



Future searches in cosmic-rays with magnetic spectrometers

Roberto Iuppa* for the ALADInO team

University and INFN of Trento

*essential contribution from M. Duranti and V. Vagelli

European Cosmic Ray Symposium
Nijmegen, 25-29 July 2022



Antimatter

Our Model of fundamental constituents of matter is the most successful theory ever constructed.
It describes very precisely standard constituents of matter, but is far from being complete.

The problem of when (how) Nature preferred matter over antimatter remains one of the most important unanswered questions of Physics.

Tens of experiments continue testing our Standard Model, still missing the smoking gun.

nature physics View all journals Search Q Login 

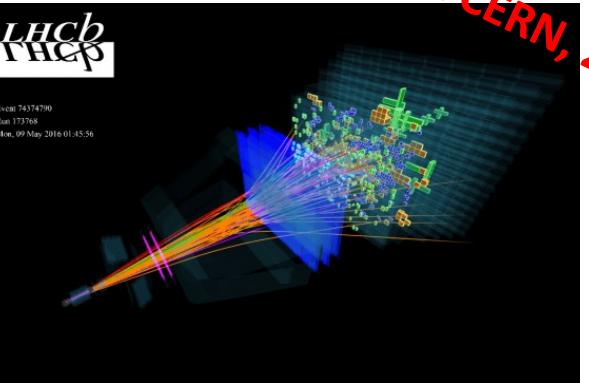
Explore content ▾ About the journal ▾ Publish with us ▾

nature > nature physics > articles > article
Open Access | Published: 30 January 2017

Measurement of matter–antimatter differences in beauty baryon decays

LHCb at CERN, 2017

The LHCb collaboration

Event 74374790 Run 177368 Mon, 09 May 2016 01:45:56

nature View all journals Search Q Login 

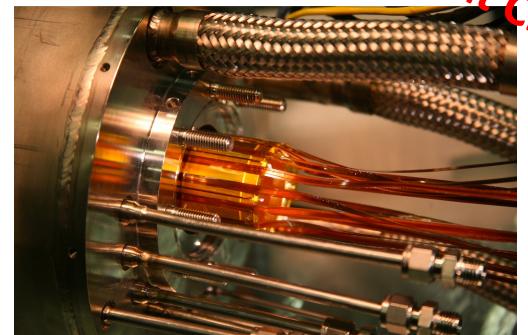
Explore content ▾ About the journal ▾ Publish with us ▾

nature > letters > article

Letter | Open Access | Published: 04 April 2018

Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi, B. X. R. Alves, ... J. S. Wurtele + Show authors



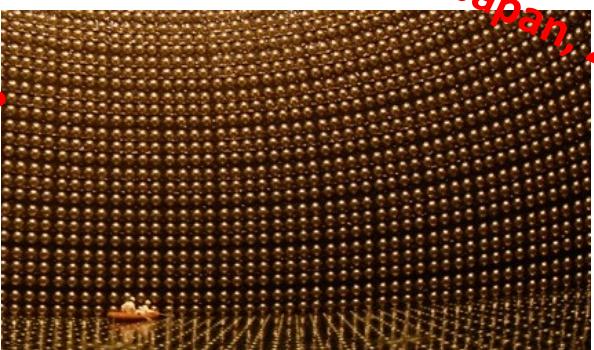
nature View all journals Search Q Login 

Explore content ▾ About the journal ▾ Publish with us ▾

nature > articles > article

Article | Published: 15 April 2020

Constraint on the matter–antimatter asymmetry-violating phase in neutrino oscillations



R. Iuppa - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

2



[Roberto Iuppa](#)



The quest for antimatter in Space

Direct searches for antimatter in space, to quantify the imbalance of matter and antimatter in the Universe.



[Roberto Iuppà](#)

AMS-01

~ 2 tons

10 days onboard Discovery
STS-91 (same orbit of ISS)

June 1998



PAMELA

470 Kg

On board Resurs-DK1 satellite

15 June 2006 – 7 February 2016



AMS-02

~ 6.7 tons

on-board ISS
in operation since 2011

Operations expected to last until 2030.



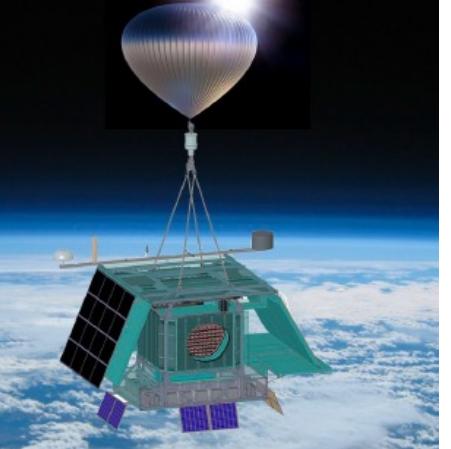
see contributions at ECRS 2022

GAPS

~ 3.6 tons

3 SPB Flights
from Antarctica (planned)

Flight instrument integration late 2022



+ many earlier space and balloon missions for direct antimatter measurements in cosmic rays

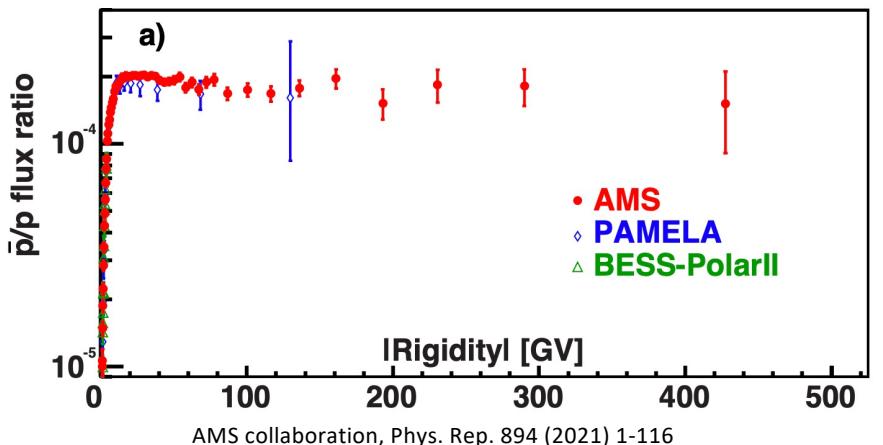
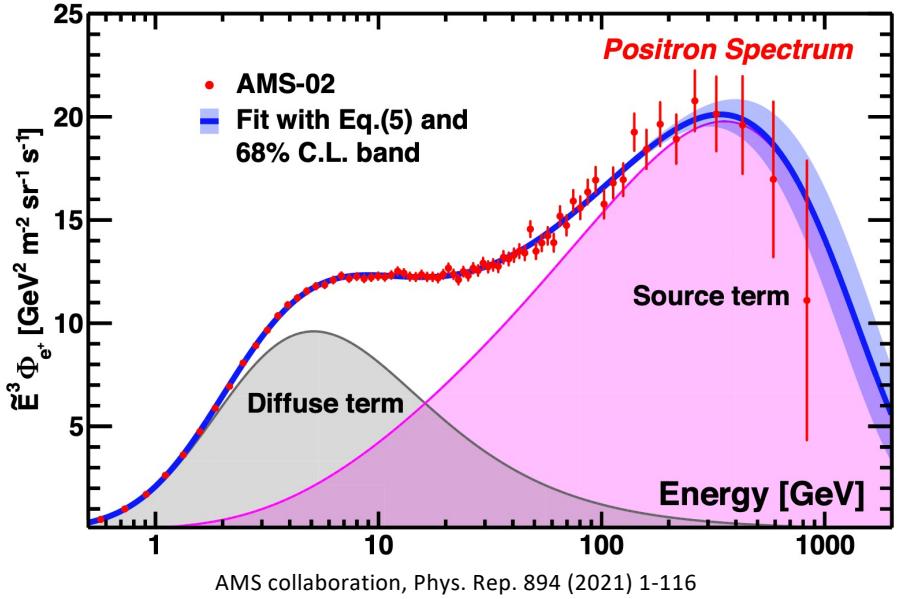
R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

3



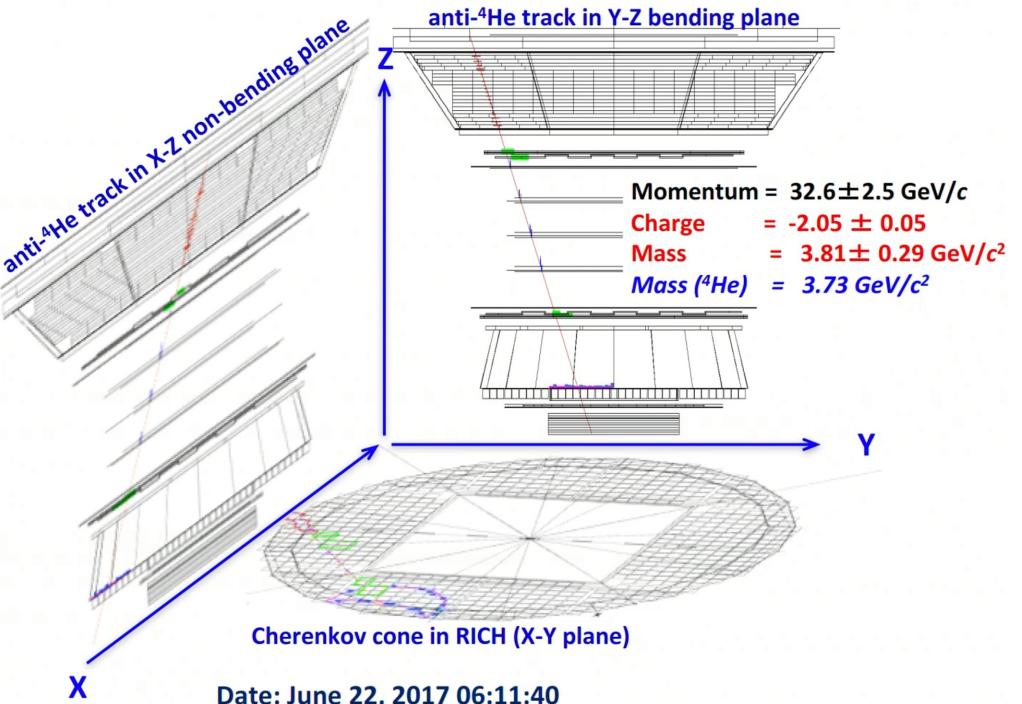
AMS-02 state-of-the-art results



AMS-02 has observed few ${}^3\text{He}/{}^4\text{He}$ antinuclei candidates (about $1/10^8$ He events), a measurement difficult to frame in the standard model of cosmic rays. Explanations invoking secondary production fail to motivate the relative abundance of claimed anti- ${}^3\text{He}/{}^4\text{He}$

S.Ting, Latest Results from the AMS Experiment on the International Space Station, CERN 2018

Important Observation of anti- ${}^4\text{He}$

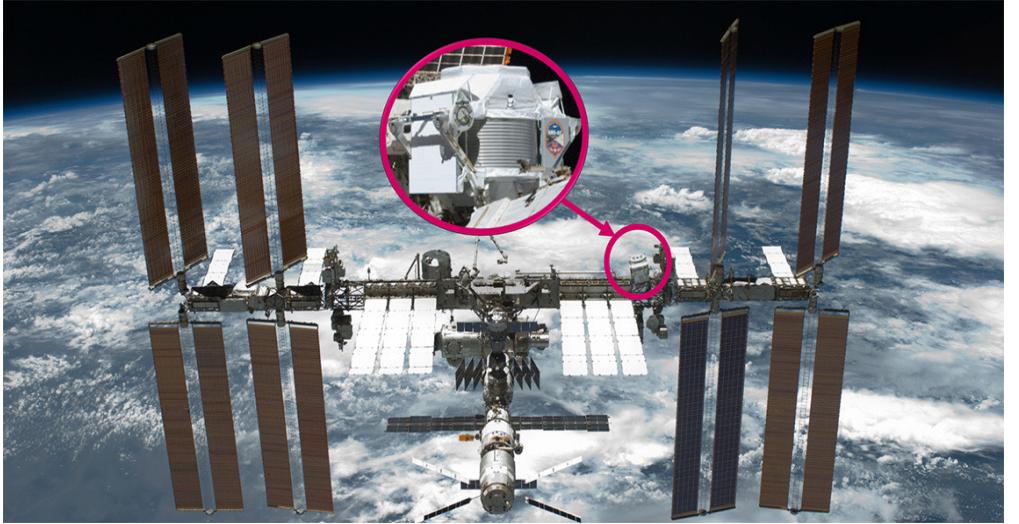


many new results based on 10 years of data collected by AMS-02 on ISS, presented at ECRS2022

R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

Breaking the frontiers



AMS-02 / 11 years / on ISS since 2011

200+ billion events collected

Unexpected results by unprecedented precision investigations

about 1 anti-He event/year

Statistical sample too small to allow for accurate MC simulation
($1/10^{10}$) particles



[Roberto luppia](#)

