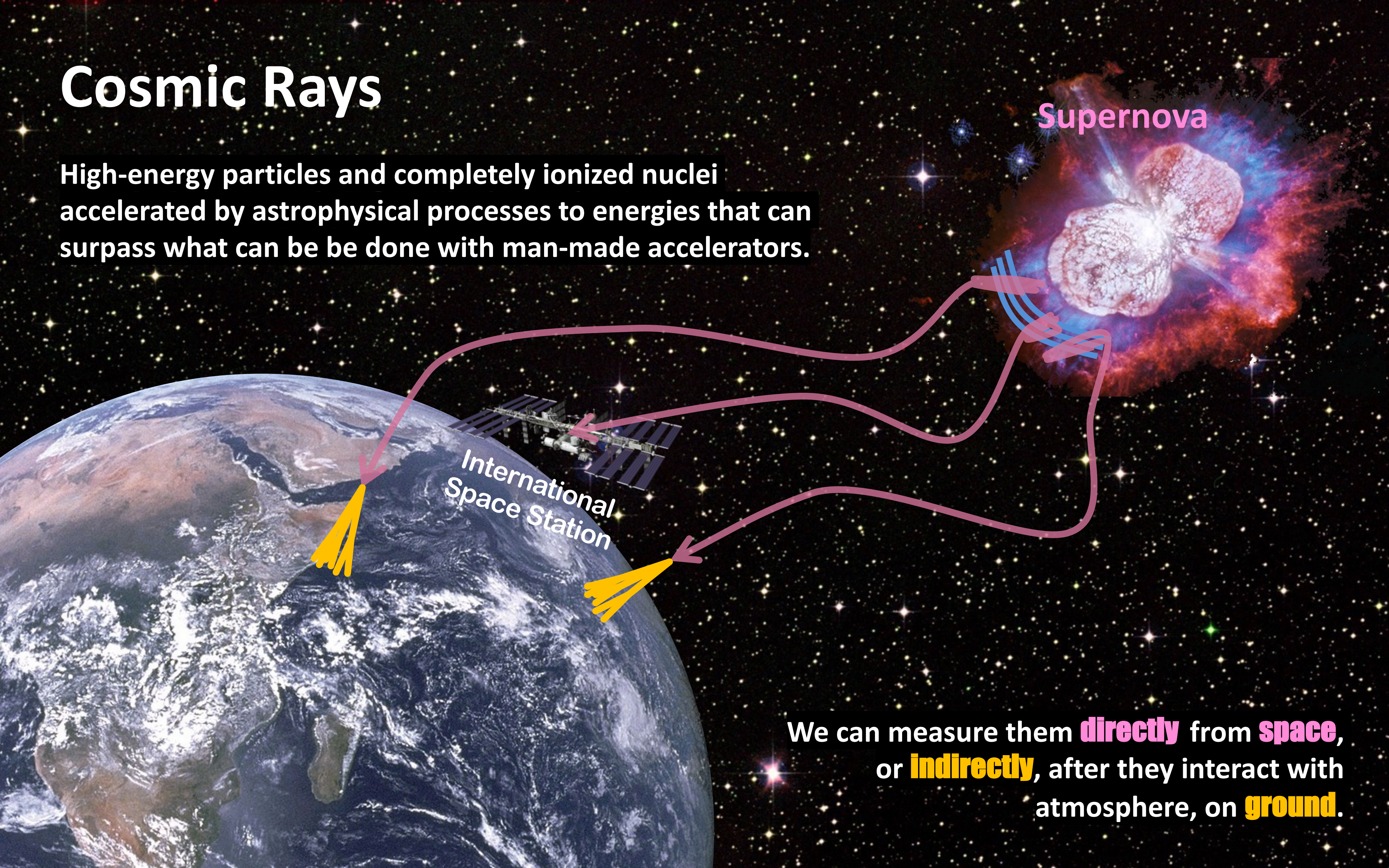
Search for Anti-matter in Cosmic Rays

13/01/2022

A. Oliva

Cosmic Rays

High-energy particles and completely ionized nuclei accelerated by astrophysical processes to energies that can surpass what can be be done with man-made accelerators.

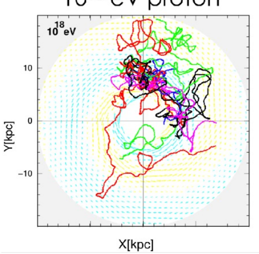


We can measure them **directly** from **space**, or **indirectly**, after they interact with atmosphere, on **ground**.

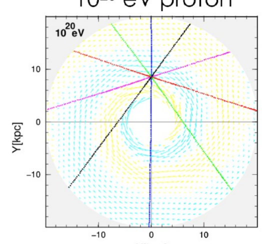
Cosmic Ray Spectrum

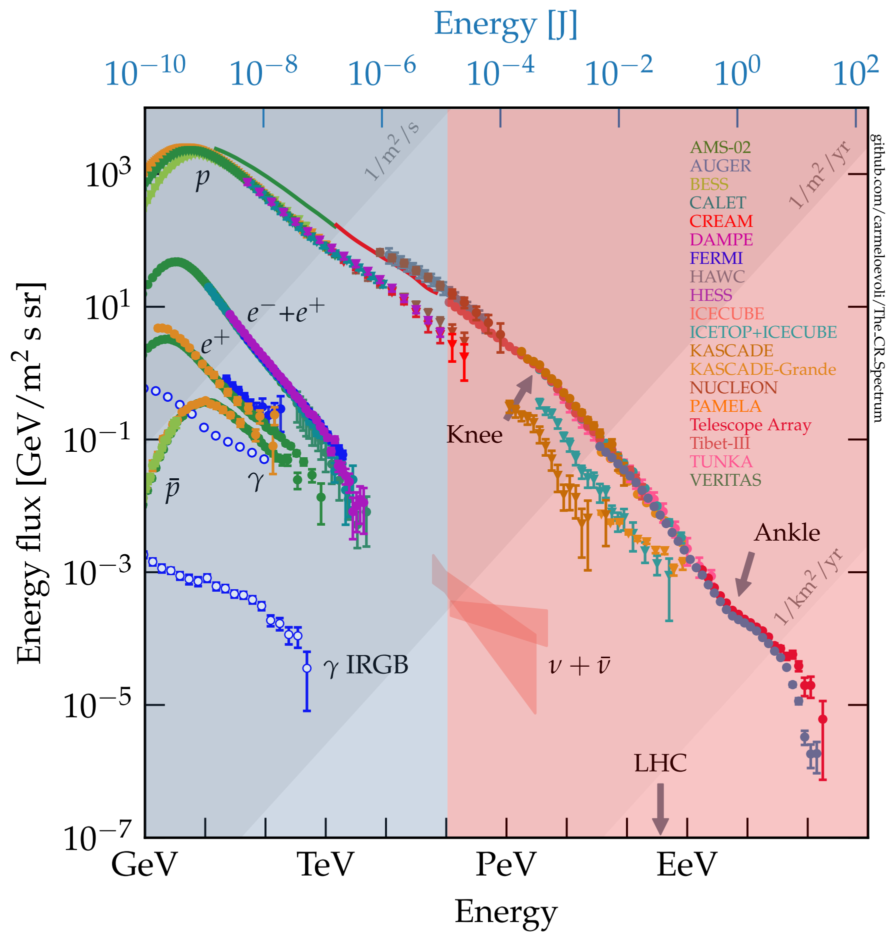
- Energetic particles and completely ionized nuclei from outer space.
- Many orders of magnitude in energy and flux
    - at low-E: *direct detection;*
    - at high-E: *Extensive Air Shower.*
- A power law several features
    - *knee & ankle (*→ different origin).
- At TeV, charged CRs are confined by the *galactic* magnetic field.

