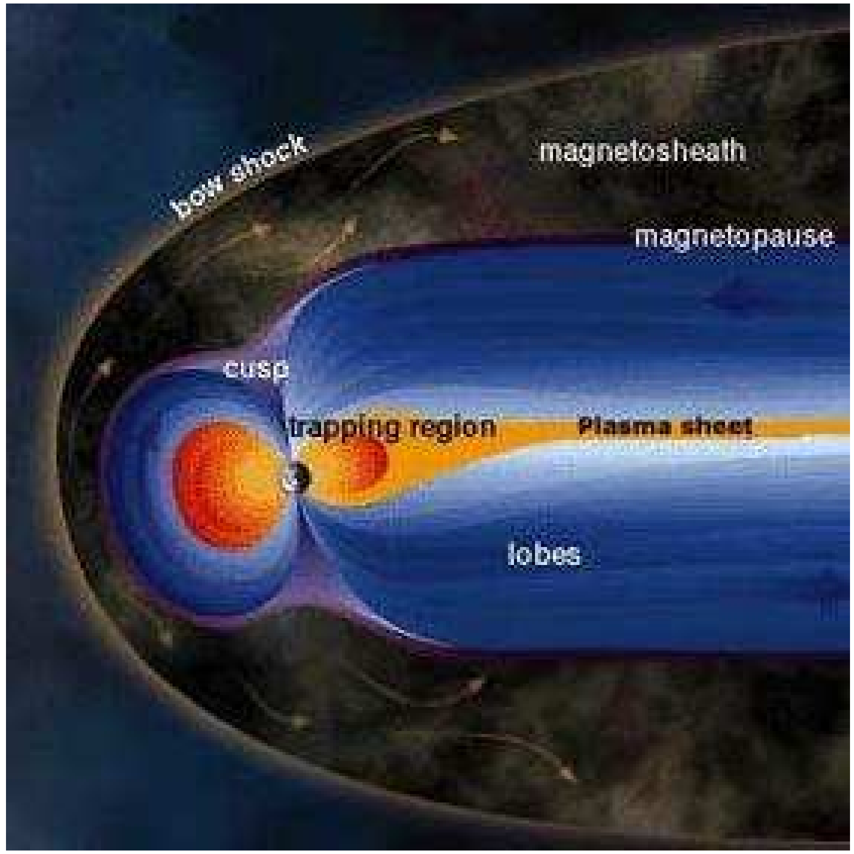



*(ROSAT)* SUPERNOVAE




TERMINATION SHOCK

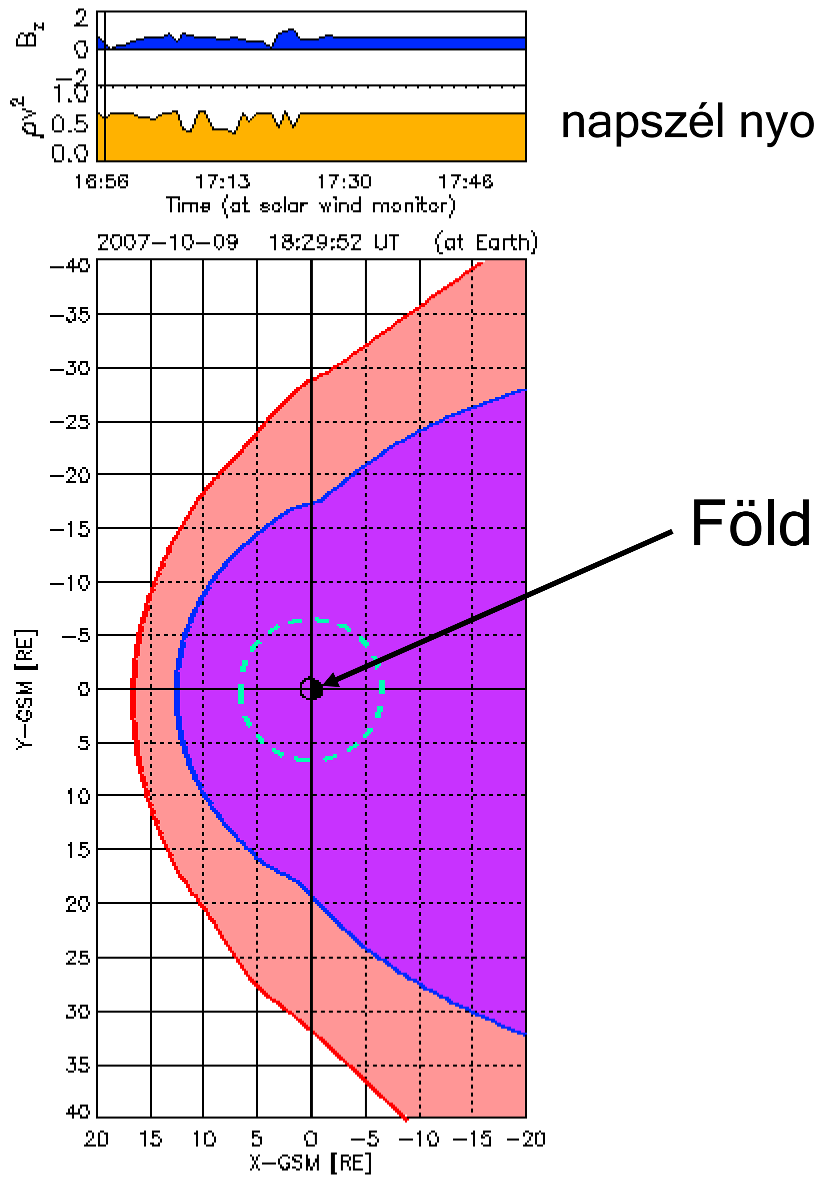
*(NASA)*




The Earth's bow shock is a natural “space plasma laboratory”.
This is the only bow shock, which characteristics and shock-related phenomena can be studied in detail by in-situ (SC) measurements, even by simultaneous multi-spacecraft measurements.

napszél nyomása

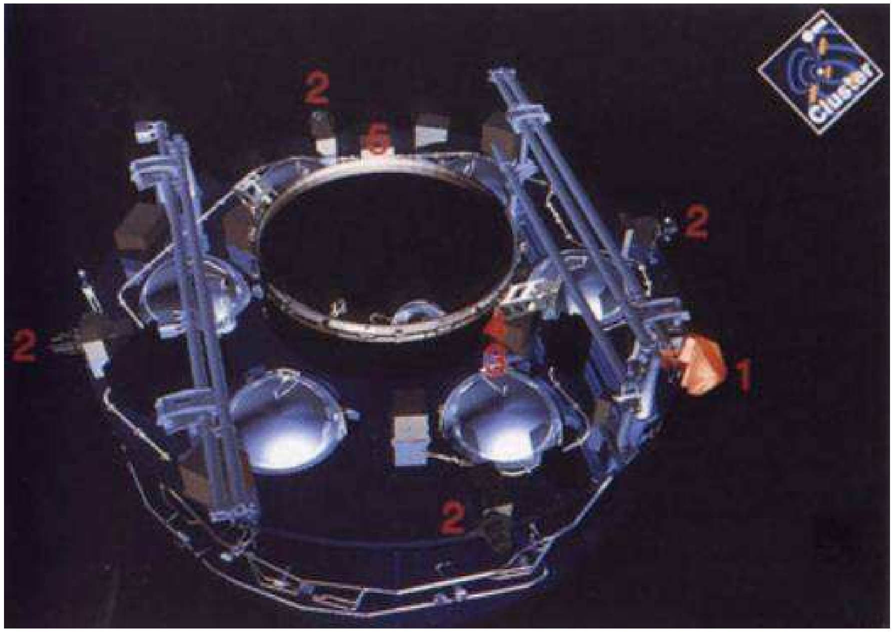
a napszél nyomásában megjelenő változásokra a földi mágneses tér és a lökéshullám igen érzékeny dinamikával válaszol



# The Cluster Mission

The **Cluster** mission of the **ESA** (European Space Agency) is one of the most successful space missions.

Since the beginning of this mission more than 2009 (!) peer-rewieved articles were published.



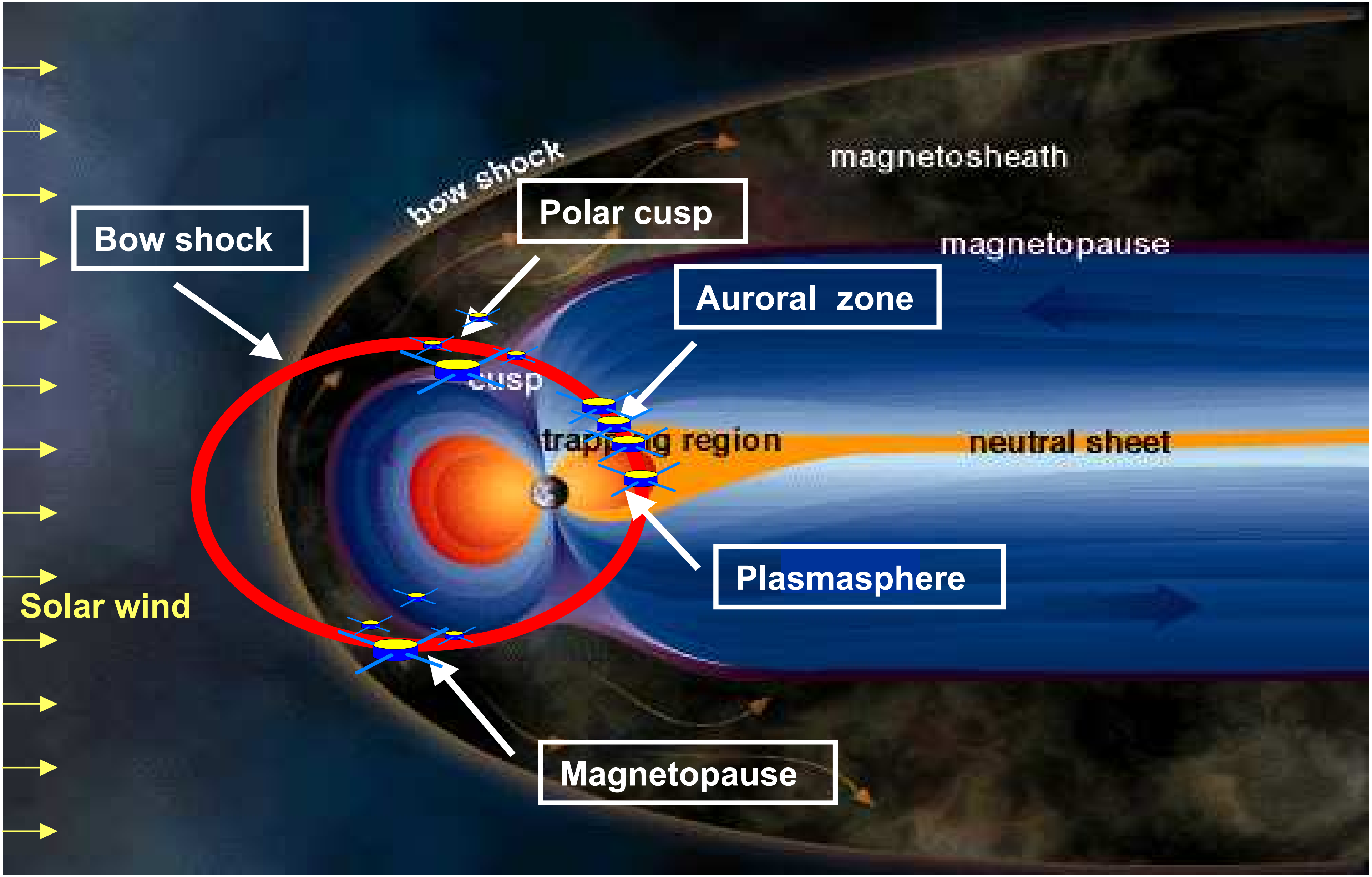


Four identical spacecraft, each contains 11 instruments.

