# PRINCIPLES OF PARTICLE SPECTROMETRY


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**Solar-Terrestrial Interactions:**

**Instruments and Techniques (STIINTE)**

**Sinaia, Romania, June 4 - 14, 2007**

# OUTLINE

1. Introduction

   The Charged Particle Environment
   - In the Heliosphere
   - In the Magnetosphere of the Earth
2. In Situ and Remote Sensing Measurements - an Overview
   - Energy Ranges of Ions and Electrons
   - In-situ Measurements
   - Remote Sensing Measurements
3. In-Situ Measurements: Techniques
4. The Cluster Ion Spectrometry Experiment (CIS)

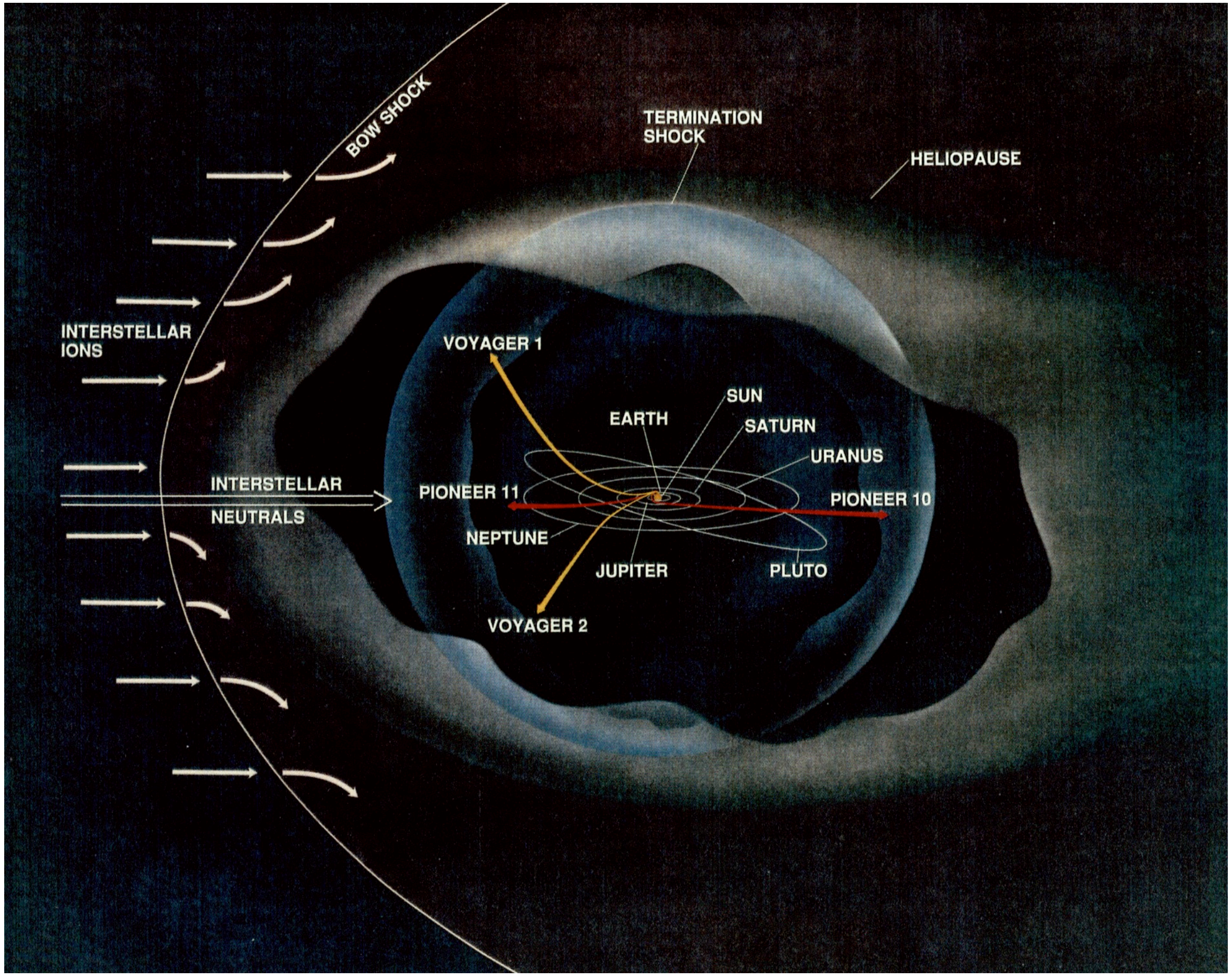
# INTRODUCTION

**1. Introduction**

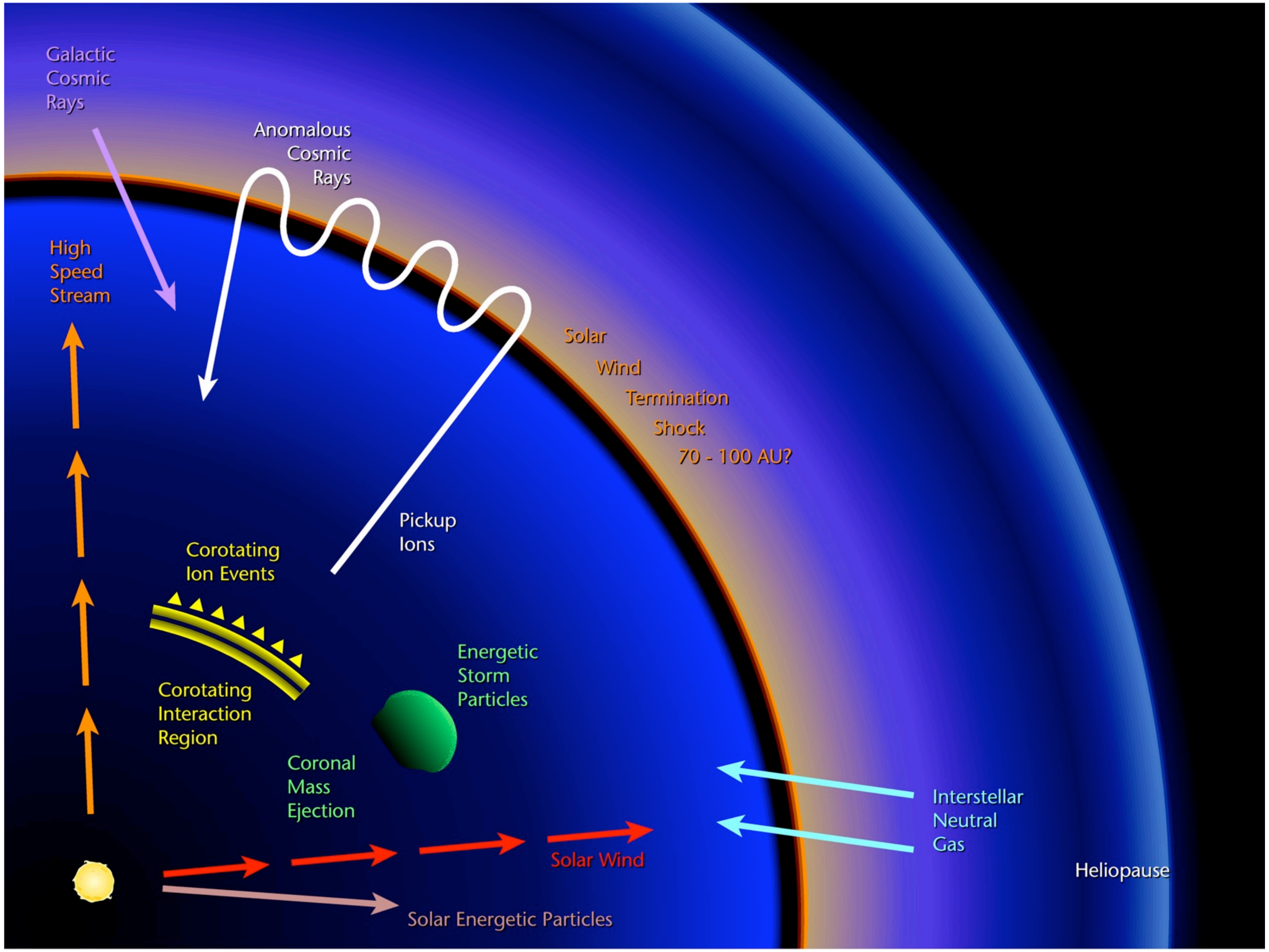
**The Charged Particle Environment**

- **In the Heliosphere**
- *In the Magnetosphere of the Earth*

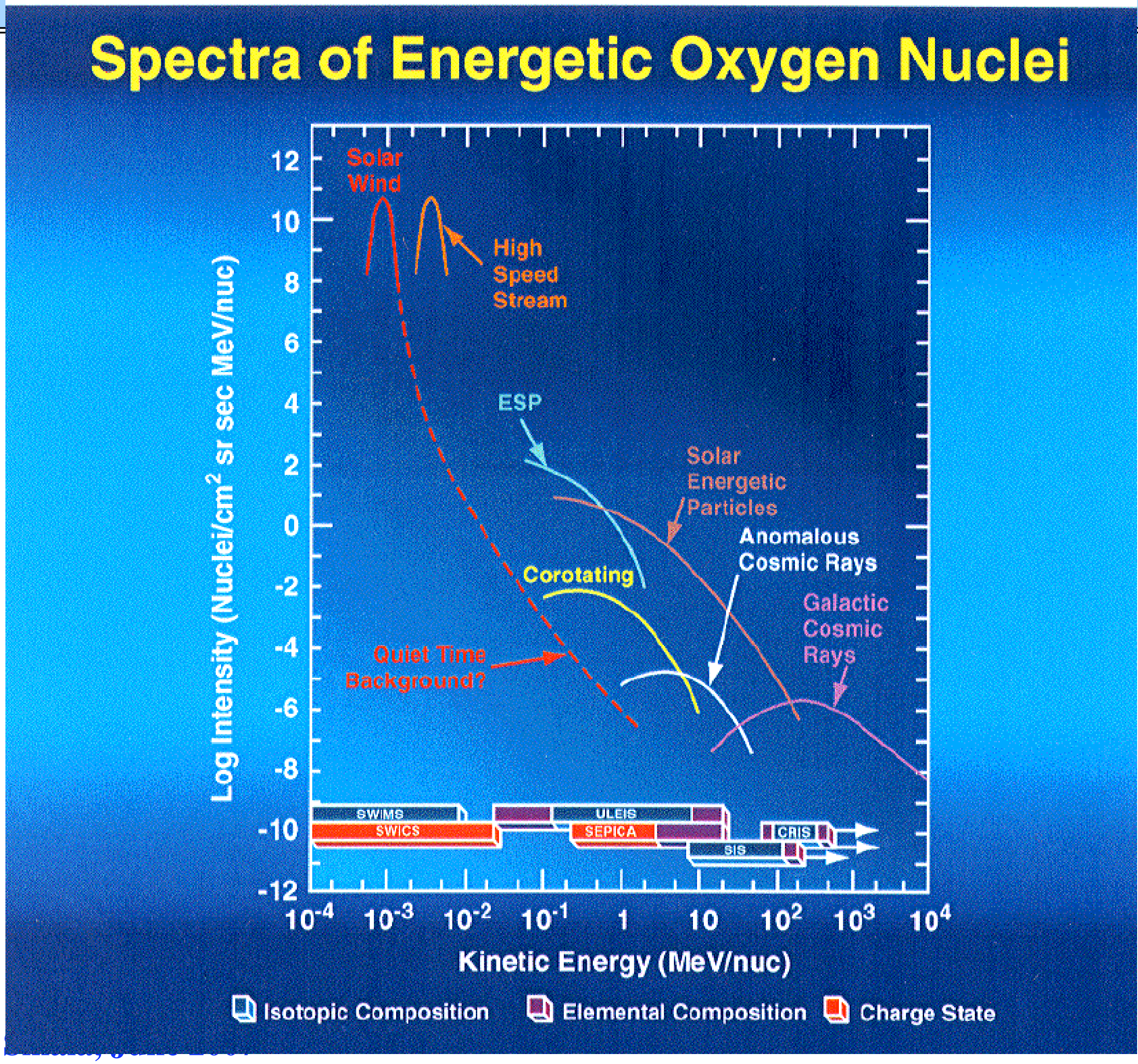
# THE HELIOSPHERE



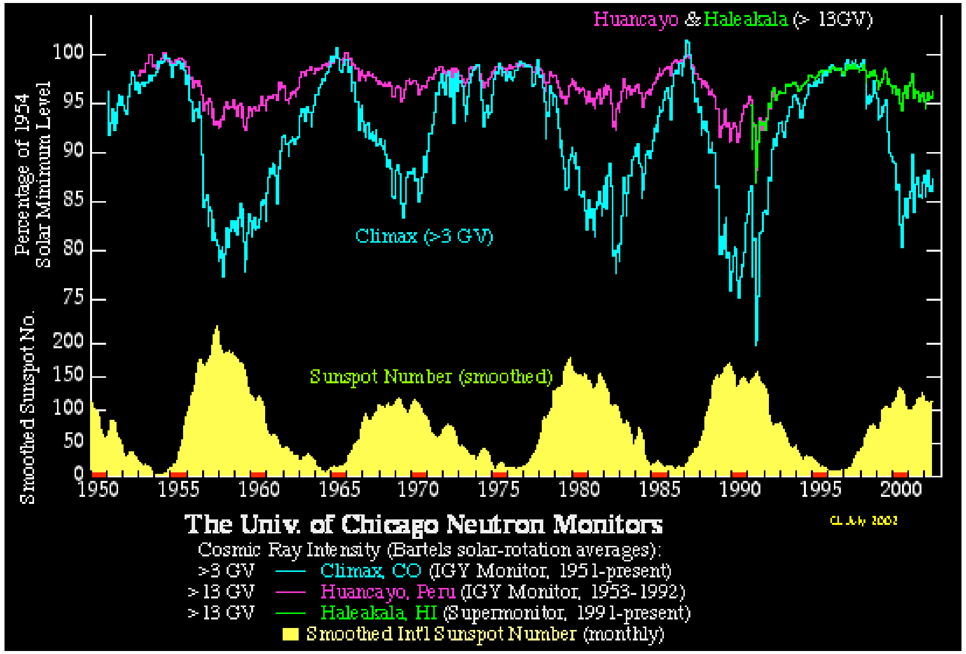
# PARTICLES IN THE HELIOSPHERE
## Acceleration Processes



