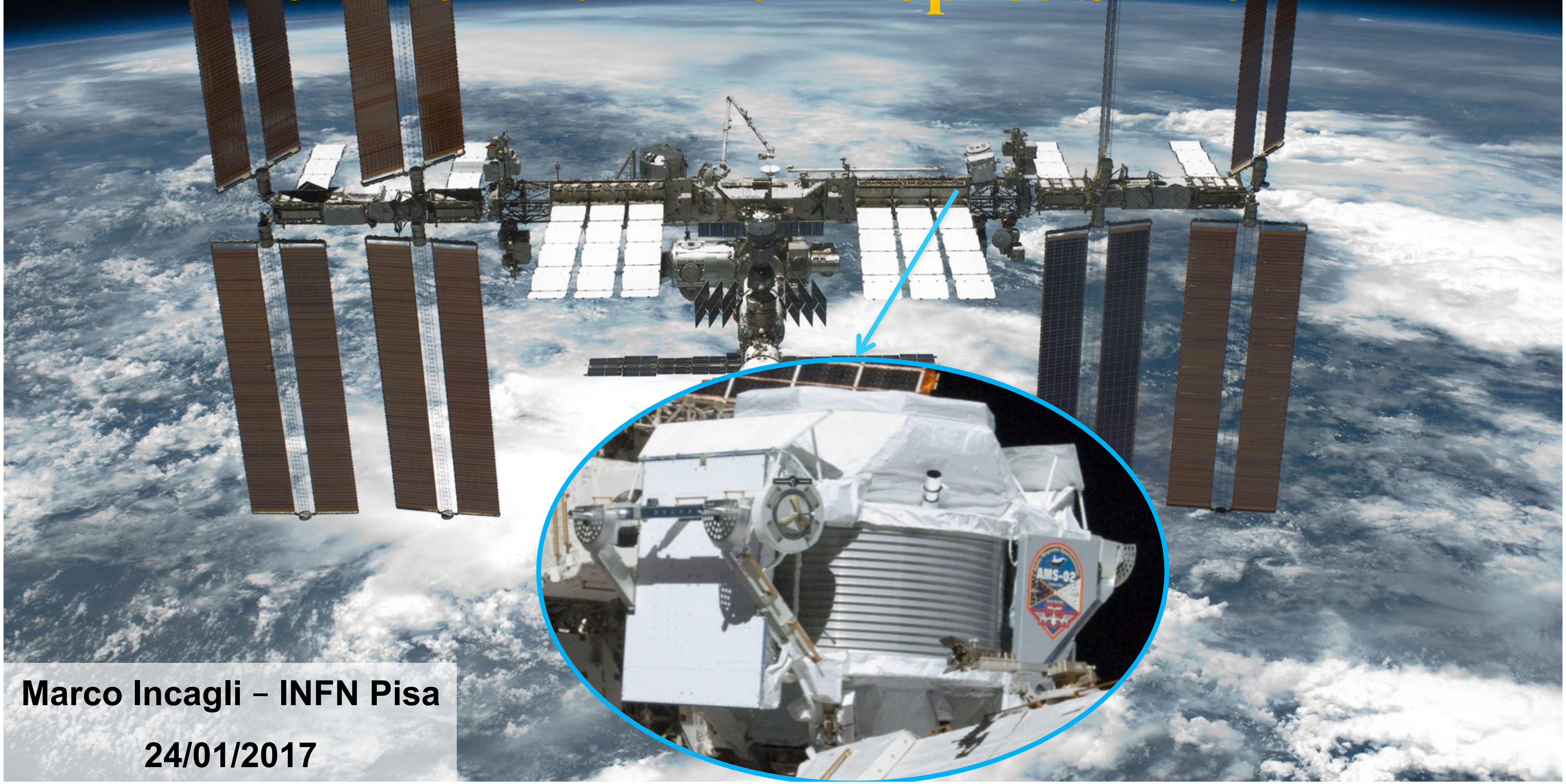
The First Five Years of the Alpha Magnetic Spectrometer on the International Space Station:

Search for New Physics in Space with the AMS02 Experiment on the International Space Station

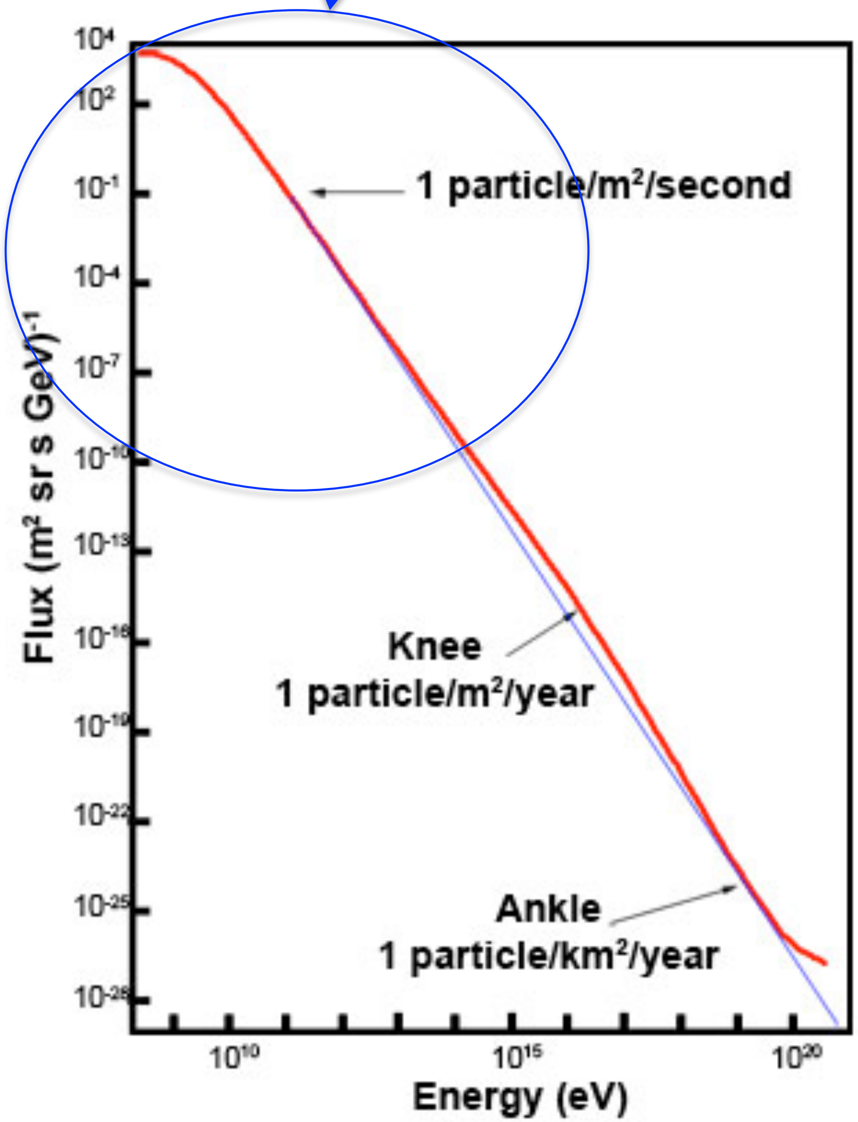


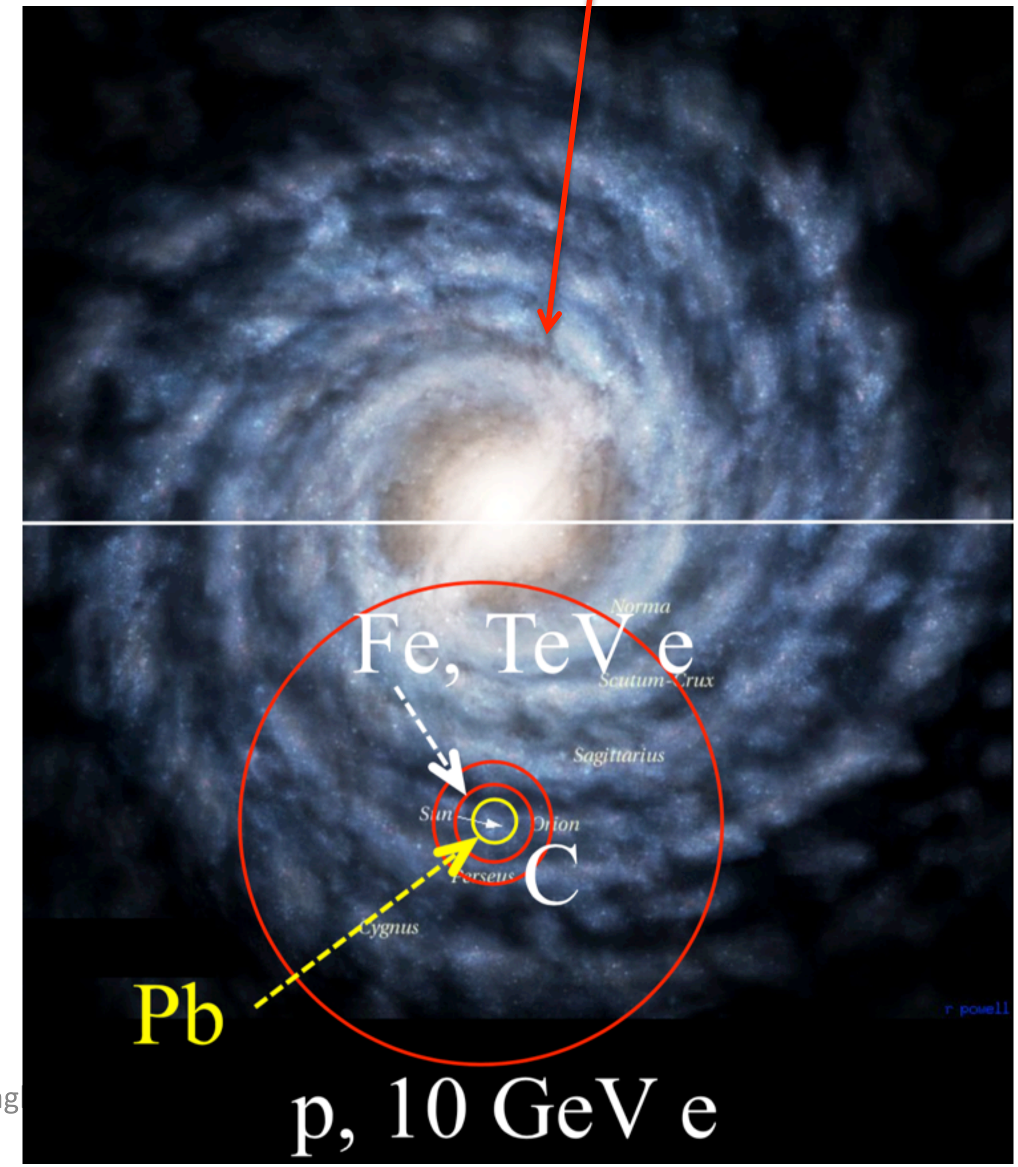
Marco Incagli – INFN Pisa

24/01/2017

Charged Cosmic Rays with Space Experiments

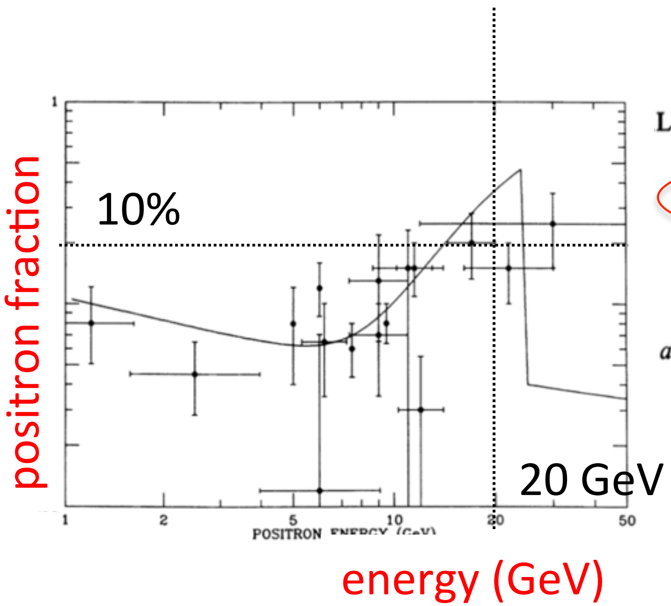
- Cosmic Rays with space experiments probe the local galaxy





The physics of AMS

- Understand the mechanisms of production and propagation of CR in the galaxy: interesting per se and to understand astrophysical background to exotic sources
- Dark Matter (DM): DM with mass of tens of GeV to few TeV can annihilate to charged (anti)particles of energy 1-1000 GeV
- Anti Matter (AM) direct search through anti-nuclei



L REVIEW D VOLUME 42, NUMBER 4 15 AUGUST 1990

Positron line radiation as a signature of particle dark matter in the halo

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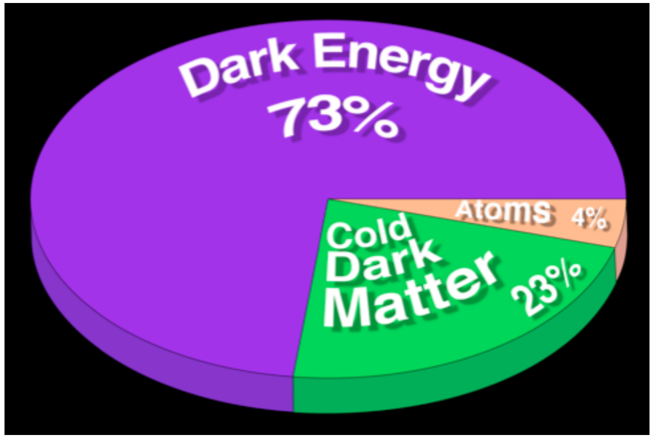
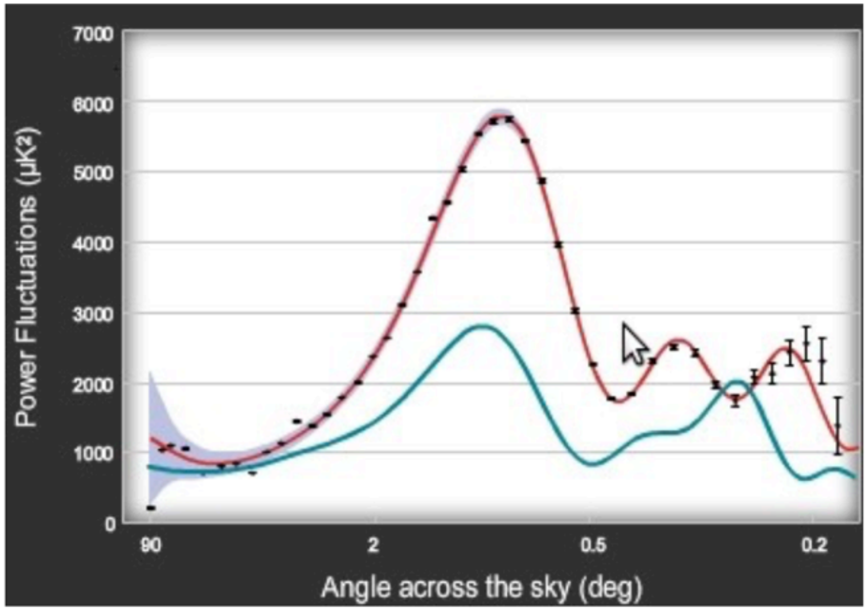
(Received 23 February 1989; revised manuscript received 21 February 1990)

Evidence for Dark Matter

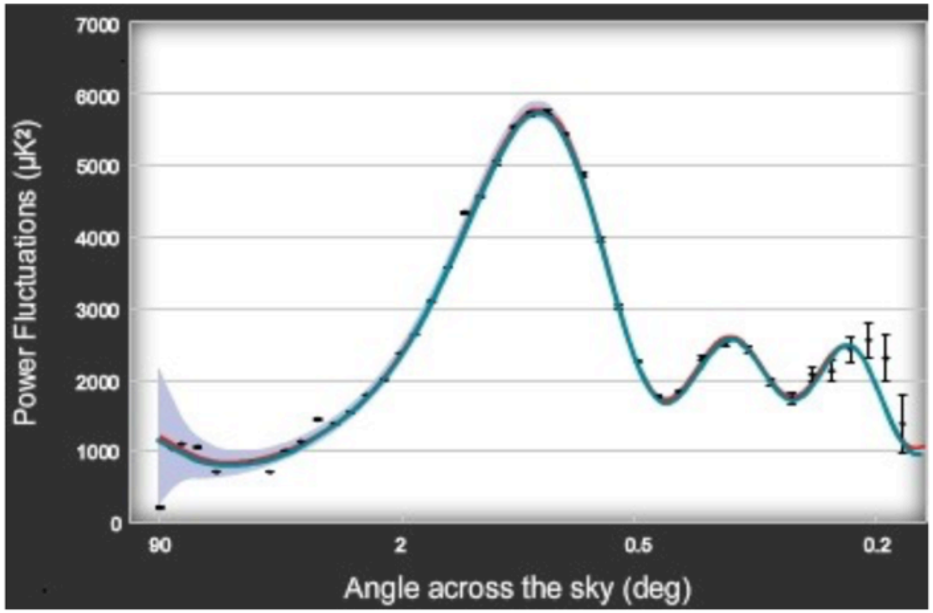
- Galaxy Rotation Curves
- Structure Formation
- Gravitational Lenses
- Cluster Collisions
- Cosmic Microwave Background Radiation



Without Dark Matter

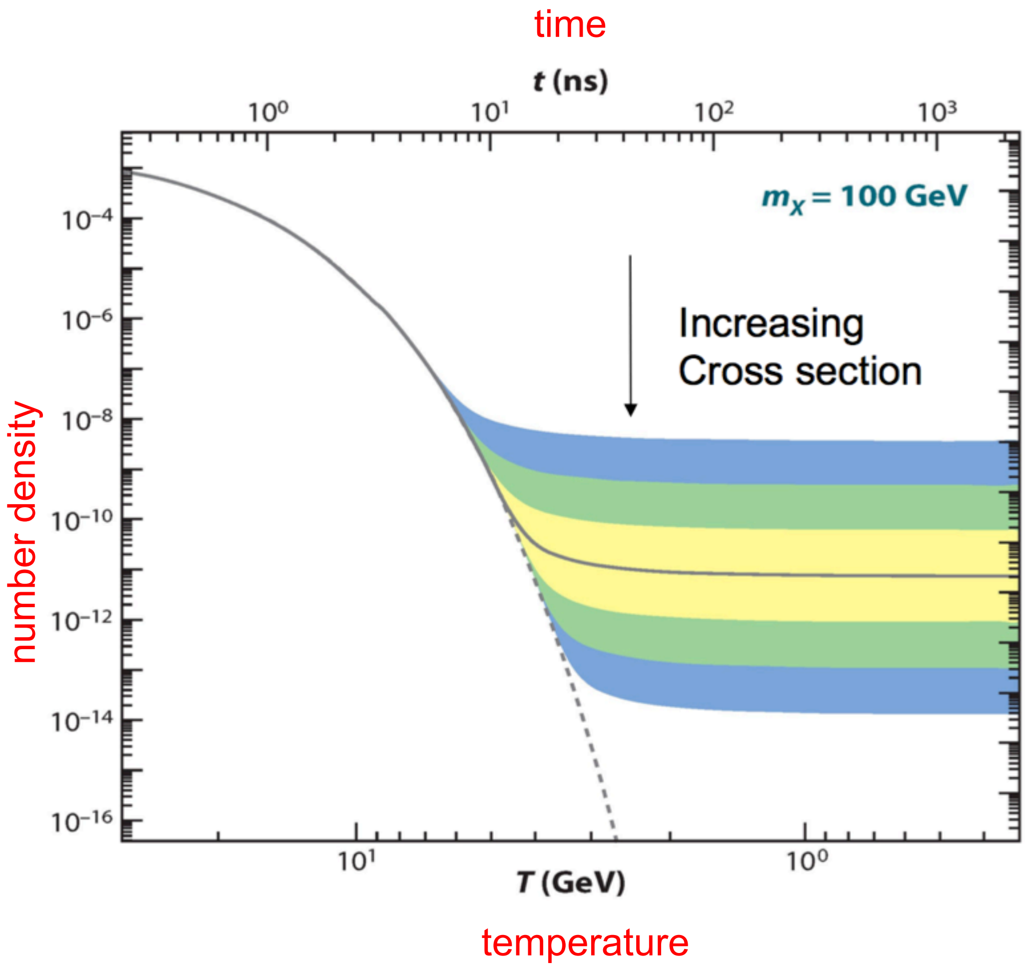


With Dark Matter



Dark Matter Abundance

- After the Big Bang, DM particles interact with Standard Model ones and reach thermal equilibrium;
- when the expansion rate equals the rate of annihilation, DM freezes-out;
- DM particles cluster forming the structures we observe today;
- DM abundance is connected to the annihilation cross section at freeze-out → *particles of masses 100-1000 GeV which interact weakly satisfy this boundary.*



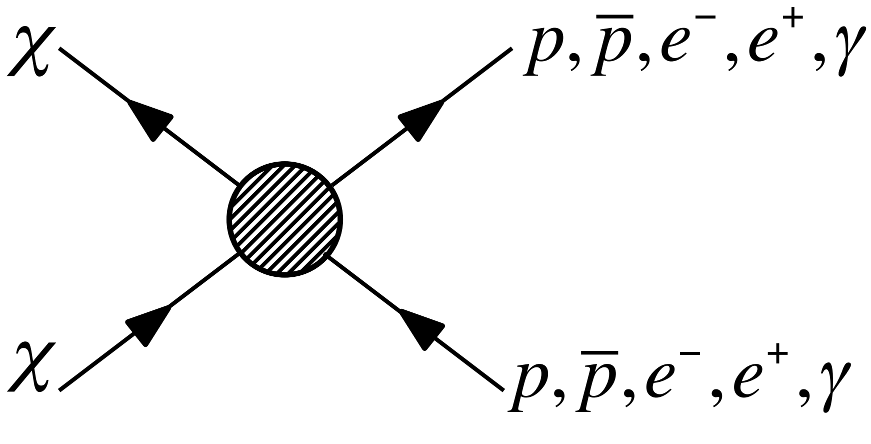
→ WIMPs = Weakly Interacting Massive Particles