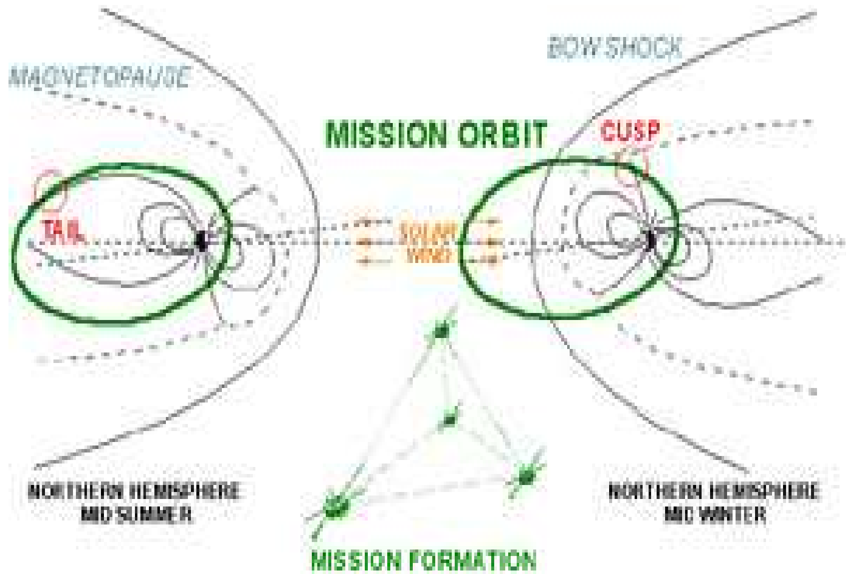
It was designed to provide information of all aspects of space plasma physics phenomena

With Cluster multispacecraft mission it becomes possible:

1. To separate the spatial variations from the temporal ones
2. To study individual upstream ion events



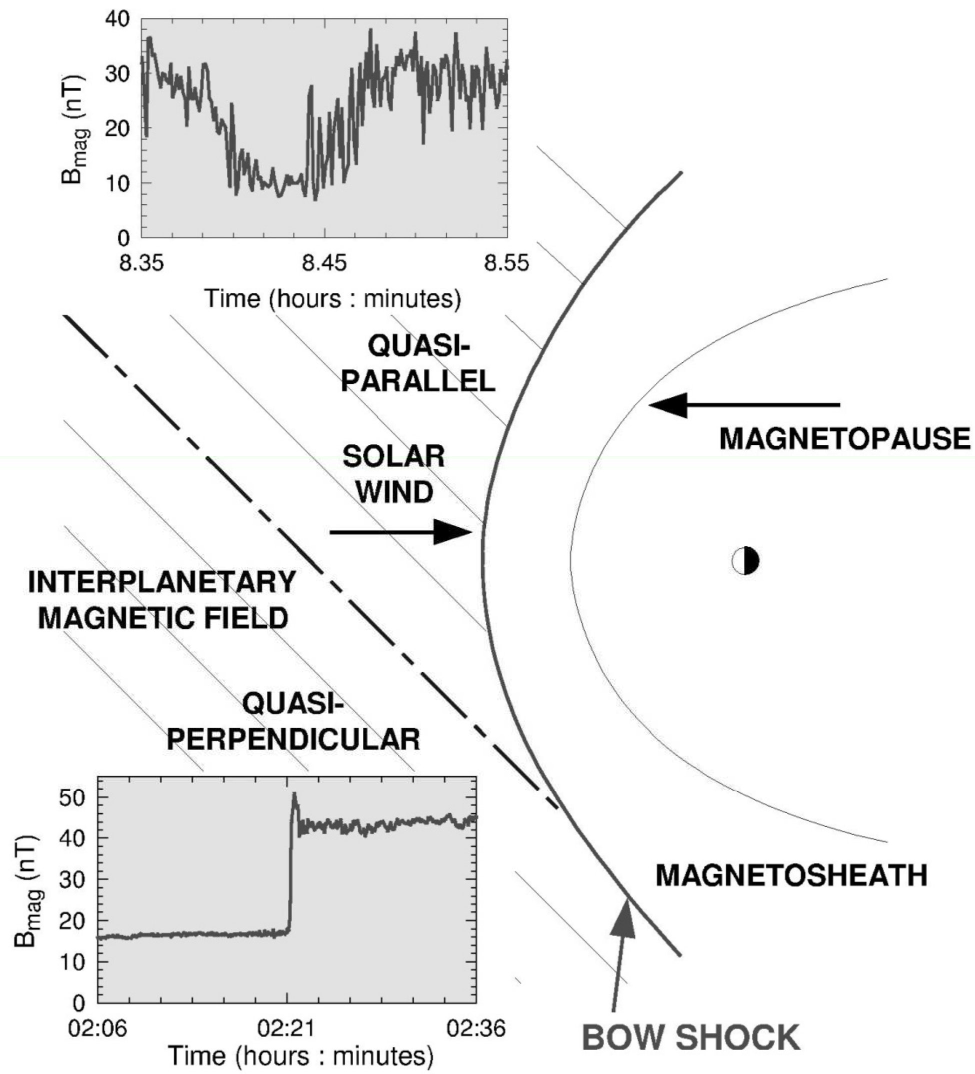

Cluster orbit in winter time period.

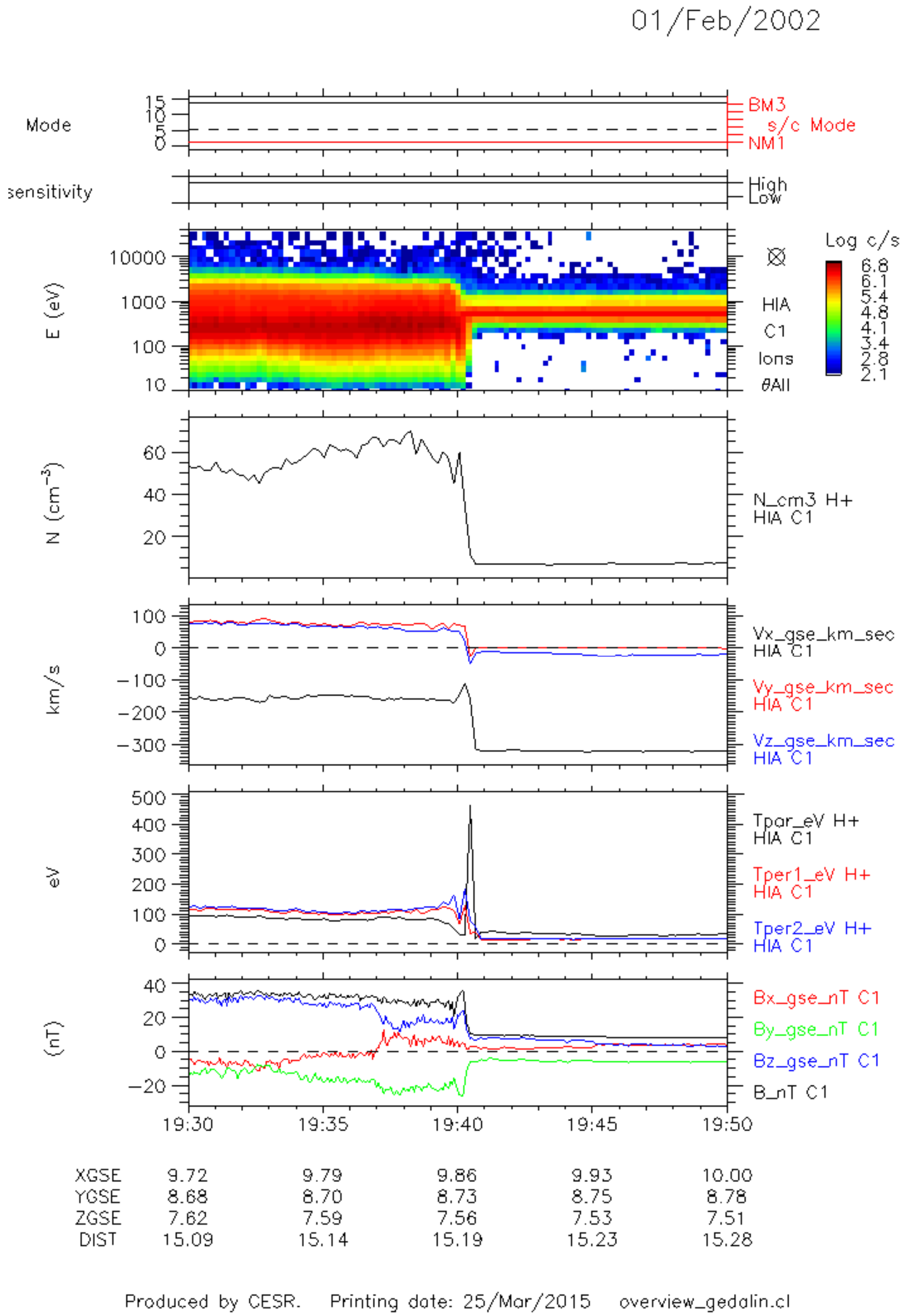



nyáron télen

A műholdak pályáit úgy tervezték meg, hogy minden fontos részét érintse a magnetoszféra területeinek, egy év alatt „végigsöpörve” a teljes magnetoszféra szerkezetét.

