# High Precision Particle Astrophysics as a New Window on the Universe

## with an Antimatter Large Acceptance Detector In Orbit

## (ALADInO)



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# 1   Executive summary

The proposed Science Theme, High Precision Particle Astrophysics, addresses fundamental topics across particle physics, astrophysics and cosmology through the accurate measurement of Cosmic Rays in space. The theme poses three fundamental questions: *1) What is the origin of the Matter-Antimatter asymmetry in our Universe? 2) What is the particle nature of Dark Matter and does it contribute to the cosmic radiation? 3) Which is the origin and the acceleration and propagation mechanism of Cosmic Rays?* During the last 25 years, these questions have been addressed with increasing accuracy and experimental performances by a number space experiments like AMS-01, PAMELA, AGILE, FERMI, AMS-02, CALET and DAMPE. The improved experimental accuracy has been accompanied by a wealth of results on topics from fundamental properties of particle and fields, to astrophysics, to cosmology. At present, this scientific field has reached a solid maturity and it is exhibiting a very interesting discovery potential complementary and competitive with ground-based experiments like LHC at CERN or underground experiments like those performed at the Gran Sasso Laboratory. Antimatter particles in Cosmic Rays (CR) represent a small fraction of the total flux, about $5 \cdot 10^{-3}$ for $e^+$, $10^{-5}$ for p-bar, $10^{-7}$ for D-bar, less than $10^{-8}$ for anti-$^4$He or heavier antinuclei: these tiny fluxes, however, carry a great amount of information, since the origin of antiparticles is intimately related to fundamental processes.

High statistics, accurate measurement of the antimatter component of CRs to the highest possible energies, together with the ultra-precise measurement of ordinary CRs, would provide a rich program of high-energy astrophysics as has been demonstrated by the amazing results of AMS-01, PAMELA and AMS-02, the first generation particle spectrometers in space.

**Matter-Antimatter asymmetry** is one of the greatest mistery of current cosmology: we have no evidence so far at ground experiments for a mechanism which could explain baryogenesis. Anti-D, anti-$^3$He and anti-$^4$He have been produced with the same relative rates as D and $^{3,4}$He in heavy ions collisions. Anti-H atoms exhibits exactly the same emission spectra as H atoms. Limits on proton life-time does not provide evidence for barion number violating interactions. At the same time, theories that either predict the existence of nuclear antimatter in segregated domains or its total absence in the current universe have no firm foundation in observational data. The detection of anti-$^4$He or heavier antinuclei in CRs would shatter our current understanding of early Universe physics with broad cosmological implications or reveal something completely unforeseen in the realm of astrophysics, such as e.g. an anomalous abundance of dense antibaryon stars or anti-cloudlets in our Galaxy.

The existence of **Dark Matter** (DM) is well established and supported by a variety of astrophysical and cosmological observations. Its particle nature is still subject of exciting speculations since no evidence has been found, neither in **direct production** at the LHC, nor in **direct detection** at underground experiments, over an amazingly large interval of masses and physical properties. Since DM is abundant in the universe, particle astrophysics in **space is the right environment for indirect searches** of DM particles. Antiparticles ($e^+$, $p^-$, $D^-$, anti-$^3$He) constitute a golden channel for this search, since the rare antiparticle component of DM annihilation/decay products, would give rise to an observable excess on these fluxes with respect to the tiny standard astrophysical expectations, not influenced by the otherwise large background of standard CRs. The knowledge of the astrophysical antiparticle background, would require, however, a substantial improvement to match the new sensitivity regime we are aiming to.

This add a further, essential topic to our Science Theme, namely the **origin, acceleration and propagation of CRs** and their interactions with the interstellar medium. This topic addresses a rich program of measurements of the cosmic radiation: energy spectra, chemical and isotopic composition, arrival directions and temporal variations at still unexplored sensitivities and energies, reaching, for the lighter CR components (p, He) up to PeV energies, the so-called "knee" region, where a flux transition from galactic to extragalactic CR sources is expected.

In order to address the above-mentioned scientific questions we also discuss a set of key requirements for a mission based on a large acceptance, superconducting magnetic spectrometer to separate charged particles/anti-particles (Antimatter Large Acceptance Detector In Orbit -ALADInO).

Access to space is mandatory to avoid atmospheric background and to ensure an extended observation time. A collection factor of $\approx 20$ m$^2$sr years is needed to increase by a factor $10^3$ current limits on anti-$^4$He or heavier nuclear anti-matter. A collection factor of ~15 m$^2$ sr years, a maximum detectable rigidity of 20 TV and a $e^\pm/p^\pm$ separation at the level of $10^6$ are needed to provide a substantial progress in the field. The same collection factor, together with a velocity measurement with 1% resolution, would allow for the measurement of O(1 GeV) anti-p, anti-D and anti-$^3$He, in an energy range where DM models predict

signals 1-2 orders of magnitude larger that the astrophysical background. With the above collection factor, the study of the lighter CR spectrum could also reach the energy range E~1 Pev shedding light on the puzzle of the composition of extragalactig cosmic rays.

All these requirements are summarized in the concept of **ALADInO** presented at the end of this paper: based on a High Temperature Superconducting (HTS) magnet, designed for a five-year mission either on L2 or on High Earth Orbit, in order to maximize the CR collection while minimizing active cooling of the cryo-magnet. The key technological challenge in ALADIno is the development of the superconducting toroid making use of HTS and operating at T≈15-30 K. R&D activities for the use of HTS in space were already started under EU-FP7 project SR2S and can further profit in the next years of the intense effort ongoing at CERN for future experiments at next generation high energy colliders.

The ALADInO sub-detectors can be based on well-known technology with high TRL developed for high-energy physics experiments: silicon and sensors, scintillators and homogeneus calorimeters have been successfully operated in long-term missions (AGILE, AMS-01/02, Fermi, PAMELA, CALET, DAMPE) or proposed for future ones (ExTP, CSES2, HERD). For the VOYAGE 2035-2050 program a new generation of detectors/electronics will be available and tested (e.g. SiPM, silicon pixel detectors) allowing to reach even better performances with reduced power requirements.

In this proposal ALADInO is discussed at the level of concept, which can be implemented also through intermediate phases in order to test the more demanding technologies while addressing part of the physics program.

# 2 Science case

Our planet is constantly bombarded by **Cosmic Rays** (CRs), high-energy charged particles reaching us from regions of space external to the Solar System. The origin of CRs remains a century-old puzzle also considering the fact that, before reaching Earth, their directions are randomized by the interstellar magnetic fields. The leading paradigm is that the bulk of CRs are generated in Galactic processes such as supernova explosions or stellar winds, although extragalactic sources and secondary production by primary CRs with the Interstellar Medium (ISM) may contribute as well to the observed flux. These particles are thus a genuine sample of solar, galactic, and extragalactic matter that includes all known nuclei and their long lived isotopes, as well as electrons and antiparticles. This makes the CR radiation a unique messenger to probe high-energy phenomena. The CR energy spectrum extends several orders of magnitude from $\sim 10^6$ eV to about $\sim 10^{21}$ eV. Since their discovery at the beginning of last century, scientists have been intrigued by the physical mechanisms of their **origin, acceleration and propagation**. CRs are a unique kind of messenger connecting fundamental physics, cosmology and astrophysics. Notable examples of open issues which can be addressed by the study of CR are the still unexplained **asymmetry between Matter and Antimatter and matter in our Universe** and the puzzling **nature of Dark Matter,** six times more abundant than matter.

It follows that the study of high-energy antiparticles in the cosmic radiation may have **groundbreaking consequences for cosmology, astrophysics and particle physics.**

**Nuclear Antimatter** seems to be extremely rare in today's visible Universe: most of the antiparticles produced after the reheating seems to have disappeared during the baryonic annihilation phase, although convincing mechanisms for this asymmetry have not been put forward. The resulting **Matter-Antimatter asymmetry** is one of the greatest puzzles in contemporary cosmology and astrophysics. At extragalactic scales, large concentrations of nuclear antimatter could still exist, but no evidence has been found yet [Blinnikov 2015, Dolgov 2016, Poulin 2019]. Unambiguous evidence for anti-$^4$He or heavier antinuclei in CR would have **profound consequences on particle physics and cosmology**.

The nature of the **Dark Matter** is another unsolved problem in contemporary astrophysics. This topic has motivated a varied, worldwide experimental effort to search for signatures of new physics via complementary approaches: underground laboratories (DM direct search), particle colliders (DM production) and observatories on ground and in space (indirect DM search). If the **dark halo** of the Milky Way is constituted by a new kind of weakly interacting elementary particles with a mass of the order of the electroweak scale then the annihilation or decay of these particles could give rise to a detectable signal, in the form of an excess in the cosmic radiation [Cirelli 2015b]. An anomalous amount of antiparticles (e$^+$, p$^-$, D$^-$, anti-$^3$He), could be observable as a distortion of the expected antiparticle spectra in CR. Indirect DM search in the cosmic radiation has motivated experiments aiming with increasing sensitivity at this goal. However, a claim of DM signature from indirect measurements would be challenging, since the production of antiparticles can be due to other mechanisms e.g. in the collisions of ordinary CRs with the interstellar matter. The level of antiparticles arising from these collisions has to be carefully calculated and it constitutes

the **astrophysical background** for indirect DM search [Salati 2015, Cirelli 2015a]. While calculations are reaching an increasing level of complexity and reliability [Boschini 2017, Boudad 2019], the existing models of astrophysical backgrounds crucially depend on our knowledge of **CR acceleration and propagation processes** through the Galaxy, which are still poorly understood. Galactic sources of CRs, such as supernova remnants, should be able to accelerate CR particles via diffusive shock acceleration mechanisms up to the PeV energy scale ($\sim 10^{15}$ eV) [Blasi 2014]. Their subsequent propagation is governed by diffusive transport in interstellar magnetic turbulence, which keeps CRs confined within the halo of the Milky Way for $\sim$0.1-10 million years. During this propagation, CRs are subjected to Coulomb/ionization losses and hadronic interactions with the interstellar gas. Along with re-shaping their energy spectrum, interactions of CRs with interstellar matter could produce also secondary CR particles, that is particles that are not accelerated at the sources. D or $^3$He isotopes, Li-Be-B isotopes and, most notably, **antiparticles** are some of the most interesting secondary CRs.

The physics mechanisms regulating the antiparticle background are the same as those producing the other secondary components. Accurate measurements of CR nuclei can consequently be used to *calibrate* the astrophysical models and enhance the sensitivity for possible anomalous antiparticle signals. The Boron to Carbon (B/C) ratio is one of the most important physics observables used to assess the expected antiparticle background [Grenier 2015].