Three independent methods to search for WIMP Dark Matter

Annihilation

AMS

$\chi + \chi \rightarrow e^+, \bar{p}, \gamma, \ldots$



Scattering

LUX
DARKSIDE
XENON 1t
CDMS II
…

$\chi + N \rightarrow \chi + N$

$\ldots + \chi + \chi \leftarrow p + p$

LHC

Production

Physics of electrons and protons

Annihilation

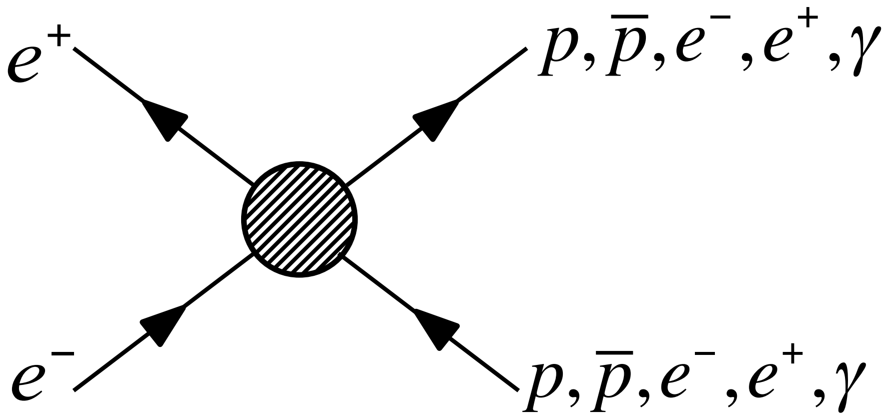
SPEAR, DORIS, PEP, PETRA, LEP, … *Ψ, τ*

$e^+ + e^- \rightarrow p, \bar{p}, e^-, e^+, \gamma$

Scattering

SLAC … *partons, electroweak*

$e + p \rightarrow p, \bar{p}, e^-, e^+, \gamma$



$\ldots + e^+ + e^- \leftarrow p + p$

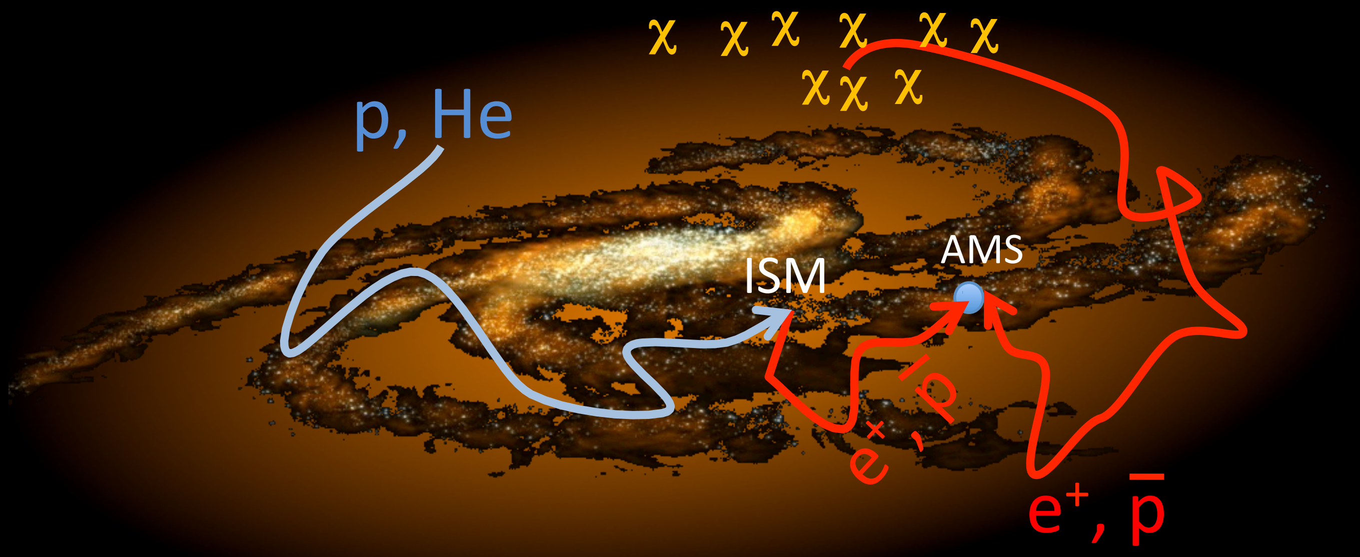
BNL, FNAL, LHC …*J, Y, t, Z, W, h^0*

Production

Dark Matter: χ

Collision of Cosmic Rays with the Interstellar Media will produce e^+, $\bar{p}$…

p, He + ISM → e^+, $\bar{p}$ + …

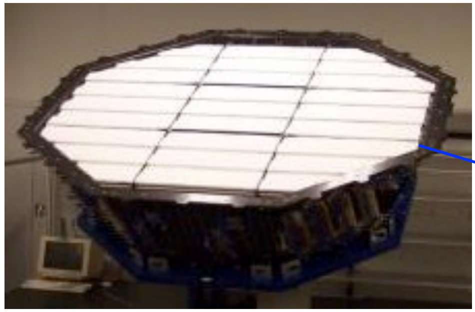


Dark Matter (χ) annihilations $\chi + \chi \rightarrow e^+, \bar{p} + \ldots$

The excess of e^+, $\bar{p}$ from Dark Matter (χ) annihilations can be measured by AMS

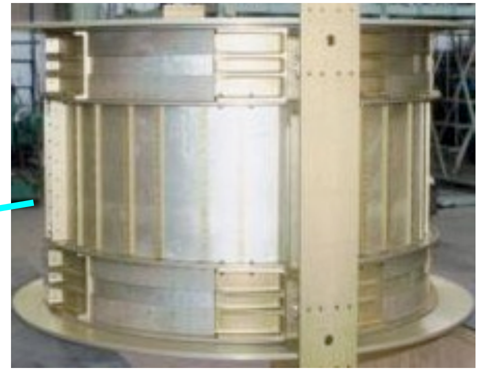
AMS: A TeV precision, multipurpose, magnetic spectrometer

Transition Radiation Detector (TRD)
Identify e^+, e^-

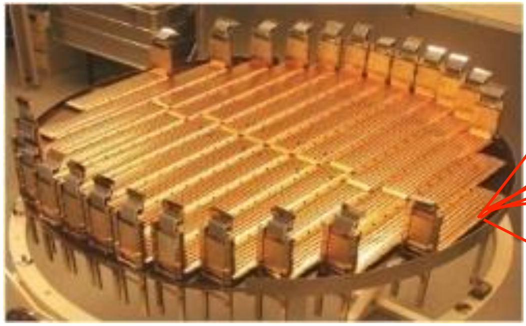


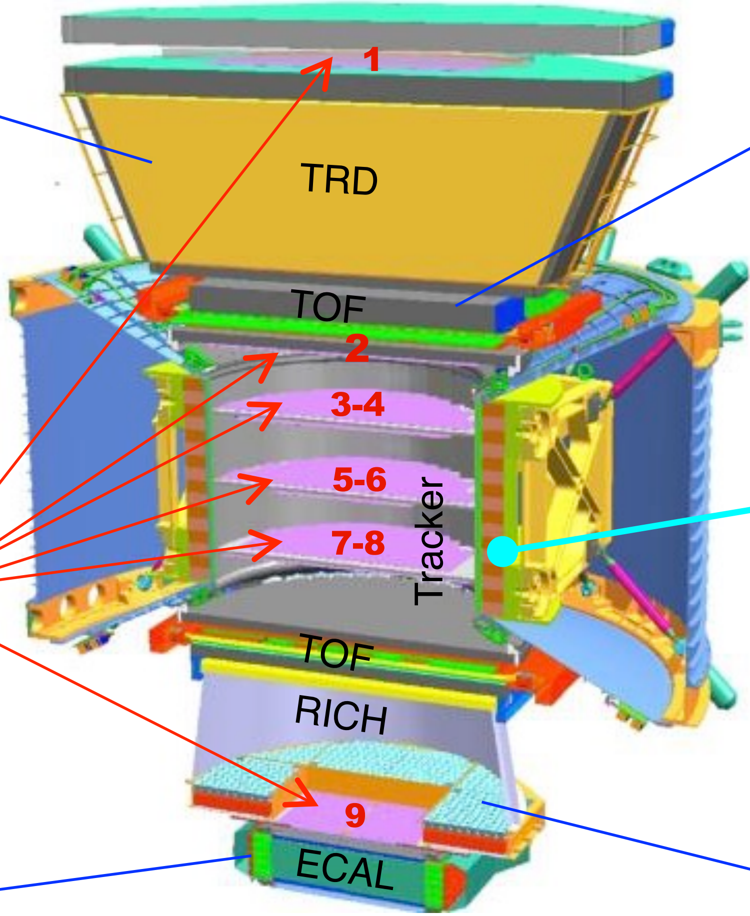
Time of Flight (TOF)
Z, E

Magnet
±Z



Silicon Tracker
Z, P or R=P/Z





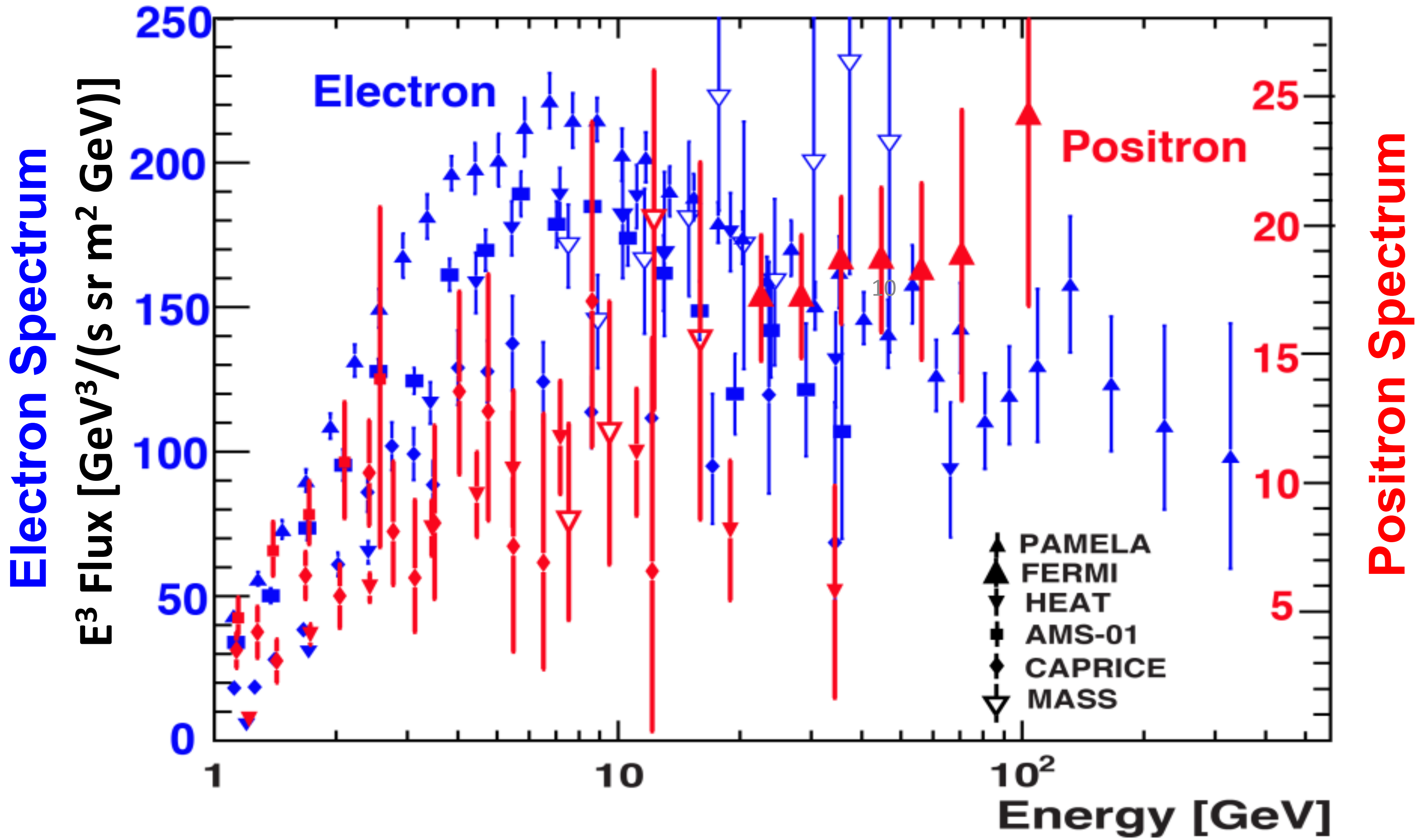
Ring Imaging Cherenkov (RICH)
Z, E

Electromagnetic Calorimeter (ECAL)
E of e^+, e^-

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

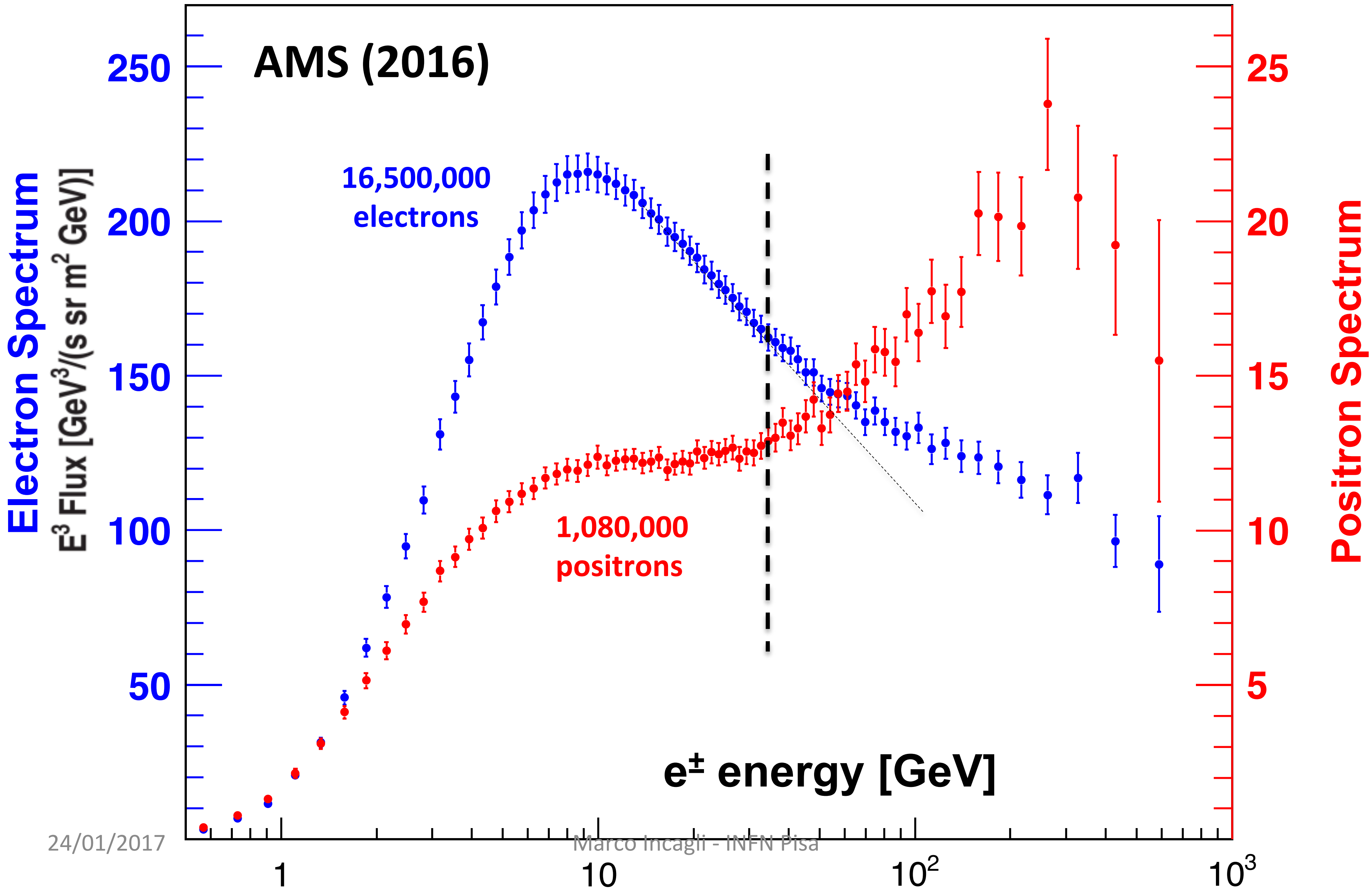
Electron and Positron spectra before AMS

1. These were the best data.
2. Nonetheless, the data have large errors and are inconsistent.
3. The data has created many theoretical speculations.



The Electron and Positron fluxes

The electron flux and the positron flux are different in their magnitude and energy dependence



Examples of Theoretical Models for positrons (and antiprotons)

From Dark Matter

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)

From Astrophysical Sources

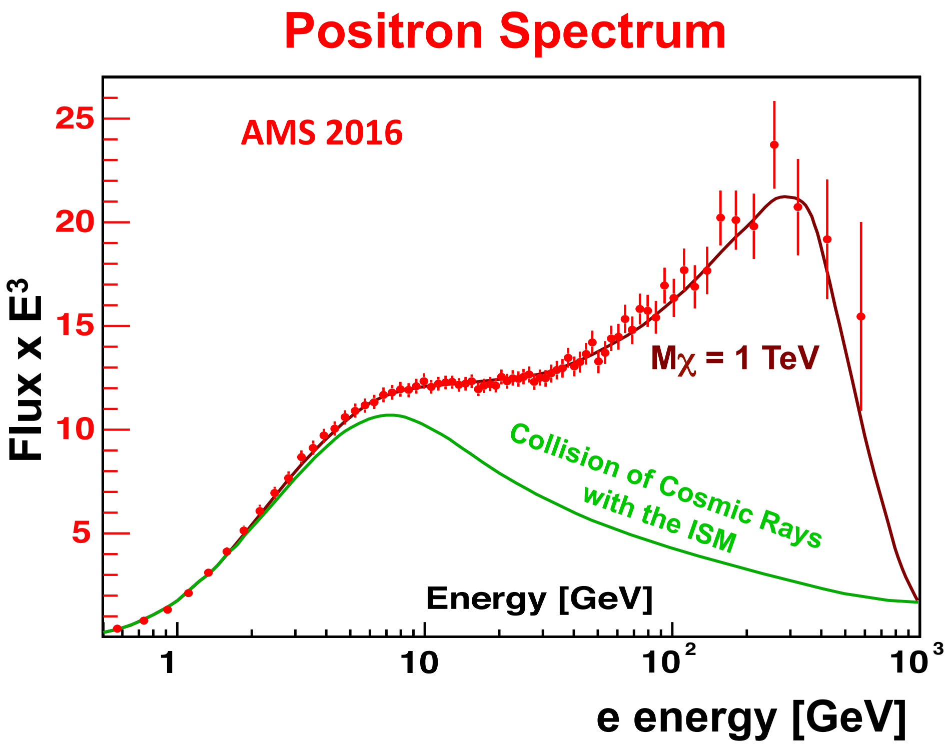
1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 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)

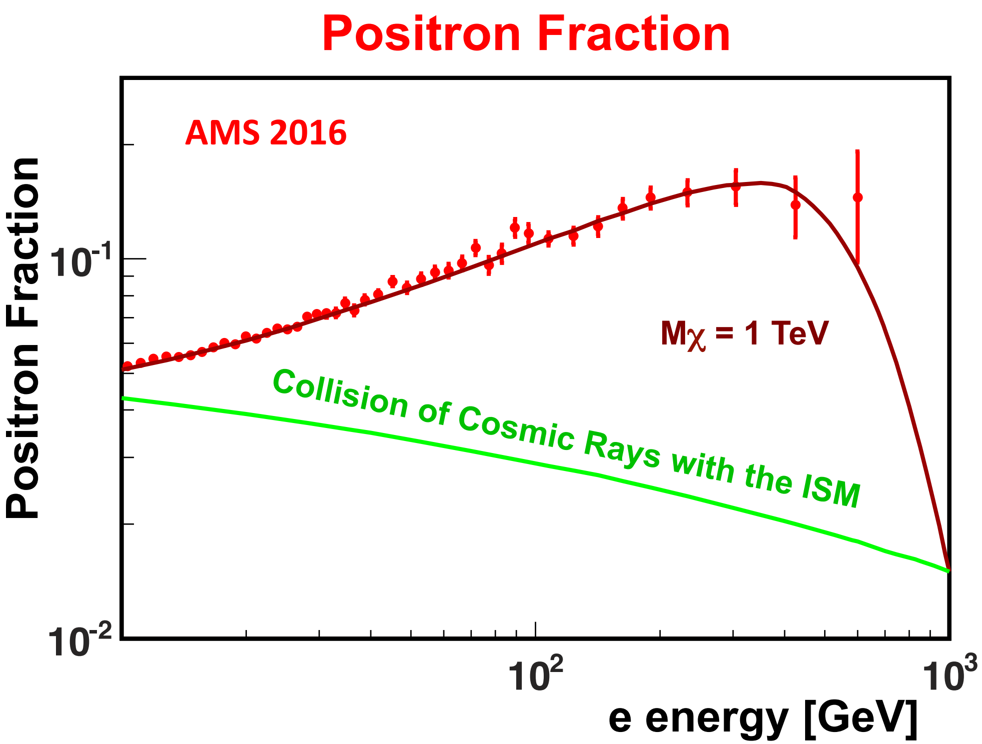
From Secondary Production

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)

The positron flux and the positron fraction require new primary sources or a modified propagation

- Can positron flux, and positron fraction, be interpreted as *Dark Matter interaction*?
- Yes, but it requires a DM cross section which is larger than the thermal one by 2-3 orders of magnitude

