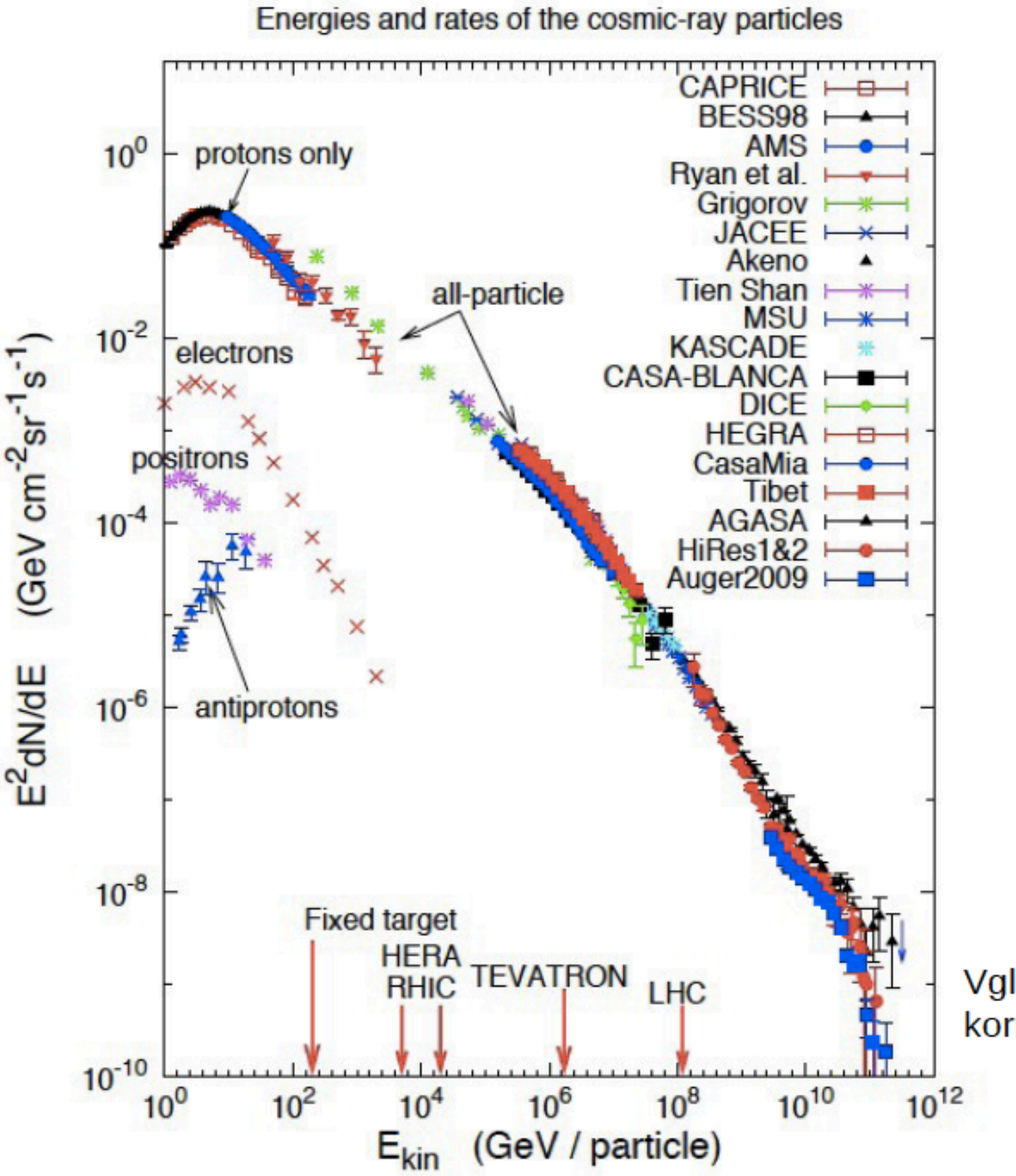
KTA 1

Folien zur Vorlesung vom 16.12.2013

Spektrum der kosmischen Strahlung

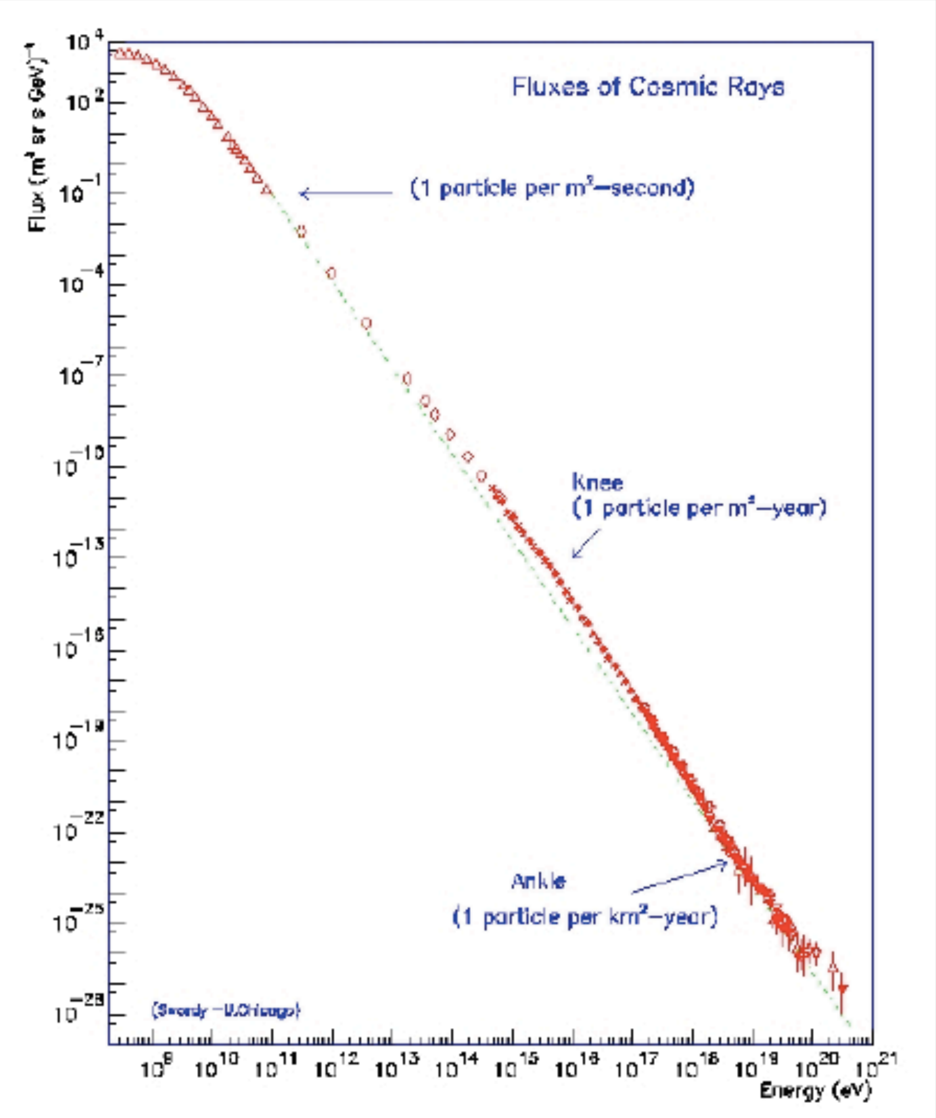


Vgl. mit collider
korrigiert auf √s

WHAT DO WE KNOW ON COSMIC RAYS?

The energy spectrum

"Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic ray radiation" (Cecil Powell, Nobel Prize Lecture, 1950)



The most striking feature of the cosmic rays is the fact that they span a very wide range of energies.

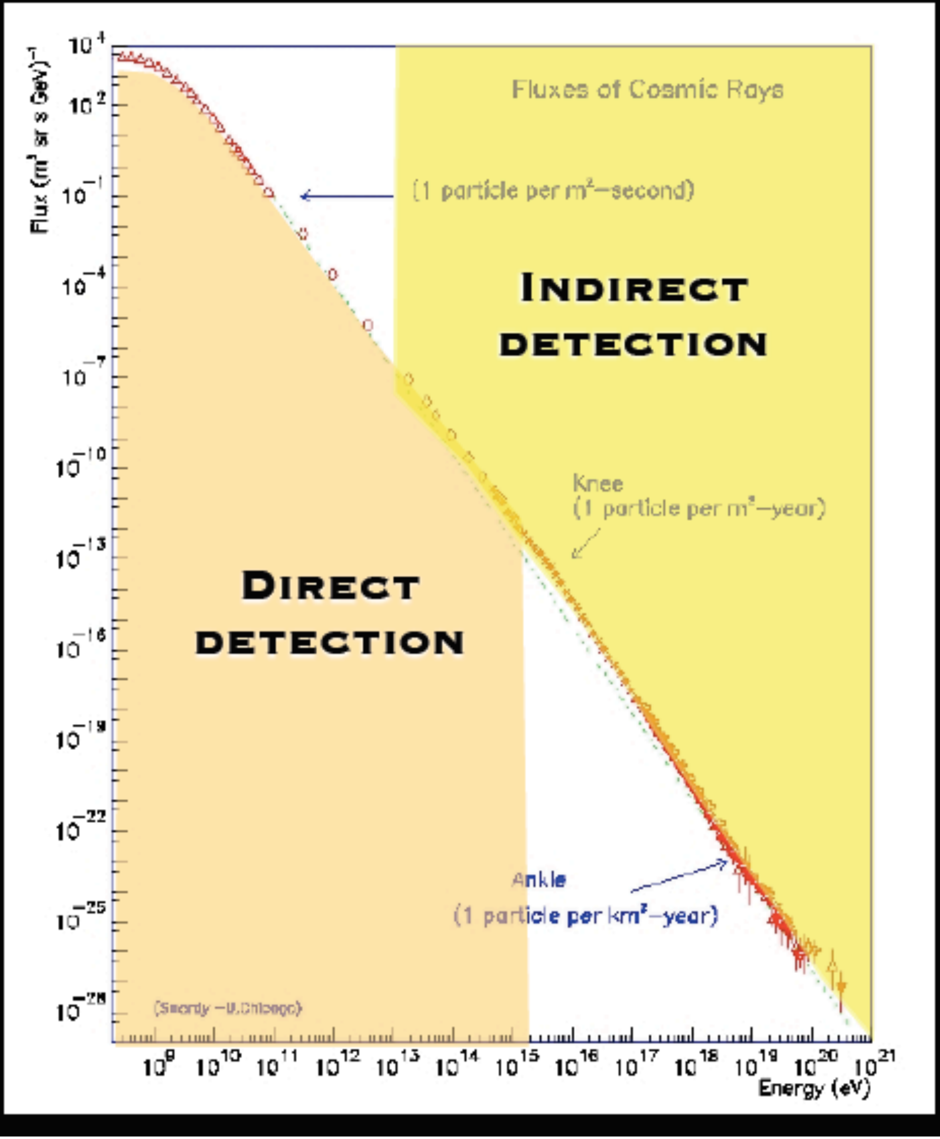
The energy spectrum is of power-law form ($E^{-\gamma}$, $\gamma \approx 3$): it is extremely regular over ≈ 13 decades (spanning 32 decades in flux!)

P. Ghia (ISAPP 2012)

WHAT DO WE KNOW ON COSMIC RAYS?

The flux (vs detection)

“Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic ray radiation” (Cecil Powell, Nobel Prize Lecture, 1950)



Low-energy CRs: rather high flux (1/m² s) but absorbed in the upper atmosphere.
Direct detection (top of the atmosphere or in space)

Balloons
Rockets
Satellites

High energy cosmic rays: very rare (1/km² y), but “penetrating” up to ground (atmospheric air-showers).
Indirect detection: long-lived large arrays (ground level)

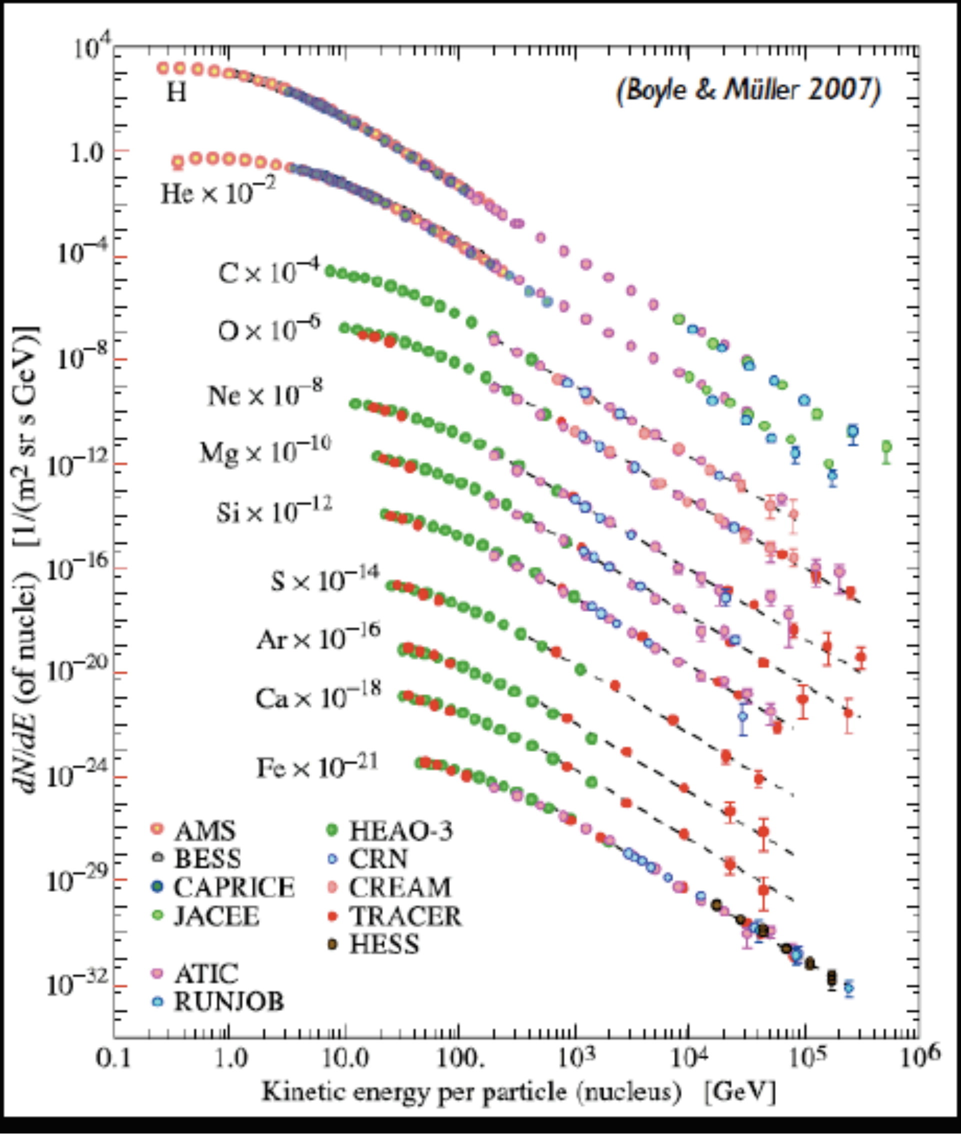
Large telescopes
Extensive Air showers arrays

P. Ghia (ISAPP 2012)

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at low energies

At energies up to ≈ 10^{14} eV, cosmic rays are directly measured, through detectors on balloons or satellites (see later ;-)



In the direct-measurement energy region, about 98% of the particles are protons and nuclei; ≈ 2% are electrons. Of the protons and nuclei, ≈ 87% are protons, ≈ 12% are helium nuclei and the remaining ≈ 1% heavier nuclei

Power laws holds also for individual elements

Index almost identical for all of them. Sligthly harder for heavier elements

P. Ghia (ISAPP 2012)

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at low energies

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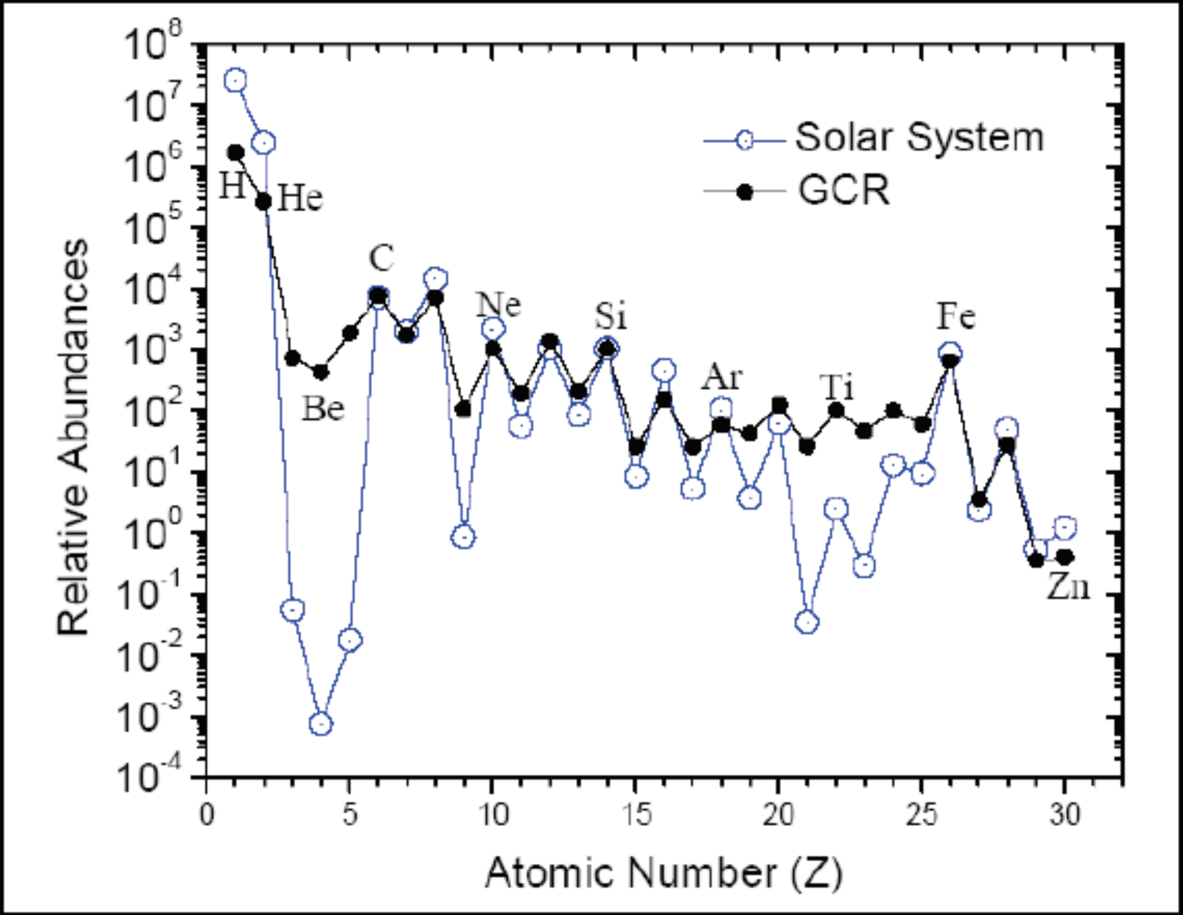


ABUNDANCES OF ELEMENTS IN CR AT ≈ 1 GEV COMPARED TO THOSE OF THE SOLAR SYSTEM

The distribution of elemental abundances in the CR is not so different from those of typical Solar System abundances.

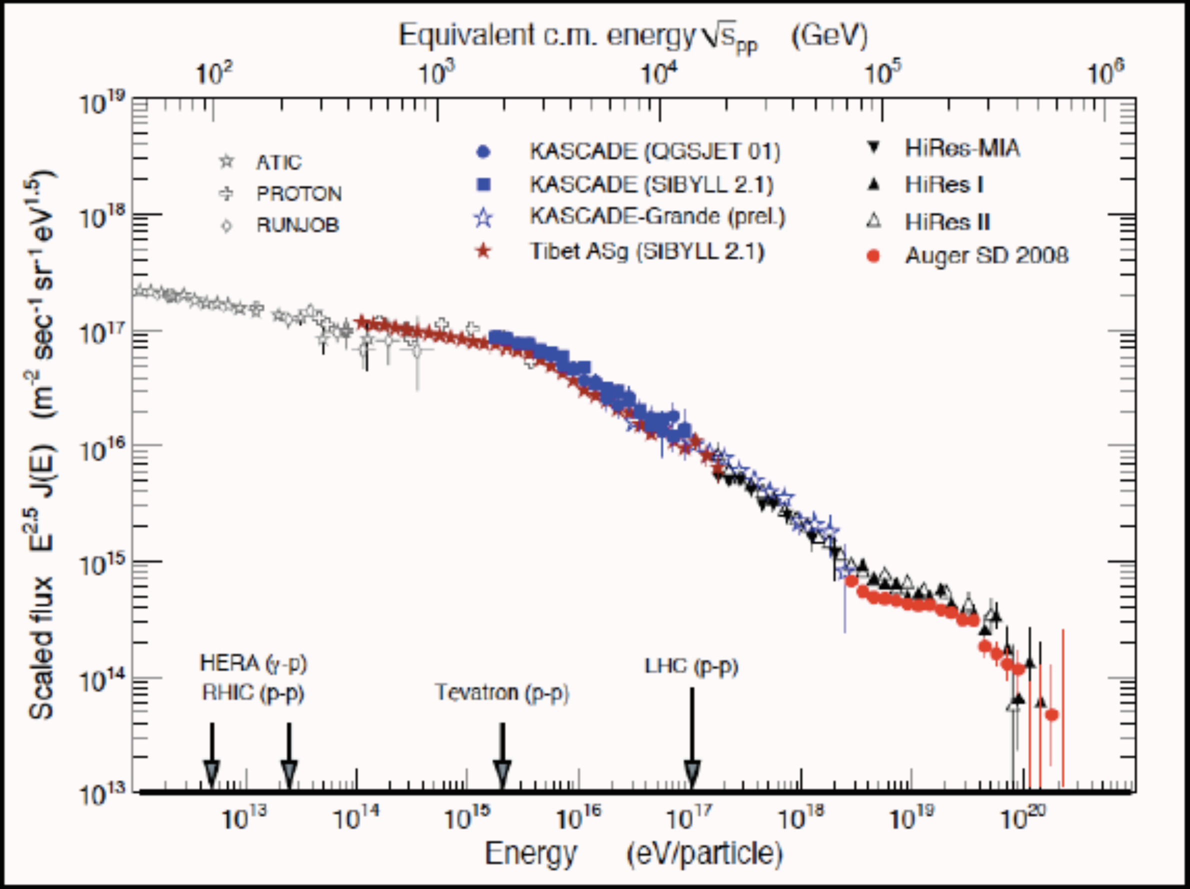
Light elements (Li, Be, B) in CRs are overabundant relative to Solar System ones. Excess also of elements with atomic number and mass just less than those of Fe (i.e., elements between Ca and Fe). This is due to CR propagation in the inter-stellar medium: spallation collisions.

