Fisica dei raggi cosmici

E. Fiandrini

AA 2017/18

Messaggeri del cosmo

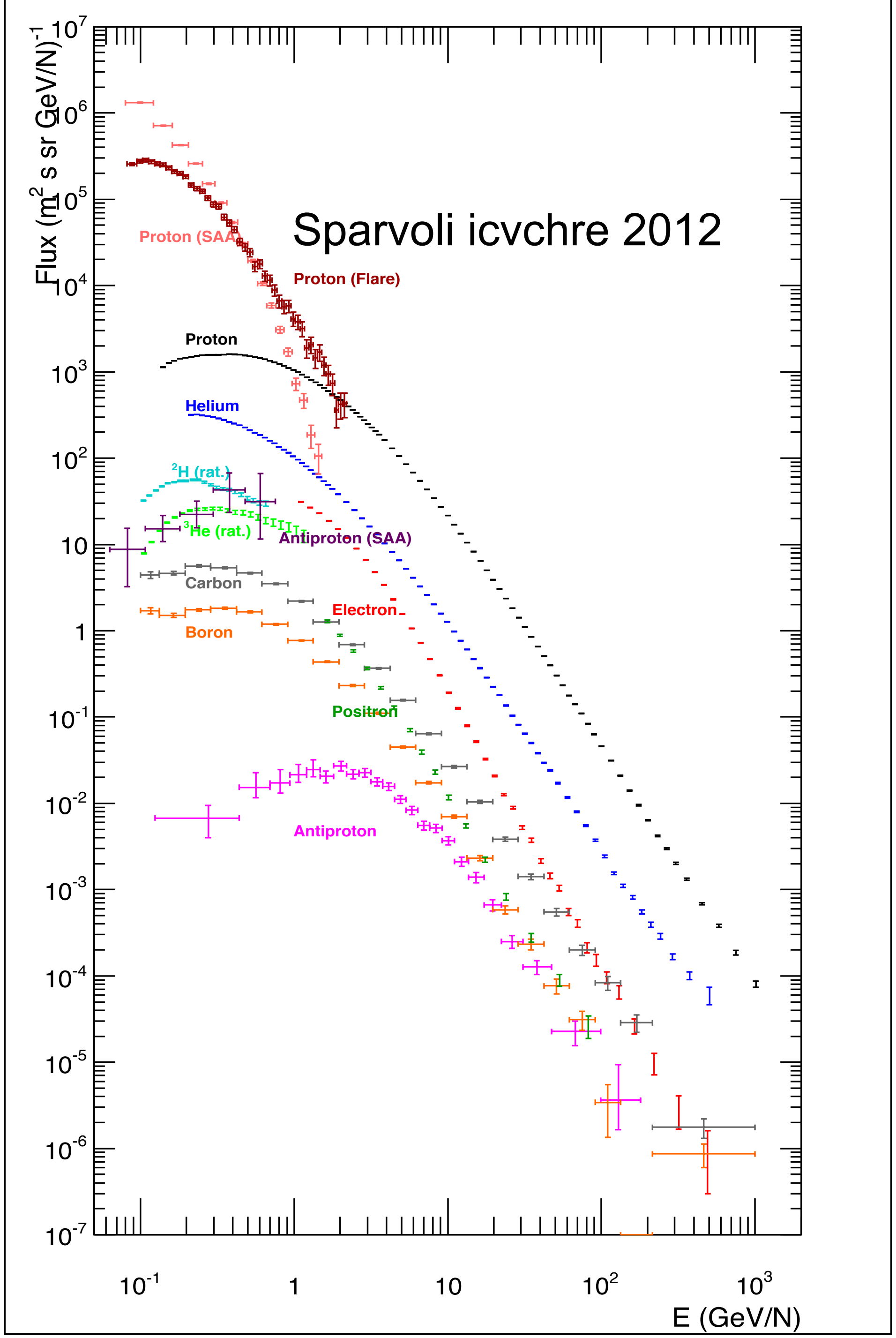
- Cosa trasporta l'informazione dallo spazio alla Terra?

➔ i Raggi Cosmici

Ovvero:

- ▸Radiazione elettromagnetica su tutto lo spettro, cioe' fotoni
- ▸ Flussi di particelle energetiche: neutre (ν) e cariche elettricamente (raggi cosmici carichi... p, e, e+, anti-p, nuclei)

- ❑ Power law for all the particles
- ❑ May be not a single power law (eg spectrum hardening at high E)
- ❑ Non thermal spectra → acceleration mechanisms at work



- Da dove vengono le particelle che osserviamo, ie quali sono le sorgenti?

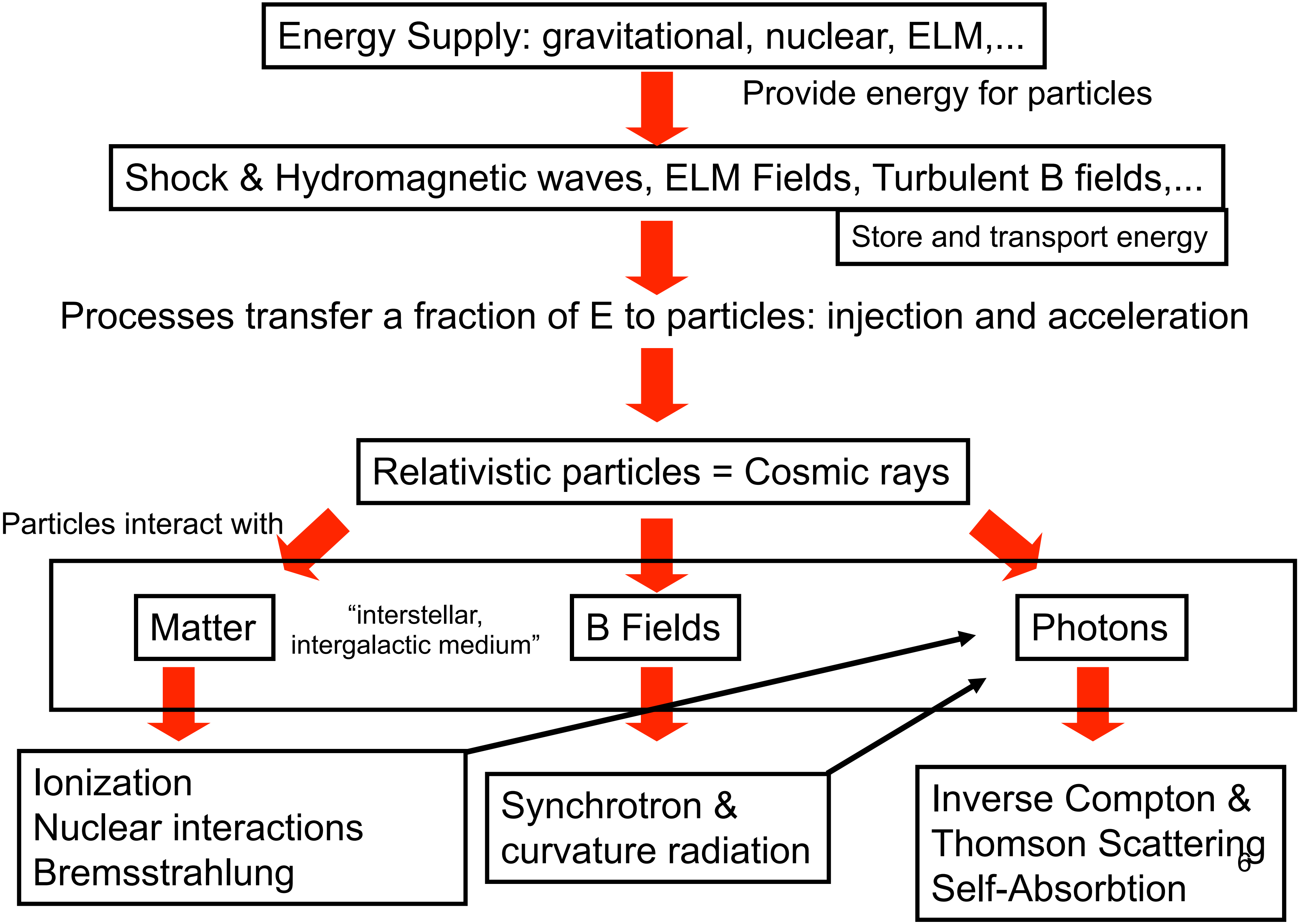
- Quali sono i processi che danno luogo alle popolazioni osservate?

- Qual'e' la distribuzione di materia e campi magnetici negli oggetti che emettono e nel mezzo in cui le particelle si propagano e come influenza le osservabili dei RC?

Fundamental questions remain unanswered!

- **What is the origin of this extra solar system matter?**
  - Do GCR come from a single class of source?
  - Can individual sources be detected?
  - What does the GCR composition tell us about the nucleosynthetic history of this matter?
- **How does this matter get accelerated to such high energies?**
  - Are there different astrophysical sites associated with different energy regimes?
- **Are there signatures of any exotic physics?**
  - Are there anti-matter regions in the universe?
  - Can we detect ‘effects’ associated with “Dark Matter”?

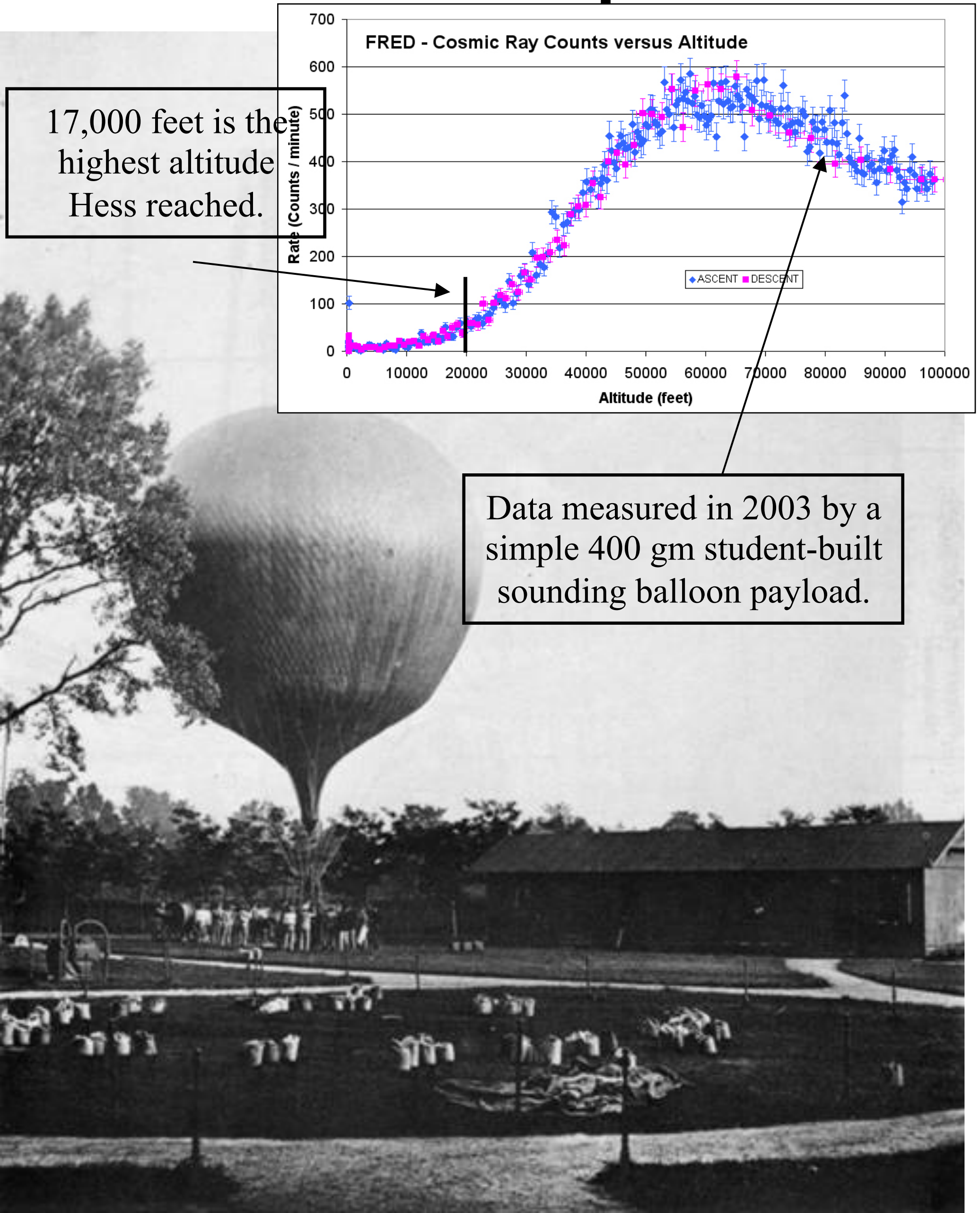
Formation and Interactions of CR's



1.1 Breve storia dei RC

- Scoperta della radioattività (1896) ad Antoine Henri Becquerel
- J. McLennan e E. Rutherford notarono (1903) che un rivelatore completamente schermato non mostrava un segnale nullo, deducendone l'esistenza di una radiazione altamente penetrante.
- Per controllare l'ipotesi che tale radiazione provenisse dalla terra A. Gockel effettuò nel 1910 misure fino all'altezza di 5 km. Il fisico austriaco **Victor Franz Hess** (Nobel nel 1936 per le sue pionieristiche ricerche), ed il fisico W. Kolhorster effettuarono ulteriori misure (1911 - 1914) fino all'altezza di 9 km utilizzando palloni aerostatici.

L’ esperimento di Hess



- Nel 1912, Hess caricò su un pallone aerostatico un dispositivo per misurare le particelle cariche.
- Nel volo, si dimostrò come la radiazione aumentava con l’ altitudine.
- Questo significava che la radiazione sconosciuta non aveva origine terrestre (come la radioattività naturale) ma proveniva dallo spazio esterno, da cui il nome di **Raggi Cosmici**

- Dopo Hess, fu Millikan, nel 1925, ad interessarsi a questa radiazione, e a lui si deve il nome di ***raggi cosmici***: egli riteneva che fossero composti principalmente da raggi gamma.
- Compton ipotizzò, al contrario, che fossero composti da particelle cariche: successive misurazioni dimostrarono la validità di questa seconda ipotesi. La distribuzione dei RC, infatti, variava con la latitudine magnetica, come ci si attende per le particelle cariche sotto l'influenza del campo geomagnetico terrestre.
- Nel 1930 il fisico italiano Bruno Rossi notò che, se la carica delle particelle era positiva, esse dovevano provenire in maniera preferenziale da est. Thomson dimostrò sperimentalmente la giustezza dell'intuizione dell'italiano.
- A partire dagli anni ’30 sino alla nascita dei primi acceleratori di particelle, la storia della fisica delle particelle coincide con quella dei Raggi Cosmici
- Si pose la questione sull'origine e la provenienza dei raggi primari. Nascita dell’astrofisica dei RC (scuola russa, anni ’60) **The Origin of Cosmic Rays**, Ginzburg&Syrovatskii. (1964)

Understanding the nature of cosmic rays

- **1920's** radiation was thought to be some form of high energy photon
  - Hence the name Cosmic **RAYS**
  - **Large debate between the photon camp and those who believed cosmic rays were charged particles (Millikan vs Compton)**
- **1930's** cosmic rays proved to be high energy charged particles **(but were they protons or electrons)**
  - Effects due to Earth's magnetic field (first 'magnetic analyzer')
    - **Latitude survey on-board ships**
    - **East-West Effect**
  - Confirmed CR as positive charged (some believed they were positrons which had been discovered some years earlier)
    - **Penetrating power through blocks of lead proved most primaries were protons (used mountaintop labs for some of these studies)**
  - 1937 - Discovery of muon

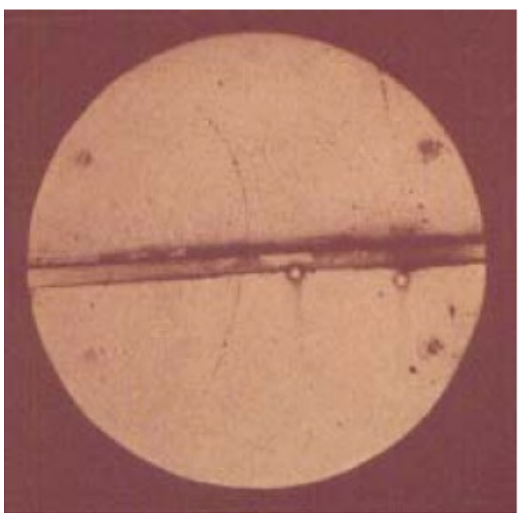
Birth of elementary particle physics

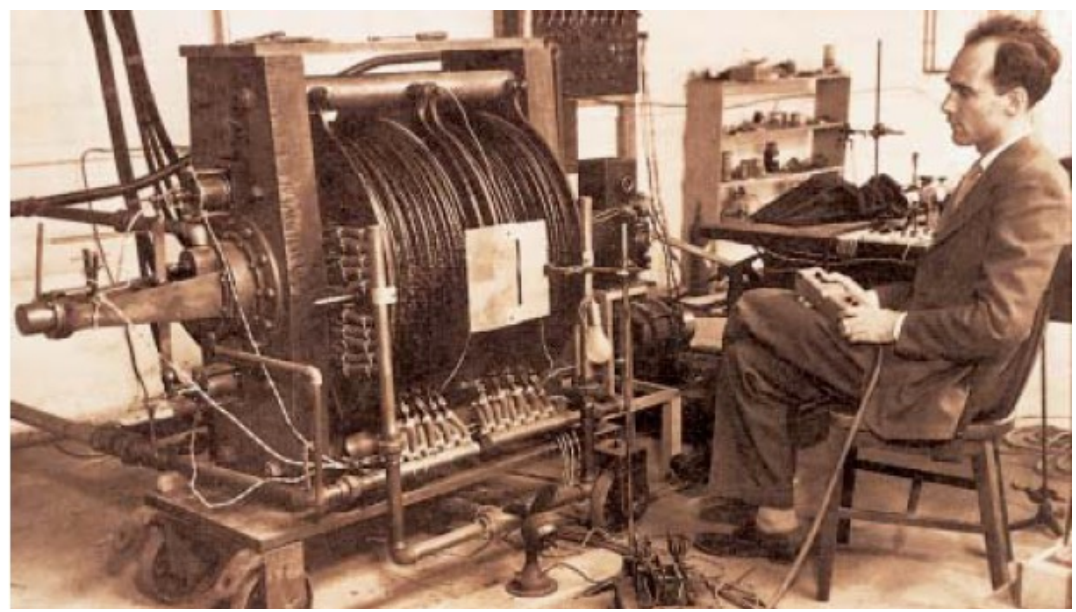
- **40's and 50's** cosmic ray "beam" was used to obtain data for studies of 'elementary particles'.