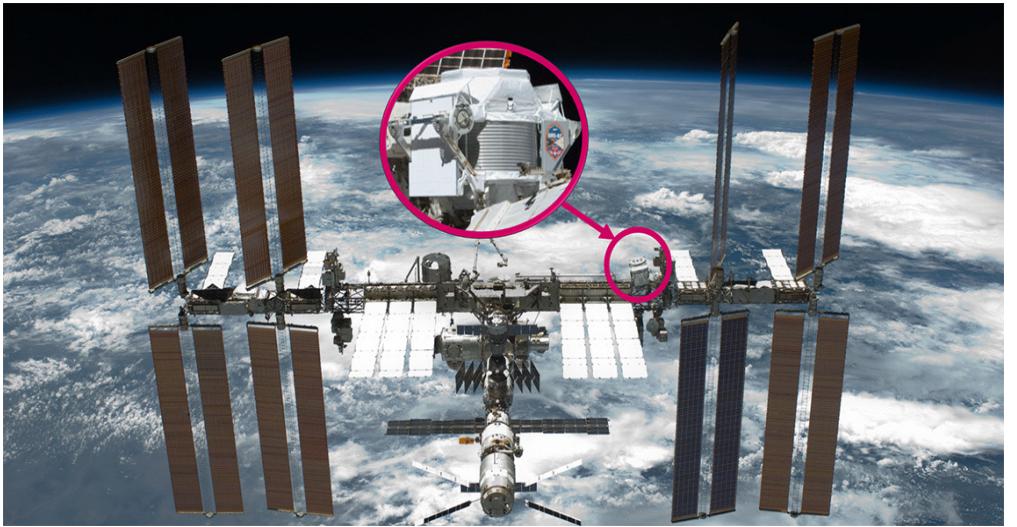
R. luppia - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

5



Breaking the frontiers



AMS-02 / 11 years / on ISS since 2011

200+ billion events collected

Unexpected results by unprecedented precision investigations

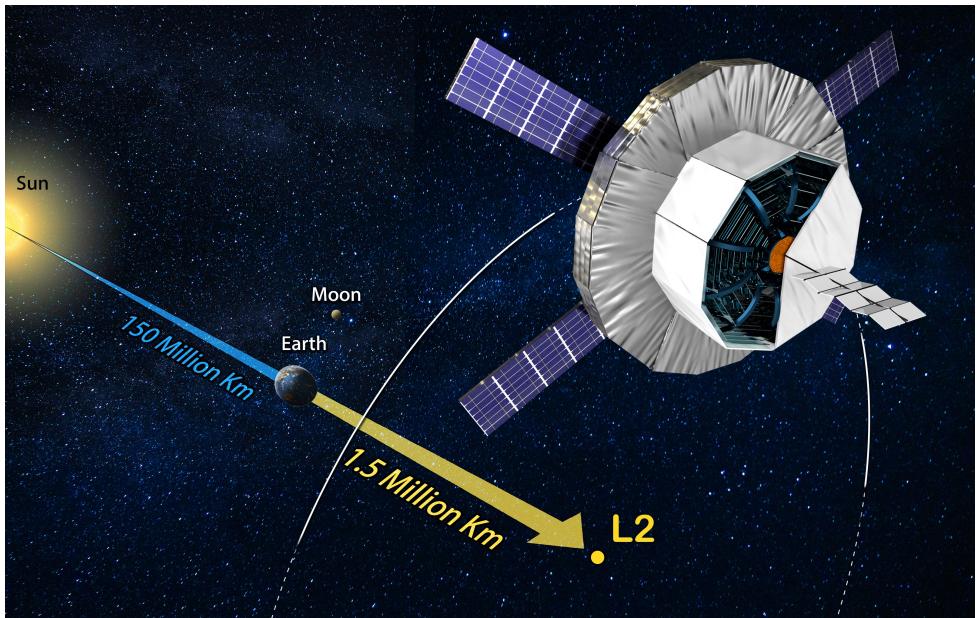
about 1 anti-He event/year

Statistical sample too small to allow for accurate MC simulation
($1/10^{10}$) particles

Towards 2050...

A factor at least 10x in AMS-02 acceptance and precise mass,
energy and charge/sign measurement capabilities for
exploration of un-accessible frontiers in cosmic rays:

Cosmic ray Composition
High Energies
Antimatter



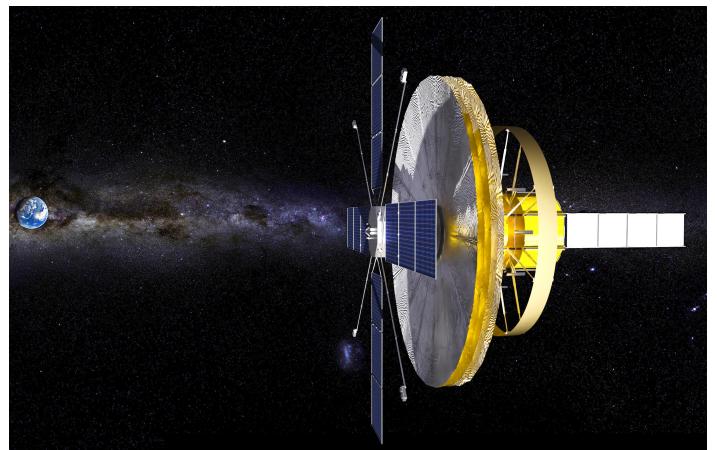
ALADInO (Antimatter Large Acceptance Detector In Orbit)

Presented for the first time in 2016 (Bertucci B. et al, ESA call for ideas).

ESA report: "[...] Scientific breakthroughs are expected in case of discoveries. [...] In the case of antimatter search, the ALADINO investigation will be state of the art, while for dark matter and cosmic radiation search, will be the only one to investigate the particle channel, and is therefore complementary and synergetic to other efforts."

Discussed in 2019 (Battiston R. et al, ESA call for VOYAGE2050)

Scientific relevance of objectives and technological roadmap confirmed: AMS-100 in L2, S. Schael, ESA call for VOYAGE2050



**High Precision Particle Astrophysics as a New Window on the Universe
with an Antimatter Large Acceptance Detector In Orbit
(ALADInO)**



A White Paper submitted in response to ESA's Call for the VOYAGE 2050 long-term plan

References:

- <https://www.cosmos.esa.int/web/voyage-2050/white-papers>
- https://www.cosmos.esa.int/documents/1866264/3219248/BattistonR_ALADINO_PROPOSAL_20190805_v1.pdf
- Battiston, R.; Bertucci, B.; et al., *High precision particle astrophysics as a new window on the universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Experimental Astronomy 2021. <https://doi.org/10.1007/s10686-021-09708-w>
- Adriani, O. et al., *Design of an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Instruments 2022, 6(2), 19. <https://doi.org/10.3390/instruments6020019>



[Roberto Iuppà](#)

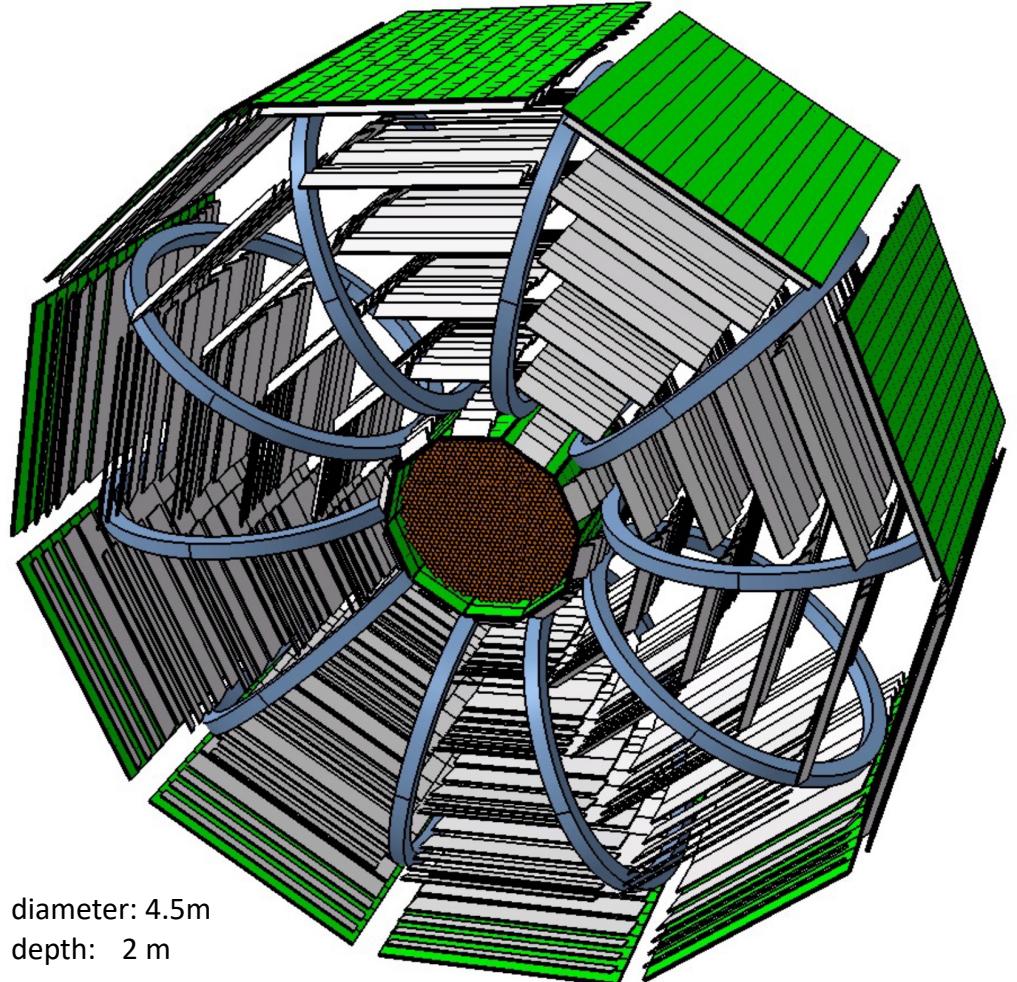
R. Iuppà - Future searches in cosmic-rays with magnetic spectrometers

February 27, 2022

7



ALADInO (Antimatter Large Acceptance Detector In Orbit)



Lightweight Magnetic Spectrometer designed to achieve MDR > 20 TV over large acceptance > 10 m²sr operated in Earth-Sun L2

Detector concept to overcome the experimental limitations for the investigations of GeV to supra-TeV antimatter CRs in space with magnetic spectrometers.

- positron and antiproton spectra up to 10 TV
- GeV anti-D and anti-He

Onboard calorimeter energy scale cross-calibration with magnetic spectrometer

- electron and positron spectra up to 20 TeV
- nuclei spectra up to PeV



[Roberto Iuppà](#)

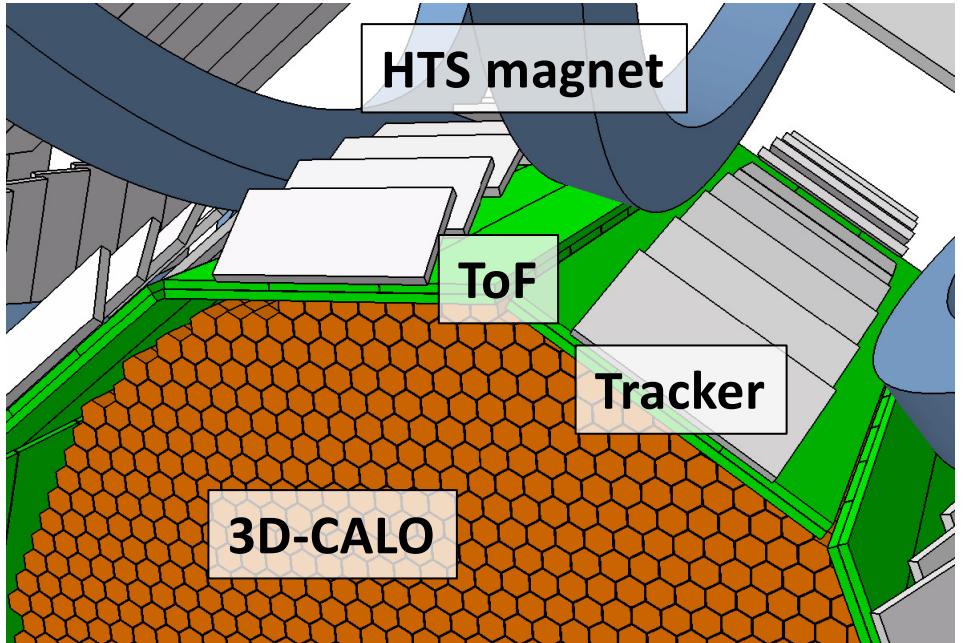
R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

8



ALADInO (Antimatter Large Acceptance Detector In Orbit)



High Temperature Superconducting (HTS) magnet
10 coils in toroidal configuration

Tracker

Double-sided Si- μ strip over 6 planes inside magnetic volume
coordinate resolution < 5 μm (bending)

Time-Of-Flight

Inner and outer layers of plastic scintillator bars
readout by SiPMs with O(10ps) time resolution

