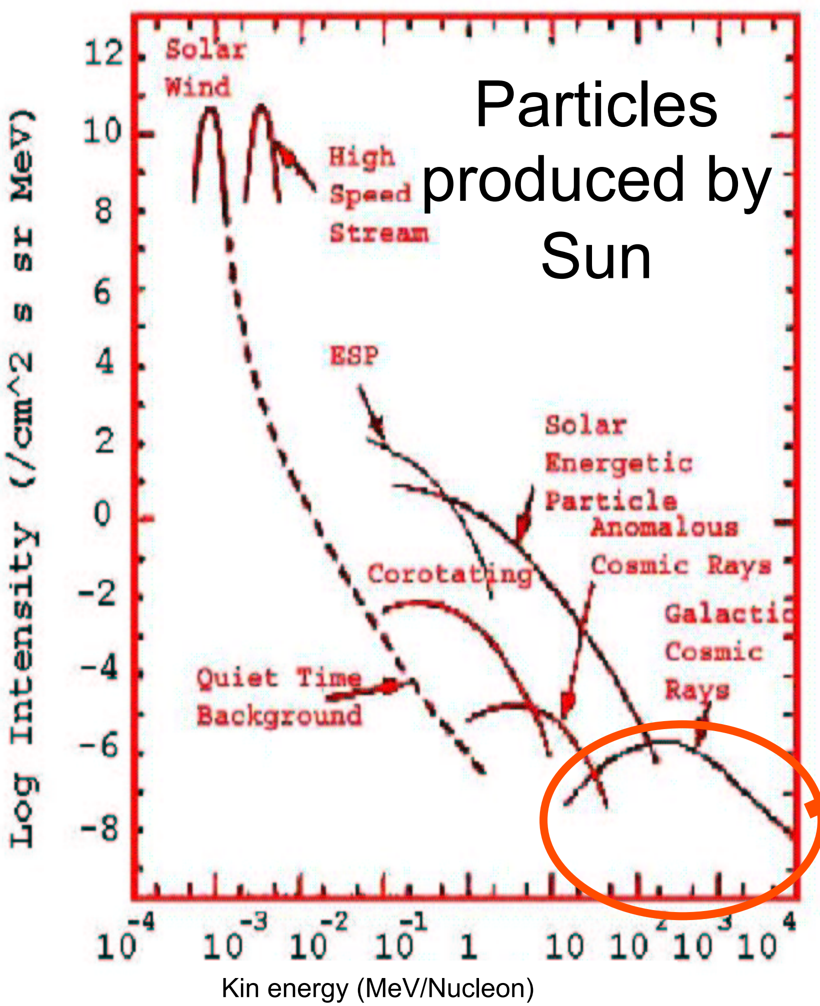
Lecture 2 161017

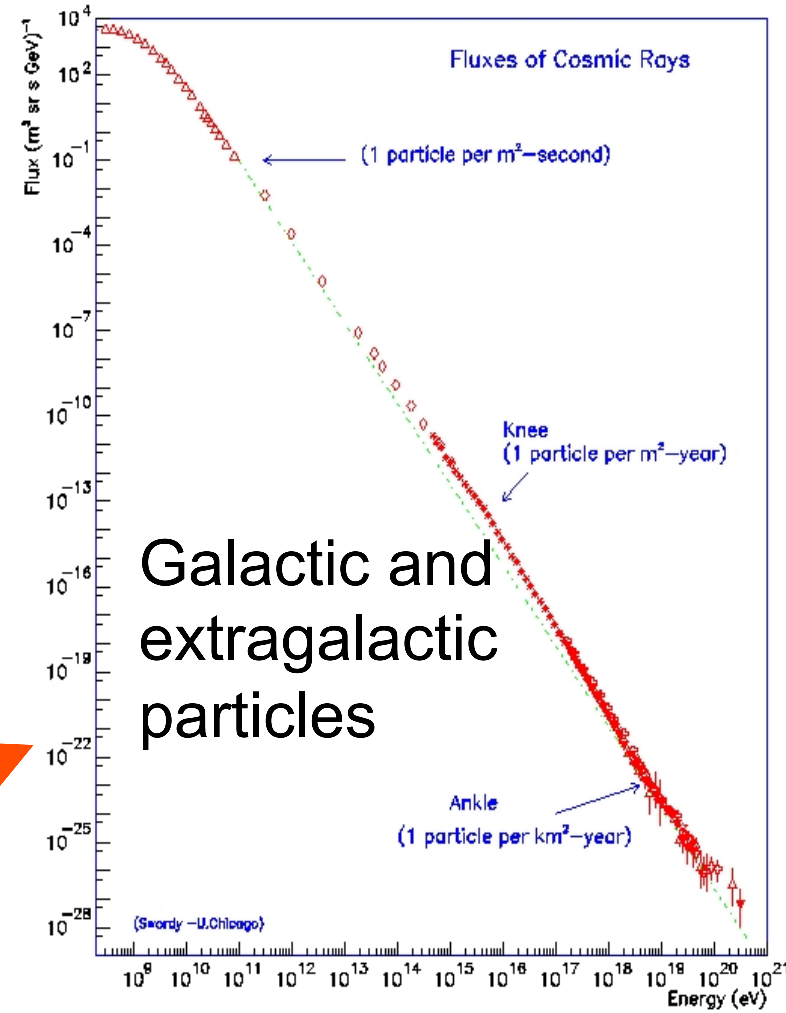
- Slides will be available at:
- https://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1718/

Lo spettro energetico dei RC primari

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

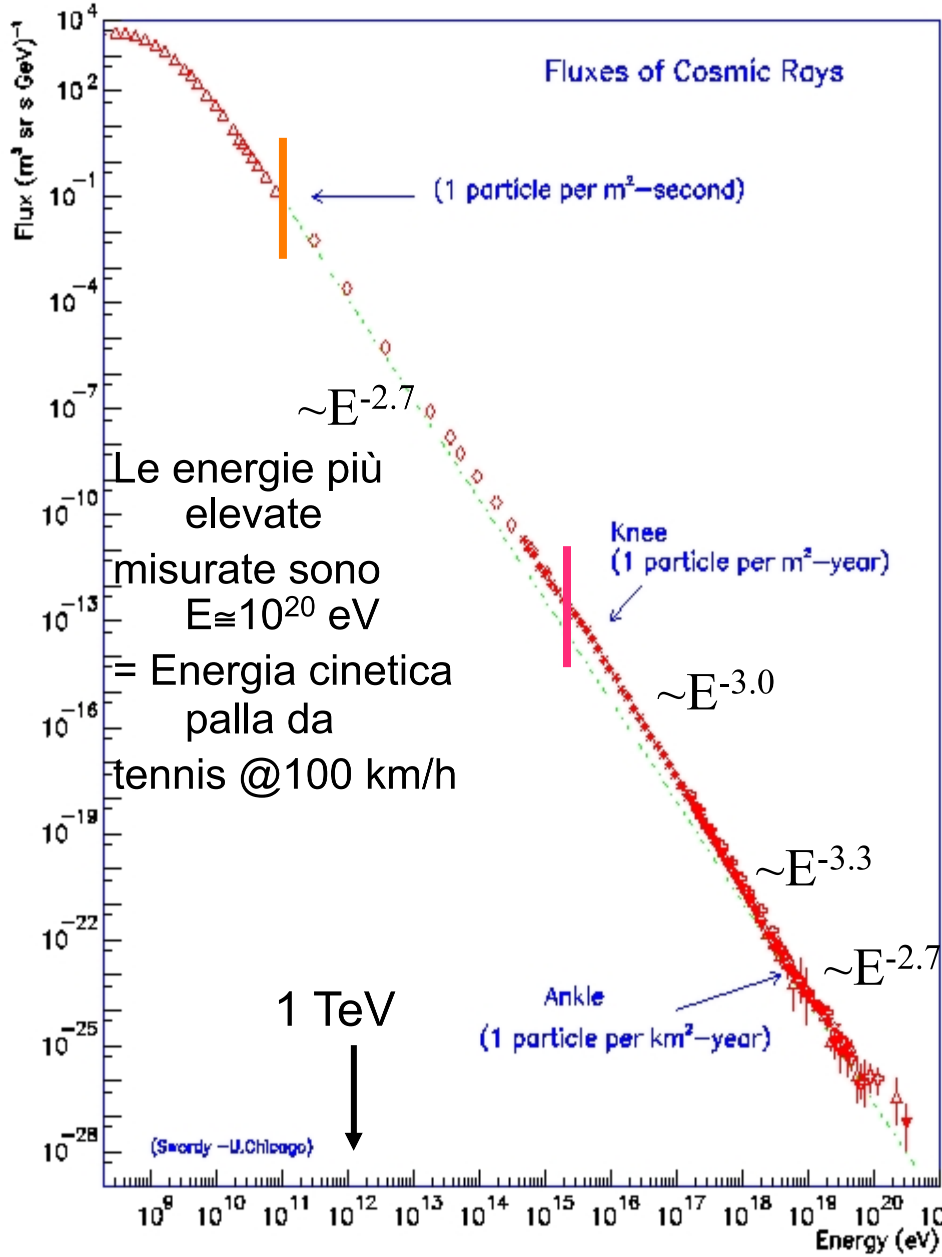
dN/dtdEdSdΩ





- Φ_{TOT}~10000 $m^{-2}s^{-1}sr^{-1}$
- Misure dirette: 85% p, 12% He, ≈1% nuclei pesanti, ≈2% $e^{\pm}$, antiprotoni + fotoni
- 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

Le energie più elevate in gioco nei RC sono irraggiungibili agli acceleratori



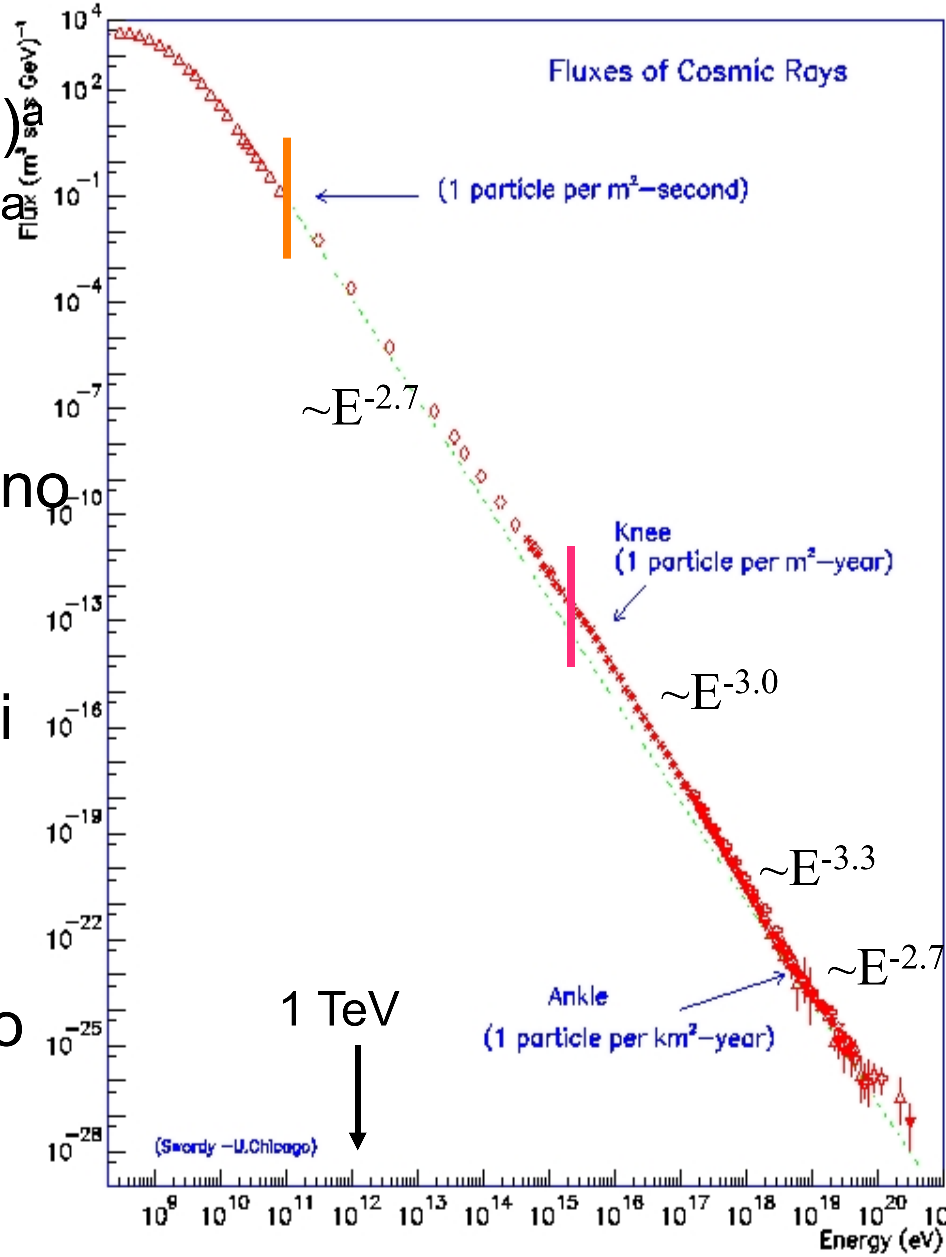
→ Legge di potenza $\Phi = K(E/GeV)^{a}$

→ Spettri non termici (quale sarebbe la distribuzione di energia di uno spettro termico?)

→ Processi di accelerazione + propagazione che producono uno spettro regolare

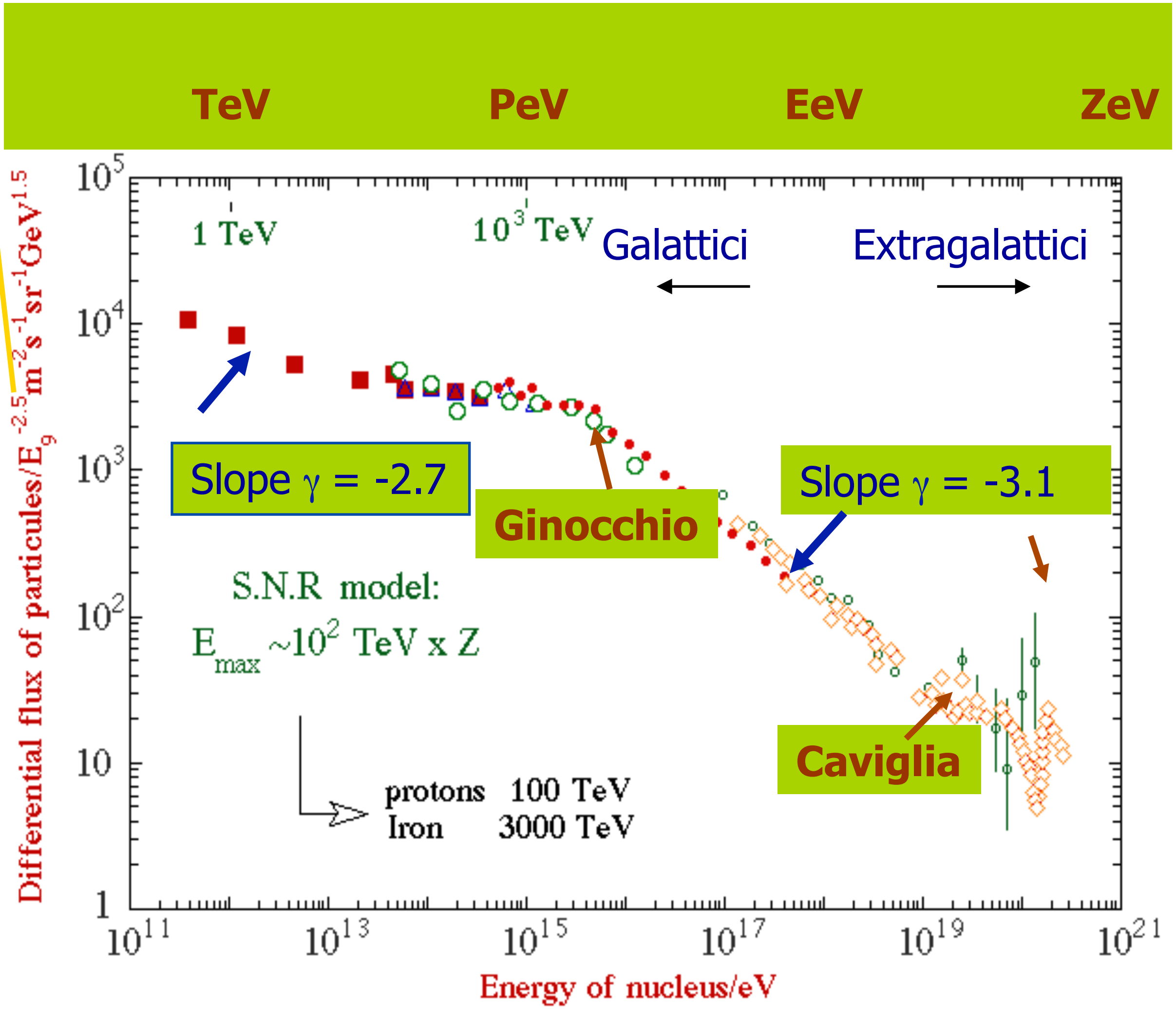
→ da informazioni sui processi di accelerazione alle sorgenti e di propagazione nel mezzo interstellare delle particelle

→ A bassa energia lo spettro e' influenzato dall'azione del vento solare



Ancora lo spettro dei RC, ma…

L'asse y viene moltiplicato per $E^{2.5}$ (o piu' in generale per una potenza di E), in modo da rendere "più piatta" la figura ed accentuare il ***cambiamento di pendenza!***



I dati sperimentali

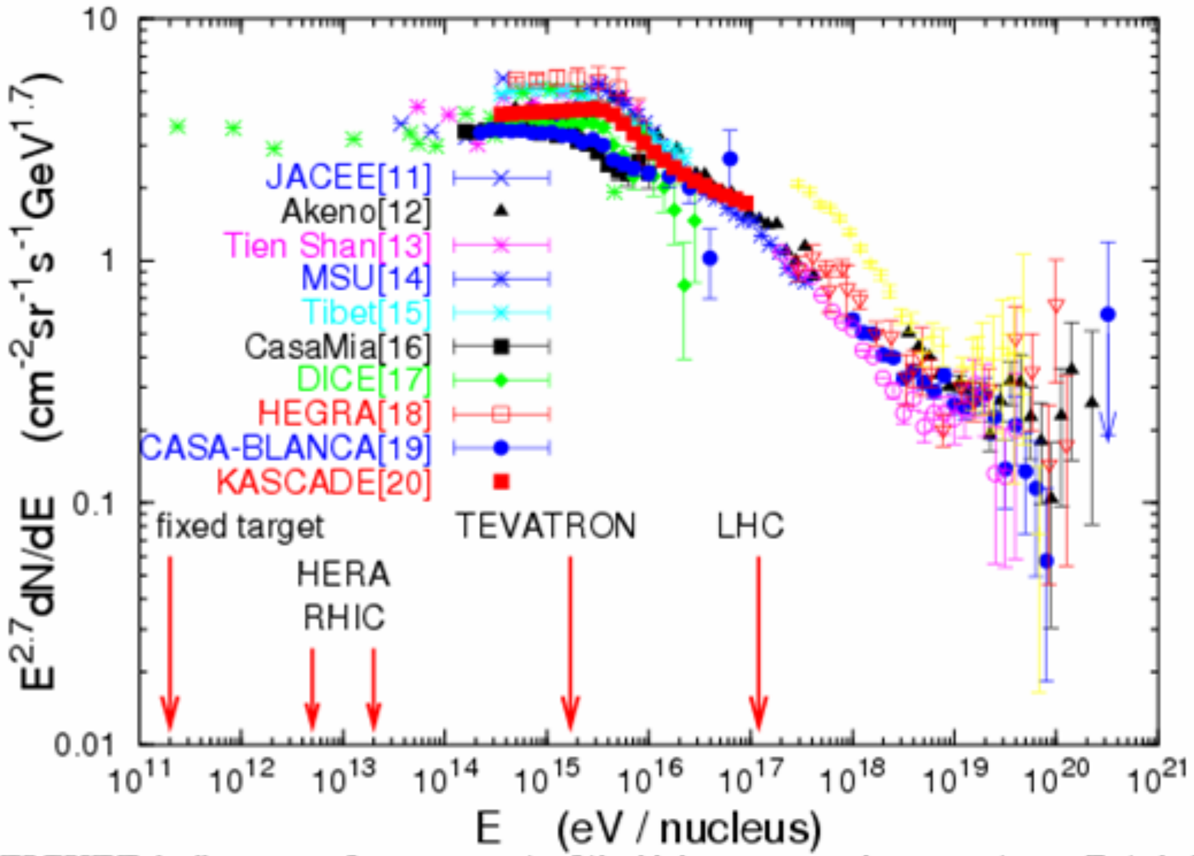
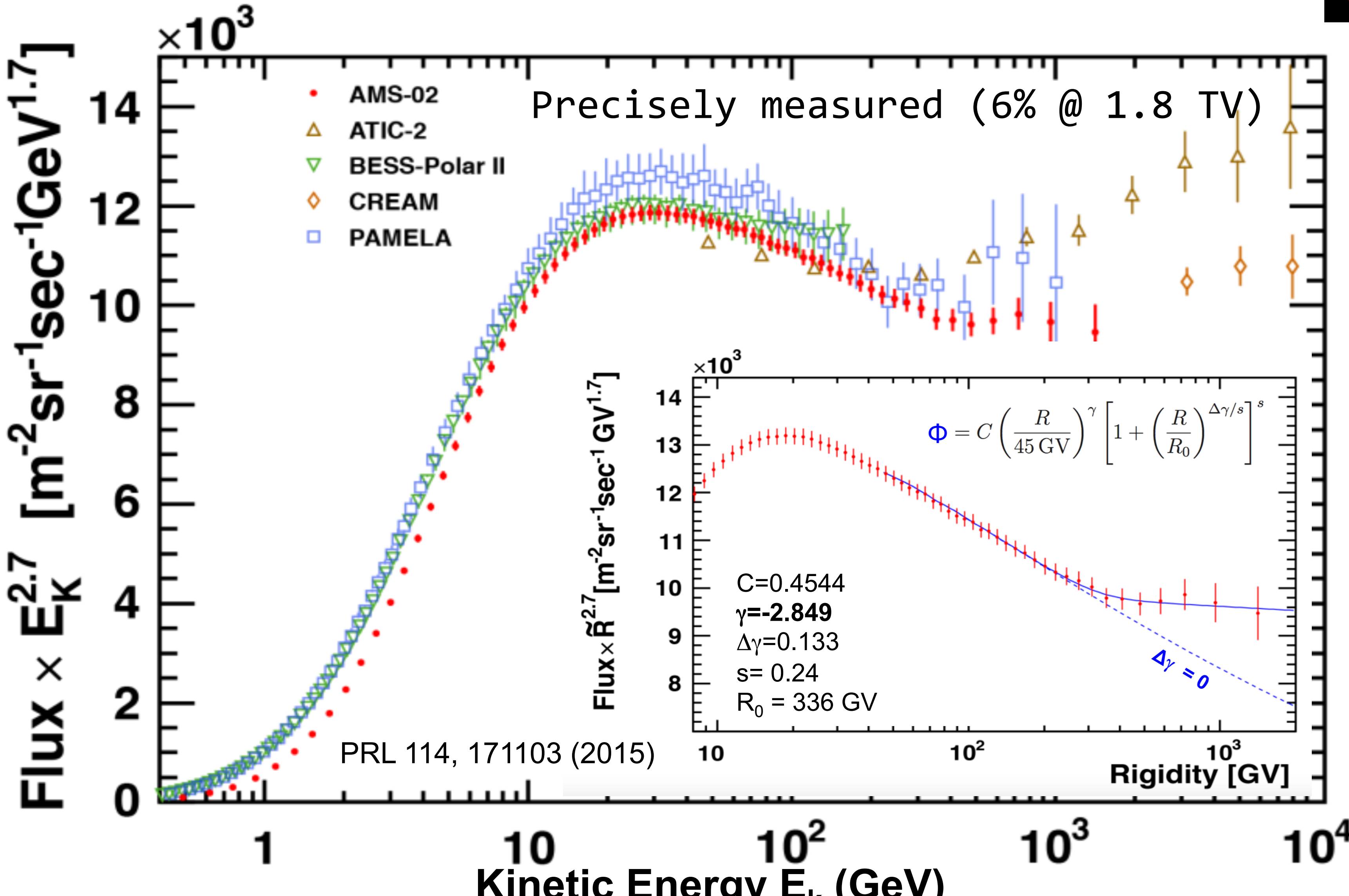


FIGURE 1. Summary of measurements of the high energy cosmic-ray spectrum. Data below 100 TeV are from a satellite detector [10]. Data in the knee region are from Refs. [11–20]. References for data above 10^{17} eV are given in Fig. 4.

