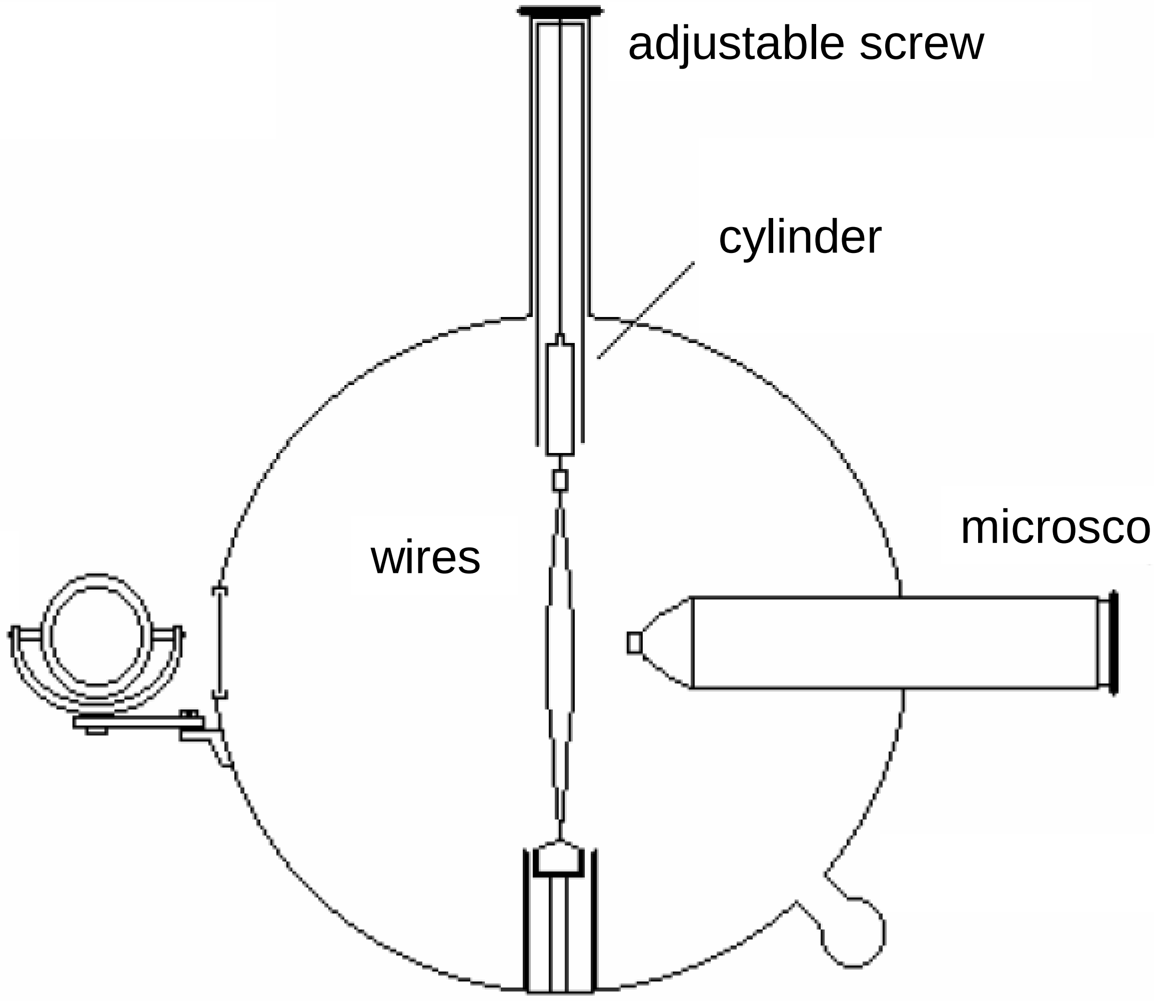
MEASURING ABUNDANCES IN COSMIC RAYS AND NEAR-EARTH SPACE

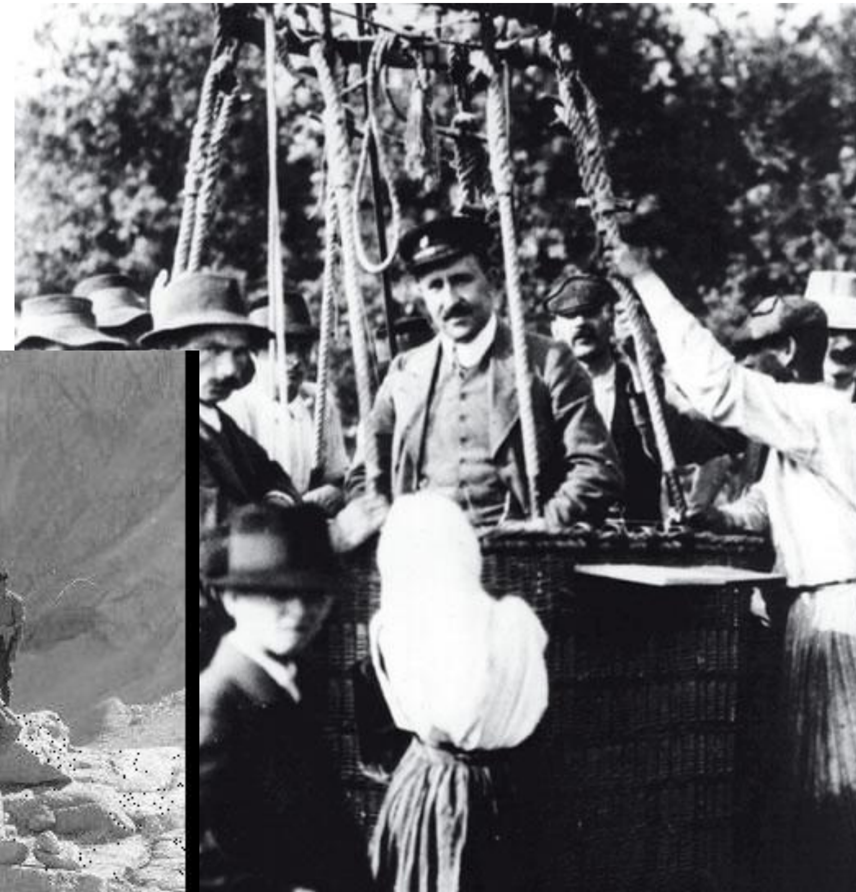
Maximilian Uhlig
14.07.2010

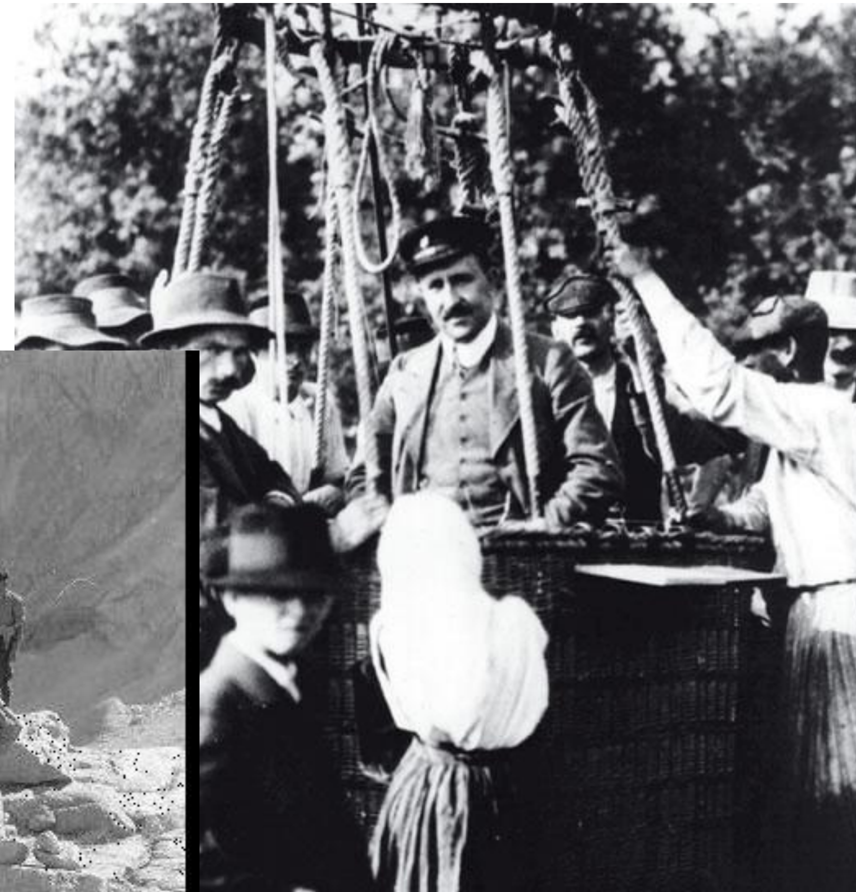
Historical Overview

- 1911-1912: Victor Hess measures radiation on balloon flights
- Result: @ 5 km: radiation about twice as high as at sea-level
- → radiation caused by particles penetrating the atmosphere from outer space
- 1925: Robert Andrews Millikan confirms the discovery, name: “cosmic rays”
- 1936: Nobel Prize in Physics for V. Hess and C. D. Anderson



Electroscope used by V. Hess





First observed in cosmic rays: Muon, Positron, Pion, Kaon,…

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Cosmic Rays

What are Cosmic Rays?

- High-energetic particles up to ~10^{20} eV (LHC: 7×10^{12} eV) arriving from outer space
- Composition well known below 10^{14} eV

  86% protons
  11% helium
  1% heavy nuclei
  2% electrons
- Very small abundance of antiprotons, positrons
- Neutral component: gamma rays, neutrinos
- Origin? Problem: isotropic due to galactic magnetic fields

Cosmic Rays Flux

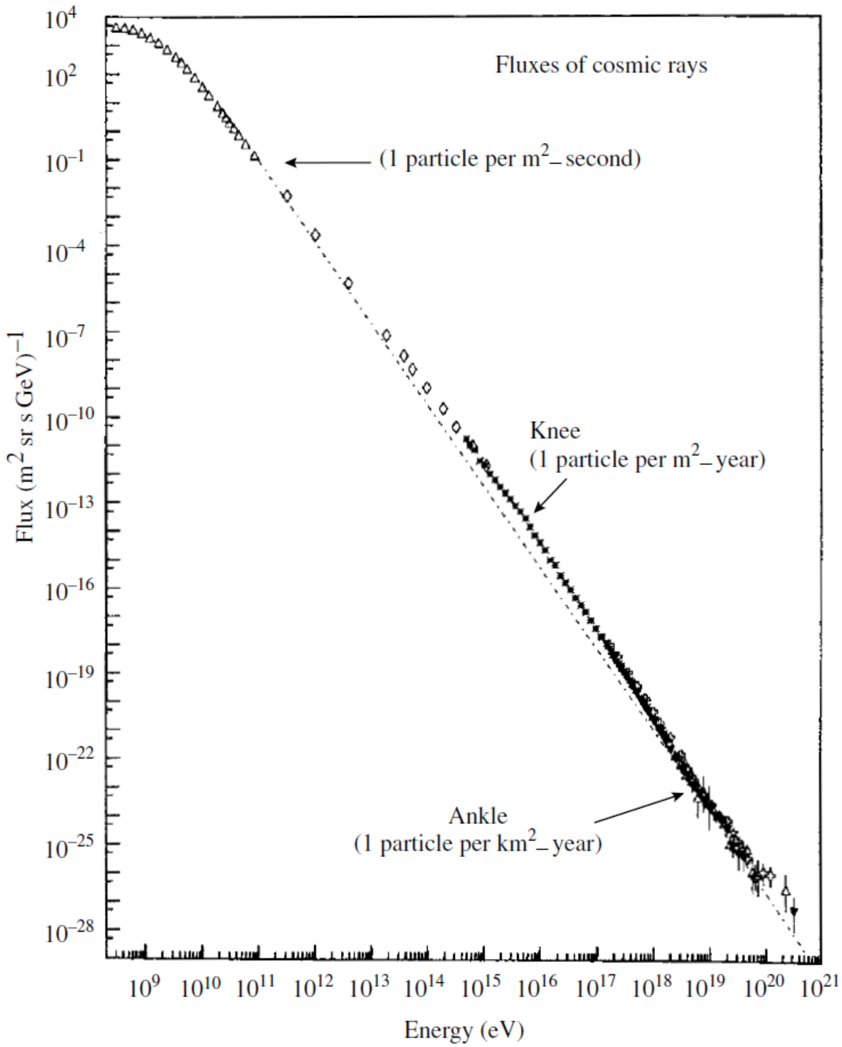
- Power law:

$$N(E)\,\mathrm{d}E = \mathrm{const}\cdot E^{-2.7}\,\mathrm{d}E \qquad E < E_{\mathrm{knee}} = 10^{16}\,\mathrm{eV}$$

$$N(E)\,\mathrm{d}E = \mathrm{const}\cdot E^{-3.0}\,\mathrm{d}E \quad E_{\mathrm{ankle}} > E > E_{\mathrm{knee}}$$

$$N(E)\,\mathrm{d}E = \mathrm{const}\cdot E^{-2.69}\,\mathrm{d}E \quad E_{\mathrm{GZK}} > E > E_{\mathrm{ankle}}$$

$$N(E)\,\mathrm{d}E = \mathrm{const}\cdot E^{-4.2}\,\mathrm{d}E \quad E > E_{\mathrm{GZK}} = 4\times 10^{19}\,\mathrm{eV}$$



