ANTIMATTER SEARCH AND AMS RESULTS

ISAPP - 17 June 2026

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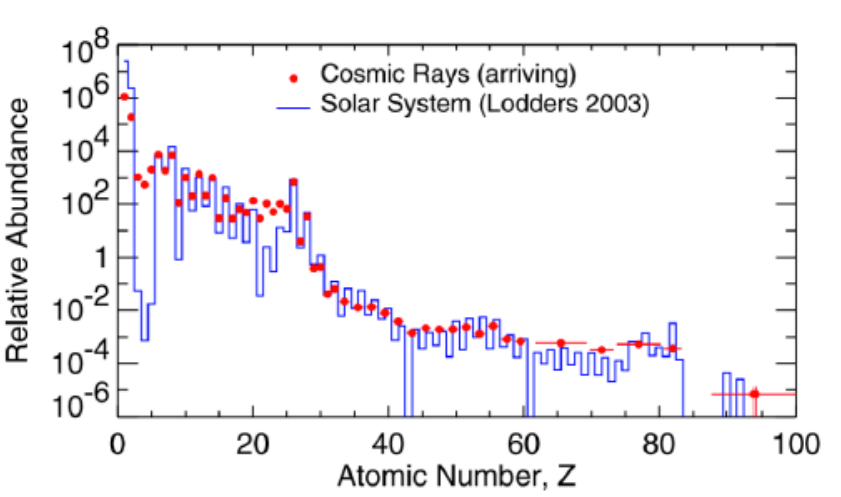
PLAN

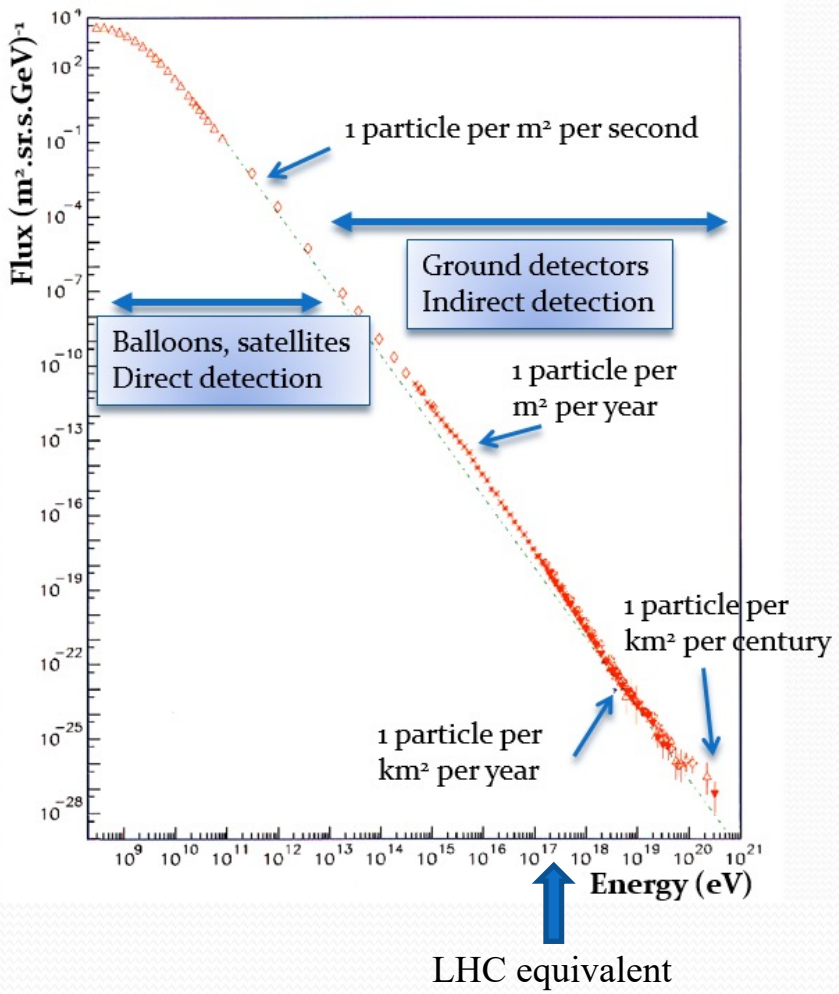
- Some reminders about cosmic rays
- Antimatter in space
- Indirect search for dark matter… via the antimatter
- Some experiments
- AMS-02: detailing a modern experiment
- Recent results
  - Positrons
  - Antiprotons
  - Antinuclei
  - Other
- The future

(REMINDERS ABOUT)
COSMIC RAYS

COSMIC RAYS

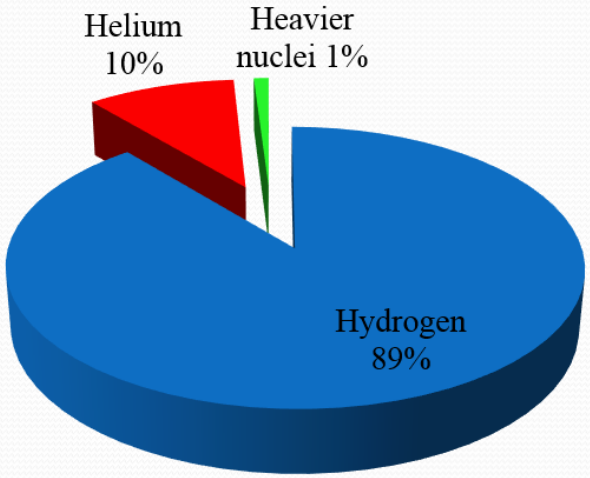
- Cosmic rays
  - 12 orders in **energy**
    - 100 MeV to 10^{20} eV
  - 30 orders in **flux**
  - Isotropic flux
- Abondance of nuclei in the cosmic rays similar to the one from the solar system

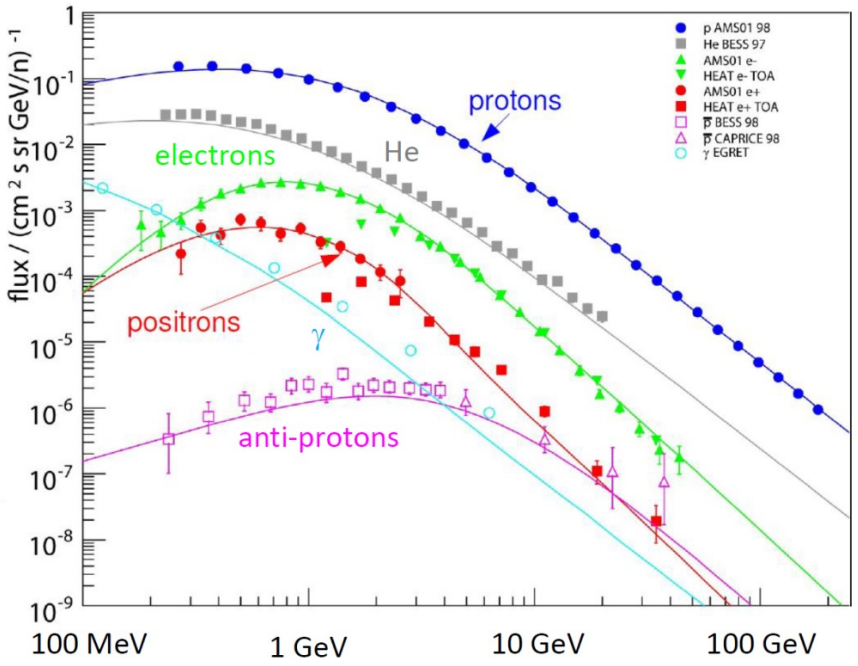




COSMIC RAYS

- Composition
  - **Charged** : electrons, protons, nuclei
  - **Neutral** : photons, neutrinos
- Charged cosmic rays

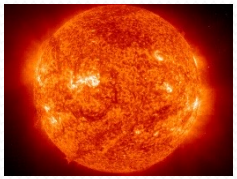




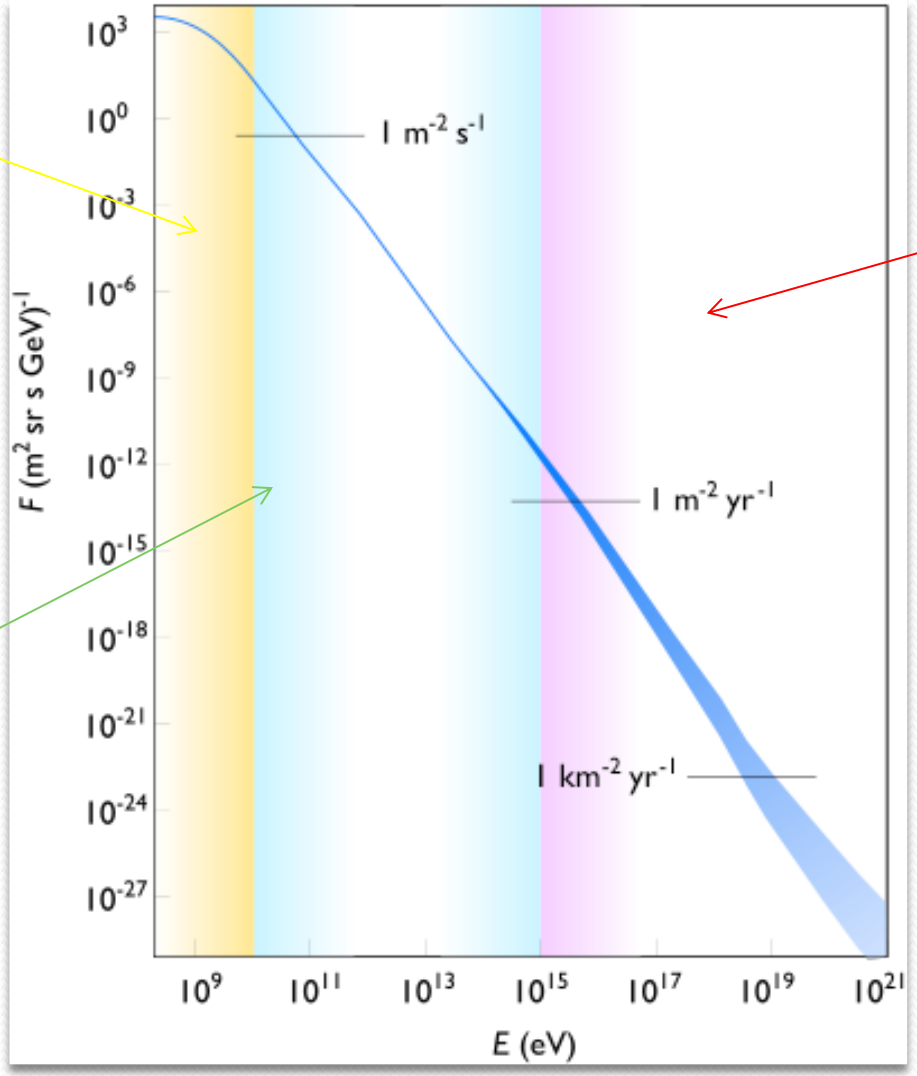
- Power law spectrum $1/E^{\gamma}$, $\gamma \sim 2.7$-3.5
  - The measured spectrum results
    - from the **production** and **acceleration** mechanisms ($1/E^{\alpha}, \alpha = 2.0$-$2.4$)
    - from the **diffusion** ($1/E^{\delta}$, $\delta = 0.3$-0.7)
  - $\gamma = \alpha + \delta$

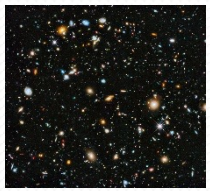
COSMIC RAYS

- Where are they coming from?



