Recent advances in the observations of high energy cosmic rays

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DPNC Seminar – April 27, 2022

Contents

- Brief history of early measurements

- Selected recent results at high energies

- Ideas for future projects

Disclaimer:

- I will not go into theoretical aspects (see May 18 DPCN seminar)

- I will concentrate on charged cosmic rays measurements
  (i.e. not going to cover neutrino and gamma ray astronomy)

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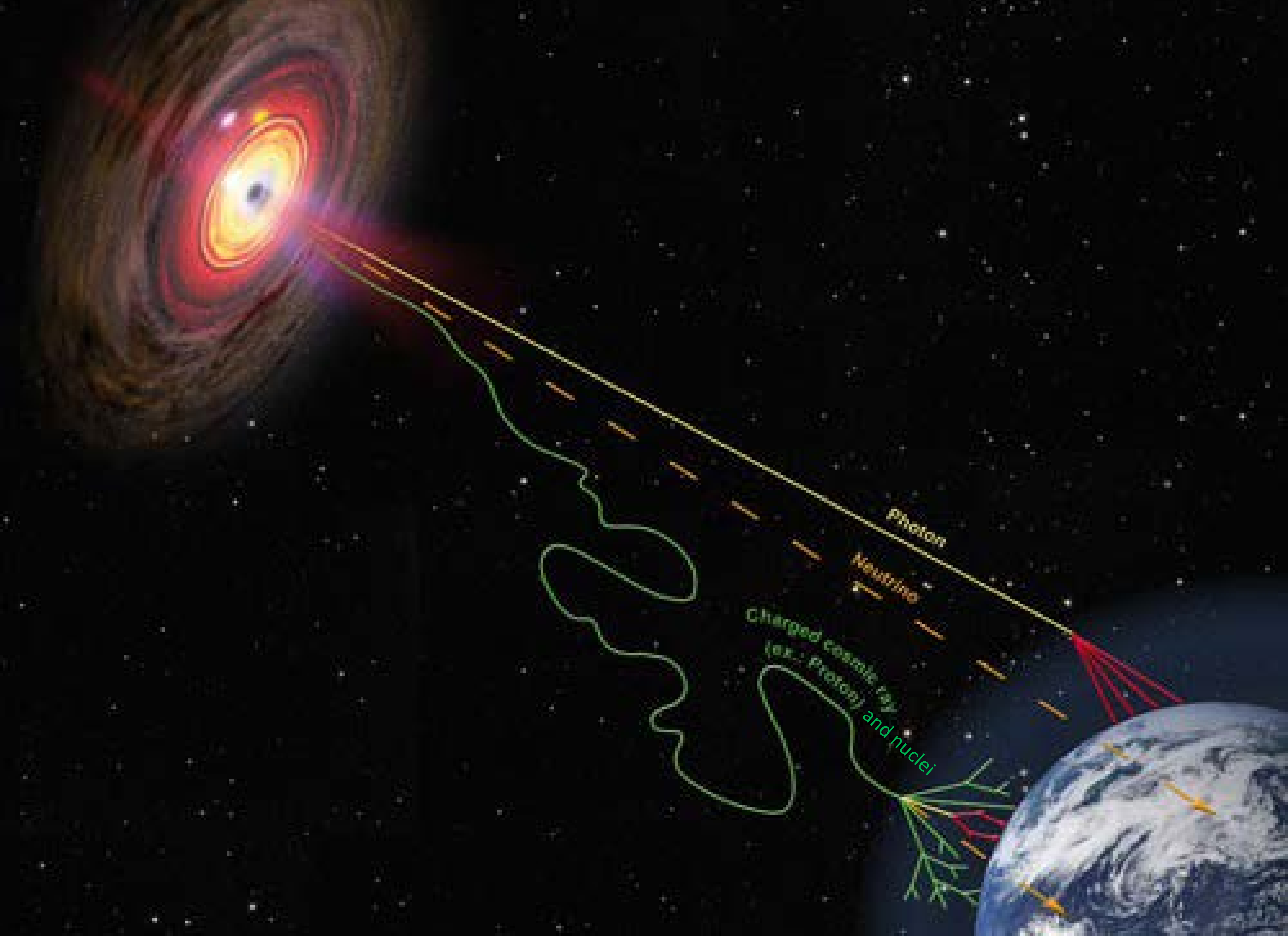
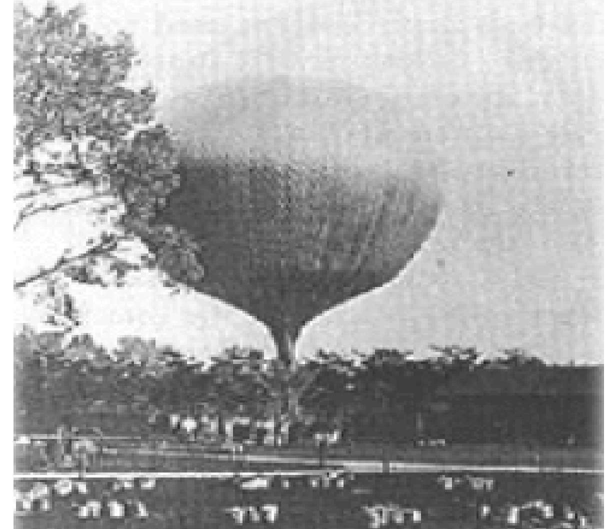
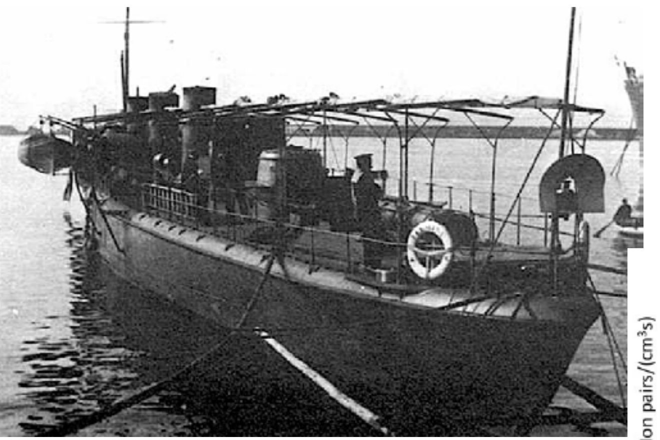
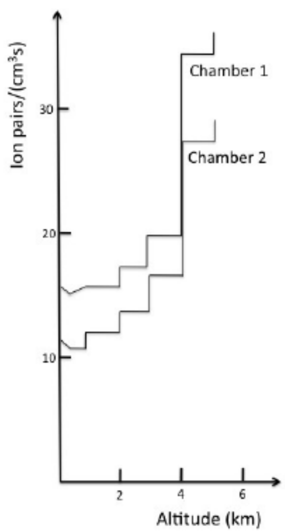

Photon
Neutrino
Charged cosmic ray
(ex.: Proton) and nuclei

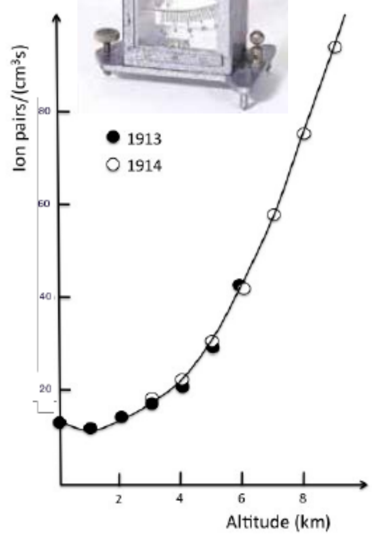
Discovery and first measurements

1887 --> 1889









EXPLORER II – 11 Nov 1935 – 22000 m

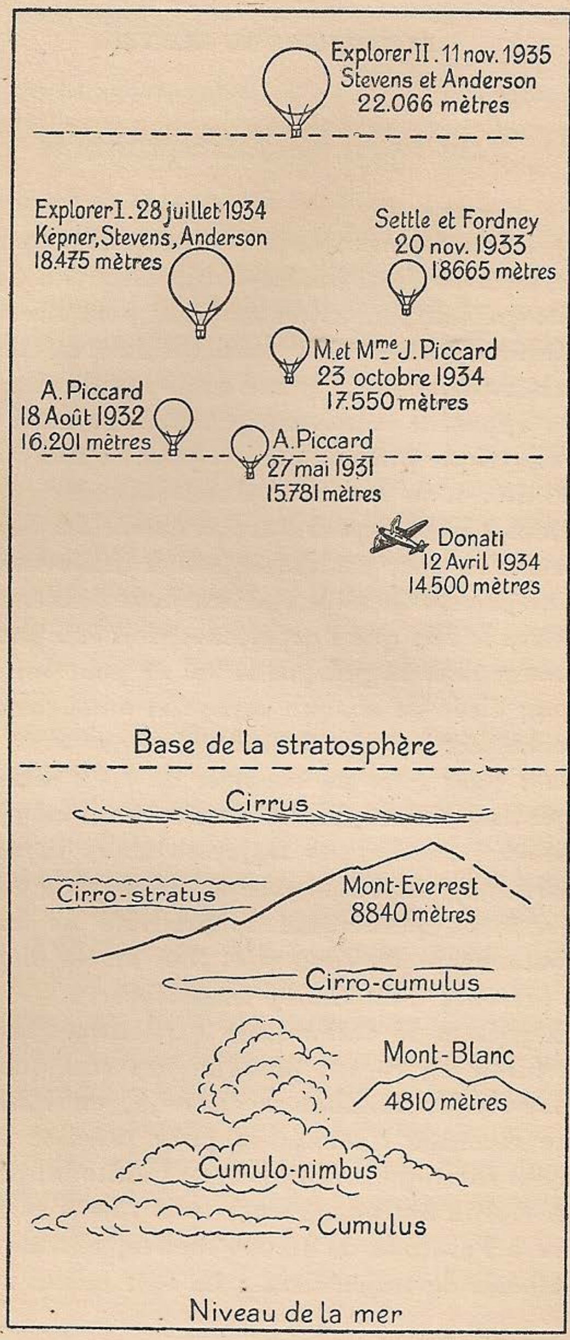
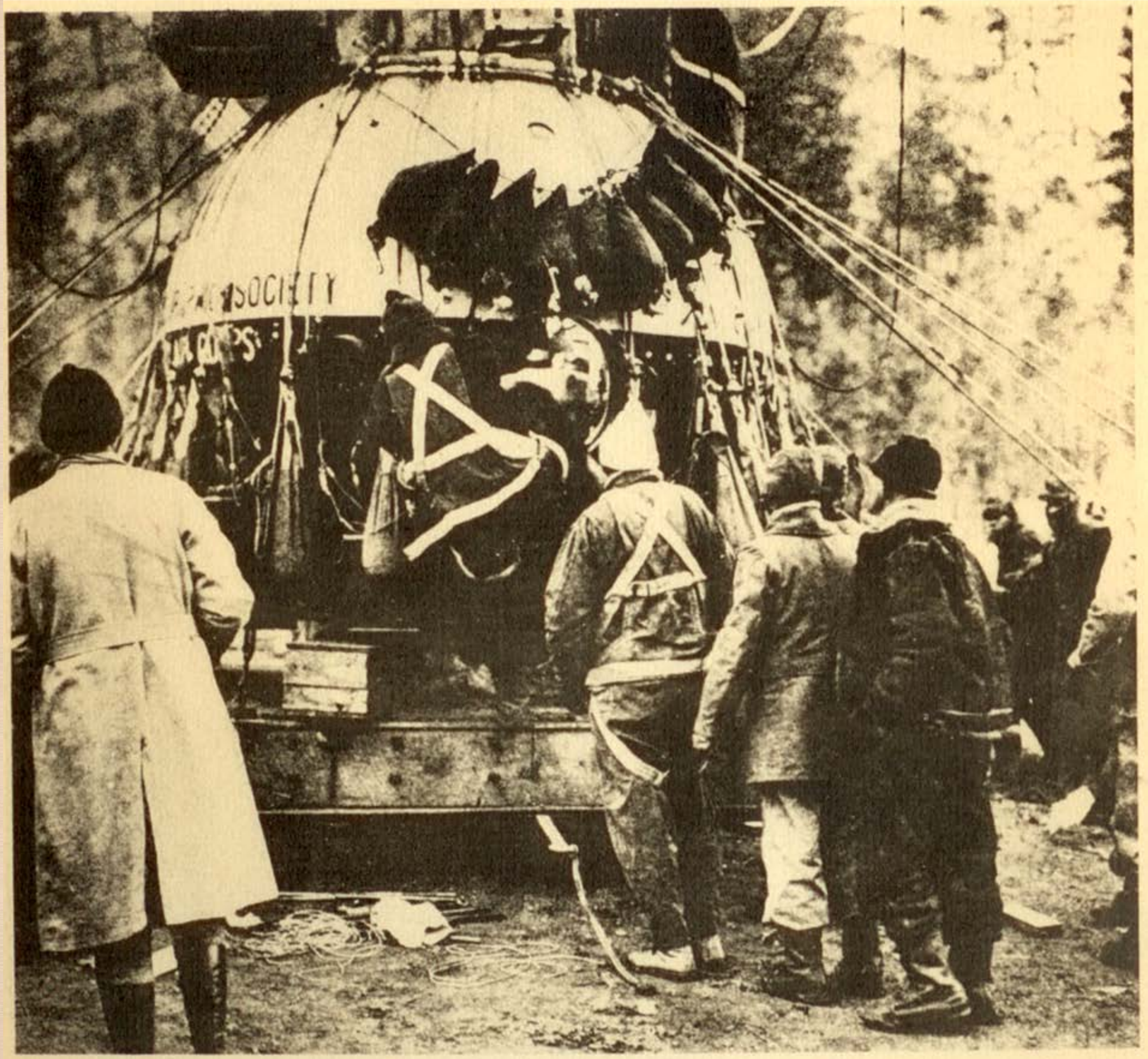


Fig. 39. — Les principaux vols stratosphériques.



MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

PROF. RUSSELL ELECTED

Astronomer Heads Association—Secret of Purple Gold in Tomb of Tut-ankh-Amen Rediscovered.

By WILLIAM L. LAURENCE.
Special to THE NEW YORK TIMES.

ATLANTIC CITY, Dec. 30.—Professor Robert A. Millikan, who won the Nobel Prize in physics for being

MILLIKAN DENIES 'CLASH' ON THEORY

Scientist Protests That the Word 'Incautious' Was Not Aimed at Compton.

DISCLAIMS ANY COOLNESS

Holds The Times Report Stated "Exactly the Opposite" of the Findings He Presented.

By Telegraph to the Editor of THE NEW YORK TIMES.

WASHINGTON, D. C., Dec. 31.—It is not customary for me to attempt to correct erroneous newspaper reports, and that for the simple reason that with many newspapers it is a well-nigh hopeless undertaking. But THE NEW YORK TIMES is usually so dependable that I assume it will welcome correction and also will know how to effect the remedy for its error.

MILLIKAN'S DATA CONFIRM COMPTON

Results of Cosmic Ray Study at Panama Tend to Back Rival's Ideas.

RAY INTENSITY VARIES

Strength Is Greater at the Poles—Equatorial Tests Are Now Projected.

PASADENA, Cal., Feb. 4 (AP).—The stratosphere above equatorial regions of the earth should be the next scene of exploration in the quest of the secrets of the cosmic ray, Dr. Robert A. Millikan said here today.

Announcing that observations of his co-workers at Panama confirmed the earlier reports of Dr. Arthur H. Compton of Chicago that the rays from interstellar space showed latitude effects, Dr. Millikan disclosed that the variance was as high as 8 per cent.

Many studies “at ground”

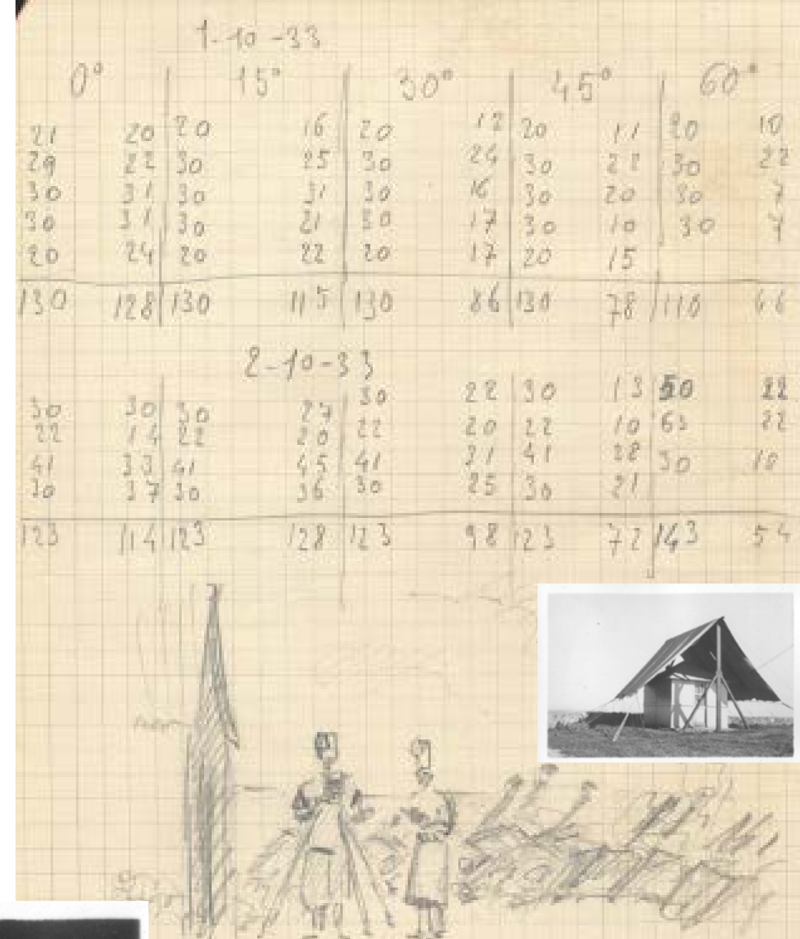
Bruno Rossi,1933.
Hints for evidence of extensive air showers

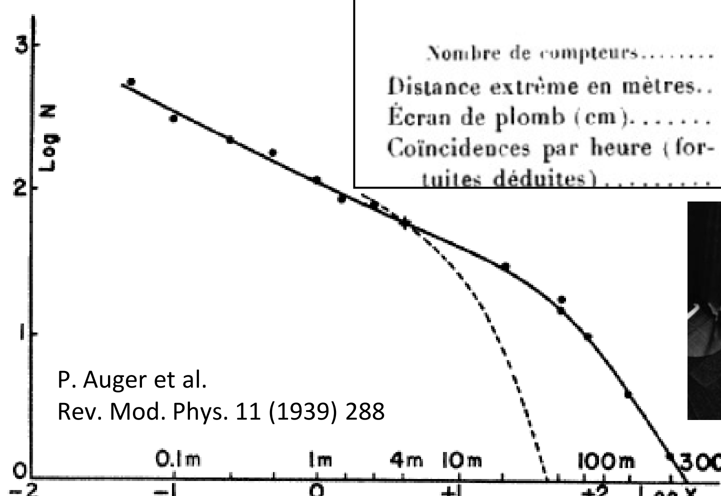
Pierre Auger, 1938
First clear Evidence for extensive air showers

PHYSIQUE NUCLÉAIRE. — *Grandes gerbes cosmiques atmosphériques contenant des corpuscules ultrapénétrants.* Note de MM. **Pierre Auger, Raymond Maze** et Mme **Thérèse Grivet-Meyer**, présentée par M. Jean Perrin.

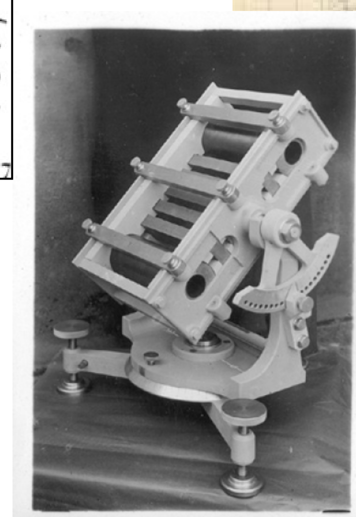
1. De nombreux travaux récents ont montré l'existence dans le rayonnement cosmique de deux espèces de corpuscules; d'une part des électrons des deux signes fortement absorbés par la matière et qui sont pratiquement totalement arrêtés par un écran de 5 à 10cm de plomb, d'autre part des corpuscules nouveaux dont la masse est probablement comprise entre 100 et 200 fois celle de l'électron et dont le pouvoir pénétrant est très supérieur. La question des relations entre ces deux groupes se pose alors de la façon suivante : les deux types de corpuscules atteignent-ils indépen-

	1re partie.		
Nombre de compteurs........	3.	3.	3.
Distance extrême en mètres..	0,20	2	5
Écran de plomb (cm).......	–	–	–
Coïncidences par heure (fortuites déduites)........	6,7	2,1	0,7

