



Physics of Anti-matter in space

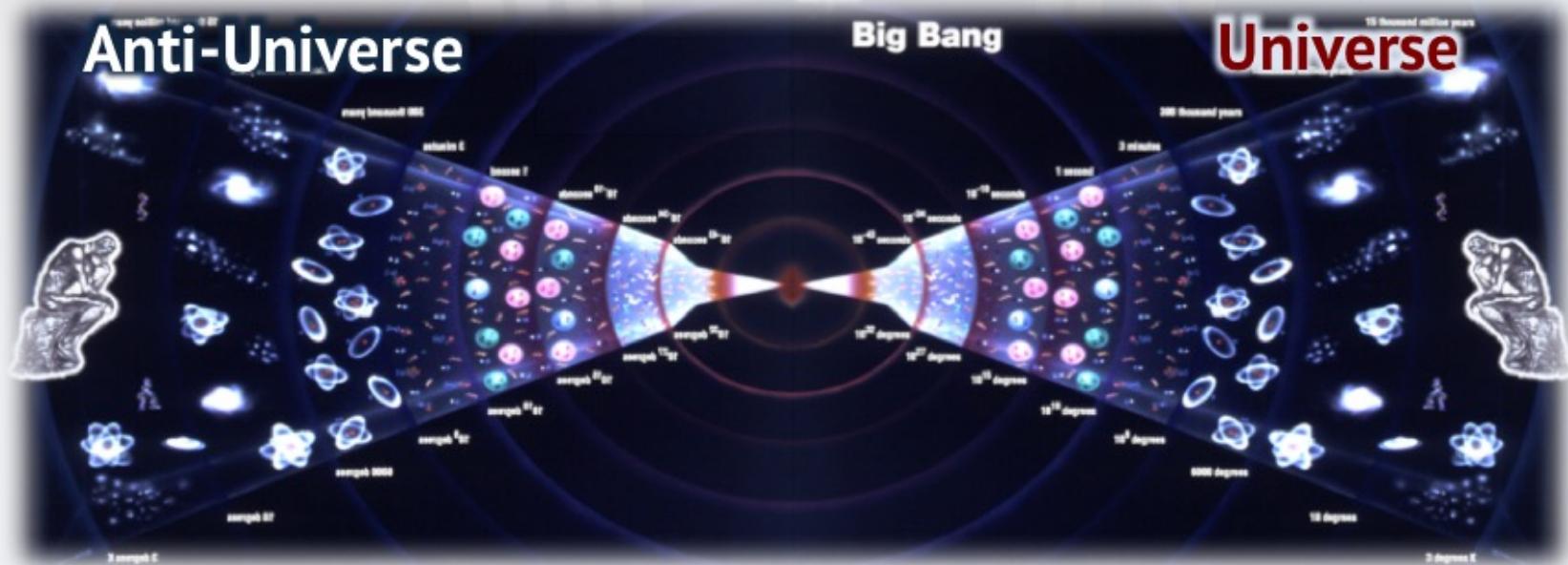
Sadakazu Haino
Academia Sinica



中央研究院
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



Paul Dirac

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.

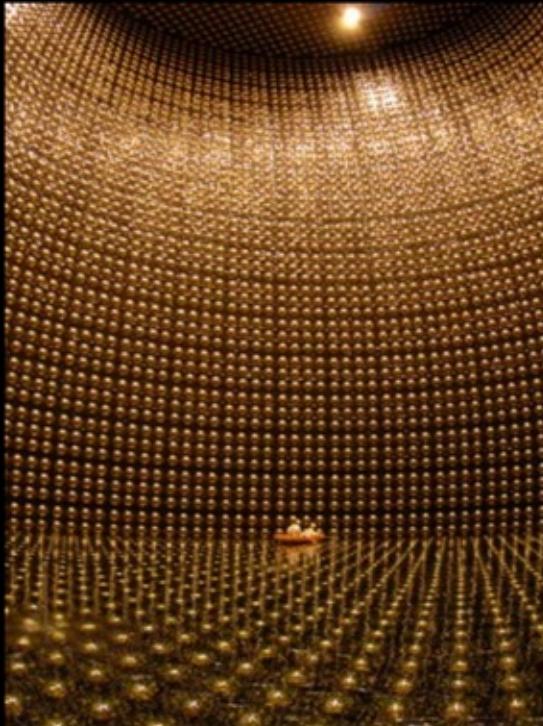
Experimental work on Antimatter in the Universe

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

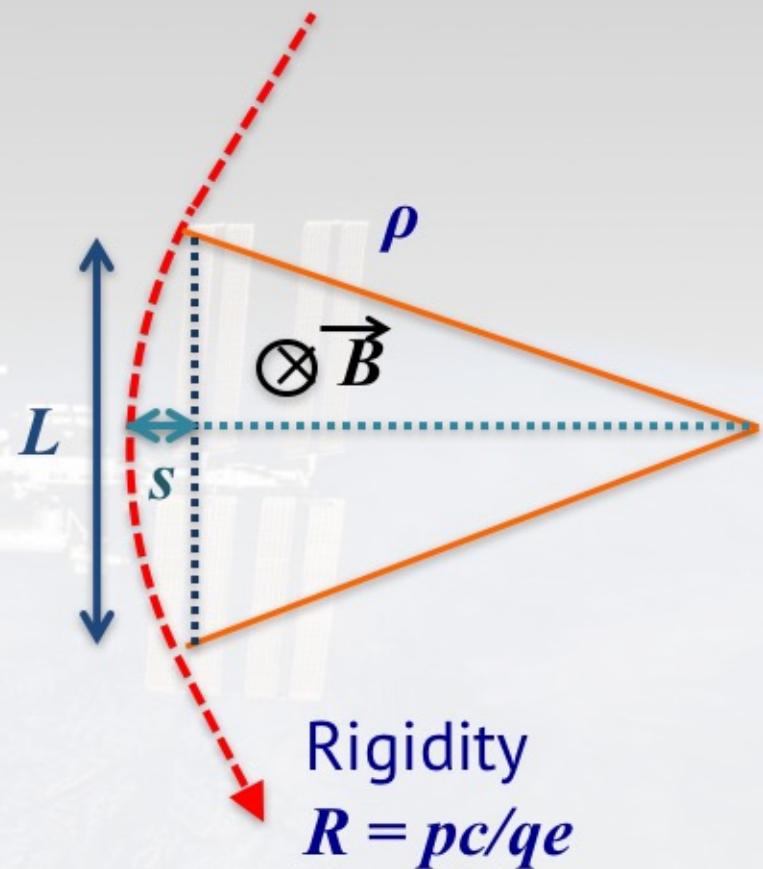
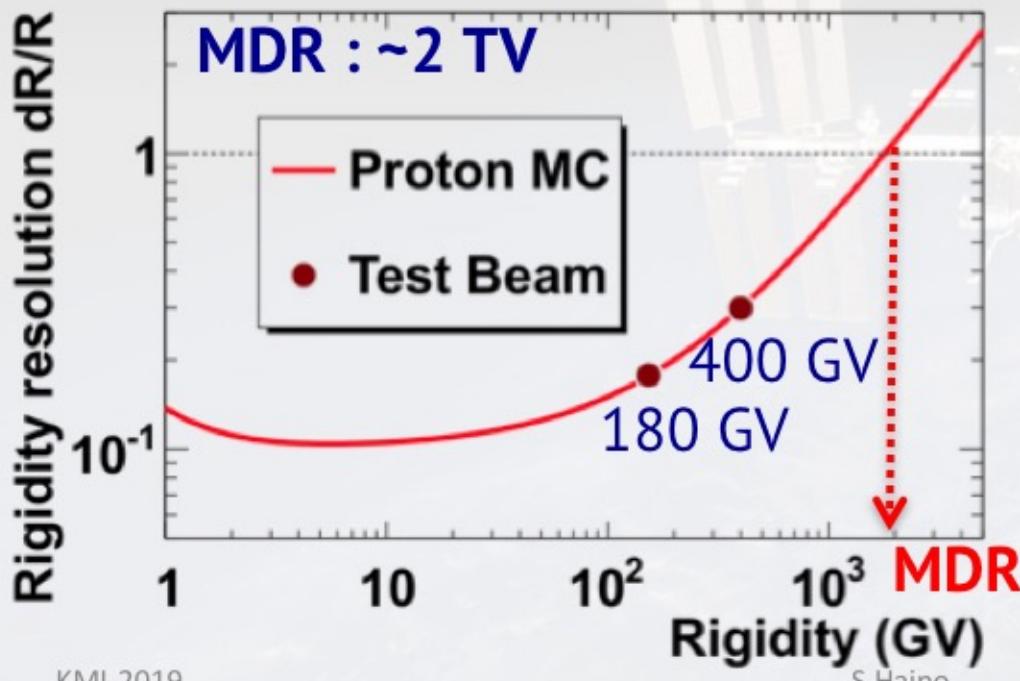
Increase in sensitivity: $\times 10^3 - 10^6$
Increase in energy to $\sim \text{TeV}$

Magnetic spectrometers balloon-borne and in space

Magnetic Rigidity Measurement

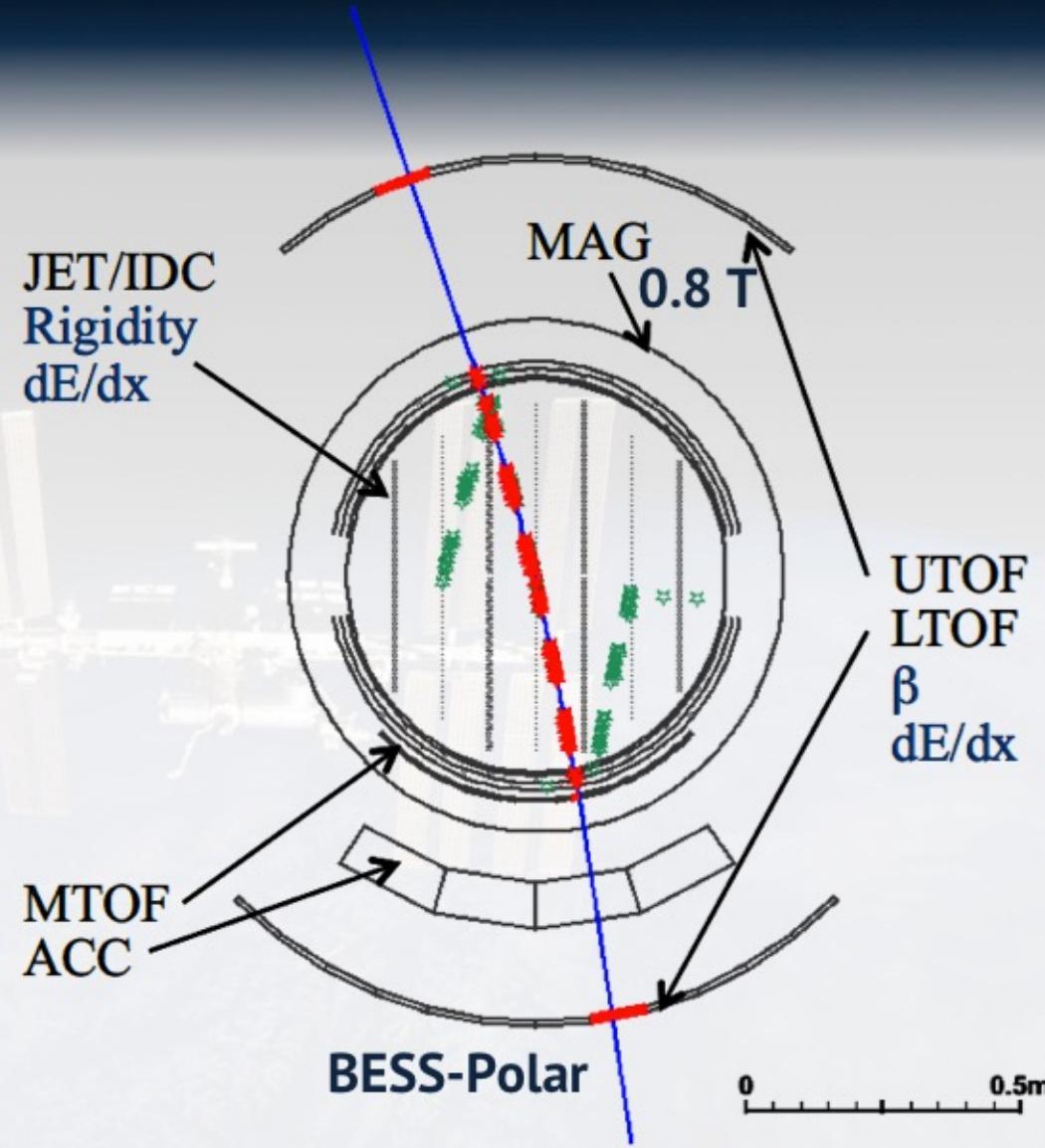
$$\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}$$

Maximum Detectable Rigidity



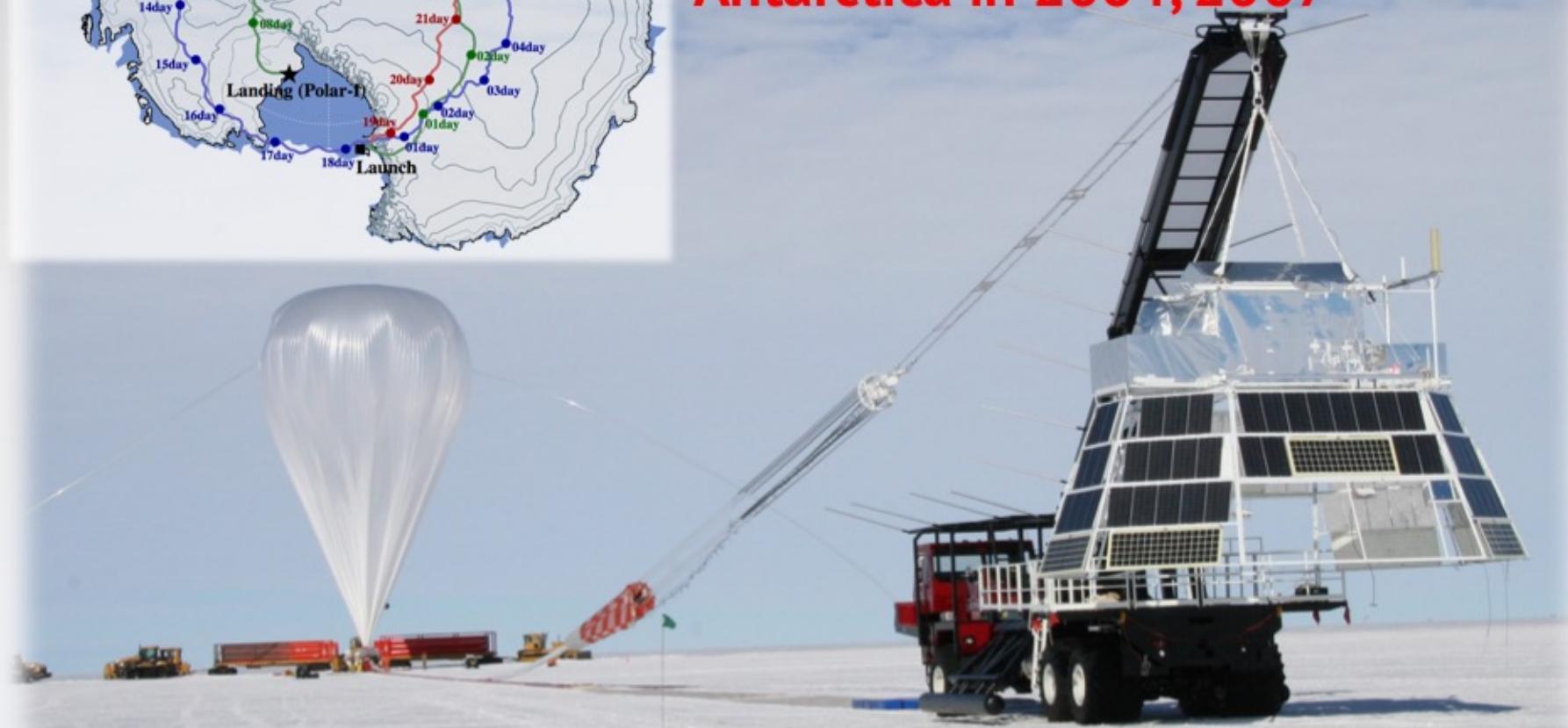
BESS / BESS-Polar

Balloon-borne Experiment with a Superconducting Spectrometer



BESS-Polar

Balloon flight over
Antarctica in 2004, 2007

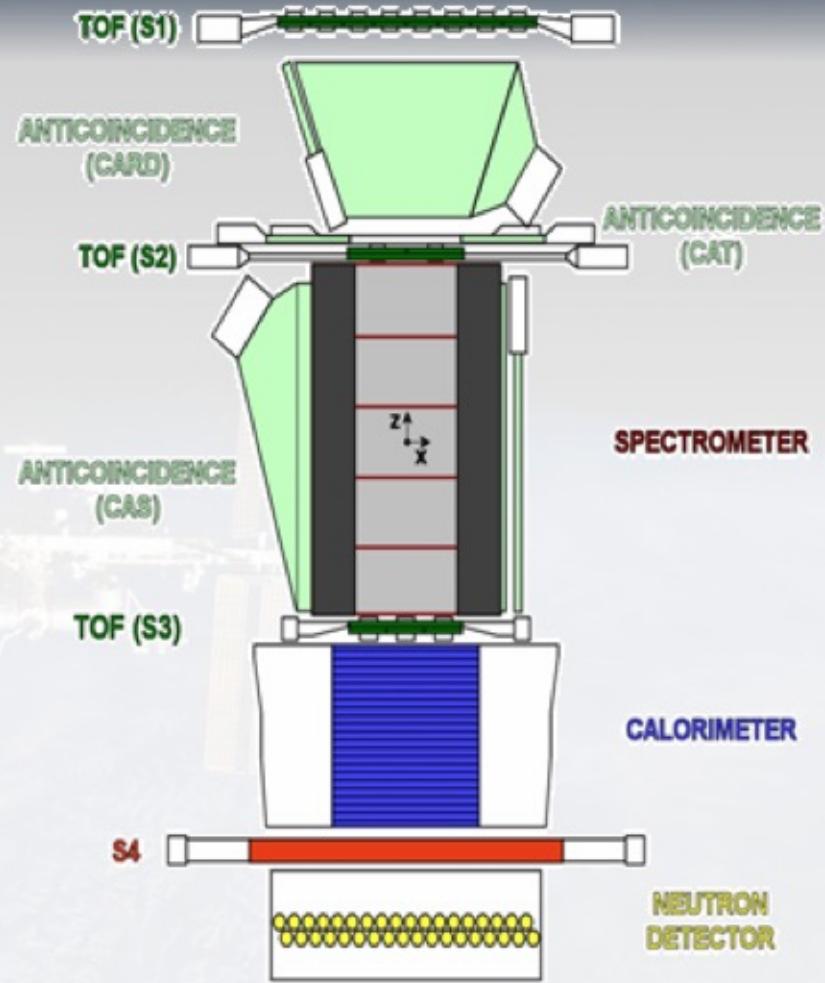


PAMELA

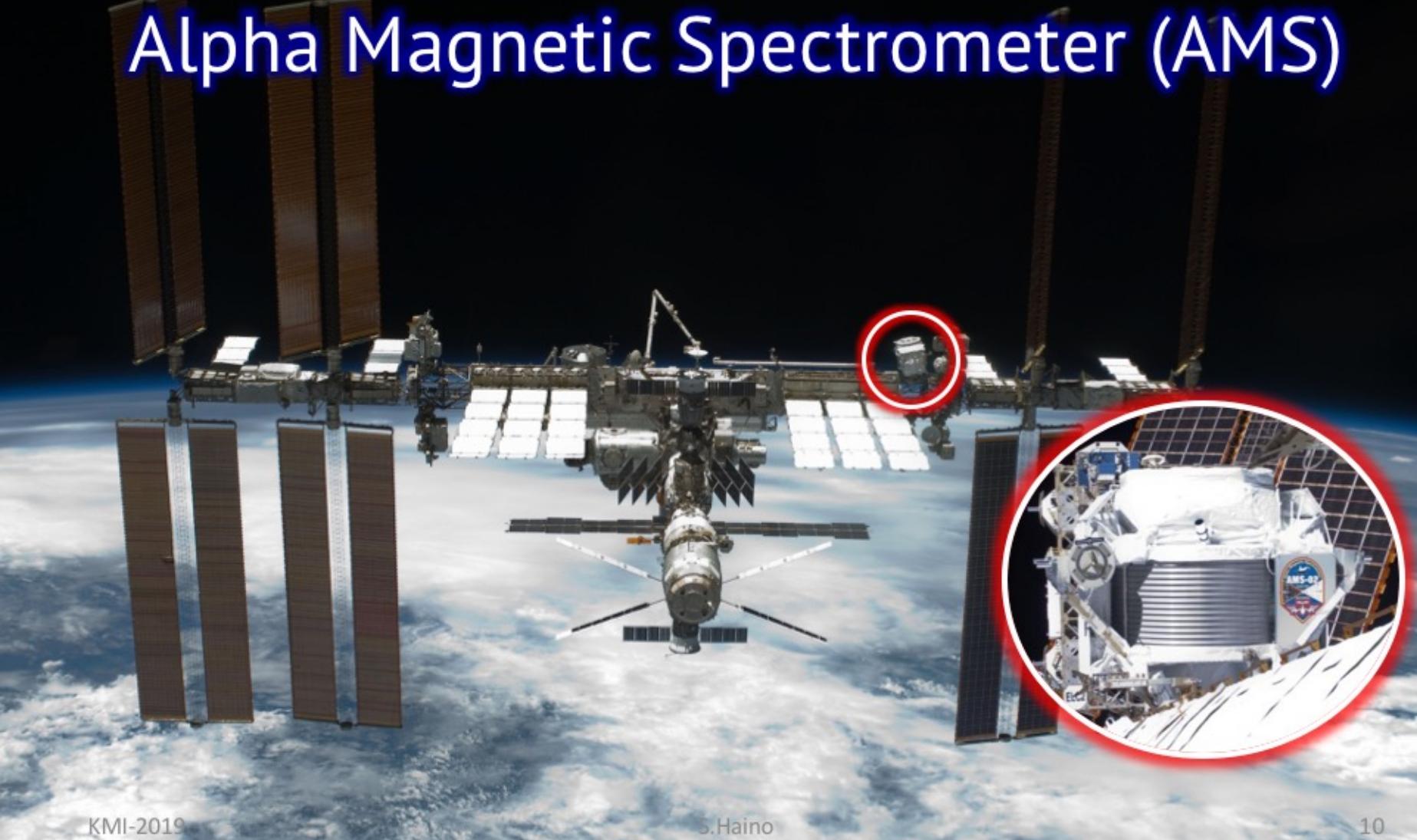
**Payload for Antimatter
Matter Exploration and
Light-nuclei Astrophysics**



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)

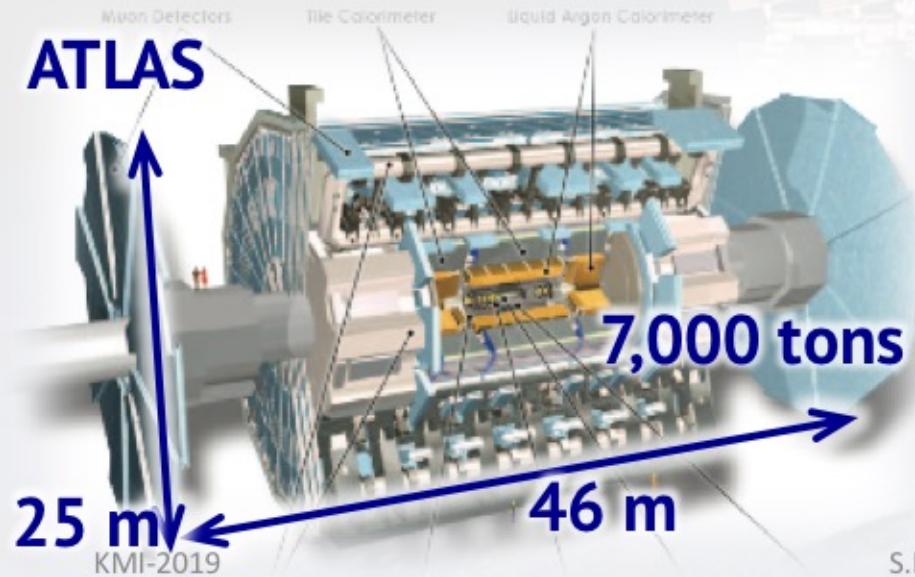
 Selected for a [Viewpoint](#) in *Physics*
PHYSICAL REVIEW LETTERS



- 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 environment without access nor repair



It took ~18 years

For

- Design
- Construction
- Space qualification tests
of sub-systems
and
- Integration of AMS-02



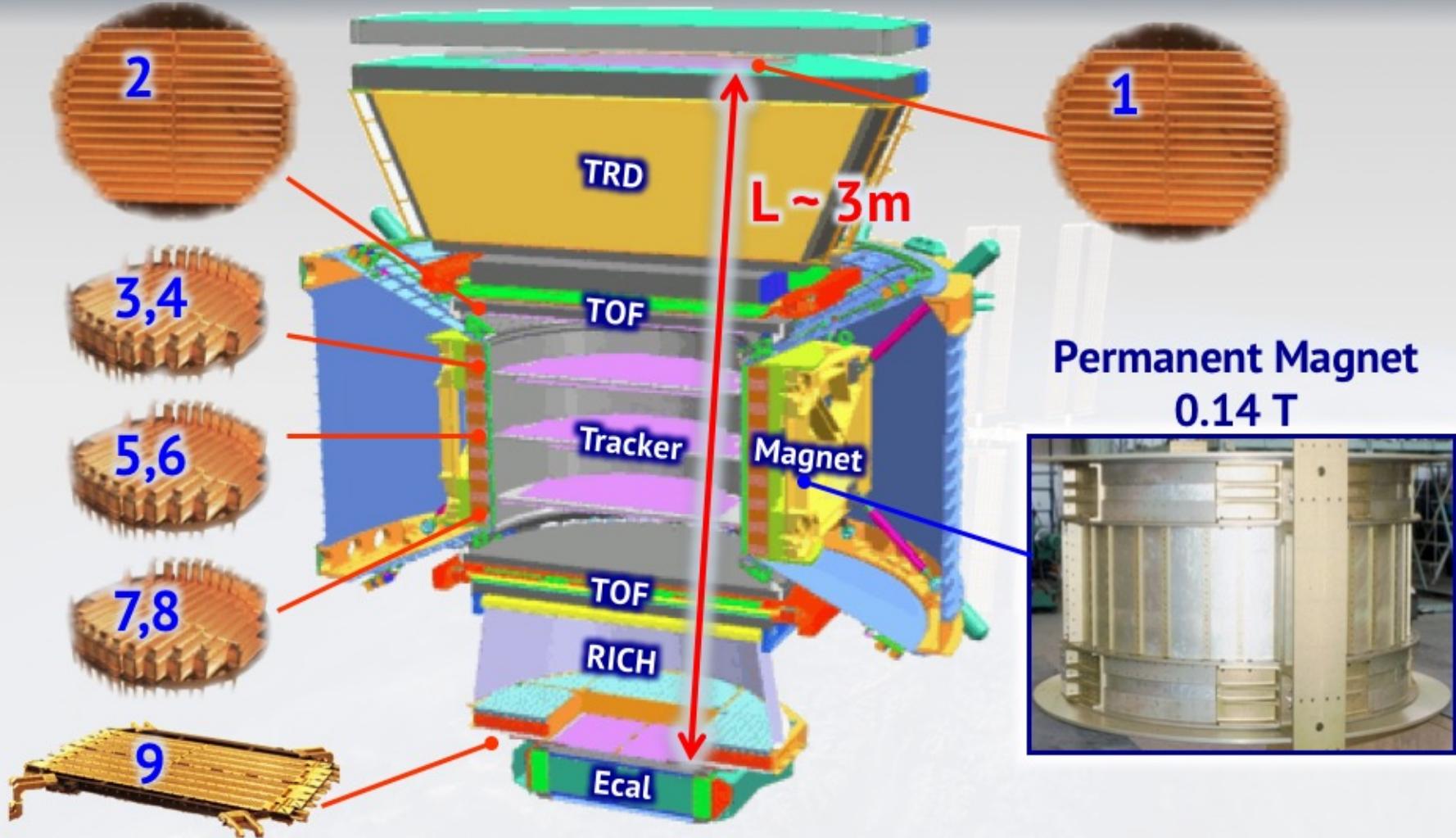
AMS installed on the ISS

19/May/2011

Start taking data only 4 hours later



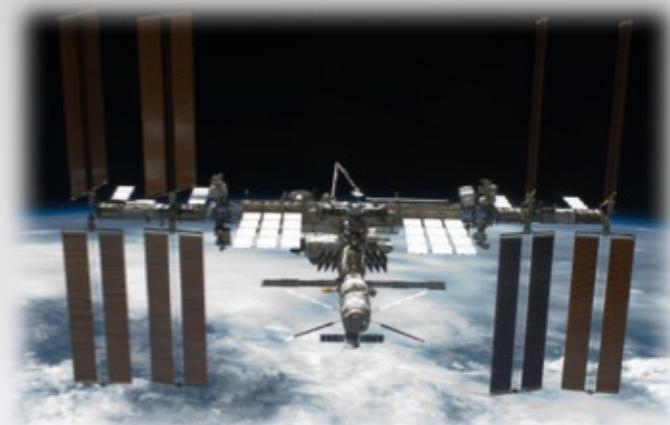
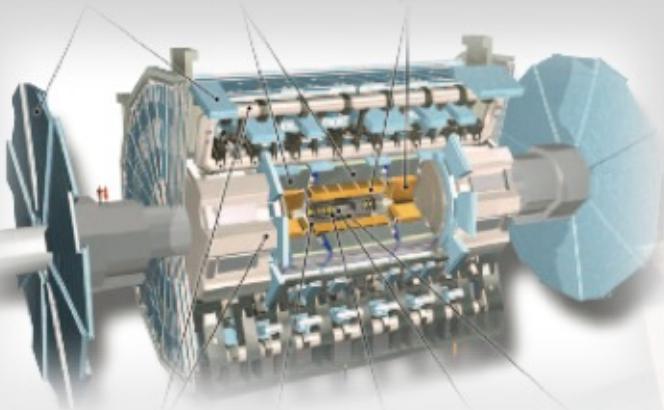
AMS – 9 layers of silicon tracker



