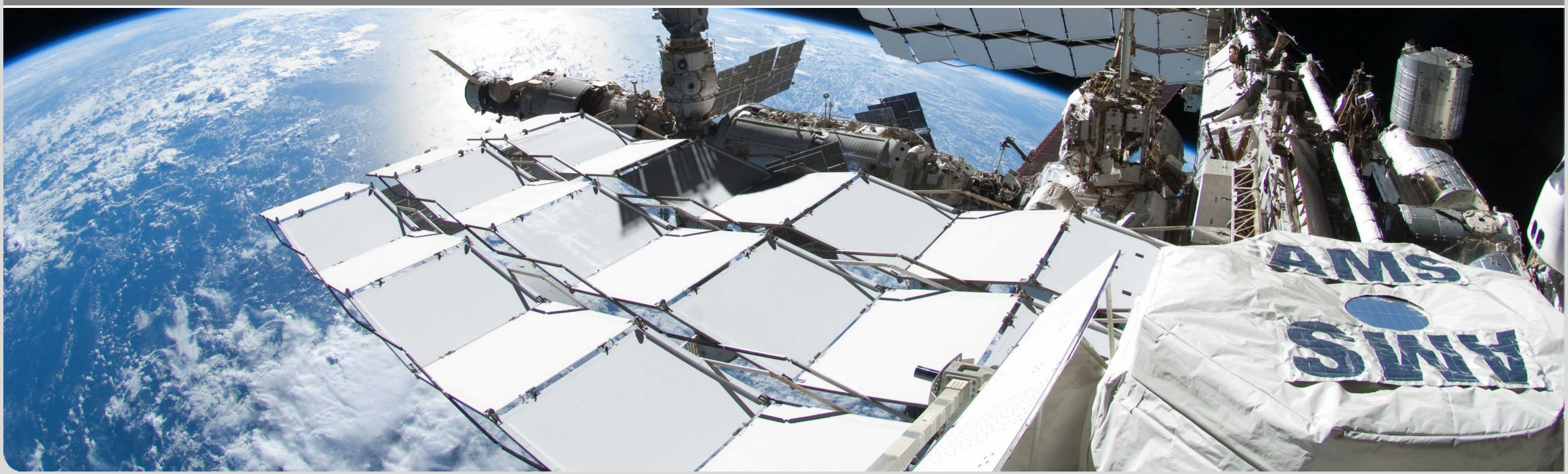
Karlsruher Institut für Technologie

Highlights from 6 years with AMS on the ISS and future prospects for direct cosmic rays measurements

September 25th, 2017
CEA Saclay

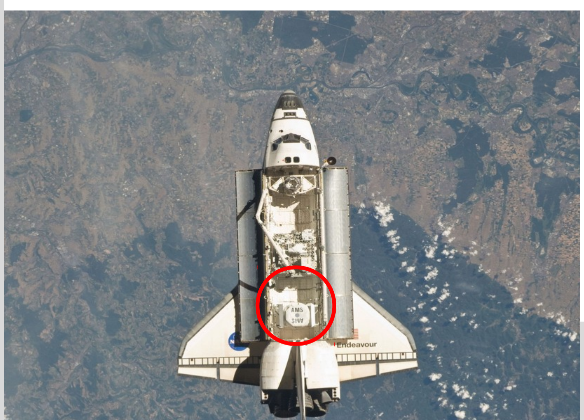
Iris Gebauer

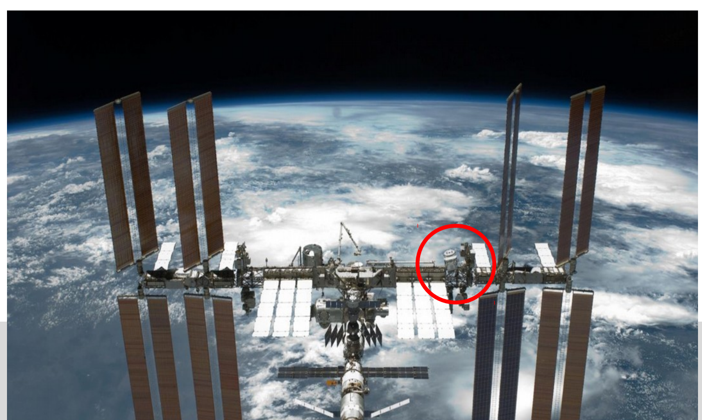
INSTITUTE FOR EXPERIMENTAL PARTICLE PHYSICS



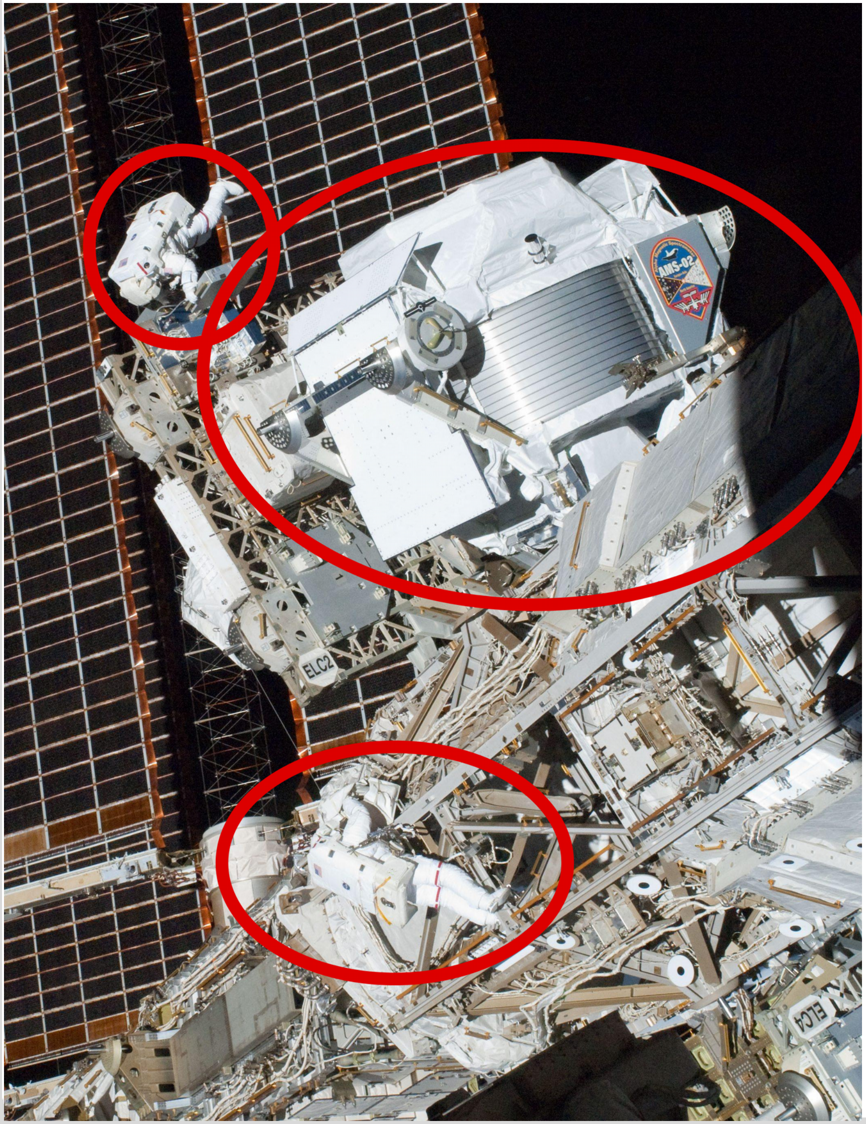

May 16th 2011


May 19th 2011





AMS-02: THE ALPHA MAGNETIC SPECTROMETER 02



- **Volume** 64 m^3, height 4 m
- **Weight** 8500 kg
- **Power consumption** 2500 W
- **Data downlink** 9 Mbps (minimum)
- **Magnetic field** 0.15 T (400 x Earth)
- **Launch** May 16th, 2011 (Endeavour)
- **Data taking** as of May 19th, 2011
- **Construction** 1999-2010 (>3 PhD generations)
- **Mission dutration:** Until the end of ISS operation (currently 2024)

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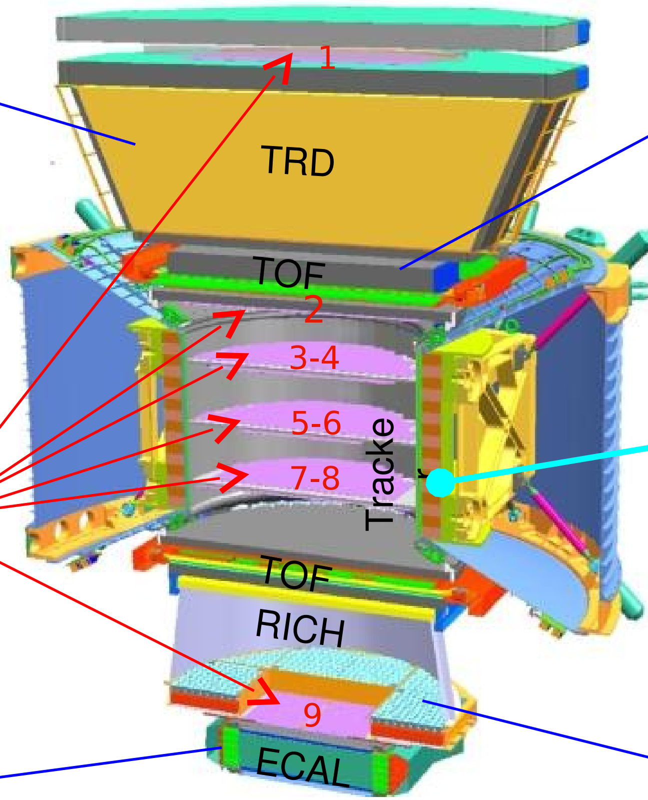
AMS: A TeV PRECISION MAGNETIC SPECTROMETER

Particles and nuclei are defined by their charge (Z) and energy (E) or rigidity (R=p/Z)

Transition Radiation Detector
Identify e^+, e^-

Silicon Tracker
Z, R

Electromagnetic Calorimeter
E of e^+, e^-



Time of Flight
Z, E

Magnet
±Z, R

Ring Imaging Cherenkov
Z, E

Charge and energy are measured independently by many detectors

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TODAY

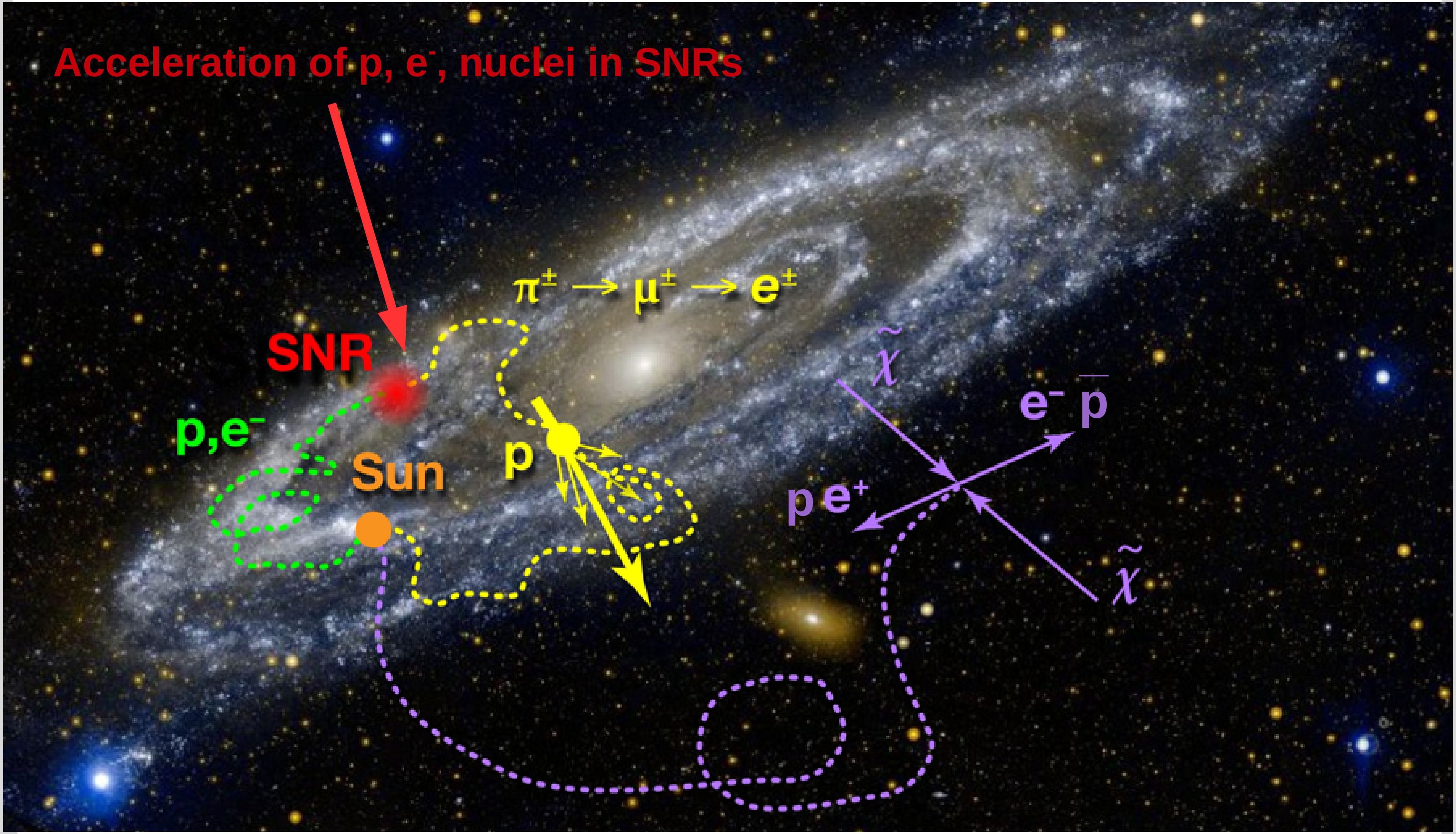
Why is it interesting to measure cosmic rays?

What did we measure?

Why is this confusing us?

What do we need to measure in the future?

GALACTIC COSMIC RAYS: SOURCE → US



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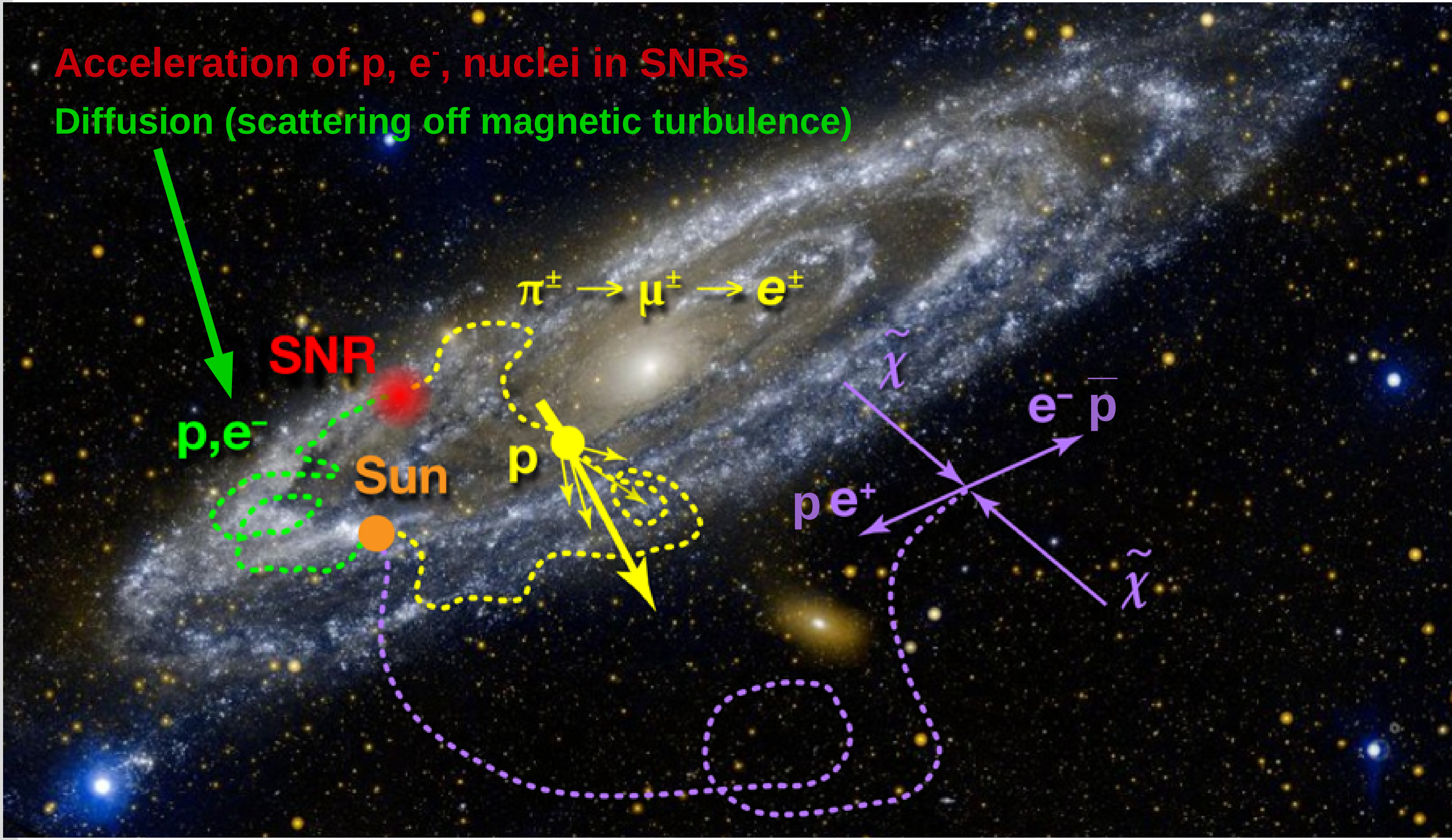
GALACTIC COSMIC RAYS: SOURCE → US



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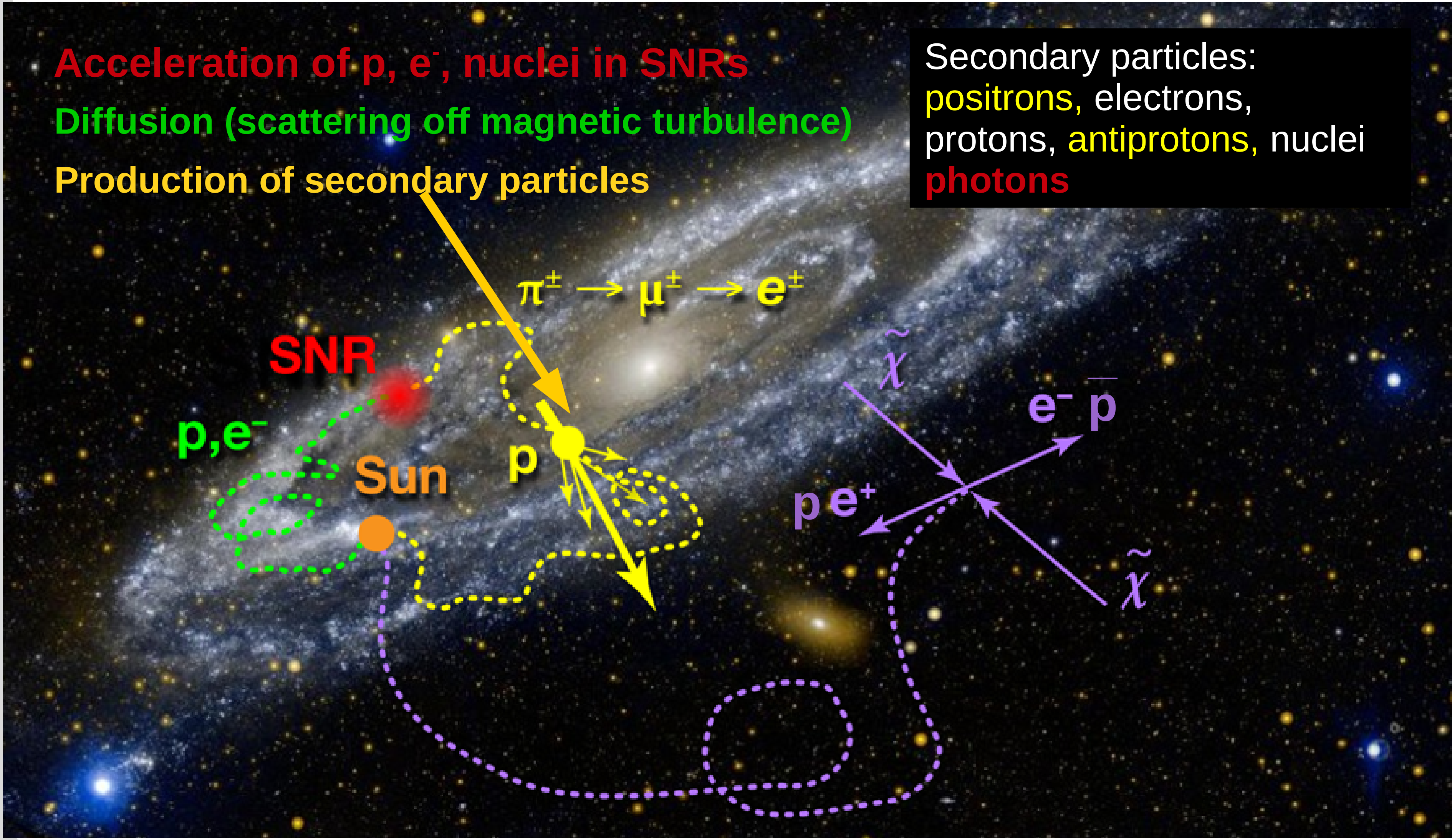
GALACTIC COSMIC RAYS: SOURCE → US



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GALACTIC COSMIC RAYS: SOURCE → US

