# Lecture 4 131016

- Il pdf delle lezioni puo’ essere scaricato da
- http://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1617/

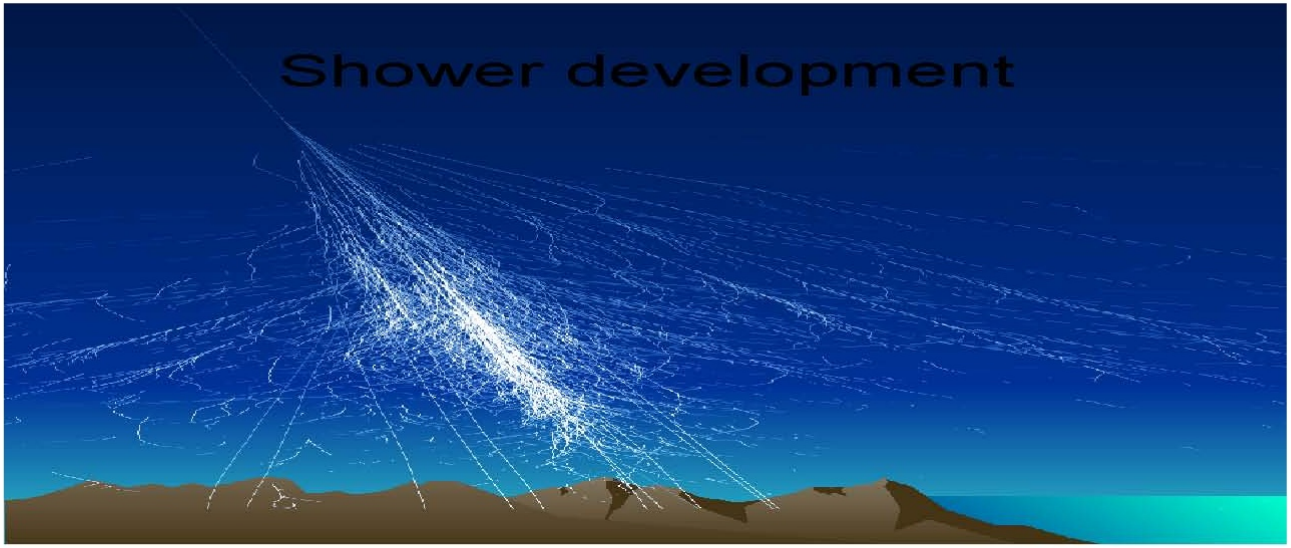
# Investigating High and Very High Energy Cosmic Rays

**(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 ….**

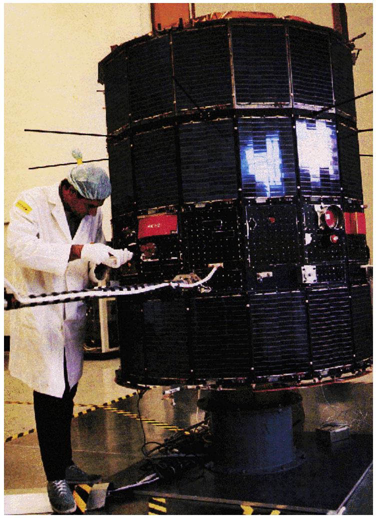
**BALLOON: JACEE, RUNJOB, ATIC, TRACER, CREAM, TIGER ….**

**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.**

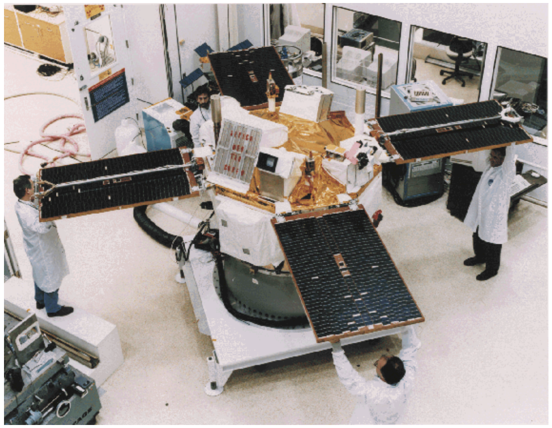
# Space Age: Cosmic Ray Astrophysics

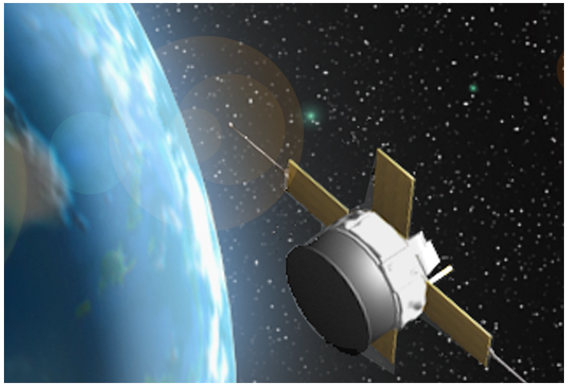


**ACE: Advanced Composition Explorer (below)**

**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**

**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**

# Connections – Cosmic Ray and High Energy Physics

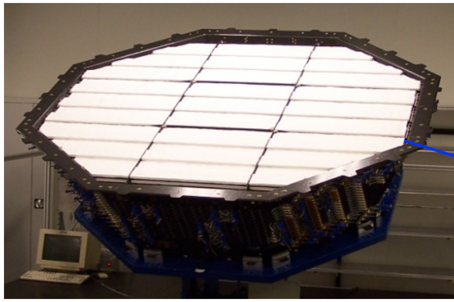
**Technology** – Detectors, Electronics, DAQ, Software (Need to adapt HE systems and techniques to the space/ near space environment.)

**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.

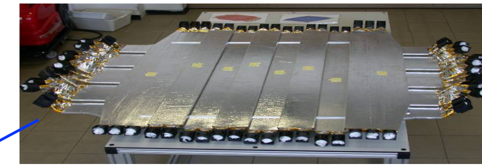
# AMS: A TeV precision, multipurpose spectrometer

TRD
Identify e+, e-

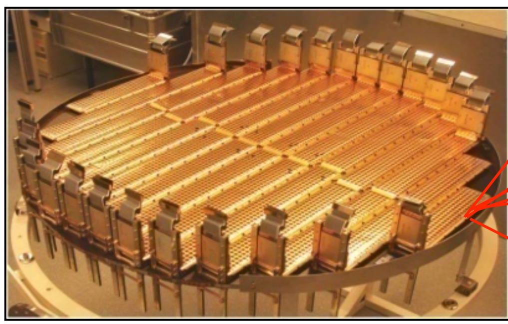


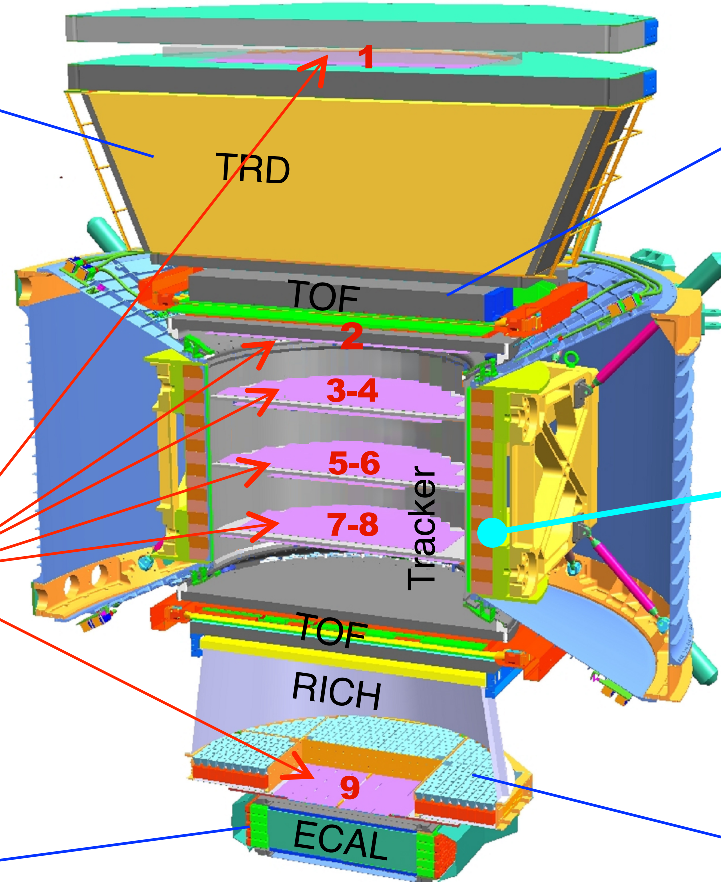
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TOF
Z, E