From the sun



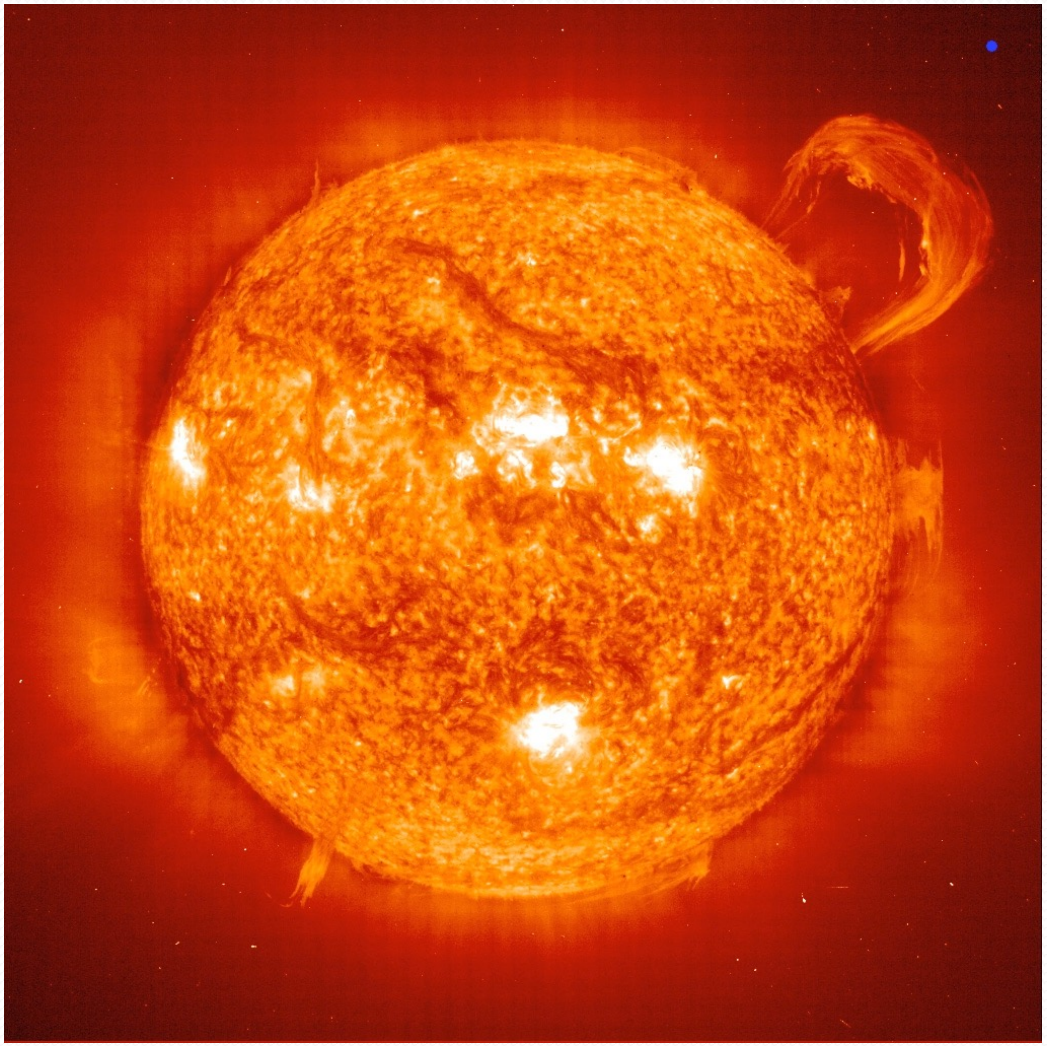


From outside our Galaxy

From our Galaxy

COSMIC RAYS

- Low energy cosmic rays are accelerated by the sun



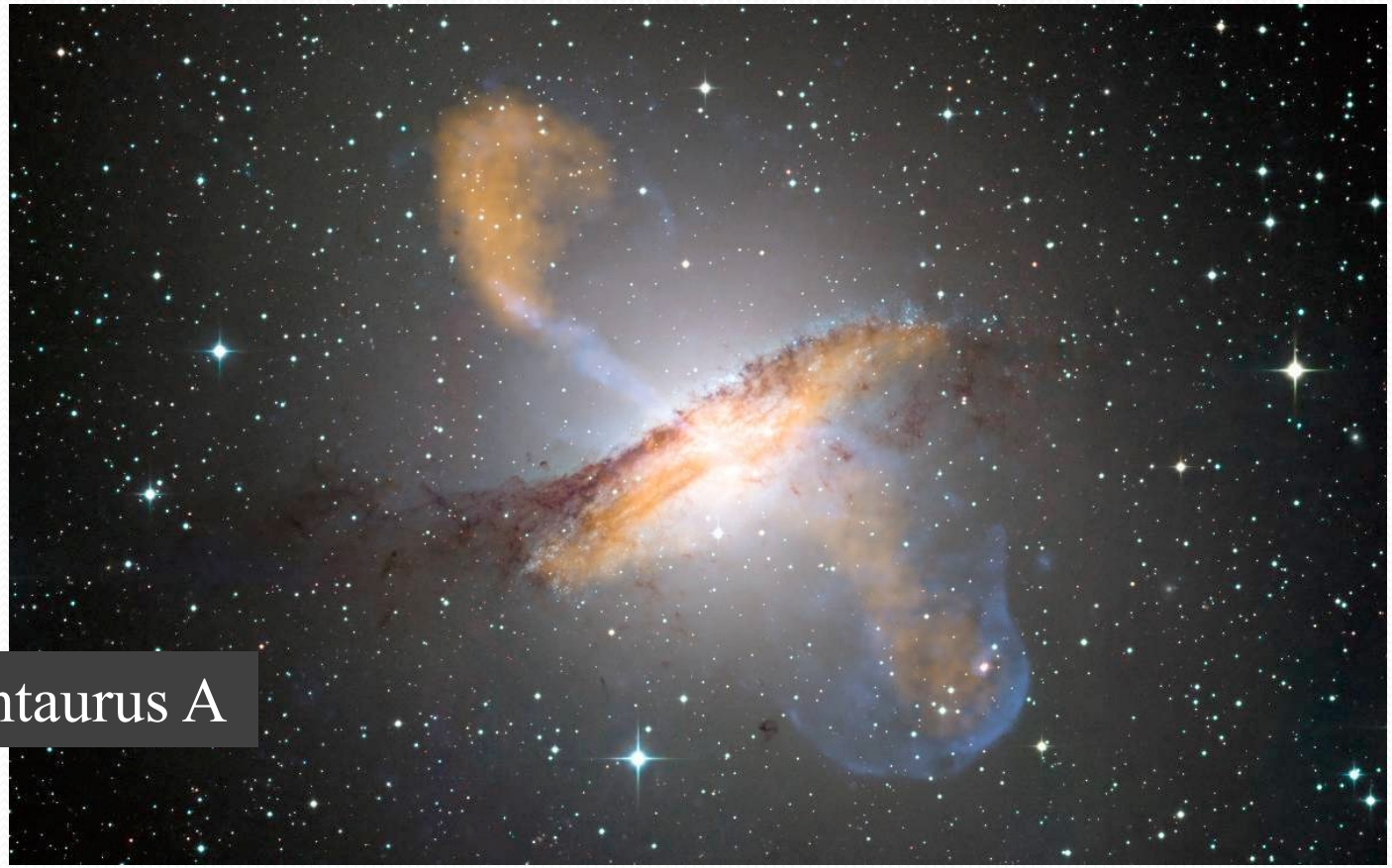
Aurora borealis

COSMIC RAYS

- At intermediate energies, supernovae remants produce cosmic rays

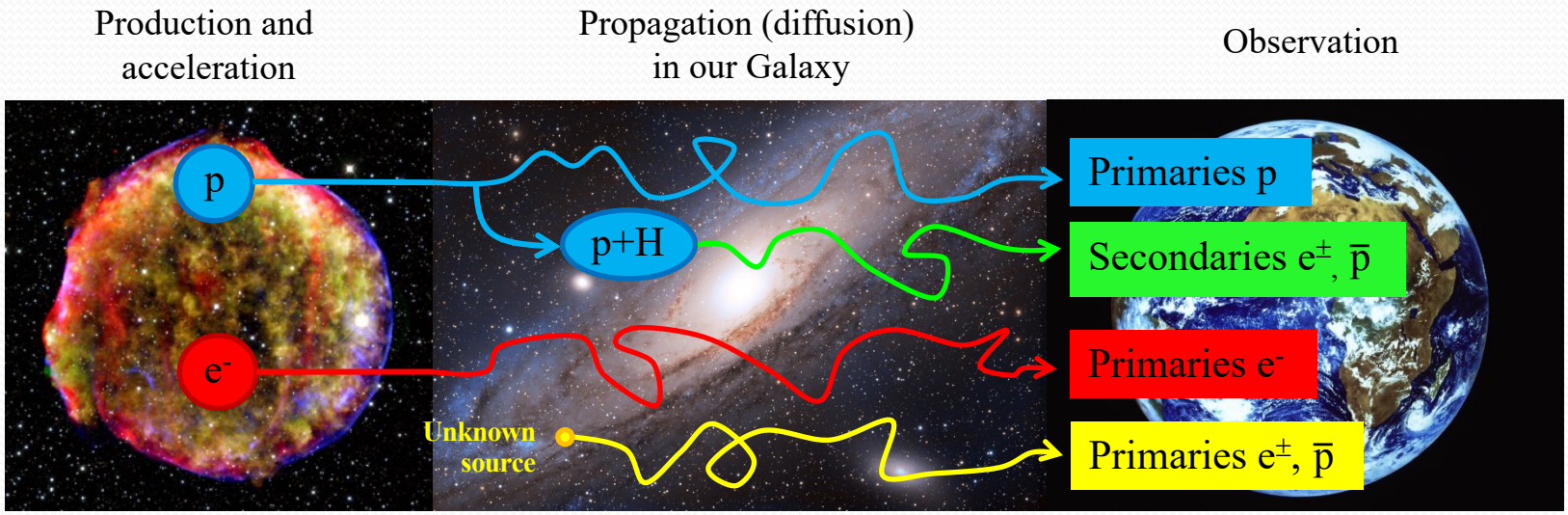
COSMIC RAYS

- At extreme energies, active galaxy nuclei, quasars, or gamma ray bursts are potential candidates



Centaurus A

COSMIC RAYS

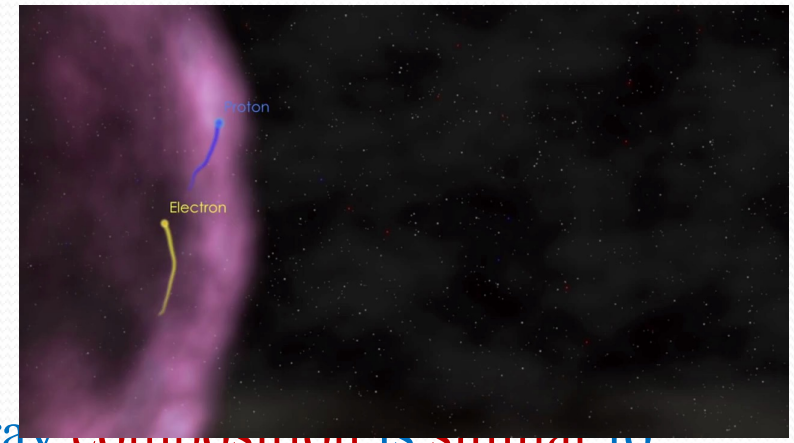


- Primary cosmic rays
  - Produced direcly **in the source**
  - Sources: **supernova remnants, pulsars**, **active galactic nuclei**, **quasars**
  - Primaries include
    - Electrons, protons, helium, carbon, …
- Secondary cosmic rays
  - Originate from the **interaction** of primaries on **interstellar medium**
  - Secondaries include
    - Positrons, antiprotons, bore, …
- Additional sources of electrons and positrons?

ACCELERATION

- In our Galaxy, main source of primary cosmic rays: supernova remnants
  - Very strong magnetic field in the **shell** of supernovas

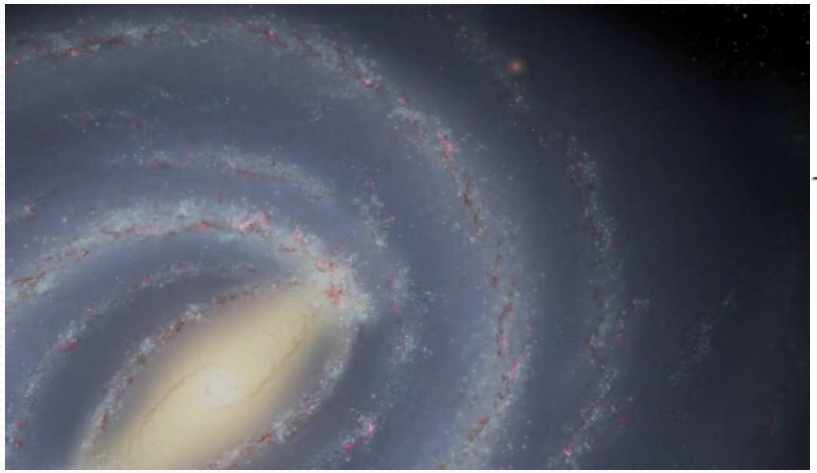
- Acceleration
  - Due to the **shock wave**
  - First order **Fermi mechanism**
  - Naturally produce a **power law** spectrum

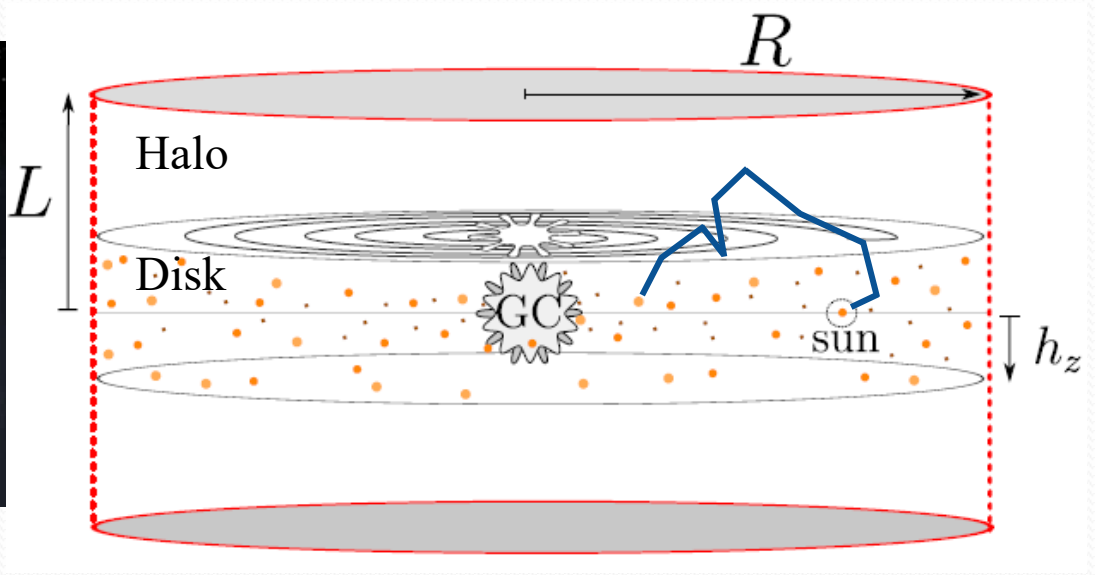


- This process explains why the cosmic ray composition is similar to the one from the solar system

PROPAGATION

- Charged cosmic rays: propagation equivalent to a diffusion in the Galactic medium
  - **Irregular magnetic field** of the diffusive halo = random walk
  - Possible to write a **cosmic ray transport equation**
    - Difficult to **solve**
    - **5 free parameters**, with large **uncertainties** on these parameters

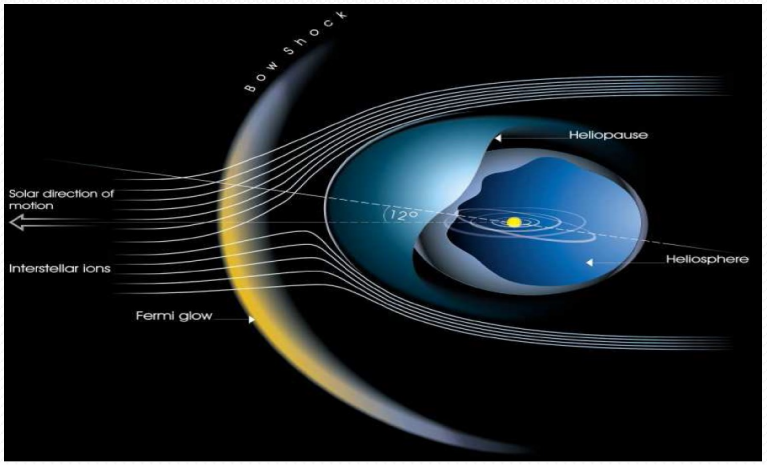


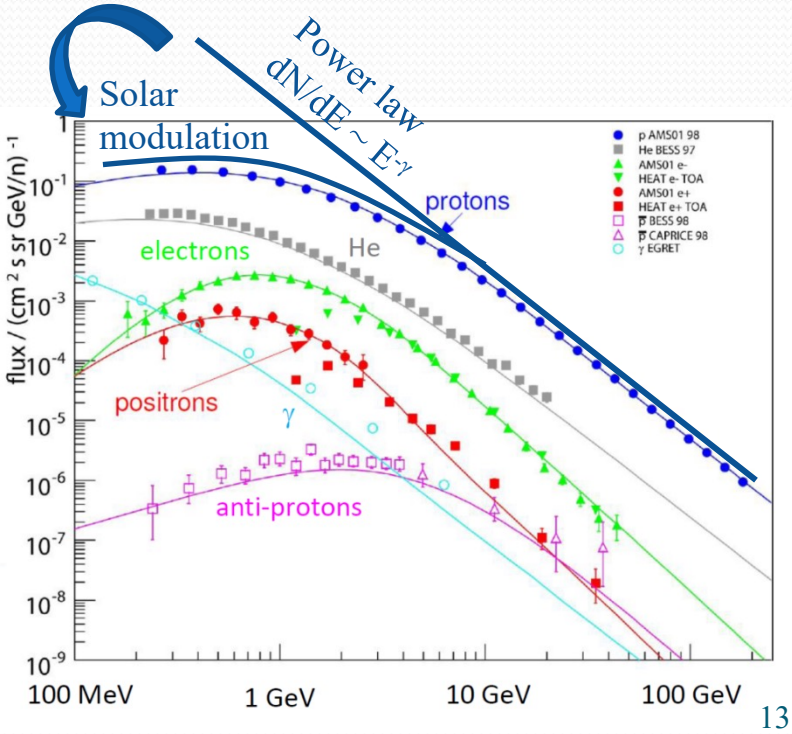


h_z=200 pc, L=1-15 kpc, R=25 kpc

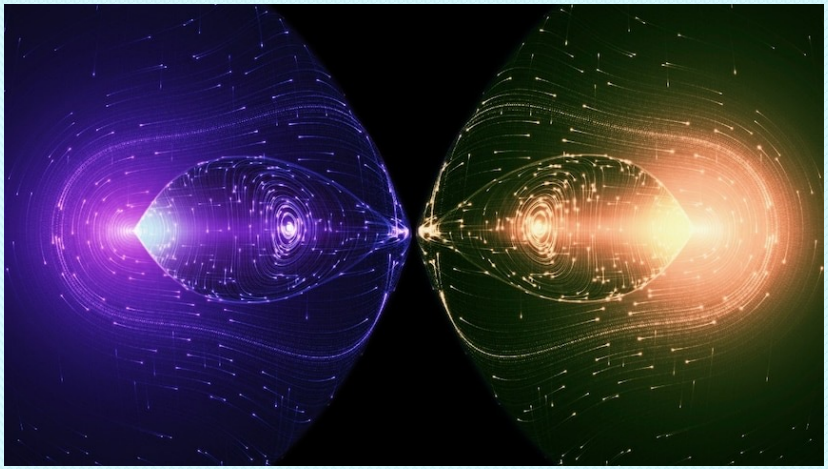
SOLAR MODULATION

- Heliosphere: a region of space influenced by the sun (solar wind)
  - **Size**: 150 AU
- Solar wind: a continous flow of charged particles from sun
  - e^- and **p**
  - Carries the **sun magnetic field** to the interplanetary space
- Solar cycles
  - **Reversal** of the sun magnetic field polarity
  - Every **11 years**
  - Solar activity going from a minimum to a maximal intensity
- Solar modulation affects cosmic rays below 20 GeV
  - **Deviation** from the power law