Stochastic Acceleration (Fermi: 1949)

- Energy after k collisions:

$$\frac{E_k}{E_{k-1}} = \xi \implies E_k = E_0\,\xi^k$$

Number of particles with energy above E_k:

$$N_k = N(E \geq E_k) = N_0 P^k$$

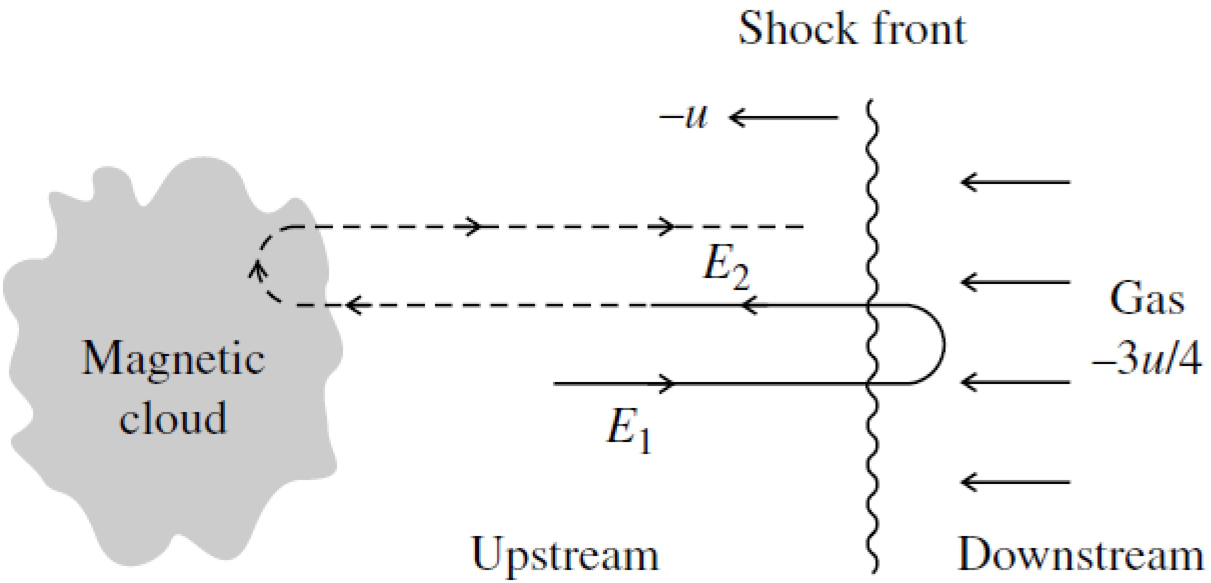
$$\frac{\ln \frac{N_k}{N_0}}{\ln \frac{E_k}{E_0}} = \frac{\ln P}{\ln \xi} \implies \frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P/\ln \xi}$$

→ Energy spectrum: $$\frac{dN}{dE} = \frac{dN}{dE}(E_0) \cdot \left(\frac{E}{E_0}\right)^{-1+\ln P/\ln \xi}$$

→ power law!

First order Fermi Acceleration

- Acceleration in shock fronts:

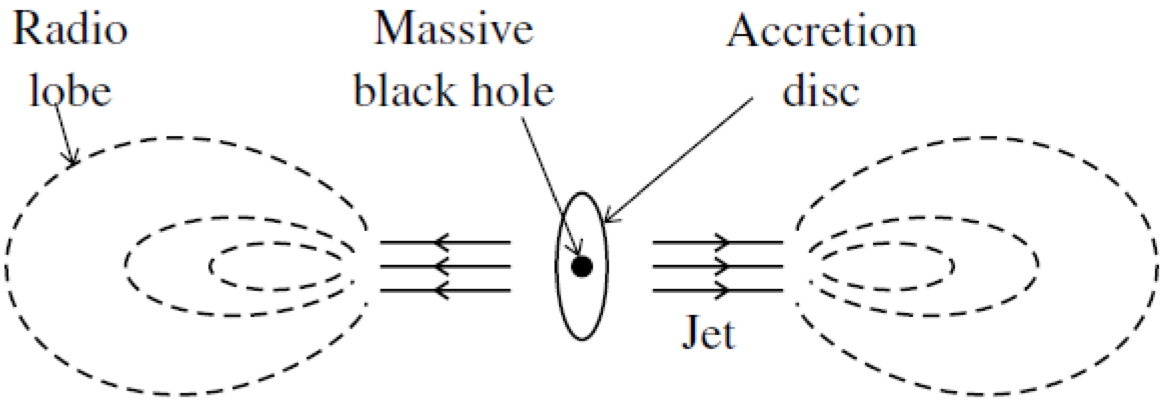


$$\langle\frac{\Delta E}{E}\rangle = \frac{\langle E_2\rangle - E_1}{E_1} \approx \beta = \frac{3}{4}u$$

High Energies?

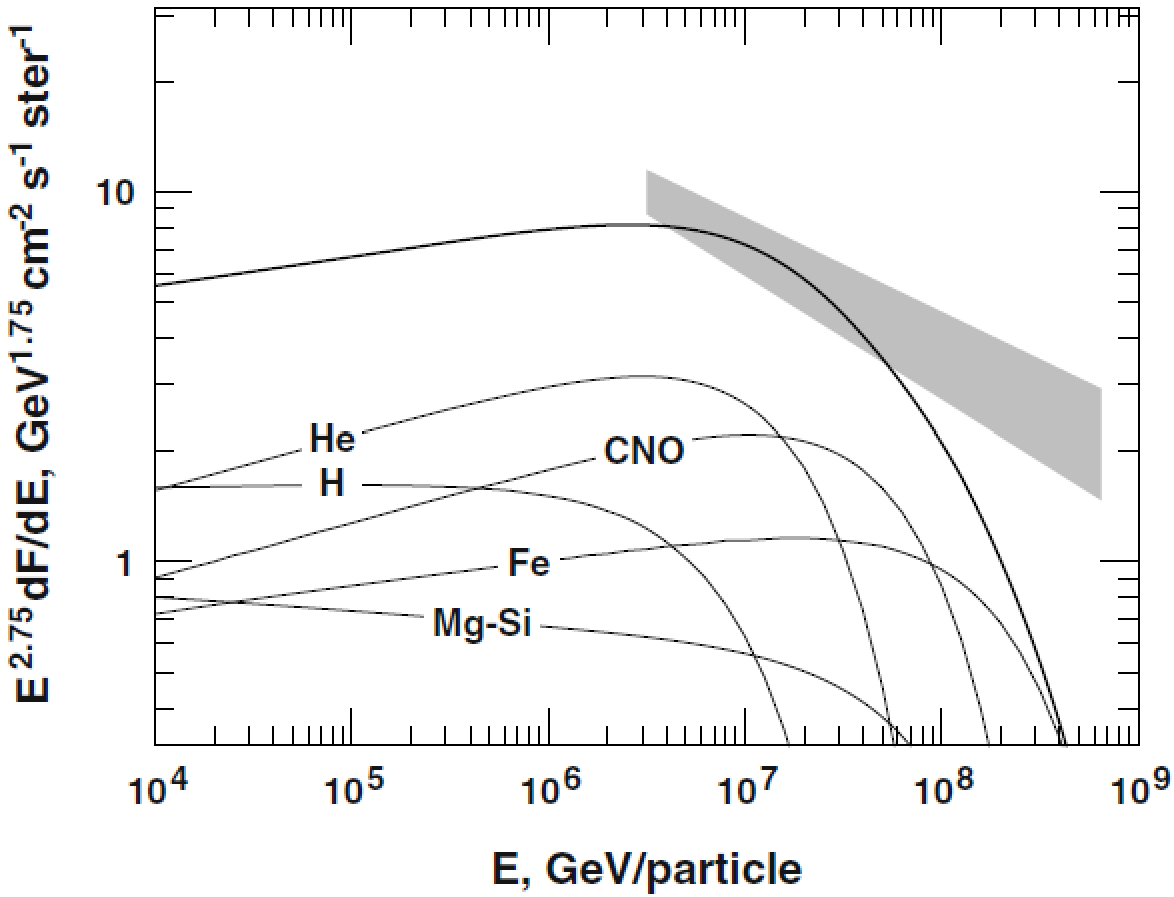
- Maximum energy at SNR: ~ Z x 10^{14} eV, proportional to
  - Particle charge
  - Magnetic field at acceleration site
  - Shock wave velocity
  - Dimension of acceleration site
  - Type of supernova explosion

- Above the knee: AGN?, GRB?



The Knee

- 10^{15} - 10^{16} eV
- Origin still a matter of debate
  - Knee could indicate escape out of the galaxy (lighter particles diffuse more easily, $E_{escape} \sim Z$)
  - or maximum energy of accelerators, $E_{max} \sim Z$
  - or new interaction mechanisms, exotic particles? ($E_{knee} = E_{threshold}$)



T. Stanev, High Energy Cosmic Rays, Second Edition

→ One should try to explore the contribution of different elements to the total flux (KASCADE)

The Ankle

- ~ 10^{19} eV
- Maybe a result of
  - Extragalactic flux starts to dominate over galactic flux

gyroradius: $\rho = \frac{p\,c}{zeB} = \frac{p}{z \cdot 0.3 \cdot B}$ > galaxy dimension

since extragalactic particles are able to escape their galaxies and reach us
→ spectrum gets harder again

GZK Cut-off

- **G**reisen, **Z**atsepin, **K**uzmin (1966): universe opaque around 10^{20} eV

$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

collision of primary protons with CMB photons

- Threshold: ~10^{20} eV
- Energy loss typically 15 % of proton energy
- Mean free path: several Mpc
- Heavier nuclei: photo disintegration

Abundances in Cosmic Rays

Measuring Abundances

- Flux:

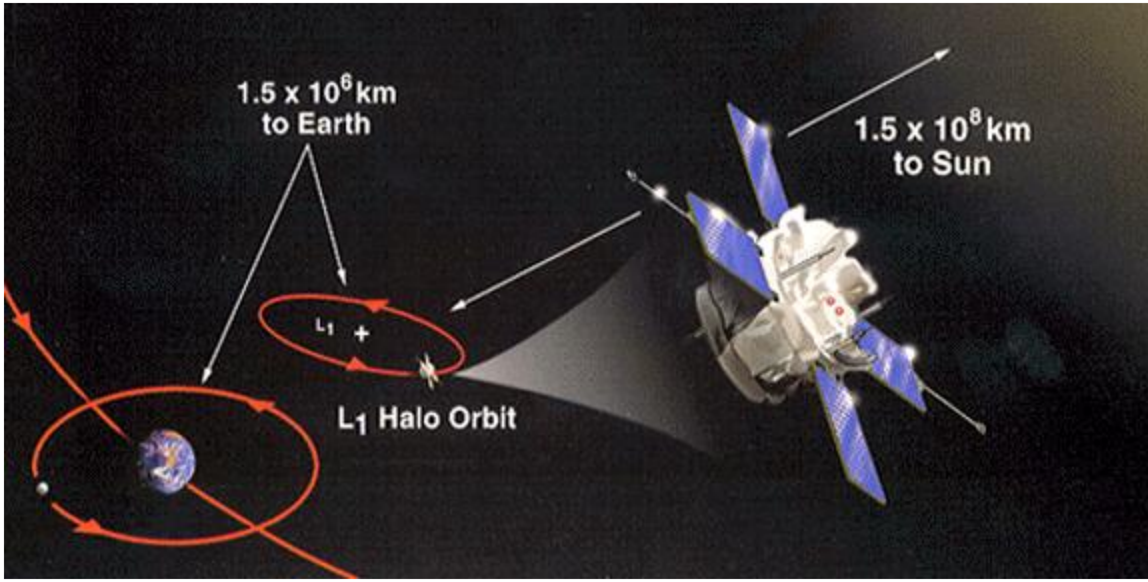
  $E < 10^{14}$ eV: 1 particle / (m^2 s)
  $E \sim 10^{16}$ eV: 1 particle / (m^2 year)
  $E \sim 10^{19}$ eV: 1 particle / (km^2 year)