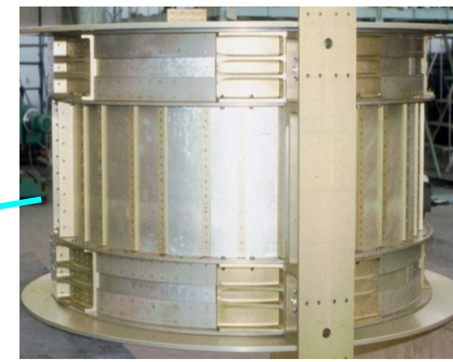


Silicon Tracker
Z, P



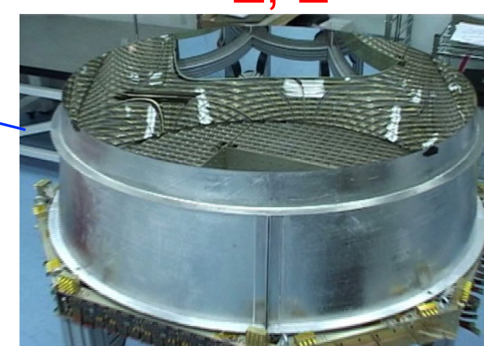



Magnet
±Z



ECAL
E of e+, e-, γ

RICH
Z, E

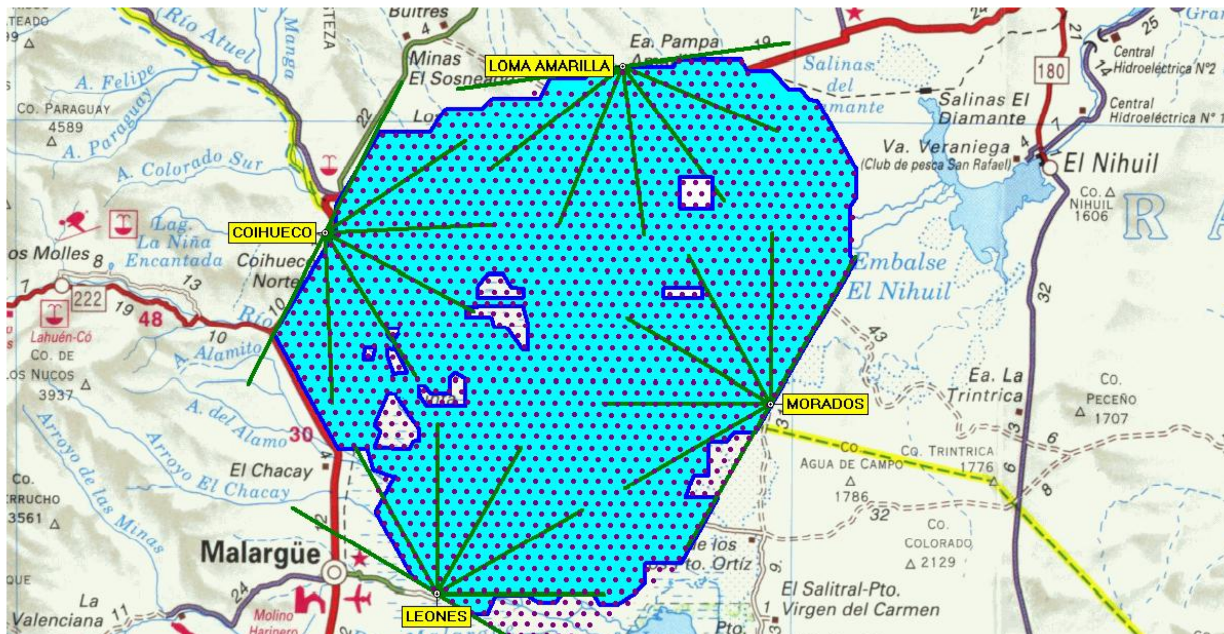


*Z, P are measured independently from Tracker, RICH, TOF and ECAL*

# From The First Cyclotron to the Highest Energies in the Universe

**Let the ‘ride’ continue ........**

**First Cyclotron**



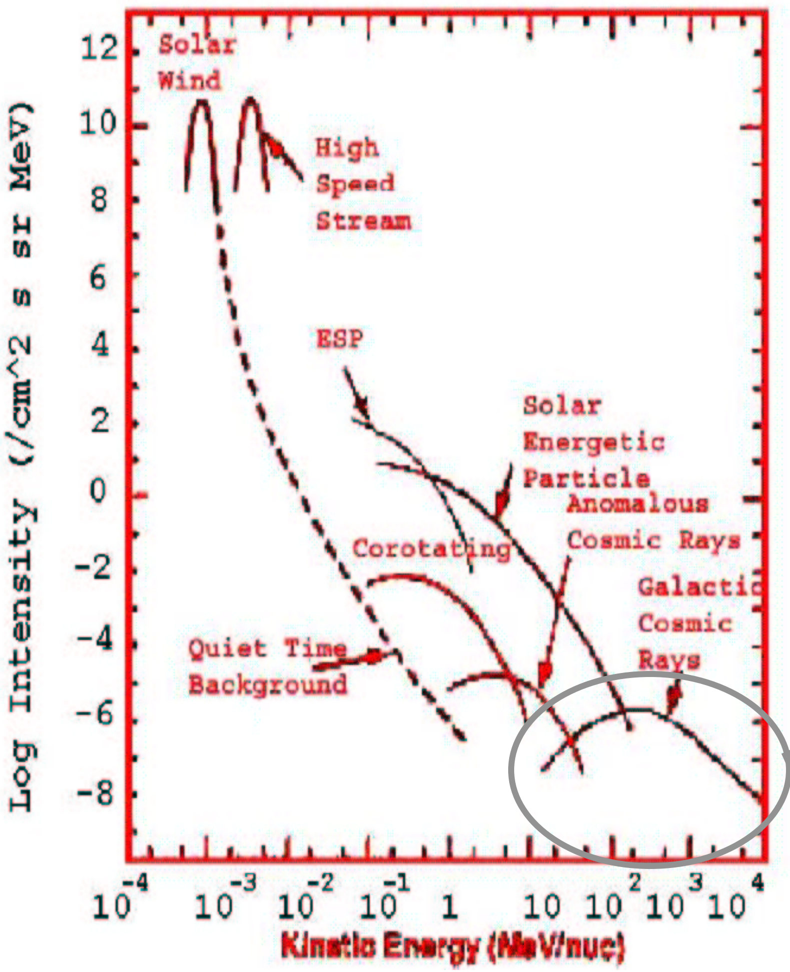

**Pierre Auger Observatory**

# Osservabili

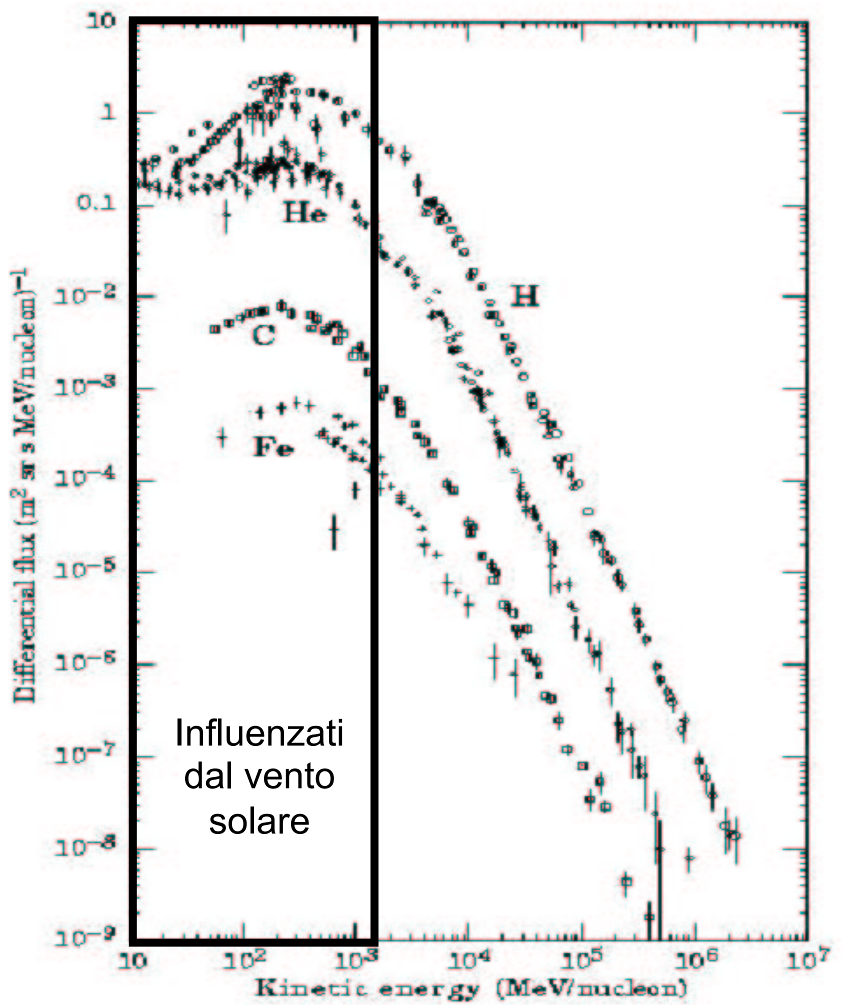
- Energy distribution → Flux and Spectrum
- Particle Type: p, He, Li, Be,..→ Composition
- Arrival Direction → Anisotropy