ANTIMATTER IN SPACE



ANTIMATTER

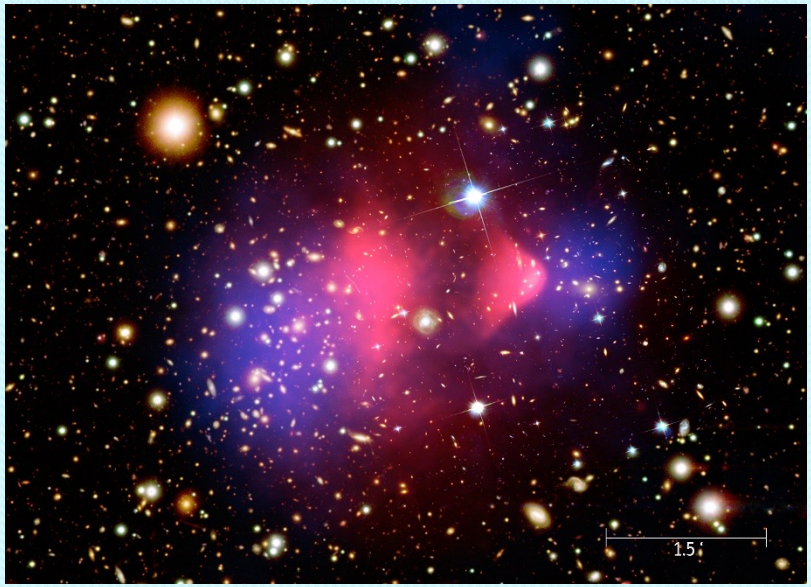
Matter	Charge	Antimatter	Charge
Electron e^-	-1	Positron e^+	+1
Proton p	+1	Anti-proton $\bar{p}$	-1
Neutron n	0	Anti-neutron $\bar{n}$	0
Neutrino ν	0	Anti-neutrino $\bar{\nu}$	0

- Why is it important to look for antimatter in space?
- At the birth of the Universe, as many antimatter than matter
- Is there somewhere an antiyou, antiplanets, antistars, antigalaxies?
  - Spoiler: no!
  - Where did go the antimatter? It annihiliated with matter
- Actual asumption: asymmetry between antimatter and matter
  - Observed in experiments (BaBar, Belle, LHCb, …)
  - But **too small** to explain the size of the asymmetry
  - **Another source** of asymmetry is needed → new physics

ANTIMATTER

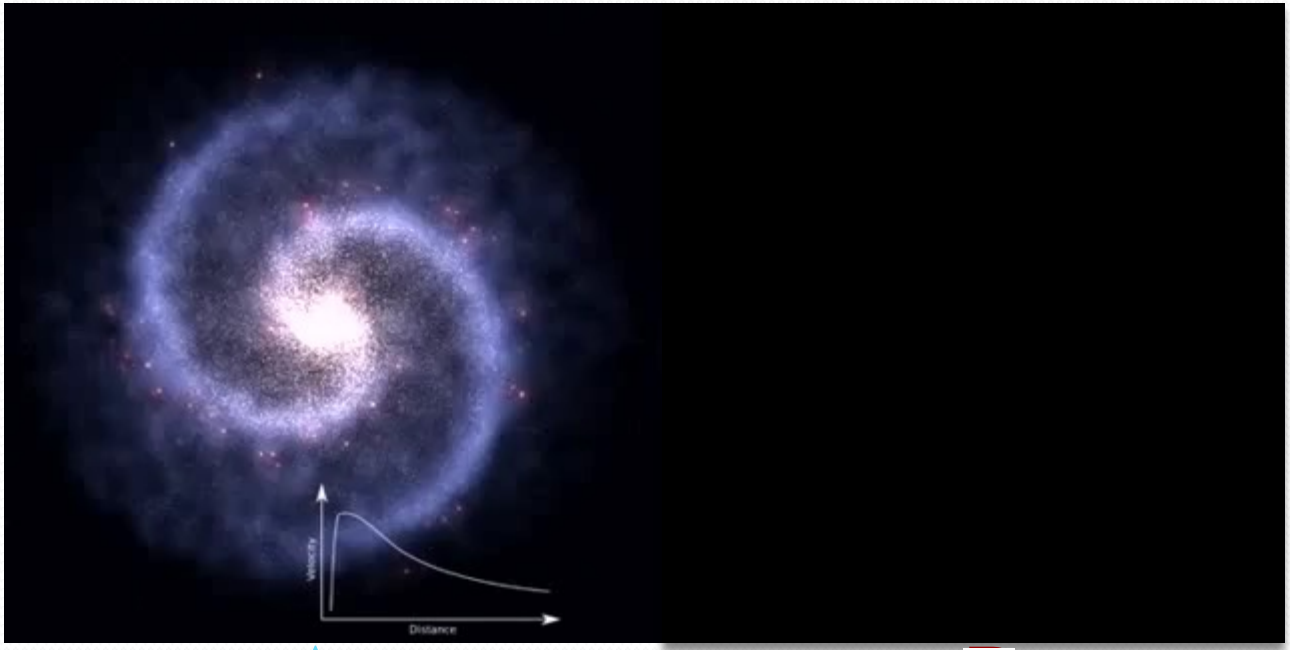
- Antimatter in space comes from
  - **Interstellar collisions** (secondaries) => can be predicted
  - Some **astrophysical** sources (pulsars, …)
- Other potential sources of antimatter
  - **Primordial** antimatter
    - Searches for antihelium and heavier antinuclei directly test the possibility that macroscopic antimatter regions survived from the early Universe
    - One antihelium would be revolutionnary
  - **Dark matter**
  - Other **exotic** sources
- Antimatter search program
  - Positron
  - Antiproton
  - Antihelium
  - Antideuteron
- Let's see how antimatter and dark matter are related

INDIRECT SEARCH FOR DARK MATTER

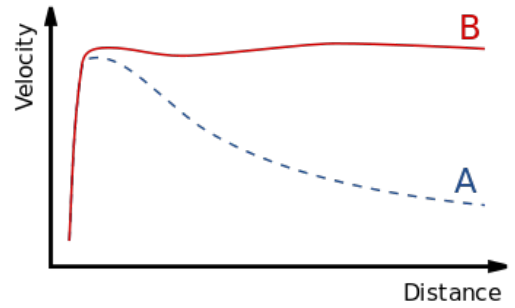


DARK MATTER

Galaxy rotation curve



A



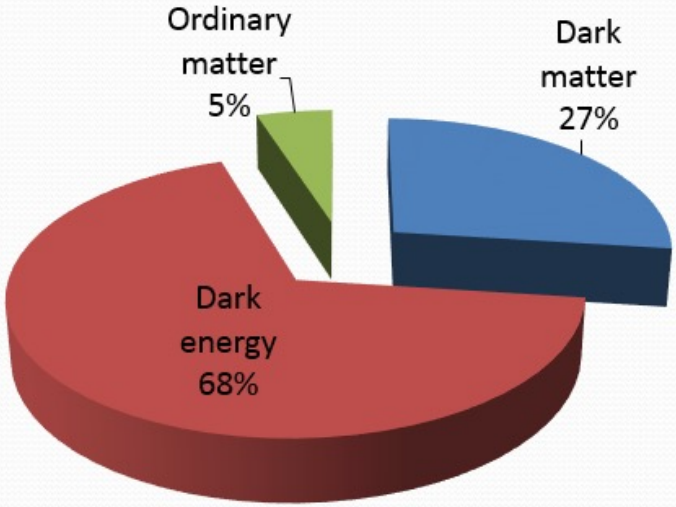
A : prediction

B : observation

To explain the observation, we have to suppose the presence of a halo containing an invisible matter around the galaxies: the dark matter!

DARK MATTER

- A very large fraction of the Universe content remains mysterious



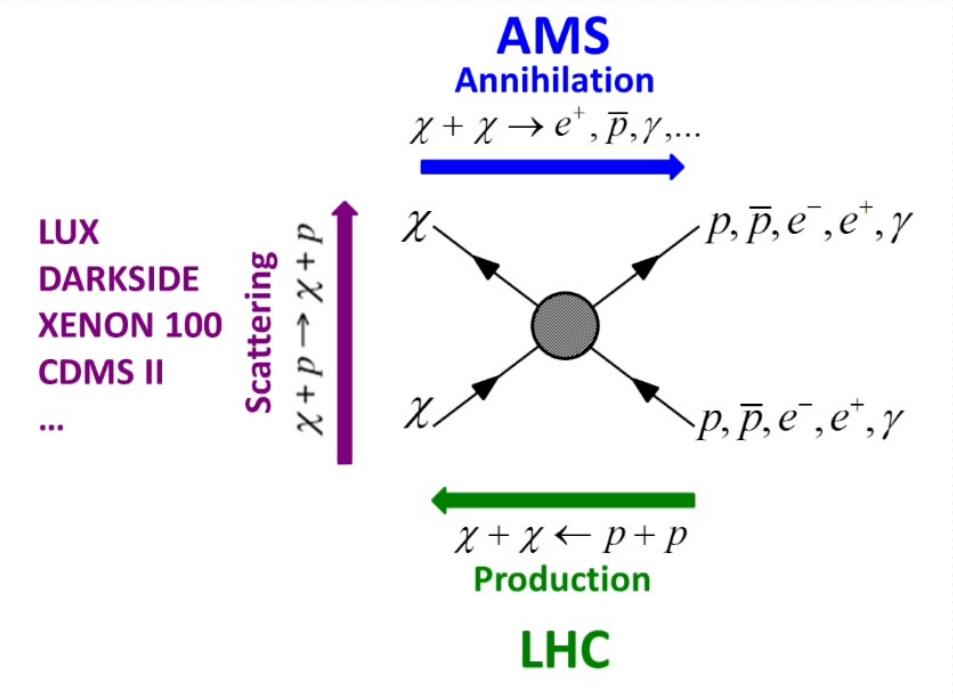
- Dark matter: 27% of our Universe is made of unknown matter (other than electrons, quarks, positrons, antiquarks, …)
- « Observation »: galaxy rotation curves, X-ray emission, gravitational lensing, cosmic microwave background

DARK MATTER

- Best (?) candidate: weakly interacting massive particle ⇒ WIMP
  - **Massive particles**: 100 GeV – several TeV
  - **Weakly** interacting with the ordinary matter

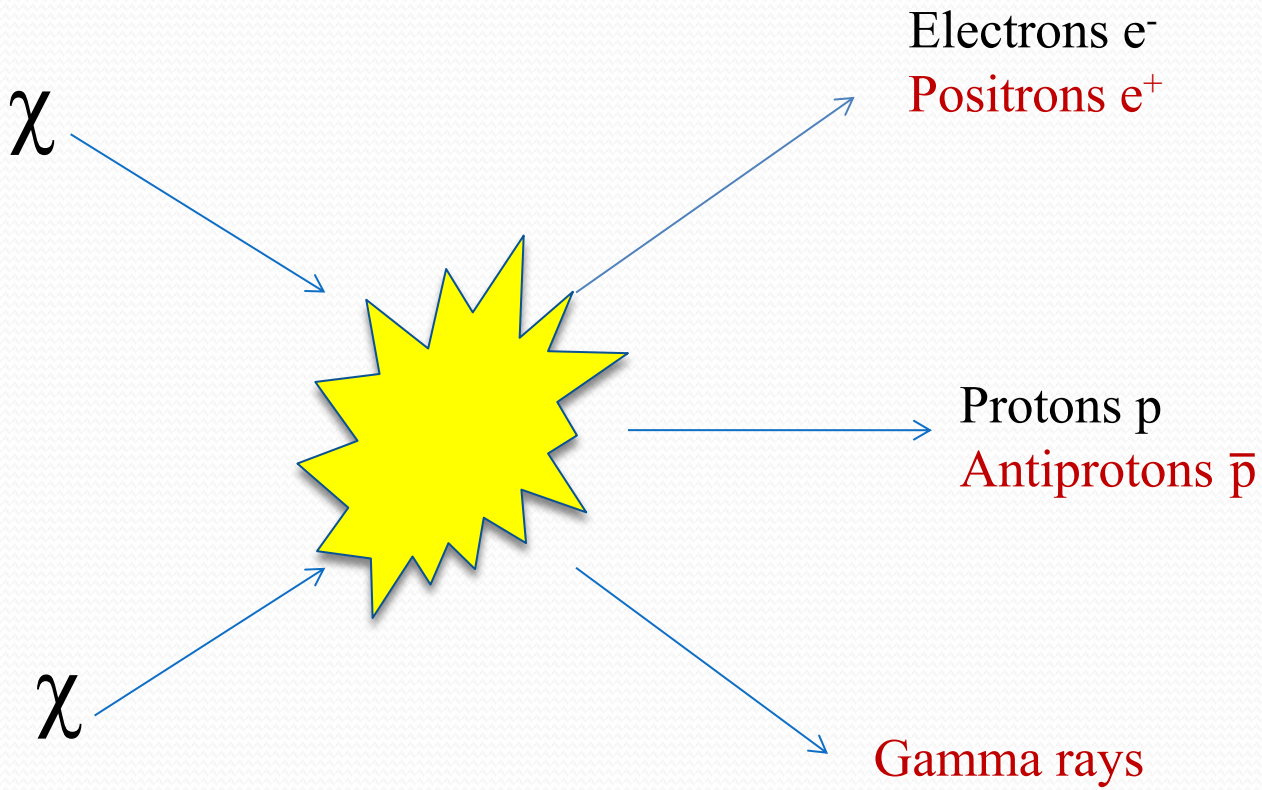
- Several ways to see its effect

Nota: search for dark matter has now opened to a very large mass range



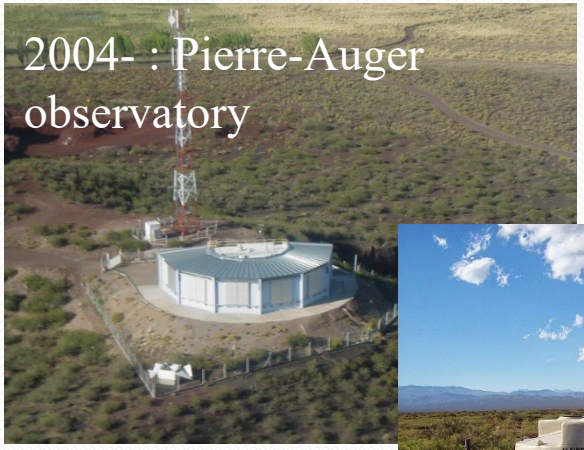
DARK MATTER

- Annihilation of the WIMPs
  - Natural cross-section from relic density: $\langle \sigma v \rangle \approx 3.10^{-26}\ cm^3 s^{-1}$

