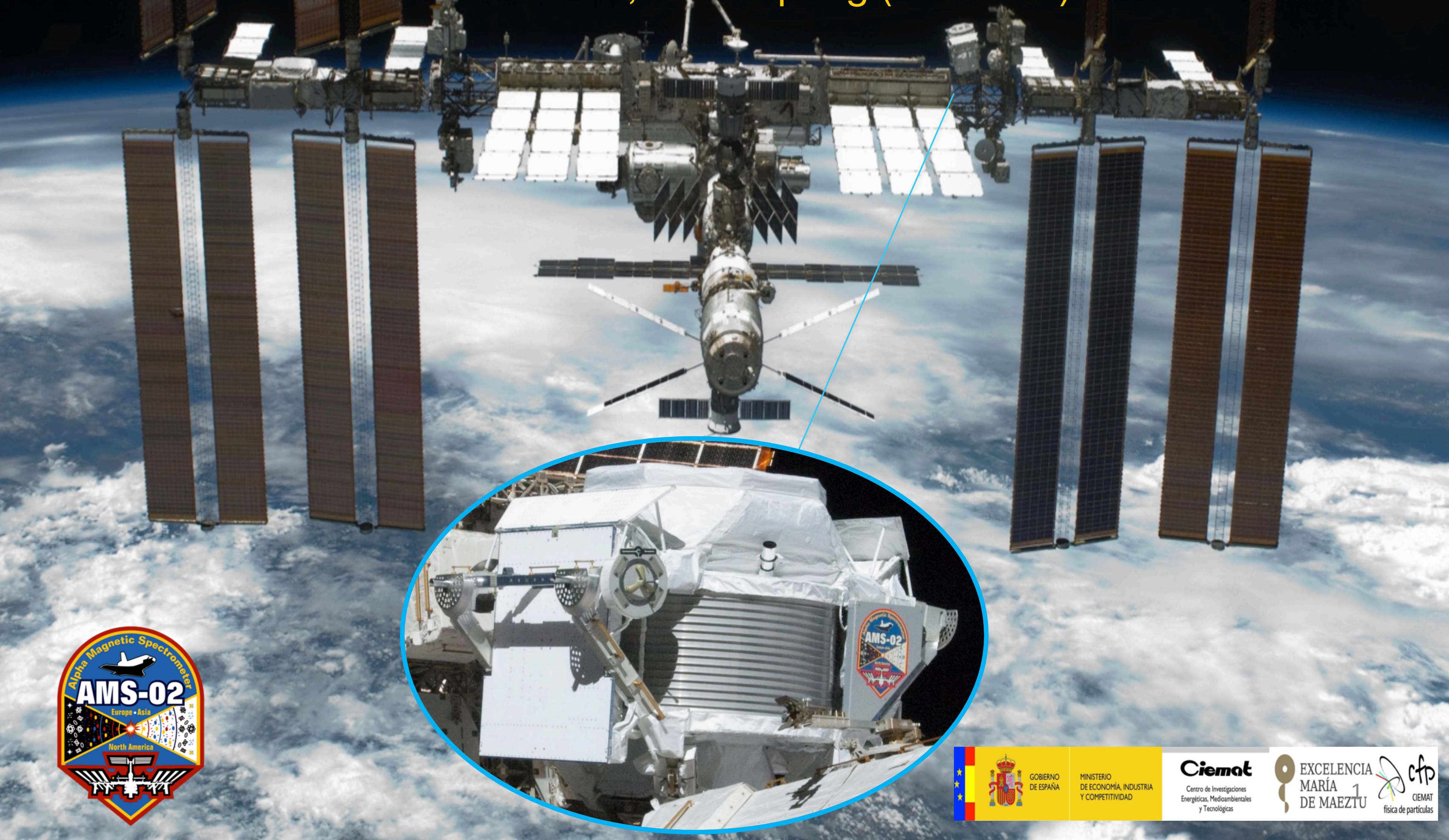
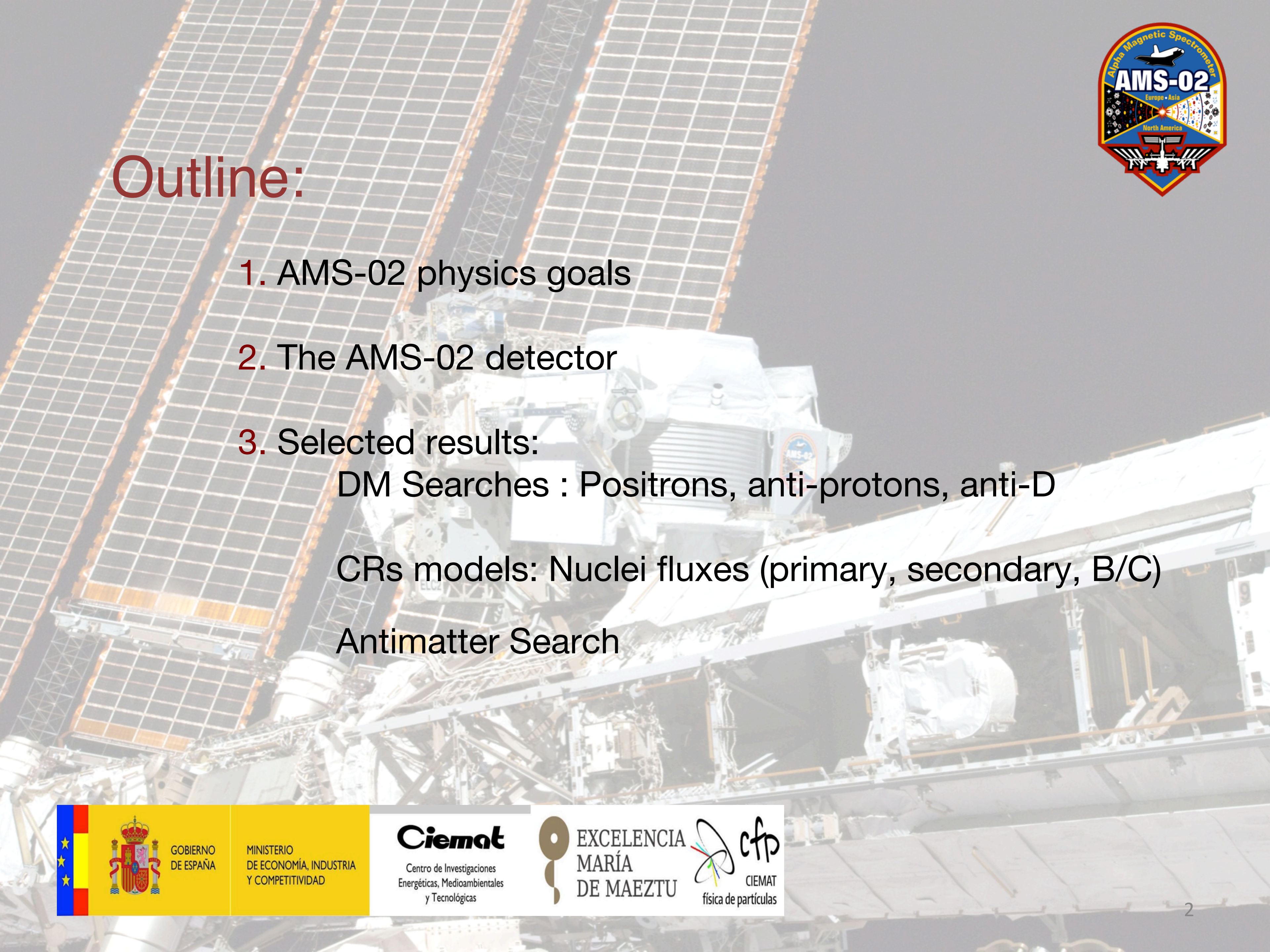
Latest Results from the Alpha Magnetic Spectrometer on the International Space Station

F. Giovacchini
on behalf of the AMS Collaboration
CIPANP 2018, Palm Spring (California)



GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
cfp CIEMAT física de partículas



Outline:

1. AMS-02 physics goals

2. The AMS-02 detector

3. Selected results:

   DM Searches : Positrons, anti-protons, anti-D

   CRs models: Nuclei fluxes (primary, secondary, B/C)

   Antimatter Search

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
cfp CIEMAT física de partículas

Outline:

1. AMS-02 physics goals

2. The AMS-02 detector

3. Selected results:
    - DM Searches : Positrons, anti-protons, anti-D
    - CRs models: Nuclei fluxes (primary, secondary, B/C)
    - Antimatter Search

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

EXCELENCIA MARÍA DE MAEZTU

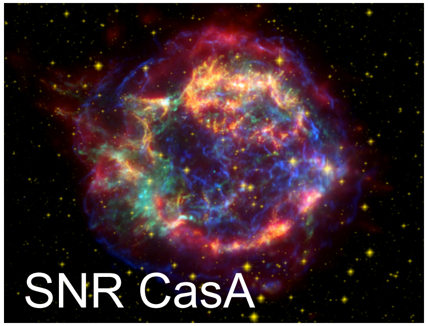
cfp CIEMAT física de partículas

Cosmic Rays

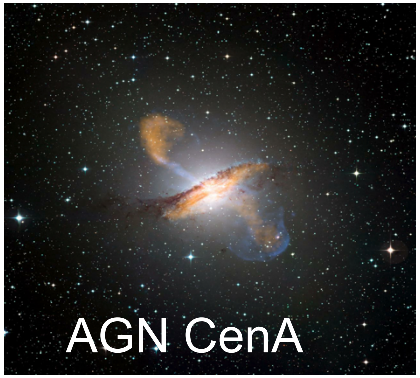
Cosmic rays are a sample of solar, galactic and extragalactic matter which includes all known nuclei and their isotopes, as well as electrons, positrons and antiprotons

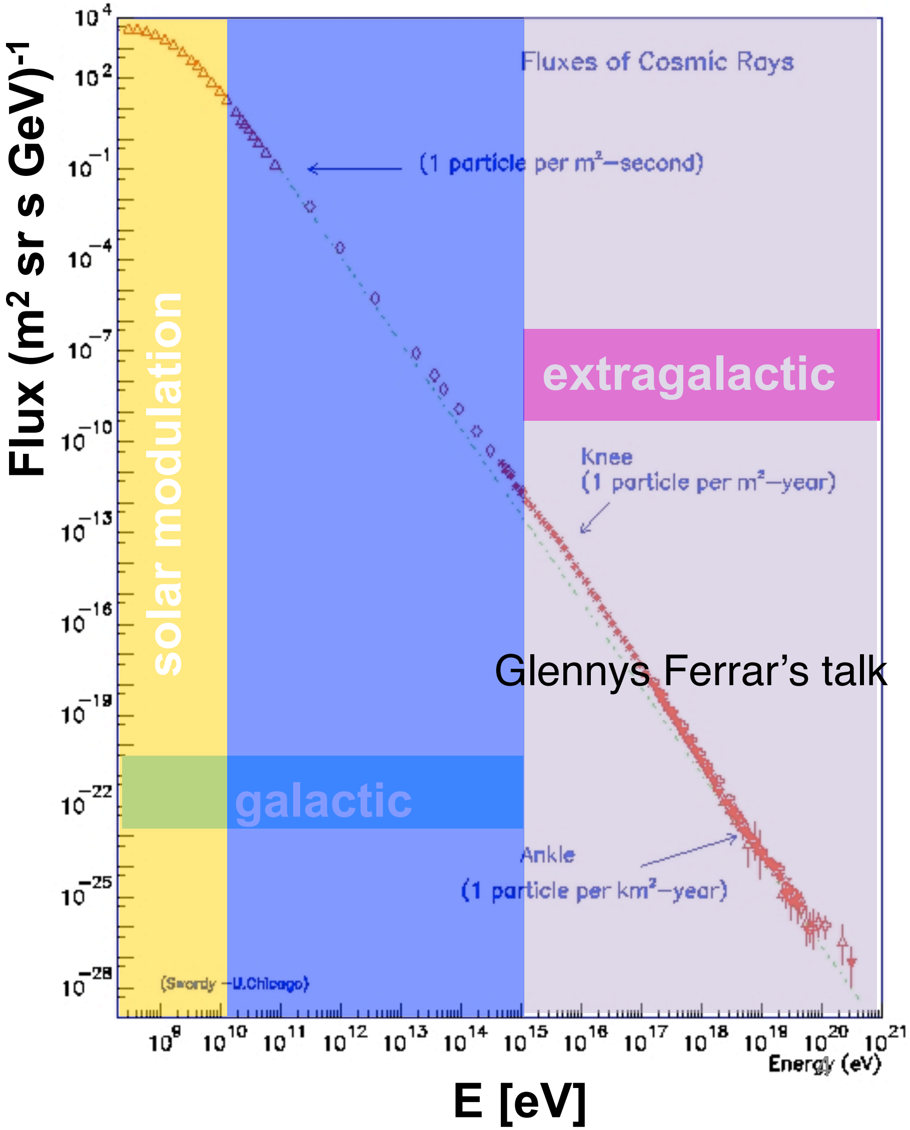
Solar CRs:
1.5 -10 keV

Galactic CRs
100 MeV-1 PeV



Extragalactic CRs
1 PeV -1 ZeV

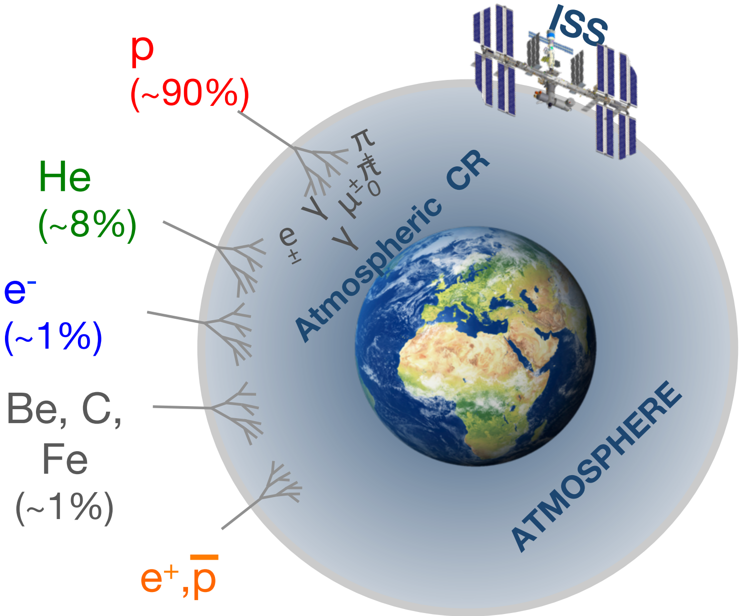


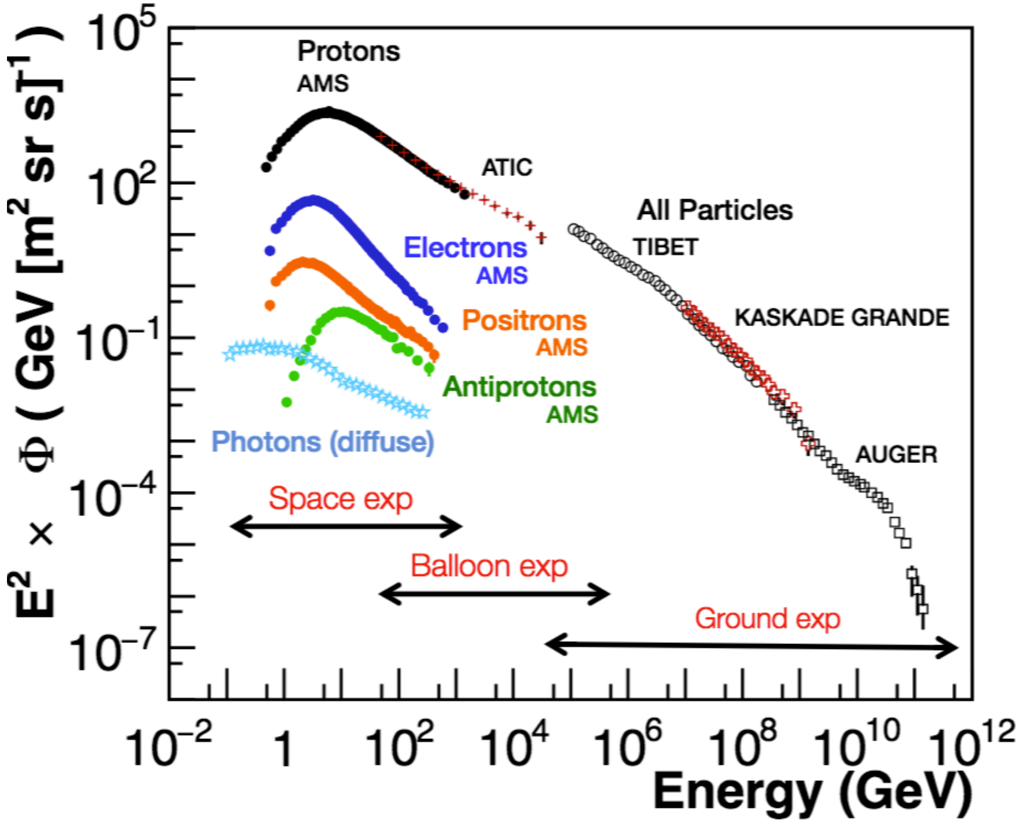


Glennys Ferrar's talk

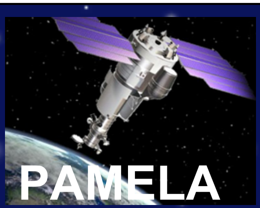
Cosmic Rays

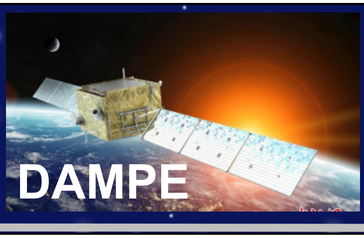
Cosmic rays are a sample of solar, galactic and extragalactic matter which includes all known nuclei and their isotopes, as well as electrons, positrons and antiprotons