# Cosmic ray spectra

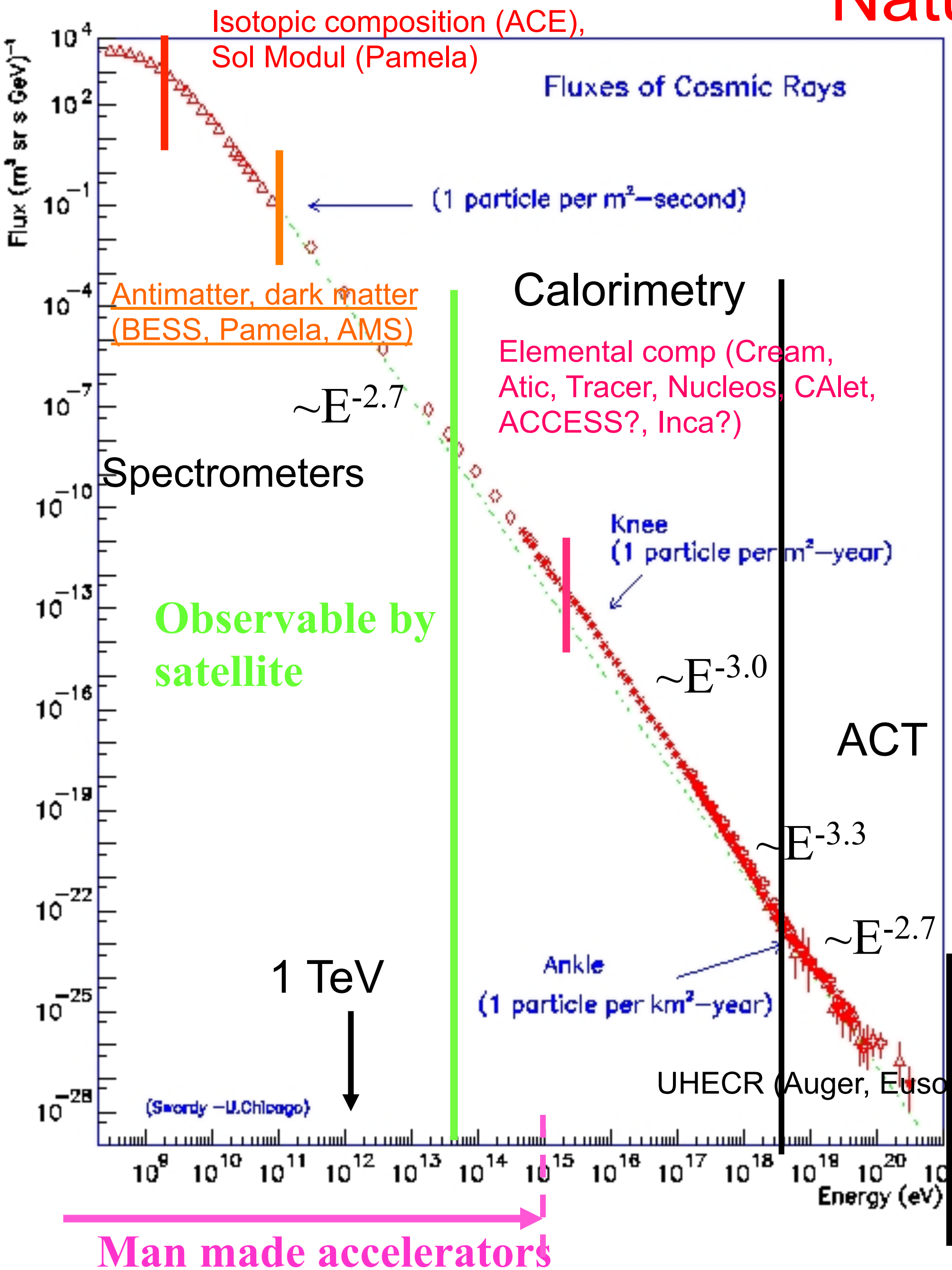
Particles produced in the heliosphere




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

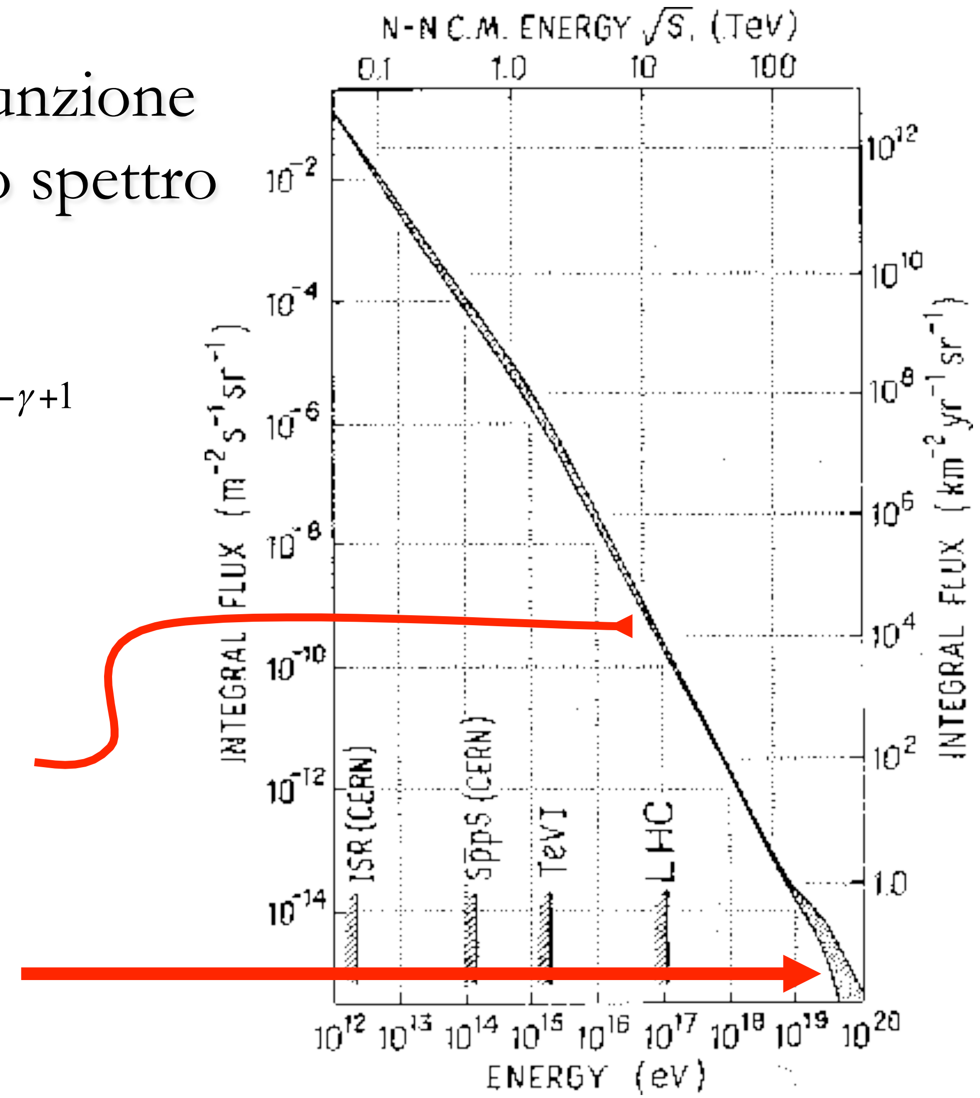
# Spettro integrale

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

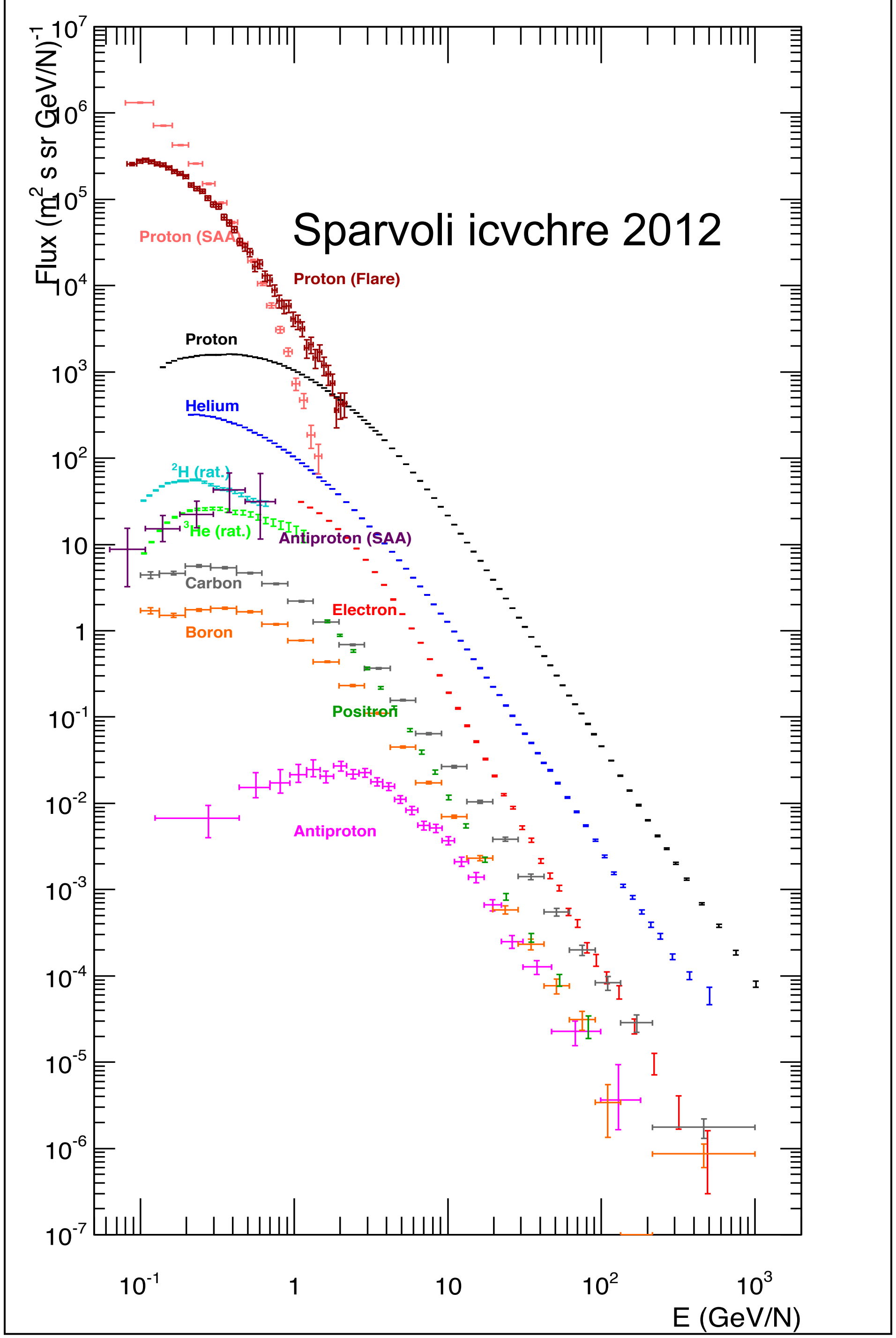
$$\Phi(>E_0) = \int_{E_o}^{\infty} \phi(E)dE = \left(\frac{k}{\gamma - 1}\right) E_o^{-\gamma+1}$$

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

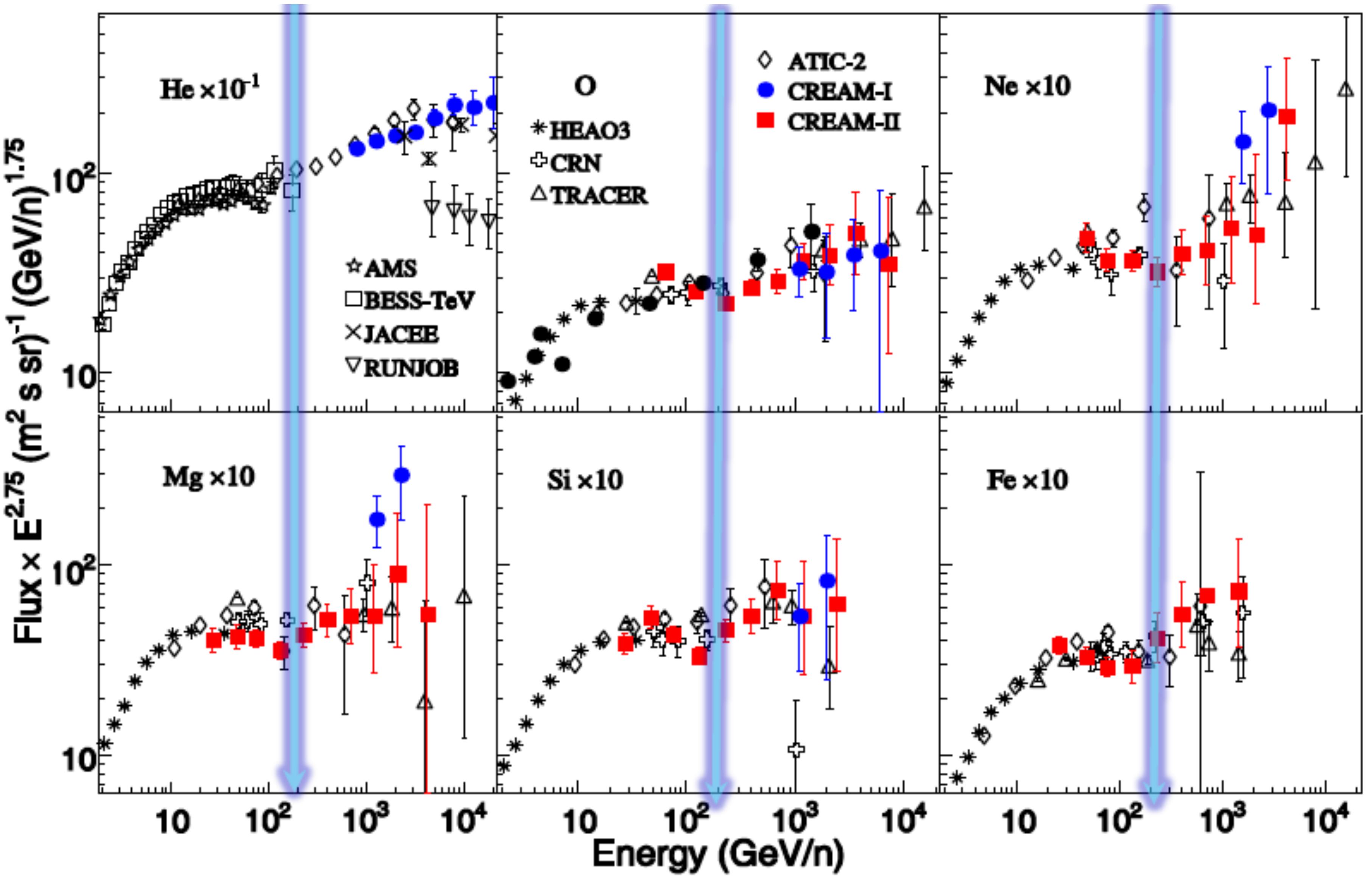
- 1 PC = 1 RC durante una partita di calcio = 3 $10^8$ $m^2 \cdot s \cdot sr$
- 1 GRAnno = 1 RC entro il Grande Raccordo Anulare all'anno= $3x10^2$ $km^2 \cdot y \cdot sr$



- ❑ 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

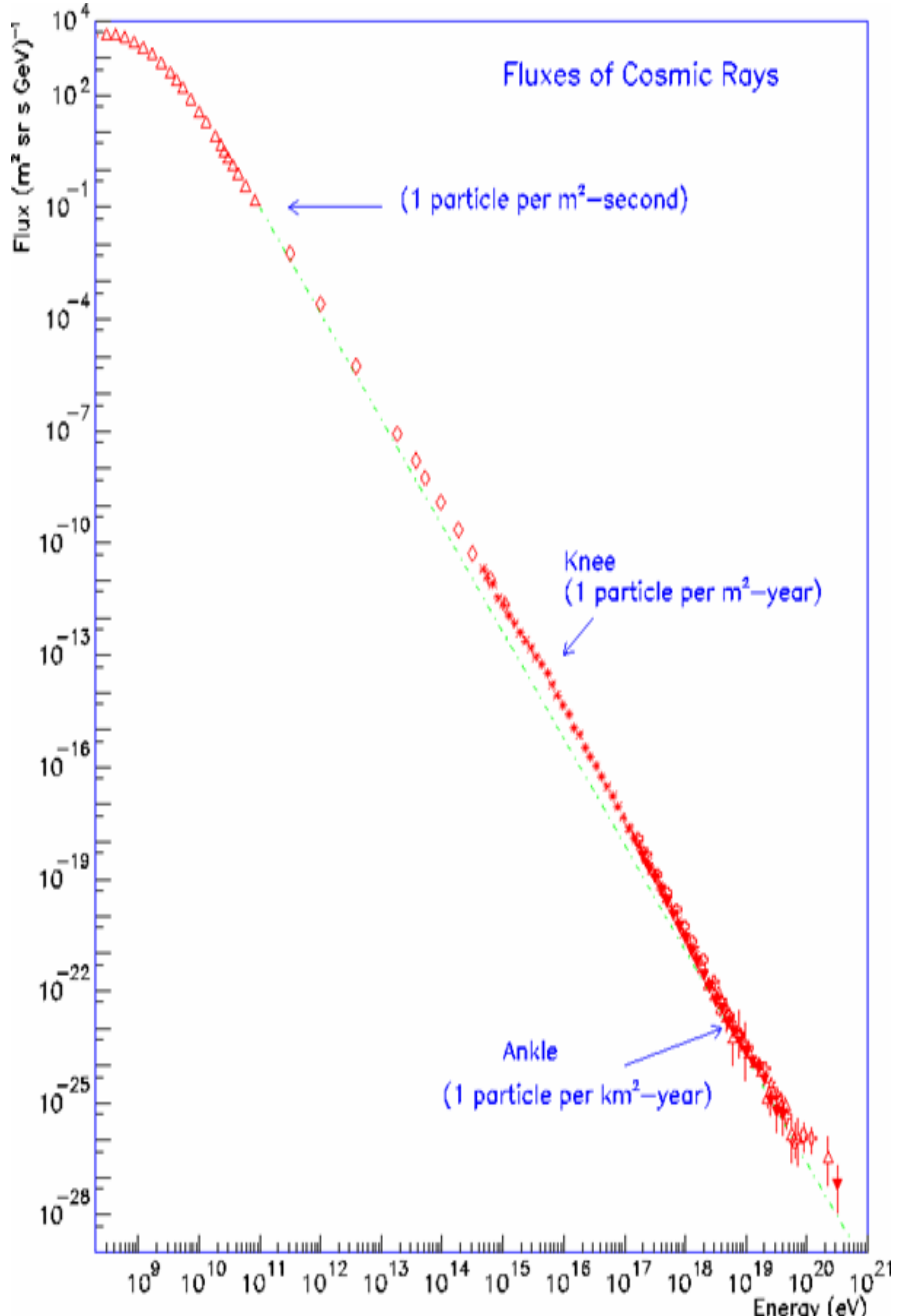


# Heavier elements: hardening



# Fig. 1

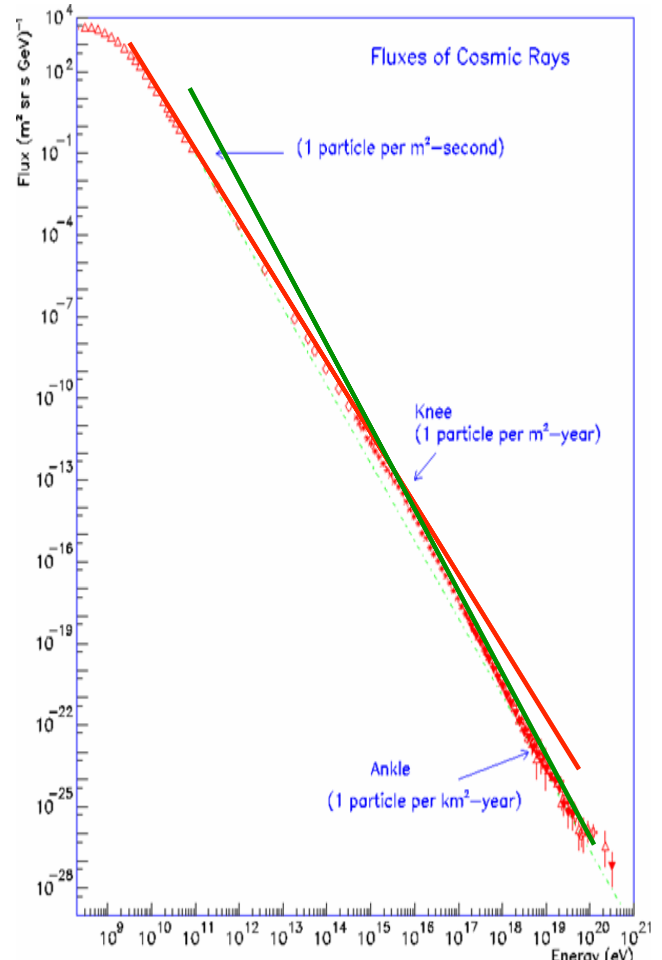
- $\Phi_{TOT}$~10000 $m^{-2}s^{-2}sr^{-1}$
- Misure dirette: 85% p, 12% He, ~1% nuclei pesanti, ~2% $e^{\pm}$ , antiprotoni
- Si estende per 13 ordini di grandezza in energia
- Per 32 ordini di grandezza in flusso
- Legge di potenza su tutto lo spettro, con almeno due cambi di pendenza



- 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 $\gamma$ 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.