# PARTICLES IN THE HELIOSPHERE



# SOLAR CYCLE VARIATION




## Neutron Monitor Observations

**Neutron monitor counting rates:**

**a measure for the intensity of Galactic Cosmic Rays (GCR) in the inner heliosphere.**

## Sunspot Number

**GCR Intensities are anti-correlated with solar activity.**

# INTRODUCTION

1. **Introduction**

   **The Charged Particle Environment**

   – *In the Heliosphere*

   – **In the Magnetosphere of the Earth**

# THE MAGNETOSPHERE OF THE EARTH
## The Early Discoveries

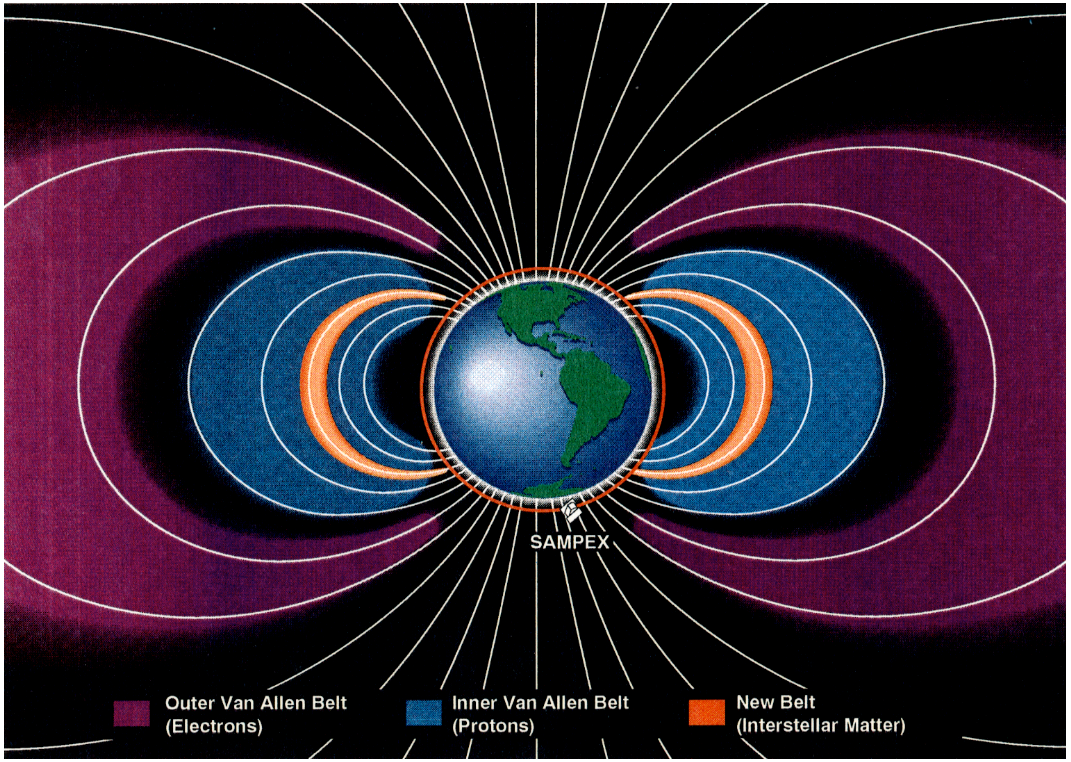
W. Pickering  J Van Allen  Wernher v.  Braun

**The Early Missions (IGY)**

| | |
|---|---|
| Sputnik 1 | Oct 1957 |
| Sputnik 2 | Nov 1957 |
| Explorer 1 | Jan 1958 |
| Explorer 3 | March 1958 |
| Sputnik 3 | May 1958 |
| Explorer 4 | July 1958 |

**Discovery of Trapped Radiation  (Explorer 1)**

# THE INNER MAGNETOSHERE
## Radiation Belts




## Inner Belt:

**predominantly $H^+$**

**Energy: ~ 0.1 - 100s MeV**

**Latitude: ± 30°**

**Altitude: $10^3$ - $10^4$ km**

## Outer Belt:

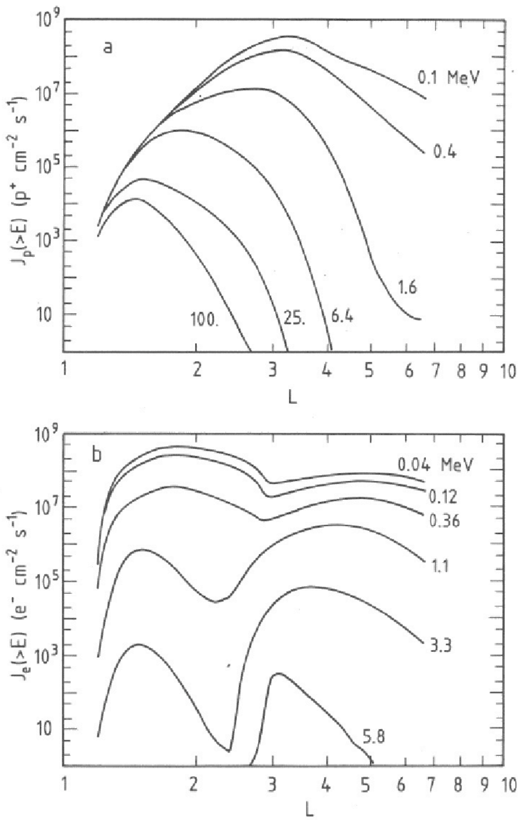
**Predominantly Electrons**

**Energy: ~ 0.04 - 10 MeV**

**Latitude: ± 60°**

**Altitude: 2 $10^4$ - 3 $10^4$ km**

# Radiation Belt Spectra




**Ions**

**Electrons**

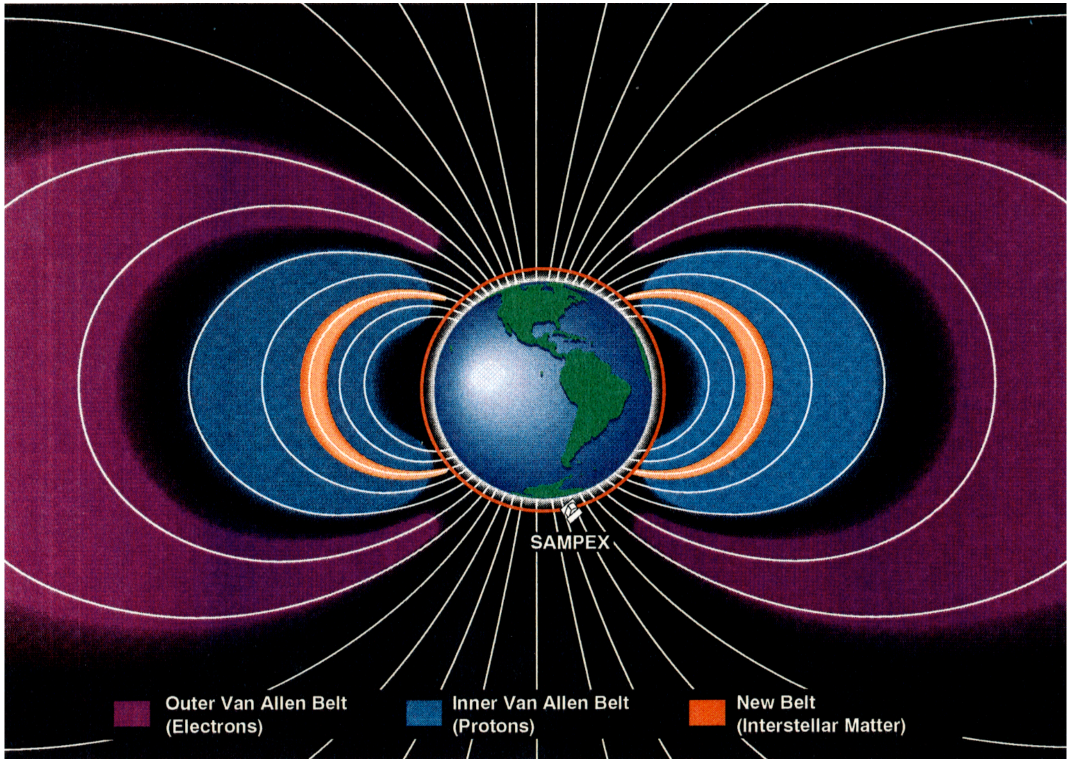
*Figure 4.5.* Equatorial distribution of the omnidirectional flux of energetic protons (panel a) and electrons (panel b) above a set of energy thresholds. These fluxes are obtained from the UNIRAD software using the NASA empirical models AE8MAX and AP8MAX corresponding to conditions of maximum solar activity (adapted from Vette, 1991a, 1991b; courtesy D. Heyndricks).