P. Ghia (ISAPP 2012)

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at high energies

At energies above ≈ 10^{14} eV, cosmic rays are indirectly measured, through detectors at ground level through extensive air showers (see on thursday ;-).



All-particle primary energy spectrum measured by different EAS arrays. Spectrum scaled by $E^{2.5}$ to better evidence the “irregularities”

The CR spectrum shows three “irregularities”:

a “knee” at 5 10^{15} eV: due to the “bending” of lighter elements, it could be due to source (maximum energy) or propagation effects (escape from the Galaxy)

an “ankle” at 3 10^{18} eV: it could either mark the transition between a galactic and an extra-galactic CR origin, or be the signature of interactions of EG protons on background photons

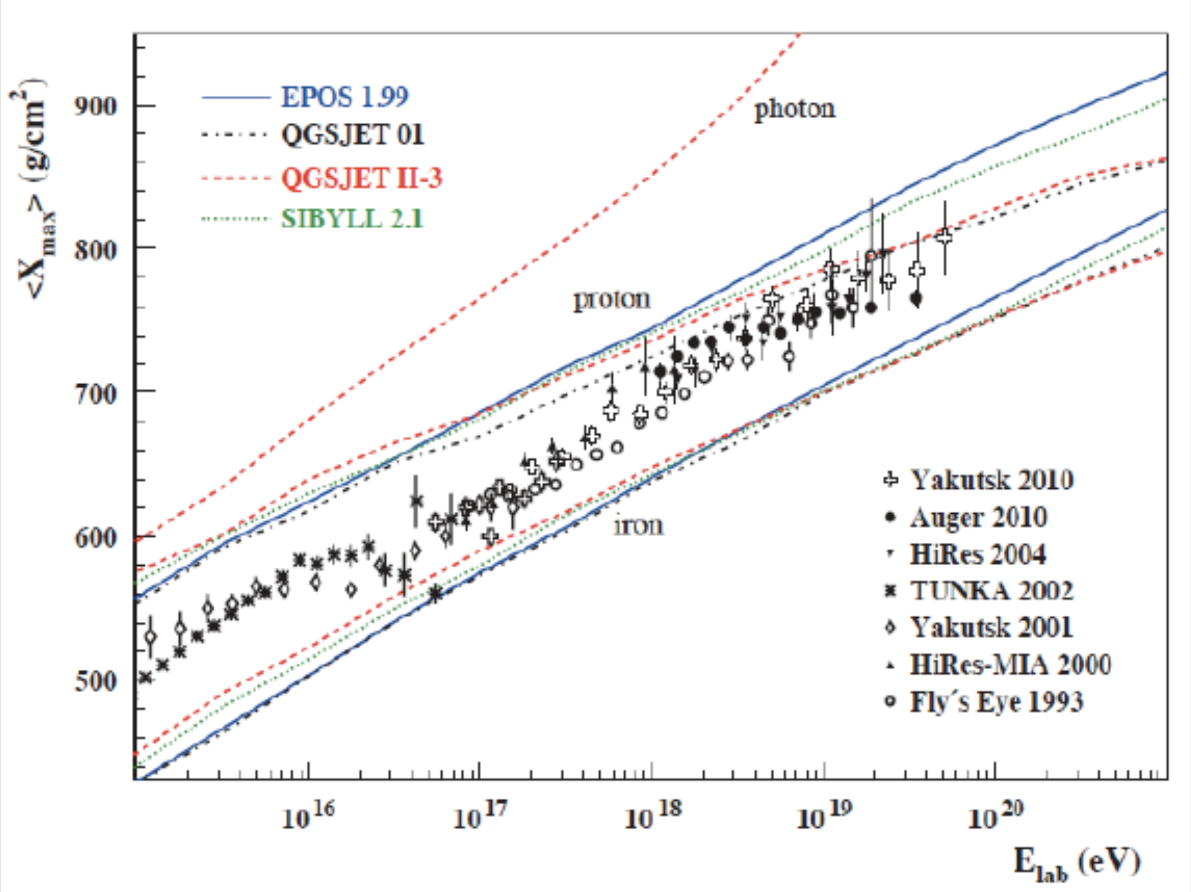
a “suppression” at 5 10^{19} eV: it could be due either to propagation (GZK effect) or source effects (maximum energy)

P. Ghia (ISAPP 2012)

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at high energies

At energies above ≈ 10^{14} eV, cosmic rays are indirectly measured, through detectors at ground level through extensive air showers (see later ;-). Single elements cannot be distinguished but only "inferred"



Xmax vs energy, as measured by different EAS arrays. Expectatations for simulated EAS are also shown

The most common way of inferring the primary composition by indirect measurements is by the determination of the depth of shower maximum in atmosphere, Xmax (see on thursday ;-)

Xmax depends on primary mass. From comparisons with what expected from shower simulations, one can infer the trend of average mass vs energy

P. Ghia (ISAPP 2012)

WHAT DO WE KNOW ON COSMIC RAYS?

Arrival directions (sources)

Although CR above 10^{12} eV are likely to preserve information about their arrival direction at the Solar System when they arrive at Earth, due to deflections in the galactic magnetic field, they do not preserve information about their original travel direction and hence, about their sources.

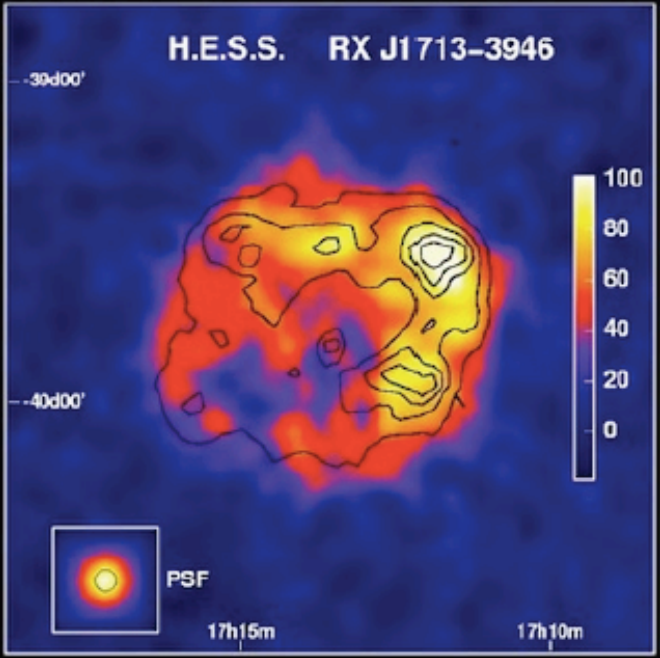
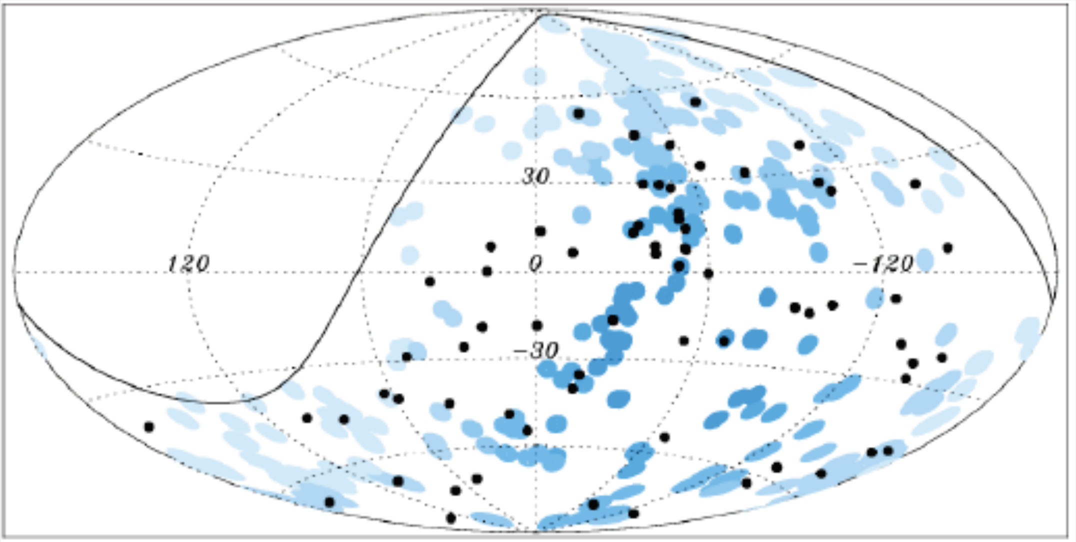


Image of a SNR in gamma (HESS experiment)



Distribution of Auger events (E>50 EeV) in the sky vs AGNs positions

Supernovae are prime candidates for the acceleration of galactic cosmic rays. Only possible observation through neutral gammas, produced by CR interactions in the source. No smoking gun found yet.

At energies > ≈ 10^{19} eV, low-Z CR are slightly deflected by magnetic fields. In principle, charged-particle astronomy may be possible. Possible source candidates: AGNs, gamma-ray bursts, radio-galaxies...

HOW DO WE DETECT COSMIC RAYS?

Cosmic rays are particles

Cosmic ray detectors are particle detectors

AMS SCINTILLATORS
(TIME OF FLIGHT)

PAMELA CALORIMETER

Wide choice of detectors:

dE/dX

Secondary/cascades measurements

Magnetic deflections

Transition radiation

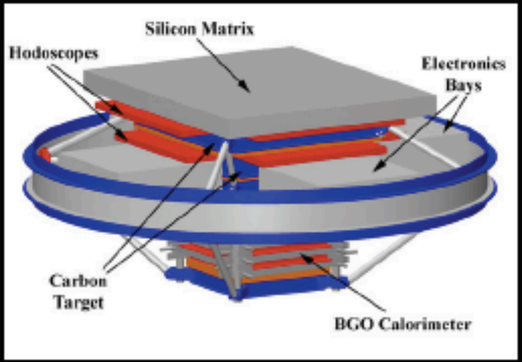
Cherenkov

Radio

HOW DO WE DETECT COSMIC RAYS?

Cosmic rays are particles

Cosmic ray detectors are particle detectors



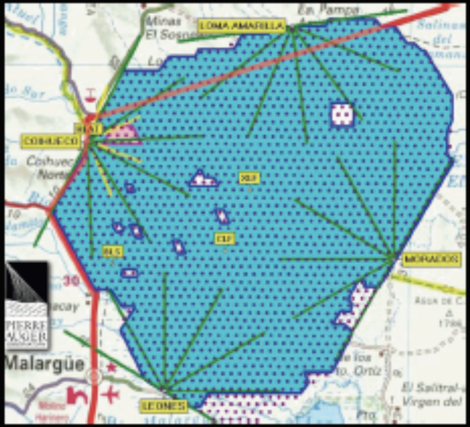
ATIC DETECTOR (60X60 CM)

Wide energy range: 10^6 - 10^{21} eV

Wide range of dimensions:

On balloon/space: O(m)

At ground: O(0.01-1000 km^2)



AUGER DETECTOR (60X60 KM)

Wide choice of detectors:

dE/dX

Secondary/cascades measurements

Magnetic deflections

Transition radiation

Cherenkov

Radio

HOW DO WE DETECT COSMIC RAYS?

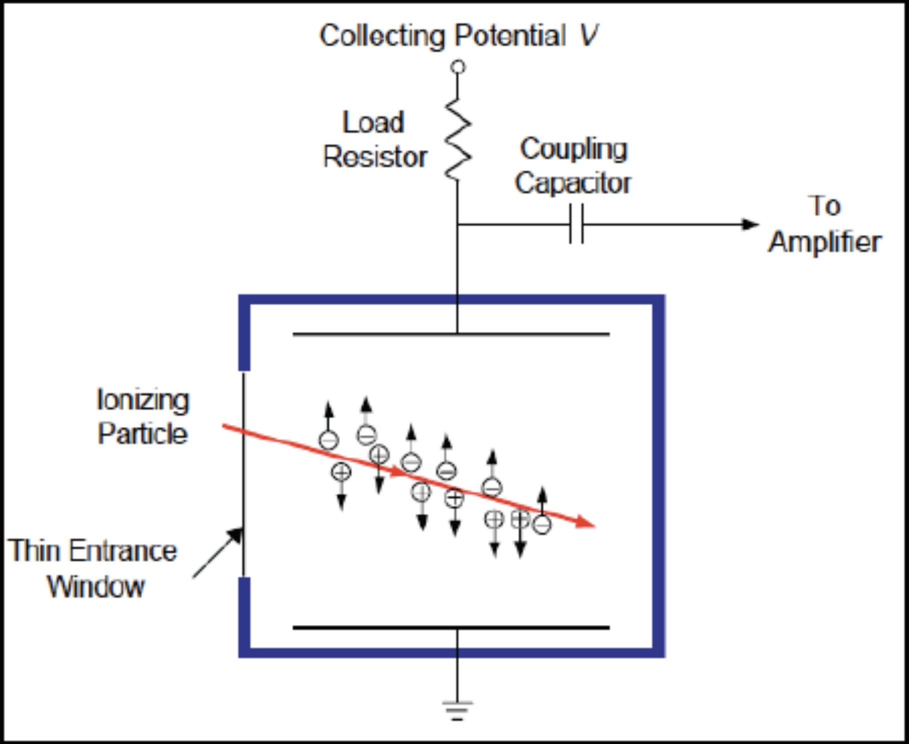
Detectors (vs observables)

Velocity:	Time-of flight	$\tau \propto 1/\beta$
	Cherenkov angle	$\cos\theta = 1/\beta n$
	Transition radiation	$\gamma \geq 1000$
Energy loss:	Bethe-Bloch	$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$
Total energy:	Calorimeter	$E = \gamma m_0 c^2$

γ,β

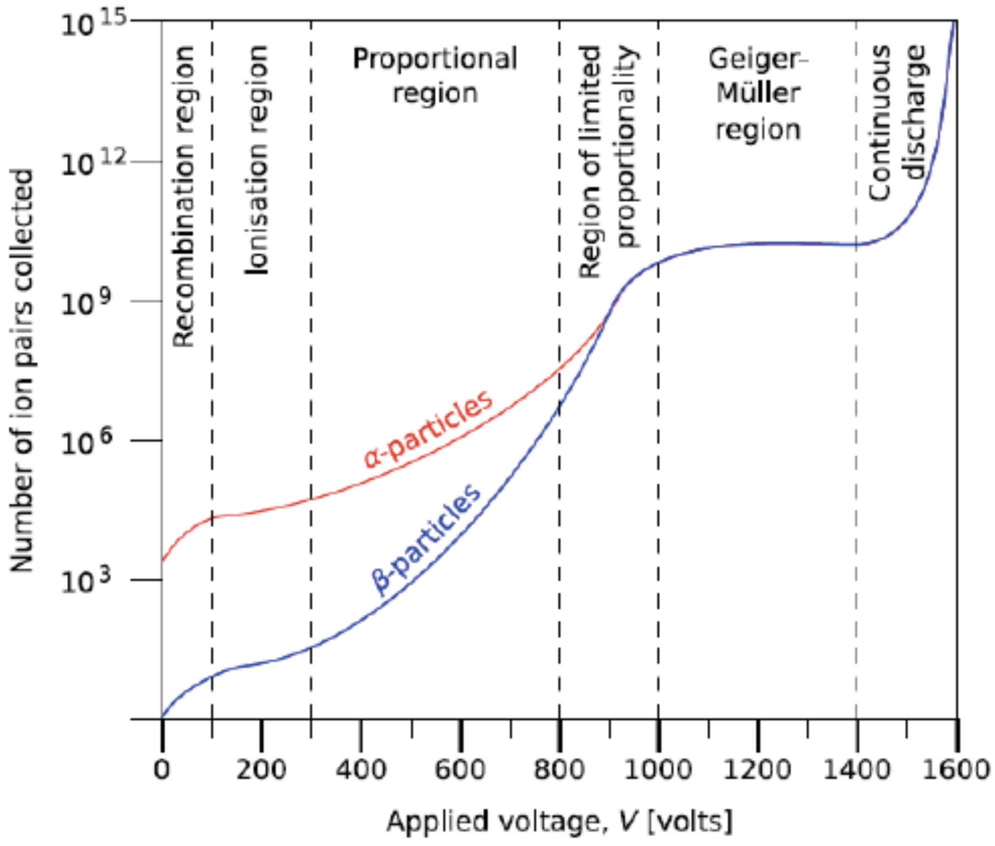
HOW DO WE DETECT COSMIC RAYS?

Ionization detectors



A particle passing through a gas-filled counter will ionize the gas along its path

The applied voltage V between the electrodes will sweep the positive and negative charges toward the respective electrodes causing a charge Q to appear on the capacitor.



The charge Q collected (amplitude of pulse) depends on voltage V.

Higher mass particles produce more initial ions pairs

HOW DO WE DETECT COSMIC RAYS?

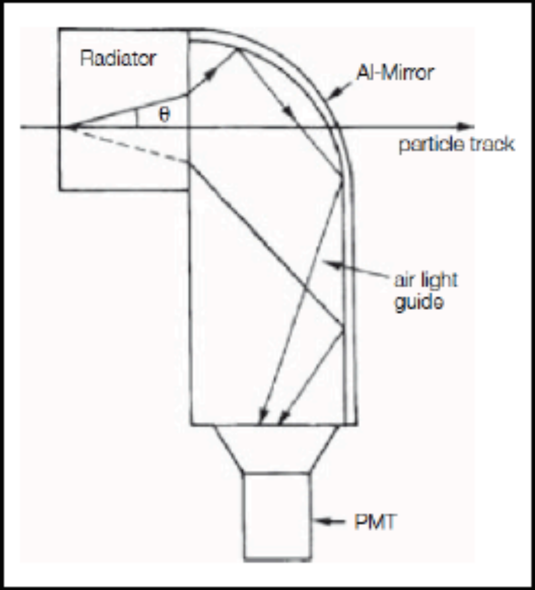
Cherenkov detectors

When a particle moves through a medium at a velocity greater than that of the light in that medium, Cherenkov radiation is emitted.

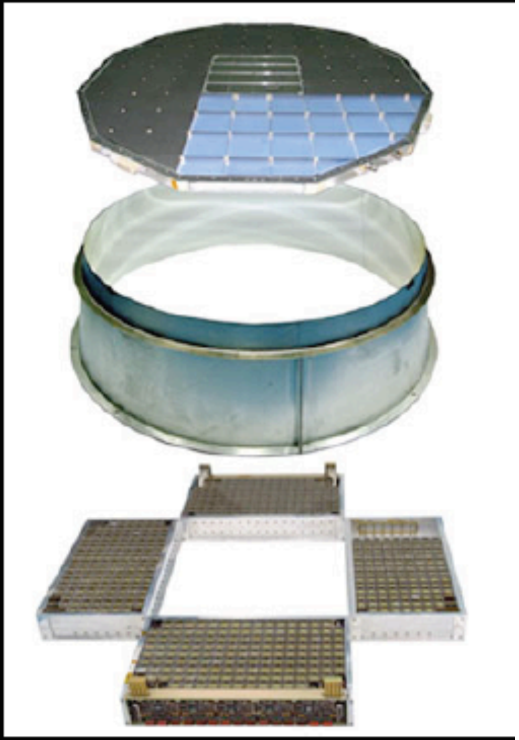
This phenomenon can be used to construct "threshold" detector, i.e., only if the velocity is large enough, it will emit radiation (and hence a signal)

The total emitted light is measured, this providing information on velocity of the particle

The light yield is very small. The light is focalized through mirrors towards PMTs used to produce a detectable signal



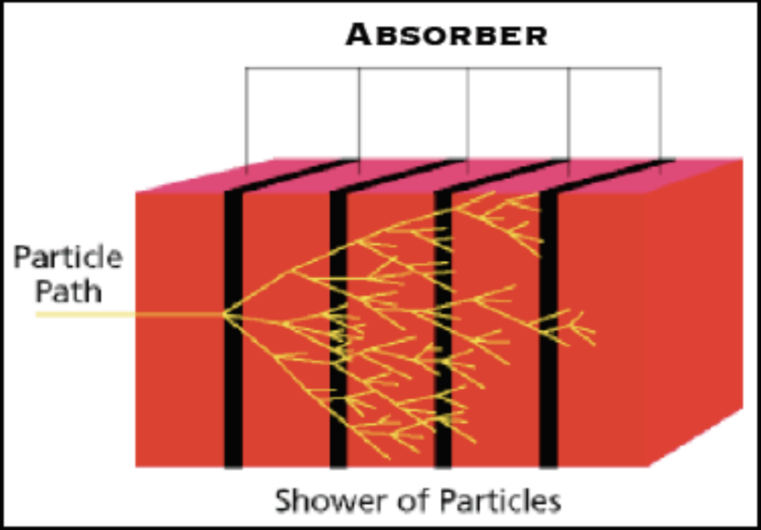
WORKING PRINCIPLE OF A CHERENKOV DETECTOR



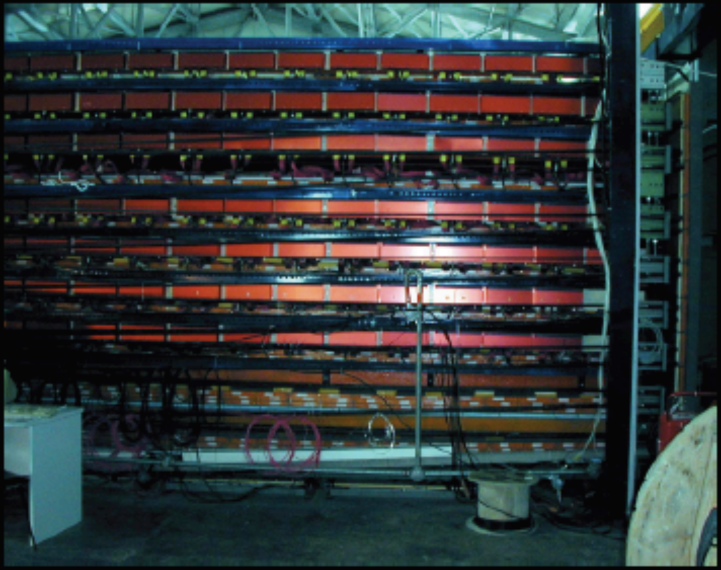
AMS CHERENKOV DETECTOR: RADIATOR, MIRROR, PMTS

HOW DO WE DETECT COSMIC RAYS?

Calorimeter



SCHEME OF A CALORIMETER



THE CALORIMETER OF THE EAS-TOP EXPERIMENT

A calorimeter measures the energy lost by a particle that goes through it. It is usually designed to entirely stop or 'absorb' most of the particles coming from a collision, forcing them to deposit all of their energy within the detector.