# Regions in front of the Earth's bow shock





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Mode
BM3
s/c Mode
NM1
sensitivity
High
Low
E (eV)
HIA
C1
Ions
θAll
Log c/s
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N_cm3 H+
HIA C1
km/s
Vx_gse_km_sec
HIA C1
Vy_gse_km_sec
HIA C1
Vz_gse_km_sec
HIA C1
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Tpar_eV H+
HIA C1
Tper1_eV H+
HIA C1
Tper2_eV H+
HIA C1
(nT)
Bx_gse_nT C1
By_gse_nT C1
Bz_gse_nT C1
B_nT C1
19:30 19:35 19:40 19:45 19:50
XGSE 9.72 9.79 9.86 9.93 10.00
YGSE 8.68 8.70 8.73 8.75 8.78
ZGSE 7.62 7.59 7.56 7.53 7.51
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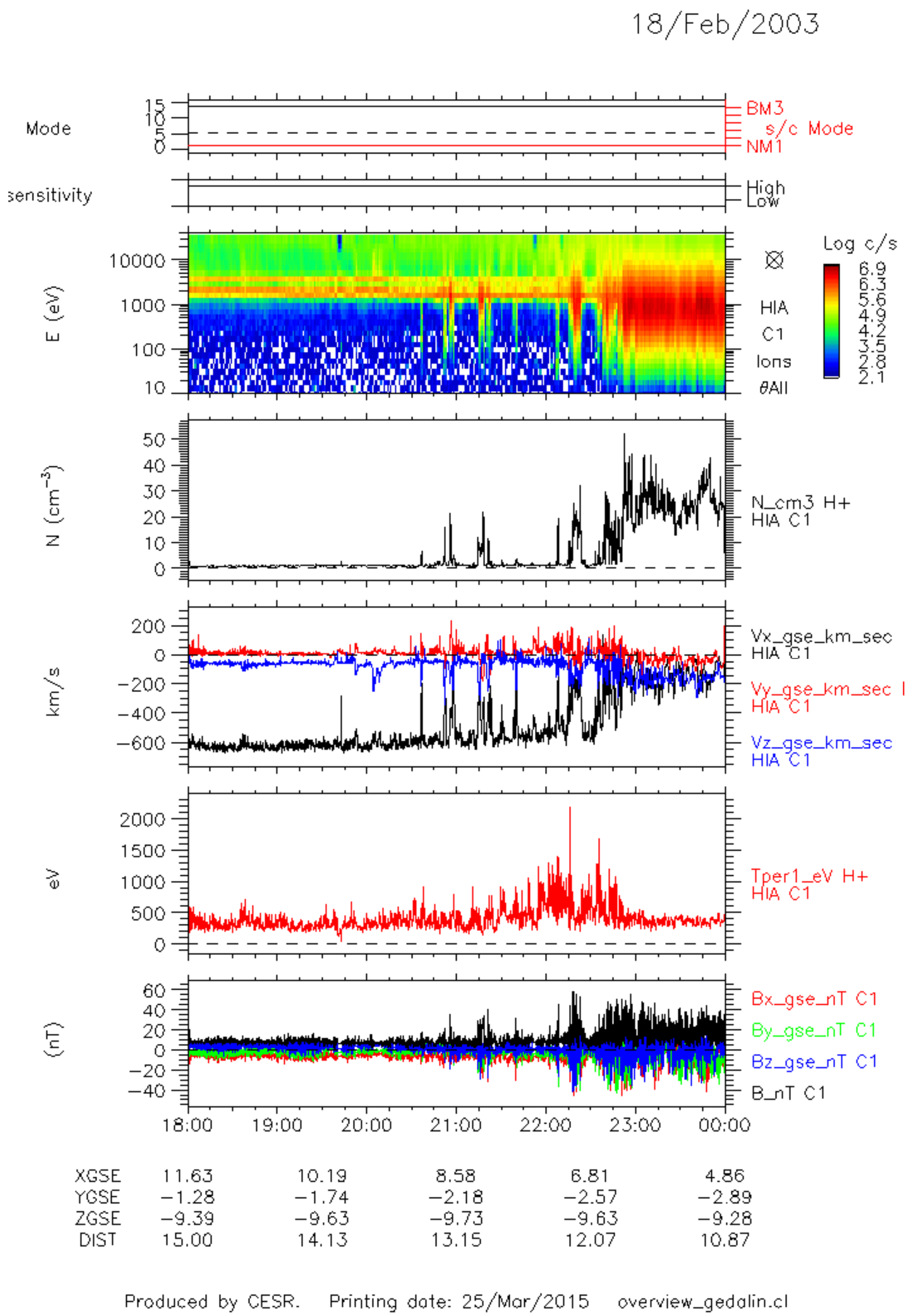
18/Feb/2003
Mode
BM3
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NM1
sensitivity
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E (eV)
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N (cm⁻³)
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Vx_gse_km_sec
HIA C1
Vy_gse_km_sec
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Vz_gse_km_sec
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18:00
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XGSE 11.63 10.19 8.58 6.81 4.86
YGSE −1.28 −1.74 −2.18 −2.57 −2.89
ZGSE −9.39 −9.63 −9.73 −9.63 −9.28
DIST 15.00 14.13 13.15 12.07 10.87
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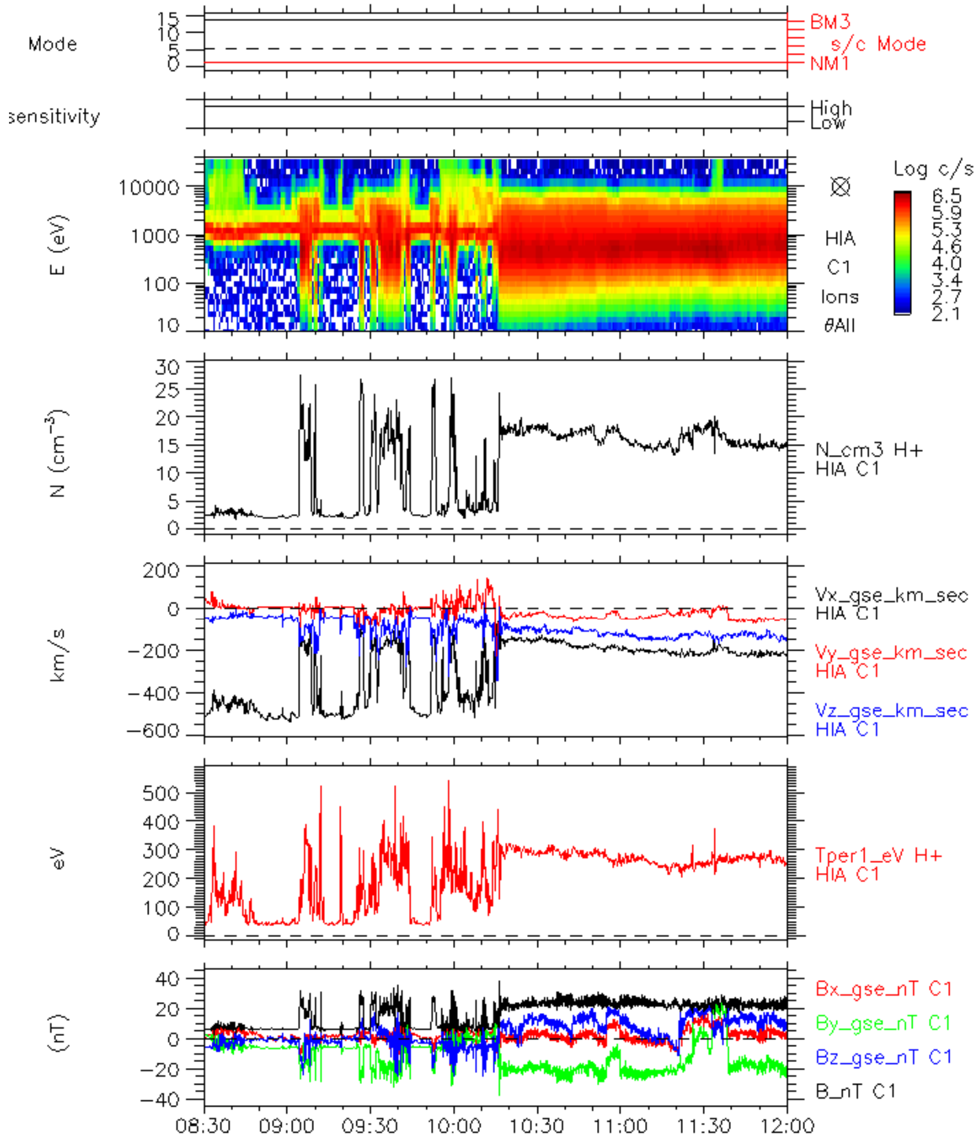
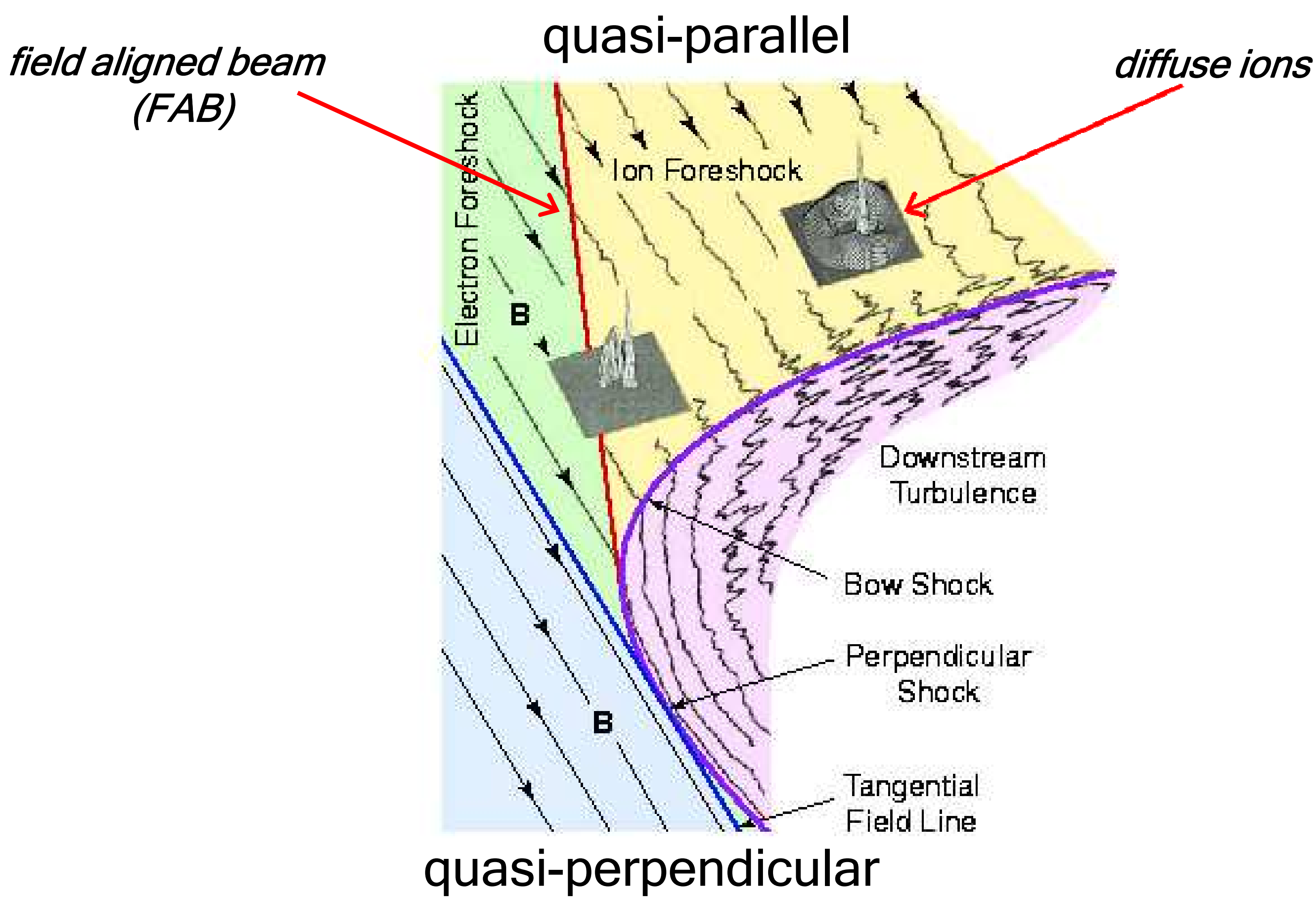


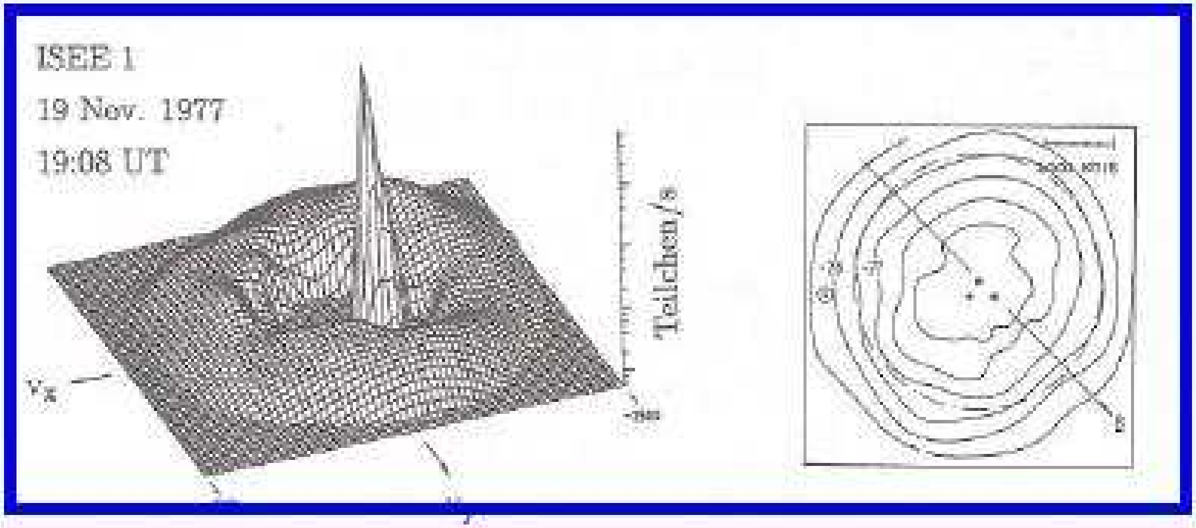

| | | | | | |
|---|---|---|---|---|---|
| XGSE | 11.92 | 11.13 | 10.28 | 9.40 | 8.45 |
| YGSE | −4.52 | −4.58 | −4.61 | −4.63 | −4.61 |
| ZGSE | −9.18 | −9.40 | −9.57 | −9.70 | −9.78 |
| DIST | 15.71 | 15.27 | 14.79 | 14.28 | 13.73 |

Produced by CESR. Printing date: 25/Mar/2015 overview_gedalin.cl

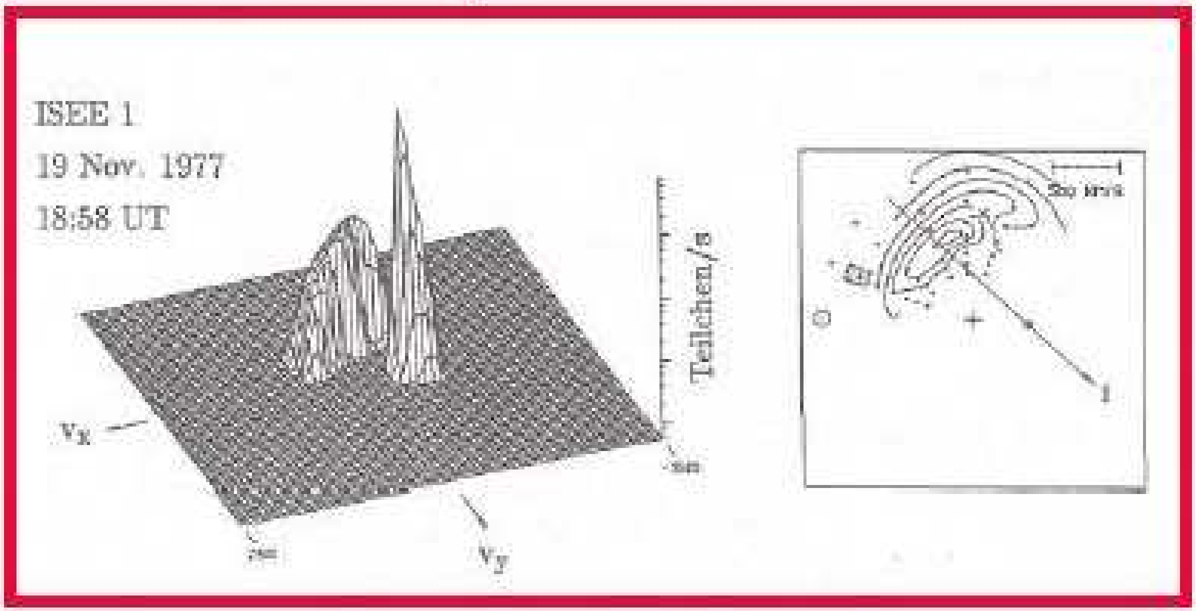
# Energized (accelerated) ions upstream of Earth's bow shock



# typical Diffuse and FAB ion distributions



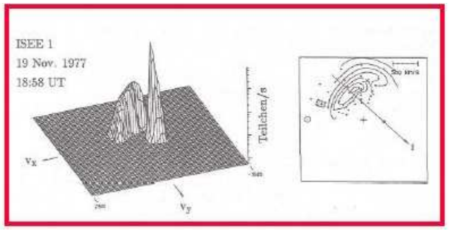

E≈10-300 keV



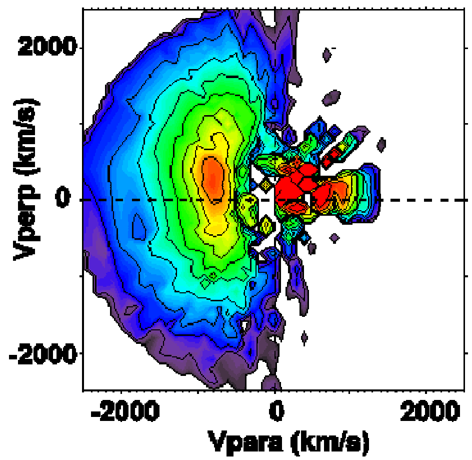

E≈4-7 keV
(v ≈ $2v_{sw}$)

