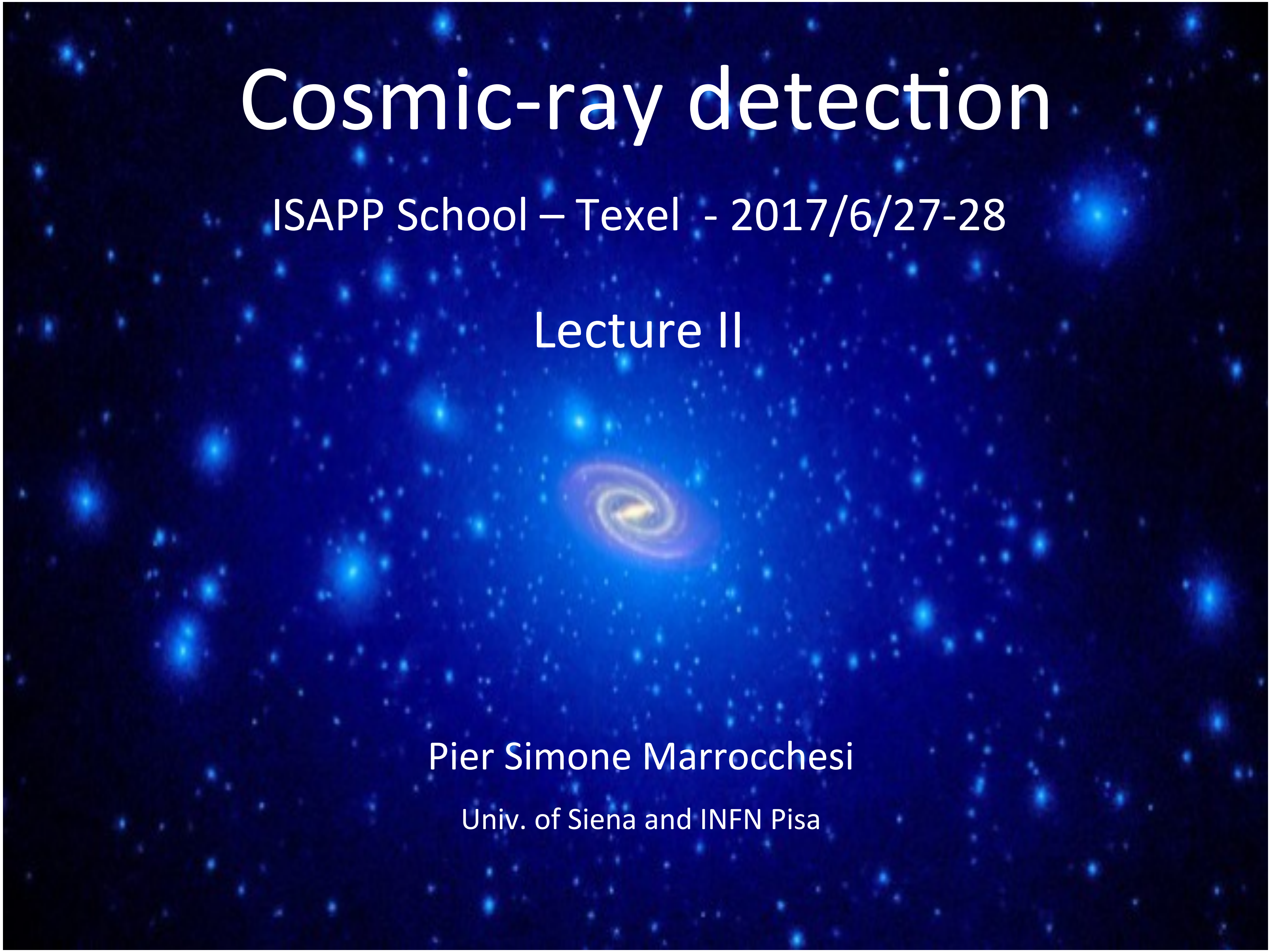


Cosmic-ray detection

ISAPP School – Texel - 2017/6/27-28

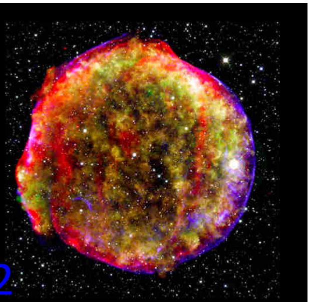
Lecture II

Pier Simone Marrocchesi

Univ. of Siena and INFN Pisa

Overview

- Energy spectra of p, He, light nuclei, sub-Fe nuclei
- Secondary-to-Primary, Primary-to-Primary, Secondary-to-Secondary ratios
- Anti-protons
- Isotope flux ratios, propagation clocks, ultra-heavy nuclei
- A glimpse to future direct measurements of VHE cosmic rays
- A fleeting glimpse to low energy CR and solar modulation



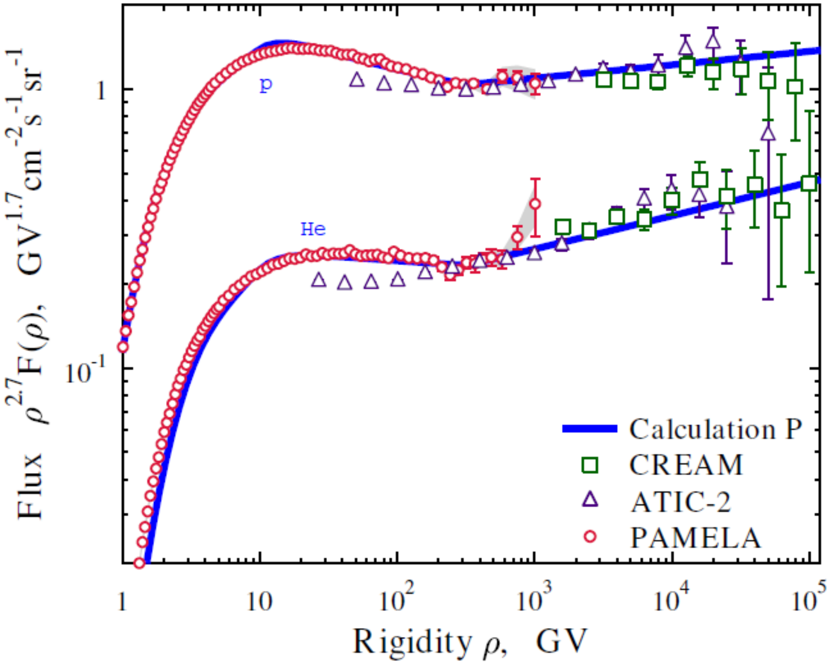
Tycho SN 1572

Charged cosmic-ray hadrons

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

Direct measurements of proton and He spectra

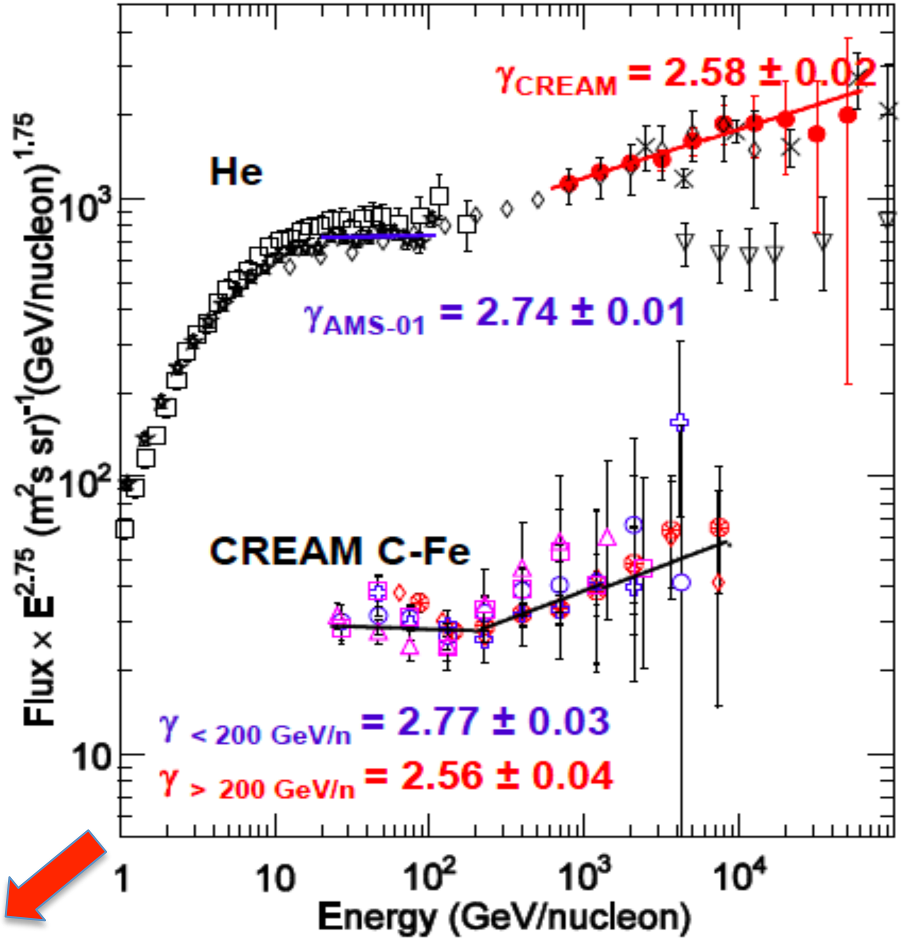
❑ PAMELA detected a spectral break in PROTON and HE spectra at R ~ 240 GV