Calorimeters typically consist of layers of 'passive' or 'absorbing' high–density material (lead for instance) interleaved with layers of 'active' medium such as scintillator or gaseous detectors (sampling calorimeters)

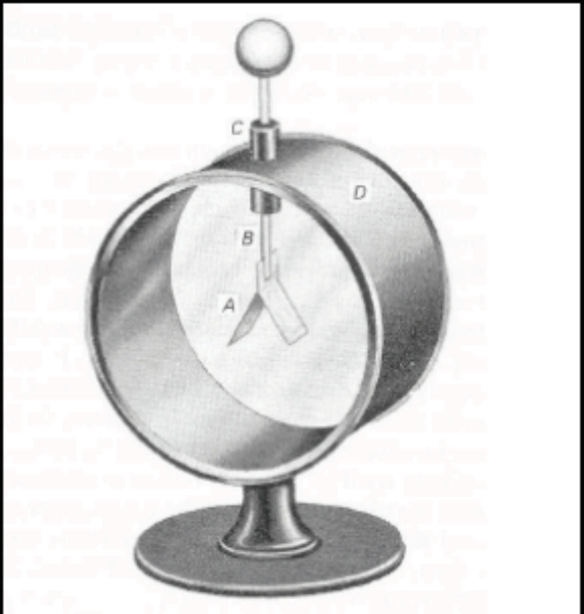
Electromagnetic calorimeters measure the energy of light particles – electrons and photons – as they interact with the electrically charged particles inside matter.

Hadronic calorimeters sample the energy of hadrons as they interact with atomic nuclei.

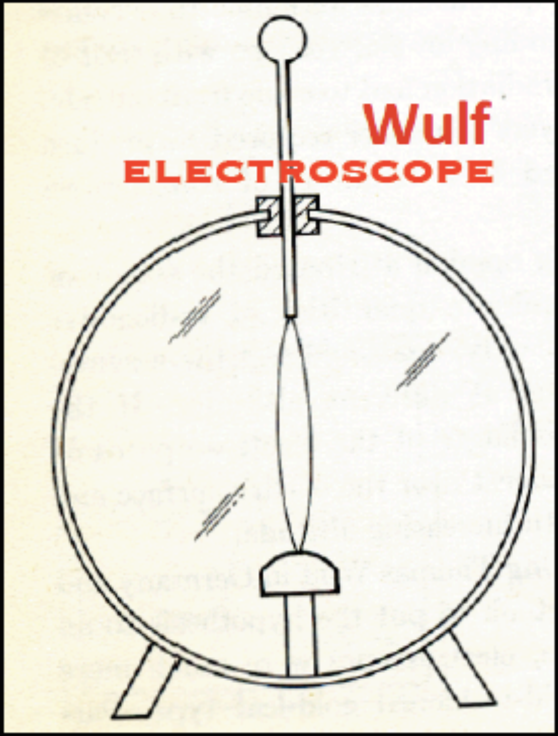
HOW DID DETECTION OF COSMIC RAYS START?

Electroscopes

First hints of the presence of cosmic rays came quite unexpectedly at the turn of 20th century, during the golden days of research into radioactivity. Radioactive elements ionize gases, enabling the gas to conduct electricity. Electroscopes were widely used to explore radioactive materials.



GOLD-LEAVES ELECTROSCOPE



Wulf ELECTROSCOPE

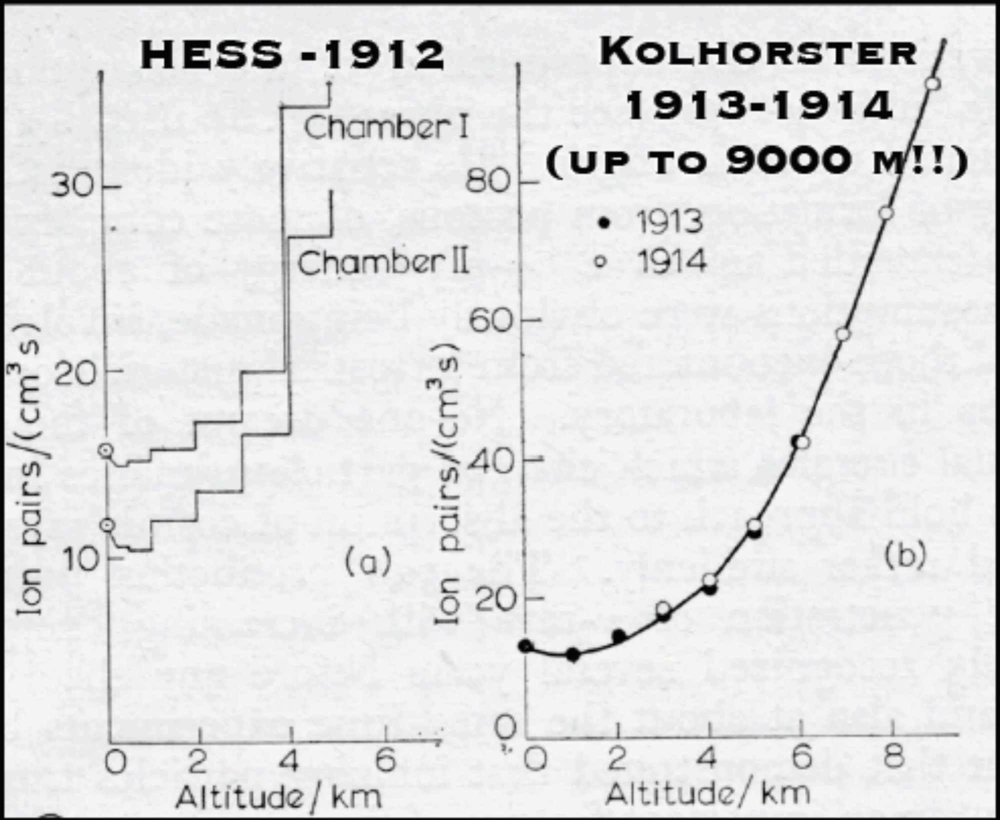
When an electroscope is given an electric charge, the leaves (or wires) repel each other and stand apart. Radiation can ionize the air in the electroscope and allow the charge to leak away: leaves or wires slowly come back together.

Puzzling inference: No matter how good the electroscopes, the electric charge continued to leak away even when there was no obvious nearby source of X-rays or radioactivity!

HOW DID DETECTION OF COSMIC RAYS START?

Electroscopes on balloons

To reduce possible effect of sources of radiation at ground, electroscopes were carried to the tops of tall buildings (Father Wulf, 1910, Eiffel Tower) or even to greater heights, using balloons (Victor Hess, 1912, Werner Kolhorster, 1913-1914)



Intensity of the ionizing radiation first decreased as the balloon went up and then was becoming more intense than at sea level. Experiments of great danger, great courage and great success

"The only possible way of interpret my findings was to conclude to the existence of a hitherto unknown and very penetrating radiation, coming from above and probably of extra-terrestrial origin" [V. Hess 1912]

Ballooning: let's come to even more recent times...

In the more recent generation of direct experiments, data is recorded electronically in-flight and transmitted to the ground. The design of the instrument usually includes a combination of charge detection and energy measurements, with detectors such as scintillator hodoscopes, Silicon detectors combined with a Calorimeter or a Transition Radiation Detector

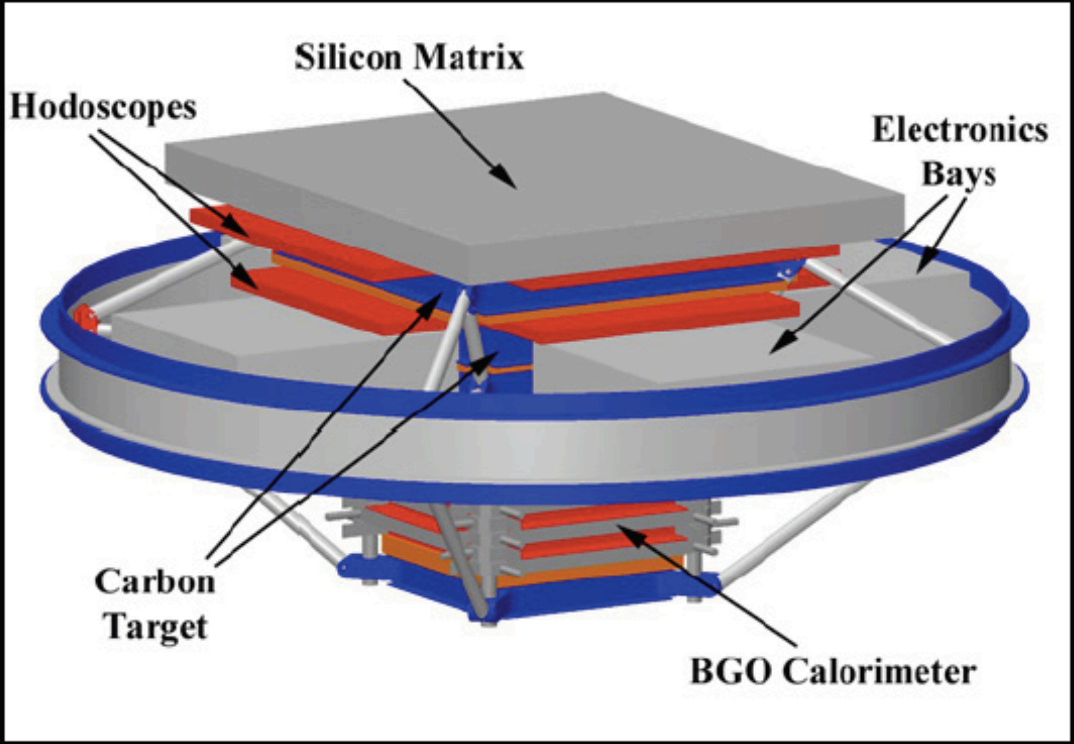

ATIC BALLOON


CREAM BALLOON


TRACER BALLOON

Ballooning: ATIC

The Advanced Thin Ionization Calorimeter (ATIC) is designed to measure the energy spectrum of individual cosmic ray elements in the energy range 50 GeV-100 TeV (flown in 2007-2008)



Charge measurement with silicon detectors

Target: hodoscopes (scintillators) and carbon. Charge and trajectory measurements

Energy measurement with ionization calorimeter. Layers of carbon and of Bismuth-Germanium-Oxide (BGO) scintillating crystals

TOTAL WEIGHT: 1500 KG

PRINCIPLES APPLICATION ON SATELLITES

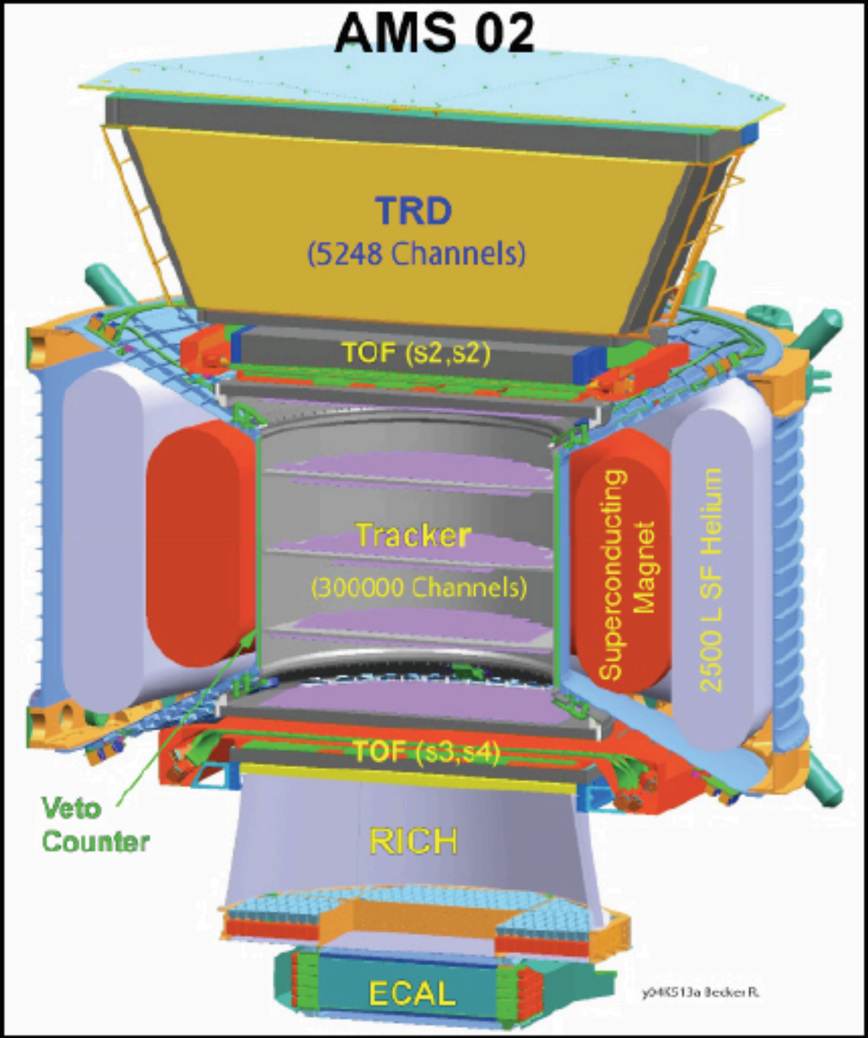
ACE [Advanced Composition Explorer] Mission mainly for solar particles
AMS [Alpha Magnetic Spectrometer]. International Space Station
ASCA [Advanced Satellite for Cosmology and Astrophysics]
Fermi Gamma-ray Space Telescope, (also cosmic rays)
NINA [New Instrument for Nuclear Analysis], low energy cosmic rays.
PAMELA (magnet spectrometer).

PAMELA LAUNCH:
15 JUNE 2006

AMS ON THE ISS
LAUNCH: 19 MAY 2011

Space: AMS

The Alpha Magnetic Spectrometer (AMS-02) is designed to operate as an external module on the International Space Station. It mainly aims to search for antimatter, but it will perform too precision measurements of cosmic rays composition and flux.



Total weight: 8500 kg

Velocity and charge measurement: Time of Flight (scintillators)

Lorentz factor measurement: Transition Radiation Detector (tube straws and plastic radiator)

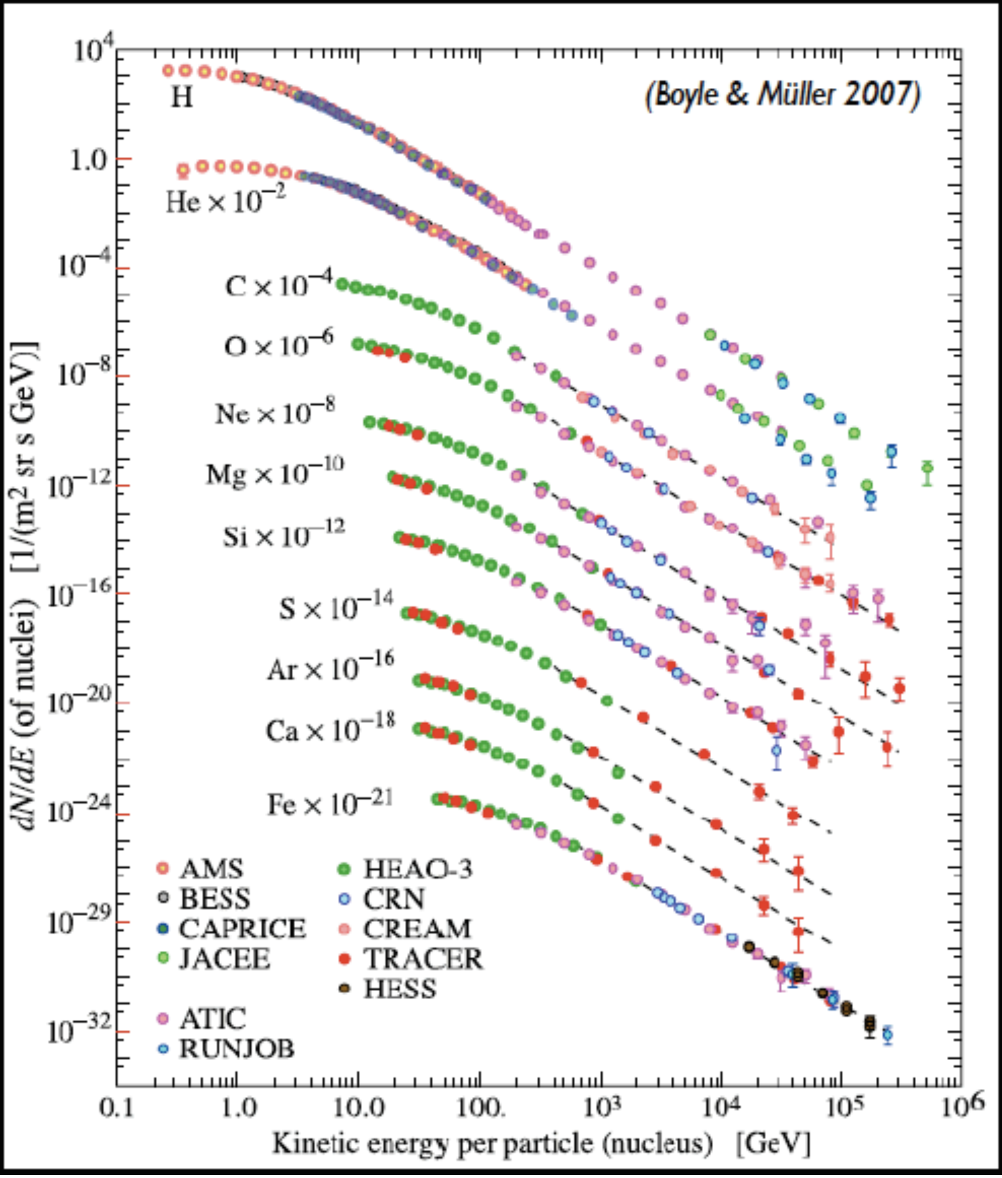
Charge sign (and value) measurement: Spectrometer (Si tracking system and magnet)

Velocity measurement: Ring Cherenkov detector (RICH)

Energy measurement: electromagnetic calorimeter . Scintillating fibers alternated to lead absorber

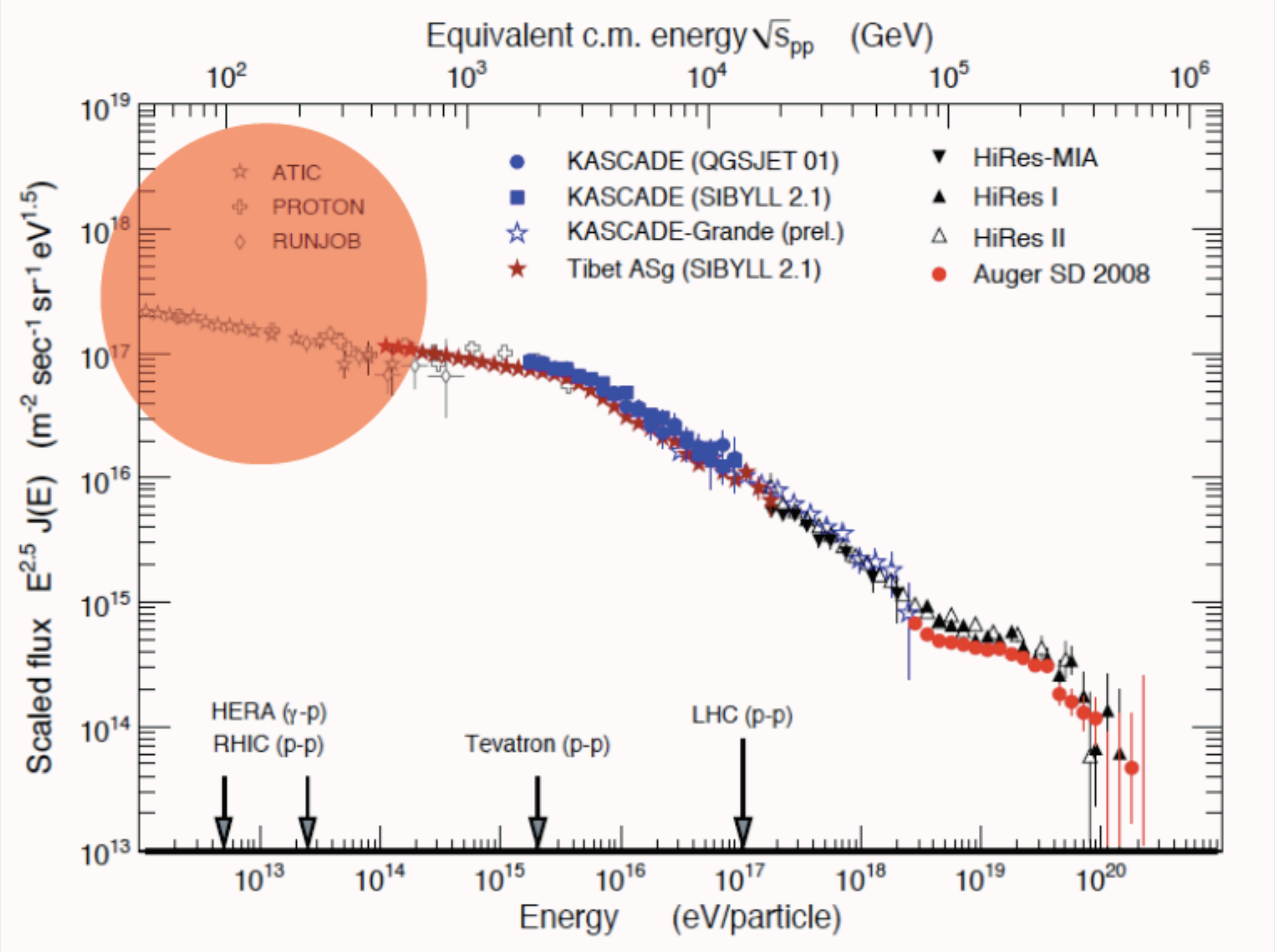
And to finish...

