Lecture 1

Introduction to Cosmic Rays

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Overview

1. Observations of Cosmic Rays, from GeV to 10^{20} eV

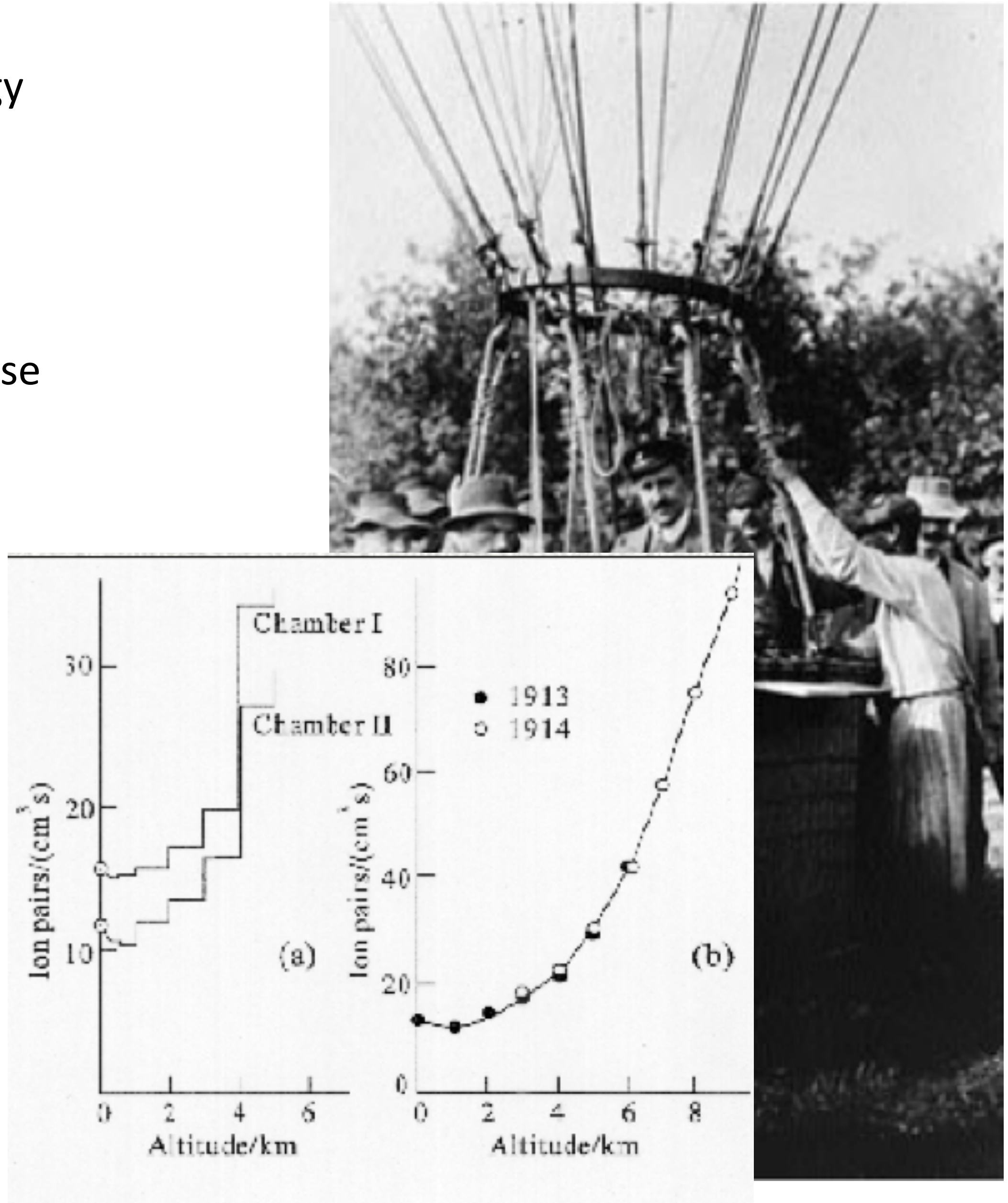
2. Problem of the origin of Cosmic Rays

3. Propagation of Cosmic Rays in the Galaxy and in the Intergalactic Medium

High-energy particles from space

Cosmic Rays (CR) are charged high-energy particles coming from outside the atmosphere.

Discovered ~100 yr ago by V.Hess, via detection of increase of the rate of discharge of an electrometer with increase fo the altitude.



High-energy particles from space

Air density on the ground $\rho_0 \approx 10^{-3}$ g/cm^3 or $n_0 \sim \rho/m_p \approx 10^{21}$ cm^{-3}. Mean free path CR protons through the air

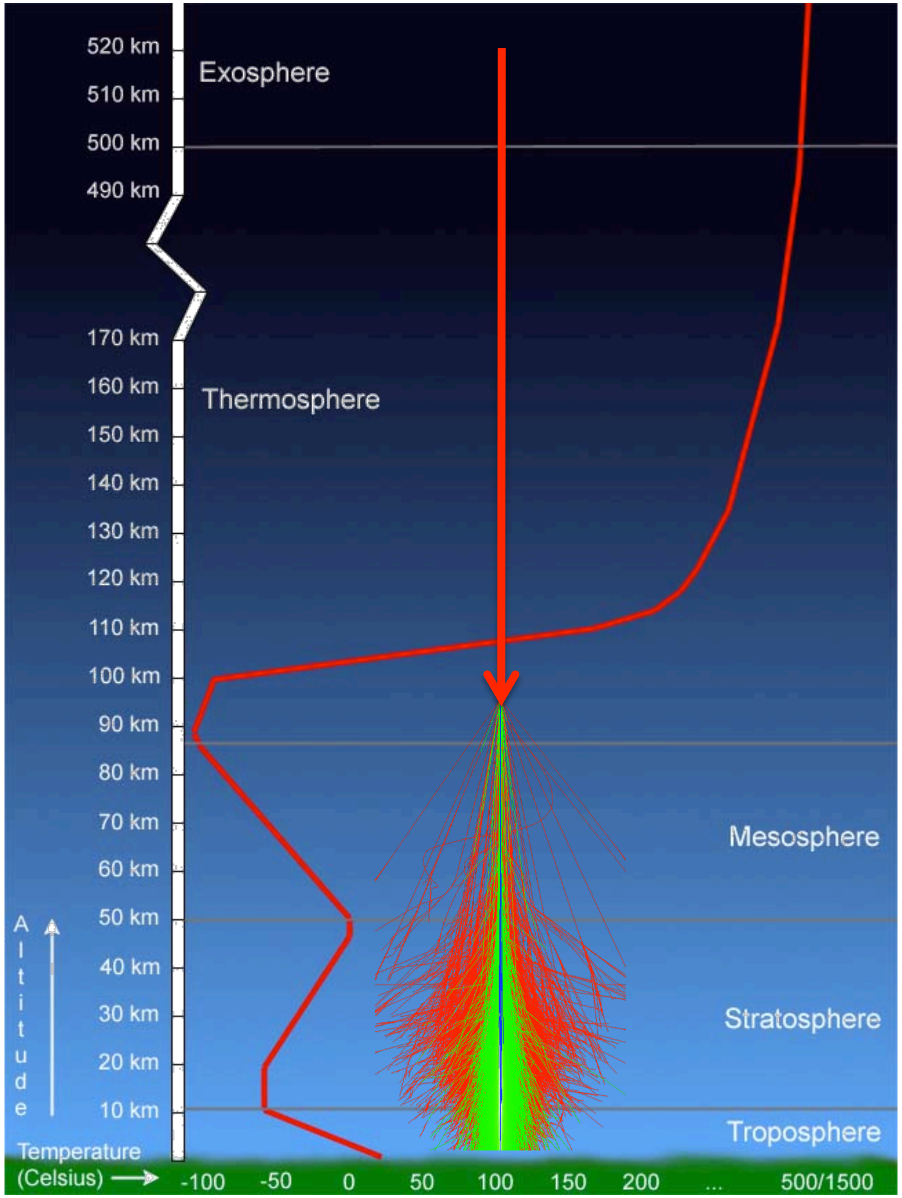
$$\lambda = \frac{1}{\sigma_{pp} n} \sim 1 \left[\frac{\sigma_{pp}}{10^{-26}\mathrm{cm}^2}\right]^{-1} \left[\frac{n}{10^{21}\mathrm{cm}^{-3}}\right]^{-1} \mathrm{km}$$

This is much smaller than the atmosphere scale height H~8 km (defined at the scale height of decrease of the density of the air: $n = n_0 \exp(-z/H)$

Primary CR particles do not penetrate through the atmosphere down to the ground level.

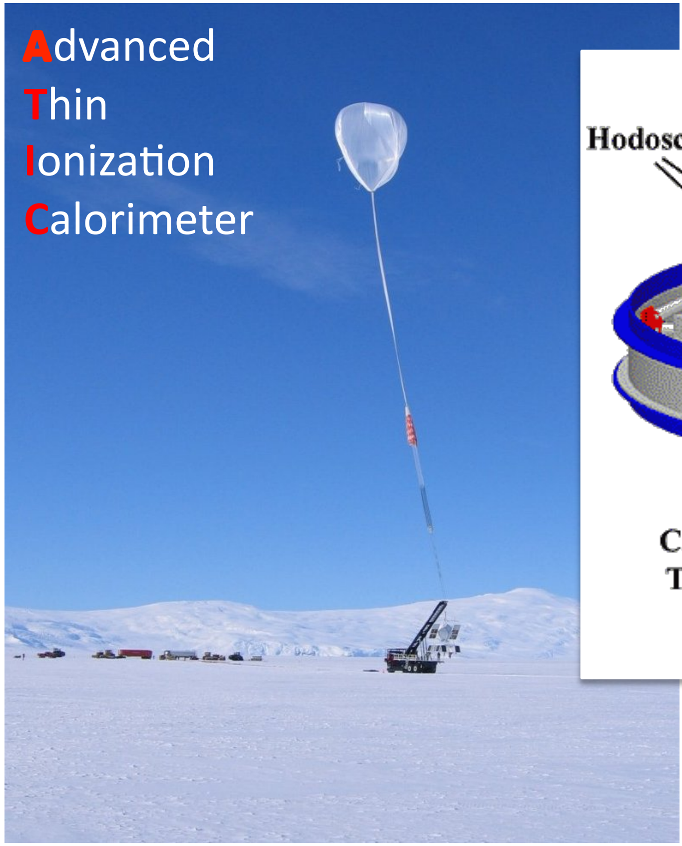
Instead, they initiate particle cascades (particle "air showers") in the atmosphere.

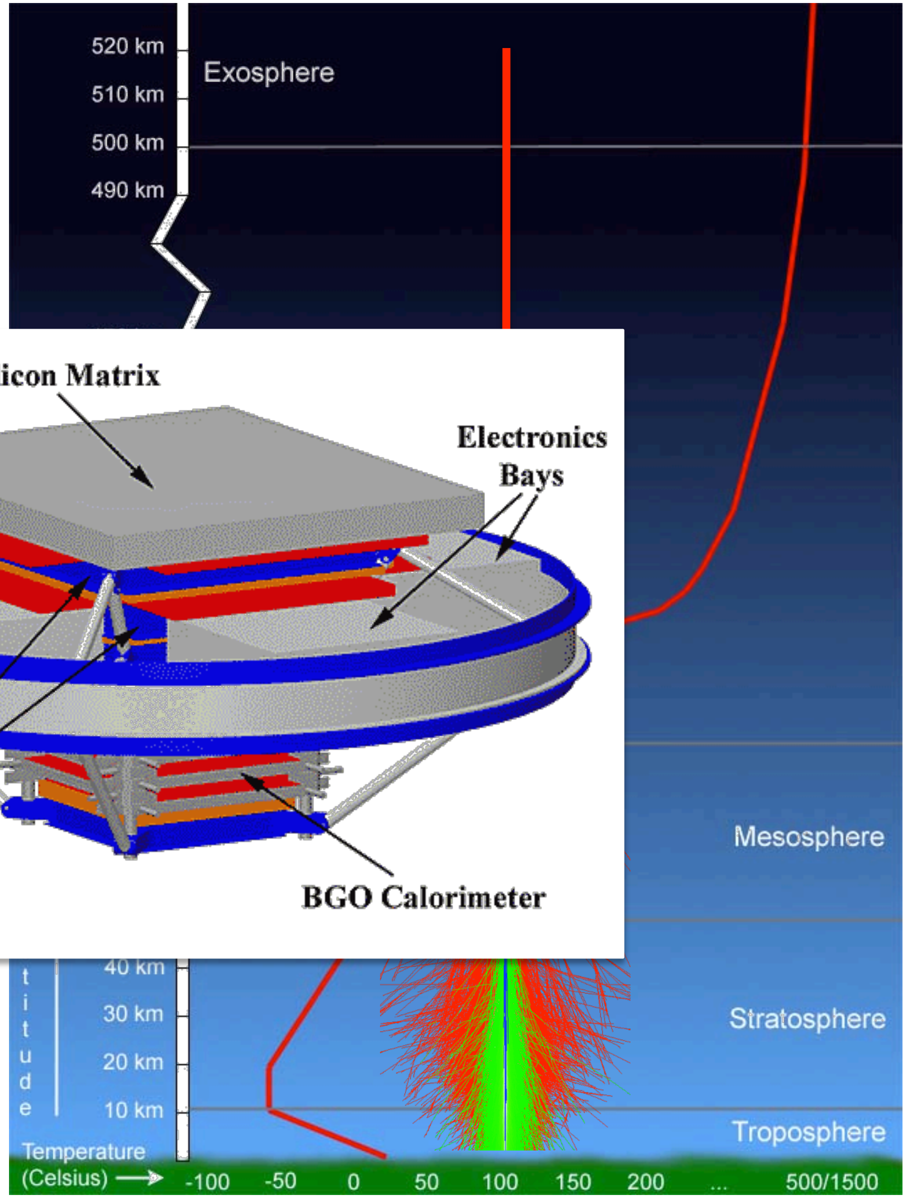
Increase of ionization of the air with altitude, measured by Hess was due to the cosmic ray air shower particles.