**Blanc et al.**

**Space Sci. Rev 88, 1999, p 137**

# THE INNER MAGNETOSHERE

## Access of Solar / Interplanetary / Galactic Particles: The Cutoff



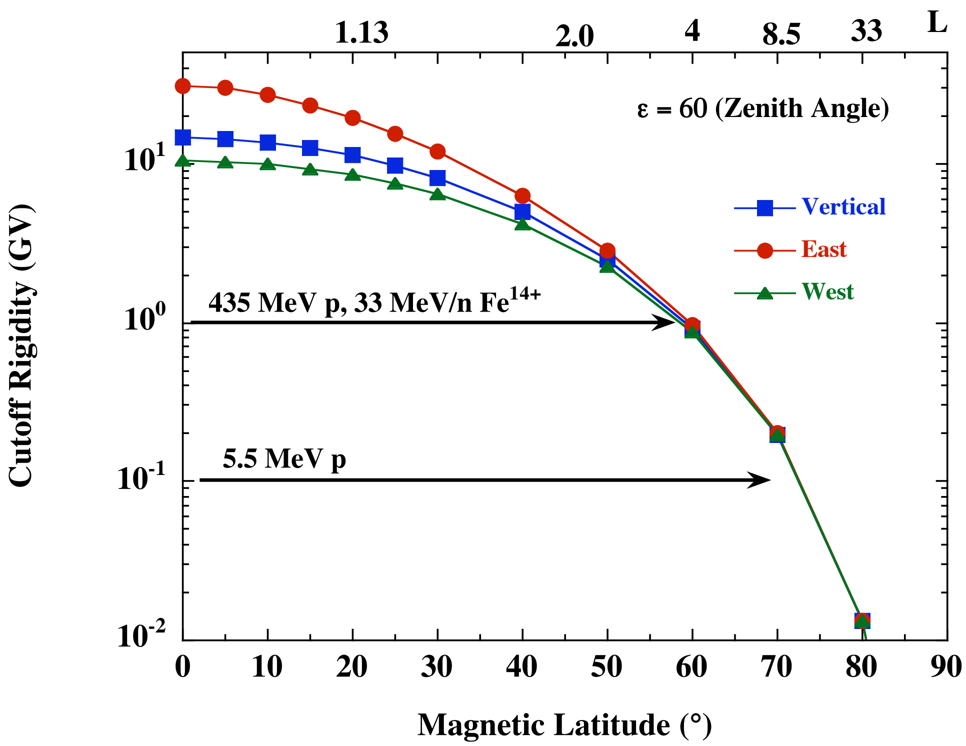

## Polar Regions:

**Easy access; Low Cutoff**

## Equatorial Regions:

**High Cutoff**

# THE GEOMAGNETIC CUTOFF




**At high magnetic latitudes, particles from interplanetary space have easy access to the near-Earth environment.**

**At low latitudes, access depends on the particle's rigidity R**

**R = m v / q,**

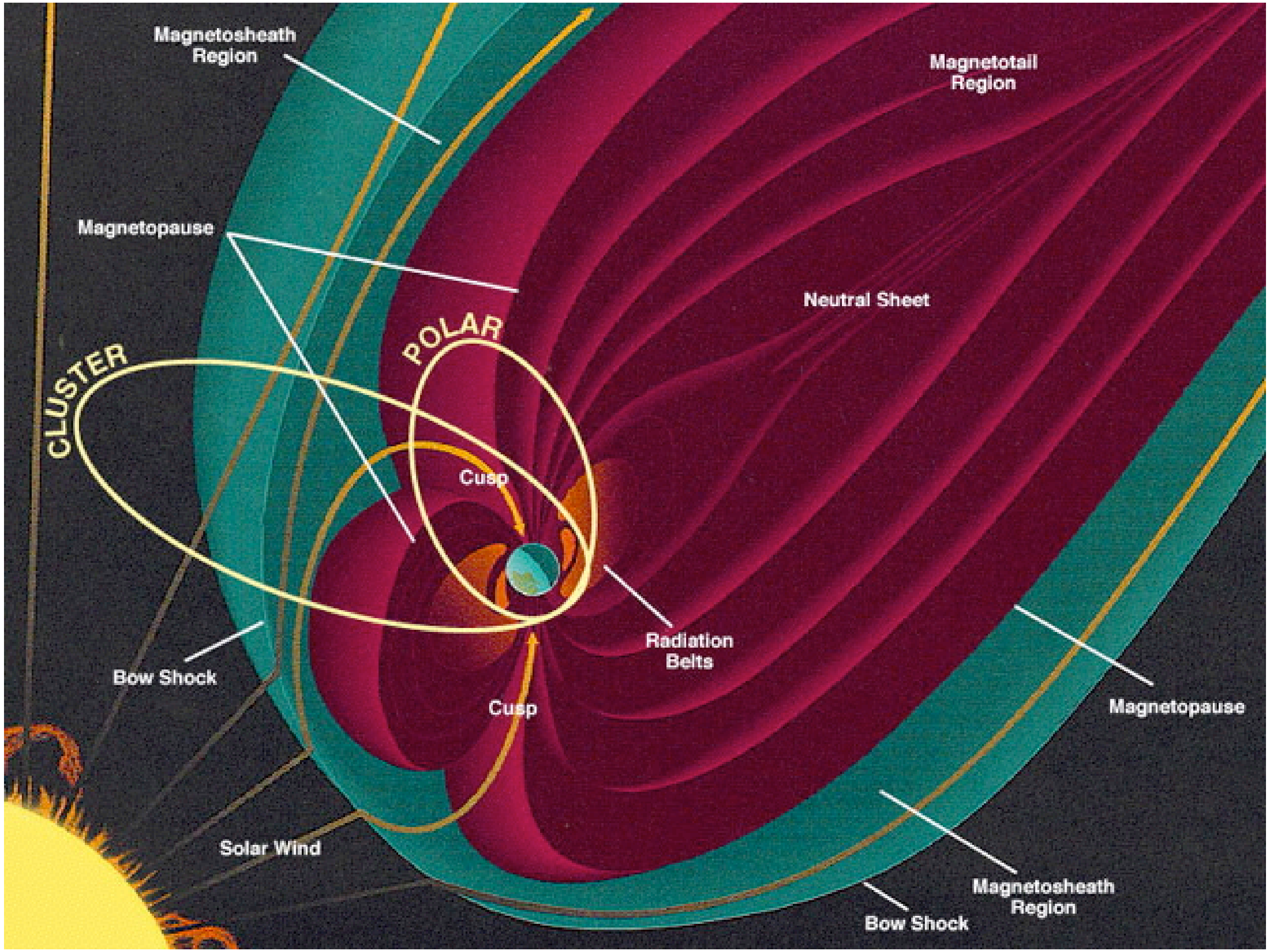
**i.e. on particle velocity v, and M/Q**

## Cutoff Variations

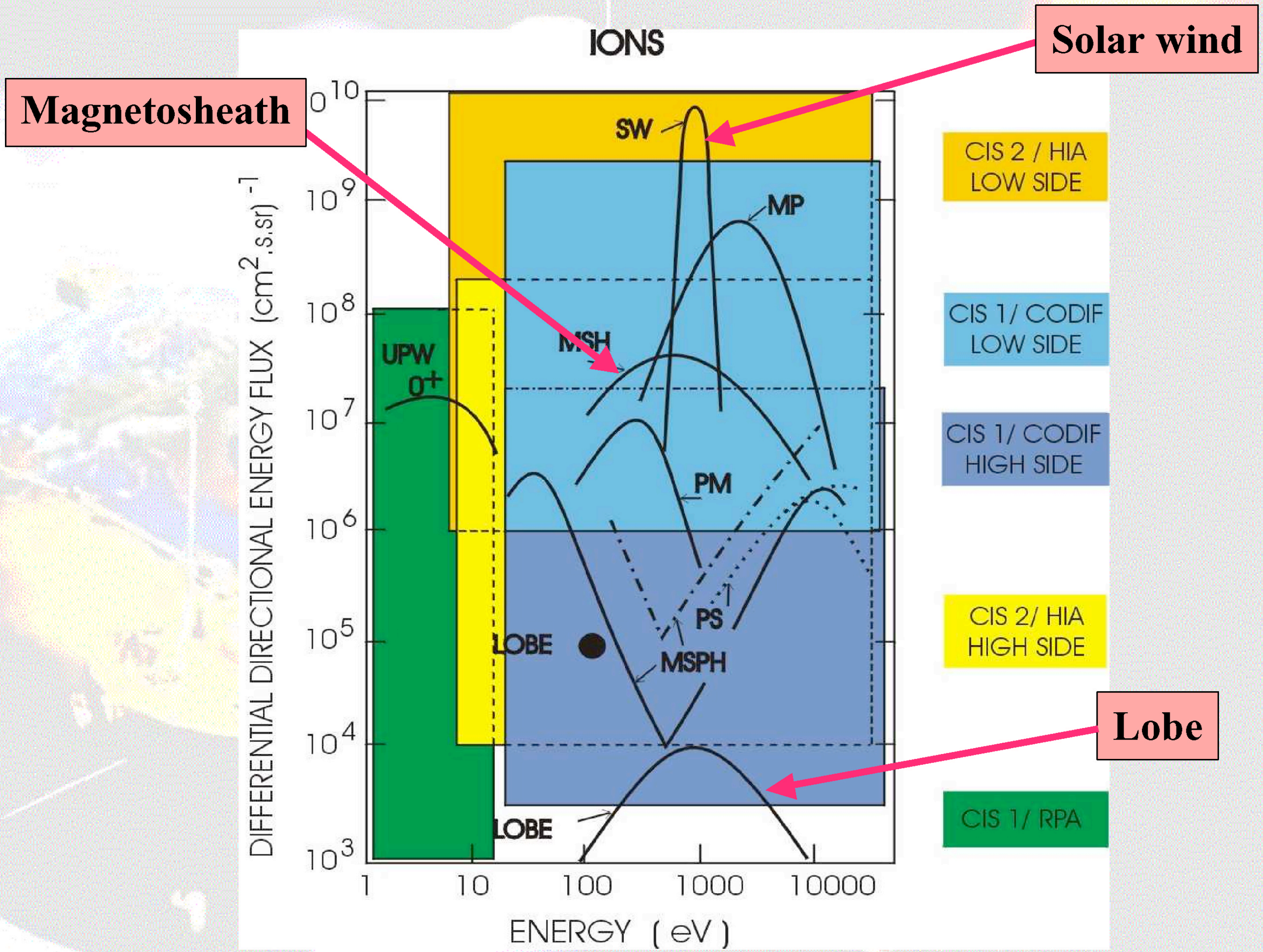
**Short-term: during magnetic storms**

**Long-term: with B**

# THE MAGNETOSPHERE OF THE EARTH



# PARTICLE POPULATIONS IN THE MAGNETOSPHERE

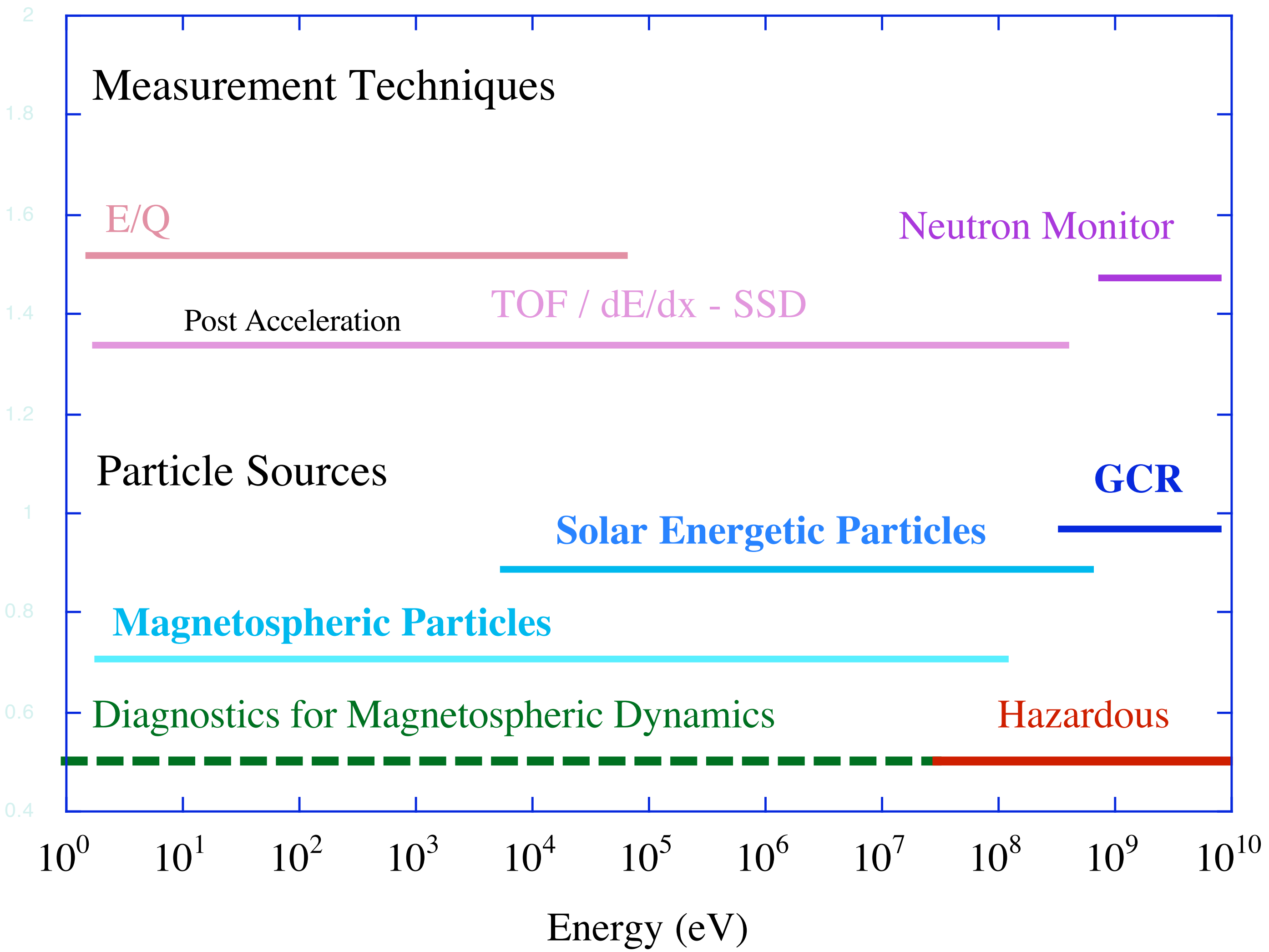


# In Situ and Remote Sensing Measurements

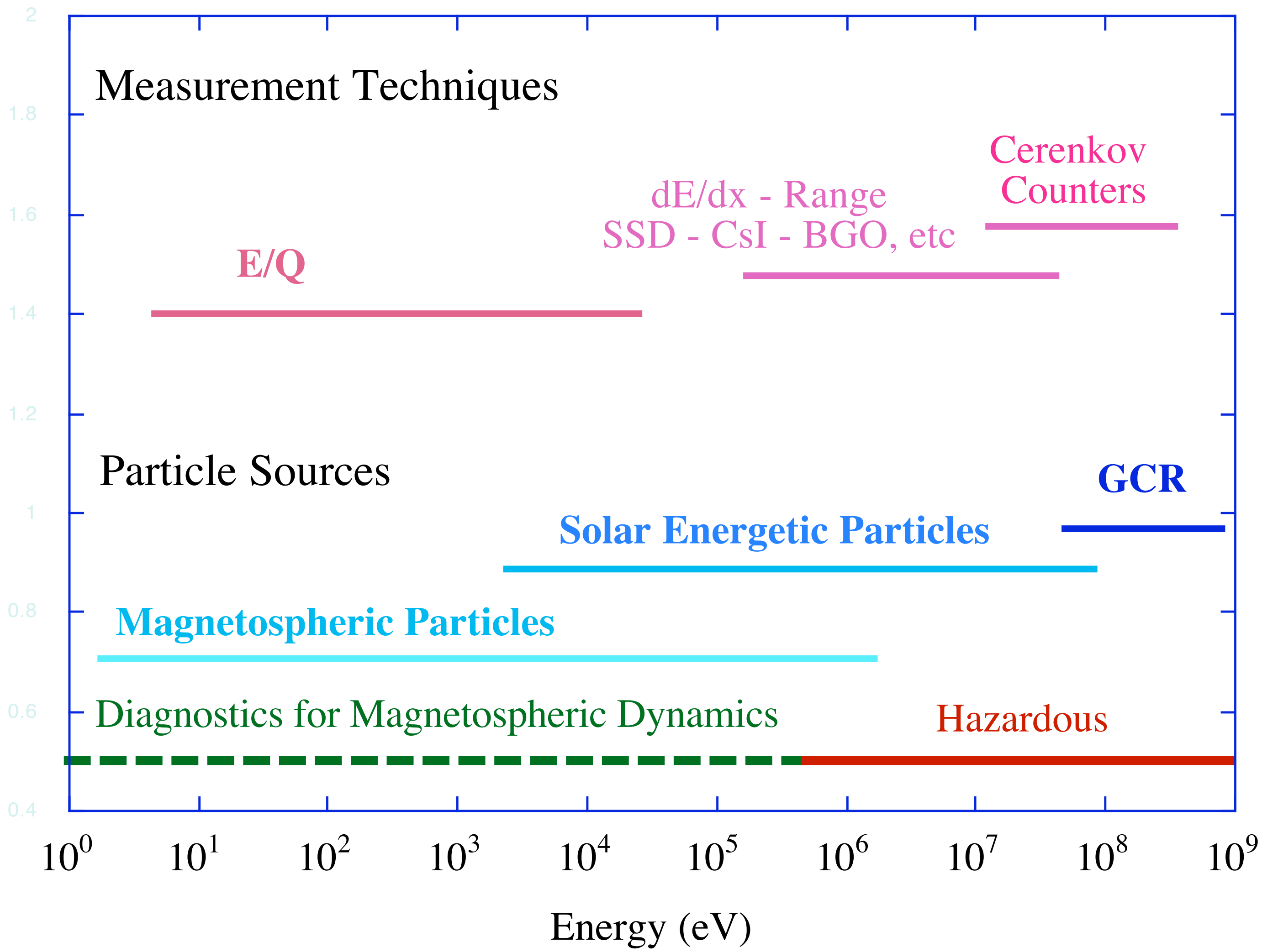
## 2. In Situ and Remote Sensing Measurements - an Overview