Proton flux

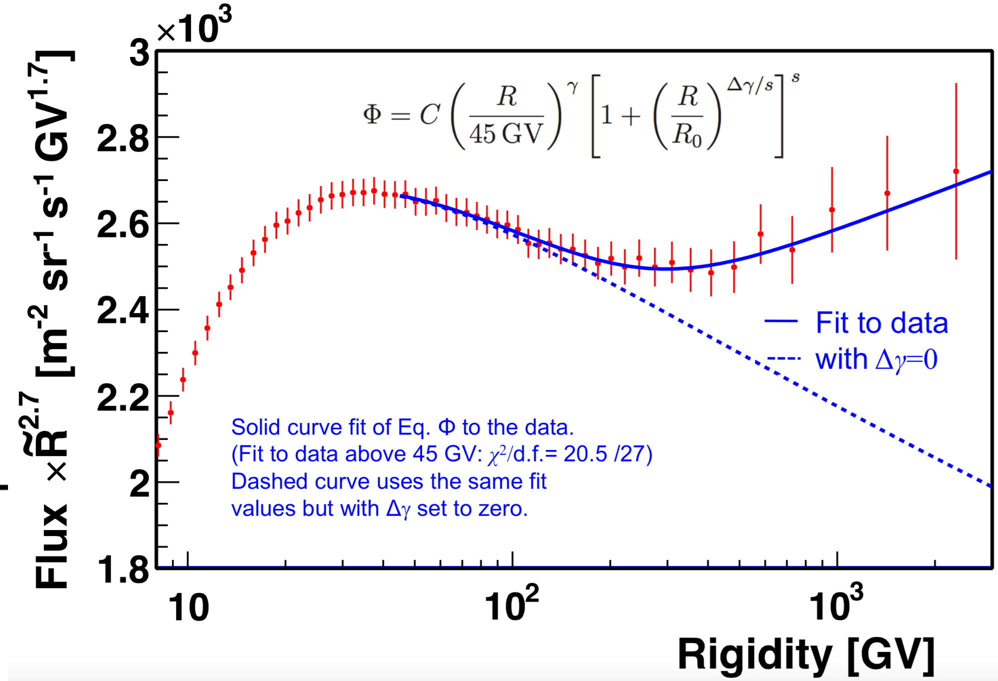


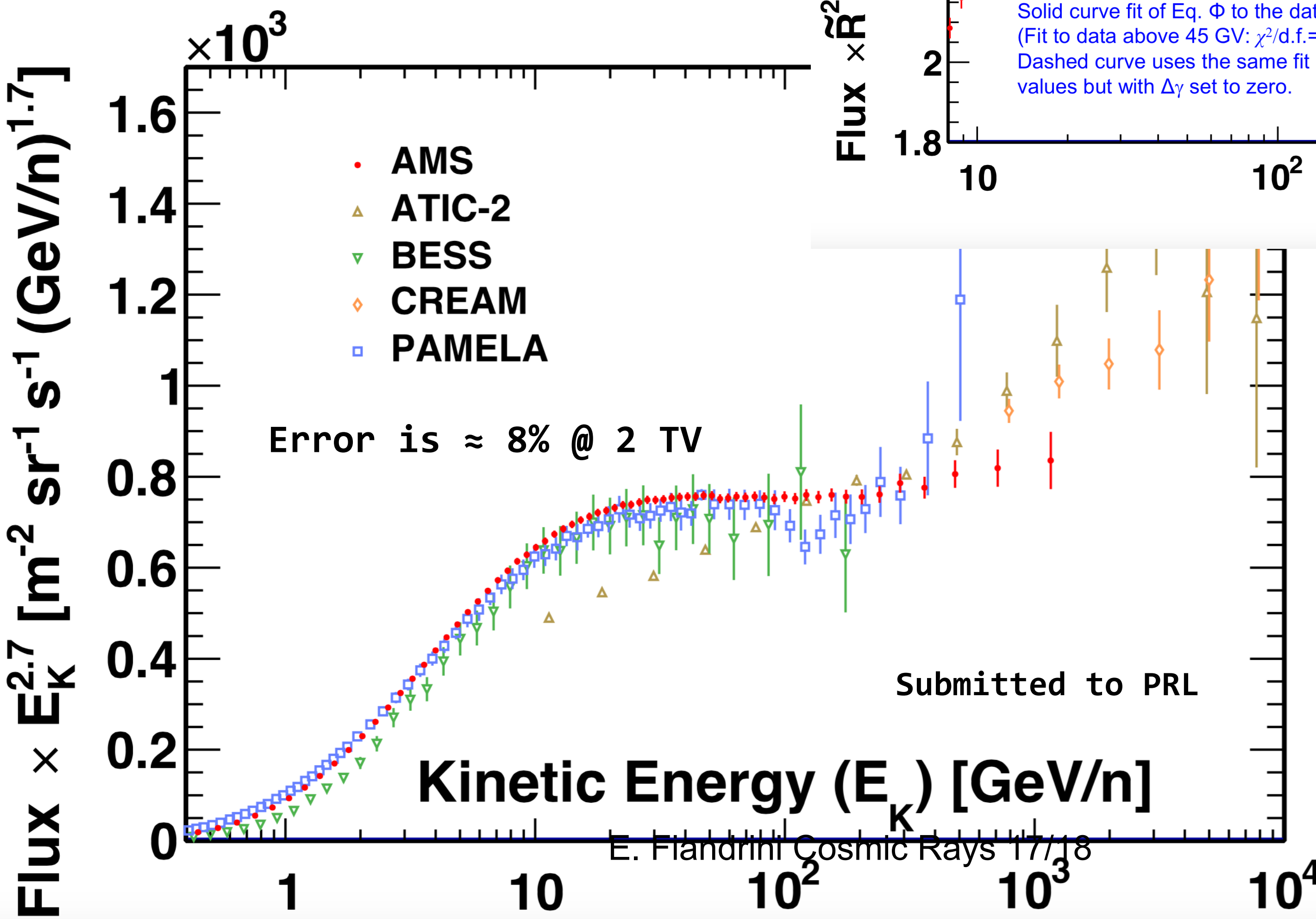
E. Fiandrini Cosmic Rays 17/18

A change in the the spectral index is observed at 336 GV

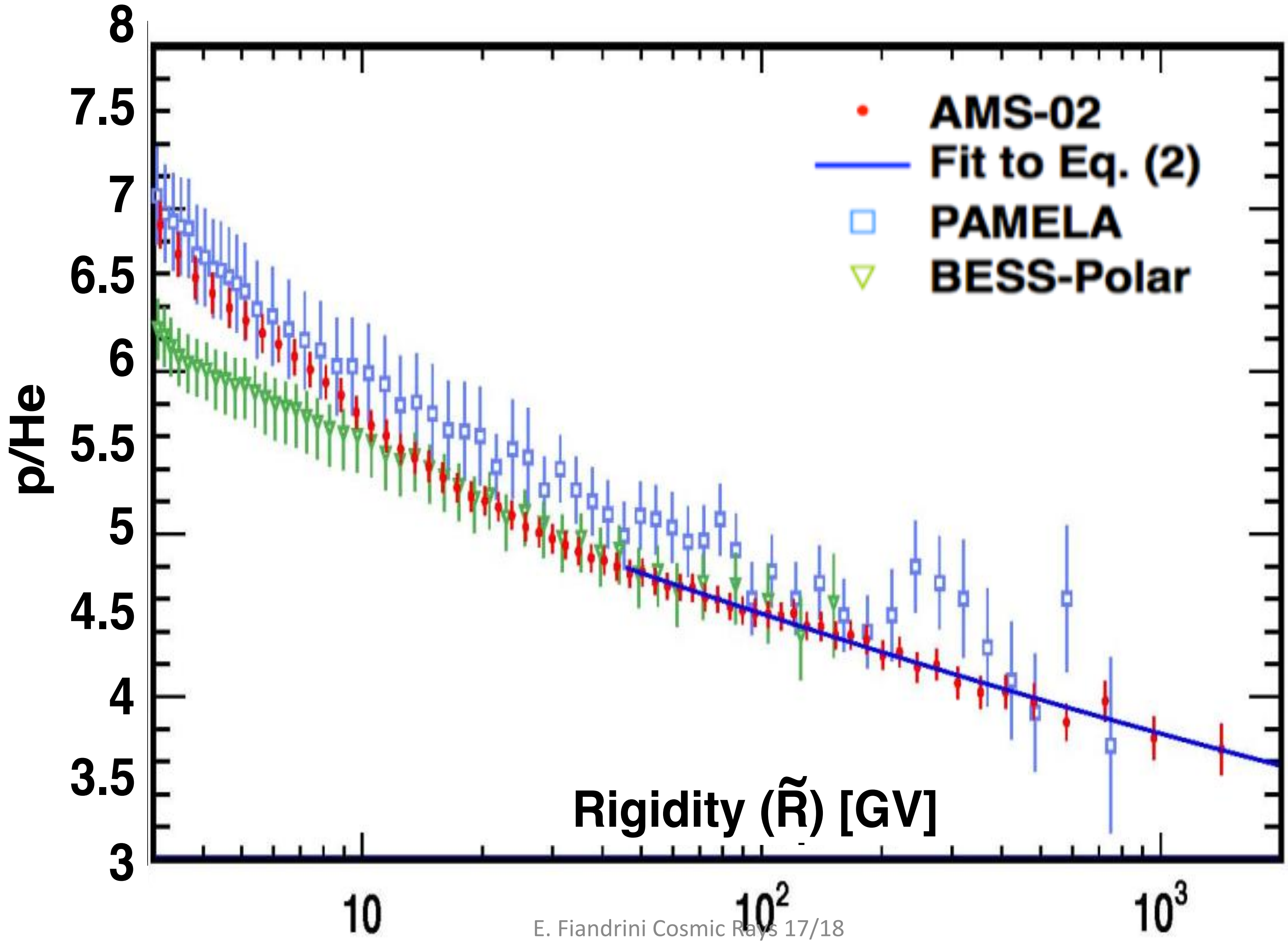
He Flux

Transition energy R_0 and smoothness parameter s are the same as for protons

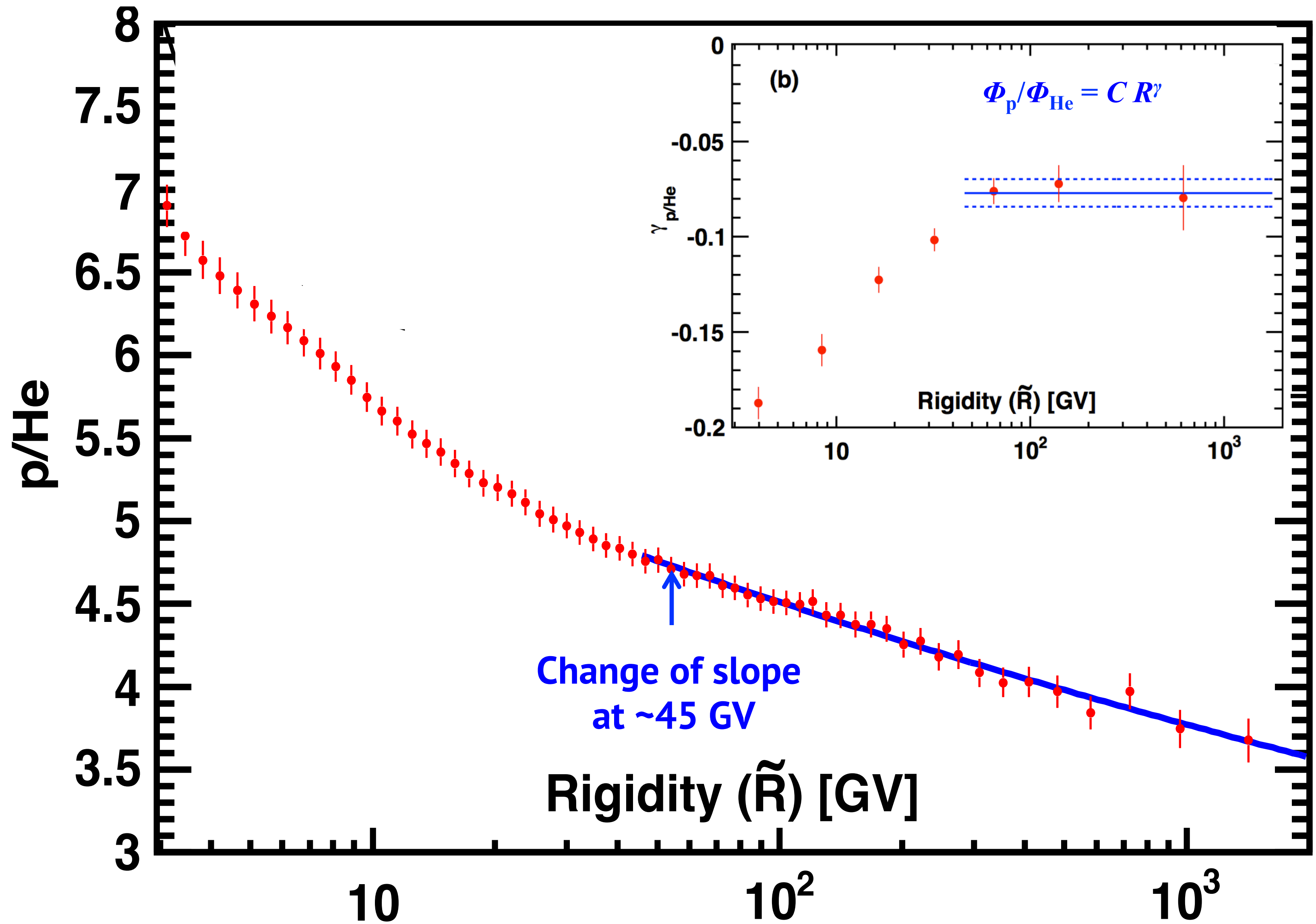


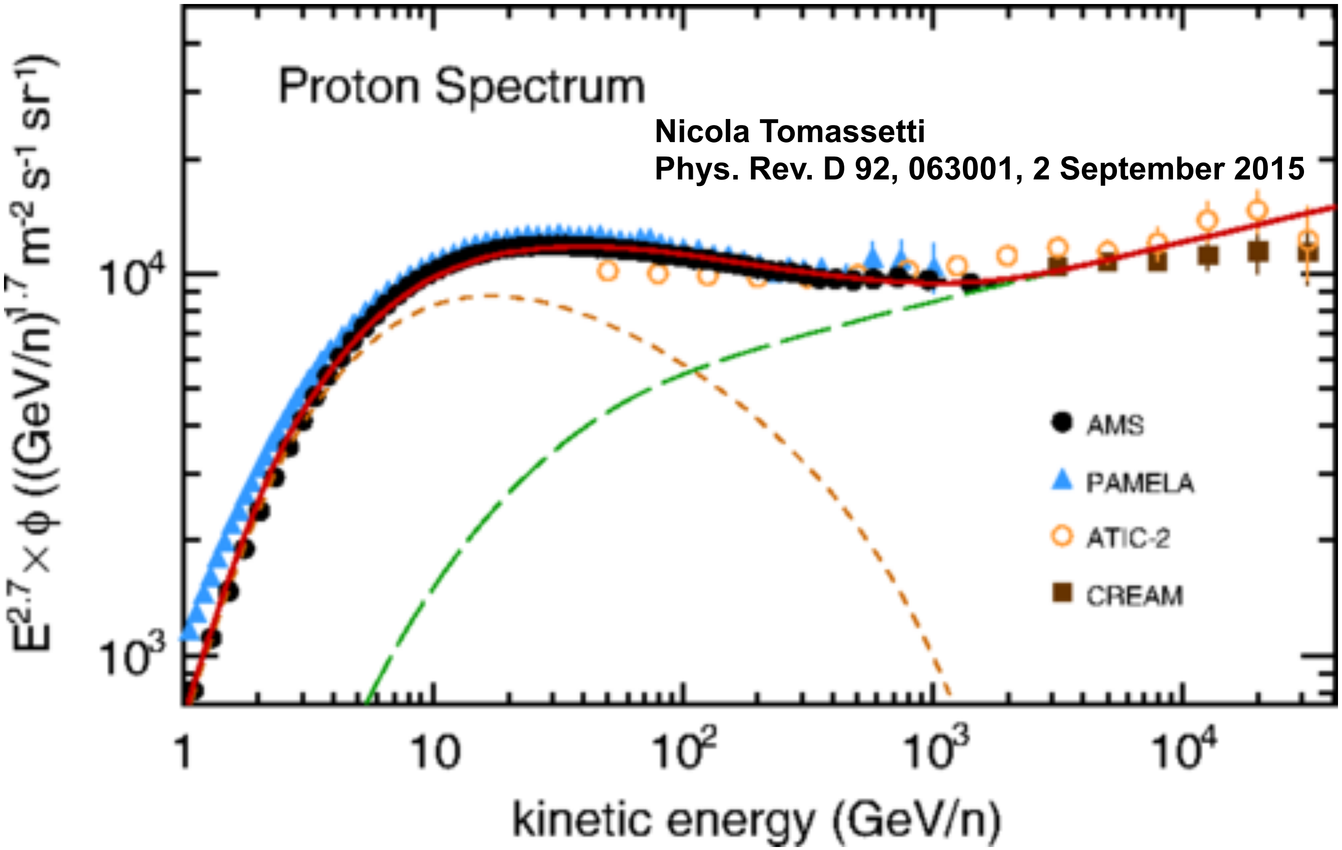


AMS p/He flux ratio

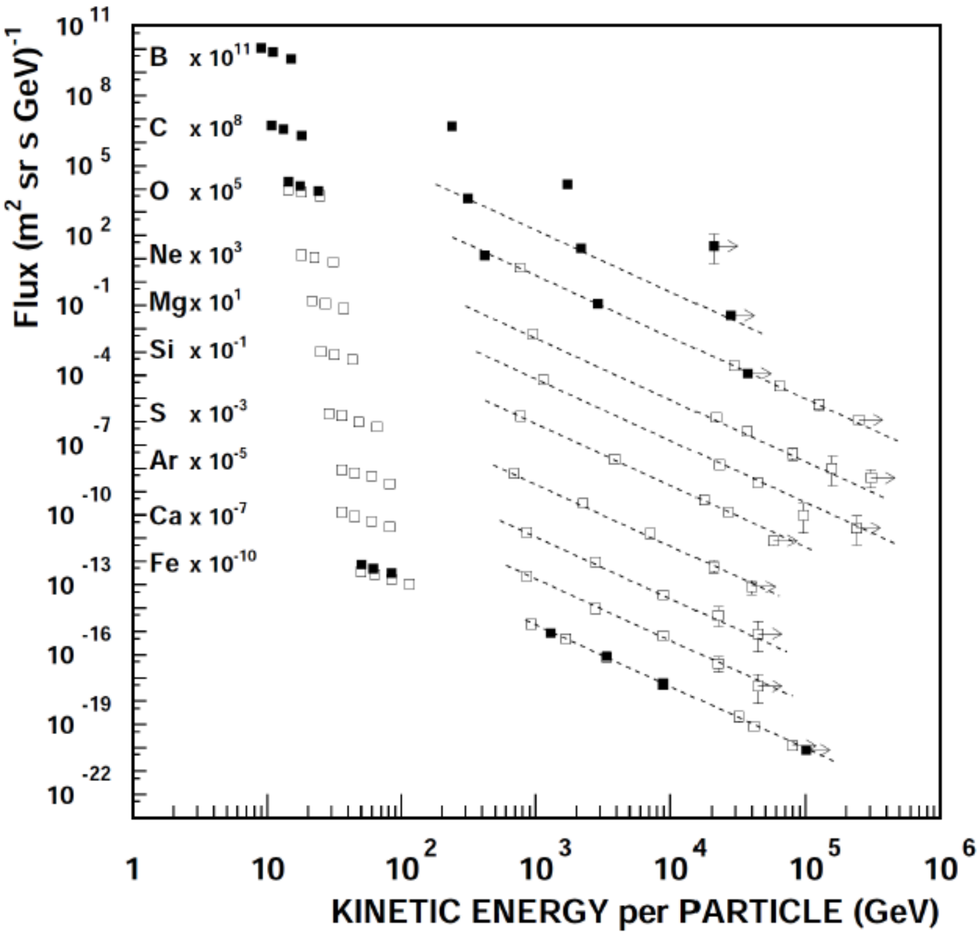


AMS p/He flux ratio




Proton Spectrum
Nicola Tomassetti
Phys. Rev. D 92, 063001, 2 September 2015
$E^{2.7} \times \phi$ ((GeV/n)$^{1.7}$ m^{-2} s^{-1} sr^{-1})
10^4
10^3
AMS
PAMELA
ATIC-2
CREAM
1
10
10^2
10^3
10^4
kinetic energy (GeV/n)