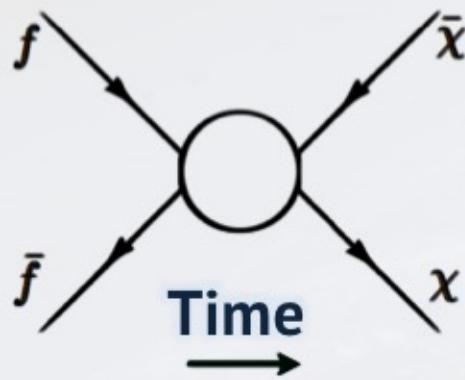
Cosmic-Ray Positrons

as a probe for indirect DM searches

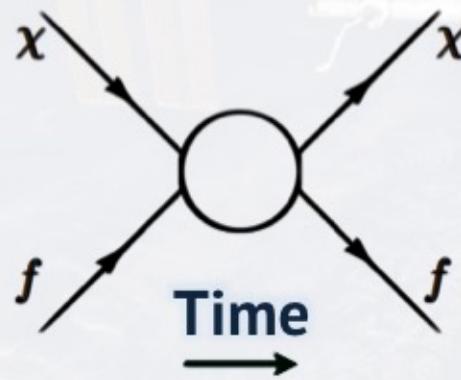
Dark Matter searches



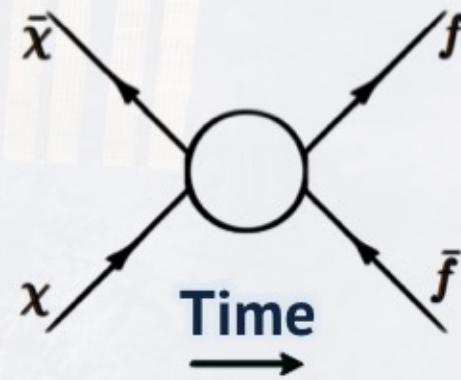
Colliders



Direct searches

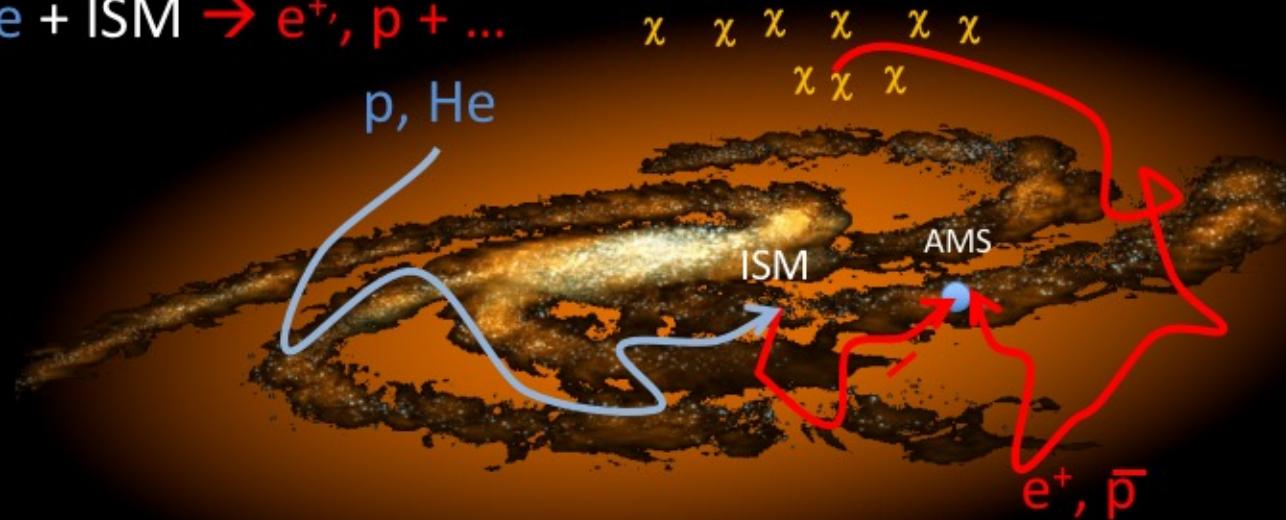


Indirect searches



Annihilaiton of Dark Matter

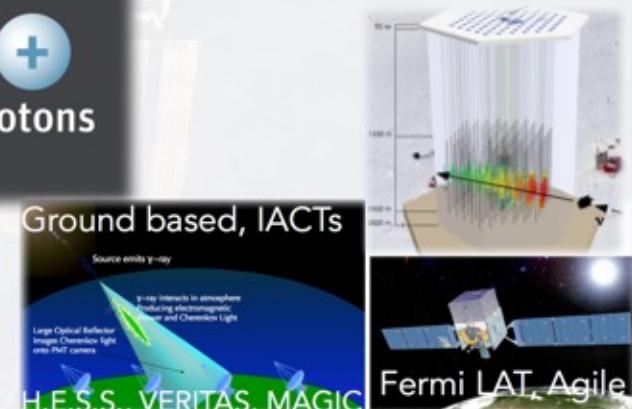
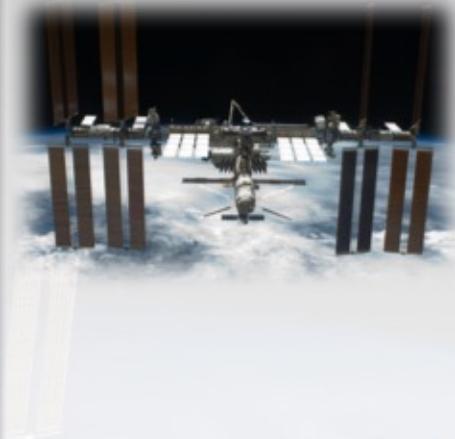
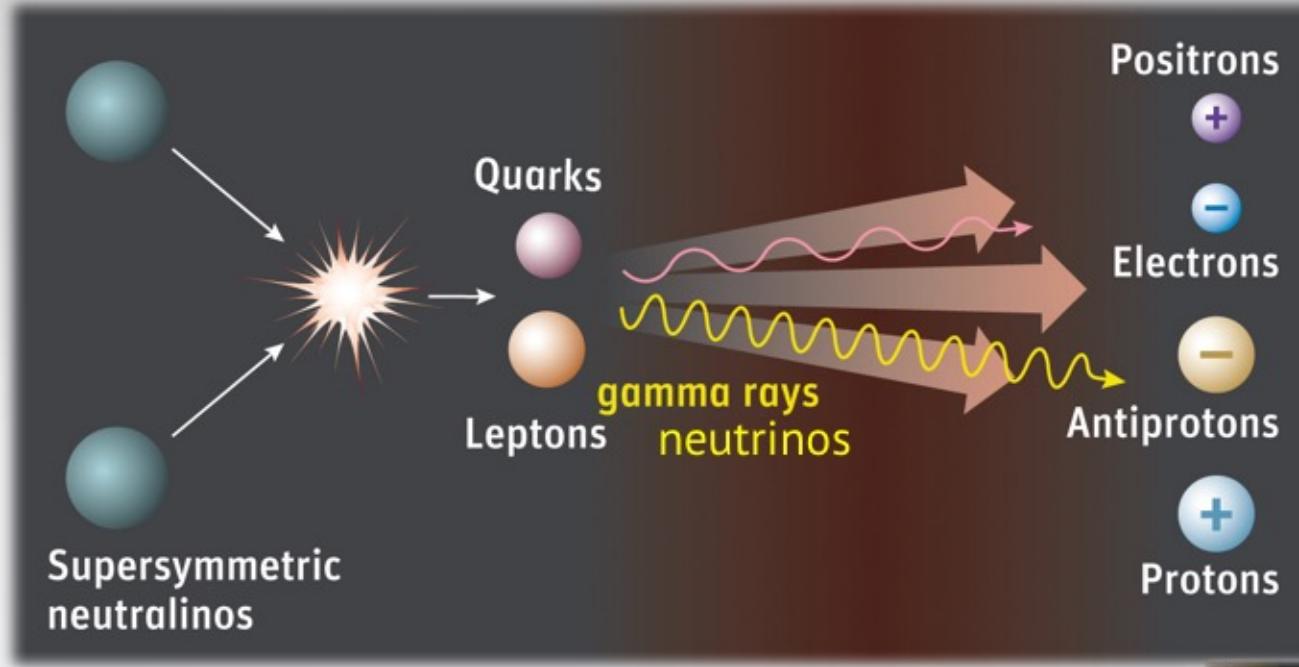
Collision of Cosmic Rays with the Interstellar Media will produce $e^+, \bar{p}...$



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

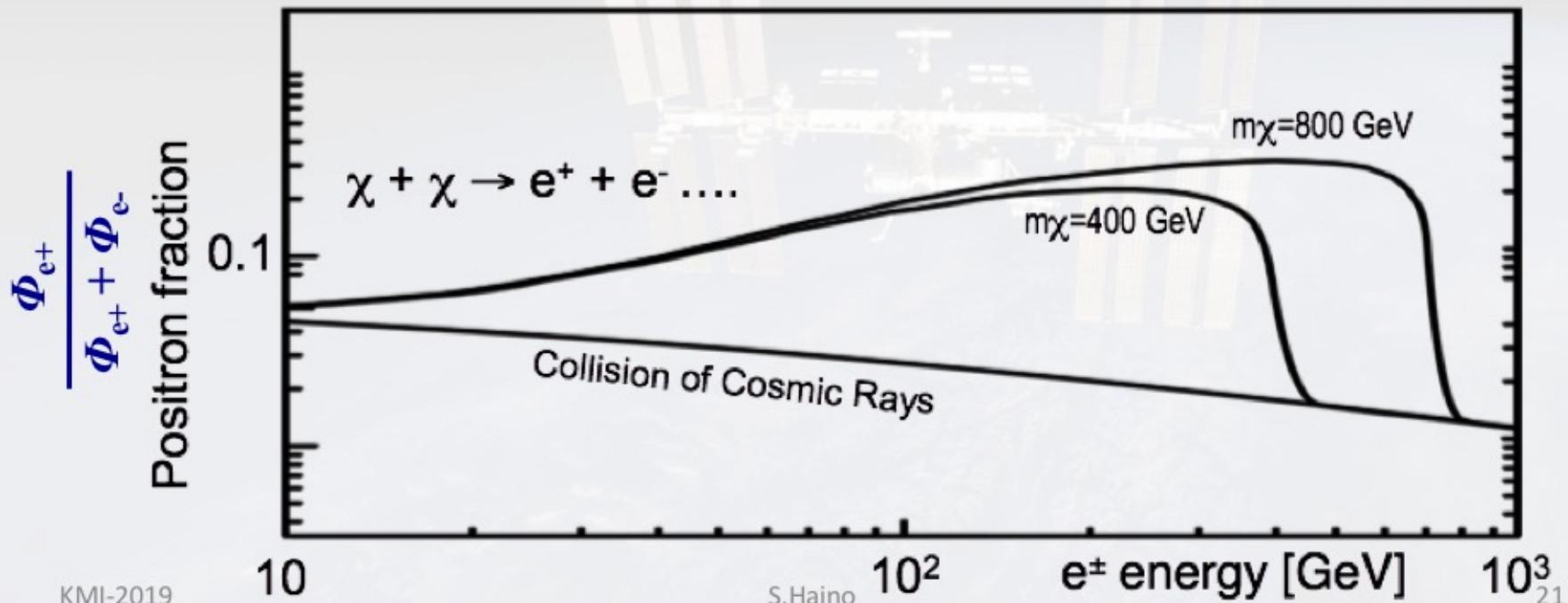
Annihilaiton of Dark Matter



**Summary talk on
Indirect searches
by G. Zaharijas**

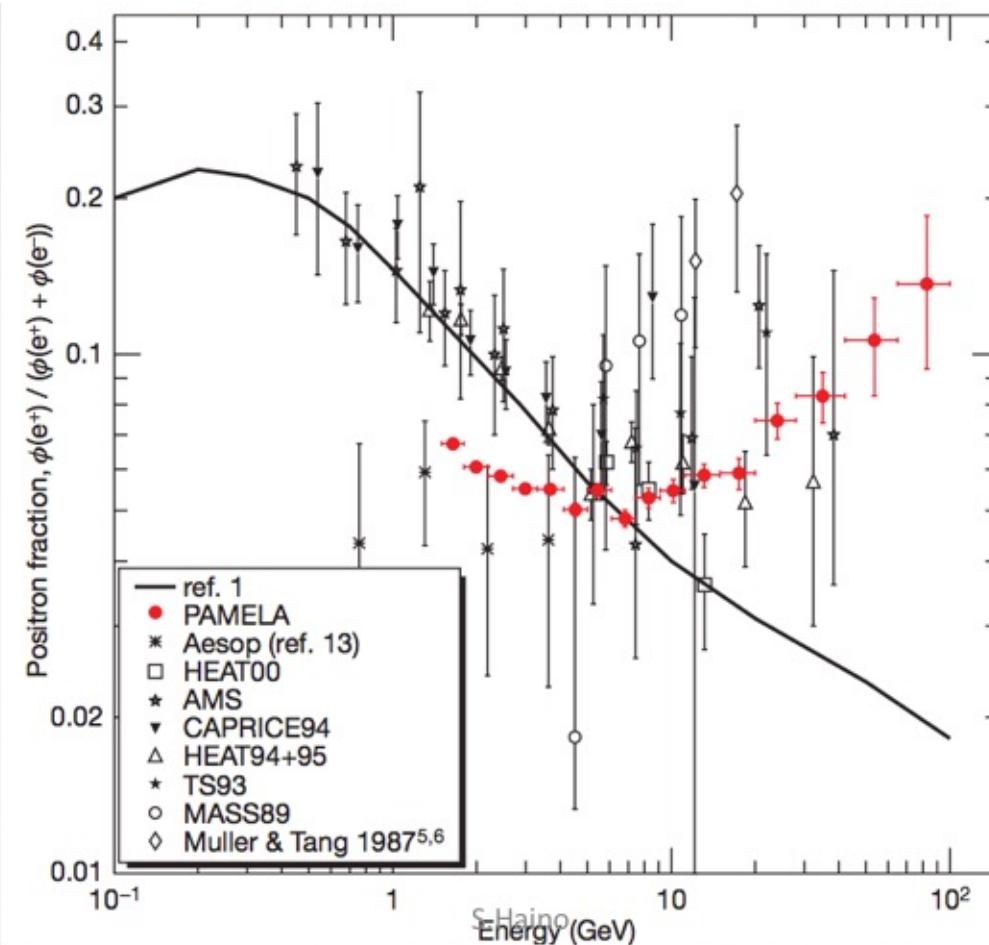
Cosmic-ray Positrons

- 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



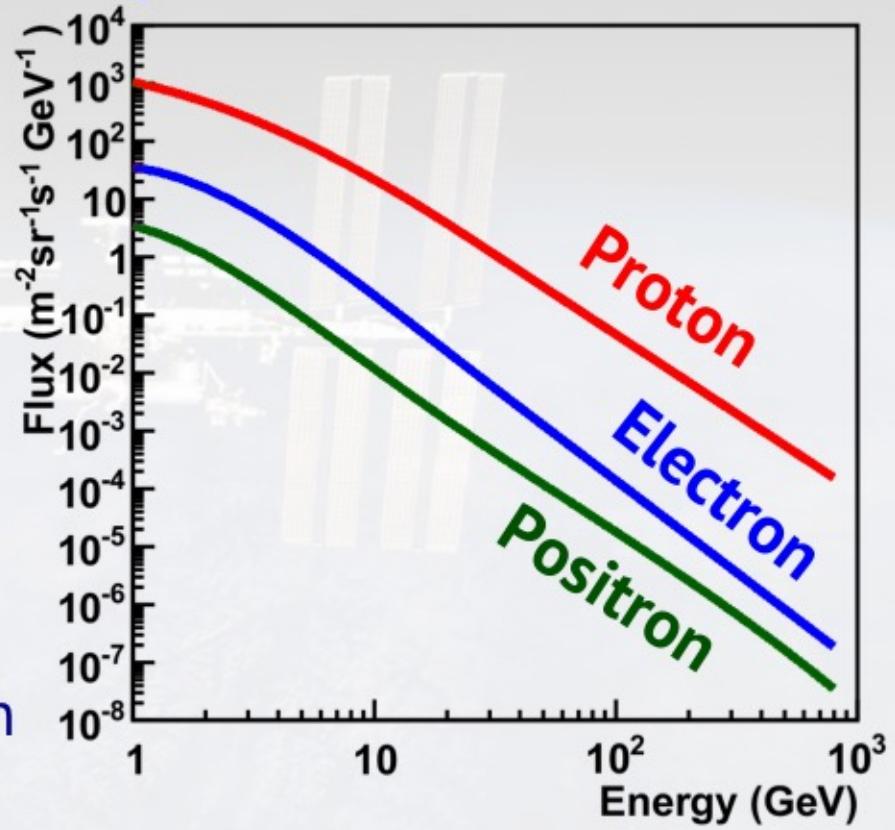
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

PAMELA: Nature 458 (2009) 607

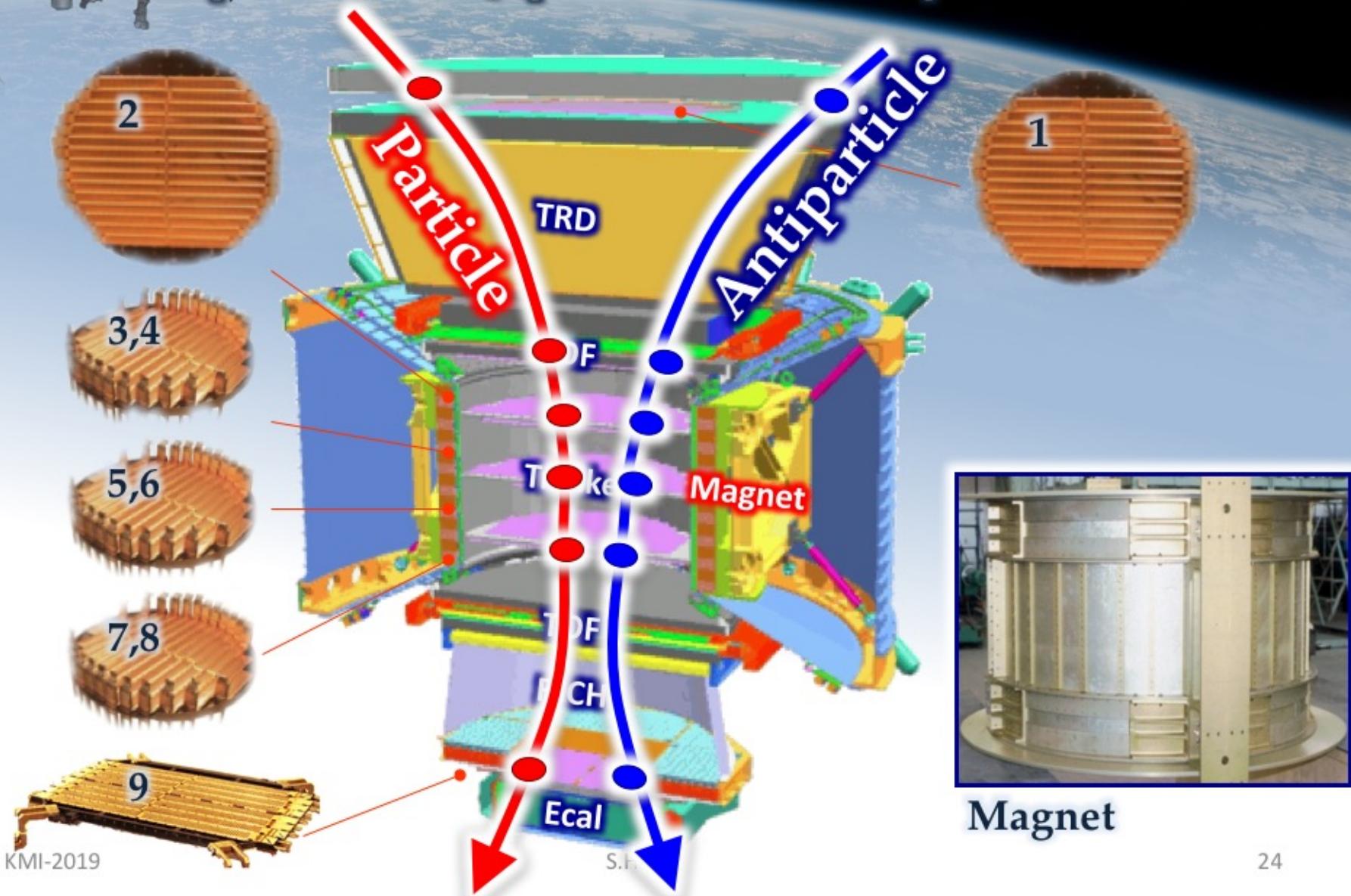


Difficulties – CR positron measurement

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

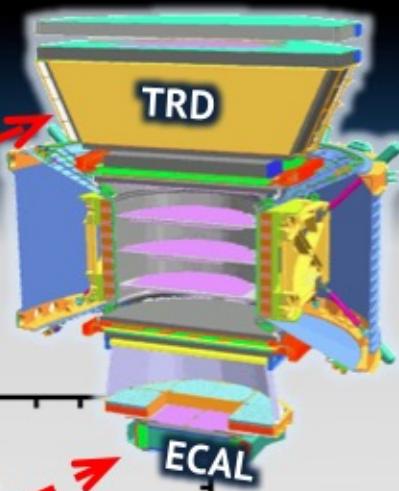
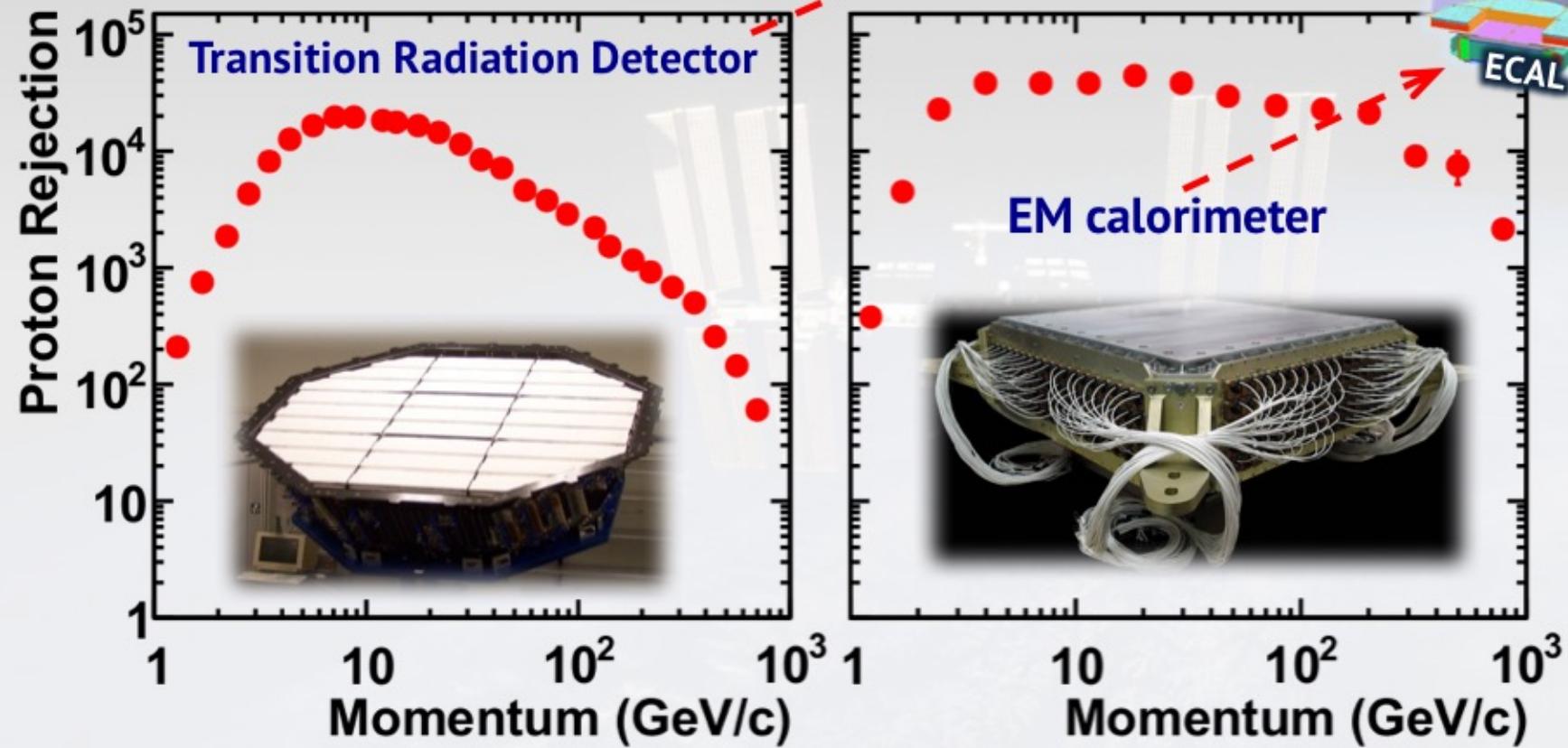


Antiparticle/particle separation



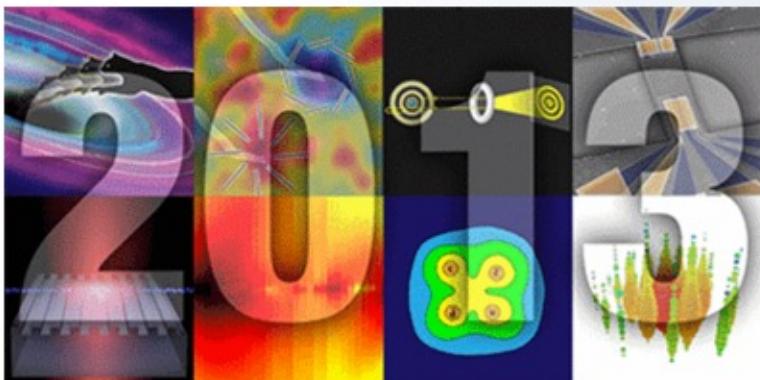
Proton rejection by AMS

With 90 % e^+ efficiency



First results of AMS

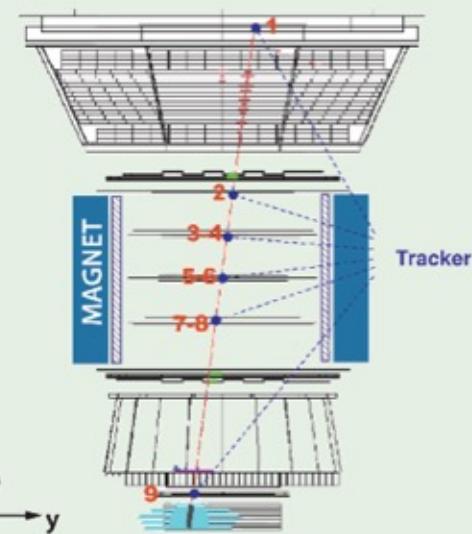
M. Aguilar *et al.*,
PRL 110, 141102 (2013)
“Precision Measurement
of the Positron Fraction
in Primary Cosmic Rays”
of 0.5-350 GeV (April/2013)
Selected as APS Highlights in 2013



PHYSICAL
REVIEW
LETTERS

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Articles published week ending 5 APRIL 2013



Published by
American Physical Society



Volume 110, Number 14

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

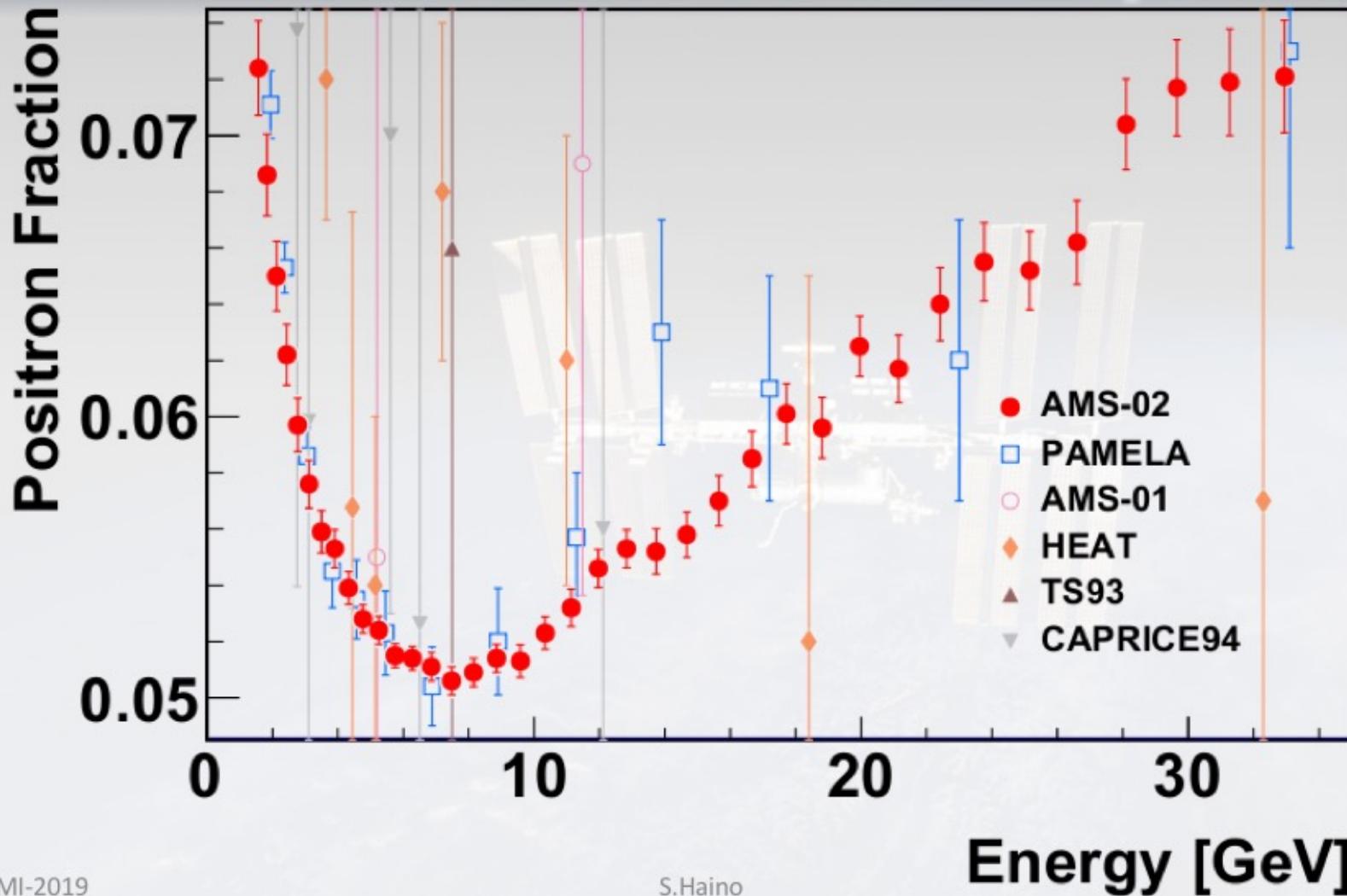
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A Decade of Editors' Suggestions

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.