Particelle scoperte nei RC

- **Il positrone** (1932).
- Carl Anderson osservò delle particelle cariche positivamente, che lasciavano nella camera a nebbia la stessa traccia degli e-. I suoi risultati furono convalidati nel 1933 da Blackett e Occhialini che riconobbero in esse l'antielettrone o positrone proposto teoricamente da Dirac, osservando la conversione di fotoni di alta E in coppie e+e-.
- Vedi: **http://www.infn.it/notiziario/not12/Art1.pdf**

Era dottorando...





- # Il muone (1937).
- Ancora Anderson, notò delle particelle che deviavano in maniera diversa dagli elettroni e da altre particelle note quando queste passavano attraverso un **campo magnetico**. In particolare, queste nuove particelle venivano deflesse ad un angolo minore rispetto agli elettroni, ma più acuto di quello dei protoni. Si assunse che la loro carica fosse identica a quella dell'elettrone e, per rispondere alla differenza di deflessione, si ritenne che avesse una massa intermedia (un valore compreso tra la massa del protone e dell'elettrone).

  - Si pensava che fosse la particella ipotizzata da Yukawa per spiegare le interazioni tra nucleoni per formare i nuclei
  - Si scoprì che questa particella aveva delle caratteristiche peculiari da renderla il cugino pesante dell'elettrone (esperimento Pacini-Piccioni-Conversi). Leggere l'articolo di Salvini:

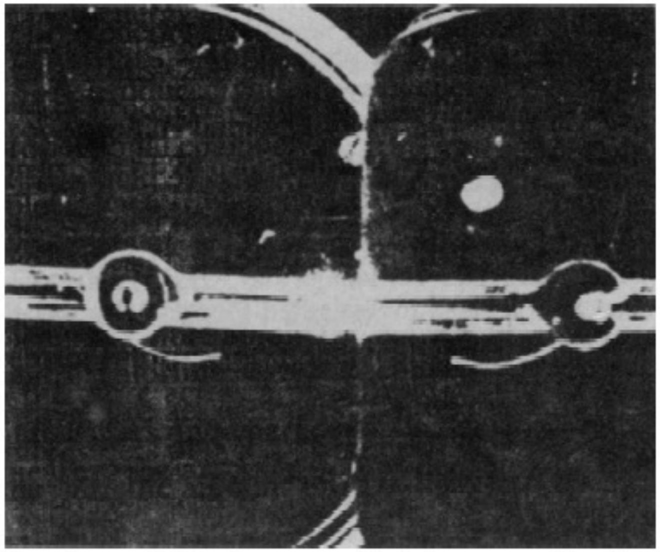
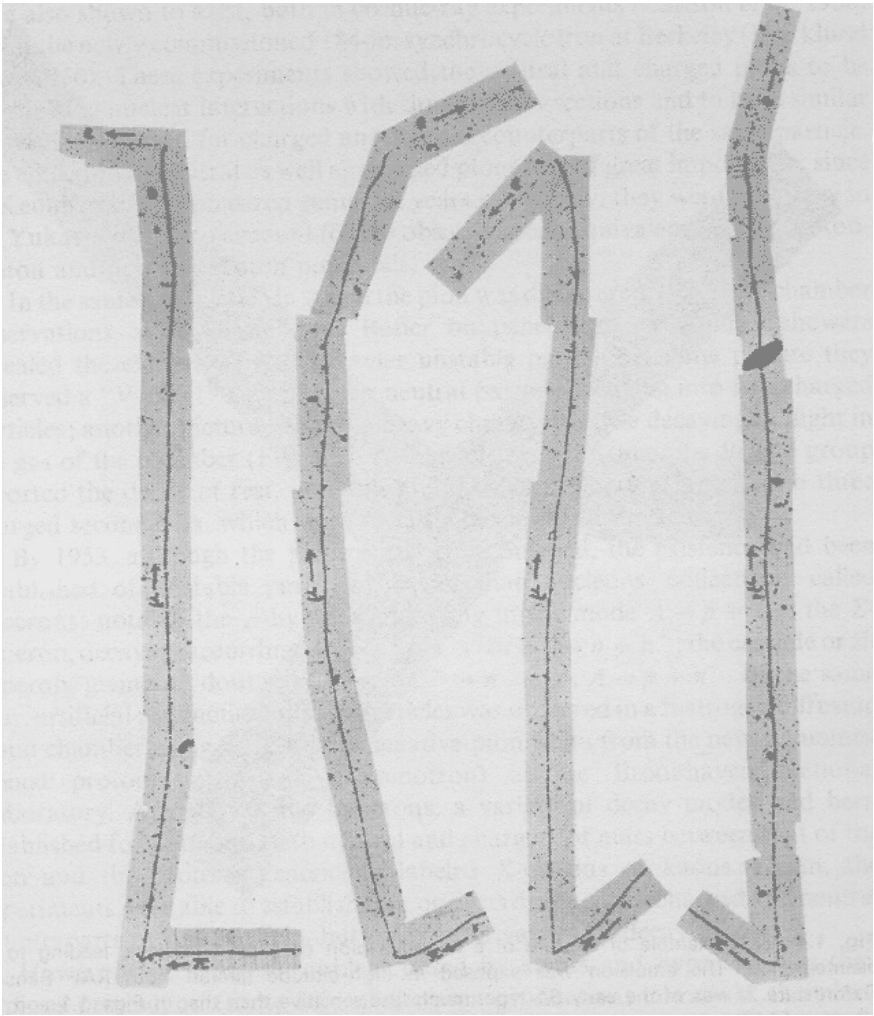


Fig. 1. – Evidenza in camera di Wilson di un muone positivo che traversa un contatore di Geiger entro la camera [1]. La sensibilità della camera non poteva arrivare a rivelare l'elettrone di decadimento.

http://www.lincei.it/pubblicazioni/rendicontiFMN/rol/pdf/S2004-04-21.pdf

- **Il pione (1947).**
- Particella predetta nel 1936 da Hideki Yukawa, il pione si osservò sperimentalmente solo nel 1947 da parte di C.F. Pawel,G. Occhialini e C. Lattes, utilizzando speciali emulsioni fotografiche per registrare la produzione di pioni da parte dei raggi cosmici e il loro successivo decadimento in muoni, che a loro volta decadono in elettroni (o positroni) e in neutrini (invisibili).
- Vedi i filmati:
- **http://www.explora.rai.it/online/doc.asp?pun_id=1140**

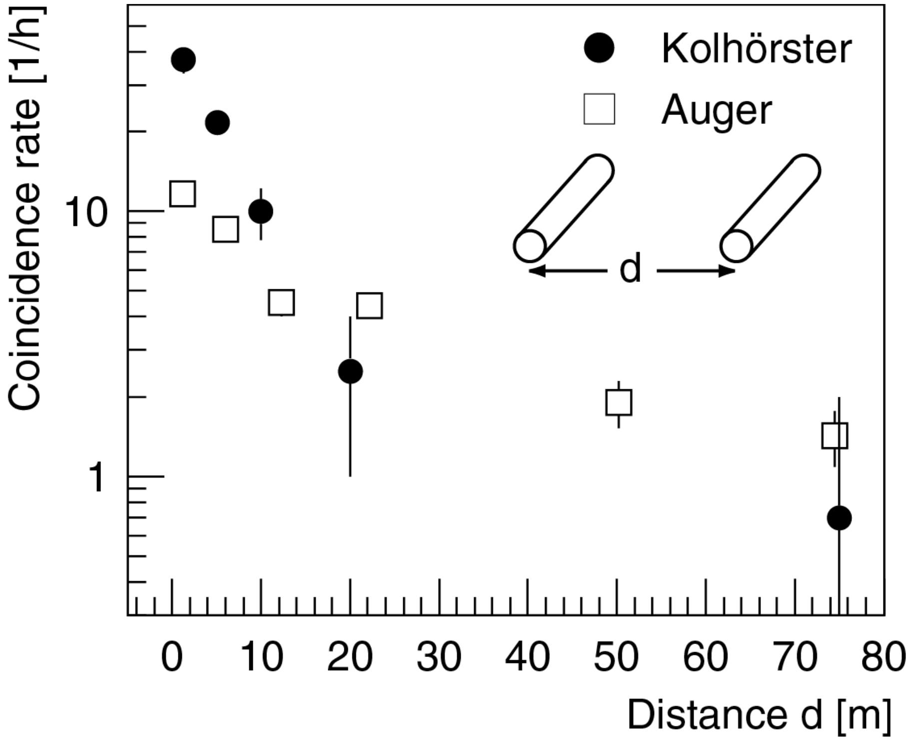


- **Gli "Iperoni" (anni '50), ossia particelle contenenti quark s (Λ, Σ, Ξ, Ω)**

Extensive air showers

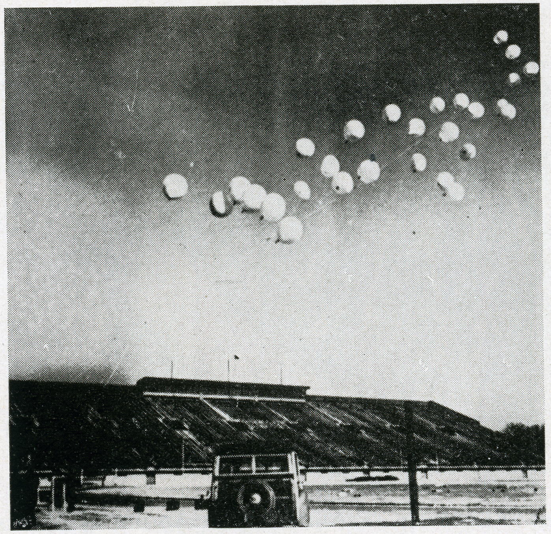
Measuring Cosmic Rays in the Swiss Alps
The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

P. Auger
Jungfraujoch



W. Kolhörster et al., Naturwiss. 26 (1938) 576
P. Auger et al., Comptes renduz 206 (1938) 1721

A



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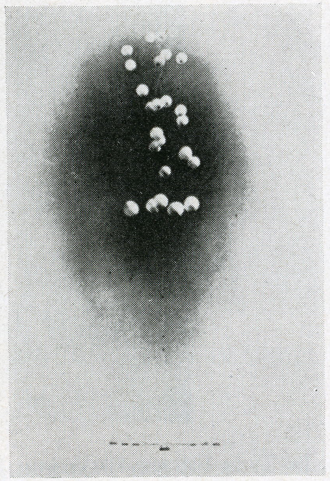


C

P. Auger

Balloon Flight of January, 1943, Conducted by the Author, Schein, and Rogozinski for the Measurement of Extensive (or Auger-) Showers in the Stratosphere

A. The balloons are assembled on Stagg Field at the University of Chicago, Chicago, Illinois. In the foreground can be seen the long frame which was required for the wide separation of the cosmic-ray counters.

B. The large cluster of balloons as it is about to be released.

C. The balloon train sails into the sky after its release. Suspended below the balloons is the frame supporting the counters and recording apparatus.

Brief Chronology

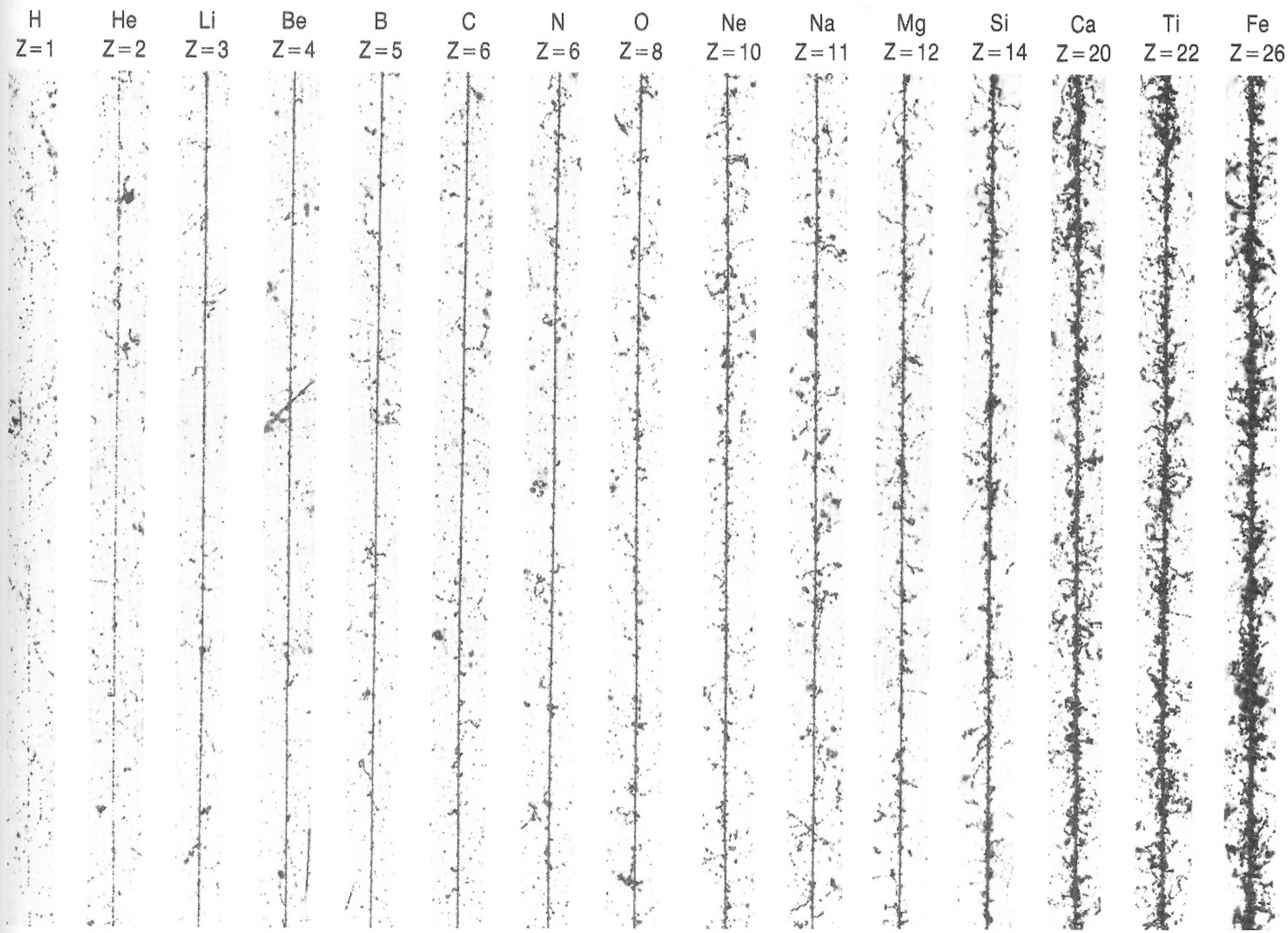
- 1912-15 – Hess and Kolhorster Manned Flights
- 1937 - Mu-Meson Discovered
- 1947 – Pi-Meson Discovered
- 1948 – Discovery of CR Helium and heavy elements
- 1940-50's – CR beam used for Elementary Particle Physics
- 1957 – Sputnik-1 - 'The Dawn of thr Space Age'
- 1961 – Primary Electrons and Gamma rays
- 1966 Discovery of UH (Z>30) Elements in CR
- 1979 – Identification of Anti-protons
- 1970's till – Isotopic Composition at low energy (mainly satellites)