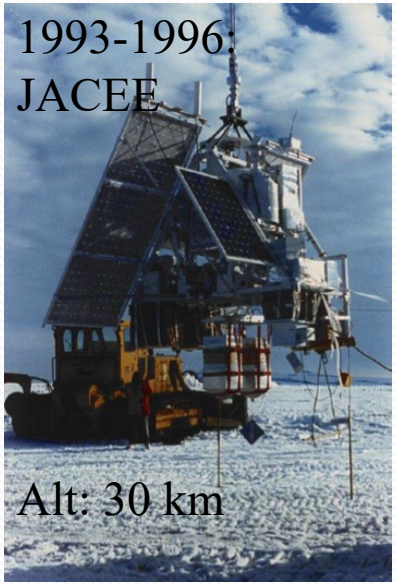


COSMIC RAY EXPERIMENTS

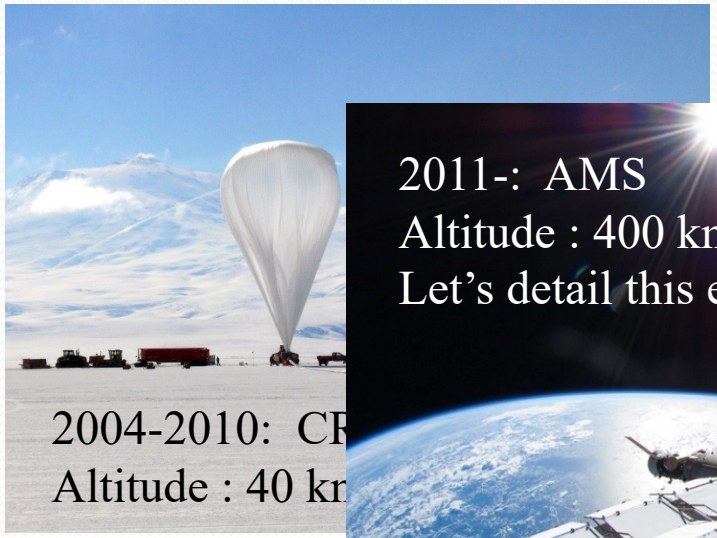
EXPERIMENTS



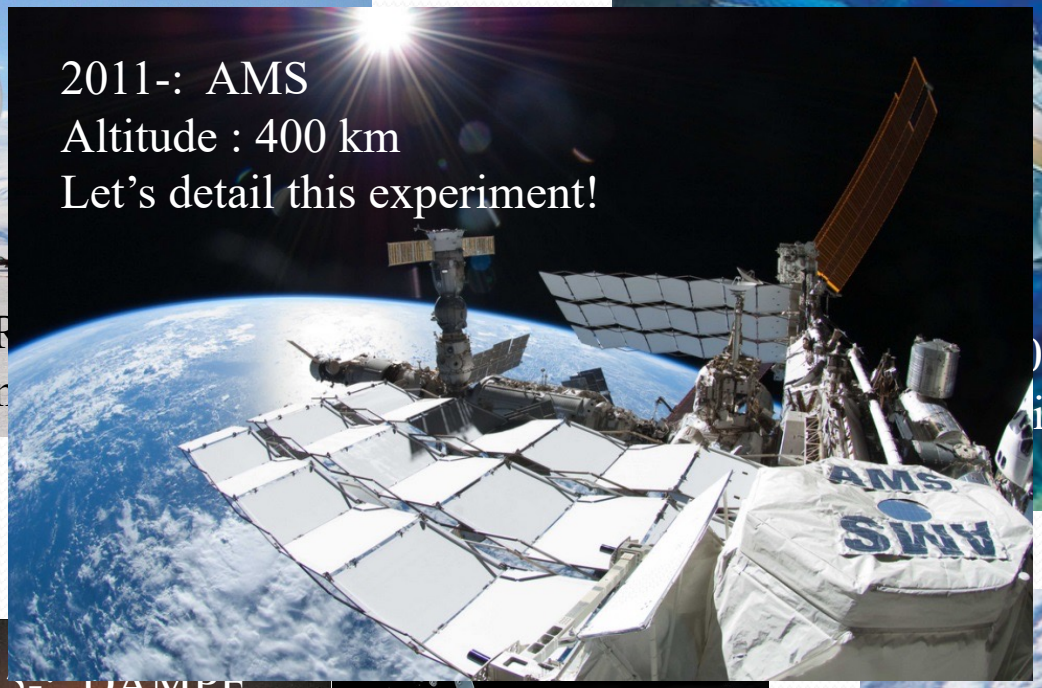
EXPERIMENTS



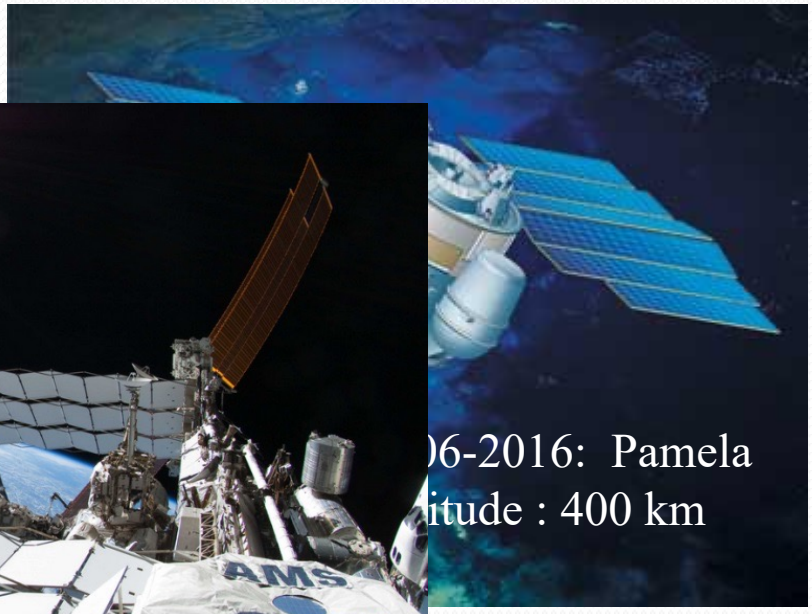
EXPERIMENTS



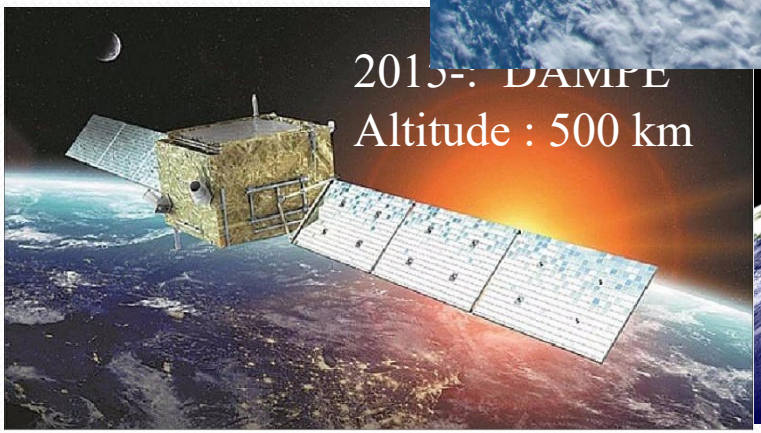
2004-2010: CR
Altitude : 40 kr



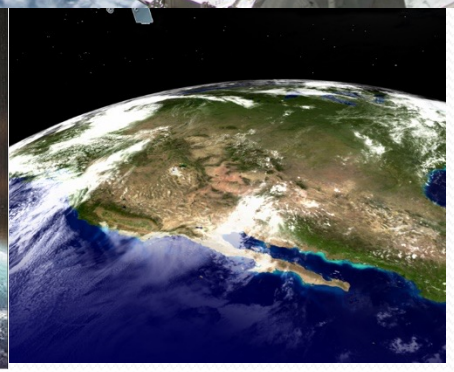
2011-: AMS
Altitude : 400 km
Let's detail this experiment!

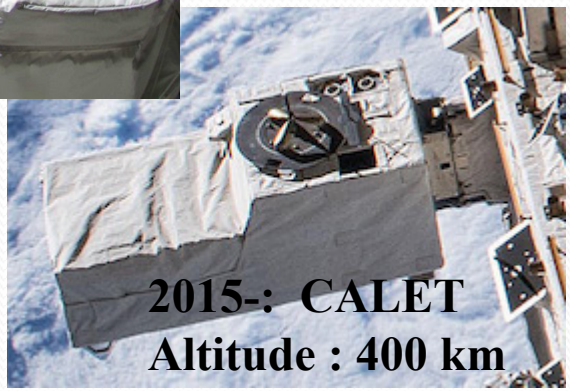


)6-2016: Pamela
itude : 400 km



2015-: DAMPE
Altitude : 500 km





2015-: CALET
Altitude : 400 km

THE AMS-02 EXPERIMENT

AMS-02

- A particle detector in space
  - Detect **charged** particles and **gamma** rays
  - From **100 MeV** to **a few TeV**

5m x 4m x 3m
7.5 tons

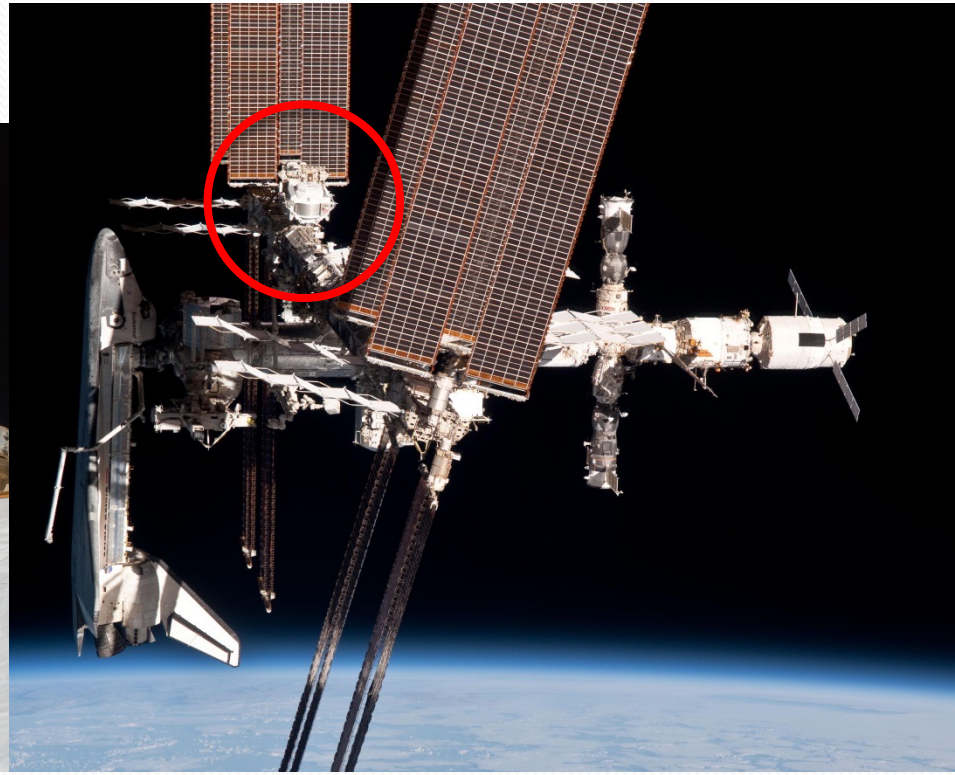
AMS-02

- Launched from Cap Canaveral on the 16th of May 2011
  - **Penultimate** American shuttle!


NASA HD
Spacevidcast Live
STS-134 Mission Coverage
T -00:00:12
Official Clock
SSME Thrust: 0.0%
Altitude (ft): -23
Speed (mph): 0
Range (nm): 0.0
Mach: 0.00
G: 0.0

AMS-02

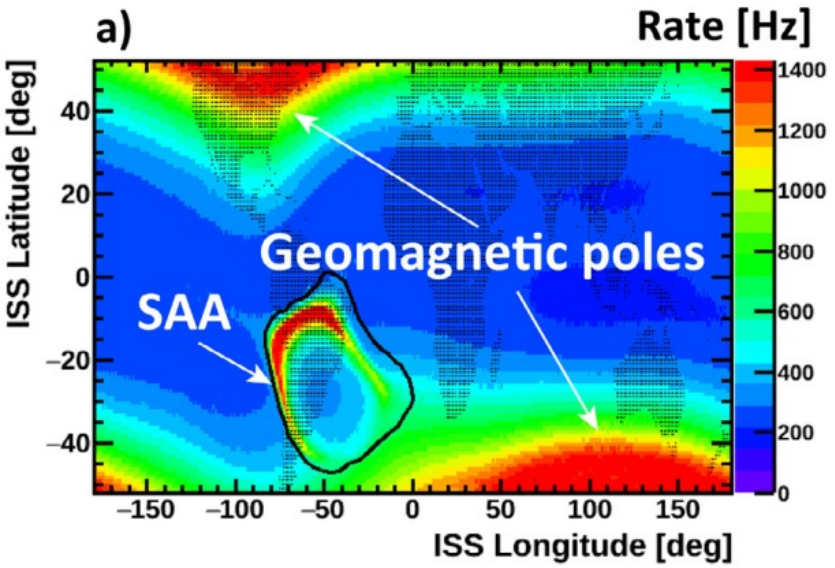
- Installation on the ISS on the 19th of May 2011
  - Orbit at **400 km** altitude
  - One orbit every **90 minutes**



- Detect the cosmic rays before they interact in the atmosphere

FLIGHT OPERATION

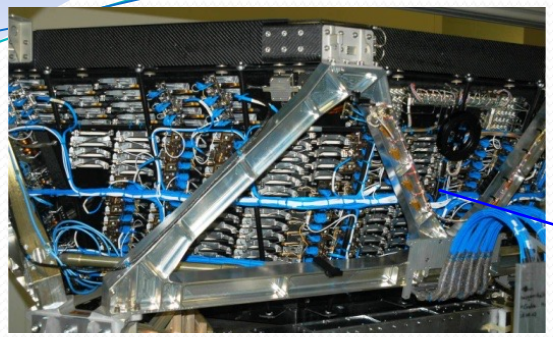
- Acquisition rate from 200 to 1500 Hz
- Continuous operation 7d/7 24h/24
- Acquisition
  - ~**40 millions** events a day
  - ~**100 GB** transferred every day
  - **35 TB** of data every year
  - **200 TB** of reconstructed data every year



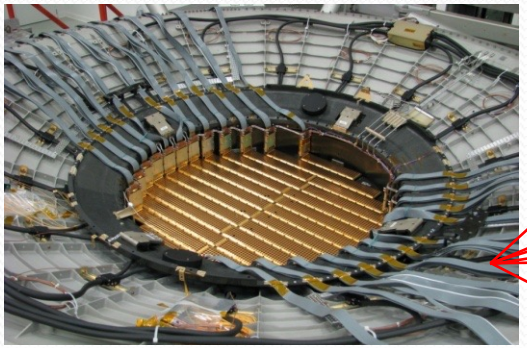
- 265,249,431,591 events recorded since May 2011
  - Much more than all the cosmic rays collected **since the beginning of humanity**
- Will operate until the end of the ISS

DETECTOR

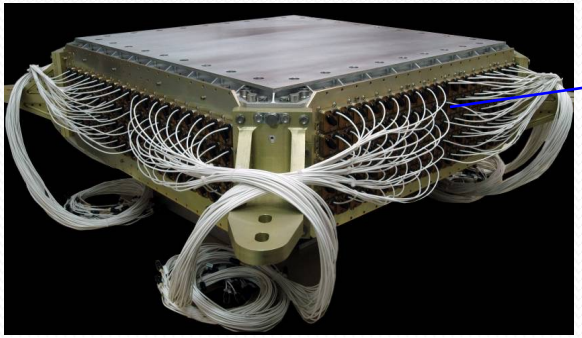
Transition radiation detector
Identifies e^+, e^-

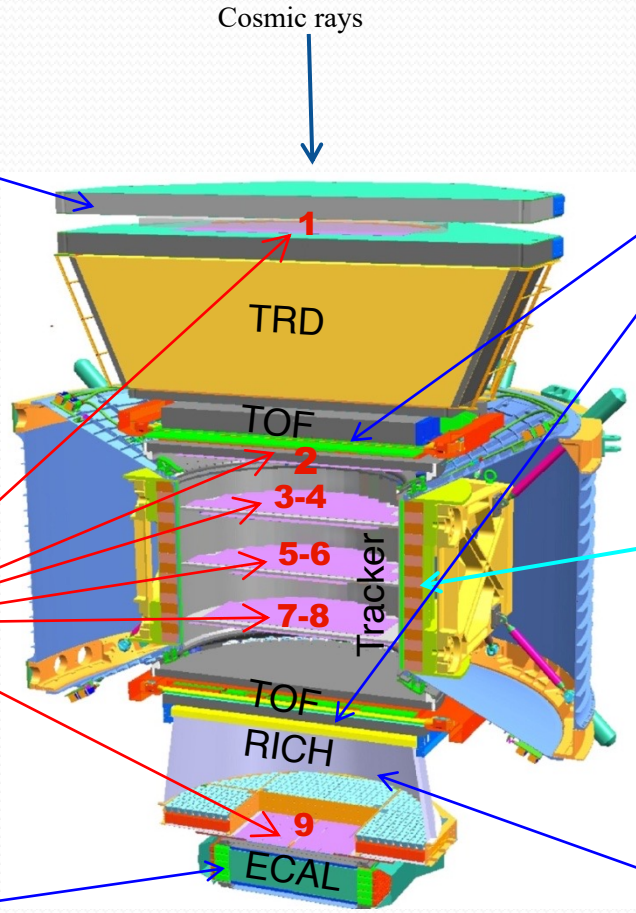


Silicium tracker
Z, P



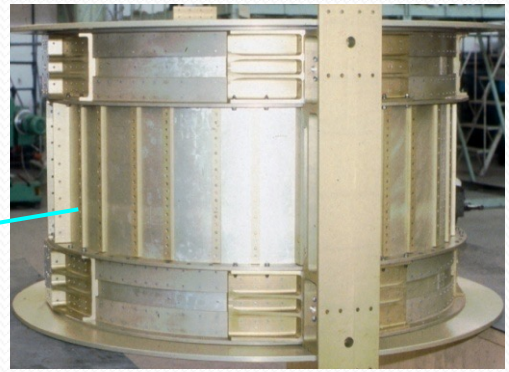
Electromagnetic calorimeter
E of e^+, e^-, γ



