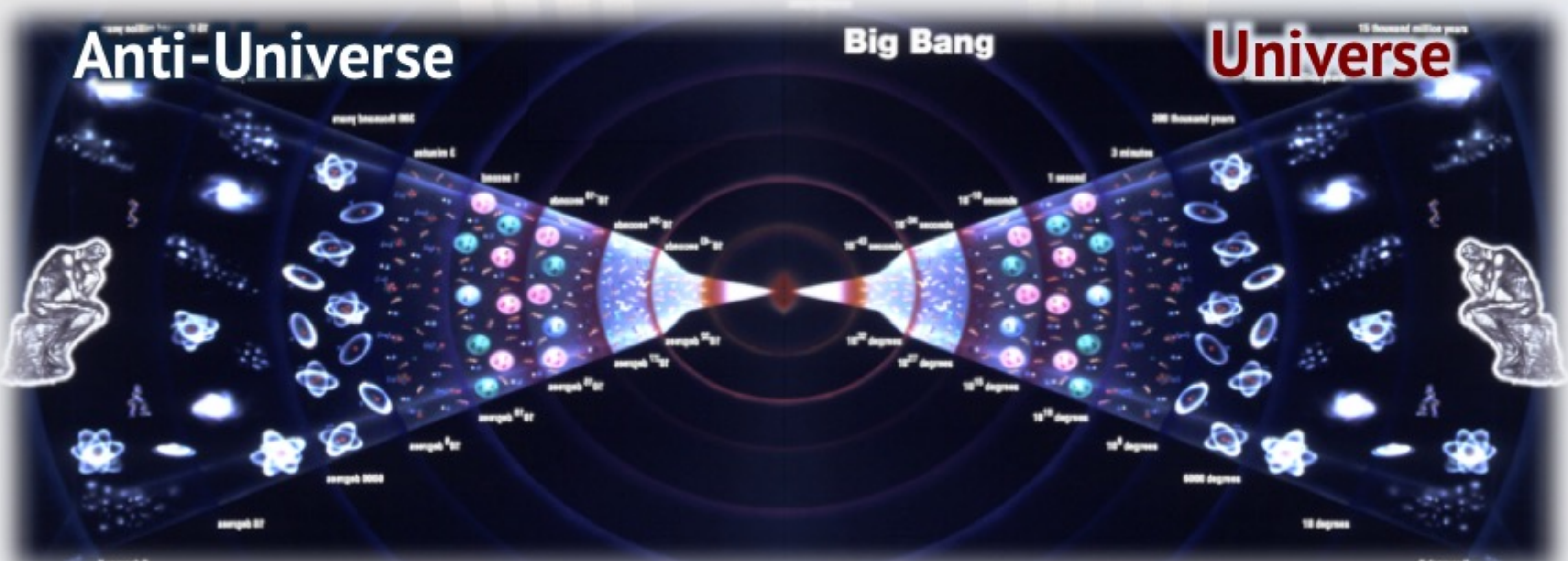
Physics of Anti-matter in space

Sadakazu Haino

Academia Sinica

Search for antimatter

- Apparent asymmetry of matter and antimatter is one of the fundamental problems in cosmology
- Detection of anti-nuclei in Cosmic Rays will be a strong evidence of primordial Anti Matter



Dirac's speech

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

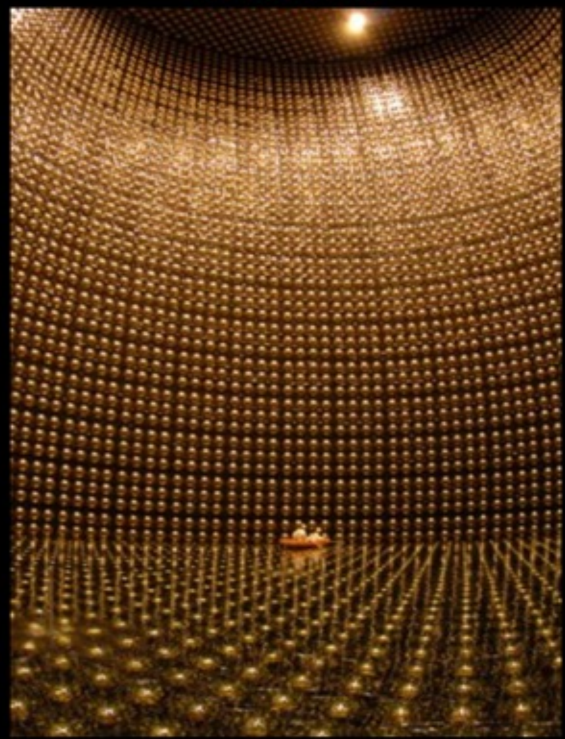
If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Experimental work on Antimatter in the Universe

Search for Baryogenesis

New symmetry breaking

Proton has finite lifetime



LHC-b, ATLAS, CMS
Belle II, ...

Proton decay searches
at Super-K, Hyper-K, ...

No explanation found for the absence of antimatter
(no reason why antimatter should not exist)

Direct search

AMS

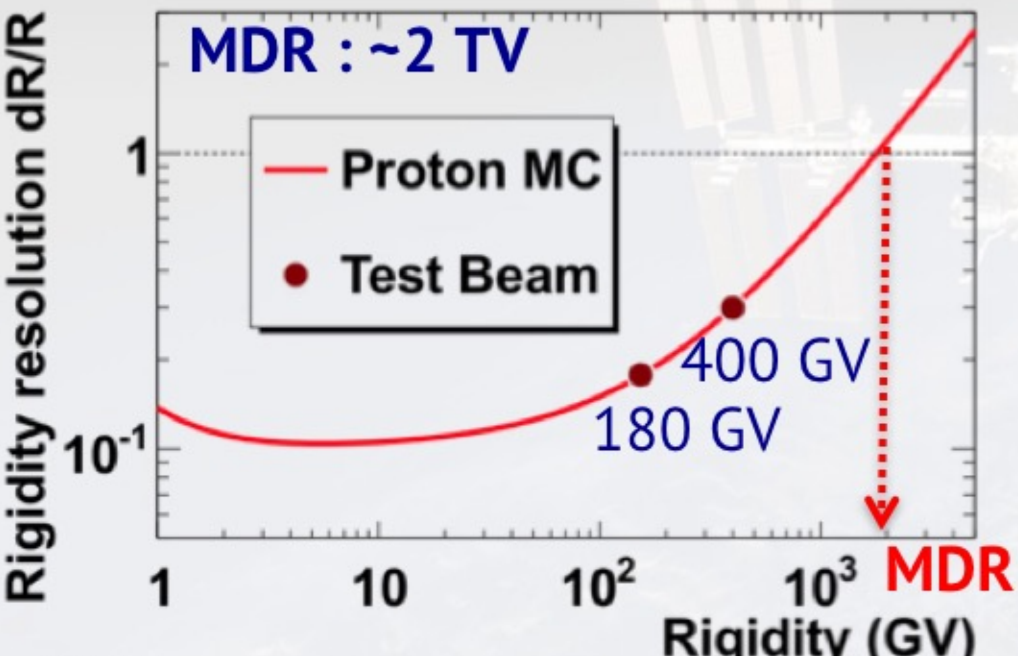
Increase in sensitivity: x $10^3 - 10^6$
Increase in energy to ~TeV

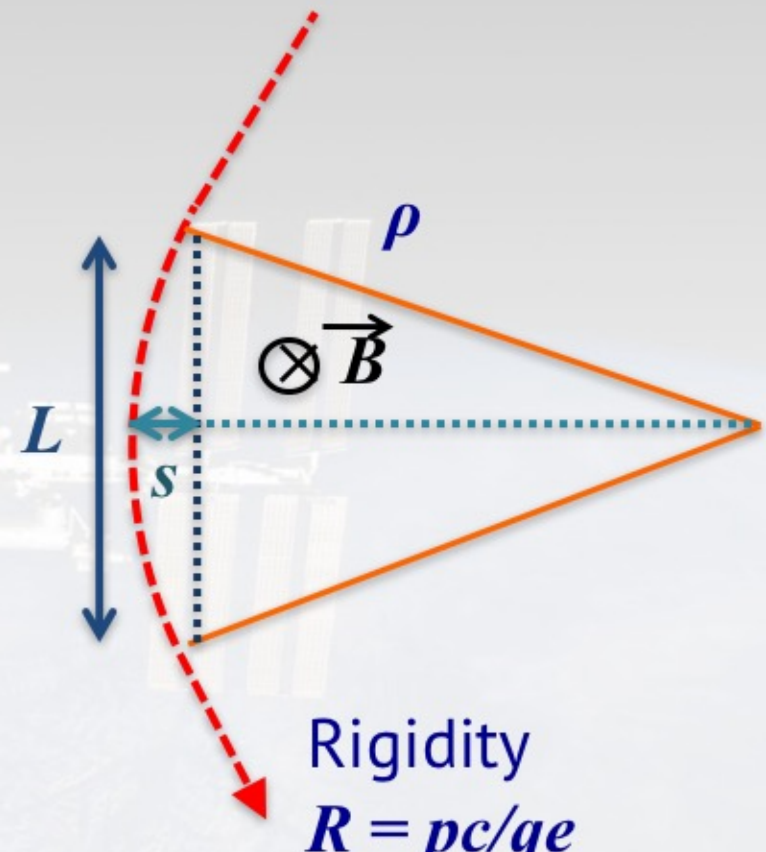
Magnetic spectrometers balloon-borne and in space

Magnetic Rigidity Measurement

$$\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}$$

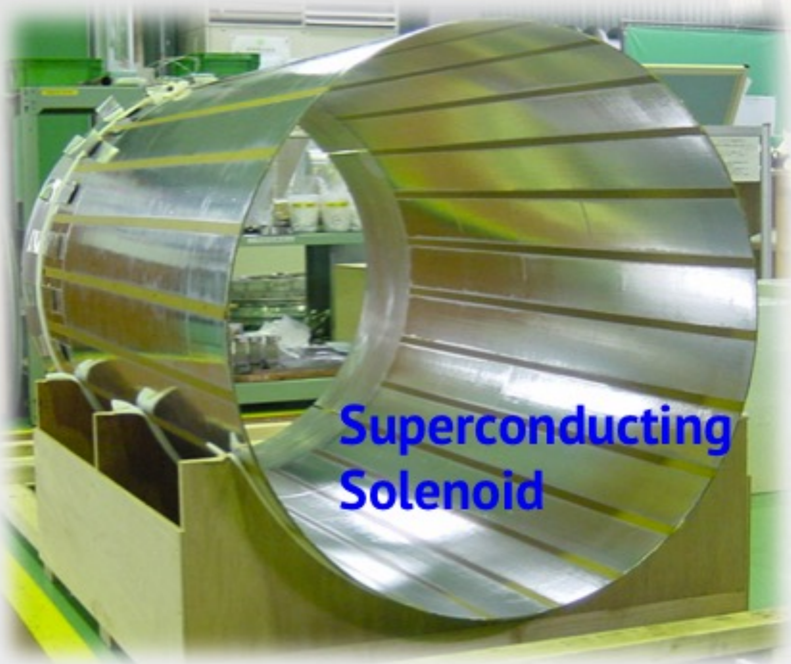
Maximum Detectable Rigidity

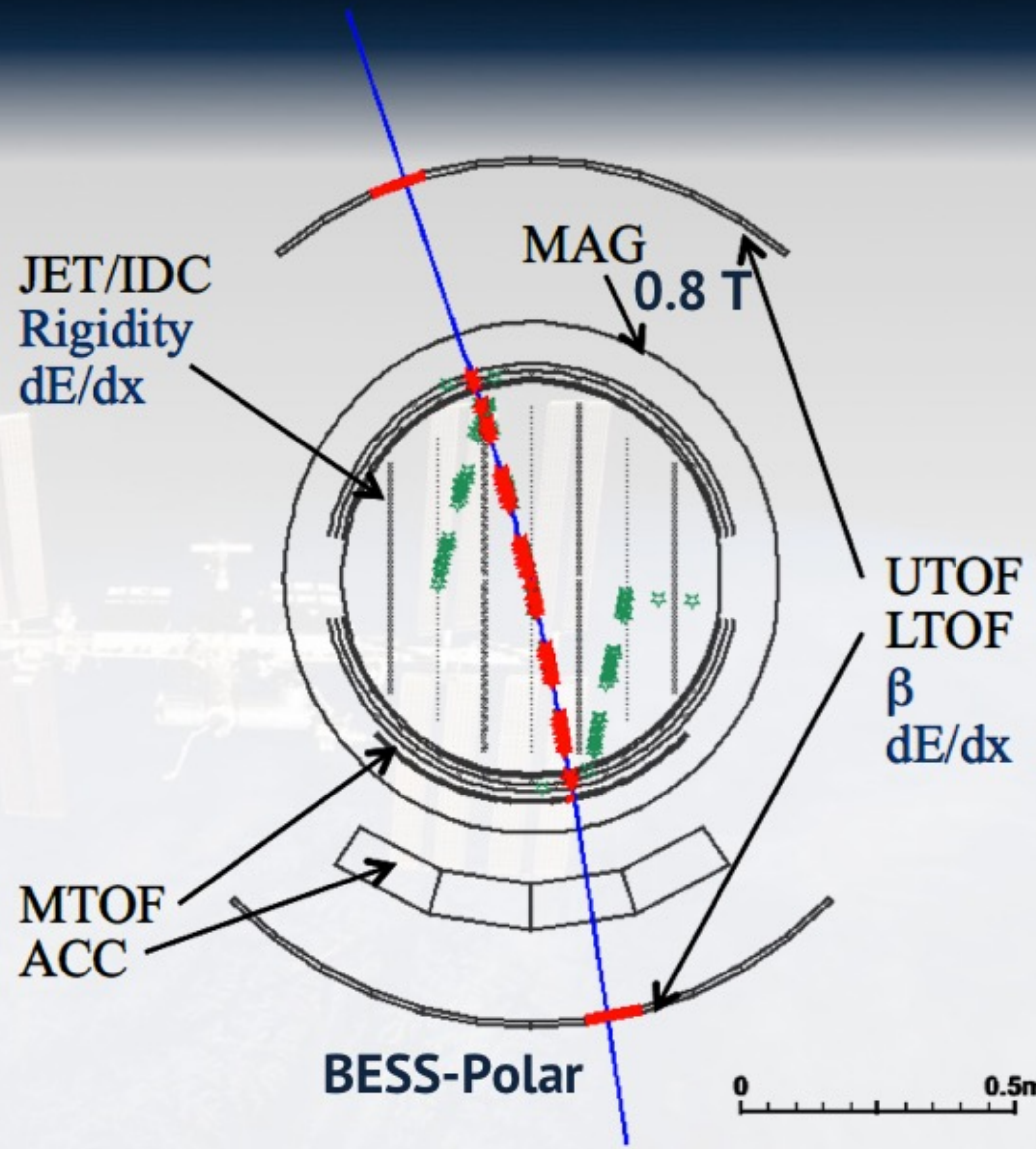




BESS / BESS-Polar

Balloon-borne Experiment with a Superconducting Spectrometer





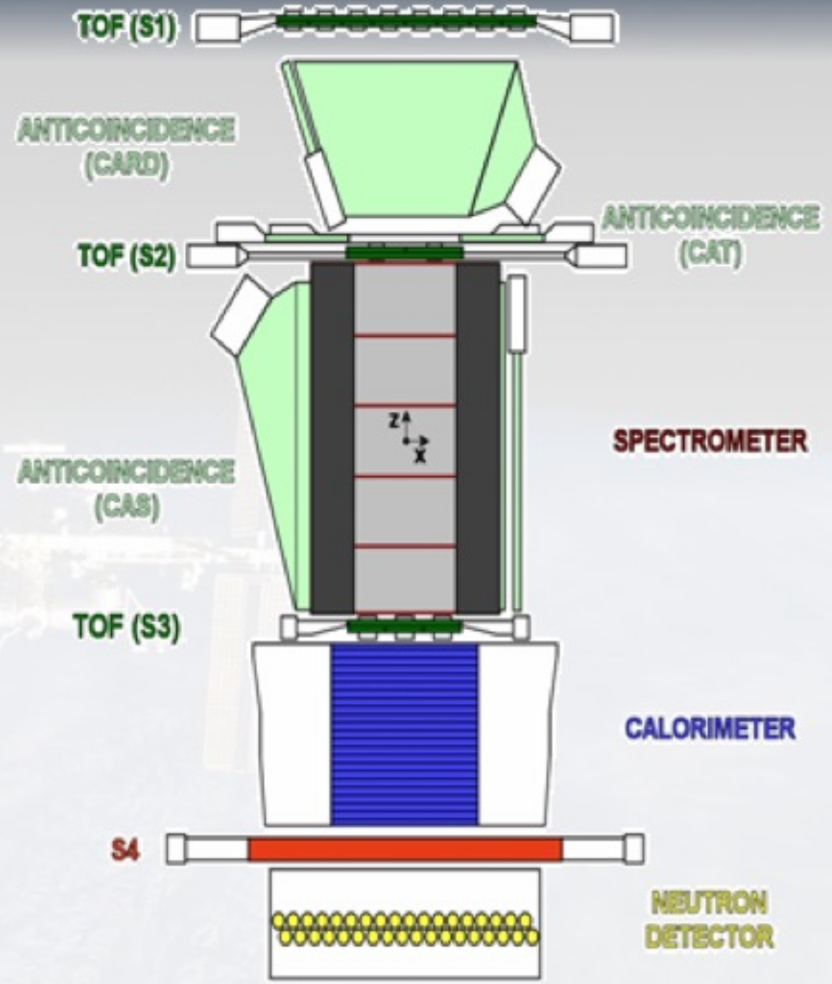
BESS-Polar

Balloon flight over Antarctica in 2004, 2007

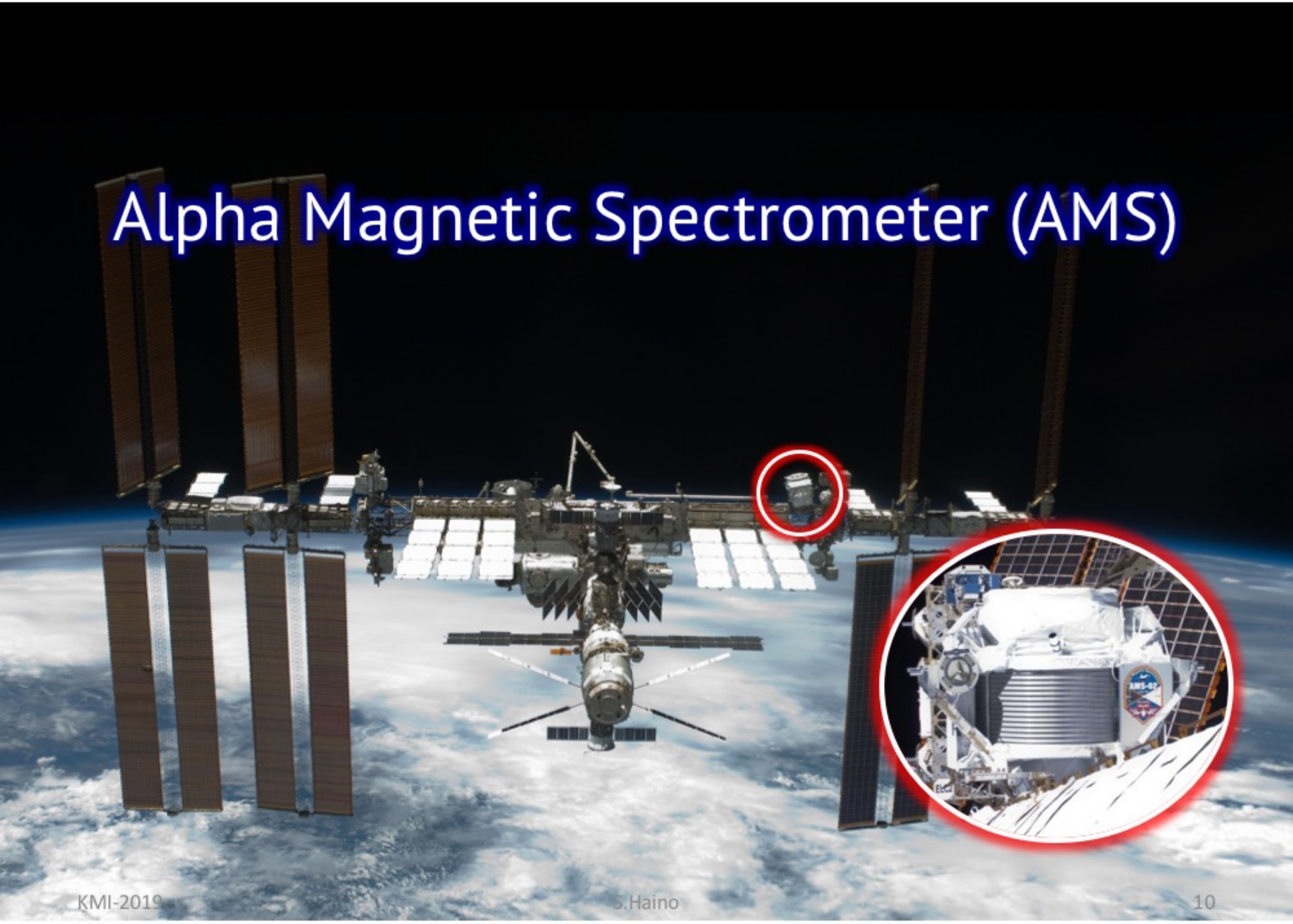
PAMELA

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

Launched in June/2006 by Soyuz-U rocket



Alpha Magnetic Spectrometer (AMS)



AMS collaboration

From Asia, Europa, and Americas

S.C.C.Ting

International Recognition of AMS Results

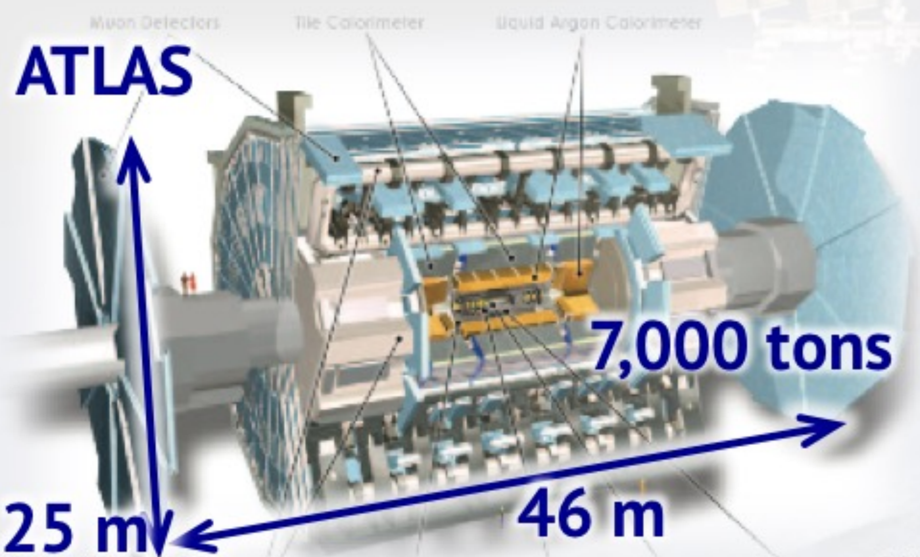
AMS Publications (~2500 inSPIRE citations)

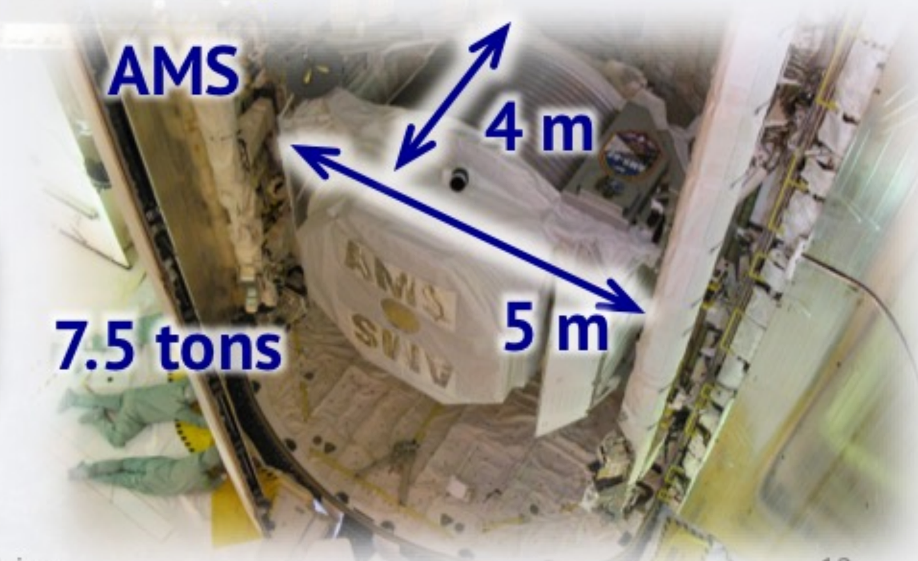
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

1) M. Aguilar *et. al*., Phys. Rev. Lett. **110** (2013) 141102. **Editor's Suggestion, Viewpoint in Physics, Highlight of the Year 2013.**
2) L. Accardo *et al*., Phys. Rev. Lett. **113** (2014) 121101. **Editor's Suggestion**
3) M. Aguilar *et. al*., Phys. Rev. Lett. **113** (2014) 121102. **Editor's Suggestion**
4) M. Aguilar *et. al*., Phys. Rev. Lett. **113** (2014) 221102.
5) M. Aguilar *et. al*., Phys. Rev. Lett. **114** (2015) 171103. **Editor's Suggestion**
6) M. Aguilar *et. al*., Phys. Rev. Lett. **115** (2015) 211101. **Editor's Suggestion**
7) M. Aguilar *et. al*., Phys. Rev. Lett. **117** (2016) 091103.
8) M. Aguilar *et. al*., Phys. Rev. Lett. **117** (2016) 231102. **Editor's Suggestion**
9) M. Aguilar *et. al*., Phys. Rev. Lett. **119** (2017) 251101.
10) M. Aguilar *et. al*., Phys. Rev. Lett. **120** (2018) 021101. **Editor's Suggestion**
11) M. Aguilar *et. al*., Phys. Rev. Lett. **121** (2018) 051101.
12) M. Aguilar *et. al*., Phys. Rev. Lett. **121** (2018) 051102. **Editor's Suggestion**
13) M. Aguilar *et. al*., Phys. Rev. Lett. **121** (2018) 051103.
14) M. Aguilar *et. al*., Phys. Rev. Lett. **122** (2019) 041102. **Editor's Suggestion**

Technical challenges for AMS

- AMS is designed with the same capability as state-of-art CERN-LHC detectors
  but small enough to fit in space shuttle
- AMS needs to work for 20 years in extreme space enviroment without access nor repair





It took ~18 years

For

- Design
- Construction
- Space qualification tests of sub-systems

and

- Integration of AMS-02

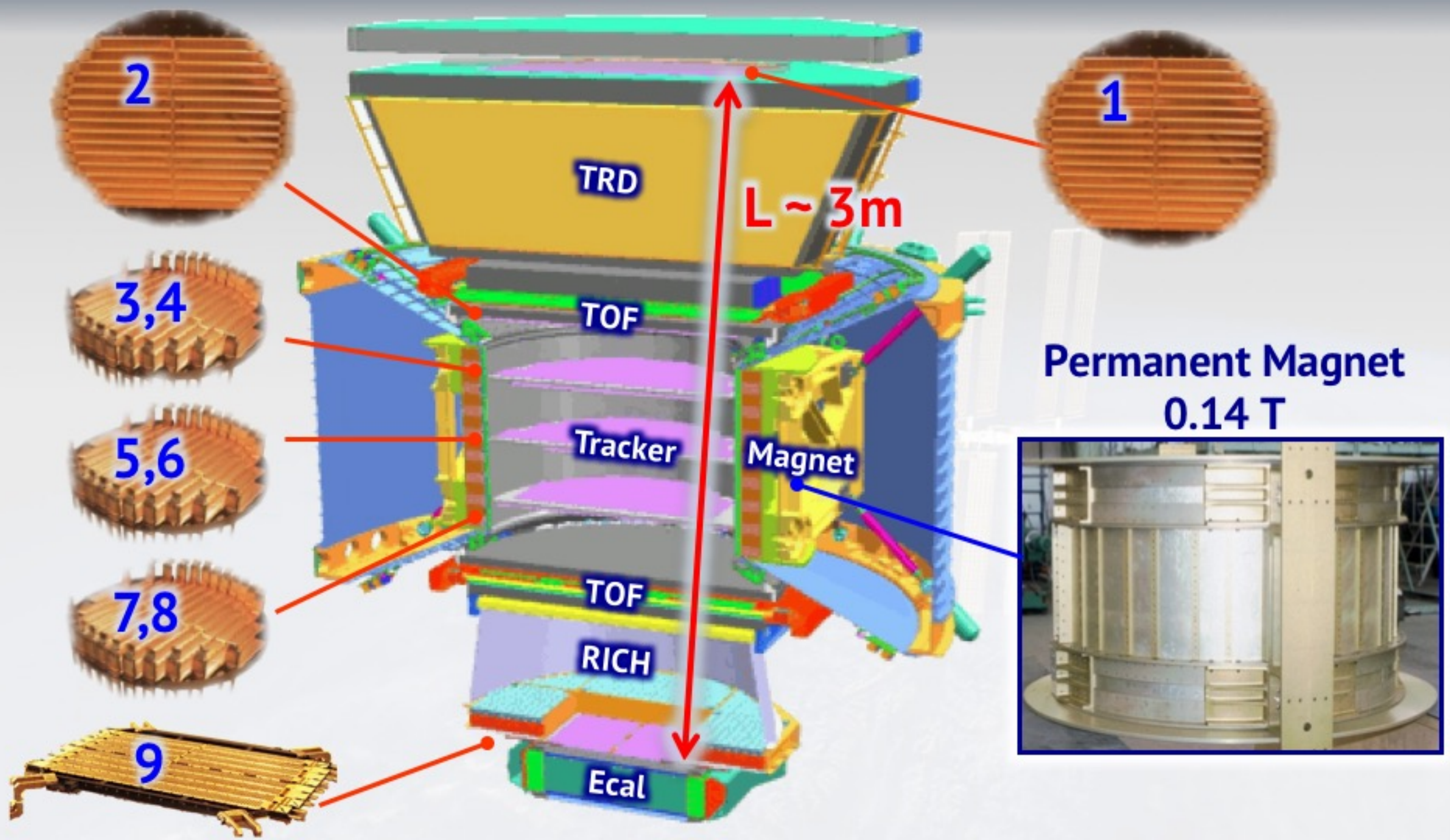
AMS installed on the ISS

19/May/2011

Start taking data only 4 hours later

Since then, AMS is continuously recording 16 billion Cosmic-Ray events every year…

