Recent advances in the observations of high energy cosmic rays

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L'Aquila , Italy

NOW 2000

Europhysics Neutrino Oscillation Workshop

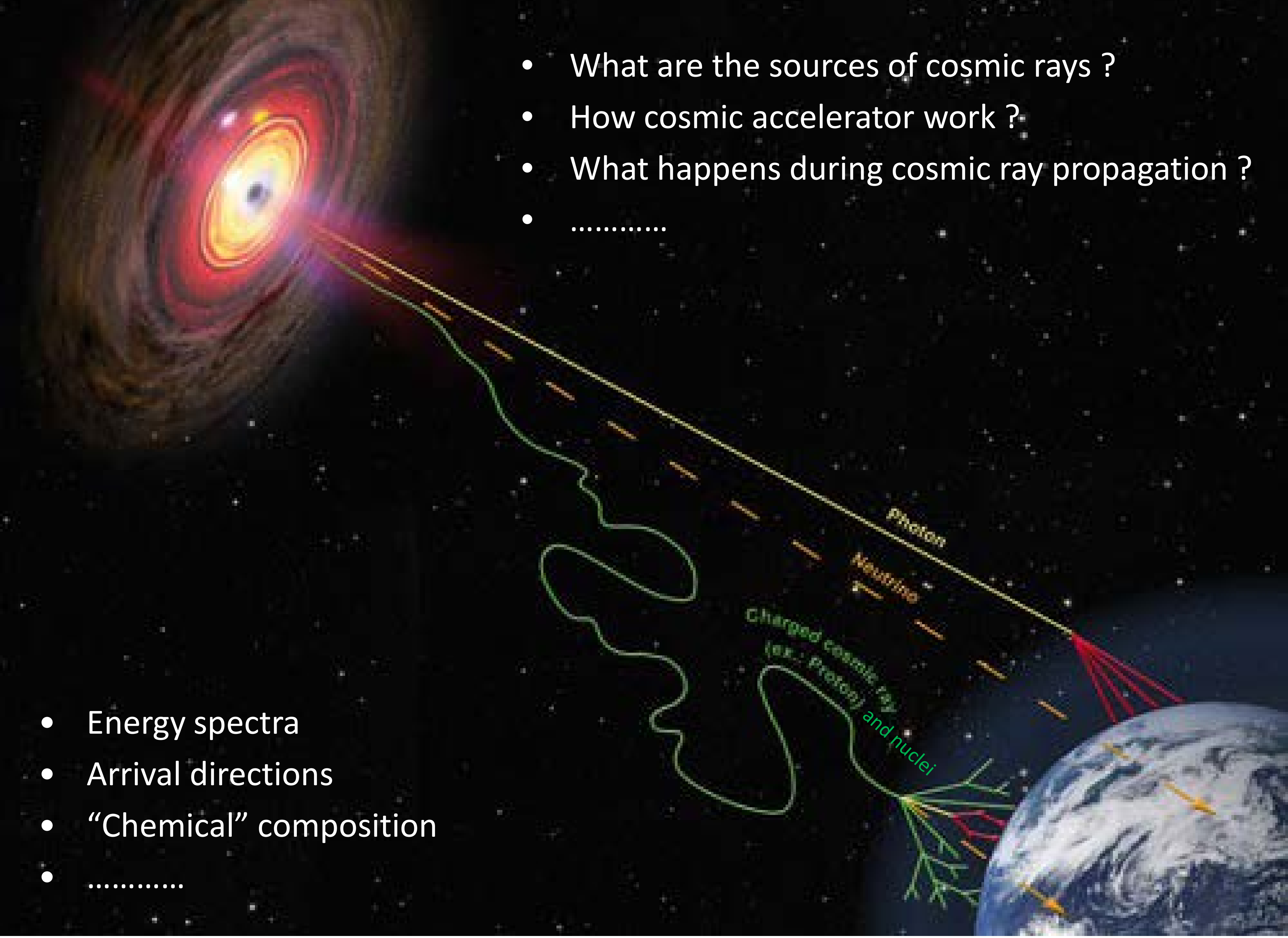
Conca Specchiulla (Otranto, Italy), September 9-16, 2000

NOW 2022

Neutrino Oscillation Workshop

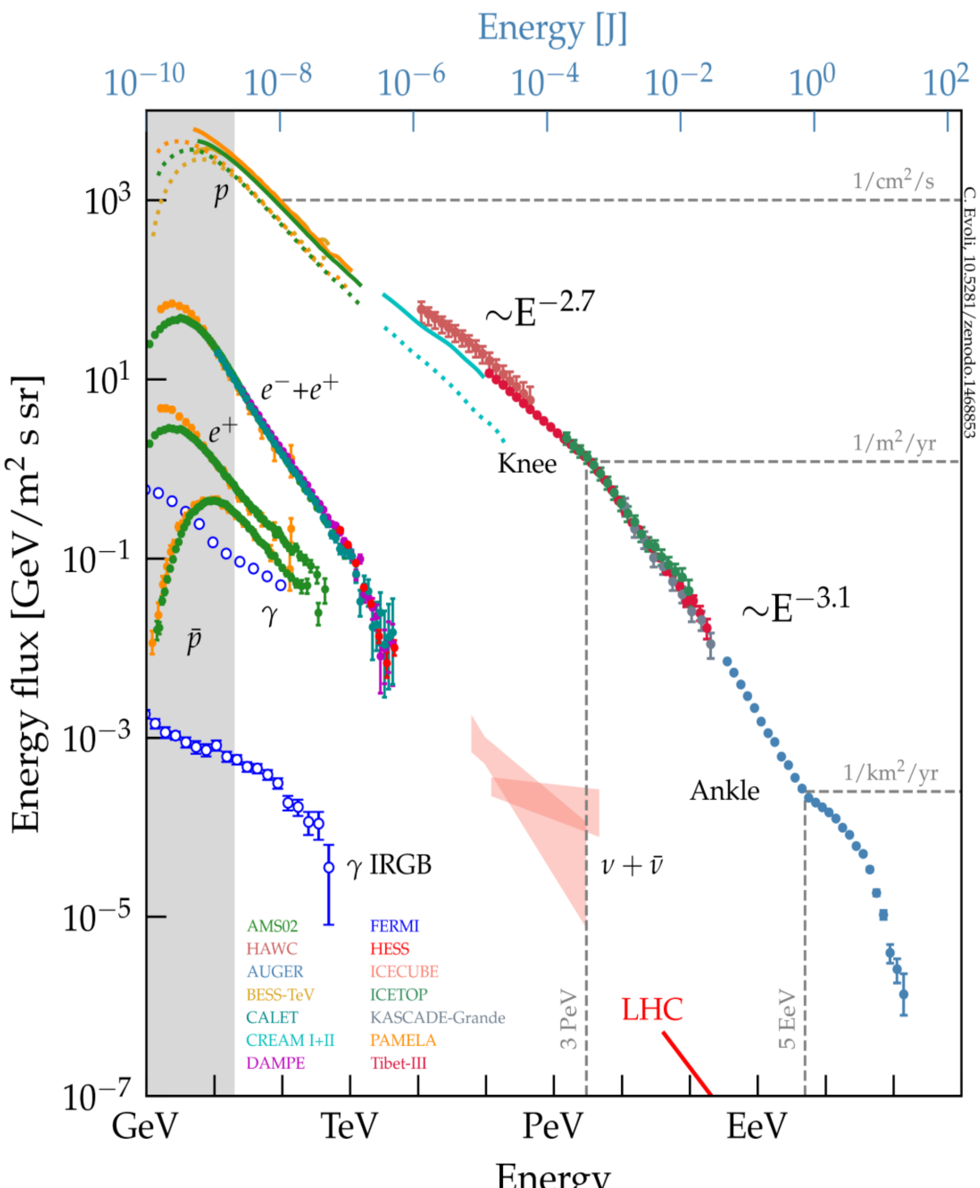
Ostuni, Italy, September 1-11, 2022

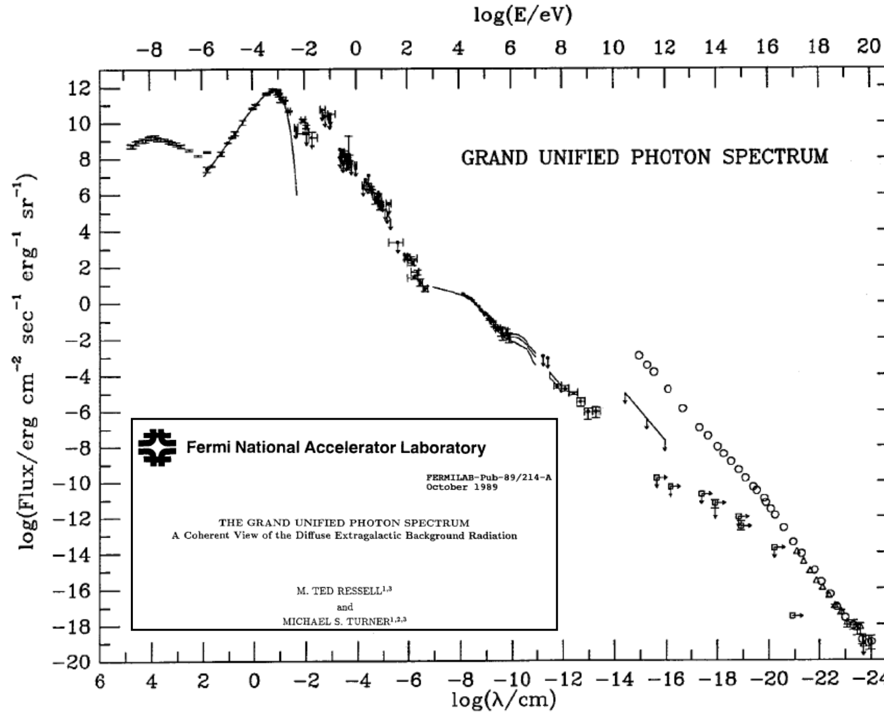
- What are the sources of cosmic rays ?
- How cosmic accelerator work ?
- What happens during cosmic ray propagation ?
- …………

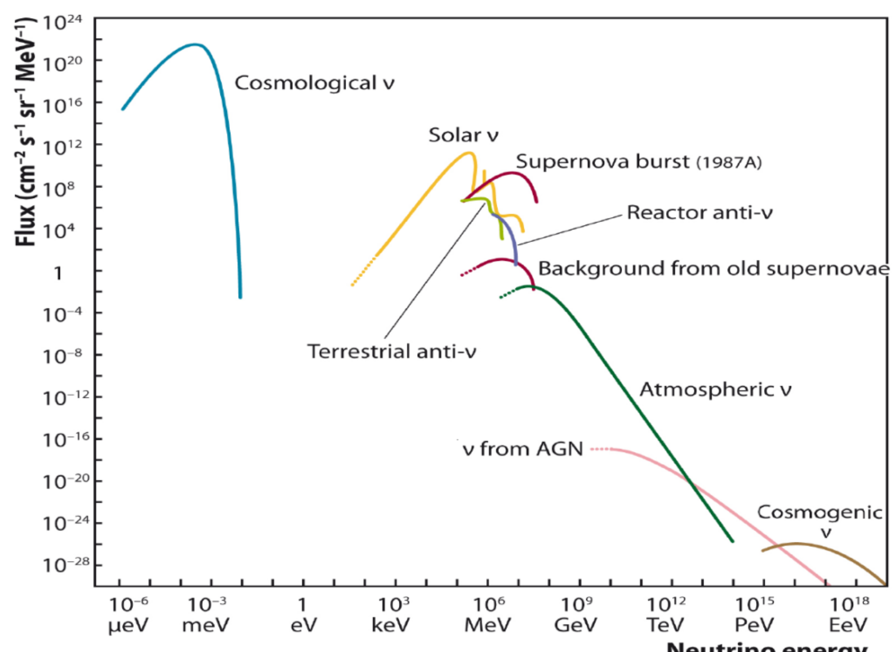


- Energy spectra
- Arrival directions
- “Chemical” composition
- …………

Our landscape(s)

