Universität Zürich[UZH]

Physik-Institut

PAUL SCHERRER INSTITUT PSI

PHY213 Kern- und Teilchenphysik II (FS 2020)

Cosmic Frontier: Cosmic rays and air showers

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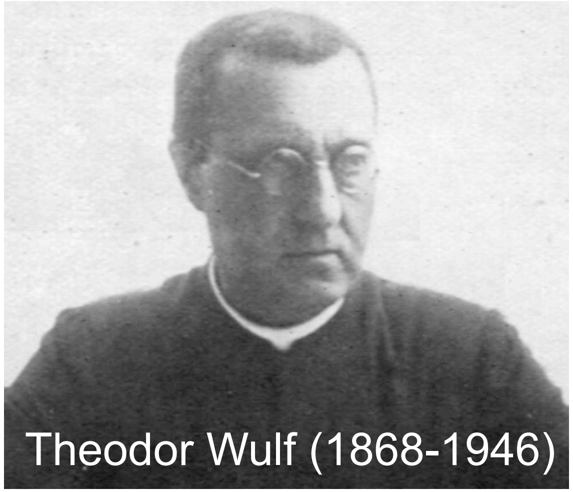
Overview

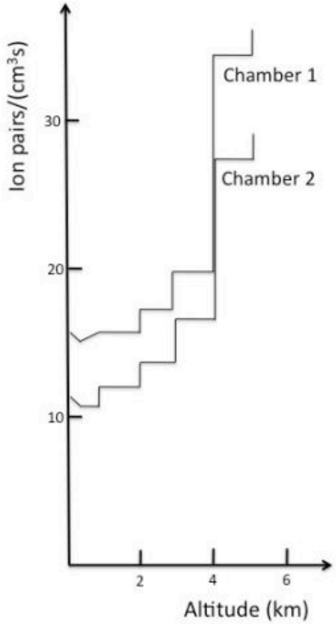
- Some history
- Composition and spectrum of cosmic rays
- Acceleration of cosmic rays
- Passage of particles through matter
- Showers
- Detection of extensive air showers

Some history

- 1910: Theodor Wulf measured radiation at bottom and top of Eiffel tower → found more ionization than expected at the top
- 1912: Victor Hess discovered radiation coming to atmosphere from above in balloon experiment
- Later confirmed by Robert Milikan → named "cosmic rays"



Theodor Wulf (1868-1946)

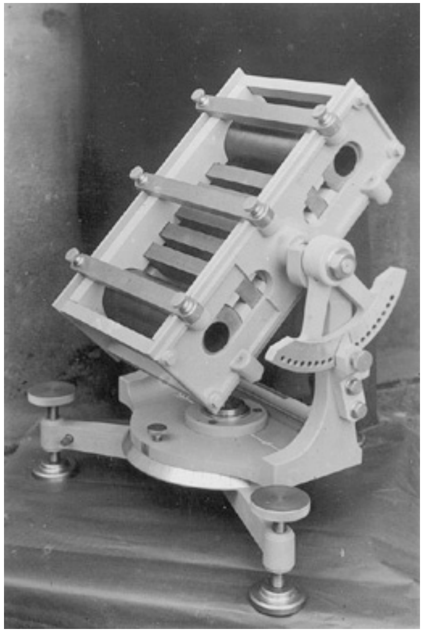


1936

Victor Hess (1883-1964)

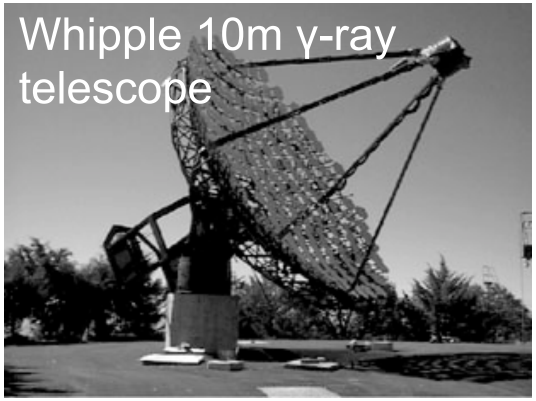
Some history

- 1934: Bruno Rossi demonstrated the production of showers of secondary particles and east-west effect in cosmic rays (more cosmic rays from the west) → primary cosmic rays are mostly positively charged particles
- 1938: Pierre Auger detects extensive air showers. Placed detectors up to 75m apart on Jungfrau and measured coincidence events → estimated energy of incoming particle to 10^{15}eV



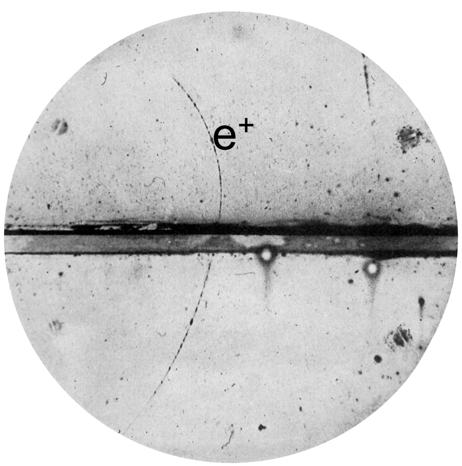
Some history

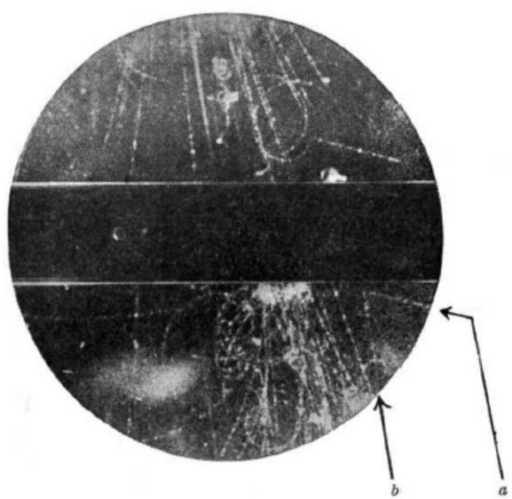
- 1952: Bill Galbraith and John Jelley discover Cherenkov light from passage of cosmic rays through atmosphere
- 1962: John Linsley detects first 10^{20}eV cosmic ray using ground based detectors at Volcano Ranch in New Mexico
- 1989: Detection of high-energy (TeV) gamma rays from Crab nebula
- 1991: "Oh-my-good particle" record breaking cosmic ray at 3.2×10^{20}eV
- More of these events observed in later experiments



Cosmic rays and particle physics

- Study of cosmic rays played a crucial role in particle physics
- Until 1950 the only available source of high-energy particles
- Many crucial discoveries:
- 1932: Discovery of the positron → anti-matter
- 1936: Discovery of the muon
- 1947: Discovery of charged pions
- 1947-1950: Discovery of strange particles





$K^0 \rightarrow \pi^+\pi^-$

Cosmic ray research

- Cosmic rays are highly energetic particles that mostly originate outside of our solar system
- Cosmic rays consist of high-energy particles incident on the earth from outer space plus secondary particles which are generated when they traverse the atmosphere
- Mostly galactic origin, for highest-energies also extra-galactic contributions
- The most fundamental questions of cosmic ray research are:
  - What are the source regions of cosmic rays?
  - How are cosmic rays accelerated?
  - How do cosmic rays propagate in the galaxy?
- Particle astrophysicists have made progress on all of these questions but much work remains..

Cosmic ray research

- The maximum energy of cosmic rays is larger than 10^{20}eV
  - Orders of magnitude greater energy than accessible by the LHC
  - Possibility to investigate particle physics at otherwise inaccessible energies
- Higher energy cosmic rays induce particle showers in atmosphere
- Difficulties:
  - Lack of experimental control
  - Lack of cross-checks with experiments at these energies
  - Rarity of most energetic events

Cosmic ray composition

- Primary cosmic rays are mainly positively charged particles

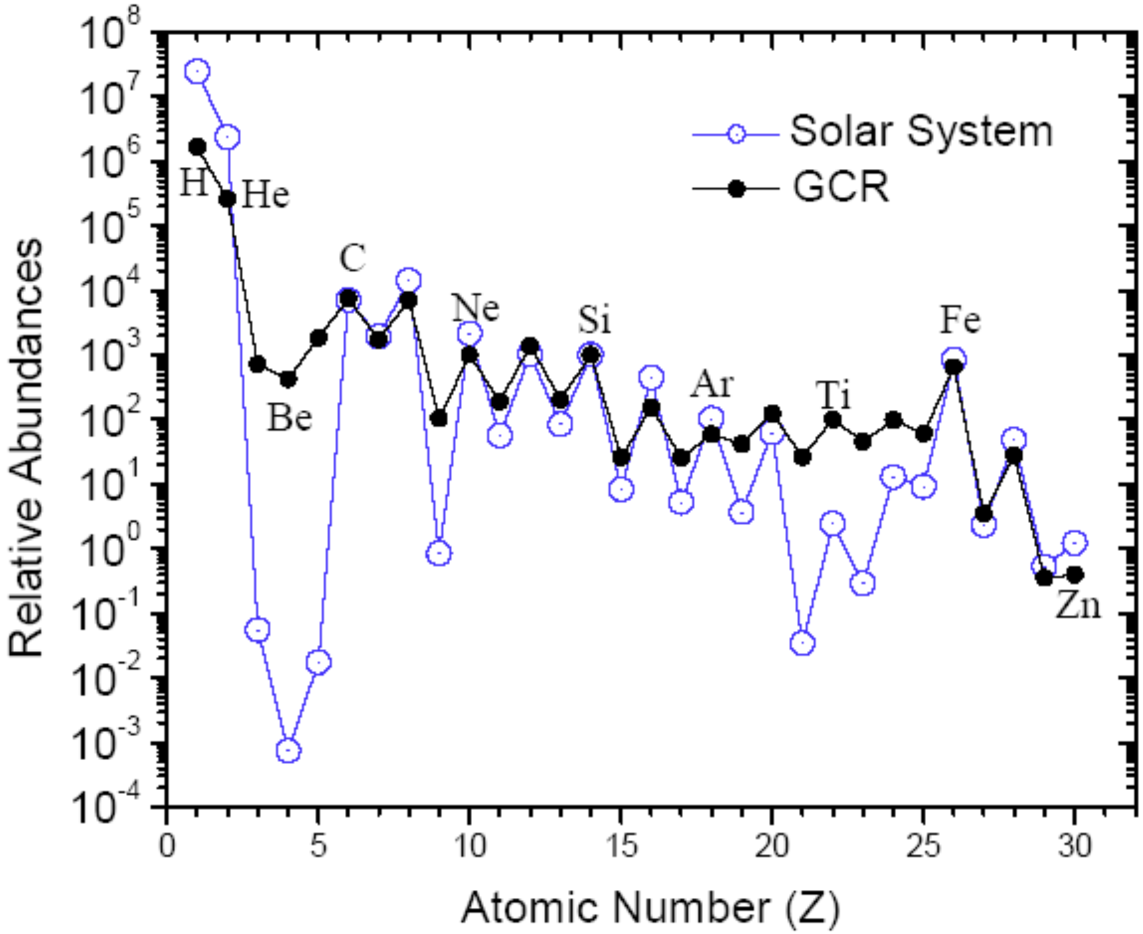
- Primary charged particles
  - Protons 86%
  - α-particles 11%
  - Nuclei of heavier elements 1%
  - Electrons 2%

Values for particles above a certain rigidity $R = pc/z|e|$ → i.e. particles reaching the earth atmosphere through geomagnetic field

- Plus very small fraction of secondary charged particles from collisions
  - Positrons, anti-protons

- Neutral particles from point sources
  - Photons (AGN, Crab Nebula,...)
  - Neutrinos (Sun, supernovae,...)

