Charged cosmic rays

A review of balloon and space borne measurements

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ECRS 2016 Torino, *September 7, 2016*

Overview

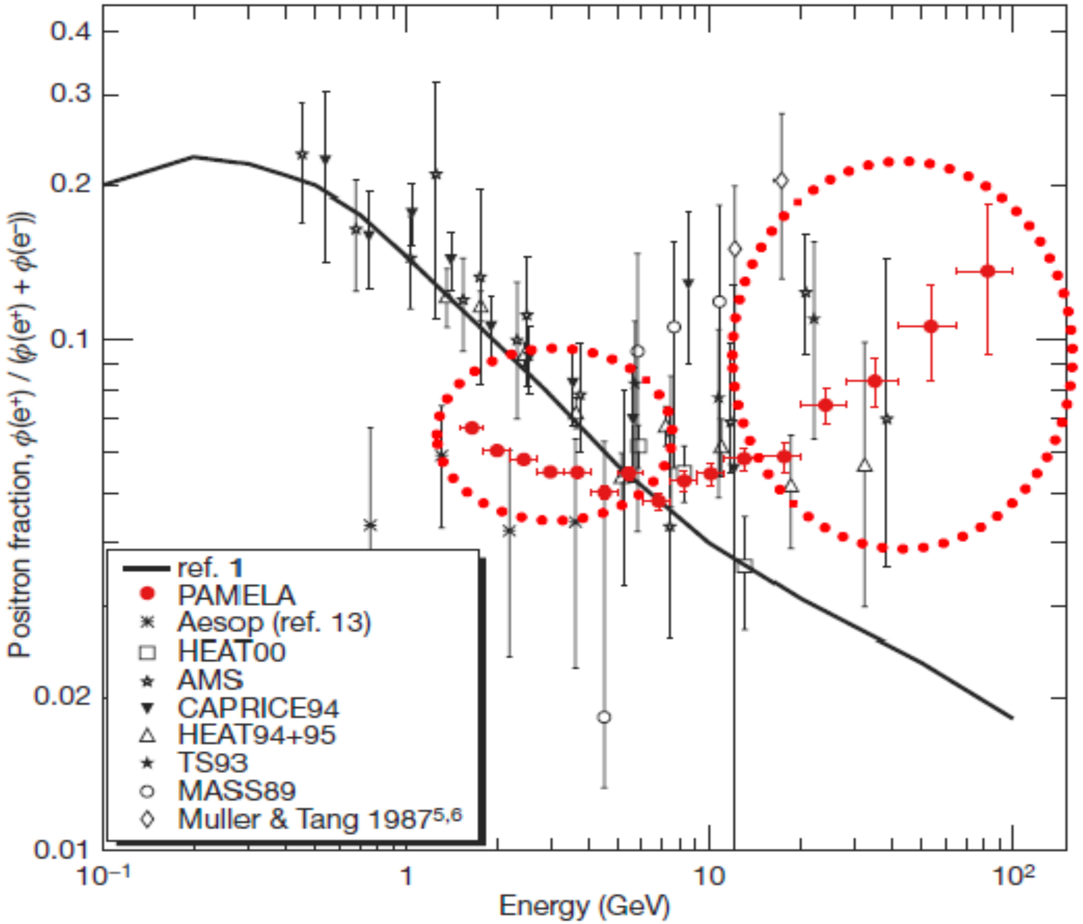
- Electron and positron measurements
- Energy spectra of p, He, light nuclei, sub-Fe nuclei
- Secondary-to-Primary Ratios
- Anti-protons
- Isotope flux ratios, propagation clocks, ultra-heavy nuclei
- A glimple to future direct measurements of VHE cosmic rays

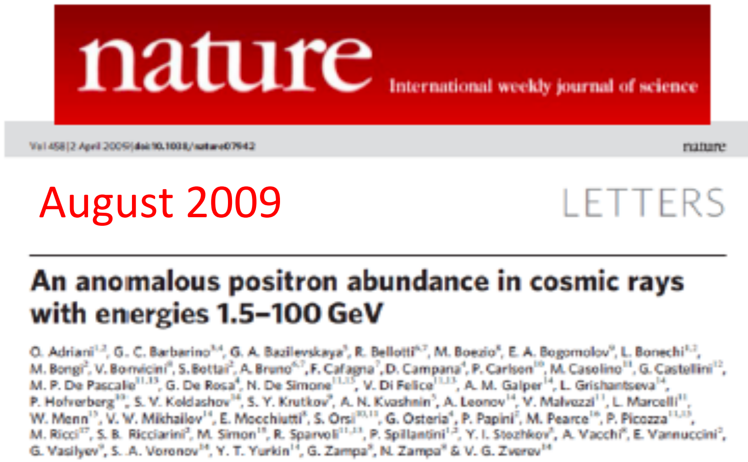
Crab Nebula

Charged cosmic-ray leptons

electron and positron measurements

PAMELA: first unambiguous evidence of the rise of the positron fraction above 10 GeV




nature International weekly journal of science

Vol 458 | 2 April 2009 | doi:10.1038/nature07942 nature

August 2009

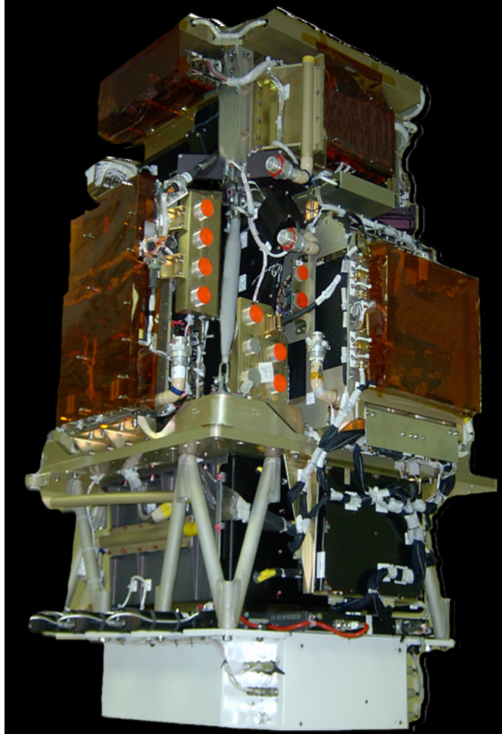
LETTERS

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

O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, M. P. De Pascale, G. De Rosa, N. De Simone, V. Di Felice, A. M. Galper, L. Grishantseva, P. Hofverberg, S. V. Koldashov, S. Y. Krutkov, A. N. Kvashnin, A. Leonov, V. Malvezzi, L. Marcelli, W. Menn, V. V. Mikhailov, E. Mocchiutti, S. Orsi, G. Osteria, P. Papini, M. Pearce, P. Picozza, M. Ricci, S. B. Ricciarini, M. Simon, R. Sparvoli, P. Spillantini, Y. I. Stozhkov, A. Vacchi, E. Vannuccini, G. Vasilyev, S. A. Voronov, Y. T. Yurkin, G. Zampa, N. Zampa & V. G. Zverev

Citations: 1338

PAMELA launched on 15th June 2006 recently celebrated 10 years



Time-Of-Flight

plastic scintillators + PMT:
Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

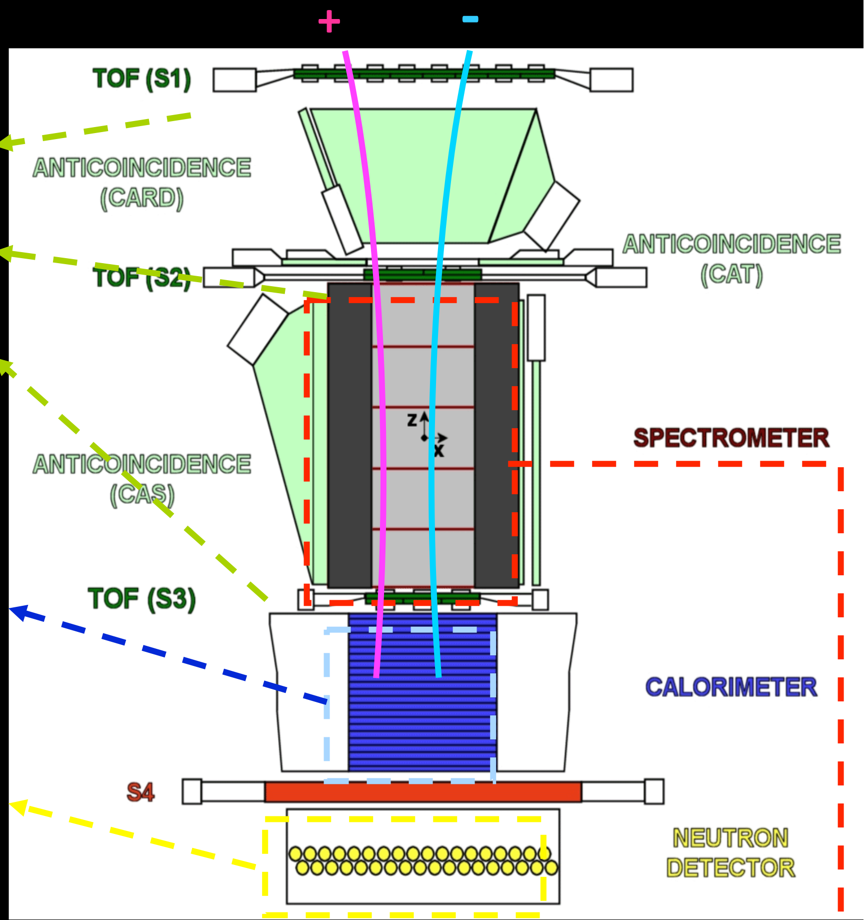
Electromagnetic calorimeter

W/Si sampling (16.3 X_0, 0.6 λI)
Discrimination e+ / p, anti-p/e^-

(shower topology)
- Direct E measurement for e^-

Neutron detector

^{3}He tubes + polyethylene moderator:
- High-energy e/h discrimination

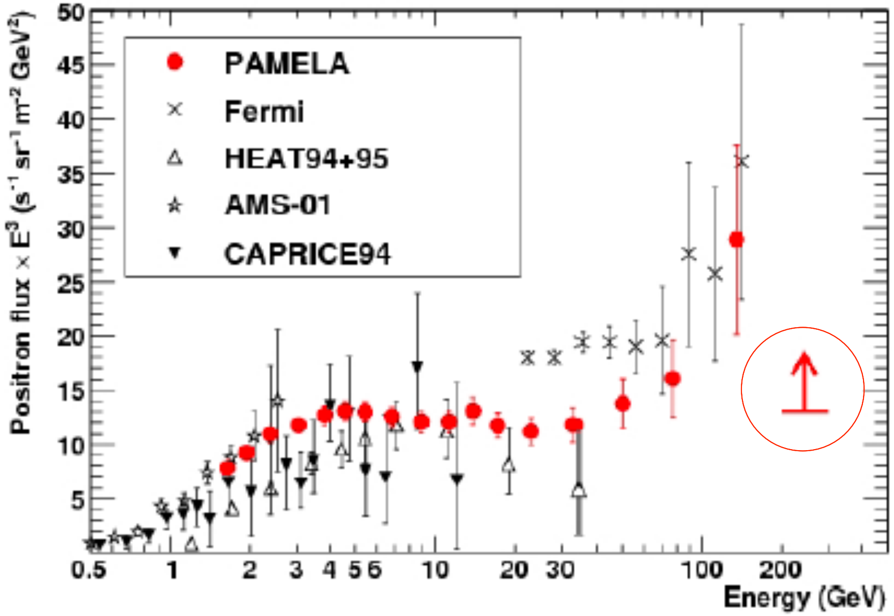


GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Elliptical orbit 350 – 610 km
70° inclination
in operation at 560 km

microstrip silicon tracking system + permanent magnet
provides: - *Magnetic rigidity* → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***

PAMELA Results: Positrons



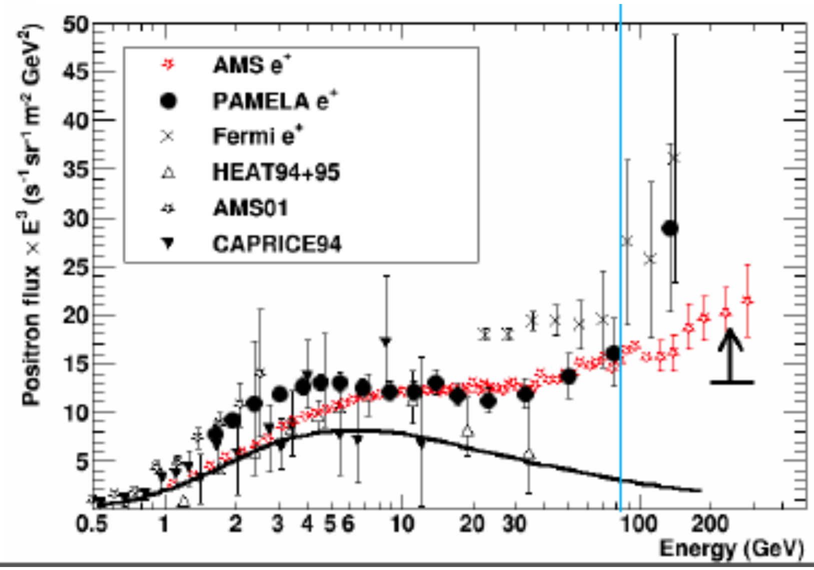
PHYSICAL REVIEW LETTERS

O. Adriani et al. , PRL 106 (2011) 201101

❖ PAMELA positron spectrum to 300 GeV

❖ AMS-02 positrons to 500 GeV

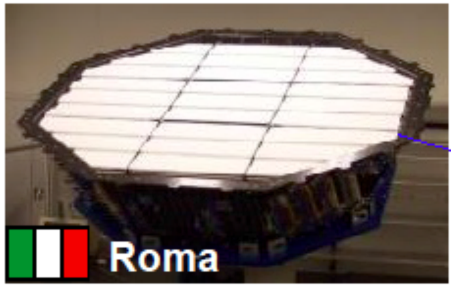
Results confirmed by AMS-02!



Launched in 2011: 5 years aboard the ISS

AMS-02: A TeV precision, multipurpose spectrometer

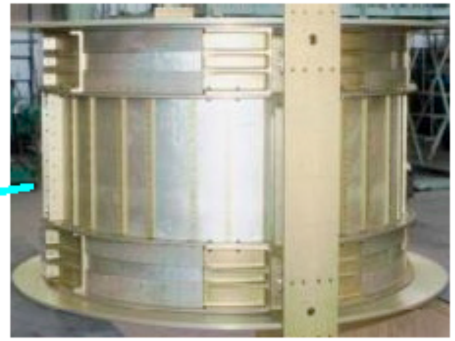
Transition Radiation Detector (TRD)
Identify e^+, e^-



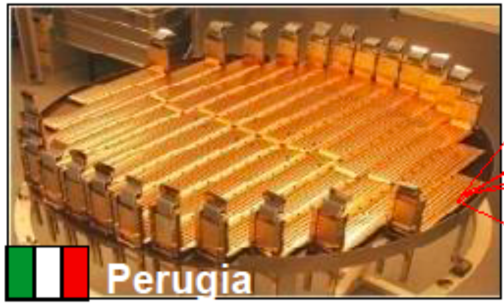
Particles and nuclei are defined by their charge (Z) and energy (E)

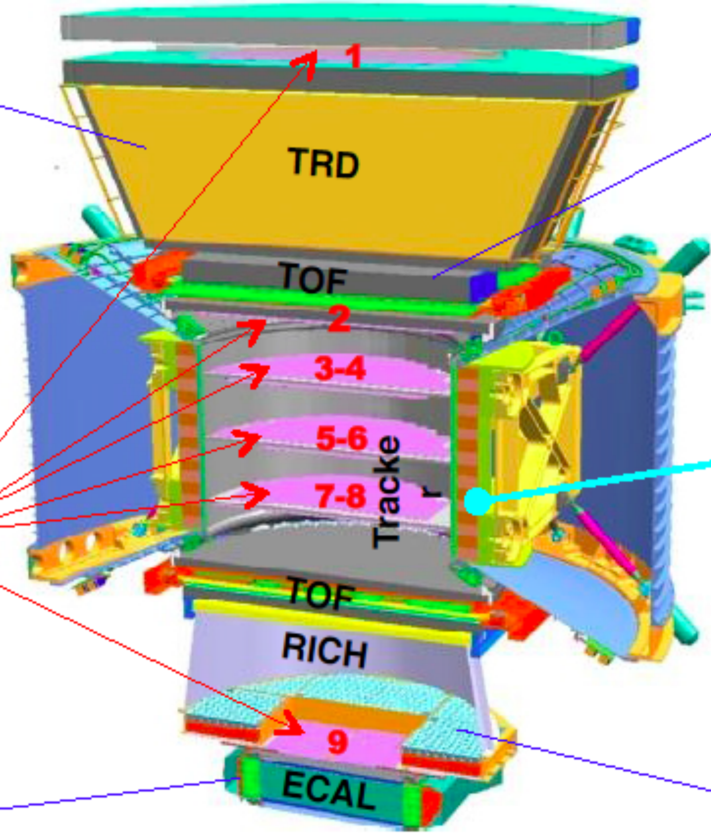
Time of Flight (TOF)
Z, E

Magnet (0.15 T)
±Z



Silicon Tracker
Z, P





Ring Imaging Cherenkov (RICH)
Z, E

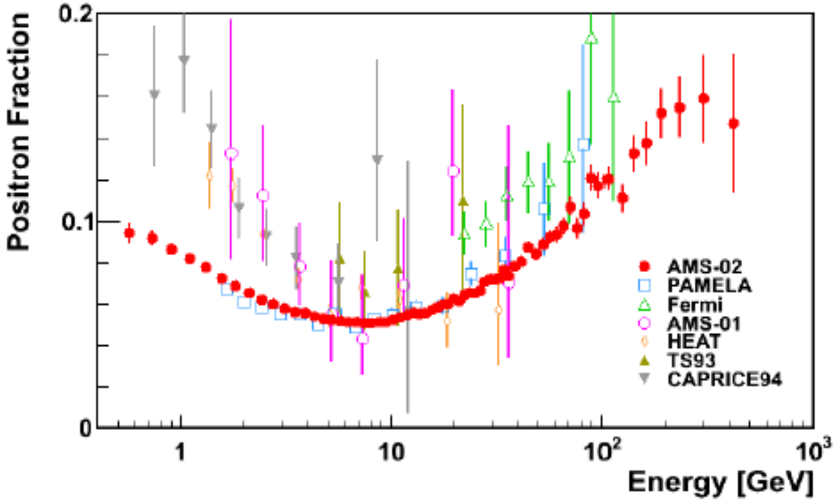
Electromagnetic Calorimeter (ECAL)
E of e^+, e^-, γ

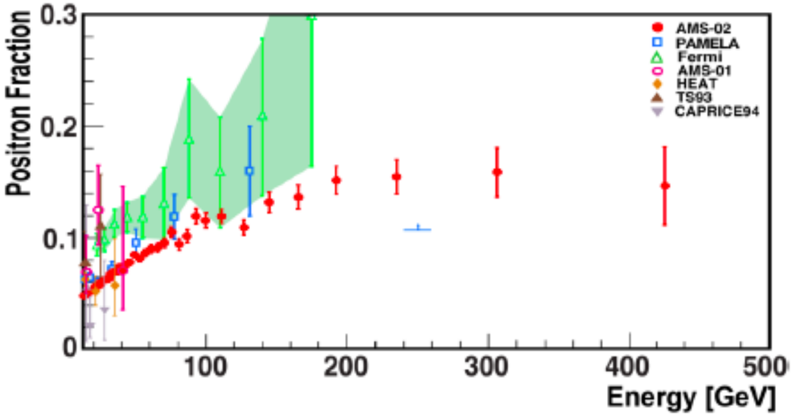
Z, E, R, β
for the same particle are measured independently by the Tracker, RICH, TOF and ECAL

AMS-02: positron fraction

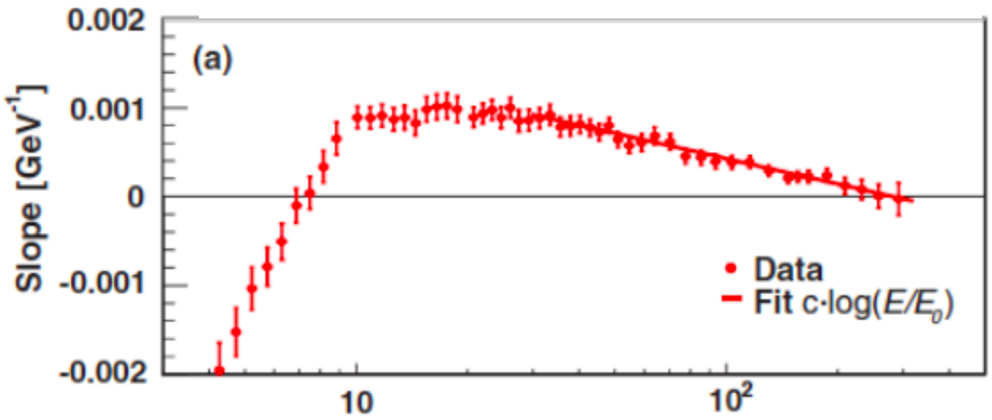
- ✓ No sharp structures
- ✓ Steady increase of the positron content up to ≈ 275 GeV
- ✓ Well described by an empirical model with a common source term for e^+/e^-

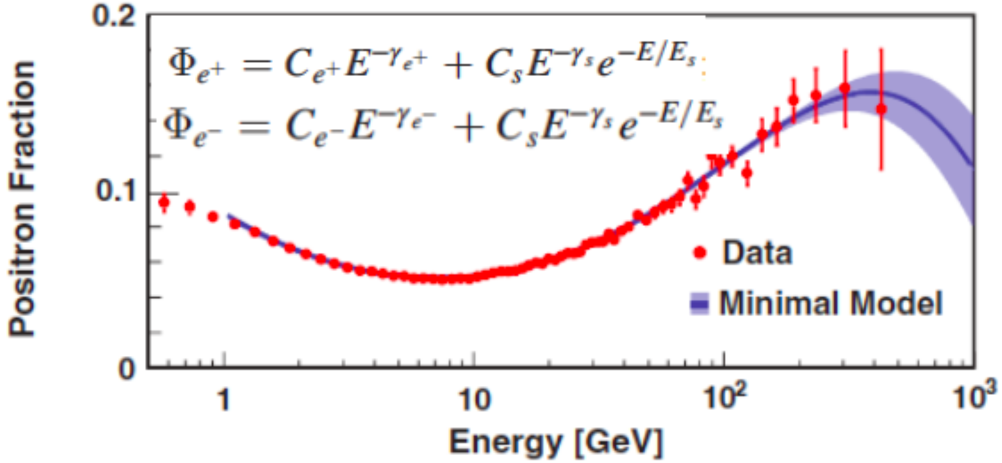
[B. Bertucci @LNGS - July 2016]



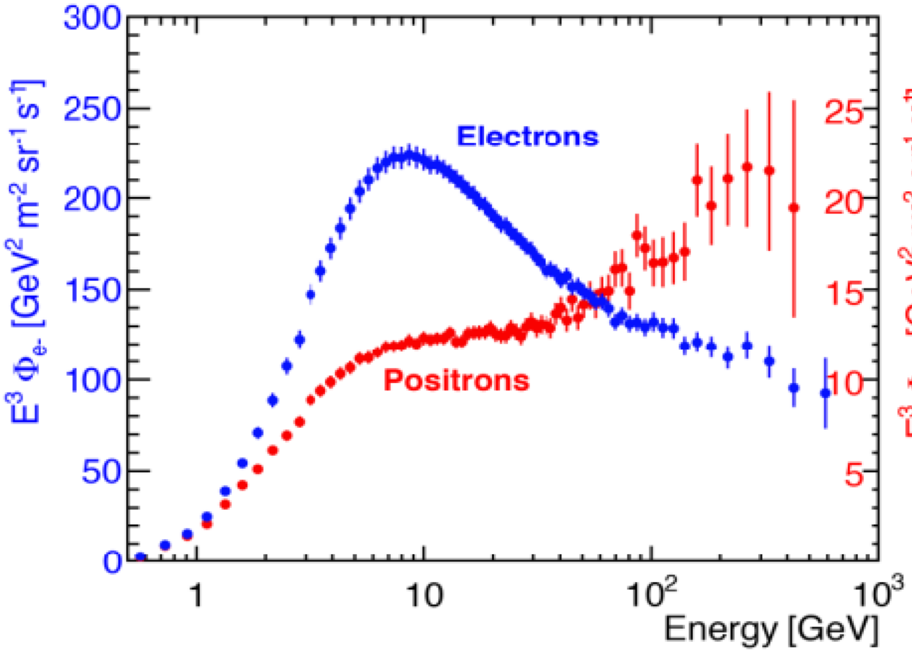


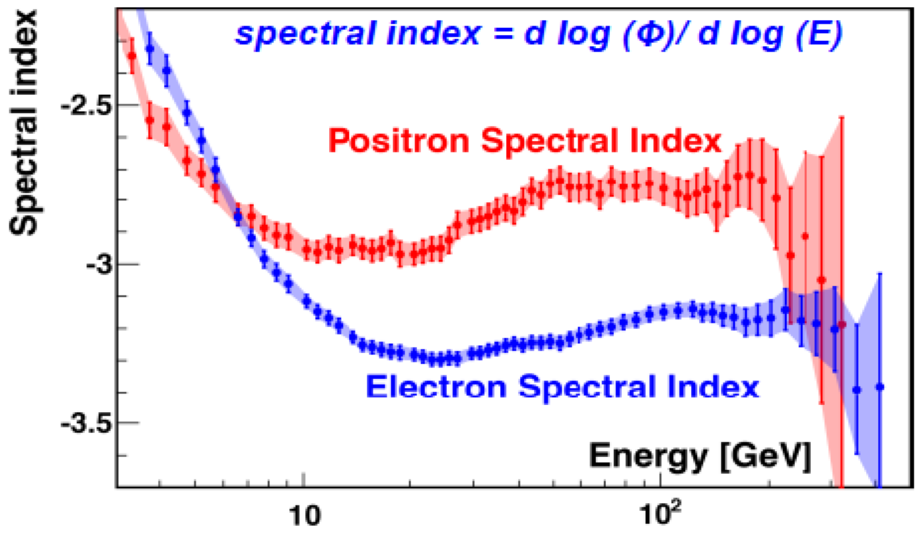
[M. Accardo et al., PRL 113 (2014) 121101]





AMS-02: Electron Flux and Positron Flux





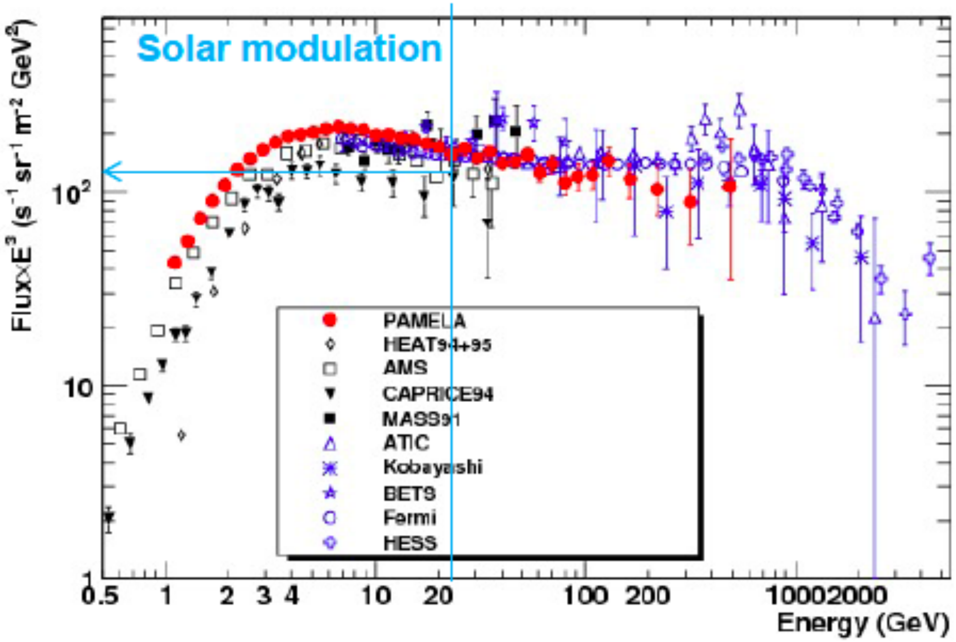
[M. Aguilar et al., PRL 113 (2014) 121102]

Observations:

1. **The electron flux and the positron flux are different in their magnitude and energy dependence.**
2. **Both spectra cannot be described by single power laws.**
3. **The spectral indices of electrons and positrons are different.**
4. **Both change their behavior at ~30GeV.**
5. **The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).**

[S.C.C. Ting, ICRC 2015]

PAMELA Results: Electrons

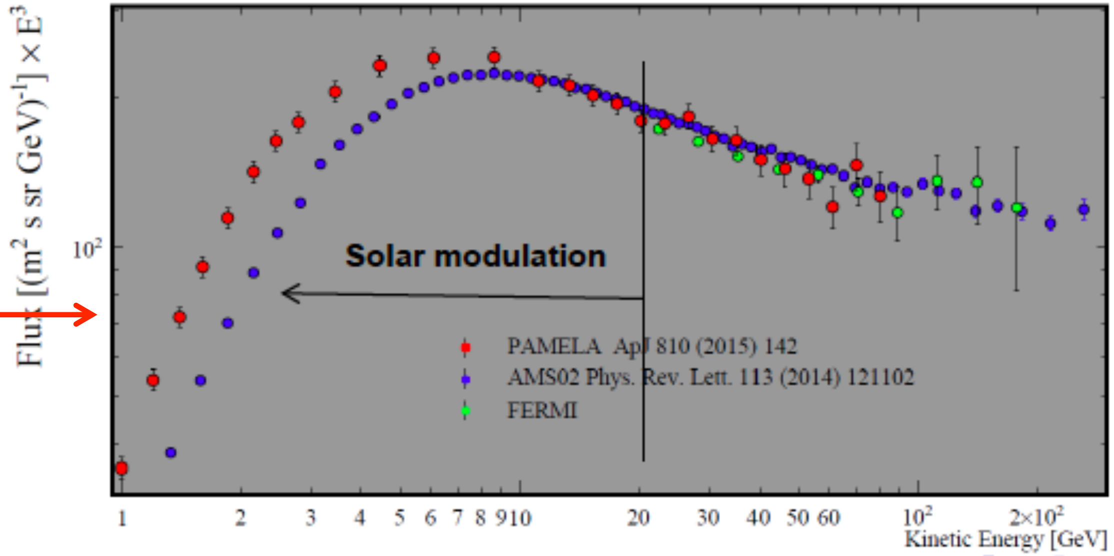


O. Adriani et al., PRL 106, 201101

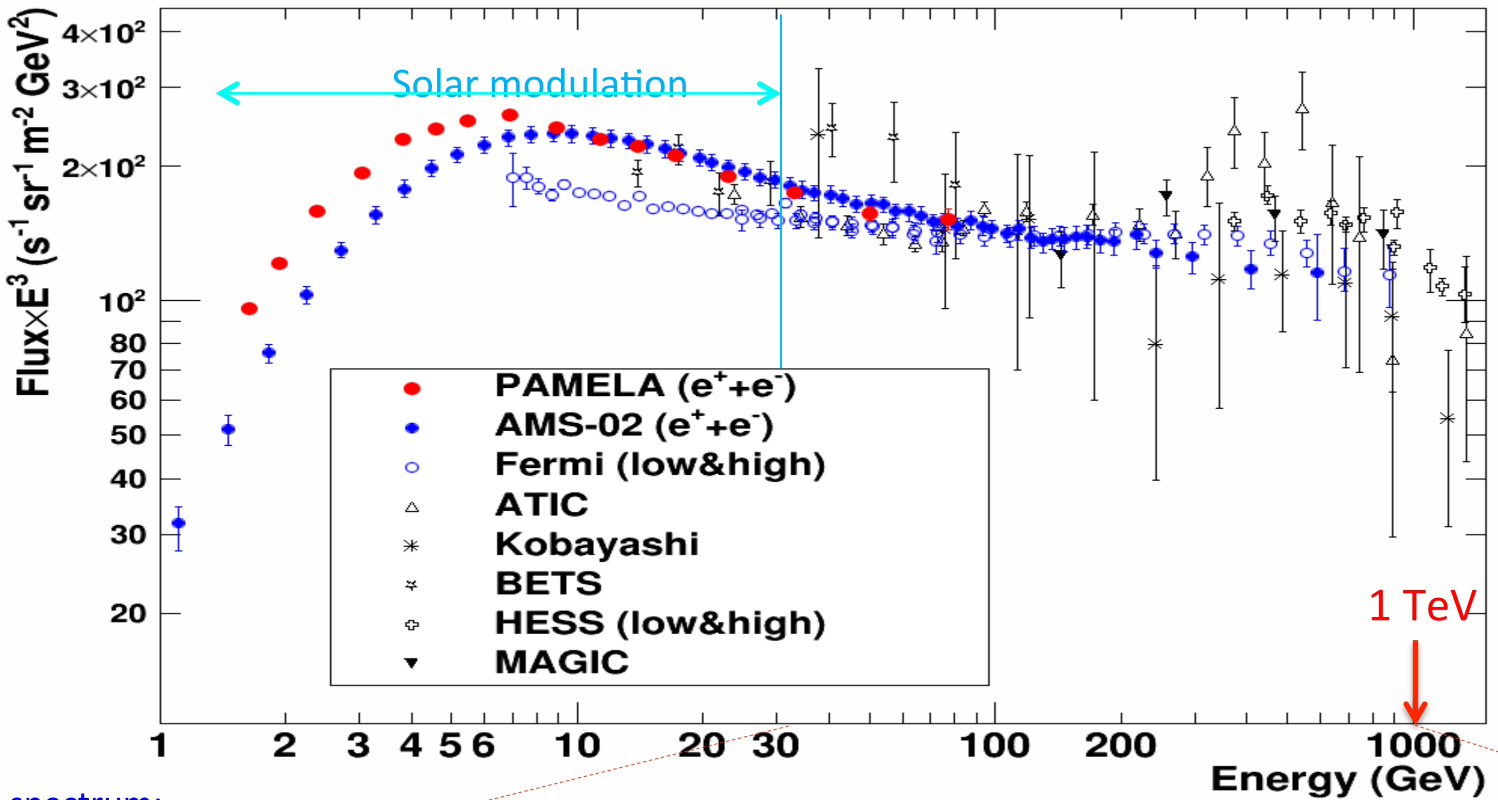
- ❖ PAMELA electron spectrum (published data to 625 GeV)
- ❖ AMS-02 electrons to 700 GeV