Cosmic Ray measurements: 100 yr later…

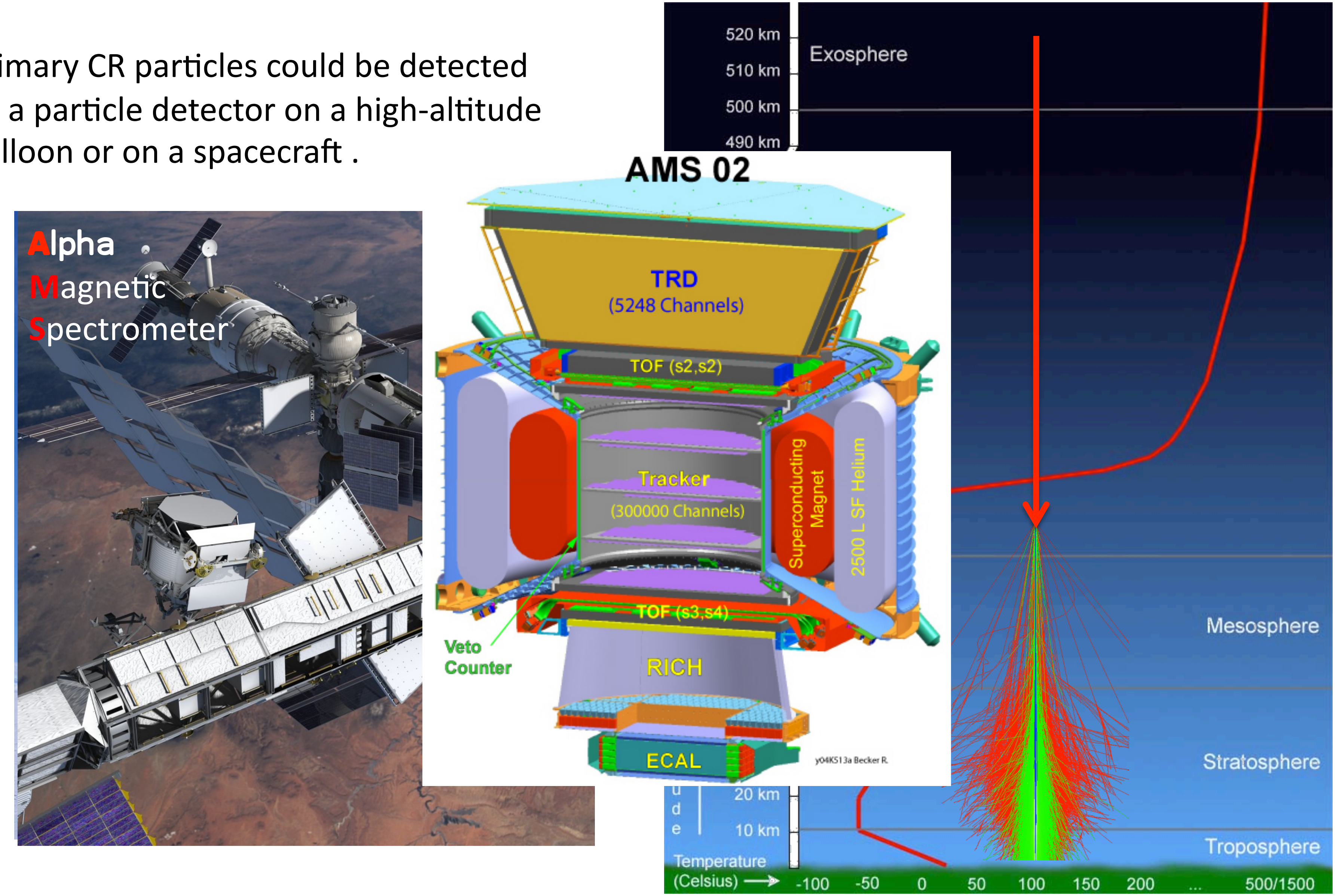
Primary CR particles could be detected by a particle detector on a high-altitude balloon





Cosmic Ray detection: direct

Primary CR particles could be detected by a particle detector on a high-altitude balloon or on a spacecraft .



Cosmic Ray detection: EAS arrays

Secondary particles produced in the CR induced Extensive Air Showers (EAS) could be detected at the ground level.

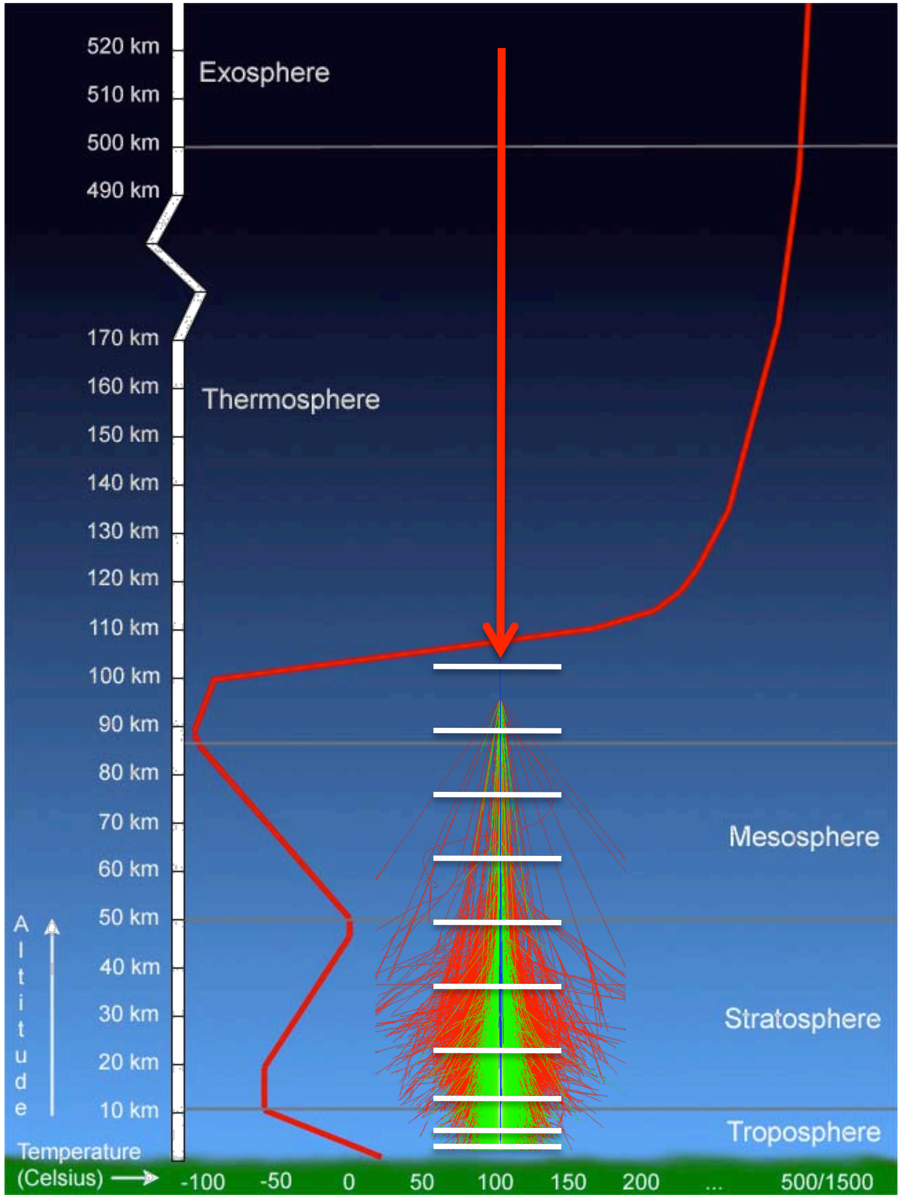
Atmosphere is used as a "calorimeter" of a particle physics experiment.

Total depth of the atmosphere in zenith direciton is $\sim 10^3$ g/cm^2.

Interaction length for protons is $X_p \approx 100$ g/cm^2. Radiation length for electrons is $X_e \approx 30$ g/cm^2.

Atmosphere provides ~ 30 radiaiton lengths for electrons and ~ 10 interaction lengths for protons.

Number of secondary particles in an EAS grows as $2^{l/X}$, up to $N_{\max} \sim E_{CR}/\varepsilon$, $\varepsilon \sim 250$ MeV, reaching maximum at $X_{max}(E_{CR})$. If E_{CR} is high enough, significant amount of particles could reach the ground level.

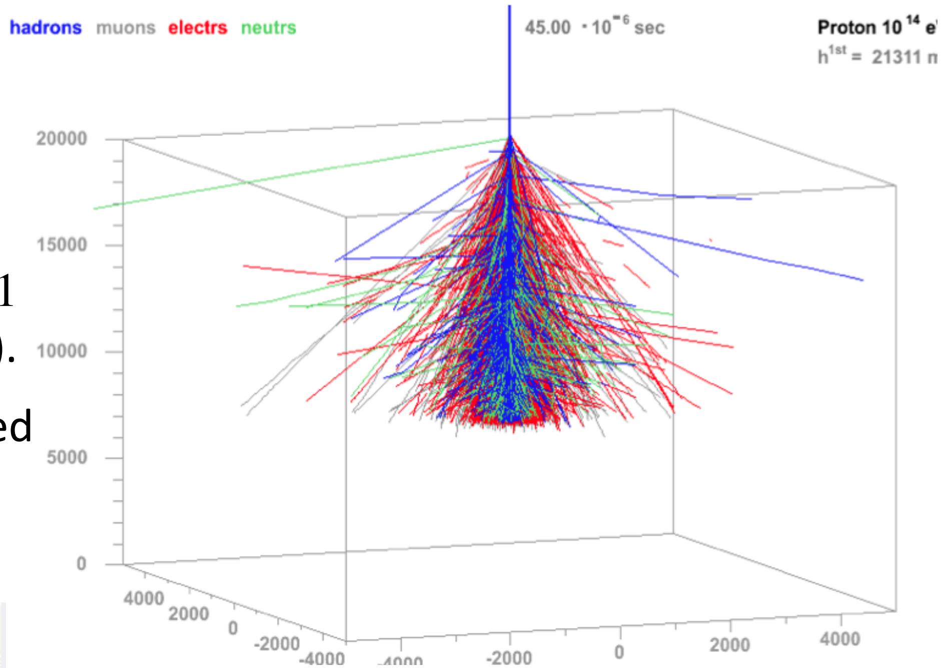


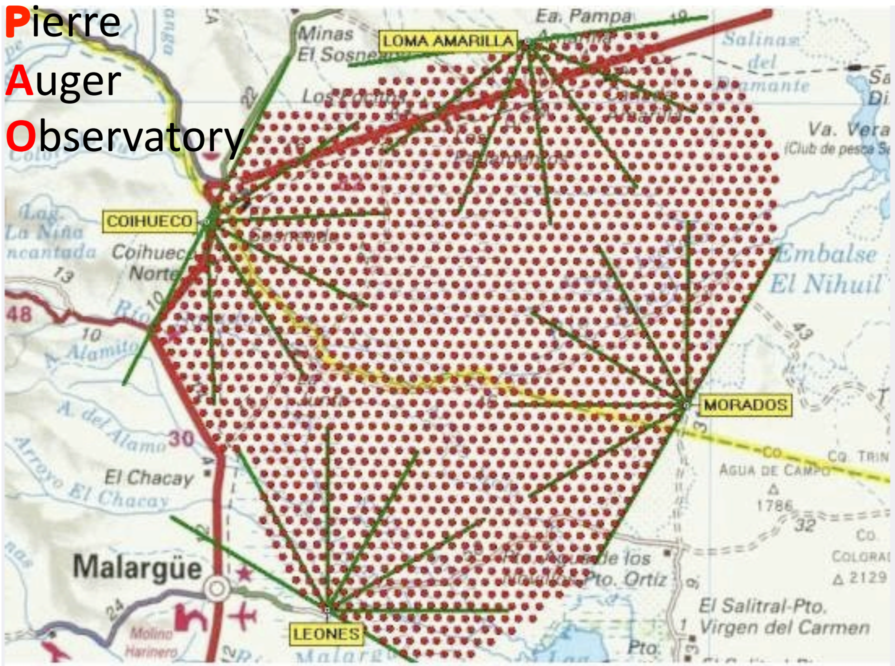
Cosmic Ray detection: EAS arrays

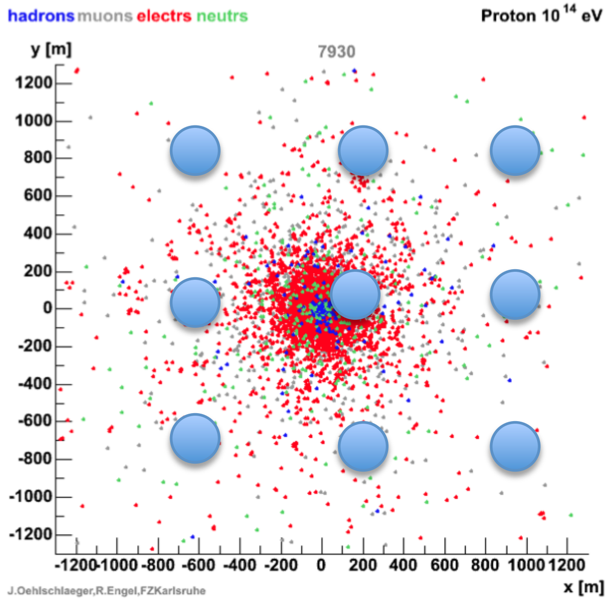
EAS particles reaching the ground level are scattered over ~100 m – 10 km area.

Secondary particles could be detected by particle detectors distributed over an area $A \gg 1$ m^2 (limit for balloon and space-based detectors).

Properties of the primary CR particle are deduced from the measurement of spatial and temporal distribution of secondary particles.