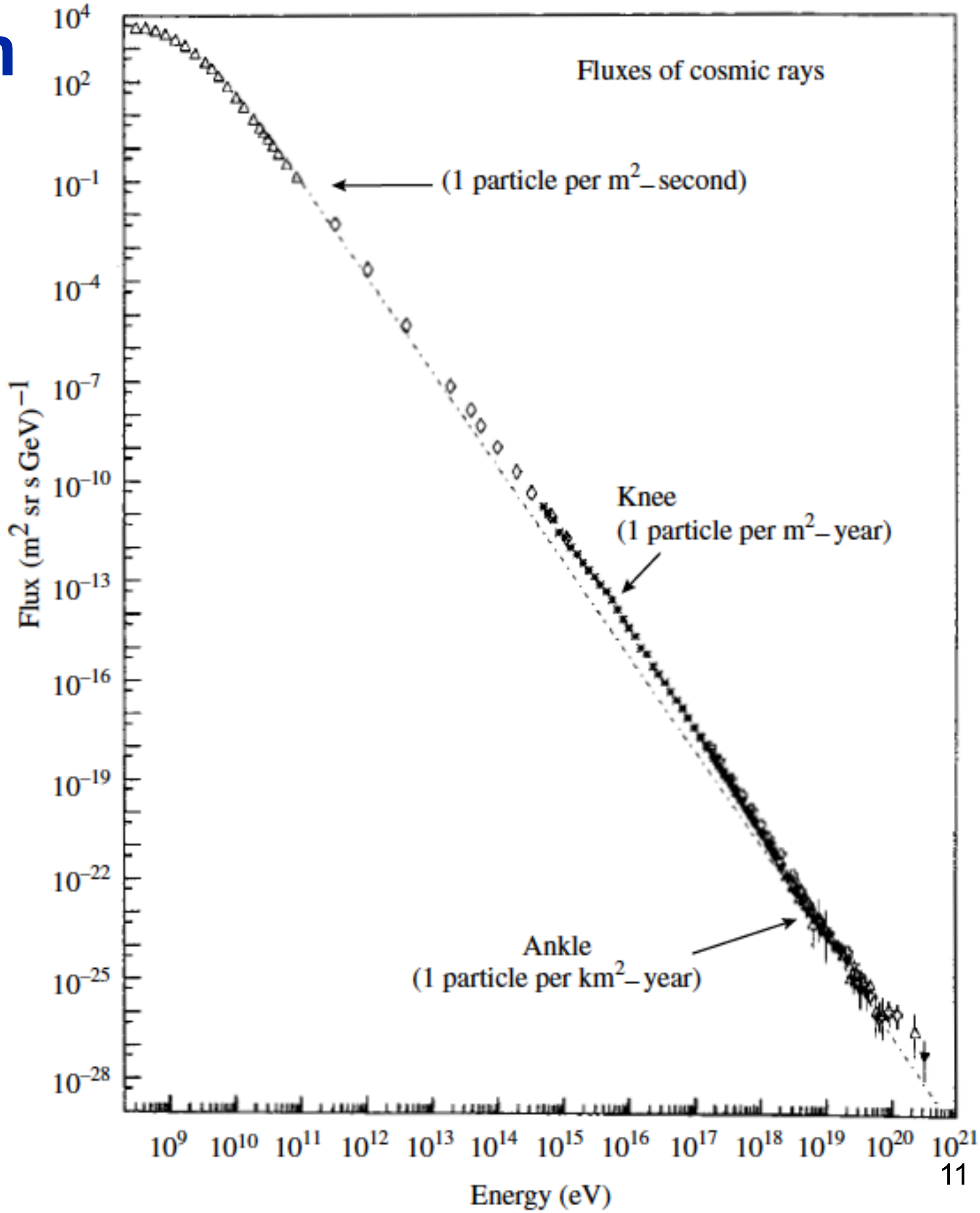
Chemical composition



- Chemical composition of cosmic rays similar (but not equal) to that of solar system
- More light elements (Li, Be, B). These are weakly bound and quickly consumed in stellar reactions. Created in collisions of cosmic rays with interstellar medium (spallation of carbon and oxygen)

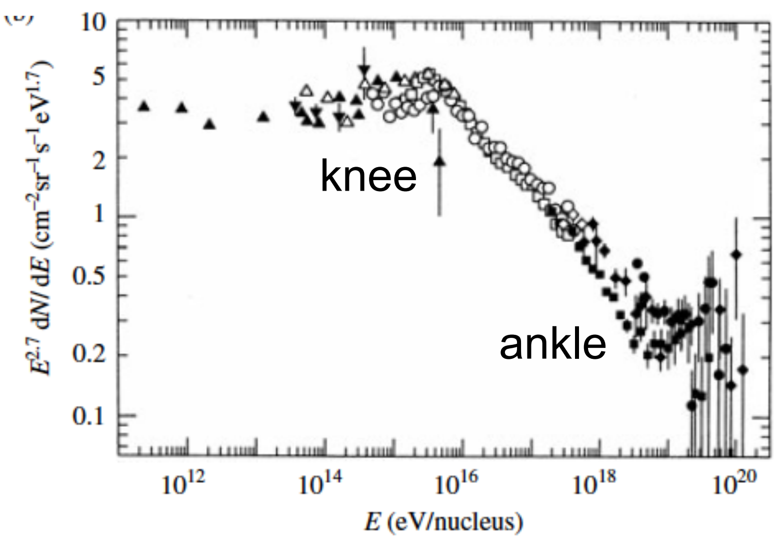
Energy spectrum

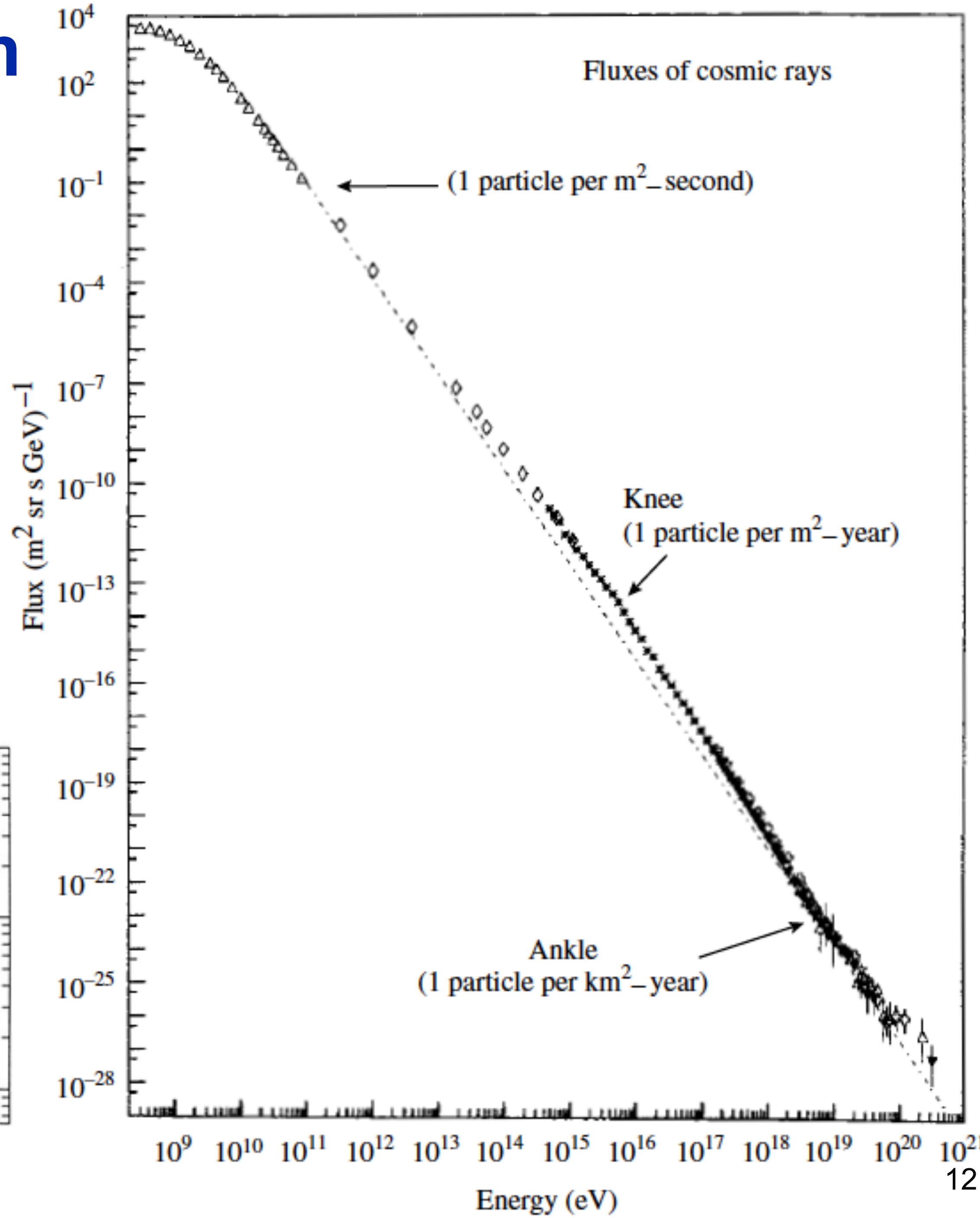
- Spectrum of primary cosmic rays extends over more than 10 orders of magnitude



Energy spectrum

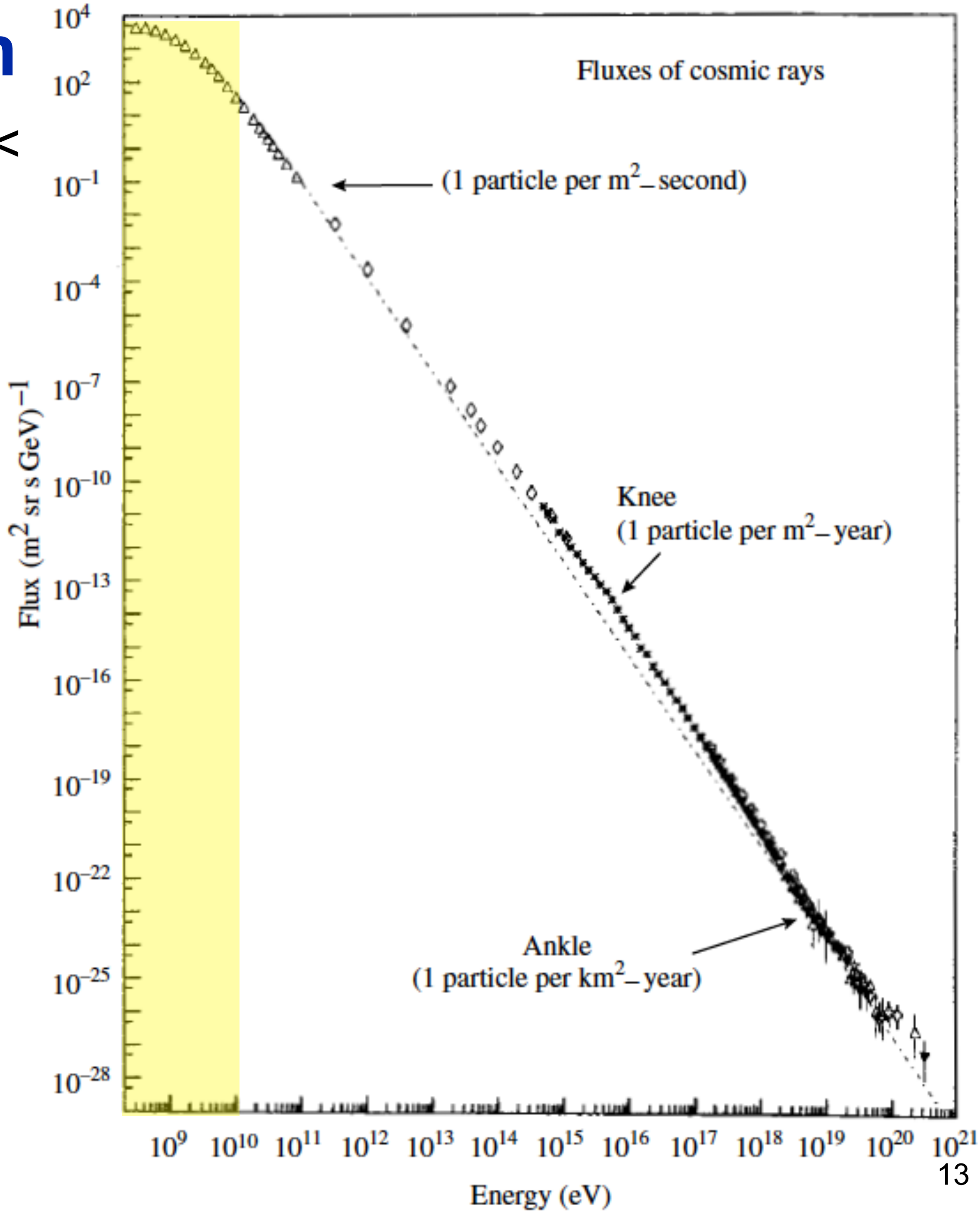
- Spectrum of primary cosmic rays extends over more than 10 orders of magnitude
- Power spectrum changing slope at "knee" and "ankle"
- Changing slope may indicate a transition in the acceleration or confinement mechanism and/or composition