3D CALO

~ 16'000 LYSO crystals readout with HDR FEE
61 X_0 , 3.5 λ_l
9 $\text{m}^2 \text{sr}$ (lateral surface)

R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

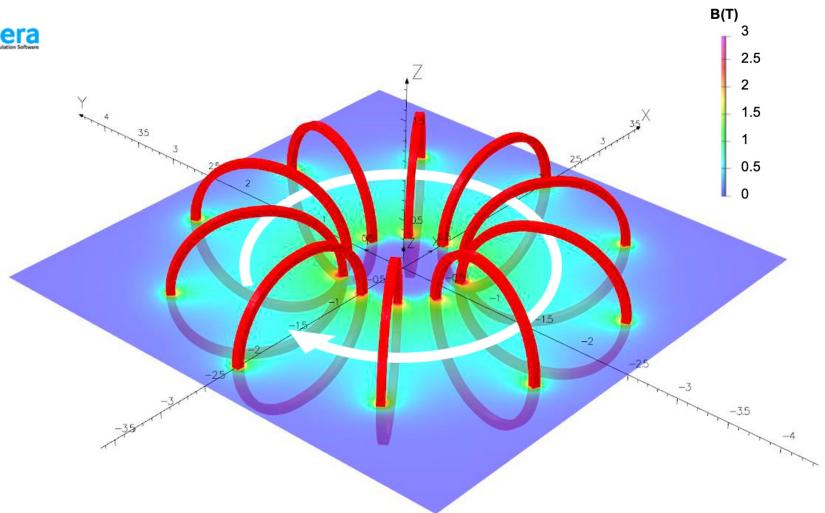
February
27, 2022

9



Superconducting magnet

Opera



HTS magnet

Number of coils	10
Current / coil	$400 \cdot 10^3$ A
Operating current	~ 250 A
Magnetic flux density	average: 0.8 T max: 3T
Bending power	1.1 Tm
Cold mass	1.2 t

High Temperature Superconducting (HTS) toroidal magnet, 10 coils

- design based on SR2S (Space Radiation Superconducting Shield) project
- confined magnetic field
- best compromise between magnetic field azimuthal homogeneity, which needs distributed conductors (large number of coils) and large field of view
- shape of coils (D, circular, ...) to be optimized

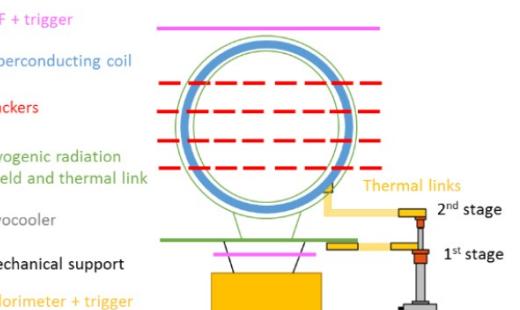
Use HTS tapes made on ReBCO (Rare Earths Barium Copper Oxide)

- avoid liquid-He cryogenics, operate at 40K
- large robustness against quench-trigger disturbances
- investigation on using NI techniques for passive quench protection

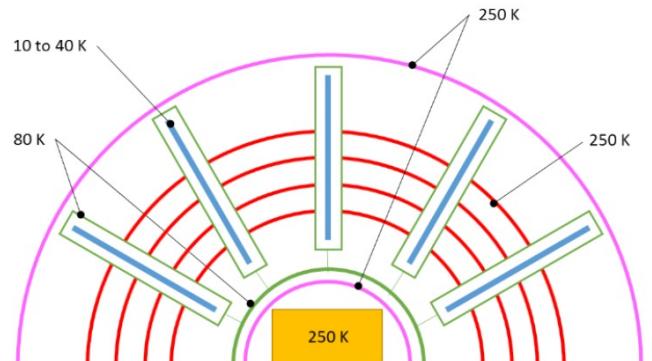
Cryocoolers used for active cryogenic instead of large area radiators

- Multi-Layer-Insulation (MLI) umbrella-like sunshield to intercept the radiation heat flux from Sun
- Cryogenics MLI + 250 K thermal shield + 80K thermal shield around coils to maintain operating temperature

Side cross-sectional view



Top cross-sectional view



R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

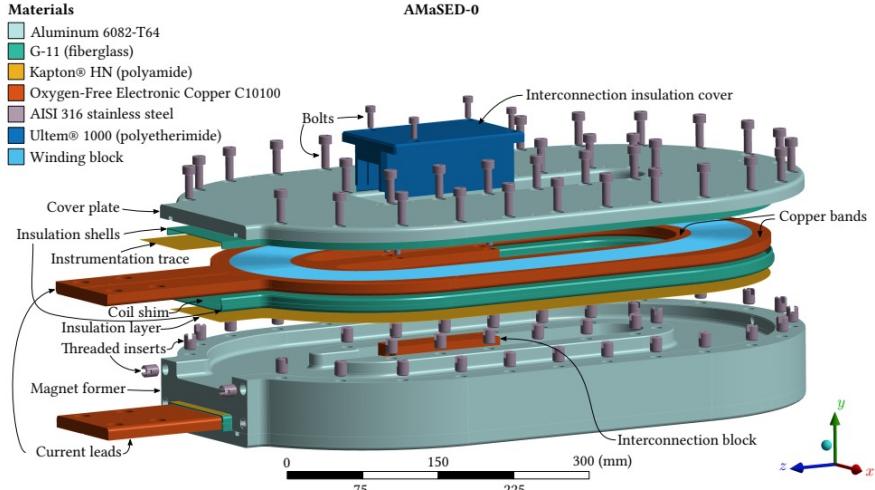
February
27, 2022

10



Superconducting Magnet

M. Dam, W.J.. Burger et al, PoS(ICRC2021) 498
Mechanical structure of the HDMS coil prototype



HTS coil demonstrator manufactured in the High temperature Magnet Demonstrator (HDMS) project increase TRL to 6 of

- copper bands as current leads and layer jumps
- no-insulation coils (radial resistance for self-quenching)
- aluminum mechanical structure

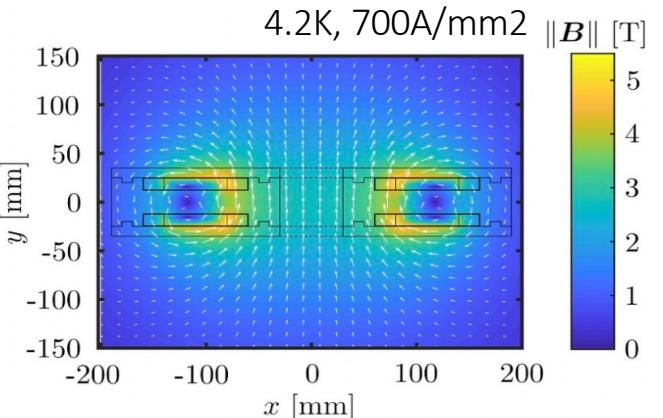
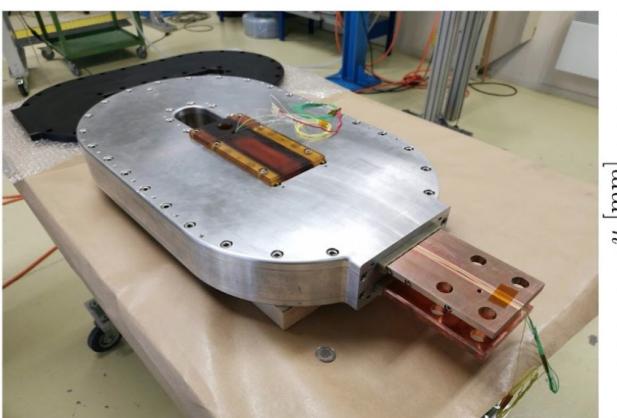
Based on current heritage:

- 5 years to increase TRL with additional R&D
- 5 years for design, construction, test and integration

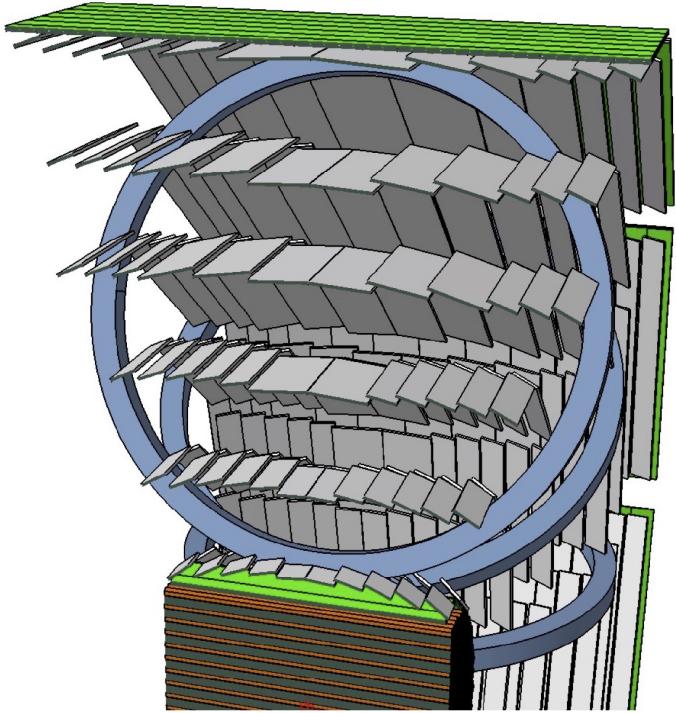
H. Reymond, M. Dam, H. Felice et al, JACoW ICALEPS2021 (2022) 473-477
Winding of the HDMS coils (CERN)



Demonstrator coil constructed for the HDMS project (funded CERN and ASI).



Tracker



Baseline design on high TRL solution

Six layers of precision tracking system,
~70m² active area

Baseline design:

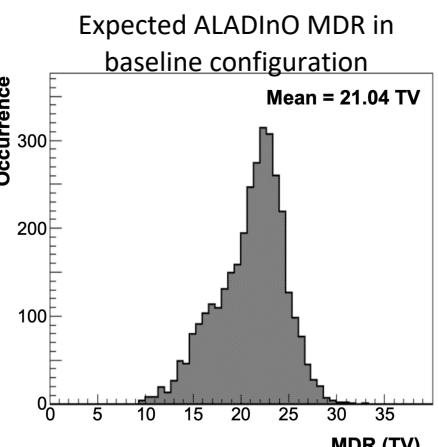
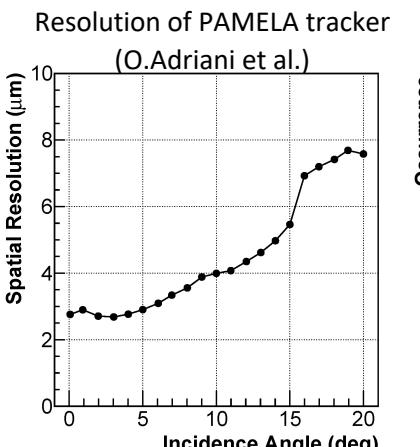
- double-sided Si- μ strips, implant pitch 25 μ m, readout pitch 100 μ m (bending)
- 2-7 sensors (95x95mm²) arranged along "ladders", max length ~70cm
- ladders arranged in adaptive geometry over 6 planes in 10 sectors

One ALADInO Tracker sector \longleftrightarrow Full AMS-02 Tracker (channels, area, ...)

