Roberto Aloisio
Eugenio Coccia
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# Multiple Messengers and Challenges in Astroparticle Physics

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# Preface

Astroparticle physics is a lively discipline arisen from the observation of many different "signal carriers" from the universe and from the understanding that the laws of physics studied on Earth can be used to make sense of the whole cosmos. In the past, similar observations and studies helped to figure out new laws of physics and it is plausible that this will continue to happen in future.

Astroparticle Physics evolved, thanks to the collaboration of scientists with diverse interests, from particle and nuclear physics to astrophysics, astronomy, plasma physics, and cosmology. In Astroparticle Physics, new exciting discoveries are all but scarce and experiments are blossoming in the hope of solving some of the mysteries of the universe, such as the nature of dark matter and dark energy, the nature of neutrino, the sources of gravitational waves, the origin of cosmic rays, the sources of gamma rays and astrophysical neutrinos, and the study of the final stages of stellar evolution.

Astroparticle Physics is one of the four pillars of the Gran Sasso Science Institute (GSSI) together with Mathematics, Computer Science, and Social Sciences. The GSSI is an internationally renowned center for advanced studies created after the devastating earthquake that hit the city of L'Aquila in 2009. Initially activated by INFN and now established as a new Italian University, the GSSI is a concrete and visible effort to help the city with the reconstruction process, contributing to make it a modern "city of knowledge". Over the years, fulfilling its original mission, the GSSI—and its talented doctoral students—became the symbol that it is possible to start anew by investing in human capital.

The present book "Multiple Messengers and Challenges in Astroparticle Physics" offers an overview of some of the most important topics in the field. The selection of the topics was guided by the intention to emphasize the current observational and theoretical challenges and to identify the most promising lines of research. World-leading experts were asked to contribute to the volume by reviewing the state-of-the-art and the most important open problems in their areas. Each chapter is devoted to a different topic, which include: cosmic rays, gamma rays (observed both from ground and space), astrophysical neutrinos, gravitation, and cosmology. It has been interesting to realize, as a sign of the extreme vitality of this field of research, that each review required multiple revisions to stay up-to-date with the numerous news coming from both experimental and theoretical research in the meanwhile.

The reviews collected in this volume also play a second—and equally important—role, i.e. provide a solid pedagogical basis for all the young researchers entering the field of Astroparticle Physics. Since its inception in 2013, the GSSI welcomed about 200 Ph.D. students, 50 of which in the area of Astroparticle Physics, and many more will come in the future. This book will hopefully become a must-read for those young researchers to help them find their own research agenda.

We are grateful to all the scientists who traveled from all over the world to participate in the activities of the GSSI giving lectures, seminars and contributing to the research activity of the Institute. The present book is also the outcome of the conducive atmosphere established at the GSSI in these years that resulted in many scientific contributions, important achievements, and new collaborations.

L'Aquila, Italy

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# Contents

# Selected Topics in Cosmic Ray Physics

**Roberto Aloisio, Pasquale Blasi, Ivan De Mitri and Sergio Petrera**

**Abstract** The search for the origin of cosmic rays is as active as ever, mainly driven by new insights provided by recent pieces of observation. Much effort is being channelled in putting the so-called supernova paradigm for the origin of galactic cosmic rays on firmer grounds, while at the highest energies we are trying to understand the observed cosmic-ray spectra and mass composition and relating them to potential sources of extragalactic cosmic rays. Interestingly, a topic that has acquired a dignity of its own is the investigation of the transition region between the galactic and extragalactic components, once associated with the ankle and now increasingly thought to be taking place at somewhat lower energies. Here, we summarize recent developments in the observation and understanding of galactic and extragalactic cosmic rays and we discuss the implications of such findings for the modelling of the transition between the two.

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## Introduction

There are different levels of understanding of the origin of cosmic rays (CRs), but a reasonable starting point is to establish some separation between the CRs that can potentially be accelerated inside the Galaxy and the ones that are thought to be produced outside the Milky Way. This separation is somewhat arbitrary and hides our fundamental ignorance of the actual conditions required to define CRs as extra-galactic. Nevertheless, the physical problems associated with galactic CRs appear to be qualitatively different from the ones involved in ultra-high energy CRs, hence we will adopt this separation in this review as well, paying special attention to the underlying assumptions and possibly their failure. While there is a substantial consensus that galactic CRs are somehow related to one or more types of supernova (SN) explosions and that acceleration is mainly due to diffusive transport in the proximity of strong shocks formed as a consequence of these explosions, less consensus exists on whether all or a subset of SNe can actually reach the knee energy. At a few PeV, there is some evidence that chemical composition changes, thereby leading to the formation of the knee in the all-particle spectrum [1], although the details of how this takes place are not well understood: some observations suggest that the knee is made by light elements [1], while others [2] find that light elements disappear at lower energies and the knee gets dominated by elements with intermediate mass. This type of problem is to be considered essentially of experimental nature at this time.

The transport of CRs inside the accelerators and throughout the Galaxy is described by models based on the same physical ingredients: spatial diffusion induced by resonant scattering of charged particles of plasma waves. Such waves are likely to be, at least partially, generated by the same particles during transport, due to instabilities induced by local streaming. This apparently simple picture is in fact deceiving, in that it hides the essentially non-linear nature of the transport phenomenon: the large-scale behaviour of CRs is determined by the superposition of microphysical particle–wave interactions. In this sense, the transport of CRs has become an instance of the so-called inner space—outer space conundrum, well known in the field of cosmology. In much the same way that the laws of particle physics shape the evolution of the universe, the laws of plasma physics on small-scales shape the behaviour of CRs on large scales.

Several instances of self-regulation have been found in such systems, ranging from particle acceleration at supernova shocks to propagation in the Galaxy in a background of self-generated turbulence. The complexity of these situations is often overwhelming and one resolves to adopt effective approaches that, while retaining the main underlying physical aspects, may still allow us to describe nature in a satisfactory way.

The ever increasing quality of observations reveals aspects of Nature that force us to improve the quality of the effective models that we adopt to describe it. This trend is a fair description of the history of CRs in the last few decades: the simple energetic argument that led to propose supernova remnants (SNRs) as sources of the bulk of galactic CRs and the diffusive paradigm for the transport of CRs in the

Galaxy explain, by themselves, the main aspects of the origin of CRs. On the other hand, this simple picture fails to describe many other pieces of observation that have come about with time.

The standard SNR paradigm predicts that the spectrum of CRs accelerated at strong shocks is very close to $\sim E^{-2}$ [3] but in the few cases in which gamma-ray emission can be unequivocally attributed to hadronic interactions, the inferred CR spectrum appears to be steeper than $E^{-2}$. Moreover, since the spectrum observed at the Earth is $\sim E^{-2.7}$, the SNR paradigm would naively suggest that CR transport is described by a diffusion coefficient $D(E) \propto E^{0.7}$, which however is in contradiction with the measured large scale anisotropy [4, 5]. In addition, such a diffusion coefficient leads to an energy dependence of the B/C ratio, proportional to the grammage traversed by CRs, that is not consistent, at high energy, with measurements from the PAMELA experiment [6] and AMS-02 collaboration [7].

If used to estimate the maximum energy $E_{max}$ of CRs accelerated at SNR shocks, the same diffusion coefficient would lead to expect that $E_{max} \leq 1$ GeV, quite at odds with observations. This fact alone is a signature that the process of particle acceleration at SNR shocks works in a much more complex manner than the basic paradigm would suggest. The recent detection of narrow rims of X-ray emission from virtually all young SNRs [8] provided indirect confirmation that the magnetic field in the shock proximity is amplified by a factor $\sim$10–100. Although the nature of the amplification process is not clear as yet, streaming instability excited by CRs themselves provides the correct order of magnitude to explain the observed rims as a result of synchrotron emission from very high energy electrons. At the same time, the inferred magnetic field would make the acceleration of CRs up to 100–1000 TeV at SNR shocks plausible [9–12]. Interestingly, in order to explain CR energetics on galactic scales, SNRs are required to accelerate CRs with a $\sim$10% efficiency, which is also required for magnetic field amplification, which in turn leads to high values of $E_{max}$: particle acceleration at a SNR shock is a typical example of a self-regulated non-linear system, in which well-known plasma physics laws combine to provide a complex outcome.