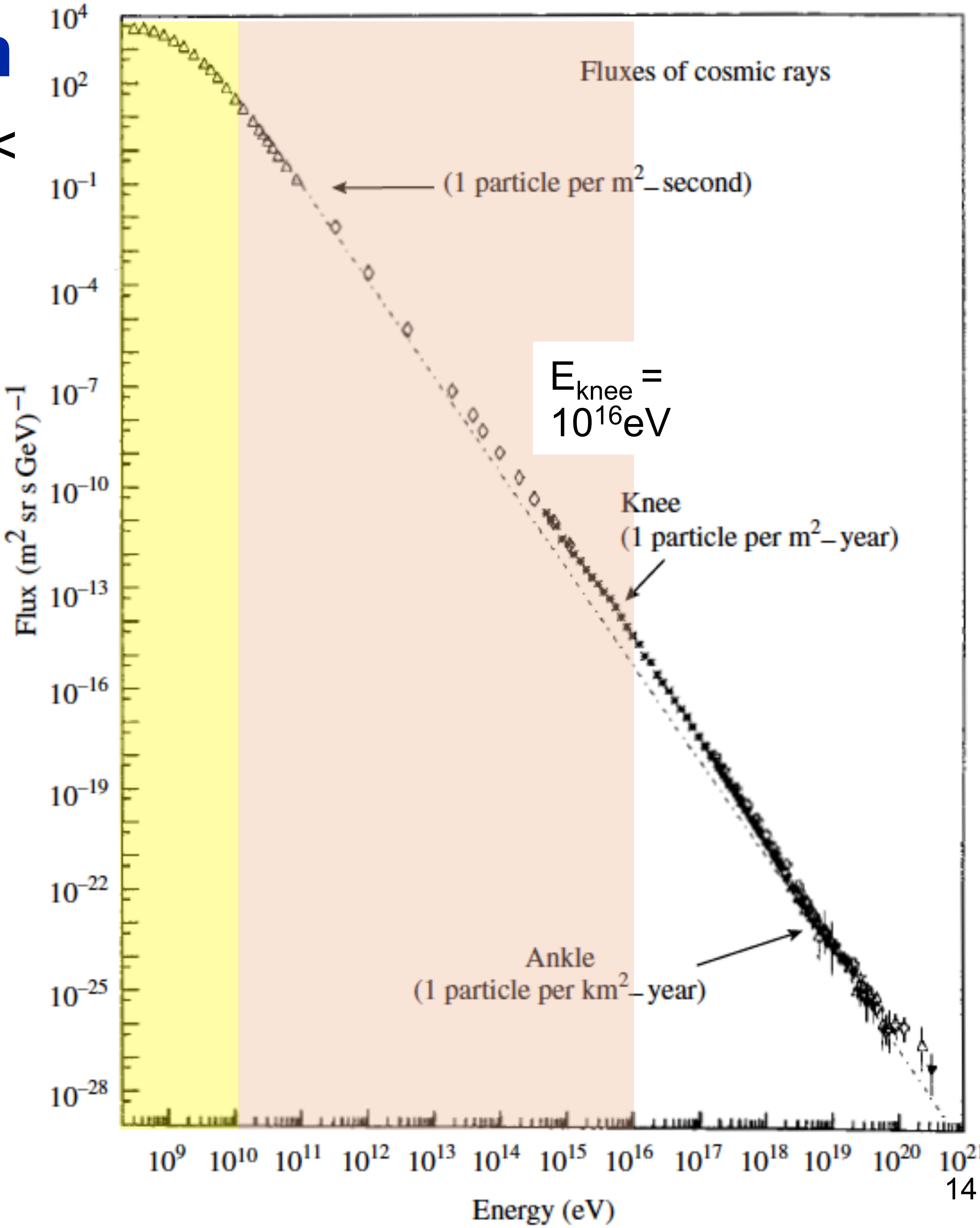
Energy spectrum

- Primary protons with E < 10 GeV affected by geomagnetic and solar effects



Energy spectrum

- Primary protons with E < 10 GeV affected by geomagnetic and solar effects
- Particles with $E<E_{knee}$ mainly have galactic origin
  $N(E)dE \propto E^{-2.7}dE$



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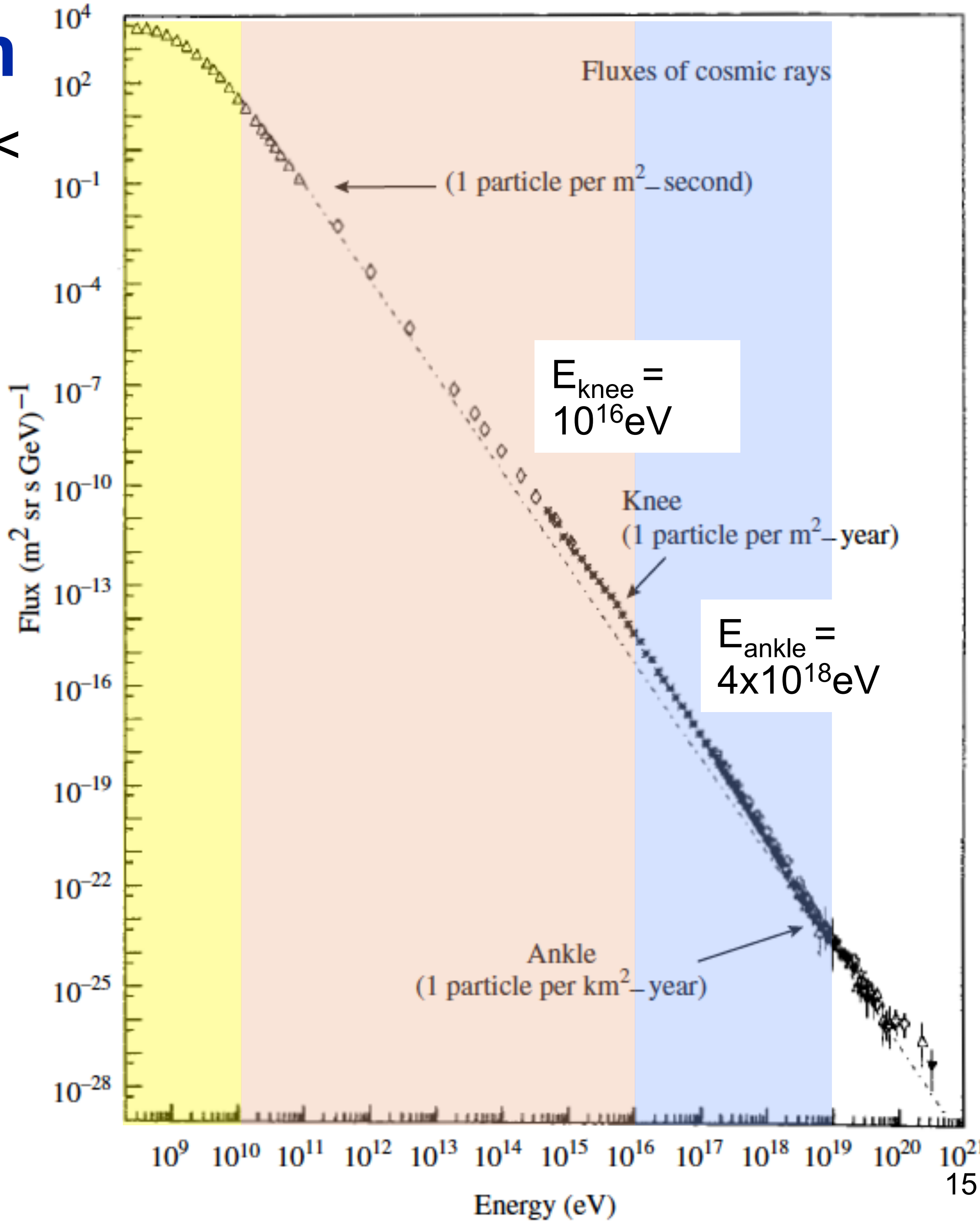
- Particles with $E>E_{knee}$ extra-galactic sources contribute. For $E<E_{ankle}$
  $N(E)dE \;\alpha\; E^{-3.0}dE$



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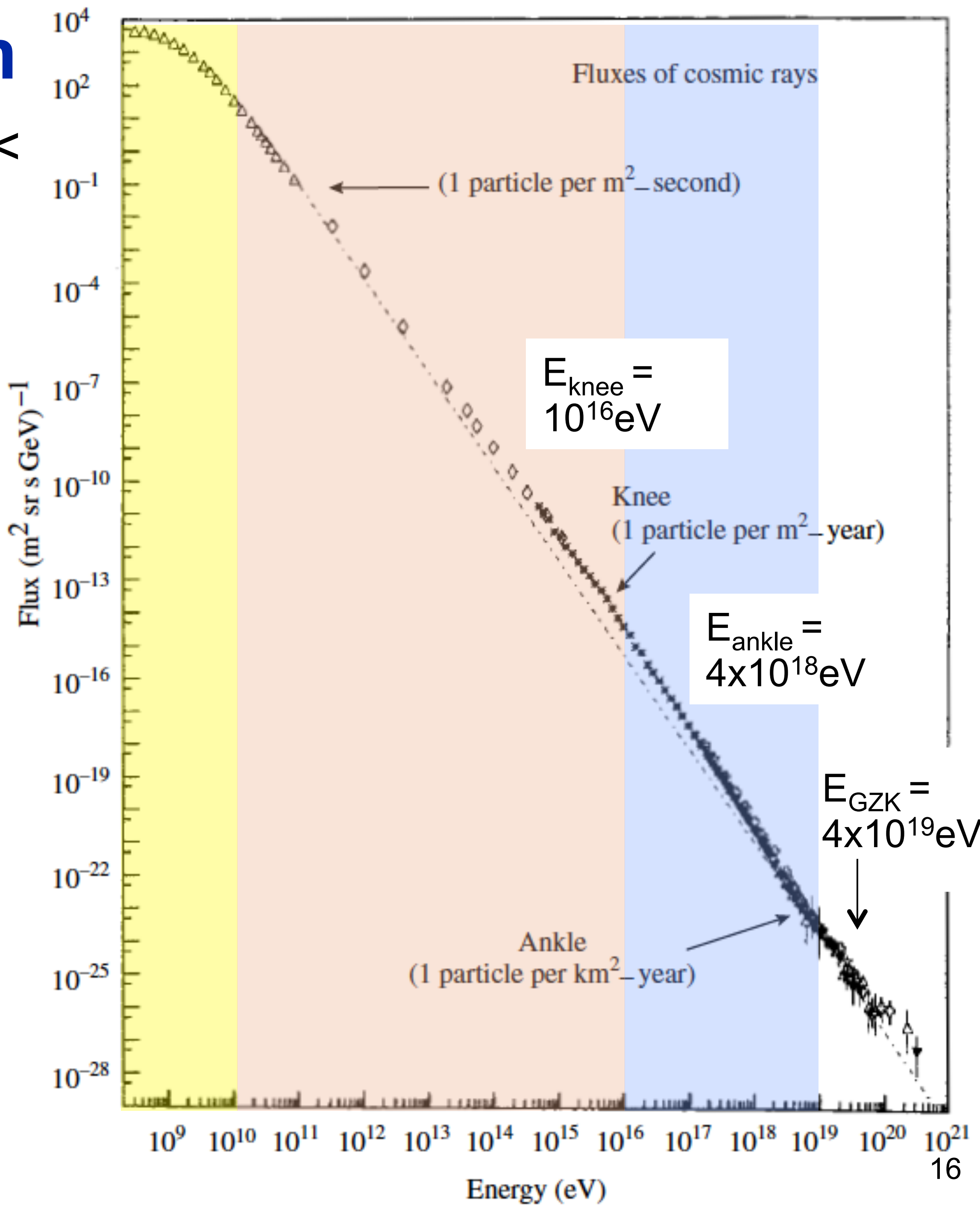
  $N(E)dE \propto E^{-3.0}dE$
- For higher energies extra-galactic sources dominate

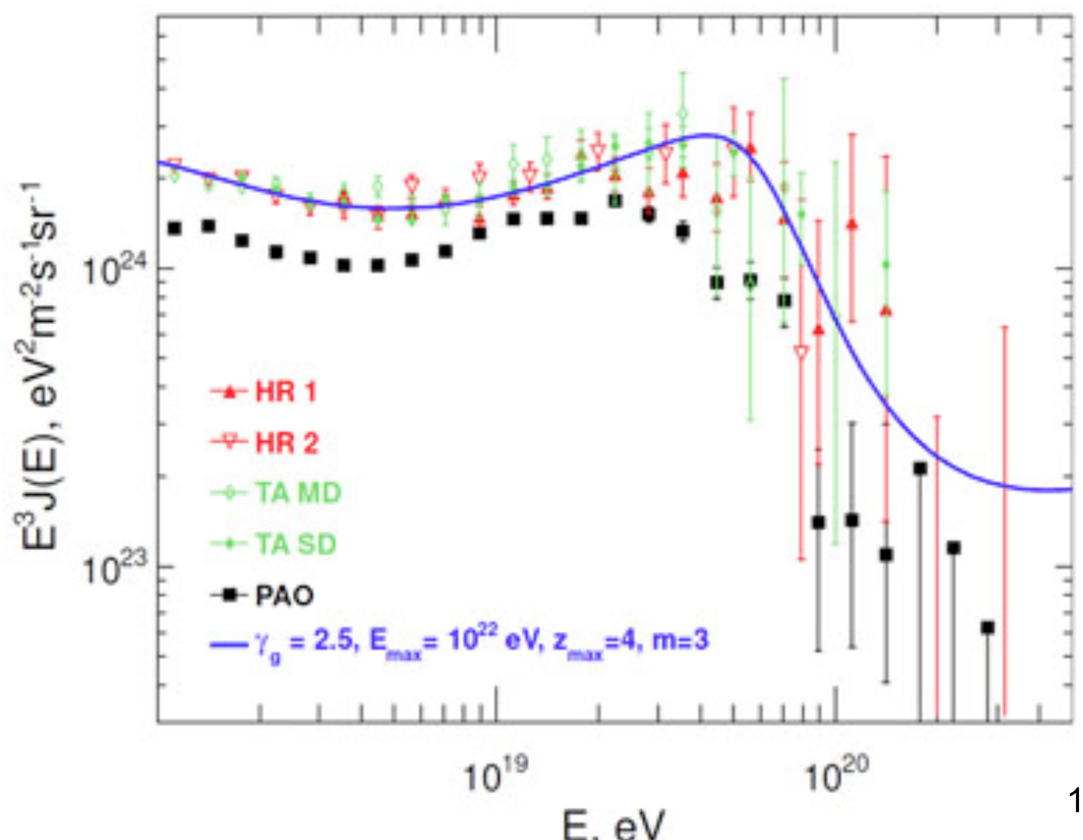


High tail of energy spectrum ultra high energy cosmic rays (UHECR)

- Protons with E > 4×10^{18}GeV would not be contained within the galaxy by the galactic magnetic field → extra-galactic origin
- Greisen, Zatespin and Kuzmin (1966): universe becomes opaque at highest energies due to collisions of protons with CMB photons:

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

$E_{GZK} = 4 \times 10^{19}$eV



What properties of cosmic rays must an acceleration mechanism explain?