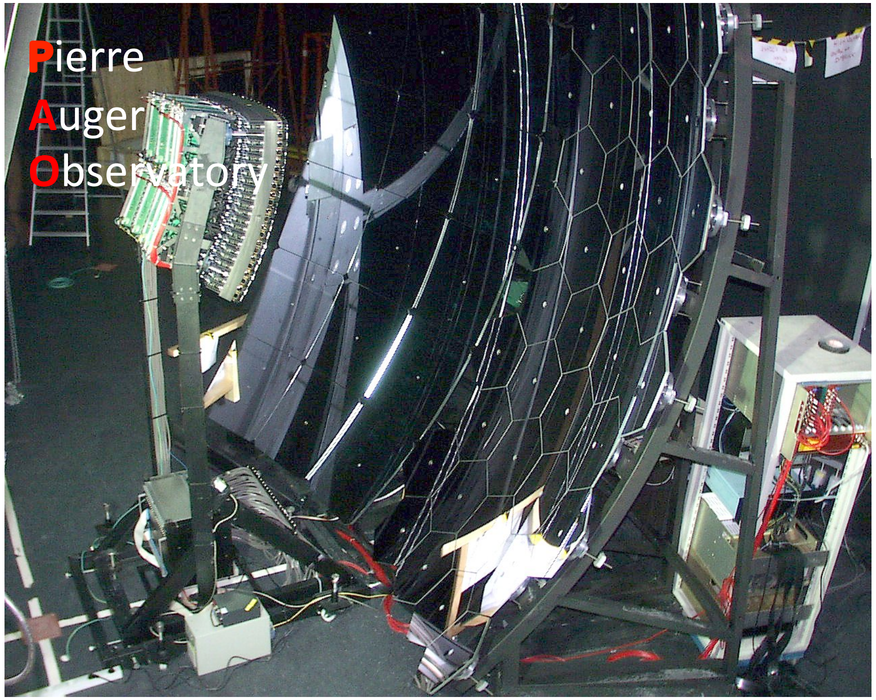


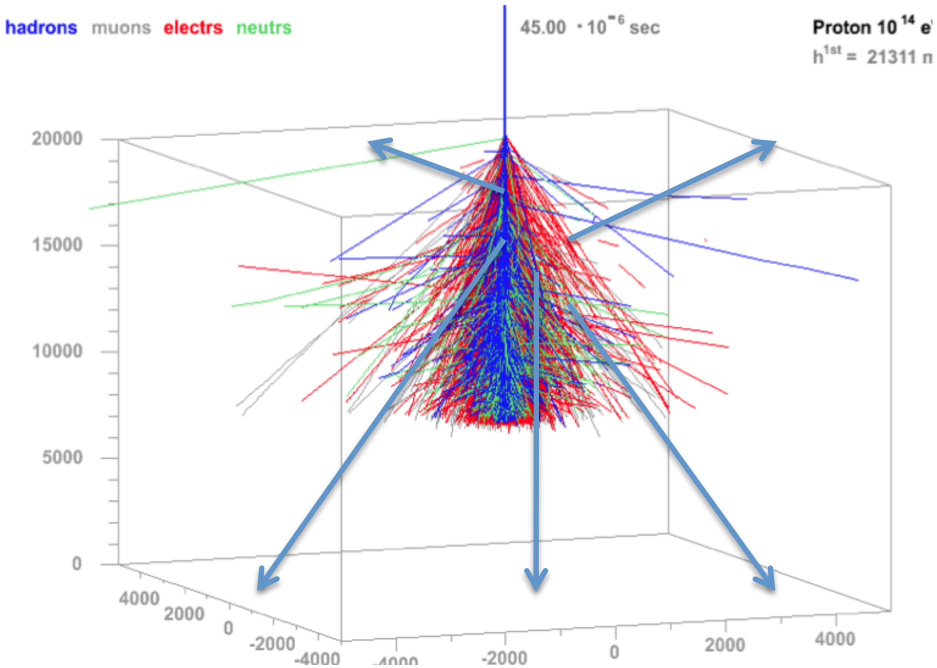


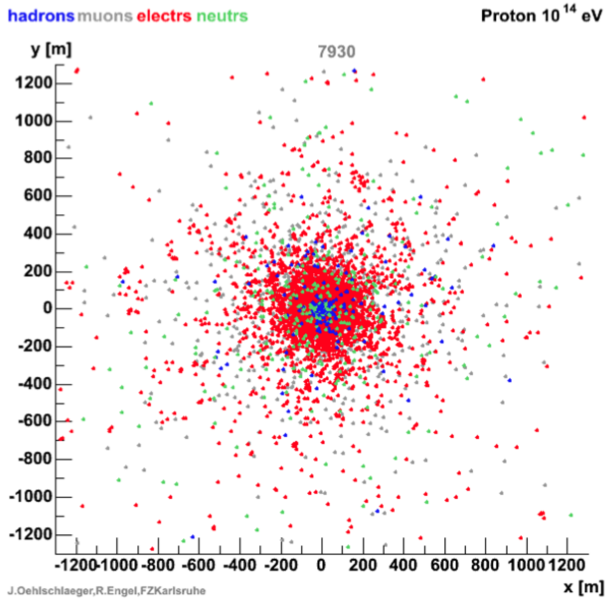
Cosmic Ray detection: fluorescence telescopes

Secondary particles in the EAS excite air molecules which subsequently emit UV fluorescence light. The fluorescent track of EAS could be detected by a telescope.

Properties of the primary CR particles are deduced from the intensity profile and temporal characteristics of the EAS image.







Cosmic Ray basic facts

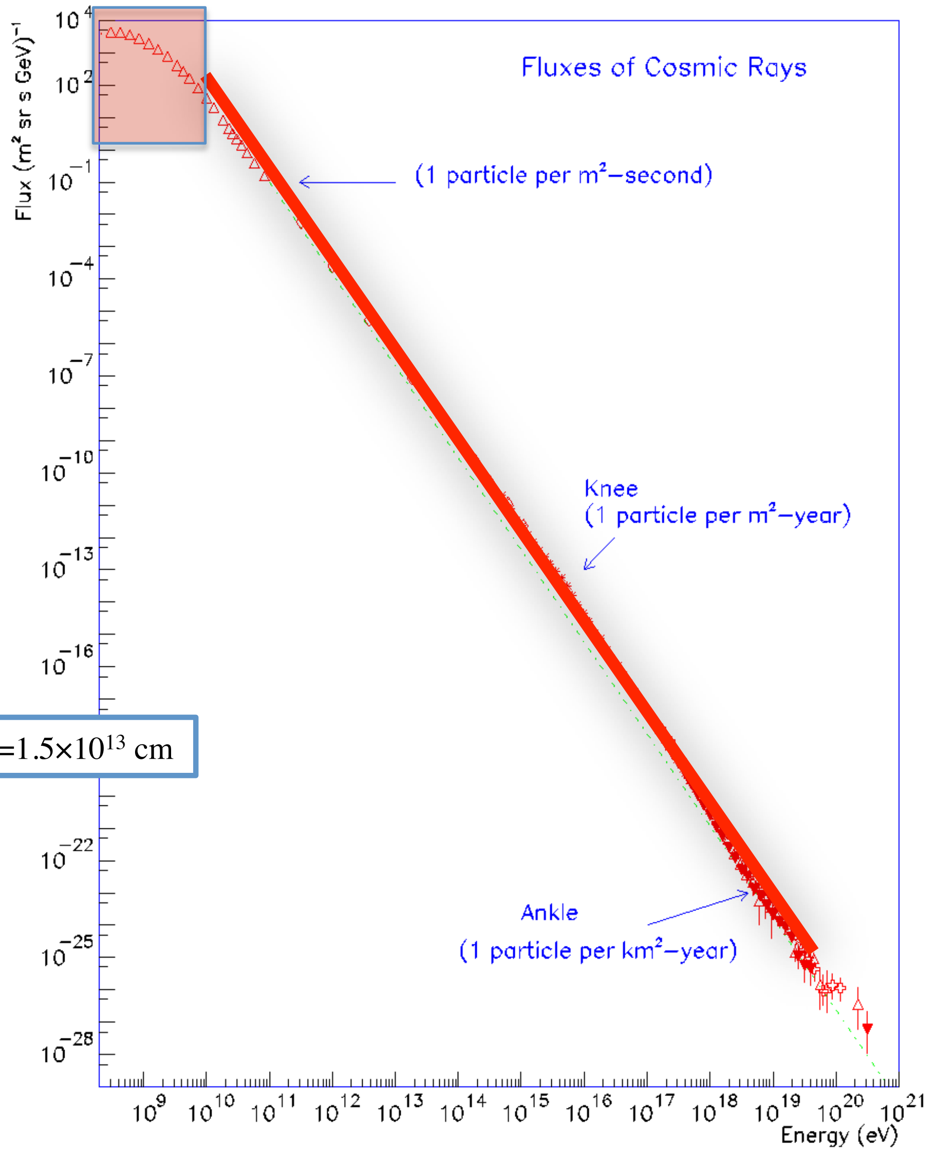
Energies of the CR particles vary between 10^6 eV$\leq E_{CR} \leq 10^{20}$ eV.

Energy spectrum of CR is approximately a powerlaw $dN_{CR}/dE_{CR} \sim E_{CR}^{-p}$, $p \approx 2.7$ at the energies above 10^{10} eV.

CR flux at the energies <10 GeV is strongly affected by the interplanetary magnetic field and depends on the solar activity ("solar modulation").

$$R_L = \frac{E_{CR}}{ZeB} \approx 2\left[\frac{E_{CR}}{10^{11}\mathrm{eV}}\right]\left[\frac{B_{IPM}}{10^{-5}\ \mathrm{G}}\right]^{-1} \mathrm{AU}$$

1 AU $=1.5\times10^{13}$ cm



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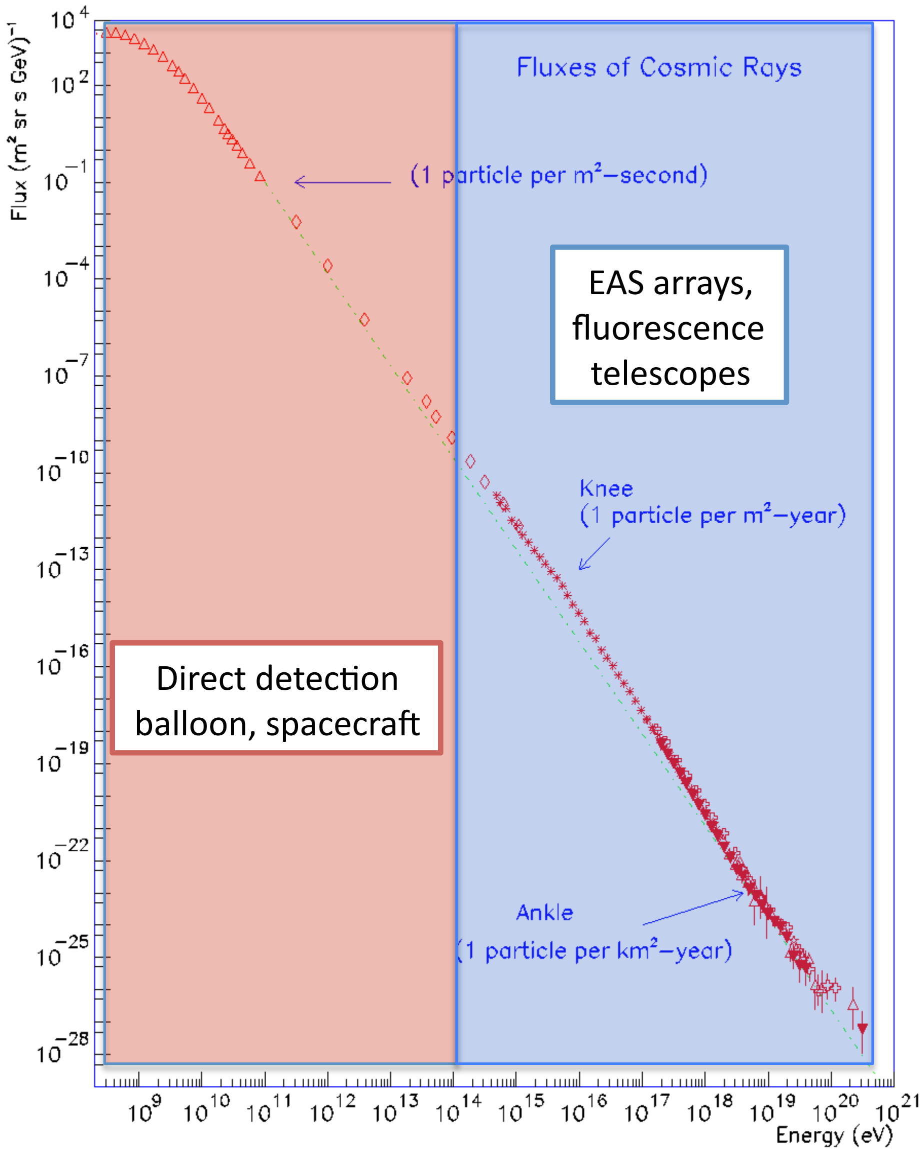
Primary CR flux incident on the detector

$$E_{CR}\frac{dN_{CR}}{dE_{CR}} \approx 10^{-6}\left[\frac{E_{CR}}{10^{15}\,\mathrm{eV}}\right]^{-1.7}\frac{1}{\mathrm{m^2\ s\ sr}}$$

i.e. a detector with wide angular acceptance (~ 1 m^2 sr) operating for ~ 3 yr (10^8 s), would detect ~ 100 CRs with energy 10^{15} eV ("knee" of the CR spectrum).



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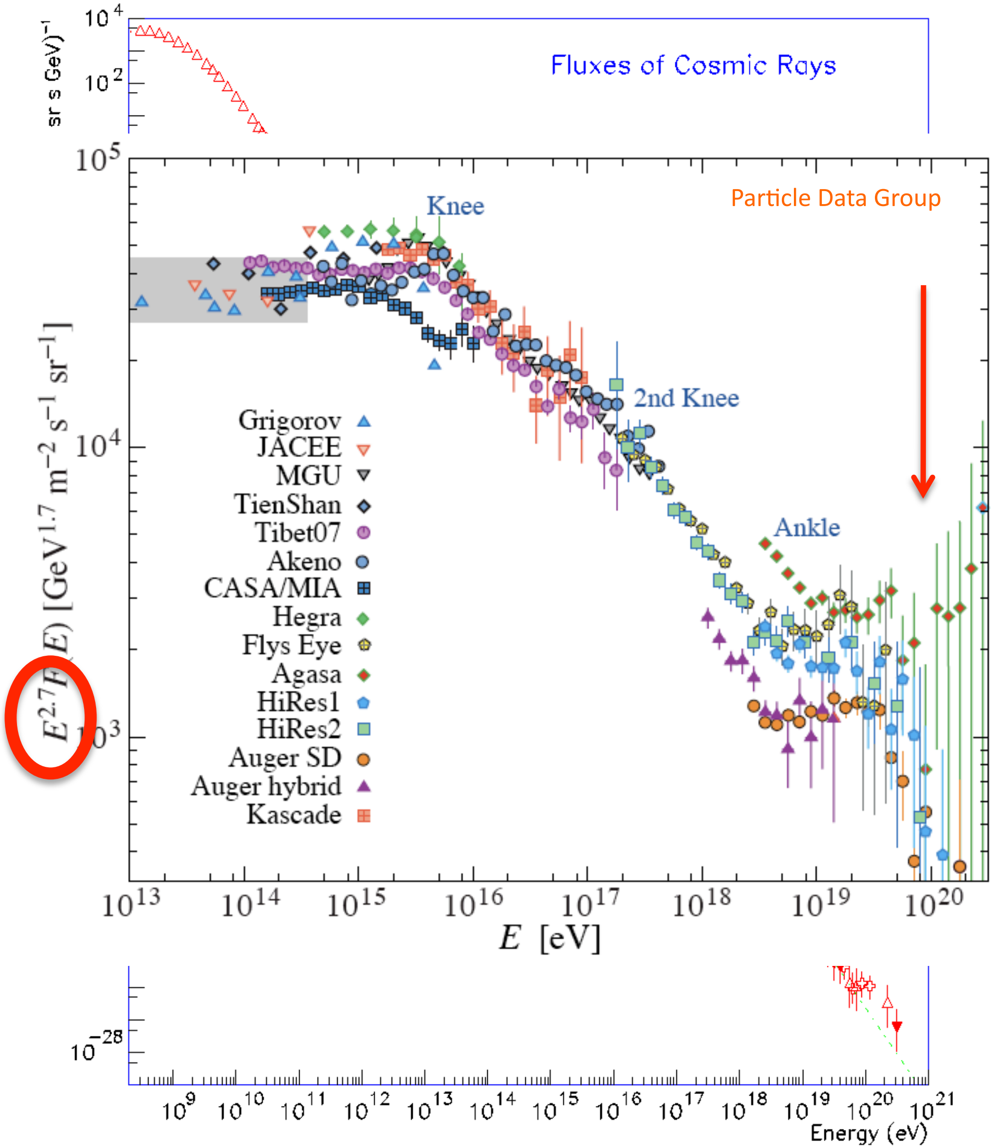
Deviations from the powerlaw behaviour are seen at the energy $E_{knee} \approx 10^{15}$ eV, called "the knee of the CR spectrum" and at $E_{ankle} \approx 10^{18}$ eV, called "the ankle of the CR spectrum".

Suppression of CR flux is observed at the energies E_{CR}~10^{20} eV.