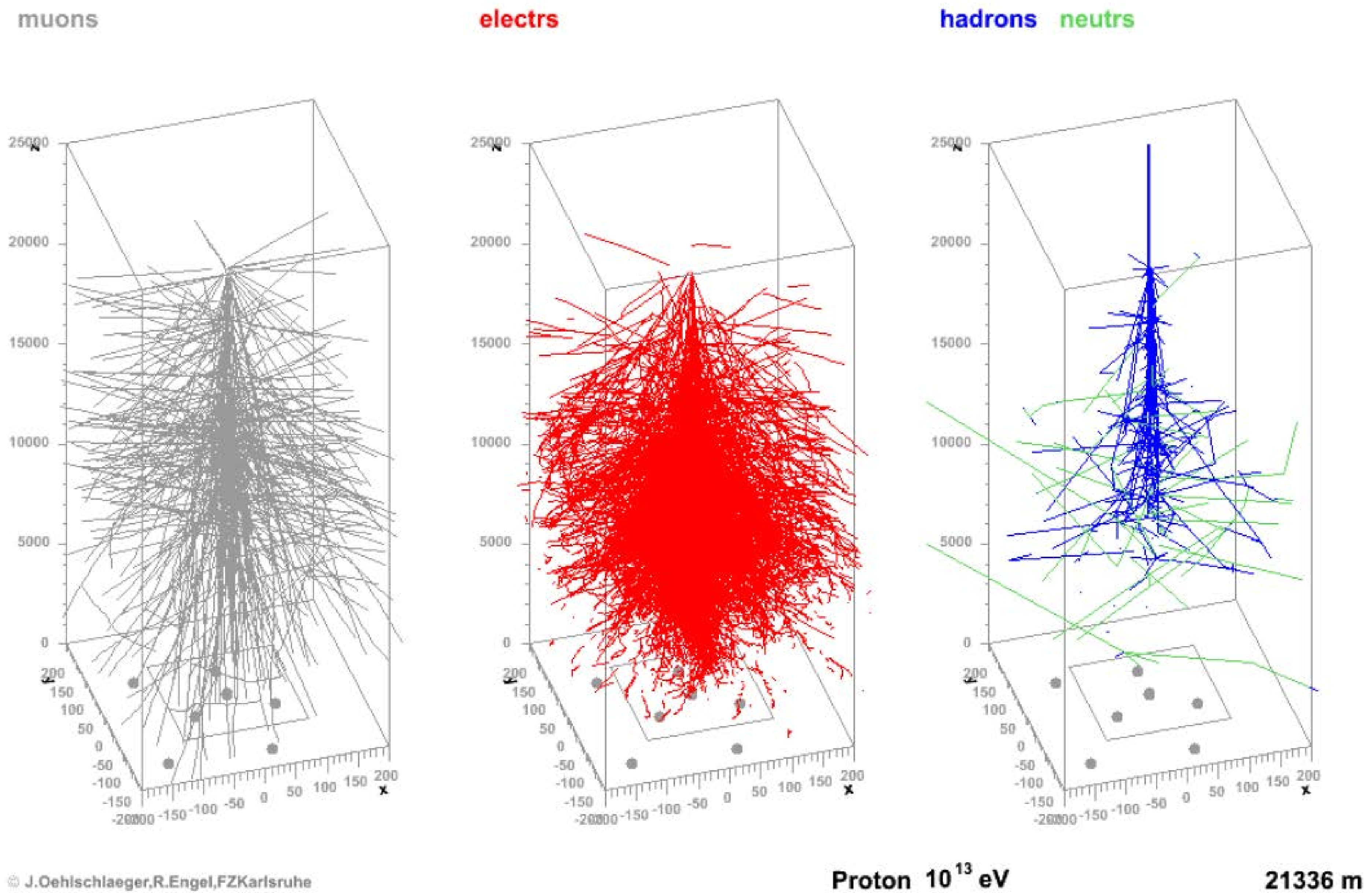


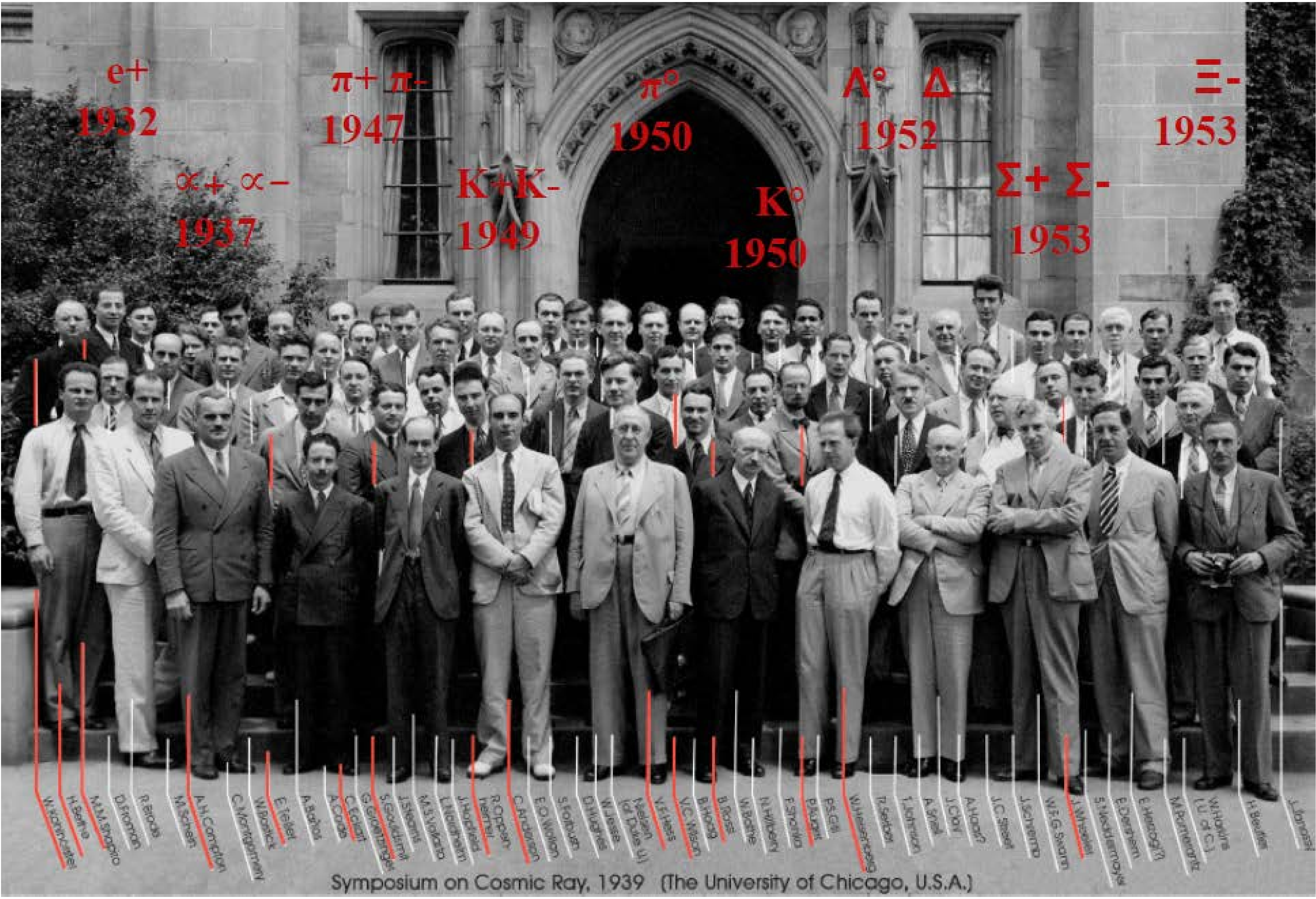


P. Auger et al.
Rev. Mod. Phys. 11 (1939) 288



A 10 TeV proton initiated Extensive air Shower

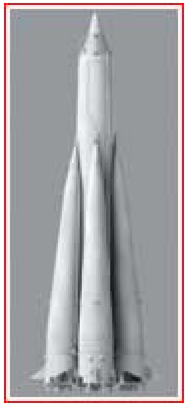



e+
1932
π+ π-
1947
π°
1950
Λ°
Δ
1952
Ξ-
1953
∝+ ∝-
1937
K+K-
1949
K°
1950
Σ+ Σ-
1953
Symposium on Cosmic Ray, 1939 (The University of Chicago, U.S.A.)

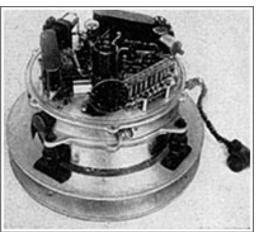
The very beginning of space exploration

USSR	USA	Notes	Detectors
Sputnik I Oct. 4, 1957		*Same time: all-particle knee discovered in EAS experiment (G.B. Khristiansen & G.V. Kulikov)*	
Sputnik II Nov. 3, 1957		**First CR detector in space !** (above Laika's, i.e. Kudrjavka's, cabin) Anomalous counting above a given altitude (S. N. Vernov)	Geiger-Muller (G-M) tubes
	Explorer I Fe. 1, 1958	Detector saturation above a given altitude !?!	G-M tubes
	Explorer III Mar. 26, 1958	Dectors saturation above a given altitude !?! May 1, 1958: J. A. Van Allen's hypothesis: particles trapped by the geomagnetic field	G-M tubes
Sputnik III		CR measurements up to about 2000km Van Allen's (belts) explanation fully confirmed	
	Explorer IV Jul. 26, 1958	Further studies on Van Allen's hypothesis (the ARGUS project)	G-M tubes, CsI(Tl) and plastic scint.

Sputnik II: november 3, 1957

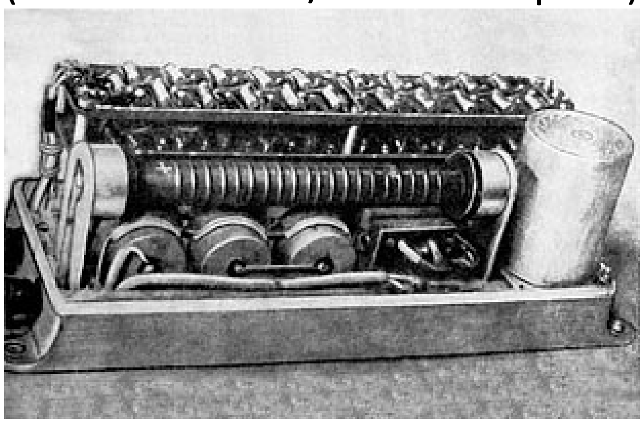


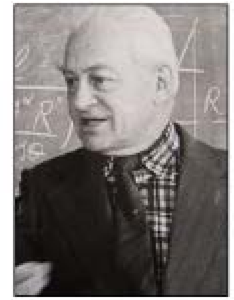
UV-Xray detector



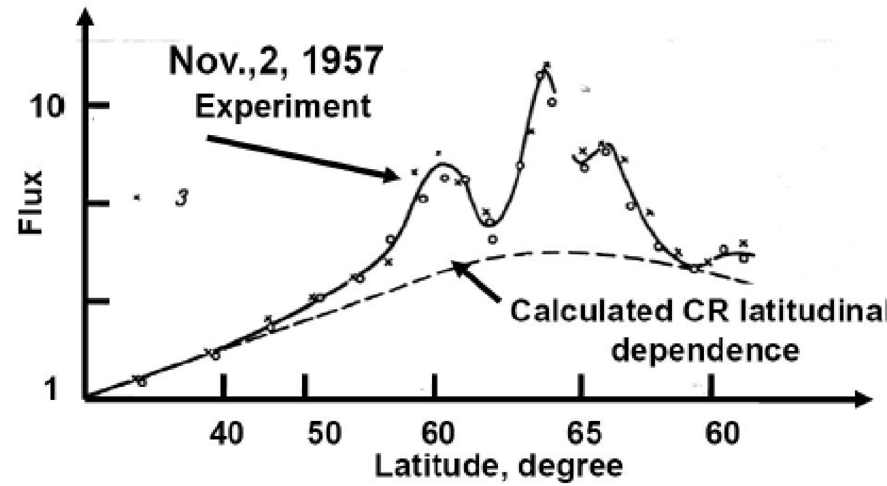
Payload mass: 500 kg

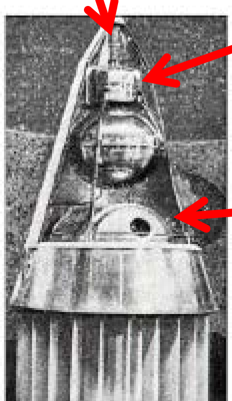
Two Geiger-Muller
10cm long tubes
(first transistors/diodes in space)





S. N. Vernov N.L.Grigorov A.E. Chudakov Yu. I. Logachev

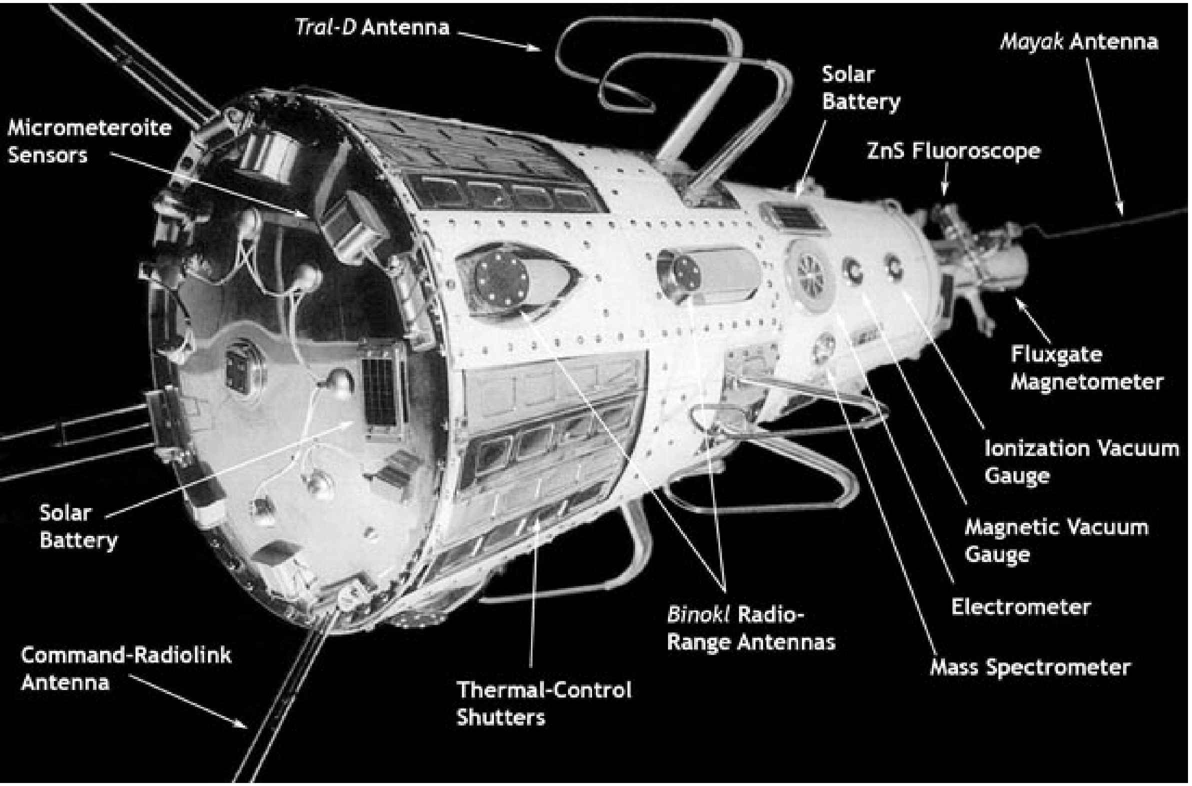


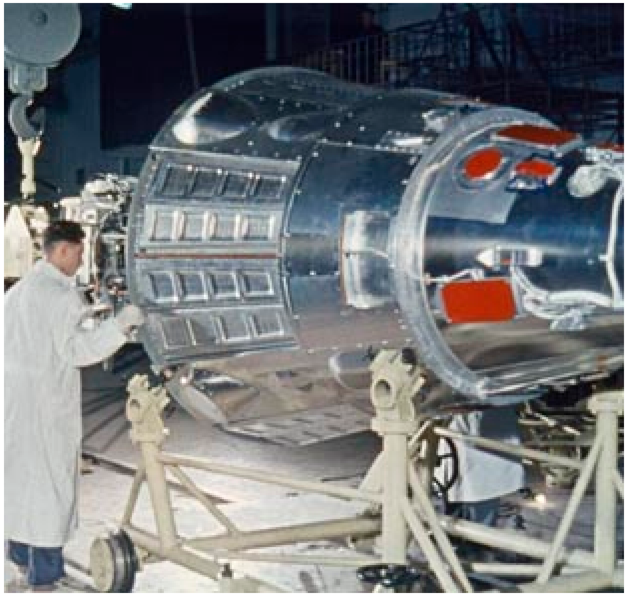


Observed anomaly where we know now that fluctuating outer radiation belt approaches Earth.

No memory elements onboard and information received only above USSR, corresponding to altitudes in the range of 225 to 600 km.

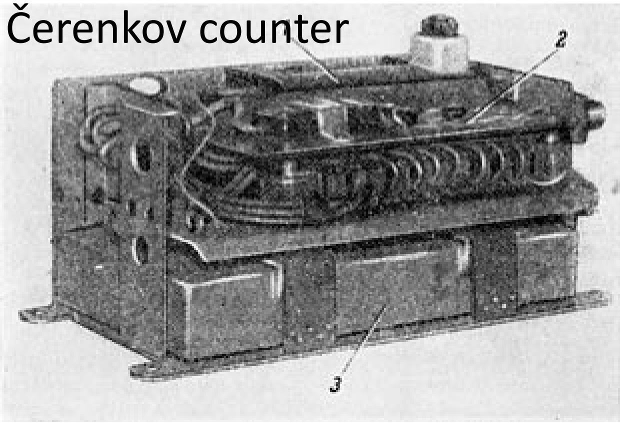
Sputnik III: may 15, 1958



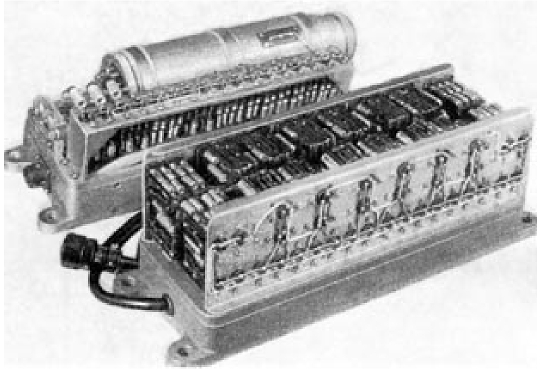


Payload mass: 1300 kg

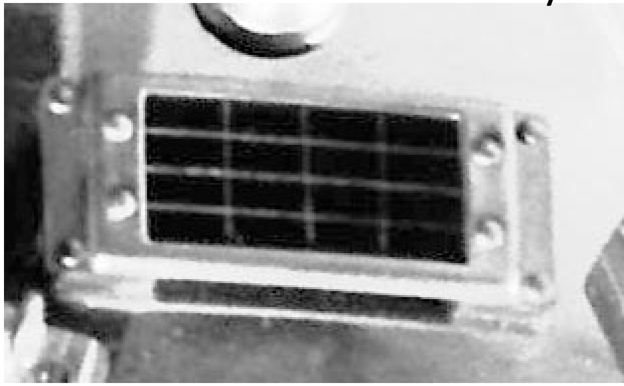
Čerenkov counter



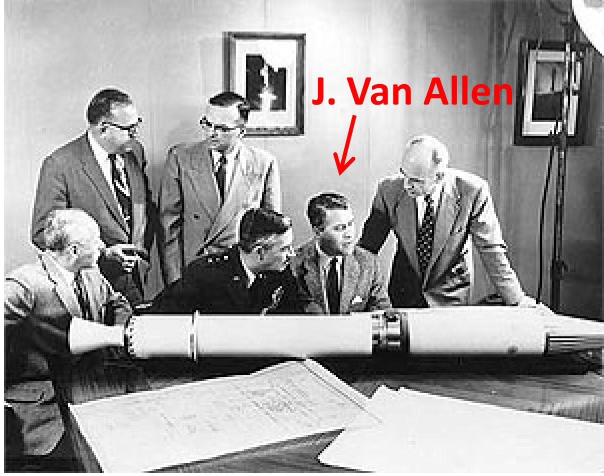
NaI scintillator counters



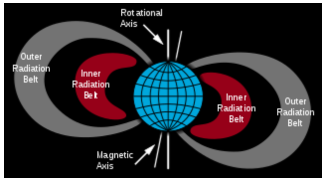
Silicon solar battery



1958:Explorer I,(II),III and… IV



JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 64, No. 8 AUGUST, 1959



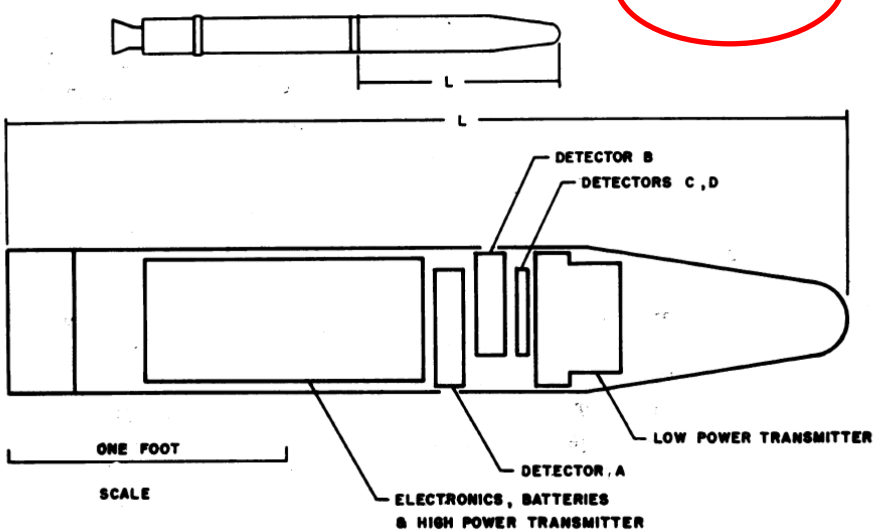
Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field*

JAMES A. VAN ALLEN, CARL E. MCILWAIN, AND GEORGE H. LUDWIG

Department of Physics
State University of Iowa
Iowa City, Iowa

Abstract—Our four radiation detectors in satellite 1958ε (Explorer IV) easily and promptly observed the geomagnetically trapped electrons resulting from the three high-altitude nuclear detonations Argus I, II, and III in August–September 1958. An account of over 160 satellite passes through the three Argus "shells" of artificially injected electrons is given herein, and a preliminary appraisal of the geophysical significance of these experiments is offered.

FIG. 1.—Block diagram of detectors and associated circuitry of Explorer IV.



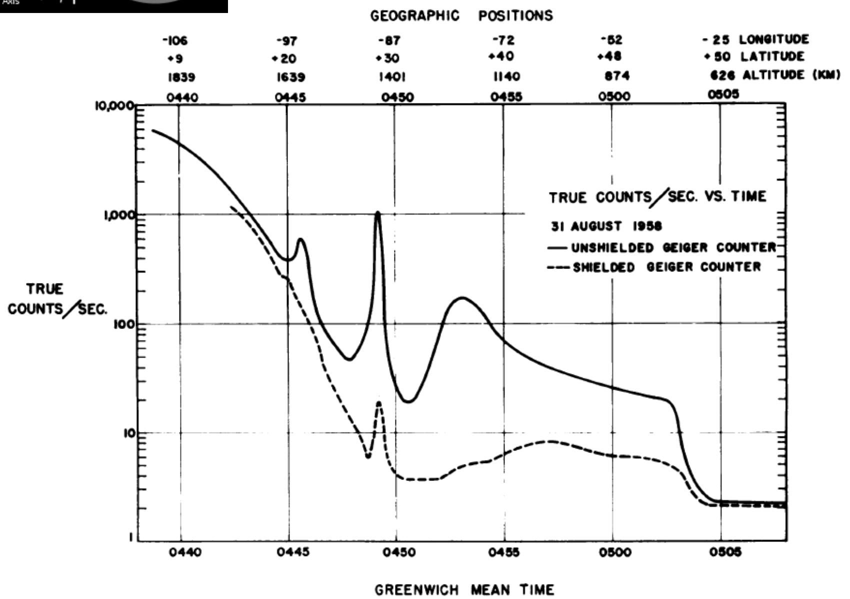


Fig. 8.—A plot of radiation observations on August 31, 1958 showing the decaying Argus I peak (at 0446 U.T.) and the fresh Argus II peak (at 0449 U.T.).

TABLE 2

DATA ON BURSTS

	Argus I	Argus II	Argus III
Nominal yield	1 to 2 kilotons	1 to 2 kilotons	1 to 2 kilotons
Approximate time of burst	August 27, 1958, 0230 U.T.	August 30, 1958, 0320 U.T.	September 6, 1958, 2210 U.T.
Approximate geographic coordinates	38° S, 12° W	50° S, 8° W	50° S, 10° W

Nominal altitude of all bursts ~480 km.

1954-57: The first "ionization" calorimeter

First samples of what we now call "sampling calorimeters" (N. L. Grigorov et al.)

1957: Tests at high altitude EAS arrays in Pamir.

N.L. Grigorov et al. Zh.Eksp.Teor.Fiz.34 (1954)506

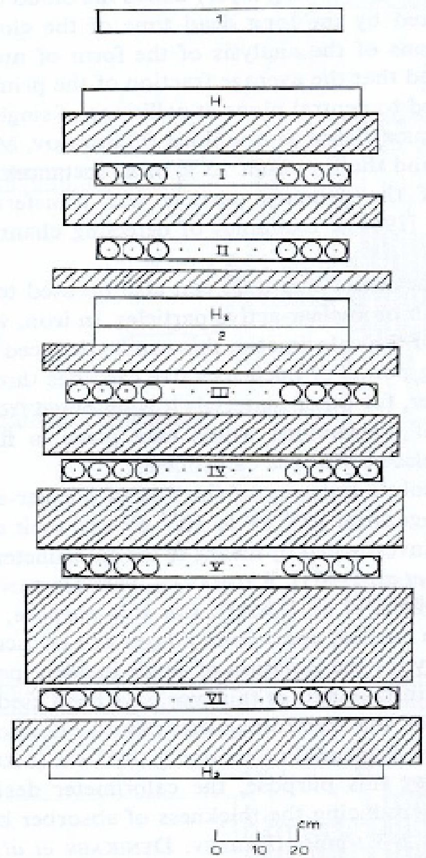
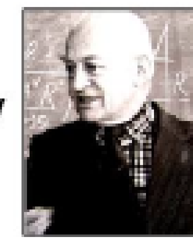


Fig. 14. Schematic diagram of the first ionization calorimeter (Grigorov, Murzin and Rapoport [1958]). The shaded areas represent absorber. Layers 1 and 2 are the rows of counters forming the controlling telescope. Layers H_1, H_2, H_3 are hodoscoped counters, while layers I, . . ., VI are the detectors (ionization chambers) of the calorimeter.