Target performances: ~3 μ m coo. resolution over "long" ladders

- achieved by PAMELA on "short" ladders, ~5-10 μ m by AMS.02 on similar "long" ladders
- FEE with dynamic range up to Oxygen with no saturation (as in AMS-02)

With specific R&D, leveraging on PAMELA and AMS-02, large likelihood to achieve target performances. Other options (MAPS, LGAD) under study



[Roberto Iuppà](#)

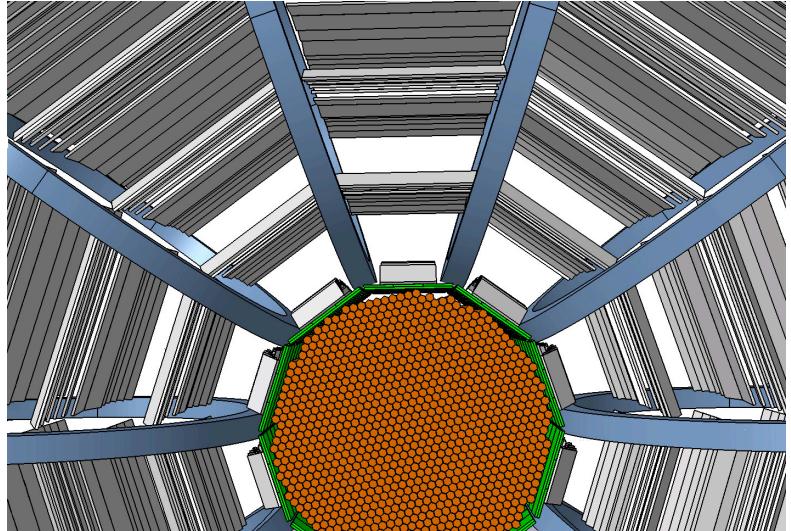
R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

12



Calorimeter



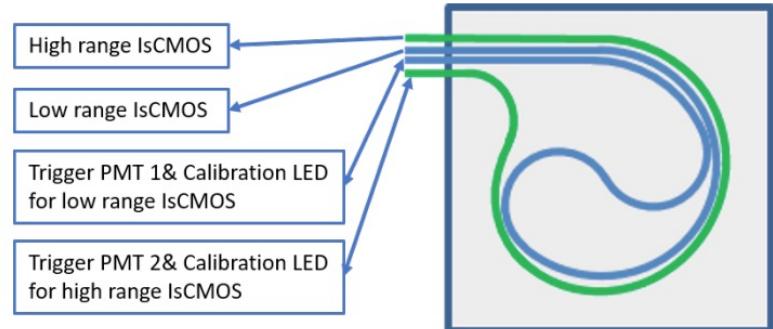
~ 16'000 LYSO crystals (~2 tons)

61 X_0 , 3.5 λ_l

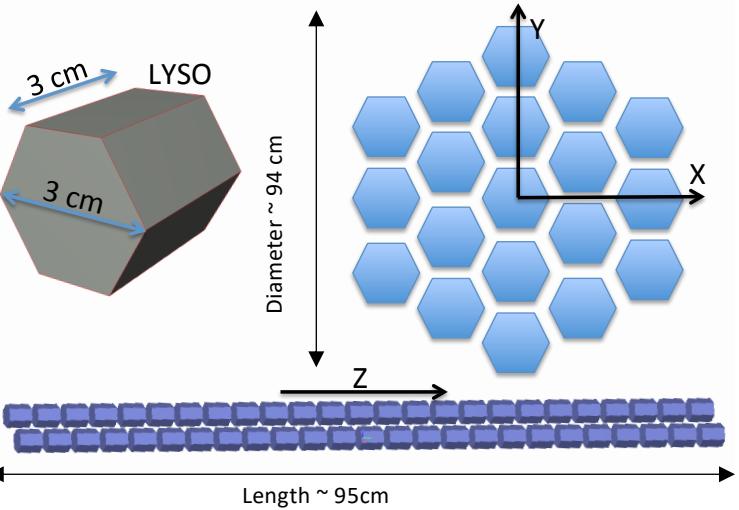
9 m²sr (lateral surface)

30% energy resolution (hadrons) @ 3 m²sr

L. Pacini et al., PoS (ICRC2021) 066



Based on the
"CaloCube"
paradigm (INFN, O. Adriani
et al.) for particle
calorimetry



- **nearly isotropic response** to particles from all directions to maximize detector effective acceptance;
- **3D shower topology imaging** for e/p separation, energy resolution and energy scale
- **heritage** from developments for application in HERD, high TRL and space qualification ongoing



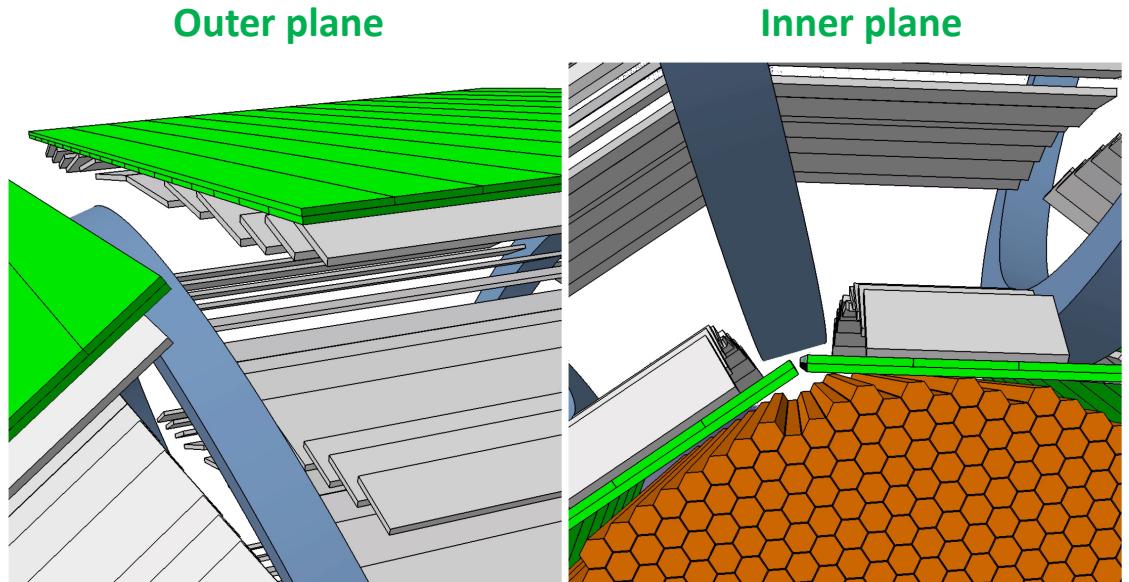
Large dynamic range (10^7) to measure MIPs and PeV showers.

- e.g. HERD: double readout (IsCMOS/PD) + PMT/SiPM for trigger + dynamic range with double-gain selection

Energy scale calibration with light double readout system

Total power expected 200 W

Time Of Flight

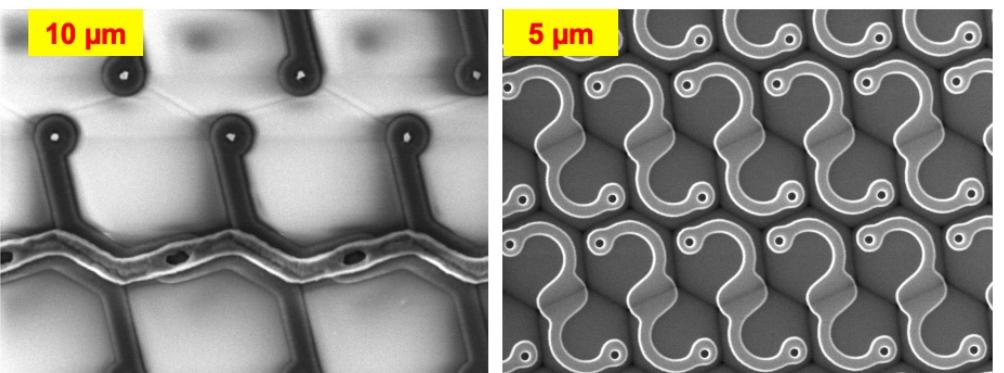


- Target resolutions below 100 ps for Dbar sensitivity at 3-4 GeV/n
- ToF demonstrator for space applications (AMS-100) feature $\Delta t \sim 40$ ps over $O(10)$ cm Sci-bars (c. Chung, Instruments 2022, 6(1), 14)

Based on established PAMELA and AMS-02 ToF systems

- **Sci-bars** up to 190 x 10 cm, 0.5 - 0.8 cm thick
- Inner and outer ToF, 1.45 m distance
- hodoscopic x-y measurement
- **SiPM** replacement to PMT for light readout

Small μ cell SiPM readout for large dynamic range (1 < Z < 26)
UHD SiPM produced at FBK (G. Paternoster. 13th Trento workshop)



worldwide R&D effort ongoing for space qualification and improvement of SiPMs and low-consumption fast FEE readout



[Roberto lappa](#)

R. lappa - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

14



Operations in space

Earth–Sun Lagrange Point L2 is the most proper stable orbit to operate a superconducting magnet in space

Design optimized in terms of layout, weight, dimensions, power consumption, and expected data throughput to fit in the limits set for transport and operation in Earth–Sun Lagrange Point L2 using a space vector that is already accessible nowadays



ArianeSpace's Ariane 5 rocket with NASA's James Webb Space Telescope onboard.

Mass budget	
Calorimeter	2.3 t
Magnet and Cryogenics	2.0 t
ToF + Si-tracker	1.5 t
Electronics and power	0.5 t
Total	< 6.5 t

Power budget	
Time of Flight	0.4 kW
Calorimeter	0.2 kW
Si-Tracker	1.4 kW
Cryogenics	1.0 kW
Total	3.0 kW

Data stream	
Electronics Channels	2 million
Transfer time window	few h/day
Peak bandwidth	50 Mbps

R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

15



Breaking the frontiers



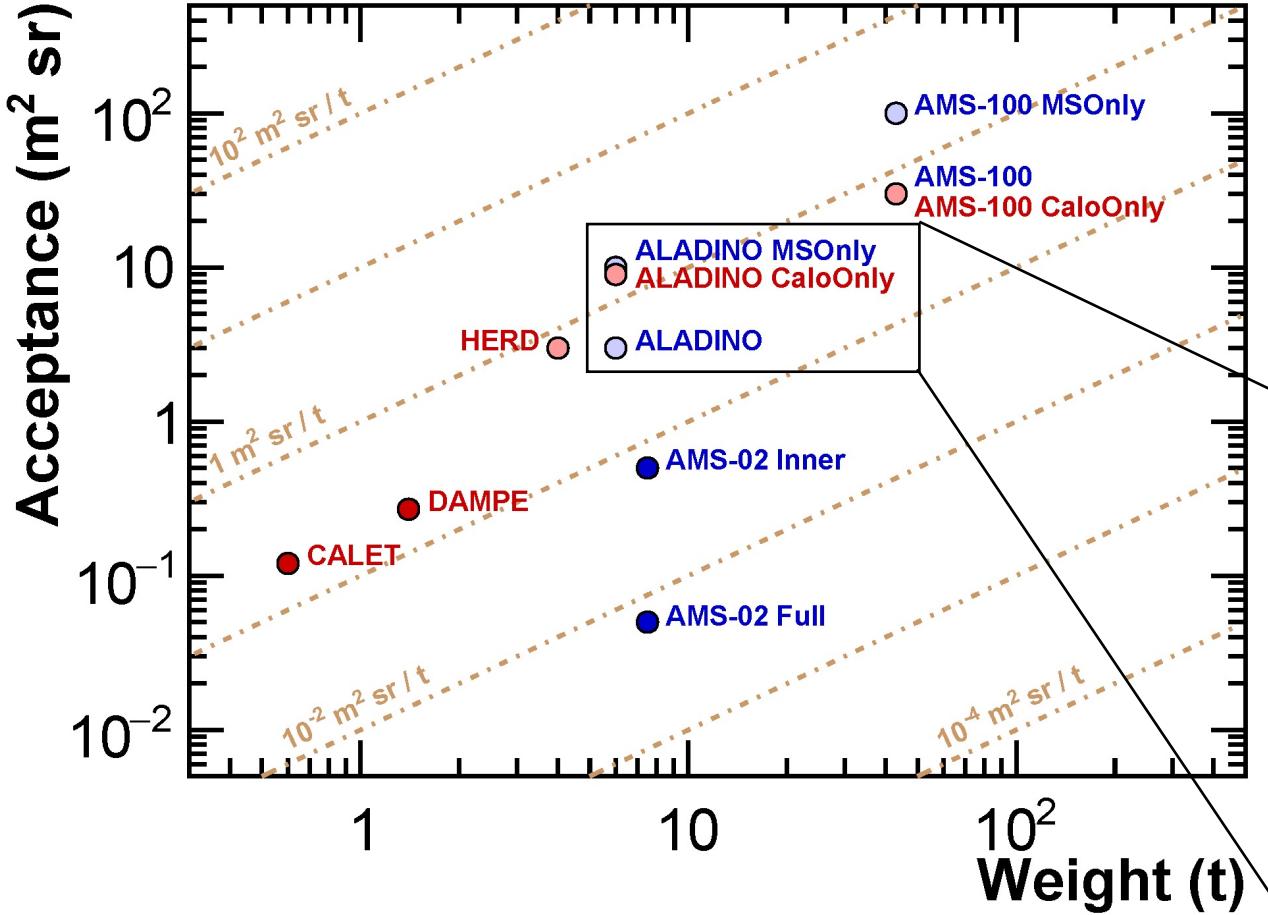
[Roberto Iuppà](#)