- A power law energy spectrum for particles of all types

  $$dN(E) \propto E^{-x} dE$$

  with x in the range ~2.7 to 3

- The acceleration of cosmic rays to maximum observed energies
  - For galactic cosmic rays, energies up to the knee ~10^{16} eV
  - For extragalactic cosmic rays, energies beyond the ankle ~10^{20}eV

- Elemental abundances of cosmic rays similar to interstellar/ circumstellar abundances

General principles of acceleration

- The equation of motion for a charged particle is

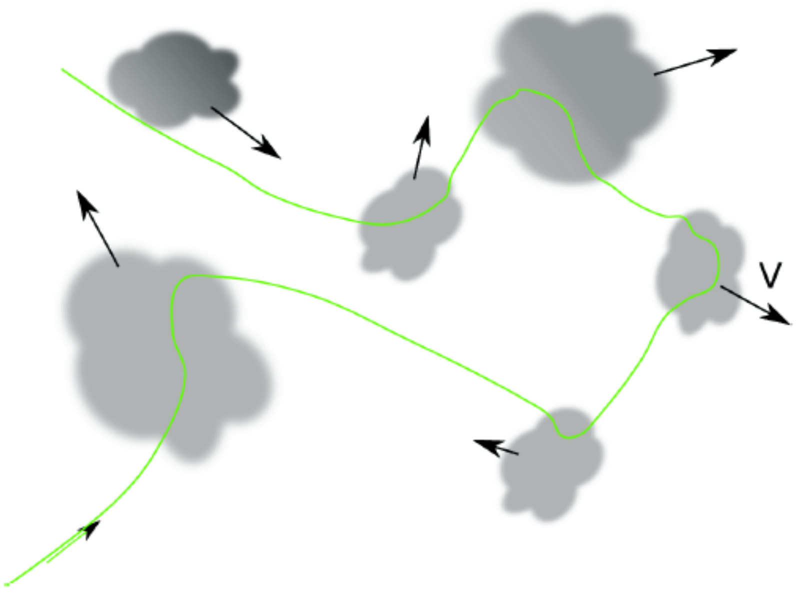
$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m \mathbf{v}) = q\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right)$$

where $\gamma \equiv \frac{1}{\sqrt{1-v^2/c^2}}$ is the Lorentz factor and q,m and v are the charge, mass and velocity of the particle

- Magnetic fields themselves cannot be directly responsible for acceleration, but changing magnetic fields lead to inductive electric field
- Direct acceleration requires nonzero average electric field. Electric fields that develop due to charge separation will quickly short themselves out by motion of free charges → will not suffice to describe cosmic ray acceleration

Second order Fermi acceleration

- In 1949 Fermi proposed a model for acceleration in which particles can statistically gain energy through collisions with interstellar clouds
- Reflection of particles at cloud due to magnetic mirror effect
- Energy is gained in head-on collisions, lost during trailing collisions
- Large probability for head-on collisions → net energy gain



Leads to second order acceleration $\frac{\Delta\mathcal{E}}{\mathcal{E}} \propto \left(\frac{V}{c}\right)^2$

V: velocity of clouds

Second order Fermi acceleration

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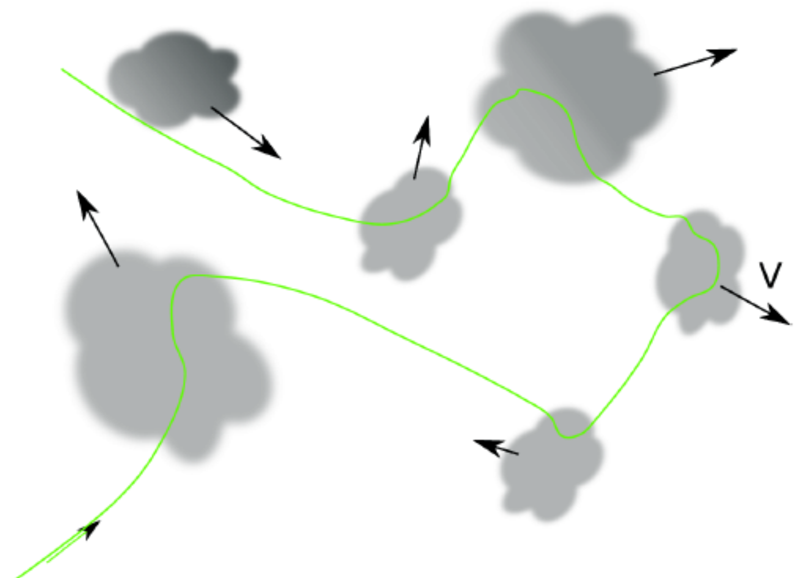


Leads to second order acceleration $\frac{\Delta \mathcal{E}}{\mathcal{E}} \propto \left(\frac{V}{c}\right)^2$

V: velocity of clouds

However, clouds are moving too slow and collisions are happening too rarely to explain observed acceleration

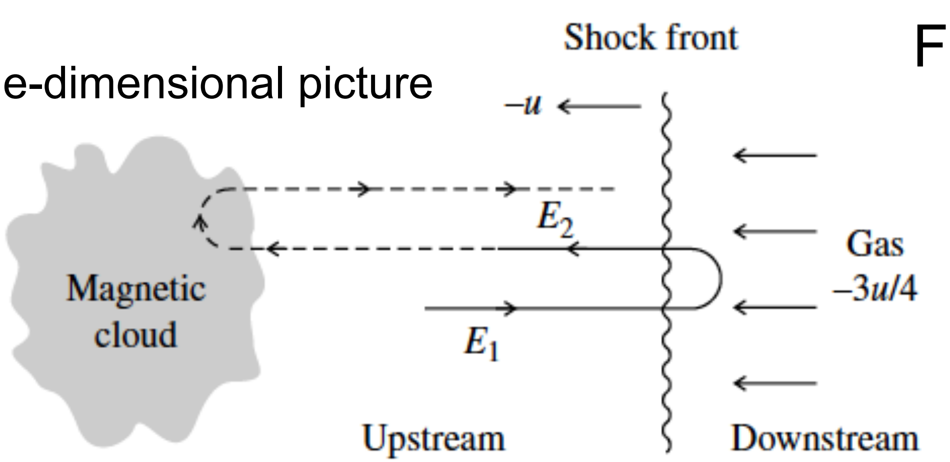
First order Fermi acceleration

- Fermi also proposed mechanism in which acceleration occurs due to shock fronts
- Relativistic particle travels with velocity u_1
- Back-scattered by the field in the gas behind the front which has a velocity component in the direction of the shock of

$$u_2 = \frac{2u_1}{(C_p/C_v + 1)} = \frac{3u_1}{4} \qquad C_p/C_v = 5/3 \text{ for ionized gas}$$

- Then scattered by magnetic could → next acceleration cycle

Simplified one-dimensional picture



Fractional energy gain

$$\frac{\Delta E}{E} \sim \frac{u_1}{c}$$

What is the maximum attainable energy by this mechanism?

- This model provides an efficient method for accelerating particles in supernova remnant shock waves
- The magnetic field must be able to confine energetic particles
- For interstellar magnetic field strengths ~1μG, the proton Larmor radius is ~ 1pc
- Supernova remnants could then not confine particles with energies $>10^{14}$ eV

→ Acceleration mechanism for highest energy cosmic rays still not understood

How are cosmic rays observed?

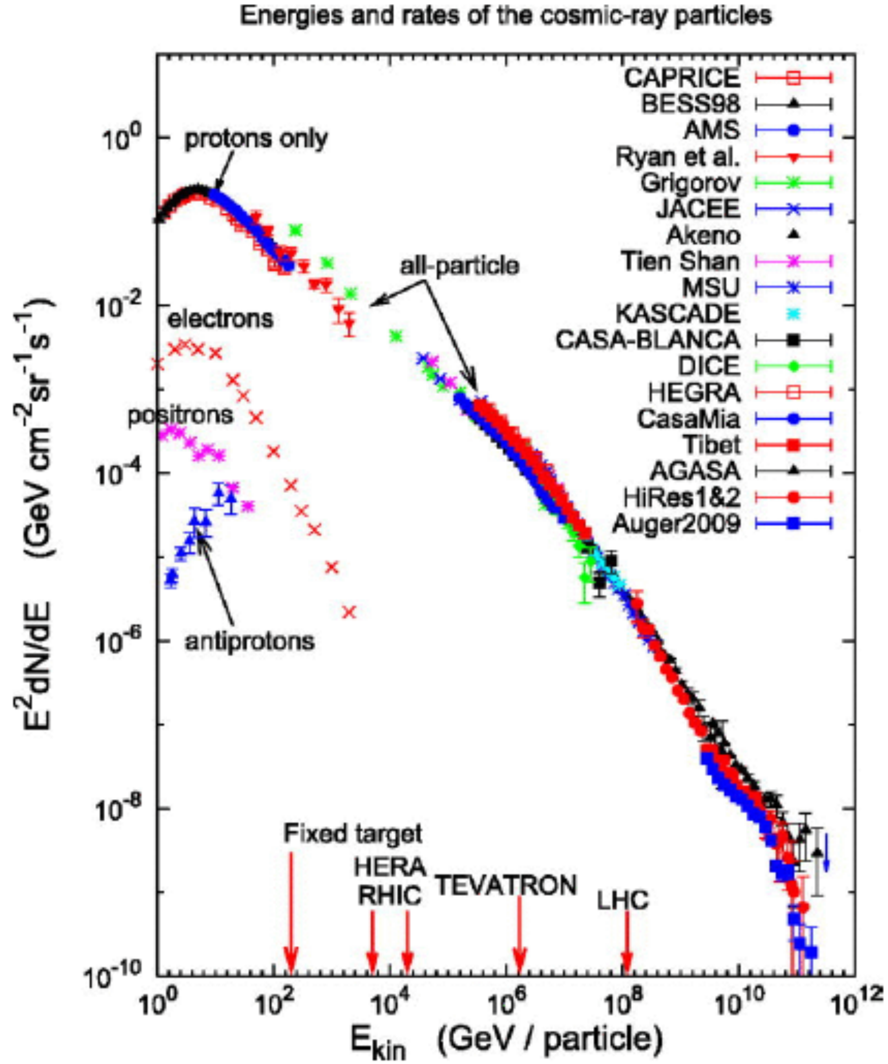
- Synchrotron radiation
- Gamma rays (from π^0 decay)
- Detection of charged particles
  - Cloud chambers (historically)
  - Magnetic spectrometers (e.g. AMS-02)
  - useful at relatively low energies
- Cherenkov radiation
  - ground-based water detectors
  - telescope observing Cherenkov radiation produced in atmosphere
- Atmospheric fluorescence
  - produced by excitations of atoms (typically nitrogen) → blue wavelength region