Vladimir Murzin

Naum Grigorov



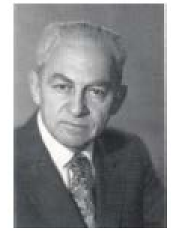
Ilya Rappoport

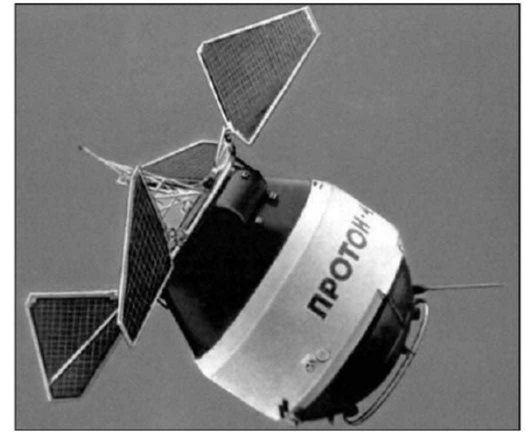
Used in the 1960's in large scale calorimetric experiments in space

1965-68. The Proton satellites

Four heavy satellites of the Proton series.
Proton-4 carried was the IK-15 calorimeter

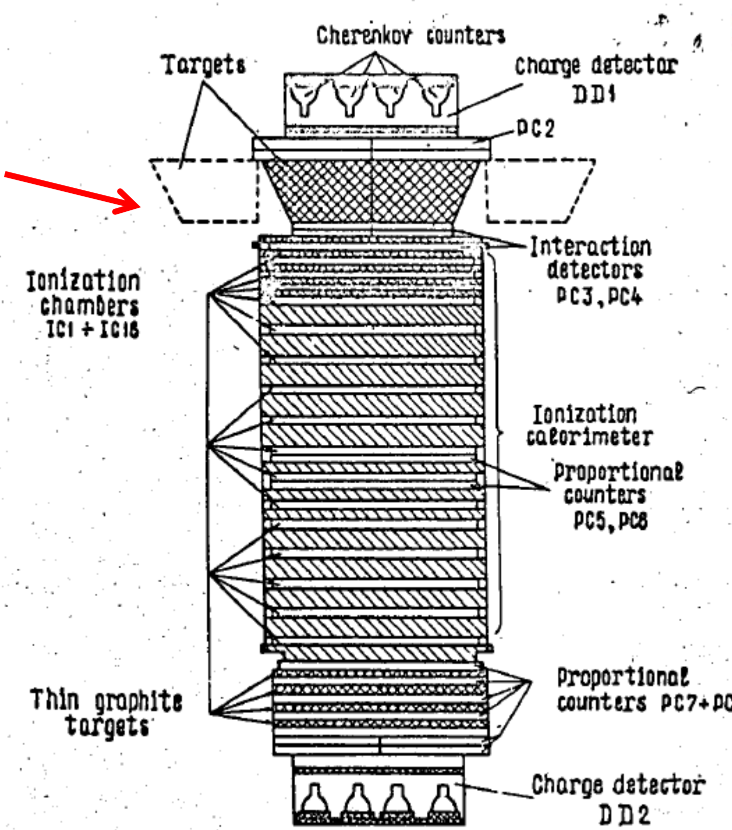

S.N.Vernov

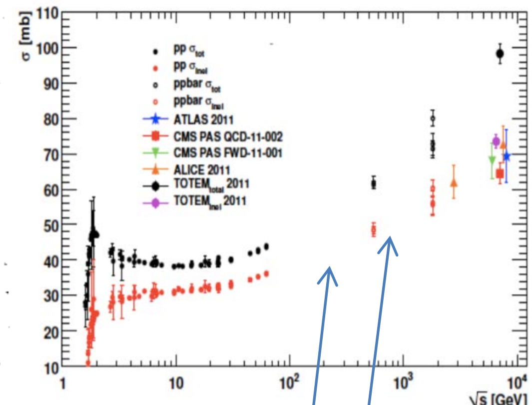

N.L.Grigorov

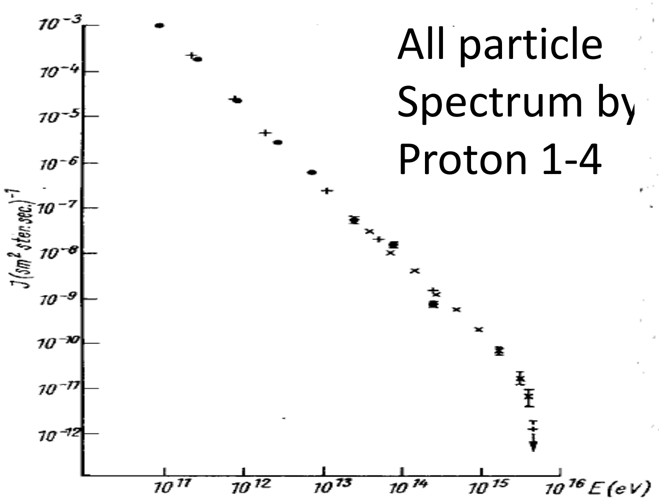


SEZ-14 (an acronym of russian words Spectra, Energy, and Charge, up to 10^{14} eV) : 7 tons

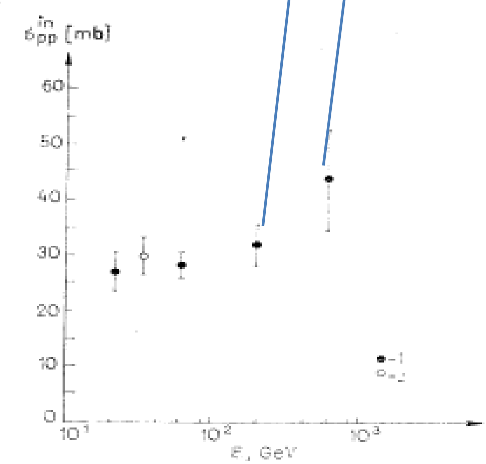
IK-15 (an acronym of russian words Ionization Calorimeter up to 10^{15} eV) : 12.5 tons
Geometric factor 10 times larger than SEZ-14







All particle Spectrum by Proton 1-4



1970: p and He with Calorimeter on a balloon

VOLUME 28, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1972

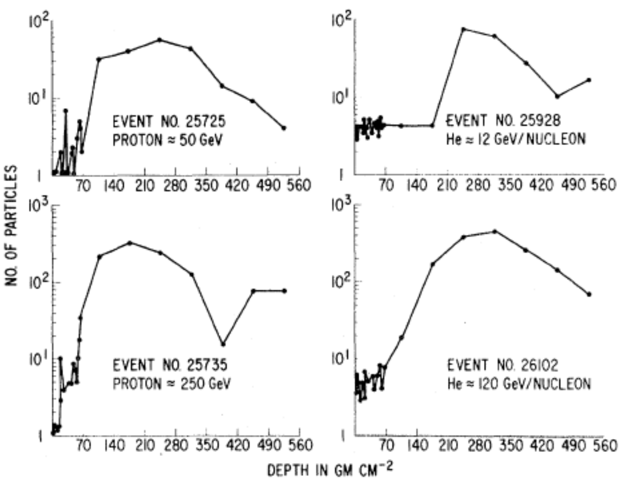
[11]S. C. Freden and R. S. White, J. Geophys. Res. 67, 25 (1962).
[12]W. W. Macy, R. S. White, R. C. Filz, and E. Holeman, J. Geophys. Res. 67, 25 (1962).
[13]T. A. Farley, A. D. Tomassian, and M. Walt, Phys. Rev. Lett. 25, 47 (1970).

The begining of a long series of experiments by GSFC

Cosmic-Ray Proton and Helium Spectra above 50 GeV

M. J. Ryan,* J. F. Ormes, and V. K. Balasubrahmanyan
Goddard Space Flight Center, Greenbelt, Maryland 20771
(Received 25 February 1972)

Differential energy spectra of cosmic-ray protons and He nuclei have been measured for the first time by an ionization spectrometer flown at balloon altitudes. The energy range extended from 50 to >1000 GeV. The observed differential intensities can be represented with power-law spectra with a slope of -2.75 ± 0.03 for protons and of -2.77 ± 0.05 for He nuclei. The proton-to-He ratio is 26 ± 3 at 40 GeV/nucleon and is constant within errors up to 400 GeV/nucleon.



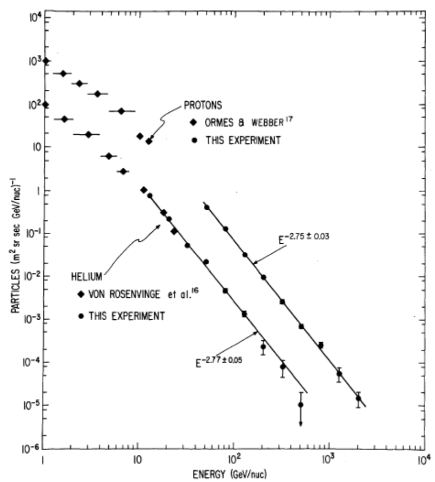


FIG. 2. Examples to show the development of nucleonic cascades in the spectrometer. The showers reach a flat maximum and generally decay away. Though individual shower curves fluctuate a great deal, most of this is because of the location of the first interaction. The area enclosed by the shower curves gives a good measure of the total energy of the incident particle.

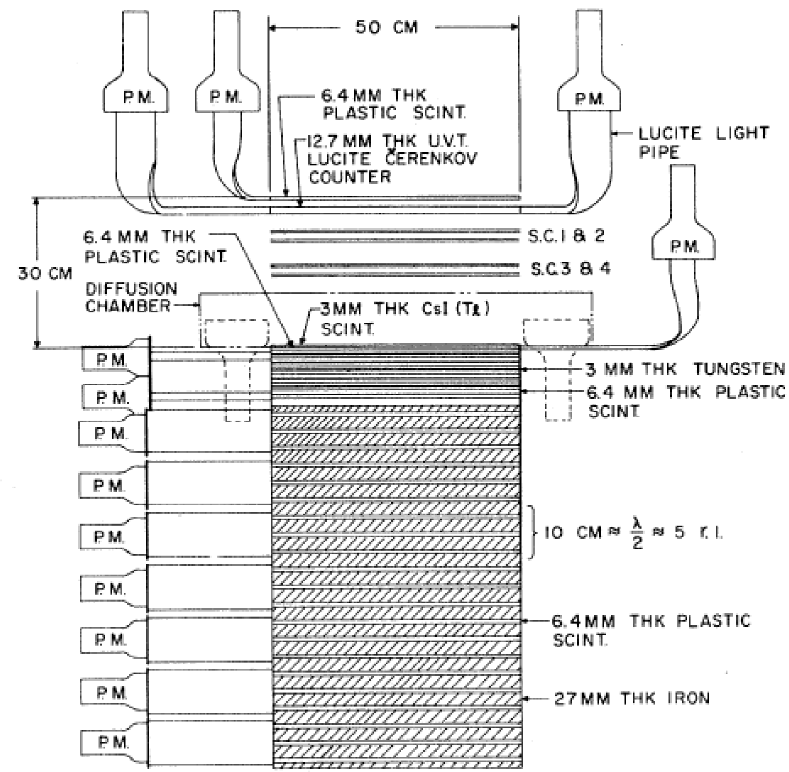


FIG. 1. Balloon-borne ionization spectrometer. SC_1, SC_2, SC_3, and SC_4 are wire-grid spark chambers with core readout to determine the trajectory of the incident particle and to help in rejecting background events. The detector system was designed so that a very wide range of charges and energies could be measured with a single instrument.

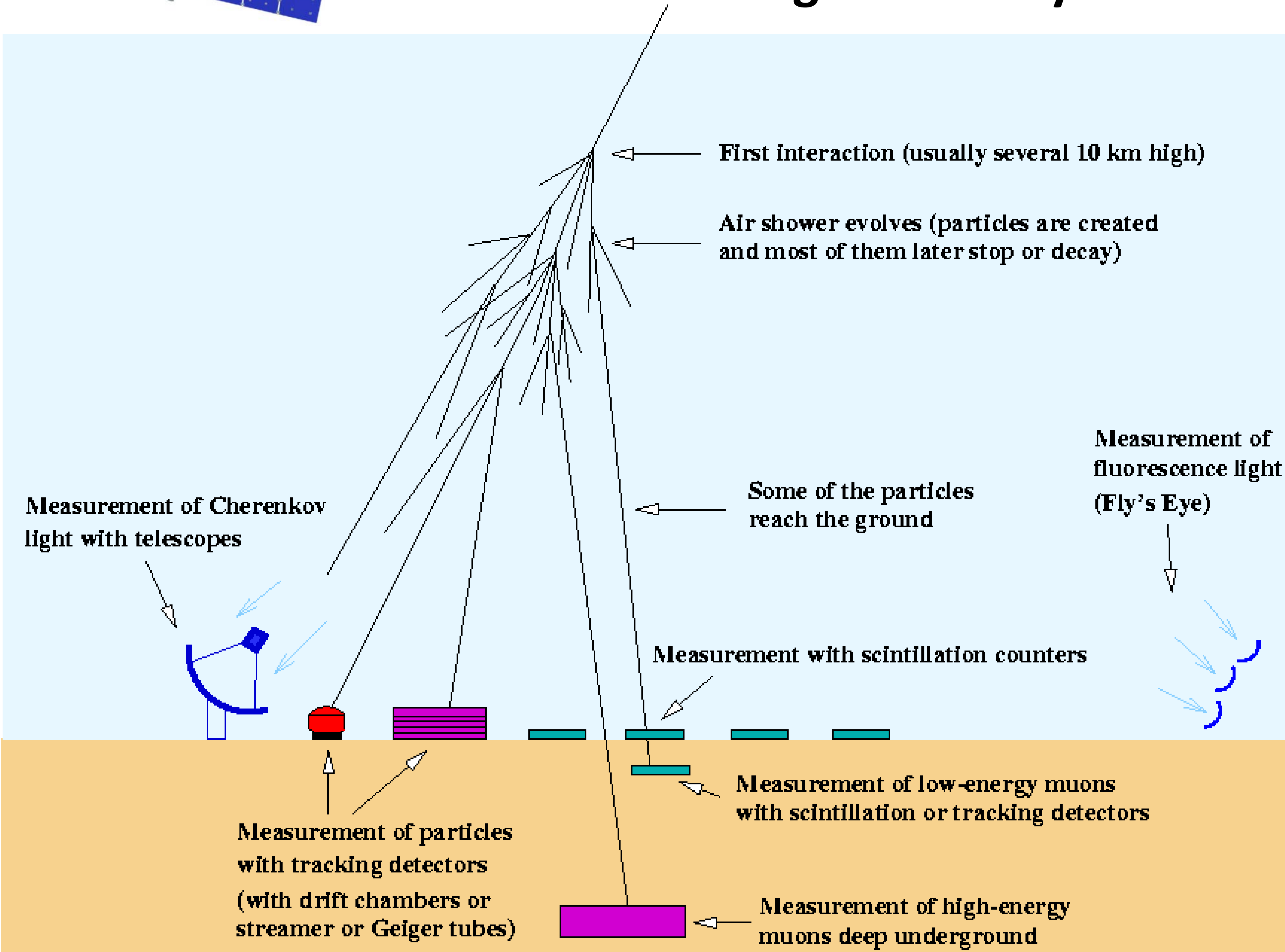
Basic questions

- What are the sources of cosmic rays ?
- How cosmic accelerator work ?
- What happens during cosmic ray propagation ?
- ………..

Observable quantities

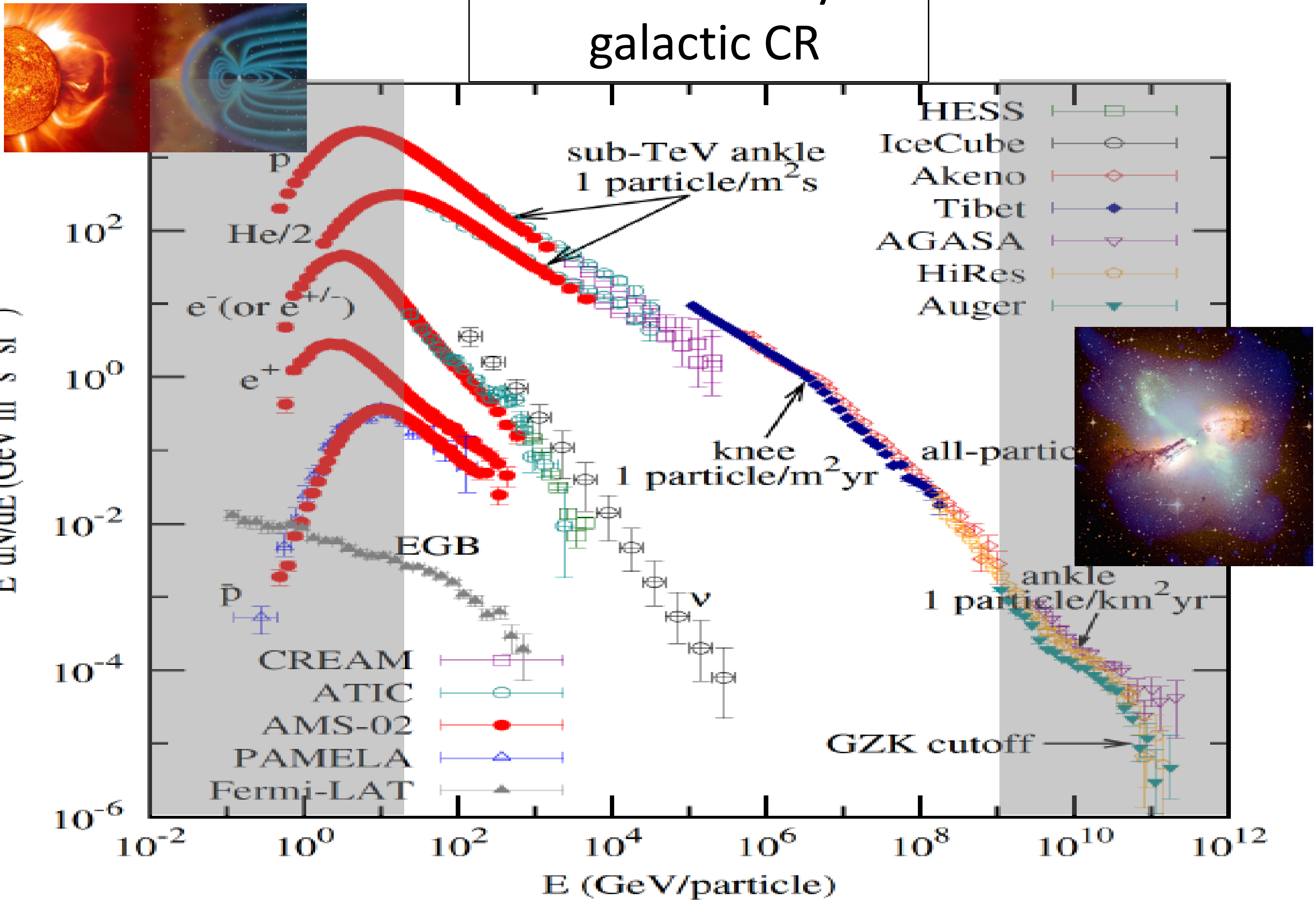
- Energy spectra
- Arrival directions
- “Chemical” composition
- ………..

Measuring cosmic rays….