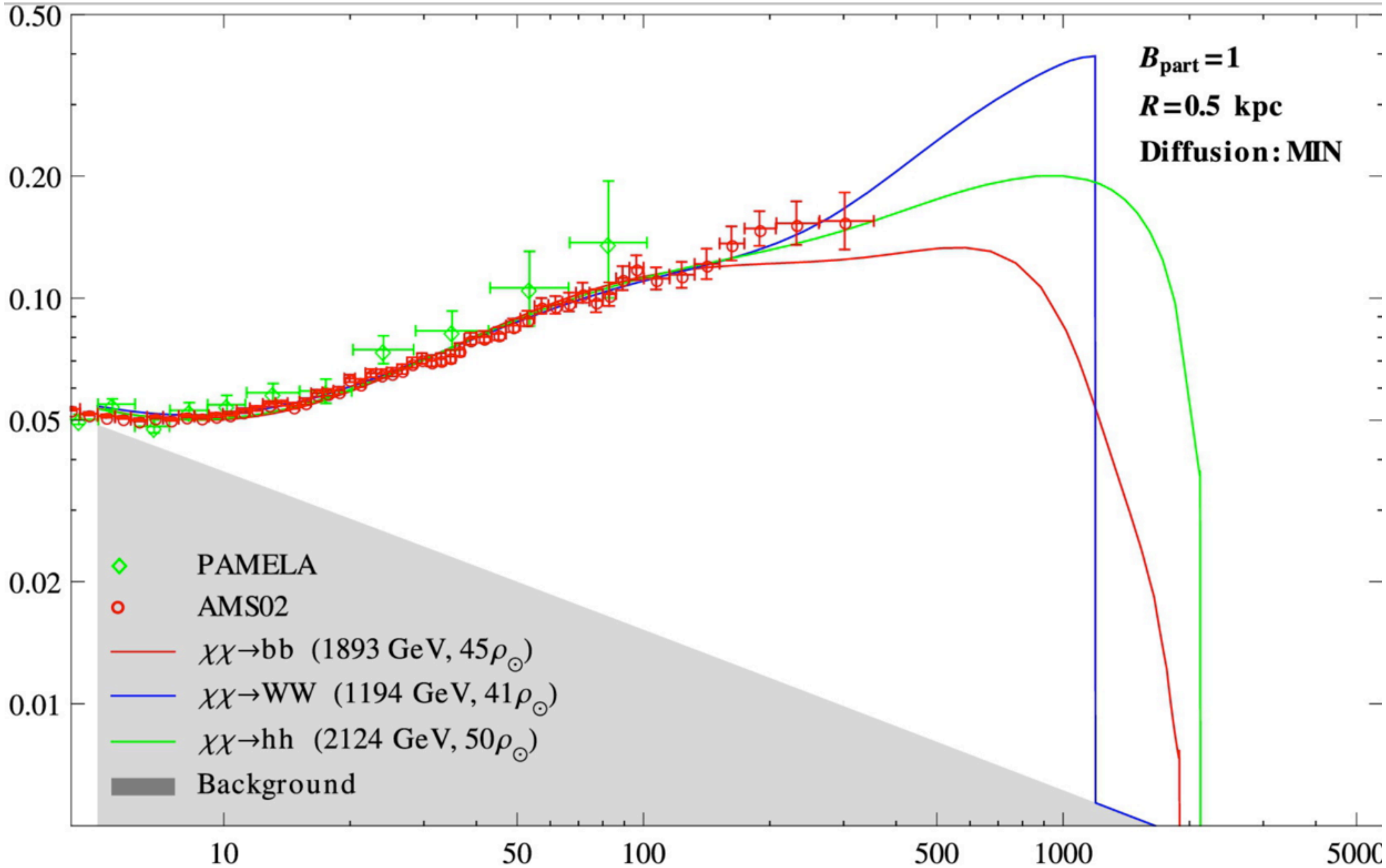




Model based on: J. Kopp, Phys. Rev. D 88 (2013) 076013

The origin of the Positron Fraction

- The excess in the cross section can be justified with the hypoyhesis of a local Dark Matter over-density



The cosmic-ray positron excess from a local Dark Matter over-density – A. Strumia, et al. , PLB 728(2014)58

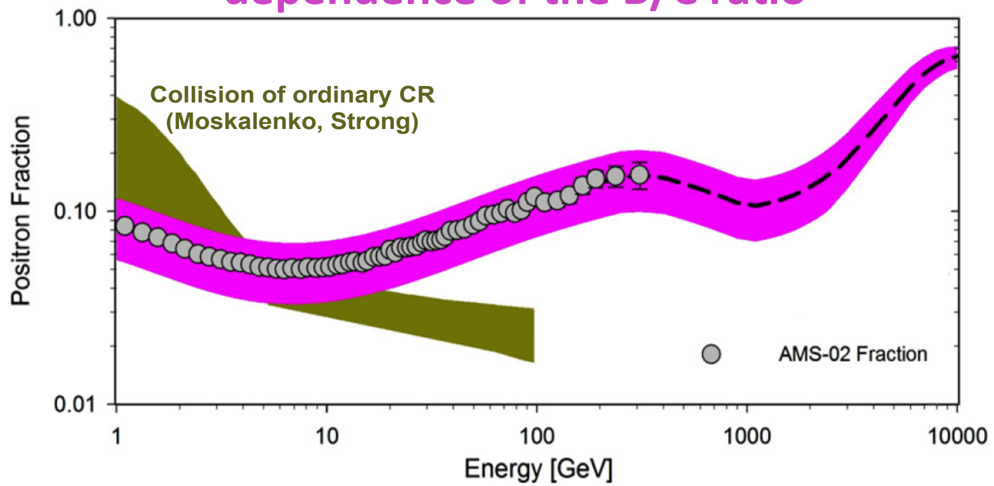
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Acceleration of secondaries in shock waves
- Pulsars
- …

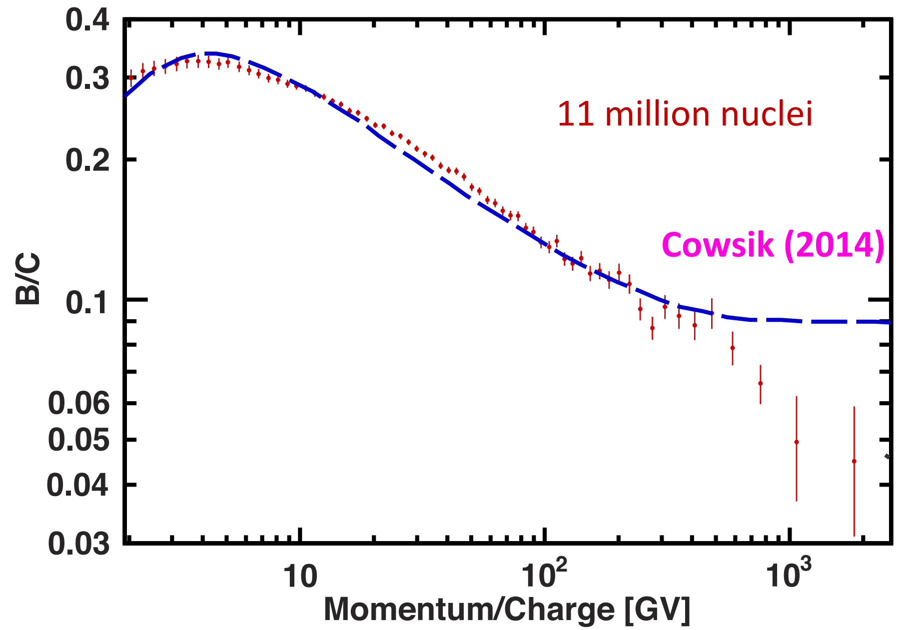
Example:

R. Cowsik *et al.*, Ap. J. 786 (2014) 124, (pink band) explaining that the AMS positron fraction (gray circles) above 10 GV is due to propagation effects.

However, this requires a specific energy dependence of the B/C ratio



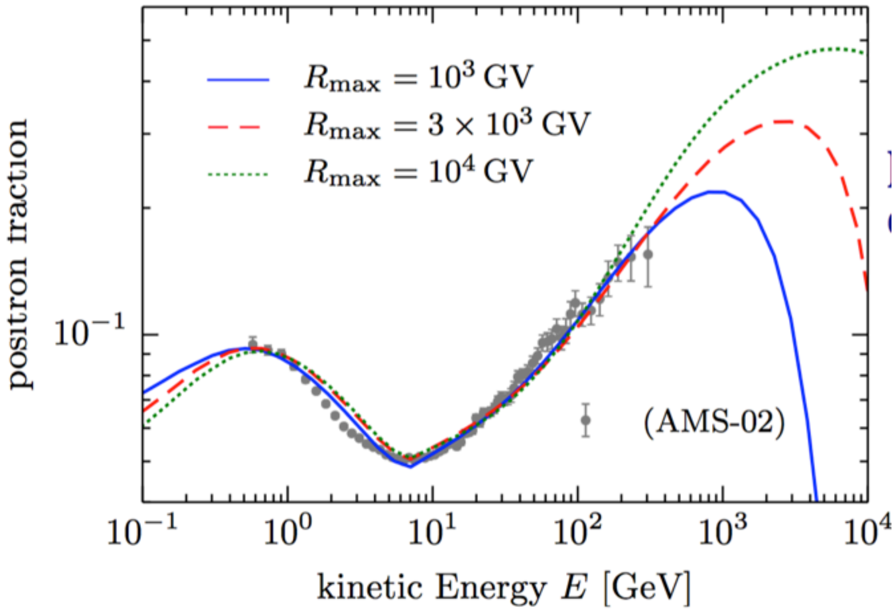
The AMS Boron-to-Carbon (B/C) flux ratio

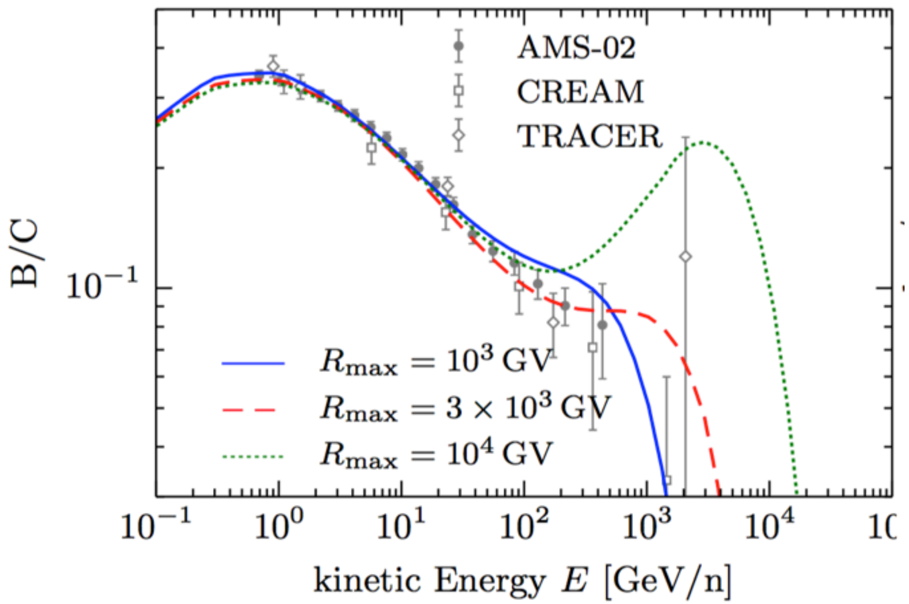


Alternative Models

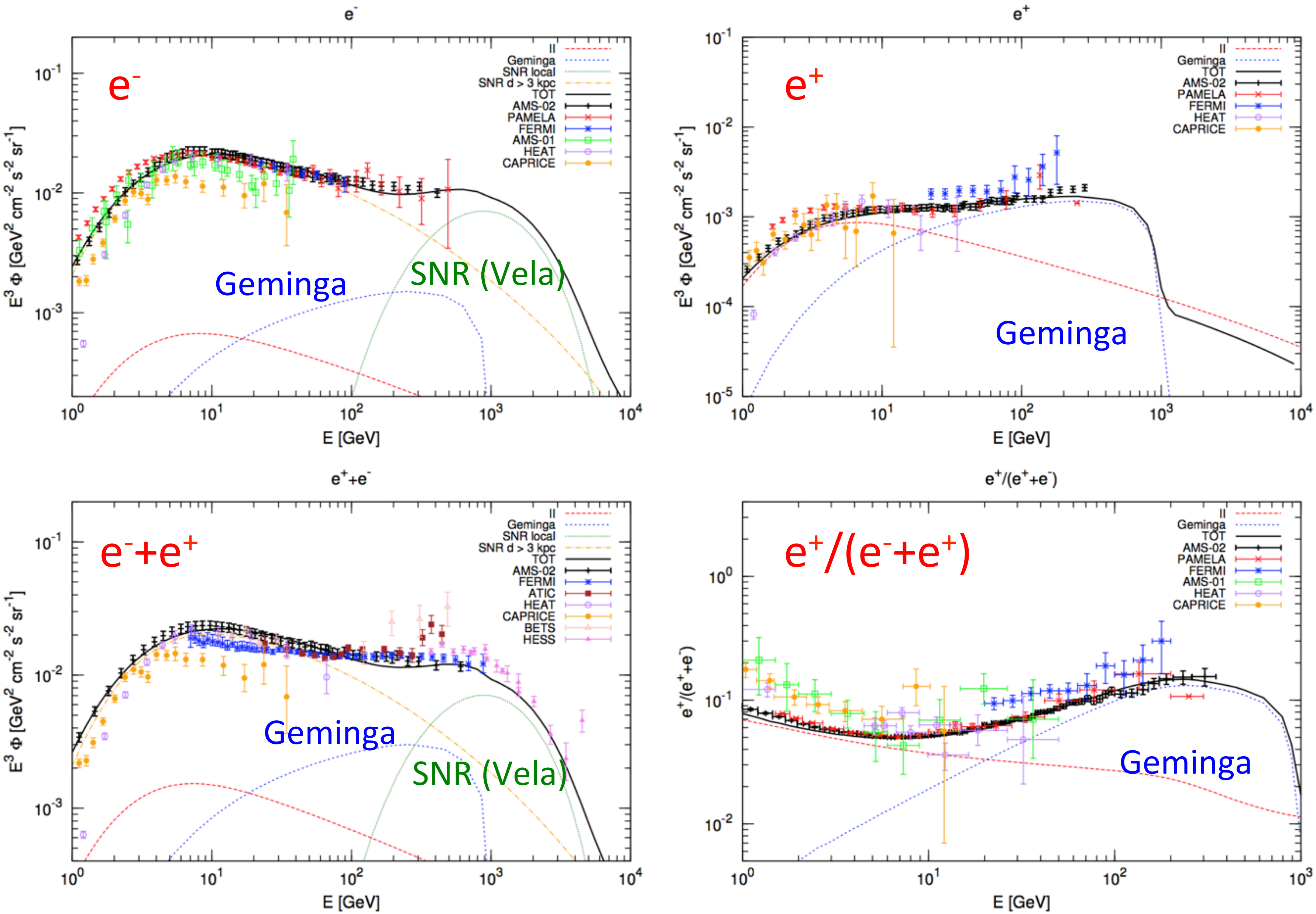
- **Modified Propagation of Cosmic Rays**
- **Acceleration of secondaries in shock waves**
- **Pulsars**
- **…**

- Secondaries are produced inside the shock wave and accelerated
- Comparison of positron fractionand of B/C data with one model which includes re-acceleration (Mertsch et al, PR D90 (2014))



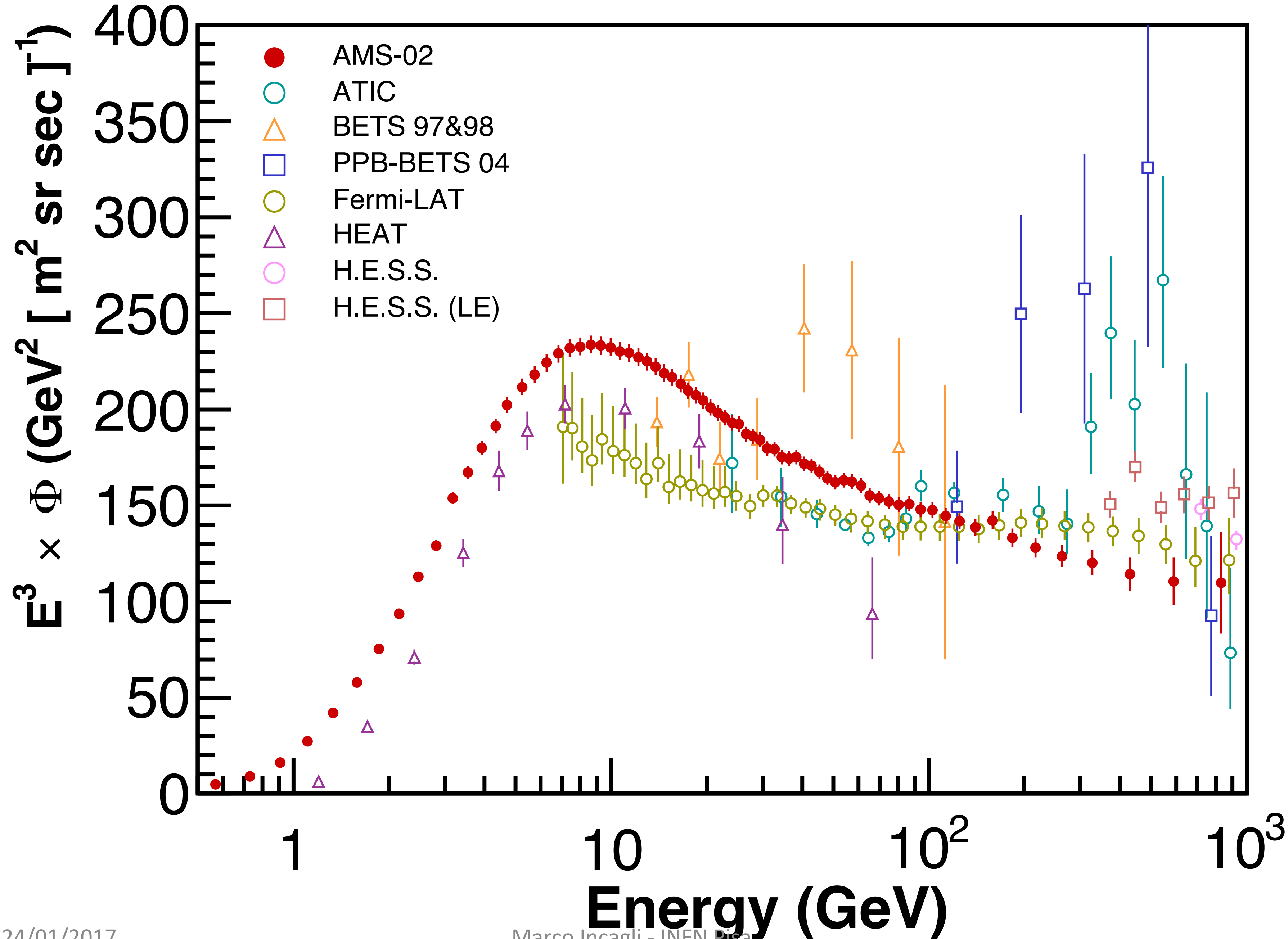


Pulsar contribution



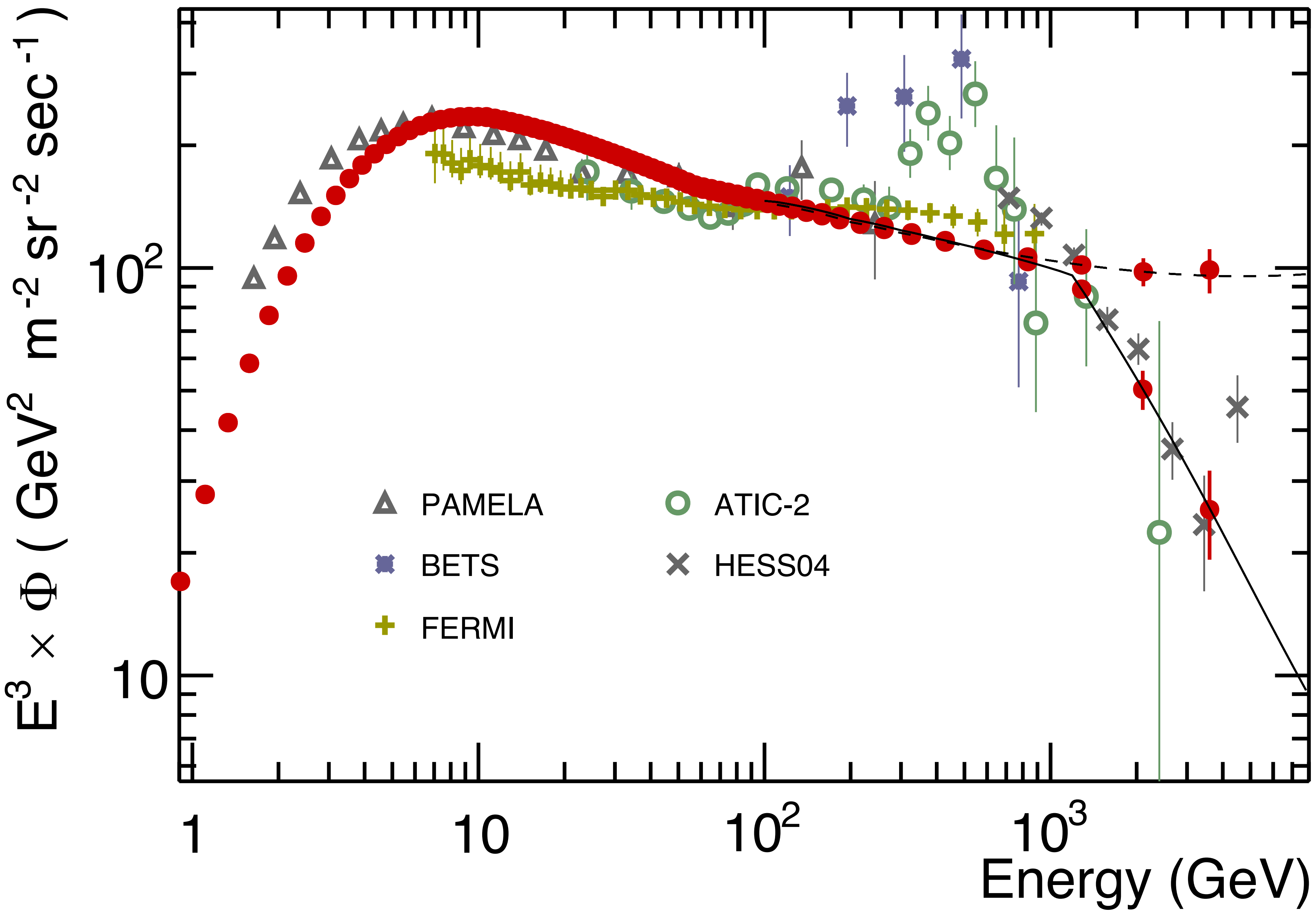
M. Di Mauro, et al. - arXiv:1402.0321 [astro-ph.HE]