A single power-law seems inadequate to fit the spectra

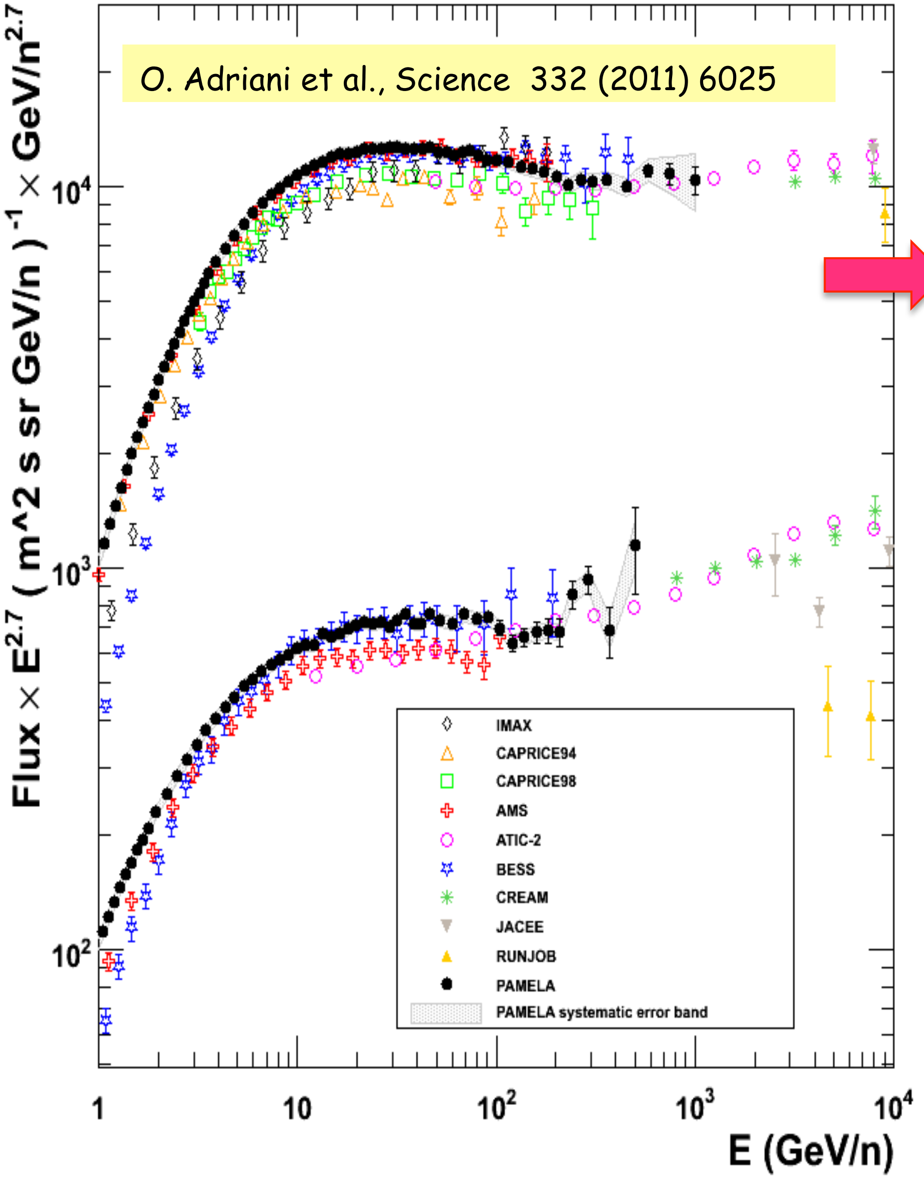
The slope of Z>2 NUCLEI at high energy looks similar to He and different from protons

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

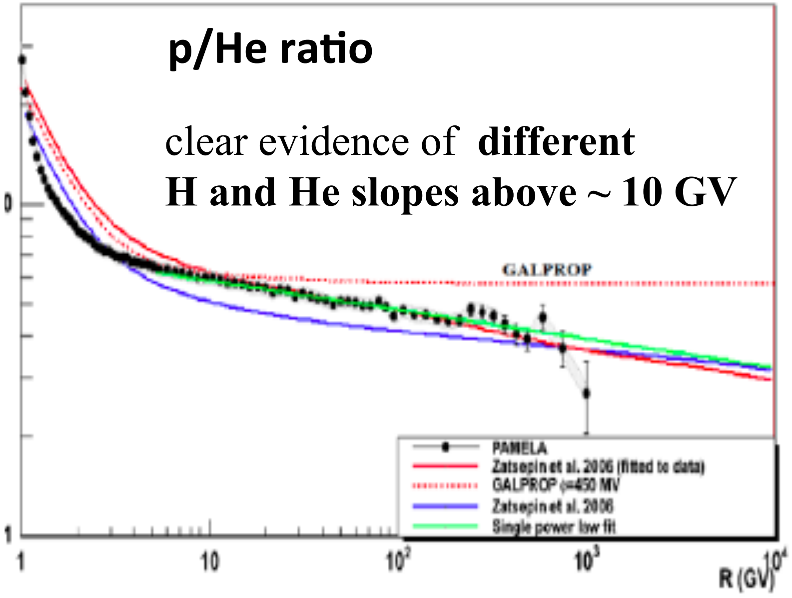


Ahn et al. ApJ 714, L89, 2010
Yoon et al. ApJ **728**, *122*, 2011

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


O. Adriani et al., Science 332 (2011) 6025

- **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 Δγ~0.2÷0.3
    Single power-law rejected at 98% CL



p/He ratio

clear evidence of **different H and He slopes above ~ 10 GV**

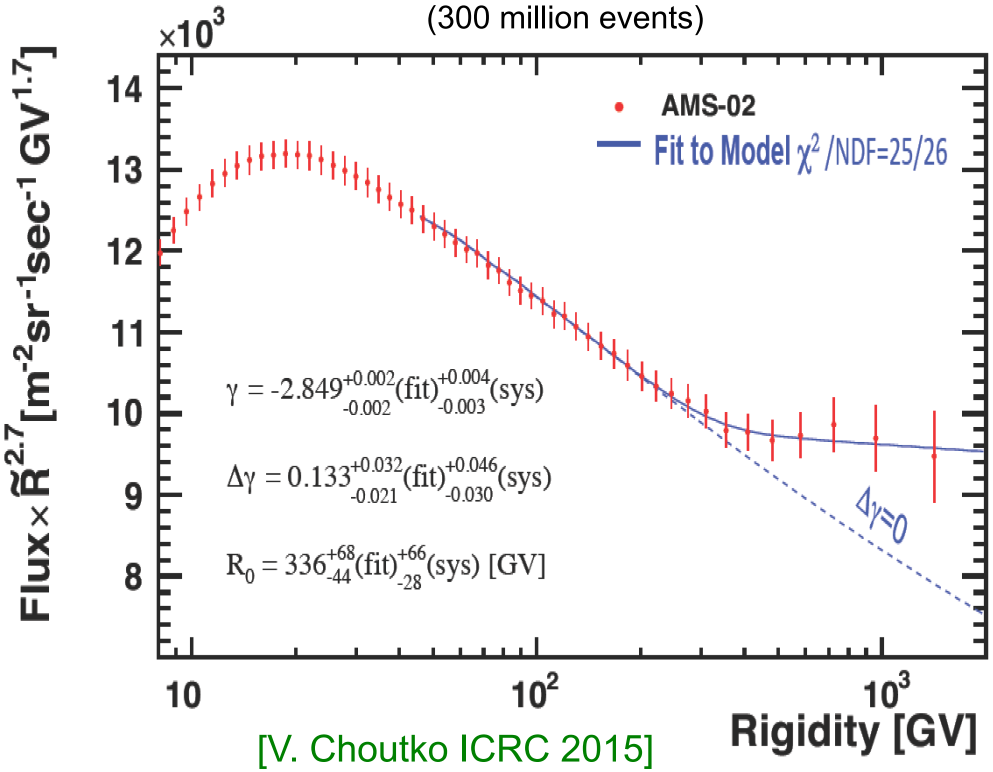
Proton and He fluxes measured by AMS-02

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

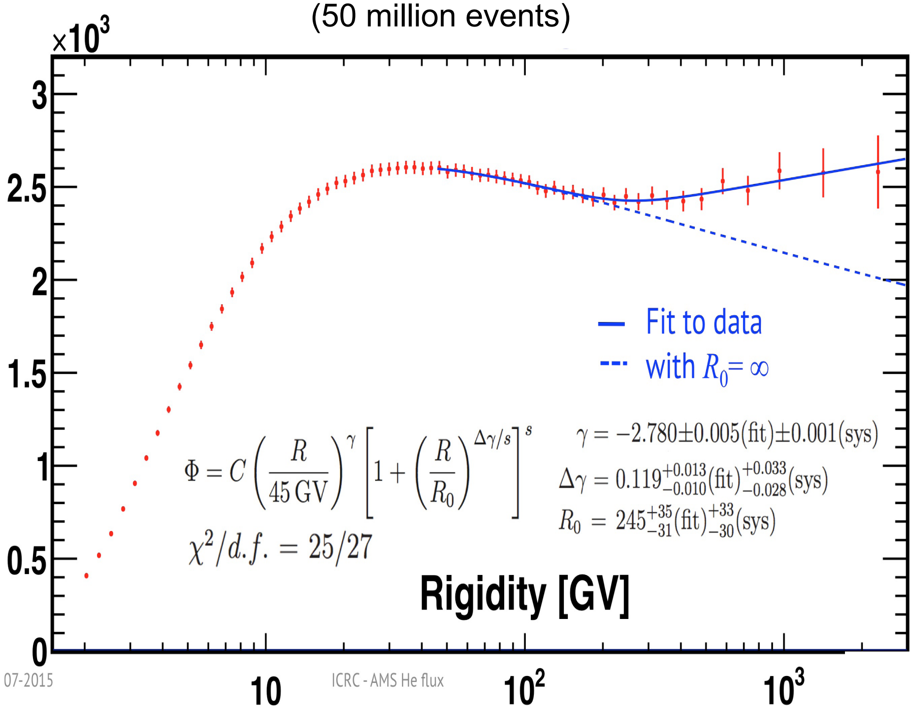
(300 million events)



[V. Choutko ICRC 2015]