Detection of cosmic rays

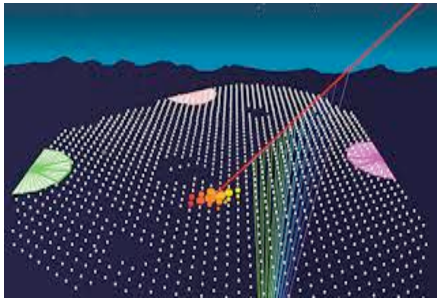
Detection of particles

Detection of air showers

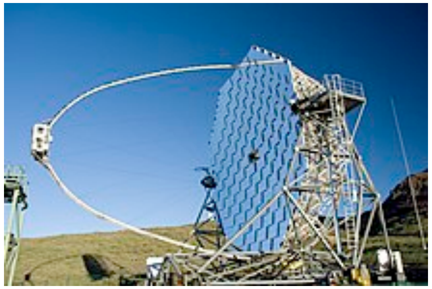
balloons, satellites and space experiments



arrays of surface detectors

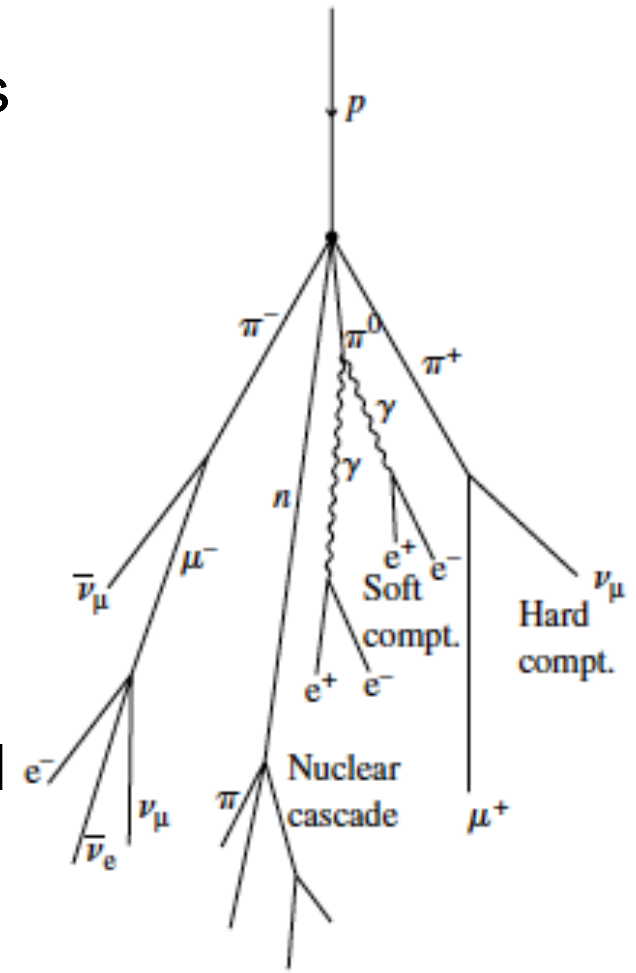


Imaging Cherenkov telescopes



Secondary particles in cosmic rays

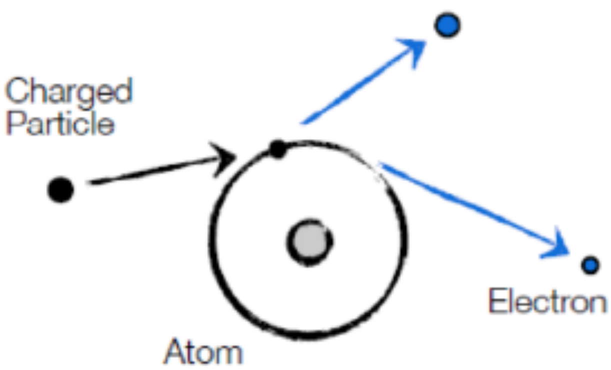
- Created in earth atmosphere
- Incoming protons mainly produce pions (π^+,π^-,π^0)
- Charged pions decay to muons
- $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$
- Muons with E<3 GeV decay in-flight $\mu \rightarrow e\nu\nu$
- Muons with larger energy can get through atmosphere and reach earth's surface or even penetrate underground
- Neutral pions decay $\pi^0 \rightarrow \gamma\gamma$
- Photons produce cascade of photons and electrons → soft component



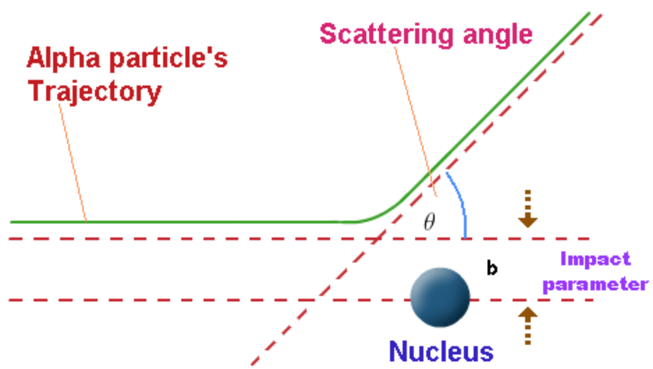
Passage of charged particles through matter

- Three main interaction mechanisms for charged particles when passing through a medium

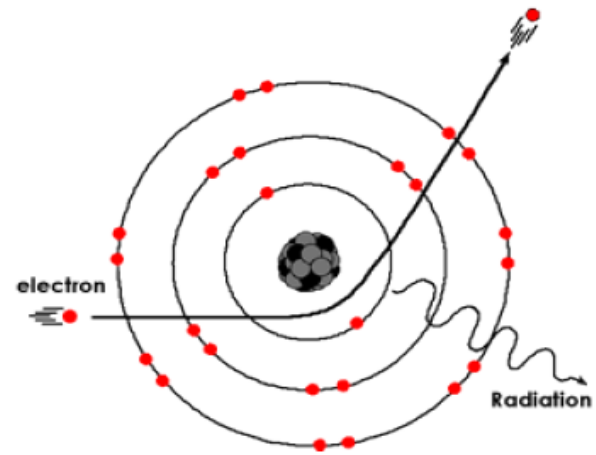
Ionization



Coulomb scattering



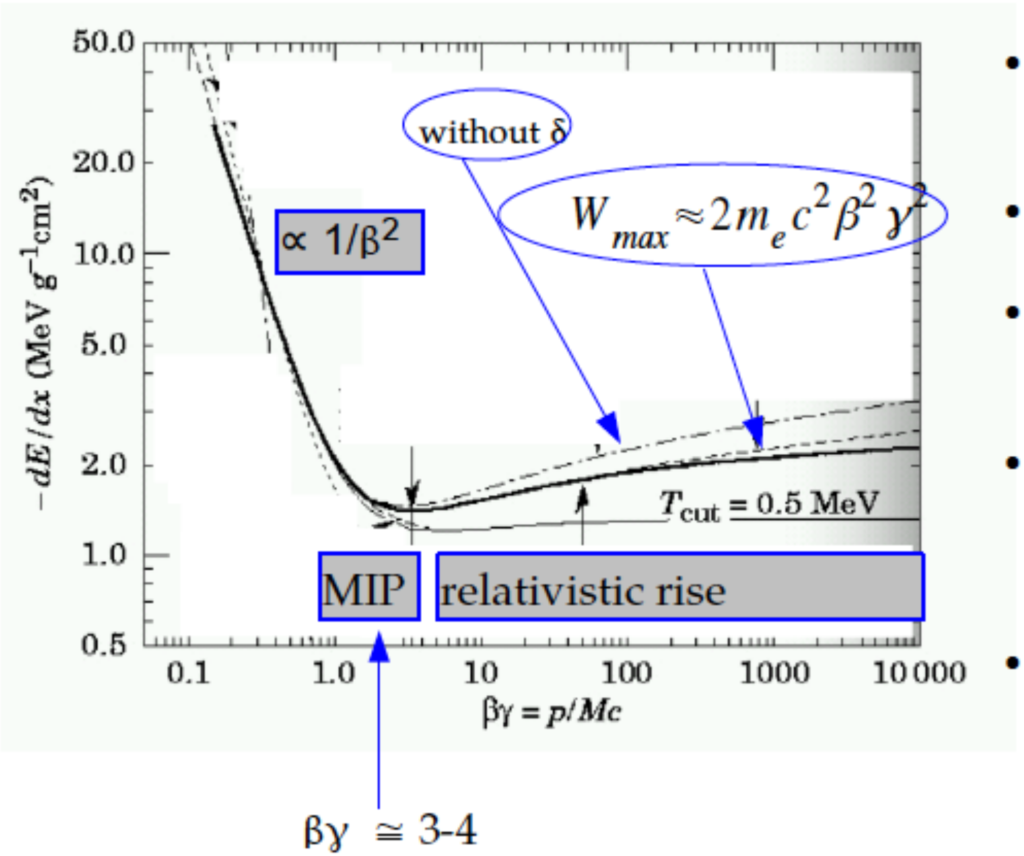
Bremsstrahlung



→ Coulomb scattering mainly changes particle trajectory, little contribution to energy loss

Ionization – Bethe-Bloch formula

$$\frac{-dE}{dX} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}]$$



- loss depends on velocity not on mass → particle identification if p is known
- $\beta\gamma$ small $dE/dx \propto 1/\beta^2$
- $\beta\gamma \cong 3.5$ broad minimum light absorbers: $Z/A \simeq 0.5$
- $dE/dx(\min) \simeq 1.5$ MeV /(g/cm^2)

  → minimal ionising particles (MIP)
- $\beta\gamma > 4$ $dE/dx \propto 2 \ln(\beta\gamma^2)$ logarithmic (relativistic) rise

I: mean excitation energy
W_{max}: kinetic energy transfer from particle to electron in single collision
δ: Density correction due to polarization (Cherenkov radiation)
C/Z: Shell correction

Bremsstrahlung

- Radiation loss with the emission of a photon

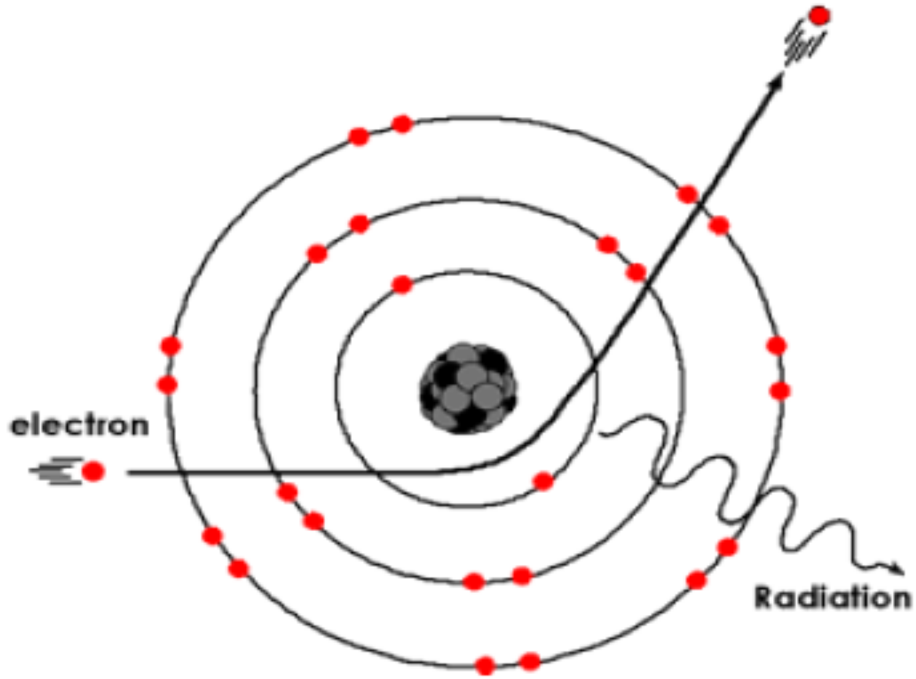
$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle_{\mathrm{rad}} = -\frac{E}{X_0}$$

- Mean energy of an electron after having passed a medium of thickness x:

$$\langle E \rangle = E_0 \exp\left(-\frac{x}{X_0}\right)$$

- Critical energy E_c, when

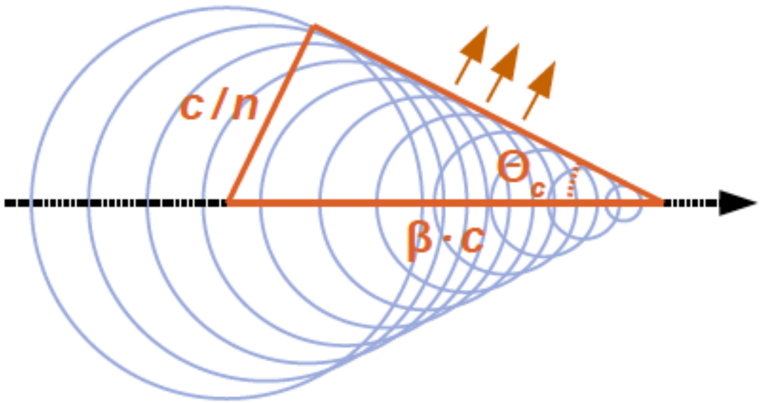
$$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{ion}} = (\mathrm{d}E/\mathrm{d}x)_{\mathrm{rad}}$$



Cherenkov radiation

- Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a medium at a speed greater than the speed of light in that medium
- Photons are emitted along a cone around the direction of motion of the particle with angle

$$\cos\theta = \frac{(ct/n)}{\beta ct} = \frac{1}{\beta n}, \quad \beta > \frac{1}{n}$$



- Most of the particles in air showers have relativistic energies → produce abundant Cherenkov light in atmosphere, typically in ultraviolet or blue region