The $(e^+ + e^-)$ flux



AMS-02
ATIC
BETS 97&98
PPB-BETS 04
Fermi-LAT
HEAT
H.E.S.S.
H.E.S.S. (LE)
$E^3 \times \Phi$ (GeV^2 [m^2 sr sec]$^{-1}$)
0
50
100
150
200
250
300
350
400
1
10
10^2
10^3
Energy (GeV)

The AMS ($e^+ + e^-$) flux in 2024



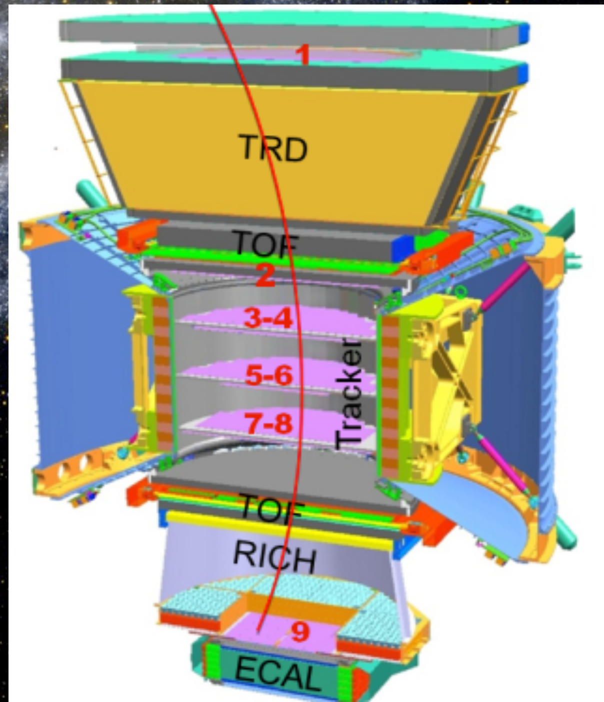
AMS will be able to distinguish the ($e^+ + e^-$) flux behavior above 1 TeV

Antiprotons

Cosmic ray + ISM $\rightarrow \bar{p} + \ldots$

$\chi + \chi \rightarrow \bar{p} + \ldots$

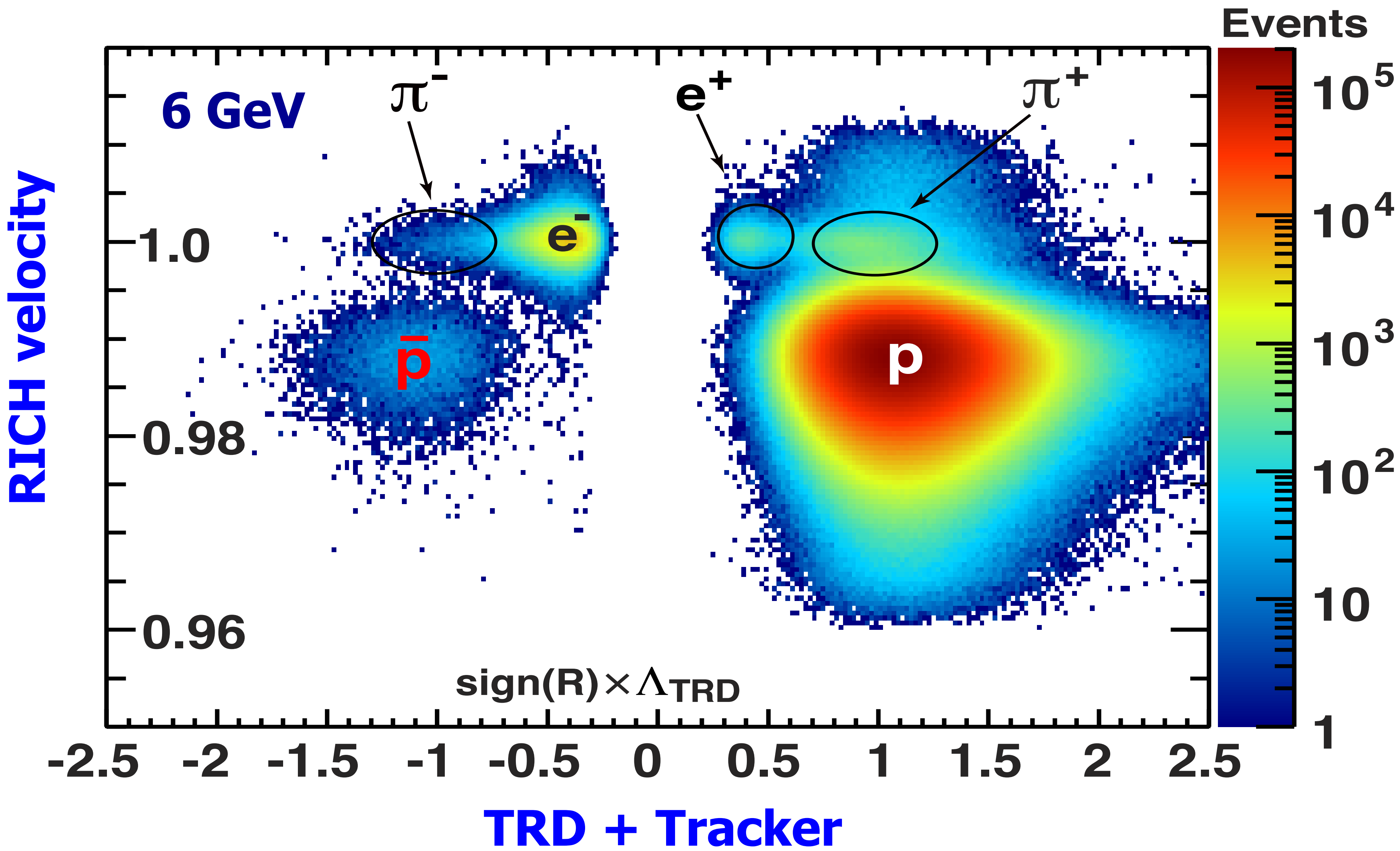
There is only 1 Antiproton for 10,000 Protons.



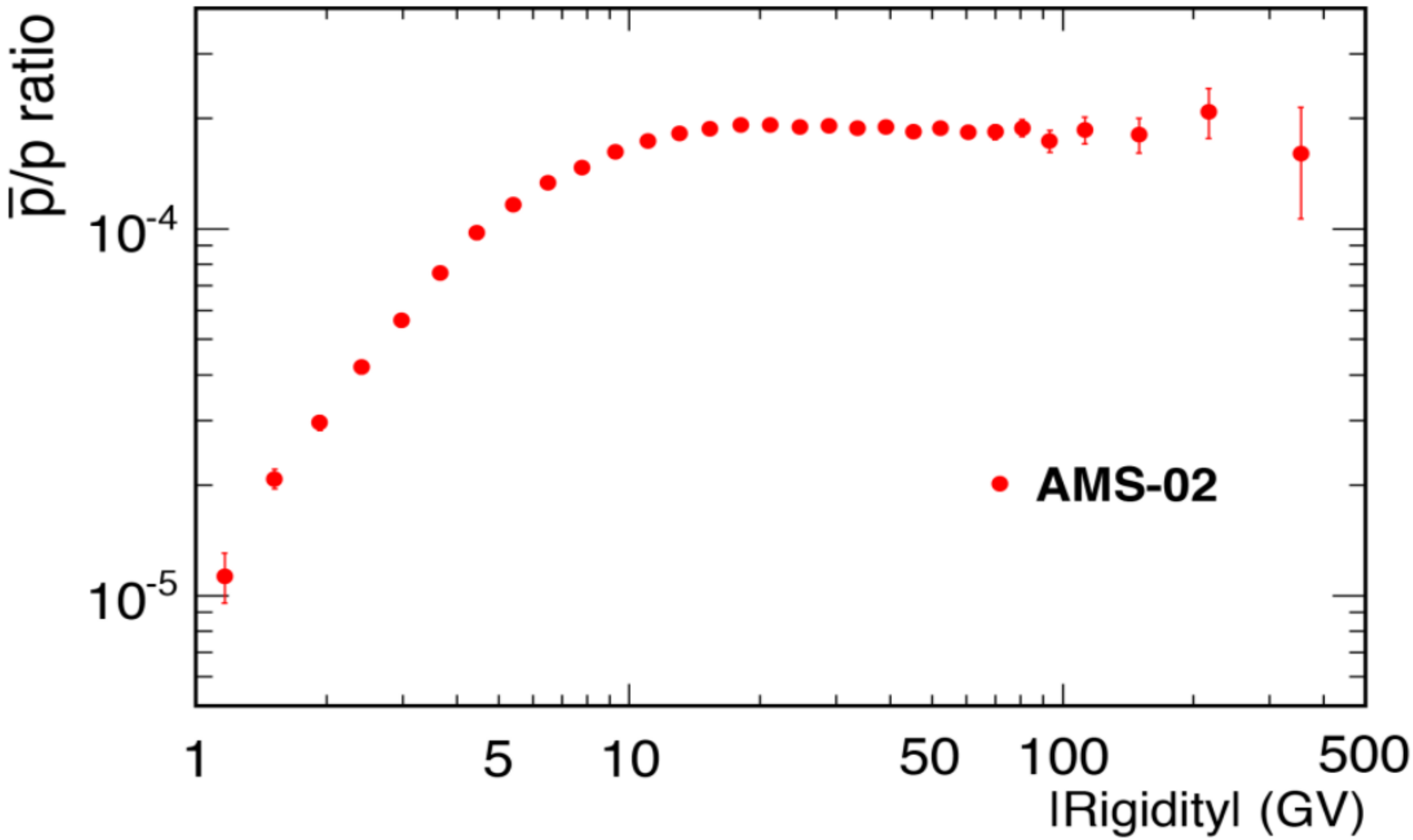
A percent precision experiment requires background rejection close to 1 in a million.

Selection of the signal:

The $\bar{p}$ signal is well separated from the backgrounds.

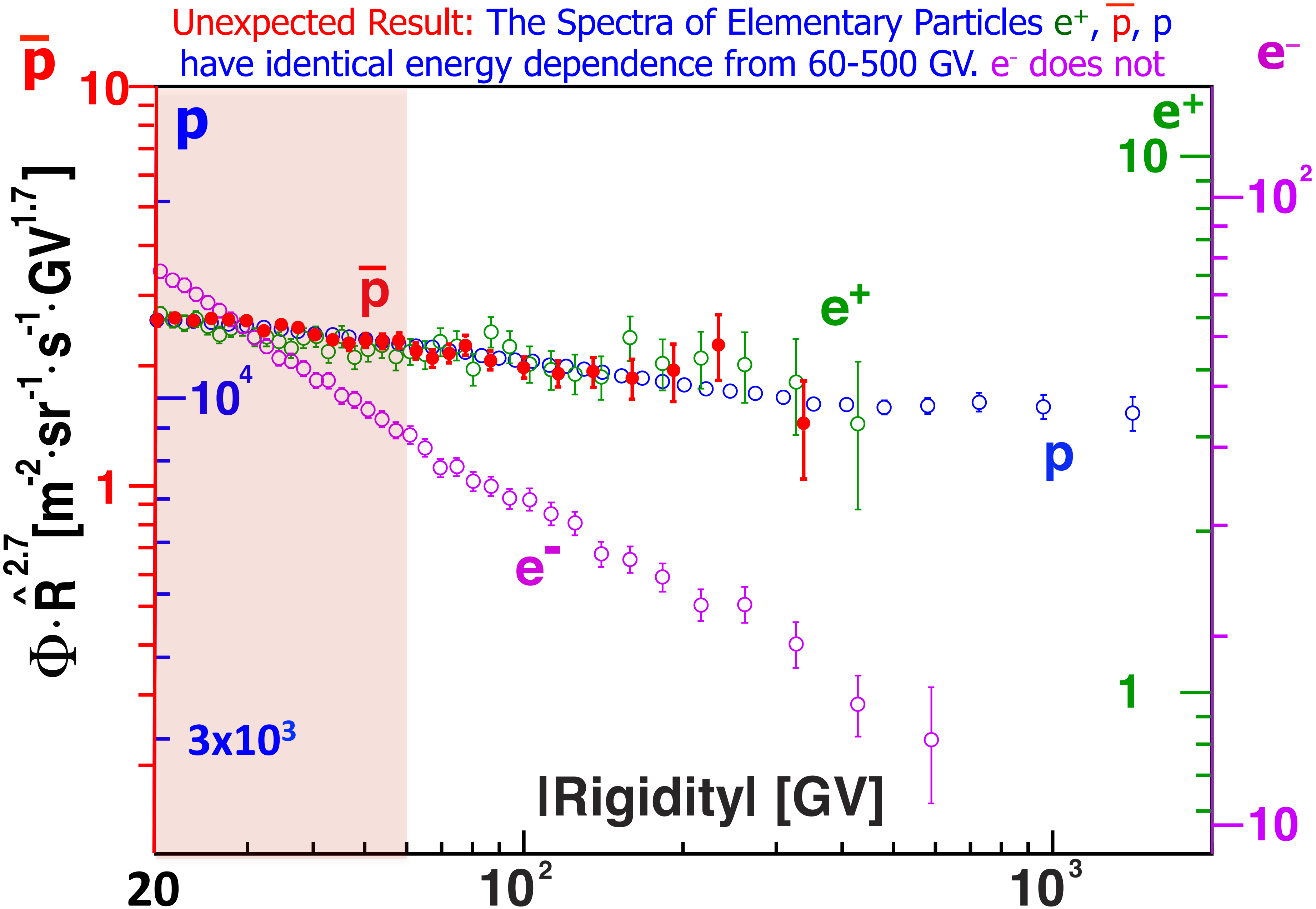


anti-proton to proton ratio



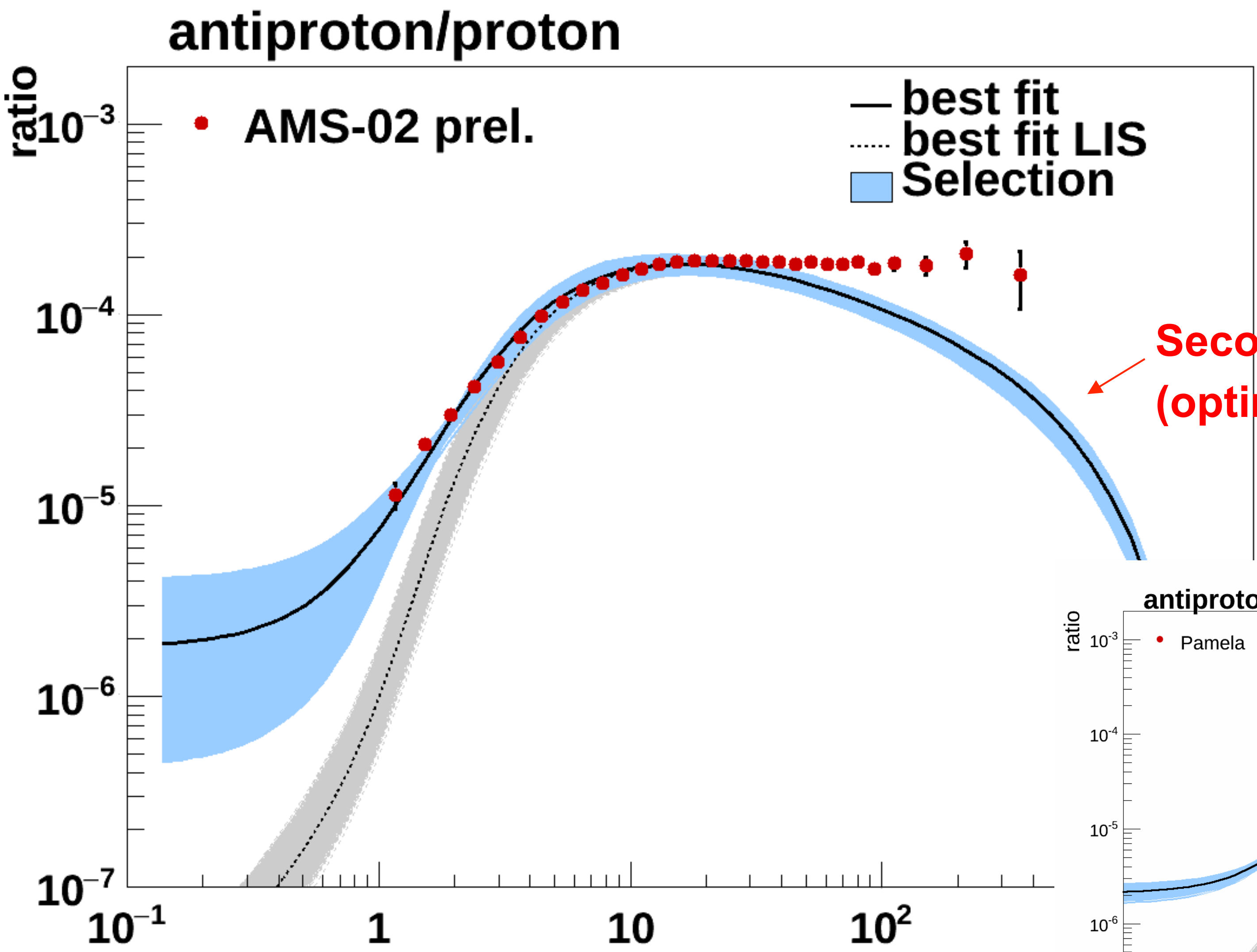
- no rise observed, as in e+/e- ratio, but the spectrum is <u>flatter than expected</u>
- precise measurement up to R=450 GeV; hard to go above.

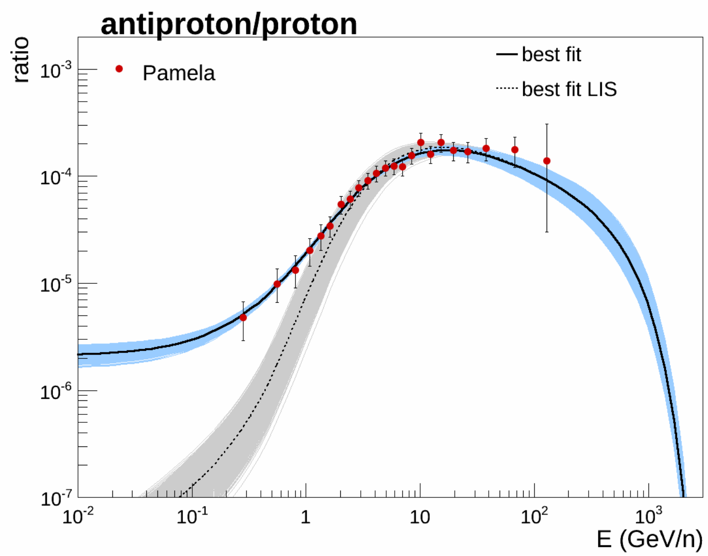
The antiproton flux



M. Aguilar *et al*., Phys. Rev. Lett. **117,** 091103 (2016)

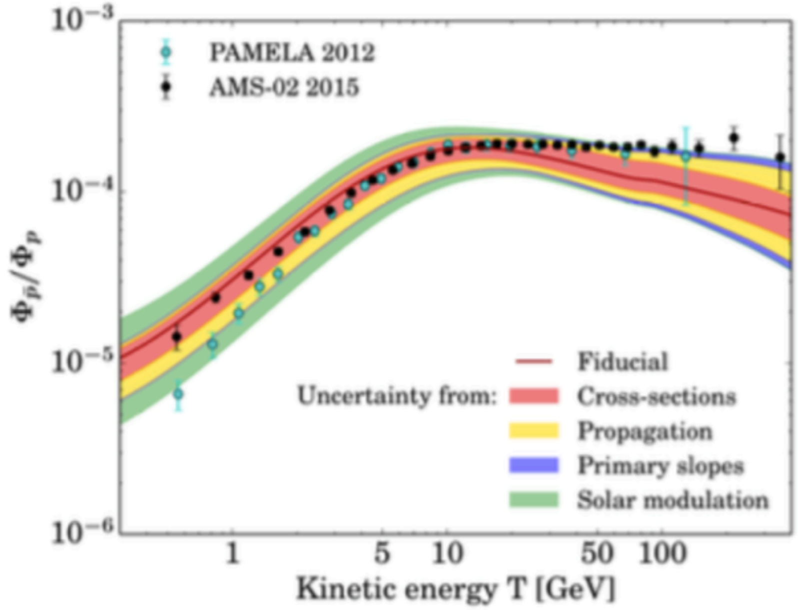
Example of a fit with a model optimized on Pamela data

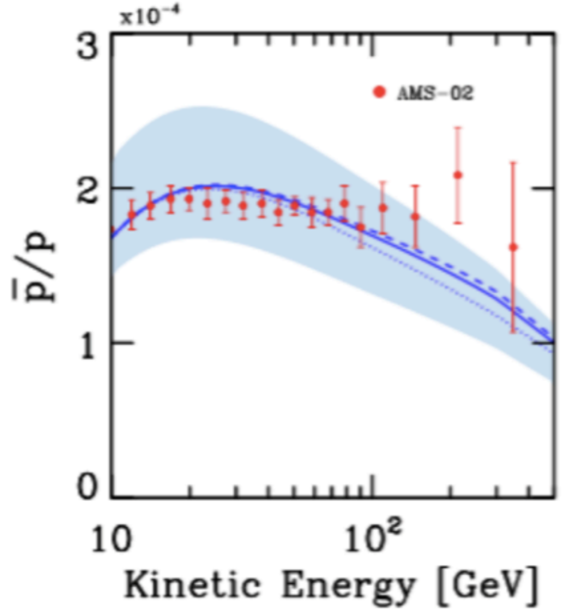




Dissertation / PhD Thesis IEKP-KA/2014-20
Simon Kunz (2014)
http://ekp-invenio.physik.uni-karlsruhe.de/record/48605

but if models are tuned on AMS ...





possible
ıodels:
lways some
ension with
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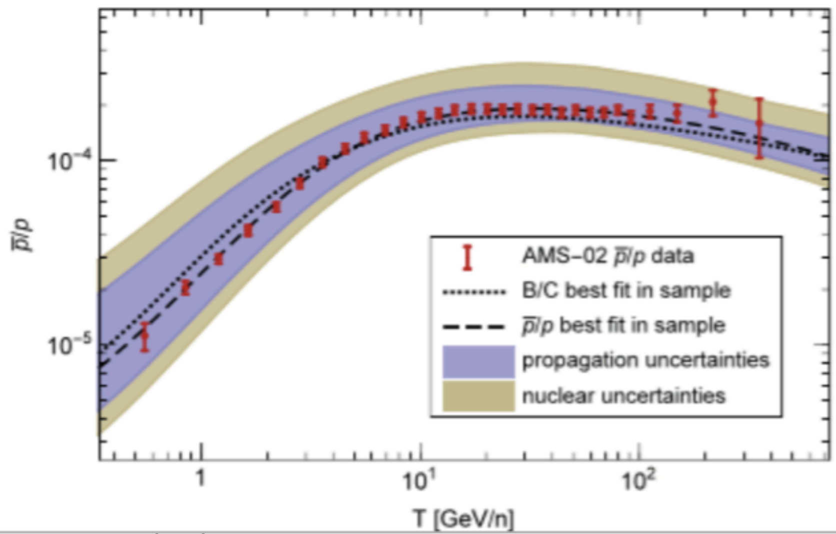


(a) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salatiand, and P.D.Serpico, JCAP1509 (2015) 09, 023 [arXiv:1504.04276 [astro-ph.HE]].