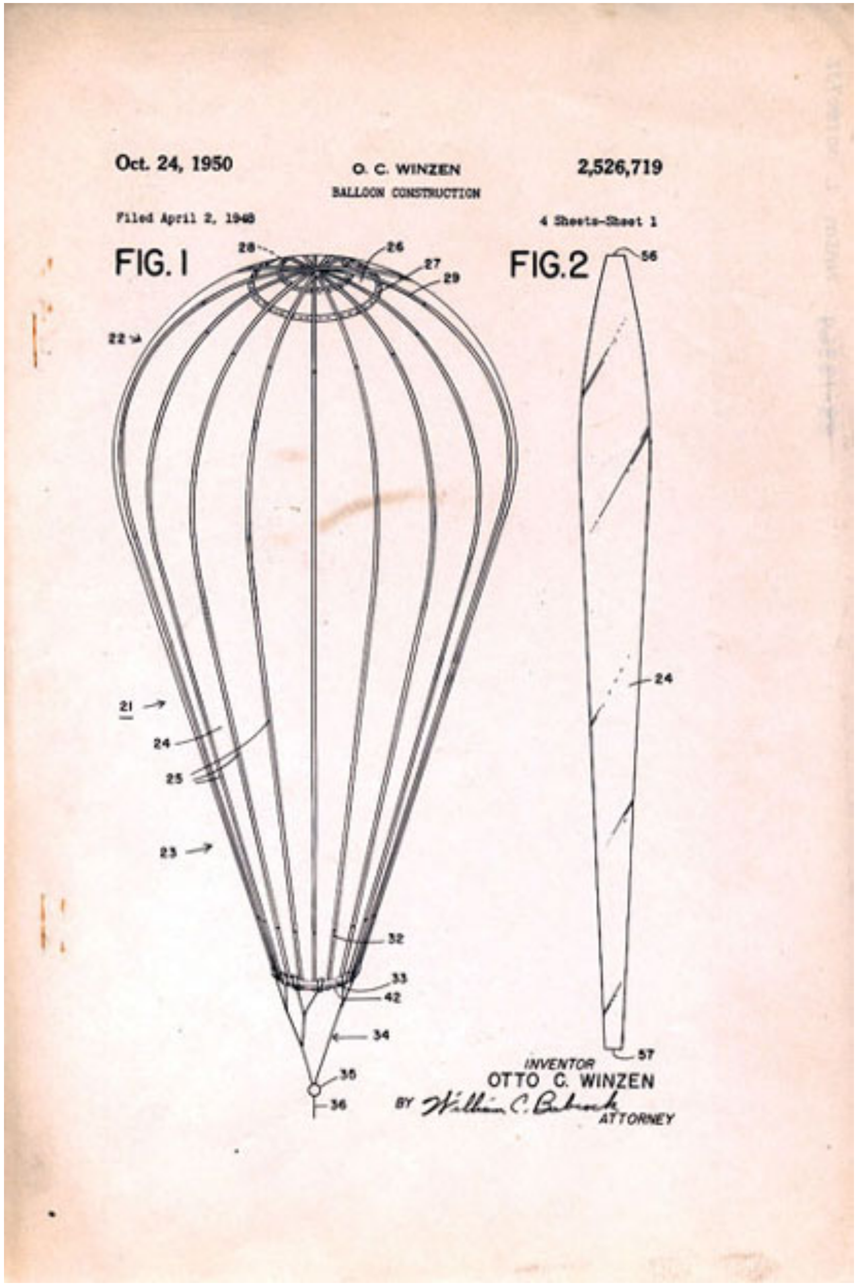
New Detector Technology

- **Geiger-Muller Tubes**
  - Allowed coincidence experiments
  - Used mostly in ground-based experiments
- **Nuclear Emulsion**
  - Particle tracks made visible in thick photographic film (requires darkroom development)
  - Passive detector – Configurable
  - Data collected/analyzed *after* the flight
  - Techniques perfected in labs all over the world
  - Basis of many International collaborations
  - Used continuously for about 60 years

Would benefit both Cosmic Ray and High Energy Physics

Figure 8.3 Tracks of cosmic-ray particles recorded in nuclear photographic emulsions. Nuclei with greater electric charge (Z) produce heavier tracks. These nuclei can eject electrons from atoms through which they pass, and the electrons themselves produce short tracks. This contributes to the track thickness and is especially marked for the heavier particle tracks. Particles can be identified from track structure. In these photographs a typical track thickness is about 2×10^{-4}cm. (P. H. Fowler, University of Bristol).





’ The Age of ‘Plastic’

Otto C. Winzen (1918-76)

- General Mills: developed techniques to produce ultra-thin polyethylene

- Winzen Research Inc. (1949) with wife Vera. Sold poly balloons to ONR

-Projects Helios, Skyhook, Strato-lab, etc.

AF Reconnaissance (Moby Dick)

An Age of Discovery with Balloons

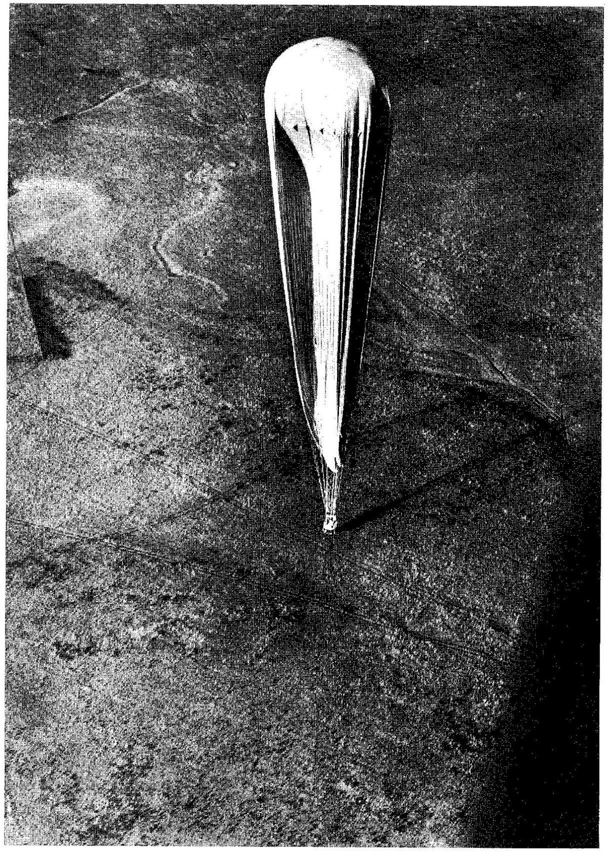


Figure 2.5 *Explorer II. Launched from Rapid City, South Dakota, on November 11, 1935, it touched down near White Lake just over 8 hours later, after a record high-altitude flight. Cosmic ray detecting equipment carried on board included ionization chambers and Geiger counters for W. F. G. Swan of the Bartol Research Foundation, and photographic plates for T. R. Wilkins of the University of Rochester. (Photograph courtesy of Richard H. Stewart and Captain James Haizlip, © 1936 National Geographic Society.)*

- "Rubberized" Balloons (left) give way to the new Plastic Balloons
- Balloon size and thus payload / altitude increases
- New scientific disciplines
  - Propelled Cosmic Ray Physics
  - Beginning of High Energy (then called Elementary Particle) Physics
  - Gamma Ray Astronomy
  - X-ray Astronomy
  - UV Astronomy
  - Aids Solar and Galactic Astronomy
  - Remote Sensing
  - Atmospheric measurements
- High Altitude human flight testing
- Continuing technical advances

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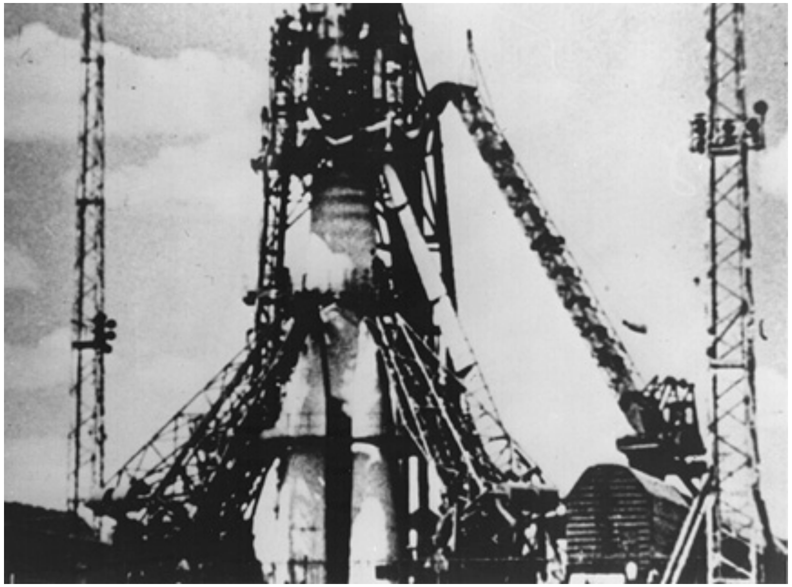
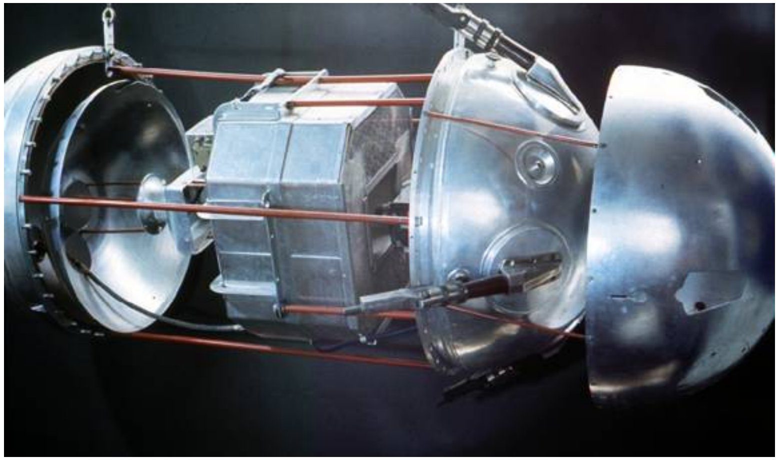
The Dawn of the Space Age – Sputnik-1





1957 October 4
19:12:00 UTC

Baikonur Cosmodrome

83.6 kg

58 cm diameter

4 antennas (2.4 – 2.9 m long)

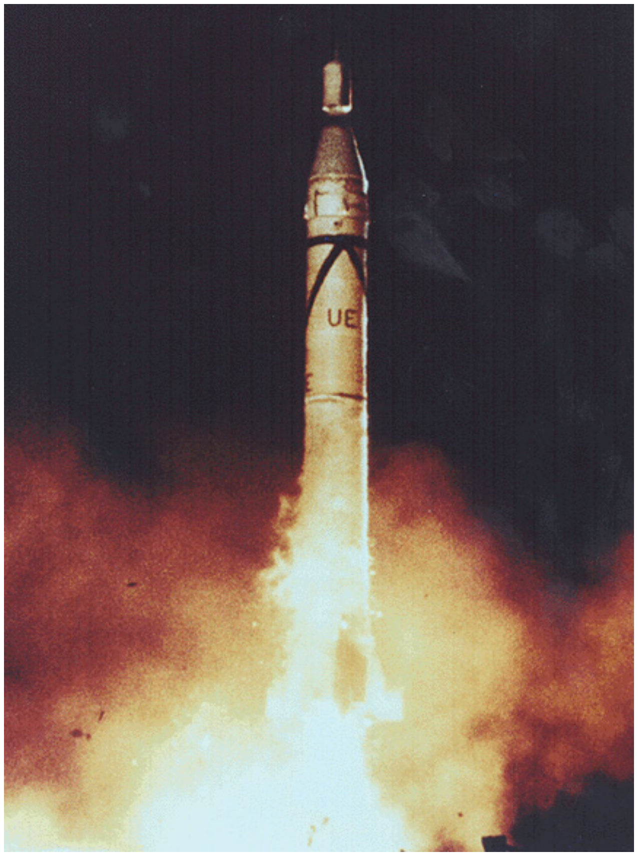
20.005 and 40.002 MHz

92 day lifetime

Iskustvennyi Sputnik Zemli

(Fellow world traveler of the Earth)

The Space Program Evolves



Explorer-I launch Jan. 31, 1958

Sputnik -2 Launched Nov. 3, 1957

Explorer-I Launched Jan. 31, 1958

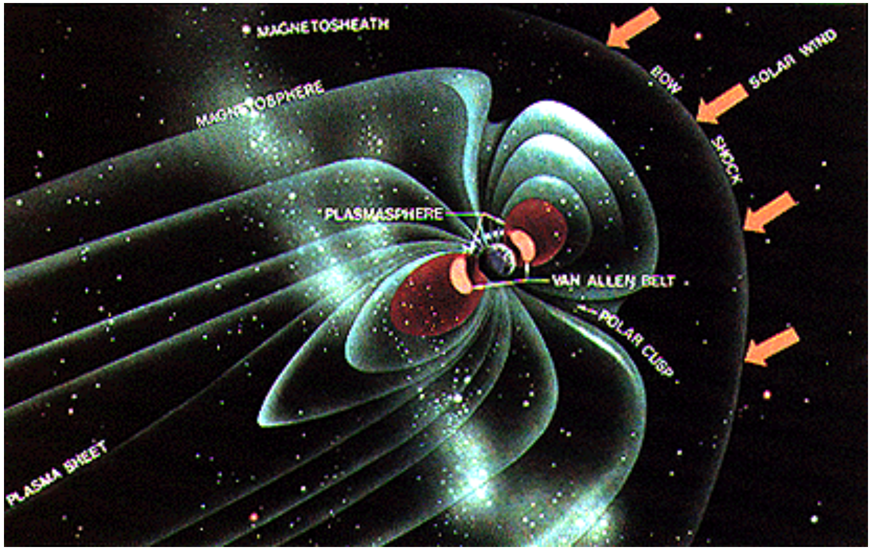
Sputnik – 3 Launched May 15, 1958 (1300 kg – first space environment laboratory)

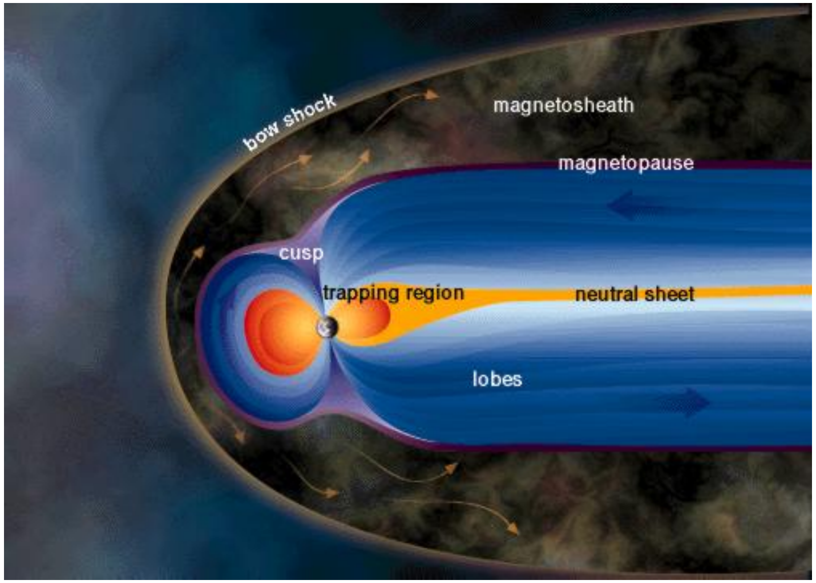
And there were many more satellites …. Explorers, Cosmos, Vanguard, Pioneers, IMP, OGO, OSO, Proton, Voyager, Sokol, to name just a few

And many countries became involved in the Space Adventure

Space Age: Magnetospheric Physics

Explorer-I carried the Geiger-Muller tube radiation experiment of James Van Allen which led to the discovery of trapped particles within the Earth's magnetic field – the 'birth' of Magnetospheric Physics





Dr. William H. Pickering, Dr. James A. Van Allen and Dr. Wernher von Braun (left to right) hoist a model of Explorer I and the final stage after the launch.

HEP -- The Era of Colliders

In the 1950's a number of places, MURA, Novosibirsk, CERN, Stanford, Frascati, and Orsay, developed the technology of colliding beams.(Bruno Touschek, Gersh Budker and Don Kerst, among others, were the people who made this happen.)