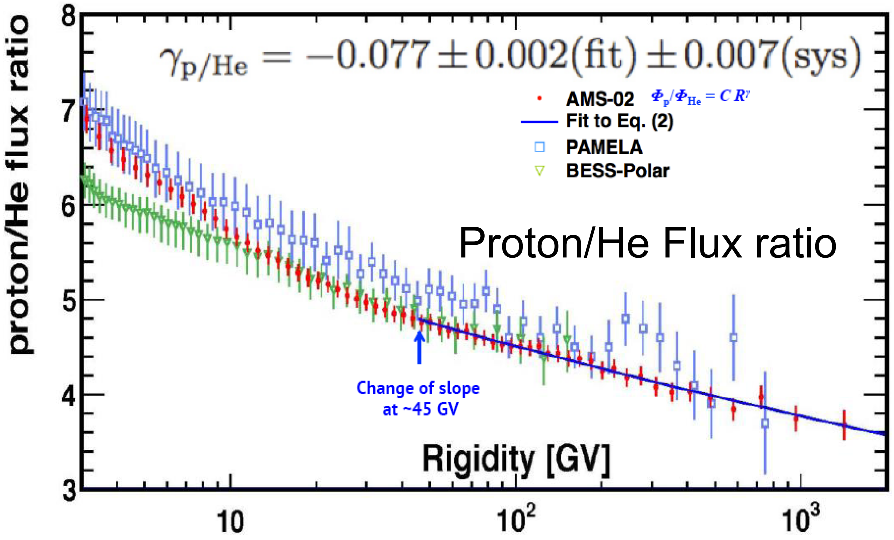
AMS He flux

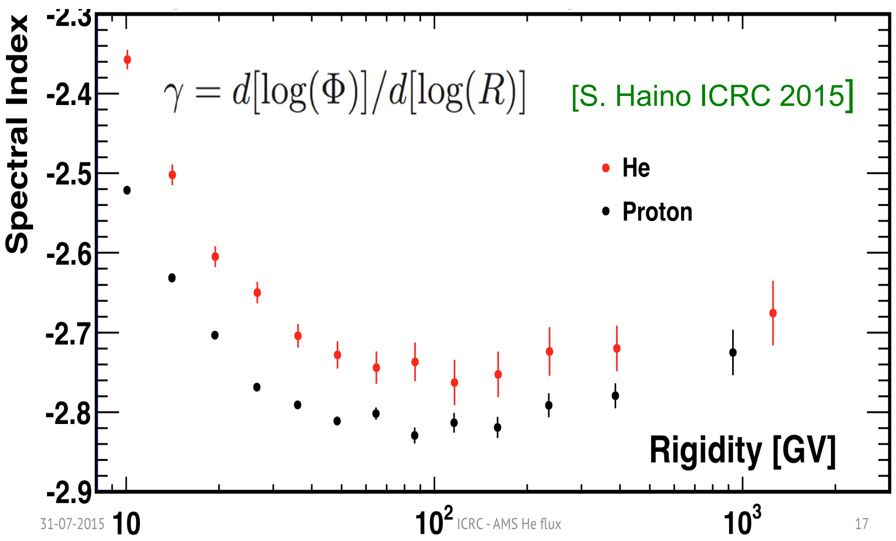
(50 million events)

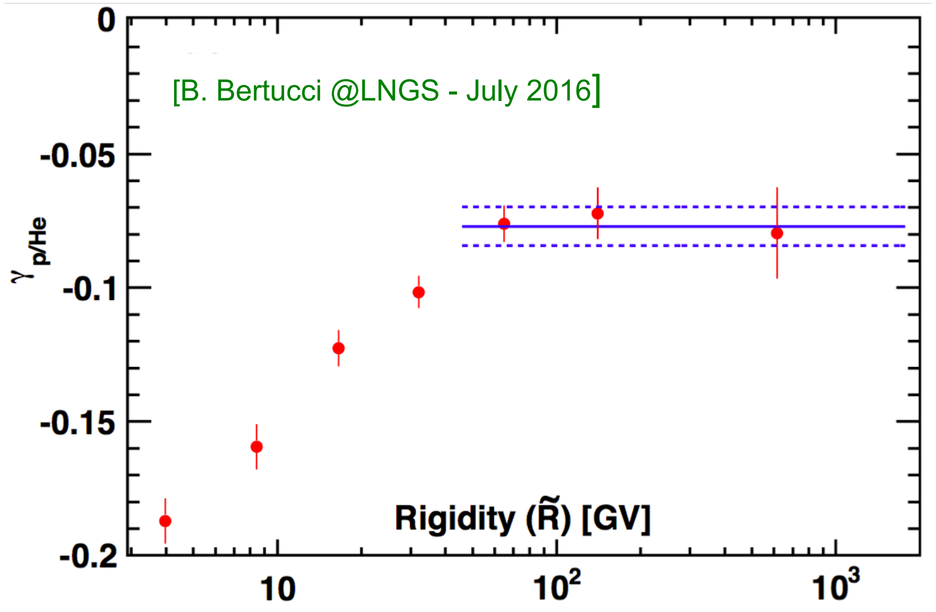


[S. Haino ICRC 2015]

AMS-02: spectral indices for p and He





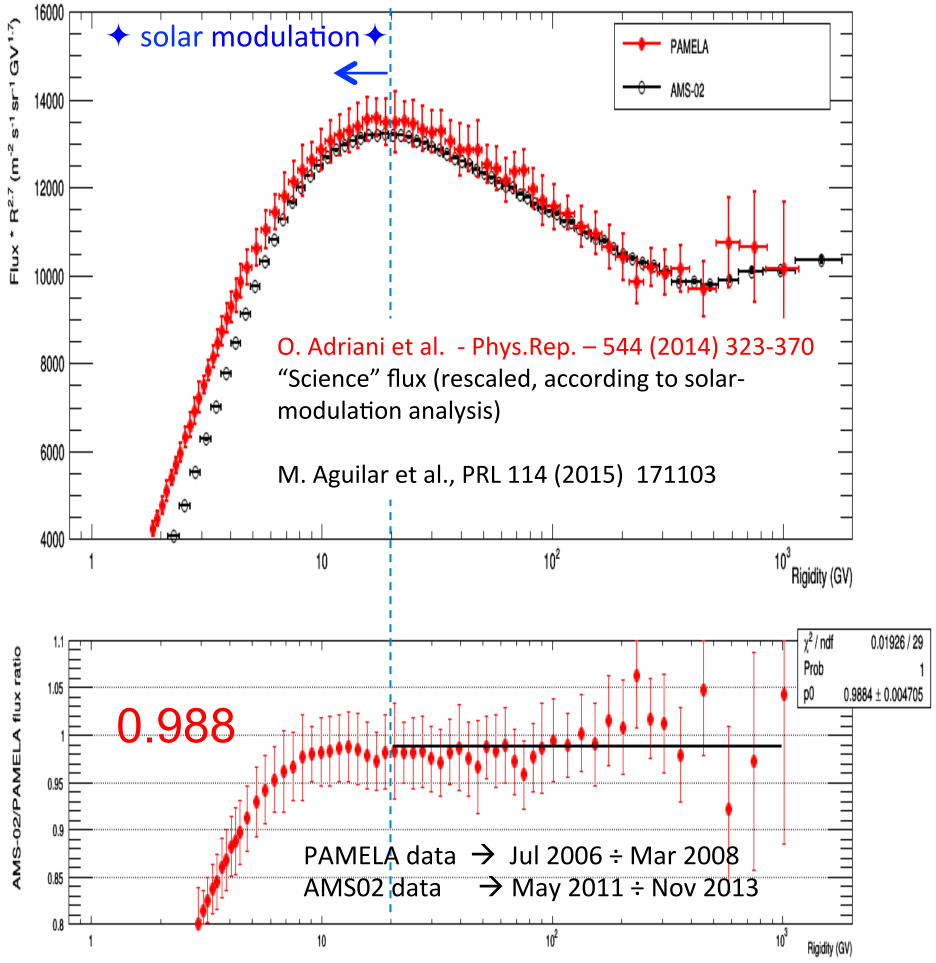


- Both spectral indices are progressively hardening above ~100 GV.
- He spectrum is harder than proton.
- the rigidity dependence of the spectral indices of p and He are similar.