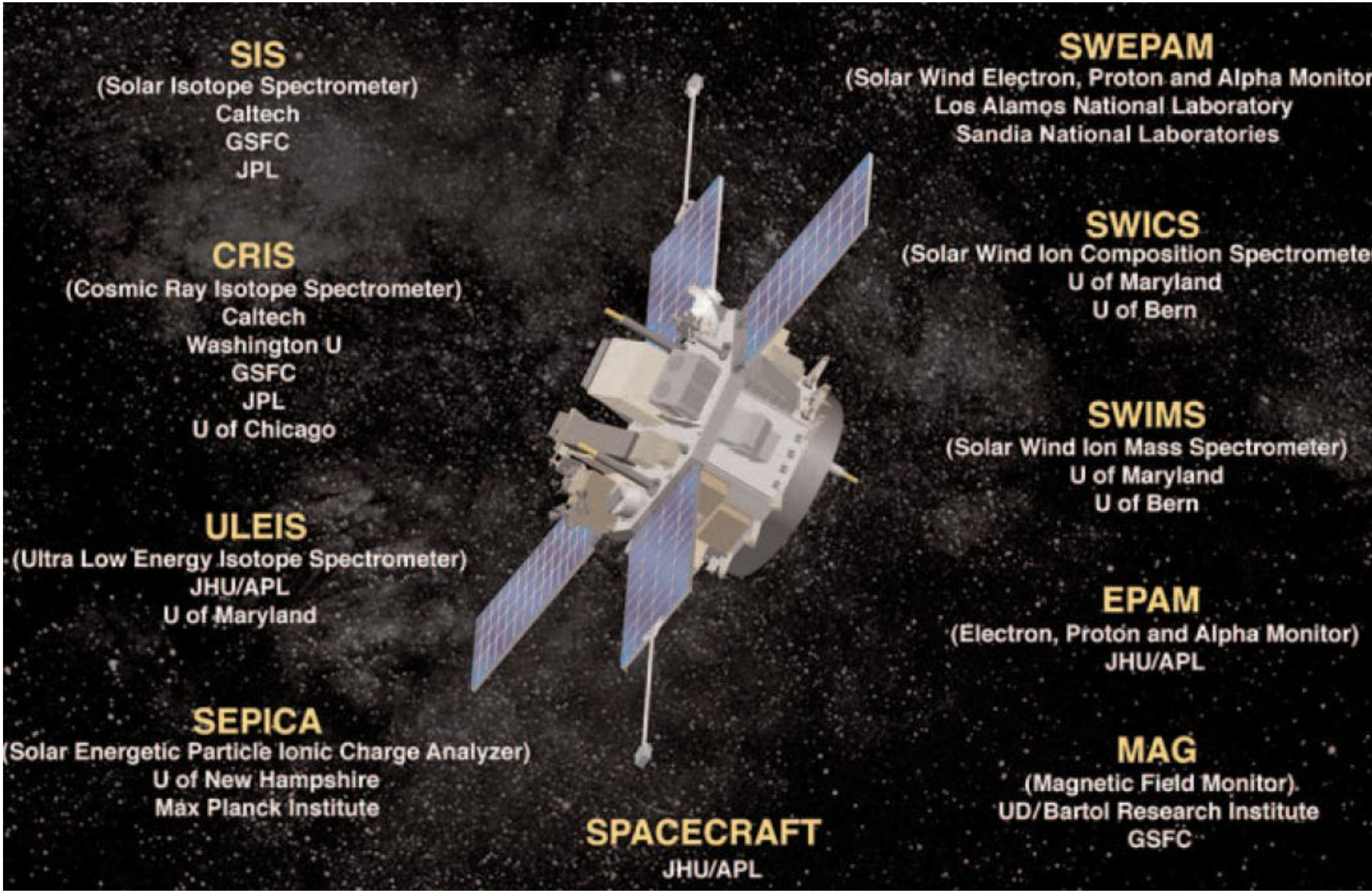
- $E < 10^{14}$ eV: direct measurements (balloons, satellites)

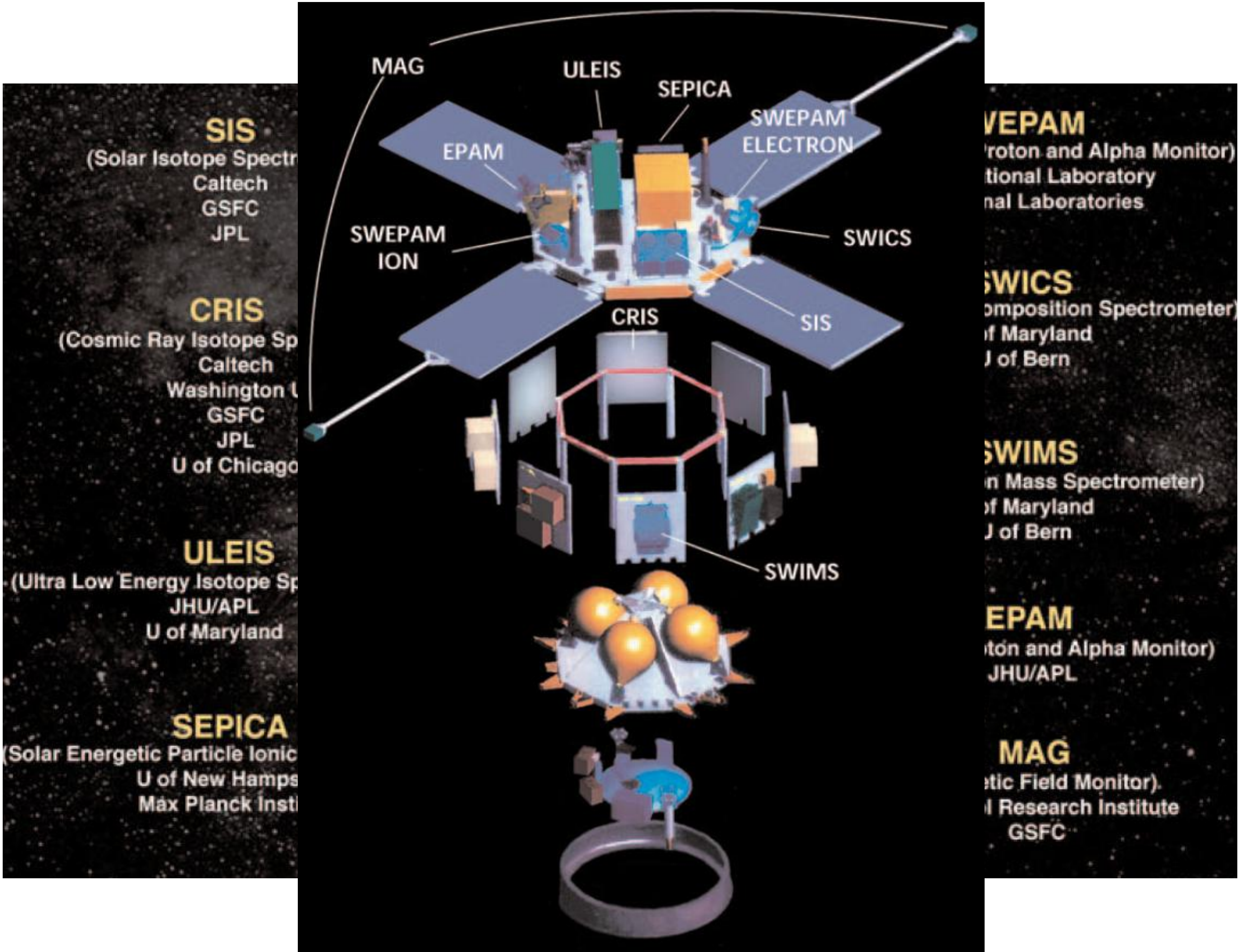
- $E > 10^{14}$ eV: indirect measurements (air shower arrays)

ACE

- **A**dvanced **C**omposition **E**xplorer (ACE)
- Satellite mission, launched in 1997 into L1
- Study of composition of solar wind and cosmic rays
  - ~ 100 eV / nucleon to ~ 500 MeV / nucleon
  - Hydrogen to Zinc (Z = 1 to 30)
- six high-resolution spectrometers
- very good mass separation for isotopic resolution < 0.25 amu




SIS
(Solar Isotope Spectrometer)
Caltech
GSFC
JPL
CRIS
(Cosmic Ray Isotope Spectrometer)
Caltech
Washington U
GSFC
JPL
U of Chicago
ULEIS
(Ultra Low Energy Isotope Spectrometer)
JHU/APL
U of Maryland
SEPICA
(Solar Energetic Particle Ionic Charge Analyzer)
U of New Hampshire
Max Planck Institute
SPACECRAFT
JHU/APL
SWEPAM
(Solar Wind Electron, Proton and Alpha Monitor)
Los Alamos National Laboratory
Sandia National Laboratories
SWICS
(Solar Wind Ion Composition Spectrometer)
U of Maryland
U of Bern
SWIMS
(Solar Wind Ion Mass Spectrometer)
U of Maryland
U of Bern
EPAM
(Electron, Proton and Alpha Monitor)
JHU/APL
MAG
(Magnetic Field Monitor)
UD/Bartol Research Institute
GSFC