Study of low energy data
(affected by solar modulation)

O. Adriani et al., ApJ 810 (2015) 142



INCLUSIVE (e^-+e^+) spectrum below 1 TeV (AMS-02, FERMI & PAMELA)

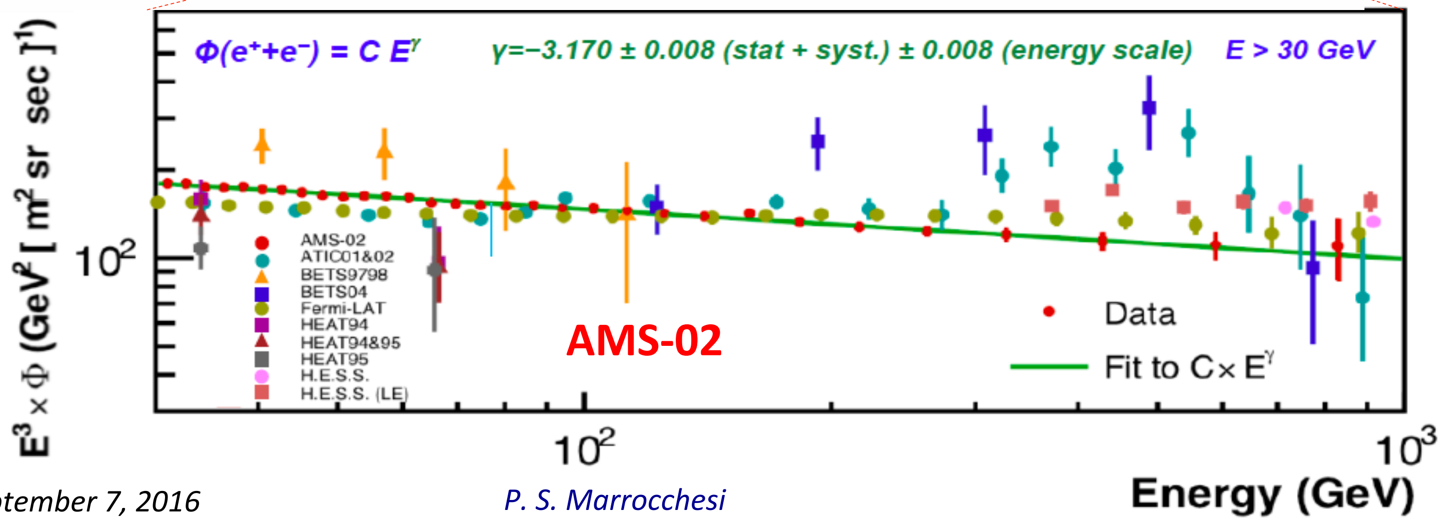


e^-+e^+ spectrum:

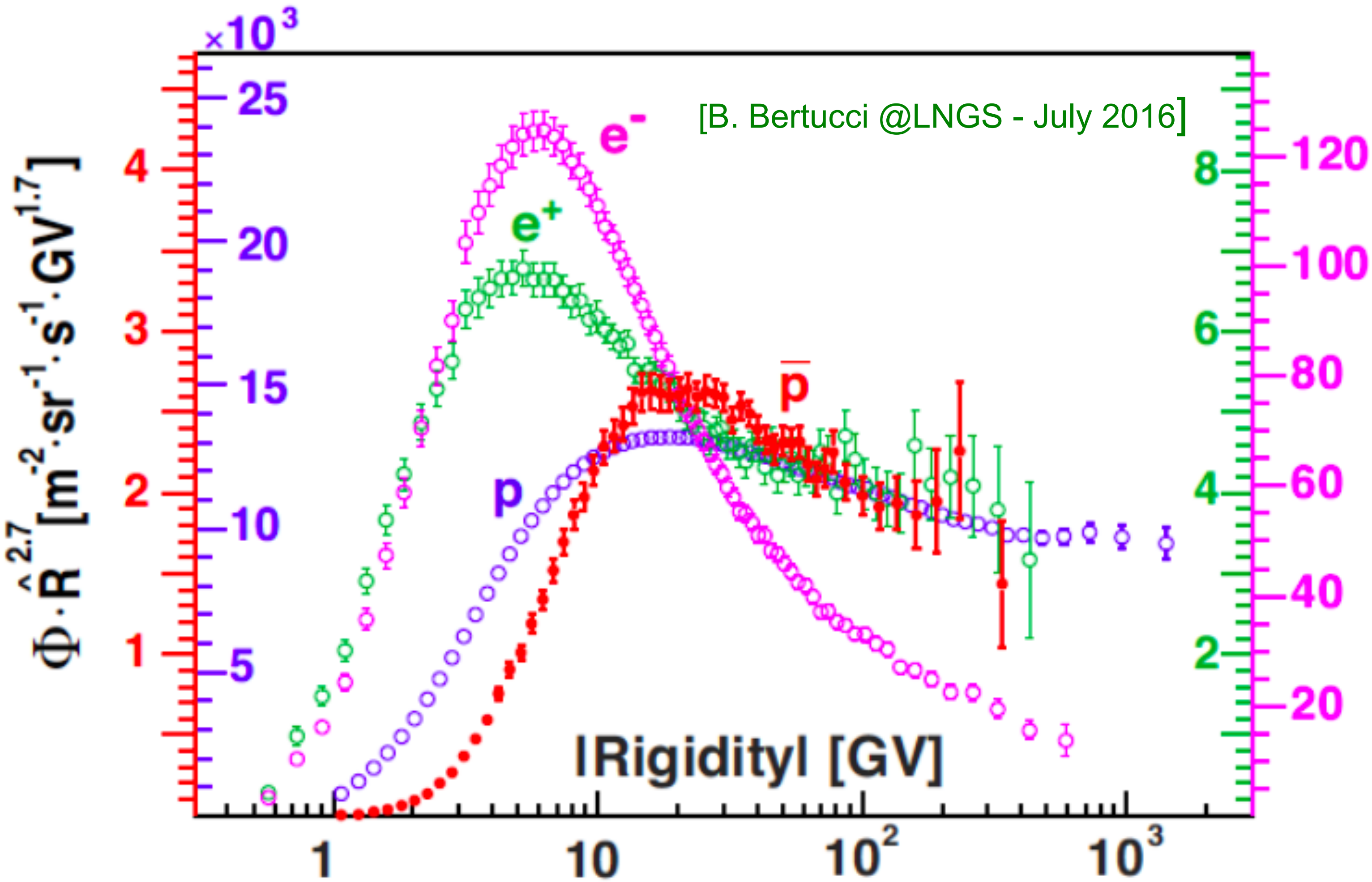
AMS-02 to 1 TeV

PAMELA (calorimeter only) to 3 TeV (*)

(*) A.V. Karelin et al.
Journal of Physics
Conf. Series
632 (2015) 01**2014**



Fluxes of e^+, e^-, p and anti-p as measured by AMS-02



- Above ~60 GV the rigidity dependence of e^+, p and anti-p are **almost identical**
- BUT electrons behave differentlly.

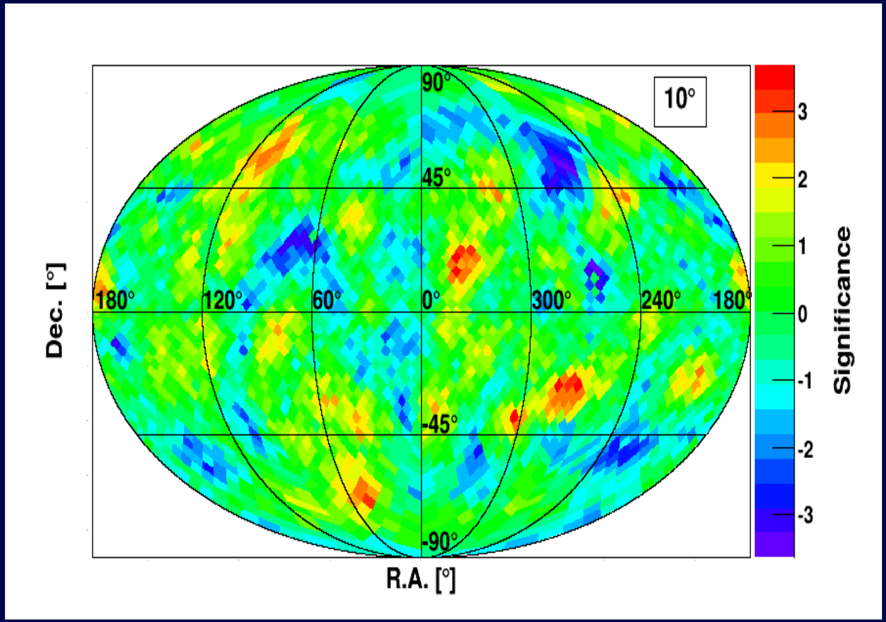
Anisotropy in e^+ and e^- data

- PAMELA

Study of arrival directions of e^+ and e^- taking into account the effects of the Earth's geomagnetic field:

- No anisotropy observed at all angular scales
- δ= 0.076 at 95% confidence level

[Panico @ICRC 2015]



PAMELA Significance sky maps

- AMS-02
- Isotropic fluctuations of the positron ratio already measured
- Measurement of the arrival directions underway [Gebauer @ICRC 2015]

The CR leptonic sector puzzle *(observations)*

① Positron spectrum: is *harder than e^-* above 50 – 60 GeV and has *similar Rigidity dependence as proton.* Incompatible with secondary origin since at these energies radiative losses (~E^2) are dominant during propagation.

② Electron spectrum: *featureless* up to at least 1 TeV and *more steep than e^+*

③ Inclusive $e^+ + e^-$ spectrum: direct measurements < 1 TeV => power law index ~ -3.17

Spectrum above 1 TeV: only preliminary or indirect measurements.

"Great Expectations" from CALET and DAMPE.

Potential discovery of local source(s) at kpc distance

✧ Anisotropy in e^+ and e^- data: *no anisotropy observed* at all angular scales by PAMELA

Electron measurements at high energy are challenging due to the large proton background. High proton rejection power (> 10^5) is required.

<u>The CR leptonic sector puzzle</u> *(theoretical interpretations)*

✧ Positron excess from Astrophysical sources including:

- **Pulsar Wind Nebulae** (PWN) where the pulsar produces e^+e^- pairs
  + acceleration away from the neutron star (at termination shock)

- **SuperNova Remnants** (SNR) for a recent eview e.g.: [P.Serpico, Astropart. Phys. 39-40 , 2]

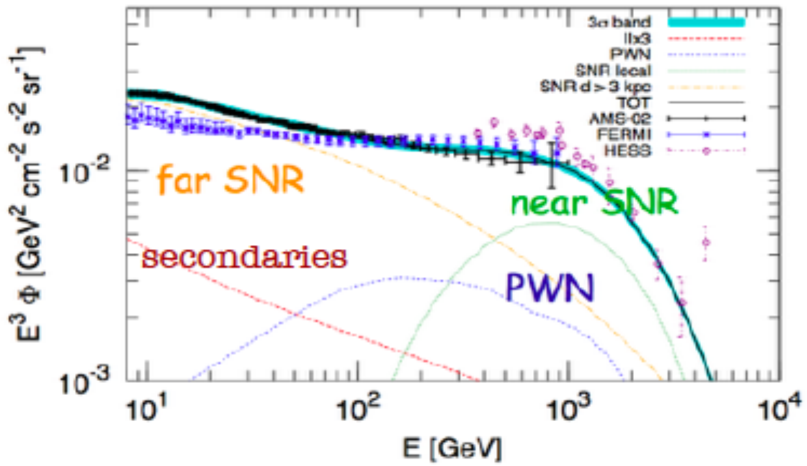
- **Local source(s)**: order 0.1% anisotropy expected at ~ 100 GeV

✧ Positron excess from Dark Matter for a recent review e.g.: [M. Cirelli - Dark Matter phenomena - Rapporteur Talk at ICRC2015]

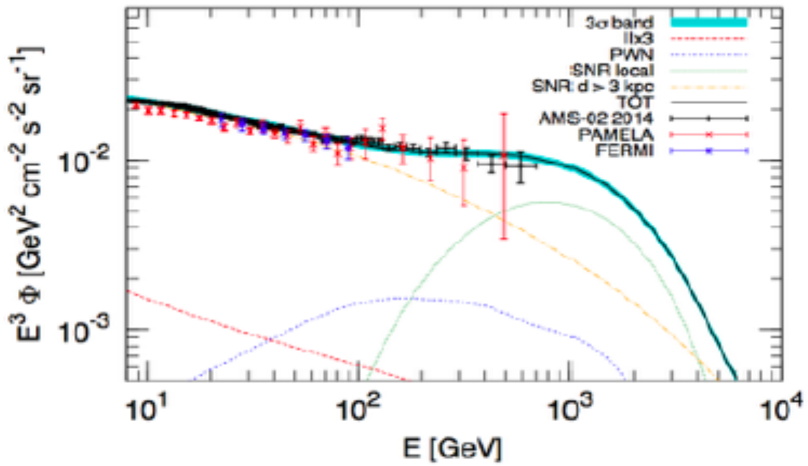
Astrophysical interpretation(s)

- try to fit simultaneously all observables with a single model.
- Large number of papers. An example below from [M.Di Mauro @ICRC2015] :

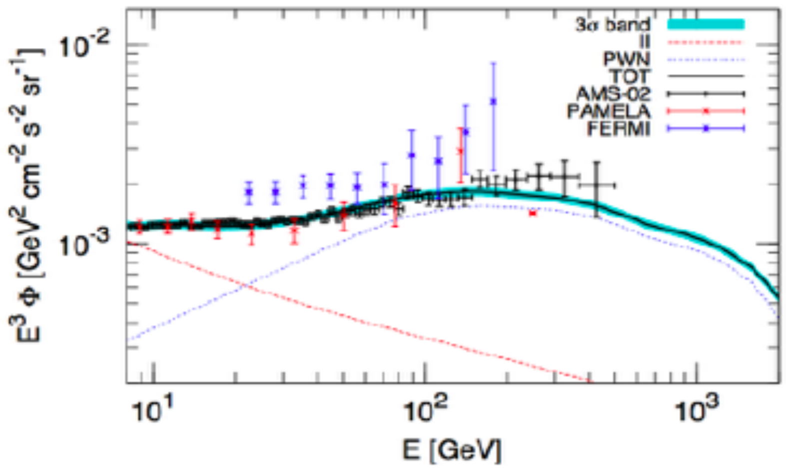
$e^+ + e^-$



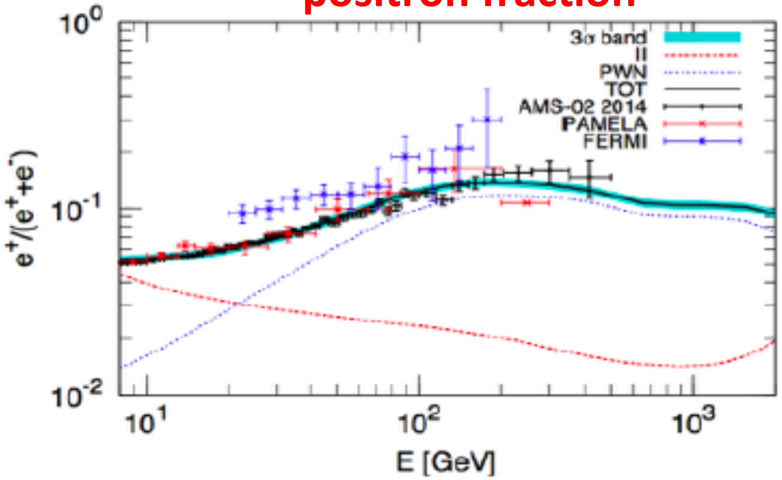
electrons



positrons

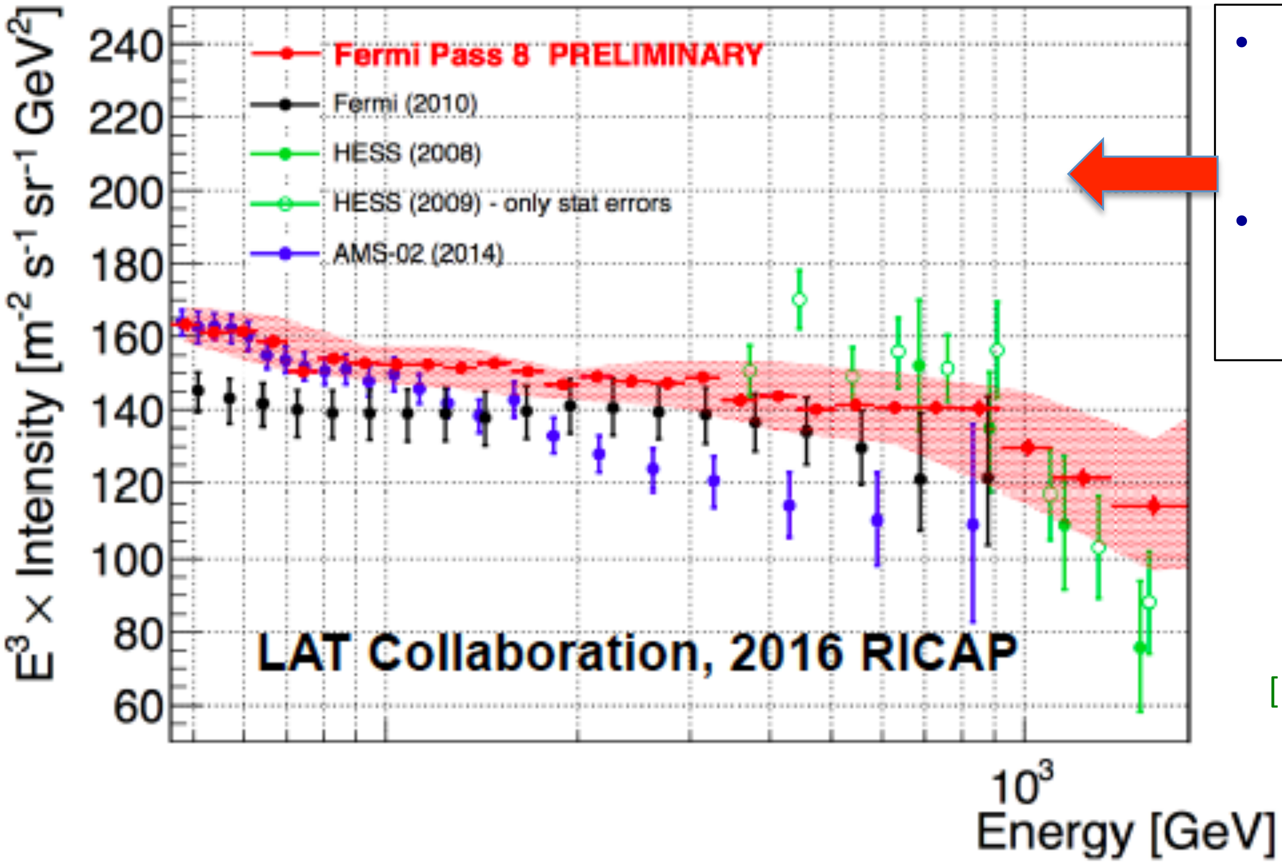


positron fraction



WANTED ! electron spectrum above 1 TeV

- Precision measurements expected from new missions CALET and DAMPE
- Present efforts by FERMI, PAMELA, AMS02



- recent direct measurements **FERMI Pass 8** (preliminary) versus AMS-02.
- indirect measurements from HESS affected by large systematic errors

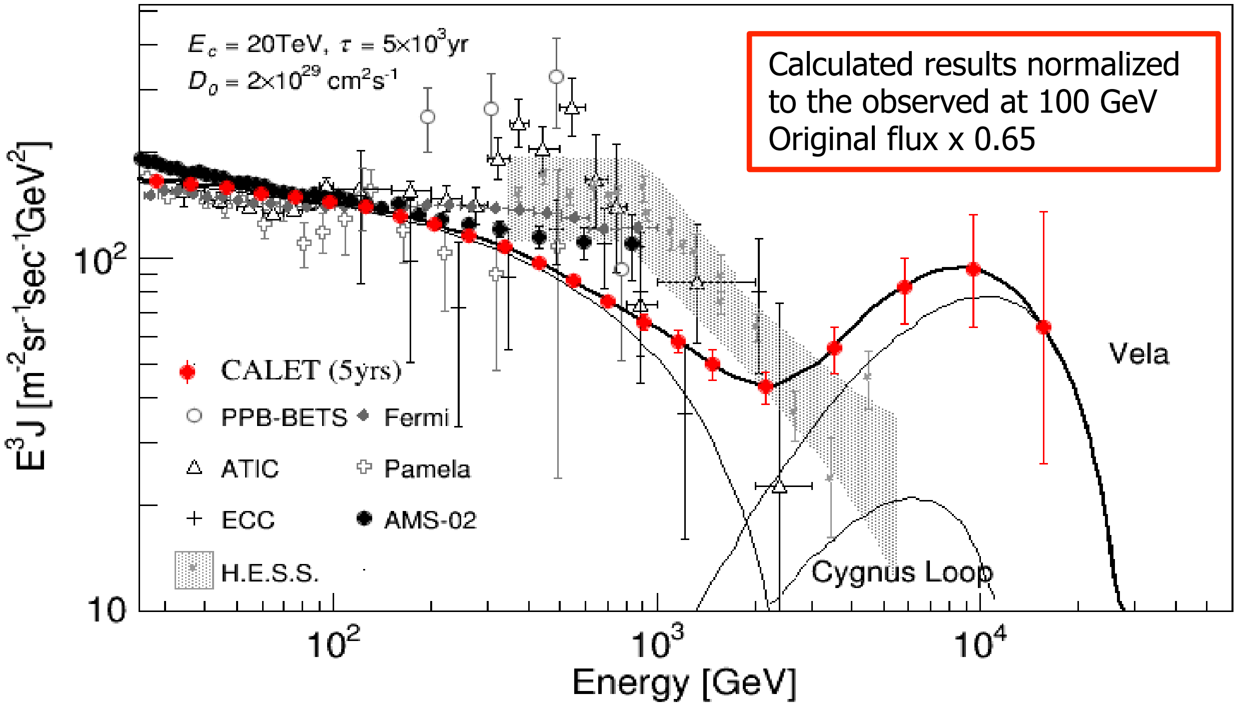
[Latronico @LNGS July 2016]

New experiments: CALET Identification of Electron Sources

Some nearby sources, e.g. Vela SNR, might have unique signatures in the electron energy spectrum in the TeV region (Kobayashi et al. ApJ 2004)

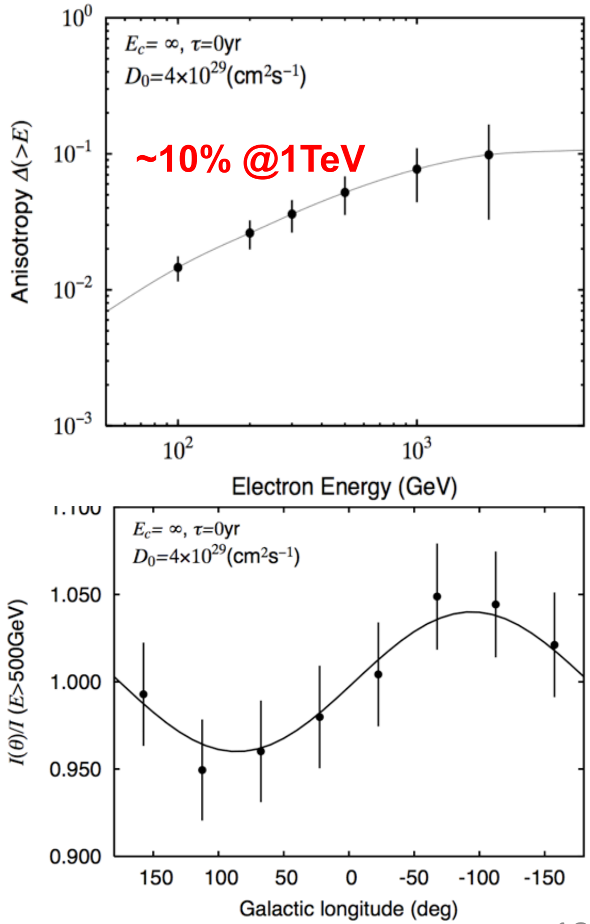
Expected flux for 5 year mission

> 10 GeV	~ 2.7 x 10^7
>100 GeV	~ 2.0 x 10^5
>1000 GeV	~ 1.0 x 10^3

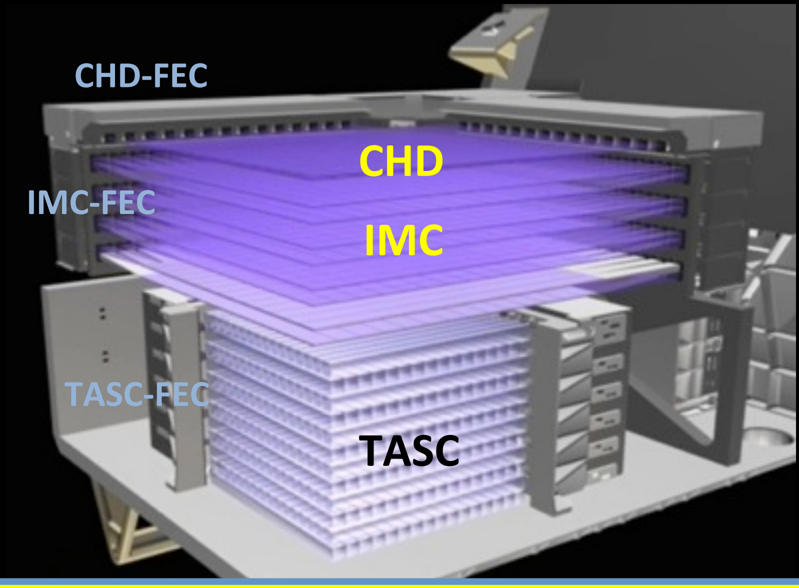


Identification of the unique signature from nearby SNRs, such as Vela in the electron spectrum by CALET

Expected Anisotropy from Vela SNR



CALET instrument overview



Geometric Factor :

1200 cm^2sr for electrons, light nuclei

1000 cm^2sr for gamma-rays

4000 cm^2sr for ultra-heavy nuclei

- **ΔE/E** :
  ~2% (>10 GeV) for e, gamma
  ~30-35 % for protons, nuclei
- **e/p separation** : ~10^{-5}
- **Charge resolution** : 0.15 - 0.3 e
- **Angular resolution** :
  0.2° for gamma-rays > ~50 GeV

- Standard Payload Size
- Mass: 612.8 kg
- Power: 507 W (Max)

- Telemetry:
  - Medium rate: 600 kbps
  - Low rate: 50 kbps

CALET: a unique set of key instruments.

- **TASC**: a **thick, homogeneous calorimeter** allows to extend electron measurements into the TeV energy region with ~2% energy resolution.
- **IMC:** a **high granularity (1mm) imaging pre-shower with tracking capabilities** identifies the starting point of electromagnetic showers.
- TASC+IMC provide a **strong rejection power ~10^5** to separate electrons from the abundant protons.
- **CHD: a charge detector** combined with multiple dE/dx samples from IMC identifies individual elements.

