ASAPP 2023 - Advances in Space AstroParticle Physics: frontier technologies for particle measurements in space

ALADinO:
Antimatter Large Acceptance Detector in Orbit

ASI Uni

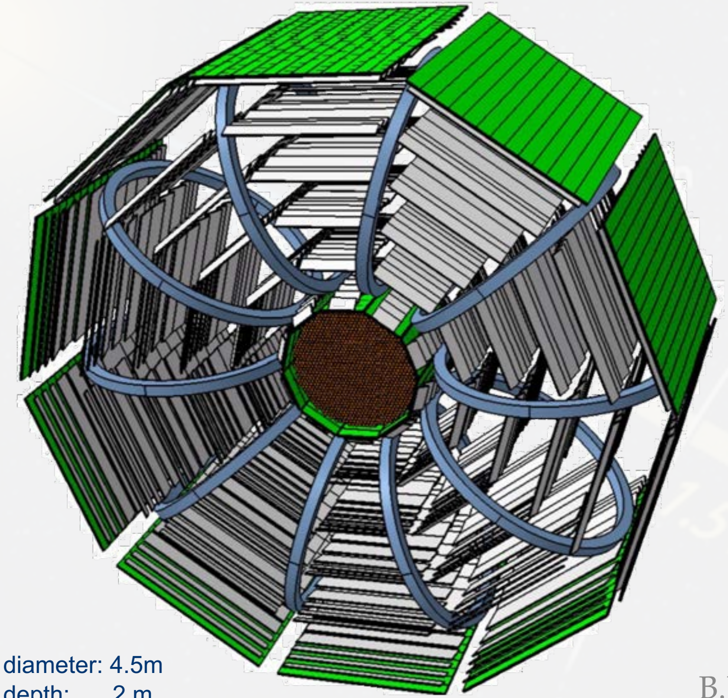
B. Bertucci
for the ALADInO collaboration

A.D. 1308 unipg
DIPARTIMENTO DI FISICA E GEOLOGIA
DIPARTIMENTO DI ECCELLENZA MUR 2023/2027

INFN PERUGIA

ALADInO

Lightweight Magnetic Spectrometer designed to achieve MDR > 20 TV over an acceptance > 10 m^2sr to be operated in Earth-Sun L2



diameter: 4.5m
depth: 2 m

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

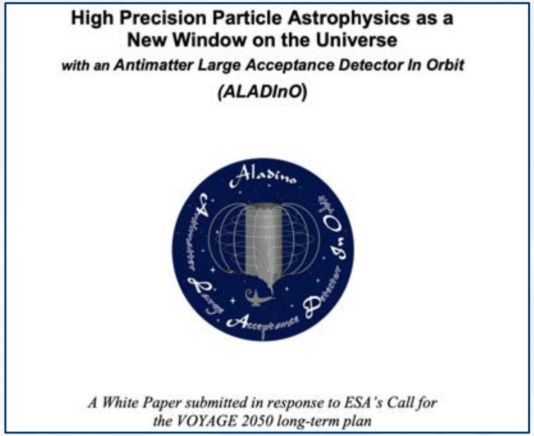
Onboard calorimeter energy scale cross-calibration with magnetic spectrometer

- electron and positron spectra up to 20 TeV

- nuclei spectra up to PeV

ALADInO

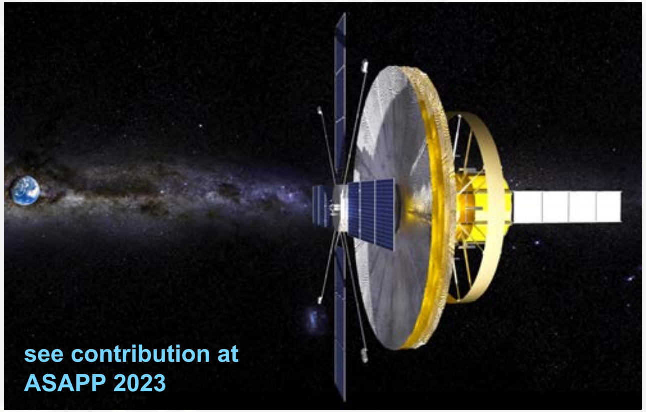
Presented for the first time in 2016 (Bertucci B. et al, ESA call for ideas).
ESA report: "[...] *Scientific breakthroughs are expected in case of discoveries.* [...] *In the case of antimatter search, the ALADINO investigation will be state of the art, while for dark matter and cosmic radiation search, will be the only one to investigate the particle channel, and is therefore complementary and synergetic to other efforts."*


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

Submitted in 2019 to the ESA call for VOYAGE2050 (Battiston R. et al,)

Battiston, R.; Bertucci, B.; Experimental Astronomy 2021.
Adriani, O. *et al.,* Instruments 2022, 6(2),19.



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

see S.Schael talk @ this conference

The quest for antimatter in Space

Direct searches in space, to quantify the imbalance of matter and antimatter in the Universe and explore DM signals

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

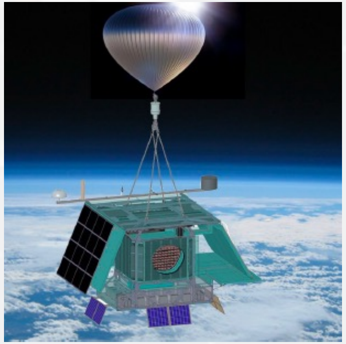
Operations expected until 2030.

J.Casaus, G.Ambrosi @ this conference

GAPS

~ 3.6 tons

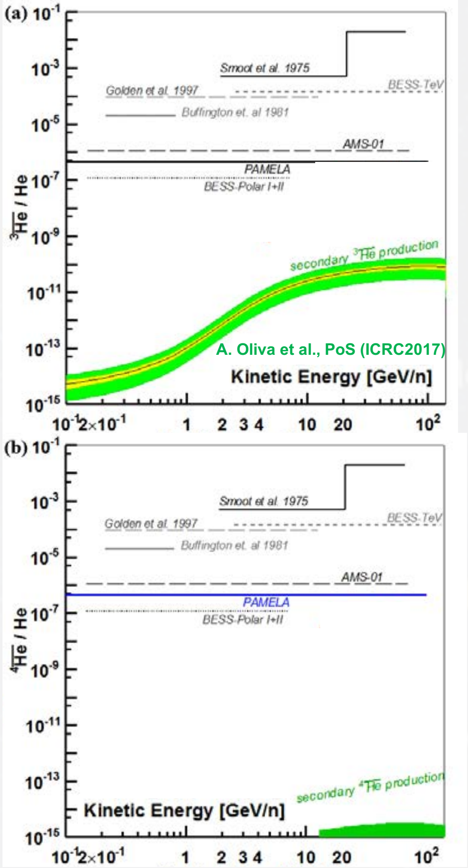
3 balloon flights
from Antartica (planned)



P.Von Doetnichem @ this conference

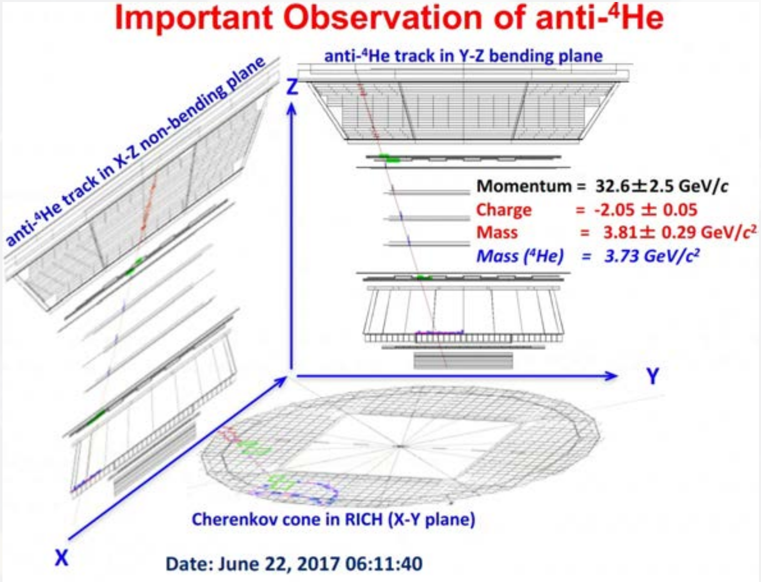
+ new approaches as ADHD (F.Nozzoli @ this conference)