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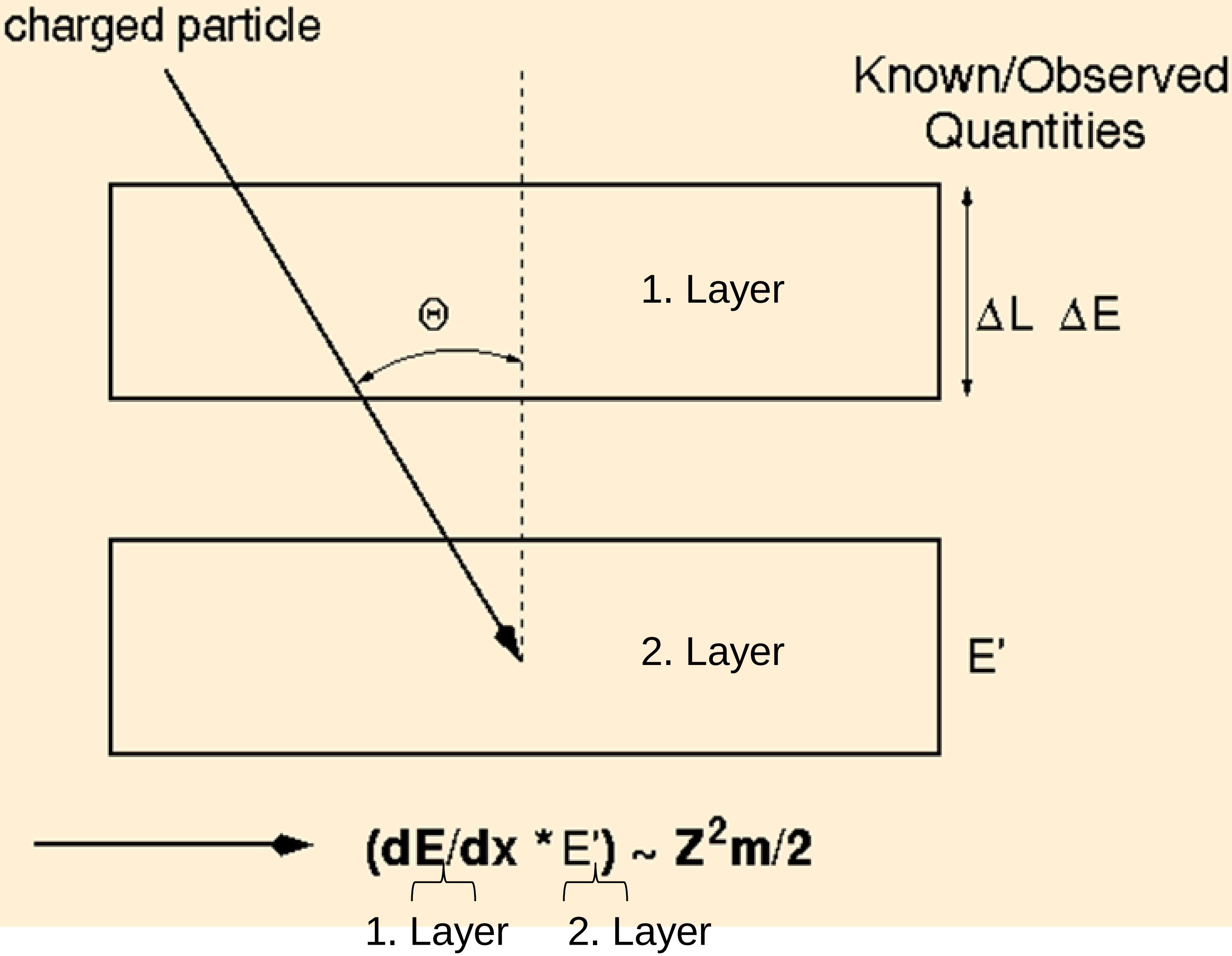
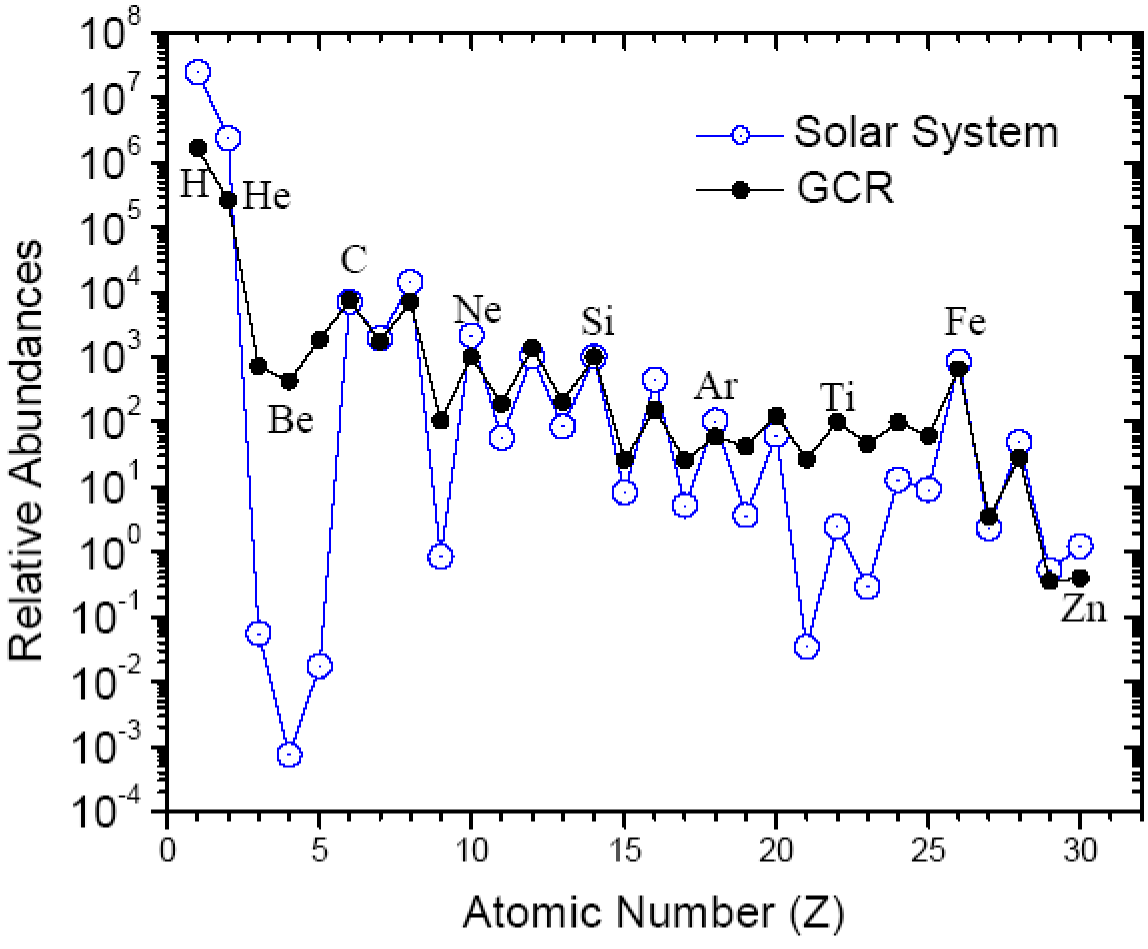
CRIS


charged particle
Known/Observed
Quantities
1. Layer
Θ
ΔL ΔE
2. Layer
E'
(dE/dx * E') ~ Z²m/2
1. Layer
2. Layer

Comparison to Solar Abundances

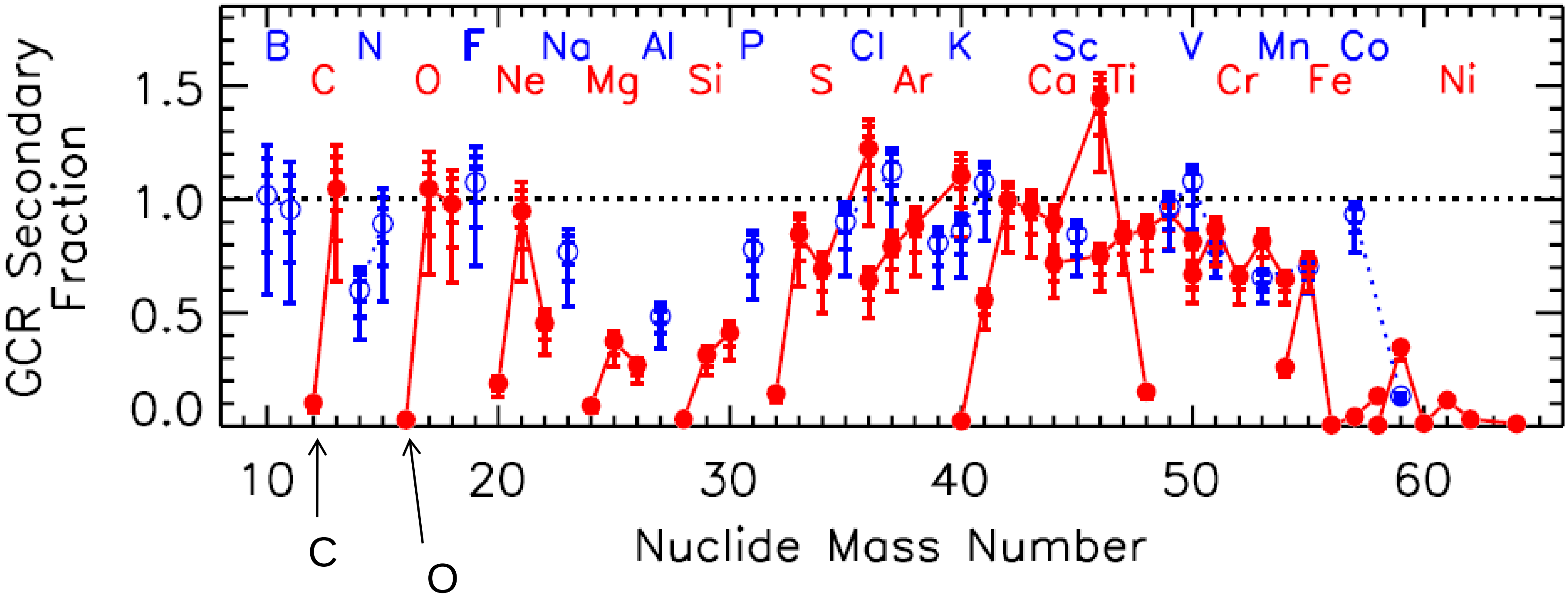


http://www.srl.caltech.edu/ACE/ACENews/ACENews83.html

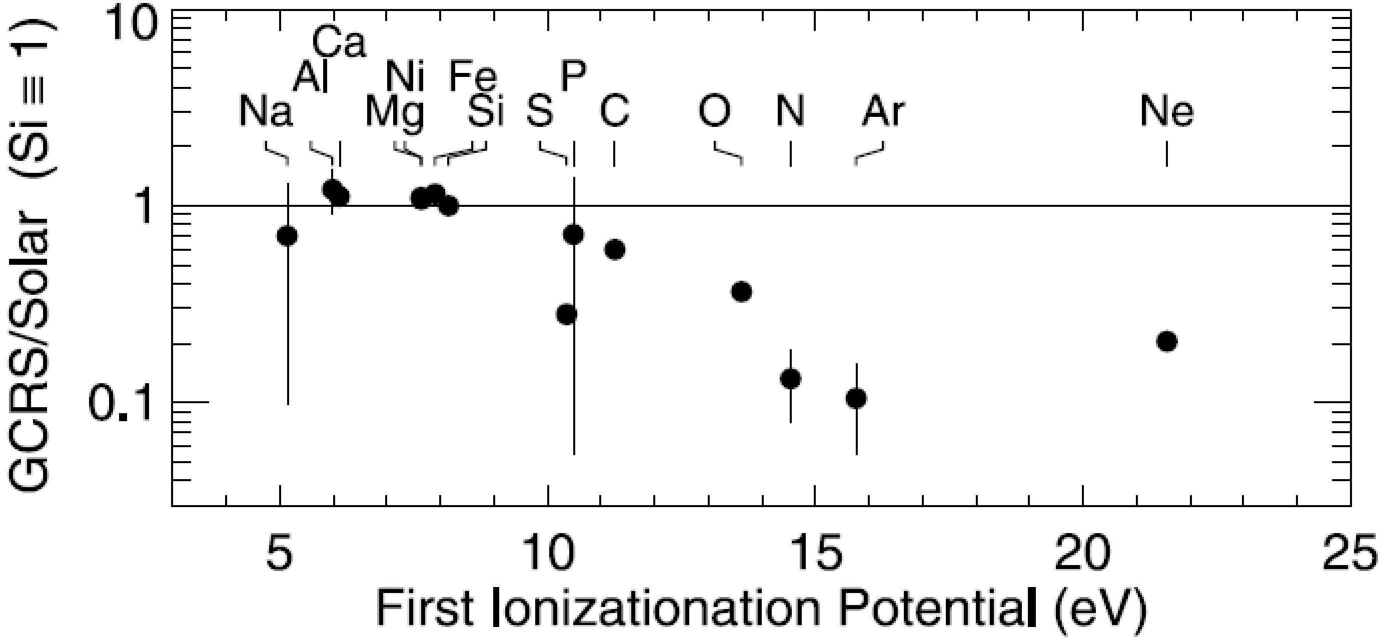
Spallation

- Primary cosmic rays: accelerated at sources,
e.g. H, He, C, O, Fe,…
- Secondary cosmic rays: produced in interactions with IM,
e.g. Li, Be, B,…
- Spallation: breakup of nuclei into lighter species due to collisions with IM
- Spallation is probably source of over-abundance
  - Spallation of primary C and O → Li, Be, B
  - Spallation of primary Fe and Ni → Sc, Ti, V, Mn
- Ratio of pure secondaries (e.g. B) to parent species → **mean escape length** (mean amount of matter traversed by CR until escape)

- Interstellar abundances of heavier nuclides + spallation cross sections + propagation models → secondary + primary contributions to each species:



M.E. Wiedenbeck et. al., Space Sci. Rev. 2007



M.E. Wiedenbeck et. al., Space Sci. Rev. 2007

- Comparison of CR and solar abundances → pattern:
  - High-FIP elements: lower abundance
  - Low-FIP elements: nearly the same abundance

- Possible explanation: low FIP elements easy to ionize which is needed for SNR acceleration

Acceleration of Grains

- Cosmic ray abundance better ordered by **volatility**
- **Volatile**: don’t form compounds such as grains that easily
- **Refractory**: condense even at relatively high temperatures
- Meyer et al., 1997: dust grains are accelerated in supernova shocks more efficiently due to higher mass-to-charge ratio
- Connection of FIP to volatility and refractoriness of elements
  - Low-FIP elements tend to be refractory
  - High-FIP elements tend to be volatile
- Take only refractory species into account (Mg, Al, Si, Ca, Fe, Co,Ni): derived CR source abundances ≈ solar abundances