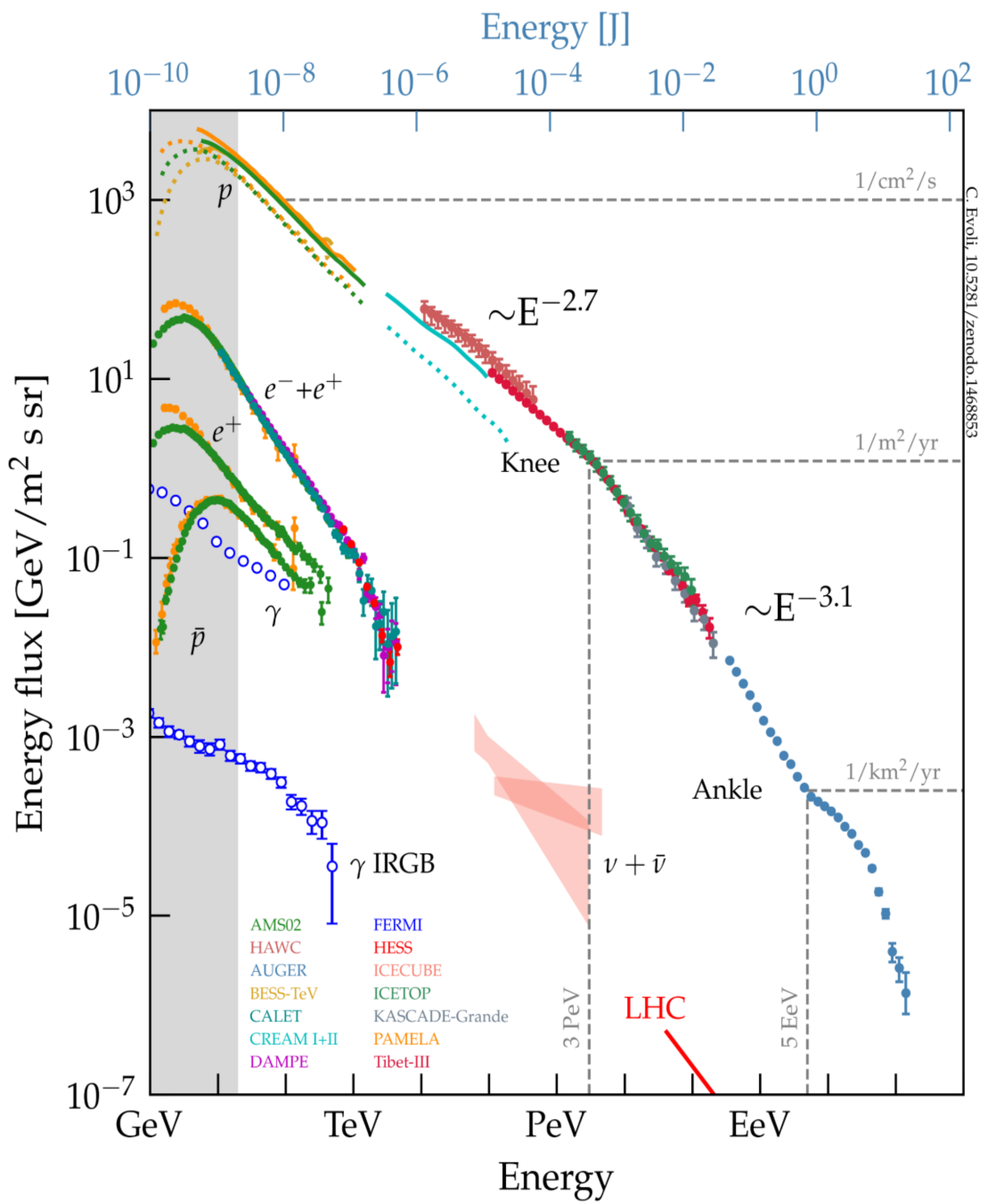


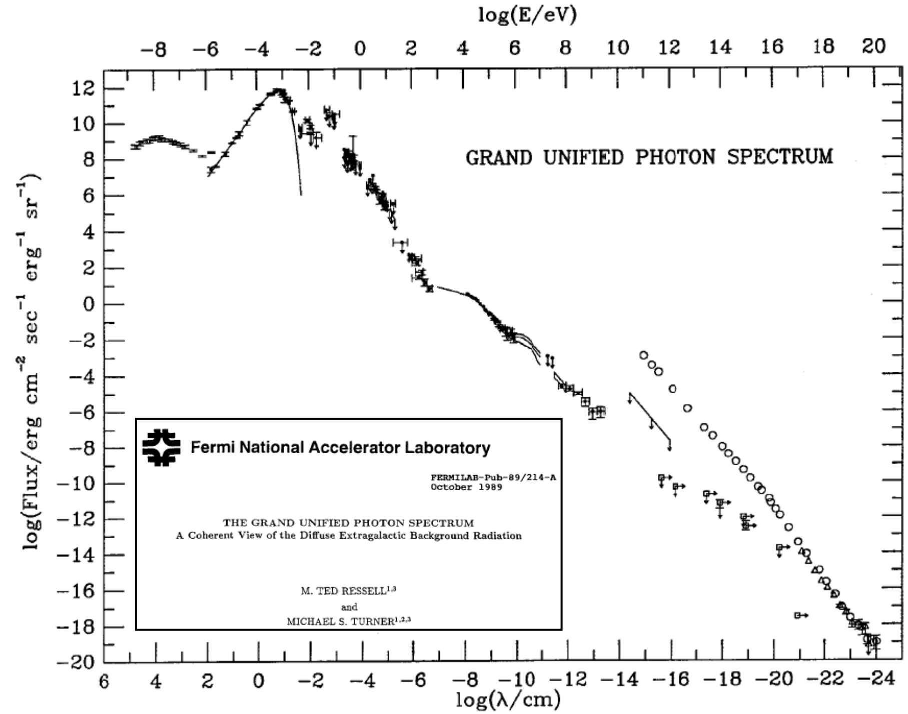

羊八井宇宙线观测站 ARGO
ARGO LABORATORY O
TST 208
16 Dec/06
MACRO

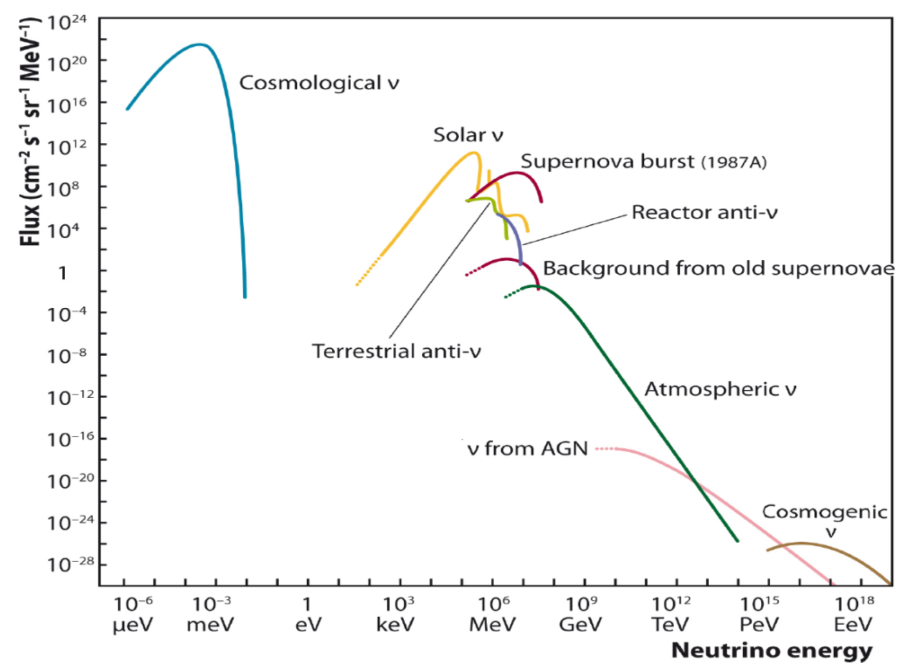
Unbiased study of galactic CR



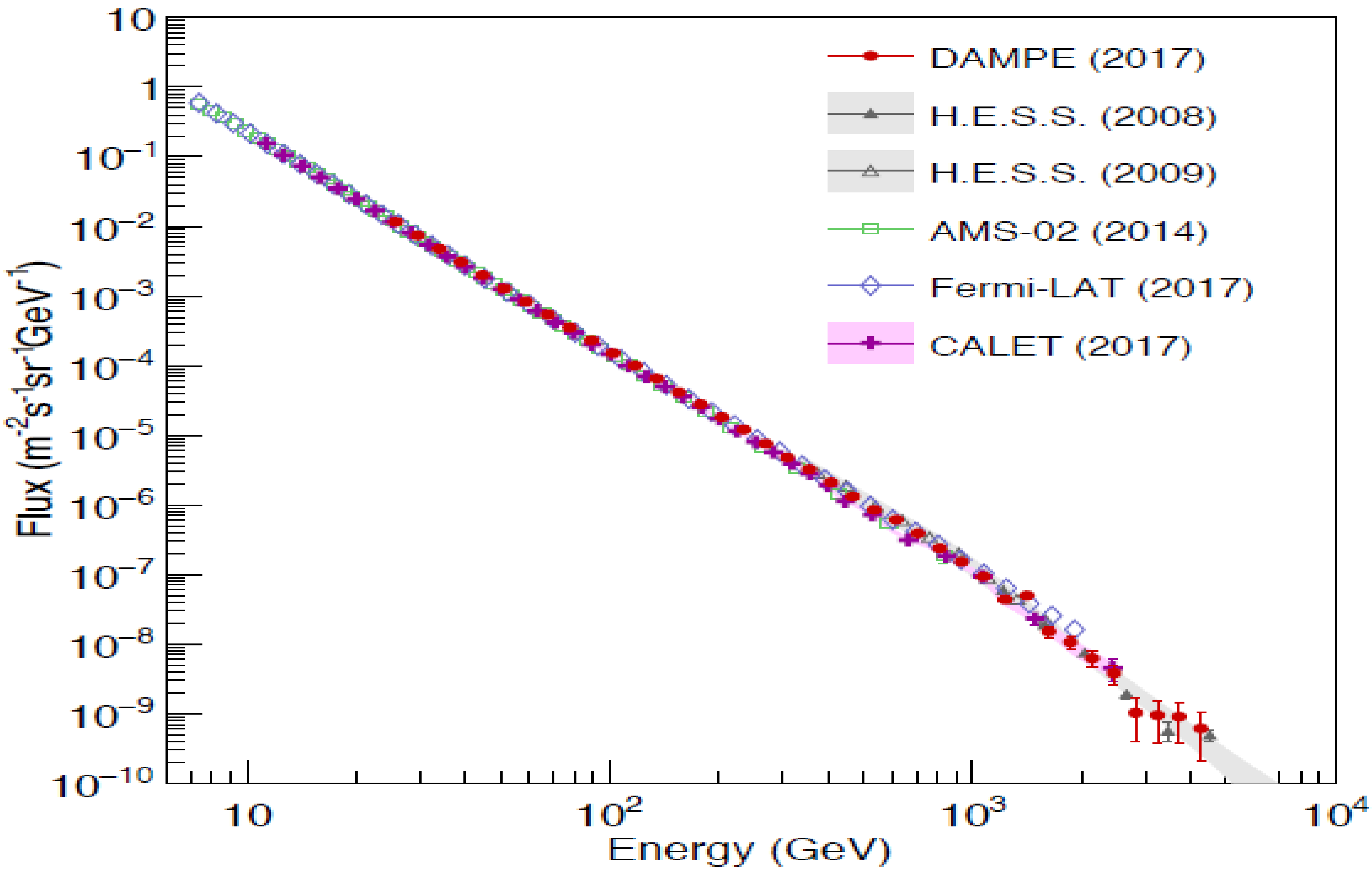
Our landscape(s)



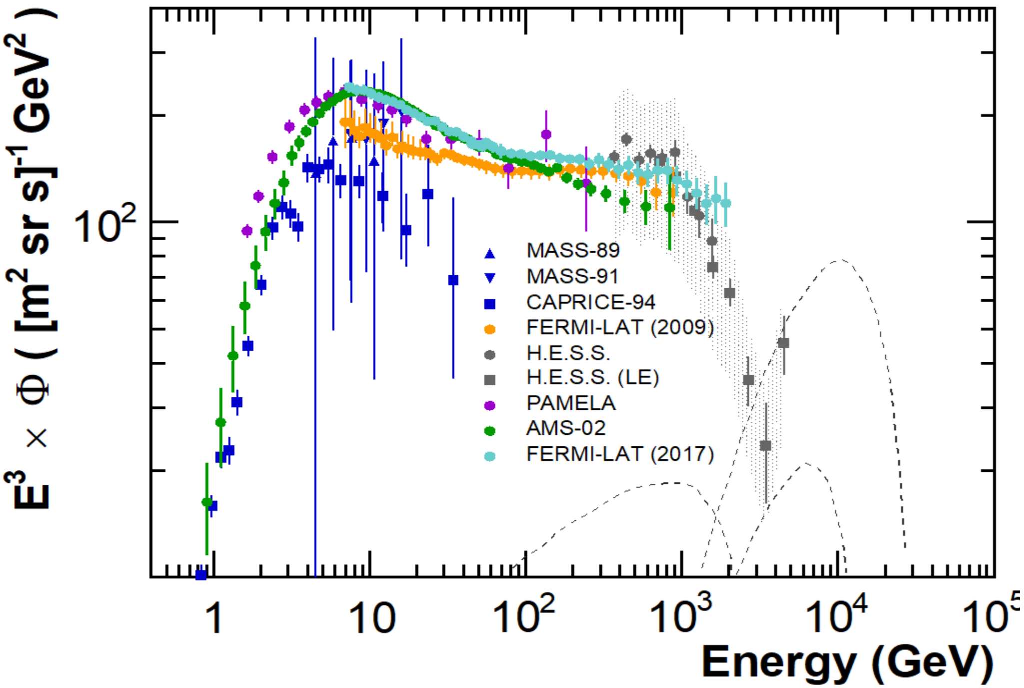


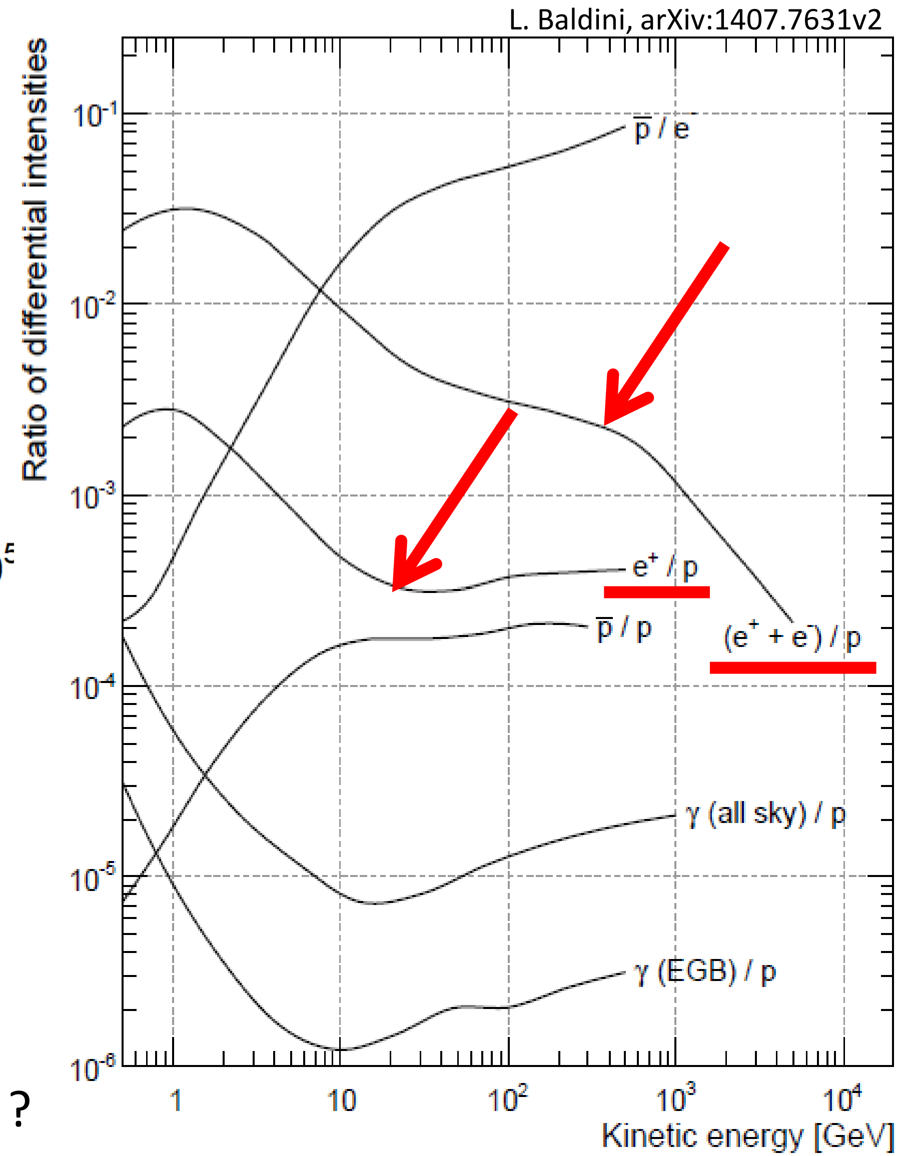


The electron+positron flux



The electron + positron signal (5yrs ago)





- Small fluxes and ~ E^{-3} spectra
- Cut-off at about 1 TeV ?

TeV sources:

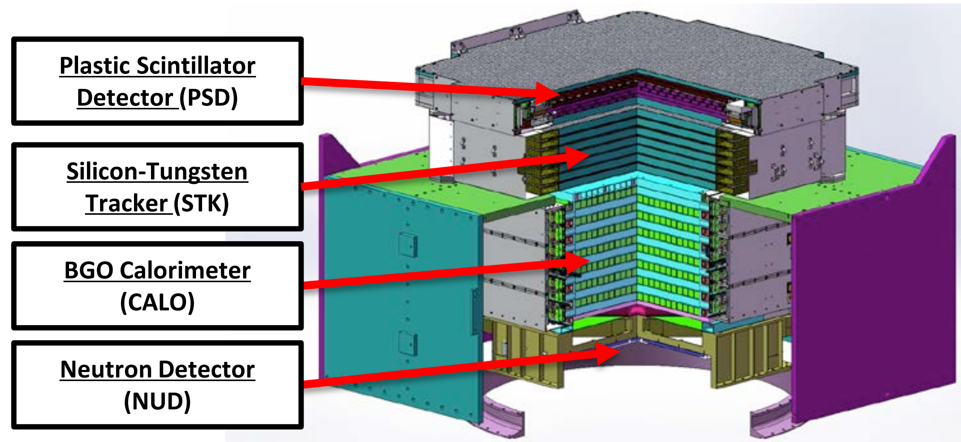
- T < 10^5 yr and D < 1 kpc
- Nearby CR sources: large anisotropies ?
- Contributions from DM annihilation/decay ?

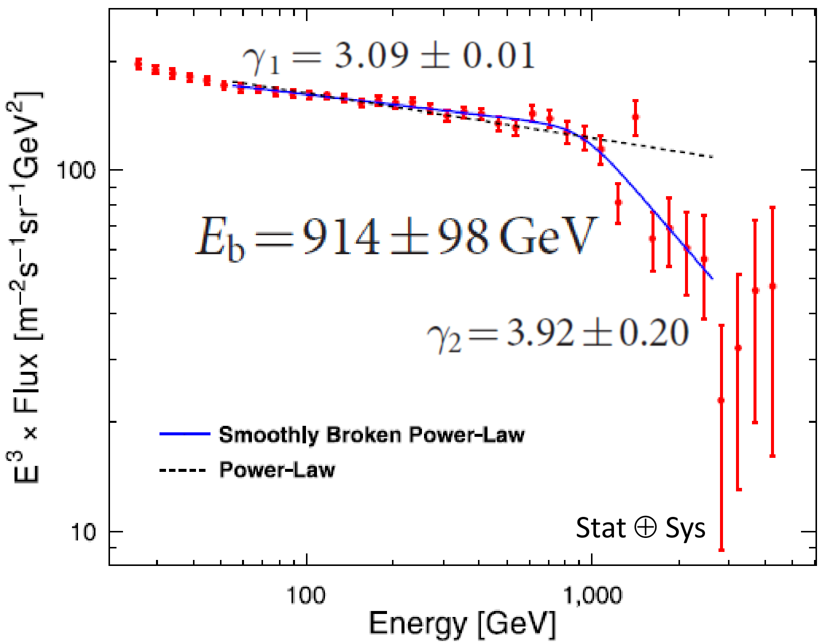
Nov 29, 2017: first DAMPE result

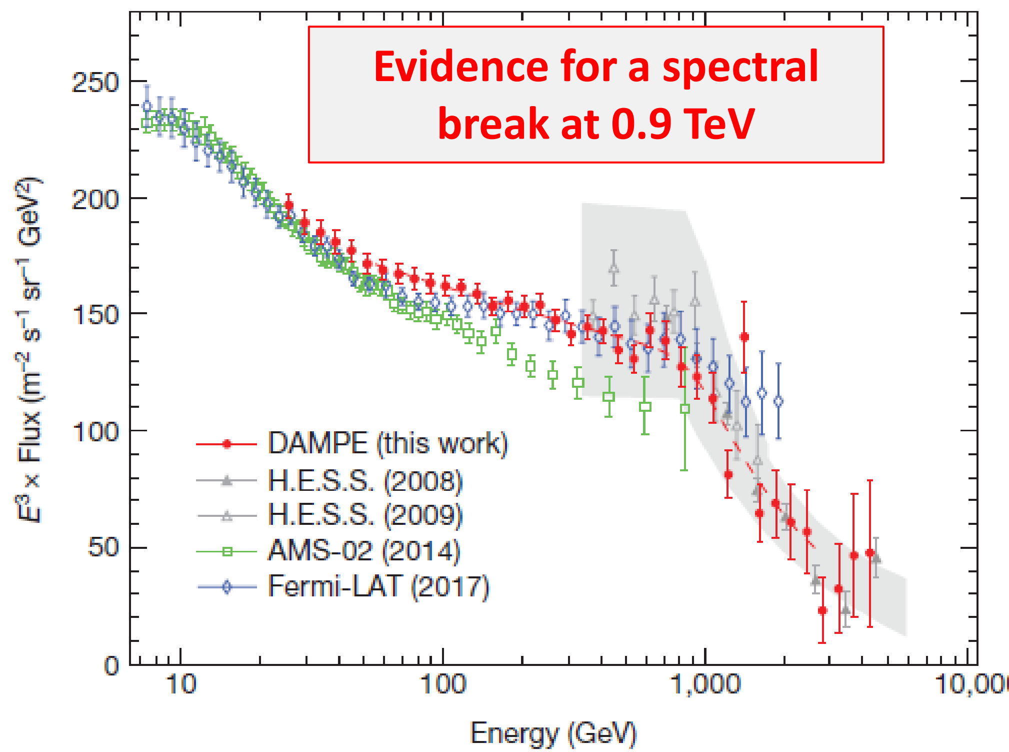
LETTER nature International weekly journal of science
doi:10.1038/nature24475

Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons

DAMPE Collaboration*

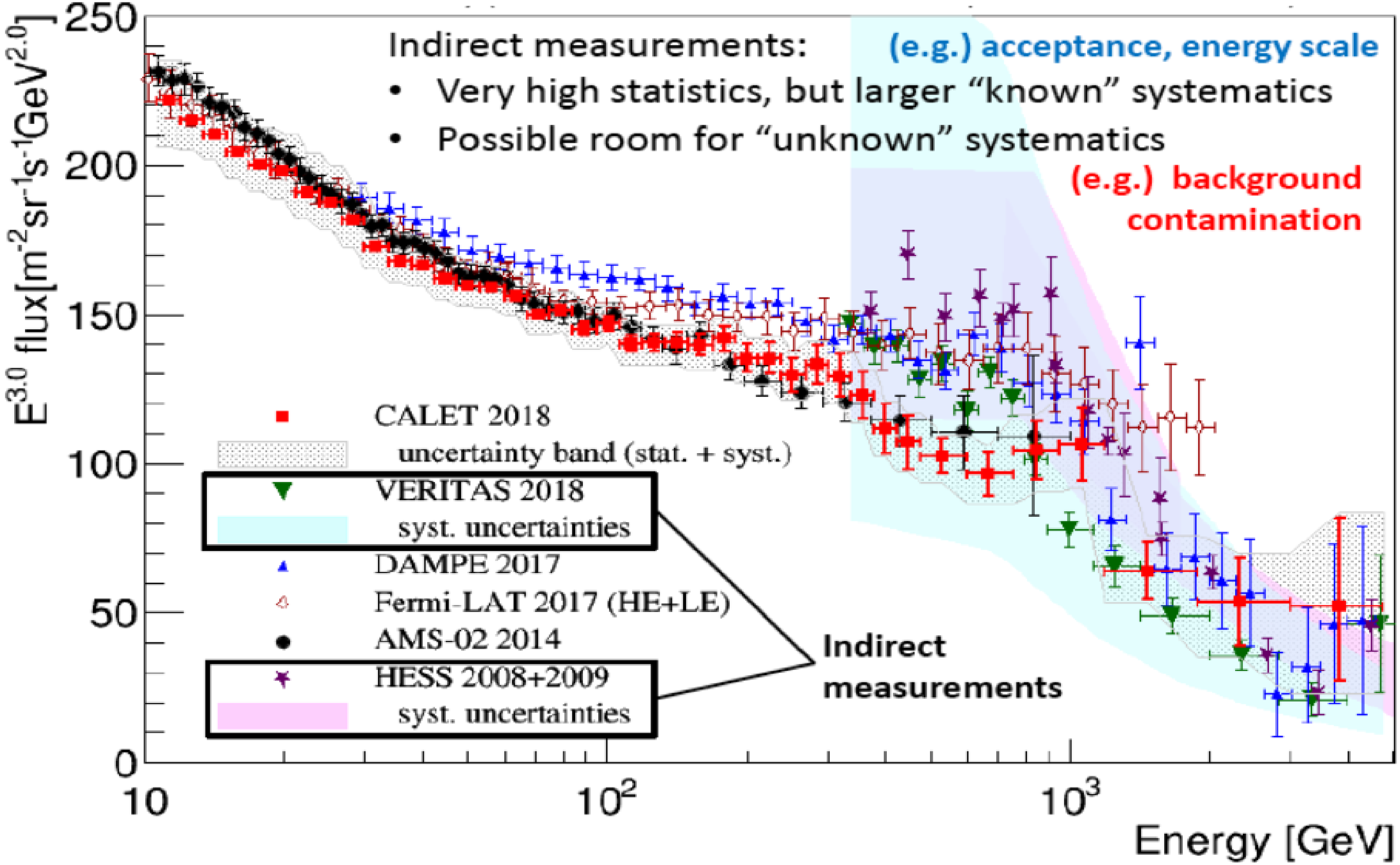




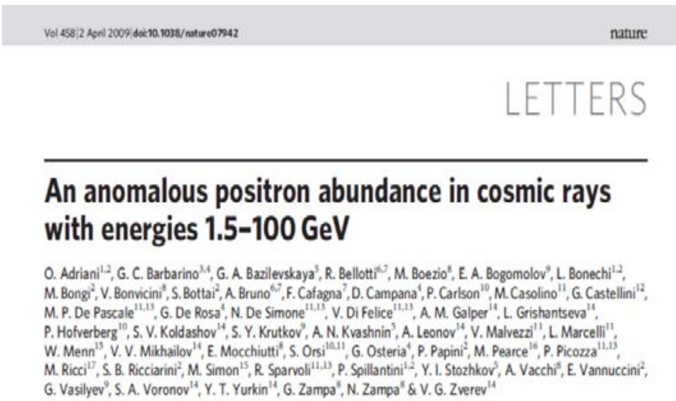


- 530 days
- 2.8 billions CR events
- 1.5 million CREs above 25 GeV

The all-electron flux today



Antimatter: the positron fraction

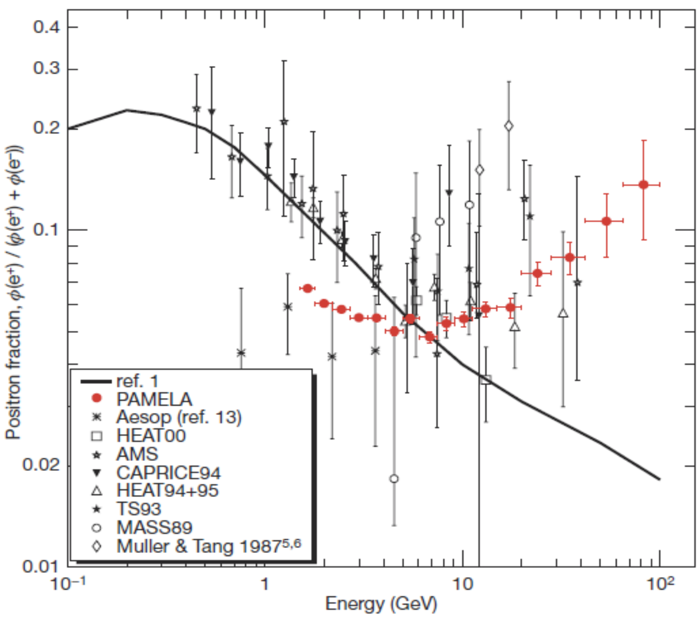


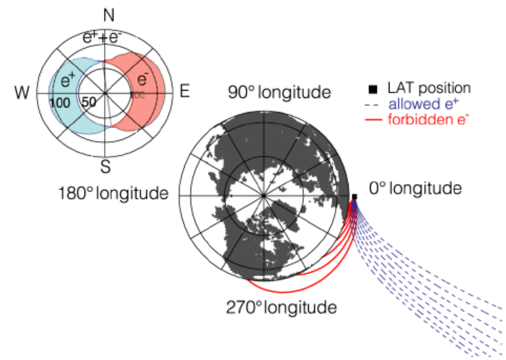
Vol 458 | 2 April 2009 | doi:10.1038/nature07942 nature