It is likely, though less clear, that a similar chain of processes also works for CR transport through the Galaxy. At present, propagation of CRs is described as diffusive with a diffusion coefficient that is tailored to fit observations. Advection with a wind is treated as an option in most propagation codes (e.g. GALPROP, DRAGON, PICARD and Usine [13–16]).

The spectrum of different elements in CRs has been recently measured at the Earth location by PAMELA [17] and AMS-02 [18, 19] and found to be characterized by small spectral breaks at a few hundred GV rigidity, quite at odds with the standard view of power law injection and diffusion. This phenomenon might be the manifestation of several effects: for instance, it might result from the stochastic overlap of discrete sources around the Sun [20], from re-acceleration in weak SN shocks [21], or it might result from a spatially inhomogeneous diffusion coefficient [22]. Finally, it might show that non-linear production of waves and pre-existing waves are both responsible for CR diffusion, each one of them being important at different energies [23, 24].

Traditionally, the ratios $e^+/(e^- + e^+)$ and $\bar{p}/p$ have also been used to infer the propagation properties of galactic CRs. However this is possible only if both positrons and antiprotons are solely generated as secondary products of CR interactions in the Galaxy, and in this case one expects both these ratios to be monotonically decreasing functions of energy above ∼10 GeV. The PAMELA experiment measured the positron ratio and found that it grows with energy [25] at least up to ∼100 GeV. This result was later confirmed and extended to higher energies by AMS-02 [26]. The absence of an increasing trend with energy in the $\bar{p}/p$ ratio [27] leads to the conclusion that the positron excess is likely due to new sources of astrophysical positrons that do not produce antiprotons. The same concept also imposes strong constraints on possible Dark Matter (DM) related models of the positrons excess (see [28] for a comprehensive review). The measurement of the spectra of electrons and positrons separately [29, 30] allowed us to conclude that the positron excess stems out of an extra contribution to the positron flux rather than a deficit of the electron flux, namely sources of positrons (but not antiprotons) are required to explain data. It has been speculated that such sources might be old SNRs [31, 32] or pulsar wind nebulae [33, 34].

On the other hand, the recent extension of the measurement of the antiproton flux and the $\bar{p}/p$ ratio to higher energies by AMS-02 [35] has stimulated an exciting discussion on a radically new view of the anomalies in secondary-to-primary ratios: it has been pointed out [35, 36] that the energy spectra of positrons and antiprotons have very similar slopes and such slope is, in turn, very close to that of the proton spectrum at high energies. A similar consideration was put forward earlier in Refs. [37, 38] based on the positron and proton spectra alone. This simple consideration is used by the authors to suggest that both positrons and antiprotons are purely secondary products of CR interactions. Clearly these scenarios are not problem free: for instance, an alternative explanation of the B/C ratio should be sought [36] since no apparent anomaly has been measured in this quantity.

A general consequence of the SNR paradigm outlined above is that the flux of galactic CRs should end with an iron dominated composition at energies ∼26 times larger than the knee in the proton spectrum. If such knee is indeed at PeV energies, as KASCADE data suggest, then galactic CRs should end below $\sim 10^{17}$ eV, well below the ankle.

The measurements carried out by the Pierre Auger Observatory [39] have shown that the mass composition of CRs, from prevalently light at $\sim 10^{18}$ eV, becomes increasingly heavier towards higher energies. Several independent calculations [40–42] showed that the observed spectrum and composition can be well explained only if sources of ultra-high energy CRs (UHECRs) provide very hard spectra and a maximum rigidity $\sim 5 \times 10^{18}$ V. One should appreciate the change of paradigm that these recent observations forced us towards: 10 years ago, the general consensus was that UHECRs are protons and that sources should accelerate them to $>10^{20}$ eV, something that would not be consistent with current Auger data. On the other hand, the Telescope Array (TA), operational in the northern hemisphere, collected data that suggest a somewhat different scenario [43], where the mass composition is compatible with being light for energies above $10^{18}$ eV, with no apparent transition to a heavier mass composition. A joint working group made of members of both collaborations has recently concluded that the results of the two experiments are not in conflict once systematic and statistical uncertainties have been taken into account. This conclusion, though encouraging on one hand, casts serious doubts on the possibility of reliably measuring the mass composition at the highest energies, unless some new piece of information becomes available. It should be noted that the spectra measured by the two experiments, though being in general agreement, differ beyond the systematic error at the highest energies: the TA spectrum shows a suppression that is consistent with the Greisen–Zatsepin–Kuzmin cutoff, while the shape of the spectrum measured by Auger appears to be in better agreement with propagation of nuclei.

On the other hand, the results of the two experiments in terms of spectra and mass composition show good agreement around $10^{18}$ eV, where CRs are found to be light. The fact that between $10^{17}$ and $10^{18}$ eV the mass composition changes from heavy to light is suggestive of a possible transition from galactic to extragalactic CRs in the same region, well below the ankle.

This paper is structured as follows: in section "Cosmic Rays Observations" we discuss the status of observations. The transport of galactic CRs is discussed in section "Transport of CRs in the Galaxy", while the status of investigation on CR acceleration is summarized in section "Acceleration of Galactic CRs". The transport of ultra-high energy cosmic rays is discussed in section "Transport of Extragalactic CRs" while some considerations about the sources are reported in section "Astrophysical Sources". The possibility to infer useful information on exotic physics (such as top-down models and violations of Lorentz invariance) are discussed in section "Exotic Models". In section "Transition Between Galactic and Extragalactic Cosmic Rays" we summarize different models of the transition from galactic to extragalactic cosmic rays. We conclude in section "Conclusions".

## Cosmic Rays Observations

In this section, a short review of experimental results on some selected topics on CR physics will be given. For each topic, a discussion on new and future projects has also been added in order to focus on the key issues that, from the experimental side, could bring to more and better information for the understanding of the relevant physics phenomena. After a section dedicated to the observation of electrons/positrons and antiprotons, the measurements on protons and nuclei will be discussed starting from ballon and spaceborne experiments up to the highest energies, currently covered with giant ground arrays.

## *Observations of Electrons, Positrons and Antiprotons*

Even if the electron/positron component, i.e. $(e^- + e^+)$, accounts for approximatively 1% only of the total CR flux, it is deeply studied in order to infer important information on propagation processes. In the standard scenario, secondary electrons and positrons are (equally) produced via interactions of primary CRs with the InterStellar Medium (ISM), therefore the observed overabundance of electrons on positrons is a clear indication that most of the electrons have a primary origin. Because of the low mass, this component suffers significant energy losses during propagation in the Galaxy. At high energies, such losses produce a steeper energy spectrum compared to that of protons and actually place upper limits on the age and distance (at about $10^5$ yr and 1 kpc, respectively) of the astrophysical sources of TeV electrons. Since the number of such nearby objects is limited, the electron energy spectrum above 1 TeV is then expected to exhibit spectral features, and a sizeable anisotropy in the arrival directions is also foreseen at very high energies [44].

Measurements of the CR electron/positron fluxes have been pursued since many years by balloon-borne and space-based experiments. Because of the low intensity of the signals and the large proton-induced background, the main requirements for these instruments are a large exposure time and a sufficient e/p separation capability. Calorimeters can be used to measure the inclusive so-called all-electron, i.e. $(e^- + e^+)$, spectrum, while separating electrons form positrons obviously requires the determination of the sign of the charge through a magnetic spectrometer, that puts anyway severe limits to the highest possible detectable energy, this being limited by the Maximum Detectable Rigidity (MDR). Important progress was made in the field in the last years, due to the use of magnetic spectrometers in space. The positron fraction was shown to grow with energy by the PAMELA experiment [25] at least up to ~100 GeV, this result being confirmed with precision measurements by AMS-02 [26], that also extended the covered range up to about 500 GeV.

These findings were also confirmed, even though with larger systematic uncertainties by the Fermi-LAT experiment [45], which is not equipped with a magnetic spectrometer but used the Earth magnetic field as a charge sign separation tool.