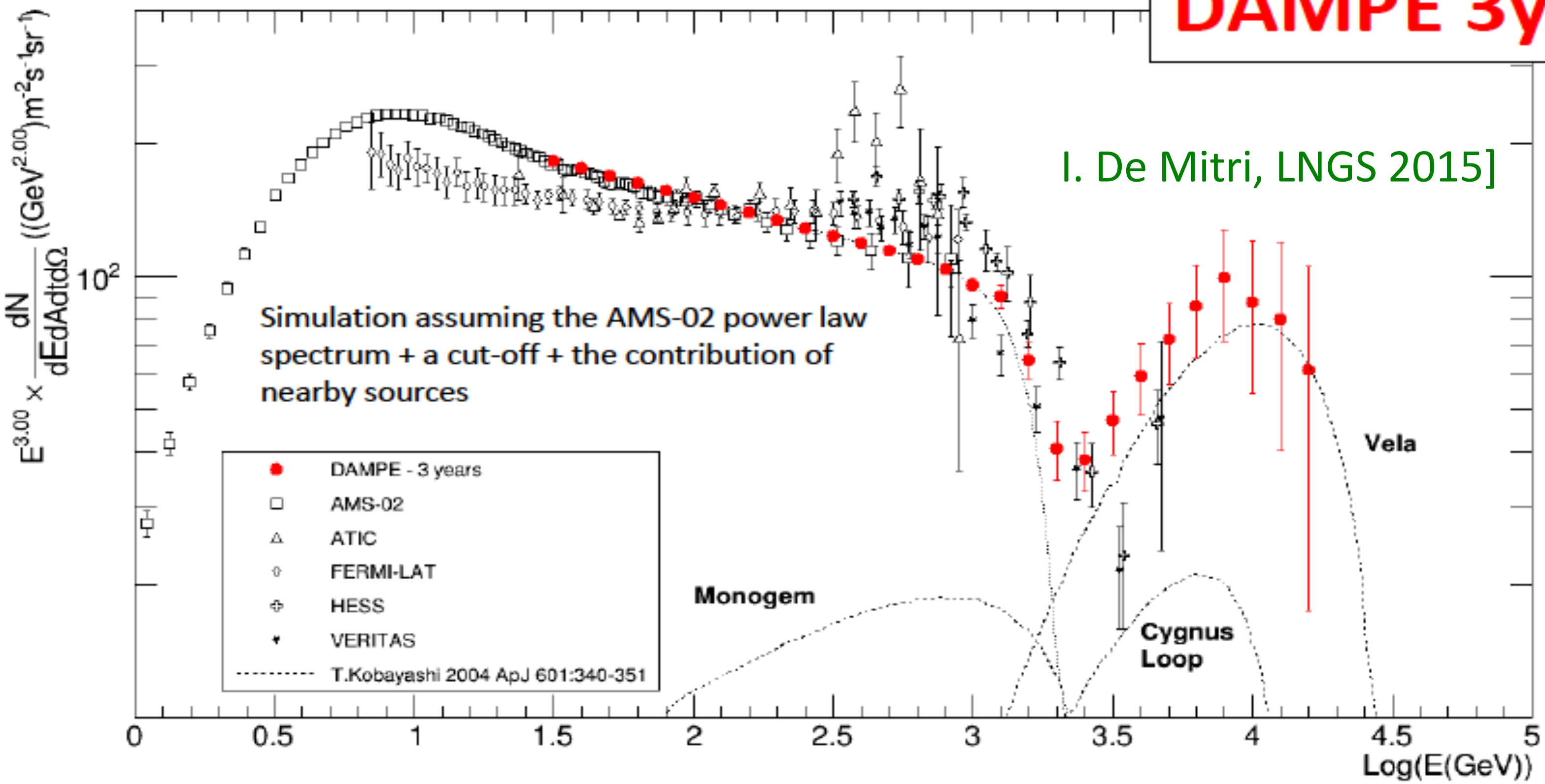
CGBM

Calet
Gamma-ray
Burst
Monitor

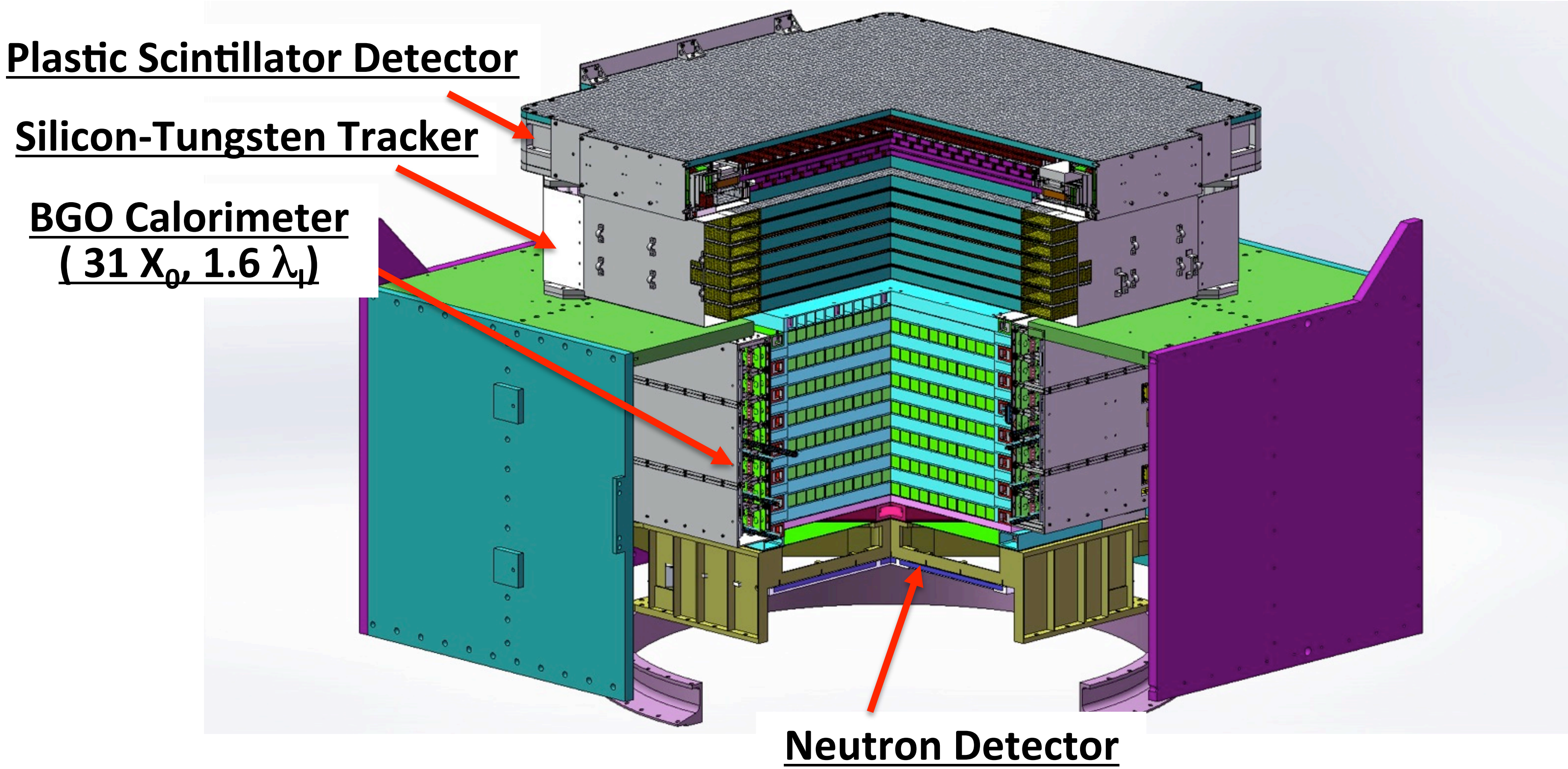
New experiments: DAMPE all-electron spectrum (expected)

- Measure the all-electron flux up to about 10TeV
- Measure with high accuracy the sub-TeV region and the possible cut-off around one TeV
- Detect structures in the spectrum due to nearby sources and/or DM induced excesses
- Detect anisotropies at high energy

DAMPE 3yrs



The DAMPE Detector



W converter + thick calorimeter (total 33 X_0) + precise tracking + chargemeasurement

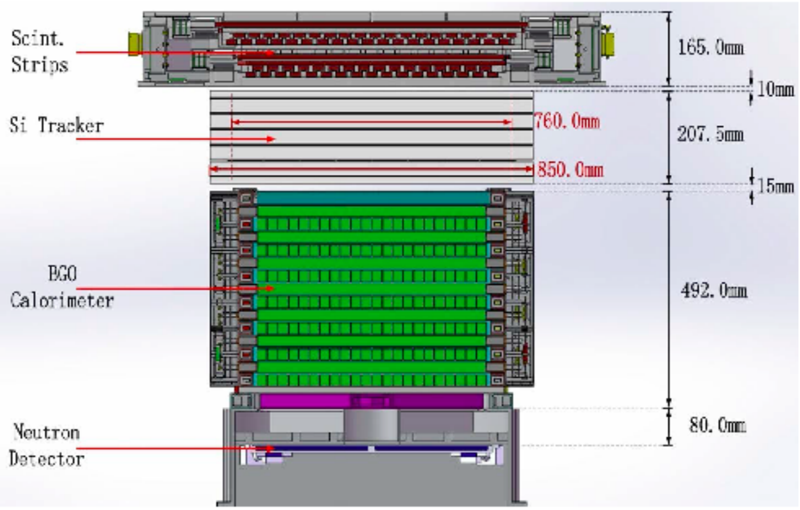
high energy gamma-ray, electron and CR telescope

DAMPE

Dark Matter Explorer Satellite

- Large geometric factor instrument (0.3 m^2 sr for p and nuclei)
- Precision Si-W tracker (40μm , 0.2°)
- Thick calorimeter (32 X_0 , σ_E/E better than 1% above 50 GeV for e/γ , ~35% for hadrons)
- "Mutiple" charge measurements (0.2-0.3 e resolution)
- e/p rejection power > 10^5 (topology alone, plus neutron detector)

	DAMPE
e/γ Energy res.@100 GeV (%)	1.5
e/γ Angular res.@100 GeV (°)	0.1
e/p discrimination	10^5
Calorimeter thickness (X_0)	32
Geometrical accep. (m^2sr)	0.29



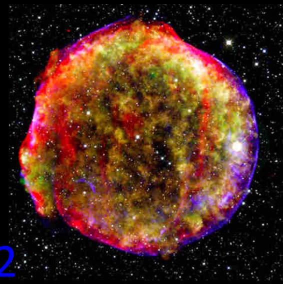
Comparison with AMS-02 and FERMI

	DAMPE	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	1.5	3	10
e/γ Angular res.@100 GeV (°)	0.1	0.3	0.1
e/p discrimination	10^5	10^5 - 10^6	10^3
Calorimeter thickness (X_0)	32	17	8.6
Geometrical accep. (m^2sr)	0.29	0.09	1

[I. De Mitri, LNGS 2015]

- **Satellite ≈ 1900 kg, payload ≈1300kg**
- **Power consumption ≈640W**
- **Lifetime > 3 years**
- **Launched by CZ-2D rockets**

- **Altitude 500 km**
- **Inclination 97.4°**
- **Period 95 minutes**
- **Sun-synchronous orbit**

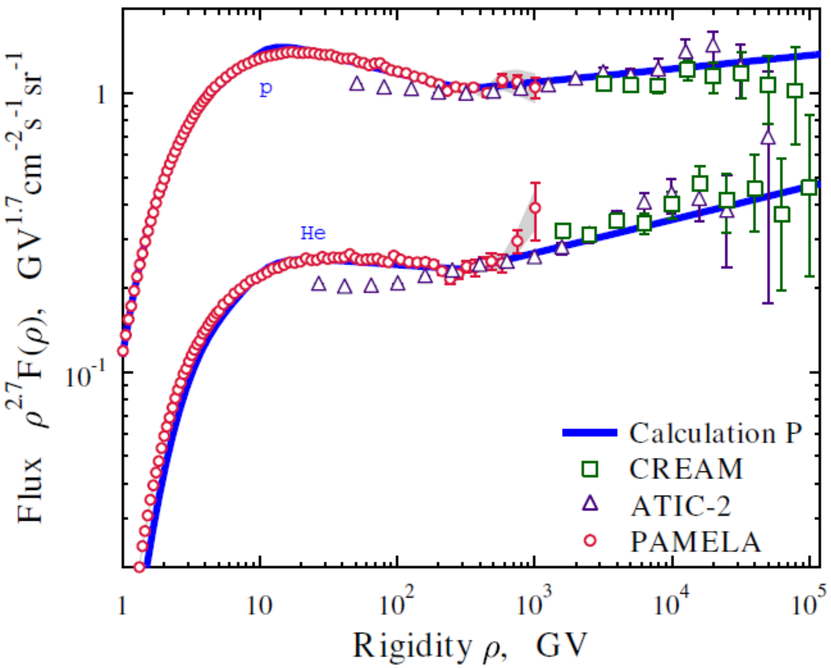

Tycho SN 1572

Charged cosmic-ray hadrons

energy spectra of p, He, light nuclei, sub-Fe nuclei, ...

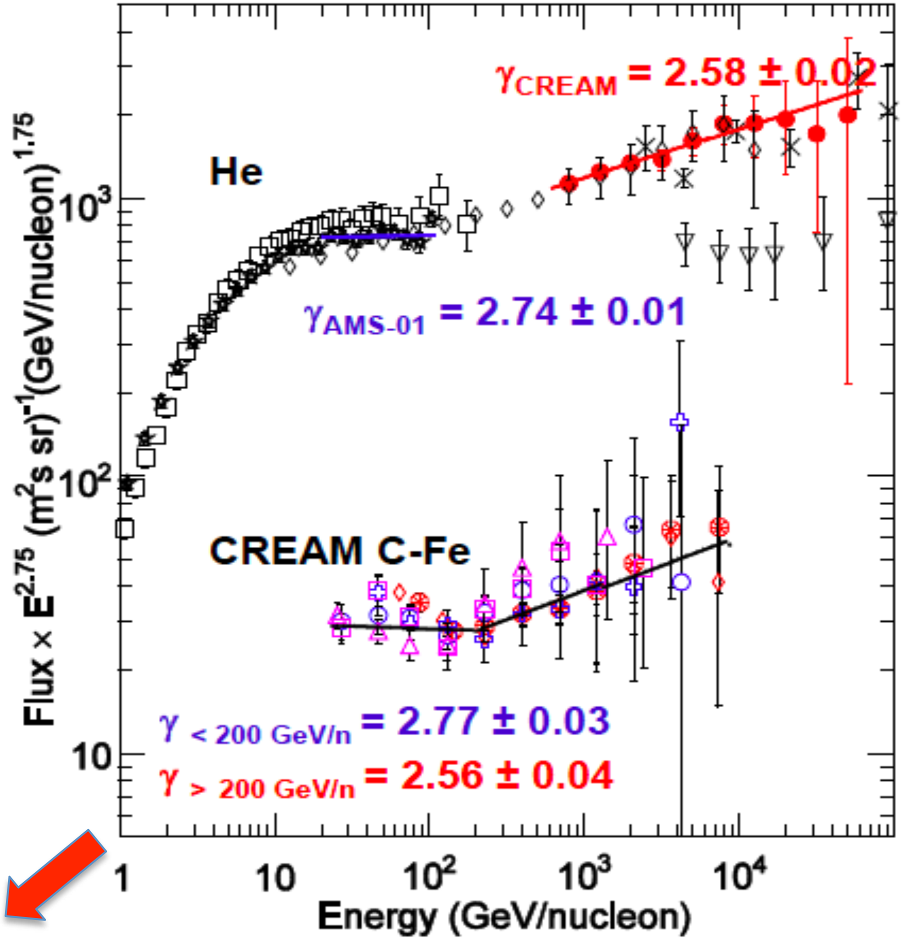
Direct measurements of proton and He spectra

- PAMELA detected a spectral break in PROTON and HE spectra at R ~ 240 GV



A single power-law seems inadequate to fit the spectra

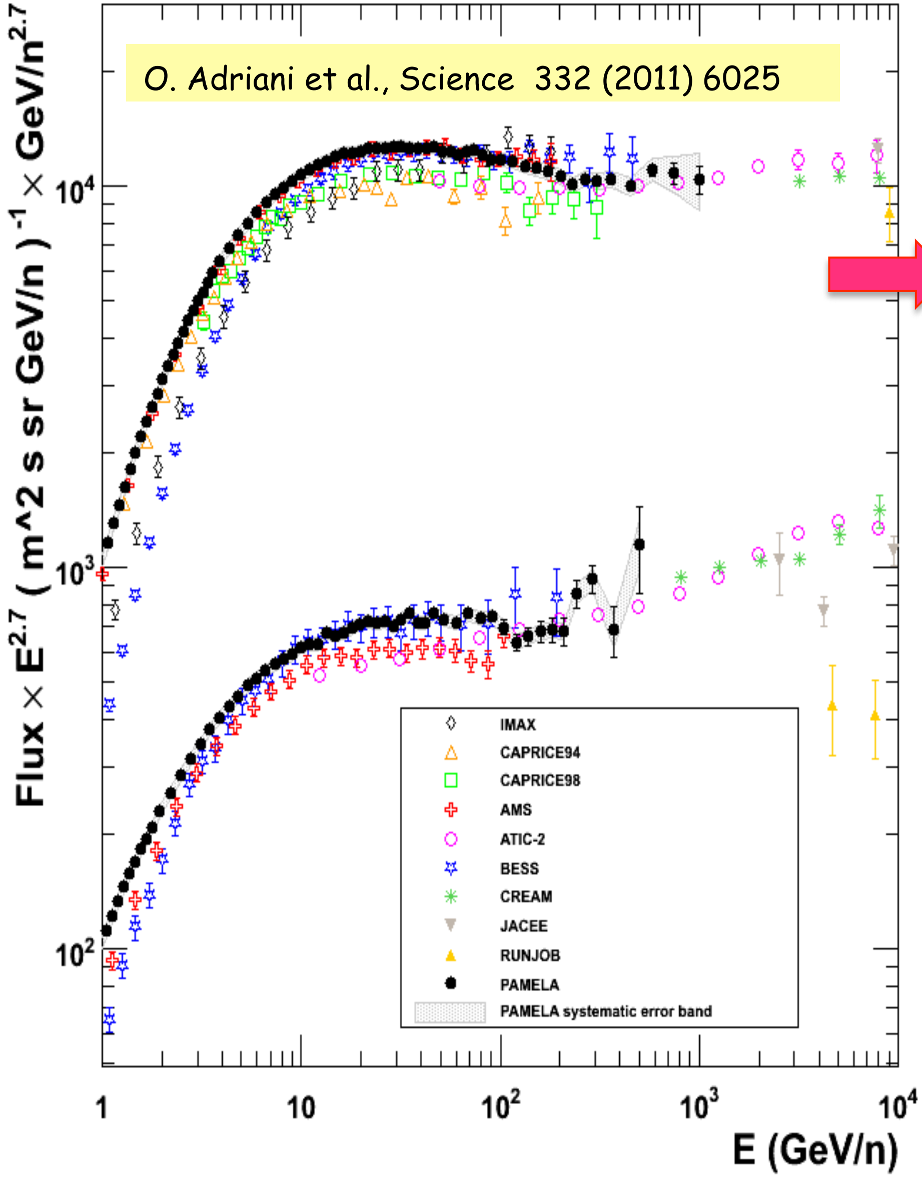
- The break also appears in the spectra of NUCLEI measured by CREAM up to several TeV/n



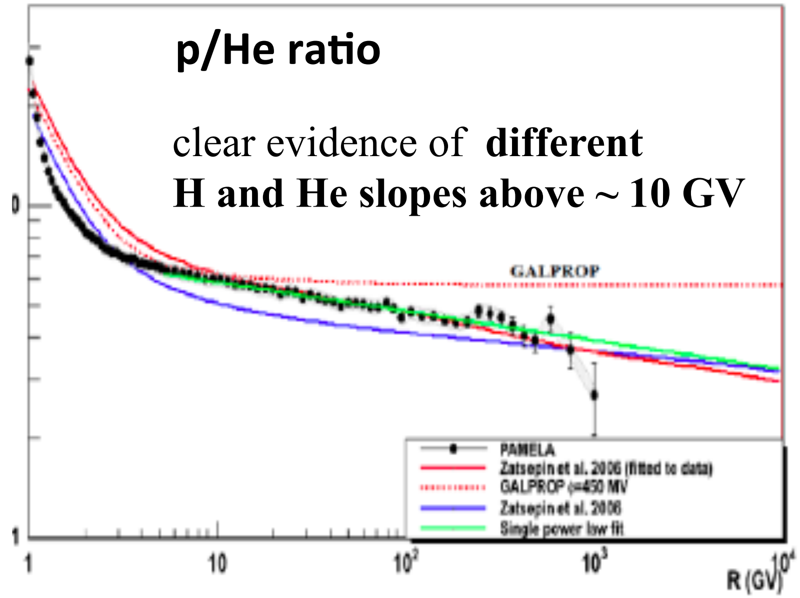
The slope of Z>2 NUCLEI at high energy looks similar to He and different from protons

Ahn et al. ApJ 714, L89, 2010
Yoon et al. ApJ **728**, *122*, 2011

PAMELA: Proton and Helium Nuclei Spectra & H/He ratio



- **First high-statistics and high-precision measurement over three decades in energy**
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV $\Delta\gamma$~0.2÷0.3
    Single power-law rejected at 98% CL

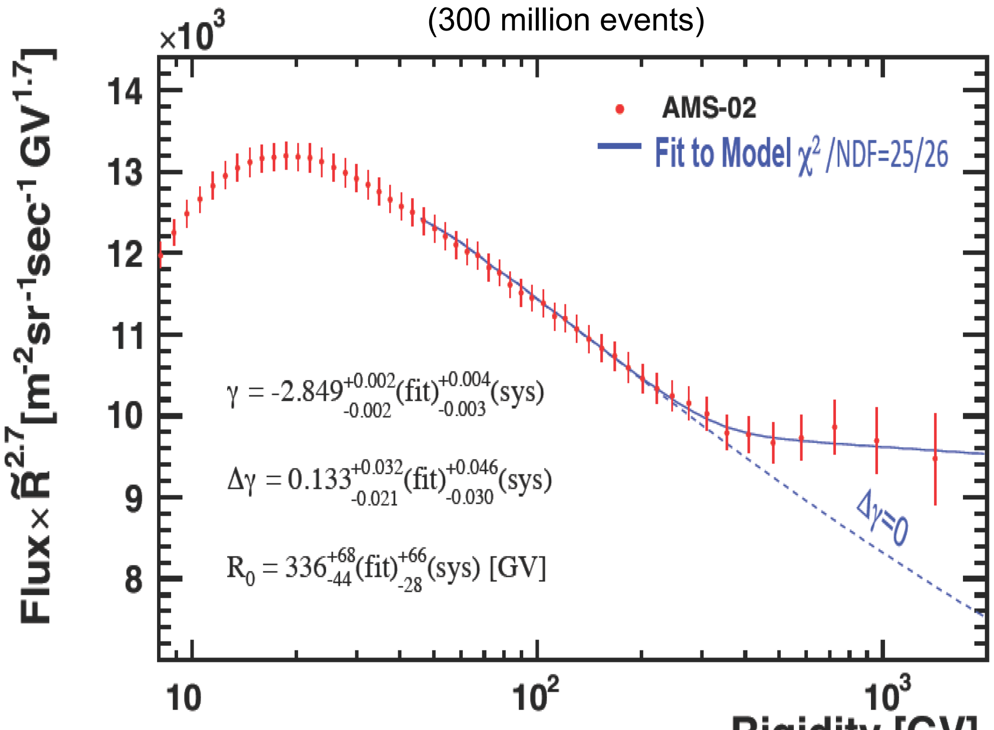


Proton and He fluxes measured by AMS-02

Two power laws with a characteristic transition rigidity R_0 and a smoothness parameter s are used by AMS-02 to fit the measured H and He spectra:

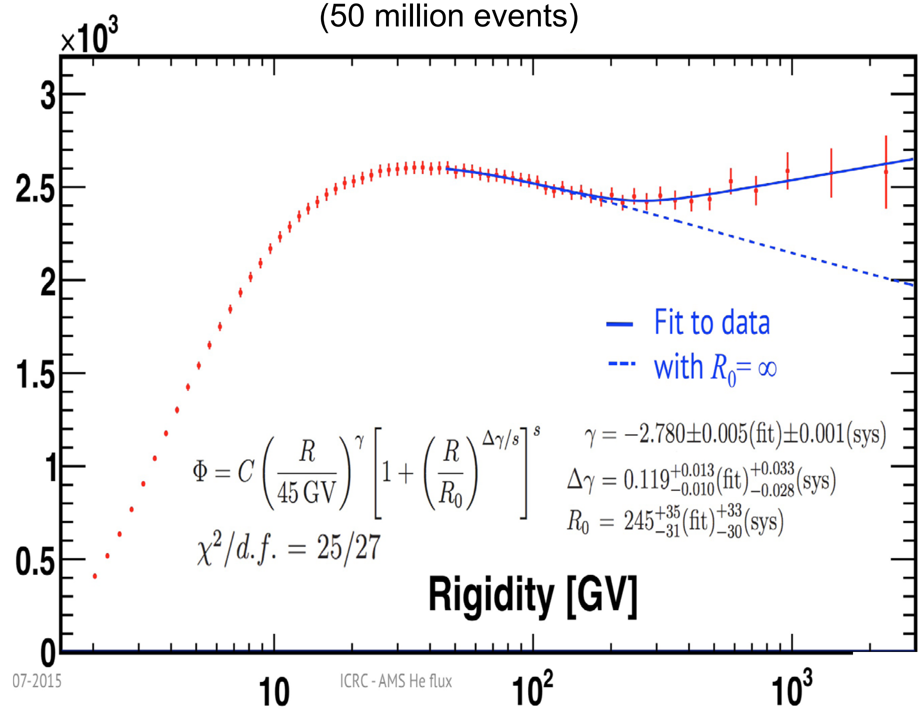
$$\Phi = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS proton flux
(300 million events)



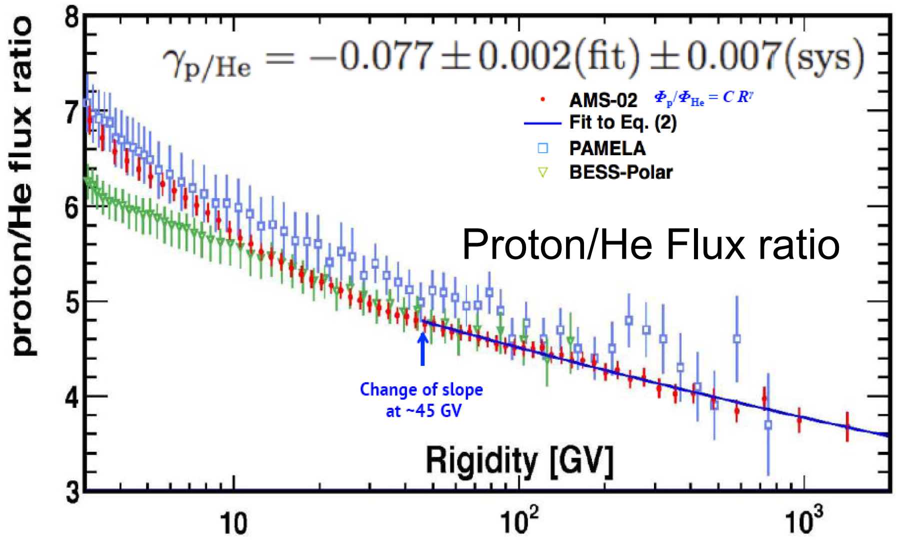
[V. Choutko ICRC 2015]

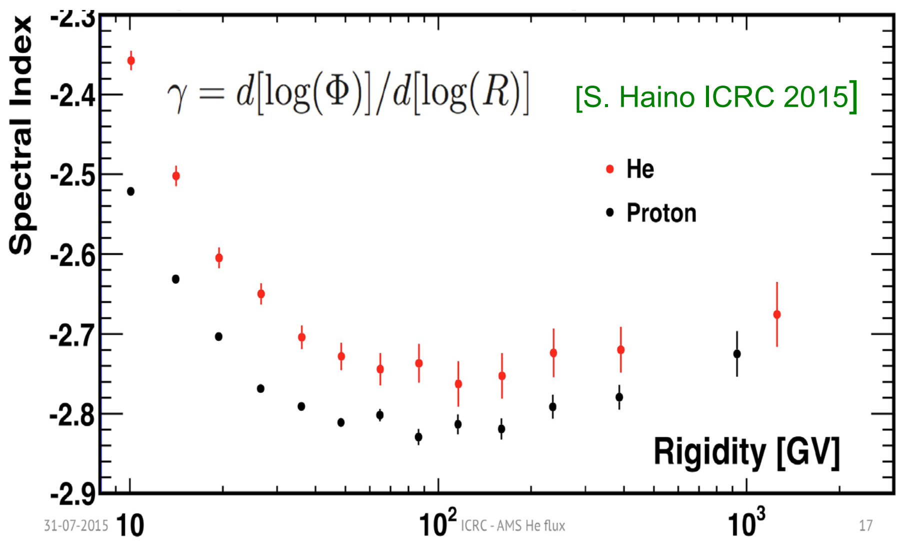
AMS He flux
(50 million events)

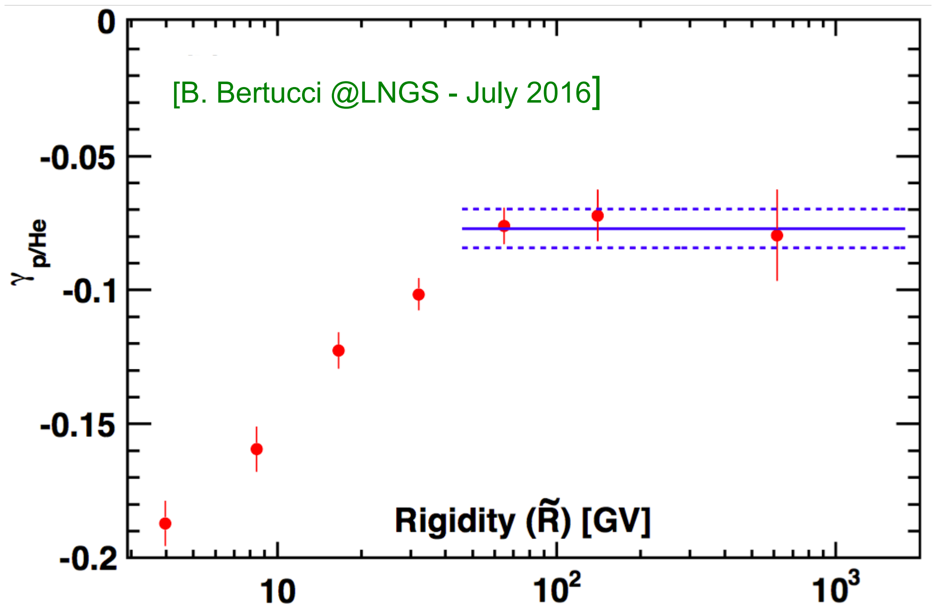


[S. Haino ICRC 2015]

AMS-02: spectral indices for p and He





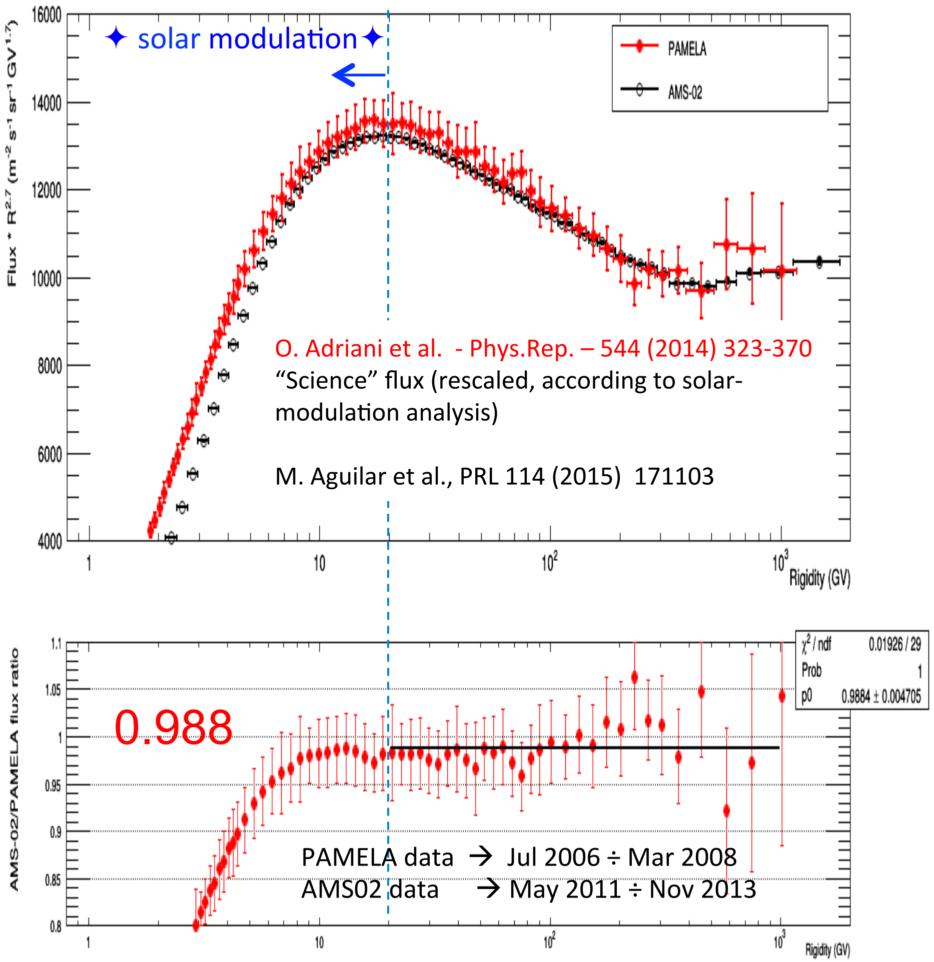


- Both spectral indices are progressively hardening above ~100 GV.
- He spectrum is harder than proton.
- the rigidity dependence of the spectral indices of p and He are similar.