10^{18} eV proton

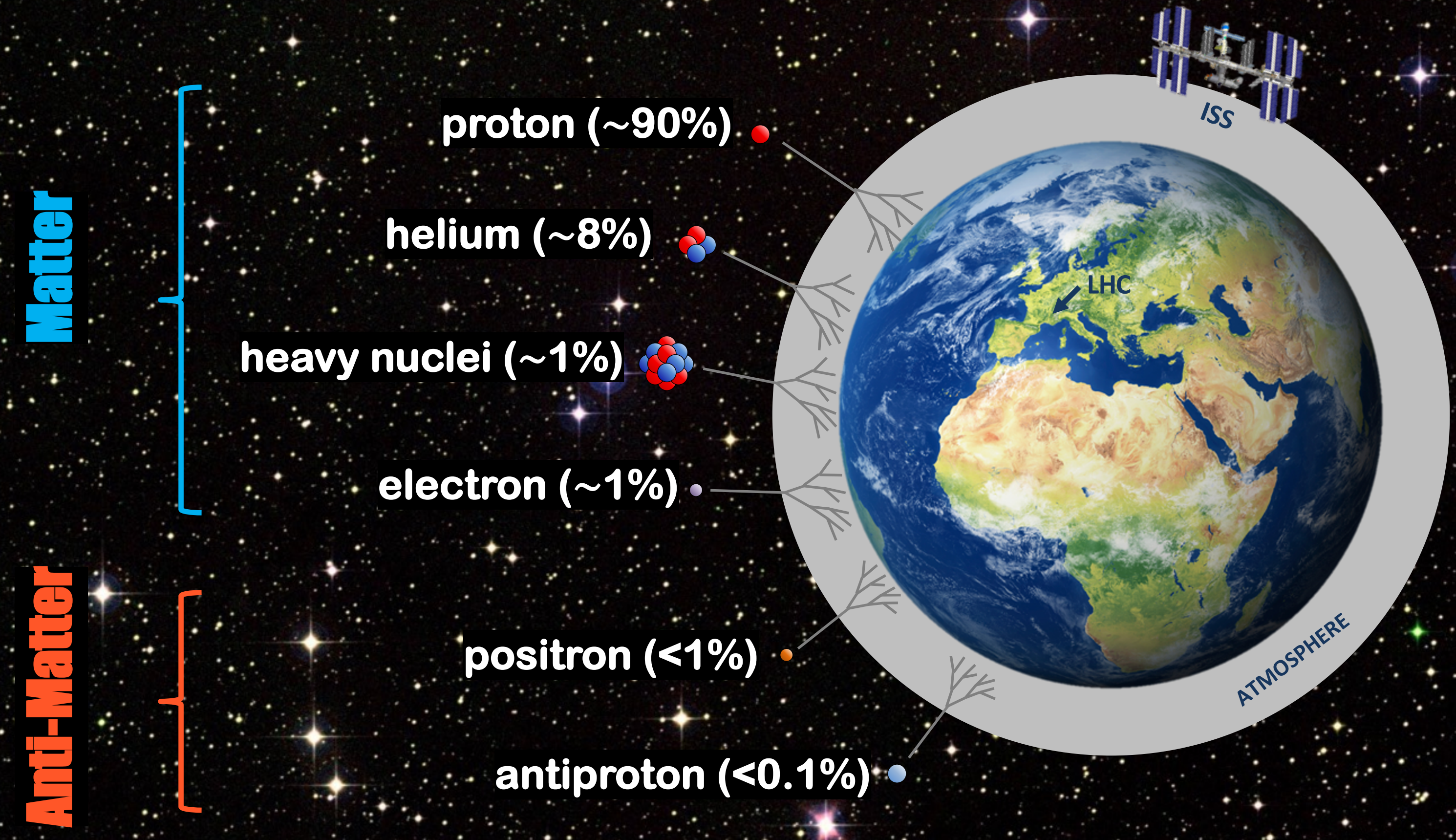


10^{20} eV proton

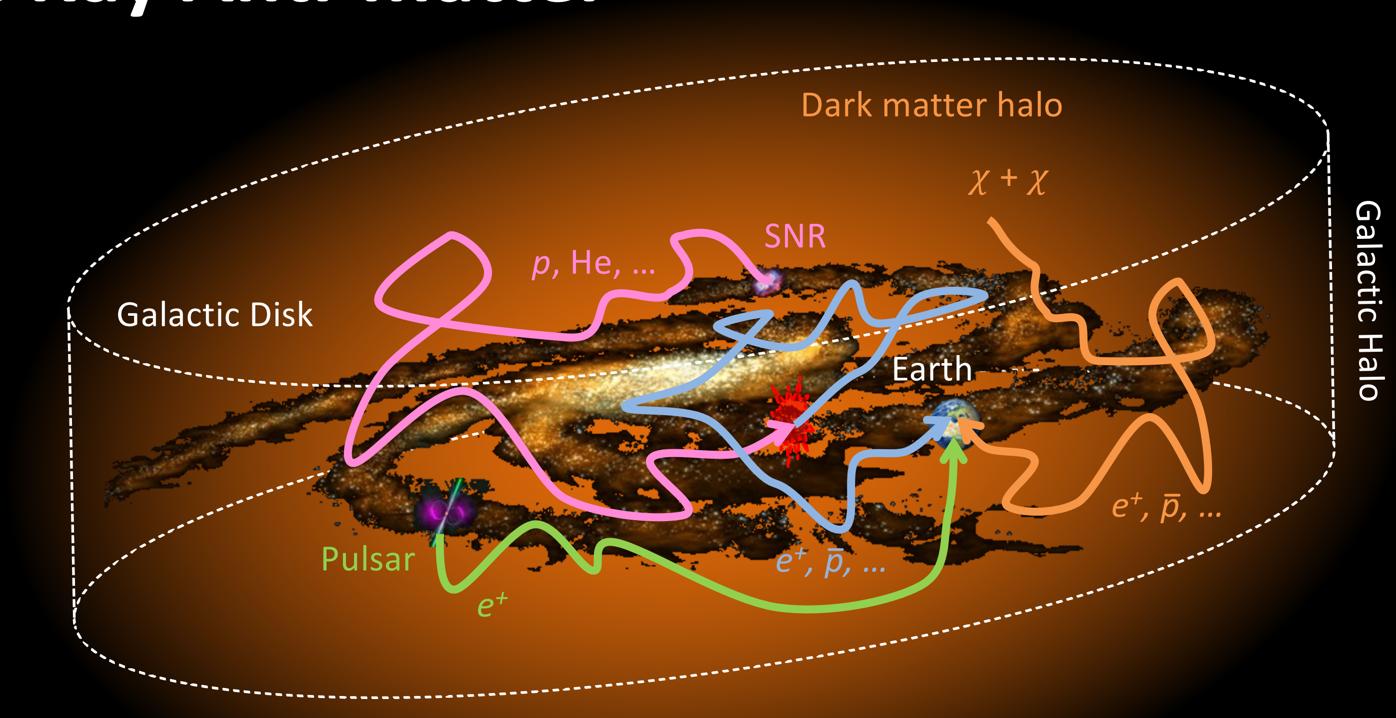




Cosmic Ray Composition

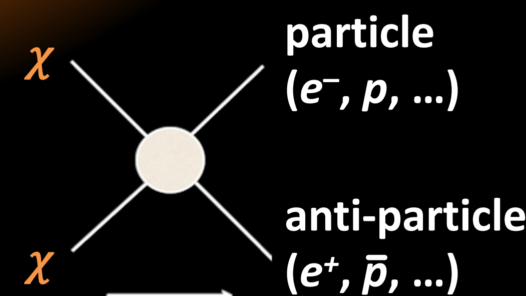


Cosmic Ray Anti-matter



Anti-matter in cosmic rays can be produced by:

- Cosmic ray collisions with the galactic medium (low-E supp. ...)
- Dark matter annihilations ($e^{\pm}$, p, $\bar{p}$, ^{2}H, $^2\overline{\mathrm{H}}$, ...)
- Astrophysical objects ($e^{\pm}$ production in pulsars, ...)
- Primordial origin ($^2\overline{\mathrm{H}}$, $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$, ...)



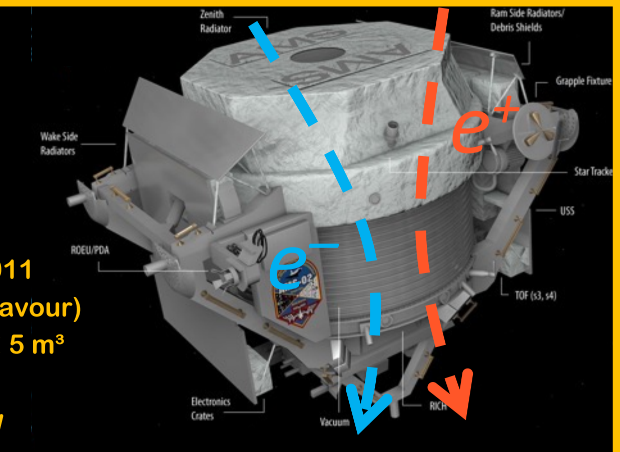
AMS-02: The Alpha Magnetic Spectrometer

Installed in 2011 on the ISS and takes data continuously since then,
with more than **190 billion cosmic** rays collected up to now.