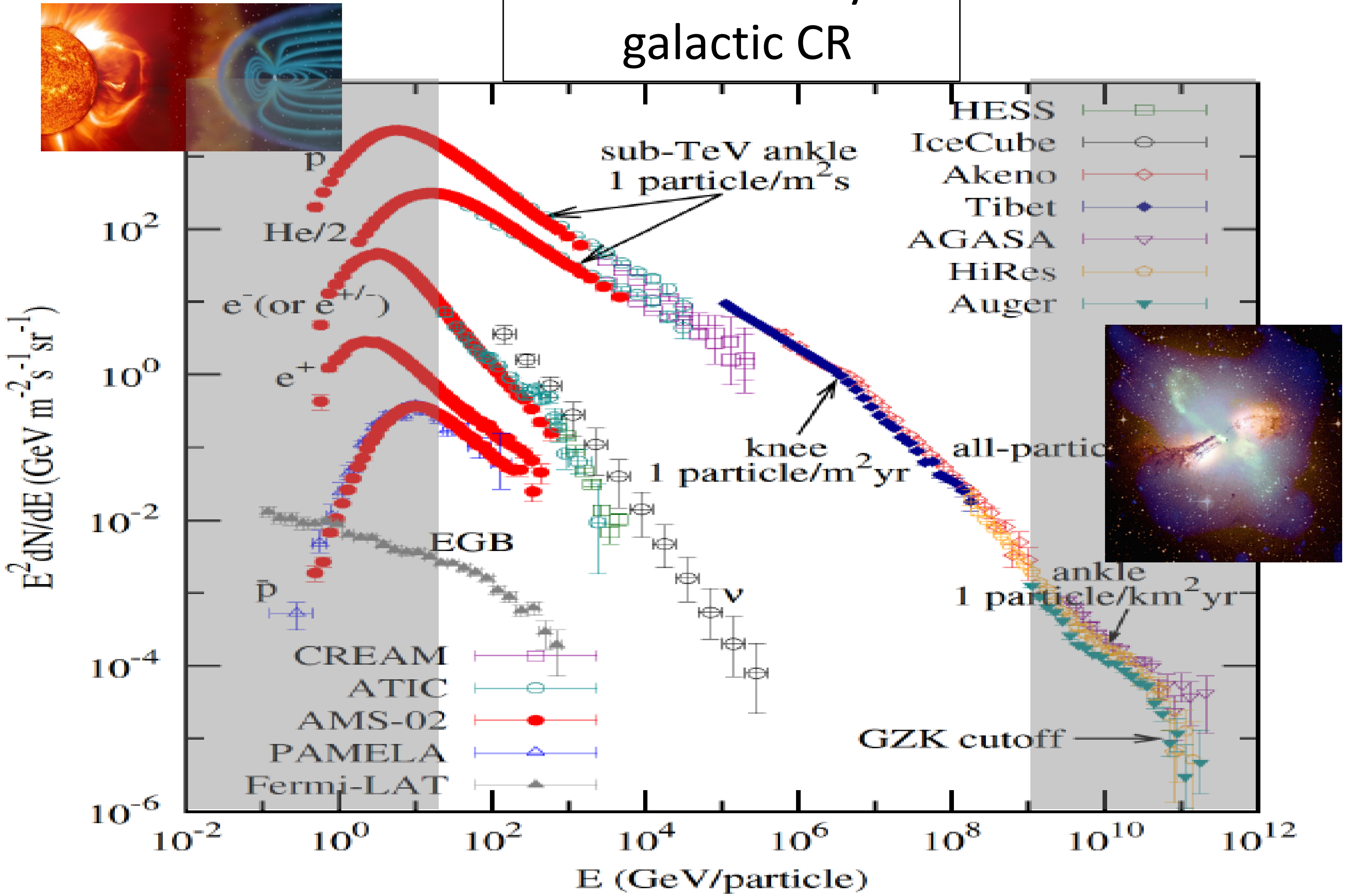




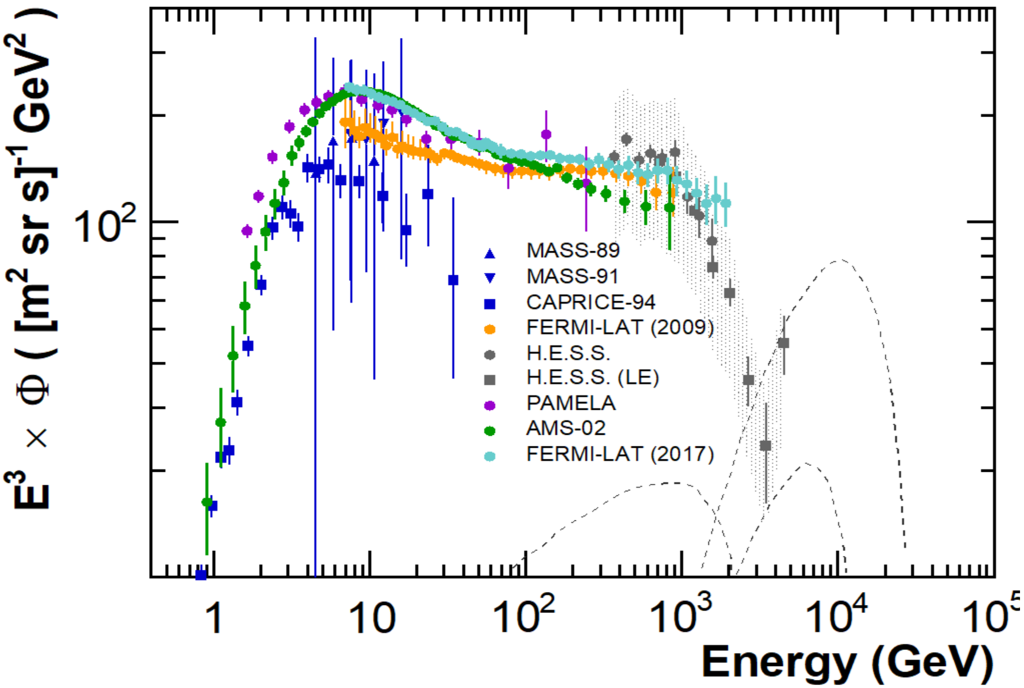


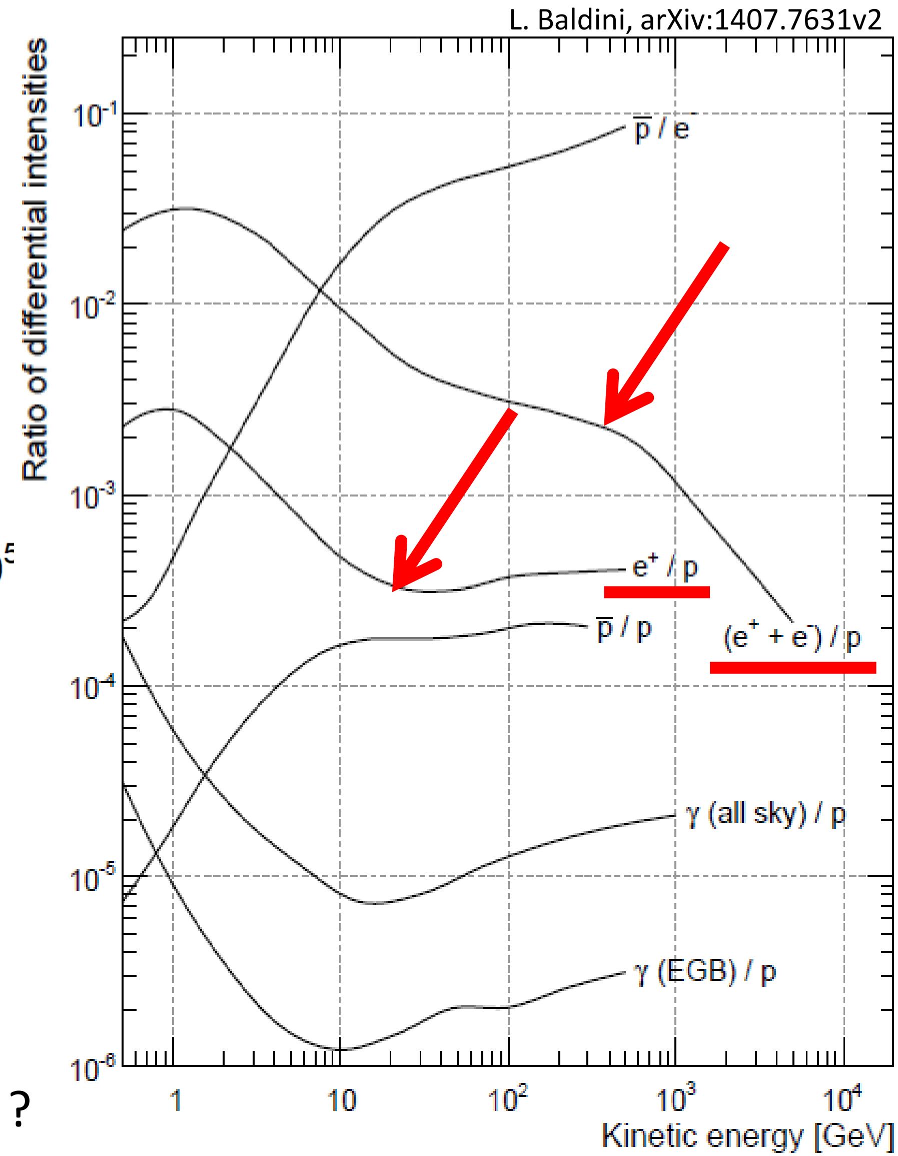
GSSI

Unbiased study of galactic CR



The electron + positron signal (few yrs ago)



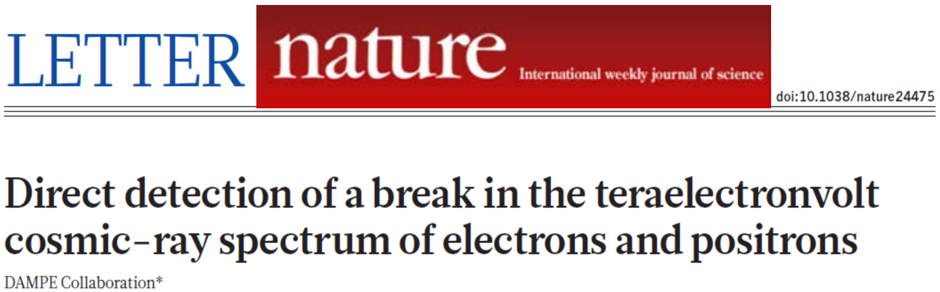


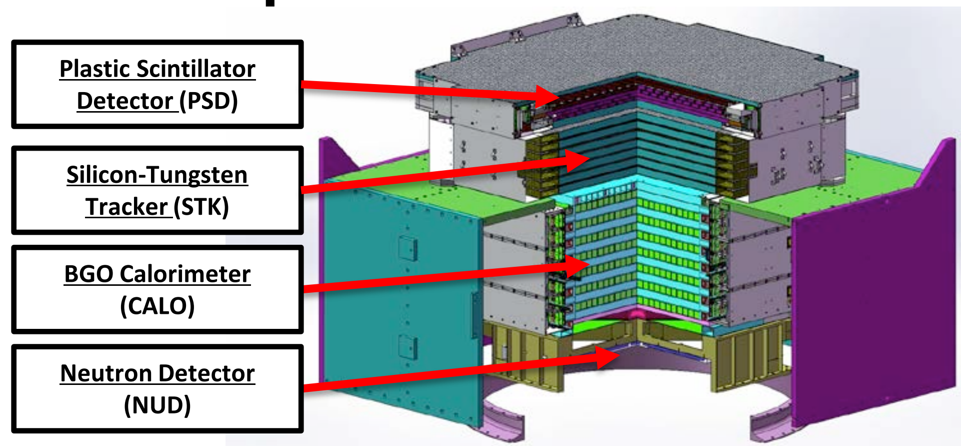
- Small fluxes and ~ E^{-3} spectra
- Cut-off at about 1 TeV ?

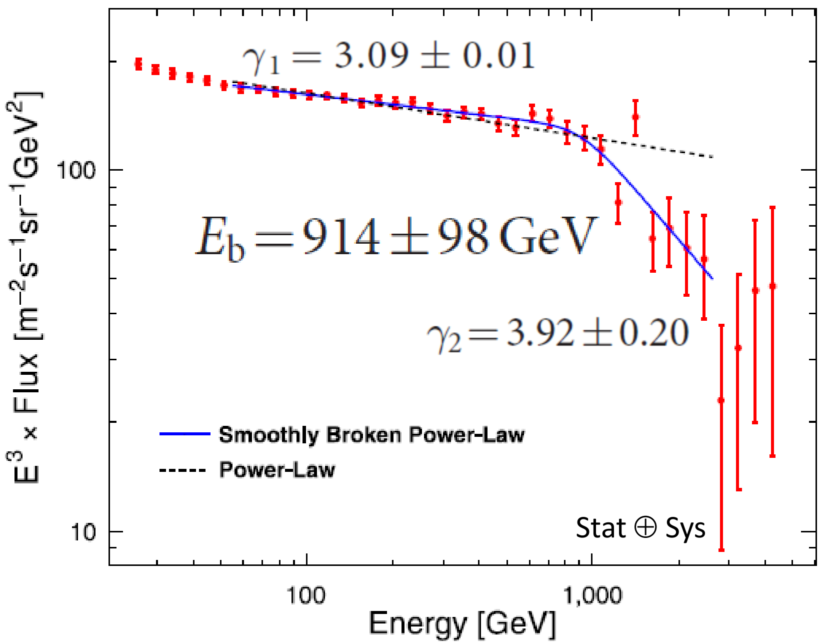
TeV sources:

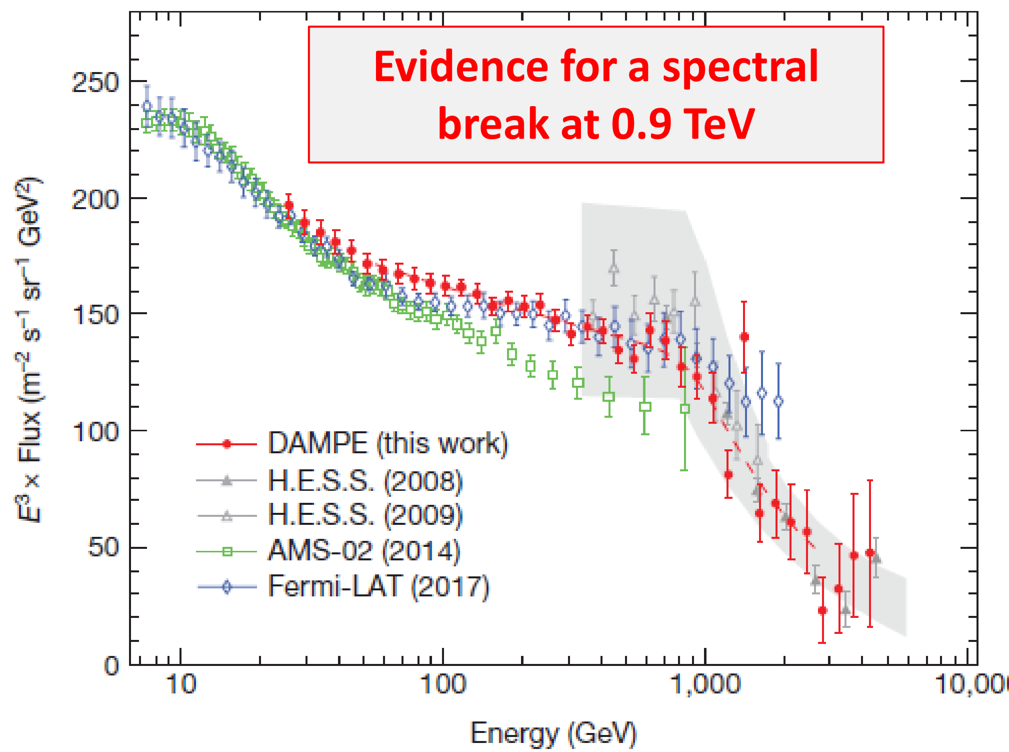
- T < 10^5 yr and D < 1 kpc
- Nearby CR sources: large anisotropies ?
- Contributions from DM annihilation/decay ?

DAMPE: evidence for a spectral break



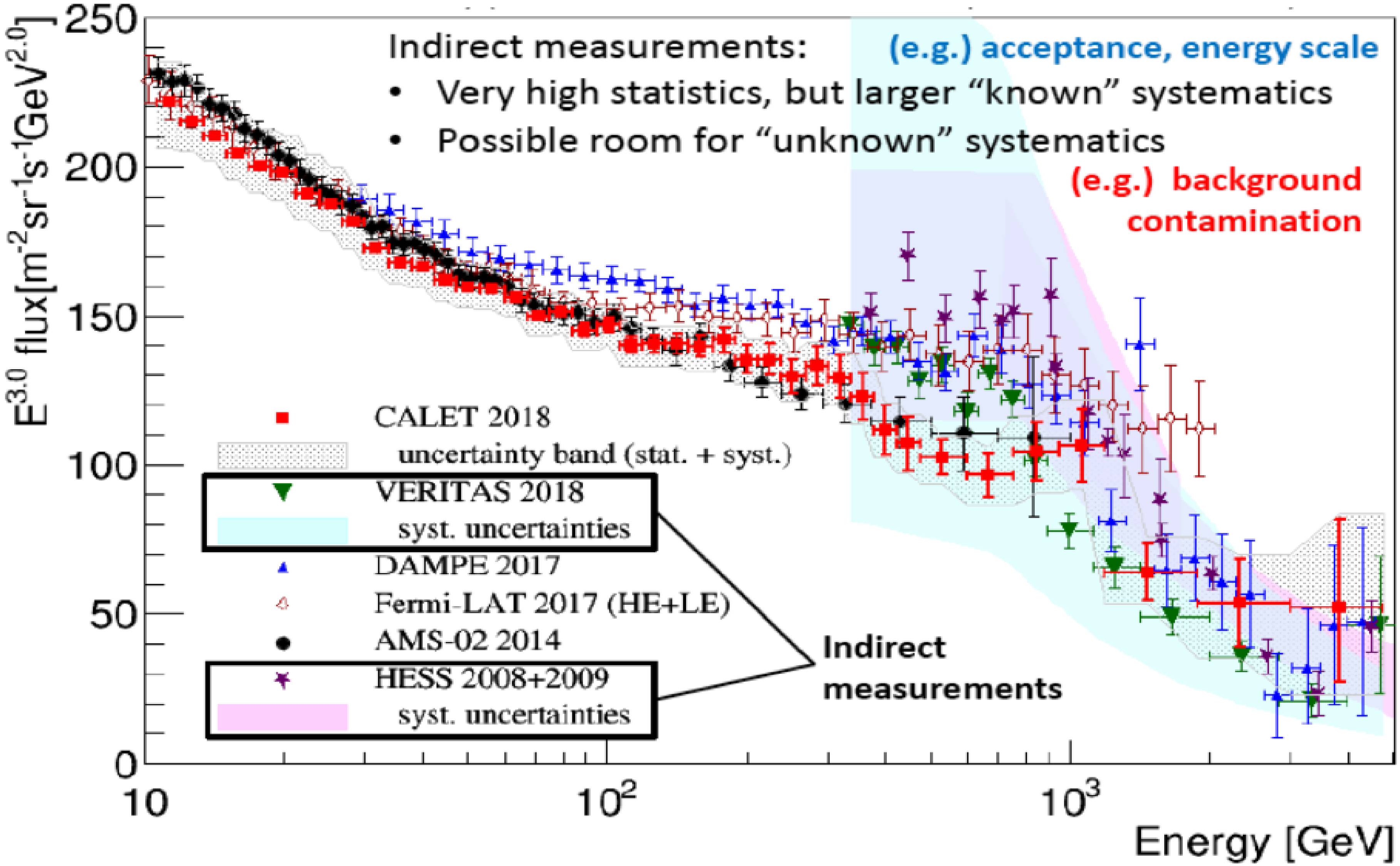




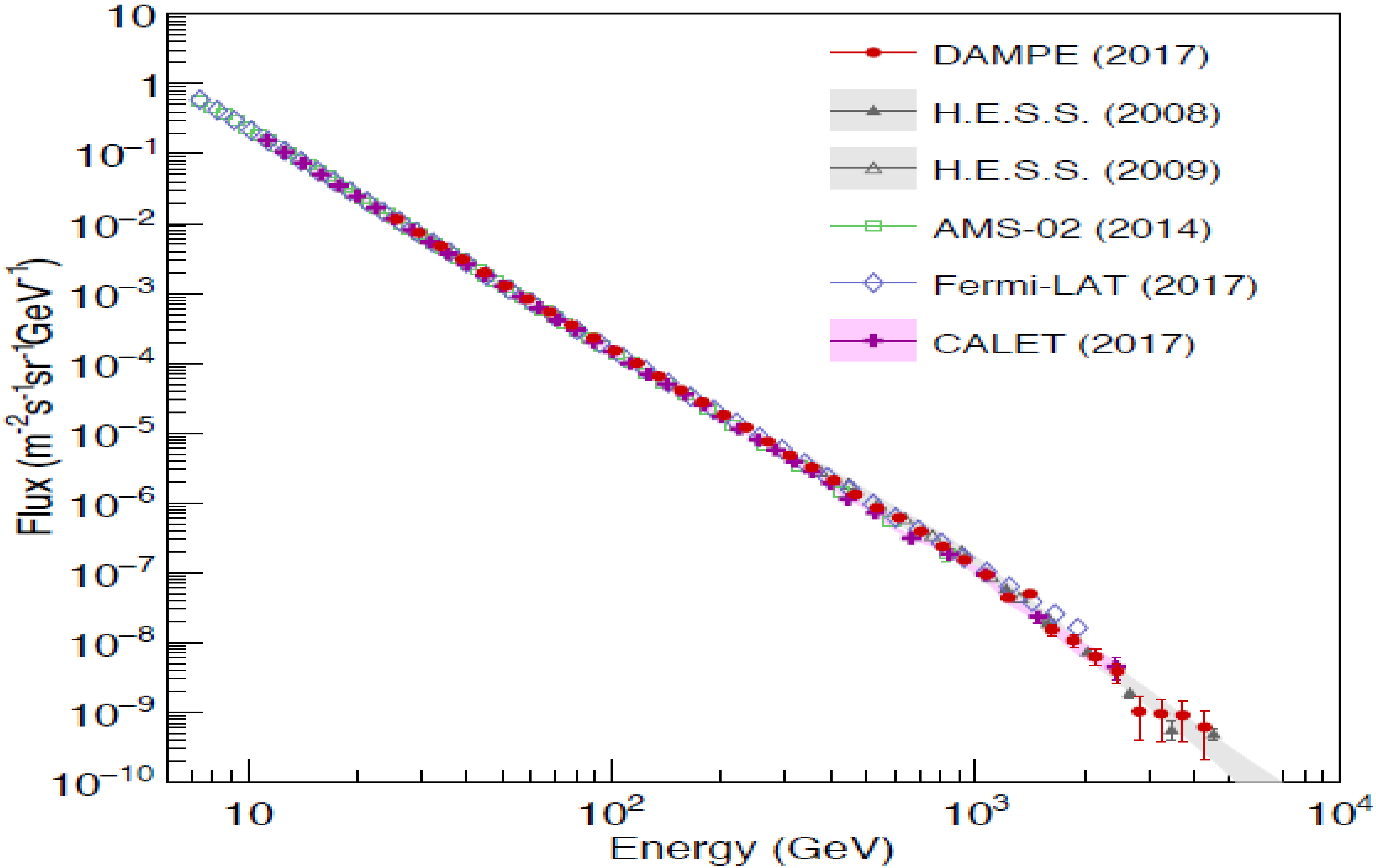


- 530 days
- 2.8 billions CR events
- 1.5 million CREs above 25 GeV

The all-electron flux today



The electron+positron flux



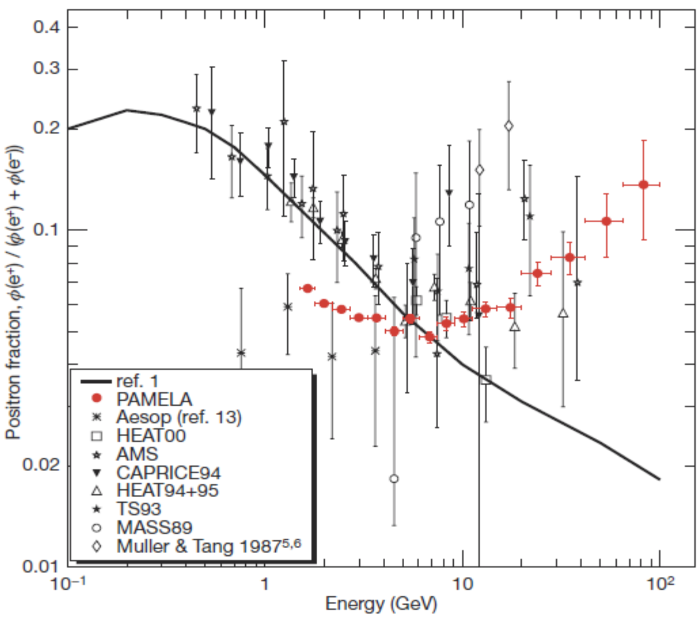
Antimatter: the positron fraction

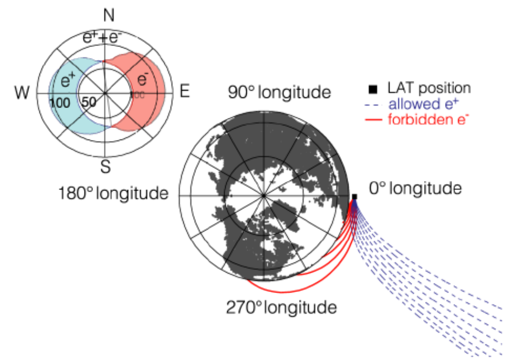
Vol 458|2 April 2009|doi:10.1038/nature07942 nature