Other important processes affecting near-Earth CR spectrum are related to **heliophysics** and **space science**. Charged particles are affected by solar generated magnetic turbulence and solar wind disturbances, which significantly "modulates" the shape of their energy spectrum. The **solar modulation** effect is a remarkable time-, space-, energy- and particle-dependent phenomenon, which is known to be connected with the Sun's magnetic activity, although the detailed mechanisms of CR interactions with the heliospheric plasma are still subjected to intense research [Potgieter 2013, Bisschoff 2019].

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**Particle Astrophysics addresses key science questions at the interface between particle physics, astrophysics and cosmology:**

What's the origin of the antimatter-matter asymmetry in our Universe?
Which is the particle nature of dark matter?
Which are the sources of CRs? How and where are they accelerated?
How do they propagate through the Galaxy? What kind of interactions do they experience?
To what extent extragalactic particles contribute to the CR flux?
Which are the physics processes that rule CR transport in the heliosphere?

**High precision investigation of the energy spectrum, composition, arrival directions, and temporal variations of CR components over an extended energy interval is the key to answer or to better understand these open questions.**

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The remaining part of this section is devoted to a better description of the various science topics addressed by our ScienceTheme

**Nuclear antimatter** – The detection of complex forms of antinuclei such as anti-$^4$He or heavier species would cause a profound impact on our understanding of the early Universe. In fact, antinuclei can be regarded as direct indicators for survival of primordial antimatter and for the possible existence of anti-nucleosyntyhesis processes at work in the core of anti-stars. Nuclear antimatter production in CR collisions and/or from DM sources is extremely suppressed for nuclear species above anti-$^3$He [Poulin 2019, Ding 2019]. Efforts to search for nuclear antimatter in CR have been developed during the last 15 years [BESS 2008, AMS01 1999, PAMELA 2014]: no observation of anti-$^4$He or heavier antinuclei in the CR flux has been published **down** to the level of $10^{-7}$. The lack of unambiguous annihilation signatures from gamma-ray sky surveys led various authors to conclude that the distance to any hypothetical domain dominated by **primordial antimatter** must be comparable to the horizon scale [Cohen 1998].

The basic recipe to explain the evolution to a barion asymmetric Universe from a symmetric one has been introduced by Sakharov [Sakharov 1967]. It involves a mechanisms of bariosynthesis requiring violation of quantum numbers for which there is not an experimental evidence: neither barion non-conservation nor

large levels of CP-violation have been observed. The detection of anti-$^4$He or heavier nuclei would point to the existence of primordial antimatter from the Big Bang nucleosynthesis, while heavier particles such as $^{12}\overline{C}$ would point to the existence of stellar nucleosynthesis, or dense lumps of antimatter at galactic scale [Bambi 2007, Dolgov 2016, Poulin 2019].

Very recently, tantalizing hints of anti-3He and anti-4He candidates have been presented by the AMS-02 magnetic spectrometer [Kounine 2017b]. Considering the huge helium statistics, about an antihelium candidate out of 100 million helium events, a daunting simulation effort is required to exclude misidentification of these events. Even if the results will be published and substantiated by a convincing and robust simulation, the enormous relevance of this result would require confirmation and extension by another experiment with different systematic uncertainties and able to collect a much larger statistical sample.

> **Observation and detailed study of nuclear antimatter would be a game changer in our understanding of the physics of early Universe and of the fundamental properties of particle and fields.**

**Dark matter** – In spite of lack of evidence for Beyond-Standard-Model (BSM) particles from experiments at the Large Hadron Collider (LHC), TeV-scale models of DM particles are nicely supported by cosmological constraints. The thermal freeze-out mechanism of Weakly Interacting Massive Particles (WIMPs) naturally predicts the required level of abundance of cosmological DM in today's Universe in fully accordance with cosmological observations [PLANCK 2016, PLANCK 2018]. TeV-scale WIMP-DM candidates have production cross-sections which extremely suppressed at the LHC [Ostdiek 2015, Boveia 2018]; even prospects for future colliders are not encouraging [Cirelli et al. 2014a]. Their **direct** detection via elastic scattering off nuclei is also disfavored for the multi-TeV masses [Hisano 2015]. On the other hand, **indirect** search appears to be the most promising approach for TeV-scale WIMP-like DM candidates. In fact, for these candidates, there is a large region of the parameter space consistent both with Fermi-LAT gamma-ray data and the CMB limits [Cirelli 2015b; Masi 2015, FERMI 2016, FERMI 2017a] as can be seen in **Figure 1.**
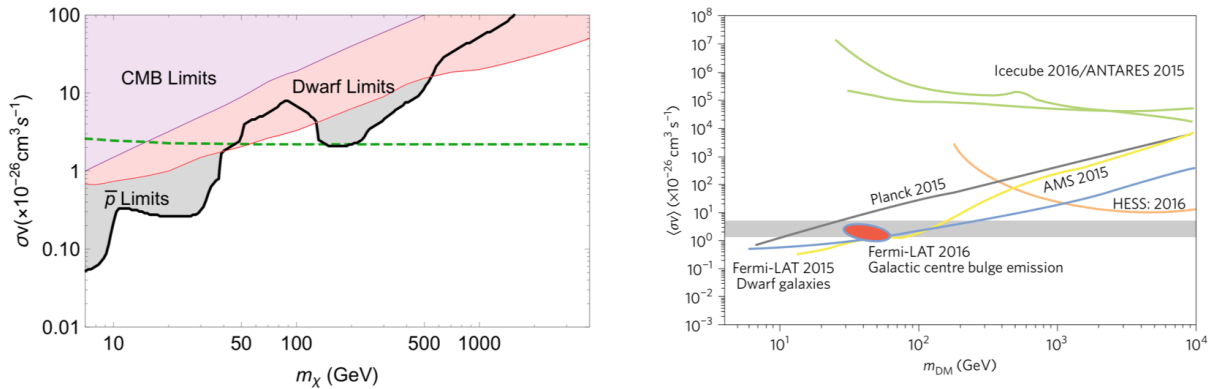


**Figure 1: Left from [Cholis 2019]**: *upper limits on the DM annihilation rate to b-quarks pairs derived from CR antiproton measurements from AMS-02 (black), along with the regions excluded by the Planck observations of the CMB (purple) and by gamma-ray data on dwarf galaxies (red). In can be seen that the regions of DM parameter space favored by AMS-02 lie either in the TeV region of DM mass or in the 50-100 GeV mass region, both consistent with the thermal DM annihilation cross-section level (green dashed line). The 50 GeV DM is also favored by the Fermi-LAT gamma-ray data, i.e. the so-called Galactic Centre excess.* **Right from [Conrad 2017]**: *multimessenger constraints on the DM annihilation to b-quark pairs, using neutrinos, CMB photons, gamma-rays, and antiprotons. The best-fit DM interpretation of the Galactic Centre excess is shown as red circle. The thermal DM annihilation cross section is shown as gray shaded band.*

The most promising channels for indirect DM searches are those involving antimatter in the final state, e.g. elementary antiparticles such as $e^+$, $p^-$ or anti-nuclei as $D^-$, anti-$^3$He. In recent years, this field has witnessed significant advancements on both experimental and theoretical sides, stimulated by new-generation space borne experiments such as PAMELA, the Fermi-LAT telescope and the Alpha Magnetic Spectrometer AMS-02. All the experiments observed a very significant and **unexpected excess** in the **positron** flux above 10 GeV: the positron energy spectrum is significantly different than the electron one and it is not compatible with the expected astrophysical background. It is now generally accepted that the positron and electron spectra can be jointly understood only assuming the existence of yet unknown sources of high-energy positrons and electrons in the Galaxy.

These observations were possible only because of the outstanding accuracy of the new generation of space borne experiments and of the high statistics samples which have been collected and analyzed. The positron excess has caused a huge interest. During the last decade, hundreds of papers have proposed diverse interpretations, either invoking annihilation/decay of DM particles [Turner 1990, Ellis 2000, Cheng 2002, Cirelli 2009, Kane 2009, Kopp 2013, Belotsky 2014, Chen 2015, Bhattacharyya 2017, Cheng 2017, Bai 2018, Feng 2018, Profumo 2019], nearby astrophysical sources such as pulsars or supernova remnants [Fujita 2009, Hooper 2009, Serpico 2012, Linden 2013, Mertsch 2014, Tomassetti 2015a,c, Hooper 2017, Liu 2017, Kachelrieß 2018, Profumo 2018, Bykov 2019, Fornieri 2019] or modifications to the CR acceleration and propagation mechanisms [Cowsik 2010, Katz 2010, Blum 2013, Cowsik 2014, Lipari 2017, Kruskal 2016, Diesing 2019, Lipari 2019]. These predictions are all compatible with the accuracy of current data; additional information is needed to disentangle the dominating sources of high energy $e^{+/-}$.

In order to better understand the source of this excess, also the arrival directions of high-energy CRs can be studied, searching for **anisotropy signals** which could be associated to localized sources. High-energy leptons lose rapidly their energy while they travel in the ISM; in order to reach the Earth, those detected at the highest energies must have been produced in the vicinity of the solar system (within ~1 kpc). Localized sources of CR positrons may then be detectable as an excess in given directions of the sky, favoring or disfavoring particular models.

> **Precision measurements of the detailed features of the energy spectra and arrival directions of CR positrons and electrons at the TeV scale are needed to clarify whether DM annihilations or new astrophysics phenomena are the surce of the anomalies observed on the positron flux.**

Evidence for detectable DM annihilation signals in the **hadronic** channels would significantly strengthen the DM hypothesis. No astrophysical sources would produce at the same time a distorsion on the positron and antiproton spectra. In this respect, an ideal signature of DM would be the observation of an **excess of CR antiprotons** at high energies, compatible with the the DM candidate mass and decay branching ratios. The scenario of a WIMP-like DM annihilating into hadronic channels (e.g. quark-antiquark pairs) is well consistent with astrophysical γ-ray bounds and it is well motivated by theories Beyond Standard Model, especially considering the absence of new physics signals from LHC [Boveia 2018, Cholis 2019, Cuoco 2019]. To find out whether a DM signal is hidden in the CR antiproton flux a reliable assessment of astrophysical background models is needed and depending upon the DM mass, antiproton measurements needs to be extended above the TeV scale.

**Light antinuclei**, in particular $D^-$ and anti-$^3$He, represent the most promising channel for DM searches in terms of signal-to-background ratio. In fact, due to kinematics, the astrophysical background of CR $D^-$ or anti-$^3$He is highly suppressed in the low energy region associated with WIMP-DM models. The detection of $D^-$ or anti-$^3$He excess in CRs is often considered as a "smoking gun" for DM searches. On the other hand, a null result would provide strong exclusion limits for a wide range of viable DM models.