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

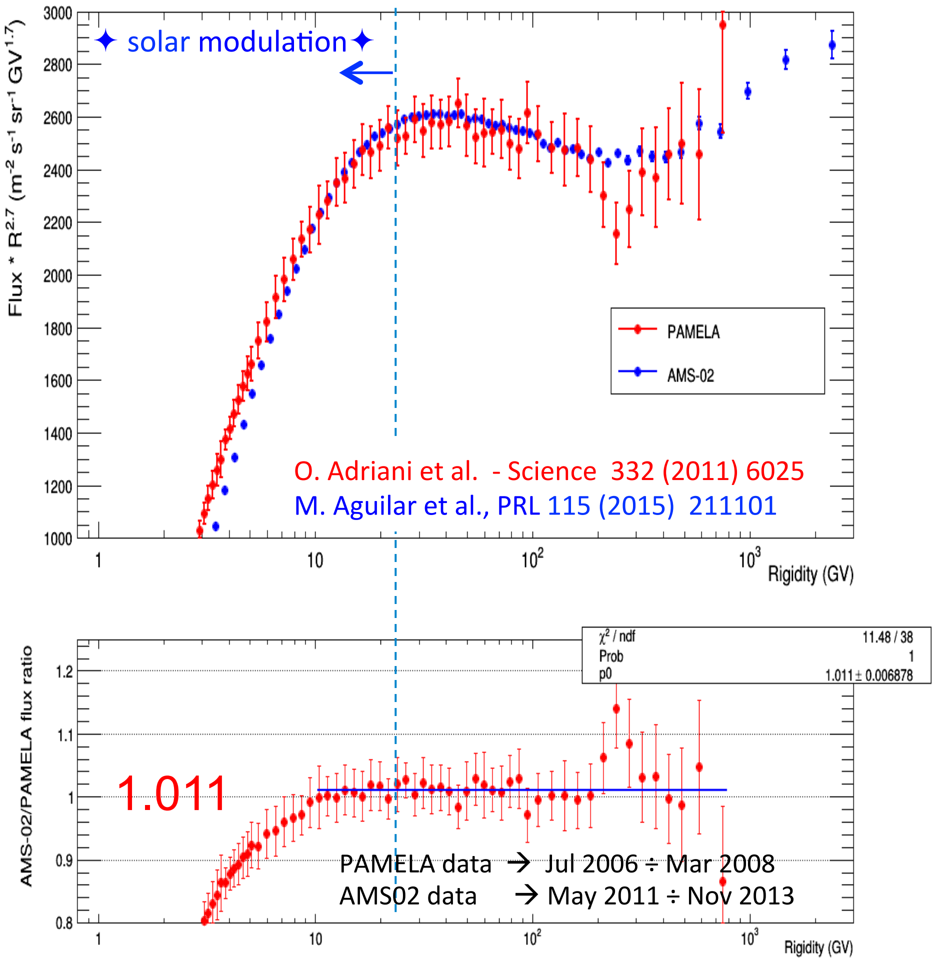


O. Adriani et al. - Phys.Rep. – 544 (2014) 323-370
"Science" flux (rescaled, according to solar-modulation analysis)

M. Aguilar et al., PRL 114 (2015) 171103

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

He

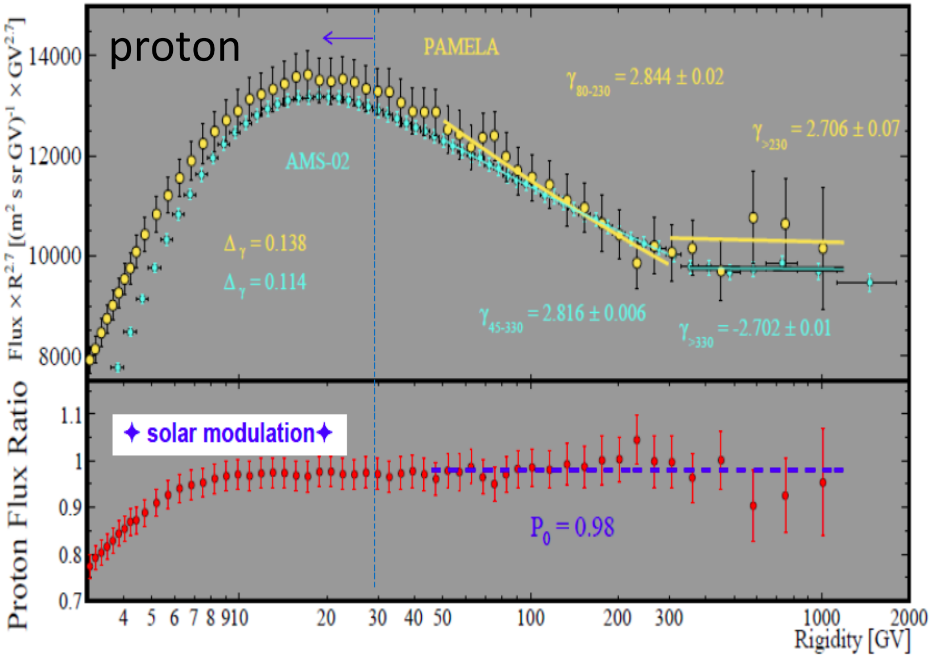


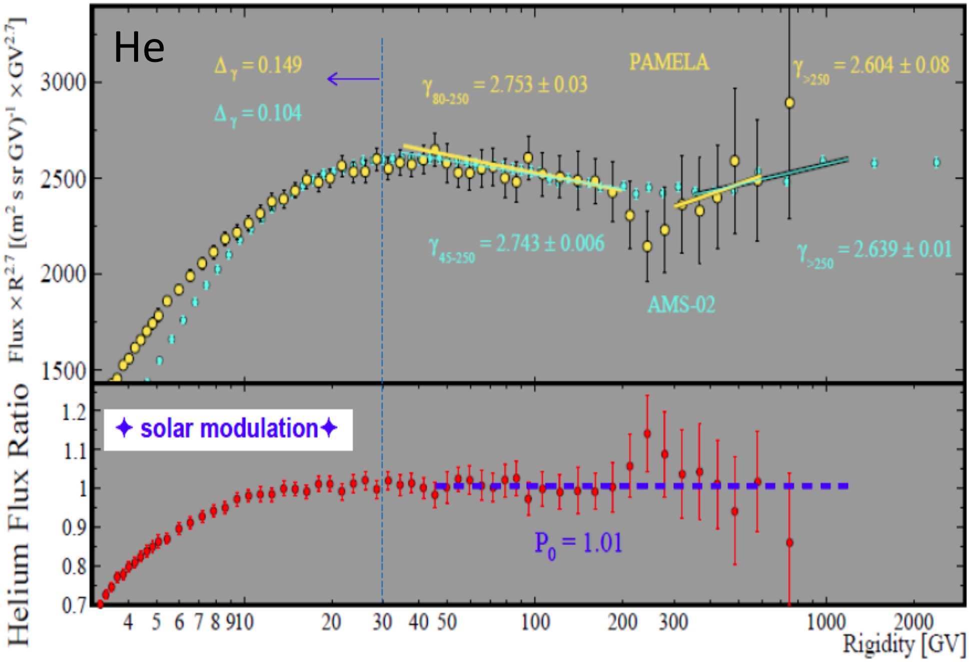
O. Adriani et al. - Science 332 (2011) 6025
M. Aguilar et al., PRL 115 (2015) 211101

PAMELA data → Jul 2006 ÷ Mar 2008
AMS02 data → May 2011 ÷ Nov 2013

New era of precision spectral measurements:

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





[M.Boezio @LNGS Jul 2016]

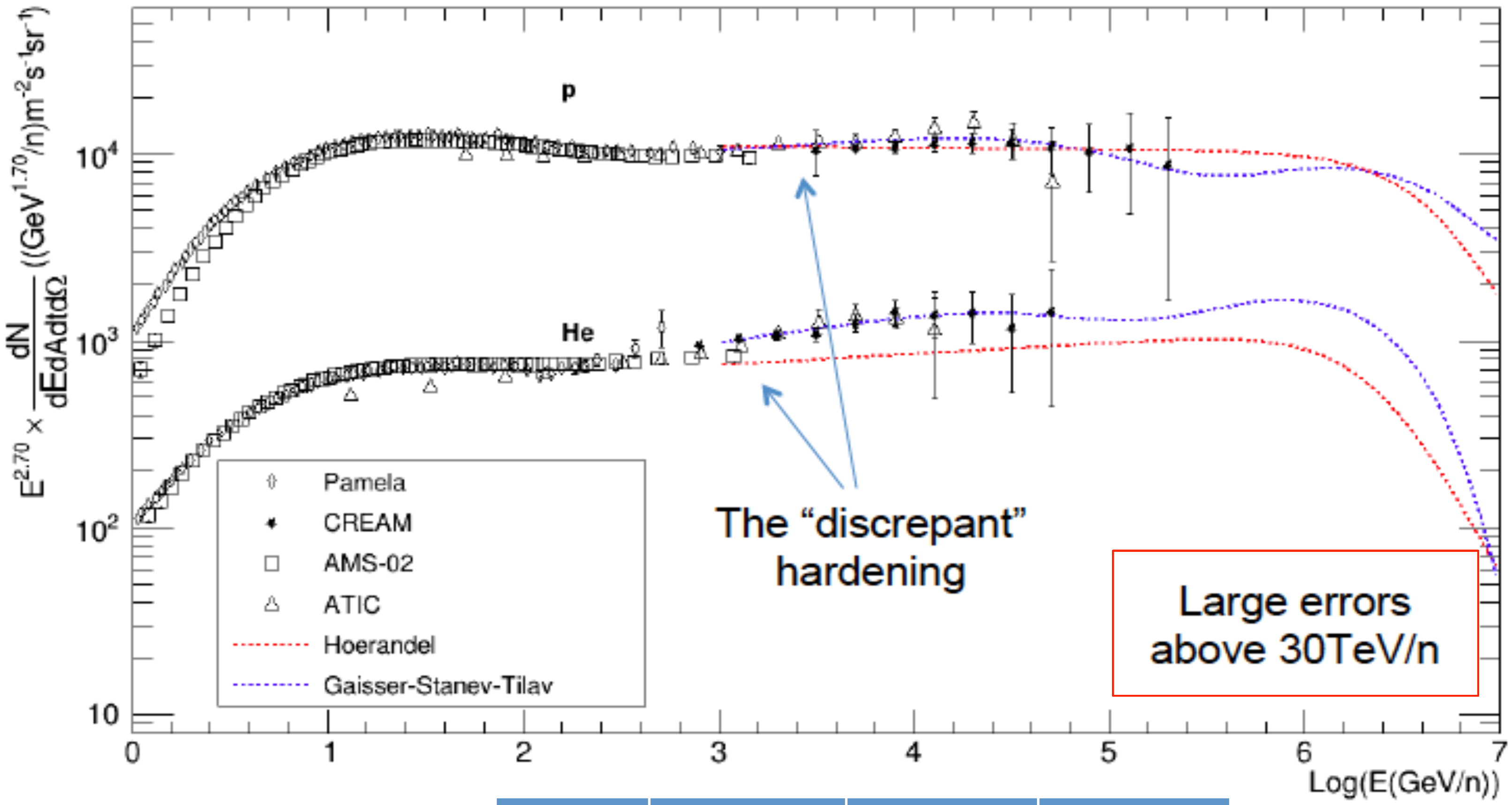
O. Adriani et al., Phys. Rep. 544 (2014) 323 ; M. Aguilar et al., PRL 114 (2015) 171103

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



The “discrepant” hardening

Large errors above 30TeV/n

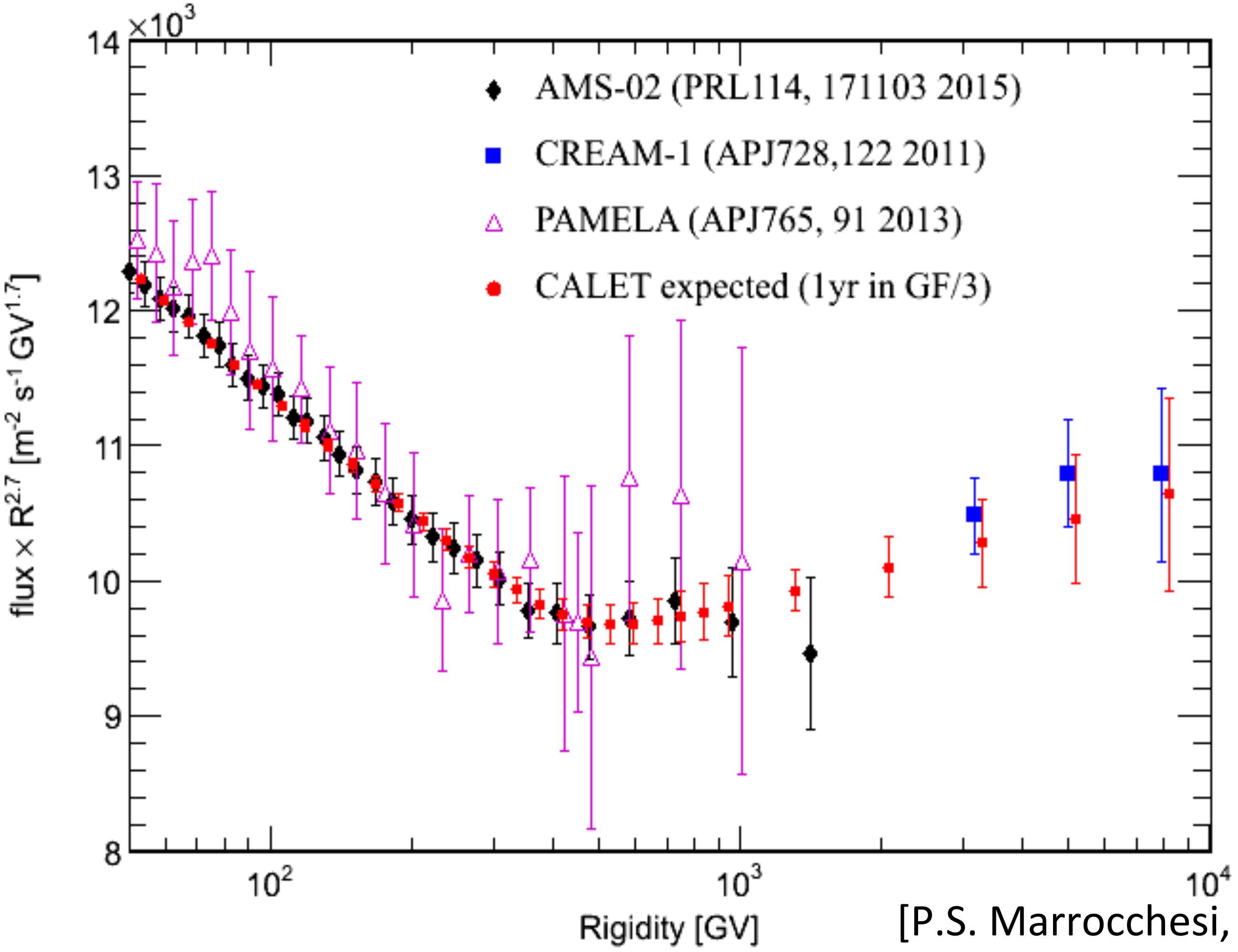
fitted slope of p, He spectra above 230 GV ➡