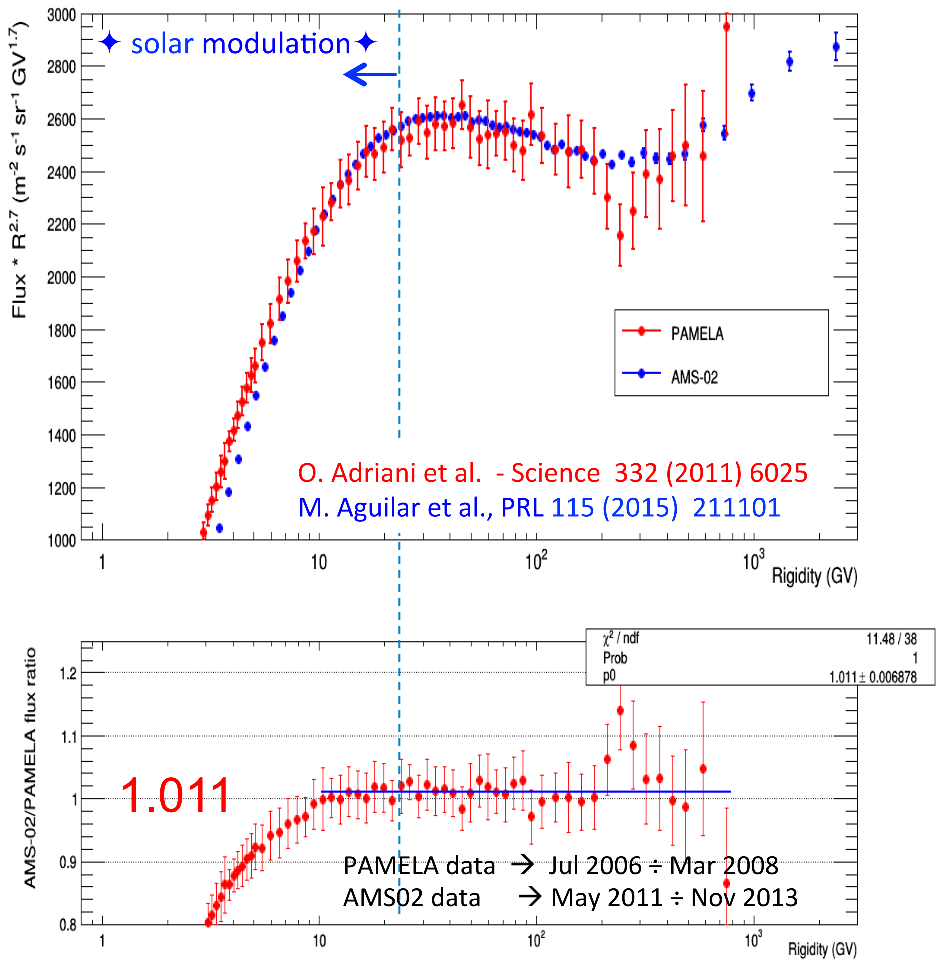
Pamela vs. AMS-02: proton and He below 1 TeV

good agreement up to 1 TeV in the energy region above a few tens of GV unaffected by solar modulation [Boezio @UCLA Dark Matter 2016, 02/17/16]

proton

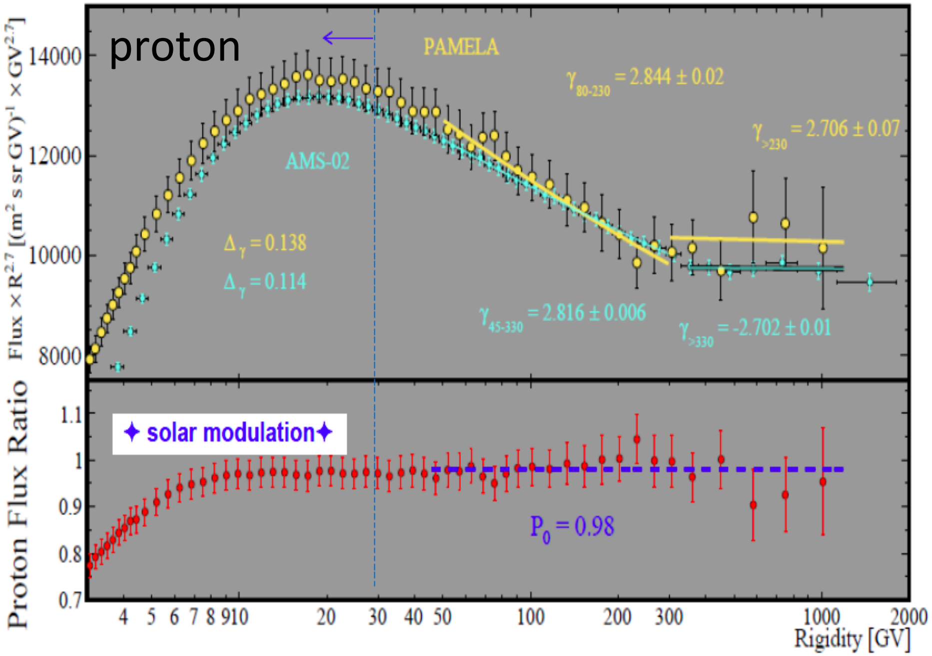


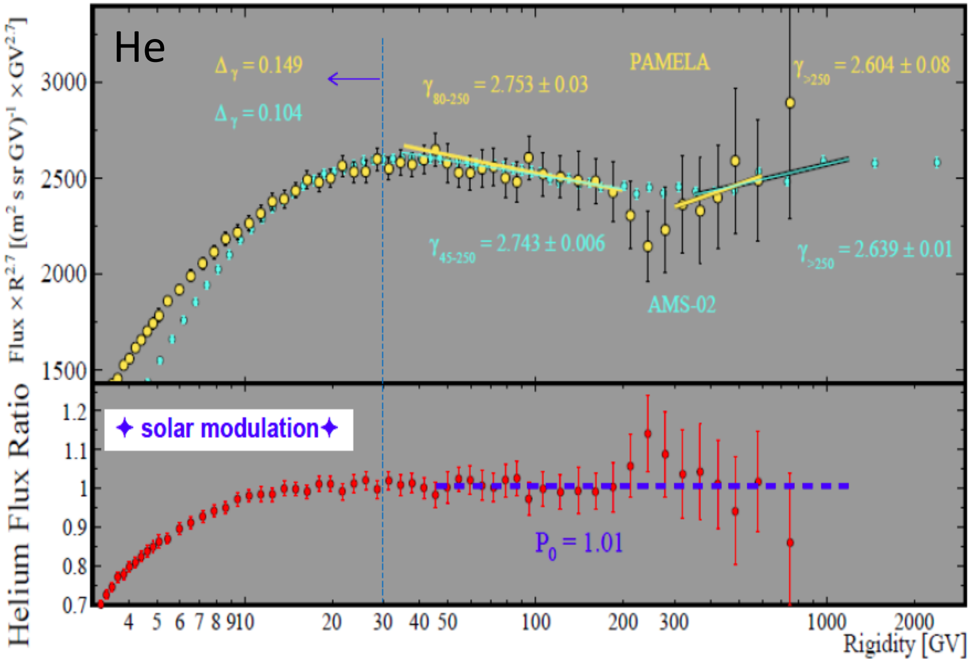
He



New era of precision spectral measurements:

✧ good agreement between PAMELA and AMS-02 on p and He spectra





[M.Boezio @LNGS Jul 2016]

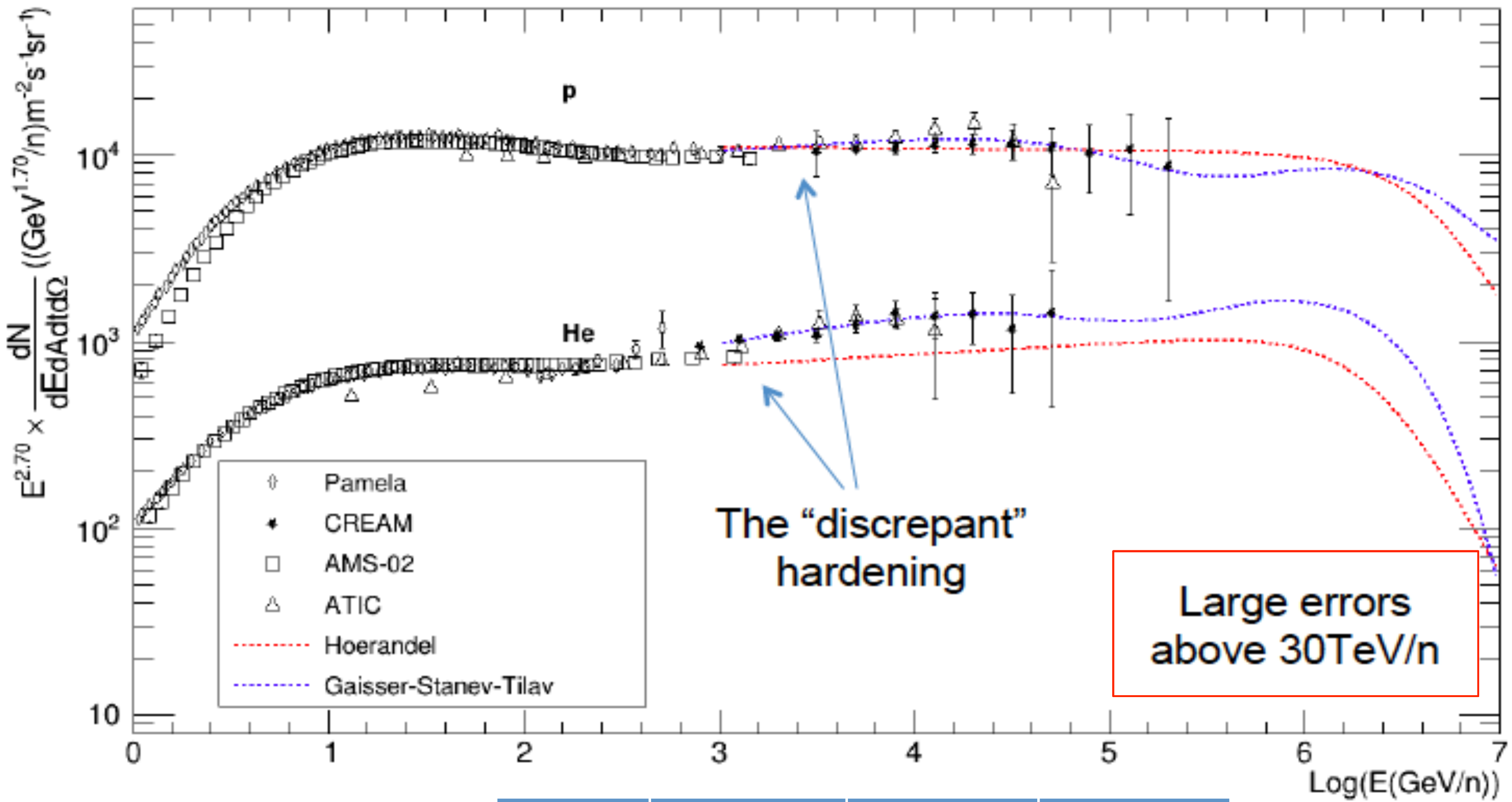
O. Adriani et al., Phys. Rep. 544 (2014) 323 ; M. Aguilar et al., PRL 114 (2015) 171103

O. Adriani et al., Science 332 (2011) 6025 ; M. Aguilar et al., PRL 115, (2015) 211101

	fit range proton	γ_p	fit range He	γ_{He}
PAMELA	80-230 GV	-2.844±0.02	80-250 GV	-2.753±0.03
AMS-02	45-330 GV	-2.816±0.006	45-250 GV	-2.743±0.006

Proton and Helium:

✧ need to extend precision measurements to the multi-TeV region



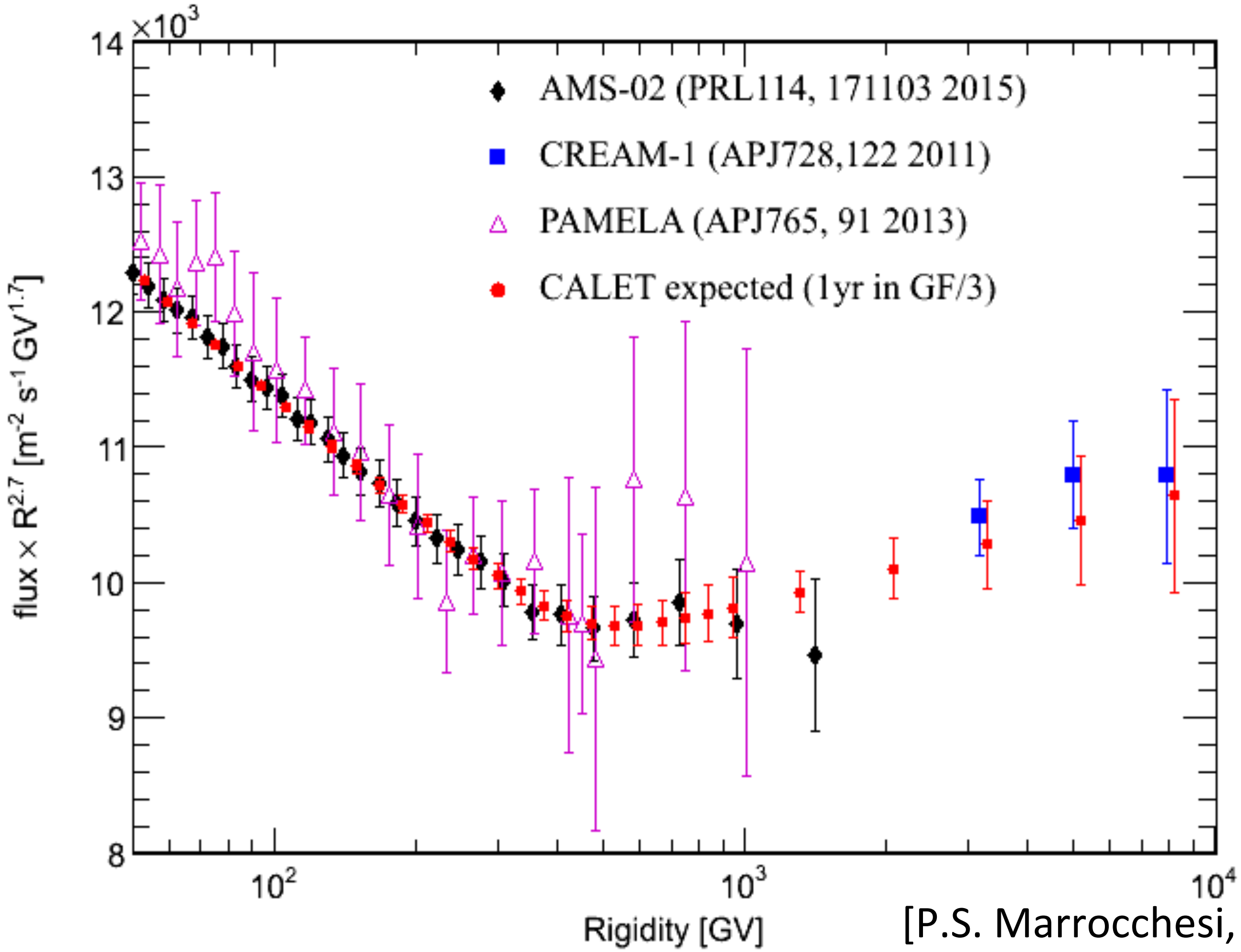
fitted slope of p, He spectra above 230 GV

	fit range p (He)	γ_p	γ_{He}
CREAM(*)	2.5 -250 TeV	-2.66±0.02	-2.58 ±0.02
PAMELA	> 230 (250) GV	-2.706±0.07	-2.604±0.08
AMS-02	> 330 (250) GV	-2.702±0.01	-2.639±0.01

(*) Ahn et al., ApJ **714**, *L89*, 2010

✧ **Precision measurements are expected** from **new missions**: CALET, DAMPE (both in flight), ISS- CREAM (to be launched)

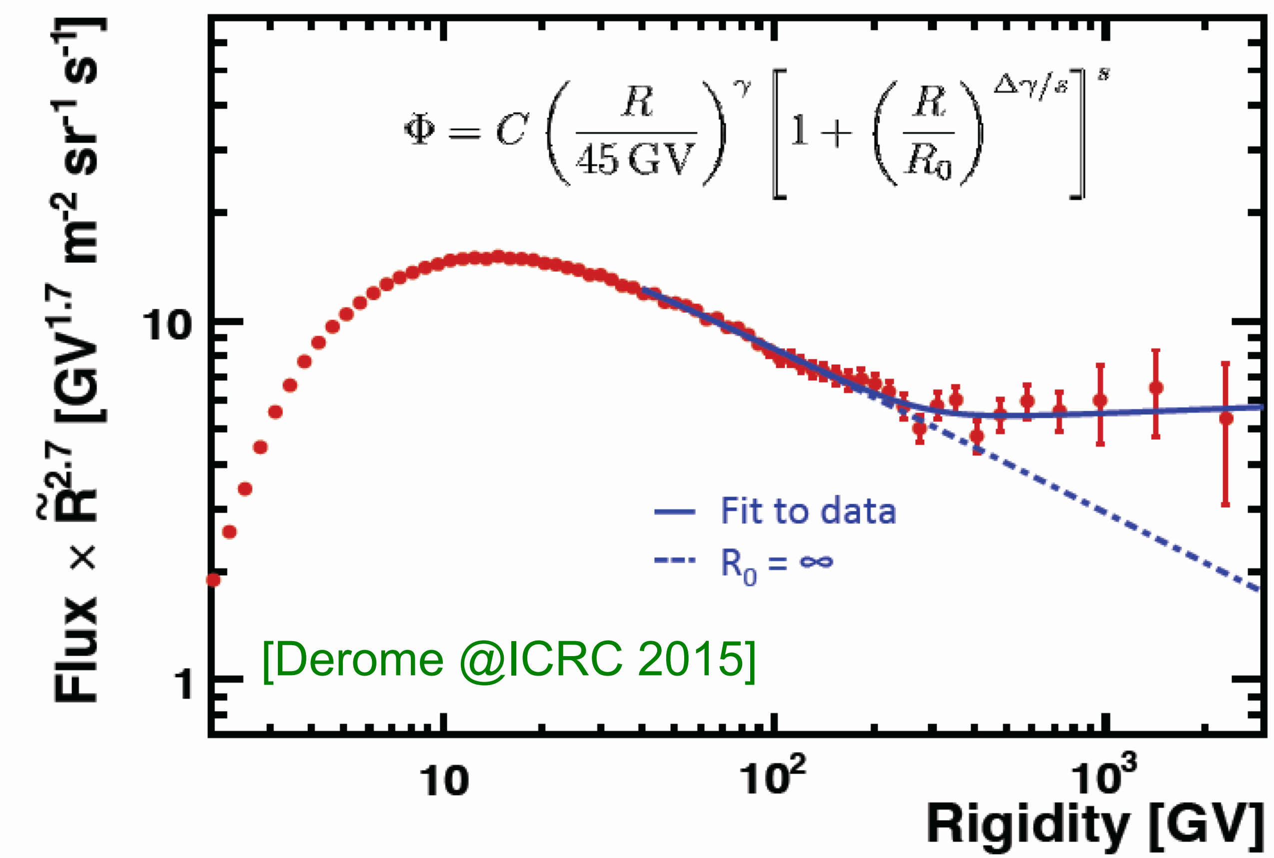
✧ for example: after one year on the ISS, CALET is expected to close the gap between AMS02 and CREAM above 1 TV. It will also extend the investigation on the spectral shapes of proton and He to the multi-TeV region.



[P.S. Marrocchesi, arXiv:1512.08059]

Lithium flux from AMS-02 shows a hardening !

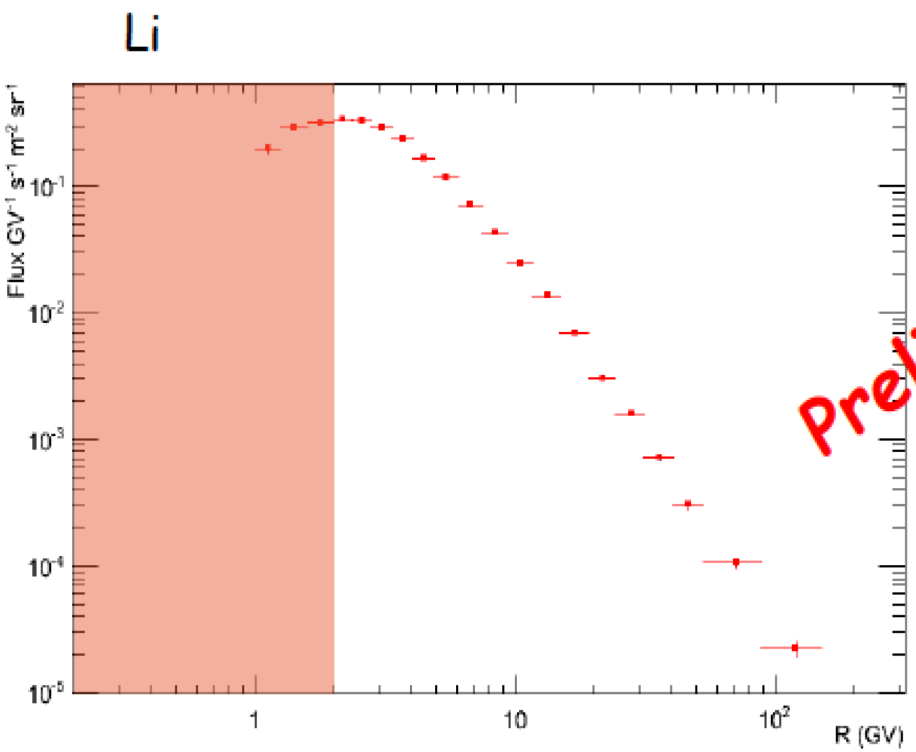
- measured in the rigidity range 2 GV – 3 TV

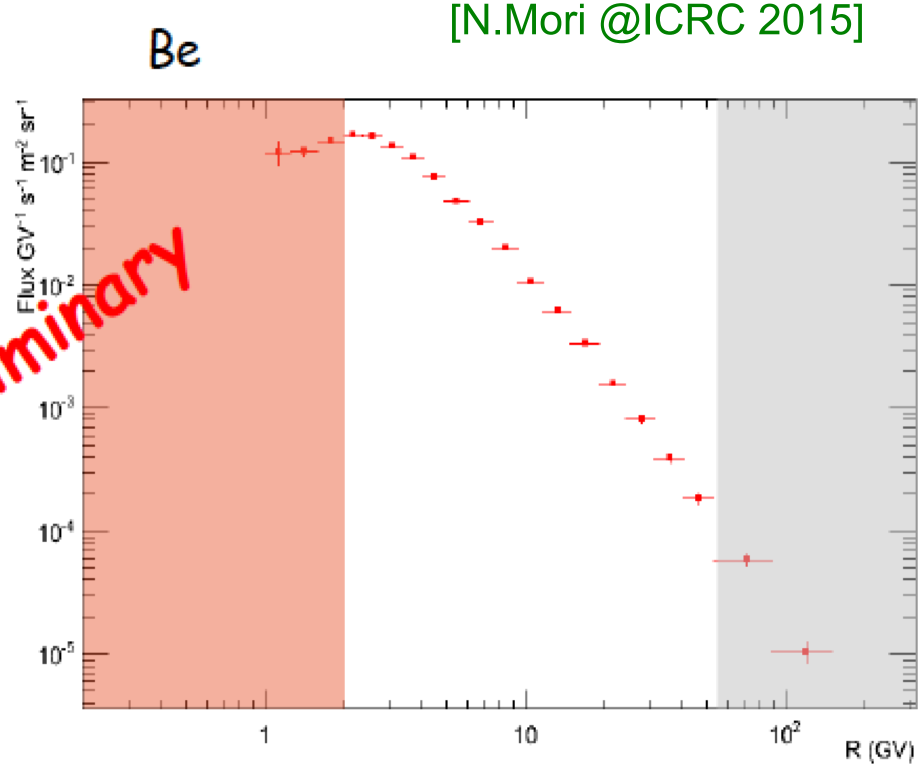


→ Lithium flux hardening in the same rigidity range than for Proton and Helium.

Preliminary Li and Be fluxes from PAMELA

[N.Mori @ICRC 2015]



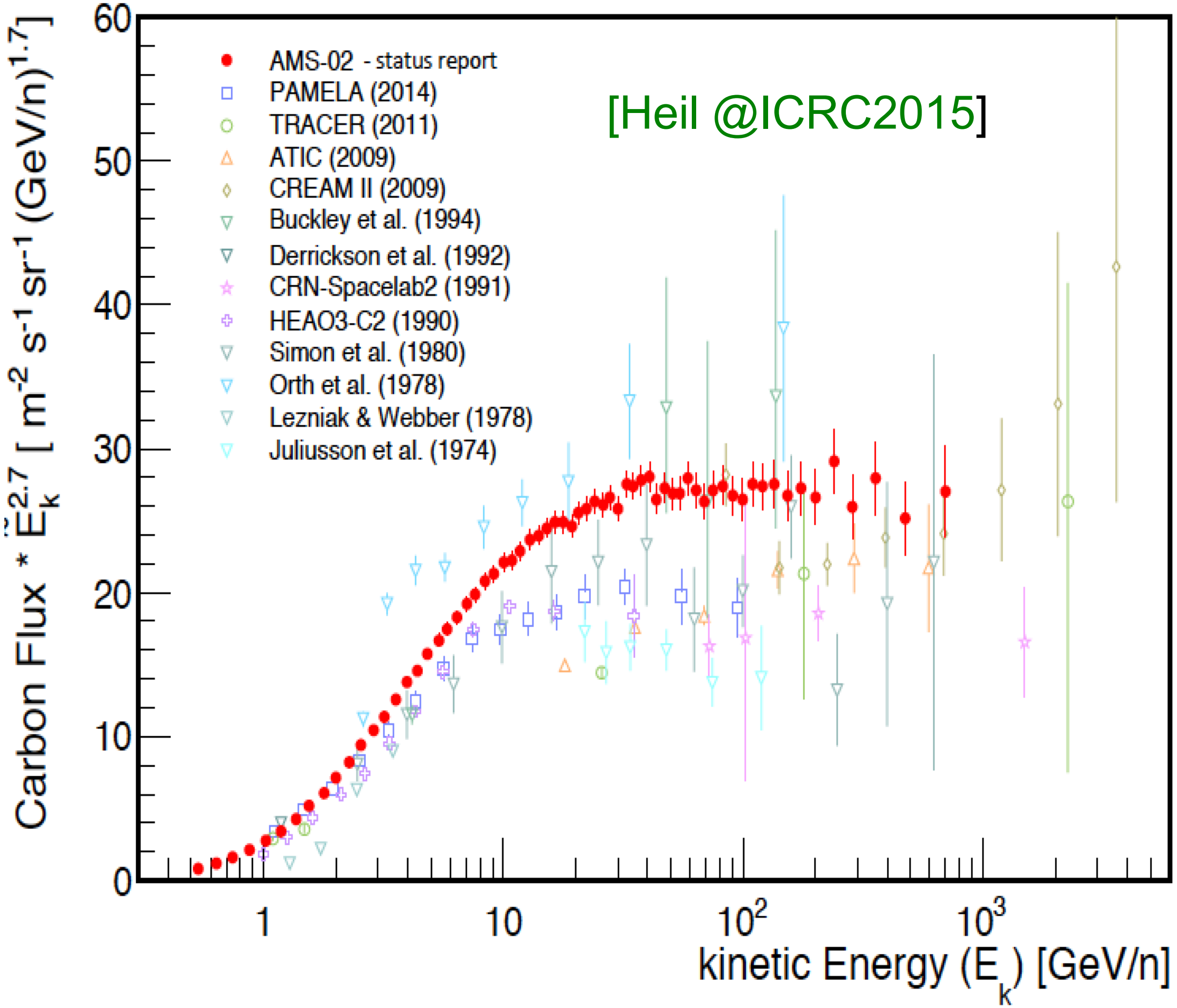


- Shaded red area: particle slow-down effects
  - Still to be corrected

- No MC corrections
- Not unfolded
- Only statistical errors

- Shaded grey area: relevant MDR effects for Be (due to saturated clusters)
  - Still to be corrected

Preliminary Carbon flux from AMS-02

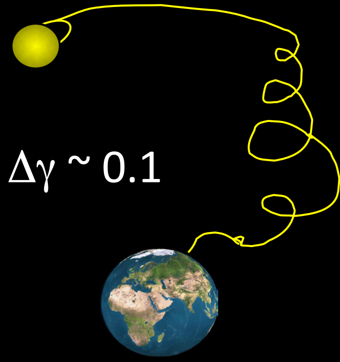


- Hardening is NOT is observed in C spectrum
- Evident disagreement with PAMELA data
- Need to increase statistics above 200 GV
- The analysis is preliminary

The CR hadronic sector puzzle (*observations*)

Emerging picture from current observations:

- break in power law in rigidity around 200-300 GV for p, He, Li, ...
- violation of univerality of spectral indices: protons spectrum is softer by $\Delta\gamma \sim 0.1$



Still to be clarified experimentally:

① sharp spectral break or continuos curvature ?

② is there a break also in C spectrum (unclear from preliminary data)

③ Is He index identical to C, O ... Fe ?

- accurate measurements of p, He bridging in energy PAMELA and AMS to CREAM data:
  - position and $\Delta\gamma$ of spectral break vs. nuclear species
  - precision differential measurement of spectral $d\gamma/dE$ + extension to higher energy

❖ Multi-TeV region largely unexplored

The CR hadronic sector puzzle *(theoretical interpretation)*

Broken power law interpretations include:

- *diffusion effects* (source spectra assumed to be single power law):
    - non factorizable spatial and rigidity dependence of diffusion coefficient [N. Tomassetti, Astrophys. J. 752 , L13]
    - non linear diffusion on external turbolence (self-generated waves) above (below) the break [Blasi,Amato,Serpico, PRL 109]
- *acceleration effects* (observed features are imprinted on production spectra):
    - DSA acceleration non-linear effects (CR feed-back) [V. Ptuskin, V. Zirakashvili and E. S. Seo, Astrophys. J. 763]
    - Acceleration by different sources (e.g.: OB associations, SuperBubbles, W-R stars) [TStanev, Biermann & Gaisser, Astron. Astrophys. 274 , 902]
    - Weak re-acceleration [E. Seo and V. Ptuskin, Astrophys. J. 431]
- *local sources*:
    - Young nearby objects accounting for He harder spectrum are in tension with anisotropy measurements [Blasi, Amato, JCAP 1201 , 011]

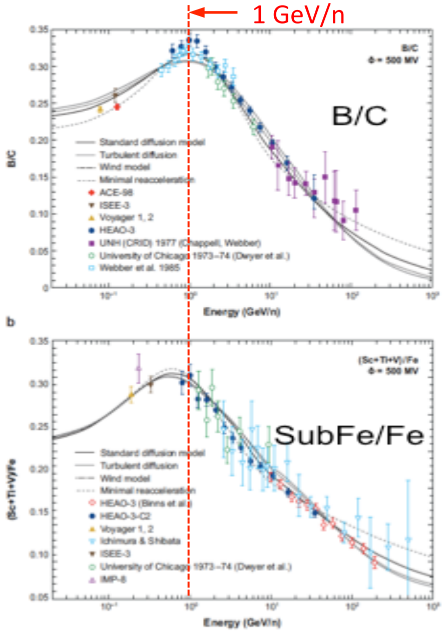
Violation of universality of spectral indices interpretations include:

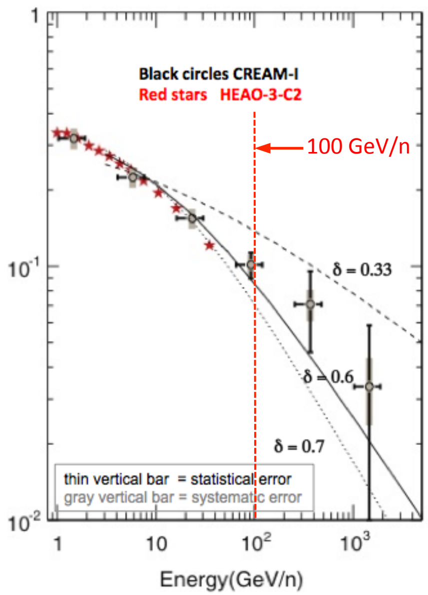
- e.g.: He accelerated "earlier" (with higherMach number than proton) ?
    - He more efficient at injection than proton + slower decline with Mach number [Malkov, Diamond & Sagdeev, Phys. Rev. Lett. 108]
    - Variable He/p ion concentration in the medium swept by shocks [L. O. Drury, Mon. Not. Roy. Astron. Soc. 415 , 1807]

SN 1604

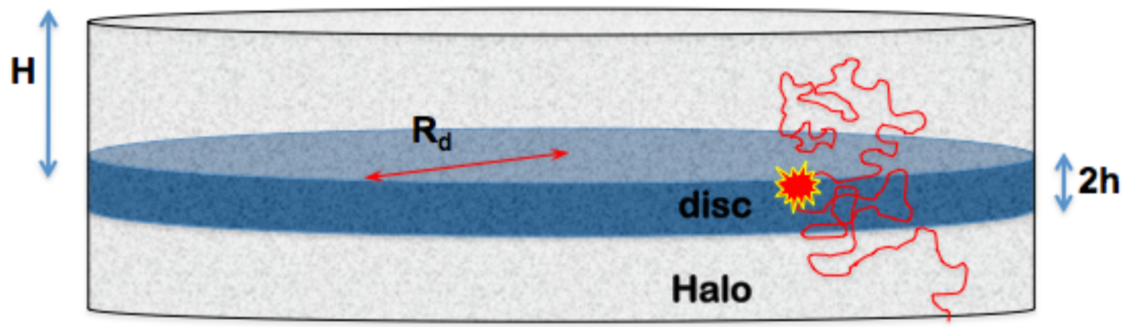
Secondary-to-Primary Ratios

Secondary/Primary Nuclei Ratios relevance





- Secondary/primary nuclei ratios decline for E > 1 GeV/n
- At high energy (E > 100 GeV/n) the S/P ratios measure the **rigidity R dependence of diffusion D(R)**
- Source spectra observed at Earth soften as a result of propagation in the Galaxy. In first approximation they factorize as $E^{-\delta}$



PRIMARY COSMIC RAY SPECTRUM AT EARTH

$$n_{CR}(E) = \frac{N(E)\,\mathcal{R}}{2\pi R_d^2}\,\frac{H}{D(E)} \equiv \frac{N(E)\,\mathcal{R}}{2H\pi R_d^2}\,\frac{H^2}{D(E)} \propto E^{-\gamma-\delta}$$

- **BUT** the diffusion coefficient might also depend on positon and have a **tensor** character (see next slide)

◆ Anisotropic diffusion in some propagation models

An example from the talk of D. Gaggero @ICRC 2015:

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

D. Gaggero @ICRC 2015

The idea:

→ we drop the over-simplified assumption of homogeneous diffusion
→ we consider a harder diffusion coefficient in the inner Galaxy