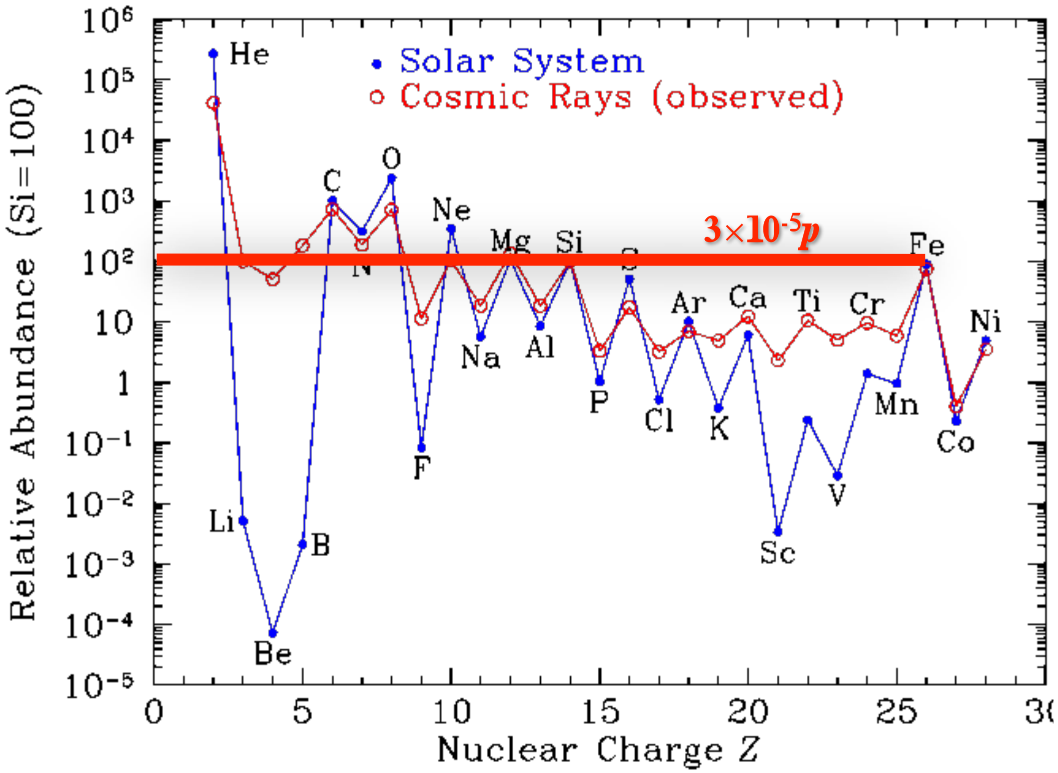
Cosmic ray nuclei

CRs are mostly composed of atomic nuclei. The most abundant is the nucleus of hydrogen: protons

Observed abundances of heavier CR nuclei roughly follow the abundances of heavy elements observed in the Solar System (e.g. the number of iron nuclei is 3×10^{-5} of that of the protons

Deviations from the Solar abundance might arise because of

- formation/disintegration ("spallation") of CR nuclei in interactions with interstellar medium during their propagation through the Galaxy
- different initial abundance of elements in the regions of CR acceleration (?)



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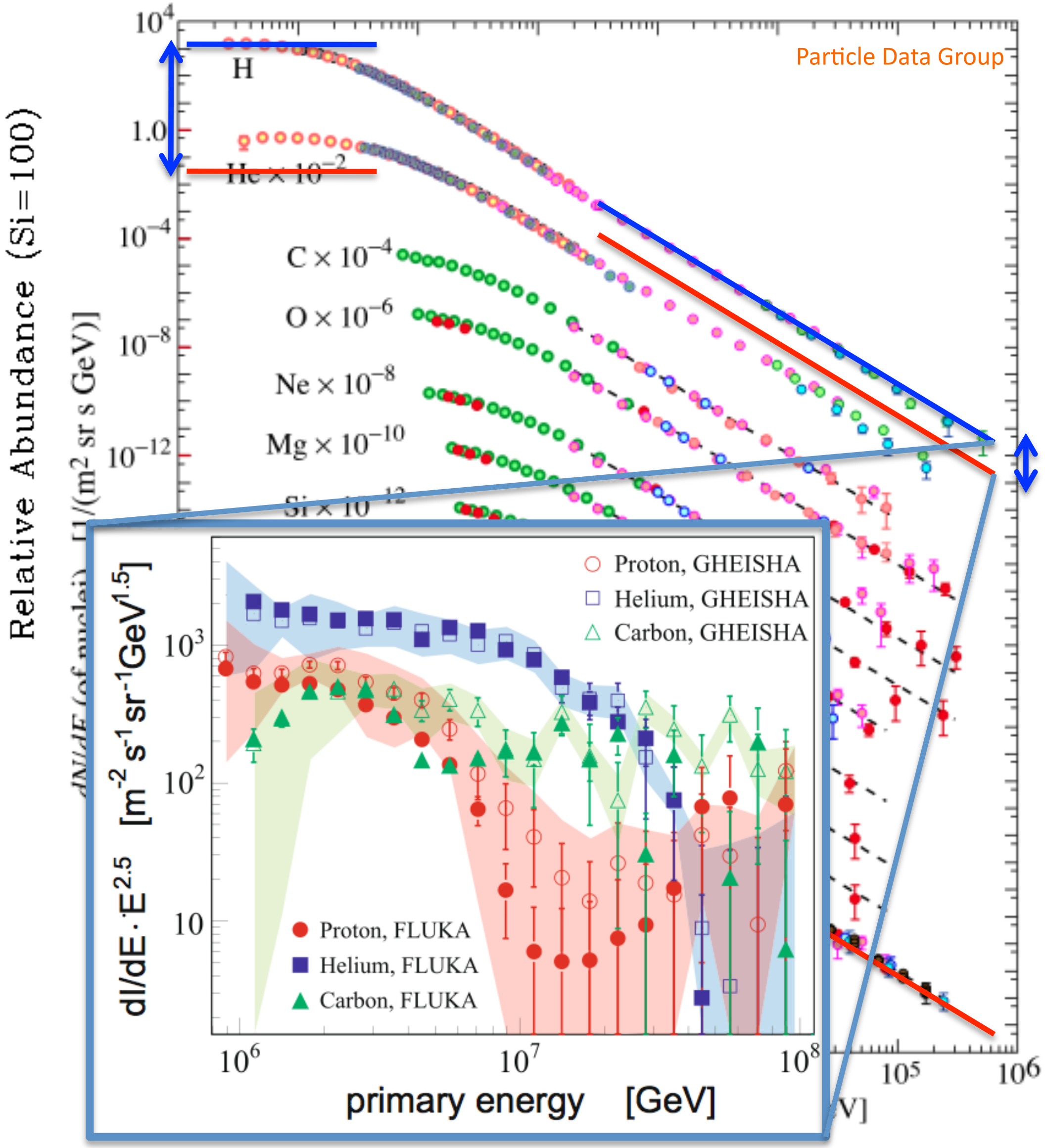
Composition of CR flux changes with energy



Apel et al. Atropart.Phys. 31, 86 (2009)

Cosmic ray antiprotons

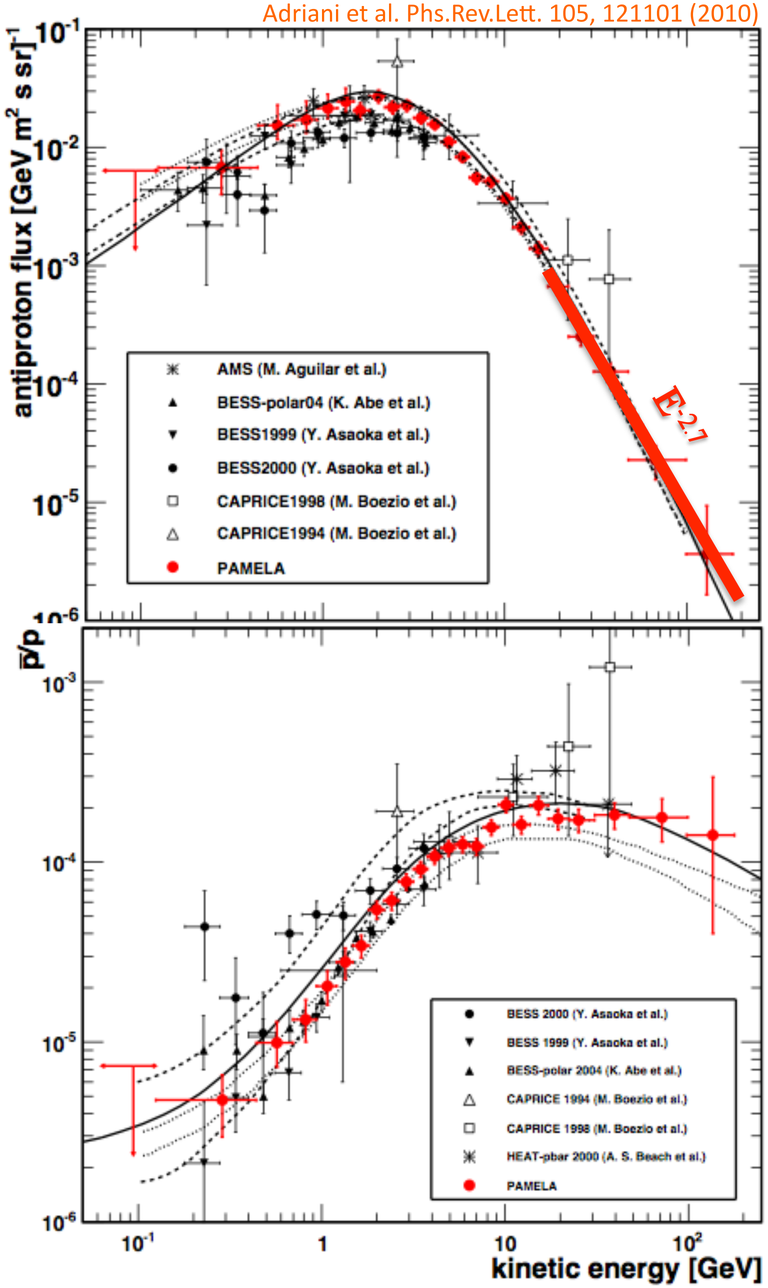
Apart from atomic nuclei, CR include also antiprotons

Abundance of antiprotons is $\sim 10^{-4}$ of proton CR abundance at the TeV energies

Anti-protons are "secondary" particles produced in interactions of CR nuclei with interstellar medium during propagation of CRs through the Galaxy

* i.e. there are no hints of possible "primary" anti-protons accelerated in CR sources and no hints of "exotic" anti-proton production channels, like Dark Matter decays.

Adriani et al. Phs.Rev.Lett. 105, 121101 (2010)



Cosmic ray electrons and positrons

CR flux includes also electrons and positrons.

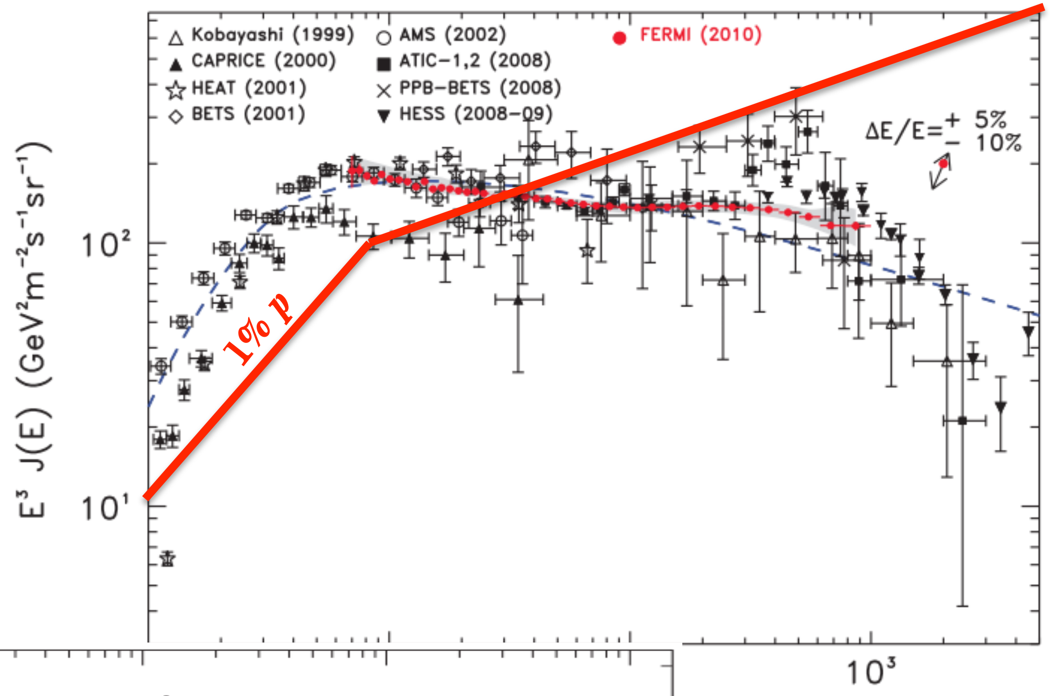
CR e^+e^- flux is by a factor ~ 100 lower than CR proton flux

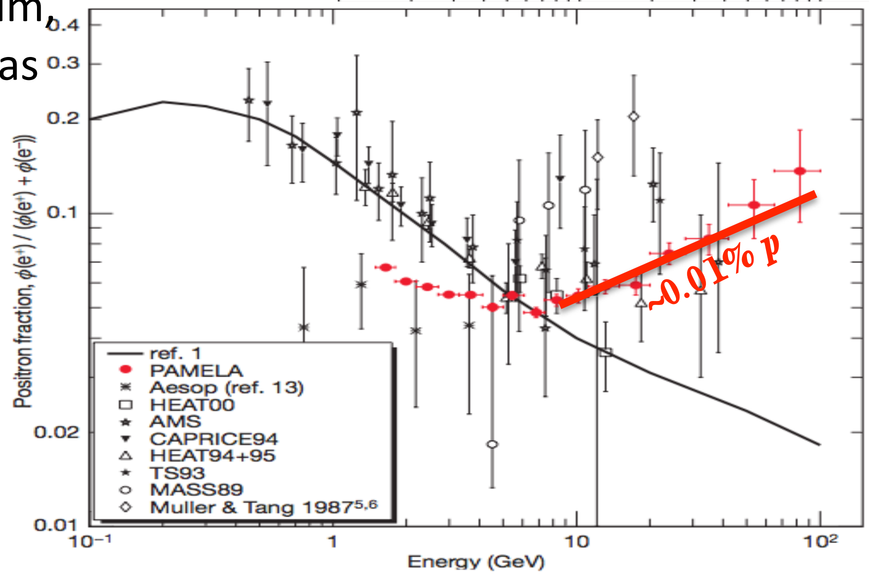
High-energy CR electrons are produced directly in CR sources, i.e. they are "primary" CR particles

CR positrons might be secondary particles produced in CR interactions.

Contrary to anti-proton spectrum, the spectrum of CR positrons has an "anomaly" above 10 GeV, which is inconsistent with their "secondary" origin.