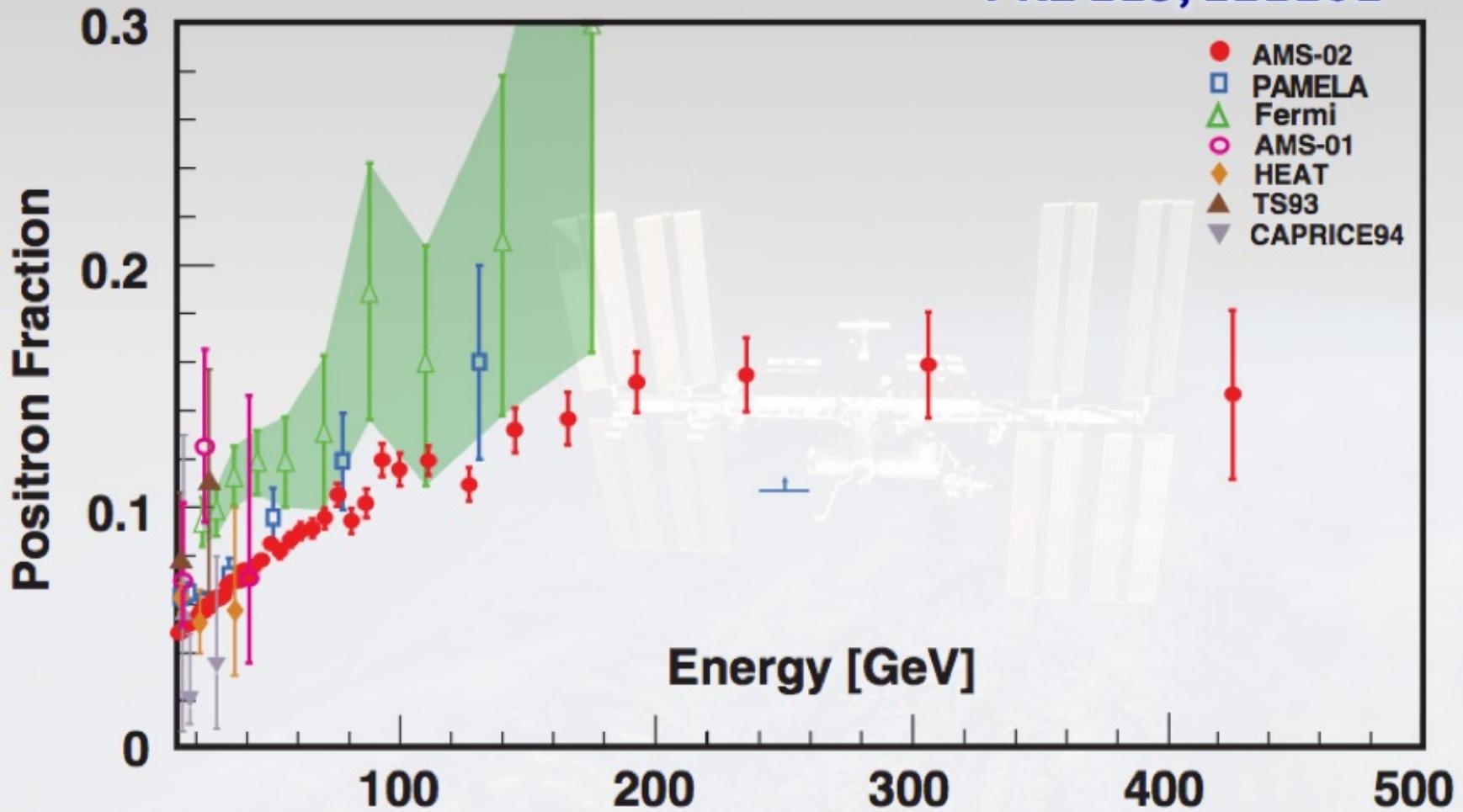
Positron fraction by AMS (low energy)

PRL 113, 121101



Positron fraction by AMS (high energy)

PRL 113, 121101



A sample of Theoretical Models explaining AMS data

- 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 ...

Propagation

- 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

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



Science 358, 911–914 (2017)

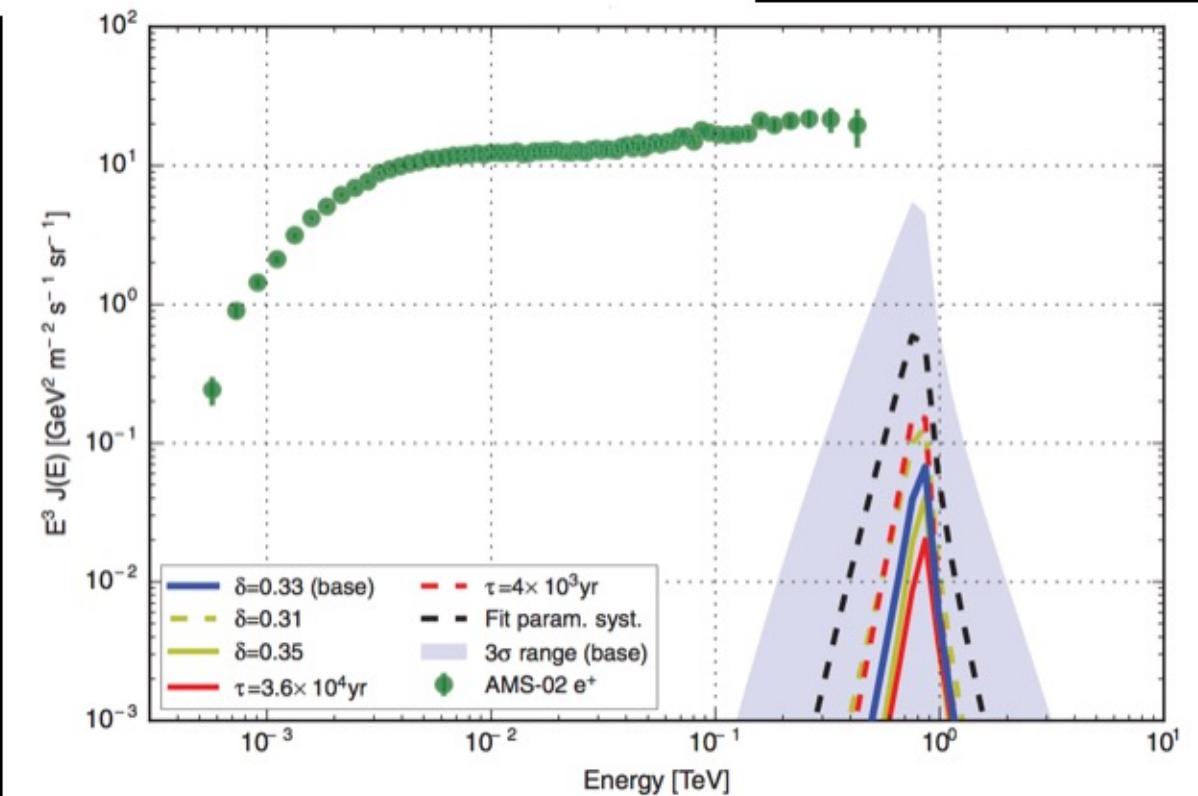
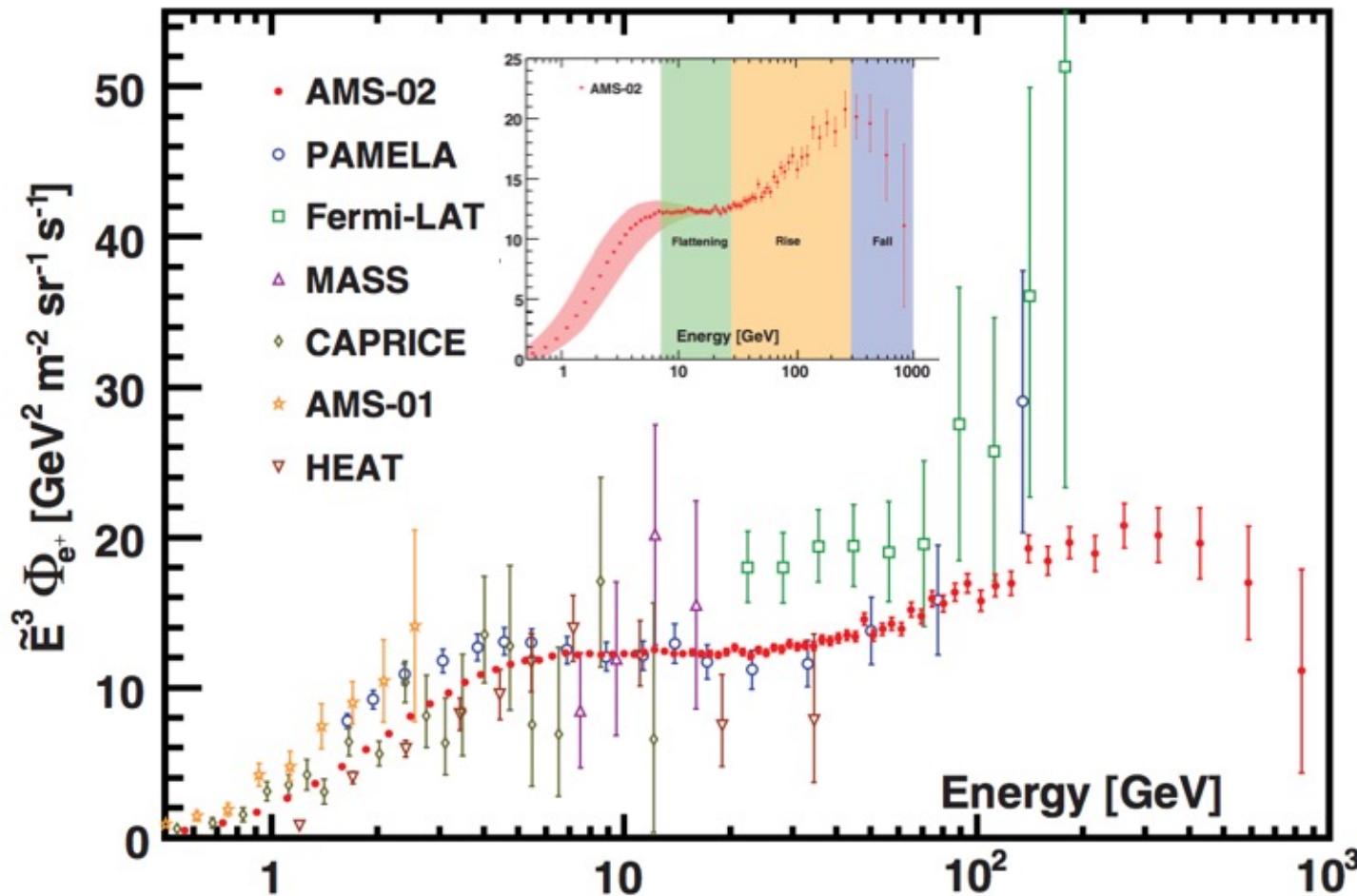
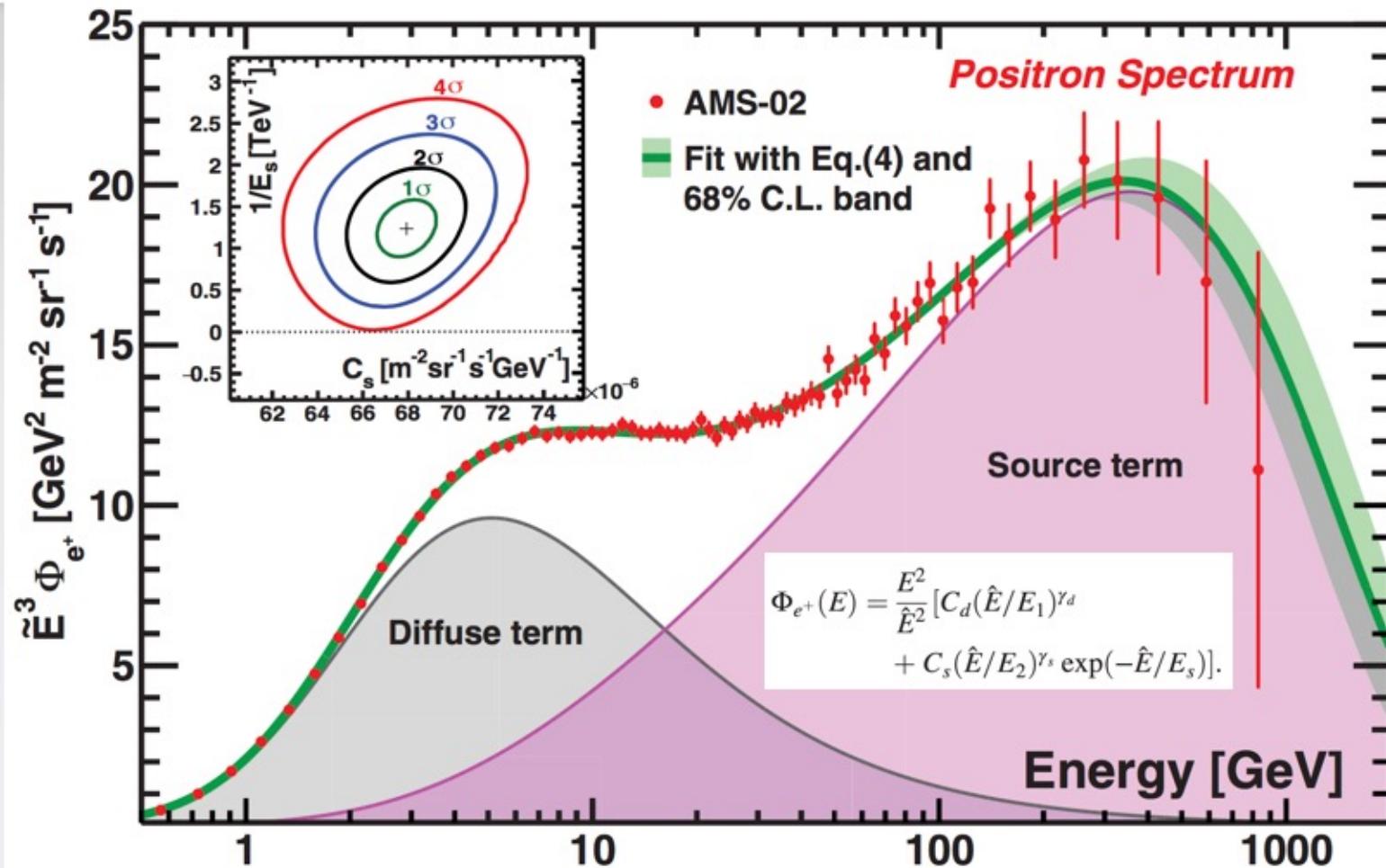


Fig. 3. Estimated positron energy flux at Earth from Geminga (blue solid line), compared with AMS-02 experimental measurements (green dots). The shaded blue region indicates the 3σ

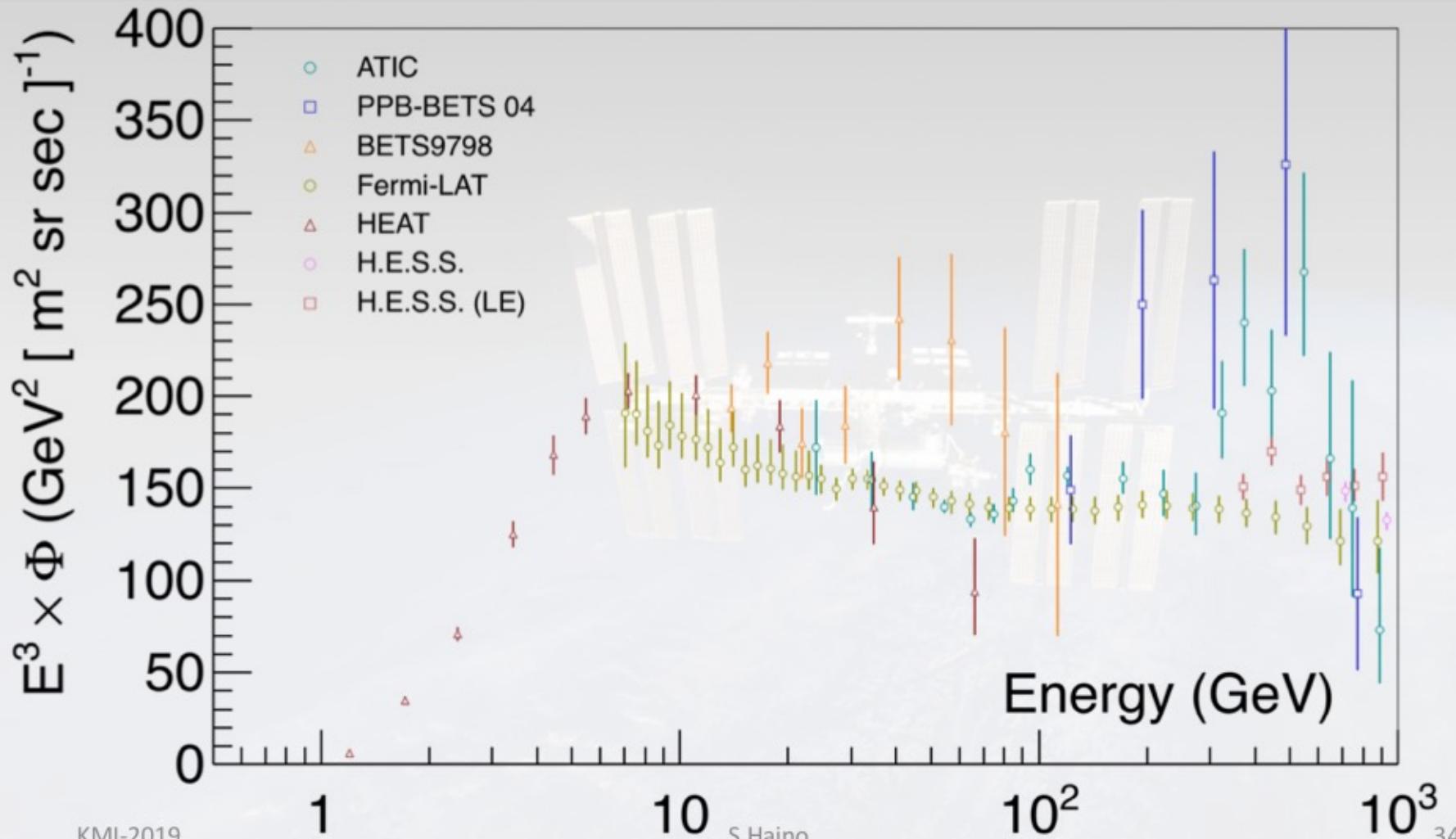
Towards Understanding the Origin of Cosmic-Ray Positrons



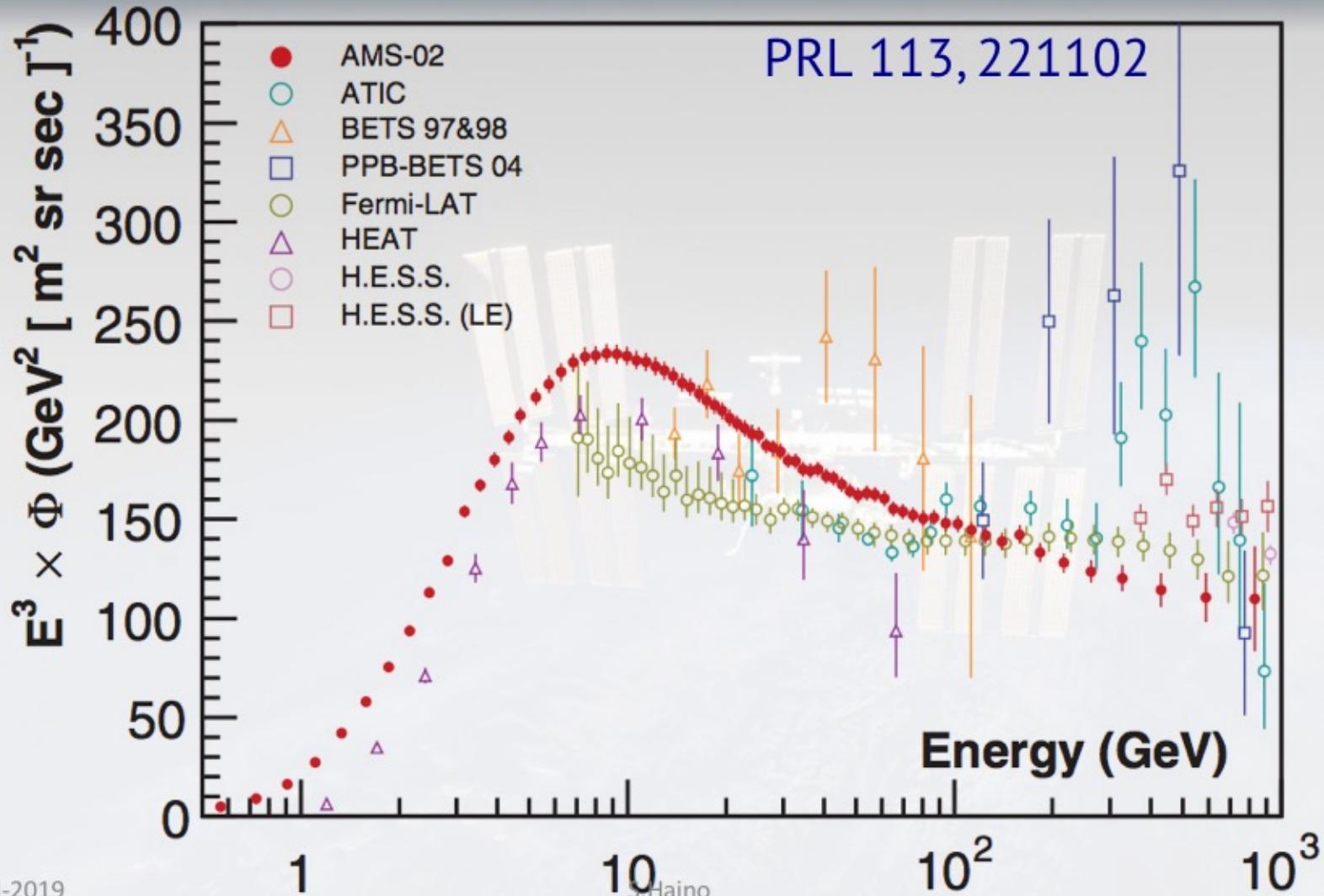
Towards Understanding the Origin of Cosmic-Ray Positrons



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



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



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

宇宙の定期便 こうのとり

「こうのとり」5号機(HTV5)
H-IIロケット5号機

- ✓ 2015年8月19日打ち上げ成功！
- ✓ 2015年8月25日ISS結合完了！



CALET installed at Kibo



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

The diagram illustrates the internal structure of the DAMPE satellite. It features a central cylindrical core surrounded by several layers of detectors. Labels with red arrows point to specific components: 'Plastic Scintillator Detector' points to the top layer; 'Silicon-Tungsten Tracker (STK)' points to the second layer from the top; 'BGO Calorimeter' points to the third layer from the top; and 'Neutron Detector' points to the bottom-most purple layer. The central core contains a grid of green rectangular modules. To the right of the satellite, there is a purple bar with four small flags: China (red), Switzerland (white with blue cross), Italy (green), and France (blue). Below this bar, the text 'Launch: Dec. 2015' is written. To the right of the satellite, a green bar contains the text '~3x GF of AMS-02'.