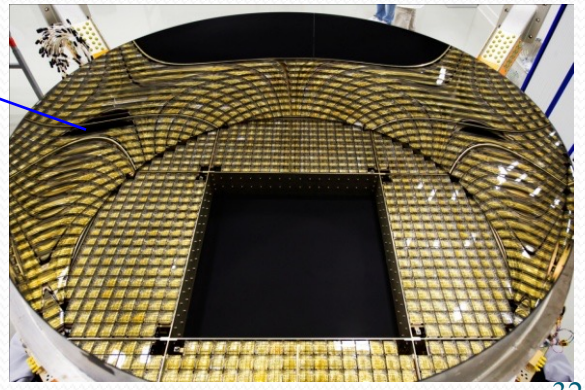


Time of flight
Z, E

Magnet 0,14 T
±Z

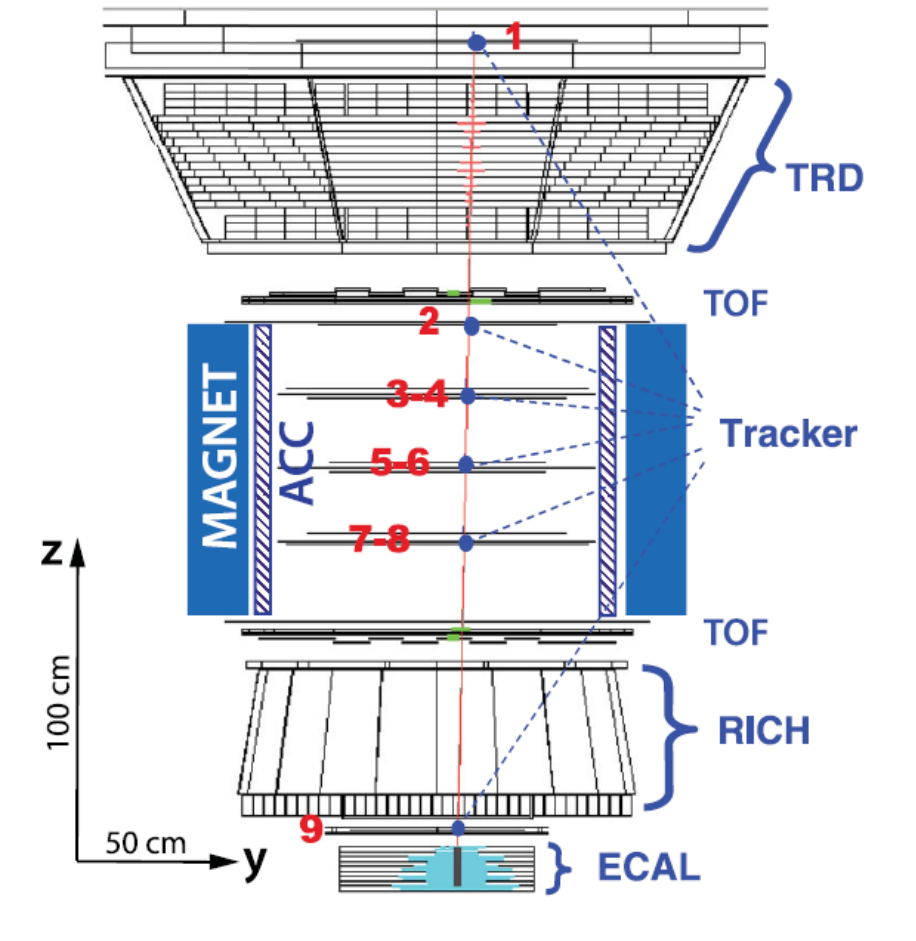


Cherenkov detector
Z, E



DETECTOR

- Rigidity
  - R = p/Z
  - Expressed in GV



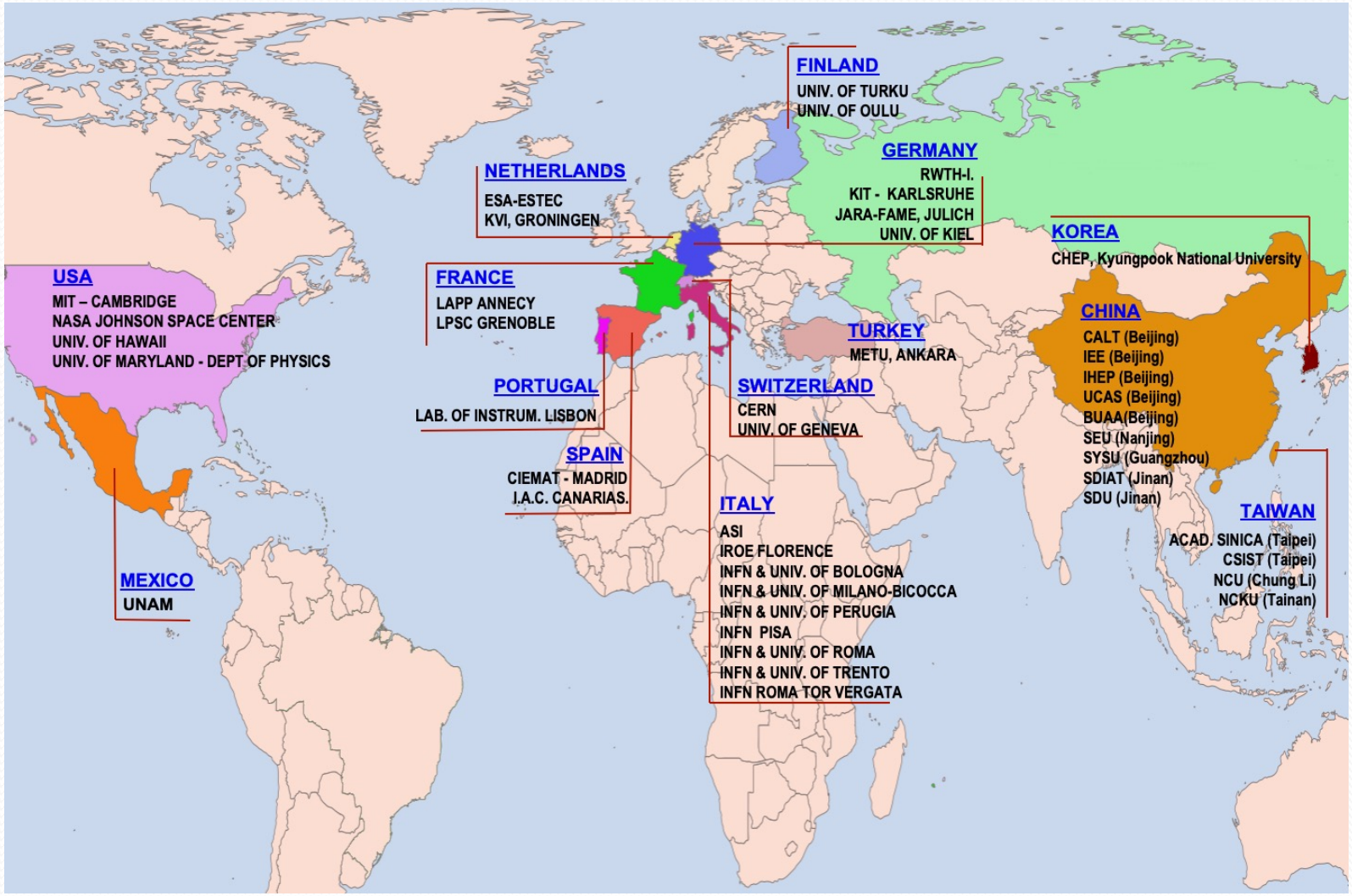
A 369 GeV positron event

COOLING PUMPS

- In 2019, the 4 cooling pumps were problematic
  - Would have been impossible to **cool down the tracker**
- Decision to install 2 new pumps – in space!!
- Most difficult repair ever attempted in space
  - 4 years of preparation at NASA
  - 30 engineers
  - 20 special tools
  - 4 spacewalks
- Realised in 2019 with sucess!
  - AMS can now last… until the **end of the ISS**

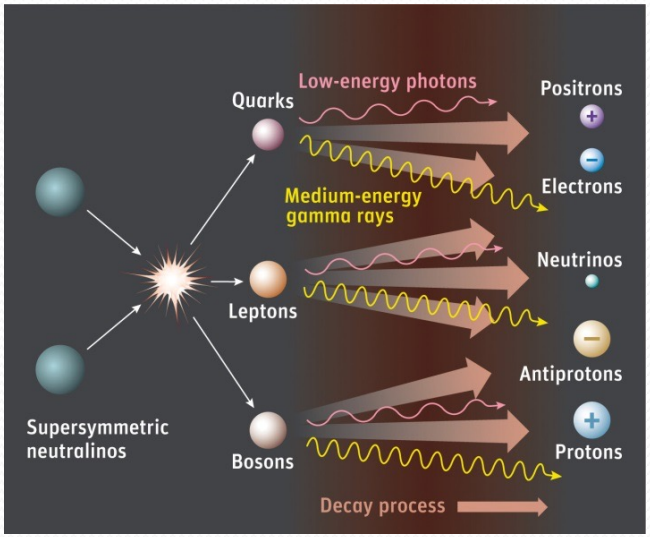
COLLABORATION

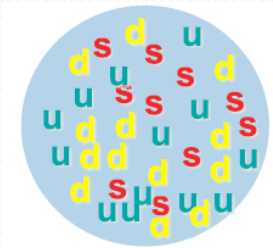
44 institutes from all over the world



AMS TOPICS

- Measurement of cosmic ray fluxes
  - Understand the cosmic ray **propagation** in our Galaxy
- Indirect search of dark matter
  - **Positrons** and **antiprotons** produced during its annihilation
- Search for primordial antimatter
  - **Anti-helium** relic of the Big-Bang or **anti-carbon** from anti-stars
- Solar physics
  - Solar **modulation** over a full cycle
- Surprises? Strangelets?





POSITRONS IN COSMIC RAYS

POSITRONS

- Positrons : expected only as secondary
- Positron excess with respect to the secondary prediction = source of primary positrons

- Challenges
  - **100 times** more protons than electrons
  - **2000 times** more protons than positrons

  $\Rightarrow$ Need to divide number of protons by $\mathbf{10^6}$

- First measurements through the positron fraction

$$F = \frac{\Phi_{e+}}{\Phi_{e+} + \Phi_{e-}} = \frac{N_{e+}}{N_{e+} + N_{e-}}$$

- PAMELA (2009): detection of a positron fraction rise above ~10 GeV $\rightarrow$ an excess?

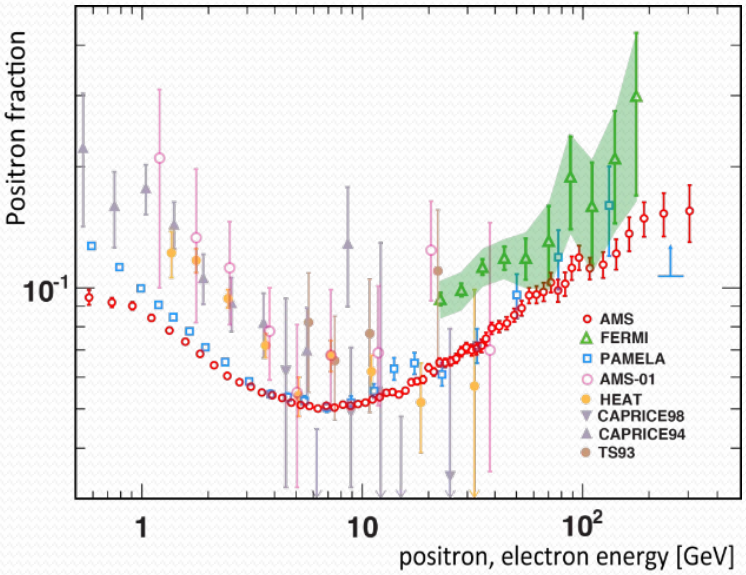
RISE OF THE POSITRONS

- AMS-02 (2013): confirmed with high precision the rise of positrons in the fraction

- Key observations
  - Rise begins at ~10 GeV
  - Reaches ~15% at ~300 GeV
  - Does not follow secondary-only prediction

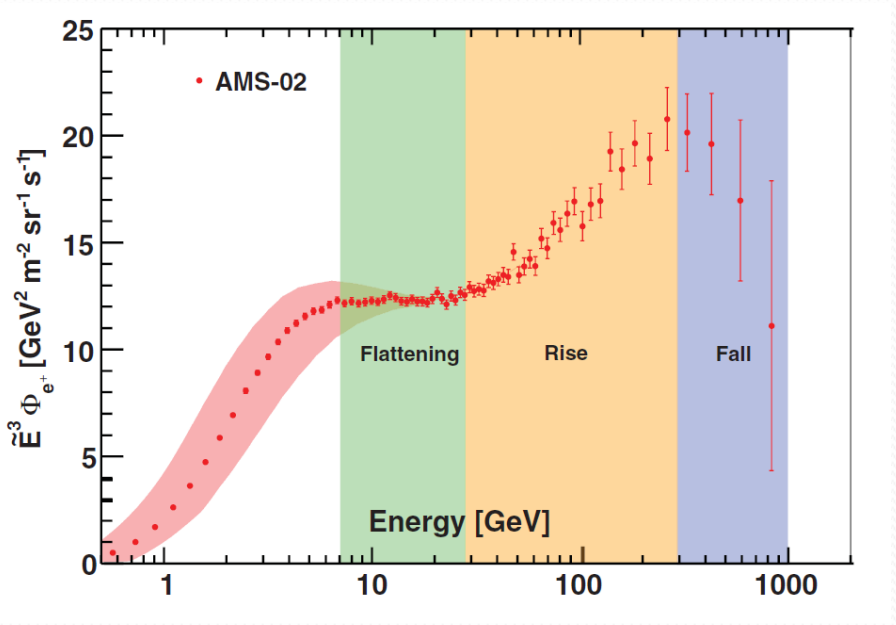
- Implications
  - Possible primary source: **dark matter** or **astrophysical source**
  - Exciting but not conclusive

- Latest AMS-02 results: higher statistics confirm and refine the measurement



FLUX MEASUREMENT

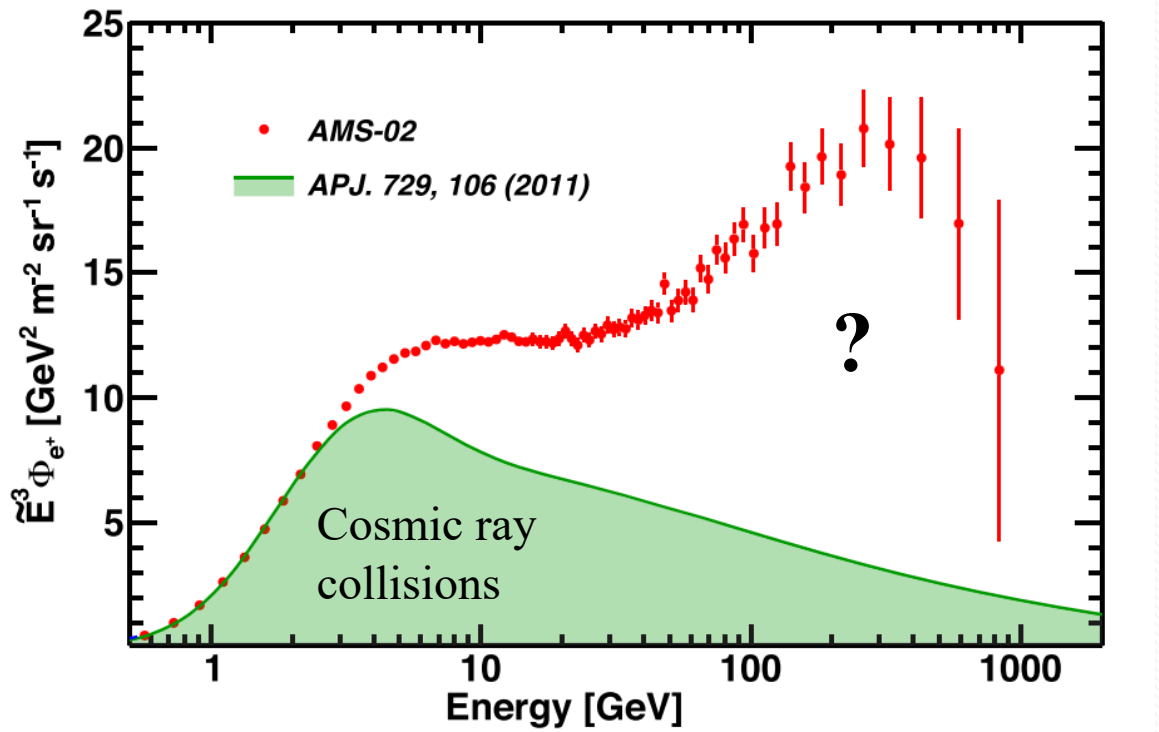
- Obtaining the flux via $\dfrac{N}{A \times \varepsilon_{Trig.} \times \varepsilon_{sel.} \times T \times dE}$
  - N **number** of positrons or electrons
  - A **acceptance**
  - ε_{Trig} and ε_{sel} **trigger** and **selection efficier**
  - T exposure **time**
  - dE energy **bin size**



- 2019 results from AMS (PRL 122, 041102)
  - ~2 M of positrons
  - Measurement **up to 1 TeV**
- Key results
  - Rise after **25 GeV**
  - Exponential cutoff at E ~ 810 GeV
  - First detection of a **cutoff** in cosmic ray positrons

POSITRON EXCESS?