International Space Station (ISS)

Altitude	~ 400 km
Inclination	51°
Period	93 min
Construction	1998 - …
Dimensions	73×109 m^2
Weight	420 t

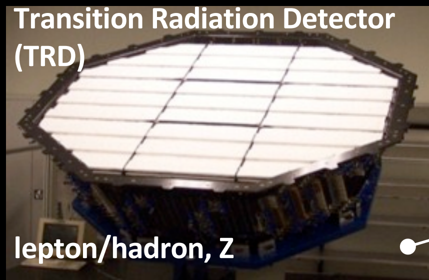
AMS-02

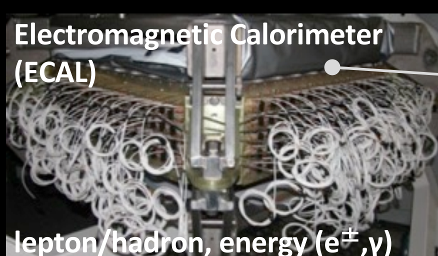


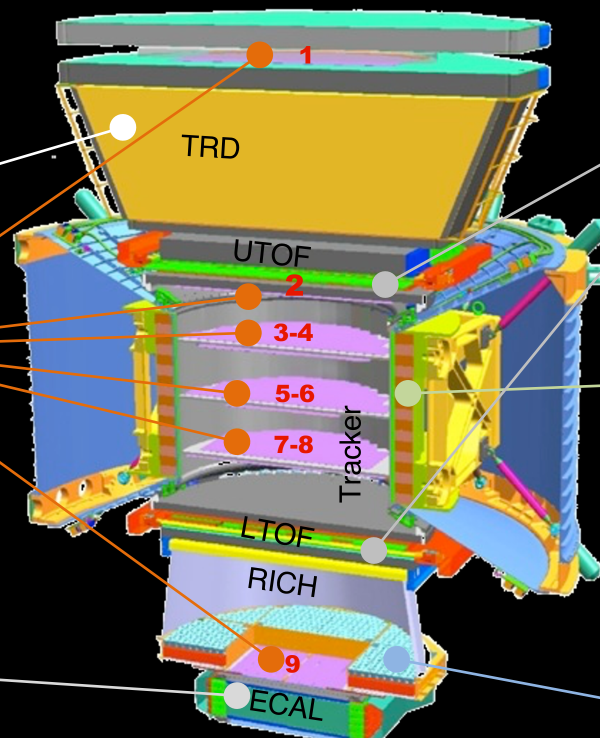
Launch	16/5/2011
(STS-134, Endeavour)	
Dim.	$3 \times 4 \times 5$ m^3
Weight	7.5 t
Power	2500 W

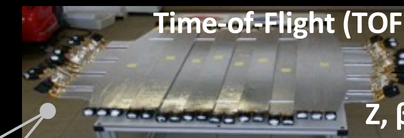
AMS-02: A TeV Multi-purpose Spectrometer

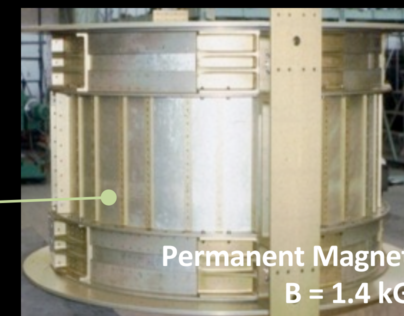
AMS-2 separates hadrons from leptons, matter from anti-matter,
chemical and isotopic composition from fraction of GeV to multi-TeV.

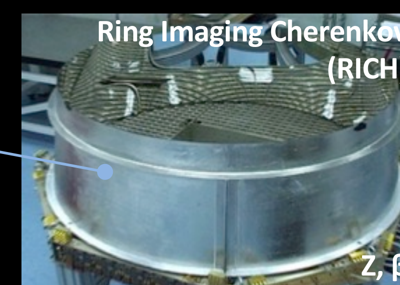








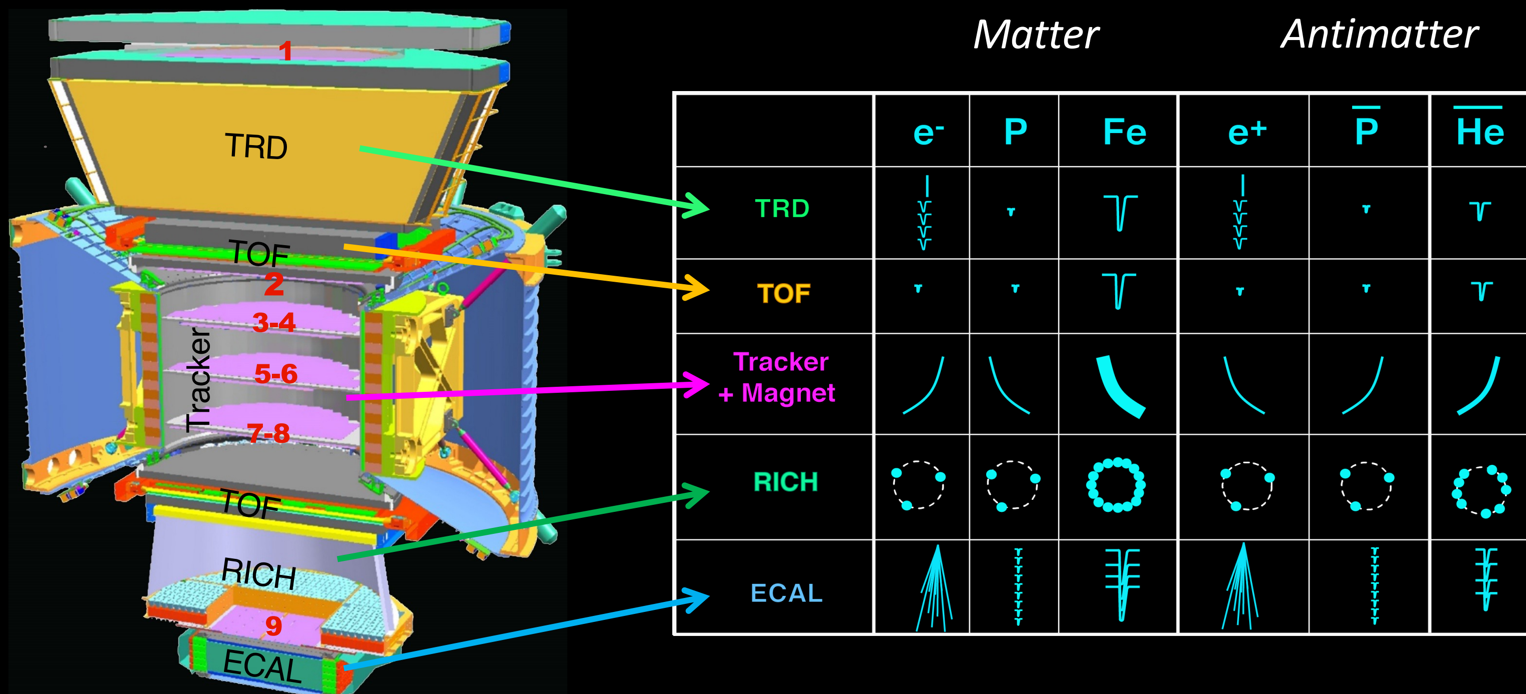




Multiple and/or Independent Measurement of
Charge (Z), Energy (β, p, E) and Charge Sign (±).

AMS-02: A TeV Multi-purpose Spectrometer

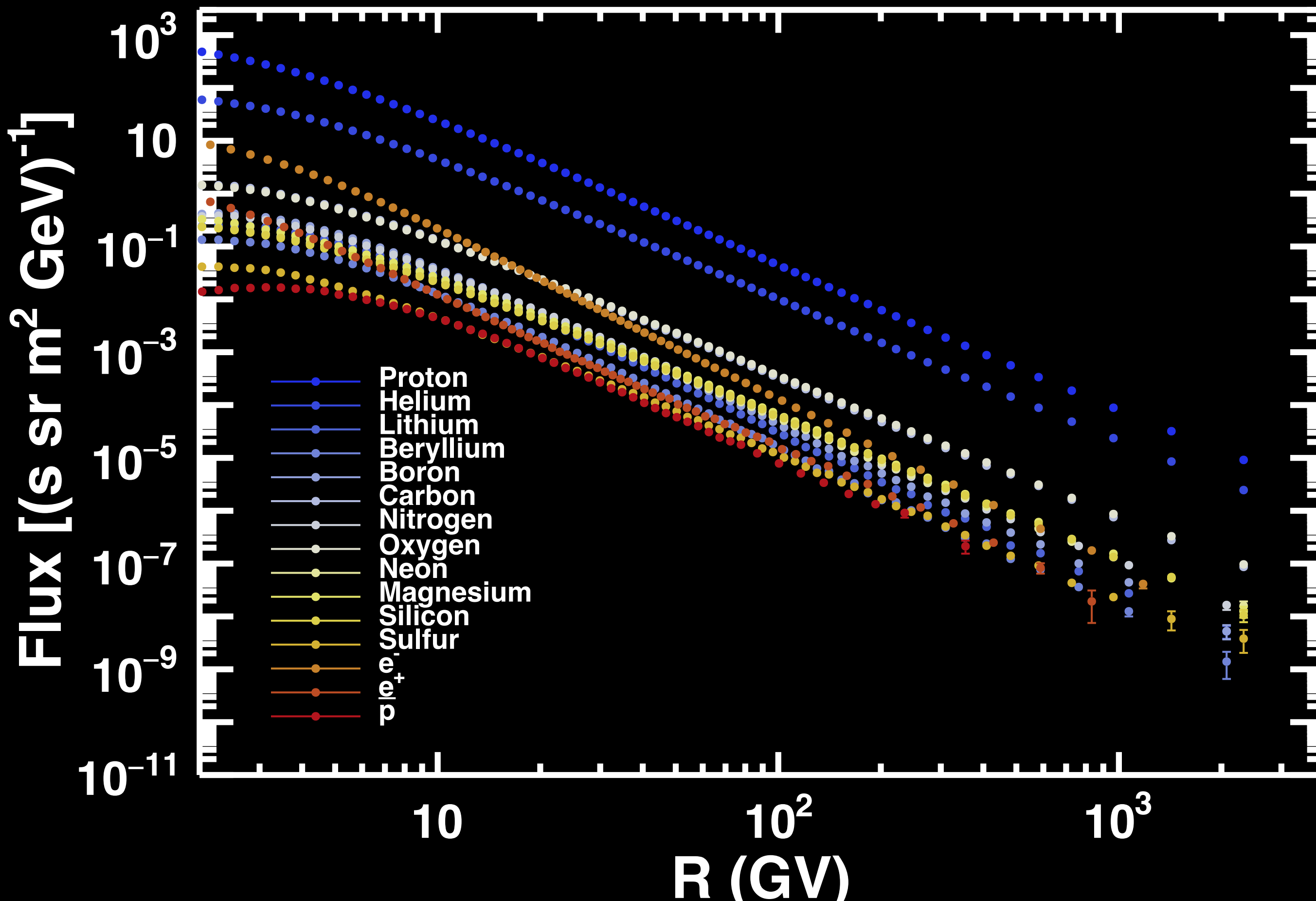
AMS-02 separates hadrons from leptons, matter from anti-matter,
chemical and isotopic composition from fraction of GeV to multi-TeV.