The quest for antimatter in Space

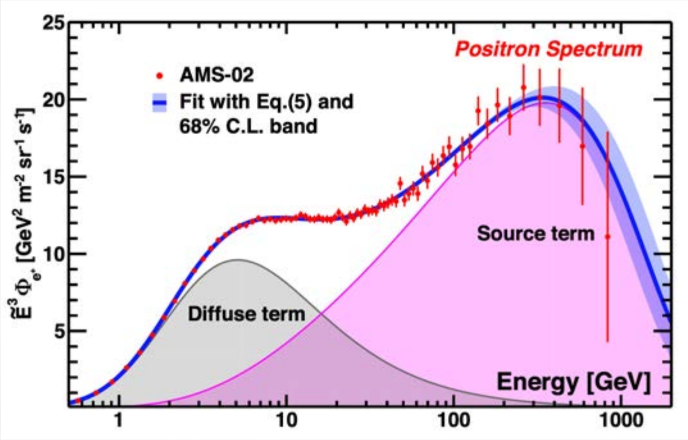


AMS-02 has observed few ^{3}He/^{4}He antinuclei candidates (about 1/10^8 He events), a measurement difficult to frame in the standard model of cosmic rays. Explanations invoking secondary production fail to motivate the relative abundance of claimed anti-^{3}He/^{4}He

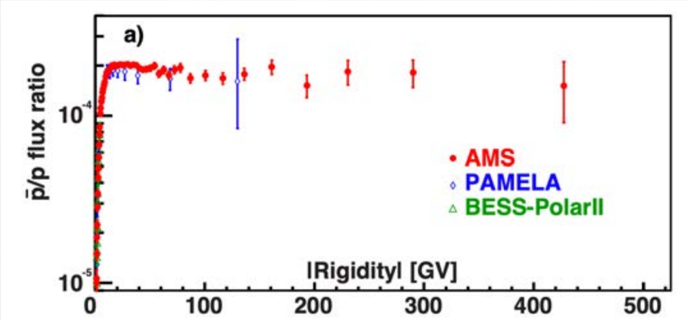
S.Ting, Latest Results from the AMS Experiment on the International Space Station, CERN 2018



AMS-02 state-of-the-art results



AMS collaboration, Phys. Rep. 894 (2021) 1-116



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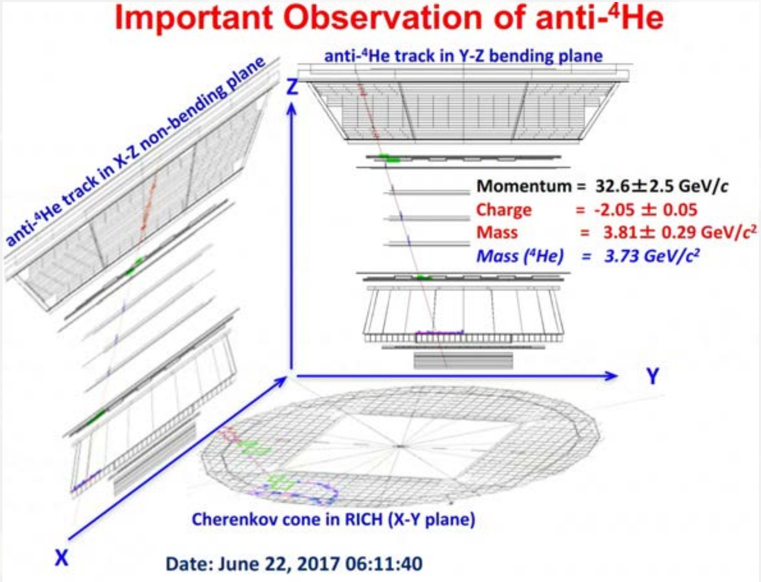
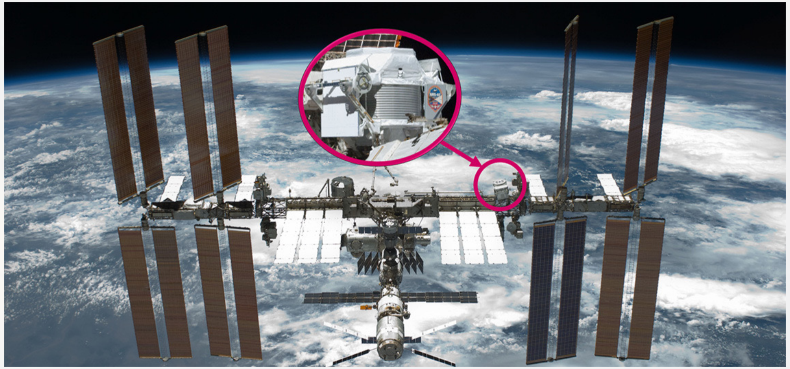


See J.Casaus @ this conference

Breaking the frontiers



AMS-02 / 12 years on ISS since 2011

220+ 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

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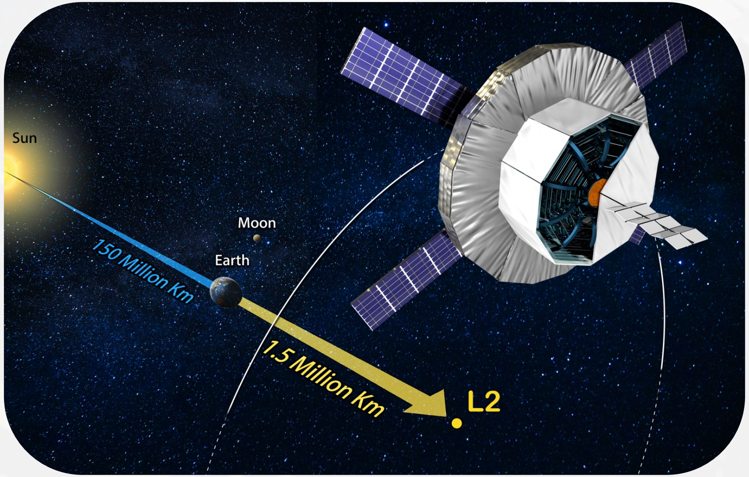
ALADinO...

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



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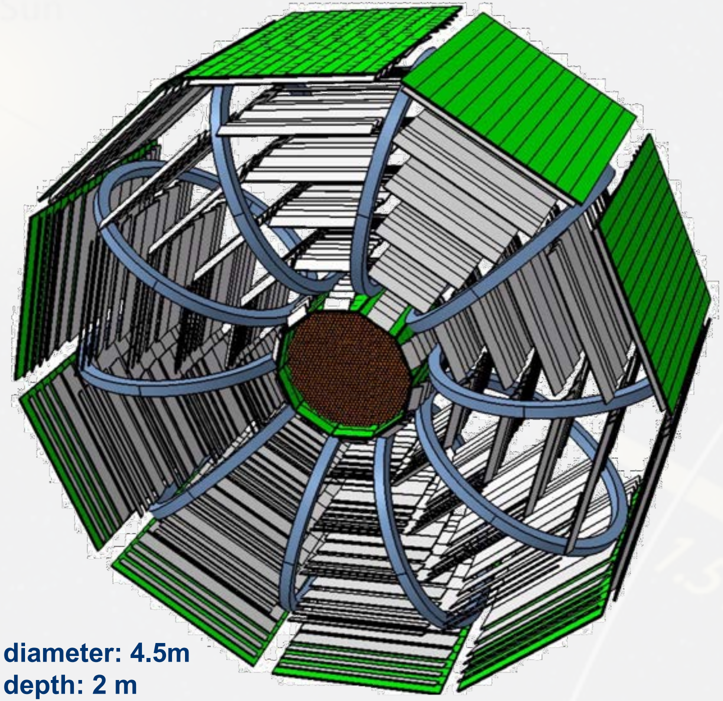

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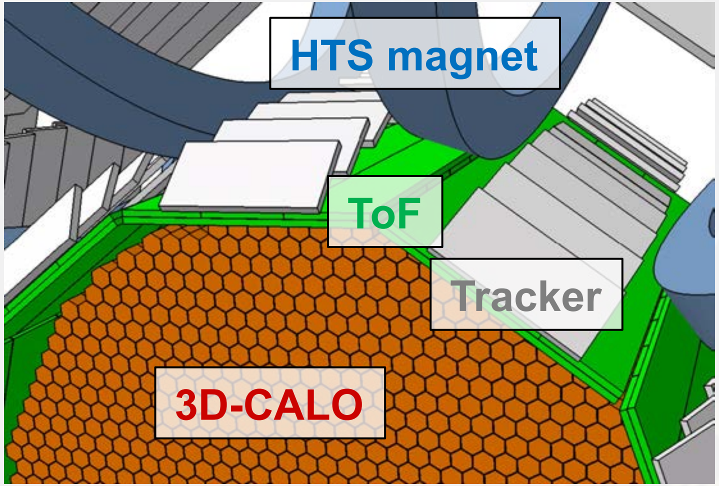