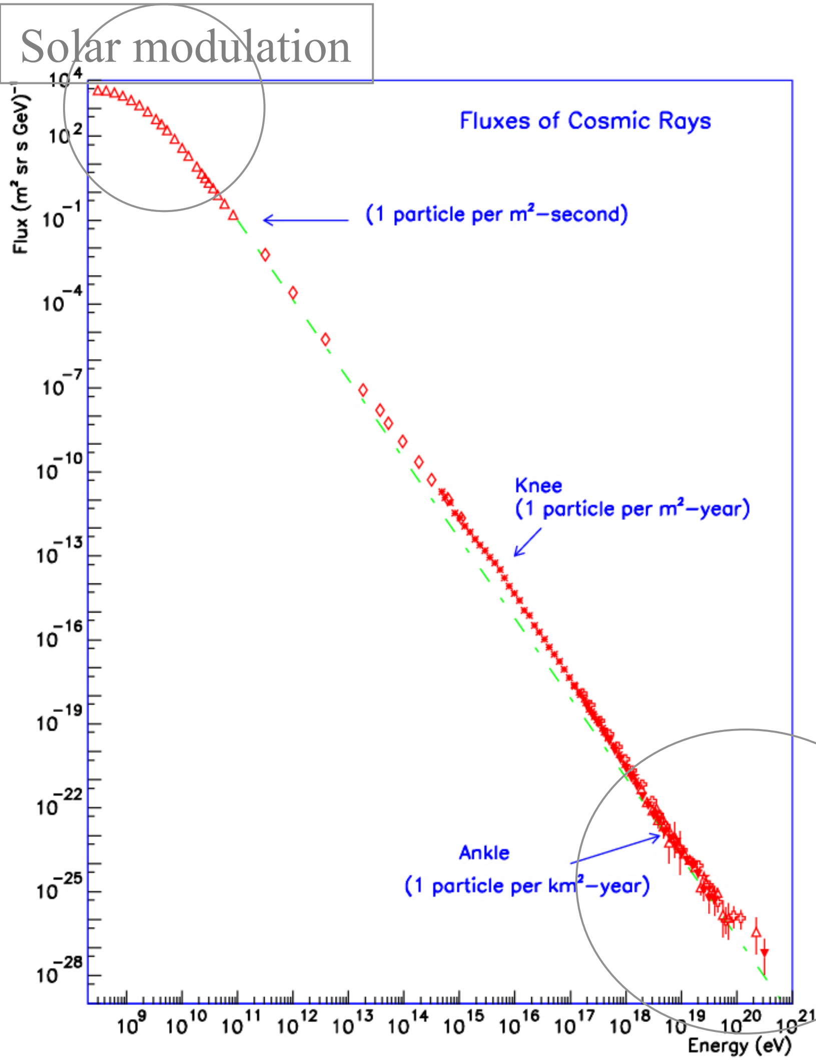


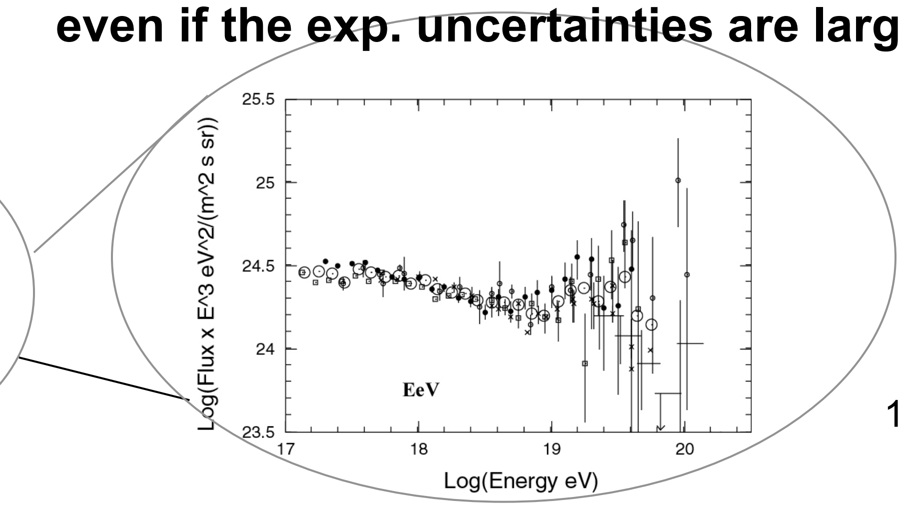
# Cosmic rays

**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 $\gamma$=2.74**

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

**And again at about $3x10^9$ 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):

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

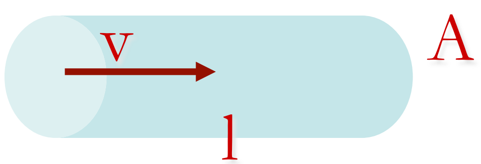
$$= 1 \quad (cm^{-2}\, s^{-1} sr^{-1})$$

- 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:

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

- 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:

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

**Esercizio: analisi dimensionale**

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

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

- **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)

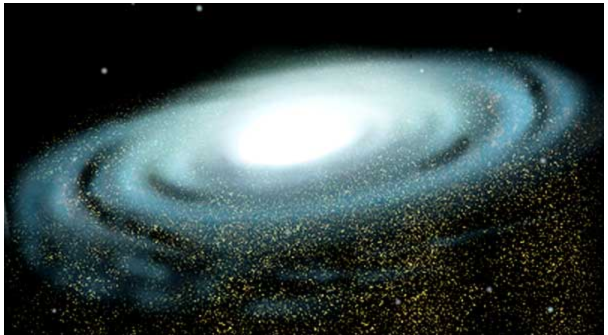
$$w_o = 10^{-2}\frac{eV}{cm^3}$$

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

# Isotropia dei RC

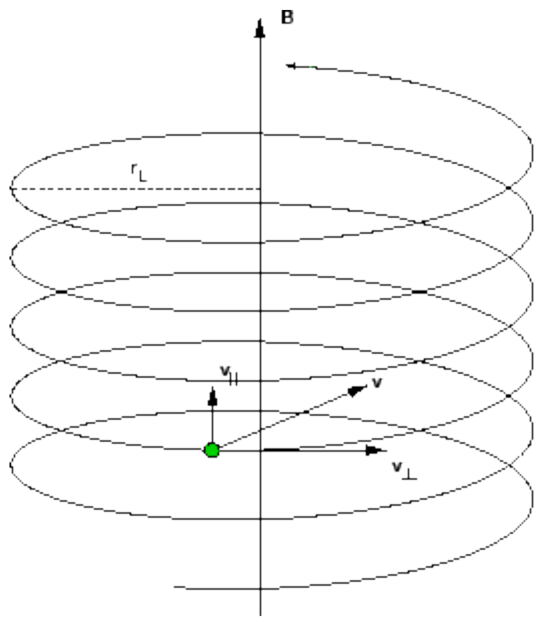
- I RC primari al di sotto di $10^{18}$ eV hanno una distribuzione di arrivo completamente isotropa sulla sommità della nostra atmosfera. **Qualè il motivo?**

- Campi magnetici **galattici**:
  - $B \cong 3\times10^{-6}$ G
  - coerenti su scale di distanza 1-10 pc
  - NOTA: 1 pc=$3\times10^{18}$ 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**.




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

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

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

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

- Utilizziamo i valori tipici del campo B ($3\times10^{-6}$ 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

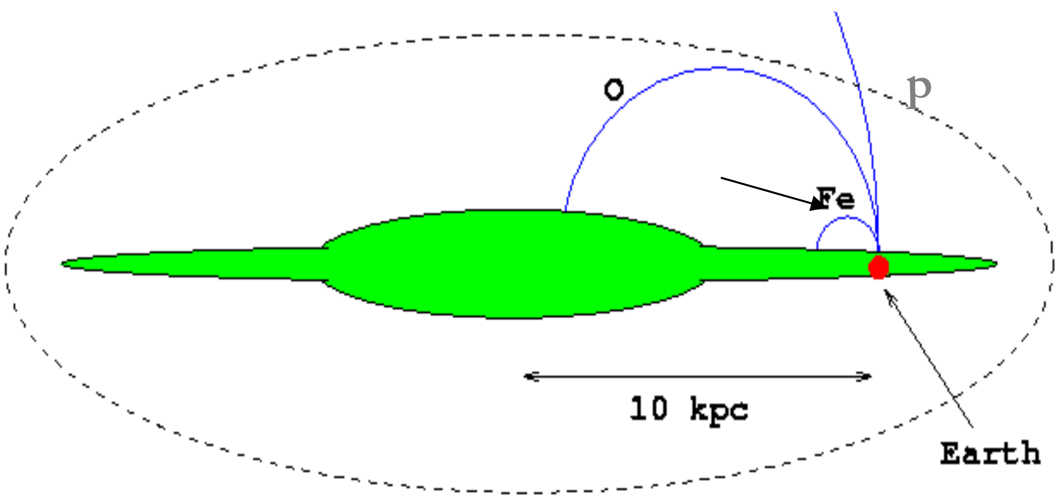
→ for a proton with $10^{14}$ eV, r ≈ $3 \times 10^{17}$ cm ≈ 0.1 pc, which is << of galactic disk (≈0.3 kpc) and galactic halo (≈10 kpc) and << of all the likely sources of CR near Earth, like Crab nebula ➔ low energy CR do not point sources (ie there are not potential sources within 1 pc), ergo they 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



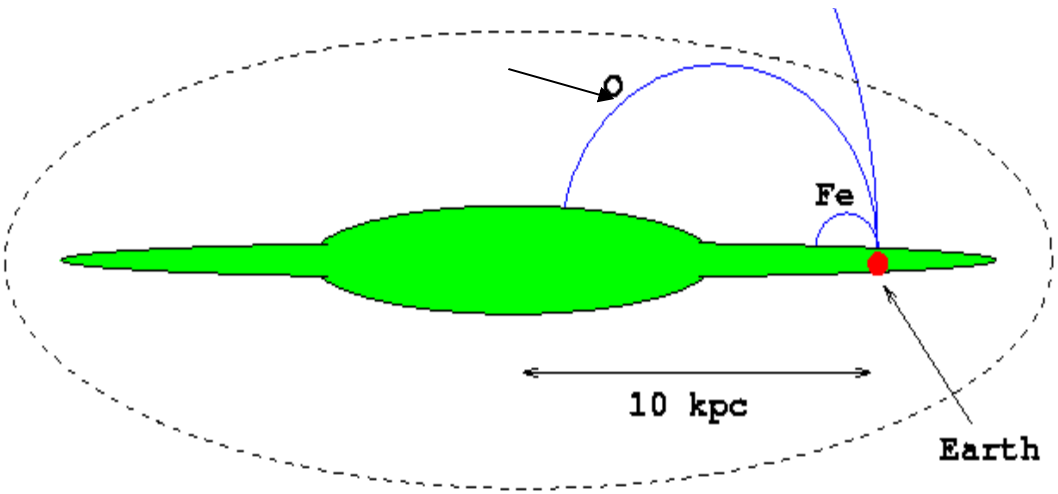
# Confinamento

→ for a proton with $10^{18}$ eV, r≈$3\times10^{21}$ 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

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

B≈$10^{-6}$ G or $10^{-10}$ T



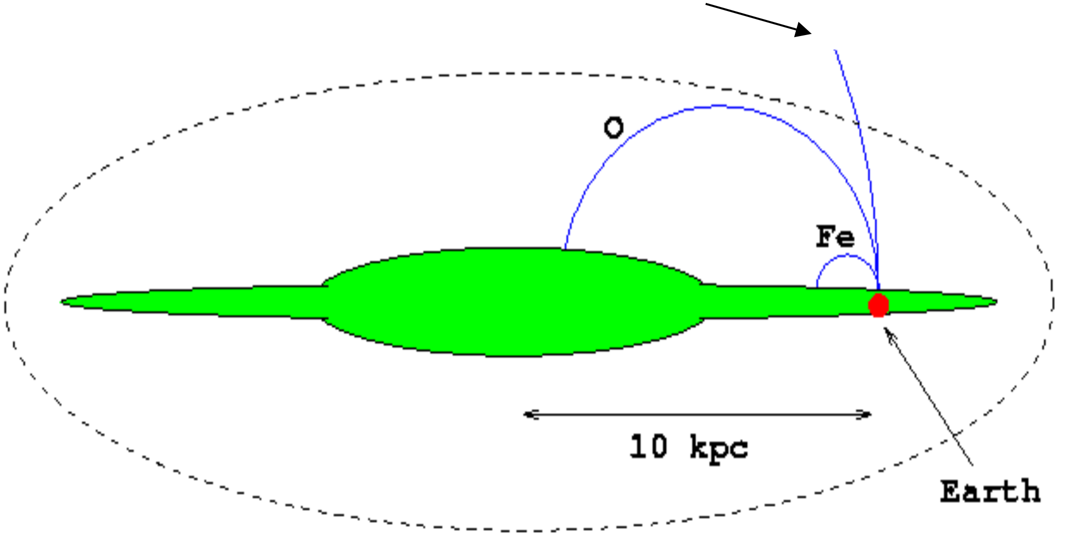
# Confinamento

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

B ≈ $10^{-6}$ G or $10^{-10}$ T

→ for a proton with $10^{20}$ eV, r ≈ $3 \times 10^{23}$ 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 $\delta$:

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

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 $\delta$ 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.

