

Direct Measurements and Origin of Cosmic Rays

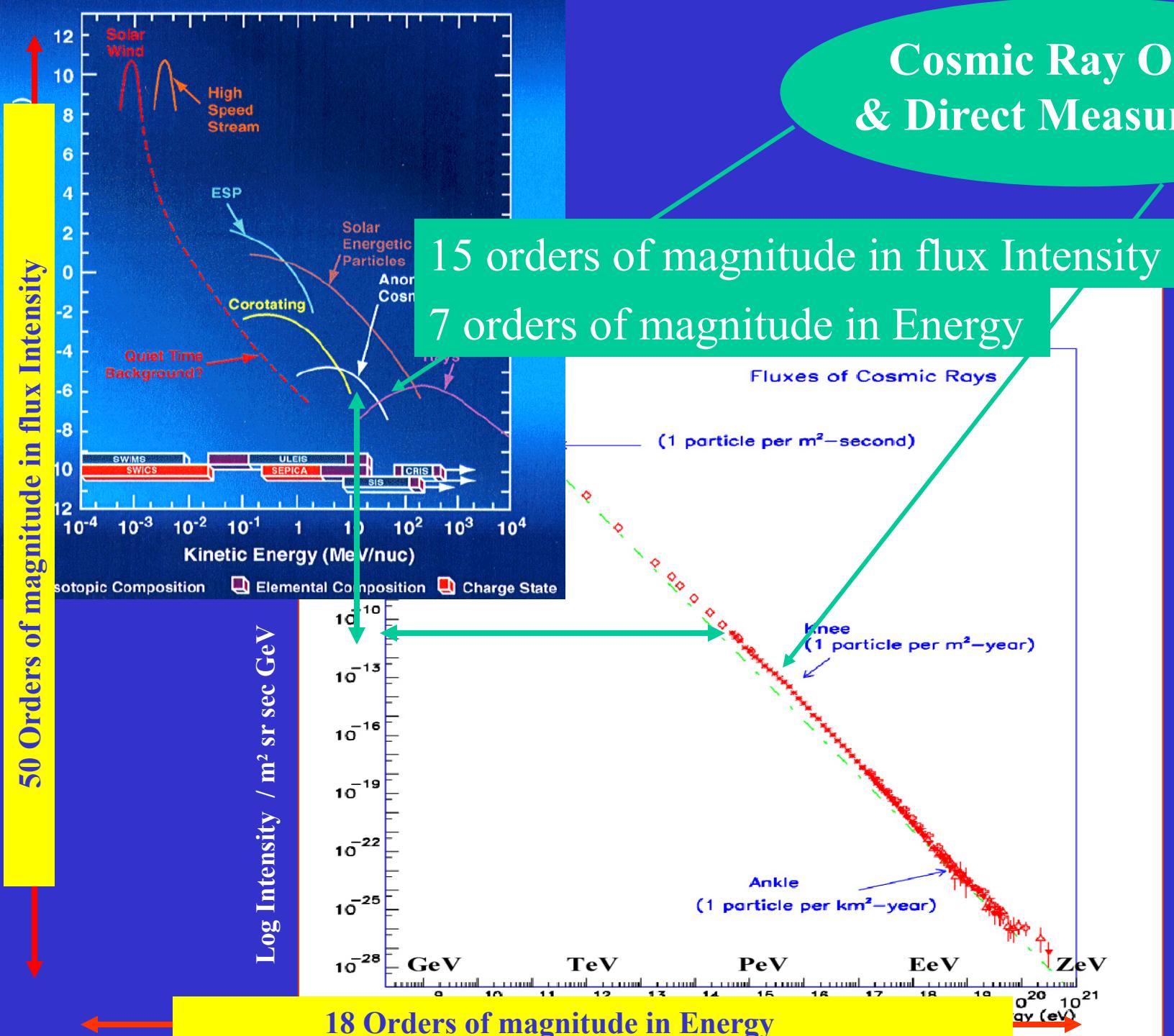
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ASI & University of Trento & INFN-TIFPA

Cogne 2019
INFN

Direct Measurements and Origin of Cosmic Rays

- 1 Instrumentation : current and future projects
- 2 Recent results on O(TeV) Cosmic Rays and indirect search for dark matter from AMS-02 and other space experiments

Cosmic Ray Origin & Direct Measurements



.....a particle physicist's view of CR physics

Step # 1

Understanding and calibrating nature's beam

More accurate measurements of CR composition and spectra

Better theory (CR origin and acceleration)

Better simulation tools

A text book example

Atmospheric neutrinos calculations vs neutrino oscillations

Neutrino oscillations

Anti-matter search

Strangelets

Indirect dark matter searches

Anti-protons
Anti-deuterons
Electrons/positrons
Gamma rays

Ultraheavy particle searches

EEHCR
Neutrinos

PART 1

1 Instrumentation : current and future projects

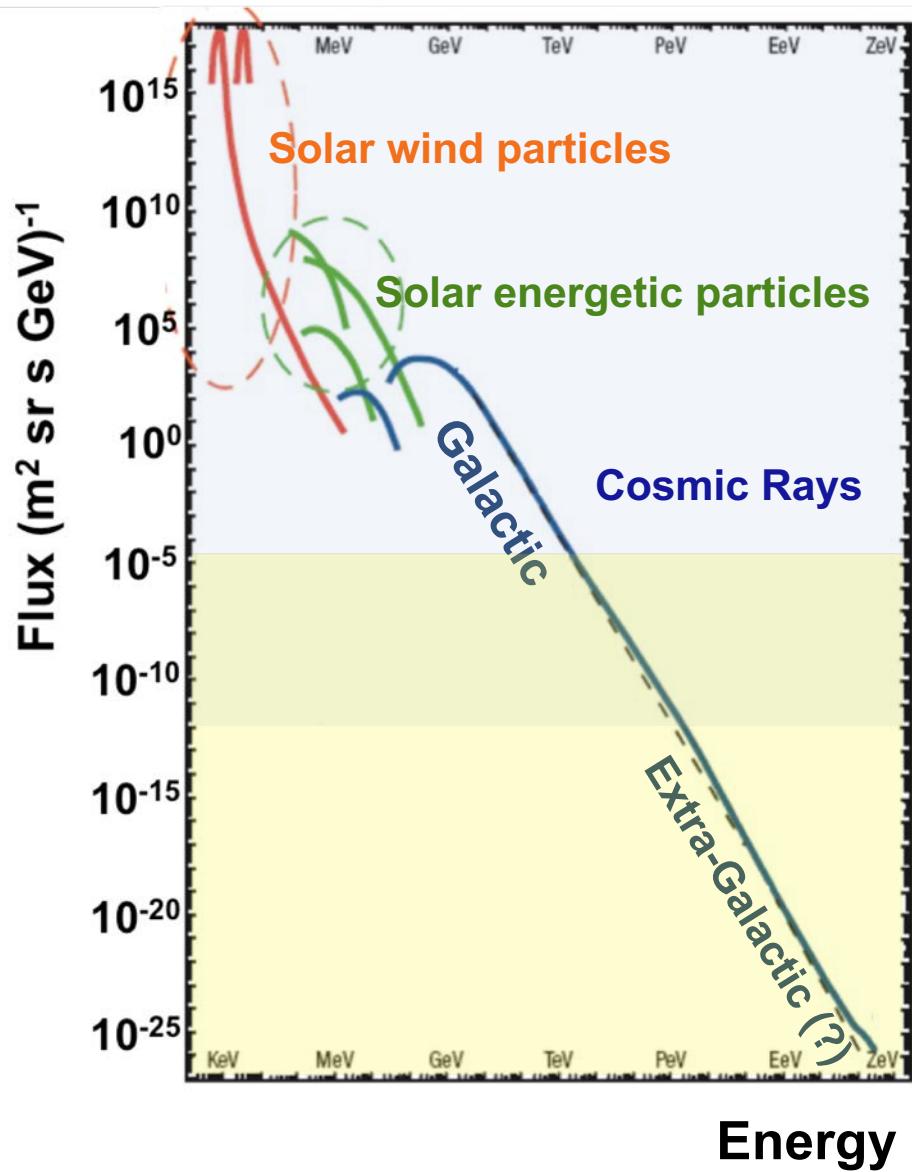
The CR spectrum: the overall picture

Direct measurements:

- ☺ Particle identification/Energy calibration, anti-matter
- ☹ Space: Weight/Size constraints limit the energy range (< ?)

Indirect measurements:

- ☺ Ground: Extended energy range (>PeV)
- ☹ Pid/Energy : dependence on modelling of atmospheric interactions

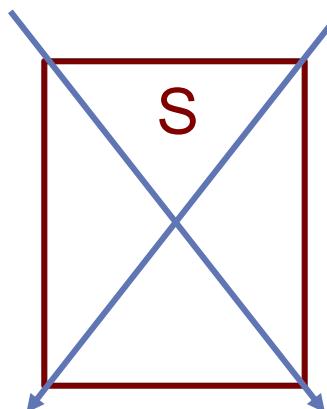
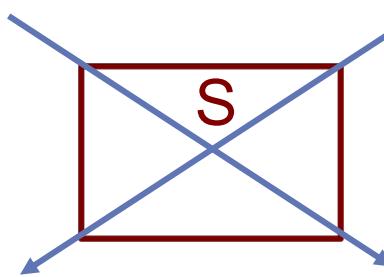
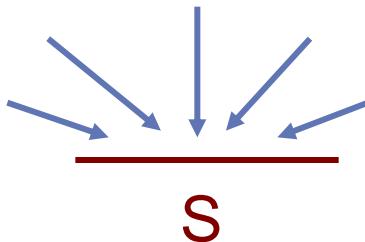


Key point: ENERGY → SIZE & TIME

$$\Phi(E) = \frac{dN}{dEdtA(E)}$$

↓

$A(E)$: acceptance of the detector ($m^2 \times sr$)
geometry (dimensions & angular acceptance)
efficiency of detection/selection



Key point: ENERGY → SIZE & TIME

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efficiency of detection/selection

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GEOMETRICAL FACTOR AND DIRECTIONAL RESPONSE OF SINGLE AND MULTI-ELEMENT PARTICLE TELESCOPES*

J. D. SULLIVAN†

Enrico Fermi Institute and Dept. of Physics, The University of Chicago, Chicago, Illinois 60637, U.S.A.

Received 26 February 1971

Key point: ENERGY → SIZE & TIME

$$\Phi(E) = \frac{dN}{dEdtA(E)}$$


$A(E)$: acceptance of the detector ($m^2 \times sr$)
geometry (dimensions & angular acceptance)
efficiency of detection/selection

To be verified with Monte Carlo Techniques (typically GEANT):

- geometry in real life is not so simple
- particles interact with the detector: not all what enters is seen!

Key point: ENERGY → SIZE & TIME

$$\Phi(E) = \frac{dN}{dEdtA(E)}$$



$$\Delta N(E, E + \Delta E) = \Phi(E) \times \Delta E \times \Delta T \times A(E)$$

Measure of a flux of $\Phi(E_1) = 6 \cdot 10^{-3}$ part/(GeV m² sr s) in a $\Delta E = 1$ GeV

- 1 % statistical error $\rightarrow \Delta N = 10^4$

$$\Delta T \times A(E_1) = \frac{\Delta N}{\Delta E \times \Phi(E_1)} \sim \frac{10^4}{6 \cdot 10^{-3}} \sim 1.67 \cdot 10^6 \text{ m}^2 \text{sr s}$$

$$\text{But : } \Phi(E) = CE^\gamma \qquad \qquad \approx 20 \text{ gg with } A_1 = 1 \text{ m}^2 \text{sr}$$

let's assume $\gamma \approx -3$, $E_1 = 30$ GeV, \rightarrow How long to get 1% @ $E_2 = 300$ GeV ?

$$\Delta T \times A(E_2) = \frac{\Delta N}{\Delta E \times \Phi(E_2)} = \frac{\Delta N}{\Delta E \times \Phi(E_1)} \times \left(\frac{E_1}{E_2} \right)^{-3} \sim 1.67 \cdot 10^6 \times 10^3 \text{ m}^2 \text{sr s}$$
$$\approx 55 \text{ yrs with } A_2 = 1 \text{ m}^2 \text{sr}$$

\rightarrow let's increase the "binning" ... $\Delta E = 100$ GeV, just wait 200 gg

\rightarrow relax the precision... 10% $\rightarrow \Delta N = 100$

(¹⁰ Binning will be a compromise between resolution & statistics)

Key point: ENERGY → SIZE & TIME

$$\Phi(E) = \frac{dN}{dEdtA(E)}$$



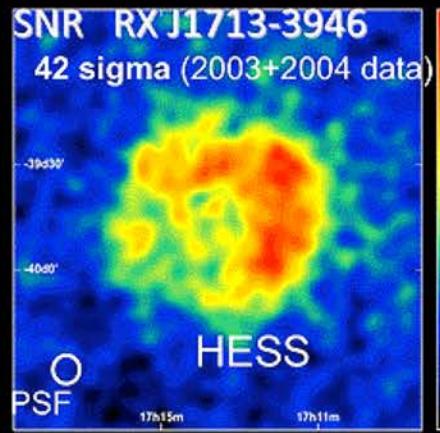
$$\Delta N(E, E + \Delta E) = \Phi(E) \times \Delta E \times \Delta T \times A(E)$$

At PeV scales flux of $\Phi \approx 10^{-11}$ part/(GeV m² sr s)

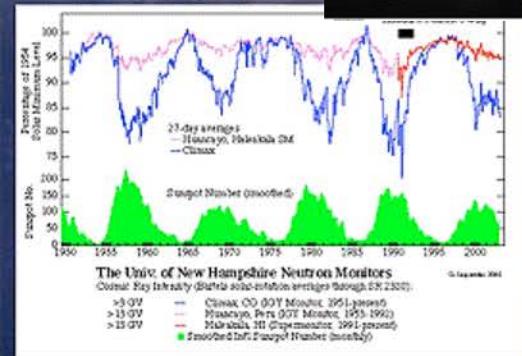
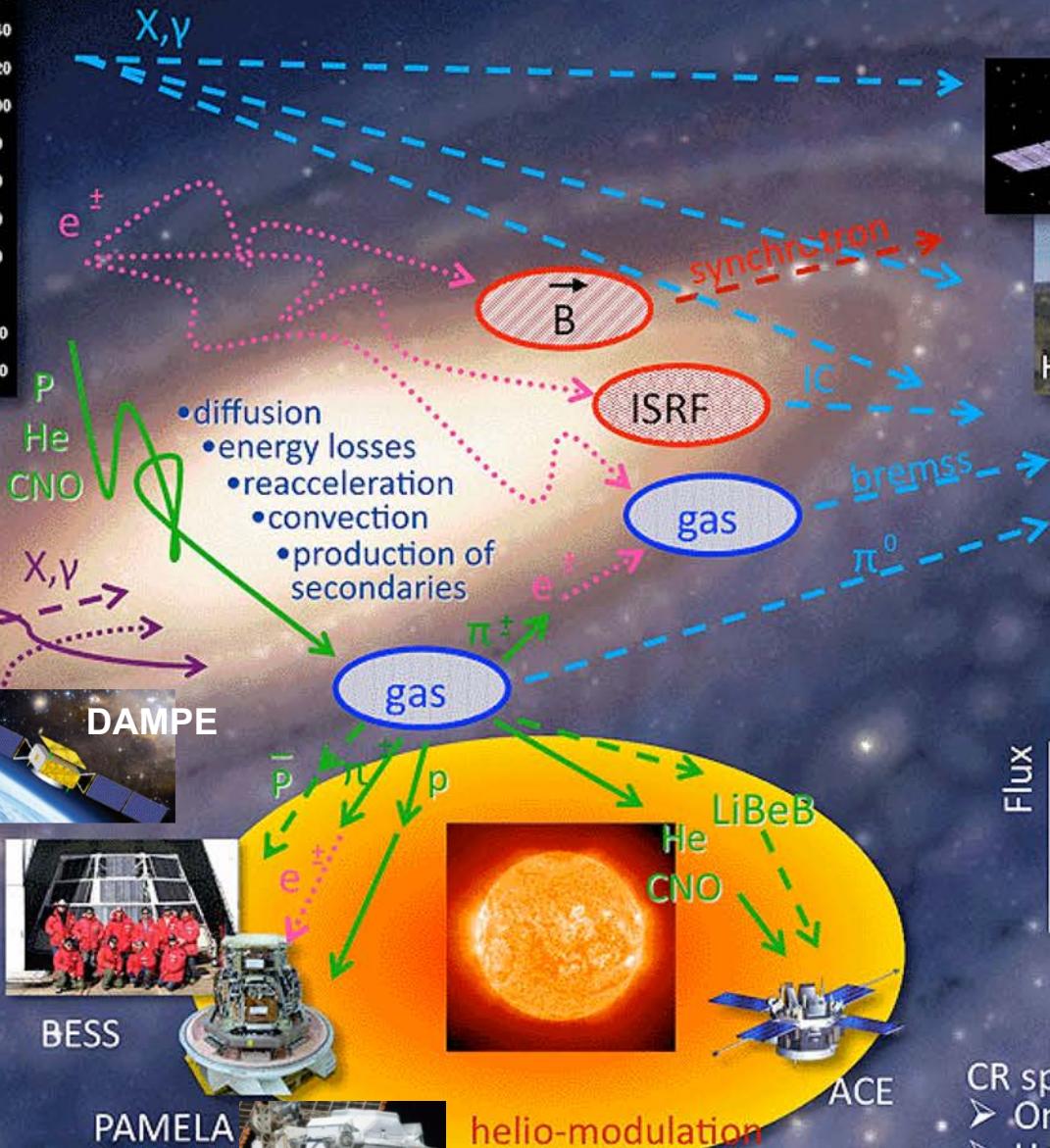
- assume 20% statistical error → $\Delta N = 25$
- assume a $\Delta E \approx 350$ TeV (i.e. 35% energy resolution @ 1 PeV)

$$\Delta T \times A(PeV) = \frac{\Delta N}{\Delta E \times \Phi(PeV)} \sim \frac{25}{3.5 \cdot 10^3 \times 10^{-11}} \sim 7.1 \cdot 10^8 \text{ m}^2 \text{sr s}$$

Collection factor of ≈ 22 m²sr yrs !



Interstellar Medium

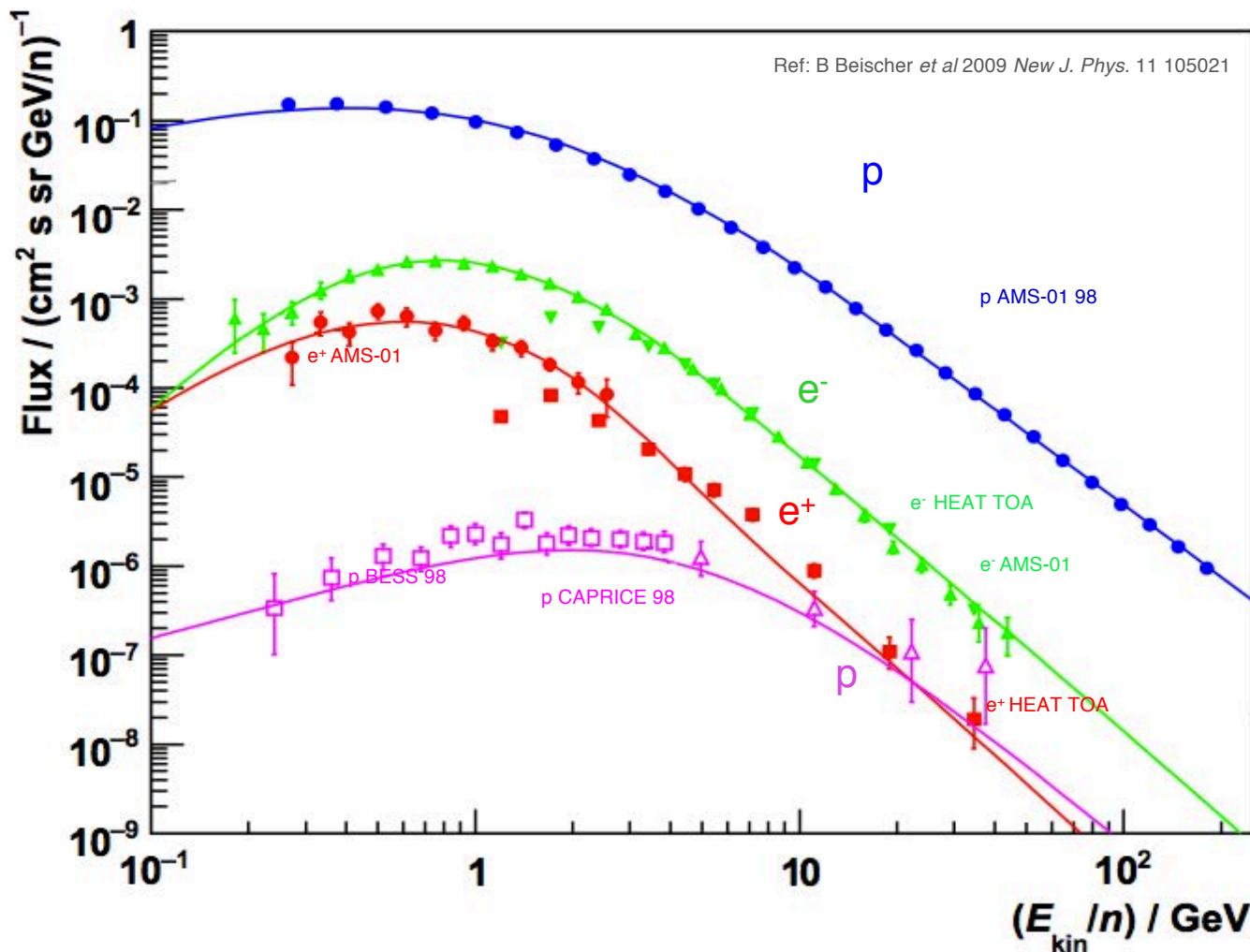


CR species:

- Only 1 location
- Heliospheric modulation

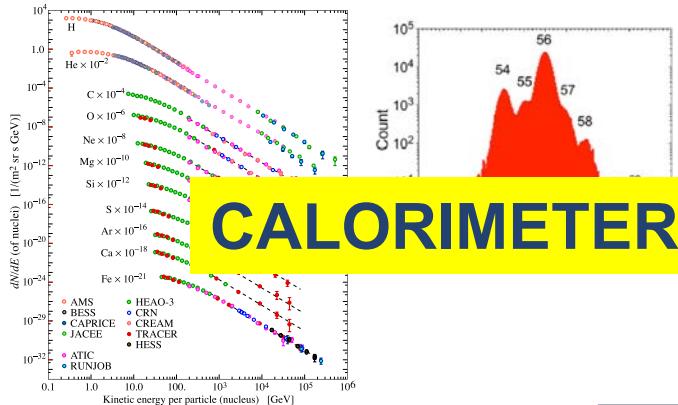
Different reaches for different particles....

Cosmic Rays Flux

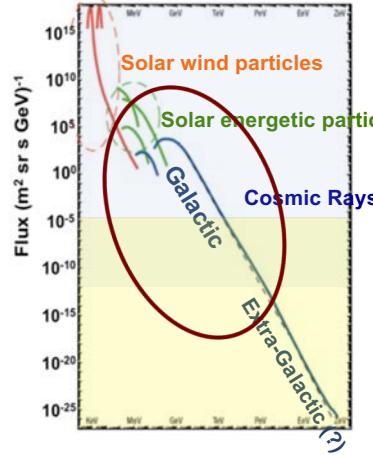
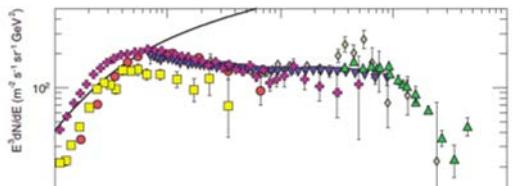


The measurements

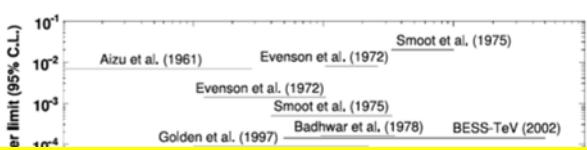
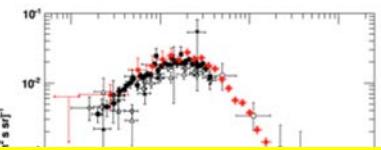
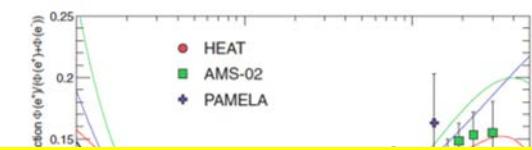
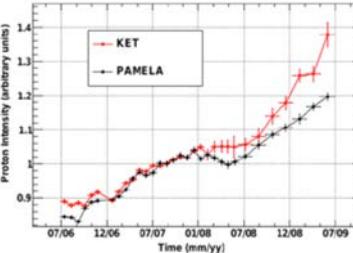
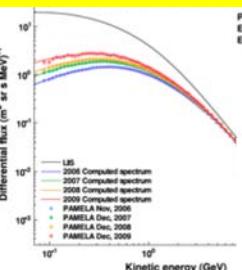
Chemical composition



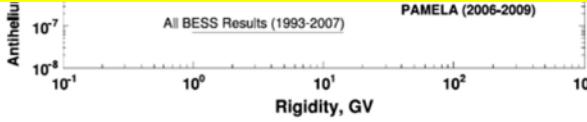
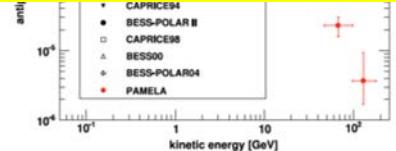
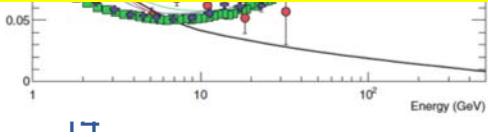
The electron component



CALORIMETERS : ENERGY / Z + other PID

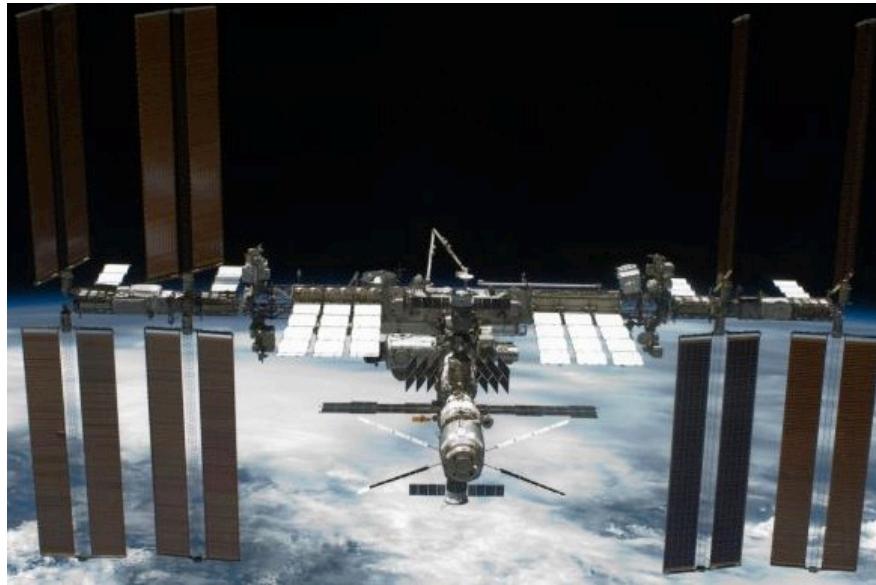


SPECTROMETERS : TRACKING + Z + other PID (Calo, TRD)



Anti-matter

The experimental challenge



DIRECT ≠ EASY

!

No atmosphere: Stratospheric Balloons
Space

Limits on size and time: Detector design focused on specific measurements

Stratospheric Balloons: from few hrs to months

Magnetic Spectrometers

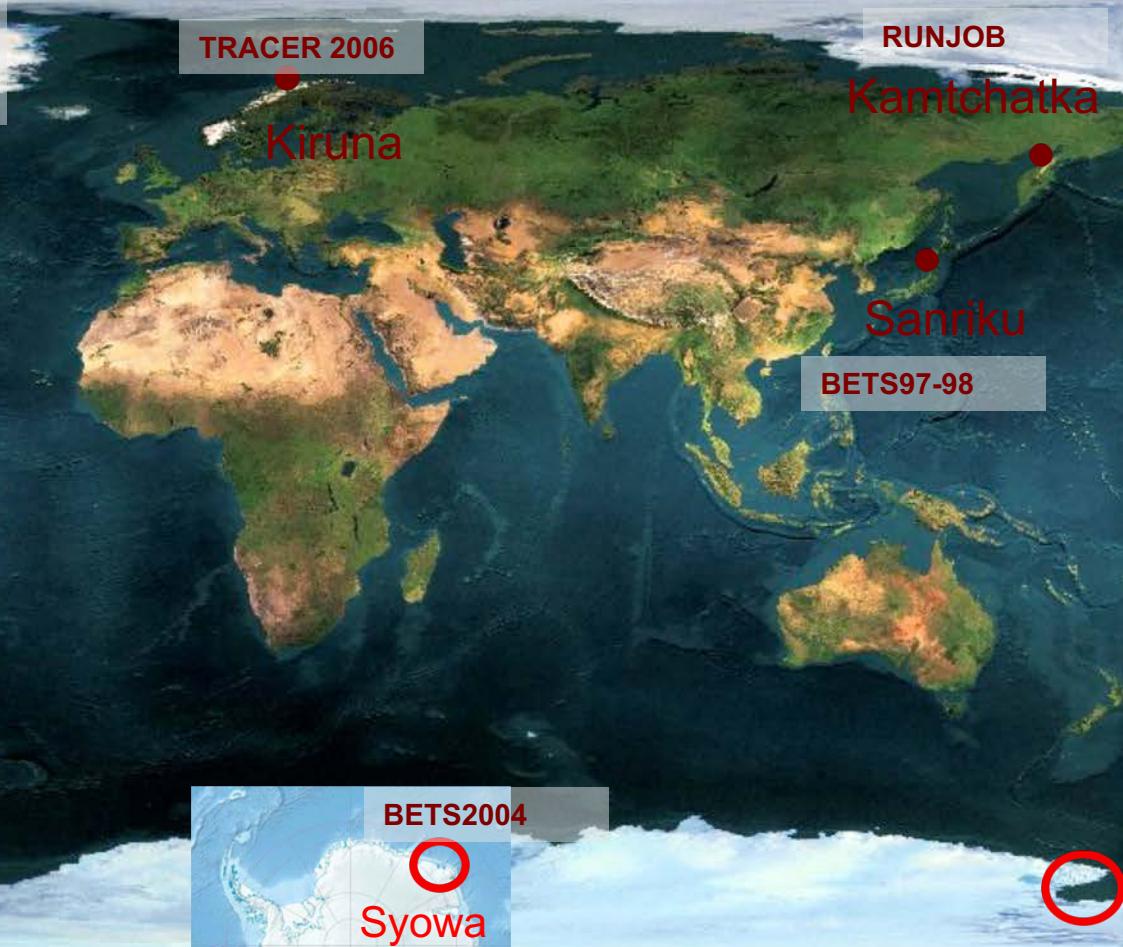
...

BESS/POLAR/TEV (9 Flights)
WIZARD (6,Flights)
HEAT/PBAR (4,Flights)

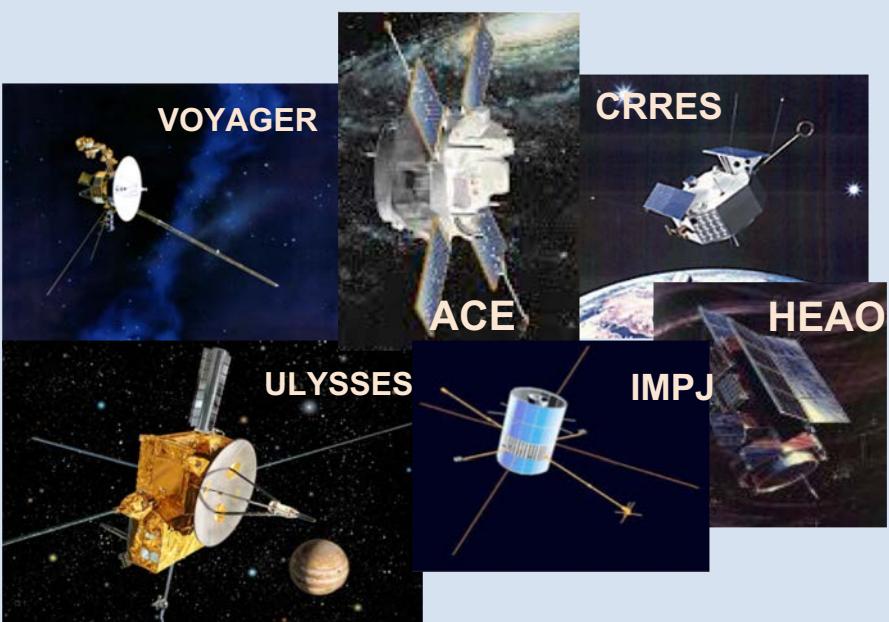
Calorimetry, TRD +..

RUNJOB (62 day, 10 Flights)
TRACER (18 days, 3 Flights)
CREAM (161 days,6 Flights)
ATIC (53 days, 3 Flights)
TIGER/S-TIGER (2/55 days)

IMAX92,BESS-TEV,BESS93-94-95-97-98-99-00,
AESOP94-97-98-00-02-,CAPRICE94,HEAT95, RICH97,
ISOMAX98..



Space:



**Long missions (years)
Small payloads
Low energies..**

IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads



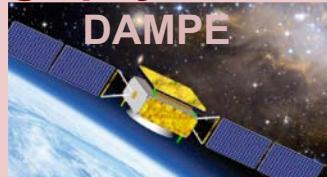
CRN on Challenger
(3.5 days 1985)



AMS-01 on Discovery
(8 days, 1998)



**Long missions
Large payloads**



Fermi-LAT

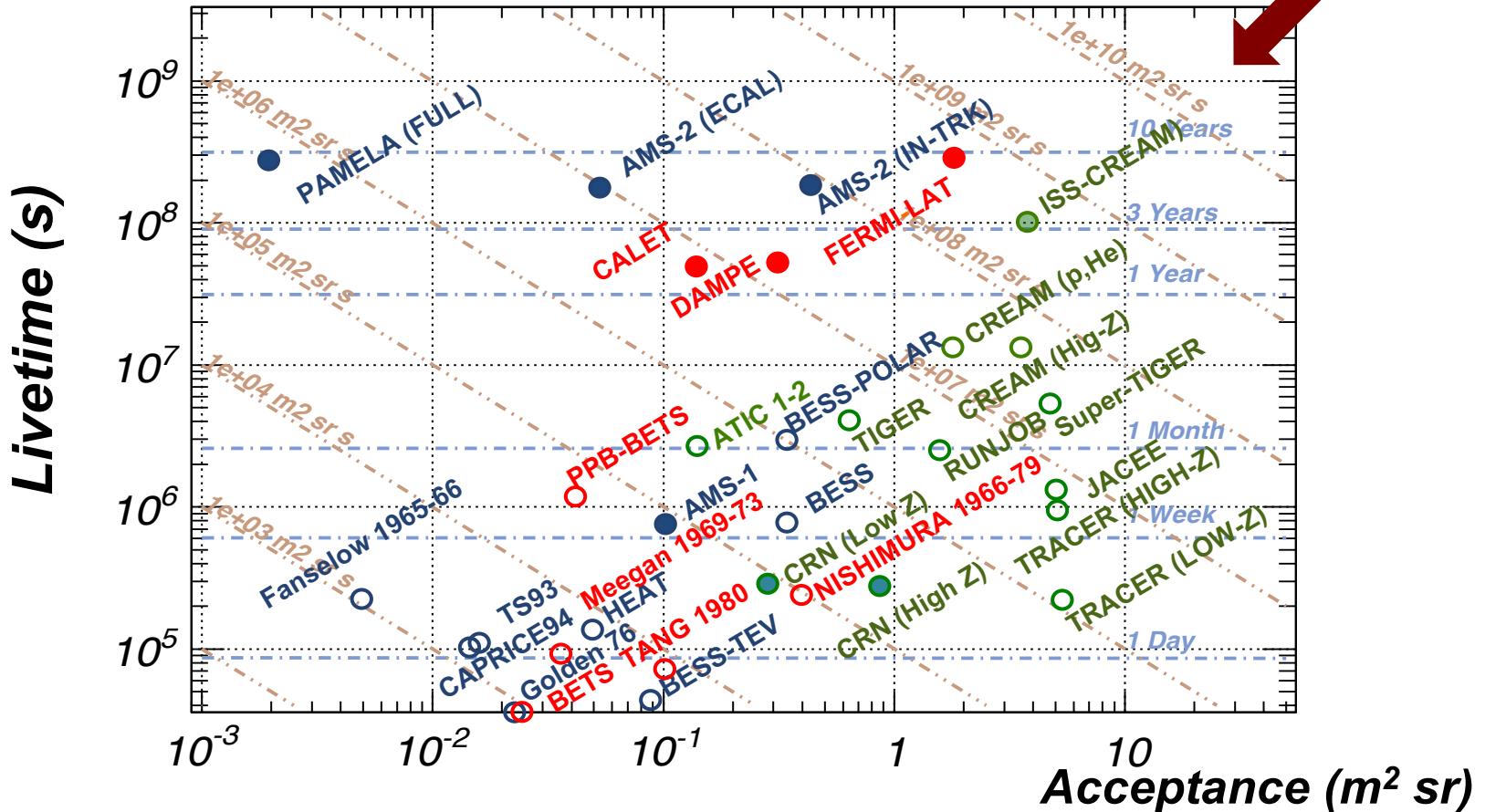


AMS-02



CALET

The experimental program



- No B field, different techniques with main focus on Z
- No B field, different techniques with main focus on e, γ
- Magnetic spectrometers

- Balloon
- Space
- Space (planned)

Calorimetric detectors

Now on orbit:

- AGILE (2006): γ -rays up to few Gevs
- FERMI (2007): γ -rays up to 300 GeV, **electrons**
- CALET (2015) : **electrons**, nuclei
- DAMPE (2015): **electrons**, nuclei, photons
- ISS-CREAM (2017) : nuclei

Magnetic spectrometers

- PAMELA (2006-2016) : **anti-particles**, p, He, light nuclei

Now on orbit:

- AMS-02 (2011): **anti-particles**, p, He ...nuclei (up to Fe..)

The experimental challenge

No atmosphere:

Stratospheric Balloons
Space



Limits on size / weight / time

- Detector design focused on specific measurements

p,He,e⁻,anti-particles



Magnetic spectrometers

Energy reach on anti-particles limited by
Maximum Detectable Rigidity



Primary spectra, Nuclei, e[±]



Calorimeters

Energy reach limited by statistics

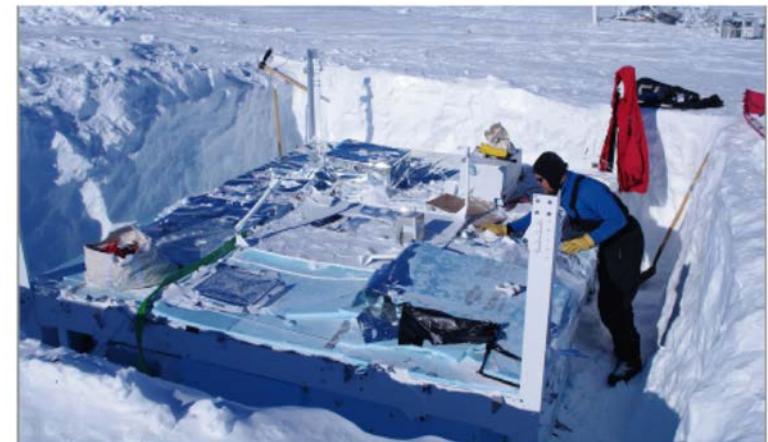
→ HEP detectors adapted to space !

Stratospheric Balloons : the pioneers of CR !

Pros:

- ✓ **construction:** less stringent mechanical/thermal/radiation requirements
- ✓ **launch:** more opportunities...a balloon is less expensive than a rocket !
- ✓ **In recovering:** typically the apparatus can be recovered and re-launched after some refurbishment (not always...)

Super-Tiger
recovered under 2m of snow
after \approx 2 years...



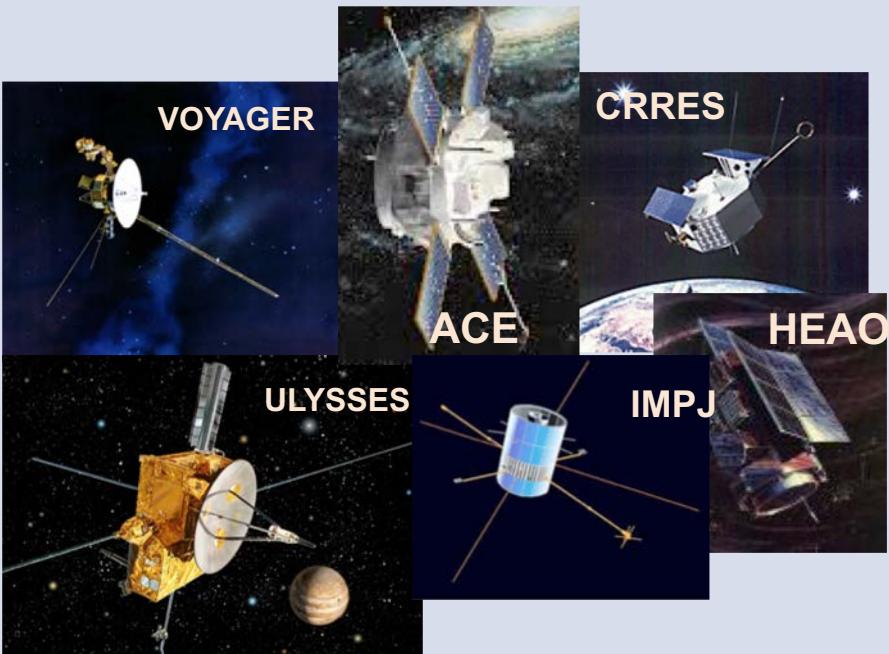
Stratospheric Balloons : the pioneers of CR !

Cons:

- ✓ **atmosphere:** still $\approx 5 \text{ gr cm}^2$ of atmosphere where particles can interact with the detector (irreducible systematics for rare signals)
- ✓ **collection factor:** constraints on max weight and size similar to space, but exposure times still limited to some months

Still relevant for specific measurements or as a test-bed for new space projects, but not competitive for high energy measurements with multi purpose apparatuses.

Space:



**Long missions (years)
Small payloads
Low energies..**

IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads



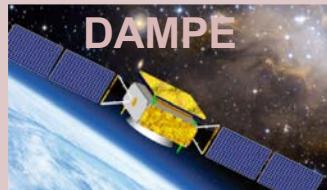
**CRN on Challenger
(3.5 days 1985)**



**AMS-01 on Discovery
(8 days, 1998)**



**Long missions
Large payloads**



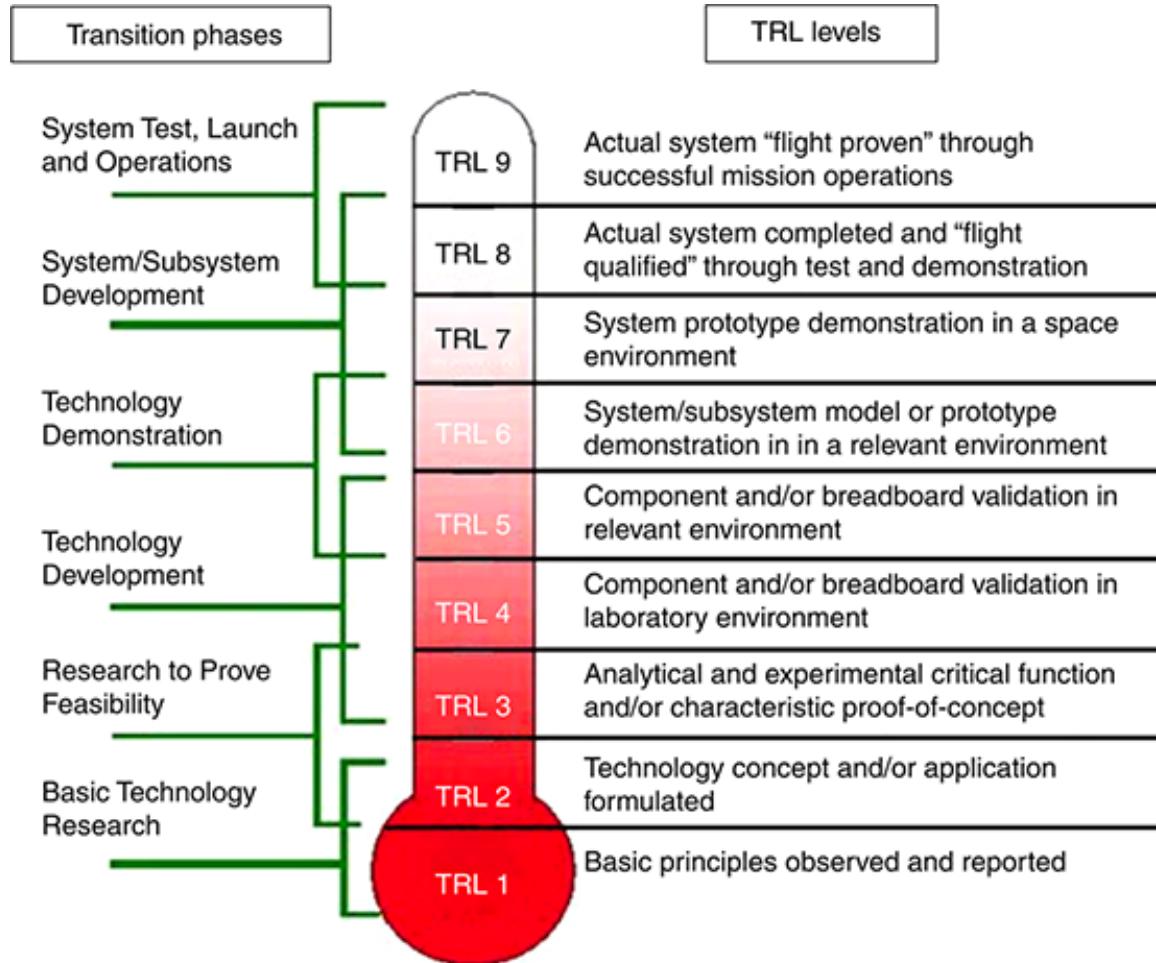
Fermi-LAT



AMS-02



Technology Readiness Level

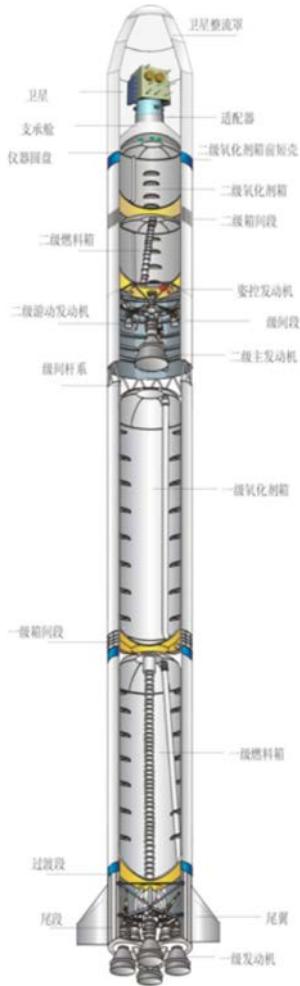


Source: Adapted from NASA and Mankins (1995)

Exported to
space



Well established
technology on
ground



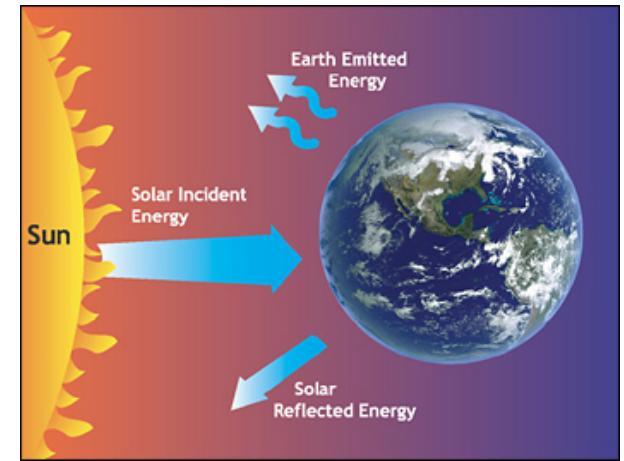
HEP detectors in Space

Mechanical stress at launch:

- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

Life in space:

- Thermal stresses due to Sun-light
(seasonal / day-night effects)
- Vacuum

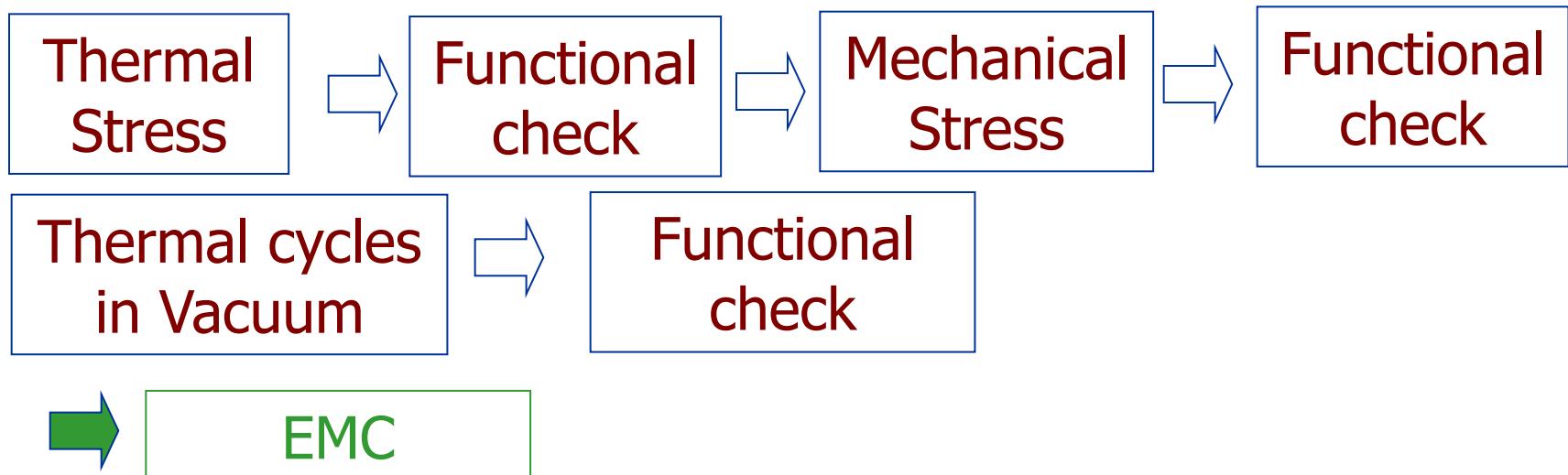


Careful Design, Model validation and Qualification are needed to ensure *highest possible reliability*

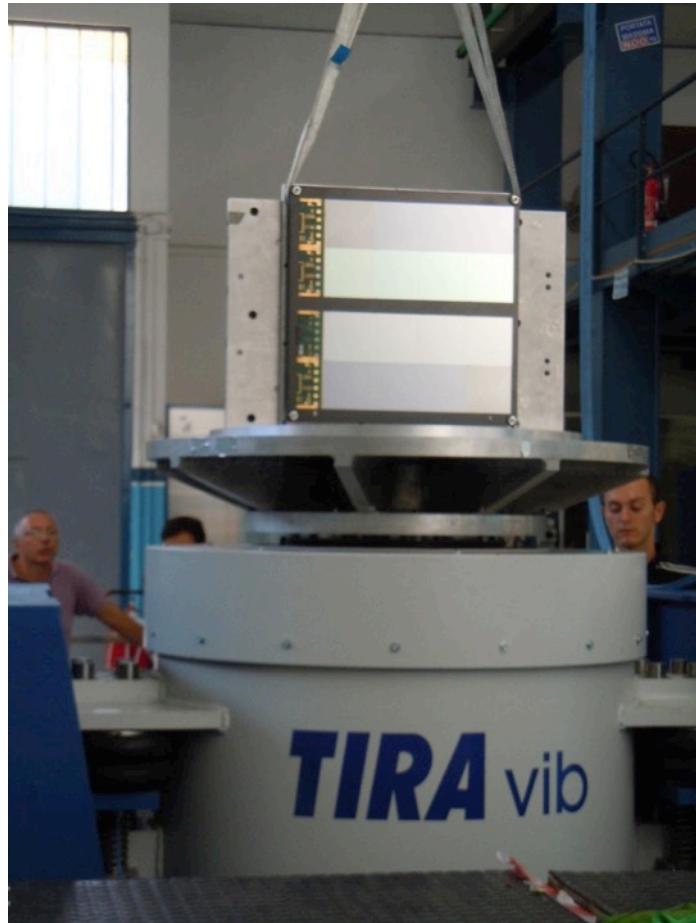
Space is an harsh environment

Full space qualification sequence before launch:

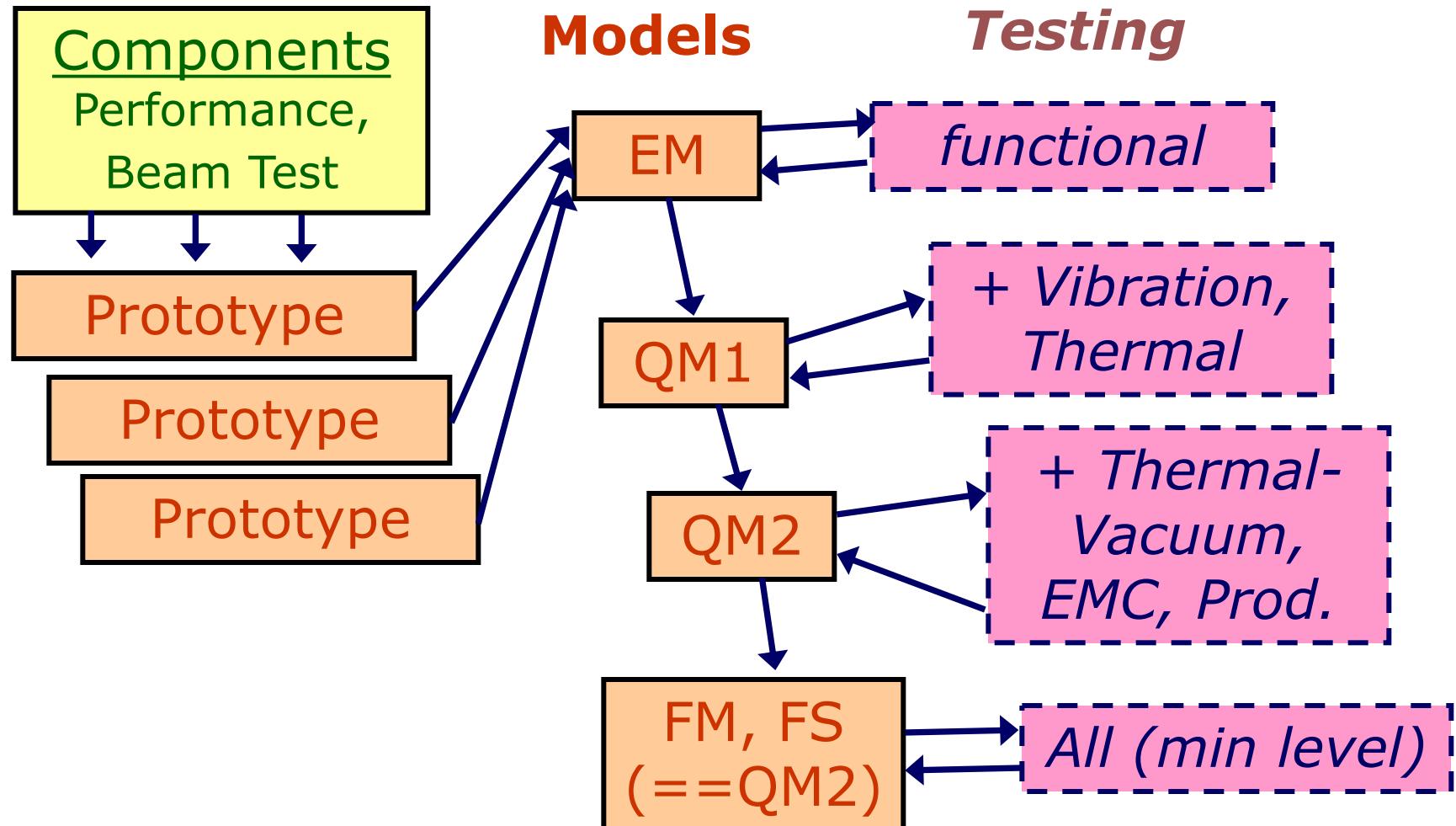
- Operational tests after stress
- Verification of dynamical behaviour
- Verification of thermal model



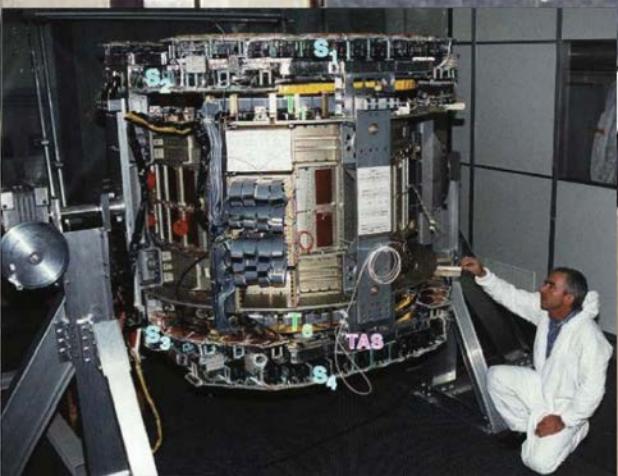
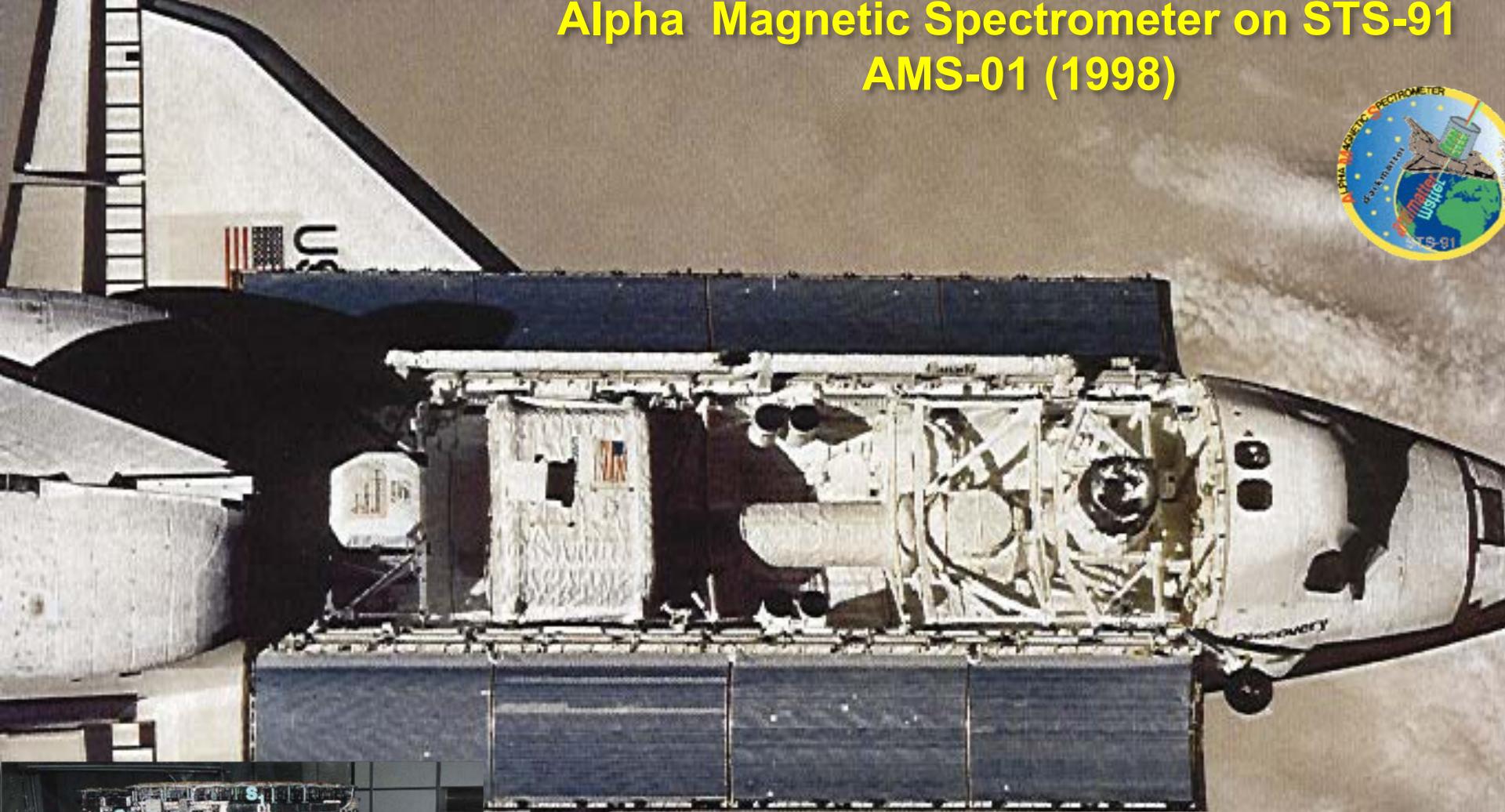
typically 3 steps: Thermal, Vibration, Thermo-Vacuum



The long process to fly...



Alpha Magnetic Spectrometer on STS-91 AMS-01 (1998)



Tracking with silicon microstrip detectors:

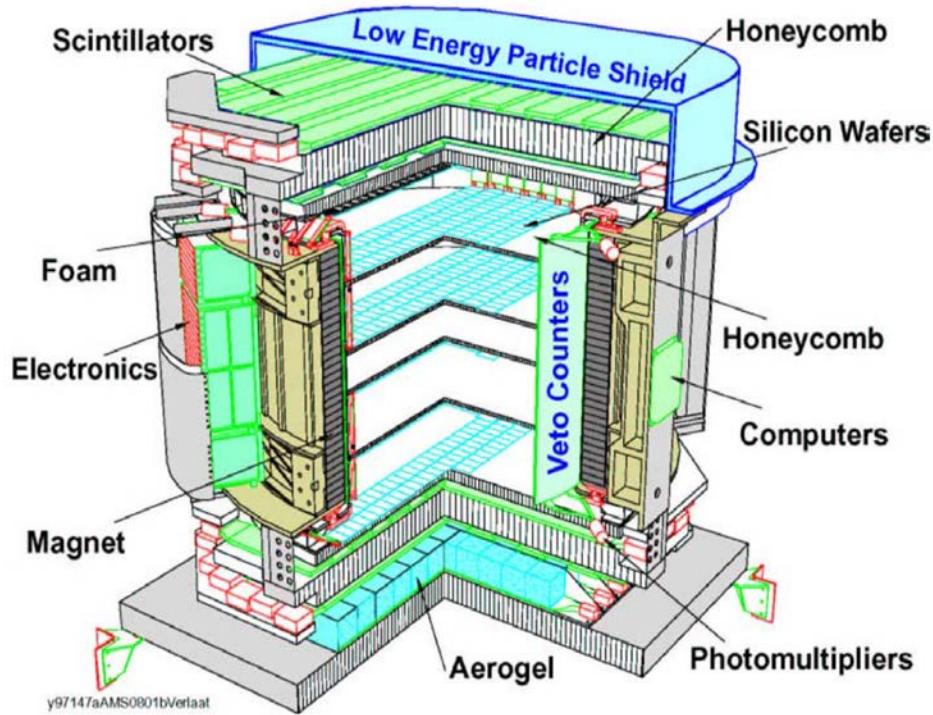
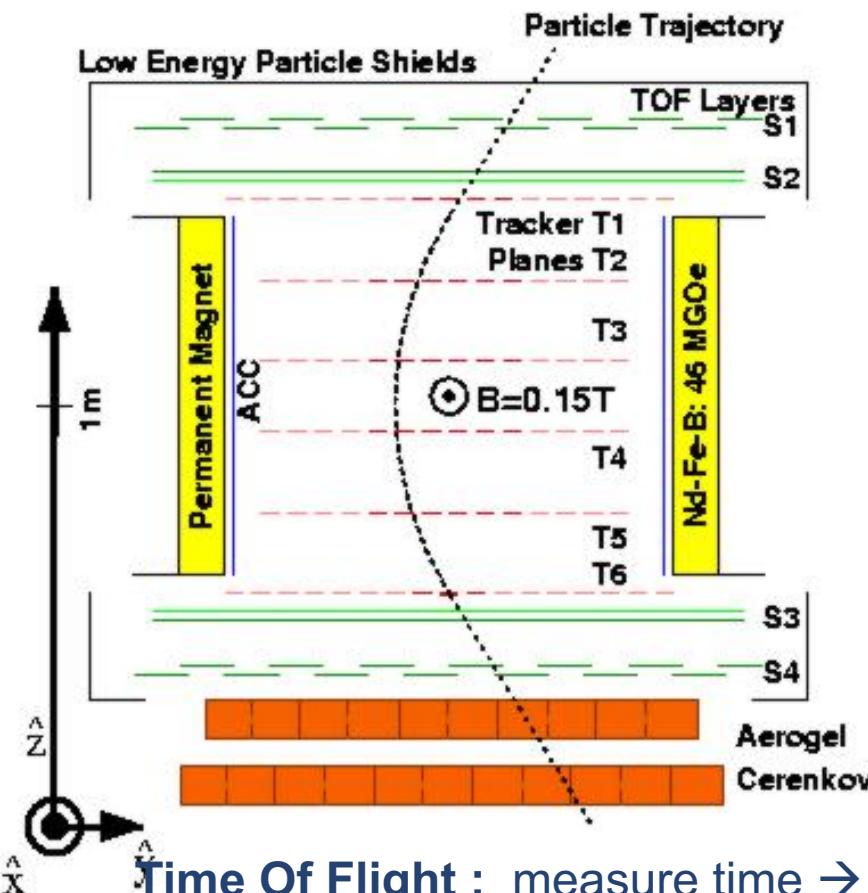
Heritage from microvertex detectors developed in the '80s
for HEP experiments at accelerators (L3 @ LEP → AMS),

- Precisions of $O(\mu\text{m})$
- Lightweight: thickness of $\approx 300 \mu\text{m}$
- No consumables (e.g. gas)
- No High Voltage ($\approx 70 \text{ V}$)

Questions in 1995:

- Never operated in space
- 300 μm thick detectors will survive the stress of the launch?
- Assembly precision should match the resolution: do we really know their position ? Alignment after launch?
- Many readout channels: electronics?