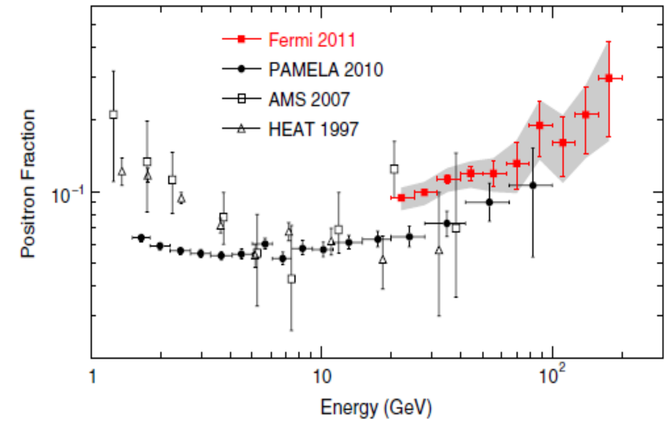
LETTERS

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

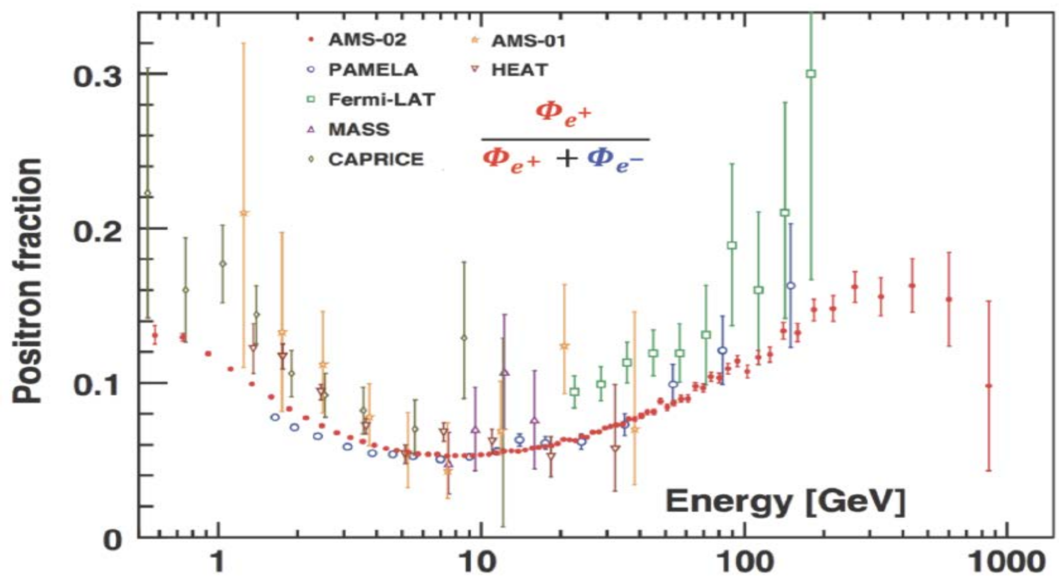
O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De 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]



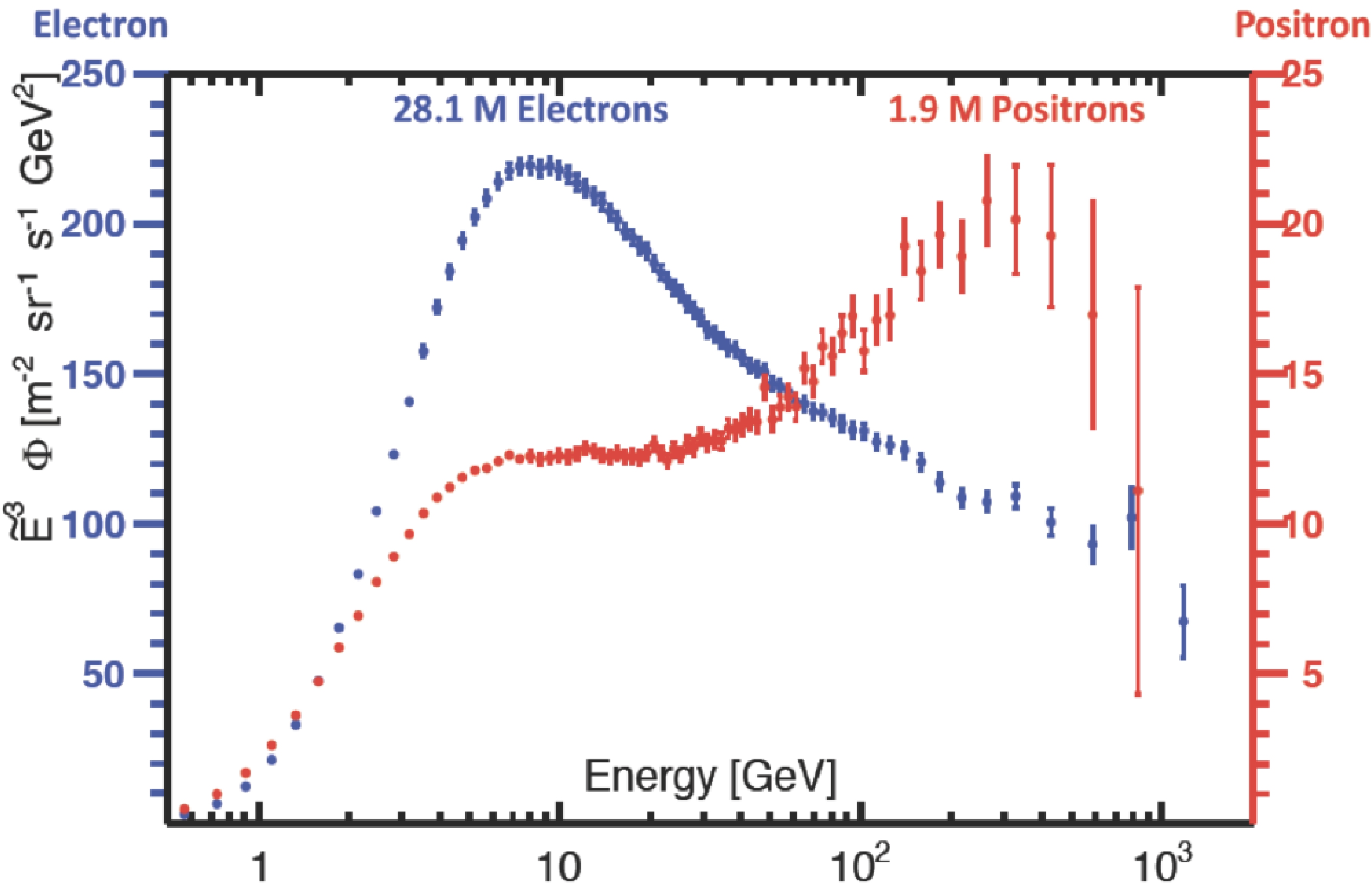




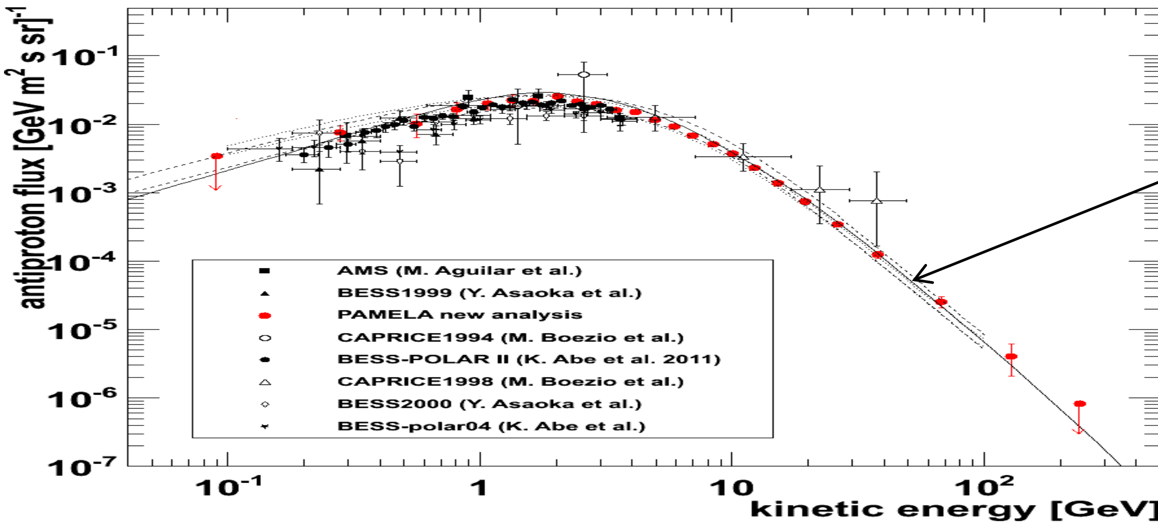
First "anomalous" results from PAMELA (april 2009)
FERMI contribution, even with large systematics.
Extended and precise measurements by AMS-02



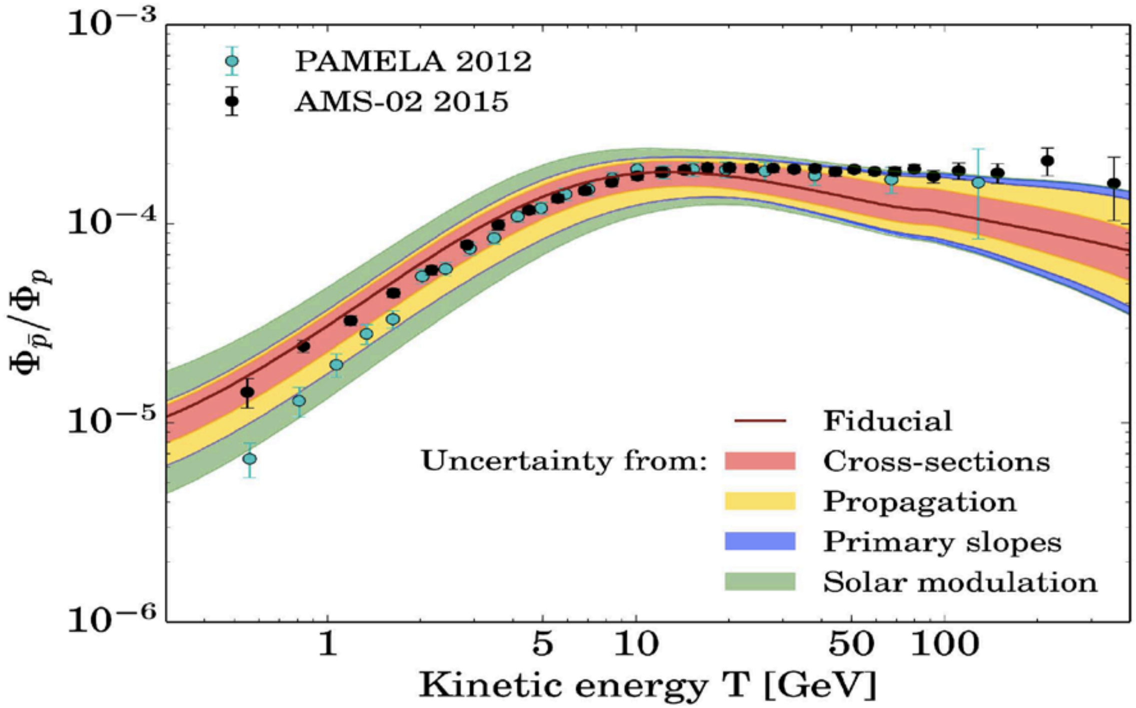
The e+ and e- fluxes with AMS-02



Antimatter: antiprotons



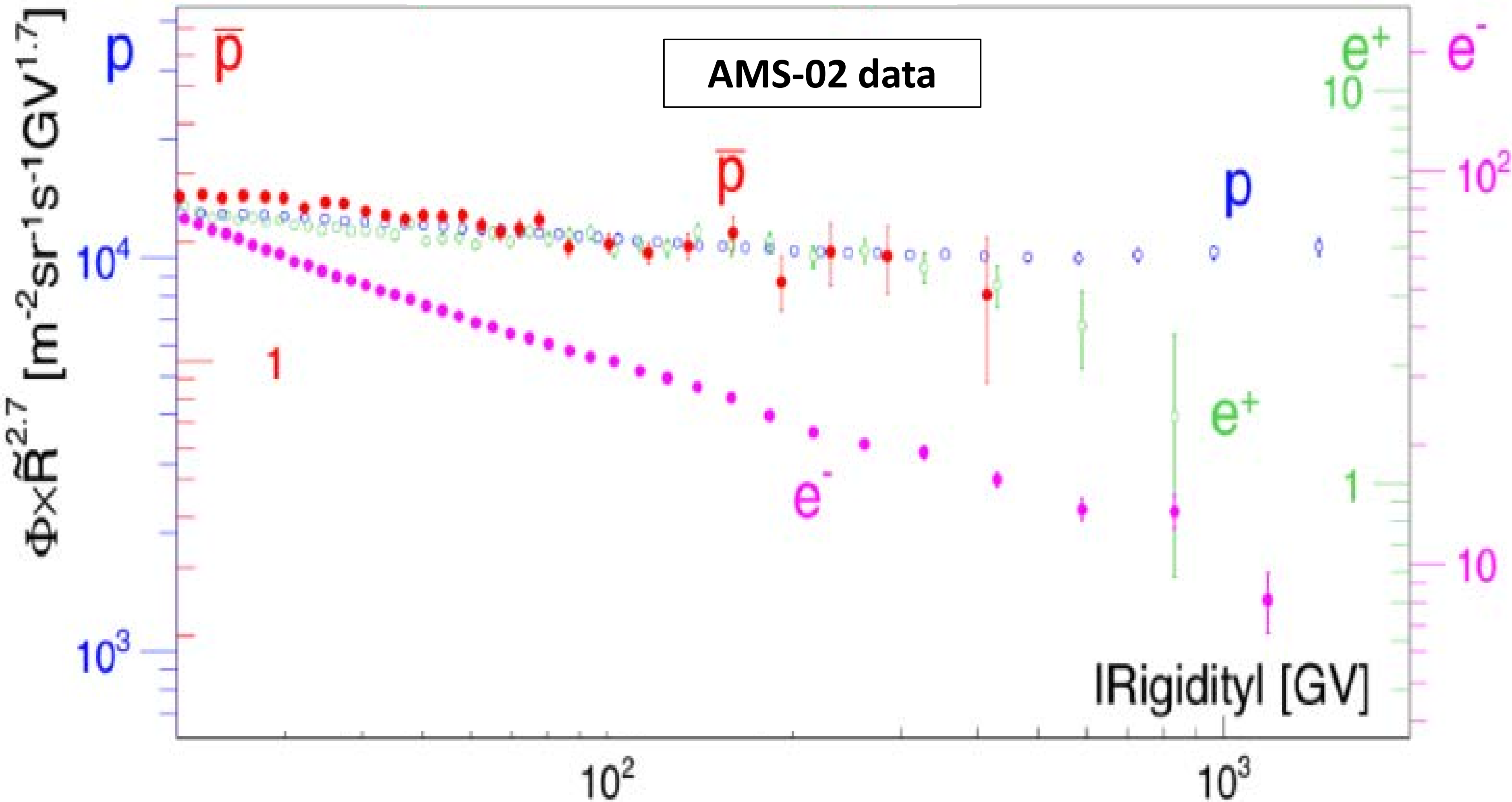
Antiproton flux consistent with secondary production calculations



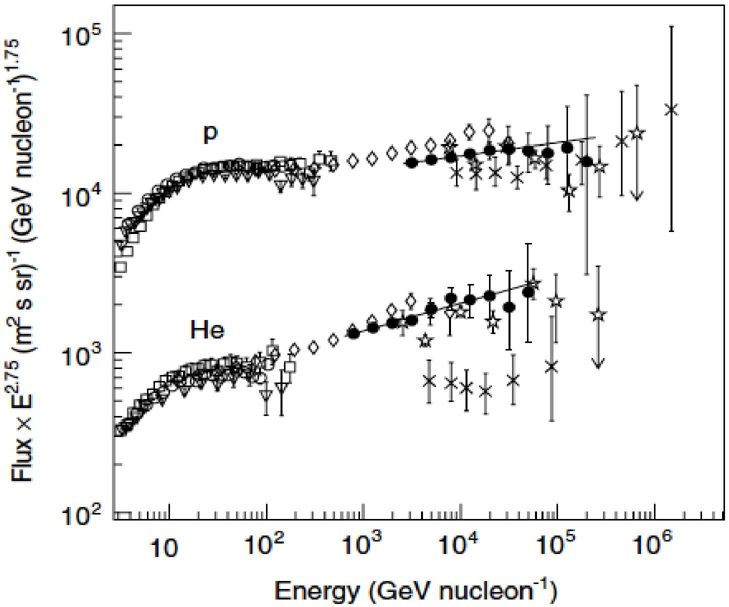
New measurements at accelerators (e.g. LHCb) in order to lower the systematic uncertainty on secondary production calculations

Secondary or primary origin ?