Experimental results show evidence for an excess of the positron fraction with respect to the standard production mechanism (i.e. primary CR interaction with the ISM), in the form of an increase with energy above approximatively 10 GeV (see Fig. 1). The latest precision measurements of the AMS-02 experiment [30] ascribe the positron fraction excess to a hardening of the positron flux, showing a spectral index above 50 GeV compatible with that of primary protons. Moreover, as Fermi-LAT recently showed [47], no anisotropy signal has been detected in the inclusive electron spectrum with current sensitivities.

Understanding the origin of this excess of positrons in the cosmic radiation requires measurements up to the highest possible energies, where both spectral features and/or anisotropies might be detected. In this context, the multi-TeV, largely unexplored, region is very interesting because of the high potential for studying local sources. Indirect measurements made by imaging atmospheric Čerenkov telescopes

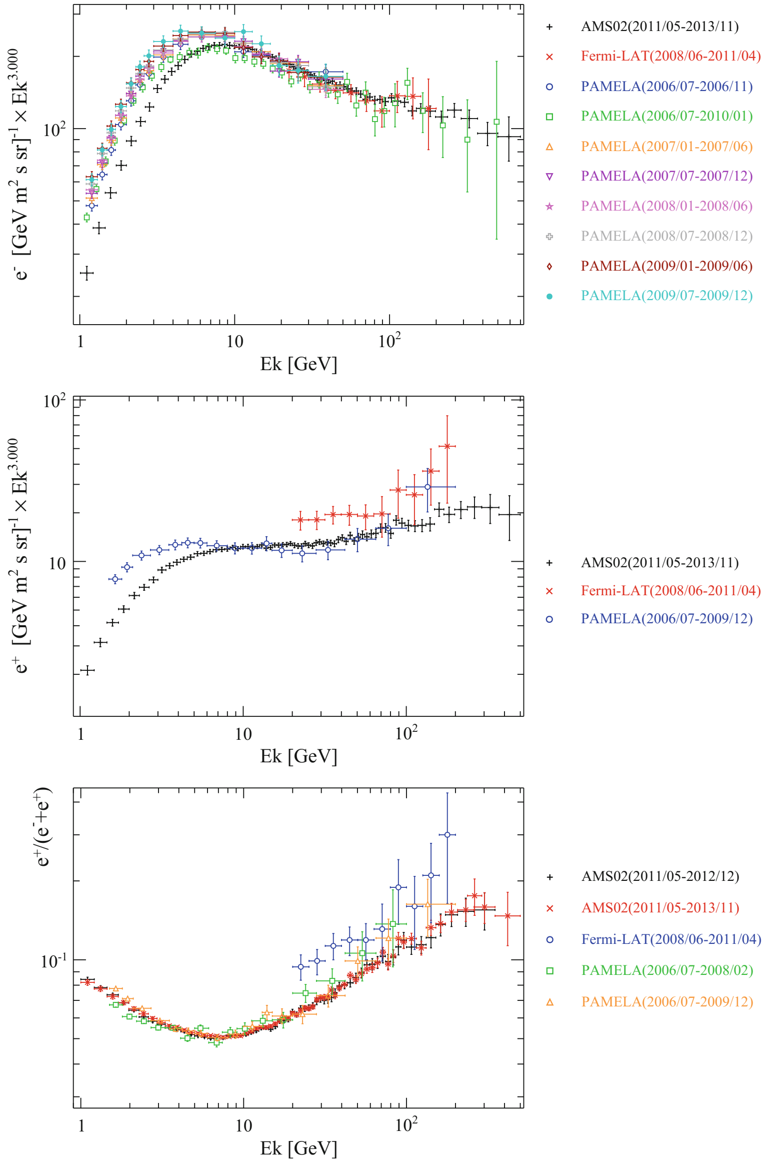



**Fig. 1** Fluxes of cosmic electrons and positrons (*upper* and *central panel*, respectively) as measured by AMS-02, PAMELA, and Fermi-LAT experiments. The positron fraction is shown in the *lower panel*. The dates in the experiment labels refer to the analyzed data sample [46]

suggest, even though with large uncertainties, an exponential cutoff at about 2 TeV [48, 49]. The analysis of 7 years Fermi-LAT data [50] recently extended the spectral measurements up to 2 TeV. Fermi-LAT data alone exclude an exponential cutoff below 1.8 TeV at 95% C.L., while a combined fit of Fermi-LAT and HESS data would lead to a cutoff at energies larger than 2.1 TeV. The exploration of the high energy part of the spectrum with high precision direct measurements is then mandatory.

New technologies might extend current MDR values up to few TeV for future missions, while deep homogeneous calorimeters in space, with large geometric factors, will reach even higher energies, but obviously without matter/antimatter separation. The recently launched CALET and DAMPE detectors might return interesting results on the high energy all-electron component.

CALET (CALorimetric Electron Telescope) is a space mission led by the Japanese Space Agency (JAXA) with the participation of the Italian Space Agency (ASI) and NASA. The payload was launched on 19 August 2015 and installed on the Japanese Experiment Module Exposure Facility (JEM-EF) of the International Space Station (ISS) on August 24. The mission is foreseen to last for 2 years, with a possible first extension to 5 years [52]. The main scientific goal is to search for possible nearby sources of high energy electrons or signatures of DM, by measuring accurately the all-electron spectrum from 1 GeV up to several TeV. It will also measure the energy spectra and elemental composition of CR nuclei from H to Fe up to hundreds of TeV (see below). The instrument consists of two layers of segmented plastic scintillators (for particle charge determination), a thin tungsten-scintillating fiber imaging calorimeter providing accurate particle tracking and identification by multiple dE/dx sampling, and a thick PWO crystal calorimeter to measure the energy of CRs with excellent resolution and electron/hadron separation up to the multi-TeV scale. The total thickness is equivalent to 30 radiation lengths and 1.3 proton interaction lengths with a geometric factor of about 0.1 $m^2$sr. An extensive campaign of beam tests for calibration was carried out at GSI and CERN [53].

The DAMPE (DArk Matter Particle Explorer) satellite was launched on 17 December 2015 and is in smooth data taking since few days after. It was designed in order to properly work for at least 3 years and, thanks to its large geometric factor (about 0.3 $m^2$sr for protons and nuclei and even larger for electrons), it already integrated one of the largest exposures for galactic CR studies in space. The detector, built and operated by a collaboration of Chinese, Italian and Swiss institutions, is made by 12 layers of Si-W tracker followed by a $32X_0$ BGO calorimeter. A plastic scintillator detector on top and a neutron detector on bottom, for ion charge and shower neutron content measurements, respectively, actually complete the setup. As also resulted from a large set of beam test measurements with a full-scale detector prototype at CERN, the BGO calorimeter actually provides an energy resolution for electrons at the level of 5% at 1 GeV and better than 2% above 10 GeV. The information from the various sub-detectors (e.g. ion charge measurement, precision tracking, shower topology) allows an efficient identification of the electron signal over the large (mainly proton induced) background. As a result, the all-electron spectrum will be measured with excellent resolution form few GeV up to few TeV [51]. The DAMPE contribution to the measurement of the all-electron energy spectrum,

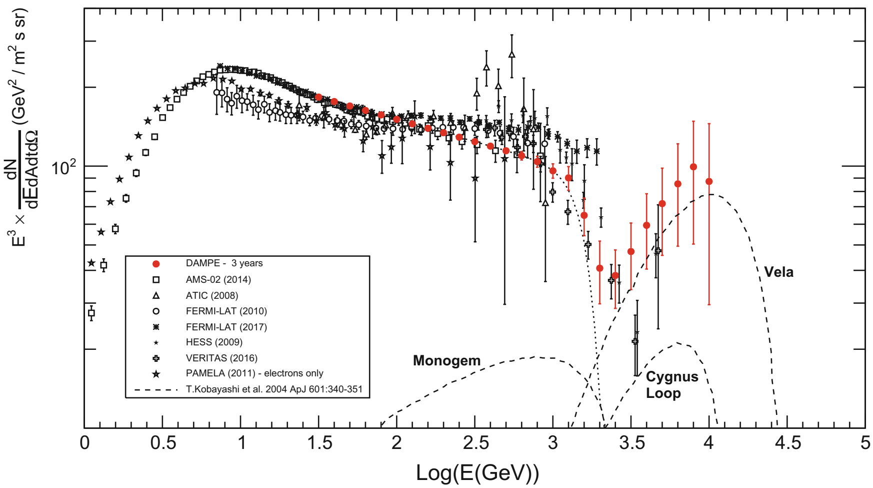



**Fig. 2** Inclusive all-electron energy spectrum as measured by several experiments. The possible contribution of the DAMPE mission after 3 years of operation is also shown (see *text* for details). Plot taken from [51]

after 3 years of operation, is shown in Fig. 2. The DAMPE spectrum was simulated by assuming a power law with a spectral index as given by AMS-02 [54] data above 30 GeV, a cutoff at about 1.5 TeV as suggested by HESS and VERITAS in [48, 49], and then a possible contribution of three nearby sources as parametrized in [44]. In the figure, the result is compared with existing measurements and with the model given in [44].