> **Accurate measurements of anti-protons, anti-deuterons and anti-$^3$He in CR are the key to investigate GeV to TeV scale DM models.**
> **Multi-channel investigation of rare CR components is central to probe/study DM provided that uncertainties on the astrophysical backgrounds are significantly reduced by means of a precise knowledge of the composition and energetics of cosmic rays in the galaxy and the heliosphere.**

**CR protons and nuclei** – Accurate, recent measurements of the most abundant CR species, such as protons and helium have recently revealed new and unexpected features in their energy spectra, that may shed new light on the acceleration and propagation mechanisms of CRs in the Galaxy. The longstanding simple picture of a featureless and universal *power-law* energy spectrum of CRs might have been finally overcome [Serpico 2015, Gabici 2019]. A remarkable change of spectral indices has been established for several CR energy spectra at a kinetic energy of about 300 GeV. The change in slope, consisting by a spectral hardening, has been suggested by CREAM, measured by PAMELA for p and He and then accurately characterized by AMS-02 for all nuclear species up to Oxygen. Such a spectral hardening appears to be *universal*, in the sense that has been detected in all charged nuclear species. However, the strength of the spectral changes appears to be more pronounced for secondary species (such as Li-Be-B nuclei) in comparison to primary elements (such as p, He, C, or O): this suggests that a **revised description of the CR diffusive propagation is needed**. At higher energies, recent calorimetric measurements reported by CREAM-III and CALET hints at the appearance of additional features in the proton energy spectrum, although the situation requires experimental clarification [Yoon 2017, CALET 2019].

On top of the hardening, the precision of recent data revealed that the rigidity spectrum of CR protons is steeper than the spectrum of helium nuclei, with the puzzling result that CR helium could becomes more abundant than hydrogen (proton) at the energy above ~10 TeV. Theoretically, the different slope between proton and helium suggests possible mechanisms of *violation* of *universality* in CR acceleration, in contrast to the basic prescription of the diffusive-shock-acceleration theory. It is unclear, at present, whether $Z>2$ heavier nuclei with follow the same energy spectrum of helium. Additional features may have been found by recent AMS-02 measurements of N, S, Si [Yan 2019] and in the spectrum of heavy nuclei such as Iron [Tomassetti 2015b].

The current situation therefore demands an experimental clarification at multi-TeV energy and high-Z charges which can only be provided by a high-precision spectrometric measurement of the individual nuclear species encompassing the relevant energy regions where indications for spectral features are emerging. Evidence for the observed hardenings will then be checked and better quantified, therefore providing strong constraints to state-of-the-art astrophysical models of CR acceleration and propagation mechanisms, also studying the possibility of a contribution of nearby sources. In particular, strong constraints are expected from multi-TeV measurements of the energy spectrum of secondary nuclei, along with secondary-to-primary ratios, which will provide a robust baseline of the astrophysical antimatter background.

> **Precise measurements of primary and secondary CR nuclei above TeV are fundamental to understand the acceleration and propagation mechanisms of CR in the Galaxy and to constrain models of astrophysical backgrounds in indirect DM searches.**

Since the first experimental evidence [Kulikov 1958], 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 [Bluemer 2009]. Several theoretical explanations have been proposed exploiting different hypotheses on source properties/populations, acceleration/propagation mechanisms and particle physics issues at high energies [Hoerandel 2004]. After the first results at the Large Hadron Collider (LHC), the hypothetical "particle physics'' origin of the knee, due to possible changes in the hadronic cross sections at high energy, is clearly disfavored, confirming that it is a genuine property of the CR spectrum itself [D'Enterria 2011]. It remains still unsolved whether the (dominant) origin of the knee is due to the reach of the maximum energy achievable at the galactic sources or to limits in the galactic confinement processes. In both cases a rigidity dependent sequence of knees in each single element spectrum is the most probable scenario [Hoerandel 2004]. For the analysis of the CR flux, direct measurements carried on space or stratospheric balloons actually give the best performance in terms of both energy resolution and charge identification. However, due to their limited acceptance and the steeply falling fluxes, they do not give clear information on the steepening of various elements nor on the knee of each species or of the all-particle spectrum itself. The measurement of the spectra of the different nuclear components in the knee region will also help to interpret the galactic component of the neutrino diffuse emission which at that time will be accurately measured by IceCube and Km3Net (photons are likely to be attenuated by the interstellar radiation field).

This will be very useful to understand if the CR knee is the same in the whole Galaxy hence to fully understand its nature [Gaggero 2015].

Chemical composition is shown to evolve towards heavier nuclei, with helium approaching hydrogen at energies of about 10-20 TeV [Seo 2012]. It is then mandatory to explore the energy region up to few PeVs with high precision direct measurements to study the energy spectra of each individual nuclear species, to detect any possible hardening of the spectral indexes and to set mass composition below the knee of the all-particle spectrum. A detection of the steepening of each single species and then ensuing explanation of the all-particle knee would be a crucial result in understanding galactic CR physics, also serving as fundamental input to the study of the extra-galactic component.

> **Direct measurement of the all particle spectrum up to the knee and study of the p and He components up to the PeV are needed to understand the origin of the knee, one of the outstanding problems in CR**

**CR transport in the heliosphere –** An improved understanding of transport mechanisms inside the heliosphere translates in an improvement on the uncertainties for indirect DM searches and of the measurement of CR interstellar spectra [Bisschoff 2019]. In recent years, the energetic particle environment has been studied in great details on Low Earth Orbit, in particular by the PAMELA experiment on polar orbit on Resurs DK1 (since 2006) and by AMS-02 onboard the ISS (since 2011)

Inside the heliosphere magnetic turbulence and solar wind disturbances affect CRs up to energies of tens of GeV, causing the so-called "solar modulation" phenomenon. To determine *how* the CR flux evolves in response to the changing conditions of the Sun's magnetic activity is a central question in solar physics. A related problem is to determine the properties and occurrence of solar energetic particle (SEP) events. In this respect, multichannel measurements of CR flux variations at various timescales will allow gaining a deep understanding on heliospheric physics, from predicting solar modulation to characterizing SEP events.

Operating ALADInO on L2, far from the Earth magnetic field, would greatly improve the study of solar effects on CRs and disentangle these effects in their Local Interstellar Space spectrum.

> **Multi-particle precision flux measurements up to several GeV and far from the Earth Magnetosphere would provide new valuable information on the CR interactions with the heliospheric plasma and significantly improve the accuracy of some DM indirect searches.**

# 3   Observational requirements

From the ambitious particle astrophysics science program discussed above we derive measurement **requirements** which we discuss in this section: we review the current experimental status on different measurement channels and discuss the expected sensitivities from **ALADInO,** whose design concept is presented in the following section 4.

The key physical quantities characterizing the basic properties of CR particles are charge magnitude and charge sign, incoming direction, velocity, momentum and/or total energy. The instrument must be capable to identify electrically charged particles with the ability to discriminate between particles and antiparticles over unexplored energies and with orders of magnitude better separation with respect to present experiments. Discrimination between leptons and hadrons, charge measurements, and mass separation will provide full particle identification. An important performance parameter is the *collection factor* (in units of $m^2$ sr yr), representing the product between exposure time and total acceptance over a given energy range. The measurement requirements depend on the specific observational goals and are outlined in the following.

## 3.1.1 Nuclear antimatter

The detection of anti-$^4$He or heavier antinuclei would have profound significance in cosmological theories and astrophysics. Conversely, an upper limit on the flux of antinuclei compatible with the range of the expected direct production from CR interaction could be interpreted as a lower limit on the antimatter content in a Universe where normal matter is dominant.

The best experimental limit on the anti-He/He flux ratio is set at  6.9 $10^{-8}$ level in a very limited rigidity range (1.6-14 GV) by the BESS experiment [BESS 2012]; in a wider interval (0.6-600 GV) the PAMELA spectrometer has published a limit  of 2.67 $10^{-7}$ [PAMELA 2014]. Hints for anti-$^3$He and anti-$^4$He candidates presented by the AMS-02 experiment [Kounine 2017b] lie just below the Pamela upper limit.

To prove unambiguously AMS-02 anti-He hints, or, conversely, to improve the current limits by at least a factor $10^3$ requires an identification capability of one anti-He out of $10^{11}$ Z=2 particles over a wide rigidity range. Similar performances are required for Z>2 anti-nuclei. Following the analysis of [Bambi 2007], the density of anti-stellar objects in our Galaxy might be approximated by the number of normal matter stars ($\approx 10^{11}$) multiplied by the   antinuclei-to-nuclei ratio or limit. Using this approach, the upper limit in case of no detection would directly limit the density of antimatter objects in the Milky Way.

 Production of anti-$^3$He can be foreseen also in some DM scenario or, although strongly suppressed, in the collision of CR with the ISM as discussed in section **3.2**. ALADInO sensitivity would  allow the first study of such a signal.

For antinuclei heavier than anti-He , the current observational limits would be improved at least of 4 orders of magnitude.

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**REQUIREMENT 1**
**A collection factor of 30 m$^2$ sr yrs is needed to extend the the current observational limits for anti-$^4$He and heavier antinuclei by at least 3 and 4 orders of magnitude, respectively.**

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## 3.1.2  Dark matter

**POSITRONS AND ELECTRONS –** Clear evidence of an unexpected e$^+$ excess in CRs, starting at 25 GeV, has been reported by PAMELA [PAMELA 2009, PAMELA 2013]; accurate measurements  by AMS-02 [AMS02-2013, AMS02-2014b, AMS02-2019b], have extended the measurement  of the positron fraction and the  separate  e$^{+/-}$ fluxes up to the TeV. The e$^+$ flux exhibits a significant excess over the expected background starting at 25 GeV, sharply dropping above 300 GeV. This behavior is compatible with a descriptive model requiring a new e$^+$ source term that dominates above 100 GeV, with a cutoff at ~800 GeV [AMS02-2019b].

Different spectral features   of  the energy spectra of e$^+$ and e$^-$ in the 200 GeV – multi-TeV energy region are key signatures to separate DM from astrophysical sources or propagation mechanism scenarios. As it can be seen on the  Figure 2-right, from the accurate measurement    of the falling part of the  e$^+$ spectrum above 300 GeV it   will  be  possible to test various hypotheses:    DM   (blue dots), pulsar (red and pink dots), or multiple pulsar (green dots ). The accuracy of the current measurements at the TeV scale, is limited by the statistics available and the energy reach. The supra-TeV (e$^+$+e$^-$) spectrum is being accurately measured by ongoing calorimetric experiments (CALET [Marrocchesi 2016], DAMPE [Chang 2017]): its accuracy will be further improved by forthcoming calorimetric missions (HERD [HERD 2017]). However, the lack of charge-sign identification of these instruments will not allow for a clear identification of the different spectral features  of the e$^+$ and e$^-$ fluxes. Conversely, accurate TeV region spectrometric measurements of the individual e$^-$ and e$^+$ fluxes at the percent level energies will dramatically restrict the parameter space region for either the DM or the pulsar hypothesis. No project, however, is currently planned to extend the spectrometric measurements by PAMELA and AMS-02.  ALADInO, taking advantage of a collection factor of 15 m$^2$ sr yrs and of a MDR larger than 20 TV, would  provide a breakthrough advance in this field. The suppression of the hadronic background  would be  provided by an hadron rejection larger than $10^5$, derived from the combined information of the spectrometer and the calorimeter, together with the suppression below $10^{-2}$ of the e$^-$ induced background in the e$^+$ channel due to charge flip: this  will guarantee a background level  in the e$^+$ channel below 1% in the e$^+$ excess region up to several TeV. The large ALADInO collection factor will guarantee a sample of  e$^+$ sufficiently large, so that  the finite knowledge of the detector efficiencies will dominate the measurement uncertainties at the percent level at the TeV scale, while the supra-TeV region uncertainties will be dominated by statistical fluctuations of the collected data. In this scenario, the positron excess will be accurately characterized in its whole development from its rise below 100 GeV up to the supra-TeV region where it is expected to drop down below the secondary astrophysical e$^+$ background.