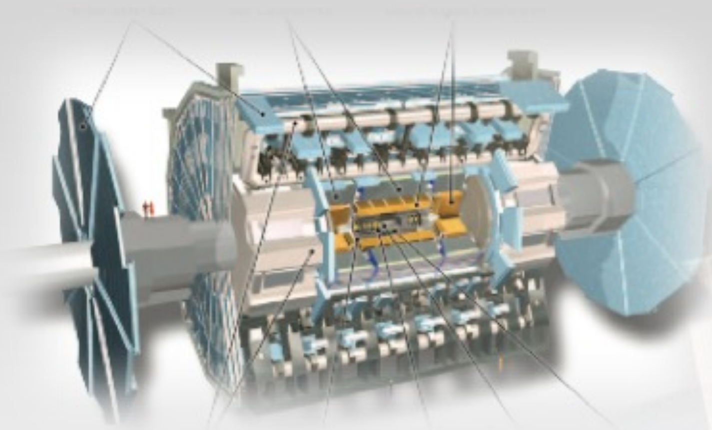
AMS – 9 layers of silicon tracker

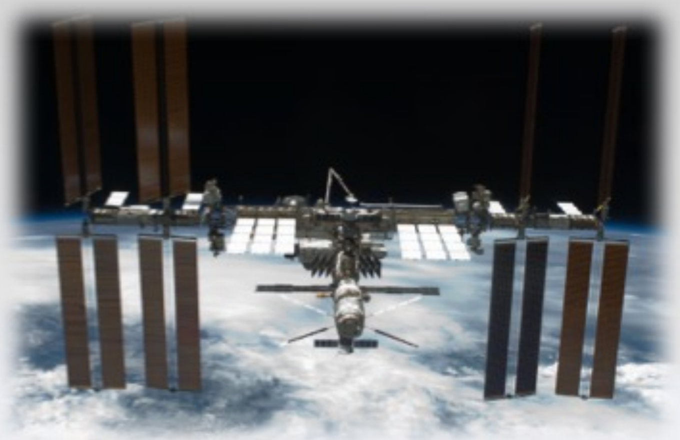


Cosmic-Ray Positrons

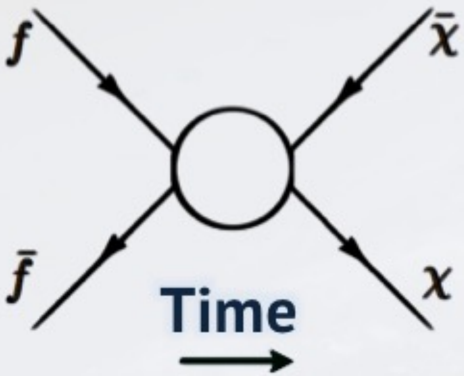
as a probe for indirect DM searches

Dark Matter searches

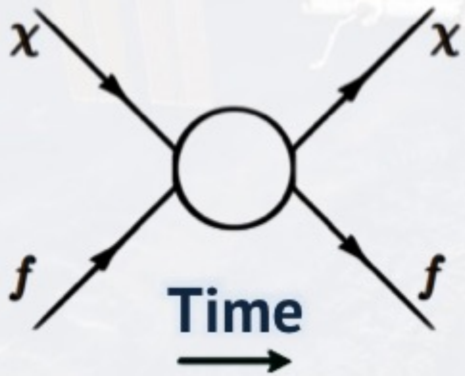




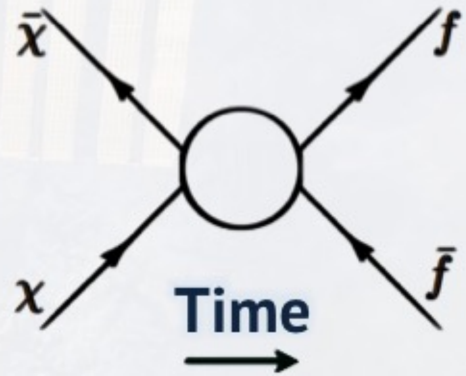
Colliders



Direct searches

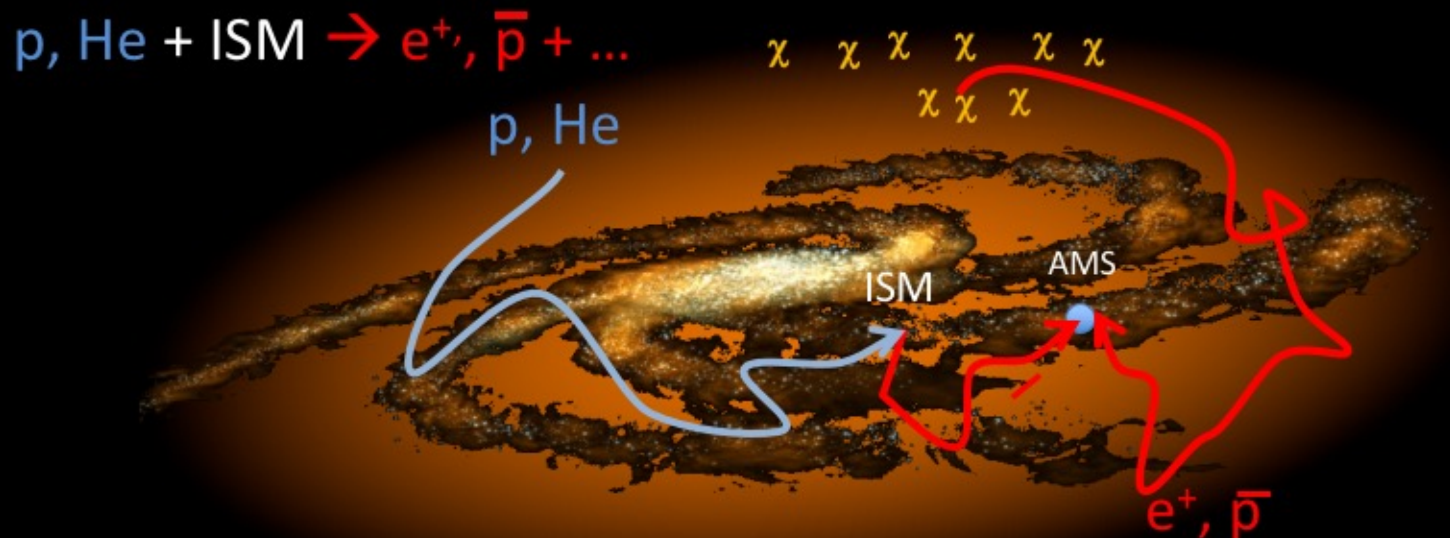


Indirect searches



Annihilaiton of Dark Matter

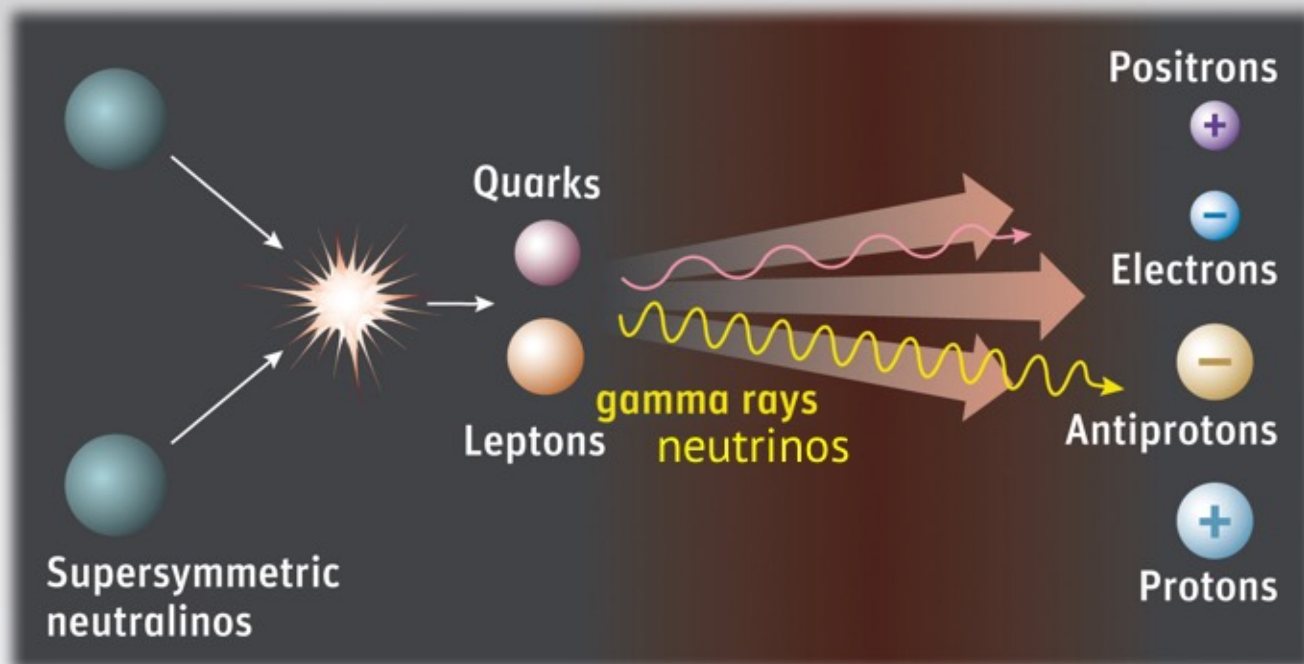
Collision of Cosmic Rays with the Interstellar Media will produce e^+, $\bar{p}$…

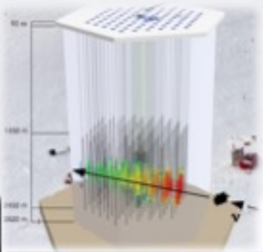


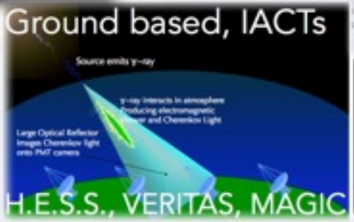
Dark Matter (χ) annihilations $\chi + \chi \rightarrow e^+, e^-, p, \bar{p}$…

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

Annihilaiton of Dark Matter



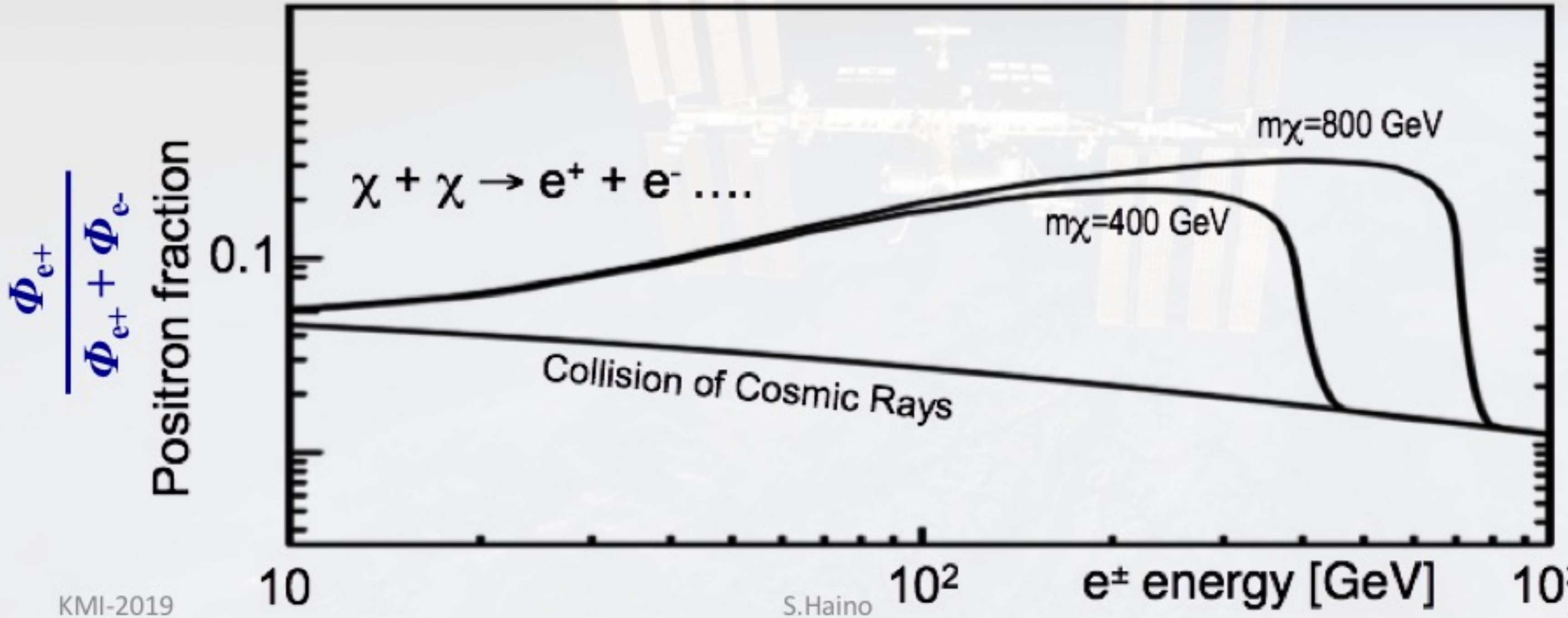




Summary talk on Indirect searches by G. Zaharijas

Cosmic-ray Positrons

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001;
J. Ellis, 26th ICRC Salt Lake City (1999) astro-ph/9911440;
H. Cheng, J. Feng and K. Matchev, Phys. Rev. Lett. 89 (2002) 211301;
S. Profumo and P. Ullio, J. Cosmology Astroparticle Phys. JCAP07 (2004) 006;
D. Hooper and J. Silk, Phys. Rev. D 71 (2005) 083503;
E. Ponton and L. Randall, JHEP 0904 (2009) 080;
G. Kane, R. Lu and S. Watson, Phys. Lett. B681 (2009) 151;
D. Hooper, P. Blasi and P. D. Serpico, JCAP 0901 025 (2009) 0810.1527; B2

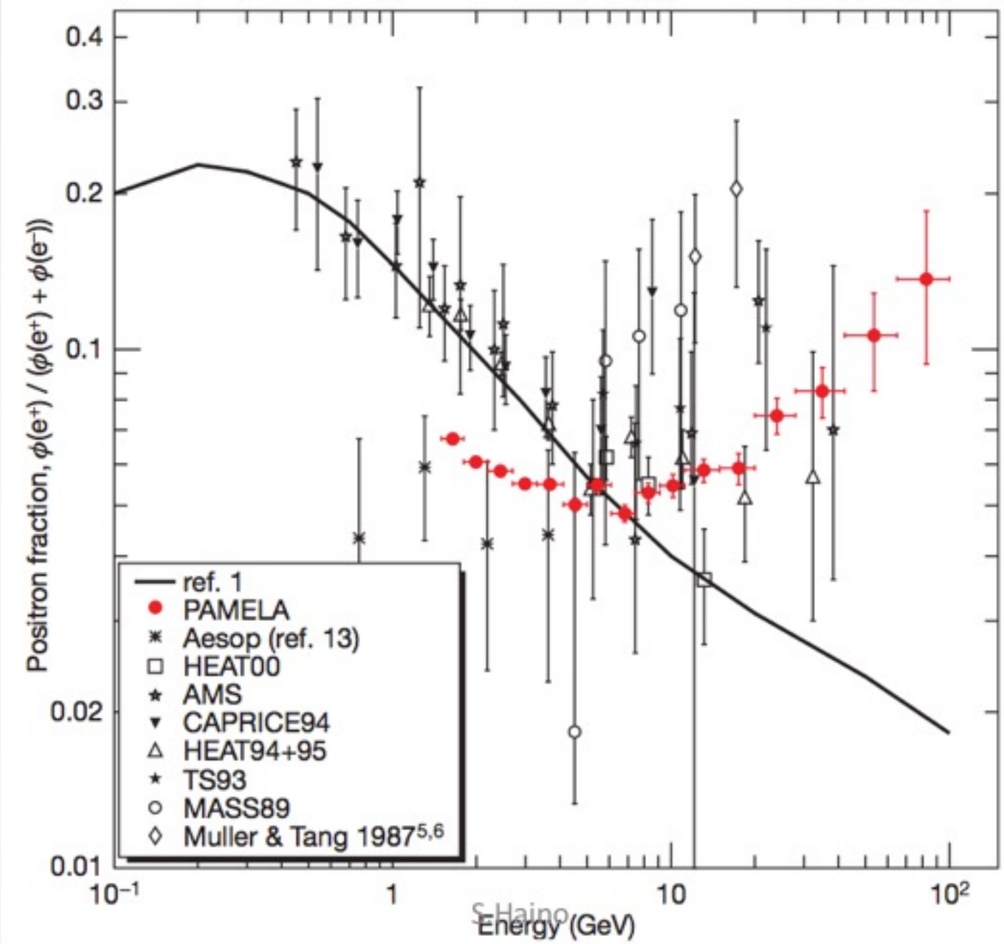


nature

LETTERS

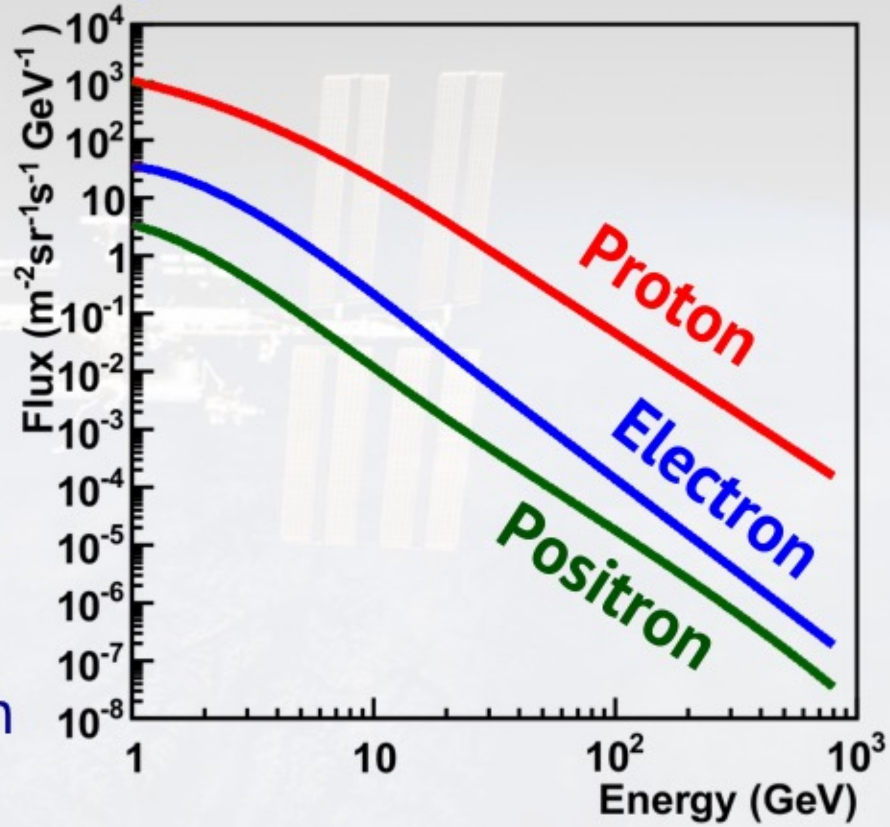
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

PAMELA: Nature 458 (2009) 607

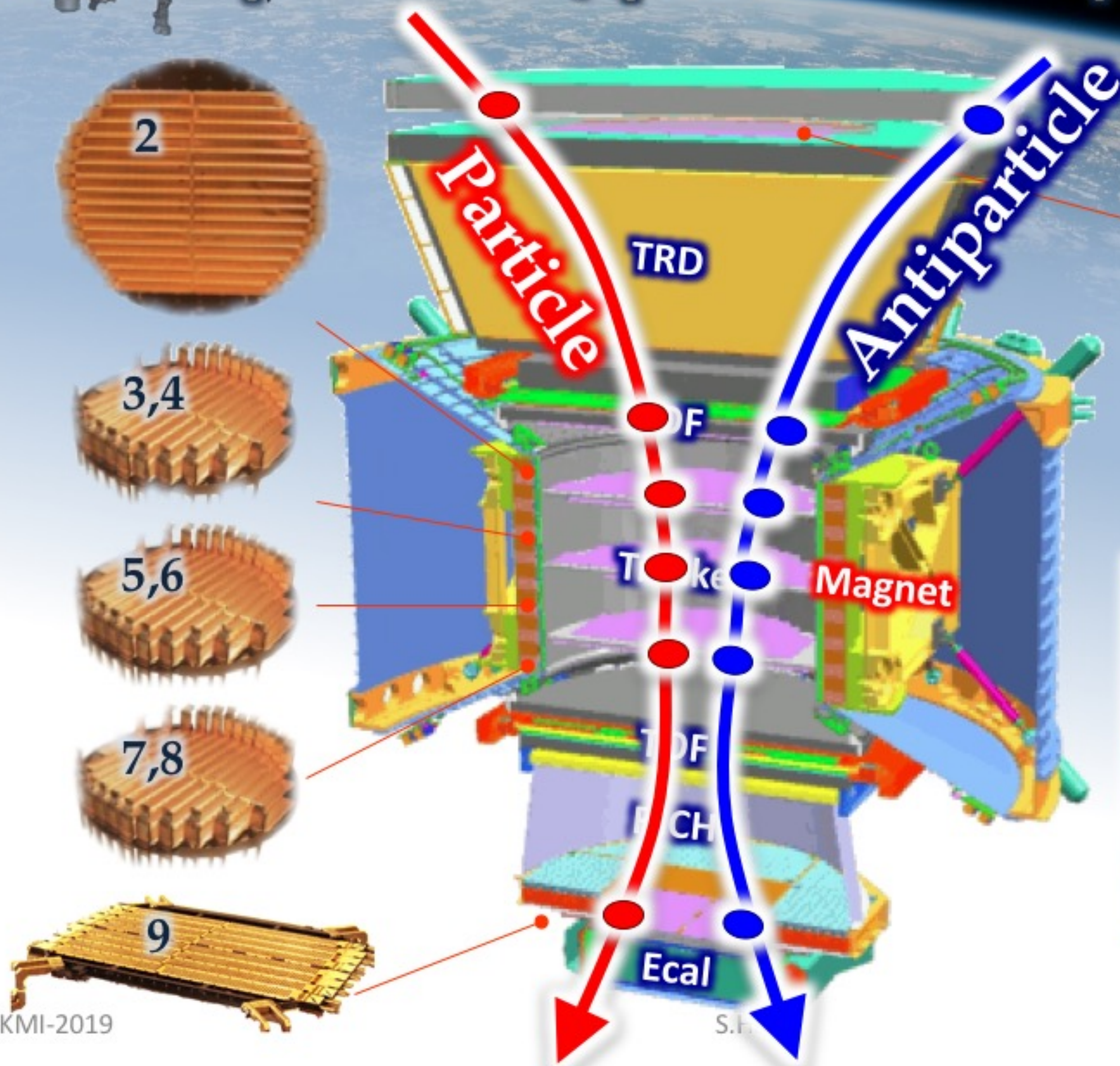


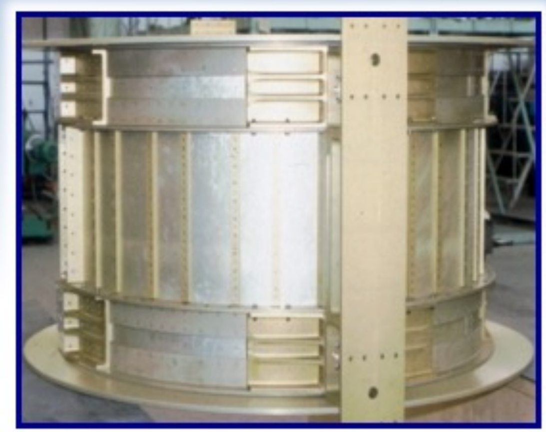
Difficulties – CR positron measurement

- **Low abundance : 0.01~0.1 % of Cosmic Rays**
  → Large acceptance and long duration needed
- **Large backgrounds**
  (1) **Protons (×10^3~10^4)**
  → Redundant e^+/p separation capability
  (2) **Electrons (×10~100)**
  → Deflection measurement in a magnetic field to determine charge sign



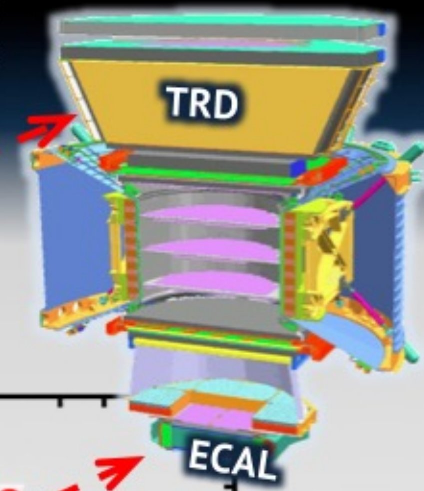
Antiparticle/particle separation



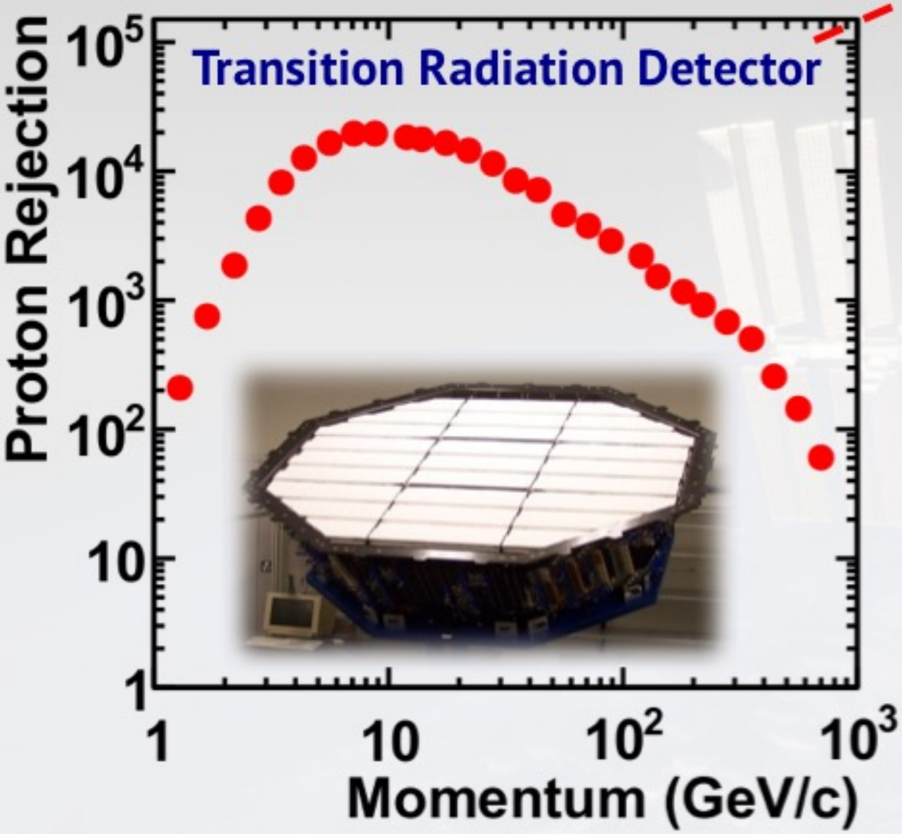


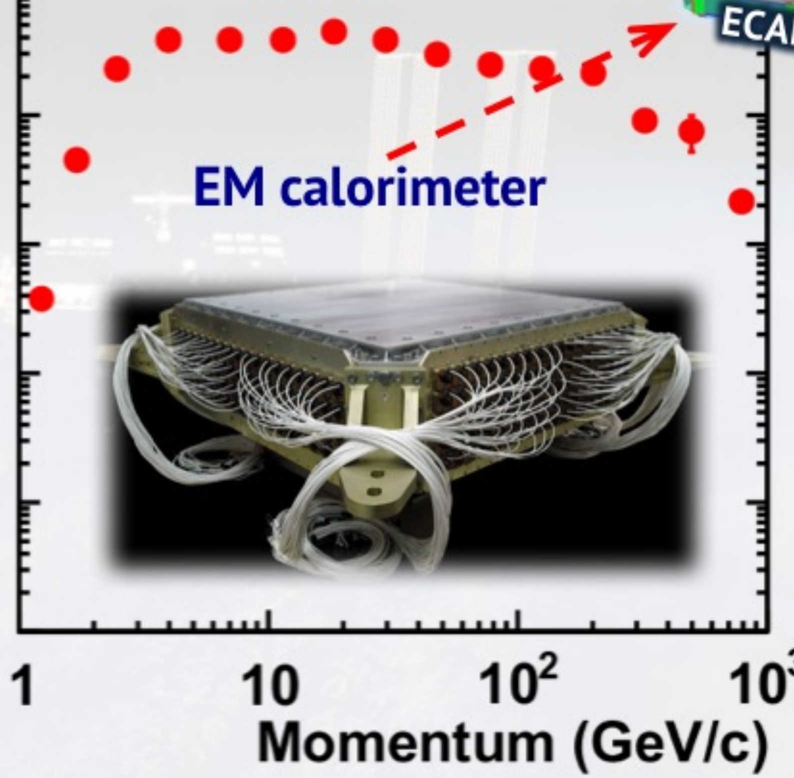
Magnet

Proton rejection by AMS



With 90 % e^+ efficiency



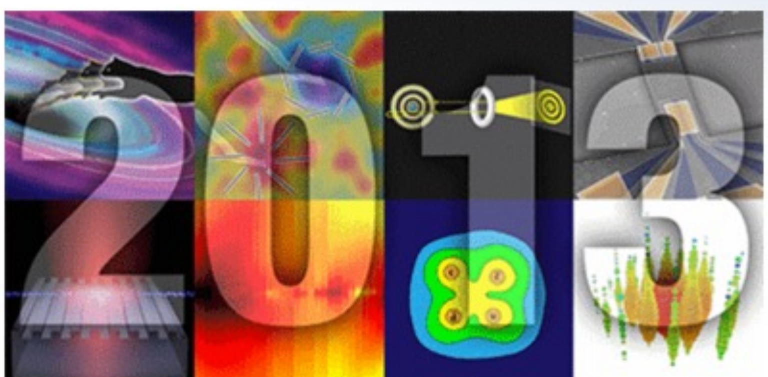


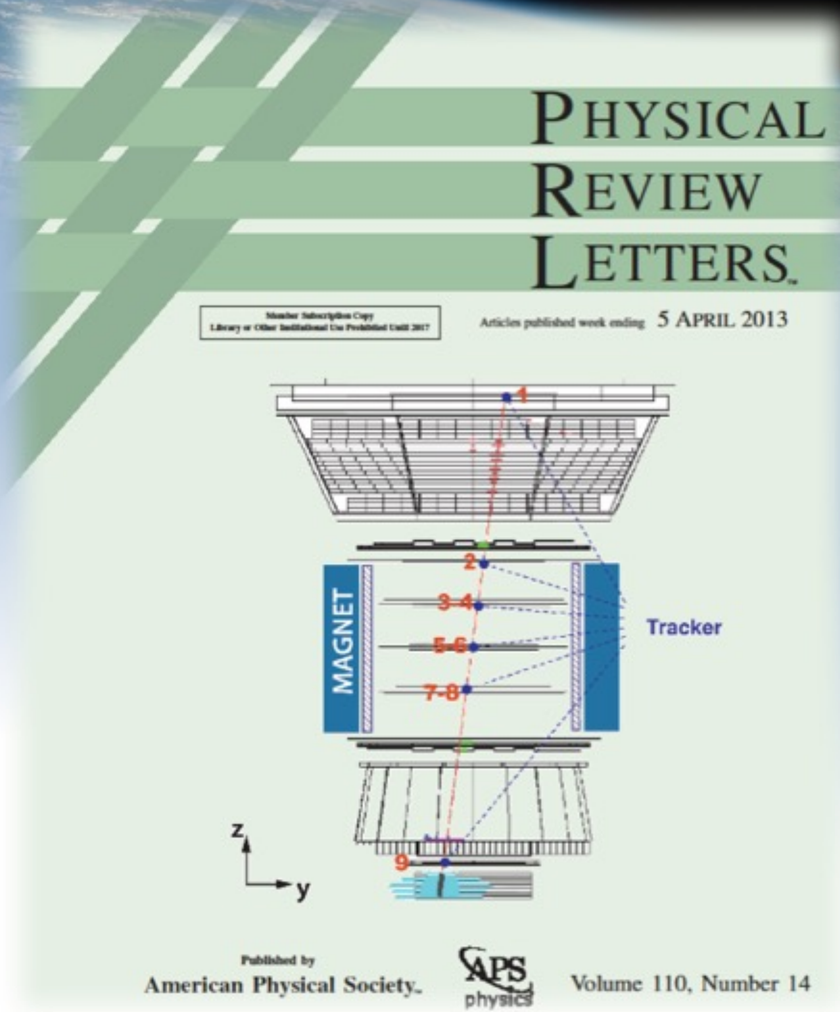
First results of AMS

M. Aguilar *et al.*,
PRL 110, 141102 (2013)

"Precision Measurement of the Positron Fraction in Primary Cosmic Rays" of 0.5-350 GeV (April/2013)

Selected as APS Highlights in 2013





First AMS paper chosen for a ten year retrospective of PRL Editors' Suggestions

I thought you should know that we chose your first AMS PRL for our ten year retrospective of PRL Editors' Suggestions. We are choosing just one paper a week out of more than 3000 Suggestions over that period.