Same spectral dependence for protons, antiprotons and positrons
Softer spectrum for electrons

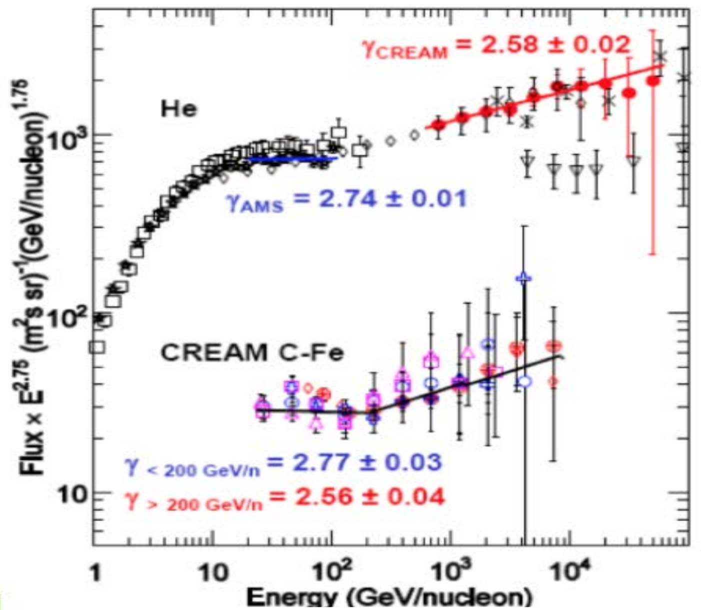


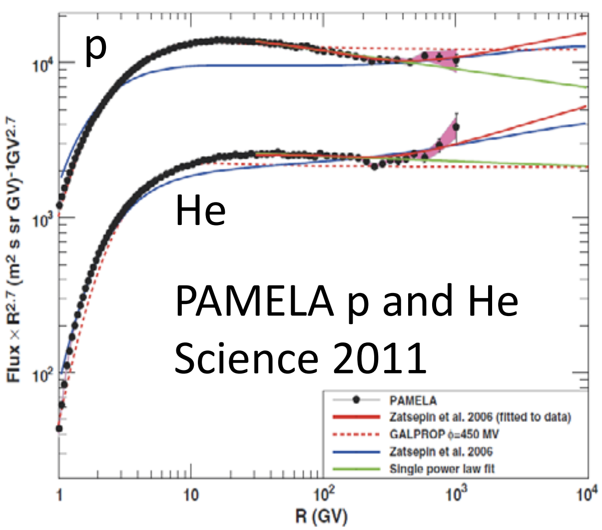
Proton and helium: (discrepant) hardenings

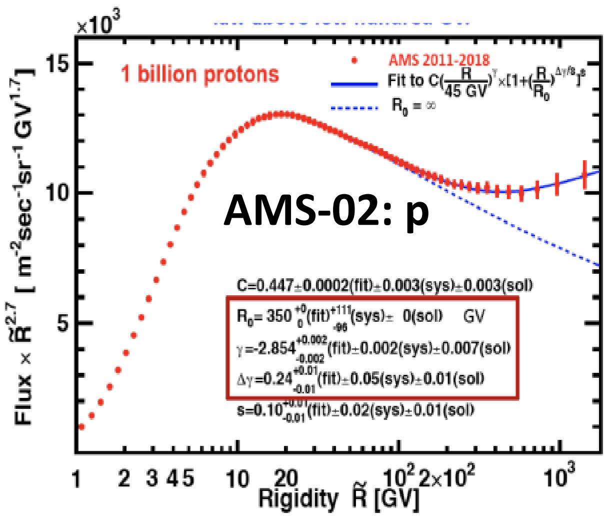


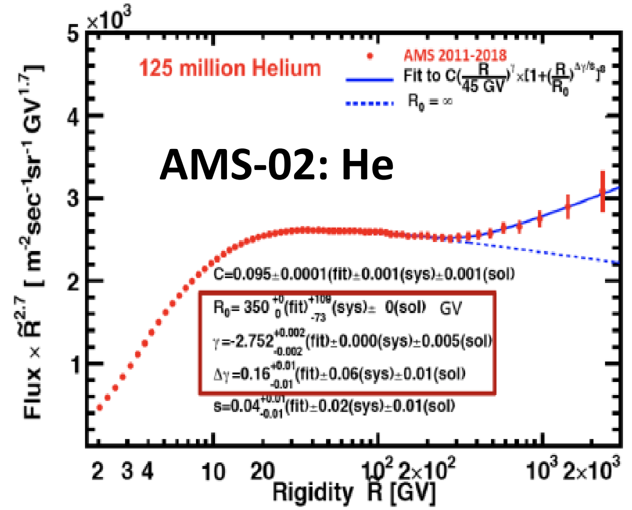
CREAM
First hints for Hardenings.

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

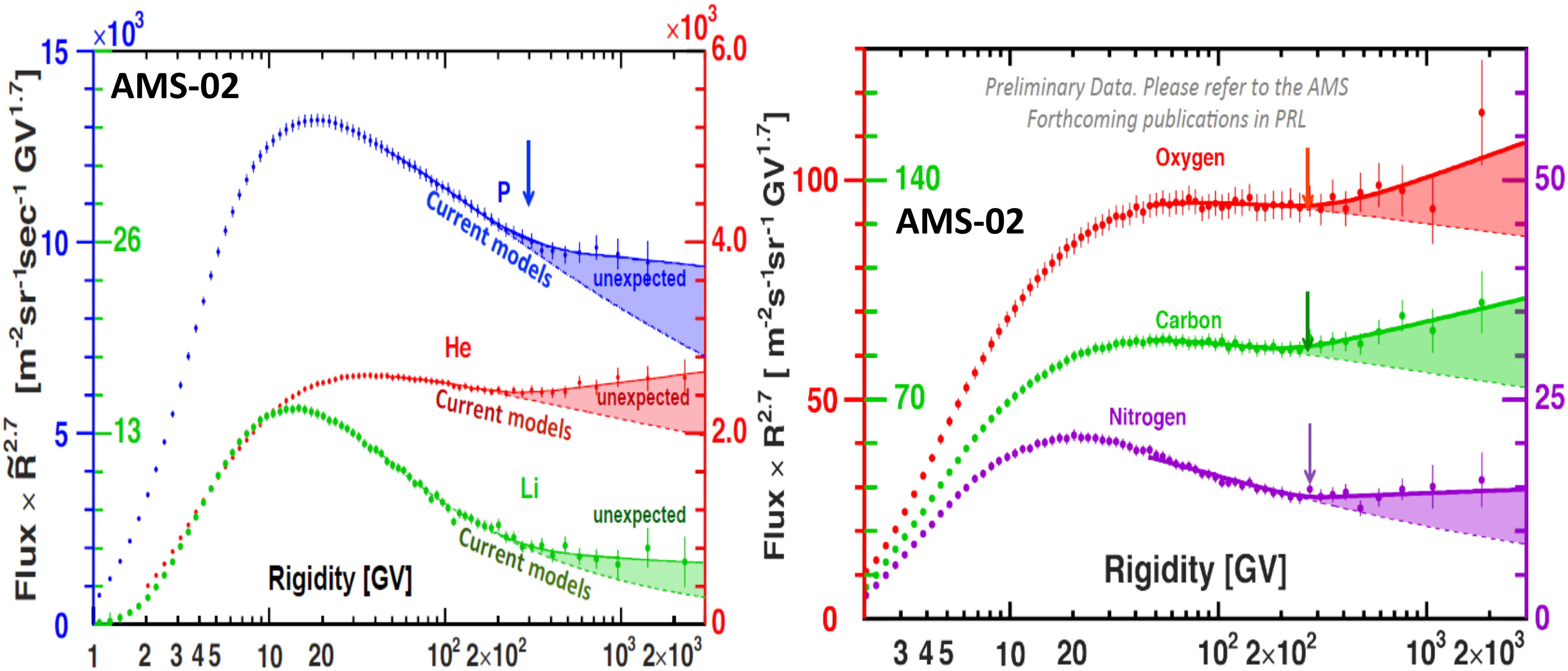








Similar hardenings for other nuclei



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

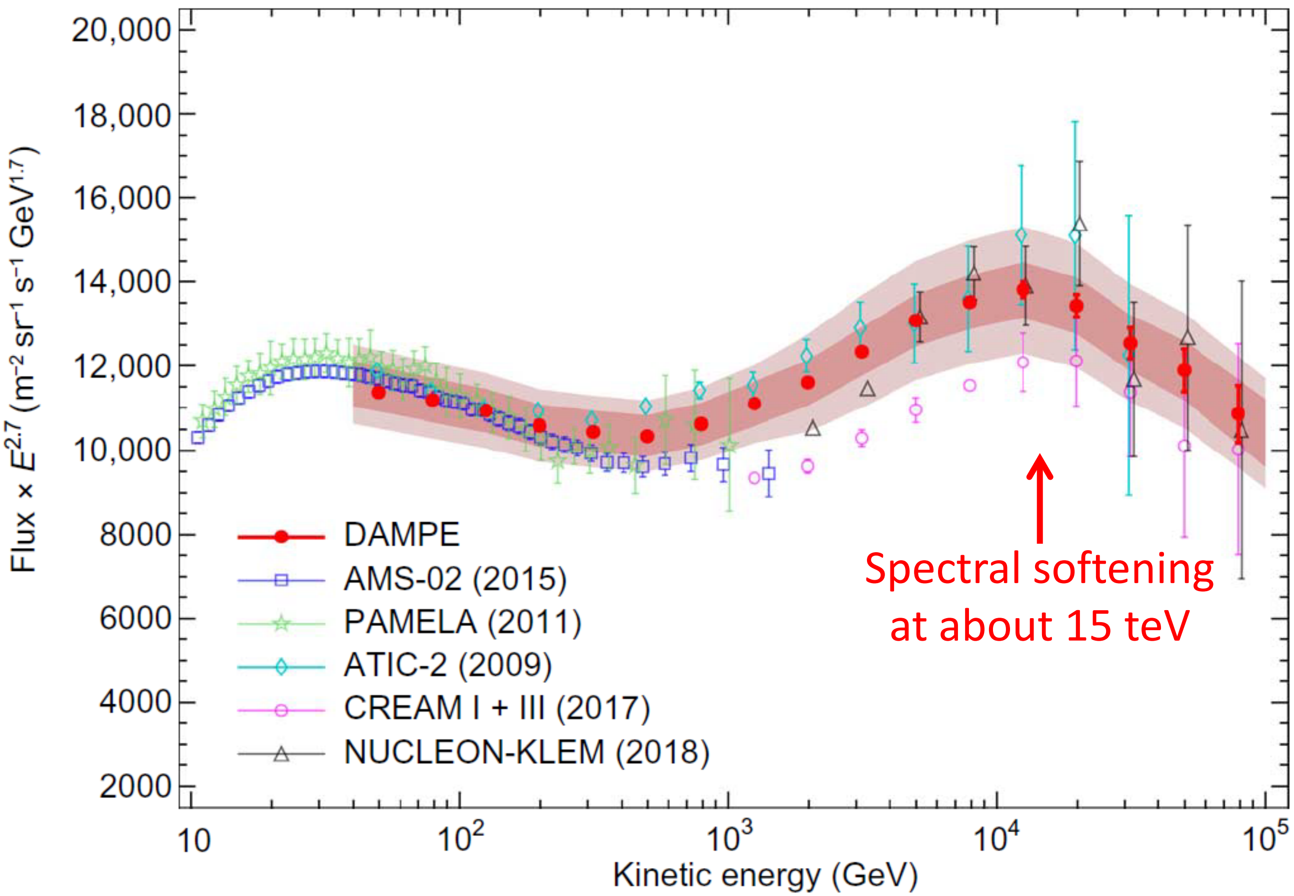
New findings by DAMPE: protons

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



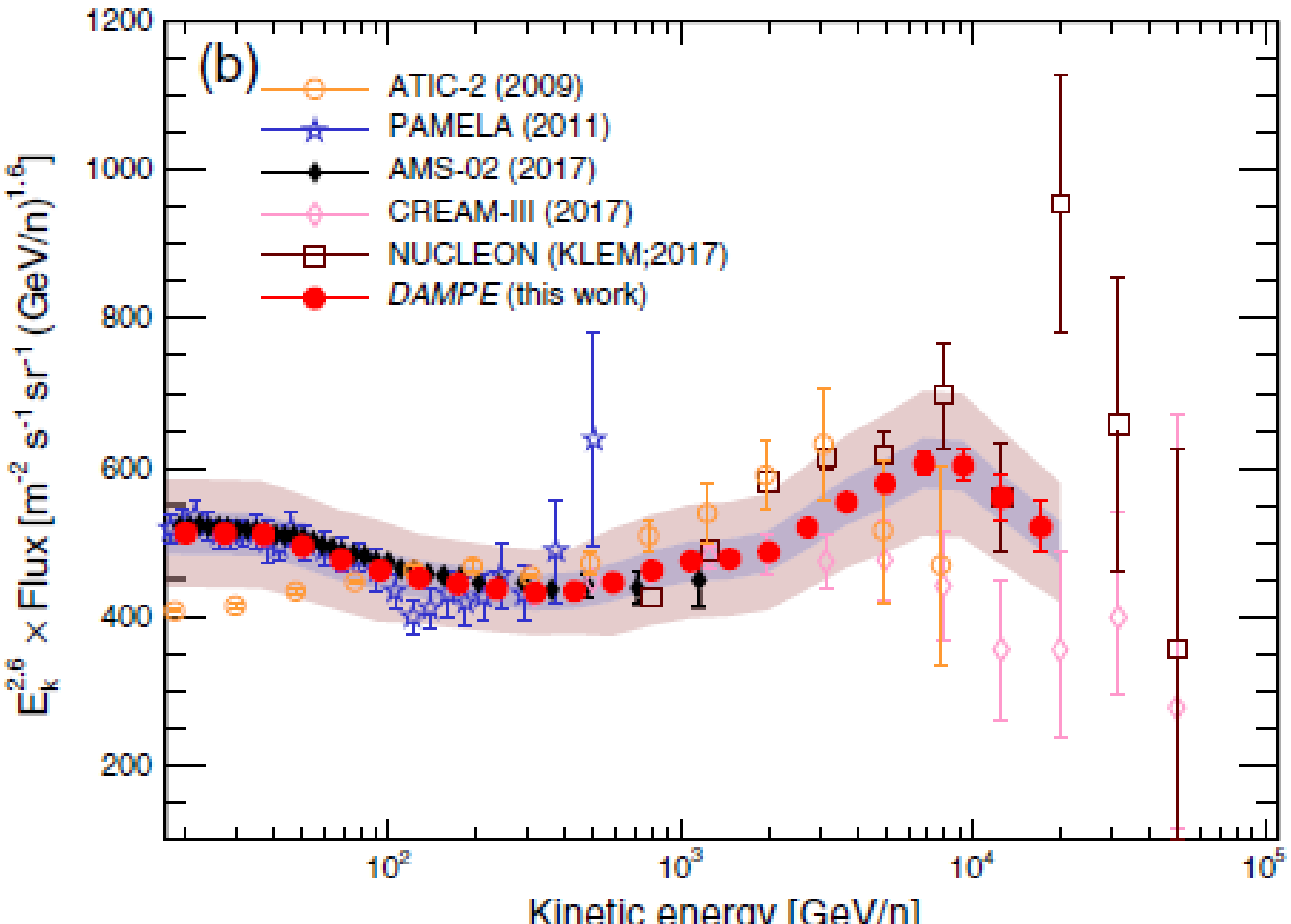
New findings by DAMPE: helium

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)