	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)

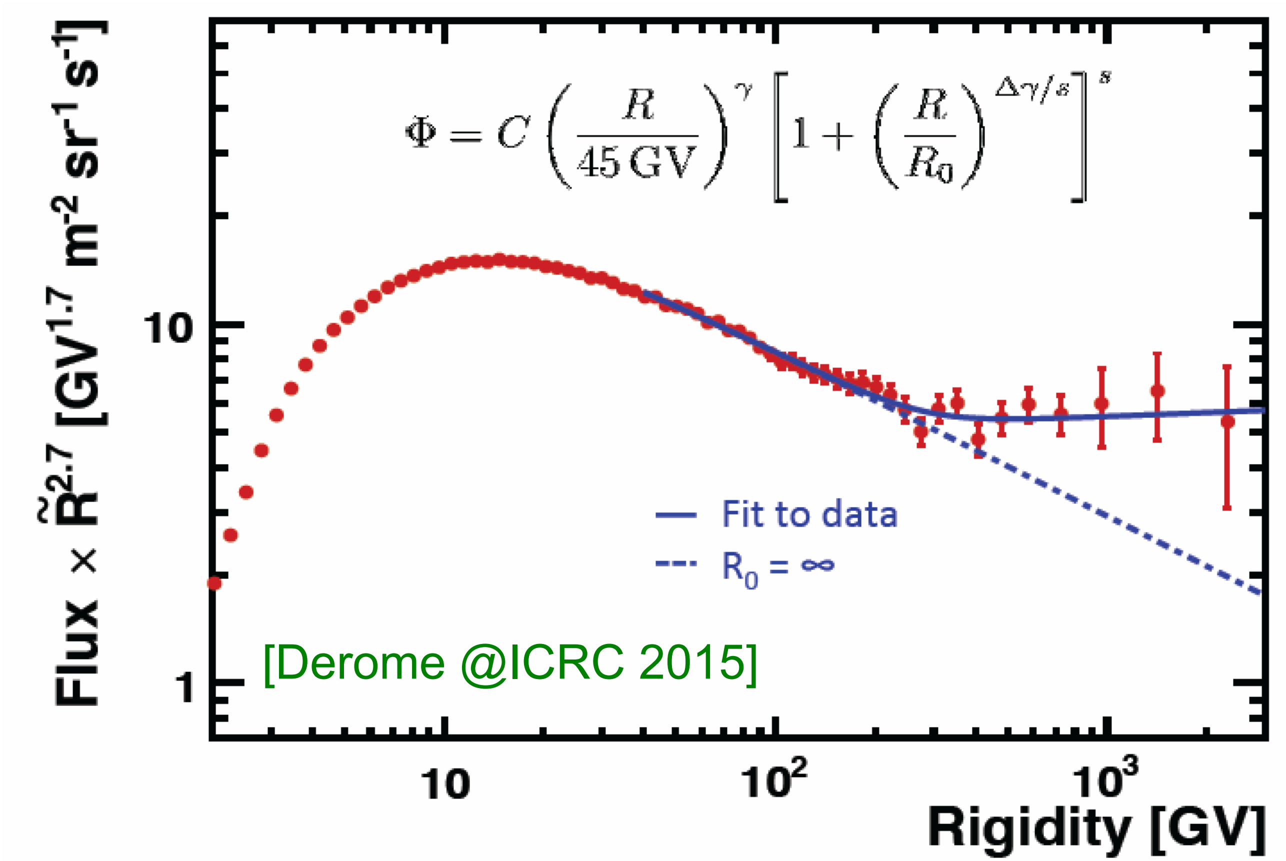
- ✧ for example: after one year on the ISS, CALET is expected to close the gap between AMS02 and CREAM above 1 TV. It will also extend the investigation on the spectral shapes of proton and He to the multi-TeV region.



[P.S. Marrocchesi, arXiv:1512.08059]

Lithium flux from AMS-02 shows a hardening !

- measured in the rigidity range 2 GV – 3 TV

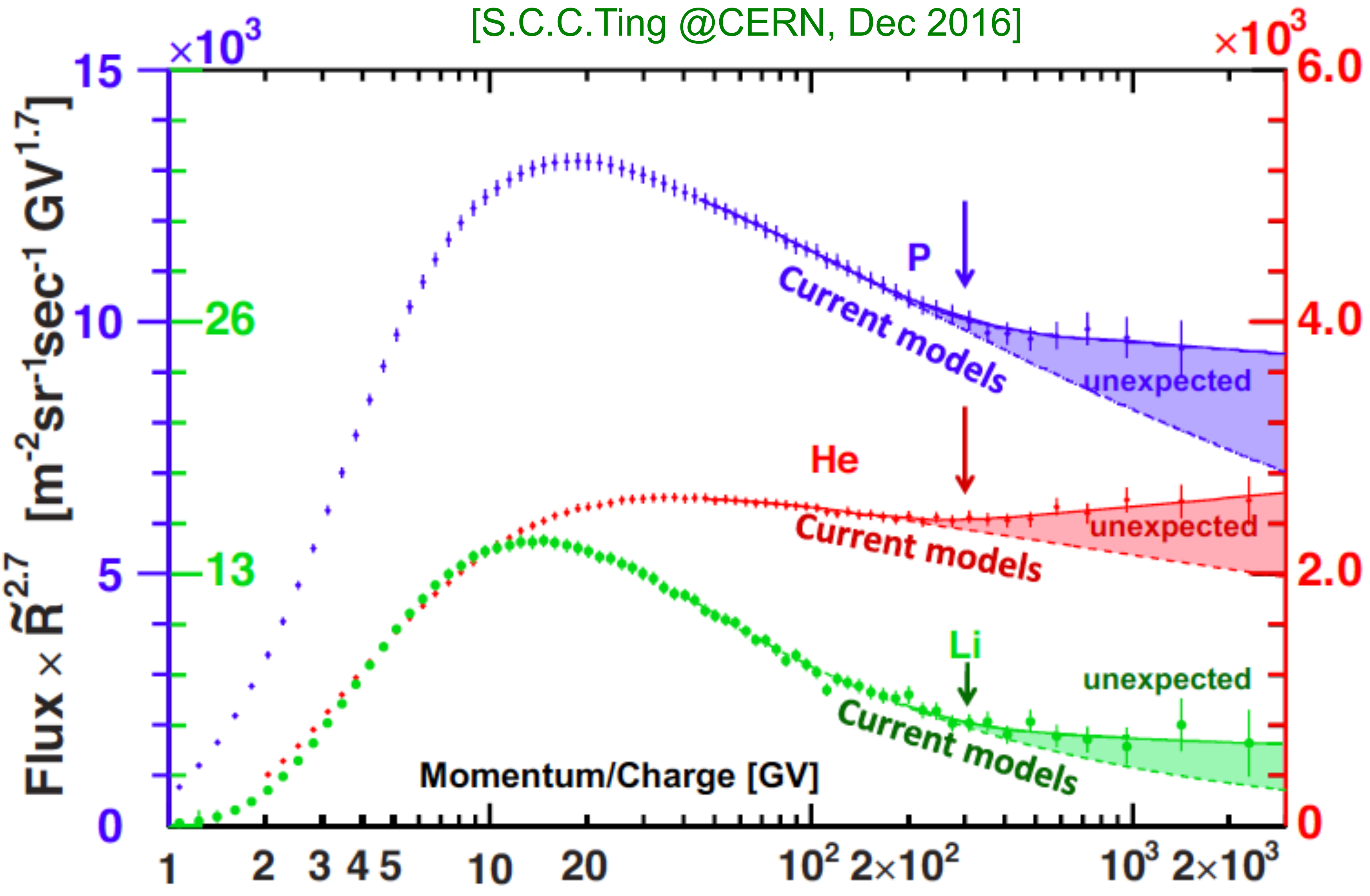


$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

[Derome @ICRC 2015]