(b) C.Evoli, D.Gaggero and D.Grasso, arXiv:1504.05175 [astro-ph.HE].

(c) R.Kappl, A.Reinertand, and M.W.Winkler, arXiv:1506.04145 [astro-ph.HE].

Low mass DM in anti-proton ratio?

A. Cuoco et al.
arXiv:astro-ph 1610.03071v1

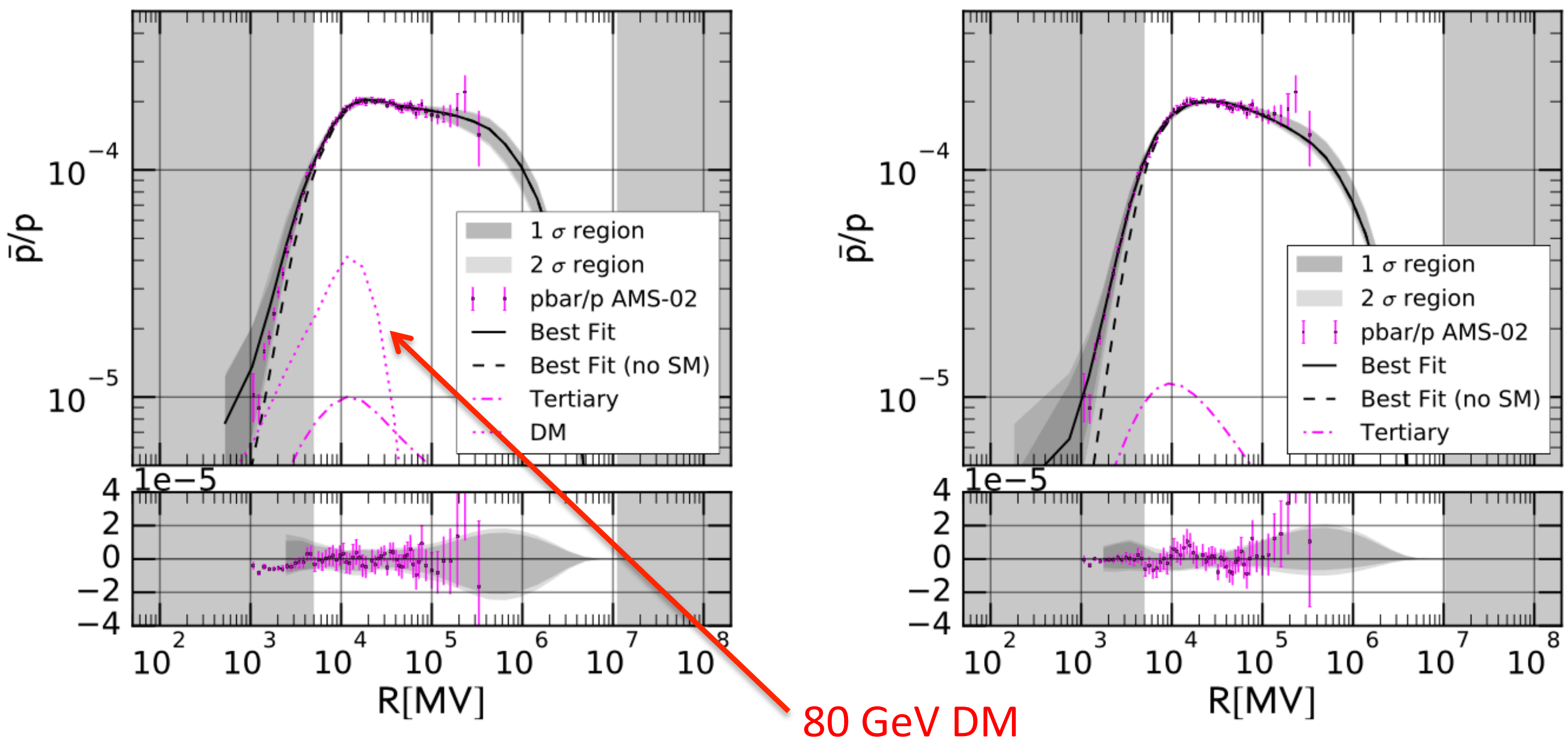
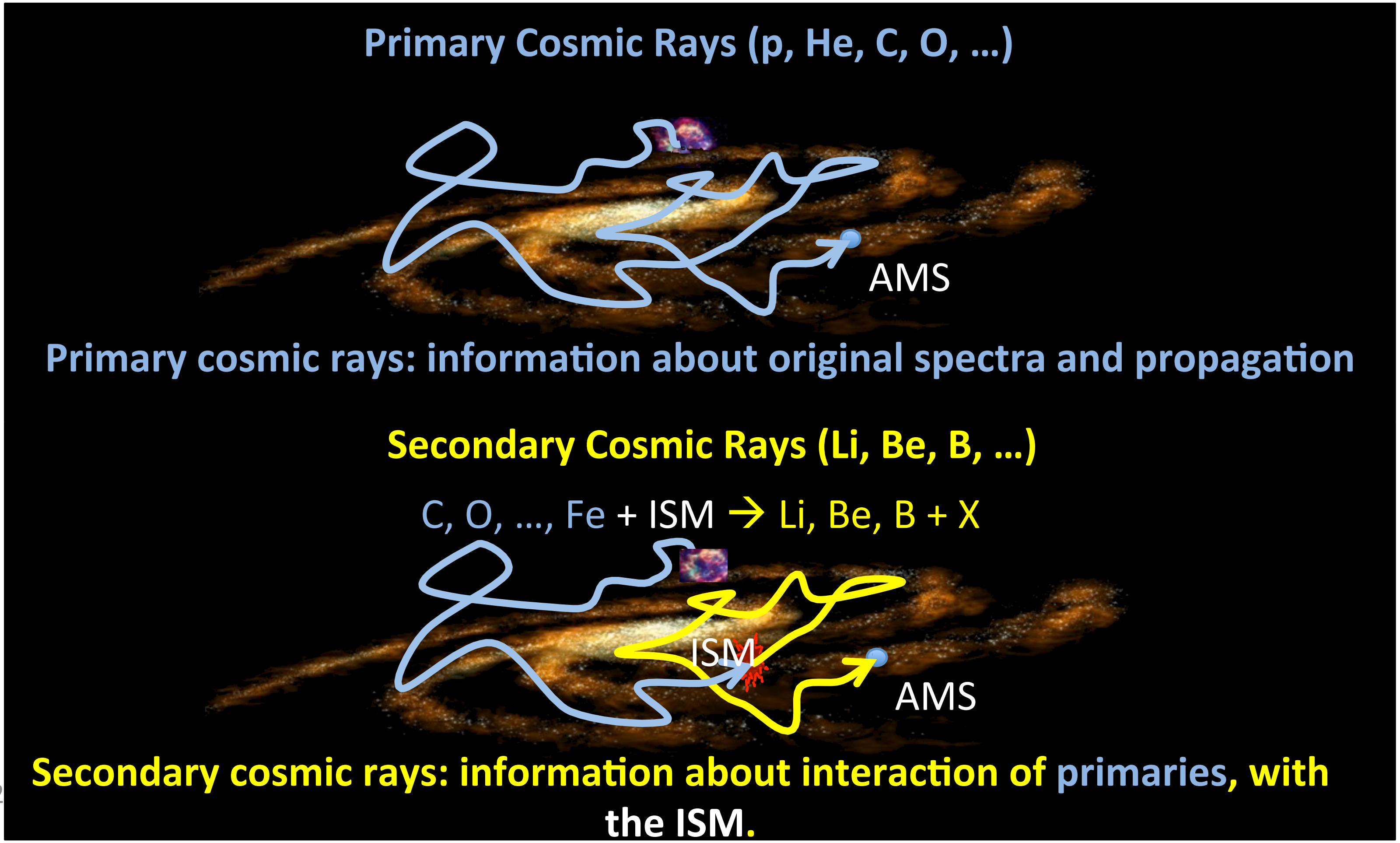


FIG. 1: Comparison of the best fit of the $\bar{p}/p$ ratio to the AMS-02 data [13], with a DM component (left panel) and without DM (right panel). The lower panels show the corresponding residuals. The fit is performed in the unshaded area, *i.e.*, for rigidities $5\,\mathrm{GV} \leq R \leq 10\,\mathrm{TV}$. The grey bands around the best fit indicate the 1 and 2σ uncertainty, respectively. The dashed black line (labeled "no SM") shows the best fit without correction for solar modulation. The dotted magenta line shows the best fit DM contribution. We also show, for comparison, the contribution from astrophysical tertiary antiprotons denoted by the magenta dot-dashed line.

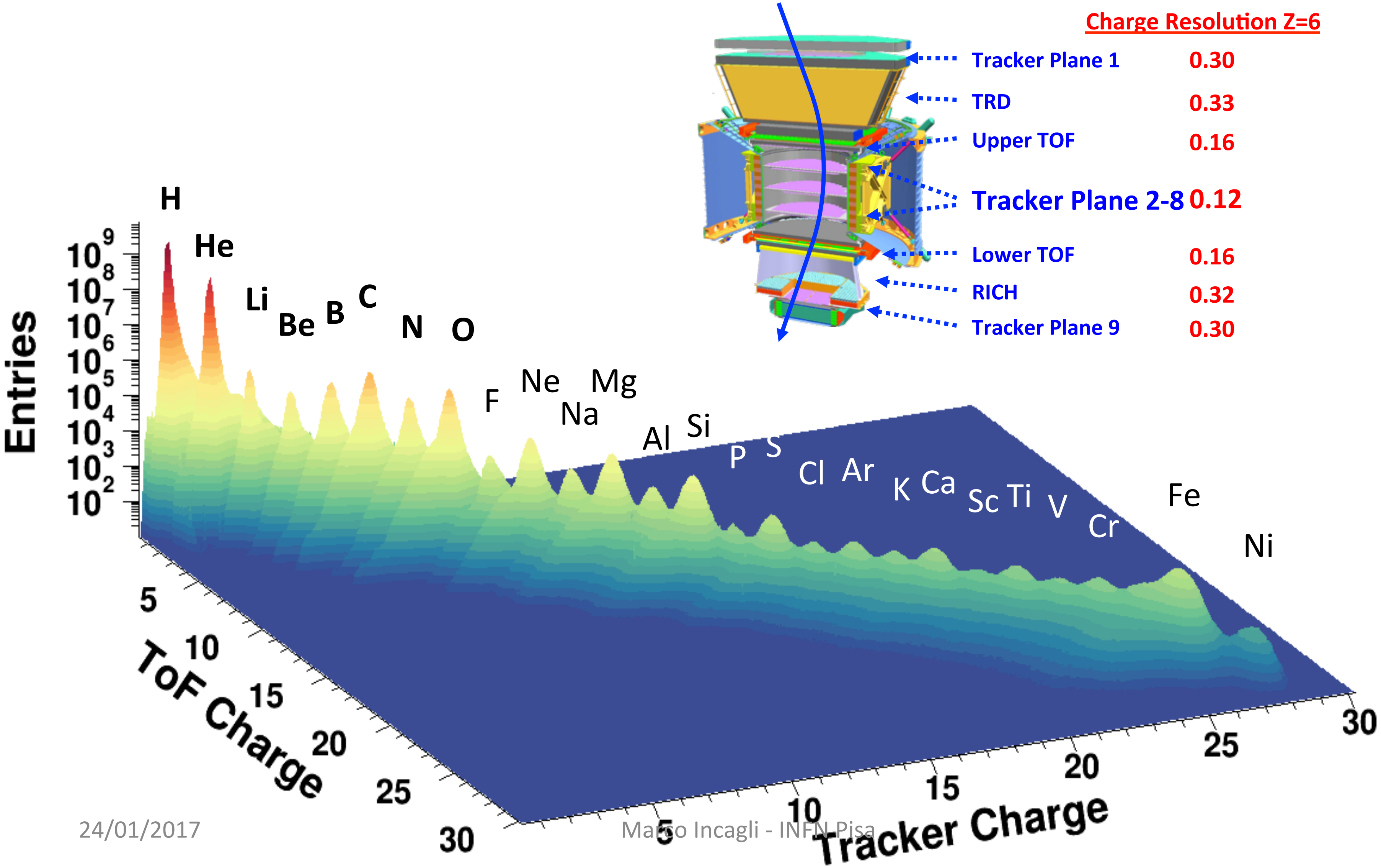
How can we distinguish among many models?

- Make precision measurements in many channels!
- In particular it is necessary to look at protons, Helium and heavier nuclei to understand the properties of "standard" Cosmic Rays: generation and propagation in the InterStellar Medium (ISM)



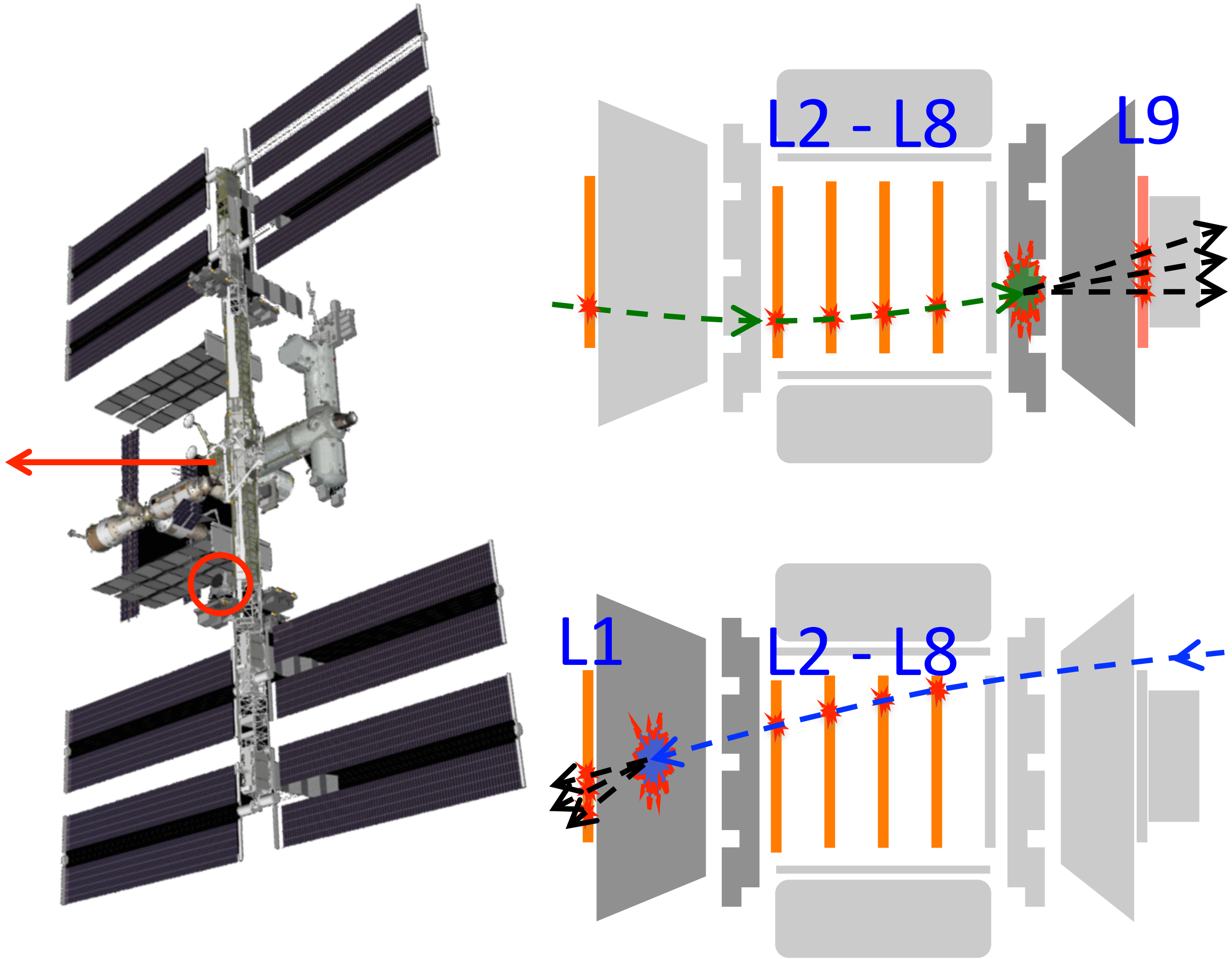
Cosmic Nuclei

AMS has seven instruments which independently identify different elements



Measuring the interactions of nuclei within AMS

AMS horizontal



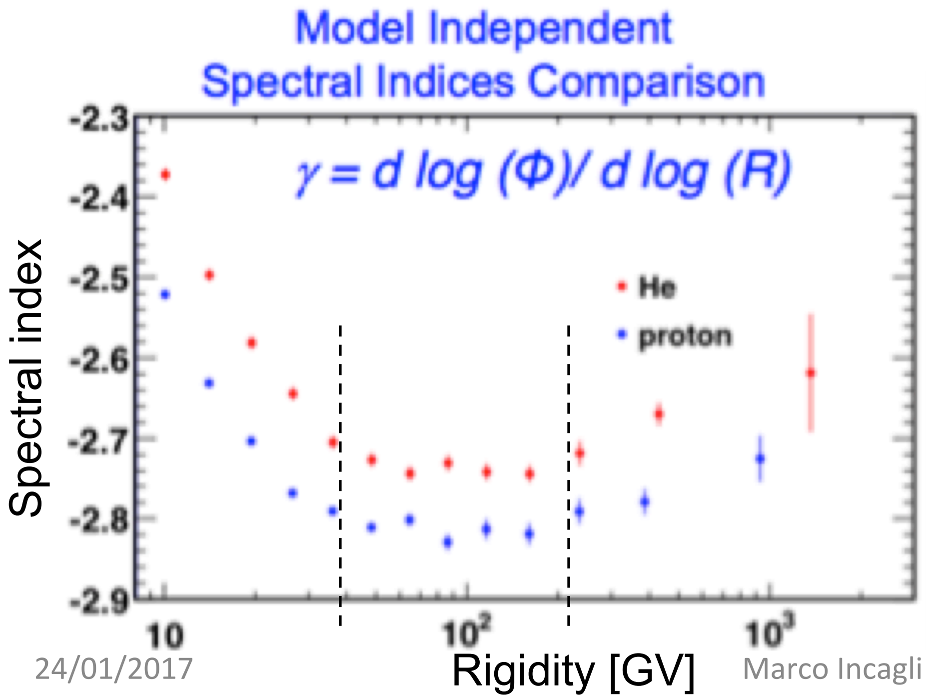
First, we use the seven inner tracker layers, L2-L8, to define beams of nuclei: O, C, B, …

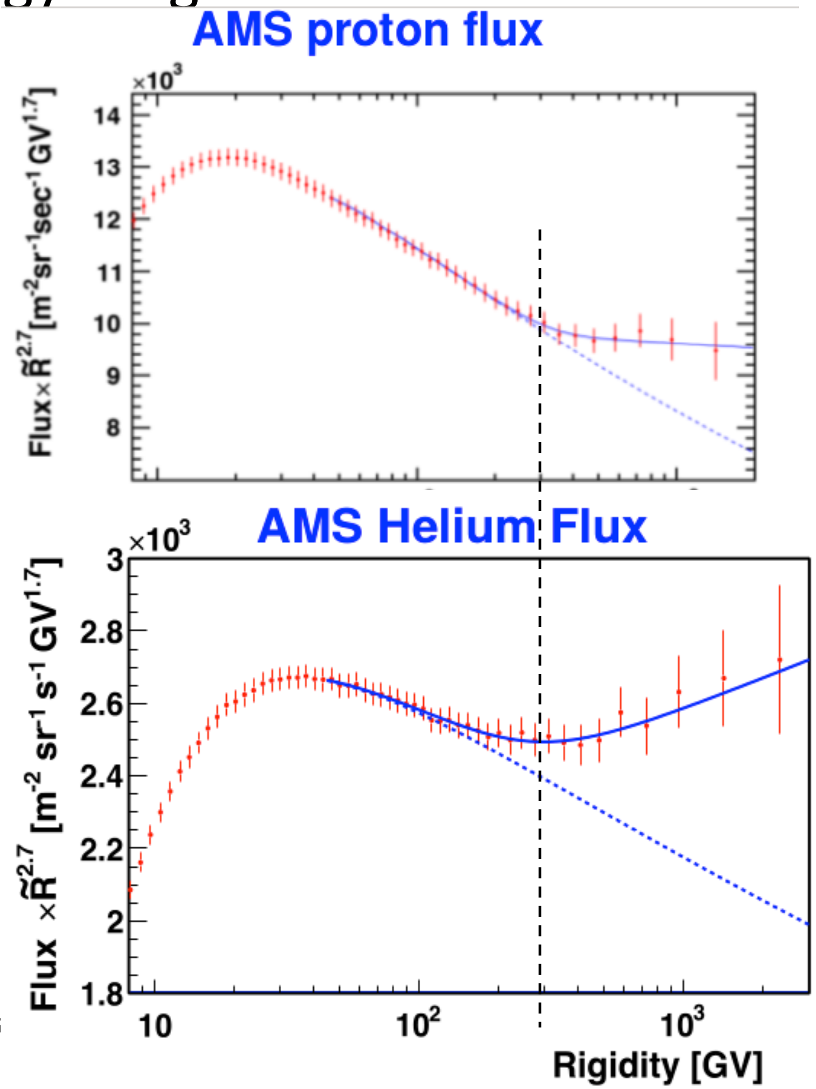
Second, we use left-to-right particles to measure the nuclear interactions in the lower part of the detector.