Plastic Scintillator Detector

Silicon-Tungsten Tracker (STK)

BGO Calorimeter

Neutron Detector

Launch: Dec. 2015

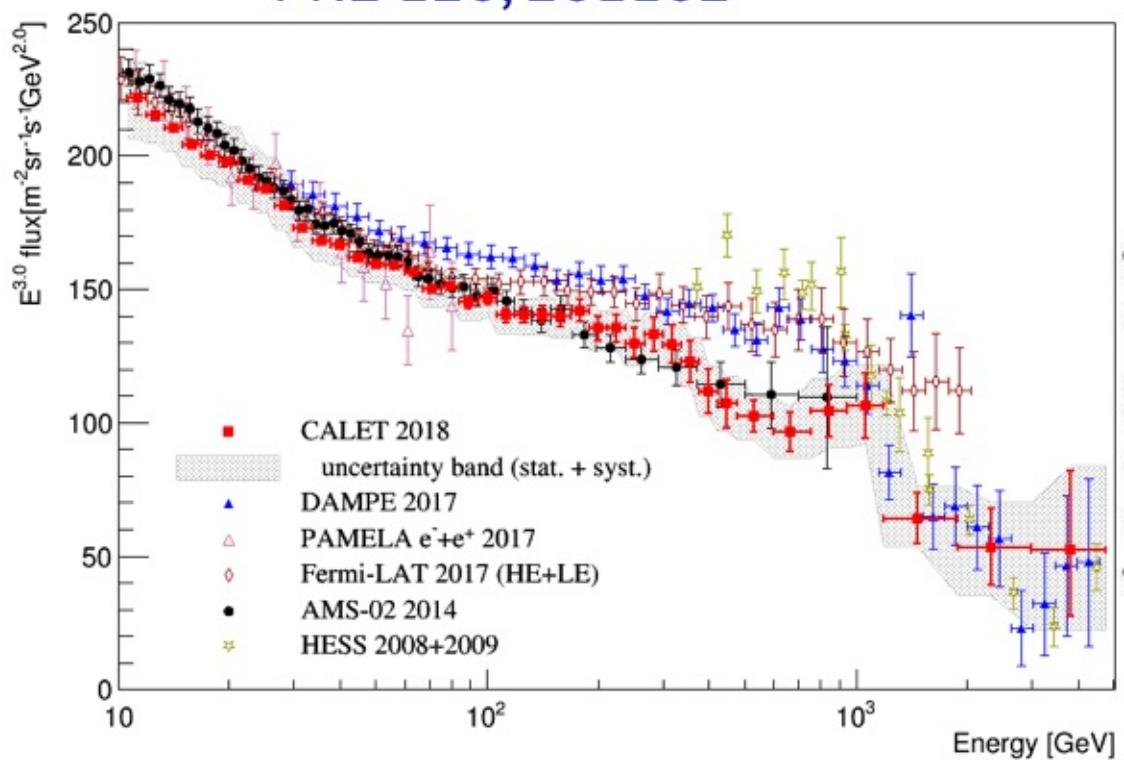
~3x GF of AMS-02

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

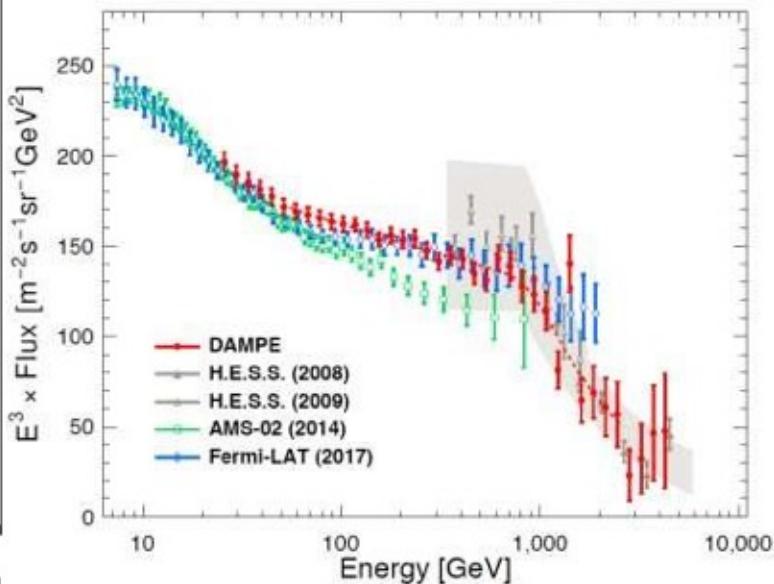
**W converter + thick calorimeter (total 32 X_0)
+ precise tracking + charge measurement \Rightarrow
high energy γ -ray, electron and CR telescope**

CALET VS DAMPE

PRL 120, 261102



Nature 552, 63

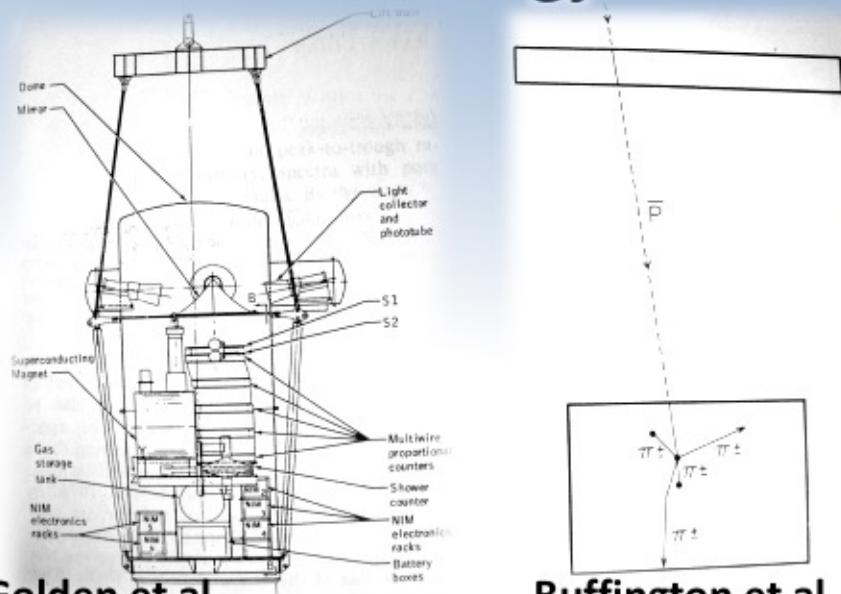


Cosmic-Ray Antiprotons



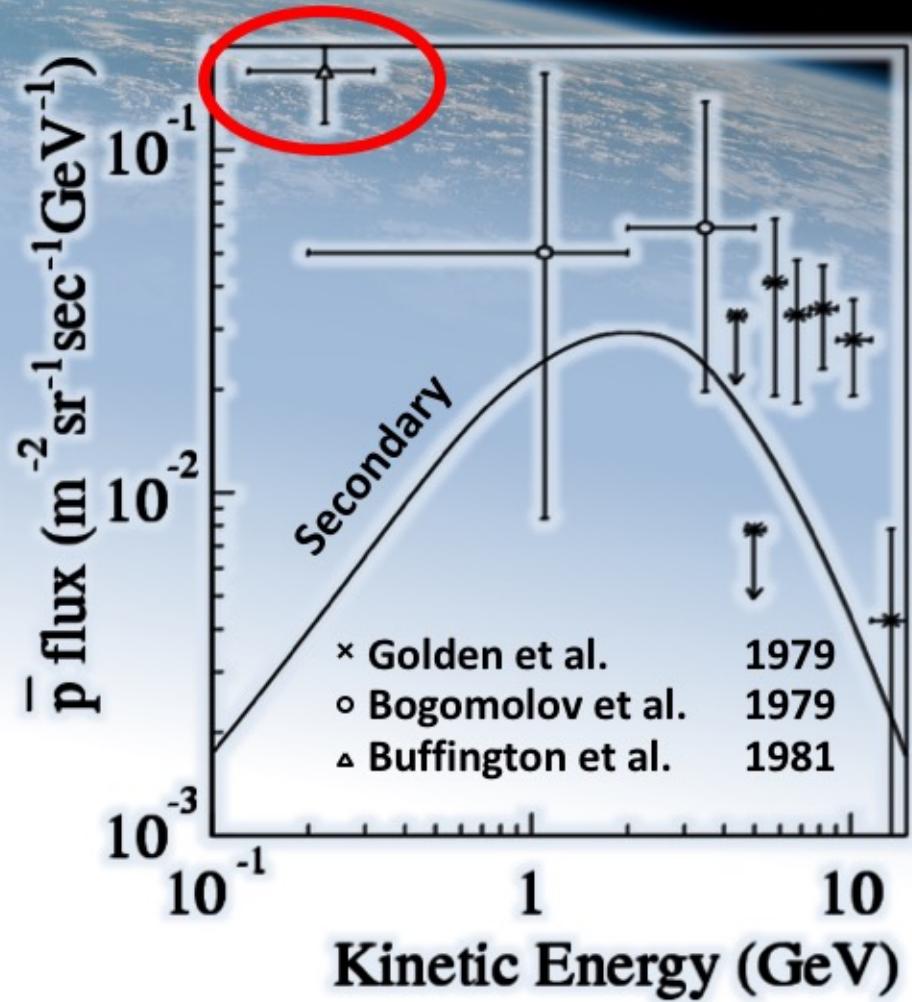
Cosmic Ray antiprotons in ~1980

First observation in 1979
Significant excess
in low energy



Golden et al.
Magnetic spectrometer

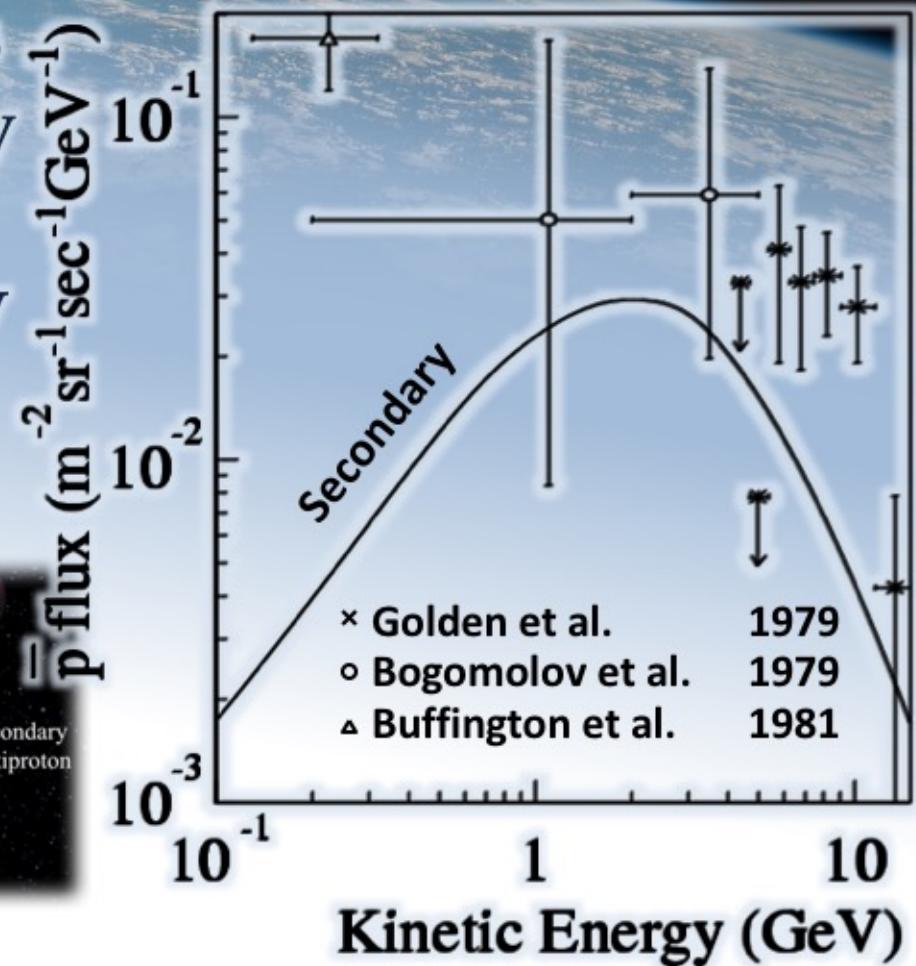
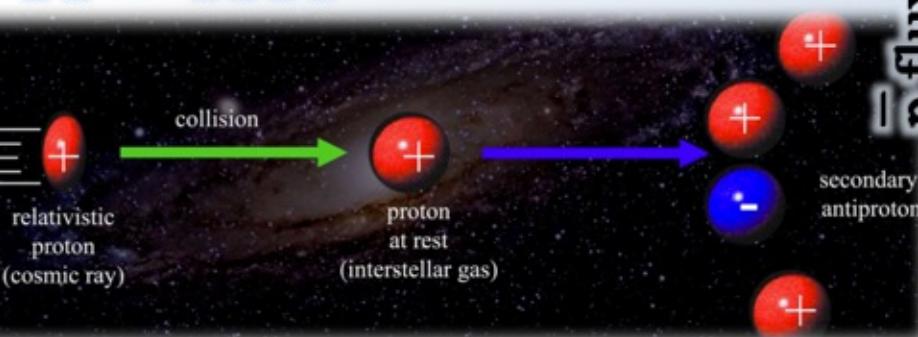
Buffington et al.
Spark chamber



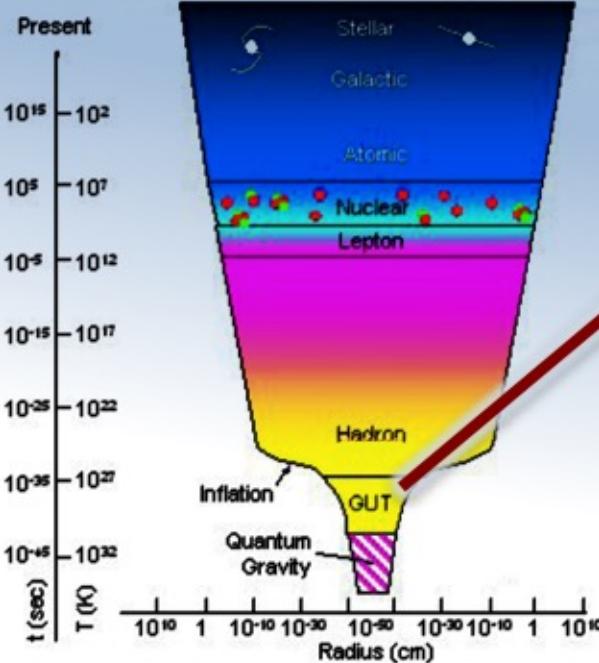
Antiproton production

- Kinematic constraints in low energy
- Spectrum has a peak at $E_{\text{kin}} \sim 2 \text{ GeV}$

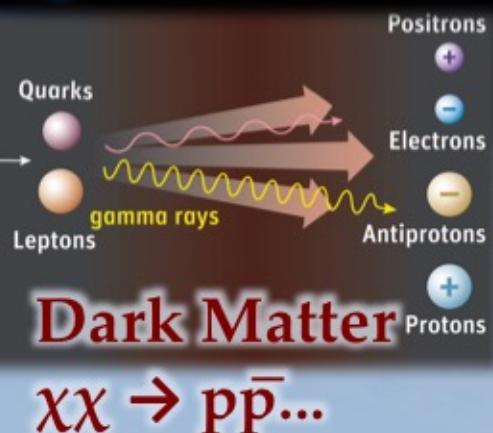
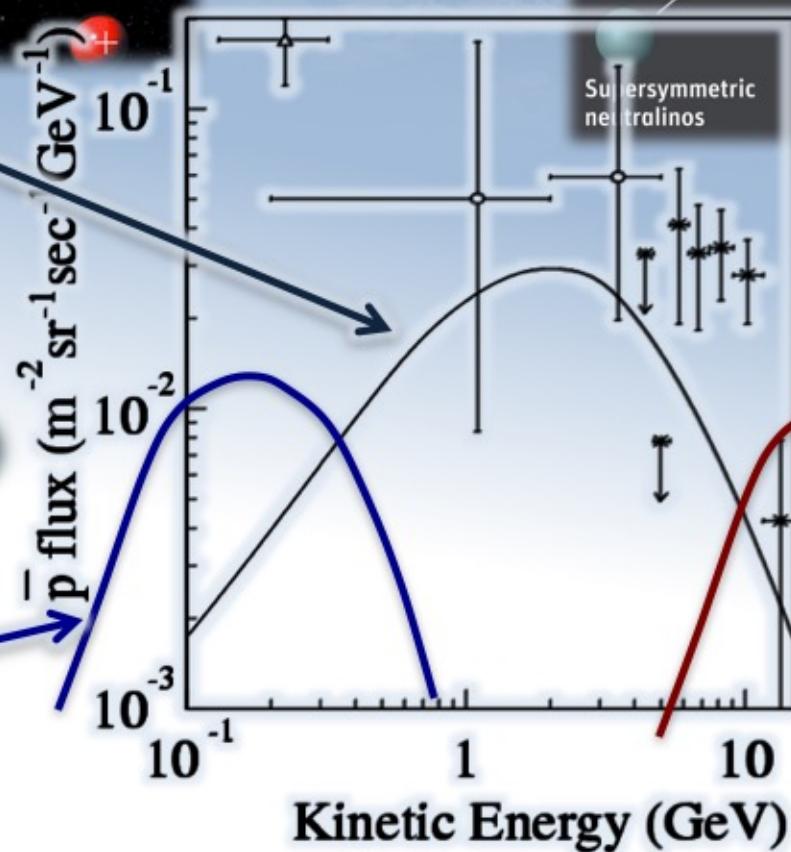
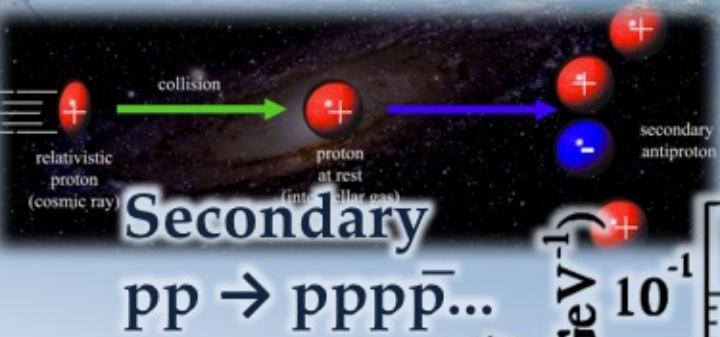
Secondary production
 $\text{pp} \rightarrow \text{ppp}\bar{p} \dots$



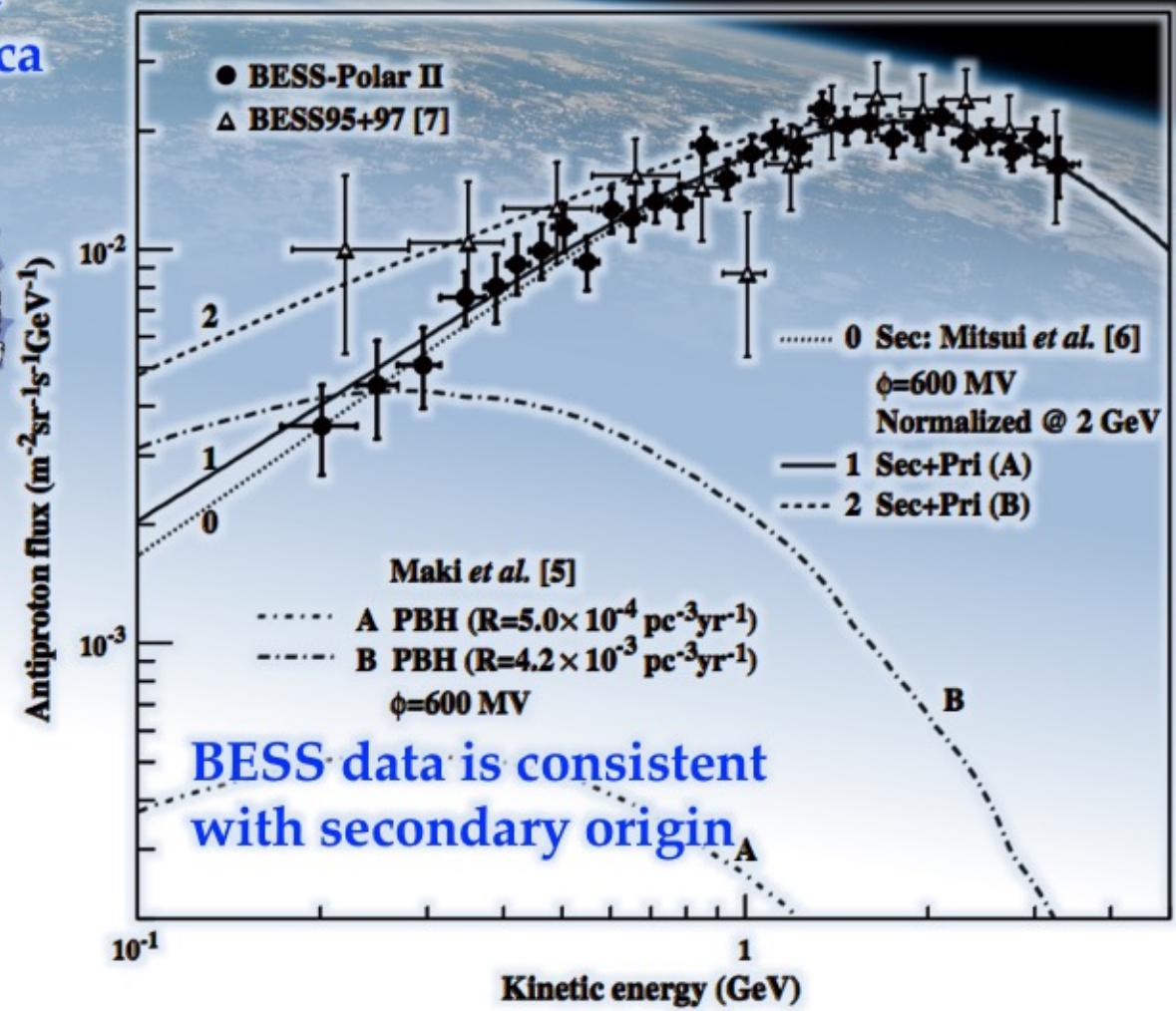
Evaporation of Primordial Black Holes



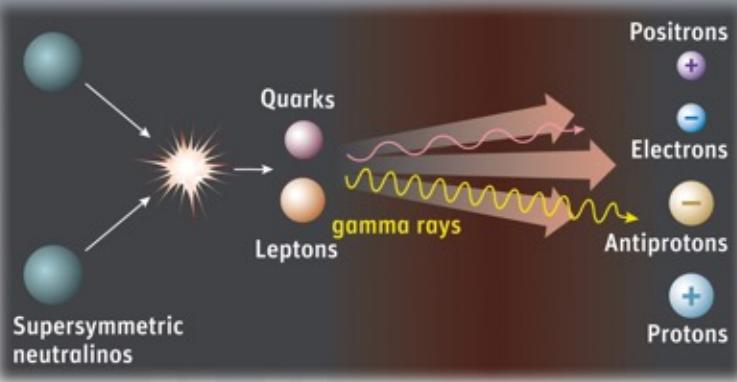
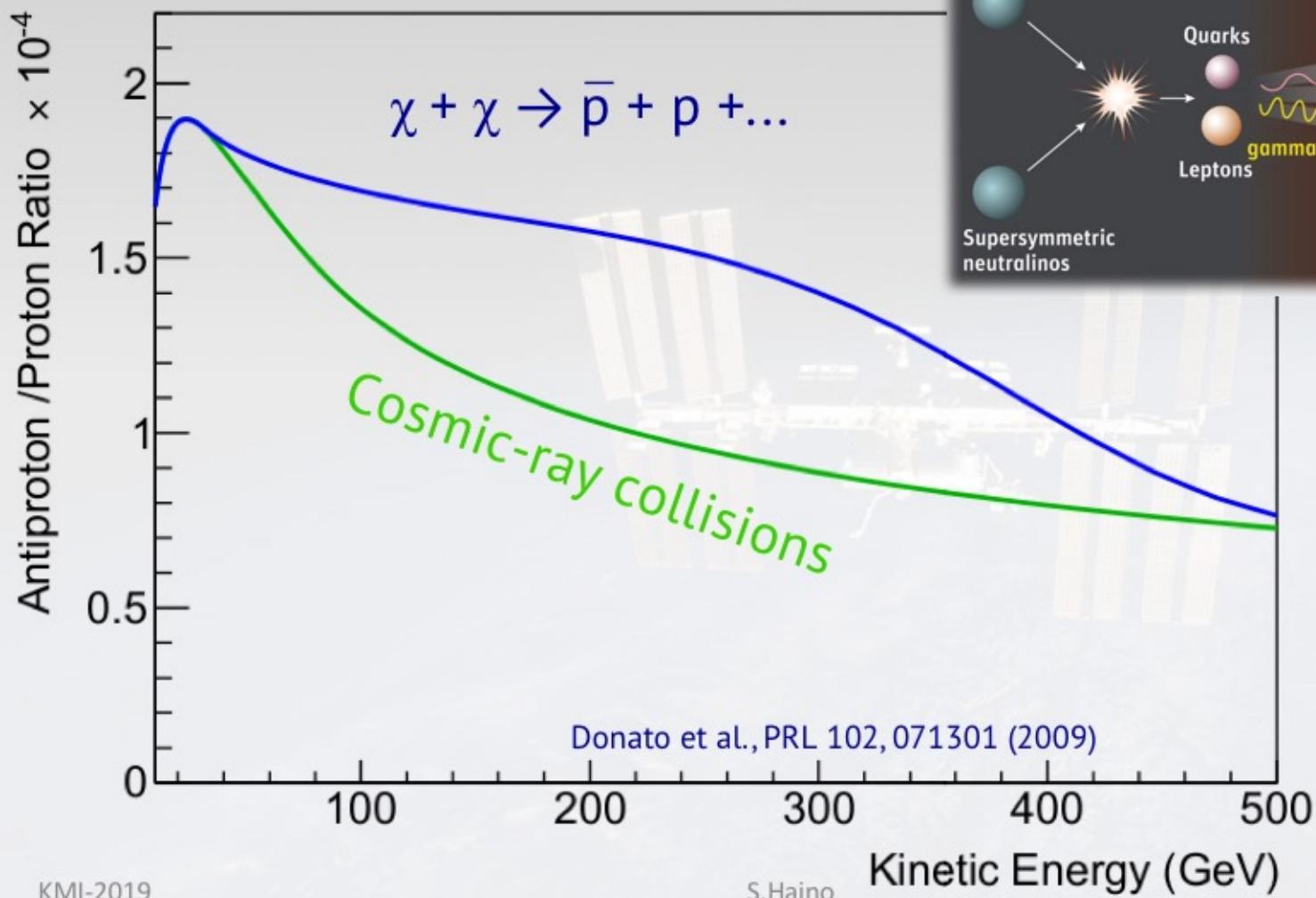
CR Antiproton summary