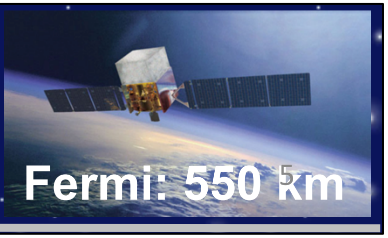




ISS: 400 km
AMS-02
CALET
ISS-CREAM

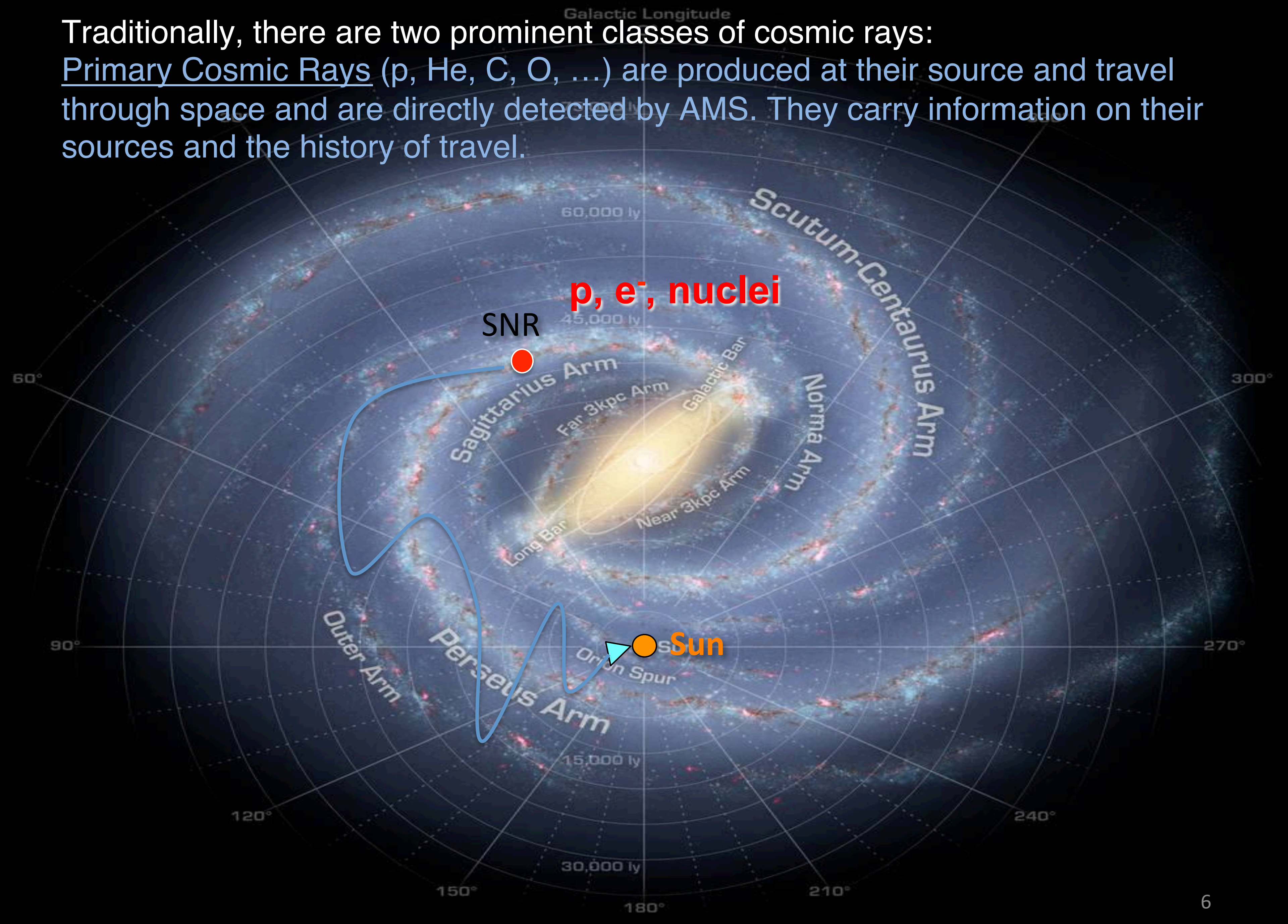






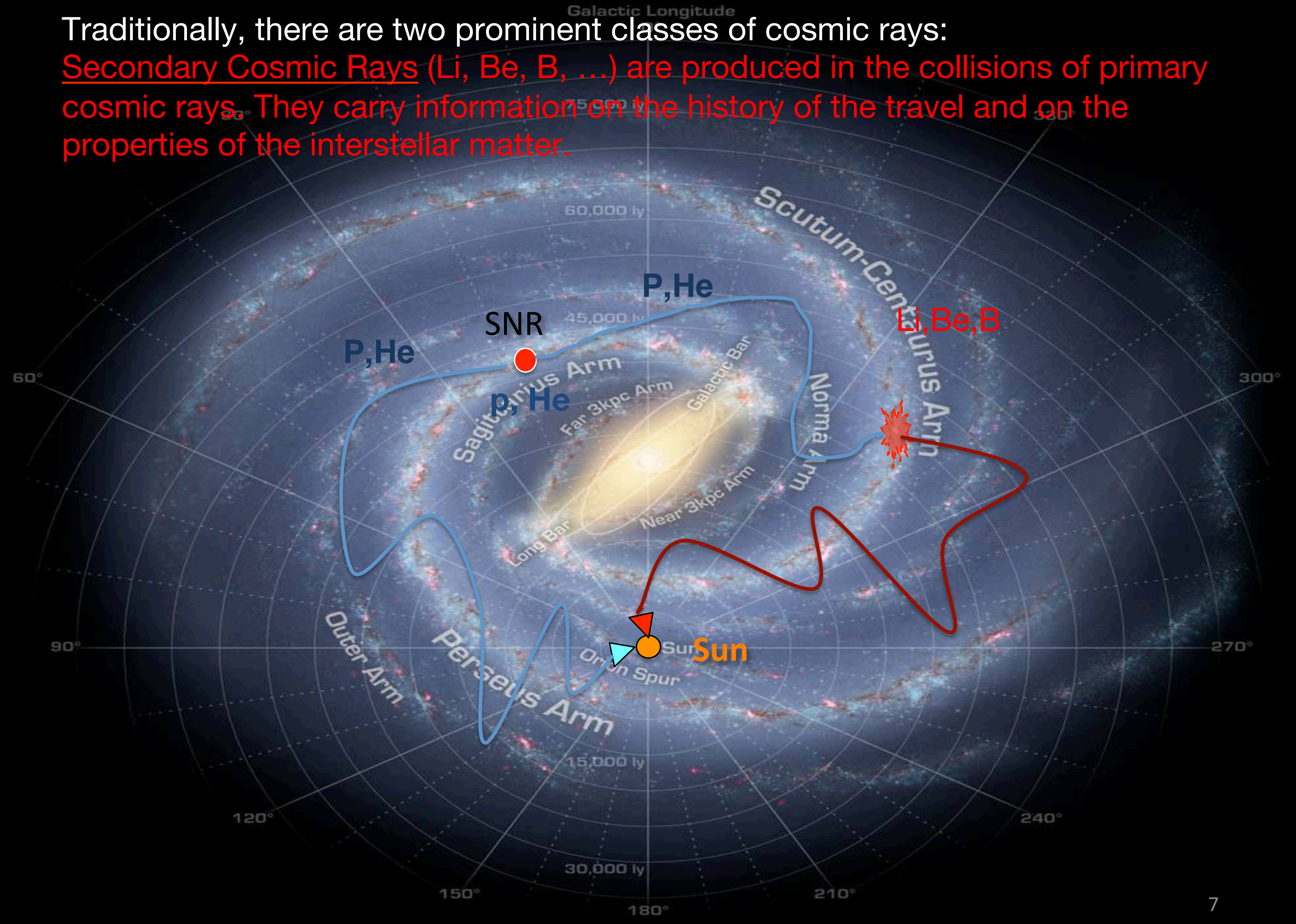
Traditionally, there are two prominent classes of cosmic rays:

Primary Cosmic Rays (p, He, C, O, …) are produced at their source and travel through space and are directly detected by AMS. They carry information on their sources and the history of travel.



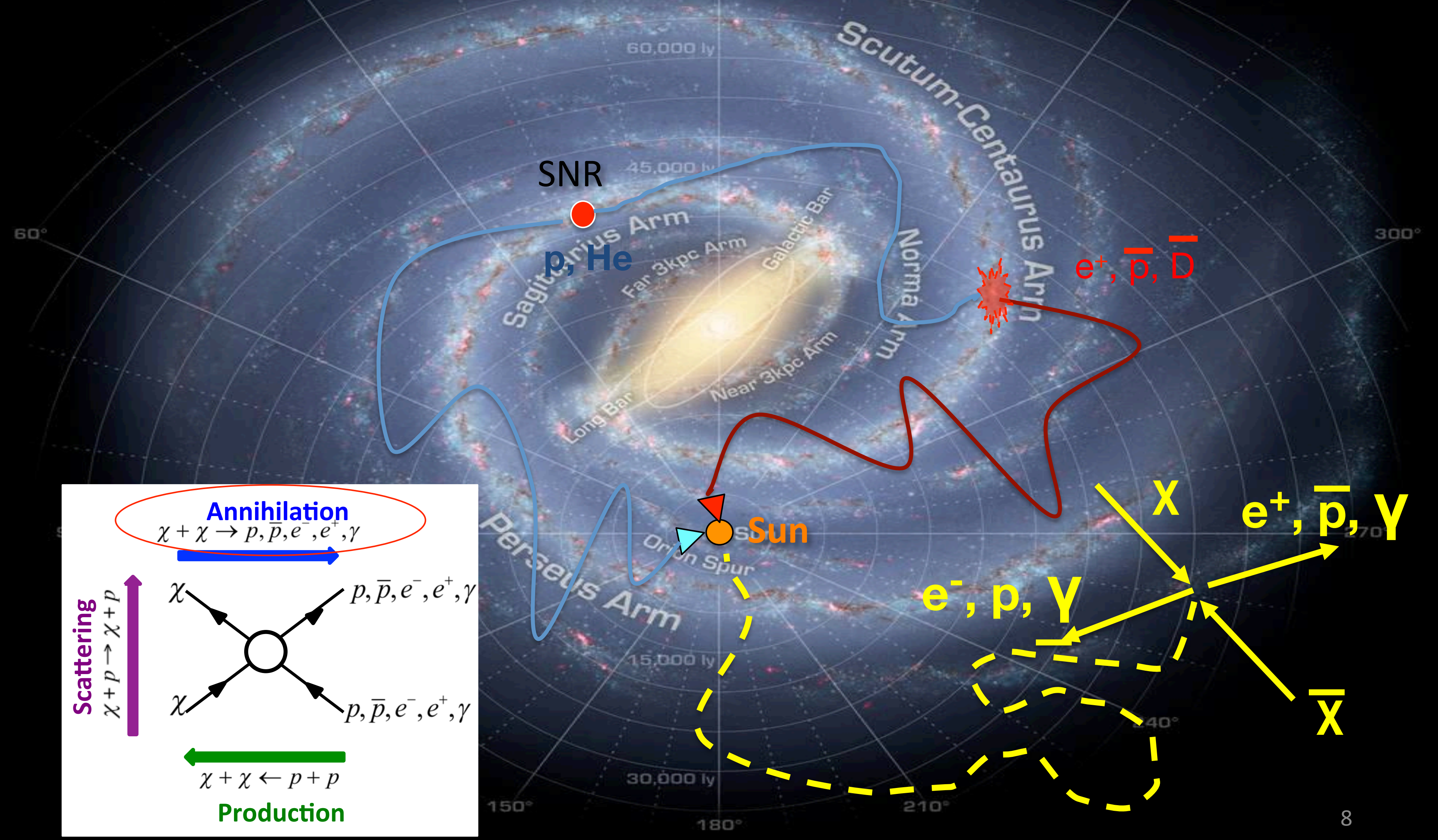
Traditionally, there are two prominent classes of cosmic rays:

<u>Secondary Cosmic Rays</u> (Li, Be, B, …) are produced in the collisions of primary cosmic rays. They carry information on the history of the travel and on the properties of the interstellar matter.



Collision of Cosmic Rays with Interstellar Matter produces e^+, $\overline{p}$, $\overline{D}$

Dark Matter annihilation also produces light antimatter: e^+, $\overline{p}$, $\overline{D}$
The excess of e^+, $\overline{p}$, $\overline{D}$ from Dark Matter annihilations can be measured by AMS



Physics goals

Accurate measurements of cosmic rays spectra (0.1 GeV to 2 TeV)

Fundamental Physics:

- Dark Matter searches:
  simultaneous observation of several signal channels (e^+ , $e^\pm$, $\bar{p}$,$\bar{d}$, …)
- Search for Primordial antimatter: $\overline{He}$, complex antimatter
- Search for new form of matter (i.e. stranglets)

Cosmic Ray energy spectrum and composition

- Source & acceleration (p,He)
- Propagation models in the ISM (relative abundances of nuclei and isotopes)

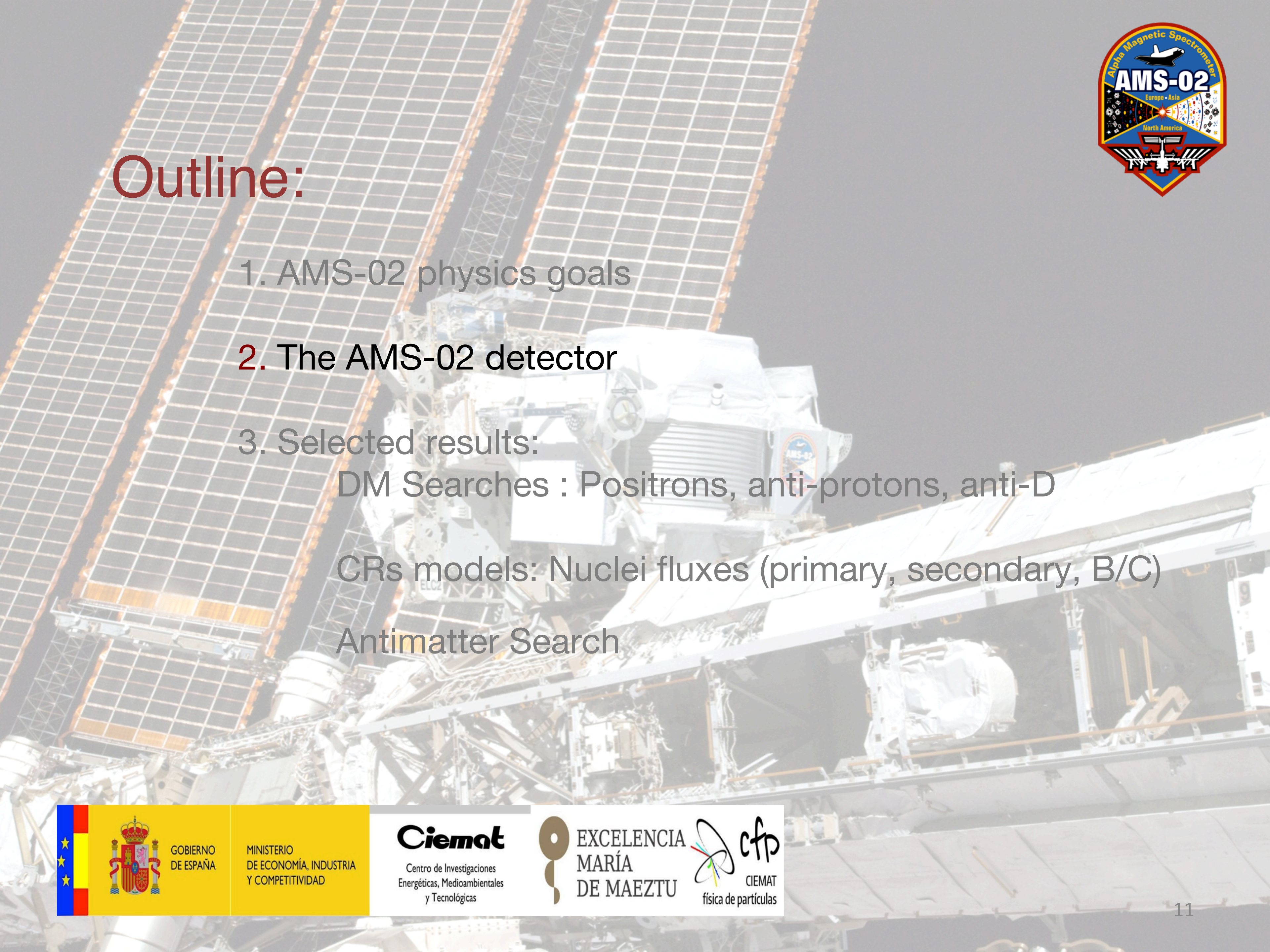
Solar modulation on low energy CR spectra over 11 years solar cycle

Physics goals

To fullfill this ambitious program of measuring simultaneously several species and their anti in a wide energy range up to TeV scale

What is needed?