AMS identifies 1 positron from 10^6 protons,
unambiguously separate positrons from electrons up to a TeV,
and accurately measure all cosmic rays to TeV.

AMS-02: A TeV Multi-purpose Spectrometer

M. Aguilar et al., Phys. Rep. **894** (2021)

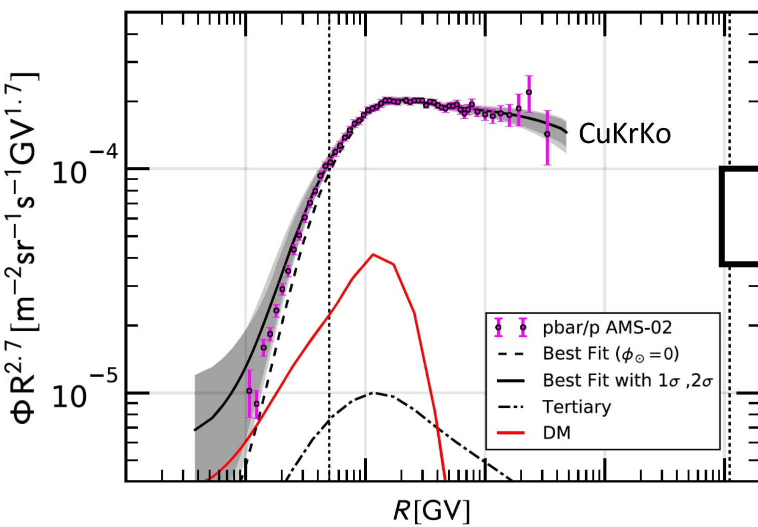


Many other results have been published since then …

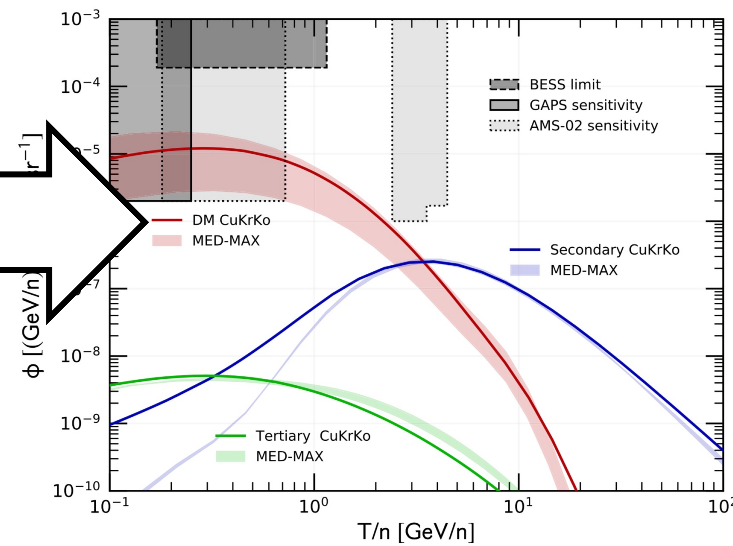
Anti-Deuterons Search

Several authors reported an **anti-proton excess** at low energy at ~ 10 GV in AMS-02 data (with different significances) that can be explained a **dark matter signal**. This signal can give a detectable **anti-deuteron** signal.
→ See Nicolò's presentation

A. Cuoco et al., Phys. Rev. Lett. **118** (2017)



M. Korsmeier et al., Phys. Rev. D **97** (2018)



Anti-deuterons (with or without anti-protons) are believed to be a clean channel for indirect dark matter search, their secondary production is very suppressed at low energy, and can be efficiently produced by dark matter annihilation.
→ original idea published in F. Donato et al. Phys. Rev. D **62**, (1999).

Anti-Deuterons Search with AMS-02

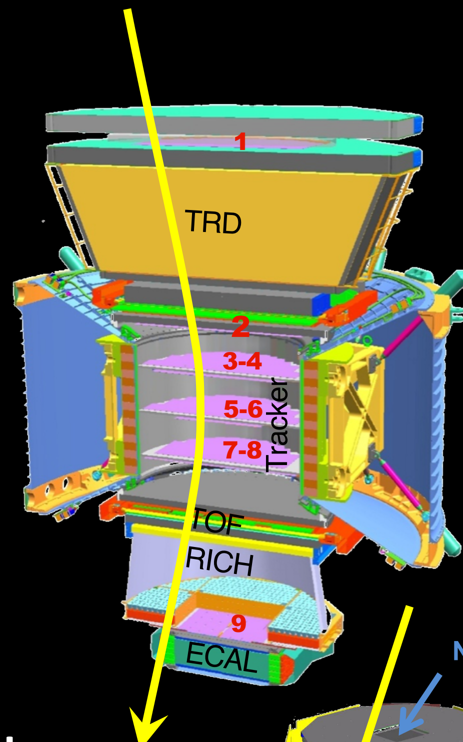
Charge Identification

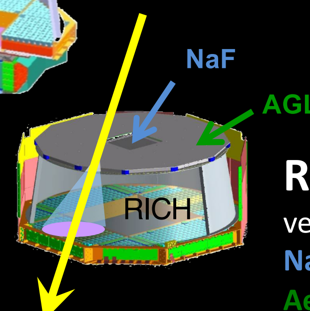
TRD
elimination of electron background
select **|Z|=1** particles ($\Delta Z/Z \approx 0.1$ c.u.)

Tracker
select **|Z|=1** particles ($\Delta Z/Z_{\text{Inner}} \approx 0.05$ c.u.)
particle sign (+/–), MDR = 1.8 TV

ToF
select **|Z|=1** particles ($\Delta Z/Z_{\text{Plane}} \approx 0.06$ c.u.)
separate **upgoing/downgoing**

RICH
select **|Z|=1** particles ($\Delta Z/Z \approx 0.3$ c.u.)