→ **Nucleosynthetic contributions from stars with a wide range of initial masses are required**

Learn from Isotopes

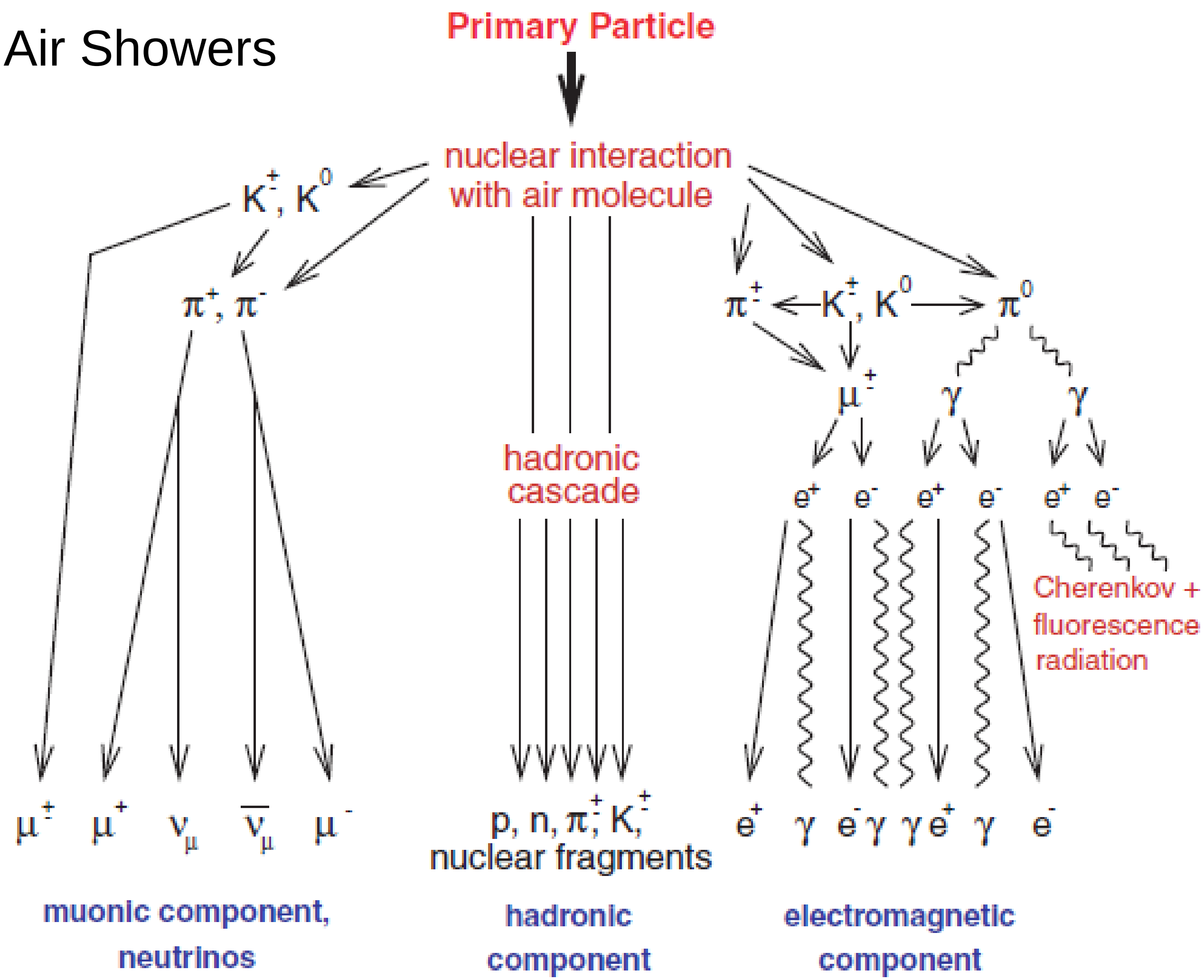
- $^{10}Be/(^{9}Be, ^{7}Be)$ ratio → **residence time** ~ 15 Myr (solar: ~ 4.6 Gyr) → CR source material much more recent than solar-system matter
- From this and mean escape length: density of traversed ISM: 0.2 – 0.3 cm^{-3}

- $^{22}Ne/^{20}Ne$ ratio much greater in CR than in solar-system
  - Most widely accepted mechanism: contribution of Wolf-Rayet stars (at beginning of He-burning phase ^{22}Ne strongly enhanced)
  - Most Wolf-Rayet stars reside in superbubbles → site of origin of the bulk of cosmic rays
- Unstable Electron capture nuclei: become effectively stable!
  - If synthesized in stars they should be abundant in CR observed near earth
  - M.E. Wiedenbeck et. al, 1999: ^{59}Ni is absent, it's product ^{59}Co over-abundant

→ Most material **not from accelerating SN** but resided in ISM > 10^5 y

Energies > 10^{14} eV

Extensive Air Showers



Extensive Air Showers

- Usually curved surface (several thousand m^2)
- Development greatly influenced by primary particle, mass, energy
  - Proton induced: electron-rich, muon-poor at ground-level
  - Heavy ion induced: electron-poor, muon-rich at ground-level

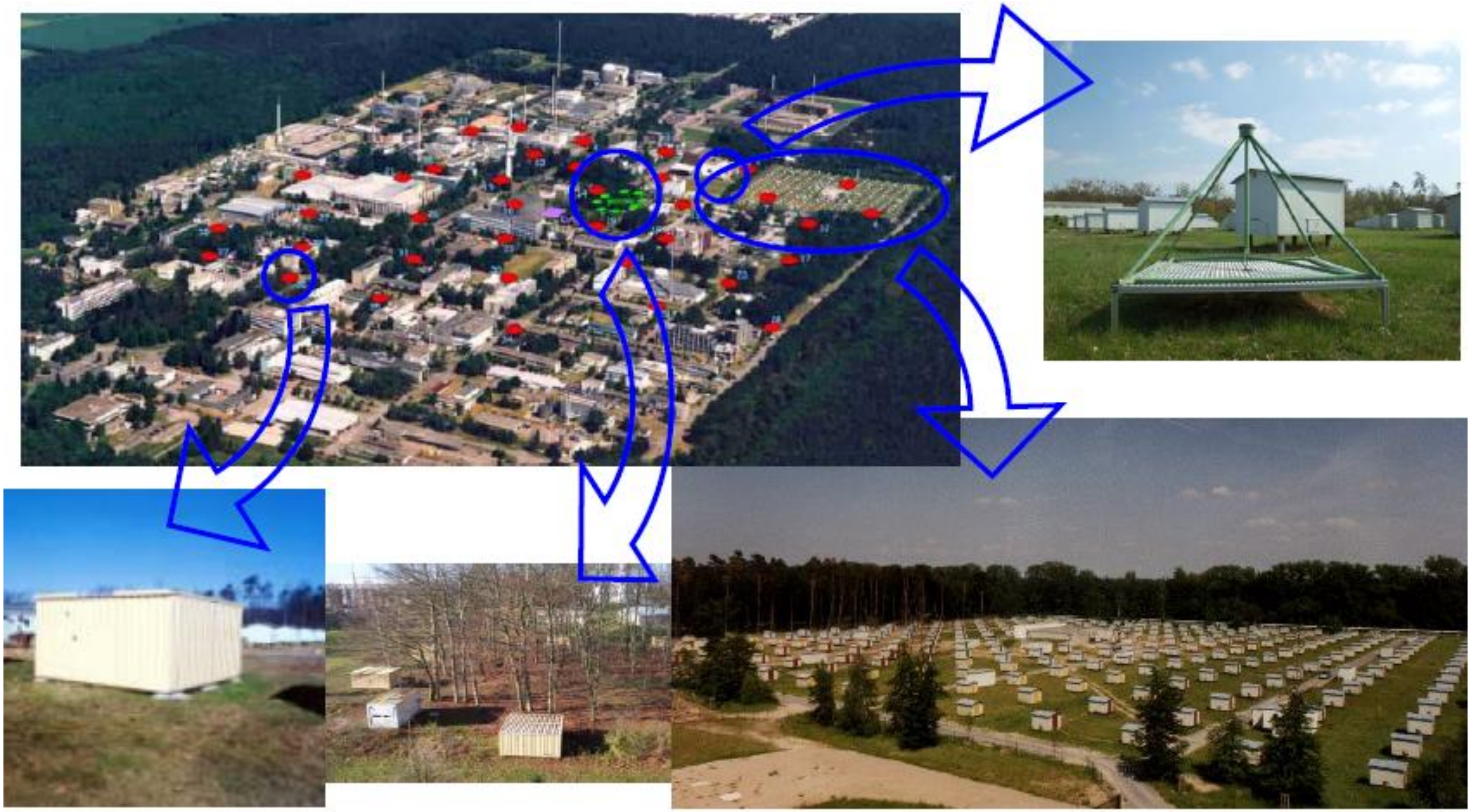
→**Way to identify particles and thus CR composition!**

- Heavy ion shower = A showers of energy E/A
  → shower maximum at higher altitude
- Shower maximum: point at which more particles are being stopped than being created
- Electrons easy to stop (unlike muons) due to bremsstrahlung → less electrons reach ground-level compared to proton showers

KASCADE (Grande)

- **K**arlsruhe **S**hower **C**ore and **A**rray **D**etector
- 1996 – March 2009
- Situated on site of the Forschungszentrum Karlsruhe
- Goal: explore the knee between 10^{14} – 10^{18} eV, spectrum, abundances
- Multi-detector system to gather as much shower parameters as possible
- Area: 700×700m^2

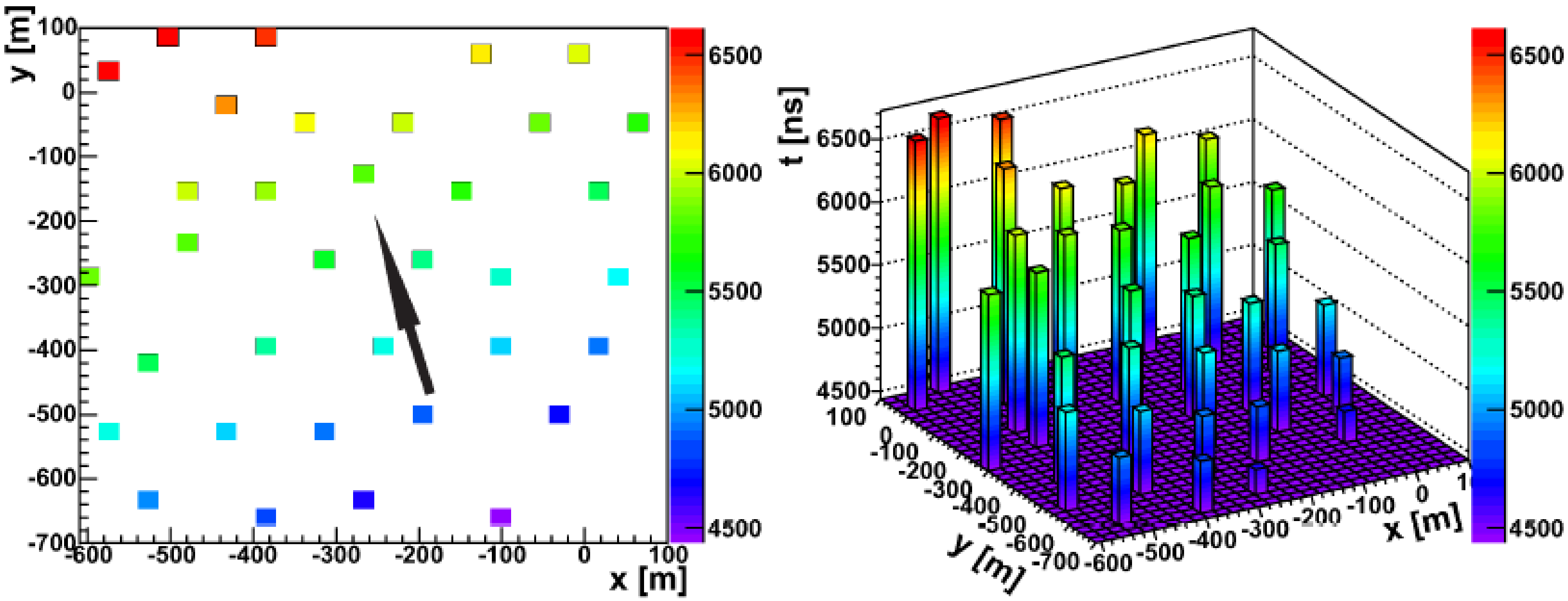
KASCADE (Grande)