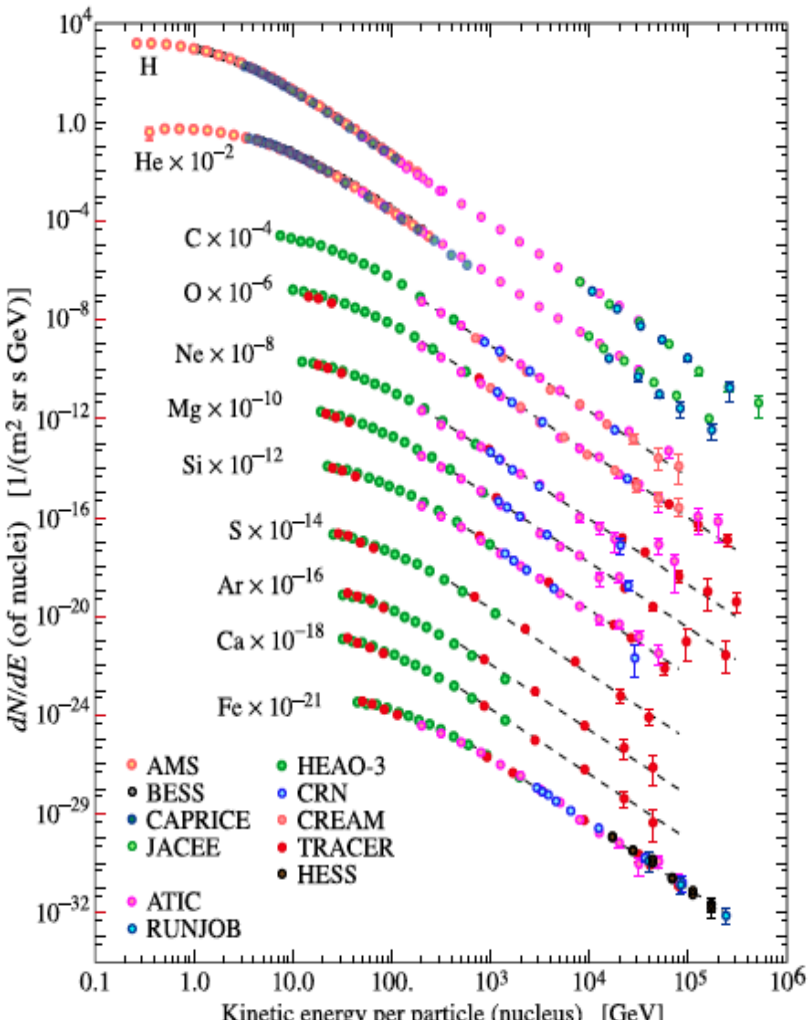
Nuclear species flux



TRACER 2 flights data:
POWER_LAW fit above 20 GeV/n:

$$\text{index } 2.65 \pm 0.05$$

Comparison between experimental results



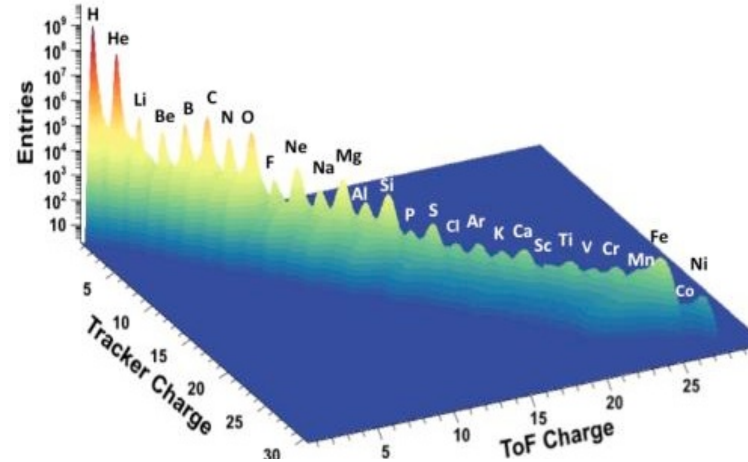
QUESTION:

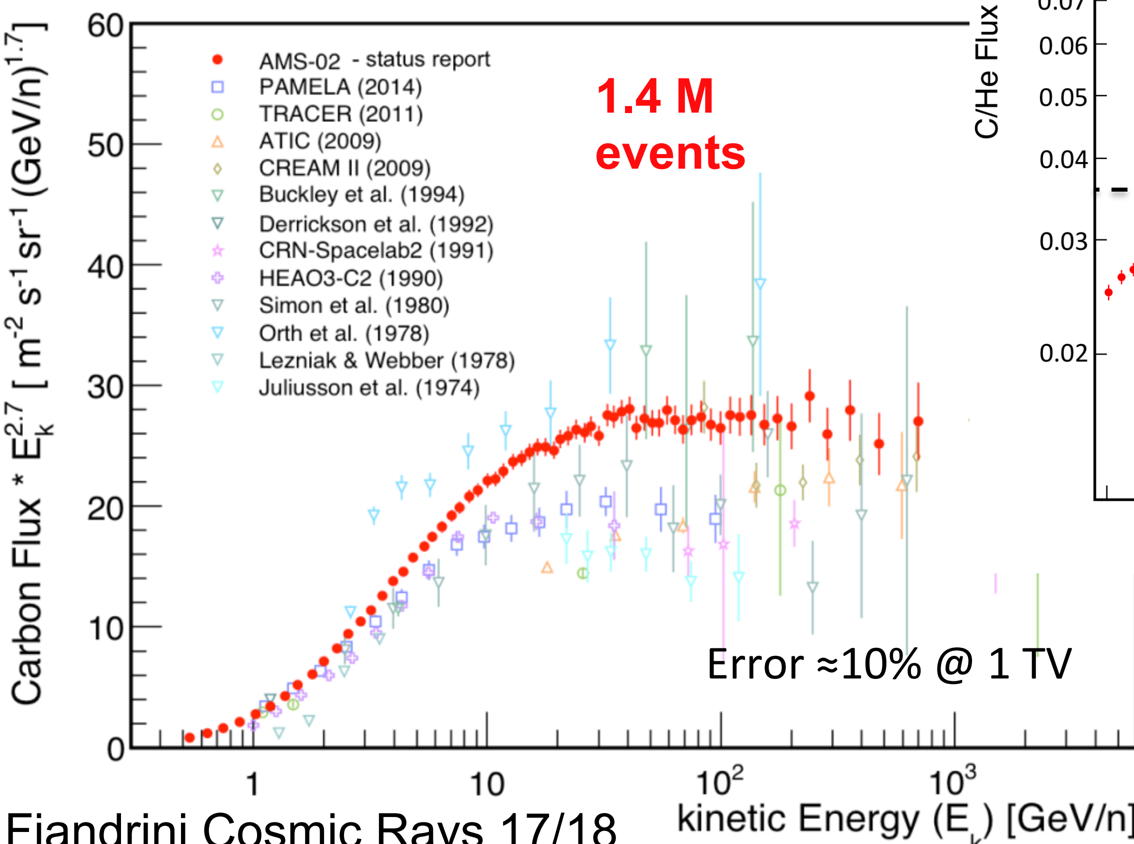
Are all the hi-Z spectra simple power laws or is there beginning to be evidence for evolution (hardening), as now seems to be the case for H and He?

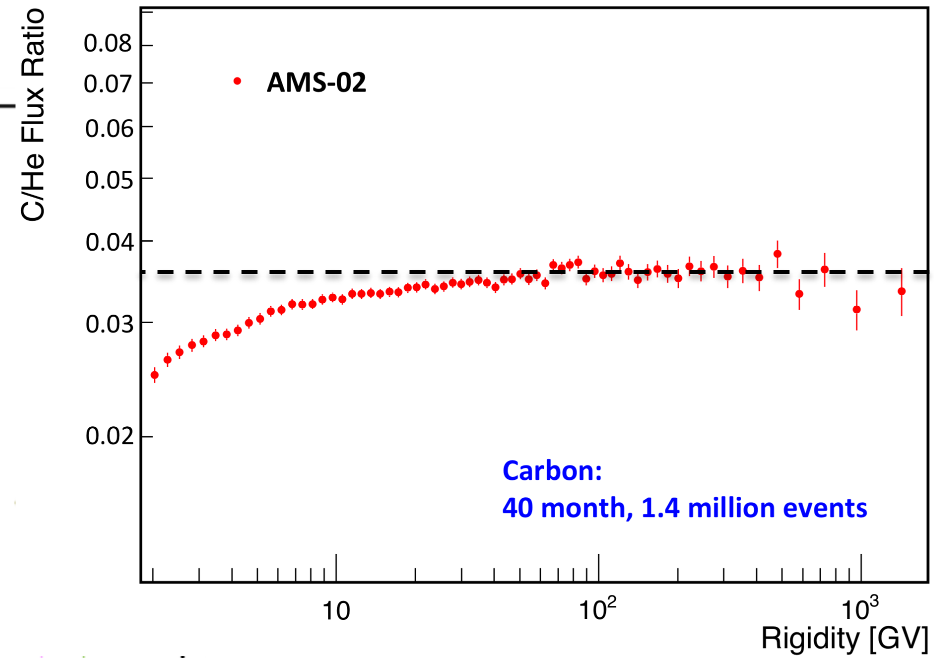
Figure courtesy of P.J. Boyle and D. Mueller

nuclear fluxes..

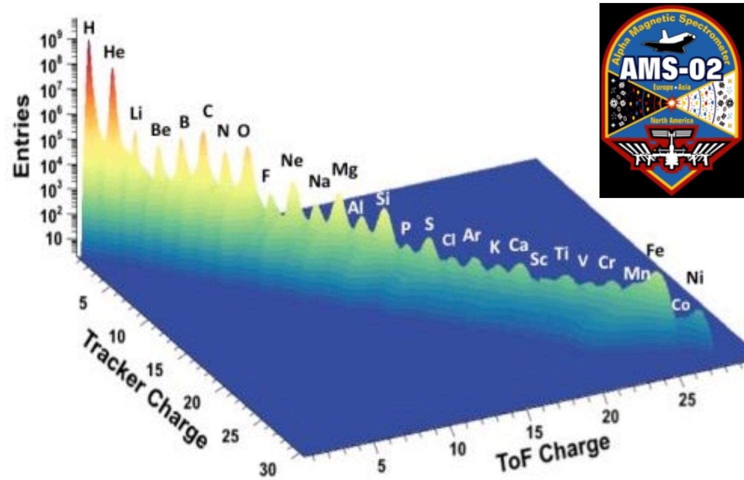
Primaries: e.g. C

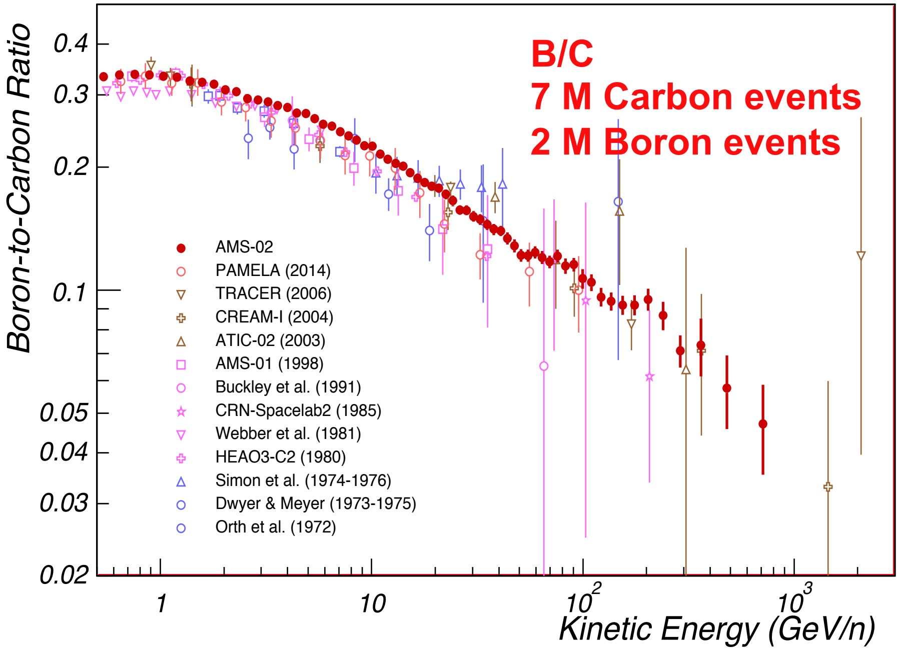


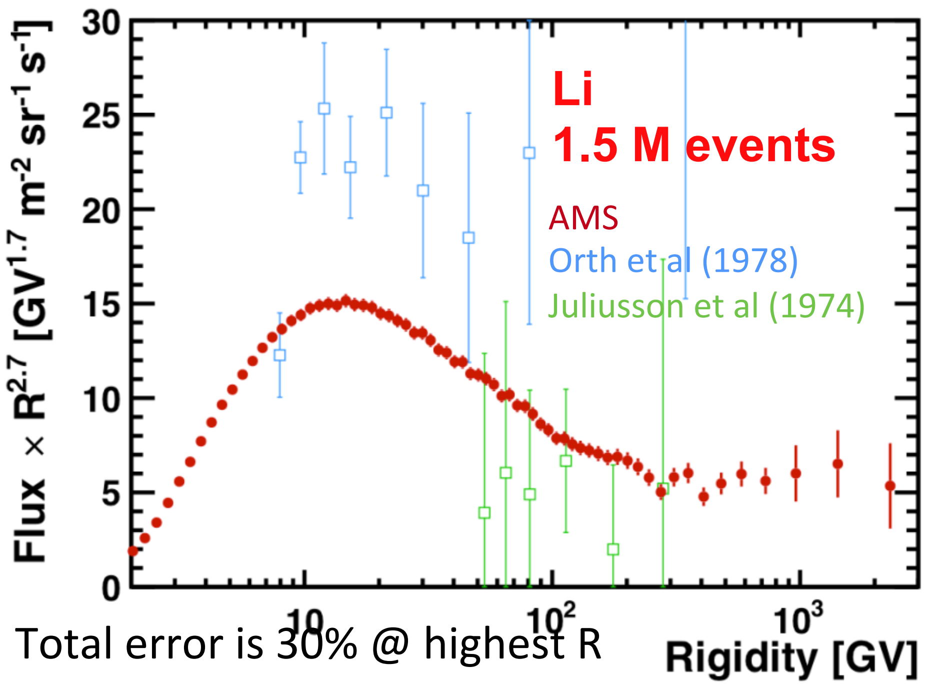




nuclear fluxes Secondaries:

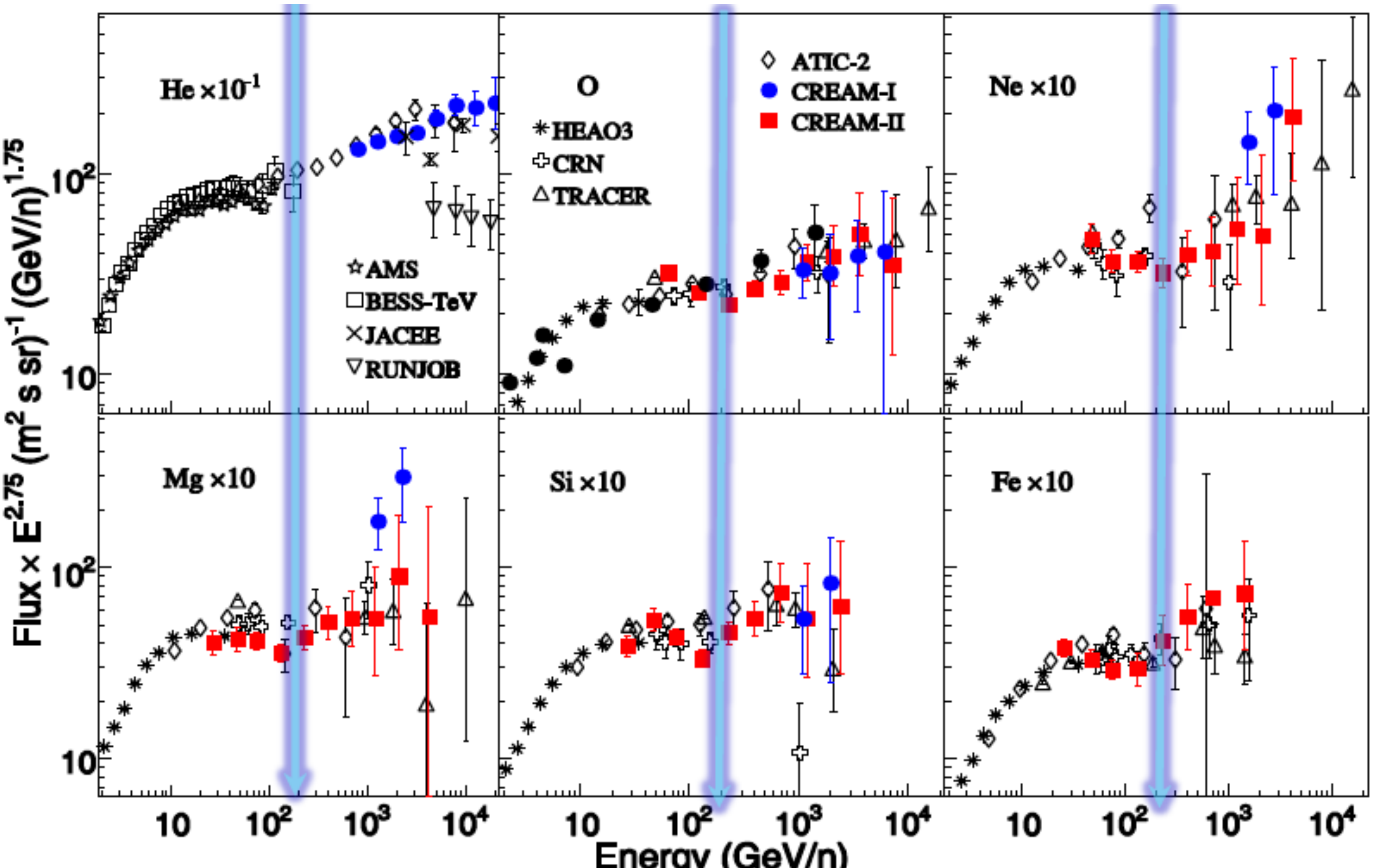






Total error is 30% @ highest R

Heavier elements: hardening



Astronomical units

Distance: an **astronomical unit** (AU or au) is the mean distance between the Earth and the Sun (technically the radius of a circular orbit with same period as the Earth).

$$1 \text{ au} = 1.496 \times 10^{13} \text{ cm}$$

Angles: a circle has 360 degrees or 2π radians

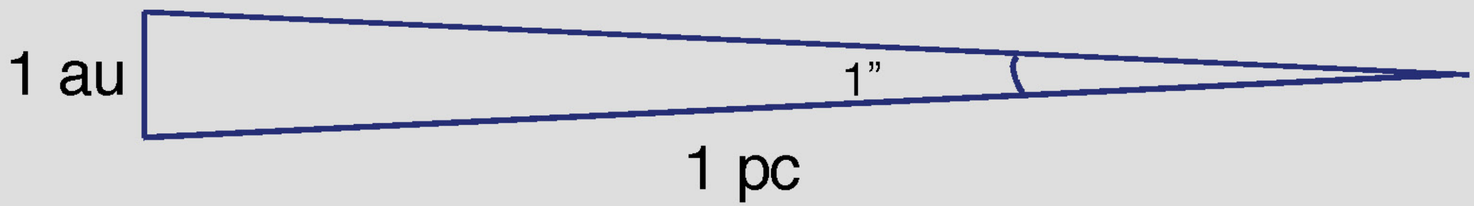
$$1^{\circ} = \frac{2\pi}{360} \text{ radians} = 0.01745\ldots \text{ radians}$$

$$1 \text{ arcminute} = \frac{1}{60} \text{ degrees}$$

$$1 \text{ arcsecond} = \frac{1}{60} \text{ arcminutes} = 4.85 \times 10^{-6} \text{ radians}$$

Best resolution of optical telescopes (HST) is about 0.1”.

A **parsec** (pc) is defined as the distance at which a `ruler' of length 1 au subtends an angle of 1 arcsecond.



$$1'' = \frac{1 \text{ au}}{1 \text{ pc}} \Rightarrow 1 \text{ pc} = \frac{1.496 \times 10^{13} \text{ cm}}{4.85 \times 10^{-6}} = 3.086 \times 10^{18} \text{ cm}$$

1 pc = 3.26 light years - roughly the distance to the nearest stars. Convenient unit for stellar astronomy.

Sizes of galaxies usually measured in kpc (galaxy scales are 10-100 kpc).

Cosmological distances are 100s of Mpc to Gpc. Observable Universe is a few Gpc across.

Electrons and positrons

- Electrons and positrons constitute about 1% of the CRs. This component provides additional information on the acceleration sites and CR propagation in the Galaxy.
- High-energy electrons are subject to a number of electromagnetic energy loss processes already in proximity of the sources, where the matter density and the magnetic fields are large.
- **The accelerated electrons are the source of most of the non-thermal electromagnetic emission from radio to gamma-rays (photoemission, bremsstrahlung, inverse compton, synchrotron)**
- These processes cause distortions of e^- injection energy spectra as they propagate through the ISM from their sources and they potentially provide information on the propagation, confinement, and production mechanisms of high-energy particles. Electrons directly produced at accelerator sites are called *primary electrons*.