AMS-01: First magnetic spectrometer with a silicon tracker



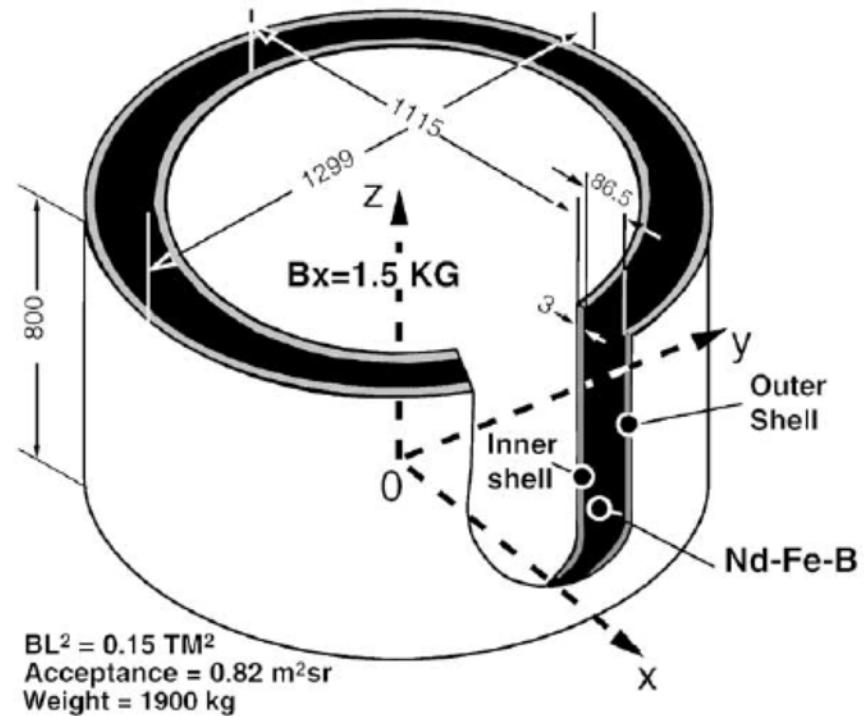
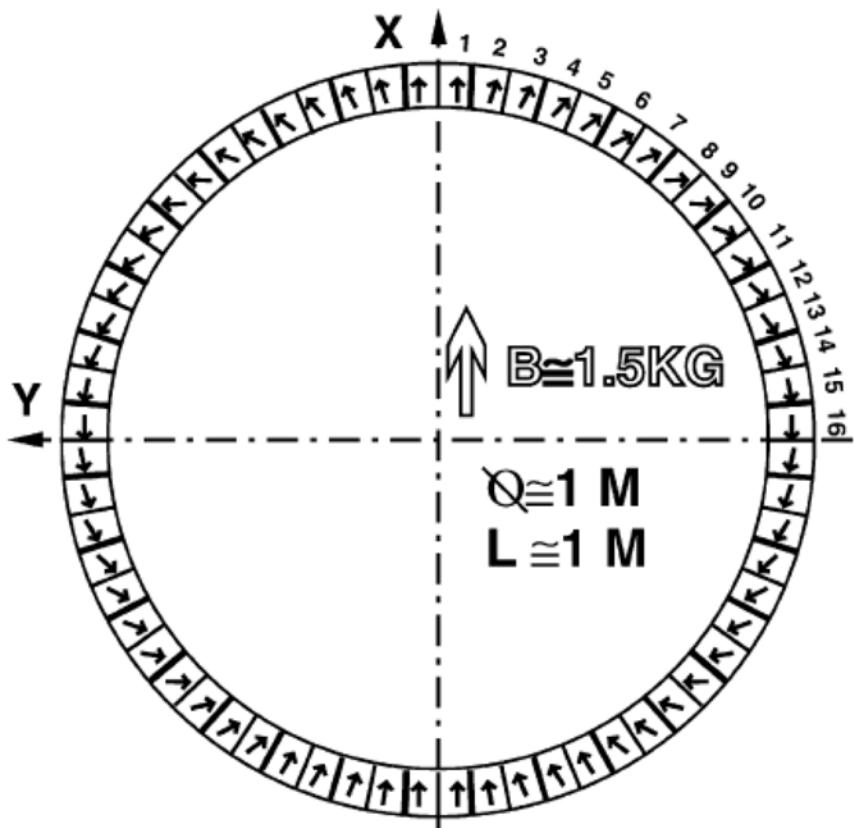
Time Of Flight : measure time \rightarrow velocity, arrival direction, $dE/dX \rightarrow Z$

Magnet: 2.2 Ton of Nd-Fe-B blocks providing a 15kGauss field inside, < 2 Gauss outside

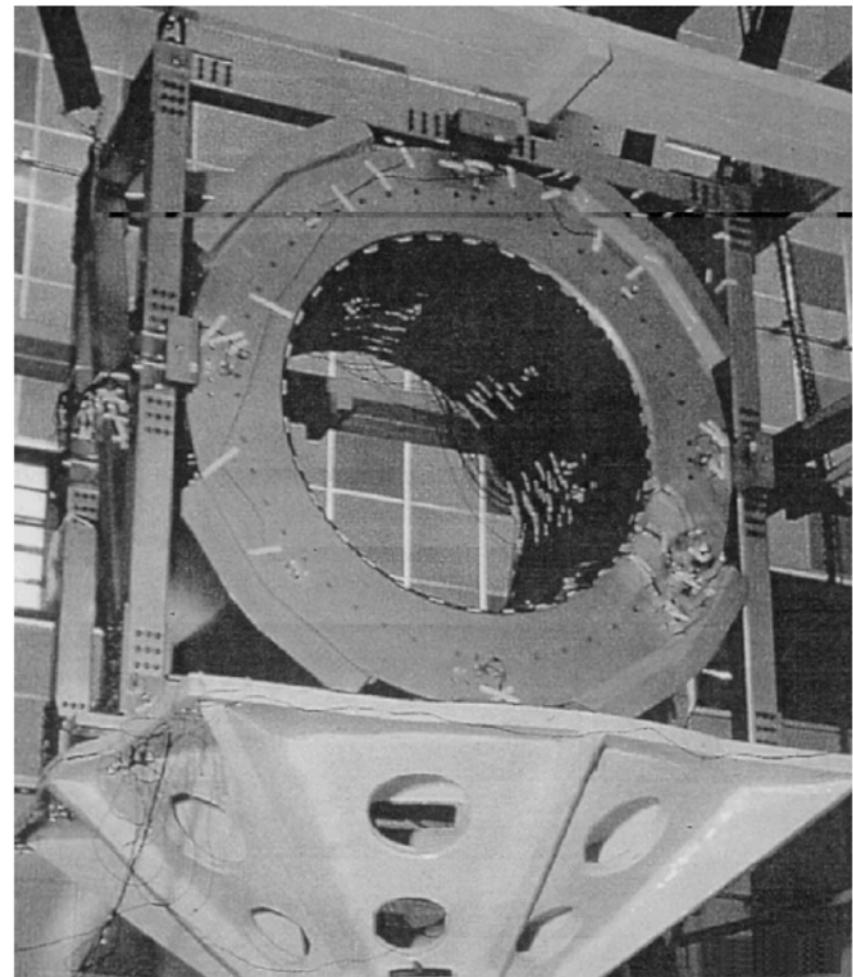
Tracker: 2m² of silicon sensors arranged in 6 planes

31 **Aerogel Cerenkov threshold counter**: discrimination of e/p based on cerenkov emission

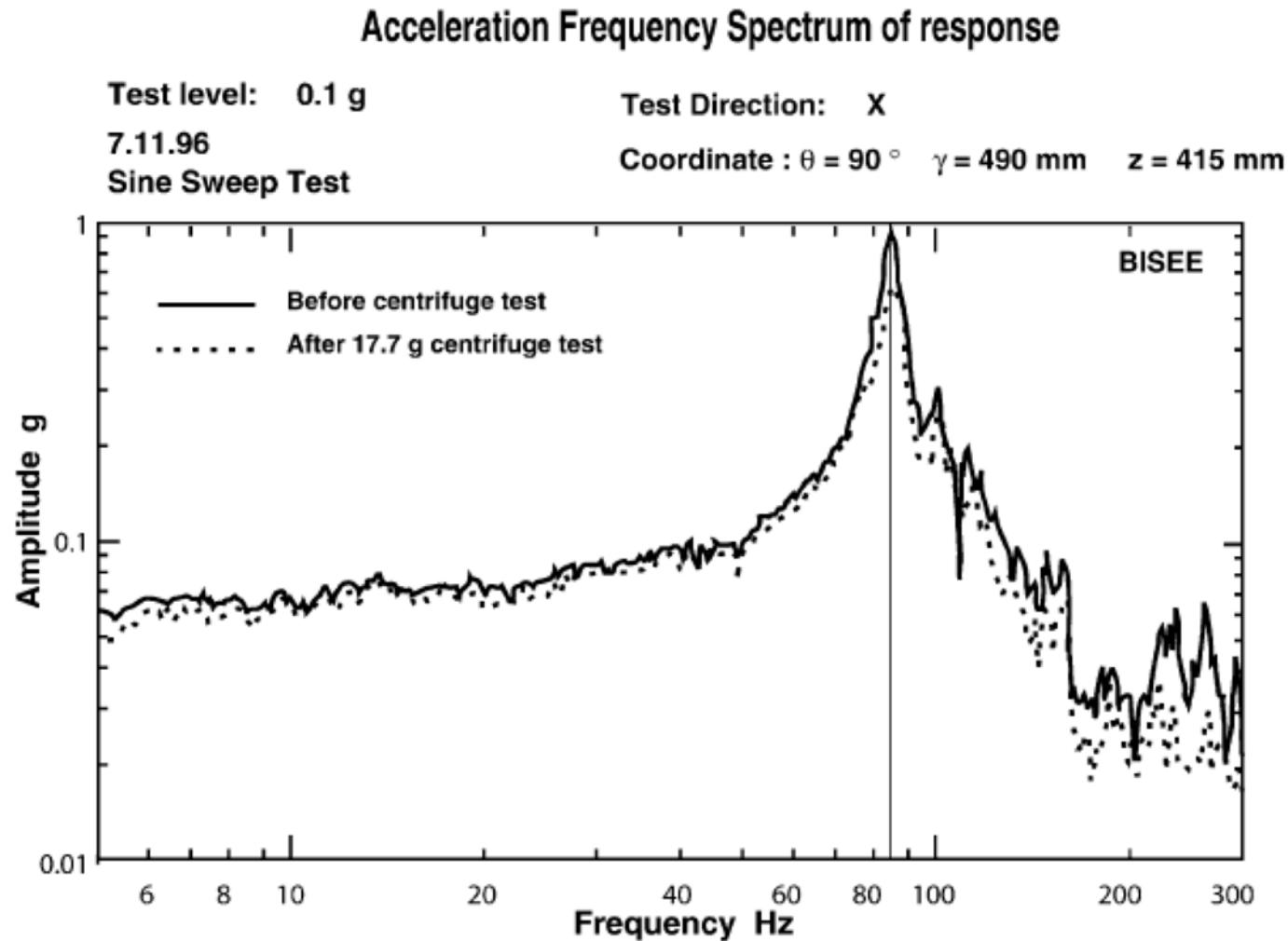
Magnetic field configuration



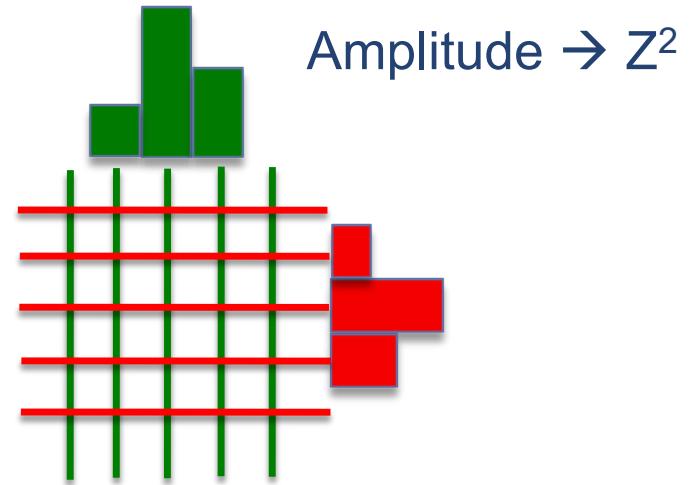
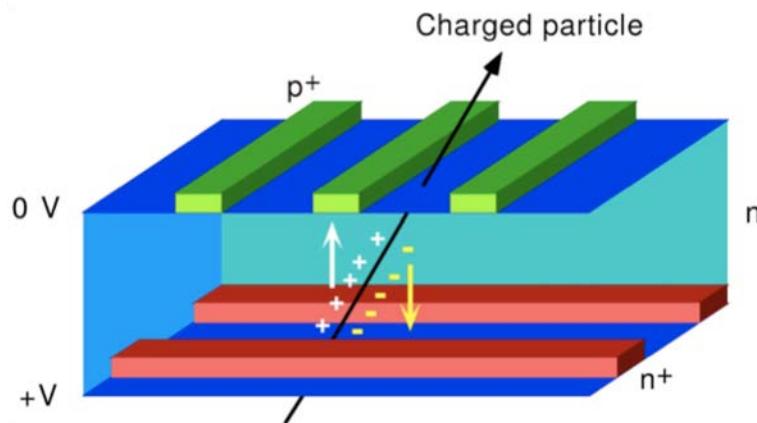
Before going to space.....



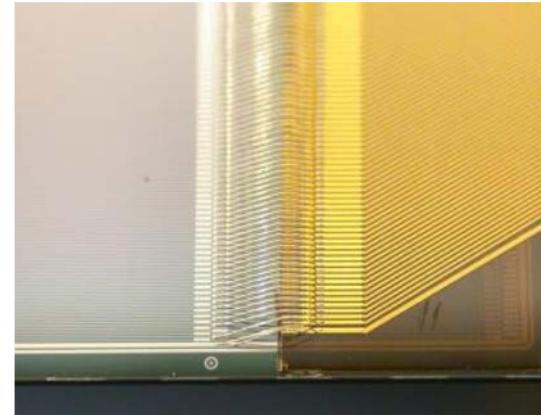
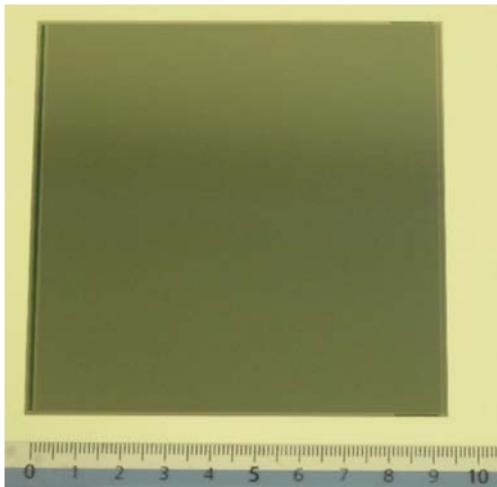
Before going to space.....



Position & Charge measurement with silicon



Single sensor $\approx 10 \times 10 \text{ cm}^2$
... or less

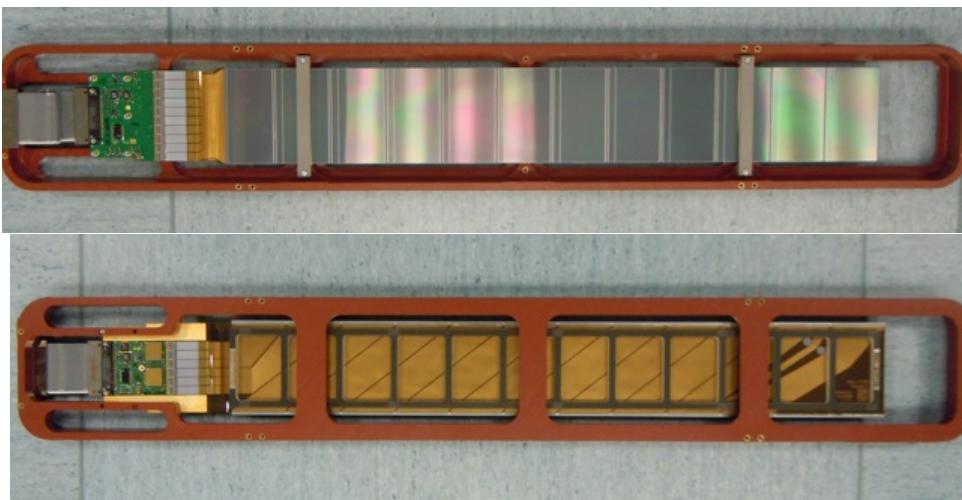
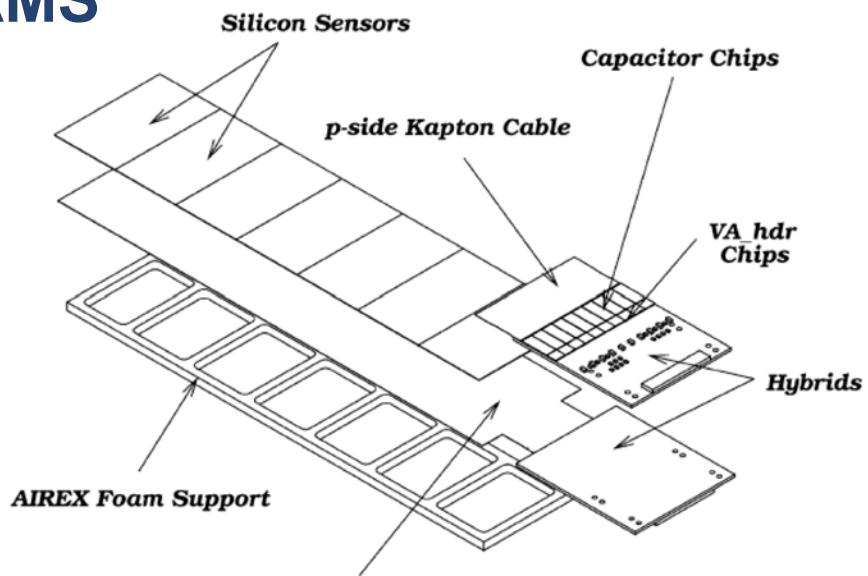


Daisy chain to cover up to m^2 !

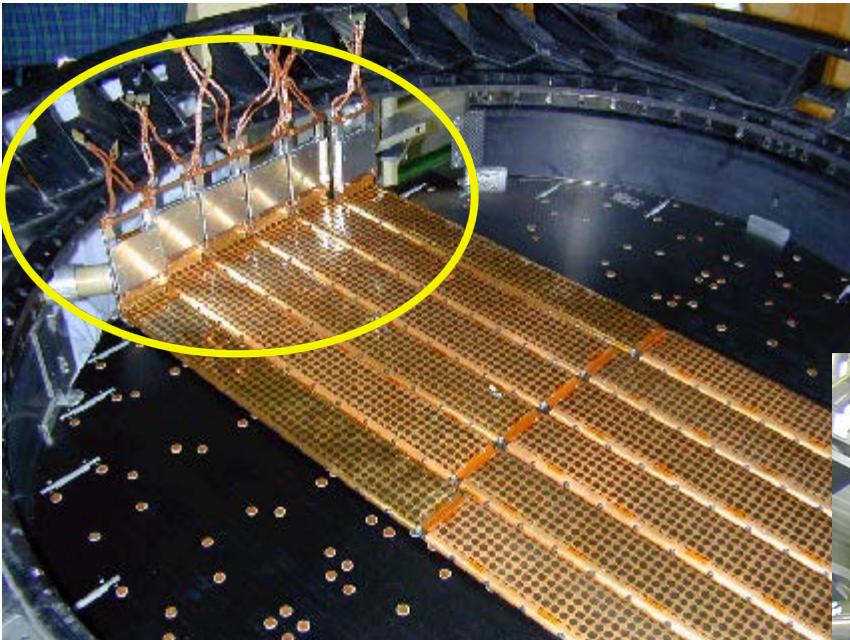
Silicon Ladders



AMS



AMS-01 Silicon Tracker

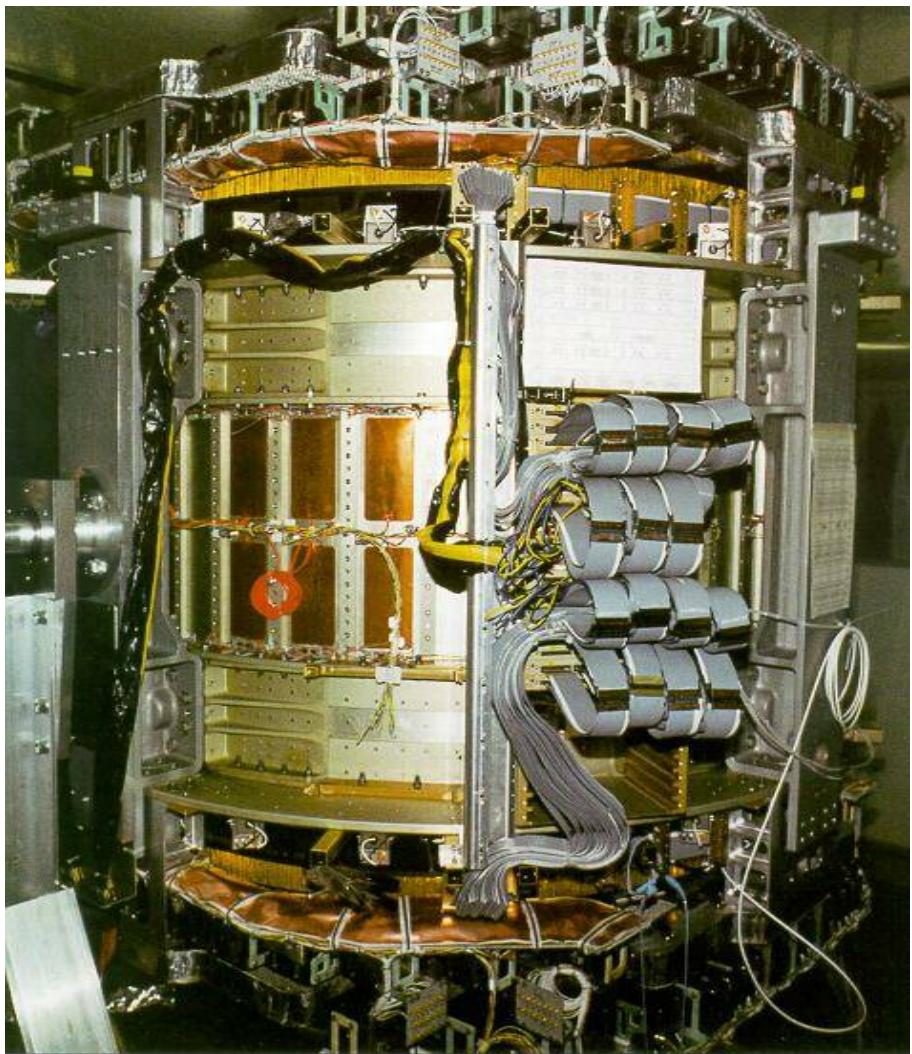


- ✓ Aluminum honeycomb + carbon fiber reinforcement layers
- ✓ Front end electronics disposed vertically on the edge of the plane to save acceptance
- ✓ Thermal bars to dissipate the power on the magnet mass outside

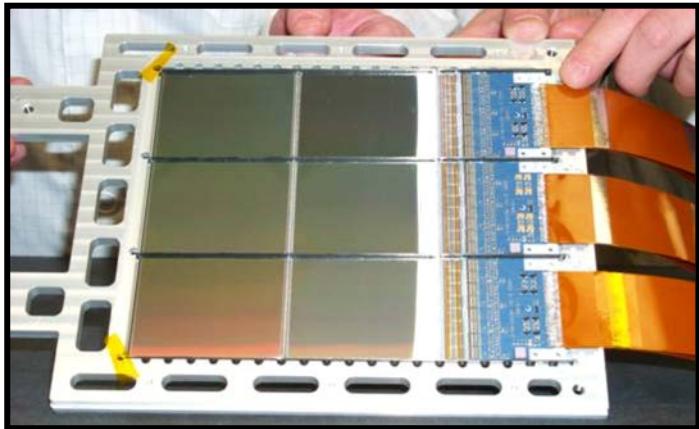


Lightweight carbon fiber shell to hold the planes

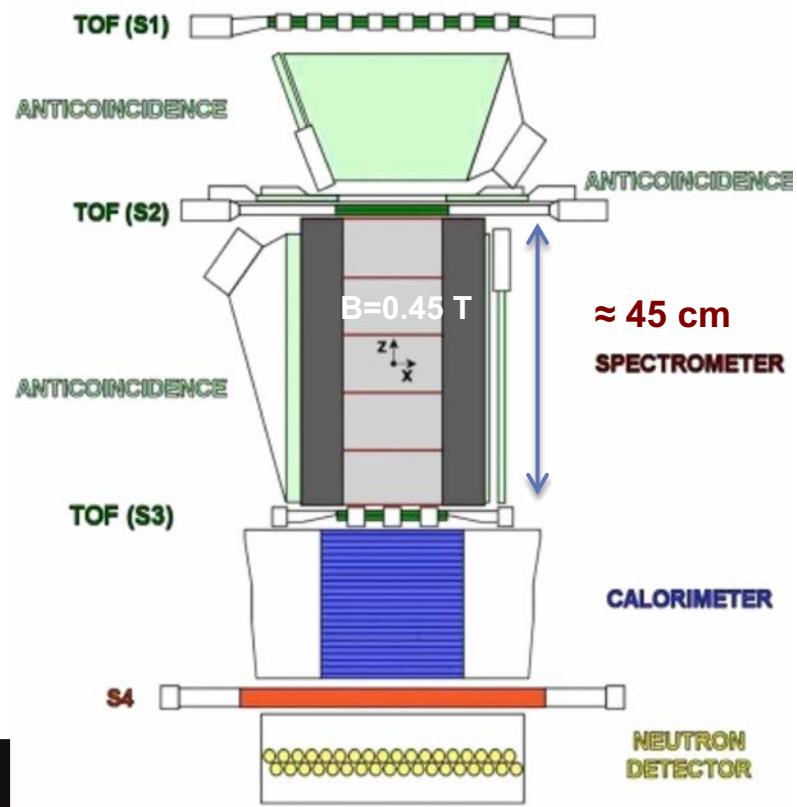
AMS-01 1998



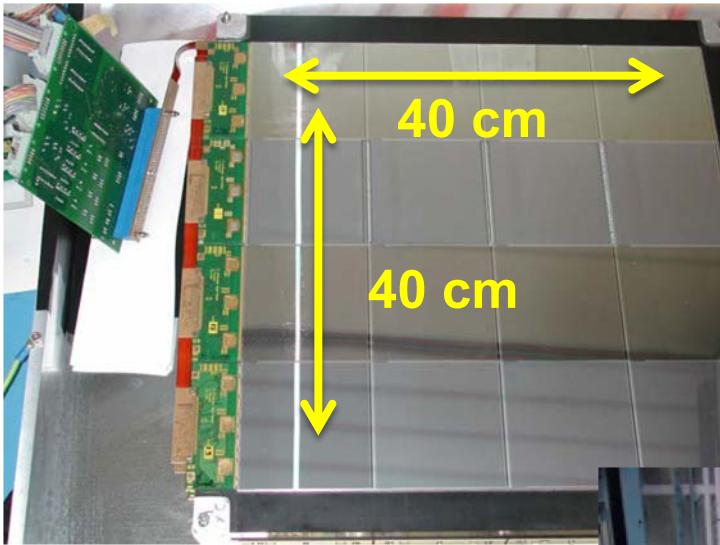
PAMELA 2006



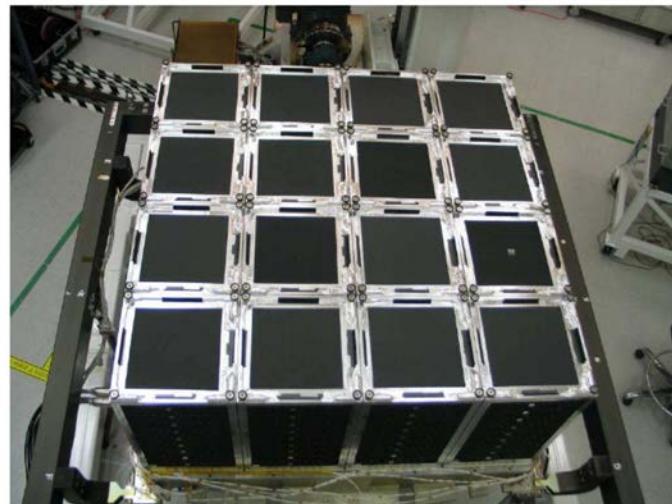
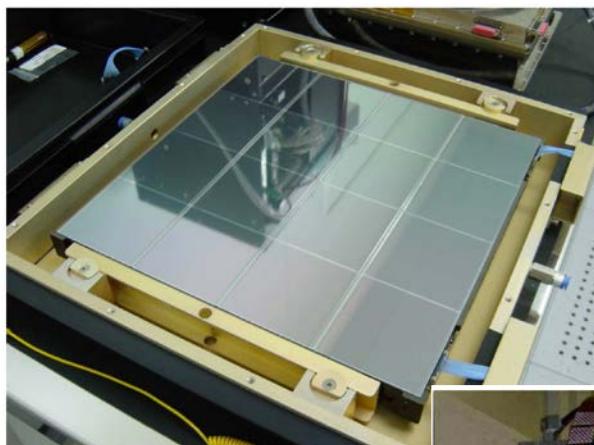
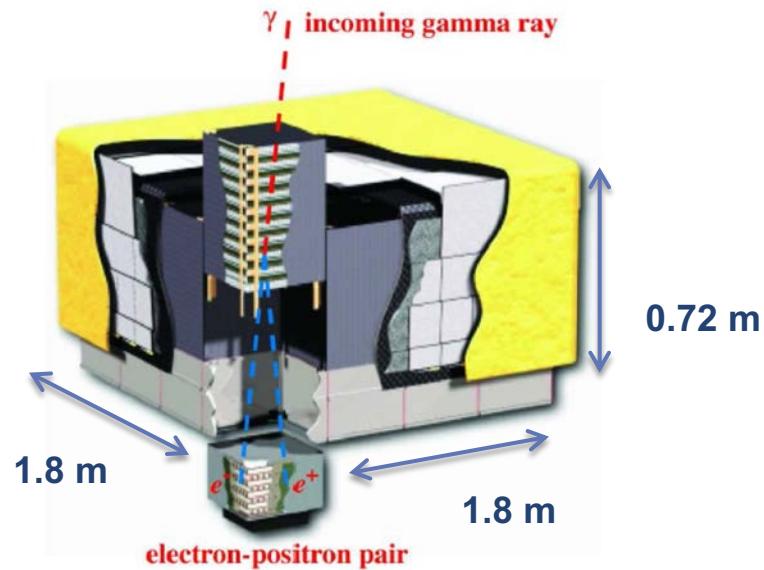
Silicon detectors with electronics
6 layers in a cavity $13 \times 16 \text{ cm}^2$



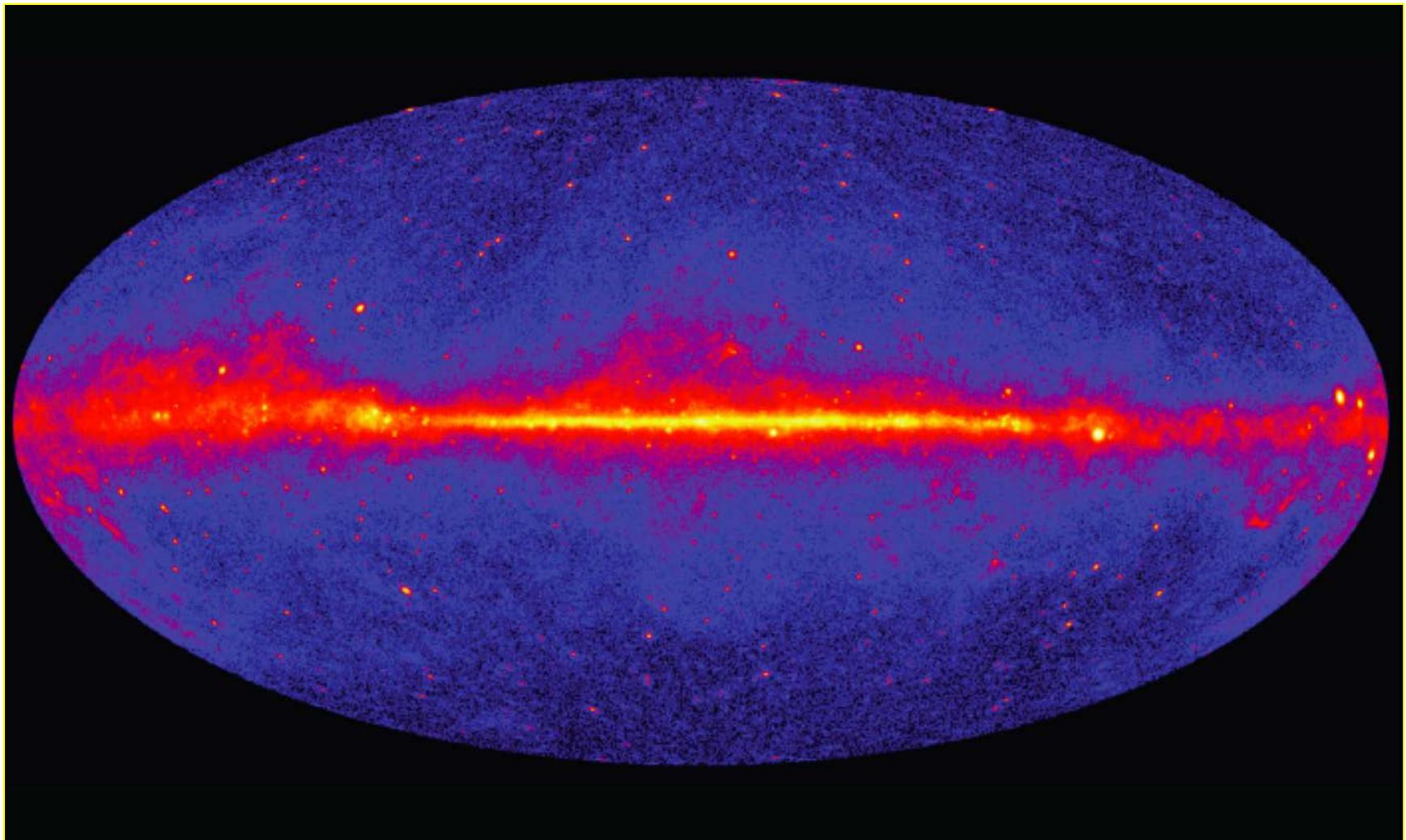
AGILE 2007



FERMI 2008 : 73 m² of silicon sensors

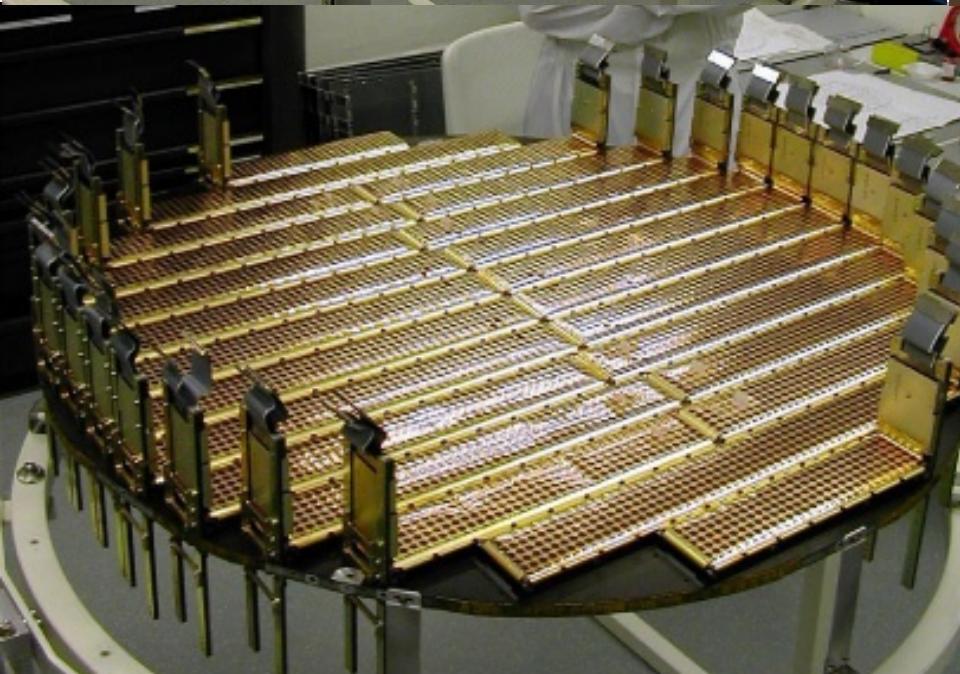
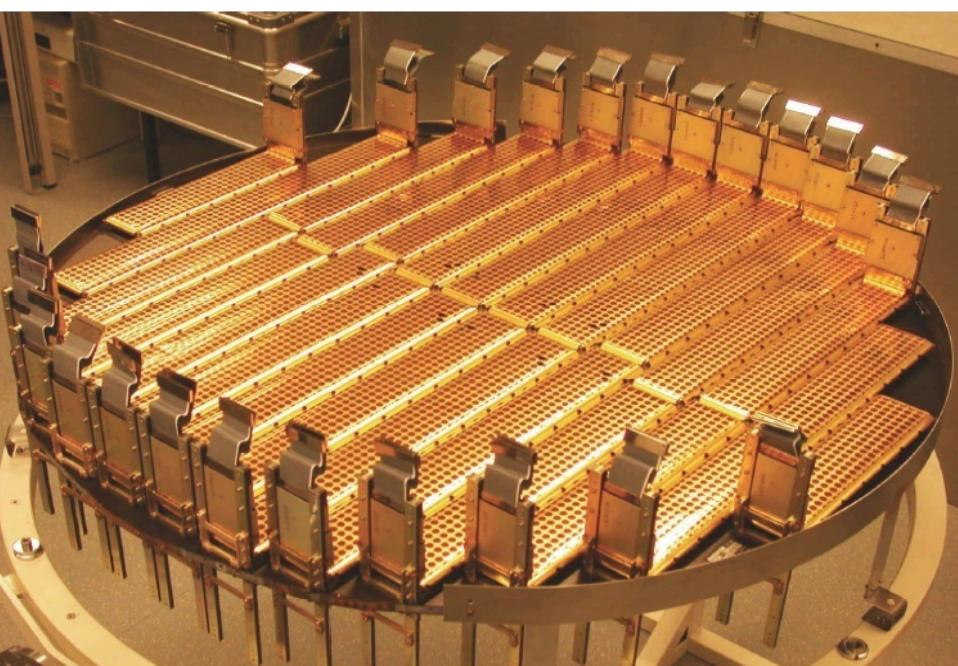
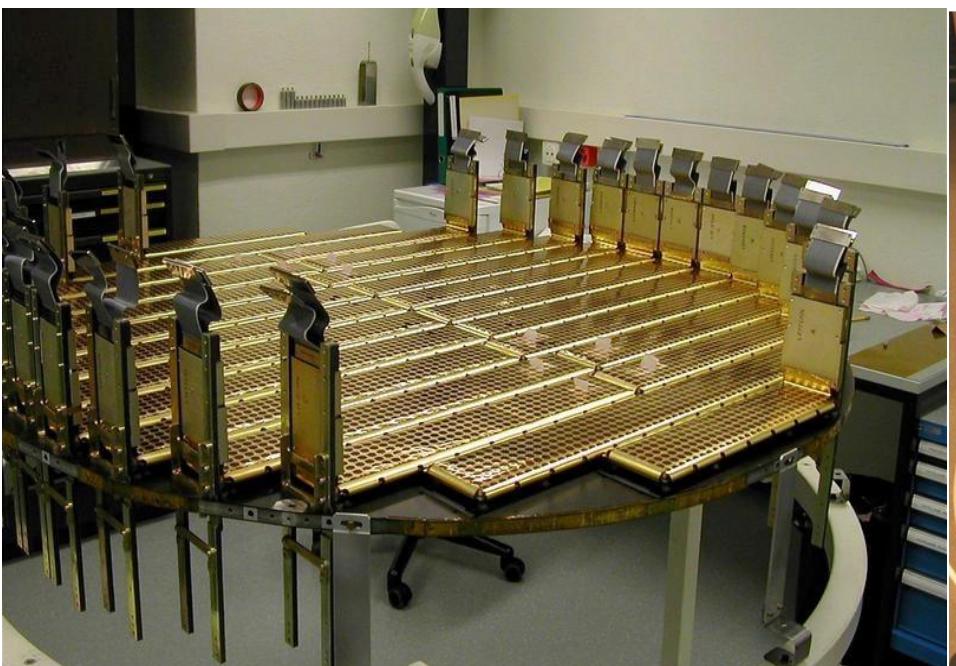


The FERMI sky



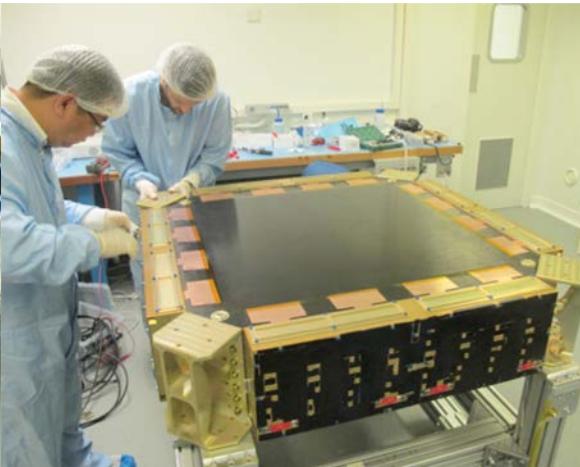
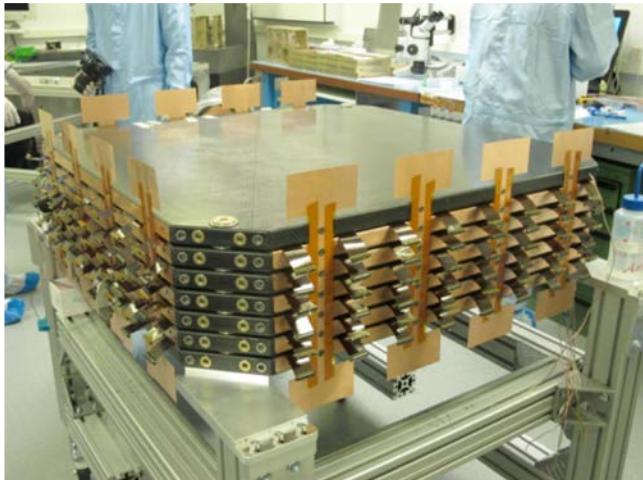
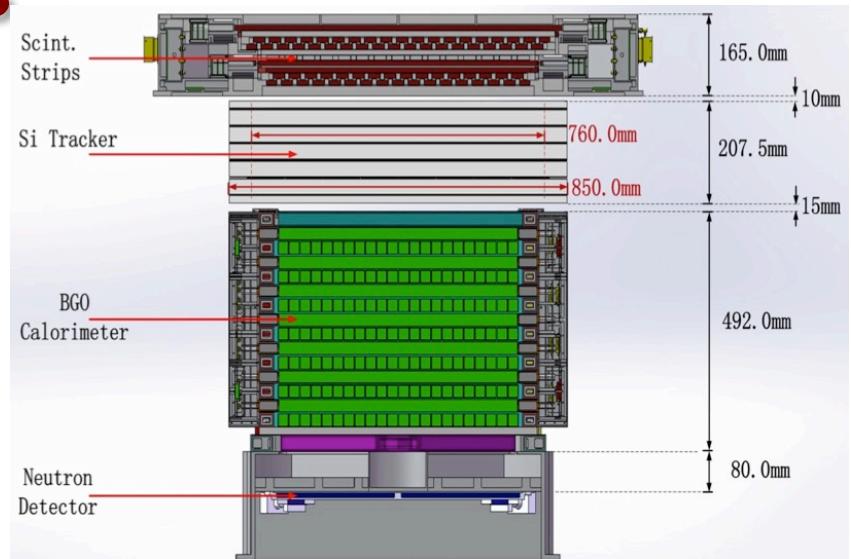
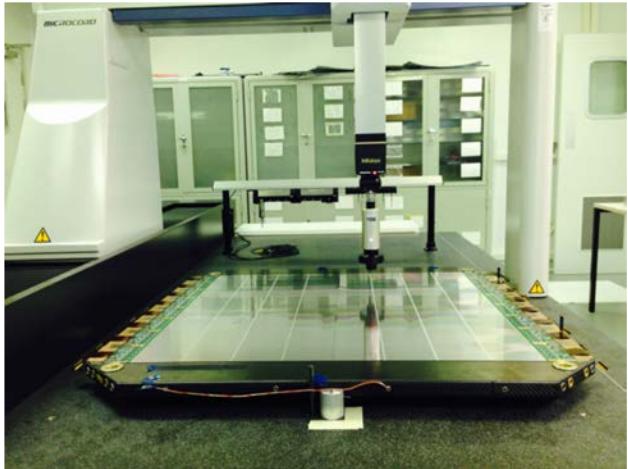
TOO CROWDED TO DISCUSS IT HERE > 3000 sources !

2011 AMS-02: 9 planes (6.4 m^2)



2015 : DAMPE

7.7 m² of silicon sensors



In orbit now: calorimetric detectors

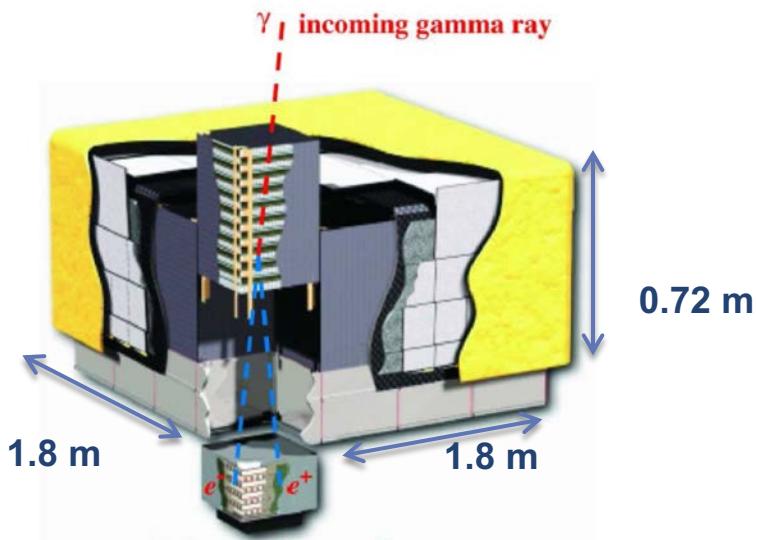
- AGILE (2006): γ -rays up to xx MeV
- FERMI (2007): γ -rays up to 300 GeV, electrons
- CALET (2015) : electrons, nuclei
- DAMPE (2015): electrons, nuclei, photons

In orbit now: spectrometric detectors

- AMS-02 (2011): anti-particles, p, He ...nuclei (up to Fe..)

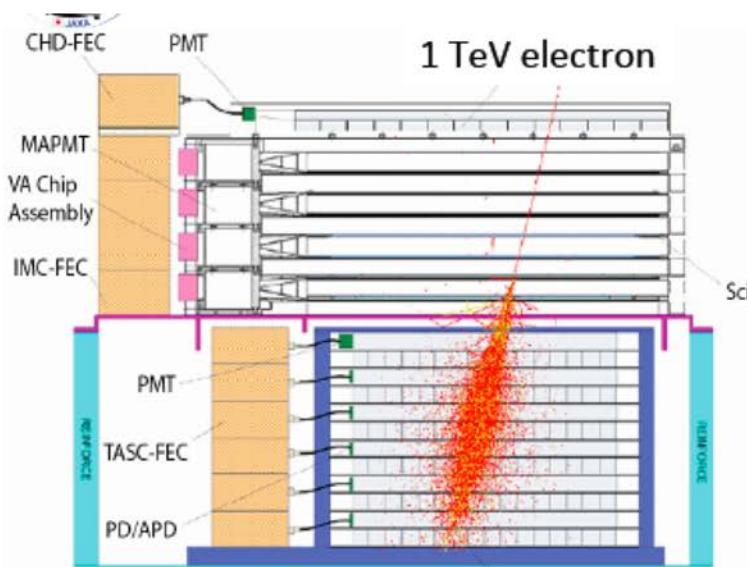
CALORIMETRIC MEASUREMENTS (NOW → 2020)

Fermi : γ , but also e^\pm



electron-positron pair

Largest acceptance, $\approx 1 \text{ m}^2\text{sr}$,
“thins” $8.6 X_0$ calorimeter



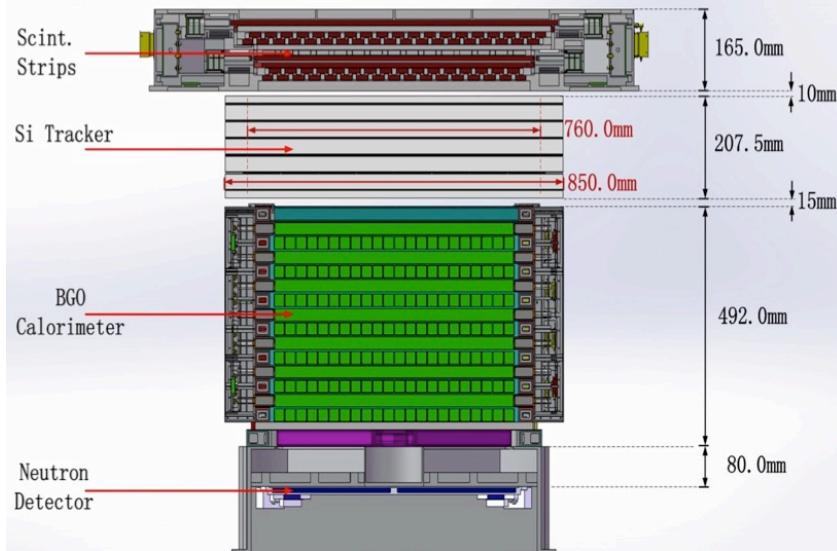
CALET: e^\pm, γ , light nuclei ($\approx 0.8-0.12 \text{ m}^2\text{sr}$)
ultra heavy nuclei, ($0.4 \text{ m}^2\text{sr}$)

CHD - **Charge Detector (CHD)**
(Charge Measurement $Z=1-40$)

IMC - **Imaging Calorimeter (IMC)**
(Particle ID, Direction)
Total Thickness of Tungsten (W): $3 X_0, 0.1 \lambda_1$
Layer Number of Scifi Belts: 8 Layers $\times 2(X,Y)$

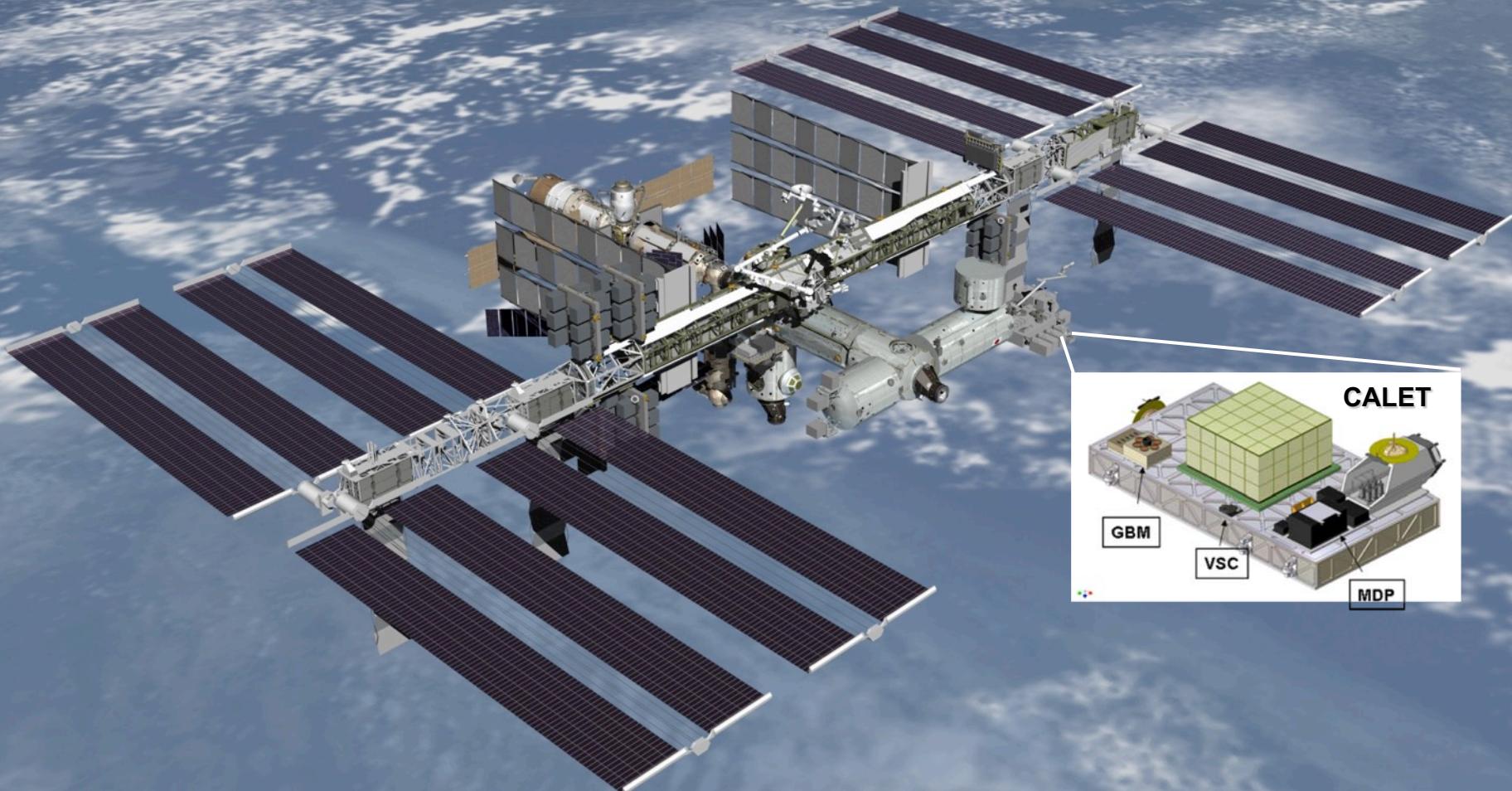
TASC - **Total Absorption Calorimeter (TASC)**
(Energy Measurement, Particle ID)
PWO 20mm \times 20mm \times 320mm
Total Depth of PWO: $27 X_0$ (24 cm), $1.2 \lambda_1$

DAMPE: e^\pm, γ , light nuclei



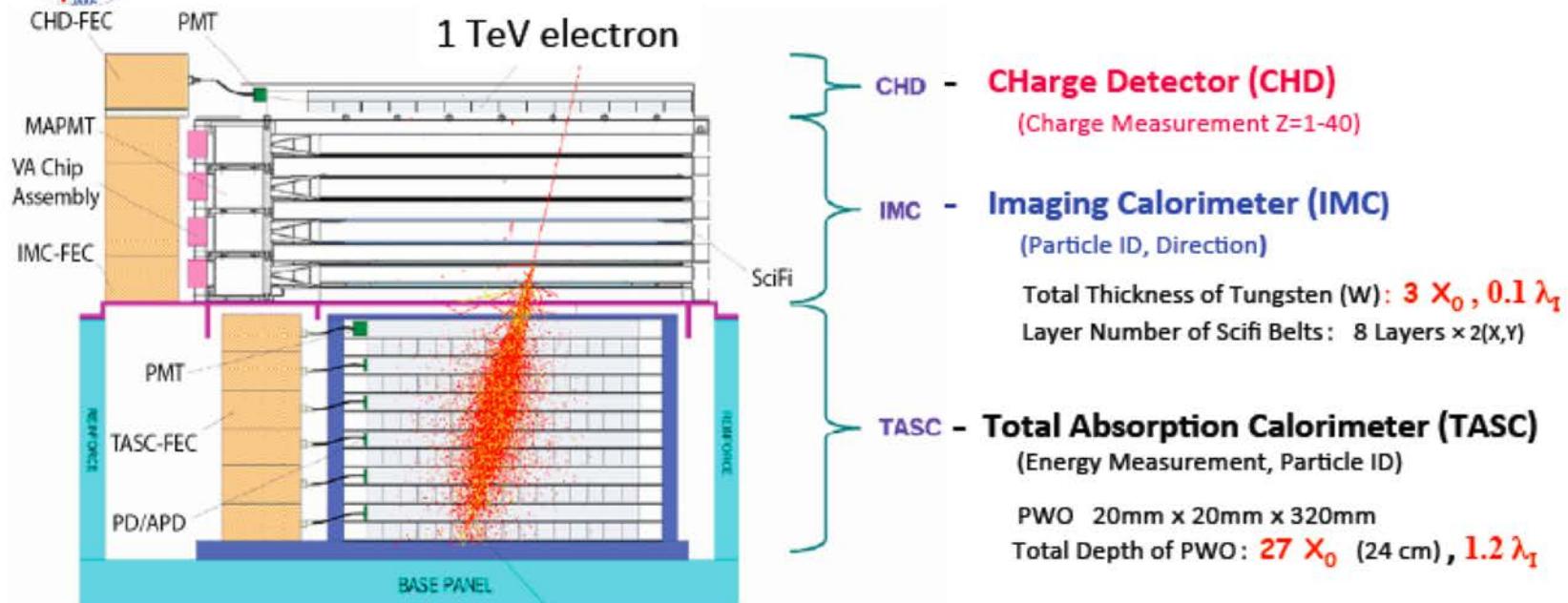
$0.3 \text{ m}^2\text{sr}$ acceptance, $32 X_0$ cal.

CALET Mission for Japanese Experiment Module on ISS





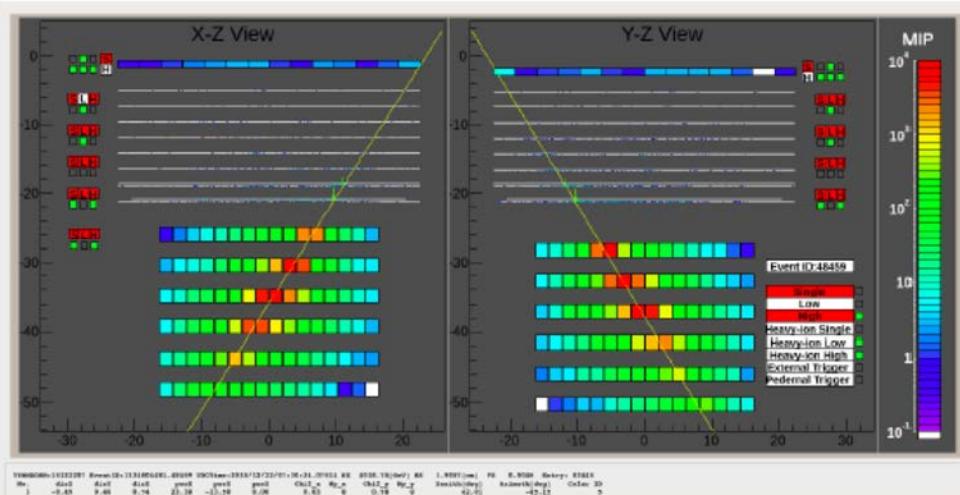
CALorimetric Electron Telescope (CALET): INSTRUMENT OVERVIEW



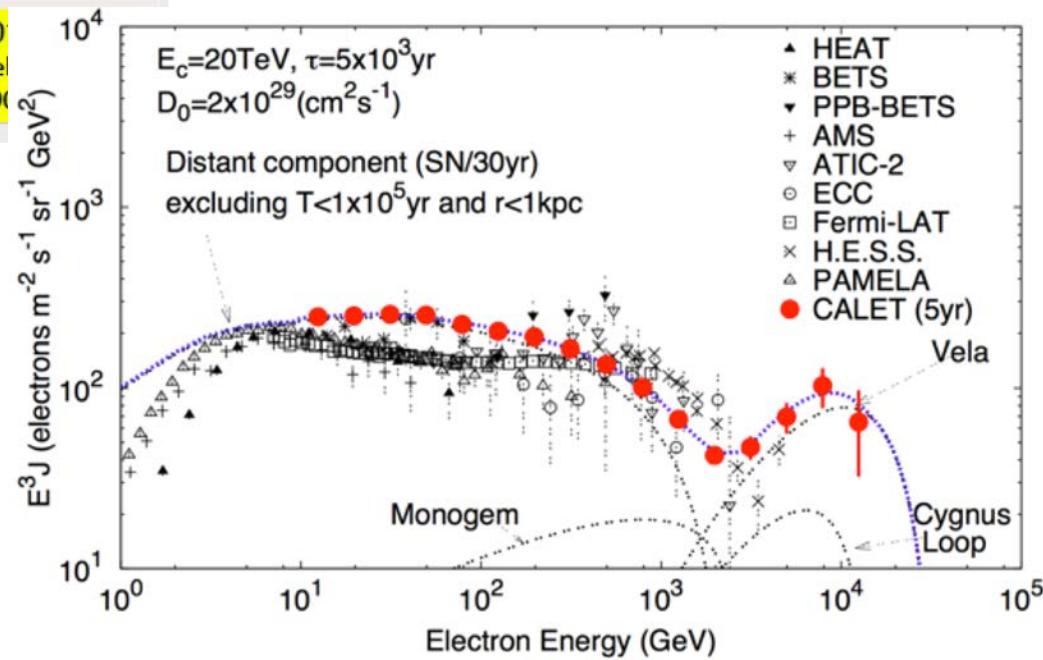
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z = 1 - 40)	Arrival Direction, Particle ID	Energy Measurement, PID
Sensor (+ Absorber)	Plastic Scintillators: 2 layers Unit Size: 32mm x 10mm x 450mm	Scintillating Fibers: 16 layers single readout: $1\text{mm}^2 \times 448\text{ mm}$ Total thickness of Tungsten: $3 X_0$	PWO logs: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: $27 X_0$
Readout	PMT+CSA	64-anode MAPMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)

CALET & e^\pm

High Energy Electron Candidate : 4.2TeV



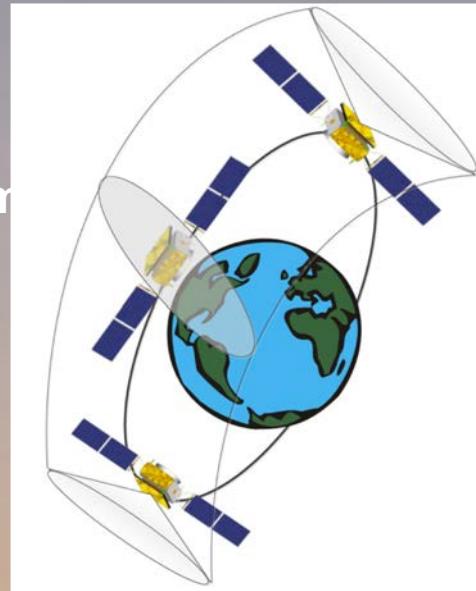
With an observation of 232 days (October 13, 2015 – May 31, 2016), the exposure reached $SQT \sim 20.5 \text{ m}^2 \text{ sr day}$, and a number of the selected electron candidates is about 1.8×10^6 event with an efficiency cut of 90%



DAMPE launch: Dec 17th 2015, 0:12 UTC

Jiuquan Satellite Launch Center
Gobi desert

Orbit: sun synchronous @ 500km
97.4°
period 95 minutes

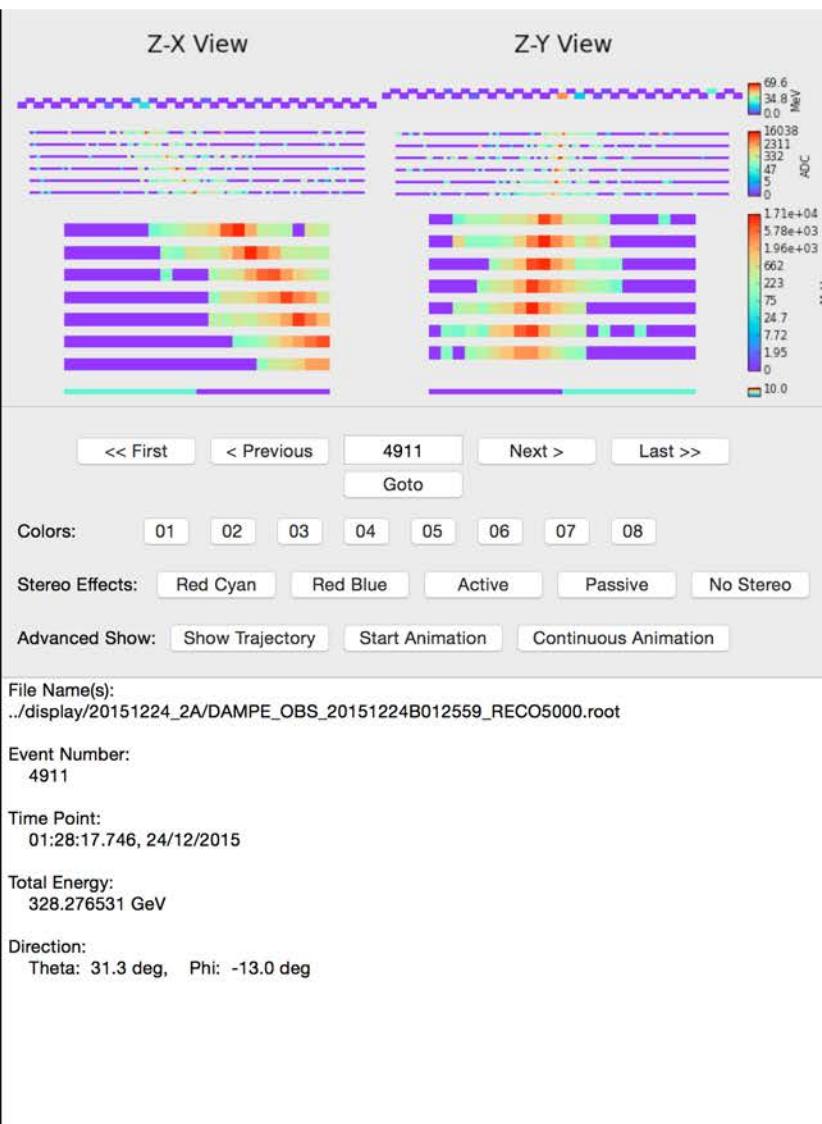
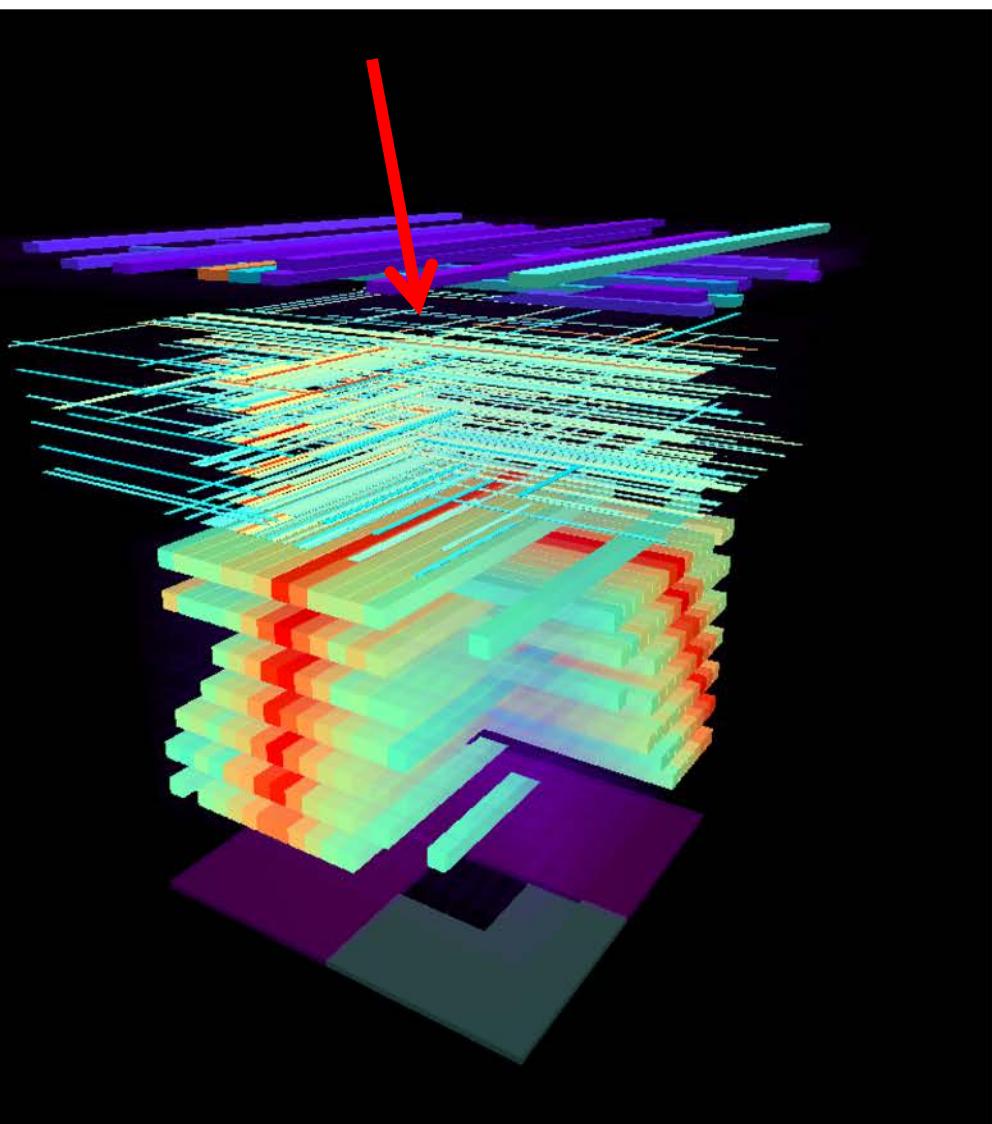