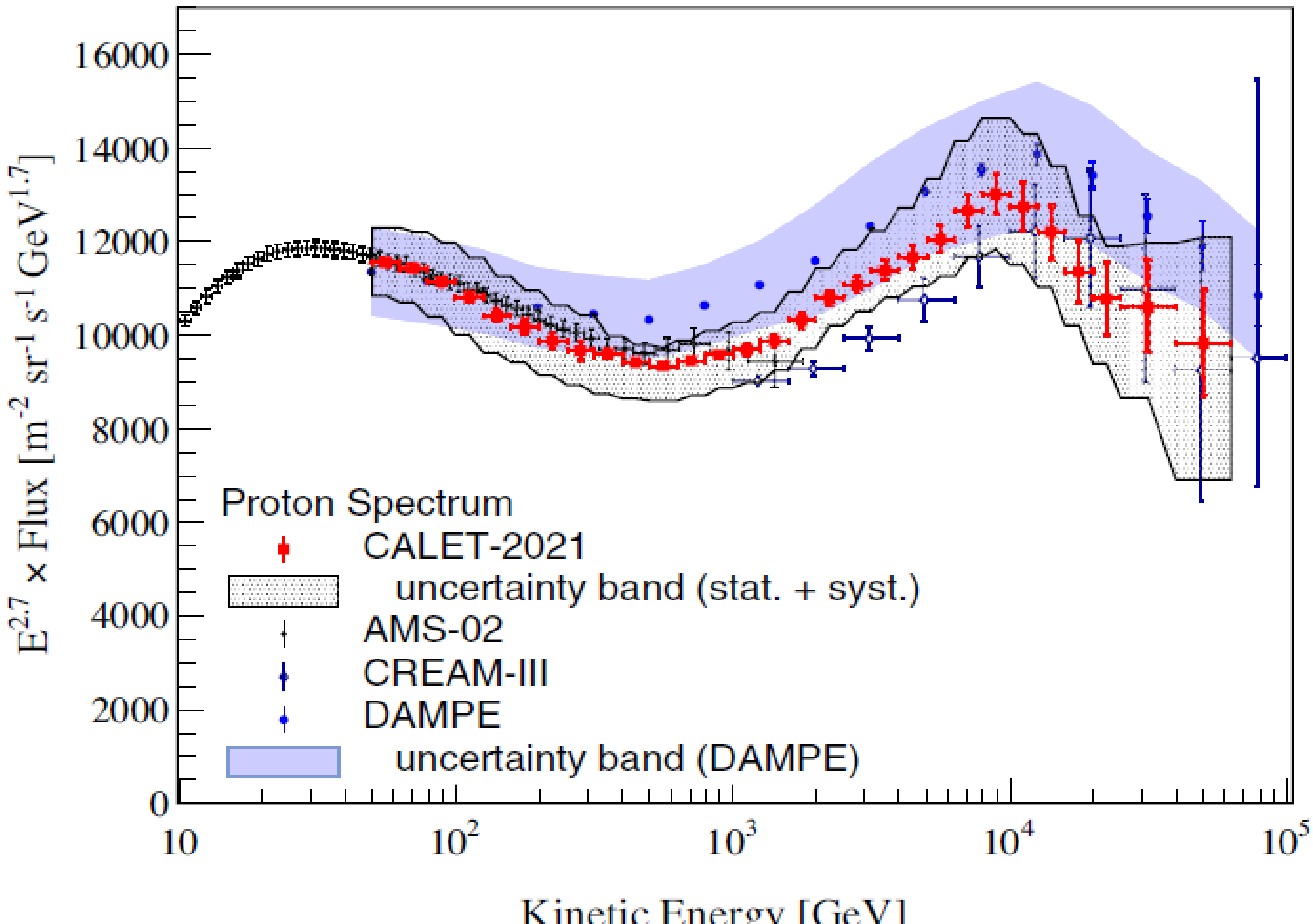
Proton softening confirmed by CALET

PHYSICAL REVIEW LETTERS **129**, 101102 (2022)

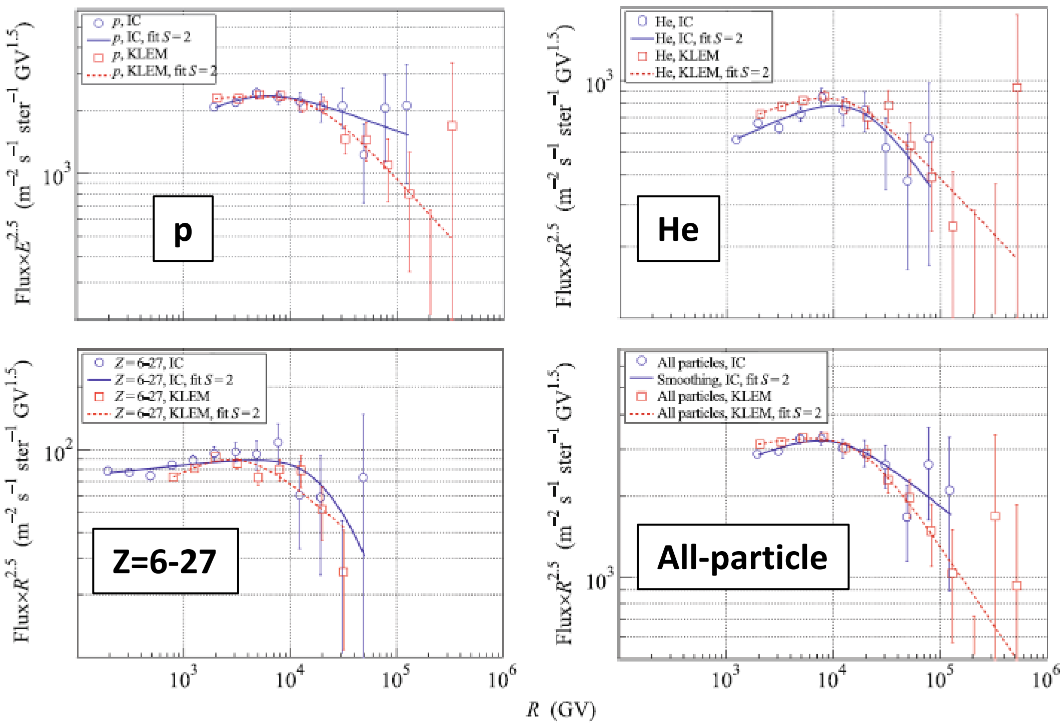
Editors' Suggestion

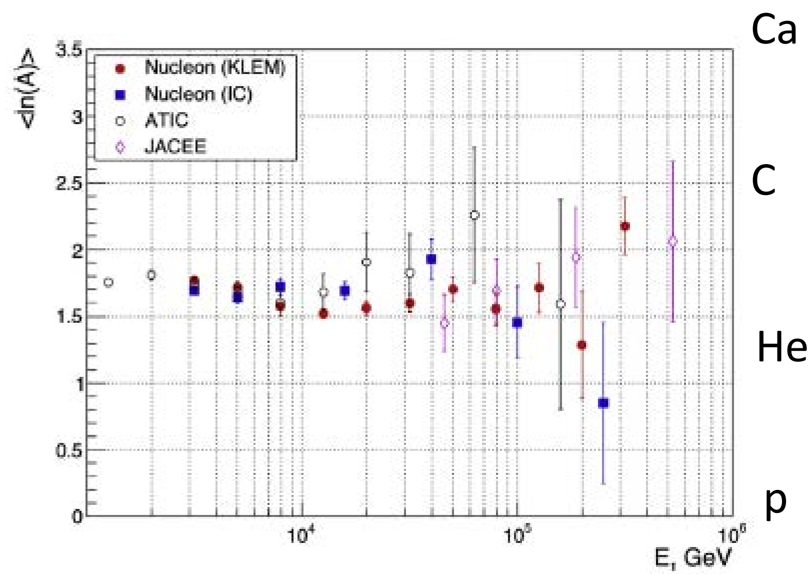
September 1, 2022

Observation of Spectral Structures in the Flux of Cosmic-Ray Protons from 50 GeV to 60 TeV with the Calorimetric Electron Telescope on the International Space Station

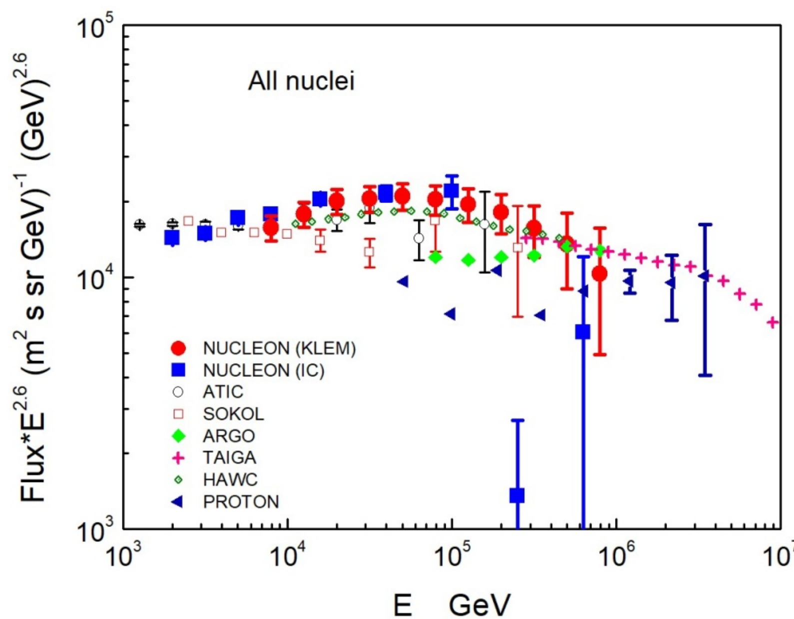


Other nuclei and larger energies



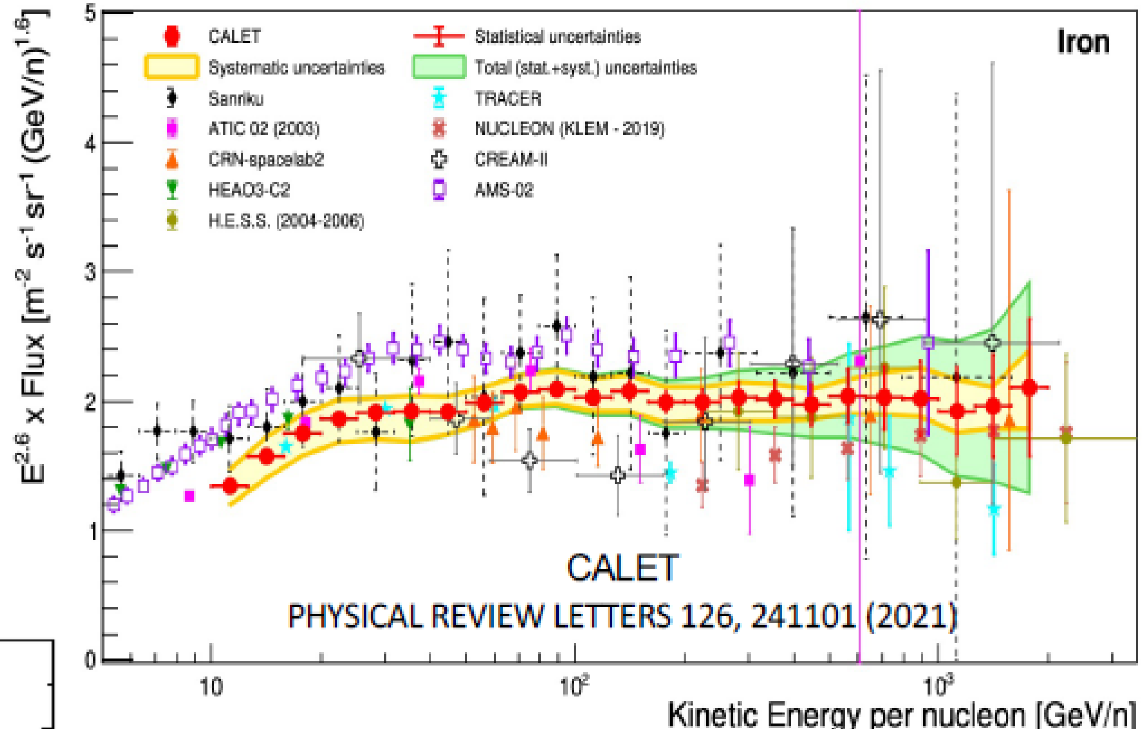


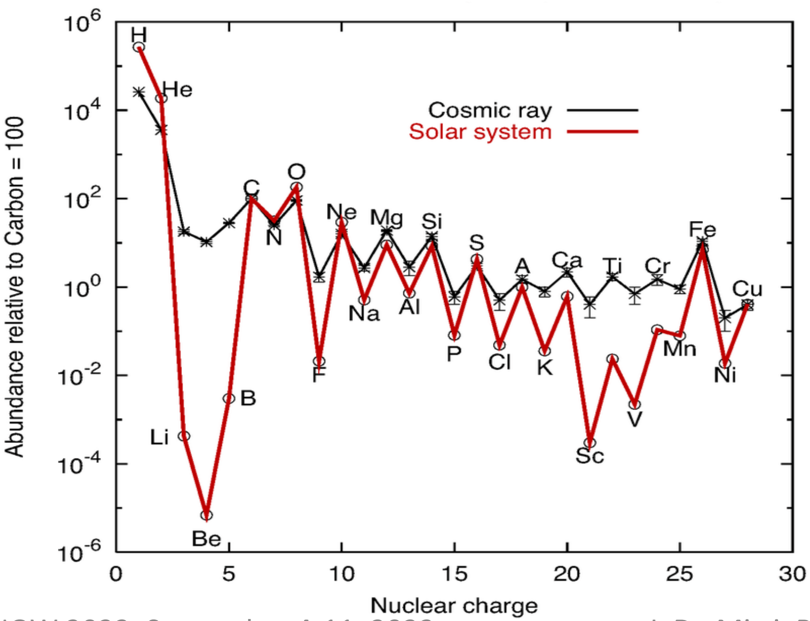
Nuclear spectra from NUCLEON



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

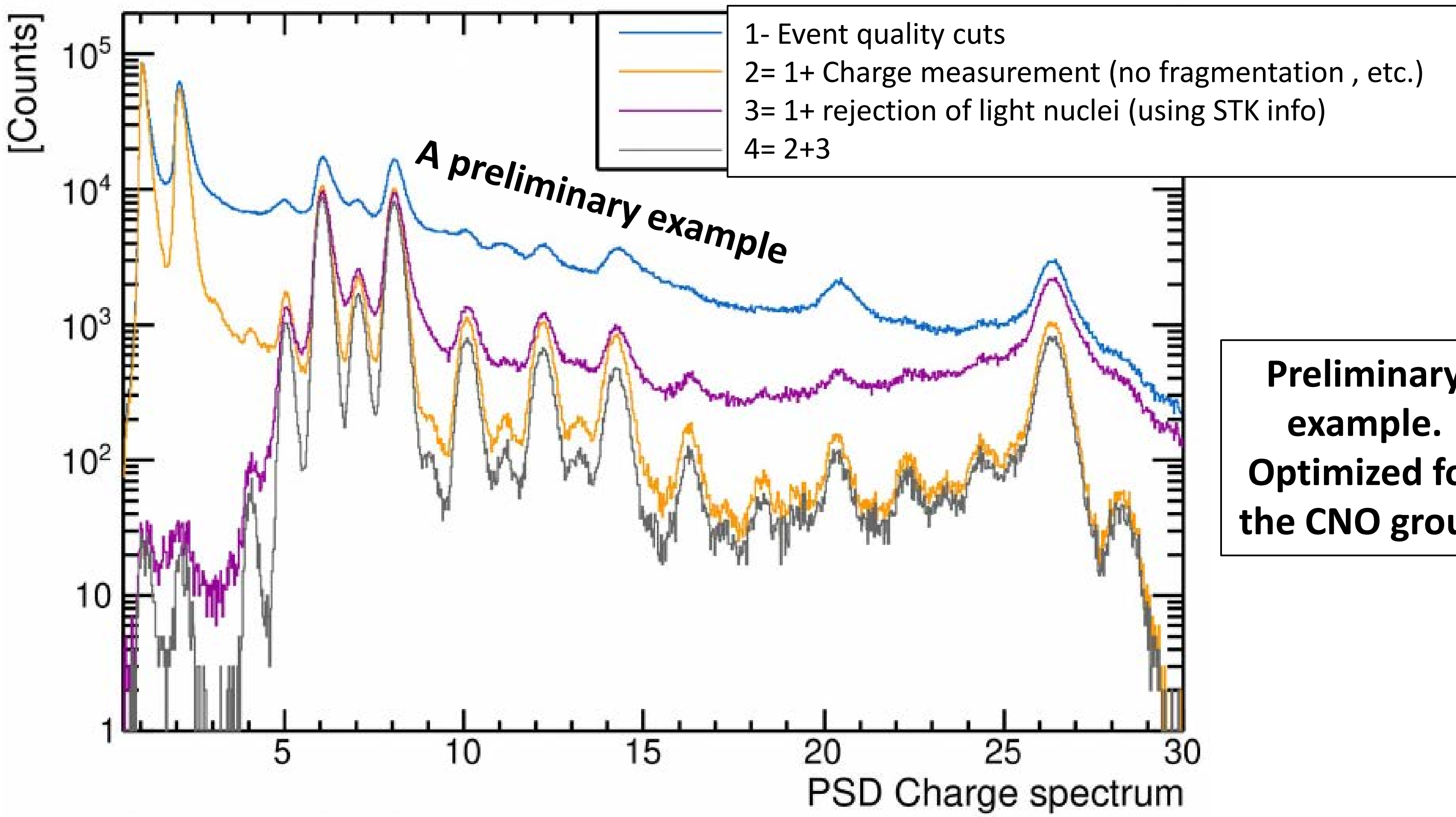
The iron flux: AMS-02 and CALET





Nuclei identification: the case of DAMPE

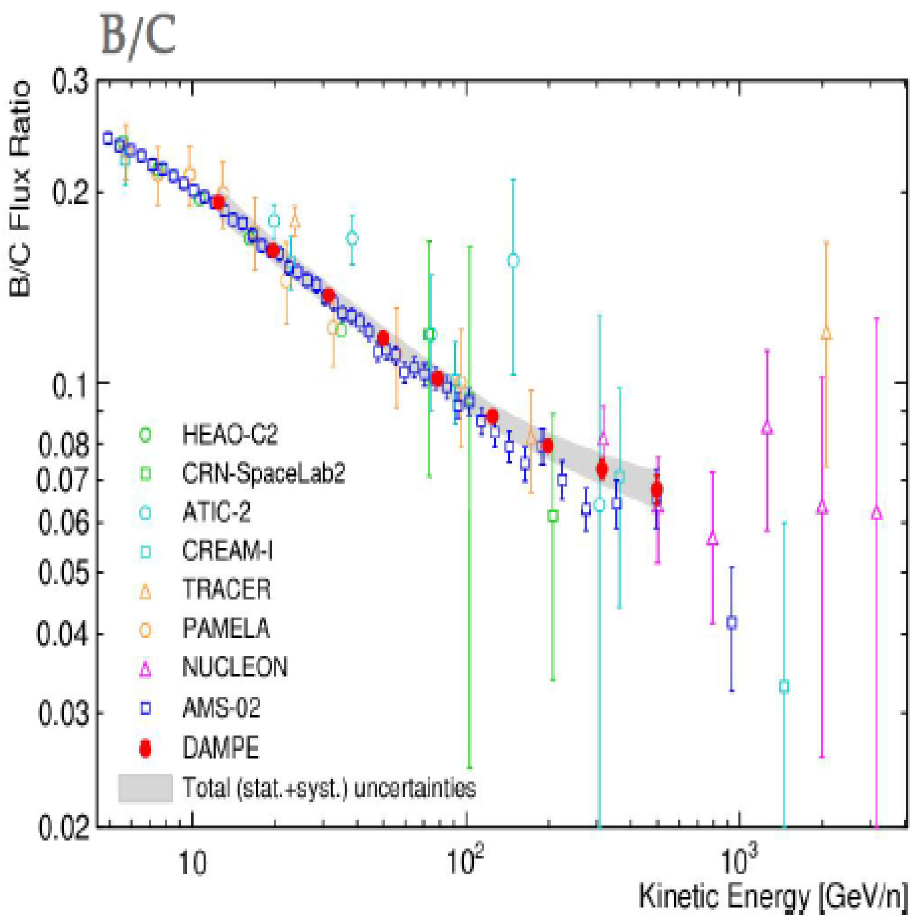
Several independent analyses are ongoing from Li up to Iron
Different selection criteria to reject other nuclei and avoid charge misidentification
Different approaches to limit and better evaluate the systematics.