R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

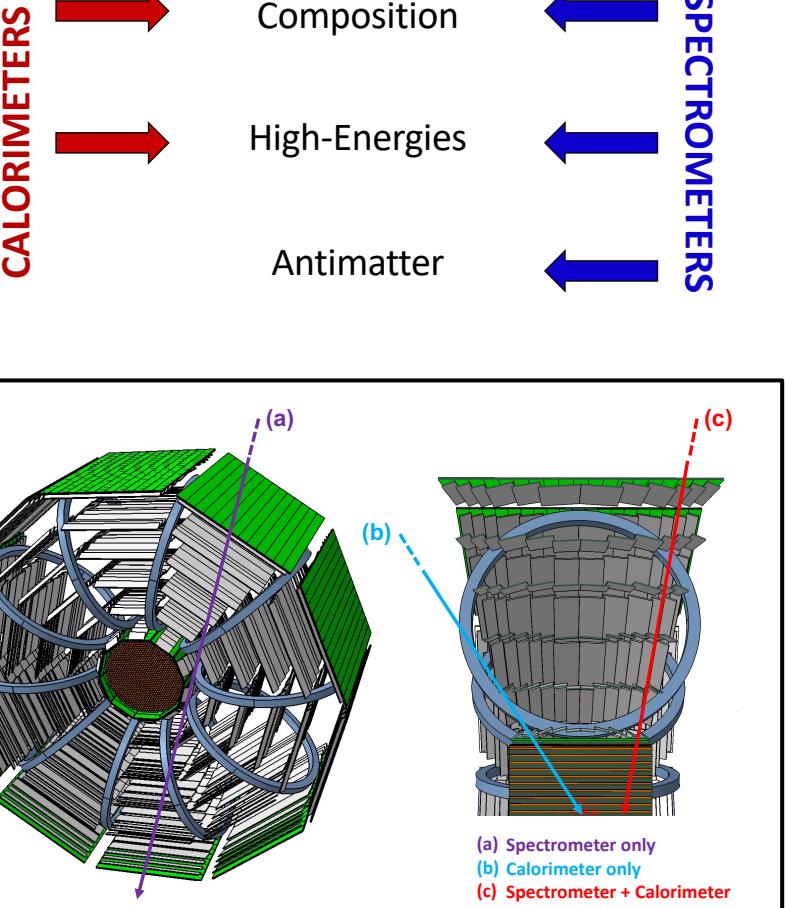
February
27, 2022

16

Large acceptance missions in Space

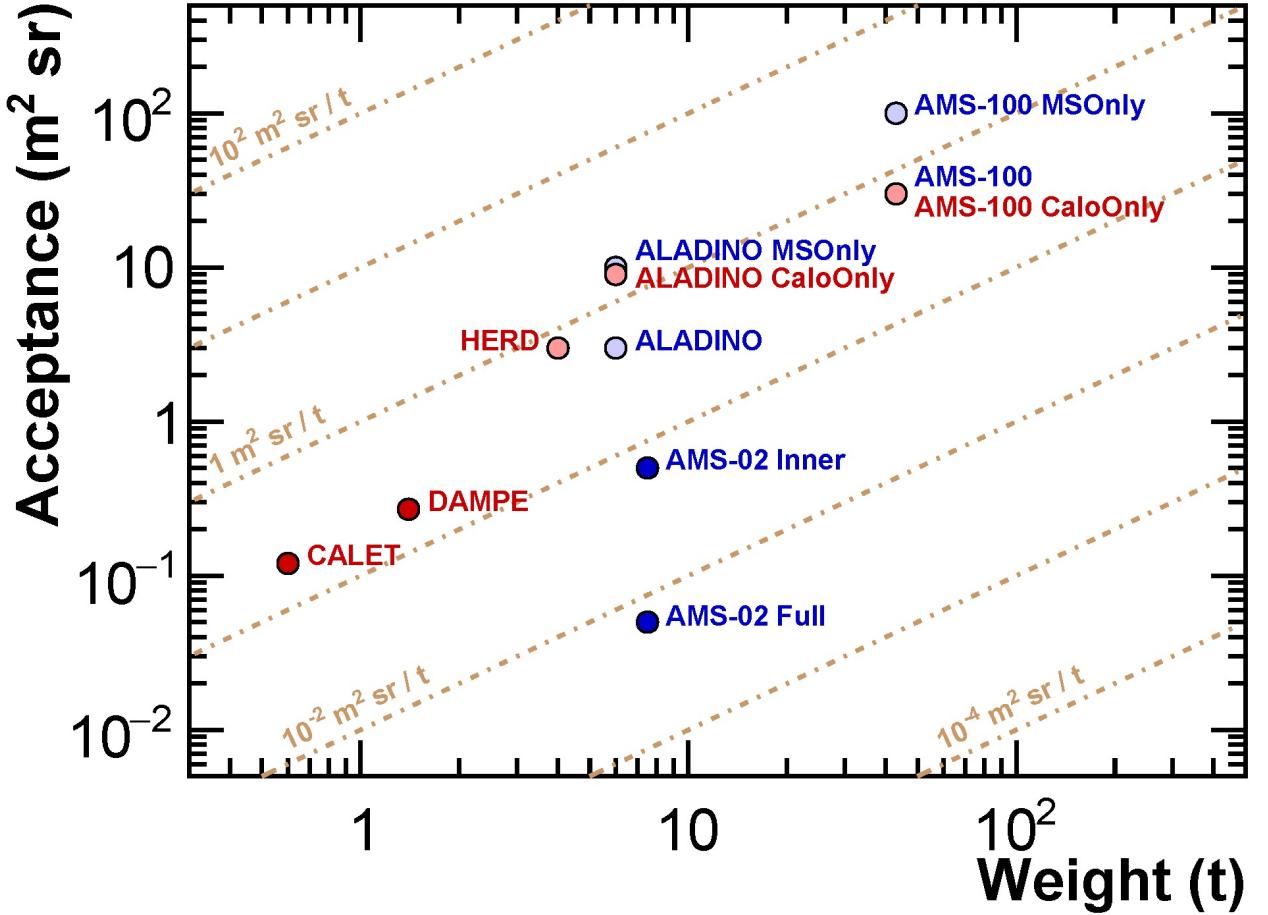


Frontiers in direct CR physics



Breaking the frontiers

Large acceptance missions in Space

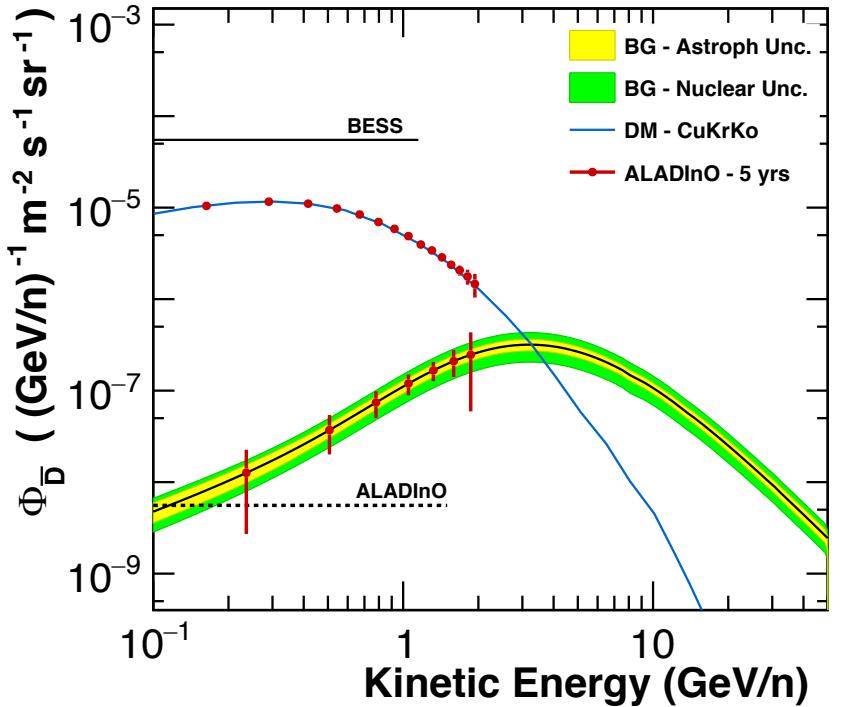


	ALADInO	AMS-02
Location	Earth-Sun L2	ISS
Operations	mid 2040s > 5 yrs operations	2011 - 2030+ fully nominal
Acceptance	a) MS only: $>10\text{m}^2\text{sr}$ b) calo only: $9\text{m}^2\text{sr}$ c) calo+MS: $3\text{m}^2\text{sr}$	Full: $0.05\text{m}^2\text{sr}$ Inner: $0.5\text{m}^2\text{sr}$
Mag. field (ave)	0.8 T, supercond	0.15 T, permanent
MDR	> 20 TV	2 TV ($Z=1$) > 3.2 TV ($Z>1$)
Calorimeter depth	$61 X_0 / 3.5 \lambda_l$	$17 X_0 / 0.6 \lambda_l$
Energy resolution	2% ($e^{+/-}$) 25% (h @ $1\text{m}^2\text{sr}$) 35% (h @ $5\text{m}^2\text{sr}$)	1.5% ($e^{+/-}$)
e/p separation	10^4-10^5	$>10^6$
Channels	2000 k	300 k
Mass	< 6.5 t	7.5 t
Power	3.0 kW	< 2.5 kW



Heavy Antimatter

Extending the antimatter frontier beyond state-of-the-art capabilities (AMS-02, GAPS)



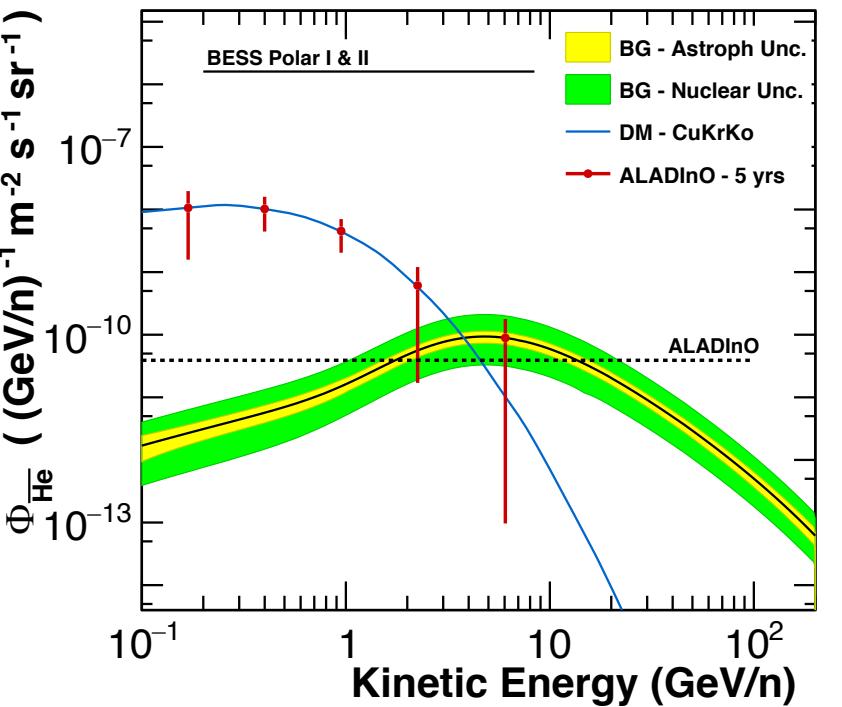
DM model from A. Cuoco et al. 2017, Phys. Rev. Lett. 118, 191102, M. Korsmeier et al., 2018, Phys. Rev. D 97 n.10, 103011

BG model from N. Tomassetti and A. Oliva, 2017, ApJ Lett. 844

Antideuteron

precise measurement of the astrophysical flux
and possible unambiguous detection of primary
anti-D.

Higher energies limited by velocity resolution



Antihelium

Possible unambiguous detection of primary anti-
He and detection or improved upper limits on
astrophysical antiHe yield
Higher energies limited by velocity resolution



[Roberto lappa](#)