As can be seen, this will allow a direct and precise detection of a possible cutoff at about 1–2 TeV. Moreover further structures/excesses due to nearby sources will be clearly identified below few TeV, together with possible indirect evidence for a DM-induced excess.

In the case of the HERD mission (see below), a larger acceptance and an even deeper calorimeter would provide a unique tool to investigate all the spectral features also above the TeV region. In particular, the contribution of nearby sources could be clearly identified and studied. In the case of sizeable contribution of nearby sources, a large anisotropy is expected at high energy, which could be easily detected by HERD, giving important clues to the understanding of diffusion processes in the Galaxy.

The CR antiproton component can only be identified by using magnetic spectrometers together with sufficient MDR and particle identification capability. Many balloon and space born experiments contributed to this field with important progress due to the PAMELA [27], AMS-02 [35], and (at low energies) BESS [55] experiments (see Fig. 3). The measurements, currently carried out up to few hundreds GeV, are in fair agreement with secondary production due to primary CR interactions with the interstellar medium. Interestingly enough, the same spectral index as the one for protons is suggested by data, for both positrons and antiprotons (see

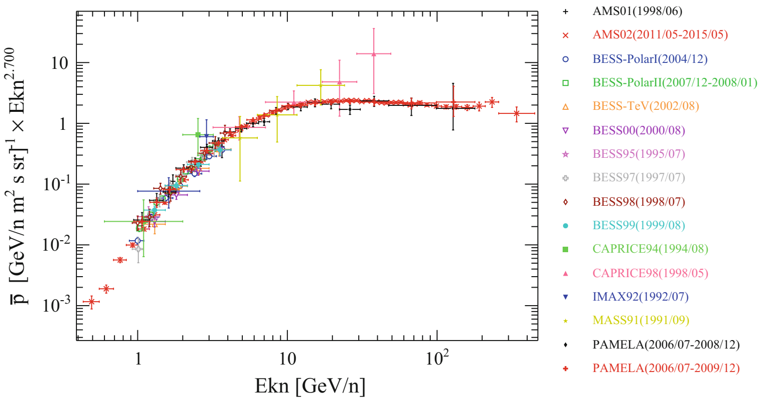



**Fig. 3** Fluxes of antiprotons as measured by several experiments. The dates in the experiment labels refer to the analyzed data sample [46]

section "Positrons and Antiprotons" for a discussion). New important inputs on this topic might be provided by the search for antinuclei (e.g. anti-deuterons) in the CR flux by both current, e.g. AMS-02, and future experiments, such as GAPS [56].

## *Observations of Protons and Nuclei up to Hundreds PeV*

### From Low Energies up to 100 TeV: Flux Hardenings and Secondary-to-Primary Abundances

Recent direct measurements of primary protons and nuclei shed new light on acceleration and propagation mechanisms. The paradigm of a unique power law energy spectrum below the knee, down to the region where solar modulation effects become sizeable, might have been invalidated. In 2010 the CREAM (Cosmic Ray Energetics And Mass) experiment showed evidence for a hardening in the spectra of protons and nuclei with different ('discrepant') spectral index changes. This is summarized in Fig. 4 where CREAM data, also fitted by (broken) power laws, are shown together with other measurements [57]. Even with large error bars (mainly at high energy and/or heavy primaries), a change of spectral index is suggested at about 200 GeV/n. Both the energy ranges and the flux uncertainties prevented anyway a clear claim for a break in the proton and helium spectra.

This became possible with the analysis of PAMELA results [17], later confirmed by AMS-02 [18, 19]. As can be seen in Fig. 5 a clear change of spectral index is shown by data, even though different experiments return slightly different slopes at energies above the breaks.

Recent results of the analysis of CREAM-III [58] and NUCLEON [59] data did confirm the scenario up to about 100 TeV but with large uncertainties. More data are

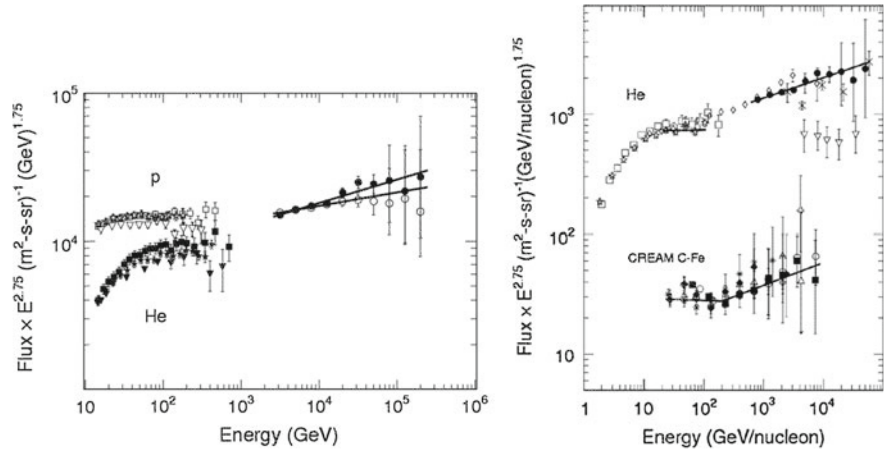
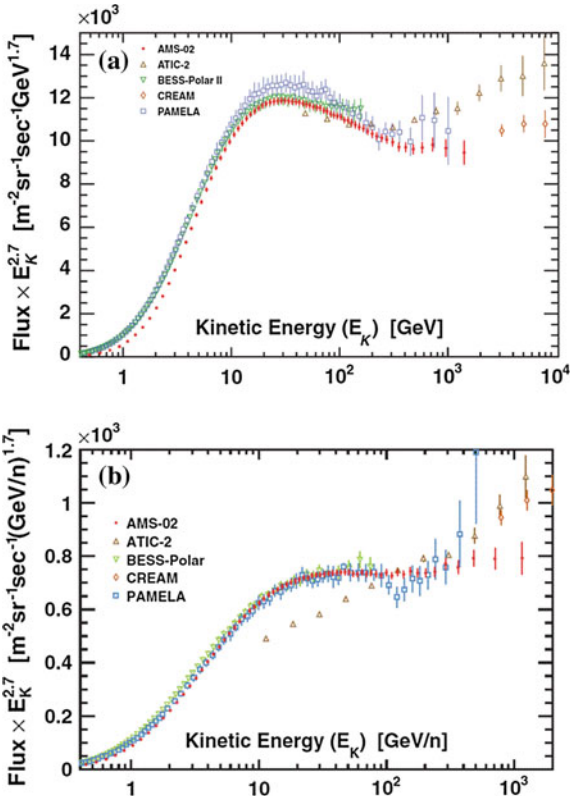



**Fig. 4** Measurements of proton, helium and nuclei fluxes as for year 2010: first evidence for discrepant hardenings by the CREAM experiment (see *text*). Plots taken from [57]

**Fig. 5** Recent measurements on proton and helium fluxes (*upper* and *lower panel*, respectively). Plots taken from [18, 19]



then needed at high energy in order to measure, with a single experiment, both the region across the breaks and the high energy one, with sufficiently small uncertainties. Current missions like CALET and DAMPE have the size and the needed resolution in order to check the break region and uniquely determine the spectral behaviour up to more than 100 TeV.