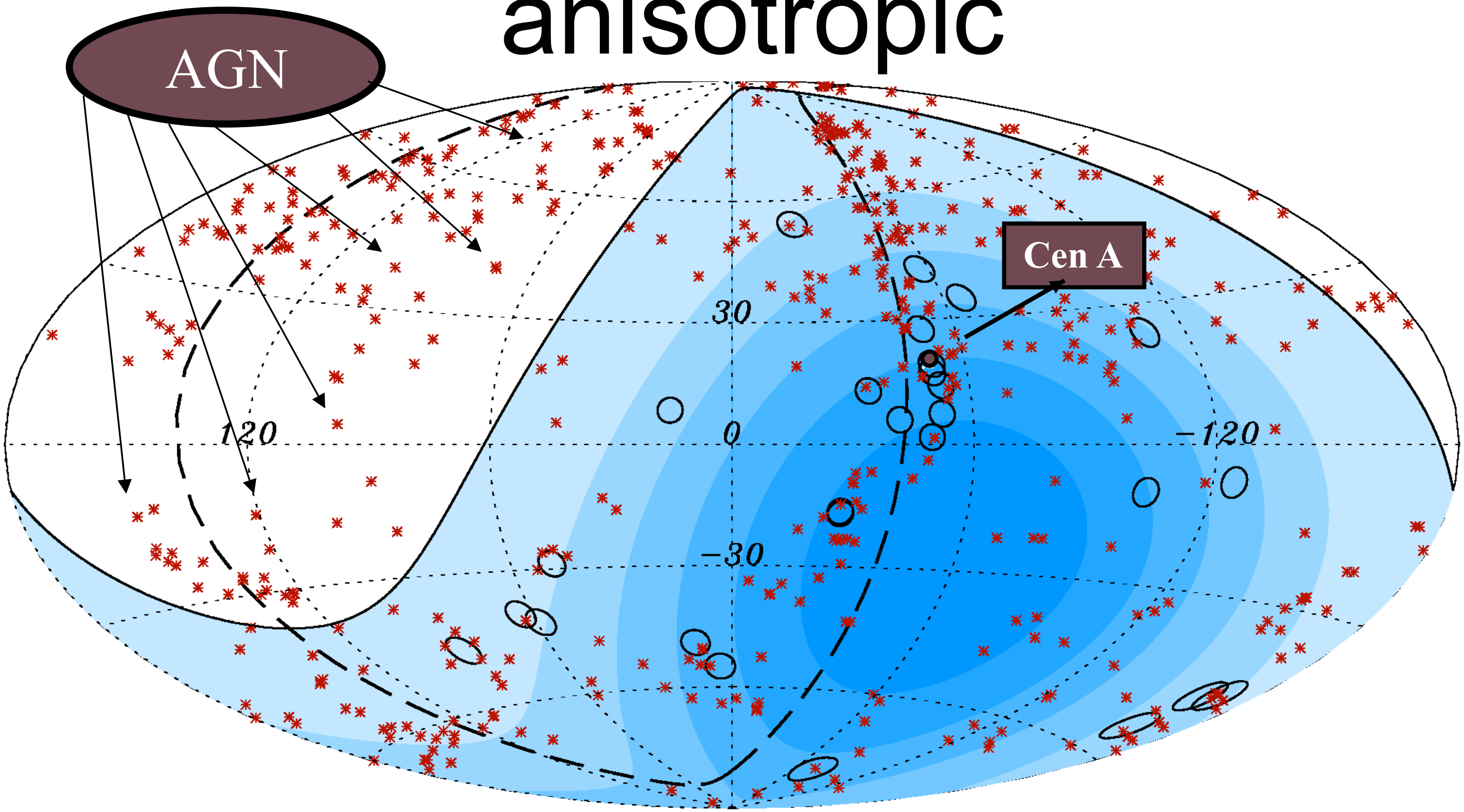
# Isotropy Table

| 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

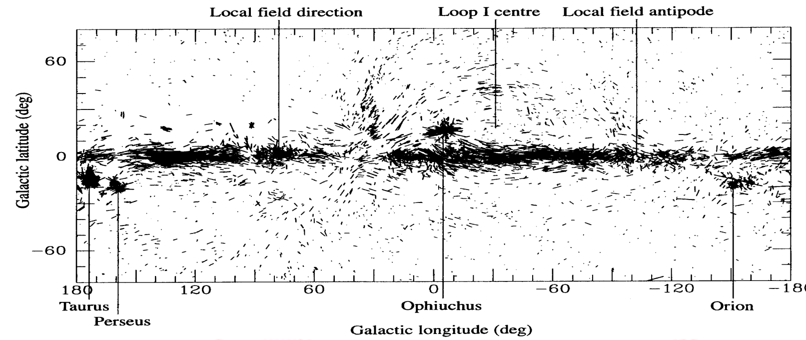
# II. The UHECR Sky is anisotropic

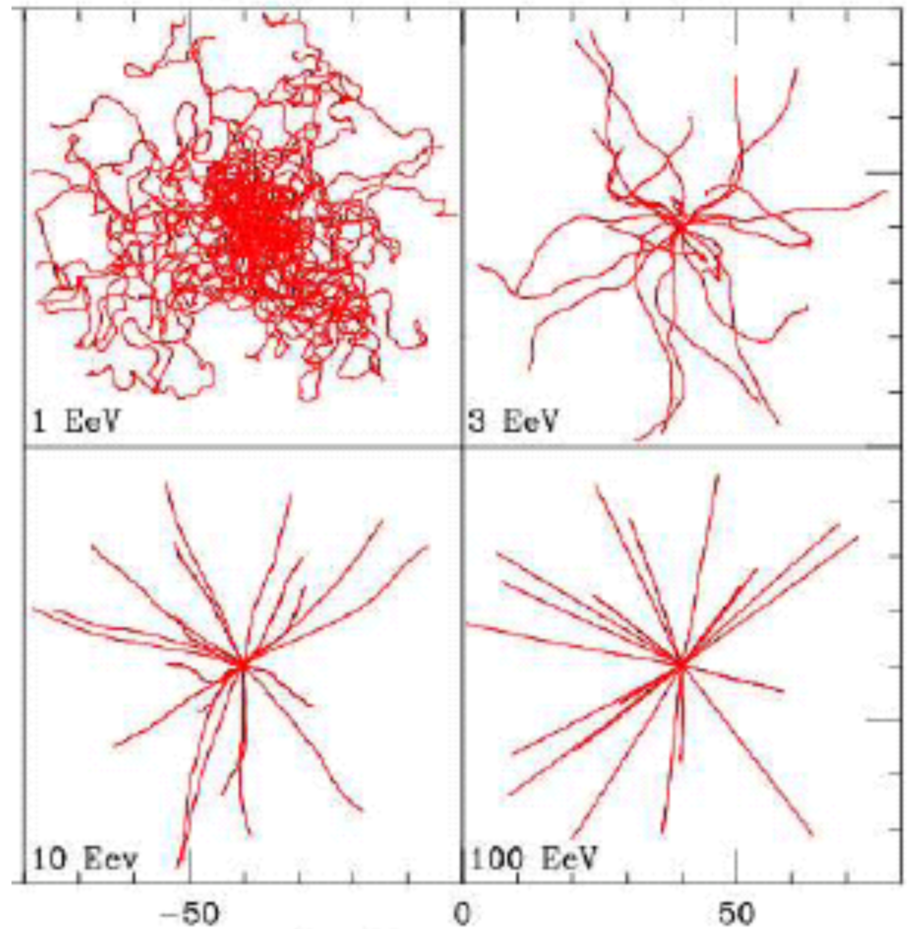



*Pierre Auger Collaboration 2007, Science, 318, 939*
*Pierre Auger Collaboration 2008, APh, 29, 188*

# 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

# Potenza delle sorgenti dei RC

- Il *confinamento* dei RC ci induce a sospettare che le sorgenti siano di origine Galattica (tranne che per i RC di energia estrema).
- Qual è *l'energetica* delle sorgenti? (necessaria per individuarle).
  - Il tempo di confinamento dei RC: $\tau = 3\times10^{7}$ y (calc. Fra poco)
  - Volume della galassia (con o senza alone) :

$$V_G = (15kpc)^2 \cdot \pi \cdot 300\,pc \cong 6\times10^{66}\,cm^3$$

$$V_G^{Alone} = 4/3 \cdot \pi (10kpc)^3 \cong 10^{68}\,cm^3$$

- Potenza necessaria per mantenere uno *stato stazionario* di RC:

$$W_{CR} = \frac{w_{CR}(erg/cm^3)\cdot V^{A}{}_{G}(cm^3)}{\tau(s)} = \frac{10^{68}\times1.6\cdot10^{-12}(erg)}{3\cdot10^{7}\times(3.15\cdot10^{7}s)} \cong 10^{41}\,\frac{erg}{s}$$

# Cosmic Rays from stars

- **Ordinary stars** *Too low!!!*
- Our Sun emits CR during flares but these have low energy particles (up to $10^{10}$-$10^{11}$ eV)
- the power is only $\sim 10^{17}$ J/s,
- Integrated on all stars in galaxy ($10^{11}$ stars in Galaxy) we get a total energy output of $\approx 10^{35}$ erg/s

# Esiste un meccanismo con una potenza tale da sostenere il flusso dei RC nella Galassia?

- Una esplosione di Supernova libera:
  - $10^{51}$ erg/esplosione
- La stima della frequenza di SN nella nostra Galassia è
  - $f_{SN} = 1/\tau_{SN} = 1/30\ y^{-1}$
- Si noti che $\tau_{SN} < \tau \cong 10^7 y$. Le SN sono un fenomeno quasi continuo su scala dei tempi del confinamento dei RC.
- Potenza energetica liberata dalle SN:

$$W_{SN} = \frac{10^{51} erg}{30 \times 3.15 \cdot 10^7 s} \cong 10^{42} erg / s$$

- Perché il quadro sia coerente, occorre trovare un meccanismo che trasferisca al più il 10% di energia dalle supernovae in energia cinetica di particelle (i RC)→ **Meccanismo di Fermi**

# Supernova Energetics

- Explosion powered by the collapse (death) of a massive core
- Energy source: Potential Energy from the collapse of the iron core down to a neutron star or black hole:

$$\text{Energy} = G\, M^2_{core}/r_{NS,BH} - G\, M^2_{core}/r_{before\ collapse}$$

$$> 10^{53} \text{ ergs}$$

$M_{core} \sim 1.4\text{-}3$ solar masses

$R_{NS,BH} \sim 10$ km

$R_{core} \sim 10{,}000$ km

Only 1% of energy goes in kinetic energy of the particles, the rest is in neutrinos

# Supernova energetics

## Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}c^2$

This shows up as

| | |
|---|---|
| 99% | Neutrinos |
| 1% | Kinetic energy of explosion (1% of this into cosmic rays) |
| 0.01% | Photons (outshine host galaxy) |

Neutrino luminosity

$L_\nu \approx 3\times10^{53}$ erg / 3 sec $\approx 3\times10^{19}\ L_{SUN}$

While it lasts, outshines the photon luminosity of the entire visible universe!

Georg Raffelt, Max-Planck-Institut für Physik (München)

- Il meccanismo di Fermi e' strettamente collegato alle onde di shock ➔ e' necessario sviluppare almeno qualche cenno di idrodinamica e magnetoidrodinamica
- per ora tralascieremo l'argomento per affrontare la propagazione dei raggi cosmici

# Novae

Novae are also promising candidates for CR sources. Novae are powered by the accretion onto a white dwarf: the matter is sucked from a companion star, perhaps a giant star or a main sequence star, under conditions that allow periodic runaway thermonuclear reactions on the white dwarf surface.