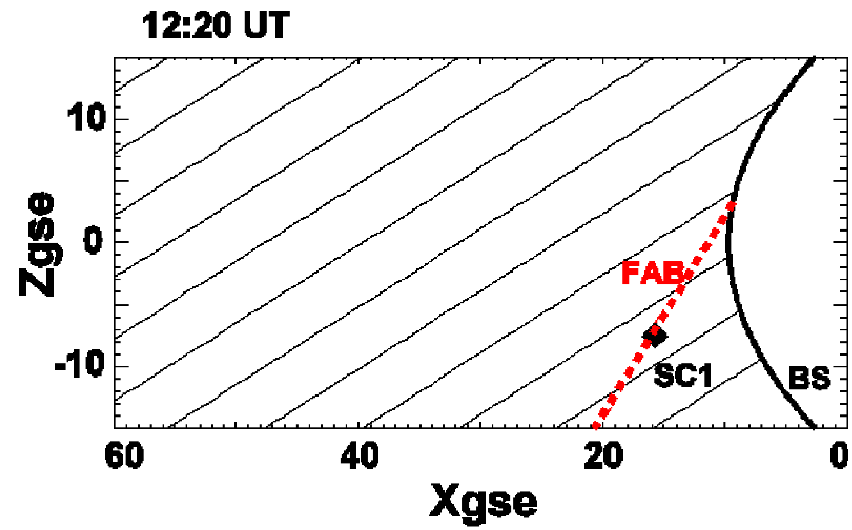
Paschmann et al (1981)

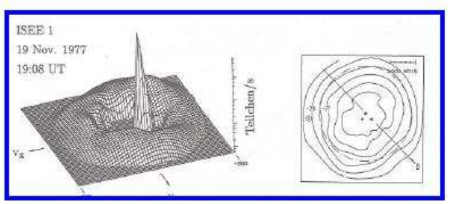
# 18 February 2003



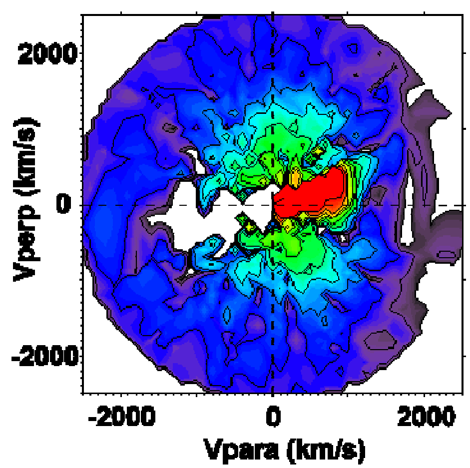

Field aligned beam ion distribution

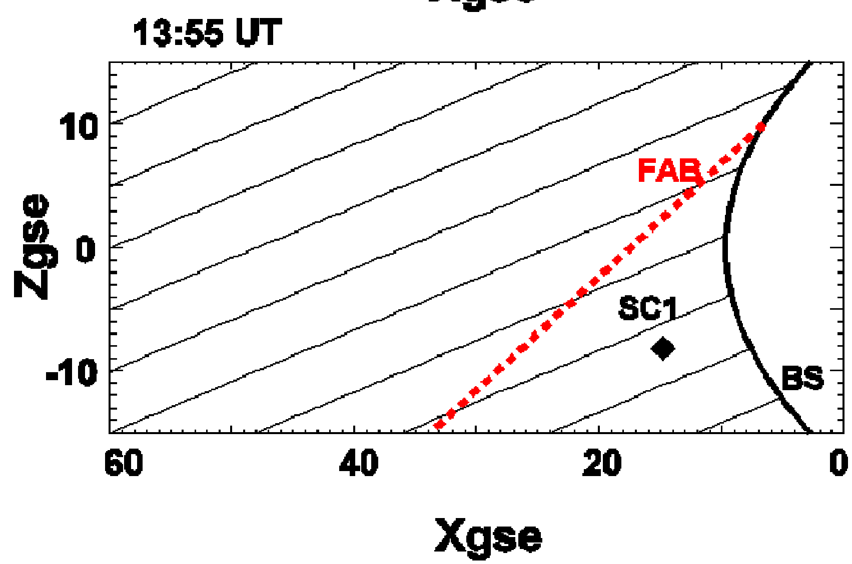


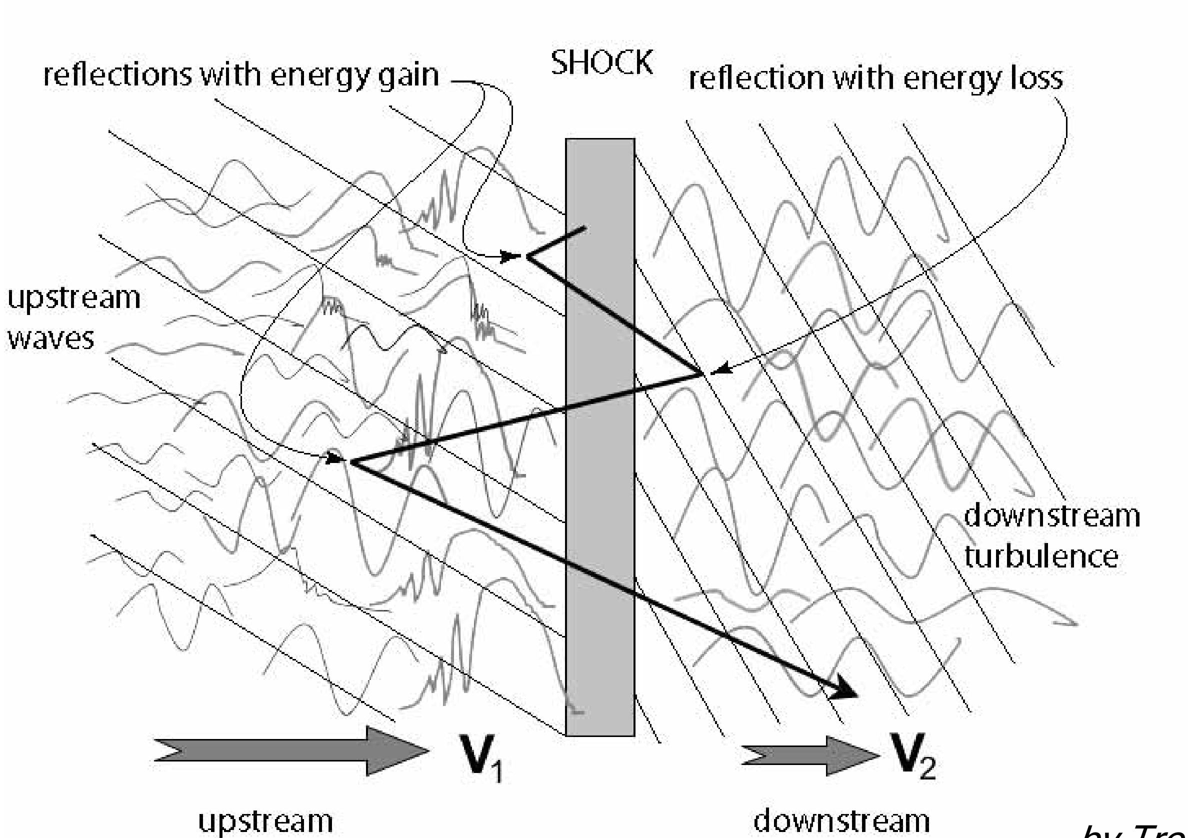

Diffuse ion distribution



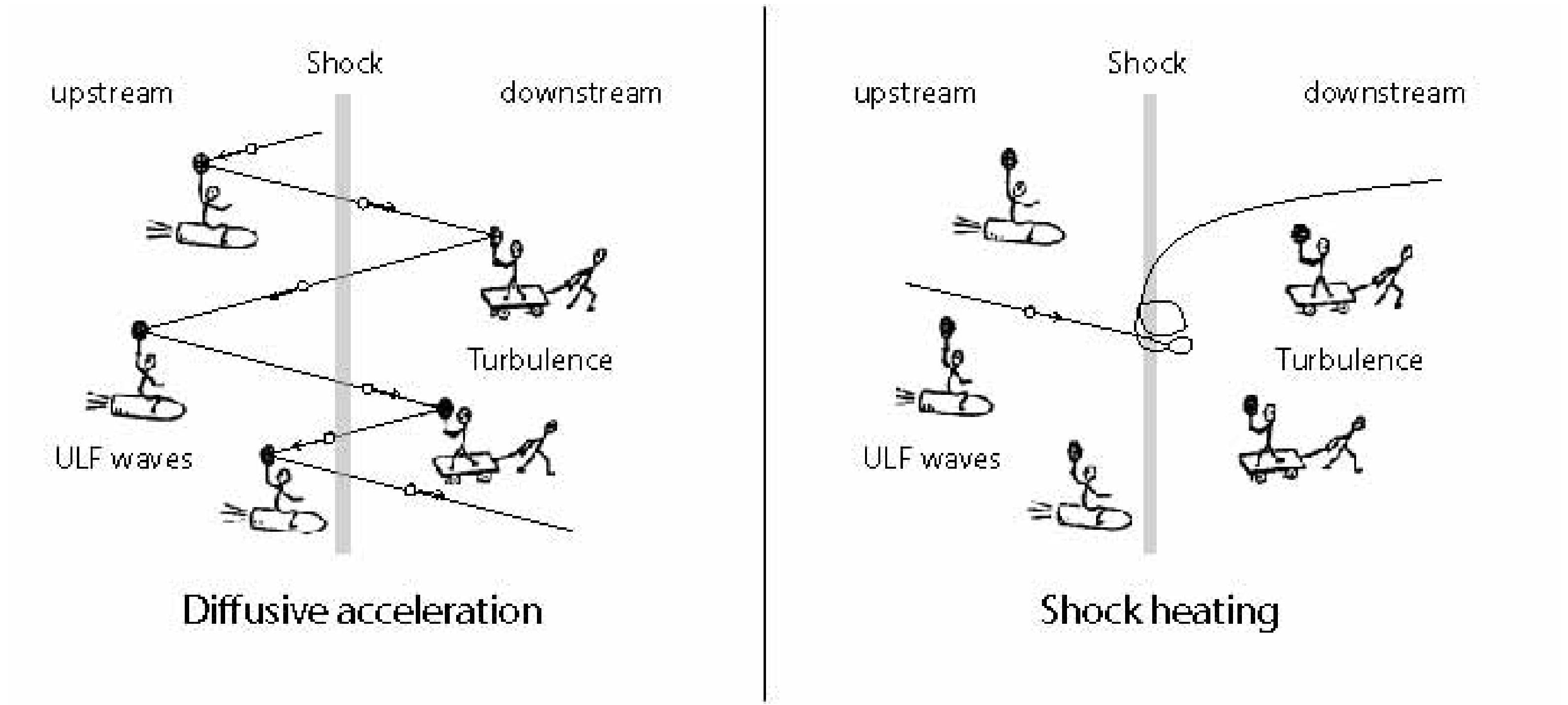
**The major mechanism responsible for particle acceleration by shock waves is the**

***Diffusive Shock Acceleration* (DSA) or *first-order Fermi acceleration***




*by Treumann et al.*

The concept




*Hoshino, 2001*

Cartoon (*manga?*) of the diffusive shock acceleration (left) and shock heating mechanism(right).

*(after an original sketch by Prof. Manfred Scholer)*

*The Earth's bow shock have been extensively studied for decades, but the details of shock acceleration are still not completely understood.*

**The acceleration to work efficiently there are some important conditions to be satisfied, as shown by**

***Malkov & O'C Drury (2001), Reports on Progress in Physics***
***and***
***D. Burgess, E. Möbius & · M. Scholer (2012), Space Sci Rev***

**These conditions are:**

a) some initial „seed” population (i. e., a lower energy supra-thermal ion population) should be created upstream or downstream of the shock that should be able to cross the shock front

***>> the question of injection***

b) there should exist scattering centers or objects around the shock front in its vicinity that will deviate particles from their free motion and will result in turning them to opposite direction

***>> pitch-angle scattering***

c) the exponential spectra of diffuse ions:

***>> free escape boundary?***

# The problem of injection

A reminder: some initial „seed" population (i. e., a lower energy supra-thermal ion population) should be created upstream or downstream of the shock that should be able to cross the shock front due to its extra energy

## Gyro-surfing (or gyroresonant surfing) acceleration

Kuramitsu, Y., & Krasnoselskikh, V. 2005,
**Physical Review Letters**, 94, 031102

The basic idea:

The mechanism itself is a very simple one: ions can be trapped by the wave which has a frequency close to their gyrofrequency. In such a situation the parallel velocity of the trapped ions oscillates around the resonance velocity; no energy gain by the ions can be observed. On the other hand, in the presence of an external force (like a changing electrostatic profile that interacts with the trapped ions) the ions can be kept in the exact resonance condition and thus they can be accelerated by the electric field of the wave monotonically in the perpendicular direction.