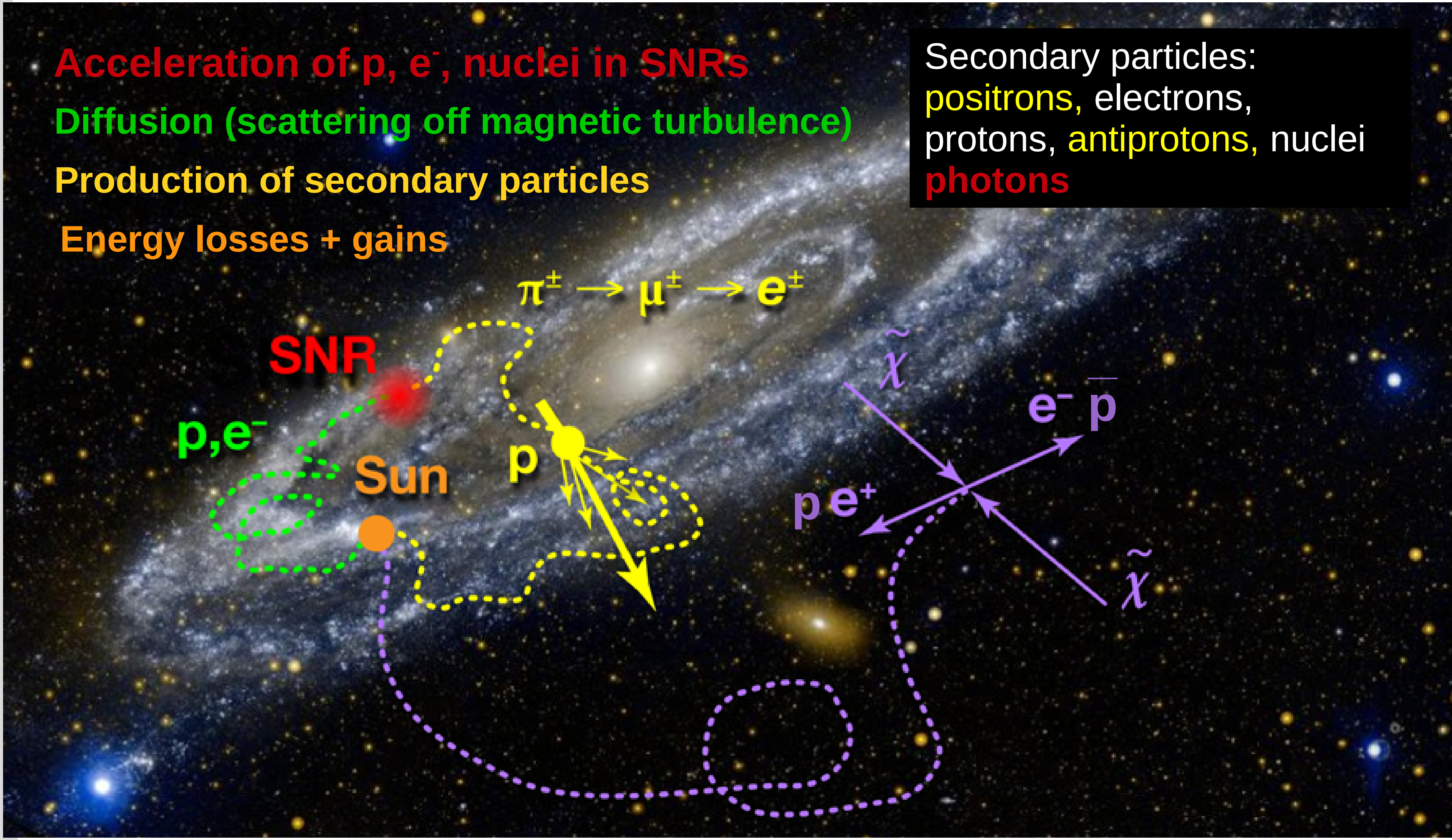
Acceleration of p, e^-, nuclei in SNRs

Diffusion (scattering off magnetic turbulence)

Production of secondary particles

Energy losses + gains

Secondary particles:
positrons, electrons,
protons, antiprotons, nuclei
photons



GALACTIC COSMIC RAYS: SOURCE → US

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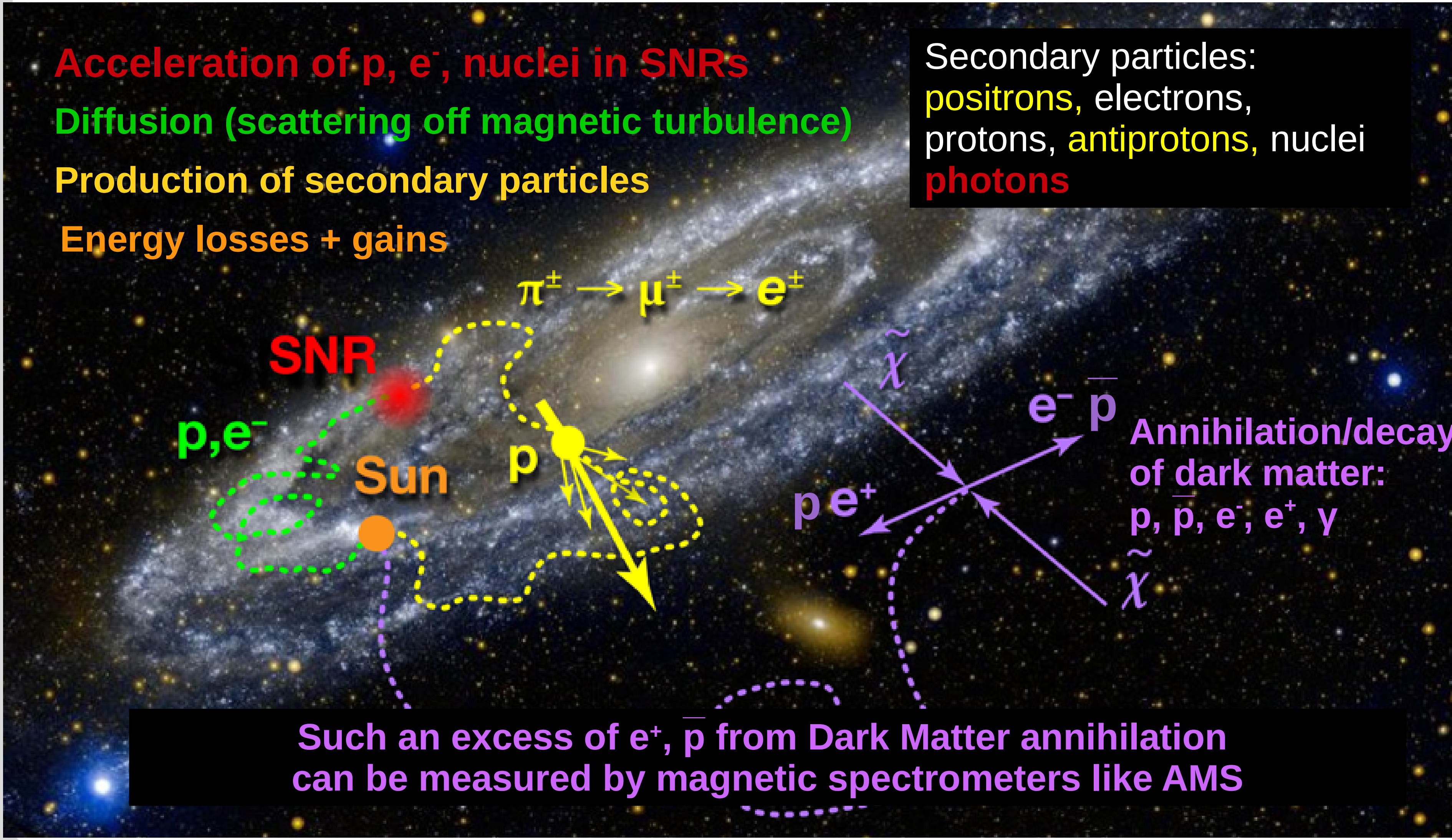
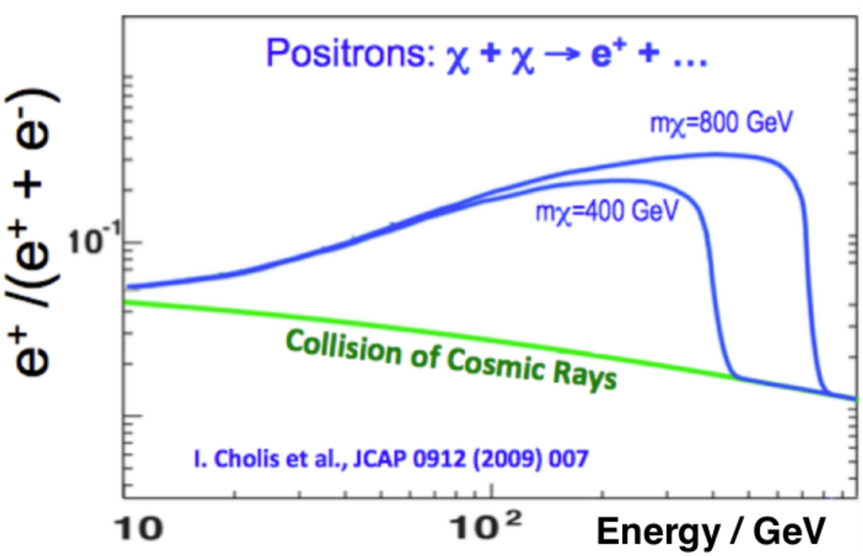


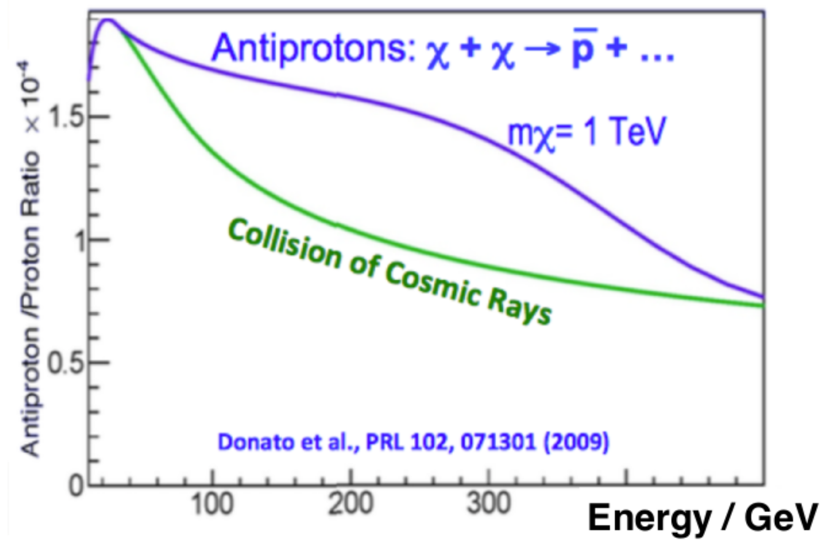
Annihilation/decay of dark matter:
p, $\bar{p}$, e⁻, e⁺, γ

Such an excess of e⁺, $\bar{p}$ from Dark Matter annihilation
can be measured by magnetic spectrometers like AMS

THE SEARCH FOR DARK MATTER IN COSMIC RAYS

Karlsruhe Institute of Technology

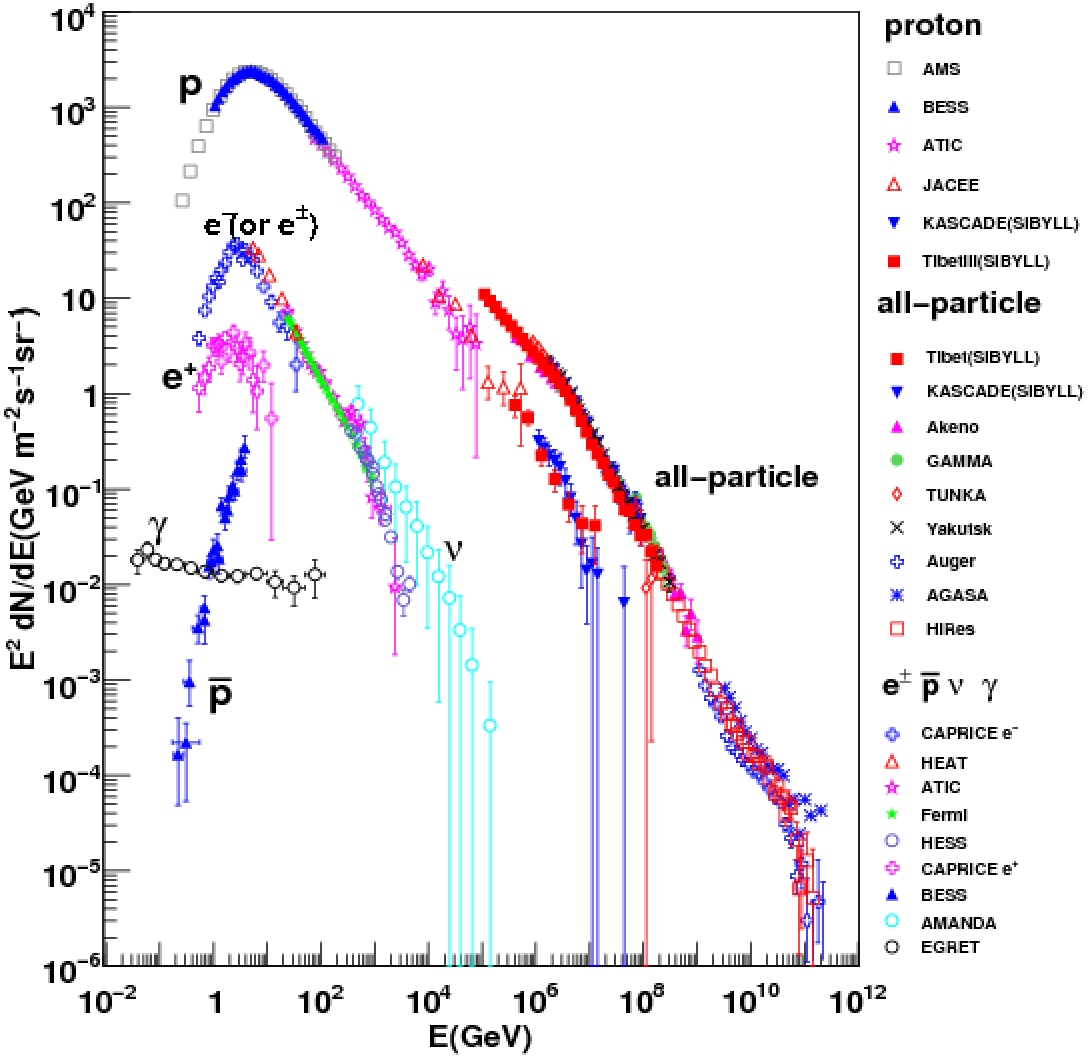




The antimatter component of cosmic rays ($e^+/\bar{p}$) are sensitive probes for dark matter....

…BUT: “collision of cosmic rays” needs to be understood.

COMPOSITION OF COSMIC RAYS



- Protons 89%
- Helium 9%
- Heavy nuclei 1%
- Electrons 1%
- Traces of antimatter ($\bar{p}$, e^+)

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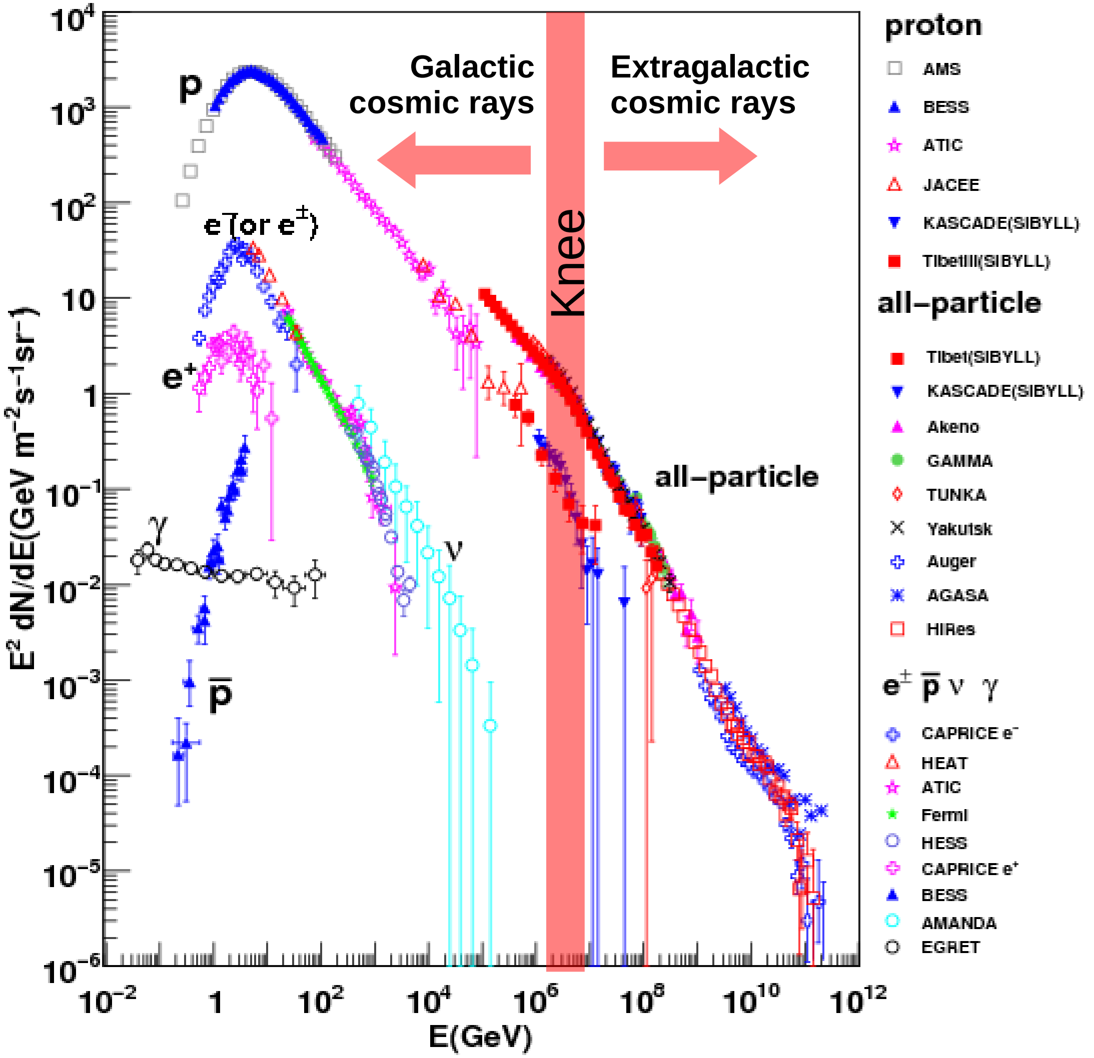
COMPOSITION OF COSMIC RAYS



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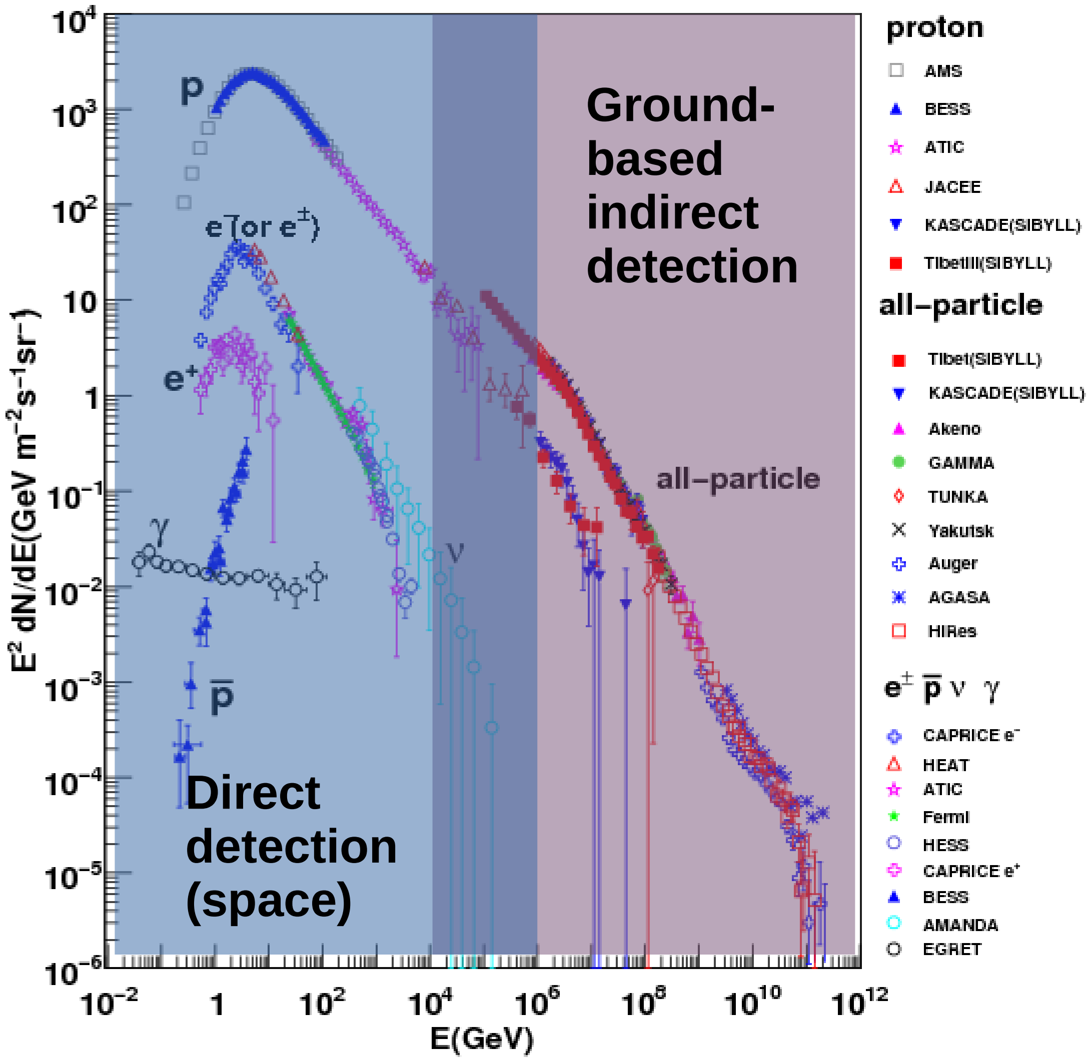