- Secondary positrons from cosmic ray collisions can be predicted



- Incompatible with secondary positrons only
- A source of primary positrons is needed!
  - **Nearby** source since positrons do not propagate more than a **few kpc**

POSITRON EXCESS?

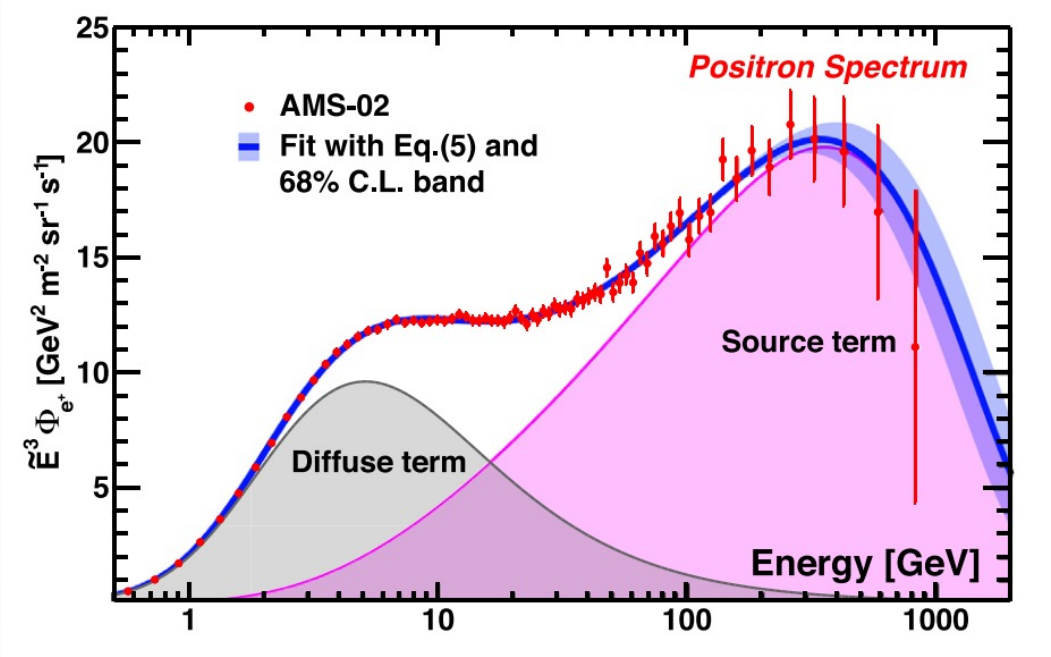
- Empirical model: let's add a term for another source
  - **Low energy part**: cosmic ray collision (diffuse term)
  - **High enery part**: pulsars or dark matter with a cutoff energy

Empirical model: $\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$

χ^2/dof = 40/66

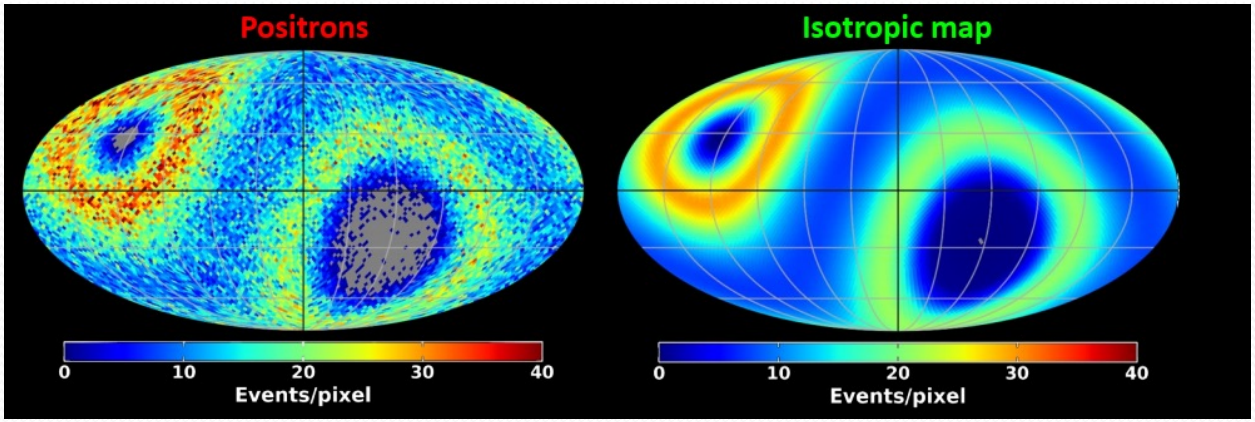
Solar Collisions Pulsars or Dark Matter

- New source
  - Dominant from 25 GeV
  - Rise until 280 GeV
  - Cutoff at 810 GeV
- What is this « source term » ?
  - Cutoff suggests primary source with finite mass
  - **Dark matter** at 1.2 TeV?
  - Alternative: nearby **pulsars**



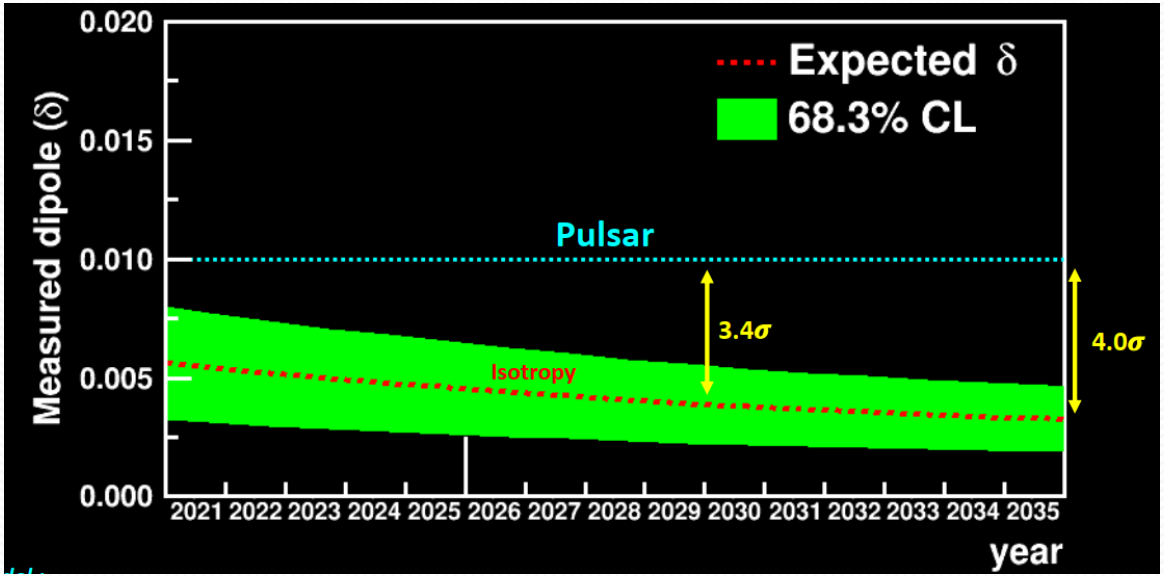
POSITRON ANISOTROPY

- To distinguish between the two scenarios, dark matter or pulsar, we look for anisotropy in the arrival direction of positrons
  - Preferential direction (pulsar) or isotropy (dark matter)?



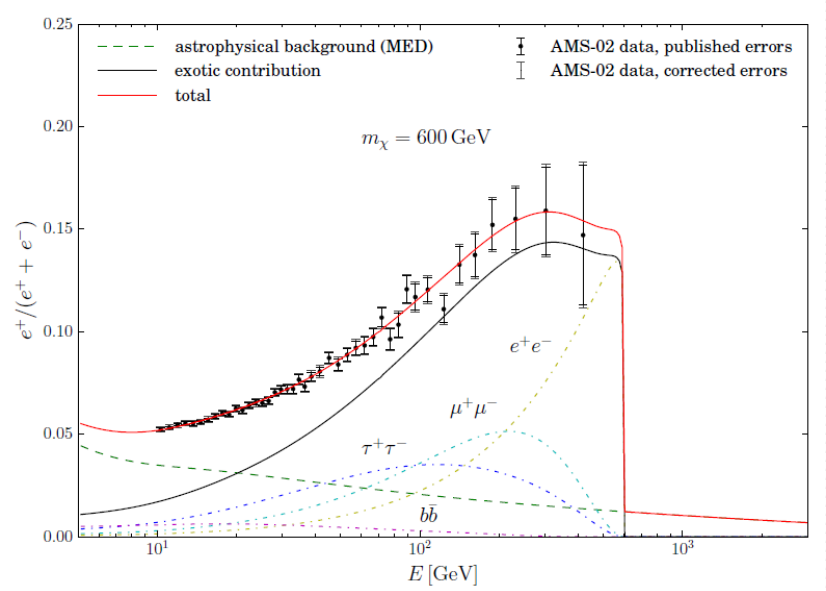
Left: measured positron sky map.
Right: expected sky map for an isotropic positron flux, accounting for the ISS orbit and detector exposure.

- Currently
  - For 16 < E < 500 GeV
  → **$\delta e^+ < 0.0144$** (95% CL)
- In a few years from now, should be able to have a **clearer answer**



INTERPRETATION: DARK MATTER

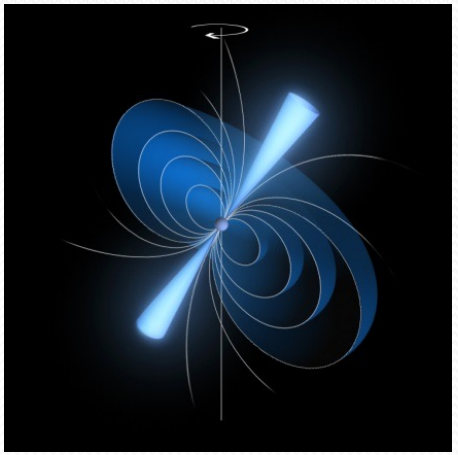
- Fitting the positron fraction using the best combination of annihilation channels



A&A 575, A67 (2015)

- Dark matter may explain the fraction, but unnatural annihilation cross-section
  - ×**1000** compared to the one expected from the relic density
- Not likely that we have observed an indirect observation of dark matter
  - **In tension** with other observables (antiprotons, gamma rays, …)

INTERPRETATION: PULSARS

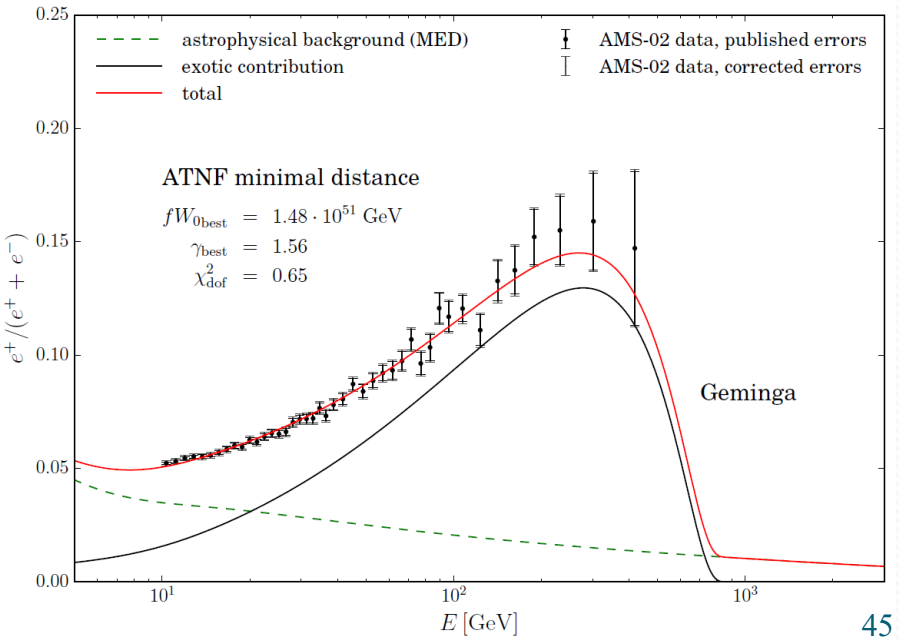


- Neutron stars spinning at high rate with a strong magnetic field
- 200 pulsars at less than 2 kpc from Earth
  - Only a **small fraction** able to emit positrons
- Mechanism
  - **Electrons extracted** from the surface by the high fields

    $\Rightarrow$ electrons produce **synchrotron photons**

    $\Rightarrow$ photons produce **e^+-e^- pairs**

    $\Rightarrow$ Some **escape** from the pulsar
- Precise prediction very difficult
- Five closeby pulsars able to explain the fraction

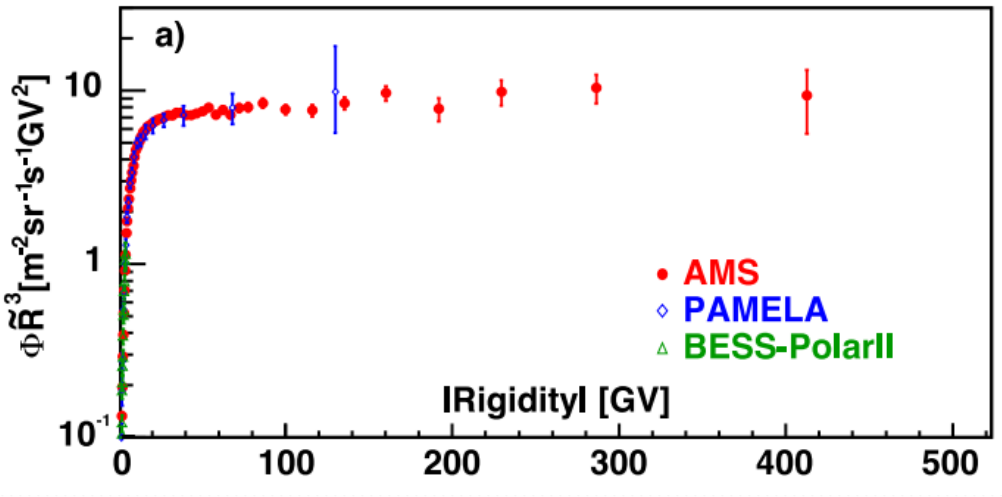


A&A 575, A67 (2015)

ANTIPROTONS IN COSMIC RAYS

ANTIPROTONS

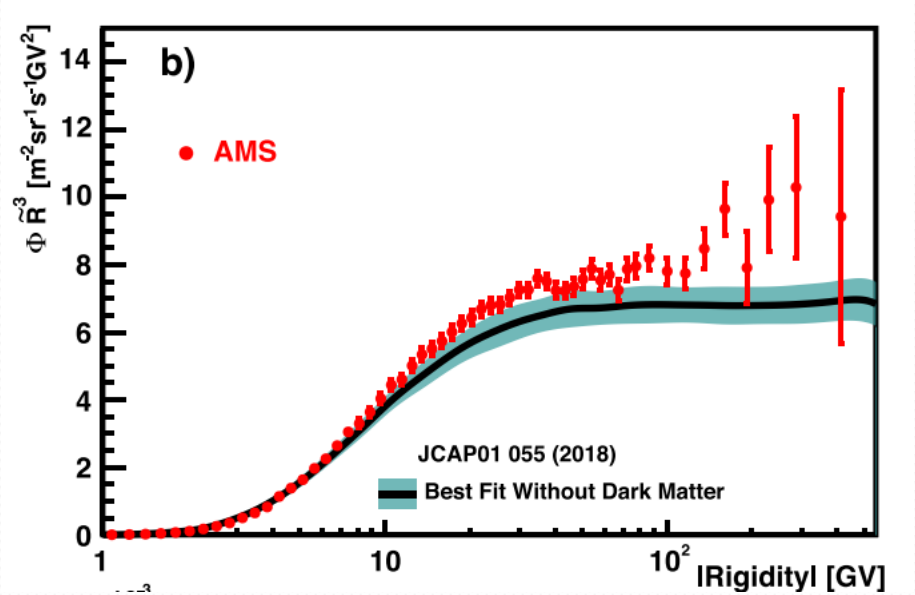
- Dark matter could create an excess of antiprotons with respect to the expectations
  - Pulsars **do NOT** produce antiprotons
- AMS measured the flux of $\bar{p}$
  - 560 000 antiprotons collected
  - $10^4 \times$ less $\bar{p}$ than p
- Constant (xE^3) after 40 GV
  - Expected?