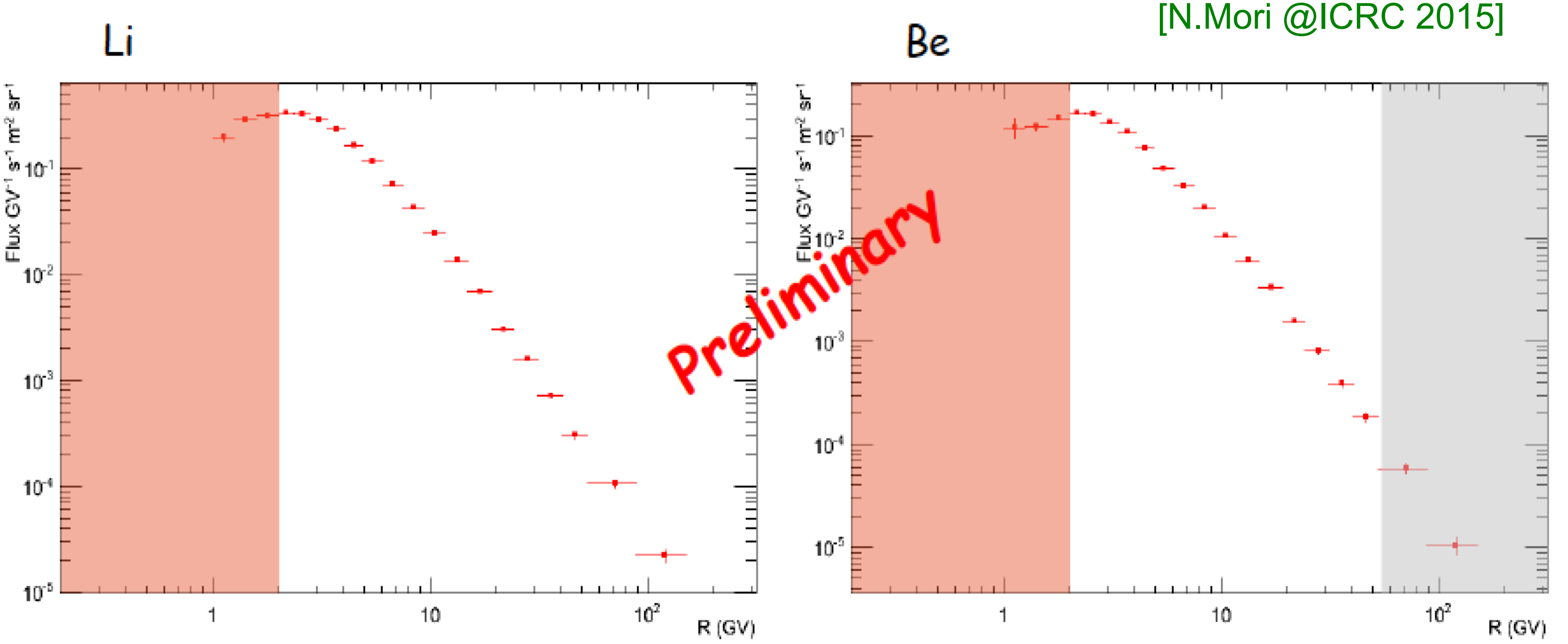
→ Lithium flux hardening in the same rigidity range than for Proton and Helium.

Lithium flux from AMS-02 shows a hardening !



Preliminary Li and Be fluxes from PAMELA

[N.Mori @ICRC 2015]

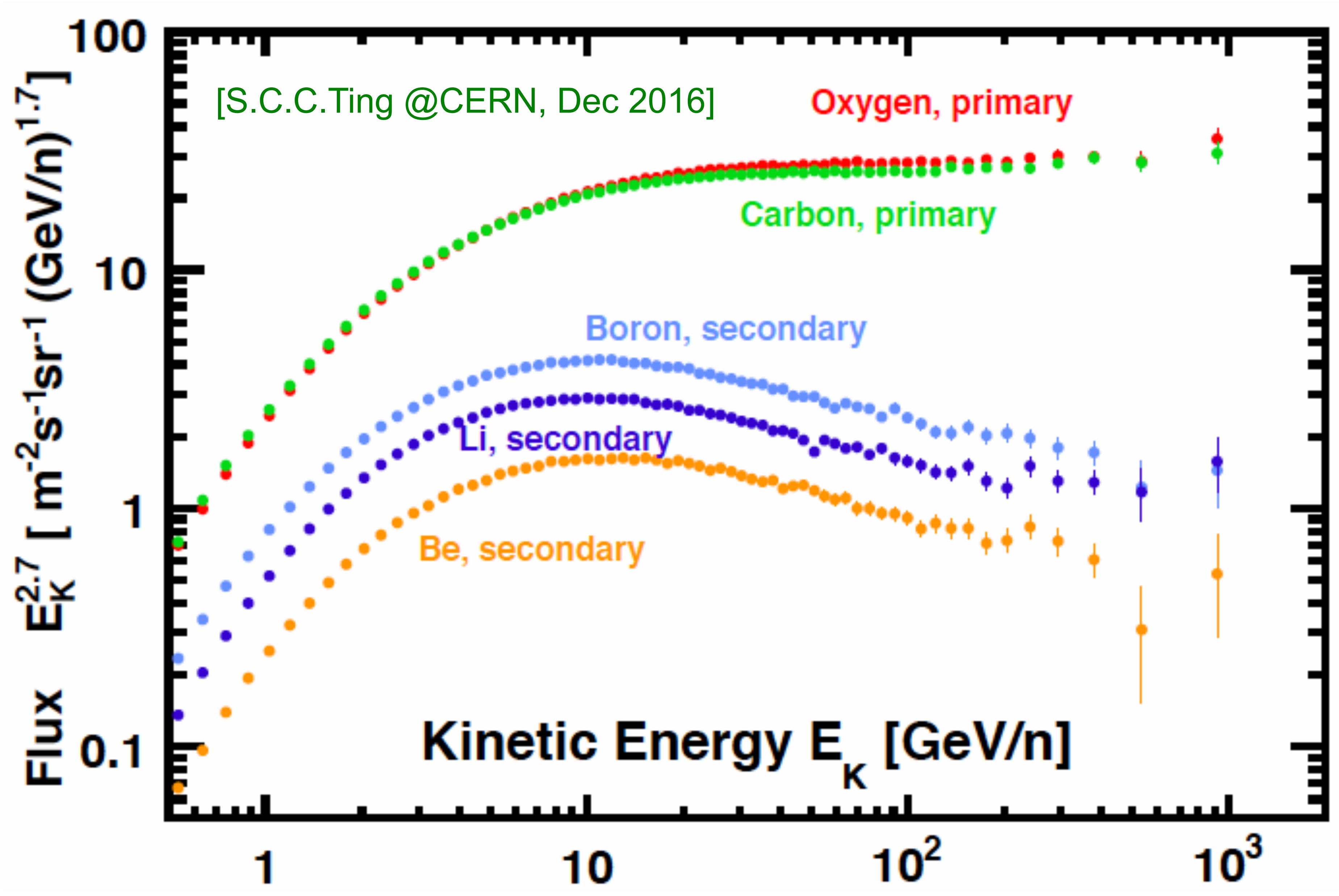


- Shaded red area: particle slow-down effects
  - Still to be corrected

- No MC corrections
- Not unfolded
- Only statistical errors

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

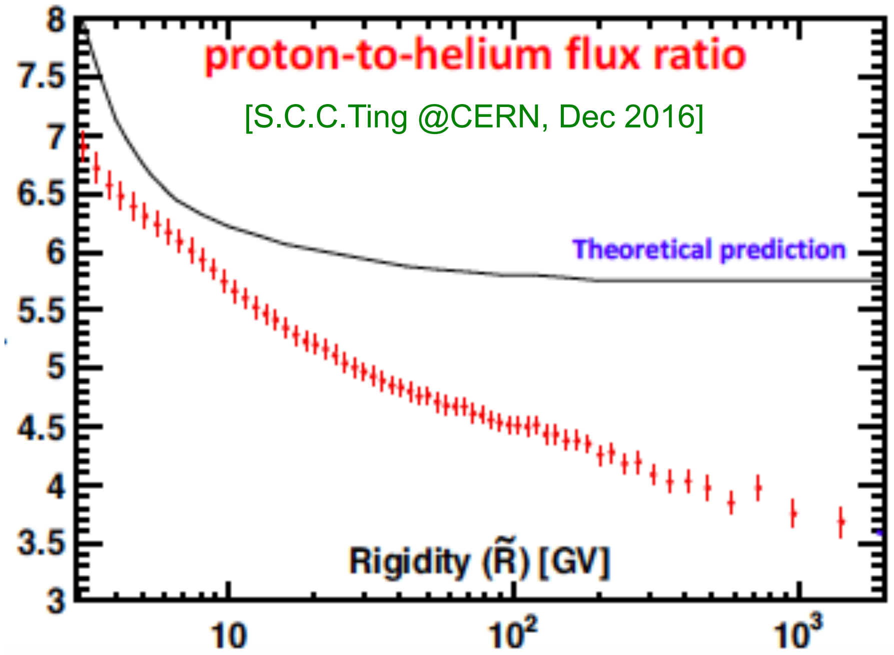
Primary and secondary cosmic rays have characteristically different rigidity dependence.



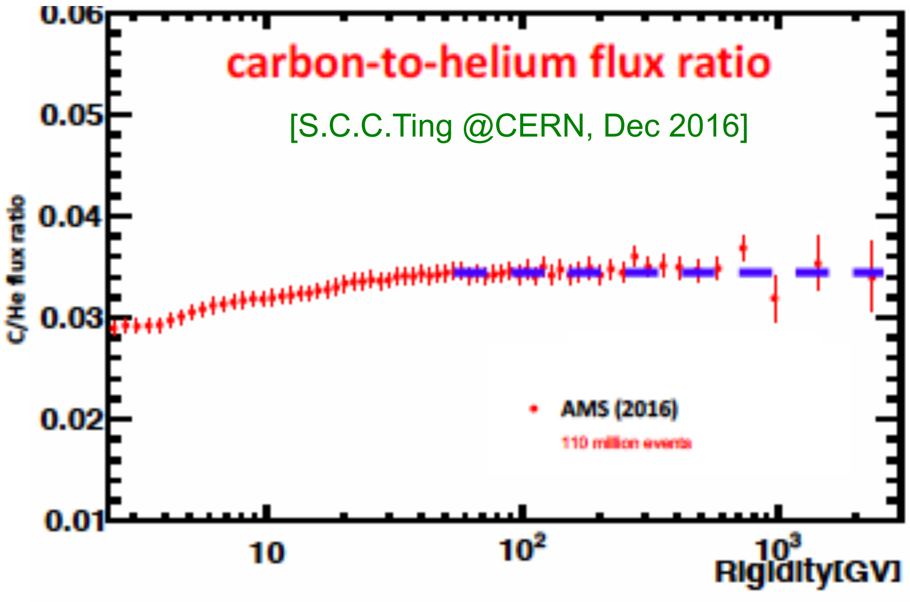
Flux Ratios of primary elements

Differently from expectations the proton-to-helium flux ratio is NOT flat in Rigidity →