- Energy Ranges of Ions and Electrons
- In-Situ Measurements
- Remote Sensing Measurements

# ENERGY RANGE: IONS



# ENERGY RANGE: ELECTRONS



# IN-SITU MEASUREMENTS

## Direct Measurement

| | | |
|---|---|---|
| • E/Q | Electric Field | (deflection ~ q/E) |
| • V M/Q | Magnetic Field | ($Br_g$ = mv/q) |
| • V (or E/M) | Time-of Flight | (E = 1/2 m $v^2$) |
| • E | Energy Measurement, e.g. with Solid State Detectors (SSD) | |

## Derived Parameters:

| | | |
|---|---|---|
| • M/Q | M/Q | = (E/Q) / (E/M) |
| | M/Q | = B $r_g$ / V |
| • Q | Q | = E / (E/Q) |
| • Mass | M | = E / (E/M) |
| | dE/dx | = k1 * $Z^{*2}$ / (E/M) * f (k2,E) |

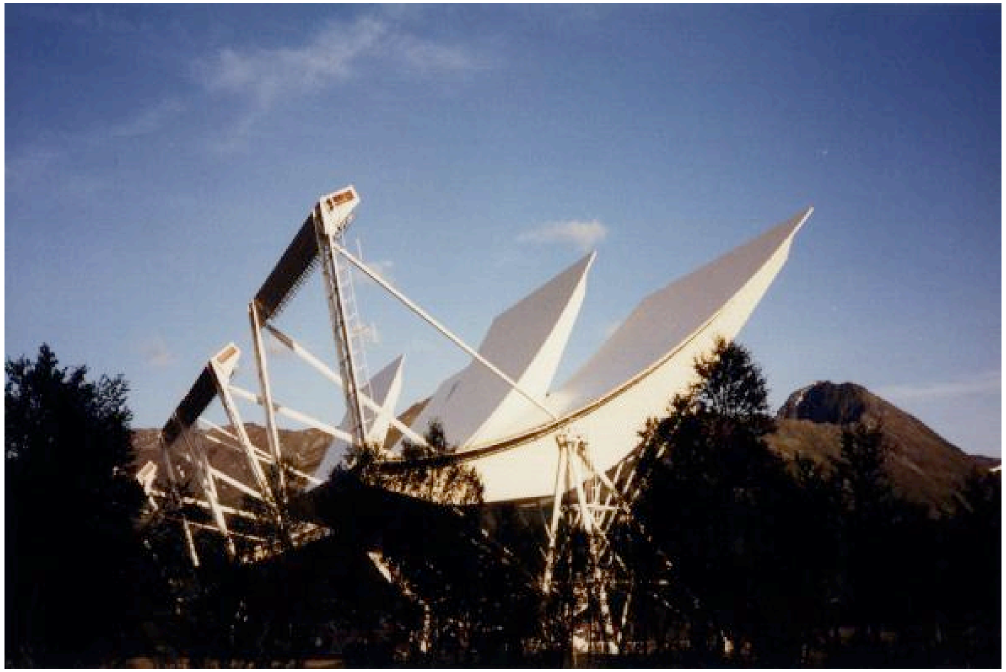
# REMOTE SENSING MEASUREMENTS
## Ground Observations

**GROUND OBSERVATIONS**
**European Incoherent SCATter Radar (EISCAT)**

**Measured Quantity:**
**Echo of radar signal, scattered by ionospheric electrons**

**Inferred Quantity**

**Ionospheric Plasma Parameters:**
**Electron Density, Temperature**
**Ion Temperature, Velocity, Composition**



**EISCAT VHF Antenna**

# REMOTE SENSING

## Imaging with Visible Light, UV, X-rays

**e.g. DE, POLAR, IMAGE**

**Images of the aurora, recorded by the Polar Visible Imaging System and Ultraviolet Imager (two upper images on right) capture the global response of the geospace environment. Geophysical Research Letters - Vol. 25, No. 14, 1998**

**POLAR**

**Experiments: VIS, UVI, PIXIE**

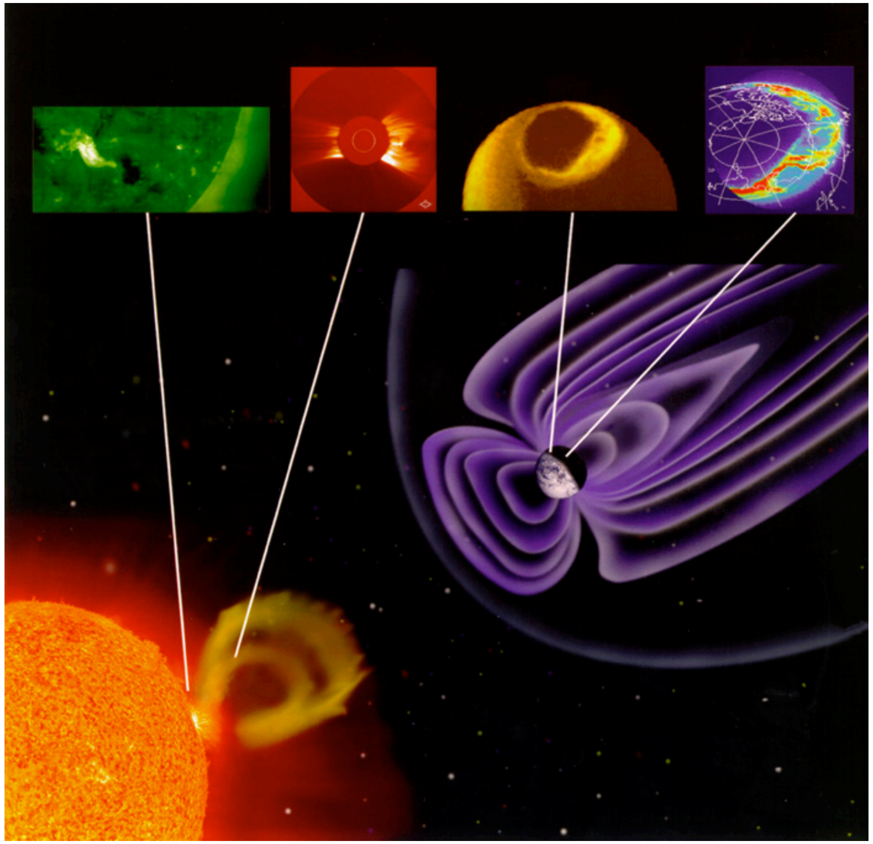
**Energy input into the polar regions of the Earth**

**Measured Quantity (e.g. Pixie):**

**3 – 60 keV X-rays from bremsstrahlung X-ray emission**

**Inferred Quantity:**

**Morphology, energy spectra, time variation of precipitating electrons**

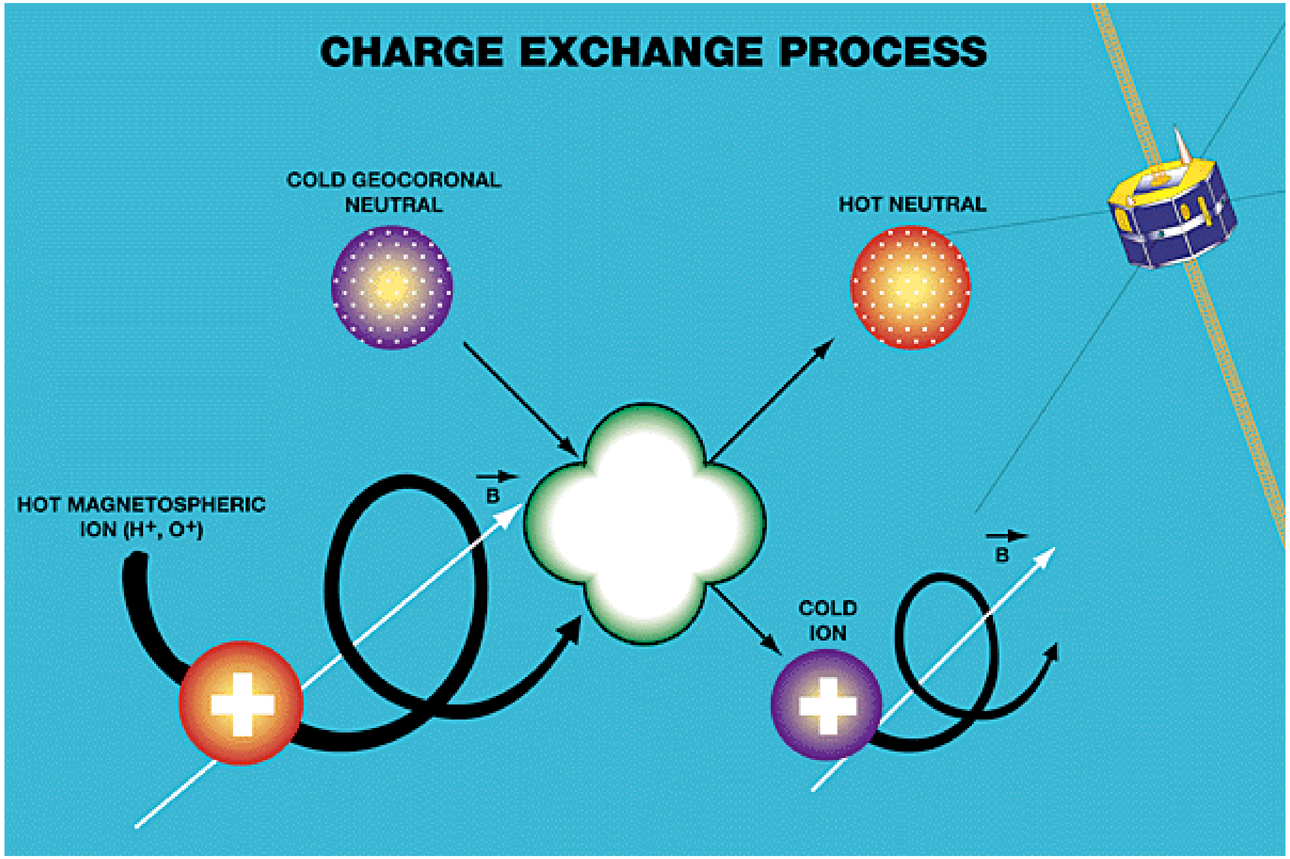


# REMOTE SENSING
## Imaging with Energetic Neutrals

**Missions:**
**e.g. POLAR, IMAGE, CASSINI**

**Measured Quantity:**
**Energetic Neutral Atoms (ENA) from charge exchange with the neutral H Exosphere.**

**Inferred Quantity:**
**Spatial distribution, energy spectra and time variation of energetic ions**

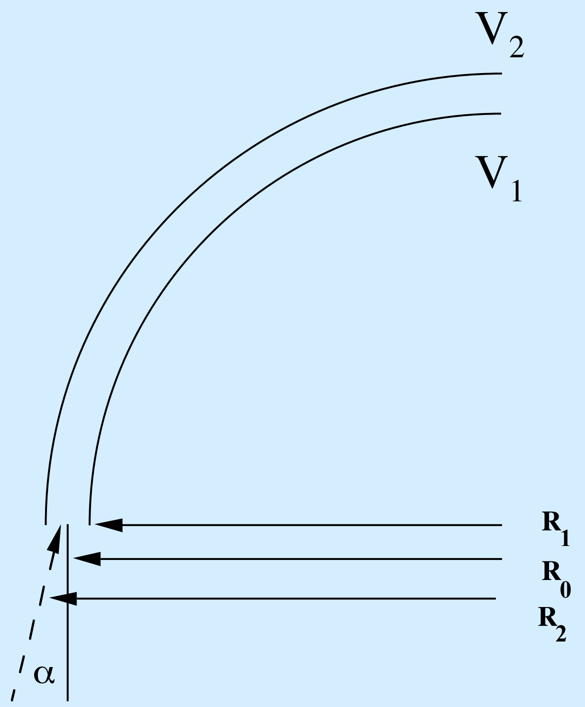


# In-Situ Measurements: Techniques

3. In-Situ Measurements: Techniques
   - E/Q Determination
   - Velocity Determination
   - E/Q + TOF (V, E/M) $\longrightarrow$ M/Q
   - Energy Determination