Novae outbursts occur with a frequency ≈100/year with an energy output of $\approx 10^{47}$ erg ($10^{-4}$ of SN), thus the integrated novae output is similar to that of galactic SN

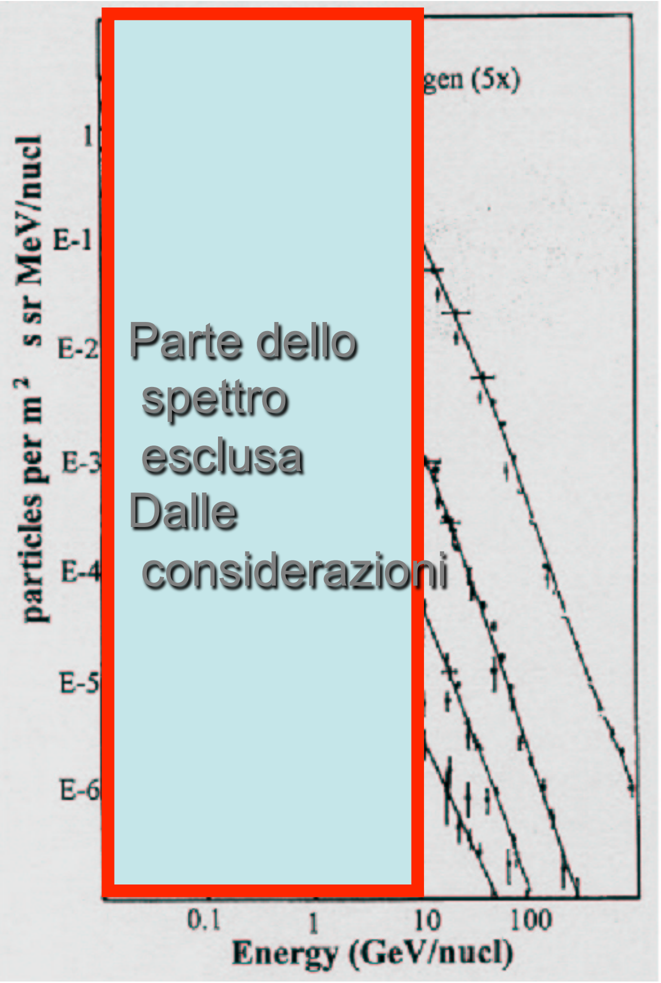
# Modulazione dei RC di bassa energia dovuta al ciclo del Sole

Le variazioni del ciclo solare hanno effetti per energie < 1 GeV

RC con E > 10 GeV non affetti dal ciclo solare

Flusso di RC di bassa energia (>1 GeV): ~ 1000 p/($m^2$s sr).

Pensateci prima di offrirvi volontari per una missione su Marte.



# Raggi cosmici

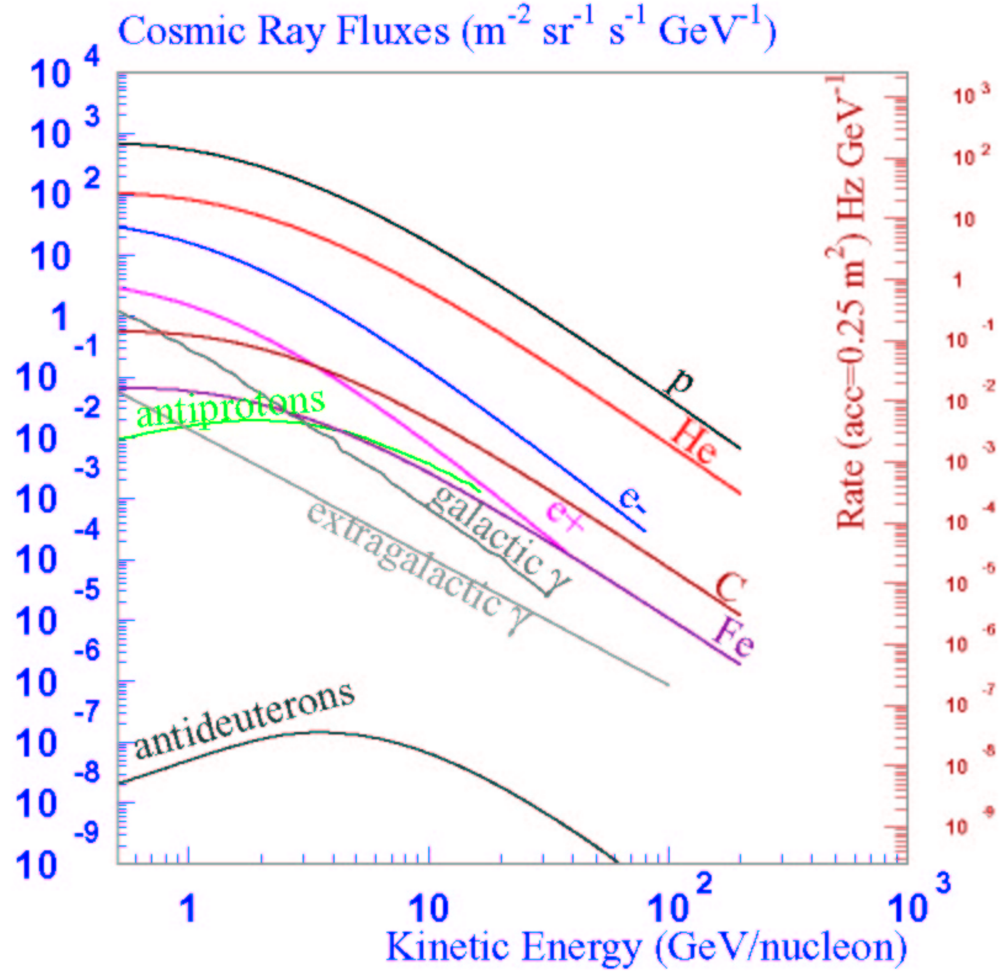
**CR Composition** c

85% protons → $\bar{p}/p \sim O(10^{-4})$

12% He → $\overline{He}/He \sim 10^{-6}$

2% e → $e^+/e^- \sim 10^{-1}$

1% Nuclei $e^+/p \sim O(10^{-4})$




<u>Rare components provide a plenty of info</u>

Electrons represents $O(10^{-2})$ of the charged CR flux but can reveal aspects of the source distribution and galactic propagation not observable in the nuclear CR component.

# Formation and Interactions of CR's

Energy Supply: gravitational, nuclear, ELM,...

Provide energy for particles

Shock & Hydromagnetic waves, ELM Fields, Turbulent B fields,...

Store and transport energy

Processes transfer a fraction of E to particles at the sources : injection and acceleration

Particles escape into ISM from the acceleration sites

Relativistic particles = Cosmic rays

Particles interact with

Matter "interstellar, intergalactic medium"

B Fields

Photons

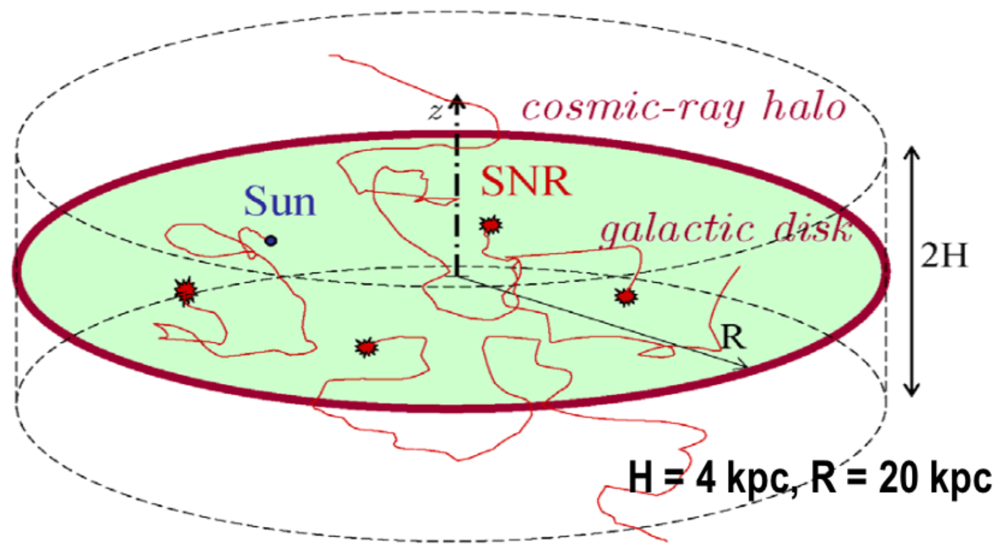
Ionization
Nuclear interactions
Bremsstrahlung

Synchrotron & curvature radiation

Inverse Compton & Thomson Scattering
Self-Absorbtion

# Formation and Interactions of CR's

- Particles get accelerated at astrophysical sources
- They leave sources and propagate in the ISM
- They interact with the ISM particles and/or decay producing new particles
- They loose energy in the ISM by elm processes (brems, IC, sync)
- They are bent randomly by ISM magnetic field
- Until they reach the galaxy border and escape the galaxy
- Therefore: Their spectum and composition at the Earth location are not representative



# Densità media del mezzo Interstellare

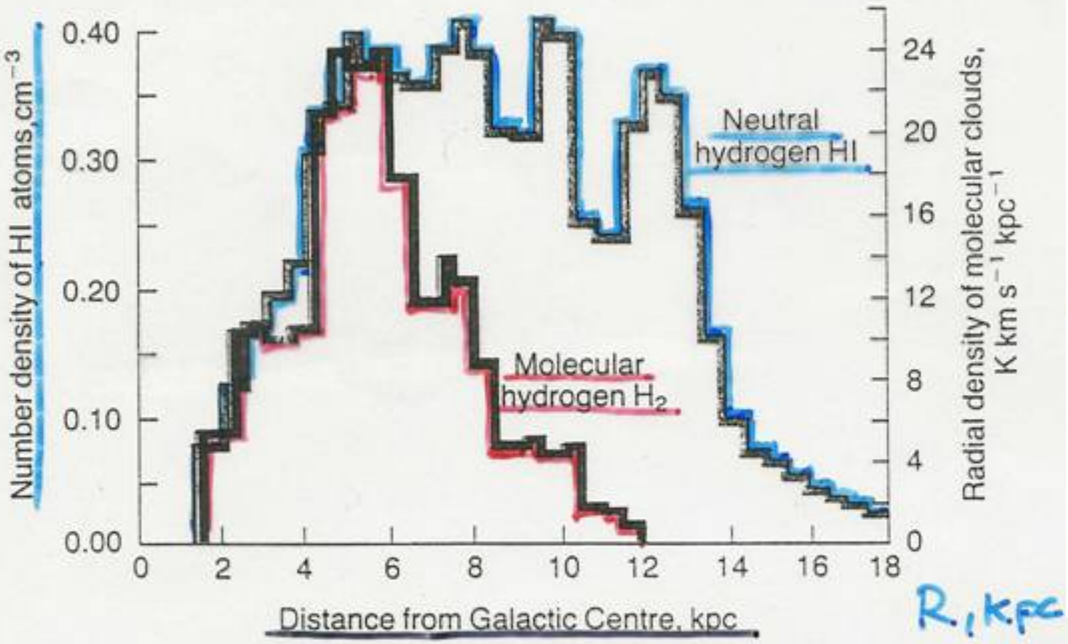



Figure 17.2. The radial distribution of atomic and molecular hydrogen as deduced from radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and from millimetre surveys of the molecular emission lines of carbon monoxide, CO. (After D. Michalis and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp. 535. 554. San Francisco: W.H. Freeman and Co.)

$\rho_{IG} = 1$ p/cm$^3$=
=1.67x10$^{-24}$ g/cm$^3$

IL MEZZO INTERSTELLARE

| NOME | COSTITUENTI | Rivelati da... | % VOLUME | e MASSA del Mezzo Int. | N cm$^{-3}$ | T (K) |
|---|---|---|---|---|---|---|
| MOLECOLARI NUBI | $H_2$, CO CS etc | Linee molecolari Emiss. Polveri | ~0.5% | 40% | 1000 | 10 |
| NUBI DI H NUBI DIFFUSE | H, C, O neutri | linea di 21 cm Linee Assorbim. | 5% | 40% | 1-100 | 80 |
| INTER NEBULE | H, $H^+$, $e^-$ (ionizz. 10%) | 21 cm + assorbim. Linee H | 40% | 20% | 0.1-1 | ~$10^4$ |
| CORONE stellari | $H^+$, $e^-$... $O^{5+}$ | soft X (0.1-2 keV) | ~50% | 0.1% | 1000 | $10^6$ |

# Il campo magnetico galattico

- Si misura tramite la polarizzazione della luce delle stelle
- Intensità media: (3 ±3) μGauss
- Coerenti su scale di 1-10 pc