BESS-Polar

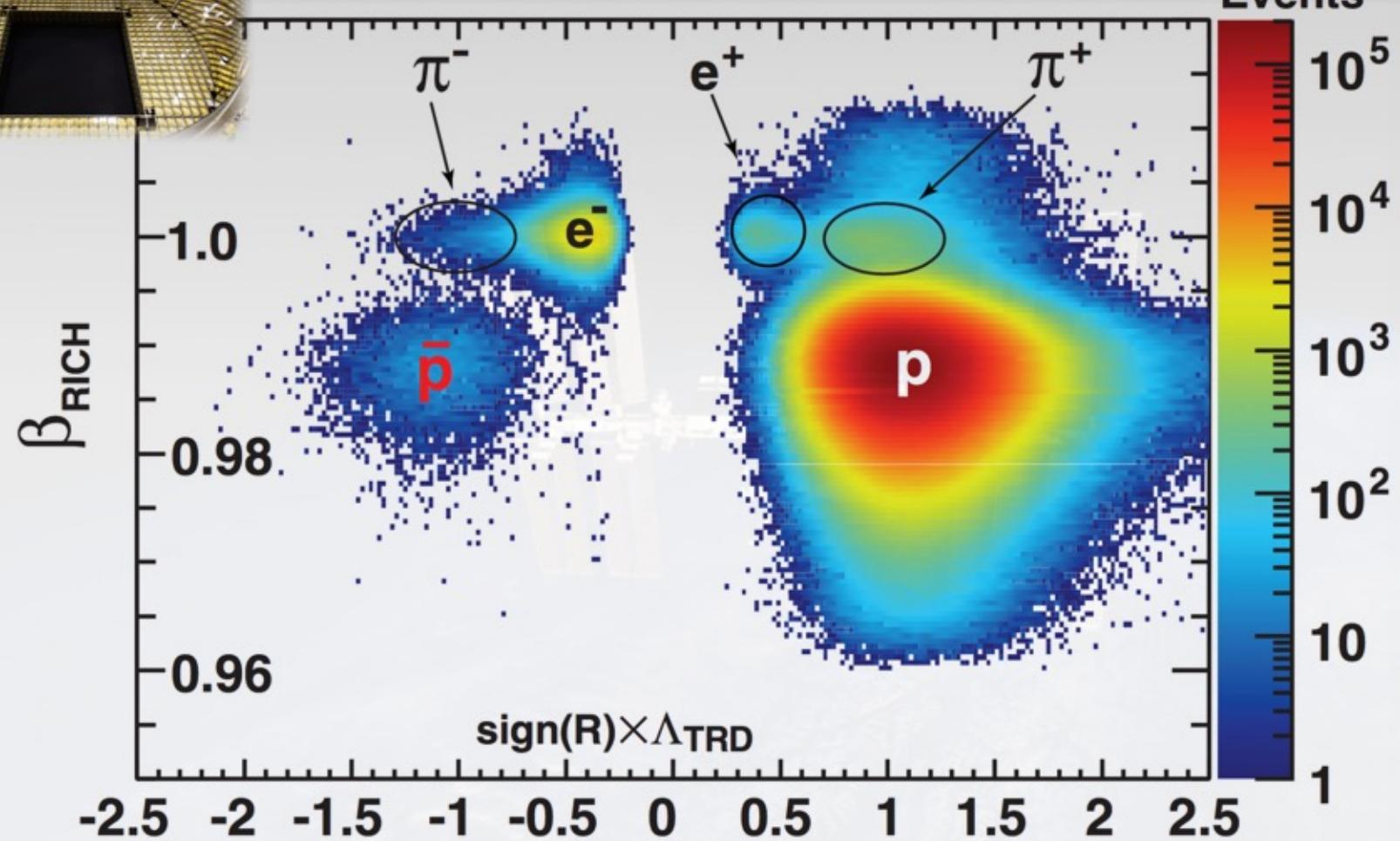


Antiprotons : another DM probe

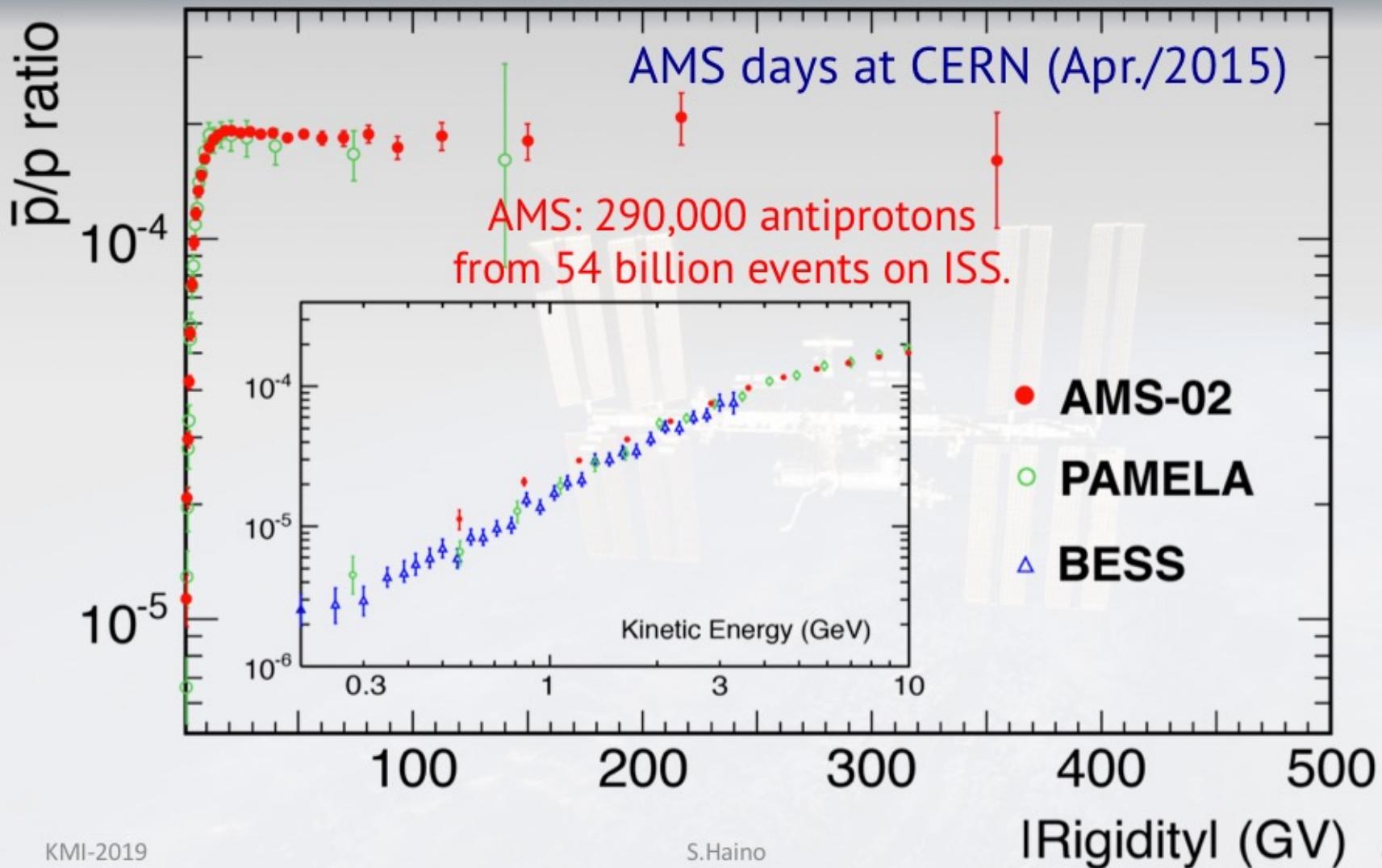


Anti-proton Identification in AMS

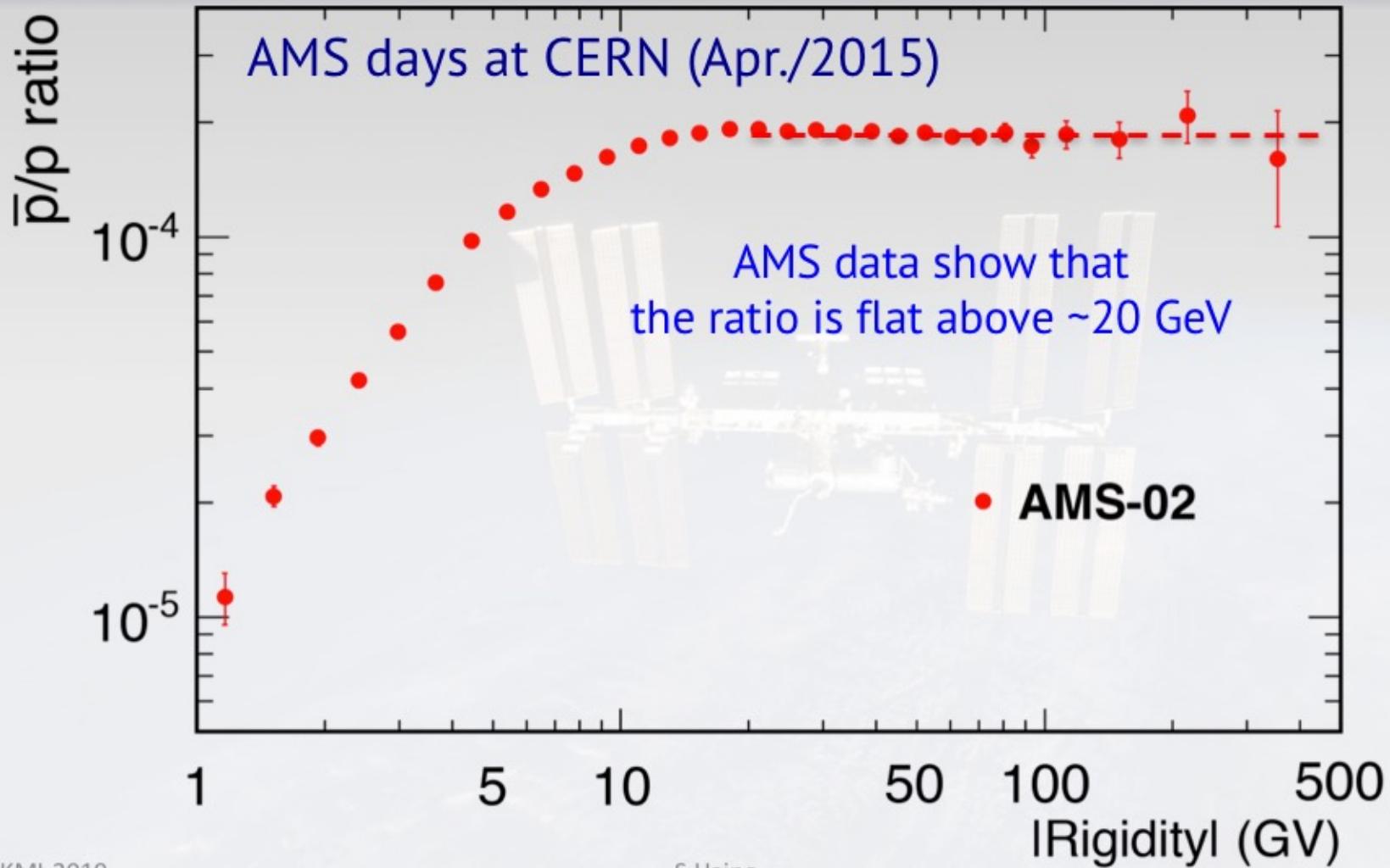
RICH



AMS Antiproton : current status

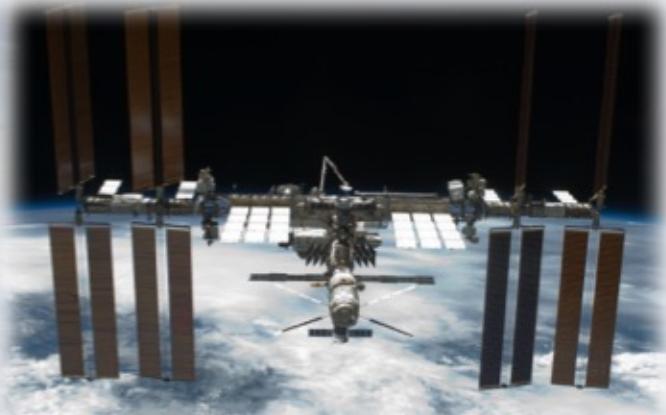


AMS Antiproton : current status



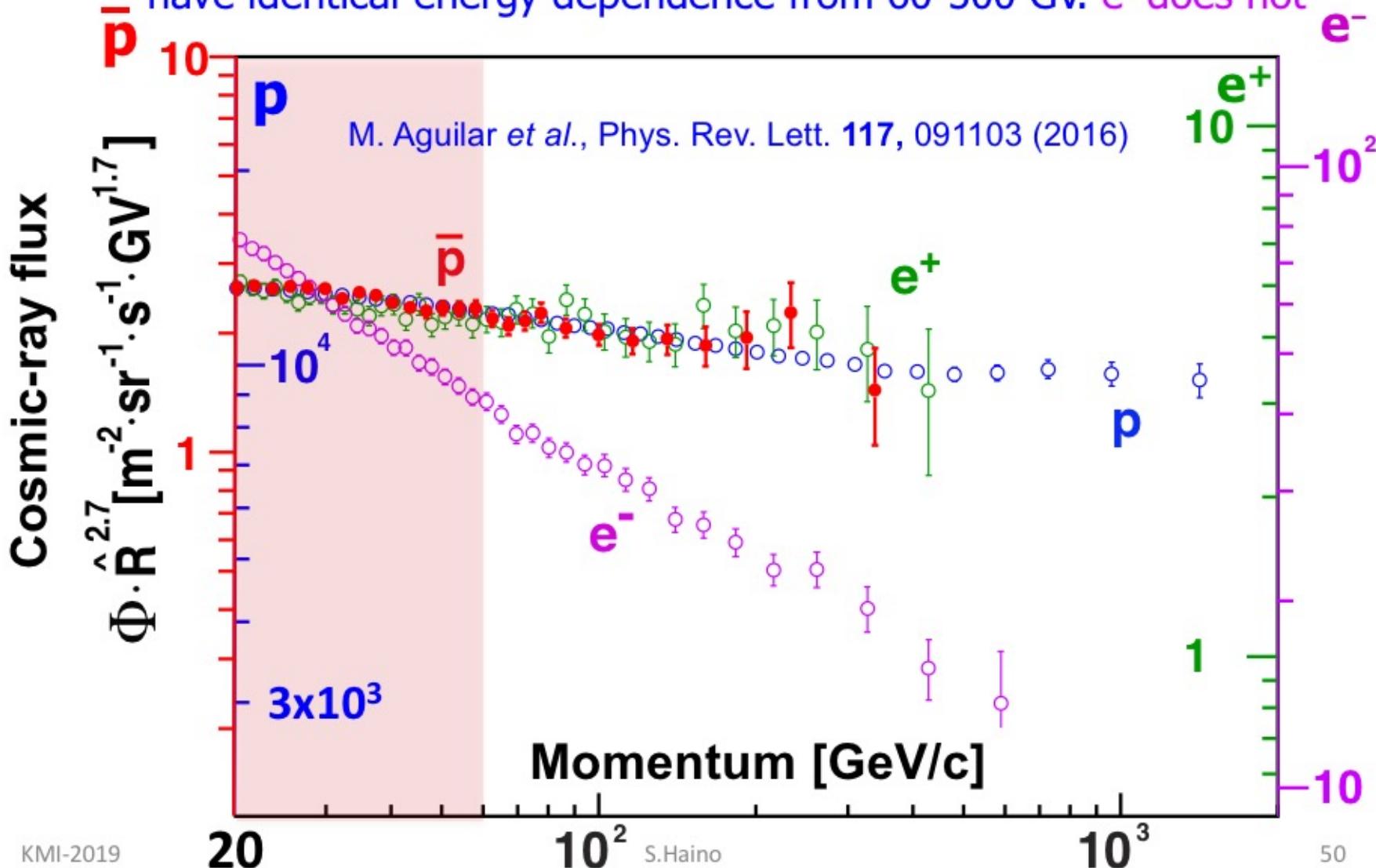
Antiprotons : history and future

Project	BESS-93	BESS-97	BESS-Polar I	BESS-Polar II	AMS (current)	AMS (expected)
Year	1993	1997	2004	2007	2011-2015	2011-2024
Np-	4	415	1,520	7,886	~350,000	>1,000,000



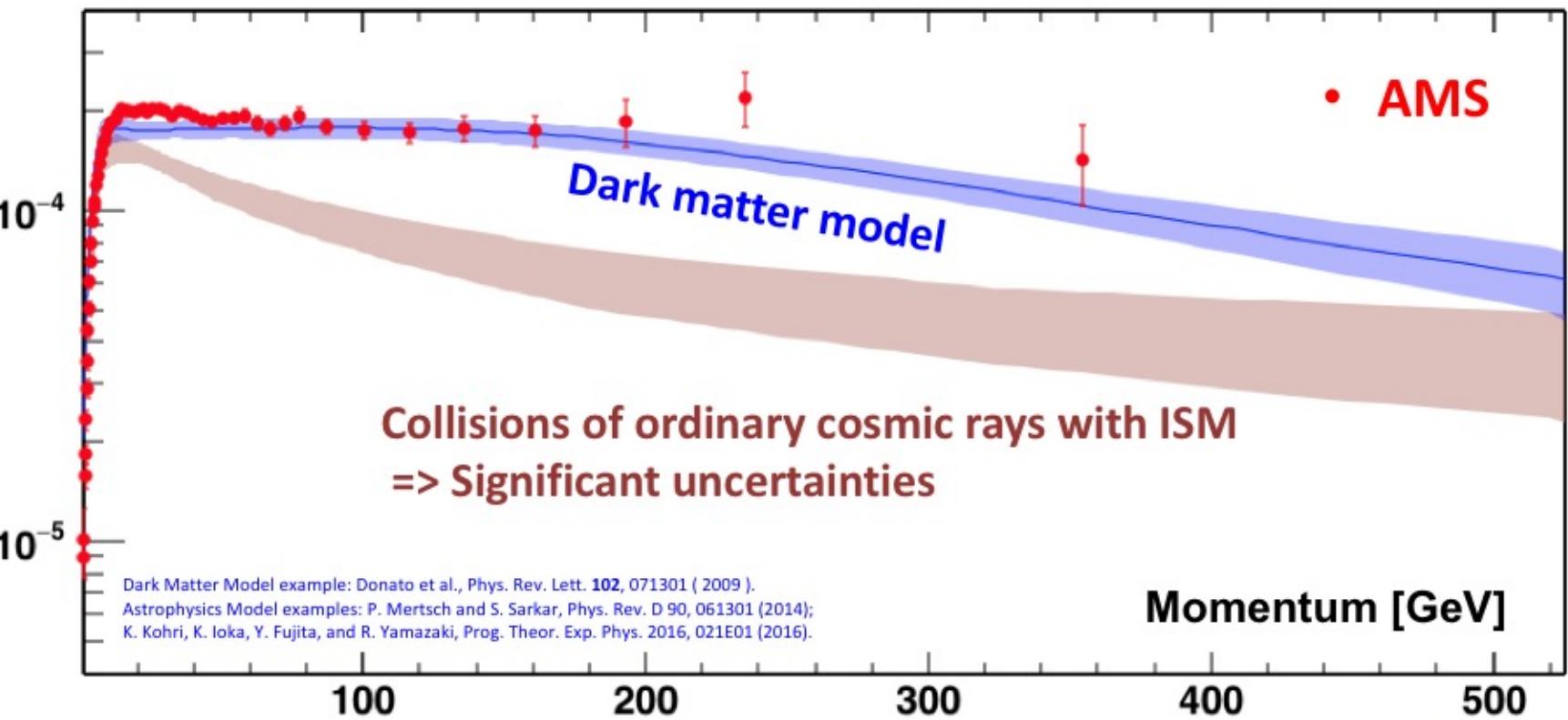
The antiproton (\bar{p}) flux and properties of elementary particles (p, e^+, e^-) fluxes

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



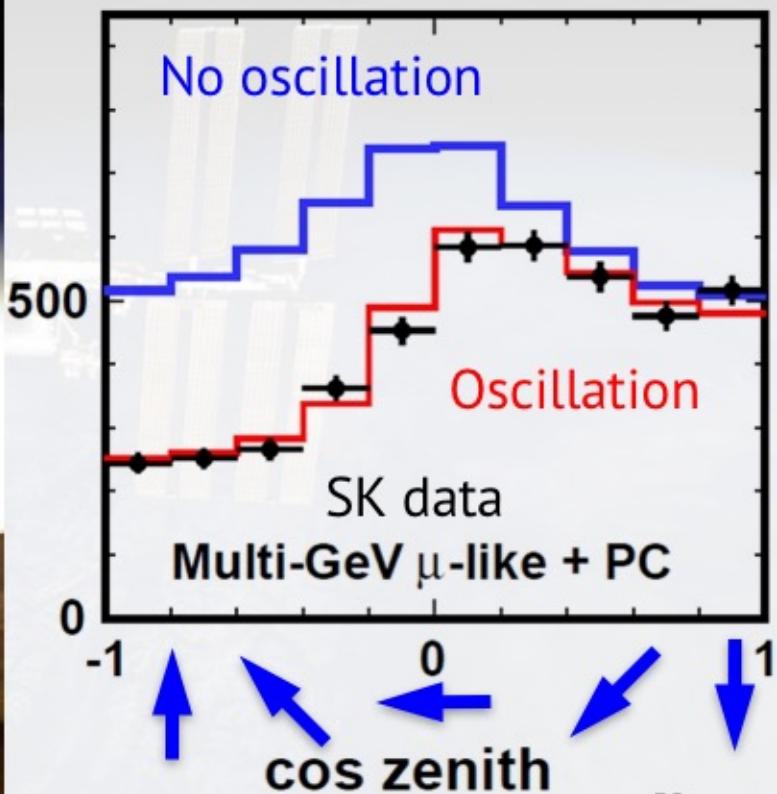
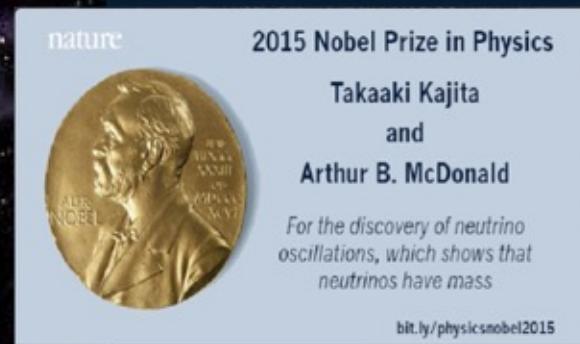
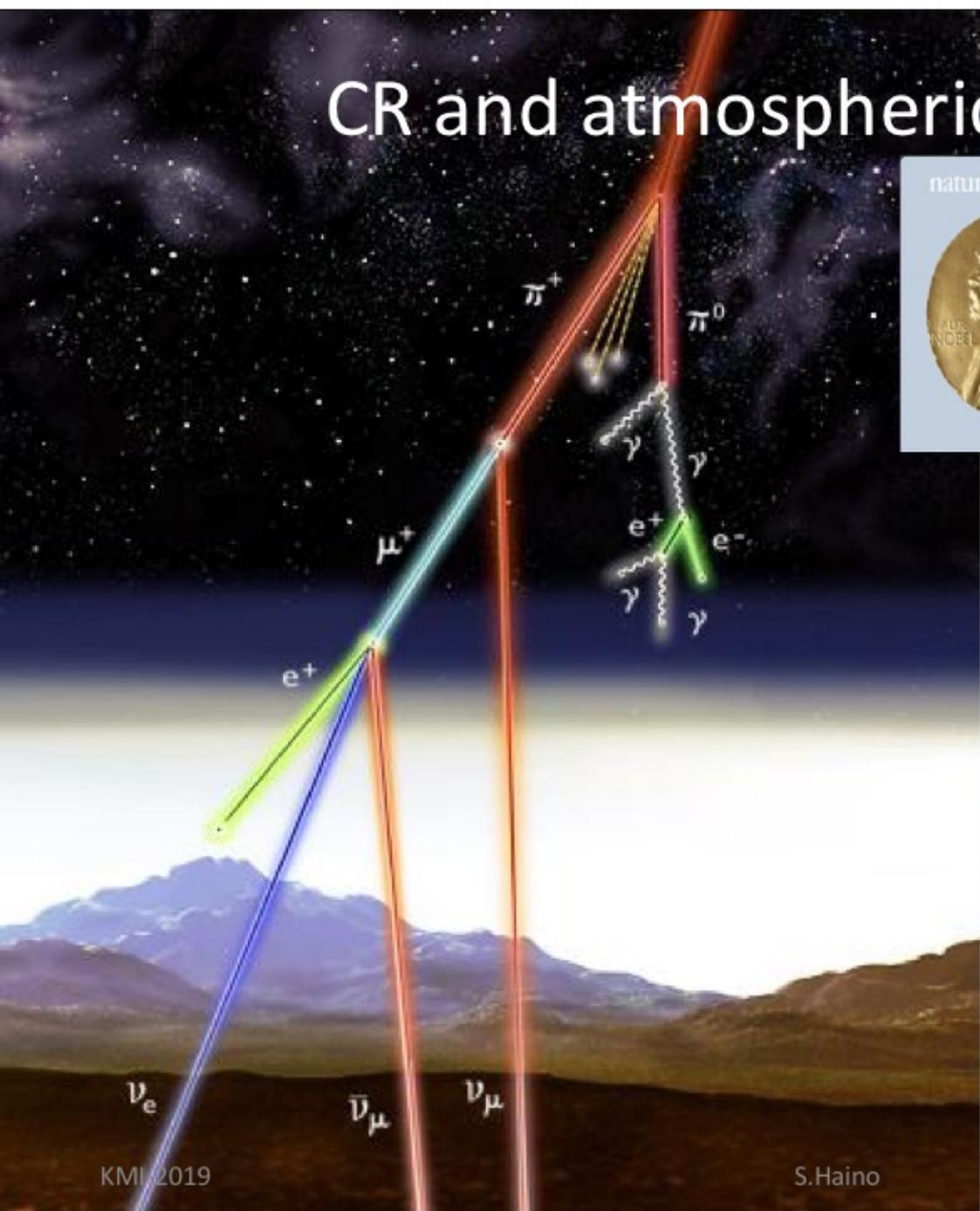
Antiprotons from Dark matter ?

\bar{p}/p ratio

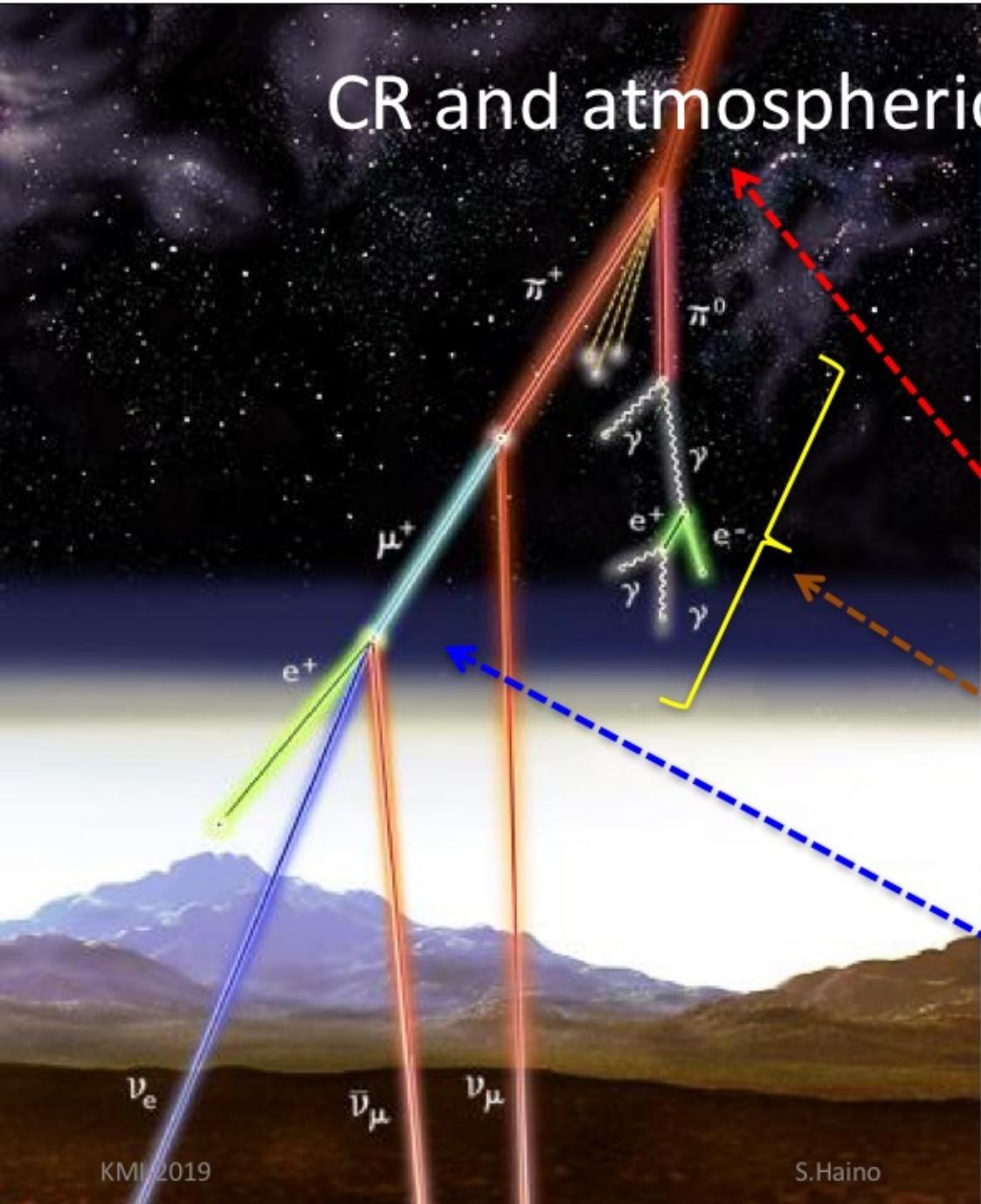


Cosmic-Ray Nuclei

CR and atmospheric neutrinos



CR and atmospheric neutrinos



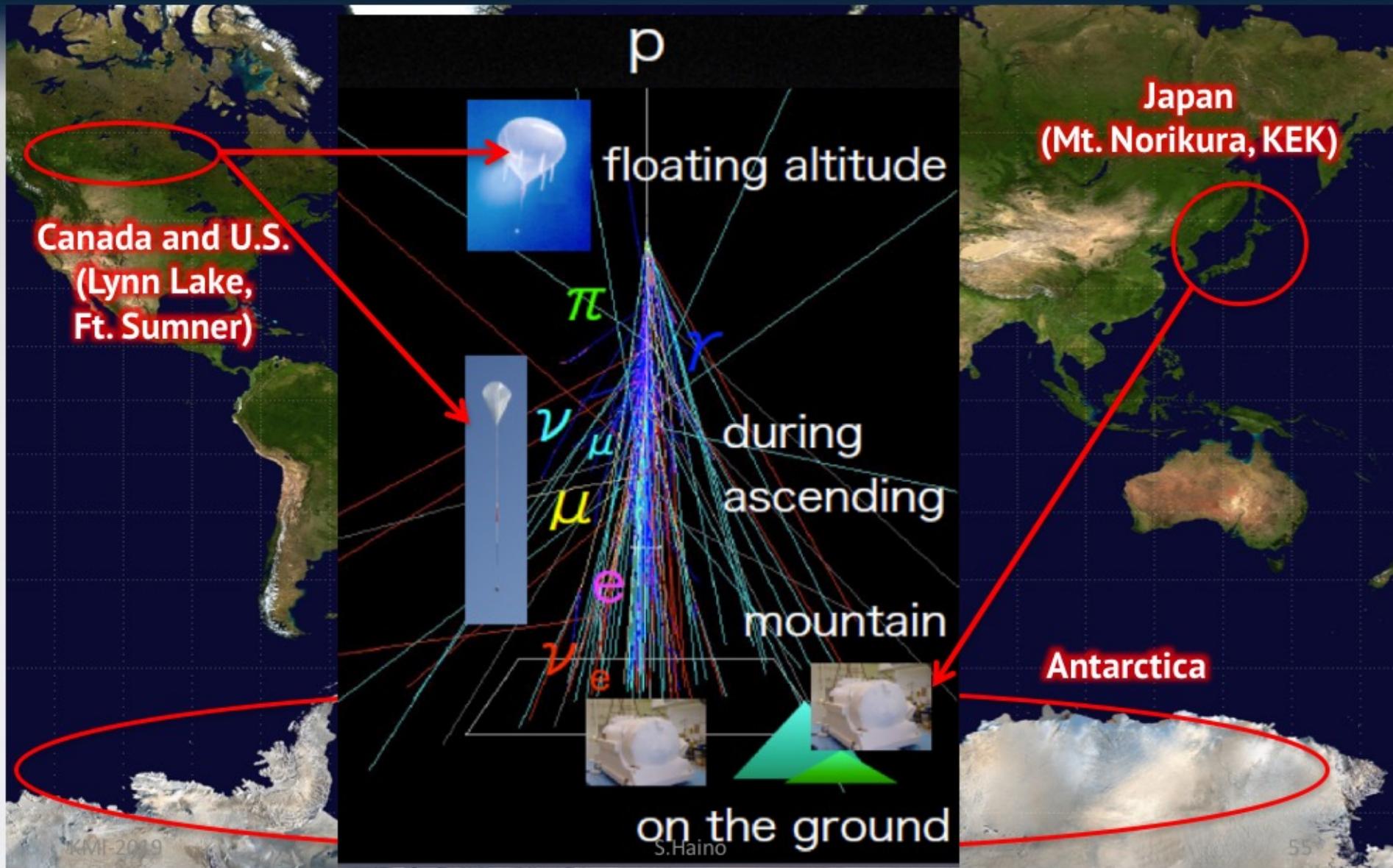
H K K M S model
onda ajita asahara idorikawa