Raggi cosmici

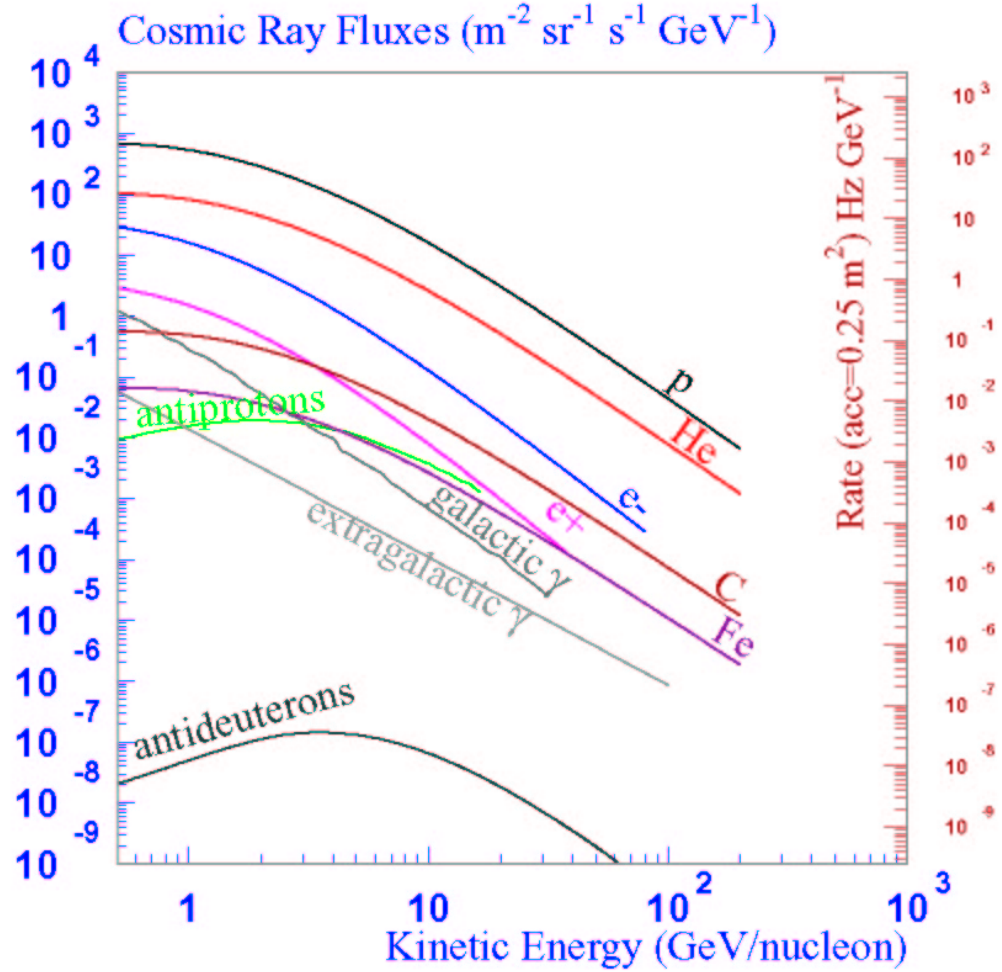
CR Composition

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

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

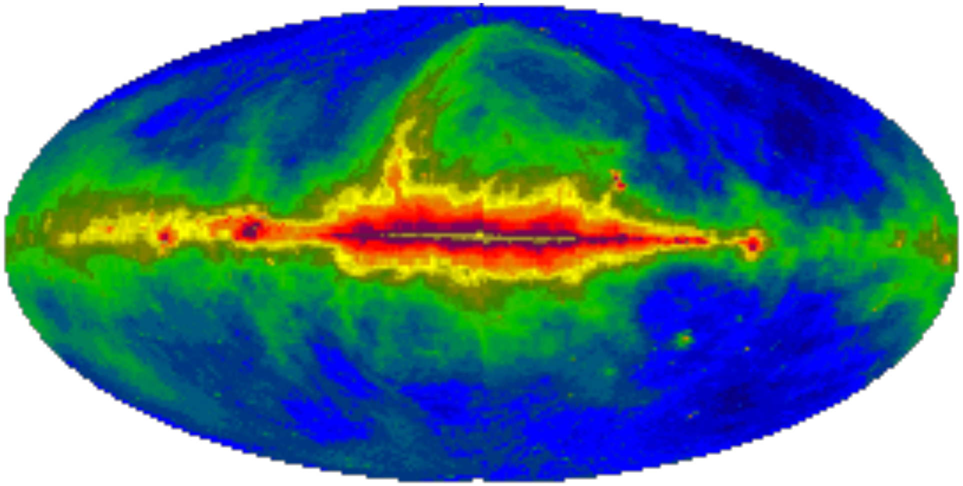
2% e → $e^+/e^- \sim 10^{-1}$

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



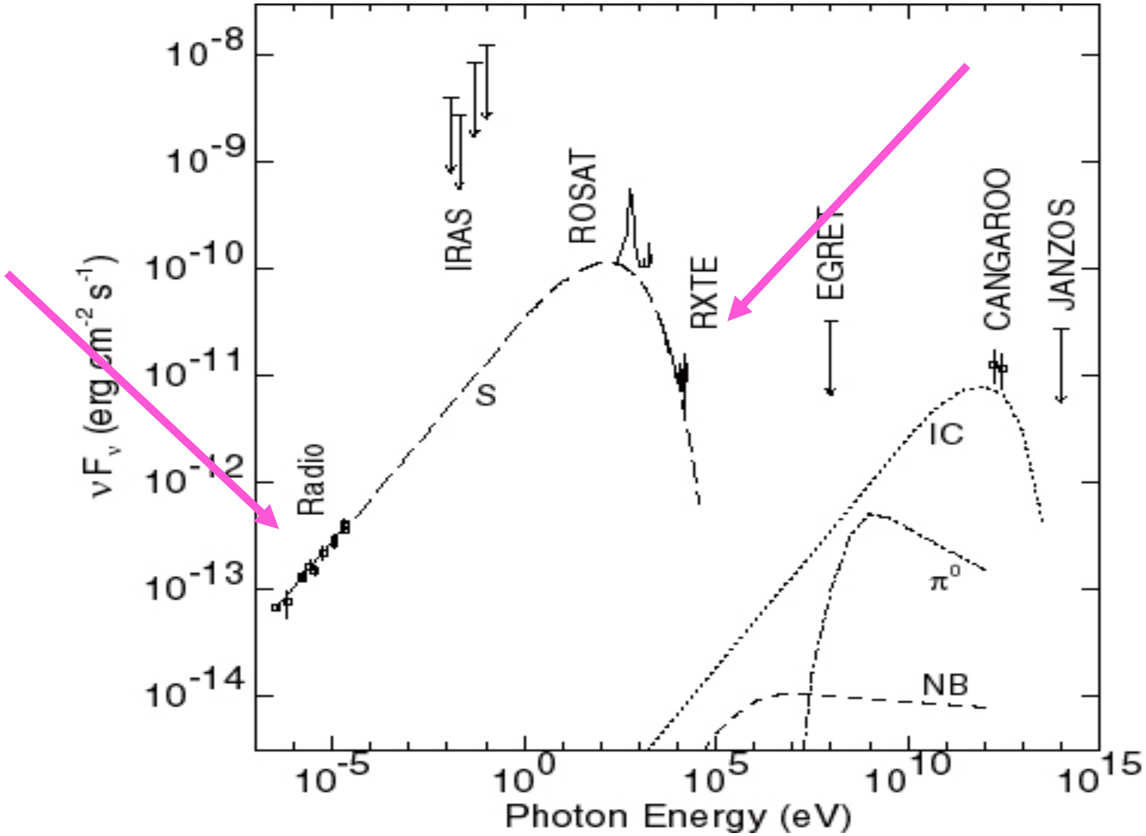
Electrons represents $O(10^{-2})$ of the charged CR flux but can reveal aspects of the source distribution and galactic propagation not observable in the nuclear CR component.

Most of our information about the Universe comes from the movement of electrons radiating photons



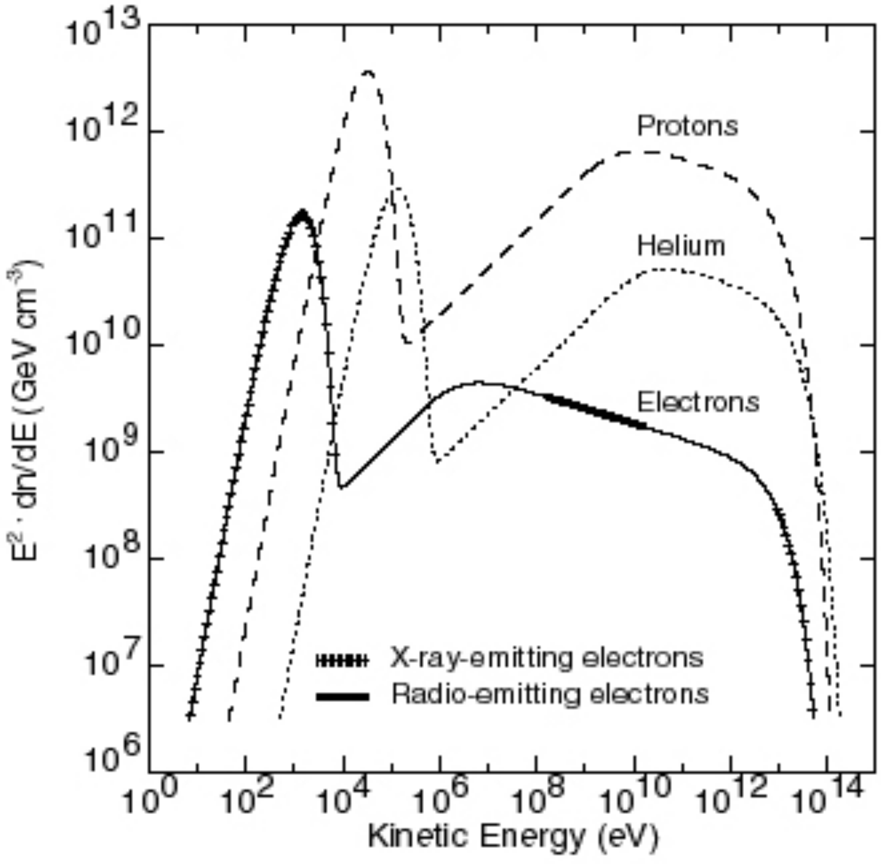
408 MHZ map of the sky : synchrotron emission of few GeV electrons in the galactic magnetic field

Direct evidence for acceleration of electrons in shocks of SNR comes from radio->gamma emission



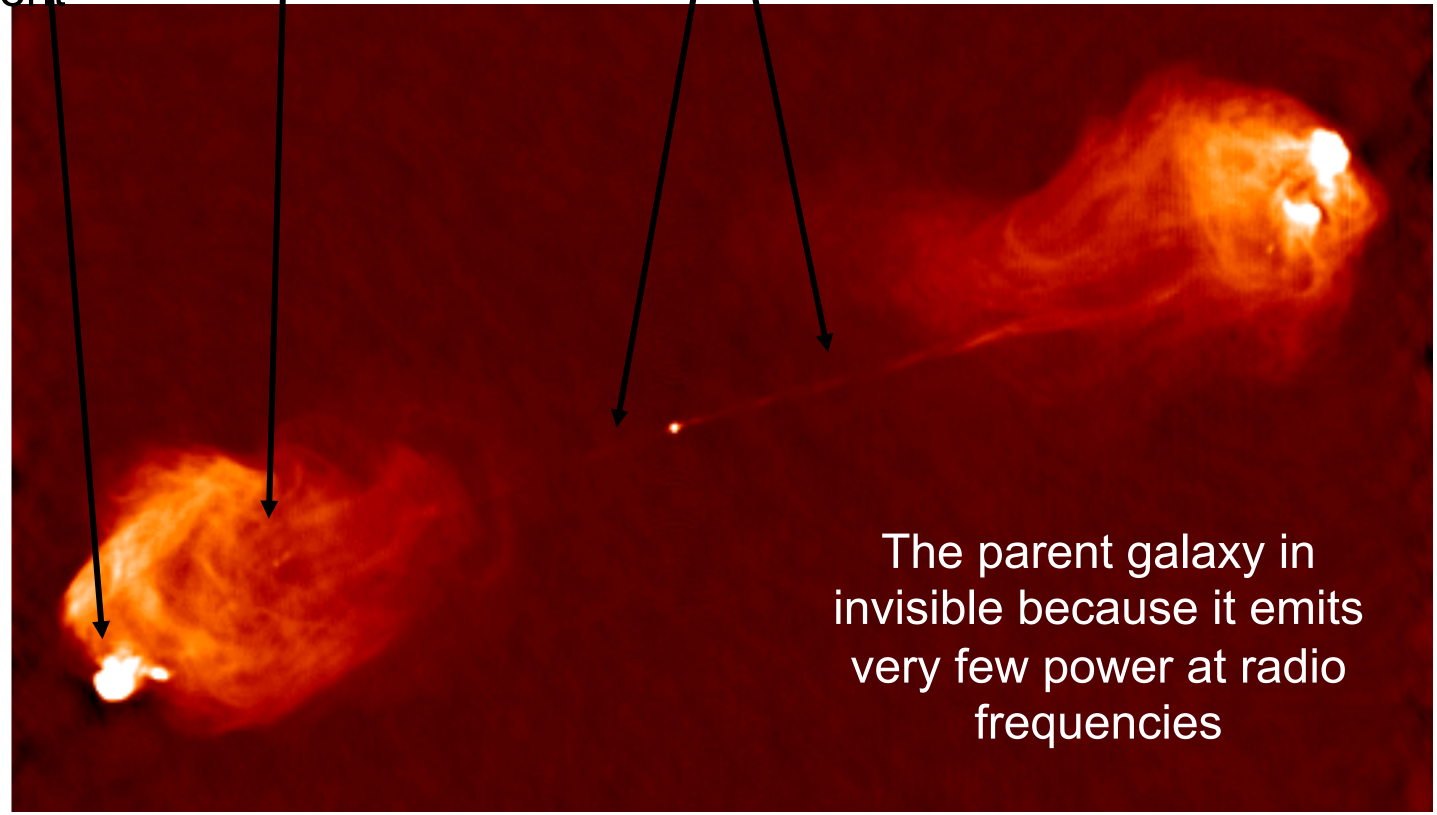
Radio to γ-ray photon energy flux spectrum of SN 1006

Fitting the radio/X-ray spectra with a power law electron injection spectra



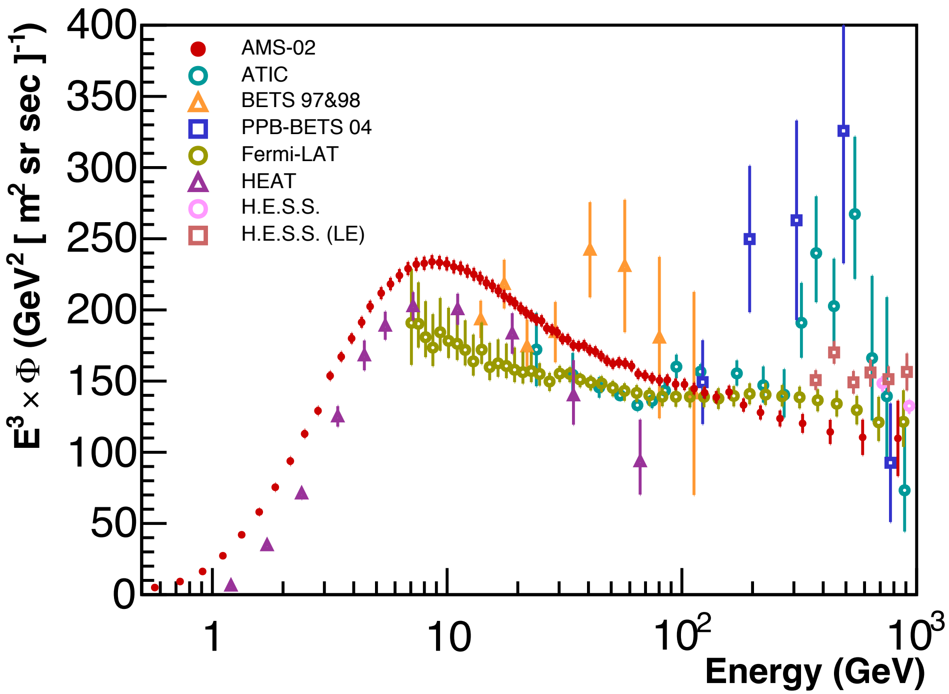
Radio galaxy Cignus A

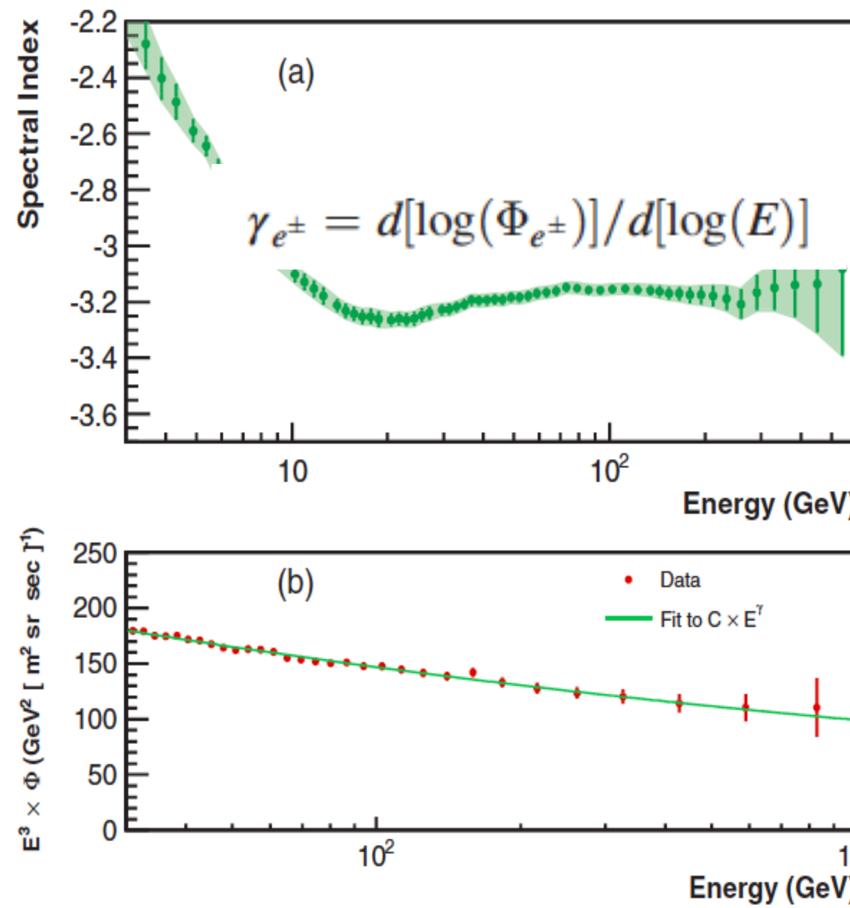
Relativistic electrons within the jets emit synchrotron radiation at the hot spots (shock wave) where the jet material hits the interstellar medium. Radiation is emitted also in the "cocoon" of the jet, where residual B field is present



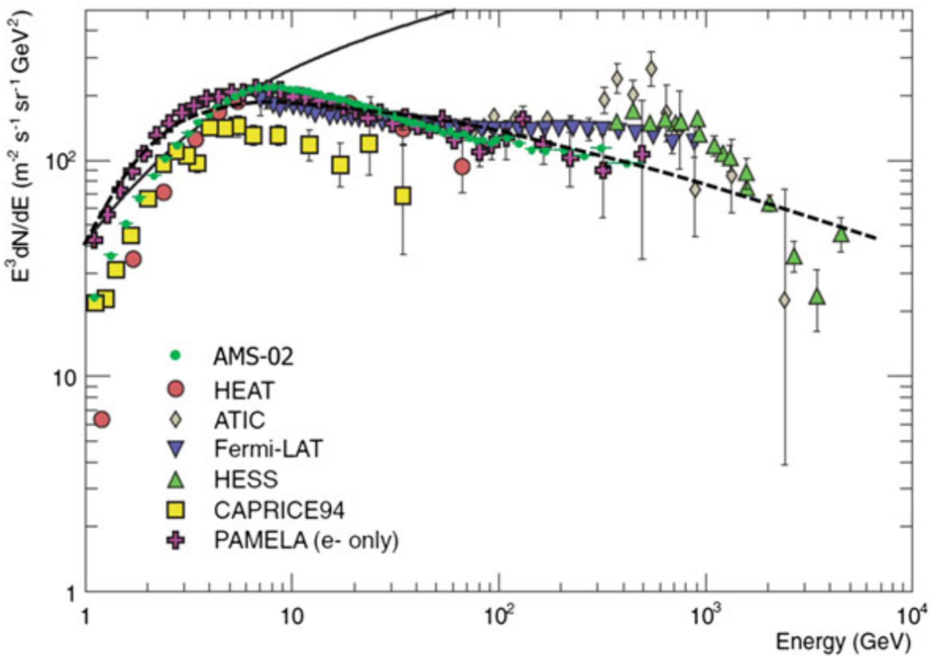
Electron + Positron total flux (“All electron flux”):

No sharp structures
A single power low describes the spectrum after 30 GeV
Measured only up ~1 TeV, well below the knee





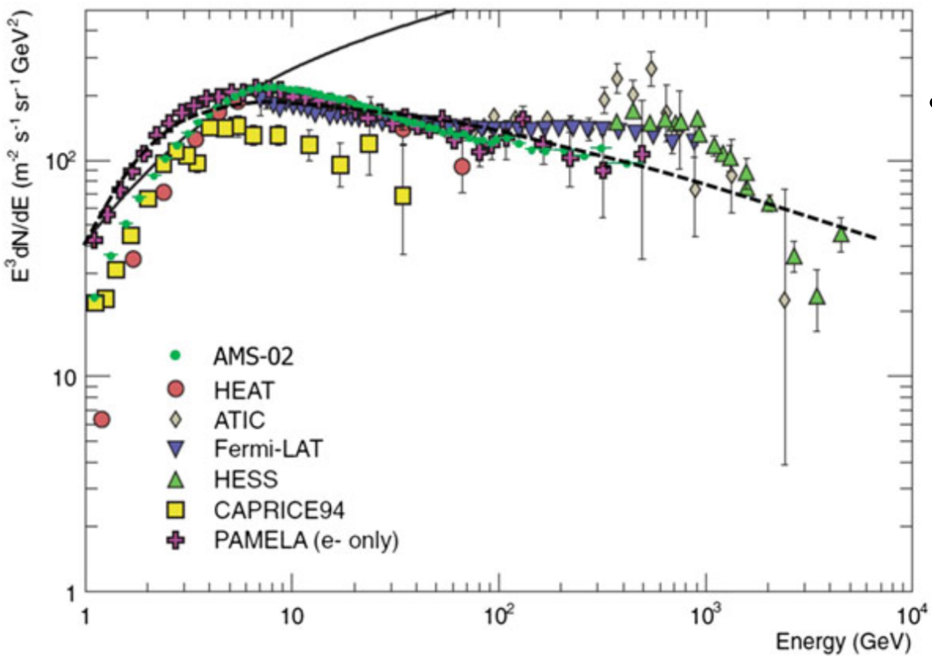
Within systematic errors the entire electron spectrum from few GeV to 1TeV can be fitted by a power law $\Phi_e(E) \propto E^{-3.1}$. If electrons are emitted by astrophysical sources with a spectral index α_e, a steepening of the spectrum by one power is expected because of the electron radiation losses. The measured spectral index ~ 3 indicates a spectral index of CR sources α_e ~ 2.



The presence of a structure in a smooth spectrum of the lepton component would represent an important signature for unexpected physics. In particular, from annihilation of dark matter candidates or from the presence of sources of nearby SNR and active galactic accelerators of CR electrons.

Fig. 3.12 The electron plus positron energy spectrum from different space-based, balloon, and ground-based experiments. The flux is multiplied by E^3. The *black full line* shows for reference the proton spectrum. The theoretical calculation (*dashed line*) is based on the prediction of secondary electrons produced by the interaction of CRs with the interstellar matter. Figure adapted from the Sect. 27. Cosmic Rays of Beringer et al. (2012) and references therein. The AMS-02 data have been extracted from Aguilar et al. (2013)

An excess of electrons in the range 300–700 GeV with respect to that expected from conventional diffuse electron sources has been reported by ATIC and PPB-BETS (a long duration balloon flight using the Polar Patrol Balloon in Antarctica). Fermi-LAT has observed a spectral flattening of the e± spectrum between 70–200 GeV and a milder excess at higher energies with respect to those of ATIC and PPB-BETS. **AMS-02 data has produced no evidence of structures in the electron energy spectrum, at present up to 350 GeV**. However, a change in the spectral distribution with increasing energies is seen, compatible with the increases in the positron component



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- Secondary e+ and e− are produced by CR interactions with the interstellar matter, as end products of the decay of short lived secondary particles (mostly pions via the decay $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$). These secondary e± add to primary electrons accelerated at sources.

- the dashed line refers to a theoretical calculation of the electron plus positron spectrum based on the propagation of CRs in the Galaxy. This computer-code calculation (GALPROP) describes in detail the propagation of primary particles (protons, electrons, and nuclei) from the sources through the interstellar medium.