Passage of radiation through matter

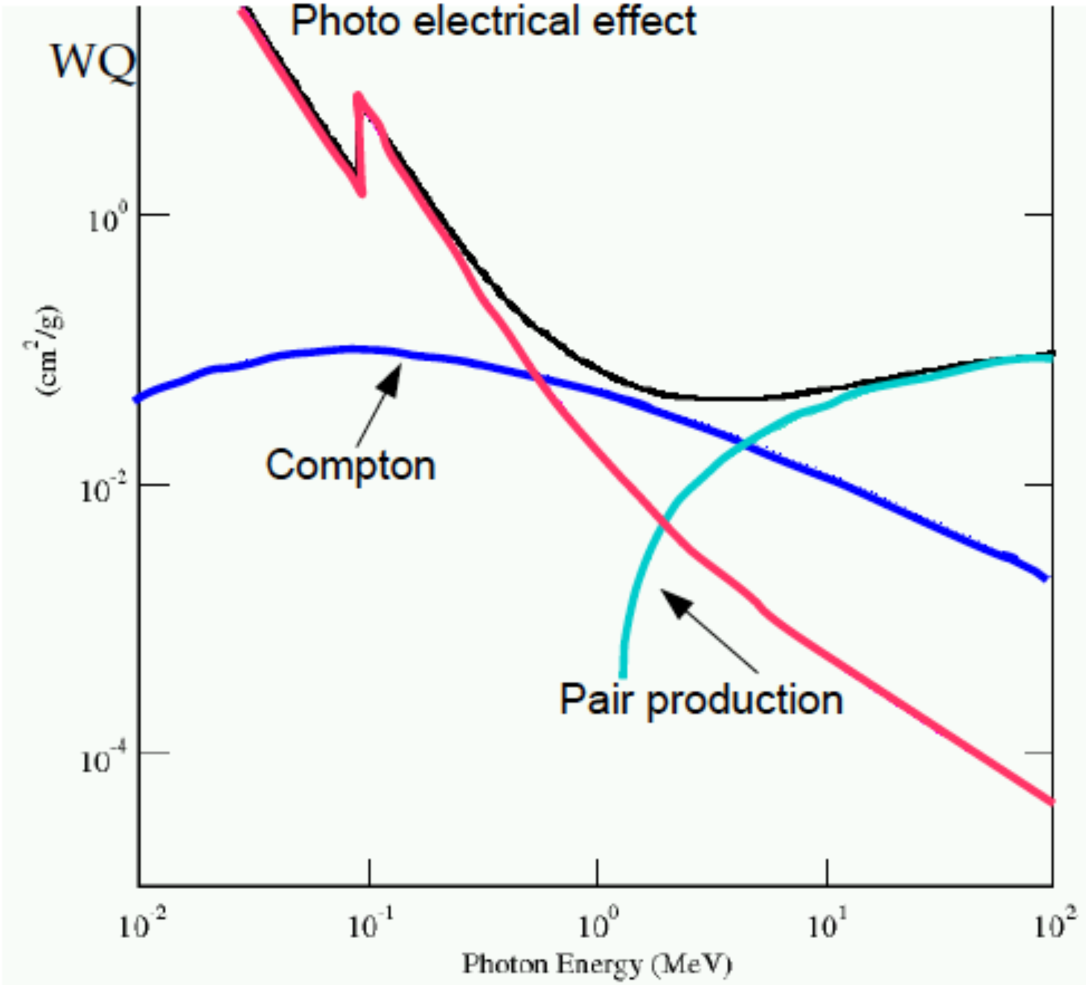


Photo electrical effect
γ + Atom $\rightarrow$ Atom$^+$ + e$^-$
$\sigma \propto Z^5/E^3$

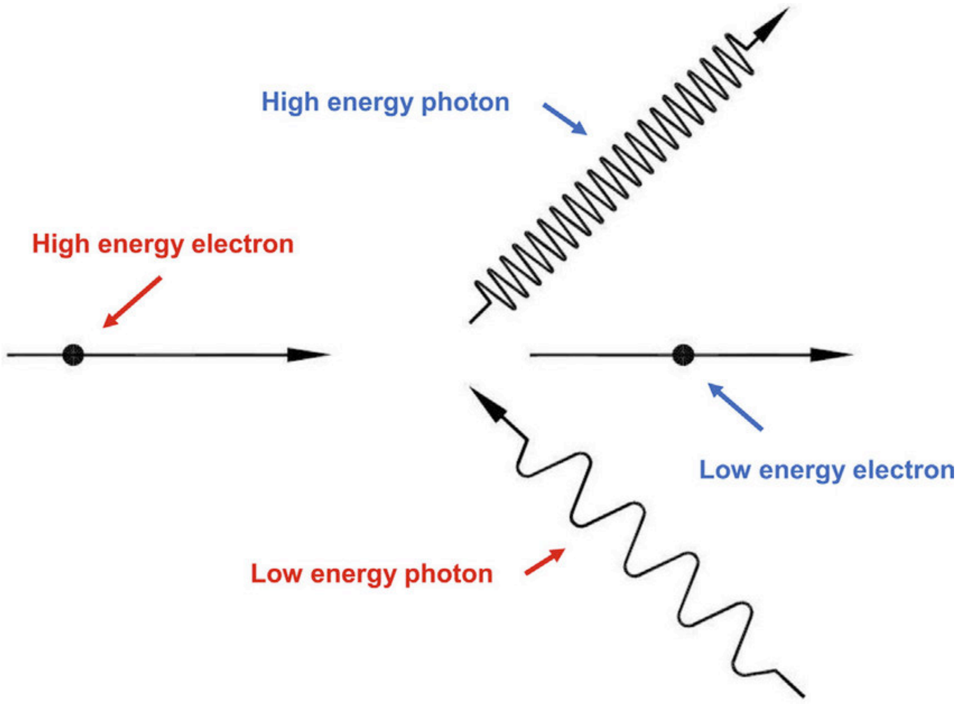
Compton scattering
photon scatters on shell electrons
$\sigma \propto Z \ln E / E$

Raleigh scattering(coherent)
without energy loss

Pair production in field of nucleus
$\sigma \simeq Z^2 \simeq 7/9\ X_0$ above threshold
characteristics: radiation lengths

Inverse Compton scattering

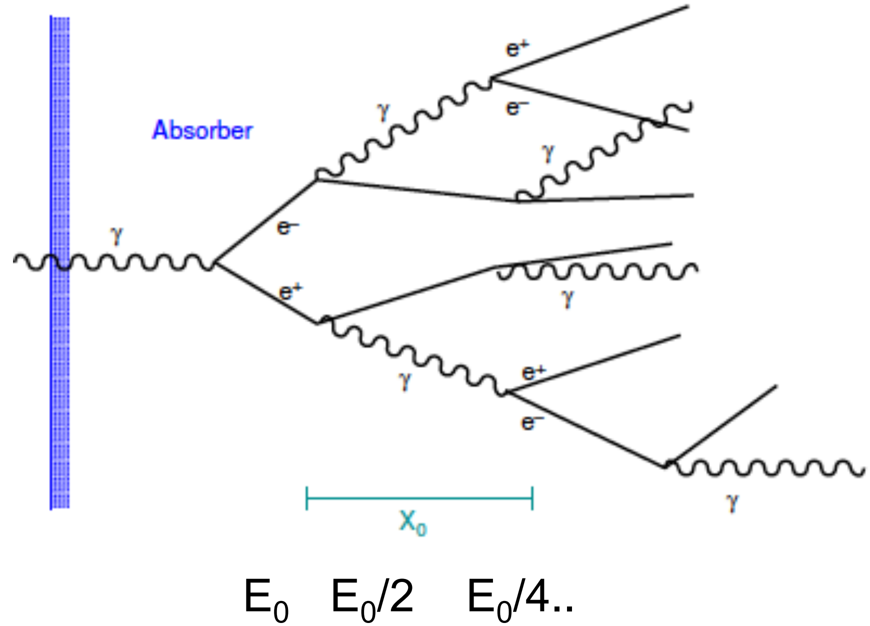
- Low-energy photons are boosted by collisions with very energetic electrons



- Important process for acceleration of photons from astrophysical sources, e.g. acceleration of CMB photons through hot gas surrounding galaxy clusters

Development of electromagnetic shower

- Very simplified description: after t radiation lengths
- $N(e^-) \sim N(e^+) \sim N(\gamma) \sim 2^t/3$
- $E(t) = E_0/2^t$
- Shower goes on until $E(t)<E_c$, now ionization loss becomes dominant
- Cascade reaches a maximum and then stops abruptly
- Shower maximum:



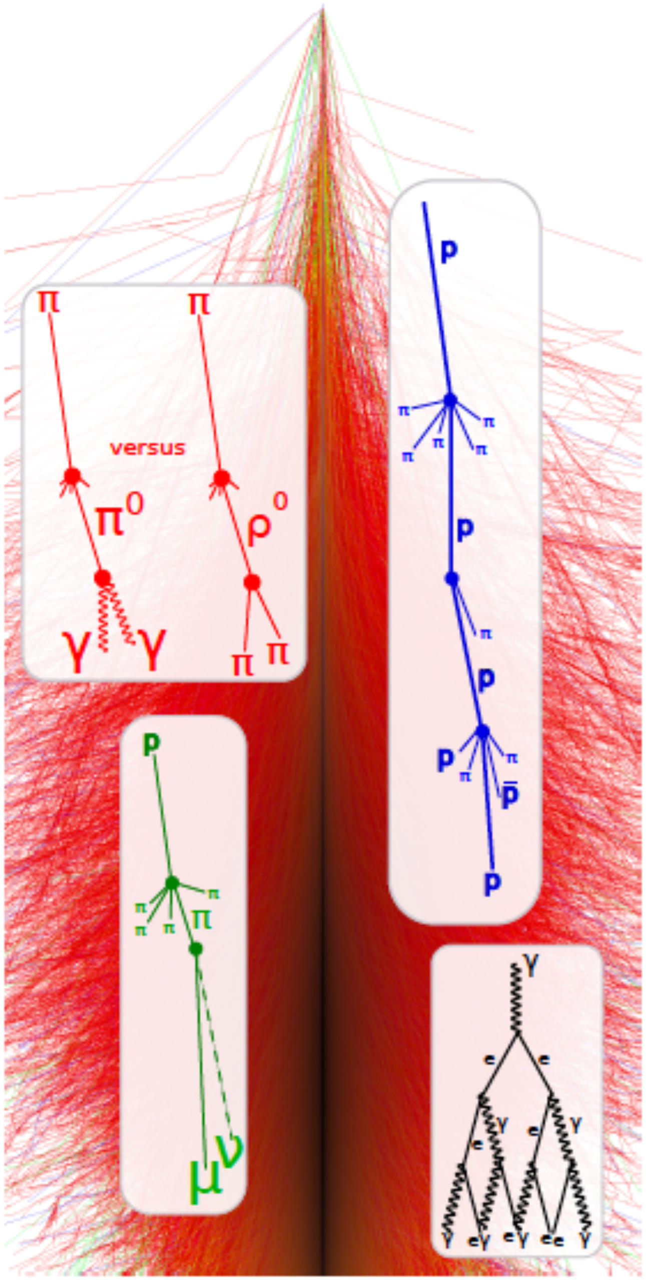
$t = t\,(\max) = \ln\,(E_0/E_c)/\ln 2$ → maximum generation logarithmic in E_0

$N\,(\max) = 2^{t(\max)} = E_0/E_c$ → number of particles proportional to E_0

$L = \left(\frac{2}{3}\right)\int 2^t \mathrm{d}t \sim \left(\frac{2}{3}\ln 2\right)\frac{E_0}{E_c} \sim \frac{E_0}{E_c}$ → total track length proportional to E_0

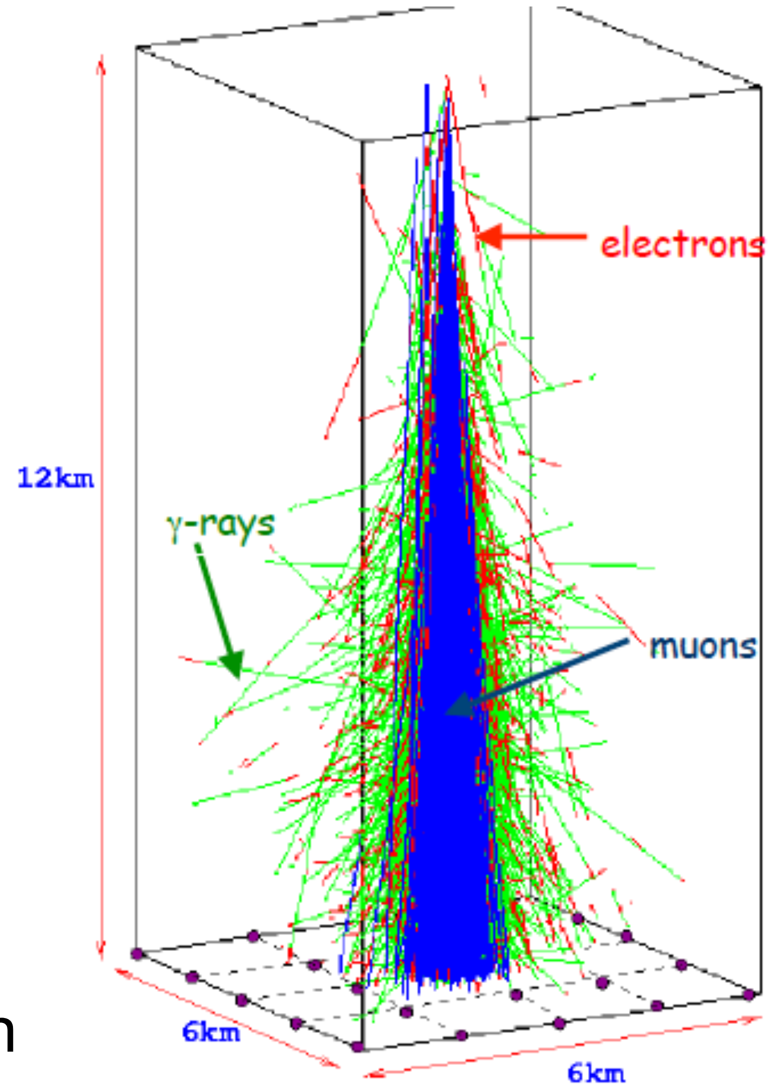
Nucleon induced shower

- While electrons lose bulk of their energies in a radiation length, nucleons can penetrate through several interaction lengths losing only a fraction of their energy → more interactions → more extensive air showers
- Contain high-energy core of nucleons surrounded by more widely spread electron-photon component
- Shower profile used to discriminate against photon-induced shower