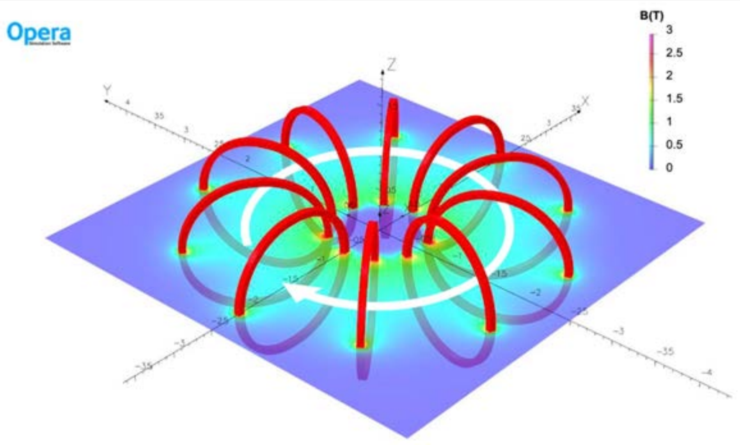
High Temperature Superconducting (HTS) magnet
10 coils in toroidal configuration

Tracker
Double-sided Si-μstrip 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_I
9 m^2 sr (lateral surface)

Superconducting Magnet

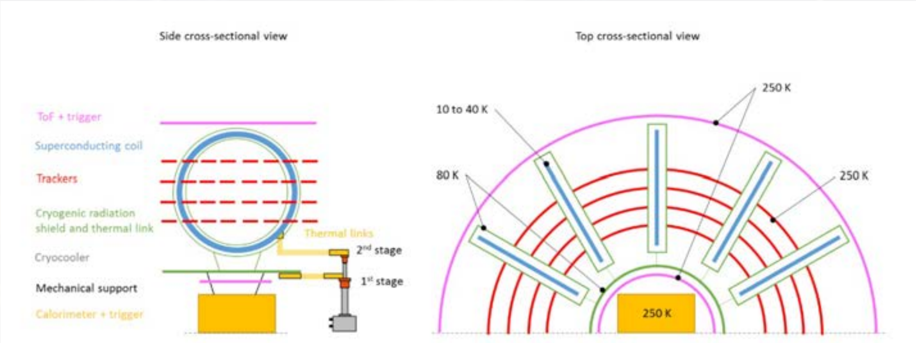


HTS magnet	
Number of coils	10
Current / coil	400 10^3 A
Operating current	~ 250 A
Magnetic flux density	average: 0.8 T max: 3T
Bending power	1.1 Tm
Cold mass	1.2 t

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

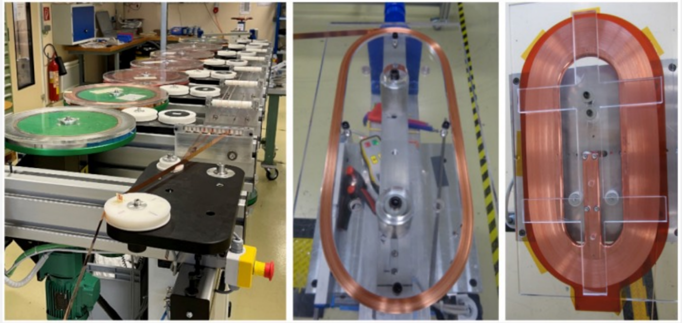
Cryocoolers used for active cryogenic instead of large area radiators
- MLI umbrella-like sunshield to intercept the radiation heat flux from Sun
- Cryogenics MLI + 250 K thermal shield + 80K thermal shield around coils to maintain operating temperature



Superconducting Magnet

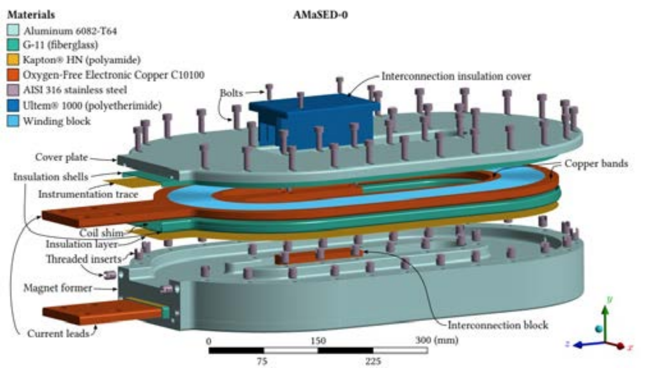
H. Reymond, M. Dam, H. Felice et al, JACoW ICALEPCS2021 (2022) 473-477

Winding of the HDMS coils (CERN)

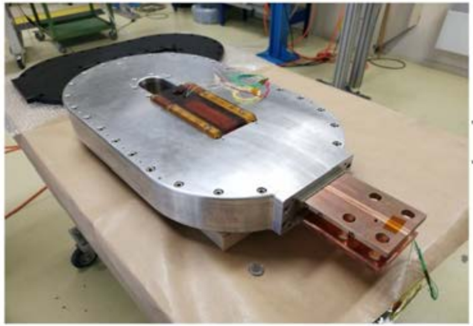


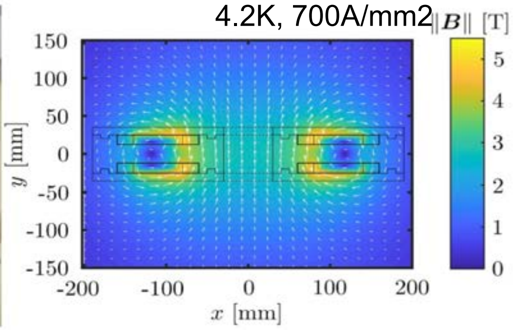
M. Dam, W.J.. Burger et al, PoS(ICRC2021) 498

Mechanical structure of the HDMS coil prototype



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





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
- mid-size soldered metal insulation coils
- aluminum mechanical structure

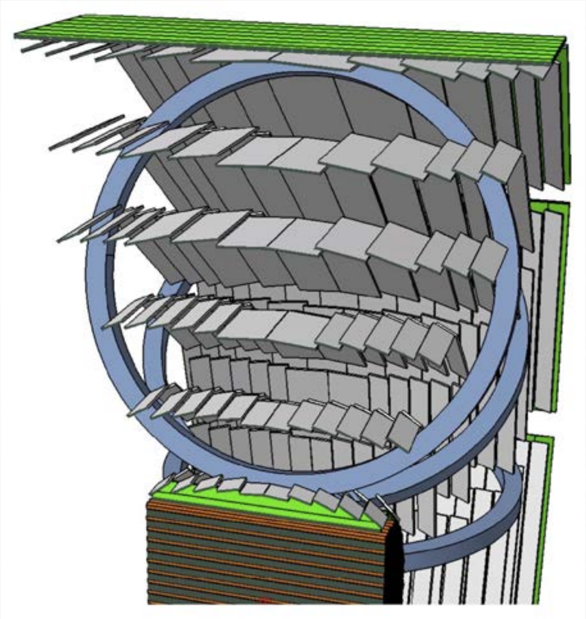
Based on current heritage:

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

More details in the contribution by R. Iuppa @ this conference

Tracker

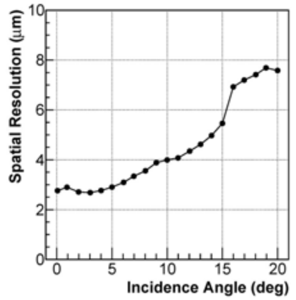
Baseline design on high TRL solution
Six layers of precision tracking system, ~70m^2 active area
Baseline design:
- double-sided Si-μstrips, implant pitch 25μm, readout pitch 100μm (bending)
- 2-7 sensors (95x95mm^2) arranged along "ladders", max length ~70cm
- ladders arranged in adaptive geometry over 6 planes in 10 sectors



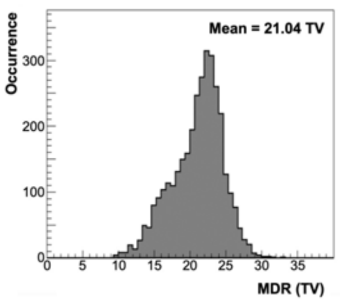
1 ALADInO Tracker sector ⟺ Full AMS-02 Tracker (channels, area, ...)