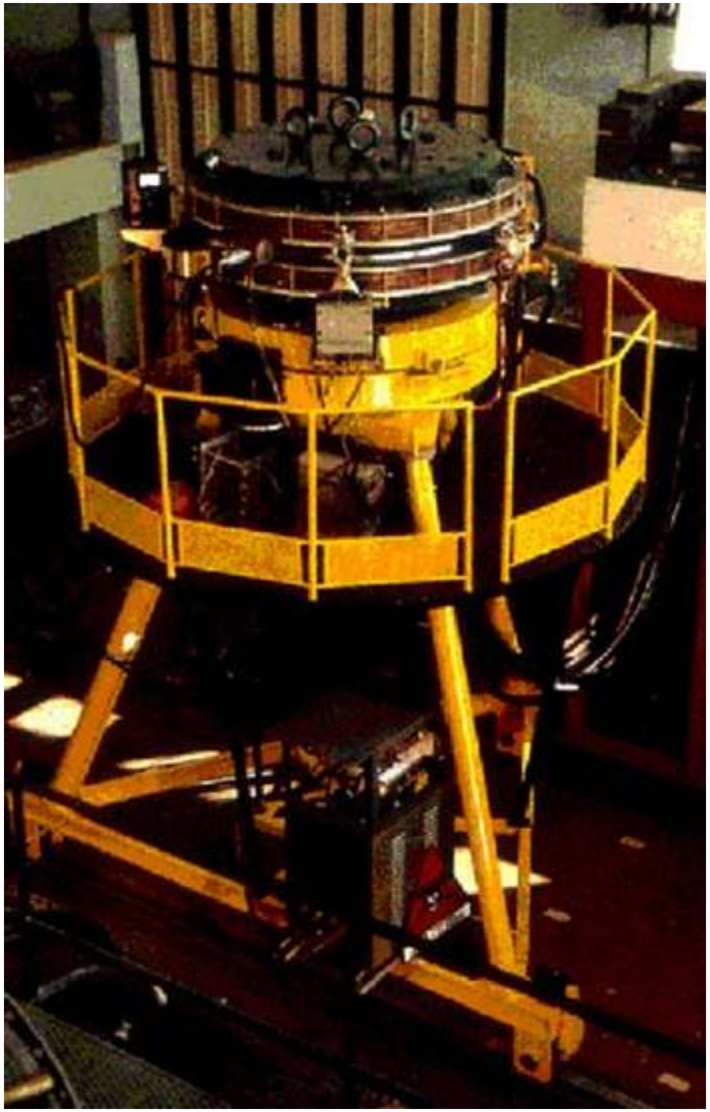
-- Electron – Positron

-- **Proton – Proton**

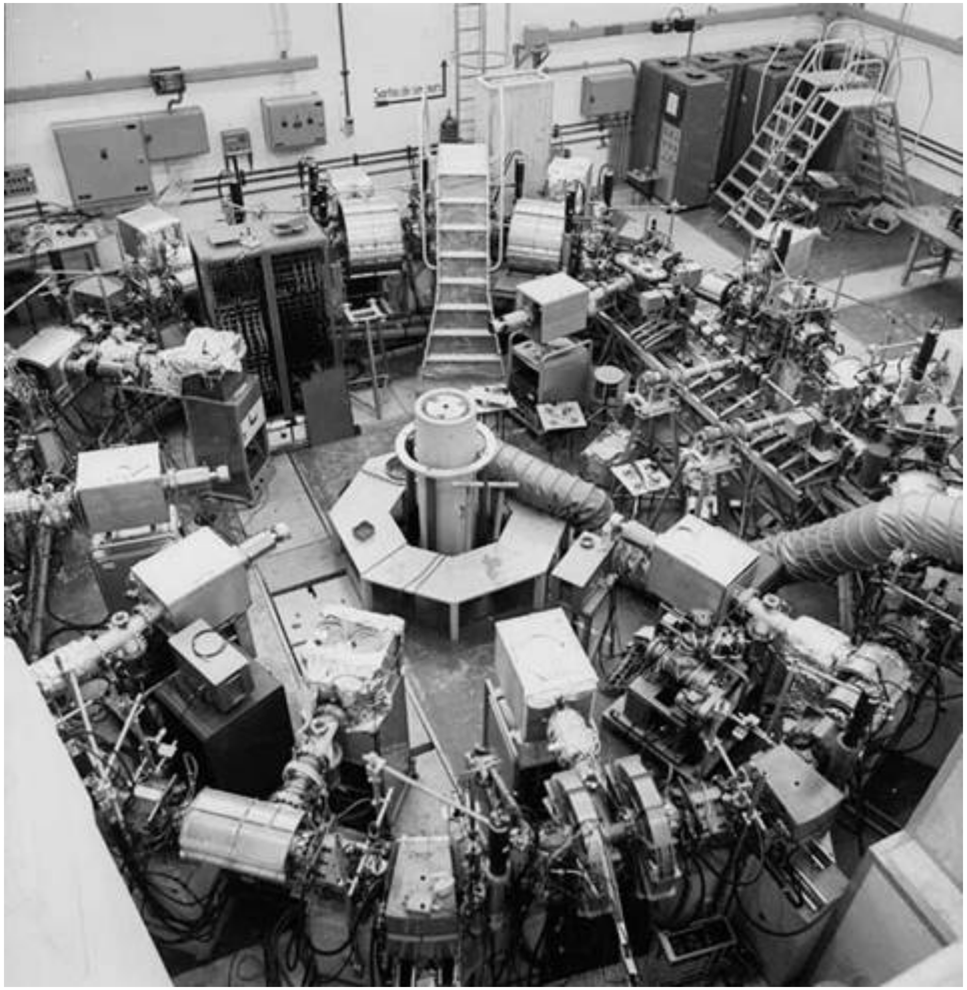
-- Proton -- Anti-proton

-- Heavy Ion

Colliders continue to be the source of the highest energy collisions

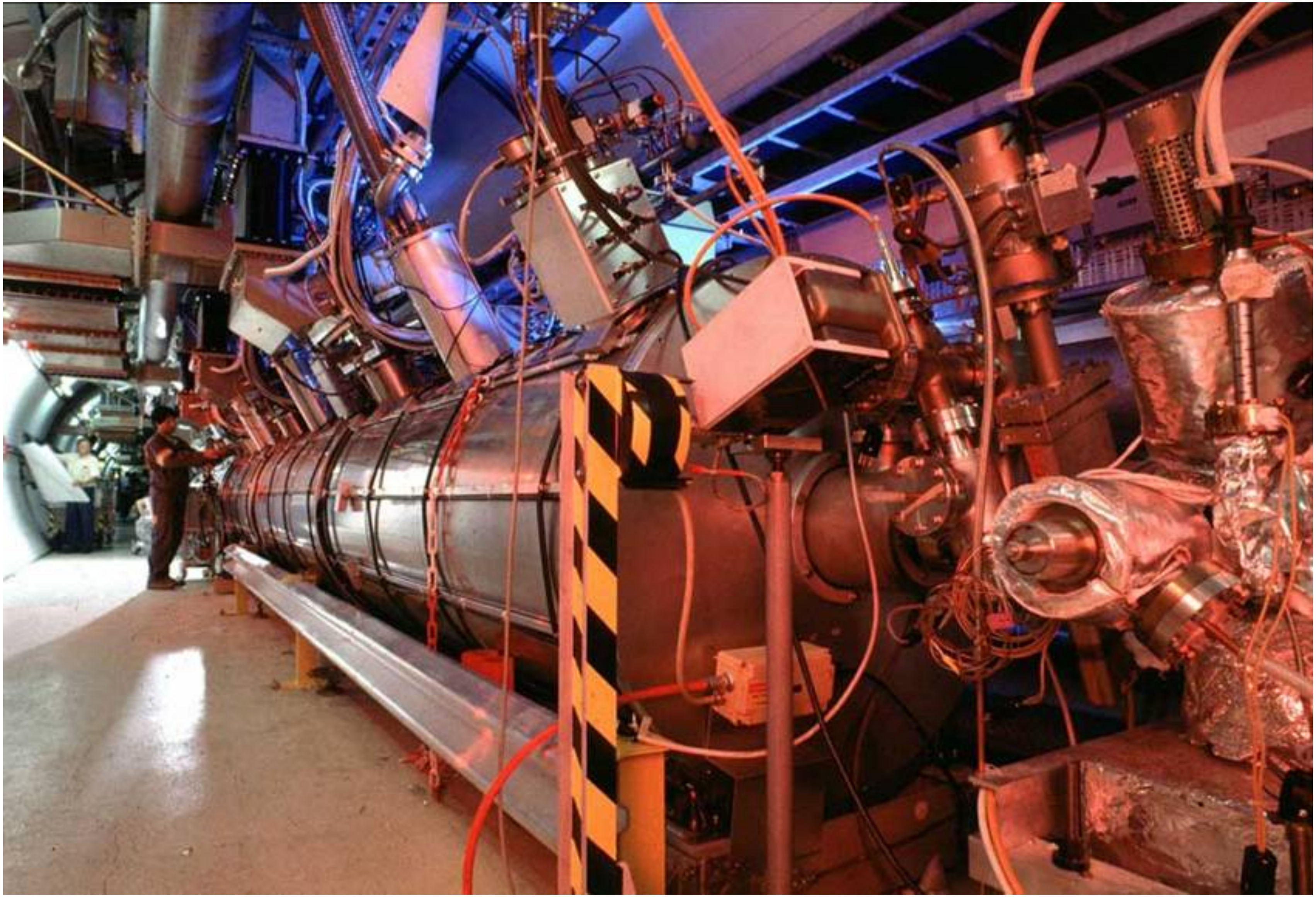


The first electron-positron storage ring, AdA. (About 1960) Built and operated at Frascati, Italy and later moved to take advantage of a more powerful source of positrons in France.



The CERN Electron Storage and Accumulation Ring (CESAR) was built, in the 1960’s, as a study-model for the ISR (Intersecting Storage Rings).

The first proton-proton collider, the CERN Intersecting Storage Rings (ISR), during the 1970’s. One can see the massive rings and one of the intersection points.



Superconducting RF cavities at the CERN Large Electron Positron Collider (LEP).

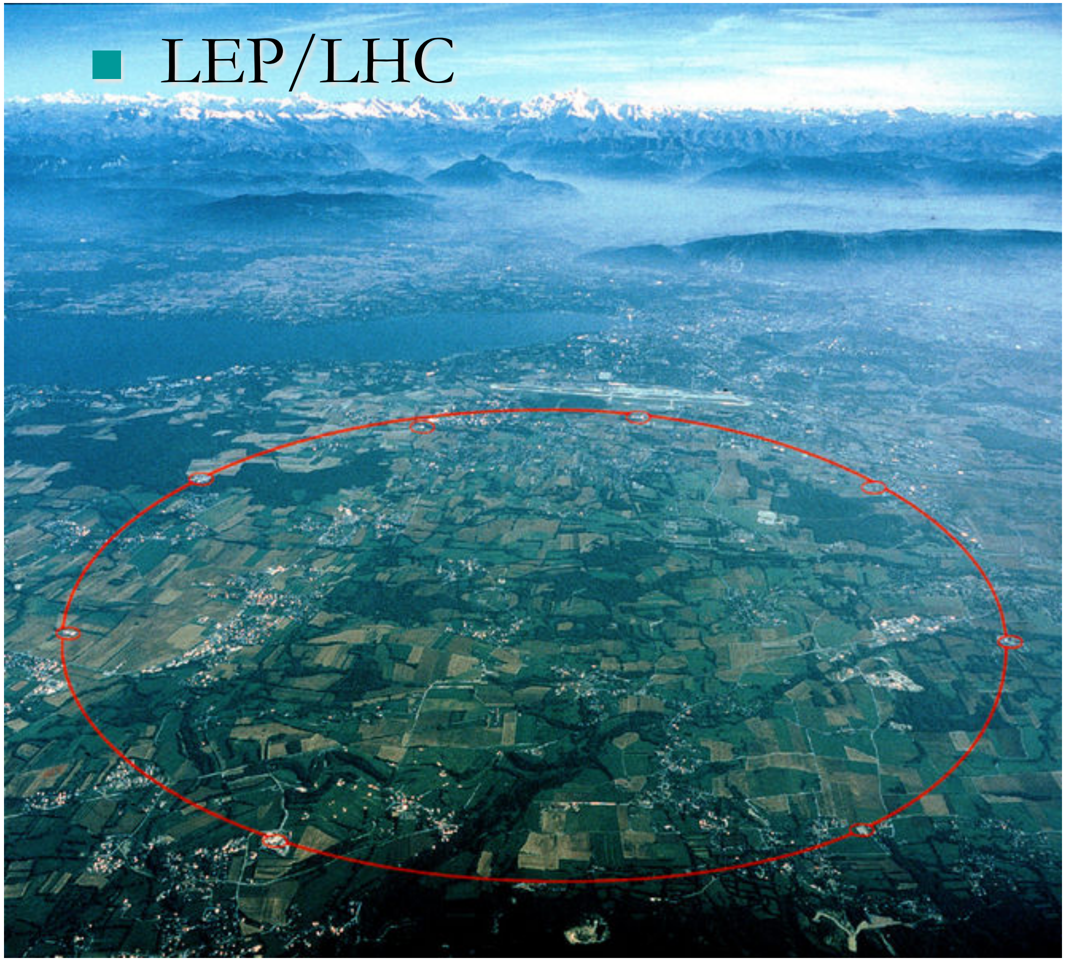
TEVATRON

At

FNAL

The anti-proton source, the “p-bar” source, built in the 1990’s at Fermilab. The reduction in phase space density, the proper measure of the effectiveness of the cooling, is by more than a factor of 10^{11}.

…acceleratori

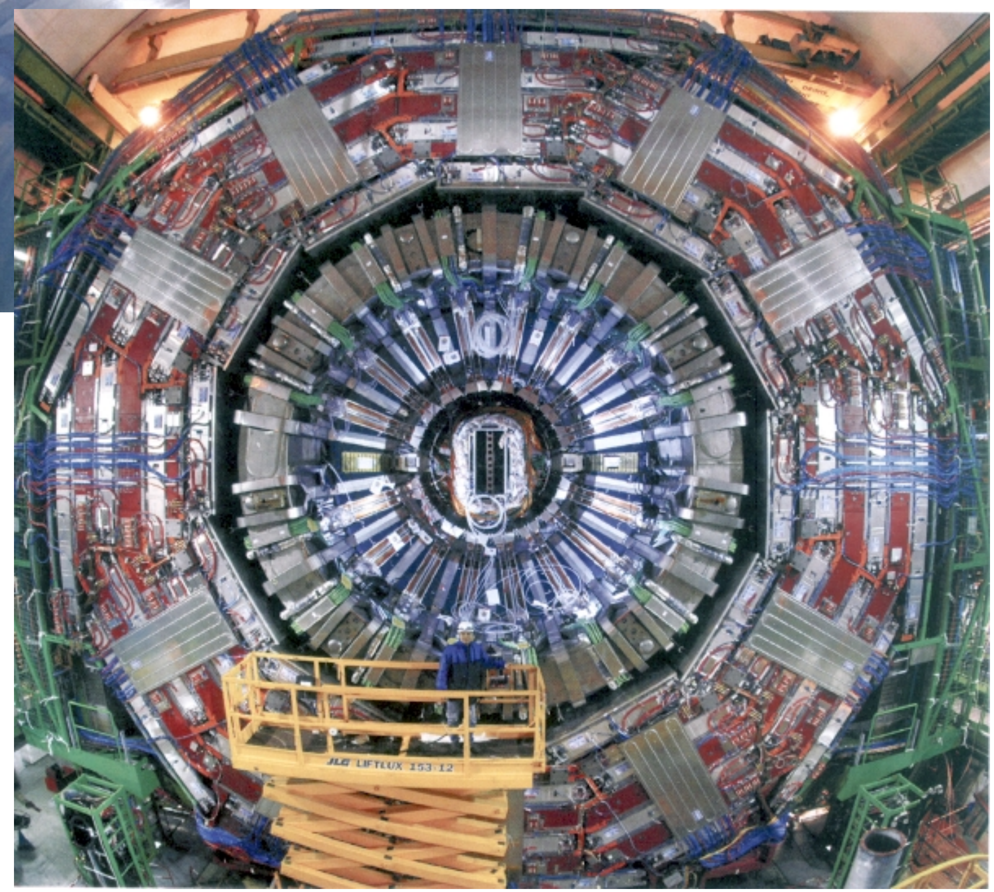


LHC (pp a 7+7 TeV) e' al limite "umanamente" raggiungibie con la tecnologia attuale.

La natura offre un fascio di particelle con energie (per "esperimenti" a bersaglio fisso) di energie fino a ≈10^8 TeV

And Today ……..

The LHC at CERN



And one of the big experiments

CMS

And …. in Space

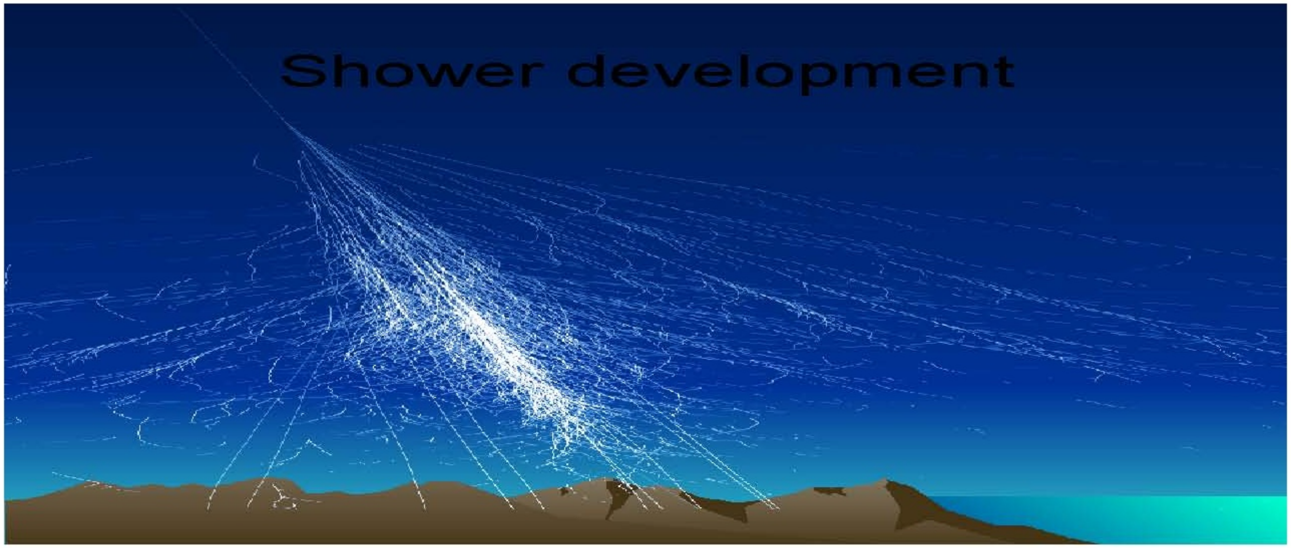
Investigating High and Very High Energy Cosmic Rays

(Combination of Space-based, Balloon-based, and Ground-based Measurements)

SPACE: **PROTON Satellites (Naum Grigorov & Colleagues – (MSU) SOKOL Mission, HEAO-C2, CRN (Spacelab 2), PAMELA, AMS ….**

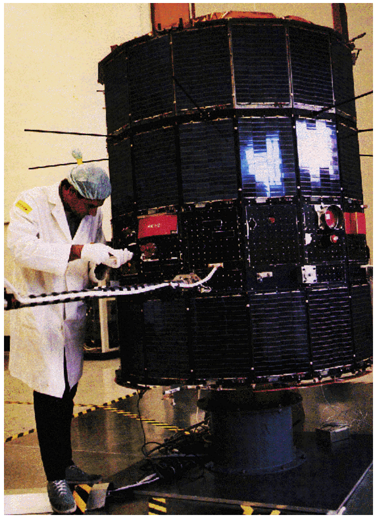
BALLOON: JACEE, RUNJOB, ATIC, TRACER, CREAM, TIGER ….