- ✓ Space
- ✓ Spectrometer (charge sign for matter-antimatter separation)
- ✓ Highly specialized and precise subdetector
  - Redundant and precise charge measurement
  - Accurate Energy measurement
  - e/p separation at the 10^4 level by means of independent detectors
- ✓ statistics: large acceptance



Outline:

1. AMS-02 physics goals
2. The AMS-02 detector
3. Selected results:
   - DM Searches : Positrons, anti-protons, anti-D
   - CRs models: Nuclei fluxes (primary, secondary, B/C)
   - Antimatter Search

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
cfp CIEMAT física de partículas

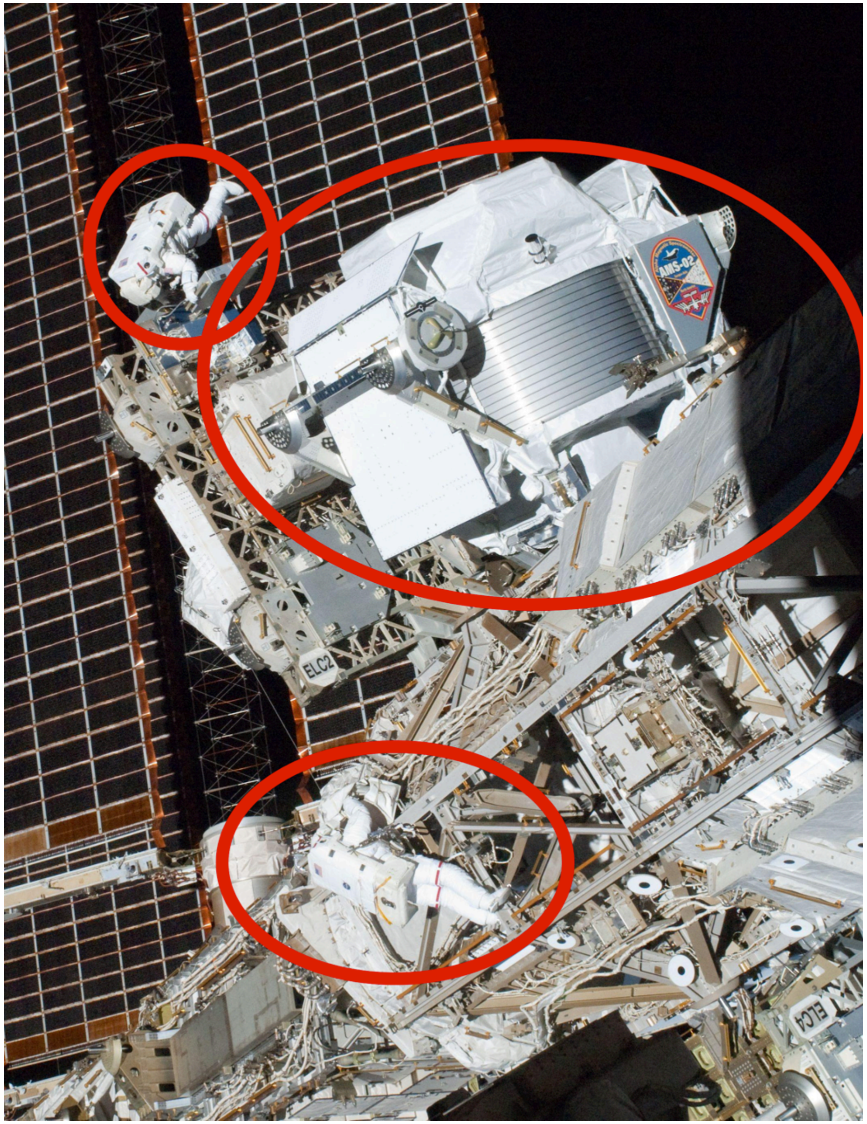
Cape Canaveral, KSC

May 16, 2011@08:56 AM

ISS - May 19, 2011 AMS installation completed

Over 119 billion charged particles have been measured

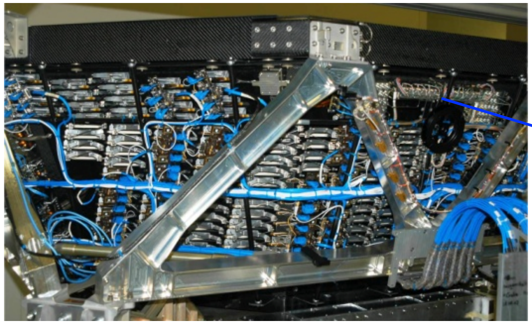
The AMS-02 detector



- 5 x 4 x 3 m
- Weight 7500 kg
- Power consumption 2500 W
- 300k readout channels
- More than 600 microprocessors
- Data downlink reduction rate from 7 Gb/s to 10 Mb/s
- Mission duration: Until the end of ISS operation (currently 2024)

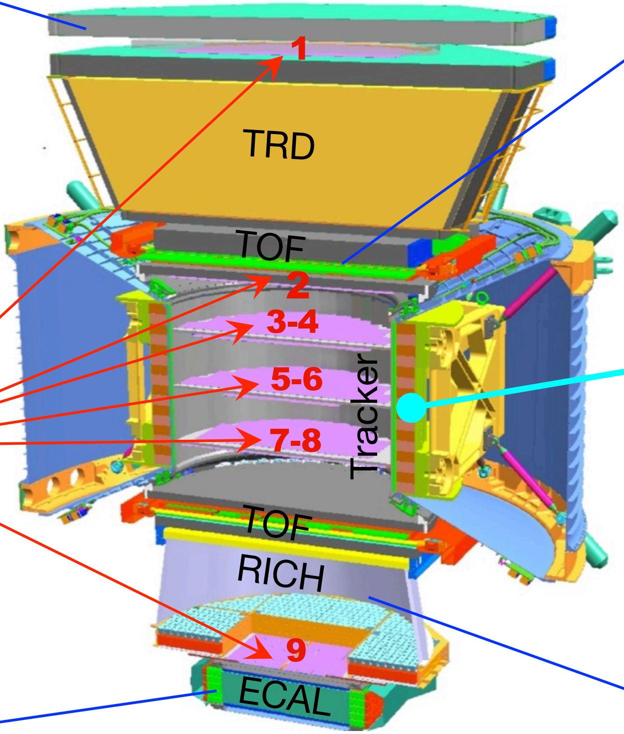
AMS: A TeV precision, multipurpose spectrometer

TRD (e /p)
Rej.Fact = 10^{-2} - 10^{-3}

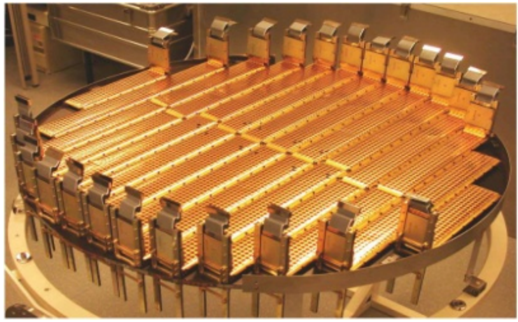


Particles and nuclei are defined by their charge (Z) and energy (E ~ p)

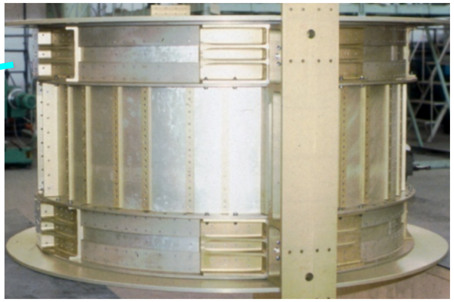
Time of Flight (Z, β)
σ(t) = 160 ps



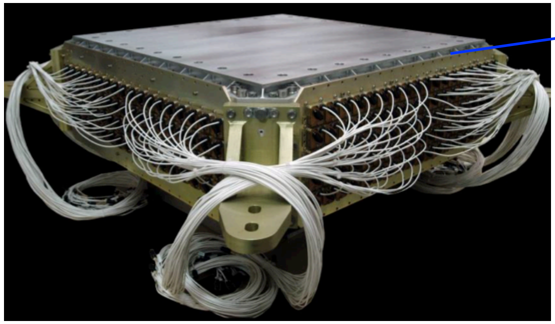
Silicon Tracker (Z, P)
σ(y) = 10 μm



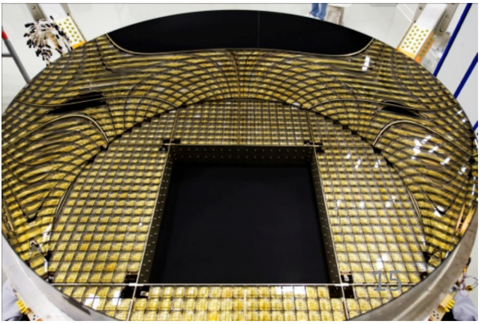
Magnet(Q sign)
B= .15 T



Calorimeter ($E_{e,\gamma}$)
σ(E) = 2-3 %



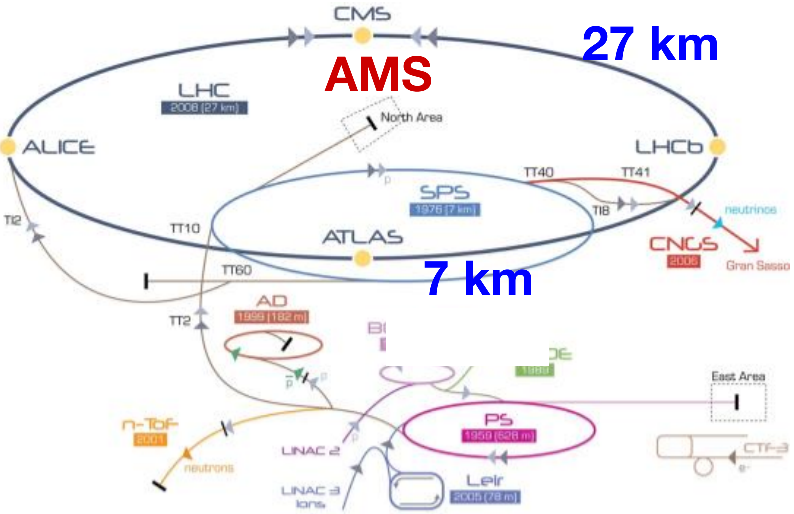
RICH(β, Z)
σ(β) ~ 0.1 %



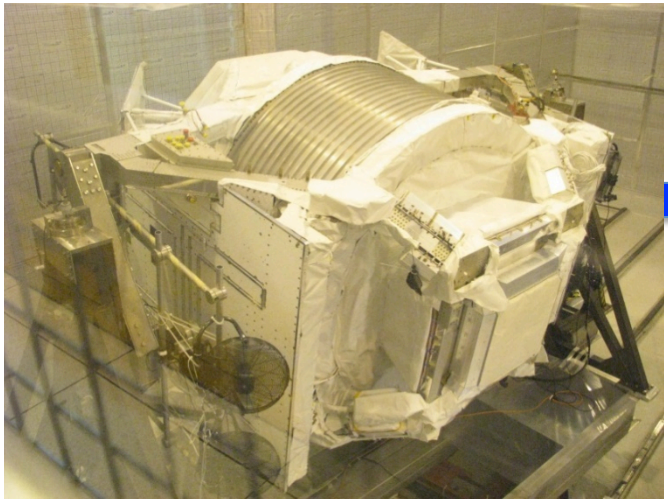
Z, P are measured independently by Tracker, RICH, TOF and ECAL

Detector calibration

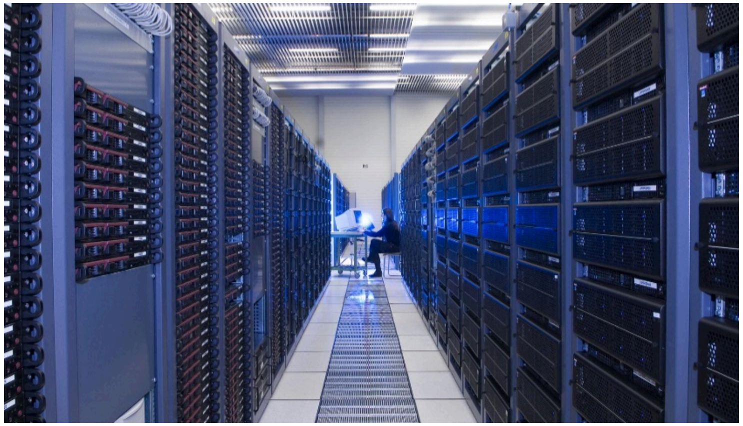
Test beam at CERN SPS:
p, e±, π±, 10–400 GeV



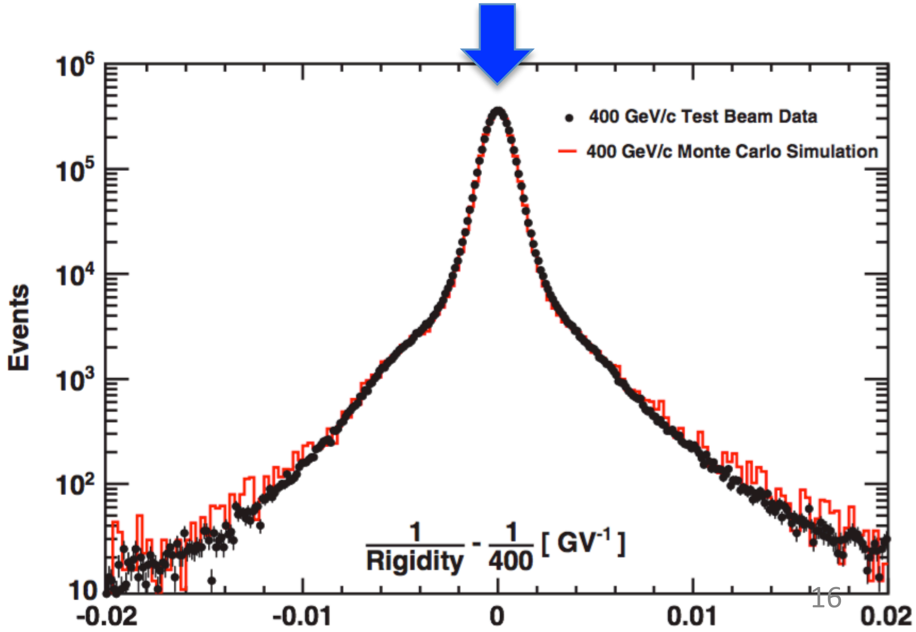
2000 positions



10,000 CPU cores at CERN



Computer simulation:
Interactions, Materials, Electronics



Outline:

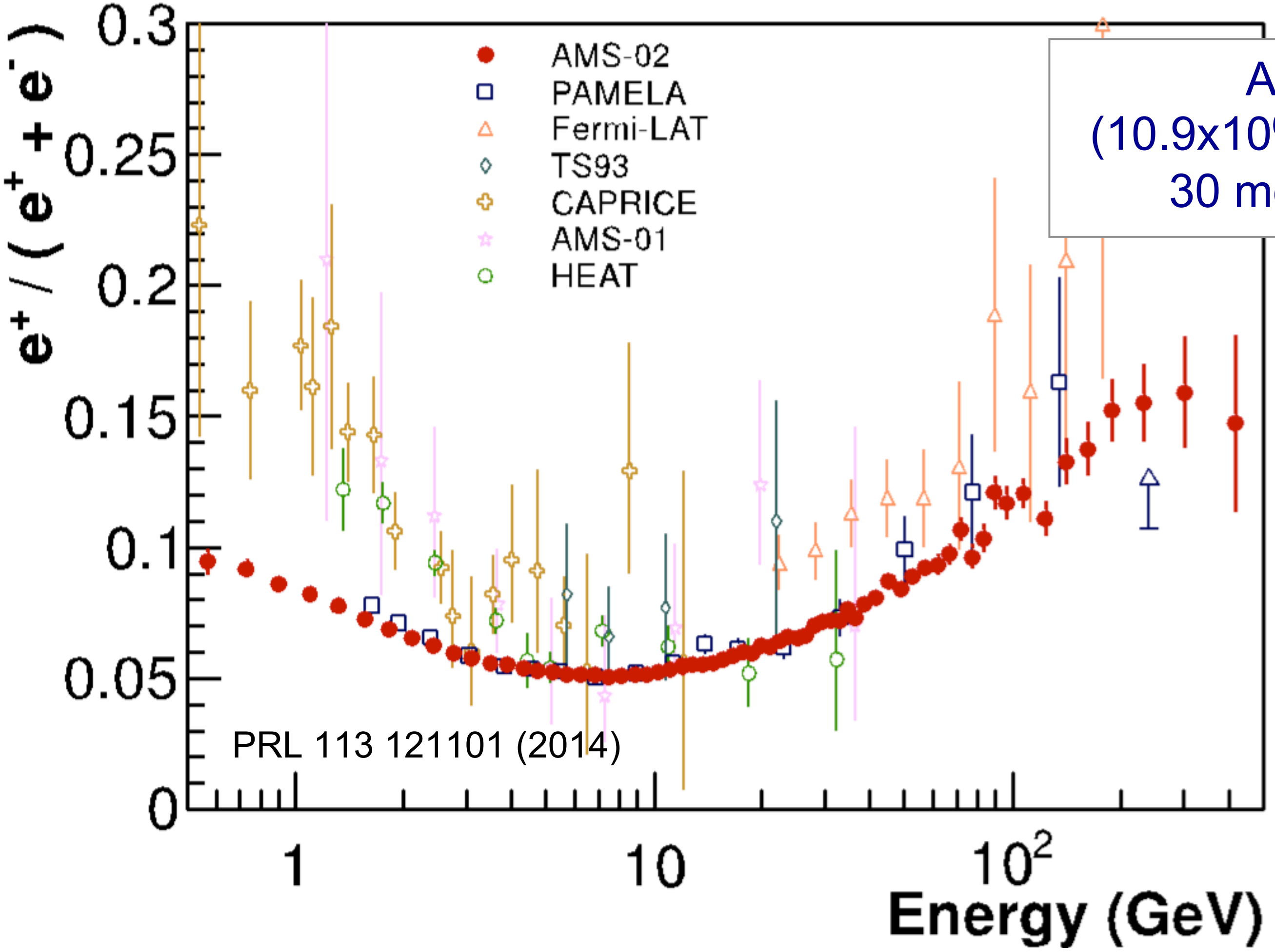
1. AMS-02 physics goals

2. The AMS-02 detector

3. Selected results:
    - DM Searches : Positrons, anti-protons, anti-D
    - CRs models: Nuclei fluxes (primary, secondary, B/C)
    - Antimatter Search