KASCADE (Grande)

Detector	Particle	Area [m^2]	Threshold
Grande array (plastic scintillators)	charged	370	5 MeV
Piccolo array (plastic scintillators)	charged	80	5 MeV
KASCADE array (liquid scintillators)	$e^{+/-}$	490	5 MeV
KASCADE array (shielded pl. scint.)	μ	622	230 MeV
Muon tracking det. (streamer tubes)	μ	3×128	800 MeV
Multi wire proportional chambers	μ	2×129	2.4 GeV
Limited streamer tubes	μ	250	2.4 GeV
KASCADE Central Detector (liquid ionization chambers)	hadrons	320	20 GeV
LOPES antenna array	radio signals	-	-

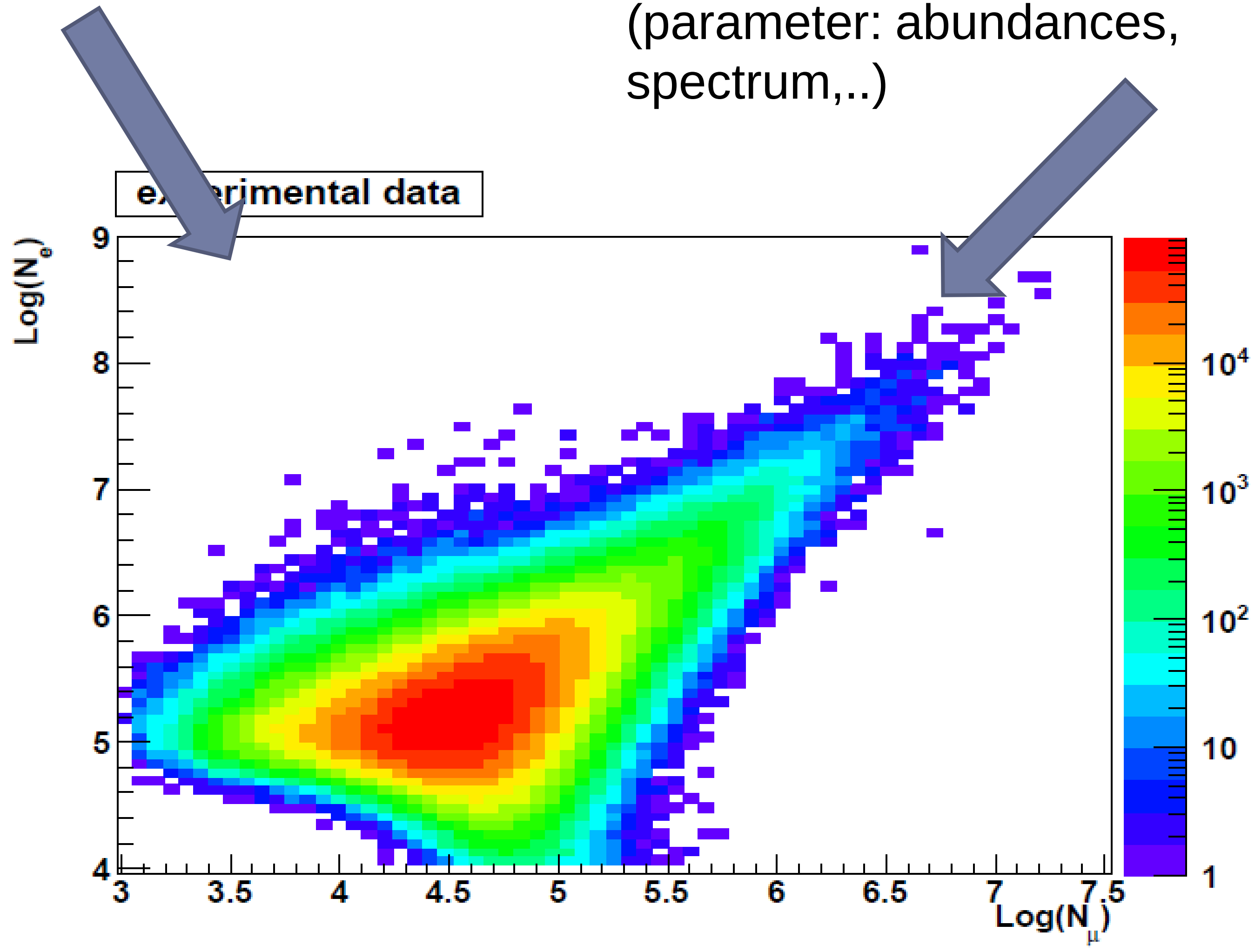
Arrival Time



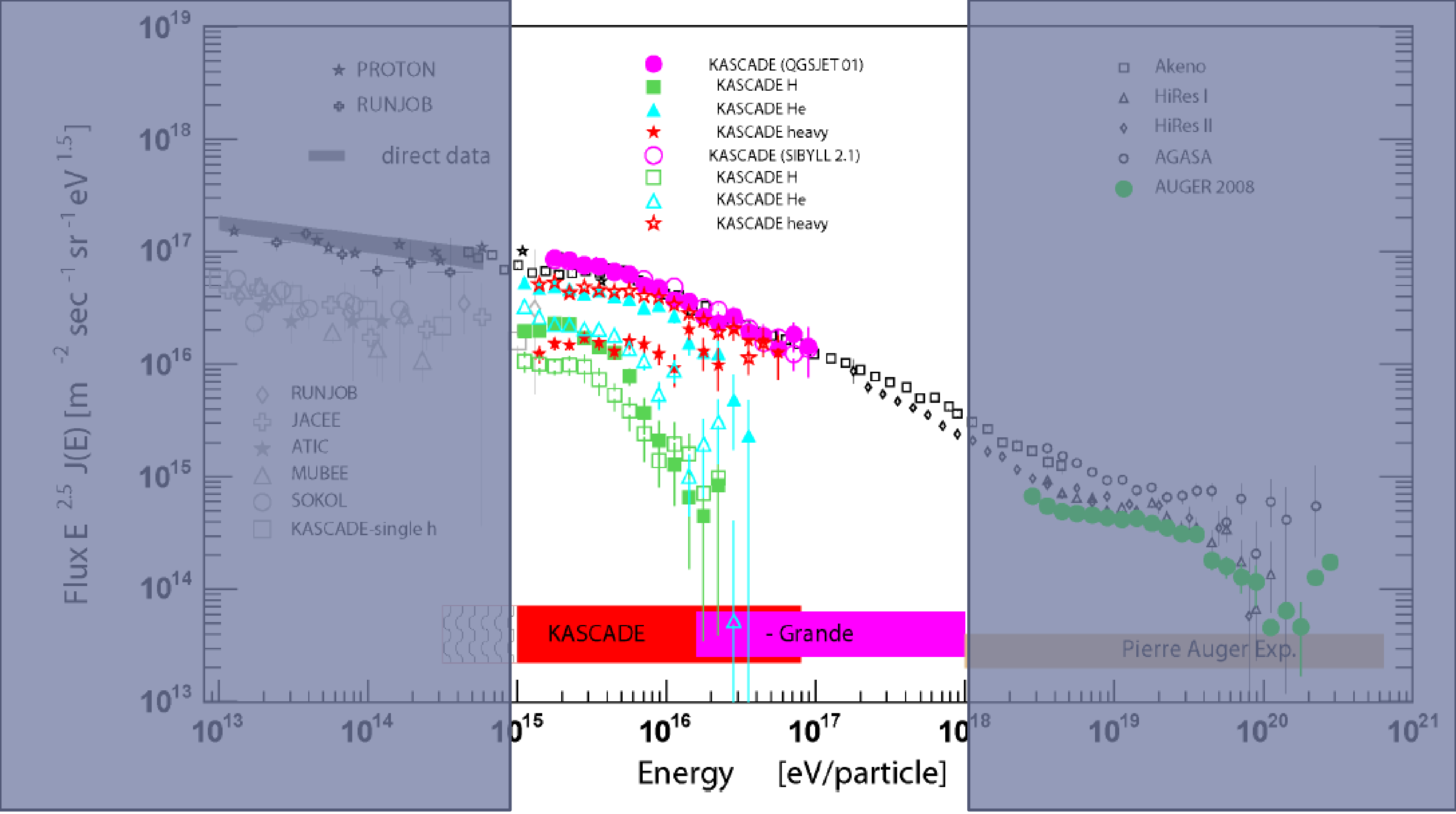
→ shower direction

Experiment

Monte-Carlo-Simulations
(parameter: abundances, spectrum,..)

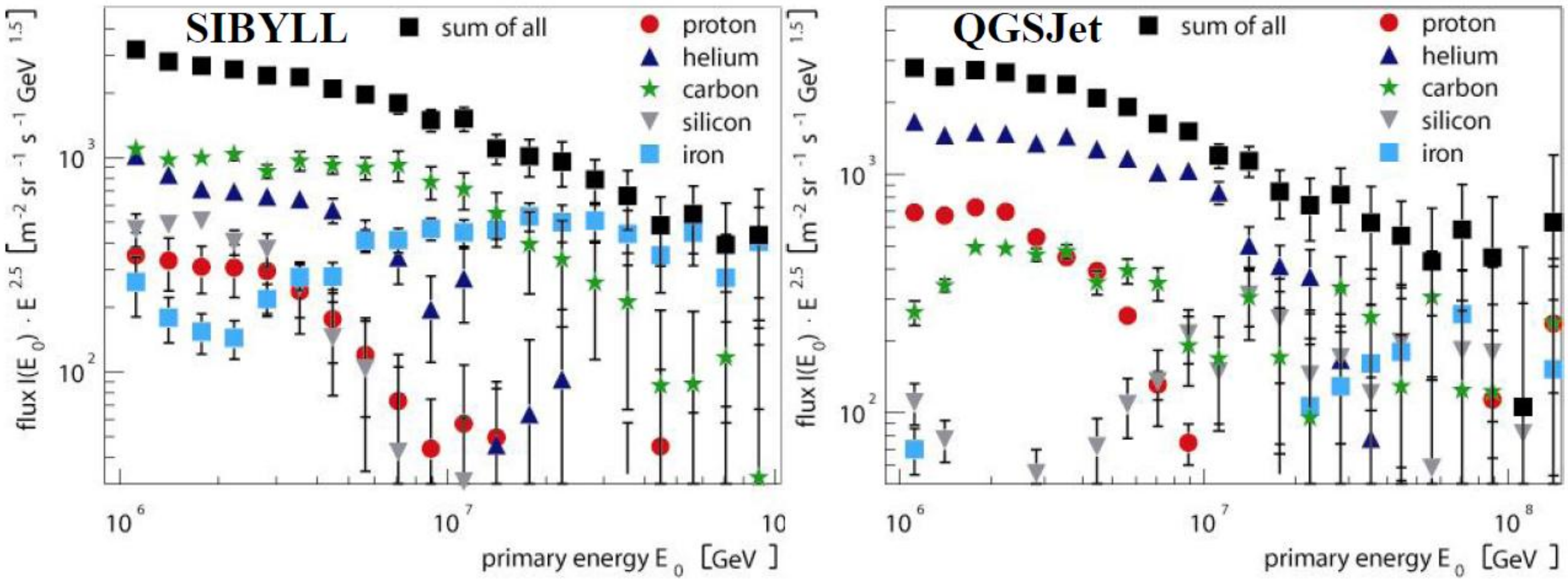


Best Fit of Theory to experiment → abundances, spectrum



- KASCADE is not able to distinguish between single elements, only H, He, CNO-group, intermediate group (around silicon), heavy group

KASCADE Results



All-particle spectrum: similar
General structure: similiar, knee for light components
But: mass group abundances very different!