PHYSICAL REVIEW LETTERS

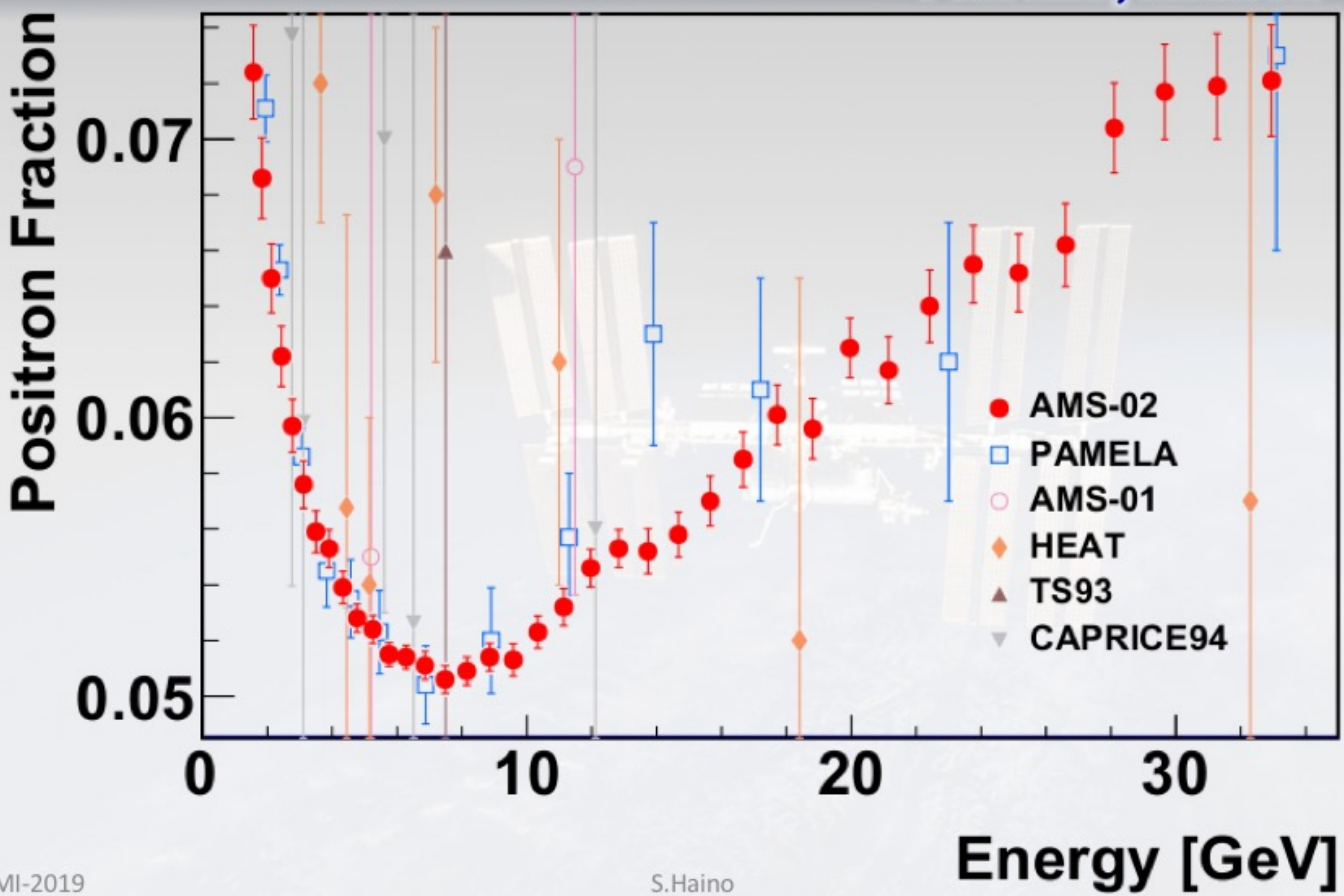
Highlights Recent Accepted Collections Authors Referees Search Press About

A Decade of Editors' Suggestions

Ten years ago this month, PRL started an "experiment" [1]: highlighting papers. Named Editors' Suggestions, these papers feature prominently on our webpages, and in print are designated by a printer's mark derived from the design of Physical Review's cover until the 1990s.

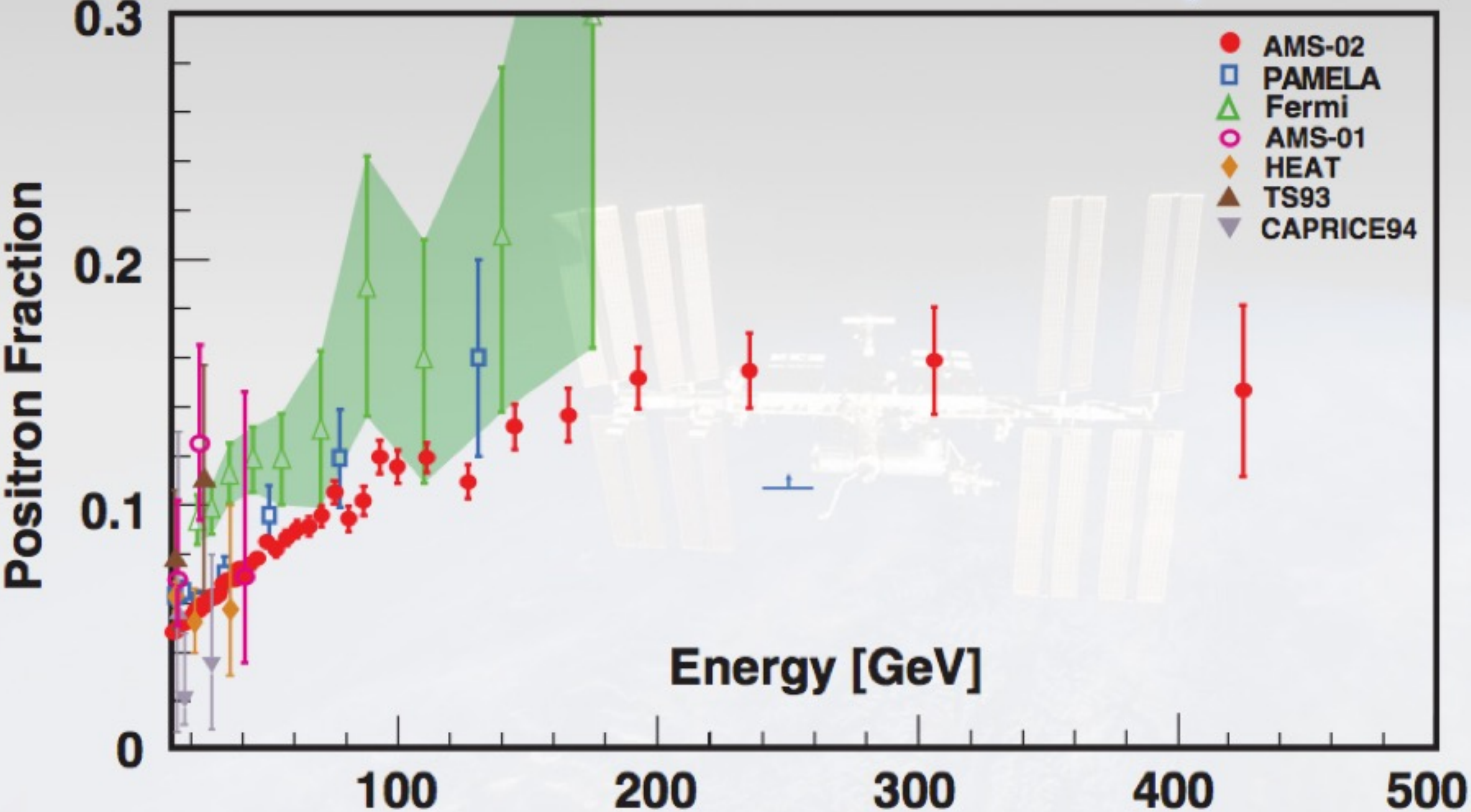
Positron fraction by AMS (low energy)

PRL 113, 121101



Positron fraction by AMS (high energy)

PRL 113, 121101



A sample of Theoretical Models explaining AMS data

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)

and many other excellent papers ...

Propagation

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 ...

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)

and many other excellent papers ...

RESEARCH

PARTICLE ASTROPHYSICS

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

Science 358, 911–914 (2017)

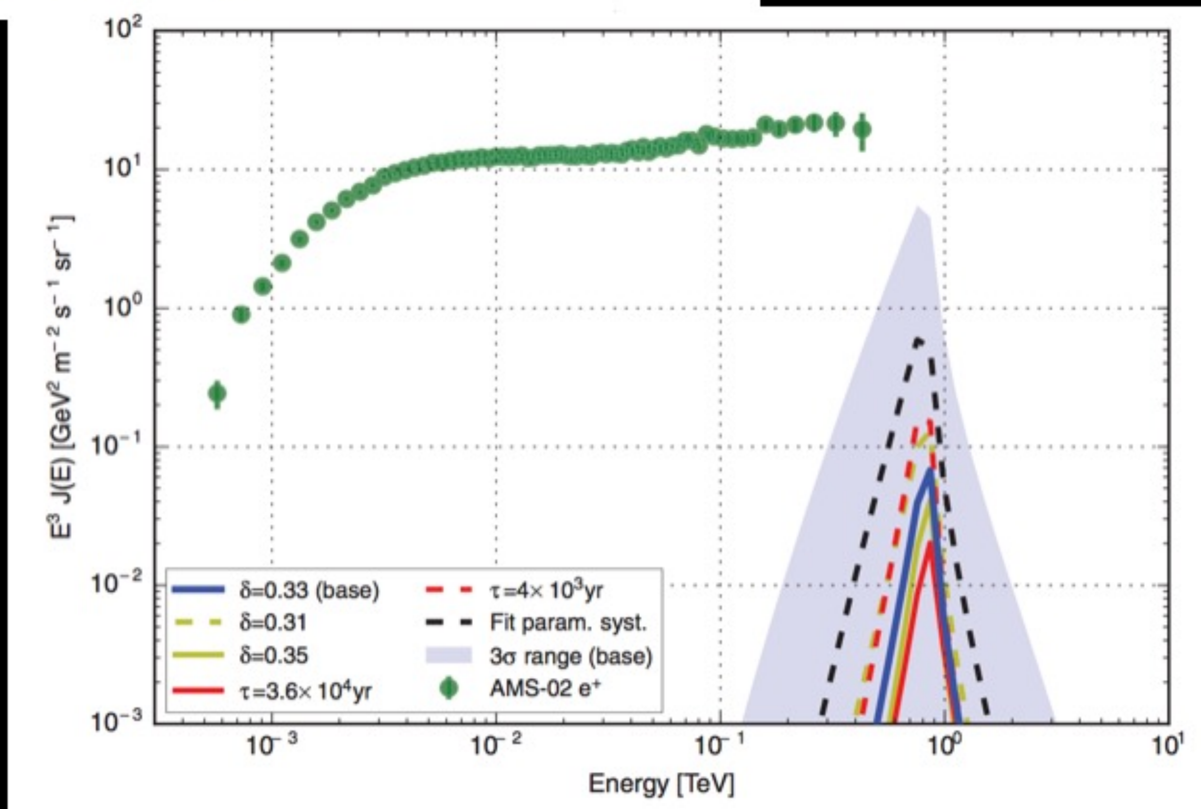
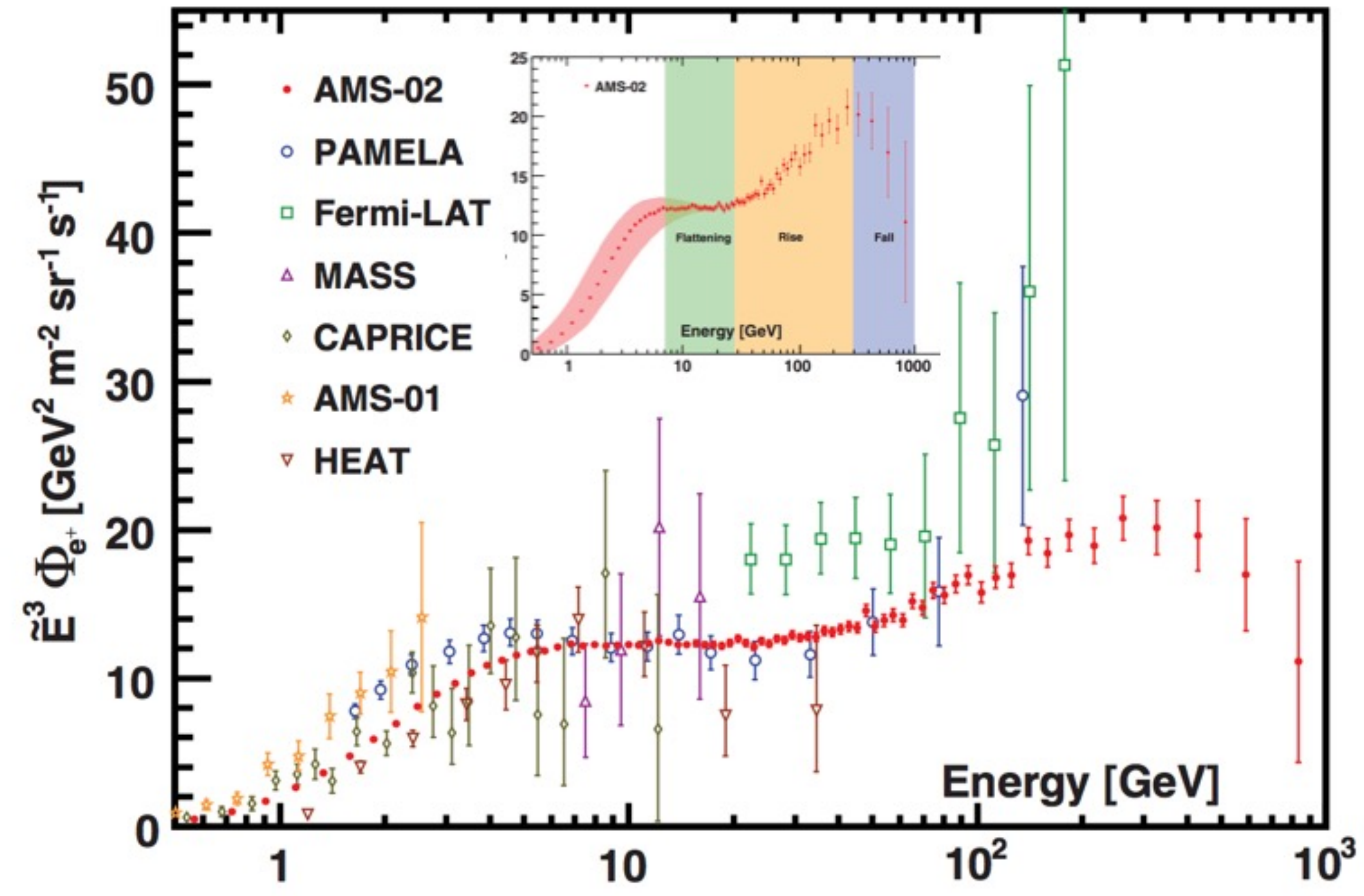


Fig. 3. Estimated positron energy flux at Earth from Geminga (blue solid line), compared with AMS-02 experimental measurements (green dots). The shaded blue region indicates the 3σ

PHYSICAL REVIEW LETTERS **122,** 041102 (2019)

Editors' Suggestion

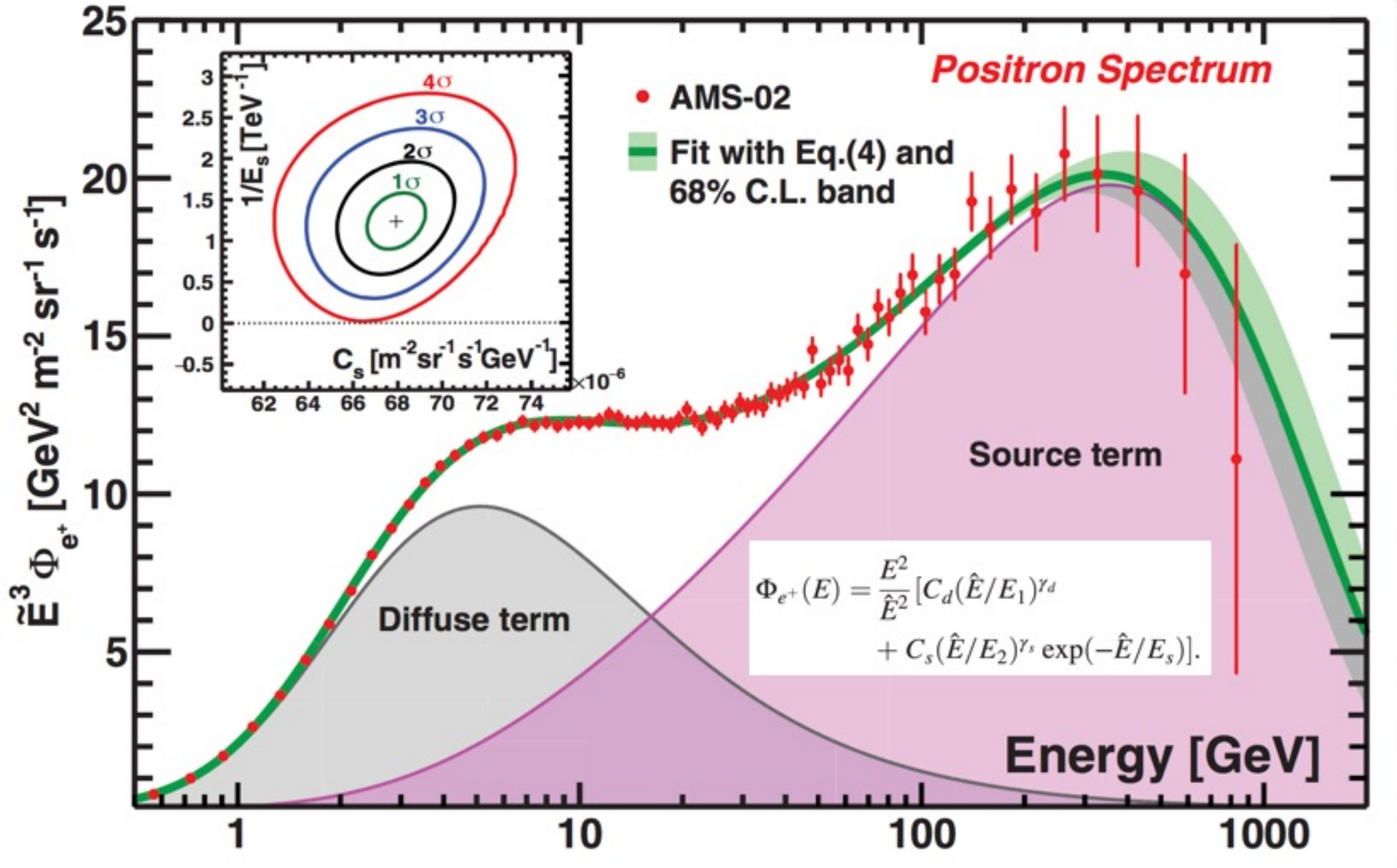
Towards Understanding the Origin of Cosmic-Ray Positrons



PHYSICAL REVIEW LETTERS **122,** 041102 (2019)

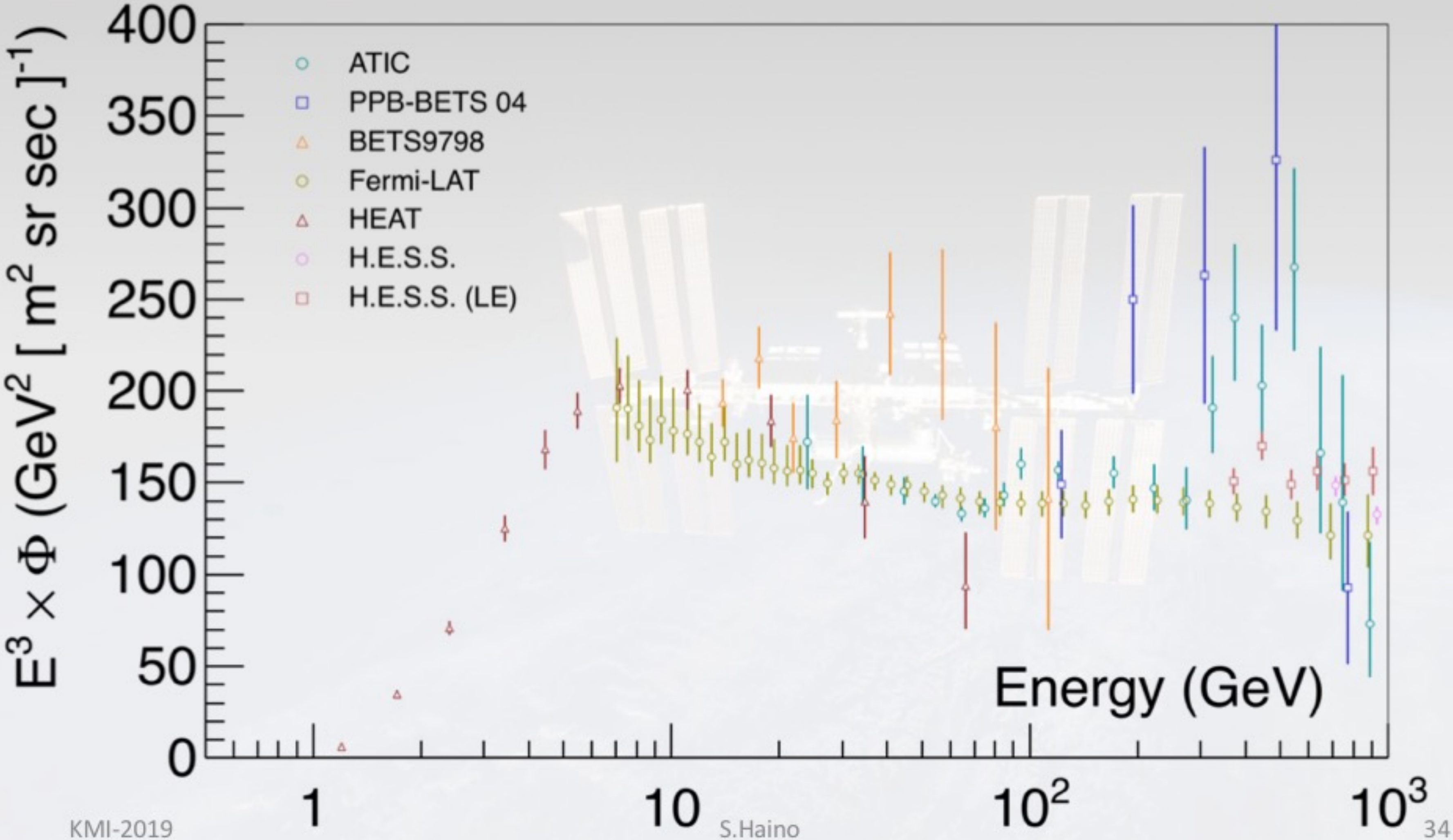
Editors' Suggestion

Towards Understanding the Origin of Cosmic-Ray Positrons

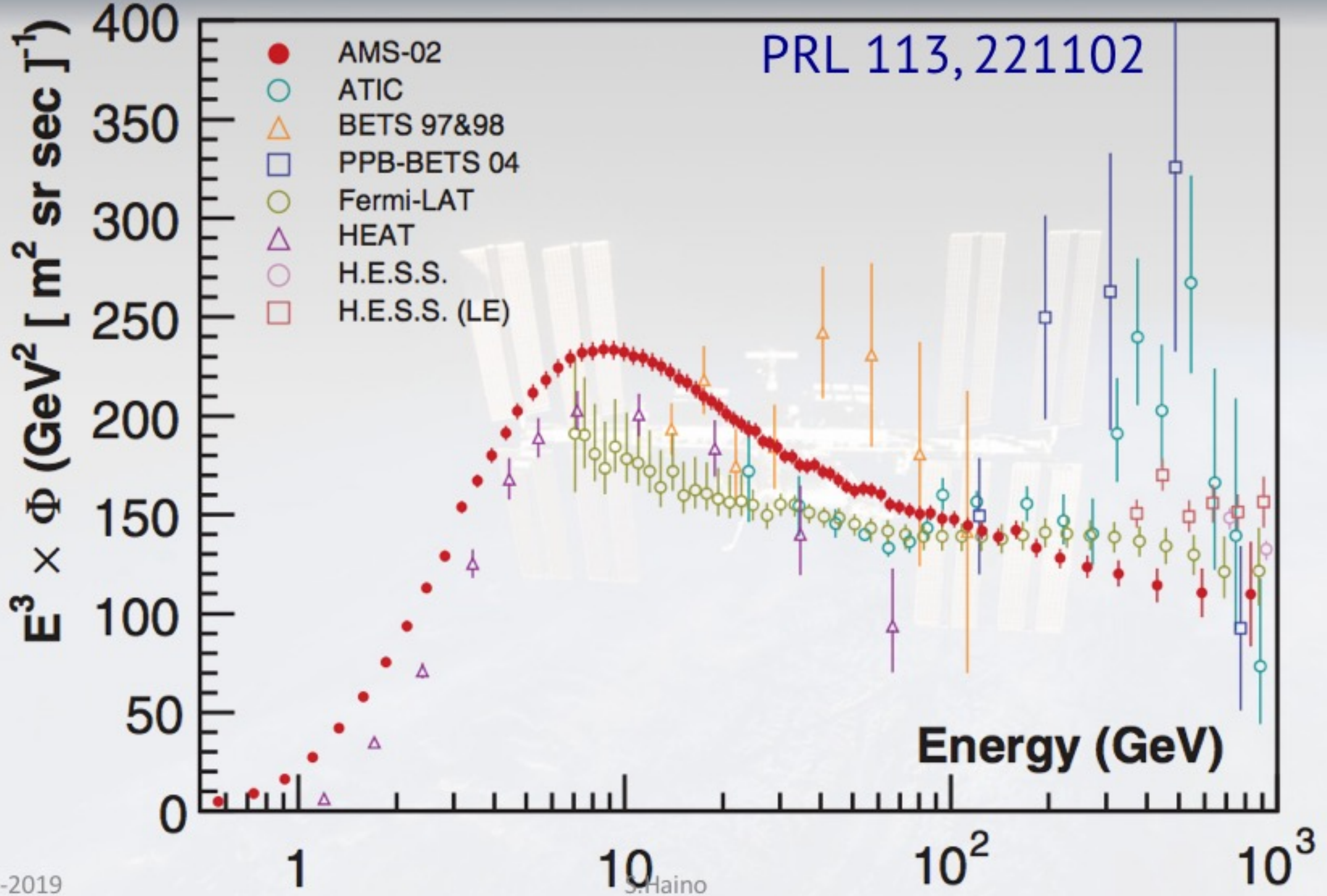


$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)].$$

All (e^++e^-) flux before AMS



AMS all (e^++e^-) flux up to 1 TeV



CALET installed on the ISS on Aug./26, 2015

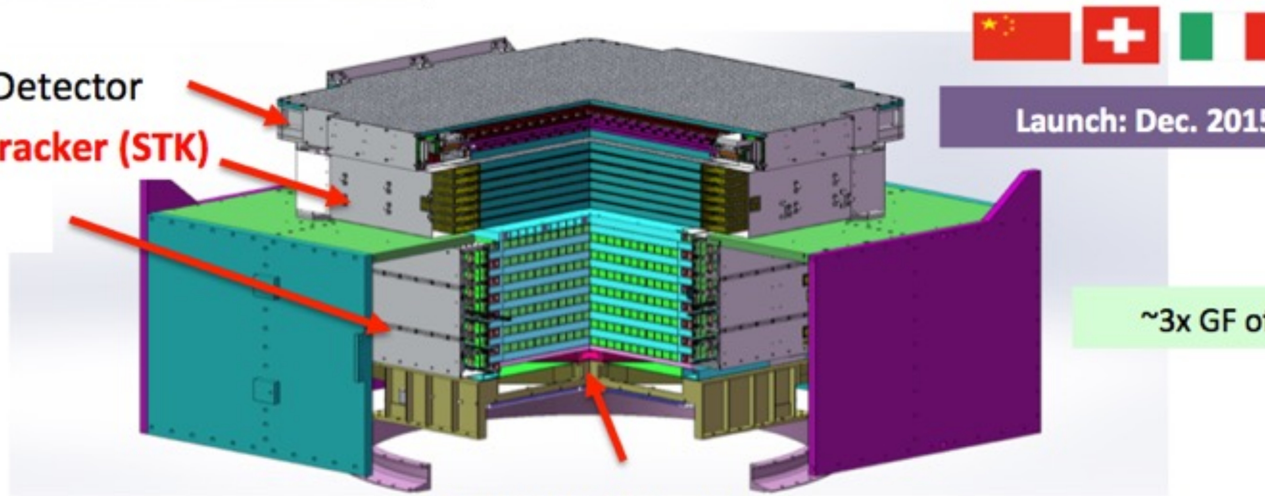
CALET installed at Kibo

DAMPE launched by Chinese rocket on Dec./17, 2015 (DArk Matter Particle Explorer)

Plastic Scintillator Detector

Silicon-Tungsten Tracker (STK)