Grandeur of inferences: Fluxes of individual elements


(Boyle & Müller 2007)

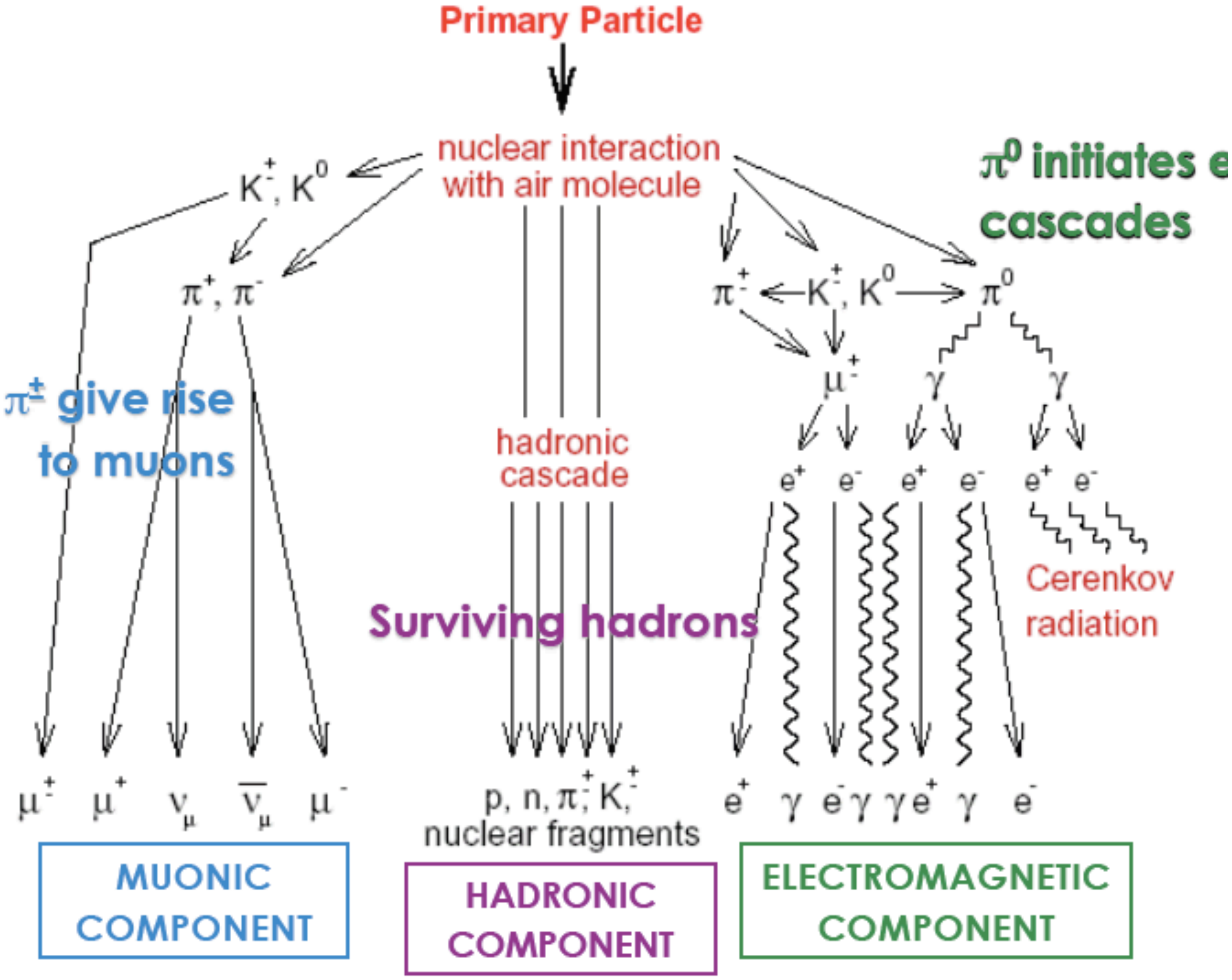
And to finish...

Grandeur of inferences: All-particle spectrum



EXTENSIVE AIR SHOWERS

A high energy primary particle, upon entering the atmosphere, initiates a chain of nuclear interactions



$\pi^{\pm}$ give rise to muons

Surviving hadrons

π^0 initiates e

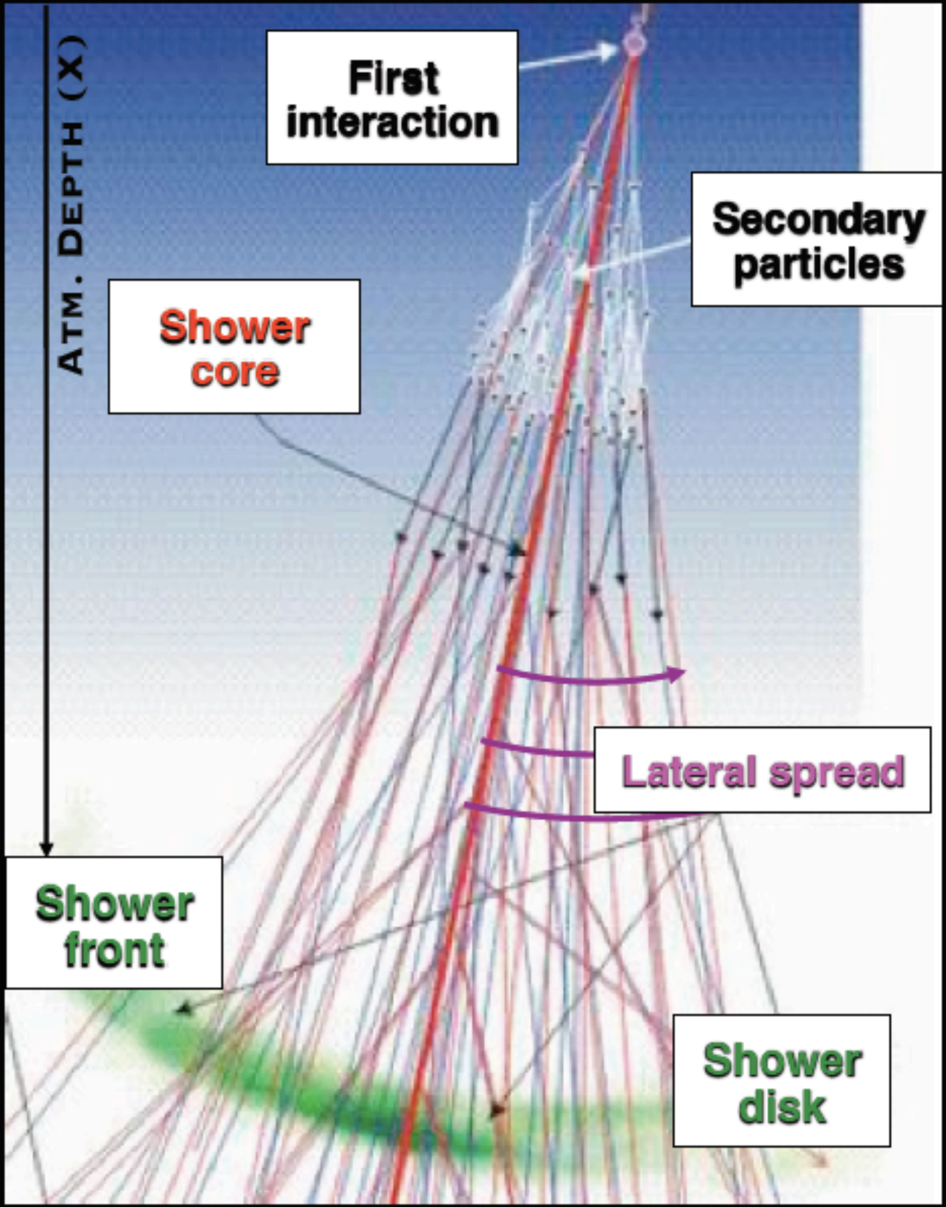
cascades

MUONIC COMPONENT

HADRONIC COMPONENT

ELECTROMAGNETIC COMPONENT

EAS LATERAL DEVELOPMENT

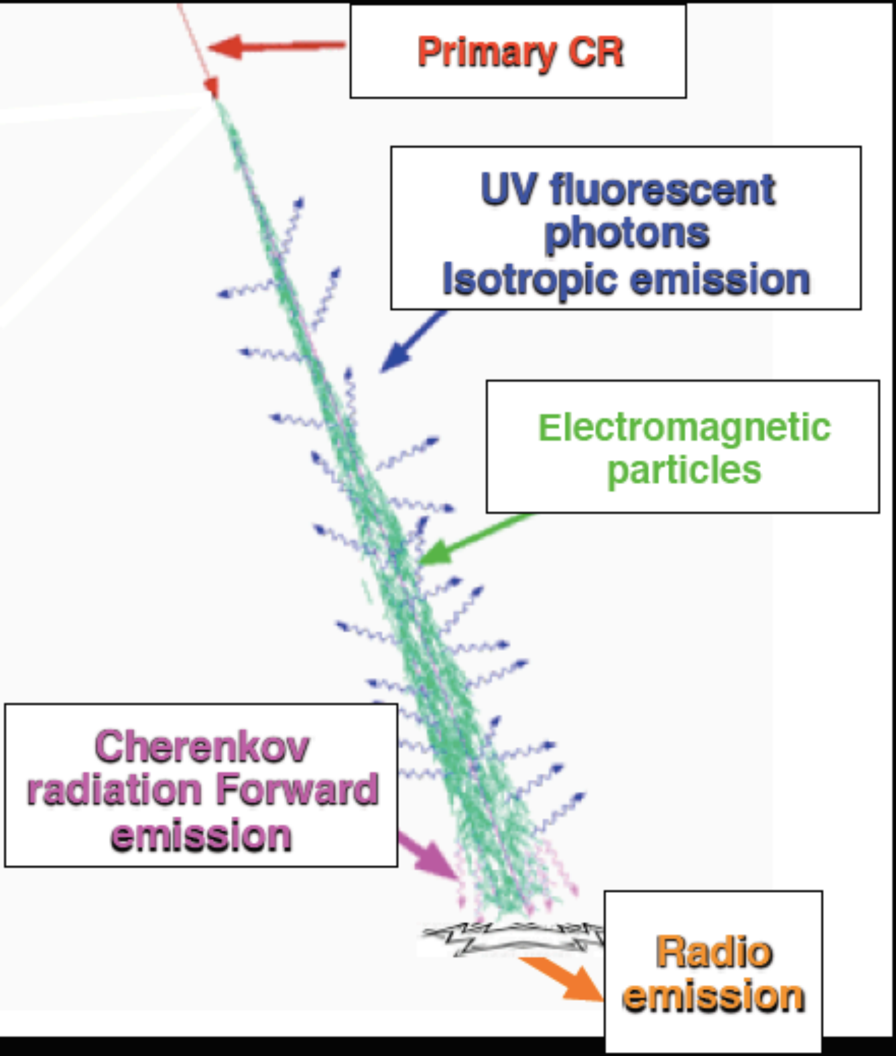


Secondary particles form a narrow "bundle": the shower core

Initial transverse momentum and multiple scattering in atmosphere causes particles to spread out laterally from the core -> lateral distribution: particle density is greatest at the core and it decreases with increasing distance from it

Due to different path lengths and velocities across the atmosphere shower particles are distributed over a wide area in a thin curved disk

RADIATION FROM SHOWER DEVELOPMENT

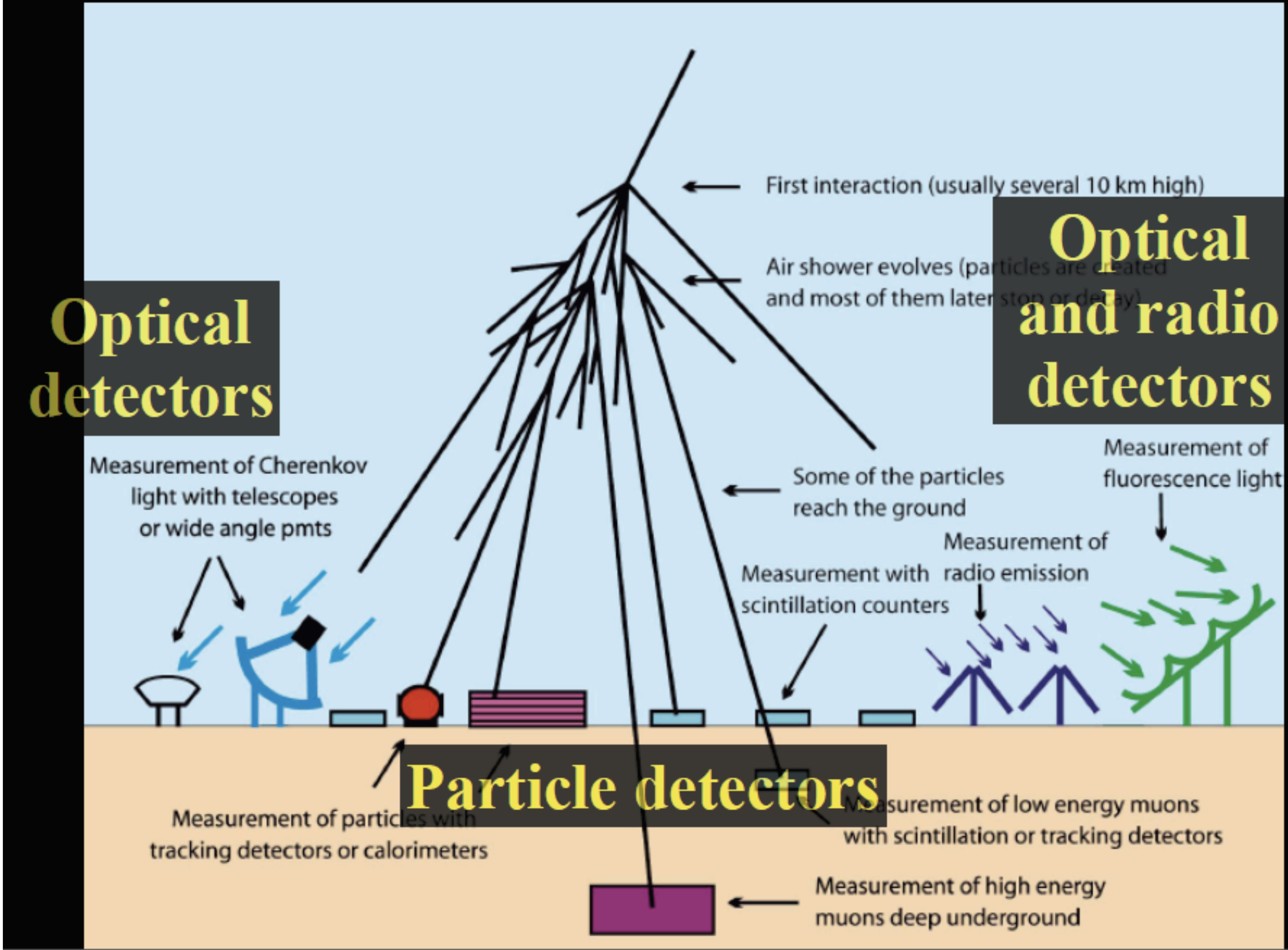


Cherenkov radiation: Electrons and positrons in the shower travel faster than the speed of light in air and emit Cherenkov radiation, mostly in the forward direction

Fluorescence radiation: The passage of air shower e.m. particles in atmosphere results in the excitation of the gas molecules (mostly nitrogen). Some of this excitation energy is emitted in the form of isotropic visible and UV radiation.

Radio emission: Air shower electrons and positrons are deflected in the Earth's magnetic field. Because of their relativistic velocities, they emit synchrotron radiation, beamed very sharply downwards, at radio frequencies below 100 MHz. Many sparkles together produce a bright radio flash

DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES



First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Optical detectors

Optical and radio detectors

Measurement of Cherenkov light with telescopes or wide angle pmts

Some of the particles reach the ground

Measurement of fluorescence light

Measurement of radio emission

Measurement with scintillation counters

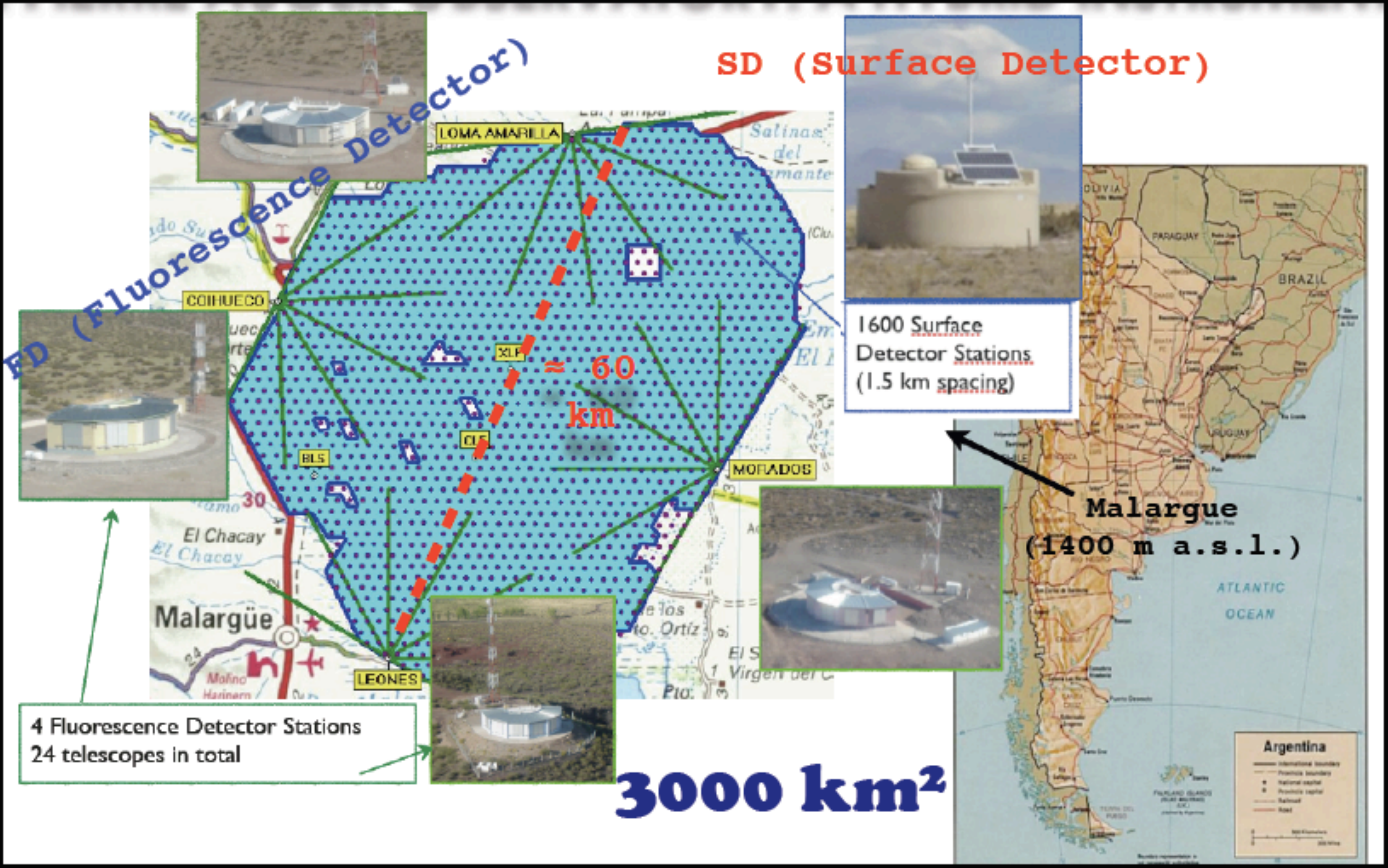
Particle detectors

Measurement of particles with tracking detectors or calorimeters

Measurement of low energy muons with scintillation or tracking detectors

Measurement of high energy muons deep underground

THE PIERRE AUGER OBSERVATORY: A HYBRID INSTRUMENT

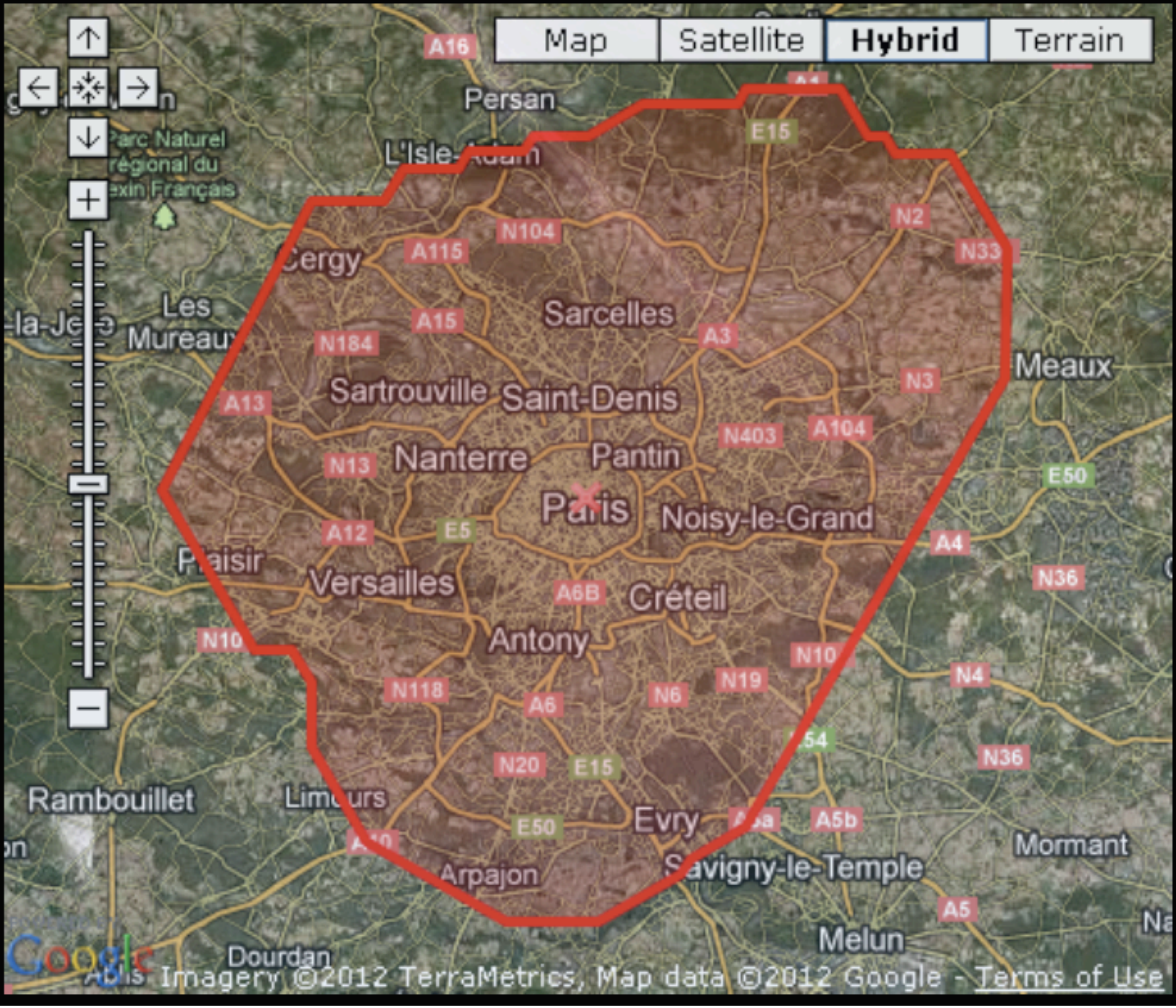


1600 Surface Detector Stations (1.5 km spacing)

4 Fluorescence Detector Stations
24 telescopes in total

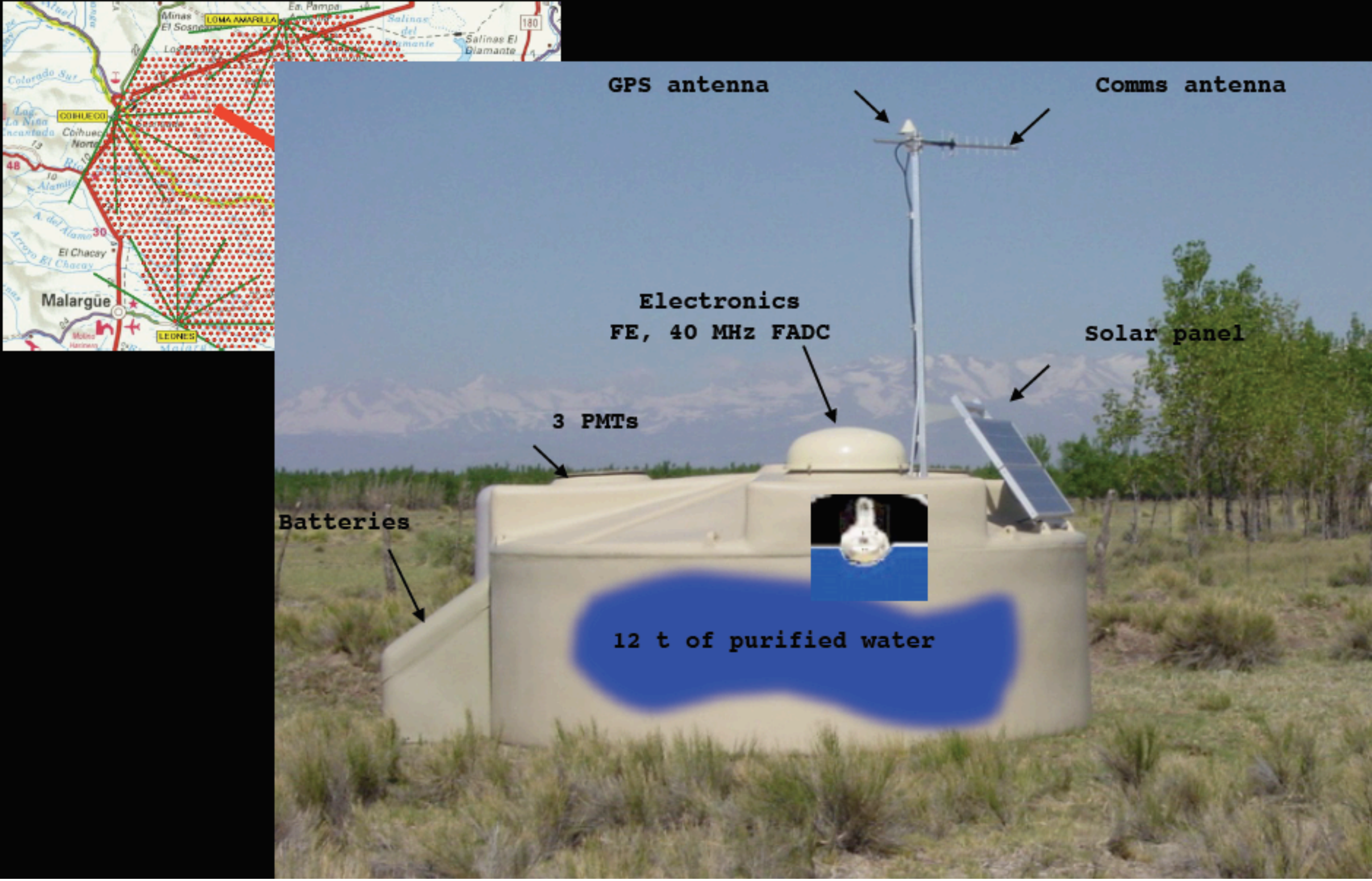
- "Hybrid" detector: 1600 water Cherenkov (SD) + 4x6 fluorescence detectors (FD)
- SD fully efficient above 3 EeV (100% d.c), FD&&SD above 1 EeV (but ≈ 13% d.c.)
- In operation from 2004 (completed in 2008)
- Full Auger: ≈ 1500 (100) (2) events/month above 3x 10^{18} (10^{19}) (5x 10^{19}) eV

THE SIZE OF THE PIERRE AUGER OBSERVATORY :-)



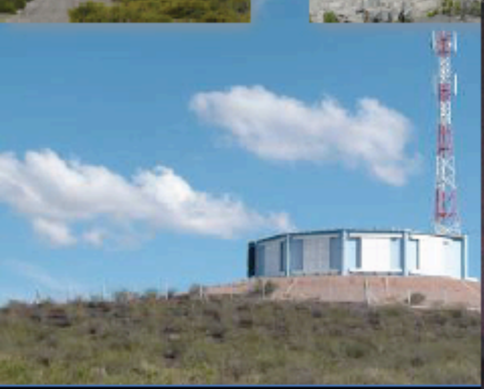
THE SURFACE DETECTOR ARRAY

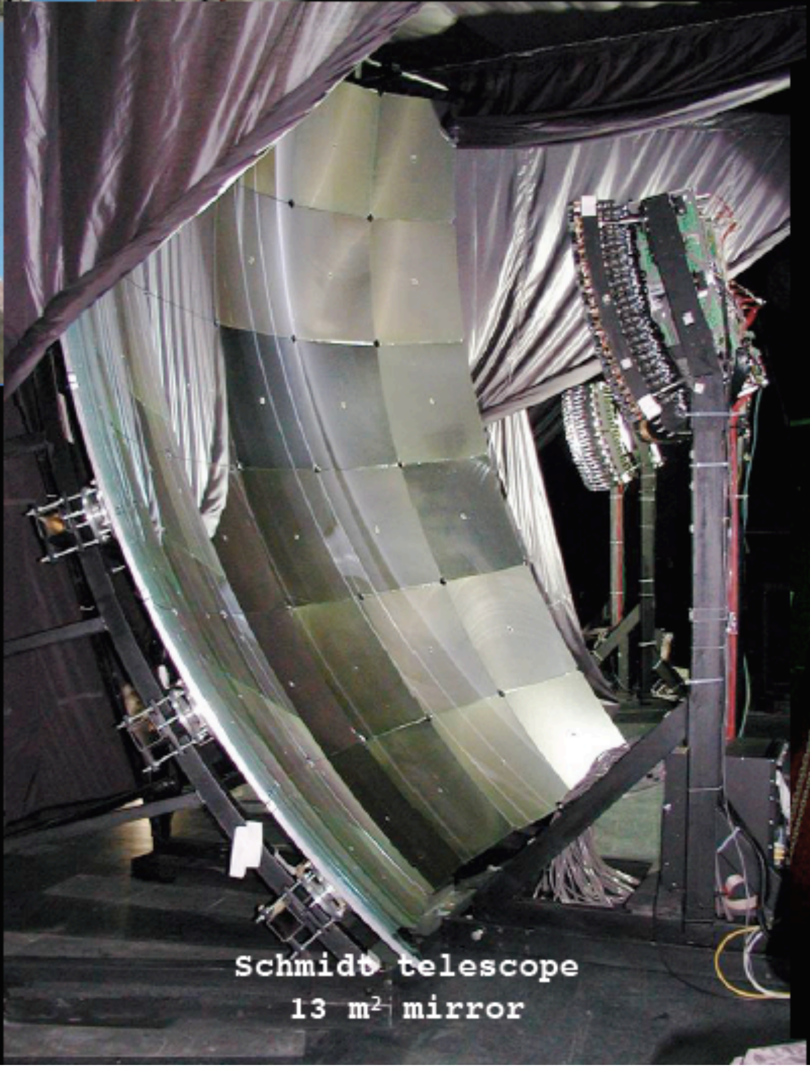
Surface Detector (SD): 1600 water Cherenkov tanks, 100% duty cycle



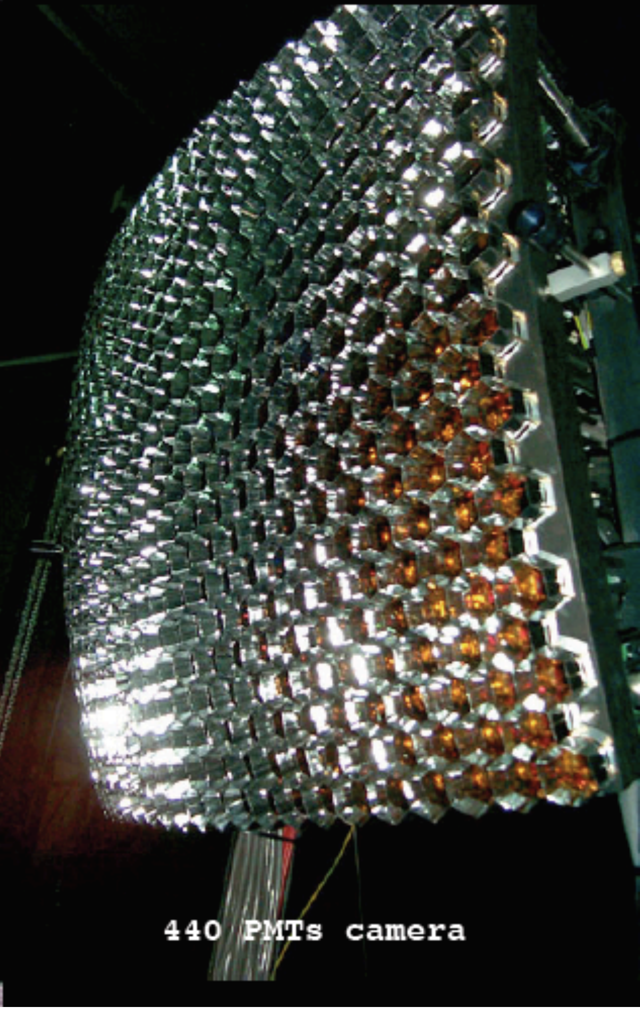
THE FLUORESCENCE DETECTOR

Fluorescence Detector (FD): 4 x 6 telescopes
10% duty cycle



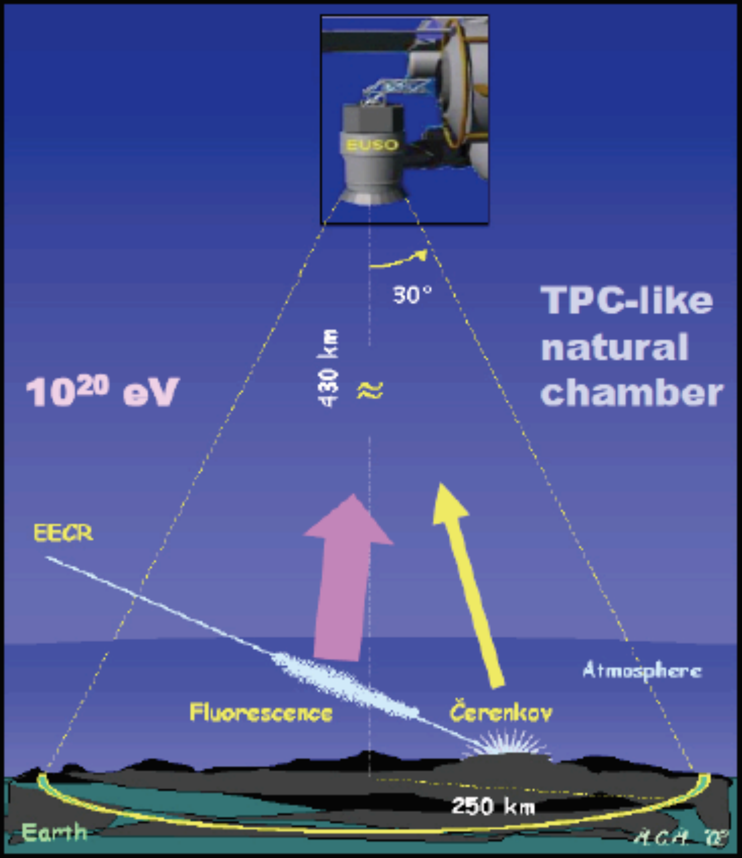


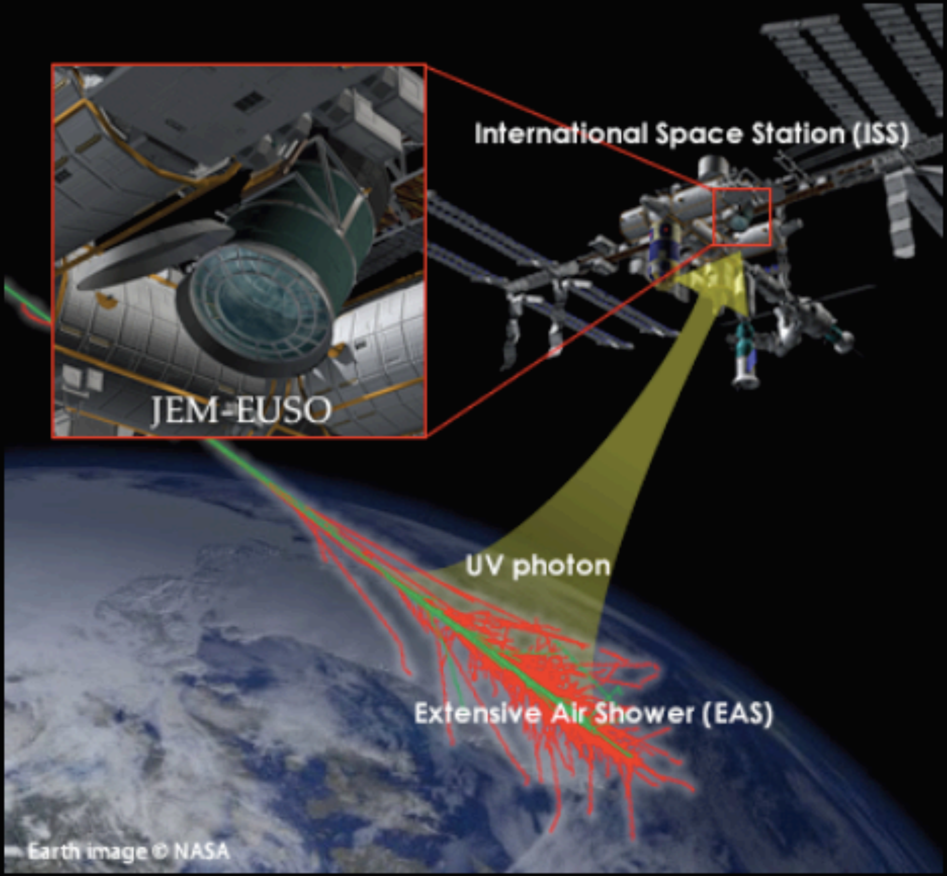
Schmidt telescope
13 m^2 mirror



440 PMTs camera

TO MEASURE COSMIC RAYS AT > 10^{20}: JEM-EUSO





In space: to be installed on ISS (altitude ≈ 400 km)

Fluorescence detector

6000 PMTs for a 2.25 m focal surface

Fresnel lenses

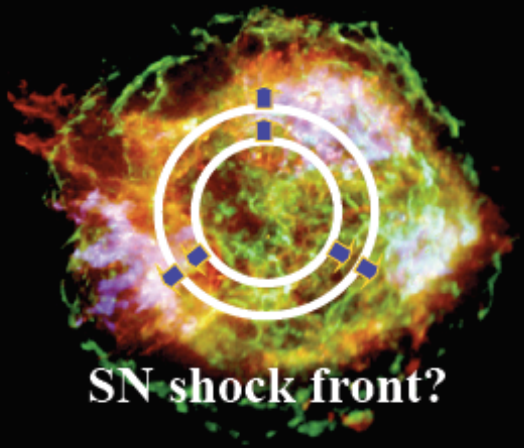
Aperture: 10^5-10^6 km2 sr; Energy range: >10^{20} eV

BECAUSE WE WOULD LIKE TO IDENTIFY THEIR SOURCES...

PRODUCTION

PROPAGATION

GALACTIC CRS



Fermi mechanism: diffusive shock acceleration.

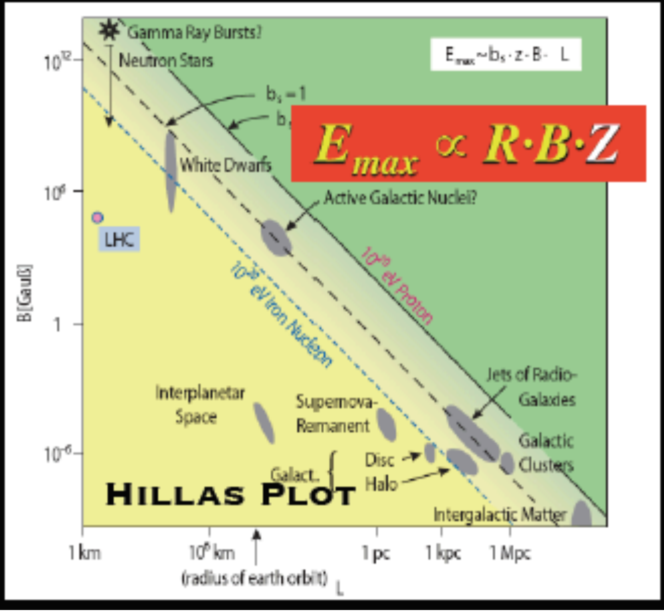
Natural power law.

Cutoff energy of different elements ≈ Z

Best candidates: SNR

Galactic CRs completely diffused and isotropized by GMF. CR-astronomy not possible. γ-rays and neutrinos smoking-gun

EXTRA-GALGALACTIC CRS

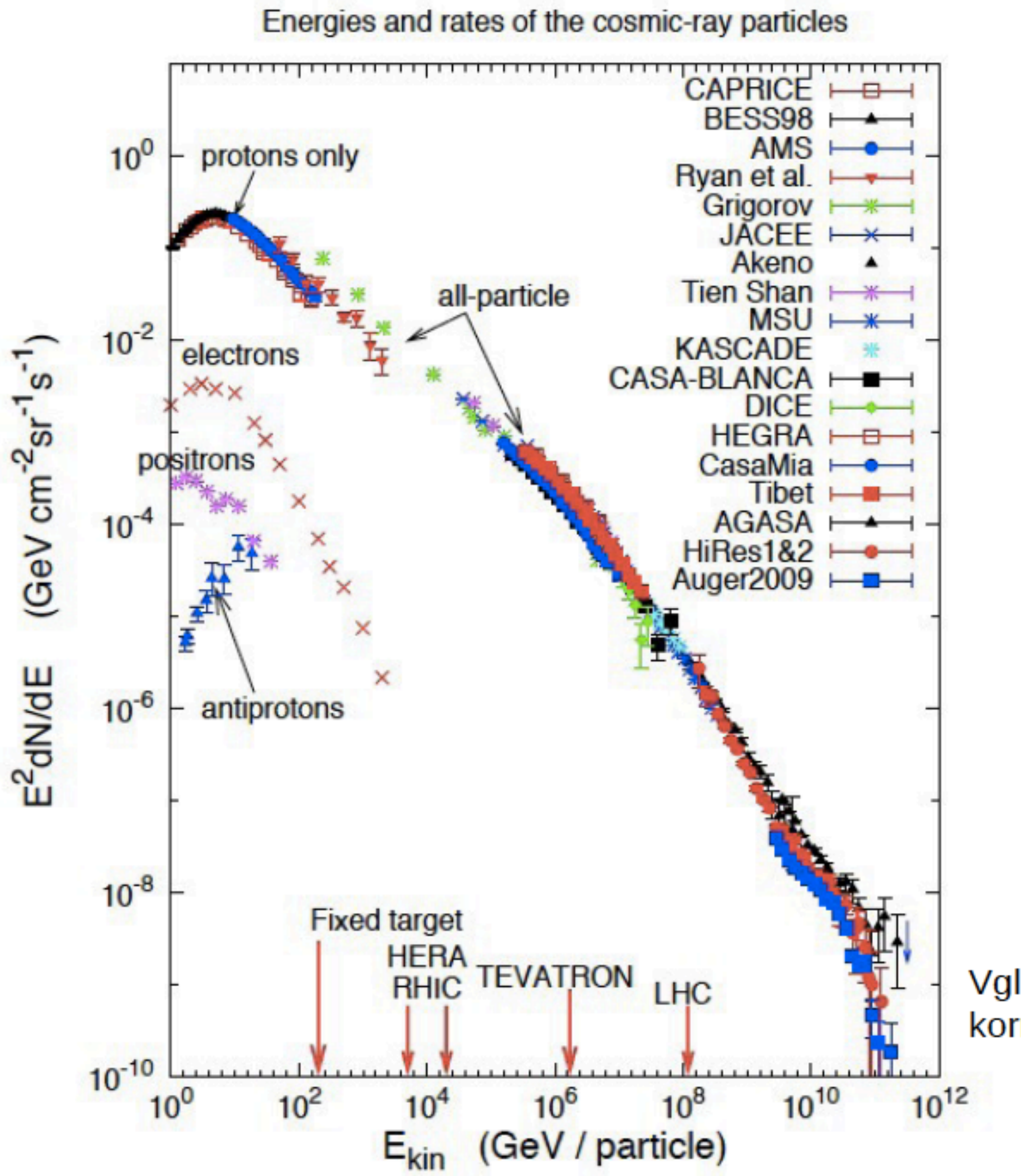

$$E_{max} \propto R \cdot B \cdot Z$$

Source size & magnetic field constraint to accelerate CRs to the highest energies: AGNs, GRBs,Radiogalaxies lobes

...

Highest energy (low-Z) CRs marginally deflected by GMF. CR-astronomy possible

Spektrum der kosmischen Strahlung



Vgl. mit collider
korrigiert auf √s

How to accelerate particles to 10^{20} eV ?