Ackerman et al. Phys.Rev..D82, 092004 (2010)





Adriani et al. Nature 458, 607 (2009)

Problem of the origin of Cosmic Rays

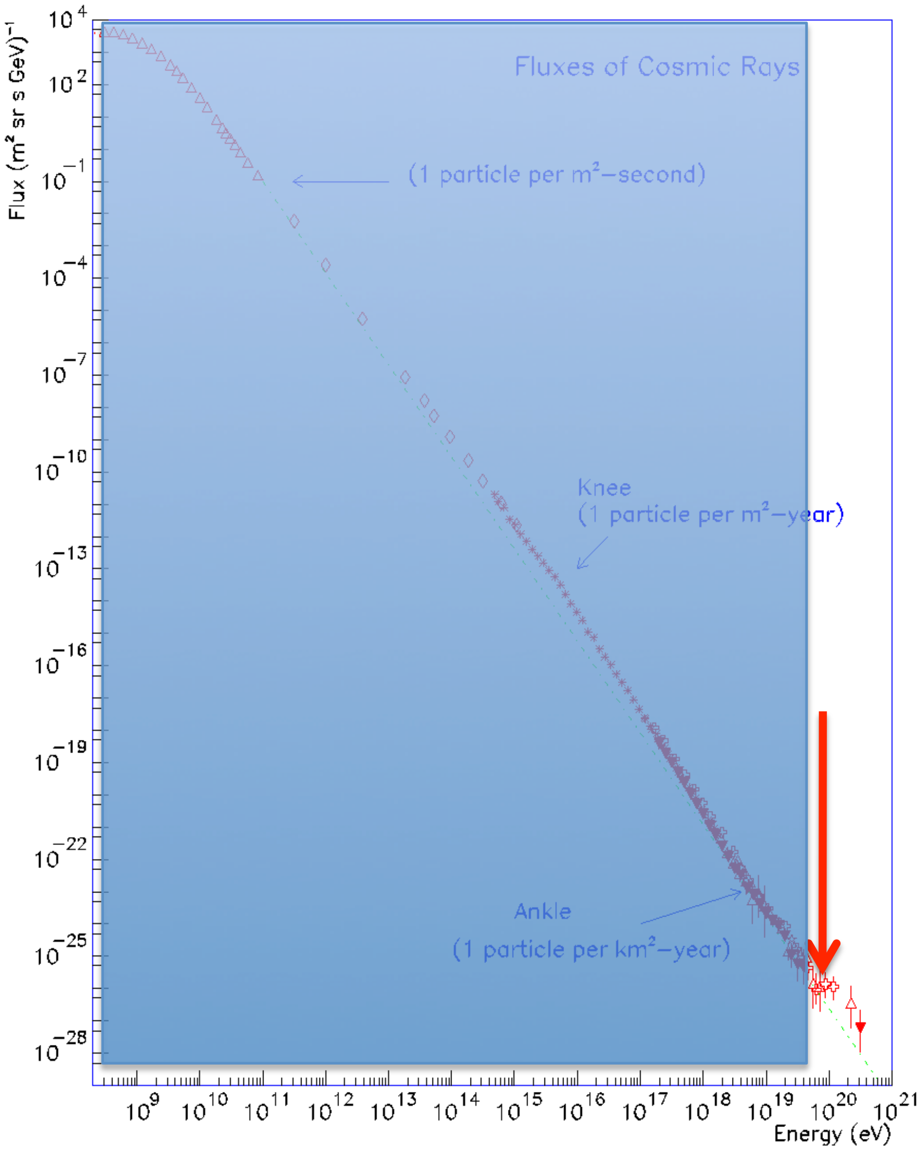
100 yr after the discovery of CR (V.Hess, 1912) the origin of CR particles remains unknown.

The main problem for identification of CR sources is that CR protons, atomic nuclei, electrons+positrons are charged particles. Their propagation is strongly affected by magnetic fields.

Galactic magnetic field strongly deviates or randomizes trajectories of CR with energies $E_{CR} < 10^{20}$ eV:

$$R_L = \frac{E_{CR}}{ZeB} \approx 10 \left[\frac{E_{CR}}{10^{20}\,\mathrm{eV}}\right] \left[\frac{B_{ISM}}{10^{-5}\ \mathrm{G}}\right]^{-1} \mathrm{kpc}$$

1 kpc $= 3\times10^{21}$ cm

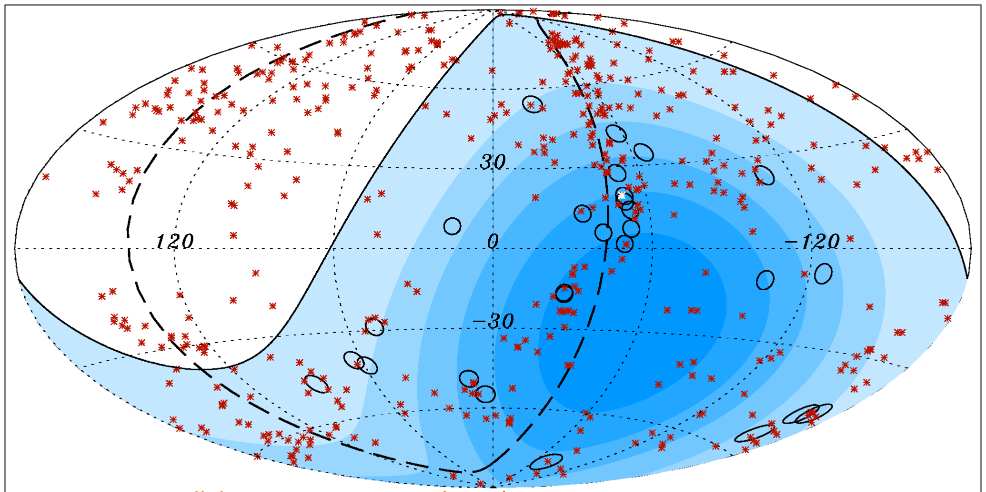


Sources of Ultra-High-Energy Cosmic Rays

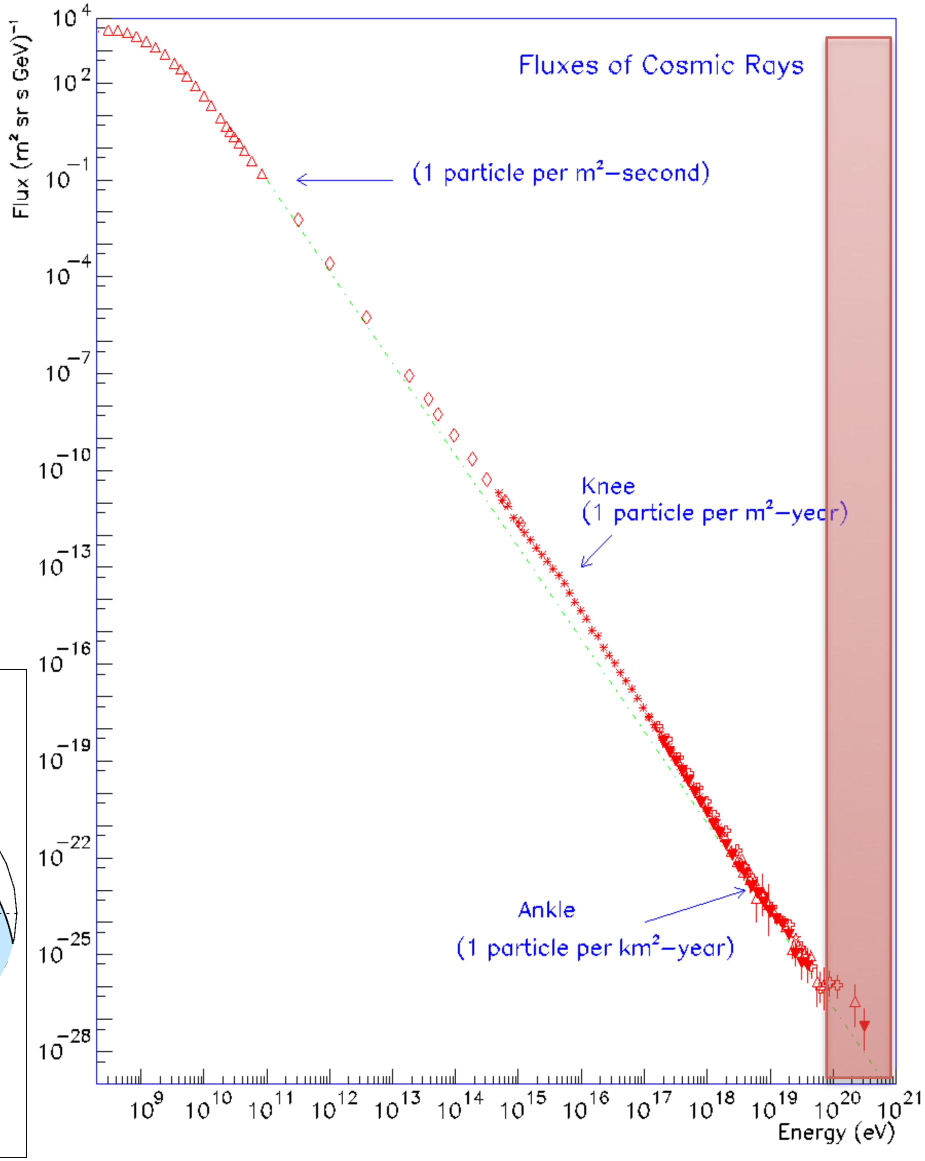
It is possible that arrival directions of Ultra-High-Energy CRs (UHECR) point to the CR sources.

Limited statistics of the signal in this energy band does not allow definite identification of UHECR production sites.

Strongest (~3σ) excess in the number of UHECR events is found in a 20º region around the nearest radio galaxy Centaurus A.



Pierre Auger Collab. Science, 318, 938 (2007)

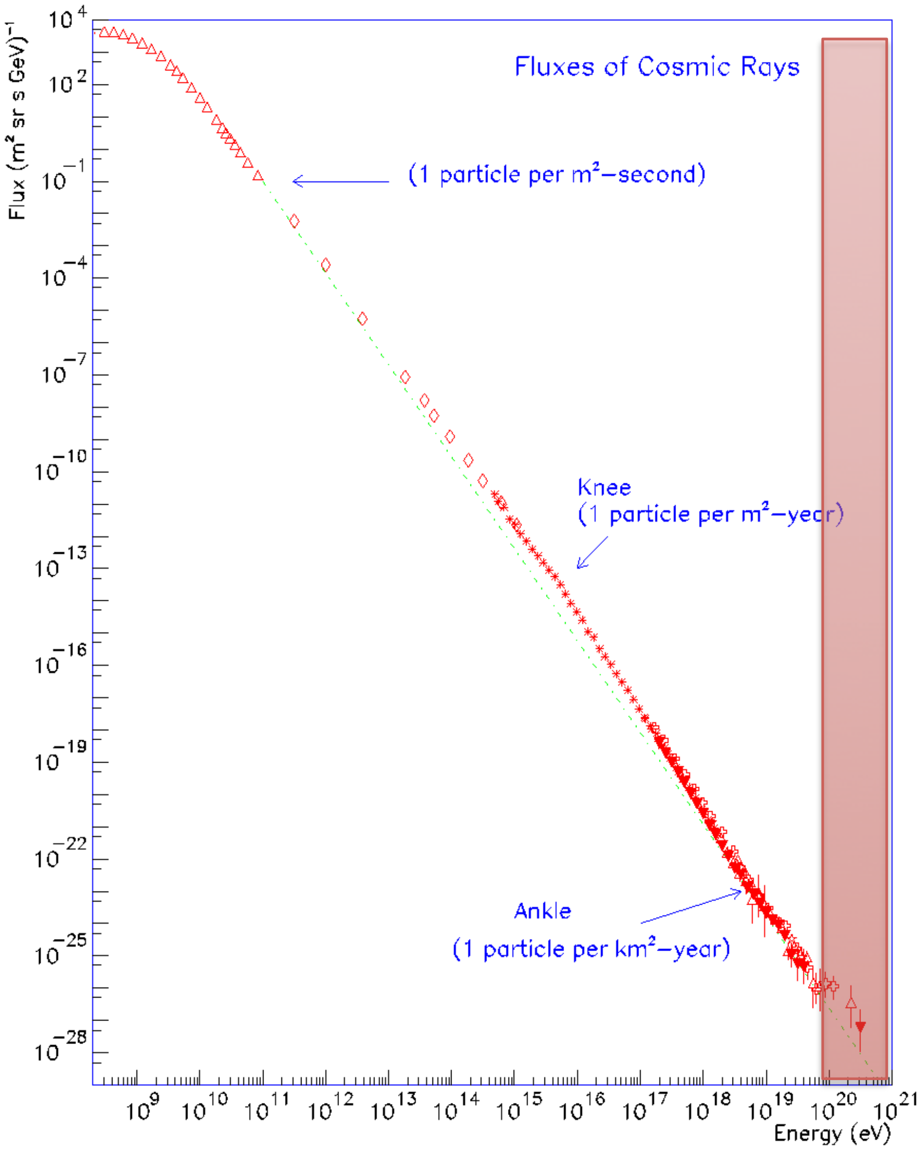


Sources of UHECR: GZK effect

UHECR with energies above the pion production threshold $p + \gamma \rightarrow p + \pi^0 \ldots.\ n + \pi^+$

$$E_p = \frac{m_\pi}{4\varepsilon_{CMB}}\left(2m_p + m_\pi\right) \approx 10^{20}\ \text{eV}$$

interact with photons of Cosmic Microwave Background radiation (typical energy of CMB photons is $\varepsilon_{CMB} \approx 10^{-3}$ eV).