BGO Calorimeter



Launch: Dec. 2015

~3x GF of AMS-02

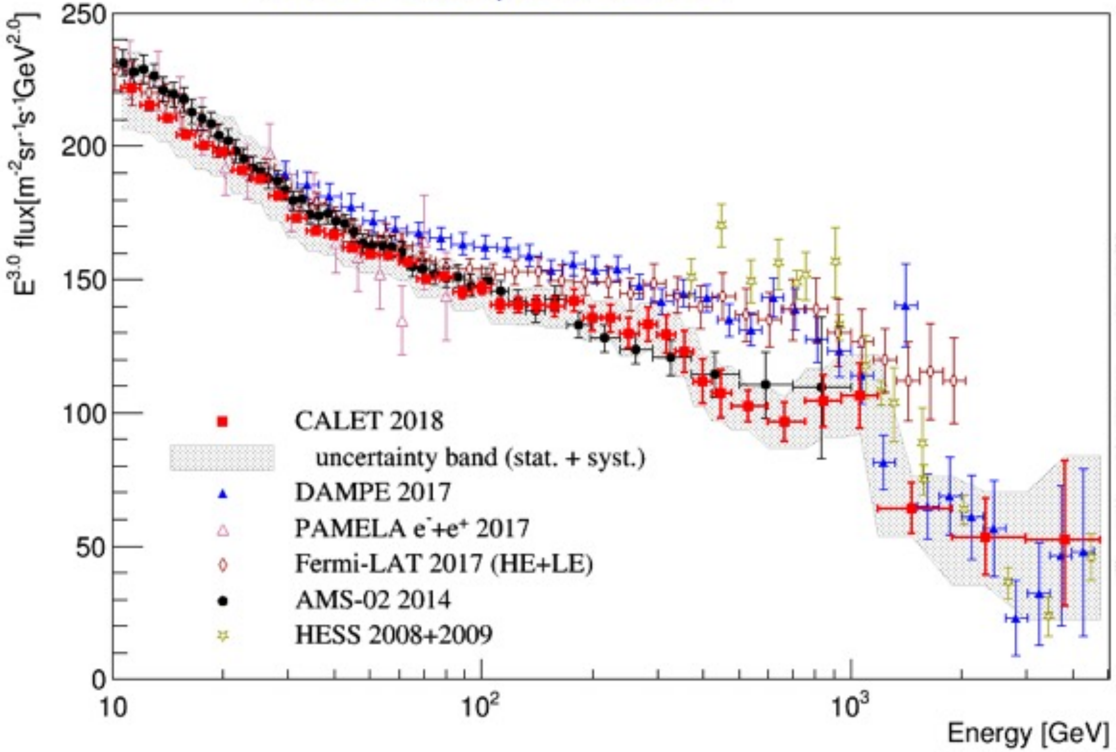
Neutron Detector

Detection of 5 GeV - 10 TeV e/γ, 100 GeV - 100 TeV Cosmic Rays Complementary to Fermi, AMS-02, CALET, ISS-CREAM

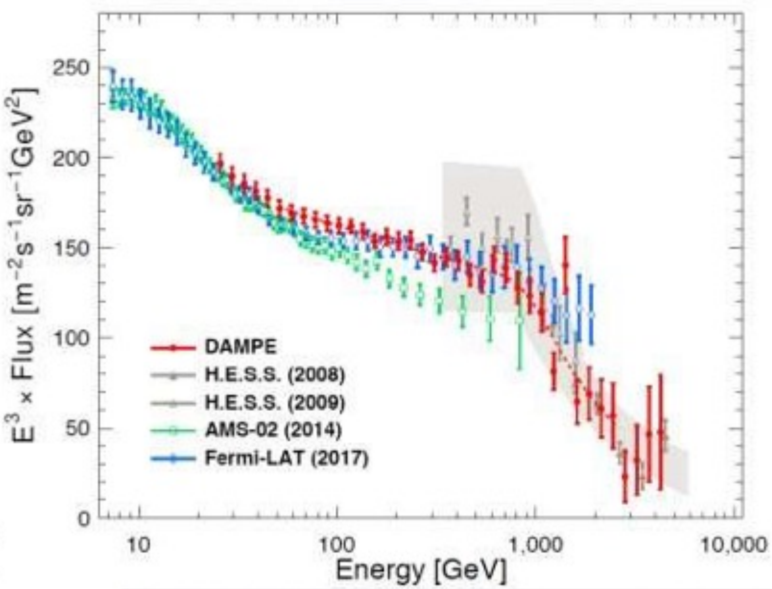
W converter + thick calorimeter (total 32 X_0) + precise tracking + charge measurement ➡ high energy γ-ray, electron and CR telescope

CALET VS DAMPE

PRL 120, 261102



Nature 552, 63

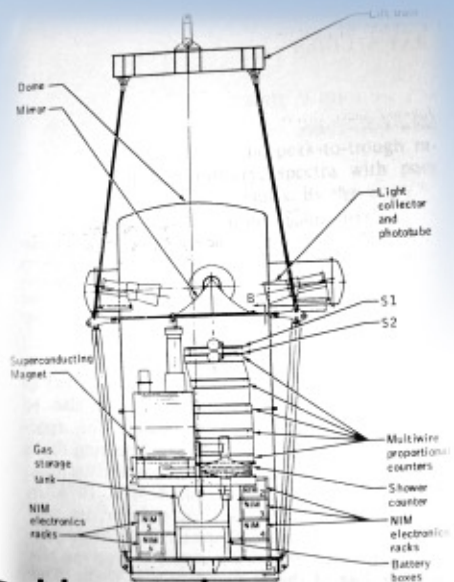


Cosmic-Ray Antiprotons

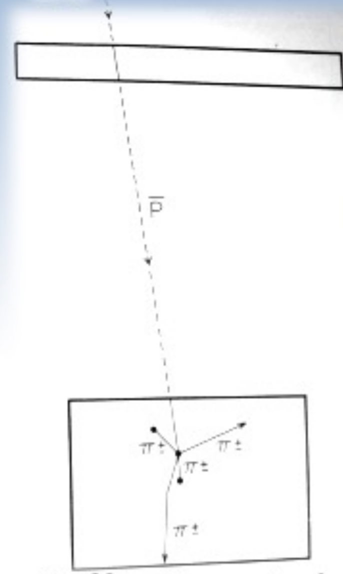
Cosmic Rray antiprotons in ~1980

First observation in 1979

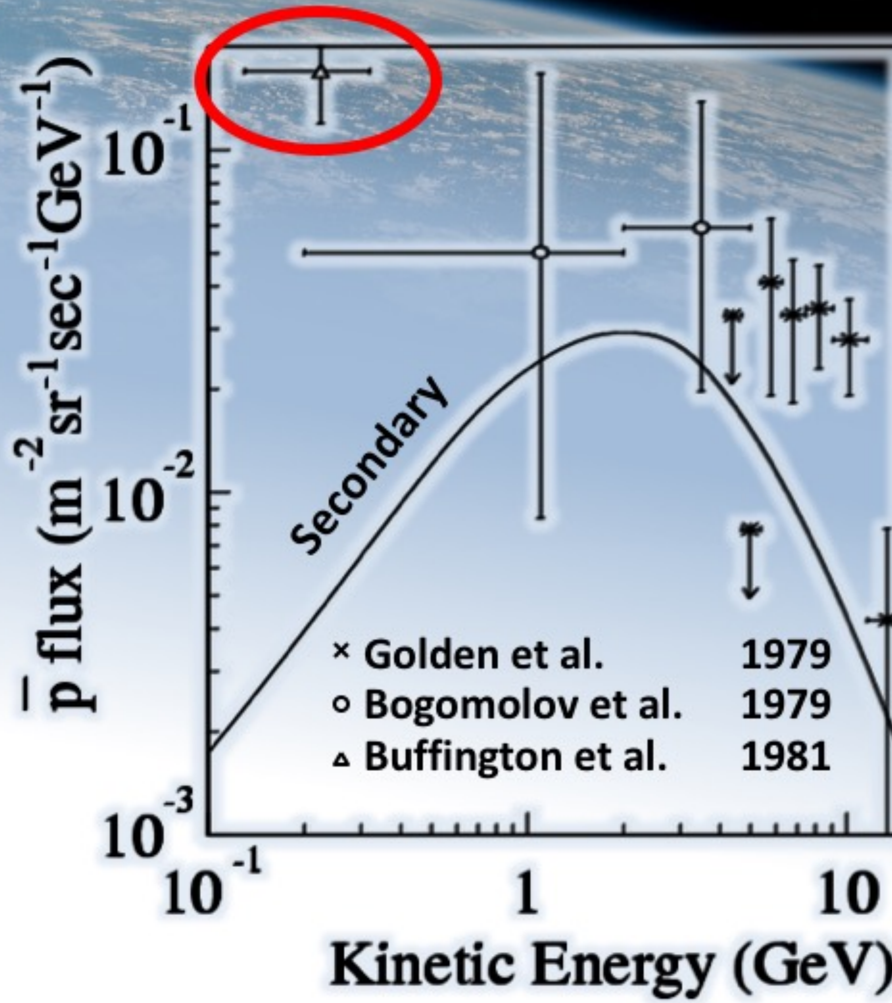
Significant excess in low energy



Golden et al.
Magnetic spectrometer



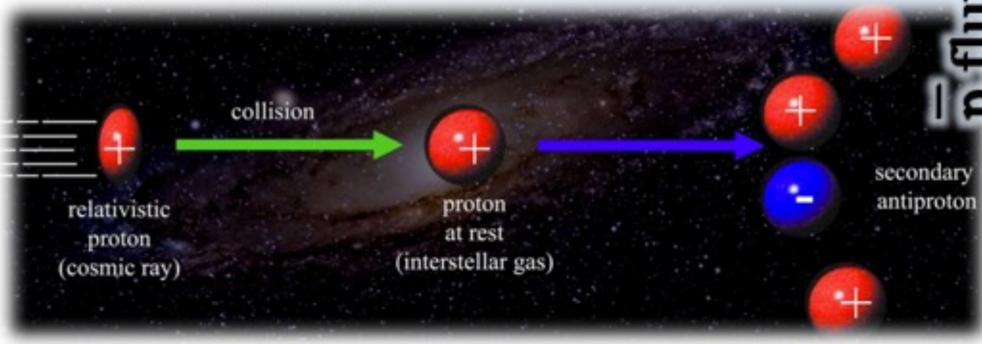
Buffington et al.
Spark chamber

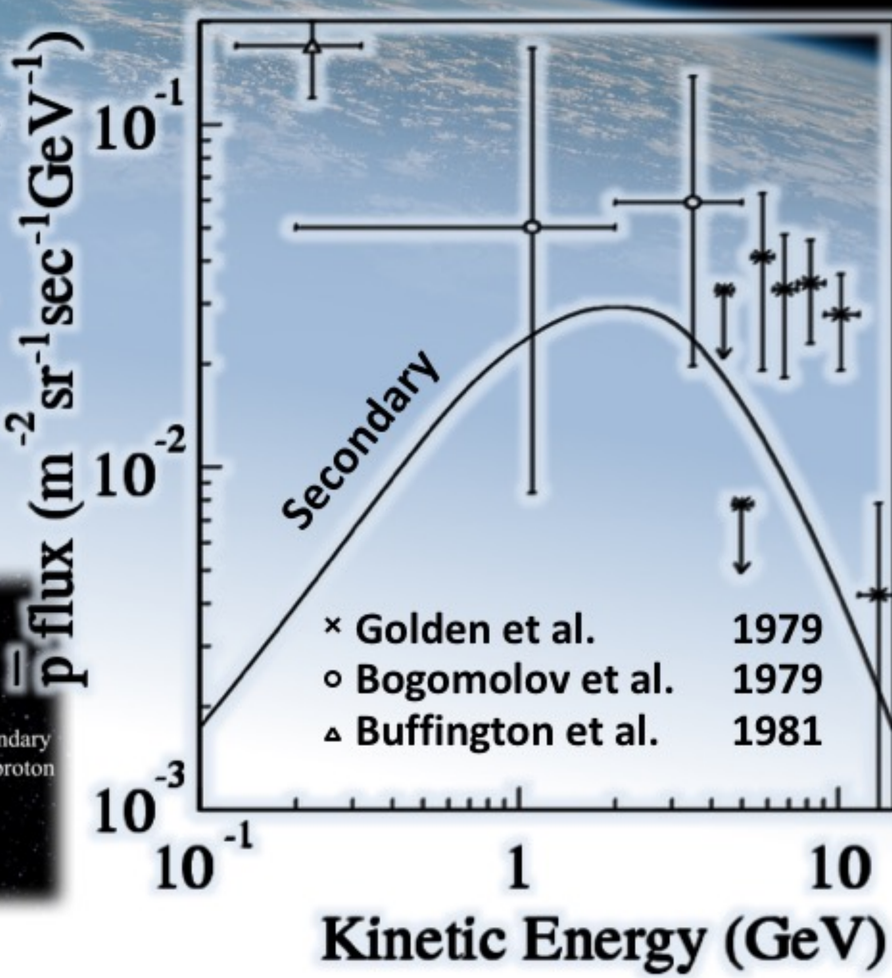


Antiproton production

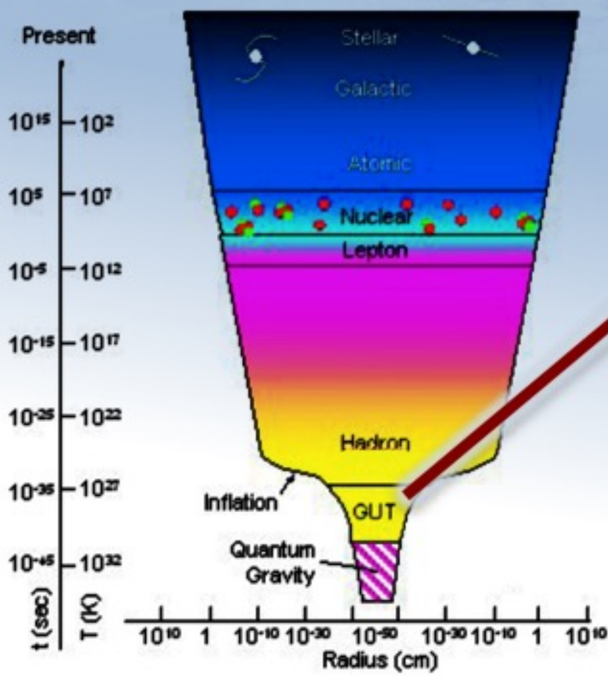
- Kinematic constraints in low energy
- Spectrum has a peak at E_{kin}~2 GeV

Secondary production
$pp \rightarrow ppp\bar{p}...$





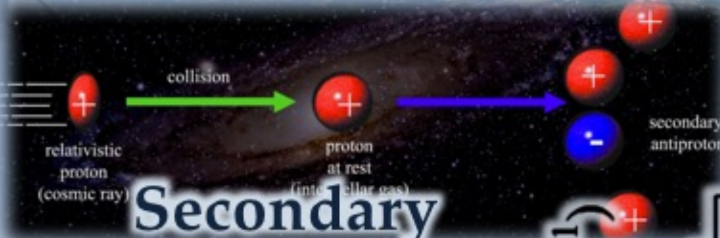
Evapolation of Primordial Black Holes



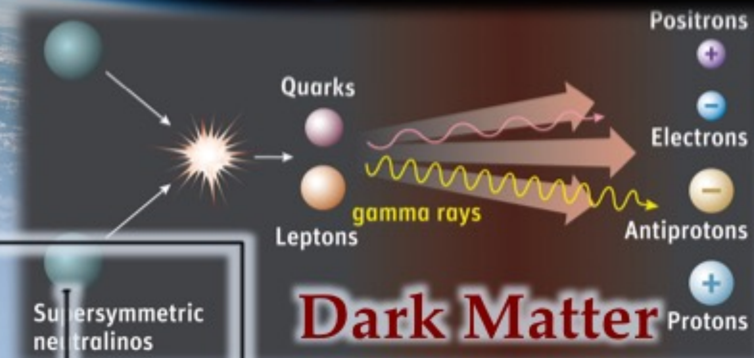
PBH ~10^{12} kg :
Evaporating now

p, pbar

CR Antiproton summary

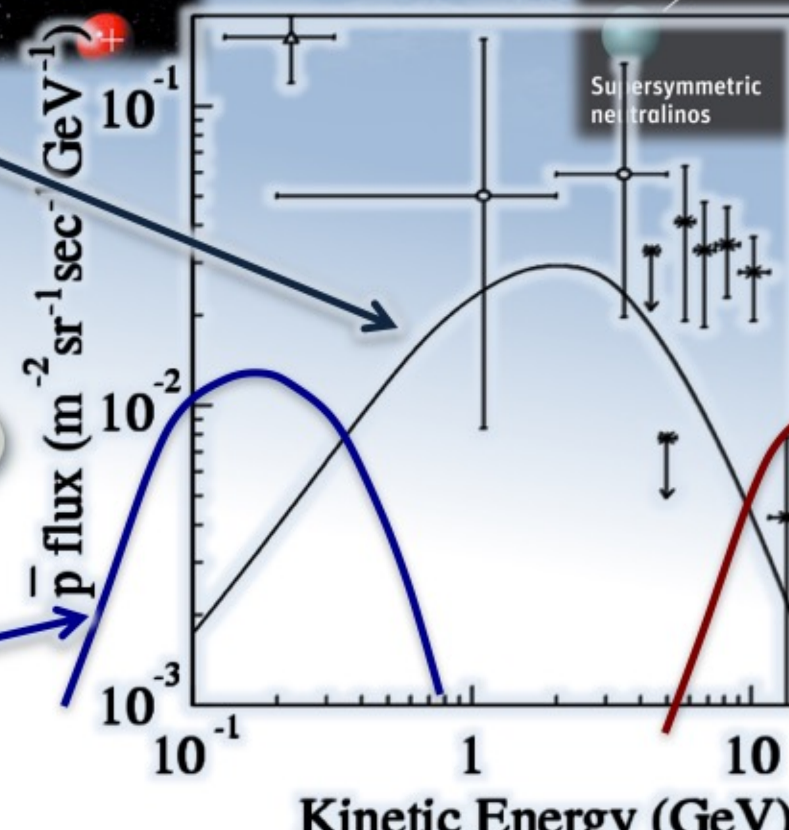


Secondary
$pp \rightarrow ppp\bar{p}...$



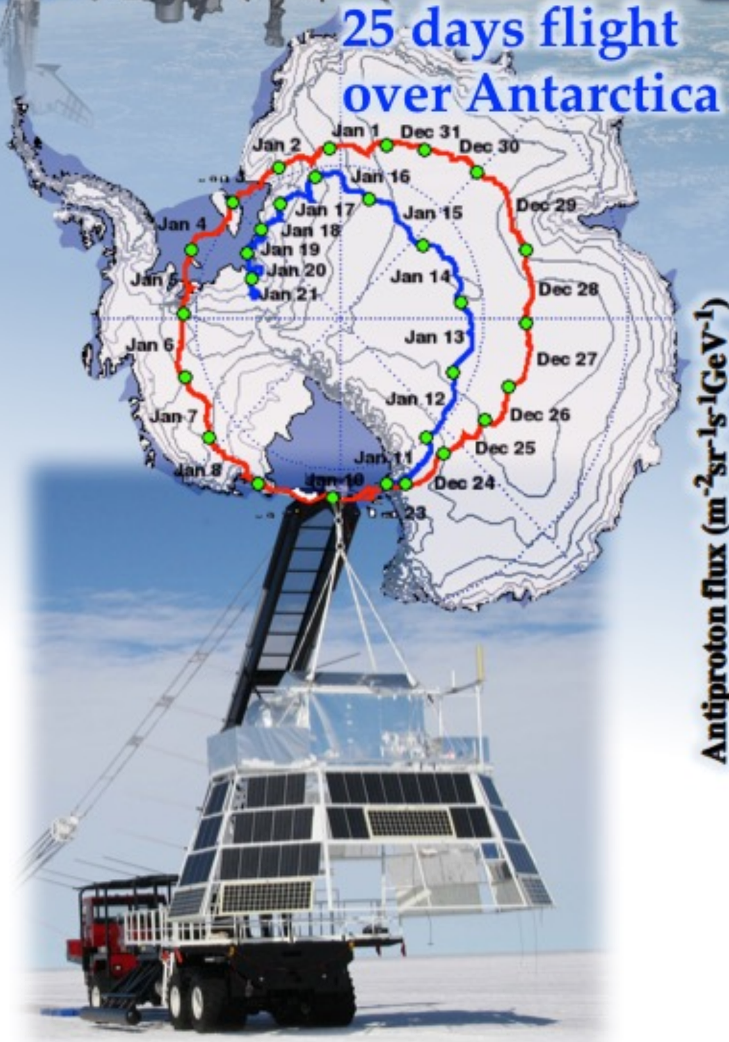
Dark Matter
$\chi\chi \rightarrow p\bar{p}...$

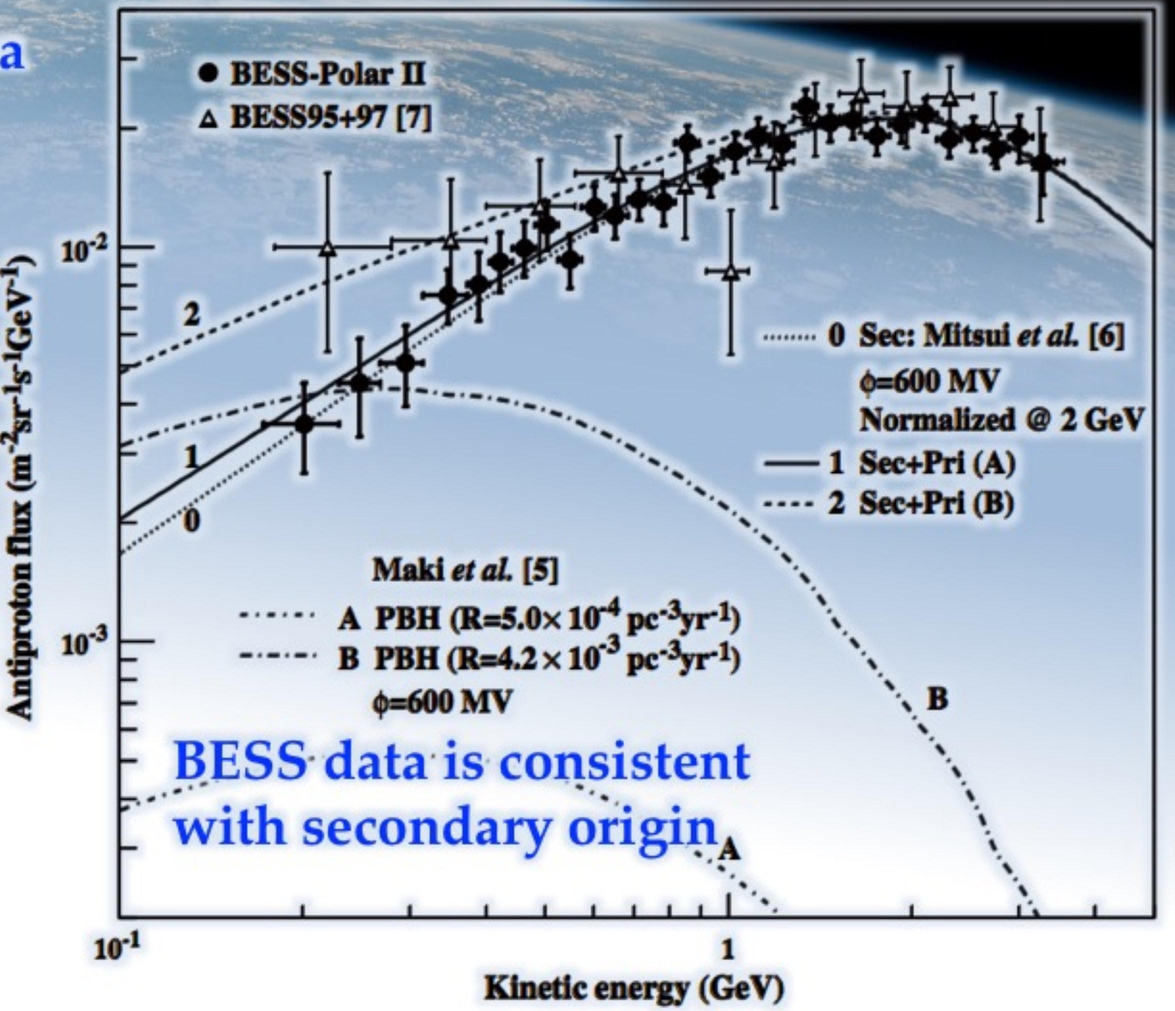
$PBH \rightarrow p, \bar{p}...$



BESS-Polar

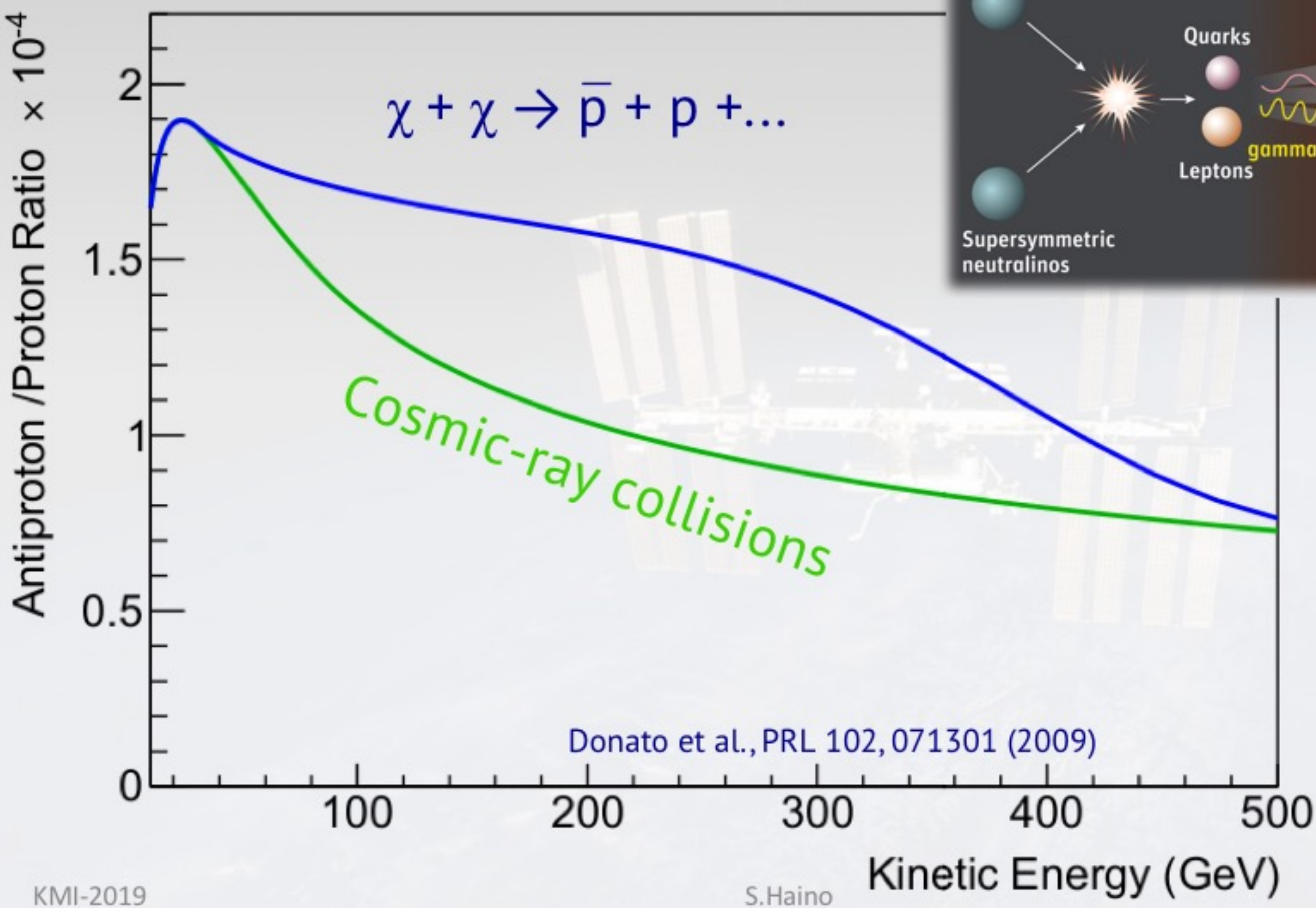
25 days flight over Antarctica

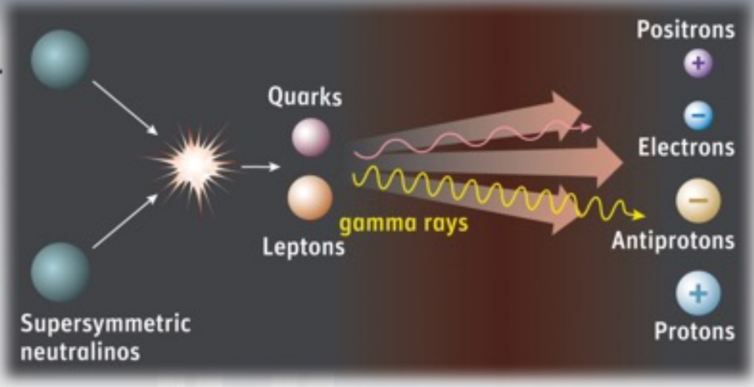




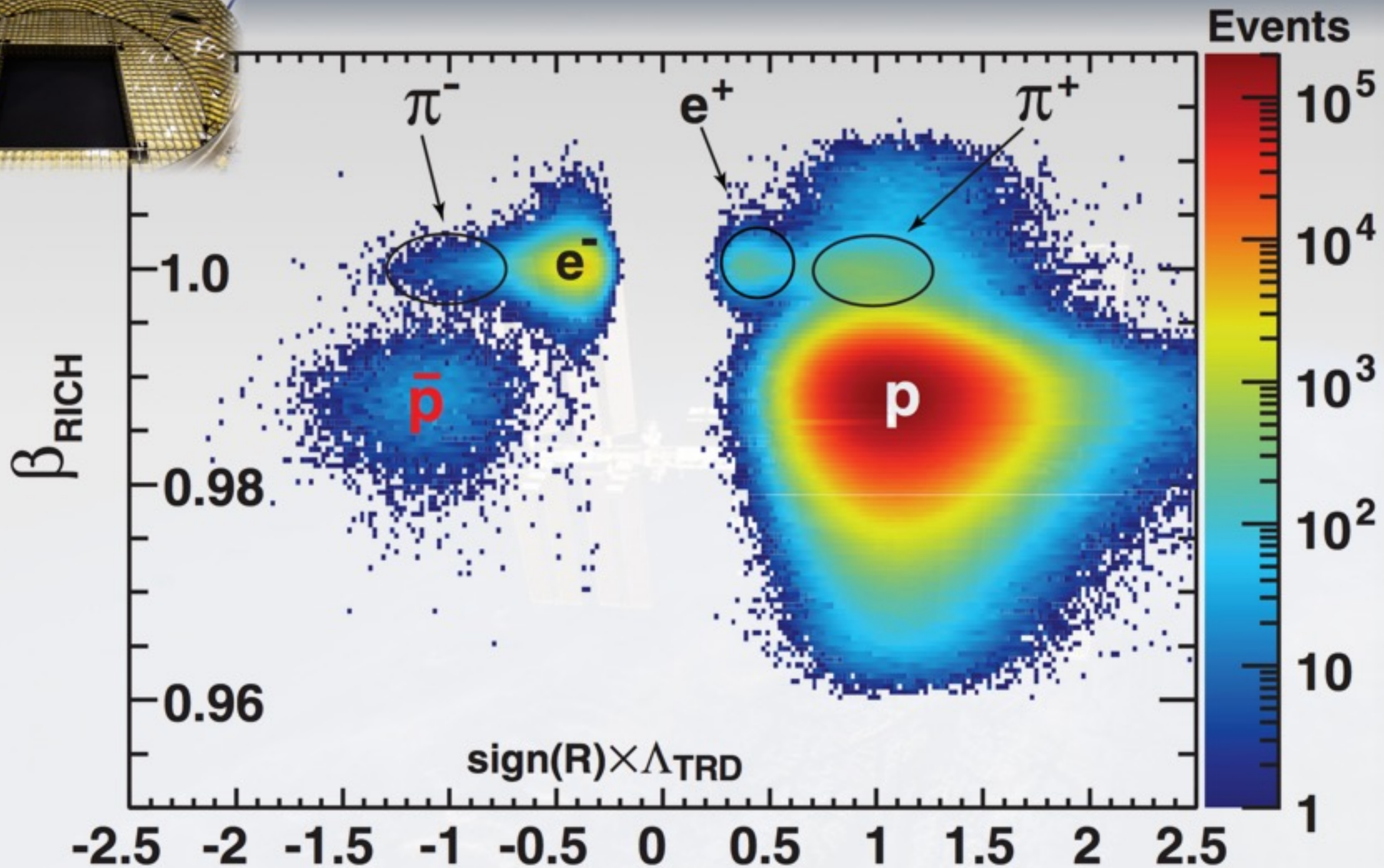
BESS data is consistent with secondary origin