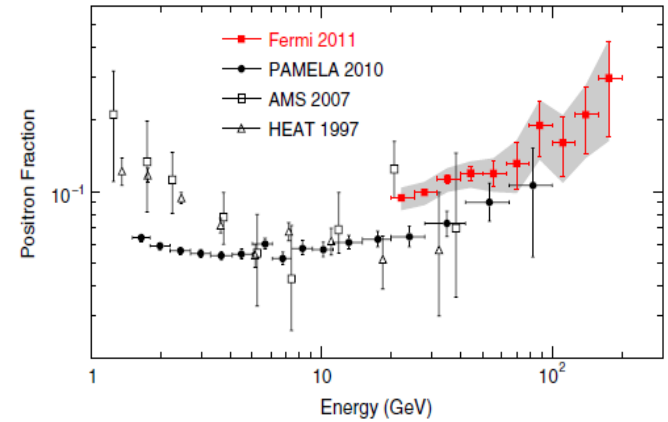
LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]



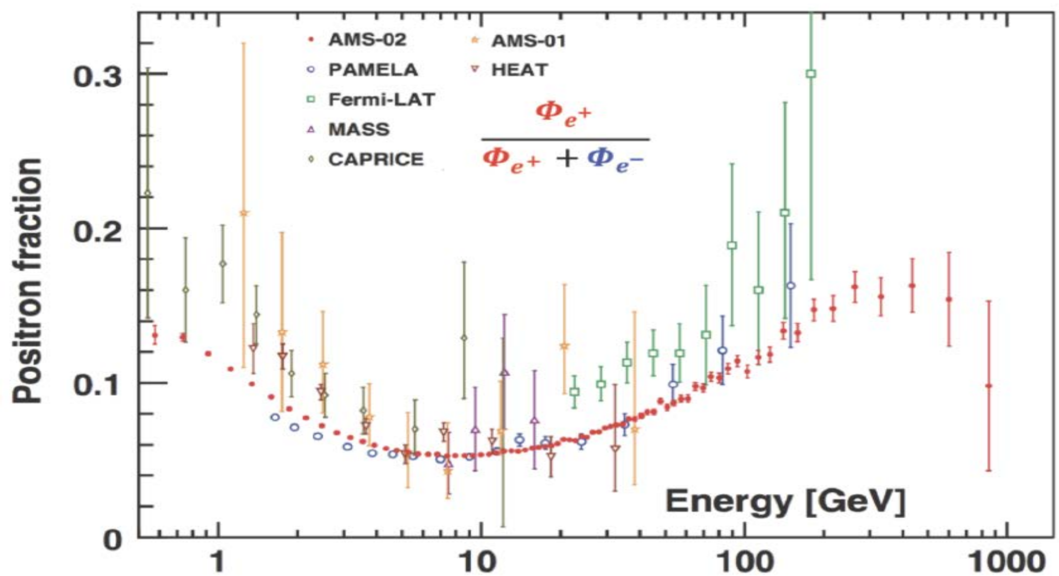




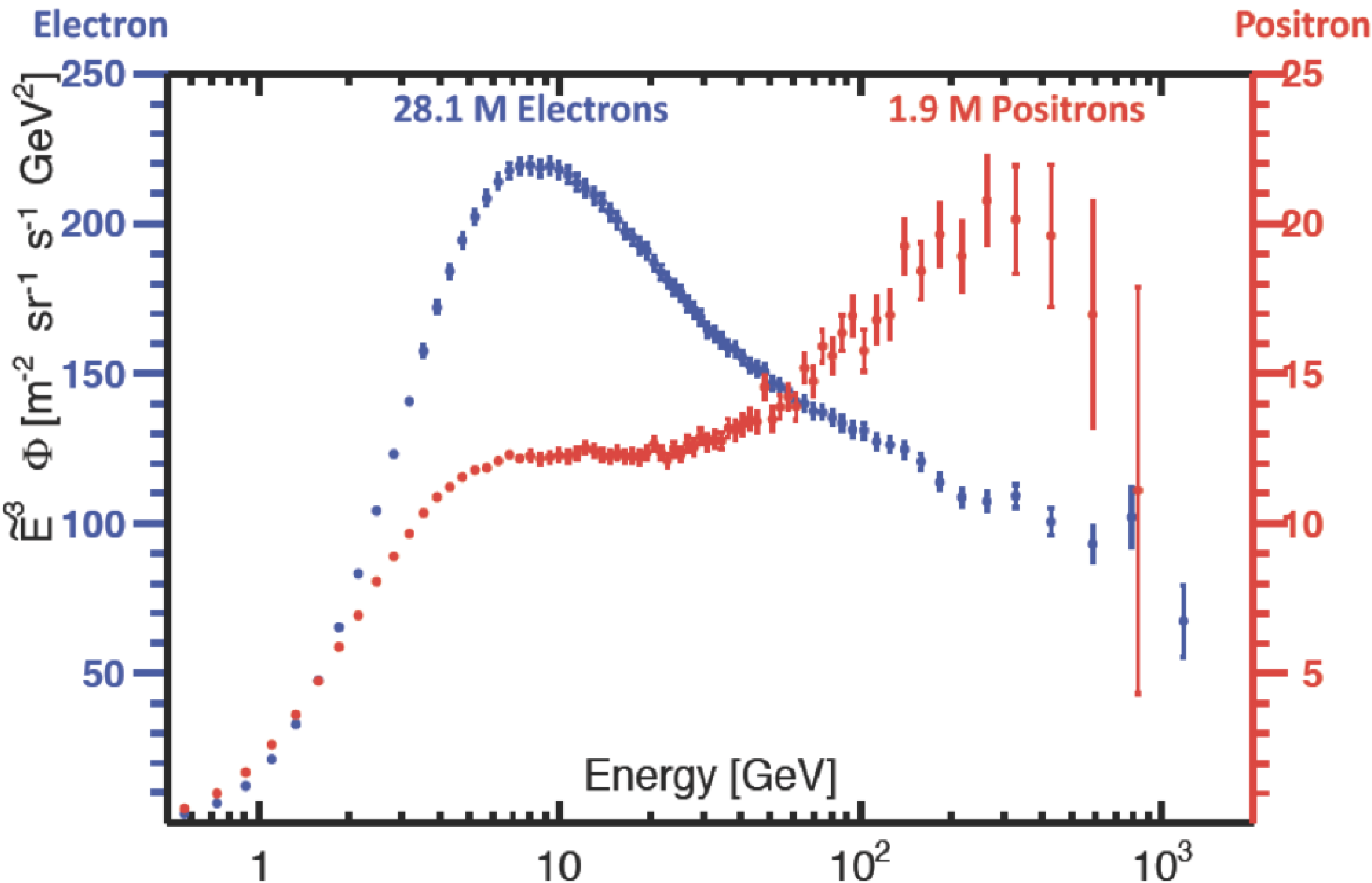
First "anomalous" results from PAMELA (april 2009)

FERMI contribution, even with large systematics.

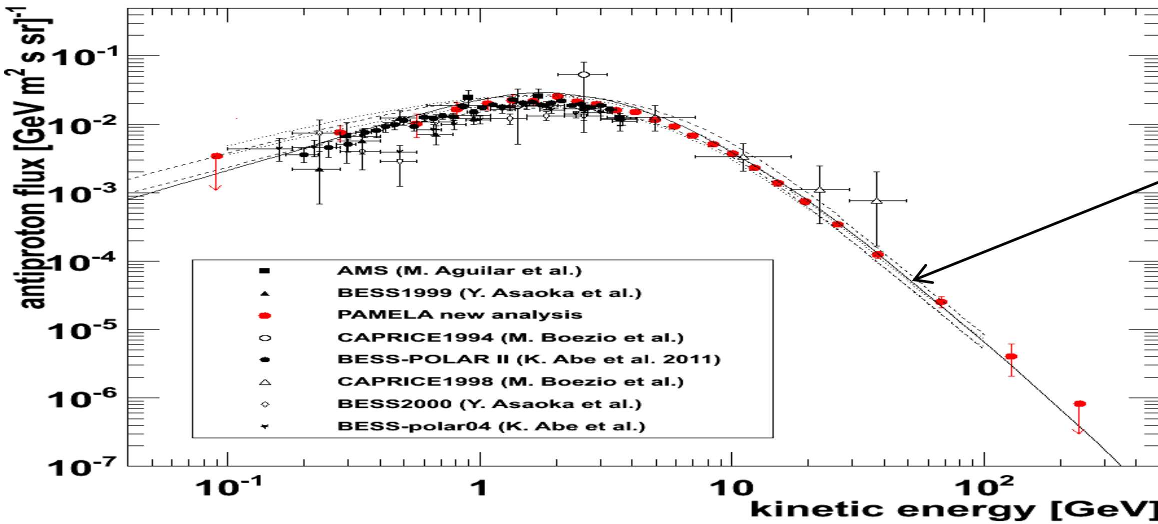
Extended and precise measurements by AMS-02



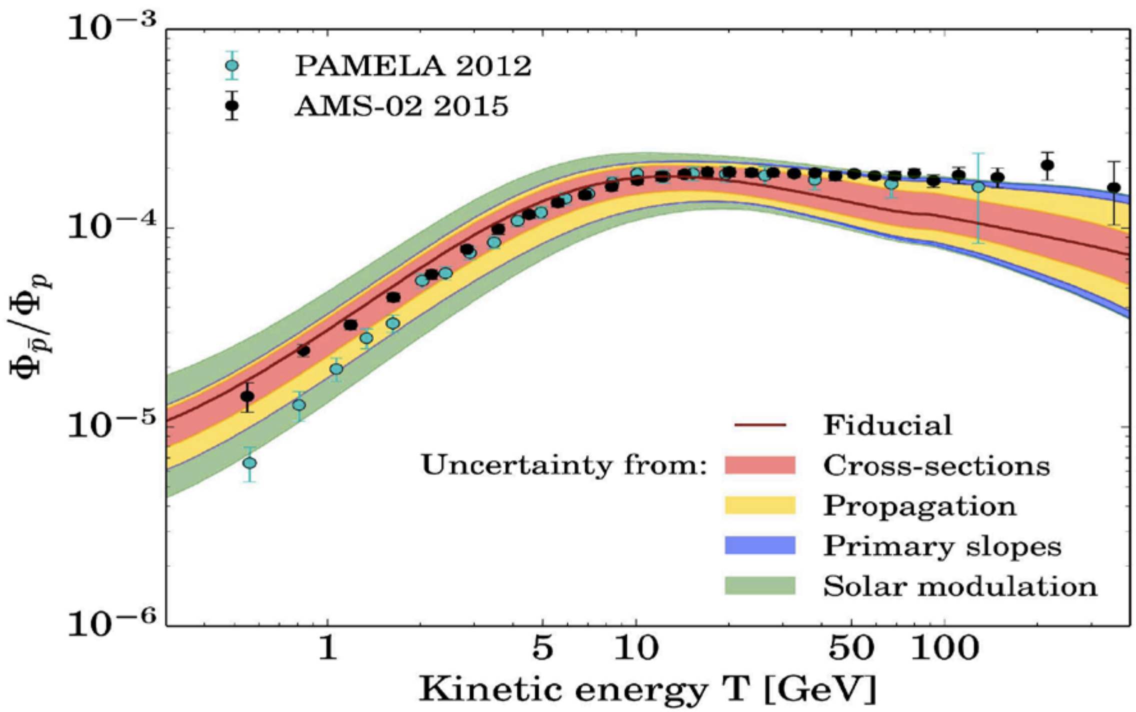
The e+ and e- fluxes with AMS-02



Antimatter: antiprotons

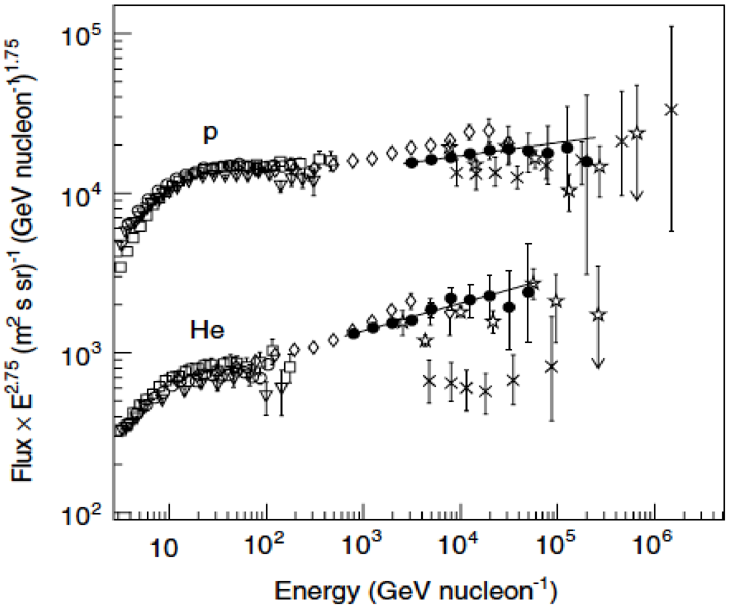


Antiproton flux consistent with secondary production calculations



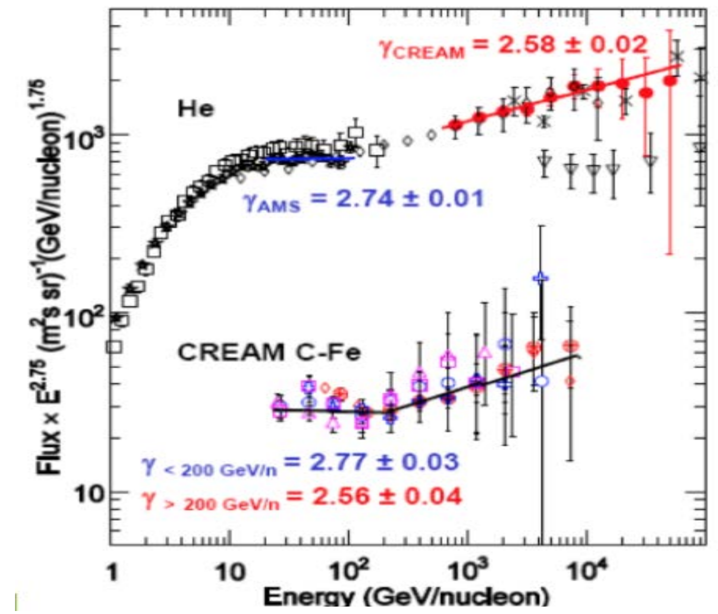
New measurements at accelerators (e.g. LHCb) in order to lower the systematic uncertainty on secondary production calculations

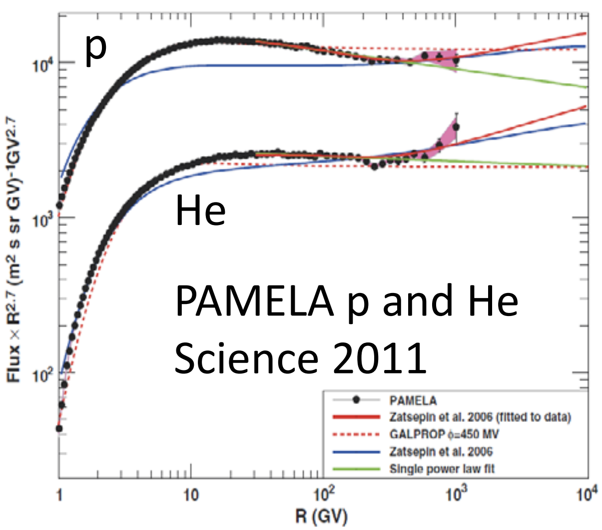
Proton and helium: (discrepant) hardenings



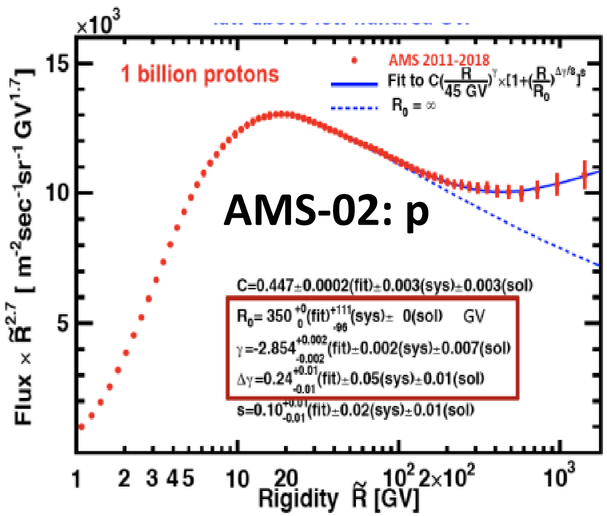
CREAM
First hints for Hardenings.

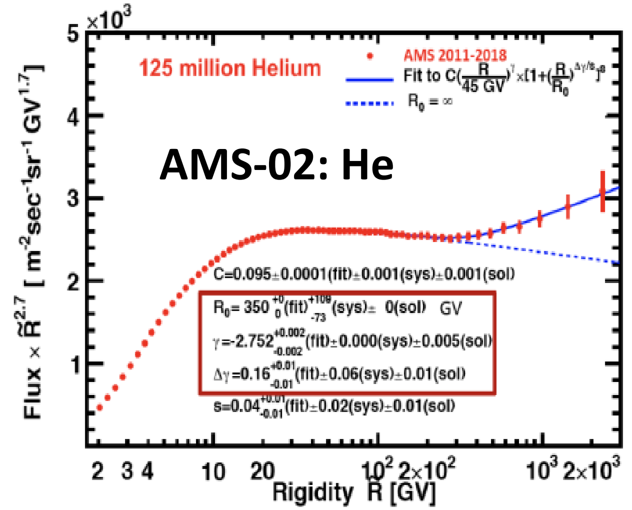
PAMELA and AMS
Direct detection fo the break at about 250GeV/n