Even though primarily optimized for the study of electrons and gamma rays (see above), the DAMPE detector provides good tracking and calorimetric performances also in the case of protons and nuclei, together with the possibility of ion identification through charge measurements in the top scintillator layer, in the tracker, and in the calorimeter itself. This allows precise measurements of proton and nuclei energy spectra from tens of GeV up to about 100 TeV, the high energy limit being essentially determined by the overall geometric factor and the calorimeter's dynamic range.

In particular, the energy region above about 50 GeV will be explored with higher precision compared to previous experiments [60]. Spectral indexes for individual species could then be well measured and evidence for the observed hardenings could be checked and better quantified. This would be very important for a comparison with state-of-the-art models of galactic CR acceleration/propagation mechanisms, and to assess the contribution of nearby sources. Moreover measurements of important quantities like the boron-to-carbon ratio will be improved and extended to higher energies. Similar contributions are expected from the CALET mission, even if the smaller geometric factor (by about a factor three) would result in larger uncertainties. Further extensions in energy, towards the all-particle knee, are expected for the ISS-CREAM and HERD projects (see below).

In the low energy range, important information can be provided by the study of the production rate of secondary CRs. Recent results from PAMELA and BESS-Polar [61] on the isotopic abundance ratios $^2$H/$^1$H and $^3$He/$^4$He in the range 0.1–2 GeV/n provide essential information to better understand the history of cosmic-ray propagation in the Galaxy. On the other hand, as discussed in section "Transport of CRs in the Galaxy", elemental secondary-to-primary ratios (such as Boron/Carbon or subFe/Fe) can be employed, to infer information on the nature and size of the cosmic-ray confinement region and on the propagation properties of CRs in the Galaxy. Current measurements of the B/C ratio are shown in Fig. 6. While measurements performed by balloon-born experiments suffer from small statistics and large systematic errors (due to short exposure times and to the effects of the residual overburden atmosphere, respectively), data from space spectrometers, like PAMELA and AMS-02, can provide an accurate spectral measurement up to about 1 TeV/n [6, 62]. Also in this case, from the experimental point of view, the challenge is then to extend the energy range to the multi-TeV/n region by using large geometric factor instruments in space.

## Approaching the Knee(s) with Direct Measurements

Since the first experimental evidence in 1958 [63], the energy region around the knee in the all-particle cosmic ray spectrum, at about 3 PeV, has been investigated by many experiments with different approaches [64].

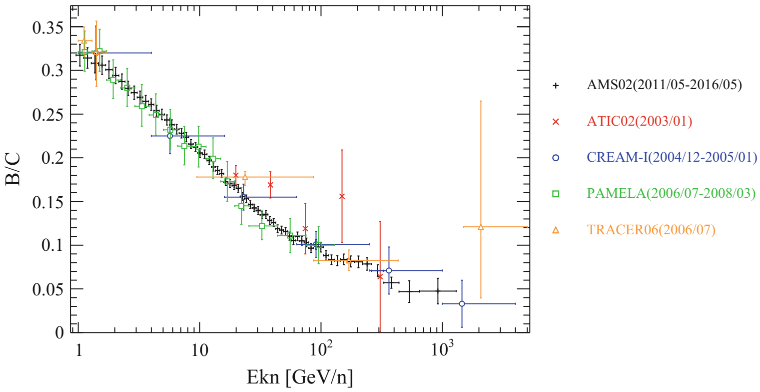



**Fig. 6** Measurements B/C ratio made by several experiments. The dates in the experiment labels refer to the analyzed data sample [46]

Several theoretical explanations have been proposed exploiting different hypotheses on source properties/populations, acceleration/propagation mechanisms and particle physics issues at high energies [65]. After the first results at the Large Hadron Collider (LHC), the 'particle physics' origin of the knee seems to be disfavoured, confirming that it is a genuine property of the CR spectrum itself [66]. It remains still unsolved whether the (dominant) origin of the knee is due to the reaching of the maximum energy achievable at the sources or to diffusion processes in the Galaxy. In both cases, a rigidity dependent sequence of knees in individual elemental spectra is the most likely scenario [65].

For the analysis of the CR flux, direct measurements carried on space or stratospheric balloons actually provide the best performance in terms of both energy resolution and charge identification. However, due to their limited acceptance and the steeply falling fluxes, they could hardly reach, up until now, energies of hundreds of TeV and then did not yet provide clear information on the steepening of the spectrum of various elements nor on the knee of each species or of the all-particle spectrum itself [60, 67].

As shown in the previous section, current data suggest a hardening of the spectra above about 0.2 TeV/nucleon and spectral indexes $\gamma$ (above that energy) of about $-2.6$ for all considered elements but for protons, that show a softer spectrum with $\gamma \simeq -2.7$ [57, 68]. Moreover, the chemical composition is shown to evolve towards heavier nuclei, with helium becoming more abundant than hydrogen at energies of about 10–20 TeV [60]. It is then mandatory to explore the sub PeV region with high precision direct measurements in order to study the energy spectra of each nuclear species, to measure the various spectral indexes, to detect any possible hardening and to establish mass composition below the knee of the all-particle spectrum. The measurement of the spectrum of individual elements and an understanding of the nature of the knee in the all-particle spectrum would represent a result of unprecedented importance in CR physics, and would provide a crucial insight into unveiling the transition between galactic and extragalactic CRs.

The ISS-CREAM detector has been built by transforming the CREAM payload, flown in several flights over Antarctica, for accommodation on the ISS for a 3-year mission [69]. The exposure will be increased by about one order of magnitude allowing to extend the measurements on nuclei up to hundreds of TeV. The detector includes four layers of Si pixels to measure the particle charge; a carbon target to induce the inelastic interaction of the incoming nuclei; a sampling calorimeter made of 20 layers of alternating tungsten plates and scintillating fibres, providing energy measurement, particle tracking and trigger; top and bottom plastic scintillator counters and a boronated scintillator detector for e/p separation. The Si charge detector and the calorimeter were already used in CREAM, while the last two detectors have been newly developed for the space mission, in order to add sensitivity also to CR electrons.

The HERD (High Energy Radiation Detector) experiment [70] is being proposed by an international collaboration as a space mission for the study of the high energy cosmic radiation with a detector characterized by an unprecedented geometric factor, to be installed onboard the CSS (Chinese Space Station) around 2023. Current detector design includes a cubic calorimeter (about $55X_0$ and $3\Lambda$ in depth) made by ($3\,\mathrm{cm} \times 3\,\mathrm{cm} \times 3\,\mathrm{cm}$) LYSO crystals, readout individually, a high precision Si-W tracker covering 5 out of the 6 calorimeter faces and an array of plastic scintillator for the charge measurements. This innovative setup allows a jump in the geometric factor, with respect to previous experiments, of more than one order of magnitude for an estimated value of the geometric factor $\sim 3\,\mathrm{m}^2\,\mathrm{sr}$. Together with the unprecedented depth of the calorimeter and the high-resolution tracker, this will allow the extension of high precision measurements on proton and nuclei spectra up to PeV energies. Moreover, a clear identification of each nuclear species will be possible through the charge measurements made by the plastic scintillators, the Si-W tracker and by the calorimeter itself. Energy resolution for the electromagnetic and hadronic showers will be at the 1% and 30% level, respectively.

Simulated HERD results for the measurement of protons and nuclei, after 3 years of operation, obtained by assuming flux parametrization as given in [71], are shown in Fig. 7. HERD points (in colour) are compared with measurements from PAMELA, CREAM, AMS-02 and ATIC experiments (shown in black) and theoretical models [71, 72].

As can be seen, features like single element spectral indexes and spectral hardenings/steepenings could be carefully studied from hundreds GeV/n up to hundreds TeV/n. In particular, the proton and helium component could be measured up to PeV energies, thus providing a test of the origin of the knee in the spectrum of the light CR component, possibly associated with the maximum energy reached by CR at the source (see next section).