Antiprotons : another DM probe

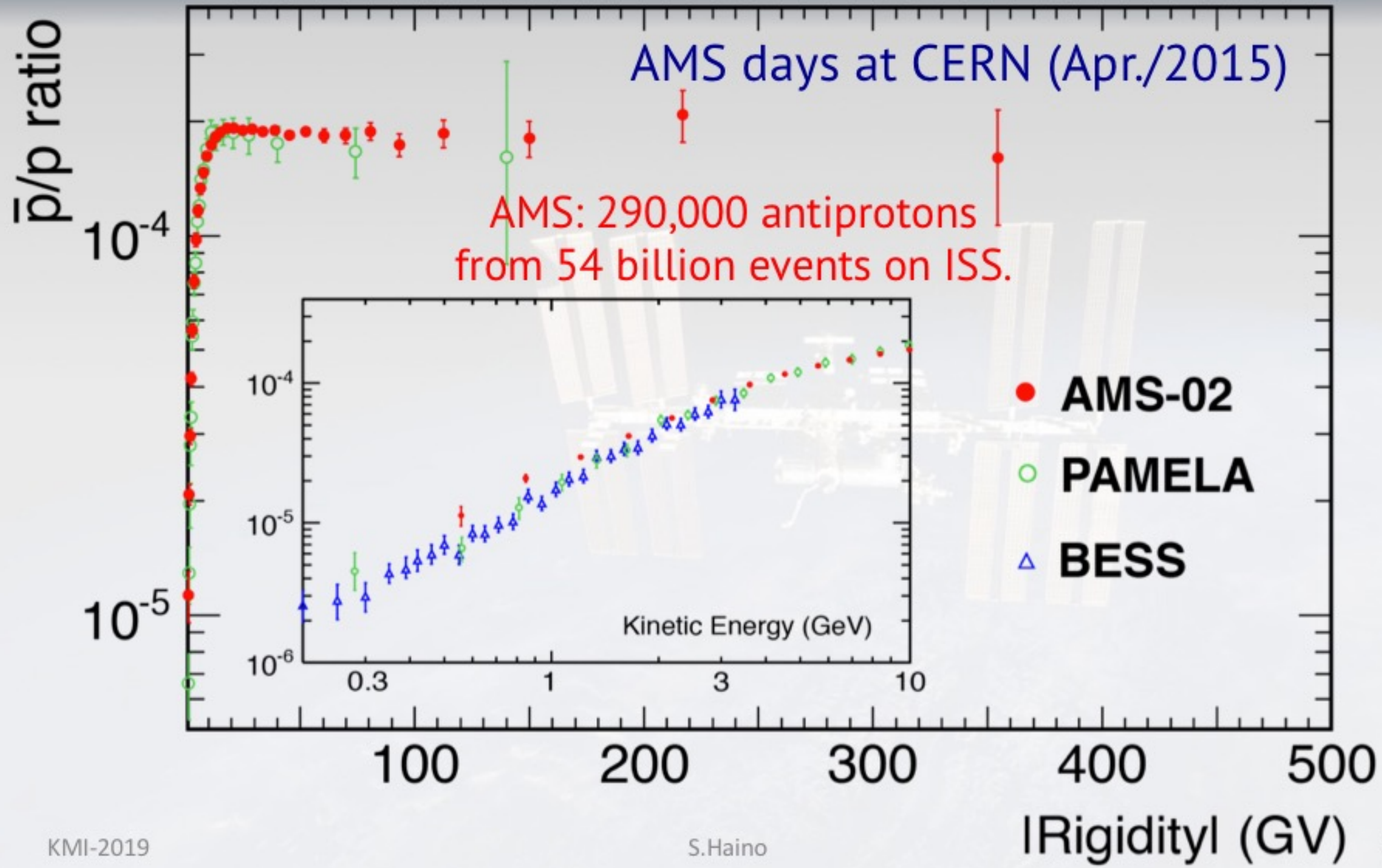




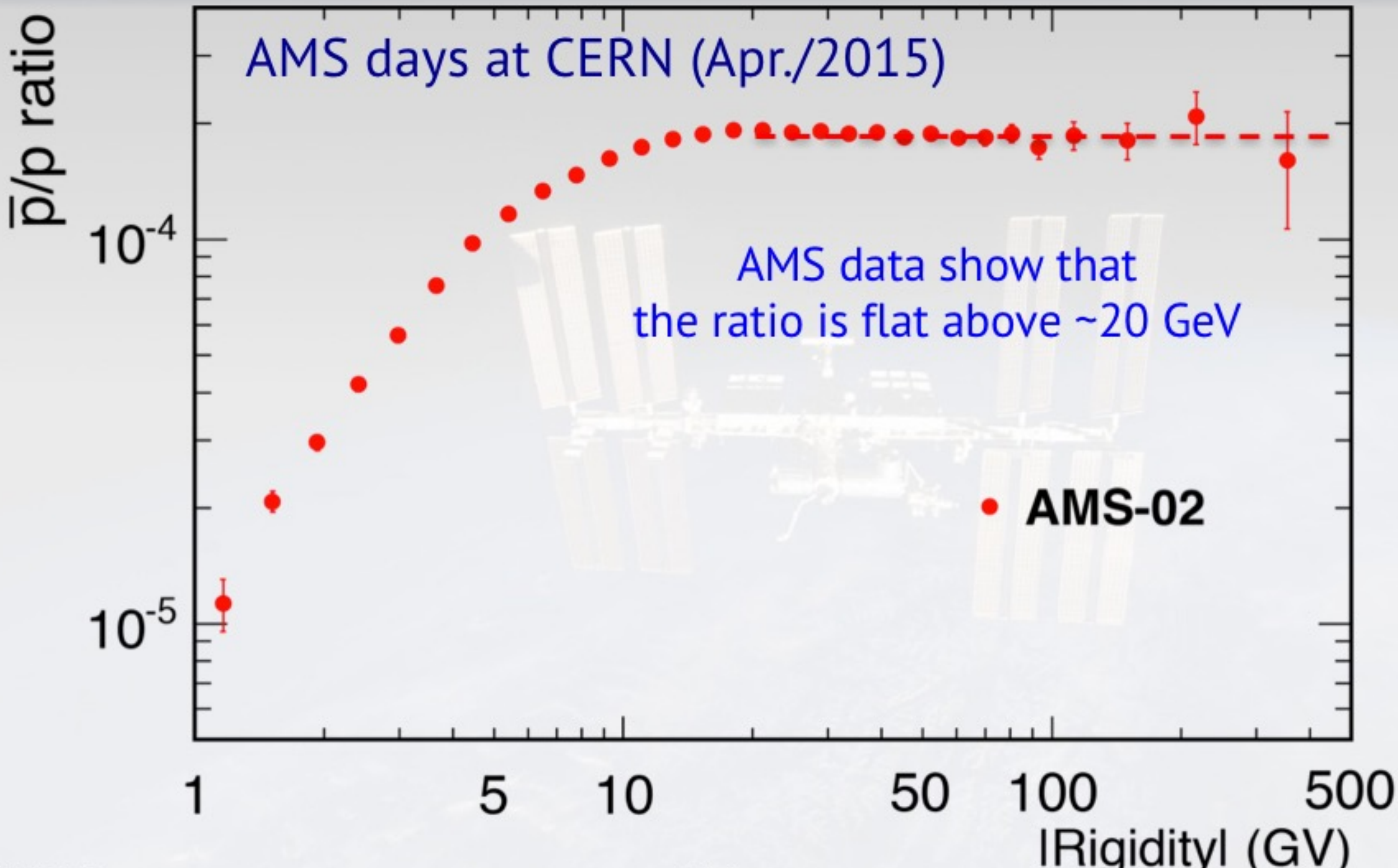
Anti-proton Identification in AMS



AMS Antiproton : current status



AMS Antiproton : current status

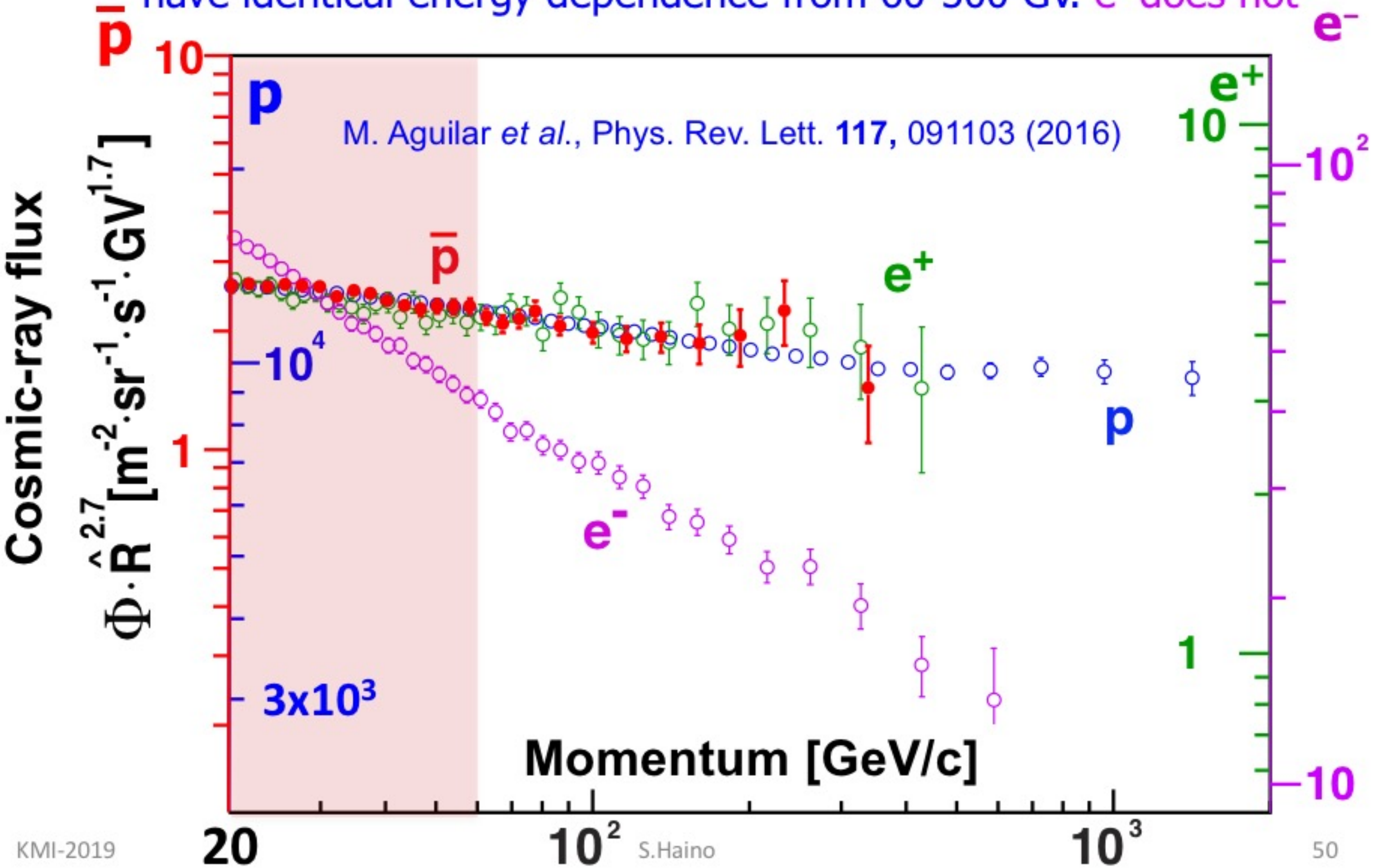


Antiprotons : history and future

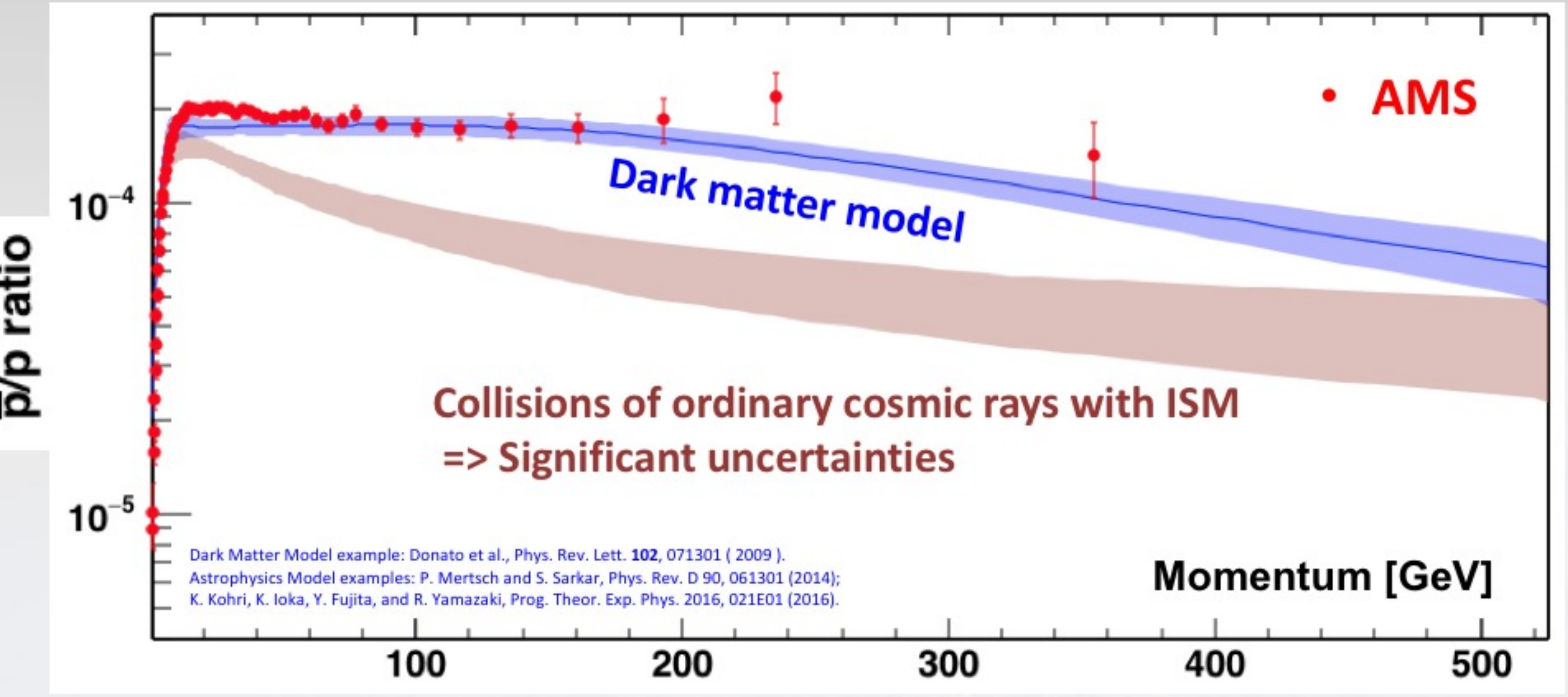
Project	BESS-93	BESS-97	BESS-Polar I	BESS-Poalr II	AMS (current)	AMS (expected)
Year	1993	1997	2004	2007	2011-2015	2011-2024
$N_{\bar{p}}$	4	415	1,520	7,886	~350,000	>1,000,000

The antiproton ($\bar{p}$) flux and properties of elementary particles (p, e^+, e^-) fluxes

Unexpected Result: The Spectra of Elementary Particles e^+, $\bar{p}$, p have identical energy dependence from 60-500 GV. e^- does not

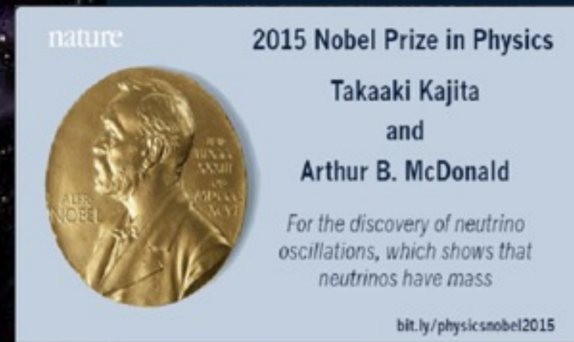


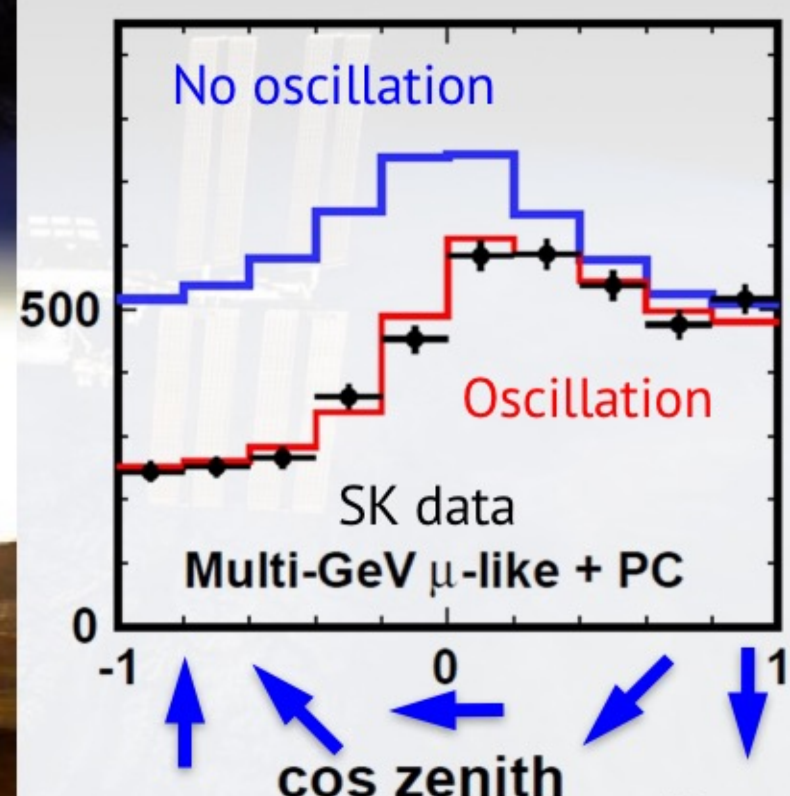
Antiprotons from Dark matter ?



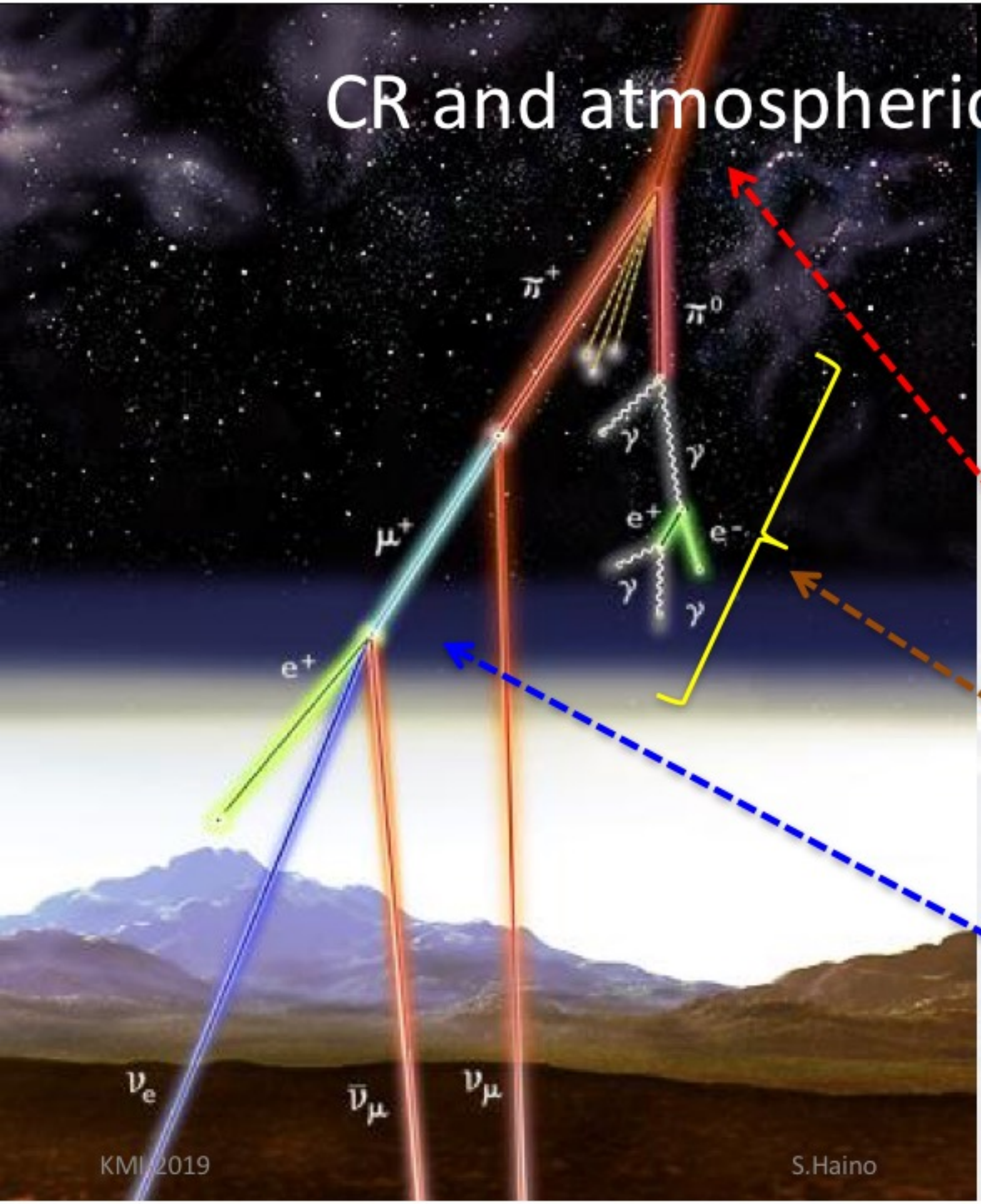
Cosmic-Ray Nuclei

CR and atmospheric neutrinos





CR and atmospheric neutrinos



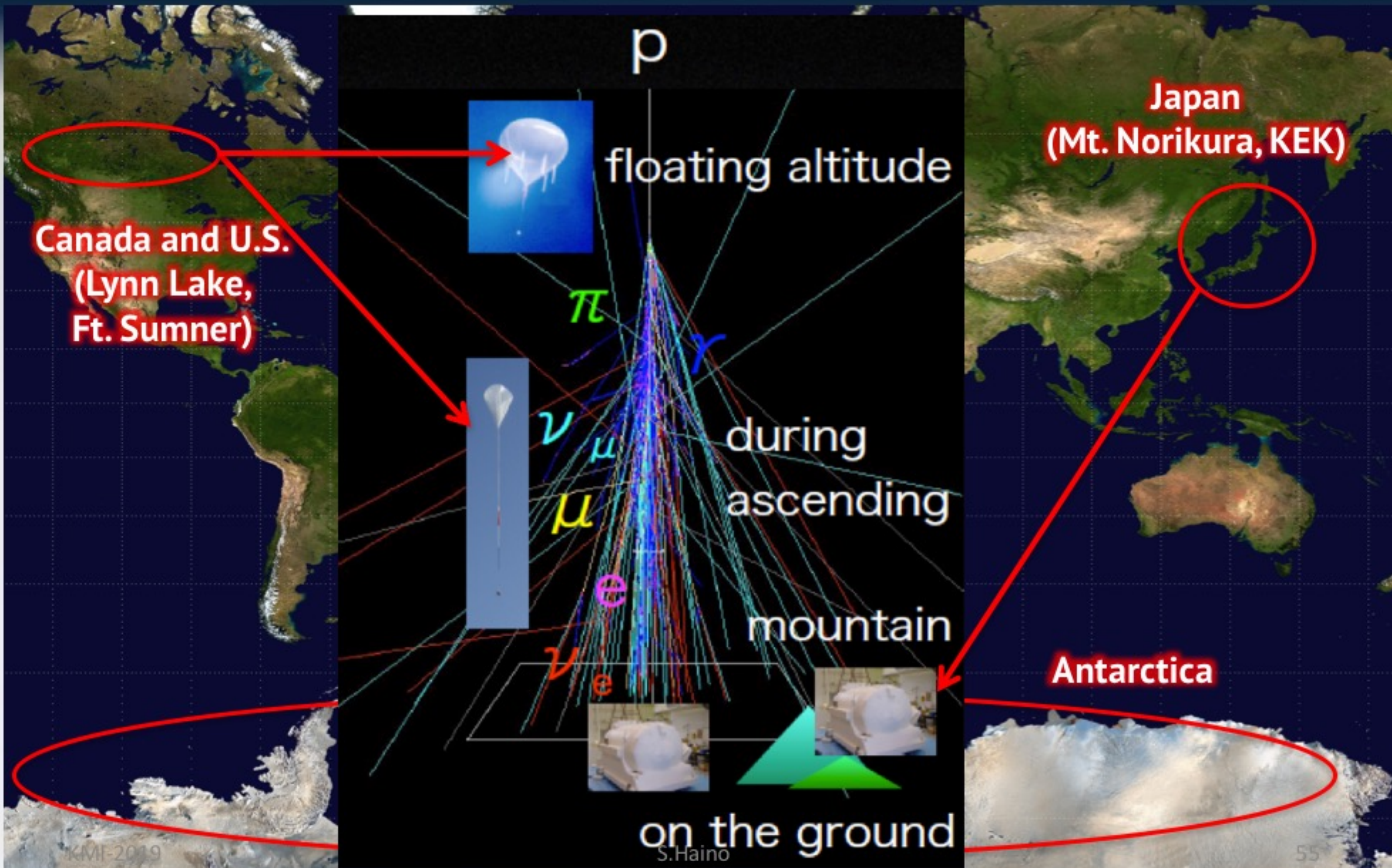
HKKMS model: Honda, Kajita, Kasahara, Midorikawa, Sanuki

Primary CR determined by direct measurements

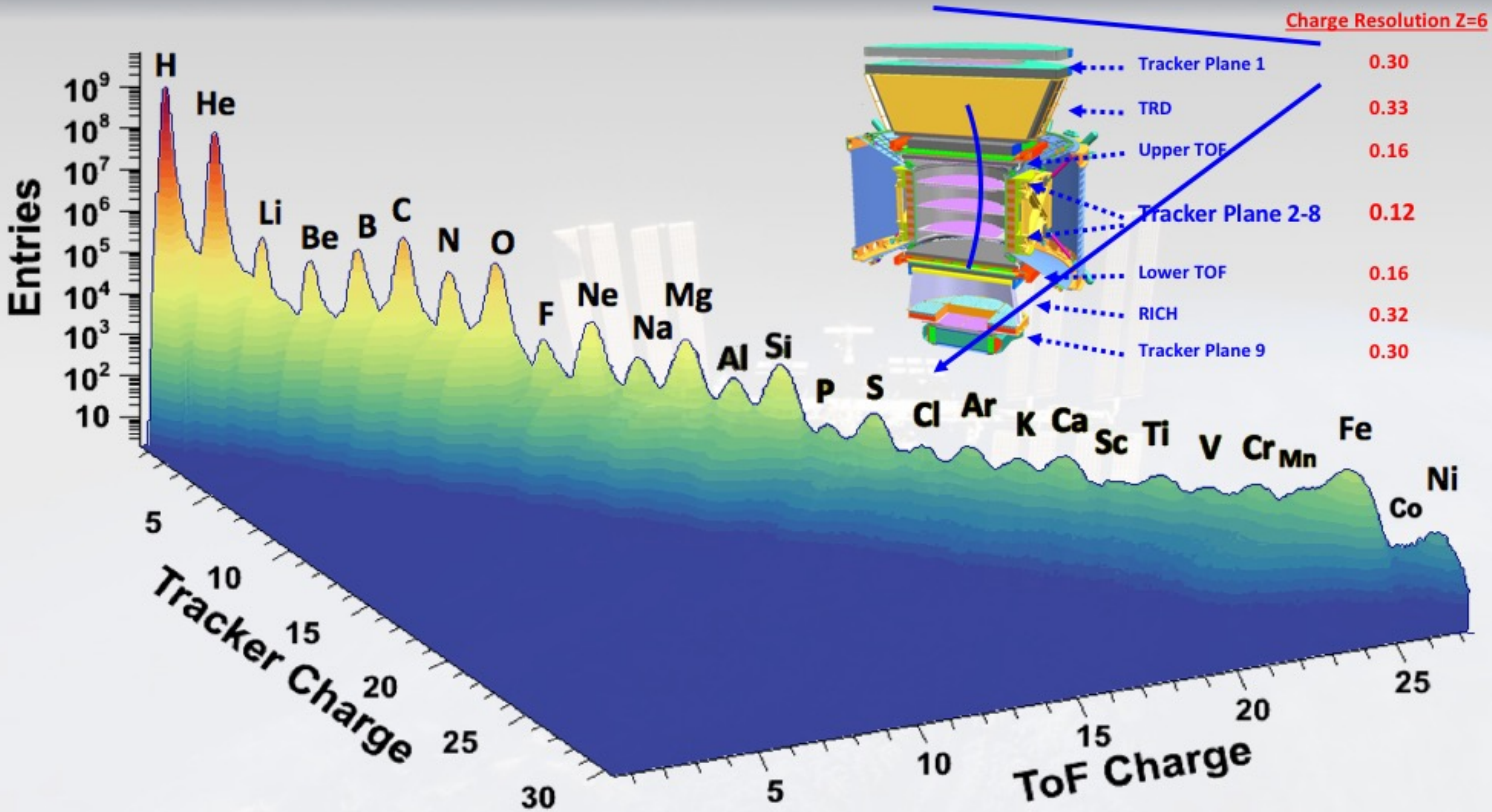
MC simulation (3D) of interactions/dedays in the atmosphere