- Protons 89%
- Helium 9%
- Heavy nuclei 1%
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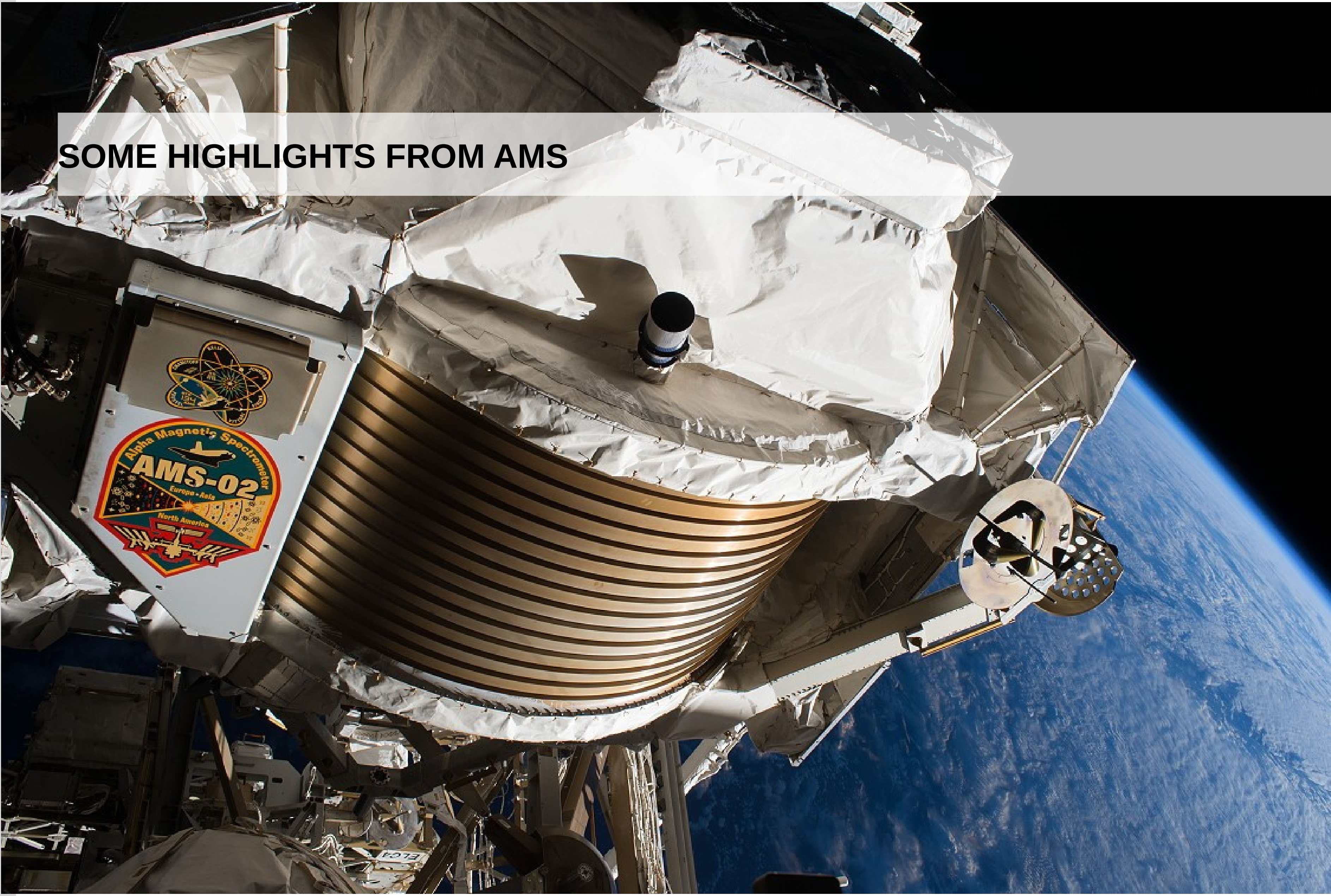
SOME HIGHLIGHTS FROM AMS



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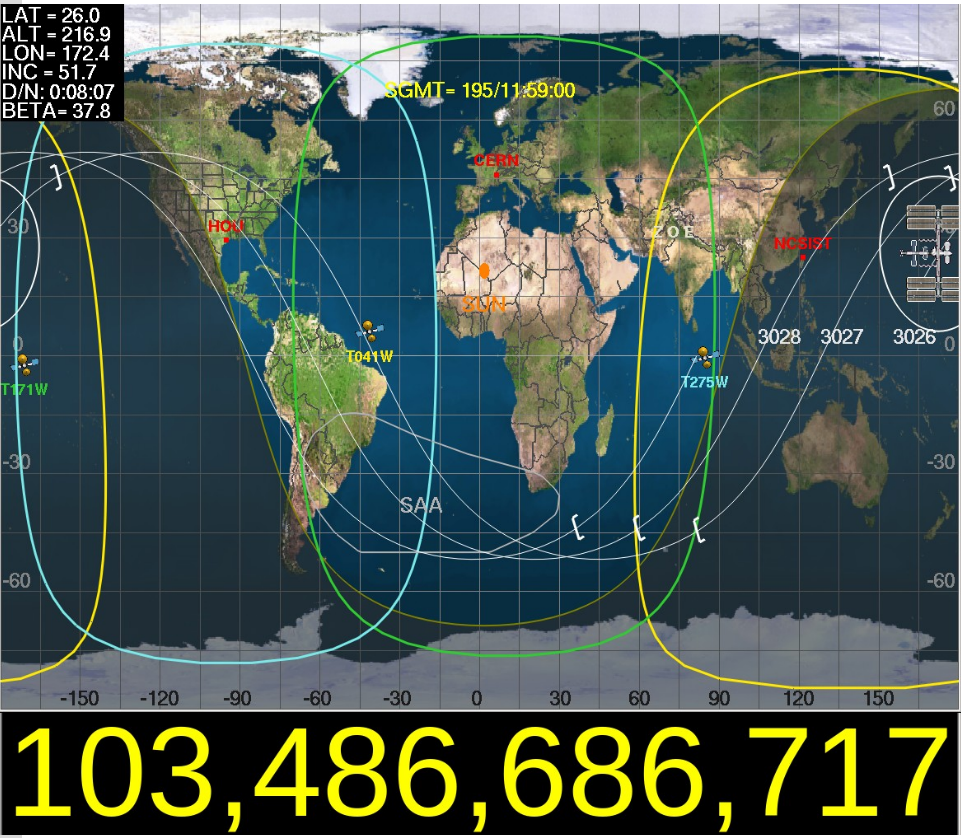
Cosmic rays measured as of 14 July 2017 13:59 CEDT



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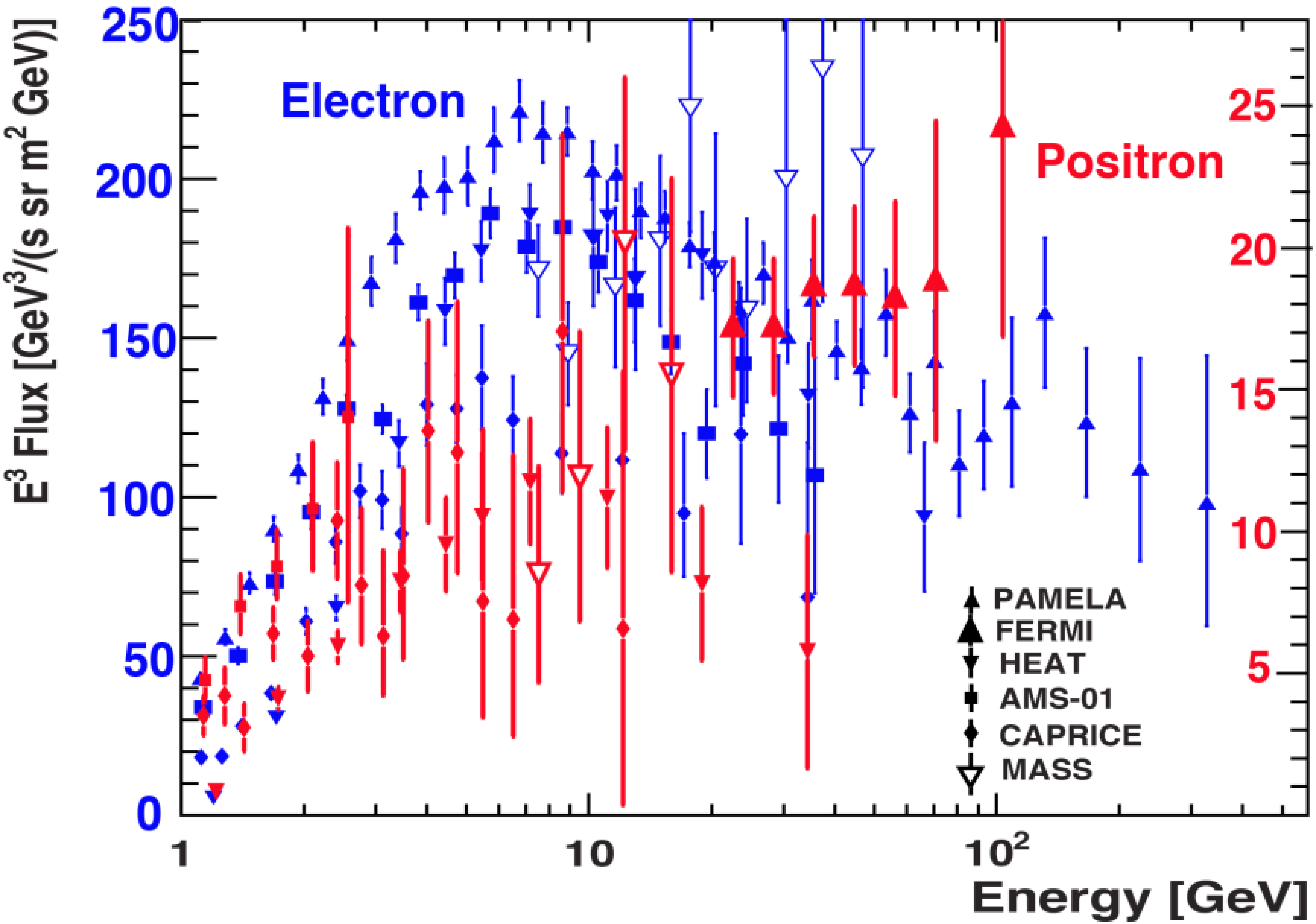
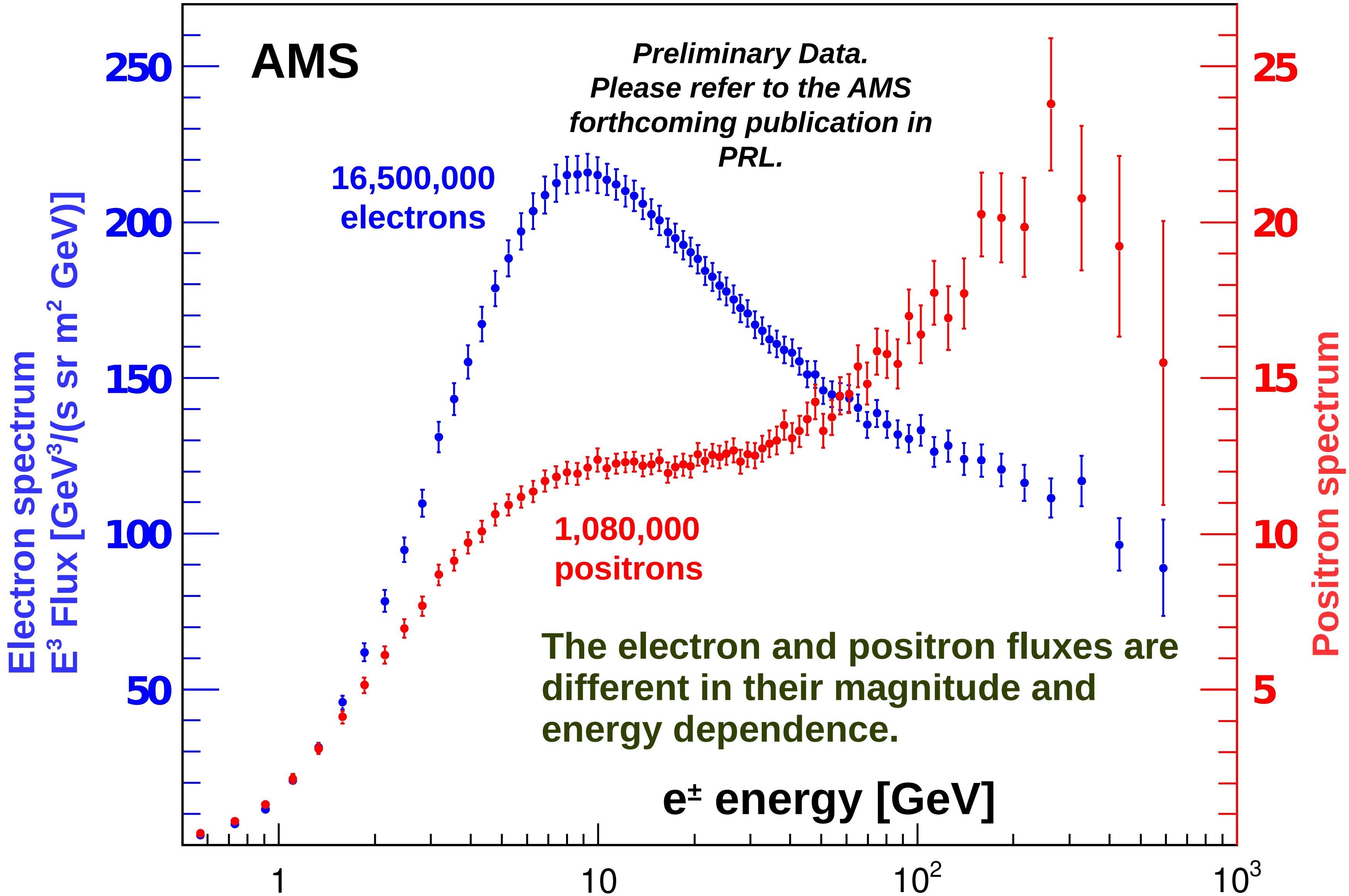
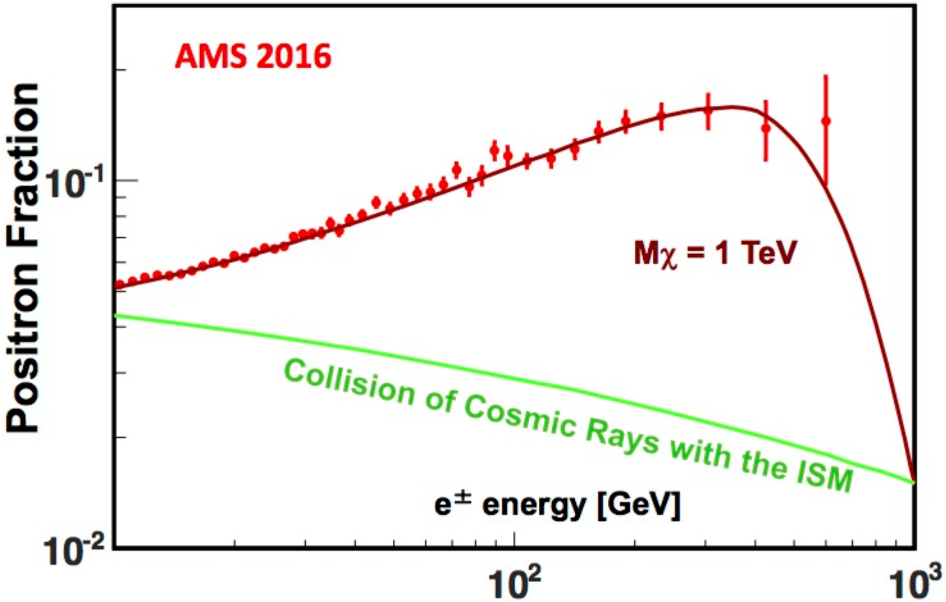
ELECTRON AND POSITRON FLUX (BEFORE AMS)



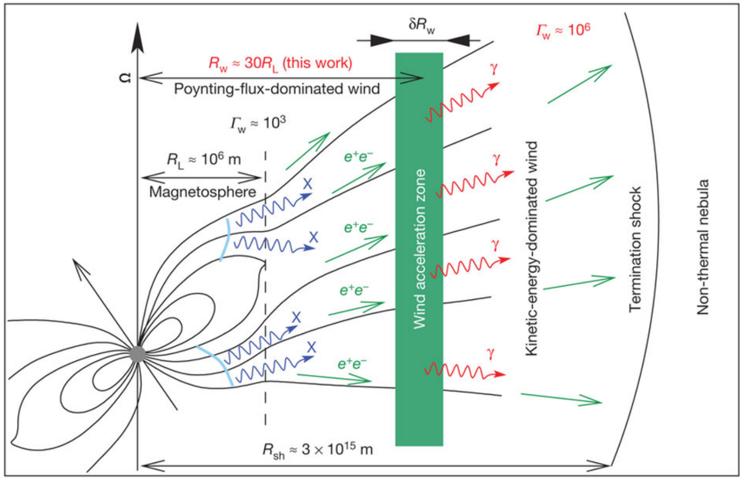
AMS RESULTS ON THE ELECTRON AND POSITRON FLUXES



POSITRON FRACTION $e^+/(e^+ + e^-)$



[Phys. Rev. Lett. 110, 141102 (2013)]



An unexpected rise in the positron fraction could be explained by dark matter annihilation...

...or new astrophysical point sources (e.g. pulsars).

THEORETICAL MODELS FOR POSITRONS AND ANTIPROTONS

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 **...**

From Dark Matter

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

and many other excellent papers ...

From astrophysical sources

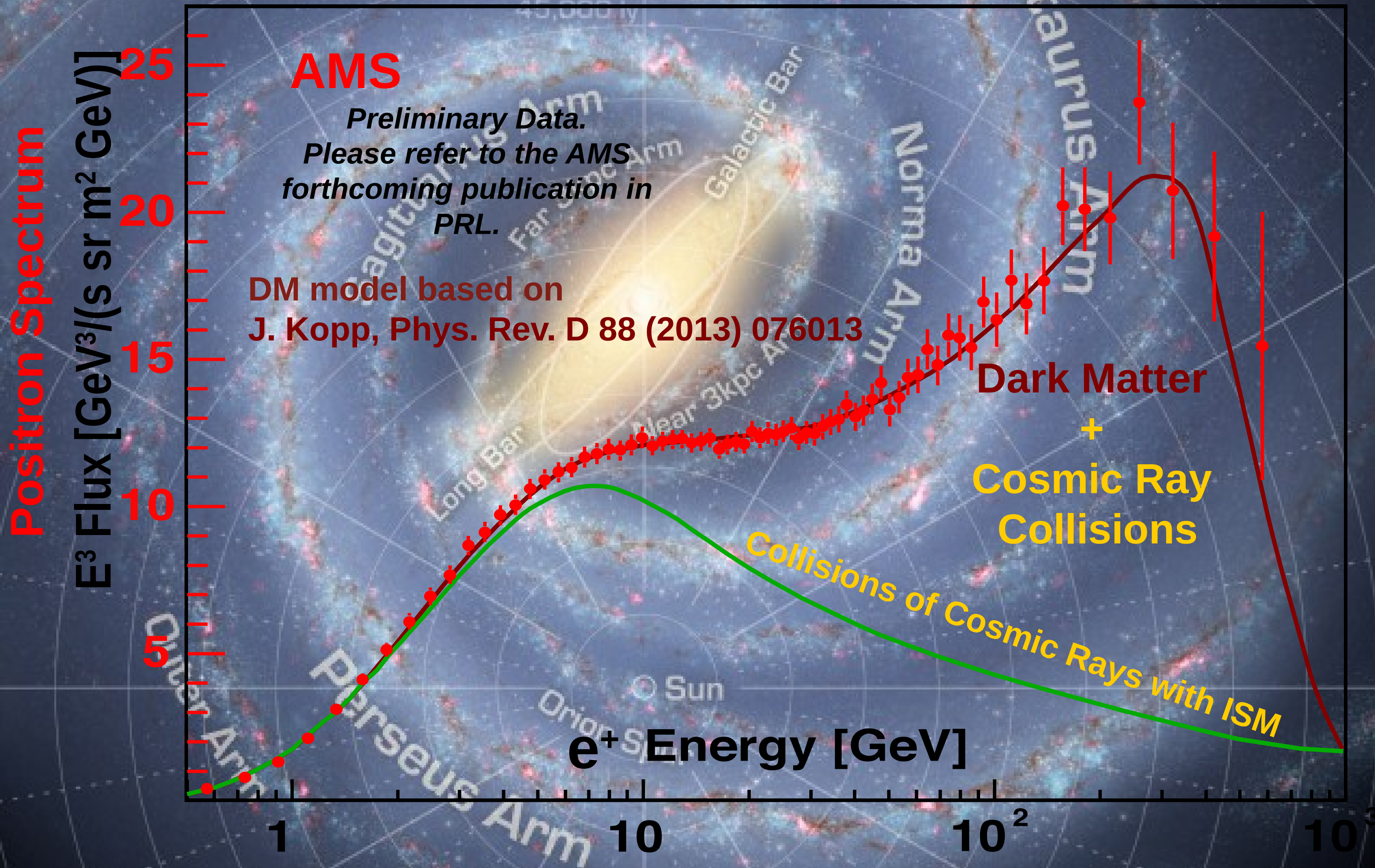
27) R.Cowsik, B.Burch, and T.Madziwa-Nussinov, Ap.J. 786 (2014) 124
28) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101
29) R. Kappl and M. W. Winkler, J. Cosmol. Astropart. Phys. 09 (2014) 051
30) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Serpico, JCAP09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

and many other excellent papers ...