- Is dark matter necessary to explain this measurement?
  - (Used to be) a controversial topic!
  - Need to compute what is expected from **secondary antiprotons**

ANTIPROTONS

- Adding the contribution of the secondary antiprotons with its uncertainty
  - Propagation uncertainties
  - Production cross-section uncertainties
- Comparison of data and expectations for $\bar{p}$ (



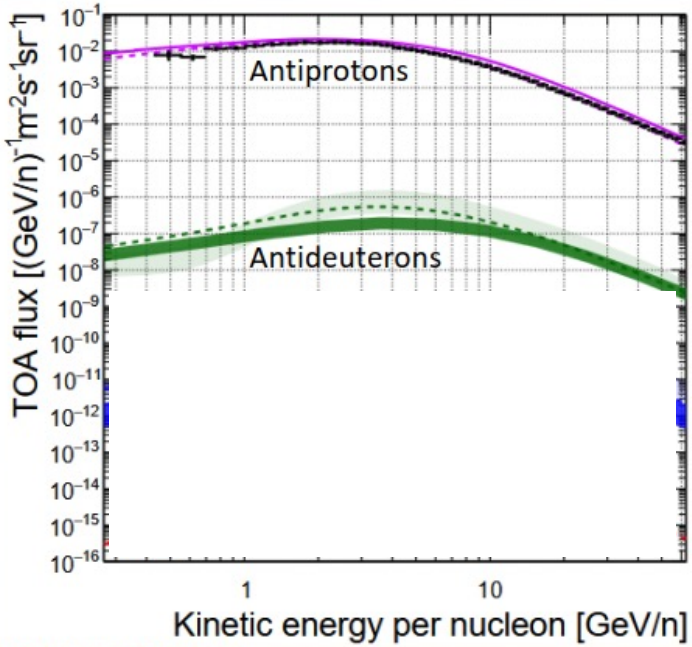
- The $\bar{p}$ flux is not in discrepancy with the expectations
  - Favored interpretation: AMS antiprotons are predominantly **secondaries**
  - **No dark matter** needed here

ANTINUCLEI

- Complex antimatter has never been observed in space
- Looking for **antideuteron** and **antihelium**

ANTIDEUTERON

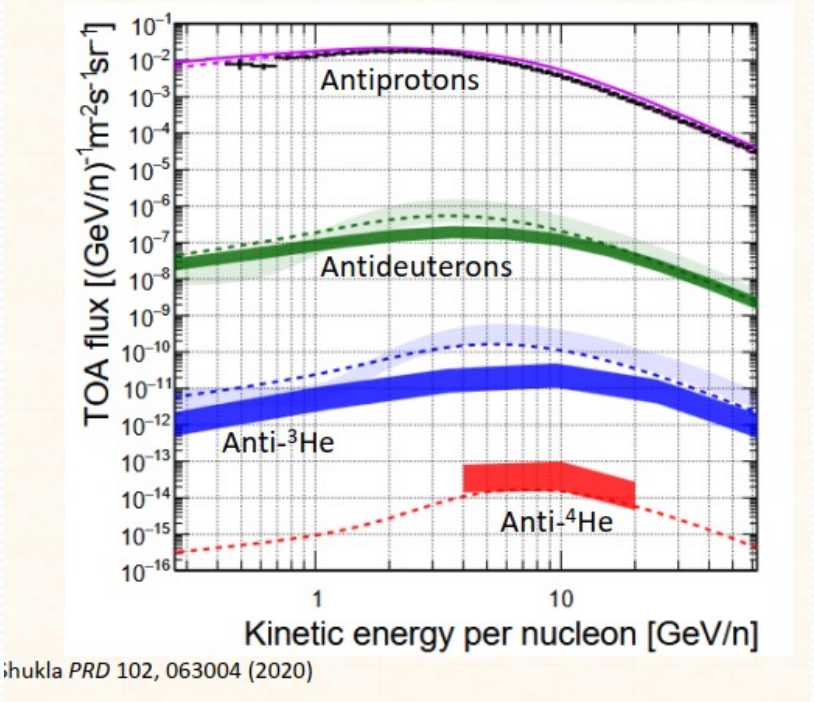
- $p+p \rightarrow \bar{p}+\bar{n}+X$, followed by coalescence $\bar{p}+\bar{n} \rightarrow \bar{d}$
  - Secondary antideuterons are **extremely rare**
- Antideuterons provide one of the cleanest indirect dark matter signatures
- AMS results
  - **Some antideuteron** candidates seen
  - Shown in conference, never published
  - Needs a confirmation
- AMS may have a first measurement of (secondary) antideuterons in the near future



hukla *PRD* 102, 063004 (2020)

ANTIHELIUM

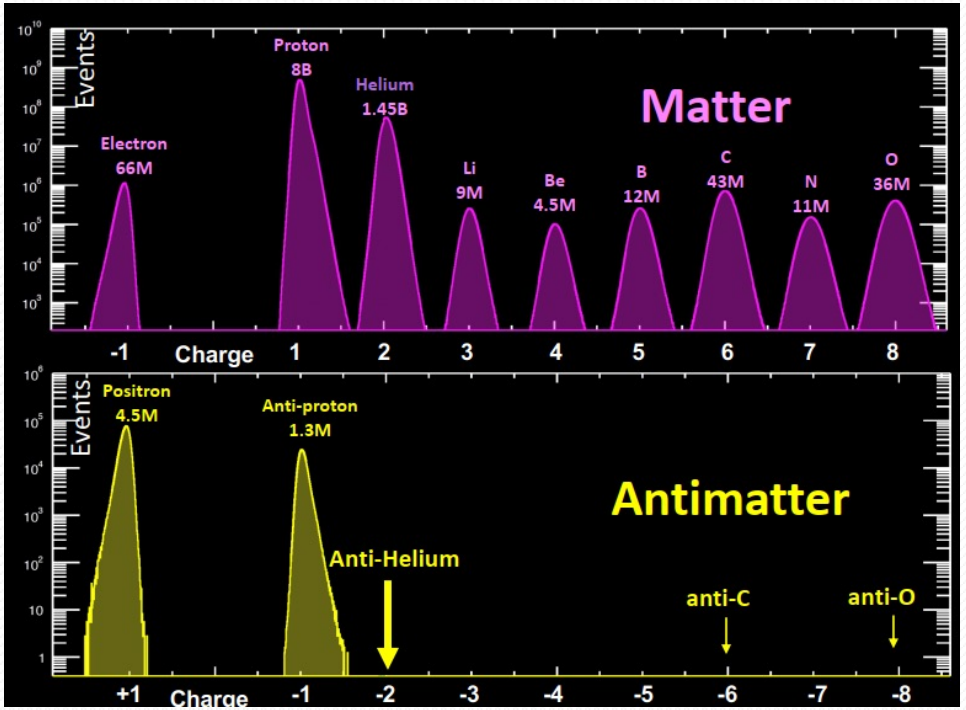
- Antihelium ($^3\overline{\text{He}}$, $^4\overline{\text{He}}$) would be unambiguous evidence of primordial antimatter domains or anti-stars
  - Secondary production **highly suppressed**
  - Almost **no background**
- Antihelium very difficult to observe
  - Goal: find couple of candidates among millions of events, with a tiny S/B



hukla *PRD* 102, 063004 (2020)

ANTIHELIUM

- AMS-02 observation
  - **A few candidate events** with Z = -2, mass consistent with $^{3}\overline{\text{He}}$, $^{4}\overline{\text{He}}$
- Never confirmed in publications
- And no candidates shown at ICRC 2025
- More statistics needed
  - **No consensus** on the origin of the events

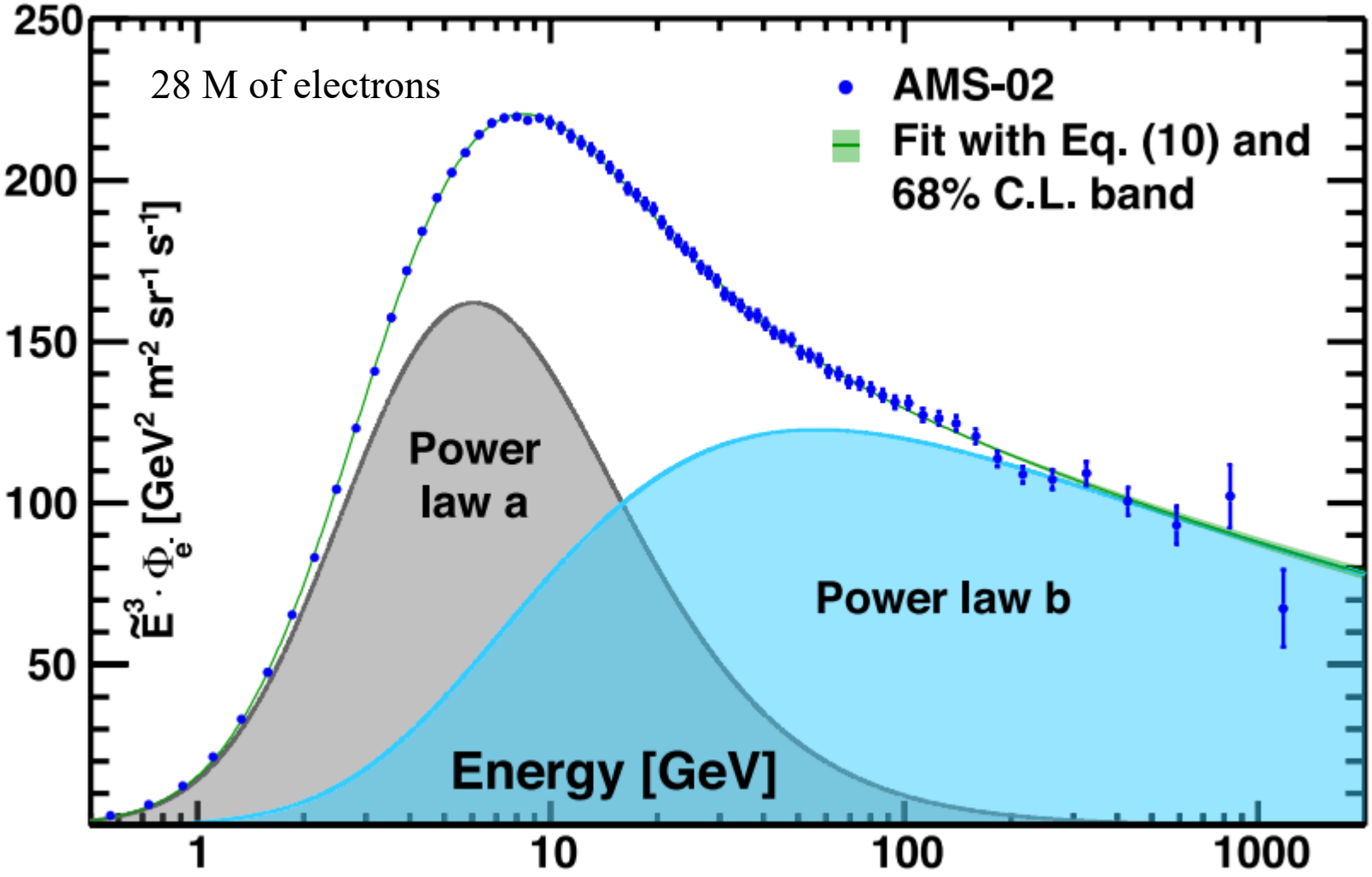


SUMMARY

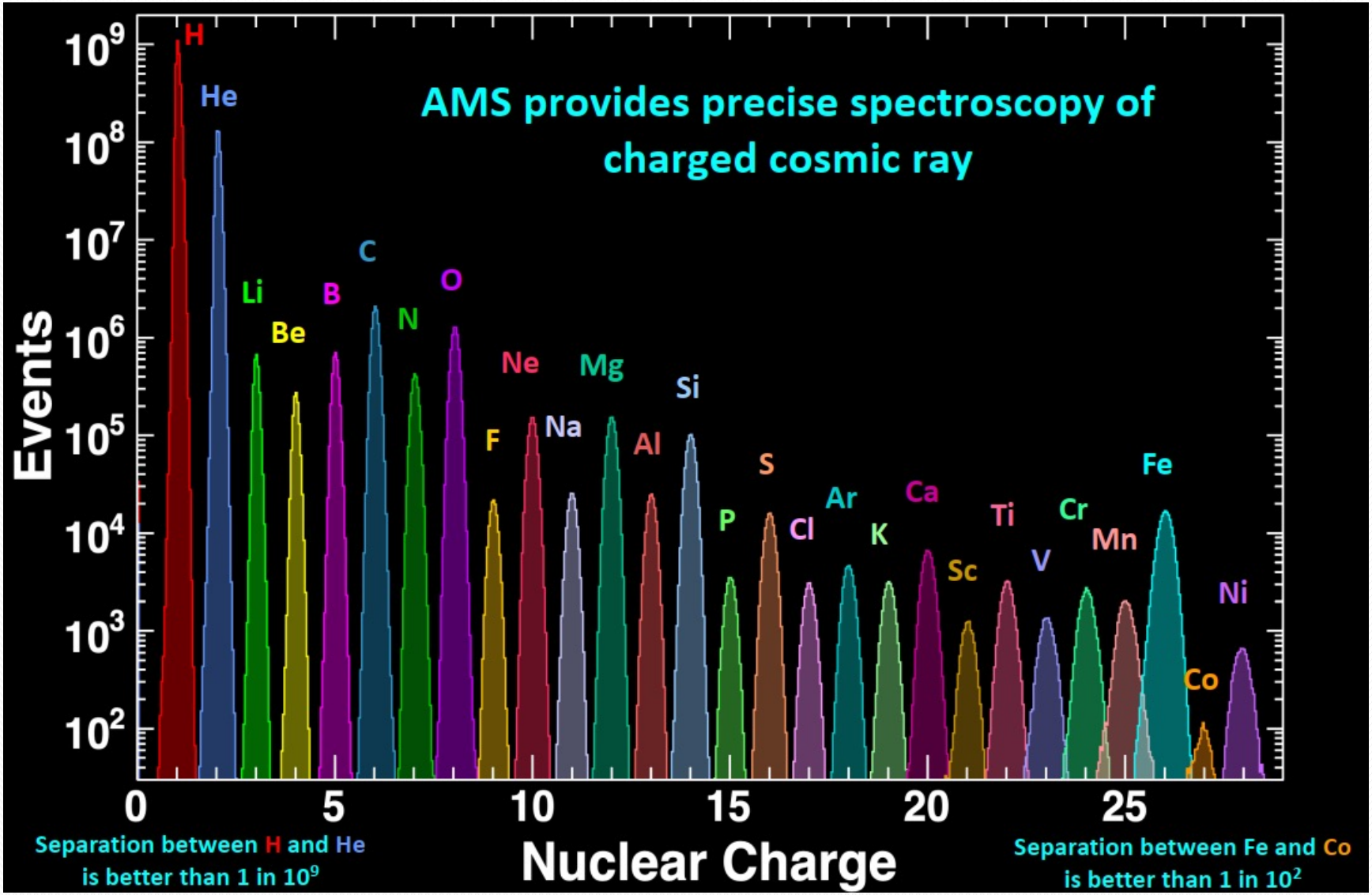
- Positrons
  - Very important background
  - Confirmed rise above 30 GeV
  - Cutoff at ~810 GeV
  - Primary source: probably pulsars
- Antiprotons
  - Important background
  - Precise measurement to 450 GV
  - Consistent with secondary
  - Strong dark matter constraints
- Antideuteron
  - Very small background
  - Candidate events observed
  - Under investigation
  - Would be the discovery of the decade
- Antihelium
  - No background at all
  - Candidate events observed
  - Under investigation
  - Would be an outstanding discovery

OTHER RESULTS ON COSMIC RAYS

ELECTRONS


28 M of electrons
AMS-02
Fit with Eq. (10) and 68% C.L. band
Power law a
Power law b
Energy [GeV]
$\tilde{E}^3 \cdot \Phi_e$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
250
200
150
100
50
1
10
100
1000