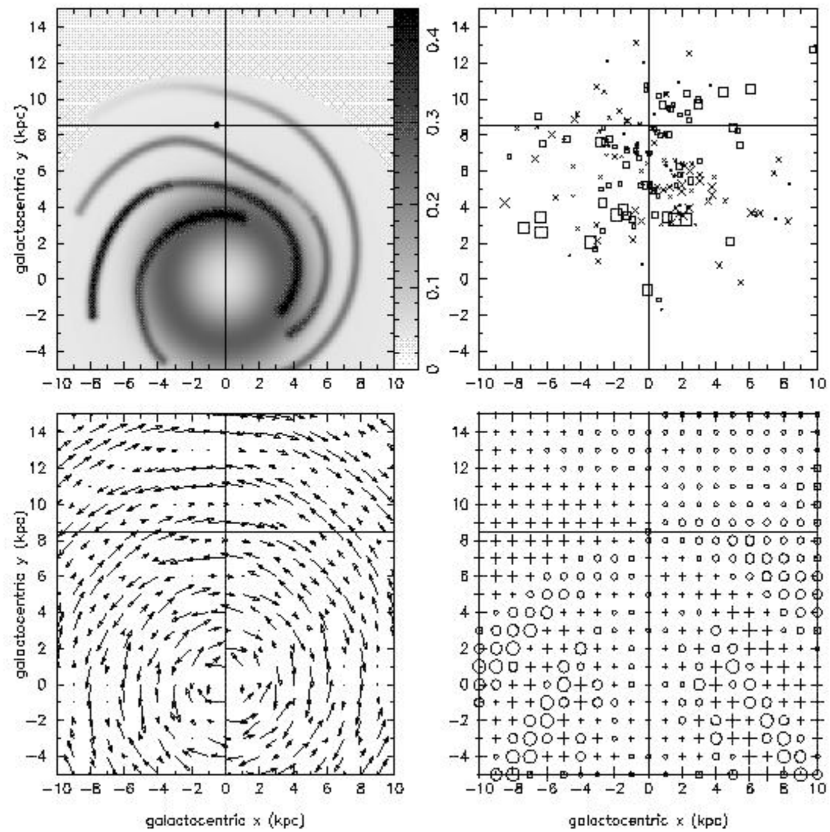
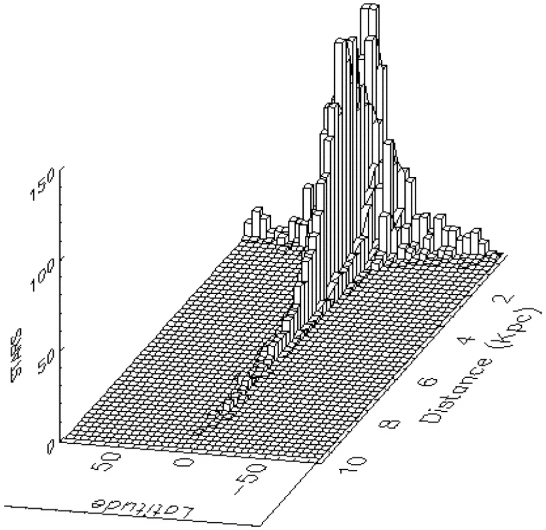
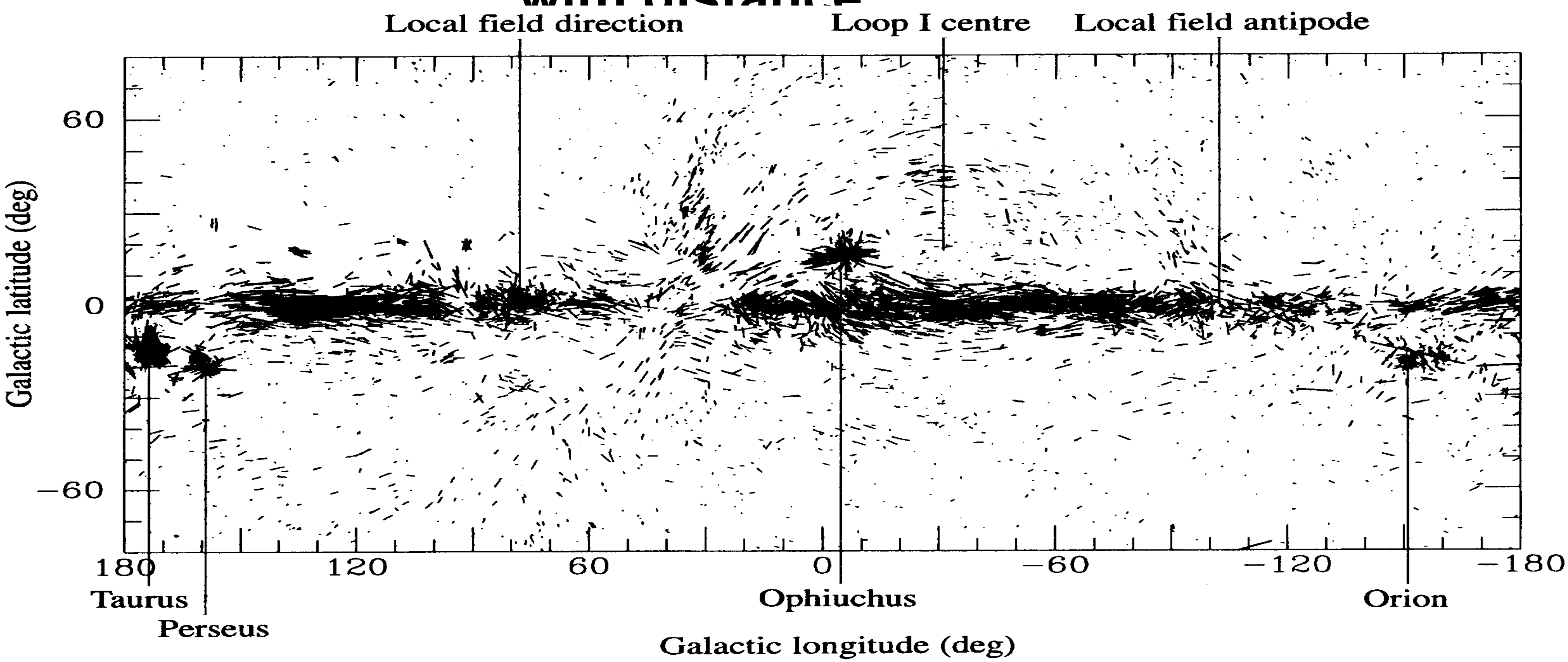



Figure 4. The large scale pattern of the magnetic field, using $p$ = -4.5° and $R_o$ = 9.3 kpc. The panels arrangement is the same as in figures 1 and 2.




# Polarizzazione della luce delle stelle: *local field // arm*

- **9000 stars have polarization measured**
- **mostly nearby (1~2kpc)**
- **polarization percentage increases with distance**

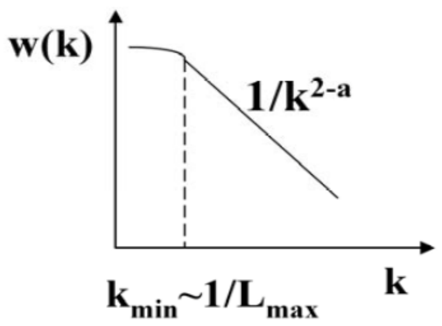


# Il campo magnetico galattico

- The galactic magnetic field can is usually decomposed in two components:
  - Regular, large scale field
  - Turbulent, random irregularities
- Particles drift in the large scale field and scatter (collisionless) on the field irregularities

spectrum of turbulence $B^2_{res} = \int_{k_{res}} w(k)dk$

$w(k)dk \sim k^{-2+a}dk$, $D_{ll} \sim vr_g{}^a$



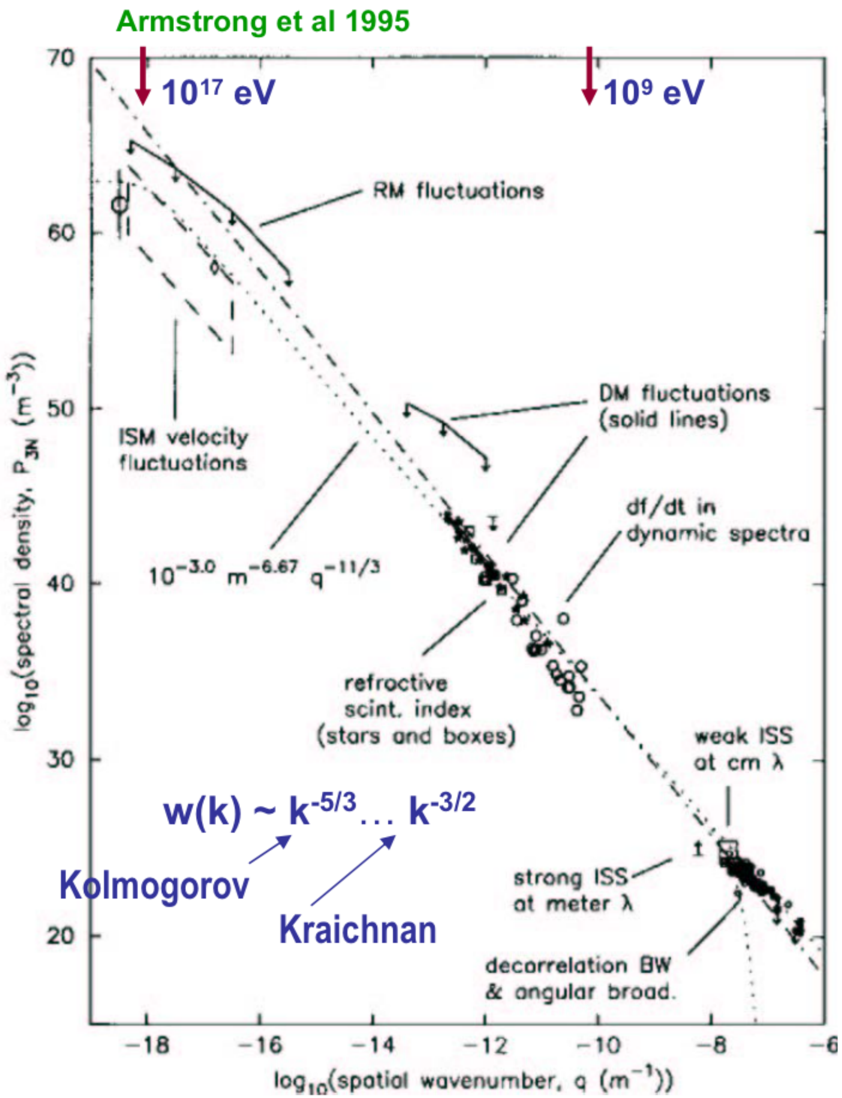

$a = 1/3$ Kolmogorov spectrum

$a = 1/2$ Kraichnan spectrum

$a = 0$ random discontinuities

$a = 1$ white noise (leads to Bohm diffusion scaling $D_B = vr_g/3$)

# interstellar turbulence

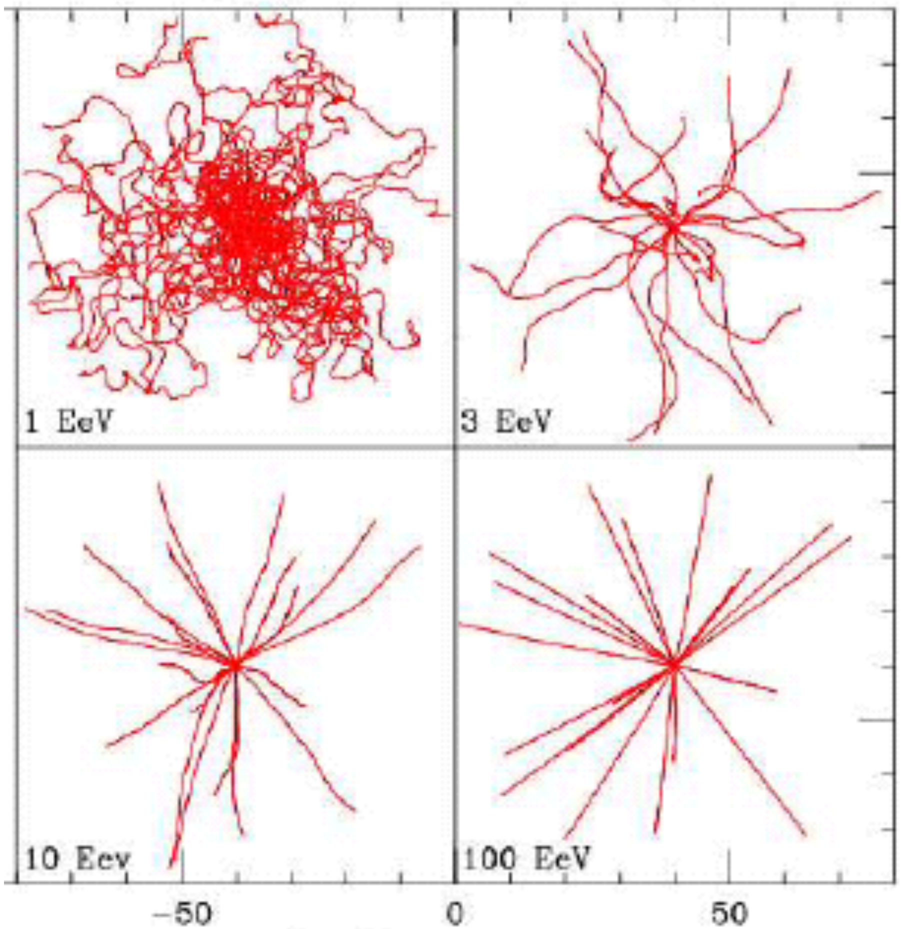


# Isotropy

- So far, experimental results indicate only small amounts of anisotropy at low energies, with $\delta$ 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

- This suggests that CR propagation may be described as a diffusion process in the ISM of galactic volume from injection sources, that is the CR trajectories are random walks on scattering centers (as we will see, CR scattering is collisionless) in the Milky Way, at least up to EeV until they reach the “border” where there is some probability to escape the galactic diffusion “volume” and ride into deep intergalactic space