GROUND: Extensive Air Showers (Technique used to discover the ‘knee’ at a few PeV by G. Khristiansen and colleagues) -- many arrays



GOAL: Extend Space and Balloon measurements to higher energy and Air Shower measurements to lower energy until there is significant overlap.

Space Age: Cosmic Ray Astrophysics



IMP-8 (J): Interplanetary Monitoring Platform (above)

Launched in 1973 & returned data for over 30 years !

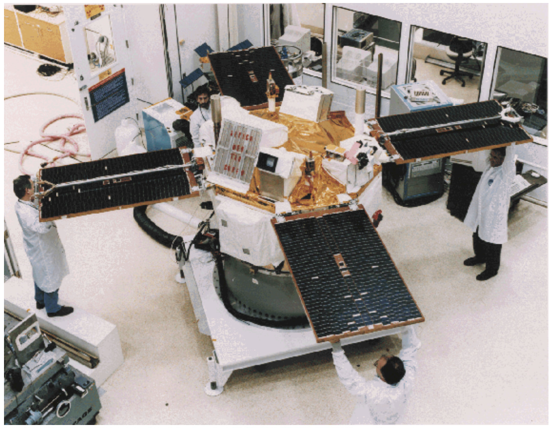
Elliptical orbit 45 x 25 Earth radii

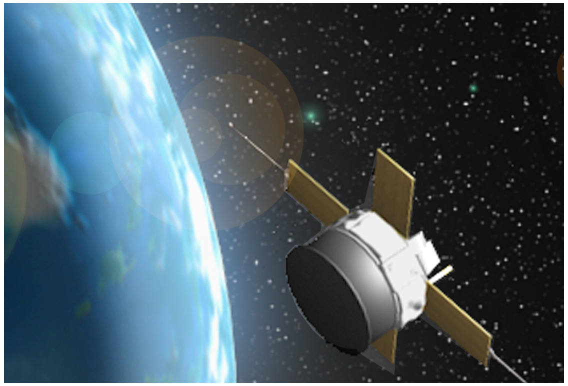
Goal: study magnetic fields, plasmas and energetic particles in near-Earth space

ACE: Advanced Composition Explorer (below)

Launched in 1997 & is still returning data

L1 Halo orbit





Goals: Determine charge state, elemental and isotopic composition of solar corona, solar wind, interplanetary particles, Interstellar medium and galactic particles over a broad energy range

Connections – Cosmic Ray and High Energy Physics

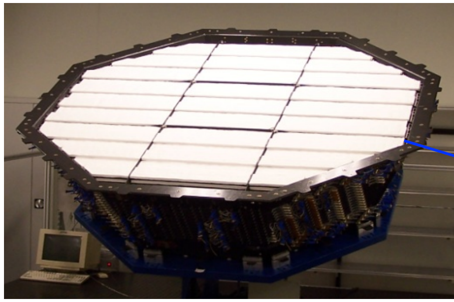
Technology – Detectors, Electronics, DAQ, Software (Need to adapt HE systems and techniques to the space/ near space environment.)

Modeling and Simulations -- Need accelerator data as input to model the extensive air showers that must be studied to extend Cosmic Ray measurements to the highest energies and for propagtion models of CR.

Instrument Development and Calibration – need accelerator beams at the highest possible energies for a variety of ions.

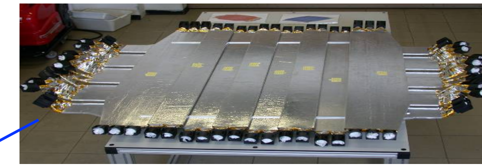
AMS: A TeV precision, multipurpose spectrometer

TRD
Identify e+, e-

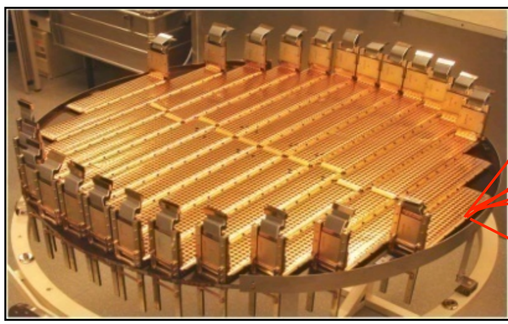


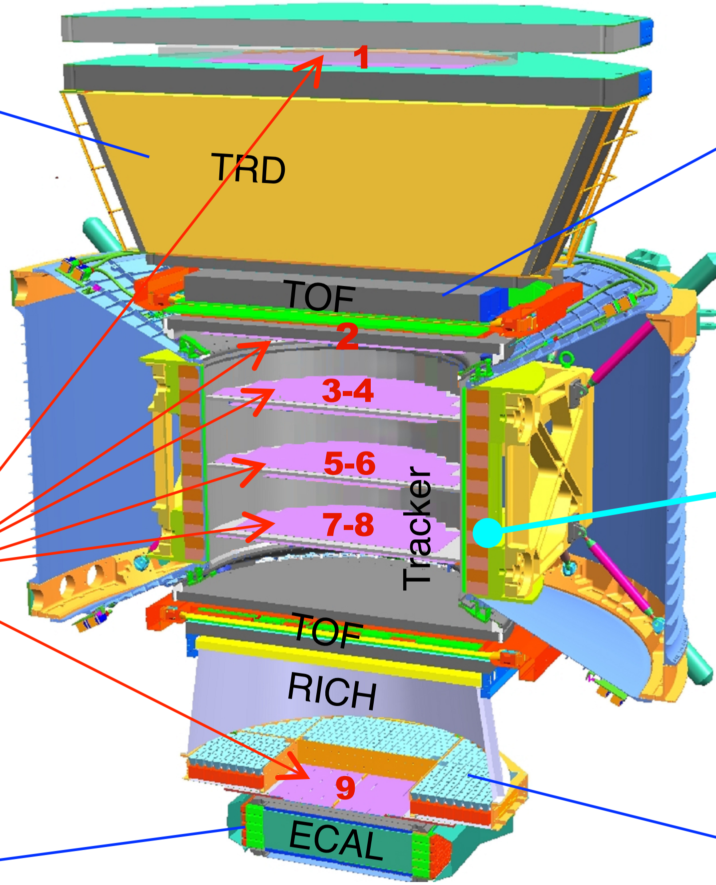
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TOF
Z, E

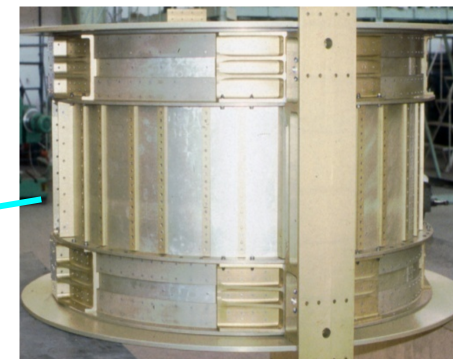


Silicon Tracker
Z, P



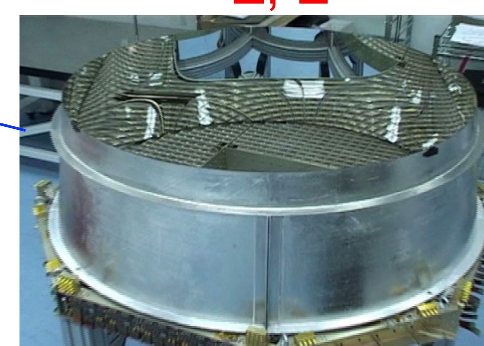


Magnet
±Z



ECAL
E of e+, e-, γ

RICH
Z, E

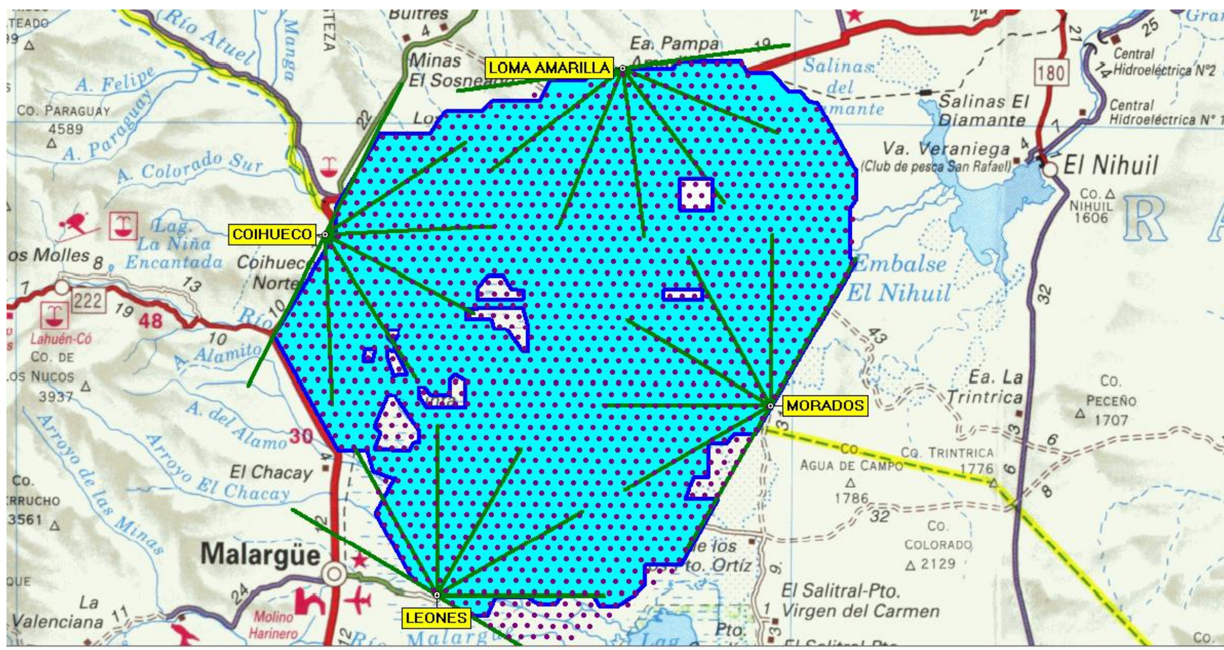


Z, P are measured independently from Tracker, RICH, TOF and ECAL

From The First Cyclotron to the Highest Energies in the Universe

Let the ‘ride’ continue ……..

First Cyclotron



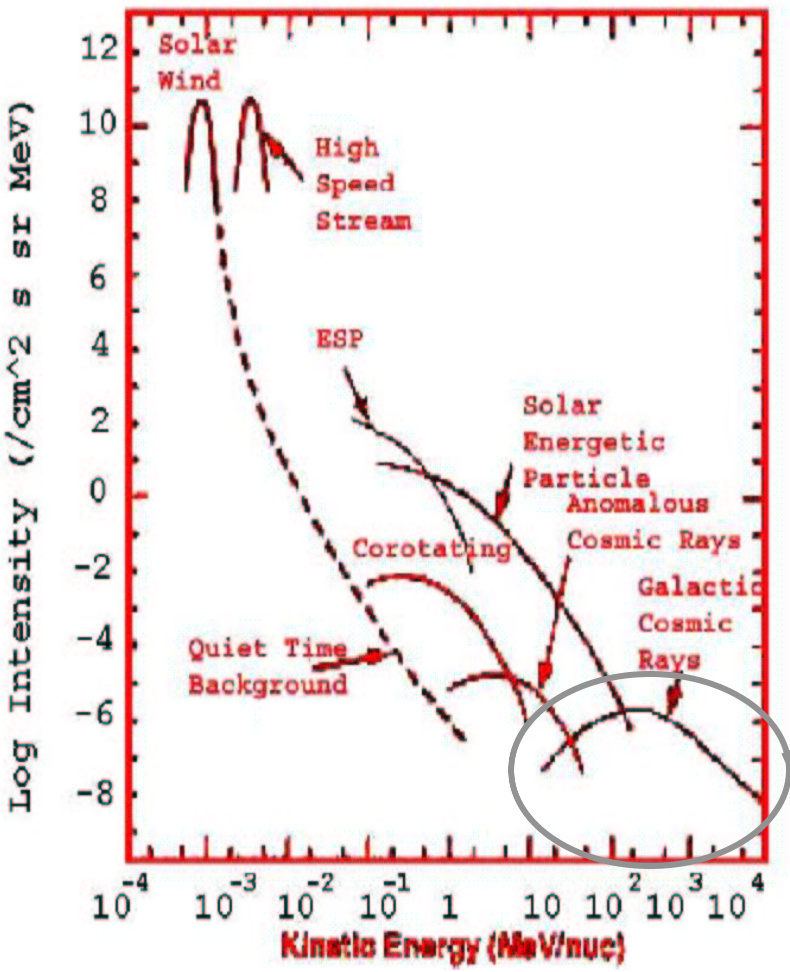
Pierre Auger Observatory

Osservabili

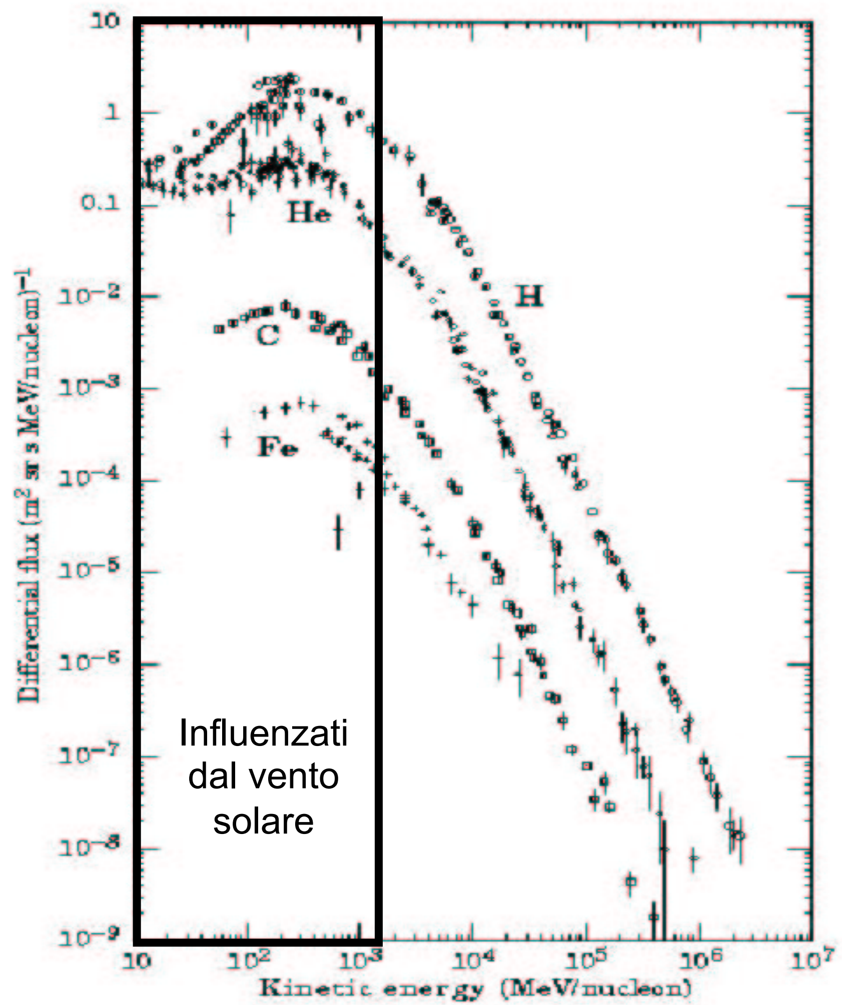
- Energy distribution → Flux and Spectrum
- Particle Type: p, He, Li, Be,.. → Composition
- Arrival Direction → Anisotropy