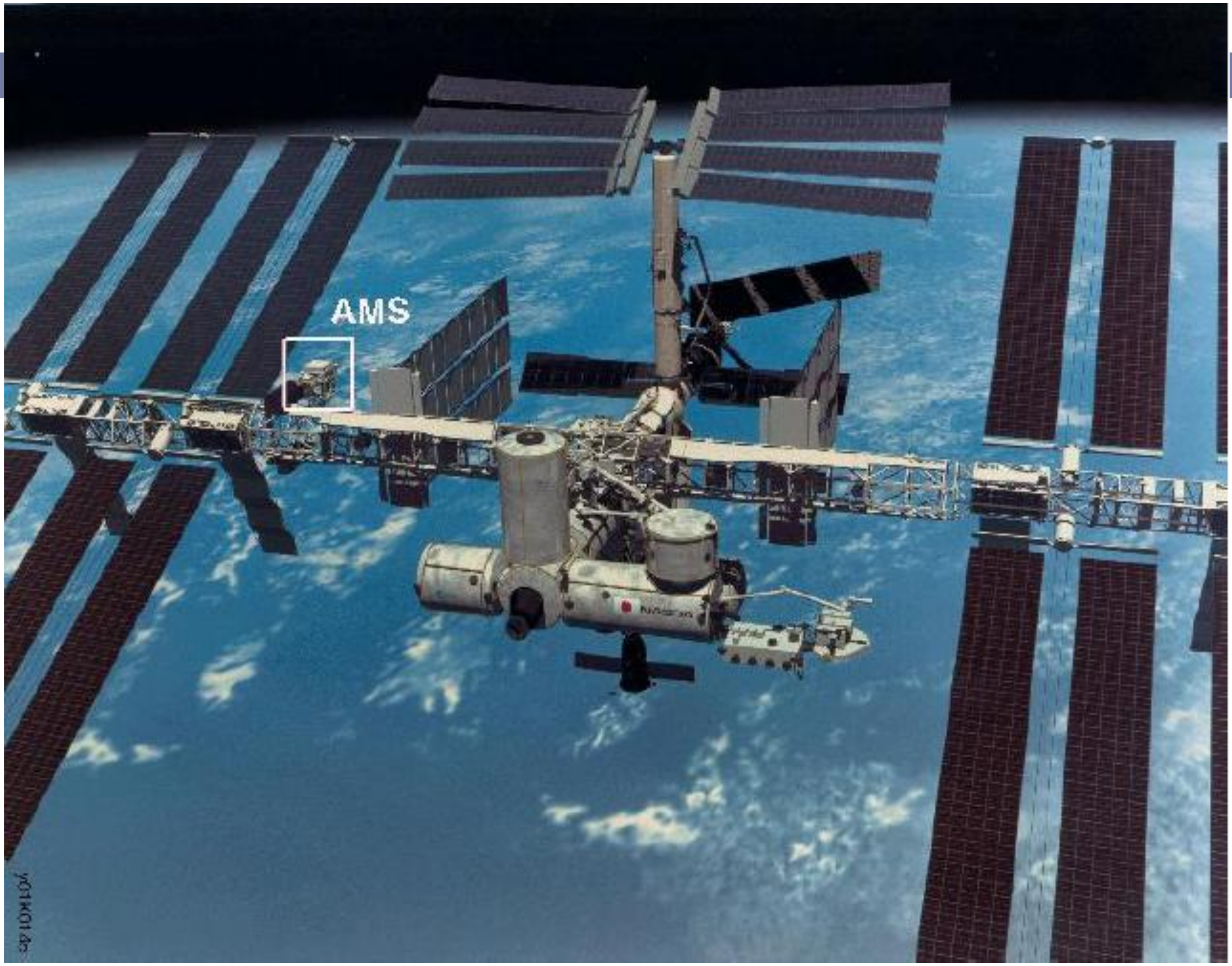
KASCADE Results

- Several knees for different primary elemental groups
- Knee caused by light primaries → composition gets heavier beyond knee
- Iron-Knee?
- Strong dependence on nuclear interaction models
- No model describes data consistently
- No evidence for anisotropy

AMS-02

- **A**lpha **M**agnetic **S**pectrometer
- Launch: 26 February 2011, 4:19 p.m. EST, on-board Endeavour
- Goals:
  - Look for antimatter (positrons, antiprotons, antihelium, …)
  - Indirect search for dark matter
  - Further investigation of CR composition and flux

- Greater acceptance, better particle identification relative to previous experiments
- Allows to separate cosmic nuclei up to iron
- Energy range: 0.5 - 10 GeV/nucleon
- Precursor mission AMS-01: 300 million measured particles, no single antihelium

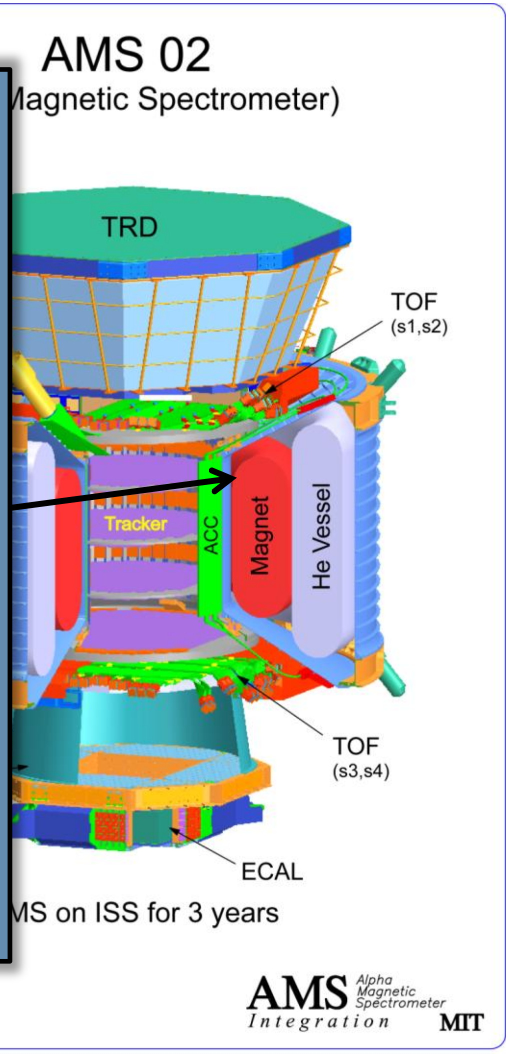

AMS

The Detector

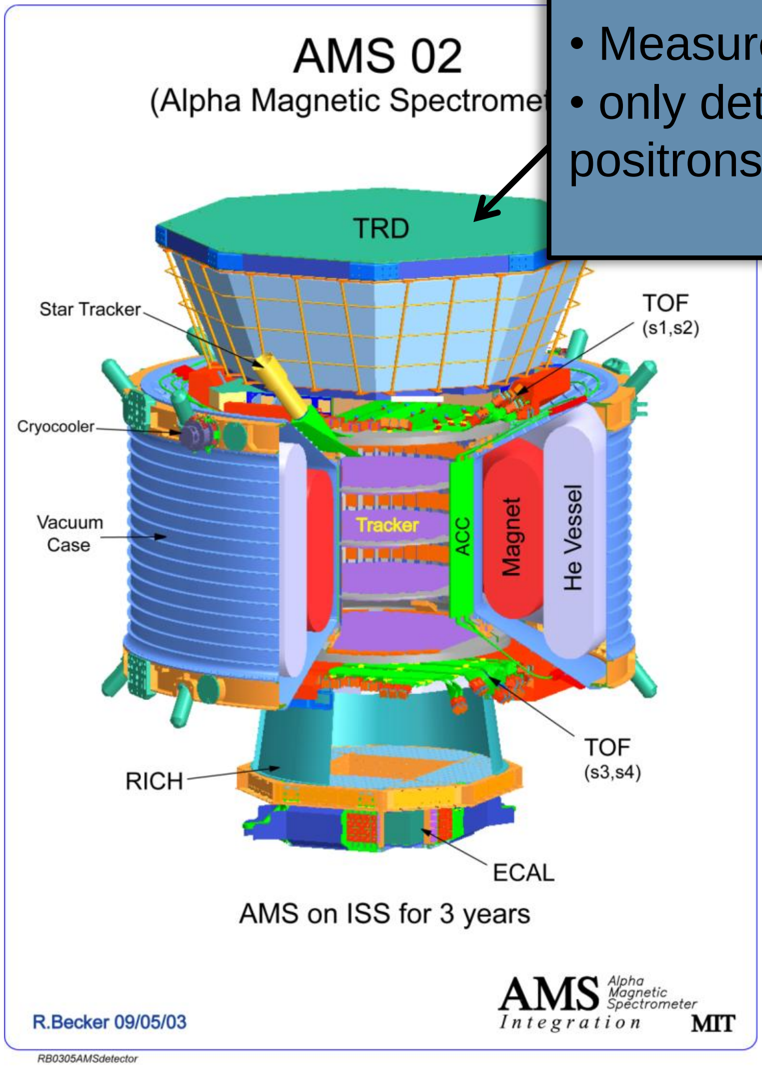
Superconducting Magnet + Silicon tracker

Weight: <u>2350 kg</u>
Helium: <u>360 kg</u>
Operating current: <u>459 A</u>
Operating temperature: <u>1.7 K</u>
Max. B field: <u>0.865 T</u>

• sensitive to p/q
•Only detector capable of telling helium and antihelium apart (counter)clockwise → charge sign



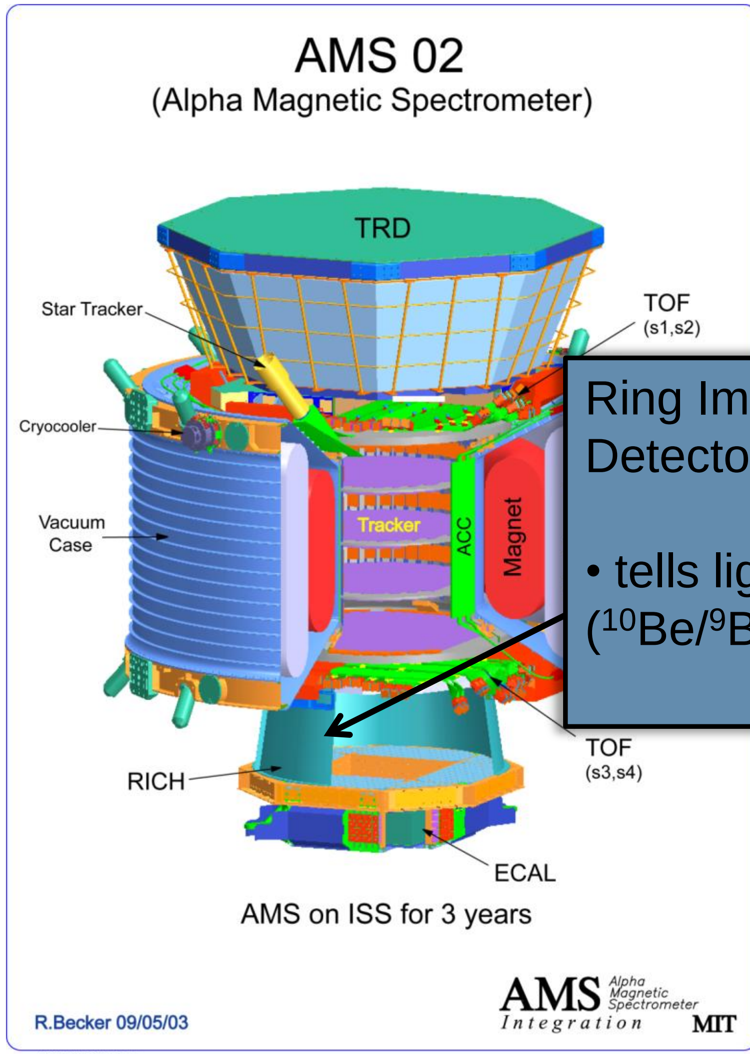
The Detector



Transition Radiation Detector

- Measures γ = E/m
- only detector capable of telling positrons and protons apart