The best limit on e$^+$ dipole anisotropy is set by AMS-02 at 1.9 % above 16 GeV [AMS02 2019b]. The search for anisotropies in the incoming directions of e$^{+/-}$ will take advantage of the high collection factor,

the background rejection capabilities and the instantaneous coverage of almost full sky of ALADInO, resulting in an expected sensitivity better than 0.2% in the $e^+$ dipole anisotropy above 16 GeV. This will reveal novel and unprecedented information, improving the current limits by a factor 10 and probing for the first time $e^+$ anisotropies at TeV energies, possibly providing conclusive information on the origin of high-energy $e^{+/-}$.
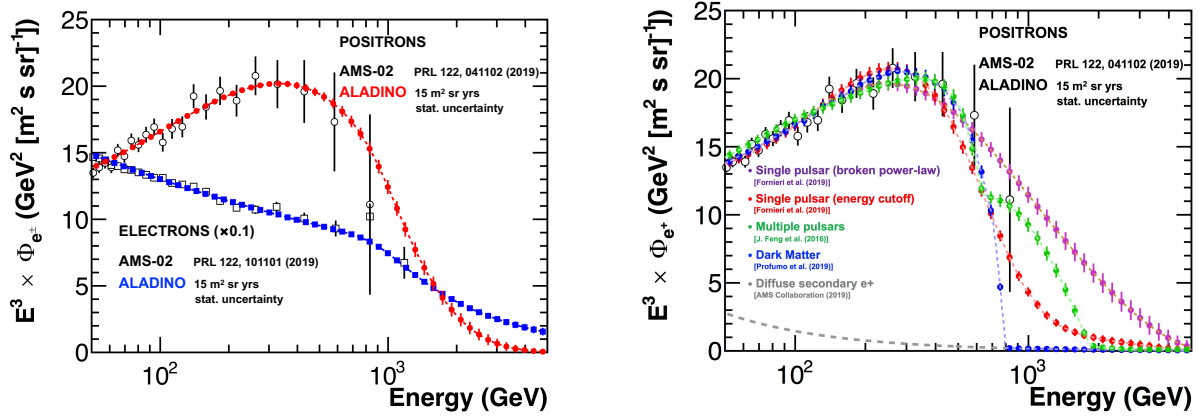


**Figure 2.** *Left) Projected measurement of ALADINO for $e^{+/-}$ fluxes in the descriptive model of [AMS02 2019a, AMS02 2019b] with a TeV break compatible with observations of [DAMPE 2017]. Fluxes are multiplied by $E^3$ and the $e^-$ flux scaled down of a factor 10 for display purposes. Right) Projected $e^+$ flux measurement in 4 different scenarios invoking astrophysical and DM origin of high-energy $e^-$. The accuracy of ALADINO data in the supra-TeV region will allow to disentangle the dominating source of high-energy $e^{+/-}$.*

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**REQUIREMENT 2**
**The measurement of electrons and positrons up to ~5 TeV of energy with a % accuracy, translates into a requirement on the collection factor of ~15 $m^2$ sr yrs. A lepton/hadron separation factor larger than $10^5$ is essential to avoid proton contamination. Misidentification of electrons as positrons due to charge confusion must be kept below $10^{-2}$ at all energies to prevent electron-induced background.**

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**ANTIPROTON/PROTON RATIO** – The most recent measurements on CR antiprotons are made by the AMS-02 experiment [AMS02 2016]. The AMS-02 data show an unexpectedly flat antiproton-to-proton ratio ($\bar{p}/p$), in the high-energy region between ~60 and 450 GeV, which is at tension with the astrophysical background models based on secondary production of antiprotons from CR collisions with the gas. In fact, background models predict a rapid decrease for the high-energy $\bar{p}/p$ ratio, similarly to the B/C ratio. Such a tension hints at scenarios with extra (DM) sources of high-energy antiprotons though, in contrast to positrons, it could in principle be ascribed to undetected uncertainties in the astrophysical background [Salati 2015, Boudad 2019]. The current $\bar{p}/p$ data favor two classes of DM scenarios, as illustrated in **Error! Reference source not found.** [Jin 2015, Jin 2017]. In the left panel of the figure, it is shown a scenario with ~60 GeV mass DM annihilating into hadronic channels $b\bar{b}$ pairs, giving rise to an antiproton signal at the 0.1-10 GeV energy scale, where the background models underpredict the antiproton flux. In the right panel, the figure shows a scenario with ~10 TeV mass scale DM and giving rise to a high-energy excess of antiprotons, from ~100 GeV to 10 TeV. In both figures, the gap between the AMS-02 data and the predicted background leaves room for DM annihilation contributions. Claims for DM evidence were recently made in many recent theoretical works, roughly based on these two classes of scenarios [Cirelli 2015b, Cui 2017, Cuoco 2017, Cholis 2019, Cuoco 2019]. From the projected antiproton measurements for ALADInO, shown in Figure 3, it is clear that the discovery potential for DM spans over a large range of mass scales, from O(10 GeV) to multi-TeV. Regarding the astrophysical background estimation, the situation with antiprotons is highly model dependent. Improved background calculations can relieve either the low-energy or high-energy tensions, but not both tensions at the same time, and not without testable consequences for the high-energy spectra of secondary nuclei (see below). Precision multi-TeV data on secondary nuclei will then be crucial at discriminating among CR propagation scenarios for astrophysical backgound.

It is also worth noticing that the pulsar scenario considered for the explanation of the positron fraction do not predict any excess in the antiproton flux. Models of extra-sources of antiprotons from astrophysical processes involve the hadronic production of secondary CR inside the shockwaves of supernova remnants [Cowsik 2014, Cowsik 2016, Tomassetti 2017, Lu 2016]. These models can be definely tested using secondary nuclei data at multi-TeV energies.

Thanks to its large acceptance, long duration and orbital operation far from the Earth magnetic field, ALADInO will provide more than two orders of magnitude increase in the existing antiproton statistics in the energy range 100 MeV-5 TeV.
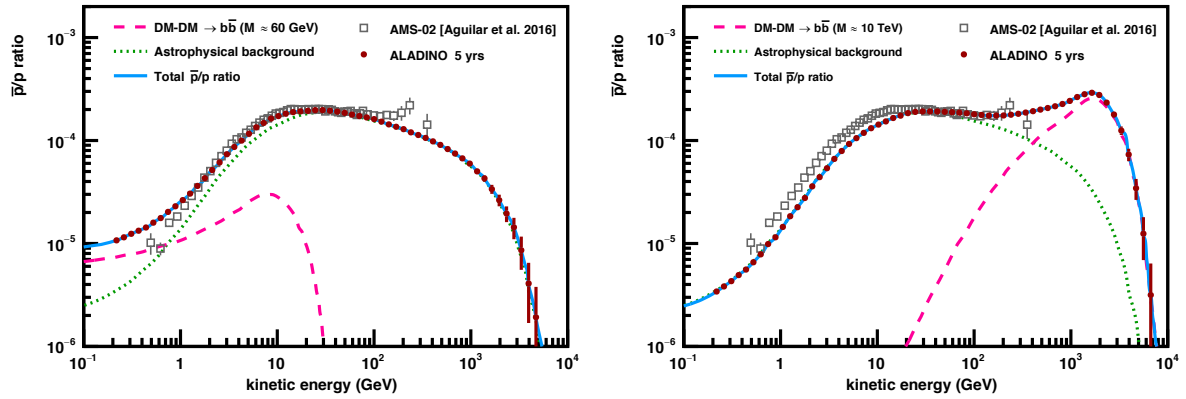


**Figure 3** *Antiproton-to-proton ratio as a function of kinetic energy according to standard calculations for the astrophysical background: the plots illustrate the effect of two benchmark models, as discussed in the text. The two scenarios represent 10 TeV (right) and 60 GeV (left) mass DM particles annihilating in b-bbar [from Jin 2015]. In both scenarios, projections for ALADINO in 5 years of observation times are shown.*

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**REQUIREMENT 3**
**Testing the TeV-scale mass DM annihilation requires a collection factor of ~15 $m^2$ sr yrs to extend at least one decade in energy the antiproton flux measurement. To achieve the needed sensitivity, the antiproton background must be suppressed. This requires a rejection factor of ~$10^5$ against mis-identified protons and an electron/proton separation of ~$10^4$.**

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**ANTIDEUTERIUM AND ANTIHELIUM** – In addition to the measurement of the antiproton spectrum, complementary DM searches with **antideuteron** nuclei (D⁻) in the sub-GeV energy region would benefit from promising DM signals and kinematically suppressed background, thereby offering a potential breakthrough for new physics discoveries [Aramaki 2016]. The situation is similar with **anti-$^3$He** in terms of signal/background ratio, although the absolute signal level is significantly suppressed at increasing mass number [Cirelli 2014b, Carlson 2014, Coogan 2017].

The ideal requirement, for these channels, would be to reach the level of astrophysical background, testing *any* model of DM annihilation that gives rise to a detectable excess above the background. **Figure 4**Error! Reference source not found. shows flux calculations for antideuteron (left) and antihelium-3 (right) as a function of kinetic energy per nucleon, including predictions for the DM models (blue lines) consistent with present antiproton data [Cuoco 2017, Korsmeier 2018]; an up to date calculation of the astrophysical background is also included, along with its uncertainties [Tomassetti 2017]. The simulated flux measurements with ALADInO are shown as red markers for the astrophysical background and for the DM signals. The best current upper limits are also shown [BESS 2012, Sasaki 2019]. Antideuteron searches are and will be performed by AMS-02 and GAPS during the coming years. These instruments combined will only approach $10^{-6}$ flux sensitivity, leaving untested a significant region of parameter space of DM models. The expected AMS-02 sensitivity in 10 years is ~$10^{-9}$ for antihelium/helium ratio at 0.1-50 GeV/n. The dotted lines show the ALADInO sensitivity level, for 10 years of exposure, over its optimal range of detection.