R. lappa - Future searches
in cosmic-rays with
magnetic spectrometers

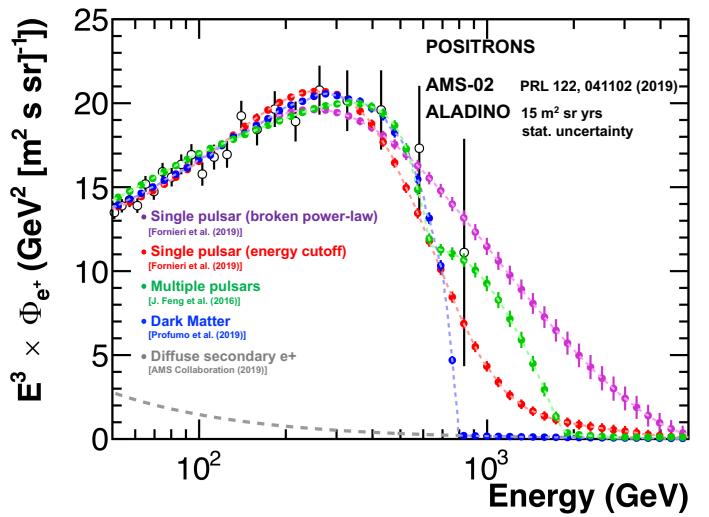
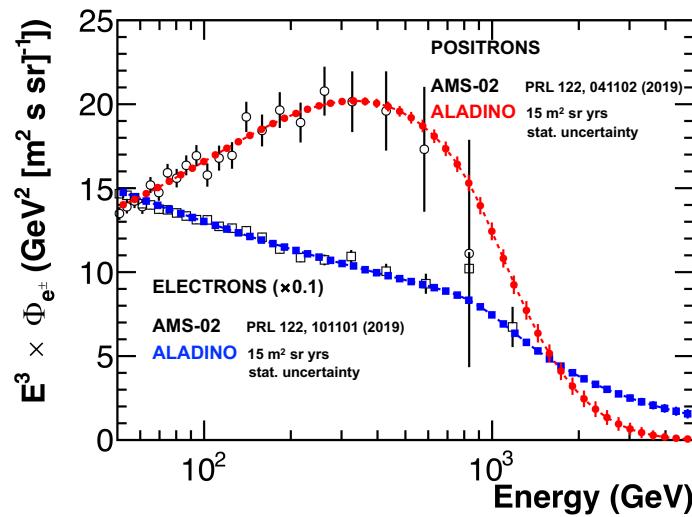
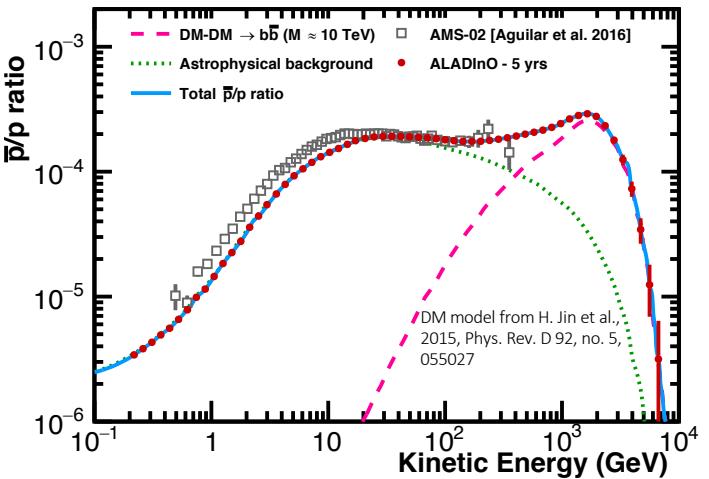
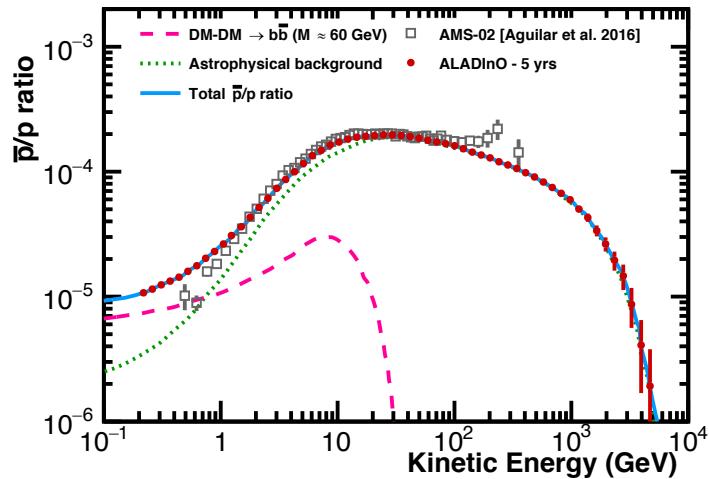
February
27, 2022

18



Light Antimatter

Extend antiproton and positron measurements in the unexplored TV energy frontier



Provide unprecedented precision measurement of GV-TV antiprotons to search for DM signatures

Explore the antiproton flux beyond its flattening and profile the antiproton production break

Fully characterize the positron excess and break

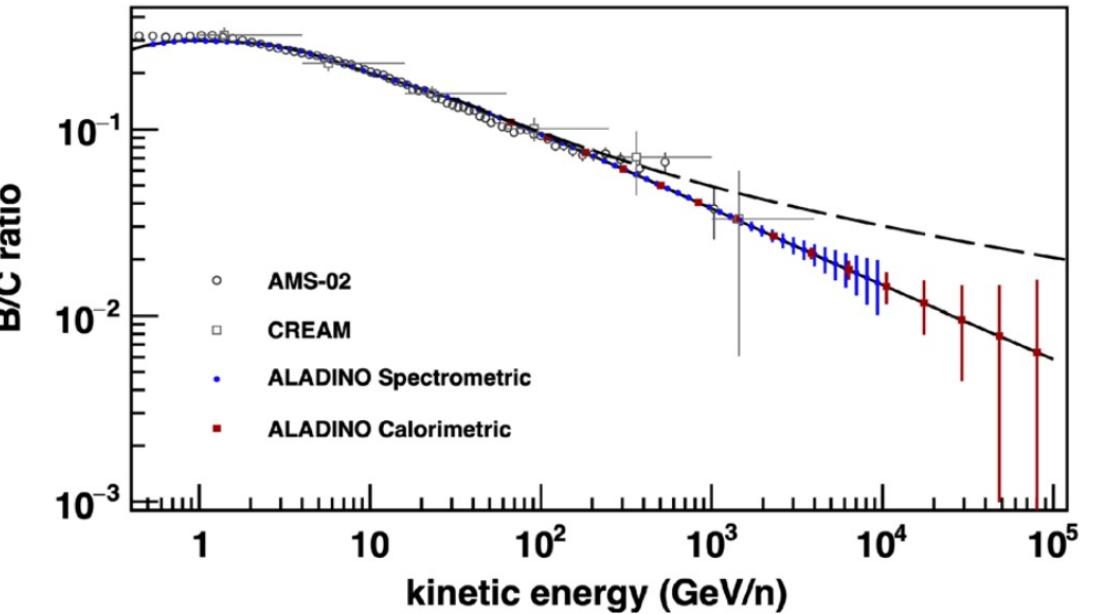
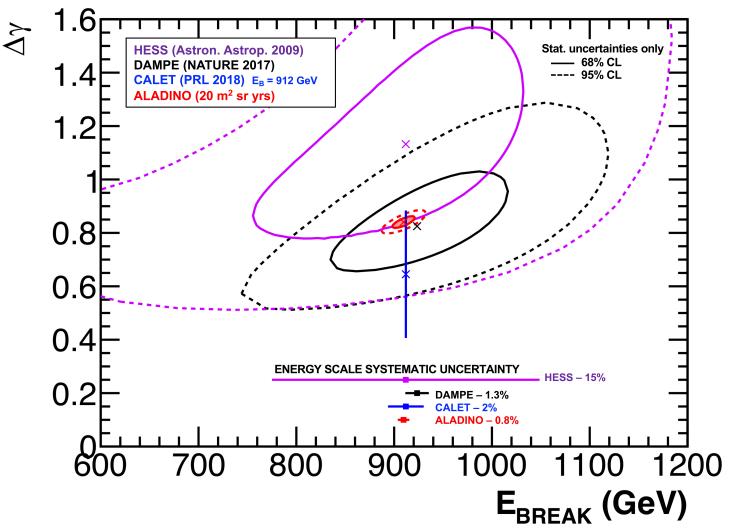
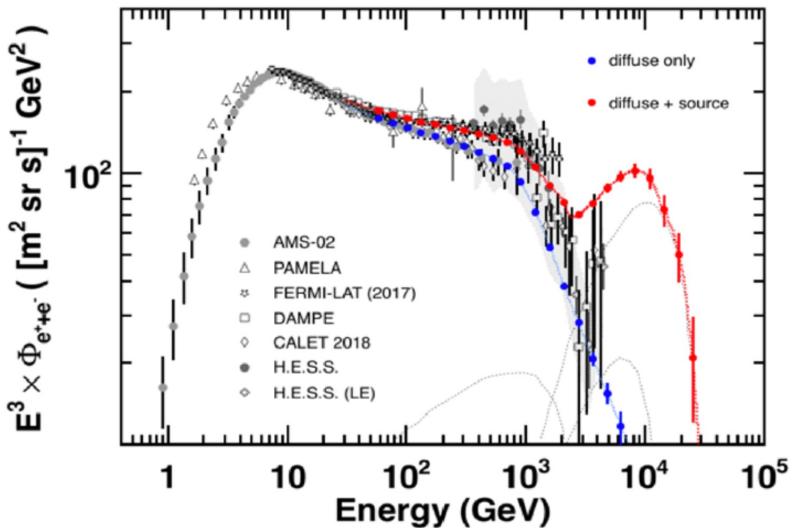
Precisely identify the **dominating source of high energy positrons**, characterize possible secondary sources of high energy positrons and characterize the amount of secondary positrons beyond the excess

Electrons and nuclei

Provide complementary information on the ($e^+ + e^-$) and nuclei flux to planned calorimetric experiments

The ALADInO calorimeter is similar in depth and approach to that of HERD

- similar statistical errors and similar energy reach
- similar energy resolution, both for electromagnetic particles and nuclei
- improved energy scale systematics **from combined calorimetric+spectrometric energy measurement**



Unprecedented precision in the characterization of the electron flux break, useful synergy with ground-based **multi-messenger** telescopes



ALADInO – pathway to science



[Roberto Iuppà](#)

R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

21



Progressing in particle astrophysics with the
Antimatter Large Acceptance Detector In Orbit

ALADInO



High Temperature Superconducting
Magnetic Spectrometer in space

Acceptance $> 10 \text{ m}^2\text{sr}$

Antimatter measurements up to 10 TeV
Established technologies for detection of particles
in space

5+ year operations in L2

Payload Weight $< 6.5 \text{ t}$

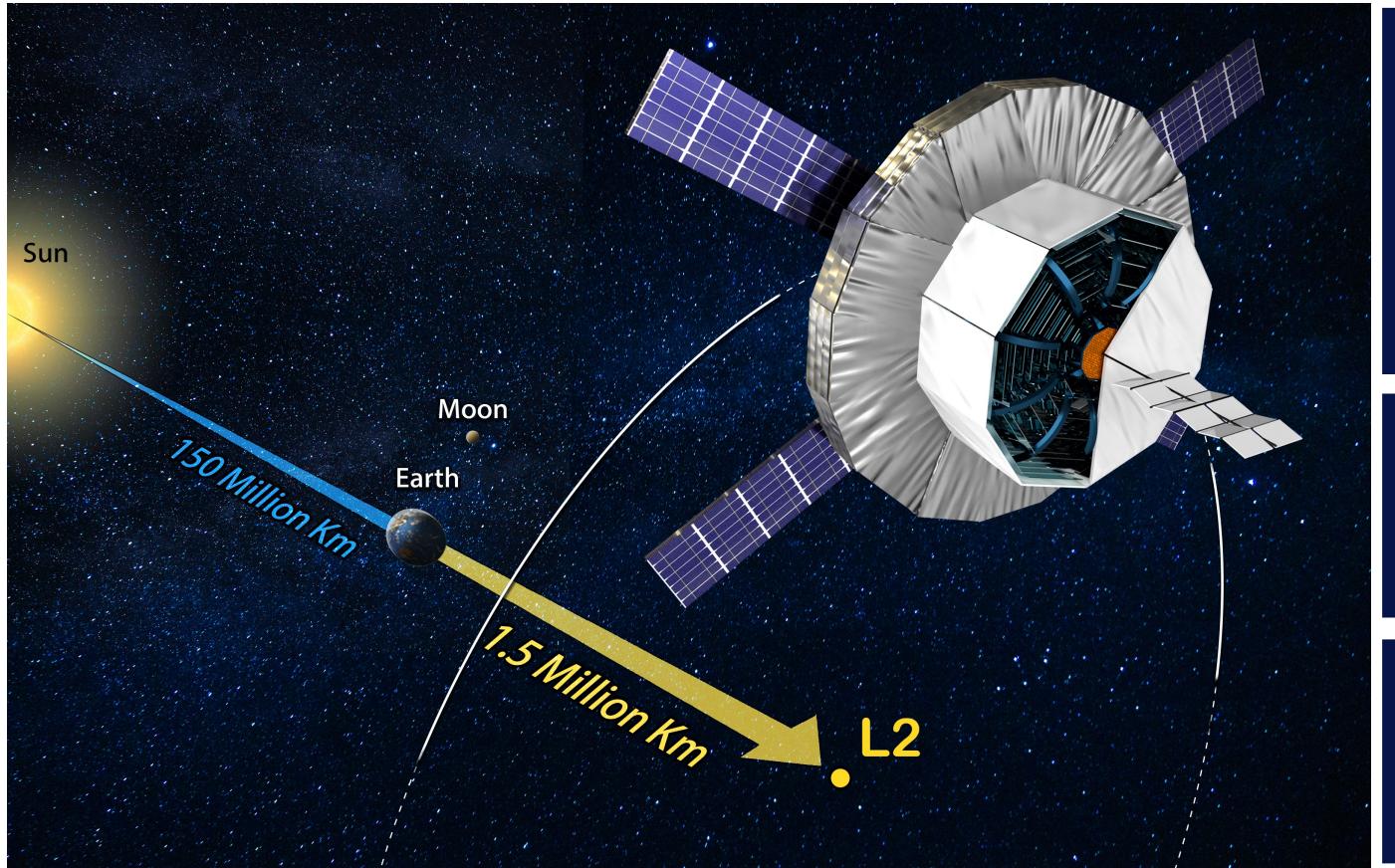
Payload power consumption 3 kW
Compact volume (fits Ariane launcher)

Roadmap for mission opportunity

mid 2030s: ALADInO Pathfinder

mid 2040s: Operations in L2

by 2050: Unprecedented results



ALADInO Pathfinder: LAMP



[Roberto Iuppà](#)

R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

22



Progressing in particle astrophysics with the
Antimatter Large Acceptance Detector In Orbit

ALADInO



High Temperature Superconducting
Magnetic Spectrometer in space

Acceptance $> 10 \text{ m}^2\text{sr}$

Antimatter measurements up to 10 TeV
Established technologies for detection of particles
in space