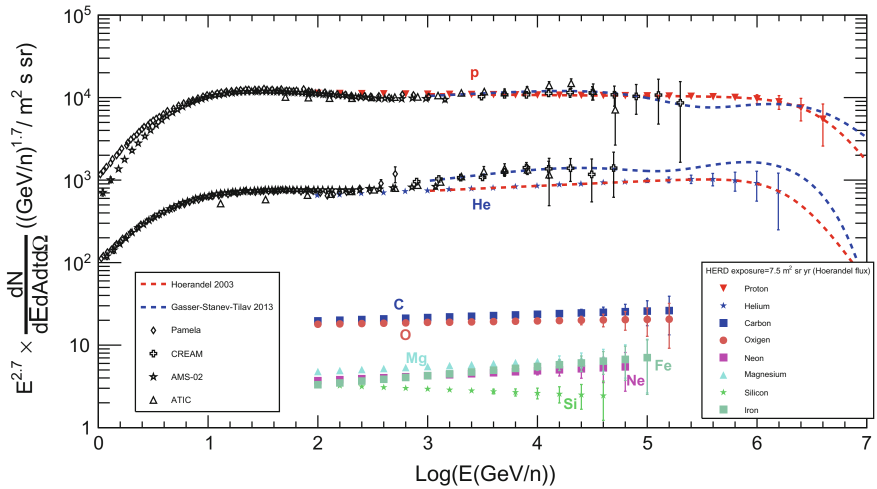



**Fig. 7** Contributions of the HERD mission after 3 years of operation: individual proton and nuclei energy spectra (see *text* for details)

## Ground-Based CR Observations up to Hundreds PeV

Indirect measurements fully explore the energy region above 0.5–1 PeV (or even few TeV, if located at high altitude) through the detection of Extensive Air Showers (EAS) in the atmosphere. Data show a general agreement, within the systematic uncertainties, on the all-particle spectrum, also suggesting evidence of a second knee at about 100 PeV [73–76]. However systematic uncertainties related to the experimental procedure itself and intrinsic in the assumptions adopted for the hadronic interaction models do not allow an easy and straightforward estimate of the mass composition nor of the single species (or mass group) energy spectra [64, 77].

One or more EAS observables (e.g. the lateral distribution of particles at the ground, the longitudinal development in the atmosphere, the muon content of the shower, etc.) are measured in order to estimate, by adopting a given assumption on the primary interaction and the shower development in the atmosphere, the CR composition. Results are often given in terms of the energy dependence of the mean logarithmic mass, defined as $\langle lnA \rangle = \sum_i \eta_i lnA_i$, where $\eta_i$ is the fraction of nuclei of mass $A_i$ in the CR beam. A compilation of $\langle lnA \rangle$ measurements can be found in [64] and [77], with a comprehensive discussion on the results and their uncertainties. As can be seen in Fig. 8, data show large uncertainties, mainly coming from the systematics associated to the adopted interaction models. Moreover, a somewhat different trend with energy might be identified by dividing experiments in two large classes: the ones measuring charged particles at the ground and those detecting the Čerenkov or fluorescence light emissions in the atmosphere [71]. Even with these uncertainties, data collected across the knee region show an evolution towards heavier mass groups as expected from acceleration/propagation models. A tendency towards

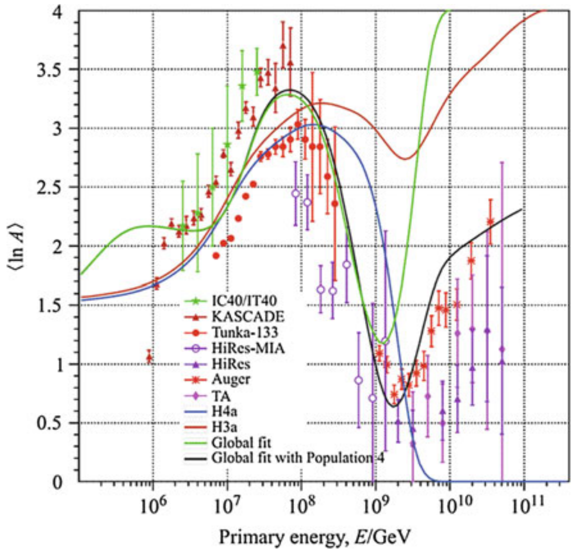



**Fig. 8** Average value of the estimated CR logarithmic mass, $\langle lnA \rangle$, from several ground-based experiments. Superimposed are the *lines* corresponding to mixed composition resulting from muti-population models as given in [72]. Plot taken from [72]

lighter elements is then observed starting at energies compatible with the position of the second knee, while a new trend towards the medium mass group can be recognized above the ankle region (see next section).

The energy spectra of individual elements (or mass groups) are even more difficult to be measured. Results from the KASCADE experiment, even with sizeable systematic uncertainties on the individual fluxes mainly coming from the dependence on the hadronic interaction model, imply an average composition at the knee that is dominated by light elements, and the knee itself is interpreted as the steepening of the p and He spectra [1]. The KASCADE-Grande experiment returned results consistent, at higher energies, with this scenario [78, 79], and ascribed the second knee to the steepening of the heavy component [73].

Several different experimental results suggested a somewhat heavier composition at energies around the knee. For instance, a hybrid measurement was carried out by the EAS/TOP and MACRO experiments (by detecting, in coincidence, EAS Čerenkov light at 2000 m a.s.l. and underground muons below about 3000 m of water equivalent depth, respectively). The result implied a decreasing proton contribution to the primary flux at energies well below the observed knee in the primary spectrum [80].

The same indication was previously obtained through the analysis of the underground muon component alone in the MACRO experiment [81]. In addition, the results of the Tibet-AS$\gamma$ experiment, located at 4300 m a.s.l, do favour a heavier composition because the proton component is no longer dominant at the knee [82]. In particular, the fraction of the light component (i.e. protons and helium nuclei) is shown to be of 50% at about 500 TeV and decreasing with energy [82], this also being consistent with later measurements of the upgraded Tibet array showing a steepening of the proton spectrum above few hundred TeV [83].

This is also in agreement with results from the CASA-MIA experiment, showing a decreasing proton content at about 600 TeV [84] and with a series of measurements on Mount Chacaltaya (about 5200 m a.s.l.) giving a steady increase of the average mass number of primary CRs with energy above $10^{14.5}$ eV [85, 86].

Furthermore, indications for a substantial fraction of nuclei heavier than helium at 1 PeV have also been obtained in measurements with delayed hadrons [87]. Finally, the compilation of measurements of the energy spectrum of the so-called CNO group (i.e. Carbon-Nitrogen-Oxygen) shows a knee at energies not larger than about 7 PeV (see for instance [64]). In a scenario with a rigidity dependent knee position, this is not consistent with a position of the proton knee at about 3 PeV.

Similar conclusions have been reached by the combined analysis of data coming from the ARGO-YBJ experiment and a wide field of view Čerenkov telescope (a prototype of the future LHAASO experiment [2]): the measured energy spectrum of the proton + helium component shows a break at $(700 \pm 230 \pm 70)$ TeV [2]. Preliminary results from two independent analyses of the ARGO-YBJ data alone do confirm this picture, within the quoted uncertainties [88, 89].

An overall picture of indirect measurements of the all-particle spectrum, below $10^{18}$ eV, is shown in Fig. 9. In the same plot, the measurements of the so-called light component (i.e. proton + helium) are also given, showing a clear bending at energies below the knee of the all-particle spectrum. For comparison, the combination of indirect measurements is shown at lower energies, while the results for the light and heavy component as identified by KASCADE and KASCADE-Grande are shown

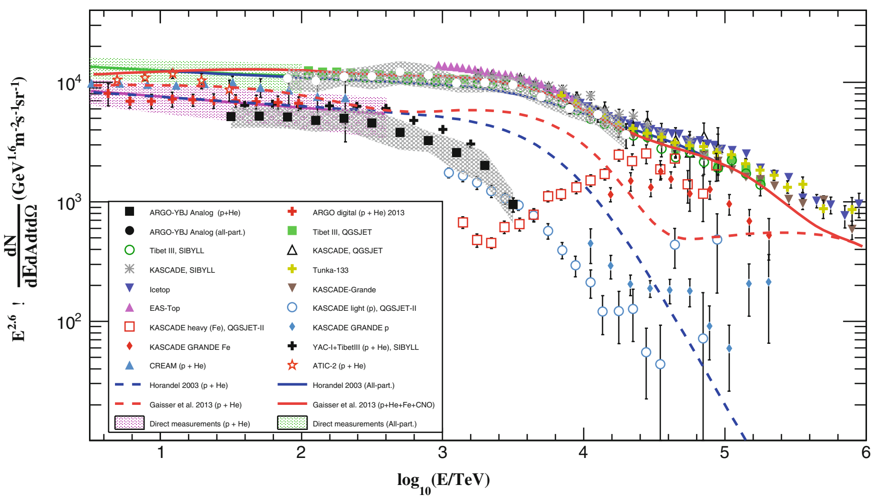



**Fig. 9** Indirect measurements of the all-particle CR energy spectrum below $10^{18}$ eV. Also shown are the combination of high energy direct measurements, and the energy spectrum for the light (i.e. proton + helium) component. Plot taken from [88]

for higher energies ([1, 78] and references therein). Besides a knee-like behaviour in the heavy elements at about $10^{17}$ eV (consistent with the second knee), KASCADE-Grande data also suggest an ankle-like structure in the light elements at the same energies [78]. The uncertainties on both energy spectra and mass composition are reduced at higher energies, due to the possibility to detect fluorescence light emission along the whole shower development in the atmosphere (see next session).