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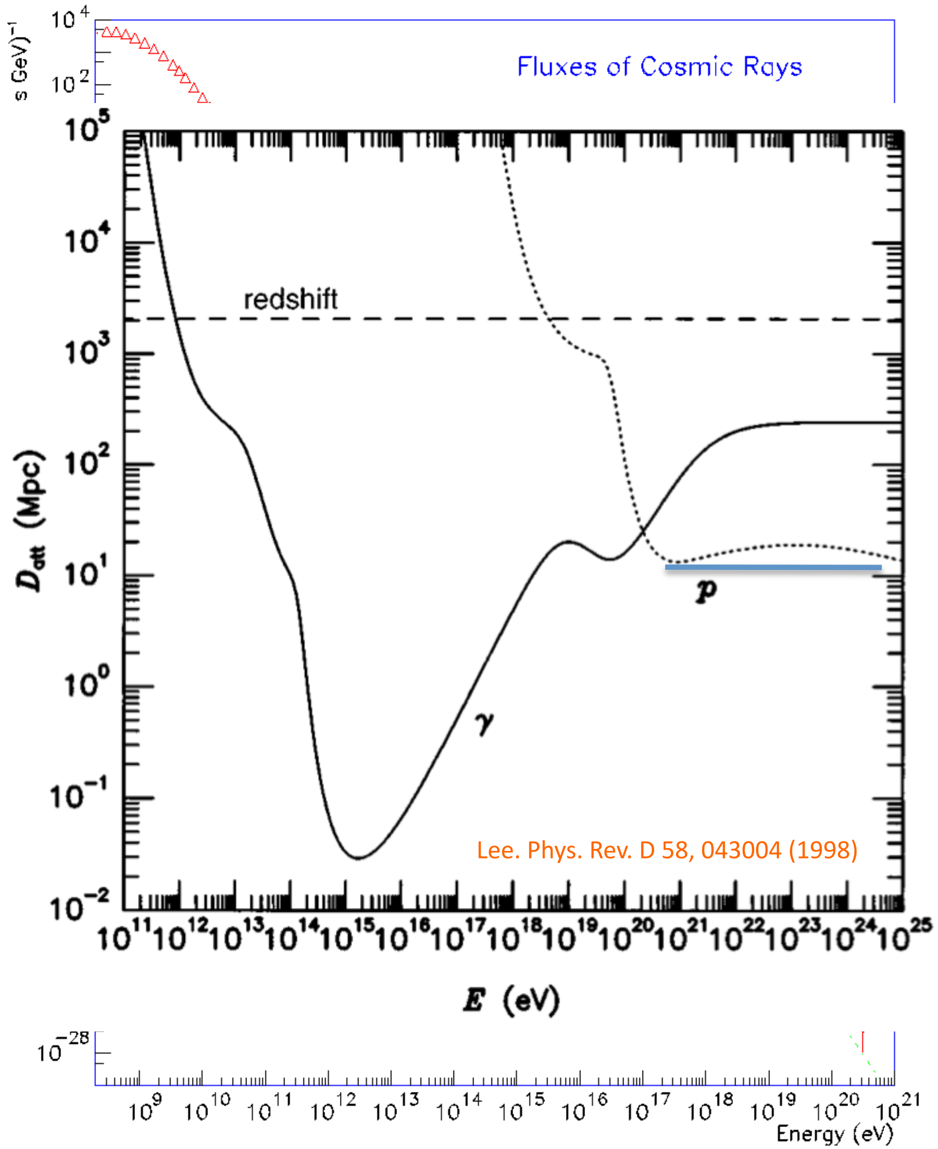
On-set of the pion production

(a) leads to suppression of CR flux above 10^{20} eV (Greisen-Zatsepin-Kuzmin, GZK effect)

(b) limits the possible range of distances to the UHECR sources to

$$D < \lambda_{p\gamma} = \frac{1}{\sigma_{p\gamma} n_{CMB}} \approx 10\ \mathrm{Mpc}$$



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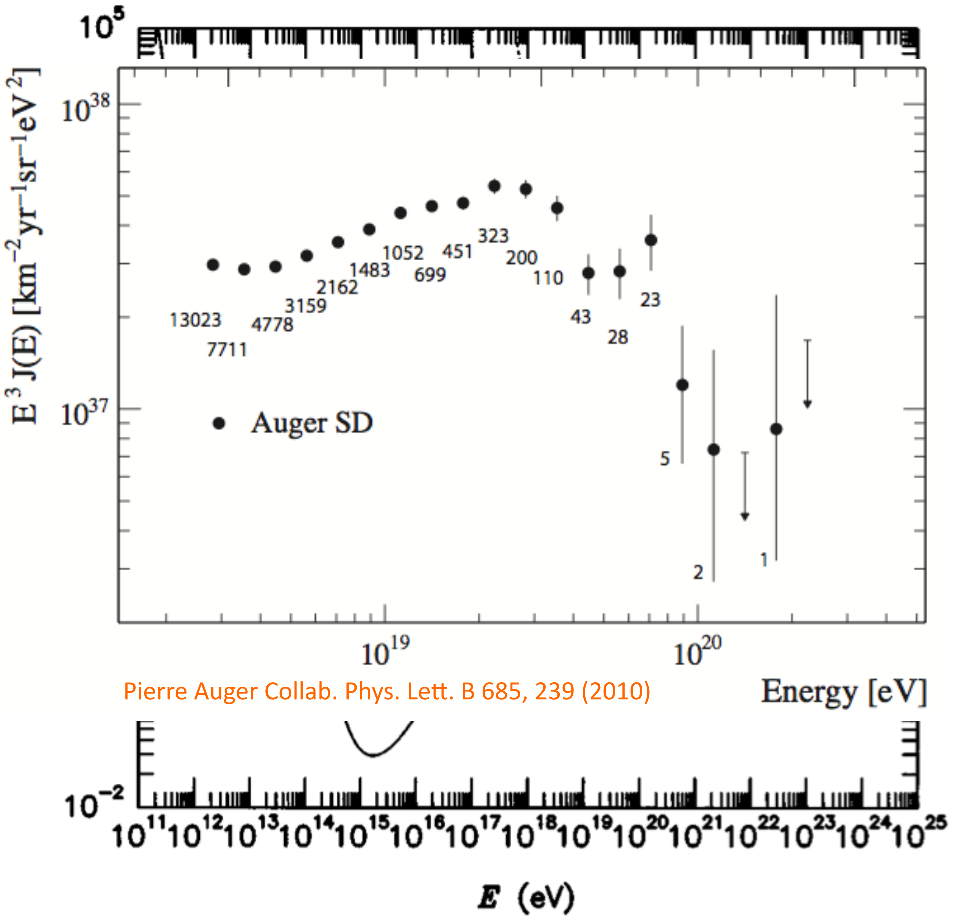
Suppression of the UHECR flux in the 10^{20} eV range is now observed by the Pierre Auger Observatory.

Detection of GZK effect implies that the sources of UHECR are at ~10-100 Mpc distance, i.e. in our "cosmological backyard".



Pierre Auger Collab. Phys. Lett. B 685, 239 (2010)

*It is not clear for the moment if the suppression is due to the GZK effect.

Sources of UHECR: heavy nuclei issue

Alternative possibilities could be

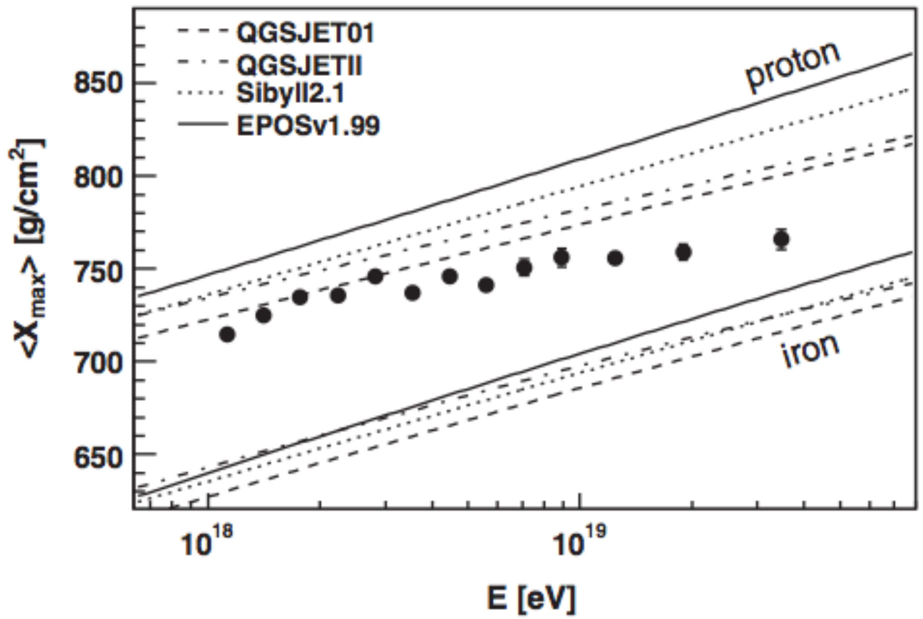
(a) feature due to disintegration of atomic nuclei component of UHECR spectrum in interactions with cosmic infrared background

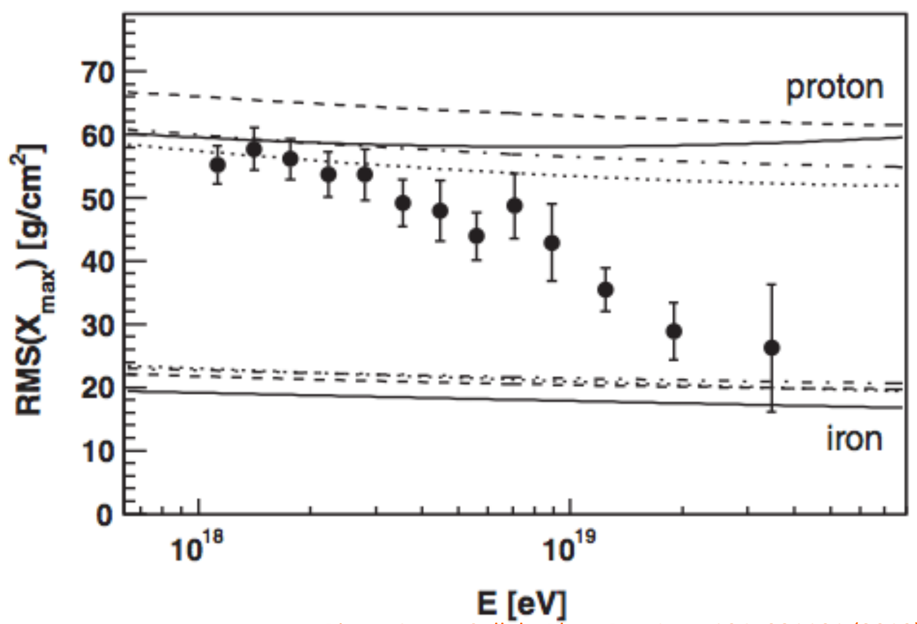
(b) lack of sources able to accelerate particles above 10^{20} eV

Measurements of the spread of the "depth of the shower maxima", X_{max} by Pierre Auger Observatory indicate the presence (or even dominance) of heavy nuclei component in UHECR flux above 10^{19} eV.

* Not confirmed by the HiRes data

Abbasi et al. Phys. Rev. Lett. 104, 161101 (2010)





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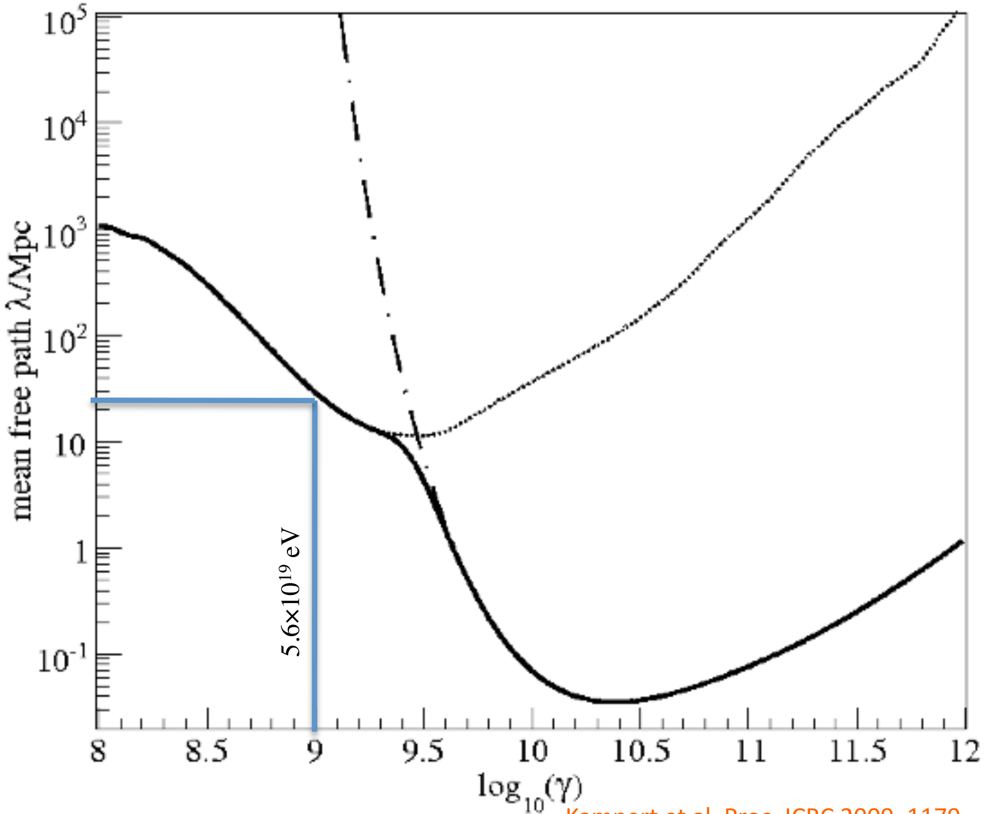


Kampert et al. Proc. ICRC 2009, 1179

Heavy nuclei are destroyed in interactions with infrared photon background.

If suppression of UHECR flux at 10^{20} eV is due to photodisintegration of nuclei, UHECR sources are still at $D\sim 10$ Mpc distances.

Identification of the sources would still be a problem because 10^{20} eV nuclei are strongly deflected by Galactic magnetic field.

Sources of UHECR: maximal energy issue

Alternative possibilities could be

(a) feature due to disintegration of atomic nuclei component of UHECR spectrum in interactions with cosmic infrared background

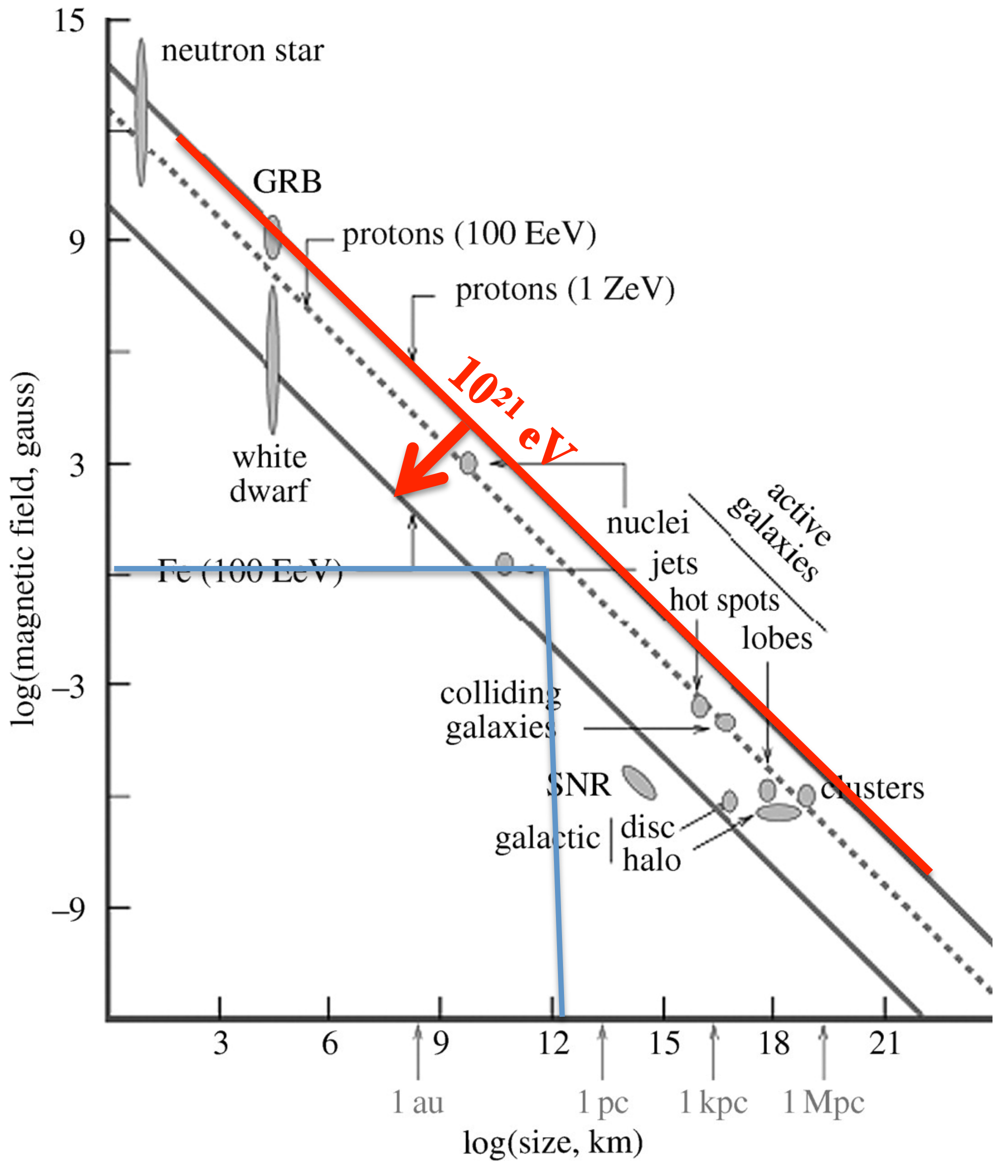
(b) lack of sources able to accelerate particles above 10^{20} eV