Primary CR determined
by direct measurements

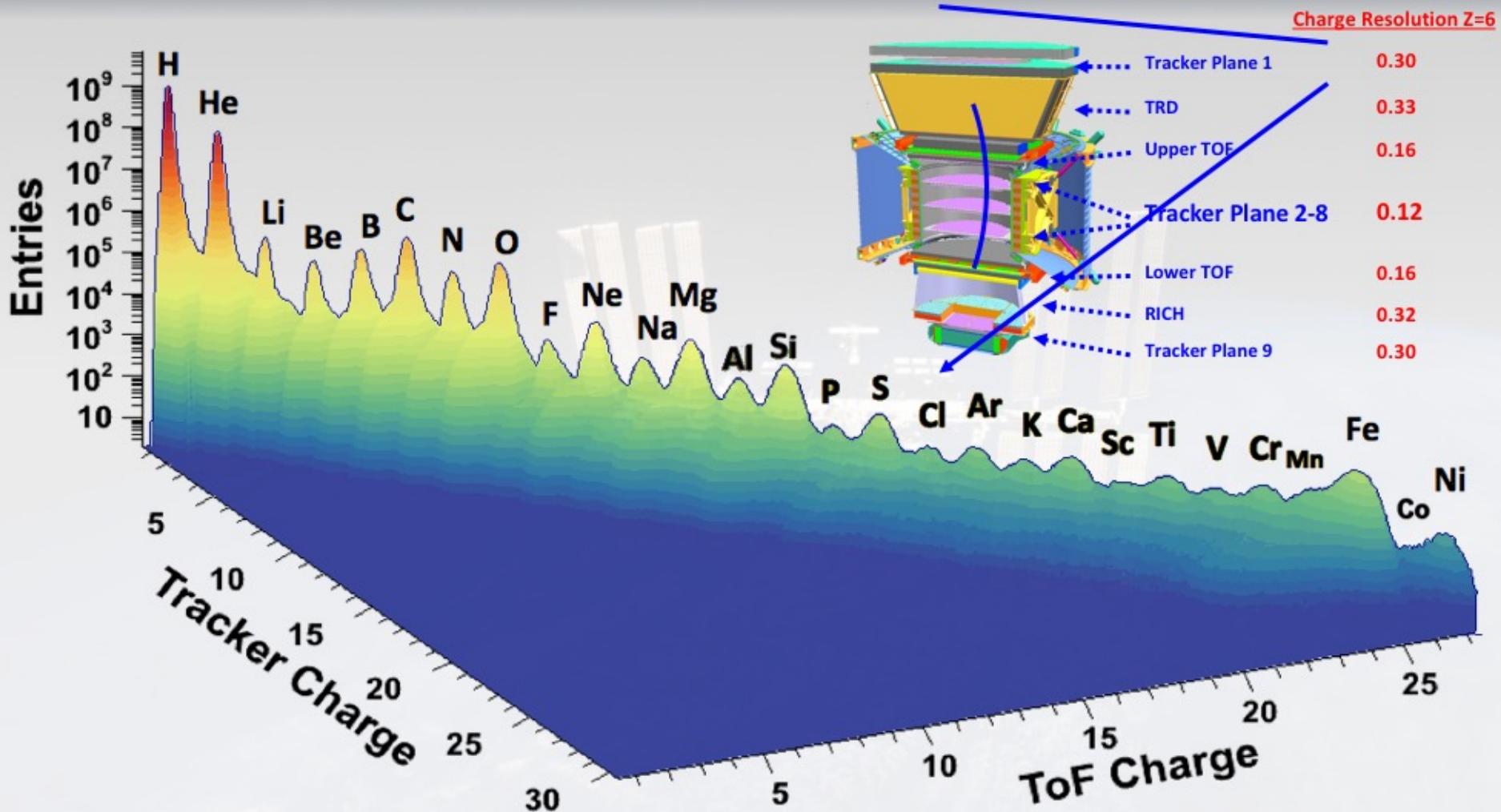
MC simulation (3D)
of interactions/dedays
in the atmosphere

Validation with muon
flux measurements

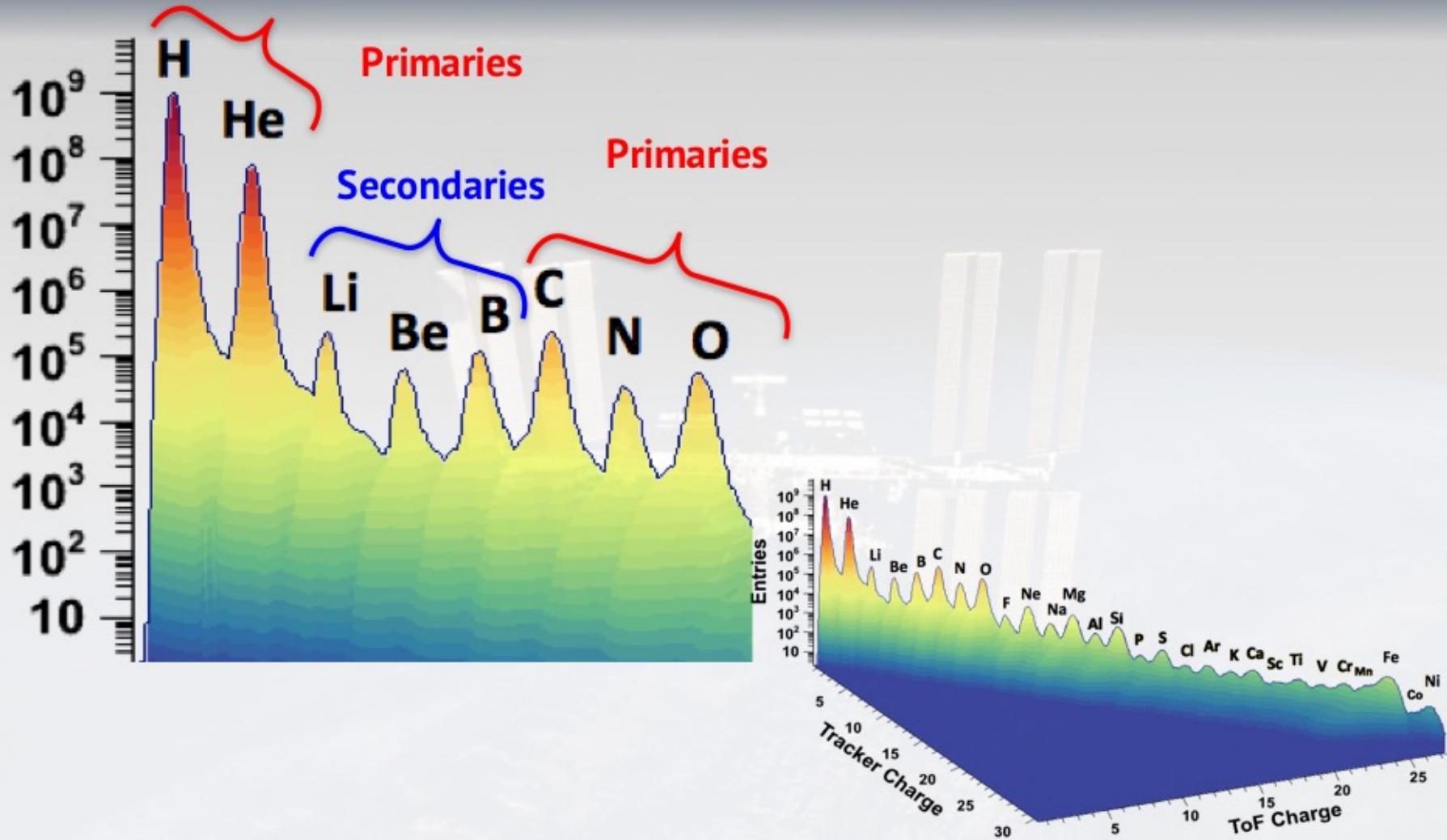
BESS is a “portable” detector



Nuclei identification in AMS



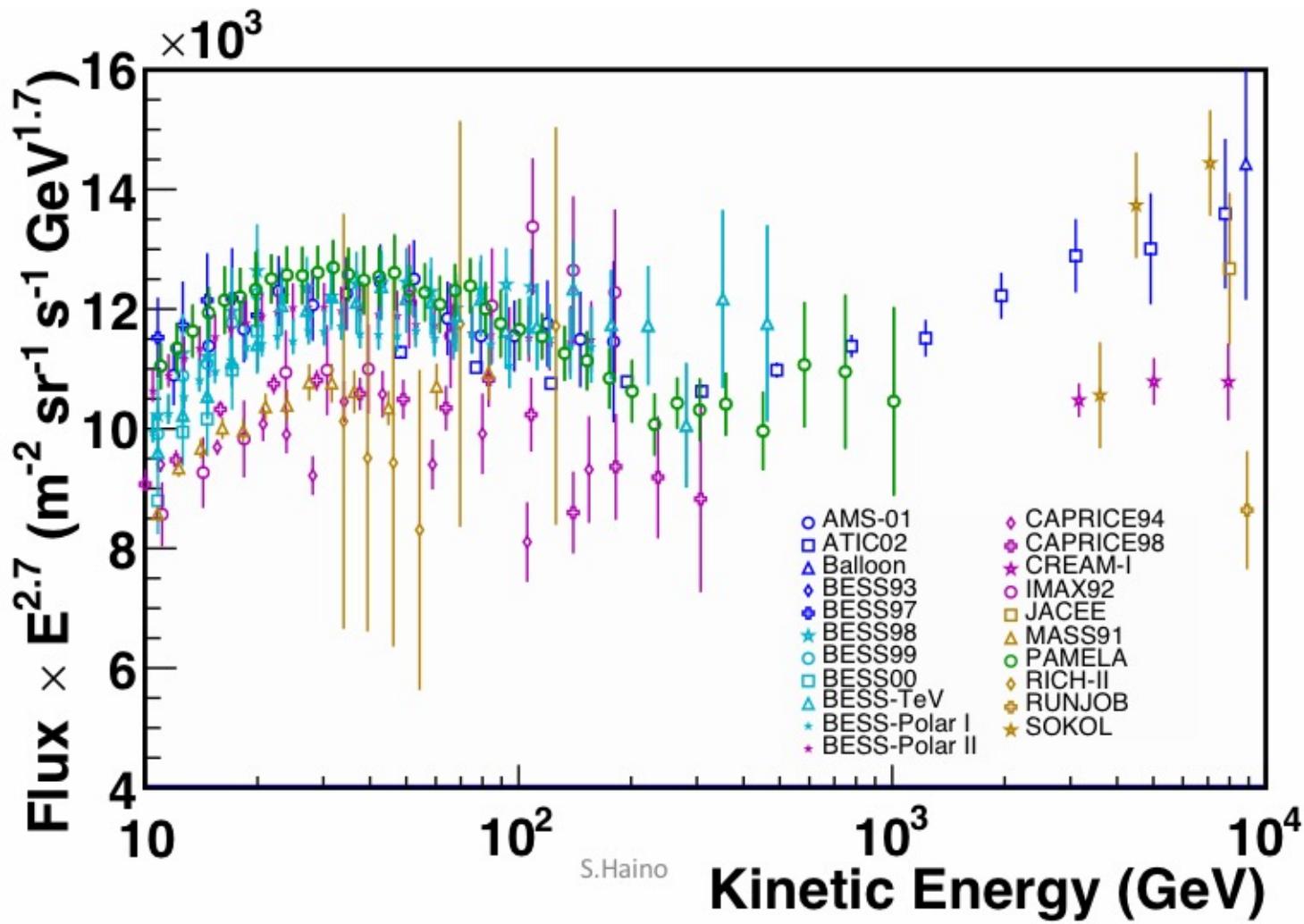
Primary and secondary CRs



Cosmic Protons

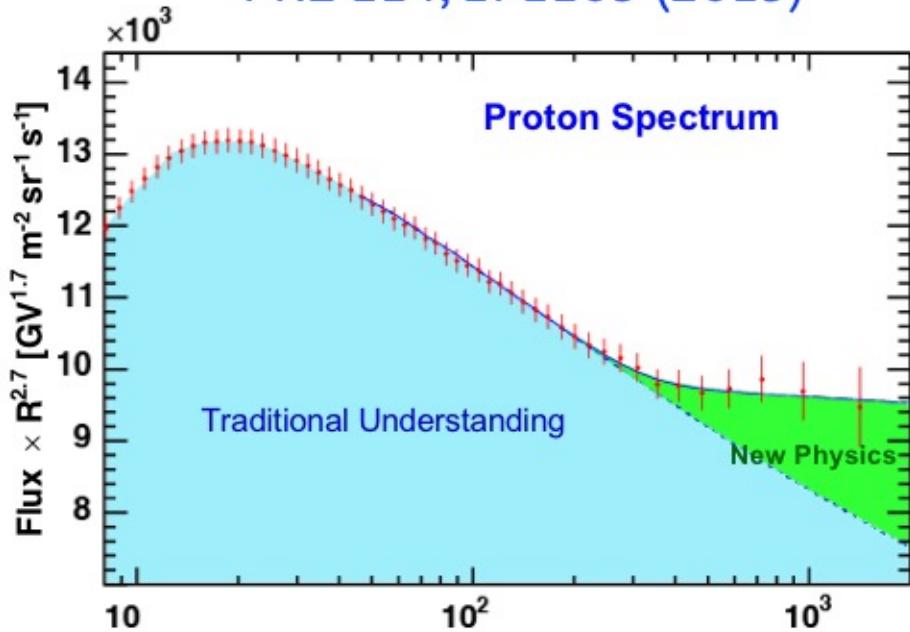
1. Protons are the most abundant cosmic rays.
2. Before AMS there have been many measurements of the proton spectrum.
3. In cosmic rays models, the proton spectral function was assumed to be a single power law $\Phi = CE^\gamma$ with $\gamma = -2.7$

Proton Spectrum

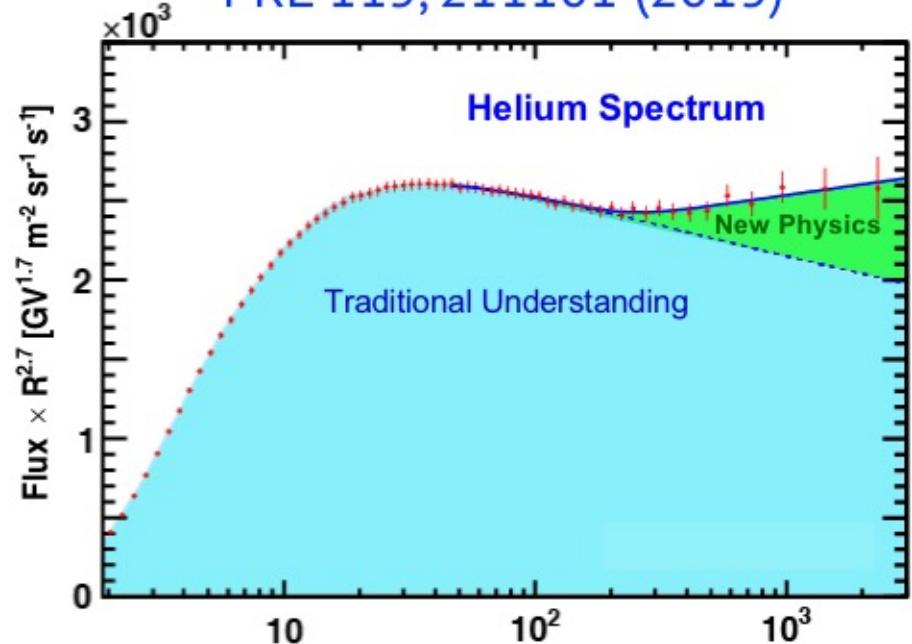


New Physics in p/He spectra

PRL 114, 171103 (2015)



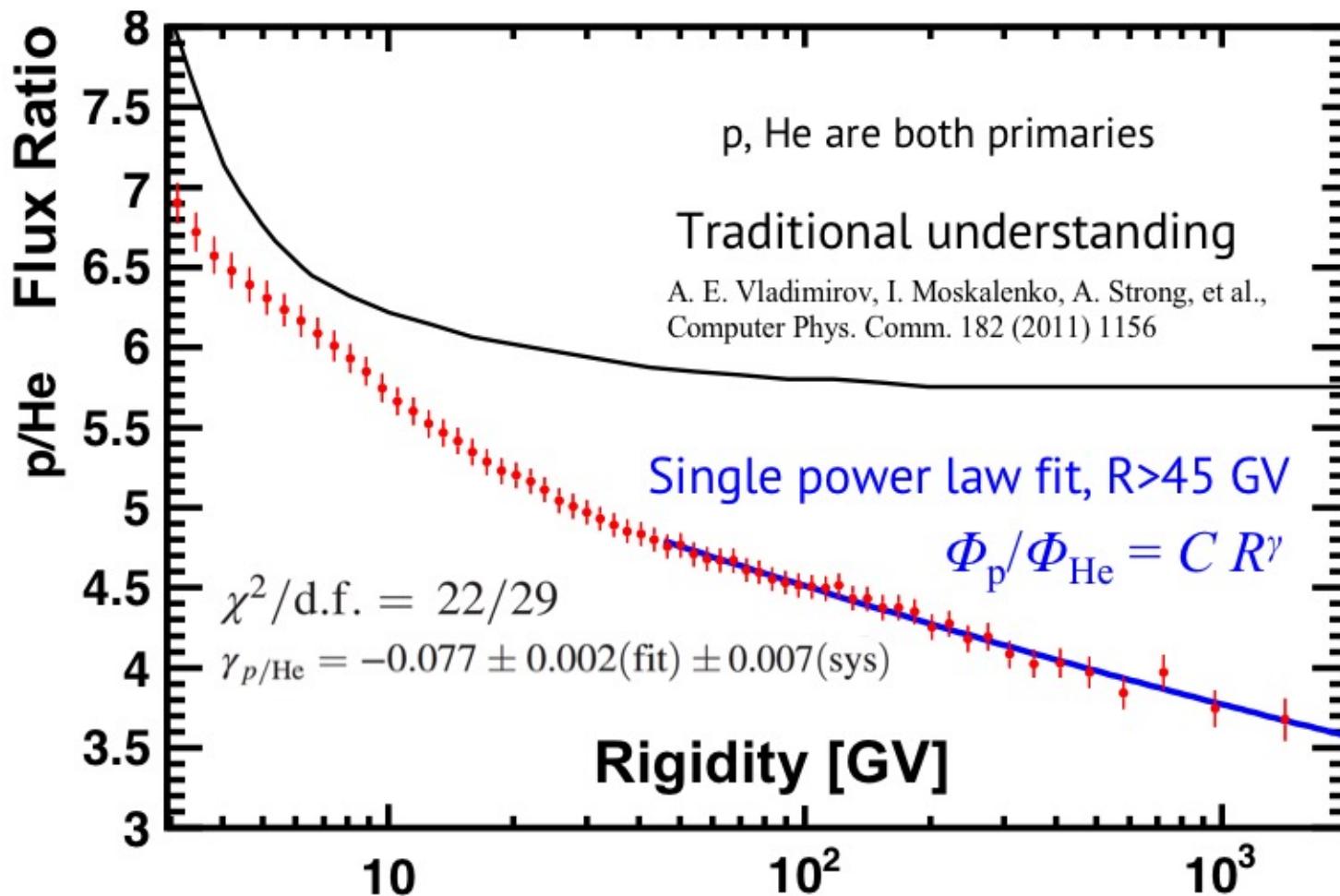
PRL 115, 211101 (2015)



Rigidity (GV)

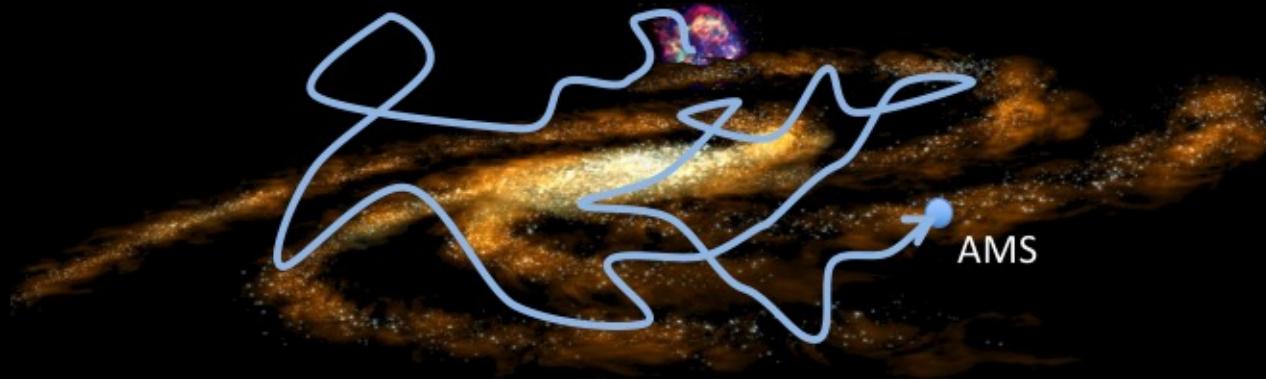
The AMS results have changed the traditional understanding of proton and He spectra

proton/He flux ratio

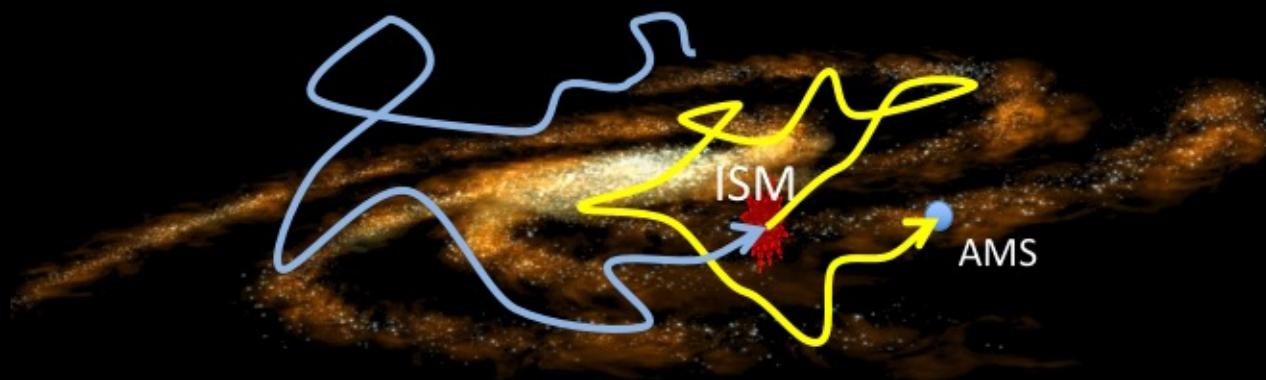


The AMS results have changed the traditional understanding of p,He spectra

Primary Cosmic Rays (p, He, C, O, ...)

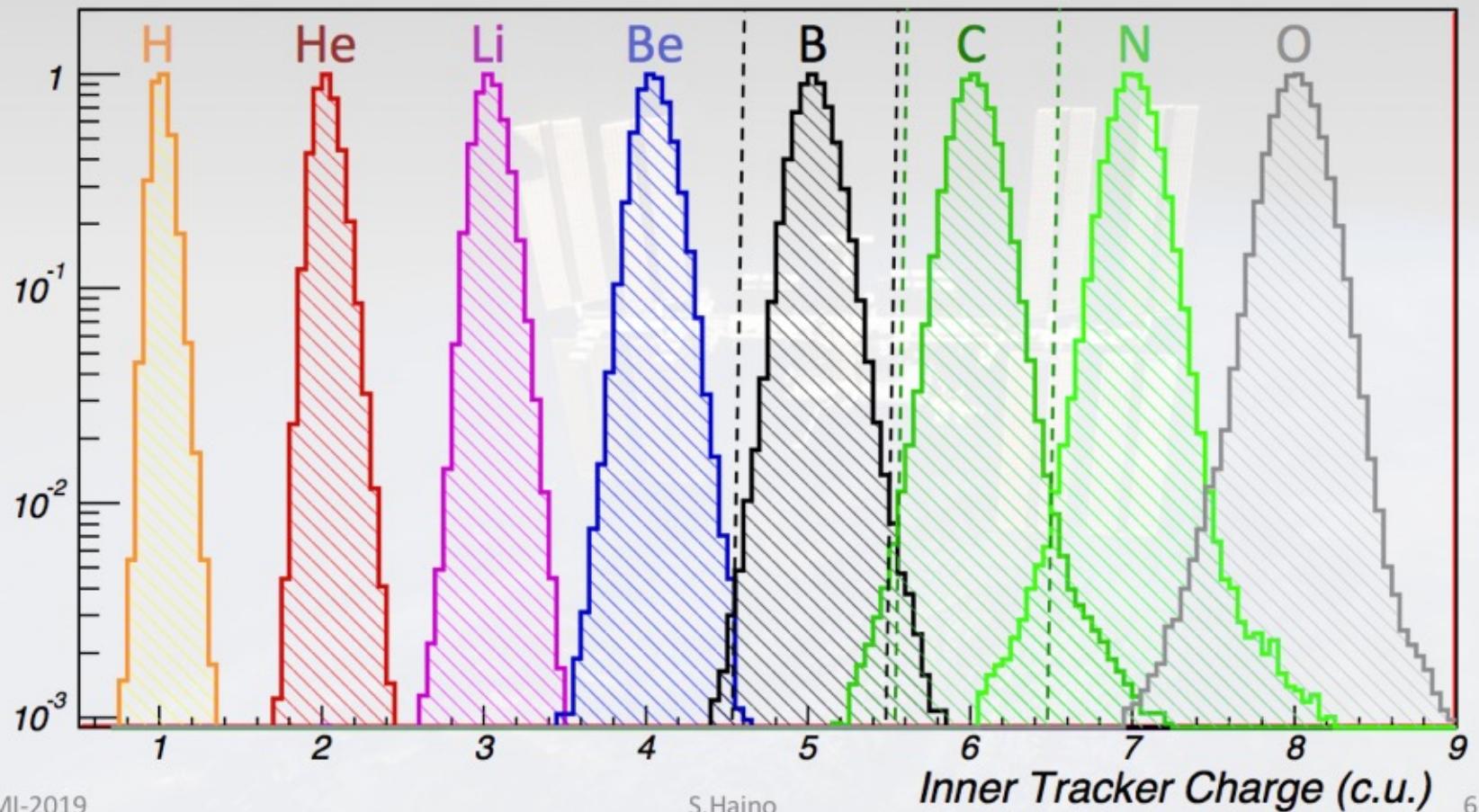


Secondary Cosmic Rays (Li, Be, B, ...)



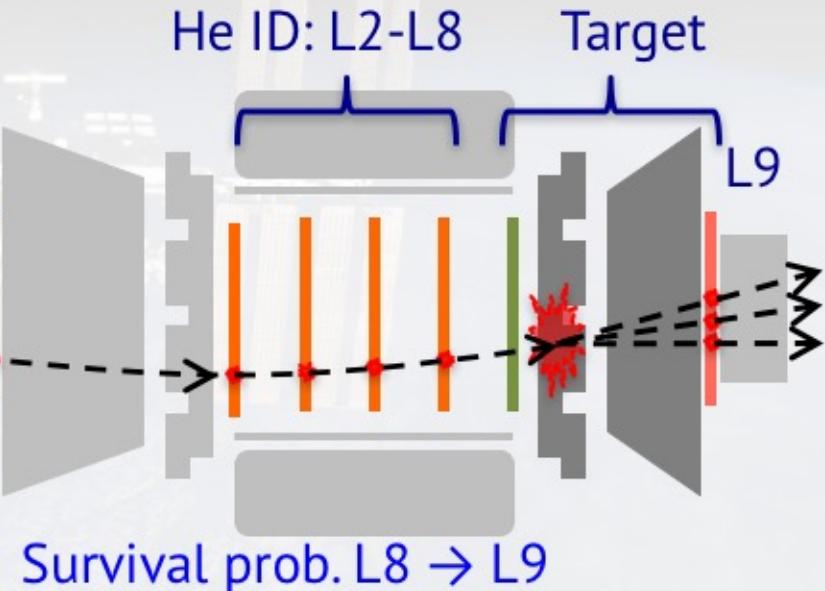
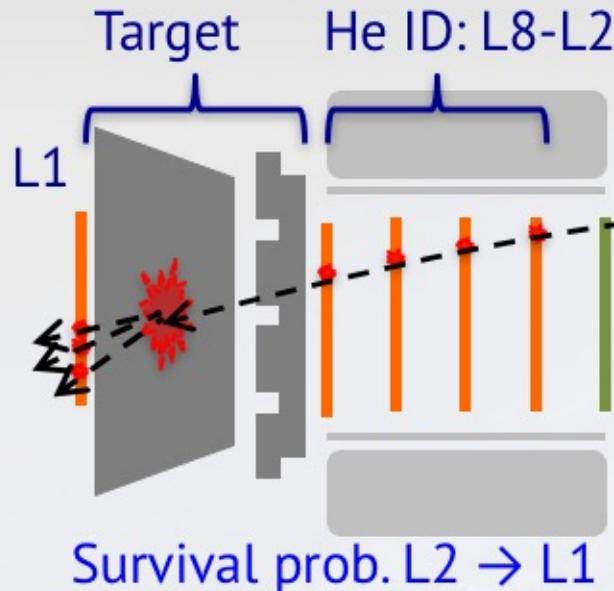
Charge separation by AMS