Validation with muon flux measurements

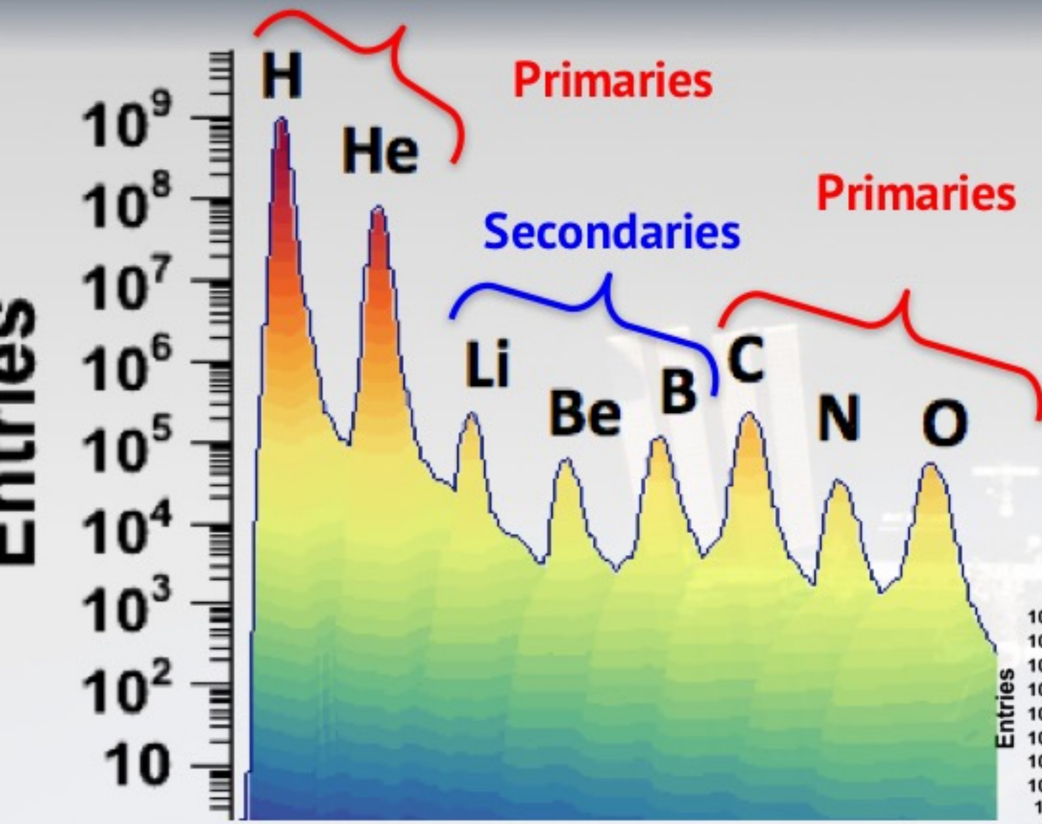
BESS is a “portable” detector

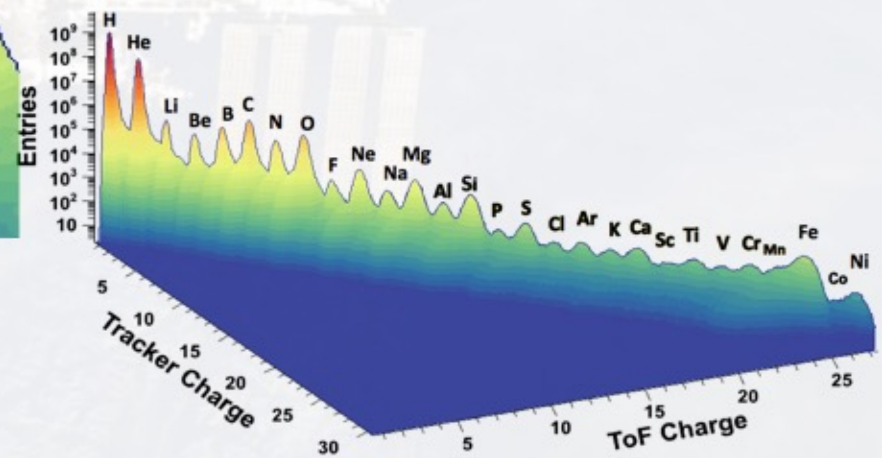


Nuclei identification in AMS



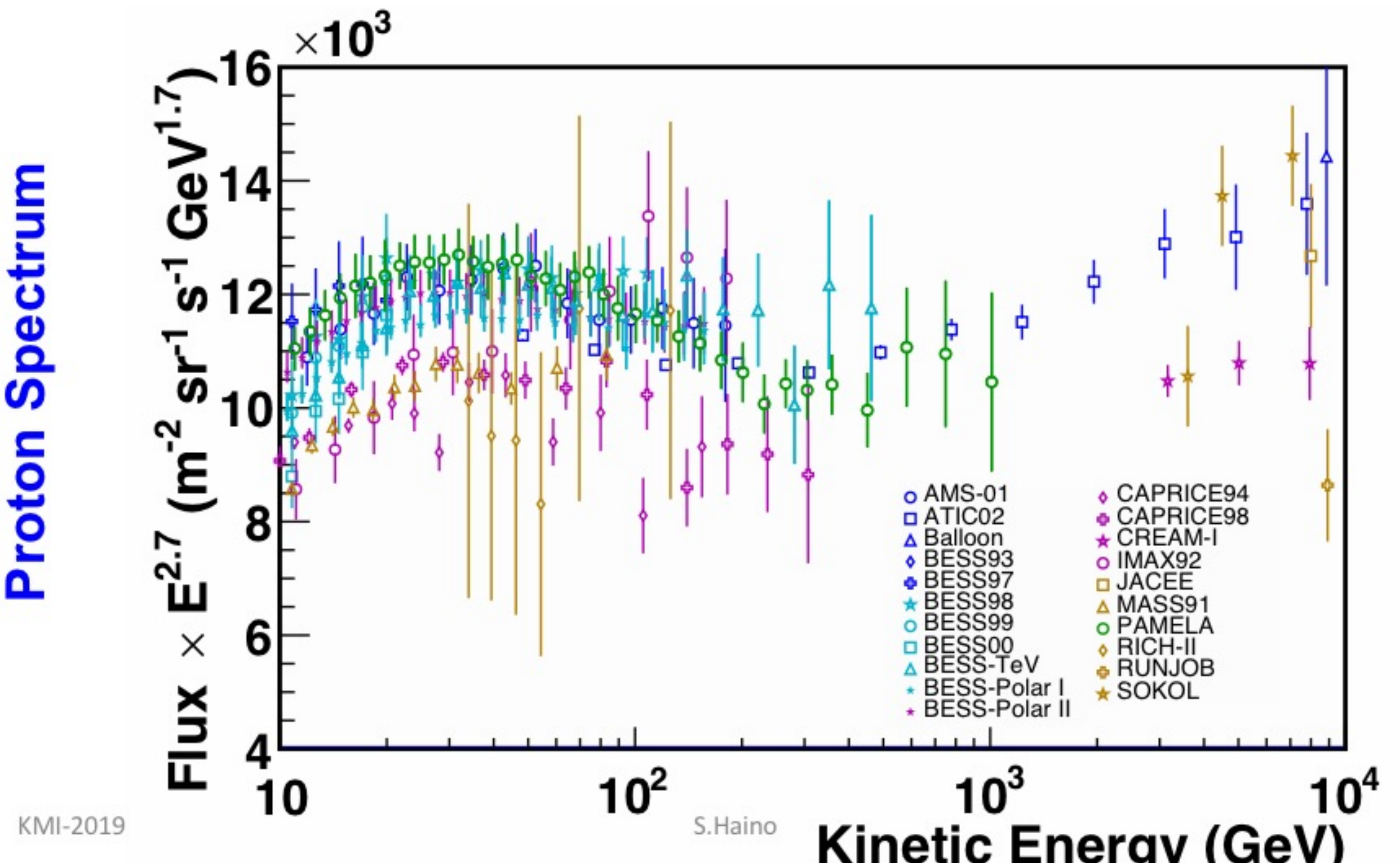
Primary and secondary CRs





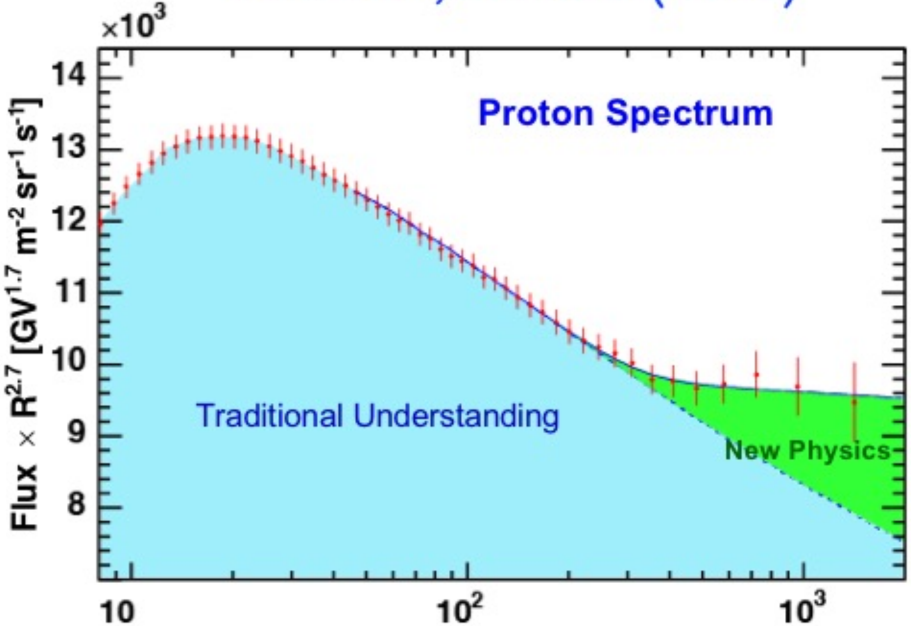
Cosmic Protons

1. Protons are the most abundant cosmic rays.
2. Before AMS there have been many measurements of the proton spectrum.
3. In cosmic rays models, the proton spectral function was assumed to be a single power law $\Phi = CE^{\gamma}$ with γ = -2.7

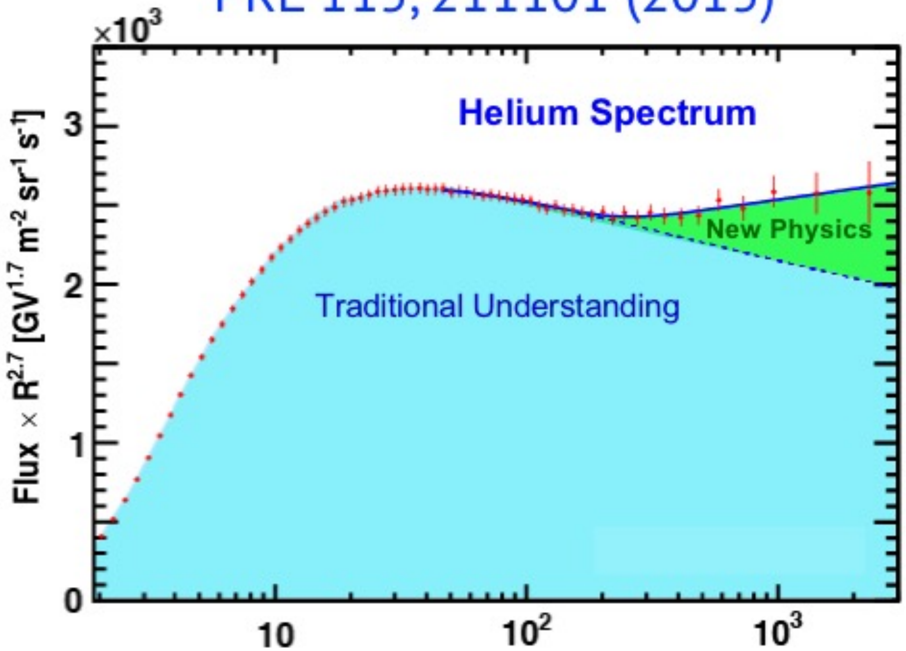


New Physics in p/He spectra

PRL 114, 171103 (2015)



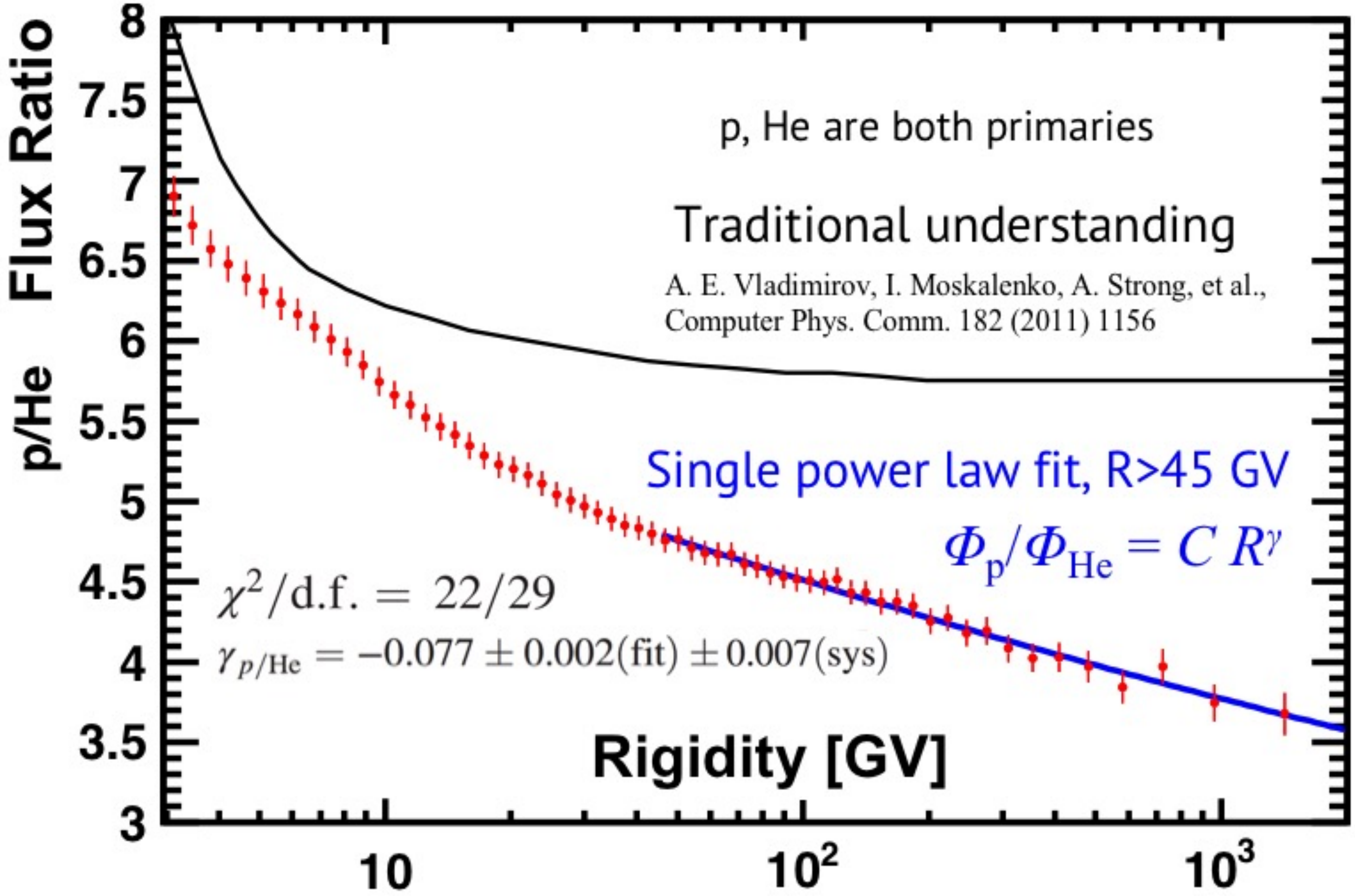
PRL 115, 211101 (2015)



Rigidity (GV)

The AMS results have changed the traditional understanding of proton and He spectra

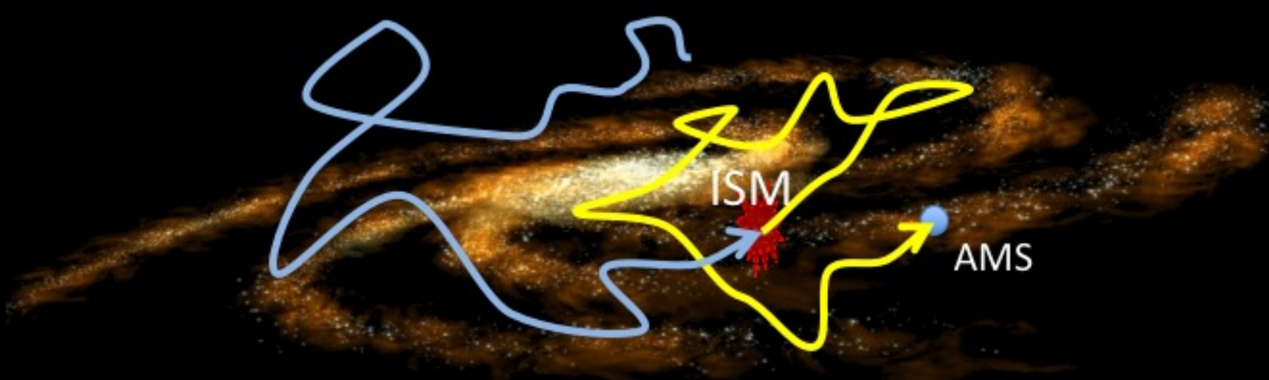
proton/He flux ratio



The AMS results have changed the traditional understanding of p,He spectra

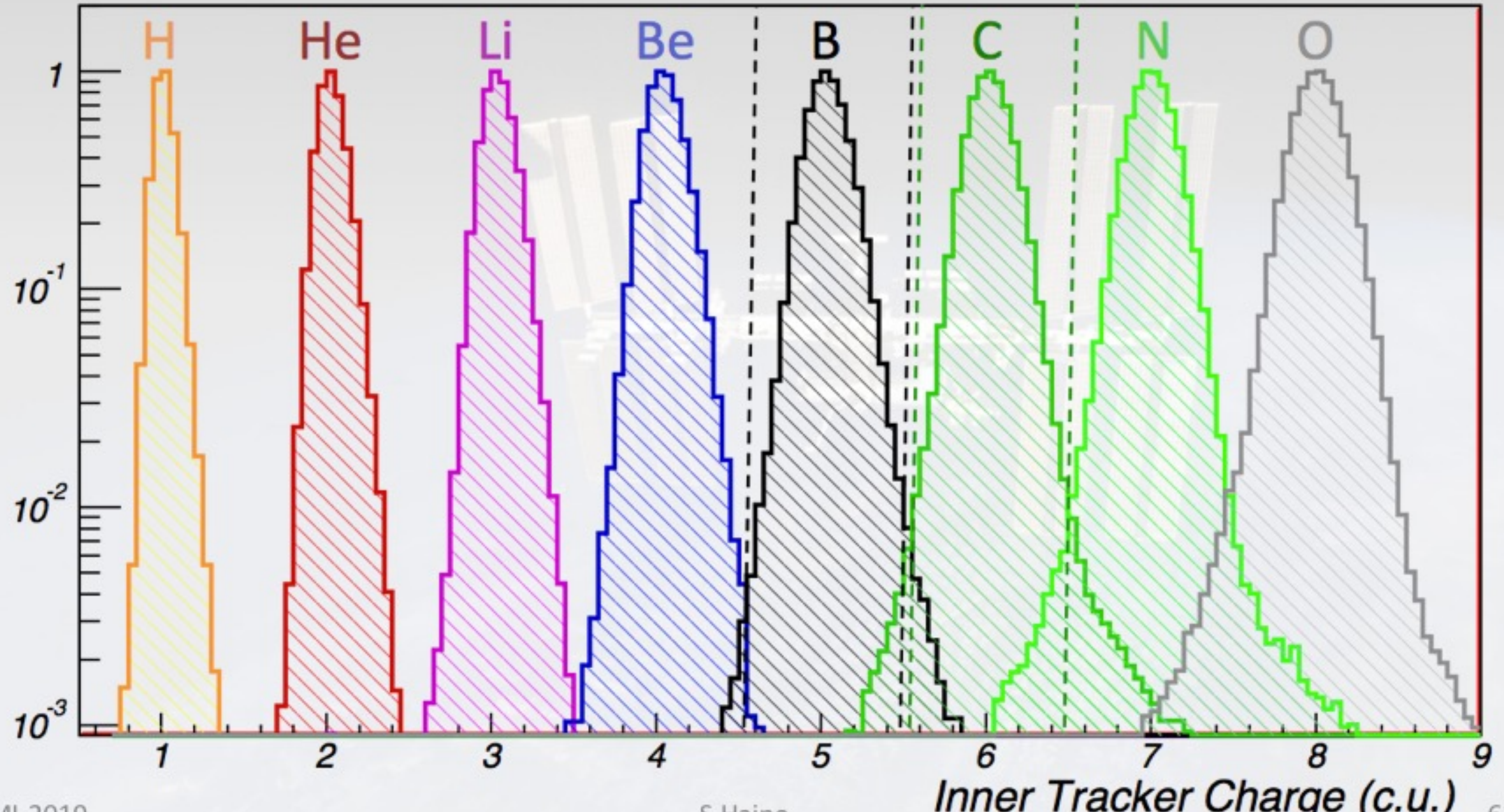
Primary Cosmic Rays (p, He, C, O, …)

Secondary Cosmic Rays (Li, Be, B, …)



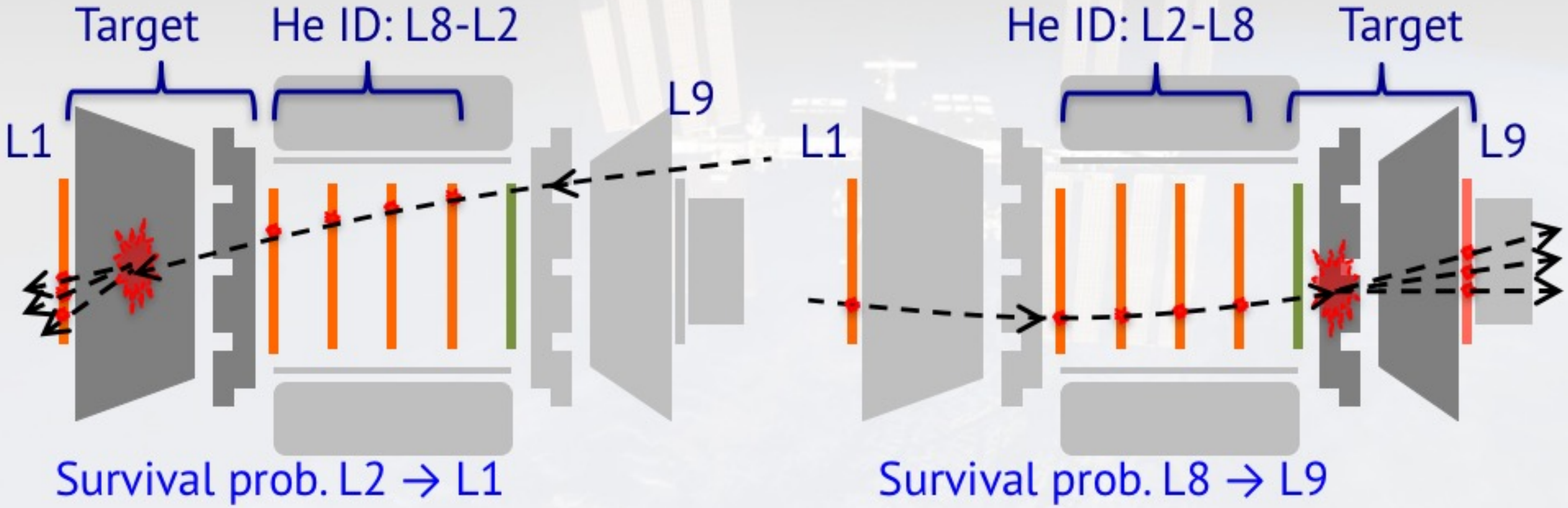
Charge separation by AMS

Misidentification < 0.1 % with > 98 % efficiency



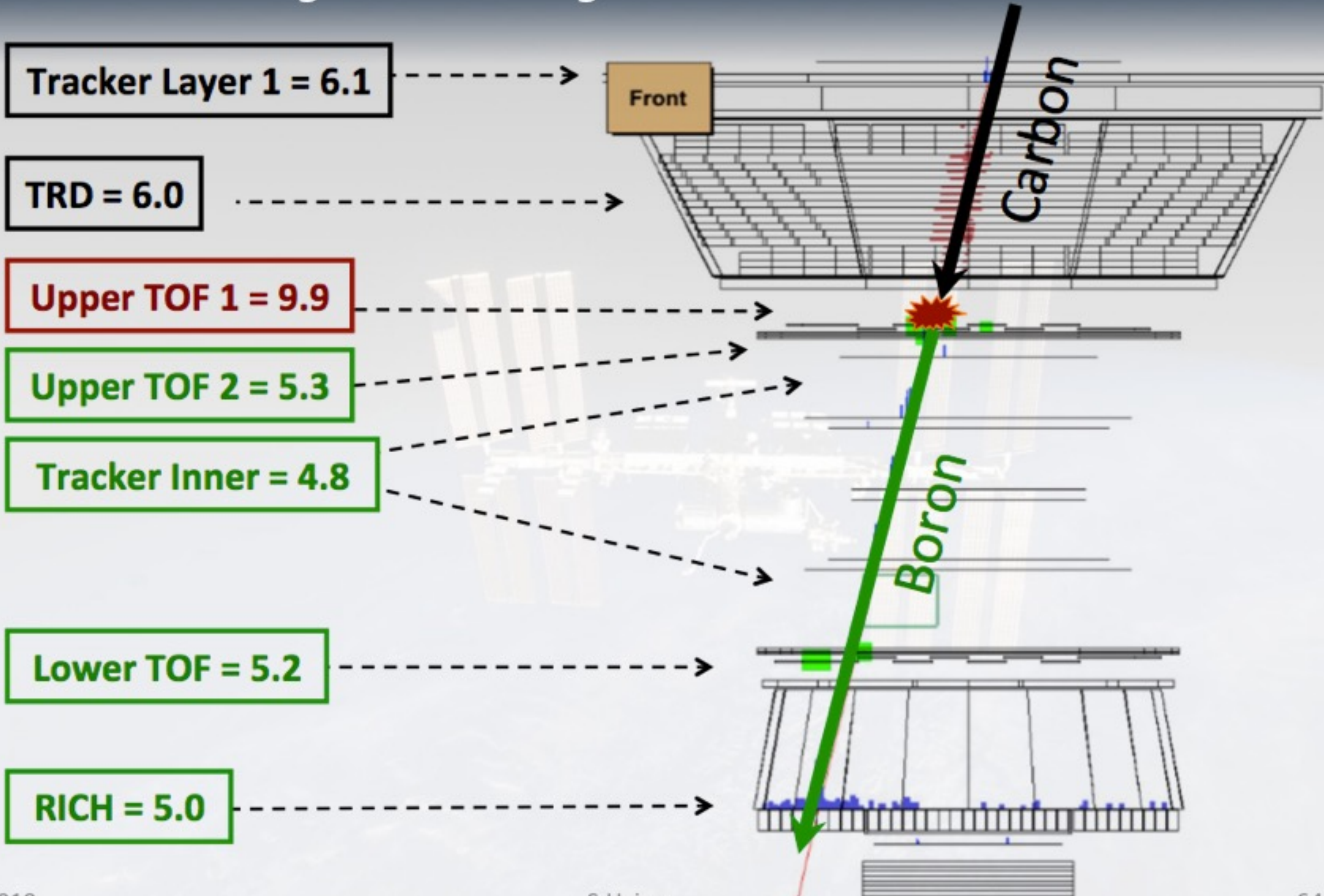
He survival probability measurement

Direct determination with ISS data where AMS is pointing horizontal direction: 2 days in total (from 4 years on ISS)