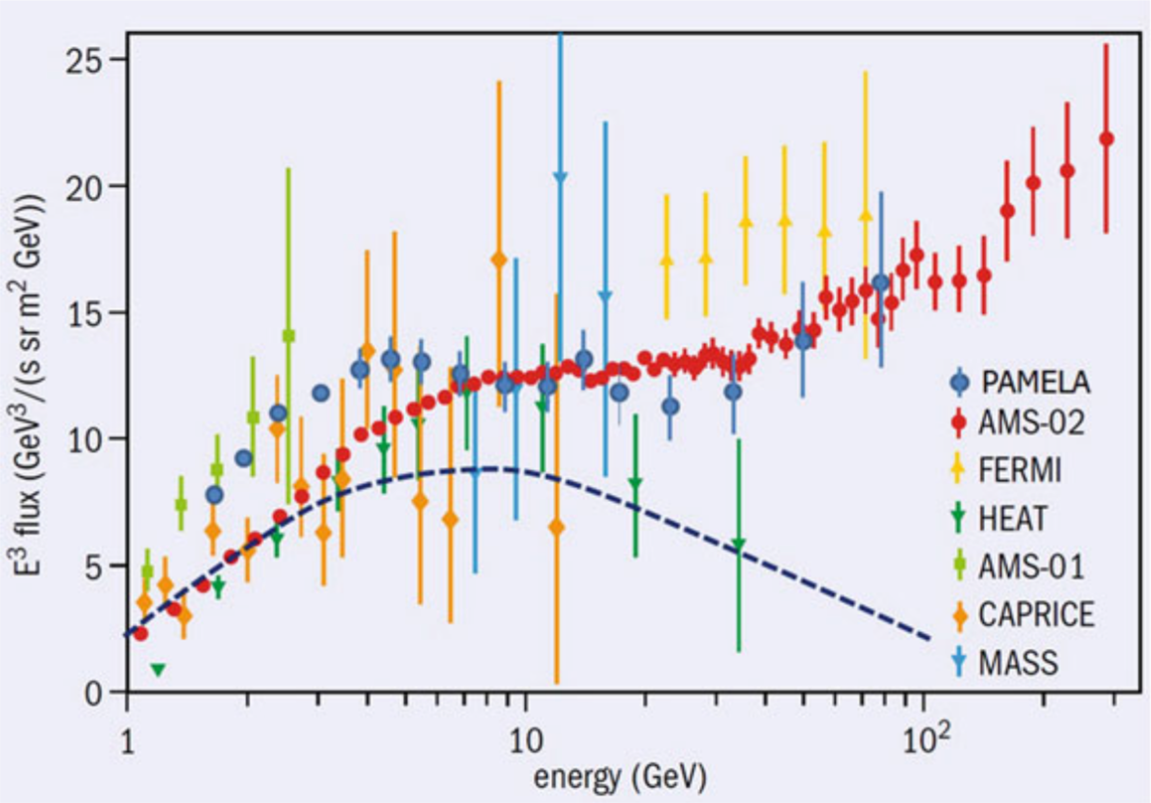


Fig. 3.13 The positron energy spectrum multiplies for E^3 measured by different balloon-borne (CAPRICE, HEAT, MASS) and space-borne (AMS-01, AMS-02, PAMELA, Fermi-LAT) experiments. The *dashed lines* show the calculation using the GALPROP program. Courtesy of prof. Manuel Aguilar Benítez. See Aguilar et al. (2013) and references therein

the positron energy spectrum $E^3\Phi_{e+}(E)$ as a function of E. The dashed line shows the prediction from the aforementioned computer code of primary propagation in the ISM. Above few GeV, a significant excess with respect to the secondary production by CR propagation is observed. PAMELA first (Adriani et al. 2009) and then Fermi-LAT observed that the $E^3\Phi_{e+}(E)$ flattens up to ~30GeV, before rising again above 30 GeV.

This behavior has been recently confirmed with high statistics and extended up to 350 GeV by AMS-02.

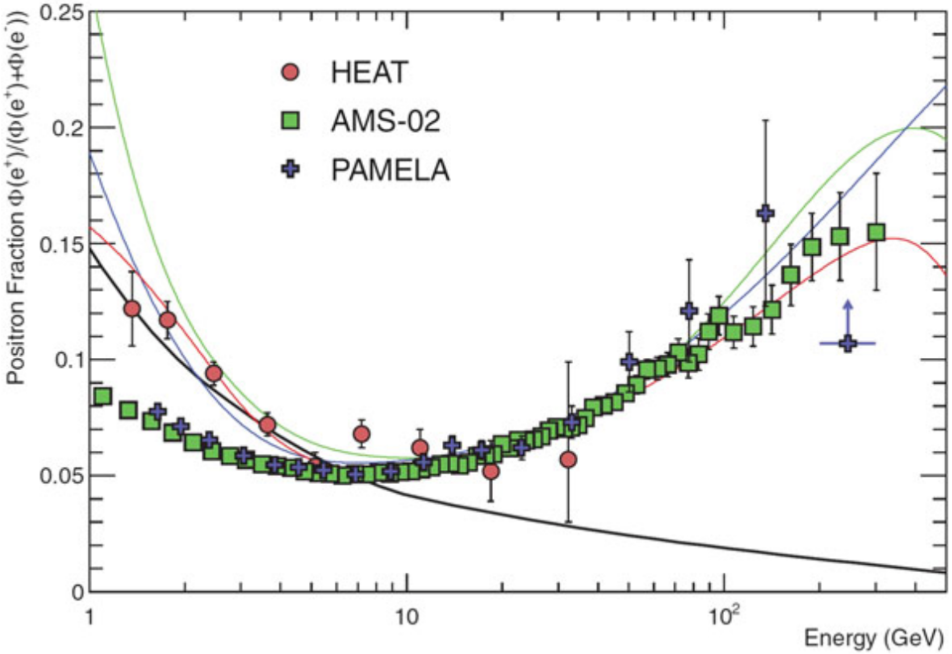
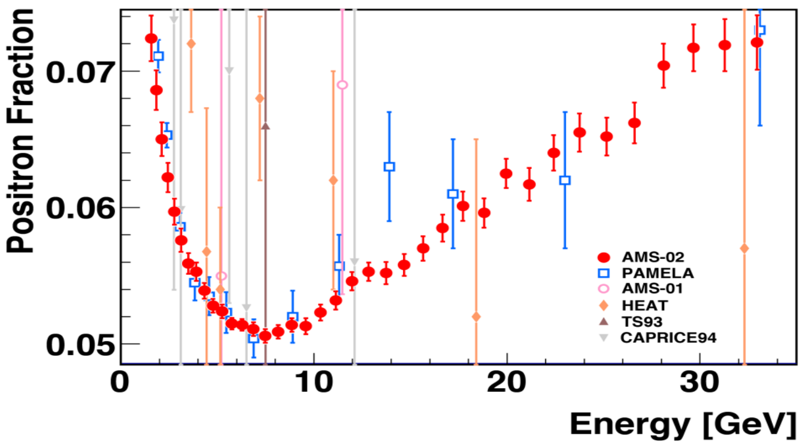


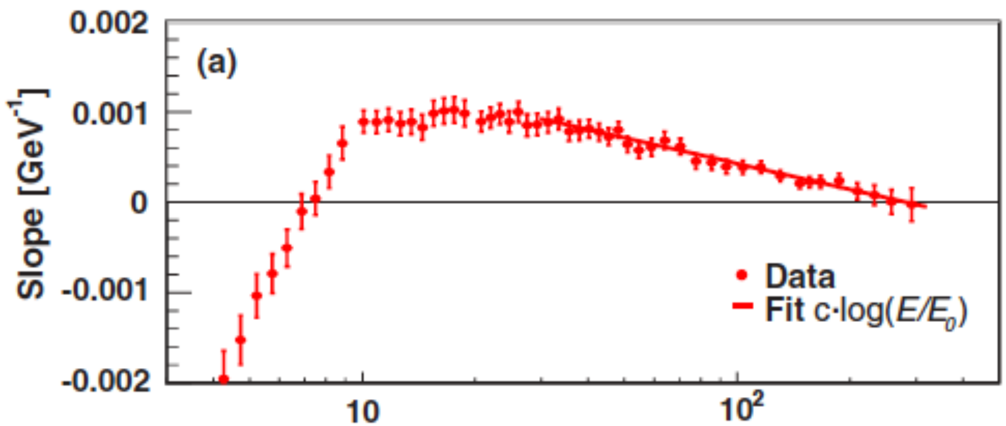
Fig. 3.14 The positron fraction (ratio of the flux of e^+ to the total flux of $e^+ + e^-$) as a function of the energy measured HEAT, PAMELA, and AMS-02. The heavy *black line* is a model of pure secondary production using a detailed propagation model of CRs (Sect. 5.4). The *three thin lines* show three representative attempts to model the positron excess with different phenomena discussed in Sect. 13.9.3: dark matter decay (*green*); propagation physics (*blue*); production in pulsars (*red*). The ratio below 10 GeV is dependent on the polarity of the solar magnetic field. Figure from the Sect. 27. Cosmic Rays of Beringer et al. (2012)

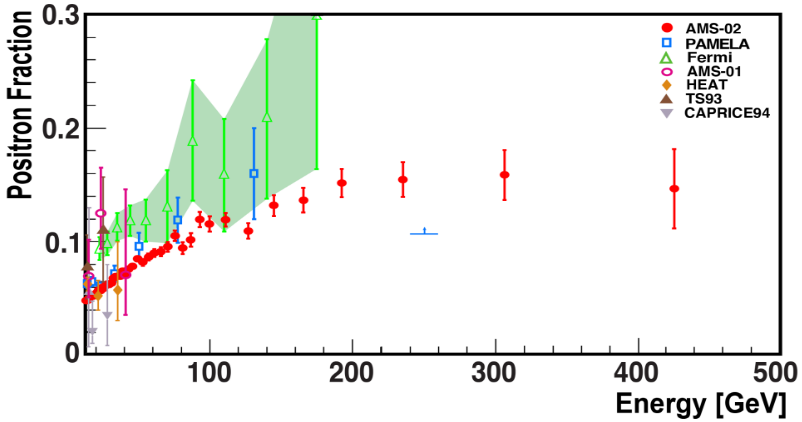
The positron-fraction spectrum does not exhibit fine structures and steadily increases in the region between 10 and 250 GeV. In the high statistics AMS-02 sample the ratio is of the order of ~10 % above a few tens of GeV. As a consequence, since positrons are always created in pair with an electron *about 90 % of the observed electrons must be of primary origin*.

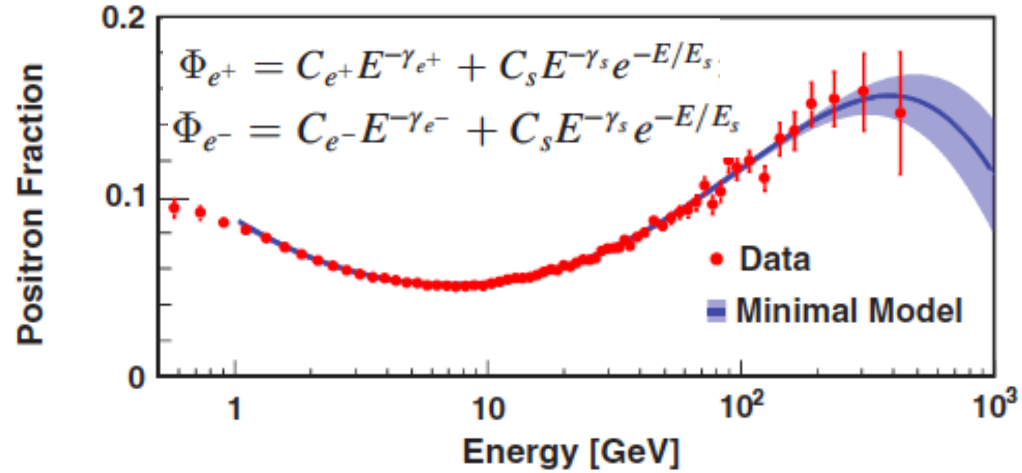
Positron fraction :

- ✓ No sharp structures
- ✓ Steady increase of the positron content up to ≈ 275 GeV
- ✓ Well described by an empirical model with a common source term for e^+/e^-



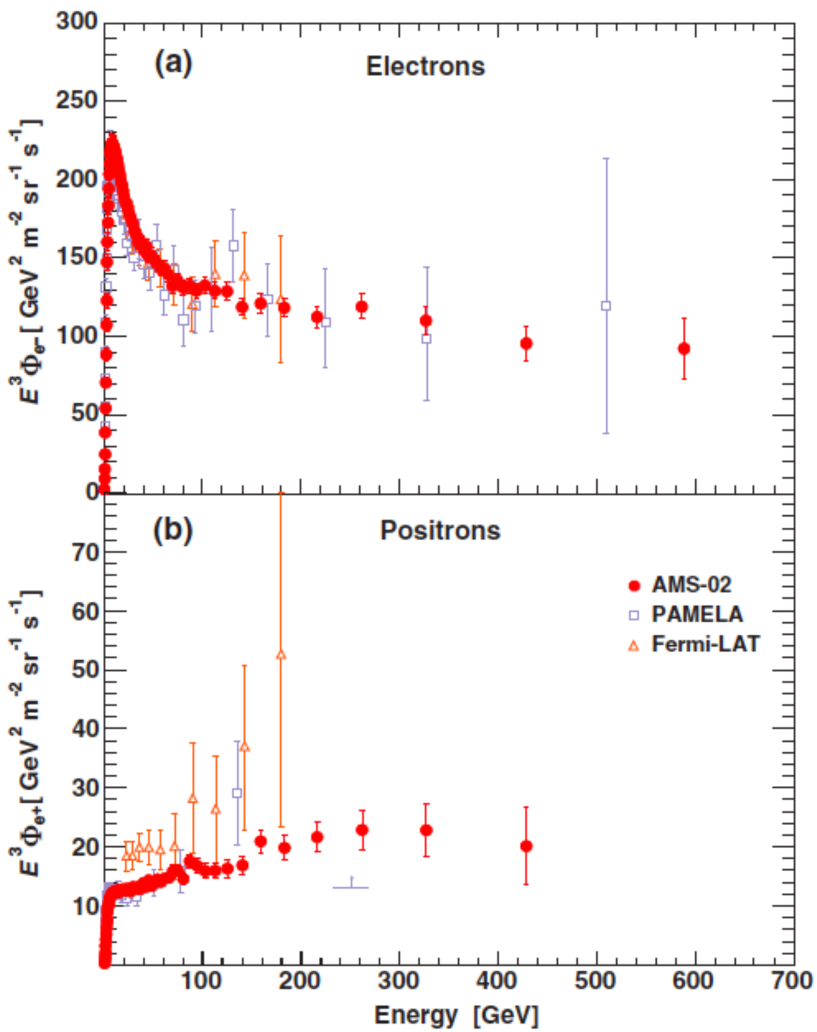


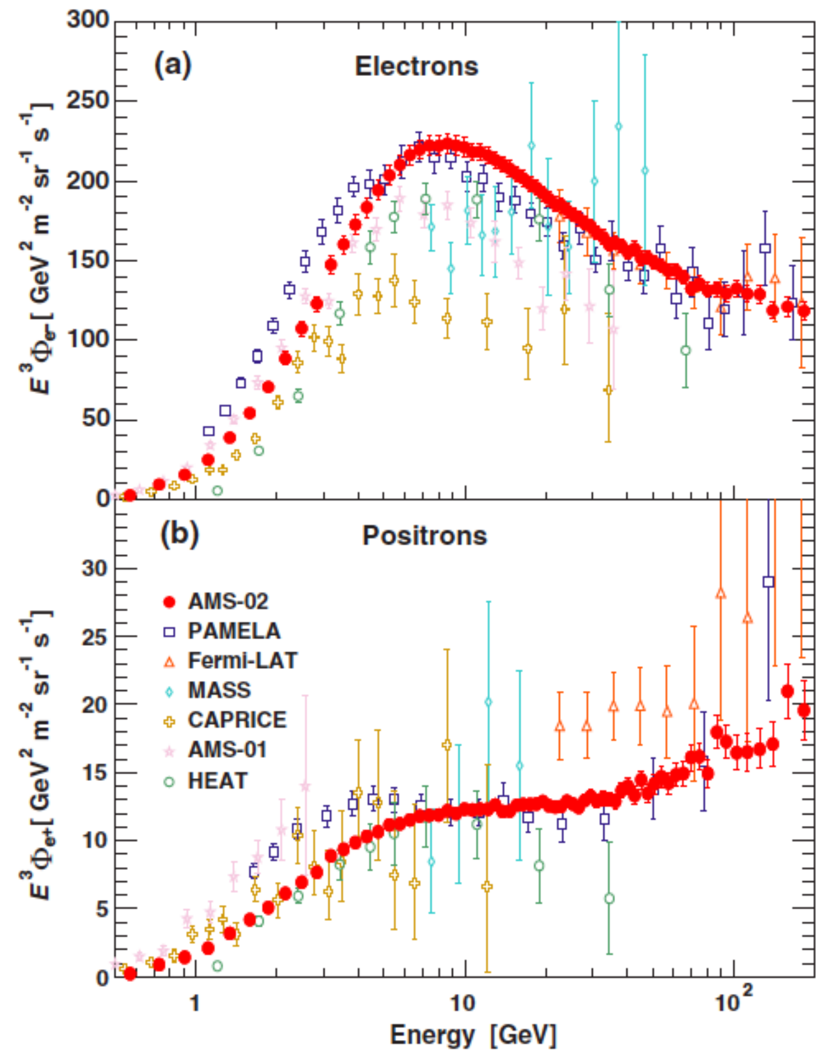




Electron/Positron fluxes:

No sharp structures

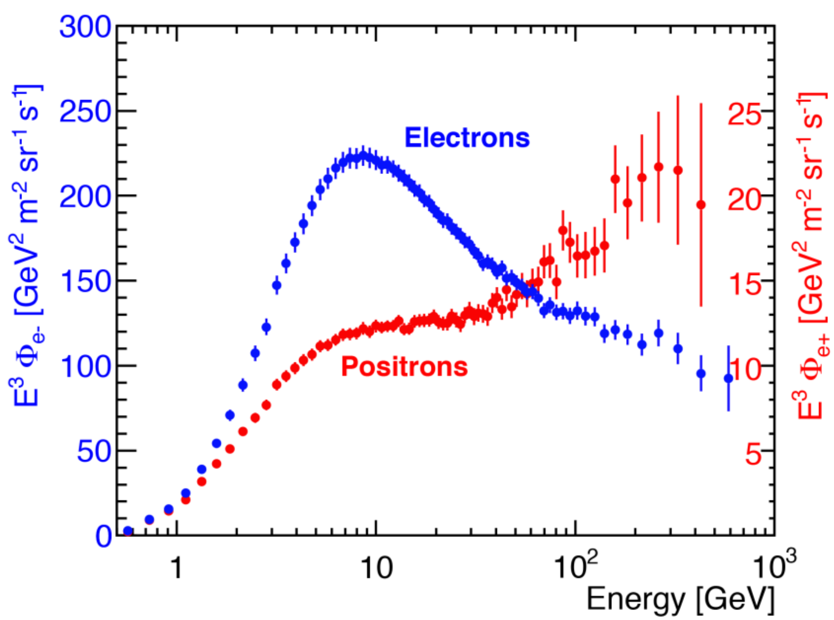


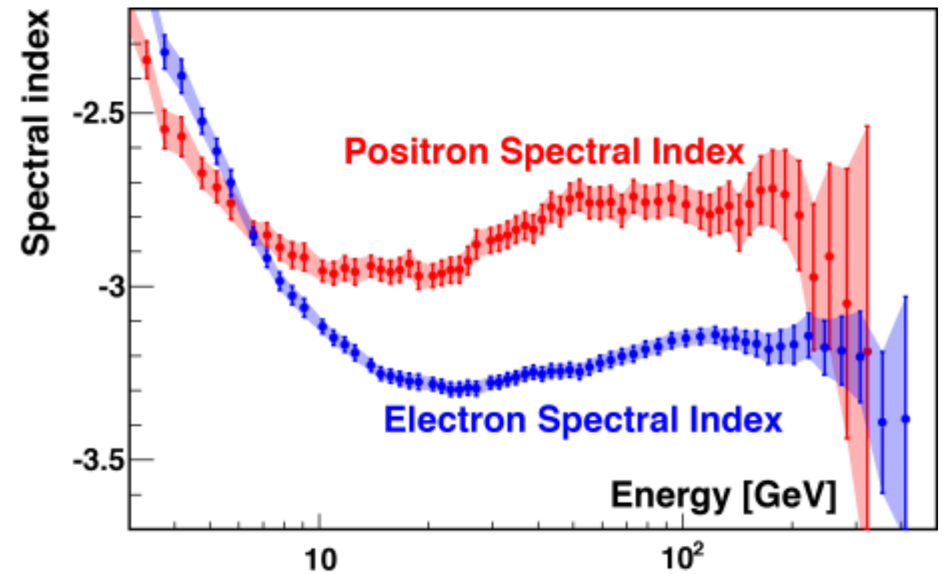


Electron/Positron fluxes:

For the first time a detailed study of the spectral index variation with energy :

$$\gamma_{e^\pm} = d[\log(\Phi_{e^\pm})]/d[\log(E)]$$





Hardening of the positron spectrum is at the origin of the positron fraction increase…

What is the excess?