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
cfp CIEMAT física de partículas

Positron Fraction (0.5-500 GeV)

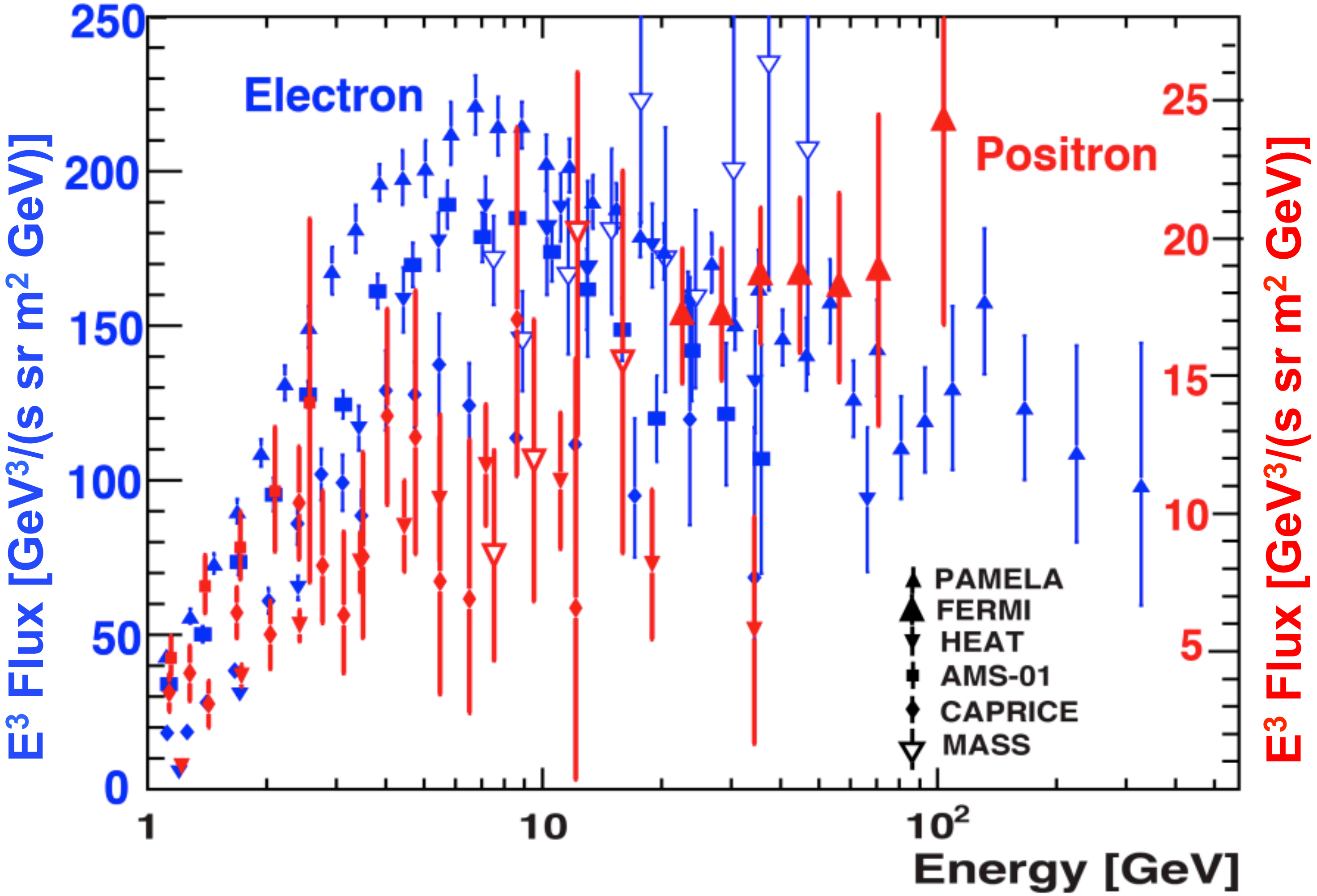


PRL 113 121101 (2014)

AMS-02
(10.9×10^6 e^+,e^- events)
30 months data

- Positron fraction shows an excess above 10GeV that is not consistent with only secondary production of positrons
- Above ~ 200GeV the positron fraction no longer exhibits an increase with energy
- Electrons decrease or positrons increase?

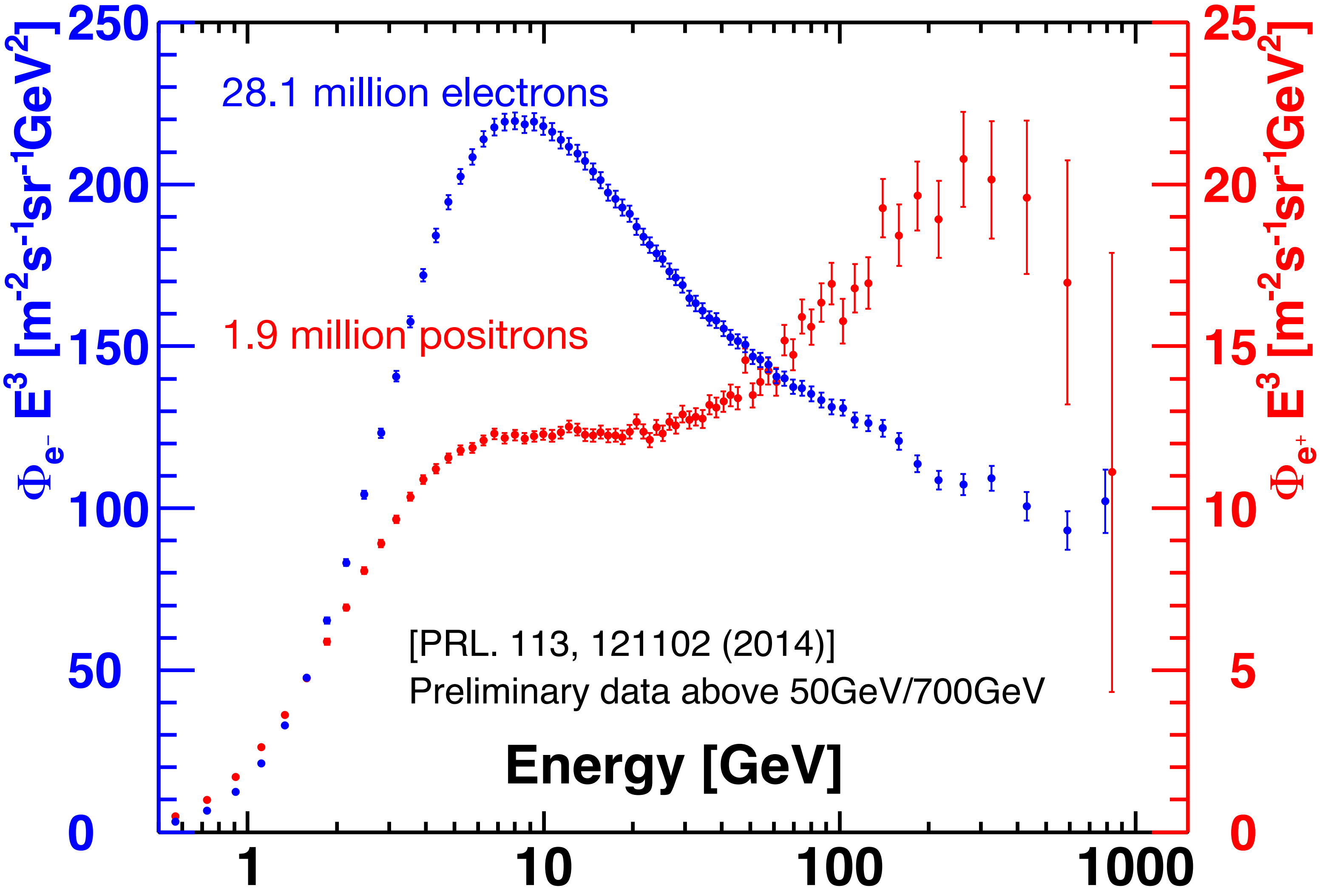
Positron and Electron fluxes before AMS



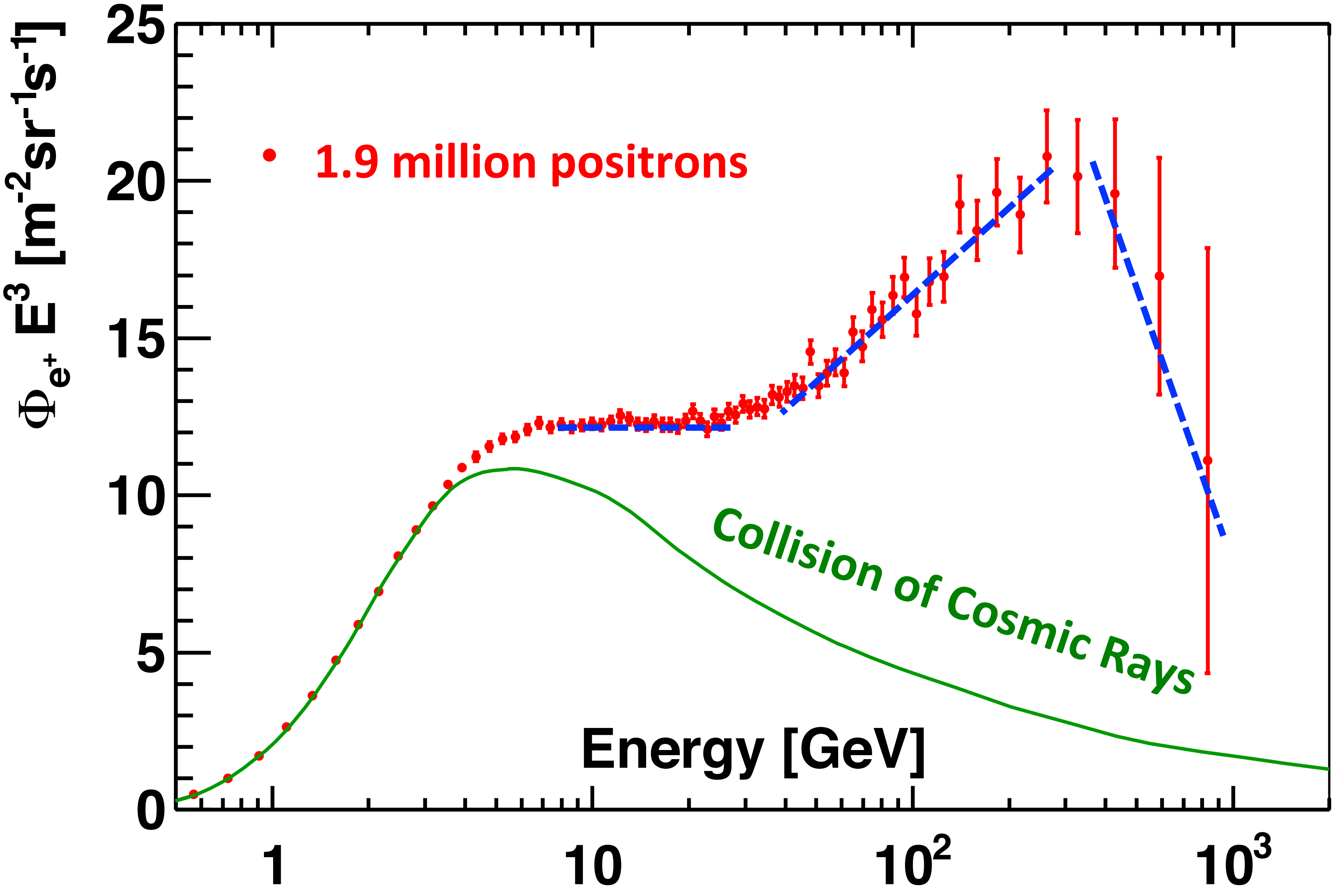
Difficult experiments:

1. A proton rejection of 1:100,000
2. A precision magnetic spectrometer to separate e^- from e^+.

Latest AMS positron and electron fluxes

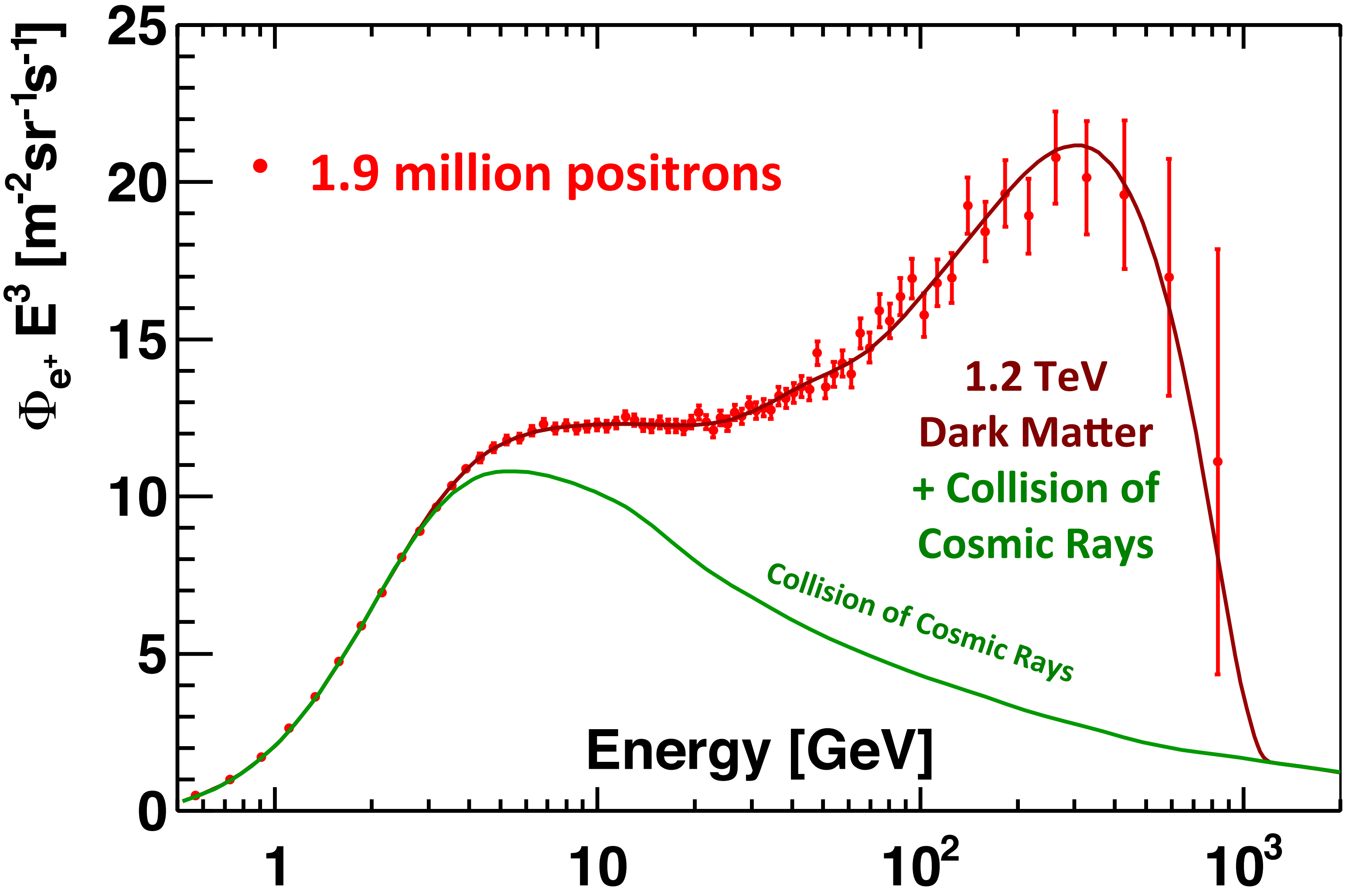


Latest AMS Positron Flux



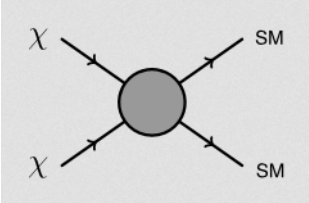
Positron Flux: interpretation

The data are consistent with a symmetric contribution in e^+ and e^-.



Dark Matter model is based on J. Kopp, Phys. Rev. D 88, 076013 (2013).