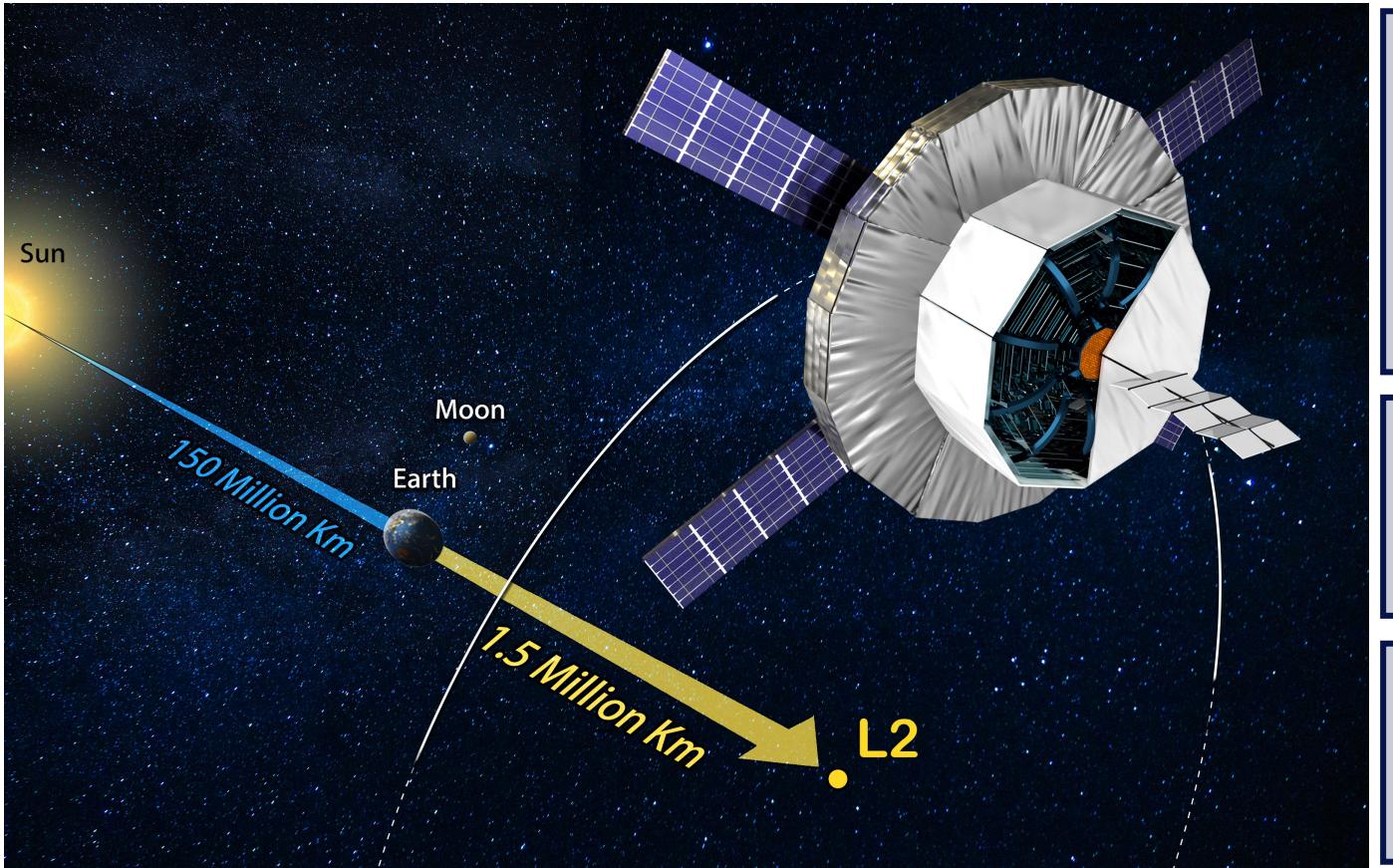
5+ year operations in L2

Payload Weight $< 6.5 \text{ t}$

Payload power consumption 3 kW
Compact volume (fits Ariane launcher)

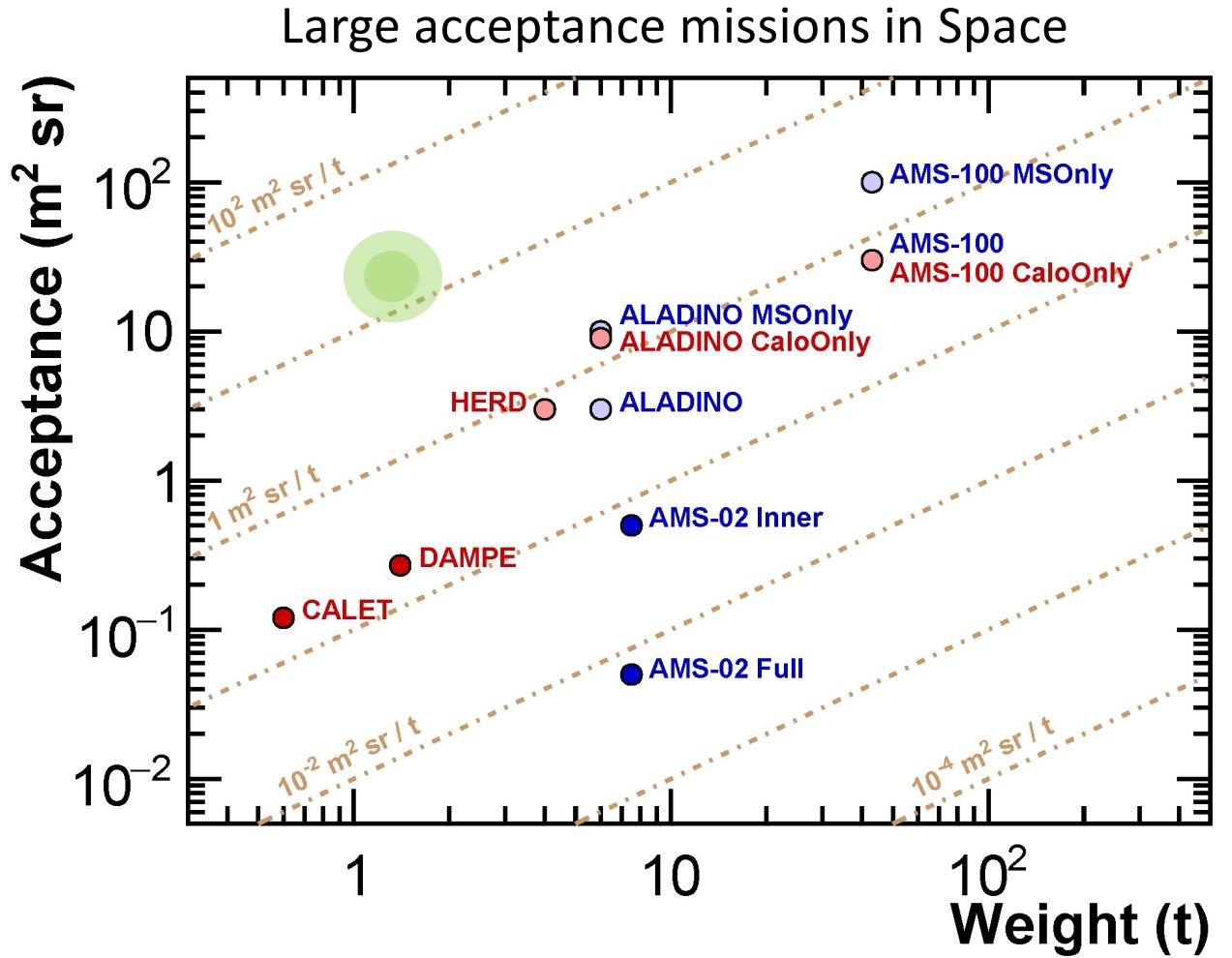
Roadmap for mission opportunity
mid 2030s: ALADInO Pathfinder

mid 2040s: Operations in L2
by 2050: Unprecedented results

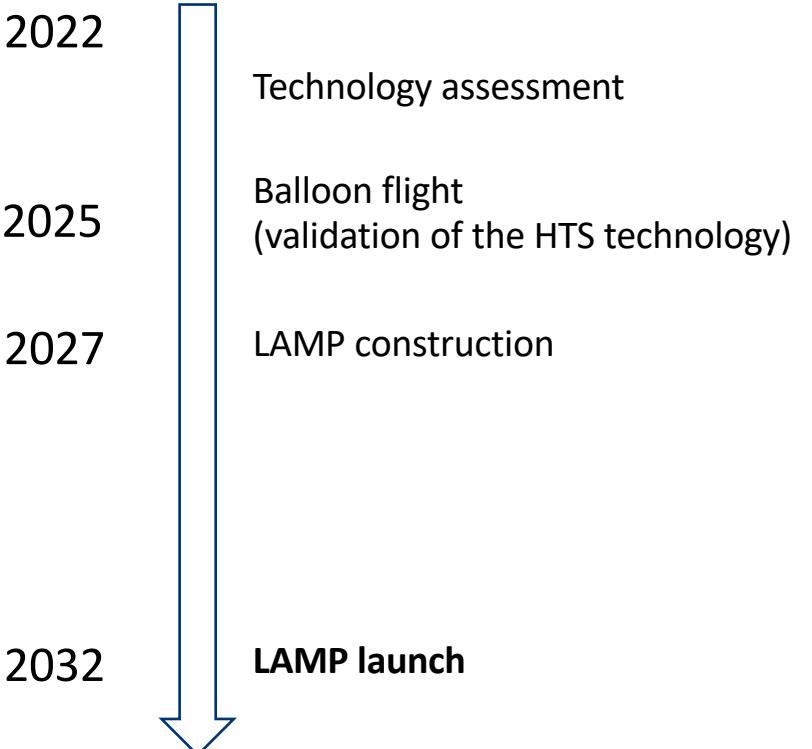


LAMP: Light Aladino-like Magnetic sPectrometer

Breaking the frontiers



LAMP maintains the geometry of ALADInO, but focuses on nuclear antimatter. It features increased acceptance for the magnetic spectrometer and auxiliary detectors (TOF, Cherenkov), saving mass with a **calorimeter-free** approach.



thank you



Design of an Antimatter Large Acceptance Detector In Orbit (ALADInO)

by Oscar Adriani ^{1,2} Corrado Altomare ³ Giovanni Ambrosi ⁴ Philipp Azzarello ⁵ ,
 Felicia Carla Tiziana Barbato ^{6,7} , Roberto Battiston ^{8,9} Bertrand Baudouy ¹⁰ ,
 Benedikt Bergmann ¹¹ Eugenio Berti ^{1,2} Bruna Bertucci ^{12,4} Mirko Boezio ^{13,14} ,
 Valter Bonvicini ¹³ , Sergio Bottai ² , Petr Burian ¹¹ , Mario Buscemi ^{15,16} Franck Cadoux ⁵ ,
 Valerio Calvelli ^{17,†} , Donatella Campana ¹⁸ Jorge Casaus ¹⁹ Andrea Contin ^{20,21} ,
 Raffaello D'Alessandro ^{1,2} Magnus Dam ²² Ivan De Mitri ^{6,7} Francesco de Palma ^{23,24} ,
 Laurent Derome ²⁵ , Valeria Di Felice ²⁶ Adriano Di Giovanni ^{6,7} Federico Donnini ⁴ ,
 Matteo Duranti ^{4,*} , Emanuele Fiandrini ^{12,4} Francesco Maria Follega ^{8,9} Valerio Formato ²⁶ ,
 Fabio Gargano ³ , Francesca Giovacchini ¹⁹ Maura Graziani ^{12,4} Maria Ionica ⁴ ,
 Roberto Iuppa ^{8,9} , Francesco Loparco ^{27,3} Jesús Marín ¹⁹ Samuele Mariotto ^{28,22} ,
 Giovanni Marsella ^{15,16} Gustavo Martínez ¹⁹ Manel Martínez ²⁹ Matteo Martucci ^{30,26} ,
 Nicolò Masi ²¹ , Mario Nicola Mazziotta ³ Matteo Mergé ^{30,26} Nicola Mori ² ,
 Riccardo Munini ¹³ Riccardo Musenich ¹⁷ Lorenzo Mussolin ^{12,4} Francesco Nozzoli ⁹ ,
 Alberto Oliva ²¹ Giuseppe Osteria ¹⁸ Lorenzo Pacini ² Mercedes Paniccia ⁵ ,
 Paolo Papini ² Mark Pearce ³¹ Chiara Perrina ³² Piergiorgio Picozza ^{33,30,26} ,
 Cecilia Pizzolotto ¹³ Stanislav Pospíšil ¹¹ Michele Pozzato ²¹ Lucio Quadrani ^{20,21} ,
 Ester Ricci ^{8,9} Javier Rico ²⁹ Lucio Rossi ^{28,22} Enrico Junior Schioppa ^{23,24} ,
 Davide Serini ³ Petr Smolyanskiy ¹¹ Alessandro Sotgiu ^{30,26} Roberta Sparvoli ^{30,26} ,
 Antonio Surdo ²⁴ Nicola Tomassetti ^{12,4} Valerio Vagelli ^{34,4,*} Miguel Ángel Velasco ¹⁹ ,
 Xin Wu ⁵ and Paolo Zuccon ^{8,9} — Hide full author list

interest expressed by more than 70 scientists from 34 institutes as of 2022



Roberto Iuppa
R. Iuppa - Future searches
in cosmic-rays with
magnetic spectrometers