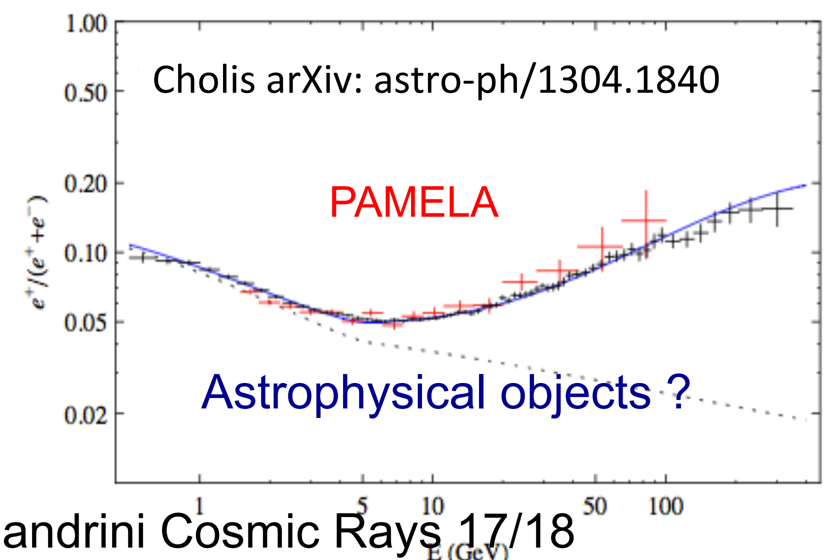
Something “different” with respect conventional models of e^+ production by collisions of CR hadrons with the interstellar matter (ISM):

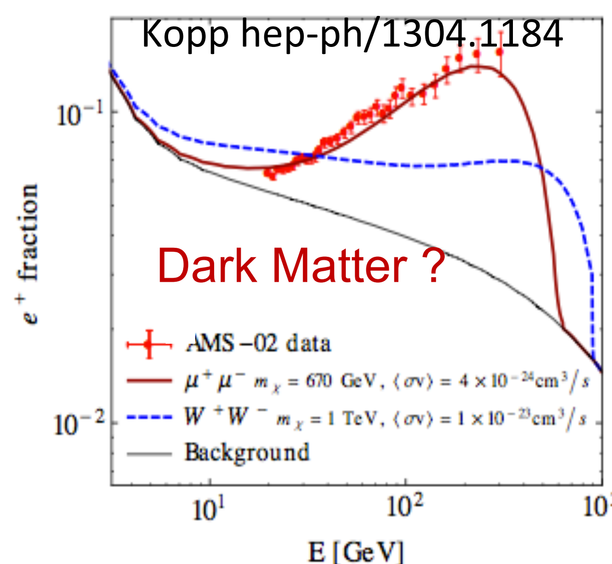
Astrophysical Sources?:

- Local sources as pulsars (slow fall at high energies, anysotropy..)
- Interactions of CR hadrons in old SNR (but this should affect also other secondary species as anti-protons, B/C)

Dark matter?:

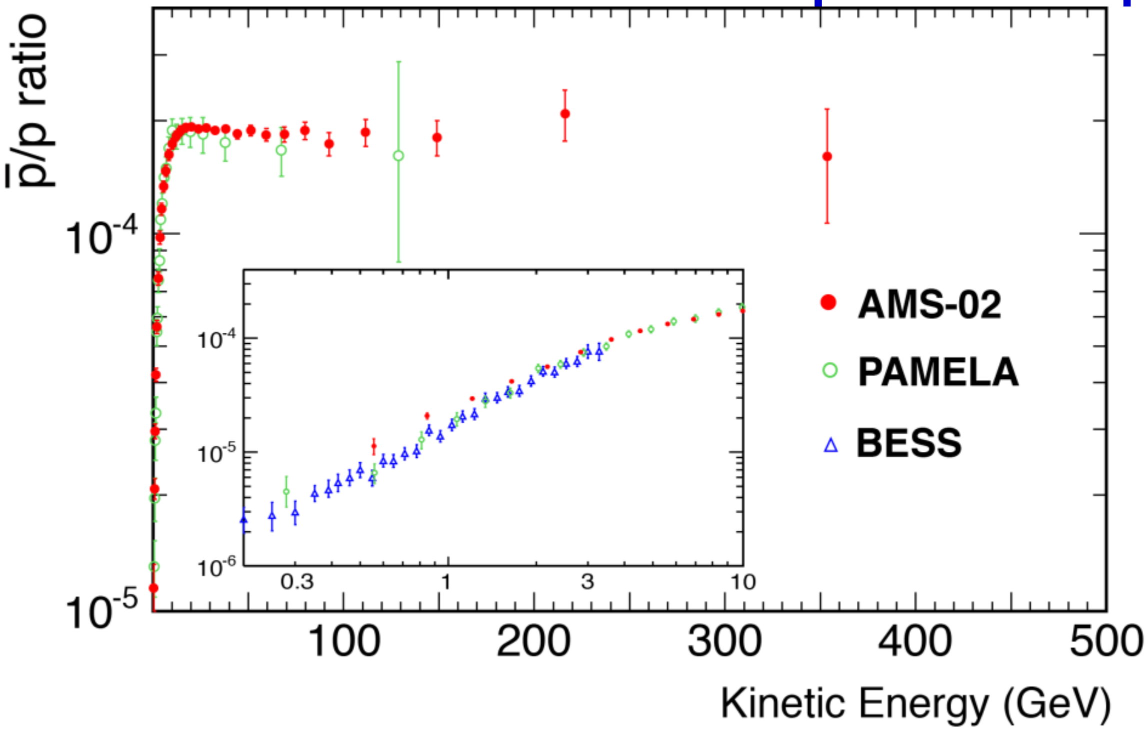
- The mass of the DM particle gives a sharp cutoff with energy
- Isotropic distribution
- Effects also on anti-p





- The electron component declines faster with increasing energy than the baryonic one. At 1 TeV, the ratio between CR electrons and protons is ~10^{-3}.
- The e+/(e− + e+) ratio (~10%) indicates that also most of the detected electrons are of primary origin, although the fraction of secondary leptons is much larger than that of secondary baryons. This is an important information concerning the astrophysical origin of the leptonic component. Due to the presence of magnetic fields, the typical distance over which 1 TeV electrons lose half their total energy is estimated to be 300–400 pc when they propagate within ~1 kpc of the Sun.
- Electrons are affected more readily by energy-dependent diffusive losses, convective processes in the ISM, and perhaps reacceleration during propagation from their sources to us.
- For these reasons, at energies above a few hundred GeV, the majority of electrons is supposed to be originated by sources closer than a few hundred pc. High-energy CR electrons really probe CR production and propagation in the nearby region of our Galaxy.
- Due to their large energy losses, it seems not plausible (contrary to the case of protons and nuclei) that the observed electrons originate from a uniform distribution of sources in the Galaxy. If the source is too far, the probability that an electron reaches the Earth is extremely small. More likely, primary high-energy electrons observed on Earth originate from a small number of sources well localized in space and relatively close (on a scale of galactic distances) to the Solar System.
- Concerning the measured data on the positron fraction above 10 GeV, it has stimulated a large scientific debate. The e+/(e− + e+) ratio cannot be understood by models describing the production of secondary CRs during propagation in the Galaxy. Several theoretical explanations have been proposed to explain the observed excess: an astrophysical origin, such as nearby pulsars or microquasars, or exotic sources, as the annihilation of dark matter particles in the proximity of our Galaxy.

antiprotons p̄/p

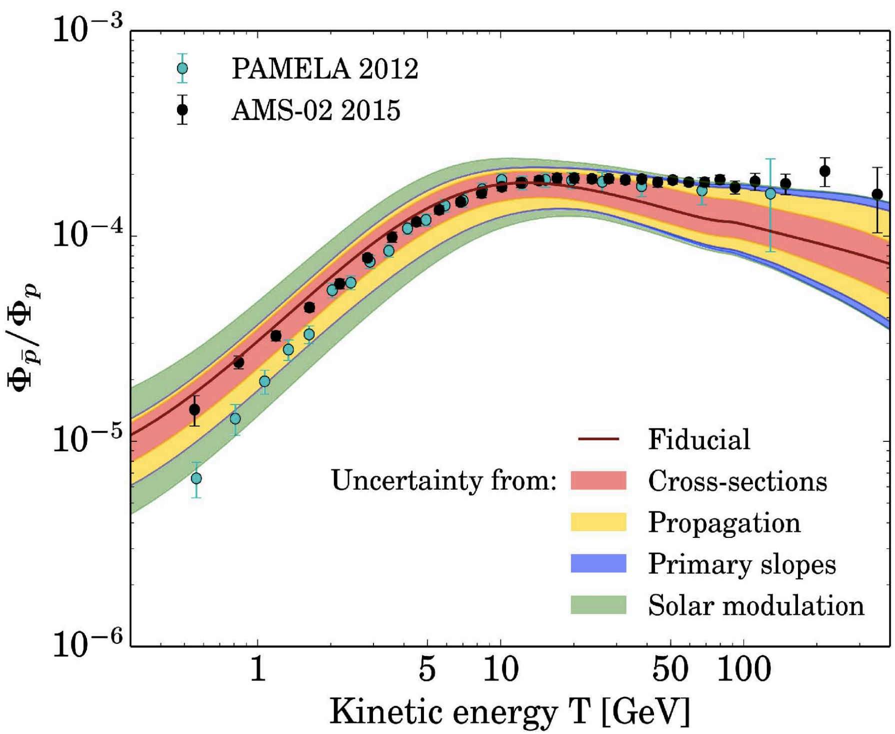


Equal amounts of matter and antimatter should have been produced at the beginning of the Universe as described by the Big Bang model. The fact that there seems to be only matter around us is one of the major unknown facts in cosmology and in particle physics. The possible presence of cosmological antimatter in the Universe is a fundamental physics issue, which can be faced from the experimental point of view.

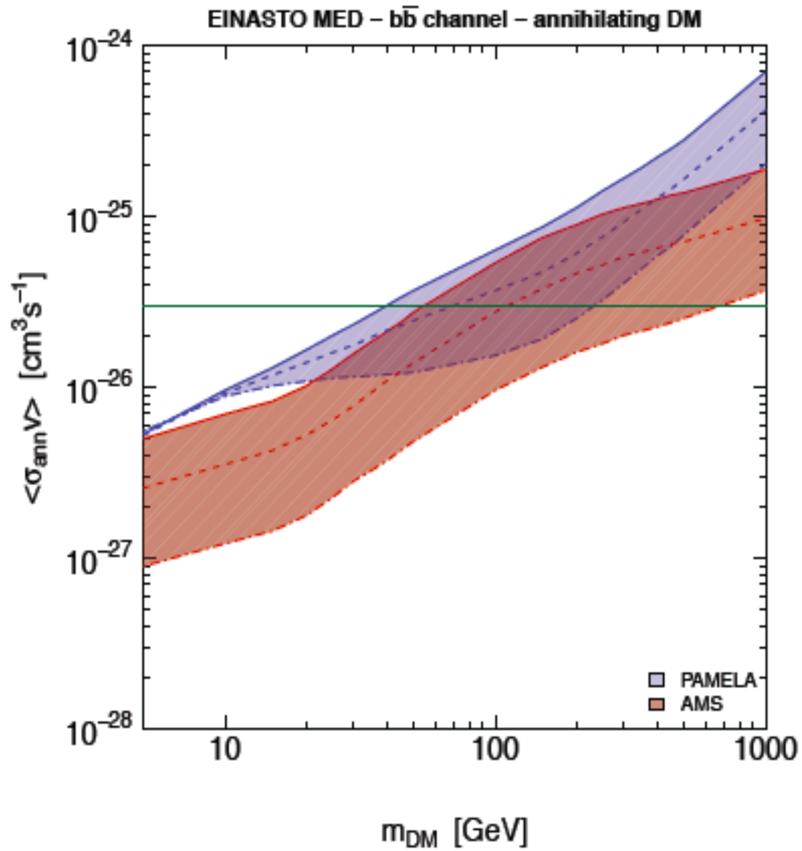
Antiprotons, as well as positrons, are a component of the cosmic radiation produced in the interaction between CRs and ISM. Positrons in CRs were already observed in 1964 and antiprotons in 1979 with balloon-borne magnetic spectrometers. Secondary antiprotons are mainly produced by CR protons interacting with ISM protons p + p → p + p +(p+p-bar) with a threshold of ~7 GeV for a target at rest.
This, together with the falling spectrum of CR (as $E^{-2.7}$), makes the p-bar fraction very small, $10^{-4} – 10^{-5}$

$\bar{p}/p$

The measured spectrum agrees with calculations, consistently with the hypothesis that the observed antiprotons are secondary particles produced by CR interactions with the interstellar medium.
Some room is left for exotic physics, as annihilating DM



Giesen et al, 2015

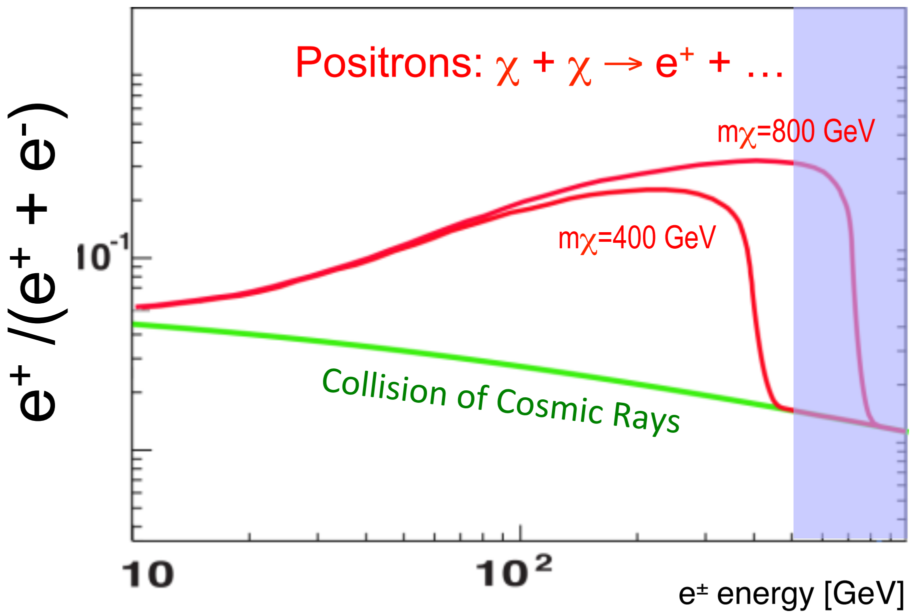


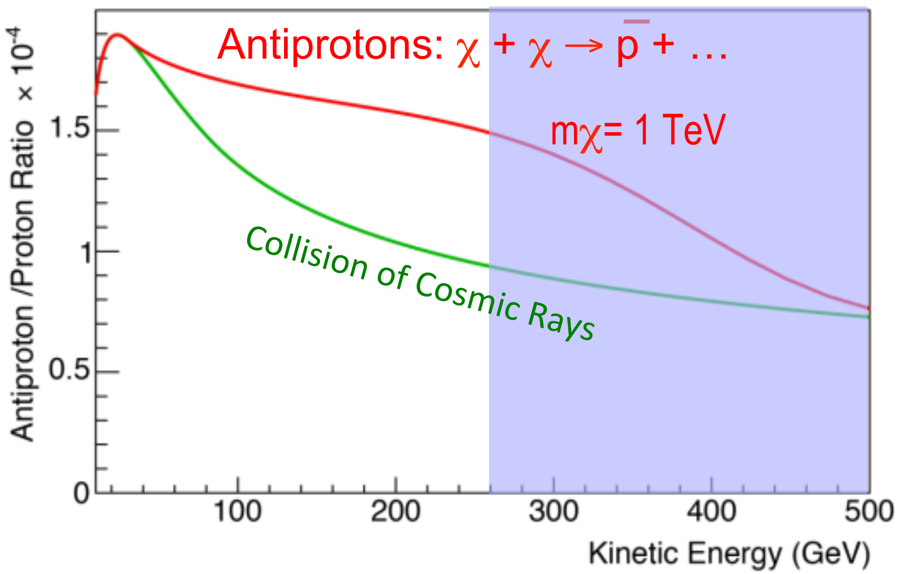
Fornengo, Maccione, Vittino, JCAP 2014

The Search for the Origin of Dark Matter

To identify the Dark Matter signal we need

to measure the e^+, e^- and $\bar{p}$ signal accurately until 2024.



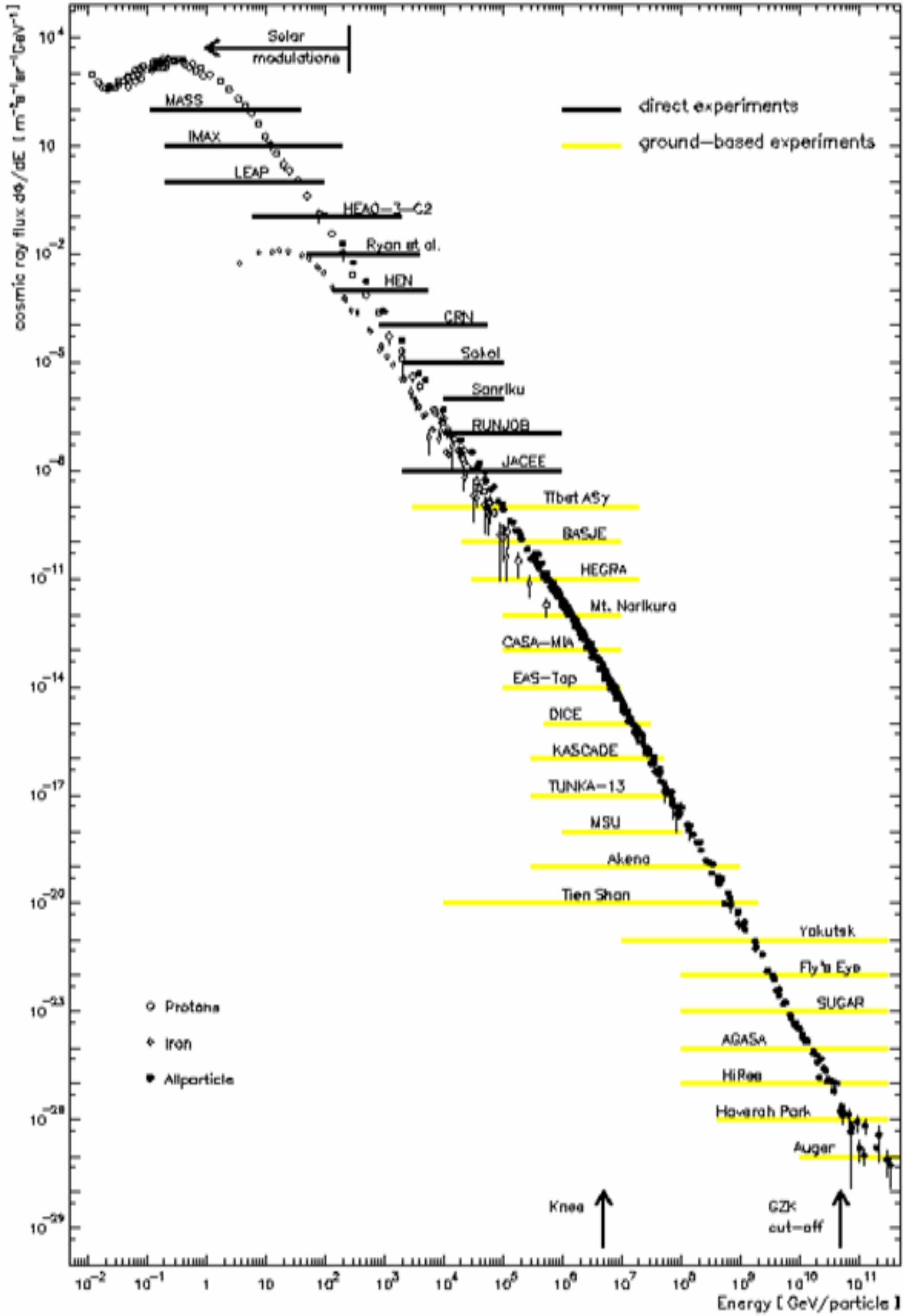


To understand background, we need precise knowledge of:

1. The cosmic ray fluxes (p, He, C, …)
2. Propagation and Acceleration (Li, B/C, …)

Ultra High Energy Cosmic Rays (UHECR)

- The particles can be “easily” identified (mass and absolute charge) up to energies of 10^6 GeV by direct measurements (spectrometric and calorimetric)
- Flux measured up to Ni
- At higher energies, searches are indirect
- At higher energies, the CR composition is still much uncertain because of avalaible experimental tecniques, as Extended Shower in Atmosphere or EAS or Imaging of Cherenkov light, as examples, affected by large systematic uncertainties and with low stat
- Flux is usually presented as “all particle” flux



Spettro dei raggi cosmici

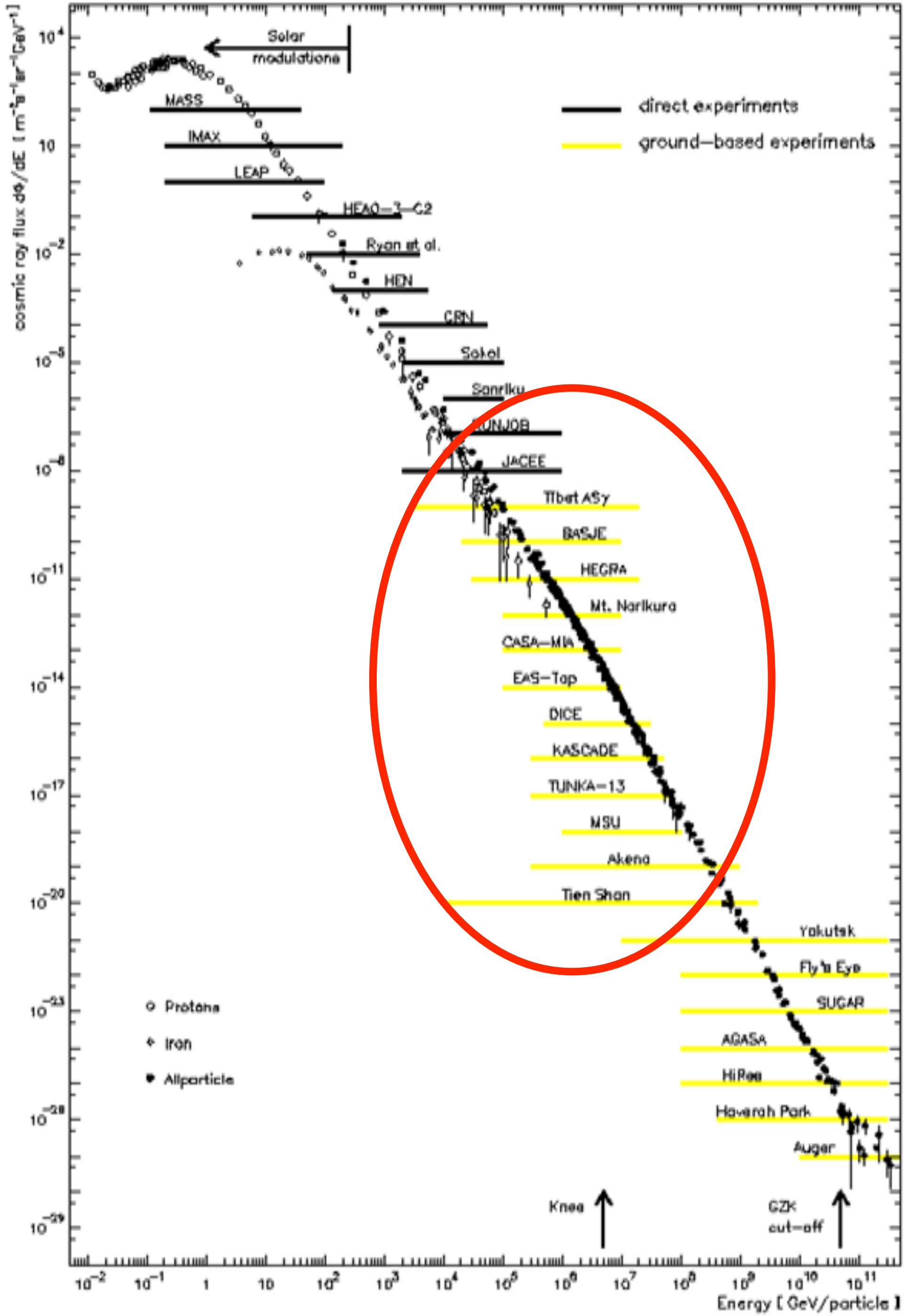
$\Phi_{TOT} \sim 1000\ m^{-2}s^{-2}sr^{-1}$