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With a predicted sensitivity in 5 years of ~5·10⁻⁹ part/(m² sr s GeV/n) at the 95% C.L in the 0.1-1.5 GeV/n kinetic energy region, ALADInO will probe most models of light and heavy DM particles in the antideuteron channel, and a vast region of parameter space for in the antihelium channel.

> **REQUIREMENT 4**
> **The astrophysics background level of secondary CR antinuclei can be reached with 20 m² sr years of exposure on antideuteron (antihelium) in the GeV energy region. The optimal energy range to detect DM-induced excesses is 100 MeV/n – few GeV/n.**
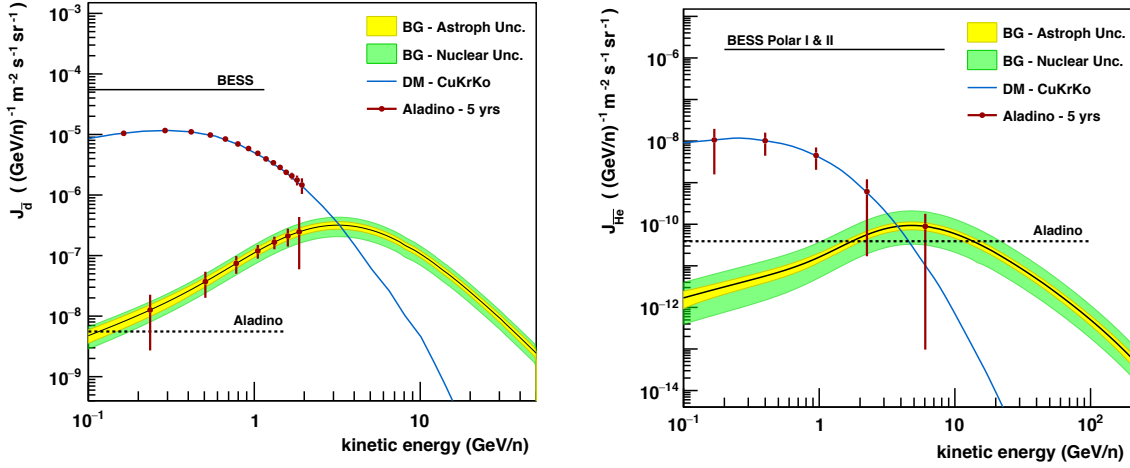


**Figure 4.** *Antideuteron (left) and anti- ³He (right) fluxes as a function of kinetic energy per nucleon. See text for description.*

### 3.1.3 **High energy CR (electrons, protons and nuclei)**

**HIGH ENERGY ELECTRONS –** The precise measurement of the supra-TeV $e^{+/-}$ spectral features could provide relevant information to assess the nature of the observed excess in the positron flux. The measurement of the total $(e^++e^-)$ flux is insensitive to charge sign identification: it is an interesting observable for both spectrometric and calorimetric space experiments, as well as for ground observatories. The experimental scenario is variegated. Indirect ground measurements first revealed, although with large uncertainties, a sudden drop in the $(e^++e^-)$ flux intensity starting at 1 TeV [HESS2009, MAGIC2011, VERITAS 2015]. The drop has been recently confirmed by direct space measurements [DAMPE 2017, CALET 2017, CALET 2018] which have studied the $e^\pm$ spectrum up to ≈5 TeV. However, no evidence of a break up to 2 TeV is observable in the Fermi-LAT measurement [FERMI 2017b] nor from the latest AMS-02 results [AMS02 2019a, AMS02 2019b]. Finally, in the [300-1000] GeV energy range, discrepancies in the flux intensities up to 30% are observed between measurements from different space detectors.

The large statistical uncertainties above the TeV region and the observed discrepancies below the TeV region add further complexities in the data interpretation of the origin of the spectral break and of the tentative feature observed at 1.4 TeV by DAMPE, which could be explained involving new astrophysical mechanisms or DM related effects [Athron 2018, Fan 2018, Jin 2018, Liu 2018, Lopez-Coto 2018, Lipari 2019, Niu 2019, Mertsch 2019, Recchia 2019]. Redundant measurements of the $(e^++e^-)$ energies and spectra are a fundamental requirement to reduce systematic uncertainties. ALADInO, taking advantage of its calorimetric collection factor of 20 m² sr yrs and an hadron rejection capabilities larger than $10^5$, will provide for a real advance in the field. Below 10 TeV the hadronic background will be kept below 0.1%. The measurement uncertainty will be consequently dominated by the knowledge of the calorimeter energy scale which, as for the AMS-02 experiment [Kounine 2017a], will be improved by at least a factor of 2÷3, with respect to calorimeter-only instruments, by the cross-calibration with the rigidity measurement of the spectrometer. The large collection factor will extend the sensitivity of ALADInO to characterize the spectrum of nearby astrophysical $e^{+/-}$ sources up to 50 TeV. In the scenario where the supra-TeV region will

also be measured by the CTA ground observatory [CTA 2019] and the calorimetric space mission HERD [HERD 2017], ALADInO will provide the most accurate characterization of the (e⁺+e⁻) flux at 1 TeV and above, determining with the unique precision the only observational feature that is planned to be used by CTA to calibrate its energy scale [Parsons 2016].

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**REQUIREMENT 5**
The measurement of (e⁺+e⁻) up to ~ 50 TeV requires a collection factor of ~20 m² sr yrs. A lepton/hadron separation larger than ~$10^5$ is essential to avoid proton contamination. The cross-calibration of the calorimeter energy scale with the rigidity spectrometer measurement will allow to determine spectral features with an accuracy better than 1%.
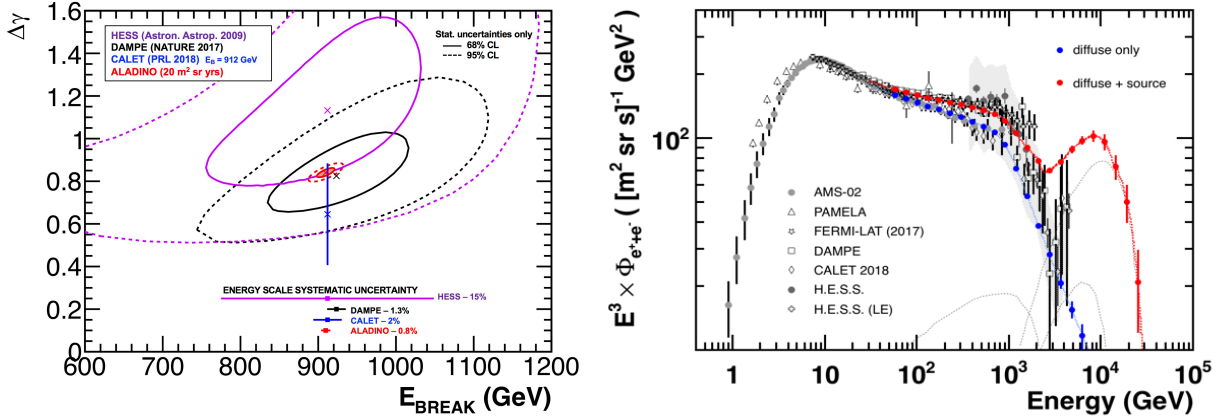
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**Figure 5.** *Left: Sensitivity for the measurement of (e⁺+e⁻) flux break energy ($E_{BREAK}$) and index variation (Δγ) based on the parametrization used in [DAMPE 2017]. **Right:** Projected (e⁺+e⁻) flux measurement with ALADInO in a scenario with a diffuse flux and with a contribution of a nearby astrophysical source in the supra-TeV energy range. Fluxes are multiplied by $E^3$ for display purposes.*

**CR PROTONS AND NUCLEI UP TO 50 TEV/n** – Recently, measurements of CR proton and helium fluxes performed by PAMELA and AMS-02 revealed **unexpected anomalies** in the high-energy range of CR spectra [Serpico 2015]. In particular, the proton spectrum from ~10 GeV up to 1.8 TeV of energy was reported to be appreciably harder than the helium spectrum while, in the energy spectra of both species, a remarkable change of the spectral index (or *spectral hardening*) was observed to occur at about 200 GeV of energy [PAMELA 2011, AMS-02 2015a, AMS-02 2015b, CALET 2019]. More recently, Z>2 measurements from AMS-02 reported that the hardening effect is present in essentially *all* charged elements of the cosmic radiation, including primary, secondary fluxes, and even in secondary/primary ratios [AMS-02 2017, AMS-02 2018, Yan 2019]. Explanations for the CR spectral anomalies may involve the interplay
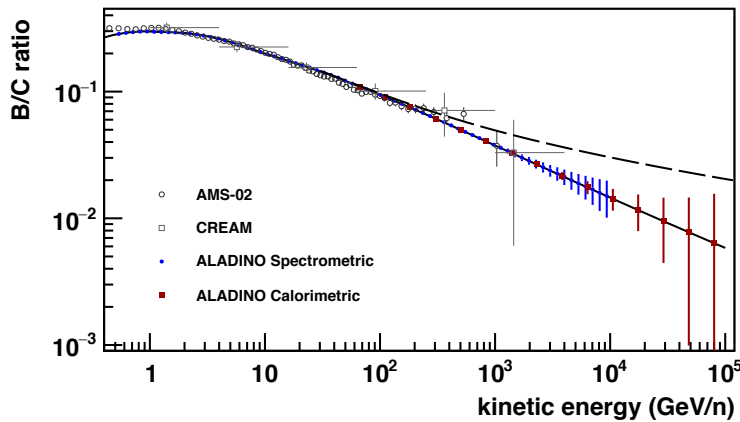


**Figure 6** *ALADINO expectation for the B/C flux ratio, for an exposure of 20 m² sr yrs. Two benchmark models for the B/C are shown, both consistent with the existing data. The simulations are shown for both the spectrometric and calorimetric modes.*

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of various physics processes at works such as, e.g., shock (re)acceleration mechanisms, nonlinear/inhomogeneous diffusive propagation, or stochasticity effects related to nearby CR sources. All these mechanisms are currently subjected to extensive theoretical research: observationally, the measurement of multichannel CR flux data at the multi-TeV energy scale is a highly-demanded experimental effort [Serpico 2015, Gabici 2019, Kachelrieß 2019].-Measurements of primary (e.g. C-N-O) and especially secondary (Li-Be-B) nuclei in the currently unexplored ~1-50 TeV/n energy range are also essential for DM searches. The different physics models for the CR spectral anomalies give distinct predictions for the secondary/primary ratios at high energies [Serpico 2015]. Thus, measurements such as the B/C ratio at multi-TeV energies will give an unvaluable asset to calibrate the astrophysical background of antiprotons and antinuclei for DM searches.