### Flux Anisotropies

A complementary approach to the study of CR sources and propagation, with respect to the analysis of energy spectra and composition, is provided by the measurement of anisotropy signals. This also possibly leads to some information on the galactic magnetic field, which is mainly responsible for the highly isotropic CR flux. Even though the first evidences for anisotropies (resulting from the CR intensity variations with sidereal time) dates back to Hess and Steinmaurer in 1932 [91], in recent years the huge event statistics collected by several experiments with good pointing accuracy allowed a detailed analysis of two dimensional arrival direction distribution maps (right ascension and declination) and their evolution with time. As a consequence, anisotropy signals at the level of $10^4$–$10^{-3}$ were found at different angular scales in both hemispheres (see for instance [90] and refs. therein).

A so-called Large Scale Anisotropy (LSA) has been measured by several experiments (e.g. Tibet-AS$\gamma$ [92], Milagro [93], ARGO-YBJ [94], IceCube [95]) showing an approximate dipole-like feature with an excess region between 40°–90° in right ascension (around the heliospheric tail) and a deficit between 150°–240° (in the direction of the galactic north pole), referred to as *tail-in* and *loss cone* regions, respectively.

These observations are likely to reflect the combination of several effects, namely the relative motion of the solar system with respect to the frame in which CRs are isotropic (Compton–Getting effect [96]), the orientation of the local magnetic field [97] and the overall gradient in the CR local density (see for instance [5, 98, 99]).

As can be seen in Fig. 10, the amplitude of the observed signal is of the order of $10^{-4}$–$10^{-3}$ with a wide maximum in the multi-TeV region and a stable phase. An increase in the amplitude and a dramatic change of phase (pointing to the opposite direction) are then suggested by data above 100 TeV up to 5 PeV (see [90] and ref. therein).

Recently an additional anisotropy signal has been found in the few TeV energy region, with excesses at angular scales of about 10° (the so-called Medium/Small-Scale Anisotropy, MSA) by Tibet-AS$\gamma$ [100], Milagro [101], ARGO-YBJ [102], IceCube [95] and HAWC [103]. Such signals have a quite large statistical significance (up to 15 standard deviations) and a nice matching between observations from both hemispheres. Moreover, there are hints for a harder energy spectrum in the excess regions with respect to the isotropic CR background. For both LSA and MSA signals, most observations suggest time stability over several years time scales, which would exclude a correlation with the solar activity.

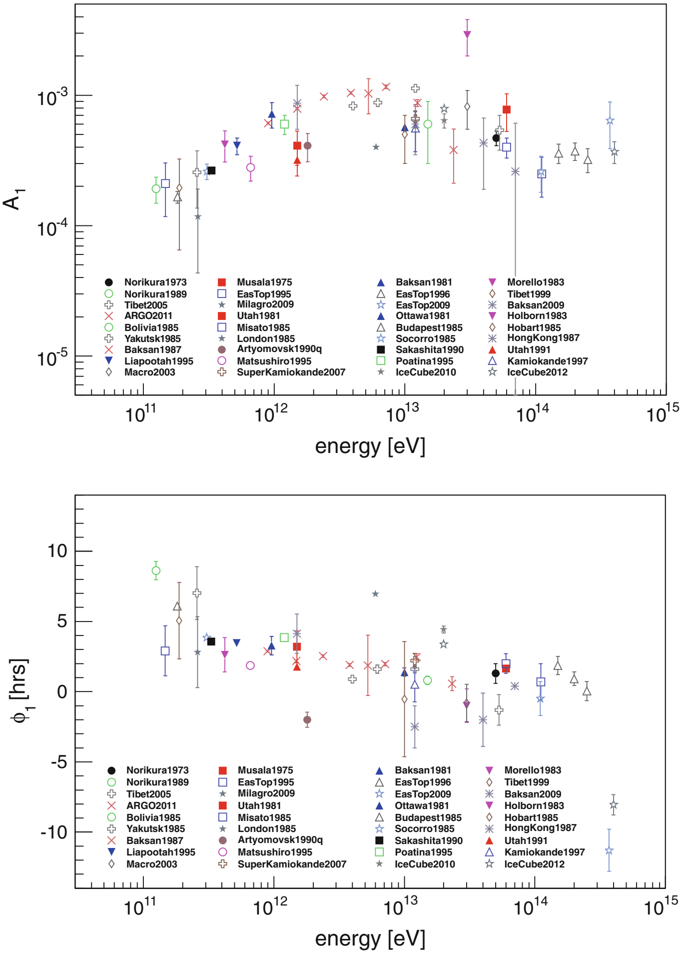



**Fig. 10** Amplitude and phase (*upper* and *lower panel*, respectively) of the sidereal CR flux daily variation (first harmonic) as measured by several (under)ground experiments. Plot taken from [90]

The discovery of anisotropy on small angular scales was rather surprising in that the basic expectation of the theory of CR diffusive transport is that only a dipole anisotropy should be expected. On the other hand, it has been noted by several authors that small-scale anisotropies may develop because of the local configuration of the magnetic field, within, say, a few pc from Earth. For instance, in Ref. [104] the author describes the propagation of CRs arriving in the neighborhood of the solar system in several realizations of the local magnetic field and small-scale anisotropies are in fact found, mainly as a result of the fact that fluctuations in the deflections are not averaged to zero. In other words, the transport is not fully in the diffusive limit. An elegant derivation of the same result was found by [105], in which the author shows that these small-scale fluctuations naturally arise as a consequence of the Liouvilles theorem.

A better knowledge of CR physics up to the ankle will need measurements of energy spectra and anisotropy maps of individual species (or at least mass groups) with better resolution and larger statistics. This will also depend on future experiments trying to use new observables (e.g. radio emission [106]) and/or to combine several techniques to be used at the same time (e.g. the LHAASO project [107]).

## *Observations of Ultra-High Energy Cosmic Rays*

Above $10^{18}$ eV (UHE), the two largest and most precise detectors to date are the Pierre Auger Observatory in Argentina (Mendoza) and the Telescope Array in the USA (Utah). Both detectors exploit the hybrid concept, combining an array of surface detectors to sample extensive air showers when they reach the ground and telescopes, overlooking the surface array, to collect the fluorescence light of the excited atmospheric nitrogen. The advent of the hybrid approach has been a major breakthrough in the detection of UHECRs since the method allows to have the same energy scale in the surface detectors and the fluorescence telescopes. In fact the absence of an energy scale common to both detection methods had led to the puzzle about the existence of the flux suppression around $5 \times 10^{19}$ eV, which was observed by HiRes [108] but not present in AGASA data [109], whose energy calibration was based on Monte Carlo simulations. The first hybrid measurements were done in HiRes/MIA [110] with a detector array of limited size; the Auger project, for the first time, adopted the hybrid approach [111] as the basis of the detector design to definitely attack the suppression puzzle.

### Pierre Auger Observatory and Telescope Array

The two detectors are very similar, but the different sizes and operation times make them differ sizably in the collected data sets and exposures. They are both located at similar average elevation, about 1,400 m a.s.l., and roughly similar longitudes, Auger in the southern hemisphere and TA in the northern. A detailed description of the experiments can be found in [112, 113]; the main features of the basic detectors are summarized in Table 1 [114].