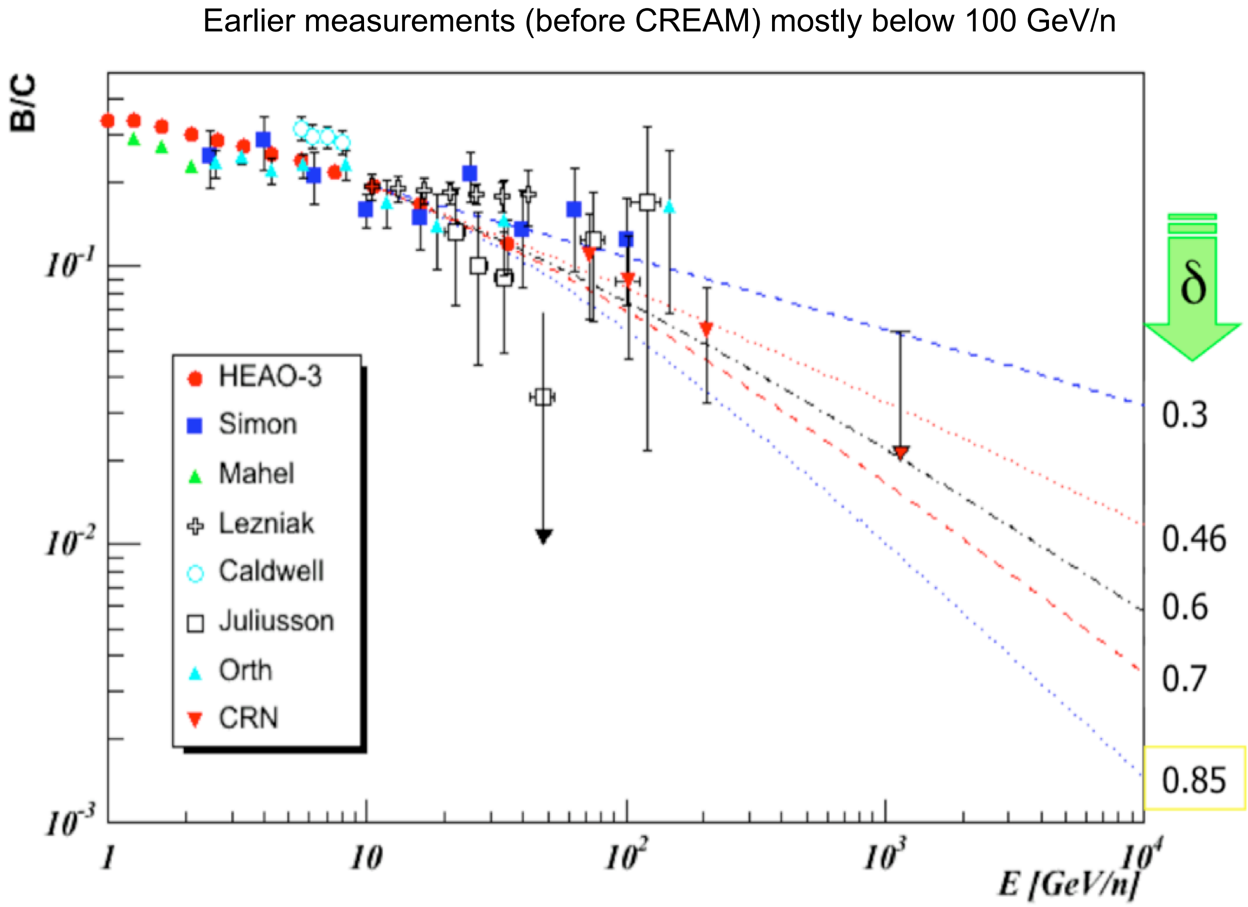
$$\delta(R) = aR + b$$

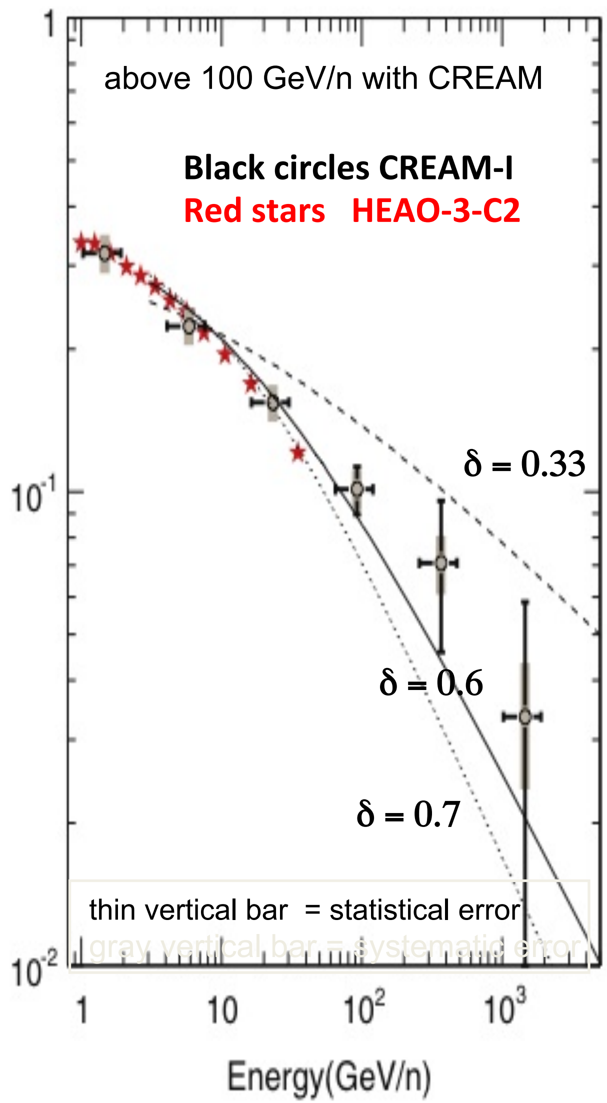
physical interpretation:

- CR near the sources propagate in SN-driven turbolence
- CR in the outer Galaxy propagate in self-generated turbolence

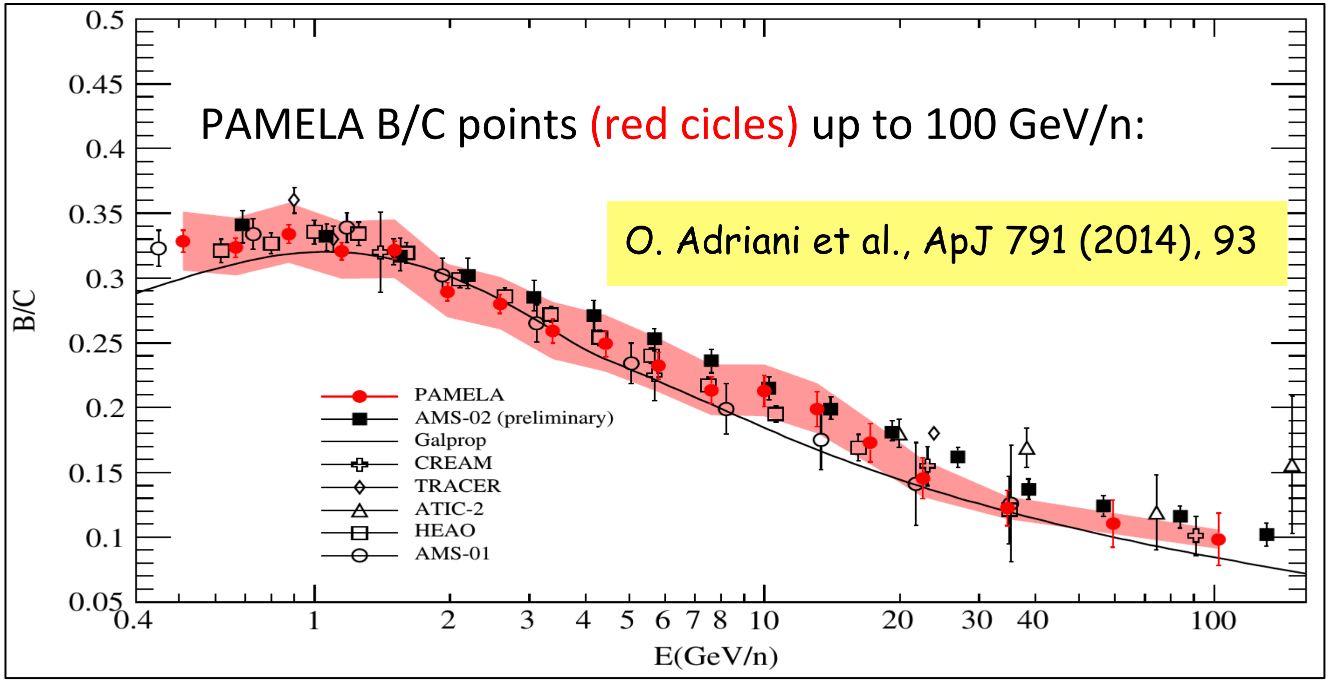
(see Blasi 2013. Tomassetti 2014)

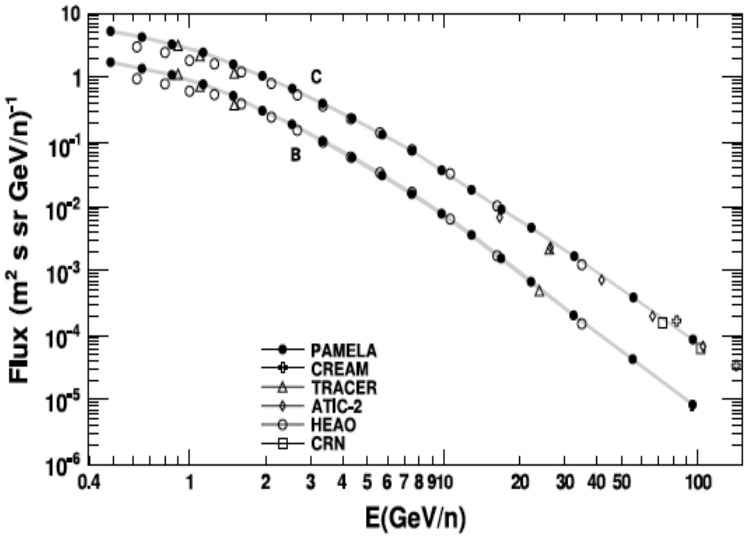
Boron to Carbon ratio vs. Energy/nucleon





PAMELA: Boron and Carbon fluxes and B/C to 100 GeV/n

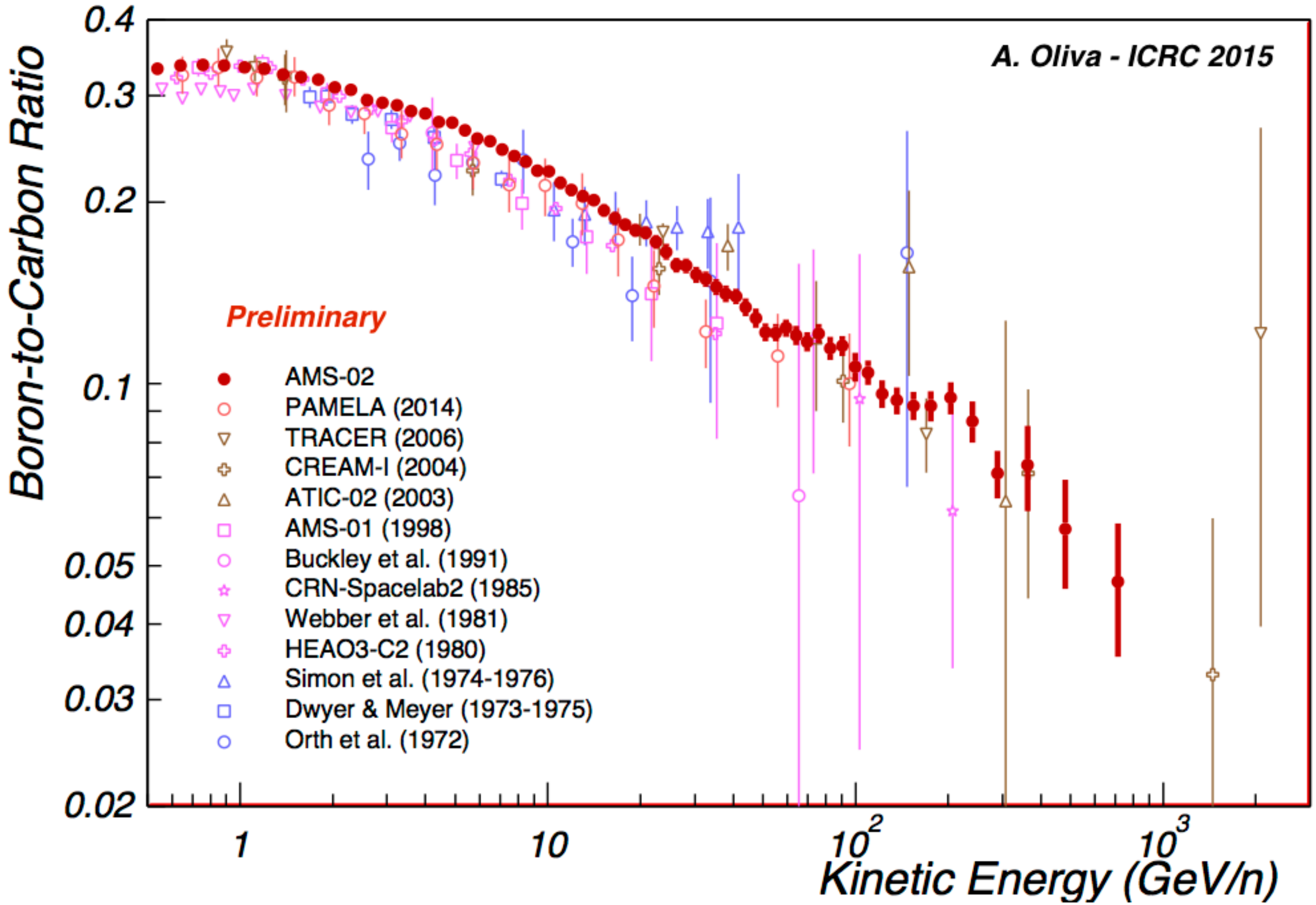




B and C differential fluxes to 100 GeV/n

O. Adriani et al.
Physics Reports 544 (2014) 323–370

Current B/C measurements (AMS-02 red points)



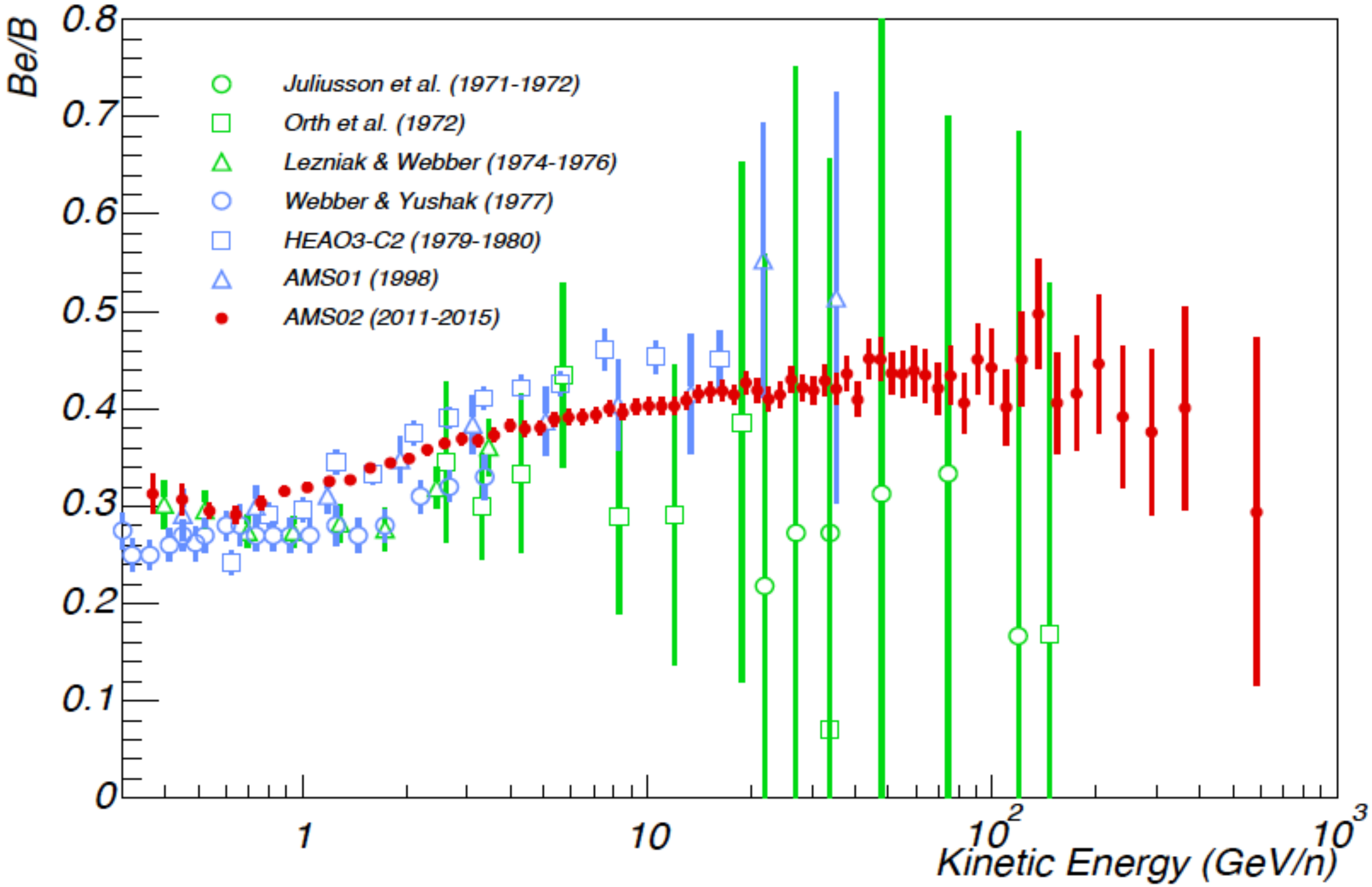
Beryllium-to-Boron Flux Ratio

C, N, O,…, Fe + ISM → Li, Be, B + X

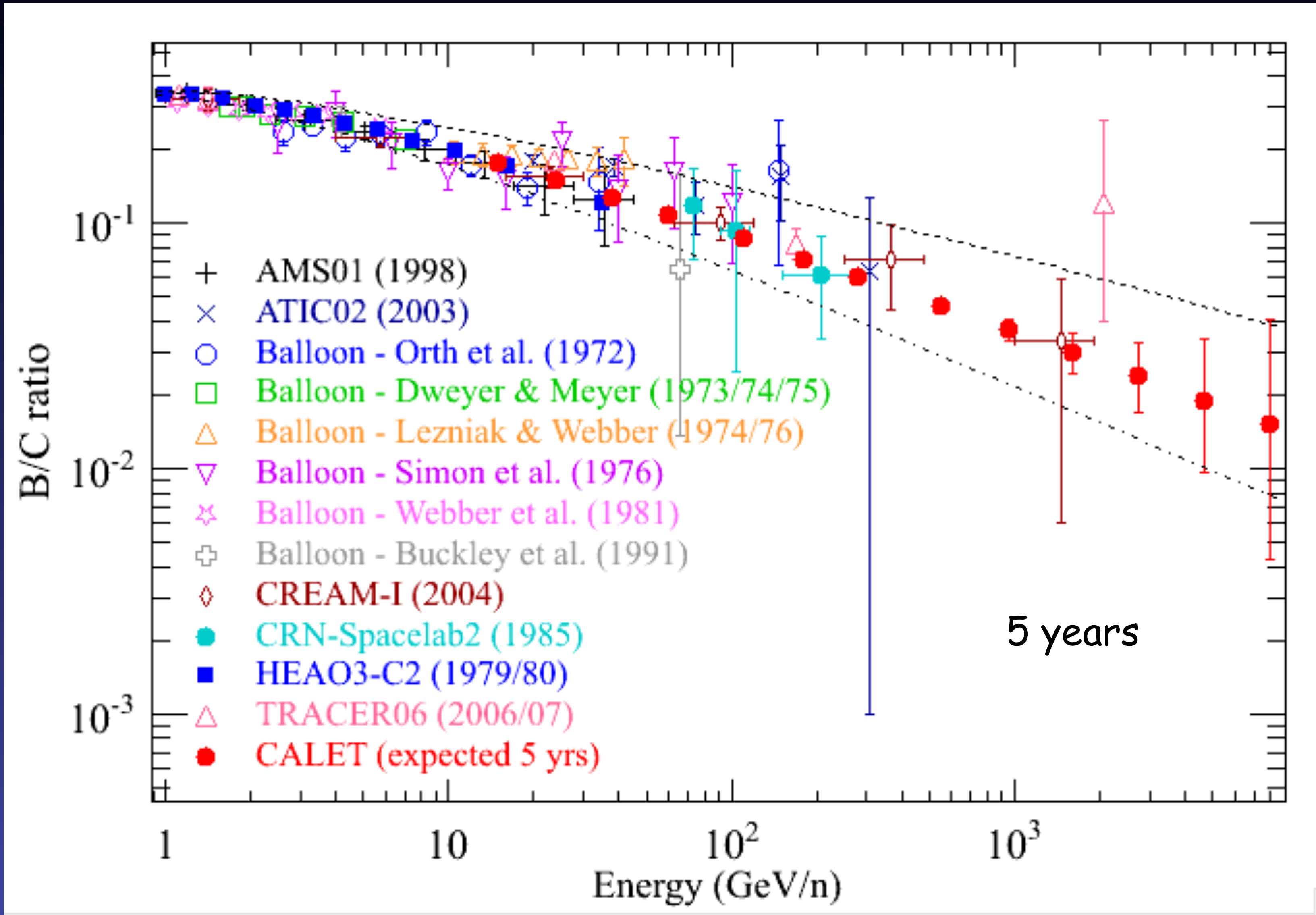
B + ISM → Li, Be + X

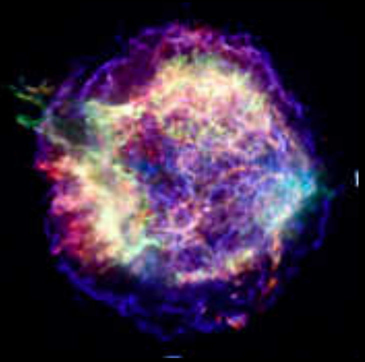
$^{10}Be \rightarrow {}^{10}B + e^- + \nu_e$

[B. Bertucci @LNGS - July 2016]

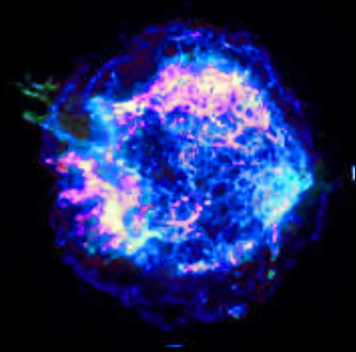


B/C ratio from new experiments: CALET expectations





Matter



Anti-Matter ?

- Energy spectra of anti-protons
- Anti-p/p ratio
- Limits on anti-matter

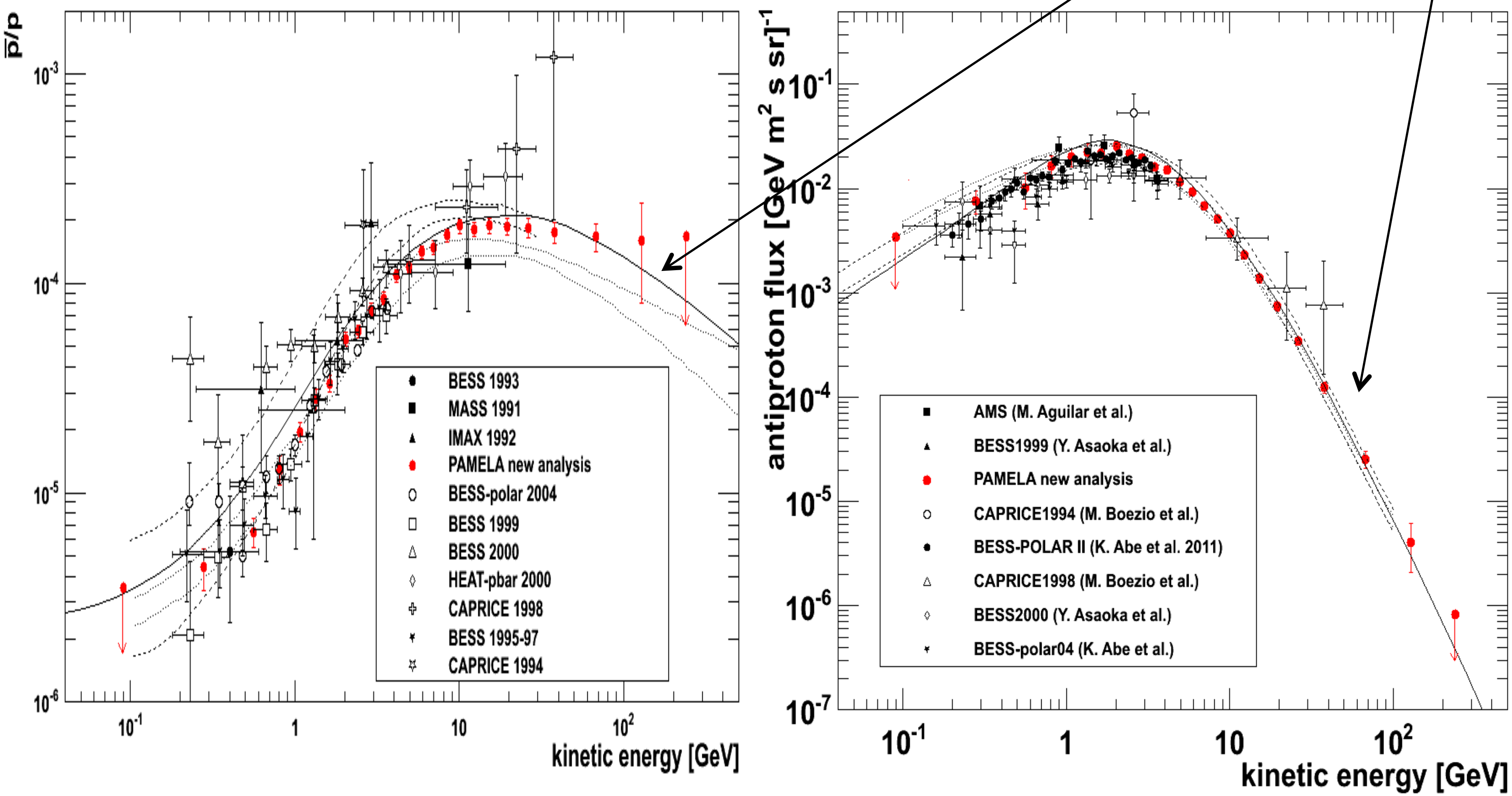
PAMELA Antiparticle Results: Antiprotons

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

- spectrum shape consistent with a *pure secondary production*

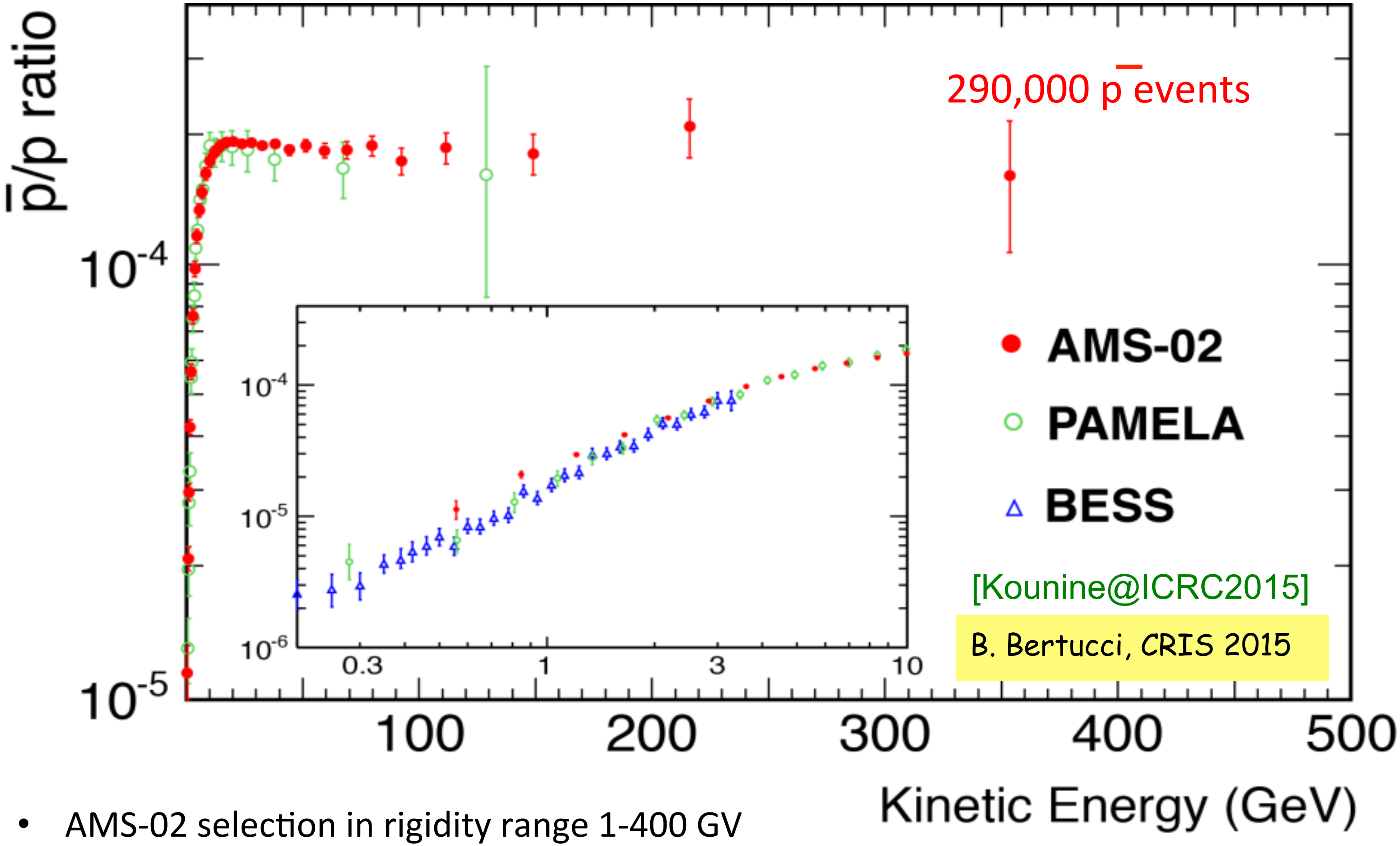
-Pamela first measurement to 180 GeV extended to ~350 GeV

Secondary production calculations



anti-proton/proton ratio

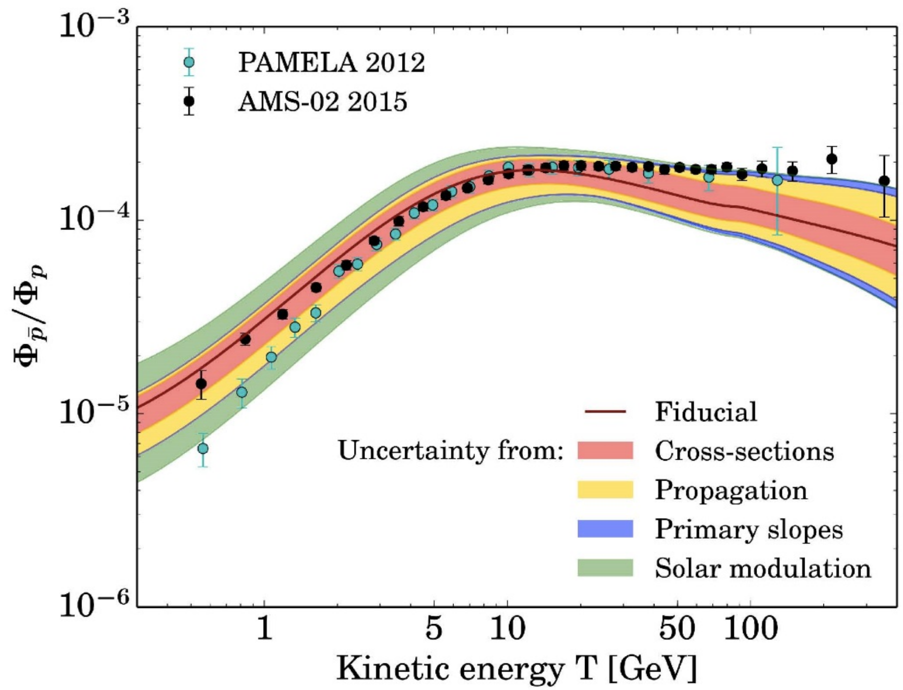
AMS-02 vs PAMELA & BESS



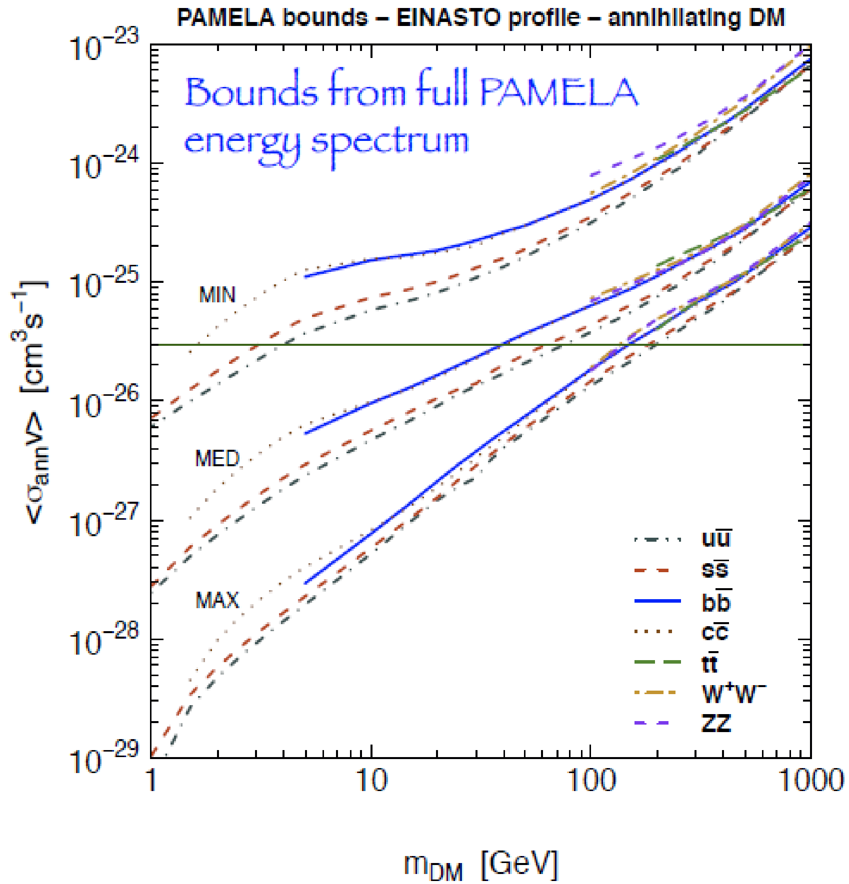
- AMS-02 selection in rigidity range 1-400 GV
- PAMELA data from 60 MeV to 350 GeV

Cosmic-Ray Antiprotons and DM limits

PAMELA and preliminary AMS-02 antiproton data constraints on various dark matter models and astrophysical uncertainties.