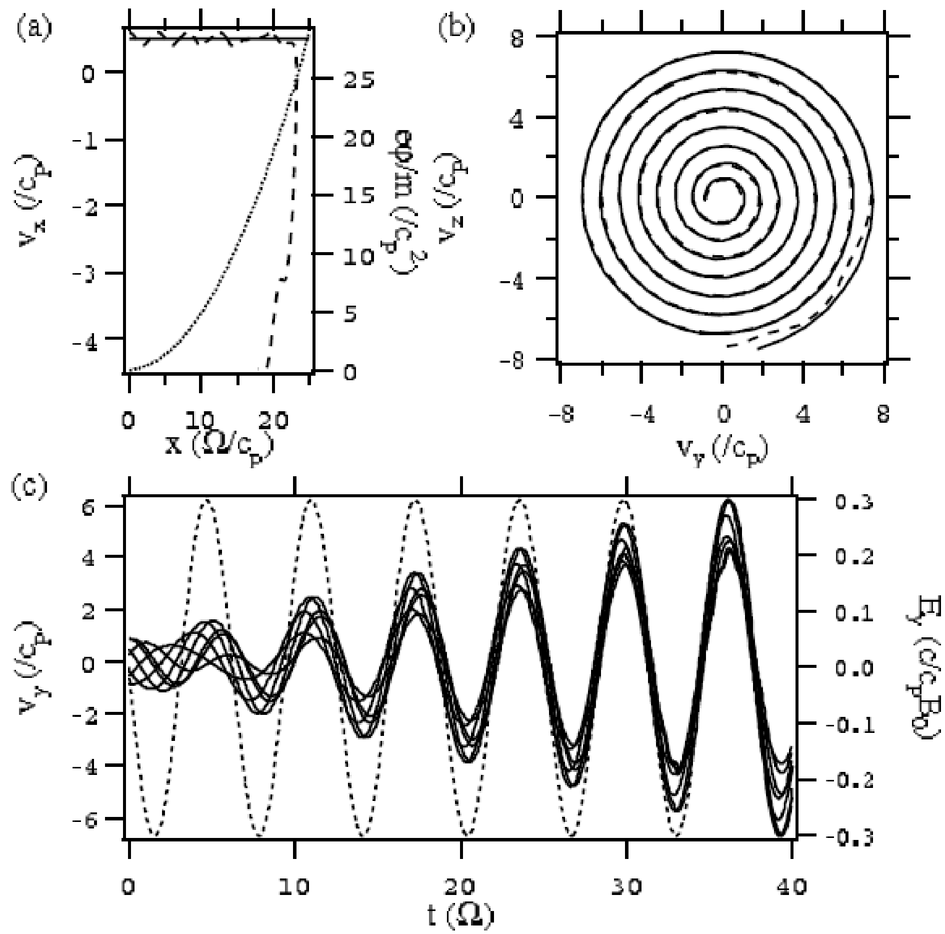
Ilustration of the idea:

Wave passes by, no energy gain alltogether...

Ilustration of the idea:

...but if the „boat" is able to remain in the optimal position,
it can gain energy.

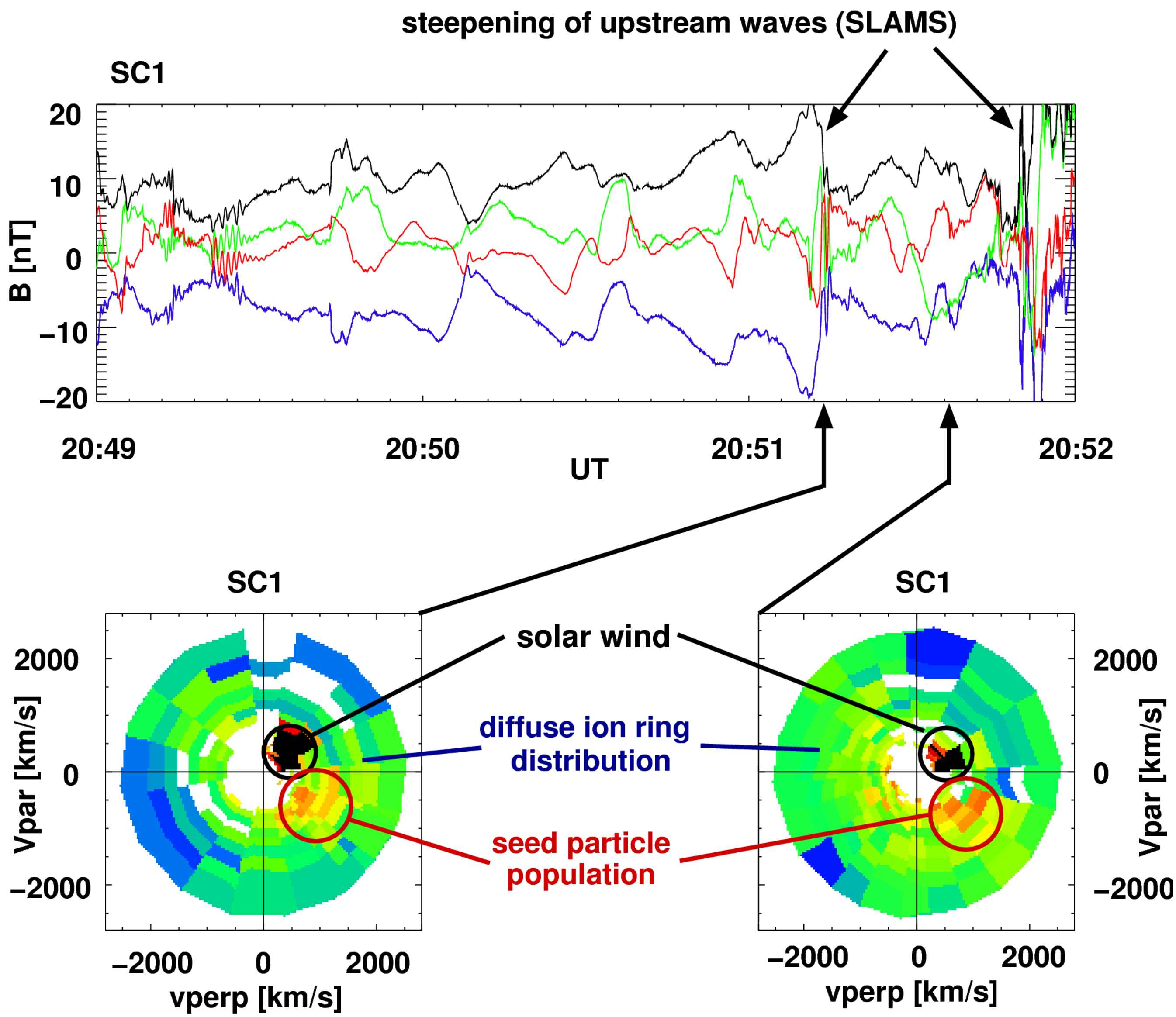
# Simulation results

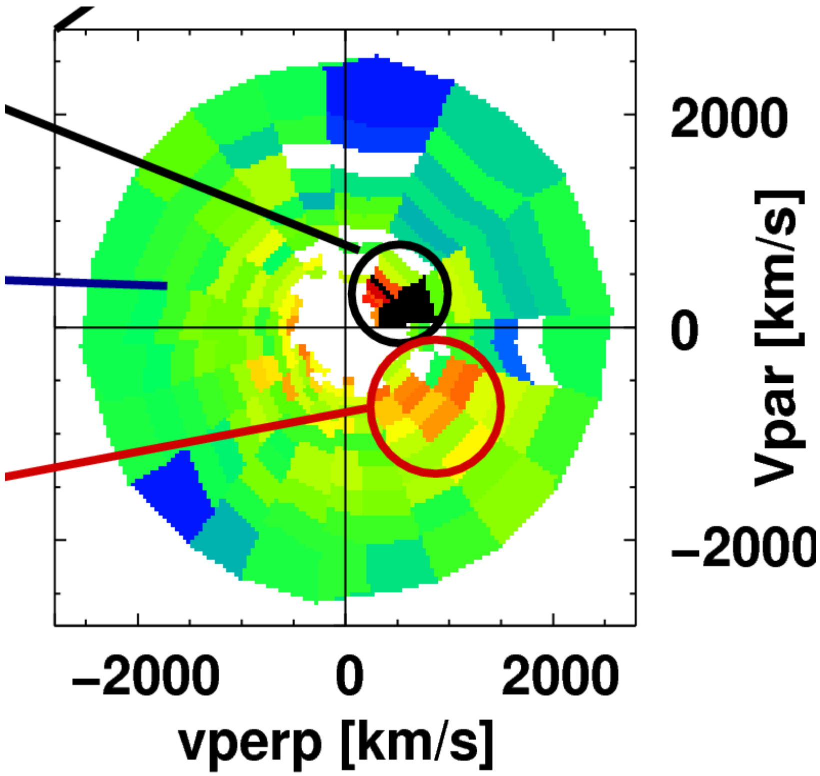



- ions gain energy in perpendicular direction
- also those ions are accelerated that are not in exact resonance condition (if the wave amplitude is large enough)
- phase synchonization effect for ions that have initially different gyro phases

*Kuramitsu and Krasnosselskikh, 2005*

# Analysis of an individual upstream ion event by using simultaneous multi-spacecraft (Cluster) data






Important points:

- the accelerated ions are highly concentrared; it's a beam-like population

- the accelerated ions velocity/energy is larger then the velocity/energy of the solar wind ions

- the velocity gained through acceleration is in the perpendicular direction

- the cyclotron resonance condition is satisfied (at least in this case) by ions that have a velocity of 440-450 km/s along the magnetic field line in the anti-sunward direction
  >> the accelerated ions are solar wind ions!!!

*efficient injection mechanism?*

*(Kis et al., 2013 Astrophysical Journal)*

# Pitch-angle scattering of diffuse ions

*Physical processes related to diffuse ions in front of the Earth's quasi-parallel bow shock:*

1. Pitch-angle scattering of diffuse ions by magnetic waves

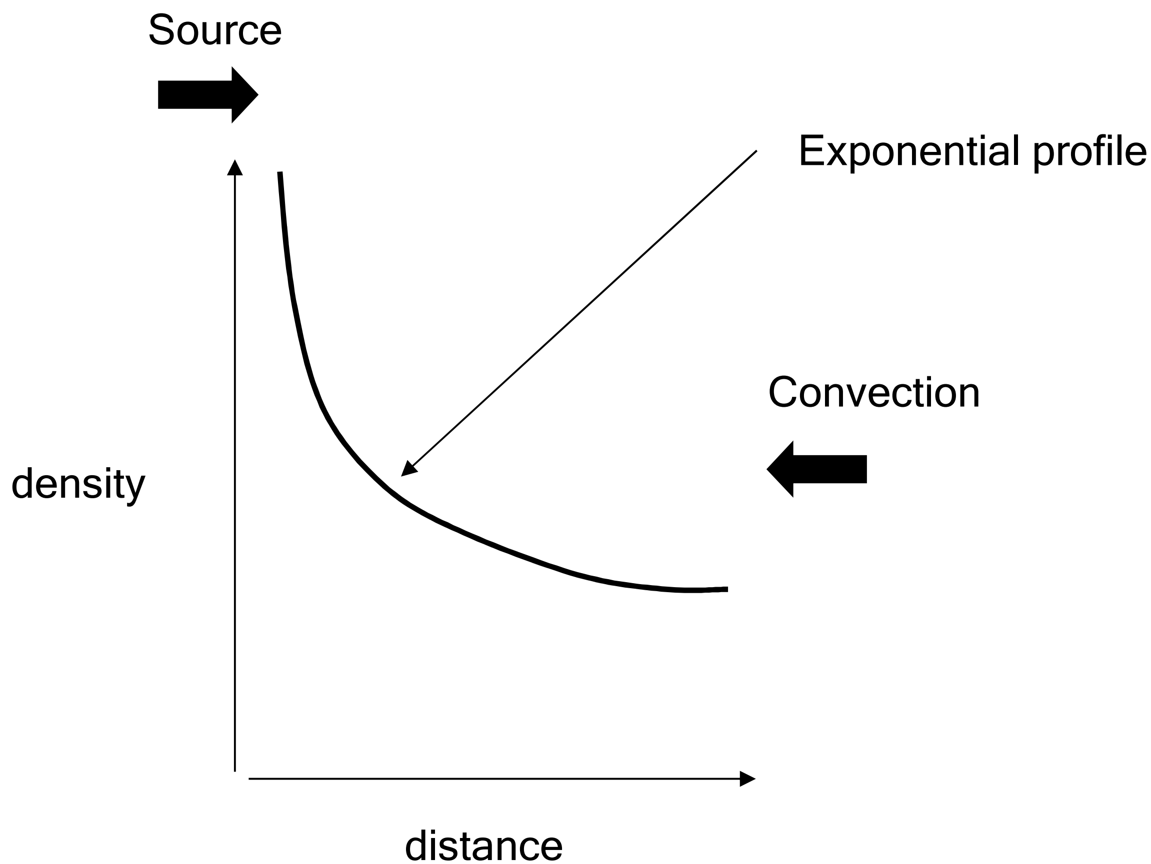
2. Excitation of magnetic waves by diffuse ions

>>> the diffuse ions are scattered by self-generated waves !