Cosmic ray spectra

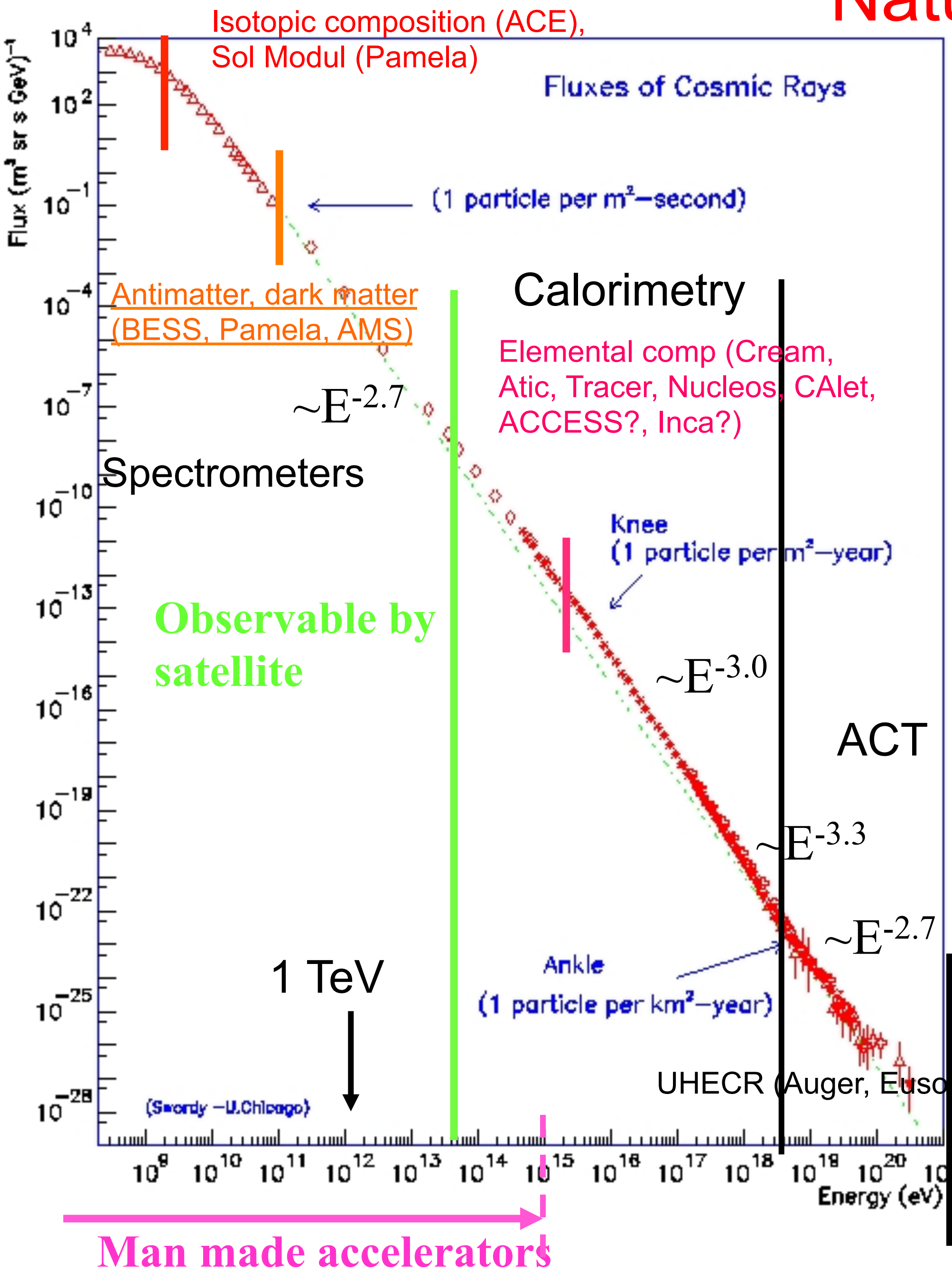
Particles produced in the heliosphere



Galactic and extragalactic particles



Nature's beam calibration



- ❑ Nature offers a very energetic beam
- ❑ Nature doesn't give us the beam parameters...
- ❑ We have to get the whole picture: we must measure precisely the entire CR flux (photons included)

- ❑ Cosmic rays: a continuous, stationary flux of charged and neutral particles (photons) reaching the top of atmosphere from space

Beam calibration:
Beam energy ←→CR spectrum at Earth
Composition ←→CR chemical elements
Luminosity ←→ CR abundances & reaction rates

Beam Calibration = CR Propagation Models

- The goal of the propagation models is to achieve a reliable physical description of the CR propagation through the Galaxy
- From the measured fluxes in the heliosphere derive source composition, injection spectra & galactic parameters
- Reliable propagation model is needed for accurate background evaluation for faint signal searches in CR
- Particularly useful measurements to validate propagation models and to constraint their free parameters are flux measurements in a wide energy range of
  - Primary (ratios, eg C/O, fix source abundances)
  - Secondary (secondary to primary ratios, eg B/C, fix the grammage crossed, constraint diff coeff and halo thickness)
  - Radioactive (provide, eg $^{10}Be/^{9}Be$, escape time information)

Spettro di energia

Lo spettro differenziale e' il numero di particelle che attraversano l'unita' di superficie per unita' di tempo, di angolo solido e di energia

$\Phi(E) = dN/dEdSdtd\Omega$ [# part. $cm^{-2}s^{-1}sr^{-1}Gev^{-1}$]

→ da informazioni sui processi di accelerazione alle sorgenti e di propagazione nel mezzo interstellare delle particelle

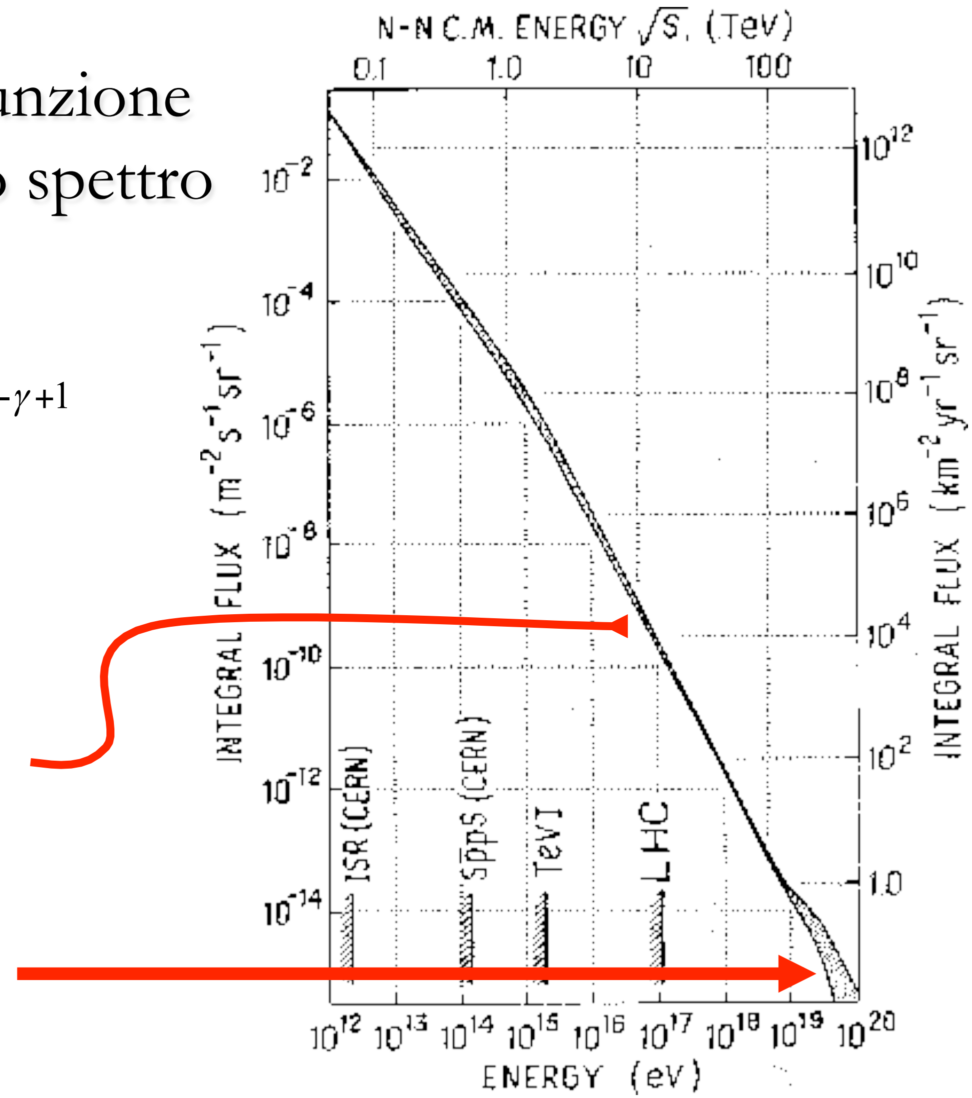
Spettro integrale

- Dallo spettro differenziale (in funzione dell'energia), si può passare allo spettro integrale:

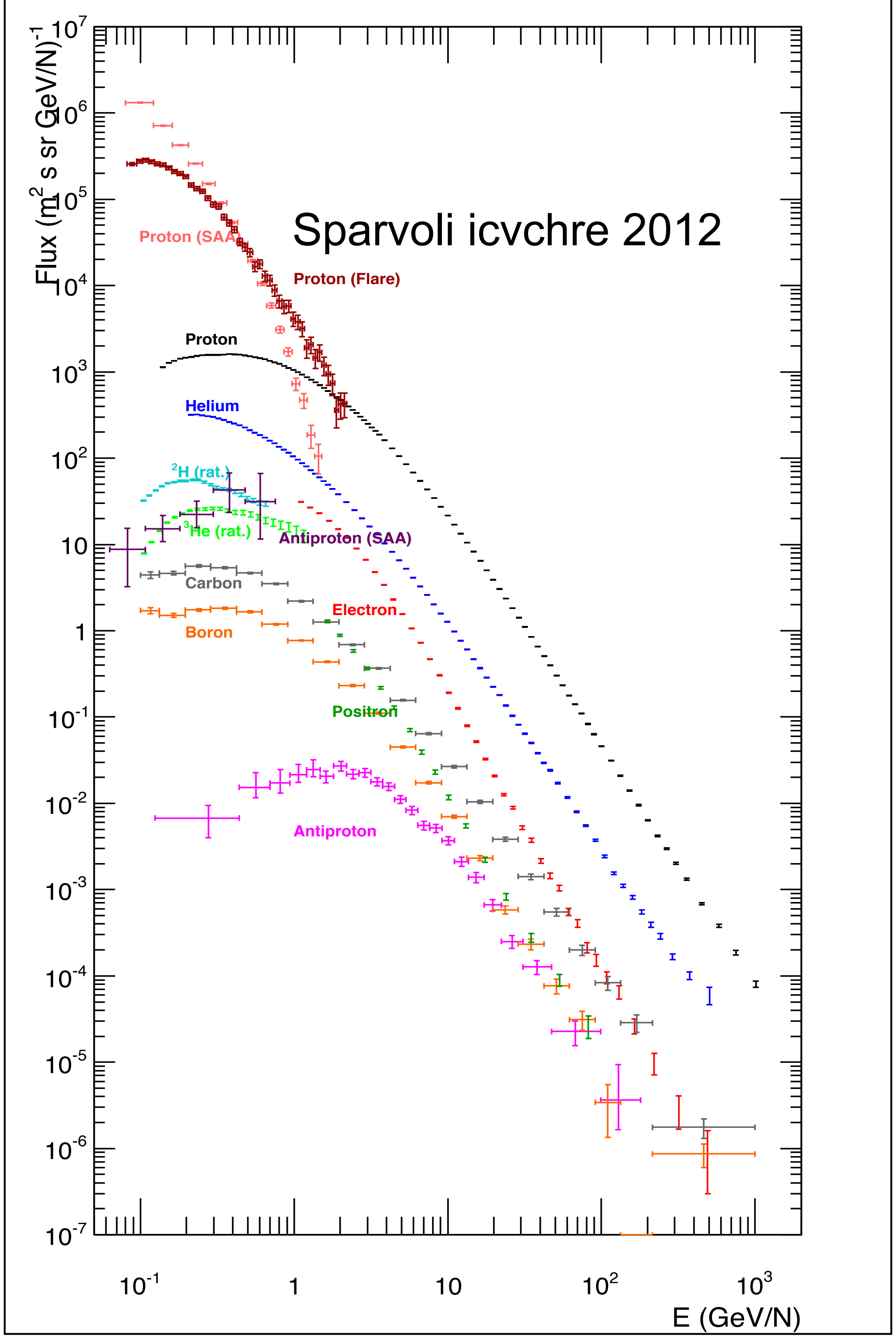
$$\Phi(>E_0) = \int_{E_o}^{\infty} \phi(E)dE = \left(\frac{k}{\gamma - 1}\right) E_o^{-\gamma+1}$$

$$(m^{-2} s^{-1} sr^{-1})$$

- 1 PC = 1 RC durante una partita di calcio = 3 10^8 $m^2 \cdot s \cdot sr$
- 1 GRAnno = 1 RC entro il Grande Raccordo Anulare all'anno= $3x10^2$ $km^2 \cdot y \cdot sr$



- Power law for all the particles
- May be not a single power law (eg spectrum hardening at high E)
- Non thermal spectra → acceleration mechanisms at work



Heavier elements: hardening

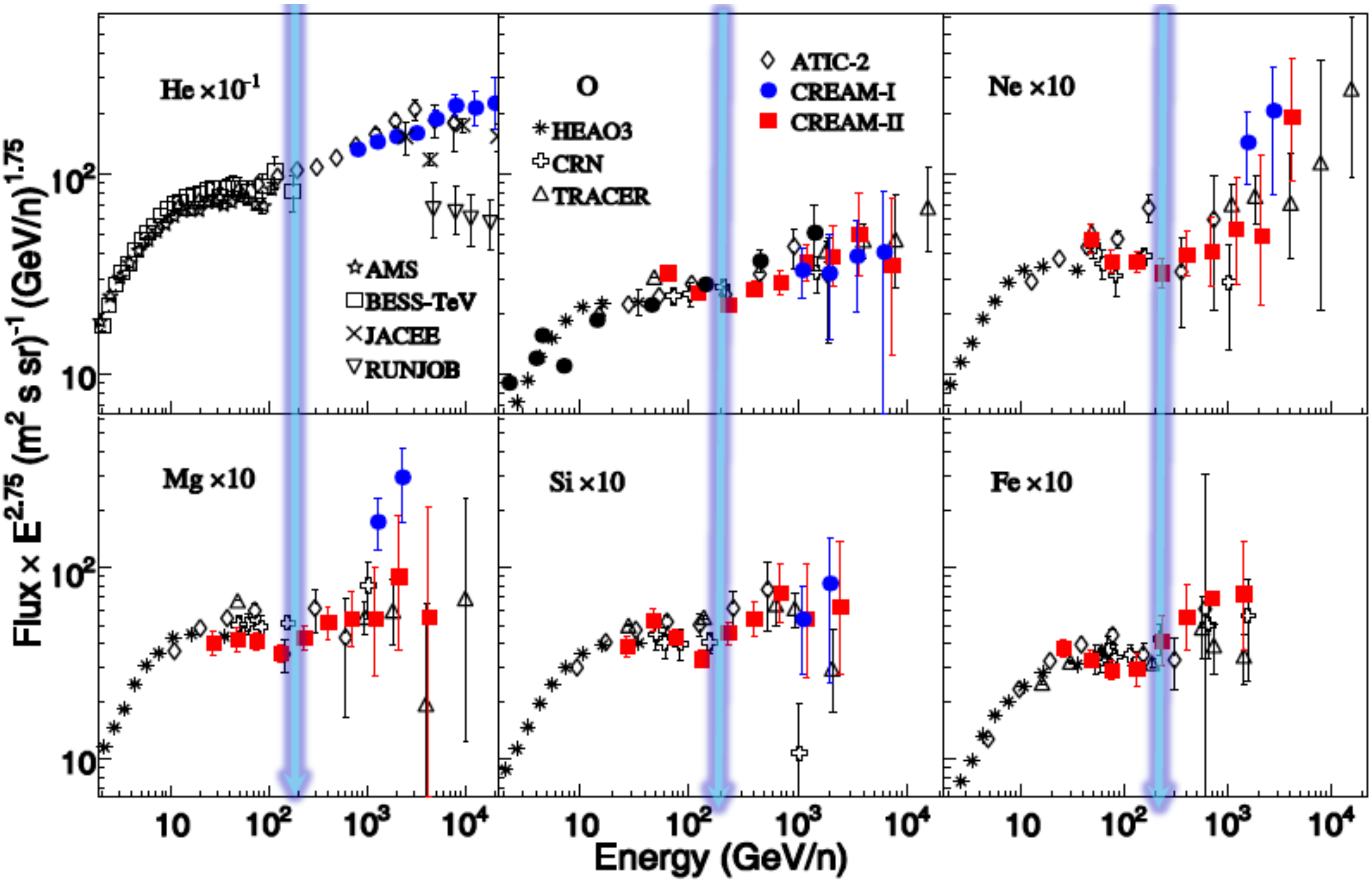
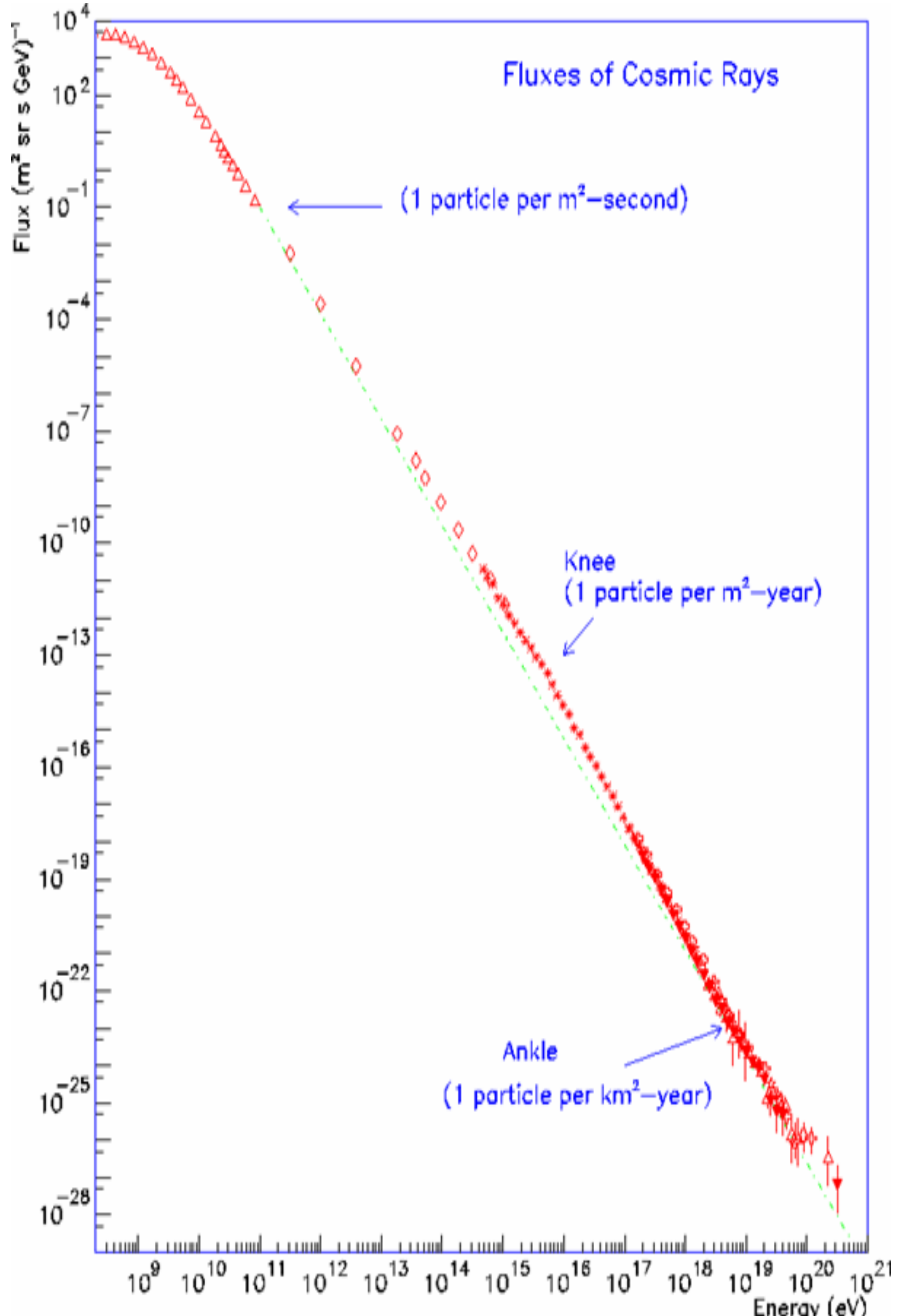