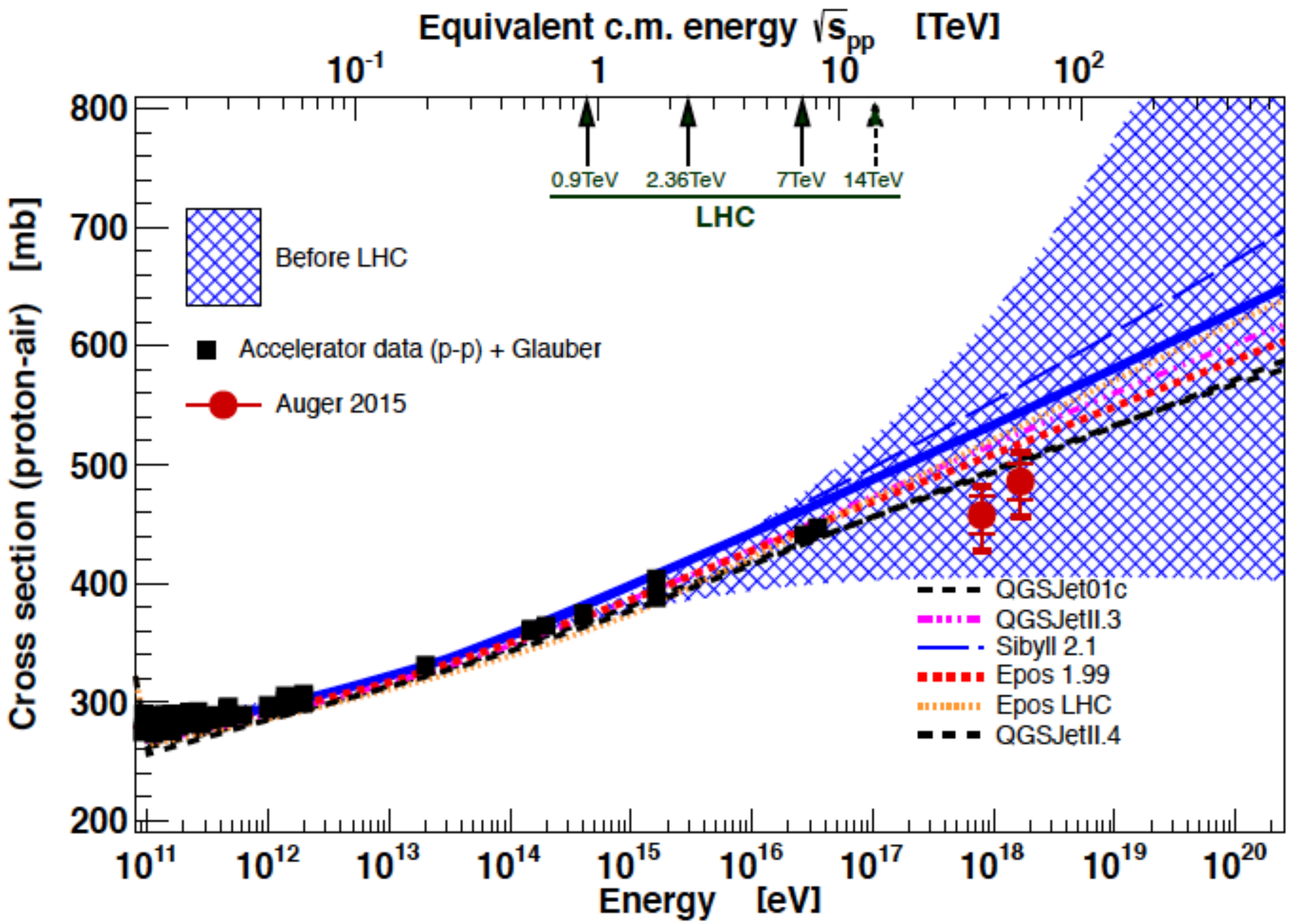
Detection of extensive air showers

- Ground arrays measure footstep of the shower
- Final particles are γ-rays, electrons, positrons, muons and hadrons
  - Typically $10^{10\text{-}11}$ photons, electrons and positrons in an area of 20-50 km^2
  - it is enough to have detectors with area of few m^2 per km^2
- Number of low energy particles connected to primary energy
- Space/time structure of signal give information on arrival direction
- Number of muons compared to number of electrons give information of primary particle kind



Modeling of shower development

- Modeling of shower development crucial for study of primary particles → input from collider data at lower energies



compare to Nucl.Phys.Proc.Suppl. 196 (2009) 335

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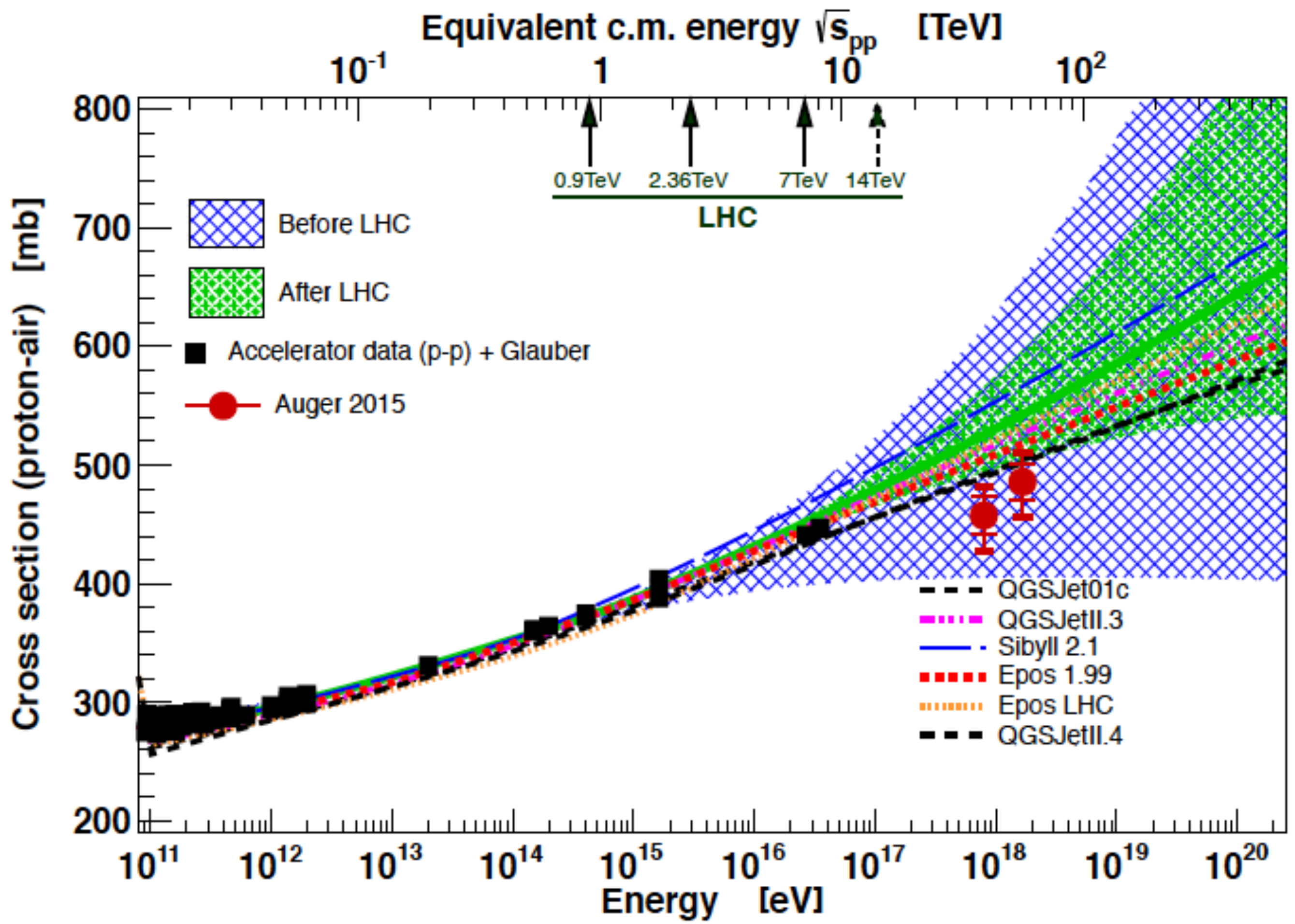

compare to Nucl.Phys.Proc.Suppl. 196 (2009) 335

Consequences for modeling of air showers

- Data compared to different hadronic interaction model
- Models tuned to LHC data improve predictions
  - Smaller cross section → deeper shower (larger X_{max})
  - Measured muon content larger than predicted

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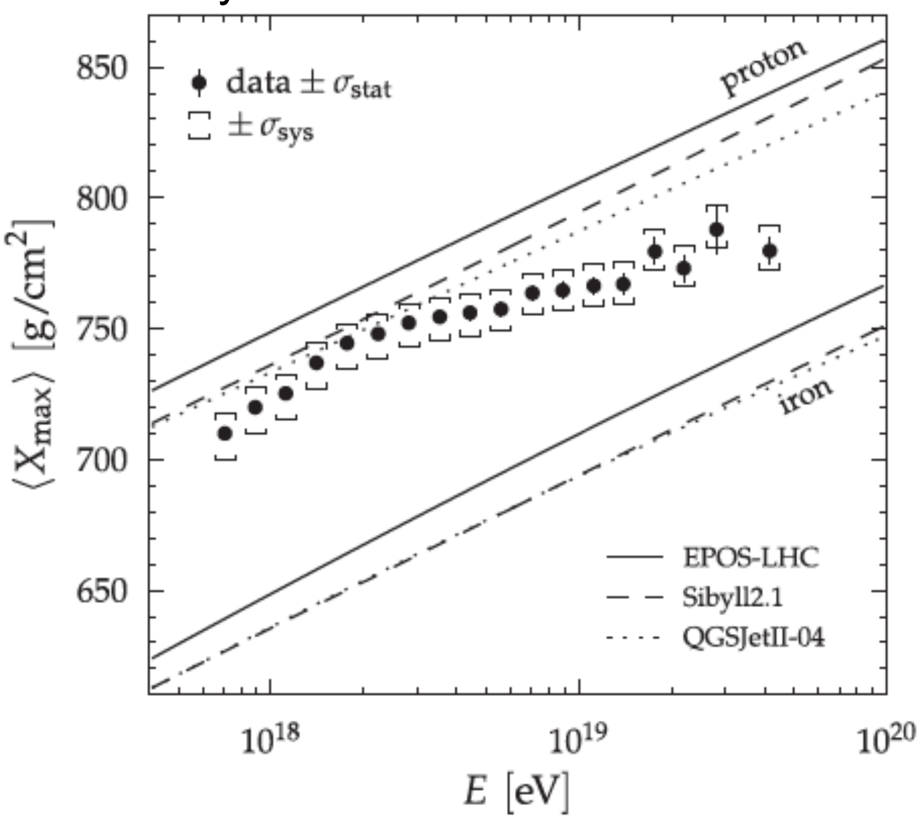
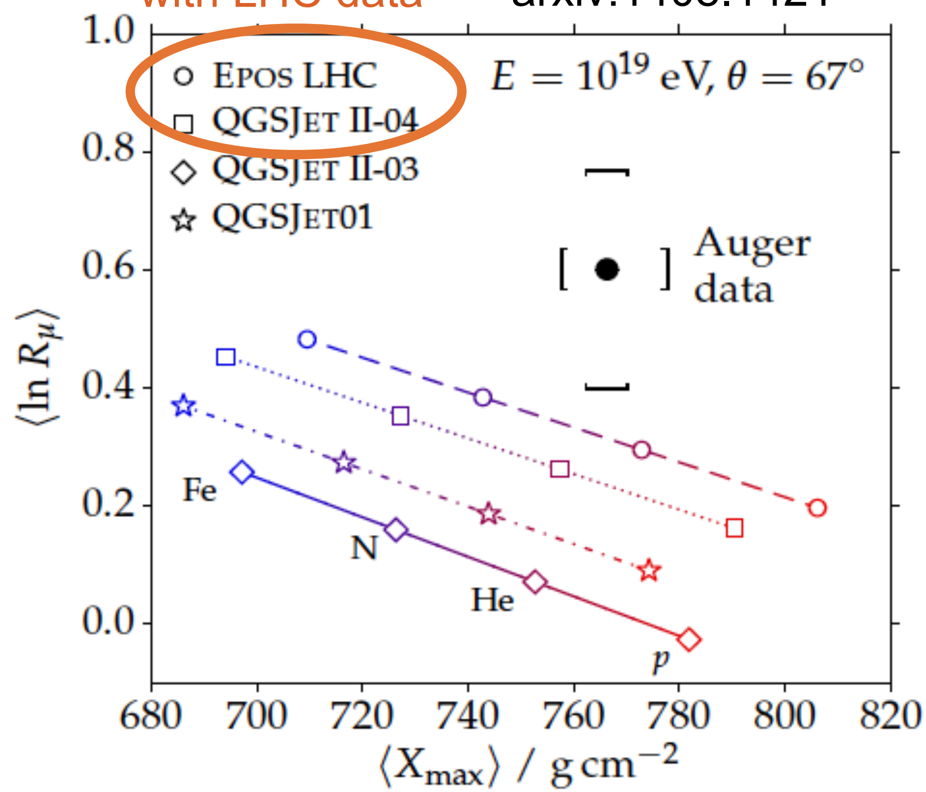