# E/Q Determination: The Electrostatic Analyzer

**Energy / Charge Analysis with Electrostatic Deflection (Spherical-Section Analyzer)**




**Energy Resolution:**

$\Delta E / E \sim \Delta R / R_0$

**Analyzer Constant k**

$E = k\, q\, V_0$

$k = R_0 / \Delta R$

**Geometrical Factor:**

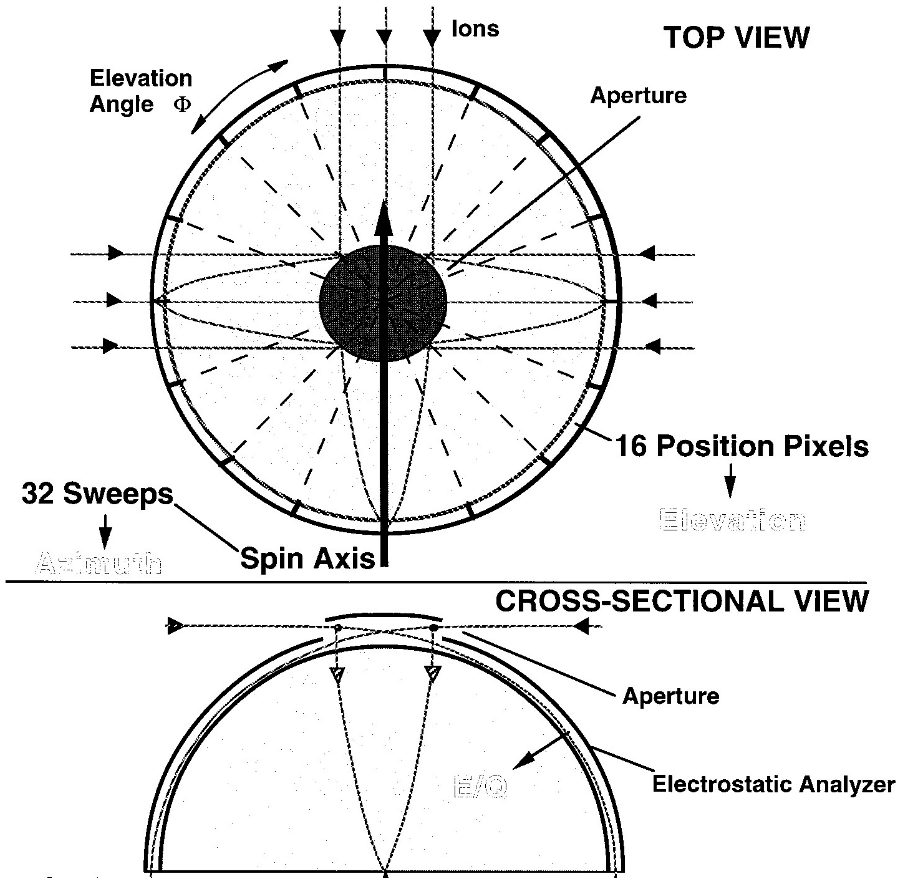
$A\Omega \sim d\alpha\ dv/v\ \Delta R\ R_0 \sim (\Delta R / R_c)^2\ (\Delta R\ R_0) \sim \Delta R^2\ (\Delta E/E)$

**Definitions:**

| | | |
|---|---|---|
| $E$ | | Energy of Particle |
| $q$ | | Ionic Charge |
| $V_{1,2}$ | | Potential of Plates 1, 2 |
| $\Delta R$ | = | $R_2 - R_1$ |
| $R_0$ | = | $(R_2 + R_1) / 2$ |

# The Next Step: 3D Resolution in 1 Spin

## A SYMMETRICAL QUADRISHERICAL ANALYZER IN "TOP HAT" CONFIGURATION




**Top View:**

**Note the focusing effect of the analyzer.**

**This configuration can be used for ions and electrons in the energy range of ~ eV to ~ 100 keV/e.**

**Carlson et al., 1983, Paschmann et al., 1985, Möbius et al., 1998**

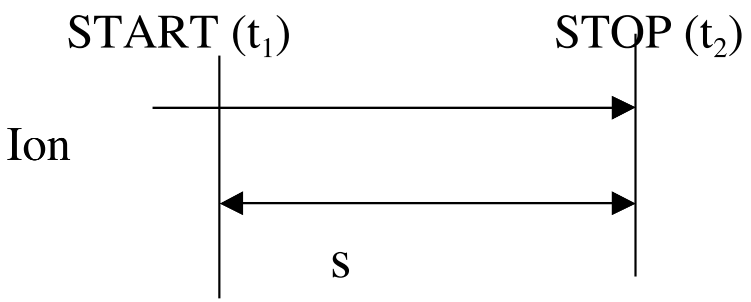
**AMPTE / IRM**

**Cluster / CIS-2**

**Cluster / PEACE**

# VELOCITY DETERMINATION

Determination of velocity by time-of-flight (TOF) measurement. Timing signal from Secondary Electron Emission (SEE) from START and STOP sensor elements.

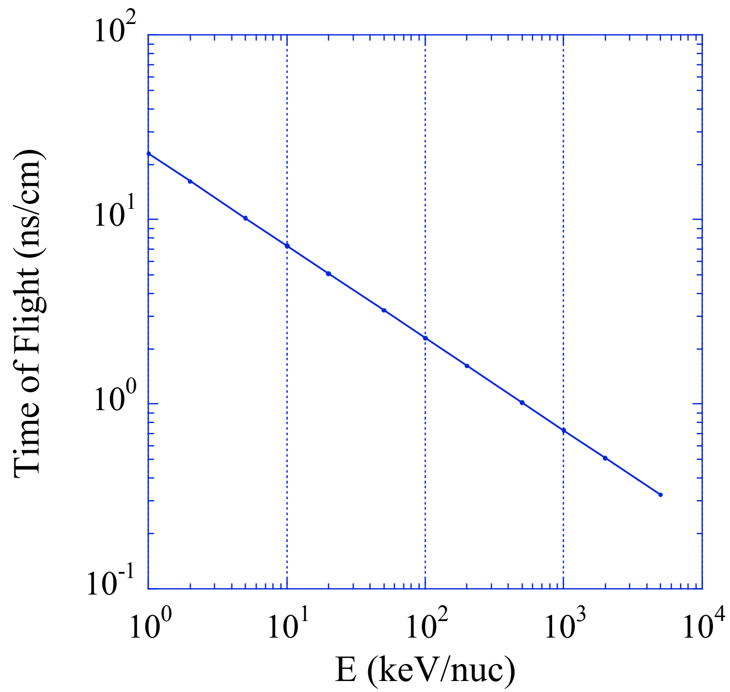



$\tau \quad = t_2 - t_1$

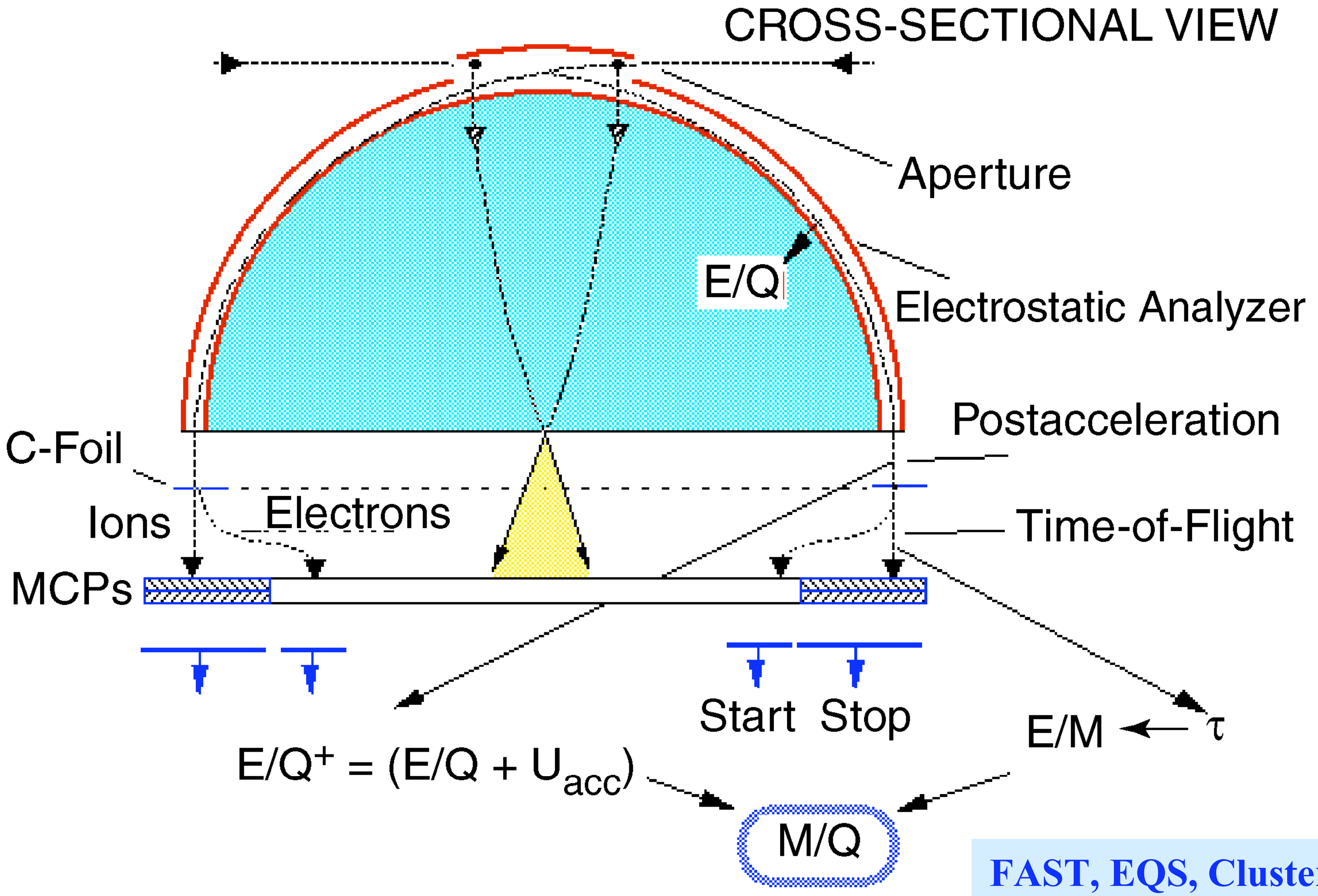
$V \quad = s / \tau$

Accuracy determined by:

- Path length variations (scattering)
- Energy variations in START element
- Variations of timing signal



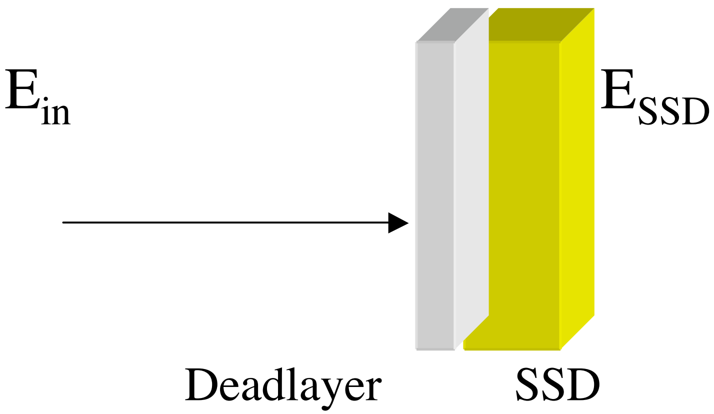
# M/Q Determination by E/Q and TOF Measurement