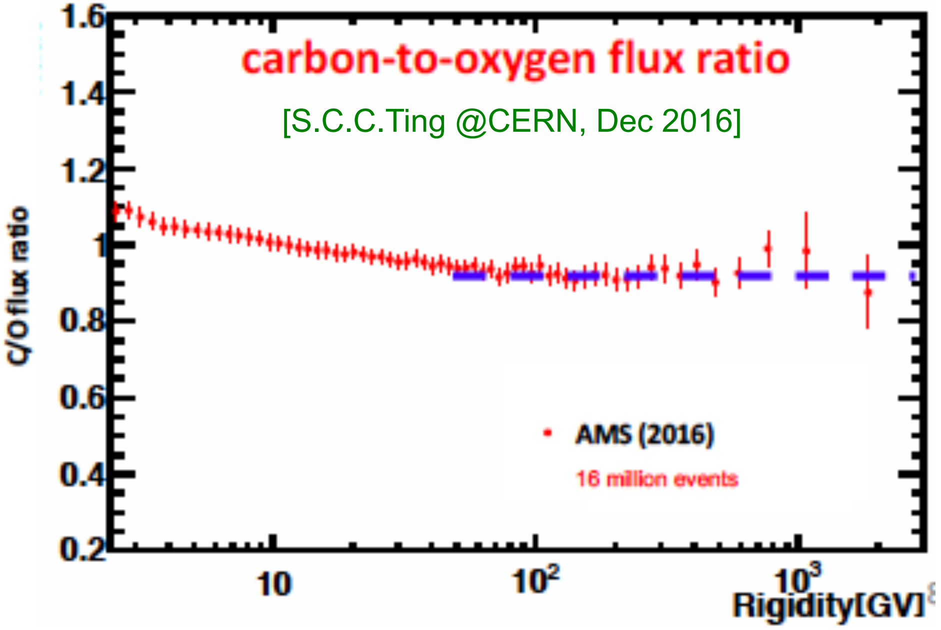
He, carbon, oxygen are primary comic rays. They are assumed to originate from the same sources. Therefore the ratio of their fluxes (e.g. C/He, C/O) is expected to be FLAT in Rigidity as confirmed by AMS-02.


proton-to-helium flux ratio

[S.C.C.Ting @CERN, Dec 2016]


carbon-to-helium flux ratio

[S.C.C.Ting @CERN, Dec 2016]


carbon-to-oxygen flux ratio

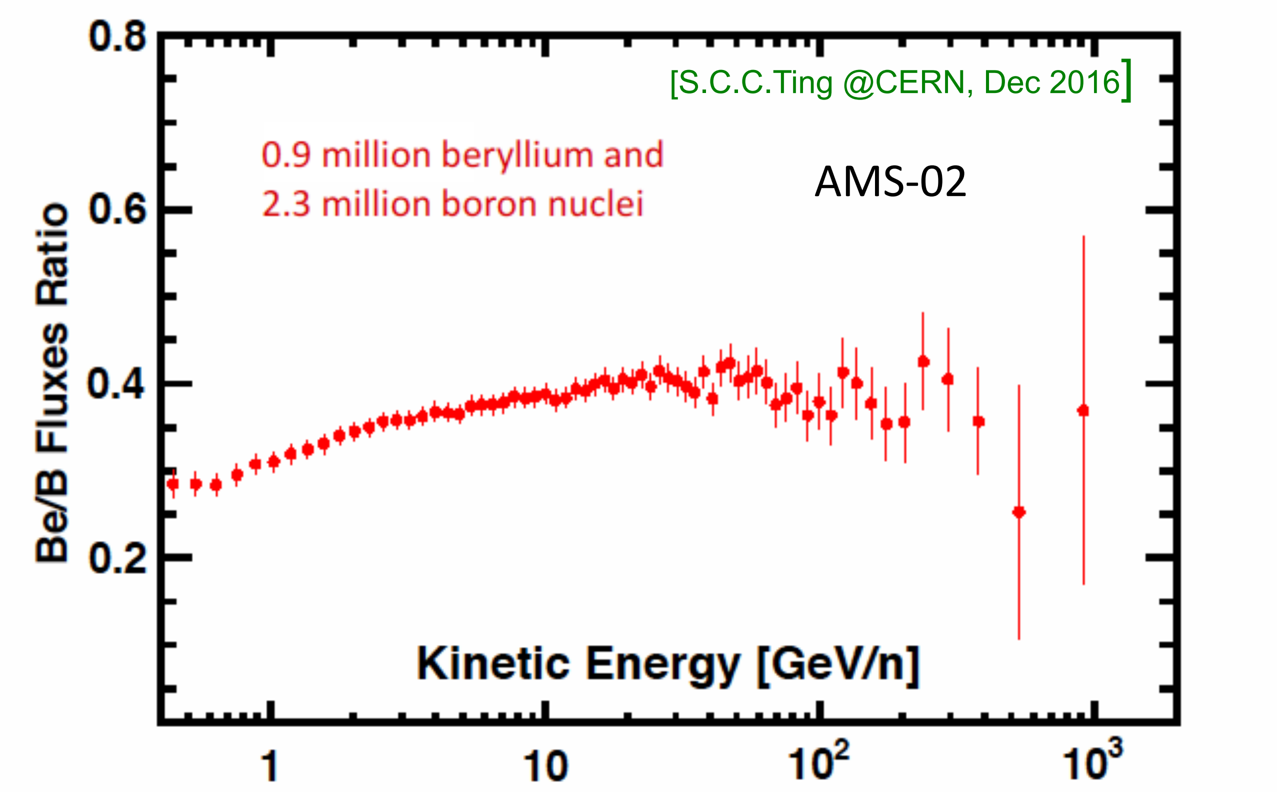
[S.C.C.Ting @CERN, Dec 2016]

Flux ratio of secondaries: Be/B

C,N,O, .. + ISM → Li, Be, B + X B + ISM → Li, Be + X

$^{10}Be \rightarrow {}^{10}B + e^- + \nu$ Half-life 1.5 Myr

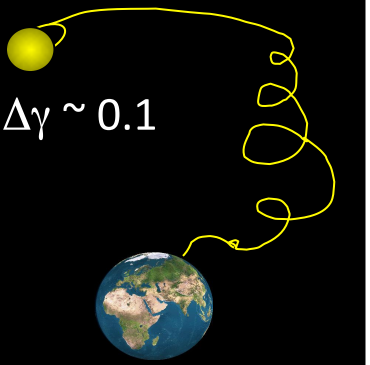
Be/B flux ratio rises with energy due to relativistic time dilatation
→ Info on CR age in Galaxy ~12 Myr



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]

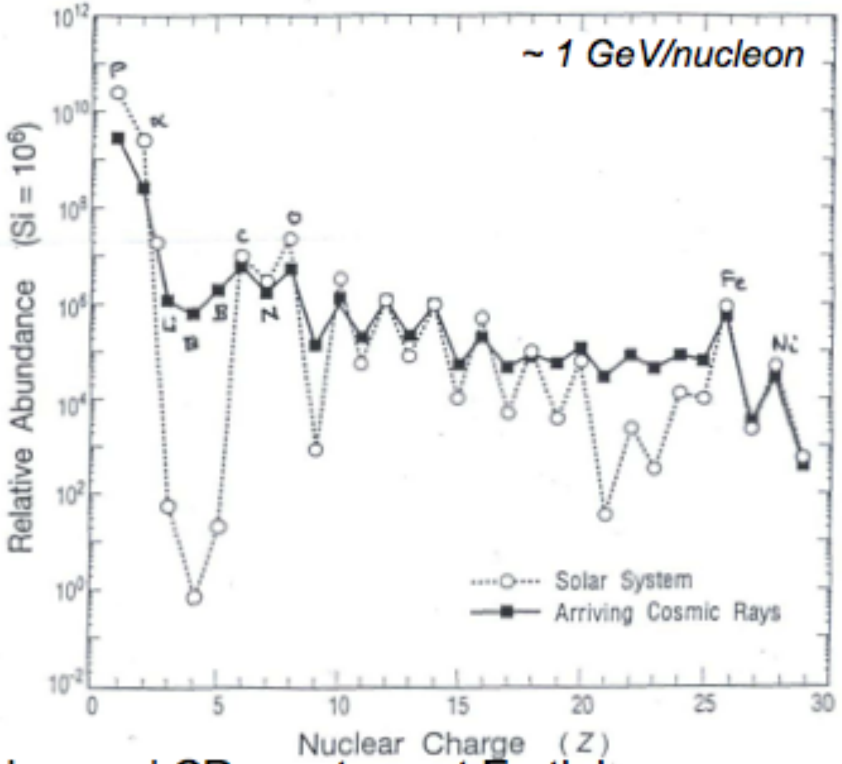
Violation of universality of spectral indices interpretations include:

- 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 vs. primary CR



- Injection of primary CR at the source

$$Q_P(E) \propto E^{-\alpha}$$

- CR propagation in the Galaxy with a diffusion escape time

$$\tau_{esc} \propto D^{-1}(E) \propto E^{-\delta}$$

- The average amount of matter traversed by CR before escaping

$$\lambda_{esc} = \rho_{ISM}\, v\, \tau_{esc} \propto E^{-\delta}$$

- Assuming a leaky-box model at high energy, the observed CR spectrum at Earth is

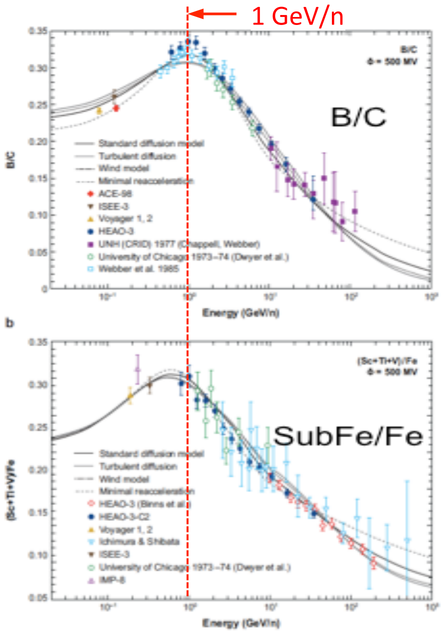
for **primary** CR $\quad N_P(E) \propto Q_P(E)\ \tau(E) \propto E^{-(\alpha+\delta)}$