Maximal energy of particles accelerated in an object of the size R possessing a magnetic field B could be estimated as

$$E_{\max} \leq ZeBR \approx 3\times 10^{20}\left[\frac{B}{1\ \mathrm{G}}\right]\left[\frac{R}{10^{18}\,\mathrm{cm}}\right]\ \mathrm{eV}$$

* energy at which Larmor radius becomes comparable to the size of the object

* energy to which a linear accelerator with electric field $|\vec{E}| \sim |\vec{B}|$ would accelerate



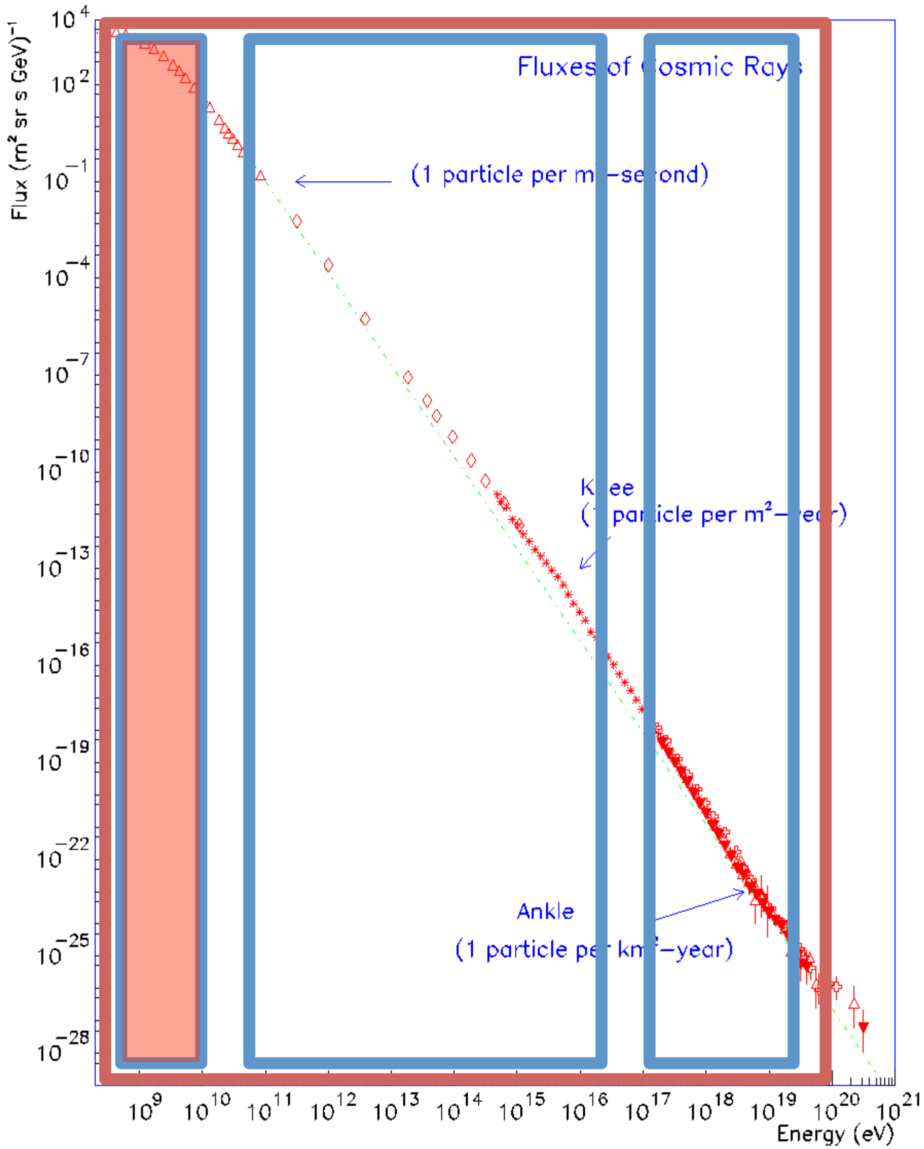
Sources of CRs: GeV – EeV range

Below (*several*)×10^{19} eV sources of CR could not be found via tracing back the trajectories of individual CR particles.

Where does most of the CR power come from?

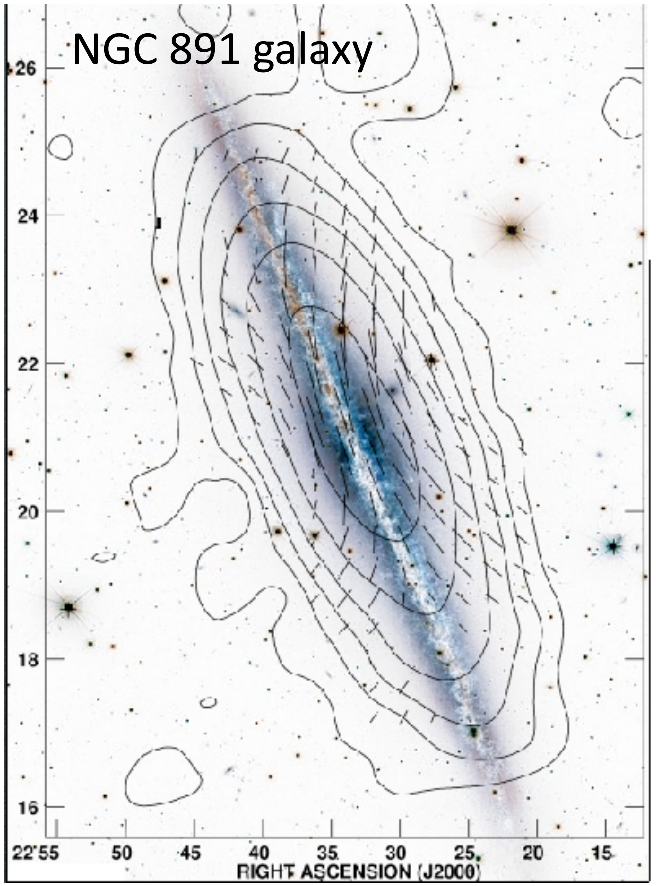
Where do Galactic CR with energies up to 10^{15} eV (knee) come from?

Where does the transition from Galactic to extragalactic CR happens (ankle)?



Cosmic Ray propagation in the Galaxy

Cosmic rays with energies E<<10^{18} eV are held in the Galactic disk of scale height H~500 pc by magnetic fields B~10 μG



Krause, Rev.Mx.AC, 2009, arXiv:0806.2060

Fletcher et al., MNRAS, 2010, arXiv:1001.5230

Cosmic Ray propagation in the Galaxy

Cosmic rays with energies $E << 10^{18}$ eV are held in the Galactic disk of scale height $H \sim 500$ pc by magnetic fields $B \sim 10$ μG

$$R_L = \frac{E_{CR}}{ZeB} \approx 100 \left[\frac{E_{CR}}{10^{18}\,\mathrm{eV}}\right] \left[\frac{B_{ISM}}{10^{-5}\ \mathrm{G}}\right]^{-1} \mathrm{pc}$$

CRs could diffuse out of the Galaxy after a long period of scattering of propagation along the ordered magnetic field and scattering on inhomogeneities of random component of magnetic field

In a stationary regime, injection rate R of CR in the galaxy should be equal to their escape rate. Energy density of CRs is equal to $U_{CR}=R/\tau_{esc}$, where τ_{esc} is typical escape time.

Fletcher et al., MNRAS, 2010, arXiv:1001.5230

Energy source of Galactic CRs

Cosmic rays with energies $E \ll 10^{18}$ eV are held in the Galactic disk of scale height $H \sim 500$ pc by magnetic fields $B \sim 10\ \mu G$

$$R_L = \frac{E_{CR}}{ZeB} \approx 100 \left[\frac{E_{CR}}{10^{18}\,\mathrm{eV}}\right]\left[\frac{B_{ISM}}{10^{-5}\ \mathrm{G}}\right]^{-1}\ \mathrm{pc}$$

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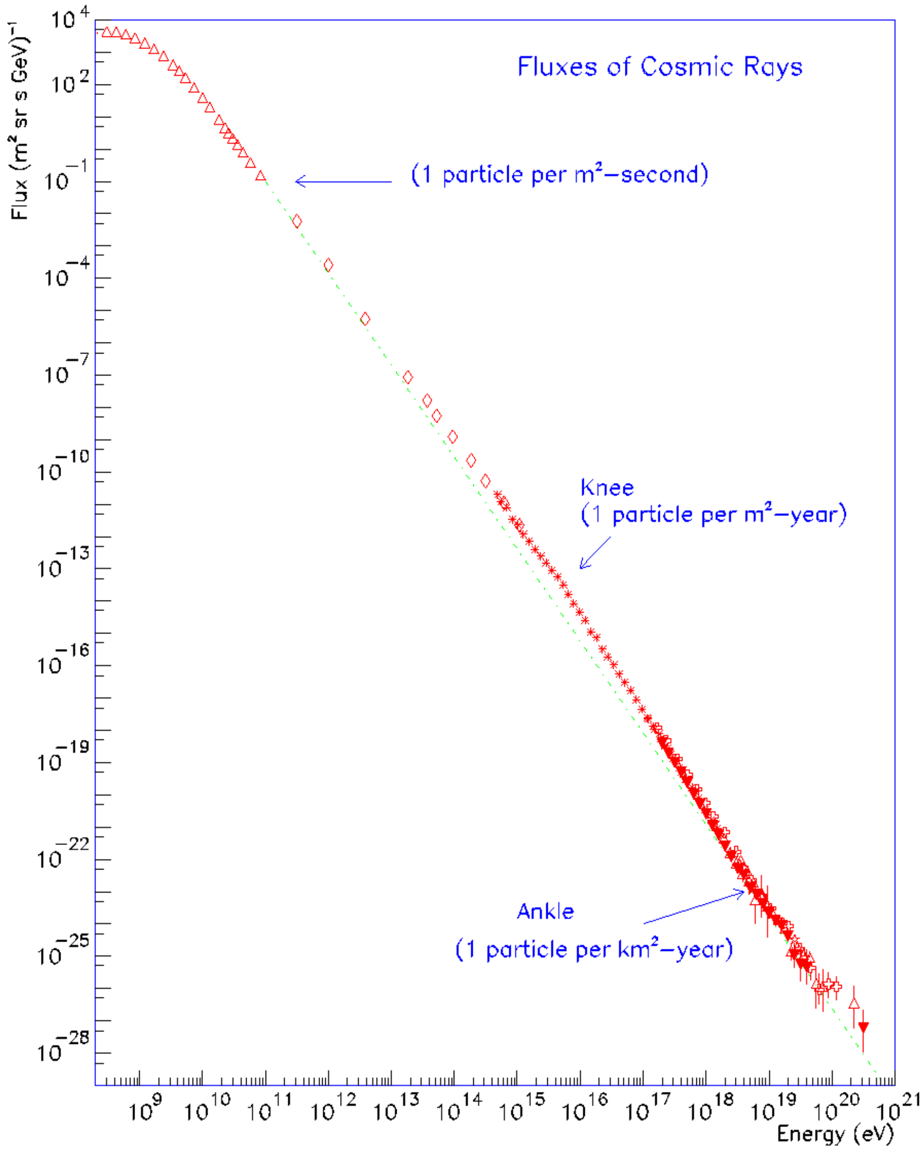
$$U_{CR} = \frac{4\pi E_{CR}^2 dN_{CR}/dE_{CR}}{c} \approx 0.4\ \frac{\mathrm{eV}}{\mathrm{cm}^3}$$



Energy source of Galactic CRs

τ_{esc} could be estimated from the amount of secondary atomic nuclei present in the CR flux, e.g. boron (B) which produced via spallation of carbon (C) and oxygen (O).

$$Q_B = n_{ISM} c \sigma_{C \to B} N_C$$

rate of produciton of B

density of ISM

spallation cross-section

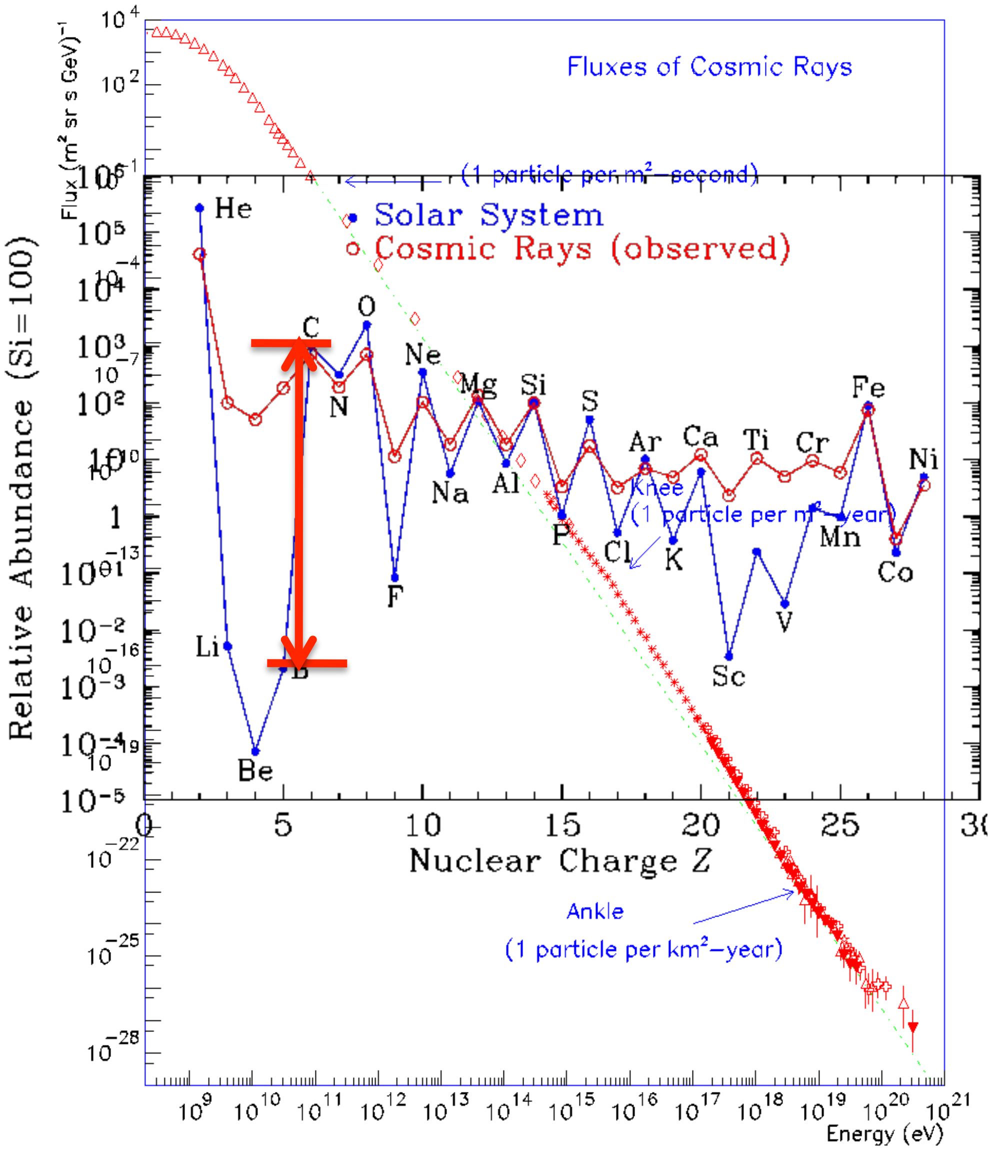
number of C

$$\frac{N_B}{N_C} = \frac{Q_B \tau_{esc}}{N_C} = n_{ISM} c \sigma_{C \to B} \tau_{esc}$$

$$\tau_{esc} \approx 10^{14} \left[\frac{E_{CR}}{1\ \mathrm{GeV}} \right]^{-0.3...-0.5} \mathrm{s}$$