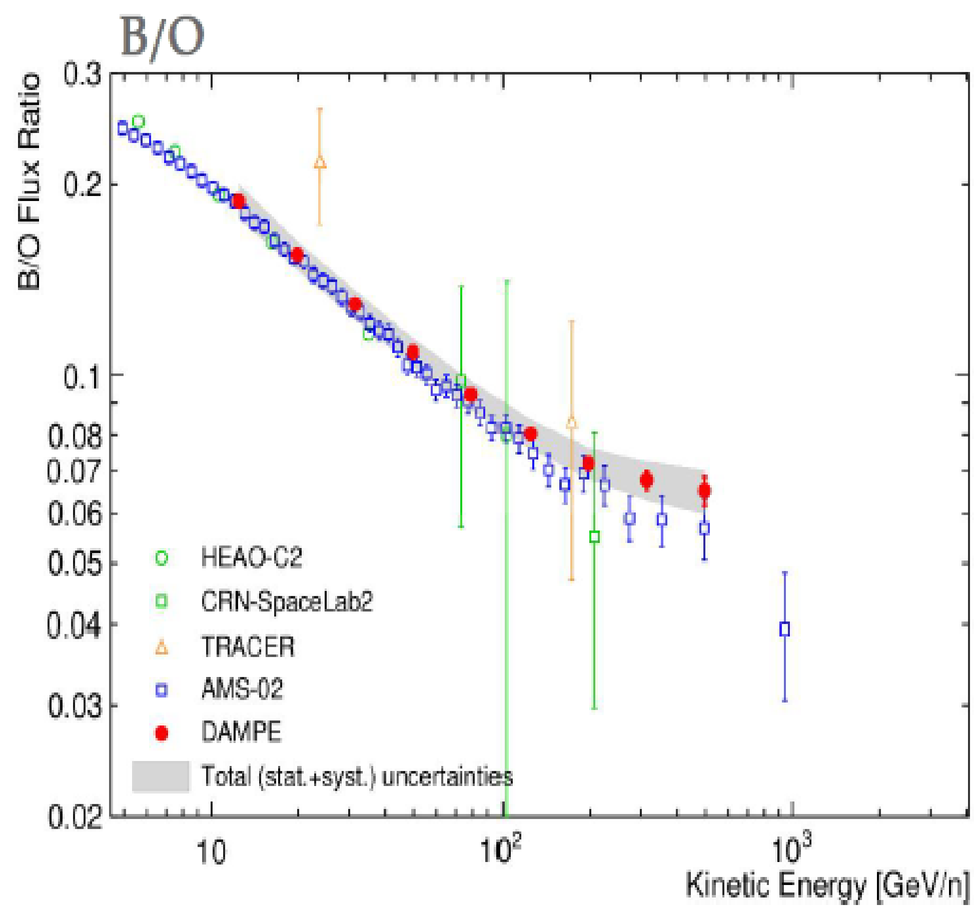


Preliminary example. Optimized for the CNO group

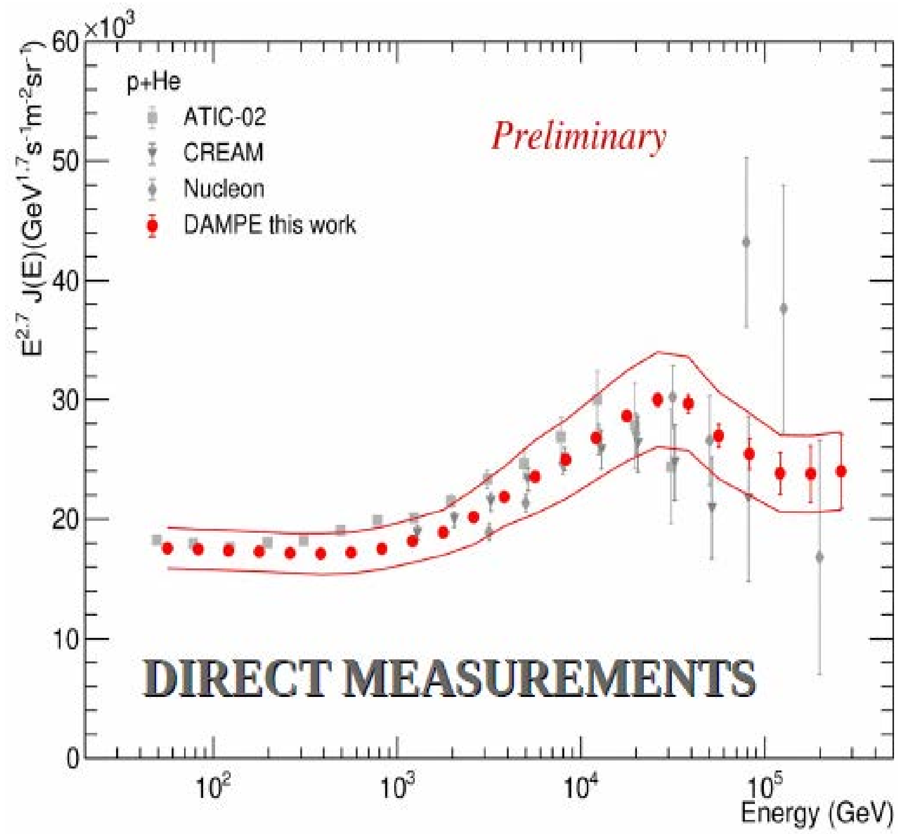
Secondary-to-primary ratios

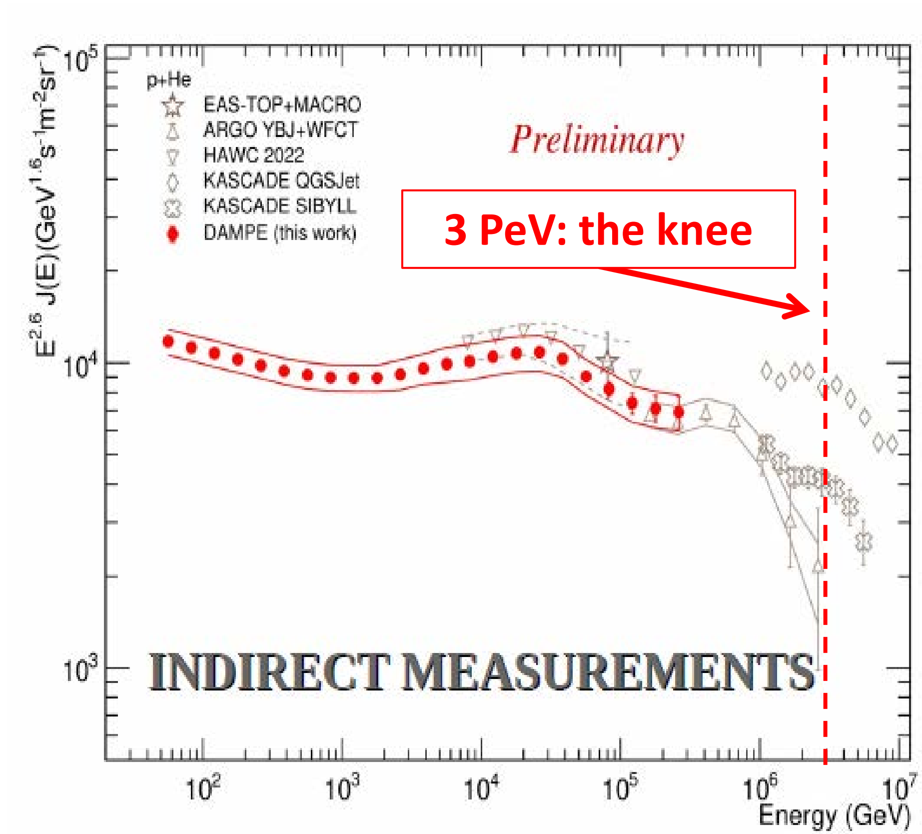
Preliminary DAMPE results for B/C and B/O.   Extension to few TeV/n in progress.





The DAMPE p+He spectrum



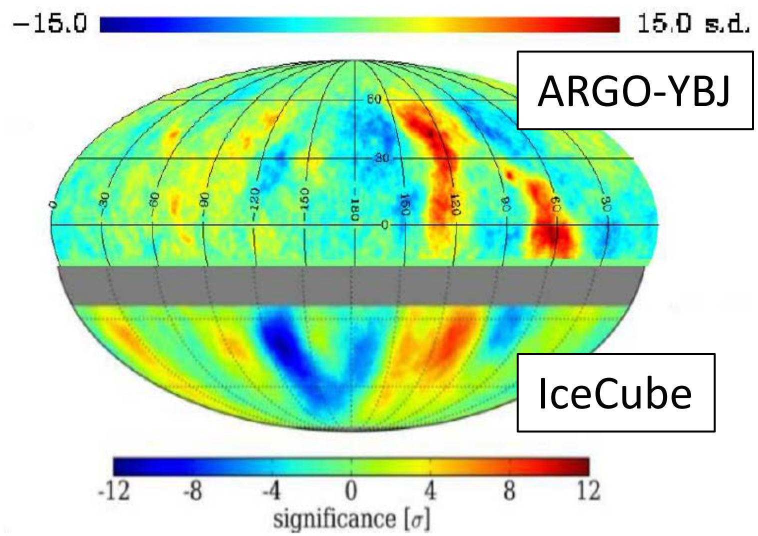


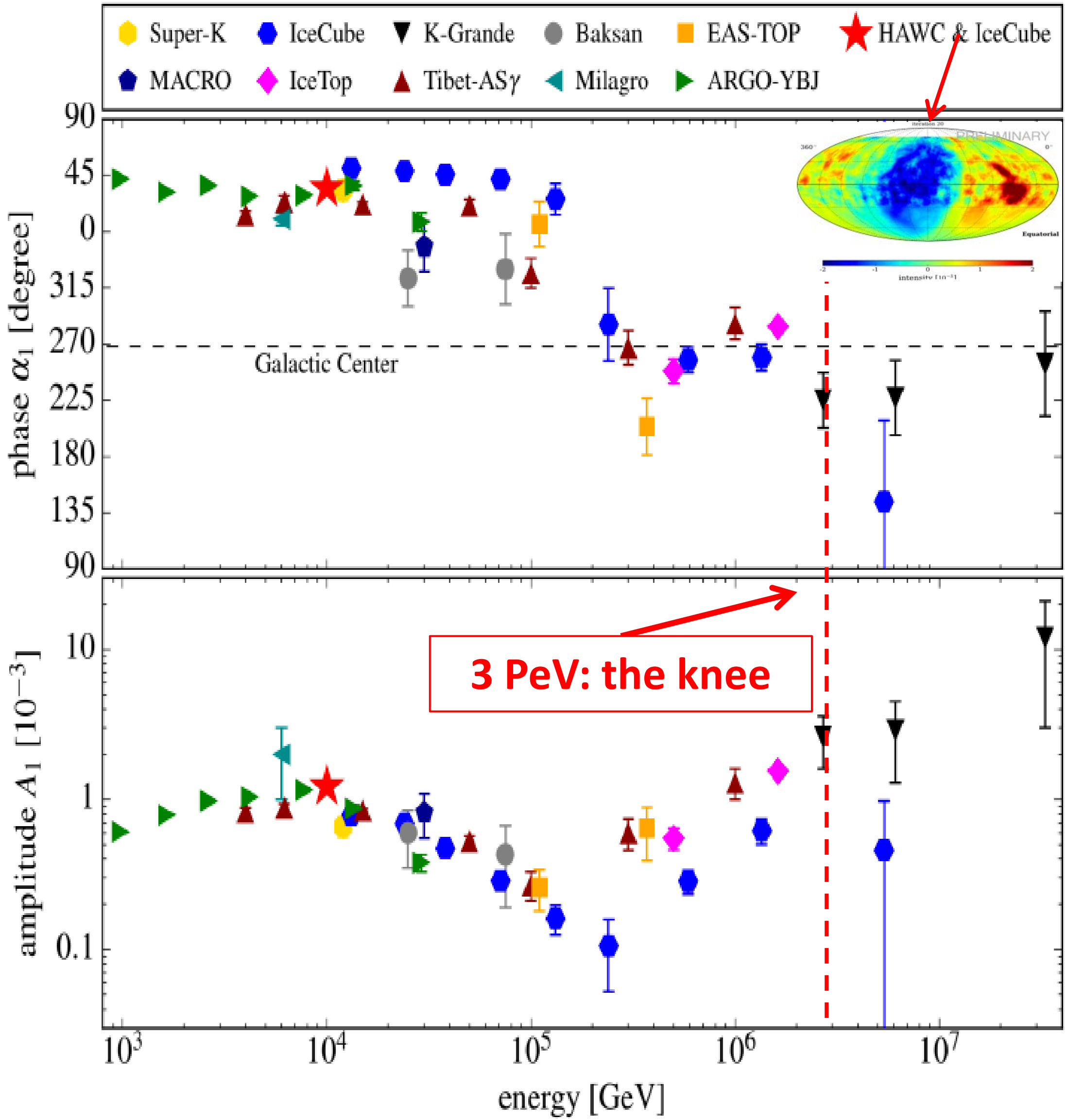
- ✓ Confirmation of the softening
  (at about 25 TeV due to the combination of p and He spectra)
- ✓ Extension to 300 TeV
- ✓ Overlapping with indirect measurements

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

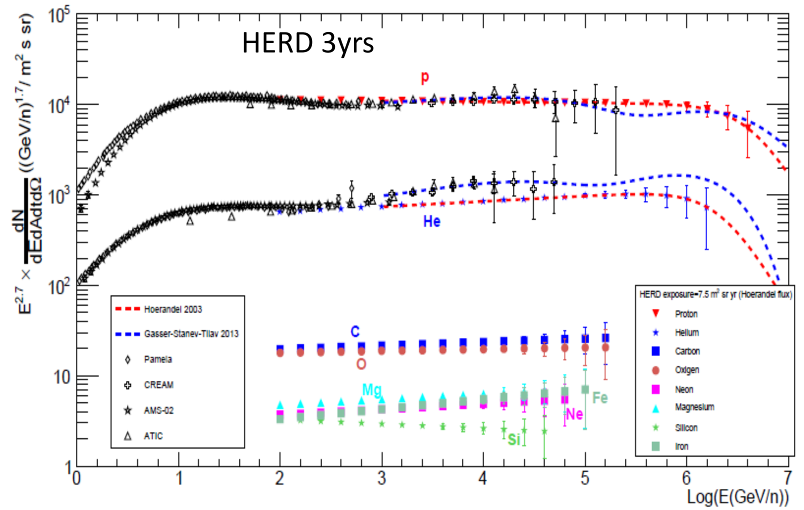


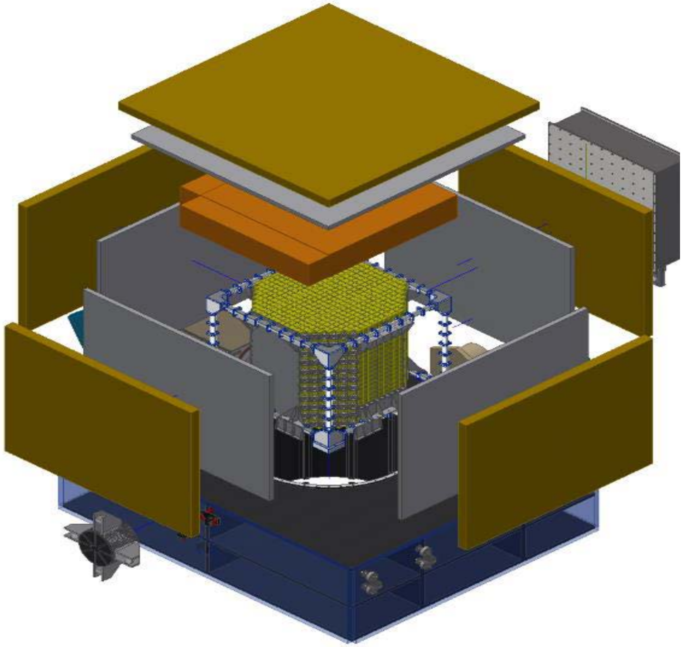


HERD: towards the knee from space

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.