Mass Identification

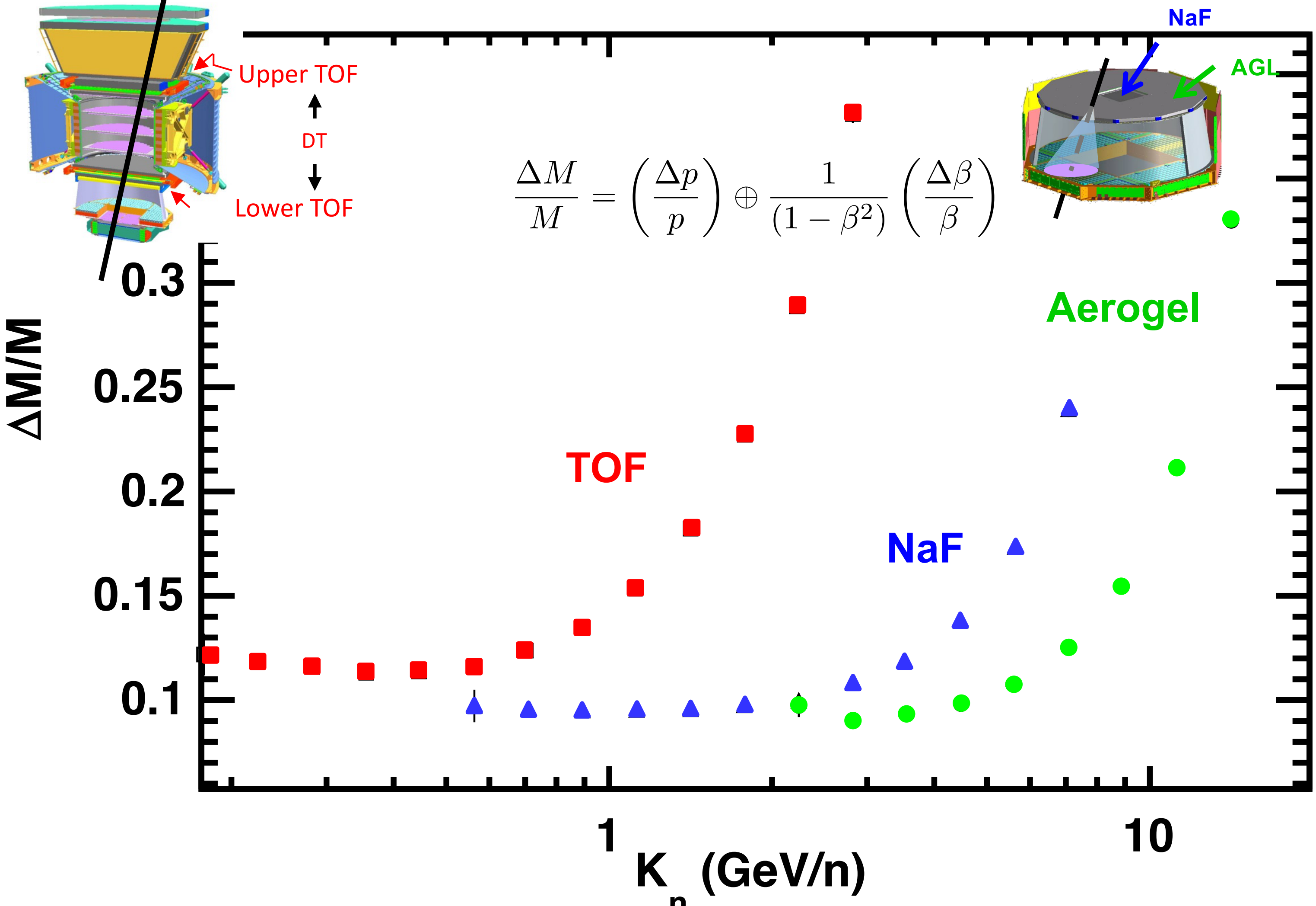
$$M = p\frac{\sqrt{1-\beta^2}}{\beta}$$

Tracker
momentum,
$\Delta p/p \approx 10\%$ up to 20 GV

ToF
velocity $\Delta\beta/\beta \approx 4\% \times \beta$

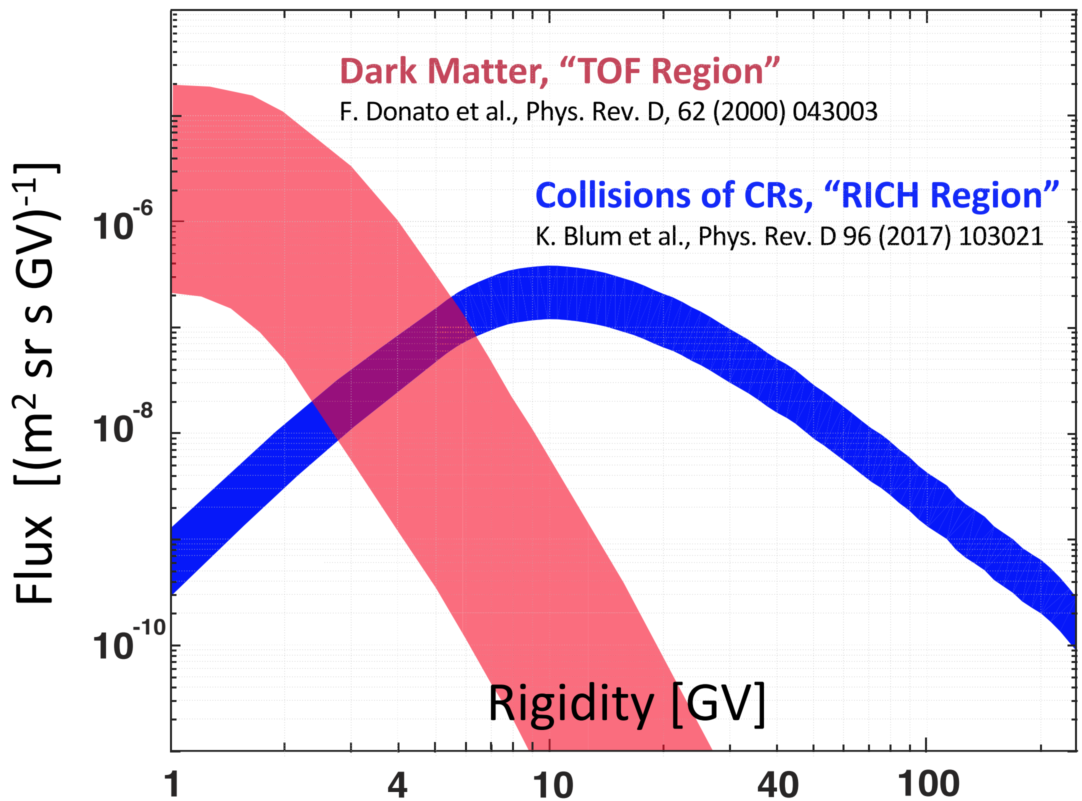
RICH
velocity β, in two radiators
NaF radiator: $\Delta\beta/\beta \approx 0.4\%$, $\beta>0.75$ ($\varepsilon=0.1$)
Aerogel radiator: $\Delta\beta/\beta \approx 0.1\%$, $\beta>0.96$ ($\varepsilon=0.7$)

AMS-02 |Z|=1 Mass Resolution



Event Selection

In more than 10 years of data taking we collected over 190 billion events.

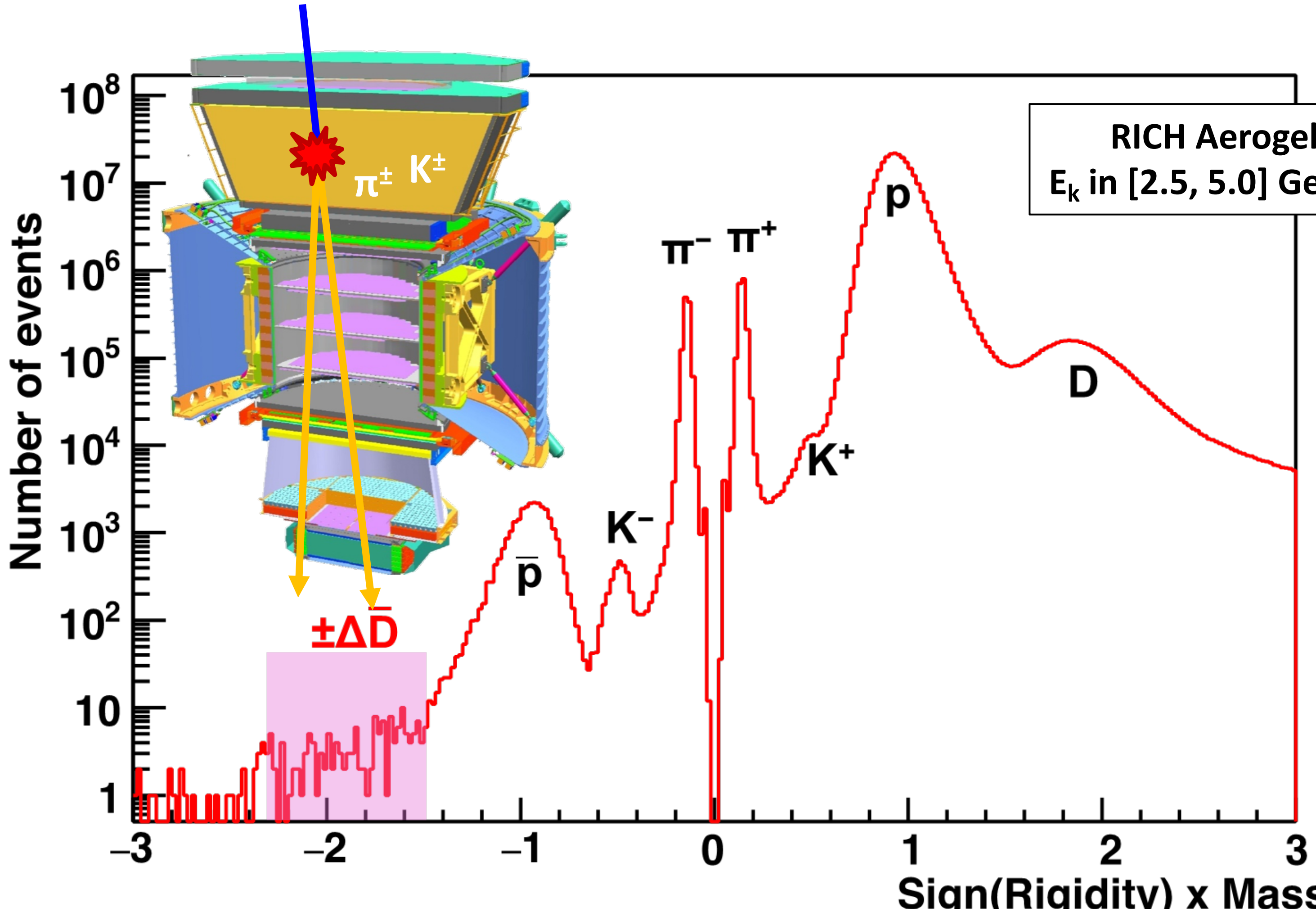


+ Very low background at low energy for indirect search of Dark Matter.