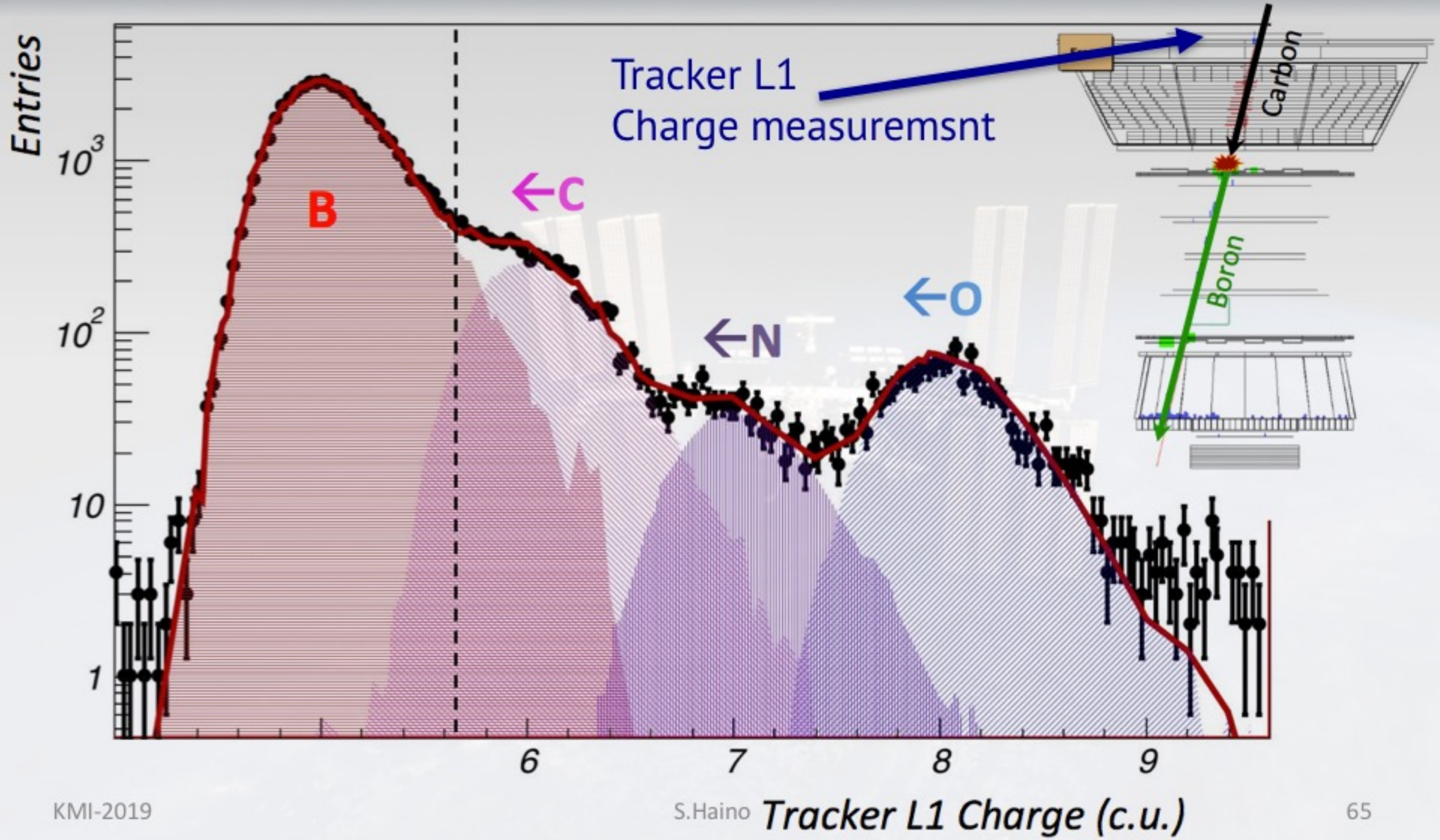
B/C sample purity control

The main backgrounds: Fragmentation events in the detector

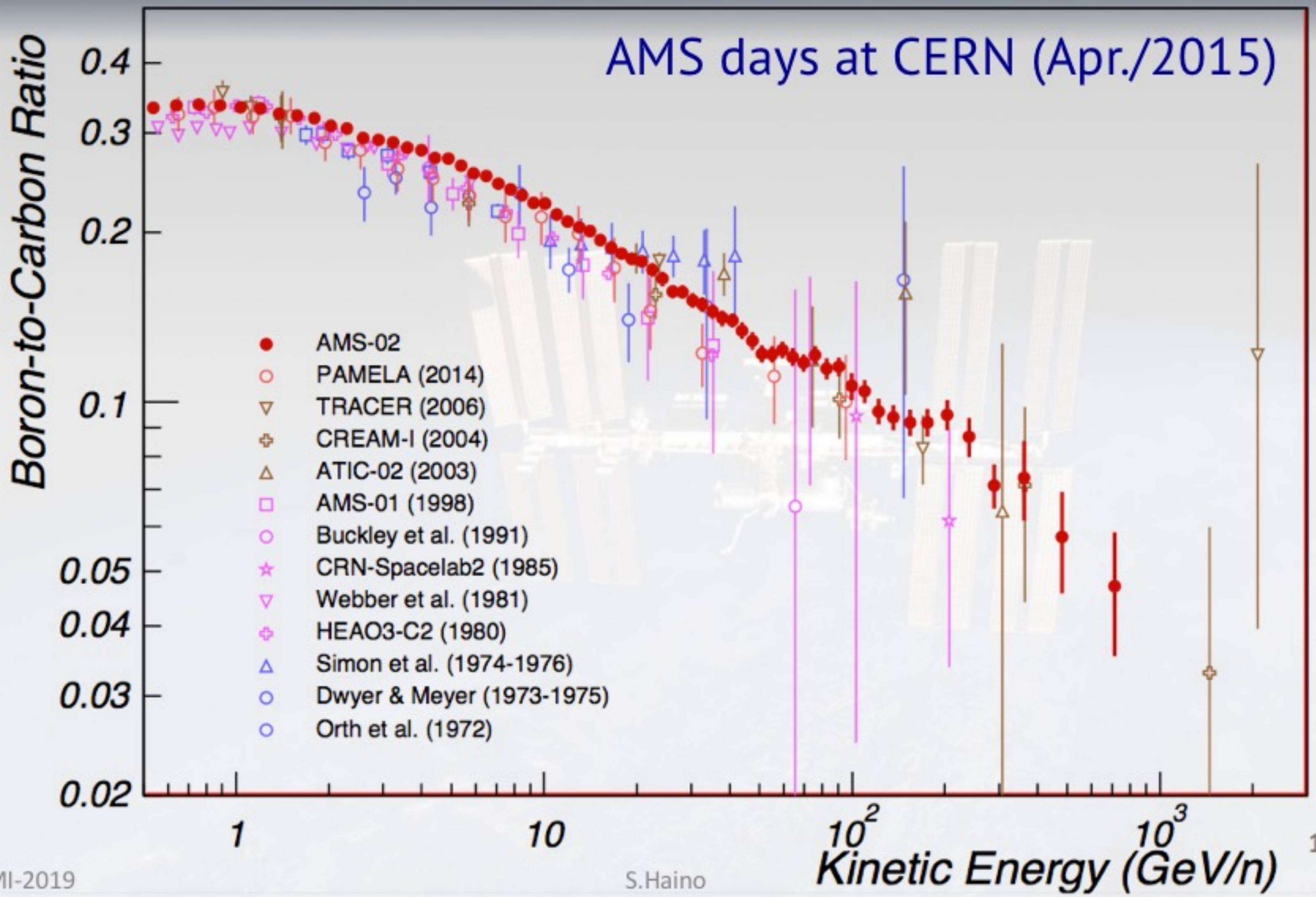


B/C sample purity control

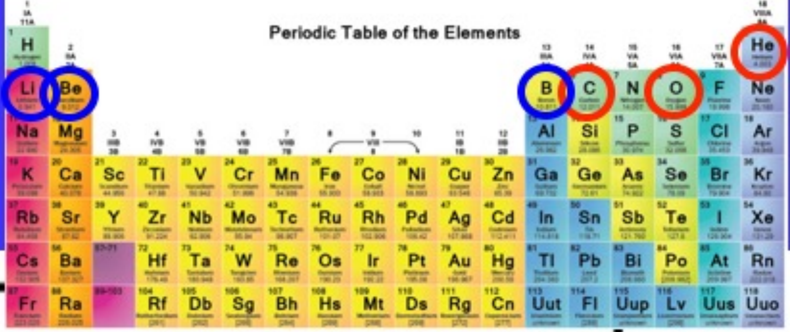
The main backgrounds: Fragmentation events in the detector

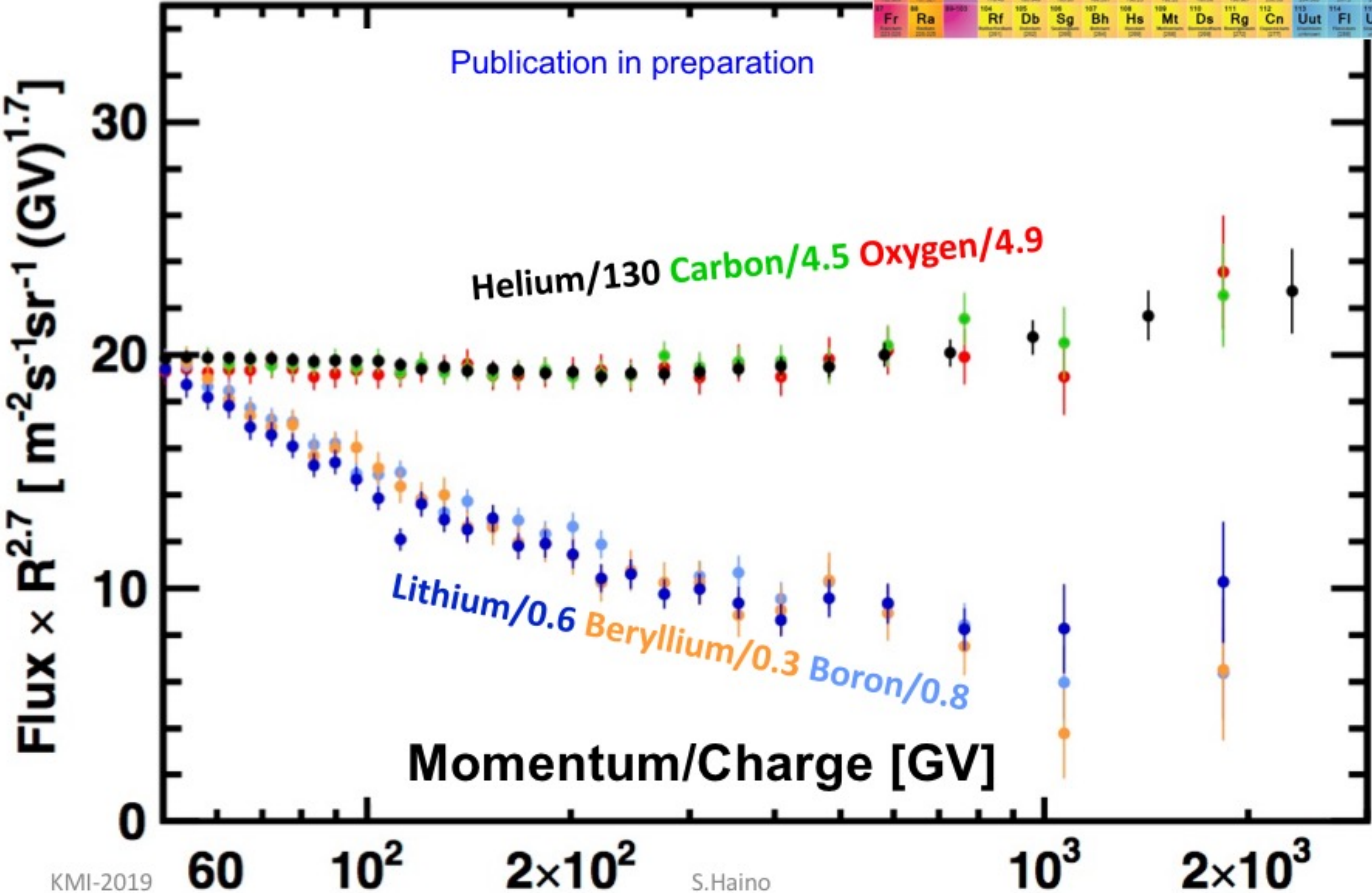


B/C by AMS with other measurements

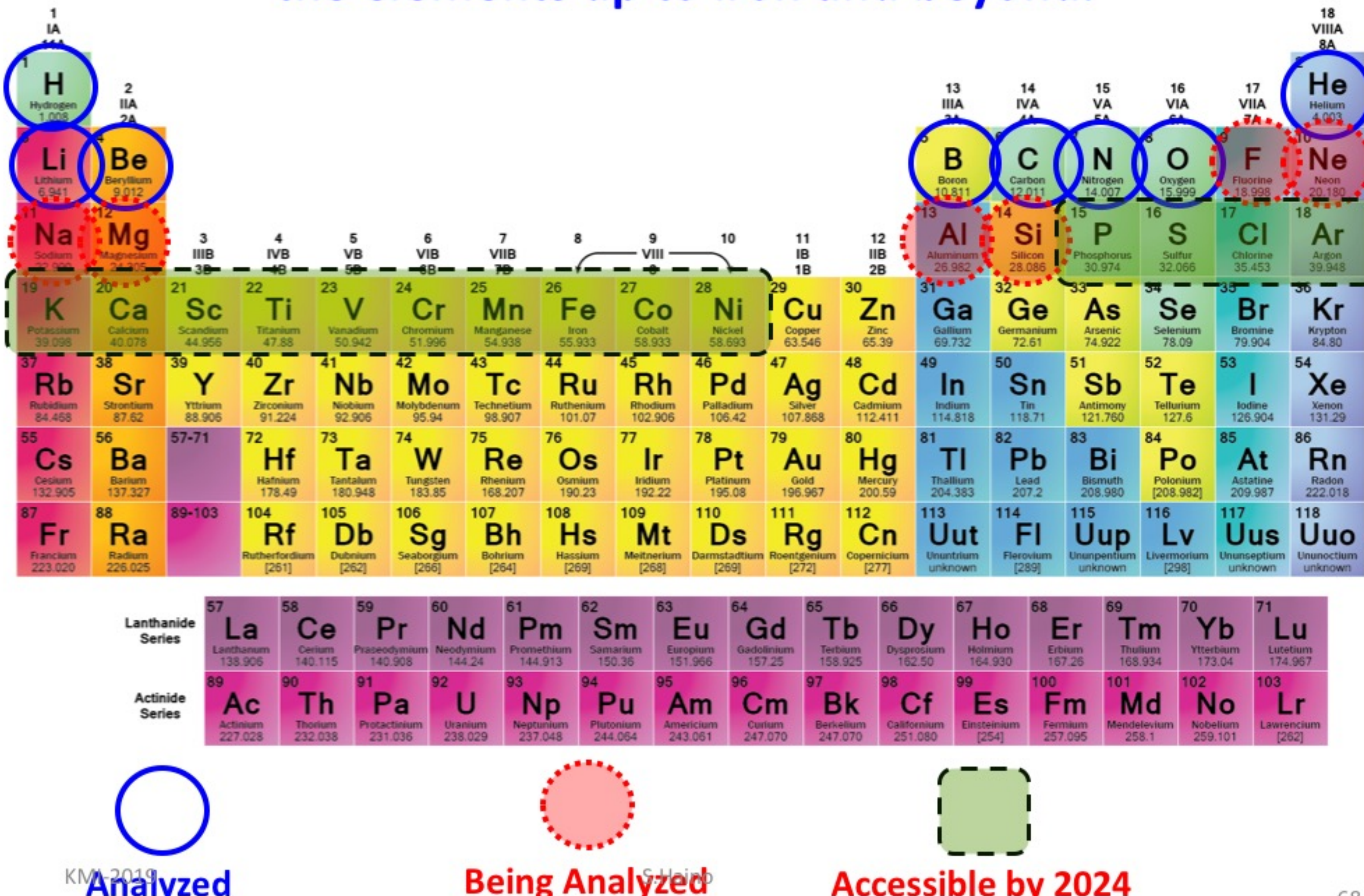


AMS New Physics Result :
"Secondary" cosmic rays have a different energy dependence than "primary"





With increasing statistics through 2024, we will measure the elements up to iron and beyond.



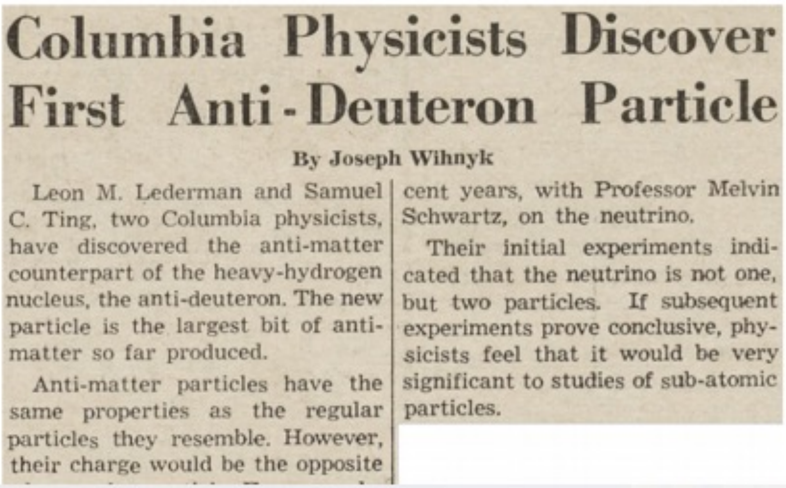
Cosmic-Ray Anti-Deuterons

Antideuteron discovery

COLUMBIA DAILY SPECTATOR

FOUNDED 1877

Vol. CIX—No. 85 NEW YORK, N.Y., THURSDAY, MARCH 11, 1965 401 FIVE CENTS



Columbia Physicists Discover First Anti-Deuteron Particle

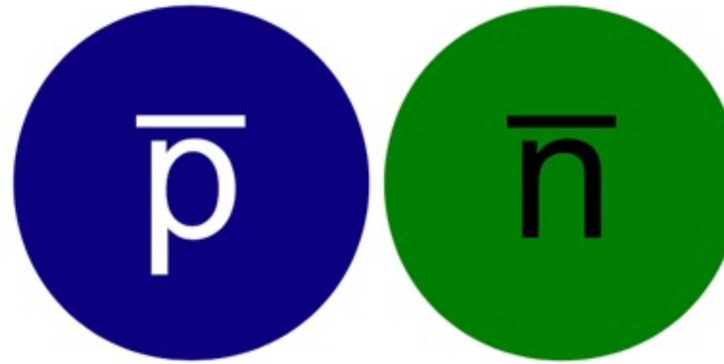
By Joseph Wihnyk

Leon M. Lederman and Samuel C. Ting, two Columbia physicists, have discovered the anti-matter counterpart of the heavy-hydrogen nucleus, the anti-deuteron. The new particle is the largest bit of anti-matter so far produced.

Anti-matter particles have the same properties as the regular particles they resemble. However, their charge would be the opposite

cent years, with Professor Melvin Schwartz, on the neutrino.

Their initial experiments indicated that the neutrino is not one, but two particles. If subsequent experiments prove conclusive, physicists feel that it would be very significant to studies of sub-atomic particles.

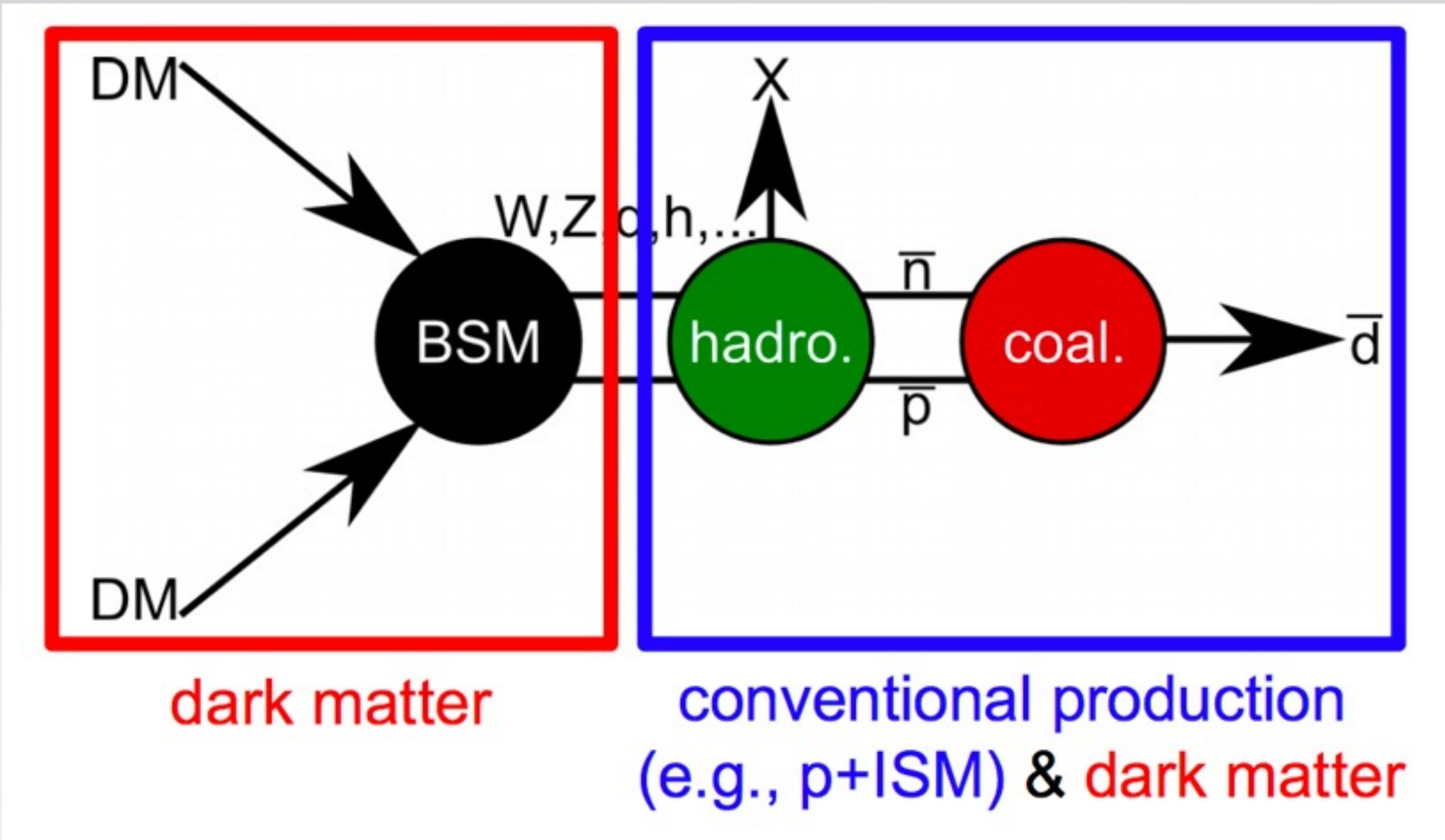


Discovered in 1965 at Brookhaven

by L.M.Lederman, S.C.C.Ting

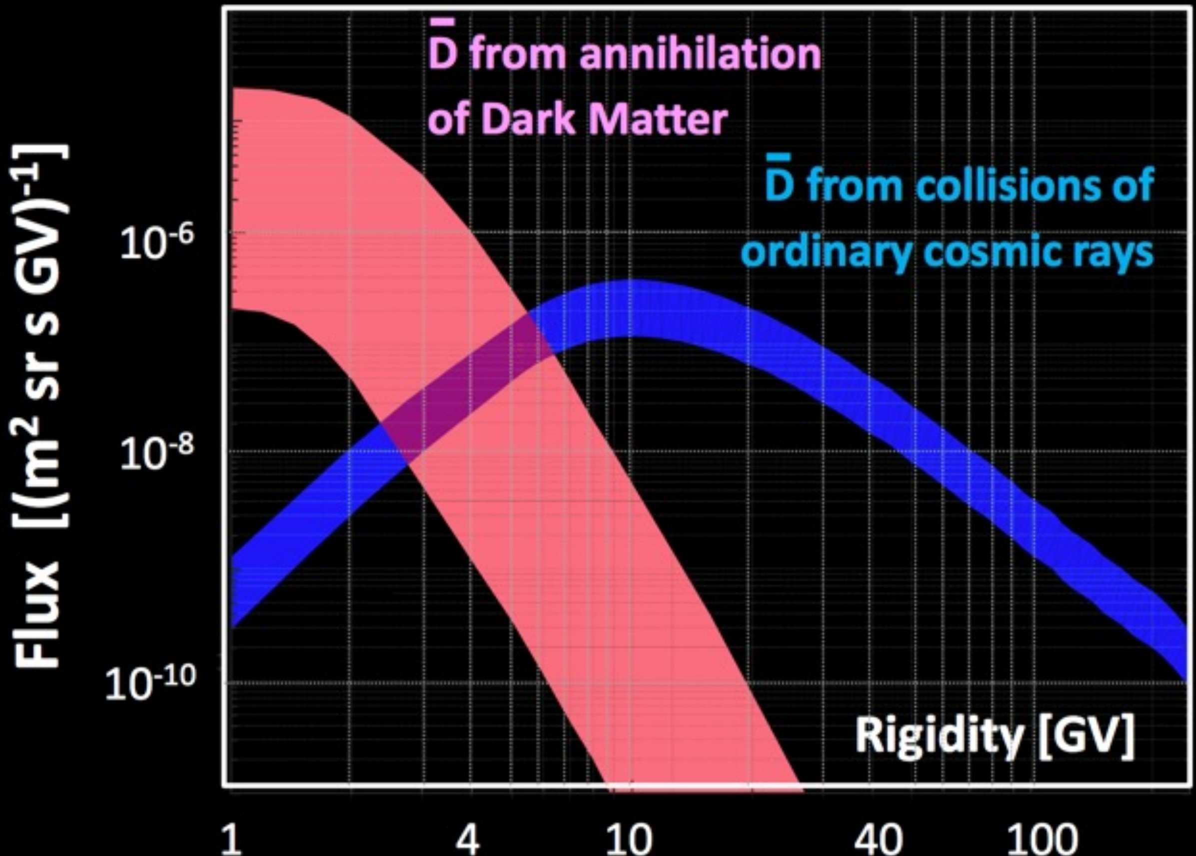
The first bound antimatter ever discovered

Possible Anti-D production from DM



Anti Deuterons in Cosmic rays

Anti Deuterons have been proposed as an almost background free channel for Dark Matter indirect detection



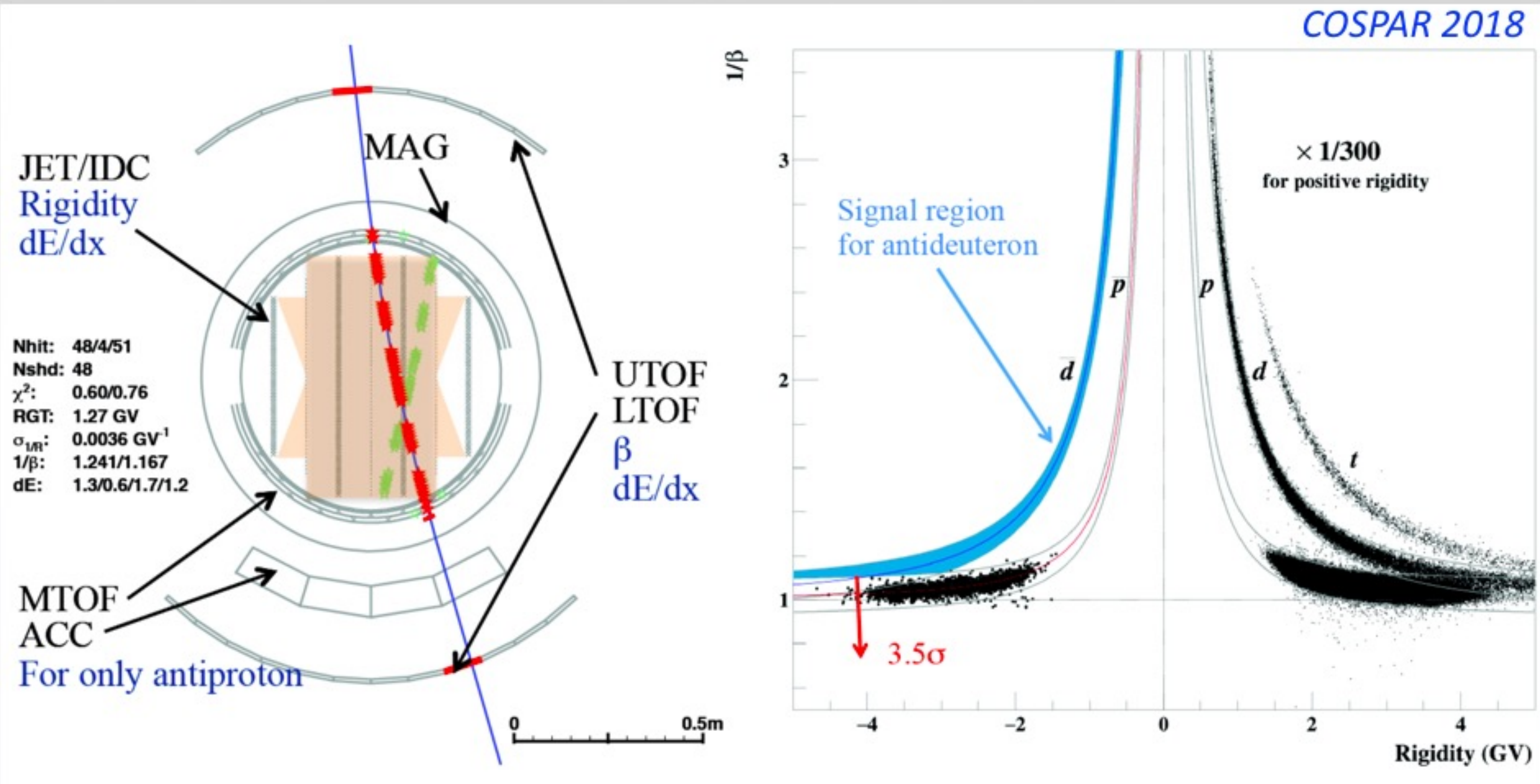
■ Dark Matter model:
F. Donato et al., Phys. Rev. D, 62 (2000) 043003

■ Collisions of CR model
K. Blum et al., Phys. Rev. D 96 (2017) 103021)

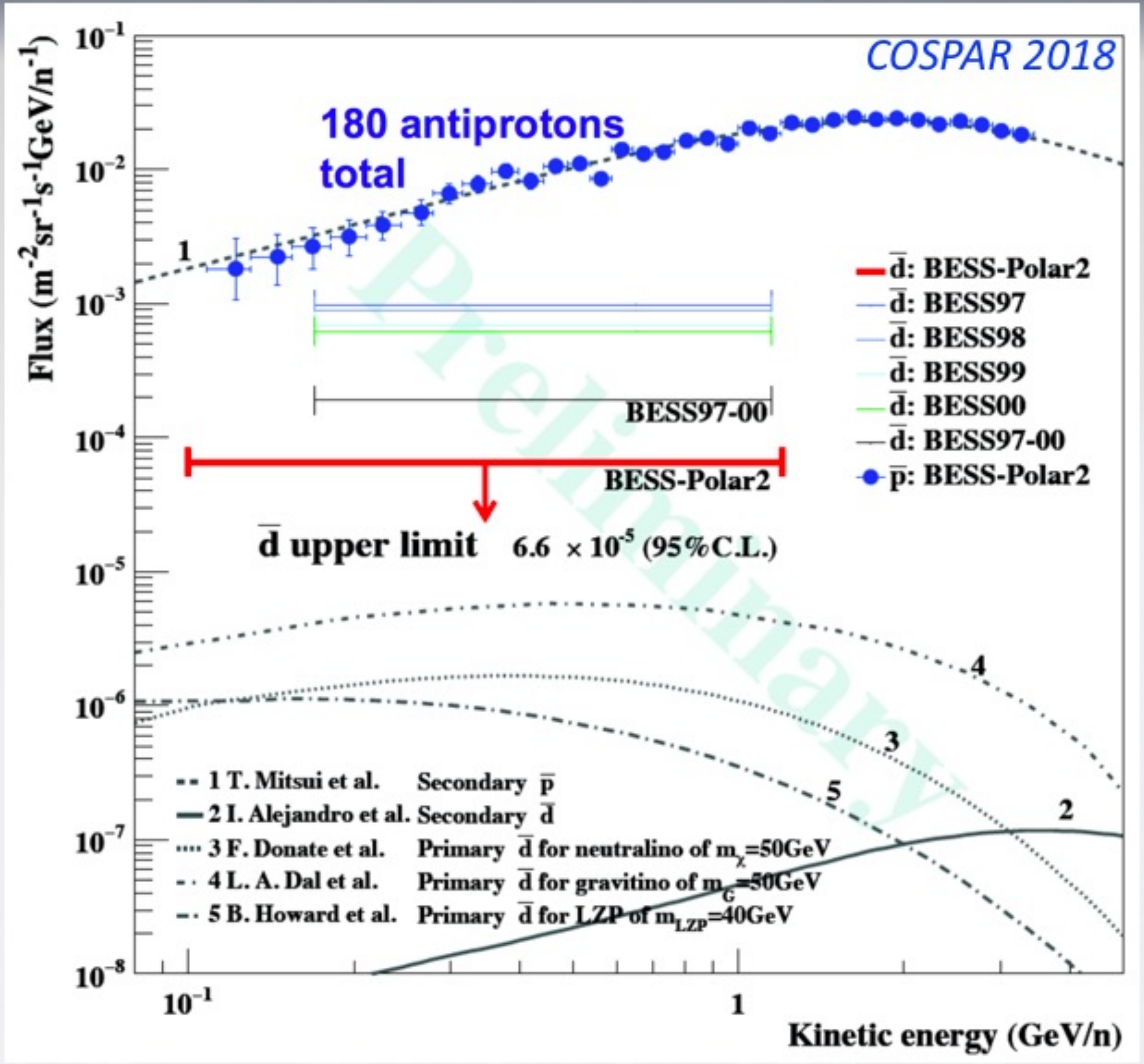
The Anti Deuterons Flux is $< 10^{-4}$ of the Antiproton Flux.