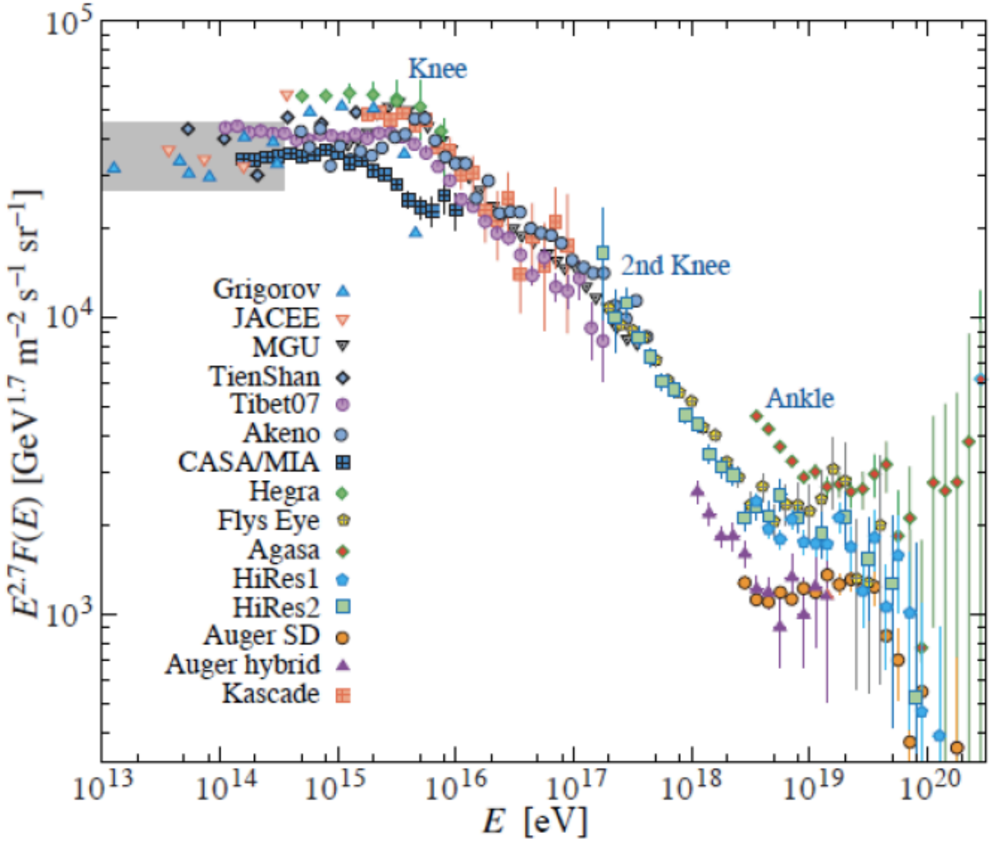
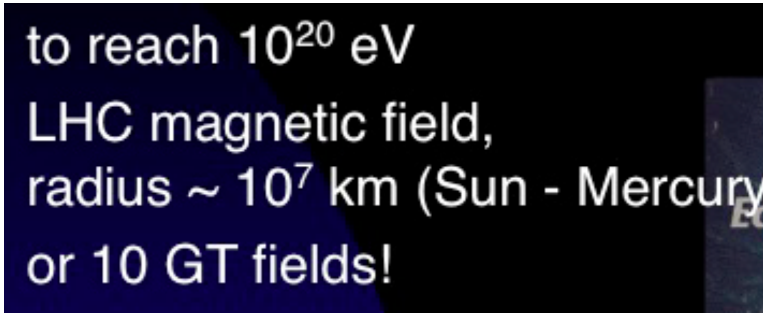


Figure 24.8: The all-particle spectrum from air shower measurements. The shaded area shows the range of the the direct cosmic ray spectrum measurements. See full-color version on color pages at end of book.

T. Gaisser, T. Stanev in www.pdg.lbl.gov

10^{20} eV = 16 Joule!!
Compare:
Tennis ball with 100 km/h: 44 J



to reach 10^{20} eV

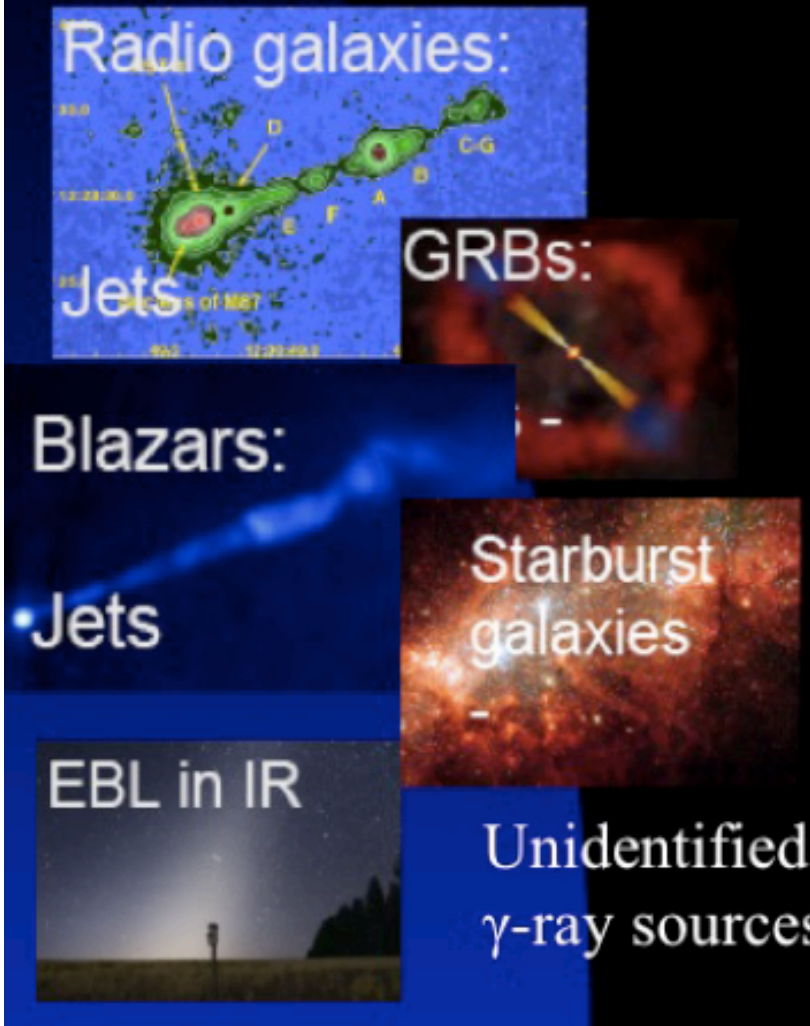
LHC magnetic field,

radius ~ 10^7 km (Sun - Mercury

or 10 GT fields!

High Energy Astrophysical Accelerators

Extragalactic



Radio galaxies:

Jets

GRBs:

s -

Blazars:

Jets

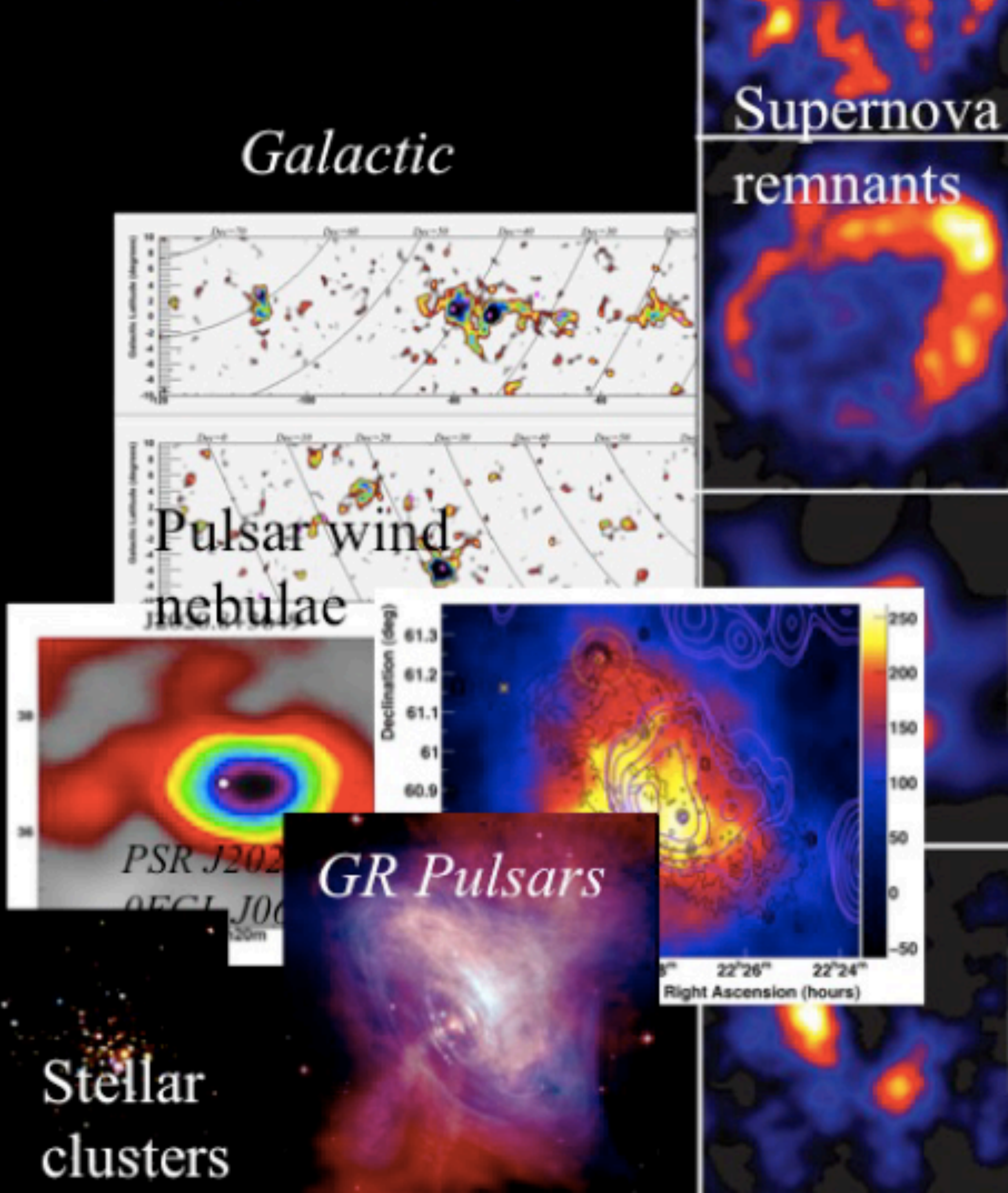
Starburst galaxies

-

EBL in IR

Unidentified γ-ray sources

Galactic



Pulsar wind nebulae

PSR J202

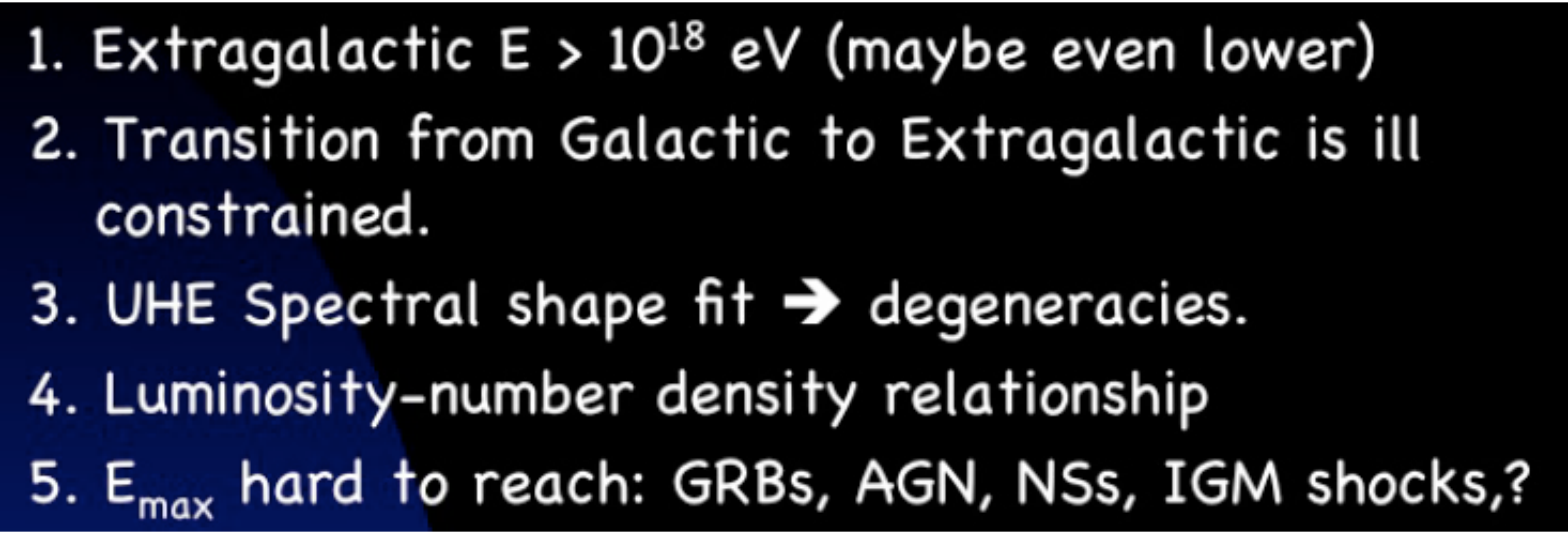
0FGL J06

Stellar clusters

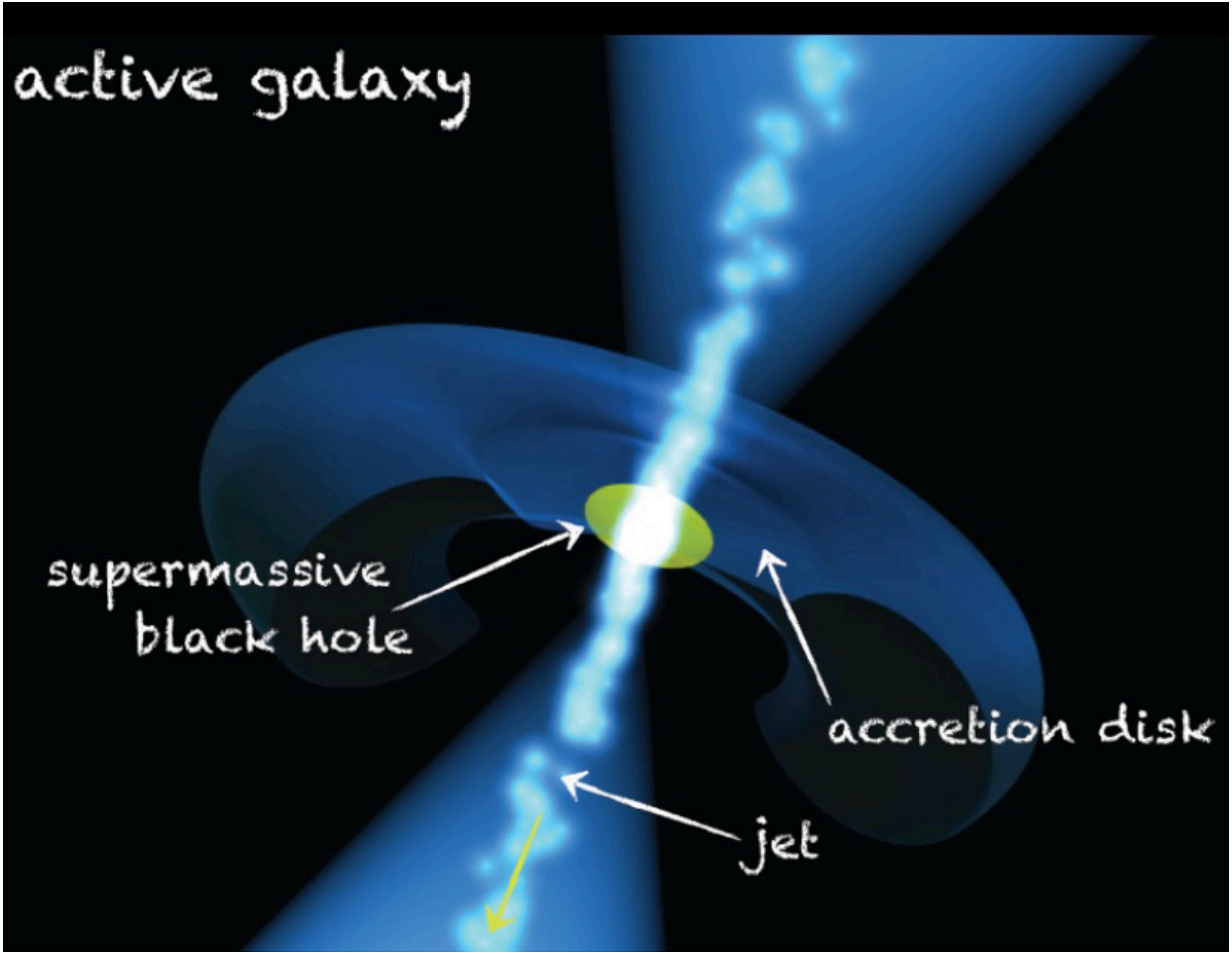
GR Pulsars

Supernova remnants

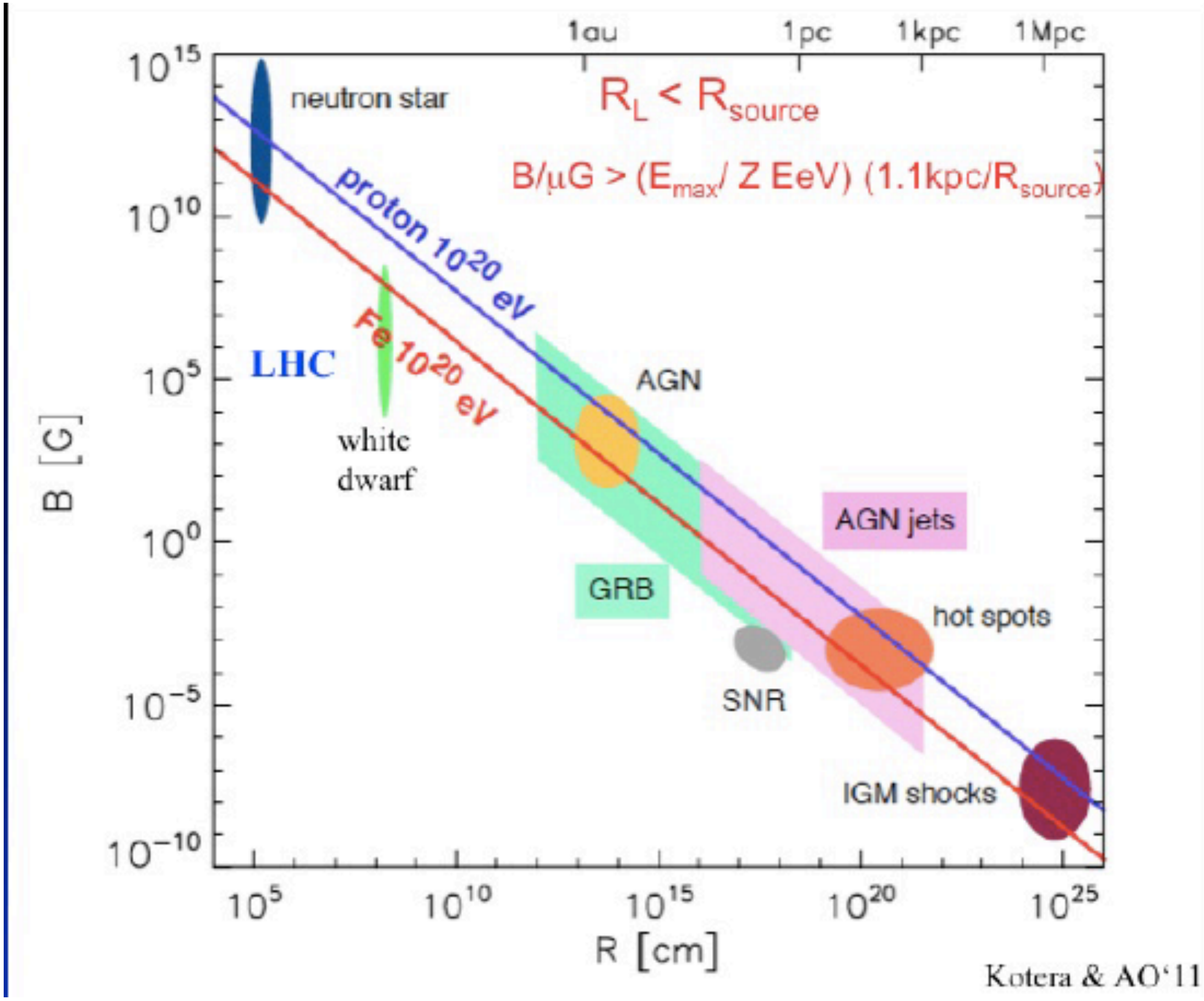
Plausible source of ultra-high cosmic rays (UHECRs)



1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape fit ➔ degeneracies.
4. Luminosity-number density relationship
5. E_{max} hard to reach: GRBs, AGN, NSs, IGM shocks,?


active galaxy
supermassive black hole
accretion disk
jet

Hillas plot



Kotera & AO'11

E. Fermi, 1948

Dec 4 1948

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Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

$$MV^2$$

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob.} = \frac{v+V}{2v}$$

Running after collision (prob = $\frac{v-V}{2v}$) gives energy gain $M(-2vV+2V^2)$

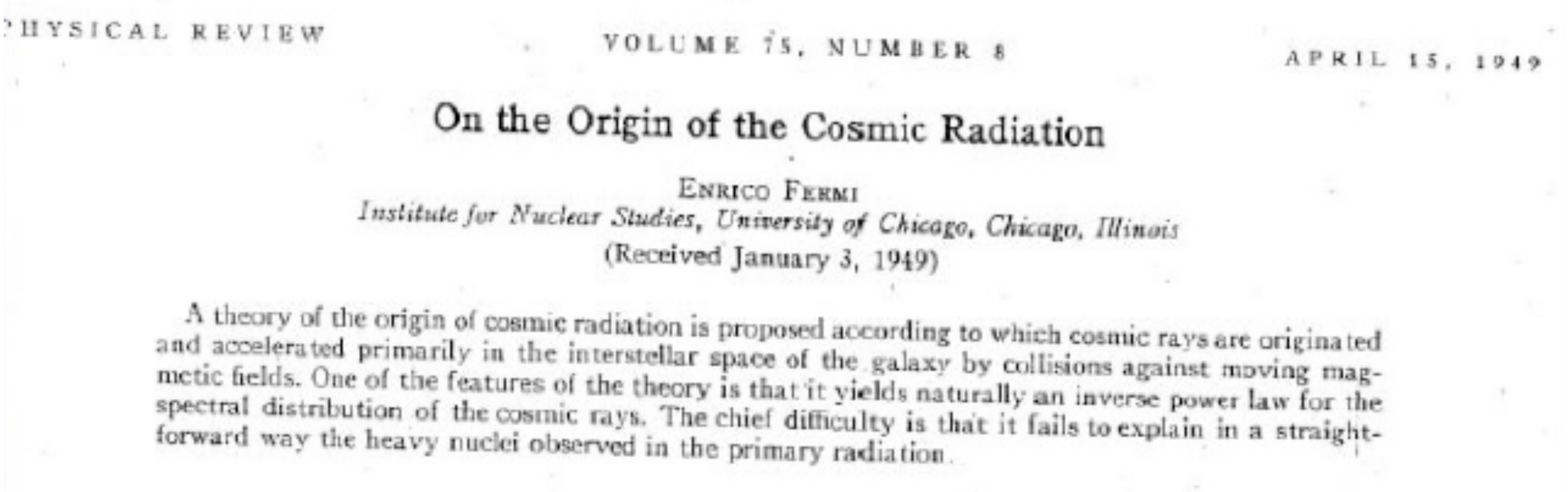
Average gain order

$$MV^2$$

Relativistic: order

$$w\beta^2$$

Shock acceleration describes spectrum from galactic sources



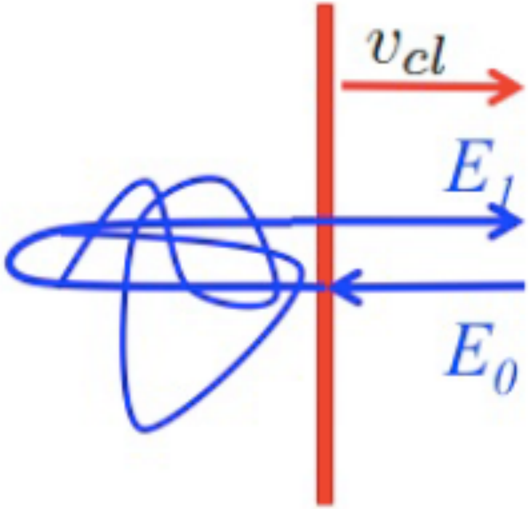
HYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