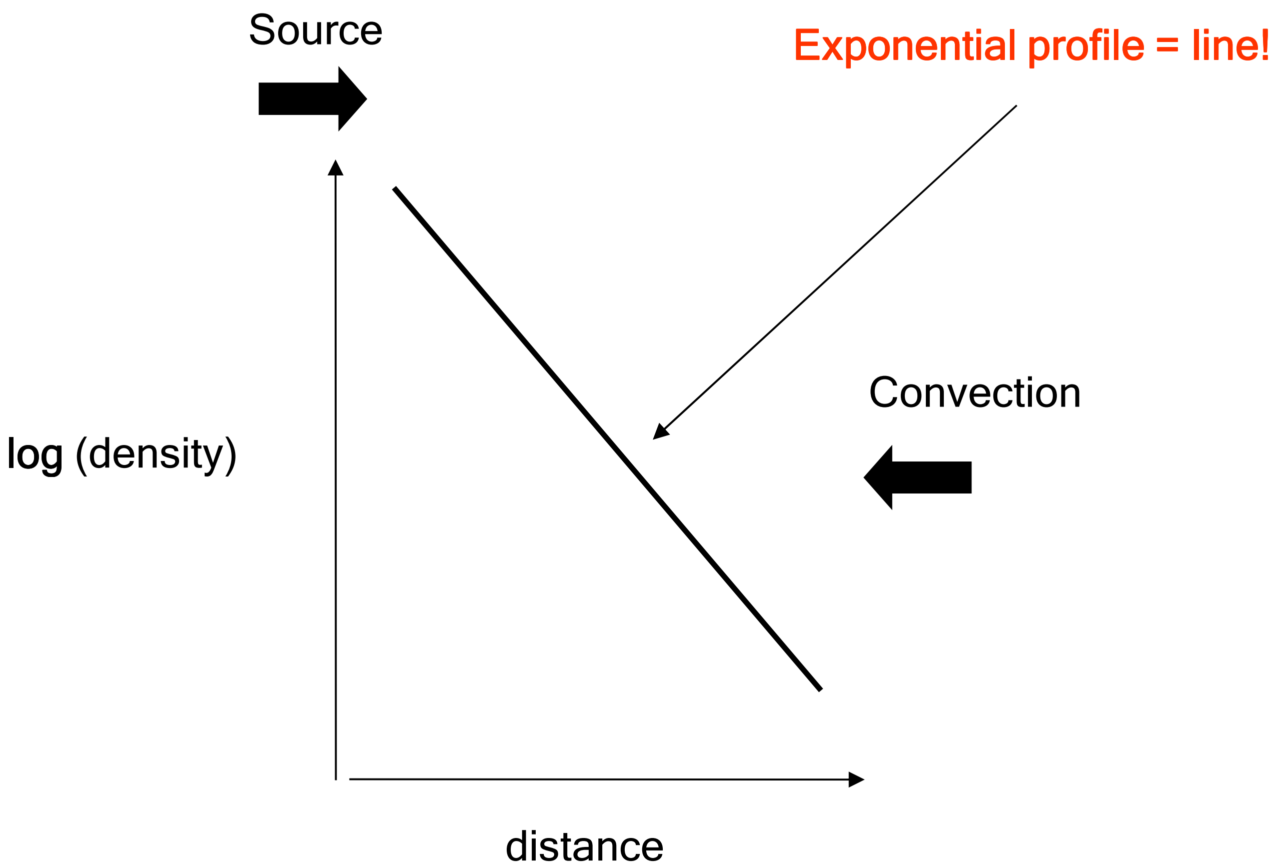
These two physical processes together form a highly complex, feedbacked system, where the energetic ions and the waves influence each other continuously. (This ultimately results in acceleration of ions at the bow shock)

The result of spatial diffusion (scattering)against convection is:
the density of diffuse ions falls off exponentially from the shock front into the upstream region along the magnetic field line.

# Diffusion against convection



# The same in linear-logaritmical scale



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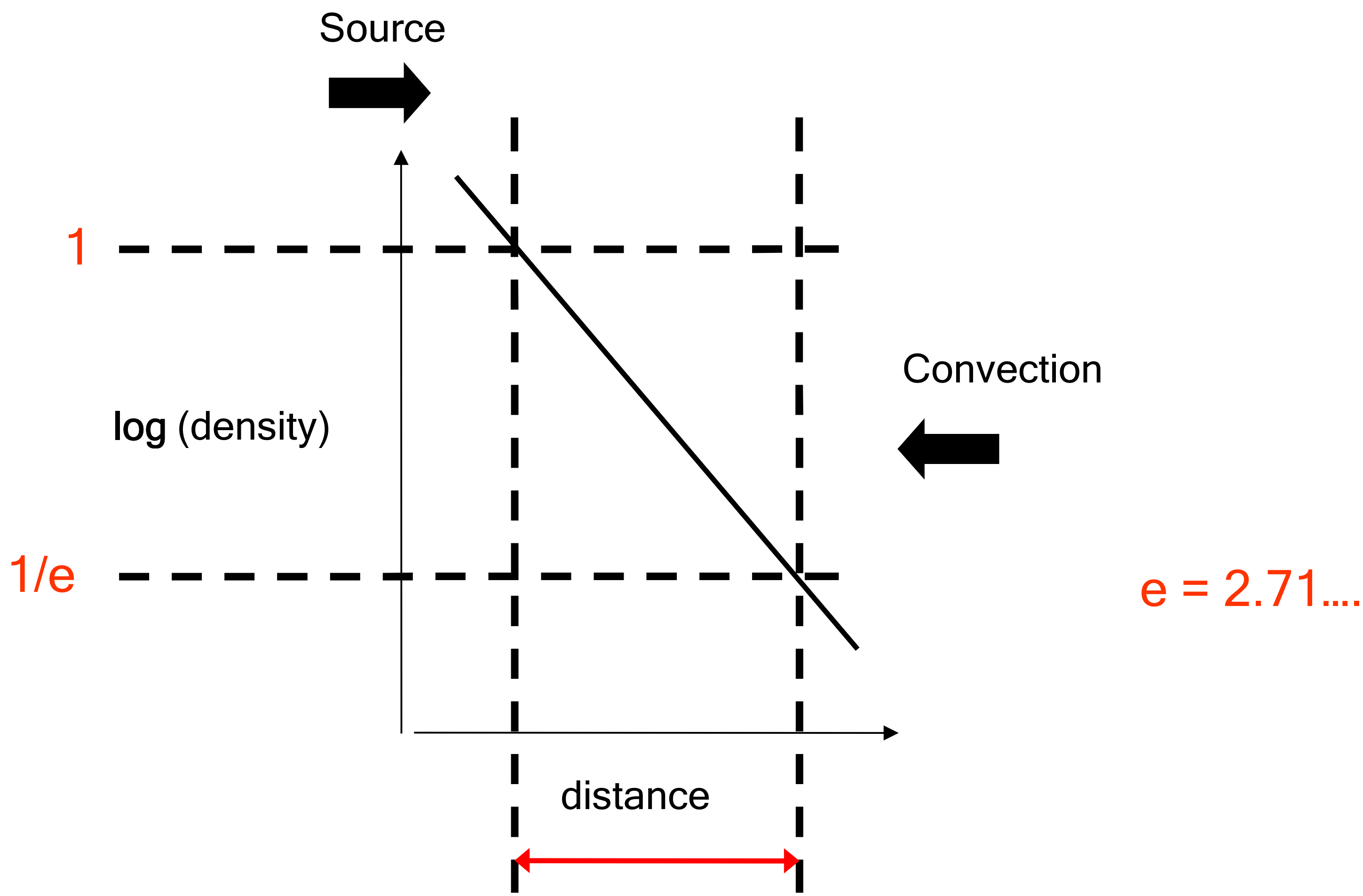



e-folding distance = the distance over which the density decreases to its 1/e-th value.

In other words: this characterizes the „steepness" of the exponential decrease

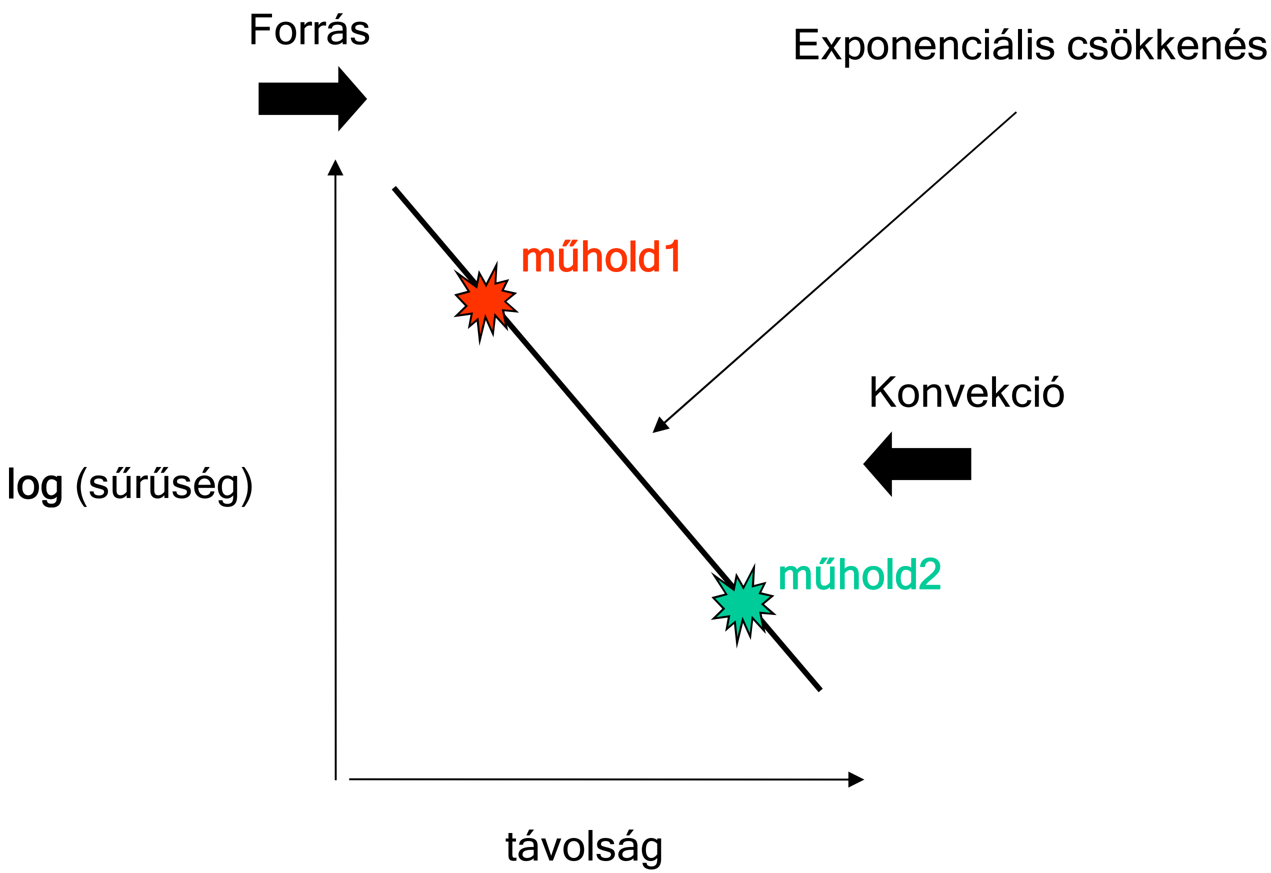
Egy komoly probléma: hogy mérhető a térbeli sűrűség változása egy műhold adatainak a felhasználásával? Nagyon nehezen. Miért?