Based on these considerations, the scientific requirement for ALADInO is to provide an accurate *spectrometric* measurement up to 20 TV (10 TeV/n), with a charge resolution of $\delta Z \sim 0.15$ (at least for Z>2), based on multiple charge measurements to ensure a background-free and fragmentation-free detection of rarer elements such as Li-Be-B. The 100 TeV/n energy scale can be realistically achieved by means of *calorimetric* measurements. In both *detection modes*, a collection factor of about 20 $m^2$sr yrs is needed to ensure statistics up to the highest measurable energy region. The simultaneous measurement of the energy/rigidity performed by the spectrometric and calorimetric modes will allow for the *in-flight* cross-calibration of the absolute energy scale, thus providing reliable measurements of CR energy spectra at unexplored regions.

An example of the expected B/C measurement from ALADInO is shown in **Figure 6**. The figure shows two benchmark models for the B/C ratio that are currently unresolved by the existing data [Kachelrieß 2019].

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**REQUIREMENT 6**
**Measuring nuclear fluxes up to 50 TeV/n will be**
**possible thanks to the large calorimetric acceptance and the redundant**
**measurements of particle charge.**
**A collection factor of 20 m2 sr yrs is required for the measurement of 2<Z<8 species.**

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**REACHING THE KNEES** – Direct measurements could hardly reach energies of hundreds of TeV due to the limited detector acceptance: it follows that no clear information exists on the knees of the individual Z-resolved CR elemental species. Conversely, ground based arrays have larger exposures but they are affected by serious uncertainties on the energy scale and very limited particle identification capabilities. Current (planned) missions such as CALET or DAMPE (HERD) are extending the measurements towards 100 TeV. ALADInO in the calorimetric mode would exhibit a collecting factor of 20 $m^2$ sr yrs; the proton and helium spectra will be measured individually up to the PeV energy scale. This would be the first direct evidence and determination of the CR knees in the single elemental components.

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**REQUIREMENT 7**
**A collection factor of at least 20 $m^2$ sr yrs is required to**
**measure the proton and He flux up to 1 PeV/n of energy.**

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**CR TRANSPORT IN THE HELIOSPHERE:** The study of long-term solar modulation of CRs requires measurements of particle fluxes over monthly, weekly, and even daily basis. This can be done with an acceptance of at least ~0.5 $m^2$ sr, in the ~0.1-50 GeV/n energy range, on an orbit with low-rigidity cutoff like on L2. The stability of the detector performance with time is an important concern for this investigation. With these requirements, and the possibility to monitor the CR fluxes over a significant fraction of the 11-year solar cycle, the ALADInO mission will enable the investigation of various subjects in heliophysics. This also includes the precise measurements of the flux, composition and arrival time of *solar energetic particle* events, in particular during rare high-energy events associated with solar flares or Coronal Mass Ejections, making ALADInO a privileged observatory of solar activity from deep space orbit.

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**REQUIREMENT 8**
**Provide daily measurements of proton and He fluxes at 0.1-50 GeV/n of energy,**
**The mission should be located on a deep space orbit with an acceptance of at least 0.5 $m^2$ sr.**
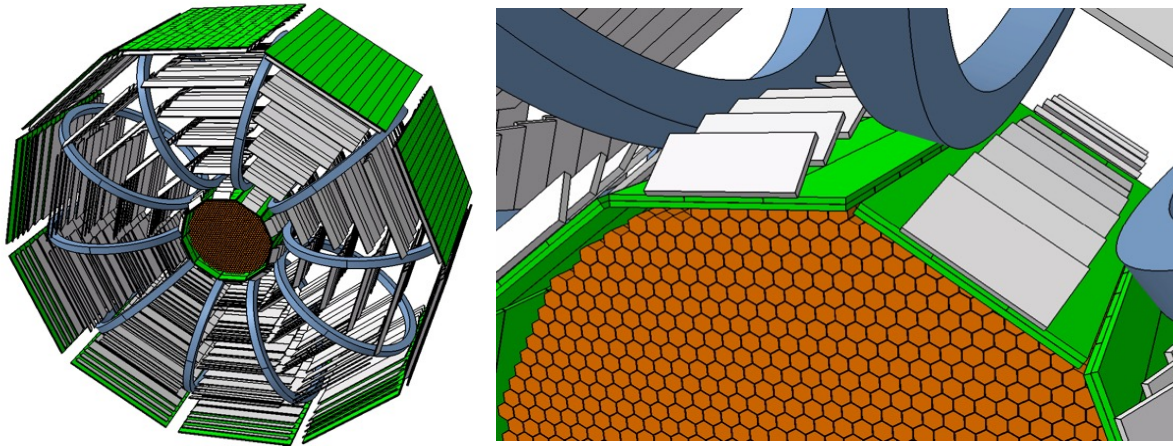
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**Figure 7** Left: *rendering of the ALADInO detector. The core of the apparatus is a cylindrical calorimeter, (dark orange). Ten circular magnetic coils (blue), surround the calorimeter. A silicon tracking syste (gray), is arranged in six layers each composed of several units (i.e. 'ladders'). Two time-of-flight layers segmented in paddle (green), are located outside the outer tracker layer and below the innermost tracker layer.* Right: *detail of the central part of the apparatus; the segmentation of the calorimeter in (x-y) view is clearly visible, as well as the time of flight inner layers placed between the calorimeter surface and the first tracker layer. The adaptive orientation of the tracker sensors is set to maximize the trajectory measurement resolution*

# 4   Measurement concept

A possible ALADInO  detector configuration matching the measurements requirements discussed in the previous chapter is briefly presented here. The   detector is equipped with a magnetic spectrometer for reliable identification of the sign of the charge of cosmic rays up to a  given Maximum Detectable Rigidity (MDR),   an imaging, high resolution 3D calorimeter for precise measurement of the $e^{+/-}$ and hadronic spectral features, and a Time of Flight for accurate velocity measurements.

The detector concept exploits the isotropy of the cosmic-ray flux, maximizing the collection power within a classical toroidal magnetic configuration: particle detection and identification  is based on well-established and reliable space qualified  technologies.

The basic ALADInO payload is based on three key elements:

1. A High Temperature Superconducting (HTS) magnetic spectrometer (SMS) to measure the particle rigidity, charge magnitude and sign, with a maximum detectable rigidity exceeding 20 TV and an acceptance $>10$ $m^2$ sr ($\sim3$ $m^2$ sr in combination with the calorimeter);
2. a Time of Flight (ToF) system to measure the particle velocity and charge magnitude;
3. a large acceptance ($\sim9$ $m^2$ sr) 3D imaging calorimeter (CALO) to measure particle energy and separate the rare electromagnetic component ($e^{\pm}$, $\gamma$) from the overwhelming hadronic component of cosmic rays.

The ToF and the CALO also provide signals to trigger the start of data acquisition on minimum ionizing and showering particles respectively.

A possible design of the ALADInO detector that maximizes the acceptance while keeping the overall payload size compact is presented in **Figure 7**. The detector has a cylindrical shape with  a diameter of  440 cm and *200* cm in length, designed to fit within the fairing volume of an Ariane 6 class launcher. This design fully exploits the CR isotropy: particles are collected over a wide solid angle on the  lateral surface of the cylinder. The axial symmetric configuration of the detectors guarantees a uniform response of detectors independent on the particle arrival direction.

It should be noted that ALADInO could also detect gamma rays in the GeV – TeV energy range: this capability would allow a variety of studies in high energy astrophysics and  fundamental physics, including indirect dark matter searches.  Thanks to its large acceptance and to the all-sky coverage, ALADInO can monitor high-energy gamma ray sources and detect transient events as well. These observations would fit in the framework of a multi-messenger and multi-wavelength strategy of the next generation of space born

and ground based instruments (gravitational wave observatories, ground-based and space-based, from keV-to TeV, gamma-ray telescopes).
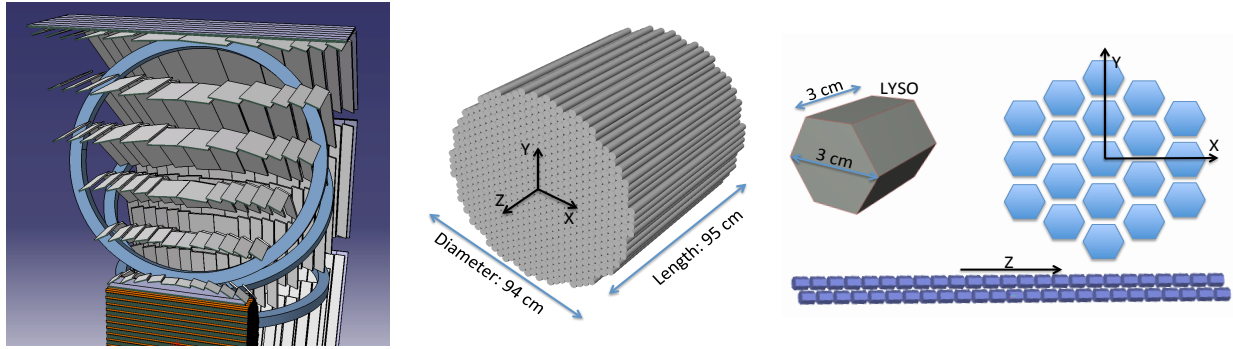


**Figure 8** *Left: silicon ladder orientation devised for ALADInO. Right: overall assembly of the hexagonal-prism-shape crystals and design of two adjacent strings of crystals – crystals are staggered by half-length to avoid dead space.*

ALADInO is based on two innovative techniques:
- the use of a superconducting magnet based on a High Temperature lightweight superconductor material. This design allows to reach an intense magnetic field over the large volume of the spectrometer. Tanks with the excellent spatial resolution of silicon strip detectors/pixel detector the maximum detectable rigidity of the spectrometer will exceed 20 TV;
- the use of a cylindrical calorimeter made of a 3D mesh of small hexagonal prism-shaped scintillating LYSO crystals. It ensures a nearly isotropic response to particles entering from different directions maximizing the detector acceptance. The highly segmented design together with the depth of $\sim$60 $X_0$ allows a good energy resolution, also for hadronic particles, and the required particle identification capability, independent on the particle incoming direction.

The ToF and silicon tracker detectors are based on the successful design used in AMS [Alvisi 1999, Alcaraz 2008] and PAMELA experiment [Osteria 2004, Straulino 2006].