G. Giesen et al., JCAP 1509 (2015) 023, arXiv: 1504:04276



Fornengo, Maccione, Vittino, JCAP 1404 (2014) 04, 003

anti-proton /proton ratio

AT HIGH ENERGY:

- a flat p-bar/p ratio above 100 GV *can be explained in terms of secondary production* using new propagation models (i.e. taking into account spectral breaks, updated cross-sections data, etc...). Weaker alternative explanation in terms of DM.

for a review see for instance:

P. D. Serpico : Possible physics scenarios behind cosmic-ray "anomalies" @ICRC 2015

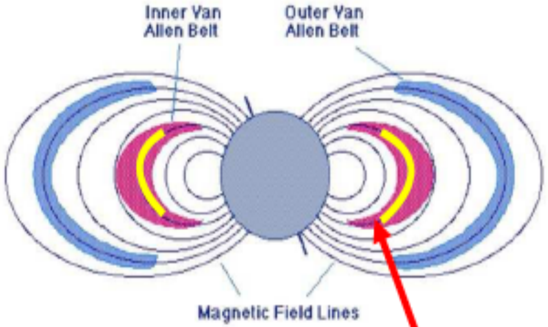
M.Cirelli: "Dark Matter phenomena" - Rapporteur Talk @ICRC 2015

AT LOW ENERGY:

- PAMELA and AMS data consistent with BESS measurements below 4 GeV

PAMELA: Geomagnetically trapped anti-protons

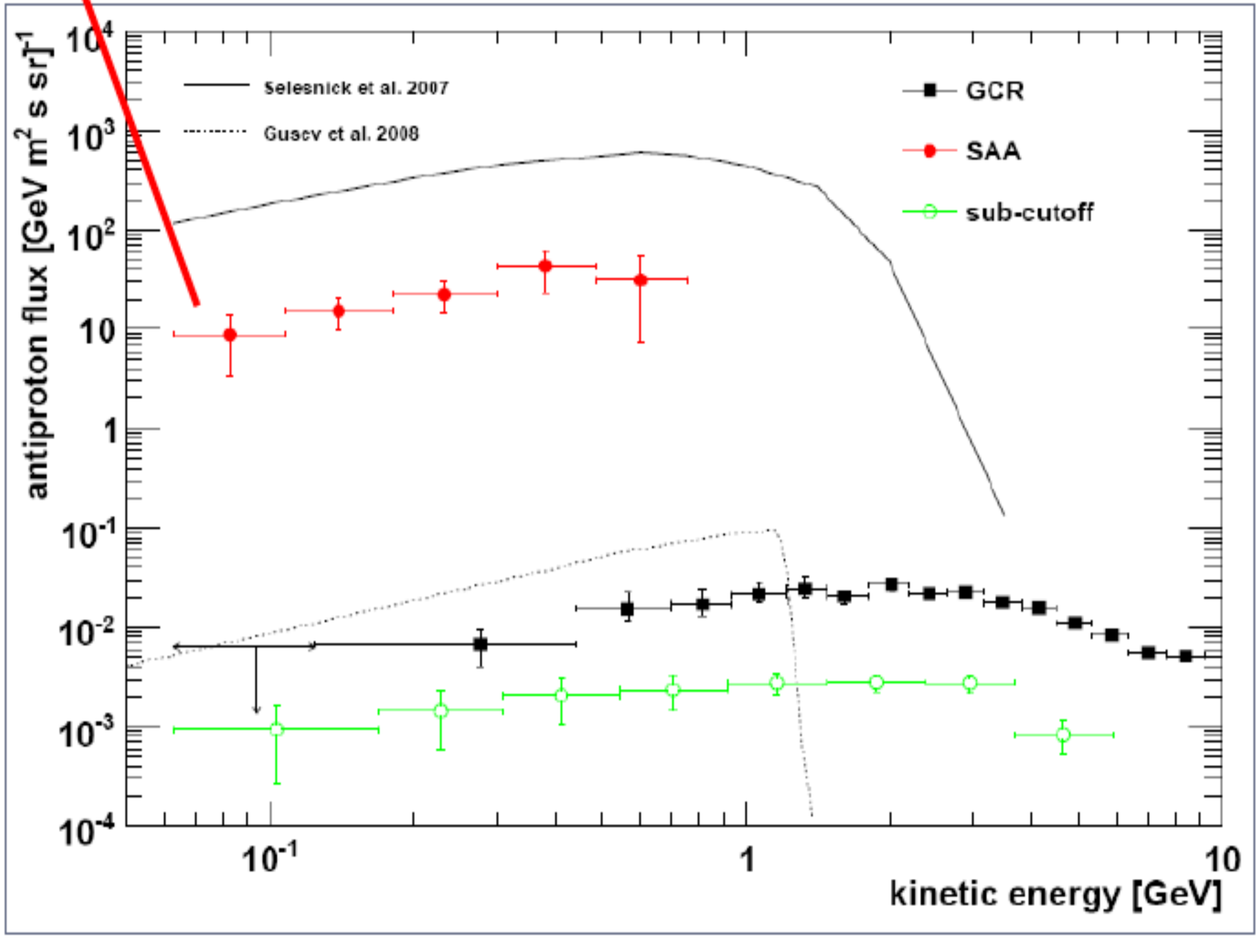
Anti-proton radiation belt



First measurement of p-bar trapped in the inner belt

29 p-bars discovered in SAA and **traced back to mirror points**

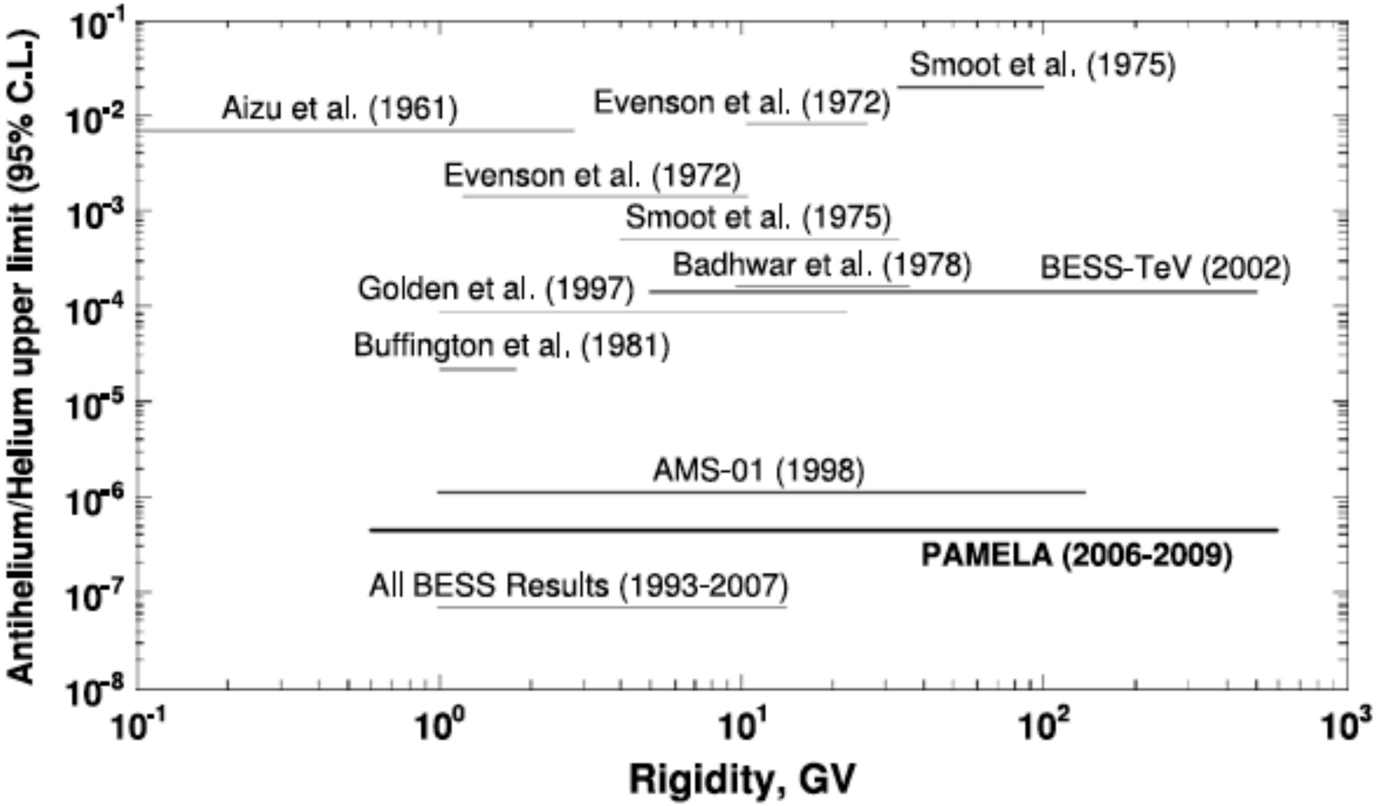
p-bar flux exceeds GRC flux by **3 orders of magnitude,** as expected by models

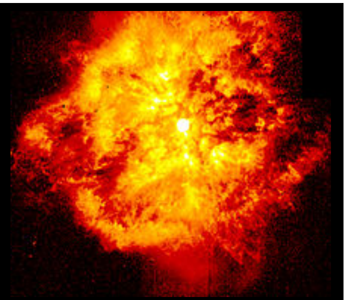


O. Adriani et al., ApJL 737 (2011), L29

Anti-matter limits

[Physics Reports 544 (2014) 323–370]

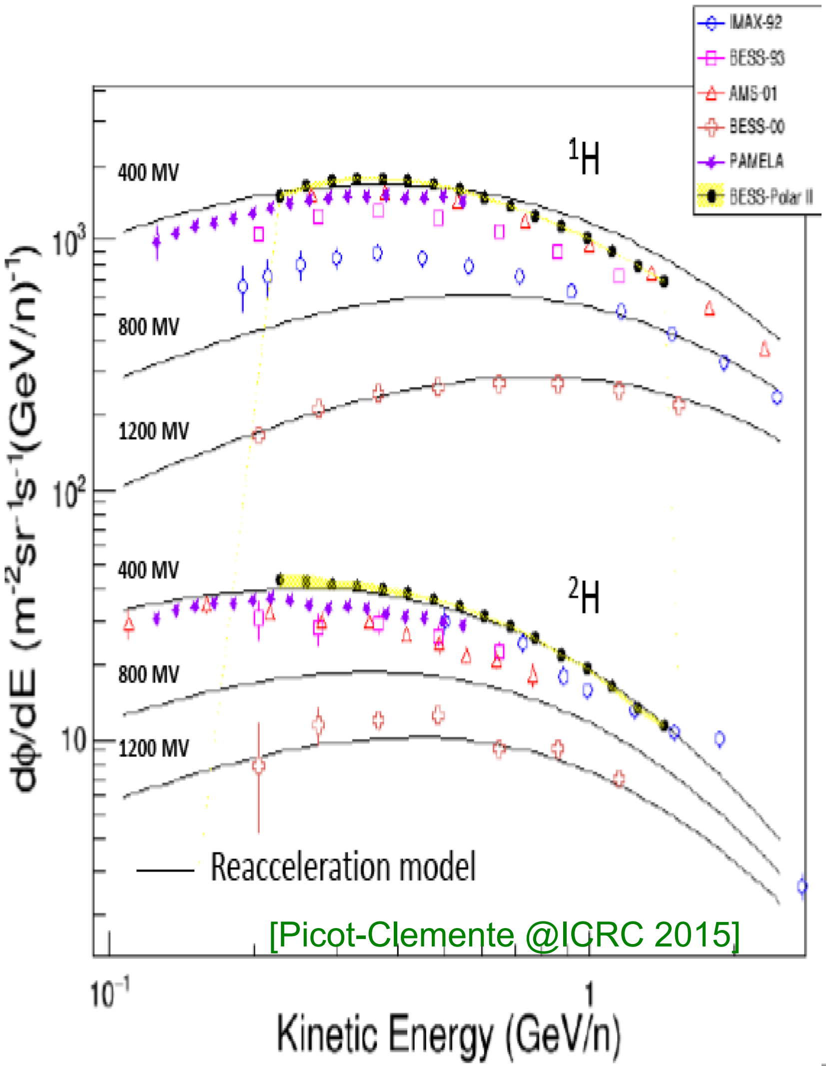


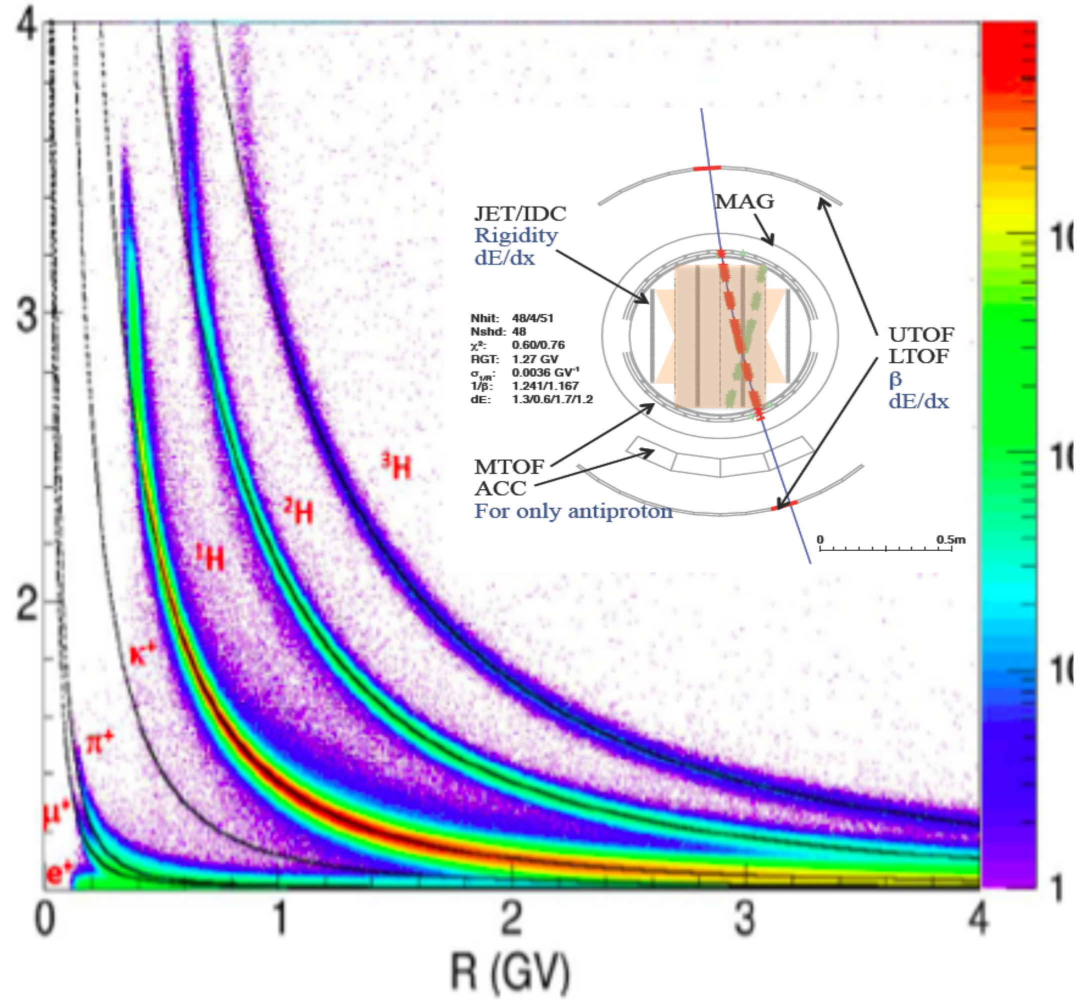


Cosmic-Ray Isotopes

- Isotope flux ratios like $^{2}H/^{1}H$ and $^{3}He/^{4}He$ are complementary to B/C measurements in constraining propagation models (data from e.g.: BESS, PAMELA)
- Li, Be are produced by spallation of primary CR with the ISM (e.g.: PAMELA data)
- Trans-Iron elements and "propagation clocks" (ACE/CRIS, Super-TIGER)

^{1}H, ^{2}H Isotope separation with BESS-Polar II

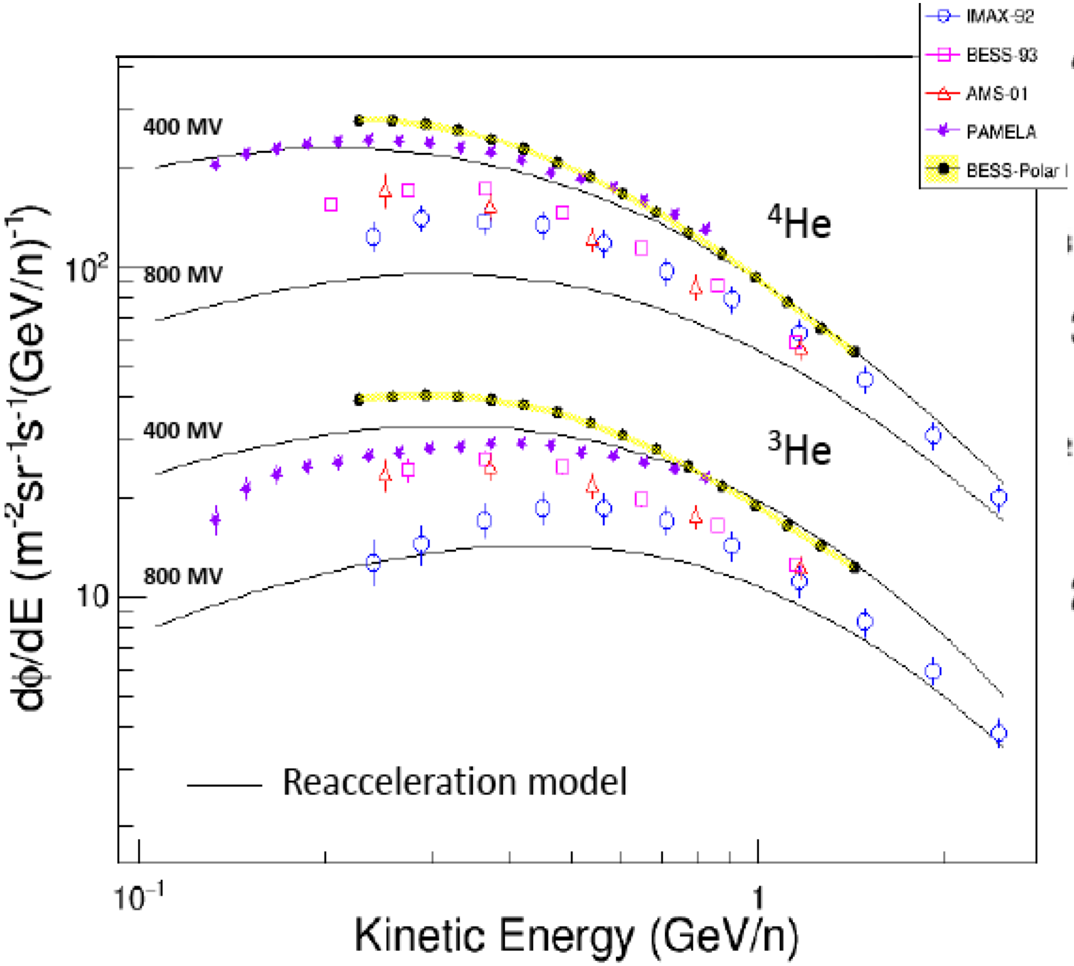


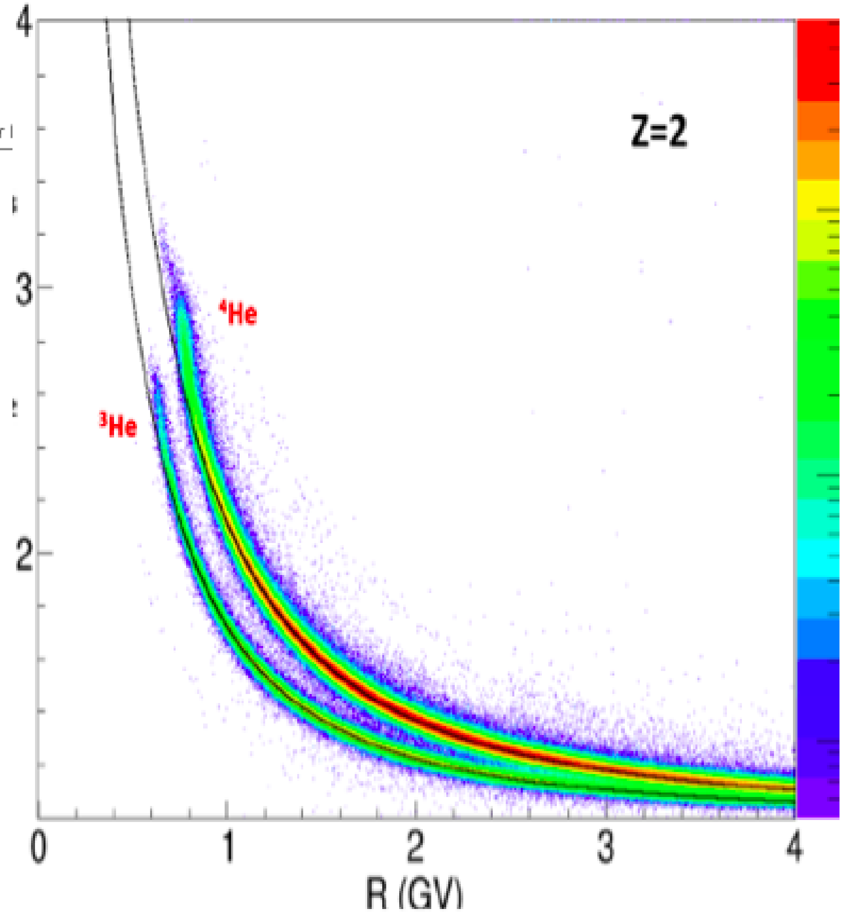


- Isotope flux ratios like $^{2}H/^{1}H$ and $^{3}He/^{4}He$ are complementary to B/C measurements in constraining propagation models as ^{2}H and ^{3}He are mostly secondaries.

53

^{3}He, ^{4}He Isotope separation with BESS-Polar II

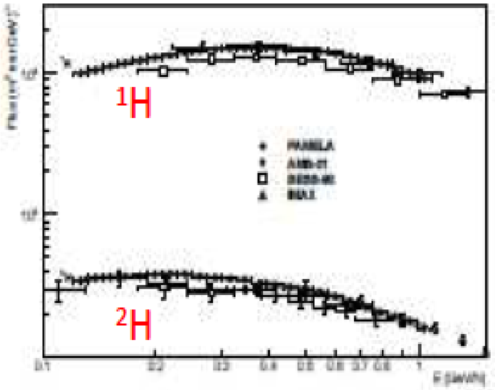


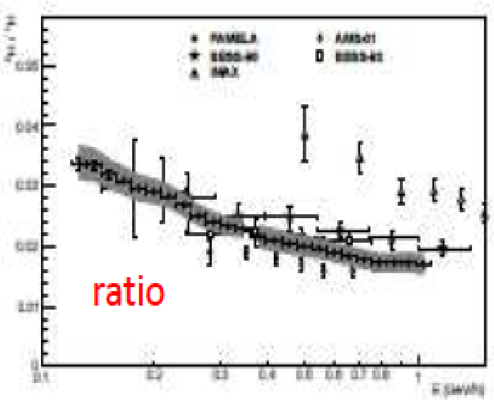


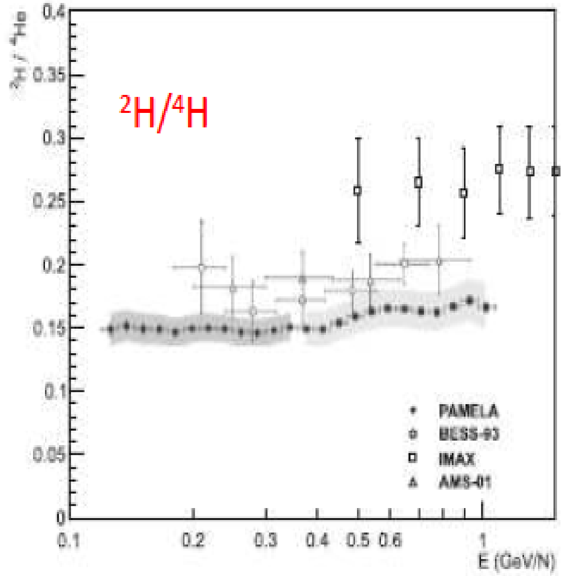
- Bess-Polar II data during solar minimum: in agreement with solar modulation expectations
- Data fitted using Reacceleration Model with ϕ ~400 MV
- Fluxes agree with PAMELA, with the exception of ^{3}He
- Bess Polar ^{3}He/^{4}He comparison vs Pamela may clarify this issue

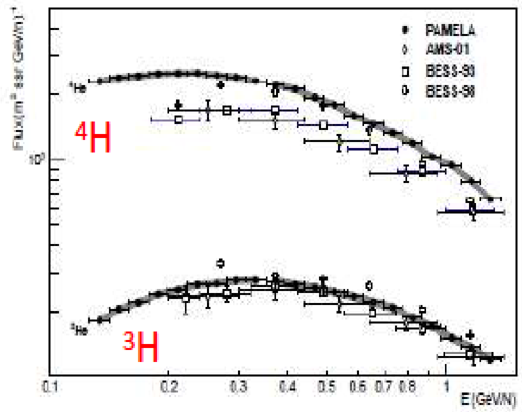
Hydrogen and Helium Isotopes

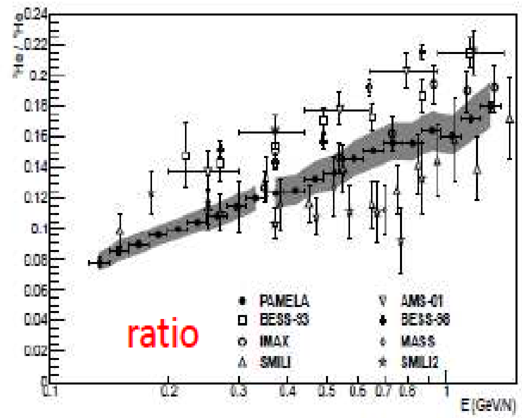
from PAMELA









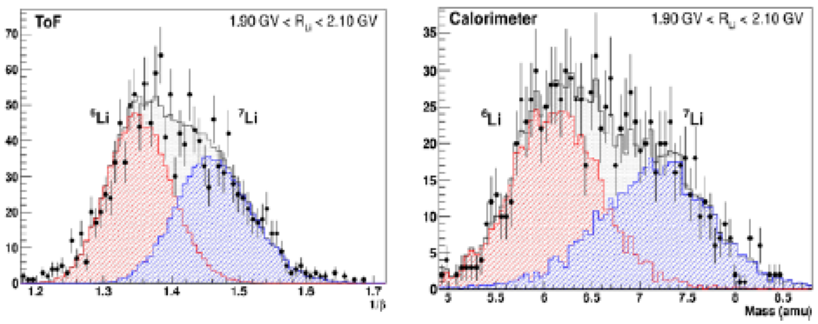


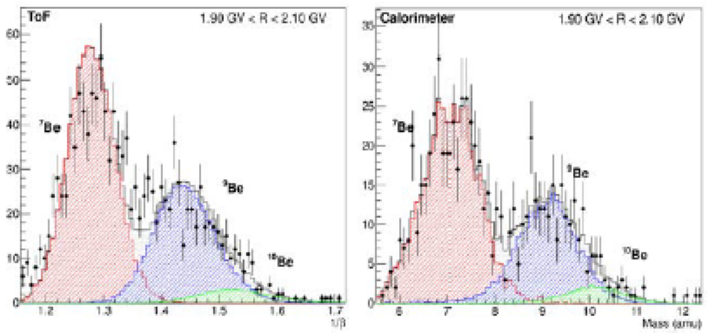
Pamela coll. APJ 818,1,68 (2016)

Lithium and Beryllium Isotopes

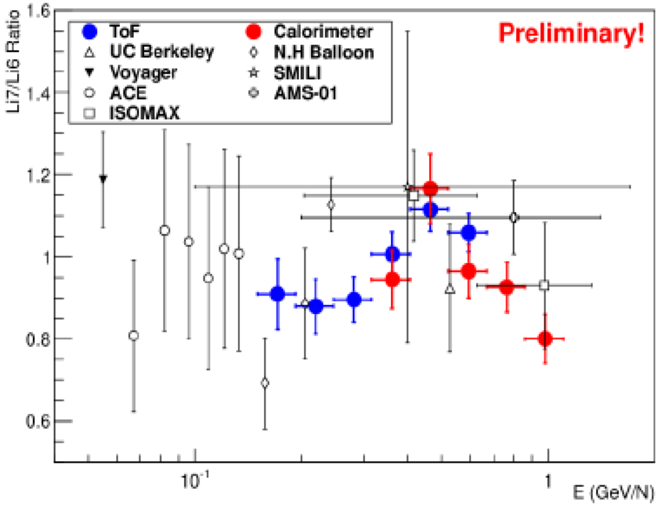
β (ToF) vs. Rigidity or Multiple dE/dx (Calorimeter) vs. rigidity

Lithium | **Beryllium**

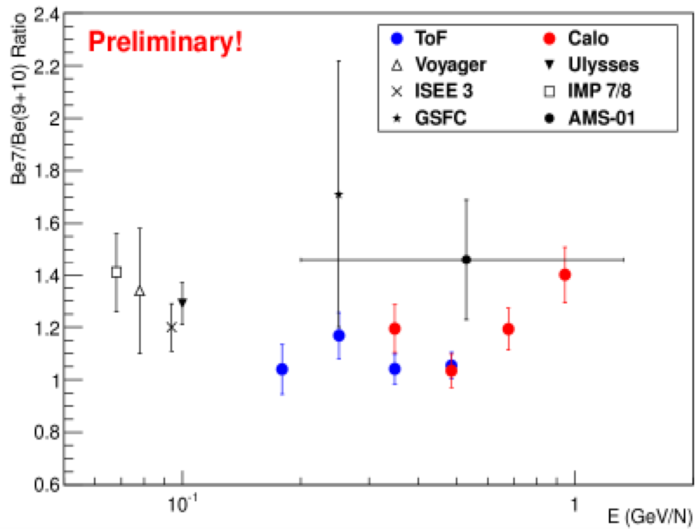




Ratio ^{7}Li / ^{6}Li



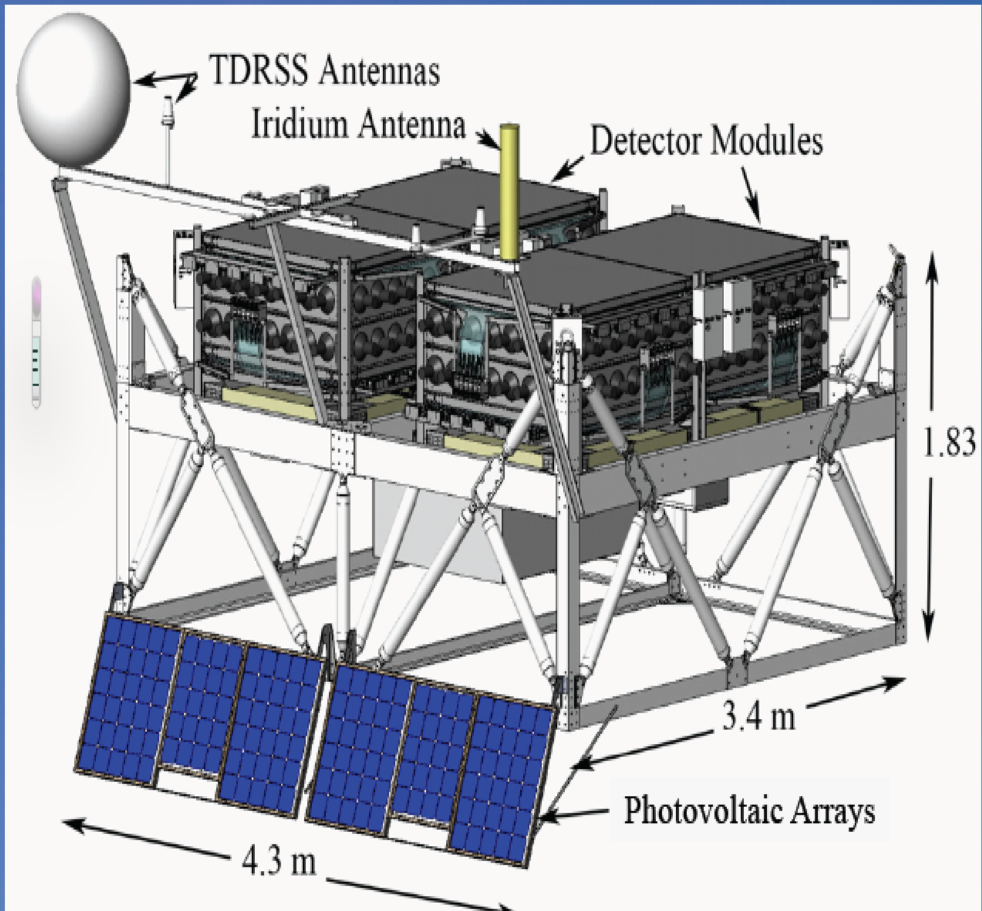
^{7}Be / (^{9}Be + ^{10}Be)