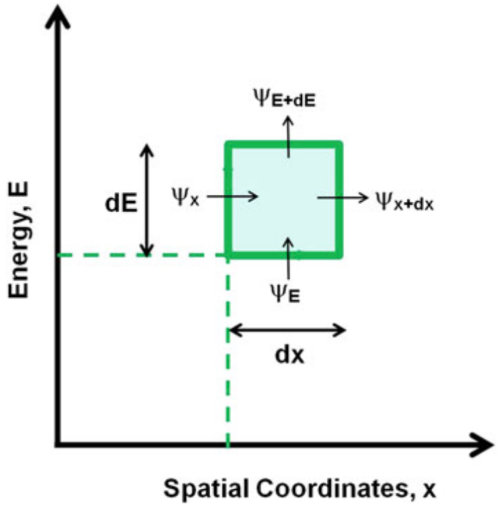


1 EeV
3 EeV
10 Eev
100 EeV
−50
0
50

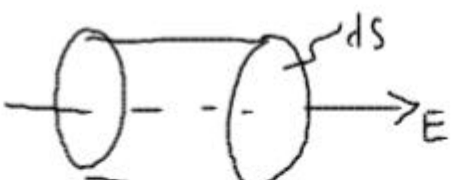
# Propagation equation

- CRs undergo a diffusion process through the interstellar medium from their sources until they exit the Galaxy. Occasionally, some CRs can be intercepted by detectors near the Earth.
- This propagation modifies also the CRs energy spectrum from the sources to the observer. As the solar system has nothing of peculiar with respect to any other point of our Galaxy, our observations are not influenced by the particular region where they are done. Particles having energies smaller than a few GeV, which are affected by the solar modulations, should not be considered.
- The galactic magnetic fields are the main factors which affect the CRs motion, as the Larmor radius for particles below the knee ($E < 10^{15}$ eV) is << than the typical spatial dimension over which the magnetic fields are coherent. A random component in the motion is induced by the presence of irregularities, associated either with fluctuations in the fields or with the induction of instabilities due to the streaming motions of the charged particles themselves.
- During their diffusion, CRs are subject to energy-loss mechanisms and absorption.
- We give a “derivation” of the diffusion-loss equation which closely follows

# Equazione di diffusione




- Spazio delle fasi (E, x): in x diffonde, lungo E si "sposta" per guadagni e perdite
- Nel volume $dE\,dx^3$ ci sono $dn = N(E,x)\,dE\,dx$ particelle; possono entrare e uscire dal volume a causa dei flussi $\phi_x$ e $\phi_E$
- $\frac{dN}{dt}\,dE\,dx$ ds $= [\phi_x(E,x,t) - \phi_{x+dx}(E,x+dx,t)]\,dE$ ds $+ [\phi_E(E,x,t) - \phi_{E+dE}(E+dE,x,t)]\,dx$ [redacted]
  $+ Q(E,x,t)\,dE\,dx$ [redacted]
- $$\frac{dN}{dt} = -\frac{\partial \phi_x}{\partial x} - \frac{\partial \phi_E}{\partial E} + Q$$
- Se $b(E) = -dE/dt \Rightarrow \phi_E = +N\frac{dE}{dt} = -b(E)N(E)$



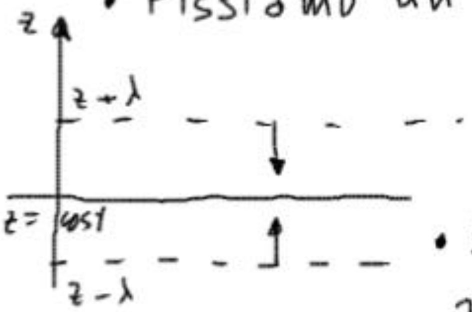

Flusso attraverso dS, lungo E.
tutte le part. nel volume $dS \cdot v_E\,dt$
attraversano dS $\Rightarrow \phi_E = \frac{N v_E\,dS\,dt}{dS\,dt}$

$v_E = \frac{dE}{dt}$ ("veloc. con cui la singola part si sposta, i.e. perde o guadagna E)

# Parentesi: moto diffusivo

- Il moto di diffusione si ha in presenza di gradienti di densità
  - Vale la legge di Fick: $\vec{J} = -D\vec{\nabla}n$
    Il parametro D e' il coeff. di diffusione: dipende dal mezzo in cui avviene la propagazione $[L^2 T^{-1}]$

Es. diffusione in un gas diluito




- Fissiamo un piano arbitrario nel gas il flusso netto e' dato dalla somma dei flussi da sopra e da sotto il piano, $J_+$ e $J_-$

  $J_{net} = J_+ + J_-$

- Se $\ell$ e' il libero cammino medio, le particelle che attraversano il piano hanno subito l'ultimo urto in media a una dist. $\pm\ell$ dal piano, cioe a $z' = z \pm \ell$

- Moto random ⇒ il # di part in moto con vel. media $\langle v \rangle$ in una direzione e' lo stesso in tutte direzioni (isotropia) ⇒ $n_x = n_y = n_z = n/3$ si muovono con vel $\langle v \rangle$ lungo le 3 direzioni ⊥ del rif. scelto
- Di queste 1/2 si muovono verso +z e 1/2 lungo −z ⇒

$$J_\pm \approx J(z \pm \ell) = \pm \frac{\langle v \rangle n(z \pm \ell)}{6} \approx \pm \frac{\langle v \rangle}{6}\left[n(z) \pm \frac{\partial n}{\partial z} \cdot \ell\right]$$

• Quind. $J_{nel} = \frac{\langle v \rangle}{6}\left[-\frac{\partial n}{\partial z}\cdot \ell\right] - \frac{\langle v \rangle}{6}\left[\frac{\partial n}{\partial z}\cdot \ell\right] = -\frac{\ell \langle v \rangle}{3}\left(\frac{\partial n}{\partial z}\right)$

$\Rightarrow D = \frac{\ell \langle v \rangle}{3}$

• Se le part. diffondono in un mezzo di densità $N \Rightarrow \ell \sim \frac{1}{N\sigma_t}$

$\sigma_t$ = sez. d'urto di collisione fra le part. che diffondono e quelle del mezzo

$\Rightarrow D = \frac{\langle v \rangle}{3N\sigma_t}$

× $\langle v \rangle \ll c \Rightarrow v \sim \left(\frac{kT}{m}\right)^{1/2}$
$p = NkT \Rightarrow \frac{1}{N} = \frac{kT}{p}$
$\Rightarrow D \propto \frac{(kT)^{3/2}}{3\sigma_t p}$

× $\langle v \rangle \approx c \Rightarrow D \approx \frac{c}{3N\sigma_t} \Rightarrow D \propto \frac{c(kT)}{3\sigma_t p}$

∗ Se il moto avviene in un campo magnetico, la dist. alla quale la part. ha cambiato "molto" la direzione è il raggio di Larmor $\Rightarrow$

$\ell \sim r_L = \frac{cp}{eZB} \approx \frac{E}{ZeB}$ (se $v \approx c$) $\Rightarrow D \approx \frac{\lambda_L}{3} = \frac{cE}{3ZeB} \Rightarrow D \propto E$

In tal caso il coefficiente di diffusione dipende da E

# Equazione di diffusione

o Quindi $$\frac{\mathrm{d}\mathcal{N}_i}{\mathrm{d}t} = D\nabla^2\mathcal{N}_i + \frac{\partial}{\partial E}[b(E)\mathcal{N}_i(E)] + Q$$

Additional terms can be added to this equation to include other physical effects, as the *escape probability*, the *radioactive decay*, and the *spallation* of nuclei during the propagation of cosmic ray nuclei from sources to

$$\frac{\mathrm{d}\mathcal{N}_i}{\mathrm{d}t} = D\nabla^2\mathcal{N}_i + \frac{\partial}{\partial E}[b(E)\mathcal{N}_i(E)] + Q - \frac{\mathcal{N}_i}{\tau_i} + \sum_{j>i} \frac{P_{ji}}{\tau_j}\mathcal{N}_j.$$

$\tau_i$ and $\tau_j$ are the lifetimes of particles of species *i* and *j*. For the spallation process, they correspond to $\tau_i = \lambda i/c$ and $\tau j = \lambda j/c$, where $\lambda i,j$ are their interaction lengths.

*Pji* is the probability that, in an inelastic collision involving the destruction of the nucleus *j*, the nucleus *i* is produced. T e τdecay of instable elements can also account for by ing that:

$$\frac{1}{\tau_i} = \frac{1}{\tau_{\mathrm{decay}}} + \frac{c}{\lambda_i}$$

The equation is time dependent. Normally, one is interested in the steady-state solution, corresponding to d*Ni*/d*t* = 0. Electrons, positrons, and antiproton propagation can be described as well by the diffusion equation. They constitute special cases, differing principally due to the energy losses and production rates of these particles

# What D means?

- Random walk: after N steps of the same length $l_0$, a particle starting from the O of a ref. Frame is at position $\mathbf{d}=\sum_N \mathbf{l}_i$
- $<d> = 0$
- $<d^2> = d \bullet d = \sum_i \sum_j l_i \bullet l_j = N l_0^2 + 2 l_0 \sum_{i \neq j} \cos\theta_{ij} = N l_0^2$
- The solution of diffusion eqn $\frac{dN}{dt} - D\nabla N = Q$

(without E loss or any other process) is found to be

$$N(r) = \frac{N_o}{(4\pi D t)^{3/2}} e^{-\frac{r^2}{4Dt}}$$

For $Q(t) = N_o \delta(t)$, an istantaneous injection at $t = 0$ in the origin

# What D means?

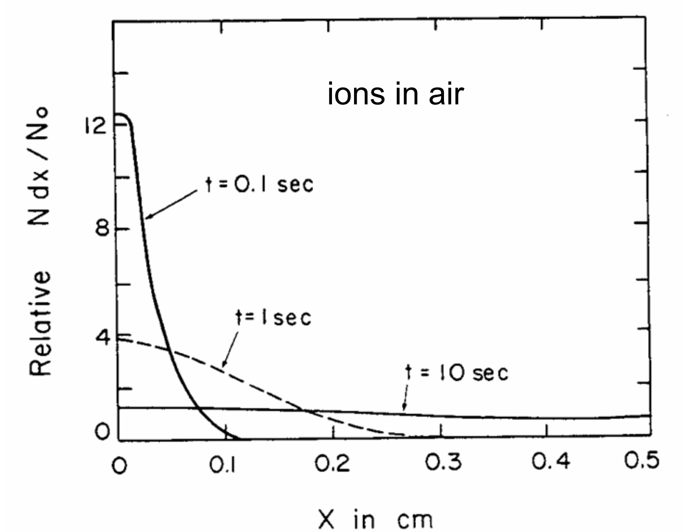
$$\frac{\partial n}{\partial t} + \nabla \cdot \left( -D \vec{\nabla} n + \vec{v} n \right) = R.$$

No convezione (per ora)

Se iniettiamo N particelle nell'origine con una distribuzione spaziale N = $N_0\delta(x)$ a t = 0, l'evoluzione temporale e' data da

$$N(x,t) = \frac{N_0}{2\sqrt{4\pi Dt}} e^{-\frac{x^2}{4Dt}}$$

(calcoletto alla lavagna?)




Il bunch di particelle rimane in media fermo nell'origine, ma si allarga nel tempo con una distribuzione gaussiana di larghezza crescente

$$\sigma_x = \sqrt{2Dt}$$

Una frazione della carica $N/N_0$, inizialmente tutta in x = 0, la si ritrova ad una distanza x dopo un tempo t

# What D means?

- After a time t, the particles is at a average quadratic distance form origin $d \sim (Dt)^{1/2}$
- Therefore $Nl_o^2 = Dt \rightarrow D = Nl_o^2/t$
- $Nl_o$ = total distance $\rightarrow Nl_o/t = v$
- So that $D \sim vl_o$

# What D means?

- An order of magnitude estimate for D can be determined from the residence times of CR in the galaxy
- If L is the characteristic scale of the system $D\nabla N \approx \frac{DN}{L^2}$
- If $\tau$ is the average residence time of CR in the galaxy $\frac{dN}{dt} \approx \frac{N}{\tau}$
- Therefore, by order of magnitude $\frac{N}{\tau} \approx \frac{DN}{L^2}$

$$D \approx \frac{L^2}{\tau}$$

- The scale L for the galaxy is the disk thickness. Assuming L = 300 pc = $9 \times 10^{20}$ cm and a typical residence time of $10^7$ years = $3 \times 10^{14}$ s, D ~ $3 \times 10^{27}$ $cm^2 s^{-1}$

# What D means?

- From $D = v l_o/3$, an estimate of the “step length” for a charged particle in the galaxy can be given
- $l_o = 3D/c \sim 3 \times 10^{17}$ cm = 0.1 pc
- More refined models give D up to $3 \times 10^{28}$ cm$^2$ s$^{-1}$
- → $l_o \sim 1$ pc
- Also the halo thickness is uncertain. Estimates range up to 1000 pc (which, for example, results in a factor 10 for D)

# What D means?

- → $l_o \sim 0.1 - 1$ pc
- Average particle density is too low for an efficient scattering by collisions
- This quantity can be interpreted as the typical scale of magnetic fields inhomogeneities of the magnetic field in the ISM
- On microscopic level, the diffusion of CR results from particle scatterings on magnetohydrodynamics waves and discontinuities (eg shock waves).