– Very low flux, **high rejection** to other species **needed**: $^2\overline{\mathrm{H}}/\overline{p} < 10^{-4}$, $^2\overline{\mathrm{H}}/p < 10^{-9}$, $^2\overline{\mathrm{H}}/e^- < 10^{-6}$

→ To achieve enough separation methods based on **multivariate analysis** have been employed.

Status of Anti-Deuteron Search with AMS-02

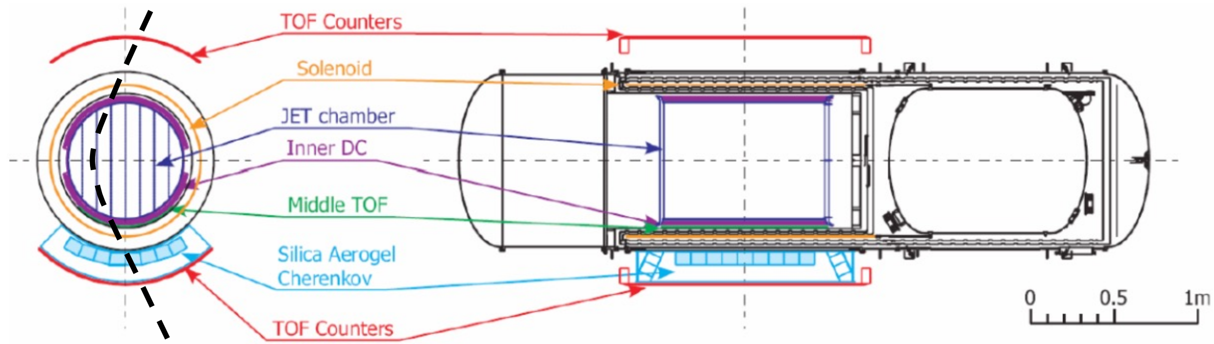


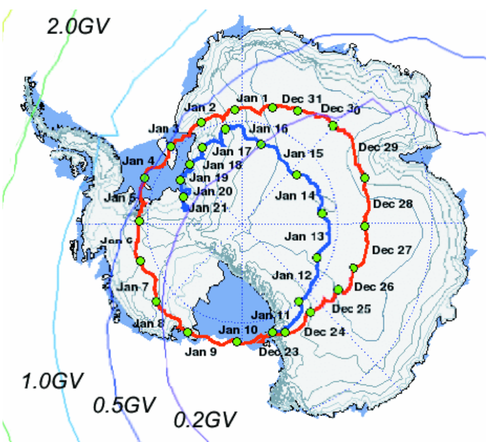
→ Under development, large background (tails of p-bar) to be understood in this energy range.

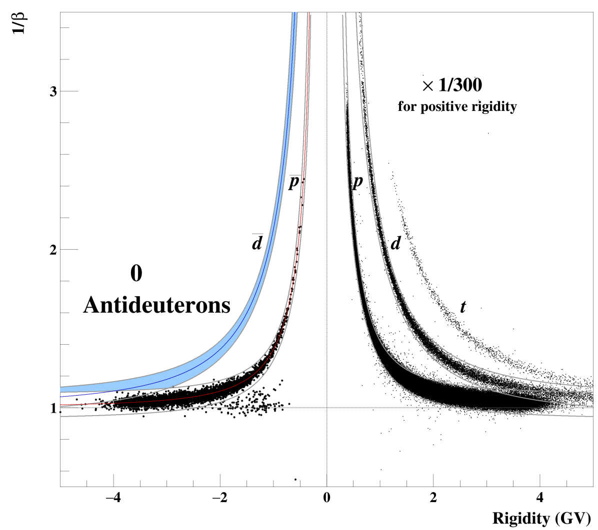
Current Best Limit on Anti-Deuteron Flux: BESS Polar-II

SC Magnet B = 0.8T
TOF $\Delta\beta/\beta$ = 2%
JET $\Delta R/R(R=1GV)$ = 0.4%
MDR = 270 GV

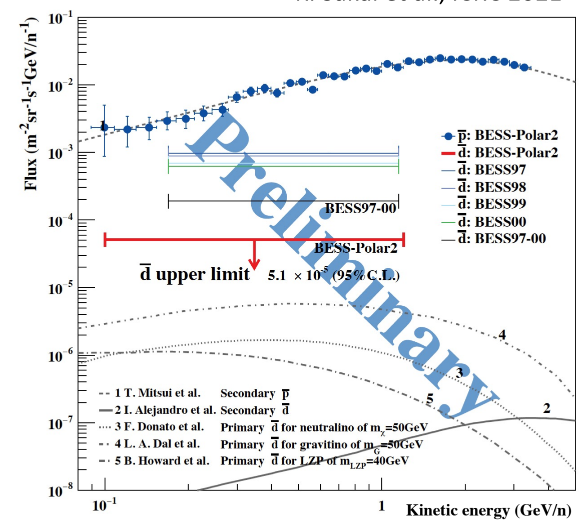
Acceptance = 0.3 m^2 sr
Exposure = 24.5 days
Geomagnetic cutoff below 0.5 GV







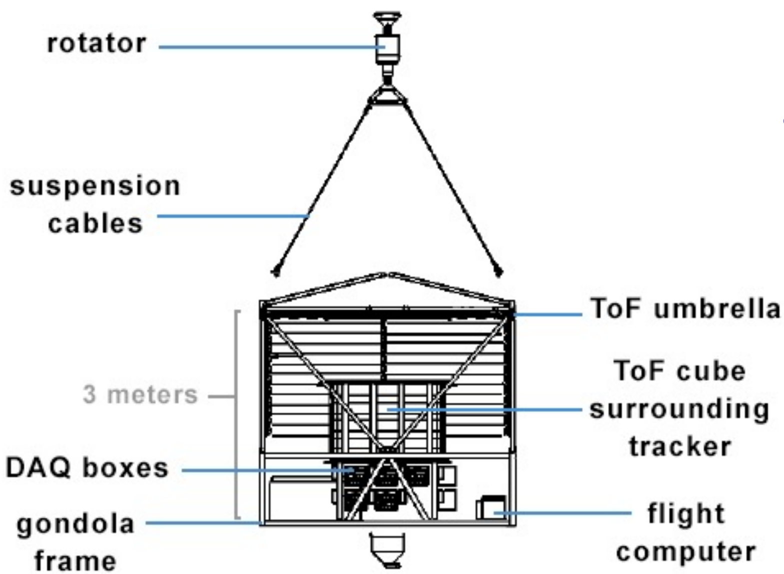
K. Sakai et al., ICRC 2021

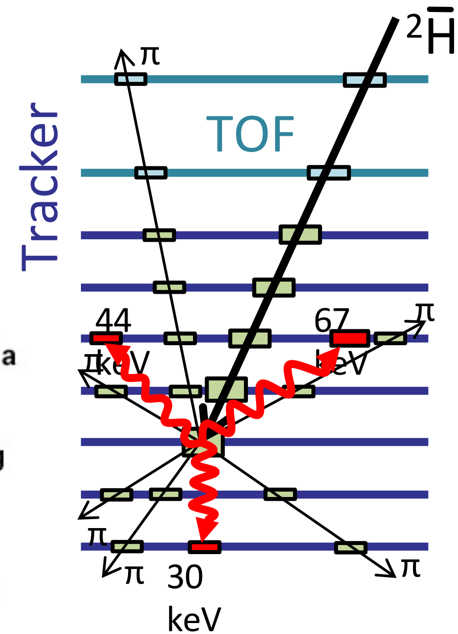


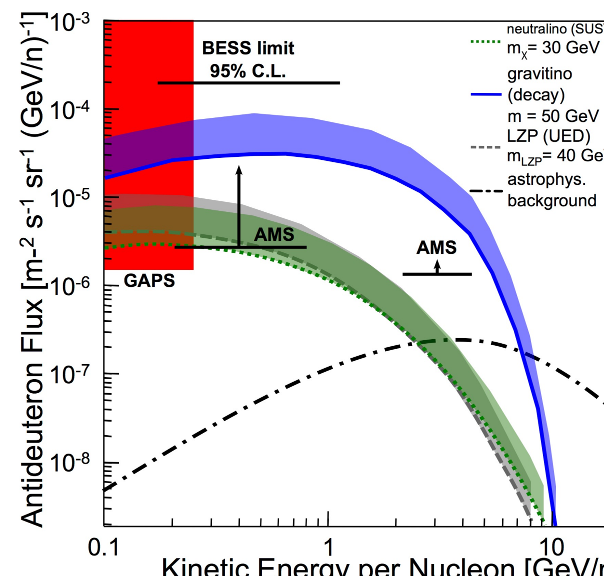
Has given the best upper limit on anti-deuteron flux: $J(^2\overline{H}) < 5.1\times10^{-5}$ $m^{-2}s^{-1}sr^{-1}(GeV/n)^{-1}$ (95% CL)

Anti-Matter Search in the Near Future: GAPS

General Anti-Particle Spectrometer (GAPS): a balloon-borne instrument designed to detect cosmic ray antimatter stopping it in material forming and exotic atom with the material and detecting the X-ray from orbital transition of the exotic atom and the pion “star” produced by final annihilation. In construction, foreseen several balloon campaigns in Antarctica.