The main characteristics of the ALADINO experiment are summarized in **Error! Reference source not found.**. A short description of the different subsystems is presented in the following sections.

| | |
|---|---|
| Calorimeter acceptance | $\sim$ 9 m$^2$ sr |
| Spectrometer acceptance | >10 m$^2$ sr ($\sim$ 3 m$^2$ sr w/i CALO) |
| Spectrometer Maximum Detectable Rigidity (MDR) | > 20 TV |
| Calorimeter depth | 61 $X_0$, 3.5 $\lambda_I$ |
| Calorimeter energy resolution | 25% $\div$ 35% (for nuclei) <br> 2% (for electrons and positrons) |
| Calorimeter e/p rejection power | > $10^5$ |
| Time of Flight measurement resolution | $\sim$100 ps |
| High energy $\gamma$-ray acceptance (Calorimeter) | $\sim$ 9 m$^2$ sr |
| Low energy $\gamma$-ray acceptance (Tracker) | $\sim$ 0.5 m$^2$ sr |
| $\gamma$-ray Point Spread Function | < 0.5 deg |

**Table 1:** *Key performance parameters of the ALADINO apparatus*

## 4.1.1 **Spectrometer**

As previously stated, the physics requirements for the ALADInO spectrometer mandate an average MDR greater than 20 TV over a large acceptance. A possible design capable of accommodating such targets must rely on:
- a high-intensity magnetic field generated by a superconducting magnet system surrounding the calorimeter. By choosing a toroidal field configuration it is possible to achieve the required

bending power over a large acceptance, while also maintaining a theoretical null magnetic momentum;

-   a tracking system, composed of silicon detector layers, to provide a measurement of the particle trajectory into the magnet field. Each of the detector layers is divided in ladders and arranged cylindrically around the calorimeter;

A proposed overall arrangement of the magnet coils and of the tracking system can be seen in **Figure 8**.

## 4.1.2 **Magnet**

Superconducting magnets (SM) allows for high momentum resolution at the TV scale and over large detection surfaces. The main requirements of SMs for space applications are: (i) low mass budget, i.e. high stored energy to mass ratio; (ii) low power consumption, i.e. efficient cryogenics; (iii) very high stability. The first requirement is obtained by using low density materials and high current density.

Stability and helium cryogenics have been the major problems which have hindered the use of SM technology in space, so far. Stability is the capability of a SM to sustain a sudden energy release without quenching. It is a sensitive issue in designing SMs operating at liquid helium temperature: the problem became less important increasing the operational temperature, due to the cubic temperature dependence of superconductor specific heat.

During the last decades, technological advances have made it possible to envisage solutions for space magnets based on high-temperature superconductors (HTS). HTS magnets are operable at temperatures up to 40 K with the double benefit of solving the problems related to stability and avoiding cryogenics based on liquid He . Among HTS, ReBCO (Rare Earths-Barium Cuprates) tapes are particularly promising for space applications. At present, commercial ReBCO can be operated at 400 A/mm$^2$ at 30 K in a 3 T field. Recent developments indicate that the current density can be pushed to 2000 A/mm$^2$ in the next years [Majkic 2018]. The use of magnesium diboride wires, despite its poorer current properties, is also a possible option, due to the low average mass density [Musenich 2016, Kovác 2018].

Quench protection techniques is quickly rapidly evolving towards fast and safe procedures guaranteeing magnet integrity even in critical conditions [Zhang 2018].
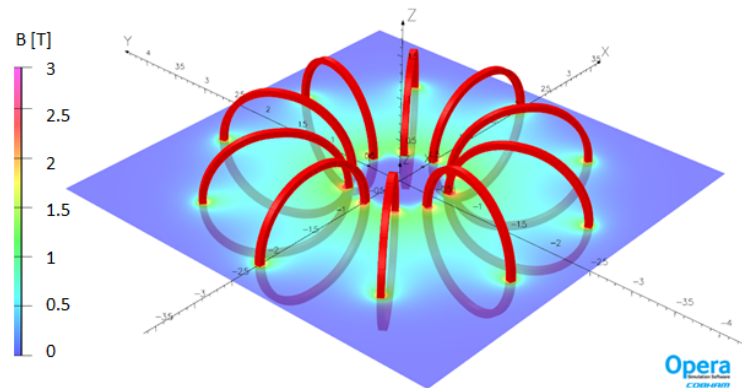


**Figure 9.** *Scheme of a possible magnet configuration with its field map*

The proposed magnet design for ALADInO is based on the SR2S design [Musenich 2014, Bruce 2015, Juster 2015]: a toroidal configuration guarantees a large geometric acceptance, confining the field within the coils and minimizing the dipole moment. Low density structural materials (Aluminum and Titanium alloys, Al-B$_4$C and Al-Al$_2$O$_3$ cermets, aramid fibers) will be used to counter the Lorentz forces. It is worth noting that one of the components of ReBCO tapes is hastelloy, therefore the conductor will contribute to the magnet mechanical structure.

**Bending power:** the coil number and shape (round, racetrack, D-shaped) will be optimized to maximize the detector performance. Error! Reference source not found. shows a possible magnet configuration having 4.3 m overall diameter dimension with a 1 m inner bore to host the calorimeter.

With 4.4 MA-turns, the average field on the tracker is 0.8 T providing a 1.1 T·m bending power. The mass of the magnet, with the present technology and including the mechanical structure, is 1200 kg. We estimate that the superconductor technology evolution and a targeted R&D will allow a mass reduction to less than 900 kg.

**Cooling:** a superconducting magnet operating at 40 K in the deep space could be passively cooled: it would, however, requires large area radiators. Therefore the use of cryocoolers looks the favorable choice.

Most of the heat flux from the Sun is passively intercepted by an umbrella-type shield made of V-groove layers [Moery 2006]. The temperature on the dark side of the sunshield can be estimated as high as 60 K, with a residual heat flux density in the region of 80 mW/m². The heat flow can be directed to the external ToF surface to maintain the ToF at its working temperature (250 K).

The superconducting coils, operating at 30-40 K, are subjected to multi-directional thermal radiation from the calorimeter, ToF and tracker (at 230-250 K). Therefore, each coil must be surrounded by two thermal shields. The external one, on the detector side, will be actively maintained at 80 K by a cryocooler and the second one, thermally passive, will be at a temperature close to the magnet working temperature (see Error! Reference source not found.).

The 80 K shields will be thermally connected with the central thermal link by pulsating heat pipes, to maximize the efficiency/mass ratio [Bruce 2018]. The 80 K thermal shield will be composed of a light structure supporting a cryogenic multi-layer insulation (MLI). The maximum radiation power to be extracted to maintain the shield at 80 K is of the order of 50 W. This heat load will be absorbed by the first stage of the cryocooler (see **Error! Reference source not found.**). The second shield will be also composed of 10 to 20 layers of MLI and will be directly wrapped around the coils. From 80 K, the MLI performance is about 0.1 W/m² which represents a heat load of 2 W on the entire coils system at the operational temperature. Mechanical supports will be necessary to maintain the entire assembly together.

Studies are in progress to reduce the tracker and calorimeter operational temperature below 230 K and consequently to reduce the heat load on the coils.

## 4.1.3 Tracker

Tracking with a O(μm) precision could be easily achieved in ALADInO using double side silicon microstrip detectors. Originally developed in the '80s for micro-vertex detectors in the High Energy Physics experiments at colliders, the precursor flight of the AMS experiment on the shuttle Discovery in 1998 has first demonstrated that thin, O(300μm), silicon microstrip detectors can be successfully operated for tracking in space. In addition to precision measurement of particle coordinates, silicon microstrip detectors are light weight, minimizing the material along the particle trajectory, thus reducing the probability of particles scattering in the detector material. In addition absence of consumables and relatively low operating voltages (~70 V) make silicon trackers an ideal trakcing detector in space, bot in calorimetric experiments (AGILE, Fermi, DAMPE) or magnetic spectrometers (PAMELA, AMS-02). Several tens of m² of silicon detectors are currently operating successfully in space in long term missions. By coupling the silicon device to a high dynamic range front end electronics, it is possible to measure the particle charge with high accuracy by looking at the amplitude of the total energy deposited, which is proportional to $Z^2$.
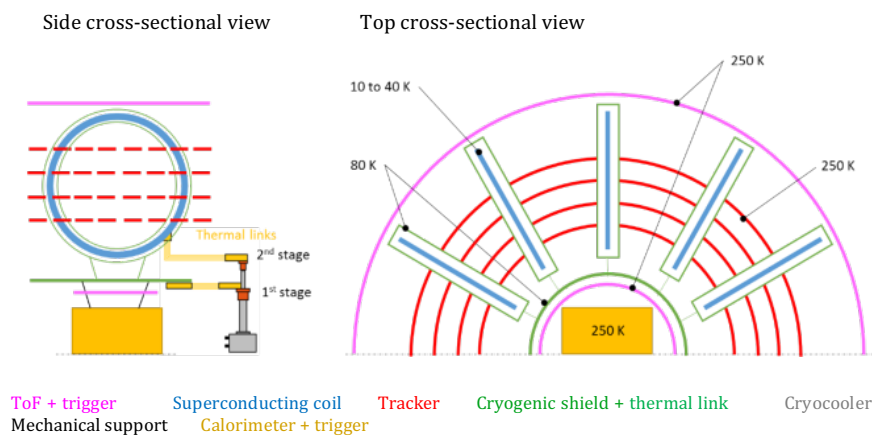


**Figure 10.** *Conceptual cryogenic design.*

The design of the ALADInO tracking system benefits from the experience of AMS and PAMELA experiments. By using capacitive charge coupling with floating strips it is possible to get optimal spatial

resolution with a reduced number of readout channels, reaching the desired O(5 μm) accuracy with a reasonable readout pitch of ~100 μm.

The silicon sensors are daisy-chained for readout and biasing into *ladders*, made of a variable number of sensors (from 2 to 7) to match the size of the different tracker planes. To reduce the material in the tracking volume, front-end electronics is usually located at the ladders end. For the p-strips, the daisy chain is then provided through direct bonding from sensor to sensor, while for the transversal n-strips a metalized Upilex film running over the ladder length is used to connect to the corresponding front-end electronics.

The readout pitch, together with low noise front-end electronics will ensure a position resolution of about 3 μm for normal particle incidence: a similar result has already been obtained with the PAMELA short ladders [Straulino 2006] while AMS-02 has demonstrated the possibility to use long detector modules (up to 60 cm) with a resolution better than 10 μm. With a moderate R&D activity to optimize the readout electronics, it should be possible to obtain the design value of 3 μm on long detector modules, with a limited power consumption (0.3 mW per channel [Azzarello 2016]).

The dynamic range of the front-end will extend such as to reach at least the Oxygen signal amplitude without saturation, similar to the performance shown by the AMS-02 tracker electronics [Ambrosi 2017]. In order to fully exploit the intrinsic resolution of the detectors and considering the worsening of the resolution with the track incident angle, a special ladder orientation is considered, as shown in the left panel of **Figure 8**.

## 4.1.4    Calorimeter

Based on the CaloCube R&D project [Mori 2013], the calorimeter consists of a 3D mesh of small LYSO scintillating crystals arranged to form a nearly regular cylinder as shown in **Figure 8** The front view of the calorimeter inside the ALADInO experiment is shown in **Figure 7**.