A sample of Theoretical Models explaining AMS data



1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
2) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B728 (2014) 250
3) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
5) Y. Kajiyama and H. Okada, Eur.Phys.J. C74 (2014) 2722
6) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
8) K. Kohri and N. Sahu, Phys.Rev. D88 (2013) 10, 103001
9) P. S. Bhupal Dev, D. Kumar Ghosh, N. Okada and I. Saha, Phys.Rev. D89 (2014) 095001
10) A. Ibarra, A.S. Lamperstorfer and J. Silk, Phys.Rev. D89 (2014) 063539
11) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
12) C. H. Chen, C. W. Chiang, and T. Nomura, Phys. Lett. B 747, 495 (2015)
13) H. B. Jin, Y. L. Wu, and Y.-F. Zhou, Phys.Rev. D92, 055027 (2015)
14) M-Y. Cui, Q. Yuan, Y-L.S. Tsai and Y-Z. Fan, arXiv:1610.03840 (2016)
15) A. Cuoco, M. Krämer and M. Korsmeier, arXiv:1610.03071 (2016)

and many other excellent papers **…**

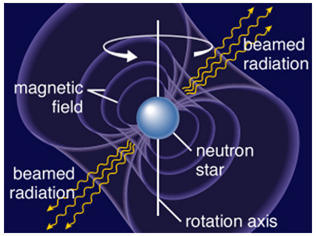
Dark Matter

---

1) R.Cowsik, B.Burch, and T.Madziwa-Nussinov, Ap.J. 786 (2014) 124
2) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101
3) R. Kappl and M. W. Winkler, J. Cosmol. Astropart. Phys. 09 (2014) 051
4) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Serpico, JCAP09 (2015) 023;
5) C.Evoli, D.Gaggero and D.Grasso, JCAP 12 (2015) 039.
6) R.Kappl, A.Reinertand, and M.W.Winkler, arXiv:1506.04145 (2015)

and many other excellent papers …

Modified Propagation Models



1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 023001
6) A.D. Erlykin and A.W. Wolfendale, Astropart.Phys. 50-52 (2013) 47
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
8) P. Blasi, Braz.J.Phys. 44 (2014) 426
9) D. Gaggero, D. Grasso, L. Maccione, G. DiBernardo and C Evoli, Phys.Rev. D89 (2014) 083007
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros and A. Vittino, JCAP 1404 (2014) 006
11) K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016)

and many other excellent papers …

Astrophysical Sources

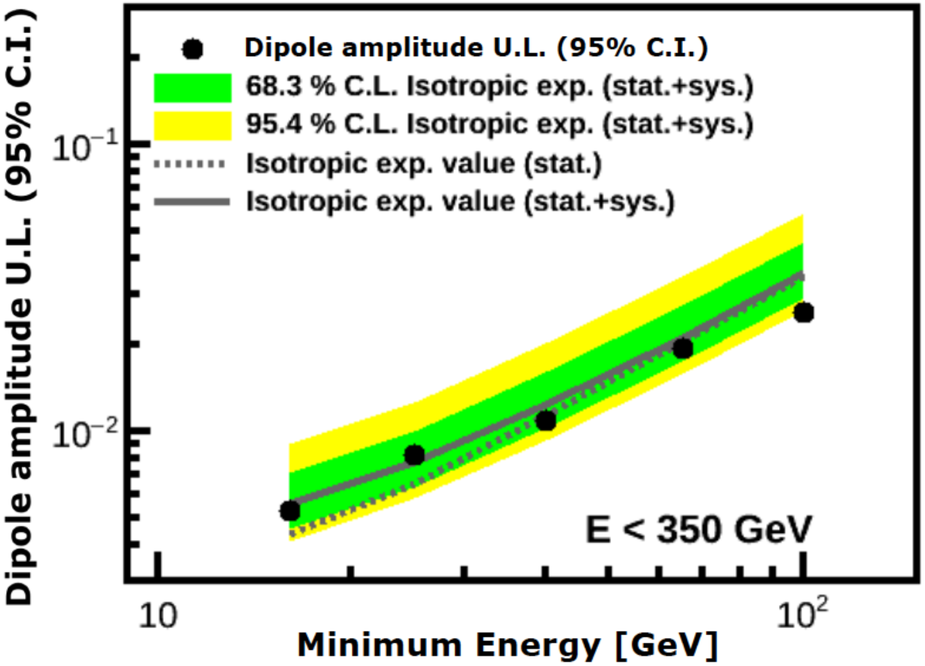
Positron Flux: interpretation (astrophysical source)

Anisotropy on e^+

AMS has measured the e^+ anisotropy in the energy range $16 < E$ [GeV]<350.
An upper limit to the dipole component has been obtained (6 years data):

δ **< 0.02 (95% C.I.)**

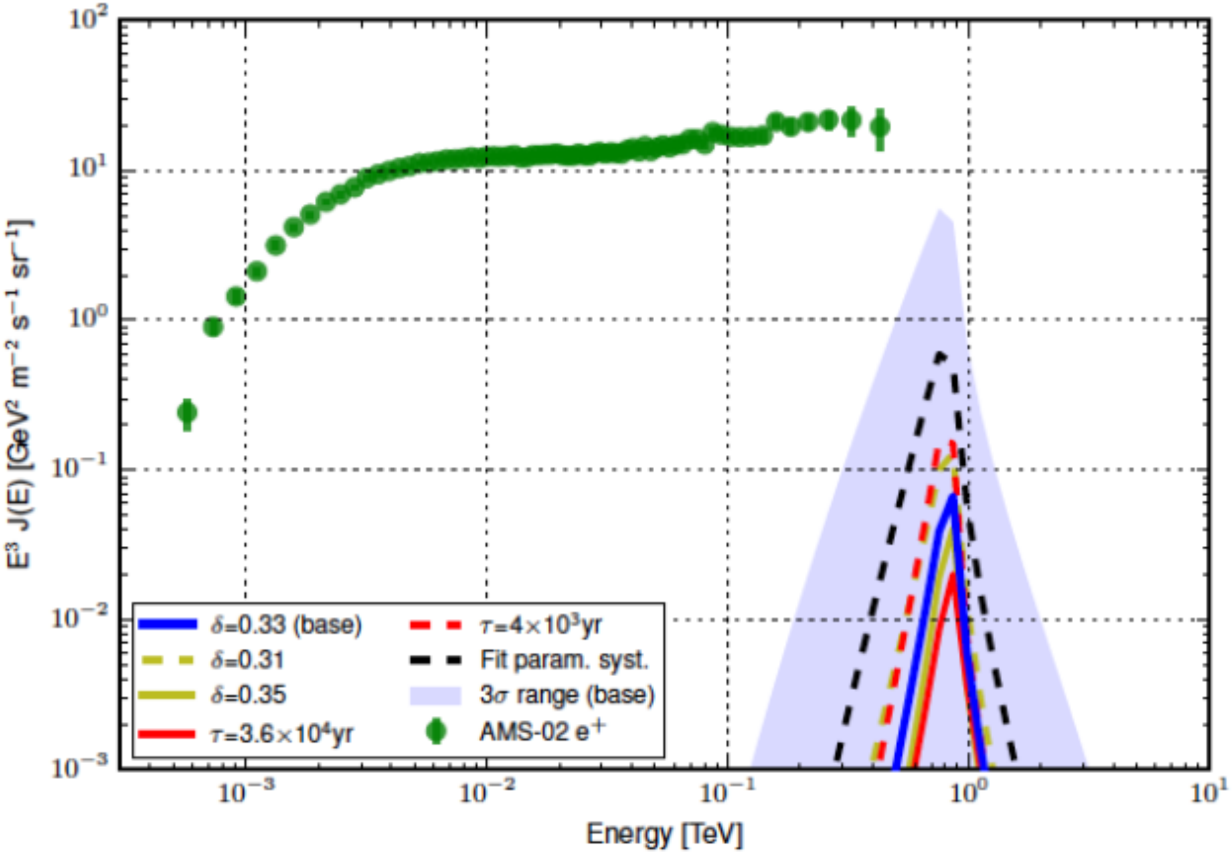
This measurement is compatible with isotropy



An extended data taking up to 2024 will allow to explore anisotropies of 1% and test models of compact astrophysical sources.

Positron Flux: interpretation (astrophysical source)

HAWC result disfavors this origin: “*leptons emitted by nearby middle-aged pulsar (Geminga, PRS B0656+14) are unlikely to be the origin of the positron excess*” [HAWC Collaboration 2017 Science 358 911]



[HAWC Collaboration 2017 Science 358 911]

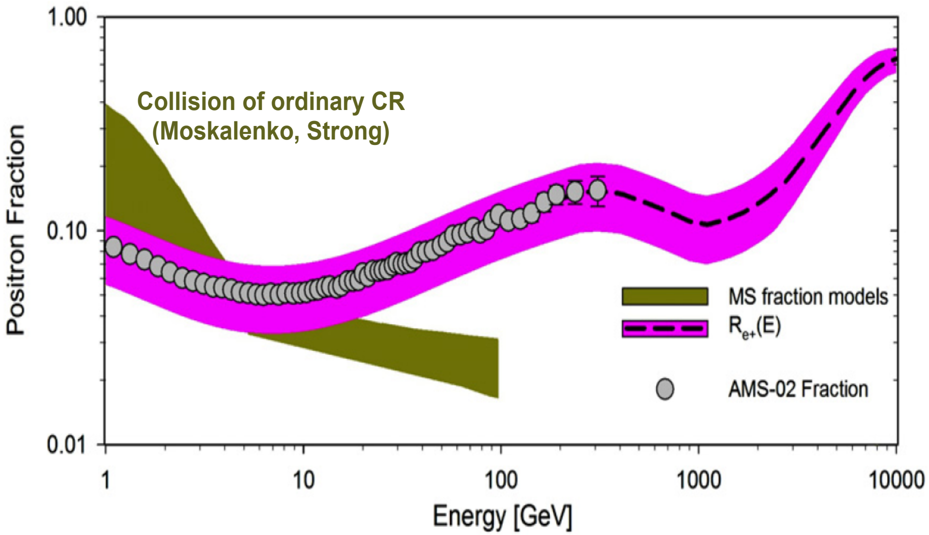
TeV gamma rays can be produced via IC scattering and used to track the e^{+-} population and distribution.

Andrea Albert‘s talk

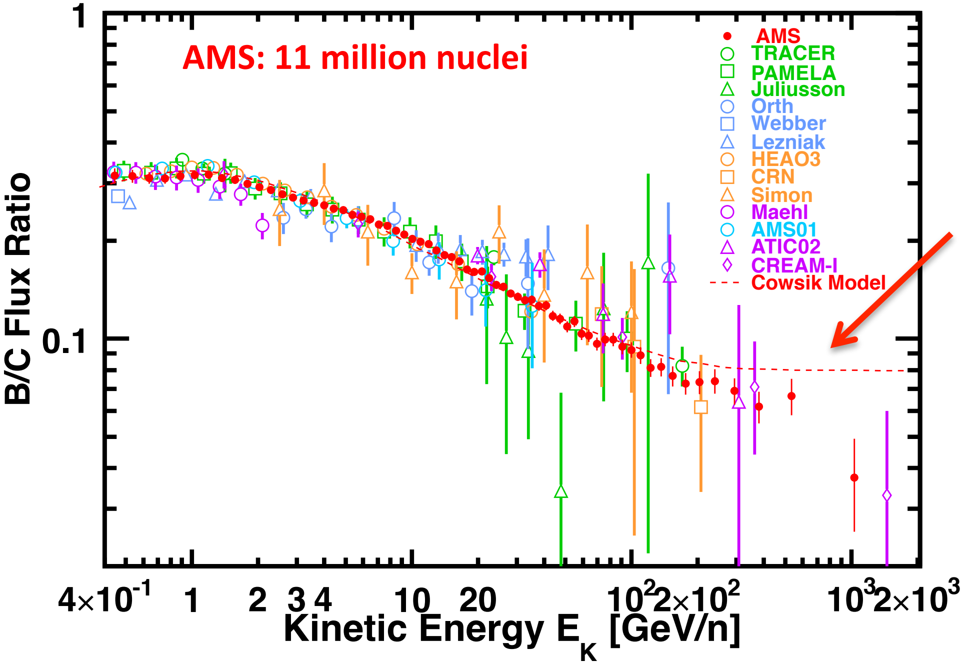
Positron Flux: interpretation (modified Propagation)

Modified Propagation models with no standard secondary e^+ production

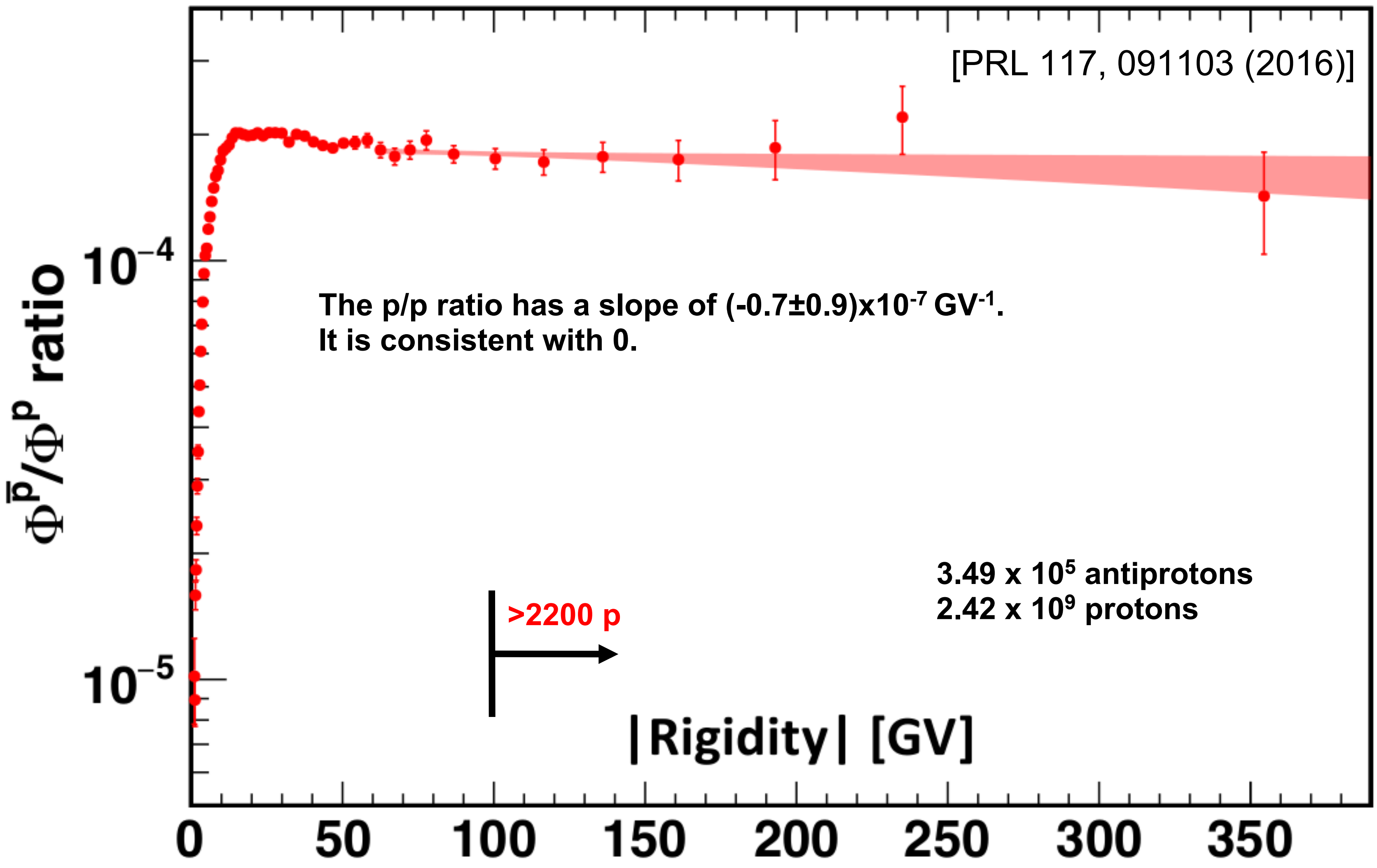
R. Cowsik *et al.*, Ap. J. 786 (2014) 124



This requires a specific energy dependence of the B/C ratio
Which is incompatible with AMS measurement



Antiproton to proton ratio



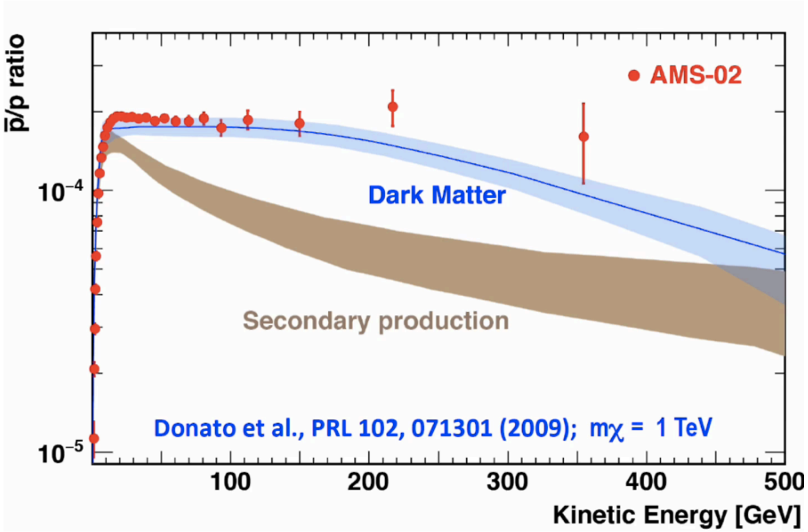
[PRL 117, 091103 (2016)]

The p/p ratio has a slope of (-0.7±0.9)x10^{-7} GV^{-1}.
It is consistent with 0.