Mert a napszél sűrűsége folyamatosan változik, fluktuál:
→ *ez időbeli változást jelent!*

A sűrűség exponenciális csökkenése a távolság függvényében:
→ *ez térbeli változást jelent!*

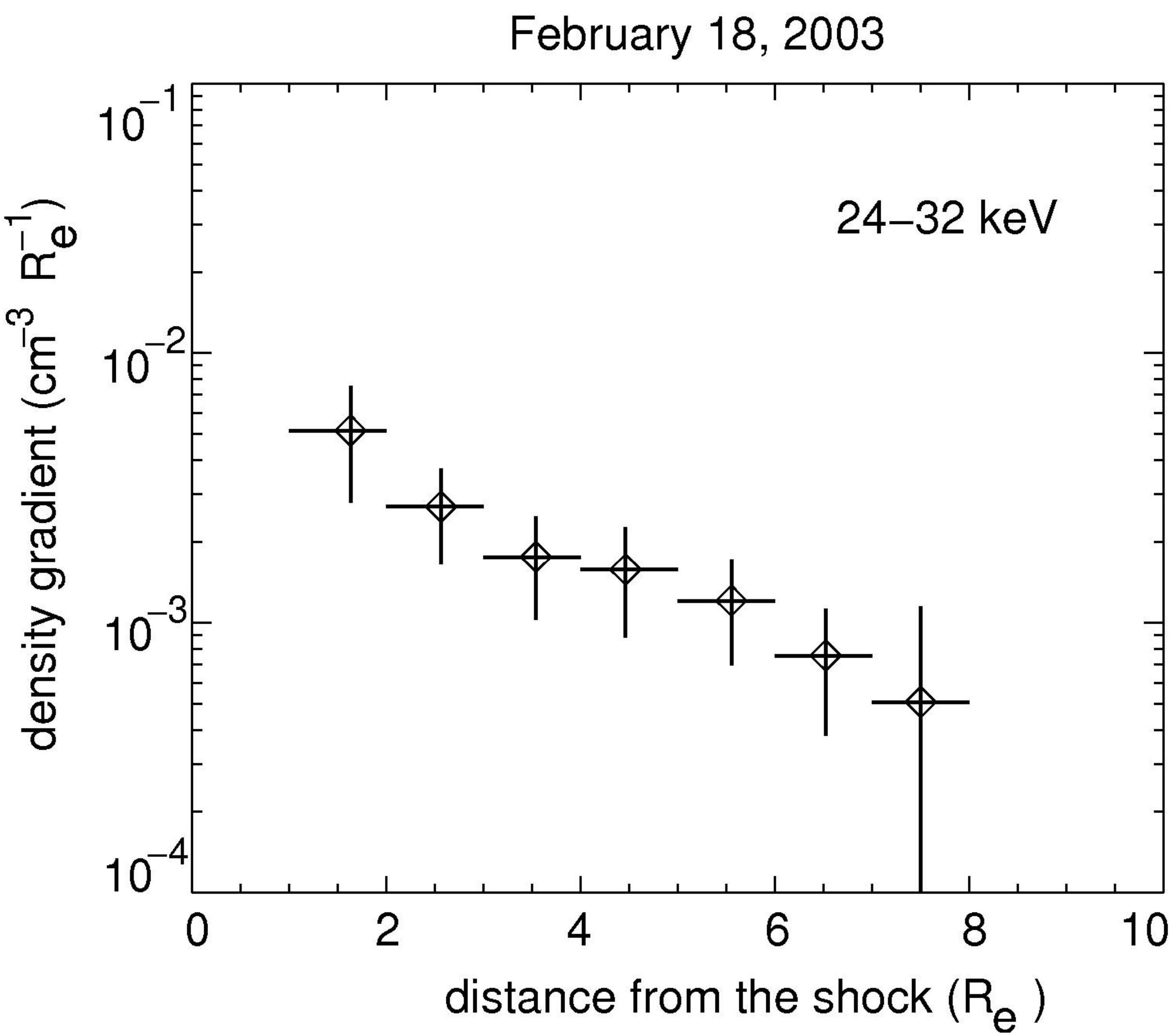
Hogyan lehet megállapítani egy változásról egyértelműen hogy az térbeli vagy időbeli változás?

A megoldás a több műhold egyidejű mérése: **Cluster**!



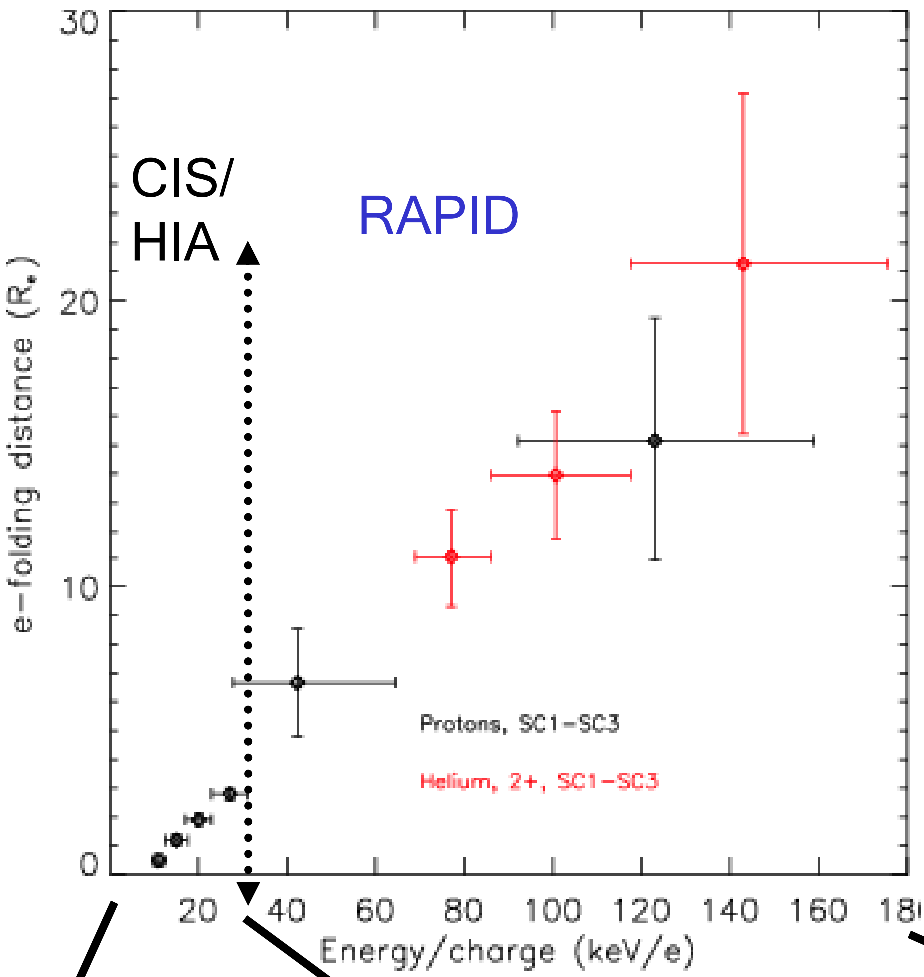

Két műhold segítségével a térbeli  gradiens közvetlenül meghatározható!
(Egy műholdnál sosem lehetünk biztosak.)

## A Cluster műholdak adatai vizsgálatának eredményei




a diffúz ionok (parciális) sűrűsége valóban exponenciálisan csökken (a lökéshullámtól való távolság függvényében)

# További eredmények:




-A 2003 február 18.-i esemény vizsgálatának kiterjesztése a magasabb ion energiájú tartományokra a RAPID által észlelt adatok felhasználásával

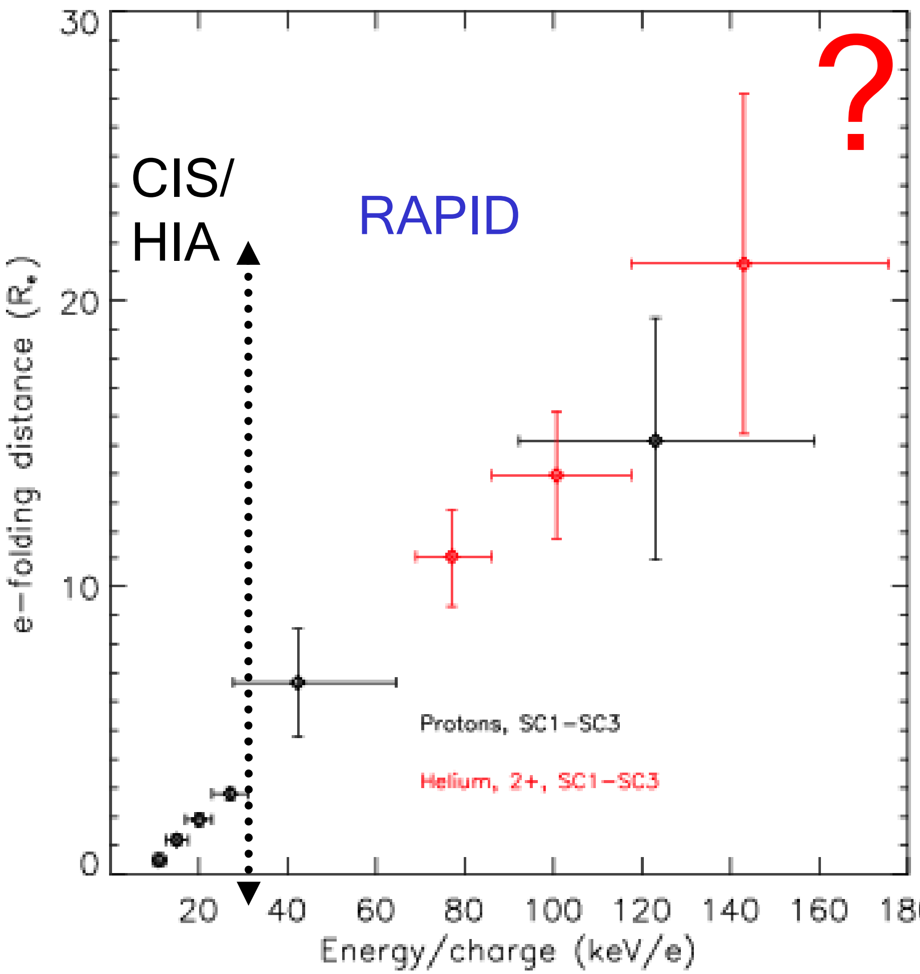
-A nagyenergiájú ionok parciális sűrűségének exponenciális csökkenése: a diffúz transzport bizonyítéka a nagyenergiájú ionok esetében is

-A karakterisztikus távolságok értékének ionenergia szerinti közel lineáris növekedésének tendenciája kimutatható a RAPID által észlelt adatoknál; a két műszer adatai jól kiegészítik egymást

Kis et al., 2004, GRL

E. Kronberg, A. Kis et al., 2009, JGR

# Kérdések:




- hogyan viselkednek a 160 keV feletti energiával rendelkező ionok?

- mi az a maximális energia, amire a lökéshullám az ionokat gyorsítani képes?

-mi határozza meg a maximális energia mértékét?

  a geometria (i.e. a foreschock kiterjedése, mérete)?

  a napszél paraméterei (i.e. sebessége, sűrűsége)?

*-> további vizsgálatok szükségesek!*

# Diffusion coefficient determination

$$L(E) = \frac{\kappa(E)}{V_{sw}}$$

$$\kappa(E) = \frac{V_{part}}{3} \square \lambda(E)$$

$L(E)$ : e-folding distance

$\kappa(E)$ : diffusion coefficient

$V_{sw}$ : solar wind velocity

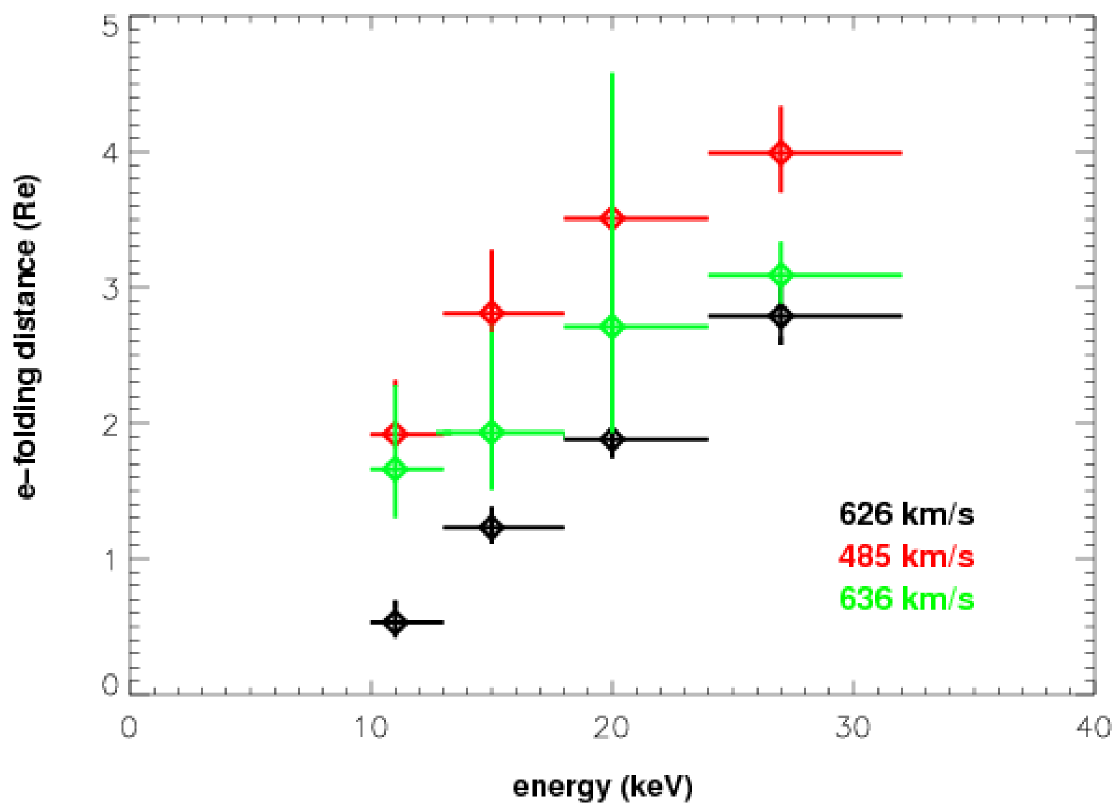
$V_{part}$ : energetic particle velocity