AMS-02 ladder made of 12 double-sided 40 × 70 mm^2 silicon microstrip sensors

Resolution of PAMELA tracker (O.Adriani et al.)



Expected ALADInO MDR in baseline configuration



Target performances: ~3 μm coo. resolution over "long" ladders
- achieved by PAMELA on "short" ladders, ~5-10 μm by AMS.02 on similar "long" ladders
- FEE with dynamic range up to Oxygen with no saturation (as in AMS-02)

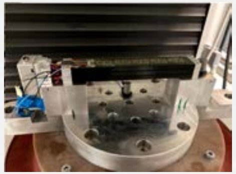
With specific R&D, leveraging on PAMELA and AMS-02, large likelihood to achieve target performances

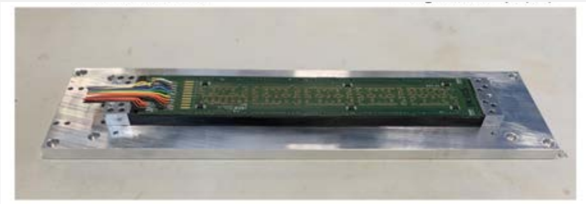
Tracker

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
- ~25µm 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

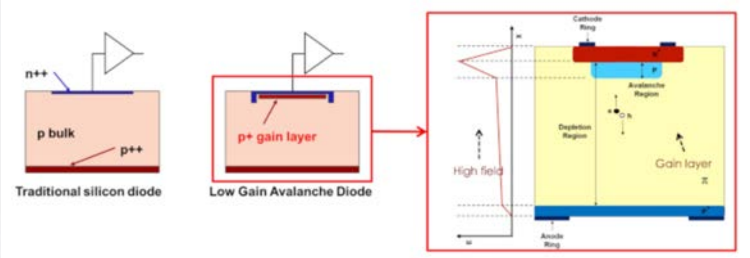


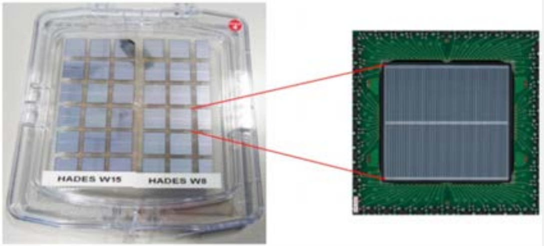


O.Adriani
@ this conference

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, µstrip layout may be used in spacd
- R&D required for readout and power consumption mitigation

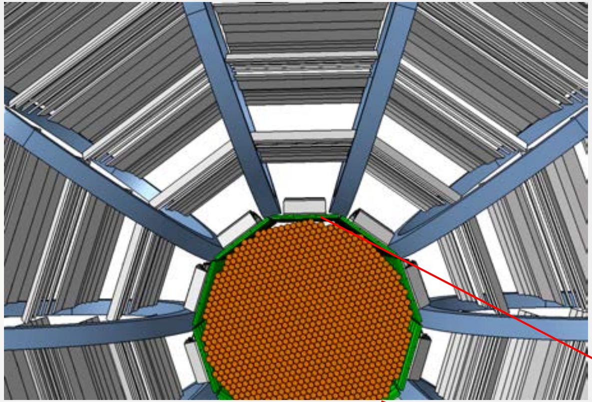


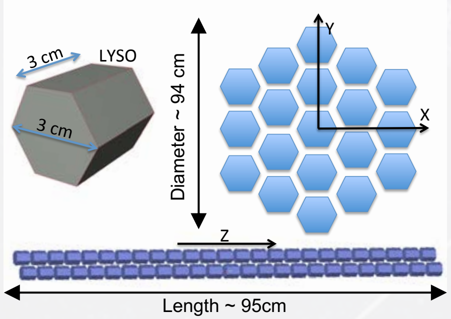


W. Krüger,
LGAD technologies for HADES, contribution to VCI 2022

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

Calorimeter



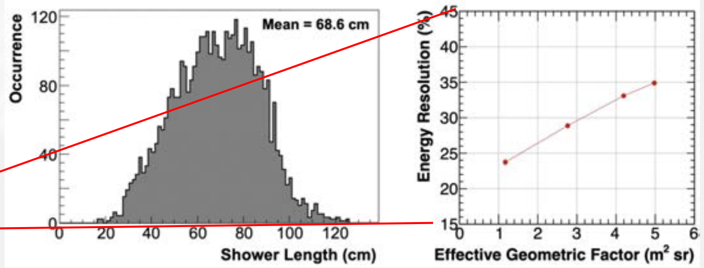


Based on the "CaloCube" paradigm (INFN, O. Adriani et al.) for particle calorimetry

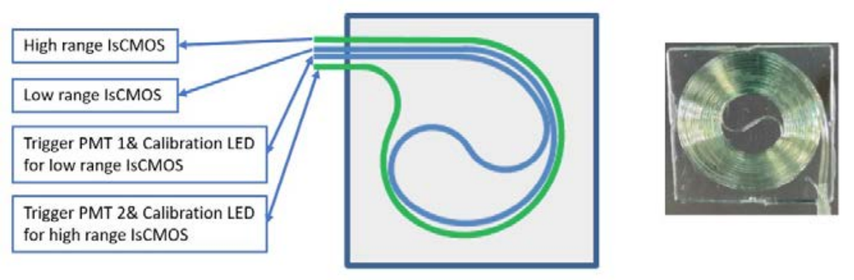
- **nearly isotropic response** to particles from all directions
  maximize detector effective acceptance;
- **3D shower topology imaging**
  e/p separation, energy resolution and energy scale
- **heritage** from developments for application in HERD
  high TRL and space qualification expected

~ 16'000 LYSO crystals (~2 tons)
61 X_0, 3.5 λ_I
9 m^2sr (lateral surface)

30% energy resolution (hadrons) @ 3 m^2sr



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



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

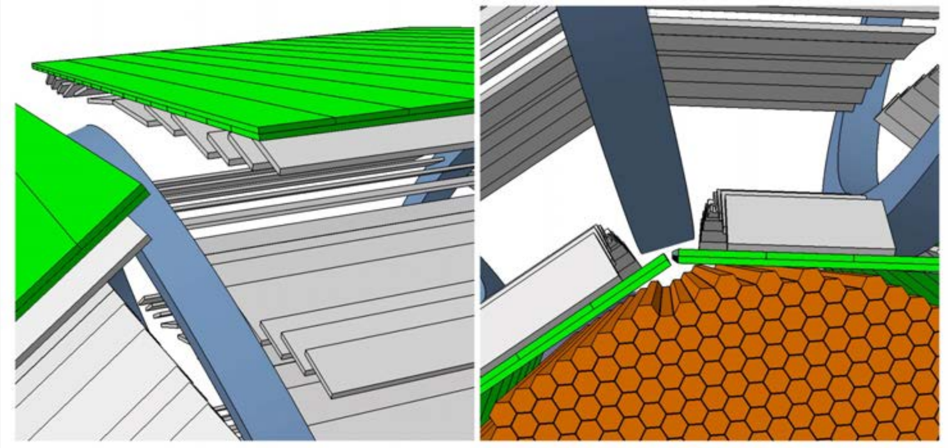
Energy scale calibration with light double readout system

Total power expected 200 W

see P.Betti & L.Pacini talks @ this conf.