Fig. 1

- Φ_{TOT}~10000 $m^{-2}s^{-2}sr^{-1}$
- Misure dirette: 85% p, 12% He, ~1% nuclei pesanti, ~2% $e^{\pm}$, antiprotoni
- Si estende per 13 ordini di grandezza in energia
- Per 32 ordini di grandezza in flusso
- Legge di potenza su tutto lo spettro, con almeno due cambi di pendenza



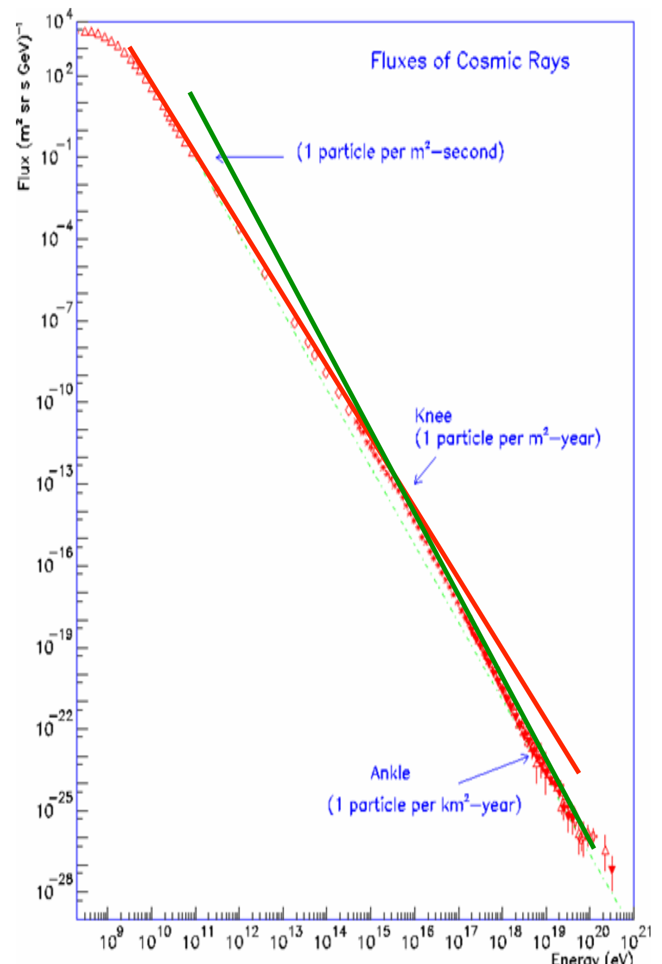
- Lo spettro energetico di Fig. 1 può essere descritto dalla legge (**flusso o spettro differenziale** dei RC:)

$$\phi(E) = k \cdot E^{-\gamma} \qquad (cm^{-2}\, s^{-1} sr^{-1} GeV^{-1})$$

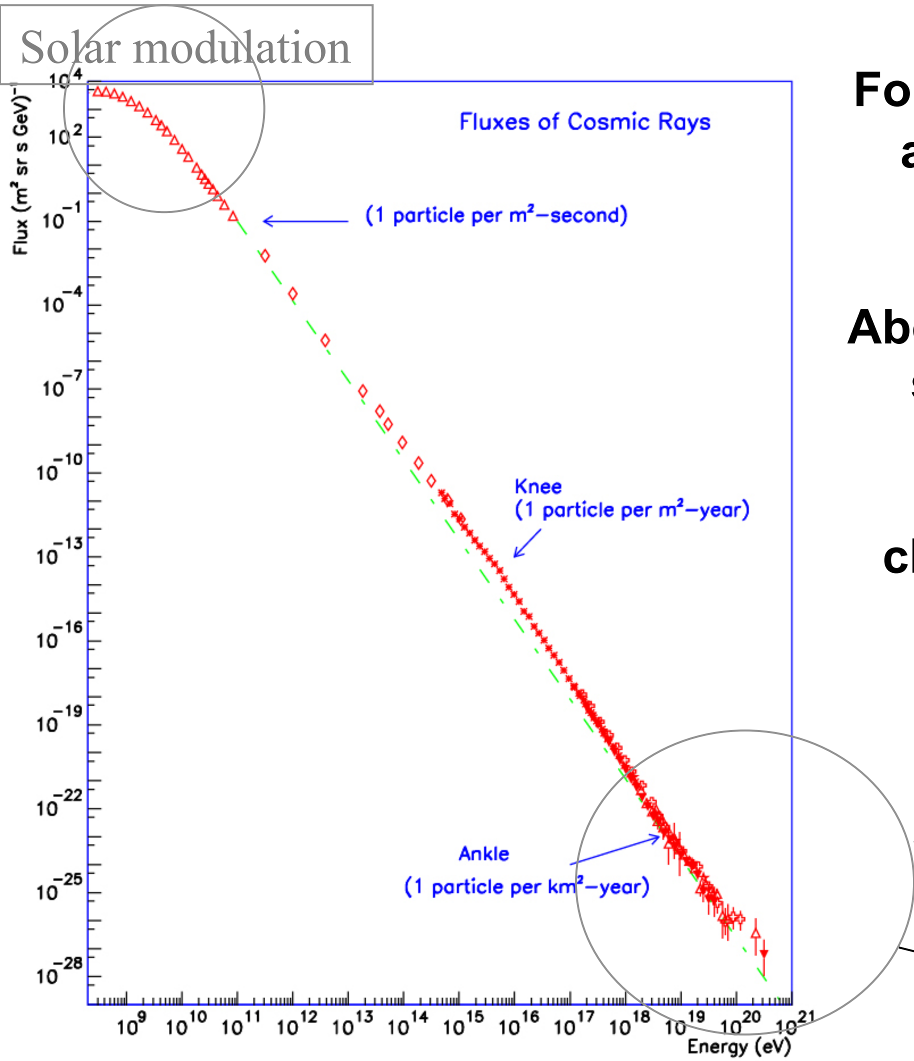
- Legge che descrive i dati sperimentali.
- I parametri k e γ vengono determinati dall'adattamento della curva coi dati
- Regolarità di un fenomeno fisico

Legge di natura!

- Occorre scoprire quali sono i fenomeni naturali che producono tale legge di natura.



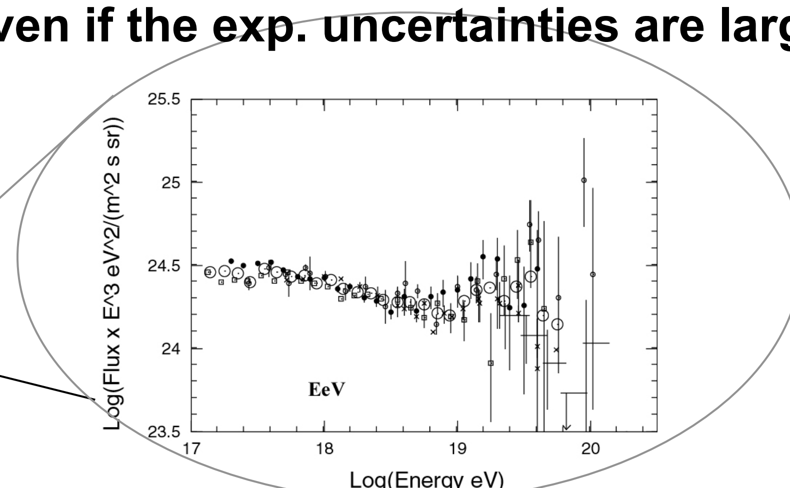
Cosmic rays



Galactic CR reaching the Earth extend from few hundreds of MeV to EeV.
At low energy (<10 GeV) the flux is modulated by solar wind.
For 10 GeV<E< 10^6 GeV, the spectrum follows a power law $KE^{-\gamma}$, with a spectral index of γ=2.74

Above 10^6 GeV the slope changes→ the Knee, steepening the spectrum up to γ= 3. - 3.3

And again at about 3×10^9 GeV, the slope changes back to a lower value close to 2.7, even if the exp. uncertainties are large



Densità numerica e di energia dei RC

- Il flusso di RC sulla terra: $\Phi(E) = k \cdot E^{-\gamma} \qquad (cm^{-2}s^{-1}sr^{-1}GeV^{-1})$

  $k = 1.8, \gamma = 2{,}7 \qquad 10 < E < 10^6\, GeV$
- Per energie E< 1 GeV dominano i contributi dal sole;
- Per E>3·10^6 GeV, cambio di pendenza nello spettro
- Possiamo calcolare il flusso di RC integrando a partire da 1 Gev (per eliminare il contributo solare):

$$\Phi(>1GeV) = \int_{E_o}^{10^6} \phi(E)dE = \frac{k}{\gamma - 1}\left(E^{-\gamma+1}\right)_{3x10^6\,GeV}^{1GeV} = \frac{1.8}{2.7-1}(1)^{-1.7} =$$

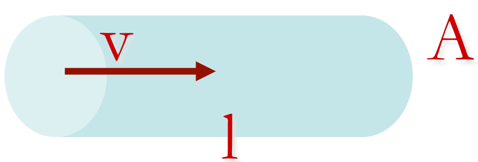
$$= 1 \quad (cm^{-2}s^{-1}sr^{-1})$$

- Dal flusso, è possibile ricavare la densità numerica dei RC:

$$N_{CR} = 4\pi \cdot \frac{\Phi(>E_o)}{c} \qquad (cm^{-3})$$

Esercizio: dal *flusso* alla *densità*

- E' situazione assai frequente in fisica dover passare dalla grandezza misurata flusso ($cm^{-2}s^{-1}sr^{-1}$) a densità di volume (cm^{-3})



- Numero di particelle entranti nell' unità di tempo:

$$\frac{\Delta N}{\Delta t} = 2\pi(sr)\cdot A(cm^2)\Phi(cm^{-2}s^{-1}sr^{-1})$$

- Il tempo di permanenza delle particelle nel volume: $\Delta t = l/v$
- Dunque: $\Delta N = (2\pi\cdot\Phi\cdot A)\Delta t = 2\pi\cdot\Phi\cdot A\cdot l/v = 2\pi\cdot\Phi\cdot\frac{\Delta V}{v}$
- Infine, per un flusso isotropo in cui particelle entrano anche dalla faccia opposta:

$$n(cm^{-3}) \equiv \frac{\Delta N}{\Delta V} = 2\left(\frac{2\pi\cdot\Phi}{v}\right) = \frac{4\pi}{v}\cdot\Phi$$

- Densità numerica dei RC, stimata dalla misura del flusso:

$$n_{CR} = \frac{4\pi}{c} \cdot \Phi(> E_o) = \frac{4\pi \cdot 1}{3 \cdot 10^{10}} \approx 4 \cdot 10^{-10} (cm^{-3})$$

- Stima della densità di energia dei RC:

$$w_{CR} = \int_0^\infty E \cdot n(E) \cdot dE = \int_0^\infty E \cdot \left(\frac{4\pi}{c} k E^{-\gamma} \right) \cdot dE =$$

Esercizio: analisi dimensionale

$$= \frac{4\pi}{c} \frac{k}{\gamma - 2} \left[E^{-\gamma+2} \right]_{3x10^6 GeV}^{1 GeV} = \frac{4\pi}{c} \frac{1.8}{2.7 - 2} (1)^{-0.7} \cong 10^{-9} GeV / cm^3$$

$$w_{CR} \cong 1 \quad eV / cm^3$$

- **Domanda: Come possiamo confrontare questo numero?**
- **E' "grande" o "piccolo" su scala dei fenomeni astrofisici?**

- Densità di energia del campo magnetico galattico ($B=3\times10^{-6}$ G)

$$w_B = \frac{1}{8\pi} B^2 = \frac{1}{8\pi}(3\cdot10^{-6})^2 = 4\cdot10^{-13}\,\frac{erg}{cm^3} = 0.2\,\frac{eV}{cm^3}$$

- Densità di energia della radiazione cosmica di fondo a 3 K

$$w_{CMB} = \left(500\,\frac{fotoni}{cm^3}\right)\cdot 3kT = 500\times3\times3\times8\cdot10^{-5}\left(ev/K\right) = 0.4\,\frac{eV}{cm^3}$$

- Luce delle stelle (da misure fotometriche)

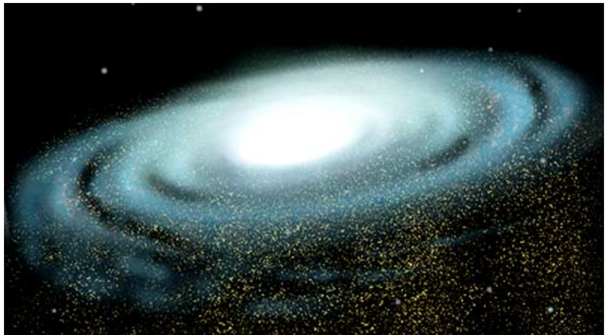
$$w_o = 10^{-2}\,\frac{eV}{cm^3}$$

- La densità di energia che compete ai RC (1 ev/cm^3) è dunque importante su scala galattica.

Isotropia dei RC

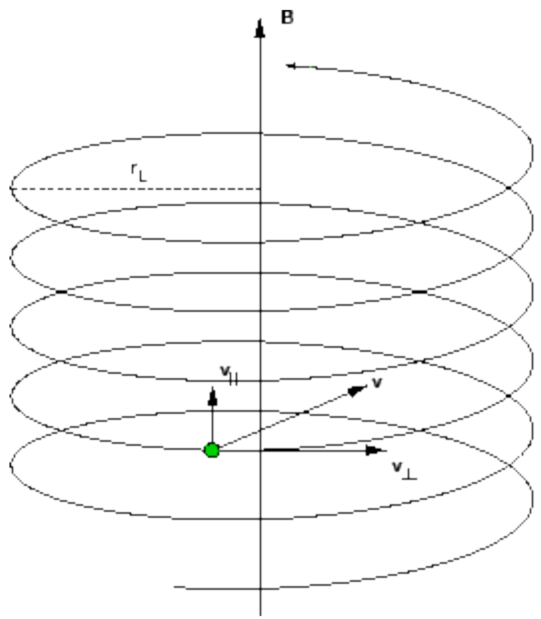
- I RC primari al di sotto di 10^{18} eV hanno una distribuzione di arrivo completamente isotropa sulla sommità della nostra atmosfera. **Qualè il motivo?**

- Campi magnetici **galattici**:
  - $B \cong 3\times10^{-6}$ G
  - coerenti su scale di distanza 1-10 pc
  - NOTA: 1 pc=3×10^{18} cm
- **Galassia≡** disco di raggio R=15 kpc, spessore h=300-1000 pc



Raggio di curvatura di una particella in moto in un campo magnetico

- Determiniamo il raggio di curvatura (denominato *raggio di Larmor*) di una particella con carica q ed energia E in moto in un campo magnetico **B**.



$$m\frac{v^2}{r} = \frac{pv}{r} \overset{Lorentz}{=} Ze\cdot\frac{v}{c}\cdot B$$

$$r = \frac{pc}{ZeB} \cong \frac{E}{ZeB}$$

$$r_{Larmor} = \frac{\mathbf{1.6\times10^{-12}}[erg/eV]\cdot E[eV]}{Z\cdot[\mathbf{4.8\times10^{-10}}u.e.s.]B[Gauss]} = \frac{\mathbf{1}}{\mathbf{300}}\frac{E}{ZB}(eV/Gauss)\ \text{[cm]}$$

Confinamento: $r_{Larmor} = \frac{1}{300}\frac{E}{ZB}(eV/Gauss)$ [cm]

- Utilizziamo i valori tipici del campo B (3×10^{-6} G) galattico per protoni:

$$r_L = \begin{cases} (E=10^{12}\,eV) & =10^{15}\,cm = 3\cdot10^{-4}\ pc \\ (E=10^{15}\,eV) & =10^{18}\,cm = 0.3\ pc \\ (E=10^{18}\,eV) & =10^{21}\,cm = 300\ pc \end{cases}$$

- I p hanno un raggio di Larmor sempre minore dello spessore del disco galattico (300 pc) se $E<10^{18}$ eV. Per questo motivo tutti i RC (meno quelli di energia estrema) sono *confinati* nel piano Galattico dal campo magnetico.