DAMPE → WUKONG



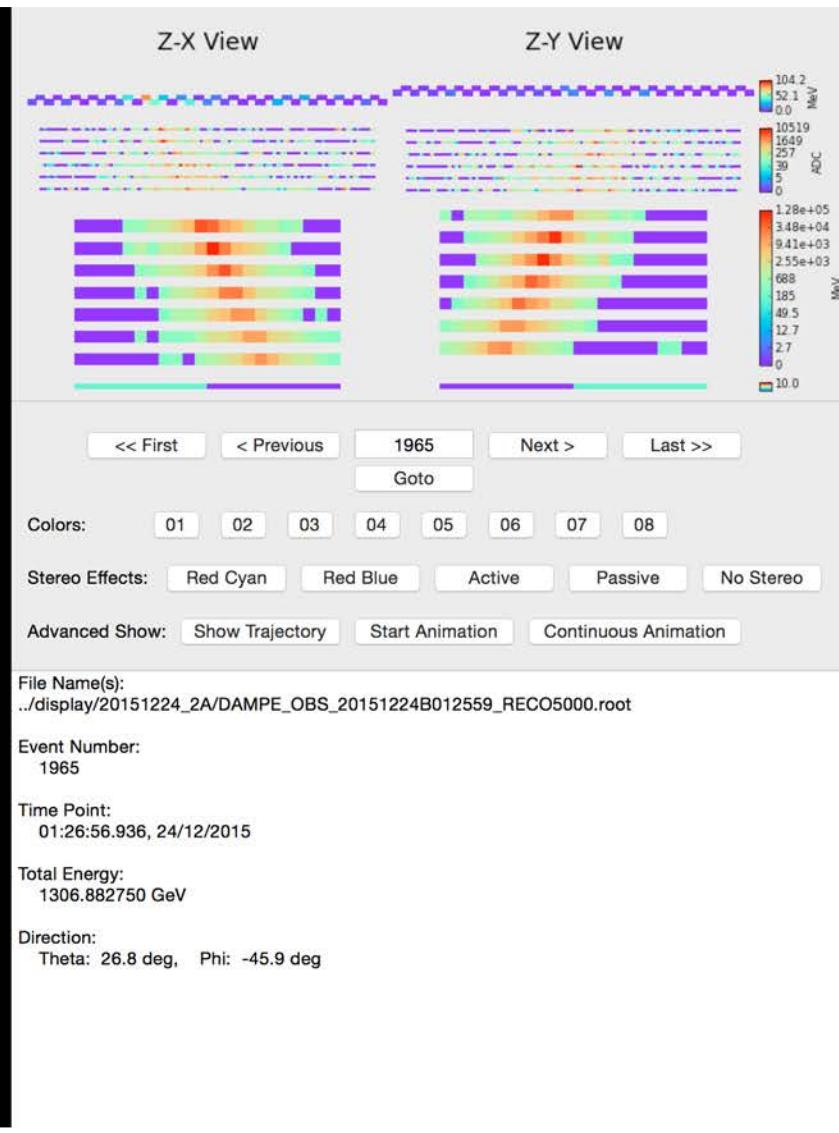
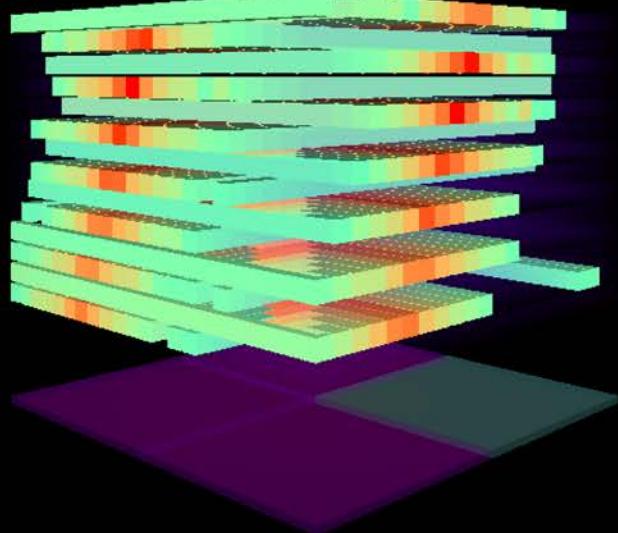
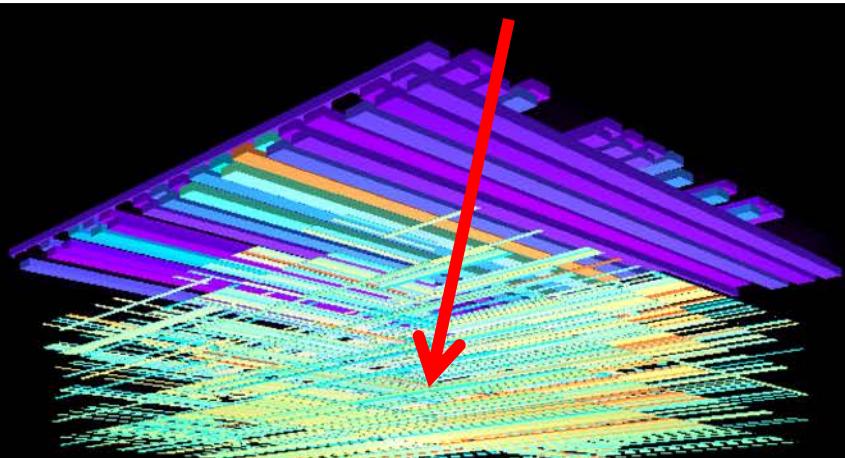
Dec 24th 2015: HV on

330 GeV electron



Dec 24th 2015: HV on

1.3 TeV carbon

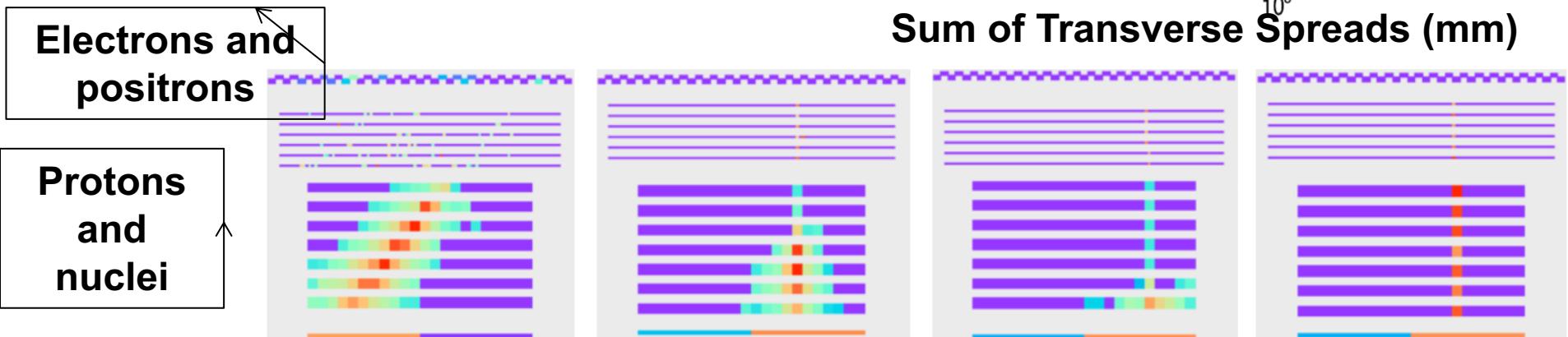
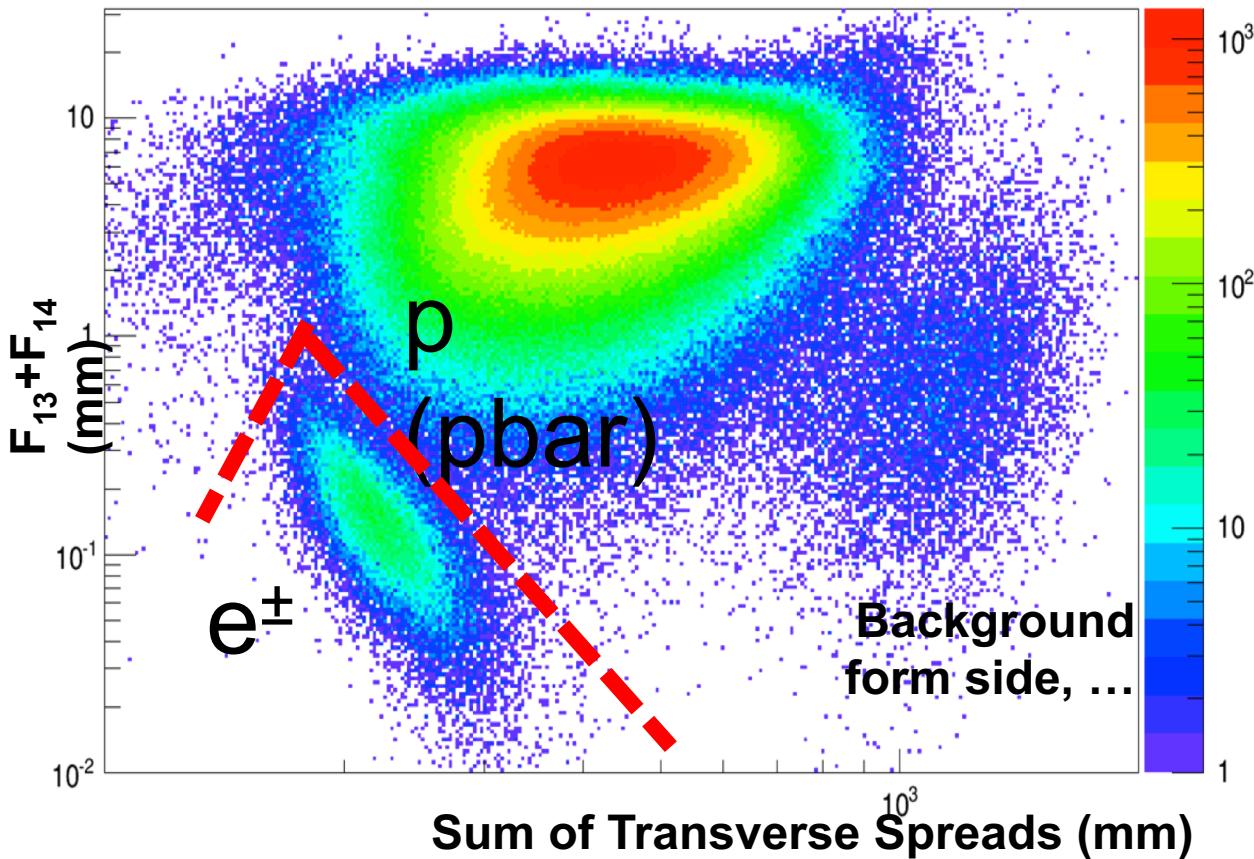
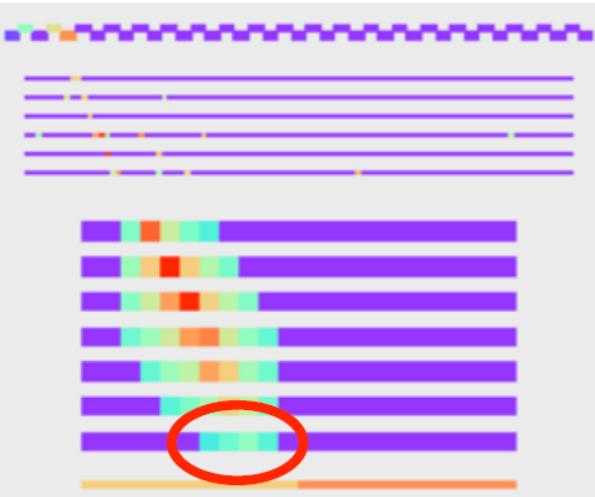


Electron identification

One possible “shape parameter”

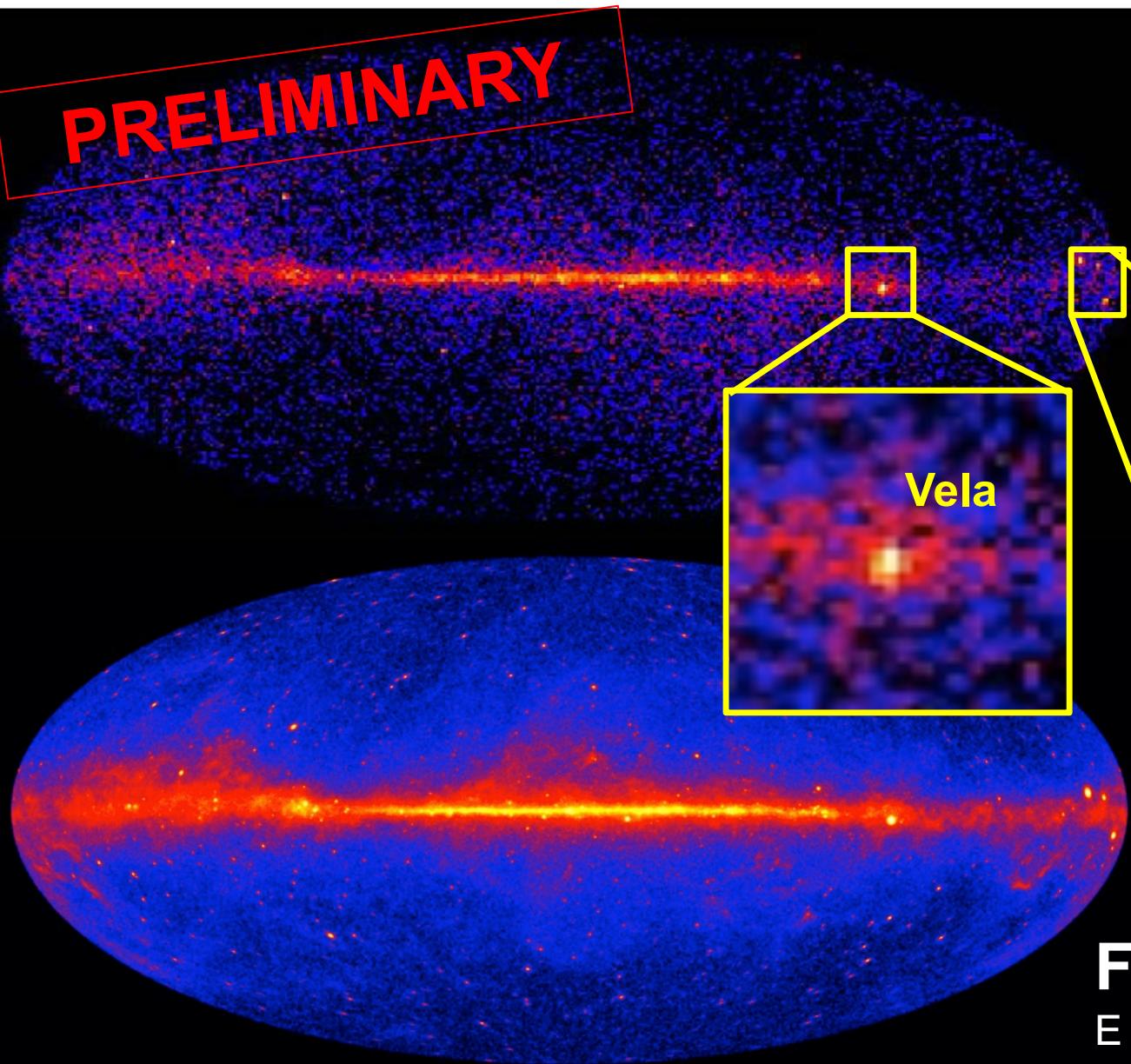
$$F_i = \text{Spread}_i \times \frac{E_i}{E_{tot}}$$

Rejection power $> 10^5$



Photons

PRELIMINARY

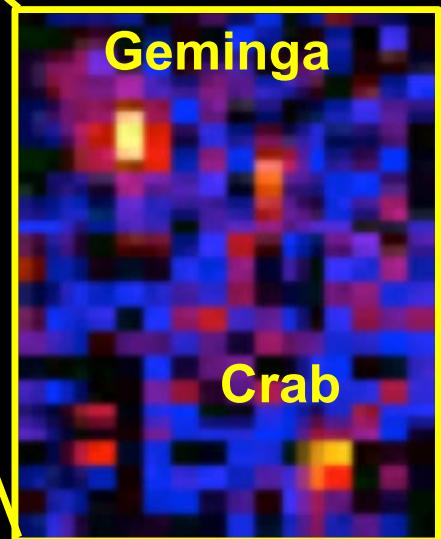


DAMPE 165 days

$E > 1\text{GeV}$

Counts / $(0.5^\circ)^2$ pixel

$\sigma_0 \approx 0.2^\circ$ @ 3 GeV



FERMI 5 years
 $E > 1\text{GeV}$

CALORIMETRIC MEASUREMENTS

(Future project...)

ISS-CREAM : coming soon..!

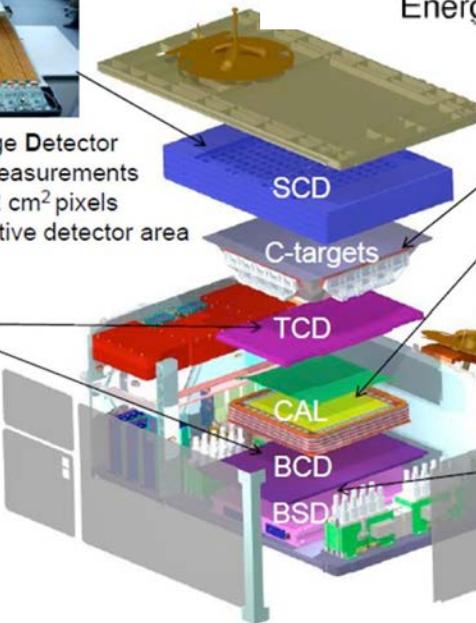


4 layer Silicon Charge Detector

- Precise charge measurements
- 380- μ m thick 2.12 cm² pixels
- 79 cm x 79 cm active detector area

Top & Bottom Counting Detectors

- Each with 20 x 20 photodiodes and a plastic scintillator for e/p separation
- Independent Trigger

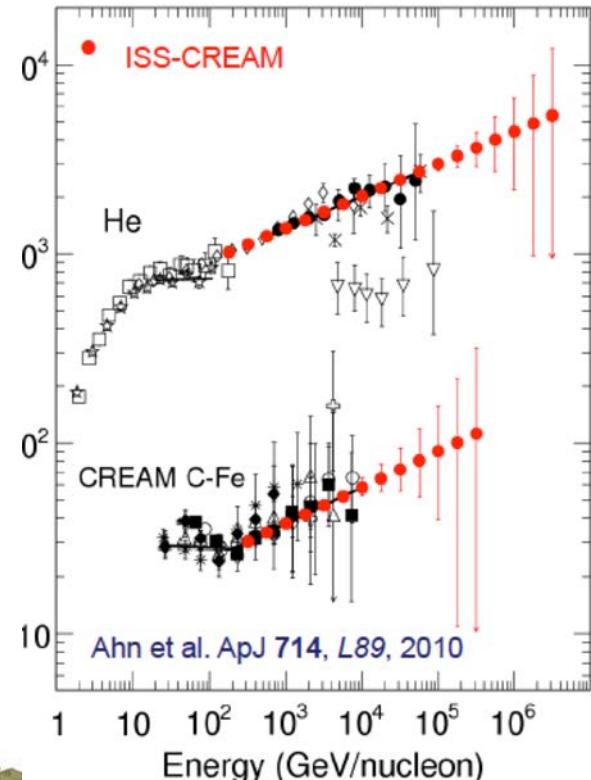


Calorimeter (20 layers W + Scn Fibers)

- Determine Energy
- Provide tracking
- Provide Trigger

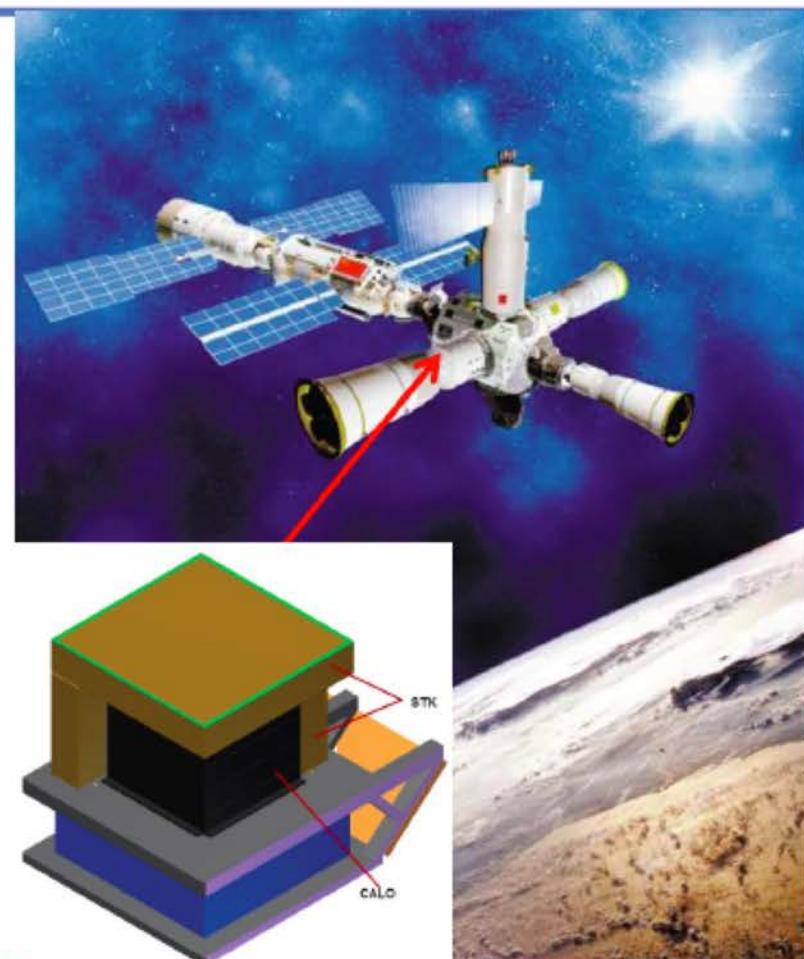
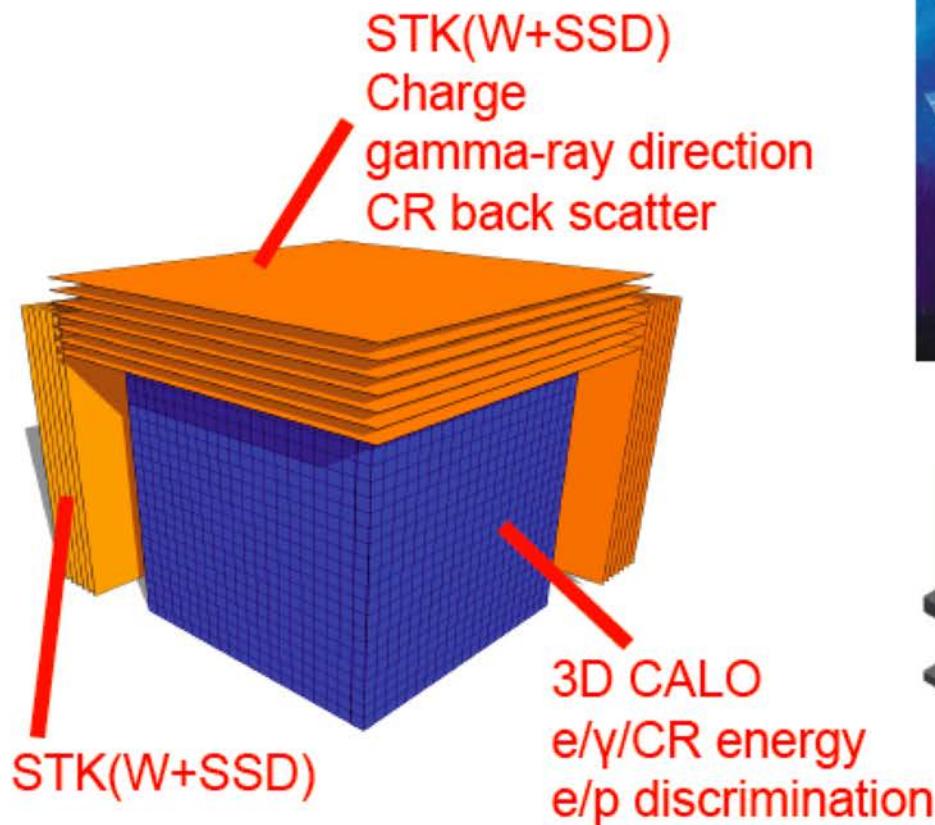
Boronated Scintillator Detector

- Additional e/p separation
- Neutron signals

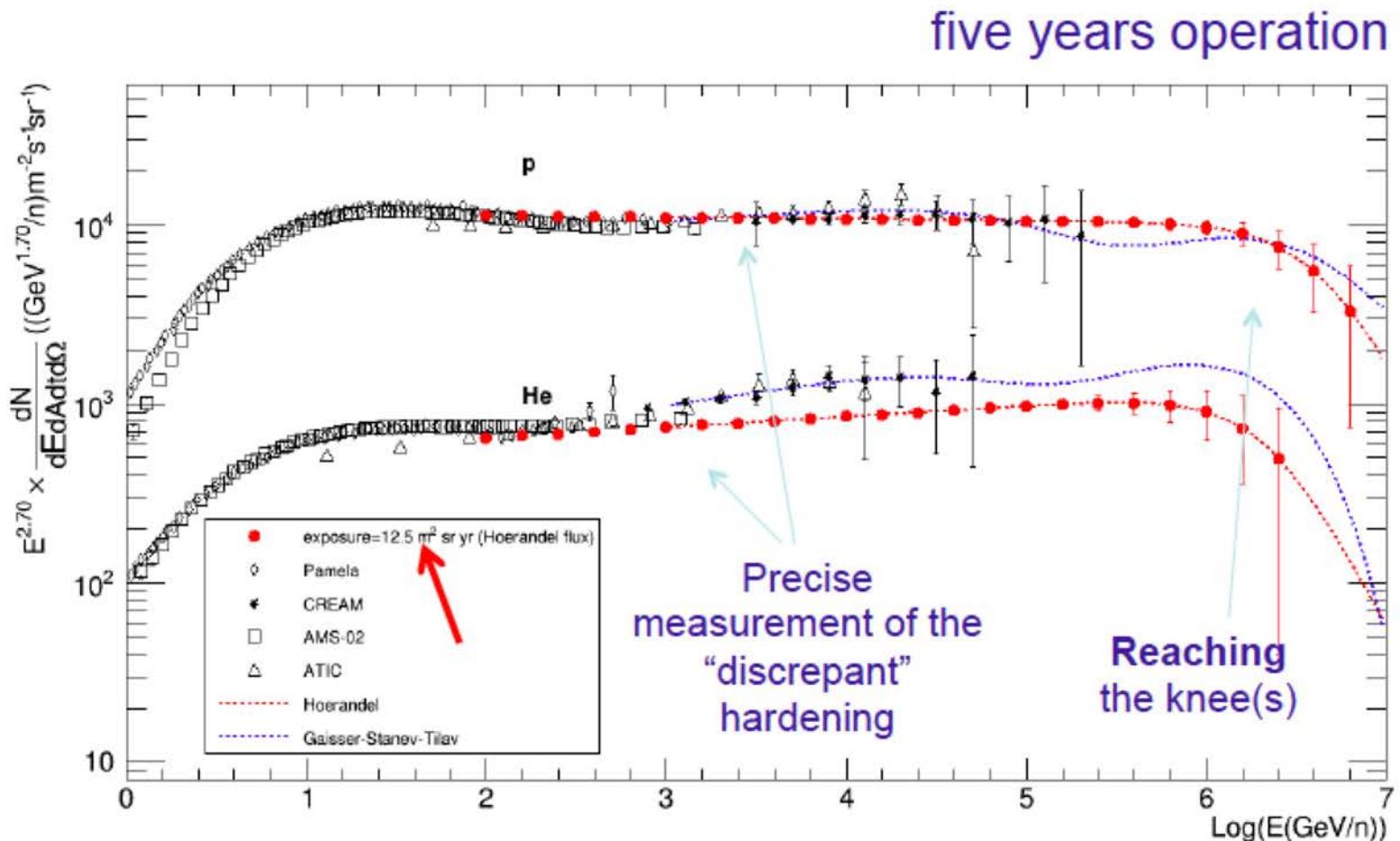


High Energy cosmic-Ray Detector (HERD)

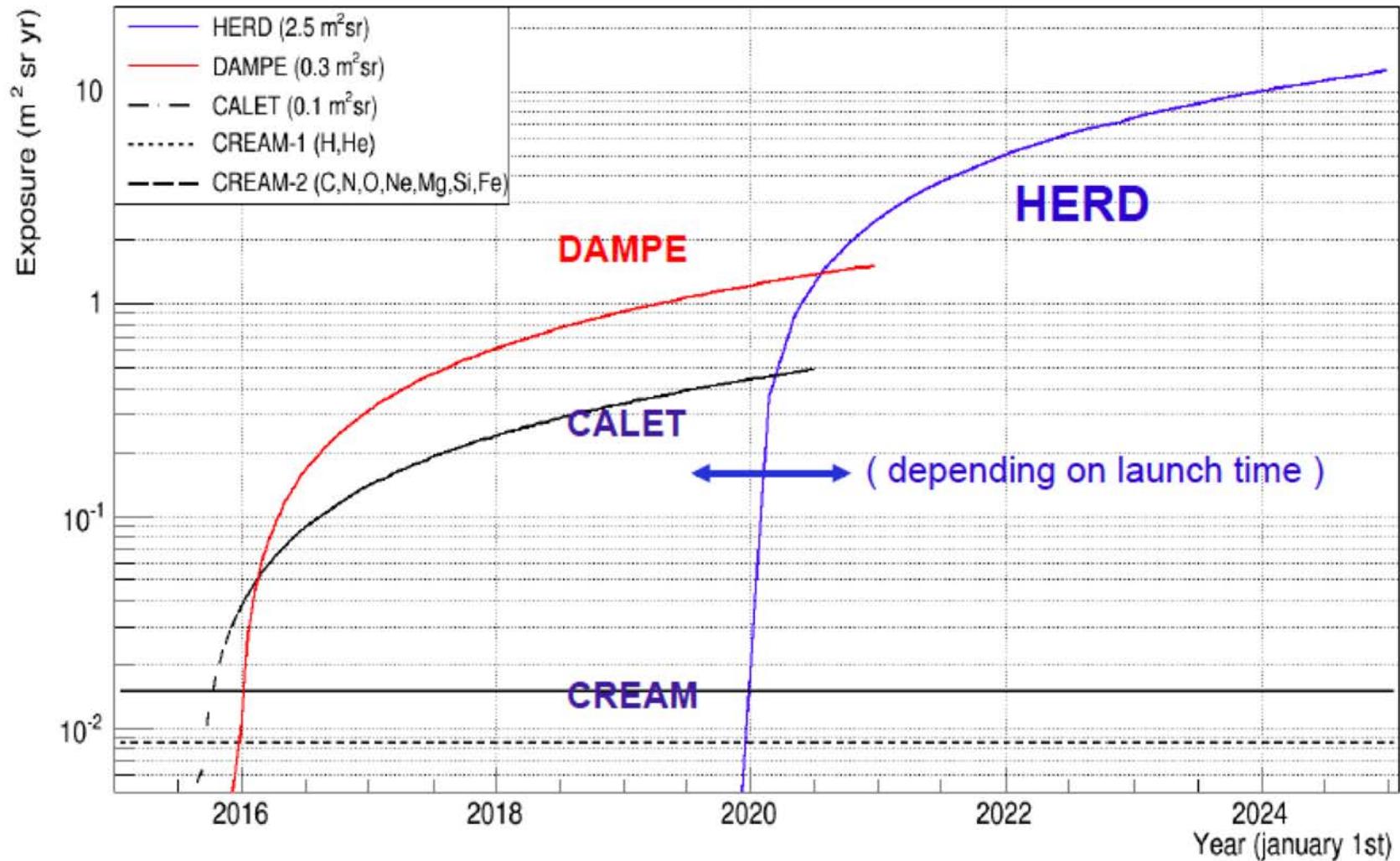
n10X acceptance than others, but
weight 2.3 T ~1/3 AMS



Expected HERD Proton and He Spectra



Exposure (assuming GF=2.5m²sr)



MAGNETIC SPECTROMETERS (NOW)

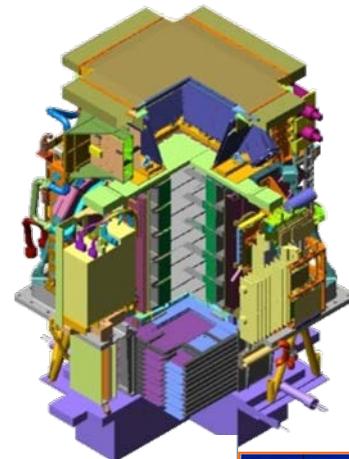
Payload for Matter/Antimatter Exploration and Light nuclei Astrophysics - PAMELA

→ Launched on 15th June 2006

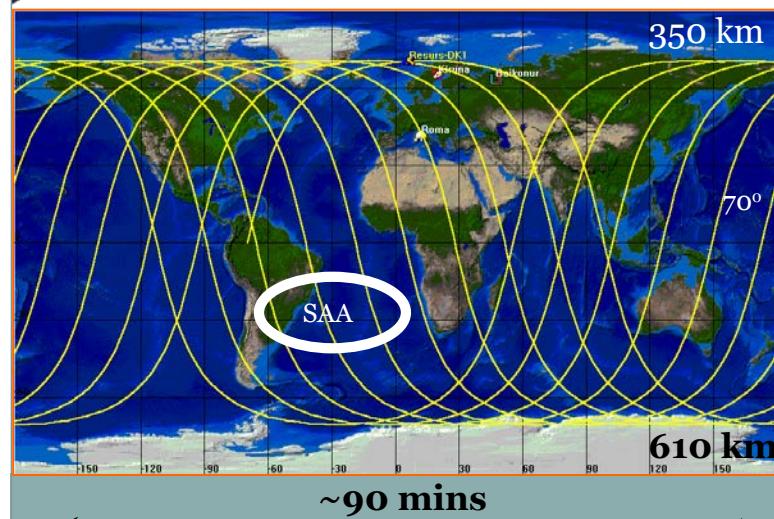
→ PAMELA in continuous data-taking mode for 10 years



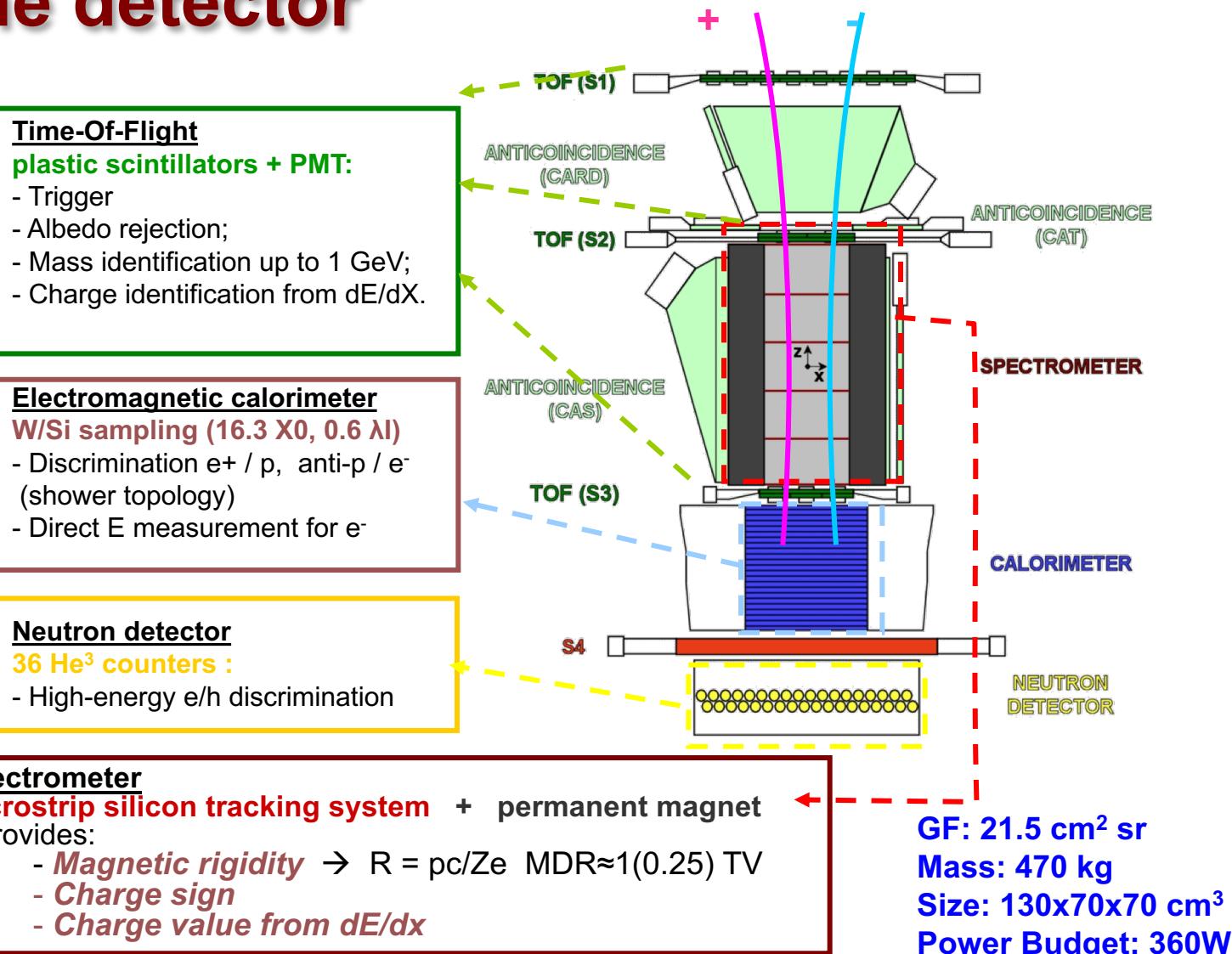
Launch from Baykonur



- PAMELA on board of Russian satellite **Resurs DK**
- Orbital parameters:
 - inclination $\sim 70^\circ$ (\Rightarrow low energy)
 - altitude $\sim 360\text{-}600$ km (elliptical)
 - active life >3 years (\Rightarrow high statistics)



The detector



All particle results

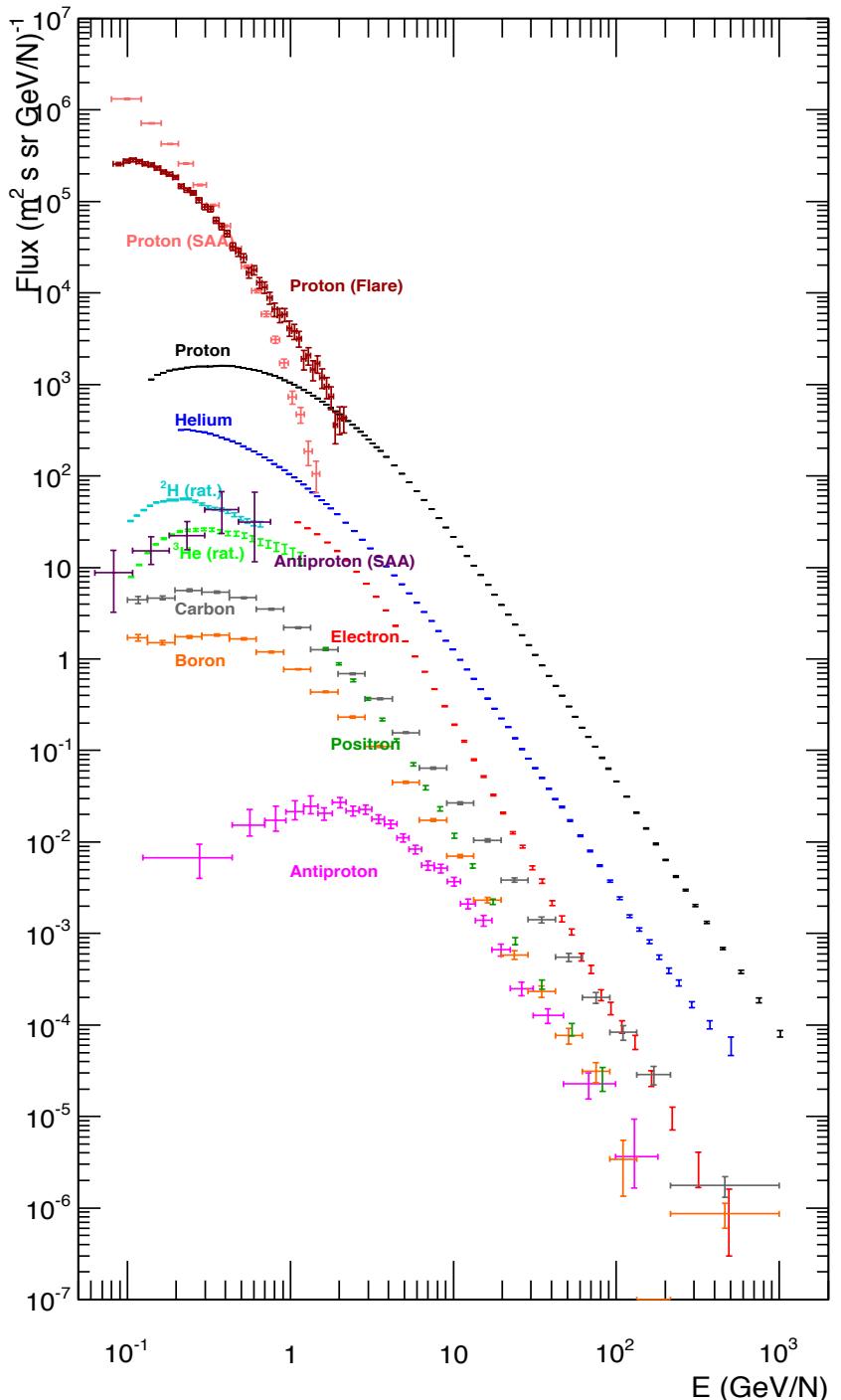
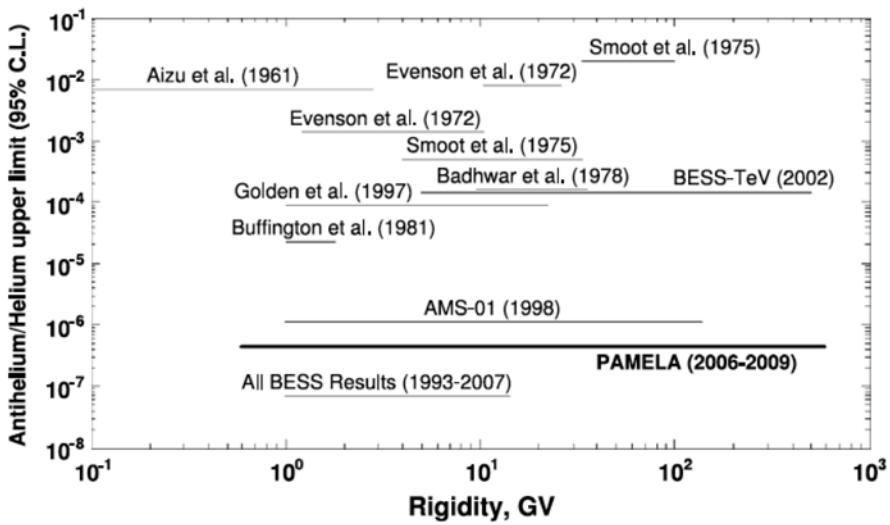
- Antiparticles
- Galactic CR
- Solar Physics
- Particles in Earth's magnetosphere

4 DECADES IN ENERGY

13 DECADES IN FLUXES

O. Adriani et al, *Physics Reports* (2014)

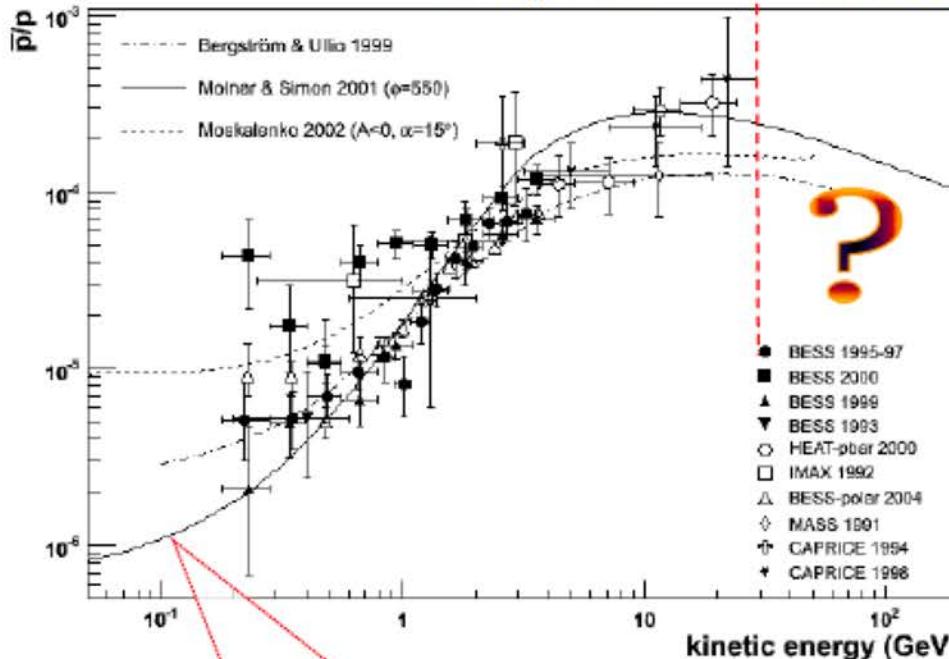
<http://dx.doi.org/10.1016/j.physrep.2014.06.003>



CR antimatter

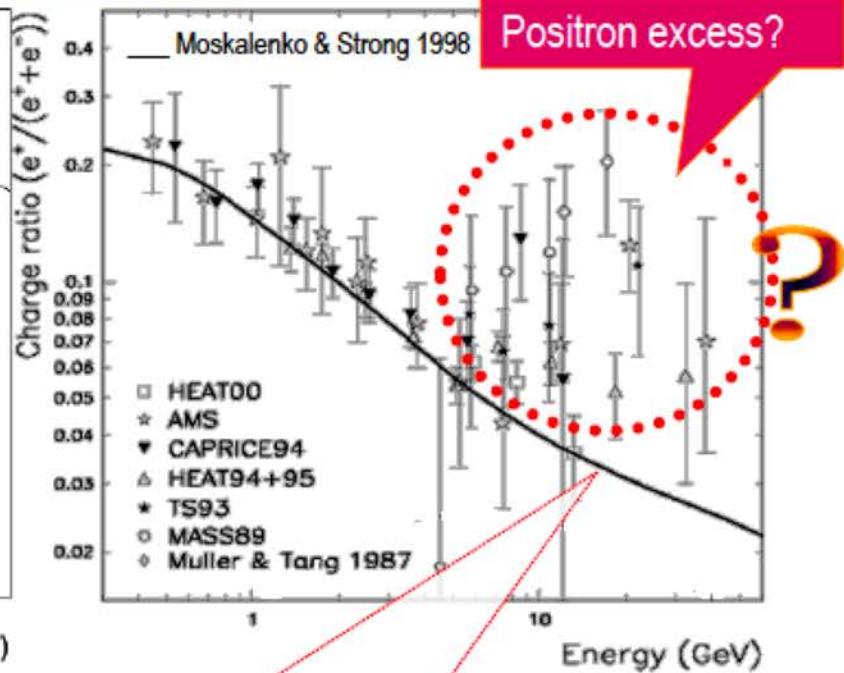


Antiprotons



Status in 2006

Positrons



Positron excess?

CR + ISM $\rightarrow \bar{p}$ + ...
kinematic threshold:
5.6 GeV for the reaction
 $p\bar{p} \rightarrow \bar{p}ppp$

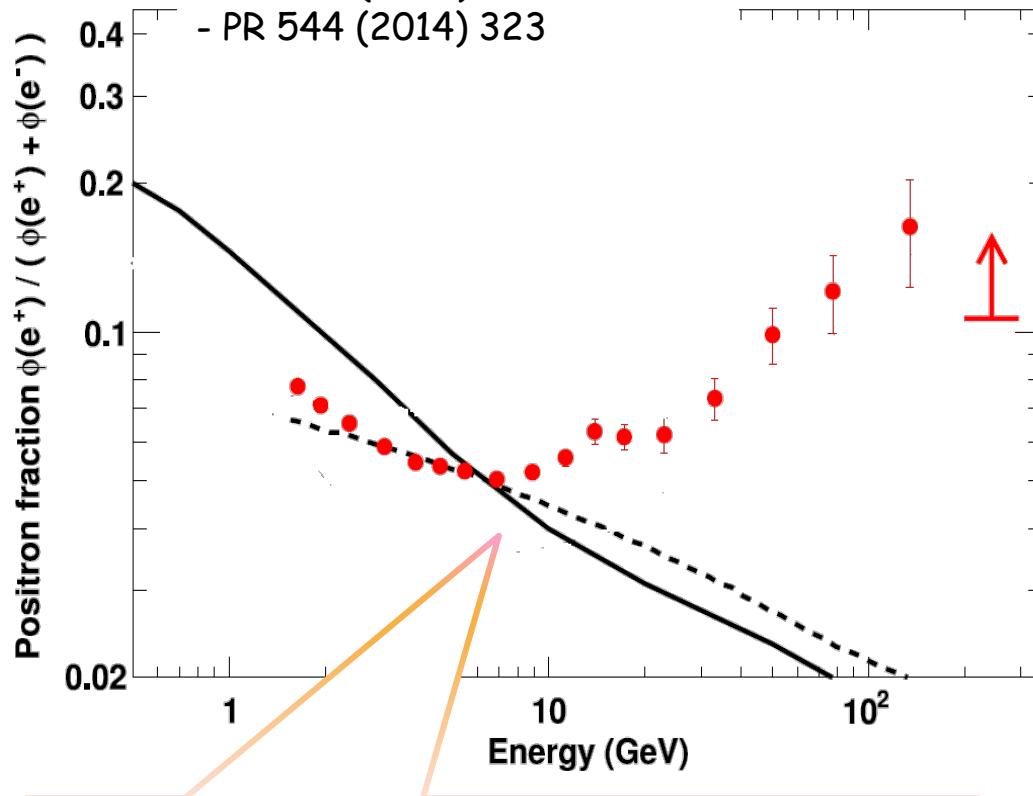
CR + ISM $\rightarrow \pi^\pm + x \rightarrow \mu^\pm + x \rightarrow e^\pm + x$
CR + ISM $\rightarrow \pi^0 + x \rightarrow \gamma\gamma \rightarrow e^\pm$

Positrons

First measurement
extending up to 200 GV

- Clear evidence for a deviation from pure secondary production

O. Adriani et al.
- Nature 458 (2009) 607;
- Astropart. Phys. 34 (2010) 1
- PRL 111 (2013) 081102
- PR 544 (2014) 323



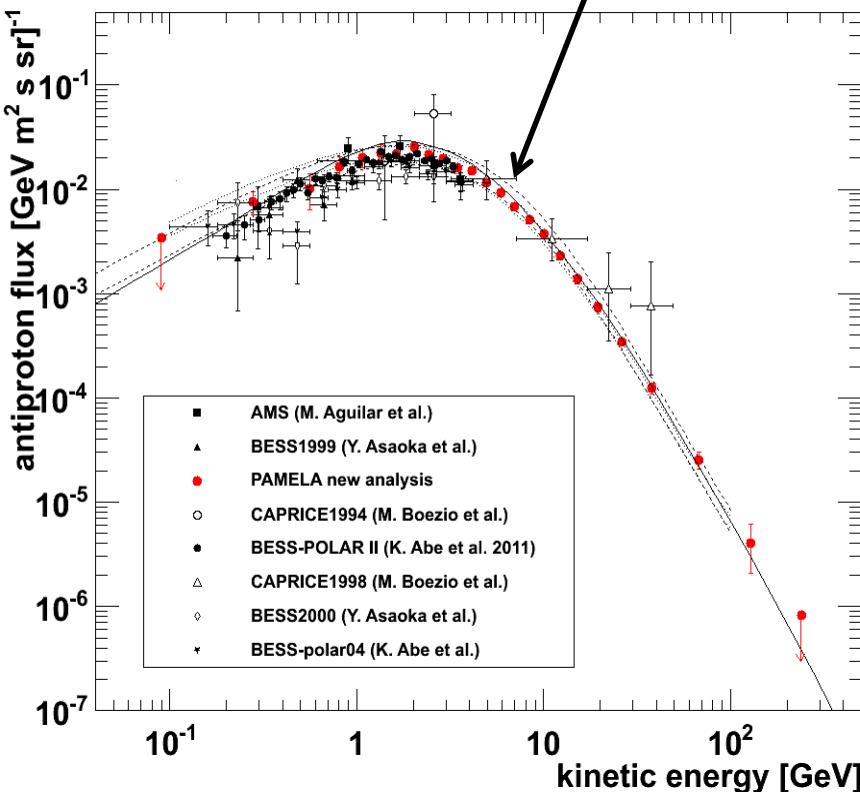
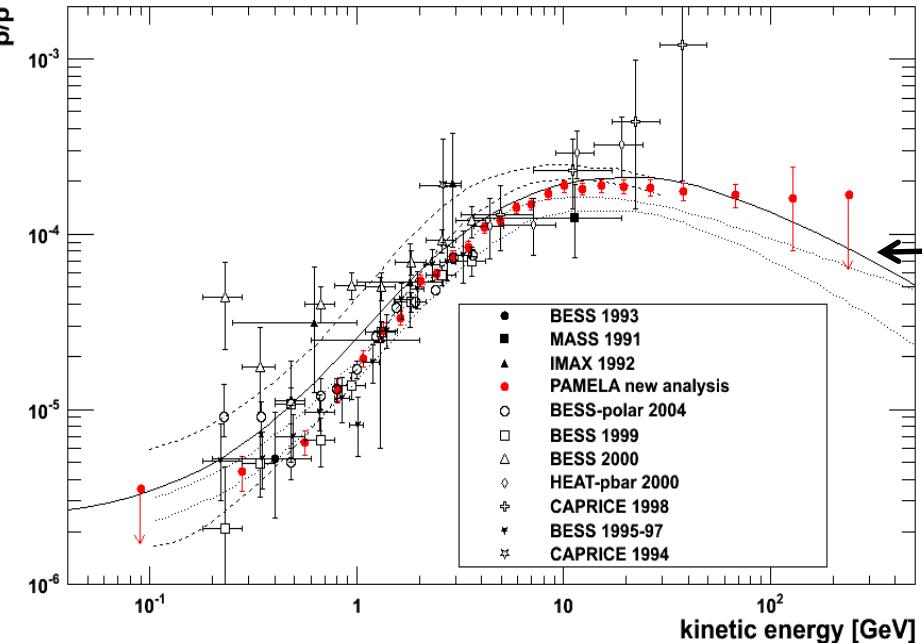
- Moskalenko & Strong 1998 (GALPROP code)
- - - Delahaye et al. 2010
- **Plain diffusion model**
- Solar modulation: spherical model ($\phi=600\text{MV}$)

PAMELA Antiparticle Results: Antiprotons

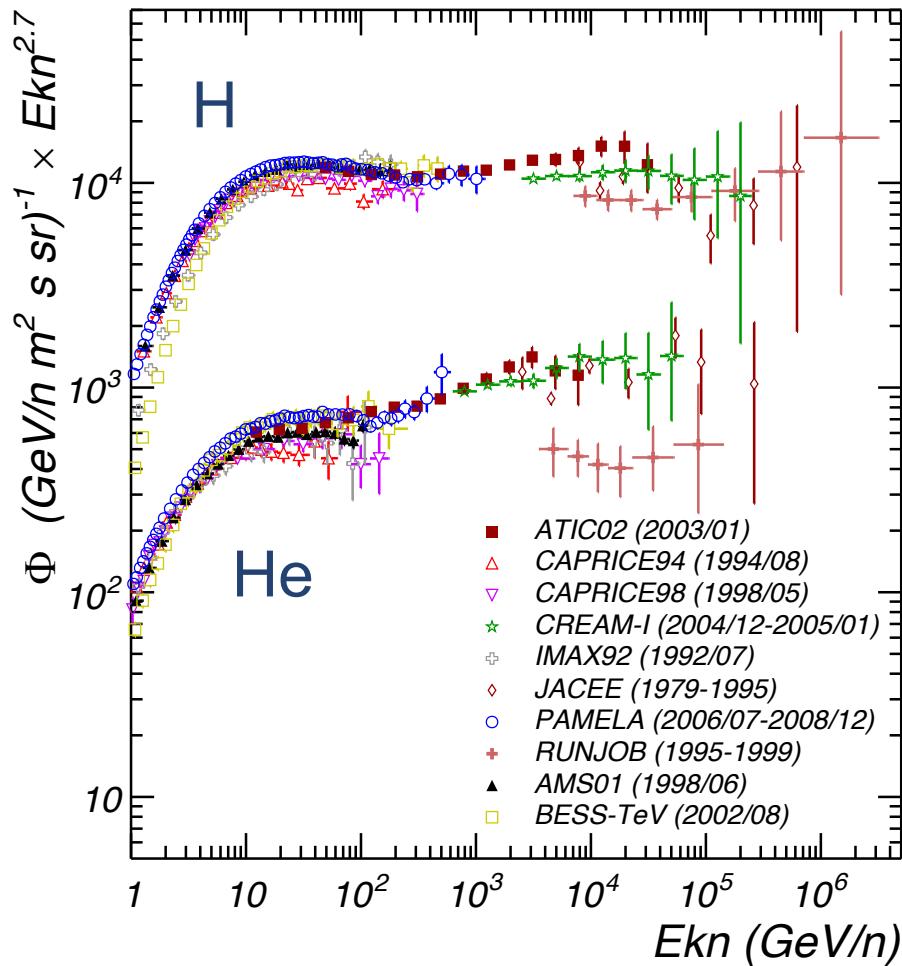


O. Adriani et al,
PRL 102 (2009) 051101;
PRL 105 (2010) 121101;
Phys. Rep. 544 (2014) 323.

Secondary production
calculations

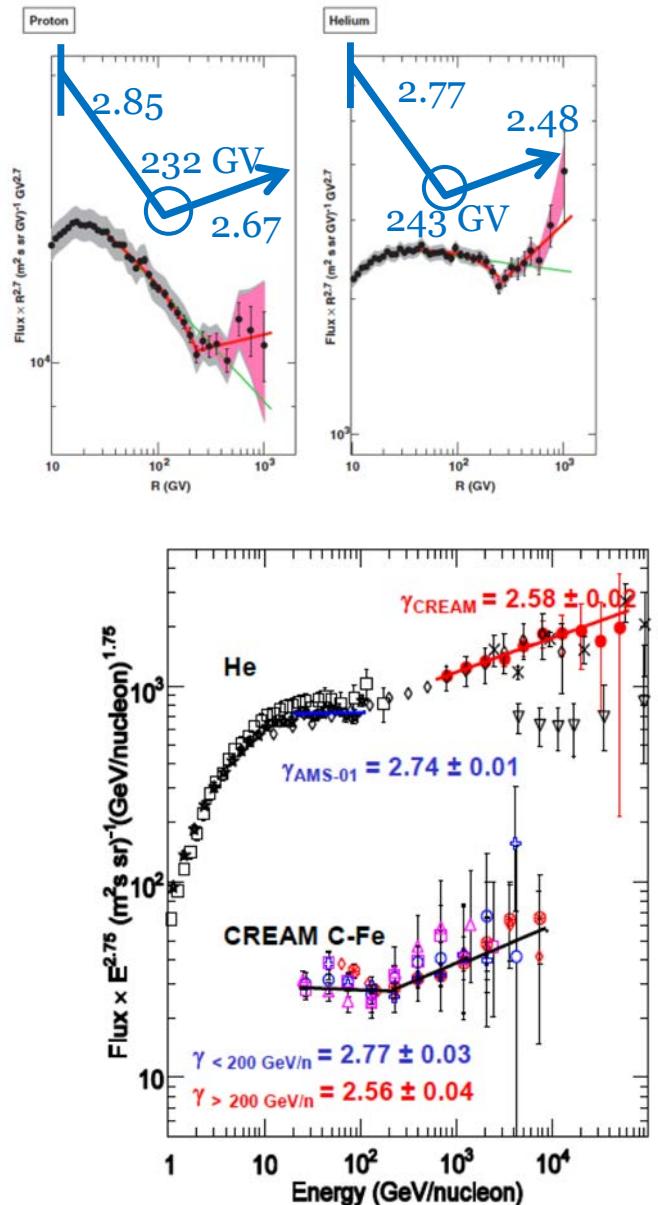


p/He spectra

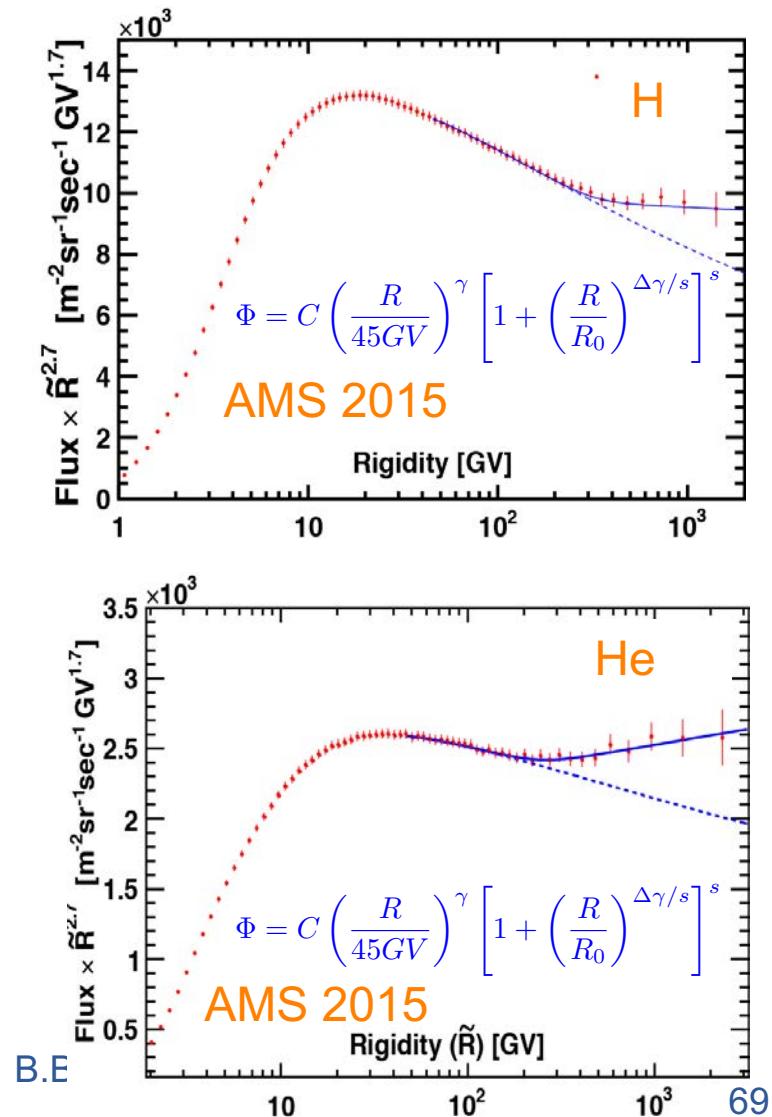
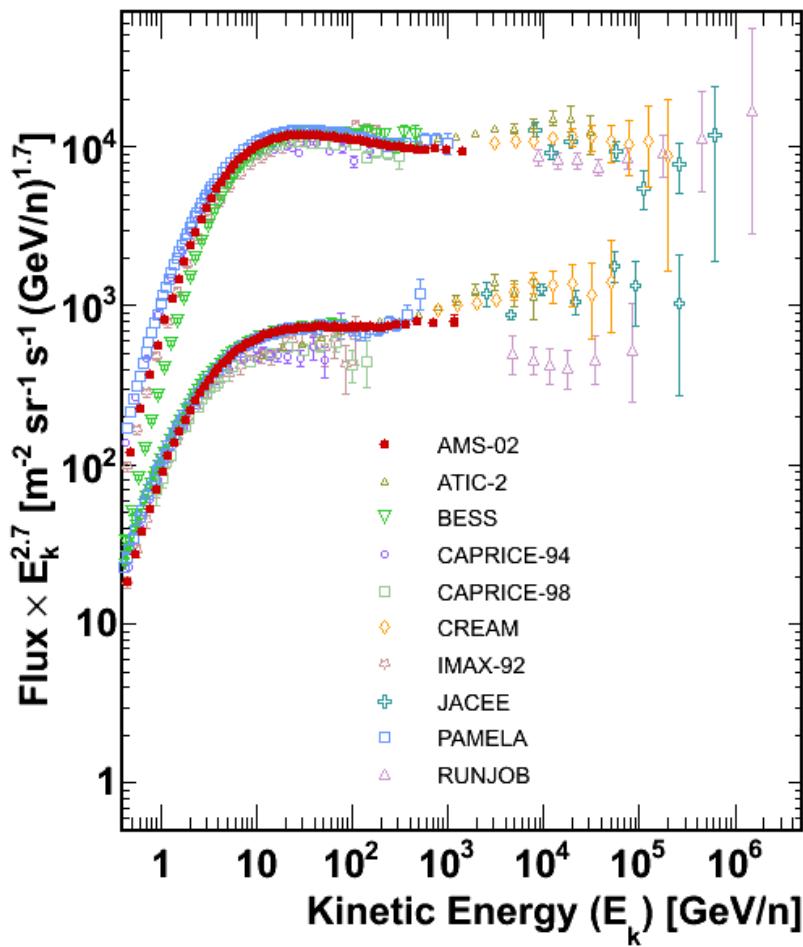


Hint of a break (change of spectral index) in the spectra?