Total power injected in CR in the Galaxy is

$$P_{CR} = U_{CR} \bullet \pi R_{disk}^2 H \tau_{esc} \approx 10^{41} \mathrm{erg/s}$$

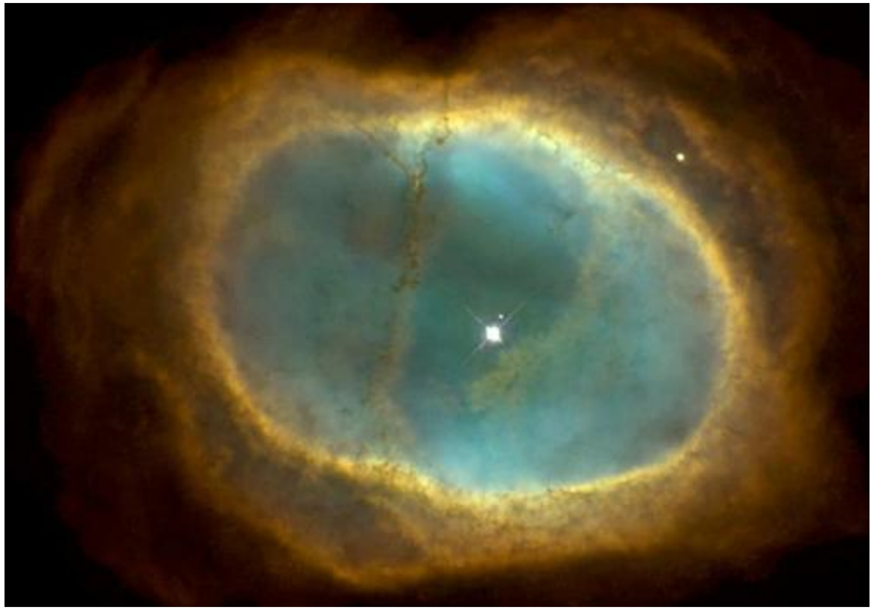


Energy source of Galactic CRs

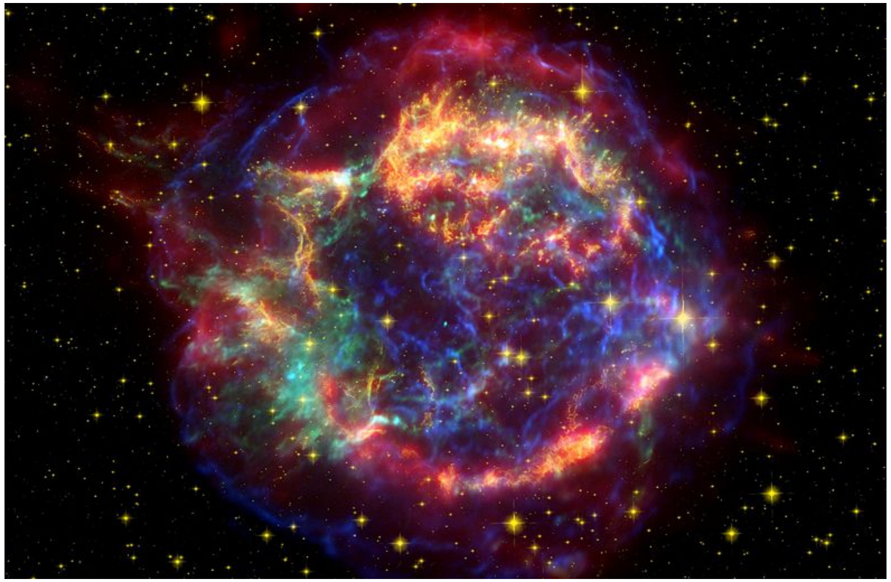
Total luminosity of the Galaxy in photons is $L_\gamma \sim 10^{44}$ erg/s

Bulk of the luminosity comes from nuclear reactions in low mass stars.

$\sim 1\%$ (10^{42} erg/s) of this power is released in gravitational contraction leading to formation of a white dwarf at the end of life of low mass star.



Comparable average luminosity is produced in the form of neutrinos $L_\nu \sim 10^{44}$ erg/s, by massive ($M \geq 10 M_{Sun}$) stars at the moment of gravitational collapse with formation of neutron stars or black holes.



1% of this power (10^{42} erg/s) goes to the mechanical energy of expansion of supernova triggered by the gravitational collapse.

10% of mechanical energy of supernova explosions (10^{41} erg/s) would be sufficient to explain the power injected in CRs.

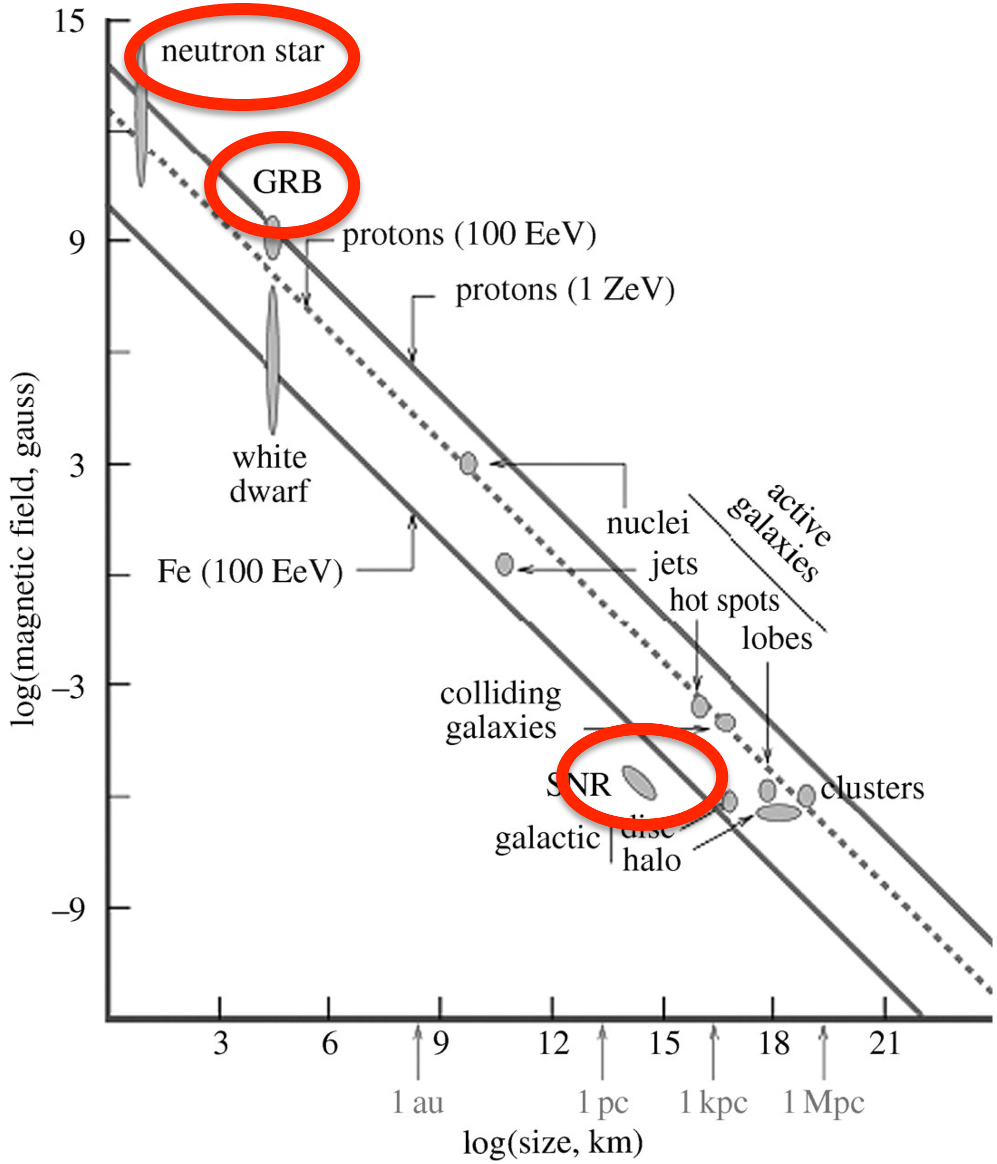
CRs and supernovae

Several suprenova-related phenomena areconsidered as possible sites of particle acceleration.

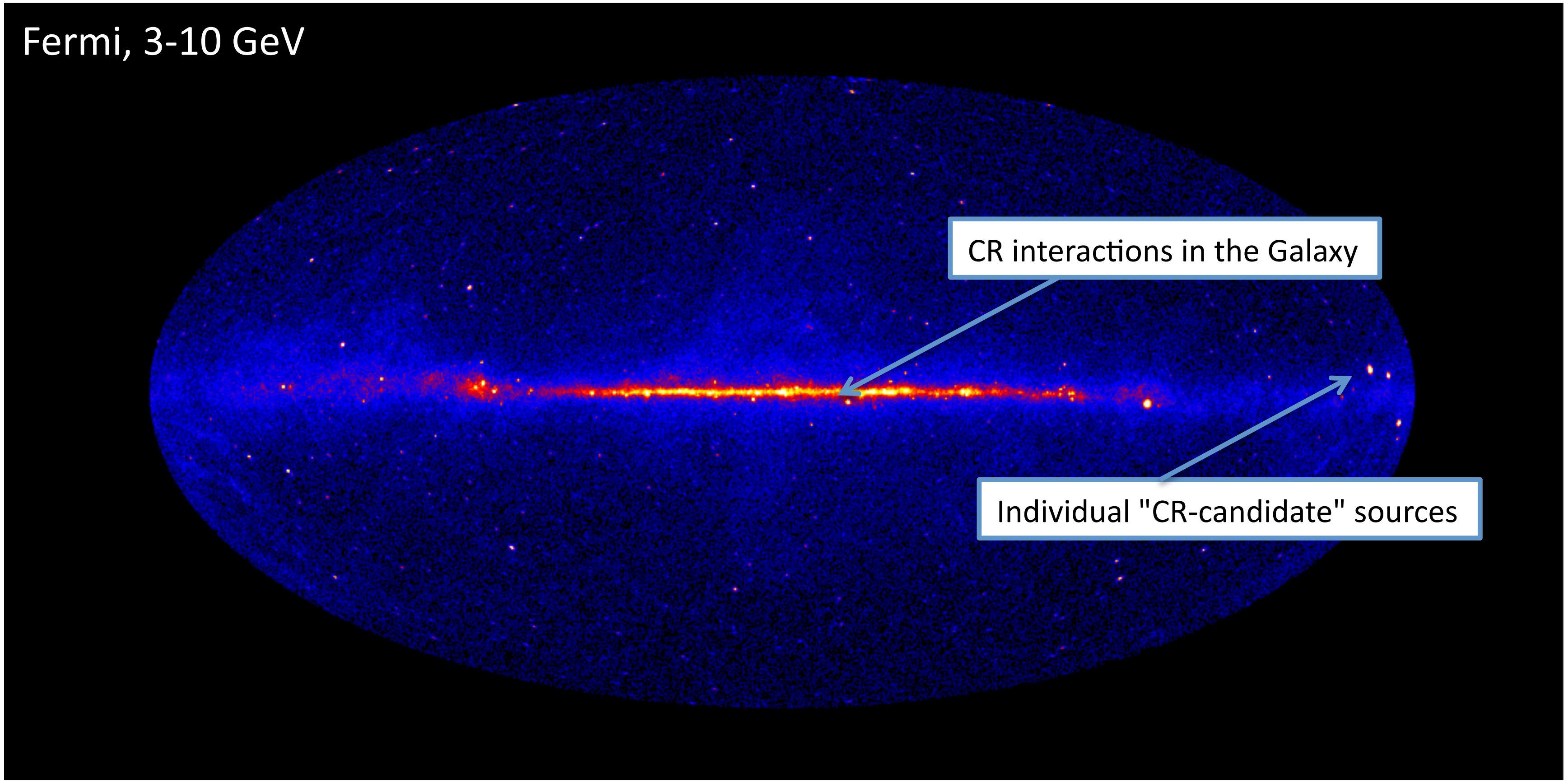
Identification of individual sources of CRs with energies in the range $1\ \mathrm{GeV} - 10^{19}\ \mathrm{eV}$ is not possible with the CR observational tools alone.

Evidence for CR production in particular (classes of) astronomical sources should come from astronomical (rather than CR) data.

Search fro CR sources has served as a driving force in the development of the fields of high-energy (HE, 0.1-100 GeV) and very-high-energy (VHE, 100 GeV-10 TeV) γ-ray astronomy. It drives the development of (yet-to-be-born) field of VHE neutrino astronomy.



Multi-messenger Astronomy



Summary

Particles with energies from <1 GeV to 10^{20} eV coming from space.

Mostly protons an heavy nuclei.

Powerlaw spectrum $dN/dE \sim E^{-2.7}$. Features at $\sim 10^{15}$ eV (knee), $\sim 10^{18}$ eV (ankle) and 10^{20} eV (cut-off?

Sub-dominant components of anti-protons, electrons and positrons.

Positron spectrum "anomaly".

Suppression of CR spectrum at Ultra-high energies. GZK effect.

Heavy nuclei component of UHECR spectrum? Photo-disintegration.

Unresolved problem of the origin of CRs.

Sources of UHECR are nearby (extragalactic) and might be found by tracing back CR arrival directions.

Sources of Galactic CRs with energies below $\sim 10^{18}$ eV could be identified only using the methods of multi-messenger astronomy.