Confinamento

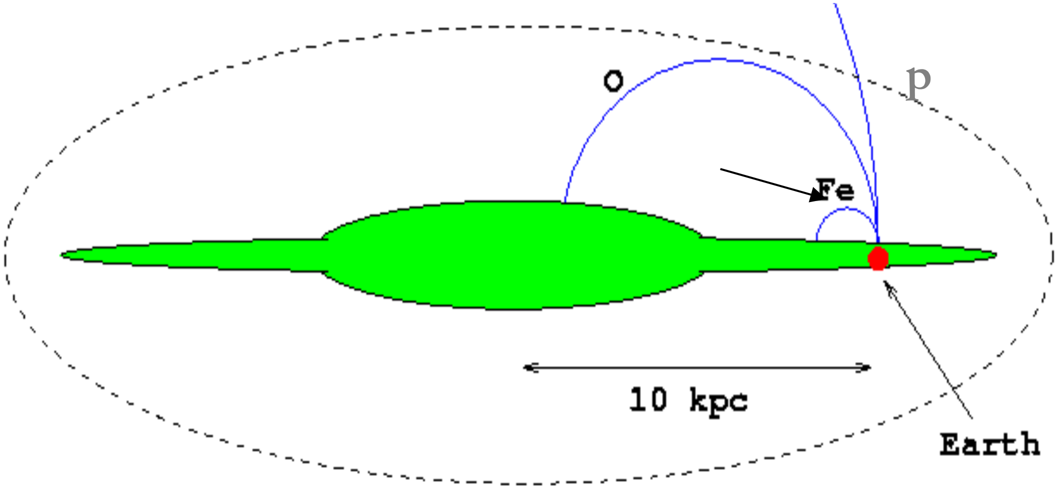
→ for a proton with 10^{14} eV, r ≈ $3x10^{17}$ cm ≈ 0.1 pc, which is << of galactic disk (≈0.3 kpc) and galactic halo (≈10 kpc) and << of all the likely sources of CR near Earth, like Crab nebula ➔ low energy CR do not point sources (ie there are not potential sources within 1 pc), ergo they dont have memory of the initial direction (said better: their directions are randomized by the magnetic field)

AND

they are fully contained by galactic magnetic field → their origin must be galactic

$$r_{Larmor}(cm) = \frac{1}{300}\frac{E}{ZB}(eV/Gauss)$$

B≈10^{-6} G or 10^{-10} T



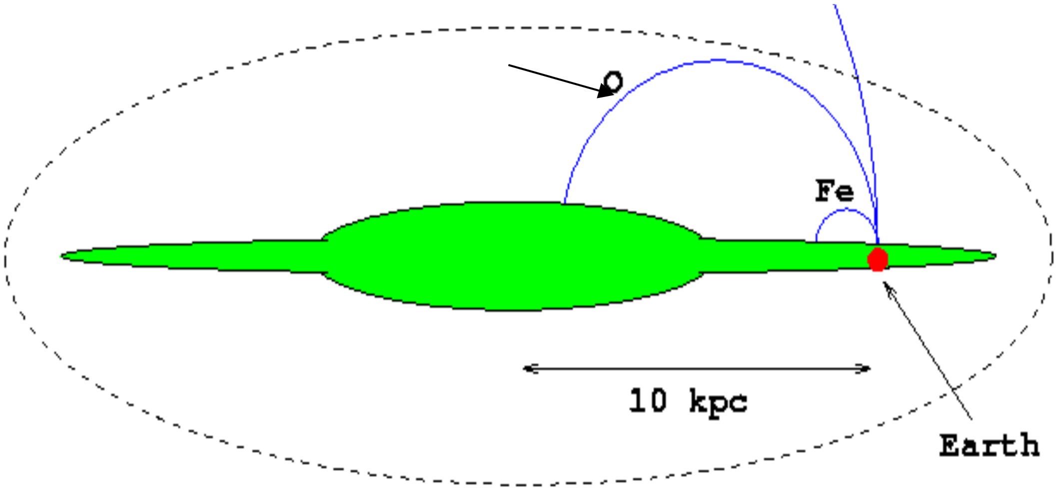
Confinamento

→ for a proton with 10^{18} eV, r≈3×10^{21} cm ≈300 pc of the same order of galactic disk thickness → the trapping by magnetic field starts to be inefficient → presumably CR with much higher E are extragalactic, unless they can be associated with a local source, which could be possible as the direction of such CR would point back to the source (on scales < of the galactic radius the deflection would be small)

NB: no local sources found up to now

$$r_{Larmor}(cm) = \frac{1}{300}\frac{E}{ZB}(eV/Gauss)$$

B≈10^{-6} G or 10^{-10} T



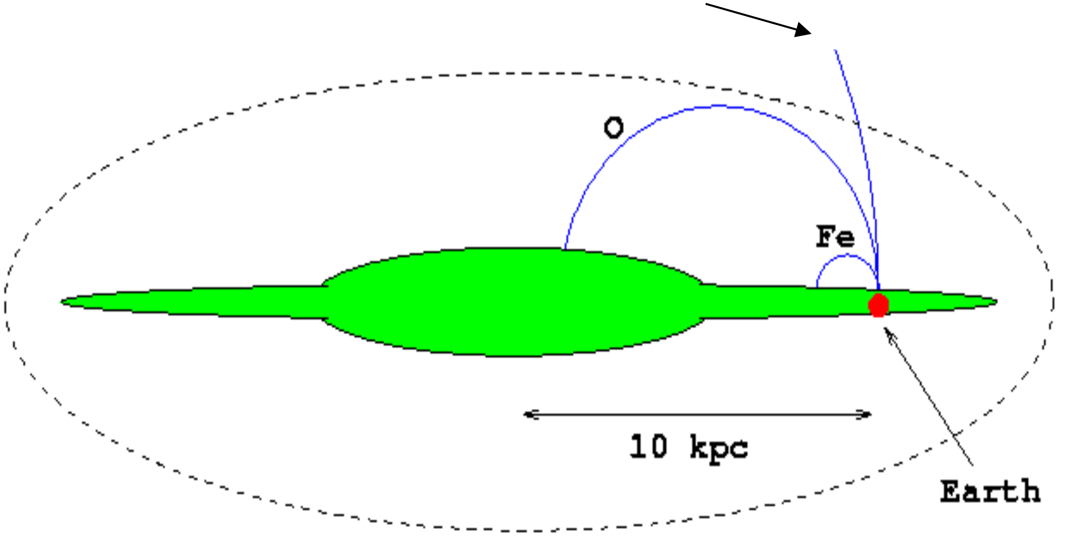
Confinamento

$$r_{Larmor}(cm) = \frac{1}{300}\frac{E}{ZB}(eV/Gauss)$$

$B \approx 10^{-6}$ G or 10^{-10} T

→ for a proton with 10^{20} eV, r ≈ $3x10^{23}$ cm ≈ 100 kpc >> galactic radius→ the B field can not trap the CR and would change the initial direction negligibly → they (would) point back to the sources, likely extragalactic, unless, as before local sources are identified (no one found yet)

If this is true one would expect a possible anisotropy in the angular distribution of CR arrival directions



Cosmic Ray Isotropy

Anisotropies are often quoted in terms of the parameter δ:

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Where I_{max} and I_{min} are the minimum and maximum intensities measured in all directions.

Isotropy

In case of ideal uniform distribution of sources, we would expect the same intensity from all directions in the sky

But the sources are not uniformly distributed and a variety of processes can alter the original direction of a cosmic ray, as for istance collision-less interactions with the irregular galactic magnetic field

Isotropy (cont.)

- So far, experimental results indicate only small amounts of anisotropy at low energies, with δ increasing with E.
- Below E~ 10^{10} eV, solar modulation hides the original directions.
- For higher energies, direction of maximum excess is close to that of the Local Supercluster of Galaxies.

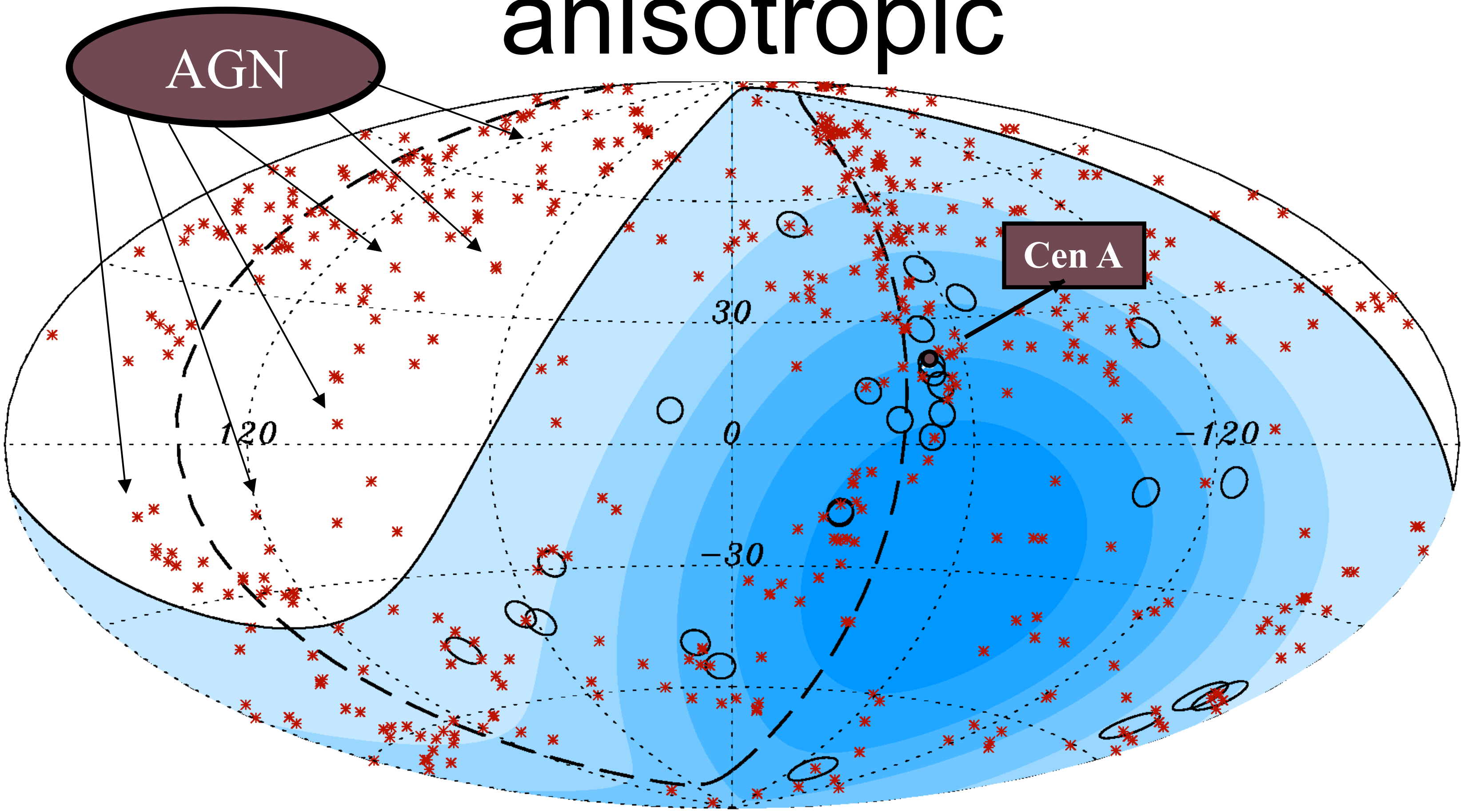
Isotropy Table

Log E (eV)	δ(%)
12	~0.05
14	~0.1
16	~0.6
18	~2
19-20	~20+

The direction of the maximum excess at the highest energies is close to that of the local supercluster of galaxies.

They would point the sources but they are so low in number that sources are not yet identified

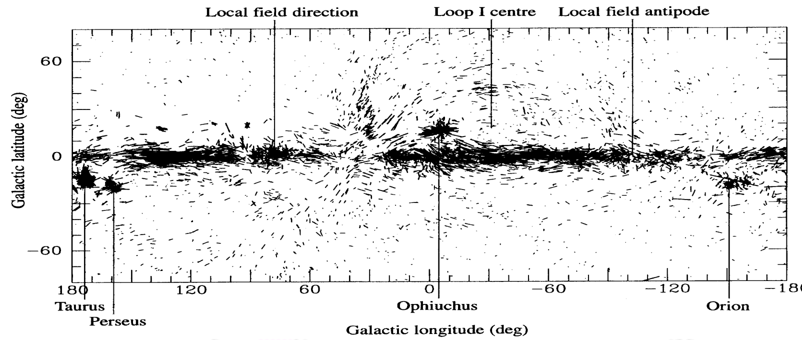
II. The UHECR Sky is anisotropic

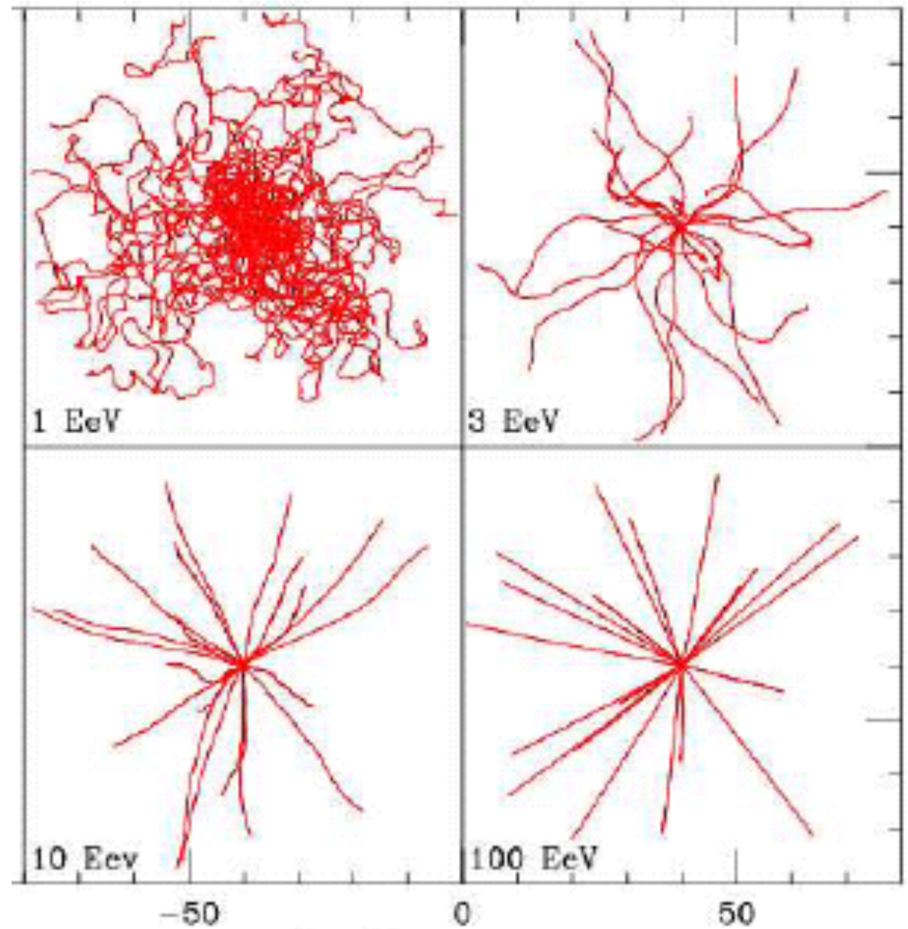


Pierre Auger Collaboration 2007, Science, 318, 939
Pierre Auger Collaboration 2008, APh, 29, 188

B field direction

- Charged particle primaries are significantly deflected by magnetic fields
- Right: proton primaries propagating through random magnetic fields
  - B direction random
  - Cell size = 1 Mpc
  - B = 10^{-9} gauss





EeV = 10^{18} eV

Diagram from Cronin (TAUP 2004),

Confinamento

Il cammino dei raggi cosmici NON e' "liscio" e continuo, ma e' assimilabile a un cammino casuale governato dalla distribuzione di radiazione, materia e campi magnetici nella galassia con cui essi interagiscono

La direzione di arrivo dei raggi cosmici carichi NON punta alla sorgente che li ha generati ma il loro flusso e' isotropo fino ad energie molto elevate