>2200 p

3.49 x 10^{5} antiprotons
2.42 x 10^{9} protons

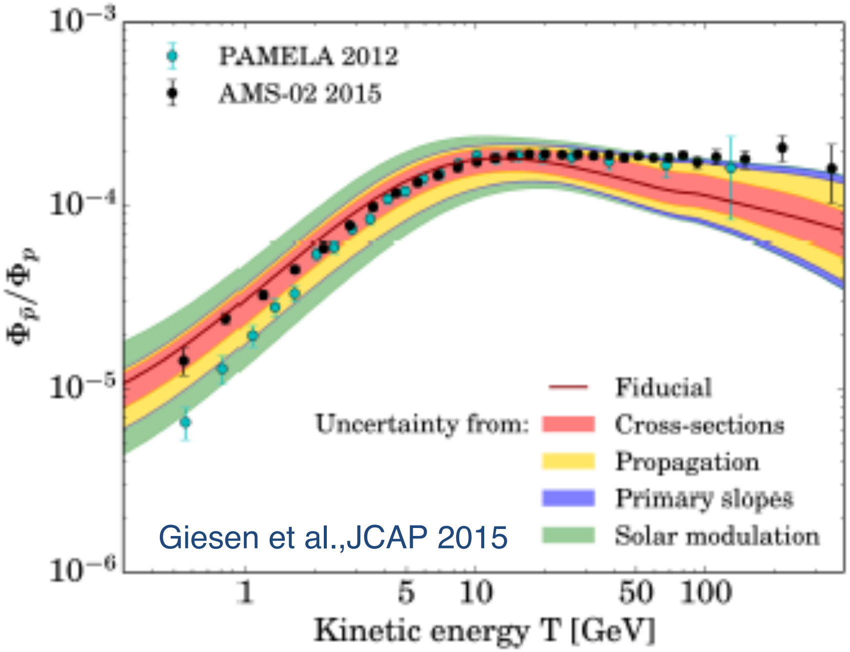
Antiproton to proton ratio



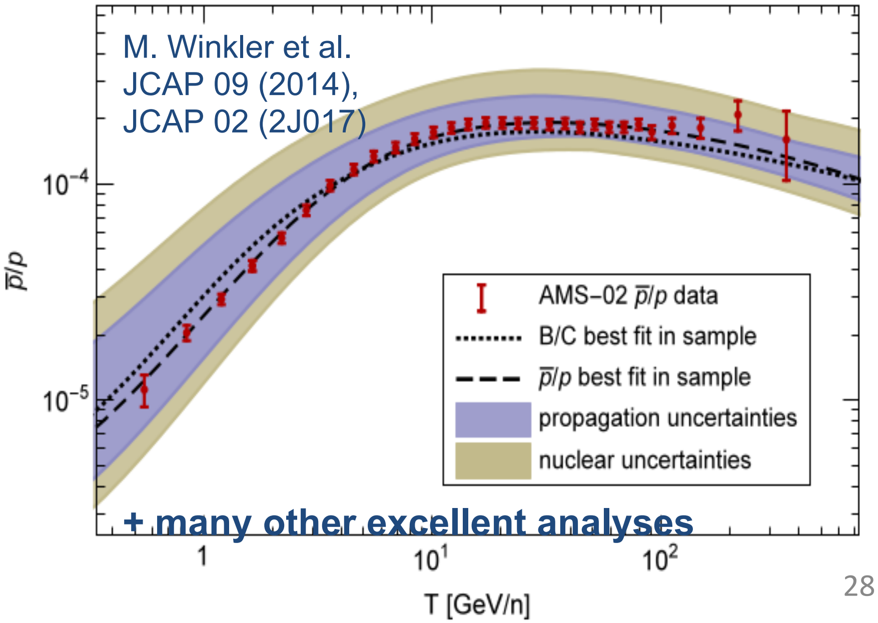
Donato et al., PRL 102, 071301 (2009); m_χ = 1 TeV

Secondary production estimated with pre-AMS data.

Tuned with AMS B/C, p and new cross sections data



Giesen et al.,JCAP 2015

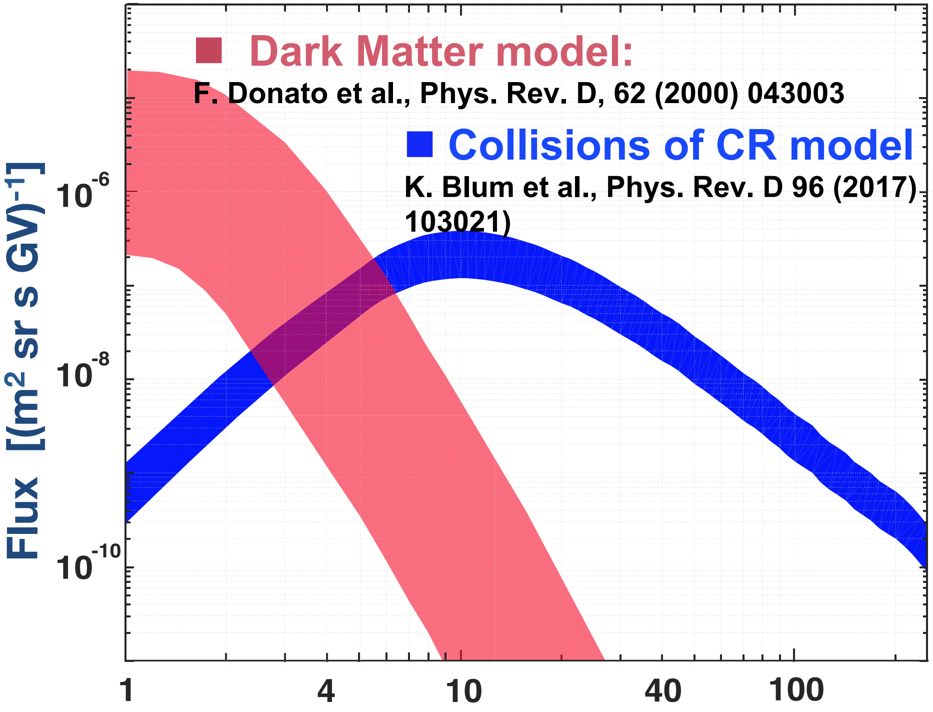


M. Winkler et al.
JCAP 09 (2014),
JCAP 02 (2J017)

+ many other excellent analyses

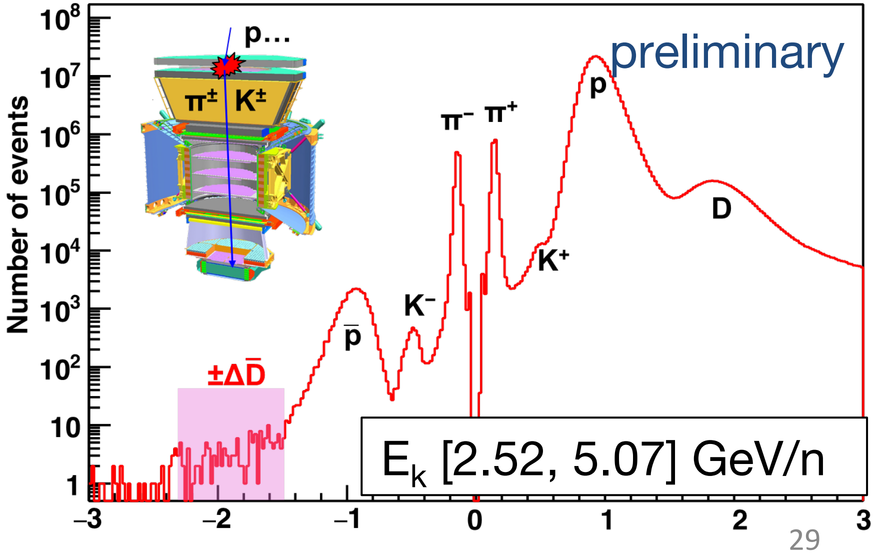
Antideuterons from Dark Matter Annihilation

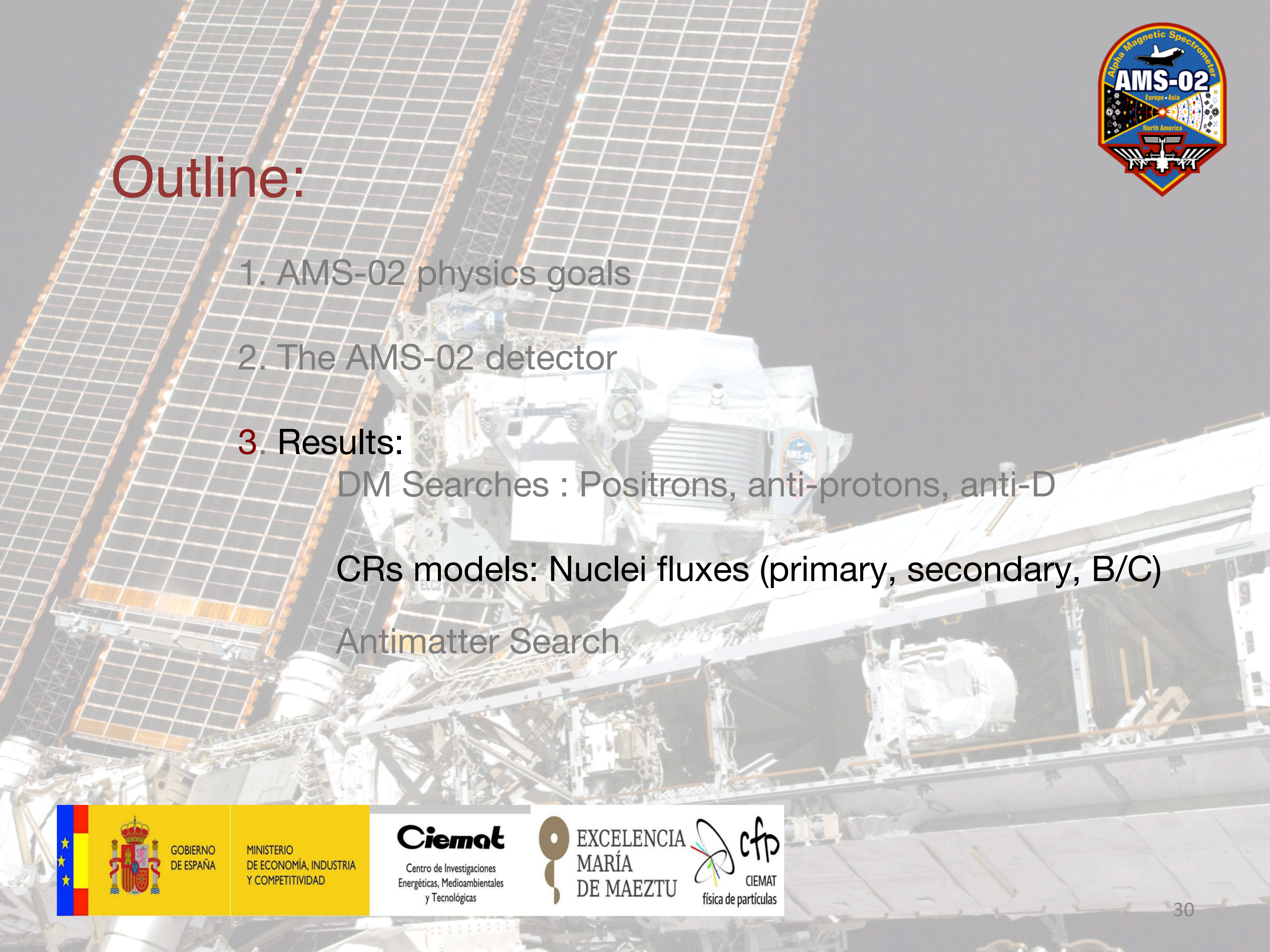
Antideuteron have been proposed as an almost background free channel for dark matter indirect detection.
The Anti Deuterons Flux is < 10^{-4} of the Antiproton Flux.



With the unprecedented statistics and accuracy of the data, AMS has an unique capability to detect heavier antimatter in Cosmic Rays

- Given the AMS acceptance we expect to see this tiny signal
- Anti-Deuterons have never been observed in space
- This analysis just started





Outline:

1. AMS-02 physics goals

2. The AMS-02 detector

3. Results:

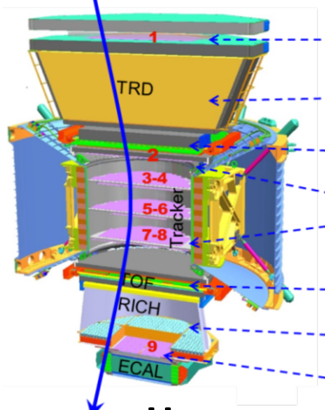
    DM Searches : Positrons, anti-protons, anti-D

    CRs models: Nuclei fluxes (primary, secondary, B/C)

    Antimatter Search

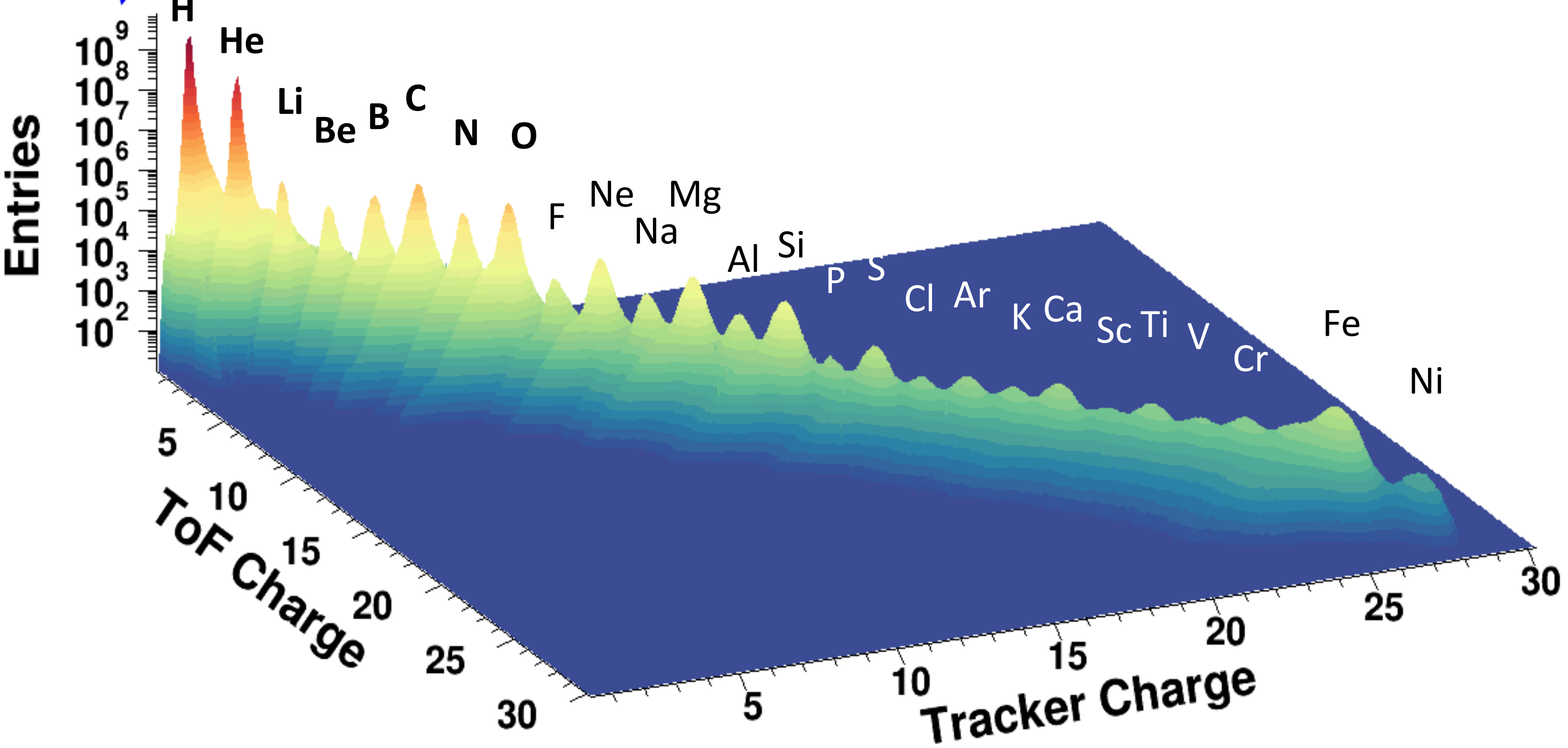
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
cfp CIEMAT física de partículas

Precision Measurements of Cosmic Rays



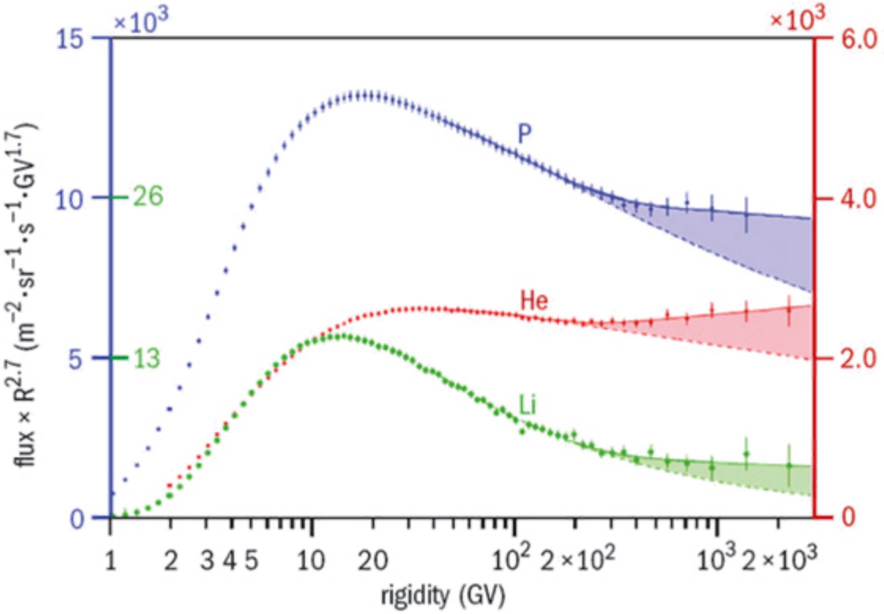
	Charge Resolution Z=6
Tracker Plane 1	0.30
TRD	0.33
Upper TOF	0.16
Tracker Planes 2-8	0.12
Lower TOF	0.16
RICH	0.32
Tracker Plane 9	0.30

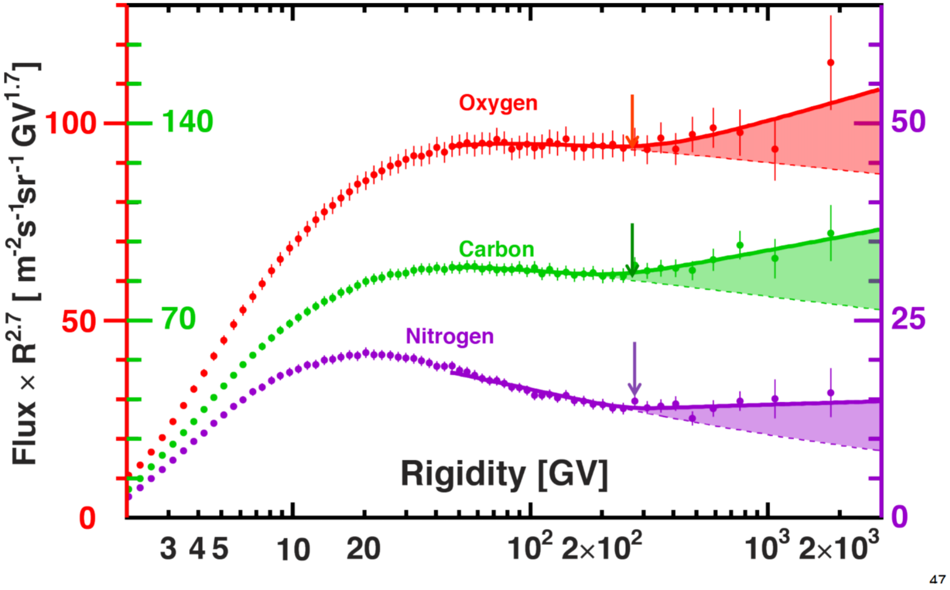
1. Fluxes
2. Flux ratios
3. (Isotopes)



Nuclei Fluxes

The spectra of nuclei do not follow the traditional power law.
A spectral hardening above 200 GV is observed for all species.