NUCLEI

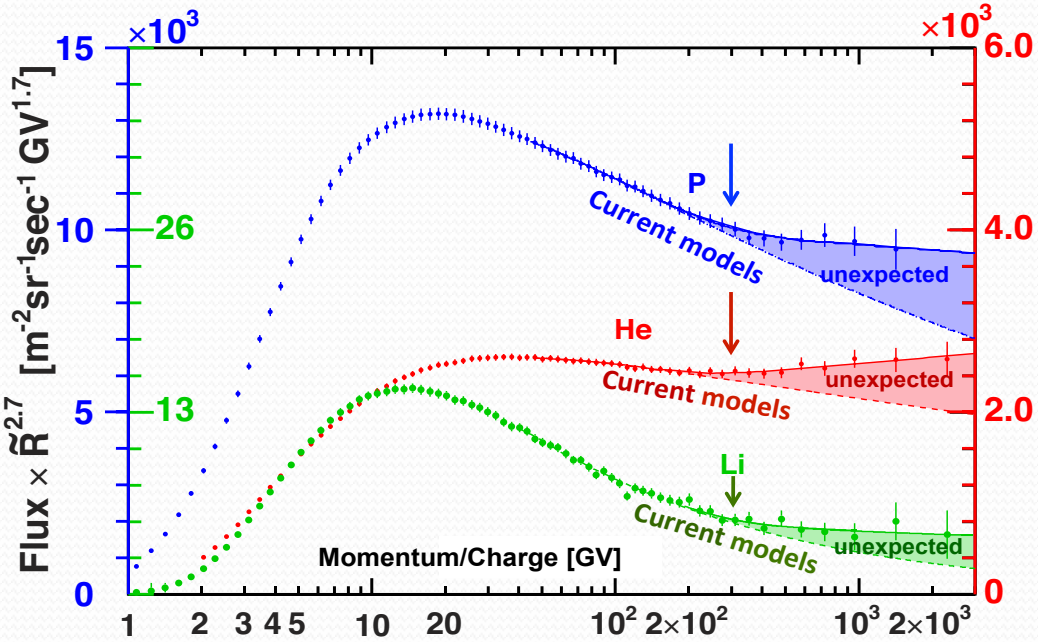

AMS provides precise spectroscopy of charged cosmic ray
Events
Nuclear Charge
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Separation between H and He is better than 1 in 10^9
Separation between Fe and Co is better than 1 in 10^2

NUCLEI

- Primaries p, He, C, O, Si, …, Fe are produced in stars and accelerated by supernovae
- Secondaries Li, Be, B, and F are produced by the collision of primaries with the interstellar medium
- Measurements of the cosmic ray nuclei fluxes are important in understanding their origin, acceleration, and propagation processes in the Galaxy

NUCLEUS ANOMALY

- Unexpected observation: the power law is broken at high energy

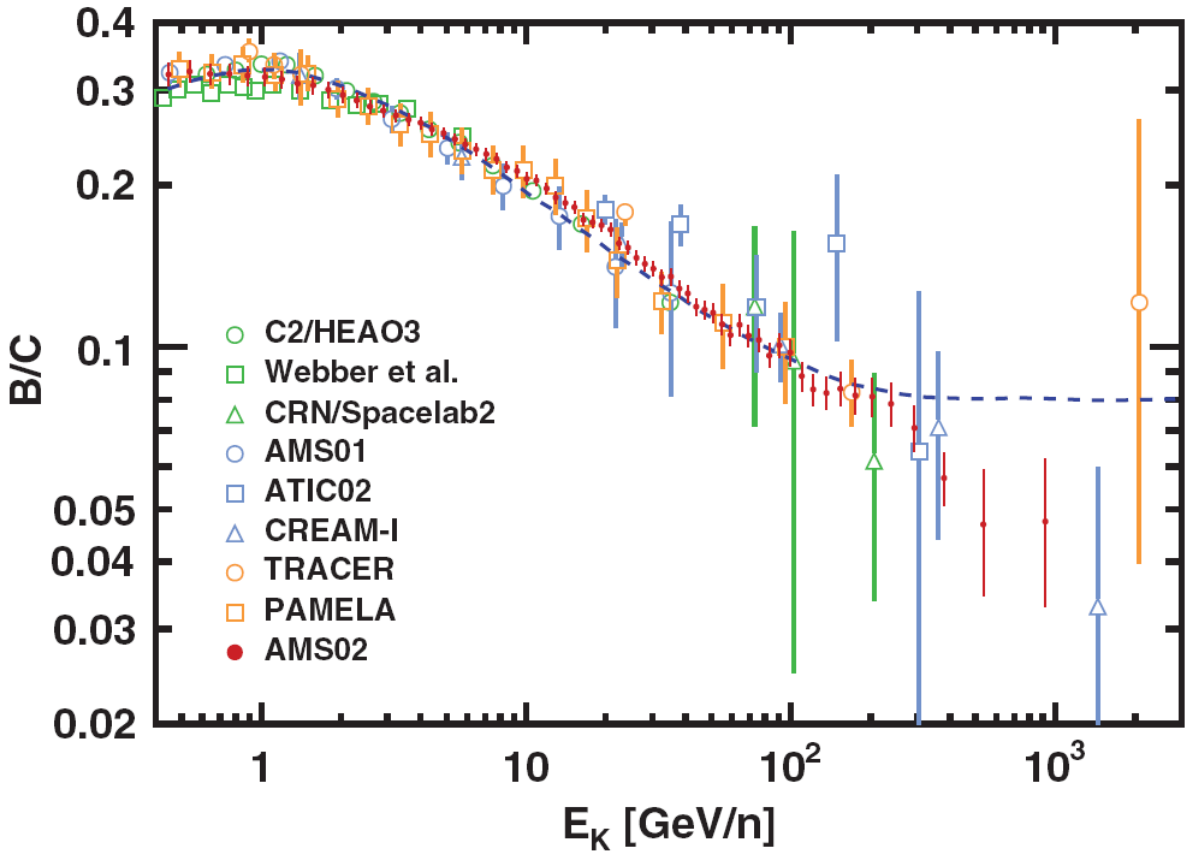


- What can cause these anomalies?
  - Sources?
  - Acceleration?
  - Propagation?
- Still an open question!

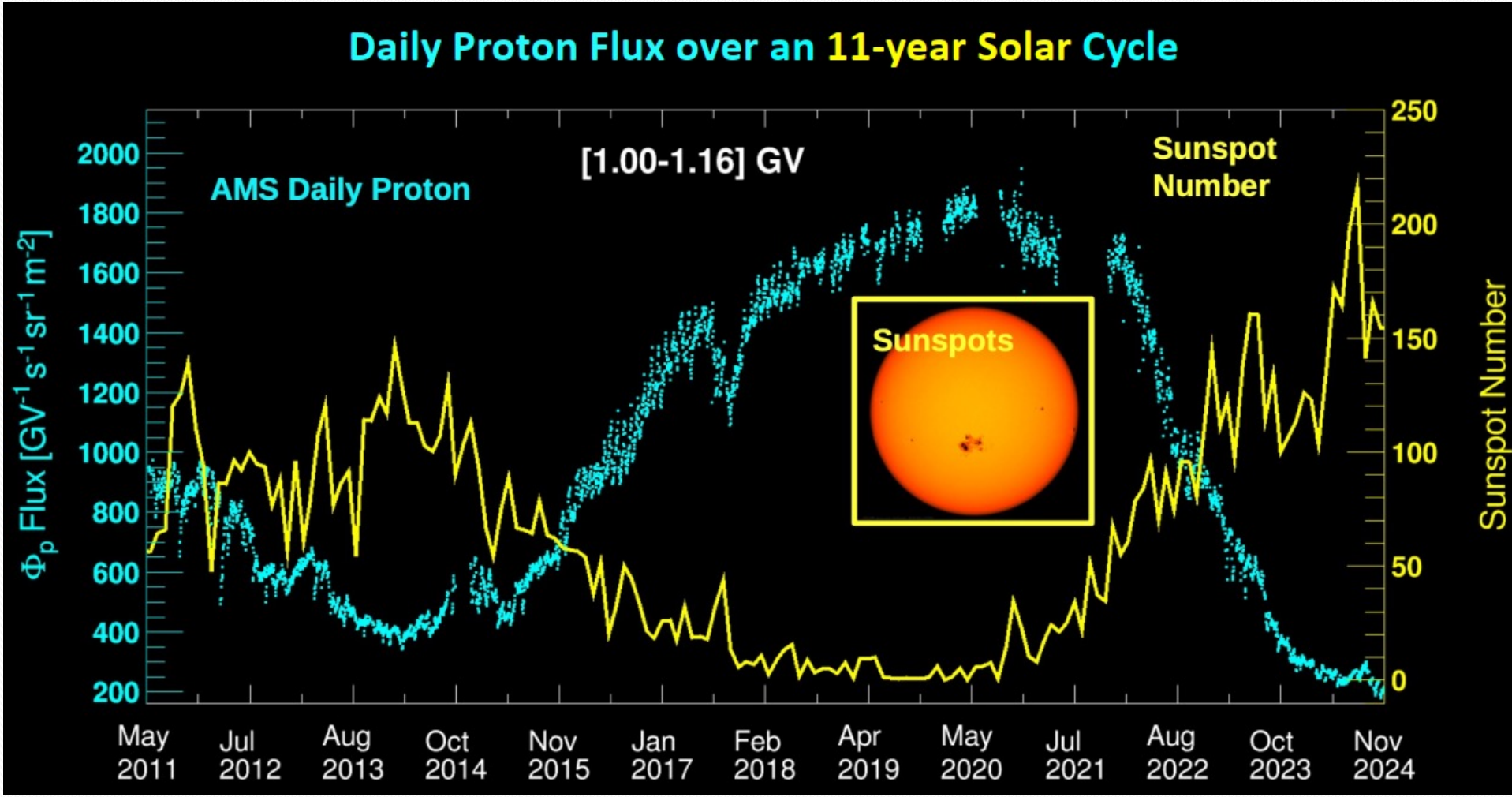
BORON/CARBON RATIO

- Ratio of secondary over primary allows to understand the propagation of cosmic rays
  - **Carbon**: primary, produced and accelerated in sources
  - **Boron**: secondary, produced by the collision of heavier nuclei on the interstellar matter
  - **Ratio** directly measures the average amount of interstellar material traversed by the cosmic rays

Bonus: a break in the B/C ratio would explain the nucleus anomaly by propagation phenomena



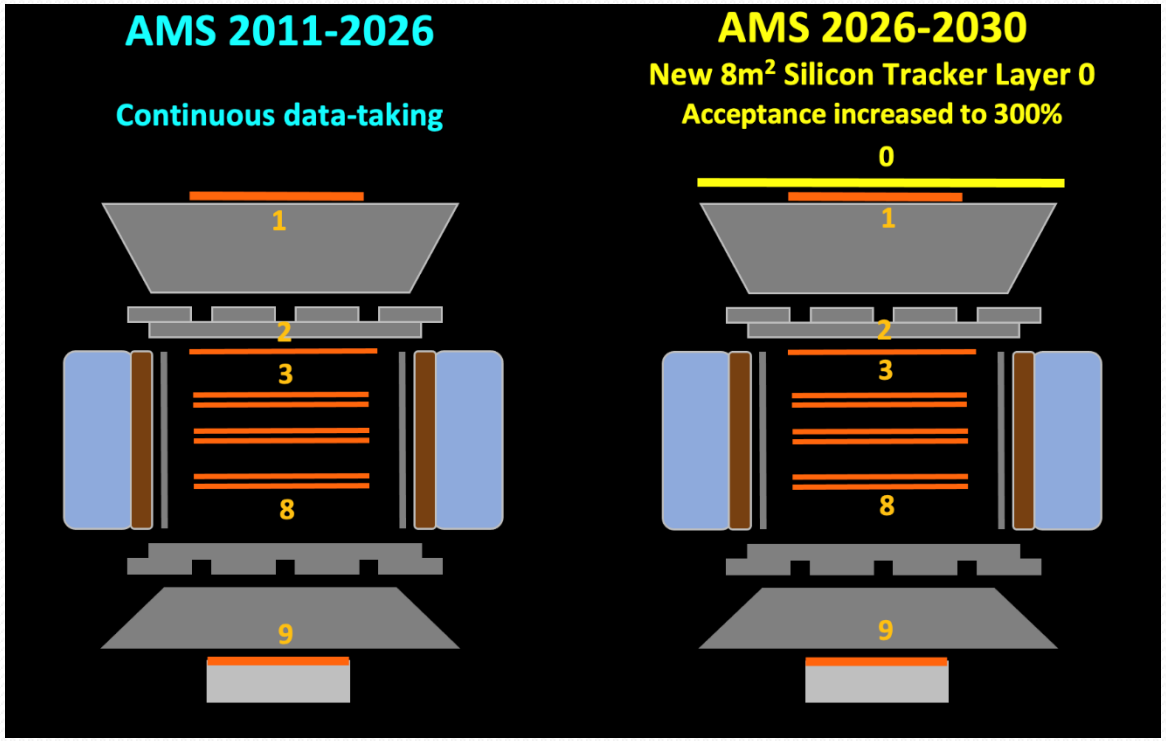
SOLAR PHYSICS



THE FUTURE

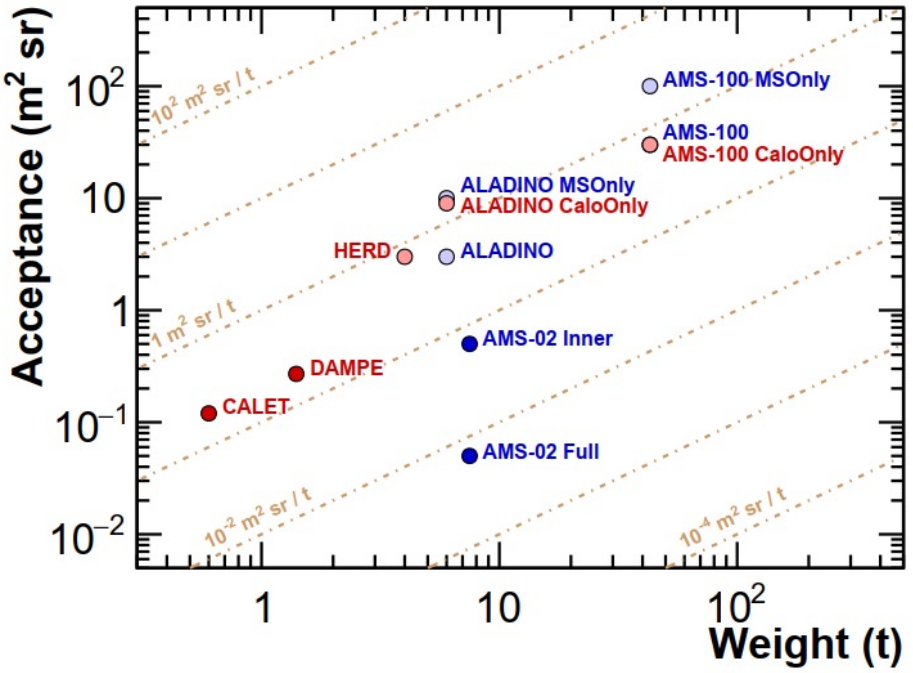
LAYER 0 UPGRADE

- In 2026, a big challenge for AMS with the layer-0 upgrade
- A new silicon tracker layer will be mounted on the very top of AMS-02 via the ISS robotic arm
  - the energy reach will extend to **2 TeV** by 2030
  - Acceptance increased by **300%**
  - Statistical error halves
  - By 2030: distinguish pulsars from DM with 99.93% confidence
- Installation in 2026
  - **Spacewalk** required
  - Stay tuned!



BEYOND AMS-02

- Experiments in operation in space
  - **DAMPE** (since 2015)
  - **CALET** (since 2015)
  - **GAPS**
    - Balloon experiment, focusing on antideuterons
    - Launched in 2025, analysis not yet published
- Projects
  - **HERD**
    - On the Chinese space station
    - Launched in 2027?
  - **HELIX**
    - Balloon experiment, focusing on isotopic measurements
    - 1 Tesla spectrometer
  - **ALADinO**
    - Superconducting magnet, large acceptance
    - At L2 Lagrangian point
    - Just a concept right now
  - **AMS-100**
    - Giant magnetic spectrometer
    - At L2 Lagrangian point
    - 100 m^2 acceptance, 100 TV rigidity reach, 1000× antimatter sensitivity
    - Just a concept right now
- Up to now, and for a long time, AMS is unique because of its magnet, its acceptance, its exposure time



IN SUMMARY

- Sources of charged cosmic rays
  - At intermediate energies, they come from **supernova remnant** in our Galaxy
  - Protons, electrons, … come directly **from the source**
  - Positrons, antiprotons, … are created by **collision** with the interstellar medium, with a rate that **can be predicted**
  - Are there some **sources of antimatter** in space?

- Positrons in cosmic rays
  - There is **more positrons** at high energy compared to the expectations
  - **New source**: dark matter? pulsars? **Most probably pulsars!**
- Antiprotons in cosmic rays
  - Antiprotons observed in AMS compatible with **secondary production**
- Antideuteron and antihelium
  - A **few events** reported (but not published) by AMS
  - Need a **strong confirmation**, would be a outstanding discovery
- AMS advanced knowledge on many other topics for charged cosmic rays

- After 15 years, AMS will be upgraded, and will extend its energy range and its acceptance
  - Stay tuned for **more results!**

THANK YOU!