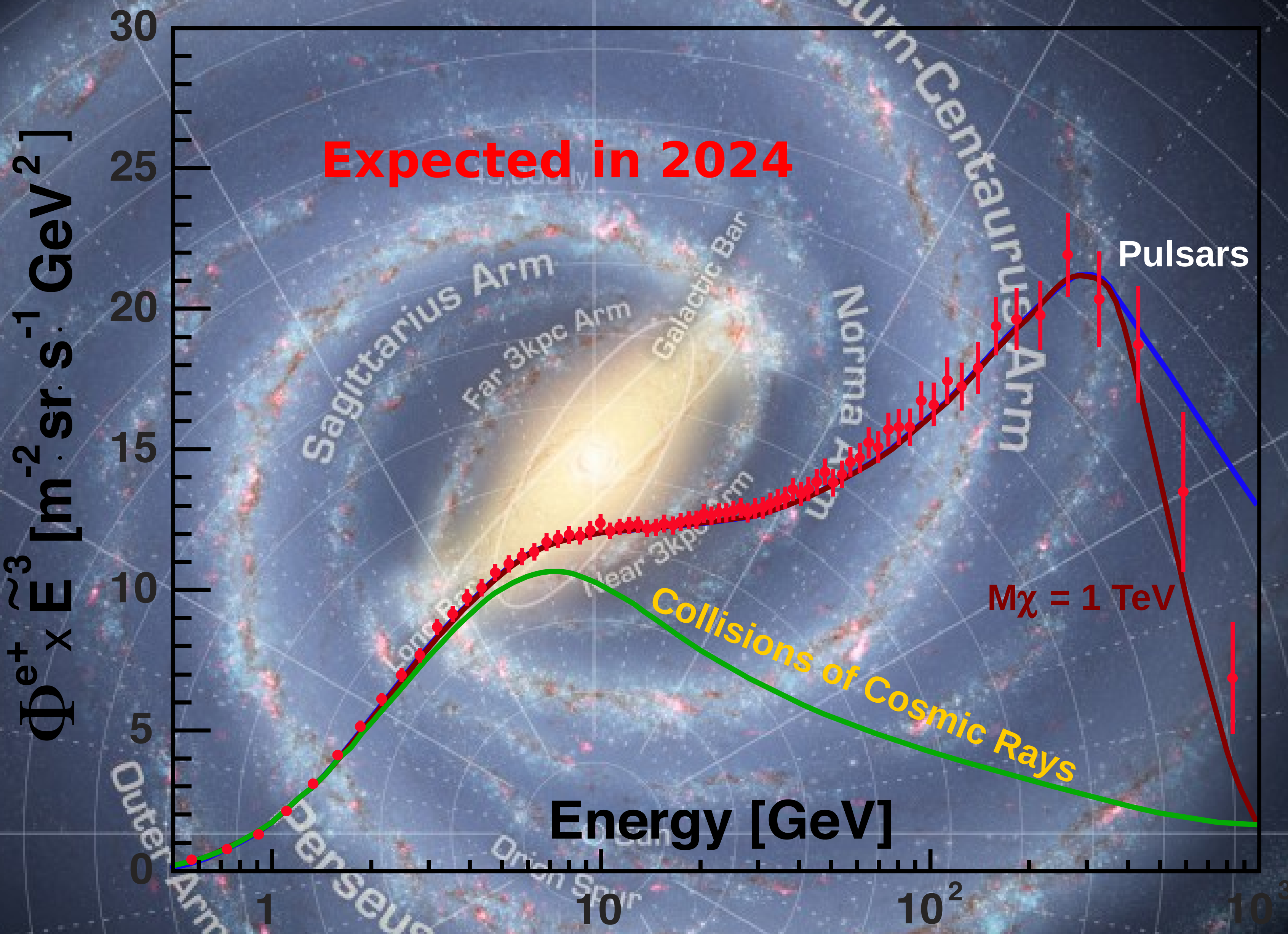
From secondary production

The origin of the positron spectrum

The AMS results are in excellent agreement with a Dark Matter Model



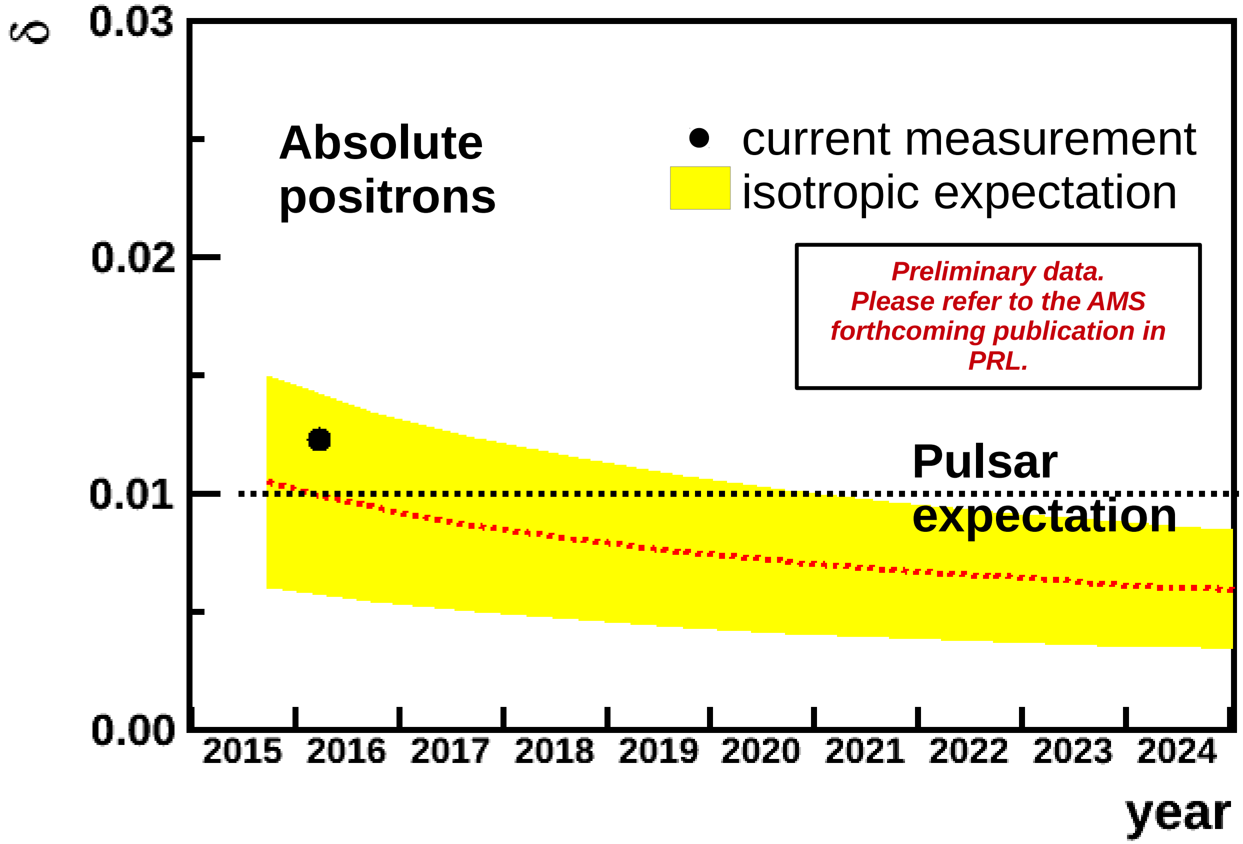
2024: Extend measurement to 1 TeV



By 2024 we will be able to understand the origin of this unexpected data.

PULSARS vs. DARK MATTER: ANISOTROPIES

Cosmic ray arrival directions might carry information on their sources.



Pulsar Model based on D. Hooper, P. Blasi & P. D. Serpico, JCAP 0901 (2009); K.Iota, PTP 123-4 (2010)743

2 CENTS ON POSITRONS

- An additional energetic positron component has been observed by AMS.
- The origin of these positrons is unknown, possible explanations include an additional source (dark matter annihilation or pulsar) or local secondary production.
- To differentiate between these hypotheses, we need to

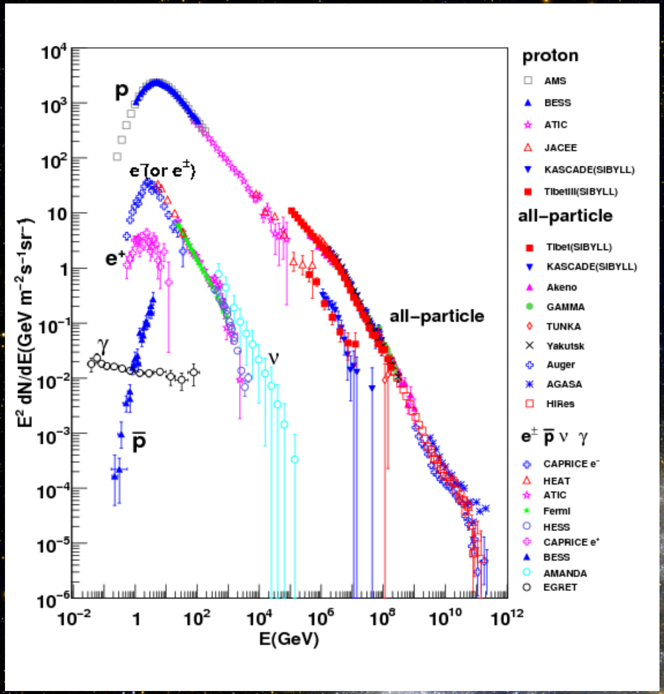
  → Extend the measurement to higher energies (more statistics)

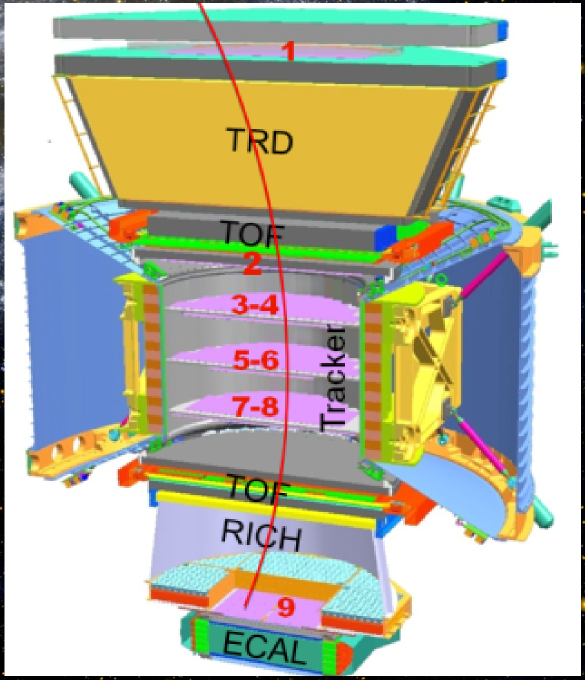
  → Improve the sensitivity of anisotropy searches (more statistics)

  → Decrease the uncertainties in the transport model (measure nuclei)

ANTIPROTONS

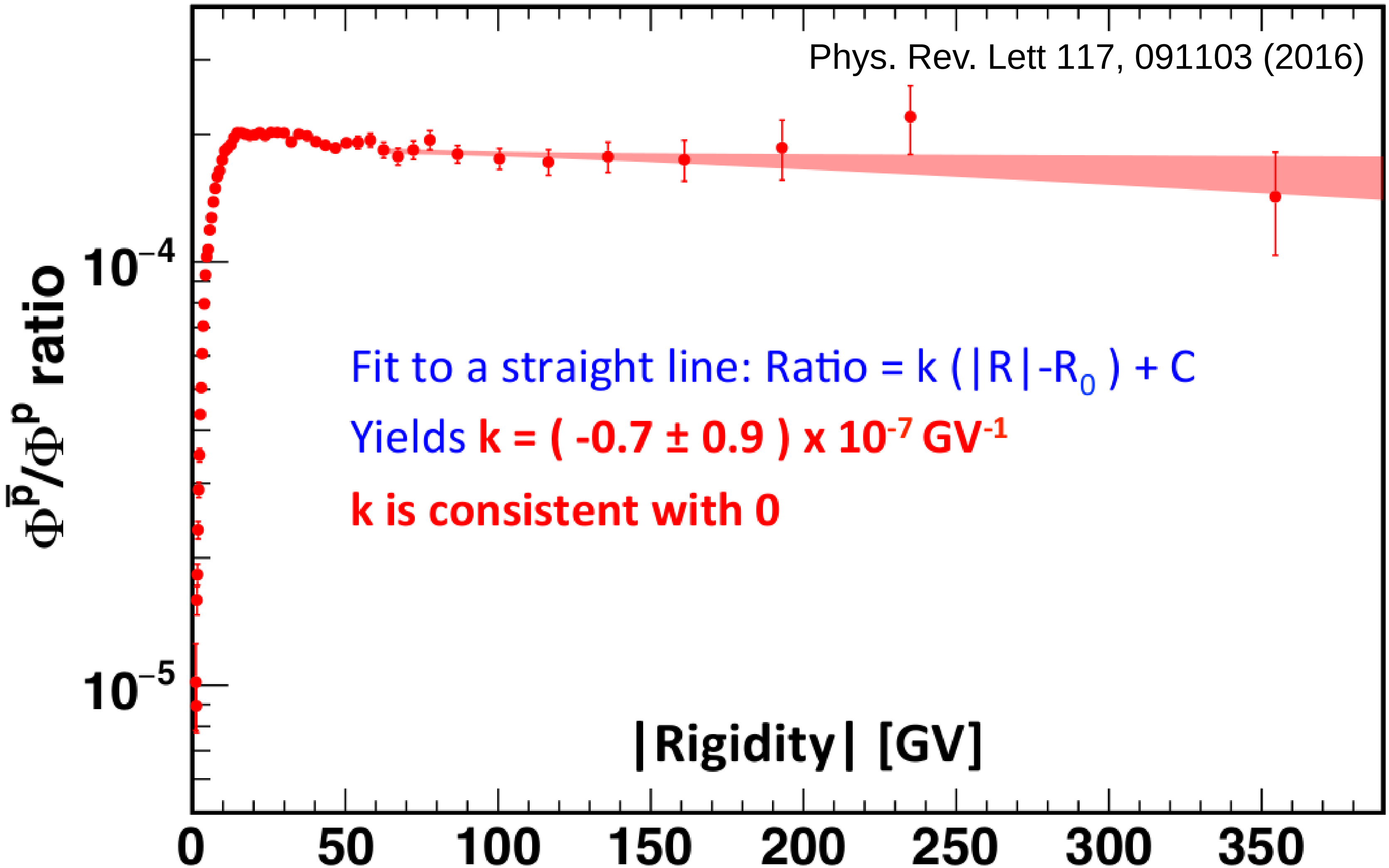
There is only 1 antiproton for 10,000 protons.





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

ANTIPROTON-TO-PROTON RATIO



SPECTRA OF PROTONS AND ANTIPROTONS

If $\bar{p}$ are secondaries, their rigidity dependence should be different from p:

$$p + \mathrm{ISM} = \bar{p} + \ldots$$

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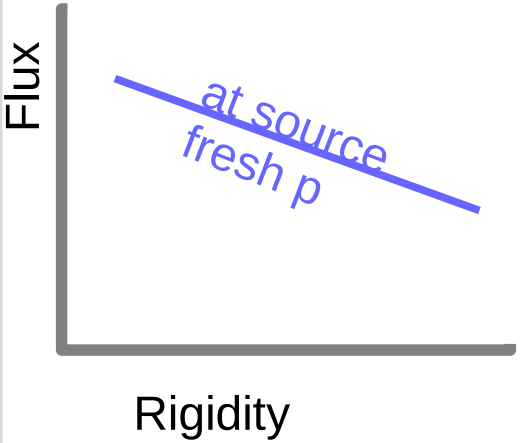

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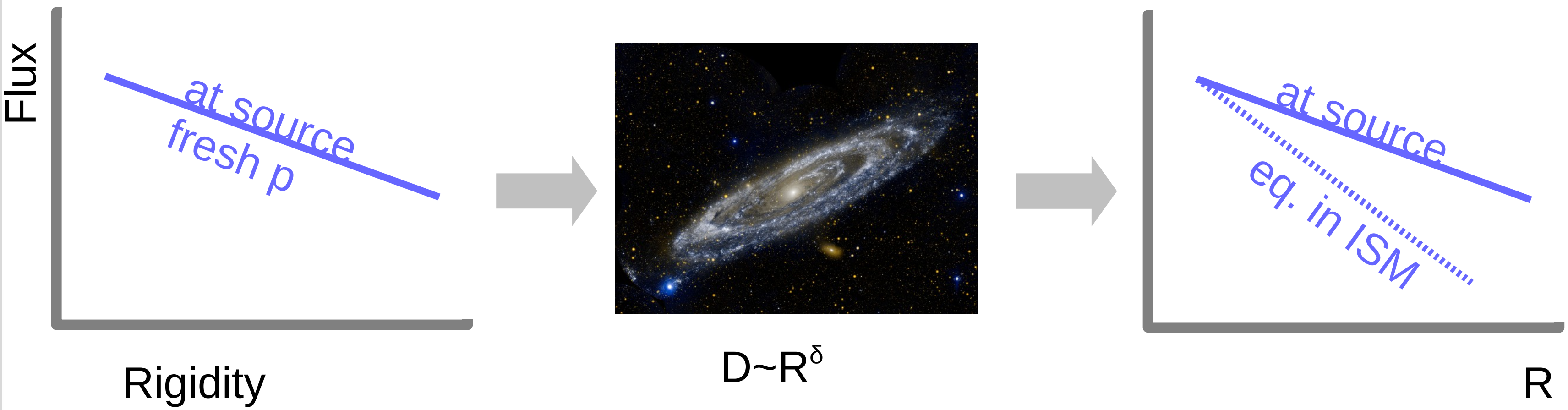

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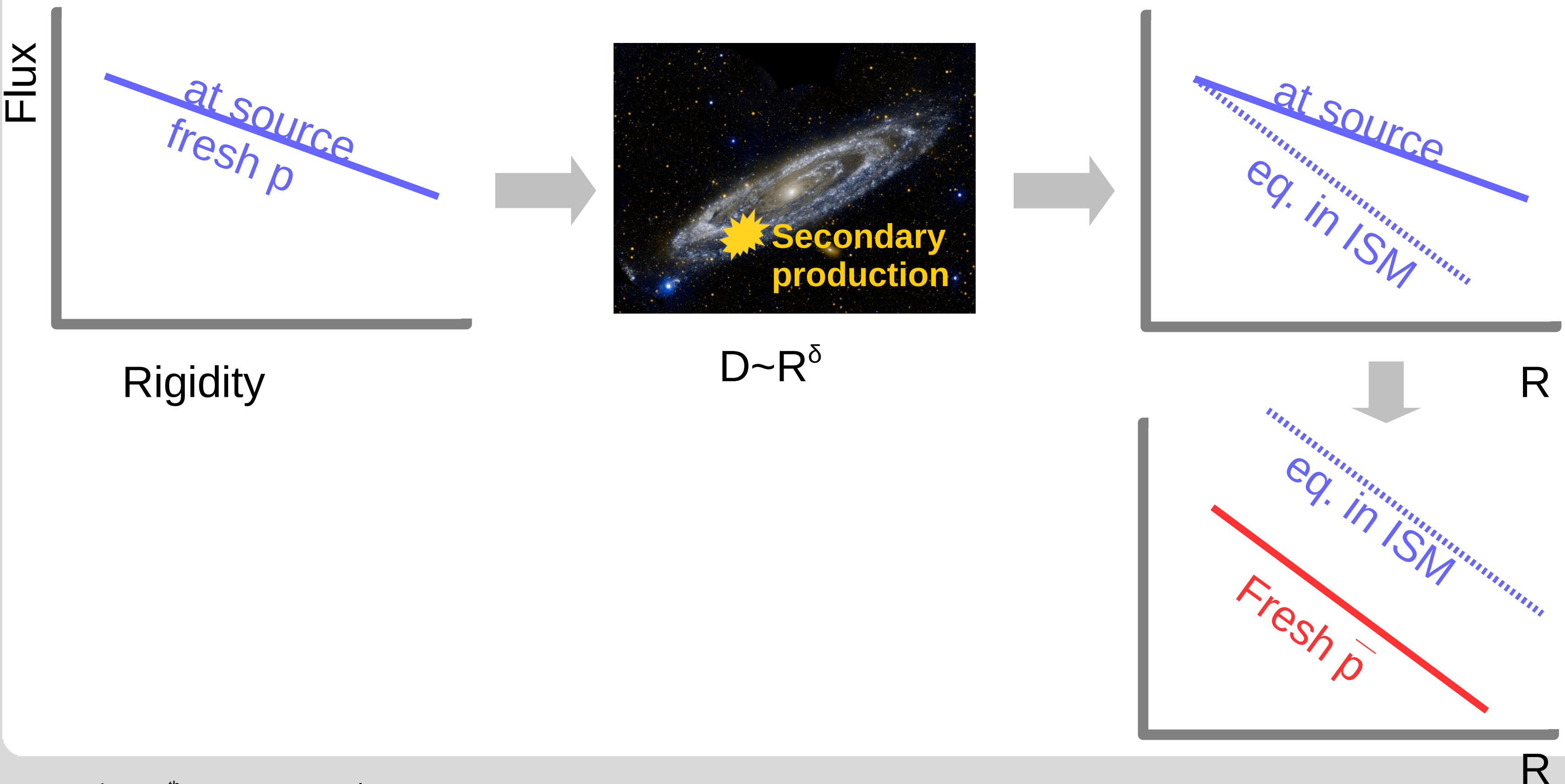