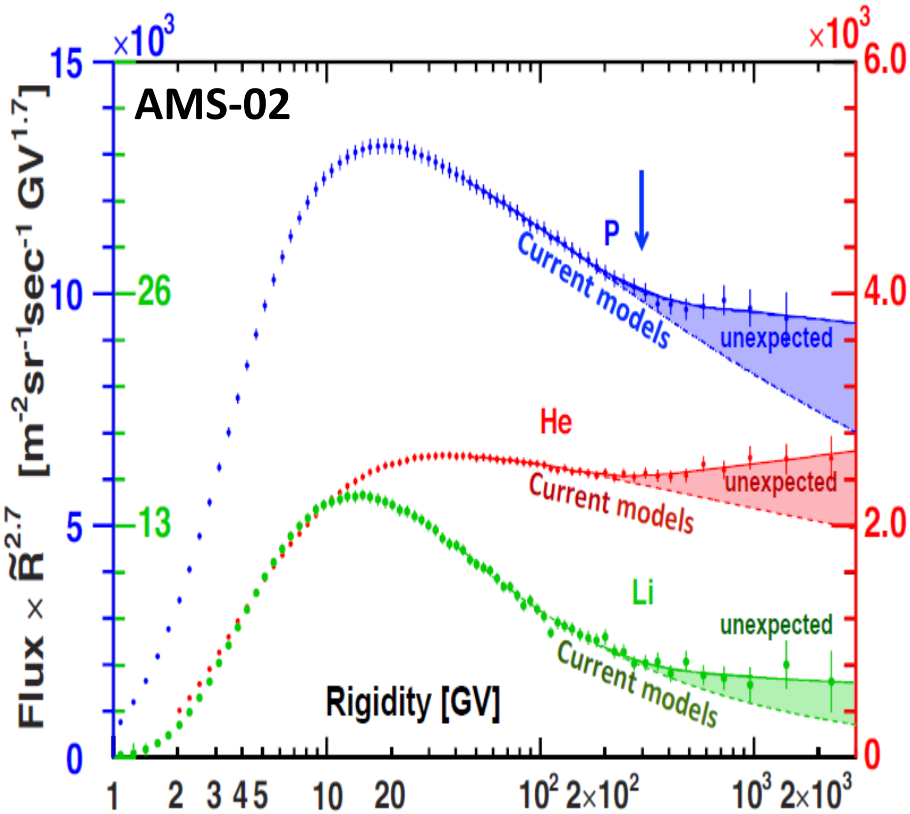


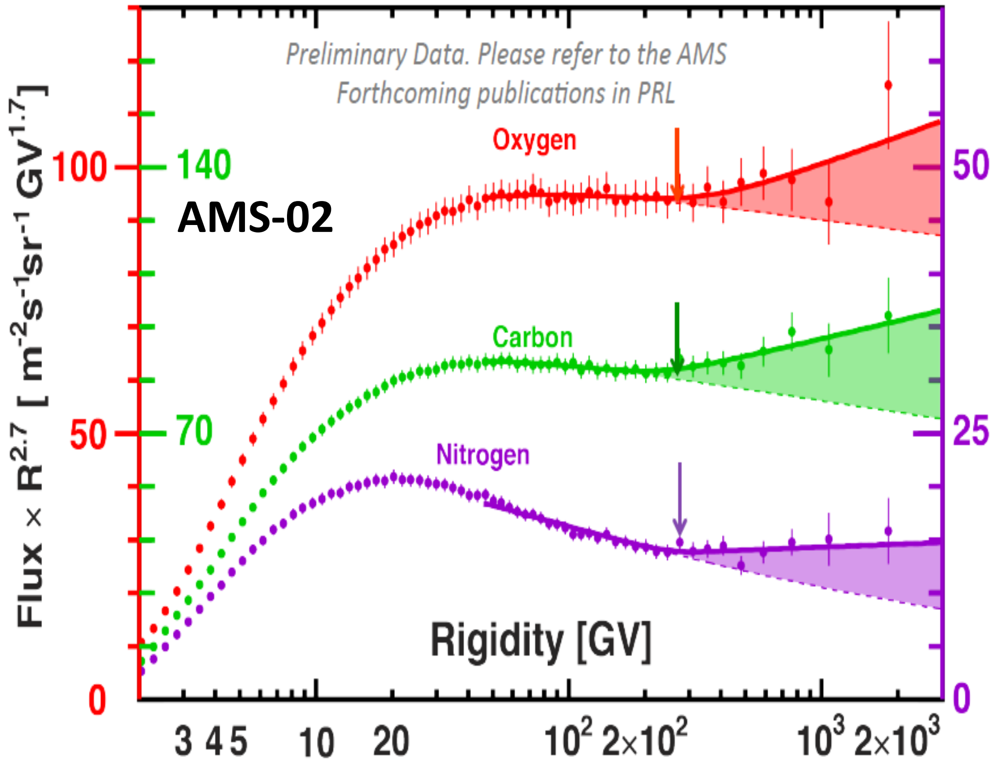
PAMELA p and He
Science 2011





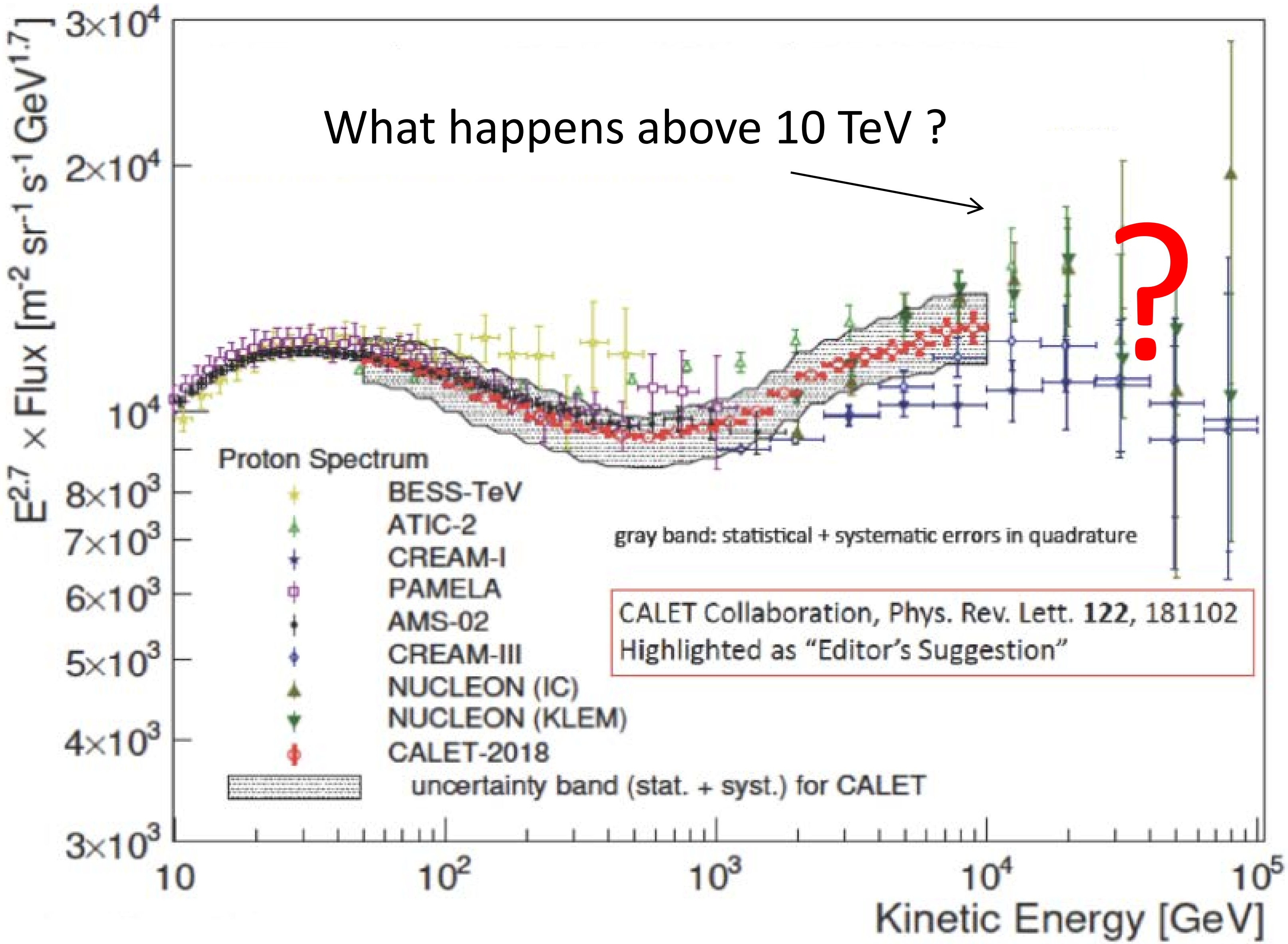
Similar hardenings for other nuclei





Acceleration or propagation effect ? Both ?
Need for precise measurements of secondary productions (B/C,..)
and
extensions in the 1-100 TeV energy region with large acceptance (an good resolution) calorimeters in space

CALET confirmation of the p hardening



CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as "Editor's Suggestion"

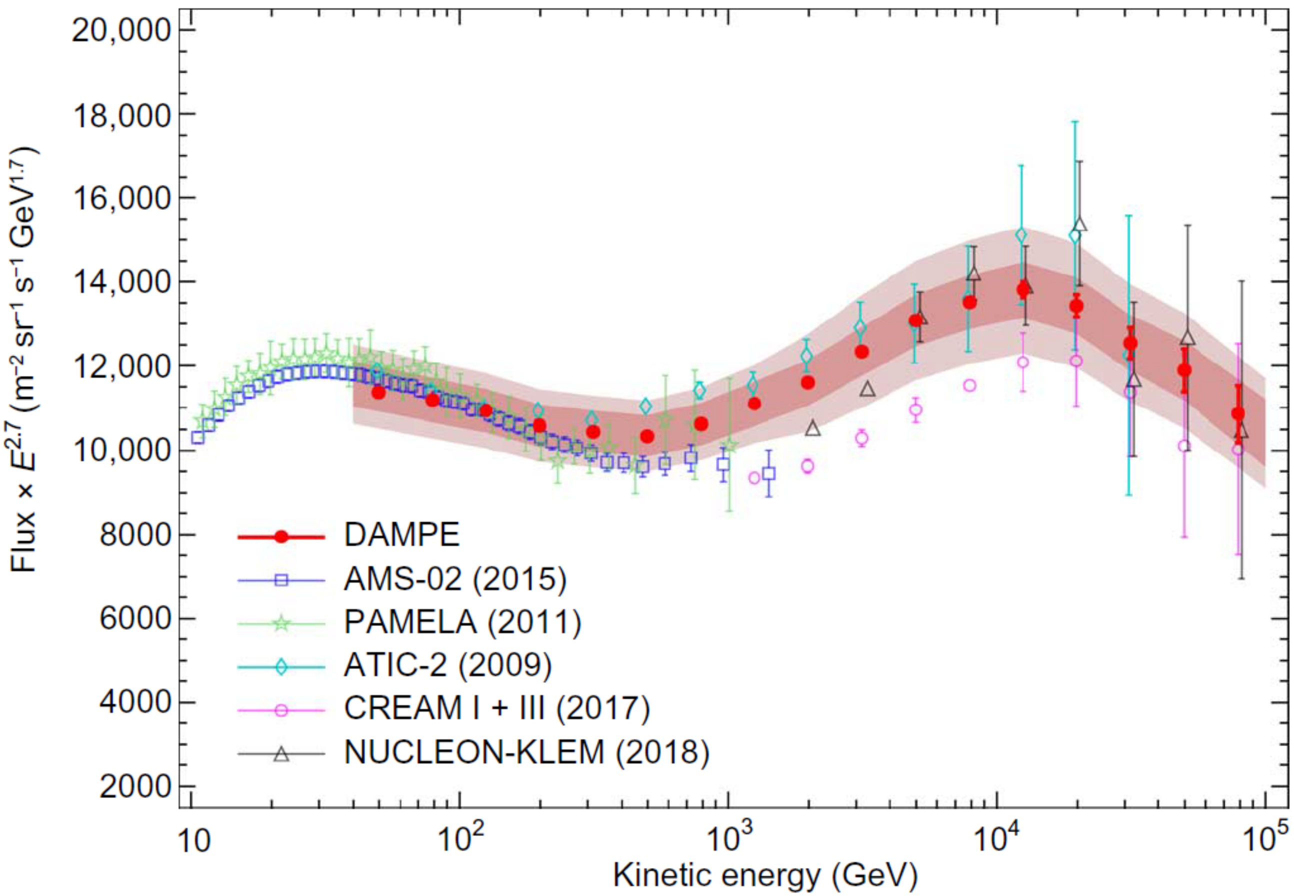
New findings by DAMPE: protons

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

September 27, 2019

Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite



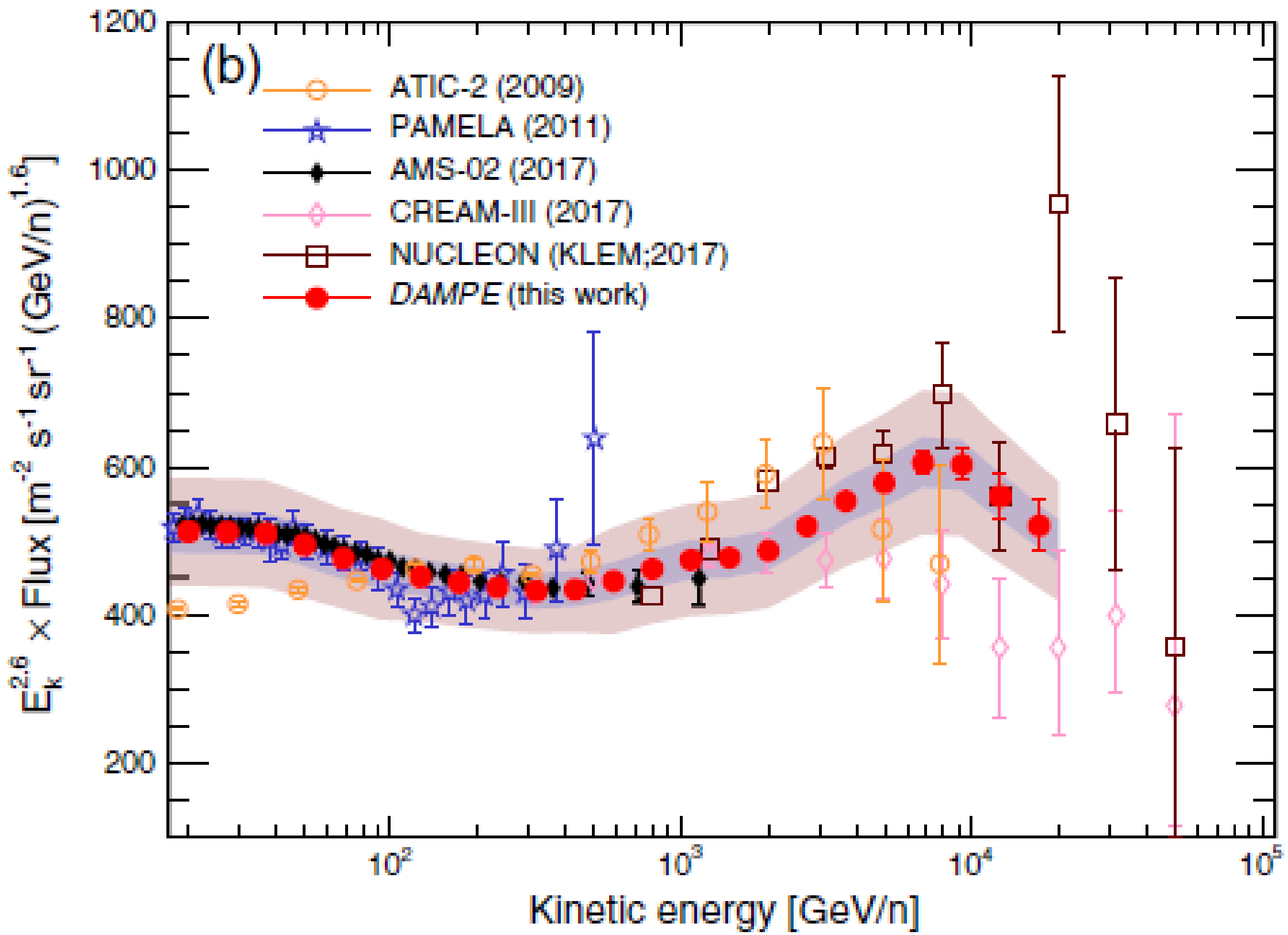
New findings by DAMPE: helium

PHYSICAL REVIEW LETTERS **126,** 201102 (2021)

Editors' Suggestion **Featured in Physics**

Measurement of the Cosmic Ray Helium Energy Spectrum from 70 GeV to 80 TeV with the DAMPE Space Mission

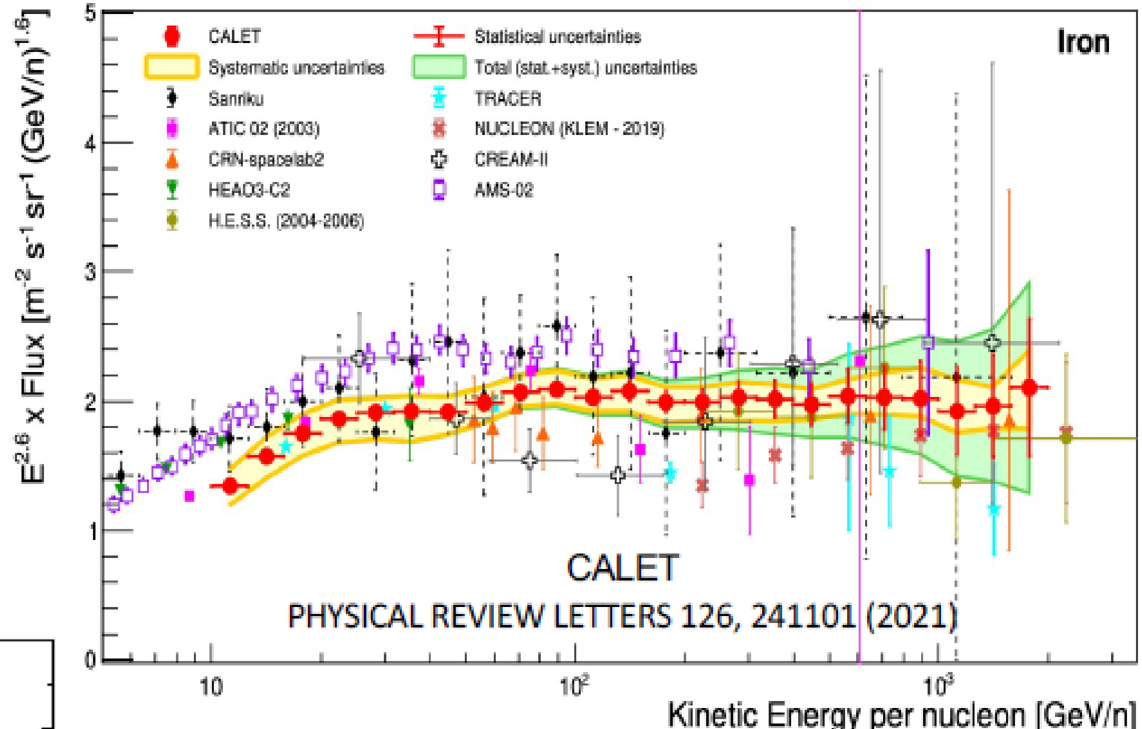
May 18, 2021

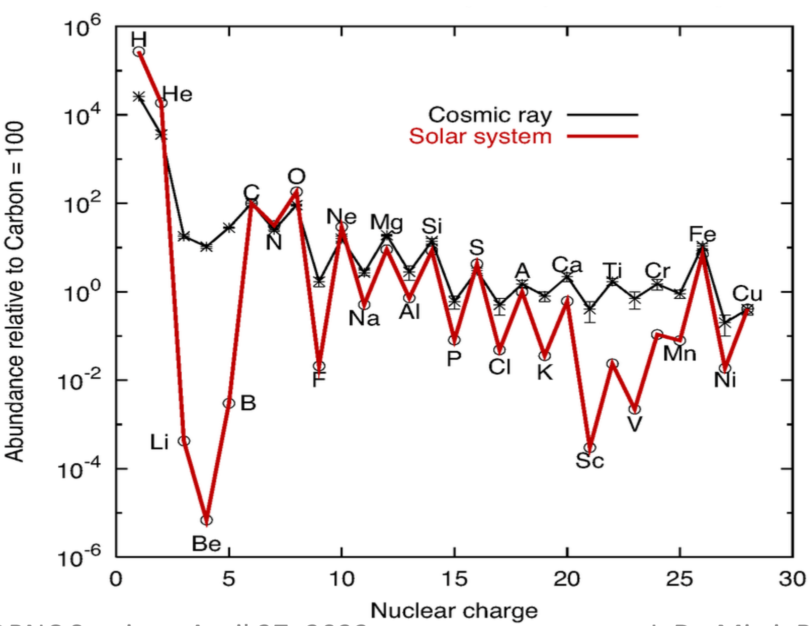


First clear evidence for a softening at about 34 TeV

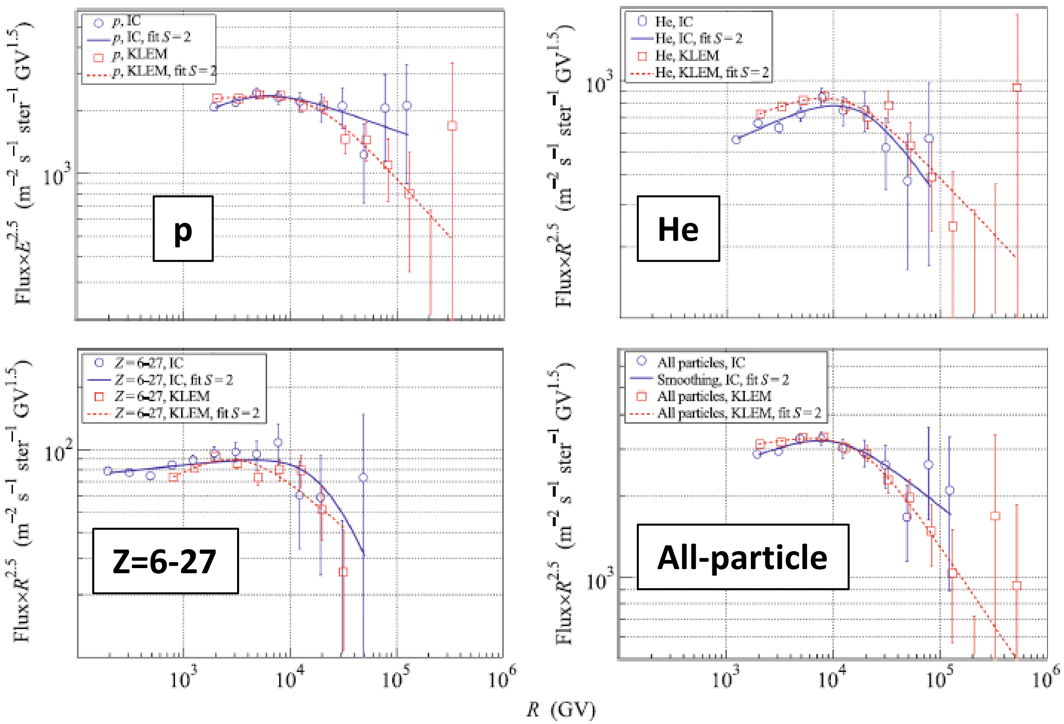
Suggesting a Z dependent softening energy (~ 14 TeV for protons)

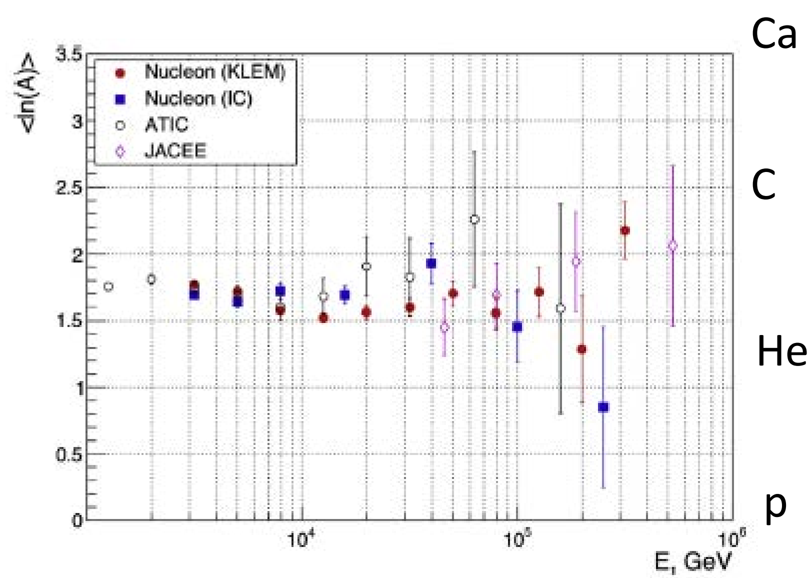
The iron flux: AMS-02 and CALET

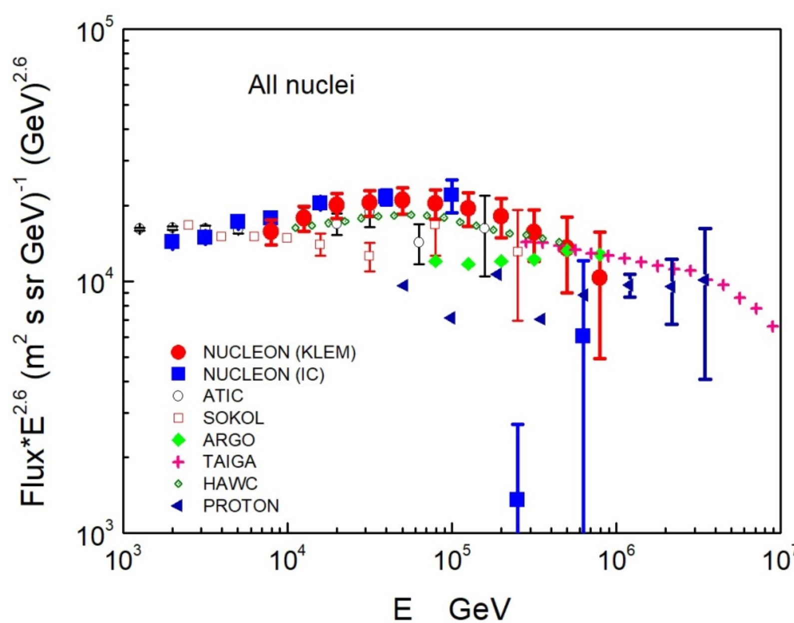




Other nuclei and larger energies





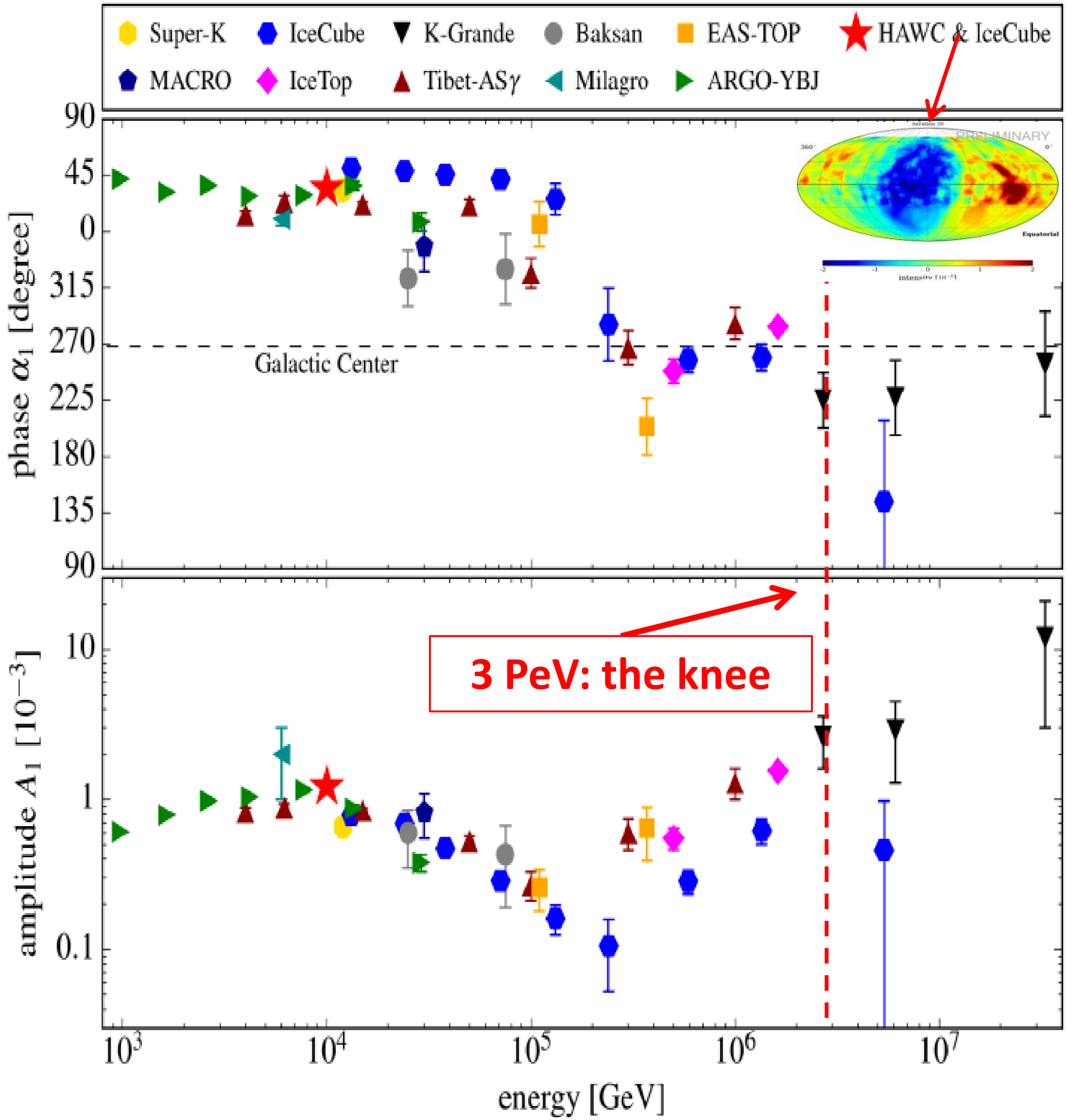


Nuclear spectra from NUCLEON

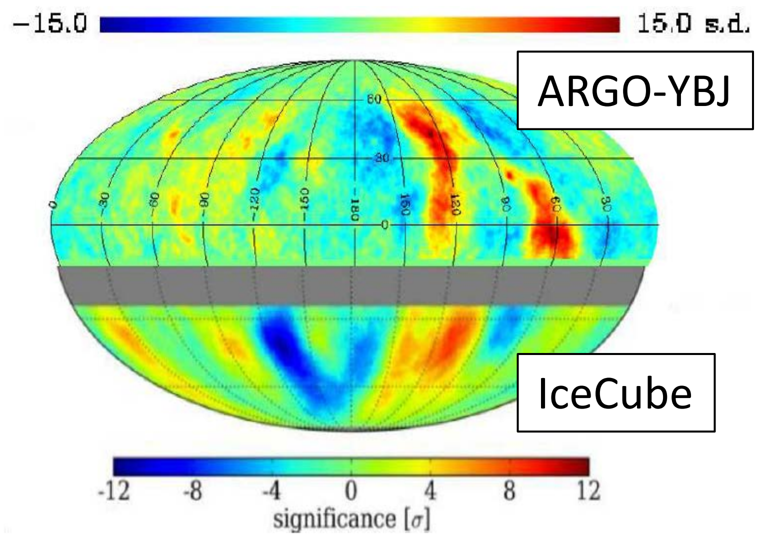
A spectra feature seems to be present in all nuclear species at the same rigidity (about 10 TV)

Anisotropies below the knee

Large Scale anosotropies (LSA) at the level of 10^{-4}-10^{-3} in the multi TeV region with stable phase.
Change in phase and amplitude above 100TeV, below the all-particle knee.