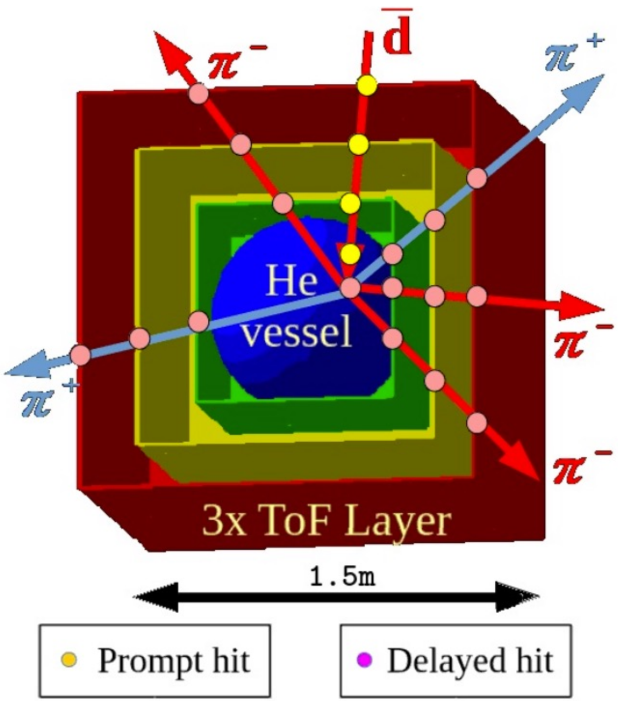


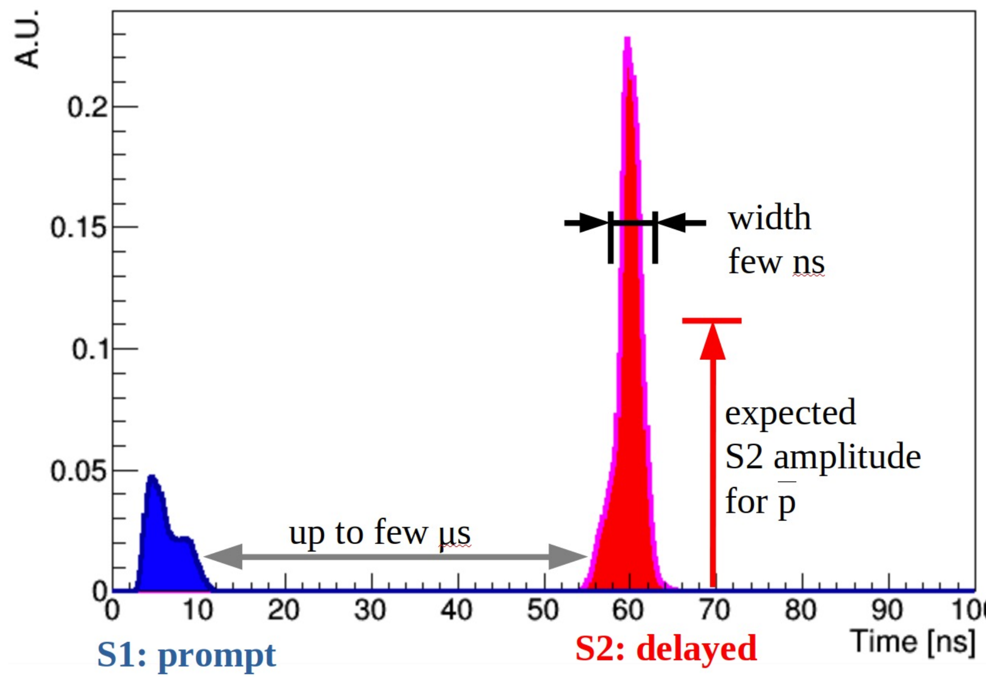




Anti-Matter Search in the Next Future: AHDH

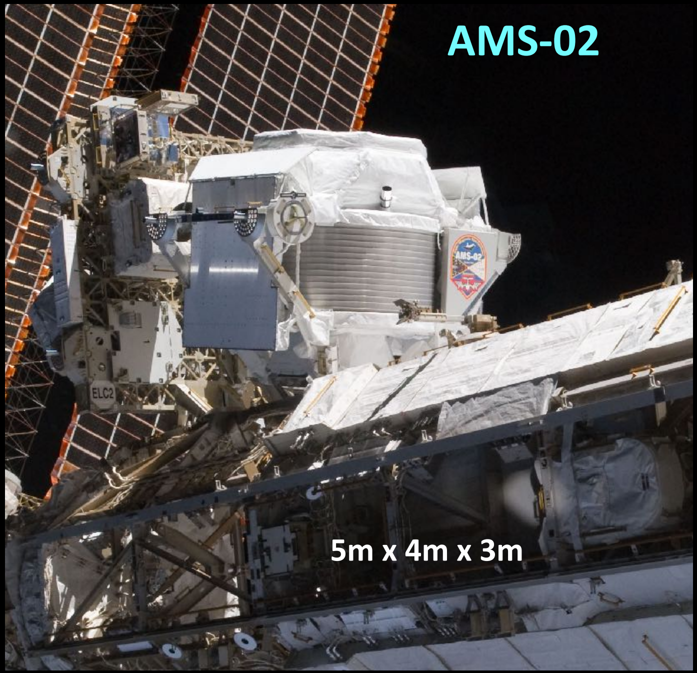
Anti Deuteron Helium Detector (ADHD): high pressure helium calorimeter for the identification of the anti-deuterons with the "exotic atom" technique (à là GAPS), profiting of the delay between anti-deuteron capture and production of pions. The project is in R&D phase.





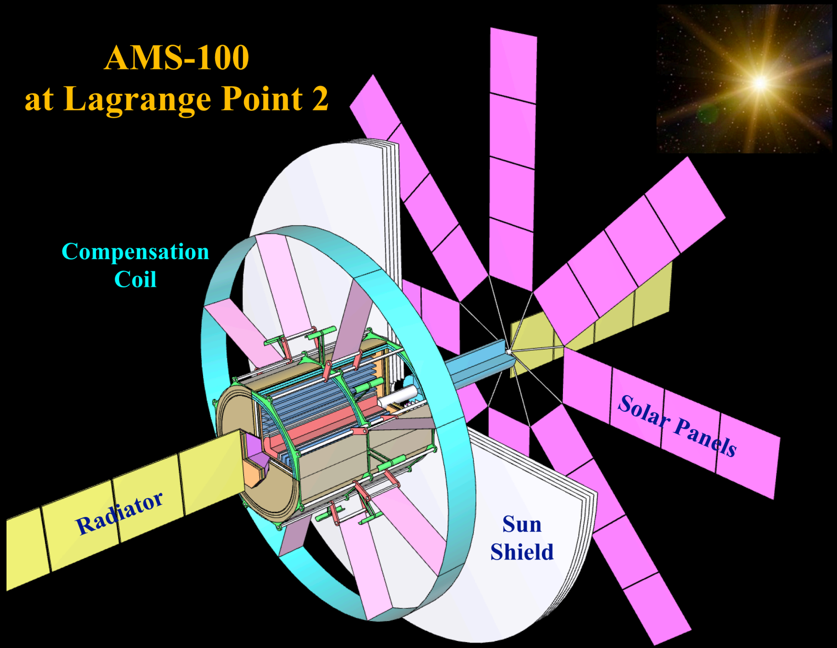
Anti-Matter Search in the Far Future: AMS-100

From ESA Voyager 2050 Call



Operational on the ISS since 2011

Weight:	7 t
Permanent Magnet:	BL^2=0.15 Tm^2
Acceptance:	0.1 m^2sr
MDR:	2 TV
Calorimeter:	17 X_0, 1.7λ