Time Of Flight

Outer plane **Inner plane**

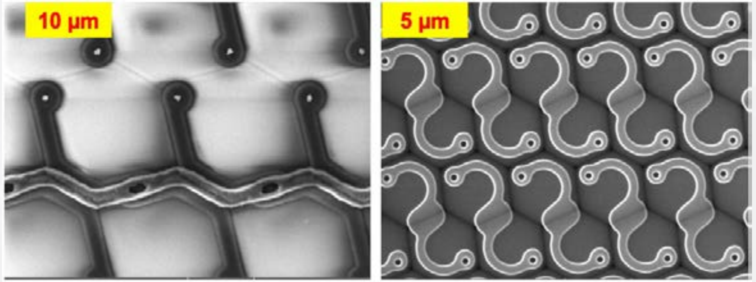


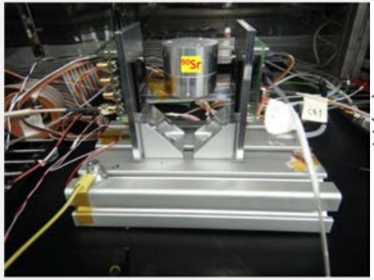
Based on established PAMELA and AMS-02 ToF systems

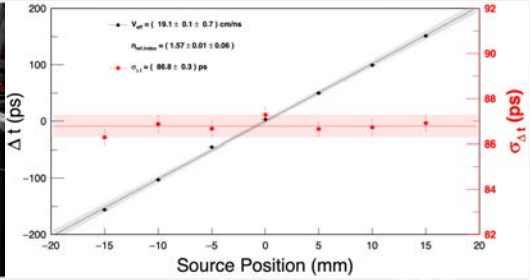
- **Sci-bars** up to 190 x 10 cm, 0.5 - 0.8 cm thick
- Inner and outer ToF, 1.45 m distance
- hodoscopic x-y measurement
- **SiPM** replacement to PMT for light readout

Small μcell SiPM readout for large dynamic range (1<Z<26)

UHD SiPM produced at FBK (G. Paternoster. 13th Trento workshop)







Target resolutions below 100 ps for Dbar sensitivity at 3-4 GeV/n

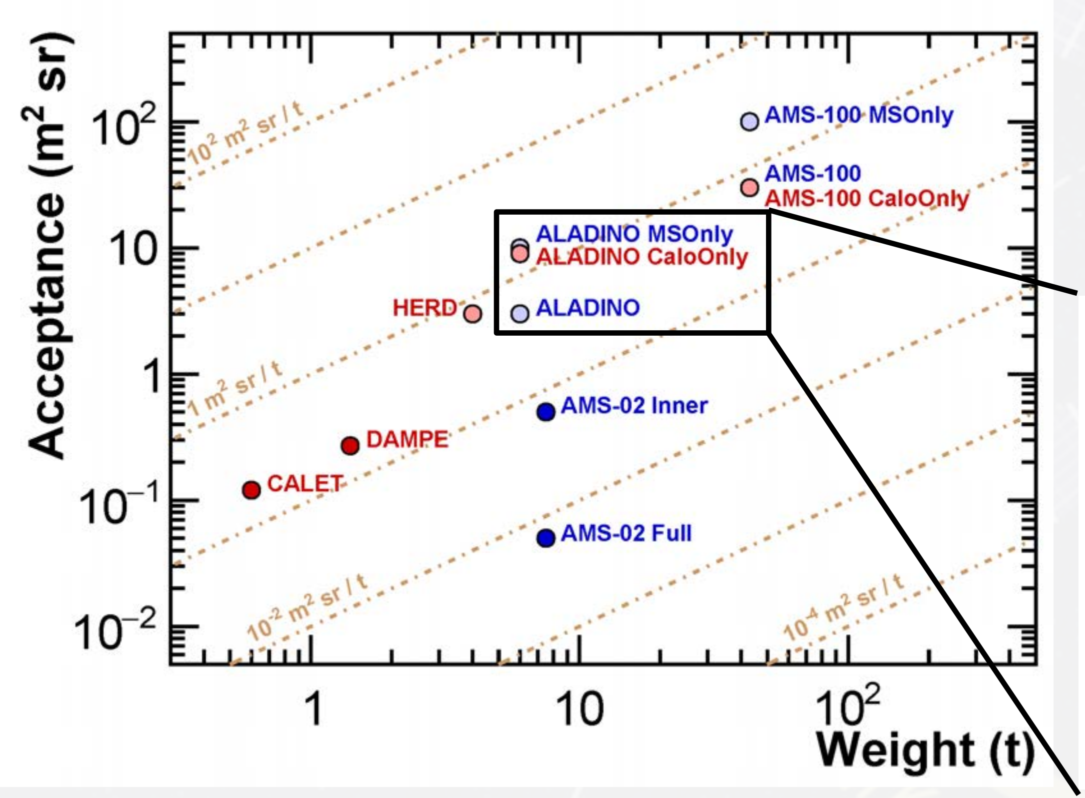
ToF demonstrator for space applications (AMS-100) feature Δt~40ps over O(10cm) Sci-bars

C. Chung, Instruments 2022, 6(1), 14

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

Breaking the frontiers

Large acceptance missions in Space

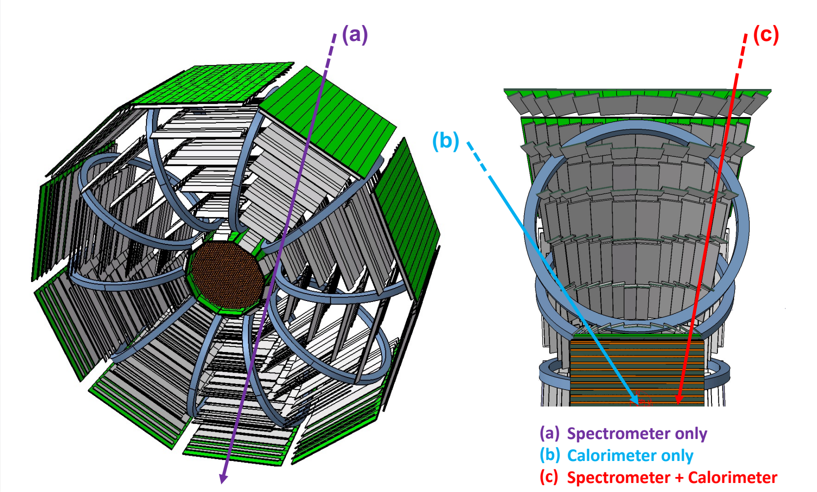


Frontiers in direct CR physics

CALORIMETERS → Composition ← SPECTROMETERS

CALORIMETERS → High-Energies ← SPECTROMETERS

Antimatter ← SPECTROMETERS



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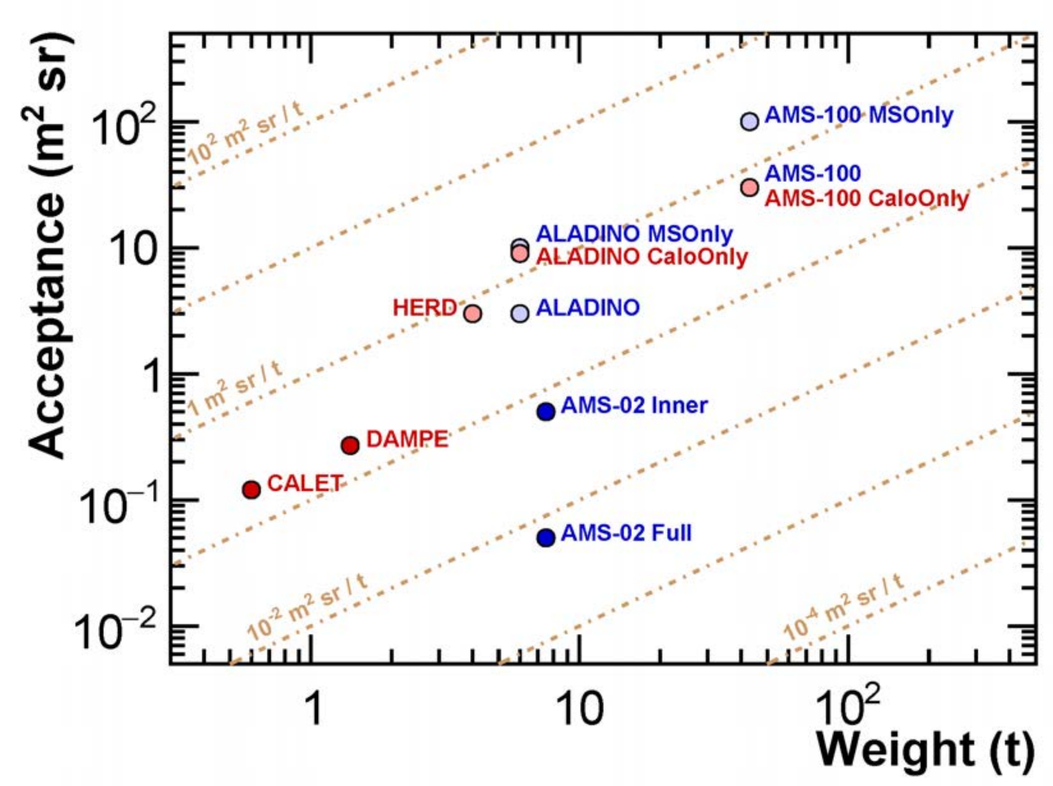
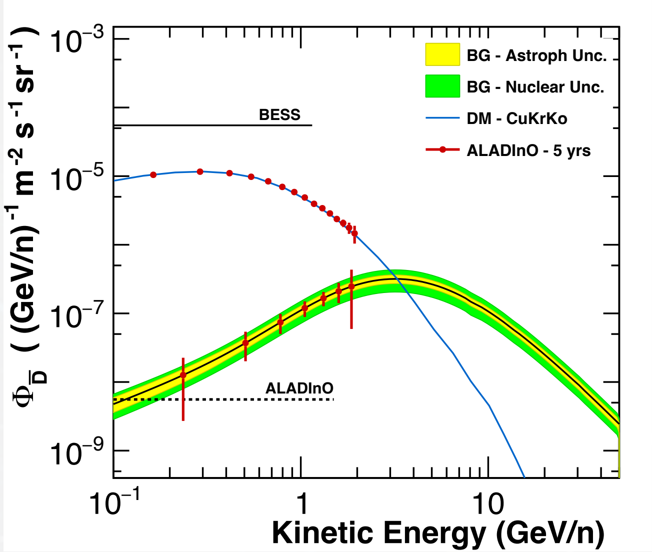