The Detector



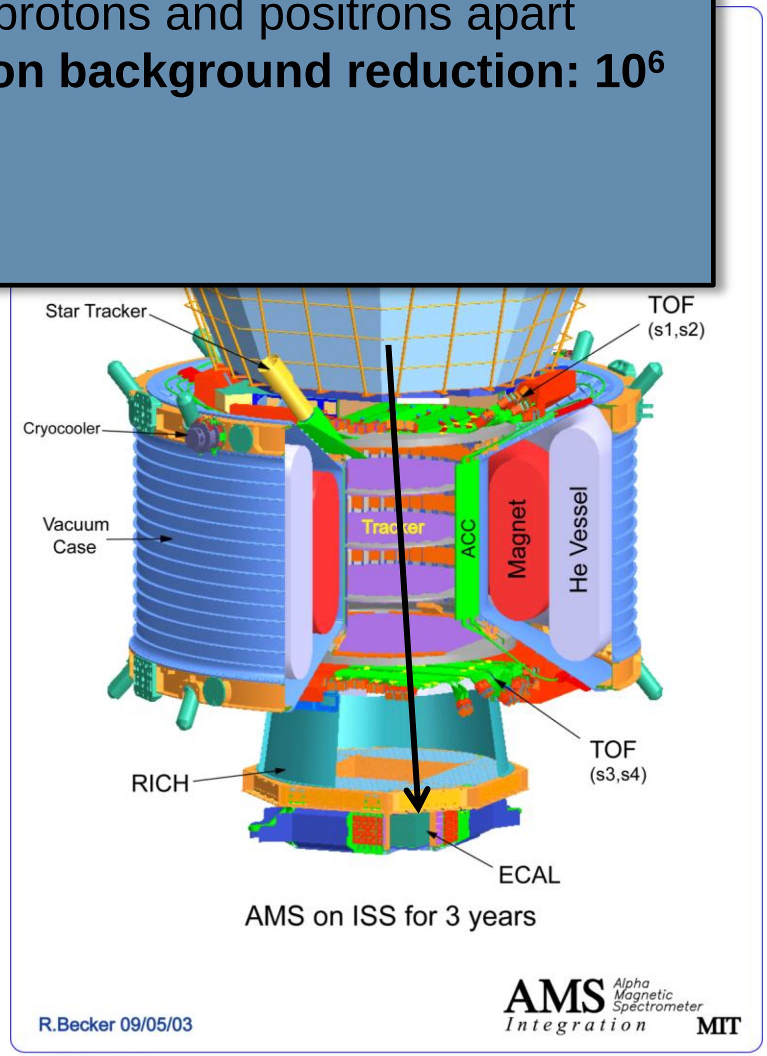
Ring Imaging Cherenkov Detector

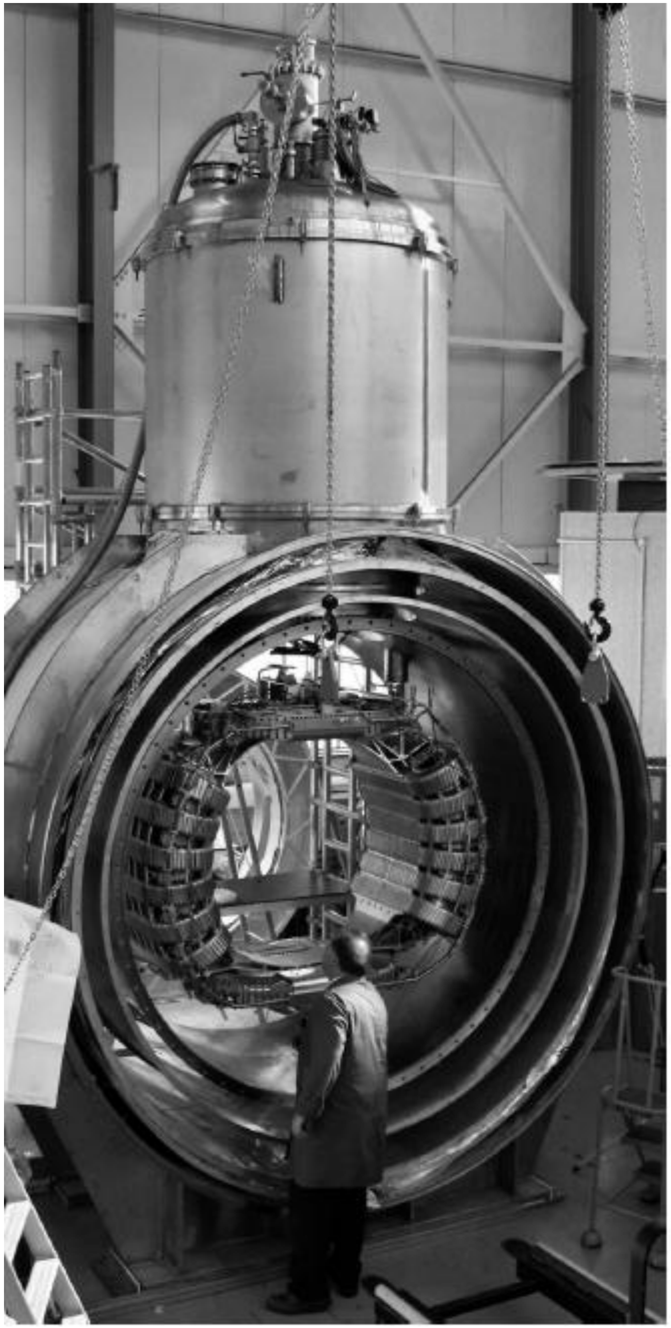
- tells light isotopes apart ($^{10}Be/^{9}Be$)

The

Electromagnetic calorimeter

- Energy measurement of electrons, positrons, gamma rays
- tells protons and positrons apart
- **proton background reduction: 10^6**





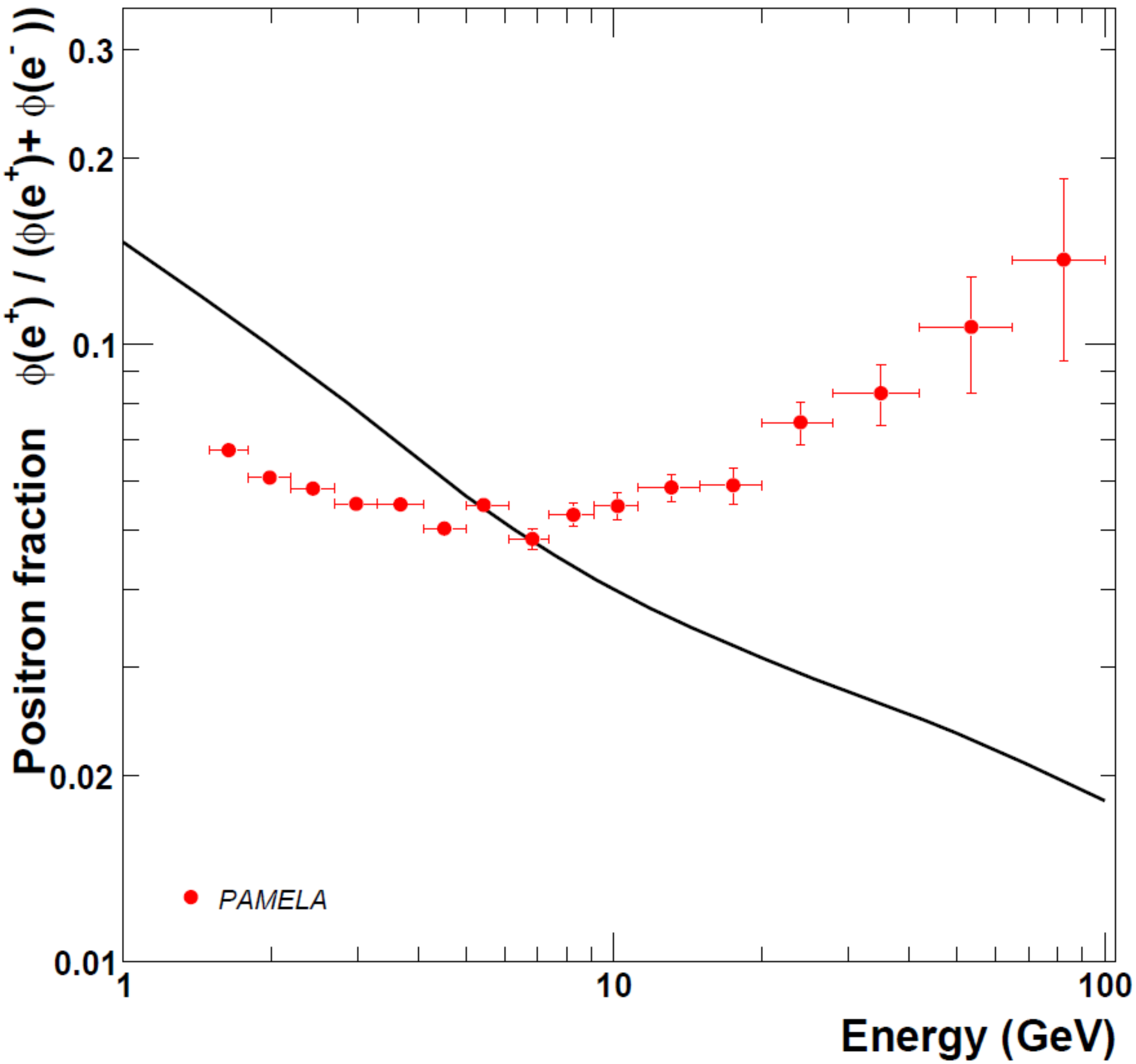
Dark Matter

- Dark Matter may consist of WIMPs
- Good candidate: lightest supersymmetric particle which is stable due to R-parity conservation, e.g. neutralino
- Stable but annihilation in high density regions (galactic centre, halo)
- Several annihilation channels

$$\chi_1^0 + \chi_1^0 \rightarrow \gamma, \bar{p}, e^+, \nu, \ldots$$

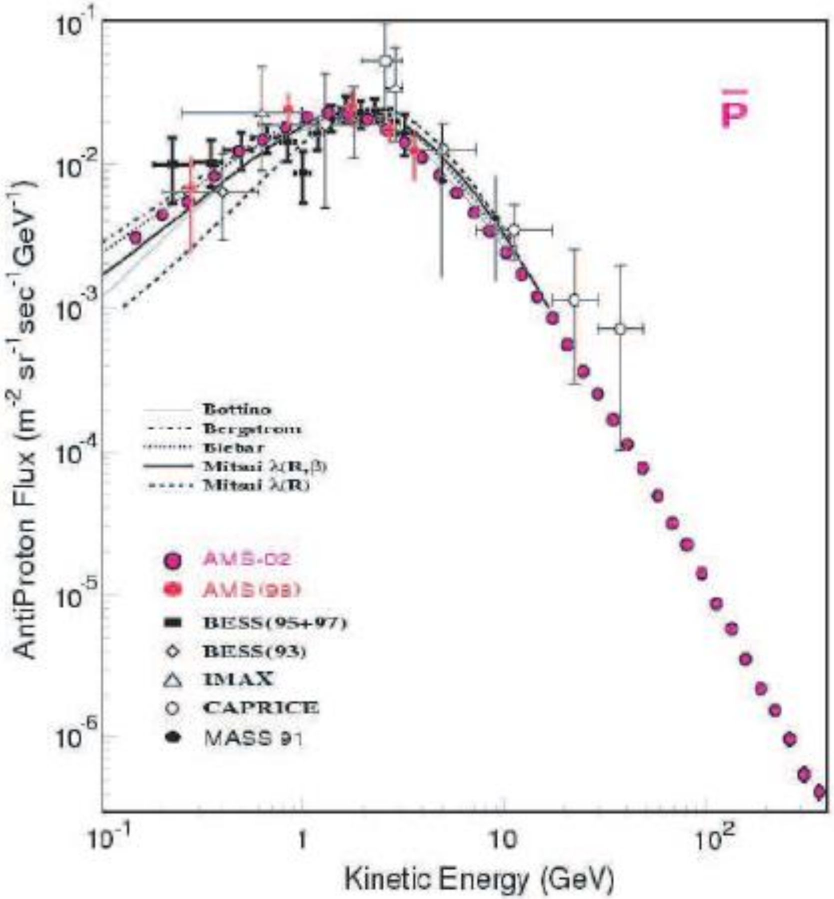
- Background of antiprotons and positrons due to interactions with ISM

O. Adriani et. al., arXiv:0810.4995v1 [astro-ph]



Geometrical acceptance PAMELA: 0.002 m^2sr (AMS-02: 0.45 m^2sr)

Antiprotons



J. Pochon, 29th International Cosmic Ray Conference Pune (2005) **00, 101.106**

Summary

- Due to low fluxes
  - Direct measurements (balloons, satellites) only for $E < 10^{14}$ eV
  - Indirect measurements (shower arrays) for $E > 10^{14}$ eV
- Abundances comparatively well known for $E < 10^{14}$ eV and $Z < 30$
  - Probably accelerated by supernovae
  - Refractory elements in good agreement with solar abundances + matter has resided in ISM for more than ~ 10^5 years (from isotopes) → CR source matter from number of stars of various types
  - $^{22}Ne/^{20}Ne$ → additional contribution of Wolf-Rayet stars
  - Acceleration site probably superbubbles
- Energy spectra and abundances for $E > 10^{14}$ eV from shower arrays
  - Only information on mass groups
  - Results strongly depend on hadronic interaction models