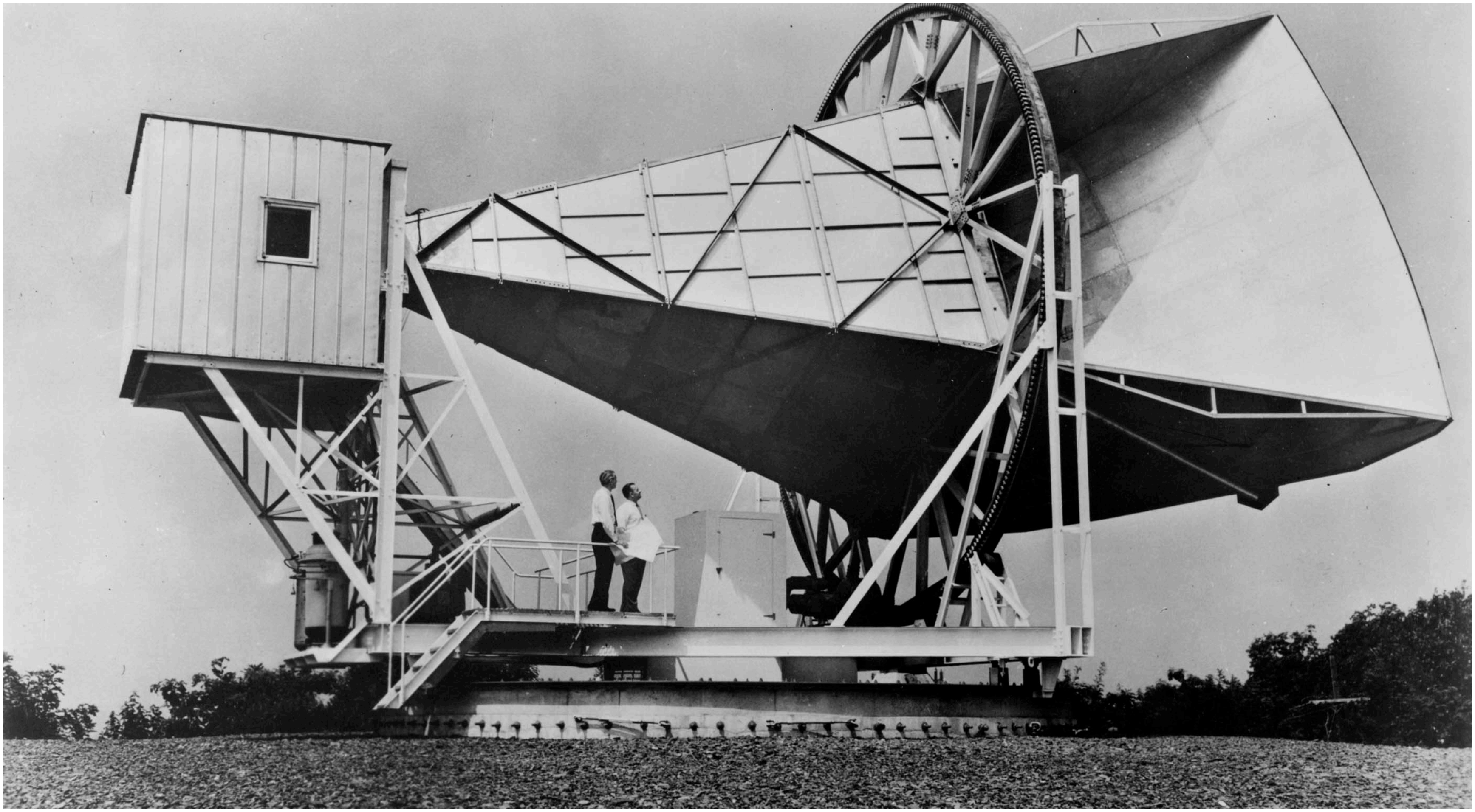
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

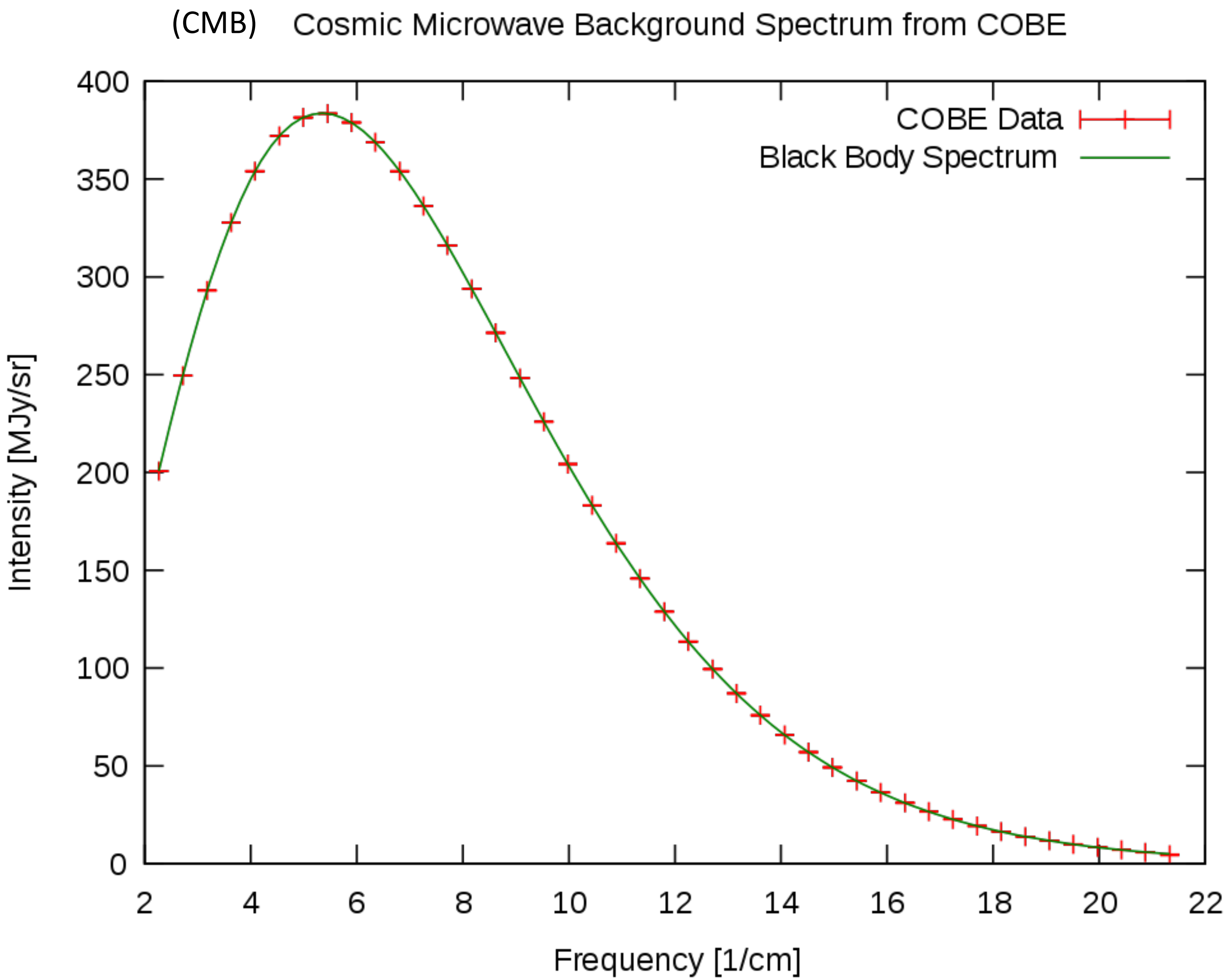
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.



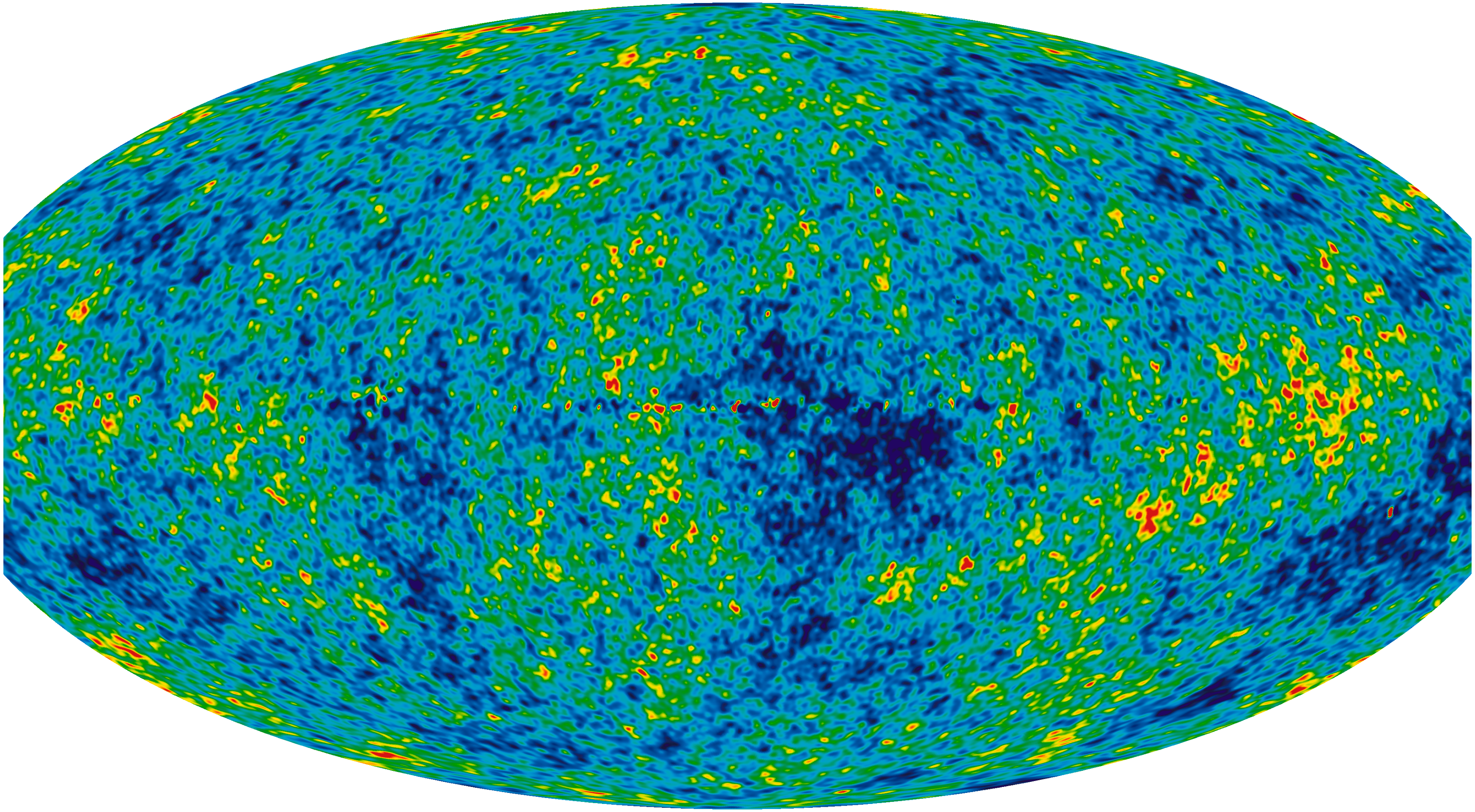
1965: Entdeckung der kosmischen Hintergundstrahlung durch Penzias und Wilson





(CMB) Cosmic Microwave Background Spectrum from COBE

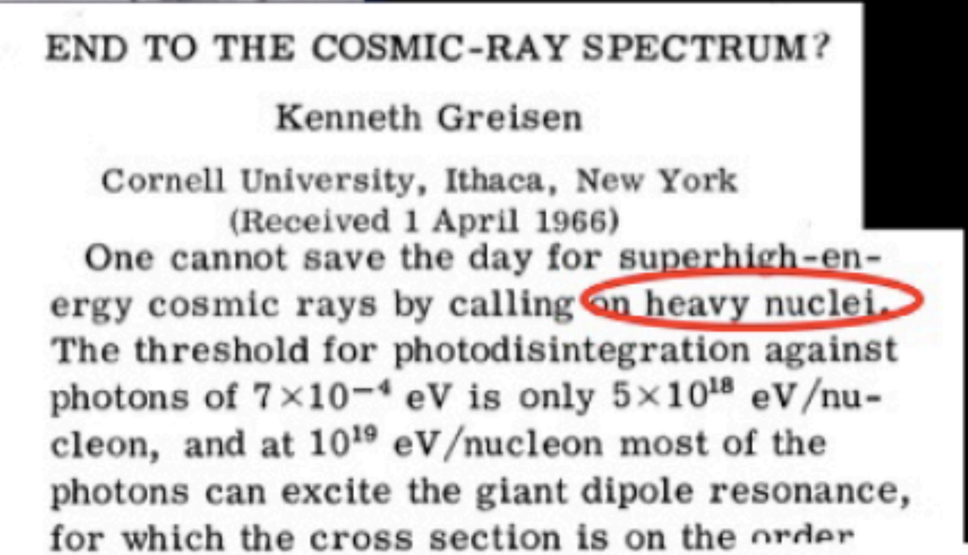
Today: Measurement of anisotropy of the CMB



Propagation of UHECRs

Greisen-Zatsepin-Kuzmin (GZK) pioneered the field in 1966

protons & nuclei

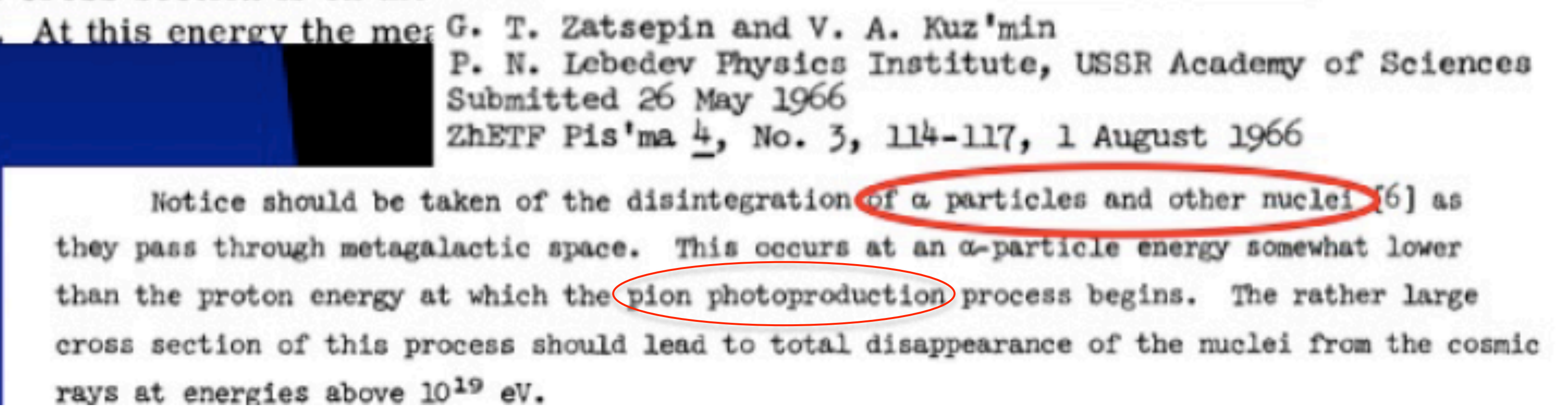


END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

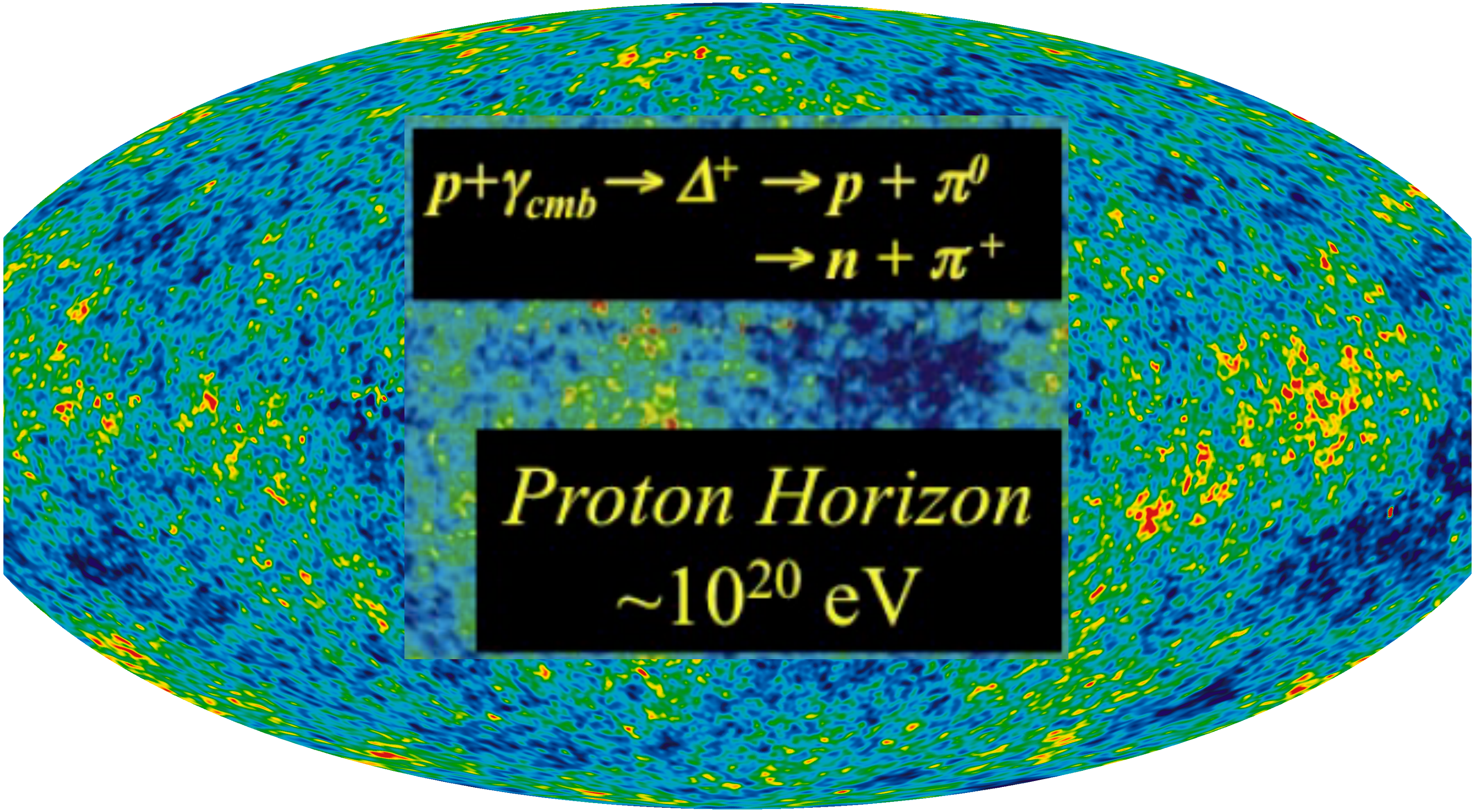
Cornell University, Ithaca, New York
(Received 1 April 1966)

One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is on the order of 10^{-25} cm^2. At this energy the me



G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

Notice should be taken of the disintegration of α particles and other nuclei [6] as they pass through metagalactic space. This occurs at an α-particle energy somewhat lower than the proton energy at which the pion photoproduction process begins. The rather large cross section of this process should lead to total disappearance of the nuclei from the cosmic rays at energies above 10^{19} eV.



$$\begin{aligned} p+\gamma_{cmb} &\rightarrow \Delta^{+} \rightarrow p+\pi^{0} \\ &\rightarrow n+\pi^{+} \end{aligned}$$

Proton Horizon

~10^{20} eV

Zazepin & Kusminov (1966)

‘time until collision’