	ALADInO	AMS-02
Location	Earth-Sun L2	ISS
Operations	mid 2040s > 5 yrs operations	2011 - 2030+ fully nominal
Acceptance	a) MS only: >10m^{2}sr b) calo only: 9m^{2}sr c) calo+MS: 3m^{2}sr	Full: 0.05m^{2}sr Inner:0.5m^{2}sr
Mag. field (ave)	0.8 T, supercond	0.15 T, permanent
MDR	> 20 TV	2 TV (Z=1) > 3.2 TV (Z>1)
Calorimeter depth	61 X_0 / 3.5 λ_I	17 X_0 / 0.6 λ_I
Energy resolution	2% ($e^{+/-}$) 25% (h @ 1m^{2}sr) 35% (h @ 5m^{2}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)



Antideuteron

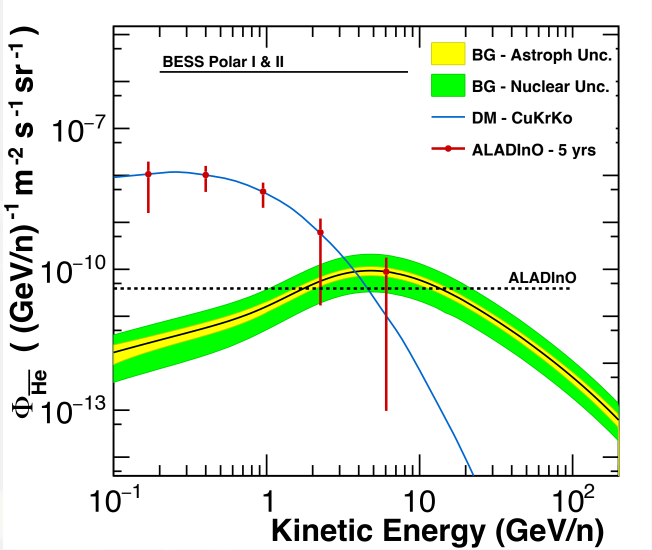
precise measurement of the astrophysical flux and possible unambiguous detection of primary anti-D
Higher energies limited by velocity resolution

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

Antihelium

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



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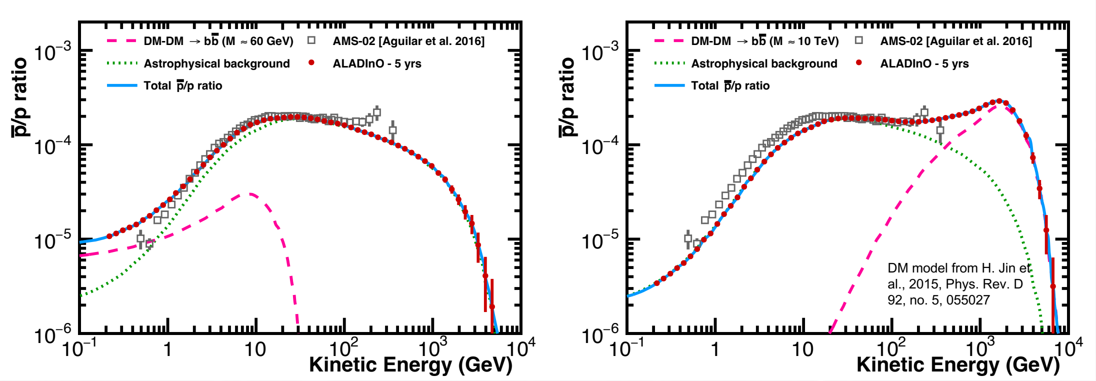
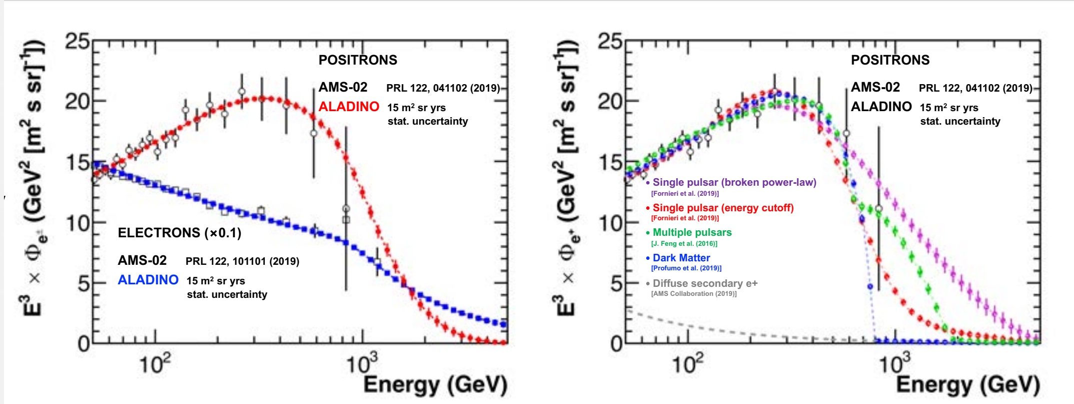
Light Antimatter

Extend antiproton and positron measurements in the unexplored TV energy frontier



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

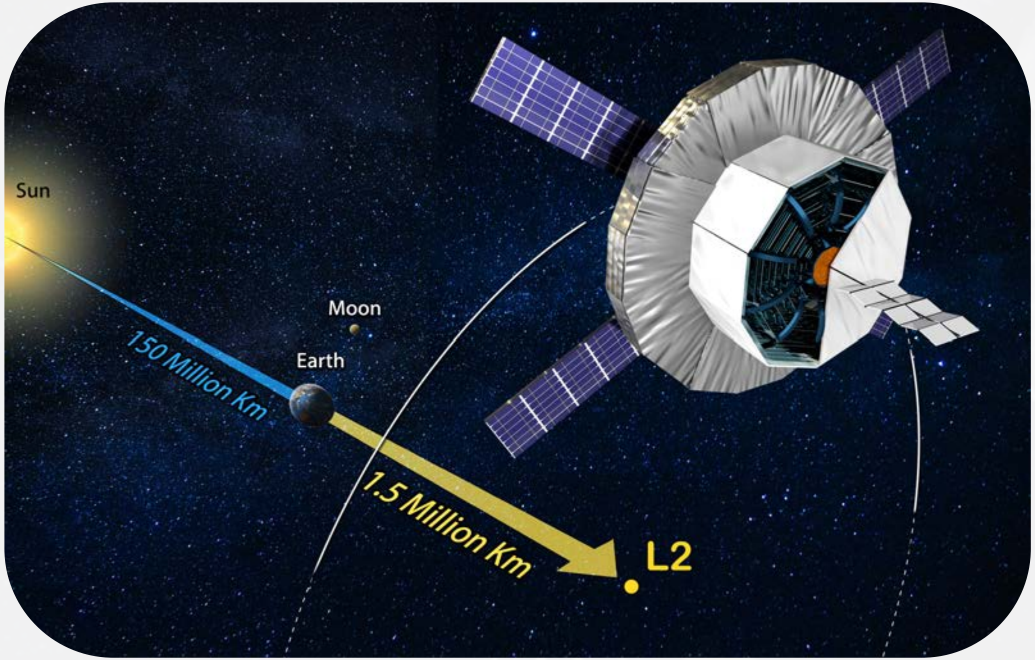
Explore the antiproton flux beyond its flattening and profile the antiproton production break