Misidentification < 0.1 % with > 98 % efficiency



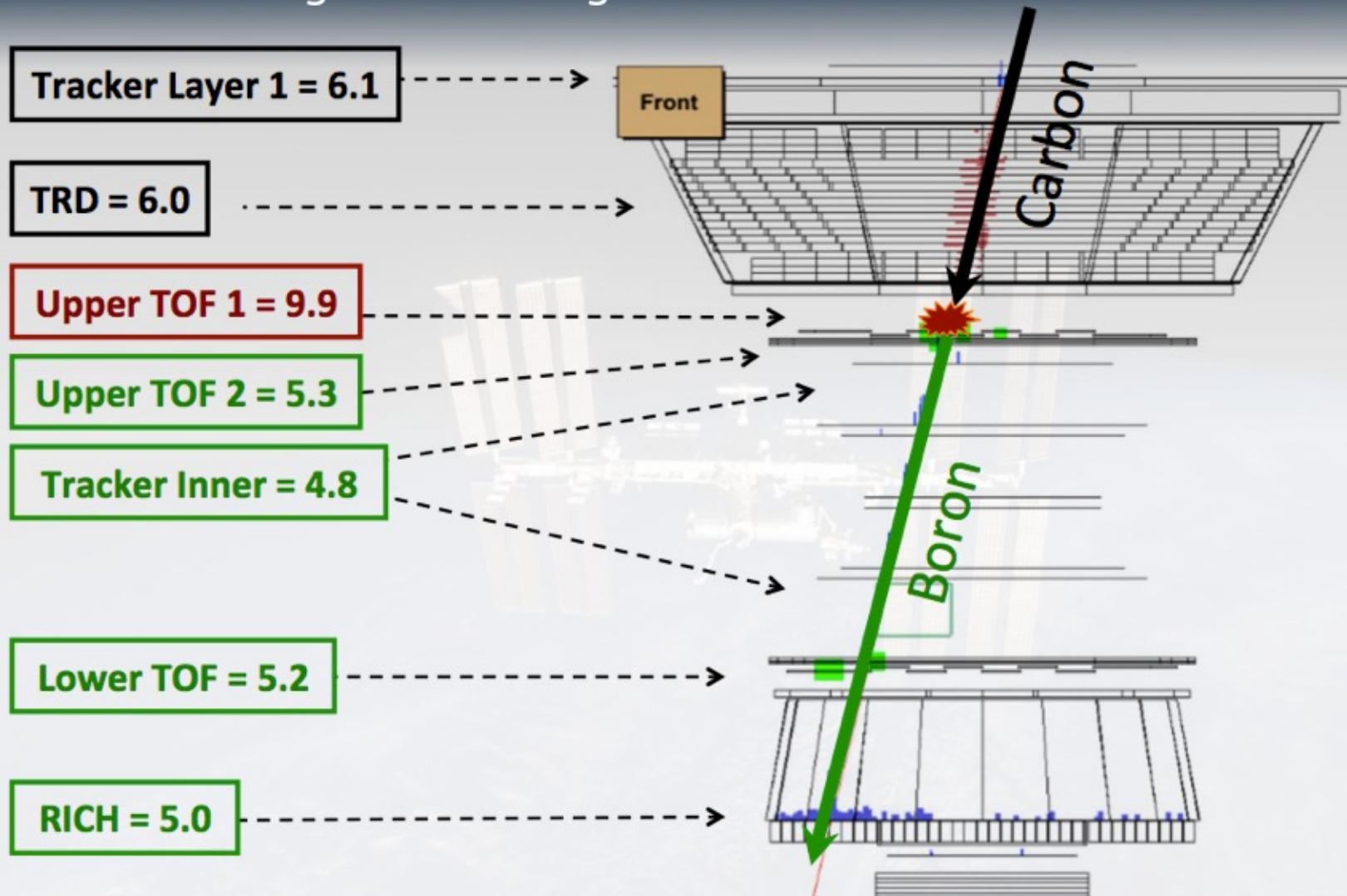
He survival probability measurement

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



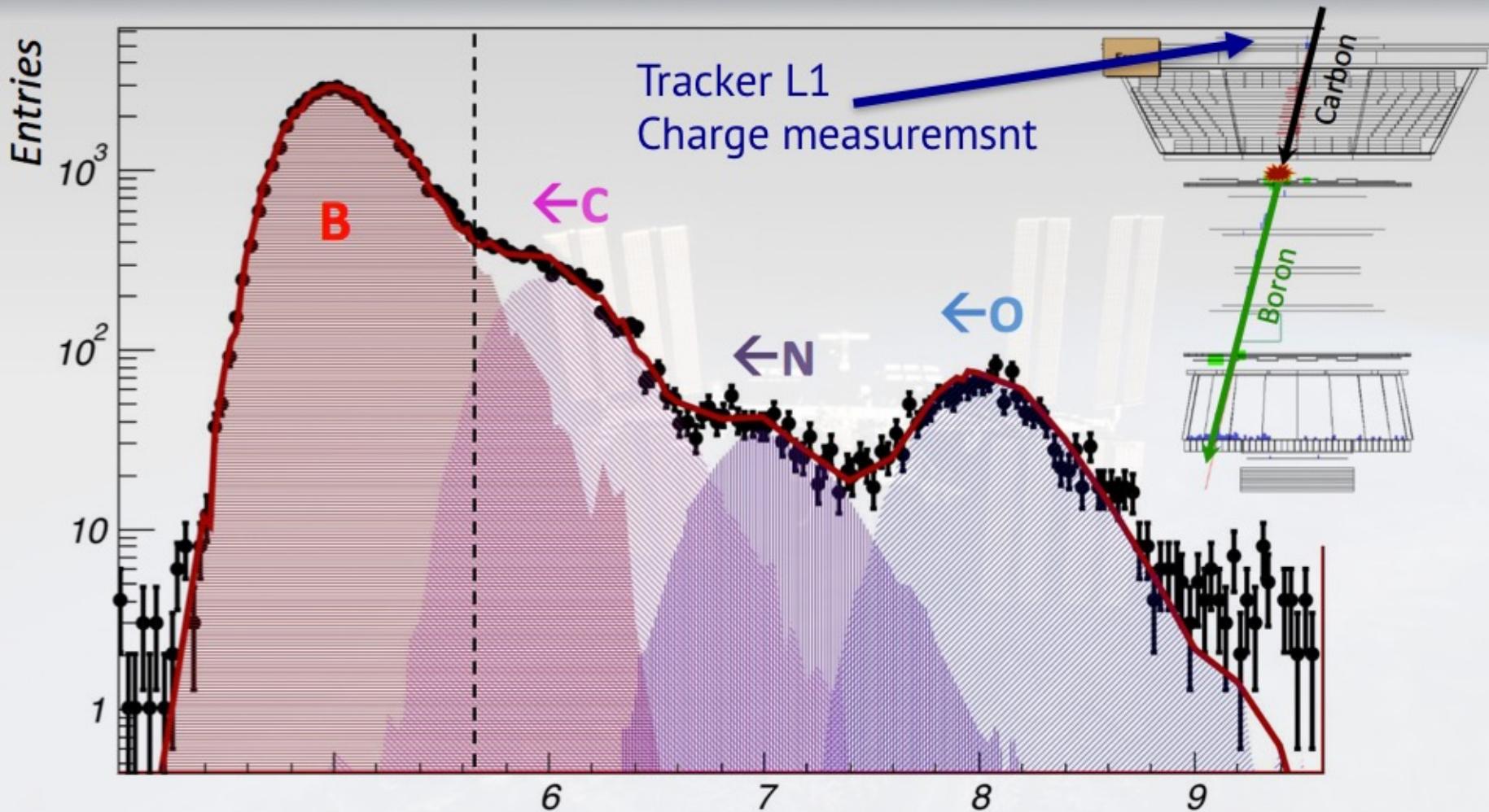
B/C sample purity control

The main backgrounds: Fragmentation events in the detector

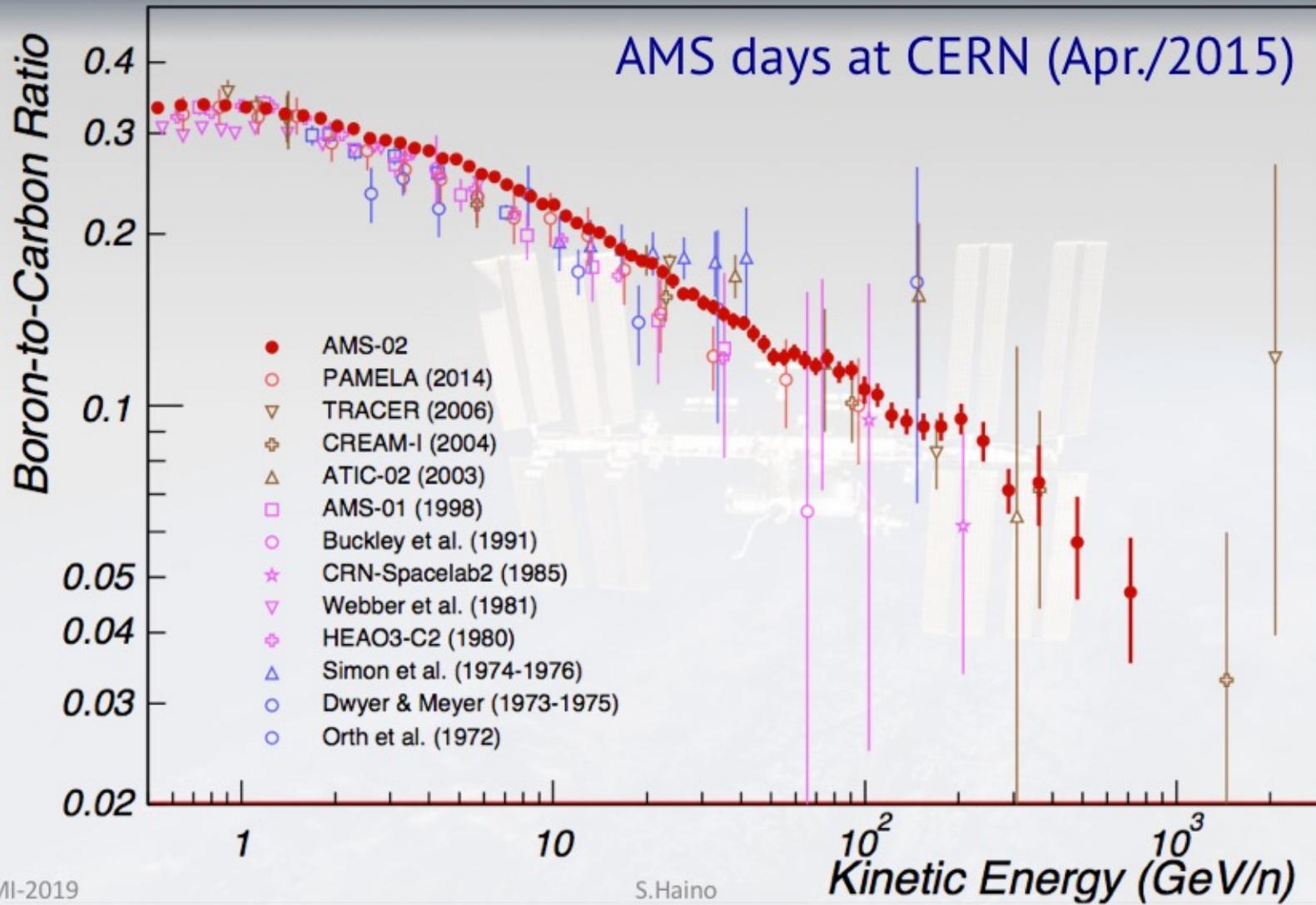


B/C sample purity control

The main backgrounds: Fragmentation events in the detector



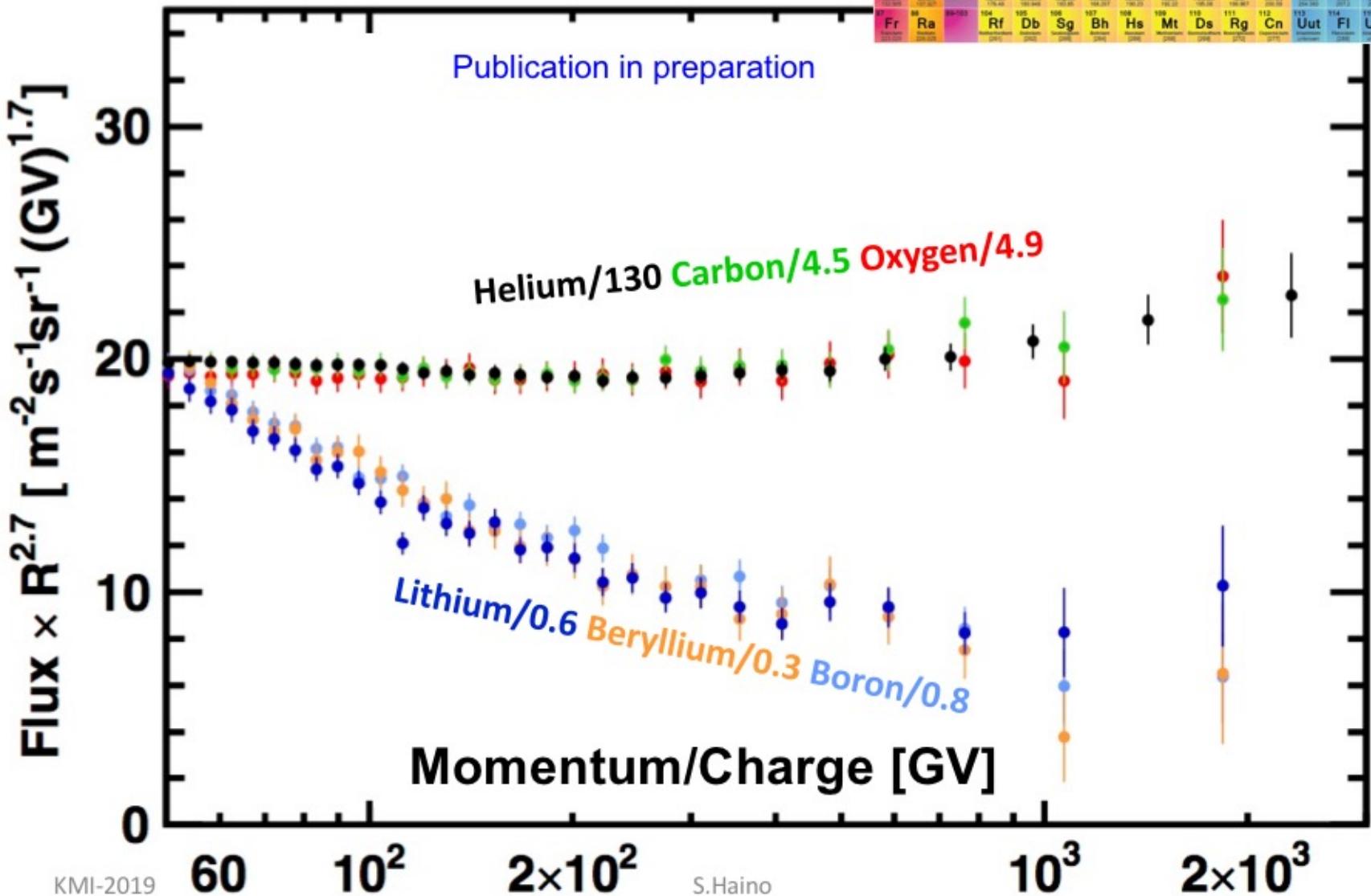
B/C by AMS with other measurements



AMS New Physics Result :

“Secondary” cosmic rays have a **different** energy dependence than “primary”

Periodic Table of the Elements																					
1	H	Li	Be	Na	Mg	Al	Si	P	S	Cl	Ar	Ne	F	Ne	O	Ne	He				
2	He	Li	Be	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
3	Li	Be	Na	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
4	Be	Na	Al	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
5	Na	Al	Si	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
6	Al	Si	P	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
7	Si	P	S	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
8	P	S	Cl	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
9	S	Cl	Ar	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
10	Cl	Ar	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
11	Ar	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
12	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
13	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
14	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
15	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
16	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
17	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
18	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
19	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
20	Ne	Ne	Ne	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
21	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne	Ne	Ne	
22	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne	Ne	Ne	Ne	
23	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne	Ne	Ne	Ne	Ne	
24	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne	Ne	Ne	Ne	Ne	Ne	
25	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne							
26	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne								
27	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne									
28	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne										
29	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne											
30	Zn	Ga	Ge	As	Se	Br	Kr	Ne	Ne												
31	Ga	Ge	As	Se	Br	Kr	Ne	Ne													
32	Ge	As	Se	Br	Kr	Ne	Ne														
33	As	Se	Br	Kr	Ne	Ne															
34	Se	Br	Kr	Ne	Ne																
35	Br	Kr	Ne	Ne																	
36	Kr	Ne	Ne																		
37	Fr	Rb	Sr	Y	Zr	Nb	Tc	Ru	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Uut	Uup	
38	Ra	Ba	Fr	Fr																	



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

1 IA H Hydrogen 1.008	2 IIA Be Beryllium 9.012	3 IIIB Sc Scandium 44.956	4 IVB Ti Titanium 47.88	5 VB V Vanadium 50.942	6 VIB Cr Chromium 51.996	7 VIIB Mn Manganese 54.938	8 VIII Fe Iron 55.933	9 VIII Co Cobalt 58.933	10 VIII Ni Nickel 58.693	11 IB Cu Copper 63.546	12 IIB Zn Zinc 65.39	13 IIIA B Boron 10.811	14 IVA C Carbon 12.011	15 VA N Nitrogen 14.007	16 VIA O Oxygen 15.999	17 VIIA F Fluorine 18.998	18 VIIIA He Helium 4.003
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.905	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 168.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
Lanthanide Series		57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.957	
Actinide Series		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]	

Analyzed

Being Analyzed

Accessible by 2024

Cosmic-Ray Anti-Deuterons



Antideuteron discovery



Columbia Physicists Discover First Anti-Deuteron Particle

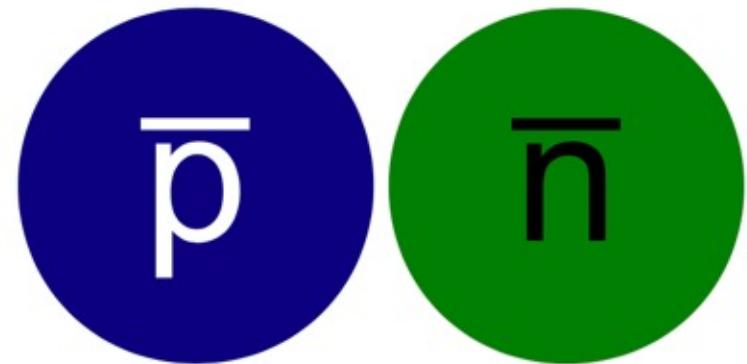
By Joseph Wihnyk

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

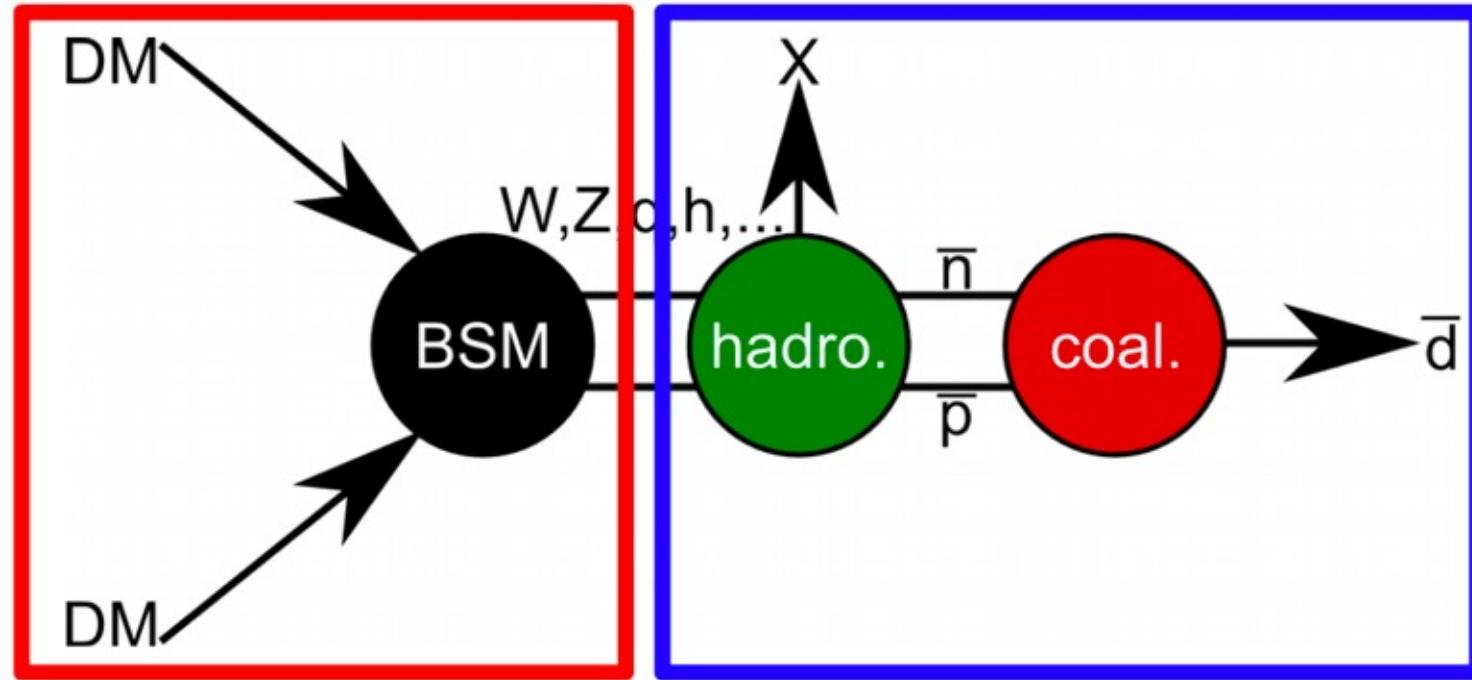
cent years, with Professor Melvin Schwartz, on the neutrino.

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.



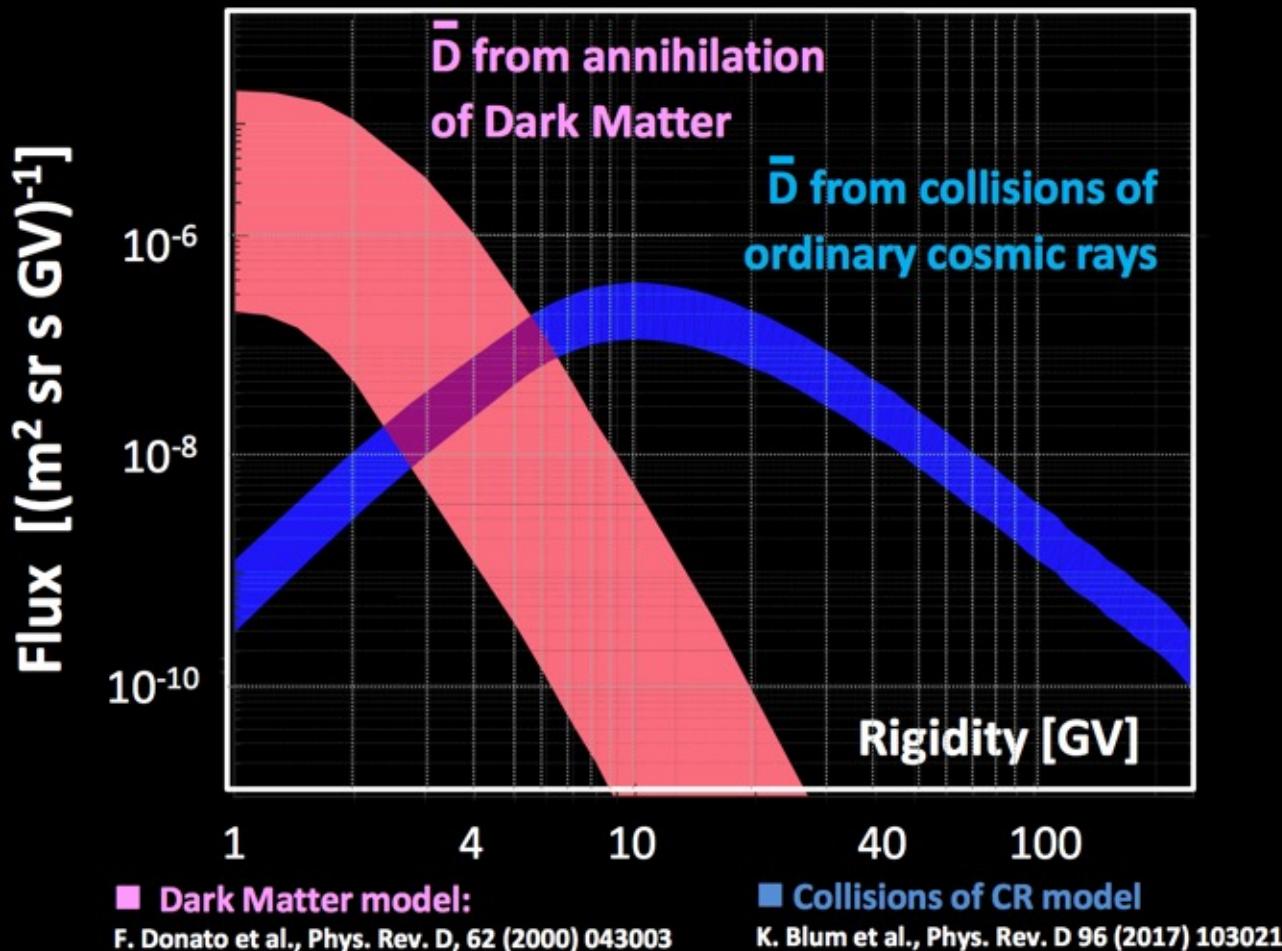
Discovered in 1965 at Brookhaven
by L.M.Lederman, S.C.C.Ting
The first bound antimatter ever discovered

Possible Anti-D production from DM



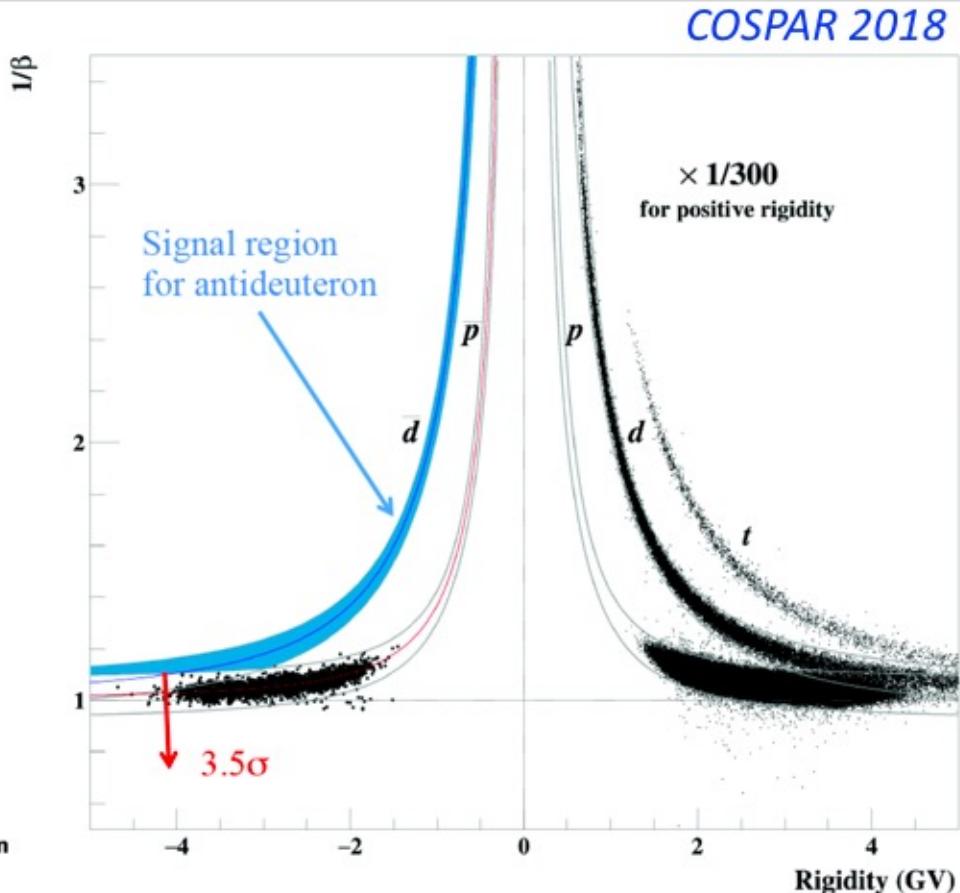
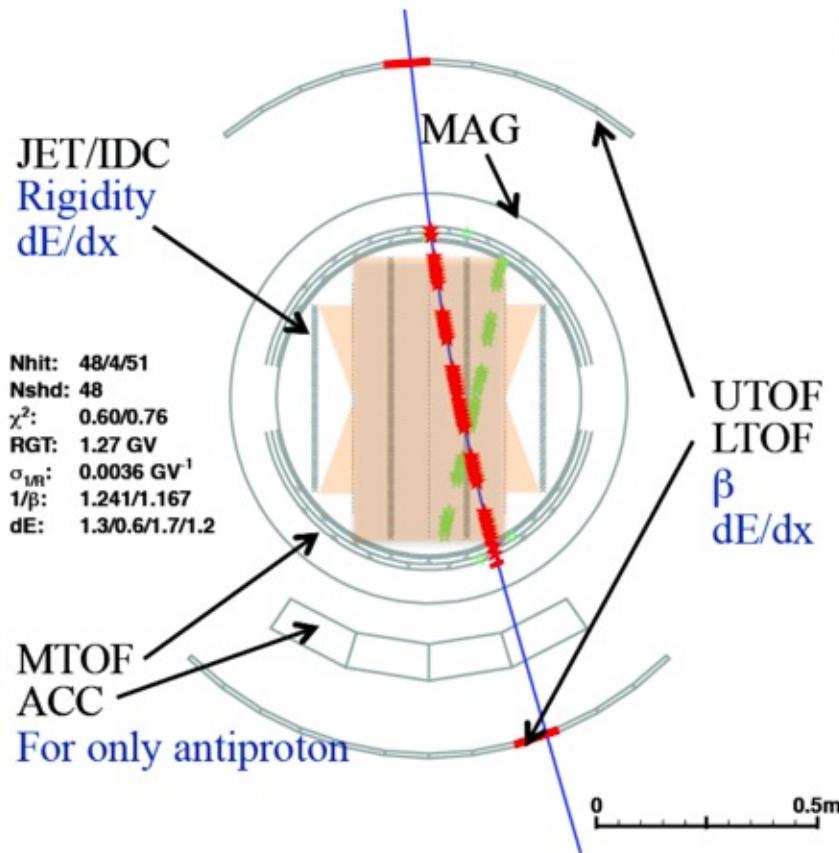
Anti Deuterons in Cosmic rays