AMS-01

AMS-02

Pamela

FERMI

DAMPE

Arina

Agile

CSES-01

24

CSES-02



February
27, 2022

R. Iuppa - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

25

backup



Tracker

Emerging technologies for improved performances and capabilities to the ALADInO tracker

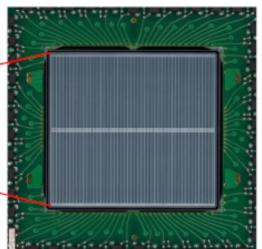
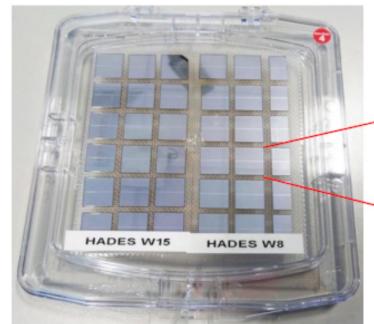
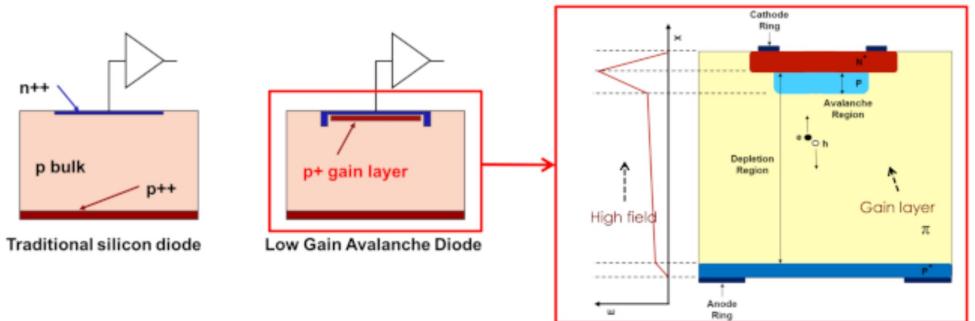
Monolithic Active Pixel Sensors (MAPS)

- based on CMOS technology
- Sensor and read-out circuit on same Si substrate
- low noise and fully zero-suppressed digital output
- $\sim 25\mu\text{m}$ pixel side, strip-like geometry possible
- space heritage from HEPD-02 onboard CSES-02
- Current ongoing developments:
 - lower power consumption
 - enable timing capabilities
 - increase sensor area



Low Gain Avalanche Diodes

- Inner gain layer in Si substrate
- provides timing capabilities < 100 ps and enhanced S/N
- developed in pixel-layout for accelerator experiments, μ strip layout may be used in space
- R&D required for readout and power consumption mitigation



W. Krüger,
LGAD technologies for
HADES, contribution to
VCI 2022

Target performances: MAPS Tracker / Tracker timing < 100 ps with power consumption < 5 kW

R. Iuppa - Future searches
in cosmic-rays with
magnetic spectrometers

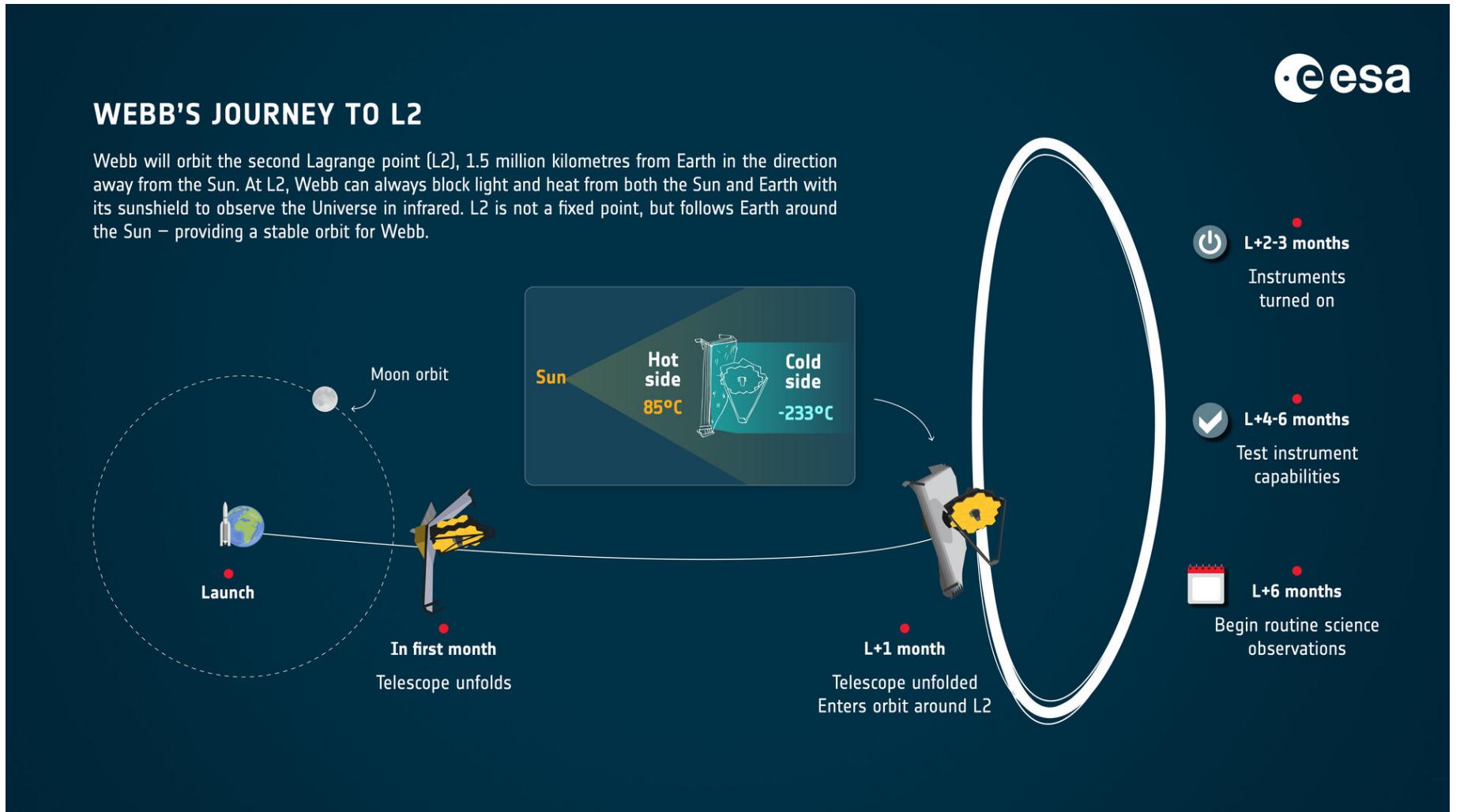
February
27, 2022

26



Operations in space

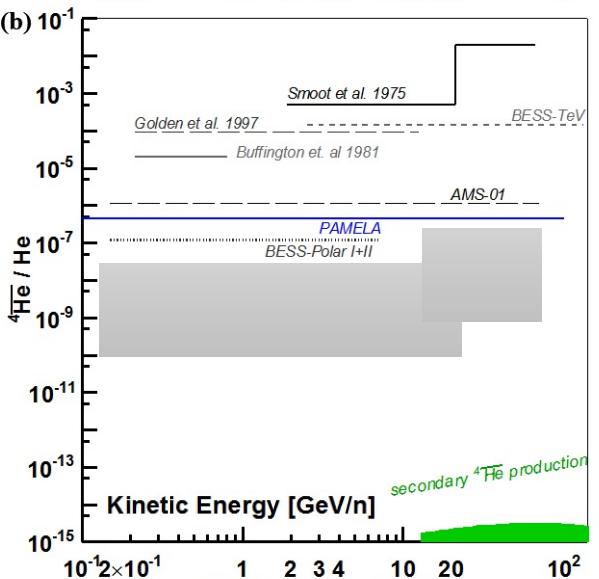
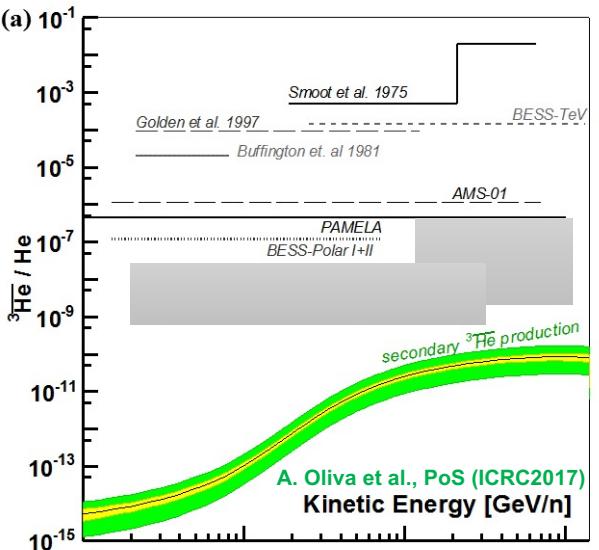
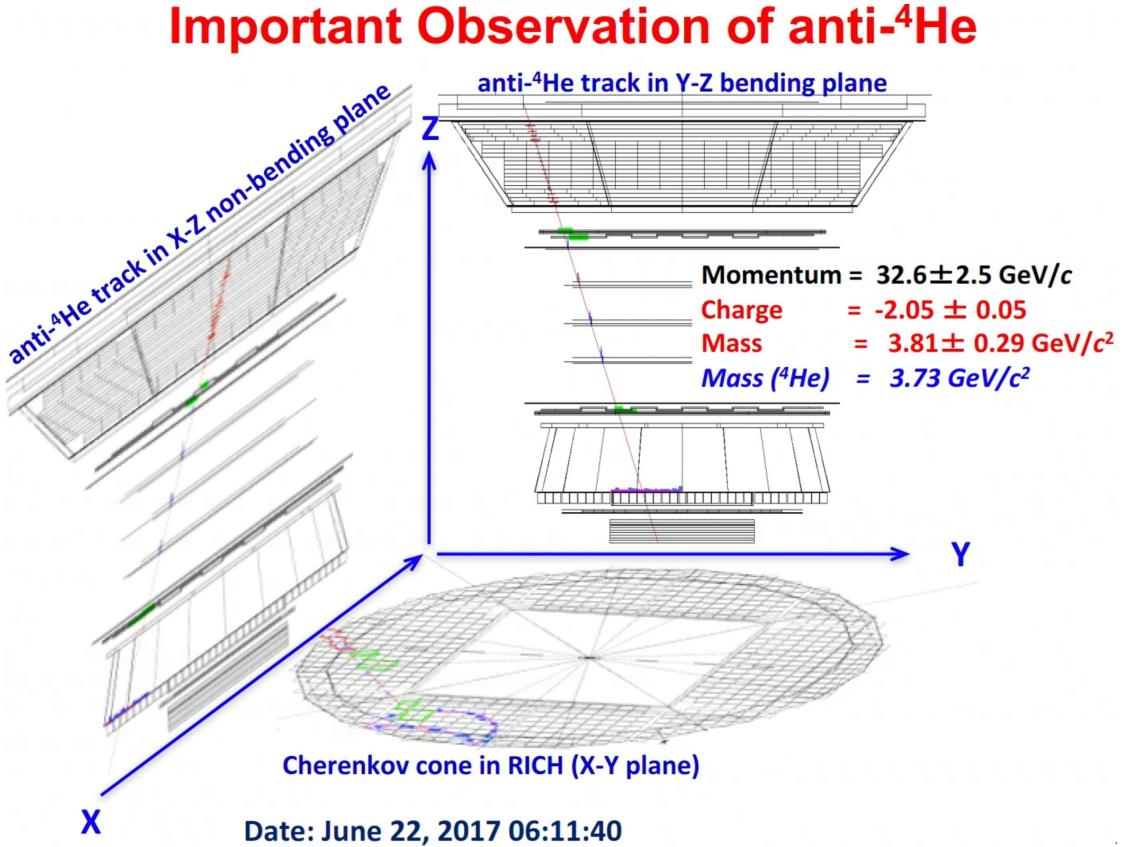
The best place to operate a superconducting magnet is Earth-Sun L2, like James Webb Telescope



AMS-02 state-of-the-art results

AMS-02 has observed few ${}^3\text{He}/{}^4\text{He}$ antinuclei candidates (about $1/10^8$ He events), a measurement difficult to frame in the standard model of cosmic rays. Explanations invoking secondary production fail to motivate the relative abundance of claimed anti- ${}^3\text{He}/{}^4\text{He}$

S.Ting, Latest Results from the AMS Experiment on the International Space Station, CERN 2018



R. Iuppà - Future searches
in cosmic-rays with
magnetic spectrometers

February
27, 2022

28