Additional background rejection

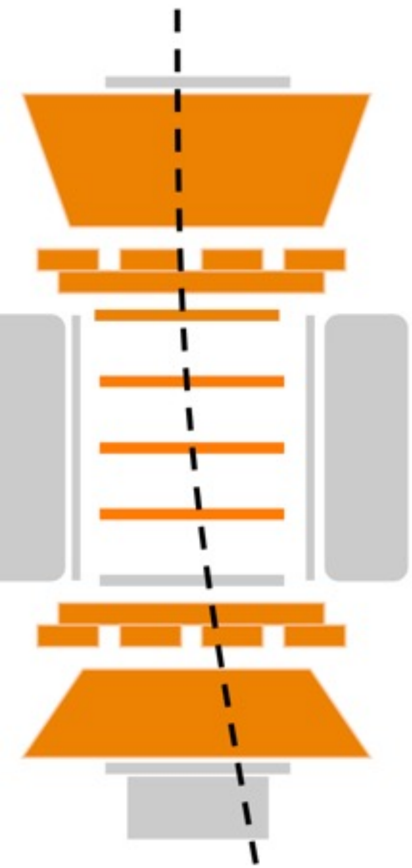
Anti-Deuteron searches by BESS



Anti-Deuteron searches by BESS



Anti-D searches in AMS



TRD → Elimination of interacting He background,
Elimination of the e^- background.

$$M/Z = R\frac{\sqrt{1-\beta^2}}{\beta}$$

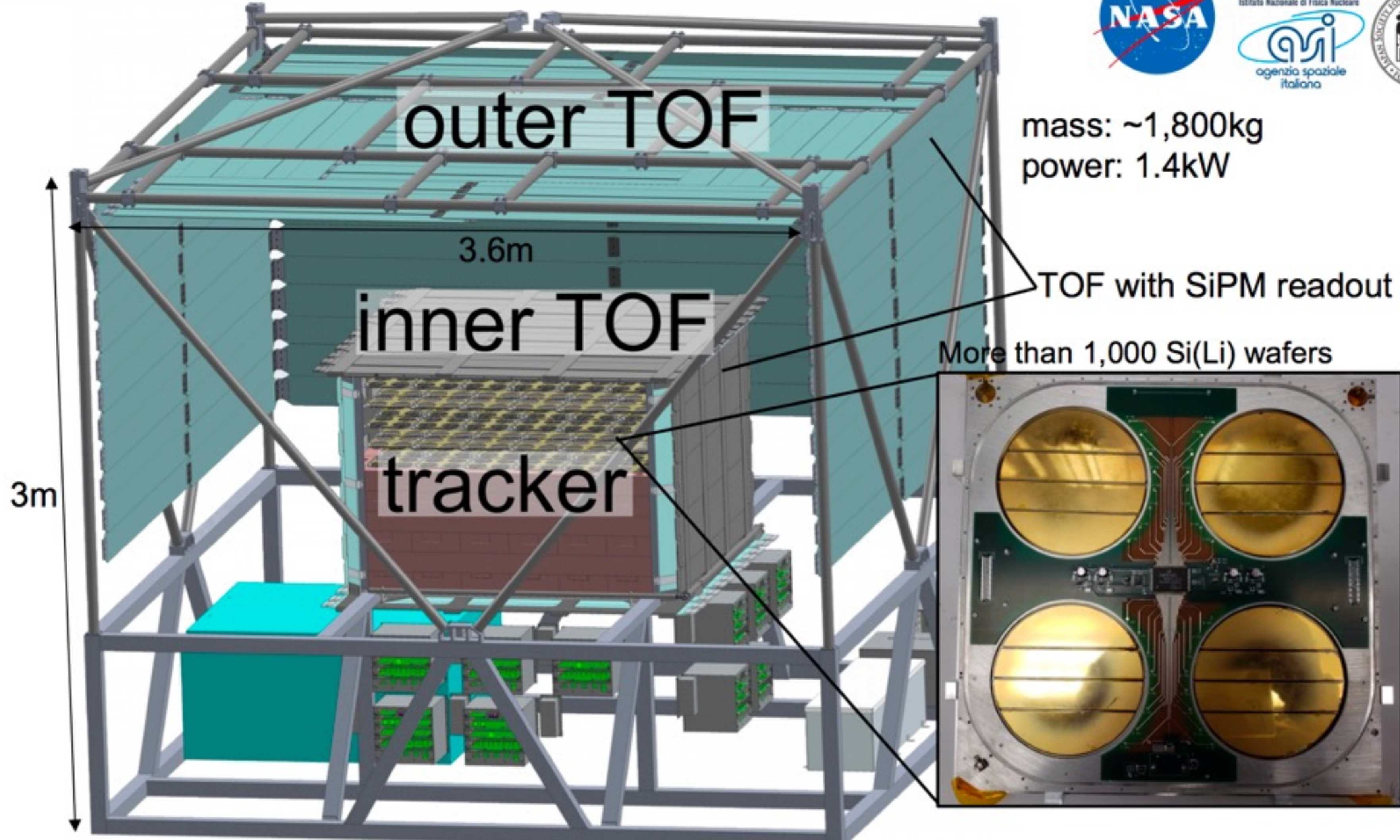
Inner Tracker → Rigidity (~ 10% up to 20 GV),
Particle sign +/-
Z = 1

TOF → Velocity ($\Delta\beta$ = 4% at β = 1 and Z =1),
Z = 1

RICH NaF → Veocity ($\Delta\beta$ = 0.4% at β = 1 and Z = 1, β_{thr} ~ 0.75)
RICH Aerogel → Velocity ($\Delta\beta$ = 0.1% at β =1 and Z = 1, β_{thr} ~ 0.96)

The GAPS experiment

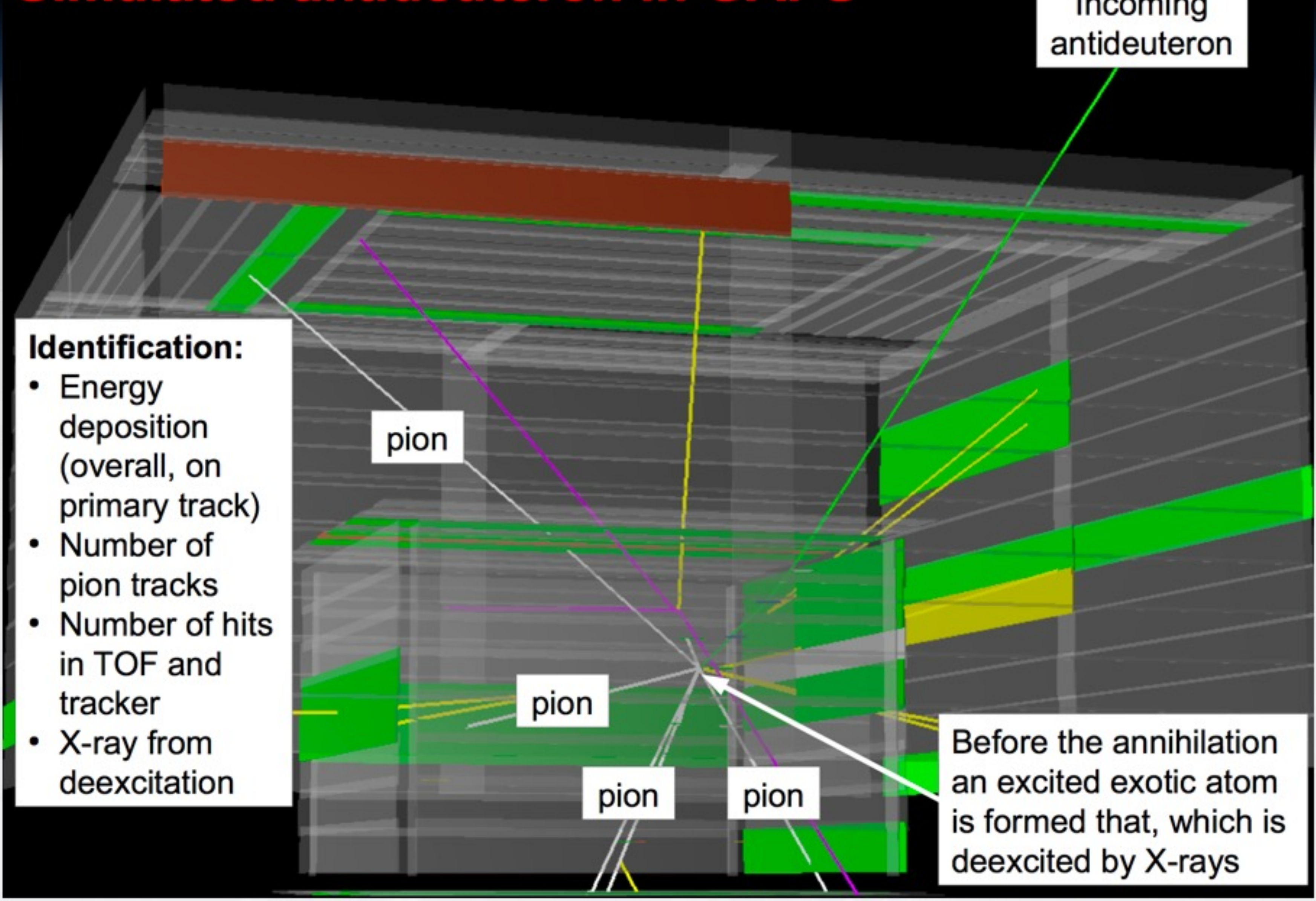
Columbia U, UCSD
UCLA, UCB,
U Hawaii, MIT



- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons, antiprotons and antihelium nuclei

P. von Doetinchem

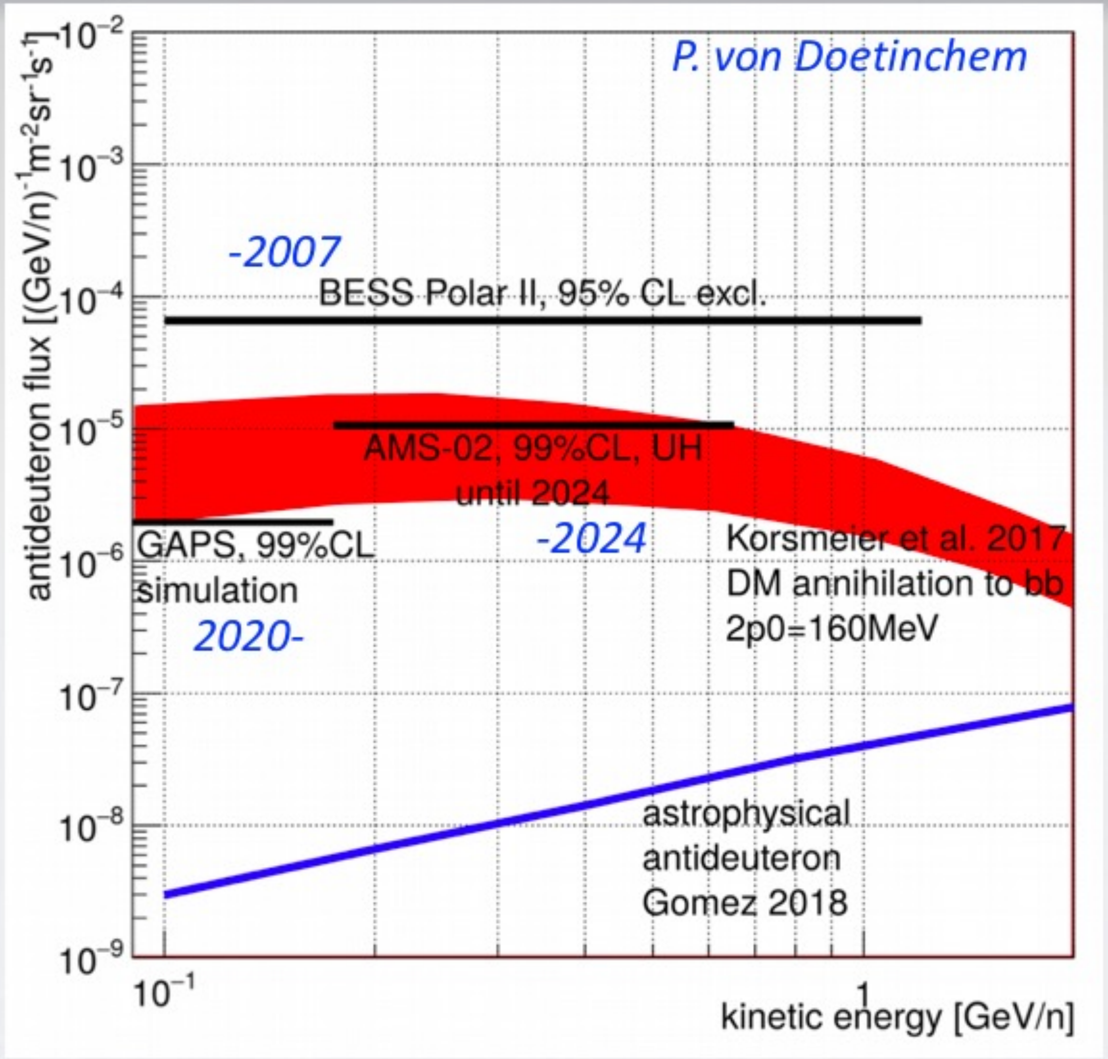
Simulated antideuteron in GAPS



Identification:
- Energy deposition (overall, on primary track)
- Number of pion tracks
- Number of hits in TOF and tracker
- X-ray from deexcitation

P. von Doetinchem

Anti-D searches - prospects



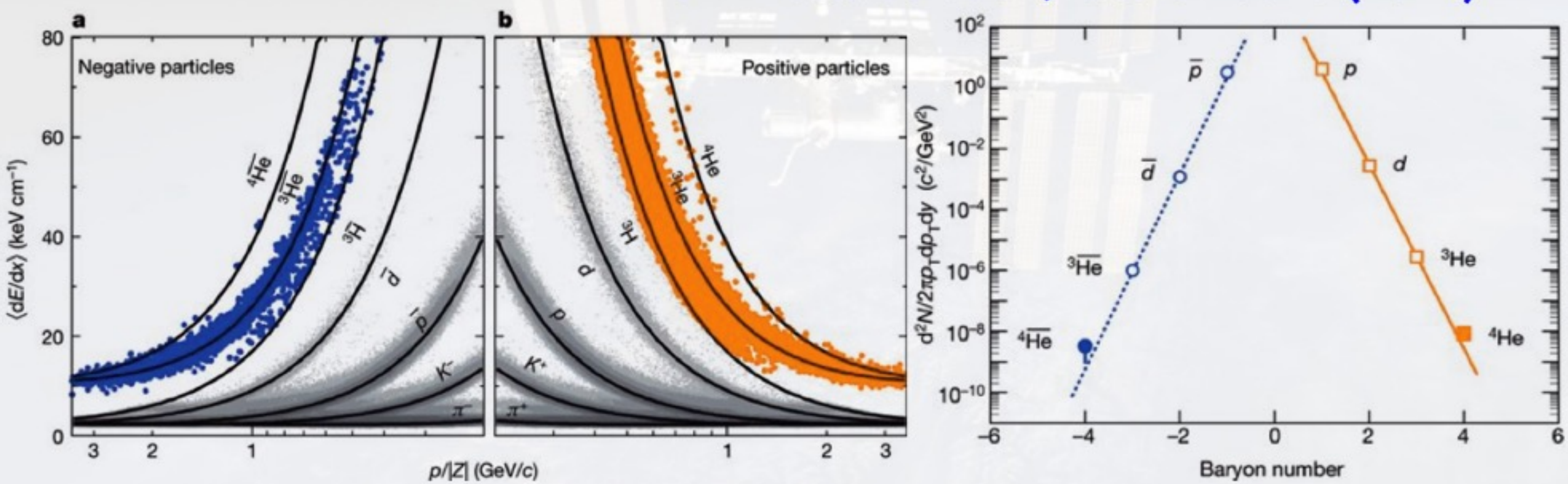
Cosmic-Ray Anti-Helium

Anti-He production by collider

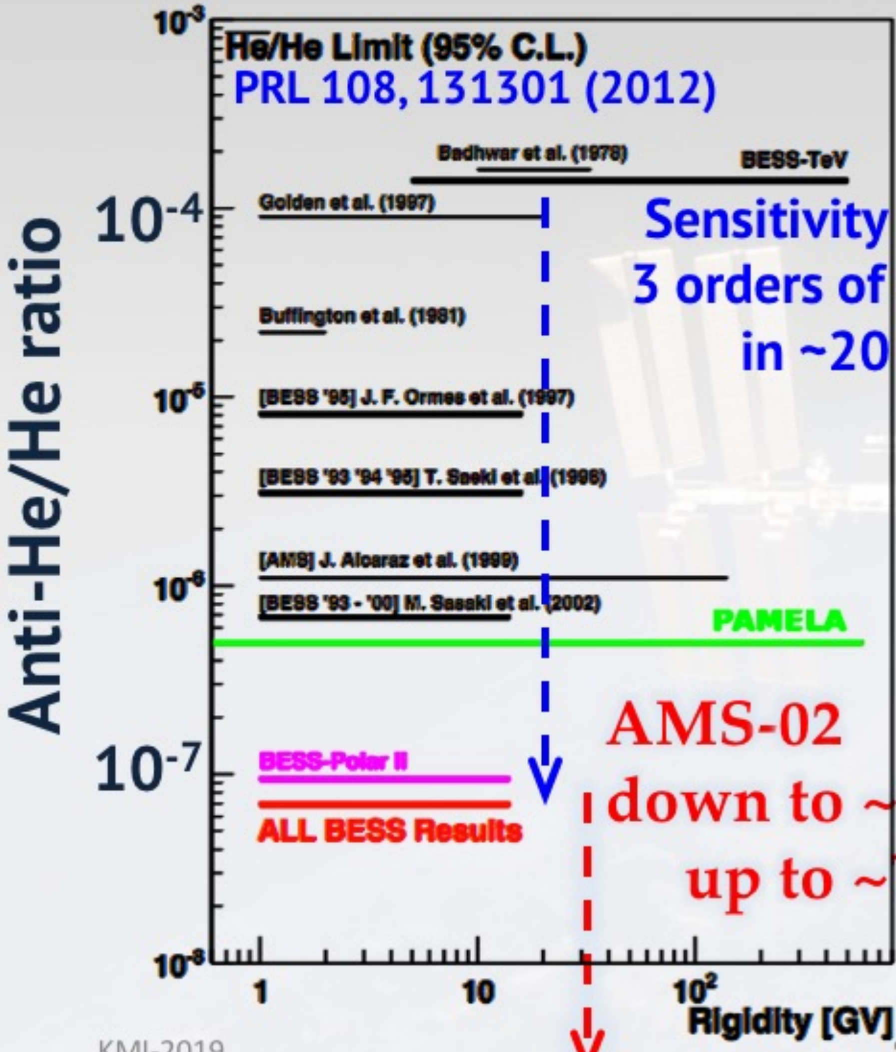
Anti-Helium

- Production in the collision is extremely small;
  the cross section is recently measured in colliders

STAR collaboration, Nature 10079 (2011)

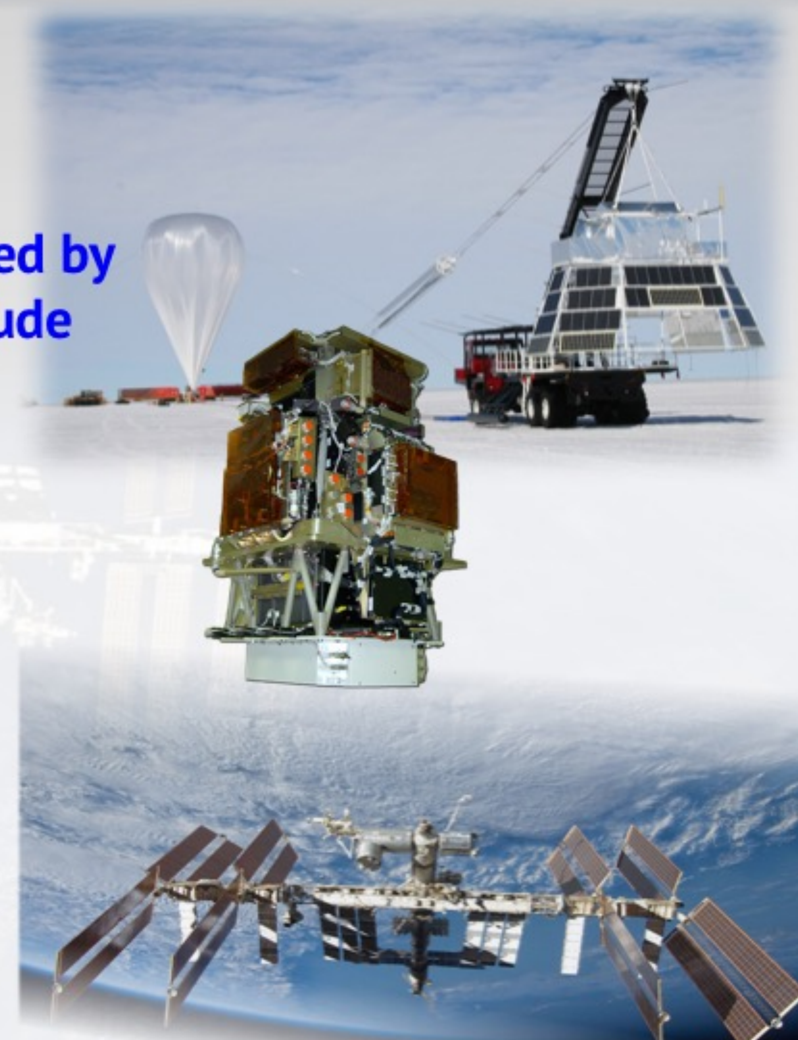


History of antimatter searches

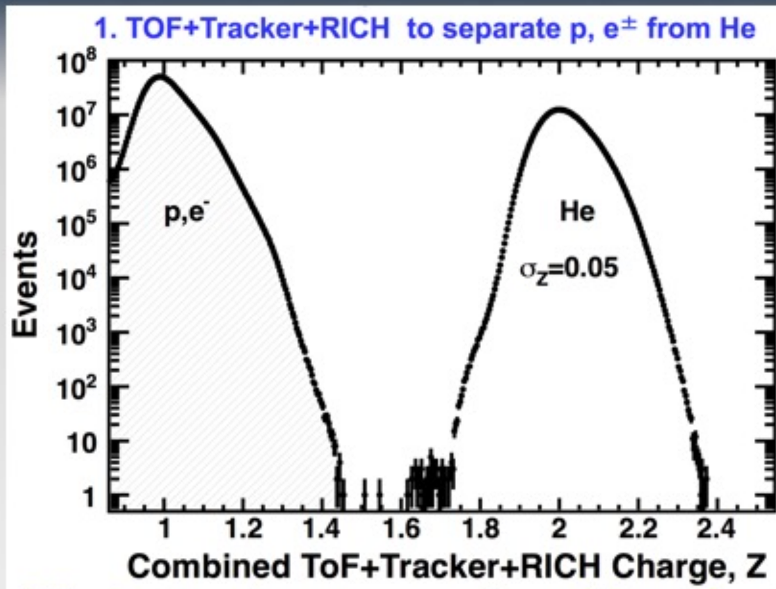


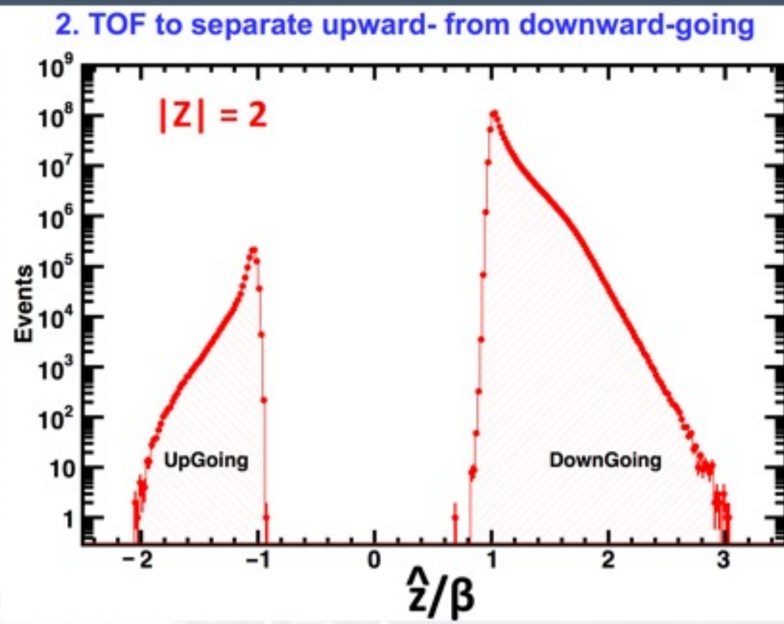
Sensitivity improved by
3 orders of magnitude
in ~20 years

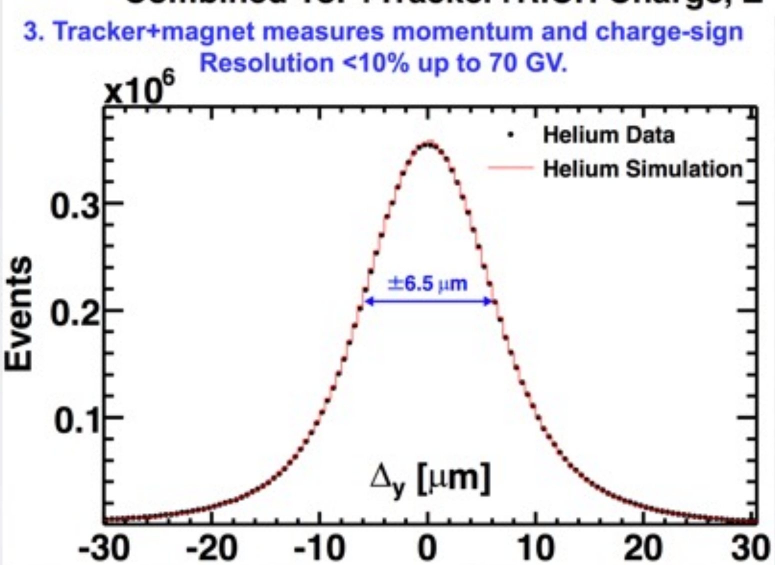
AMS-02
down to $\sim 10^{-9}$
up to ~TeV



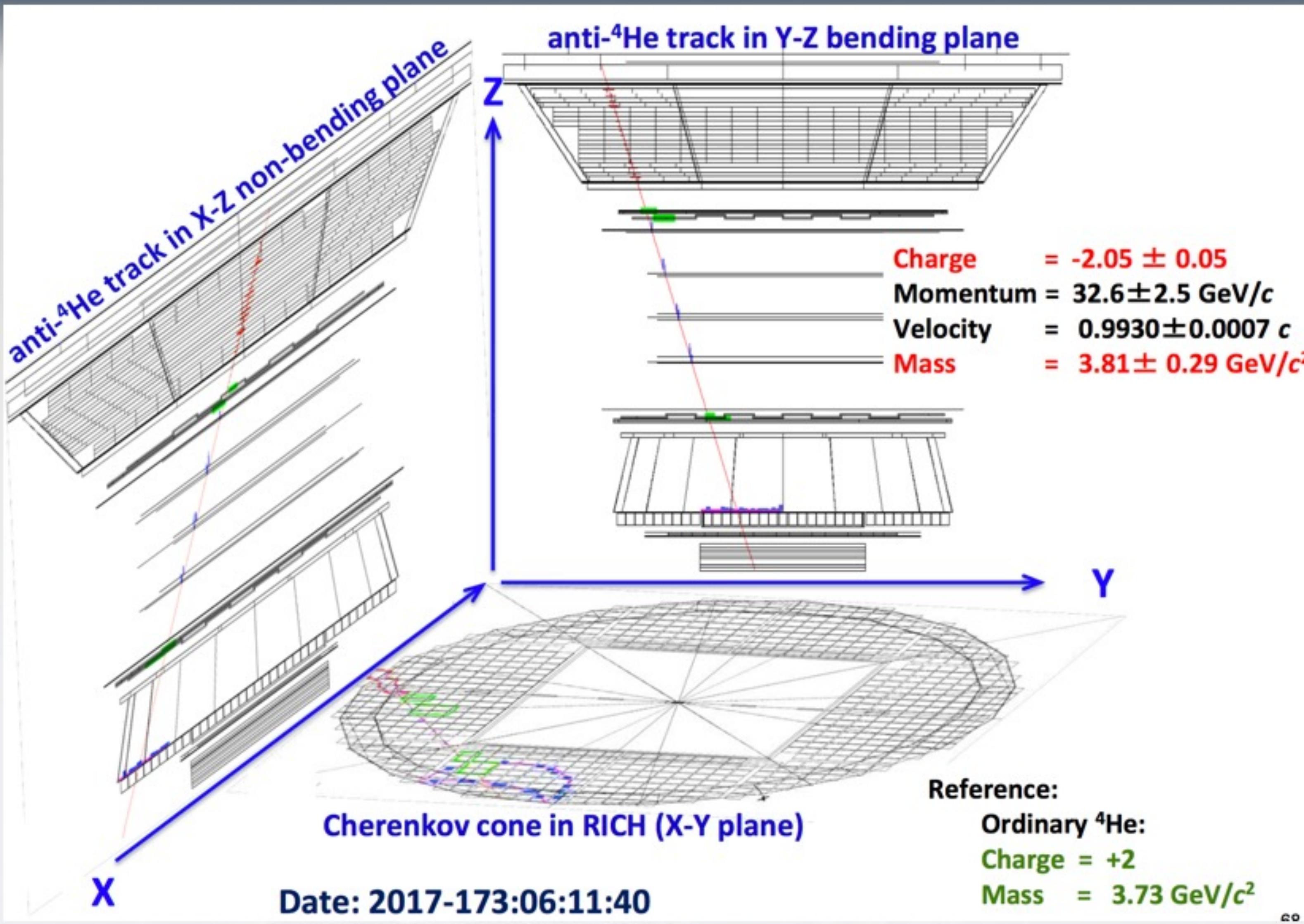
Anti-He searches in AMS







Anti-He candidates ?



- After a century since the discovery, cosmic rays open a new channel to study particle physics and cosmology
- AMS provides the data in an unprecedented precision with a single instrument
- On-going balloon and space experiments will complement the measurements and searches