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

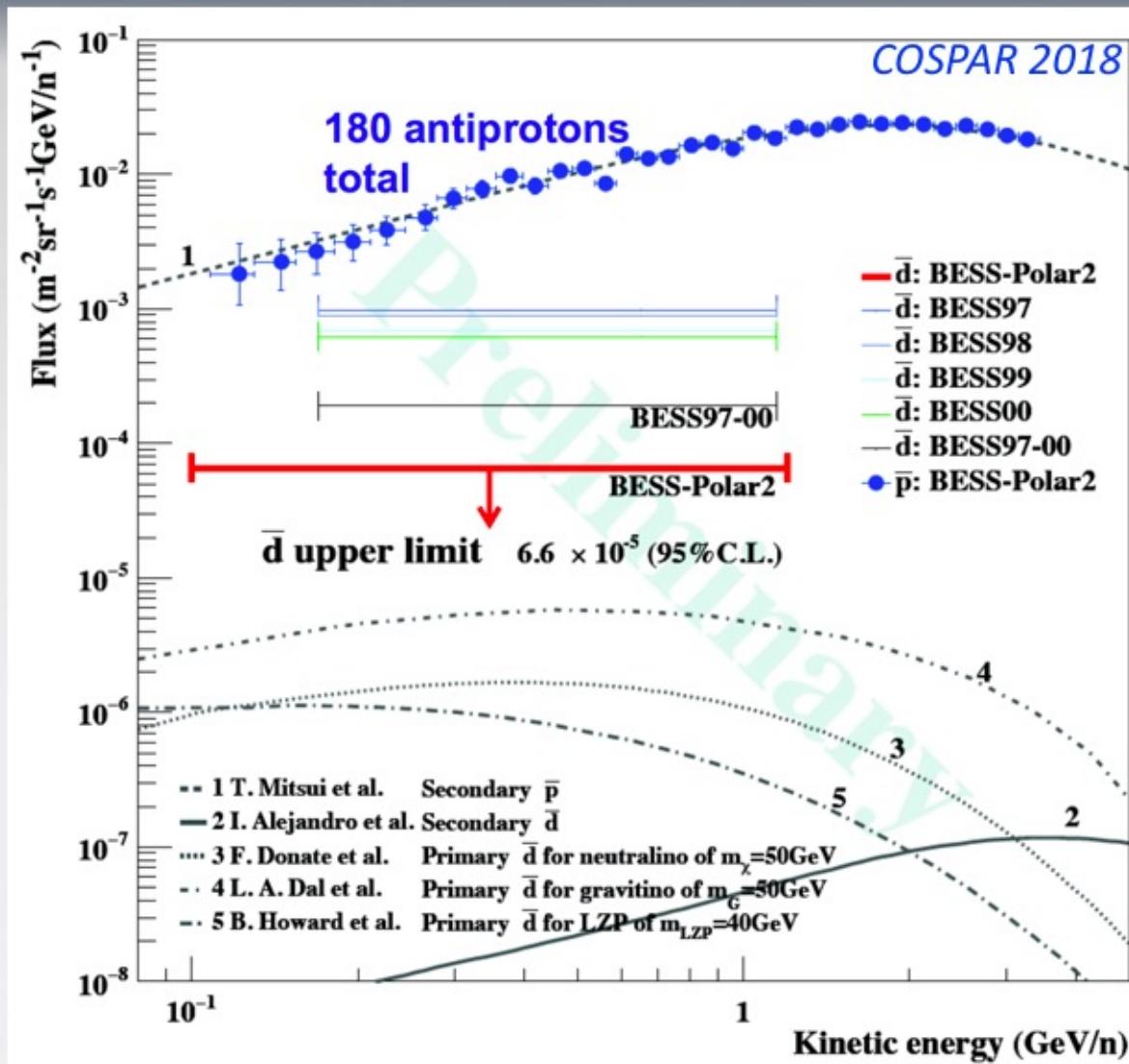


The Anti Deuterons Flux is $< 10^{-4}$ of the Antiproton Flux.
Additional background rejection

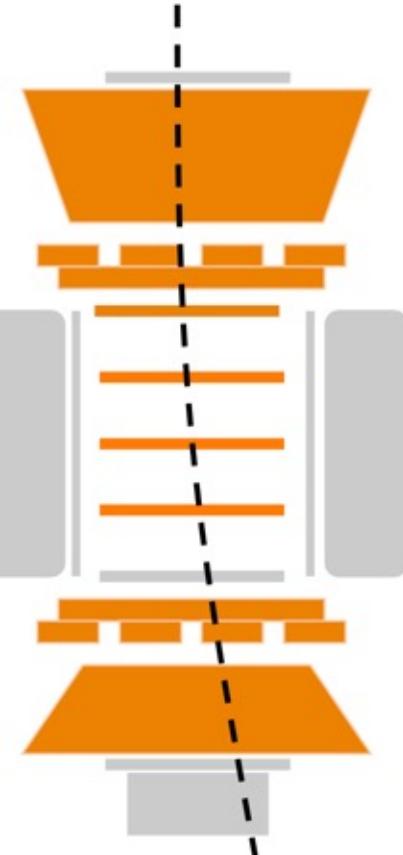
Anti-Deuteron searches by BESS



Anti-Deuteron searches by BESS



Anti-D searches in AMS



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

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

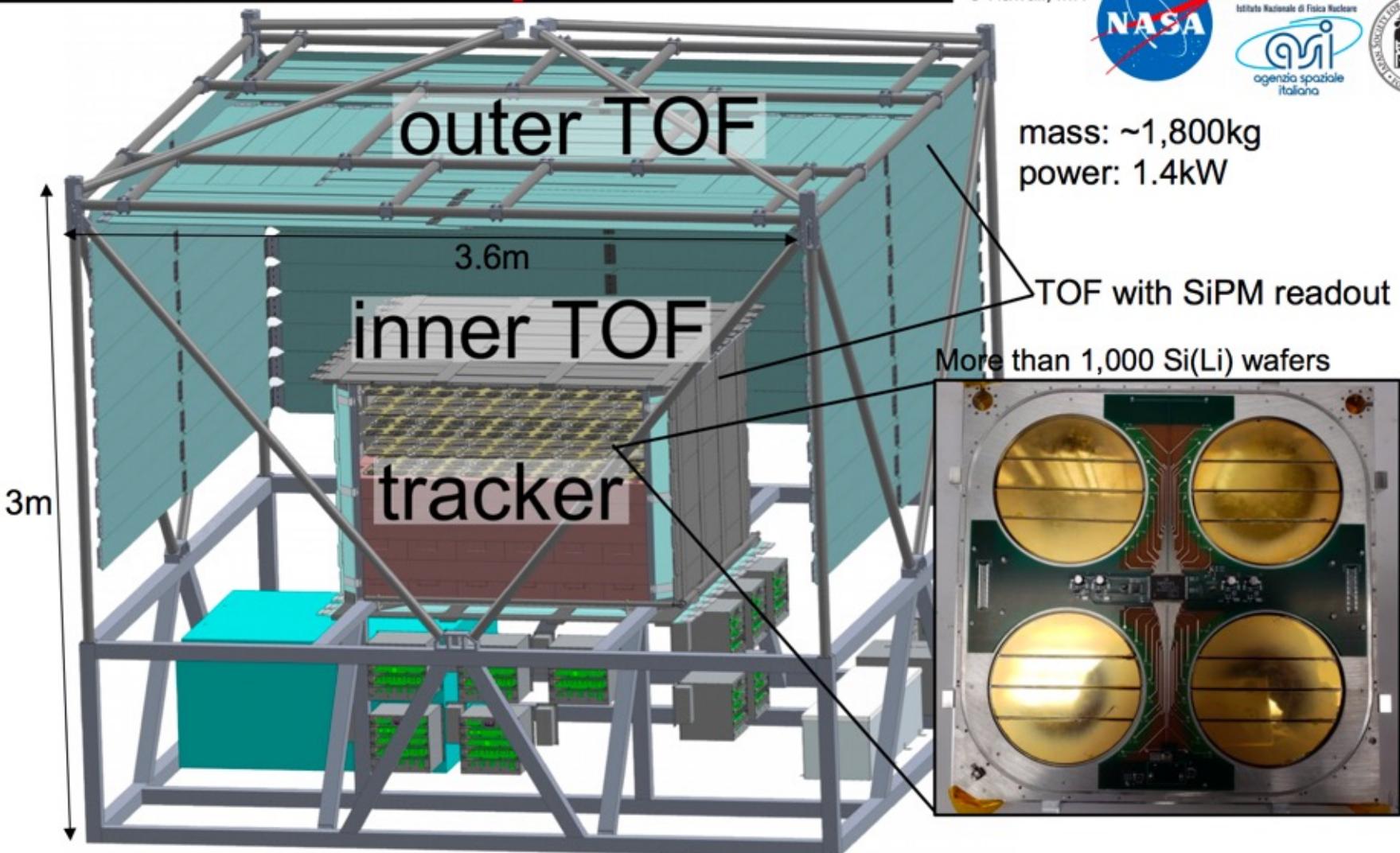
TOF → Velocity ($\Delta\beta = 4\%$ at $\beta = 1$ and $Z = 1$),
 $Z = 1$

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

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

The GAPS experiment

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



mass: ~1,800kg
power: 1.4kW

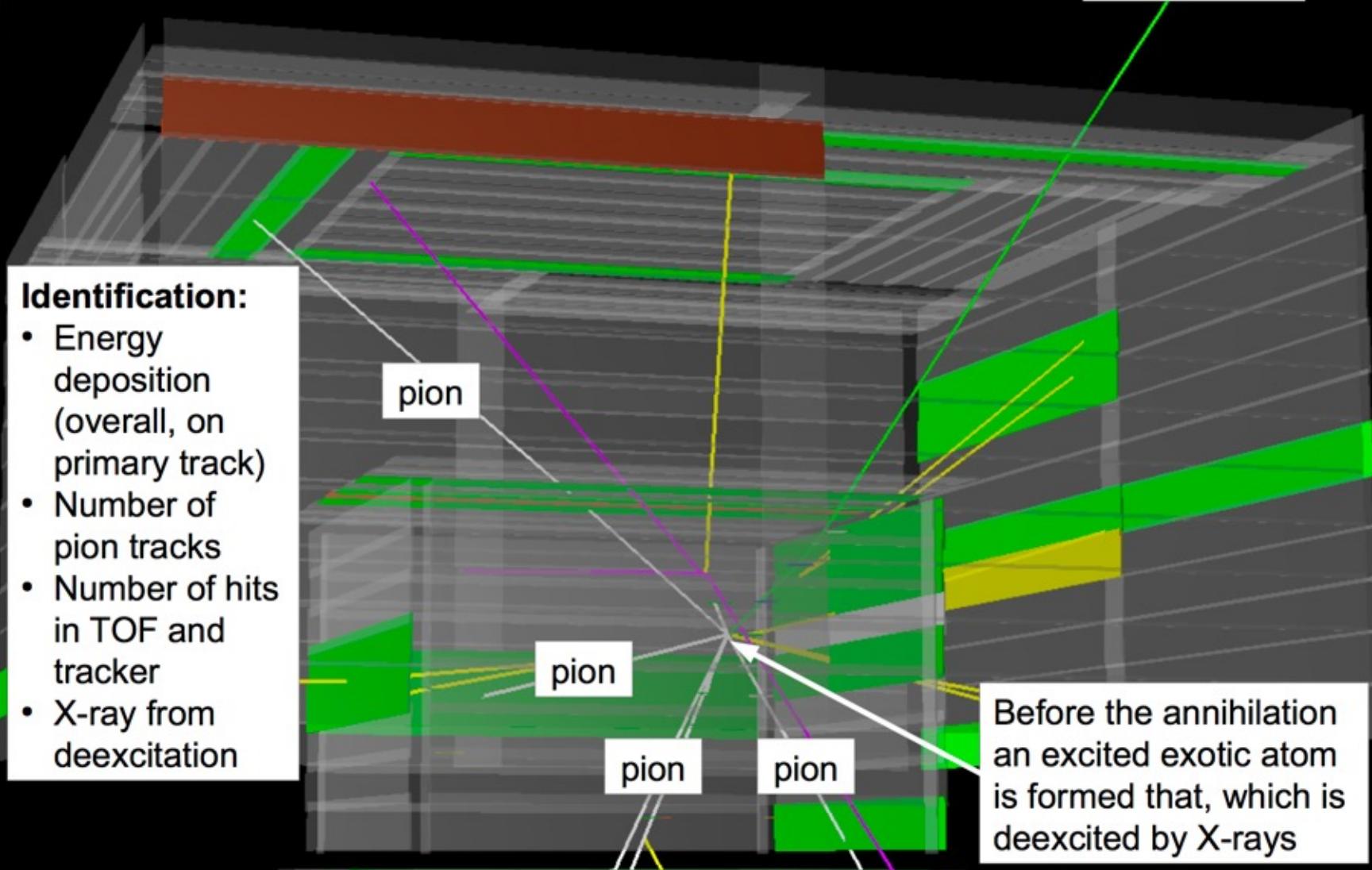
TOF with SiPM readout

More than 1,000 Si(Li) wafers

- the **General AntiParticle Spectrometer** is specifically designed for low-energy antideuterons, antiprotons and antihelium nuclei

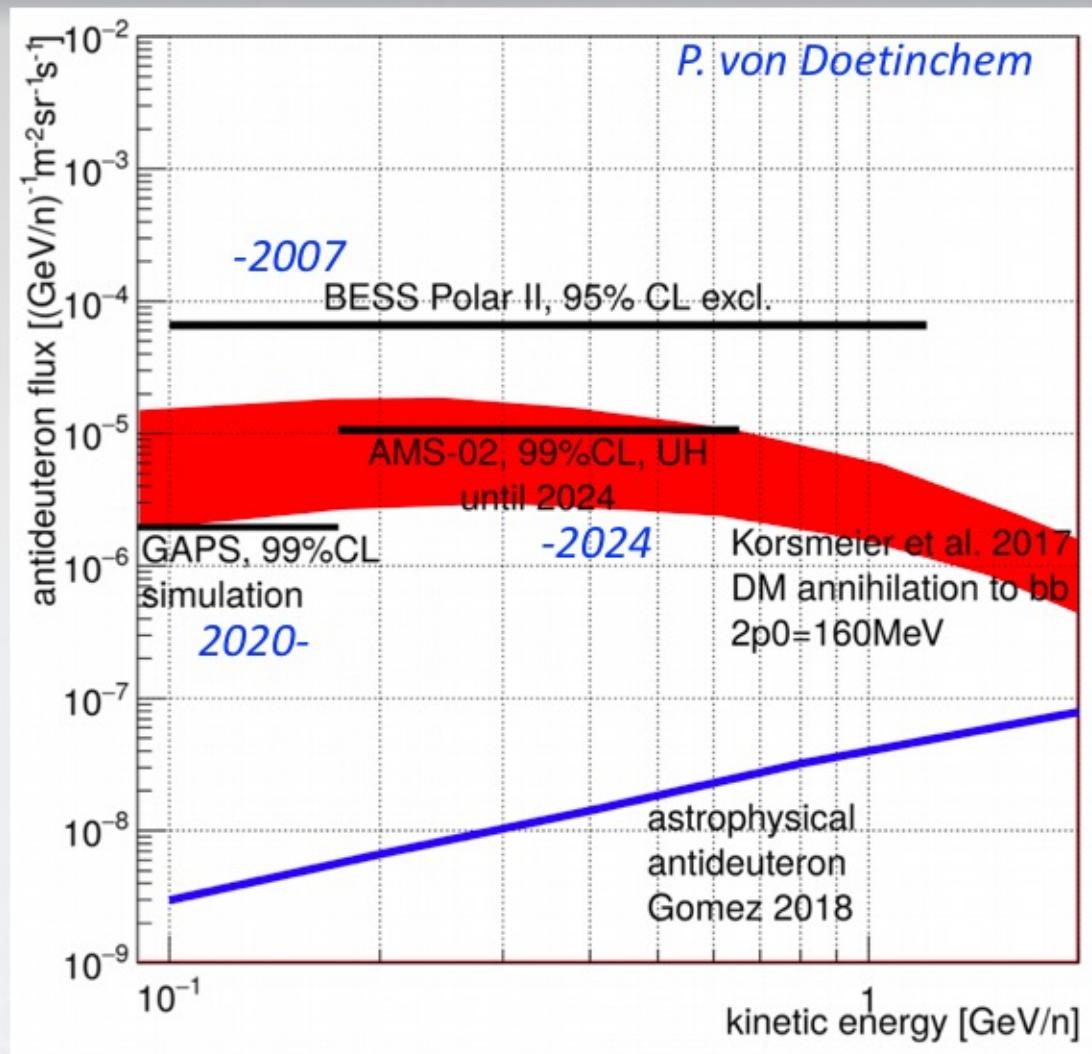
P. von Doetinchem

Simulated antideuteron in GAPS



P. von Doetinchem

Anti-D searches - prospects



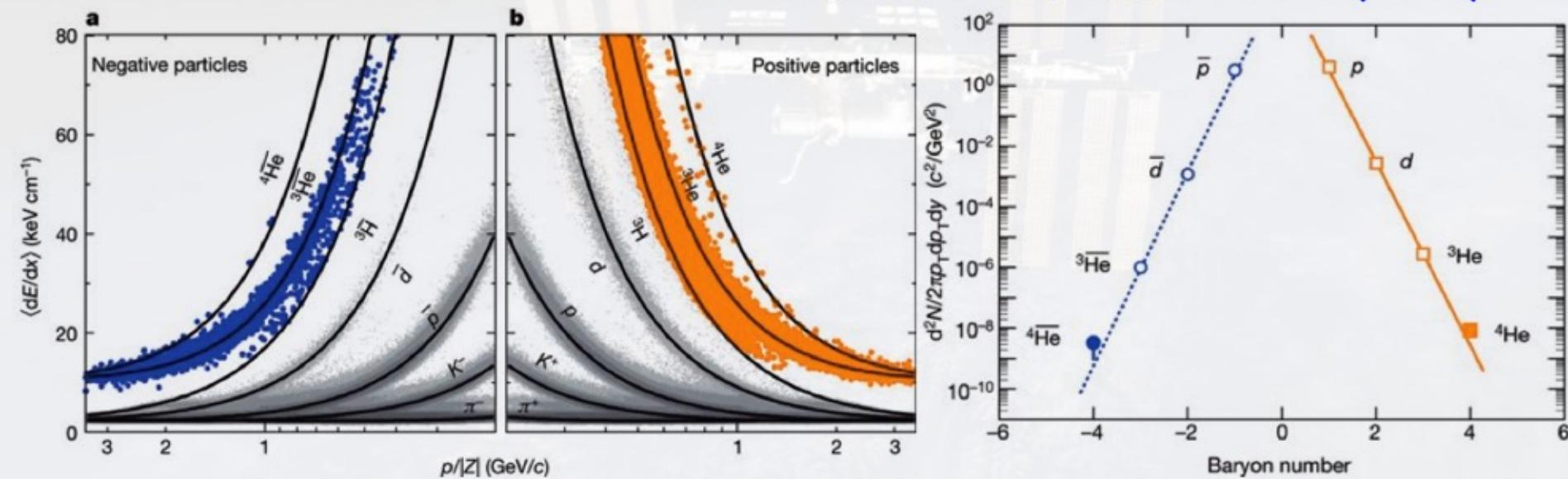
Cosmic-Ray Anti-Helium

Anti-He production by collider

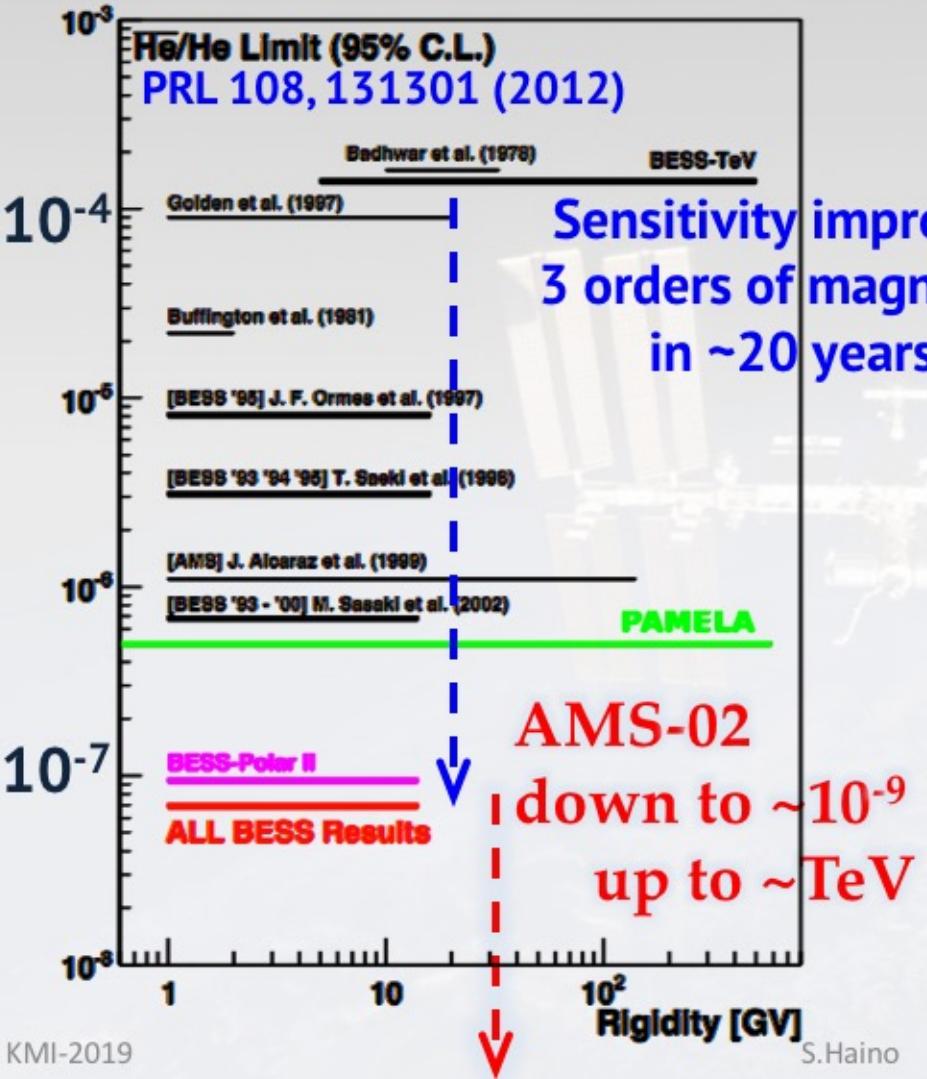
Anti-Helium

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

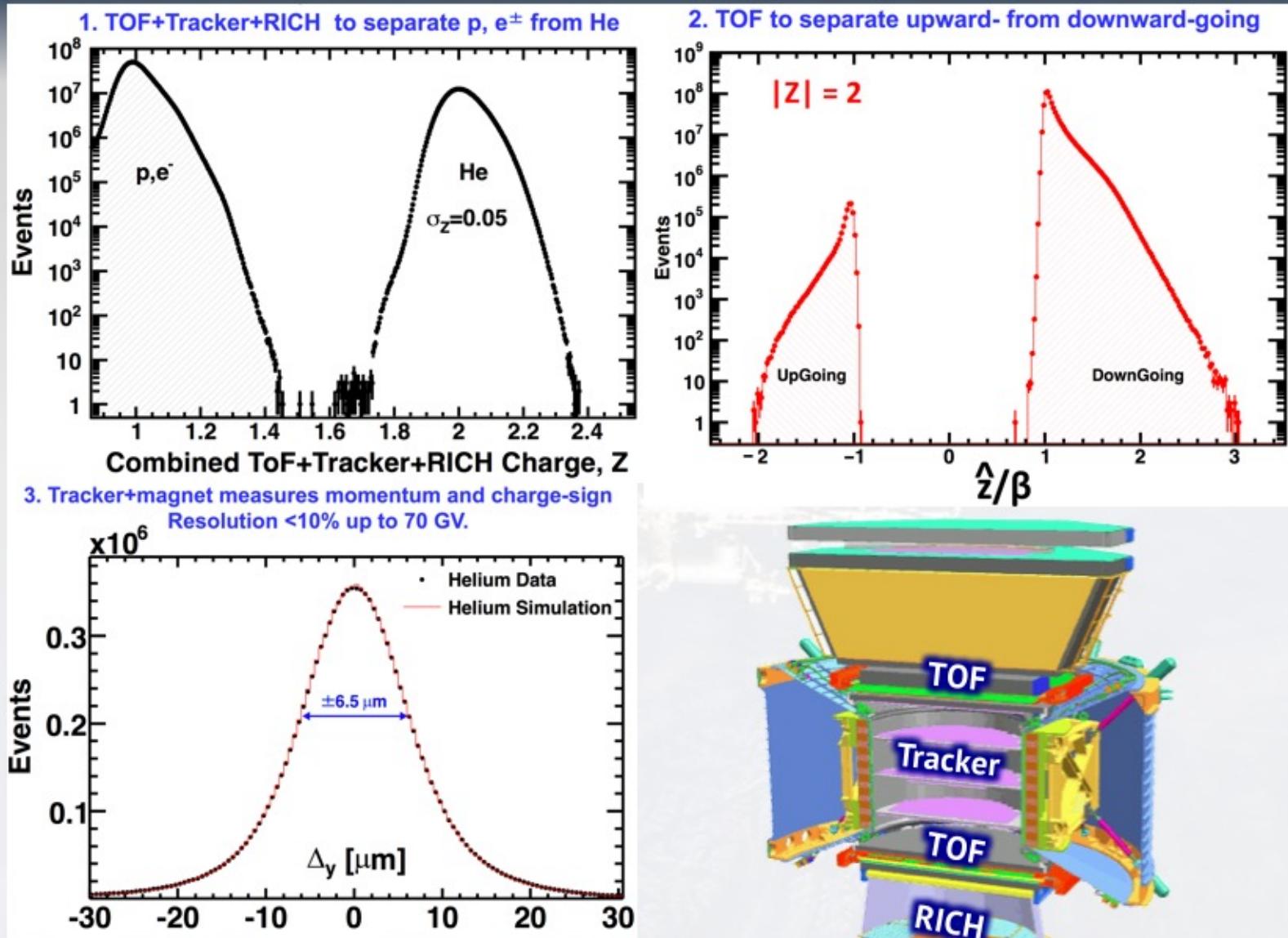
STAR collaboration, Nature 10079 (2011)



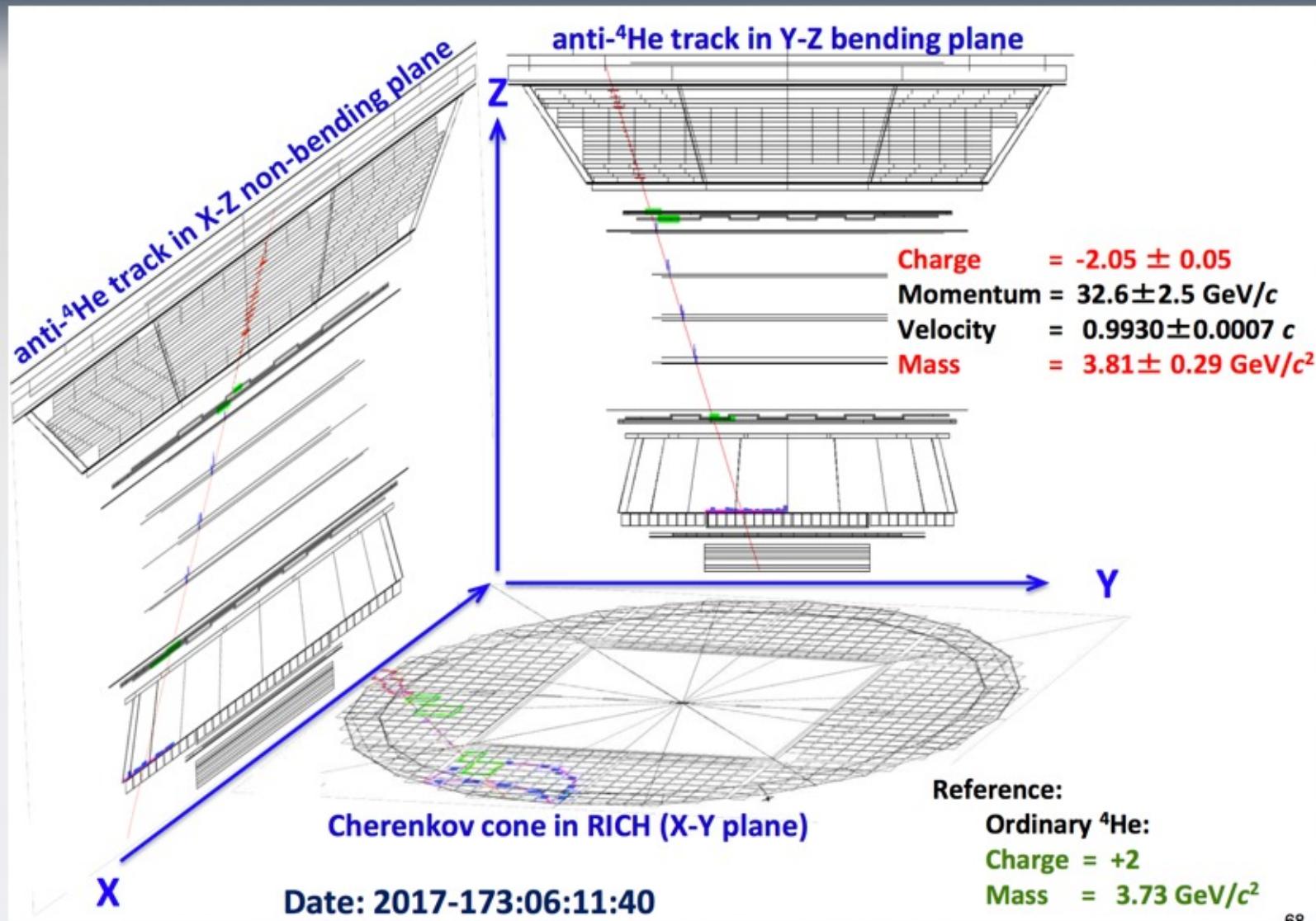
History of antimatter searches



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