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

ALADInO – pathway to science

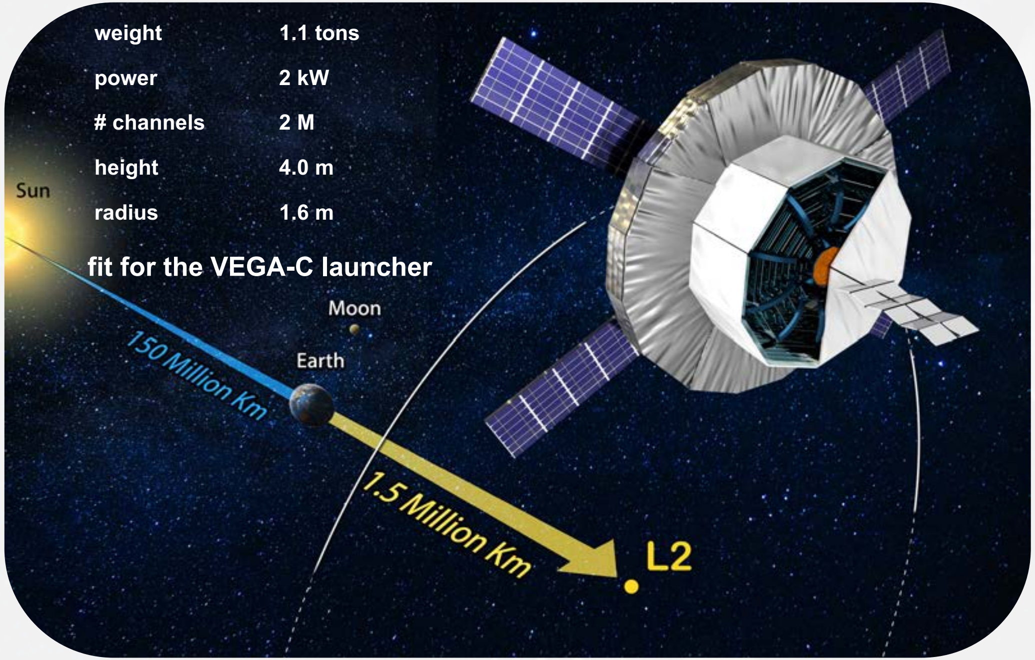


High Temperature Superconducting Magnetic Spectrometer in space
Acceptance > 10 m^2sr
Antimatter measurements up to 10 TeV
Established technologies for detection of particles in space

5-year operations in L2
Payload Weight < 6.5 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



High Temperature Superconducting Magnetic Spectrometer in space
Acceptance > 10 m^2sr
Antimatter measurements up to 10 TeV
Established technologies for detection of particles in space

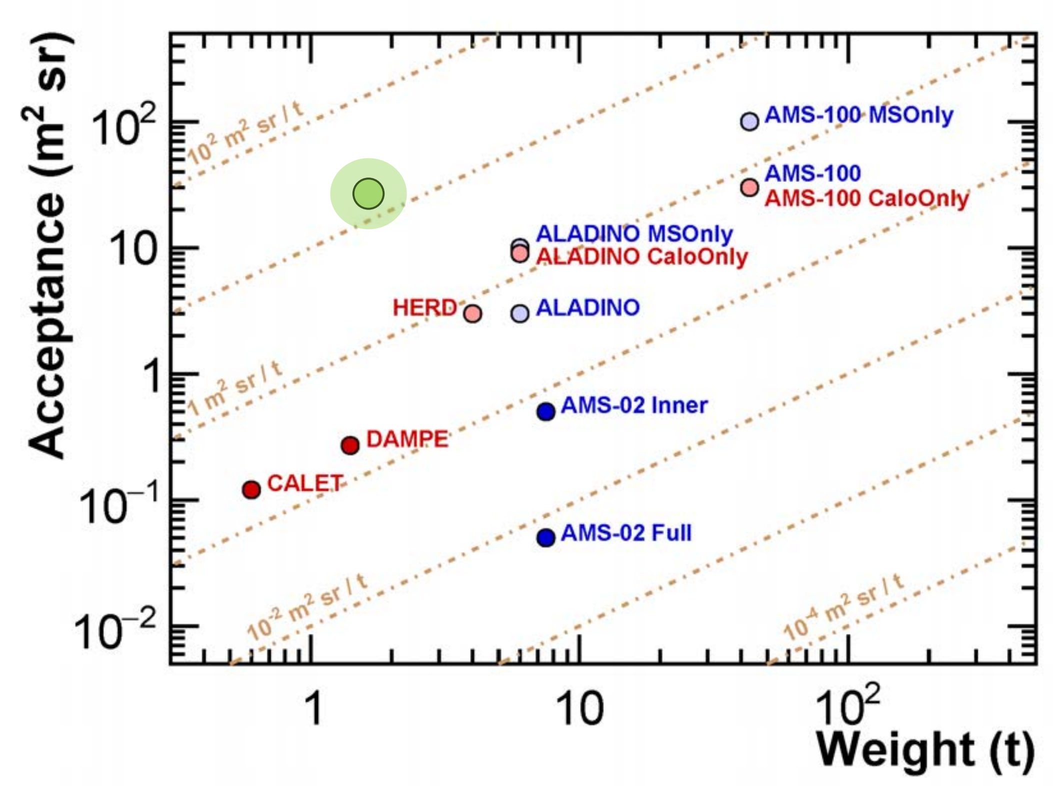
5-year operations in L2
Payload Weight < 6.5 t
Payload power consumption 3 kW
Compact volume (fits Ariane launcher)

Roadmap for mission opportunity
mid 2030s: ALADInO Pathfinder
mid 2040s: Operations in L2
by 2050: Unprecedented results

LAMP: Light Aladino-like Magnetic sPectrometer

ALADInO – pathfinder: LAMP

Large acceptance missions in Space



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.

More than a factor 30 is gained over AMS-02

LAMP
~ 2.0 tons
L2 or LEO
Launch by 2033
10 years of operations

LAMP: technology roadmap

Tracker: *silicon strip detectors*, already space qualified (AMS, PAMELA, Fermi, AGILE, DAMPE...); *pixel detectors*, space qualification ongoing (ASI - CSES2), *LGAD μstrips*, space qualification starting (ASI-INFN)

Superconducting Magnet: *YBCO magnets* developed at CERN for LHC upgrade and future accelerators. Long standing collaboration between ASI, INFN and CERN. *Space qualification needed*.

Low-power cryogenics: *very efficient Pulsed Heat Pipes* developed through the H2020 SR2S program (CEA Saclay). *Space qualification needed*

Electronics: extensive experience and space qualification of *CERN experiments (micro) electronics* up to O(10^6) channels : AMS, PAMELA, Fermi, AGILE, DAMPE...

Thermal shield: passive thermal shield to be derived from, e.g., Planck, Gaia

Launch in a decade, if large sectors of high-technology industries are involved in the project. The project would be the first to launch and operate in space HTS magnets → unprecedented challenge for the entire system of space-companies in Italy

2023	Technology assessment
2026	Balloon flight (validation of the HTS technology)
2028	LAMP construction
2033	**LAMP launch**

ALADInO scientific collaboration

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

AMS-01
AMS-02
Pamela
FERMI
DAMPE
Arina
Agile
HEPD-1
HEPD-2
....

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

Thanks for your attention !