Adriani, Science 32,69 (2011)

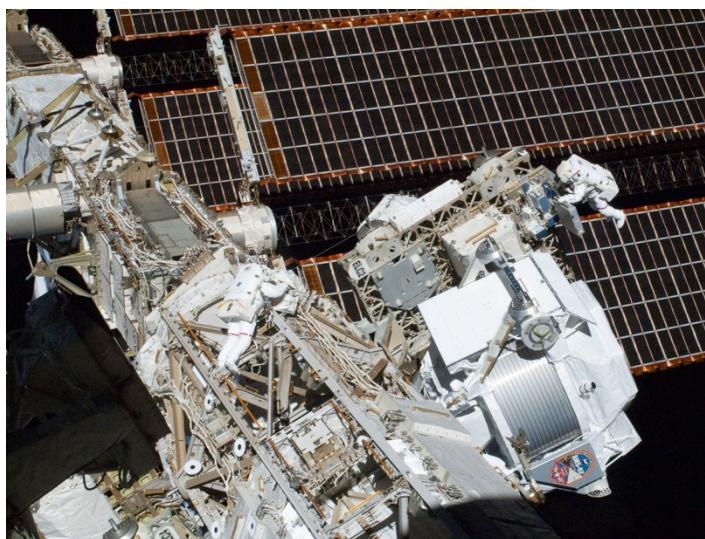


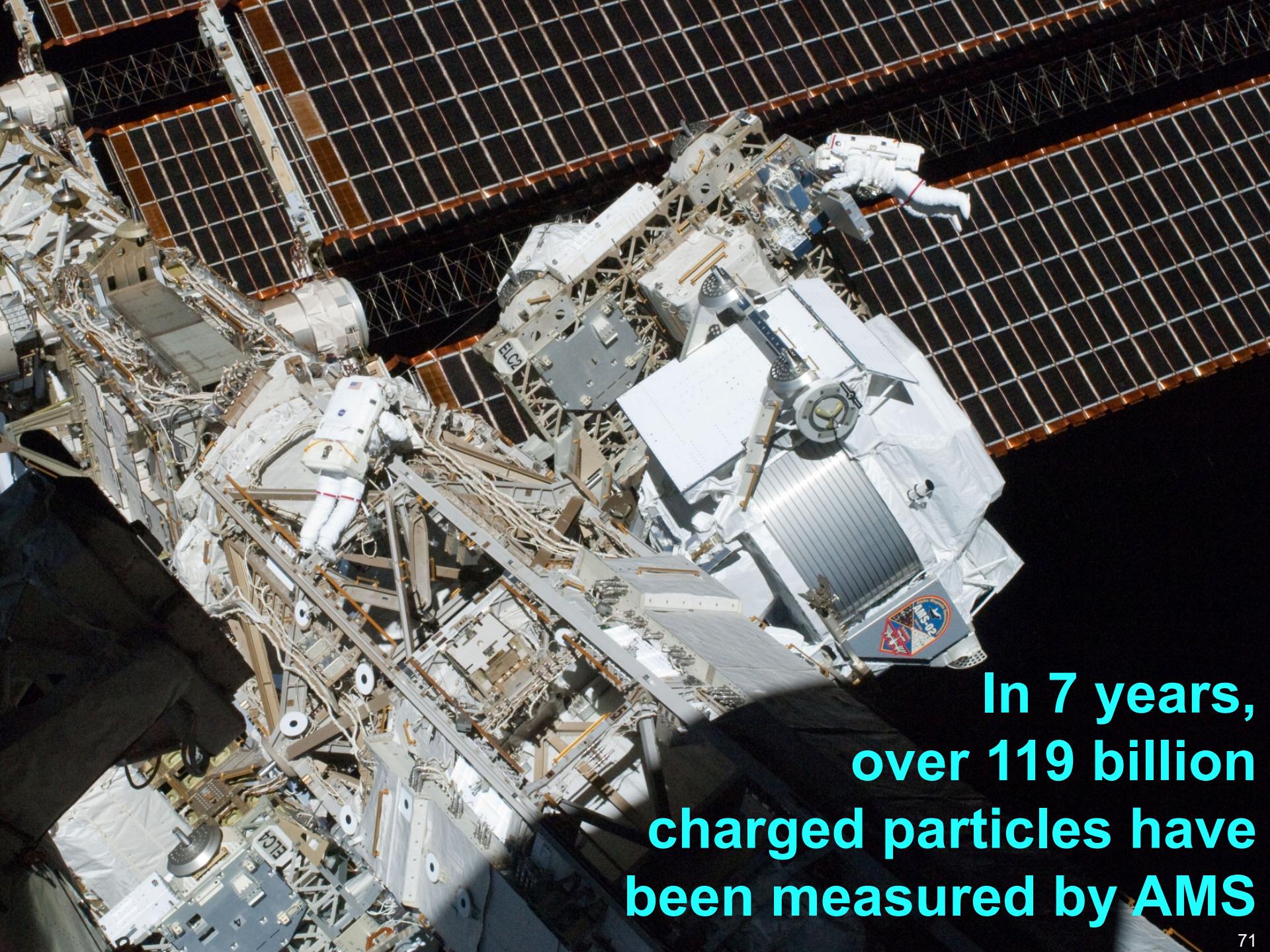
AMS-02 : the smooth change of spectral index



Alpha Magnetic Spectrometer on the ISS: AMS-02

- Launched on May 16, 2011
- Installed on ISS May 19, 2011
- AMS-02 foreseen to operate for the entire ISS lifetime (2024)

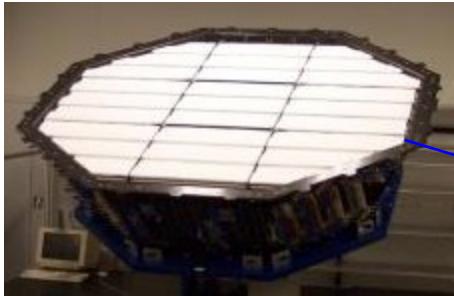




In 7 years,
over 119 billion
charged particles have
been measured by AMS

AMS-02: the detector

Transition Radiation Detector
Identify electrons

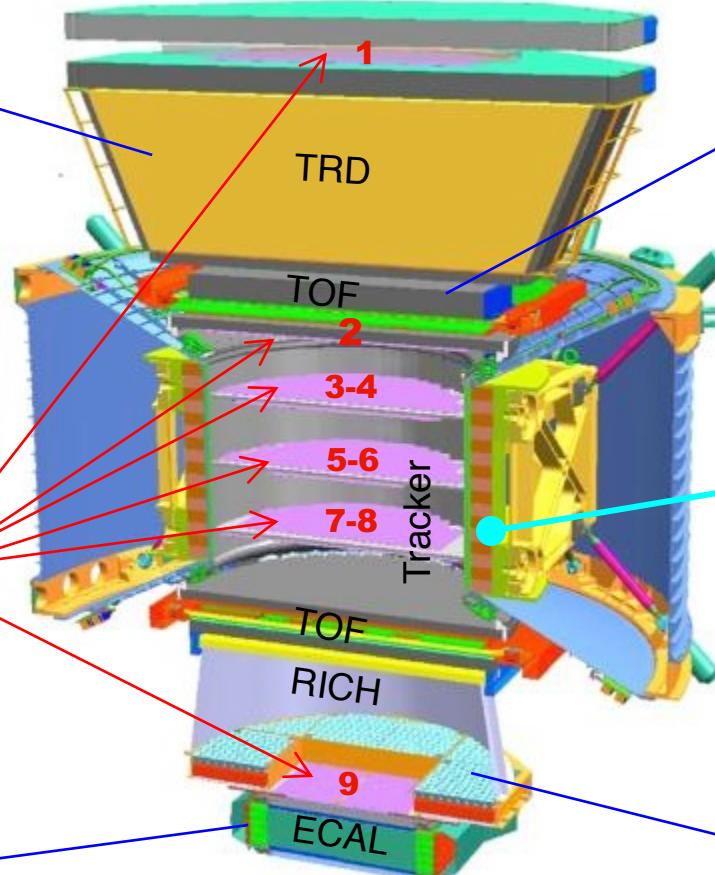


Particles are defined by their
charge (**Z**) and energy (**E**) or momentum (**P**)

Silicon Tracker
Z, P



Electromagnetic Calorimeter
E of electrons



*The Charge and Energy (momentum)
are measured independently by many
detectors*

Time of Flight
Z, E



Magnet
 $\pm Z$

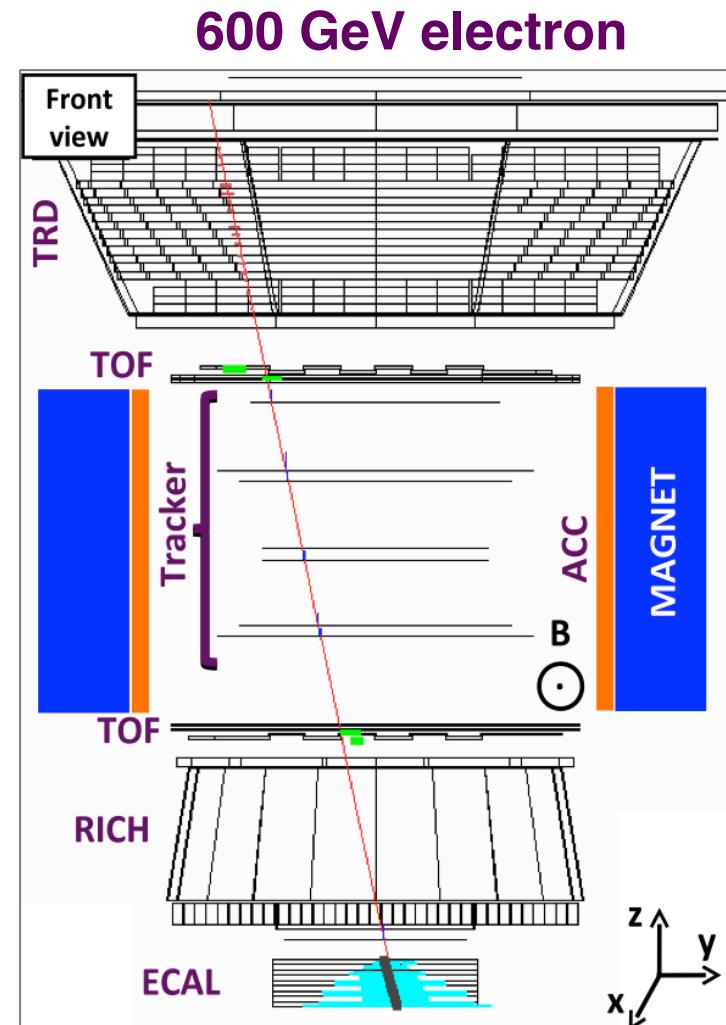


Ring Imaging Cherenkov
Z, E

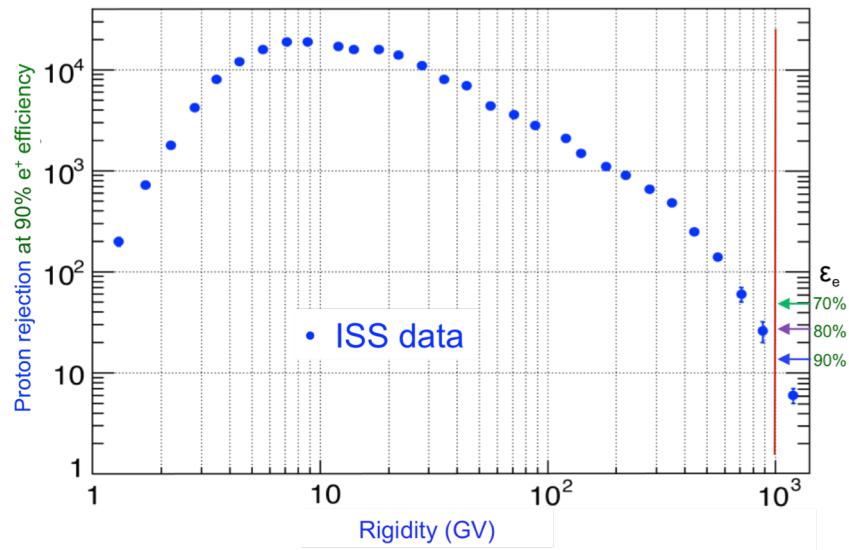
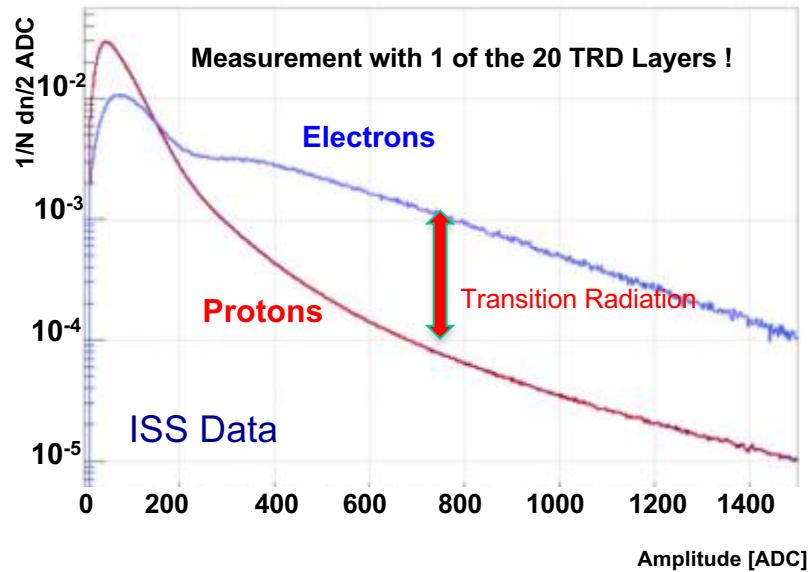
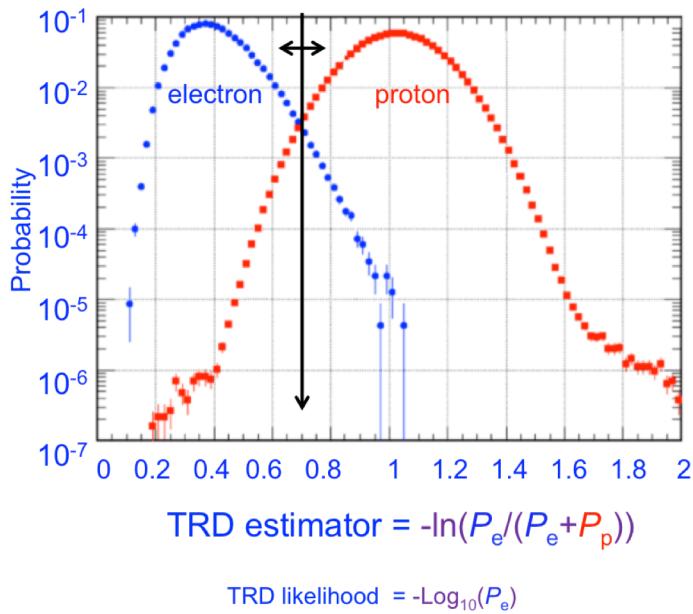
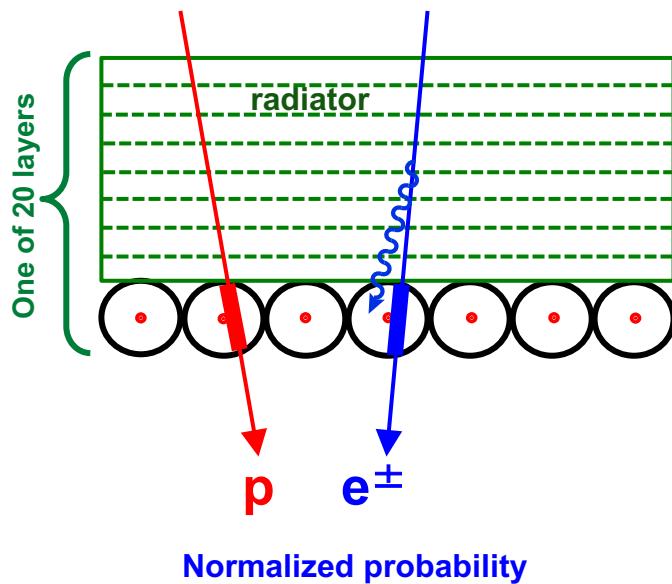


Full coverage of anti-matter & CR physics

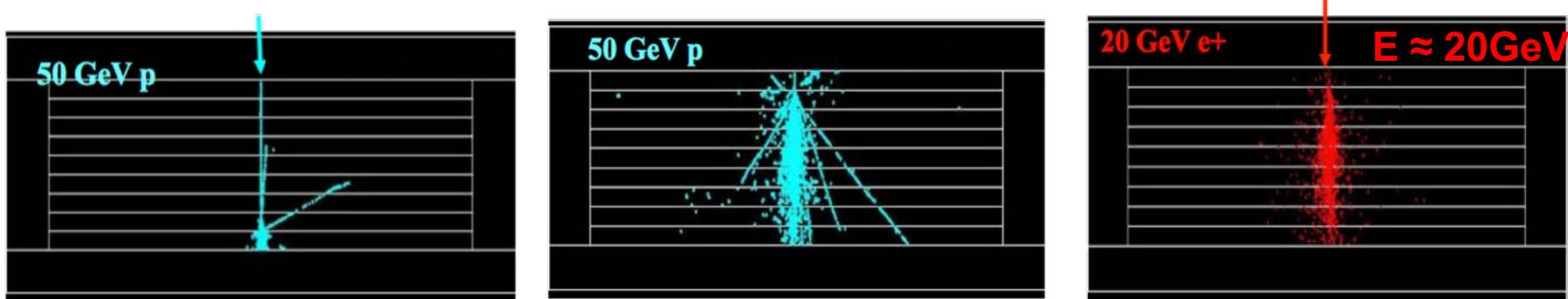
	e^-	P	He,Li, Be,..Fe	γ	e^+	\bar{P}	\bar{He},\bar{C}
TRD	 VVV	T	T		 VVV	T	T
TOF	T T	T T	T T	T	T T	T T	T T
Tracker +Magnet	U	U	U	八	U	U	U
RICH	O O O	O O O	O O O → O O	O O	O O	O O	O O
ECAL	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑
Physics example	Cosmic Ray Physics			Dark matter		Anti matter	



e/p separation : TRD



e/p separation : ECAL



Two complementary techniques can exploit electron/proton differences in ECAL

- 1) Matching measured momentum in tracker with the deposited energy in ECAL [E/R used to select control samples]
- 2) 3D imaging of the energy shower allows to discriminate electron or proton initiated showers [ECAL classifier, used to preselect events for further analysis]

e/p separation : ECAL

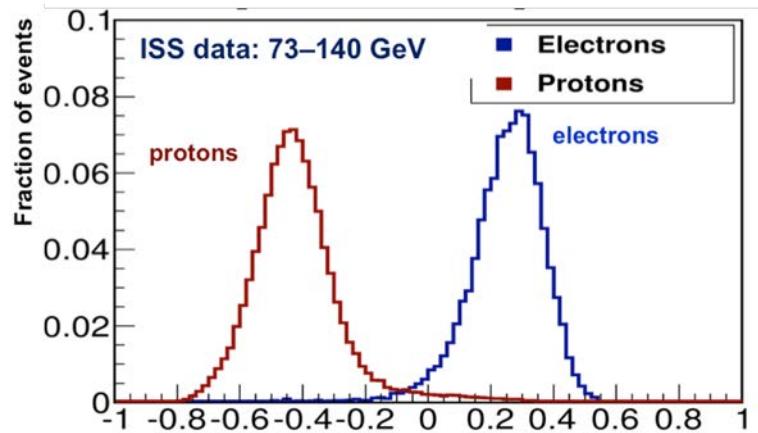
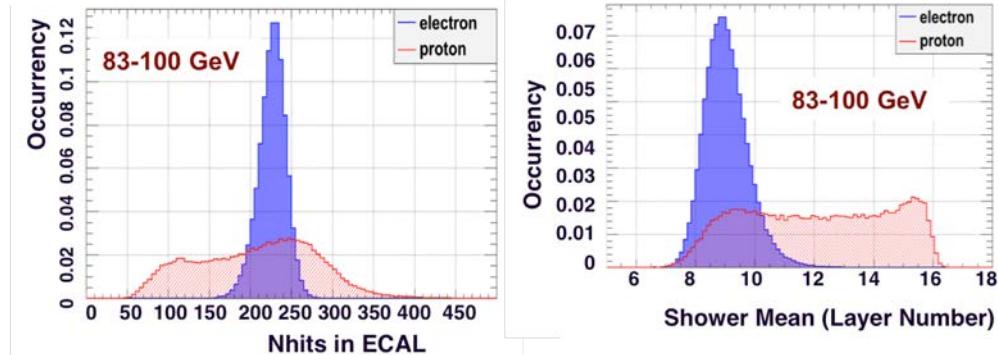
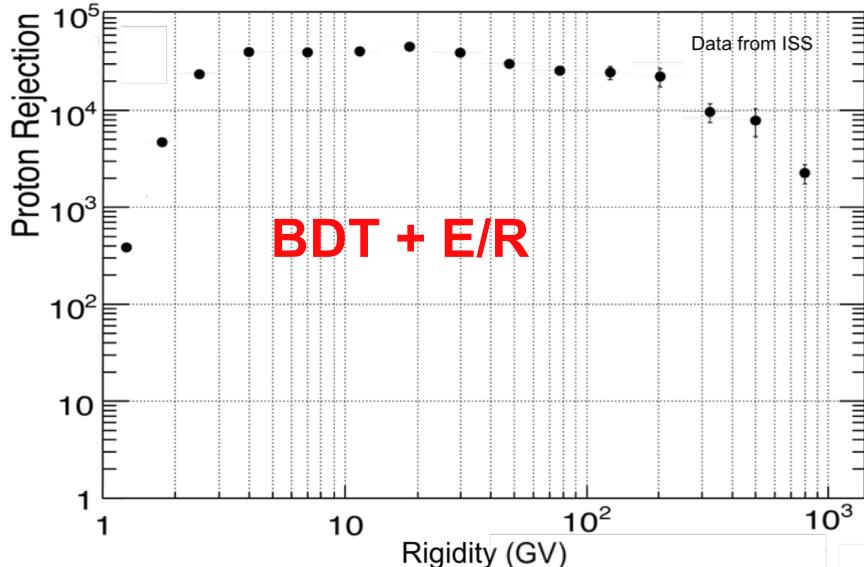
1) Define a set of variables related to the shower:

NHITS: number of hits in the ECAL

Shower Mean: weighted average of the longitudinal energy deposit

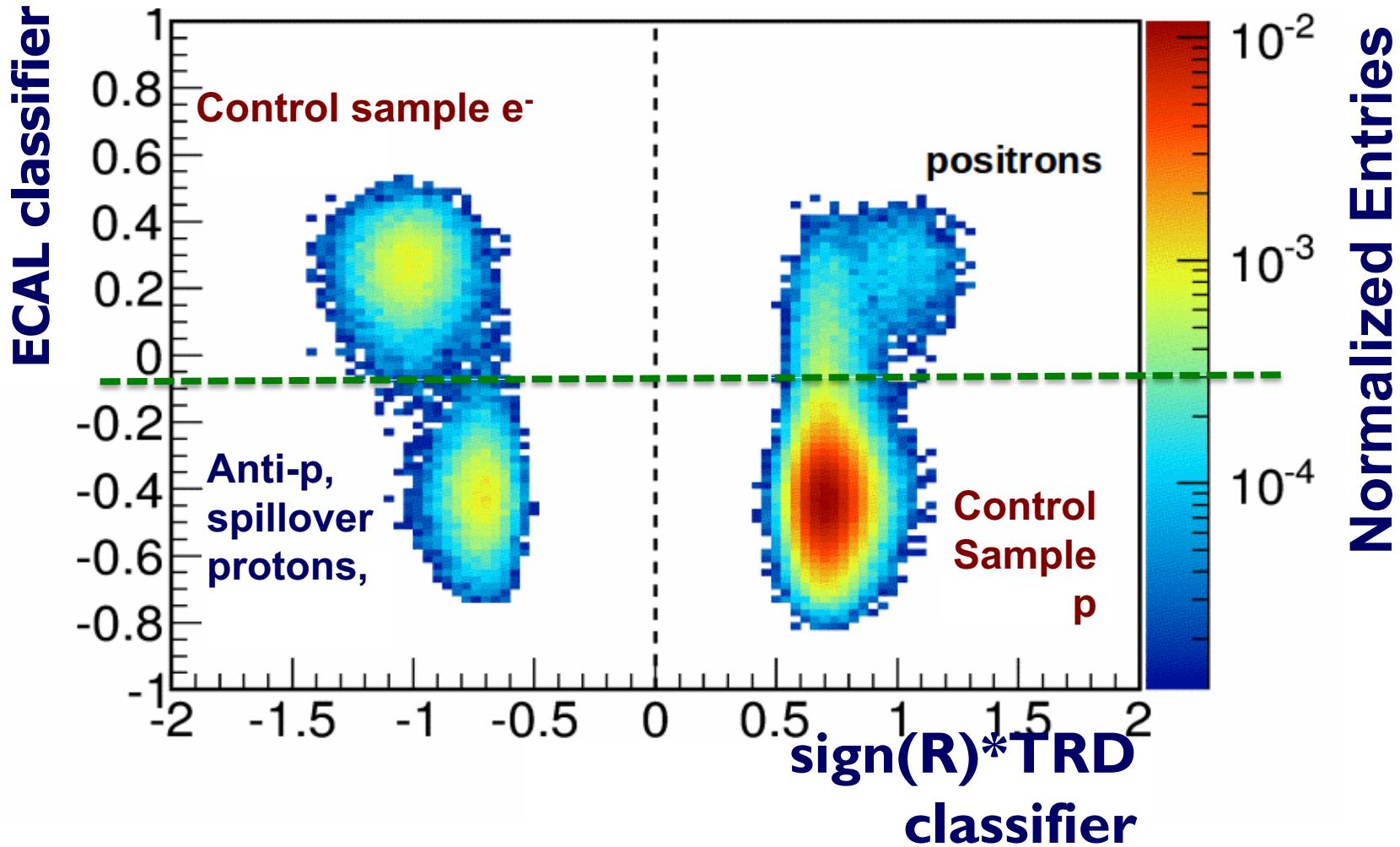
2) combine them statistically by means of a multivariate analysis based on Boosted Decision Tree (BDT) technique

3) Select e-/protons with TRD, Tracker, Energy/Momentum ratio to train the classifier



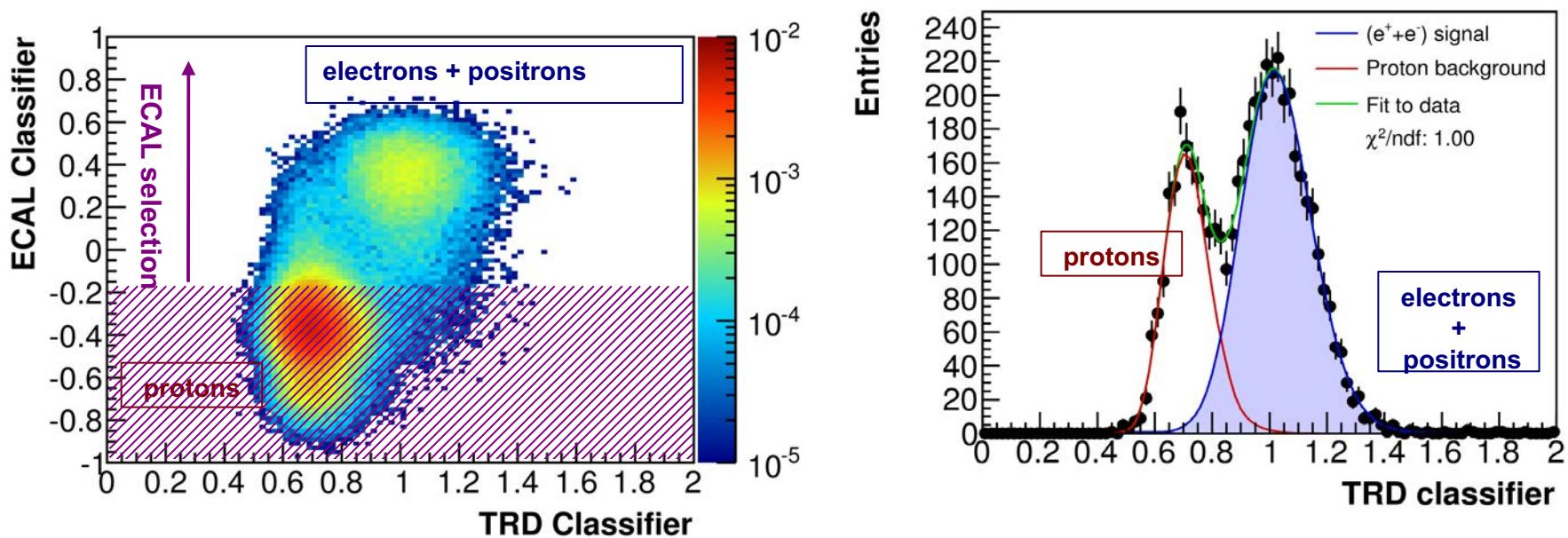
e/p separation: TRD/ECAL/TRK

ISS Data: 73-140 GeV



Measurement strategy

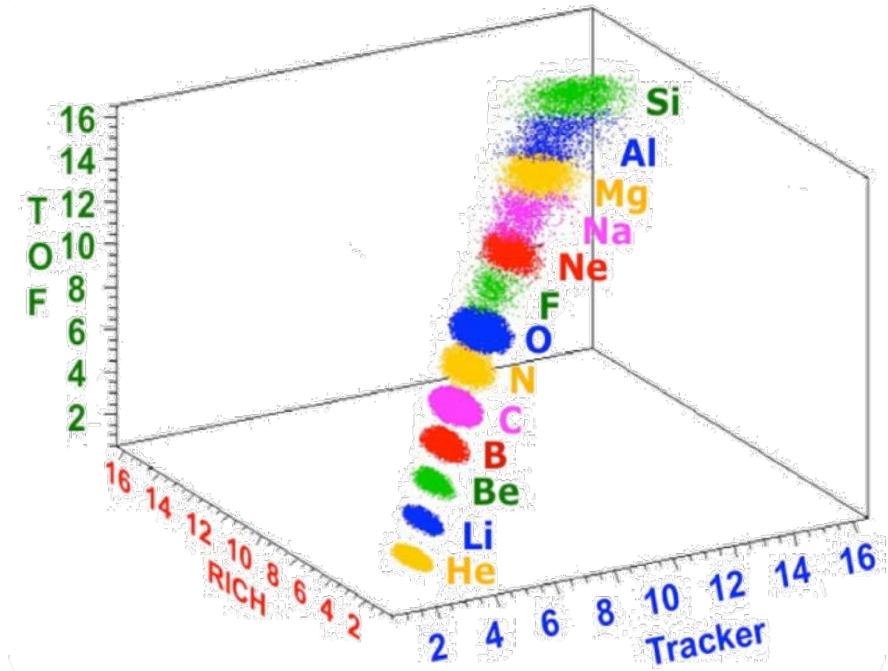
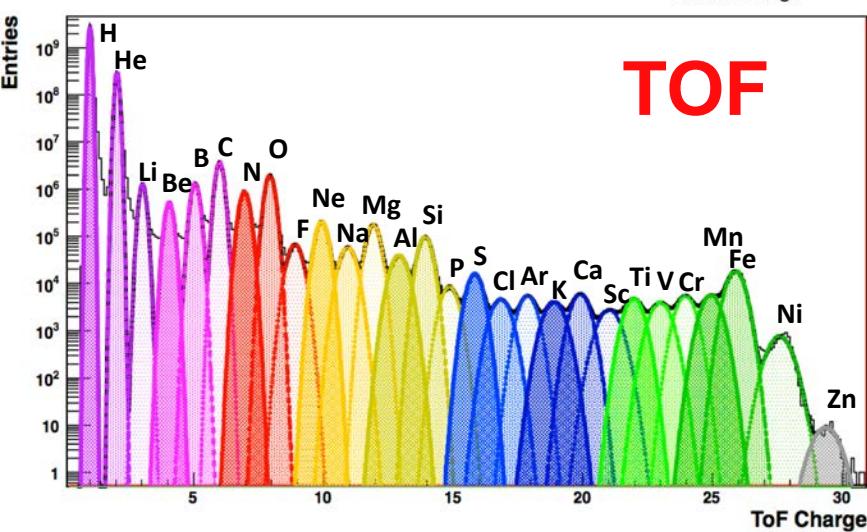
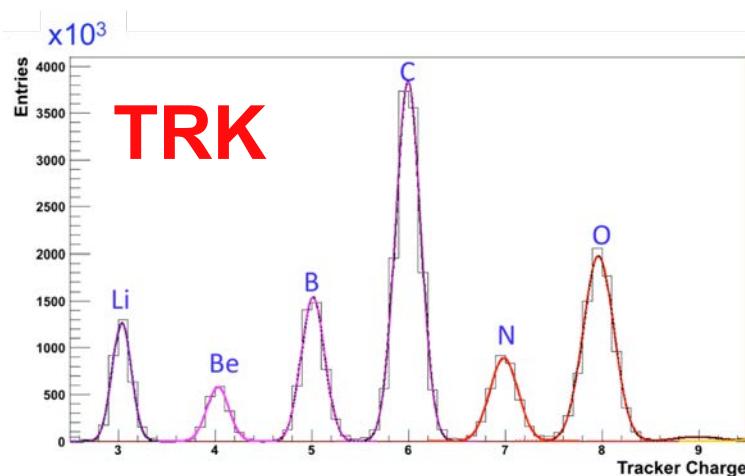
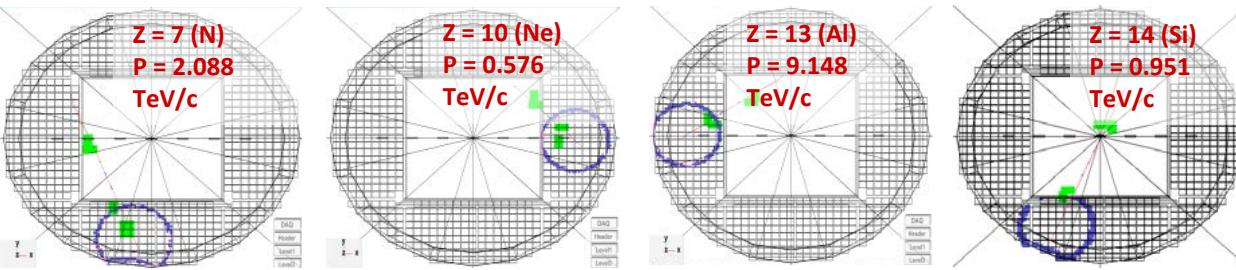
Reference spectra for the signal and the background are fitted to data as a function of the TRD classifier for different cuts on the ECAL BDT estimator



Measurement is performed for the cut on the ECAL classifier that minimizes the overall statistical + systematic uncertainty ($\rightarrow \varepsilon_{\text{BDT}}$)

RICH

Z measurement



Z measurement

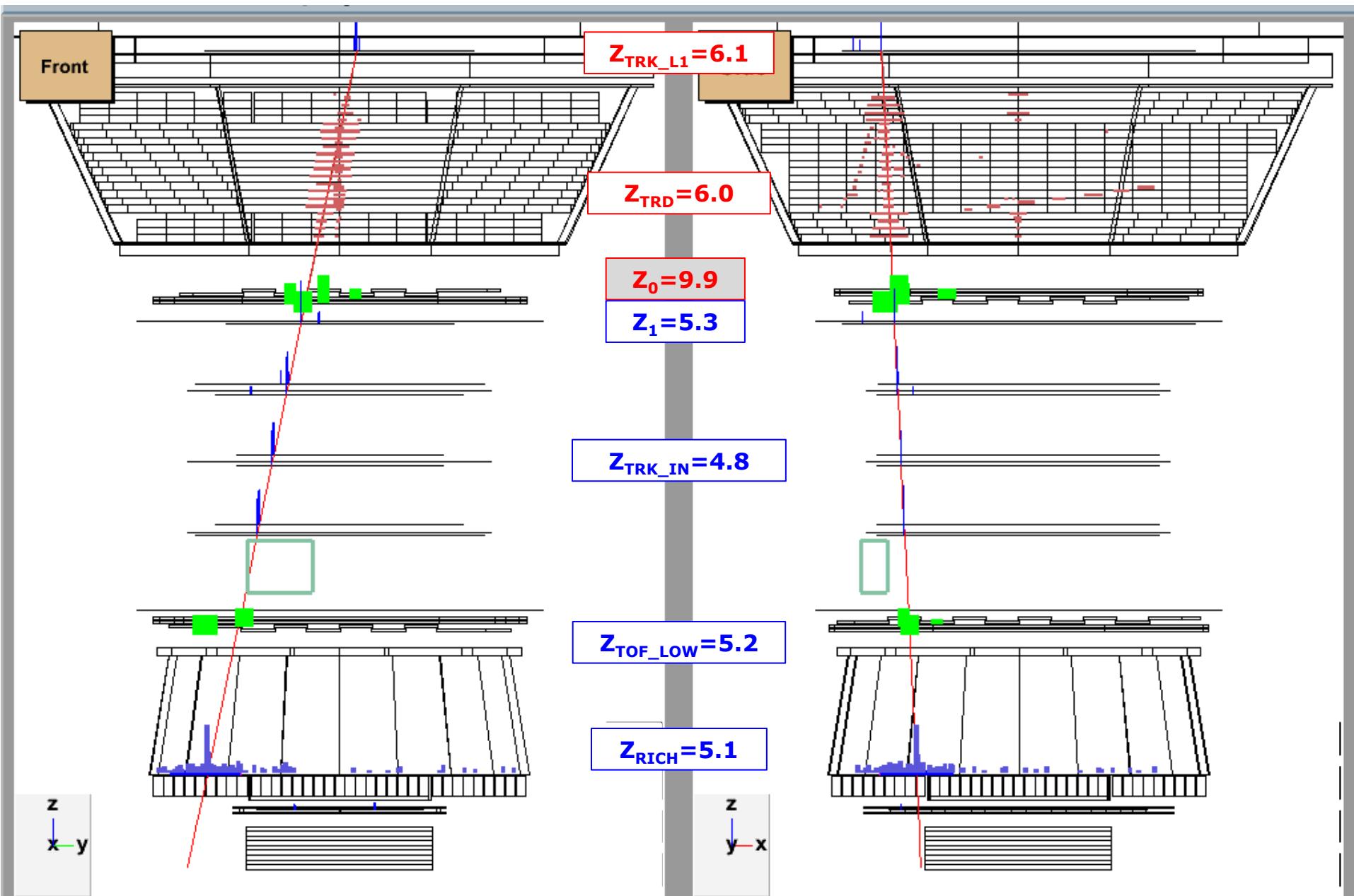
Multiple Independent Measurements of $|Z|$

Carbon ($Z=6$)	ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30

The diagram illustrates a 3D model of a particle detector, likely the ATLAS experiment. It shows the following components from top to bottom: a green ECAL (Electromagnetic Calorimeter) layer, a grey RICH (Ring Imaging Cherenkov) layer, a blue TOF (Time-Of-Flight) layer, a yellow TRD (Transition Radiation Detector) layer, a grey Tracker layer with internal planes labeled 3-4, 5-6, and 7-8, and a red TOF layer. Dashed lines connect specific points of interest to the corresponding measurement methods listed in the table. Point 1 is at the top of the TRD. Point 2 is at the interface between the TRD and the first TOF layer. Point 3 is at the interface between the first TOF layer and the Tracker. Points 4, 5, and 6 are located within the Tracker volume. Point 7 is at the interface between the Tracker and the RICH layer. Point 9 is at the bottom of the ECAL.

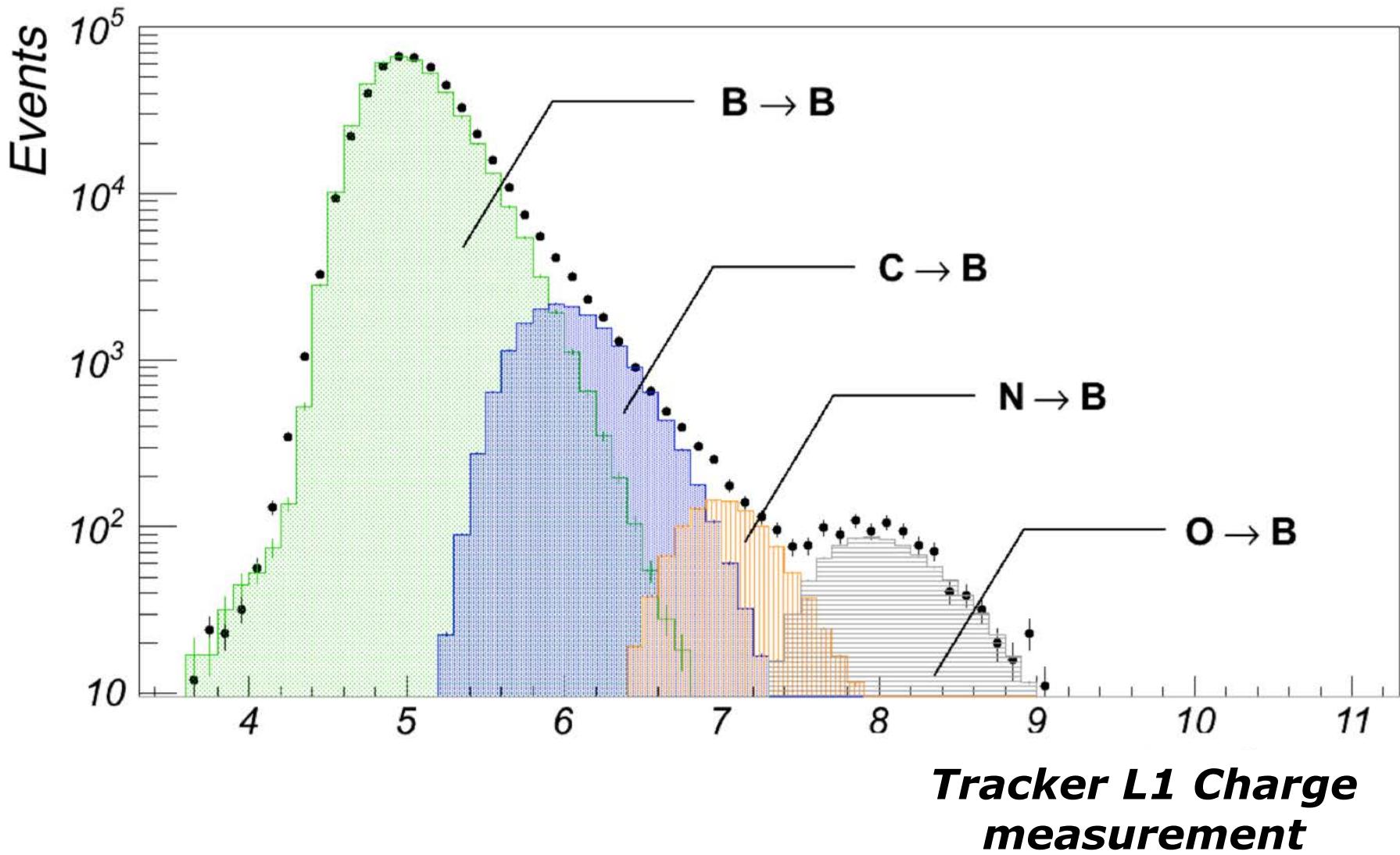
Carbon Fragmentation to Boron in Upper TOF

Rigidity 10.6 GV



Boron and Carbon: Sample composition

Particles Identified as Boron in the Inner AMS show signals compatible with higher charges on the 1st



Results

“Rare” channels:

- ✓ **Positron fraction $e^+/(e^++e^-)$ (0.5 GeV- 500 GeV)**
PRL, 110, 141102 (2013), PRL 113, 121101 (2014)
- ✓ **e^+ (0.5-500 GeV) , e^- flux (0.5 – 700 GeV)**
PRL 113, 121102 (2014)
- ✓ **e^++e^- flux (0.5-1 TeV)**
PRL 113, 221102 , (2015)
- ✓ **pbar/p (1-450 GV)**
PRL 113, 221102 , (2015)

30 months of data
 $\approx 10^6 e^- / 5 \cdot 10^5 e^+$

First 4 years of operation: 349 k pbar ($2.42 \cdot 10^9$ p)

Nuclear components:

- ✓ **Proton flux (1 GV – 1.8 TV)**
PRL, 114, 171103 , (2015)
- ✓ **Helium flux (2GV -3TV, He/P ratio)** [*PRL 115211 (2015)*]
- ✓ **B,Be,C,Li,N,O,...ongoing analyses**
- ✓ **Isotopes (d, He3/He4)**

30 months of data
 $\approx 30 \cdot 10^7 p / 5 \cdot 10^7 He$

up to now..
 $\approx O(10^6) B, O(10^7) C, O(10^5) Li ..$

CR fluxes time dependence (solar modulation effects):

- ✓ **Proton, He, anti-p,...** ongoing analyses
- ✓ **$e^+/e^-/e^+/(e^++e^-)$**

MAGNETIC SPECTROMETERS: the future?

**Basic Requirements to extend anti-particle measurements
of at least one decade in energy**

- acceptance $\times 1000 \approx 0(m^2sr)$
- MDR $\times 20$: either longer L or higher B

...and PID

e/p separation : Independent Rigidity/Energy measurements
Z : multiple charge measurements inside

New technologies, new ideas

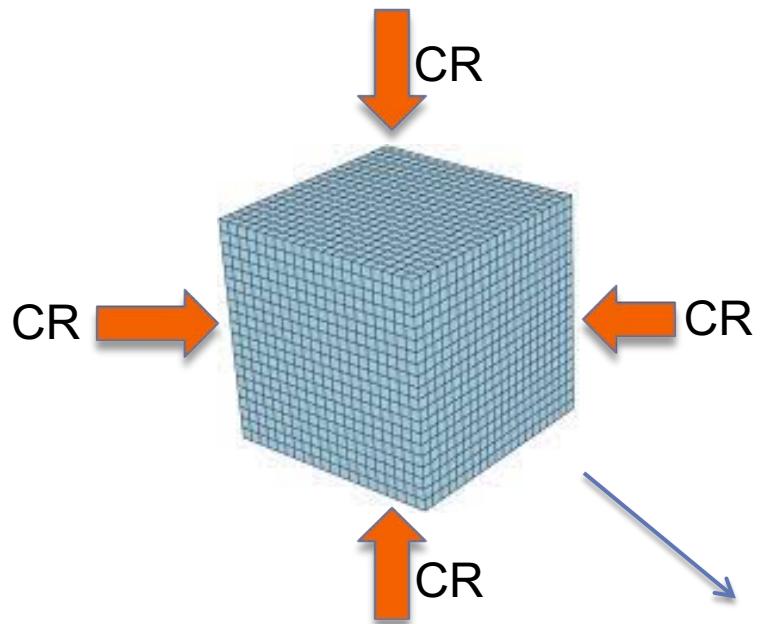
A new concept

Antimatter Large Acceptance Detector IN Orbit



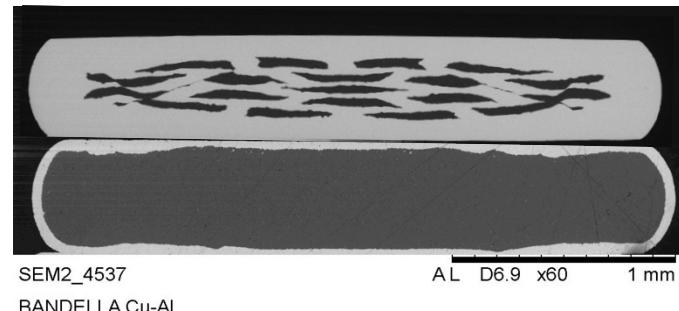
CaloCube (INFN gruppo V)

- Exploit the CR isotropy to maximize the effective geometrical factor, by using all the surface of the detector (aiming to reach $\Omega = 4\pi$)
- The calorimeter should be highly isotropic and homogeneous



SR2S (INFN and UE)

- R&D of high temperature superconducting magnets (MgB_2) for space applications ($T \approx 10 \div 20 \text{ } ^\circ K$)



Materials percentages:

titanium: 40%

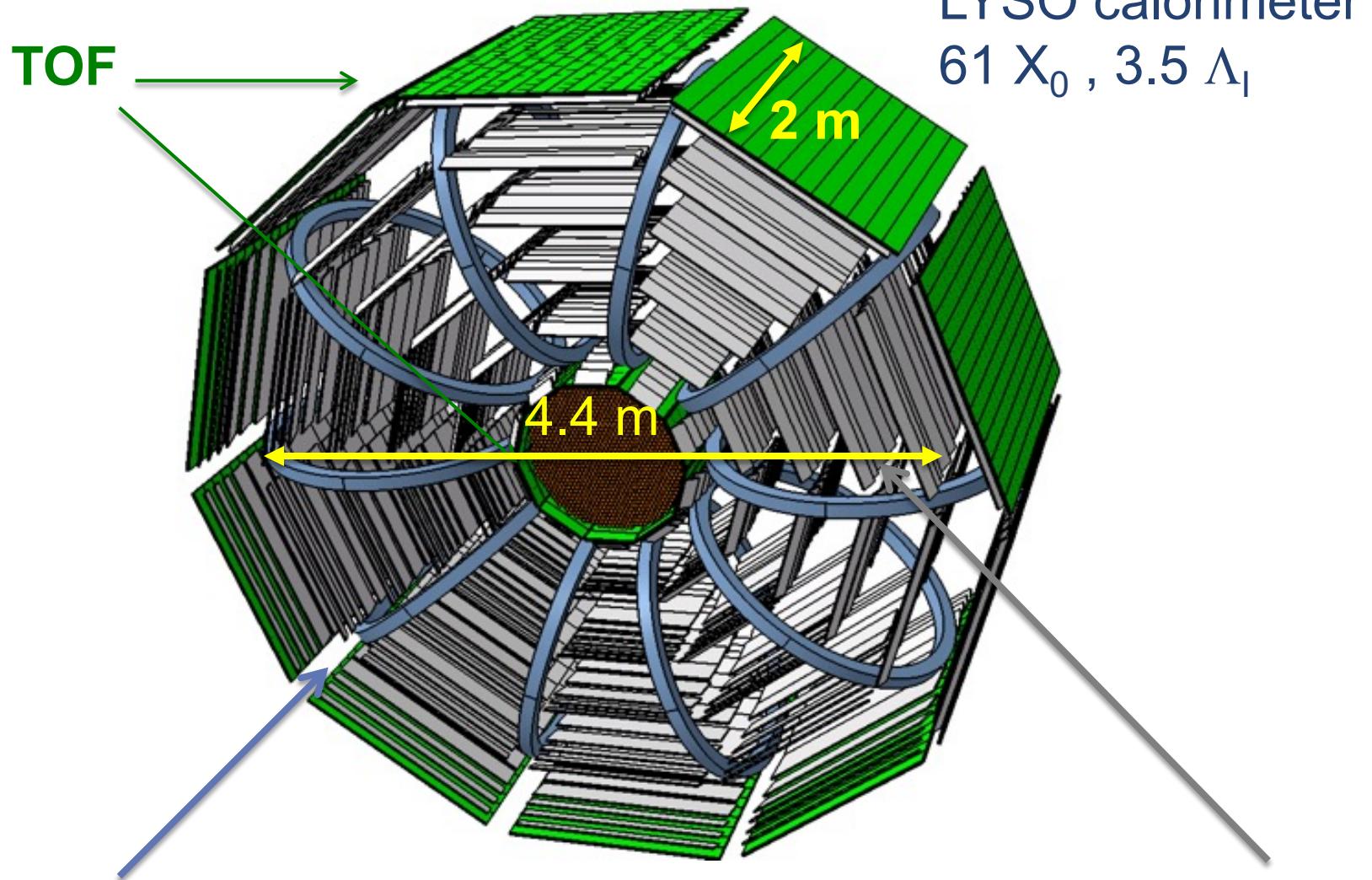
alluminium: 50%

MgB_2 : 10%

Quite small density: $\approx 3.4 \text{ g/cm}^3$

A novel idea for a
next generation
cosmic ray
experiment in
space

ALADINO CONCEPT

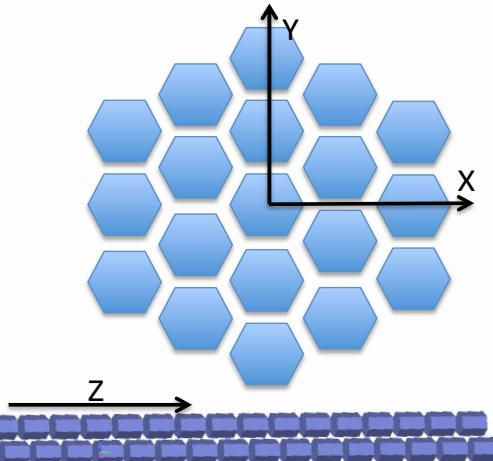
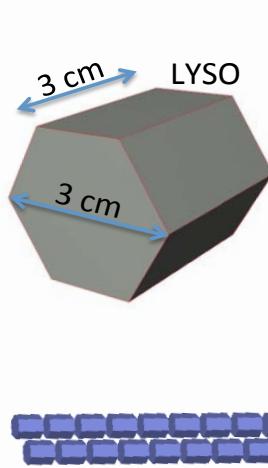
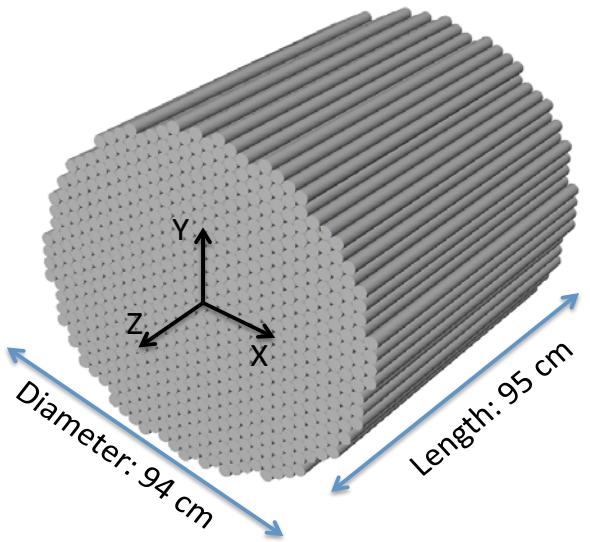


**Superconducting
magnet coils**

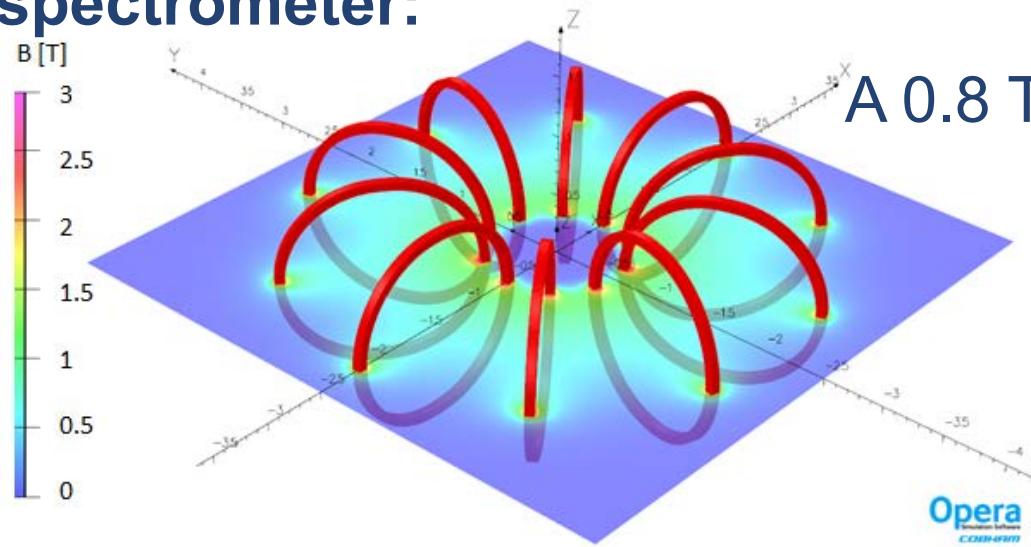
**6 layers of double side
microstrip detectors ($\approx 65 \text{ m}^2$)**

The core: a symmetric LYSO calorimeter $61 X_0$

88

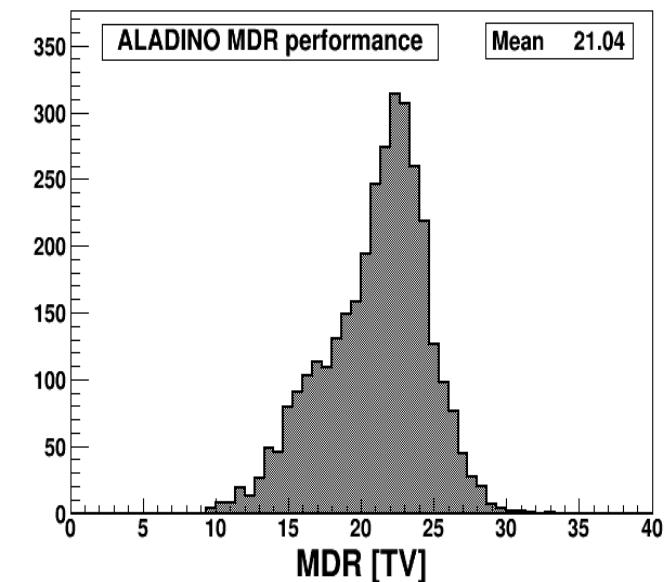
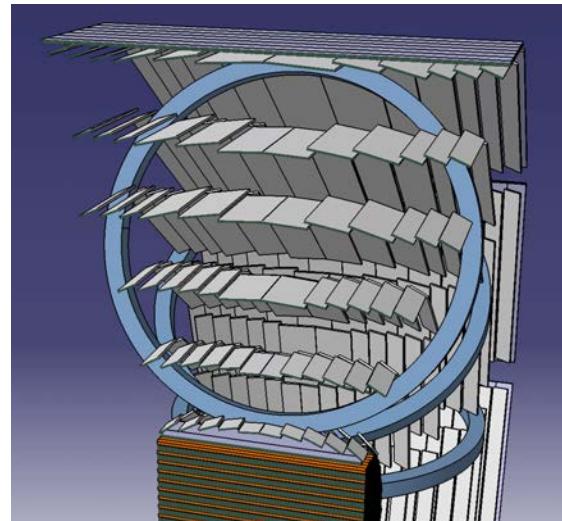
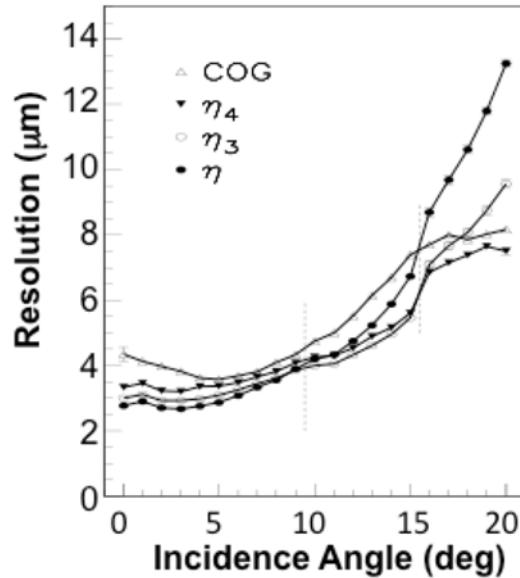


The spectrometer:



A 0.8 T average field

+ an optimized tracker design



Summarizing...

Space is challenging → but also rewarding !

Huge progress → precision measurements !!

Current programs in CR :

- 100 TeV scale for nuclei : but still not enough to reach the knee(s)
- electrons: gain one decade in e^\pm measurements
- positron/anti-protons → O(TeV) but after?

To further improve → will require new concept of detectors...
... and young people !!