Misure dirette: 85% p, 12% He, 1% nuclei pesanti, 2% e+,e-, γ

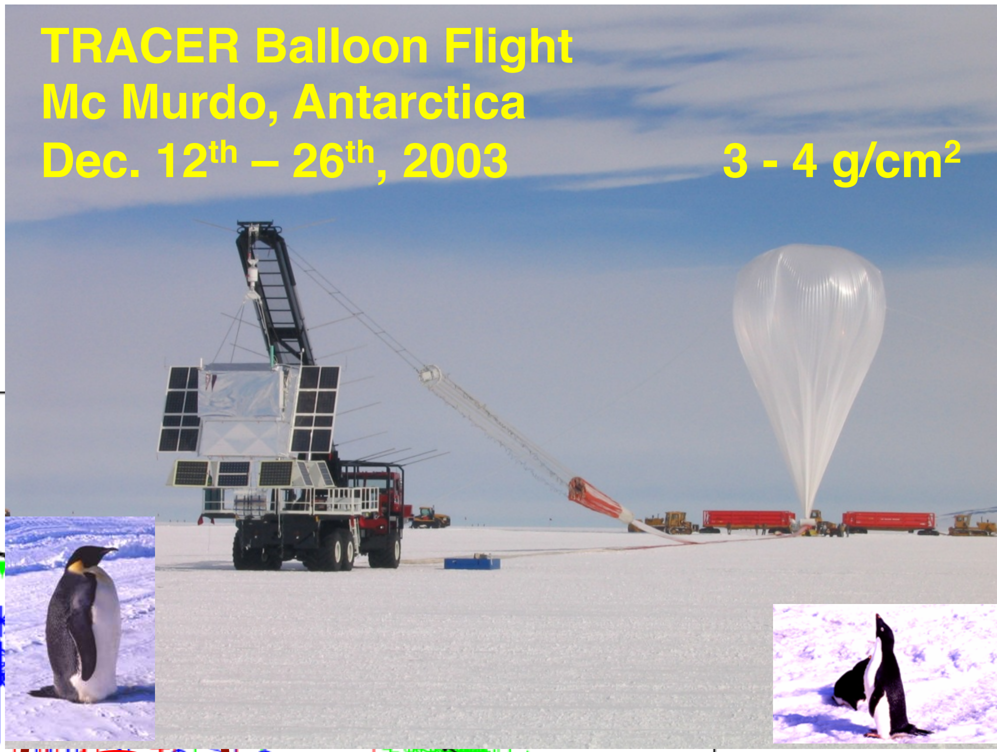
Si estende per 13 ordini di grandezza in energia

Per 32 ordini di grandezza in flusso

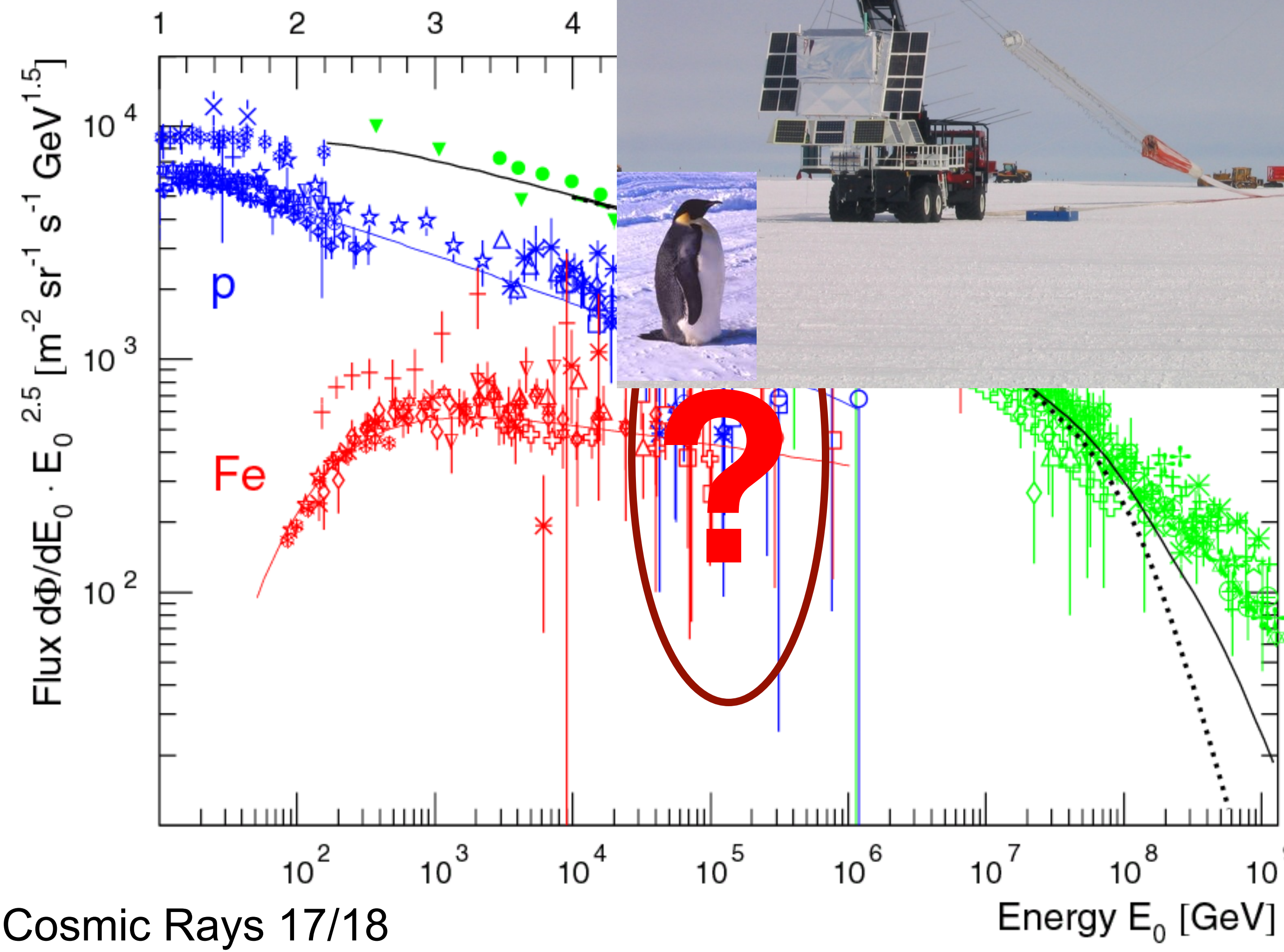
Legge di potenza su tutto lo spettro, con due cambi di pendenza



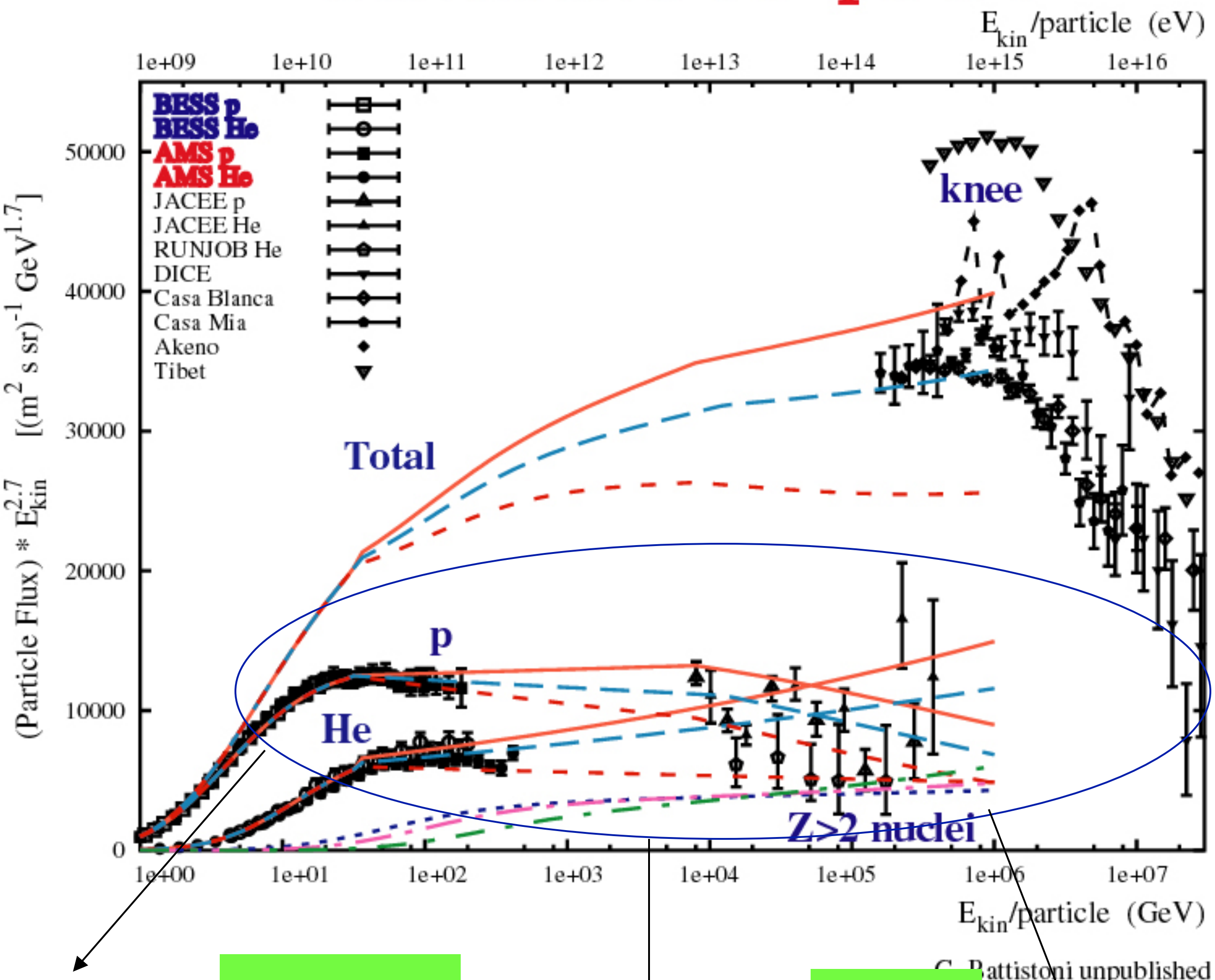
The Knee in the Energy Spectrum of Cosmic Rays



Cosmic-ray energy spectrum



CR Hadronic Component



Hydrogen

- 0.1 GeV $\lesssim$ E $\lesssim$ 100 GeV

  Spectrometers: within 5%

- 100 GeV $\lesssim$ E $\lesssim$ 1 TeV

  Calorimeters: within $\approx$ 25%

- 1 TeV $\lesssim$ E $\lesssim$ 1000 TeV

  Emulsion Chambers: within $\approx$ 25%

Helium

- 0.1 GeV $\lesssim$ E $\lesssim$ 100 GeV

  Spectrometers: within 10%

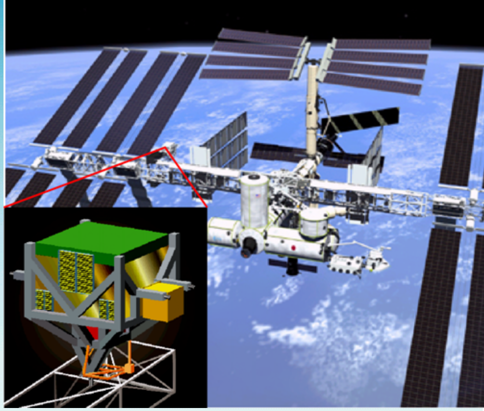
- E $\gtrsim$ 100 GeV

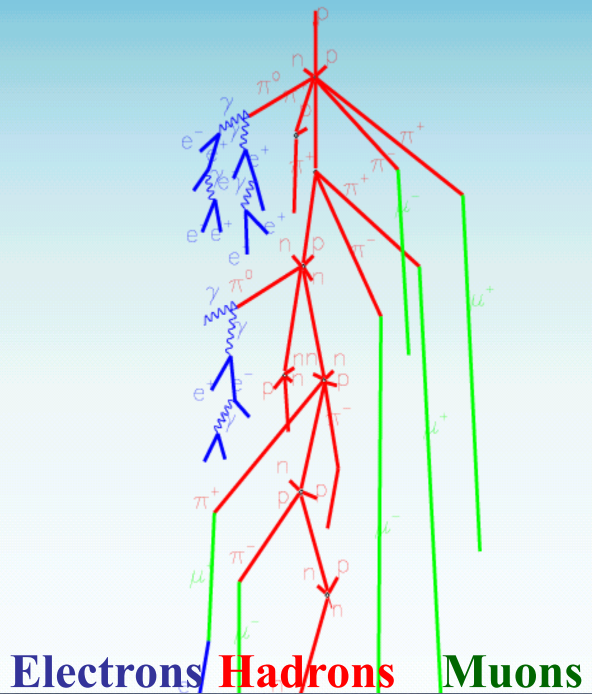
  Emulsion Chambers: Poor statistics

Z>2

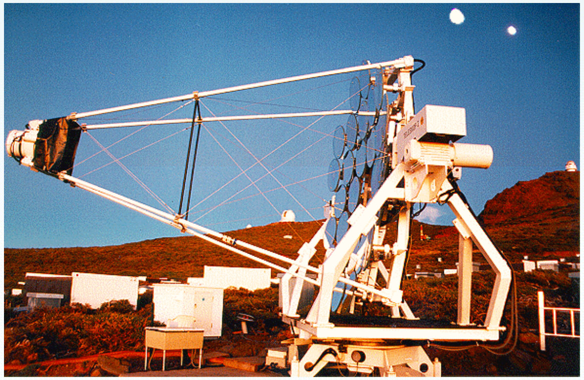
- Absolute fluxes from 0.6 to 35 GeV/n
- Systematic Errors $\sim$ 5%

Observation of cosmic rays

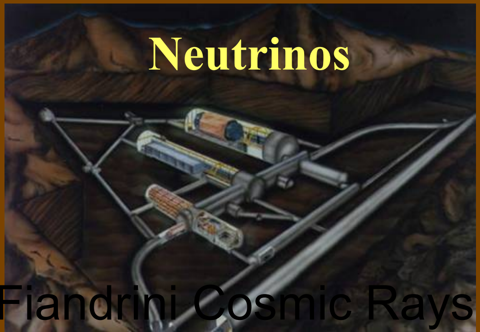




Fluorescence light



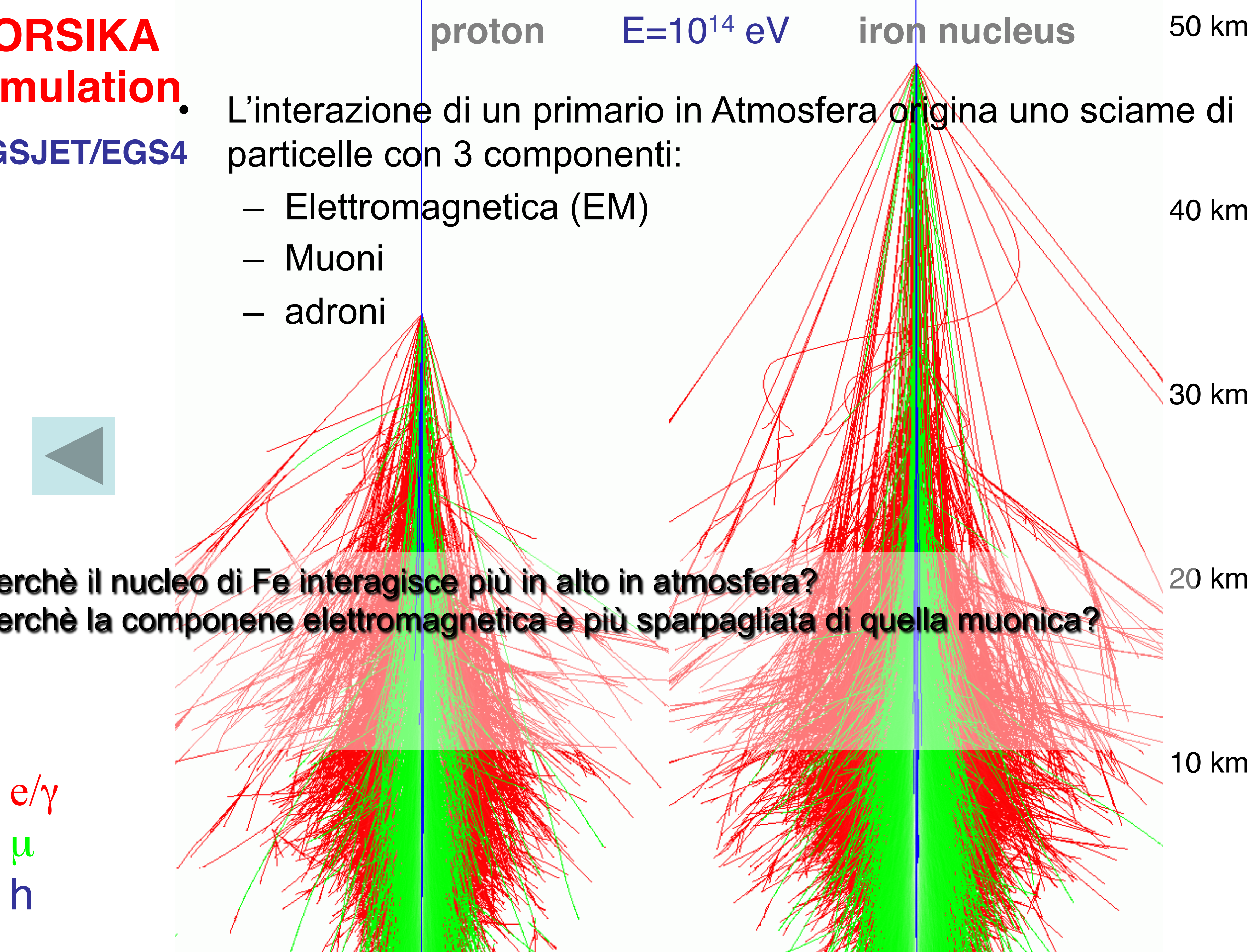
Cerenkov light
(imaging & non-imaging)



CORSIKA Simulation

QGSJET/EGS4

- L'interazione di un primario in Atmosfera origina uno sciame di particelle con 3 componenti:
  - Elettromagnetica (EM)
  - Muoni
  - adroni



Perchè il nucleo di Fe interagisce più in alto in atmosfera?
Perchè la componene elettromagnetica è più sparpagliata di quella muonica?

- P e nuclei interagiscono sulla sommità dell'atmosfera con lunghezza interazione λ

$$\lambda = \frac{A}{\sigma_{p-Aria} N_A} \cong 65 g \cdot cm^{-2}$$

- Spessore atmosfera= 1000 g cm^{-2}
- Numero di lunghezze di interazione = 1000/65 ~15
- I RC interagendo coi nuclei dell'atmosfera generano uno sciame

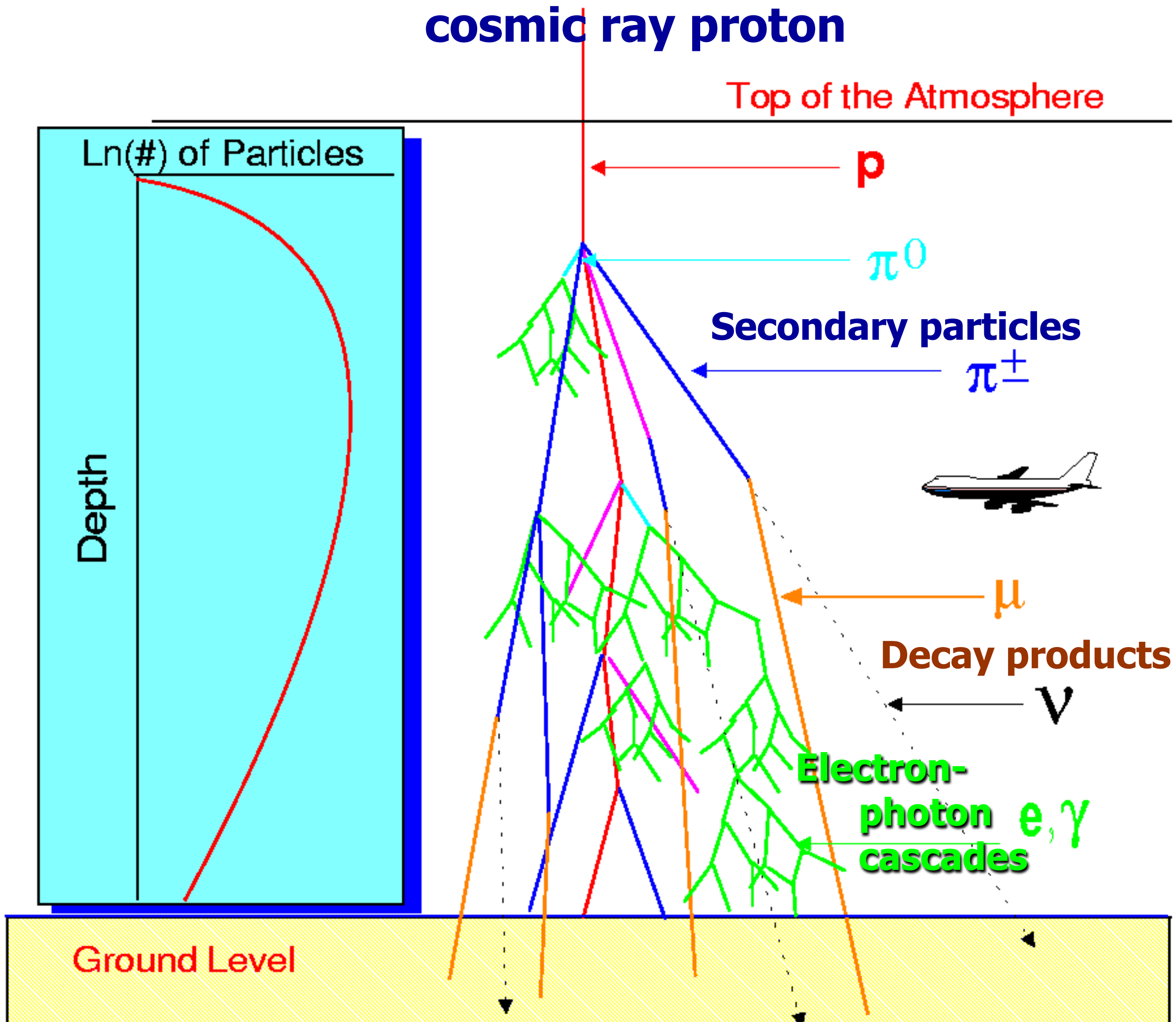
$$p + N \longrightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K, p, n, +....(exotic)$$

$$\pi^{0} \longrightarrow \gamma\gamma \qquad \tau_{\pi} = 1.8 \cdot 10^{-16} s$$

$$\pi^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu} \qquad \tau_{\pi} = 2.5 \cdot 10^{-8} s$$