FAST, EQS, Cluster / CIS-1

# Energy Determination

## Energy Measurement




$$E_{SSD} = E_{in} - \Delta E_{deadlayer} - \Delta E_{NC}$$

**$E_{SSD}$** **Measured Energy**

**$\Delta E_{deadlayer}$** **Energy loss in inactive SSD surface layer, front foil, etc.**

**$\Delta E_{NC}$** **Non-electronic energy loss (nuclear collisions)**

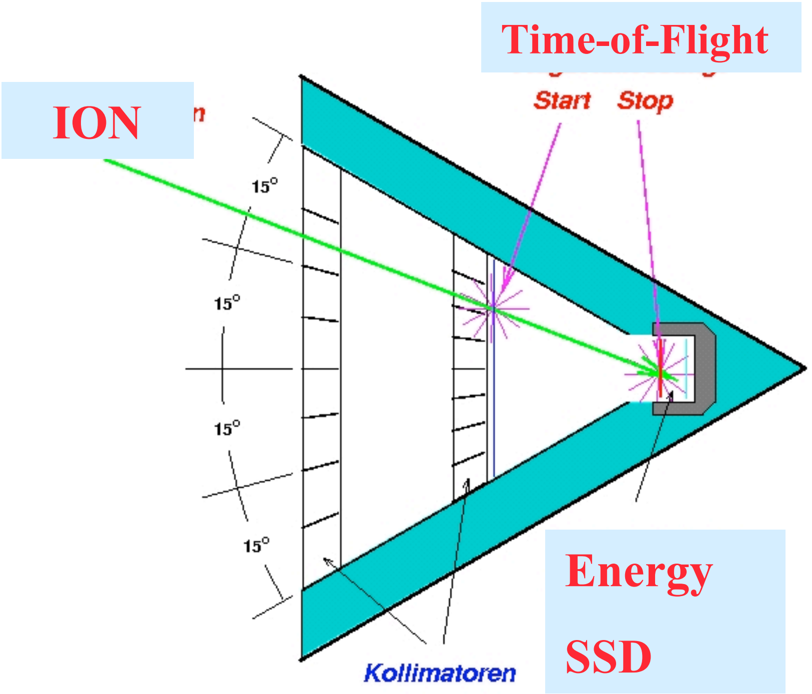
**ENERGY and POSITION Determination:**

**Use of 'Stripe'-Detectors or of 'Pixel' Detectors.**

**Minimum Energy : ~ 20 keV**

**(depends on electronic noise)**

# Energy + Time-of-Flight




Energy → Mass

TOF (E/M) → Mass

Cluster / RAPID
IIMS / Ion Sensor

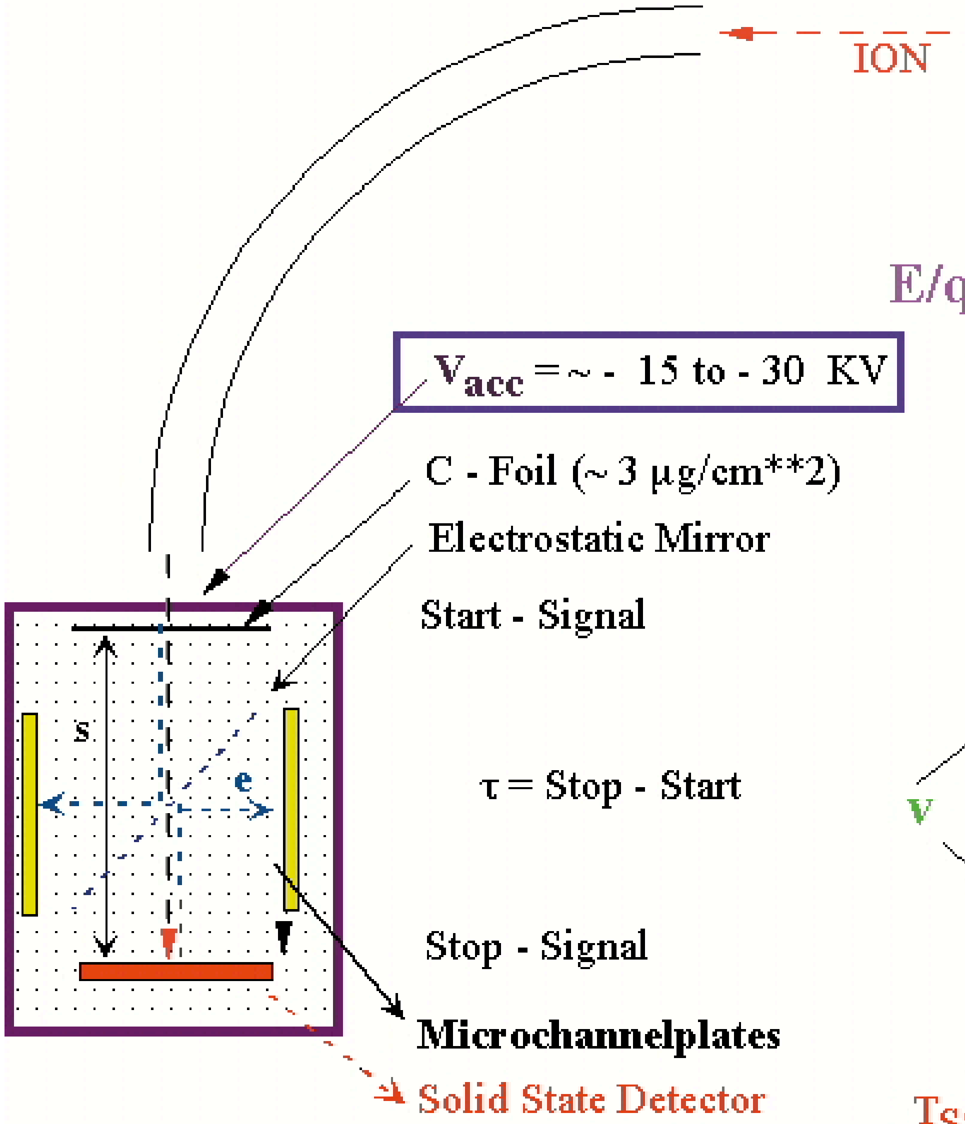
Wilken et al., 1997

# MASS / CHARGE AND MASS ANALYSIS

**Typically used for**

**Solar Wind Sensors**

- **WIND**
- **Ulysses**
- **SOHO**
- **ACE**




E/q

v

$T_{SSD}$

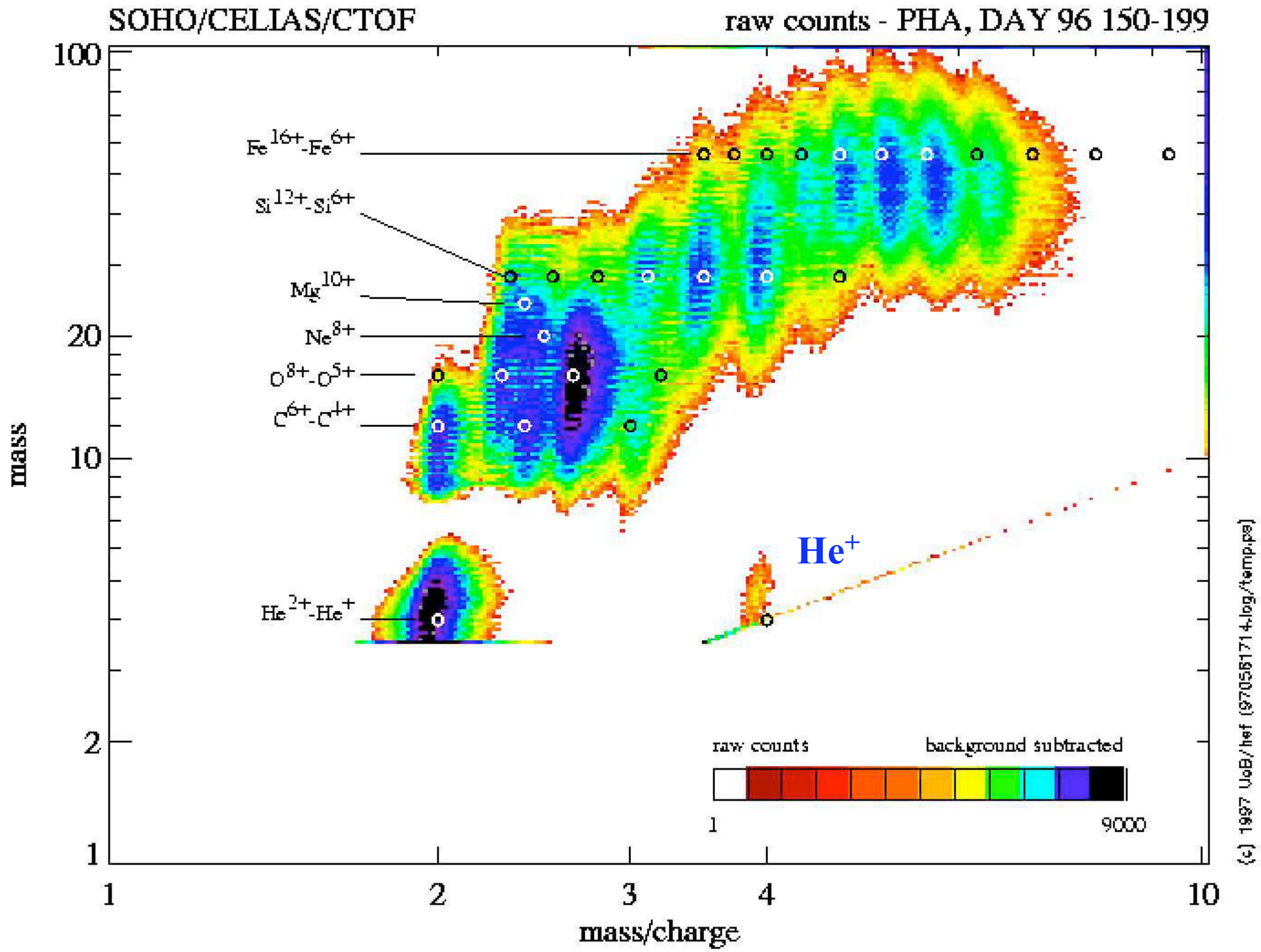
$$M/q = (E/q + eV_{acc}) \,/\, (E/M^{*}\alpha_1)$$

$$E/M^{*} = 1/2 * (s/\tau)^2$$

$$M = \alpha_2 T_{SSD} \,/\, E/M^{*}$$

# Solar Wind Ionic Charge Spectra (SOHO)

M



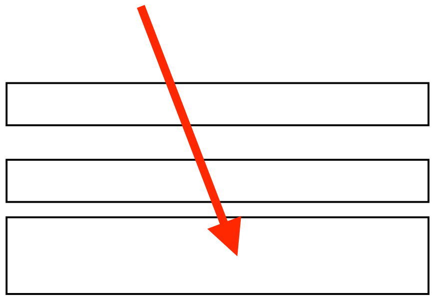

M/Q

# THE DE/DX-E TECHNIQUE
# Particle Telescopes

The dE/dx – E Method

$\Delta E1$ — SSD or Gas Counter (PC, IC)

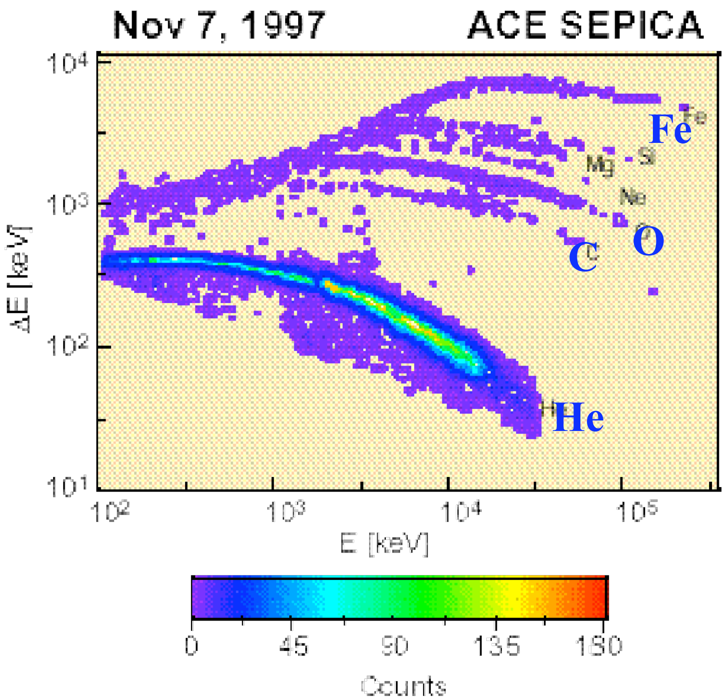
$\Delta E2$



$E_{res}$ — SSD

The measurement of Energy Loss (**dE/dx**), Range, and Residual Energy ($E_{res}$) of ions and electrons can be used to determine the total energy E, Nuclear Charge, and Mass.

$$dE/dx = k1 * Z^{*2} / (E/M) * f(k2,E)$$



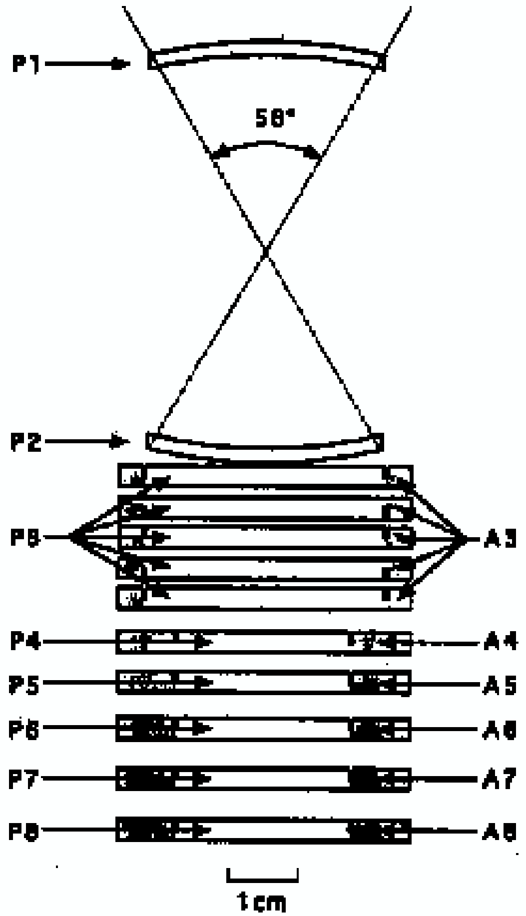
# HIGH ENERGY ELECTRONS
## PET: The Proton-Electron Telescope Onboard SAMPEX