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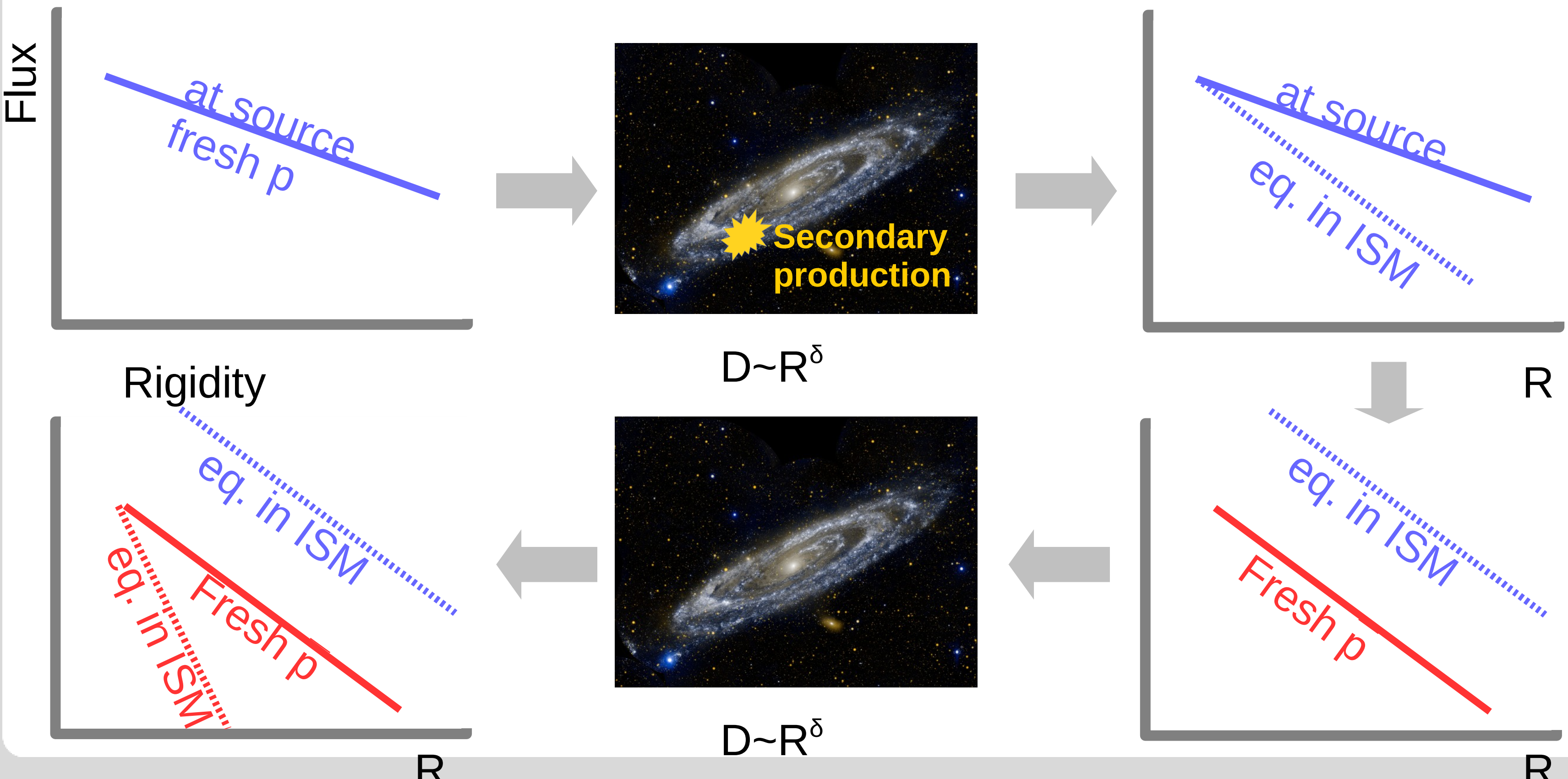

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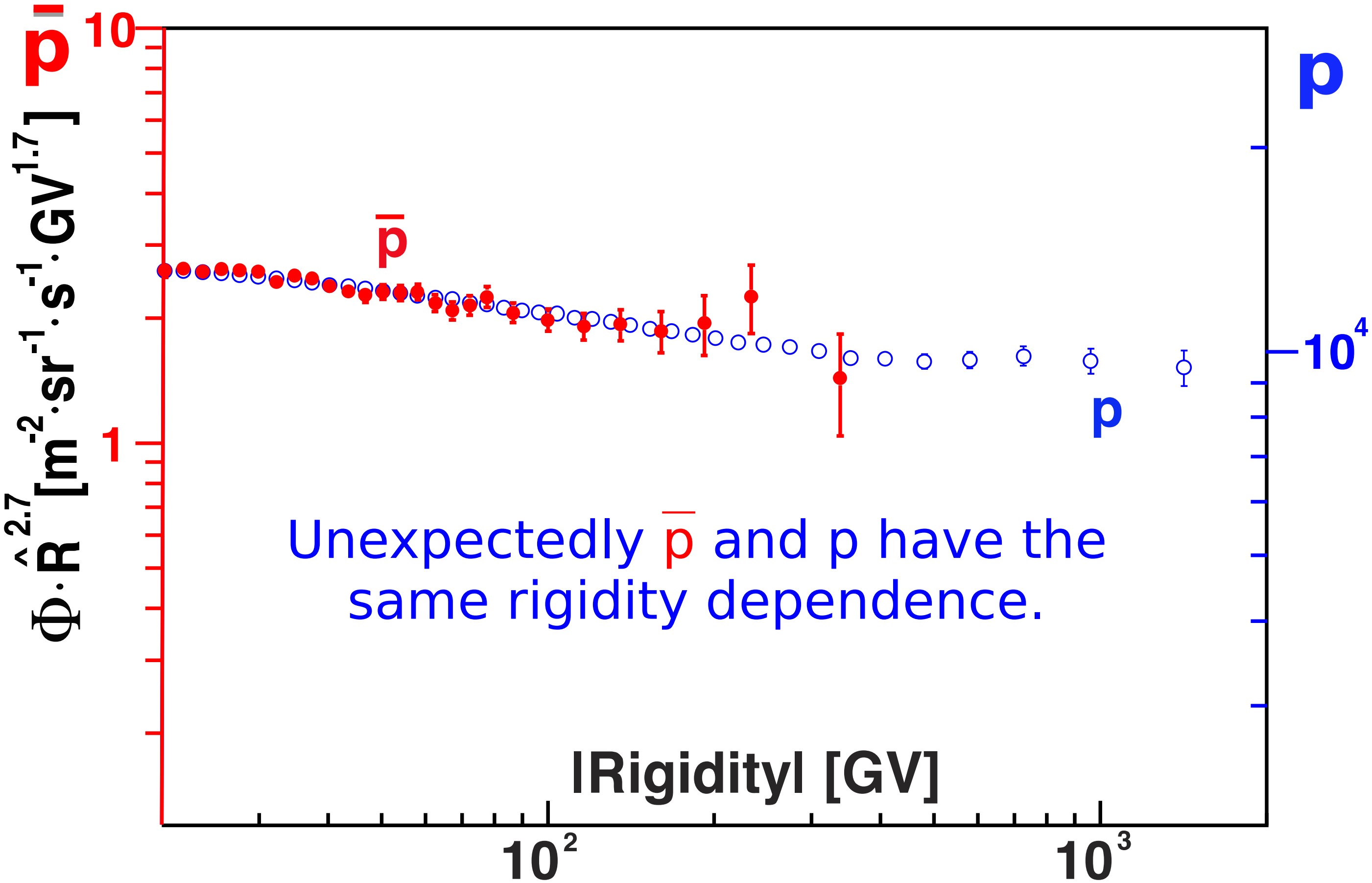
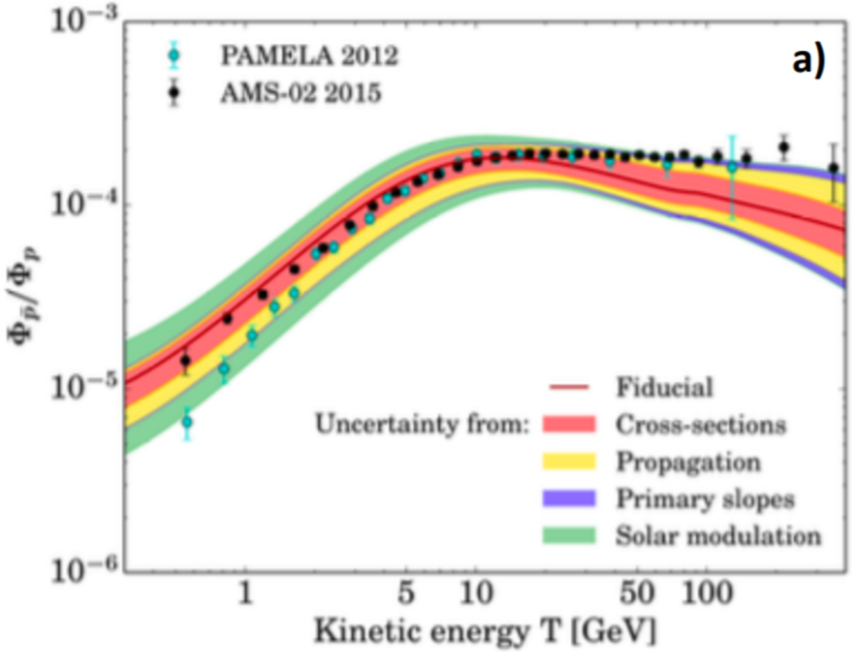
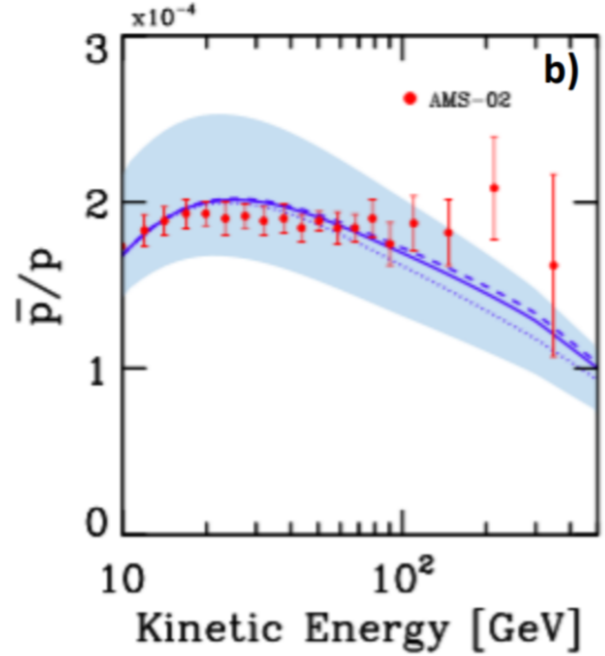


Phenomenological Models for the $\bar{p}/p$ ratio





The AMS data on antiprotons challenge the standard paradigm of secondary production and cosmic ray transport. There is

either a new source of antiprotons

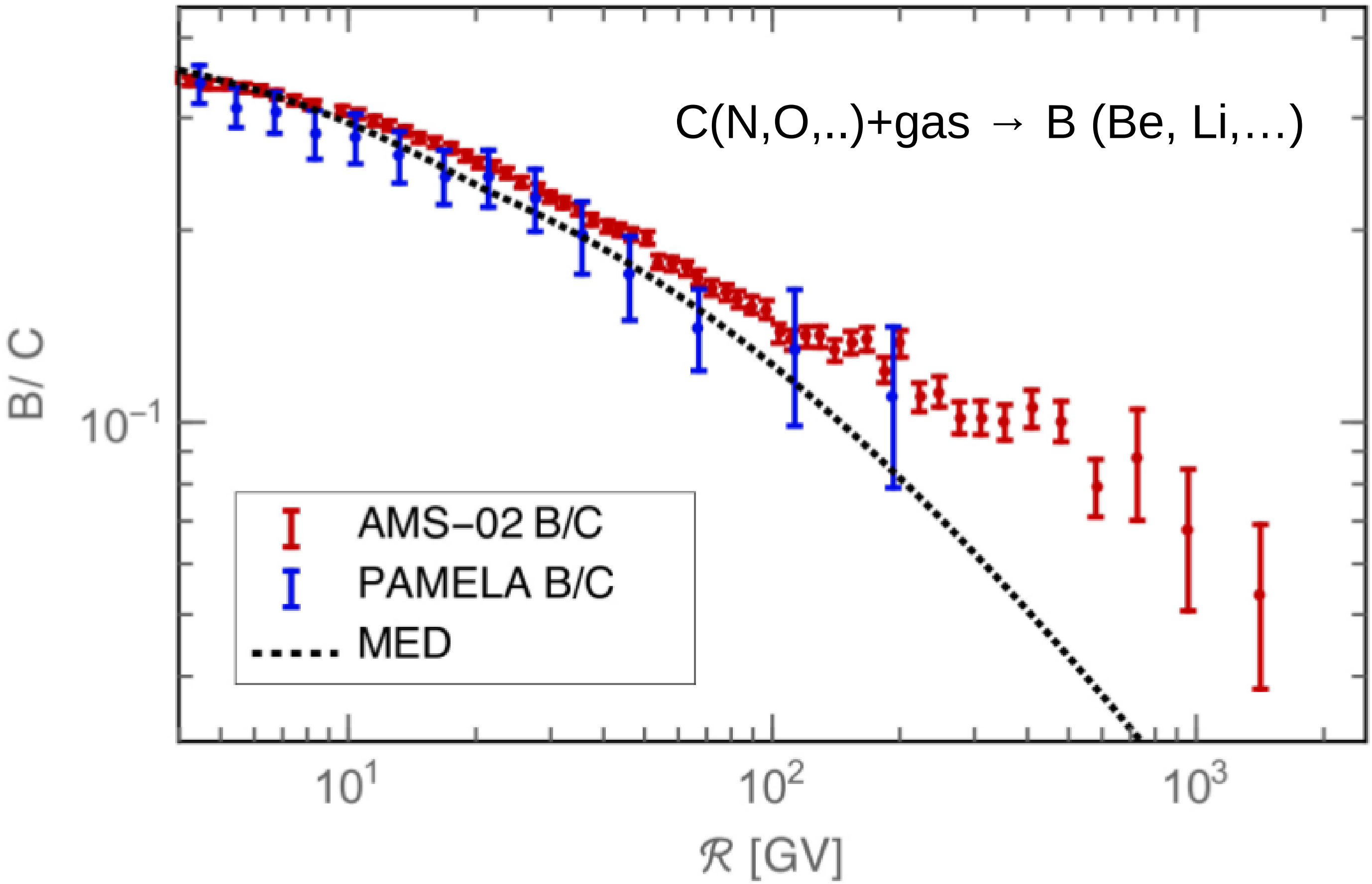
or our transport models are wrong.

(a) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Serpico, JCAP09 (2015) 023; [arXiv:1504.04276].

(b) C.Evoli, D.Gaggero and D.Grasso, arXiv: 1504.05175; JCAP 12 (2015) 039.

THE BORON/CARBON RATIO

The propagation parameters were extracted from pre-AMS data.

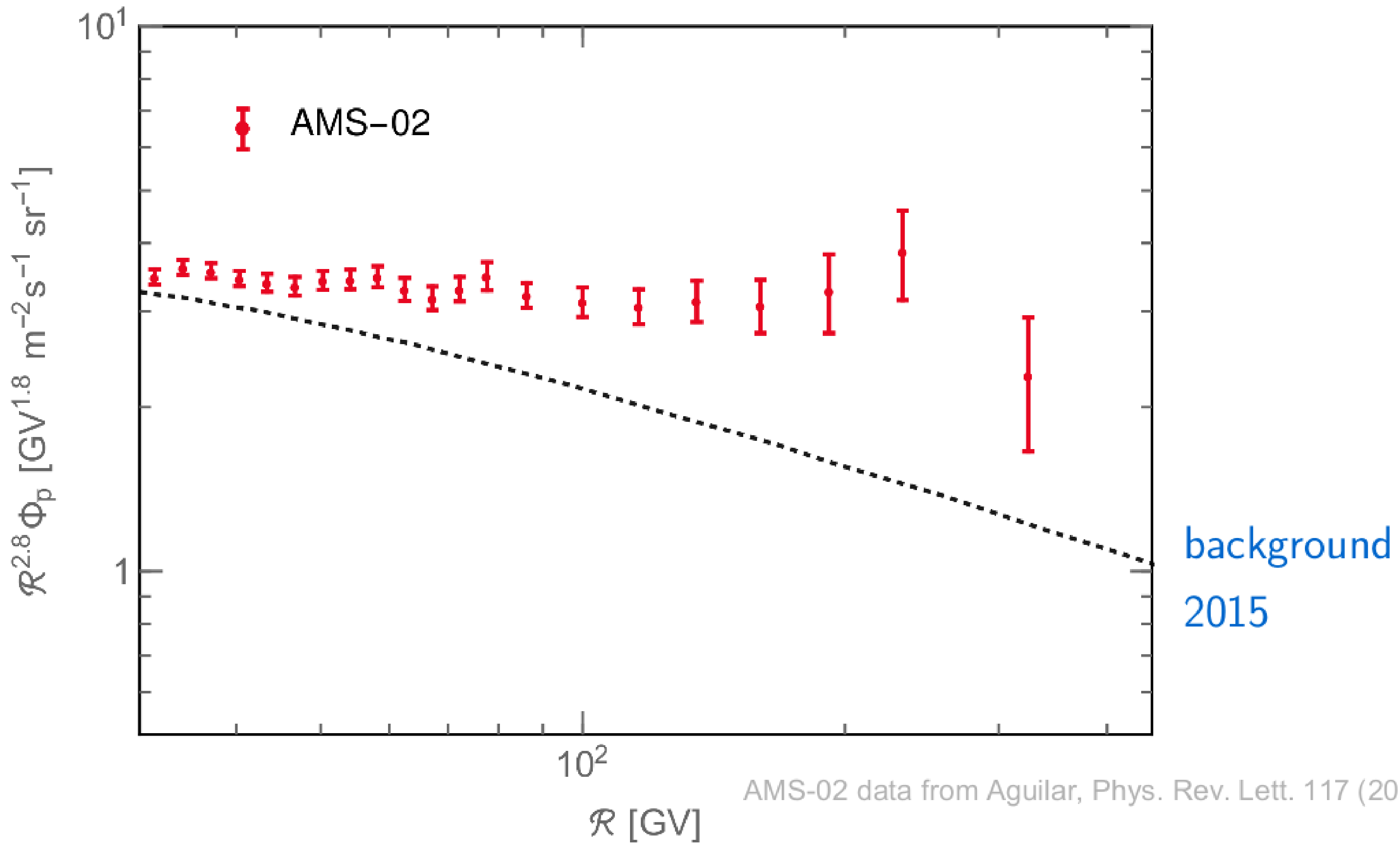


M. Winkler et al.
JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017)

AMS B/C indicates less cosmic ray escape at higher energies.

PRE-AMS ANTIPROTON FLUX

Based on pre-AMS B/C:

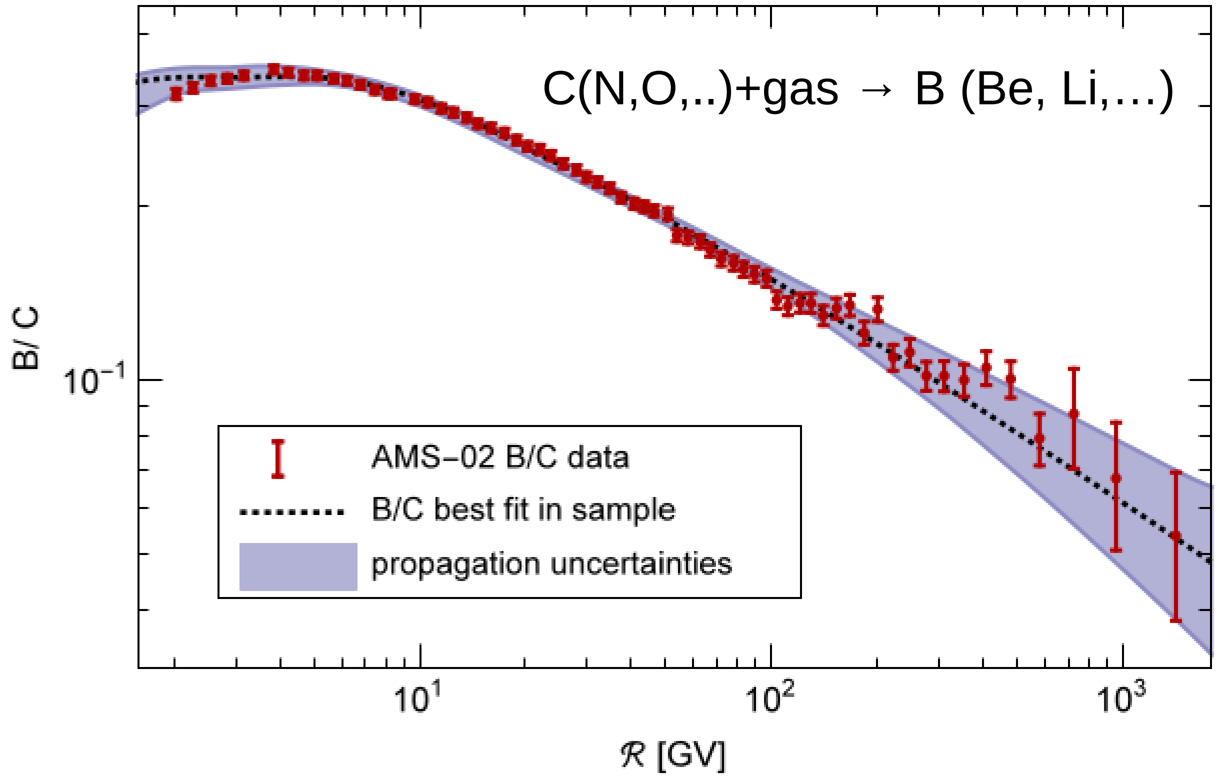


AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

M. Winkler et al.
JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017)

THE BORON/CARBON RATIO

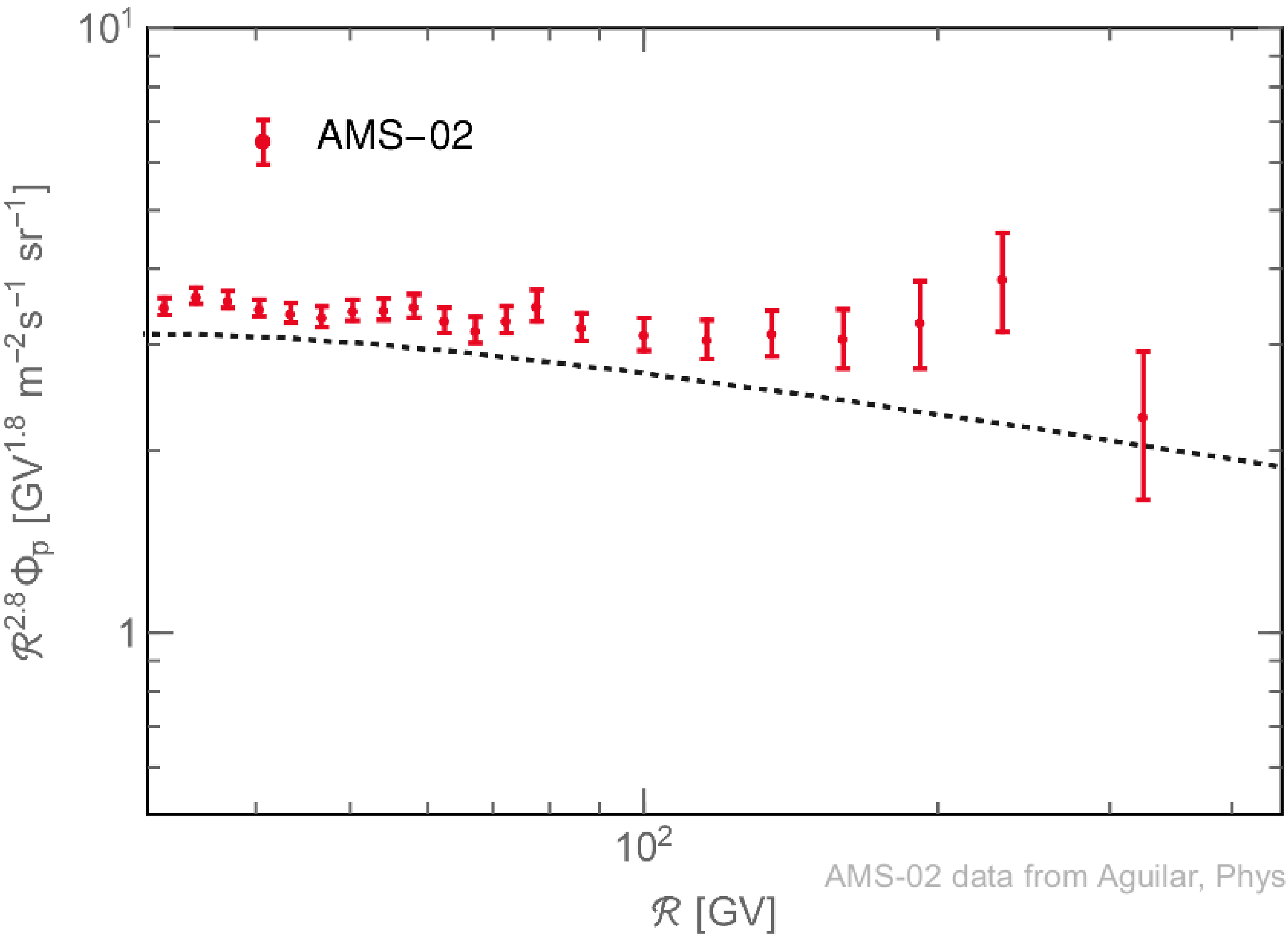
Propagation parameters tuned for AMS data.