Third, we use right-to-left particles to measure the nuclear interactions in the upper part of detector.

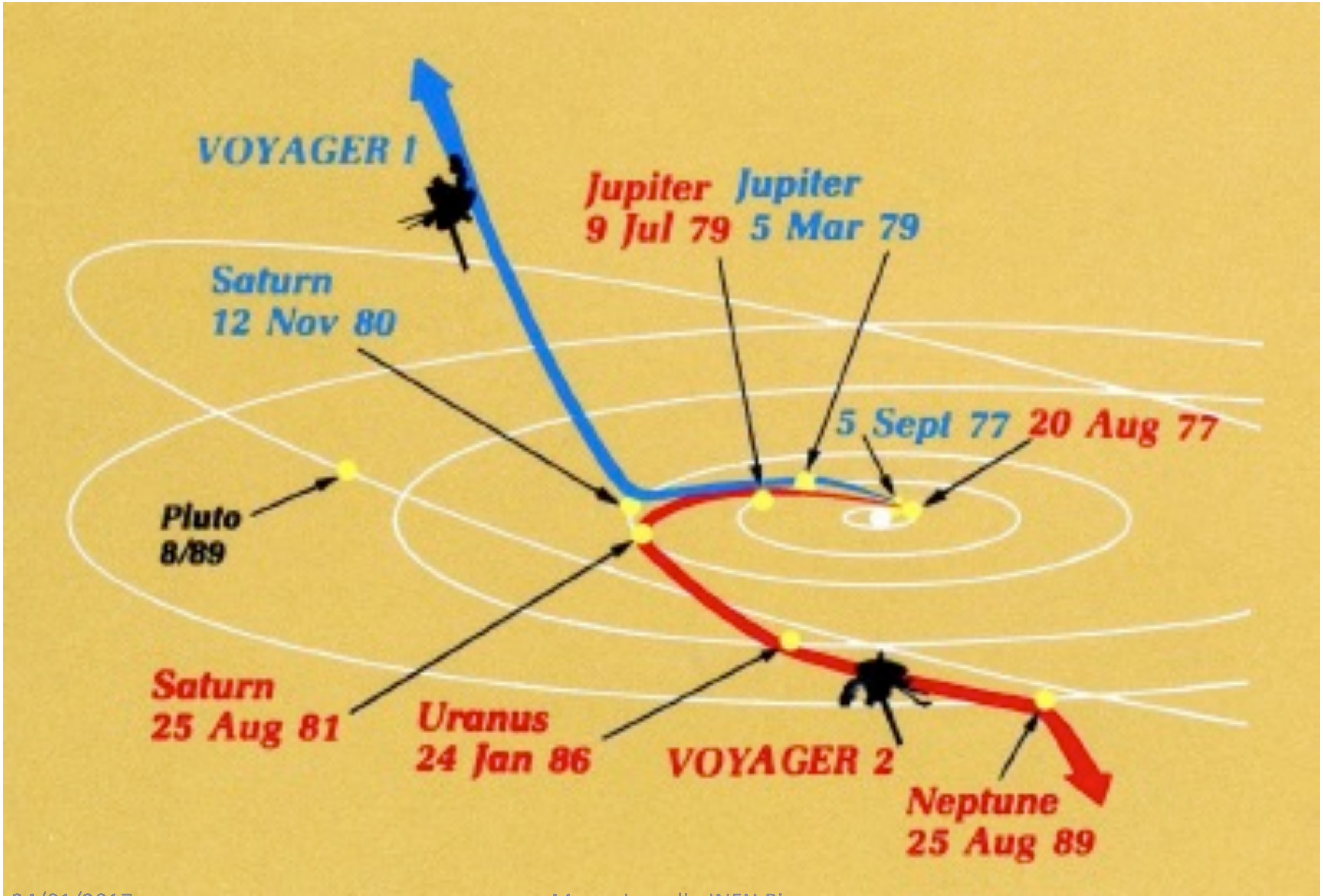
p and He fluxes

- proton and Helium fluxes show 2 puzzling features: a (soft) break at similar rigidities (~200-300 GeV) and a spectral index which differs by ~0.1 in a large energy range
- Some possible reasons:
  - acceleration in SNR
  - propagation in ISM
  - local or distance sources



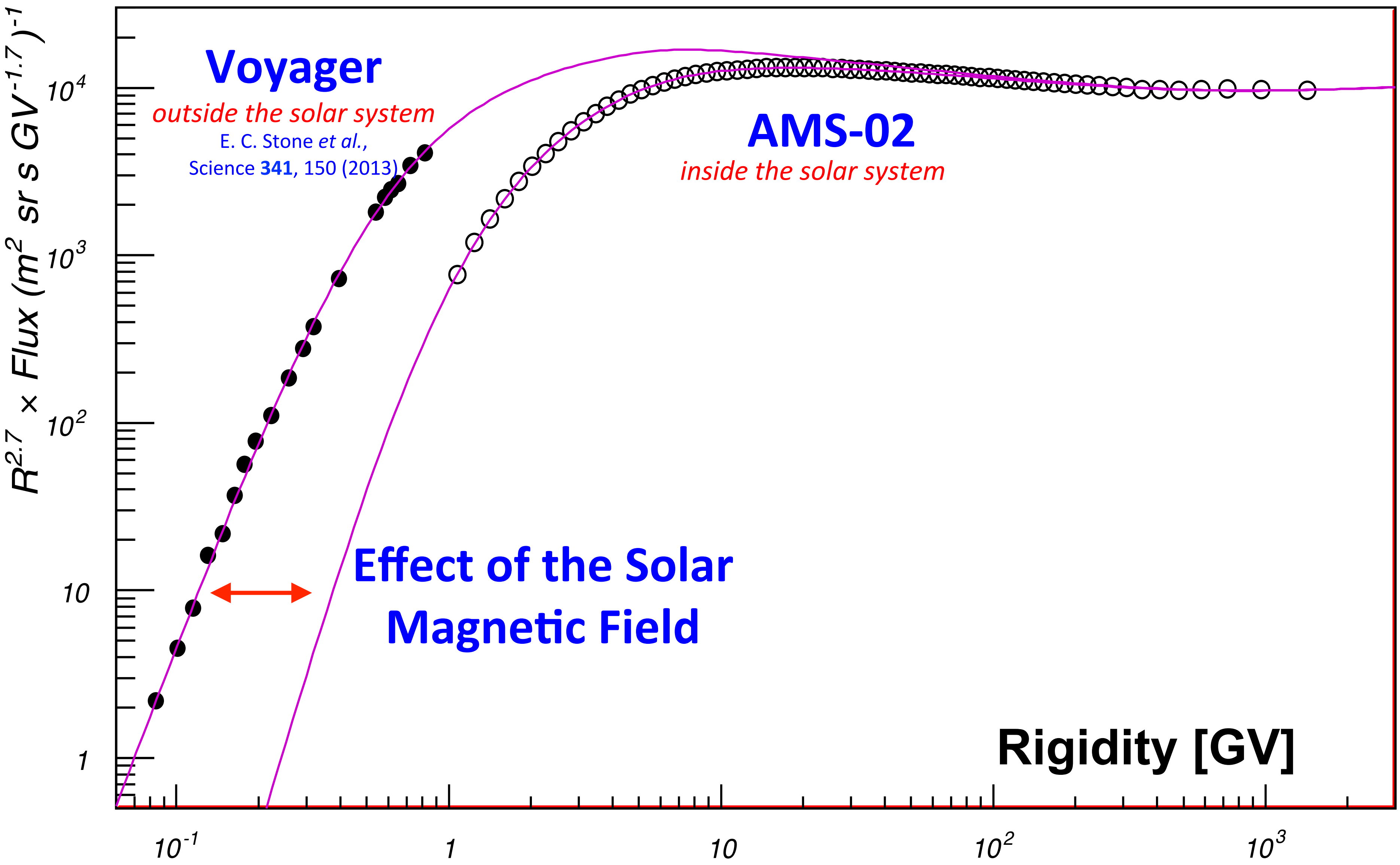


Comparison of fluxes inside/outside heliosphere: Voyager vs AMS02



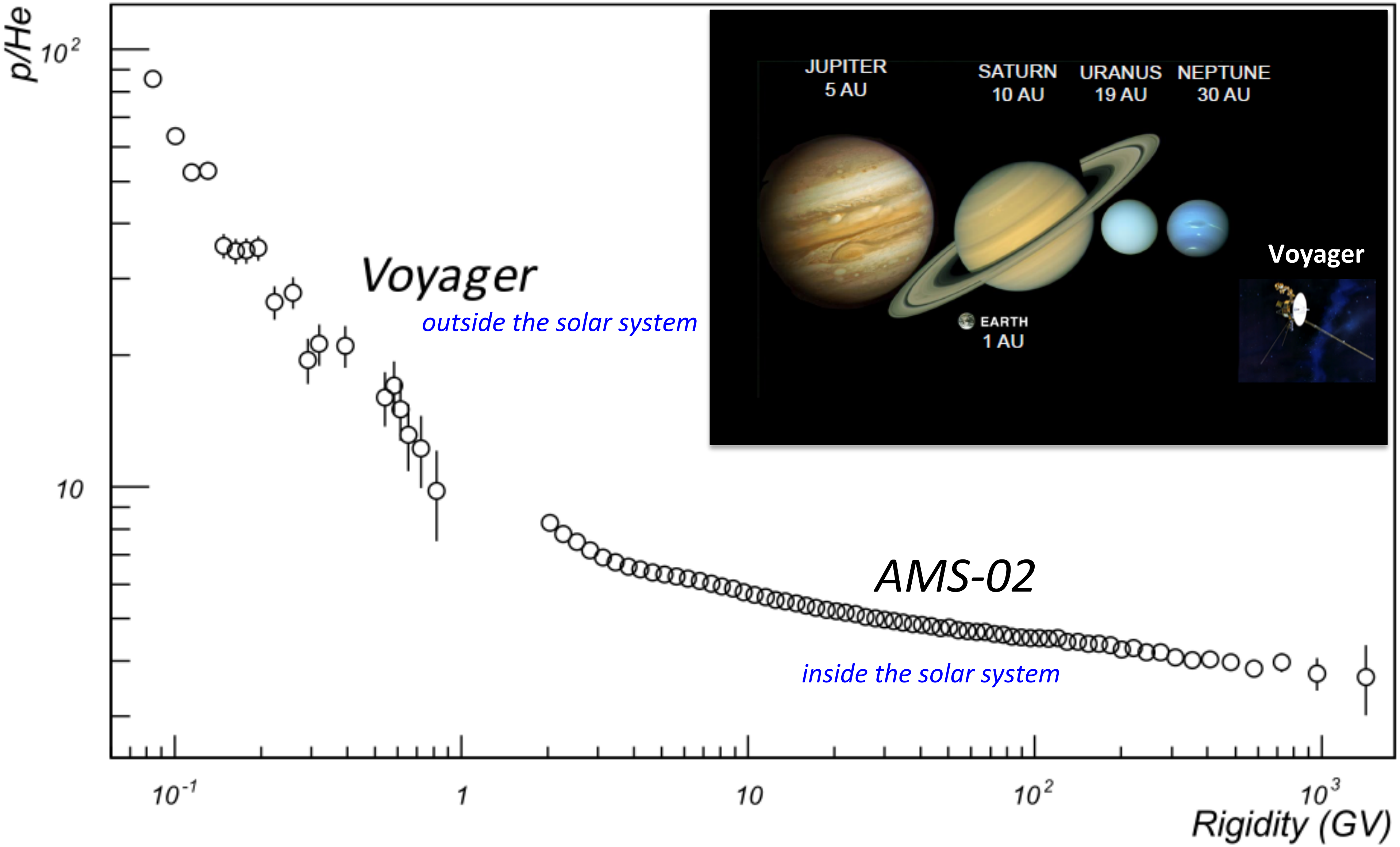
Understanding of the Solar Magnetic Field:

The proton flux and the effect of the solar magnetic field



C. Corti *et al.*, ApJ **829**, 8 (2016)

Proton to Helium Flux Ratio

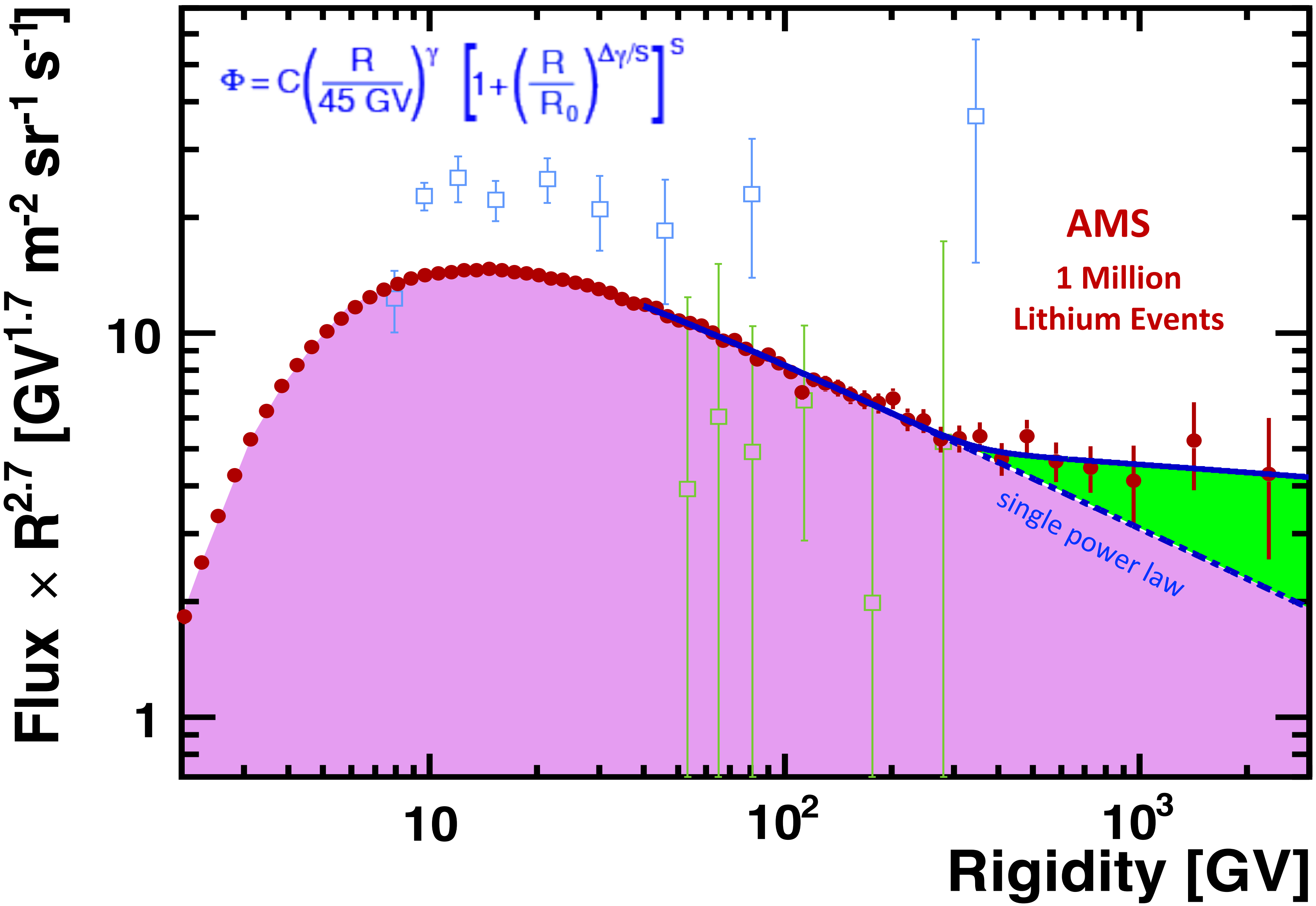


The p/He ratio is independent of solar activity

The Lithium flux

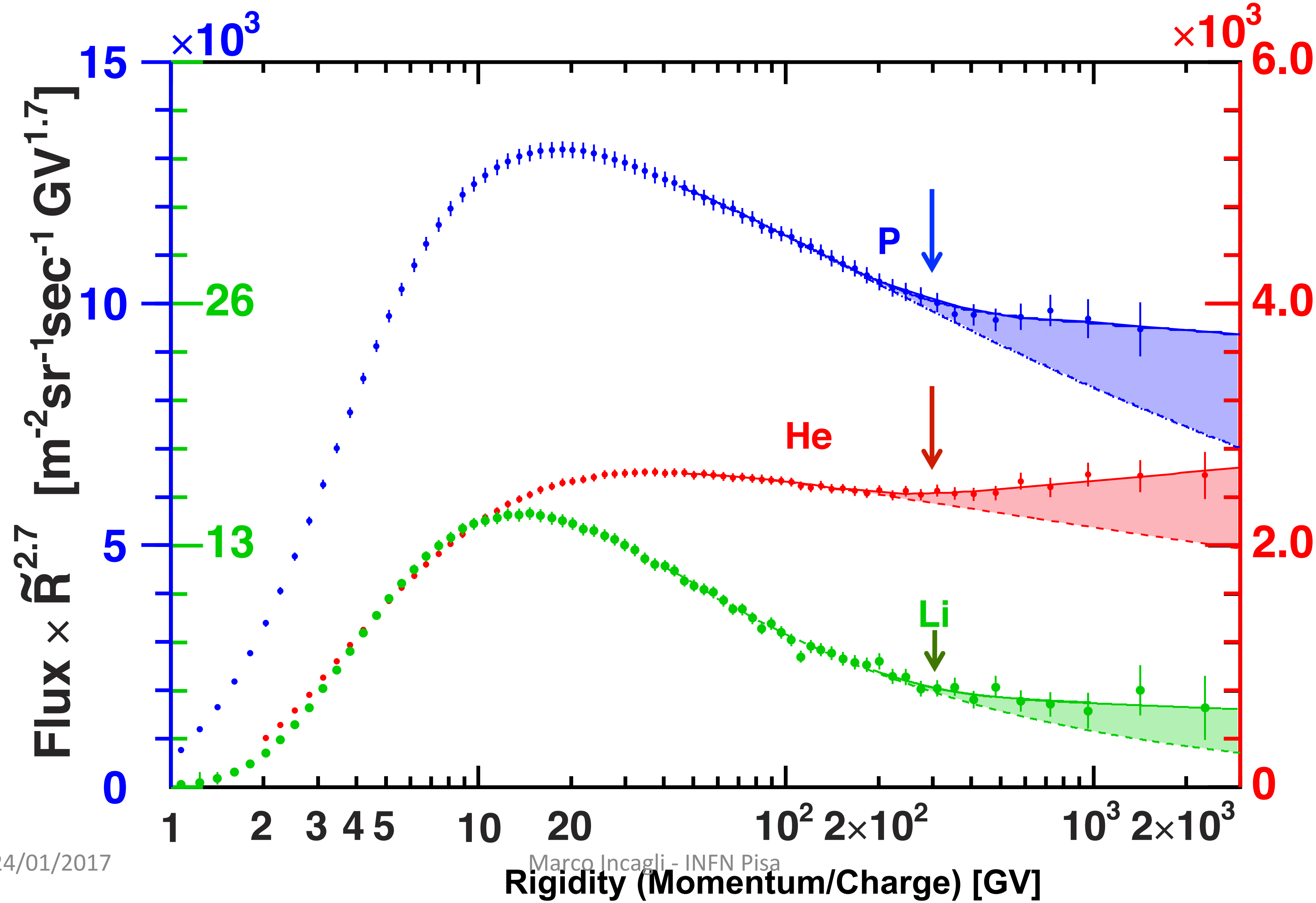
New AMS results on Secondary Cosmic Rays (Lithium)

New information: The Lithium spectrum behaves similar to protons and Helium and the Lithium flux cannot be described by a single power law.