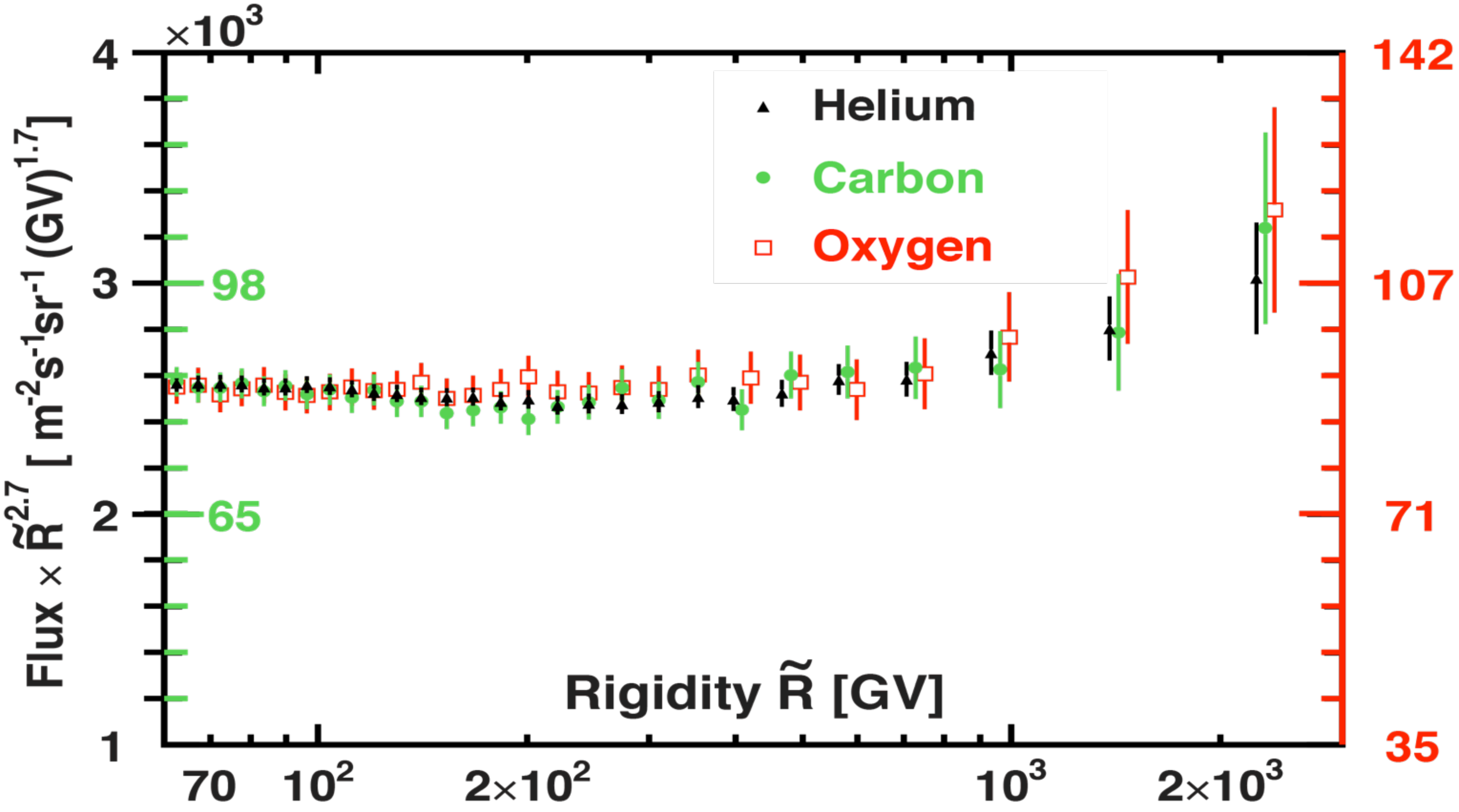




[PRL 114, 171103 (2015)]
[PRL 115, 211101 (2015)]
[PRL 119, 251101 (2017)]
[PRL 120, 021101 (2018)]

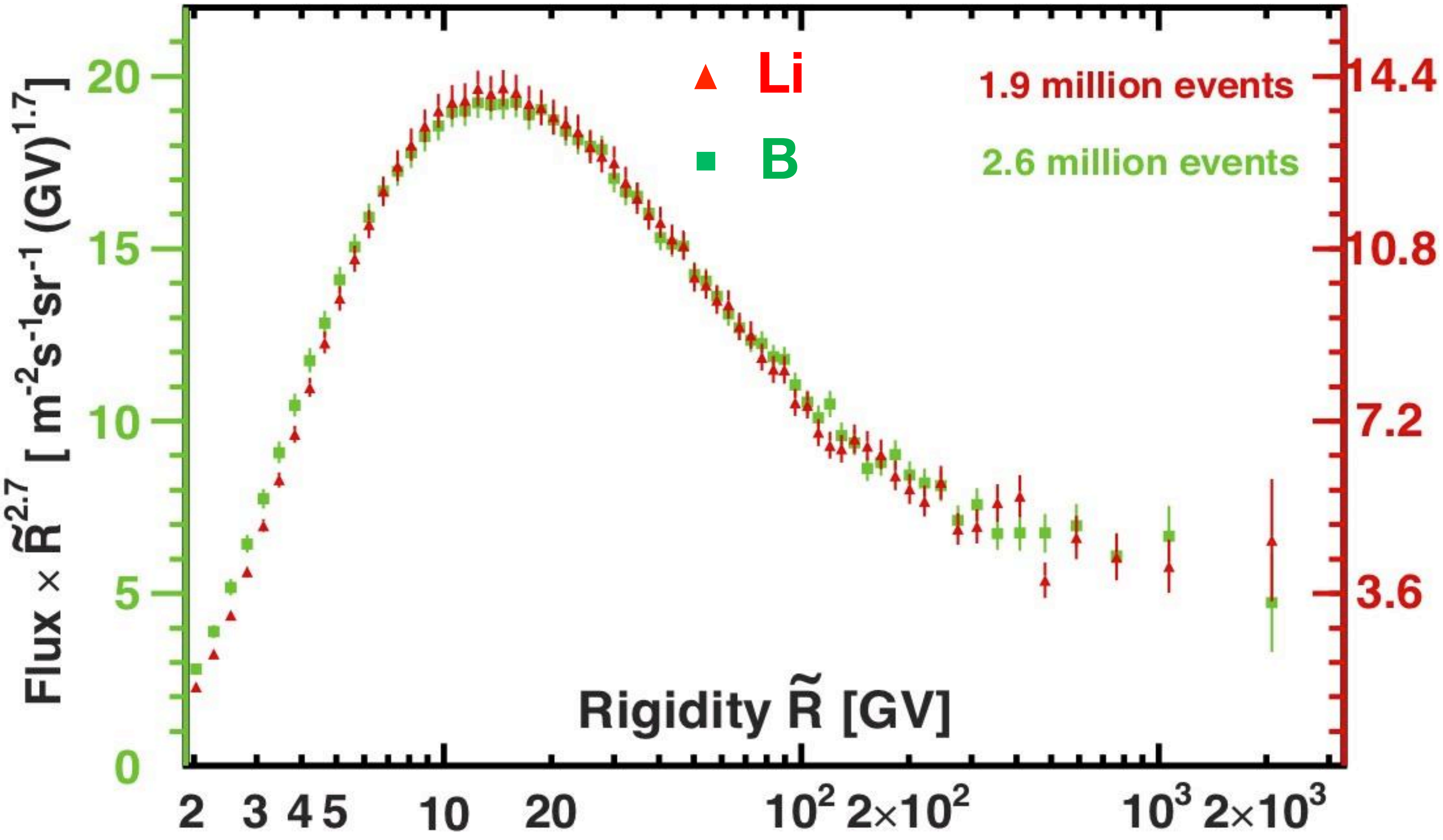
Nuclei Fluxes: primaries

The AMS results show that the primary cosmic rays (He, C, and O) have an identical rigidity dependence.
Above 200GV they all increase in identical way.



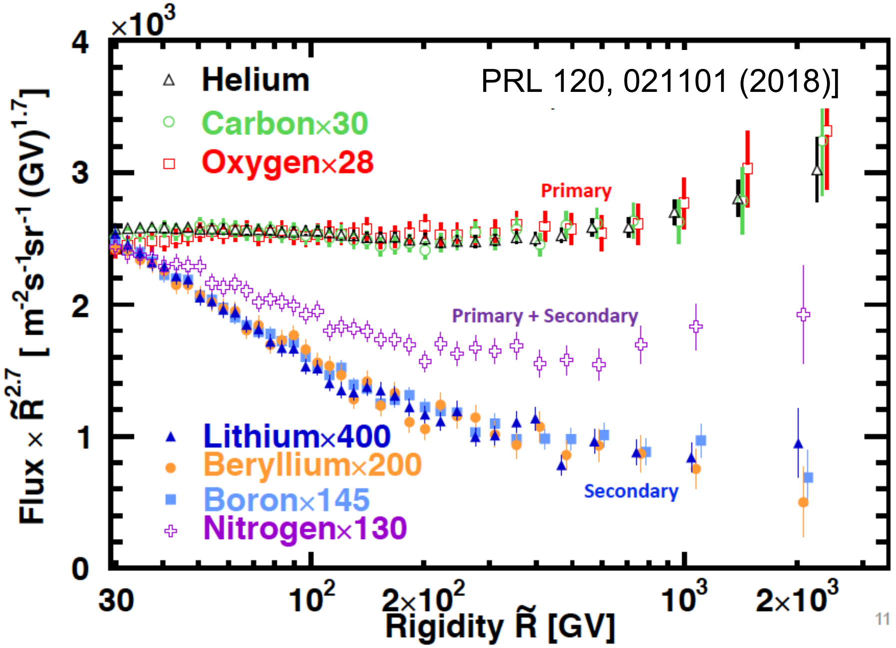
Nuclei Fluxes: secondaries

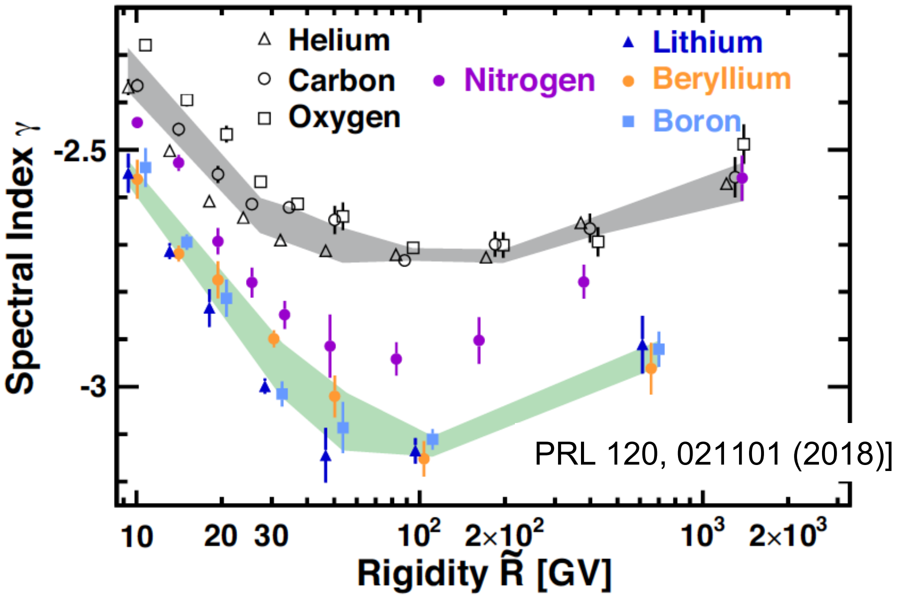
Secondary Cosmic Rays (Lithium and Boron) above 7 GV have identical rigidity dependence



Nuclei Fluxes: energy dependence

Rigidity dependence of Primary and Secondary Cosmic Rays

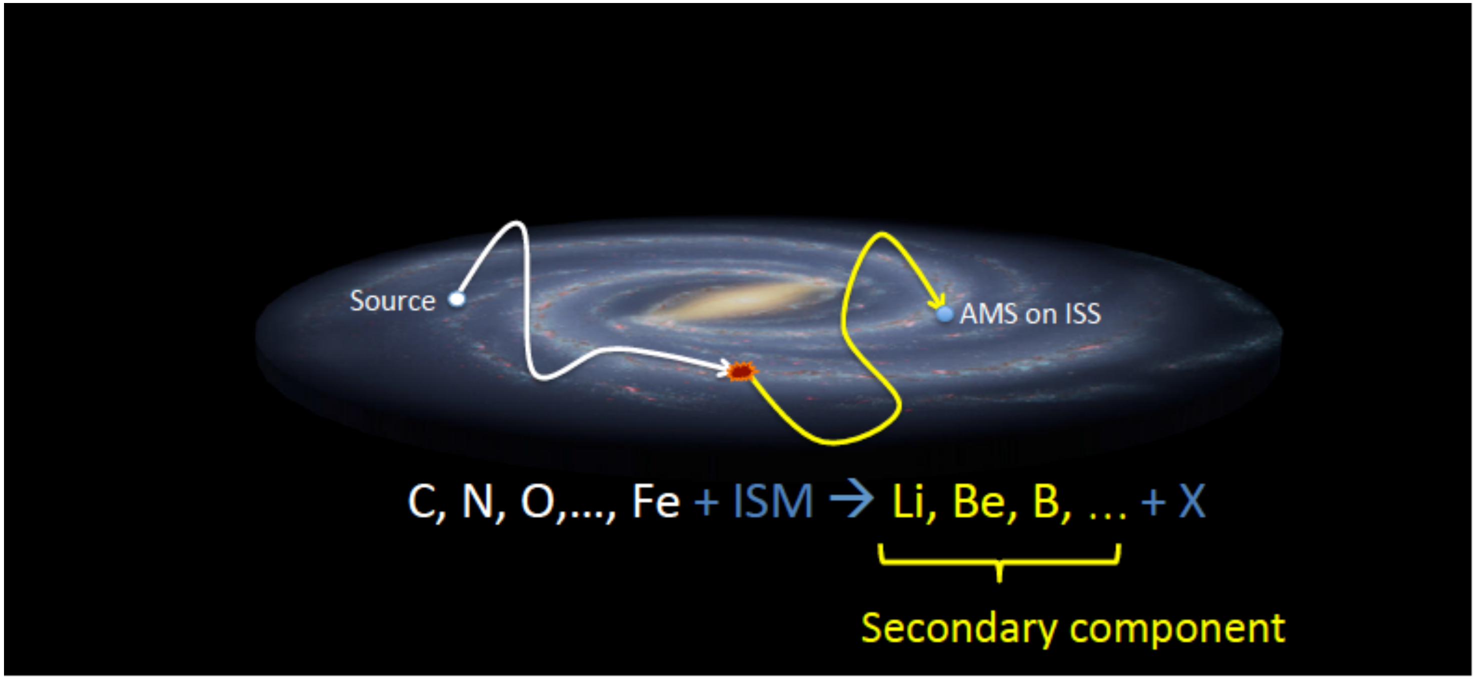




- Both deviate from a traditional single power law above 200 GeV.
- But their rigidity dependences are distinctly different.
- The nitrogen flux can be presented as the sum of its primary component and secondary one (secondary component ~70% @ ~GeV, <30% @TeV).