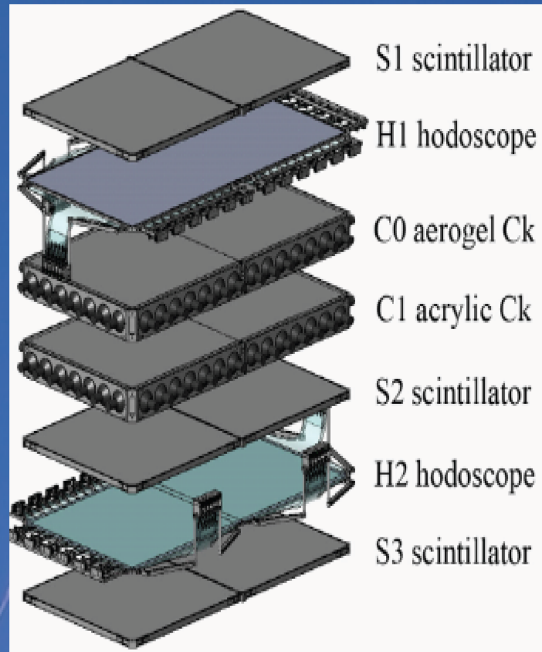


[Menn @ICRC 2015]

Super-TIGER (Trans-Iron Galactic Element Recorder)

Antarctic flight in 2012-13: 55 days





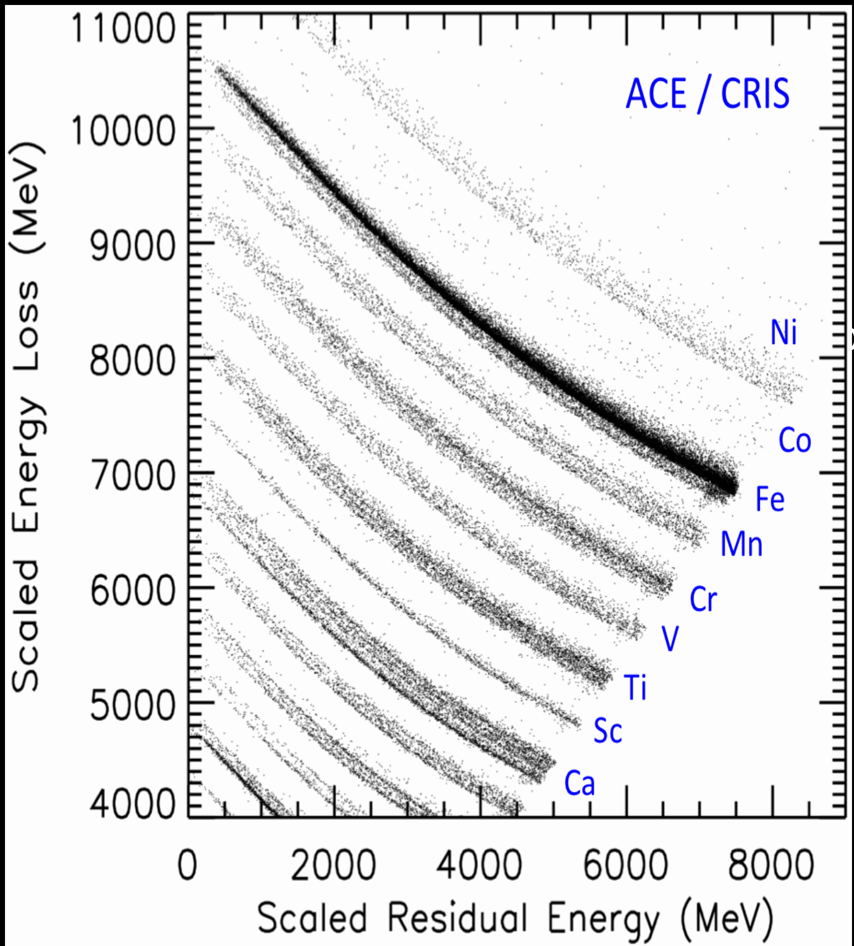
- Two identical modules
- Each module consists of
  - Scintillating fiber hodoscopes (H1, H2)
  - Three scintillator detectors (S1, S2, S3)
  - Aerogel Cherenkov detector (C0)
  - Acrylic Cherenkov detector (C1)

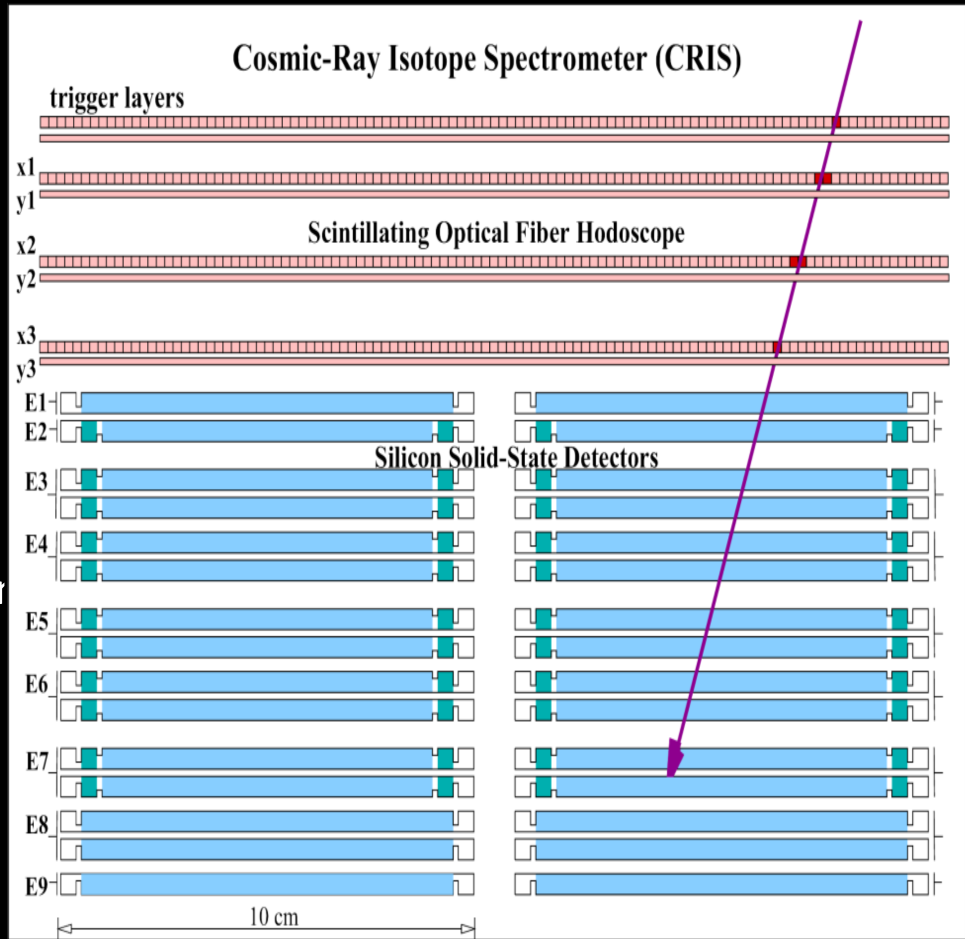
Acceptance ~8.3 $m^2 sr$

TIGER & SuperTIGER energy range 0.8-10 GeV/n

Cosmic-Ray Isotope Spectrometer (CRIS)

CRIS aboard ACE at Lagrangian Point L1 has been taking data for almost 18 years!

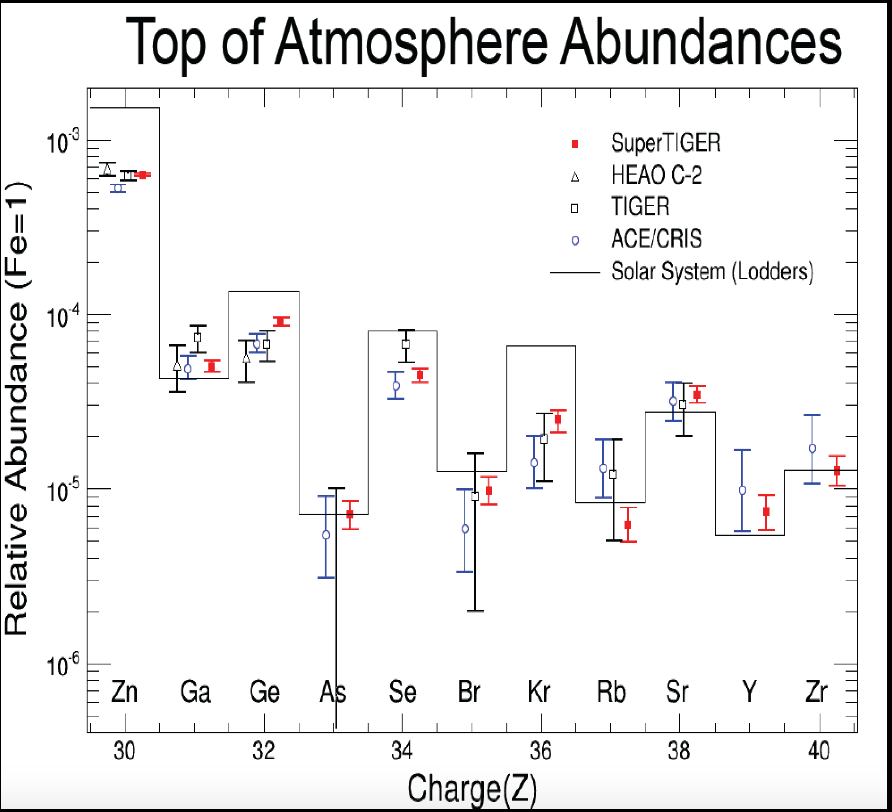


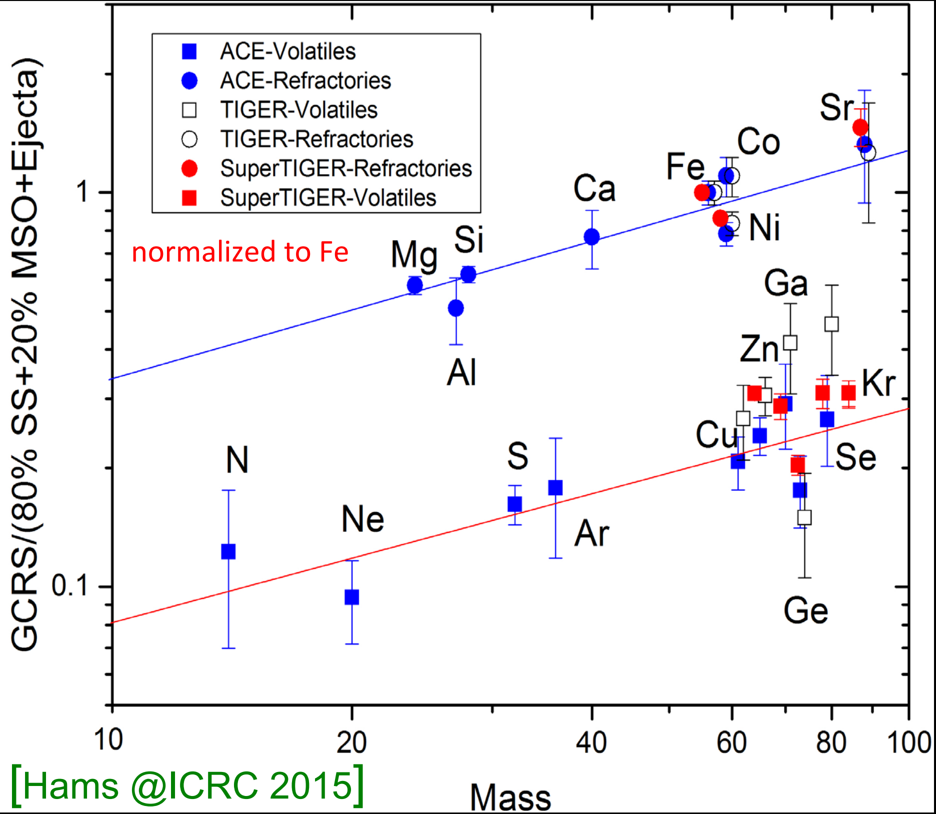


CRIS determines the charge and mass of cosmic rays stopping in a stack of silicon detectors using the dE/dx vs E technique

ACE energy range: 150-600 MeV/n

Ultra Heavy Nuclei





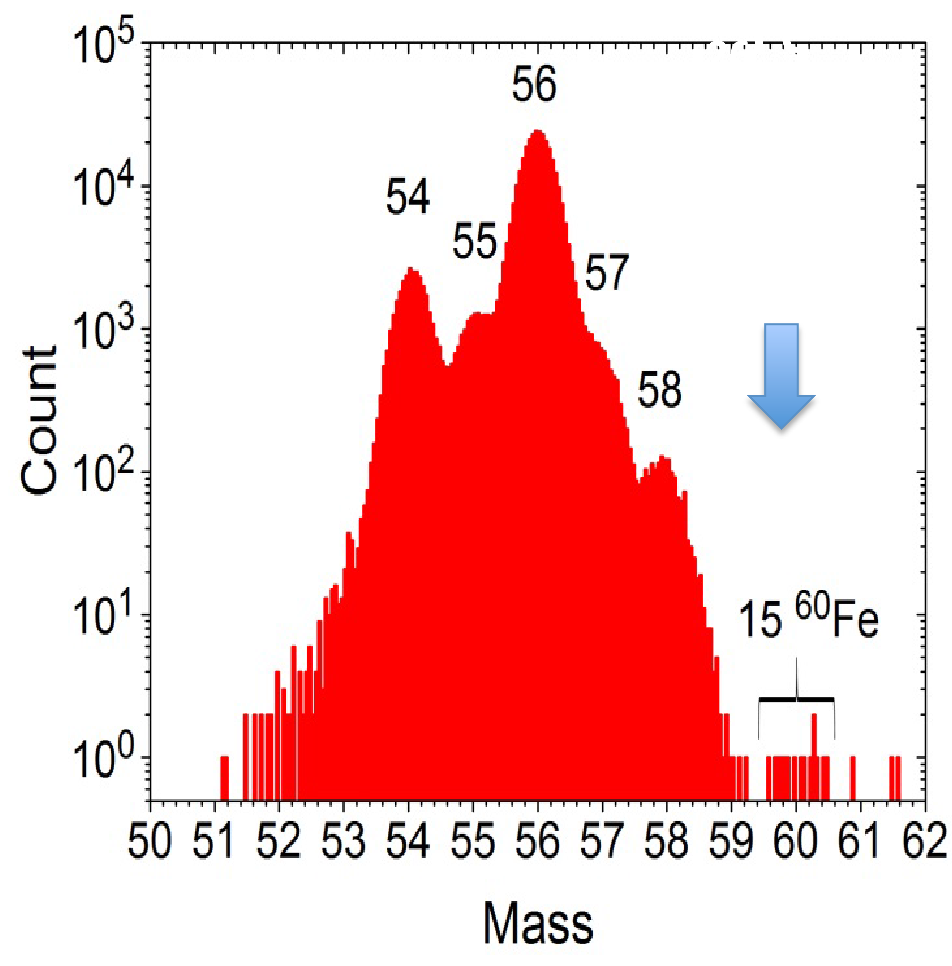
- Refractory elements (those likely found in interstellar grains) more effectively accelerated (enhanced by a factor ~4) compared with volatile elements.

- For both refractory and volatile elements efficiency of acceleration increases with mass.

- Better separation of refractory and volatiles by mass assuming a CR source mixture of about 20% ejecta of massive stars (including Wolf–Rayet stars and core-collapse supernovae) mixed with 80% material of solar system composition

- GCR origin in OB associations ?

First measurement of a primary cosmic-ray clock



With 16.8 years of data, CRIS detected 15 ^{60}Fe and 2.95×10^5 ^{56}Fe.

^{60}Fe β-decay with half-life of 2.62 Myr.

^{60}Fe observeed are almost all primaries

Neither products of ISM fragmentation, nor spill-over from ^{58}Fe.

[Israel @ICRC 2015]

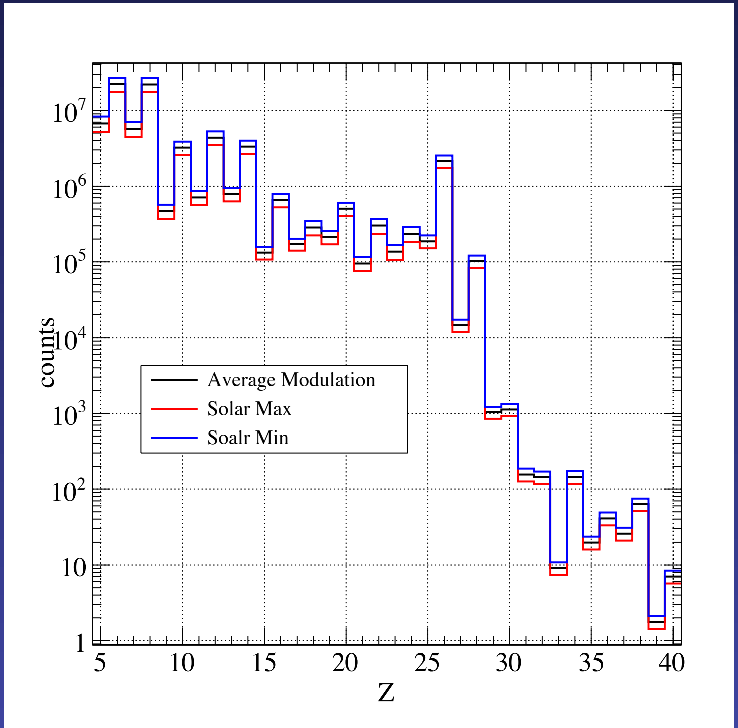
- CR acceleration occurs within several Myr of nucleosynthesis.
- Combined with lack of ^{59}Ni → ~10^5 years < T < ~several x 10^6 years
- Supports the idea of OB associations as CR acceleration sites.

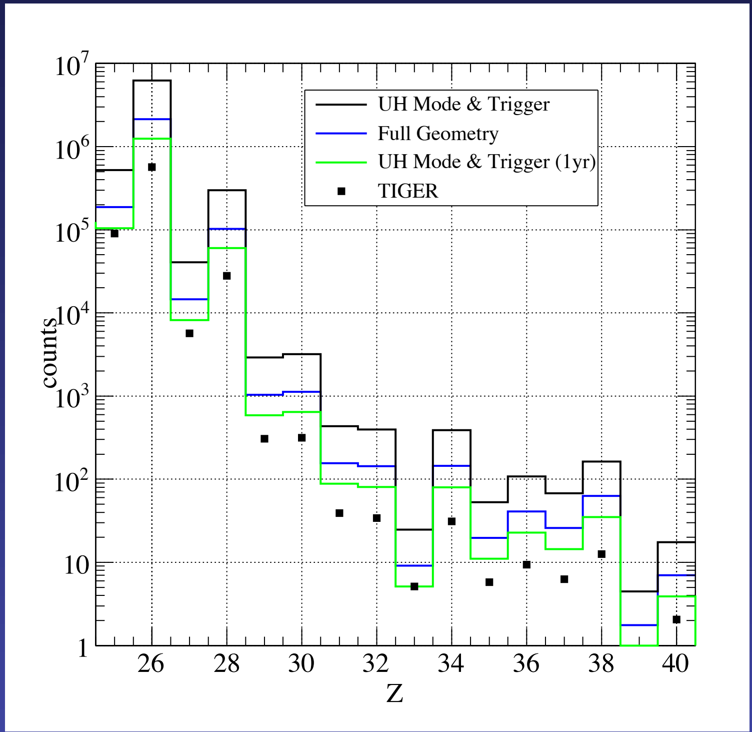
Future measurements on Ultra Heavy nuclei: CALET (expected)

- Cleaner measurements wrt balloons (smaller hadronic interaction corrections above the atmosphere)
- charge measurement up to Z = 40
- Expected Statistcs in 5 years : dedicated UH trigger: larger trigger acceptance → 0.4 m^2sr

≅ 10 x TIGER (with UH trigger)

≅ 4 x TIGER (with full geometry and energy reconstruction)





Direct measurements of VHE cosmic-rays

- Space missions in flight at present:

  PAMELA, FERMI, AMS-02, NUCLEON, CALET, DAMPE ...

- Ready-to-go:

  ISS-CREAM

- Proposed balloon or space missions:

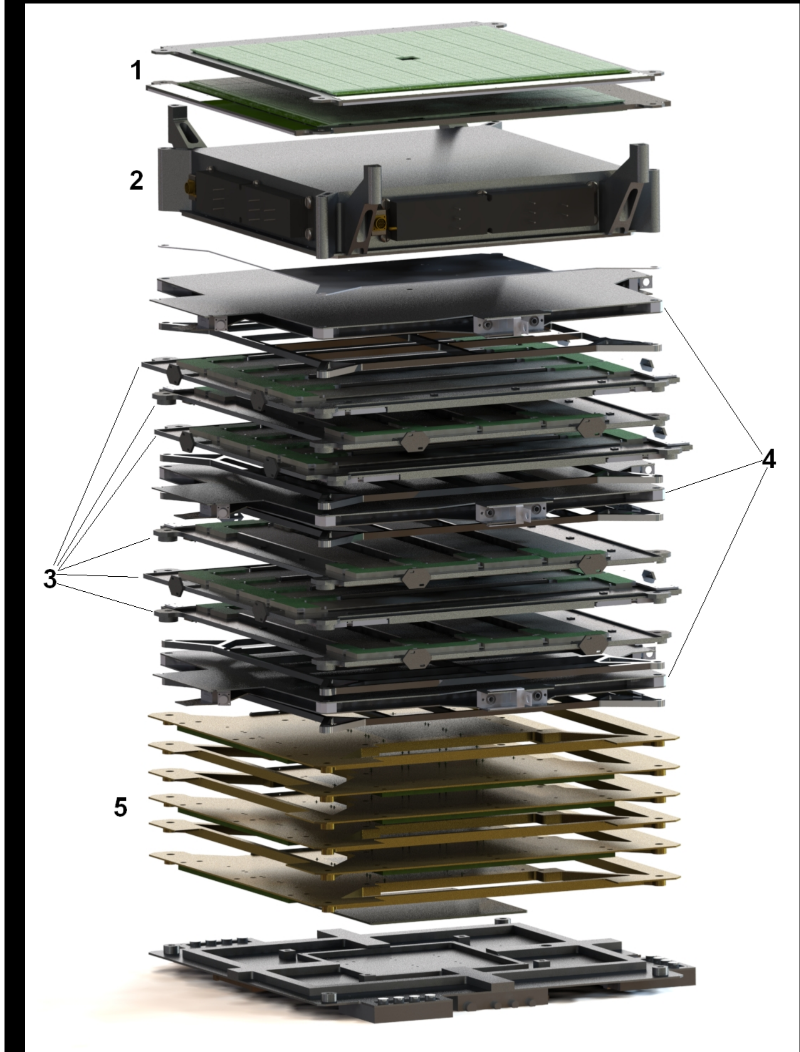
  HERD, GAMMA-400, GAPS, CSES, HELIX, HNX, ...

Experiment	$e^+ \mid e^-$ (present data)	$e^+ + e^-$ (Energy range)	CR nuclei (Energy range)	charge Z	gamma	Type	Launch
PAMELA	$e^+ < 300$ GeV $e^- < 625$ GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	$e^+ < 500$ GeV $e^- < 700$ GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014/12/26 Dec 26
CALET	-	1 GeV-10 TeV (extendable -> 20TeV)	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	~ 2017
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	~ 2017
GAMMA-400	-	1 GeV-20 TeV	1 TeV-3 PeV	1-26	20 MeV-1 TeV	SAT	~2023-25
HERD	-	10(s) GeV–10 TeV	up to PeV	TBD	10(s) GeV–10 TeV	CSS	~2022-25
HELIX	-	-	< 10 GeV/n	light isotopes	-	LDB	proposal
HNX	-	-	~ GeV/n	6-96	-	SAT	proposal
GAPS	-	-	< 1GeV/n	Anti-p, D	-	LDB	proposal

NUCLEON

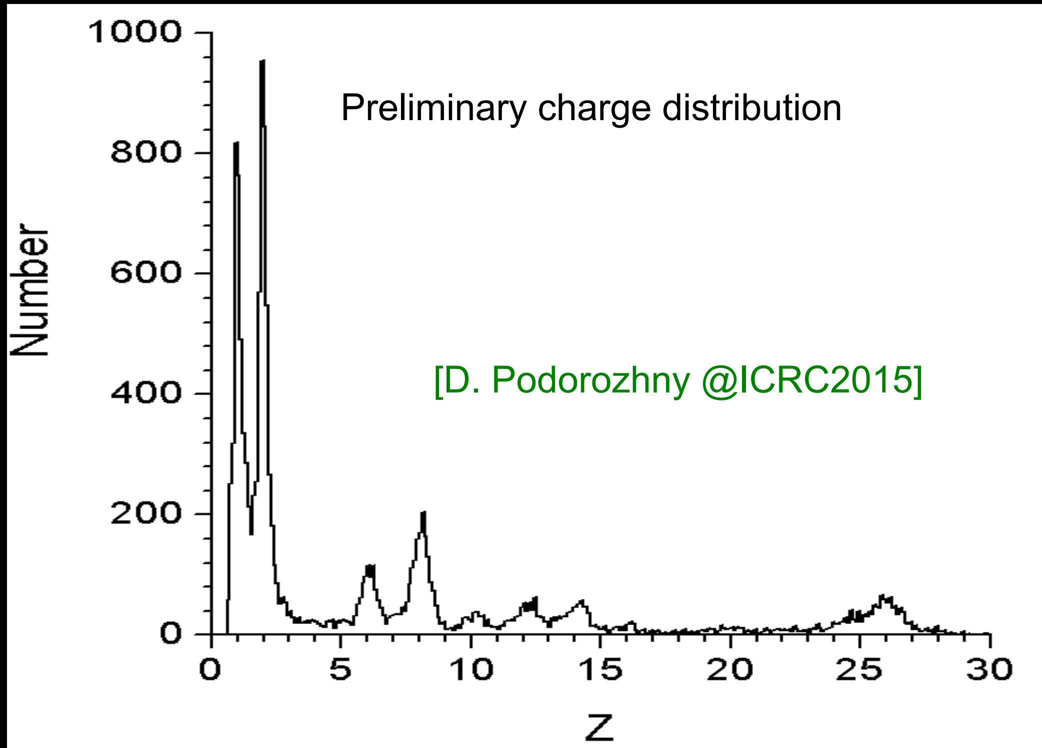
- Launched on Dec. 26th 2014 on Resurs-P satellite
- uses the Kinematical Method (KLEM) to estimate the energy

> 0.2 m^2sr for nuclei
0.06 m^2sr for lectrons

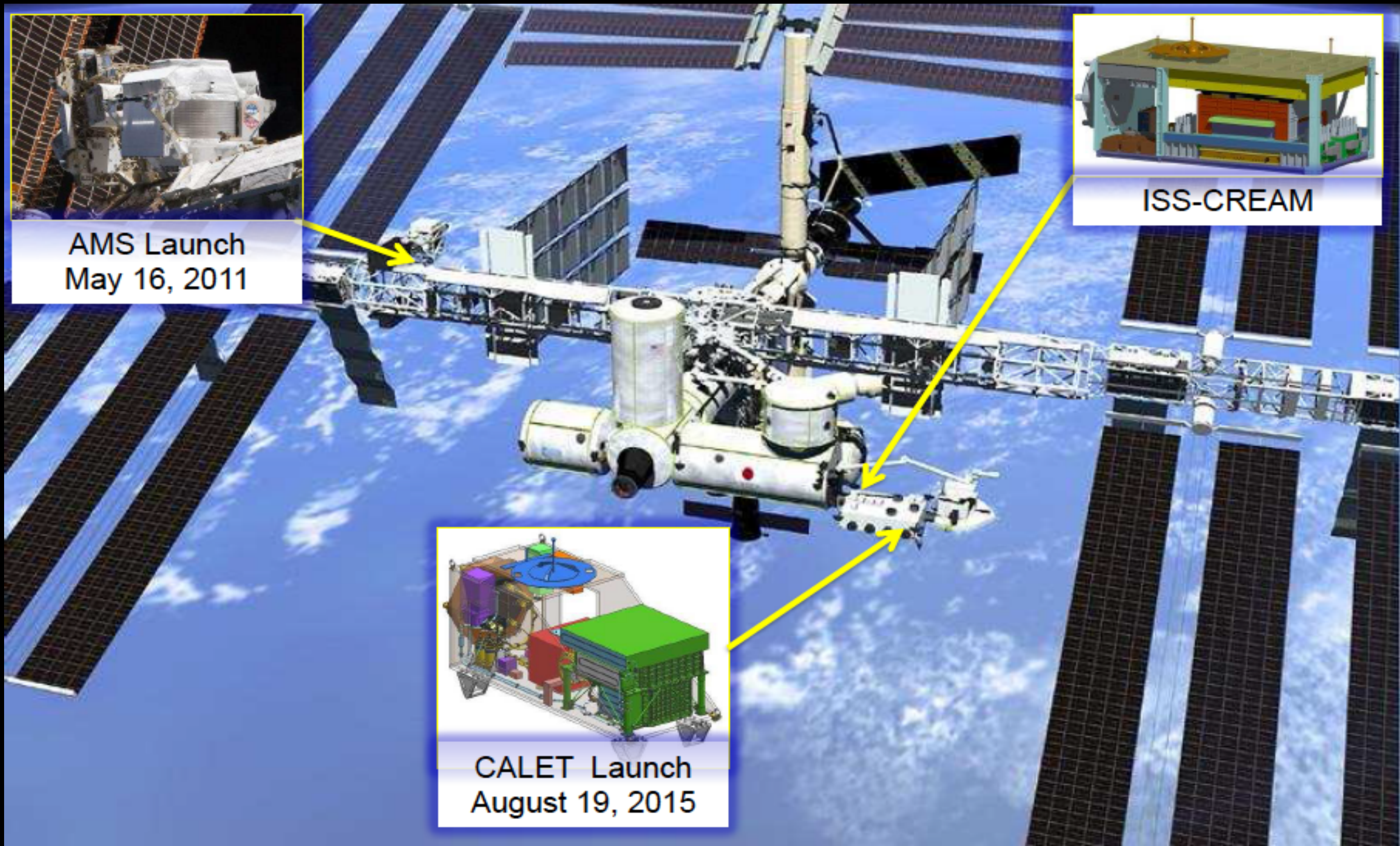


- charge measurement: 4 Si pad detectors
- carbon target to induce hadronic interaction
- Si microstrip/W (0.50x0.50 m^2) ➔ tracking ➔ KLEM
- Si/W calorimeter (0.25x0.25 m^2)

Total: 10604 channels depth ~16 X_0



ISS: a cosmic-ray observatory in Low Earth Orbit



CALET on the ISS explores the Multi-TeV region

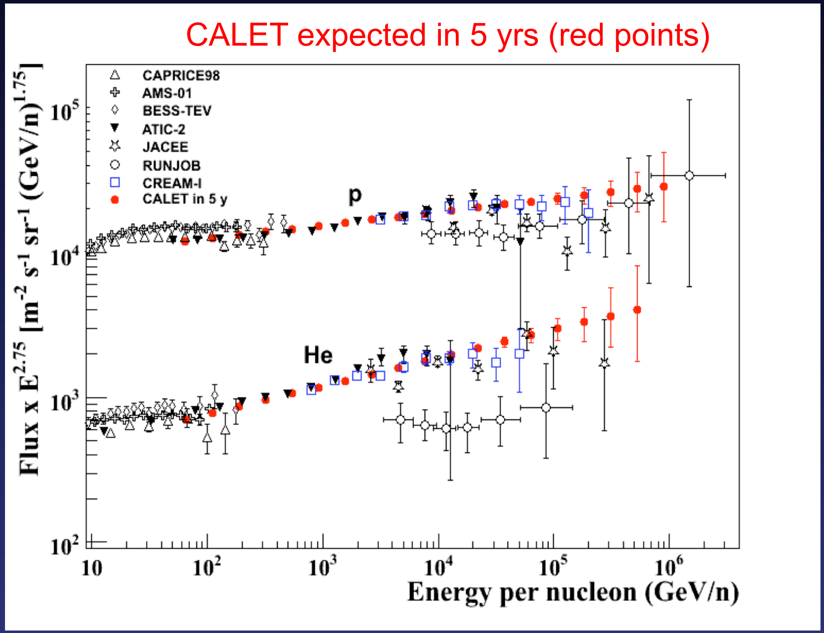
Elemental spectra

CALET Energy reach in 5 years:

- ✧ Proton spectrum to ≈ 900 TeV
- ✧ He spectrum to ≈ 400 TeV/n
- ✧ Spectra of C,O,Ne,Mg,Si to ≈ 20 TeV/n
- ✧ B/C ratio to ≈ 4 - 6 TeV/n
- ✧ Fe spectrum to ≈ 10 TeV/n

	λ_{INT}	X_0 (normal incidence)
CREAM	0.5 + 0.7	20
CALET	1.3	30
AMS-02	0.5	17
DAMPE	1.6	31

Proton and He



Requirements for proton calorimetry:

- proton interaction requires > 0.5 λ_{INT}
- at 100 TeV energy scale, longitudinal containment of the e.m. core of the shower requires > 20 X_0

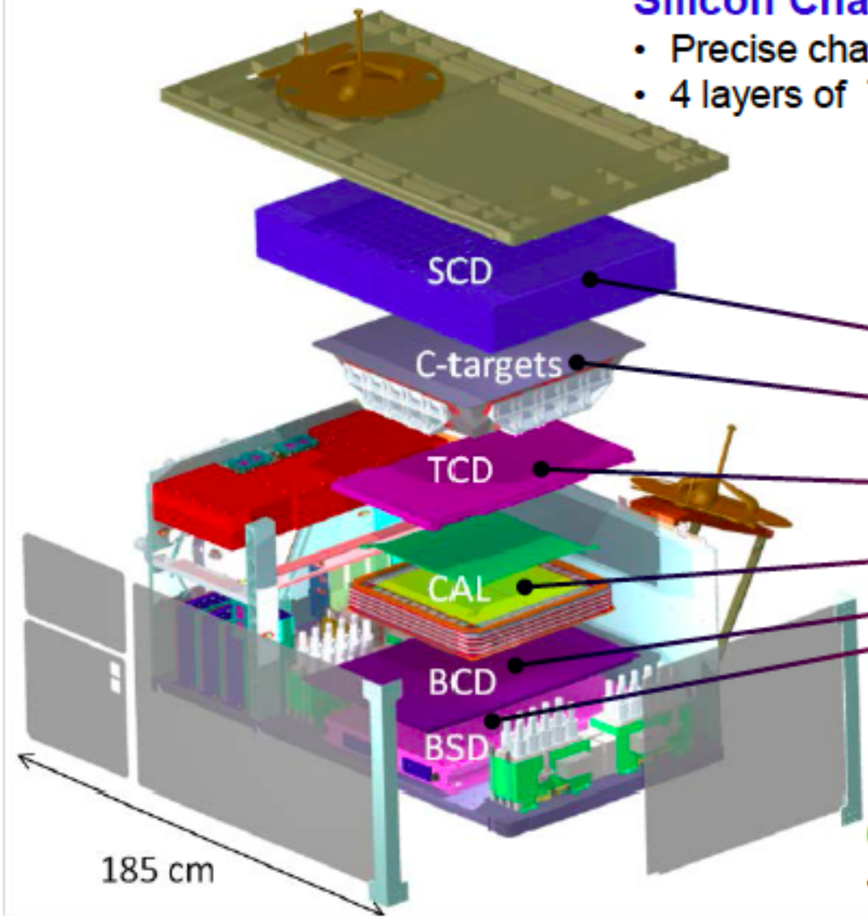
ISS-CREAM Instrument

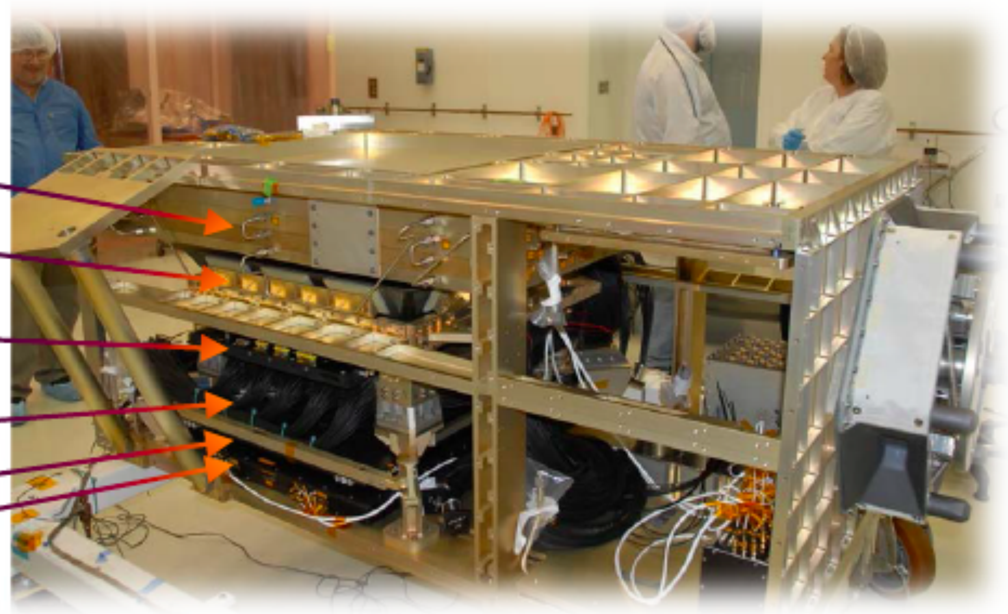
[Seo@Vulcano 2016]

Seo et al. Adv. in Space Res., **53**/10, *1451*, 2014; Hwang et al. JINT10 (07), P07018, 2015

Silicon Charge Detector (SCD)

- Precise charge measurements with charge resolution of ~ 0.2e.
- 4 layers of 79 cm x 79 cm active area (2.12 cm^2 pixels).





Boronated Scintillator Detector (BSD)

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

Calorimeter (CAL)

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

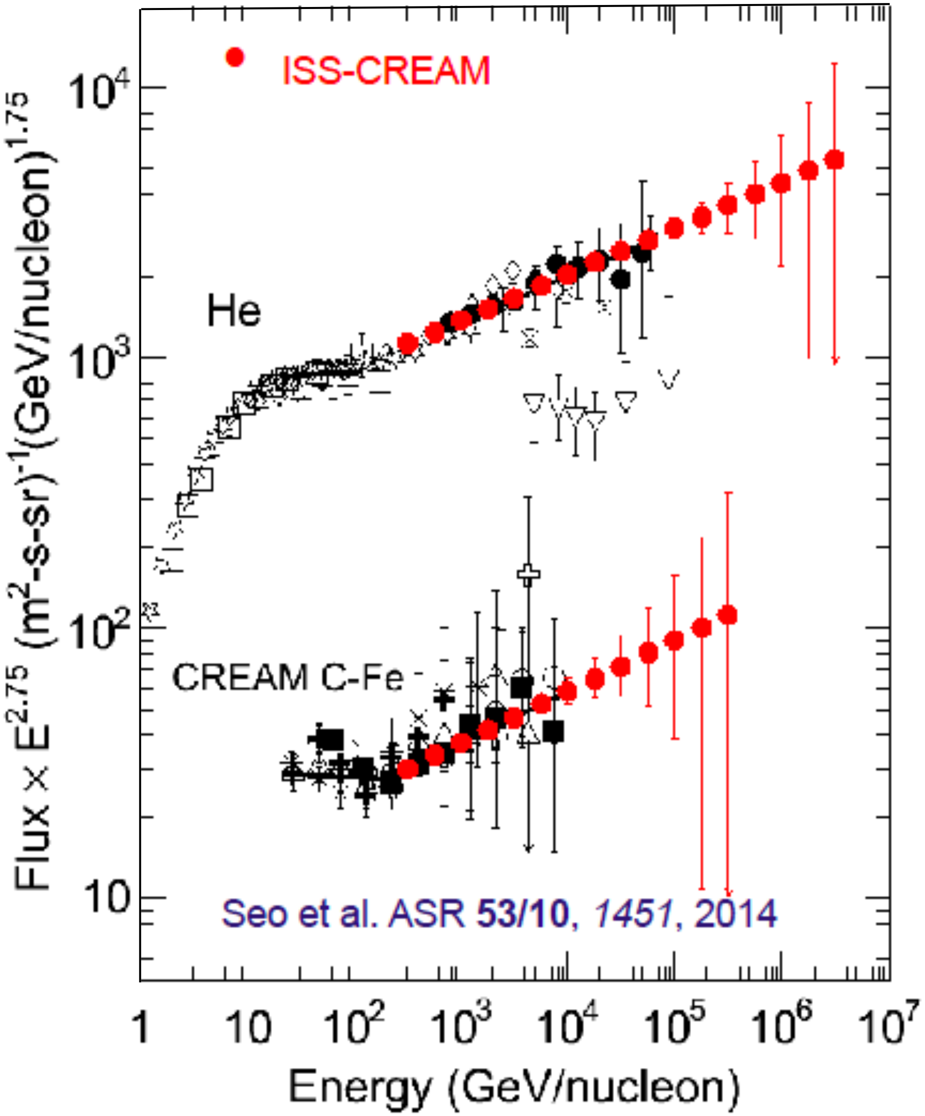
Top/Bottom Counting Detector (T/BCD)

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

ISS-CREAM takes the next major step

Increases the exposure by an order of magnitude!

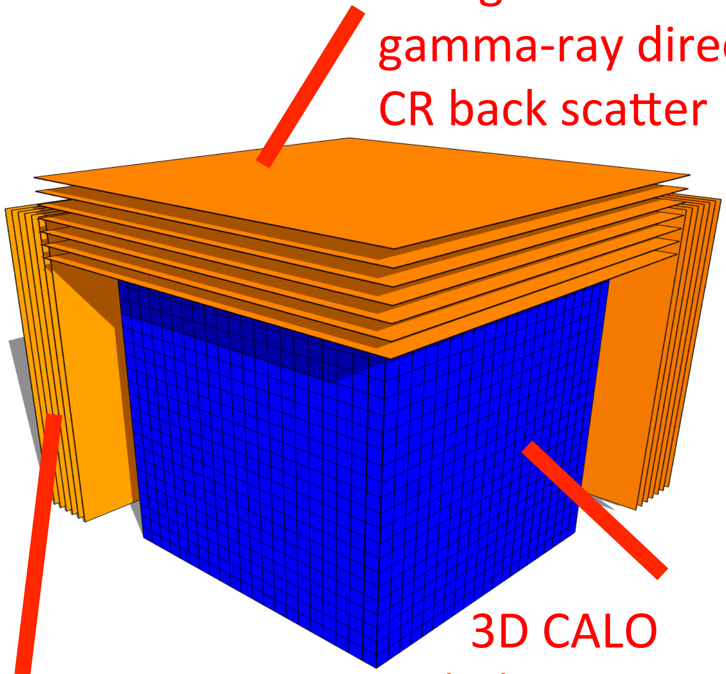
- The ISS-CREAM space mission can take the next major step to 10^{15} eV, and beyond, limited only by statistics.
- The 3-year goal, 1-year minimum exposure would greatly reduce the statistical uncertainties and extend CREAM measurements to energies beyond any reach possible with balloon flights.



[E.S.Seo @Vulcano 2016]

HERD Design： 3D Calo & 5-Side Sensitive

About a factor 10 increase in statistics respect to existing experiments with a weight 2.3 T ~1/3 AMS

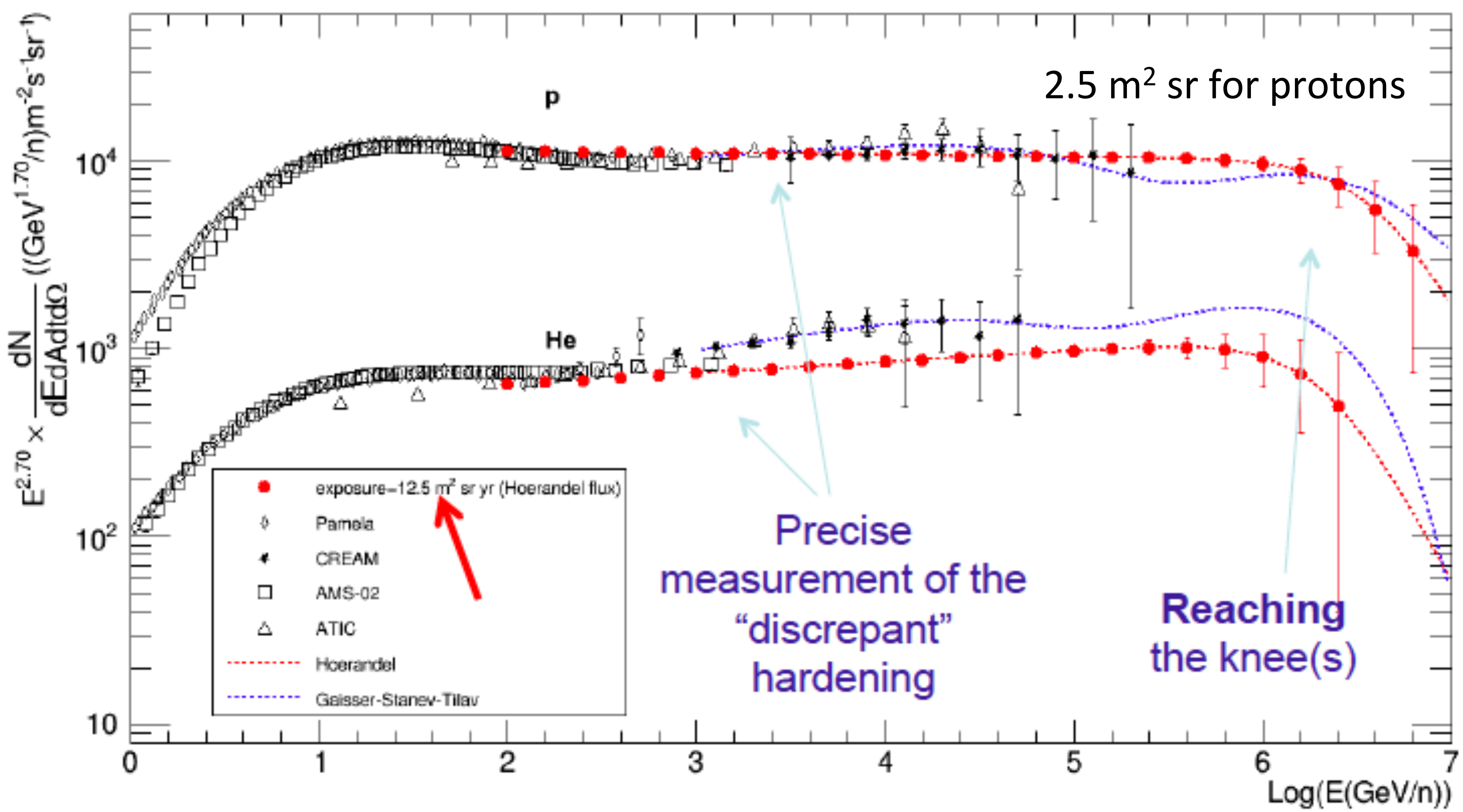


Expected performance of HERD

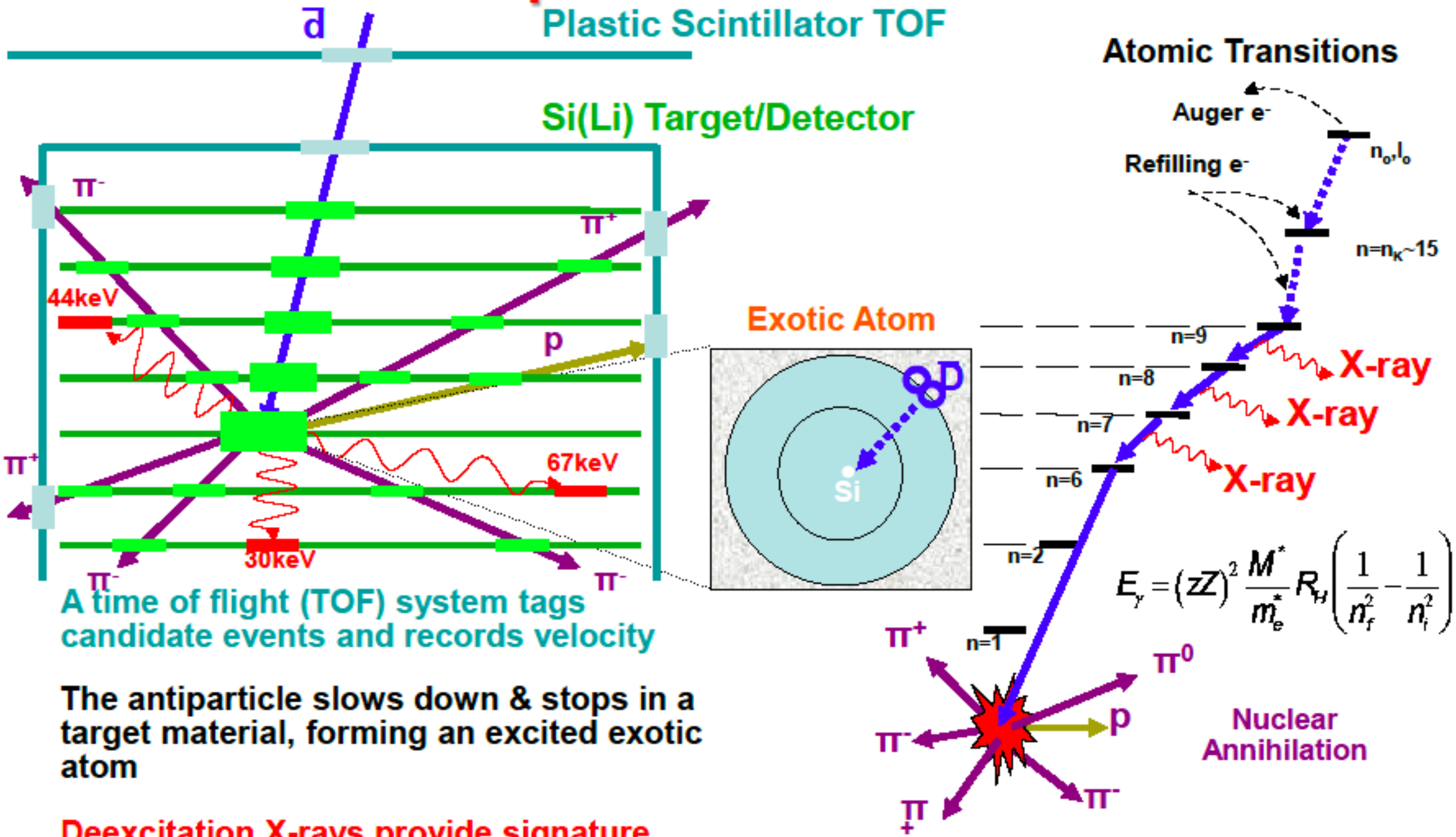
γ/e energy range (CALO)	tens of GeV-10TeV
nucleon energy range (CALO)	up to PeV
γ/e angular resol.	0.1°
nucleon charge resol.	0.1-0.15 c.u
γ/e energy resolution (CALO)	<1%@200GeV
proton energy resolution (CALO)	20%
e/p separation power (CALO)	$<10^{-5}$
electron eff. geometrical factor (CALO)	3.7 m^2sr@600 GeV
proton eff. geometrical factor (CALO)	2.6 m^2sr@400 TeV

Expected HERD Proton and He Spectra

five years operation



GAPS detects atomic X-rays and annihilation products from exotic atoms



$$E_\gamma = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

A time of flight (TOF) system tags candidate events and records velocity

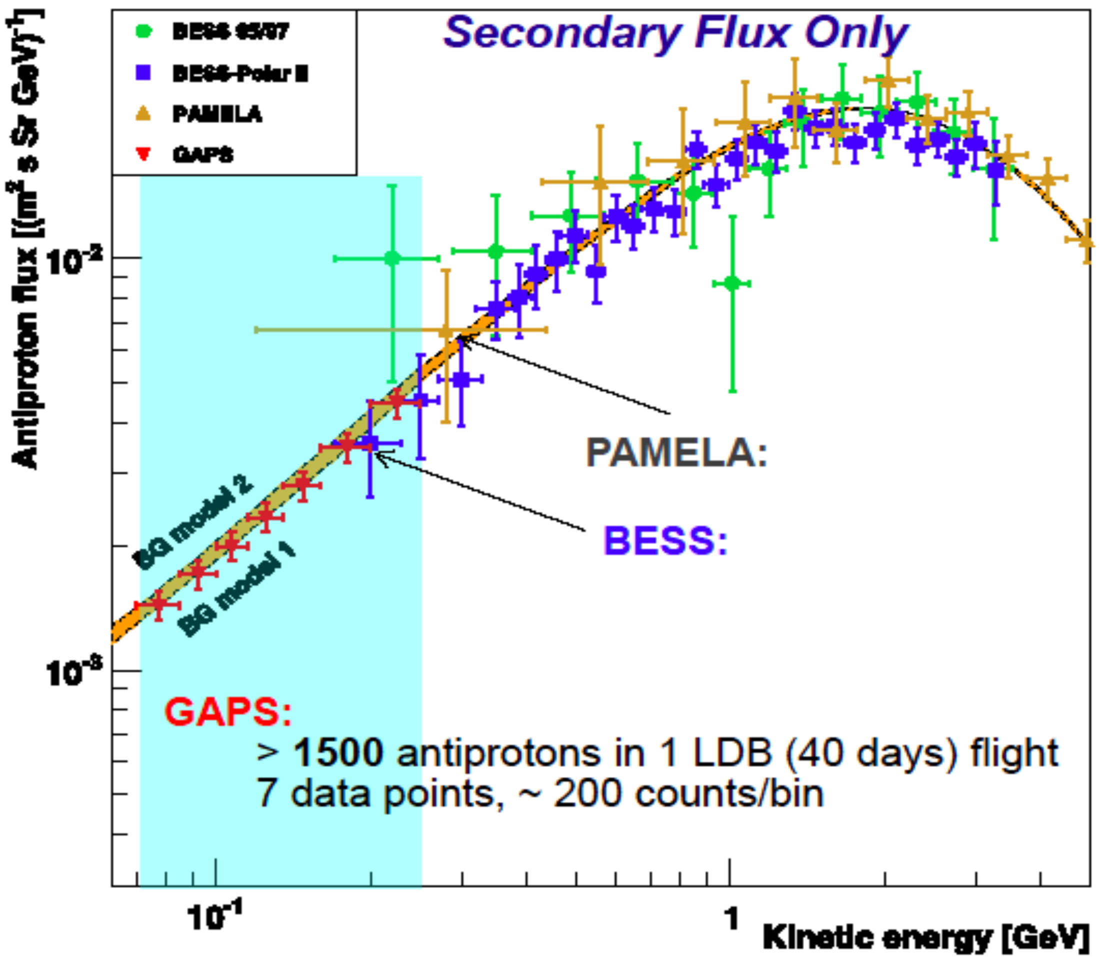
The antiparticle slows down & stops in a target material, forming an excited exotic atom

Deexcitation X-rays provide signature

Annihilation products provide added background suppression

X-ray yields were measured at KEK in 2004 and 2005

GAPS precision antiproton flux measurement provides strong constraints on DM and PBH models



Antarctic Science Flight forseen in December 2020

Primary flux

$$\Phi_p \propto \langle \sigma V \rangle_{ann} \left(\frac{\rho_{DM}}{M_{DM}} \right)^2 \otimes \text{propagation}$$

x 10 for Max
x 0.1 for Min
due to Halo model

Secondary flux

- constrained by B/C ratio

M. Hailey, Dark Matter 2014, UCLA

Complementary to direct/indirect DM searches and collider experiments for light DM

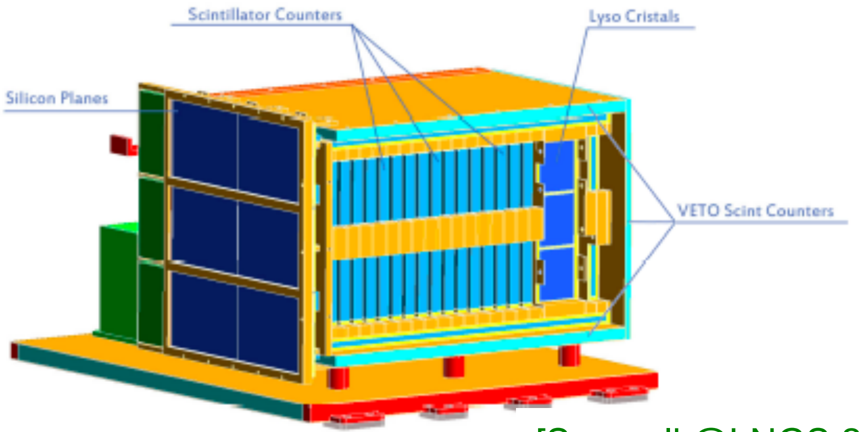
CSES (China Seismo Electromagnetic Satellite)

The HEPD instrument aboard CSES will study low energy CR cosmic rays of Galactic, Solar and Magnetospheric origin in the energy range 3-300 MeV

Measurements	Instruments
Measurement of the electrical and magnetic fields and their perturbations in ionosphere	Search-Coil Magnetometer Fluxgate Magnetometer Electrical Field Detector (CHN/ITA)
Measurement of the disturbance of plasma in ionosphere	Plasma analizer Langmuir probe
Measurement of the flux and energy spectrum of the particles in the radiation belts	High Energy Particle Detector (ITA)
Measurement of the profile of electronic content	GPS Occultation Receiver Tri-frequency transmitter

High Energy Particle Detector (HEPD)

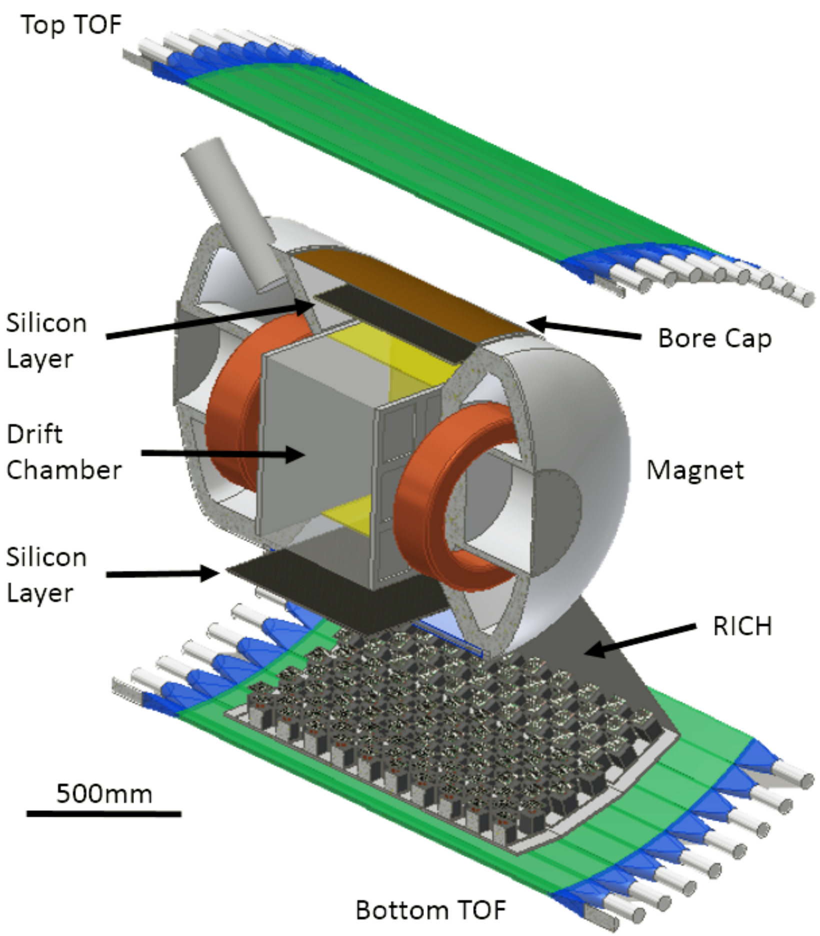
The detector consists of: the **Silicon Detector** [direction of the incident particle - two planes of double-side silicon microstrip detectors], the **Trigger Detector** [triggering the experiment - two layers of plastic scintillators], the **Energy Detector** [layers of plastic scintillators followed by a matrix of an inorganic scintillator LYSO] and the **Veto Detector** [plastic scintillators].

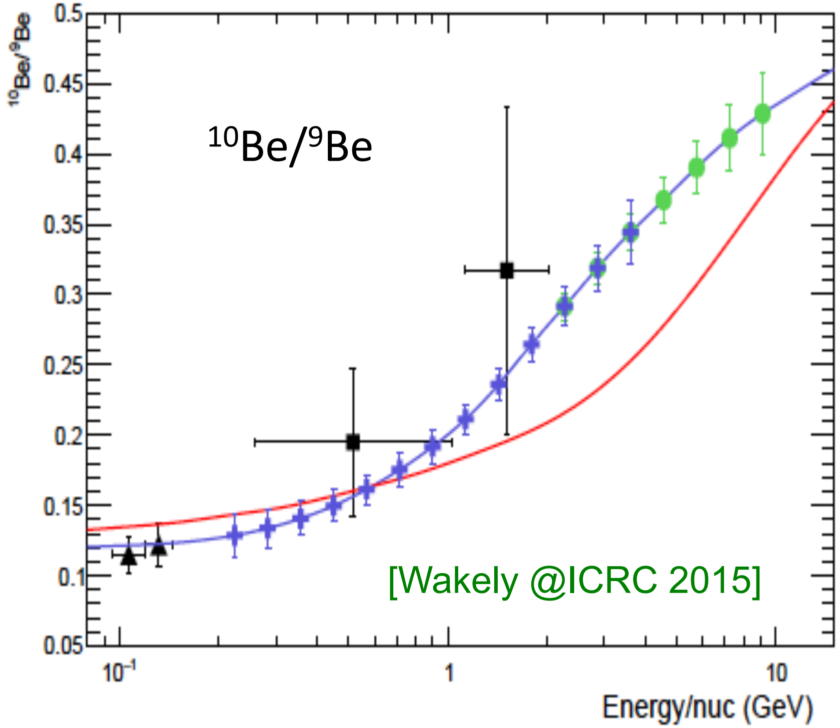


[Sparvoli @LNGS 2015]

HEPD specifications:	
Energy range electrons:	3 MeV~200 MeV
Energy range protons:	30 MeV~300 MeV
Angular resolution	<8° @ 5 MeV
Energy resolution	<10% @ 5 MeV
Particle Identification	> 90 %
Mass (including electronics)	≤ 35 kg
Power consumption	≤ 38W

HELIX: High Energy Light Isotope (balloon) Experiment





- 1T superconducting magnet (ex-HEAT)
- Thin hybrid gas/silicon tracker
- Trigger/Time-of-flight
- RICH (Aerogel radiator with SiPM readout)

- Performance Goals:
  - 0.1 m^2sr aperture
  - 7-14 day LDB
  - **0.25 amu for ^{10}Be mass resolution**
  - up to ~3 GeV/n (blue)
  - upgrade to ~10 GeV/n (green)

HNX Mission Concept

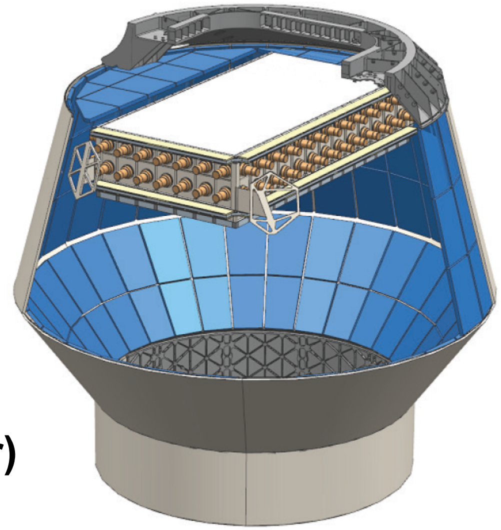
- **HNX uses two complementary instruments to span a huge range in atomic number 6 ≤ Z ≤ 96 and measure Actinides (Th,U,Pu) clocks**

  –**ECCO (Extremely-heavy Cosmic-ray Composition Observer)**

  Uses ~21m^2 of Barium Phosphate (BP-1) glass tiles covering the walls and part of the top of the DragonLab Capsule

  –**CosmicTIGER (Cosmic-ray Trans-Iron Galactic Element Recorder)**

  2m^2 electronic instrument using silicon strip detectors and Cherenkov detectors with acrylic and silica-aerogel radiators



[J. Mitchell @ICRC 2015]

- **HNX accommodation in DragonLab for 2 yr is straightforward**

  –Pressurization reduces complexity of CosmicTIGER – no high-voltage potting, convective/forced air cooling

  –ECCO glass mounts directly to capsule isogrid walls

[Mitchell@ICRC 2015]