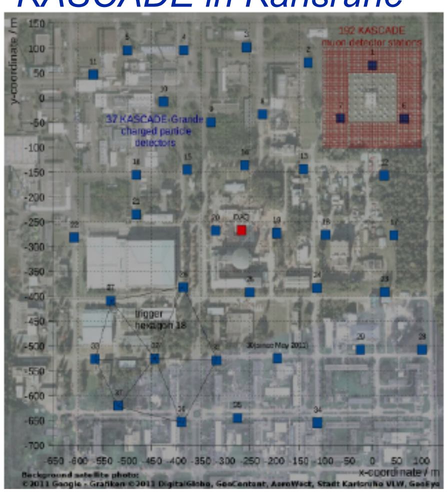
with LHC data arxiv:1408.1421



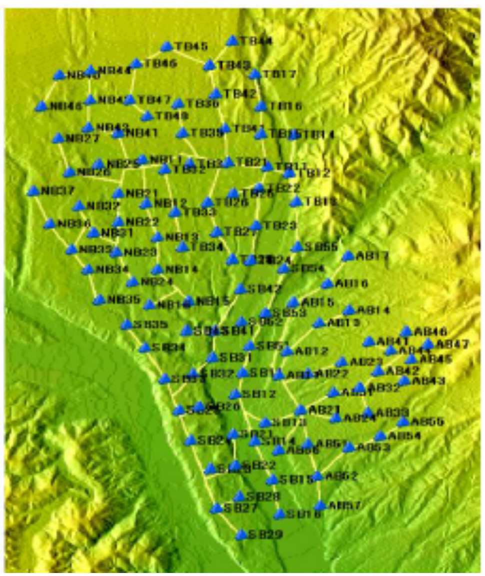
Detection of extensive air showers in array of ground-based detectors in coincidence

- Sample the charged particles in the shower (tanks with liquid scintillators or water Cherenkov counters)
- E>10^{15} eV (sea level)
- Direction of primary particle obtained by timing shower front as it crosses the array
- Examples: KASCADE, AGASE, HiRES, Auger

KASCADE in Karlsruhe

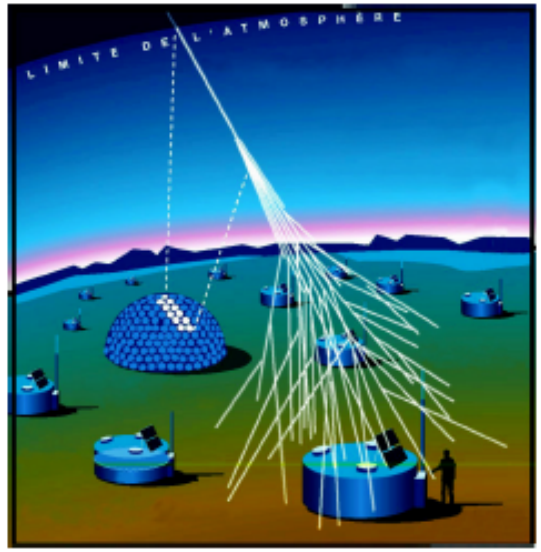


Akeno Giant Air Shower Array



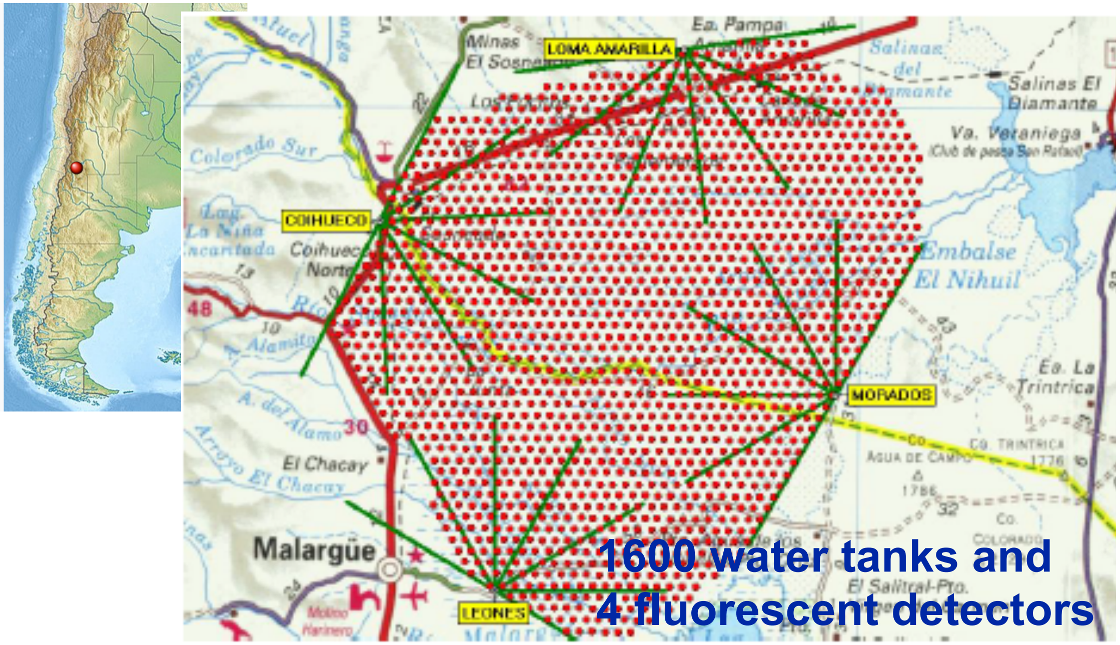
HiRES

Pierre Auger Observatory



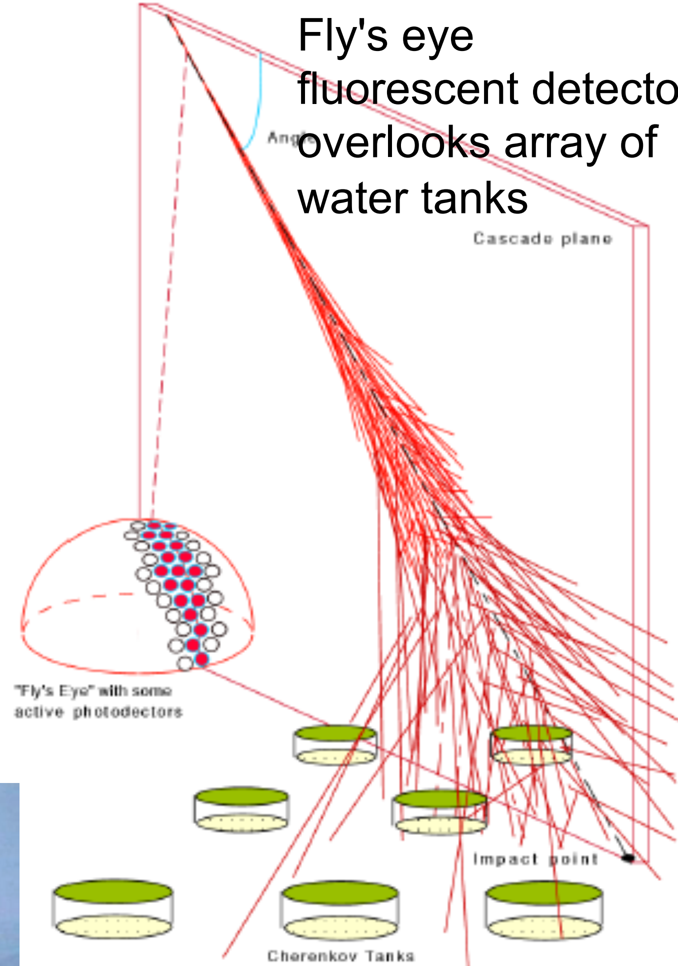
- Observes air showers of secondary cosmic ray particles
- Rate of ultra-high energy cosmic rays is $\sim$1 km^{-2} century^{-1}
- Effective area is $\sim$3000 km^2
- Fluorescence detectors to observe air showers in atmosphere
- Cherenkov detectors to detect secondary particles on ground
- Combination of both methods reduces systematic errors that resulted during prior work

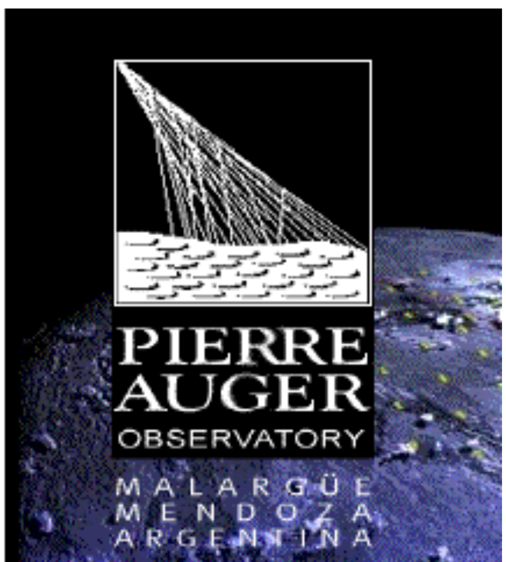
Pierre Auger Observatory



1600 water tanks and
4 fluorescent detectors

Fly's eye
fluorescent detector
overlooks array of
water tanks





Detection of extensive air showers using Cherenkov telescopes

- Use Cherenkov and fluorescent light produced in atmosphere
- Cherenkov appears in narrow angle → restricted radius O(100m) around shower axis
- Imaging air Cherenkov telescopes (IACTs) consist of large upward-facing mirrors to focus the Cherenkov light on array of UV-sensitive photomultipliers

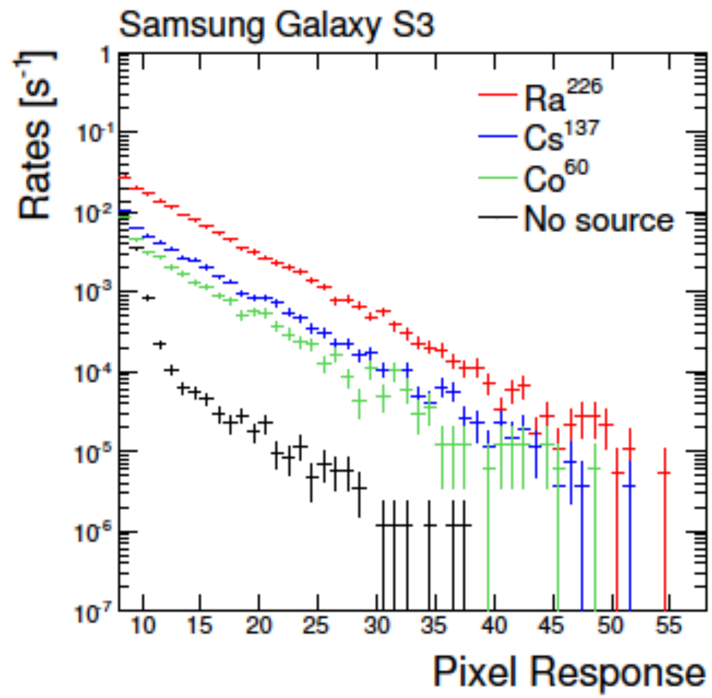
→ more in Alison Mitchell's lecture

CRAYFIS

https://crayfis.io/

arxiv:1410.2895

- Idea: use smartphones as cosmic ray detectors
- Contain high-resolution cameras with sensors that are sensitive to passage of particles in cosmic ray showers
- Contain GPS for location and wi-fi for data upload
- Spread all around the world
- App that starts data-taking when phone is connected to power and screen goes to sleep
- Looking for coincidence in user data



Summary

- Study of cosmic rays is a unique way to investigate particles at highest energies (>10^{20}eV)
  - What are the source regions of cosmic rays?
  - How are cosmic rays accelerated?
  - How do cosmic rays propagate in the galaxy?
- Primary cosmic rays are mainly positively charged particles
- Lower energy cosmic rays measured in balloon or satellite experiments, higher energy cosmic rays observed as airshowers in atmosphere
- Shower shape and composition gives information about primary particle type, energy and direction

References

- Lecture includes material prepared by L. Baudis, A. Kish, A. Mitchell, N. Murphy, D. Perkins, D. Semikoz, O. Steinkamp

- Further reading:

- Donald Perkins, "Particle Astrophysics", Chapter 9: Cosmic Rays
- Nick Murphy, "Cosmic Ray and Particle Acceleration", https://www.cfa.harvard.edu/~namurphy/teaching.html
- Lectures by Dmitri Semikoz
  http://www.apc.univ-paris7.fr/~semikoz/

- More on this topic in Master level class:
  Phy465: Experimental Astroparticle Physics
  https://www.physik.uzh.ch/en/teaching/PHY465/FS2020.html