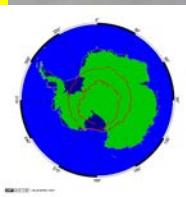
Exposure

Pamela AMS
Calet EUSO
KLEM

Satellites, Space Station

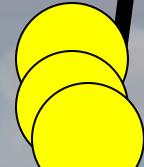
Ground based arrays

BESS-Polar
Tiger, Tracer
ATIC, BETS



Very Long Duration Flights (100 days)

CREAM



LDF

Tracer, ATIC
INCA, Intrepid

Balloons

Geometry Factor

PART 2

2 Recent results on O(TeV) Cosmic Rays and indirect search for dark matter from AMS-02 and other space experiments

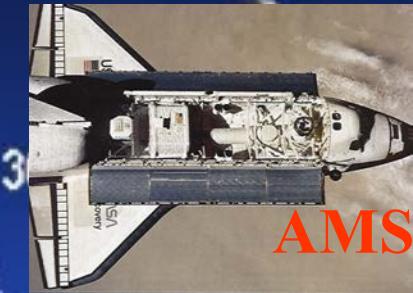
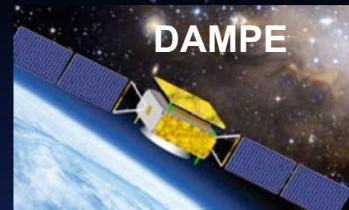
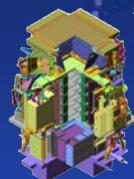
PARTICLE ASTROPHYSICS

AGILE

FERMI
 >400 Km

Direct

40 Km



Neutrinos
AMS
PAMELA
Phi Ray
Particles

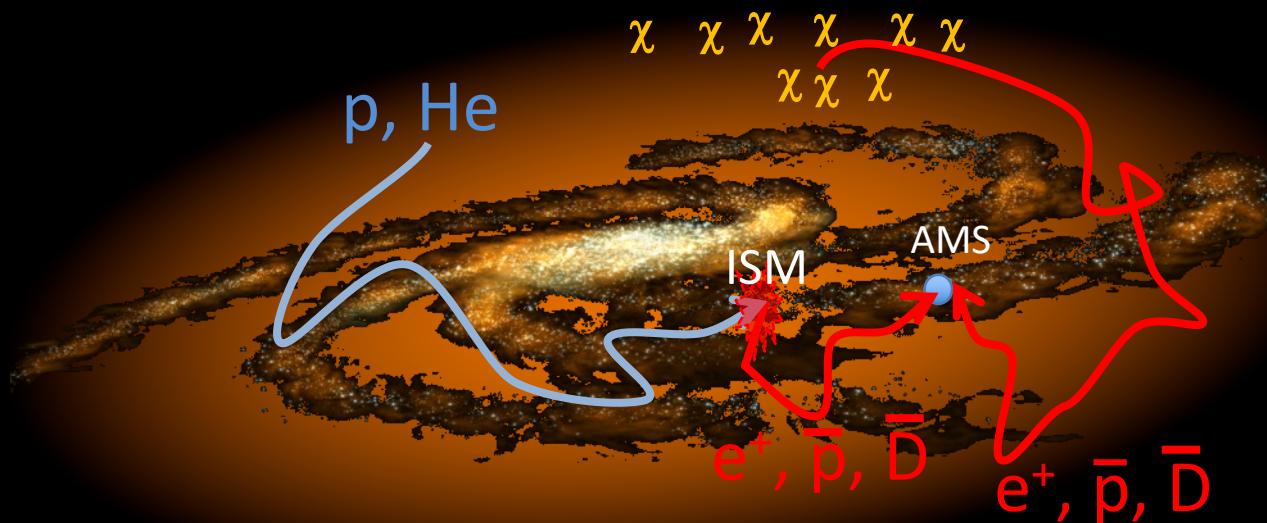
NEW MEASUREMENTS FROM AMS-02 AND OTHER SPACE EXPERIMENTS

Dark Matter

Collision of Cosmic Rays with Interstellar Matter (ISM) produces e^+ , \bar{p} , \bar{D}

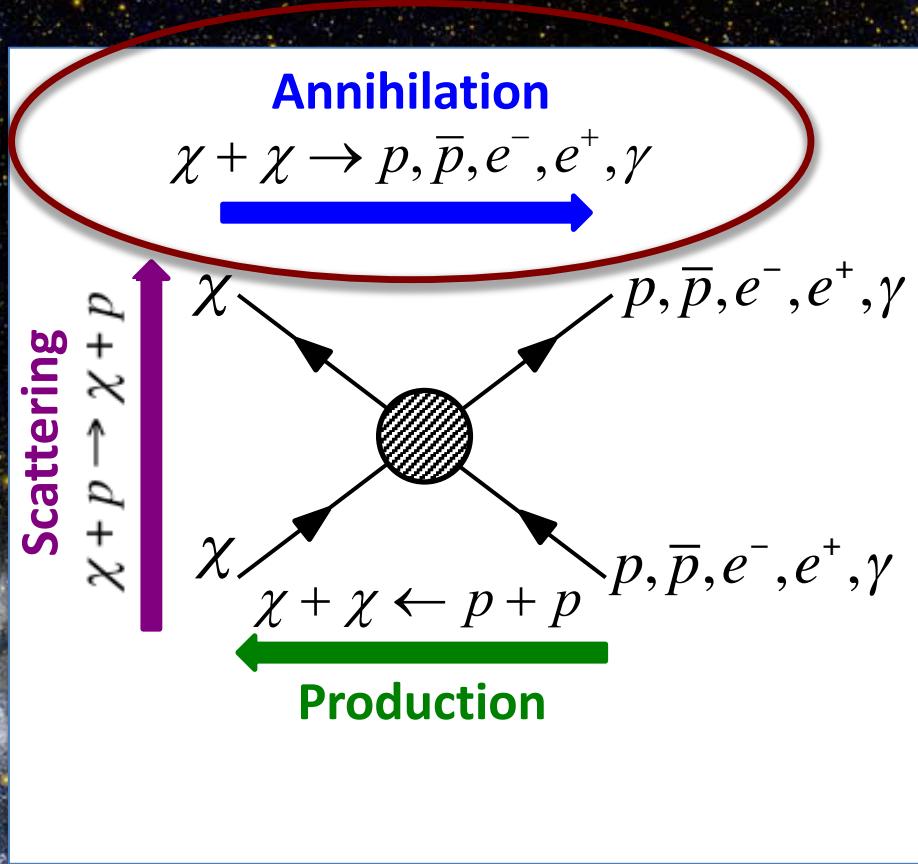
Dark Matter annihilation also produces light antimatter: e^+ , \bar{p} , \bar{D}

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

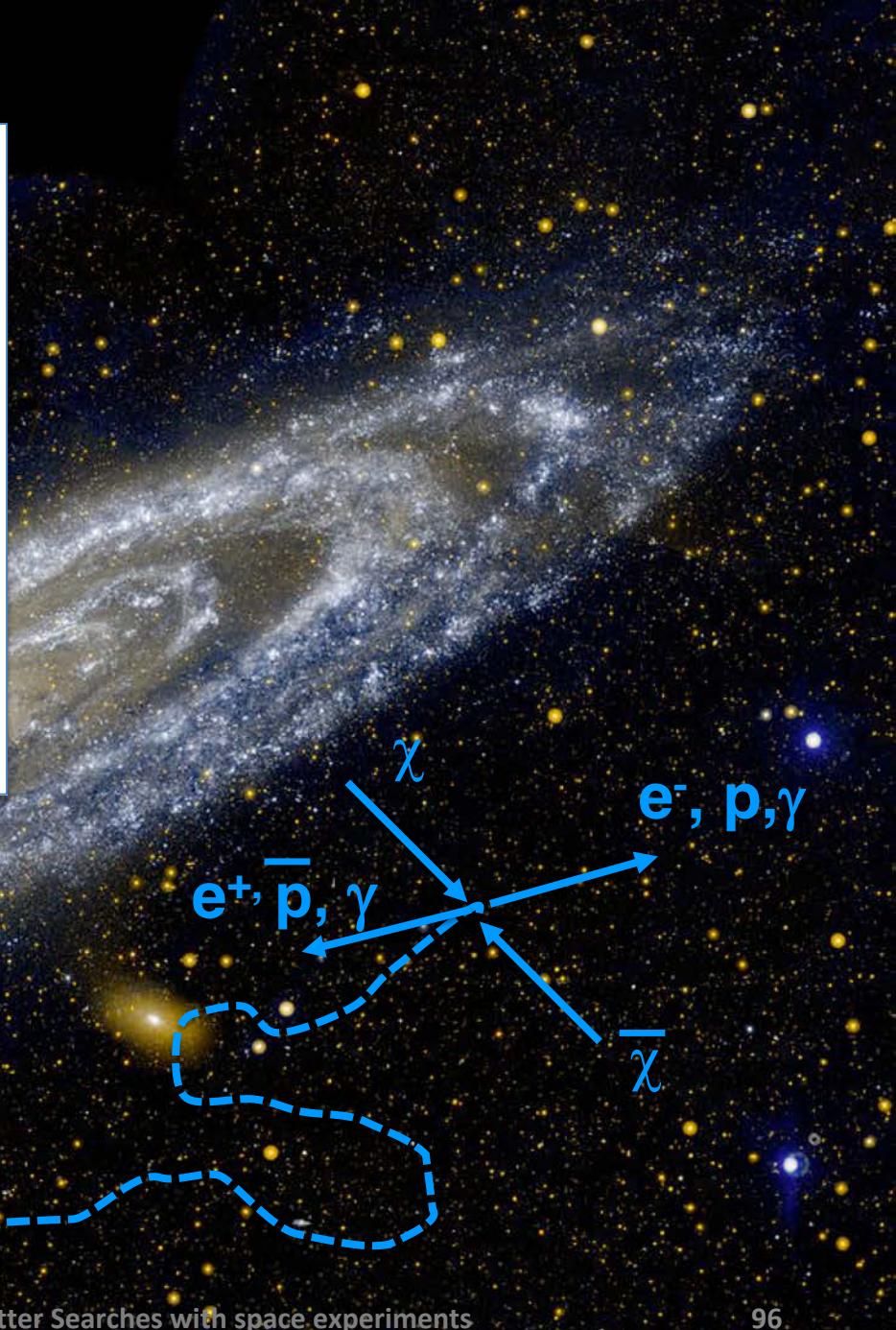
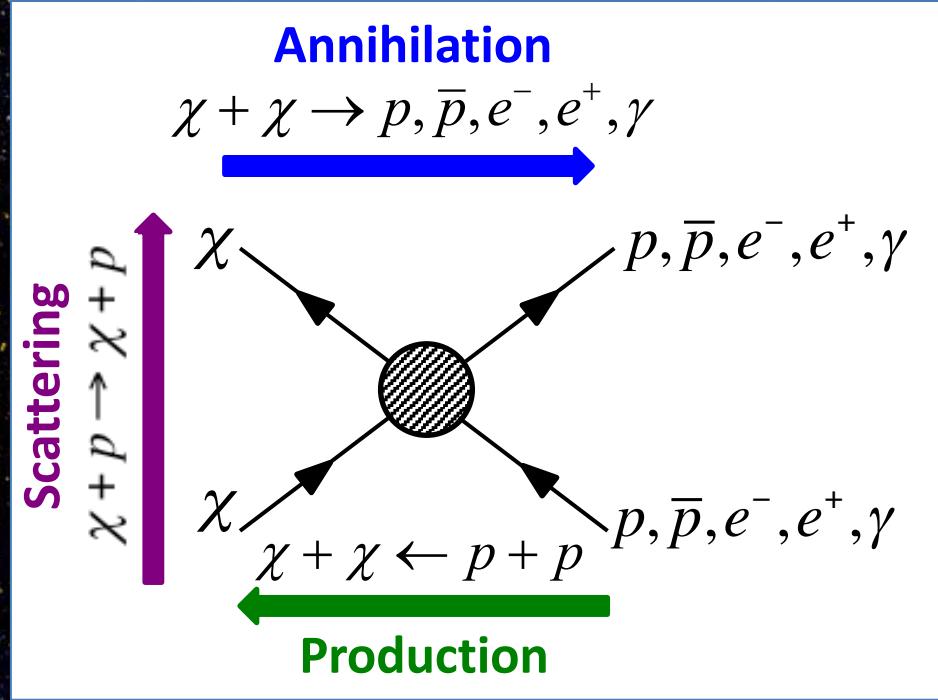


M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)

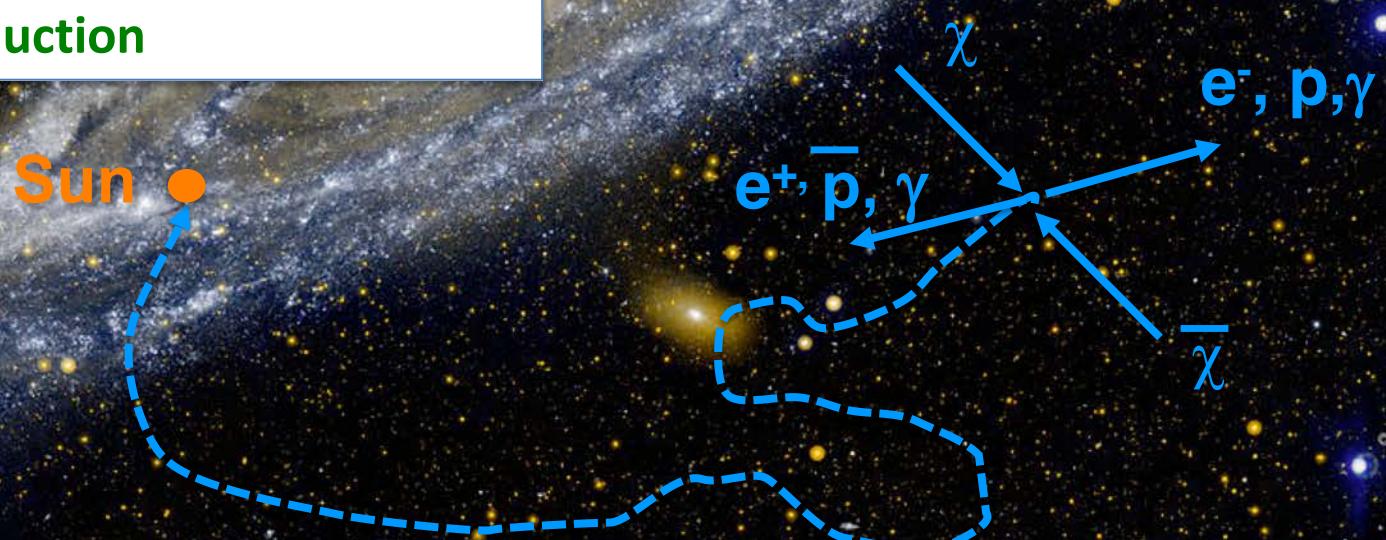
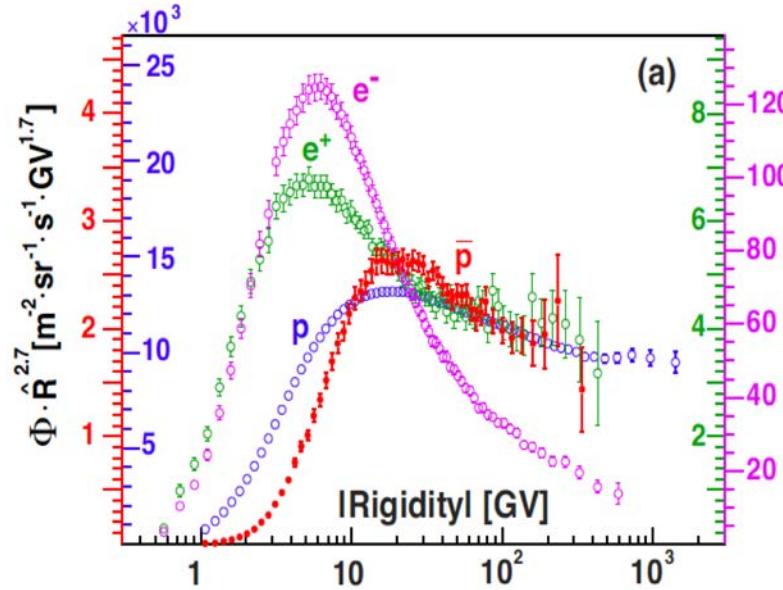
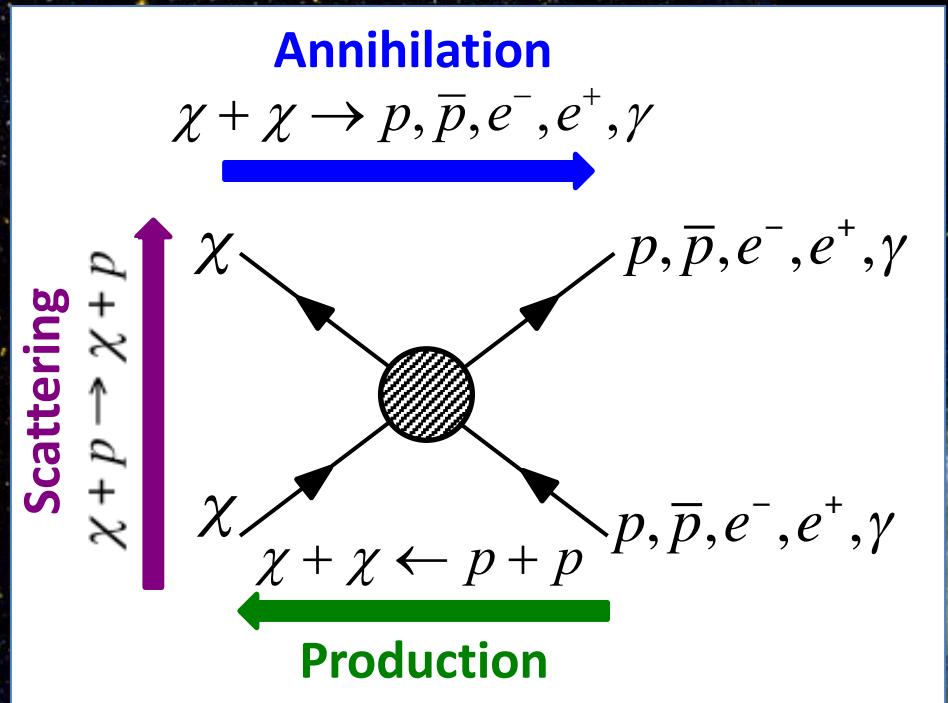
The quest for Dark Matter



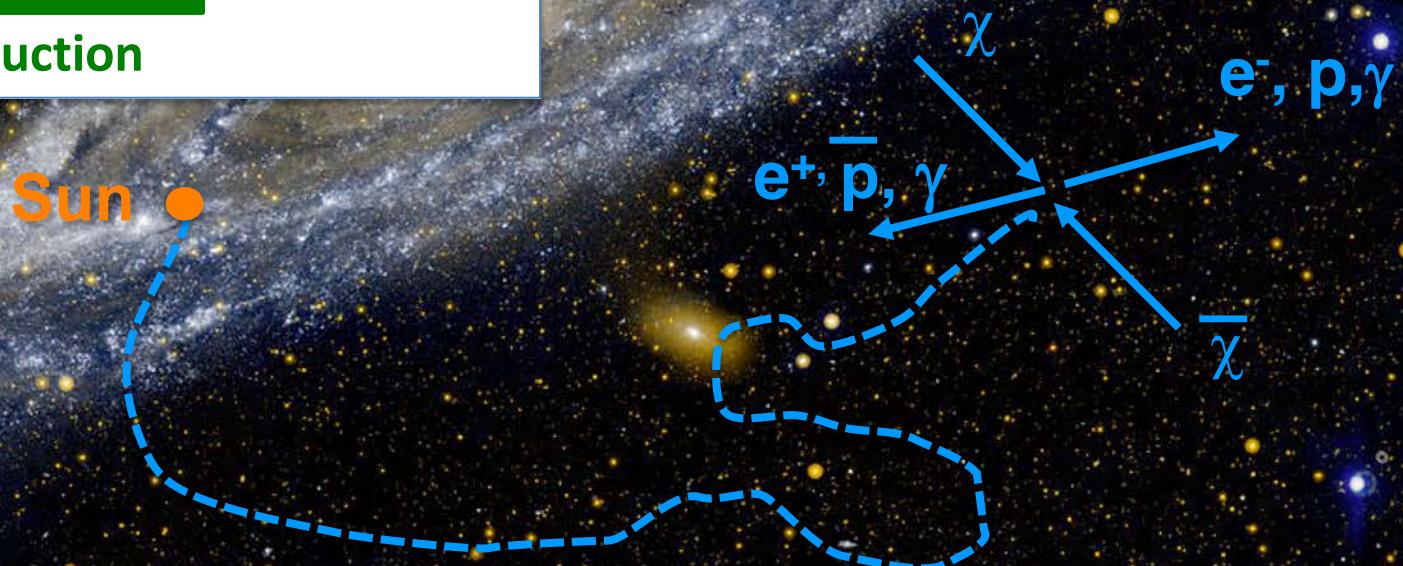
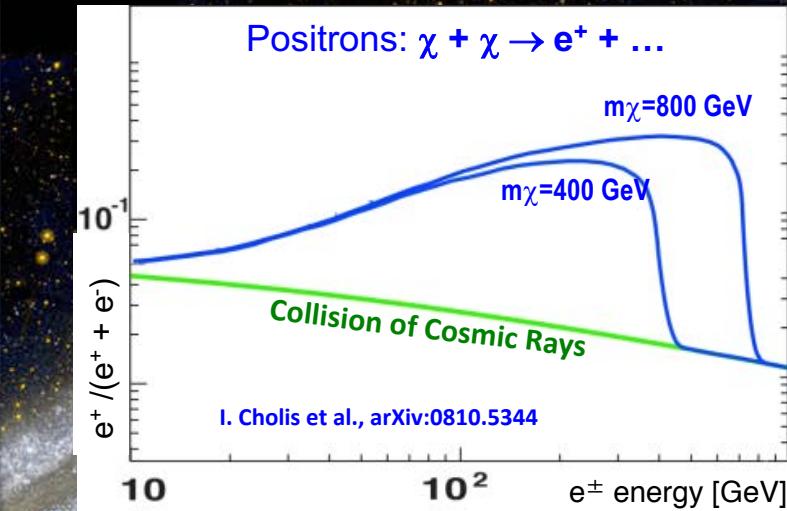
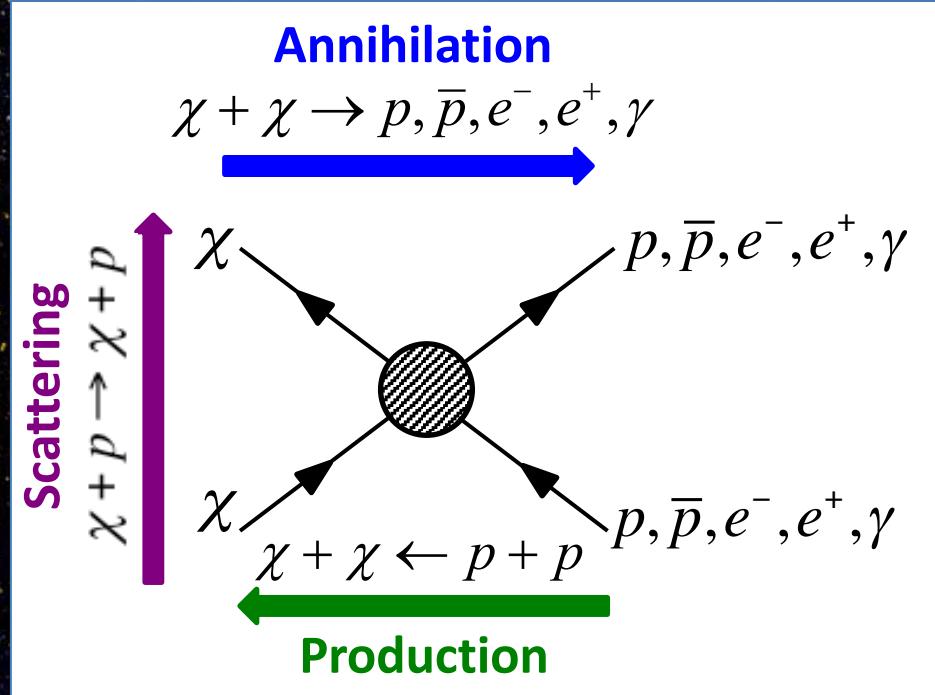
The quest for Dark Matter



The quest for Dark Matter

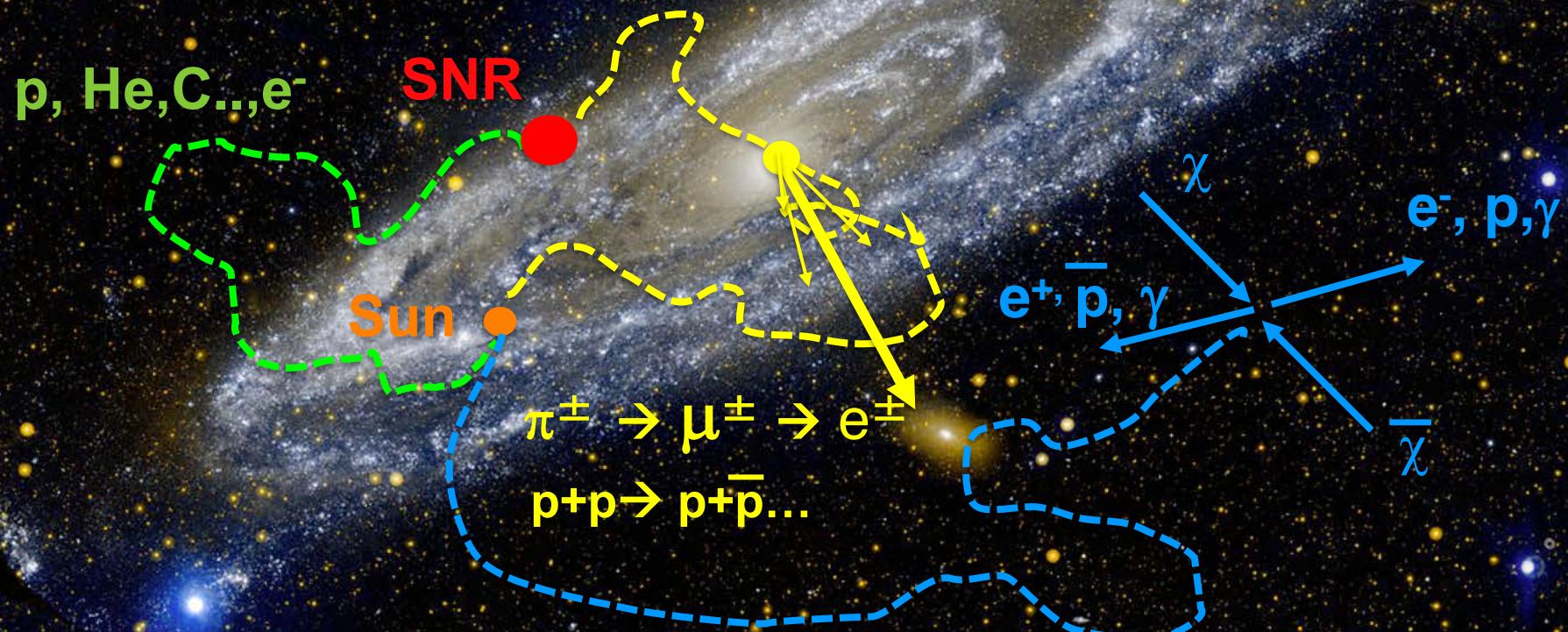


The quest for Dark Matter



The Astrophysical Background:

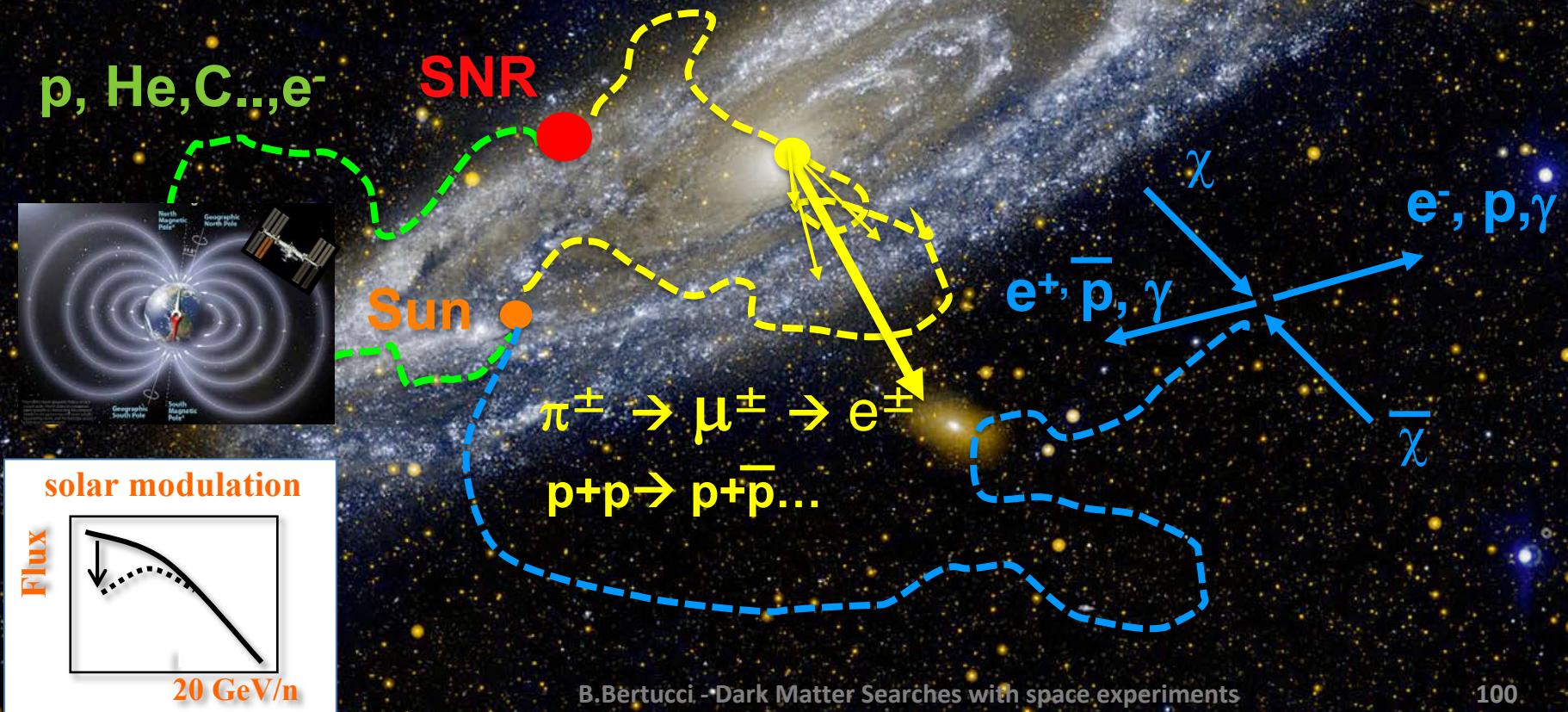
Origin, propagation and production of CRs and their secondaries in the galaxy



The Astrophysical Background:

Origin, propagation and production of CRs and their secondaries in the galaxy

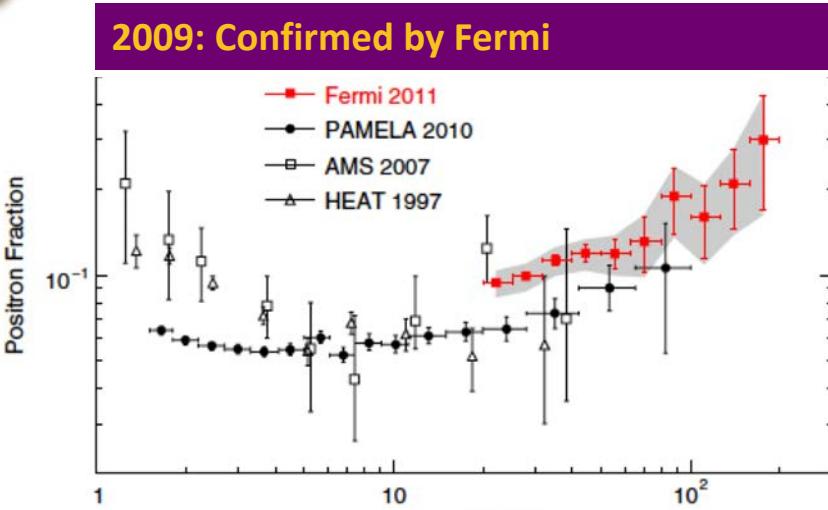
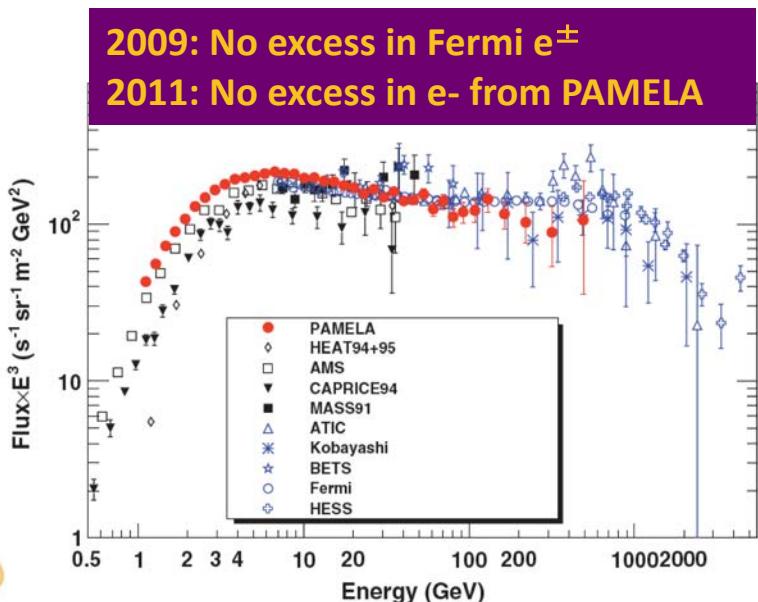
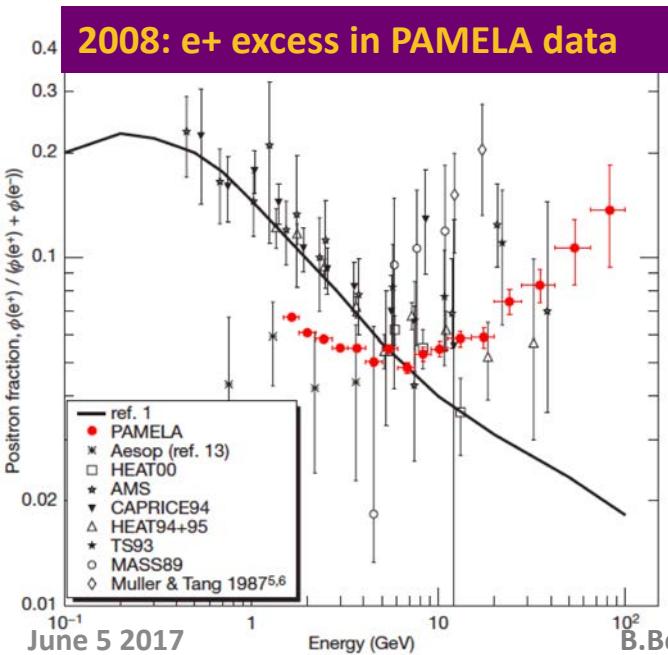
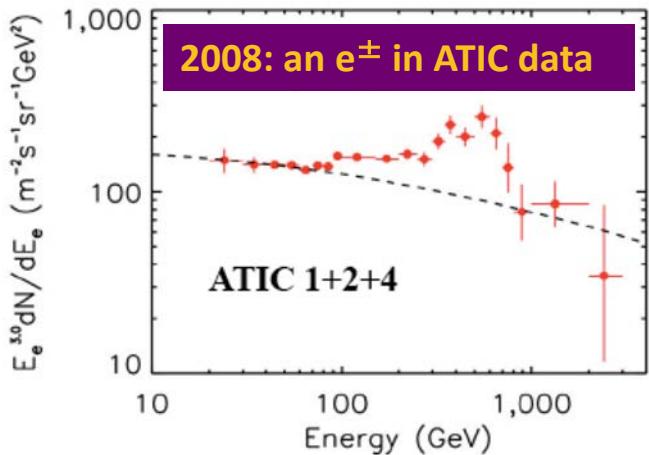
+ heliospheric / magnetospheric effects...



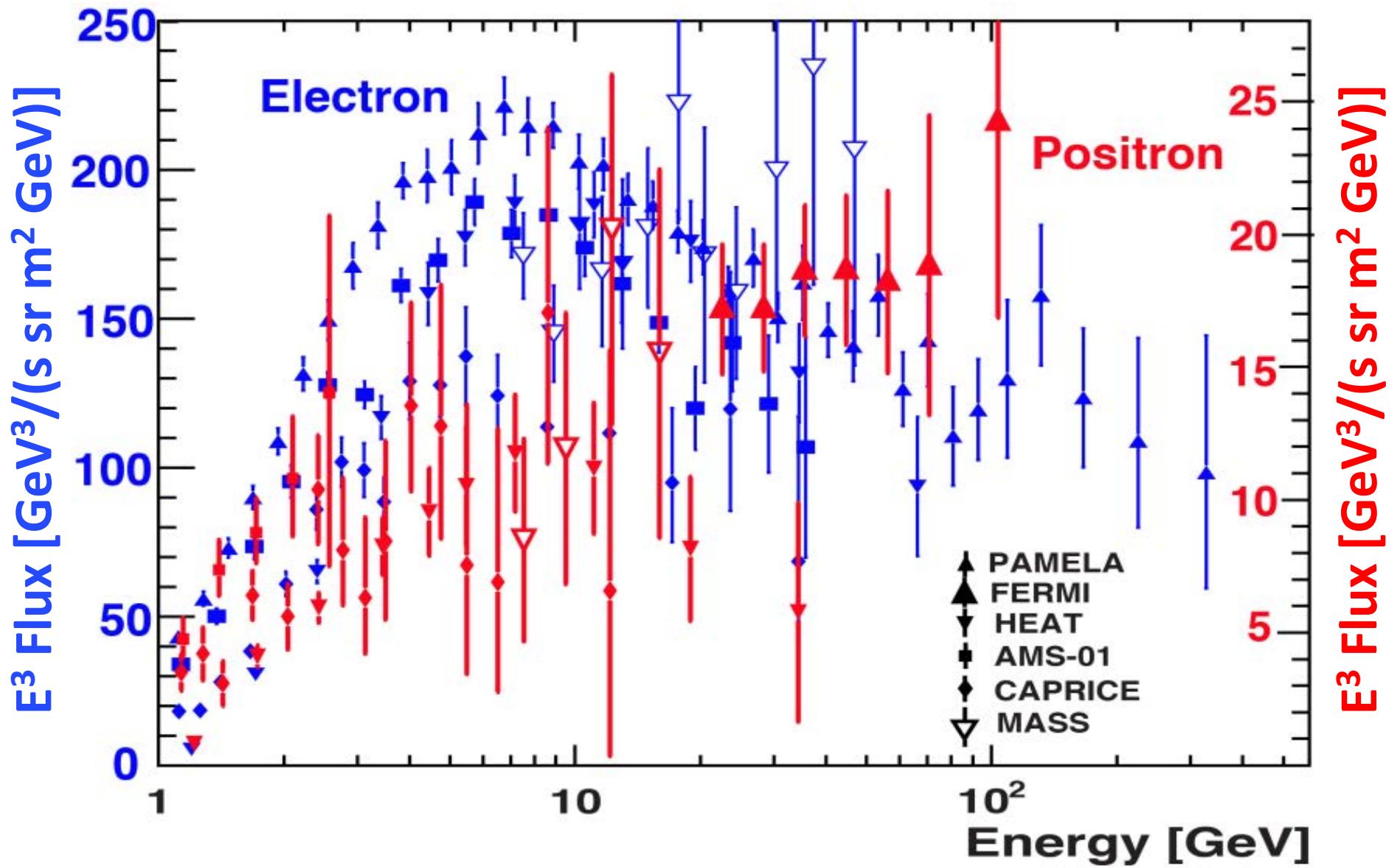
**Indirect Dark Matter search
BUT**

Direct CR Measurements !

The electron/positron puzzle

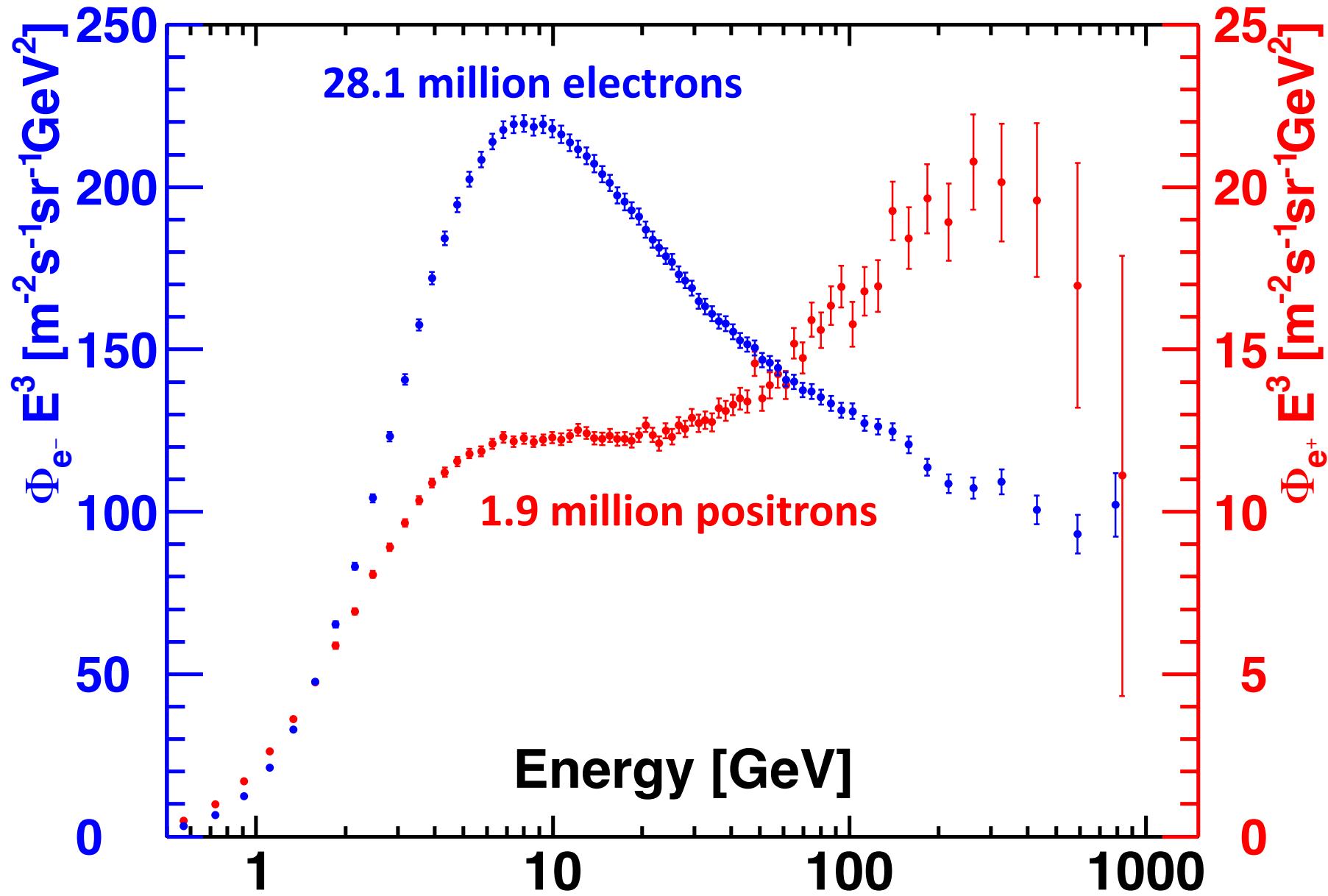


Data of the Electron and Positron spectra before AMS



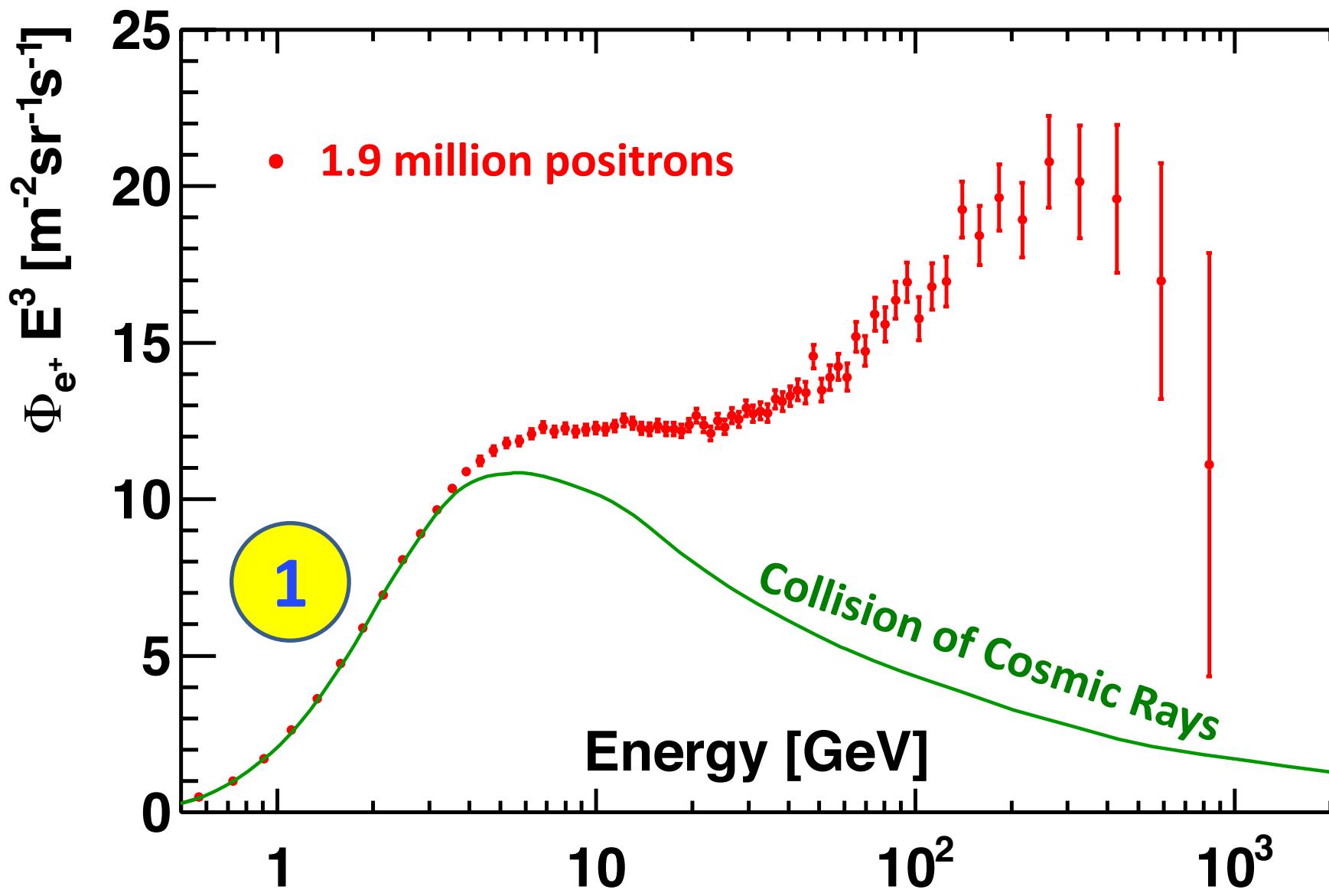
These are very difficult experiments

Latest AMS results on positron and electron fluxes



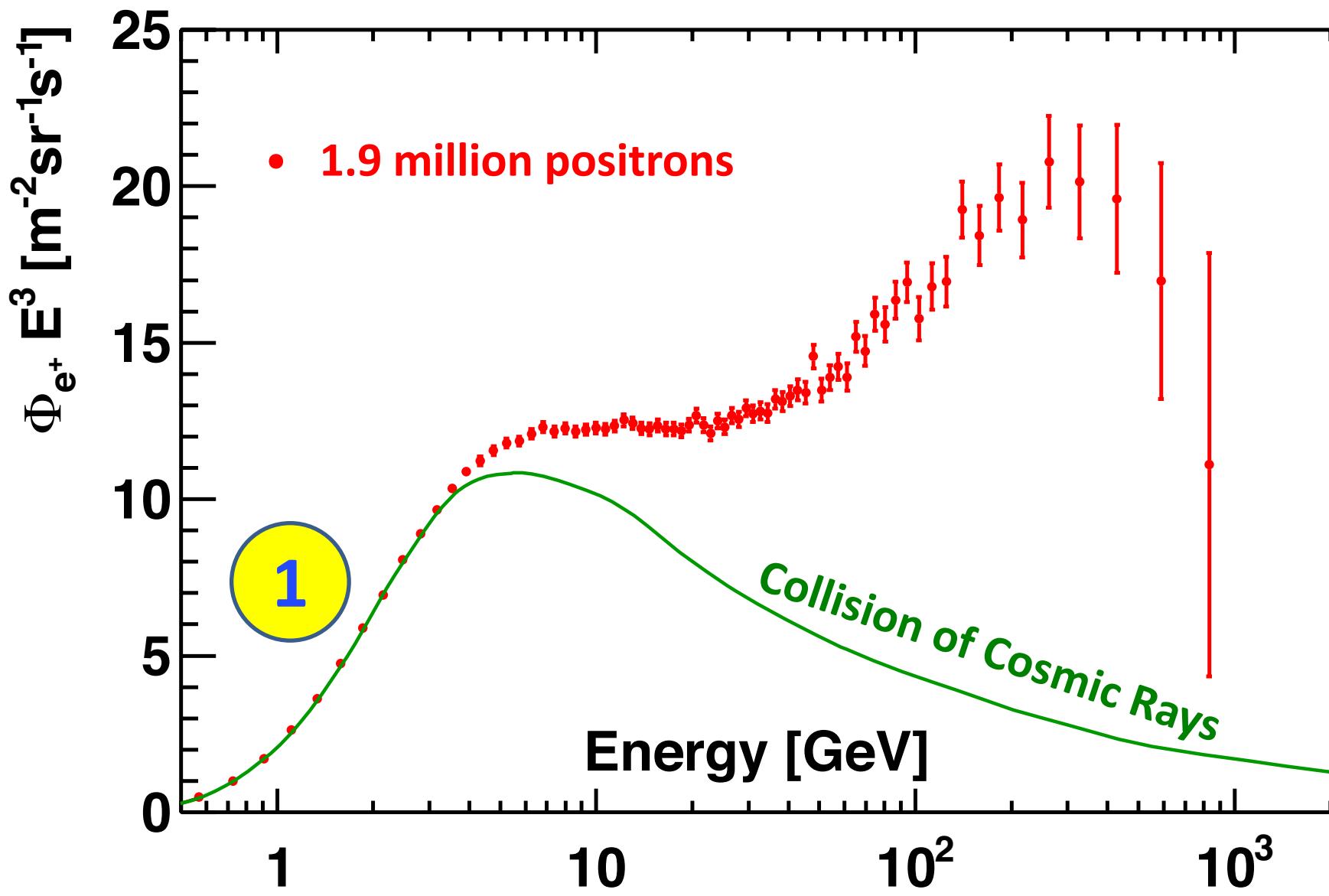
Properties of the Positron Flux

Observation 1: At low energies, the data agrees well with the predictions from the collisions of cosmic rays



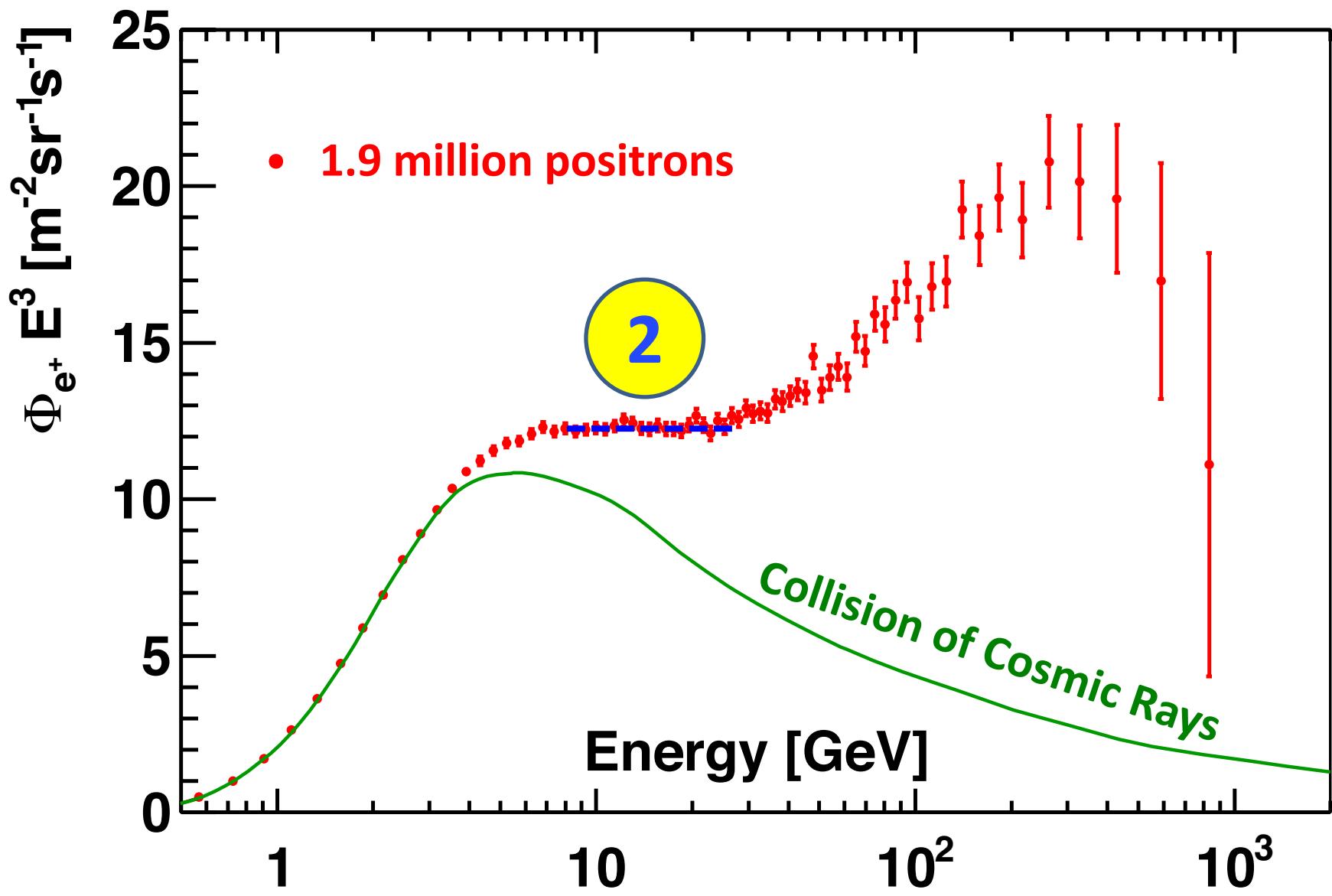
Properties of the Positron Flux

Observation 1: At low energies, the data agrees well with the predictions from the collisions of cosmic rays



Properties of the Positron Flux

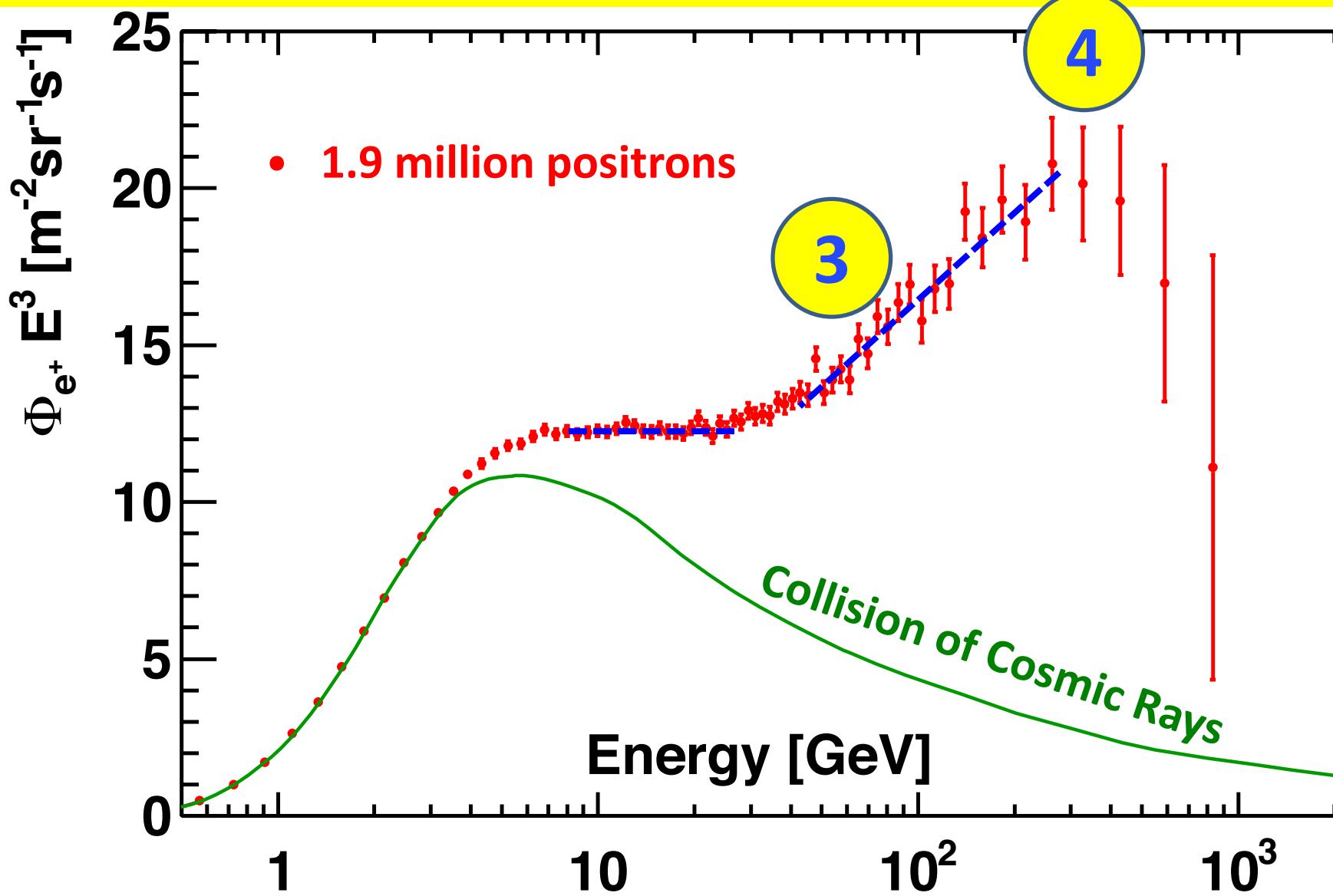
Observation 2: Above 8 GeV, the data flatten out



Properties of the Positron Flux

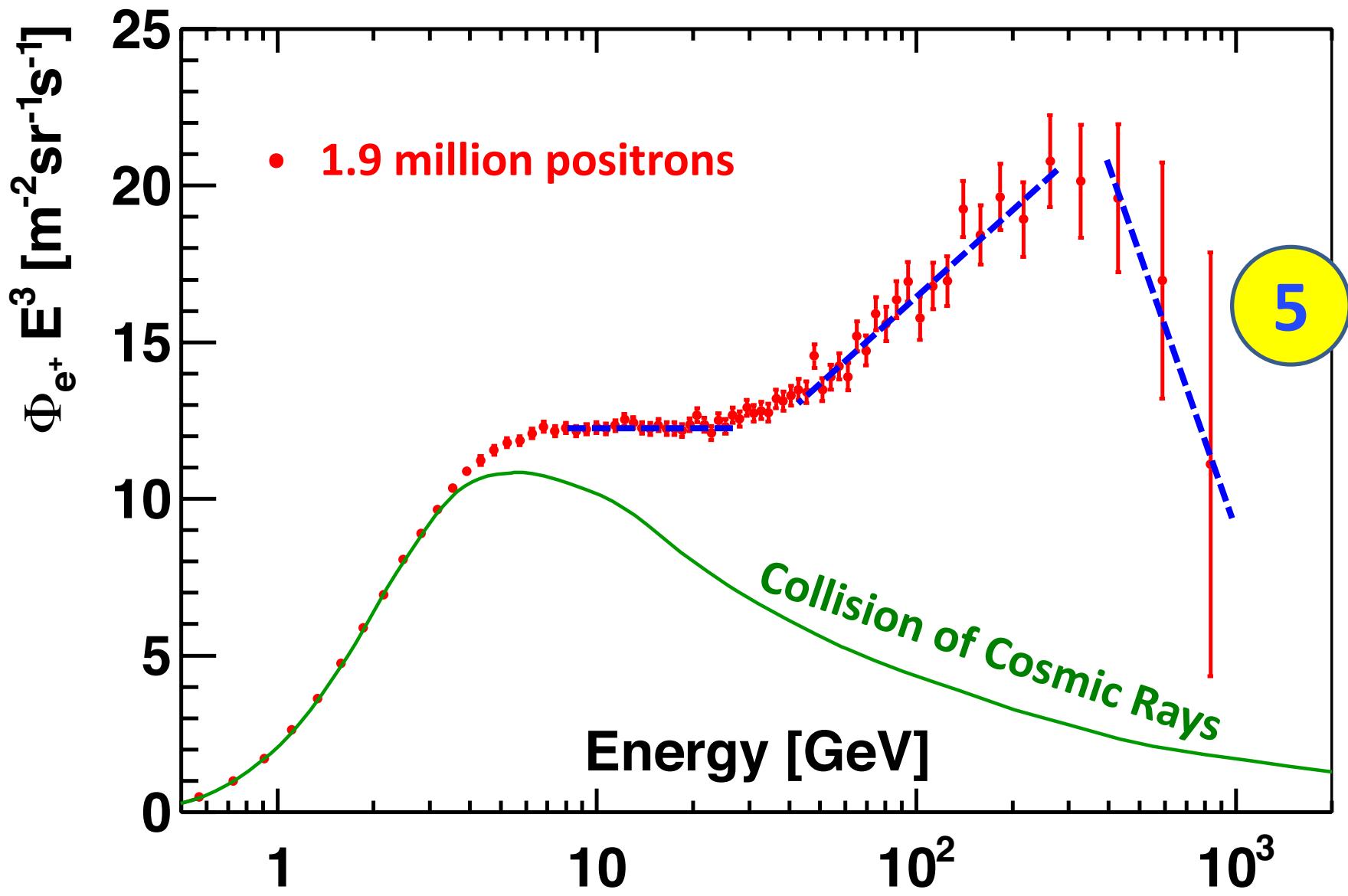
Observation 3: Above 30 GeV, the data increase again.

Observation 4: It reaches a maximum at ~ 300 GeV

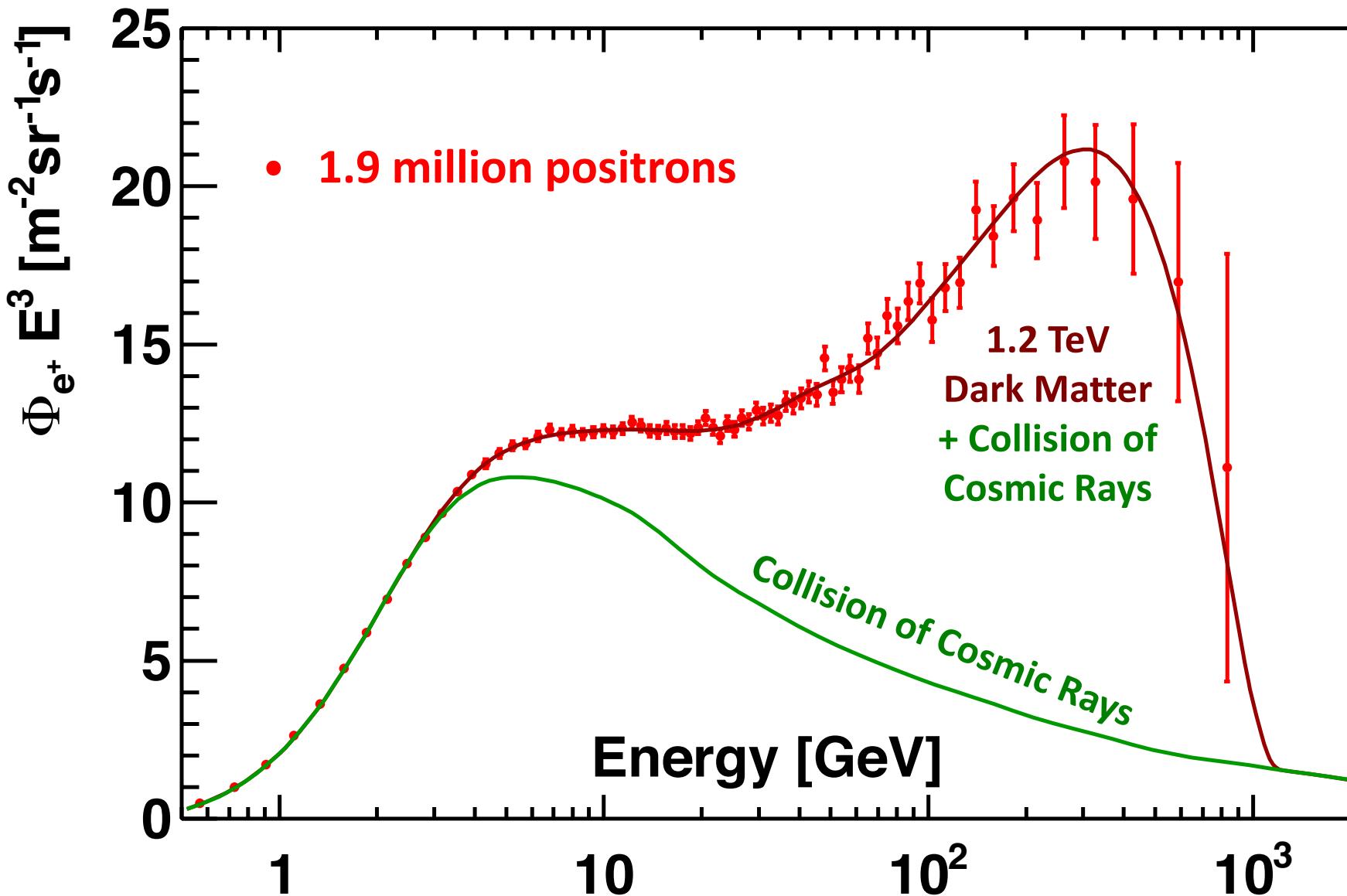


Properties of the Positron Flux

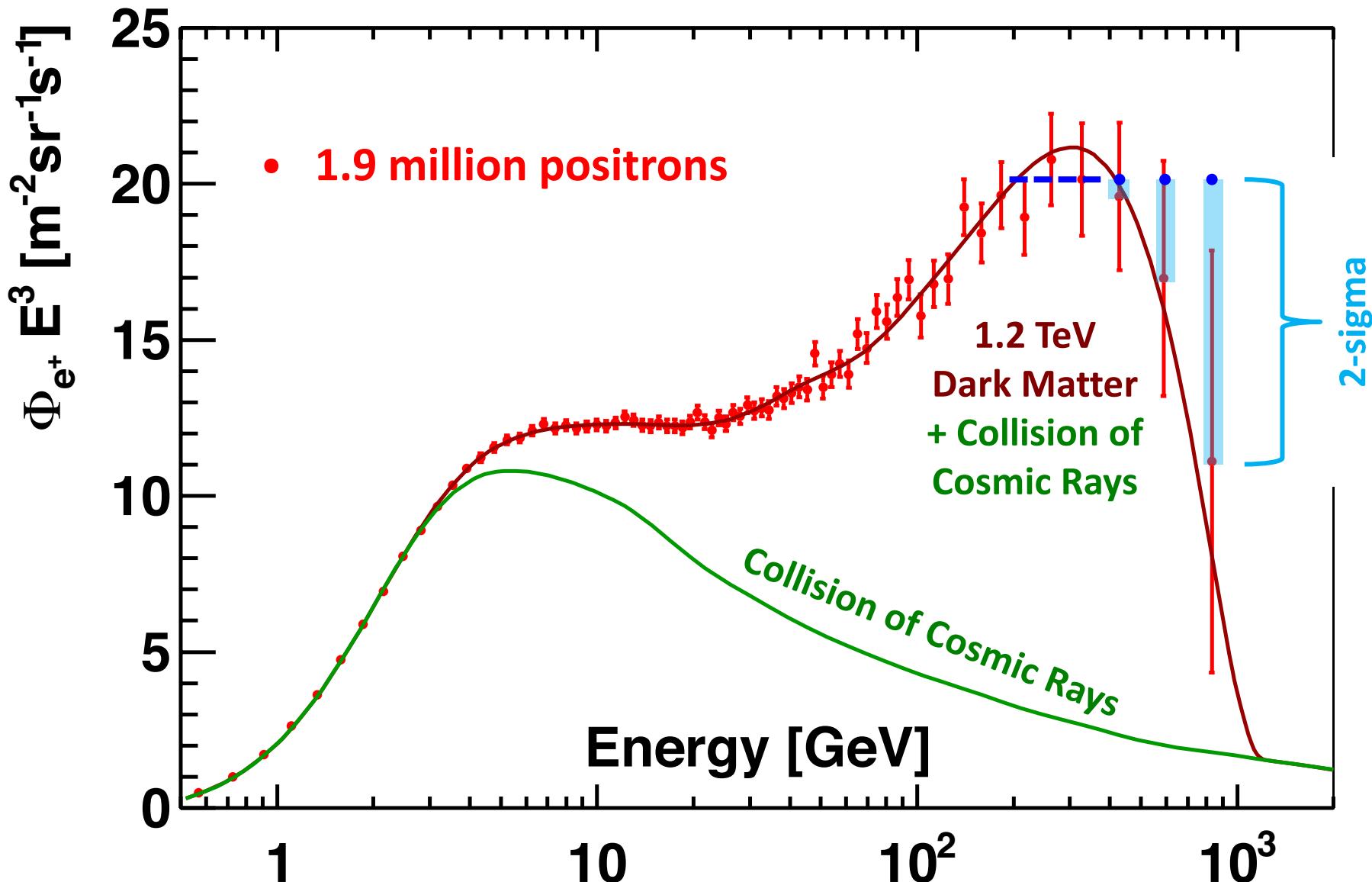
Observation 5: The data drops sharply above 300 GeV



The positron flux appears to be in agreement with predictions from a 1.2 TeV Dark Matter model (J. Kopp, Phys. Rev. D 88, 076013 (2013))



The positron flux appears to be in agreement with predictions from a 1.2 TeV Dark Matter model at the 2-sigma level



A sample of papers on AMS data from more than 2300 publications

- 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) A. Ibarra, A.S. Lamperstorfer and J. Silk, Phys.Rev. D89 (2014) 063539
- 10) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
- 11) C. H. Chen, C. W. Chiang, and T. Nomura, Phys. Lett. B 747, 495 (2015)
- 12) H. B. Jin, Y. L. Wu, and Y.-F. Zhou, Phys.Rev. D92, 055027 (2015)
- 13) A. Reinert and M. W. Winkler JCAP 01 (2018) 055
and many other excellent papers ...

Dark Matter explaining the AMS e+ data

- 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.Reinert, and M.W.Winkler, arXiv:1506.04145 (2015)
and many other excellent papers ...

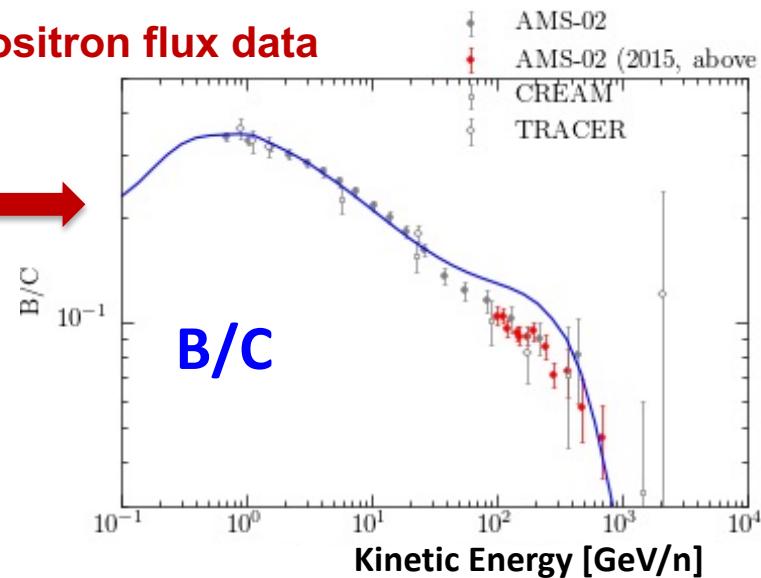
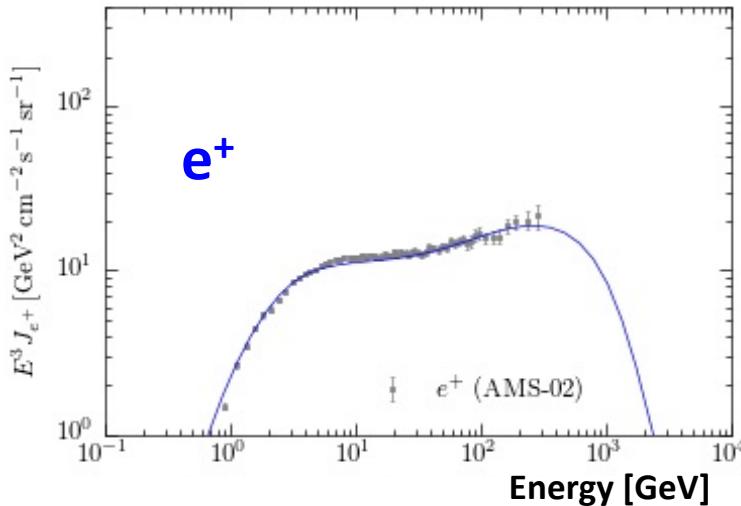
New Propagation Models explaining the AMS e+ data

- 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 ...