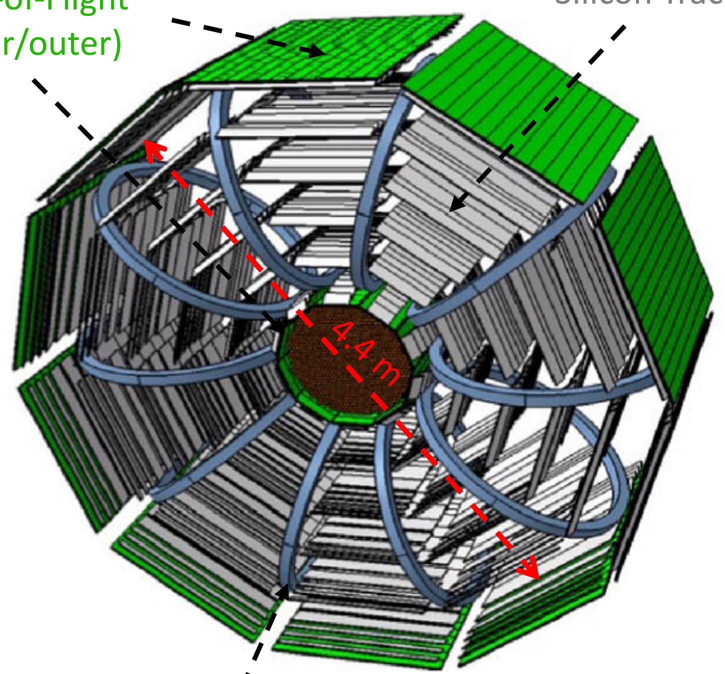
Lagrange-Point 2, 2030

Weight:	40 t
Thin coil Solenoid :	BL^2=13 Tm^2
Acceptance:	100 m^2sr
MDR:	100 TV
Calorimeter:	80 X_0, 4λ

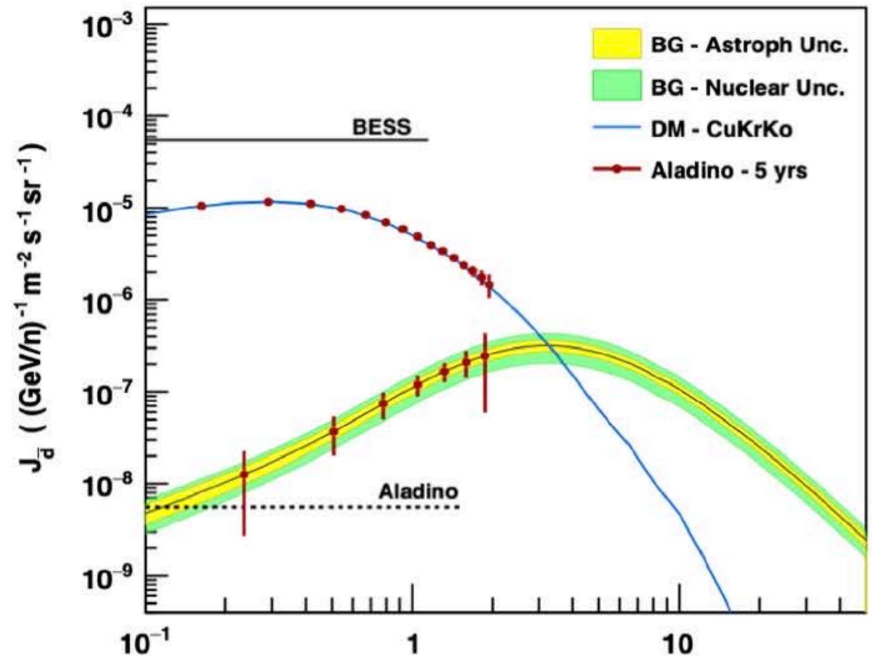
→ A factor "100" in energy scale and acceptance with respect to AMS-02.

Anti-Matter Search in the Far Future: ALADInO

Antimatter Large Acceptance Detector In Orbit (ALADInO): large spectrometer (acceptance > 10 m^2 sr), based on a superconducting toroidal magnet, with a high resolution (3 μm) tracker, a time-of-flight detector, and an 3D imaging electromagnetic calorimeter in LYSO. To be installed in L2.



From ESA Voyager 2050 Call

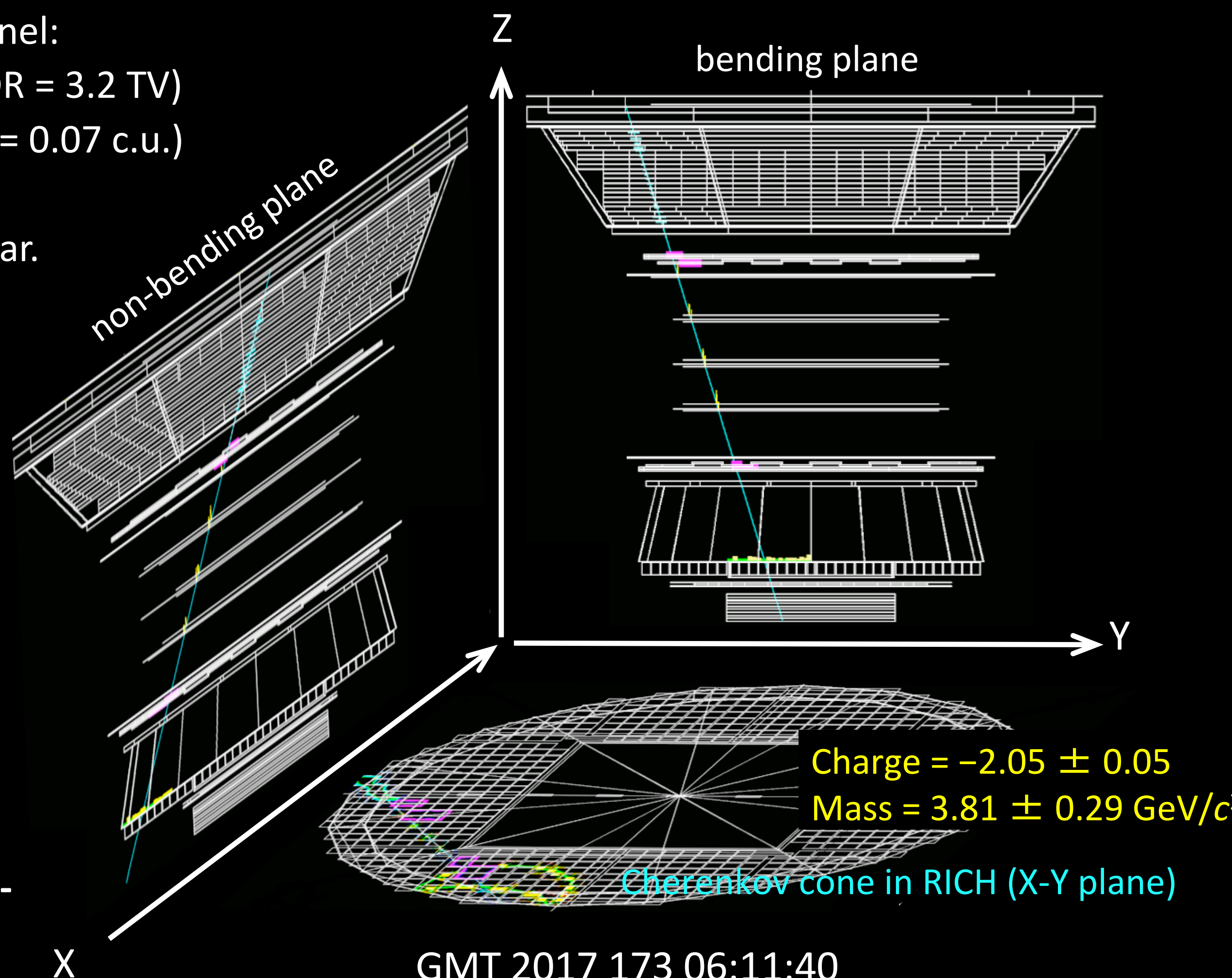


Our group participates in this proposal …

An AMS-02 Anti-Helium Candidates

Anti-helium is a golden-channel:
- Best rigidity resolution (MDR = 3.2 TV)
- Best Z separation ($\Delta Z/Z_{\text{Inner}}$ = 0.07 c.u.)
- No p, K, π contamination

Observed with a rate of 1/year.



If confirmed, this would have huge consequences on the understanding of **matter/anti-matter asymmetry**.

Conclusion

> Complex anti-matter has never been detected firmly in cosmic rays. Its observation would have important consequences for our understanding of dark matter or matter/anti-matter asymmetry in universe.

> AMS-02 has been operating continuously in the Space Station since May 2011 performing precision measurements of cosmic rays and showing some possible signal of anti-matter.

> New project in the near and far future will be realized for the search of anti-matter in cosmic rays.