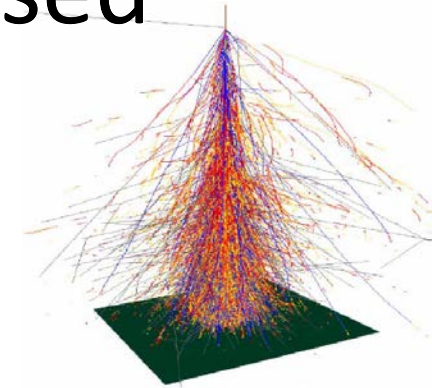
One order of magnitude jump in exposure wrt current generation CR experiment: 10-15 m² sr yr





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

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

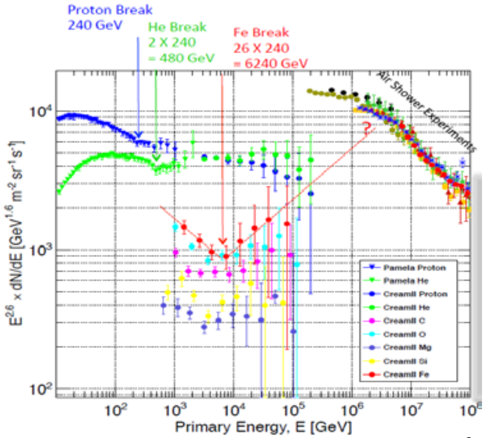
Detect small anisotropies

Limitations:

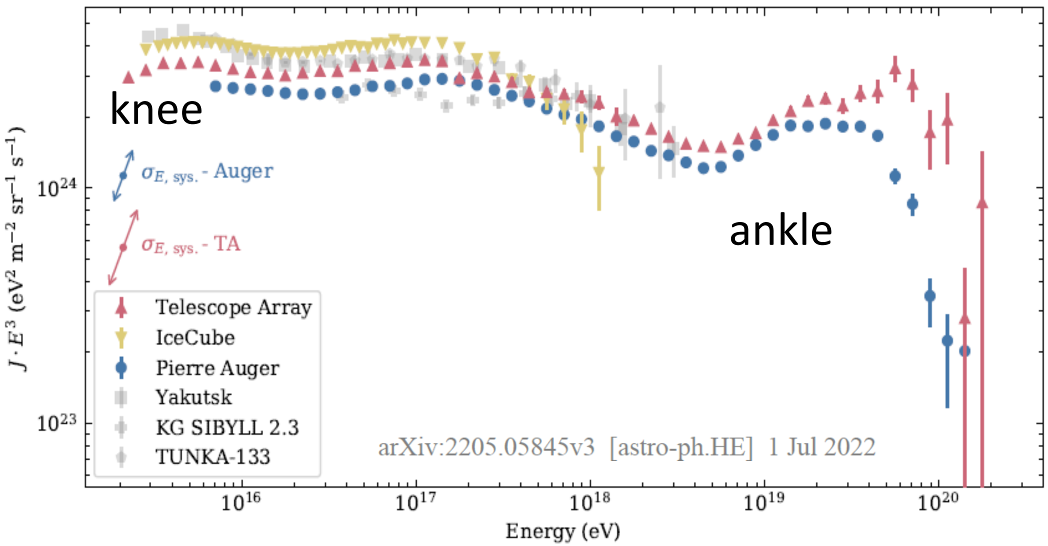
Poor mass resolution

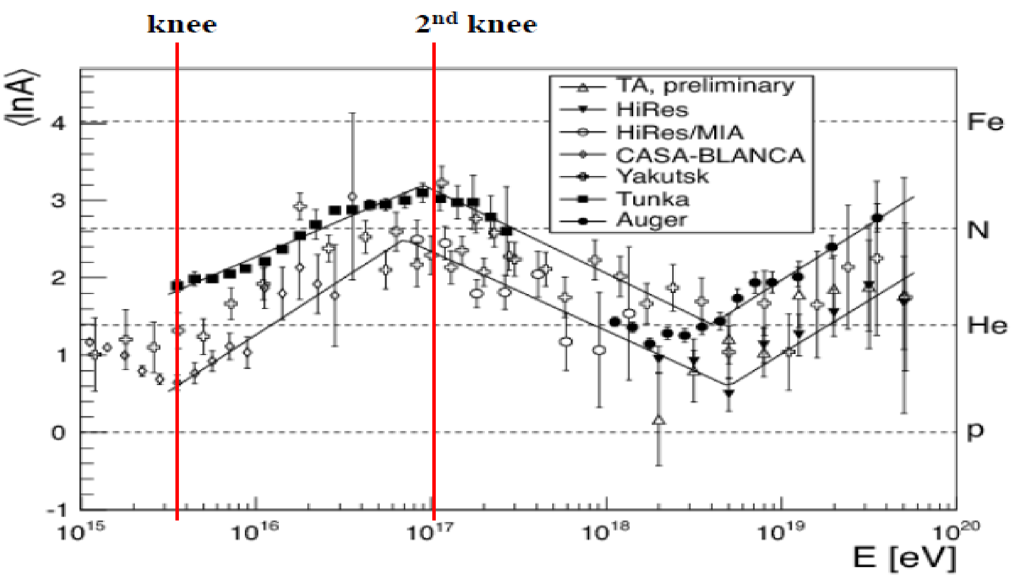
Intrinsically limited by systematics

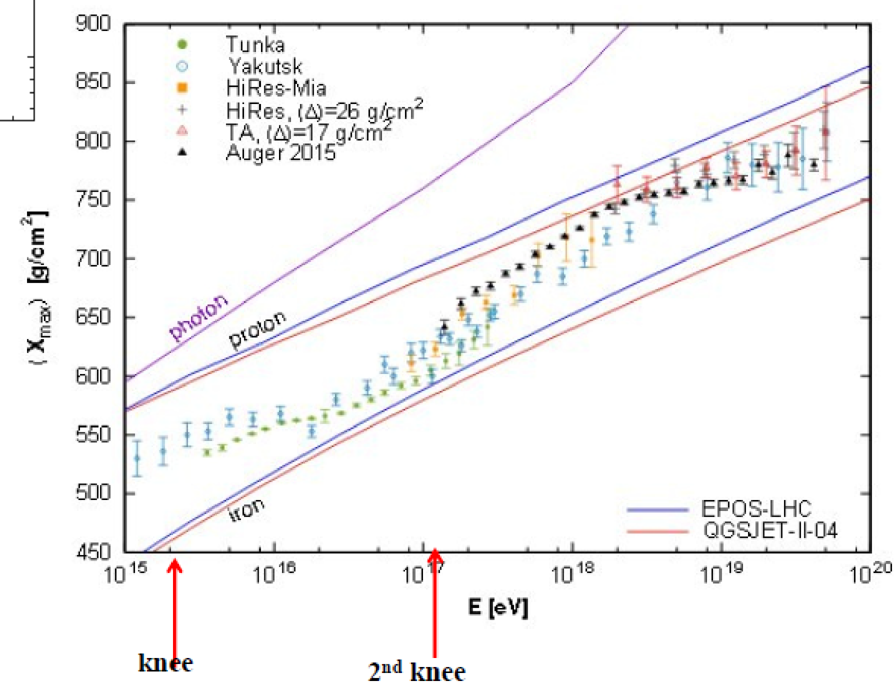
Large model dependence



Not simple evolution toward the ankle

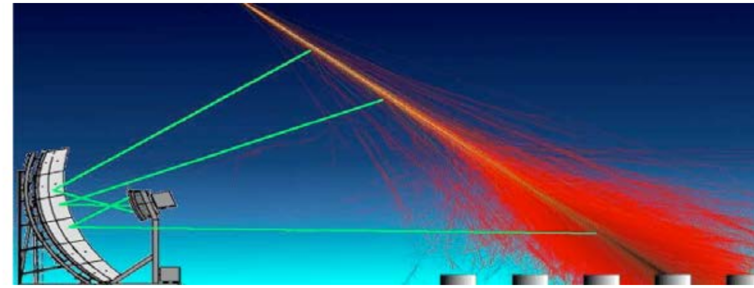






The Pierre Auger Observatory

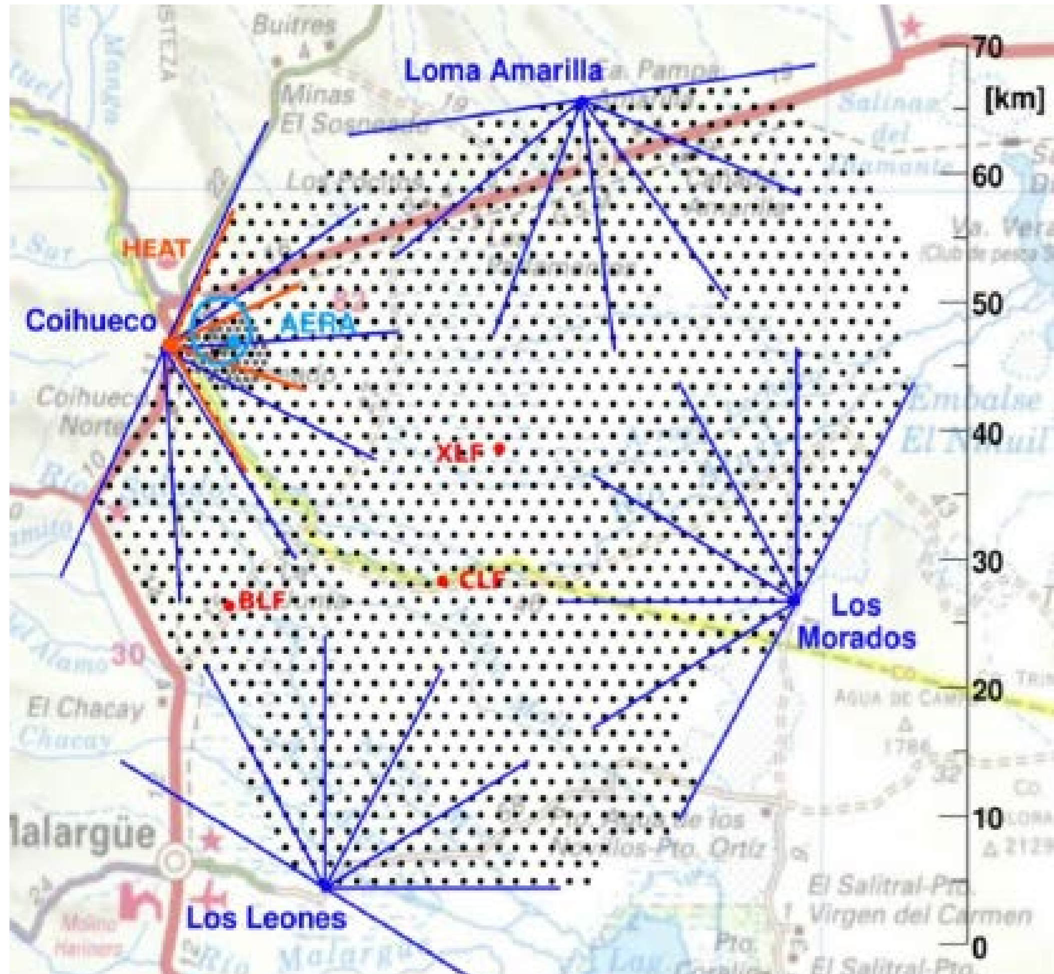
- Malargue (Arg, 35°S), 1400 m a.s.l.
- E range: 10^{17} eV – 10^{21} eV
- Multi-detectors, hybrid reconstruction
- **Surface Detector** array (SD)
  - Sampling EAS particles at ground
  - 1670 WC tanks, 1500 m spacing, 3000 km².
  - SD-750, SD-433 (→ ~10^{16} eV)
- **Fluorescence Detectors** (FD)
 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



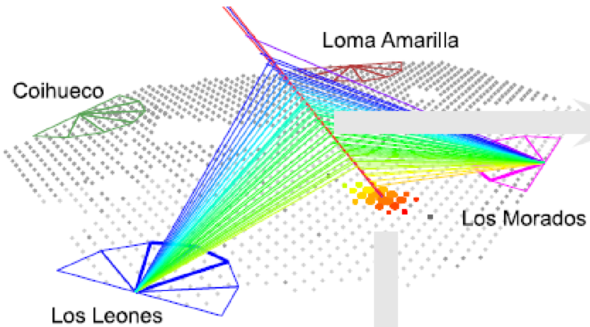
Surface Detector
1670 Water Cherenkov tanks
3.6 m diameter , 1.2 m depth
3 9'' PMTs + 1 Small 1'' PMT

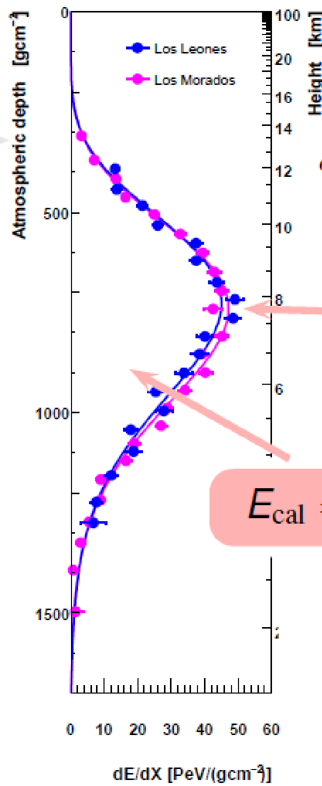
Plus a Scintillation detector on top

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





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

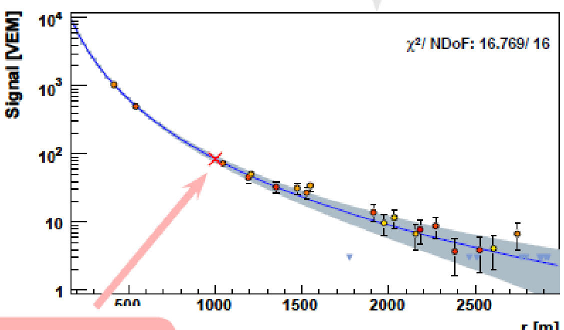
$X_{\max}$

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

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

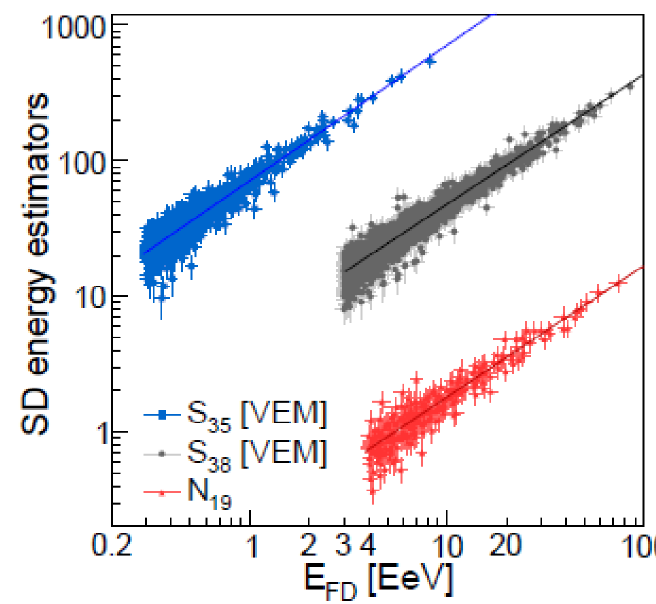
Calorimetric energy measurement with the FD