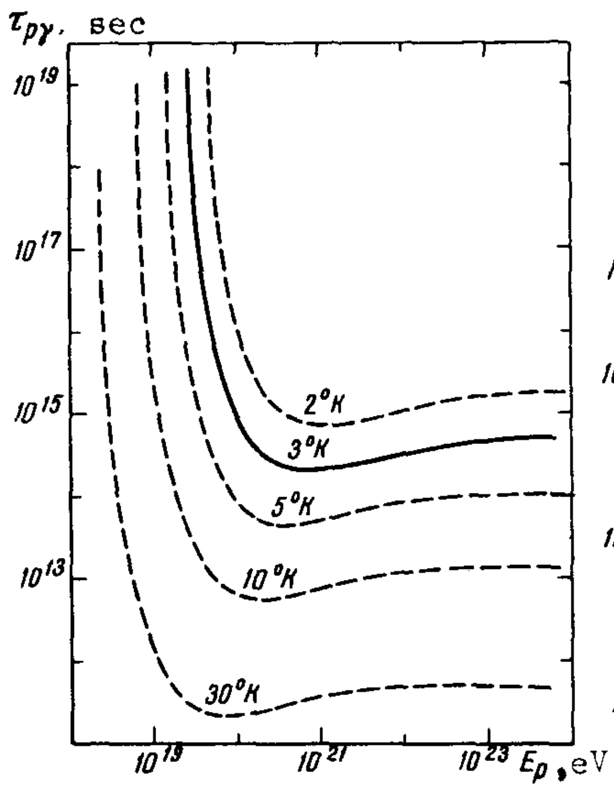


Fig. 1

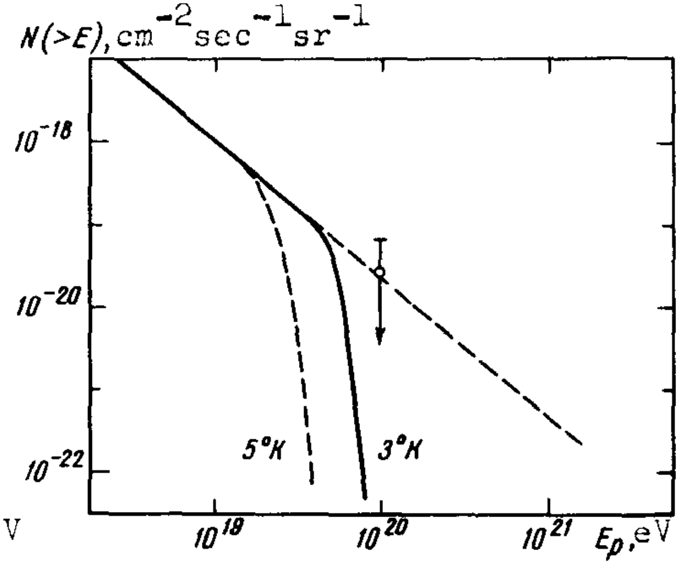
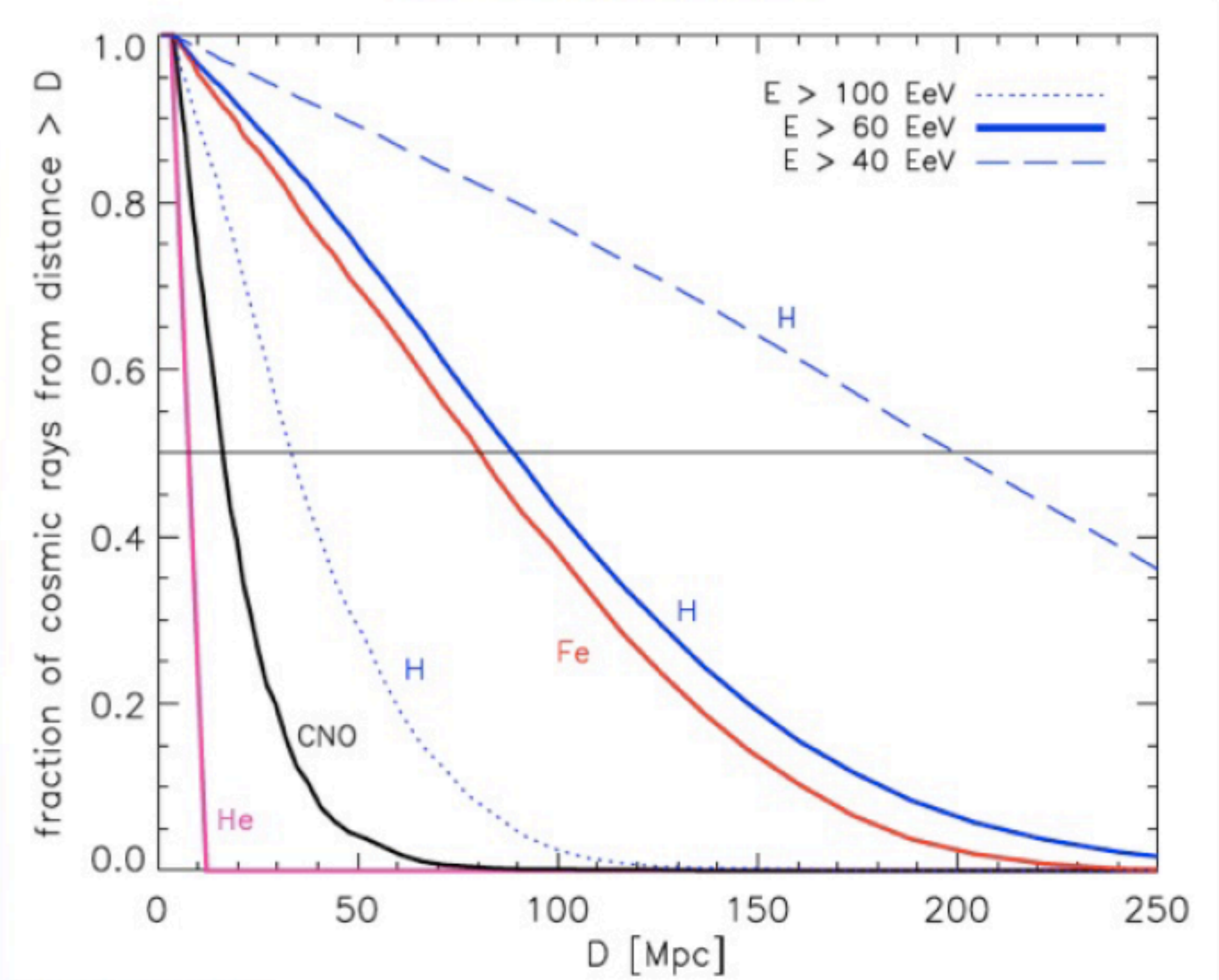


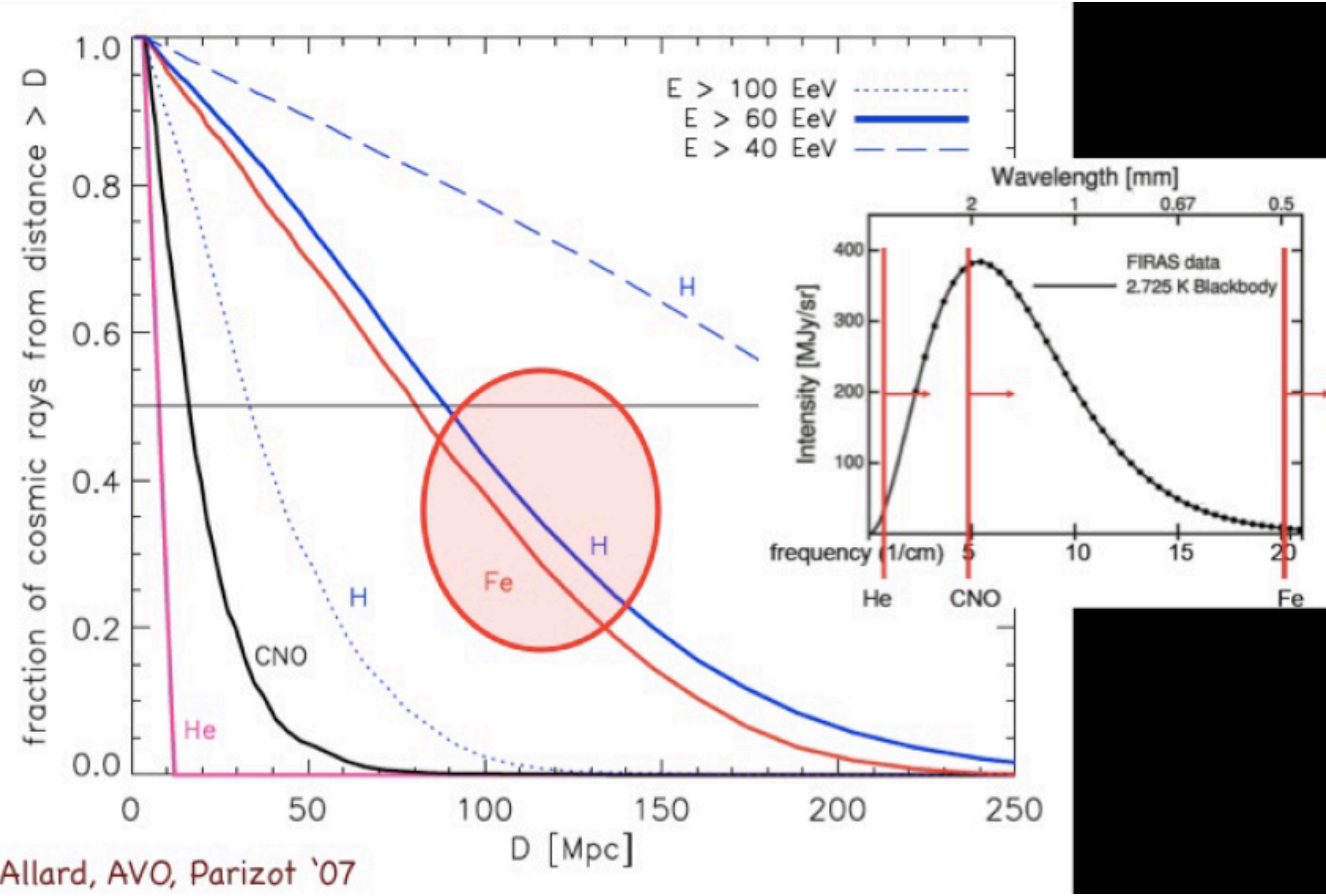
Fig. 2

The values of $\tau_{p\gamma}$ calculated by formula (1) for different proton energies are shown in Fig. 1 for several photon gas temperatures, T = 2, 3, 5, 10, and 30. We see that at proton energies $E_p \gtrsim 10^{20}$ eV, proton interactions with the photon gas become quite frequent, $\tau_{p\gamma} \approx 10^7$ years. This means that at the age $t \gtrsim 10^8$ of the cosmic rays with energies under consideration, their initial spectrum should be cut off in the high-energy region, even if the acceleration mechanism had been sufficiently effective in producing particles having these

GZK Horizon

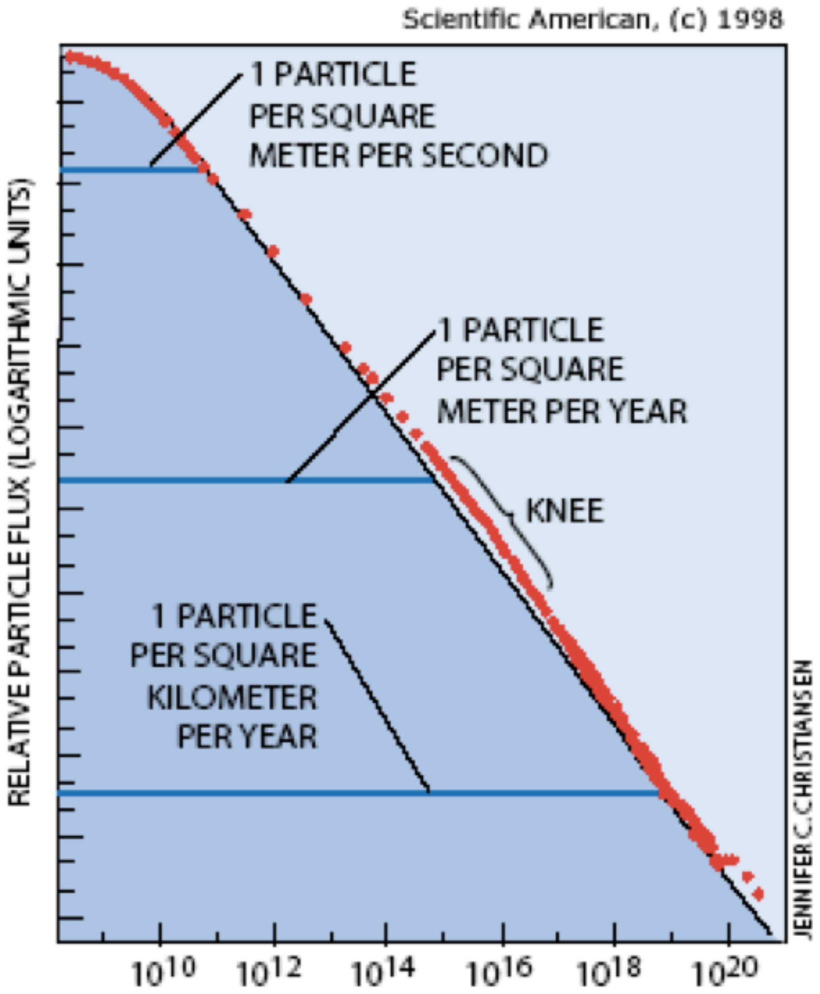


fraction of cosmic rays from distance > D
D [Mpc]
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
E > 100 EeV
E > 60 EeV
E > 40 EeV
H
H
Fe
H
CNO
He

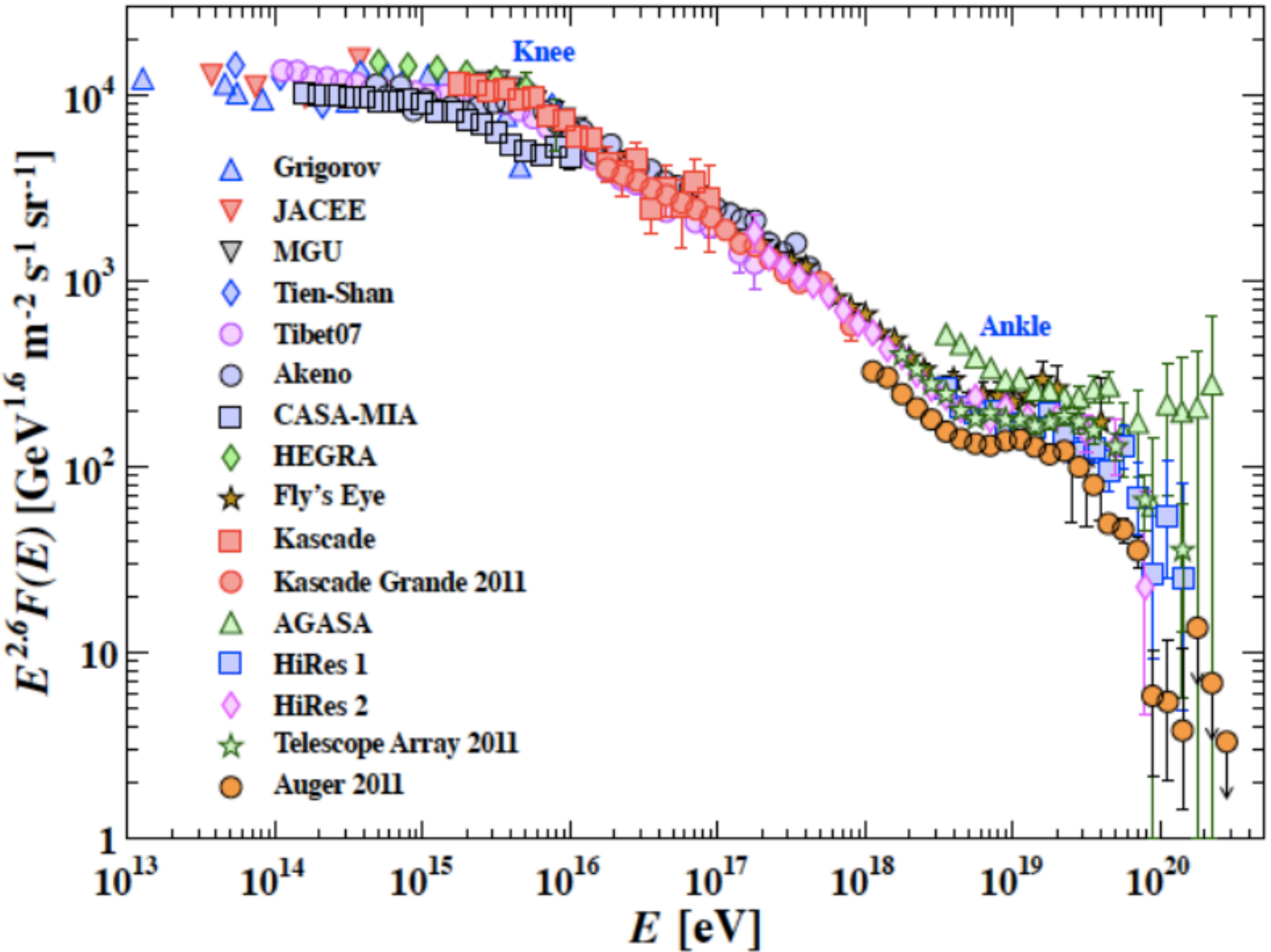


Allard, AVO, Parizot '07

The cosmic ray spectrum



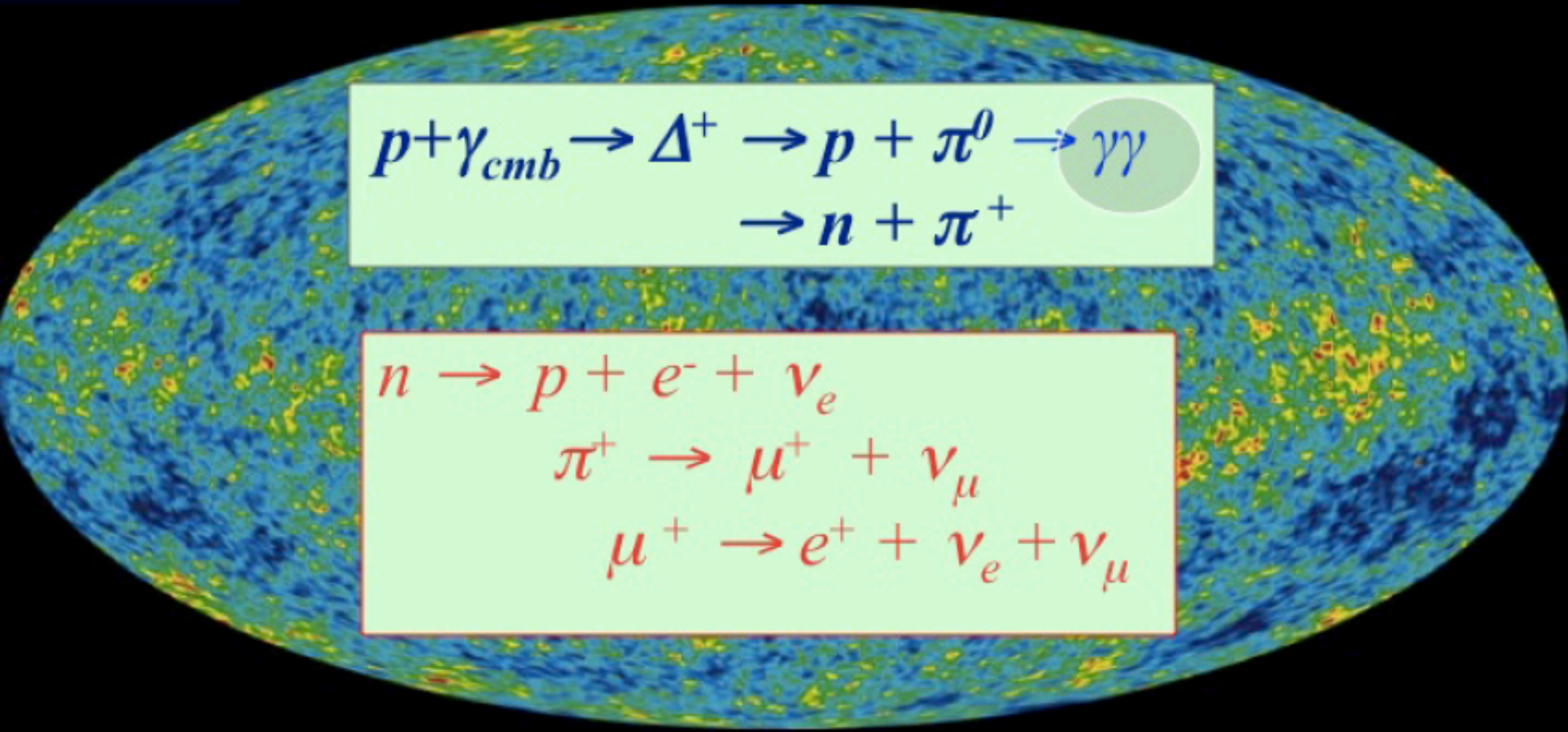
The all-particle energy spectrum of cosmic rays.



Particle data group 2011

Cosmogenic (GZK) Neutrinos & Photons

and UHECR composition



$$p+\gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$

$$\rightarrow n + \pi^+$$

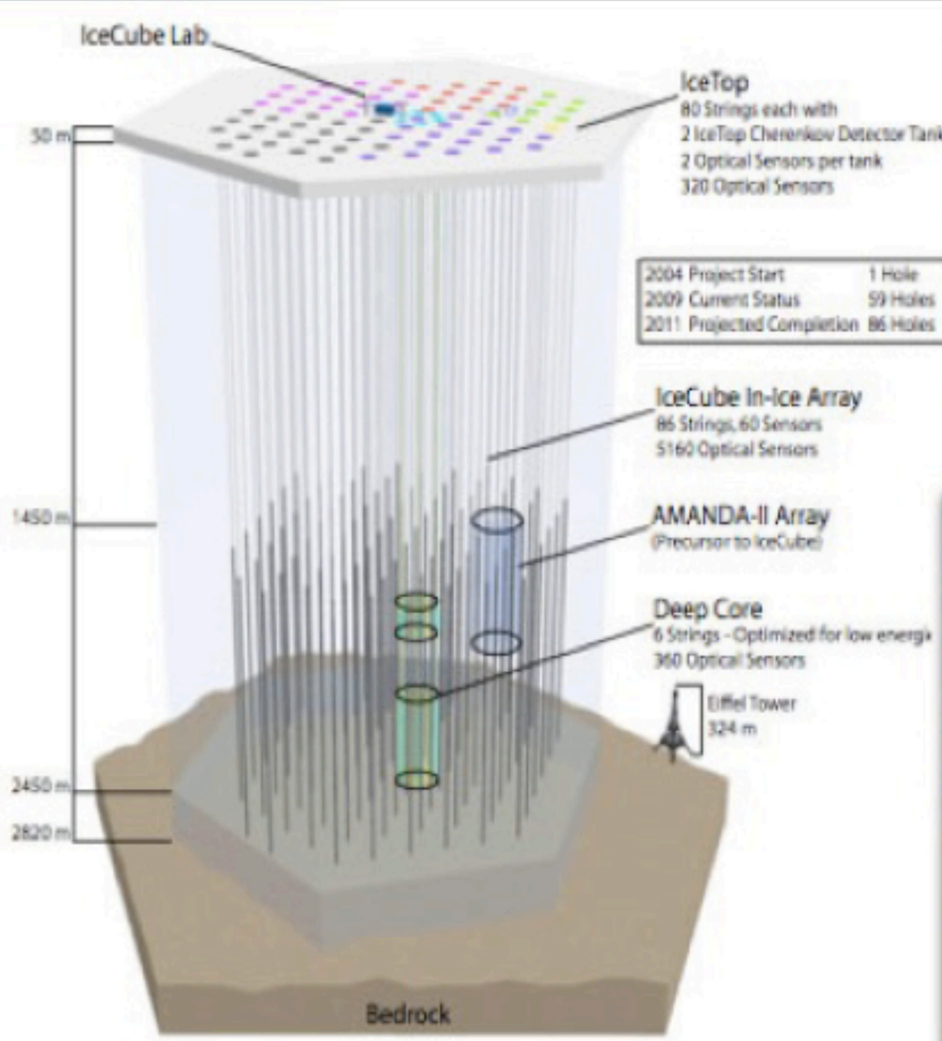
$$n \rightarrow p + e^- + \nu_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$

Highest Energy Neutrino Observatories

IceCube



ANITA