The chosen geometry is the most effective compromise between a fully isotropic calorimeter, i.e. a sphere with uniform response to particles over its entire surface, and the need to use part of the field of view for electronics/mechanical structures and services for the payload.

Single elements are shaped as regular hexagonal prisms and disposed to completely avoid escape planes, i.e. particle trajectories completely sneaking in between the calorimeter gaps. This is particularly relevant for energy resolution. Thanks to the adopted geometry, relatively large gaps (8 mm) can be then left between crystals increasing the total acceptance, at equal mass, without a significant loss of energy resolution.

The crystals are made of Cerium-doped Lutetium Yttrium Orthosilicate (LYSO). LYSO is a dense, bright inorganic scintillator, which is nowadays commercially available, being industrially produced by several companies, for high-precision Positron-Emission Tomography. Its features make it a competitive material for compact calorimeters. It is rather insensitive to temperature changes and thus suitable for high-precision calorimetry in the harsh space environment. Following the design of **Figure 8**, and assuming a mass envelope of 2000 kg, it can be shown that a calorimeter depth along the diameter corresponding to $3.5 \lambda_I$ or to 61 $X_0$, and a geometric factor of ~9 $m^2$ sr can be achieved.

The calorimeter performances have been studied using the GEANT4 package [Agostinelli 2003, Allison 2006]. The full geometry was implemented, including the carbon fibre support structure in between crystals. Preliminary results show that an energy resolution of 2% for electrons and 25% for protons can be achieved. The latter is valid for well-contained events, selected at the cost of reducing the effective geometric factor (i.e. the geometric factor times the selection efficiency): for a 1 TeV proton it corresponds to 1 $m^2$ sr. By loosening the containment criterion, the resolution reaches 35% at 5 $m^2$ sr. The electron/proton rejection factor is expected to be better than $10^5$, since the CaloCube project achieves this performance while being much shallower than ALADInO and with a similar detector segmentation.

**TIC – Tracker in Calorimeter:** the calorimeter layout is focused on optimizing the detection of charged cosmic rays, but, in a general multipurpose experiment in space, the detection and tracking of gamma rays plays also an important role. The pair-conversion telescopes used by Fermi-LAT [FERMI 2009] and DAMPE [Chang 2017] experiments exploit the gamma conversion in tungsten layers to track the $e^+e^-$ pair in Si detectors and reconstruct the incidence direction of the original photon. Pairing such a device with the calorimeter would however induce ion fragmentation in tungsten, reducing the charge ID performance; also, the lever arm required for obtaining good tracking performance would reduce the overall geometric factor of the whole detector. All these drawbacks are solved by the TIC approach [Bigongiari 2019], which use the calorimeter itself as active pair-conversion material in place of the tungsten layers. The photon trajectory is then reconstructed by sampling the lateral development of the induced EM shower at different calorimeter depths by Si microstrip layers intertwined with the external crystal layers of the calorimeter. Different TIC

geometries have been investigated using simulations [Bigongiari 2019], leading to an angular resolution (Point Spread Function, PSF) of the order of 0.5 deg for vertical particles above 10 GeV, better with respect to Fermi-LAT [FERMI 2009].

## 4.1.5 ToF

The proposed ALADInO ToF system is designed to provide a precise measurement of the particle velocity based on the time-of-flight technique, of the particle travelling direction and of the particle charge, as well as to provide the trigger signal to the acquisition system for charged particles.

The ToF is based on the PAMELA and AMS mission systems: bars of thick plastic scintillators are placed before and after the tracking system over two staggered layers and running in both directions, to provide *x-y* hodoscopic information and to avoid dead space maximizing the veto inefficiencies for photon candidate backgrounds. In a benchmark design, the system is made of four layers of 0.8 cm thick plastic scintillators, placed in pairs before and after the tracker. Counters can be read out on each end by Photomultipliers (PMT) (like in the AMS of PAMELA subdetectors) or by Silicon Photomultipliers (SiPM), insensitive to magnetic fields.

Even with these long counters the expected time resolution is of about 100 ps, easily allowing, for example, the identification of anti-deuterons against anti-protons in the kinetic energy region up to few GeVs.

**TECHNOLOGY DEVELOPMENTS -** During thenext years wse expect to improve the existing technologies discussed above. At the same time we are **investingating and performing R&D on new technologies** which could replace existing one. The following gives a sample list.

**SiPM:** SIPMs can replace traditional photomultipliers for photodetection applications in space. SiPMs are in fact more robust, can be operated in external magnetic fields with low power consumption (<10 mW / channel [Dorosz 2018]) and without requiring high-voltage supply while providing similar timing performances [Piemonte 2018]. Devices with microcell size smaller than 30μm [Gola 2019], already available for production [Acerbi 2017], will increase the dynamic range [Bretz 2016, Acerbi 2018] improving the resolution for heavy nuclei charge measurement (opening the possibility to identify trans-Iron elements) and may feature higher resilience towards radiation damage [Link 2017, Garutti 2019]. The interest in SiPMs for space payloads is evident from the variegate amount of past, present and future R&D activities [Kim 2013, Arkhangelskiy 2015, Perrina 2019]. Results from ground tests of SiPM readout of scintillator bars with similar dimensions to those foreseen for ALADInO already show promising time resolutions much better than 100 ps [Böhm 2018, Betancourt 2017];

**Timing layers:** Low Gain Avalanche Diode (LGAD) Si sensors [Cartiglia 2015], which feature thinner layers (i.e. less material budget) with the same, or even higher, signal/noise electronic level, could be considered to replace standard micro-strip Si sensors. This technology may grant timing capabilities with performances similar to those of the ToF (i.e. <100 ps) to the tracking layers, providing the apparatus with a second time-of-flight detector to improve the overall performances (e.g. isotopical distinction) and give further redundancy to cross-calibrate the detectors. The timing capability will also allow to identify energy deposits in the tracking layers due to back-scattering particles from the calorimeter, further improving the overall identification capabilities of the apparatus [Duranti 2019];

**Pixel technology:** Monolithic Active Pixel Sensors (MAPS) [Turchetta 2001] represent a possible replacement of micro-strip Si detectors. MAPS do not suffer multi-hit degeneracy and are thinner than micro-strips, limiting multiple scattering effects [Mager 2016]. They feature in-pixel amplification, with significant gain in terms of signal-to-noise ratio and data throughput optimisation. MAPS pixel dimensions can ensure single-hit resolution down to 1 μm [Arai 2018]. Large-scale fabrication processes and infrastructures shared with image sensors for mobile phone cameras, reduce the cost to 10 times lower than current micro-strip detectors. Similar application of MAPS technology (ALPIDE [Mager 2016]) for space application is also considered, for example, for the HEPD-02 tracker to be launched on board the CSES-02 satellite in 2021 [Iuppa 2019] and for the Timepix series hybrid pixel detectors [Ballabriga 2018] for dosimetry measurements and in space [Turecek 2011] and space weather analyses [Gohl 2016]. Future developments of MAPS focus on the reduction of power consumption (halving every 3 years since 2002 [Baudot 2009, Arai 2018]), and techniques for large area production (hundreds of cm$^2$).

**Capability for γ-rays:** the spectrometer can be also used as an excellent tracker-converter for γ-rays. The e$^+$/e$^-$ pairs produced by conversion of γ-rays with the silicon tracker material are traced and their momentum measured by the spectrometer. The low material budget garantees a PSF better than 0.5 deg up to the lowest

energies (~100 MeV), coherently to what expected for similar proposed detectors [PANGU 2014, Wu 2014]. Despite of the limited conversion probability due to the low amount of material, the large spectrometer geometrical factor will result in a ~0.5 m$^2$ sr effective acceptance, effectively enabling for competitive measurements in the low energy γ-ray field [e-ASTROGAM 2003].

**ORBITAL REQUIREMENTS -** Access to space is necessary to avoid antimatter background from CR collisions with the Earth's atmosphere. Geomagnetic flux modulation, back-scattered albedo particles, and geomagnetically trapped particles represent known limiting factors for low-Earth orbiting experiments that affect acquisition capabilities (via radiation damage) and CR flux (via Galactic CR flux suppression at p/|Z|<~30 GV). The latter is critical for the observational goals related to low energy anti-deuteron, anti-helium measurements and Heliospheric studies. All these issues can be resolved by a high-Earth orbit or L2 orbit. Moreover, these types of orbit are most appropriate for a proper thermal environment required by the scientific payload. It is important to note that no active attitude control is required for the mission, provided that appropriate sky coverage is guaranteed.

**WEIGHT AND POWER BUDGET – Considering the technology currntly available,** about 2 Tons of the mass budget are allocated to the magnetic system, including cryogenics and insulation. The next heavy part is the LYSO crystal of the calorimeter, weighting 2.3 Tons including 300 kg of mechanical structure. The Tracker and ToF systems are estimated to about 1.5 Ton and about 500 kg are allocated for the power, readout and control electronics of all the subsystems. The current total mass estimate is thus about 6.4 Tons for the experimental apparatus.

This mass estimation does not include the improvements expected during the next years by ongoing R&D on most of the subsystems.

The ALADInO detector, in spite of its high acceptance has a limited number of readout channels, thanks to its innovative design, but still is quite demanding in term of power for a space application. The most consuming detector subsystem is the Tracker, with ~2'500'000 channels and a total power consumption of about 2 kW. The Calorimeter is read-out through 31'000 electronics channels, with an estimated power consumption of about 200 W. The ToF, with about 2'000 channels of high-speed electronics has a power consumption of about 400 W. The cryogenic system will consume about 1 kW to keep the magnets coil at the nominal operating temperature. The total power budget is thus estimated to ~4 kW.

Also the power consumption does not include the improvements expected during the next years by ongoing R&D on most of the subsystems

**PATHFINDER STRATEGY-** The physics goals together with the technology development needs, suggest a staging and technology demonstrator strategy which would likely better suit ESA long term science program. The pathfinder version of ALADInO would be based on a superconducting magnet with a reduced magnetic field (about 10 times) but with the same collecting area: from the science point of view this demonstrator would be able to address the important theme of nuclear antimatter up to 100 GV of rigidity, providing a MDR of 1 TV. The magnet weight would be reduced to about 400 kg : assuming a 20% weight reduction due to R&D optimization for the Tracker and the ToF subsystems, the pathfinder weight would be about 2.0 tons, less than a third of the weight of the full version, still providing first class science.

**OPERATIONAL REQUIREMENTS -** The experiment must be operational 24 hours a day, 7 days a week, and 365 days a year without human interventions or on-orbit maintenance activities. It must provide a continuous stream of data at a rate of the order of ~50 Mbps. This requires the development of sophisticated onboard data reduction and compression techniques and related hardware.

# 5  Bibliography

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