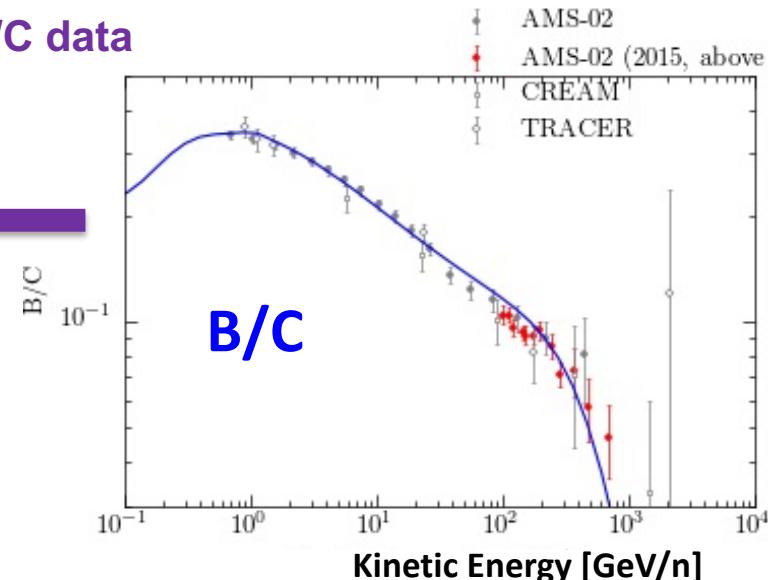
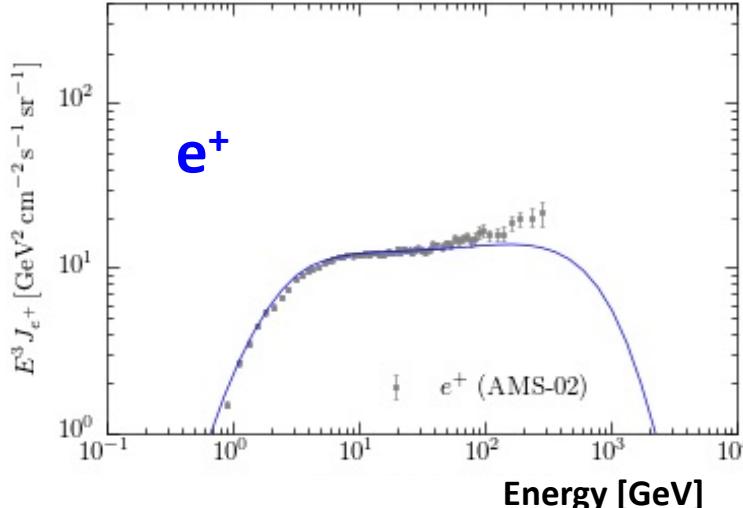
New Astrophysical Sources explaining the AMS e+ data

New Astrophysical sources (Supernova Remnants)

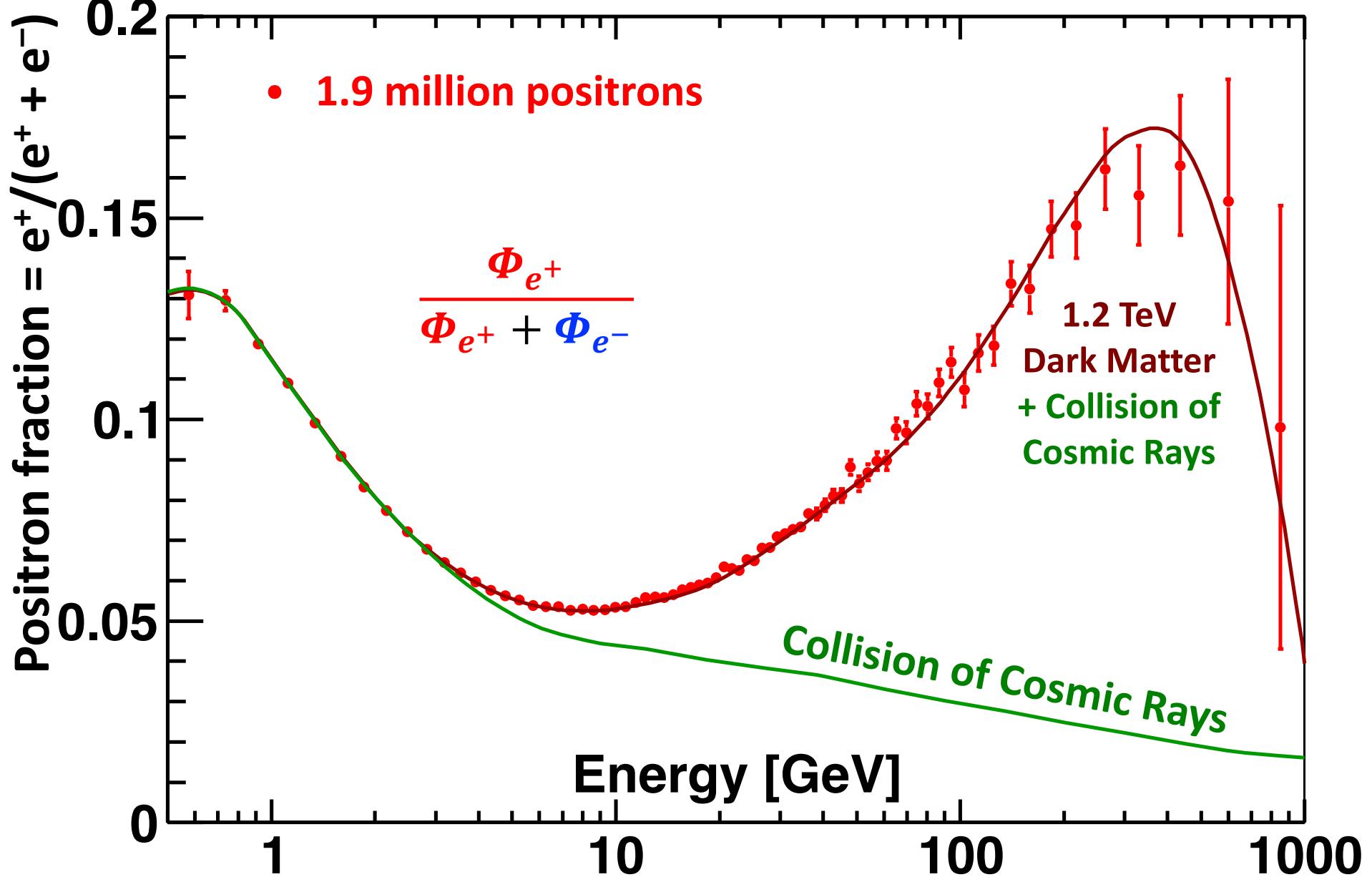
Model parameter tuned to fit the positron flux data



Model parameter tuned to fit the B/C data



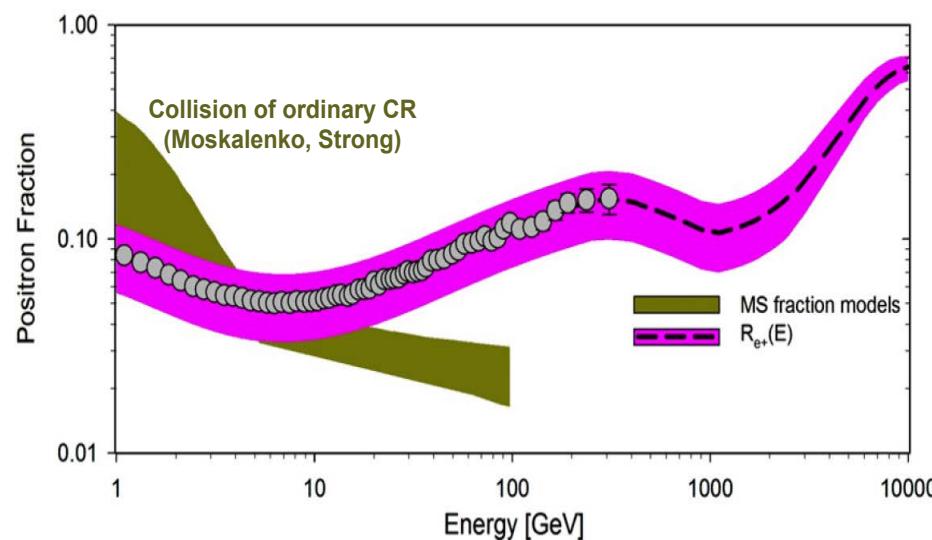
Positron excess also can be expressed in terms of the positron fraction, which explores the same physics



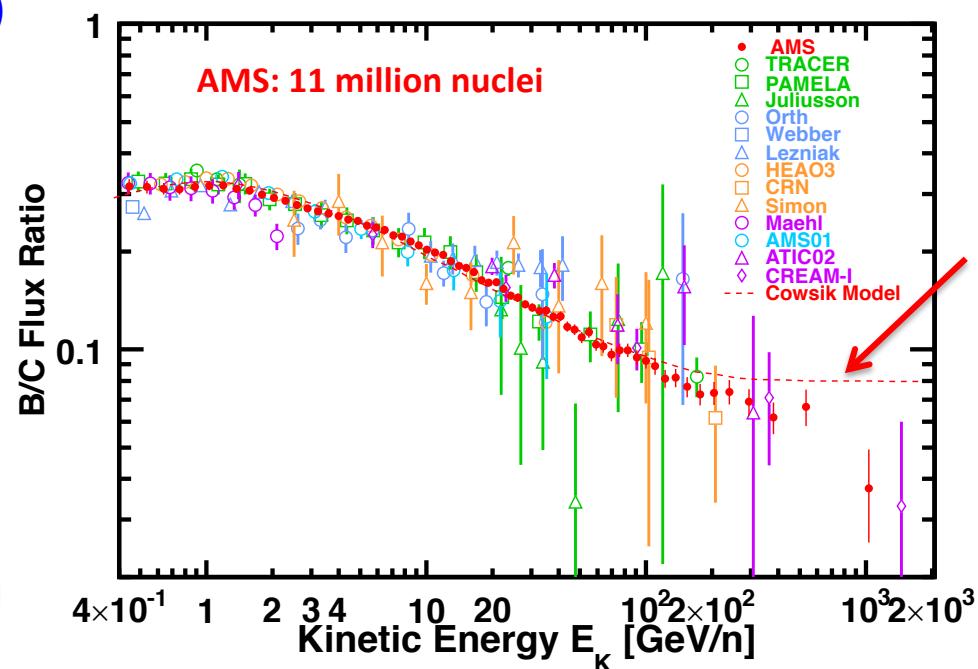
New Propagation Models explaining the AMS e+ data

Explaining the AMS positron fraction (gray circles) is due to propagation effects.

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



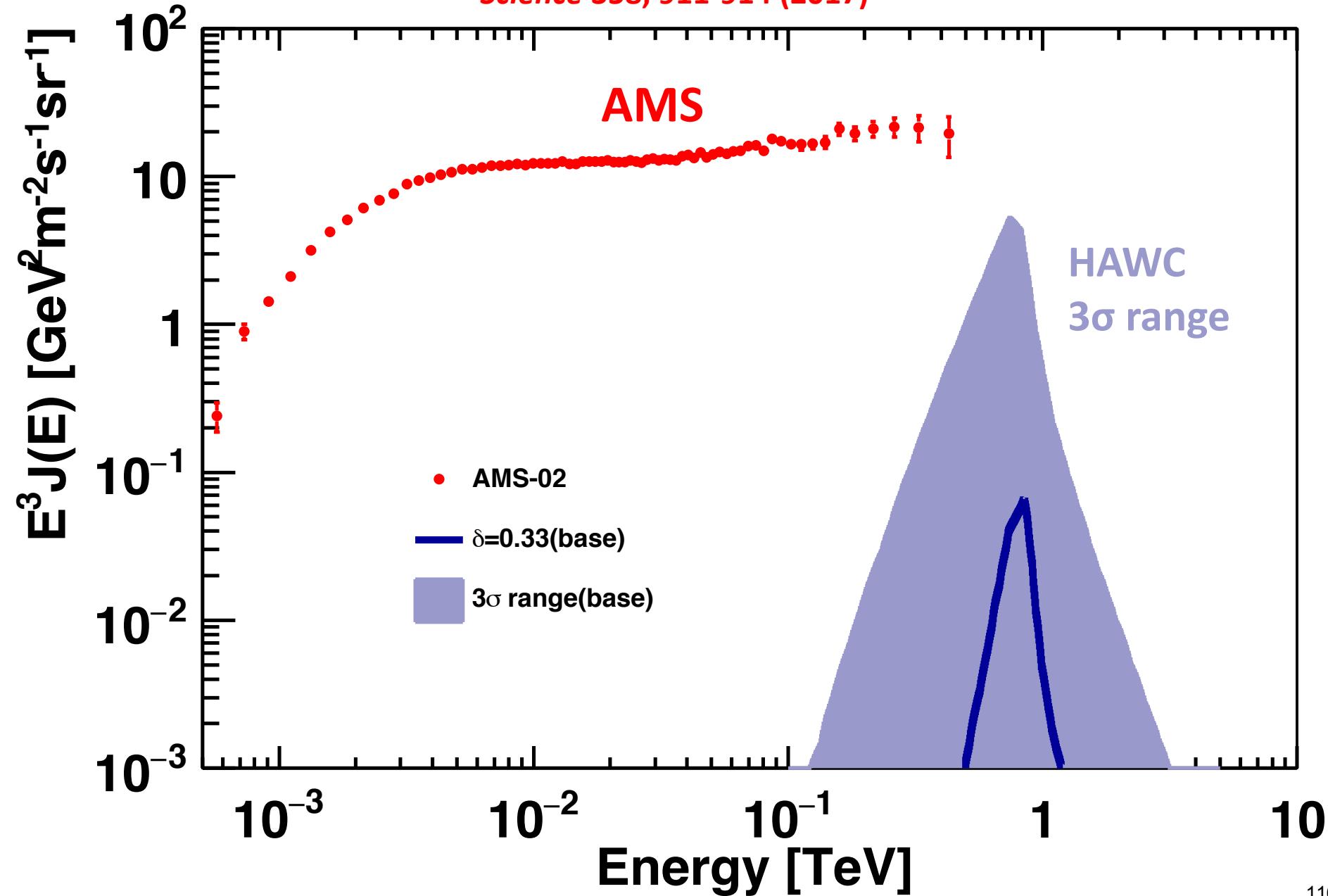
This requires a specific energy dependence of the B/C ratio



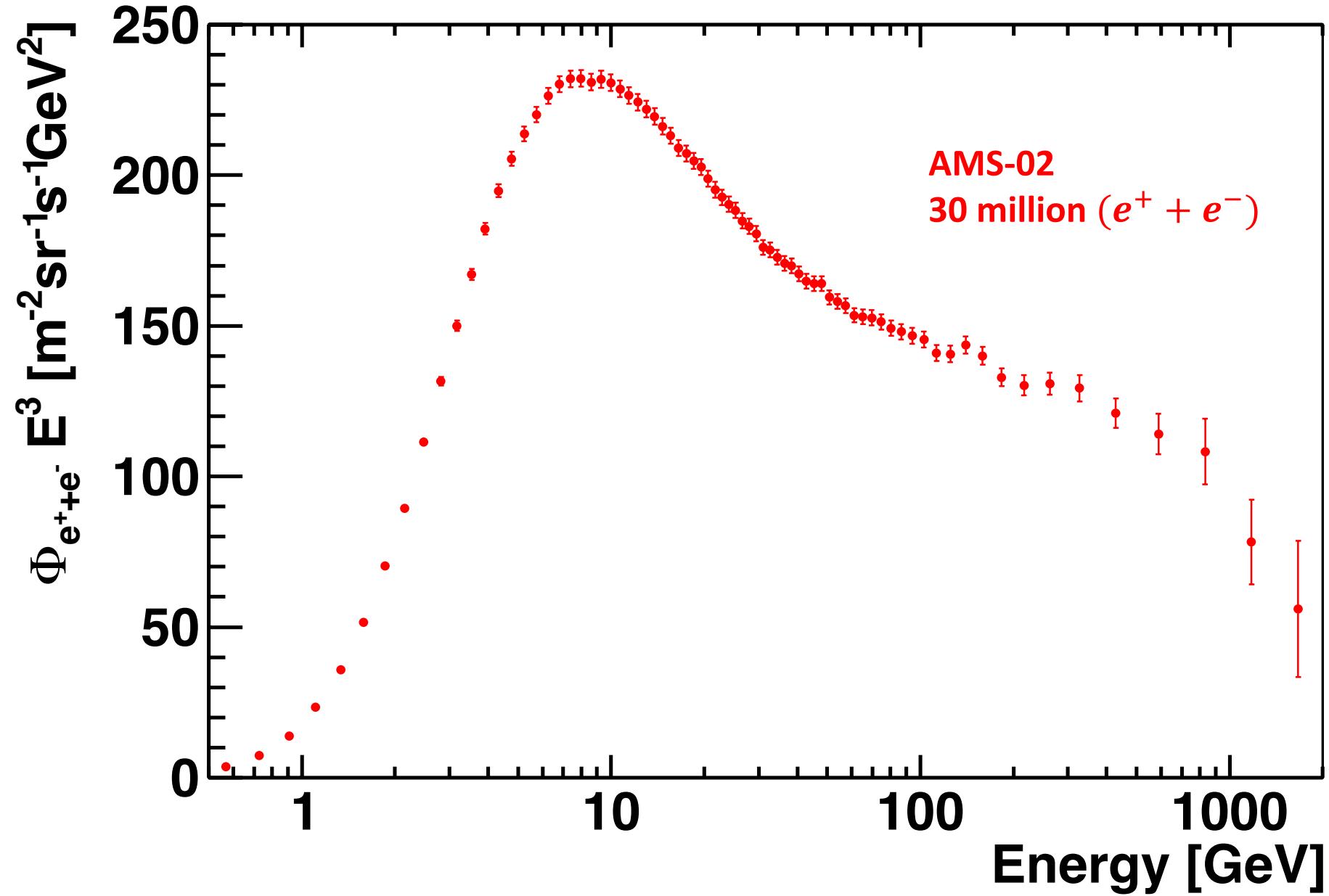
The observed features of the AMS e+ data cannot be explained by standard propagation models

HAWC rules out that the AMS positron excess is from nearby pulsars

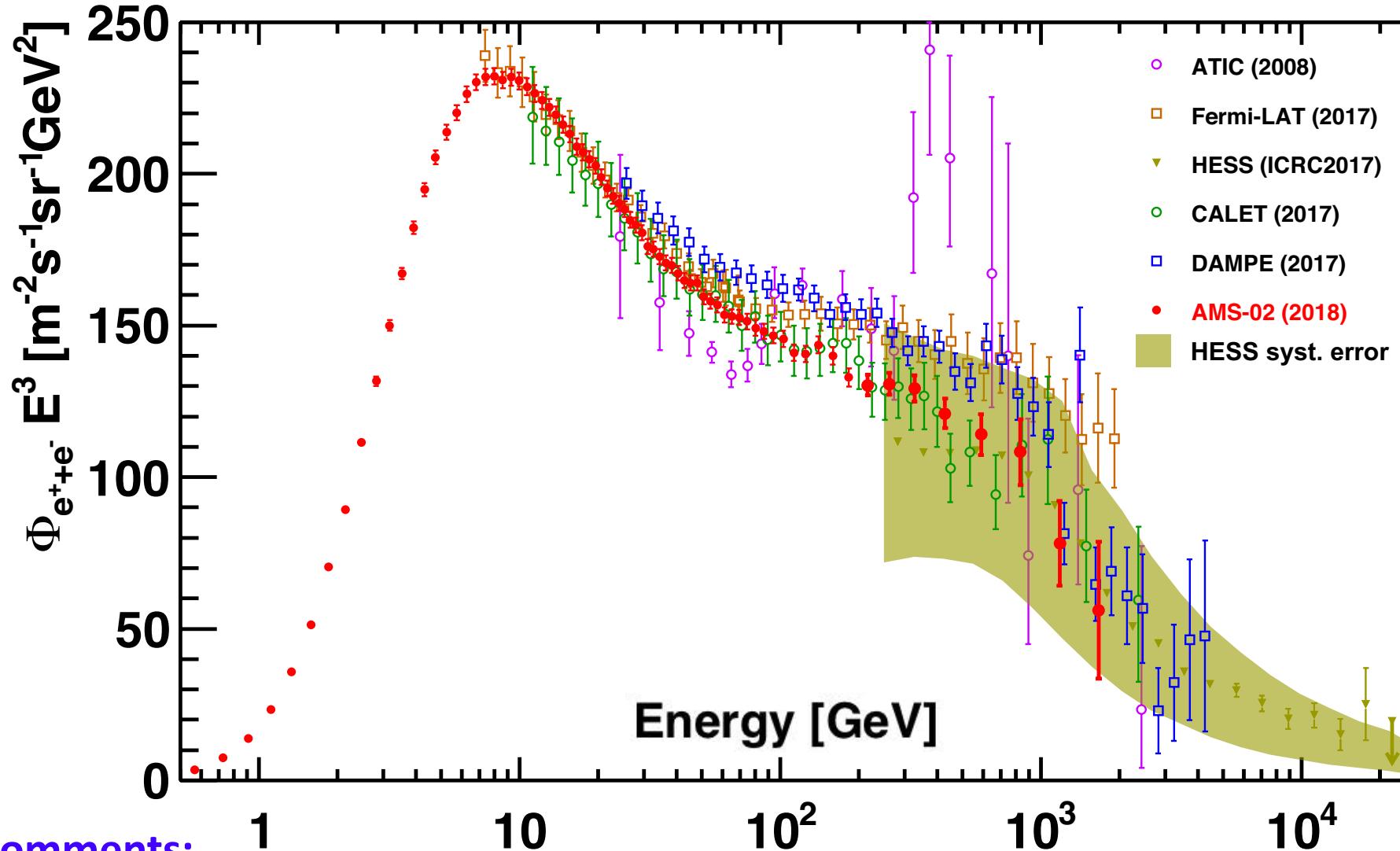
Science 358, 911-914 (2017)



The AMS combined (electron + positron) flux



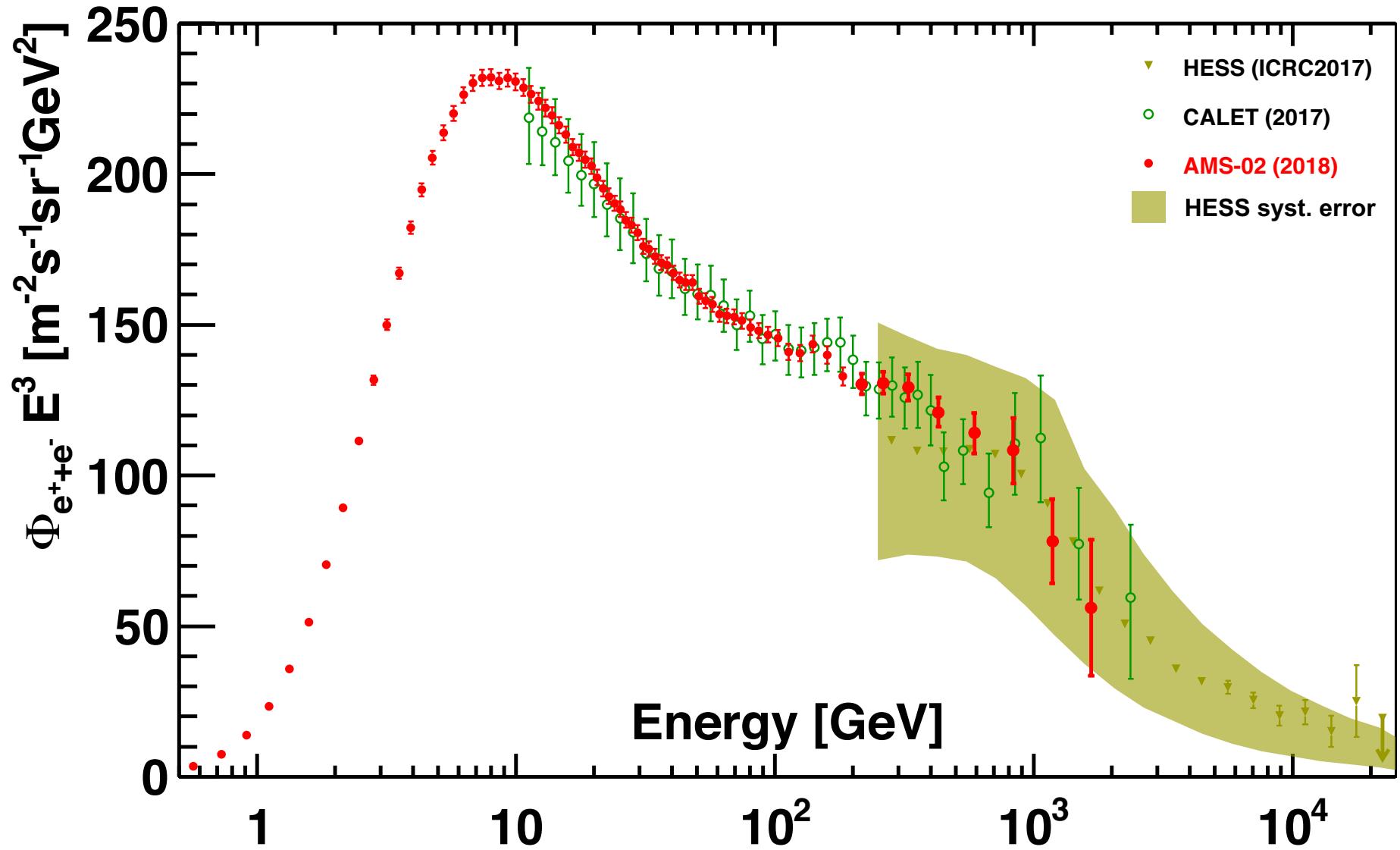
$(e^+ + e^-)$ data with AMS and with non-magnetic detectors



Comments:

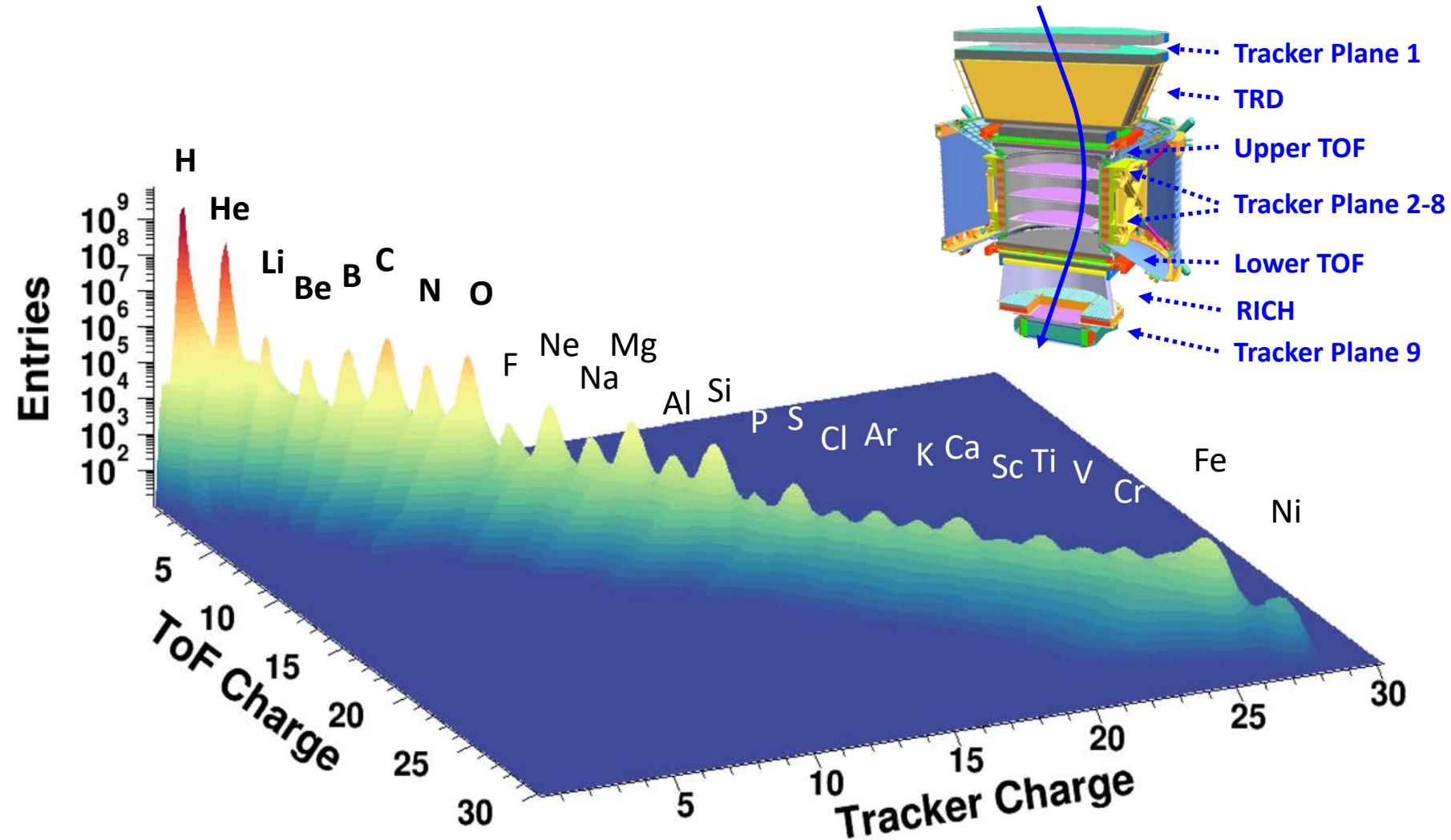
1. HESS, DAMPE and AMS all observed a spectral break at ~ 1 TeV
2. Measuring e^+ is the most sensitive way to identify χ via $\chi + \chi \rightarrow e^+, e^-$, ...
Measuring $(e^+ + e^-)$ is much less sensitive to χ due to the large e^- background

AMS ($e^+ + e^-$) data with a few non-magnetic detectors



Precision Measurements of Cosmic Rays:

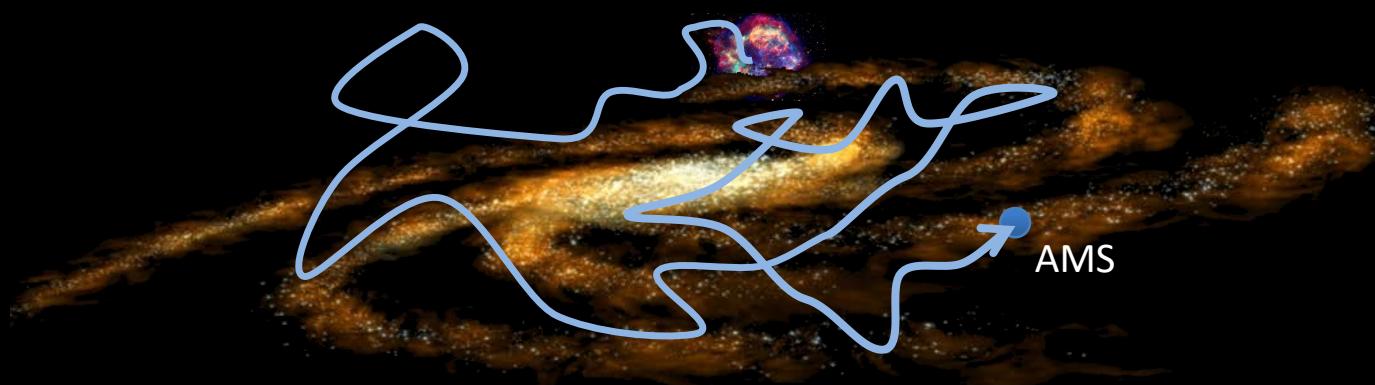
AMS has seven instruments which independently measure Cosmic Nuclei



Traditionally, there are two prominent classes of cosmic rays:

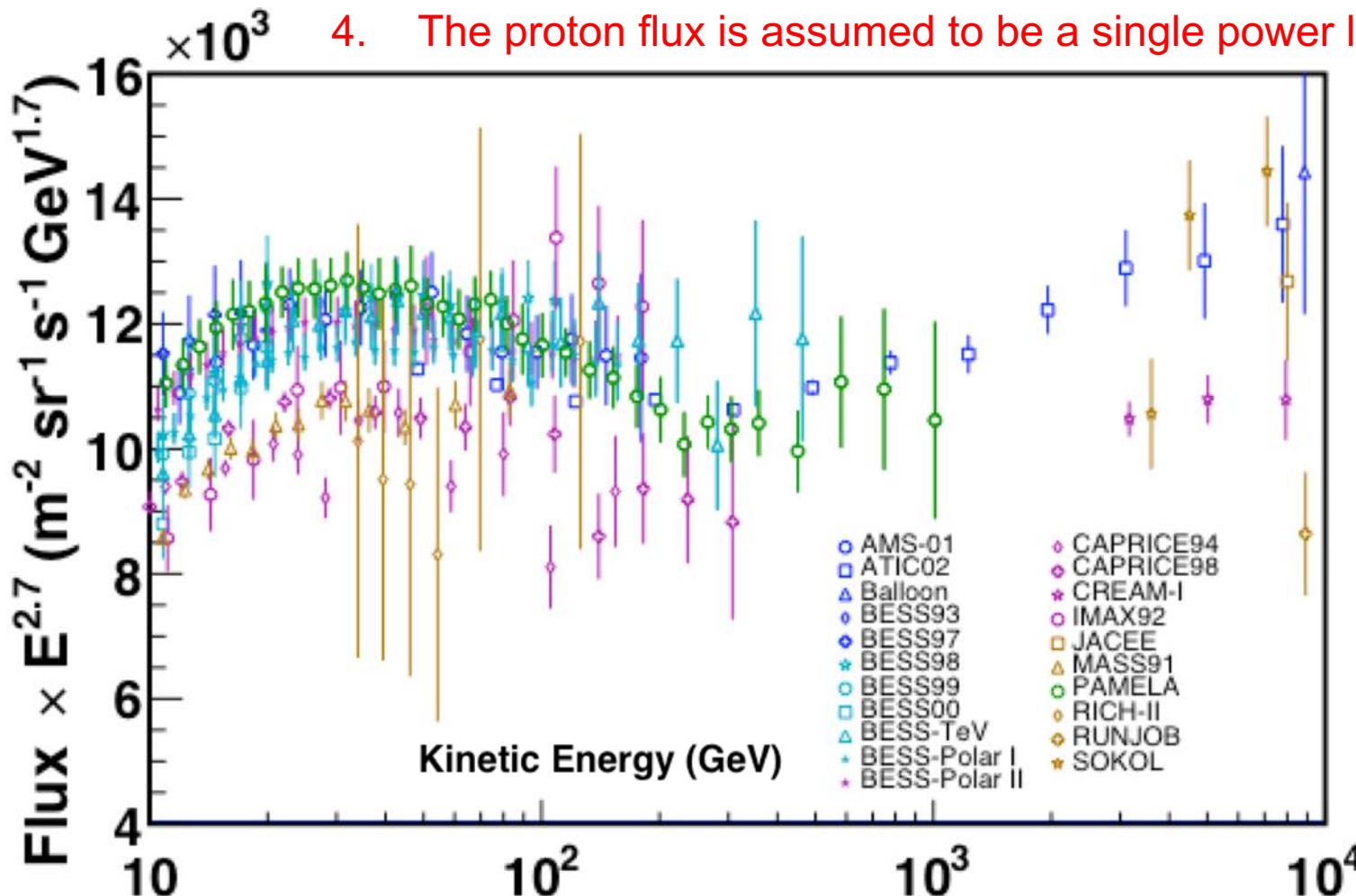
Primary Cosmic Rays (p, He, C, O, ...)

are produced at their source and travel through space and are directly detected by AMS. They carry information on their sources and the history of travel.

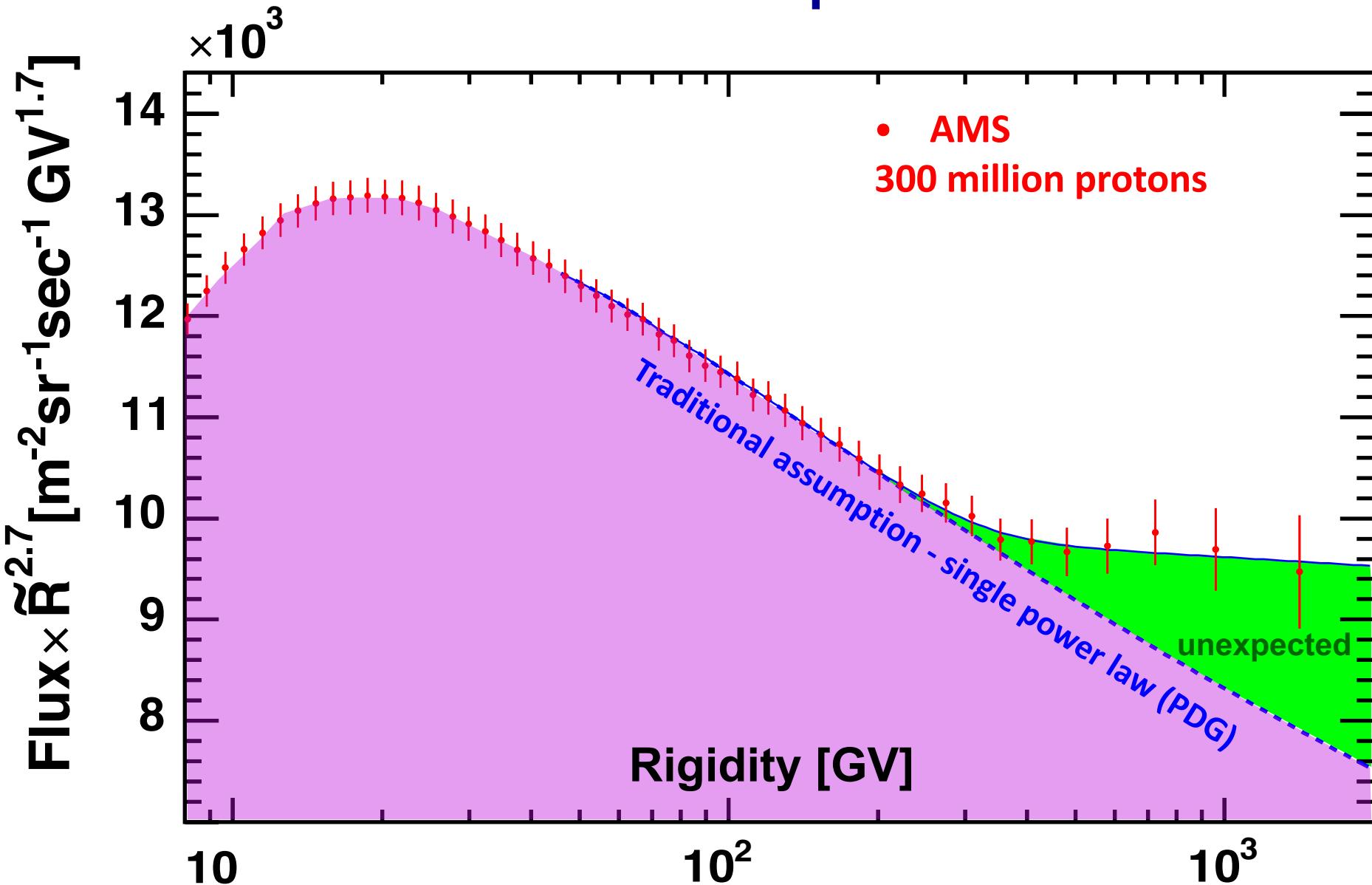


Measurements of proton spectrum before AMS

1. Protons are the most abundant charged cosmic rays.
2. Before AMS, there were many measurements but the data have large errors and are inconsistent.
3. These data limit the understanding of the production, acceleration and propagation of all cosmic rays.
4. The proton flux is assumed to be a single power law = CR^γ

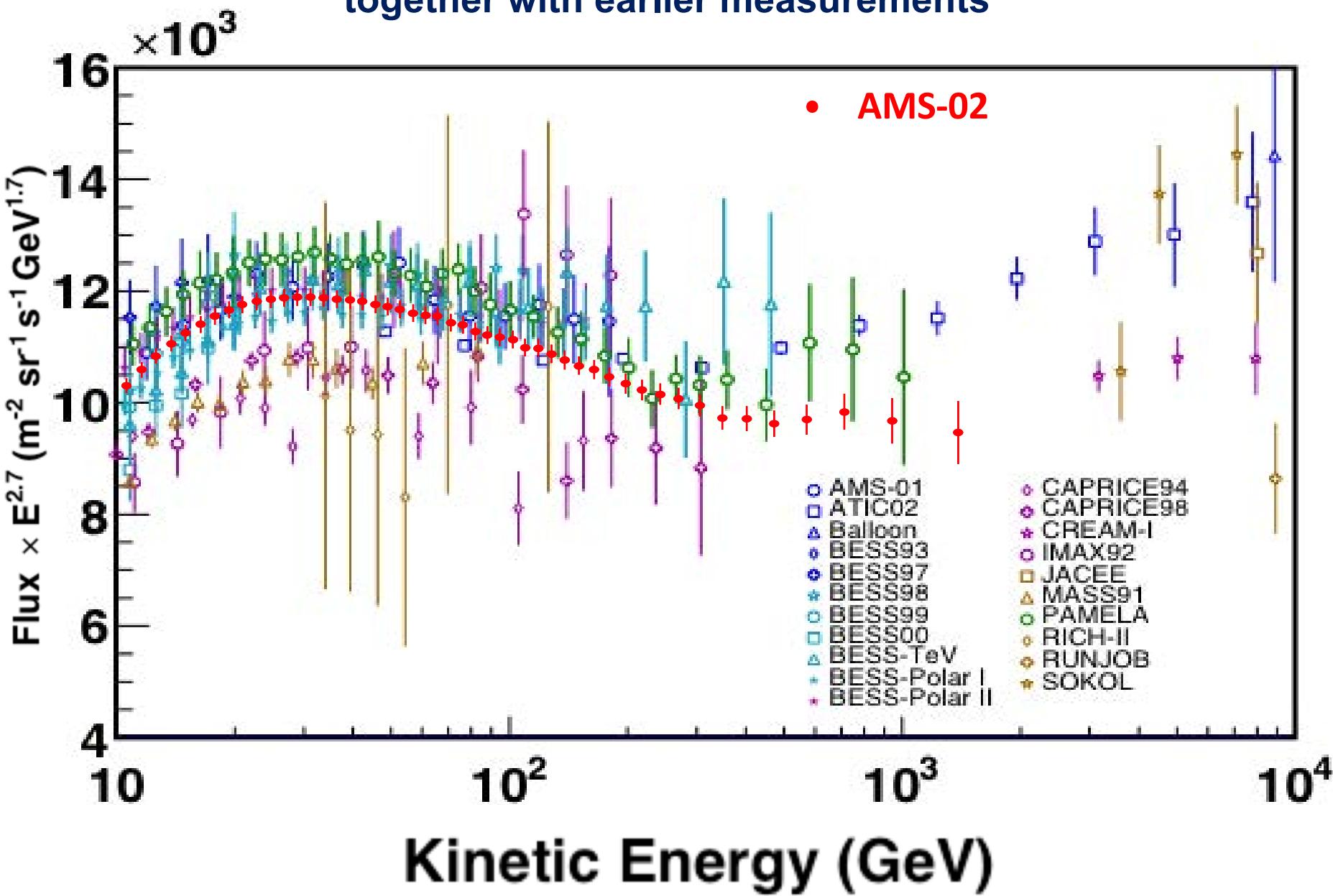


AMS results on the proton flux



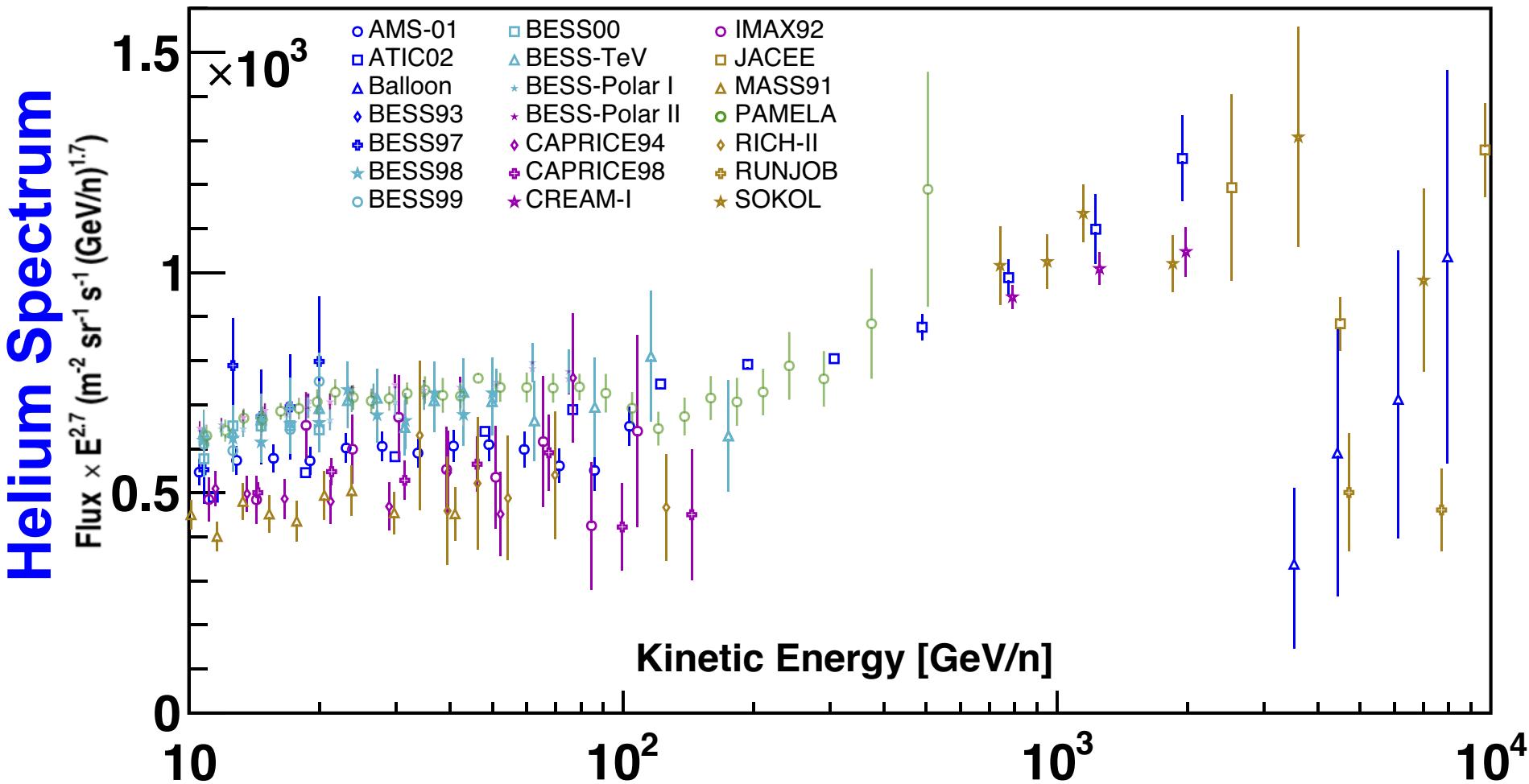
The proton flux **cannot** be described by a single power law = CR^γ

AMS Measurement of the proton spectrum together with earlier measurements



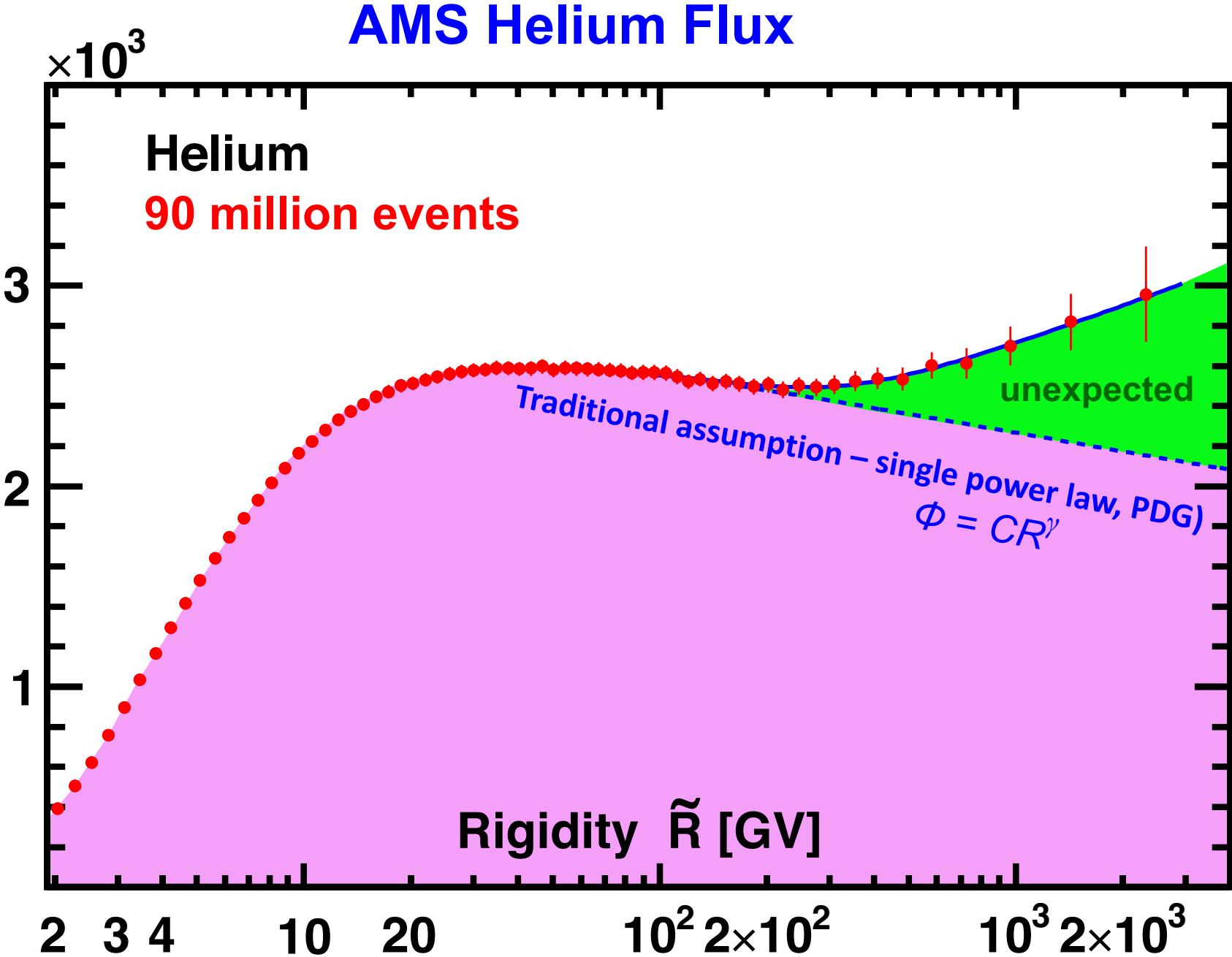
Measurements of the Helium Flux before AMS

Helium is the 2nd most abundant cosmic ray.



AMS Helium Flux

Flux $\times \tilde{R}^{2.7}$ [$m^{-2}sec^{-1}sr^{-1}GV^{1.7}$]

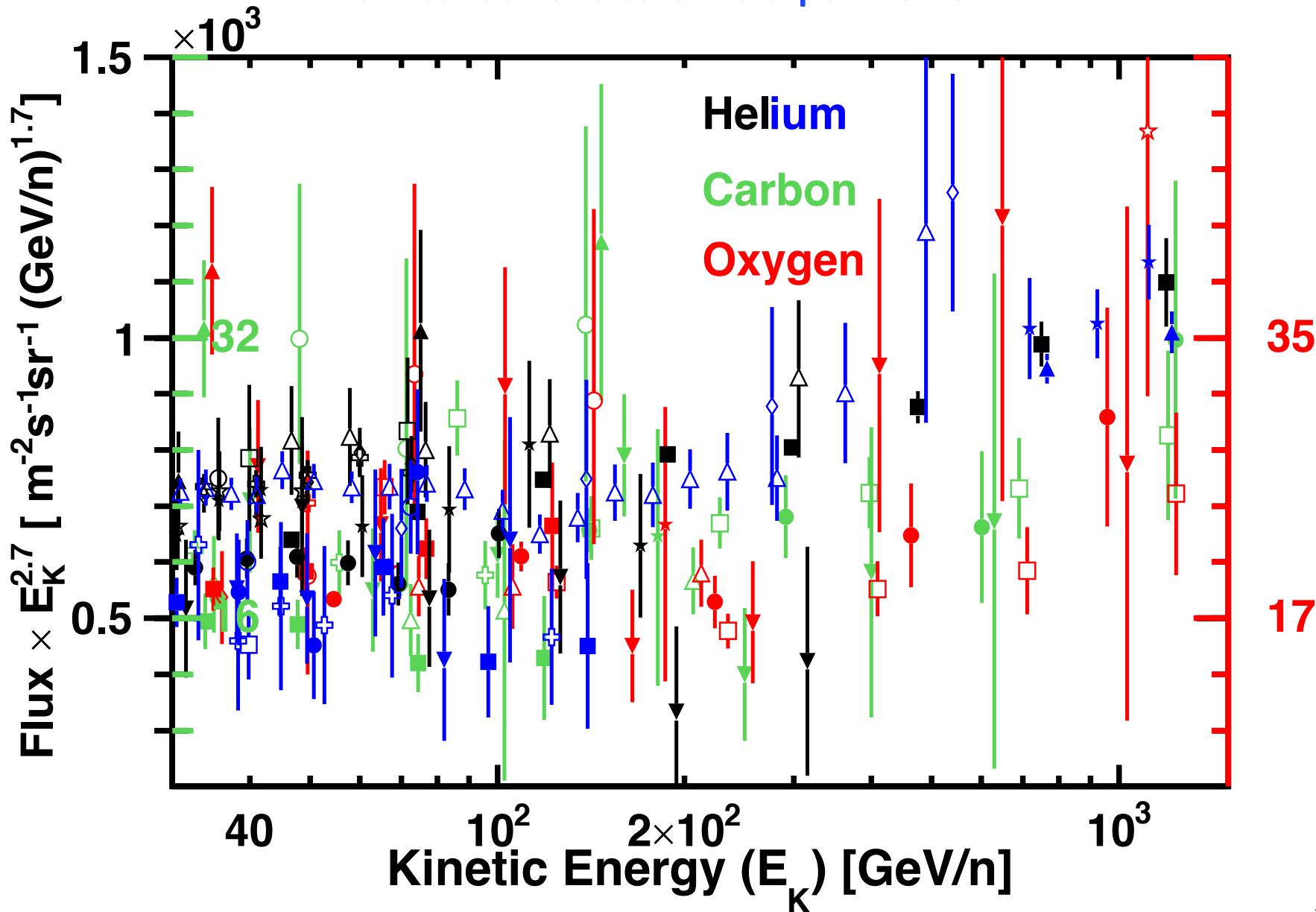


The Helium flux cannot be described by a single power law.

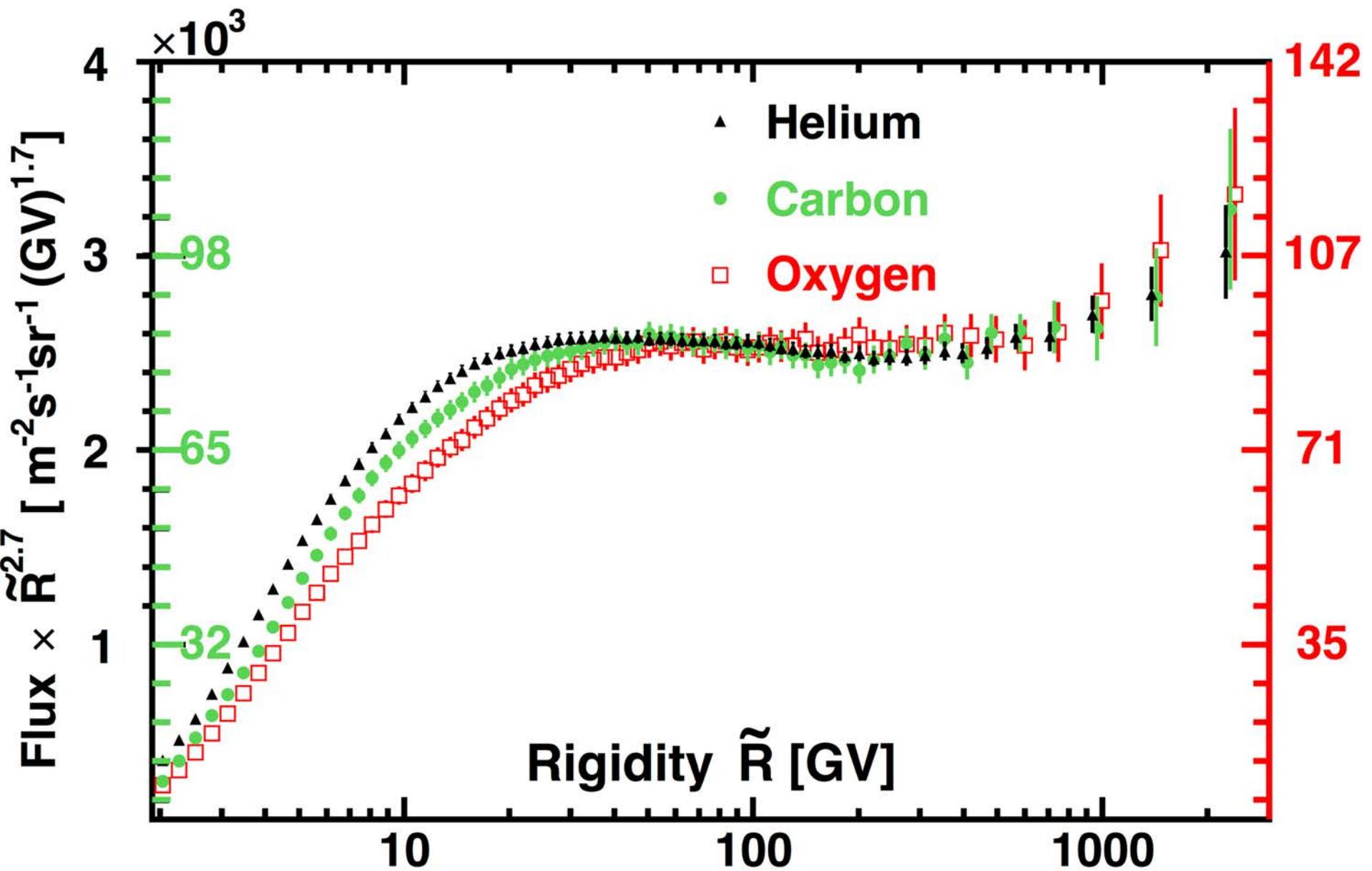
Before AMS: results on Primary Cosmic Rays (Helium, Carbon, Oxygen) from balloon and satellite experiments

- AMS01(1998/06)
- ATIC02(2003/01)
- ▲ Balloon(1970/09+1971/05)
- ▼ Balloon(1970/11)
- Balloon(1976/05)
- Balloon(1979/06)
- △ Balloon(1991/09)
- ◊ BESS-PolarI(2004/12)
- + BESS-PolarII(2007/12-2008/01)
- ★ BESS-TeV(2002/08)
- ☆ BESS98(1998/07)
- CAPRICE94(1994/08)
- CAPRICE98(1998/05)
- ▲ CREAM-I(2004/12-2005/01)
- ▼ IMAX92(1992/07)
- LEAP(1987/08)
- MASS91(1991/09)
- △ PAMELA(2006/07-2008/12)
- ◊ PAMELA-CALO(2006/06-2010/01)
- + RICH-II(1997/10)
- ★ SOKOL(1984/03-1986/01)
- ATIC02(2003/01)
- Balloon(1971/09+1972/10)
- ▲ Balloon(1972/10)
- ▼ Balloon(1976/10)
- Balloon(1991/09)
- CREAM-II(2005/12-2006/01)
- △ CRN-Spacelab2(1985/07-1985/08)
- ◊ HEAO3-C2(1979/10-1980/06)
- + PAMELA(2006/07-2008/03)
- ★ TRACER06(2006/07)
- ATIC02(2003/01)
- Balloon(1971/09+1972/10)
- ▲ Balloon(1972/10)
- ▼ Balloon(1976/10)
- Balloon(1991/09)
- CREAM-II(2005/12-2006/01)
- △ CRN-Spacelab2(1985/07-1985/08)
- ◊ HEAO3-C2(1979/10-1980/06)
- + TRACER03(2003/12)
- ★ TRACER06(2006/07)
- TRACER99

Before AMS: results on Primary Cosmic Rays
(Helium, Carbon, Oxygen)
from balloon and satellite experiments

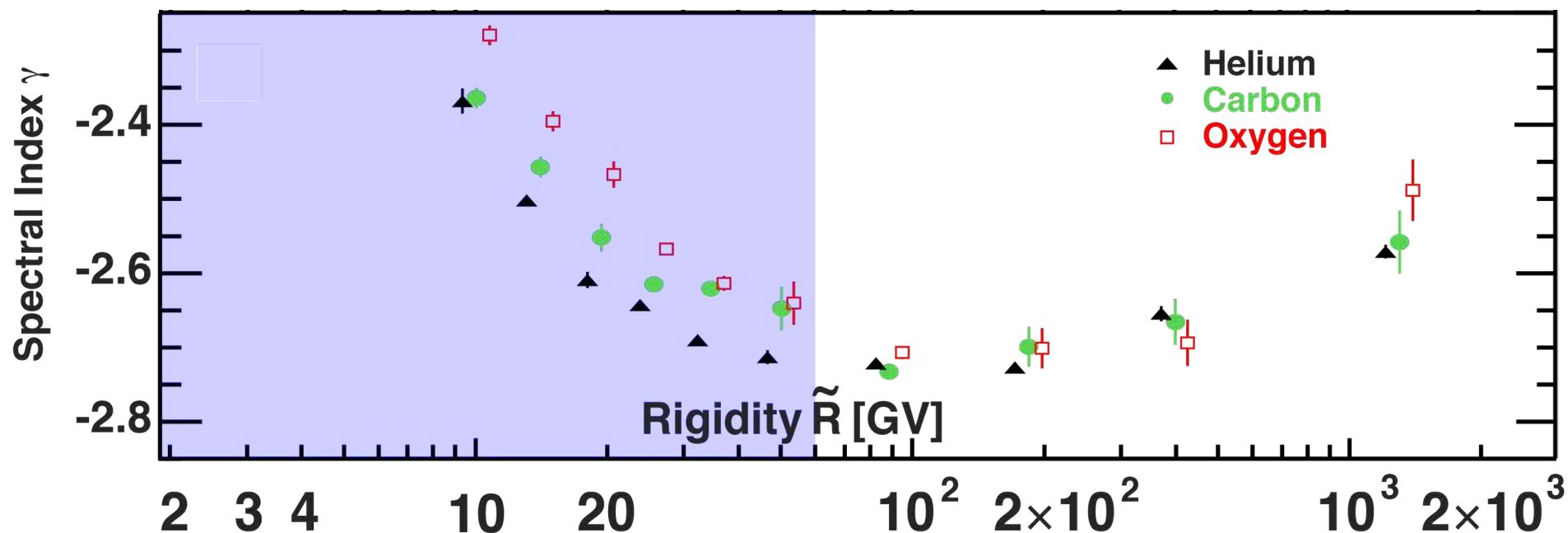


The AMS results on primary cosmic rays He, C, and O.



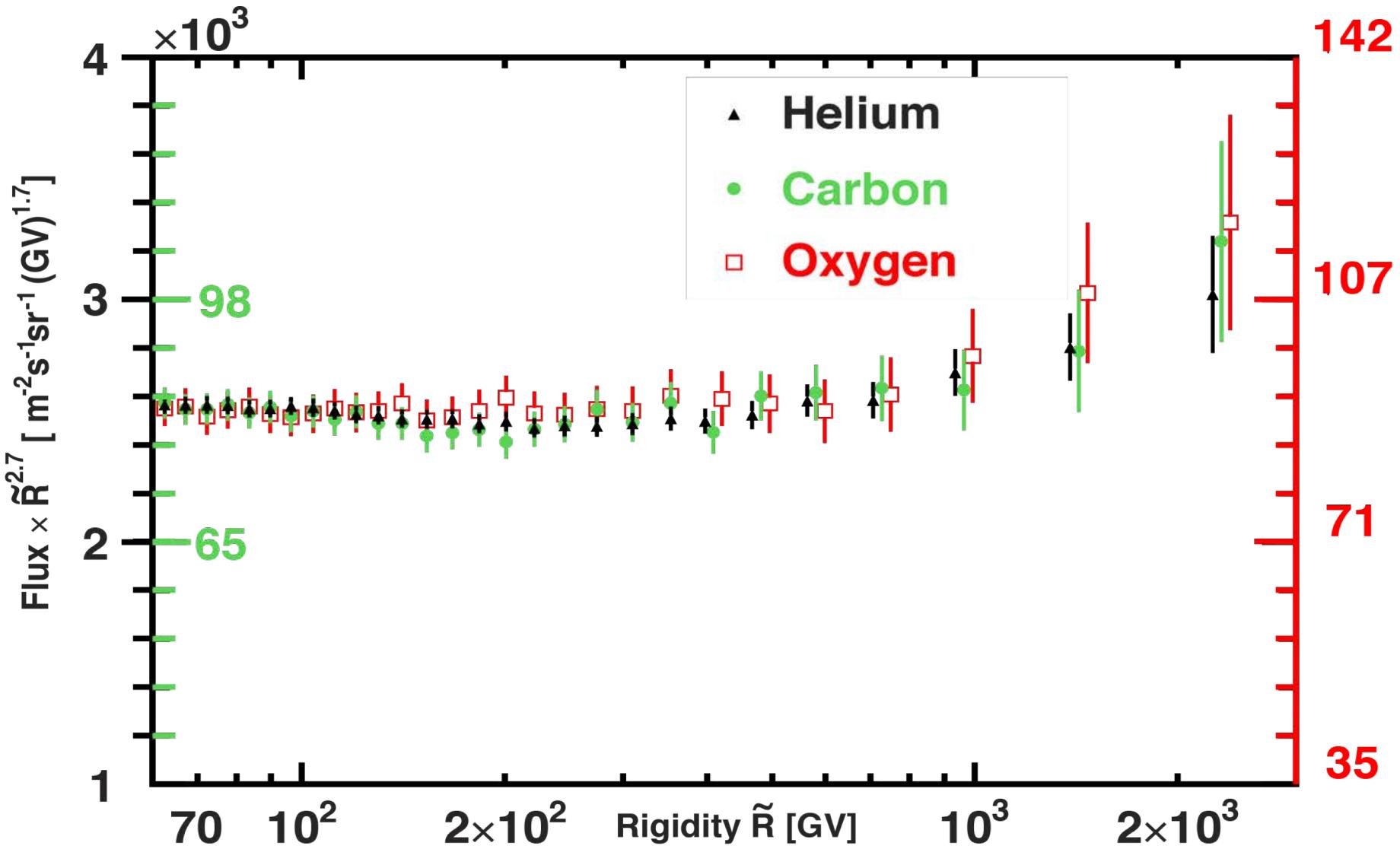
The AMS results on primary cosmic rays He, C, and O.

$$\phi = CR^\gamma$$



Above 60 GV the spectral indices are identical

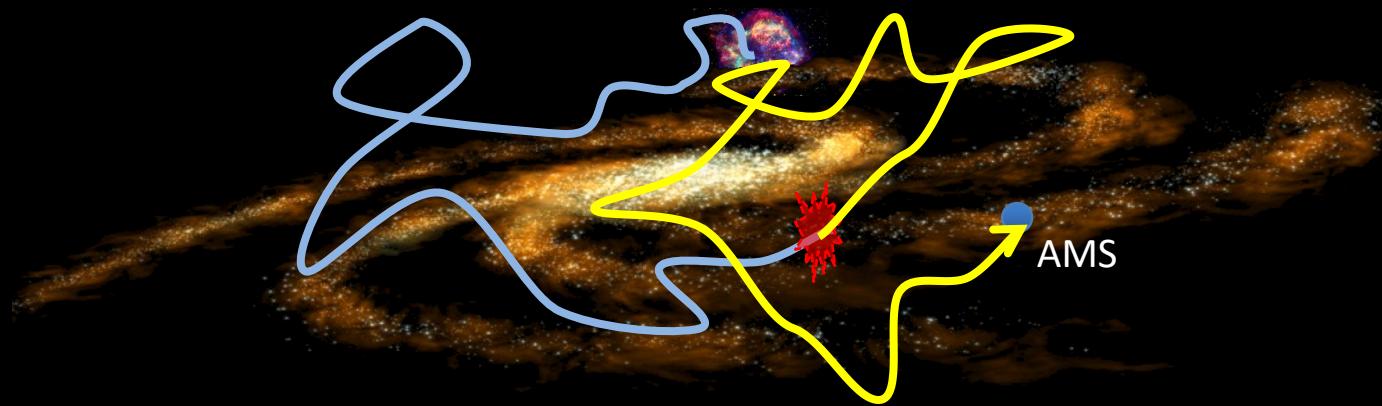
The AMS results show that the primary cosmic rays (He, C, and O) have identical rigidity dependence.