Energy calibration of SD observables using FD data



S_{1000}

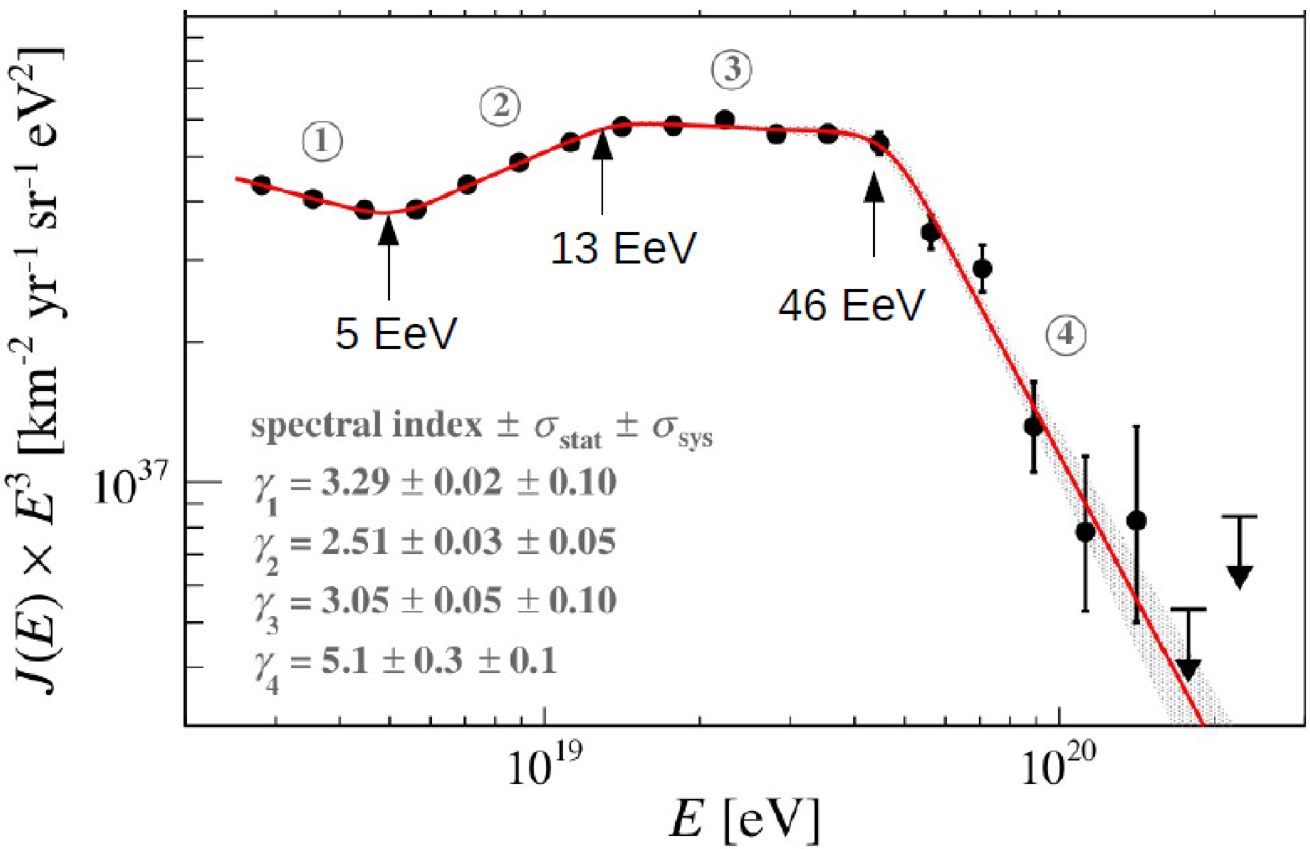
$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

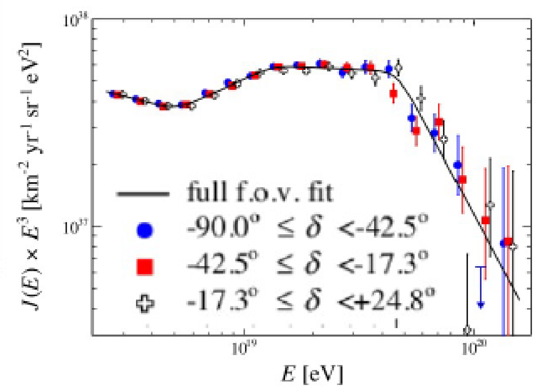


Very good **energy** (8% stat , 15% sys)
and $\mathbf{X_{max}}$ (lower than 10g/cm2 stat and 10g/cm2 sys)
resolutions and uncertainties.

At the highest energies….

The UHECR energy spectrum measured by
 the Pierre Auger Observatory



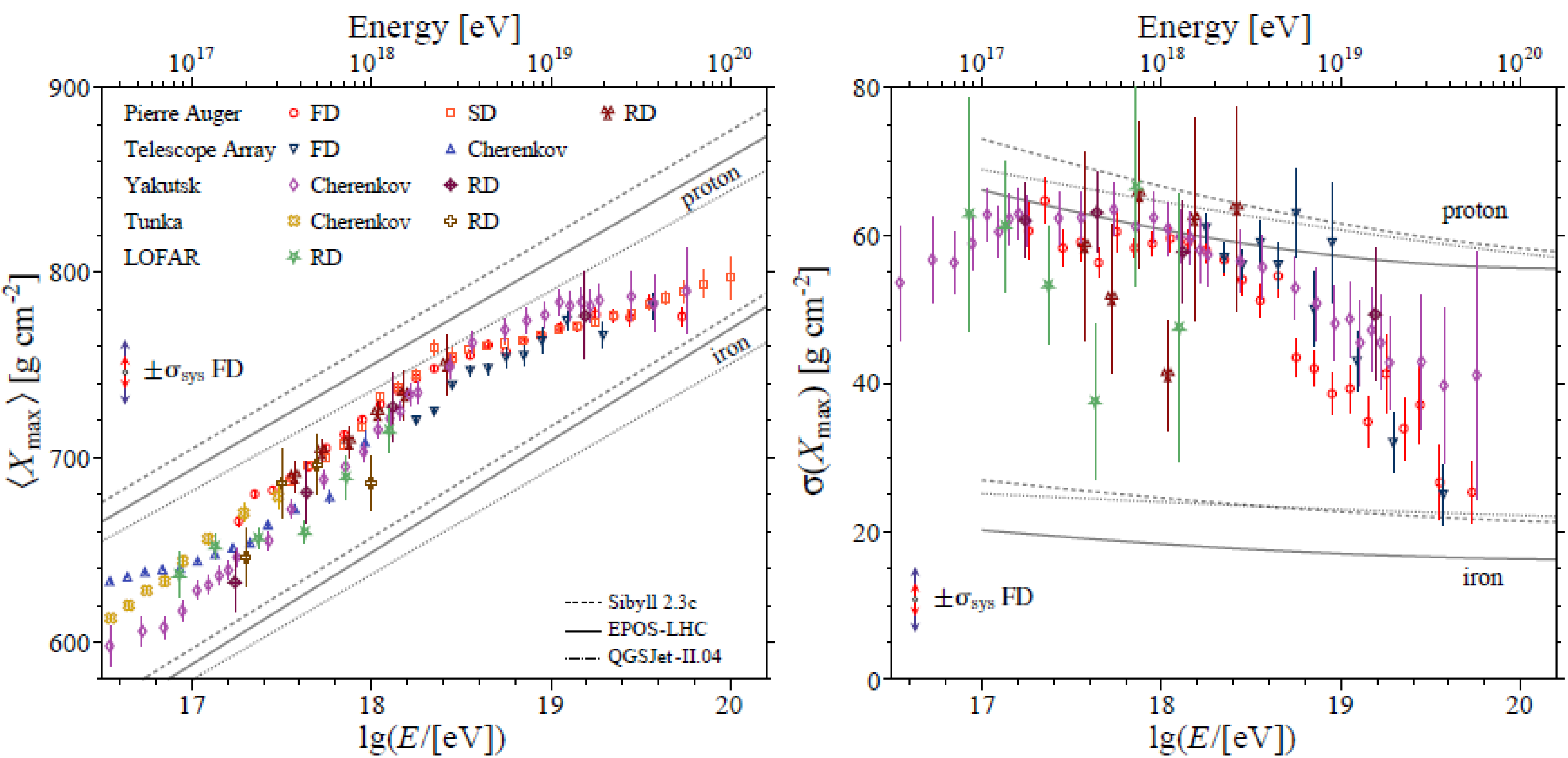


No dependence on the declination has been observed

At the highest energies….

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

arXiv:2205.05845v3 [astro-ph.HE] 1 Jul 2022



At the highest energies: AUGER large scale anisotropy

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

COSMIC RAYS

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.

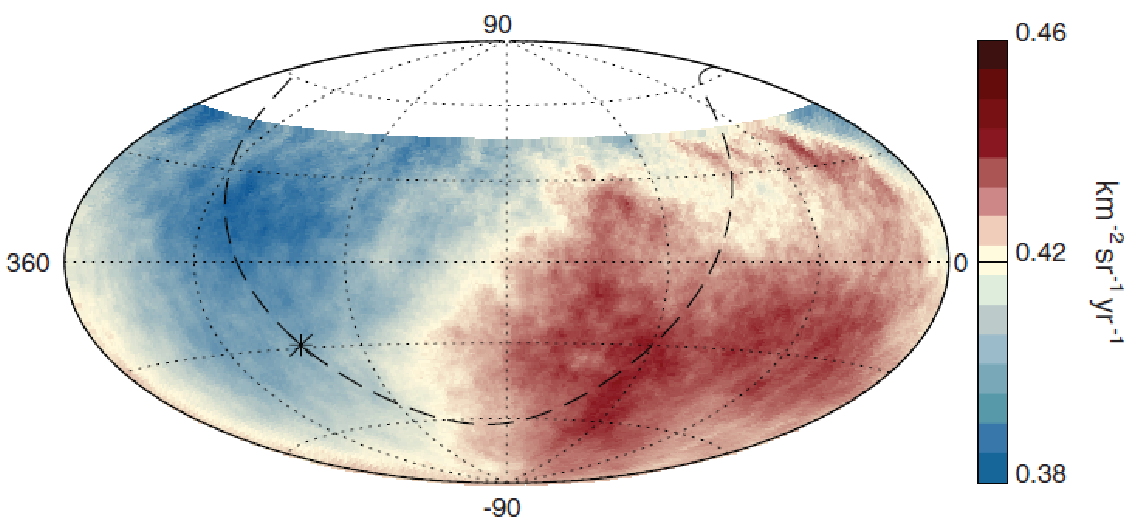


Fig. 2. Map showing the fluxes of particles in equatorial coordinates. Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The galactic center is marked with an asterisk; the galactic plane is shown by a dashed line.

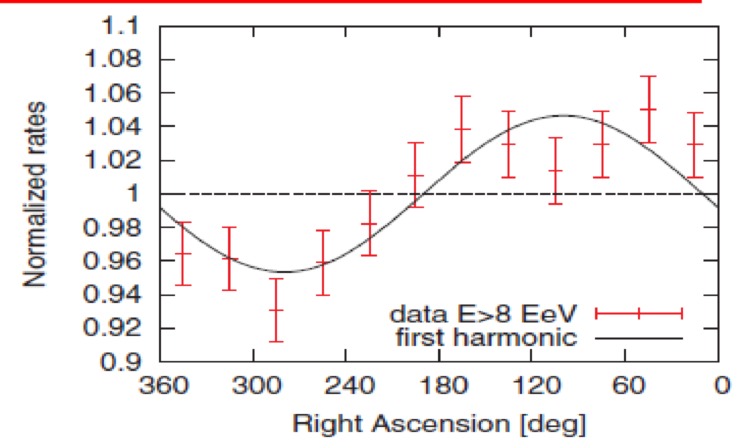
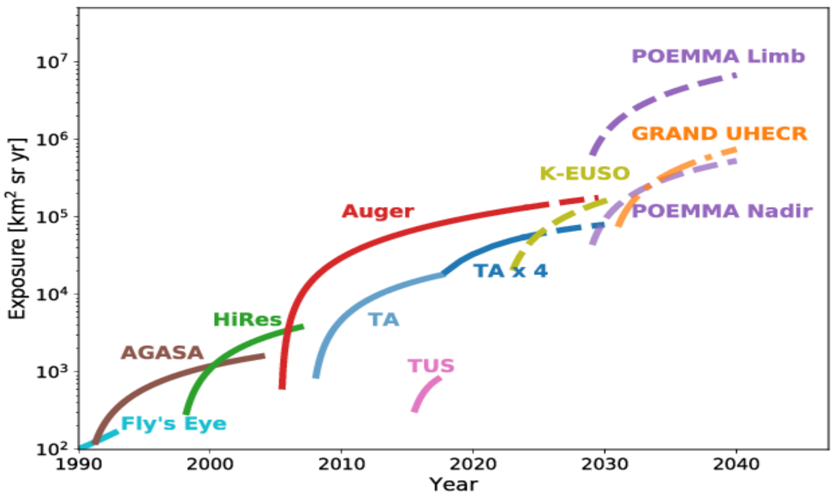


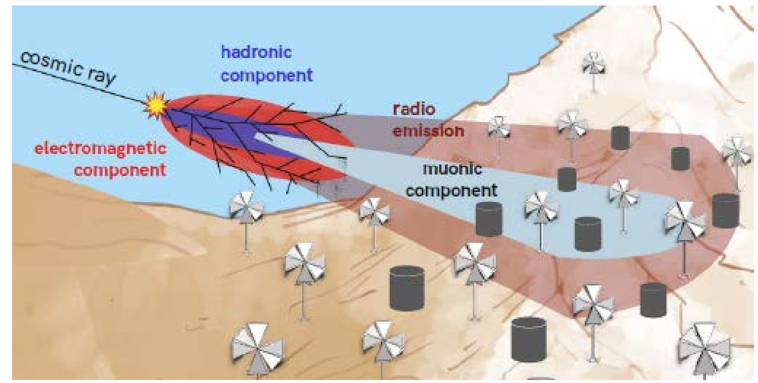
Fig. 1. Normalized rate of events as a function of right ascension. Normalized rate for 32,187 events with $E \geq 8$ EeV, as a function of right ascension (integrated in declination). Error bars are 1σ uncertainties. The solid line shows the first-harmonic modulation from Table 1, which displays good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

New techniques at the highest energies

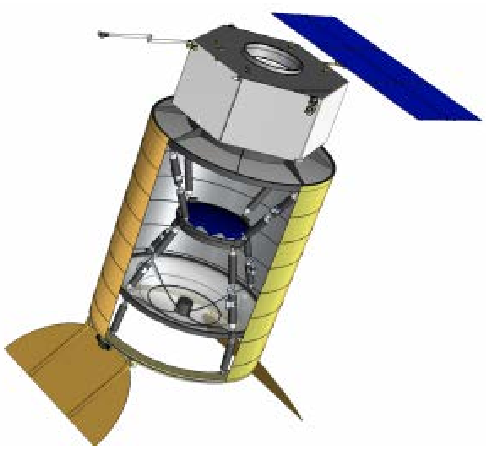
Improve the statistics by a jump in exposure, for UHE CR and neutrinos:
a giant ground arrays (GCOS, GRAND,..) and/or space-based (POEMMA,...) observatories

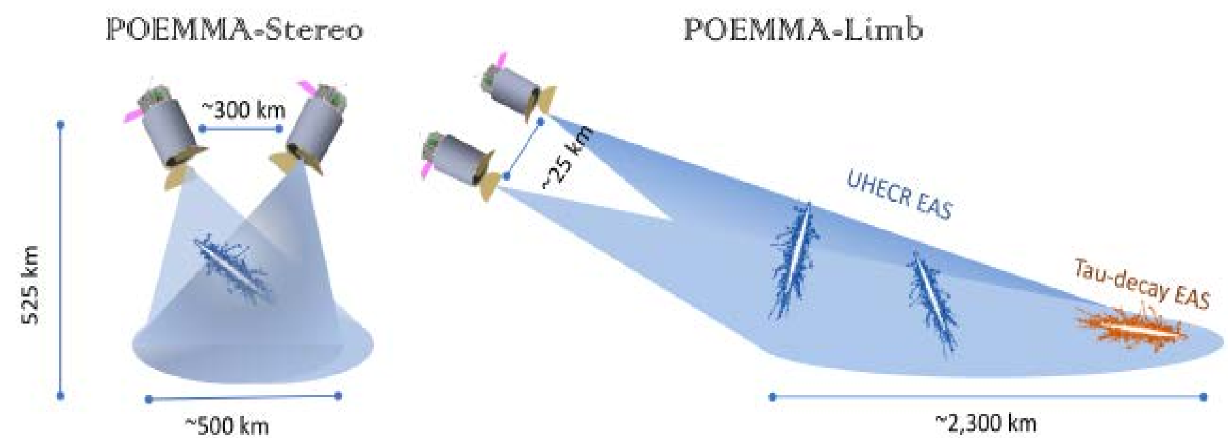


GRAND: Giant Radio Array for Neutrino detection



POEMMA: Probe Of Extreme Multi-Messenger Astrophysics





UHECR2022 at GSSI

UHECR2022:
6th International Symposium on Ultra High Energy Cosmic Rays

3-7 October 2022
Gran Sasso Science Institute, L'Aquila, Italy
Europe/Rome timezone

- Overview
- General information
- First Circular
- Second Circular
- Invited Review Speakers
- Special Lectures
- Poster Sessions
- Proceedings
- Call for Abstracts
- Registration
- Fee Payment
- Participant List
- Timetable
- Accomodation
- Venue and travel information
- Visit to LNGS and Social Events
- International Advisory Committee
- Local Organizing Committee
- Statement on the current international crisis

Contact
uhecr2022@gssi.it

General information

The UHECR2022 symposium will be held at the Gran Sasso Science Institute (GSSI) and jointly organized by GSSI, INFN - Laboratori Nazionali del Gran Sasso (LNGS) and the University of L'Aquila.

It will be the sixth edition of the series of meetings that started in Nagoya in 2010 and continued in CERN (2012), Springdale, Utah (2014), Kyoto (2016) and Paris (2018).

The event is dedicated to the discussions of the latest UHECRs observations and theoretical developments, also reviewing future plans in the field.

Topics will include the following subjects:

- Acceleration to the highest energies
- Source scenarios and CR propagation
- Galactic and extragalactic magnetic fields
- Transition from galactic to extragalactic CRs
- Hadronic interactions related to EAS interpretation
- Multi-messenger connections of UHECRs, neutrinos, gamma rays and gravitational waves
- Physics beyond the standard model

Invited reviews, contributed talks and posters will be presented.

You are invited to submit your abstract by July 25 (**postponed to August 5**).

The symposium will be held in person, in compliance with the relevant COVID-19 regulations at the time of the meeting.

Due to possible COVID-19 restrictions, the participation to the workshop might be limited to the first registrants. We then recommend you to register as soon as possible, and anyway not later than August 31 (**postponed to September 9**).

3-7 October at GSSI
More than 145 participants
About 70 talks + 35 posters

www.uhecr2022.gssi.it

GRAN SASSO SCIENCE INSTITUTE

UNIVERSITÀ DEGLI STUDI DELL'AQUILA

Summary

Continuous , steady improvements in CR physics.

New data gave some anwers but also raised new questions.

Many “unexpected” results:
→Exciting opportunities

New ideas/tools will (as always)
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