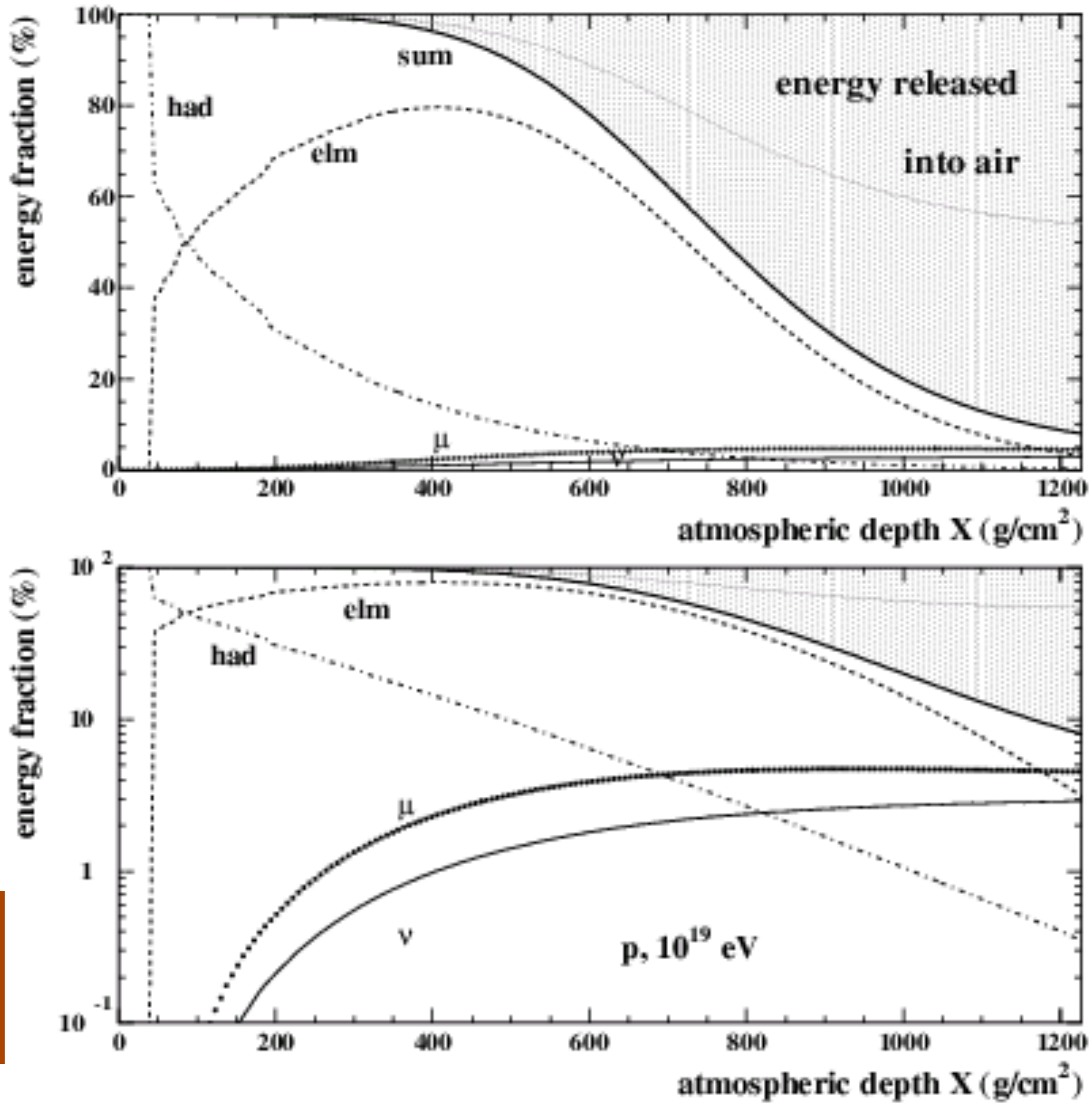
$$\mu^{\pm} \longrightarrow e^{\pm}\nu_{e}\nu_{\mu} \qquad \tau_{\pi} = 2.2 \cdot 10^{-6} s$$

Le componenti dello sciame



Caratteristiche generali dello sciame

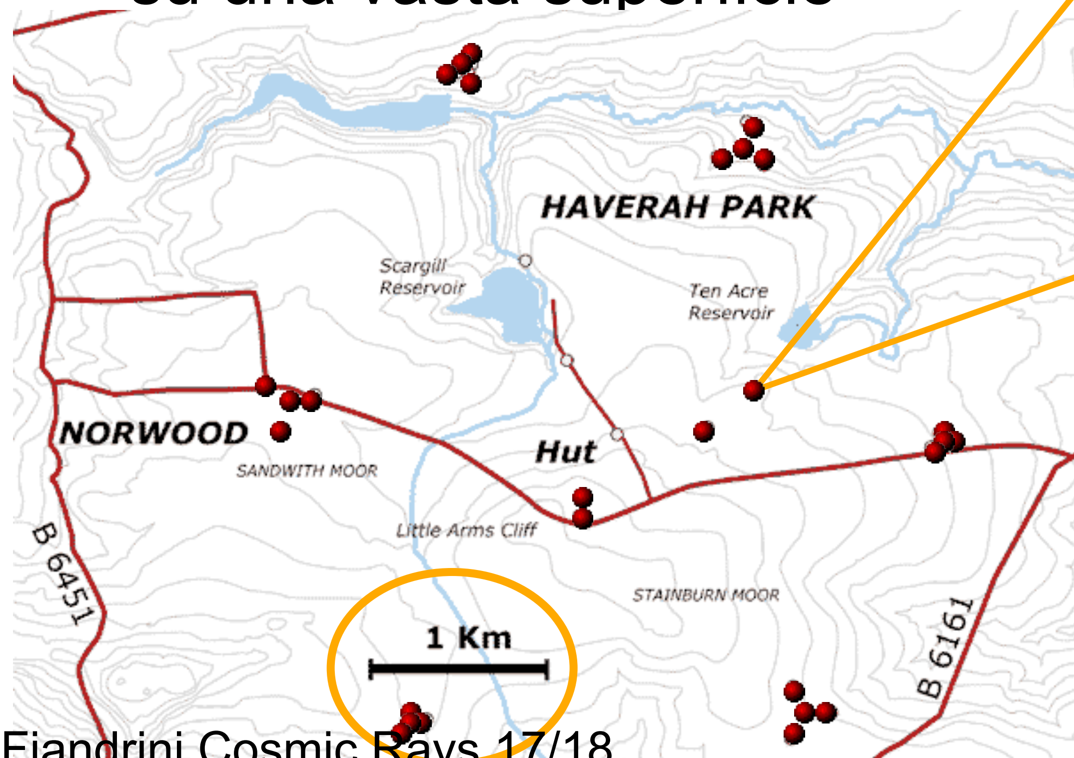
- Gli adroni vengono esponenzialmente attenuati
- Lo sciame EM si sviluppa esponenzialmente sino ad un massimo, la cui profondità aumenta con E_o (E primario)
- Sulla superficie terrestre (ed underground), prevalentemente muoni

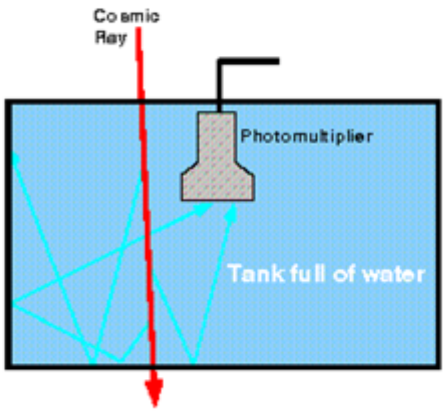


Domanda: *che differenza c'è tra le 2 figure?*

Rivelatori di Sciami

- Apparati sperimentali (Extensive Air Shower Arrays, EAS) che misurano sciami estesi sono in genere situati in alta quota.
- Misurano lo sciame “campionandolo” su una vasta superficie

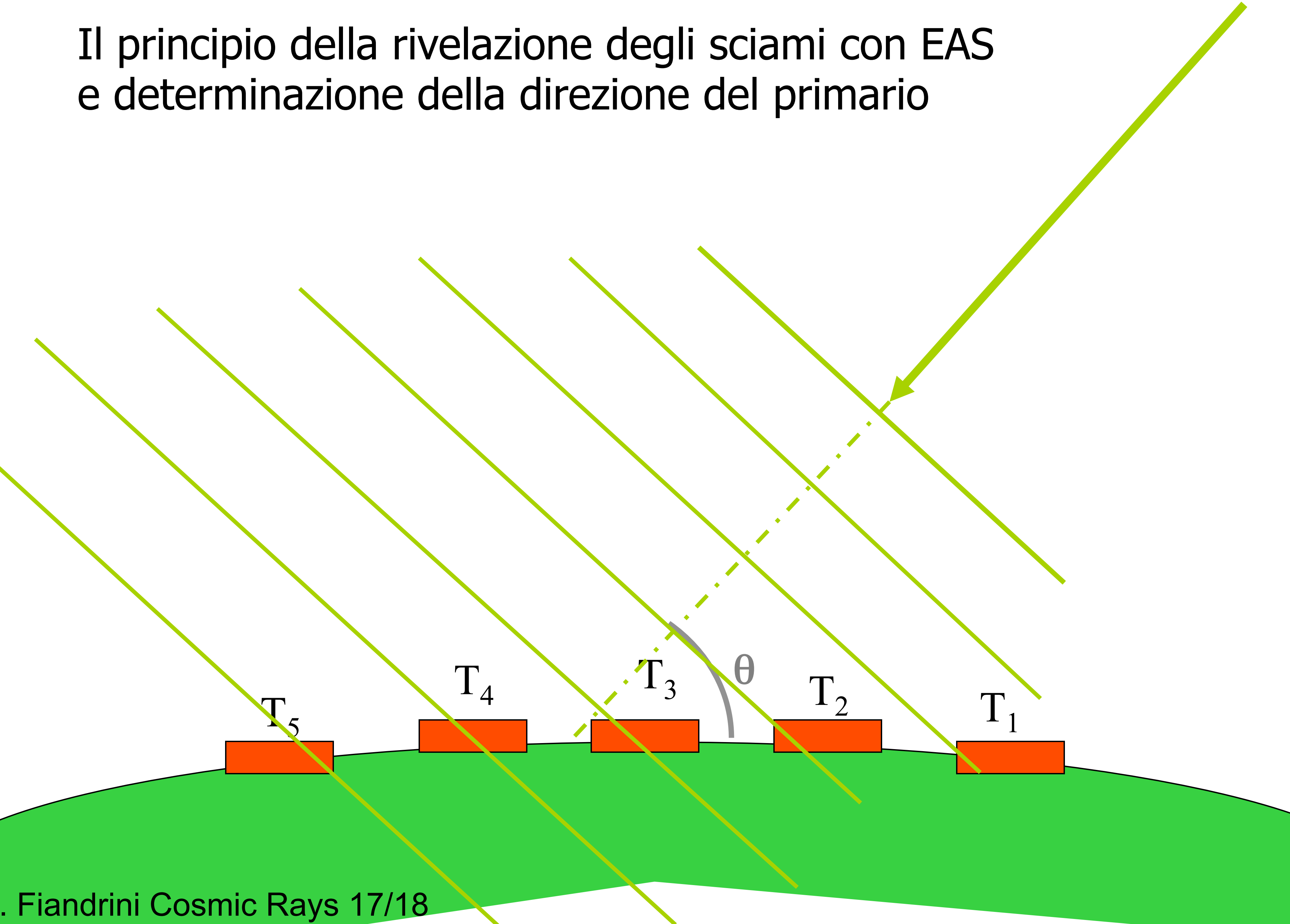




LA FISICA DELLO SCIAME ESTESO

- La distanza media tra i contatori determina la *energia minima* dello sciame rivelabile.
- Il numero dei contatori, la *precisione* della misura
- L'area totale coperta, determina la *massima energia* misurabile.
- Ciascun contatore (*casetta*) misura in modo proporzionale la perdita di energia delle particelle che lo attraversa; da qui, si risale al numero di particelle incidenti
- Dalle misure della densità di particelle in ciascuna casetta dell'array, si risale alla distribuzione laterale *D(r)*.
- Dalla misura di *D(r)* si risale all'energia del primario, *e dalla frequenza del numero di conteggi* si risale al flusso.
- La direzione dello sciame può essere determinata dalla *misura dei tempi di ritardo temporale* nell'arrivo dello sciame su diverse casette (le particelle dello sciame sono ⊥ al suo asse)

Il principio della rivelazione degli sciami con EAS
e determinazione della direzione del primario



La misura del flusso RC con EAS

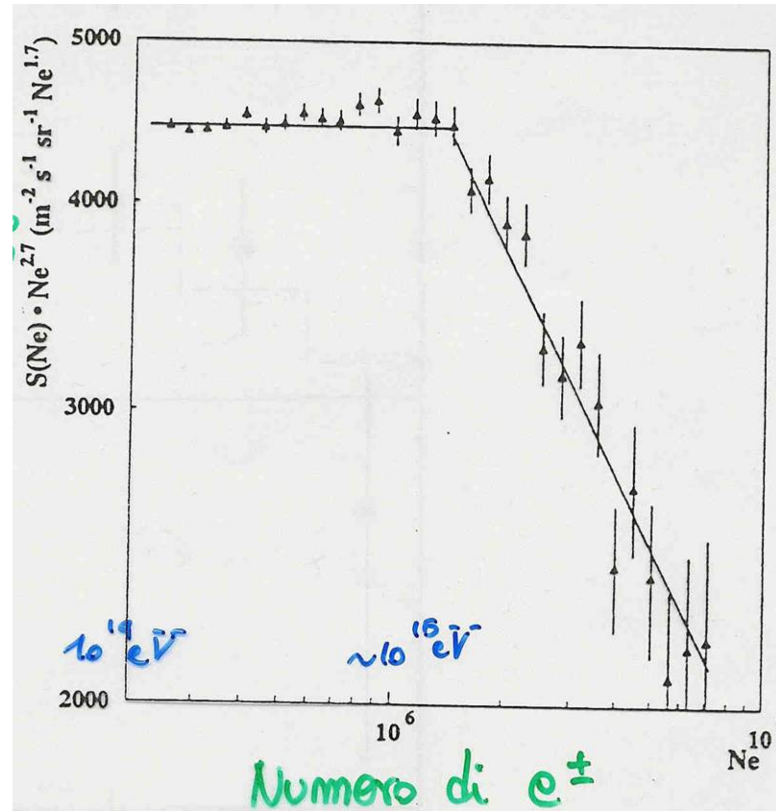
- Gli EAS sono diversi, ed errori sistematici del 20% sono tipici per la misura dell'energia del primario
- Lo spettro energetico misurato nell'intervallo $10^{16}<Eo<10^{19}$ eV è dato dalla funzione:

$$\Phi(E) = K \cdot E^{-3.1} \qquad cm^{-2}\, s^{-1} sr^{-1} GeV^{-1}$$

- La regione tra $10^{14}<Eo<10^{15}$ eV è detta ***Ginocchio***, a causa del cambiamento di pendenza.
- I RC sono completamente isotropi.
- I RC si arricchiscono di nuclei pesanti nella regione oltre il ginocchio, sino ad energie $Eo<10^{19.}$

Esempio: EAS-TOP

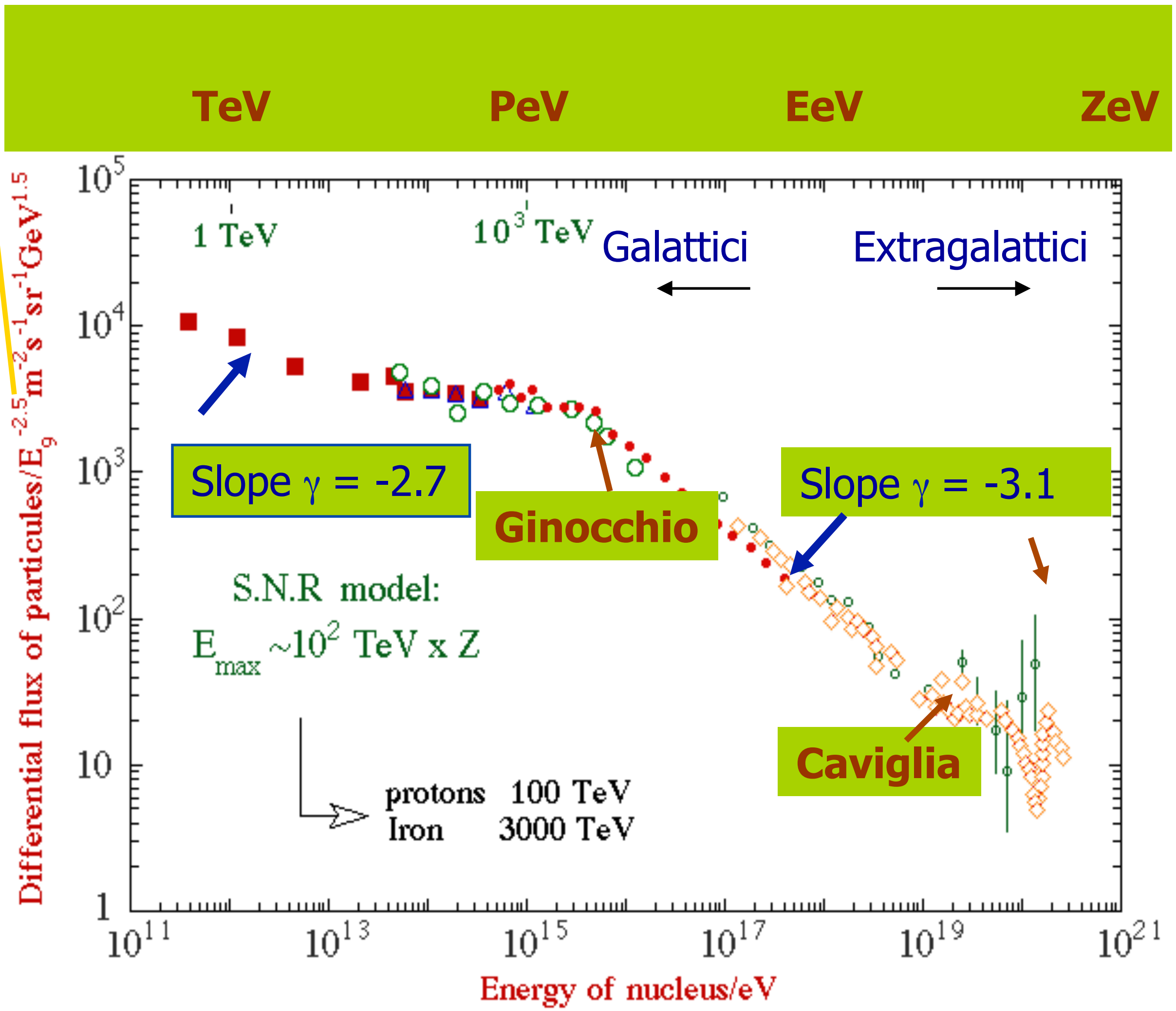
- In figura, un esempio della misura del flusso di primari a Campo Imperatore (EAS-TOP, x_o=810 g cm^{-2})
- Si nota un cambiamento nella frequenza di conteggi, quando il numero di particelle rivelate è Ne>1.5 10^6.
- PROBLEMA: Il cambiamento di pendenza è dovuto a ***variazioni delle interazioni tra RC e nuclei***, oppure ad effetti di ***propagazione*** o ***produzione*** dei RC?



Differential shower size spectrum measured at x_0

Ancora lo spettro dei RC, ma…

L'asse y viene moltiplicato per $E^{2.5}$, in modo da rendere "più piatta" la figura, ed accentuare il ***cambiamento di pendenza!***



I dati sperimentali

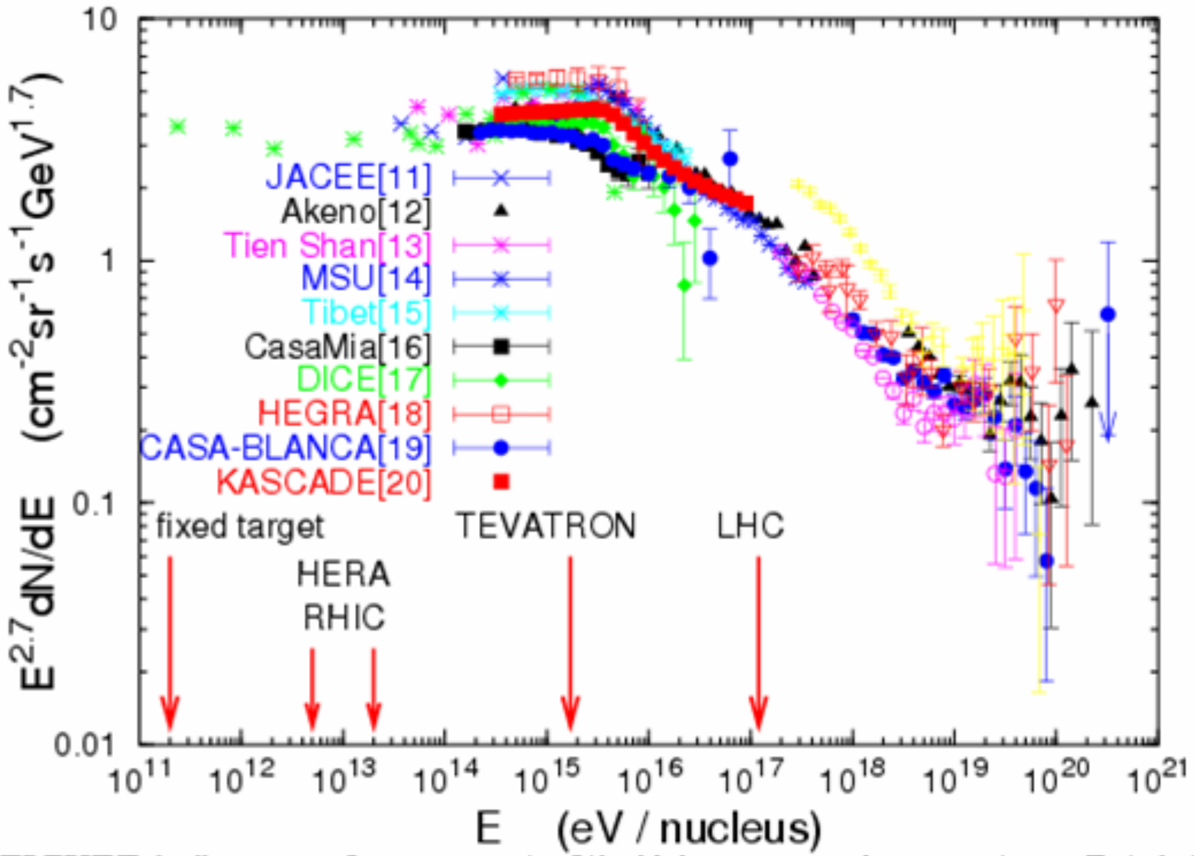


FIGURE 1. Summary of measurements of the high energy cosmic-ray spectrum. Data below 100 TeV are from a satellite detector [10]. Data in the knee region are from Refs. [11–20]. References for data above 10^{17} eV are given in Fig. 4.

Composizione chimica dei RC nella regione degli EAS

- I modelli di propagazione prevedono un arricchimento di elementi pesanti nei RC sino al ginocchio.
- Gli EAS possono misurare <A> con difficoltà.
- Le misure possono essere poi confrontate con *modelli estremi* (solo p o Fe) via MC