P1

P2

P3

P8




**P1, P2: DE Measurement**

- **Curved detectors to minimize loss of resolution due to path length variations.**

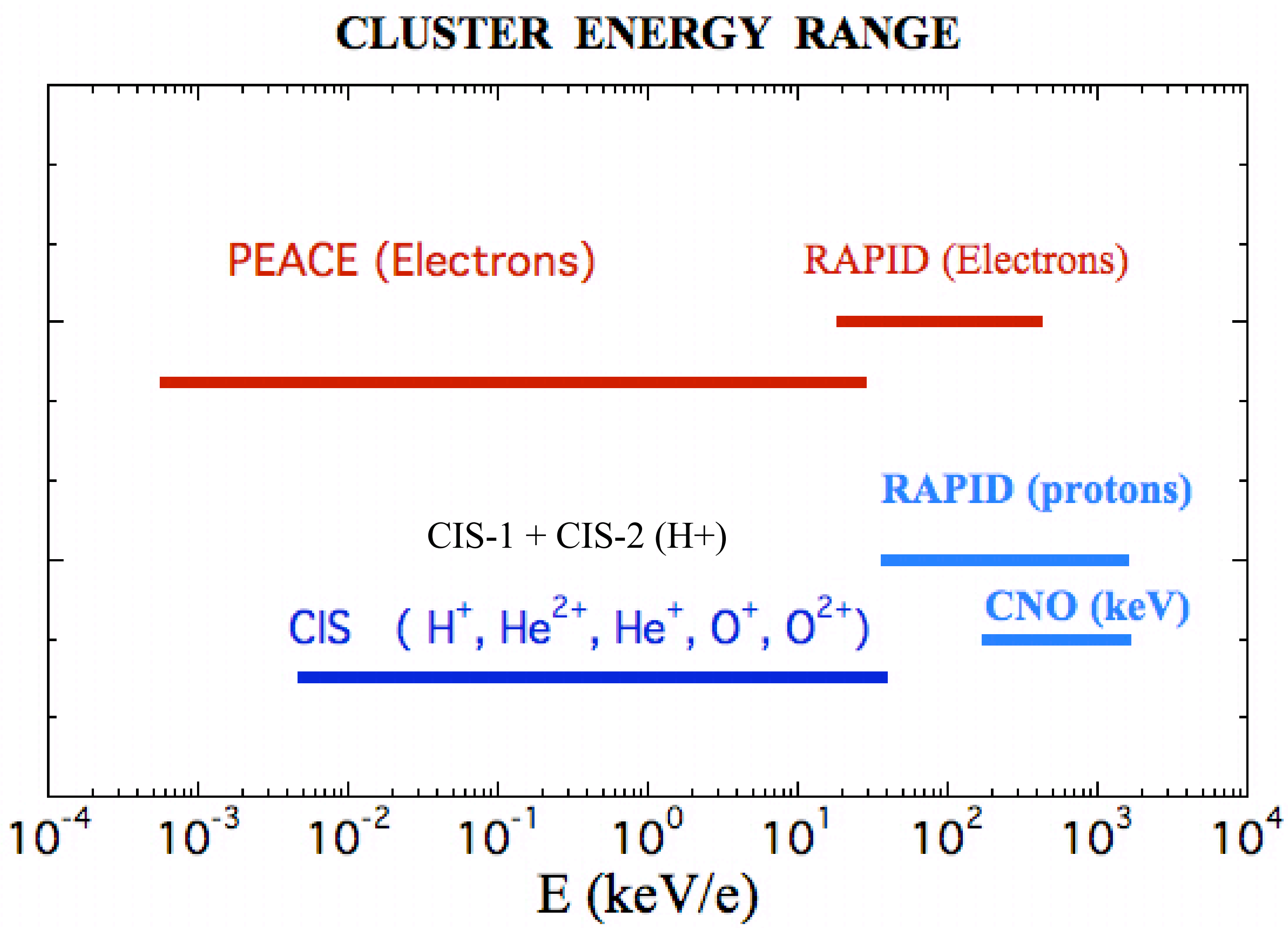
**P3 - P8: E Measurement**

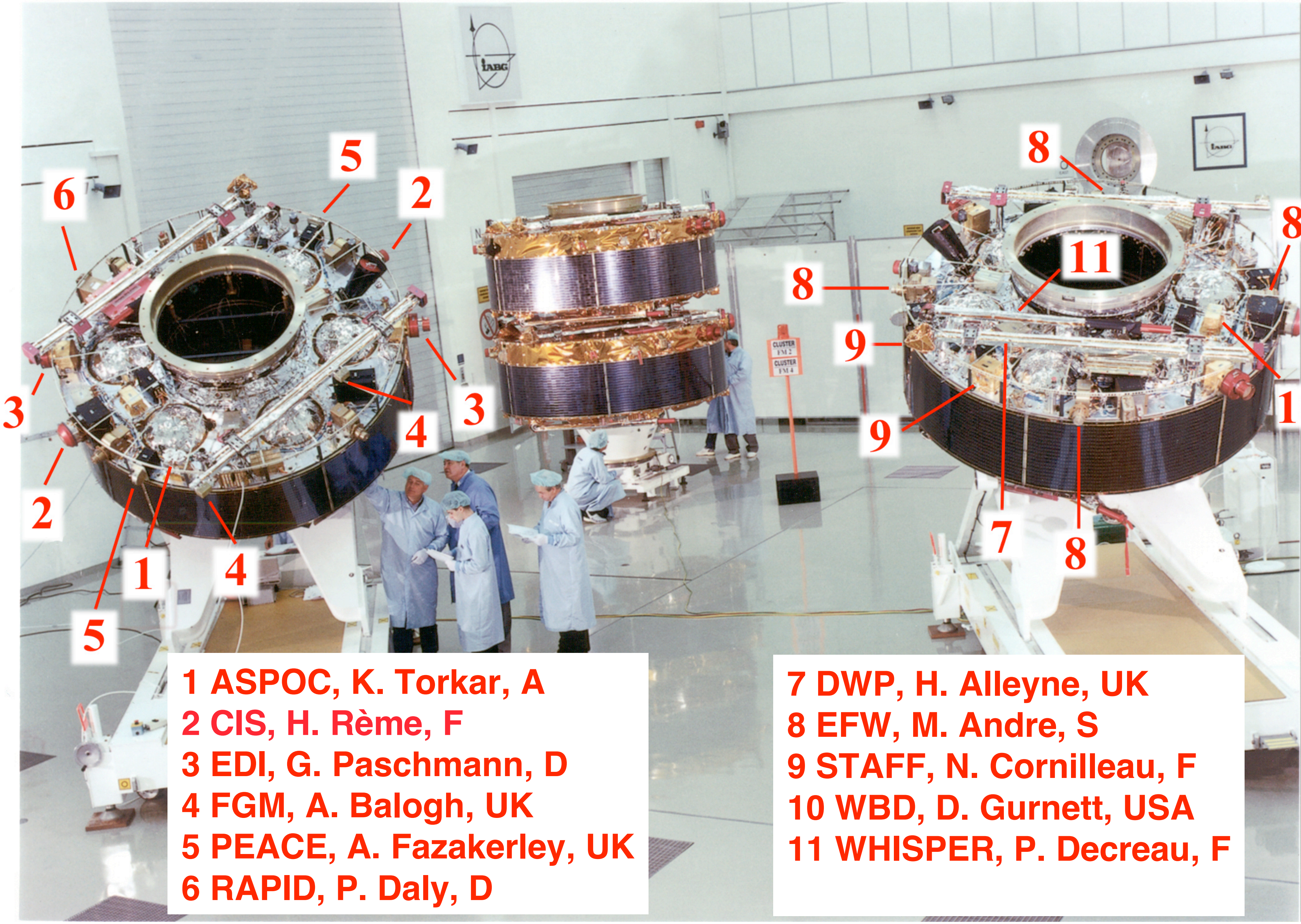
- **Stack of SSDs to measure the energy deposition**

| | p | e | |
|---|---|---|---|
| **Energy Range** | **~ 19 - 85** | **0.4 – 30** | **MeV** |

Cook et al., 1993

# THE CLUSTER PARTICLE EXPERIMENTS

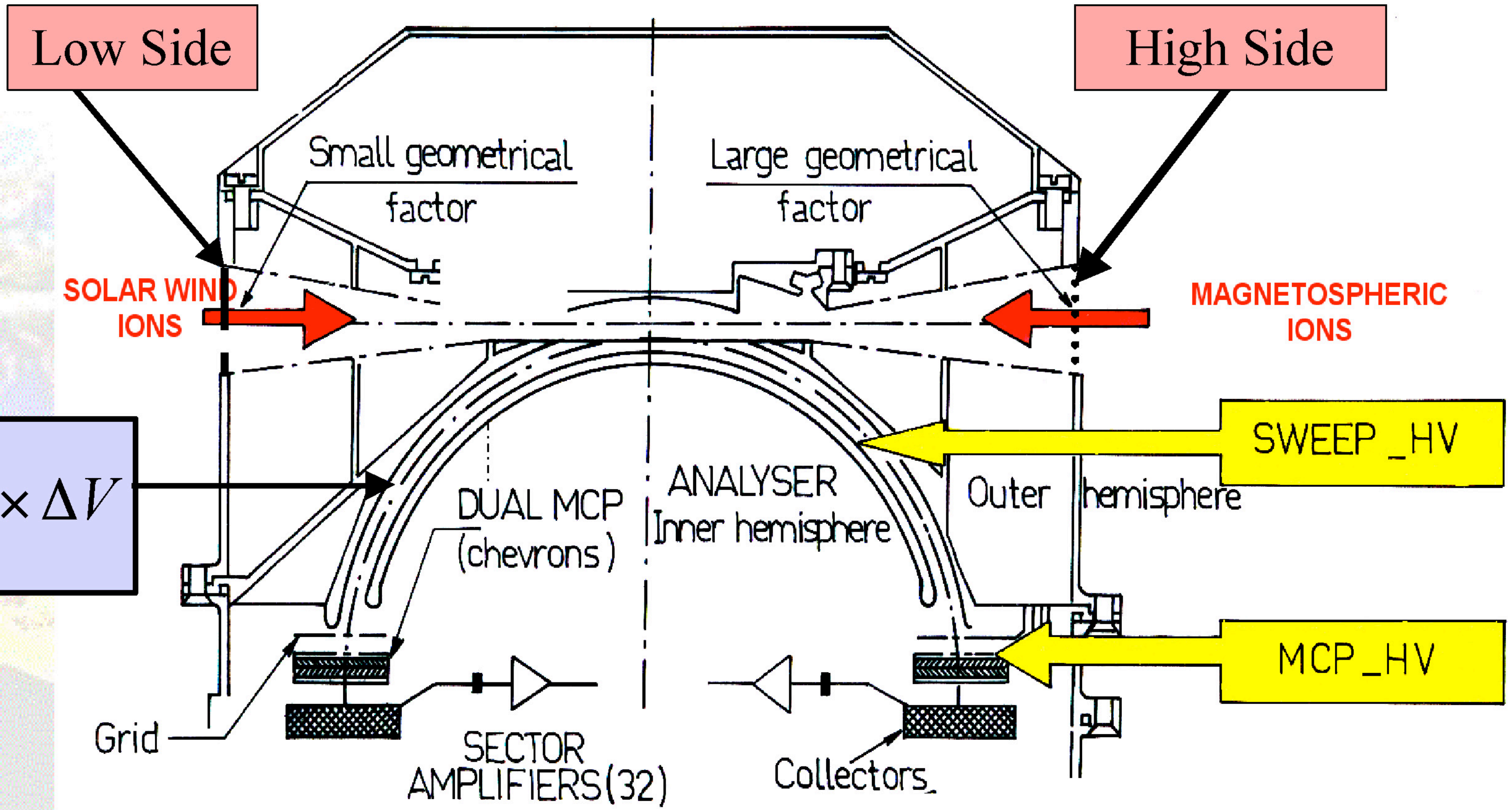




1 ASPOC, K. Torkar, A
2 CIS, H. Rème, F
3 EDI, G. Paschmann, D
4 FGM, A. Balogh, UK
5 PEACE, A. Fazakerley, UK
6 RAPID, P. Daly, D
7 DWP, H. Alleyne, UK
8 EFW, M. Andre, S
9 STAFF, N. Cornilleau, F
10 WBD, D. Gurnett, USA
11 WHISPER, P. Decreau, F

Cluster Ion Spectrometry:

## **HIA**: Hot Ion Analyser



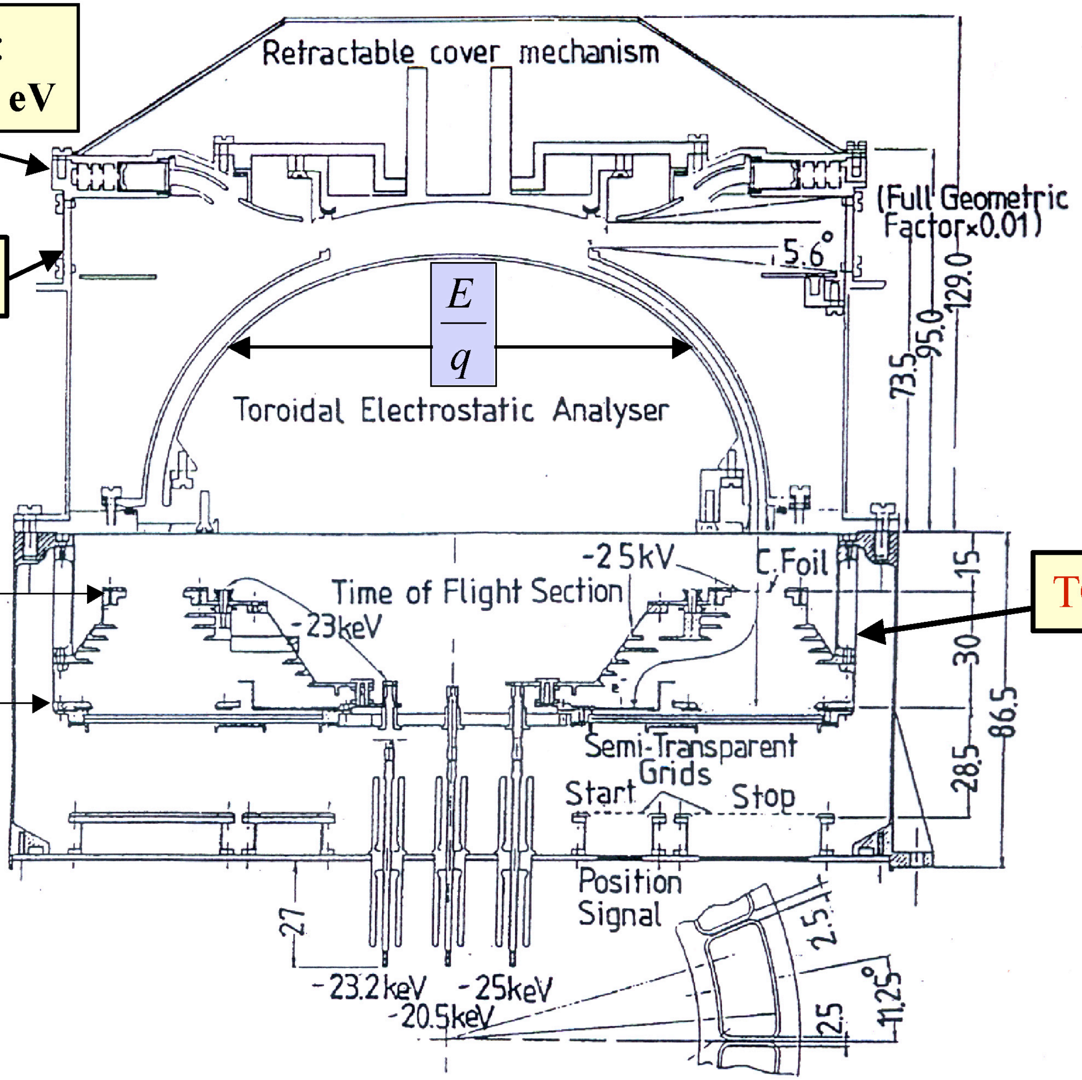

$$\frac{E}{q} = k \times \Delta V$$

**E/Q, Φ, θ**

# CODIF: Ion Composition and Distribution Function Analyser

RPA entrance :
$\approx 0\ eV \leq E_{RPA} \leq 25\ eV$

Main entrance




**Reduced Entrance**

**X 0.01**

TOF system

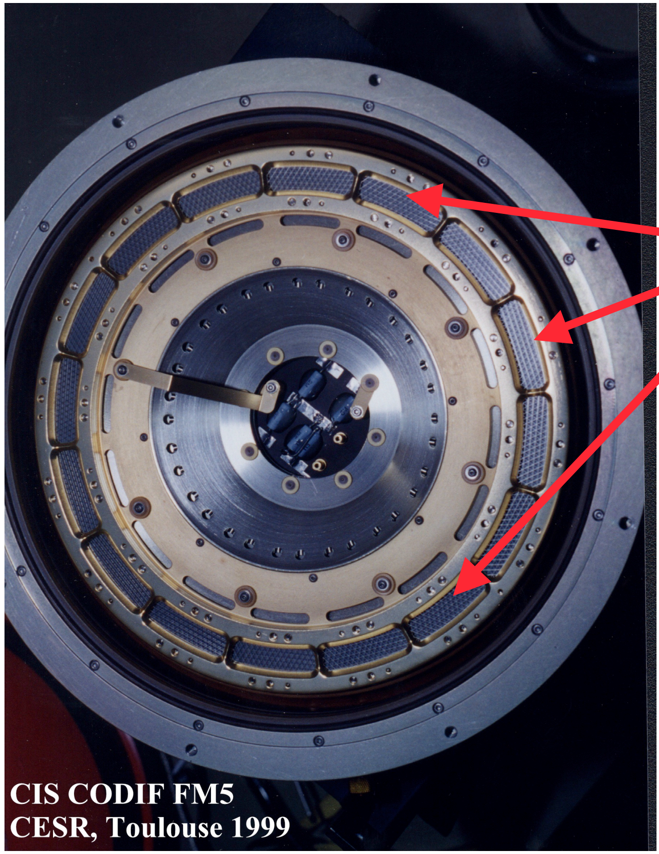
L

$$\frac{m}{q} = \frac{2 \times \left(\frac{E}{q}\right)}{\left(\frac{L}{TOF}\right)^2}$$

**E/Q, Φ, θ, TOF -> M/Q**

# CODIF SENSOR
# 3D COVERAGE

**View on C-Foils +**
**Support Grids**




## 3D Coverage:

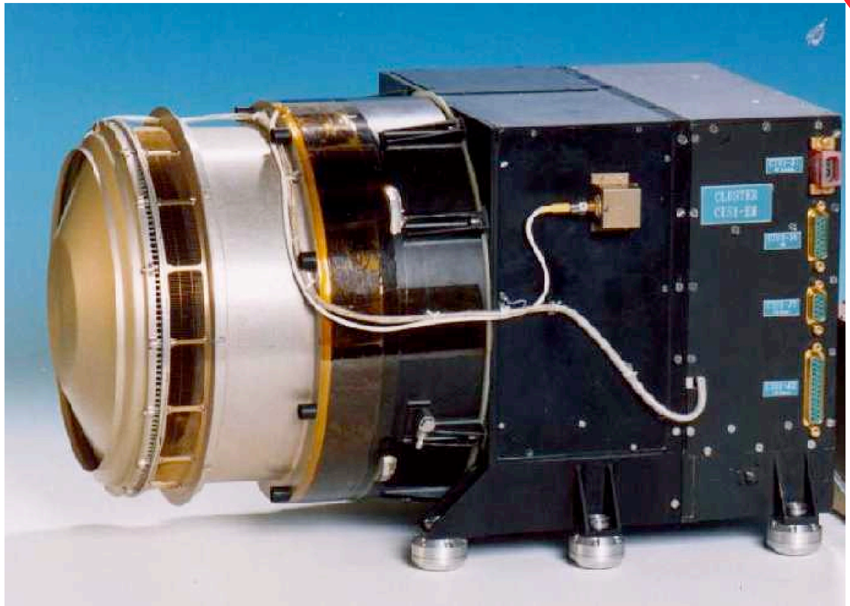
**Azimuth: 32 Sectors (by S/C Rotation)**

**Elevation: 8 Sectors (per Hemisphere)**

# AN EXAMPLE FOR M/Q ANALYSIS

## CODIF onboard FAST, Equator-S and Cluster

ESA TOF EBOX DPU




SPIN AXIS

**FAST:**

Launch: 21.08.1996
Orbit: polar, 400 x 4000 km

**Equator-S:**

Launch: 2.12.1997
Orbit: äquatorial,
500 km x 11.3 $R_E$

**Cluster**

Launch: 16.7 + 9.8.2000
Orbit: polar, 4 x 19.5 $R_E$

**CODIF / CLUSTER**

**CO**mposition and **DI**stribution **F**unction Analyzer

# ON BOARD DATA PROCESSING

## Full Information for Each Ion

| Parameter | Range | Bits |
|---|---|---|
| Time-of-Flight | 0-255 | 8 |
| Azimuth (Φ) | 0-31 | 5 |
| Mode Bit | 0-1 | 1 |
| Energy Step | 0-127 | 7 |
| Elevation (θ) | 0-7 | 3 |
| **Total** | | **24** |

## Event Rate:

**up to several 100 kHz**

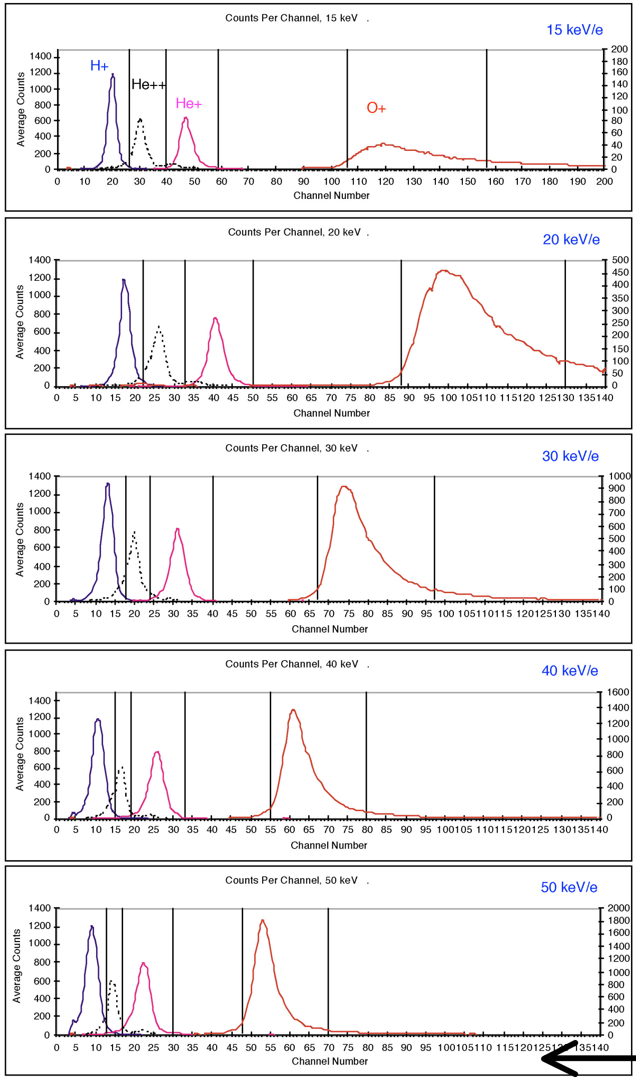
**Telemetry needed for full transmission:**

**several MB/s**

**Typical available: 5 - 10 kb/s**

**Onboard Processing is essential for data reduction !**

# ON BOARD DATA PROCESSING




TOF

**Figure 6.** FM7 time-of-flight spectra for the four major species at 4 energies. The spectra are averaged over all positions. The lines show the thresholds used to distinguish species.

## Fast Particle Identification (M/Q) Using Time-of-Flight Measurement

**Calibration Measurements for**

**$H^+$, $He^{2+}$, $He^+$, $O^+$**

**On-board M/Q Classification:**

**The vertical lines show the thresholds used onboard for fast M/Q classification (~100 kHz).**

# ON BOARD DATA PROCESSING

- **Fast Particle Identification (M/Q) Using Time-of-Flight Measurement**
- **Compute Plasma Parameters (N, V, T, P) for $H^+$, $He^{2+}$, $He^+$, $O^+$**
- **Compute 3D Distributions (E/Q, $\theta$, $\Phi$) for $H^+$, $He^{2+}$, $He^+$, $O^+$**
- **Transmit (small) Sample of Events with full (24 bit) Information**
- **Transmit Plasma Parameters once per Spin (4s)**
- **Accumulate 3D Distributions of $H^+$, $He^{2+}$, $He^+$, $O^+$ over several Spins (can be adjusted by command)**
- **Transmit various Telemetry Products to Ground**

**MORE TO COME IN**
**INTERPRETATION AND MODELING**
**OF PARTICLE SPECTRA**

# REFERENCES


Carlson, et al., Adv. Space Res., 2,7, 67, 1982

Paschmann, G., et al., IEEE Trans. Geosc. Remote Sens. GE-23, 262, 1985.

Möbius, E., et al., In: “Measurement Techniques in Space Plasmas: Particles“, AGU Monograph, 102 , 243-248, 1998

Rème, H., et al., Space Science Rev. 79, 399-473, 1997

Rème, H., et al., Annal. Geophys., 19, 1303-1354, 2001

Wilken, et al., Space Science Rev. 79, 399-473, 1997

# NEXT LECTURE

**INTERPRETATION AND MODELING**
**OF PARTICLE SPECTRA**