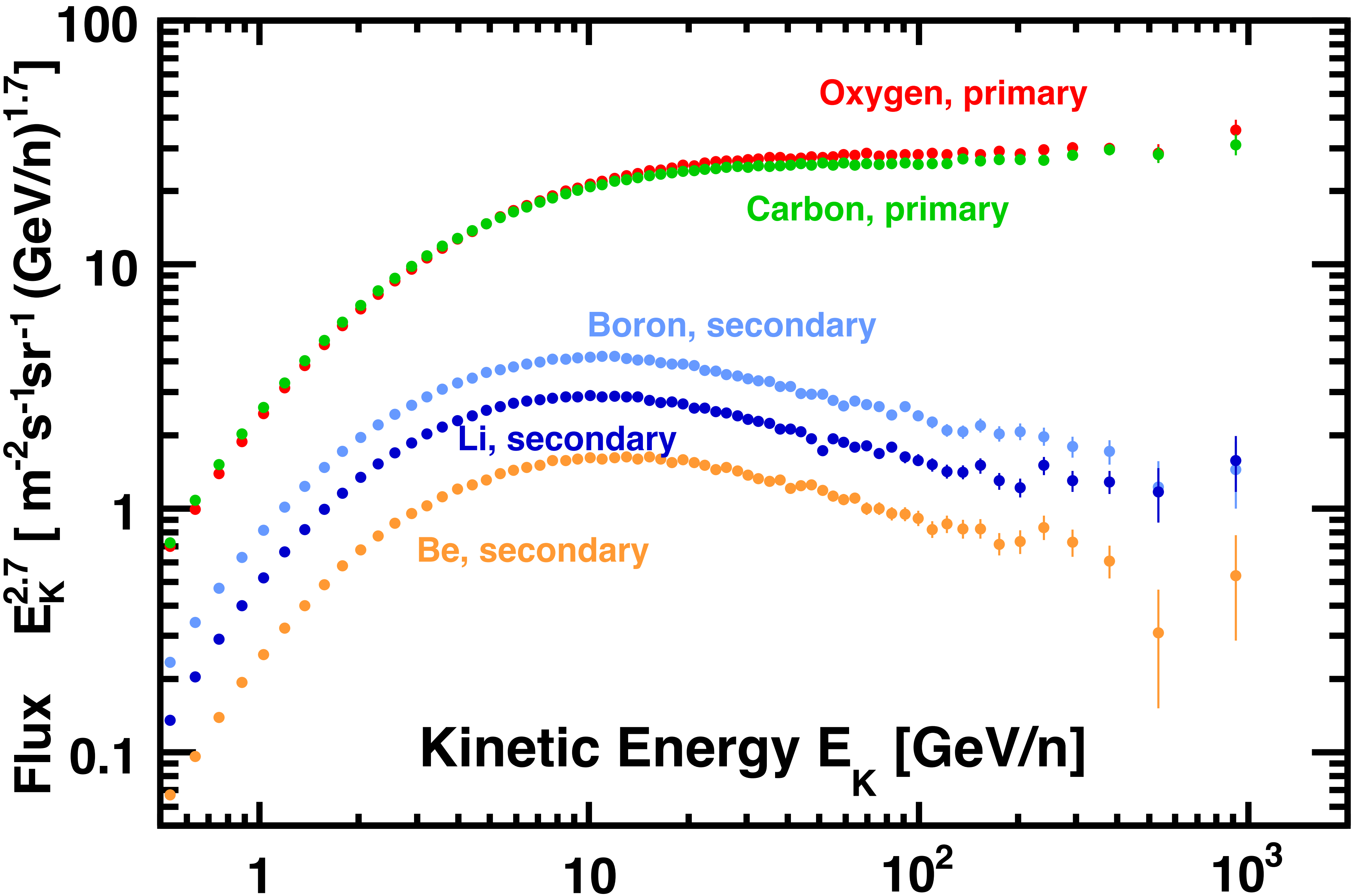


Summary (on nuclei)

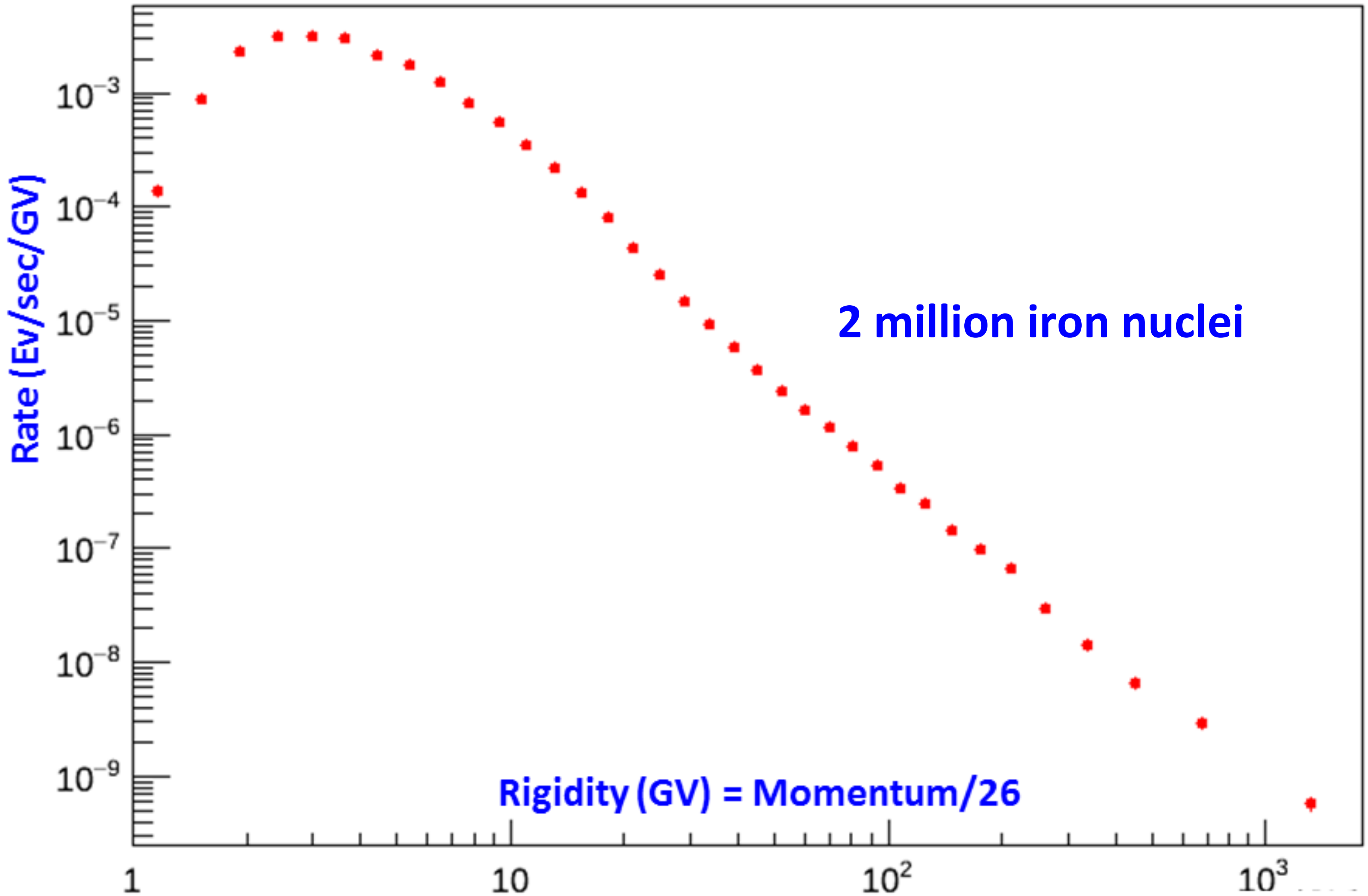
The spectra of protons, helium and lithium do not follow the traditional single power law. They all change their behavior at the same Rigidity.



Primary and secondary Cosmic Rays have very different momentum dependence



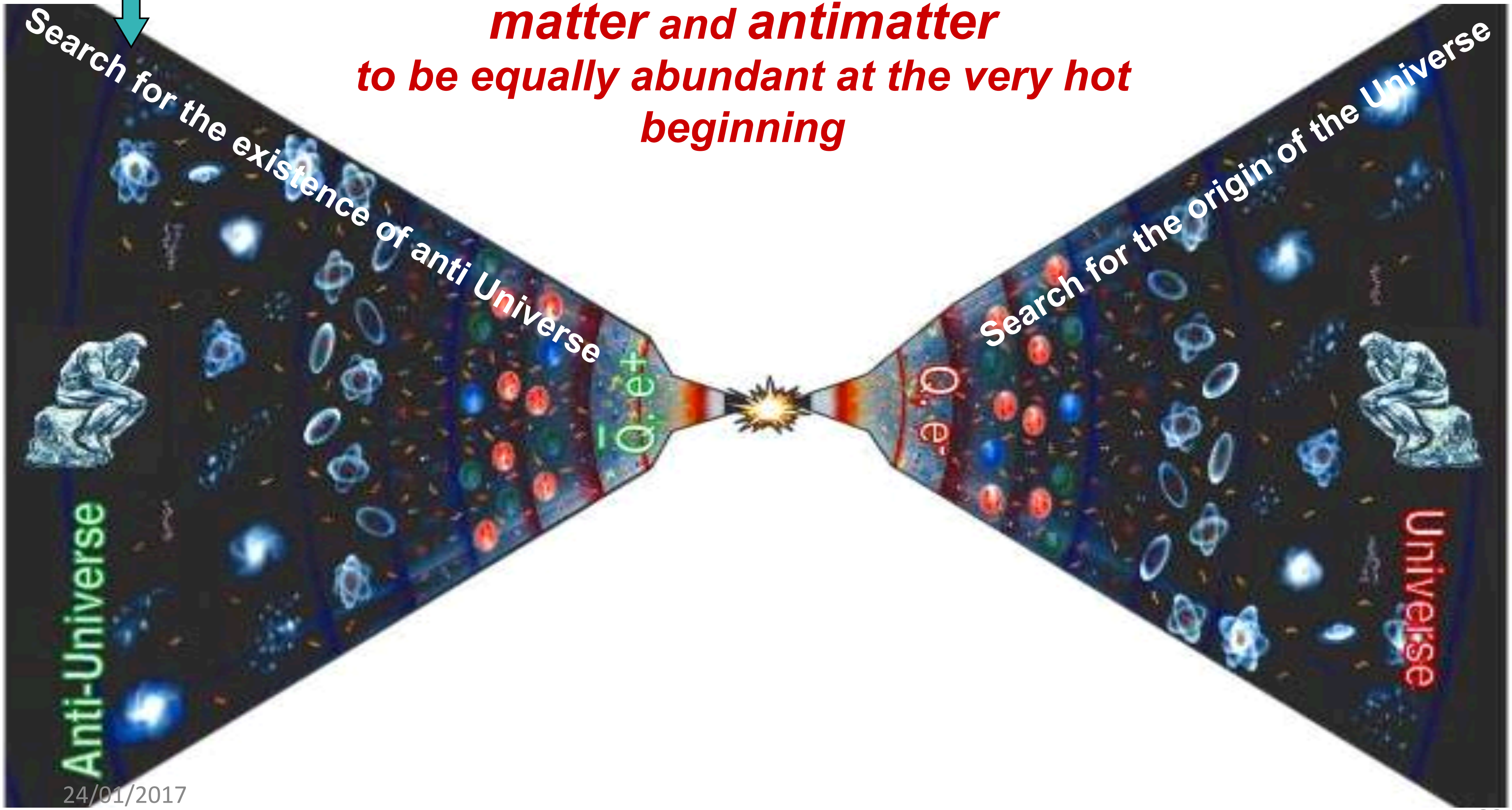
Physics Result: Iron rate



A Status Report

AMS in Space

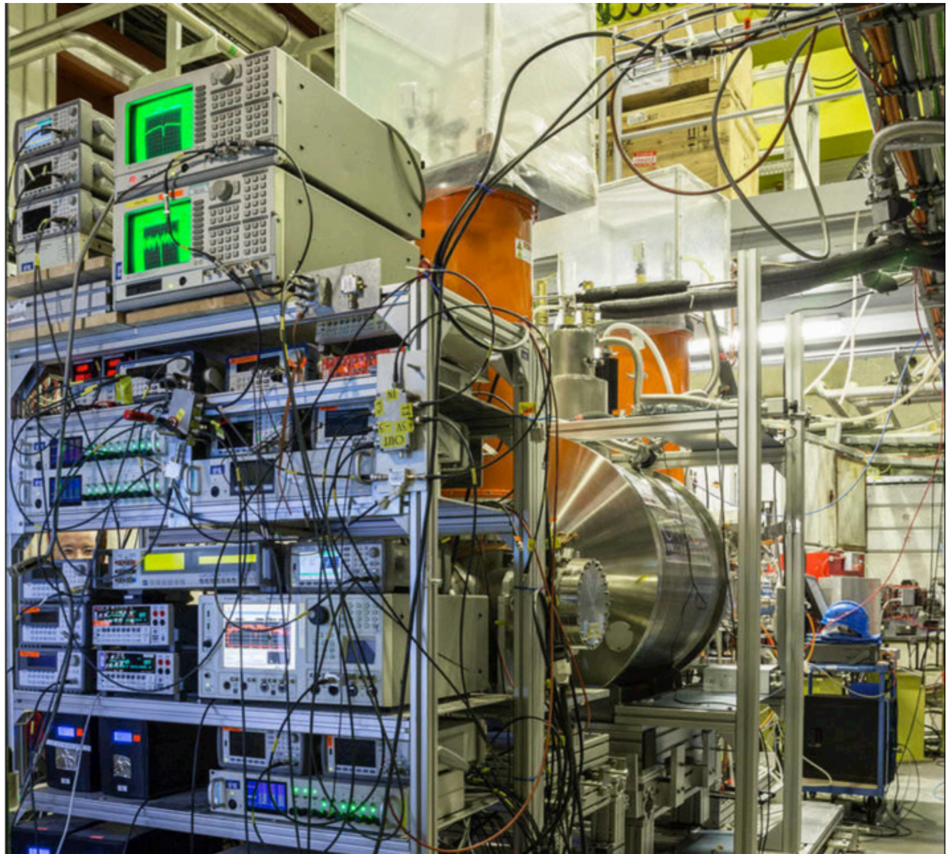
The Big Bang origin of the Universe requires
matter and antimatter
to be equally abundant at the very hot beginning



matter-antimatter symmetry

- several experiments attempt to measure the symmetry between matter and anti-matter
- most recent result (18/01/2017) from the BASE collaboration at CERN: magnetic moments of anti-p and p are the same (apart the sign) at 0.8ppm
- CERN press release:

At the scale of elementary particles, an almost perfect symmetry between matter and antimatter exists. On cosmological scales, however, the amount of matter outweighs that of antimatter. Understanding this profound contradiction demands that physicists compare the fundamental properties of particles and their antiparticles with high precision.



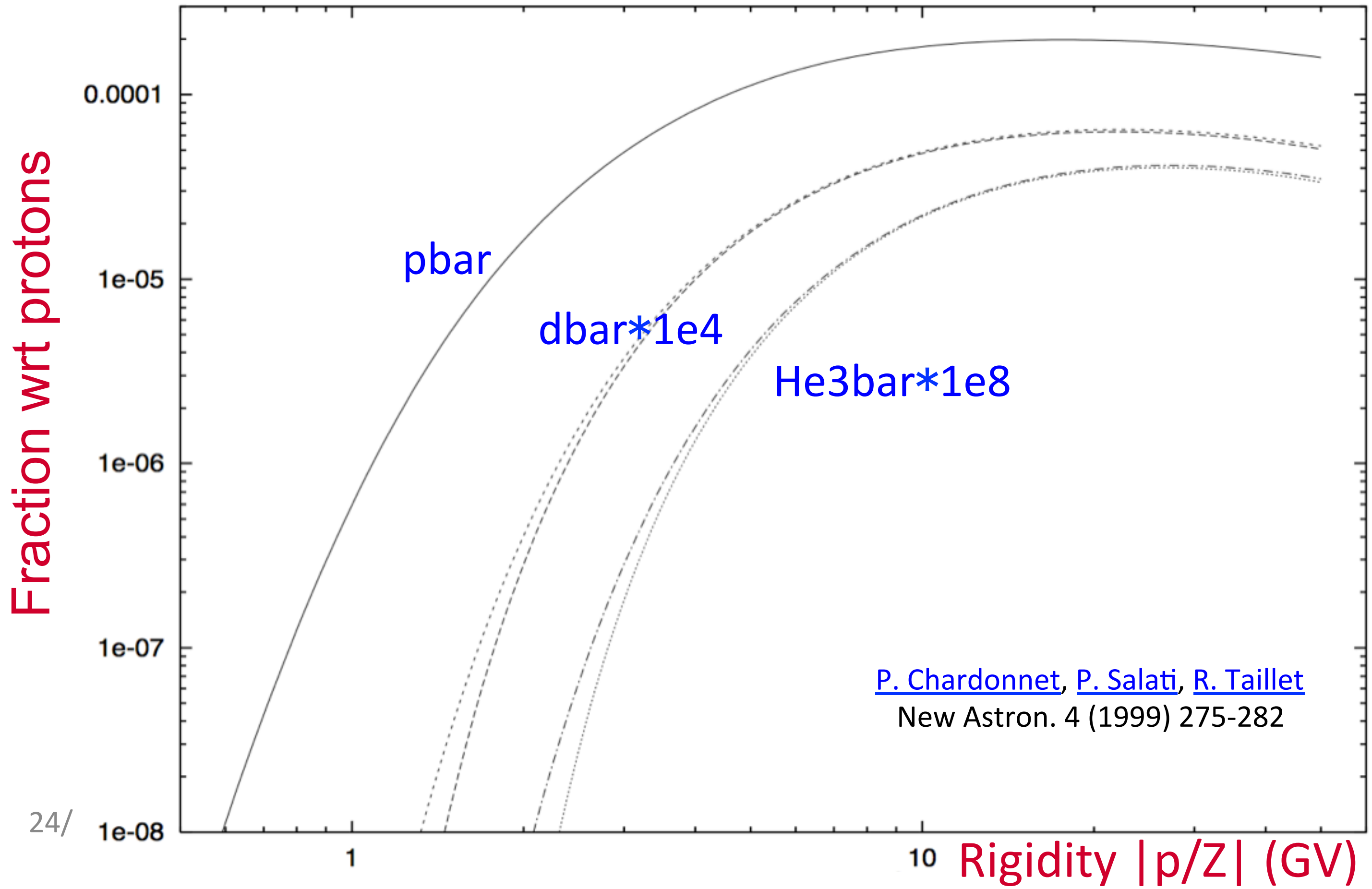
The BASE experiment zone with the antiproton transfer line and the superconducting magnet. The screens show the signals from single antiprotons stored in the BASE measurement traps. (Image: Stefan Sellner/CERN)

Evidence of non existence of anti-matter?

- In "our neighbourhood" no anti-barions exist: the failure of observing a γ-ray excess above the thermal spectrum implies *a limit anti-b/b < 1ppm*
- The largest "neighbourhood" on which a uniform composition has been tested is a *cluster of galaxies of size ~20Mpc*
- given the size of the Universe, several millions of such *domains* exist; is it possible that part of them are made of antimatter?
- not easy (but not impossible) to build theories with *patchwork structure of the Universe*
- the uniformity of CMB ($\sim 10^{-5}$) put strong constraints on the presence of such domains during recombination at $z \sim 1100$ (arXiv:astro-ph/9707087)

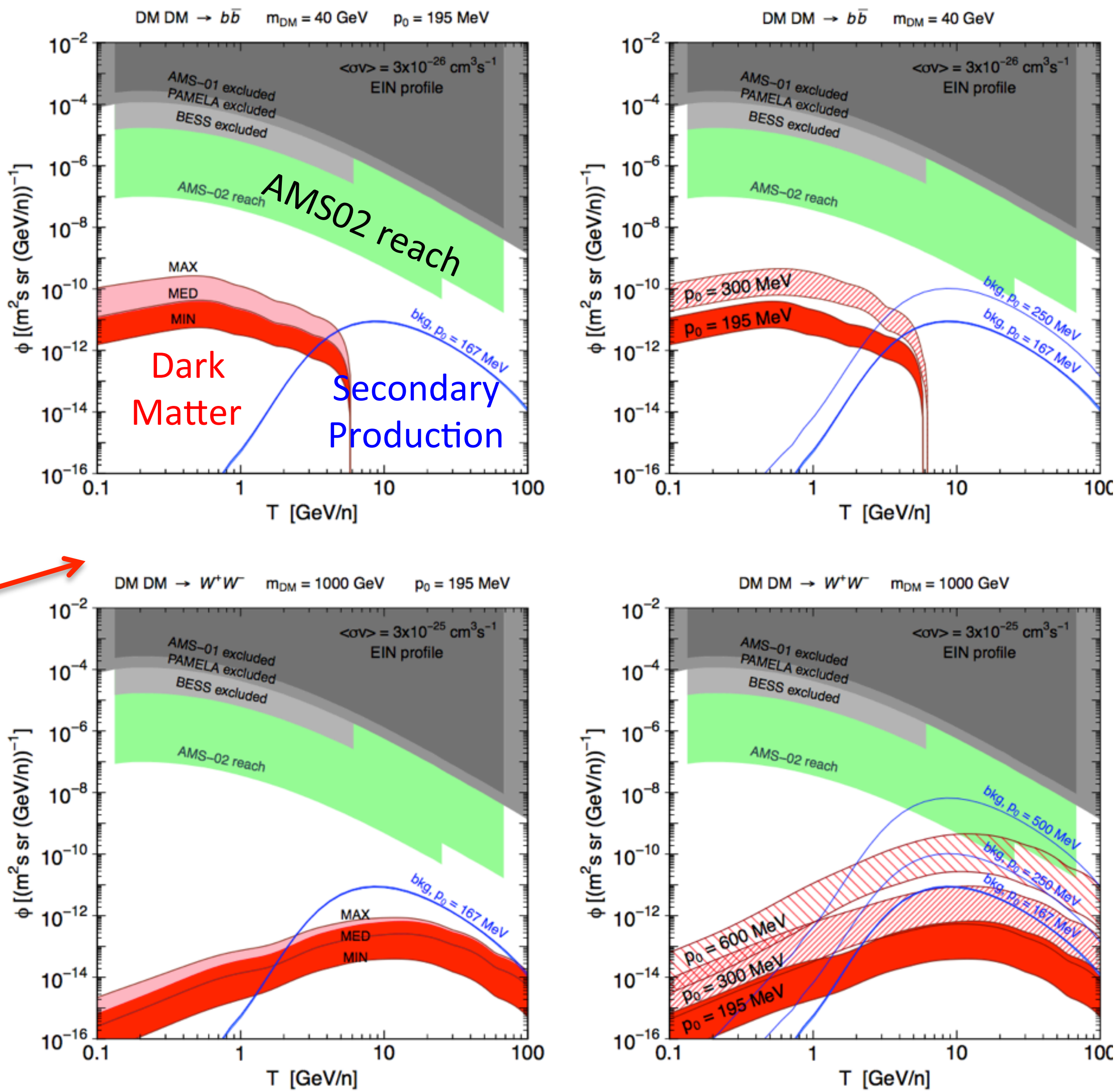
Secondary production of anti-nuclei

- Can anti-nuclei be produced by "standard secondary production"?
- As a rule of thumb, each anti-nucleon adds a suppression factor 10^3-10^4 wrt anti-proton production



What about DM->anti-He3 ?