The most remarkable difference lies in their surface detectors (SD) which are based on different detection methods. The particle detectors in the Auger SD are cylindrical tanks of 10 $m^2$ surface and 1.2 m height, filled with purified water, with three photomultiplier tubes (PMT) to detect the Čerenkov light of particles in the shower front. In the TA they consist of two 3 $m^2$ slabs of plastic scintillator on top of each other which give light pulses also read by PMTs. The water tanks are relatively much more sensitive to shower muons which usually traverse the tank from wall to wall while the counts in the TA detectors are dominated by electrons and positrons in

**Table 1** Comparison of characteristics of the Pierre Auger Observatory and the Telescope Array. The low energy extensions for each observatory, HEAT and TALE, are not included

| | | | Auger | TA |
|---|---|---|---|---|
| SD | Average latitude | | 35.3° S | 39.4° N |
| | Average altitude | | 1,400 m | 1,400 m |
| | Surface area | | 3,000 km$^2$ | 700 km$^2$ |
| | Lattice | | 1.5 km hexagon | 1.2 km square |
| | Detector | Type | water-Čerenkov | Plastic scintillator |
| | | Size | 10 m$^2$ × 1.2 m | (2×) 3 m$^2$ × 1.2 cm |
| | | Sampling | 25 ns | 20 ns |
| FD | Sites | | 4 | 3 |
| | Telescopes | Number | 24 | 36 |
| | | Size | 13 m$^2$ | 6.8 m$^2$/3 m$^2$ |
| | | Field of view | 28.5° × 30° | 16° × 14°/18° × 15° |
| | | Pixels | 440 | 256 |

the shower front. Furthermore, because of their height, the Auger detectors are well suited to detect highly inclined showers, thereby increasing the exposure and the sky coverage. Inclined showers are also used for neutrino searches and to establish the muon content of the showers. In Auger, an array of radio antennas (AERA) complements the data with the detection of the shower radiation in the hundred MHz region.

The fluorescence telescopes are located on the boundary of the two observatories to overlook the whole atmospheric volume just above the surface arrays and are based on similar detector components. The Pierre Auger Observatory contains a smaller area of 23.5 km$^2$ with stations separated by 750 m (*infill* array) which can be combined with three additional telescopes pointing at higher elevations (HEAT) for lower energy measurements. Similarly, TA has two sub-arrays of 46 and 35 stations separated by about 600 and 400 m over a surface of 20 km$^2$, together with ten telescopes covering from 31° to 59° of elevation (TALE).

## *Event Classes and Energy Calibration*

A hybrid experiment collects shower events of different classes. The separation into classes is a natural consequence of the different on-time (generally called *duty cycle*) of the two detector components: the surface array is able to collect showers at any time, whereas the fluorescence detectors can operate only during clear moonless nights (≈15% duty cycle). Taking into account geometry and quality cuts applied at the event reconstruction level, the common dataset is only few percent. Therefore only a small part of the SD showers are actually reconstructed by the FD. Nonetheless, this sub-sample (the *hybrid* dataset) is very valuable, including events having both the footprint of the shower at ground and the longitudinal profile measured. The advantage of this approach is twofold:

- the energy estimator used in the surface detector can be compared on an event-by-event basis with the shower energy reconstructed by the FD. The latter measurement is based on the total amount of light emitted along the shower, which is in turn proportional to the energy deposited by the shower particles. Apart from the missing energy carried by neutrinos and energetic muons, the FD performs a calorimetric measurement of the shower energy. The SD estimator is given by the particle density at 1000 m (800 m) from the shower core in Auger (TA), corrected for the shower attenuation in the atmosphere depending on the zenith angle. The correlation between the FD energy and the SD energy estimator provides the energy calibration that is used for the whole SD data set [114, 115].
- The hybrid events are higher quality showers, because the availability of the longitudinal profiles allows to access the most prominent information about the primary mass (the maximum of the shower depth). These events have also a superior definition of the shower geometry, even if the SD data are coming from a single surface detector [111]. Therefore the hybrid dataset, though being reduced in size, constitutes a selection of well-reconstructed events and a reference for all methods, based on SD data, aiming to obtain mass discriminating parameters.

The SD energy calibration through the hybrid dataset is a technique adopted by both collaborations. The Pierre Auger collaboration calculates the correlation between the energy estimators (for the three classes: standard, inclined and infill) and the FD energy [116]. TA has found that the SD energy derived from the energy estimator via Monte Carlo simulation has to be multiplied by a constant factor of 1.27 to ensure a good matching to the measured FD energy [117]. The latter result is a remarkable evidence of the inadequacy of energy calibrations based on Monte Carlo methods as done in the past.

It has finally to be noted that the relation between the longitudinal profile density and the measured light is provided by the combination of the fluorescence yield and the measured light transmission. The former has been established experimentally, the latter is obtained from the atmospheric monitoring data system operated at each site. Unfortunately, the collaborations use different parameterizations of the fluorescence yield. Including all that the quoted systematic uncertainty in the energy scale is 14% for Auger and 20% for TA.

### The Energy Spectrum

The energy spectra measured at the two observatories are shown in Fig. 11. A more comprehensive review of spectrum data, including other experiments, e.g. IceCube and Yakutzk, can be found in [115]. Yet, especially for energies above $10^{18}$ eV, the

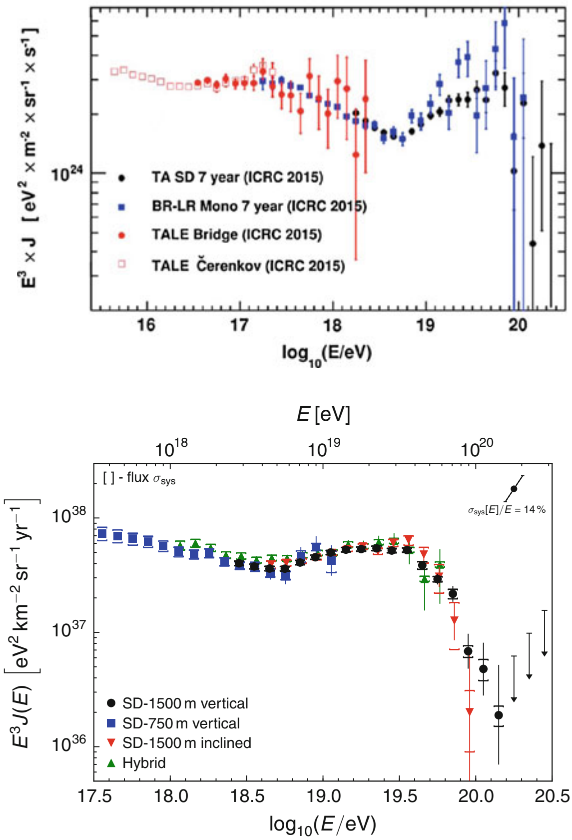



**Fig. 11** Energy spectra presented at ICRC 2015 by the Telescope Array (*upper panel*) and Auger (*lower panel*) collaborations. The data from the different sub-detectors are shown separately

bulk of the data comes from Auger and TA. The two panels show the spectra as originating from different detector components for TA (upper panel) and Auger (lower panel).

The most prominent features appear similar in the common energy interval with a break (the *ankle*) at around $10^{18.7}$ eV and a flux suppression, quite evident (at several standard deviations for both experiment) in both cases, but exhibiting somewhat different shapes. It has to be noted that for both experiments the data above the ankle are dominated by the respective ground arrays.

Both the collaborations exploit procedures to combine the different spectrum components into a unique spectrum. For a better comparison, the combined energy spectra are superimposed in Fig. 12, which provides also the values of the main spectral features [115]. The corresponding exposures are about 6,300 km$^2$ sr yr for TA and 50,000 km$^2$ sr yr for Auger. Comparing the values of the ankle energy ($E_{ankle}$) and of the cutoff ($E_{1/2}$) (the energy at which the integral flux drops to half of what is expected in the absence of a cutoff) one finds that the ankle energies are consistent within the systematic uncertainties in the energy scale, but the discrepancy between the cutoff energies is not explained by systematics.