Above 200 GV the data all increase in identical way.
This is unexpected.

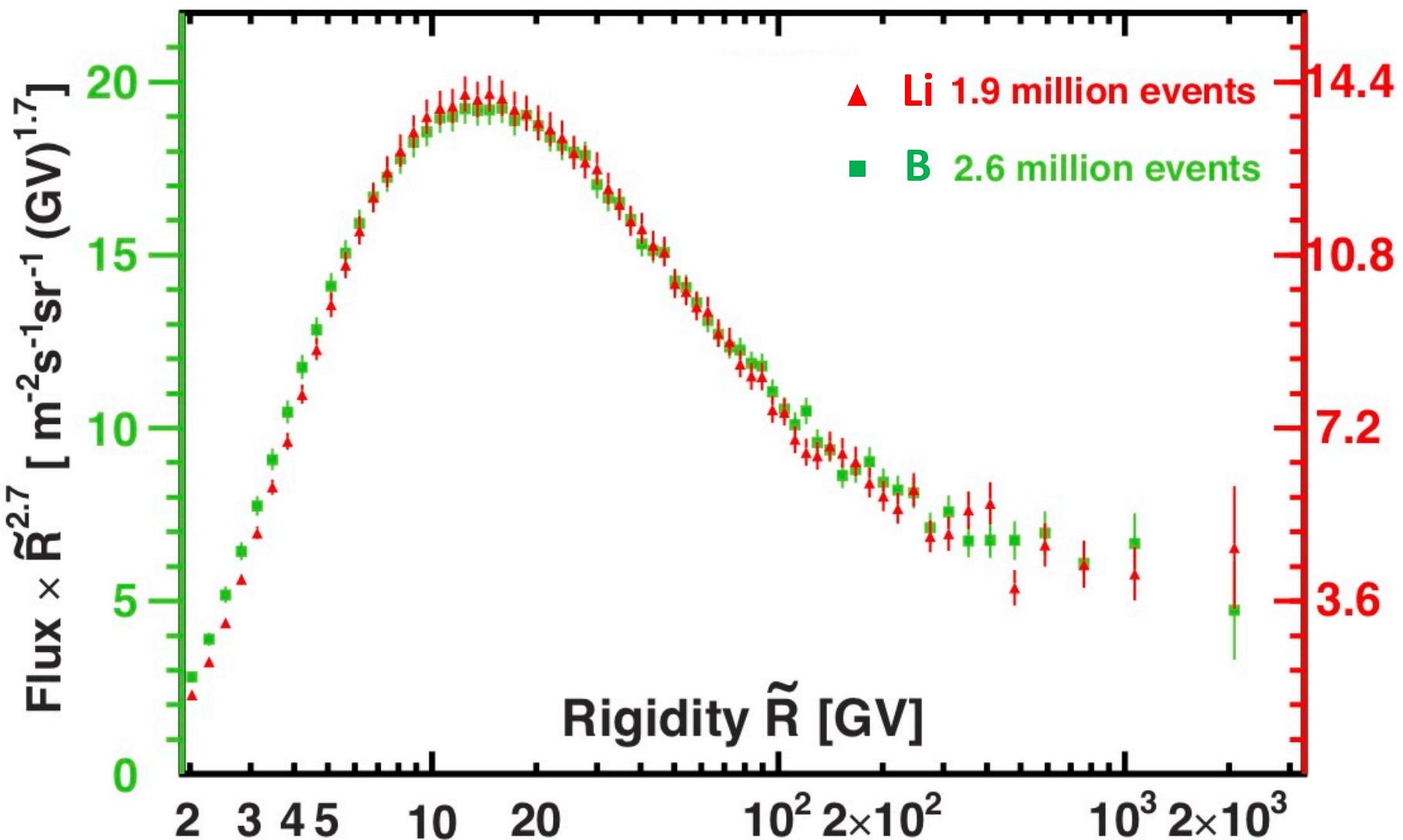
Secondary Cosmic Rays (Li, Be, B, ...)

are produced in the collisions of primary cosmic rays. They carry information on the history of the travel and on the properties of the interstellar matter.



Secondary Cosmic Rays: Lithium and Boron

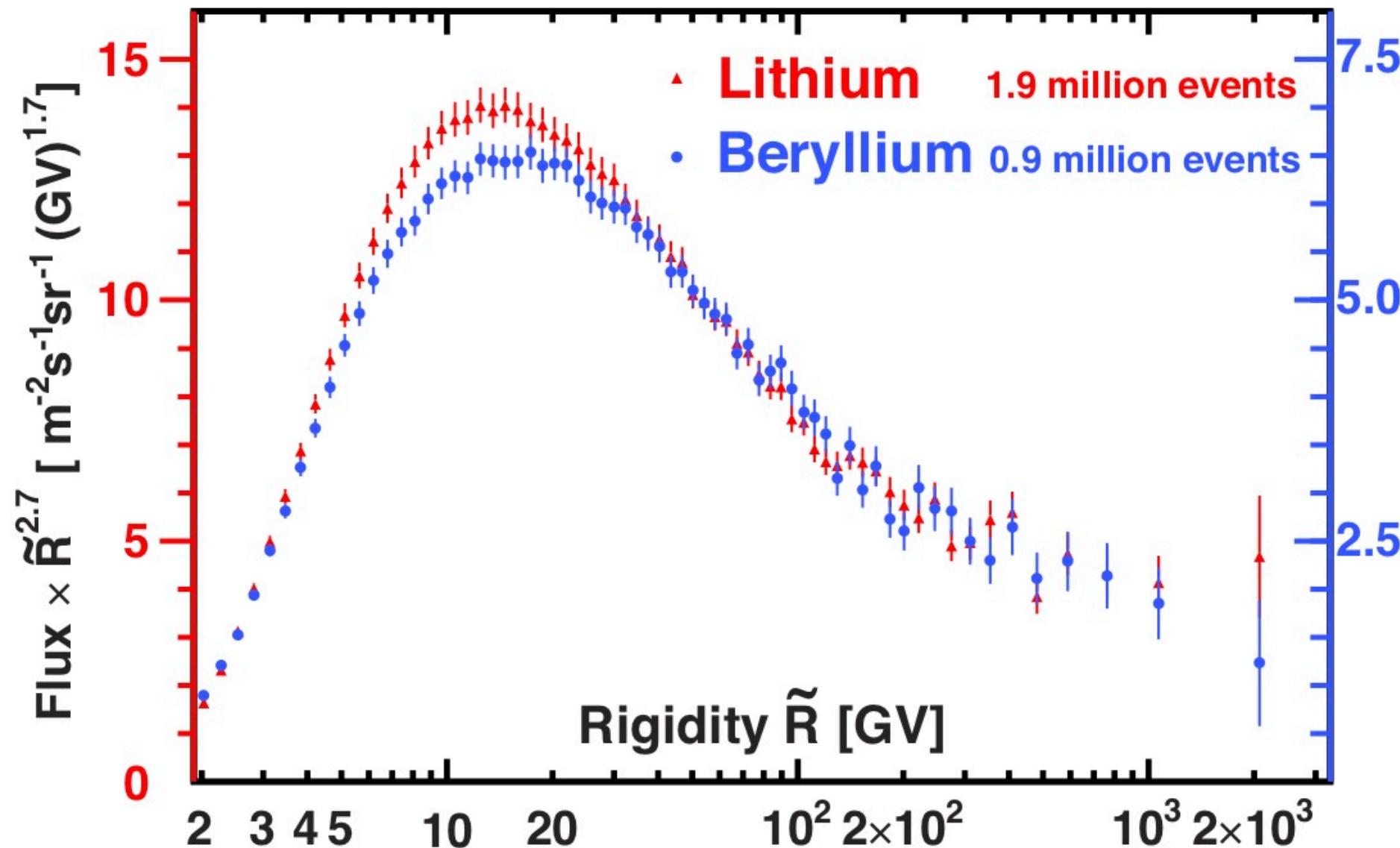
Above 7 GV Li and B have identical rigidity dependence



Secondary Cosmic Rays: Lithium and Beryllium

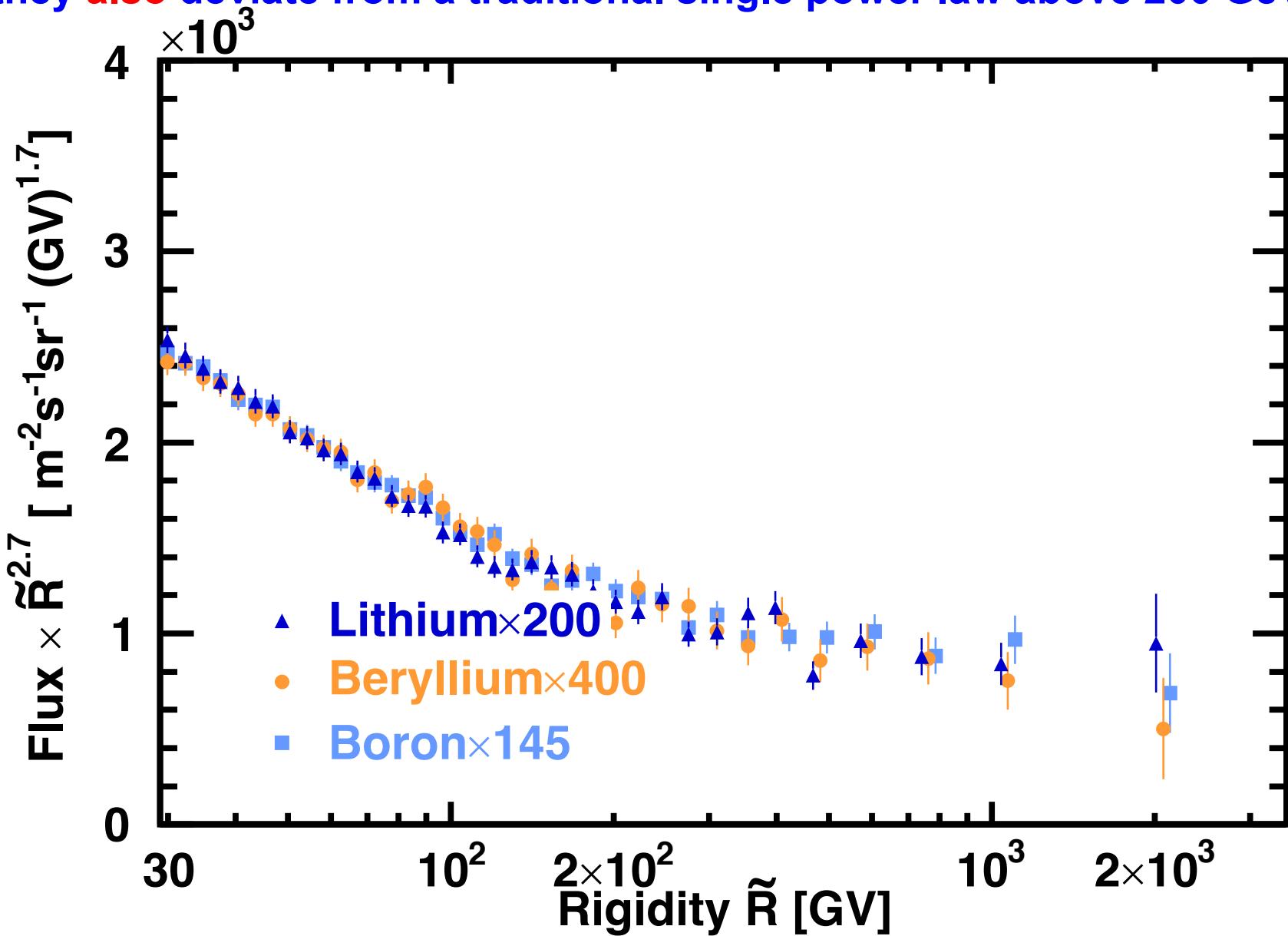
Above 30 GV Li and Be have identical rigidity dependence.

The fluxes are different by a factor of 2.



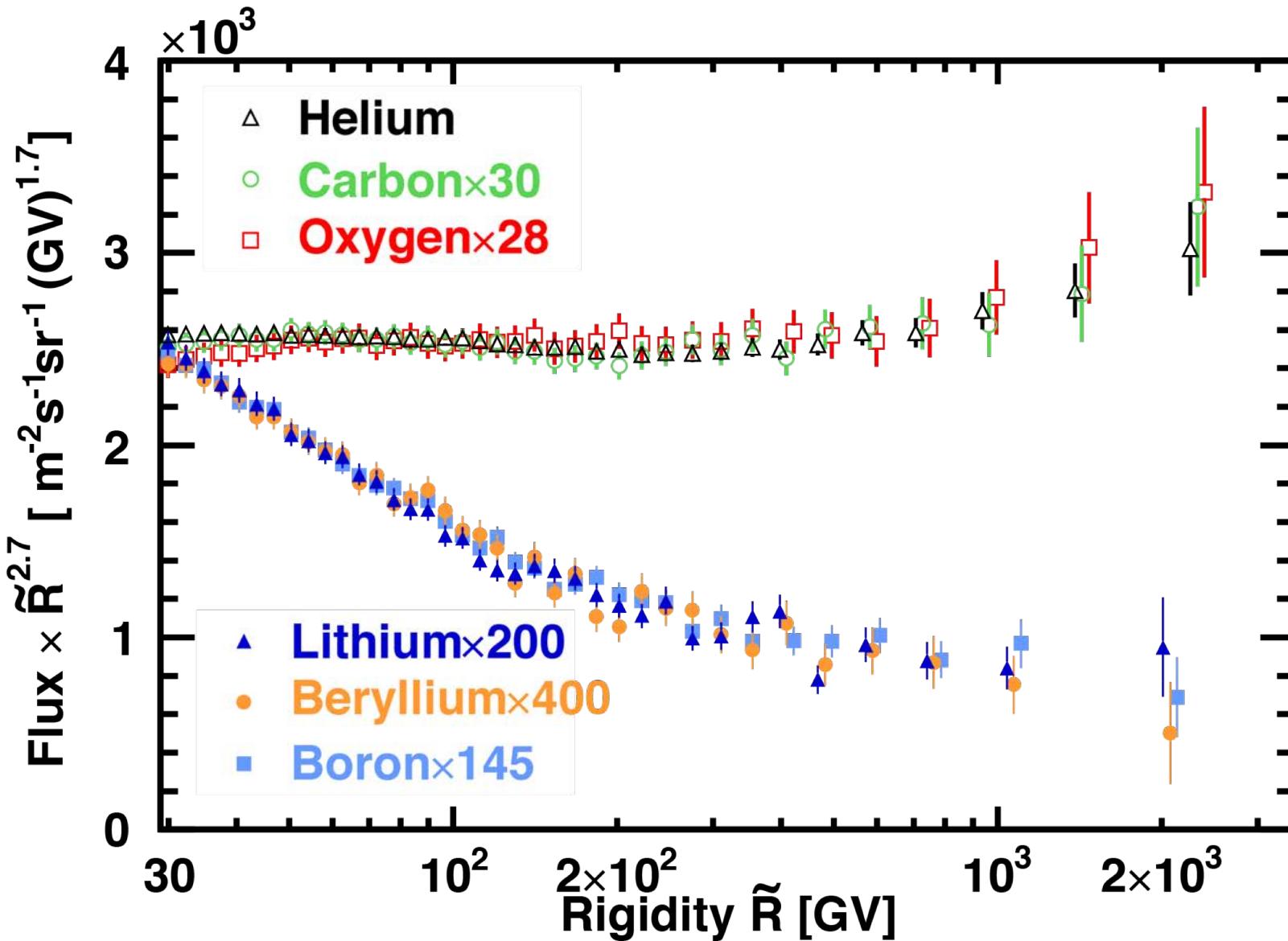
Rigidity dependence of Secondary Cosmic Rays

(Li, Be, and B) have identical rigidity dependence and they also deviate from a traditional single power law above 200 GeV.

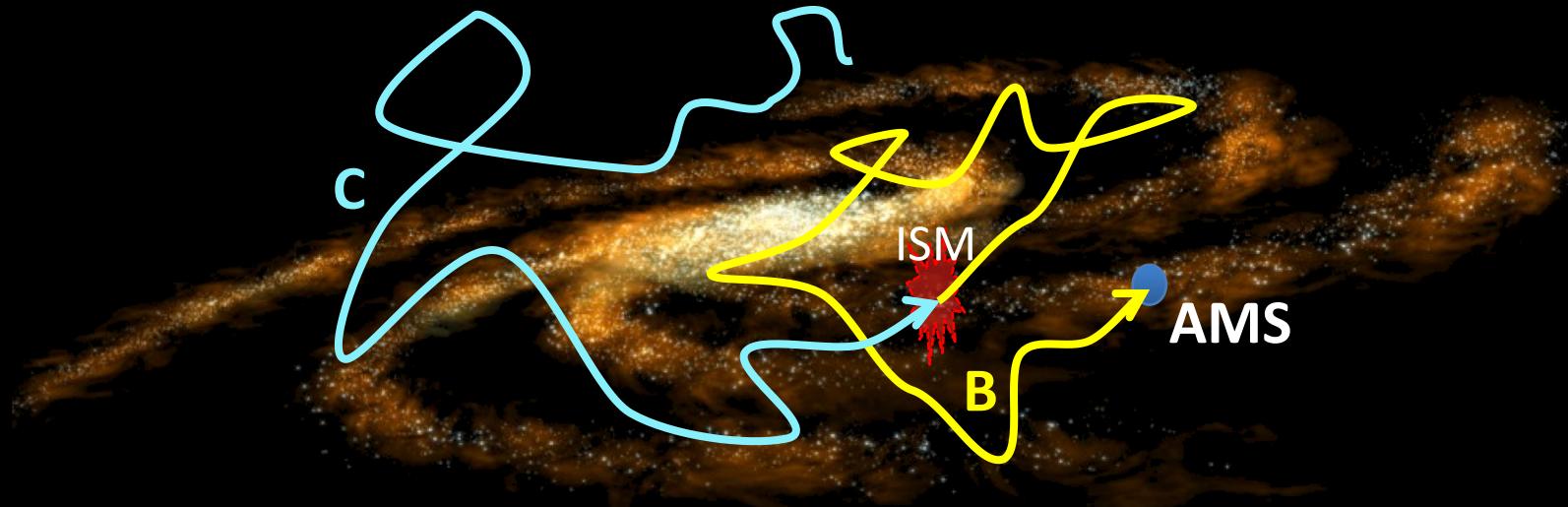


Rigidity dependence of Primary and Secondary Cosmic Rays

Both deviate from a traditional single power law above 200 GeV.
But their rigidity dependences are distinctly different.



The flux ratio between primaries (C) and secondaries (B) provides information on propagation and on the Interstellar Medium (ISM)

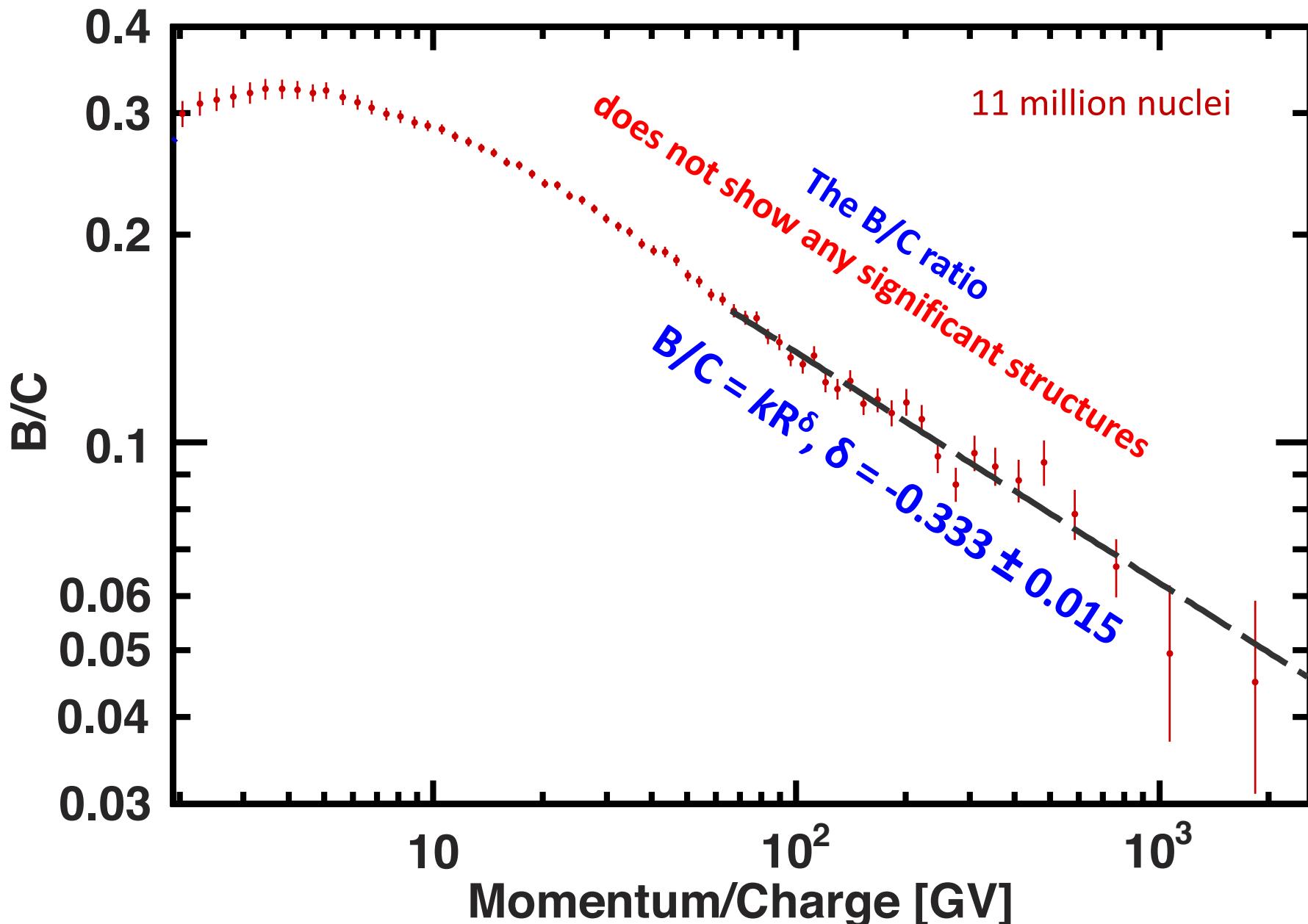


Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

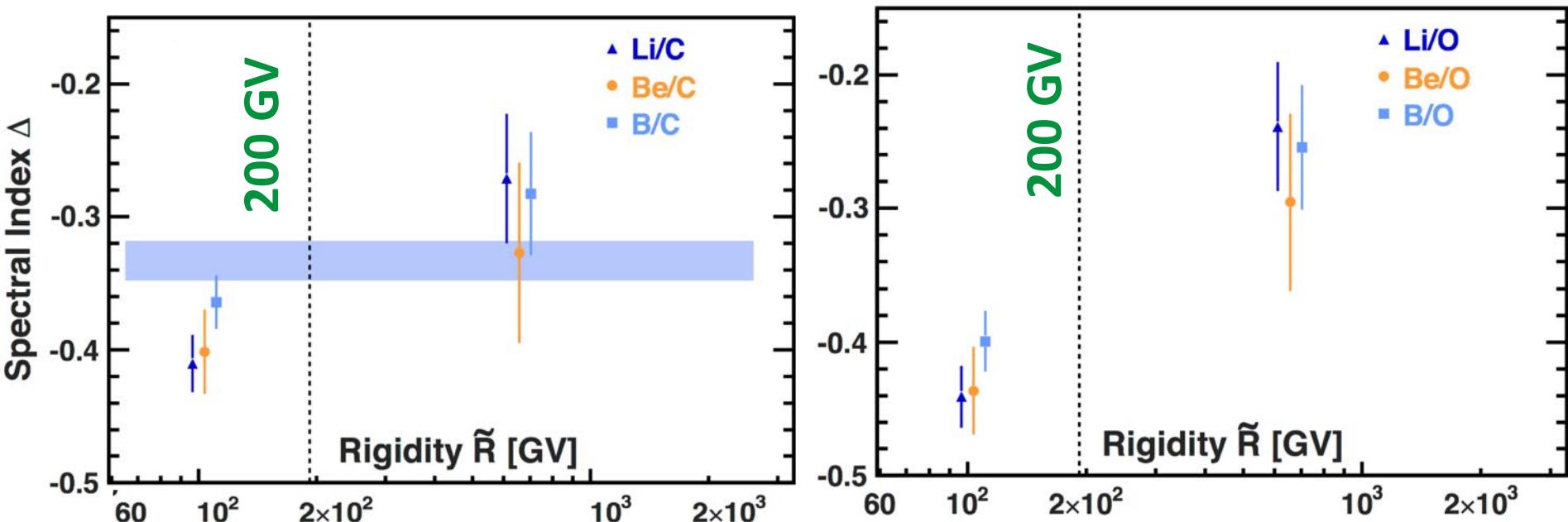
At high rigidities, models of the magnetized plasma predict different behavior for $B/C = kR^\delta$.

With the Kolmogorov turbulence model $\delta = -1/3$

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



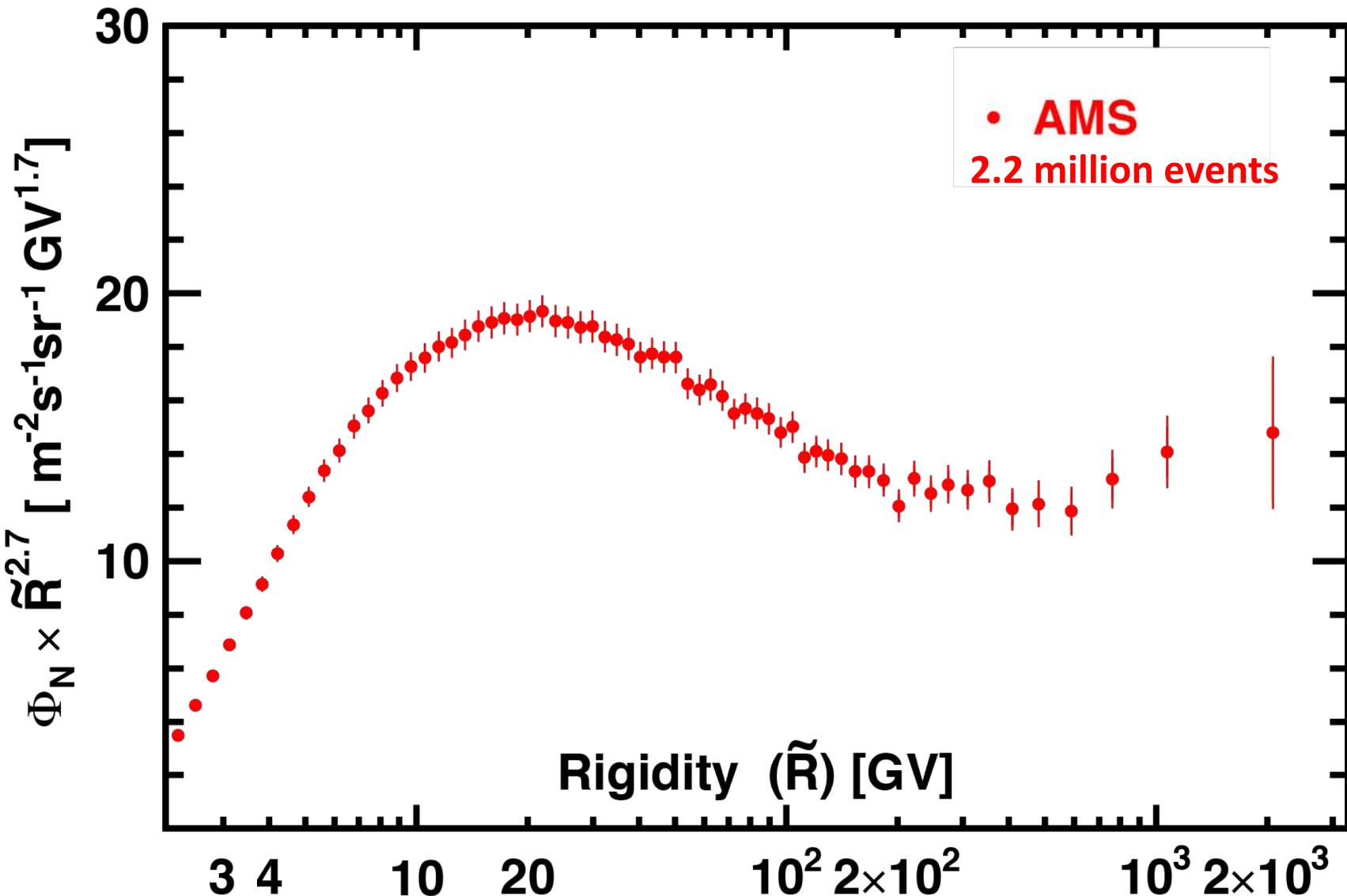
New result on Secondary/Primary Flux Ratios = KR^Δ



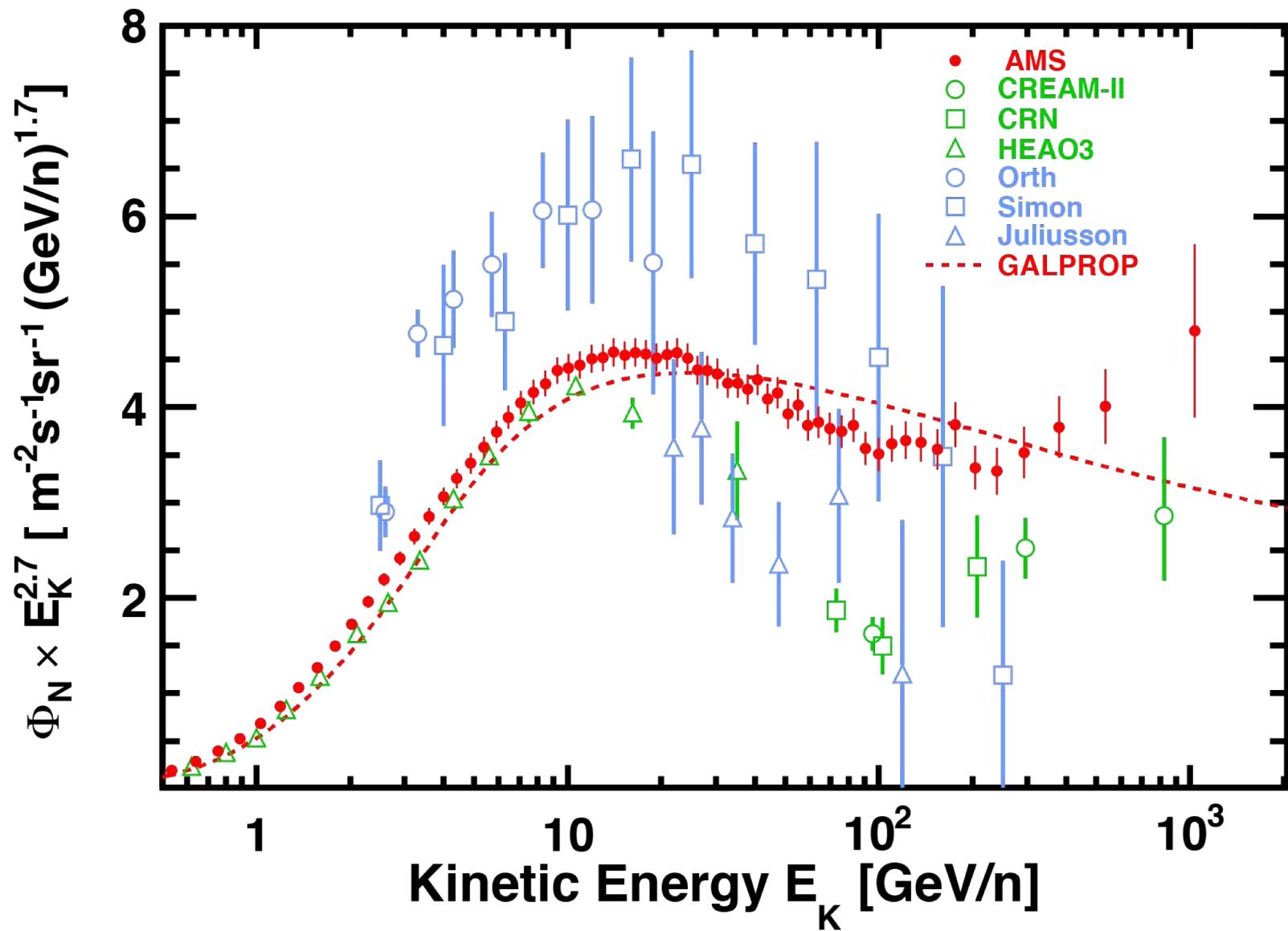
Combining the six ratios,
the secondary over primary flux ratio (B/C, ...),
deviates from single power law above 200 GV by 0.13 ± 0.03

$$\Delta[200-3300\text{GV}] - \Delta[60-200\text{GV}] = 0.13 \pm 0.03$$

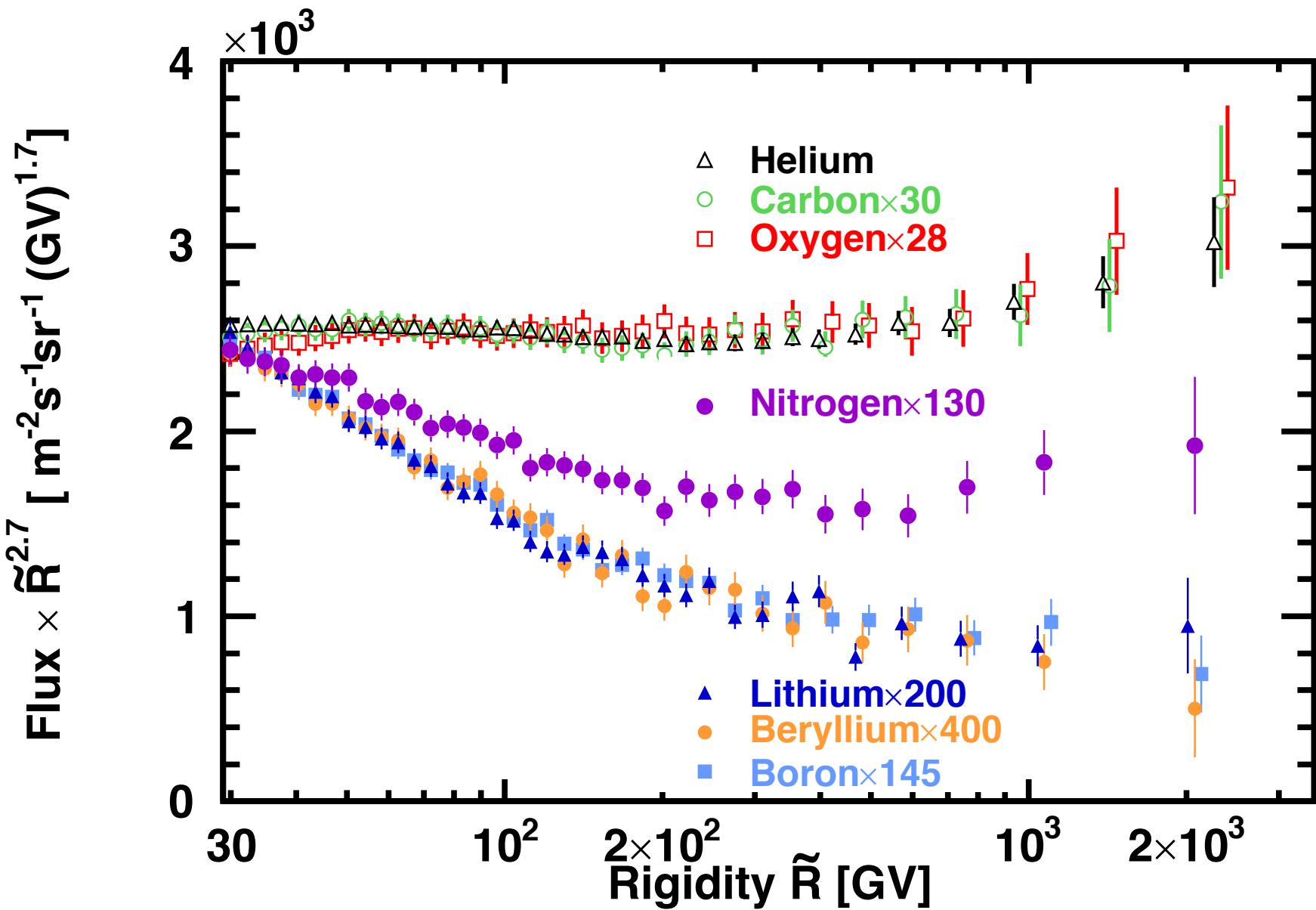
The AMS nitrogen flux Φ_N



The AMS nitrogen flux compared with earlier measurements



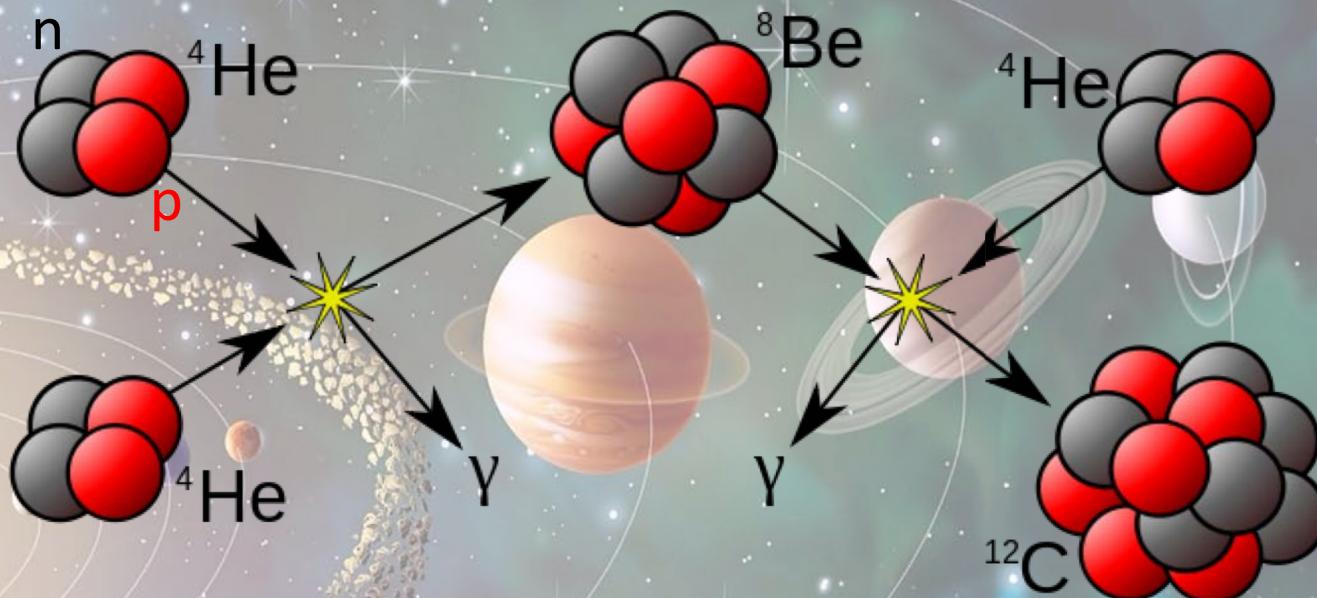
The AMS measurements of the primary cosmic ray fluxes and the secondary cosmic rays fluxes with the nitrogen flux.



Nucleosynthesis in Stars:

^{12}C and ^{16}O production via He Burning

- ^{12}C is produced through triple-a reaction:



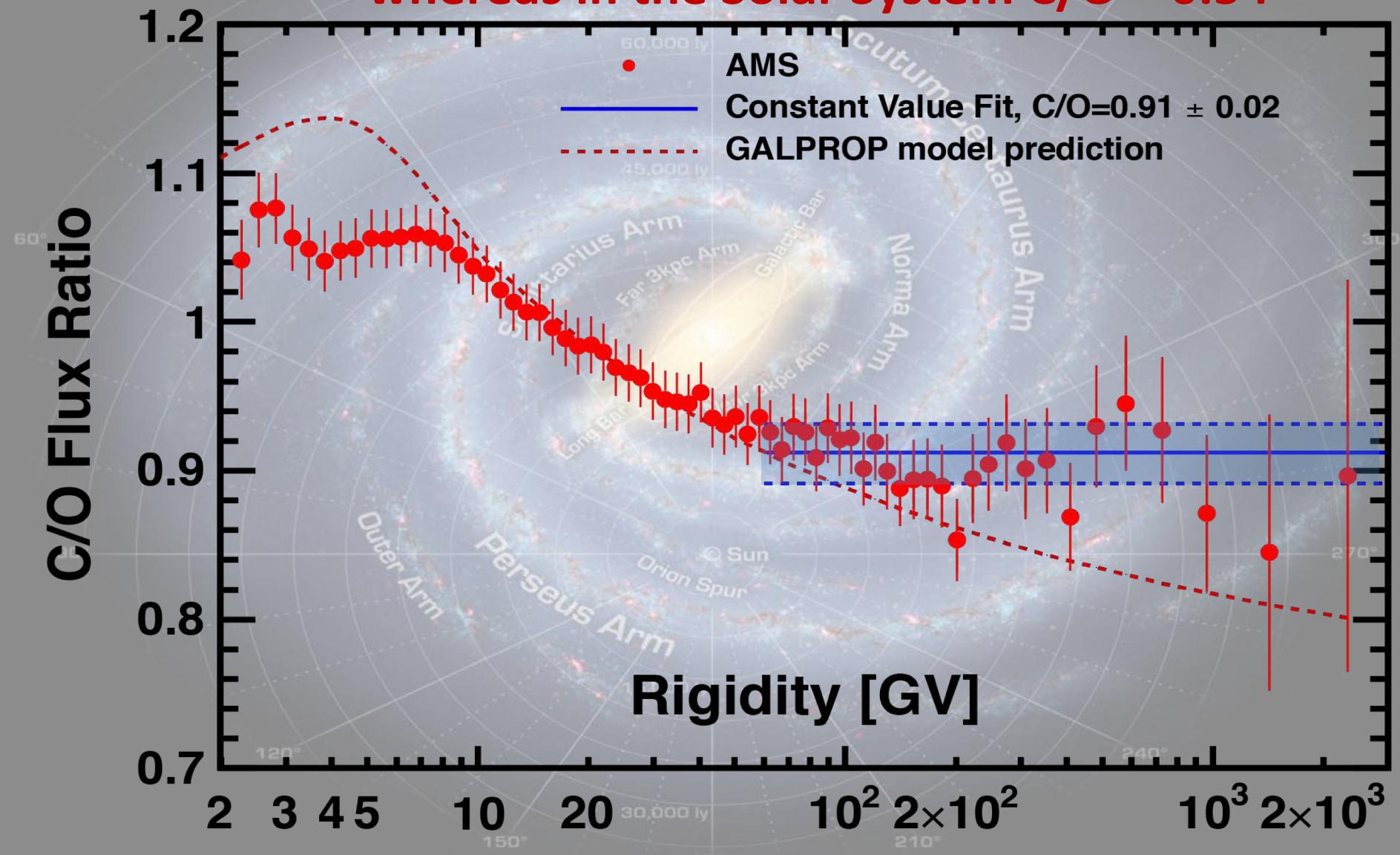
- Carbon nuclei fuse with additional Helium to produce Oxygen nuclei ^{16}O :



In the Solar System: C/O = 0.54

AMS measurement:

Galactic cosmic rays (rigidity >60 GV) C/O = 0.90
whereas in the Solar System C/O = 0.54



Energy Production in Stars

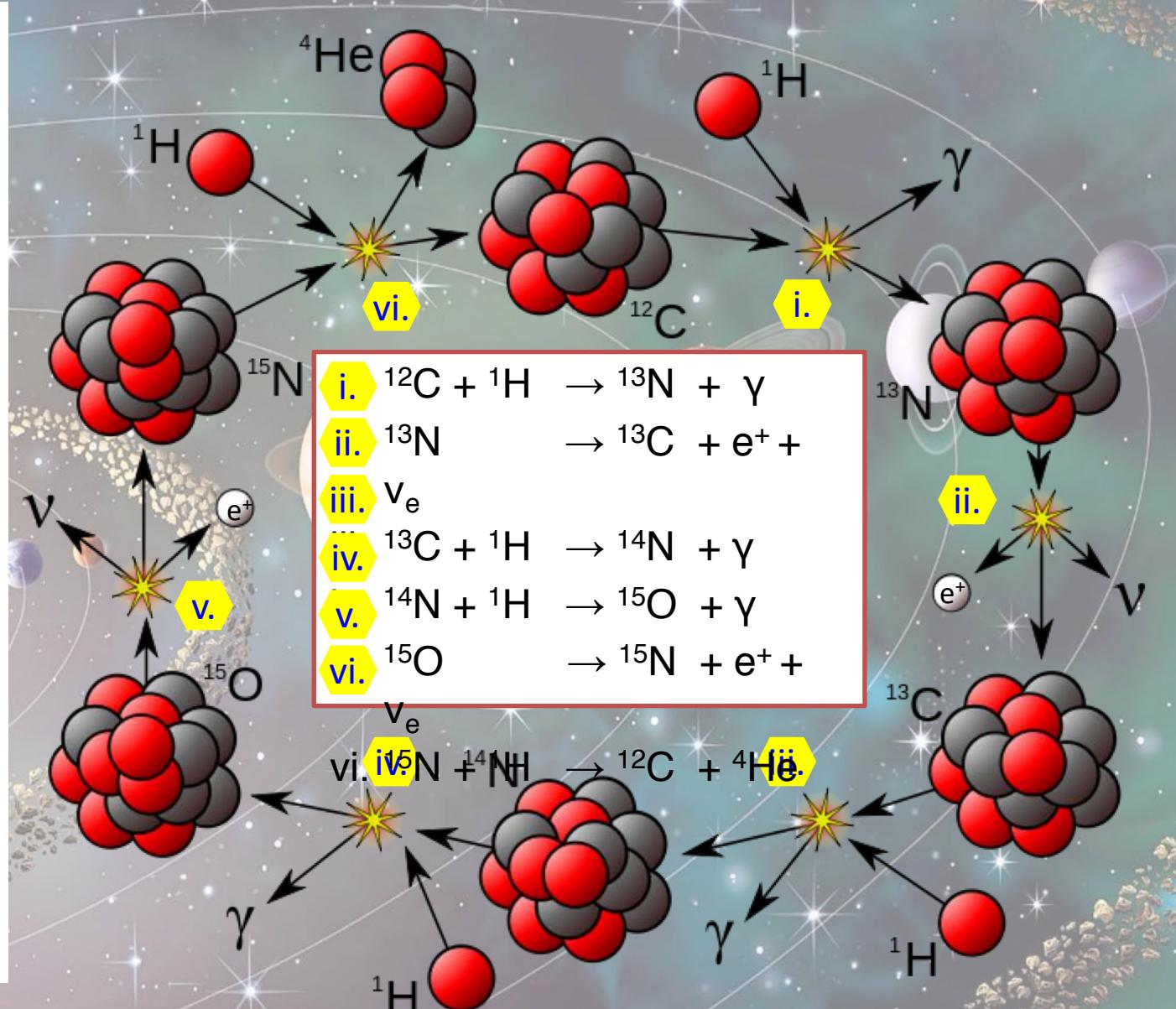
Phys. Rev.
Mar. 1, 1939

H.A. Bethe

Abstract

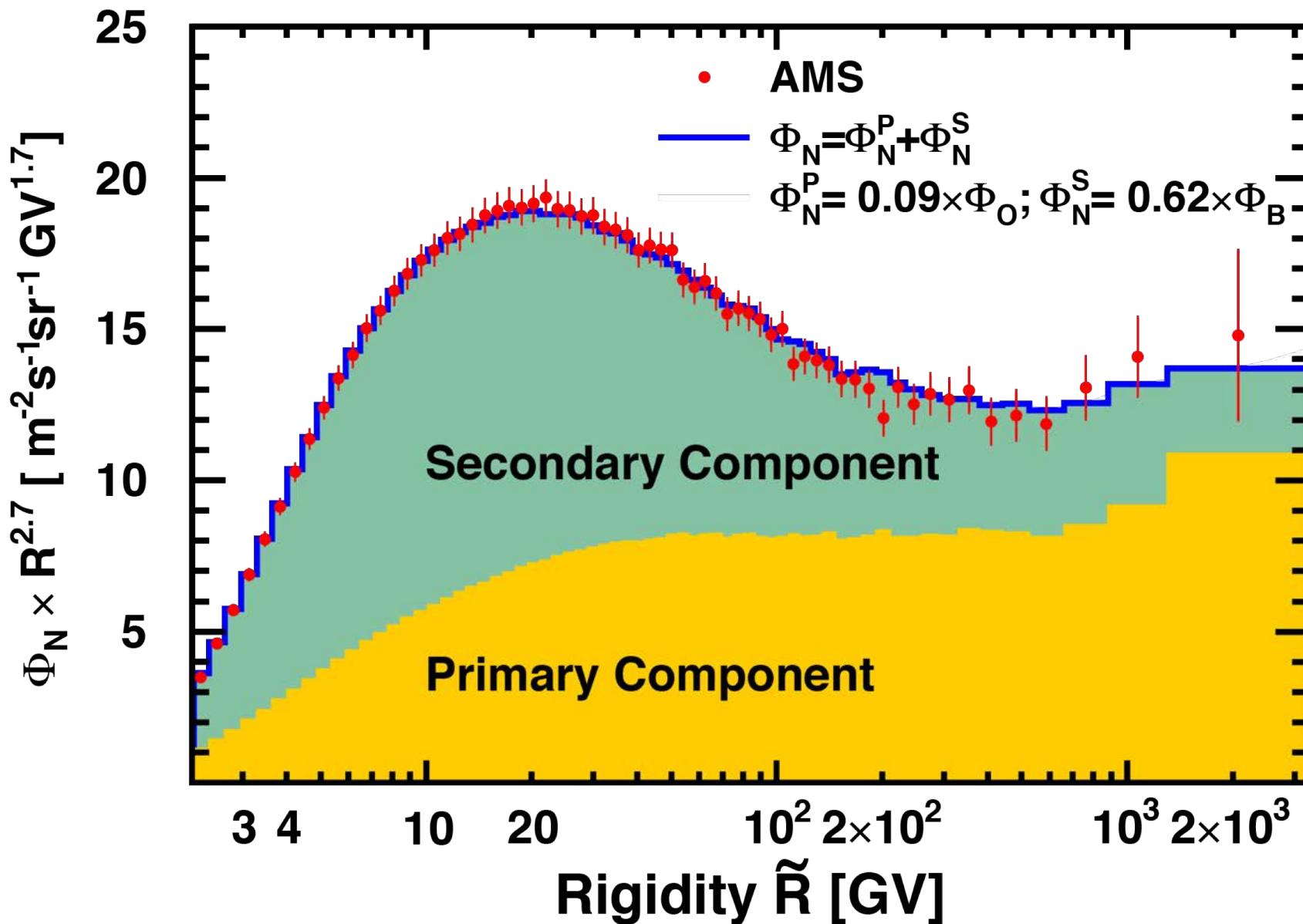
It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced ...

Nobel Prize 1967



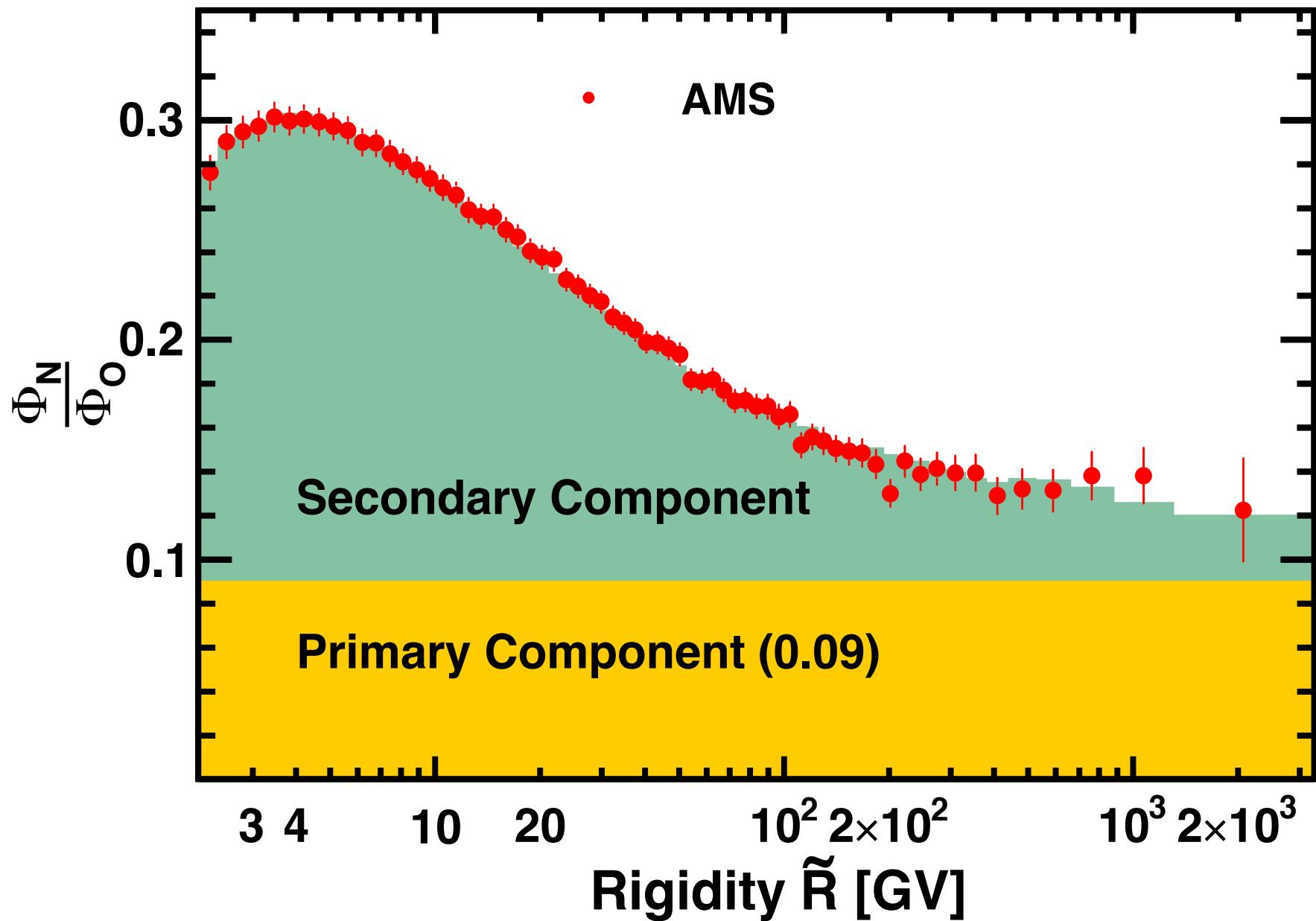
In the Solar System: N/O = 0.17

The Nitrogen flux Φ_N is composed of a Primary flux Φ_N^P and a Secondary flux Φ_N^S

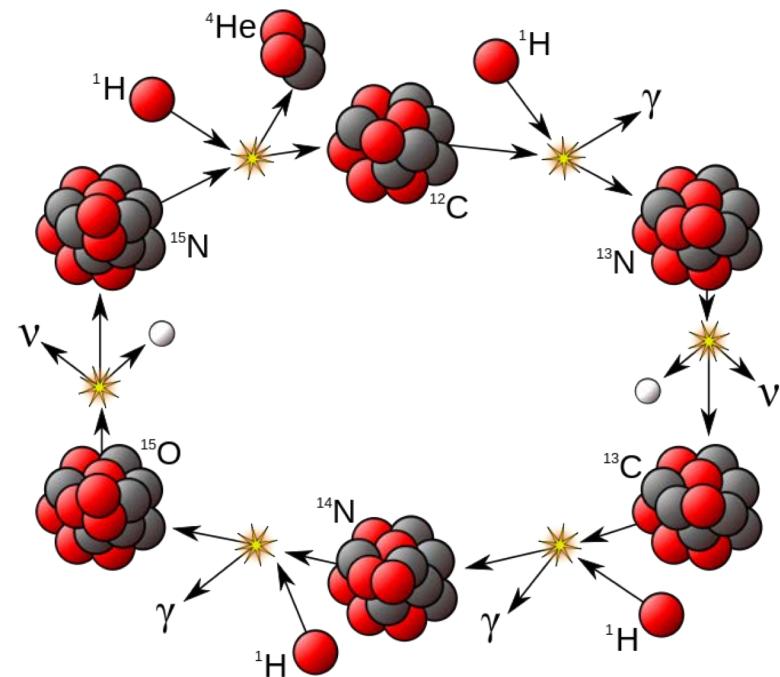
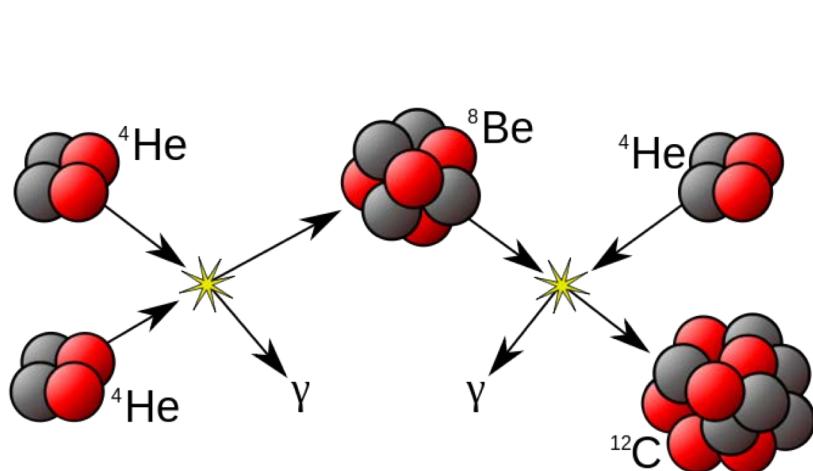


AMS measurement in galactic cosmic rays N/O = 0.09

Whereas in the Solar System N/O = 0.17



Nucleosynthesis in Stars:



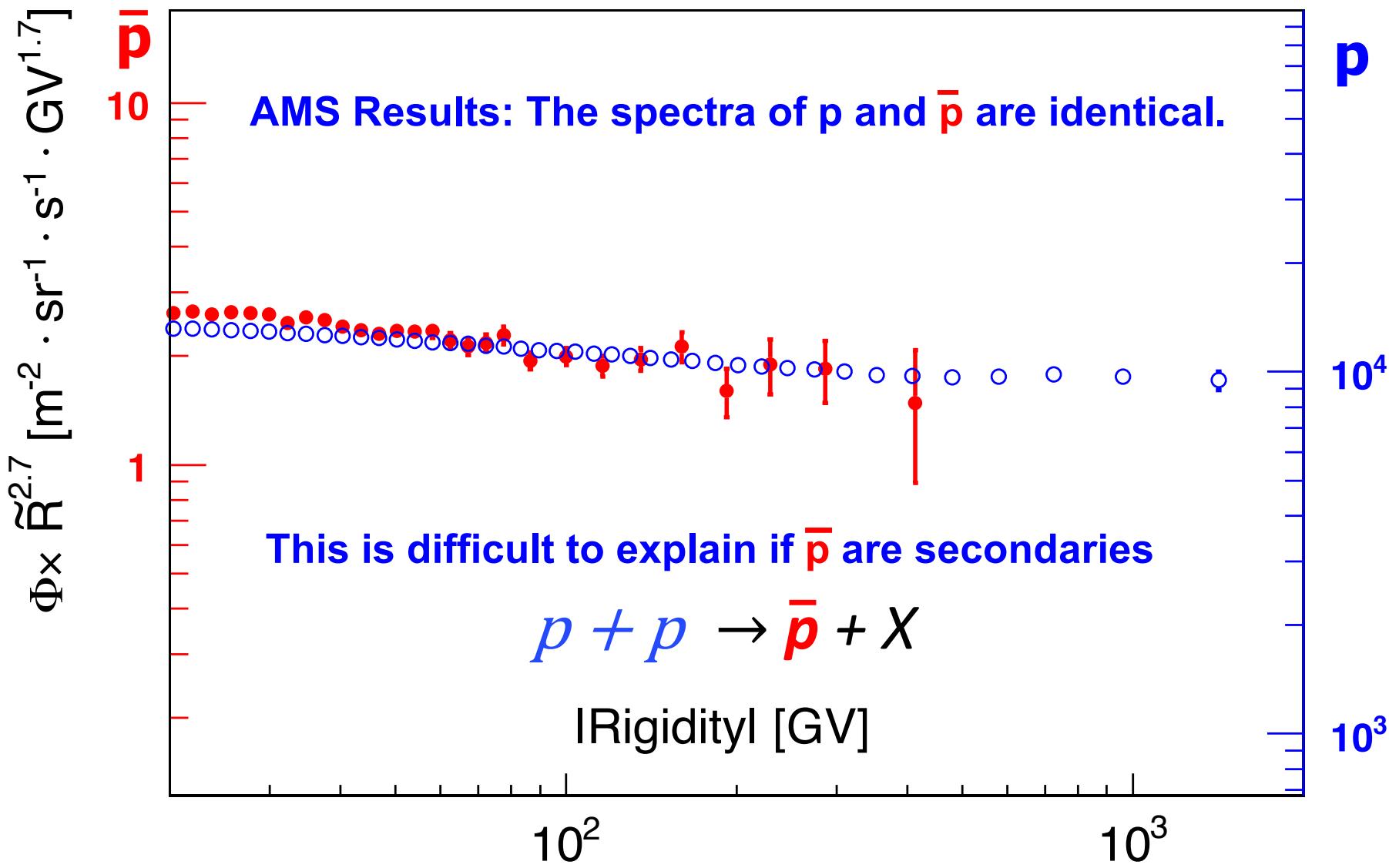
In the Solar System: $\text{C/O} = 0.54$ $\text{N/O} = 0.17$

In Galactic Cosmic Rays: $\text{C/O} = 0.90$ $\text{N/O} = 0.09$

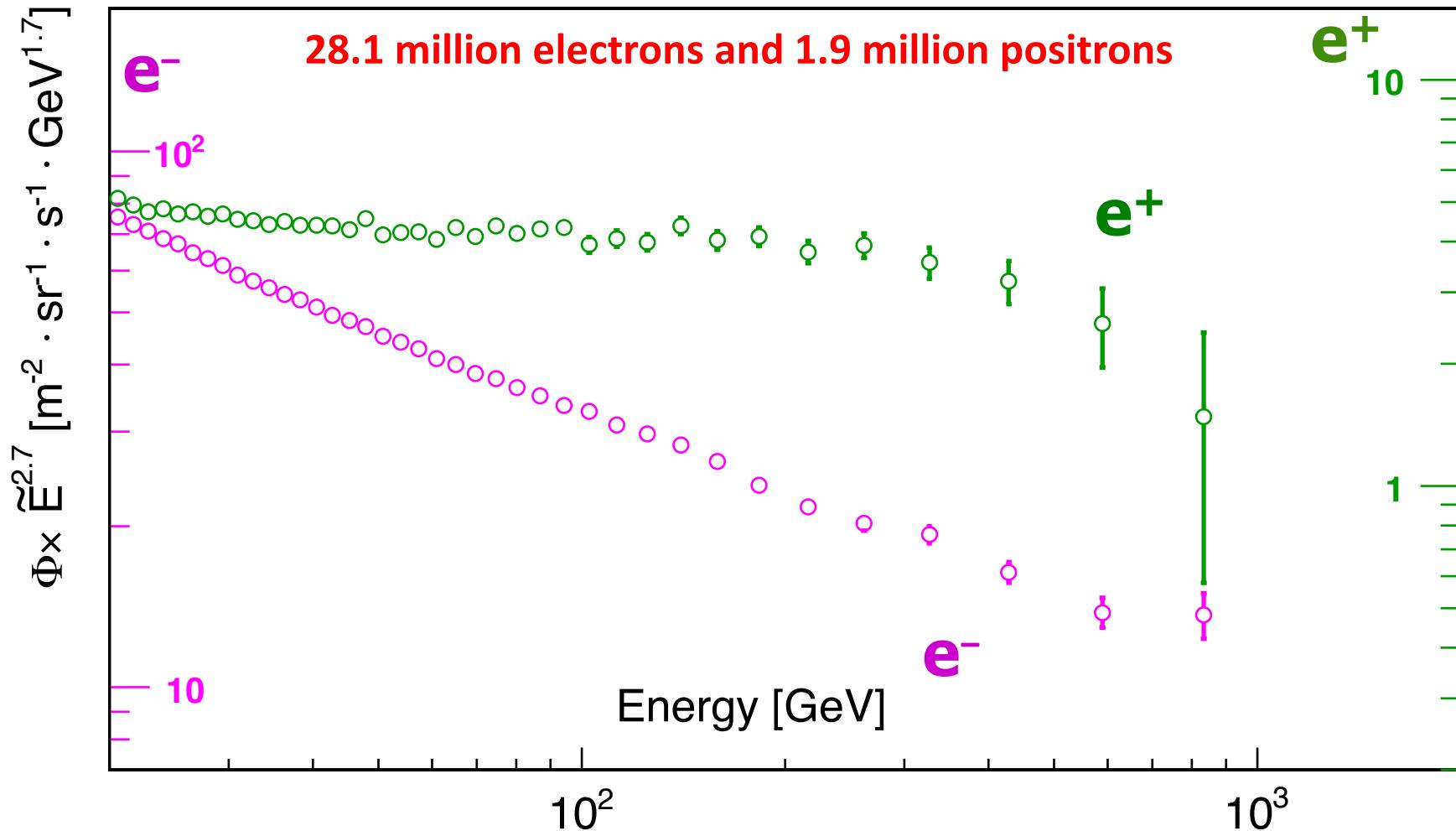
This is an unexpected new result

Elementary Particles in Space

Of the hundreds of charged particles only four of them, e-, e+, p, and \bar{p} , have infinite lifetime, so they travel in the cosmos forever.