M. Winkler et al.
JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017)

AMS ANTIPROTON FLUX

Based on AMS B/C:



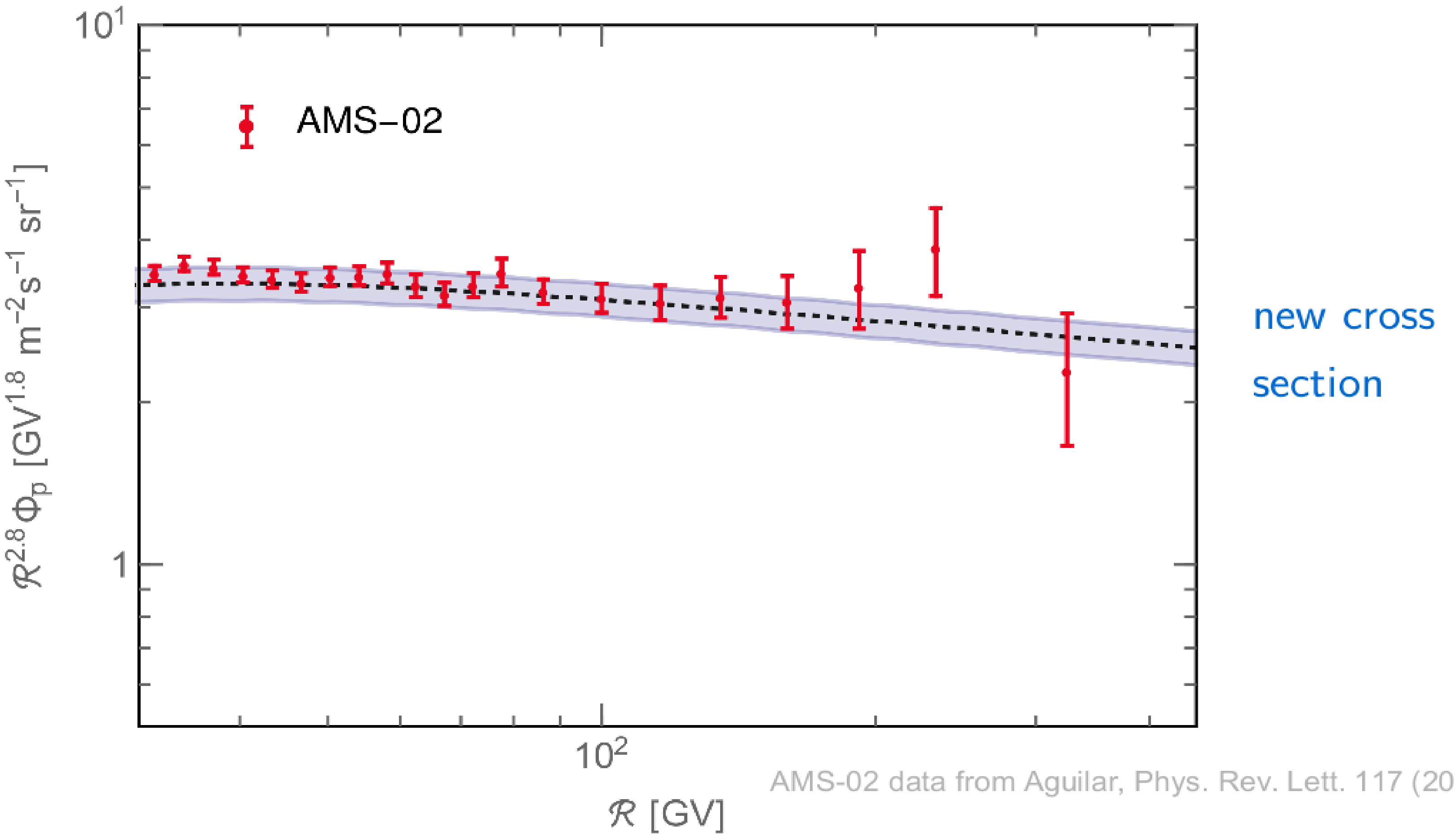
updated propagation

AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

M. Winkler et al.
JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017)

AMS ANTIPROTON FLUX

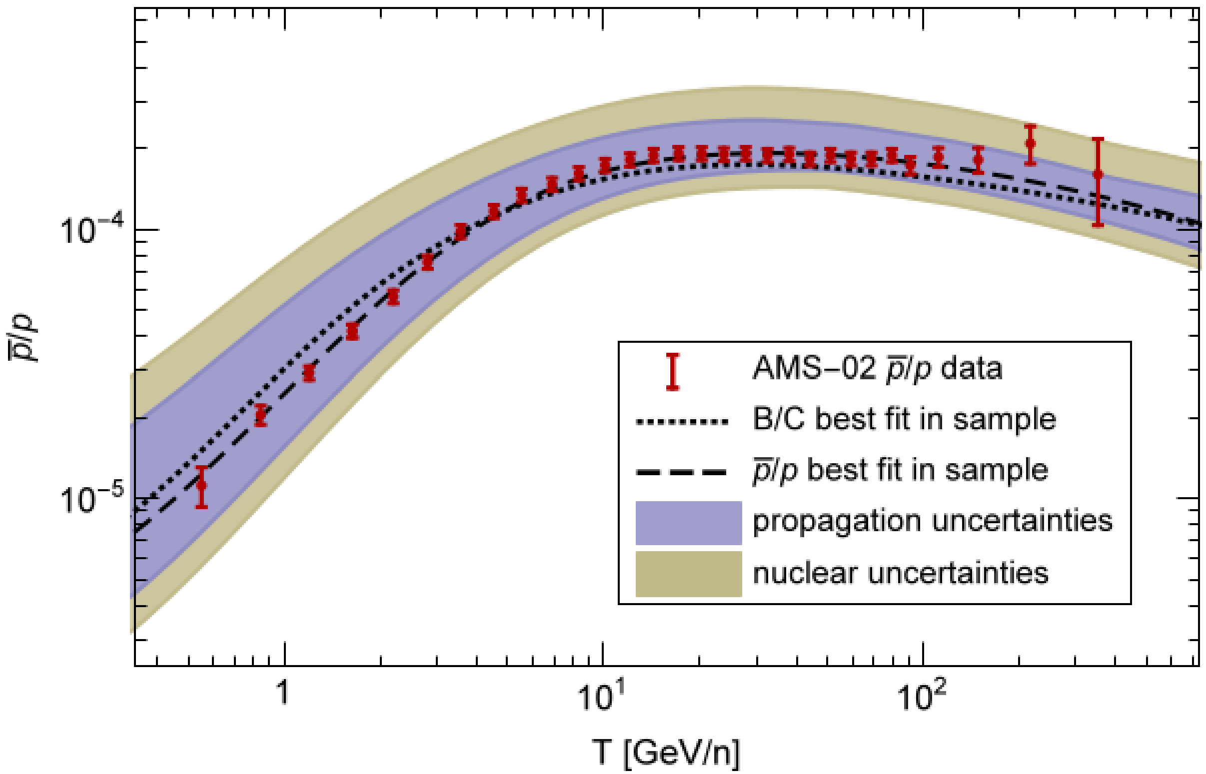
Based on AMS B/C and new cross-section evaluation:



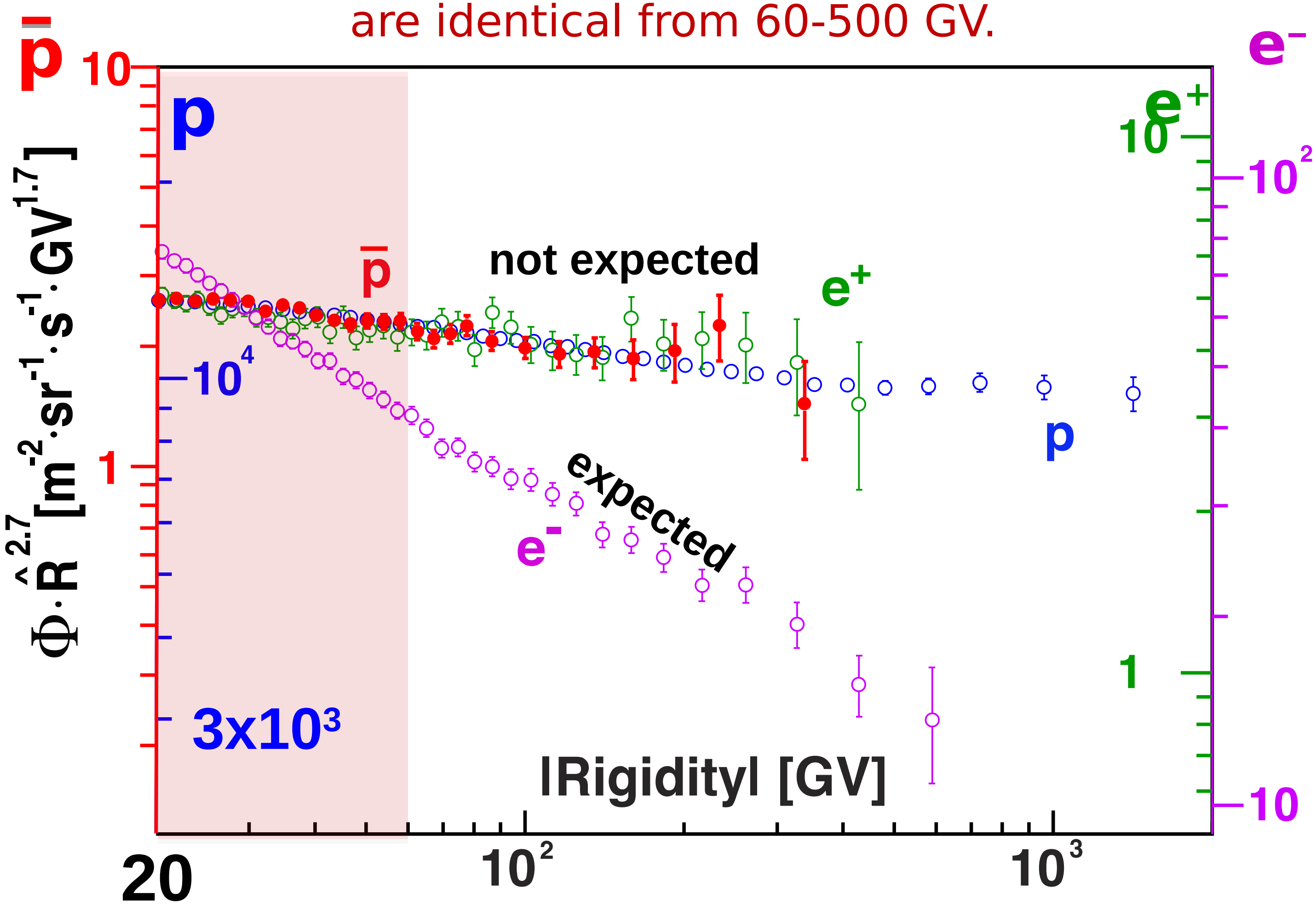
AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

M. Winkler et al.
JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017)

AMS ANTIPROTON FLUX

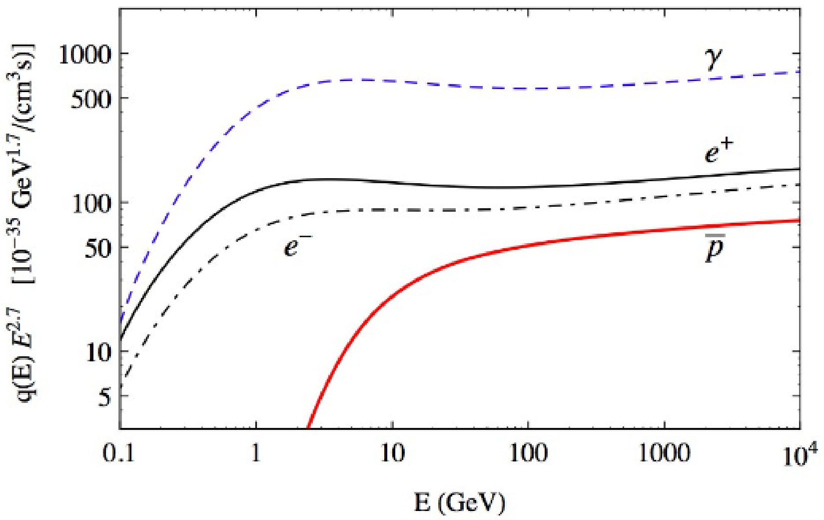


The rigidity dependences of e^+, $\bar{p}$, p are identical from 60-500 GV.



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

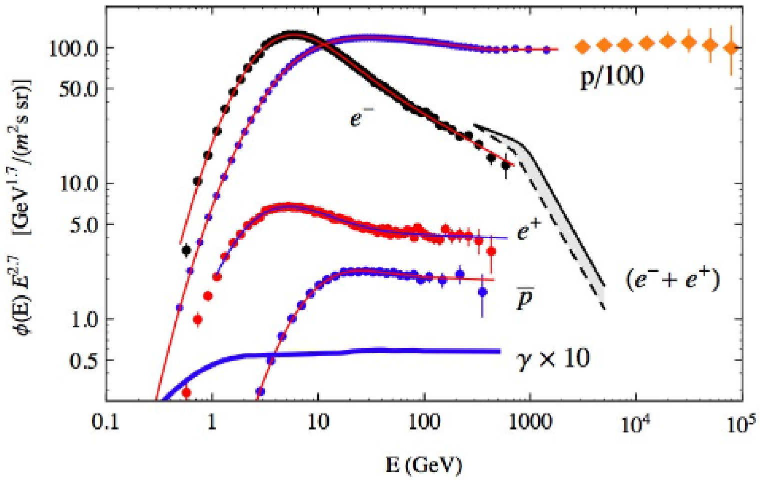
DO WE REALLY KNOW WERE SECONDARIES ARE PRODUCED?



Local production rates of secondaries

$e^+ \quad \overline{p}$

"striking" similarity

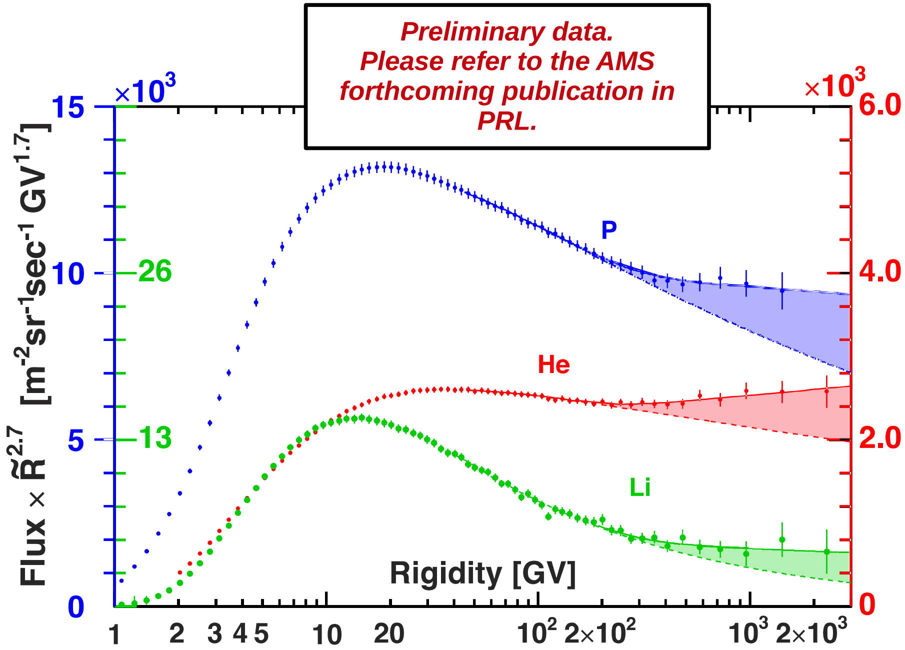


Observed fluxes

P. Lipari@ICRC2017

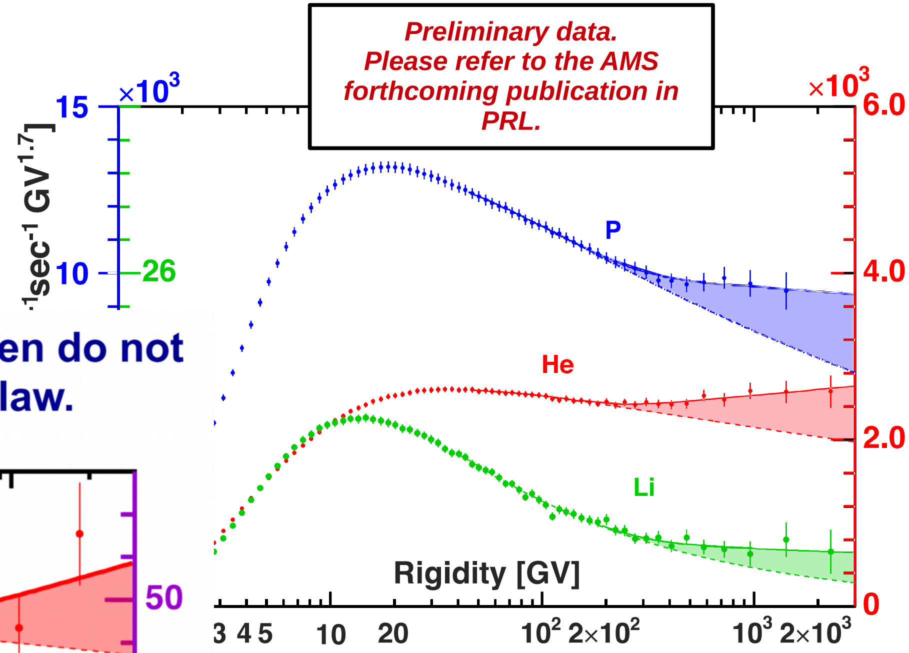
Iris Gebauer
Institute for Experimental Particle Physics

AMS DATA ON NUCLEI

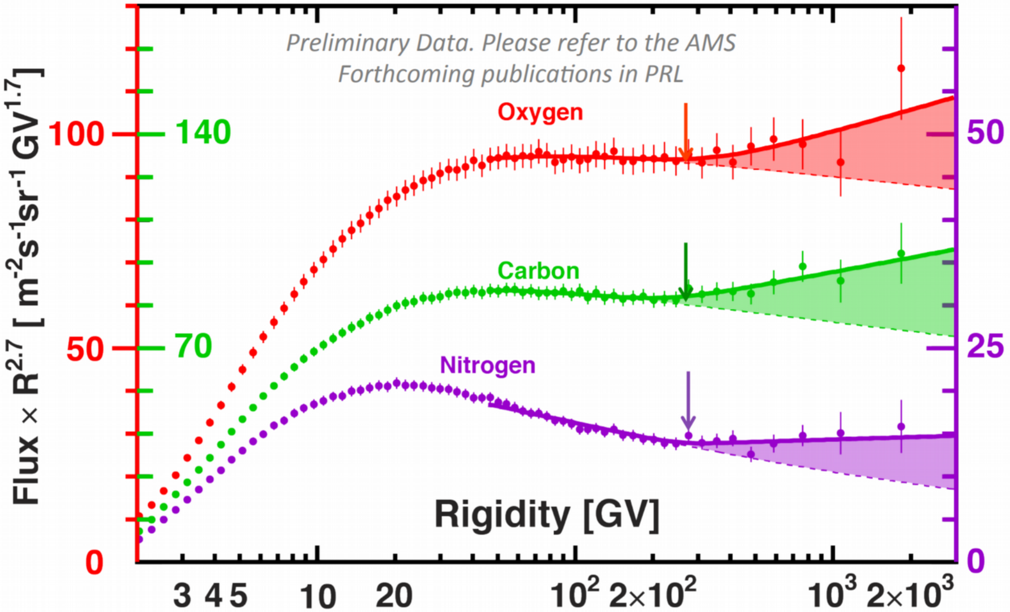


The fluxes of protons, helium and lithium show a spectral hardening at ~300 GV....

AMS DATA ON NUCLEI



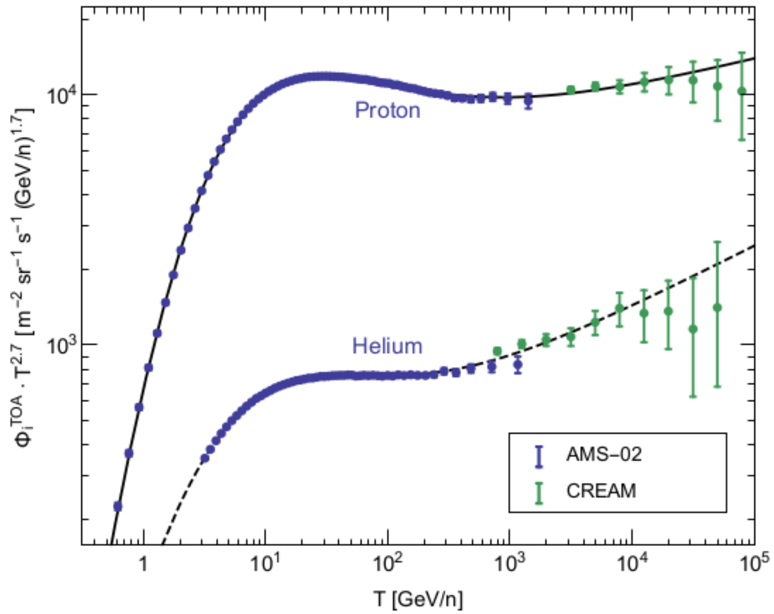
The spectra of oxygen, carbon and nitrogen do not follow the traditional single power law.