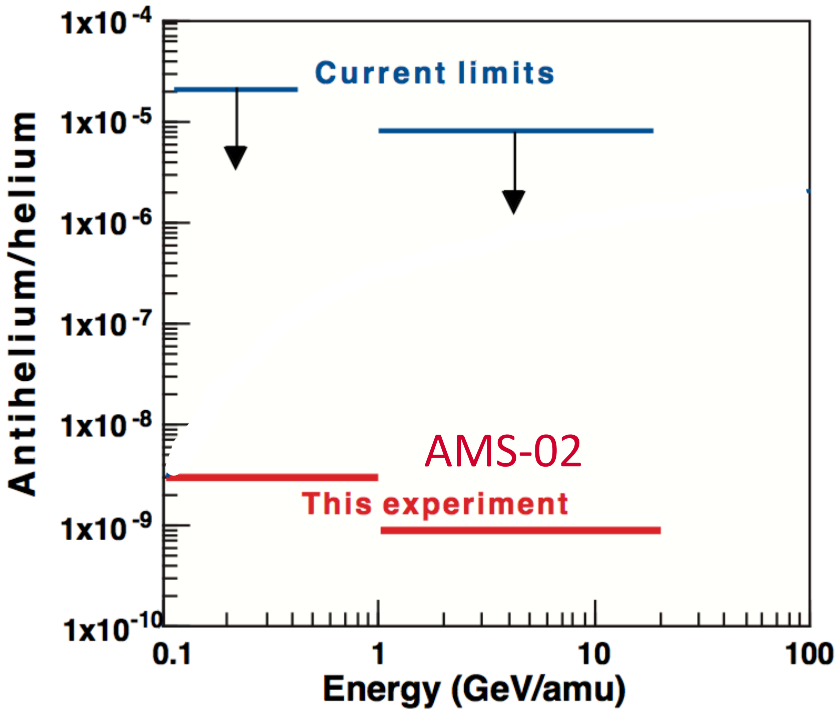
- DM annihilation can produce anti-nuclei
- Like for secondary production, the flux rapidly decreases with the number of anti-nucleons involved
- example for anti-He3
- Both DM and secondary production seem to be below AMS-02 reach

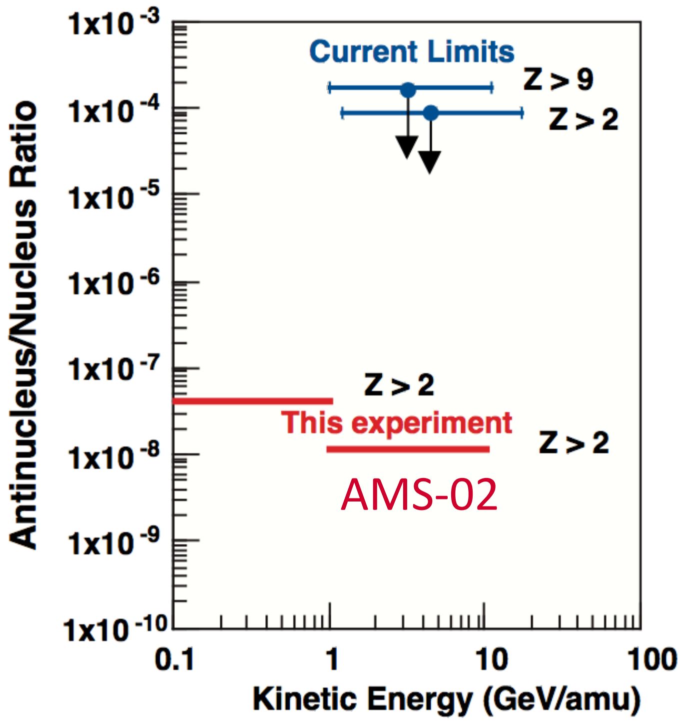


M.Cirelli et al arXiv:hep-ph1401.4017v3
E.Carlson et al. arXiv:hep-ph1401.2461v2

Direct measurement of anti-nuclei

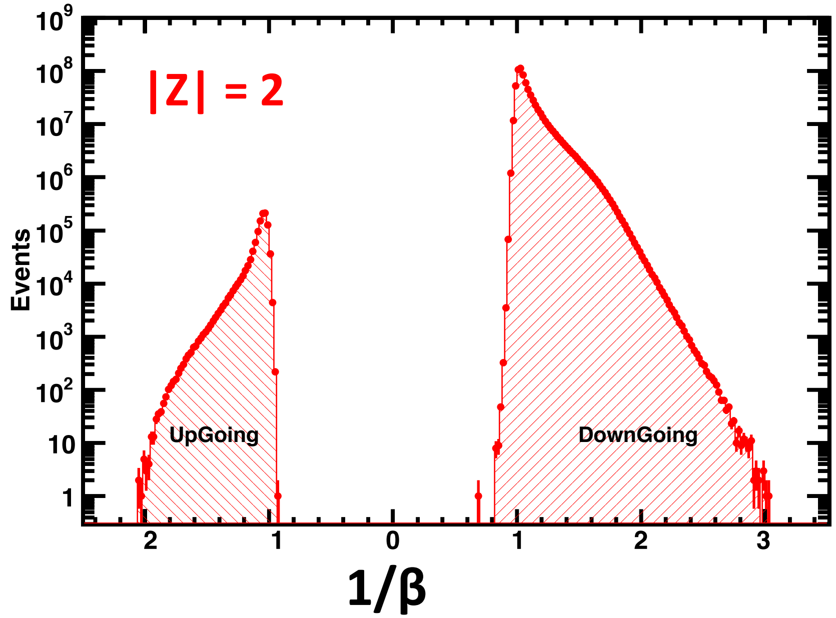
- A direct mearurement of anti-nuclei in CRs can indicate the presence of anti-galaxies or effects of antu-nuclosynthesis
- This measurement requires:
  - a magnetic field ✔
  - a measurement Z ✔
  - a measurement of A (d/H, He^3/He^4, ...) ✔



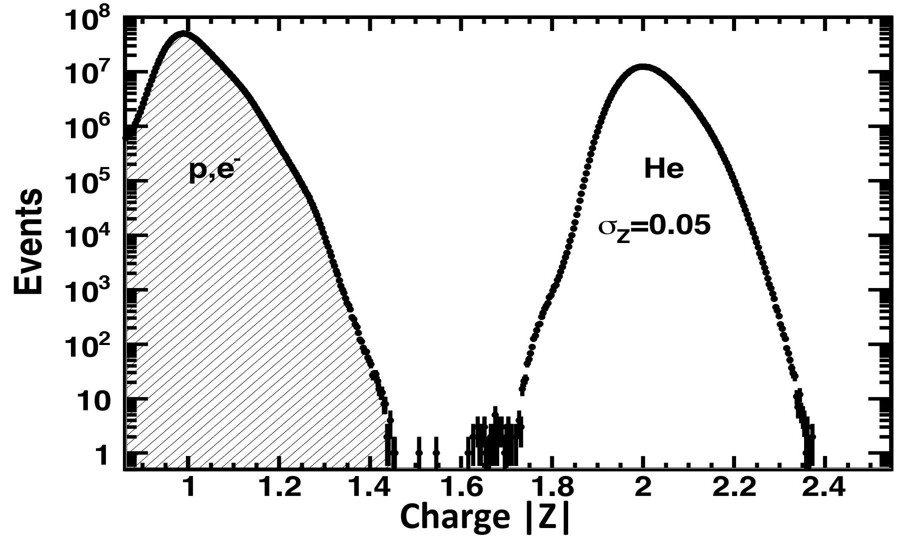


Identification of antihelium

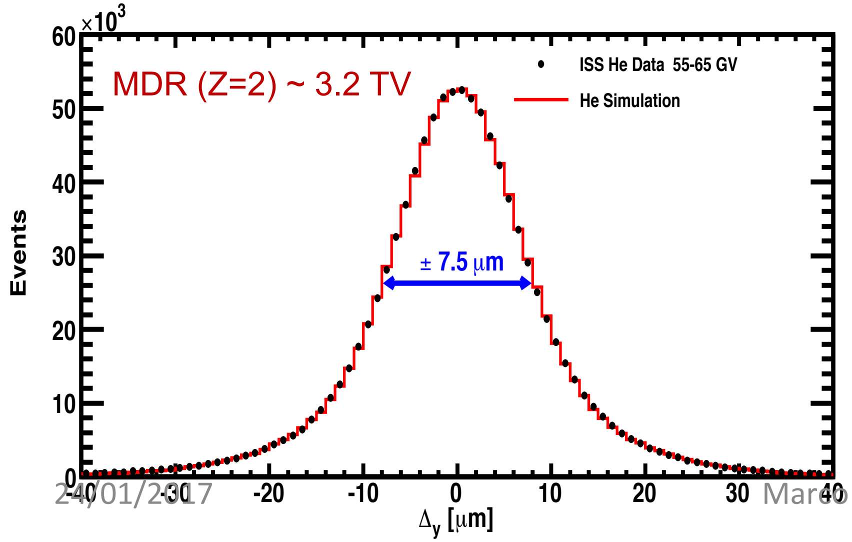
1. Determine direction with TOF.



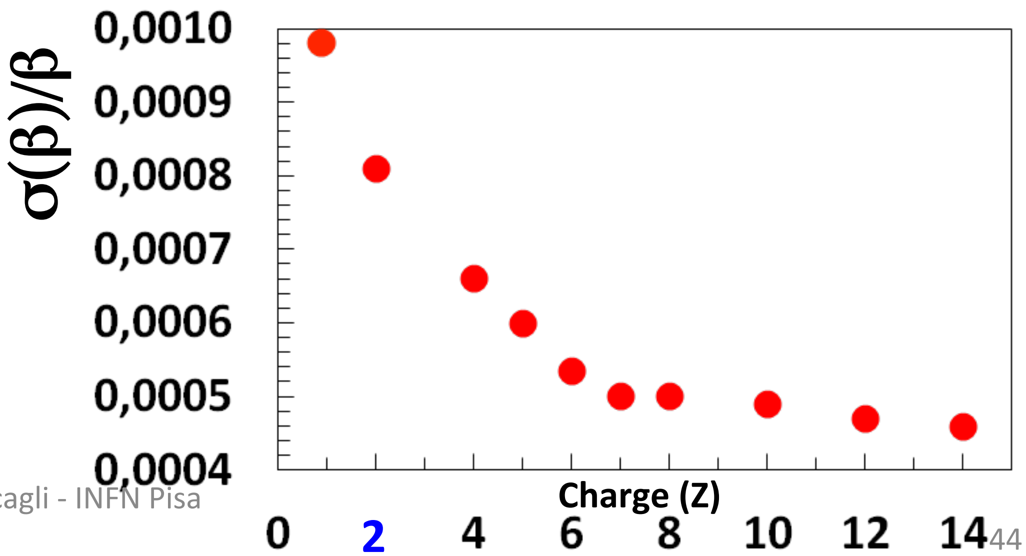
3. To measure |Z|, use the TOF+Tracker+RICH to separate p,e± from He



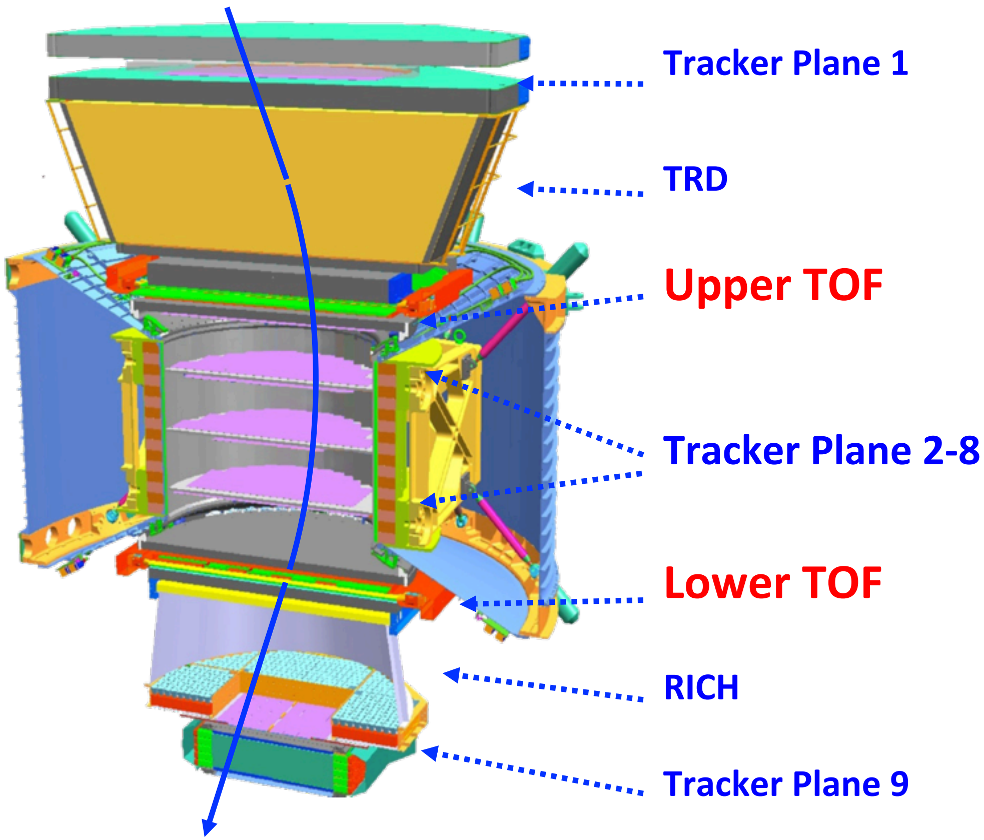
2. To measure momentum and sign of the charge, use Tracker



4. To determine mass, use the RICH to measure the velocity.



In five years, 0.7×10^9 helium events have been collected by AMS (using tracker planes 2-8)



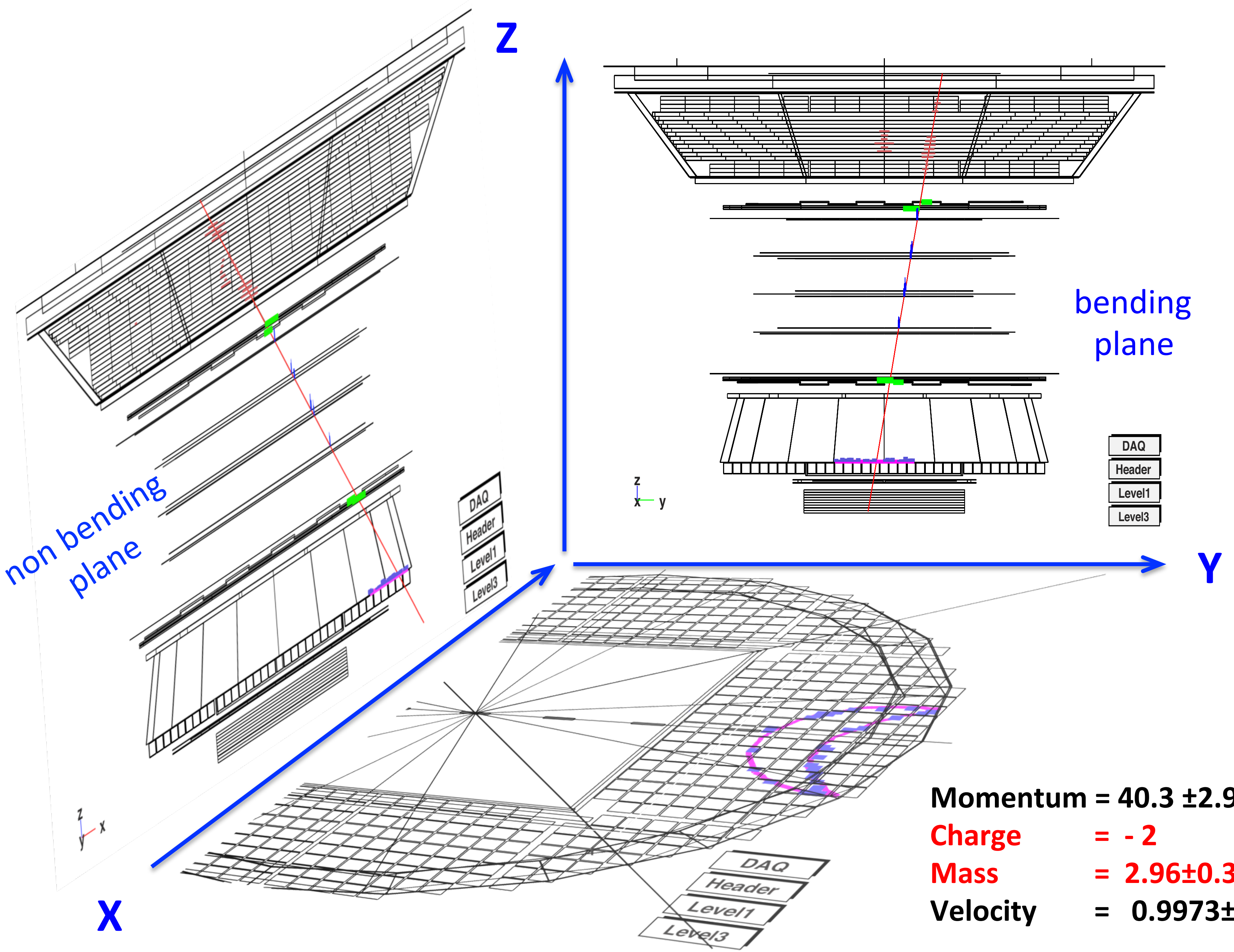
To date we have observed

a few events

with Z = -2 and

with mass around ^{3}He.

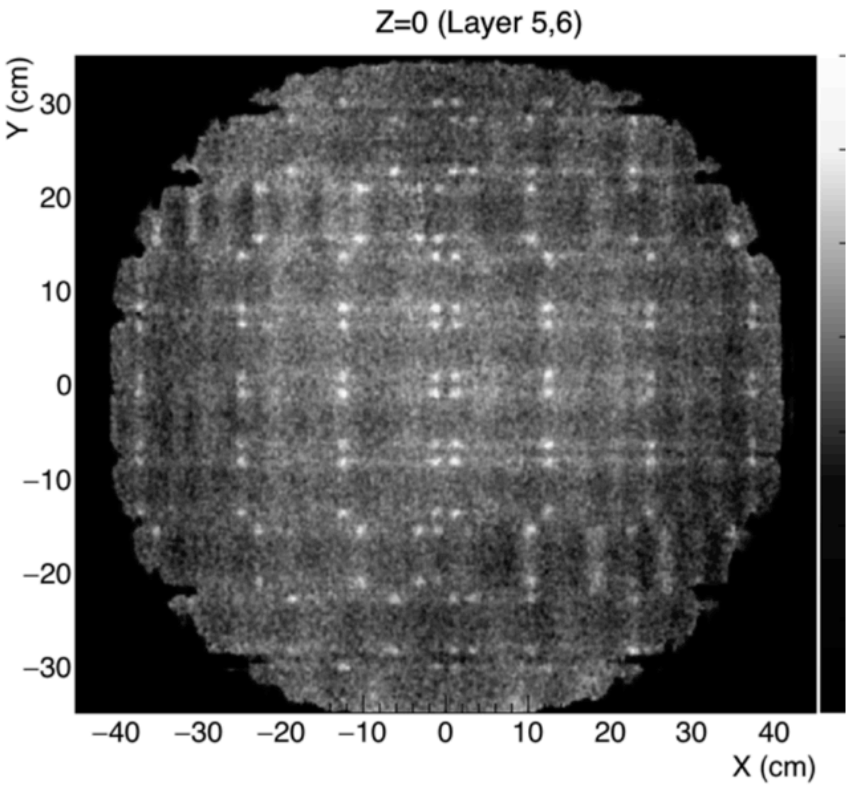
An anti-Helium candidate:

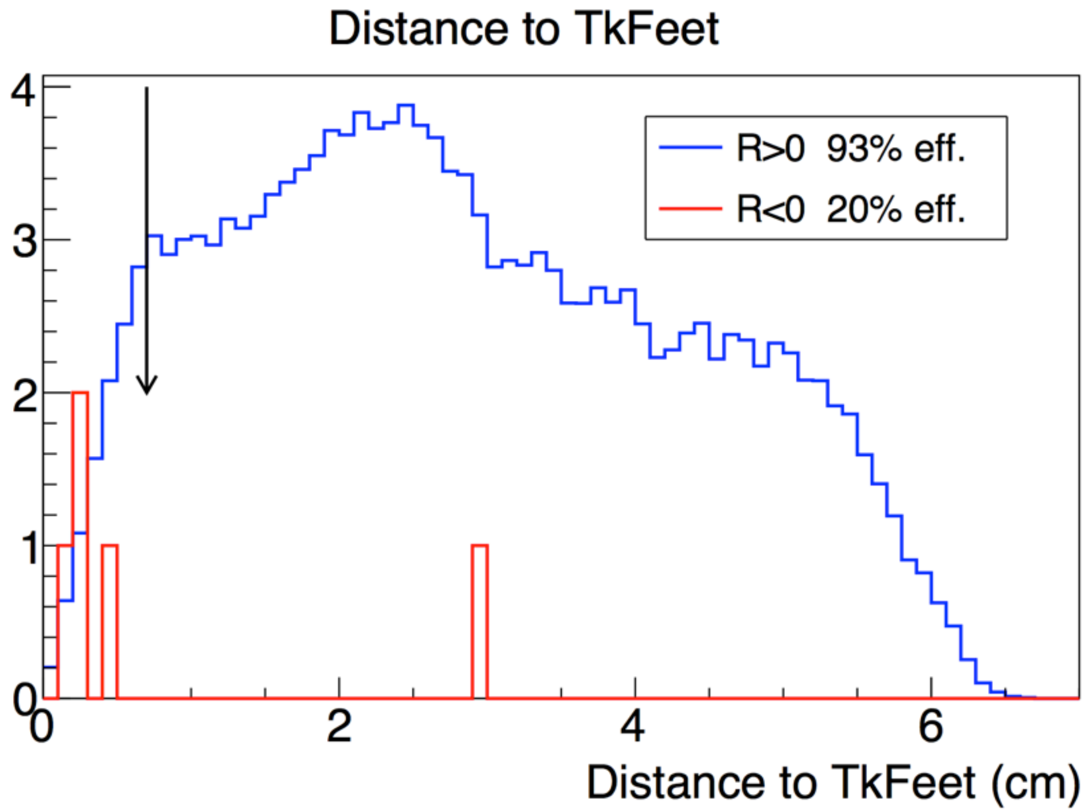


Momentum = 40.3 ±2.9 GeV/*c*
Charge = - 2
Mass = 2.96±0.33 GeV/c^2
Velocity = 0.9973±0.0005 *c*

anti-He candidates

- the number of candidates is not yet stable, as it depends on the fiducial cuts applied
- Ex: by looking at *Helium survive probability*, it is possible to build an"x-ray" image of the inner tracker structure
- Few "anti-helium" candidates observed close to tracker hot-spots → removed by fiducial cuts





Antihelium and AMS

At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.

Detector verification is difficult.

1. The magnetic field cannot be changed.

2. The rate is ~1 per year.

3. Simulation studies: 35 billion simulated helium events show the background is small, but how to ensure that simulation is correct to 1ppb?

The few candidates have mass 2.8 GeV and charge -2 like $^{3}\overline{He}$.

It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.

Many new and precise results on charged particles, nuclei and anti-nuclei in GeV-TeV Rigidity range.

There is no other magnetic spectrometer in space in the foreseeable decades.

It is fundamental to exploit these data as much as possible, working closely with the theoretical community to develop a comprehensive model to explain all of our observations.

AMS-02 is foreseen to take data through 2024.