Nuclei Fluxes: secondary/primary

- The interaction of CR with the ISM produce by fragmentation the secondary component

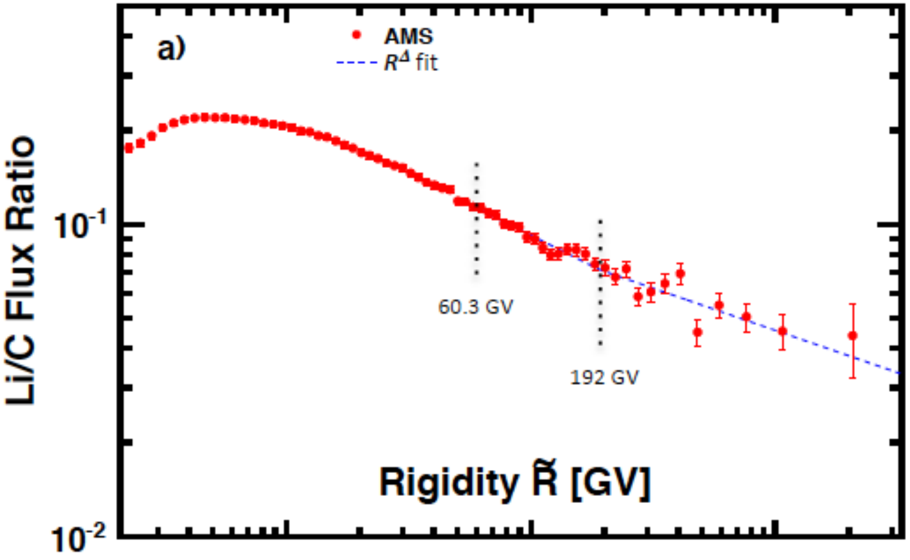


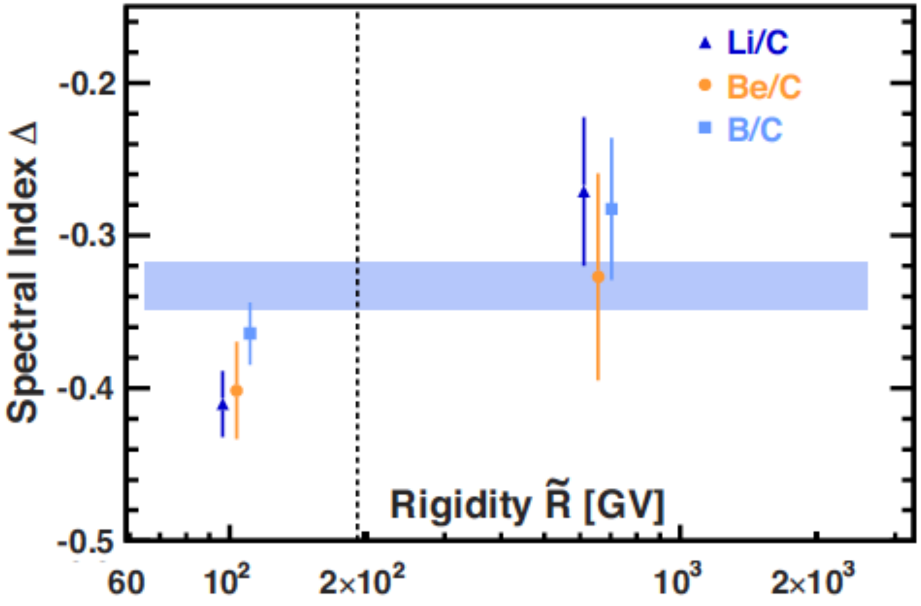
- Li,Be,B are 100% secondary. C,O are dominated by primary component
- Li,Be, B are sensitive to CR propagation parameters (diffusion, convenction, reacceleration) and provide information on propagation models.
- Secondary/primary used to constrain propagation models.
- Lack of accurate and large energy range measurements before
- Models tuned on B/C Only so far

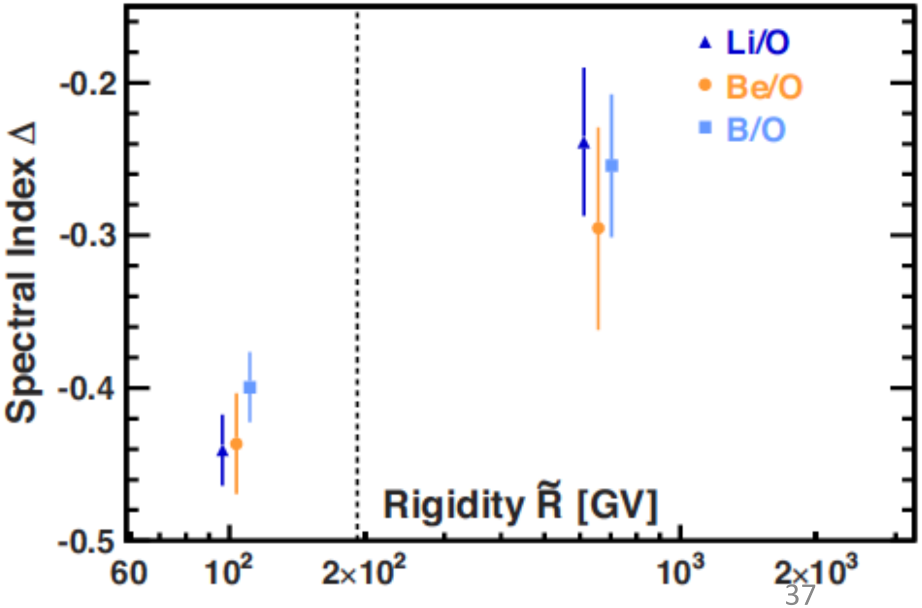
Nuclei Fluxes: secondary/primary

- Li/C,Be/C, B/C andLi/O, Be/O, B/O test the universality of propagation
- Provide information to understand the origin of the spectral index at high rigidity

➢ AMS data show indication of hardening on the ratio which support the interpretation in term of a change in the propagation properties of the galaxy (Ave et al. 2009, Tomassetti 2012,Blasi et al. 2012,..)

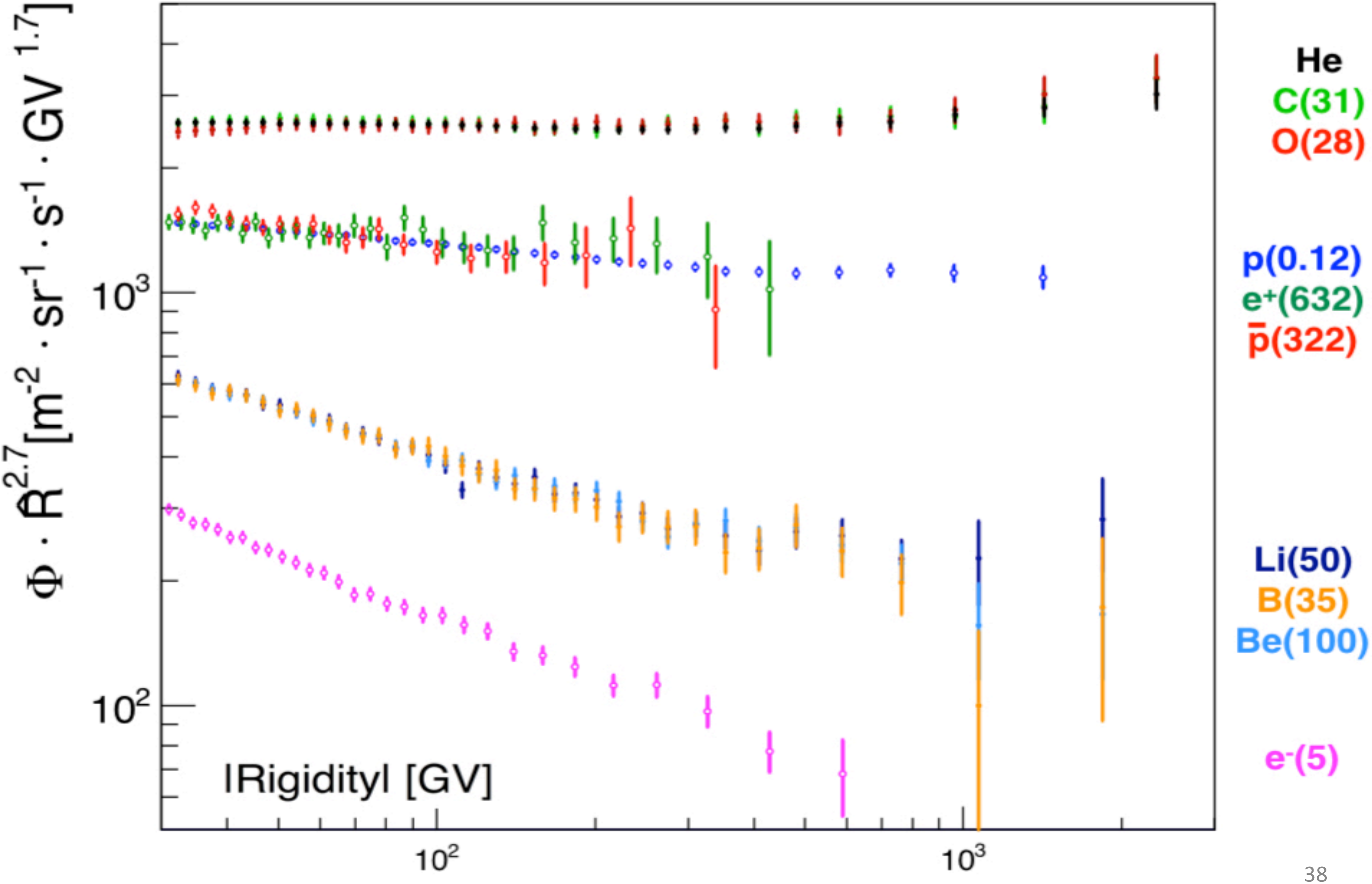






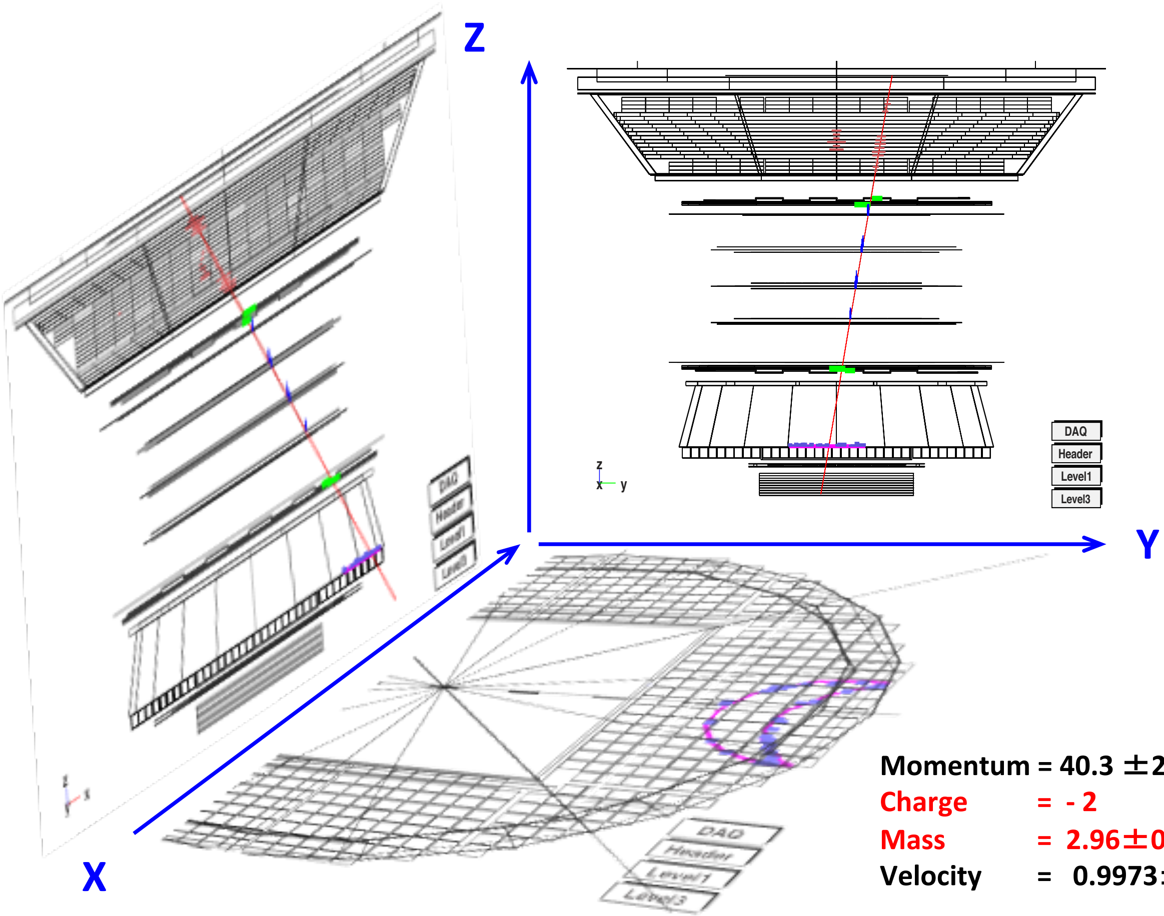
M. Aguilar *et al*., Phys. Rev. Lett. **120,** 021101 (2018)

Summary of AMS results on CRs fluxes



Anti Matter Search

We have observed a few events with Z = -2



Momentum = 40.3 ±2.9 GeV/*c*
Charge = - 2
Mass = 2.96±0.33 GeV/c^2
Velocity = 0.9973±0.0005 *c*

At a signal to background ratio of one in one billion, more data and detailed understanding of the instrument are required.

Summary

Since 2011 AMS has collected a total of 119 billion events.

Provided very precise results for wide energy range, multichannel

The accuracy of the data is challenging our understanding of CRs

AMS will operate on the ISS until 2024…

more physics is coming!

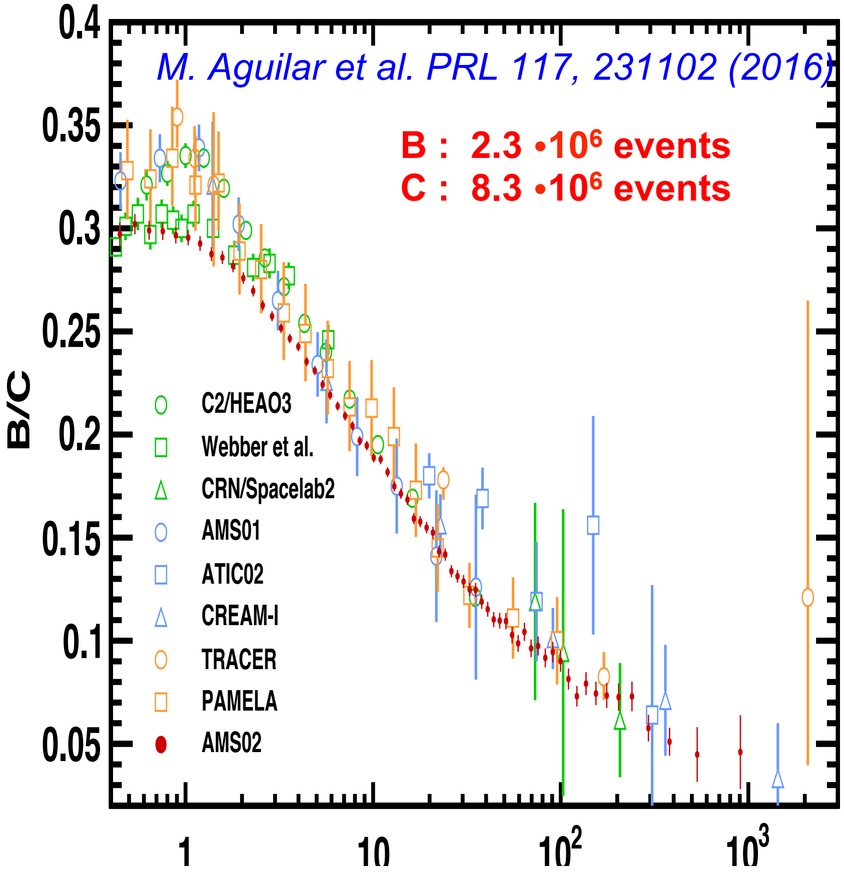
Thank you!

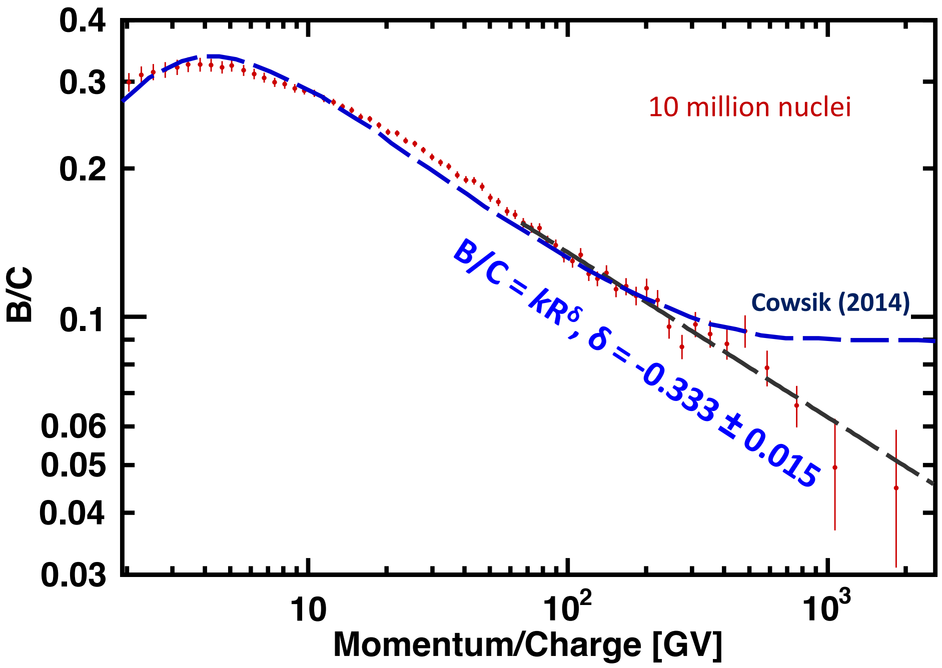
BackUp

Positron Flux: interpretation (modified Propagation)

Modified Propagation models with no standard secondary e^+ production

The B/C ratio measured by AMS does not show any significant structures in contrast to many cosmic ray models that require such structures at high rigidities. Above 65 GV, the B/C ratio is well described by a single power law





Combined Electron + Positron Flux

You don't need a spectrometer