...as do the fluxes of oxigen, carbon and nitrogen.

Iris Gebauer
Institute for Experimental Particle Physics

TOWARDS CREAM



The CREAM balloon experiment has previously observed harder spectra in the TeV range. The AMS data confirm that a transition between two power laws occurs around 300 GV.

The source of this deviation might be

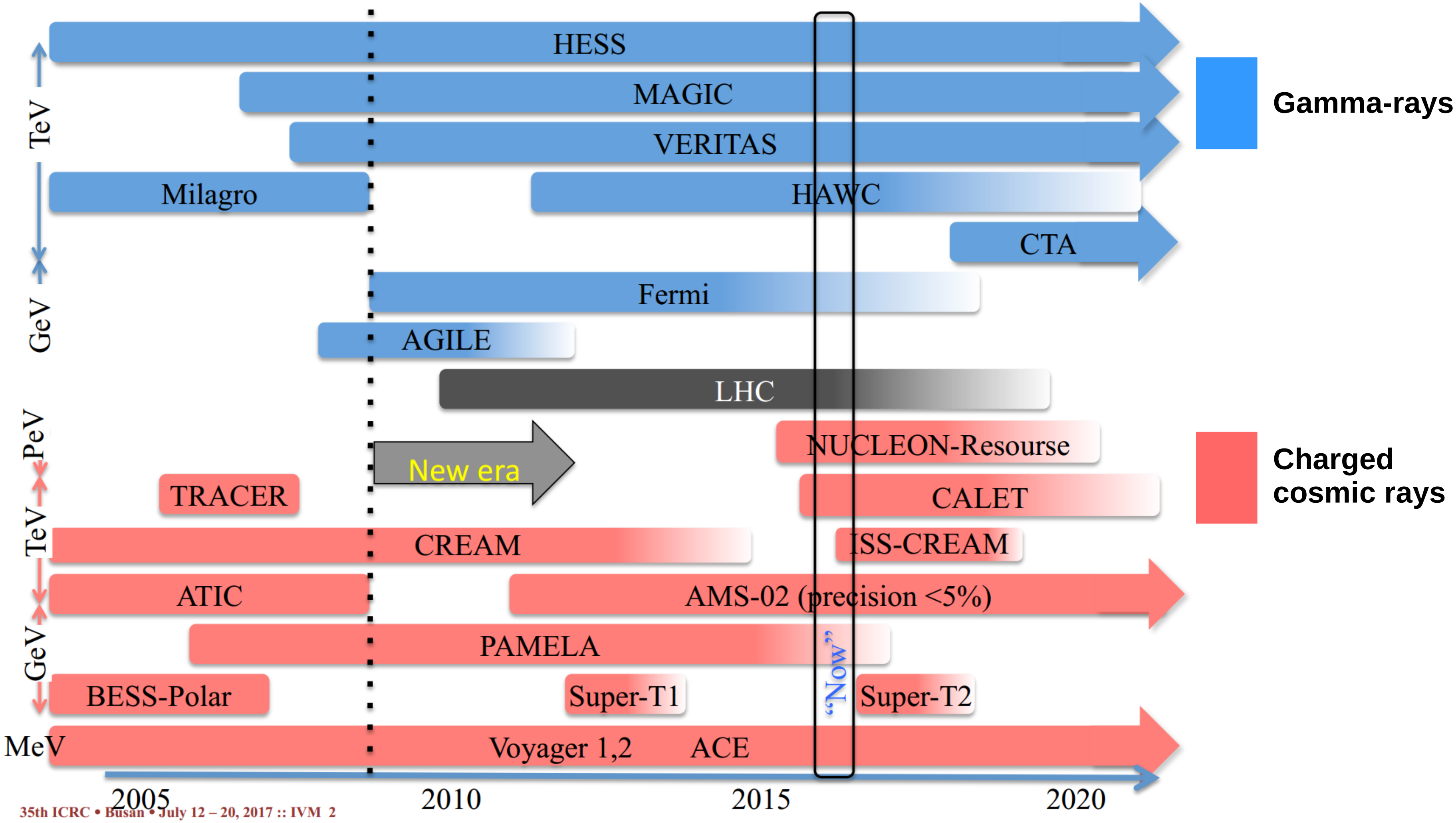
→ a **local cosmic ray accelerator** dominating at high energies
→ a **change in the energy dependence** of cosmic ray escape

WHAT WE NEED TO MOVE ON

- Extend the positron flux measurement to higher energies (**only AMS**)
- Improve the sensitivity of anisotropy searches in positrons (**only AMS**)
- Further decrease the uncertainties in the transport model (**AMS+future measurements**)
- Improve the sensitivity of anisotropy searches in nuclei (**AMS+future measurements**)

THE NEAR FUTURE

Timeline of γ-ray, CR, and particle experiments



Igor Moskalenko, ICRC2017

MISSIONS AND SELECTED RESULTS

Experiment	e^+|e^- (present data)	e^++e^- (energy range)	CR nuclei (energy range)	Charge	Gamma-ray	Type	Launch	
PAMELA	e^+<300 GeV e^-<625 GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (ext. -> 2TeV)	1-8	-	SAT	2006 Jun 15	
FERMI	-	7 GeV -2 TeV	50 GeV-1TeV	1	200 MeV-300GeV GRB 8 keV-35 MeV	SAT	2008 Nov 11	
AMS-02	e^+<500 GeV e^-<700GeV	0.5 GeV-1 TeV (extendable)	0.5 GV-1.9 TV (extendable)	1-26++	1 GeV-1TeV (calorimeter)	ISS	2011 May 16	
NUCLEON	-	100 GeV–3 TeV	100 GeV-1TeV	1-30	-	SAT	2014 Dec 26	
CALET	-	1 GeV -20 TeV	10 GeV-1PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19	1^{st} results
DAMPE	-	10 GeV -10 TeV	50 GeV-500TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17	1^{st} results
ISS-CREAM	-	100 GeV-10 TeV	1TeV-1PeV	1-28++	-	ISS	2017 Aug 14	Soon!
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	2017	
GAMMA-400	-	1 GeV-20 GeV	1 TeV-3 PeV	1-26	20 MeV – 1 TeV	SAT	2023-25	
HERD	-	10(s)-10^4 GeV	Up to PeV	TBD	10(s)-10^4 GeV	CSS	2022-25	
HELIX	-	-	<10 GeV/n	light isotopes	-	LDB	proposal	
HNS	-	-	~GeV/n	6-96	-	SAT	proposal	
GAPS	-	-	<1GeV/n	$\bar{p}$, $\bar{D}$	-	LDB		

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Do not look here

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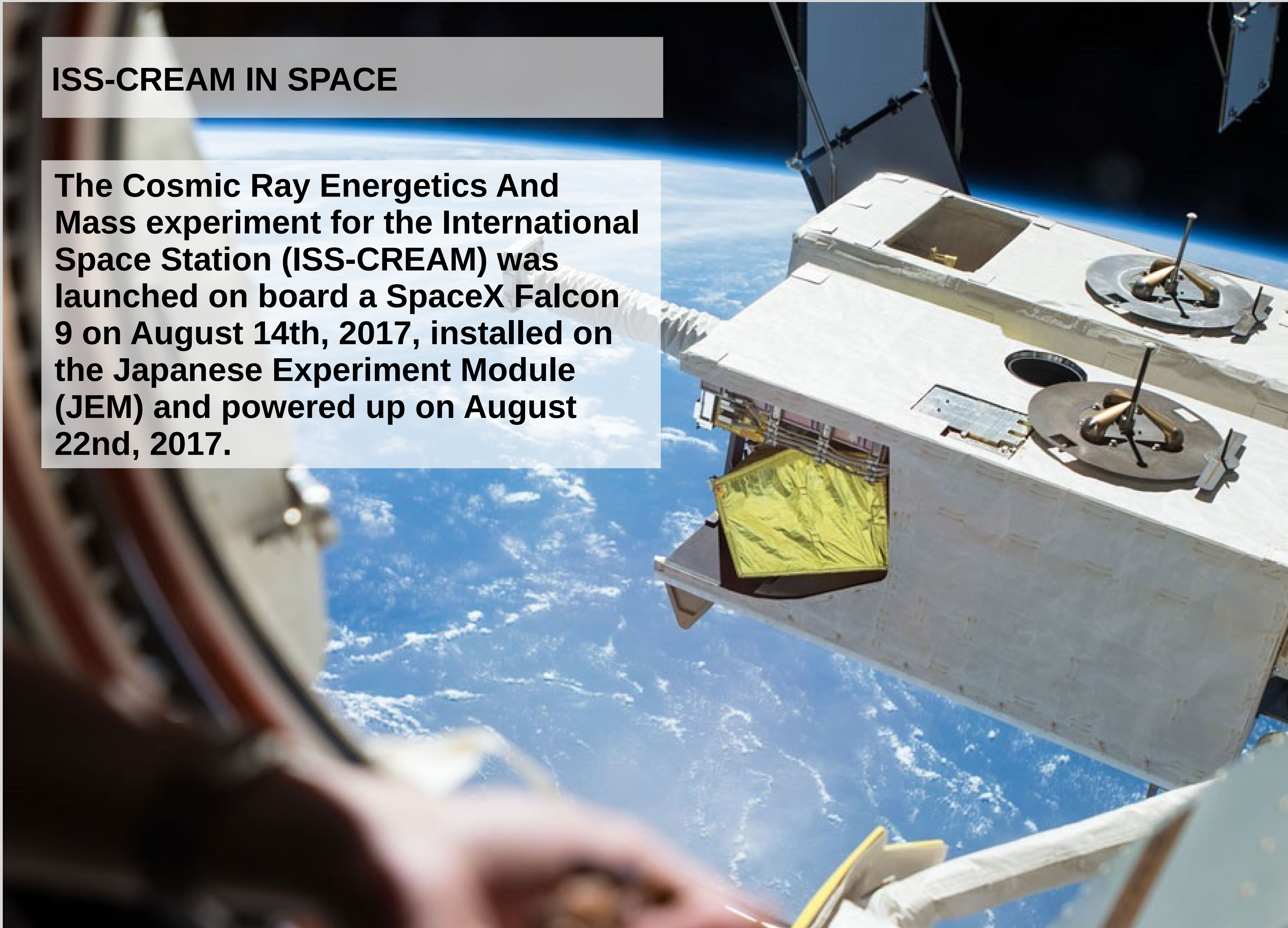
We did this

Do not look here

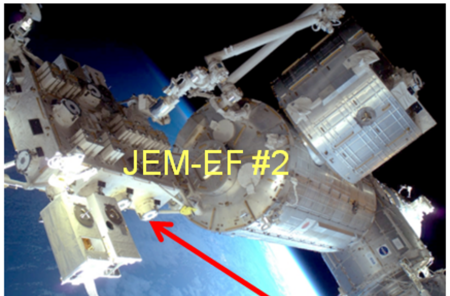
ISS-CREAM IN SPACE

The Cosmic Ray Energetics And Mass experiment for the International Space Station (ISS-CREAM) was launched on board a SpaceX Falcon 9 on August 14th, 2017, installed on the Japanese Experiment Module (JEM) and powered up on August 22nd, 2017.



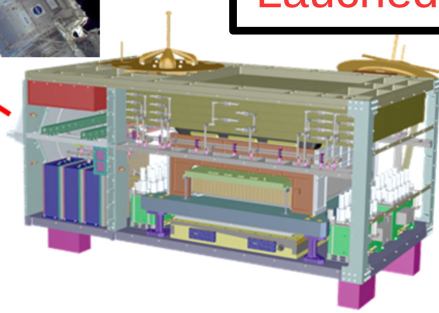
ISS-CREAM: CREAM for the ISS

E. S. Seo et al, Advances in Space Research, **53**/10, *1451*, 2014

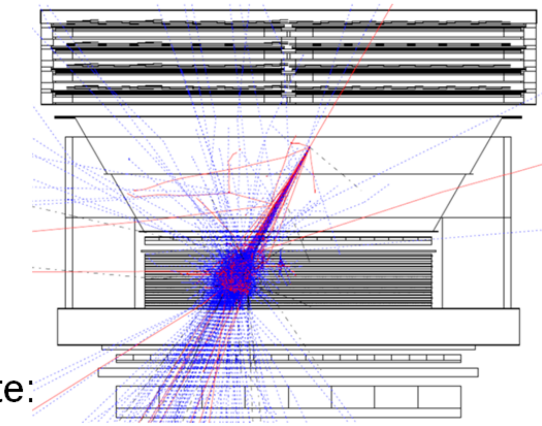


To be installed on the ISS
by SpaceX-12 in 2017

Lauched Aug 14th



Mass: ~1258 kg
Power: ~ 415 W
Nominal data rate:
~500 kbps



- Building on the success of the balloon flights, the payload has been transformed for accommodation on the ISS (NASA's share of JEM-EF).
  - Increase the exposure by an order of magnitude
- ISS-CREAM will measure cosmic ray energy spectra from 10^{12} to $>10^{15}$ eV with individual element precision over the range from protons to iron to:
  - Probe cosmic ray origin, acceleration and propagation.
  - Search for spectral features from nearby/young sources, acceleration effects, or propagation history.

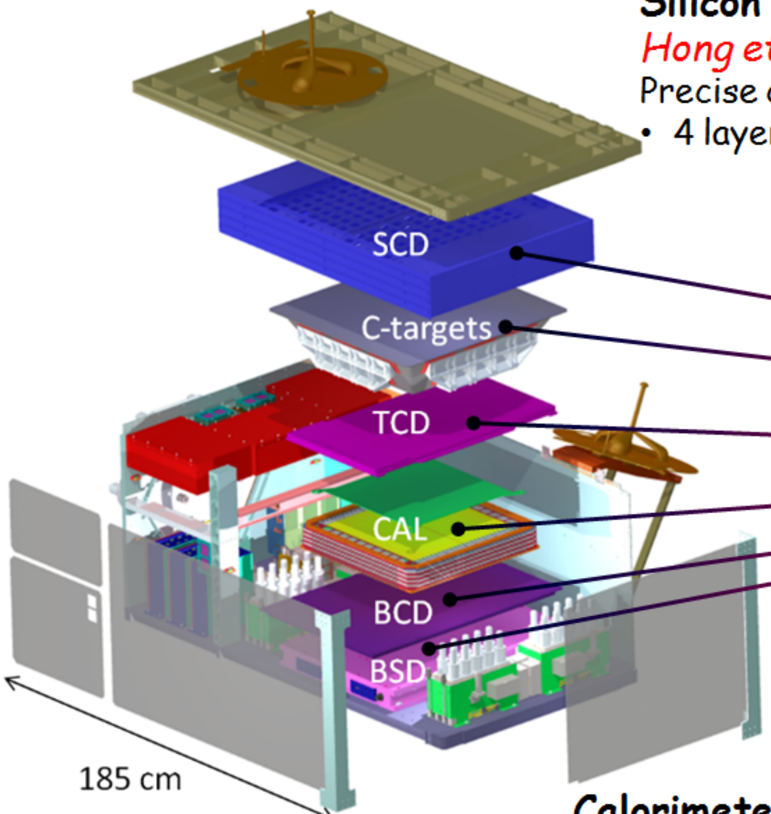
ISS-CREAM Instrument

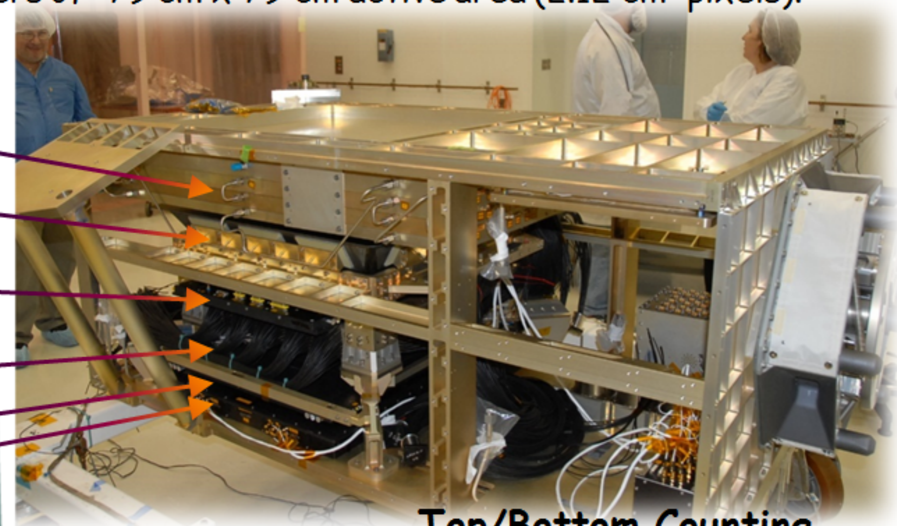
Seo et al. Adv. in Space Res., **53**/10, *1451*, 2014; Smith et al. ICRC 2017

Silicon Charge Detector (SCD) *Lee et al. (CRD042) & Hong et al. (CRD122) ICRC 2017*

Precise charge measurements with charge resolution of ~ 0.2e.

- 4 layers of 79 cm x 79 cm active area (2.12 cm^2 pixels).





Boronated Scintillator Detector (BSD)

- Additional e/p separation by detection of thermal neutrons.

Calorimeter (CAL) *Picot-Clemente et al. ICRC 2017*

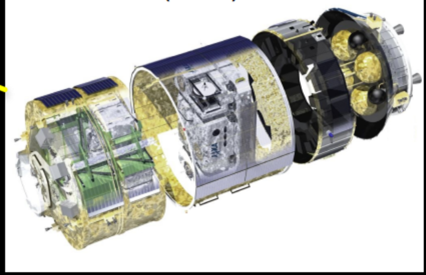
- 20 layers of alternating tungsten plates and scintillating fibers.
- Determines energy.
- Provides tracking and trigger.

Top/Bottom Counting Detector (T/BCD) *Shin et al. ICRC 2017;* Hwang et al. JINT10 (07), P07018, 2015.

- Plastic scintillator instrumented with an array of 20 x 20 photodiodes for e/p separation.
- Independent trigger.