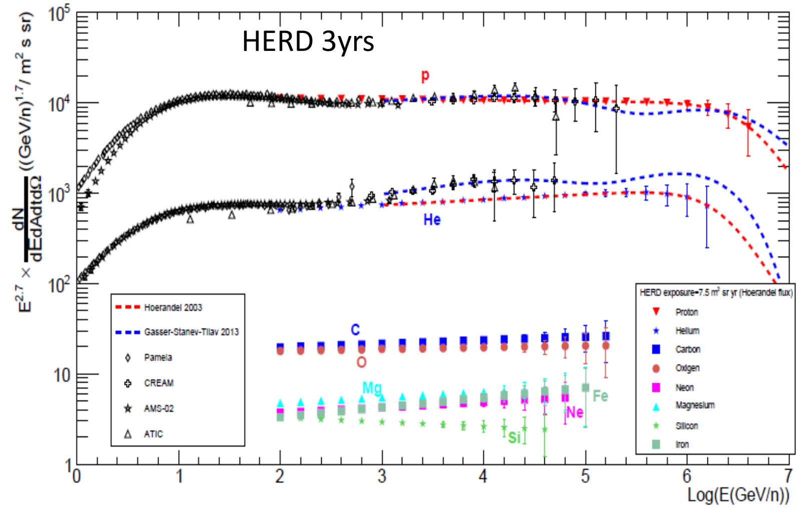
Medium/Small scale anisotropies (MSA) in the few TeV range

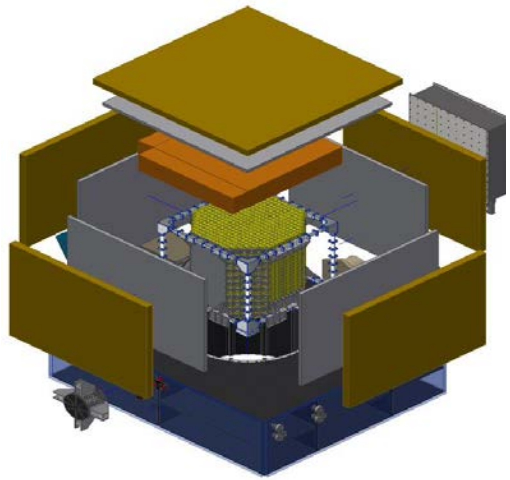


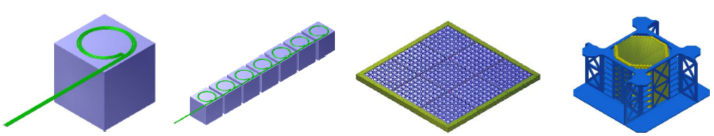
HERD: towards the knee from space

Large acceptance, deep, 3D calorimeter, equipped with silicon tracker and plastic scintillators for primary identification, onboard the Chinese Space Station for a long duration mission.

One order of magnitude jump in exposure wrt current generation CR experiment: 10-15 m² sr yr







item	Value	Note
Type of crystal	LYSO	
Nuclear Interaction Length	3	~ 21 LYSO crystals
Number of crystals	~7500	
Crystal dimension	3cm*3cm*3cm	
Fiber readout	3 WLSF/crystal	Low range, high range & trigger

HERD: collaboration and main features

CHINA

Institute of High Energy Physics, CAS (IHEP)
Xi'an Institute of Optical and Precision Mechanics, CAS (XIOPM)
Guangxi University (GXU)
Shandong University (SDU)
Southwest Jiaotong University (SWJTU)
Purple Mountain Observatory, CAS (PMO)
University of Science and Technology of China (USTC)
Yunnan Observatories (YNAO)
North Night Vision Technology (NVT)
University of Hong Kong (HKU)
Academia Sinica

ITALY

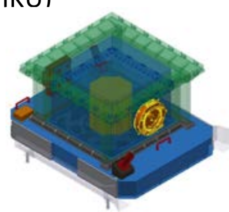
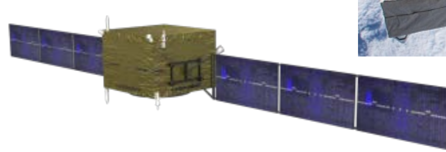
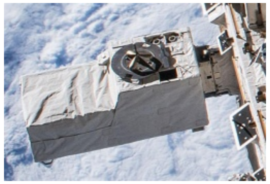
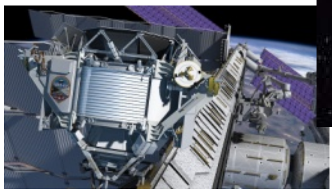
INFN Bari and Bari University
INFN Firenze and Firenze University
INFN LNGS and GSSI Gran Sasso Science Institute
INFN Lecce and Salento University
INFN Napoli and Napoli University
INFN Pavia and Pavia University
INFN Perugia and Perugia University
INFN Pisa and Pisa University
INFN Roma2 and Tor Vergata Universit
INFN Trieste and Trieste University

SPAIN

CIEMAT - Madrid
ICCUB – Barcellona
IFAE – Barcellona

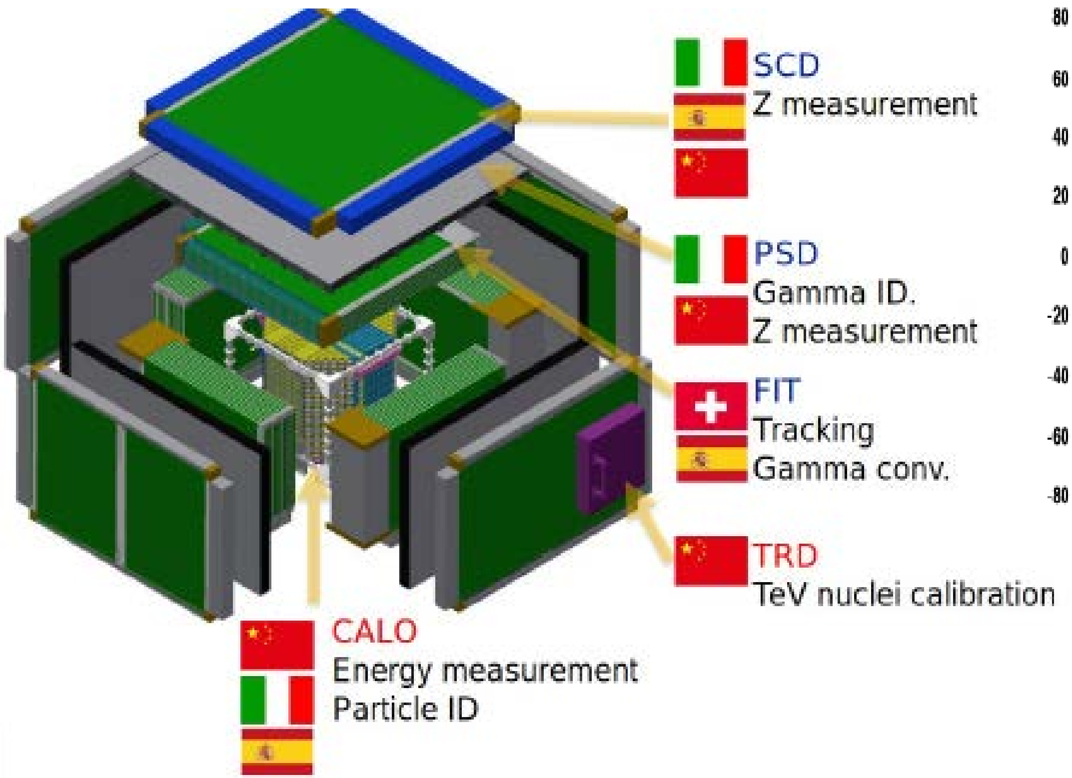
SWITZERLAND

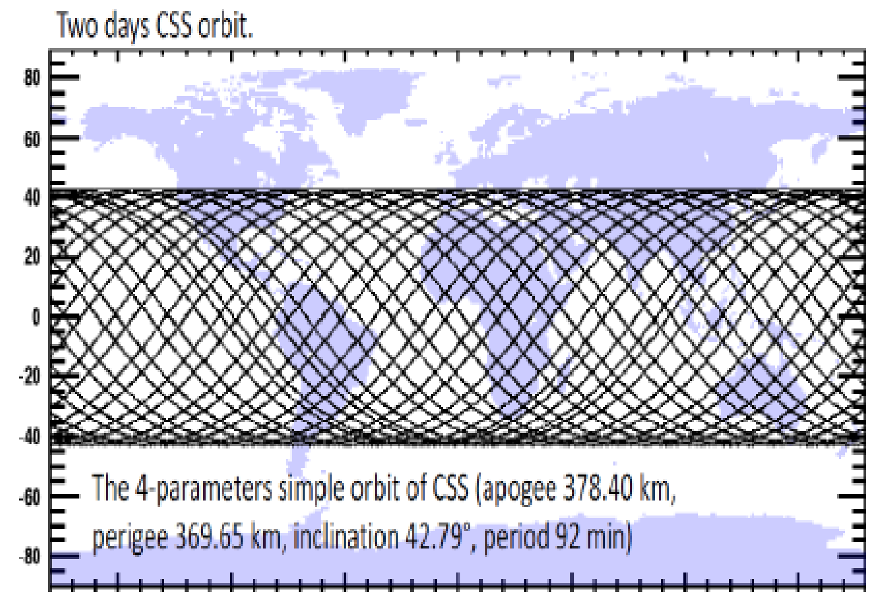
University of Geneva


	HERD	DAMPE	CALET	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	<1	1.5	2	3	10
e/γ Angular res.@100 GeV (deg)	< 0.1	0.1	0.2	0.3	0.1
e/p discrimination	$>10^6$	10^5	10^5	10^5 - 10^6	10^3
Calorimeter thickness (X_0)	55	32	27	17	8.6
Geometrical acceptance (m^2sr)	>3	0.29	0.12	0.09	1

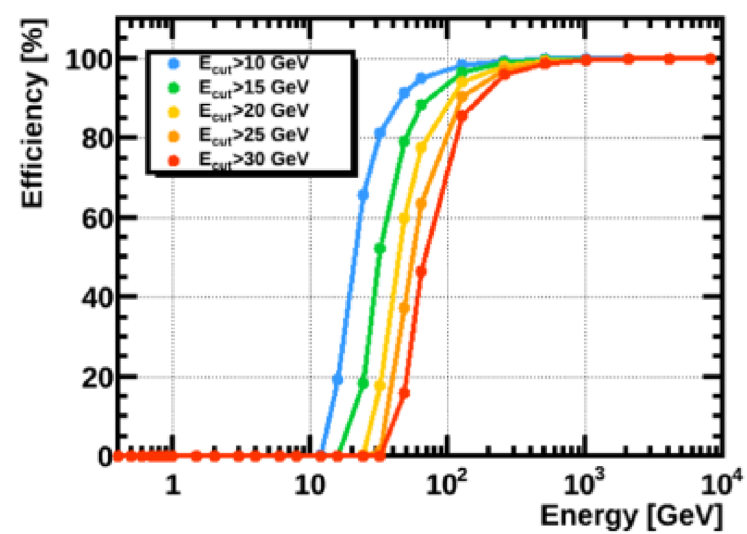
HERD: the detector and the CSS orbit





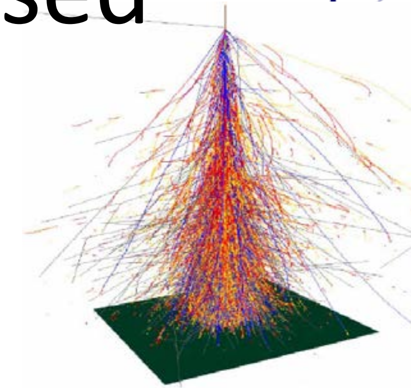
~7500 LYSO crystals (55 R.L, 3 N.I.L.)
Dual readout with IsCMOS & PD

Threshold at tens of GeV



Envelope (L*W*H)	~ 2300*2300*2000 mm^3
Weight	~ 3500 kg
Power Consumption	~ 1400 W

Space-Balloon vs Ground based



Direct measurements

Requirements:

Calorimetry vs Spectrometry
Large acceptances
<20% resolutions

Output:

Fully explore the sub-PeV region
Individual spectra

Limitations:

Surface/weight limited
Hard to reach the all-particle knee
Need high technology

Indirect measurements

Requirements:

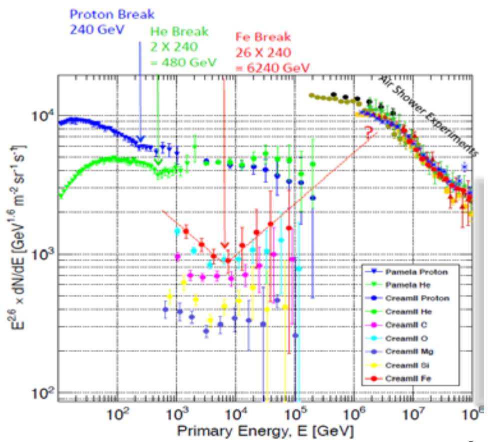
Multi-Hybrid approach
Operate at (not too) high altitude
Large surfaces / samplings

Output:

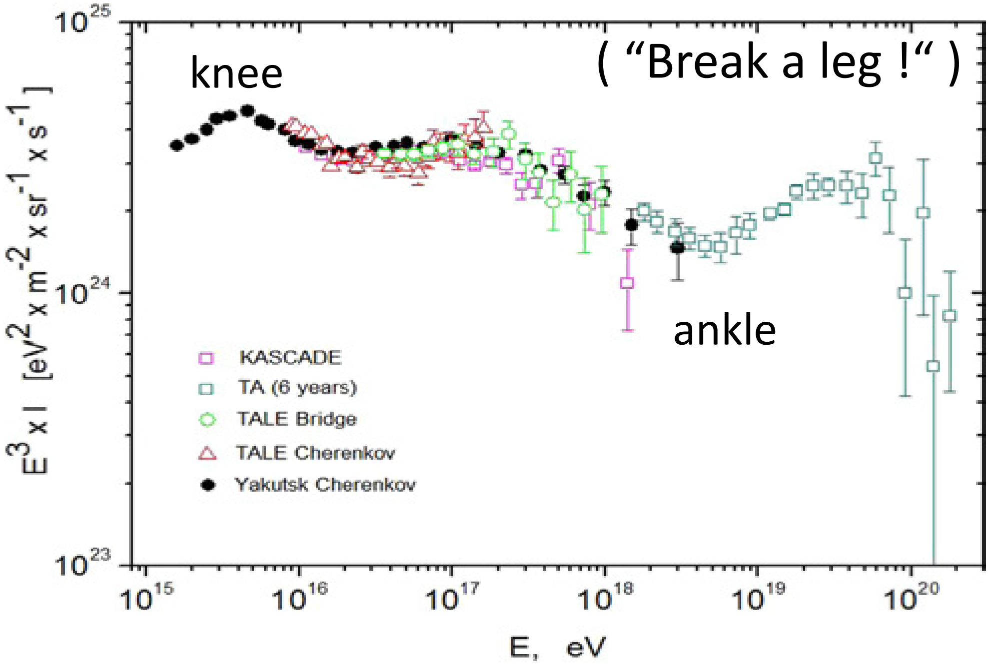
Reach the highest energies
Detect small anisotropies

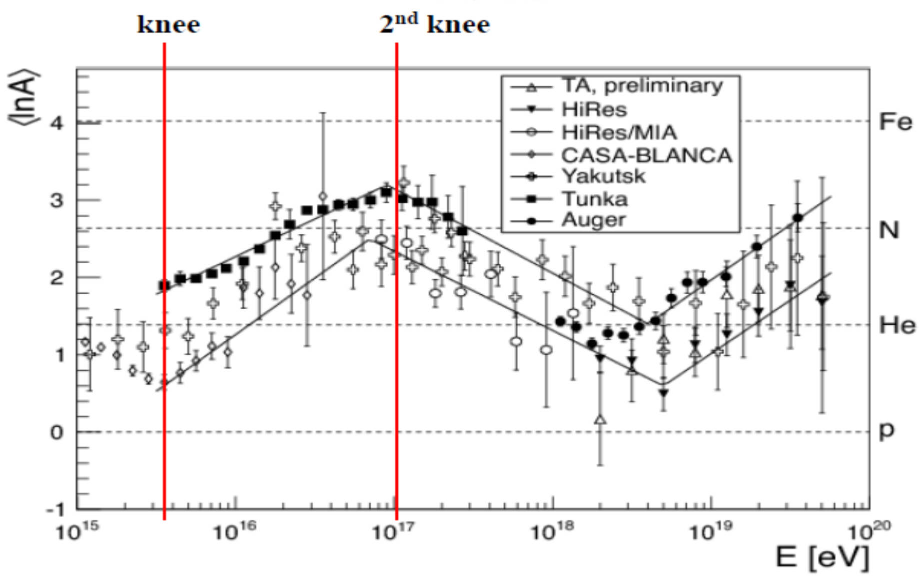
Limitations:

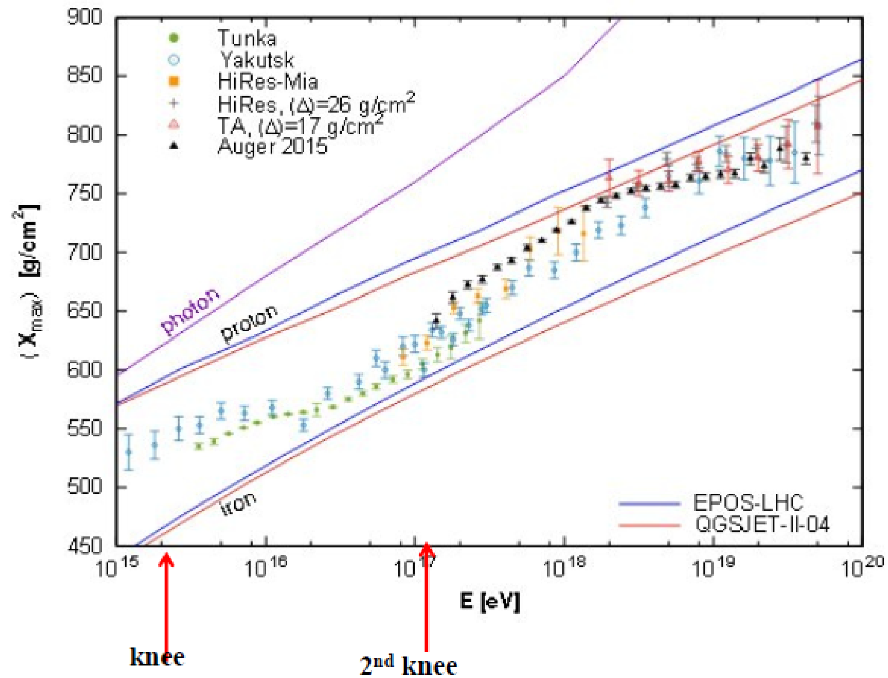
Poor mass resolution
Intrinsically limited by systematics
Large model dependence