Operations in space

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**

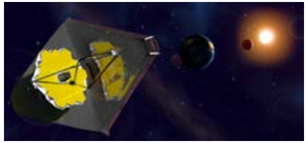
Mass budget	
Calorimeter	2.3 t
Magnet and Cryogenics	2.0 t
ToF + Si-tracker	1.5 t
Electronics and power	0.5 t
Total	**< 6.5 t**

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

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

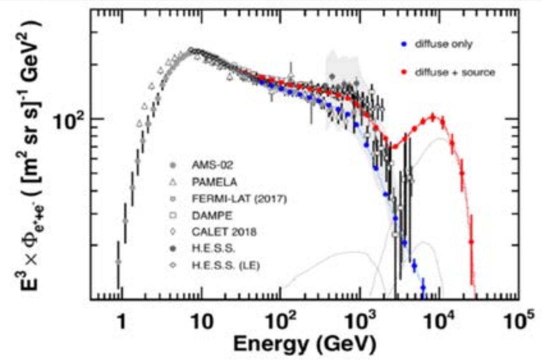
Design optimized in terms of layout, weight, dimensions, power consumption, and expected data throughput to fit in the limits set for transport and operation in Earth–Sun Lagrange Point L2 using a space vector that is already accessible nowadays

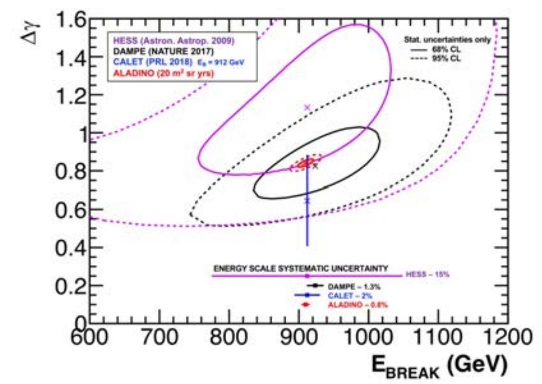
Arianespace's Ariane 5 rocket with NASA's James Webb Space Telescope onboard.



Electrons and nuclei

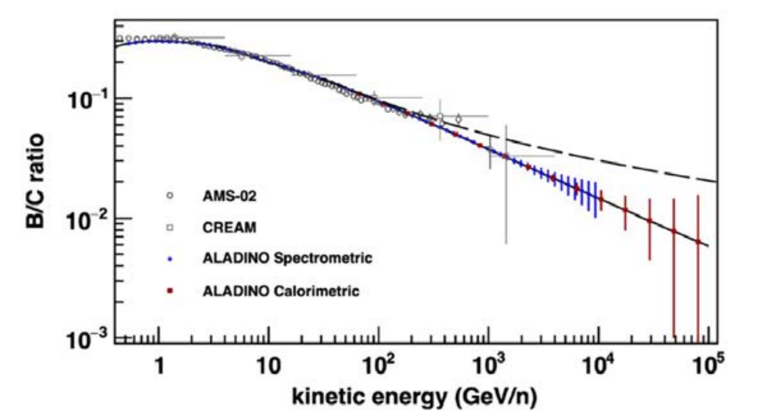
Provide complementary information on the (e^++e^-) and nuclei flux to planned calorimetric experiments





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 **multimessenger** telescopes

Matter-Antimatter

A.D. 1308 unipg

INFN PERUGIA

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**.

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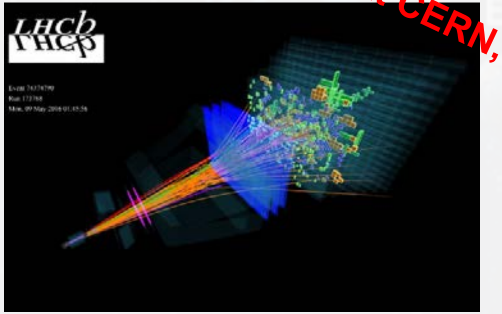
Open Access | Published: 30 January 2017
Measurement of matter–antimatter differences in beauty baryon decays
The LHCb collaboration

LHCb at CERN, 2017



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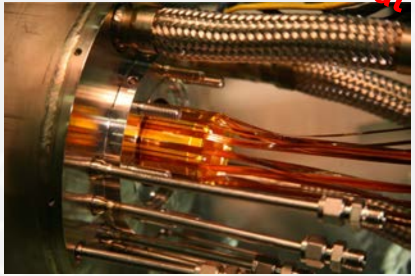
Characterization of the 1S–2S transition in antihydrogen
M. Ahmadi, B. X. R. Alves, ... J. S. Wurtele + Show authors

ALPHA at CERN, 2018



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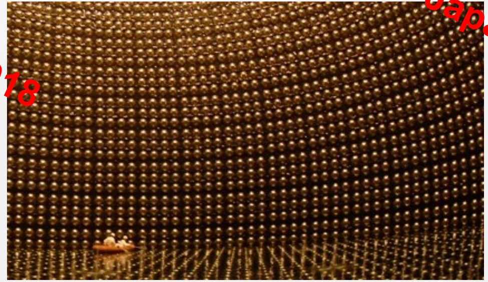
Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

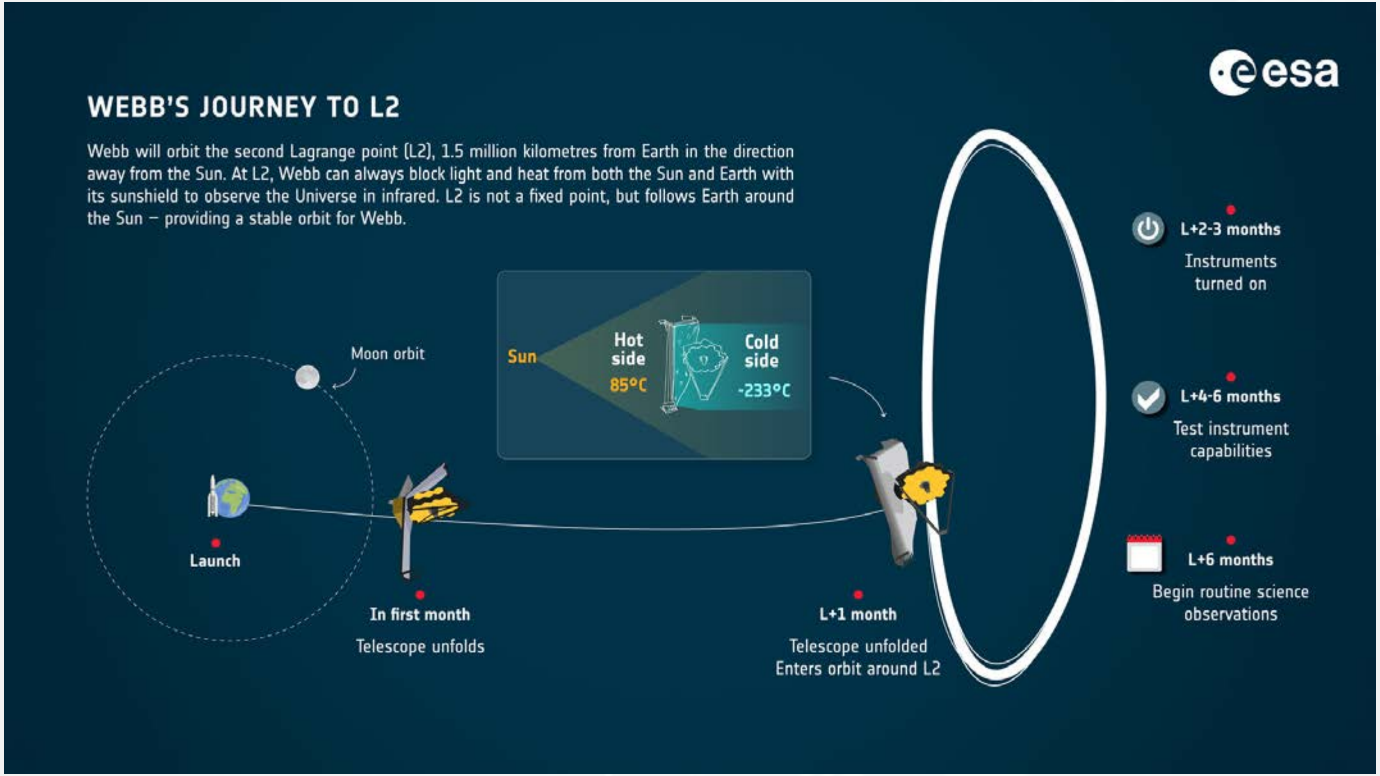
T2K in Japan, 2020



Direct searches for antimatter in space have the objective of **quantifying** the imbalance of matter and antimatter.

Credits: R. Iuppa

Operations in space



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