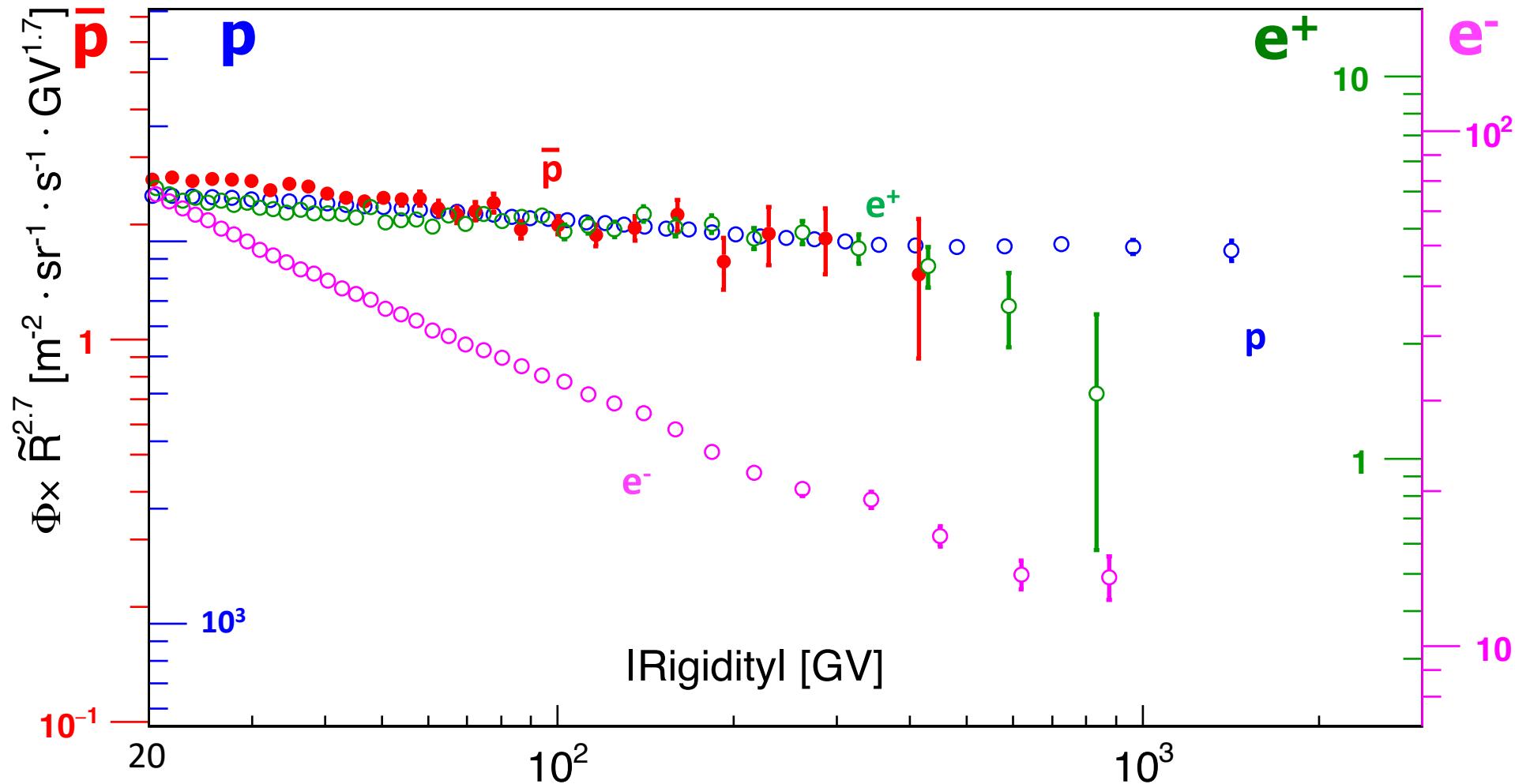


The spectra of electrons and positrons are very different despite the fact that they have identical mass



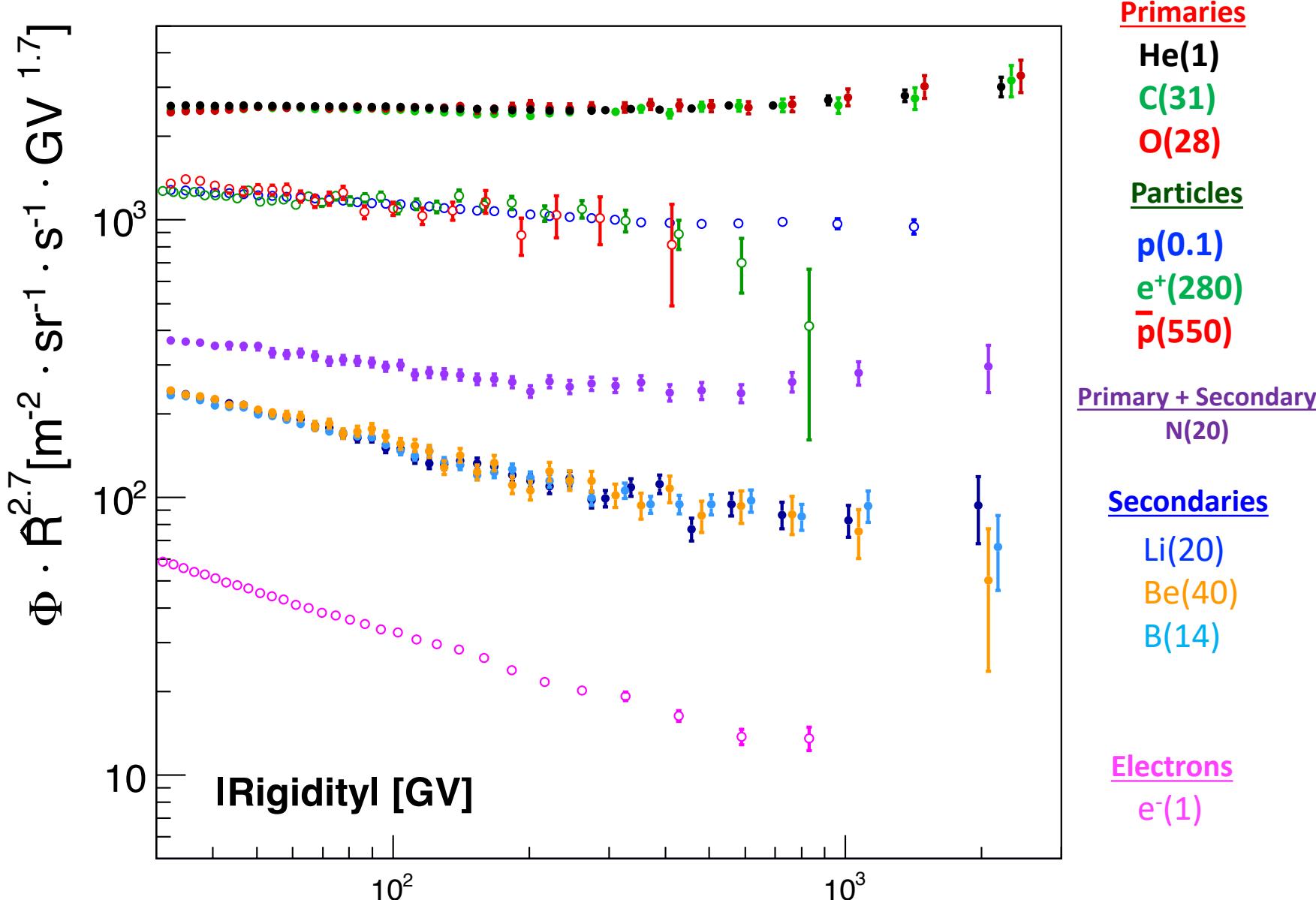
Most surprisingly:

The spectra of positrons, antiprotons, and protons are identical,
but the proton and antiproton mass is 2000 times the positron mass.
The electron spectrum is different



Summary of AMS results on Cosmic Ray Fluxes

High energy cosmic ray fluxes have 5 classes of rigidity dependence.

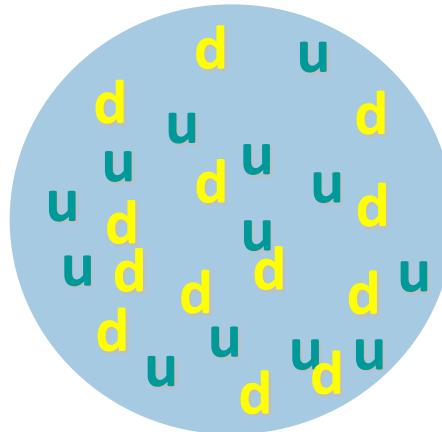


Strange Quark Matter – “Strangelets”

E. Witten, Phys. Rev. D, 272-285 (1984)

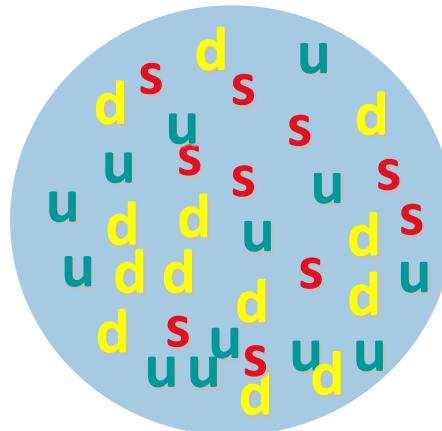
There are six quarks – u, d, s, c, b, and t.

All the material on Earth is made out of u and d quarks



Diamond ($Z/A \sim 0.5$)

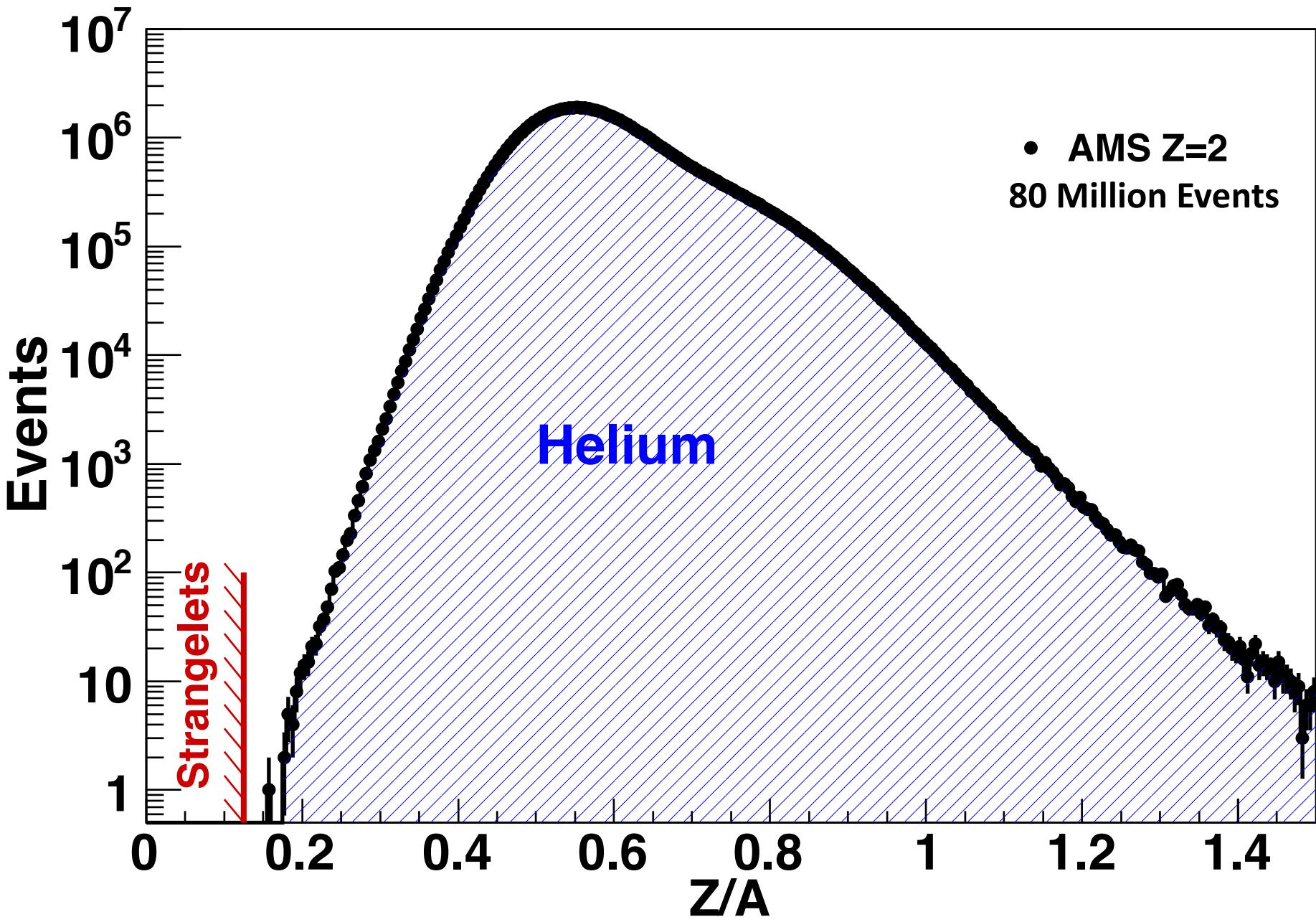
Is there material in the universe made up of u, d, & s quarks?

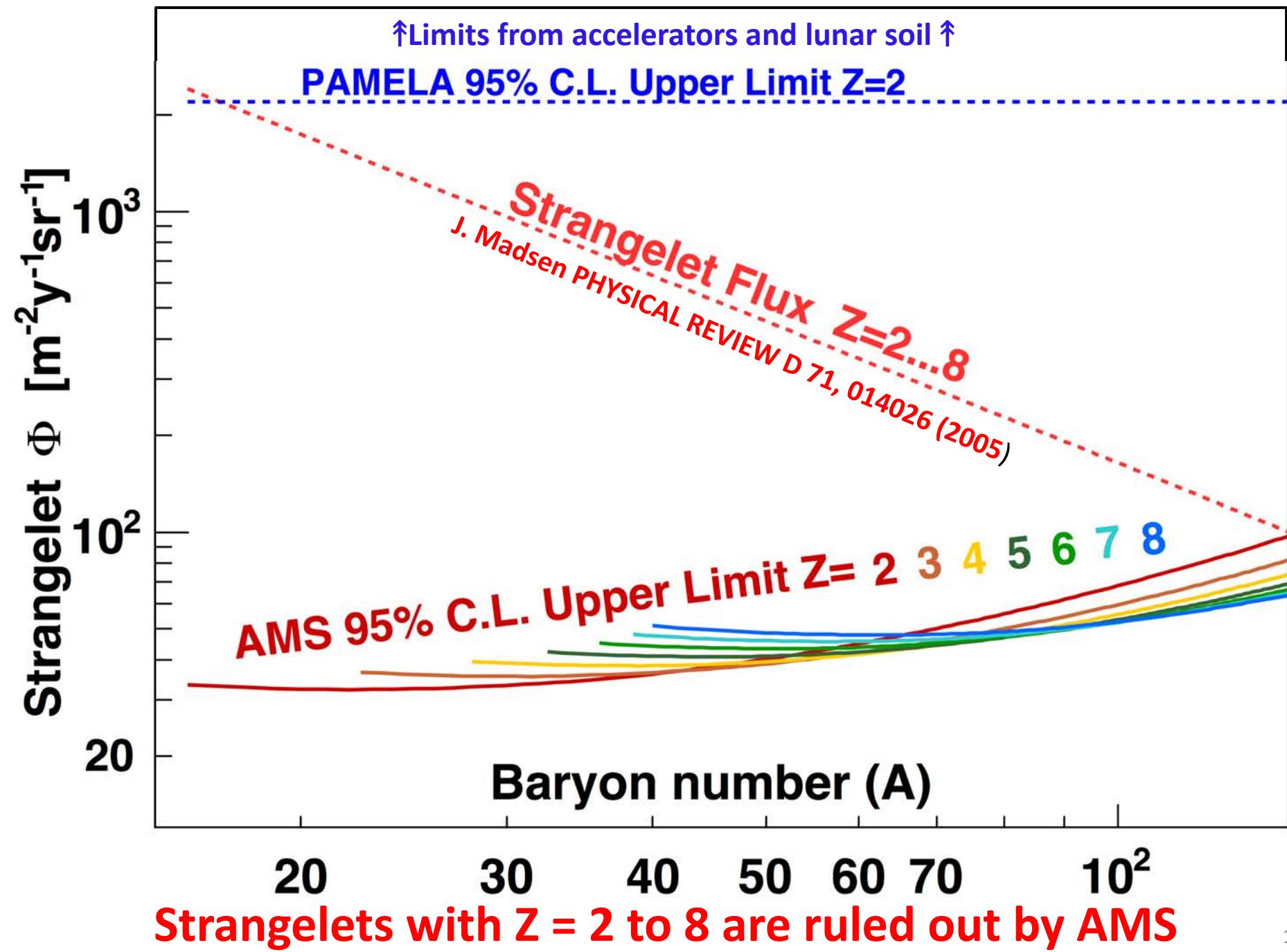


Strangelet ($Z/A < 0.1$)

This is being answered by AMS.

Search for Strangelets Z =2



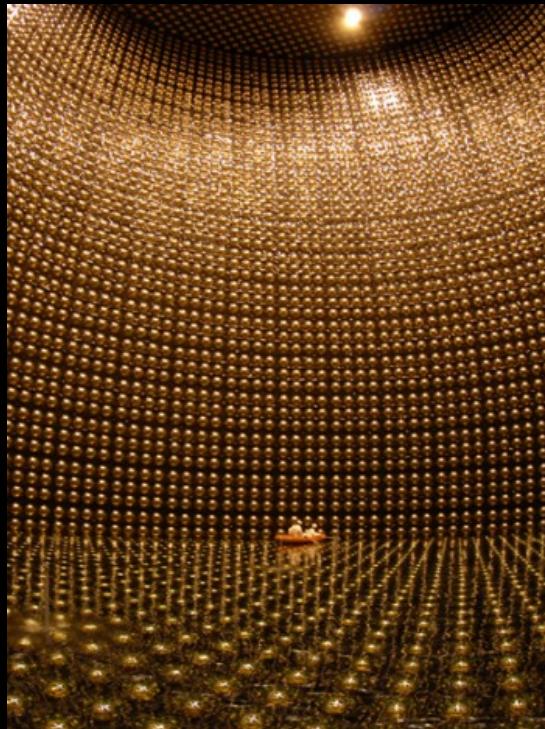


Experimental work on Antimatter in the Universe

Search for Baryogenesis

New symmetry breaking

Proton has finite lifetime



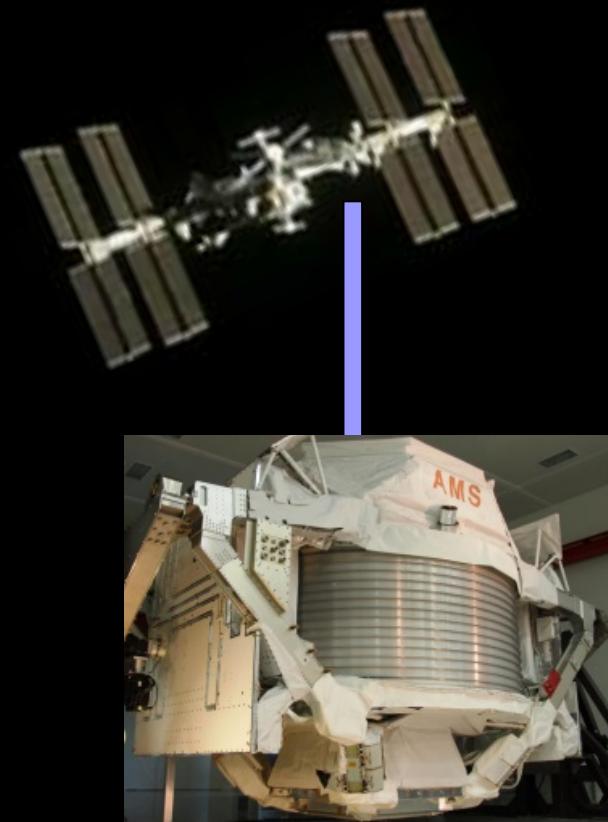
LHC-b, ATLAS,CMS

Super Kamiokande

$$\tau_p > 6.6 * 10^{33} \text{ years}$$

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

Direct search

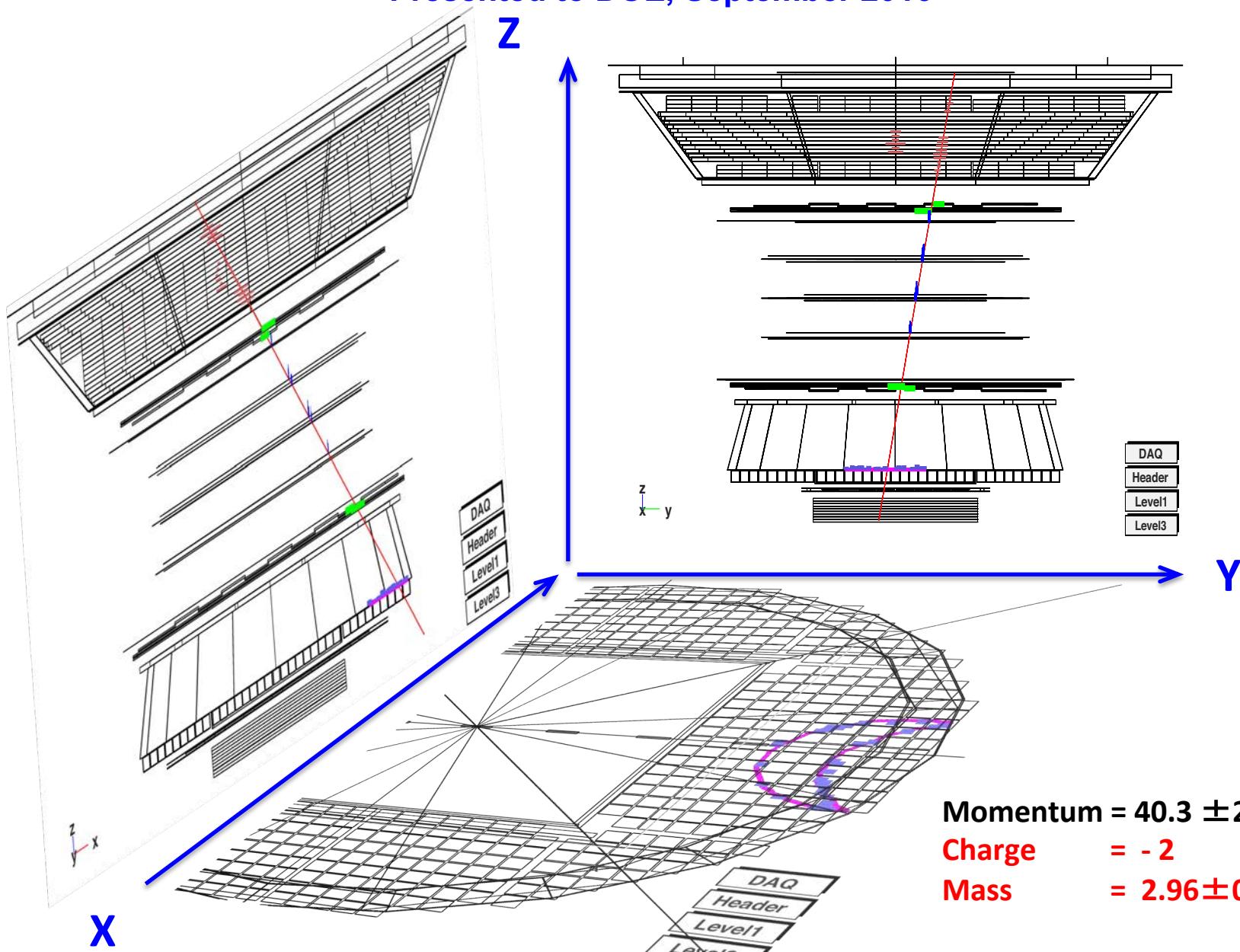


AMS

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

An anti-Helium candidate:

Presented to DOE, September 2016



Momentum = $40.3 \pm 2.9 \text{ GeV}/c$

Charge = -2

Mass = $2.96 \pm 0.33 \text{ GeV}/c^2$

Mass (${}^3\text{He}$) = $2.83 \text{ GeV}/c^2$

To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$.

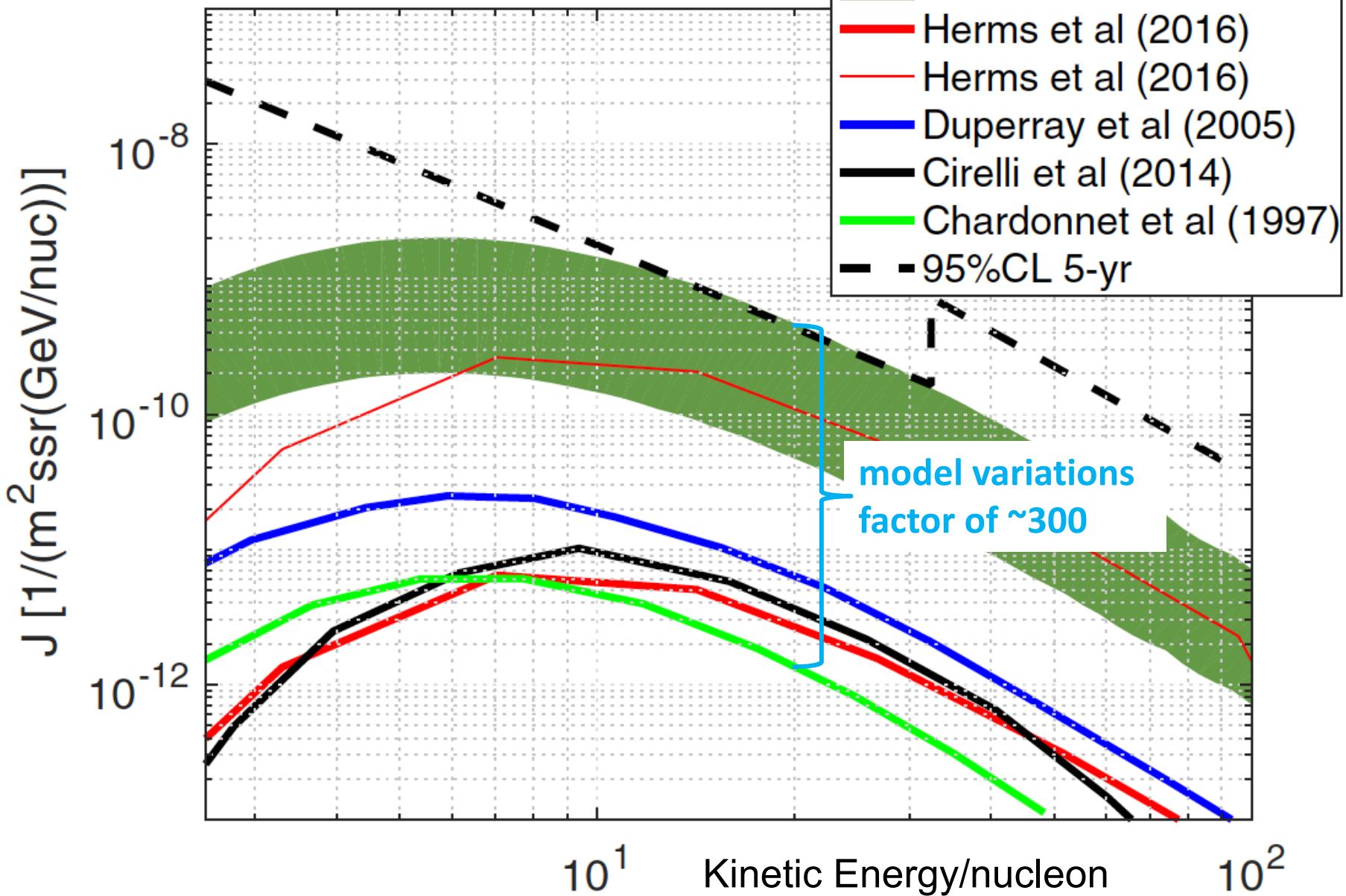
All eight events are in the helium mass region.

All eight events are clean single-track events without additional hits.

All eight events are in the momentum range $< 100 \text{ GeV}/c$ (where the momentum resolution is better than 10%).

^3He flux models from collisions of cosmic rays

K. Blum et al., Phys. Rev. D 96, 103021 (2017)



${}^3\overline{\text{He}}/\text{He}$ flux ratio predictions

R. Duperray et al., Phys. Rev. D **71**, 083013 (2005)

From the collision of ordinary cosmic rays: ${}^3\overline{\text{He}}/\text{He}[8\text{-}40]\text{GV} = 6 \times 10^{-12}$

M. Cirelli et al., JHEP **8**, 9 (2014):

From the collision of ordinary cosmic rays: ${}^3\overline{\text{He}}/\text{He}[8\text{-}40]\text{GV} = 3 \times 10^{-11}$

K. Blum et al., Phys. Rev. D **96**, 103021 (2017)

From the collision of ordinary cosmic rays: ${}^3\overline{\text{He}}/\text{He}[8\text{-}40]\text{GV} = 6 \times 10^{-10}$

E. Carlson et al., Phys. Rev. D **89**, 076005 (2014)

From dark matter annihilation: ${}^3\overline{\text{He}}/\text{He}[8\text{-}40]\text{GV} = 1.4 \times 10^{-9}$

AMS Measurement:

${}^3\overline{\text{He}}/\text{He}[8\text{-}40]\text{GV} = 2 \times 10^{-8}$

Origin of the tentative AMS antihelium events

Adam Coogan^{*} and Stefano Profumo[†]

*Department of Physics and Santa Cruz Institute for Particle Physics, University of California,
Santa Cruz, California 95064, USA*

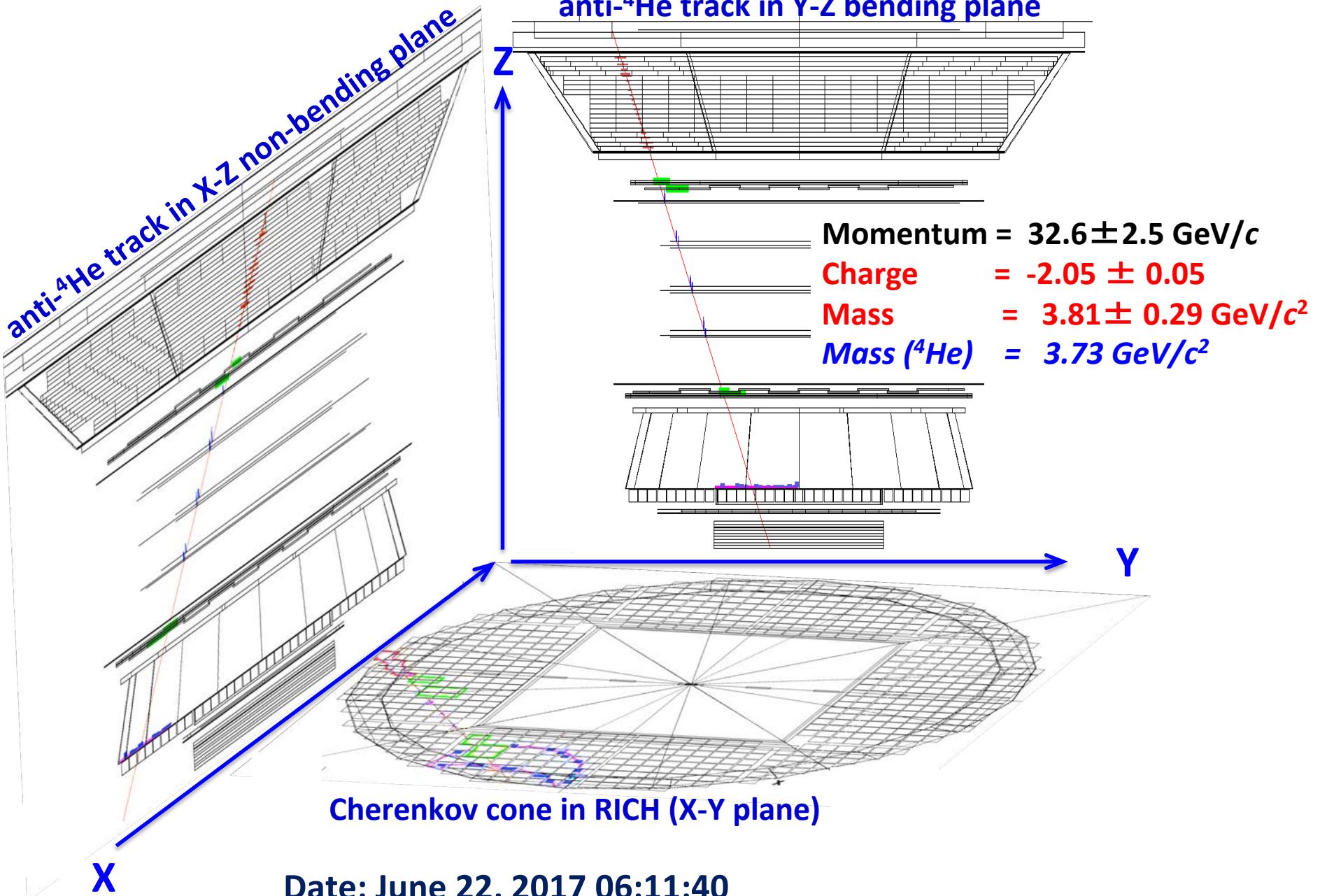
(Received 31 May 2017; published 31 October 2017)

We demonstrate that the tentative detection of a few antihelium events with the Alpha Magnetic Spectrometer (AMS) on board the International Space Station can, in principle, be ascribed to the annihilation or decay of Galactic dark matter, when accounting for uncertainties in the coalescence process leading to the formation of antinuclei. We show that the predicted antiproton rate, assuming the antihelium events came from dark matter, is marginally consistent with AMS data, as is the antideuteron rate with current available constraints. We argue that a dark matter origin can be tested with better constraints on the coalescence process, better control of misidentified events, and with future antideuteron data.

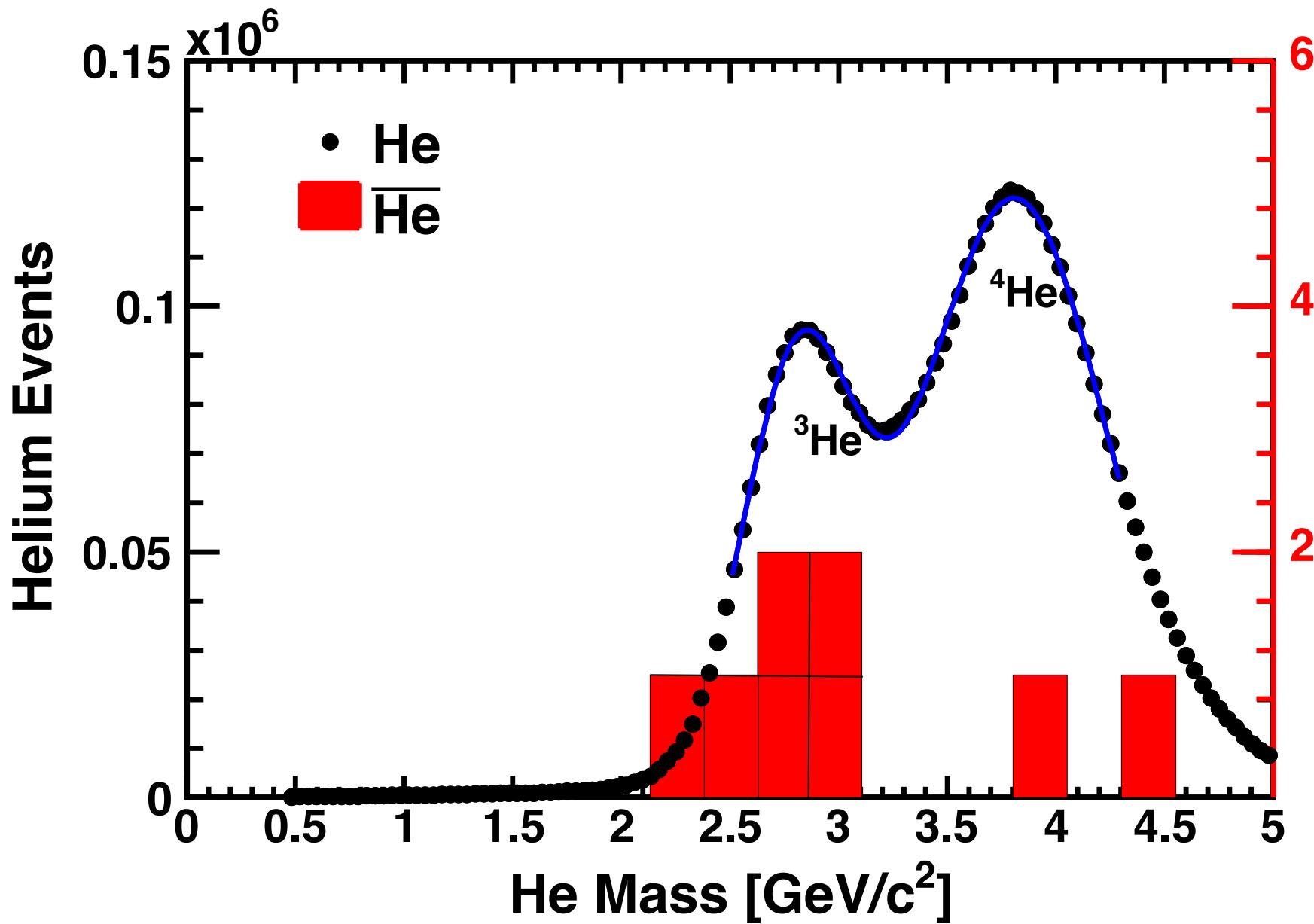
Conclusion:

There are large uncertainties in models to ascertain the origin of ${}^3\bar{\text{He}}$

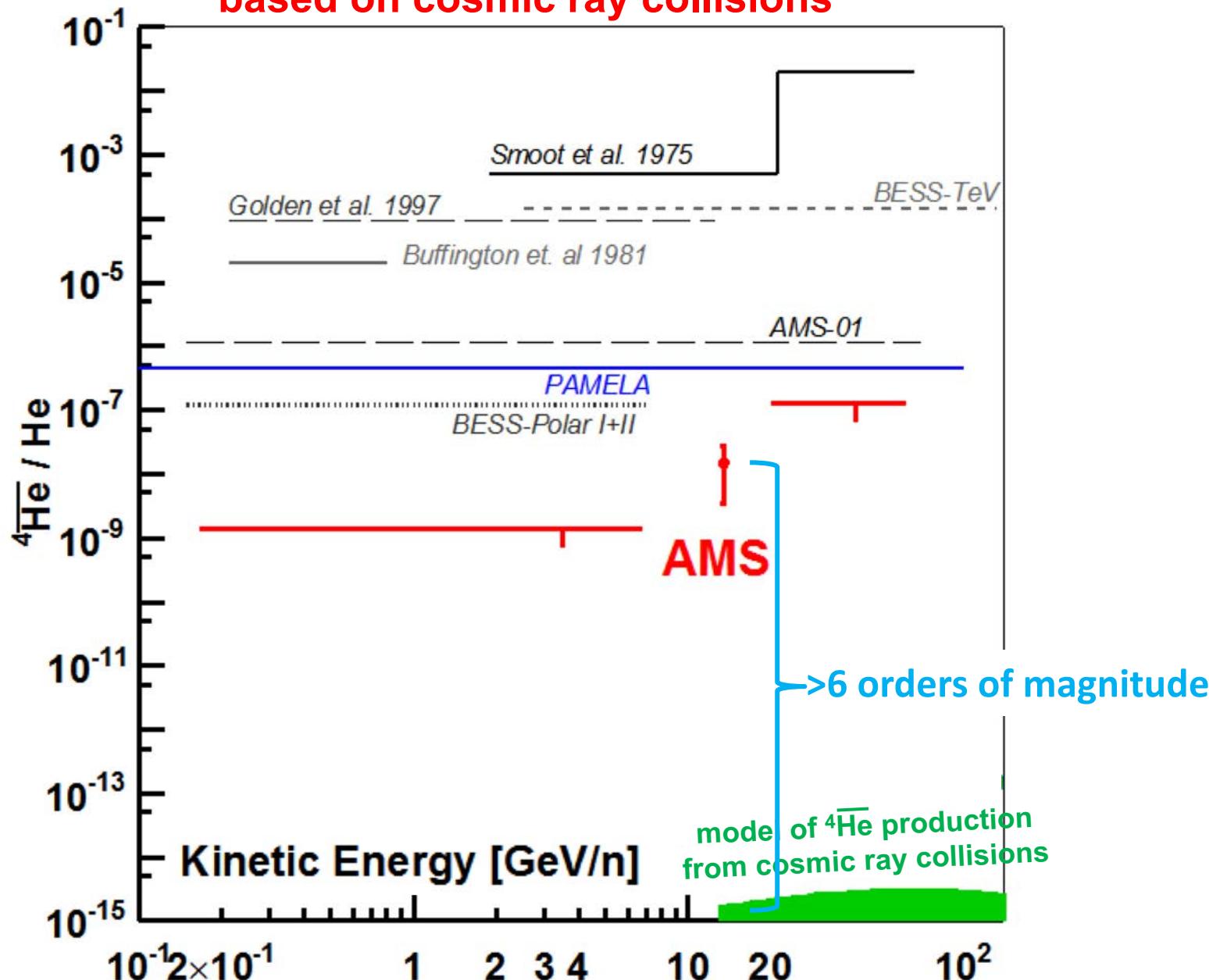
Important Observation of anti- ${}^4\text{He}$



Mass distribution of the anti-helium events



To ascertain the origin of antihelium, it is most important to study ${}^4\overline{\text{He}}$.
The AMS ${}^4\text{He}/\text{He}$ ratio is six orders of magnitude greater than predictions
based on cosmic ray collisions

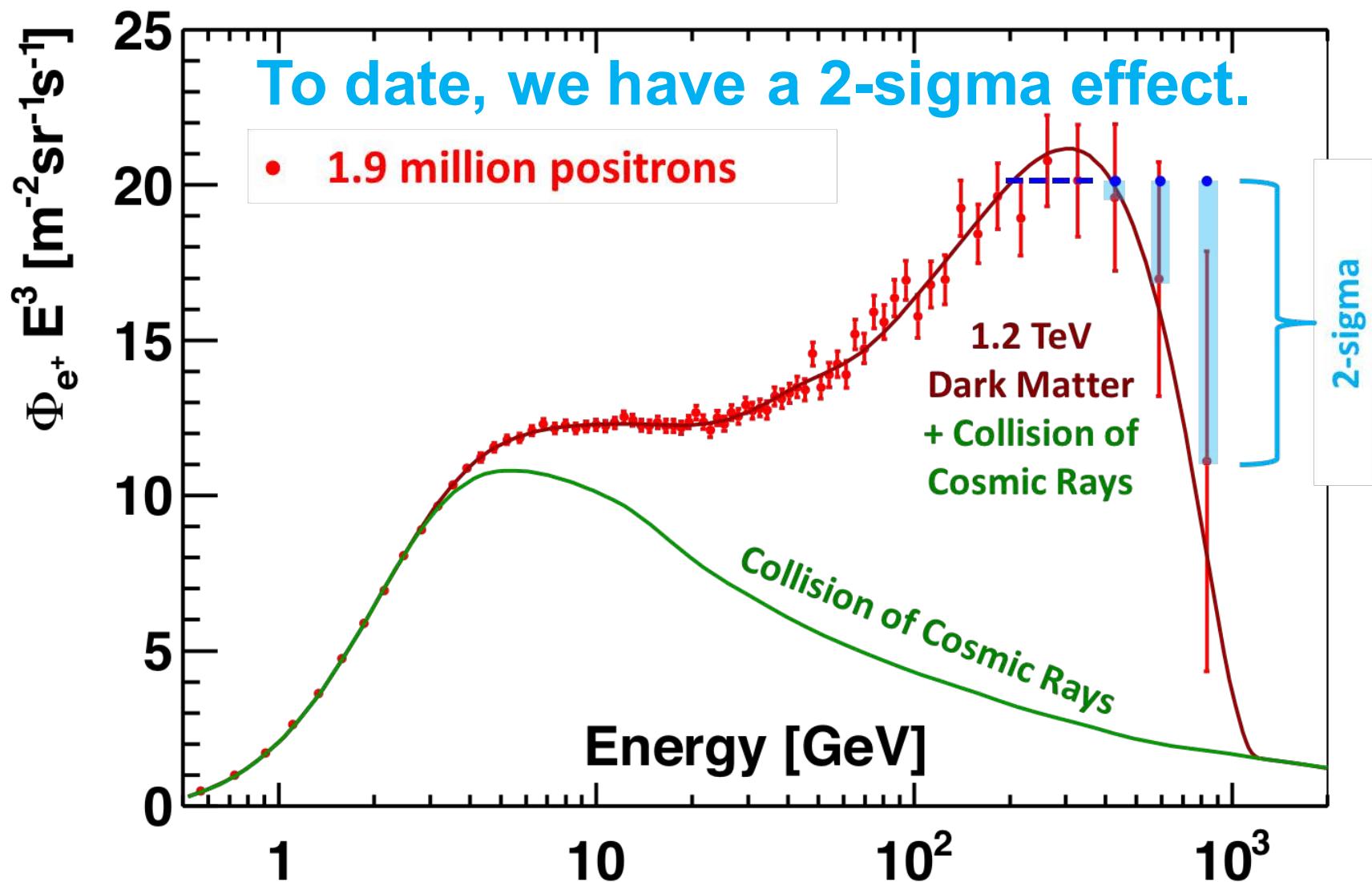


Observations on ${}^4\overline{\text{He}}$

1. We have two ${}^4\overline{\text{He}}$ events with a background probability of 3×10^{-3} .
2. Continuing to take data through 2024 the background probability for ${}^4\overline{\text{He}}$ would be 2×10^{-7} , i.e., greater than 5-sigma significance.
3. The ${}^3\text{He}/{}^4\text{He}$ ratio is 10-20% yet ${}^3\overline{\text{He}}/{}^4\overline{\text{He}}$ ratio is 300%. More data will resolve this mystery.

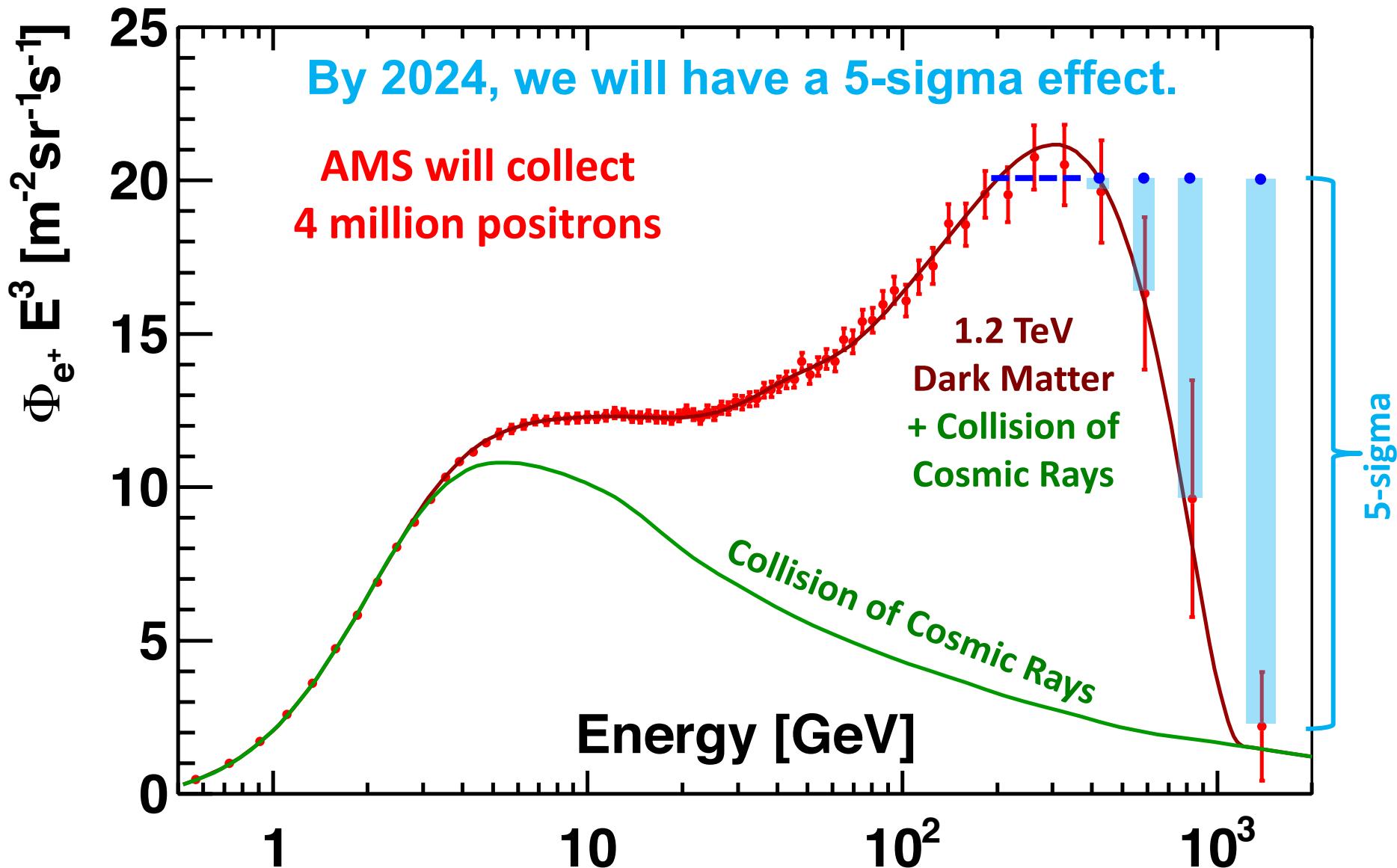
Projection for the Positron Flux through 2024

Extend the measurements to 2 TeV and determine the sharpness of the drop off.



Projection for the Positron Flux through 2024

Extend the measurements to 2 TeV and determine the sharpness of the drop off.



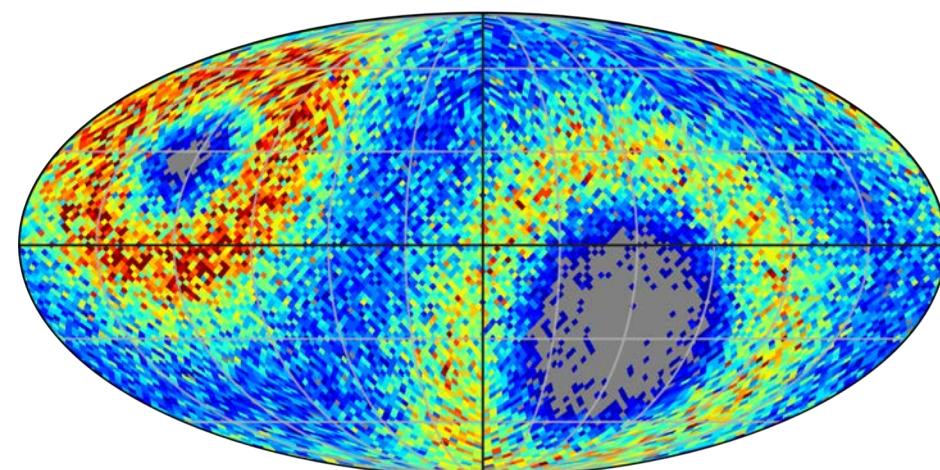
Physics of AMS to 2024:

3. e+ & e- Anisotropy

Astrophysical point sources like pulsars will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

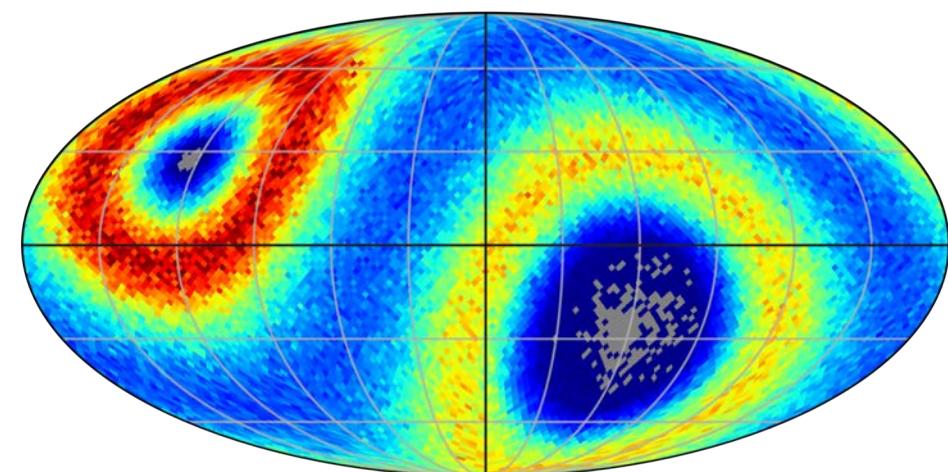
The anisotropy in galactic coordinates $\delta = 3\sqrt{C_1/4\pi}$ C_1 is the dipole moment

positrons



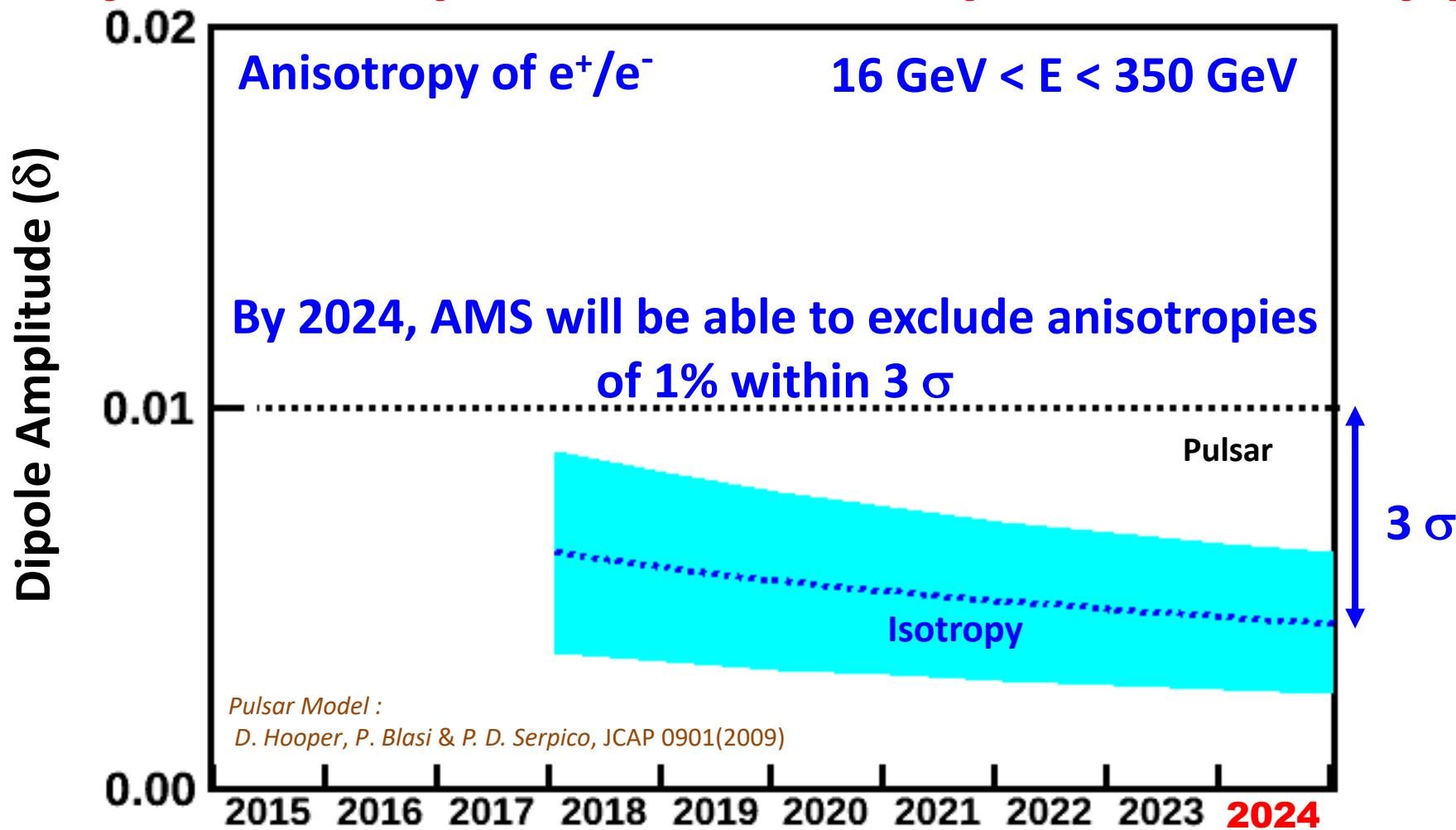
0 5 10 15 20
Events/pixel

electrons



0 60 120 180 240
Events/pixel

Projected amplitude of the dipole anisotropy

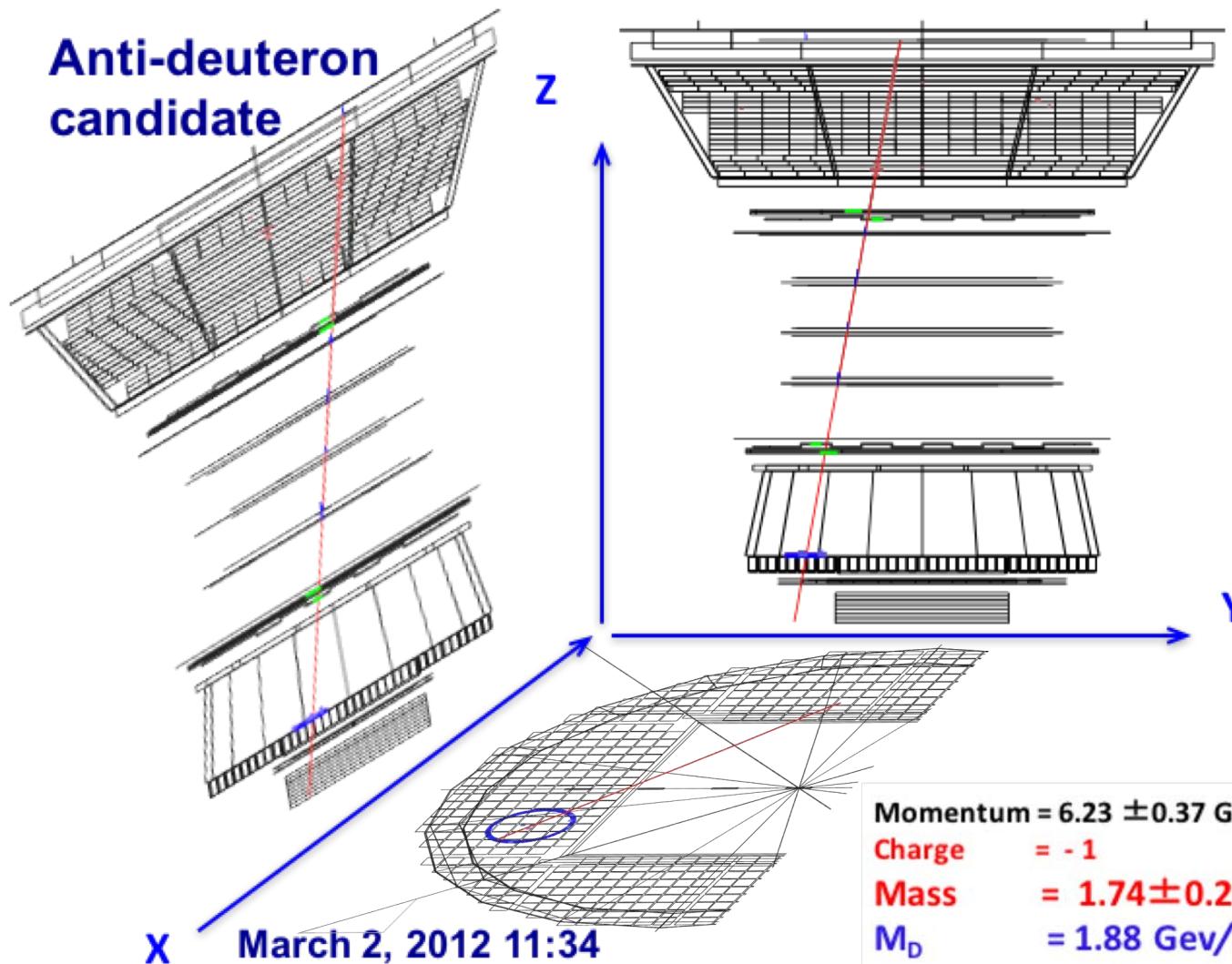


The observation of isotropy at the 3-sigma level is an important confirmation of the projected 5-sigma effect in the positron flux.

Physics of AMS to 2024:

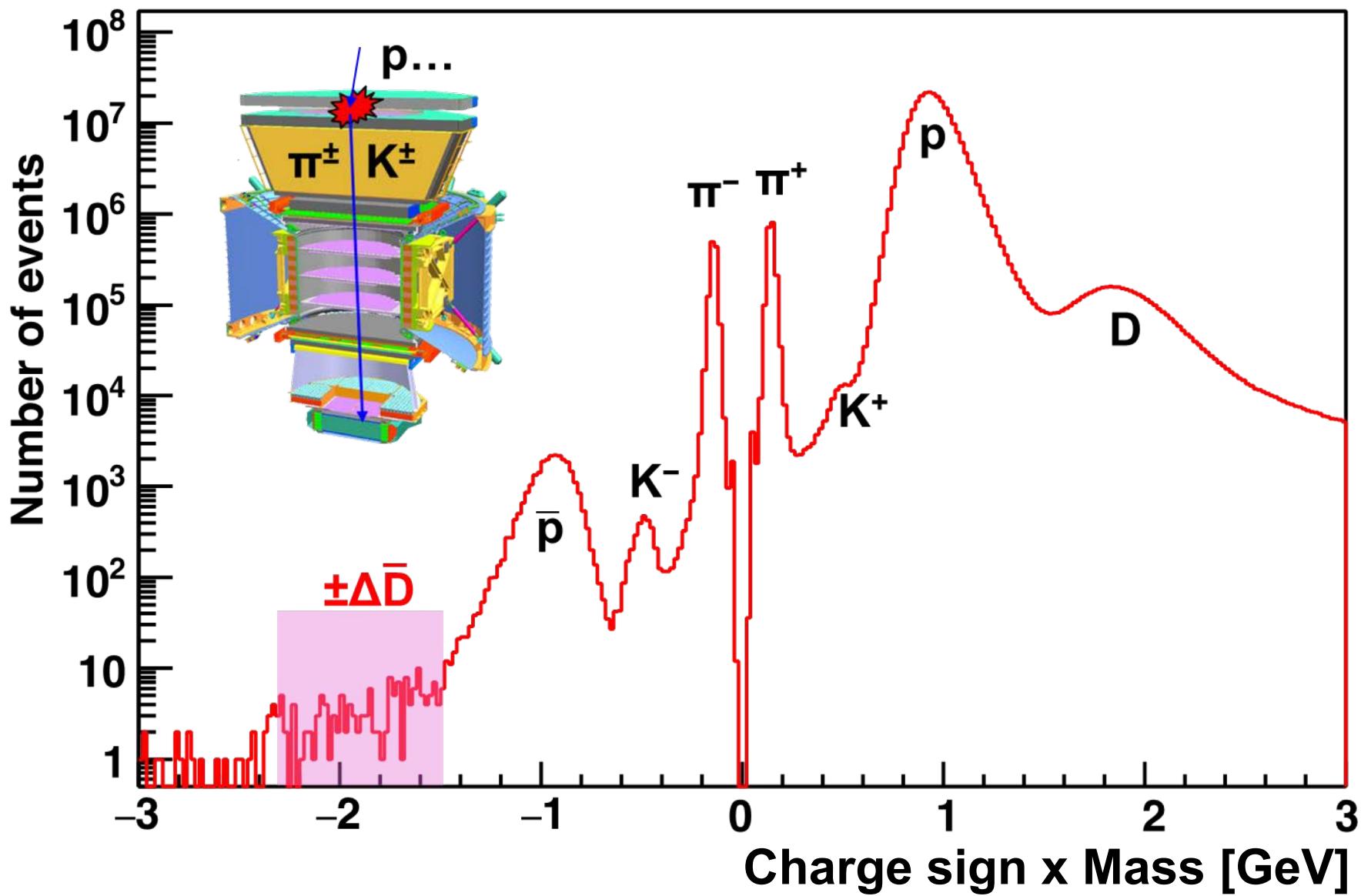
4. Anti-deuterons

Anti-deuterons have never been observed in space

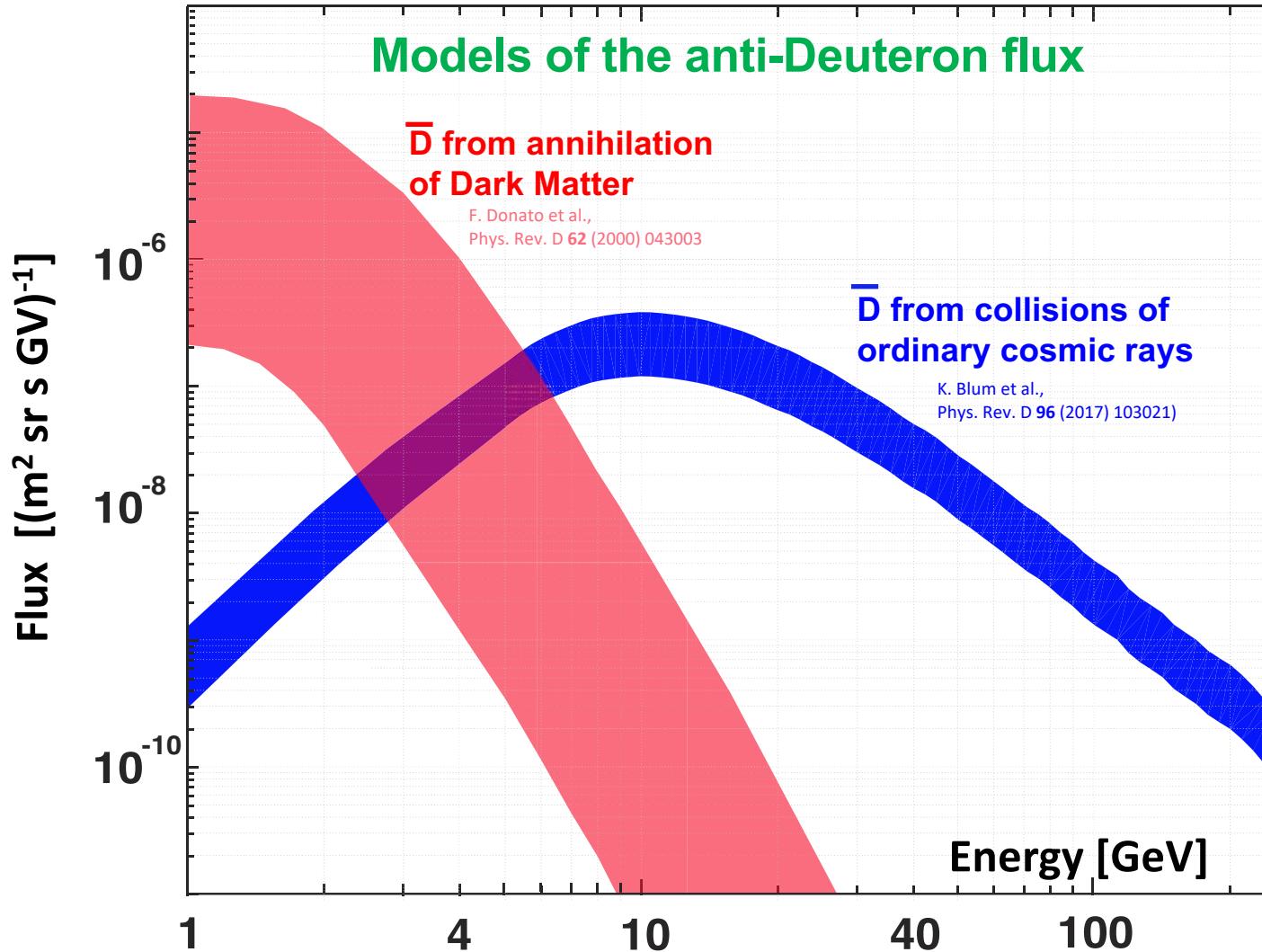


Anti-Deuteron Analysis

As seen, the rate of anti-deuterons is low.



Similar to the case of e^+ ,
we will need a large number of \bar{D} to ascertain their origin.



Physics of high Z cosmic ray spectra at high energies

1. AMS will obtain precise data on heavy nuclei, $Z=9$ to $Z=28$, up to the TV region. Particularly interesting is evidence of the flux break at ~ 200 GV. In addition, ^{26}Al , ^{36}Cl , ^{54}Mn are radioactive clocks. The measurements of the Al, Cl, Mn spectra will precisely establish the age of cosmic rays.
2. Like B/C, ratios of secondary/primary such as Al/Si and $(\text{Sc}+\text{Ti}+\text{V})/\text{Fe}$ will provide new constraints on propagation.
3. The first elements that can be created by supernova are Ni and Zn. AMS will be able to study their properties for the first time and compare them with elements produced by stellar nucleosynthesis.

AMS is the only magnetic spectrometer in space.

AMS new results were not predicted.

The results from AMS are unlocking the secrets of the cosmos.