Not simple evolution toward the ankle

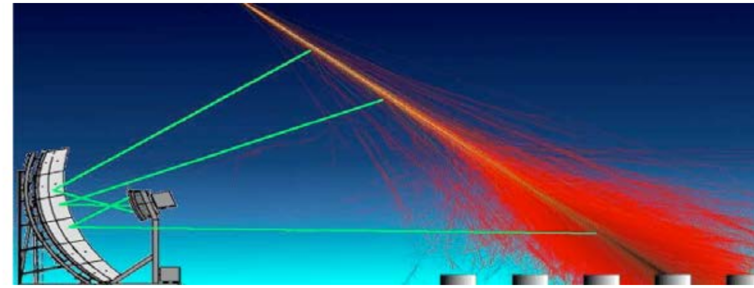


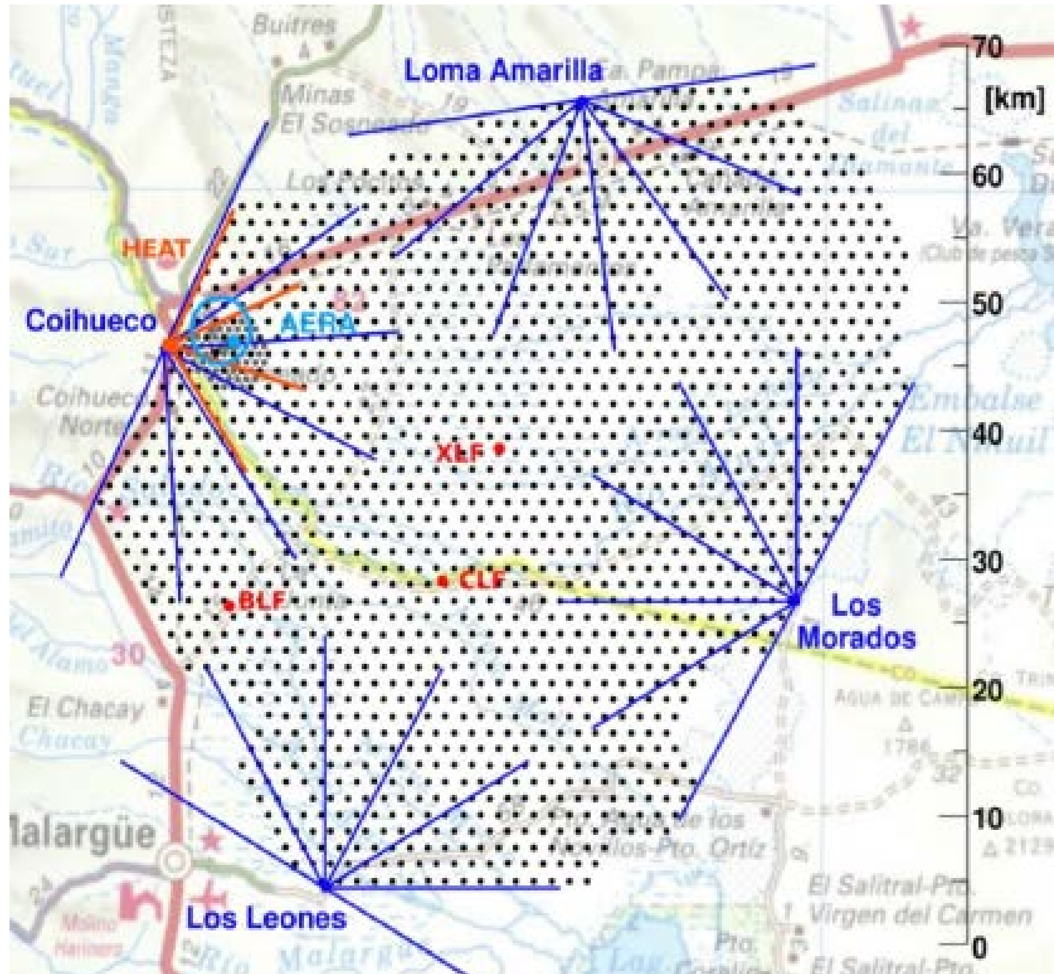




The Pierre Auger Observatory

- Malargue (Arg, 35°S), 1400 m a.s.l.
- E range: 10^{17} eV - 10^{21} eV
- Multi-detectors, hybrid reconstruction
- **Surface Detector** array (SD)
  - Sampling EAS particles at ground
  - 1670 WC tanks, 1500 m spacing, 3000 km².
  - SD-750, SD-433 (→ ~10^{16} eV)
- **Fluorescence Detectors** (FD)
  - EAS longitudinal profile
  - 24 Telescopes in 4 sites + 3 HEAT



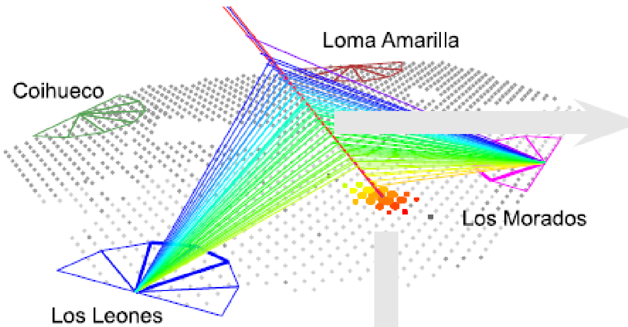


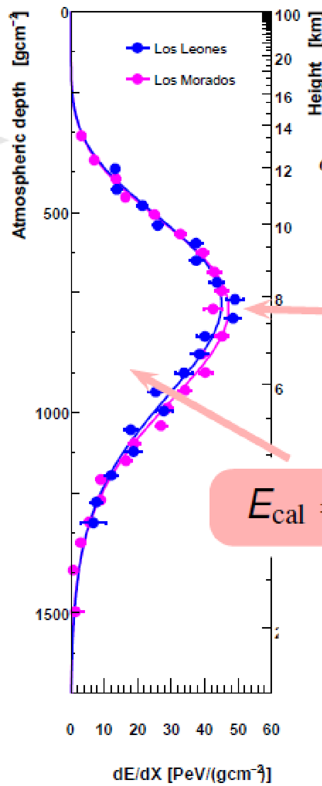
Surface Detector
1670 Water Cherenkov tanks
3.6 m diameter , 1.2 m depth
3 9'' PMTs + 1 Small 1'' PMT

Plus a Scintillation detector on top

Fluorescence Detector
6 telescopes /eye x 4 eyes
3.6 x 3.6 m2 spherical mirrors
80x80 cm2 cameras
440 PMTs, 30x30 deg2 FoV
+ HEAT telescopes

AUGER : hybrid detection of EAS





$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

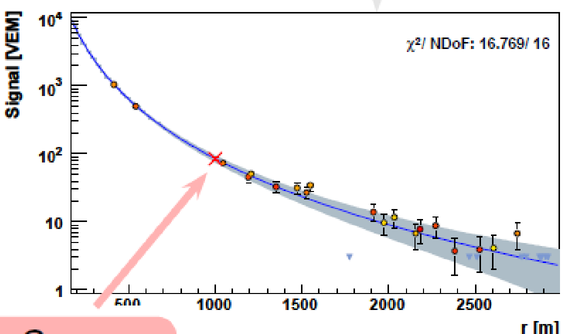
$X_{\max}$

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

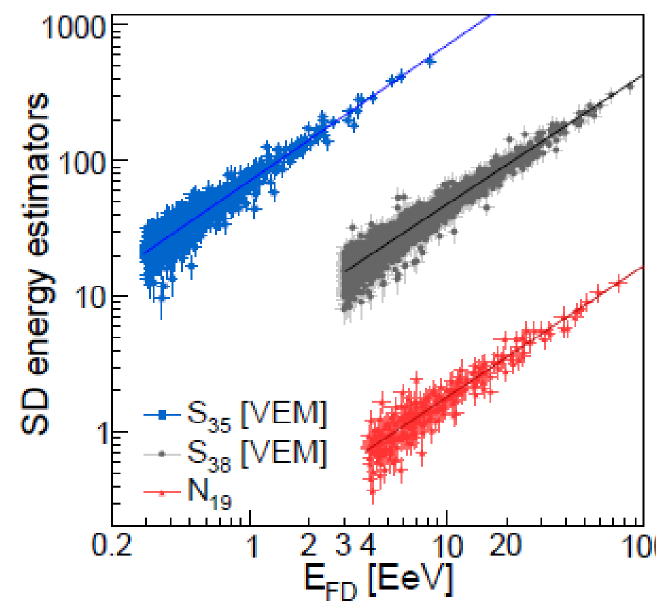
Calorimetric energy measurement with the FD

Energy calibration of SD observables using FD data



S_{1000}

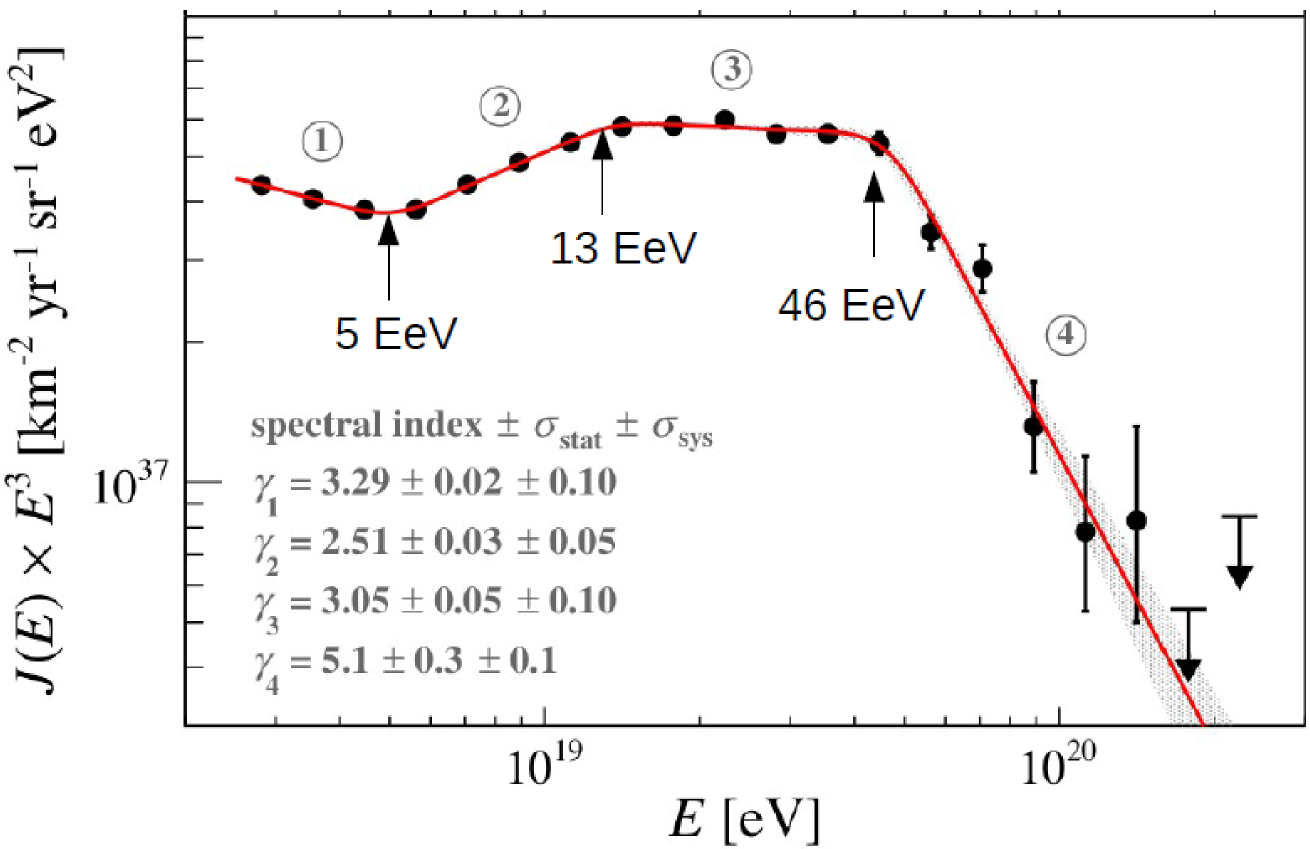
$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

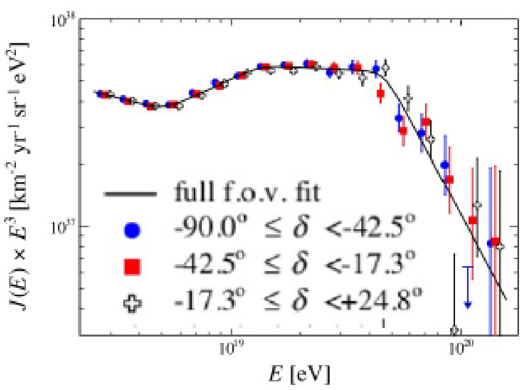


Very good **energy** (8% stat , 15% sys)
and $\mathbf{X_{max}}$ (lower than 10g/cm2 stat and 10g/cm2 sys)
resolutions and uncertainties.

At the highest energies….

The UHECR energy spectrum measured by
the Pierre Auger Observatory

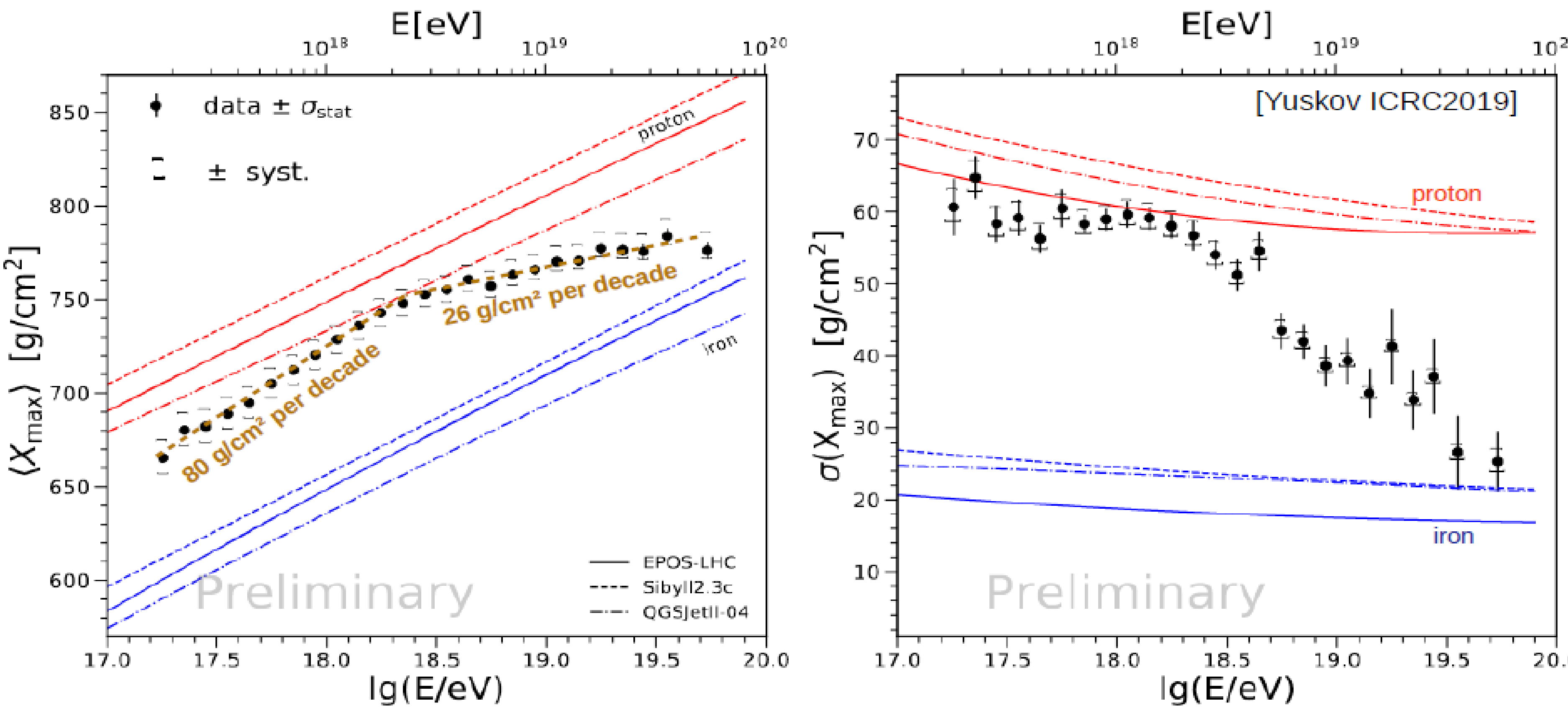




No dependence on the declination has been observed

At the highest energies….

UHECR mass composition studies performed by the Pierre Auger Observatory,
using the atmospheric depth of the shower maximum and its fluctuations



At the highest energies: AUGER large scale anisotropy

Science **357**, 1266–1270 (2017) 22 September 2017

COSMIC RRAYS

Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV

The Pierre Auger Collaboration*†

Cosmic rays are atomic nuclei arriving from outer space that reach the highest energies observed in nature. Clues to their origin come from studying the distribution of their arrival directions. Using 3×10^4 cosmic rays with energies above 8×10^{18} electron volts, recorded with the Pierre Auger Observatory from a total exposure of 76,800 km^2 sr year, we determined the existence of anisotropy in arrival directions. The anisotropy, detected at more than a 5.2σ level of significance, can be described by a dipole with an amplitude of $6.5^{+1.3}_{-0.9}$ percent toward right ascension $\alpha_d = 100 \pm 10$ degrees and declination $\delta_d = -24^{+12}_{-13}$ degrees. That direction indicates an extragalactic origin for these ultrahigh-energy particles.

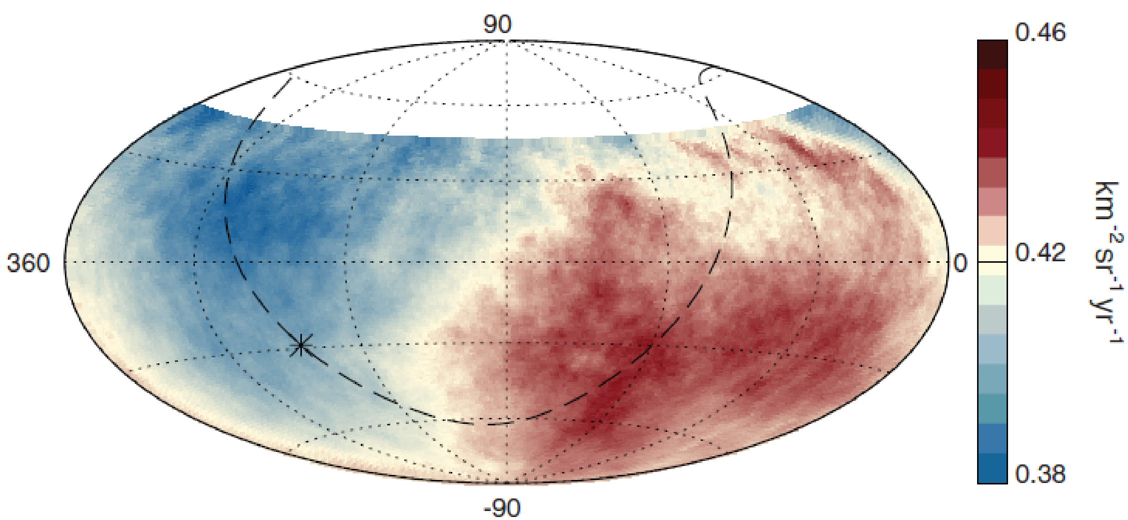


Fig. 2. Map showing the fluxes of particles in equatorial coordinates. Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The galactic center is marked with an asterisk; the galactic plane is shown by a dashed line.

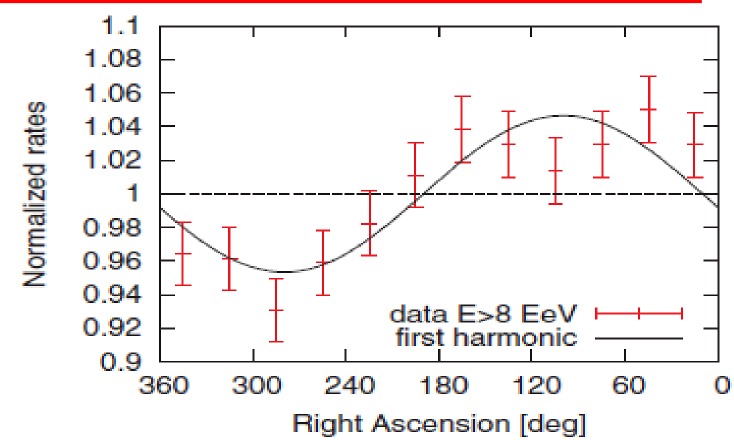
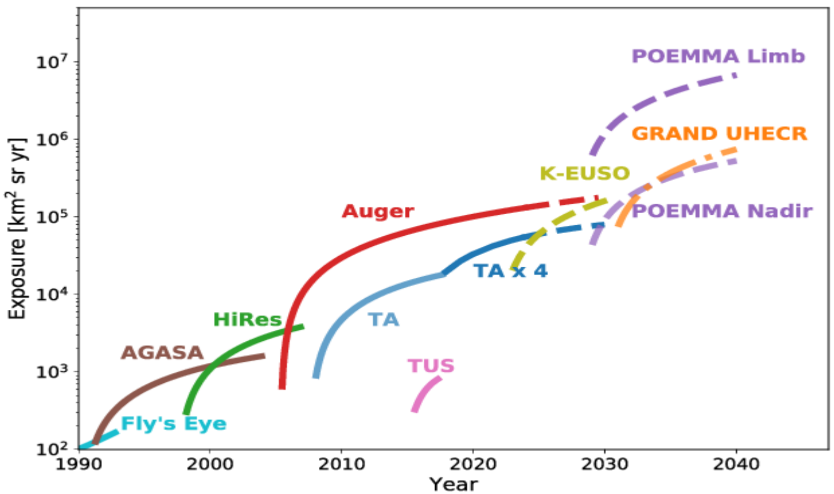


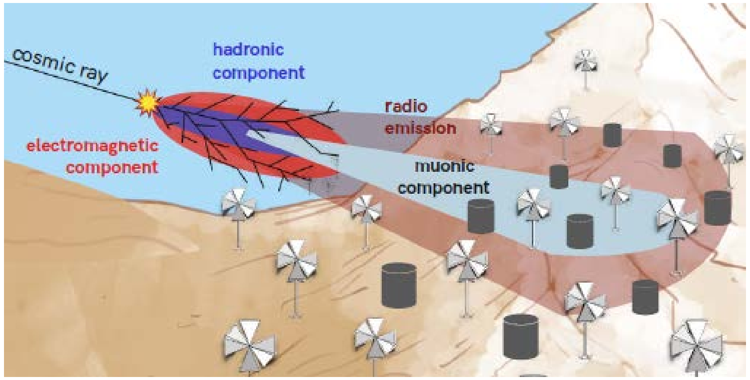
Fig. 1. Normalized rate of events as a function of right ascension. Normalized rate for 32,187 events with $E \geq 8$ EeV, as a function of right ascension (integrated in declination). Error bars are 1σ uncertainties. The solid line shows the first-harmonic modulation from Table 1, which displays good agreement with the data (χ^2/n = 10.5/10); the dashed line shows a constant function.

New techniques at the highest energies

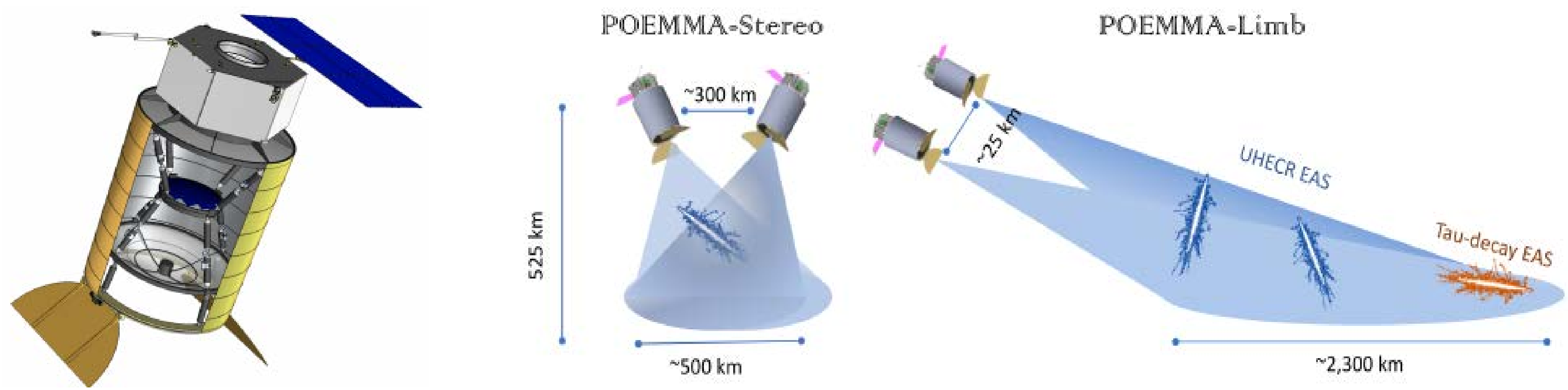
Improve the statistics by a jump in exposure, for UHE CR and neutrinos:
a giant ground array and/or a space-based observatory



GRAND: Giant Radio Array for Neutrino detection



POEMMA: Probe Of Extreme Multi-Messenger Astrophysics



Summary

Continuous , steady improvements in CR physics.

New data gave some anwers but also raised new questions.

Many “unexpected” results:
→Exciting opportunities

New ideas will (as always)
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Merci !