$\lambda(E)$ : mean free path

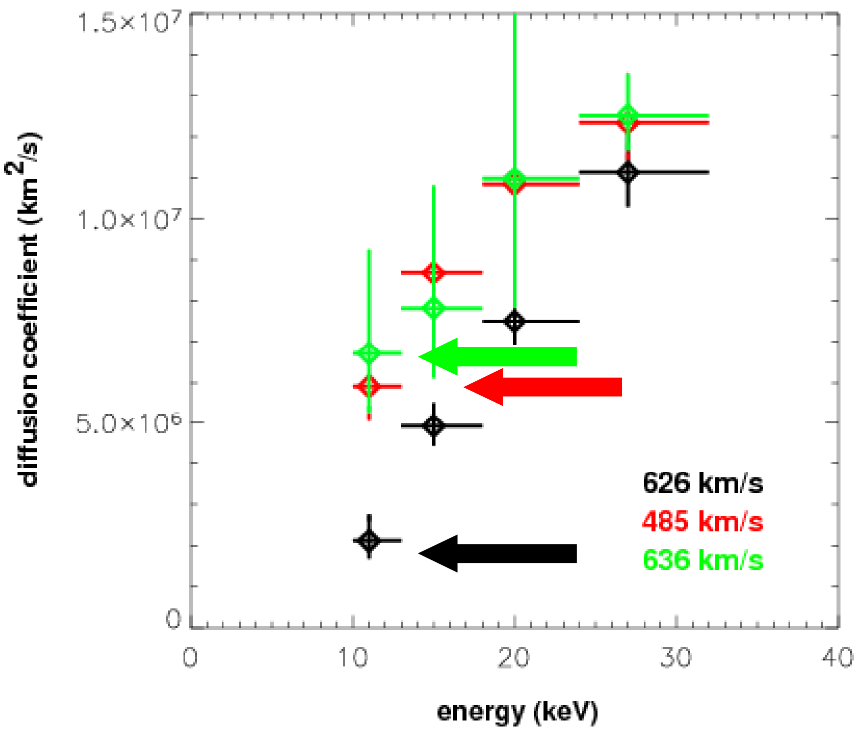
# Important points to remember:

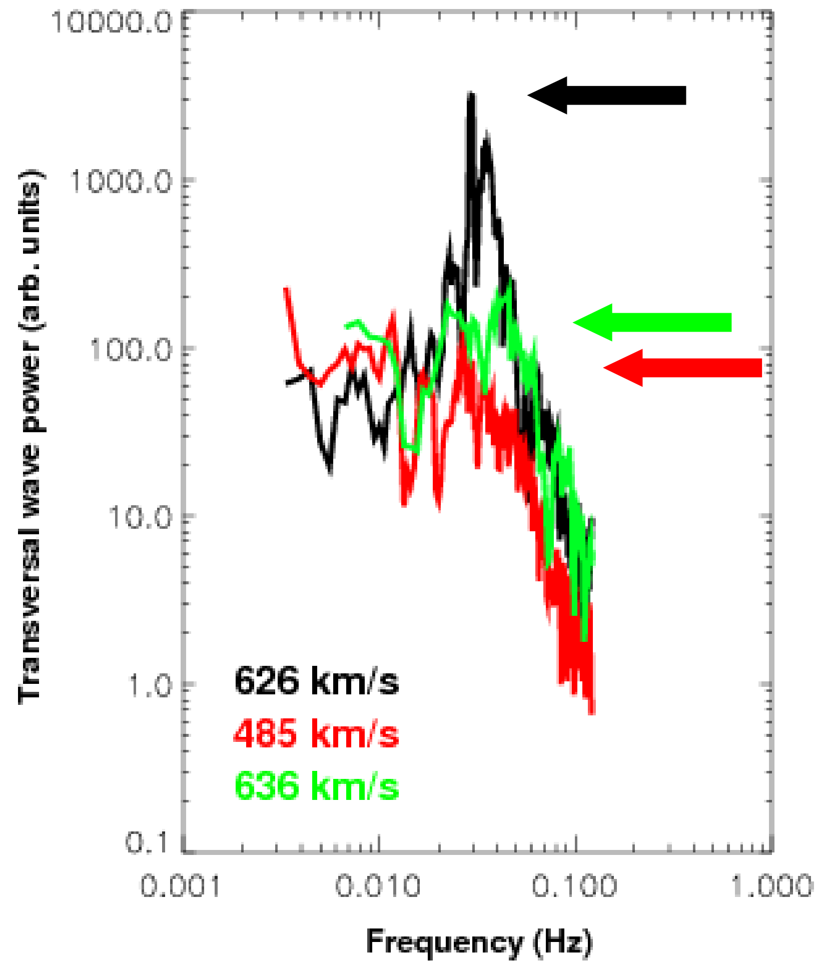
Smaller e-folding distance → smaller diffusion coefficient

Smaller diffusion coefficient → more effective aceleration!



Analysis of three individual upstream ion event by using simultaneous multi-spacecraft (Cluster) data



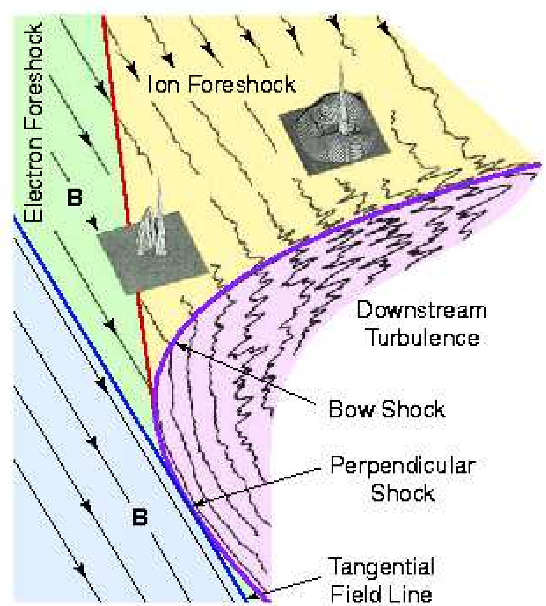

*Data analysis shows a huge difference between cases! WHY?*

Kyushu University (KU) – Hungarian Academy (HAS)

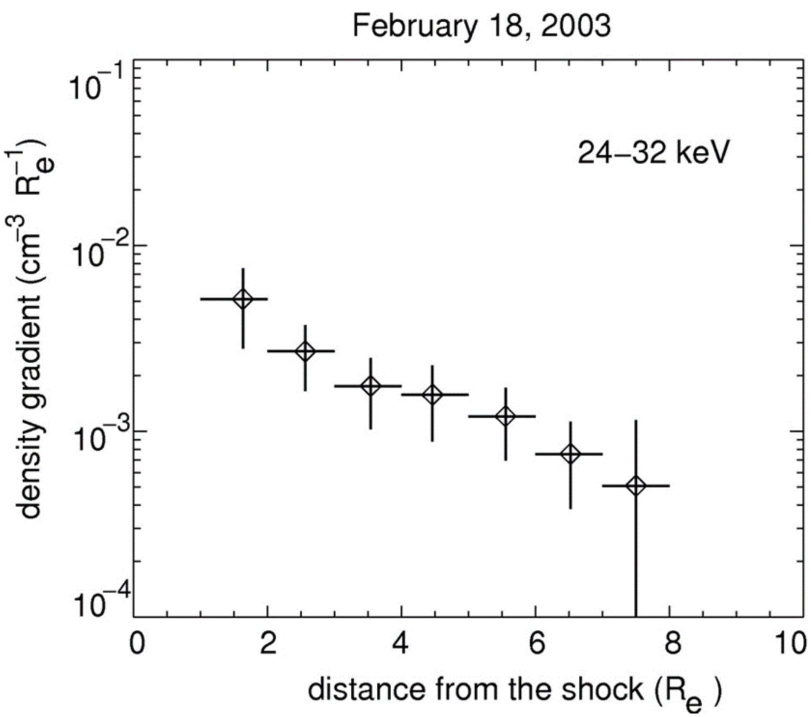
Bilateral Research Program

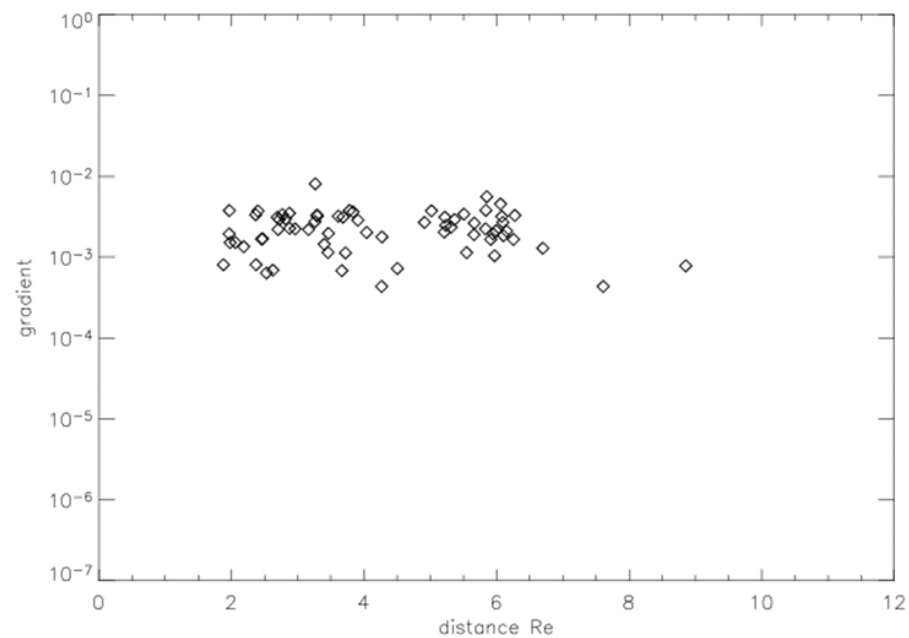
KU members:
**Shuichi Matsukiyo**, Tohru Hada, Fumiko Otsuka, Kento Nakanishi, Masaru Nakanotani

HAS members:
Arpad Kis, Istvan Lemperger



Ions above 160 keV:
no exponential slope can be seen!



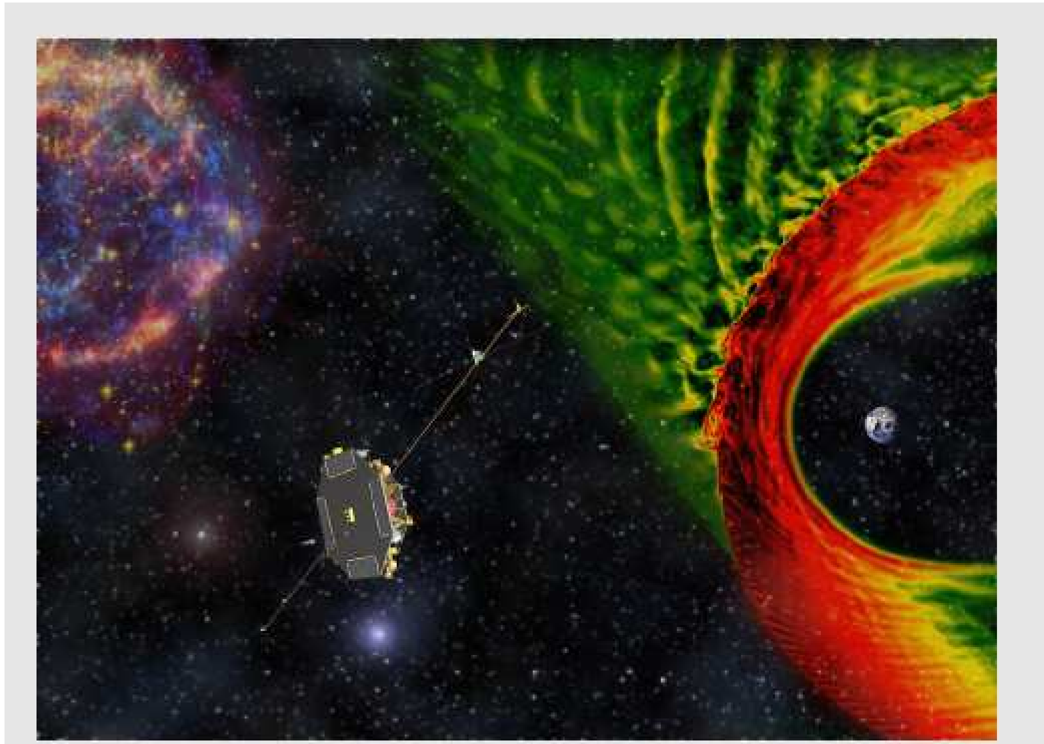




Is this the free escape boundary?

Theory vs observations?

More study needed!

# Turbulence Heating ObserveR – THOR



THOR will address the fundamental science theme Turbulent energy dissipation and particle energization which ties in with ESA's Cosmic Vision. In particular, THOR will address the following specific science questions:

- How is plasma heated and particles accelerated?
- How is the dissipated energy partitioned?
- How does dissipation operate in different regimes of turbulence?

Thank you for your attention!