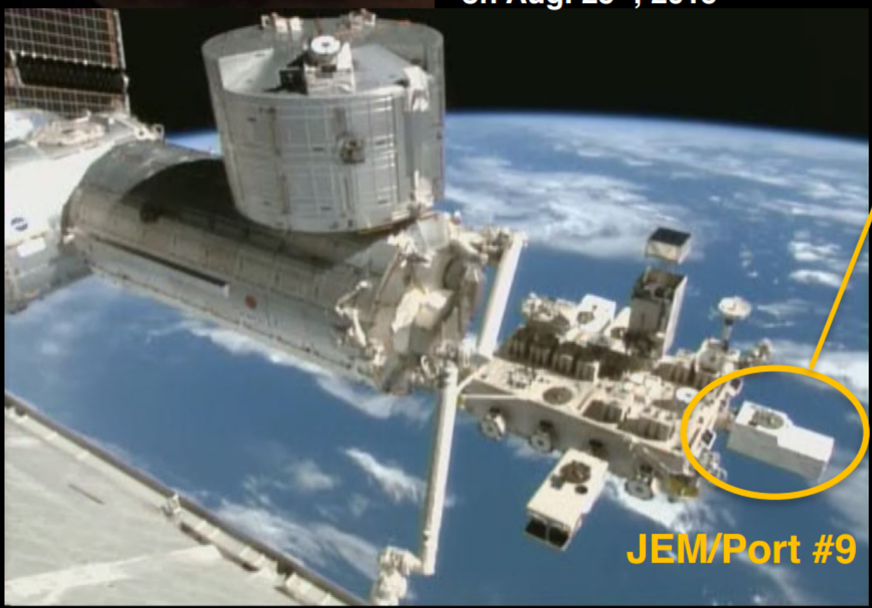
CALET Payload

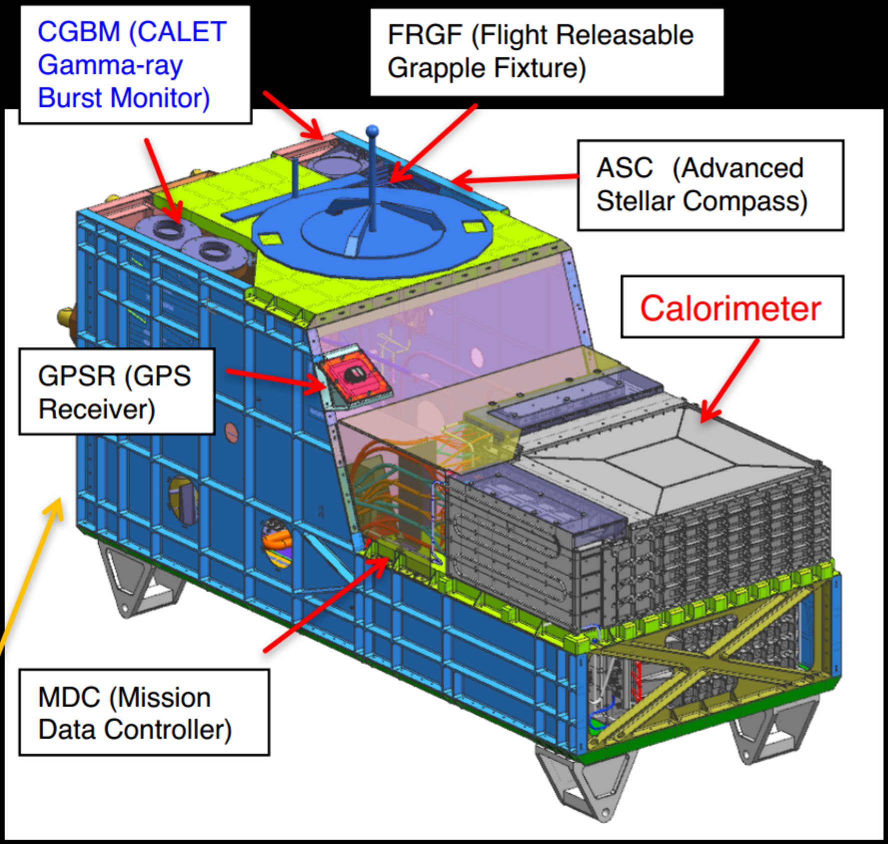
Kounotori (HTV) 5



Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

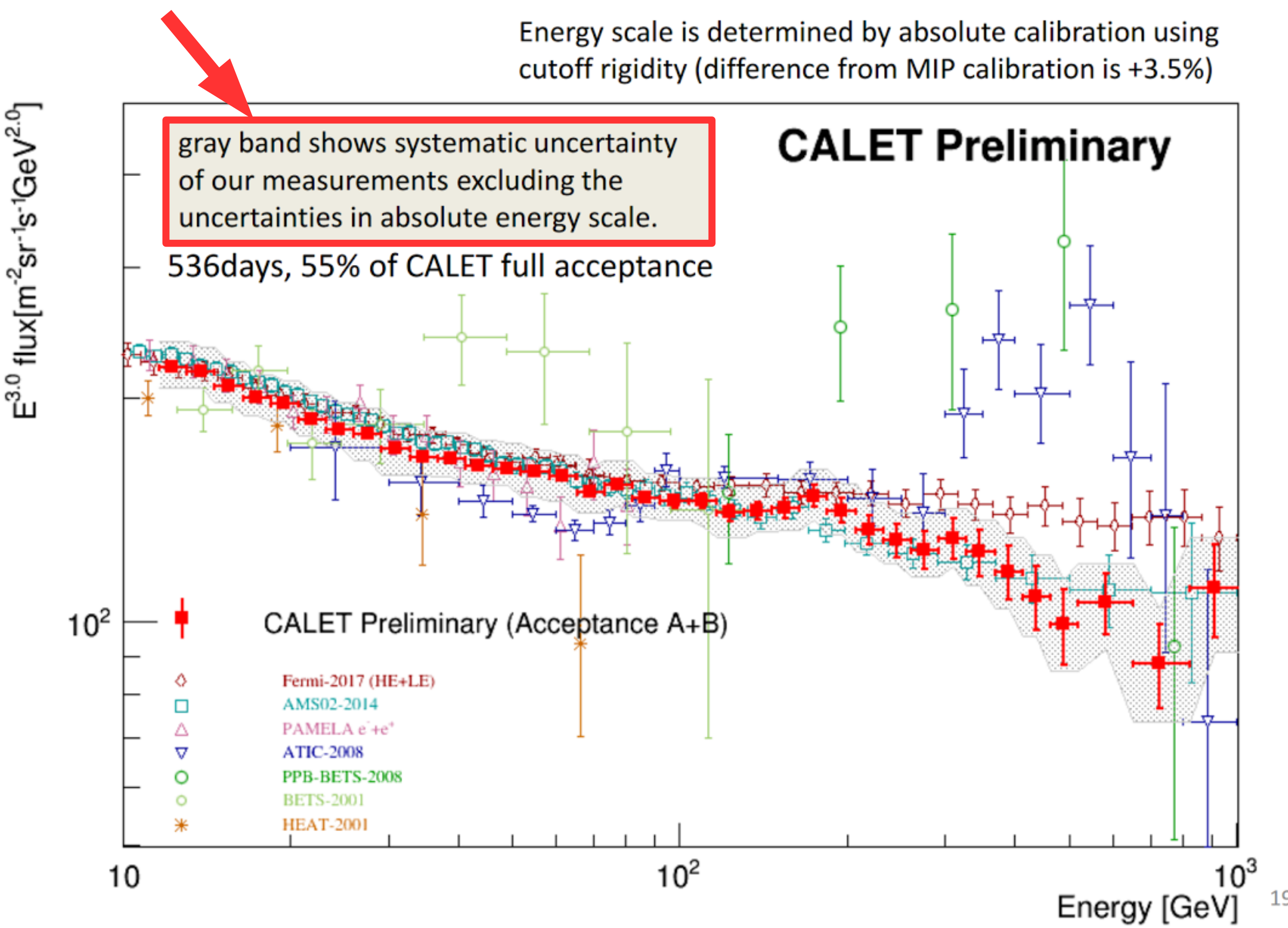
Emplaced on JEM-EF port #9 on Aug. 25th, 2015





- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W (max)**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

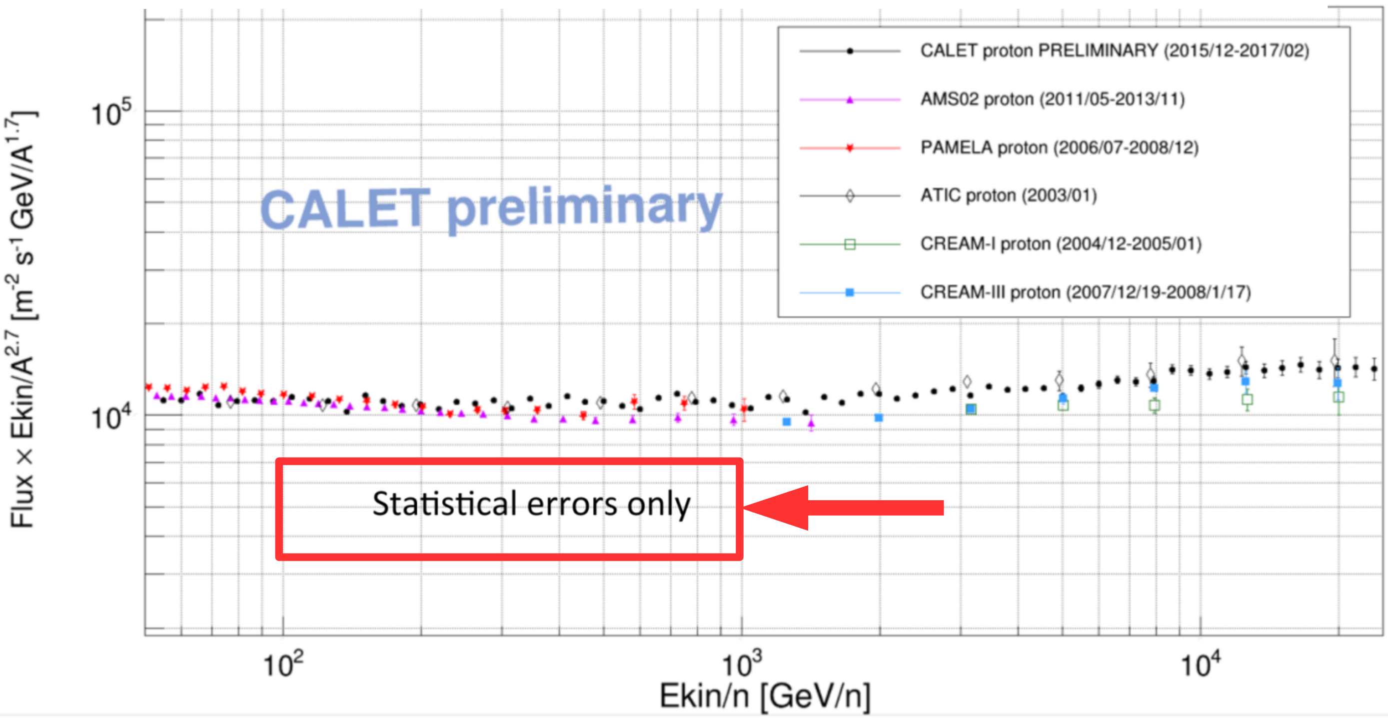
CALET TOTAL $e^+ + e^-$ SPECTRUM UP TO 1TeV (**PRELIM.**)



Future:
20TeV

Shoji Torii, ICRC2017

CALET PROTON SPECTRUM UP TO 22 TeV (**PRELIM.**)



Future:
1 PeV

- 15 months of observation from December 1st , 2015 to February 28th, 2017
- subset of total acceptance: acceptance A (fiducial) with SΩ = 416 cm^2 sr
- Assessment of the systematic errors: IN PROGRESS

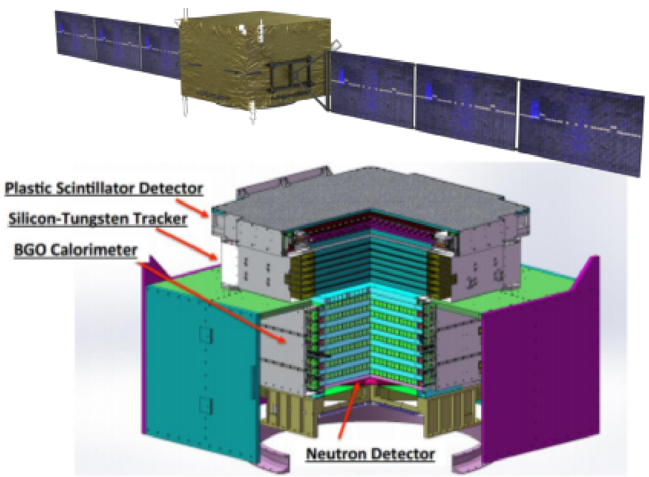
Pier S. Marrocchesi – ICRC 2017 – Busan – July 2017, 14

Iris Gebauer
Institute for Experimental Particle Physics

DAMPE

DAMPE Collaboration:

- Purple Mountain Observatory, National Space Science Center, Inst. High Energy Physics, Inst. Modern Physics, University of Science and Technology
- Geneva University
- Bari, Lecce, Perugia (Universities and INFN)

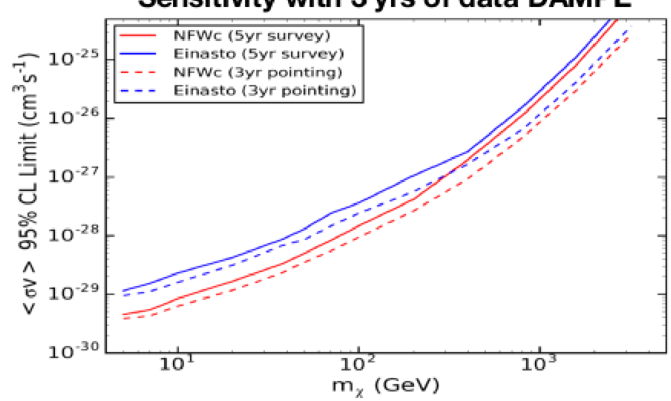


- DAMPE detector, consists of 4 subsystems:
  - the plastic scintillator strips detector (PSD),
  - the silicon-tungsten tracker-converter (STK),
  - the BGO imaging calorimeter (BGO), and
  - the neutron detector (NUD).

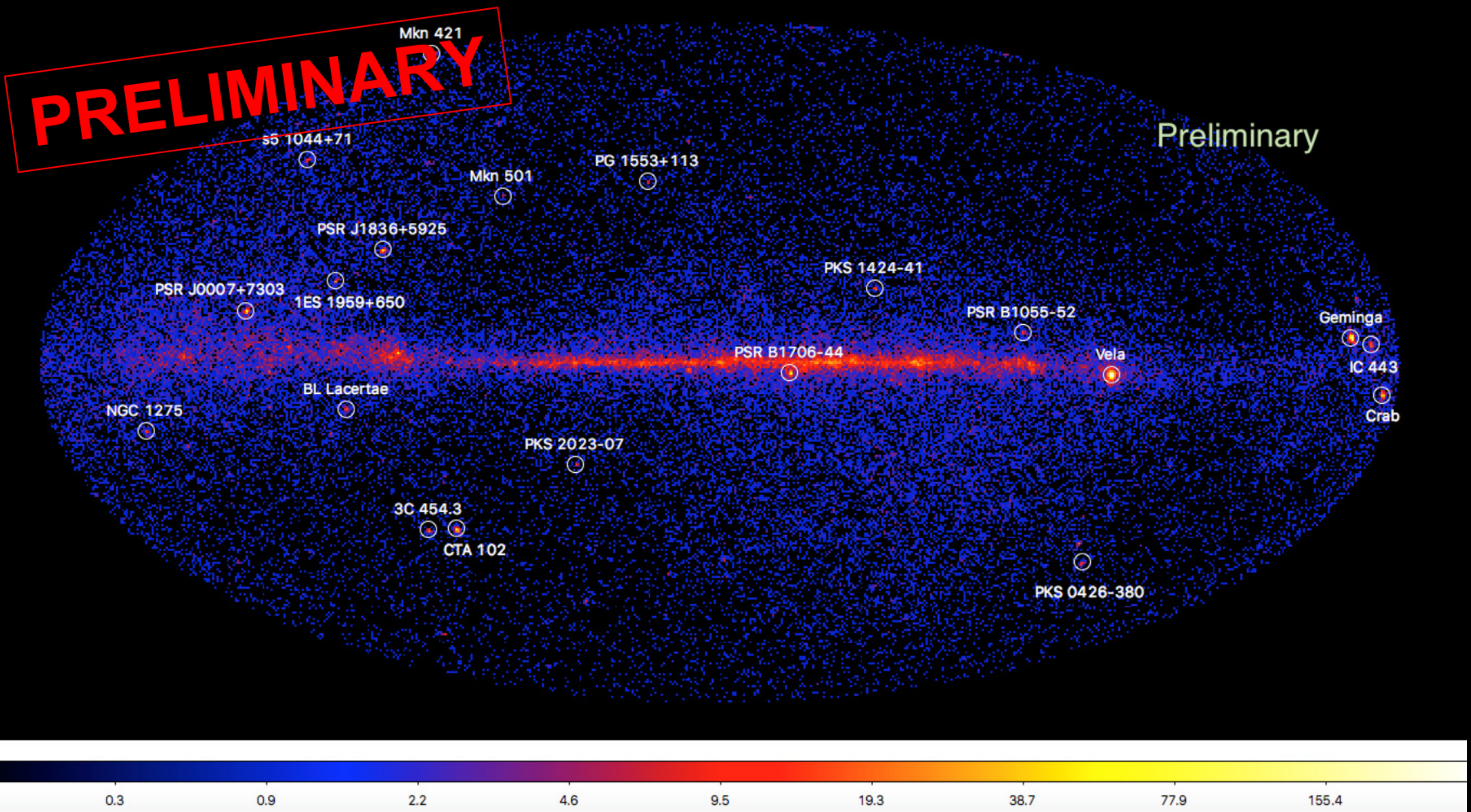
https://arxiv.org/pdf/1706.08453.pdf

DAMPE

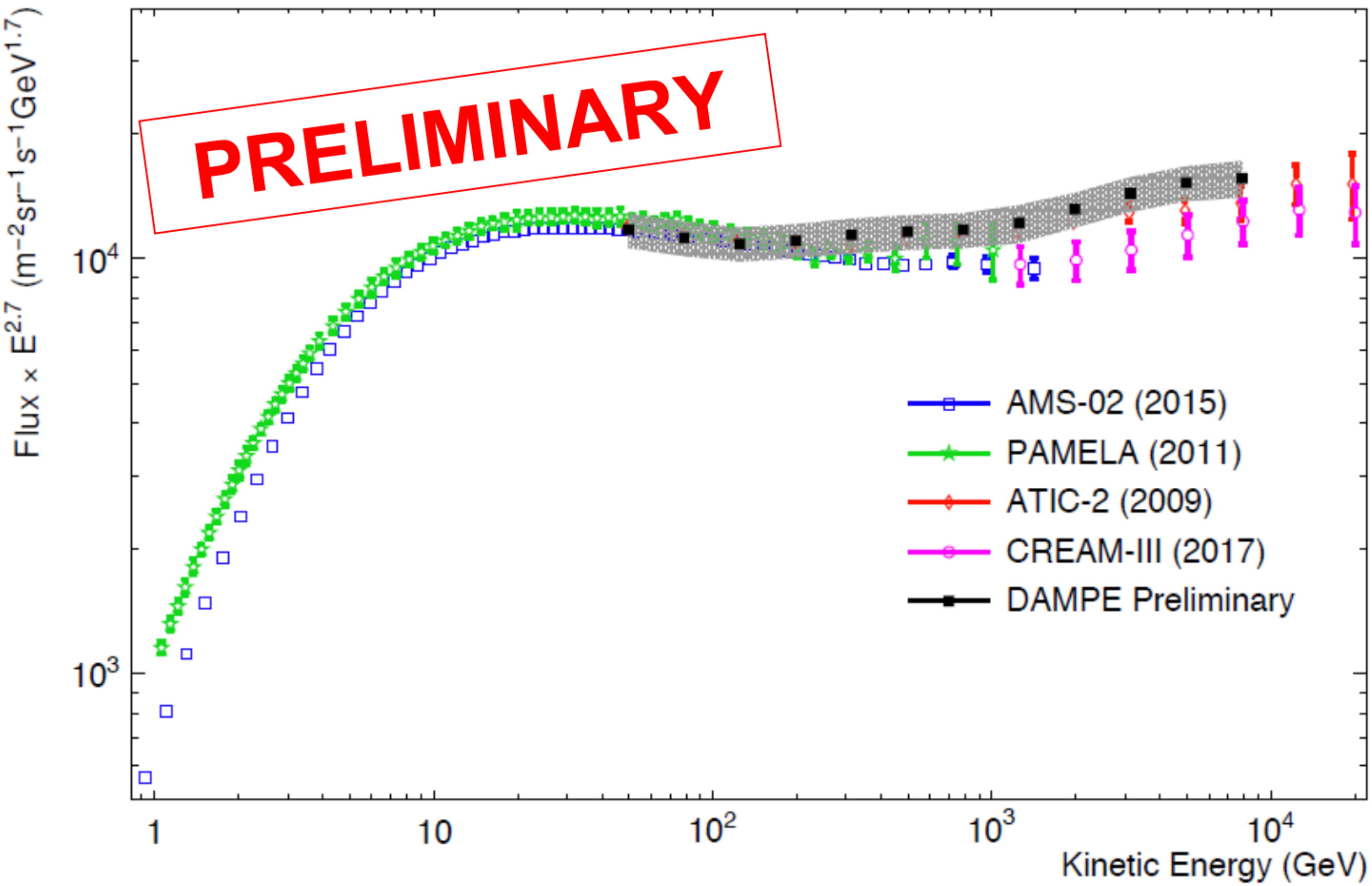
Sensitivity with 3 yrs of data DAMPE



First results: bright gamma-ray sources



First results: proton flux



Expect protons and nuclei up to 100 TeV

See Chuan Yue's talk at ICRC (CRD082)

Helium: See Paolo Bernardini's talk at ICRC (CRD096)

CONCLUSION & PERSPECTIVES

Space offers a unique environment to study the properties of cosmic rays directly. Space-based measurements continue to play a key role in cosmic ray measurements and therefore indirect dark matter searches.

- **AMS-02** will remain on the ISS and continue to take data until the end of ISS operations (2024 or beyond...)
  → more CR species, more statistics and higher energies.... more surprises?

- **CALET/DAMPE** are releasing first data
  → calorimetric measurements of electrons and nuclei

- **ISS-CREAM** is calibrating
  → calorimetric measurement of electrons and nuclei

The most exiting objective of CR measurements is to probe the unknown, to search for new phenomena which we have not yet imagined nor had the tools to discover!

These are very exiting times for cosmic ray measurements!

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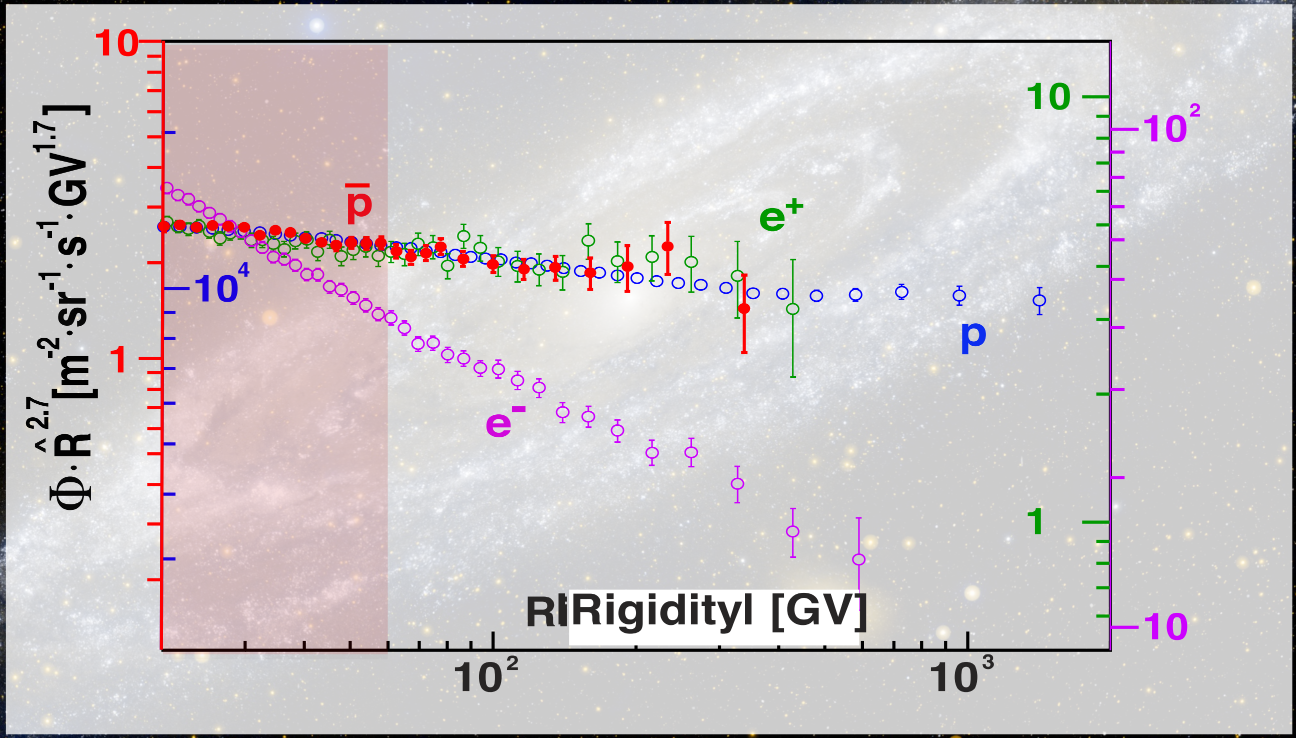
….who will be providing charge sign information after AMS?



There is no problem that can not be solved by more data.