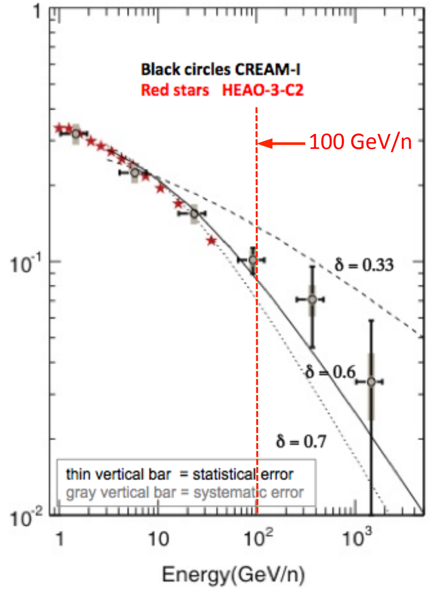
for **secondary** CR $\quad N_S(E) \propto Q_P(E)\ \tau^2(E) \propto E^{-(\alpha+2\delta)}$

$$\Rightarrow \boxed{\frac{N_S}{N_P} \propto E^{-\delta}}$$

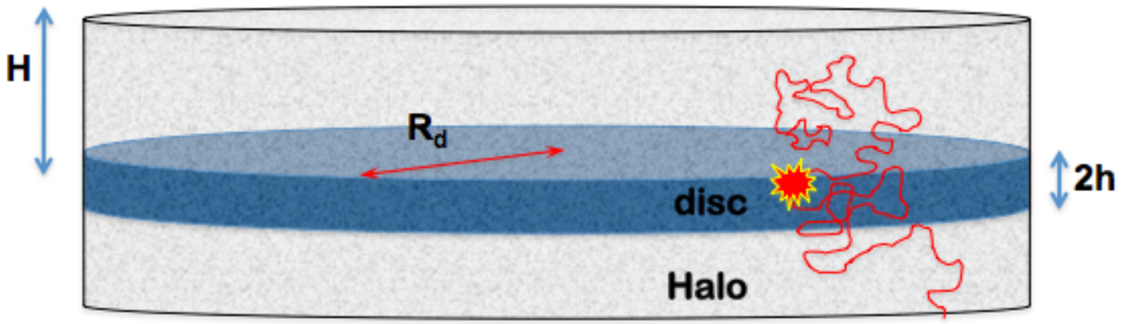
- At high energy (>10 GeV/n) the S/P ratio measures the energy dependence of the escape path-length λ
- Energy spectrum of particles injected by the source is different from observed spectrum

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 $E^{-\delta}$



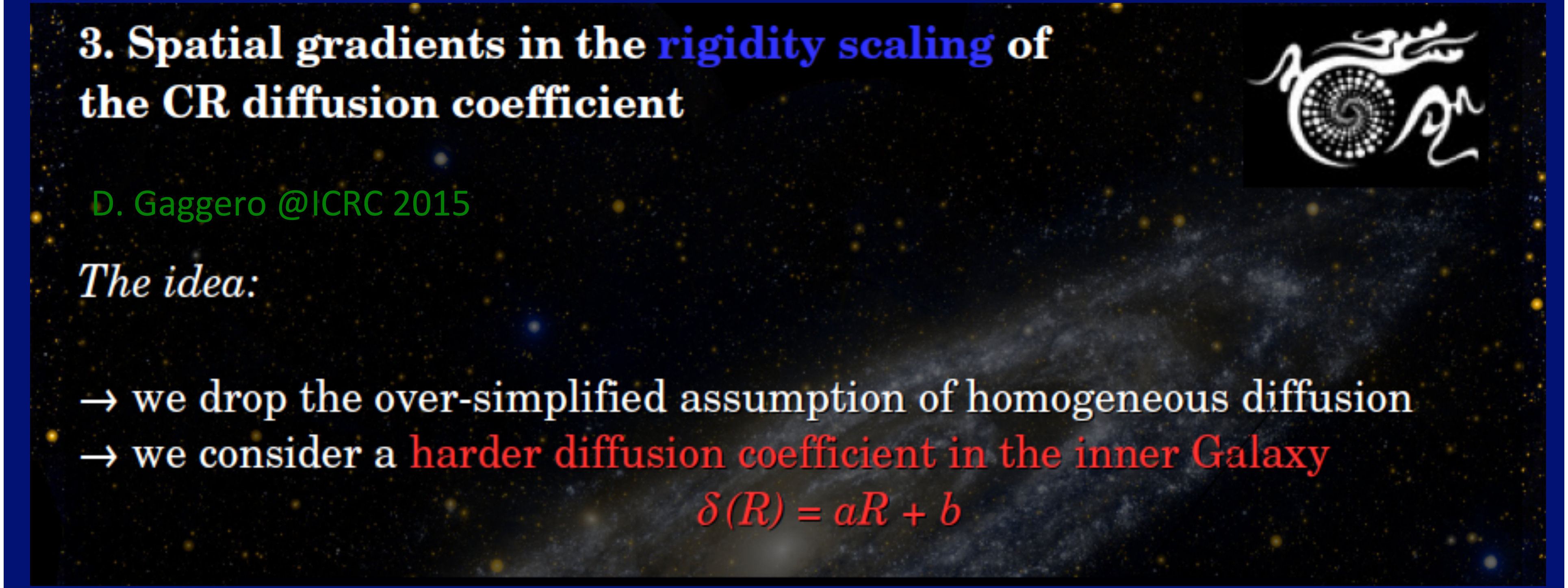
PRIMARY COSMIC RAY SPECTRUM AT EARTH

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

- **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

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

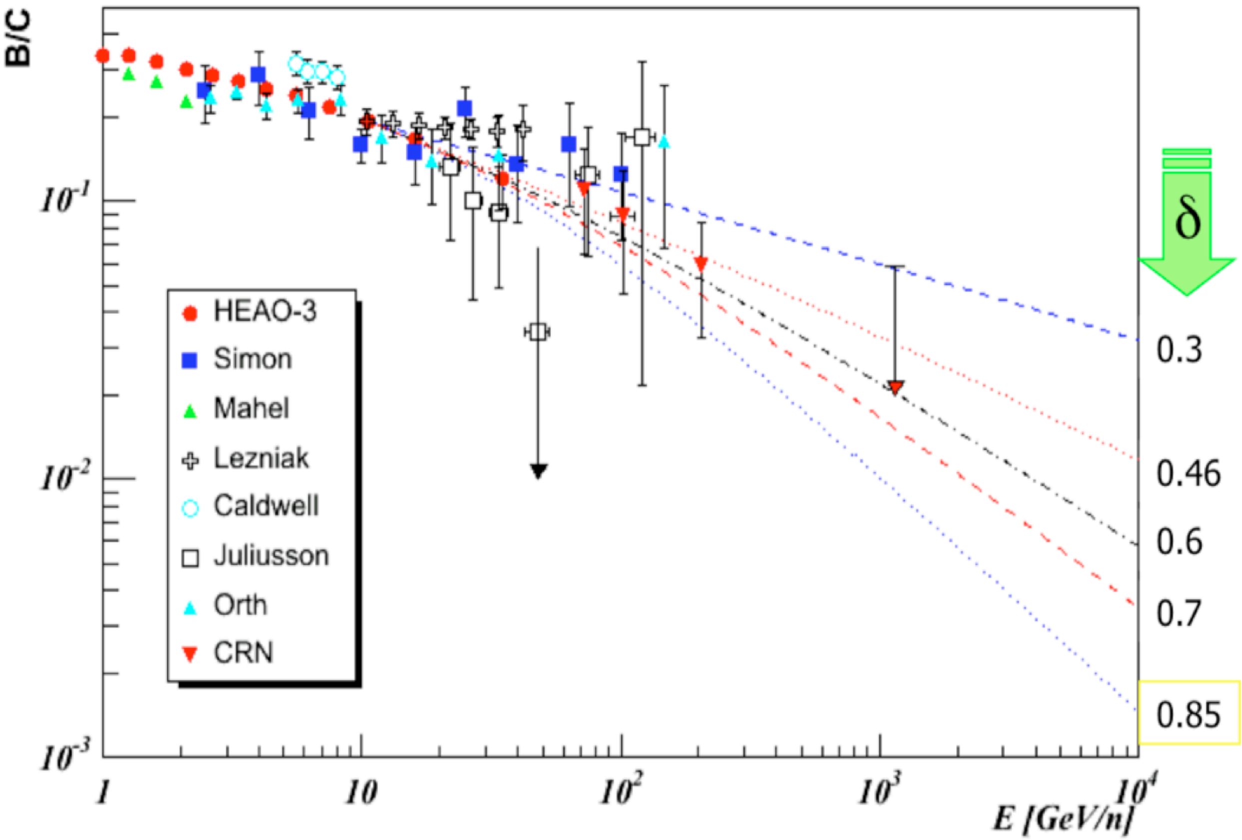
physical interpretation:

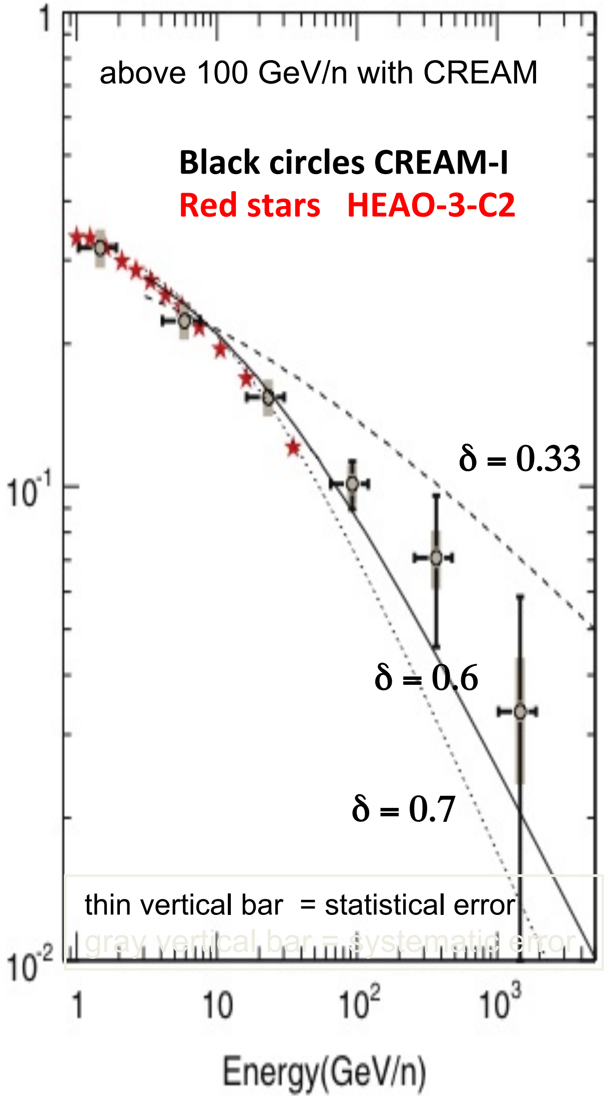
- CR near the sources propagate in SN-driven turbolence
- CR in the outer Galaxy propagate in self-generated turbolence

(see Blasi 2013. Tomassetti 2014)

Boron to Carbon ratio vs. Energy/nucleon

Earlier measurements (before CREAM) mostly below 100 GeV/n





above 100 GeV/n with CREAM

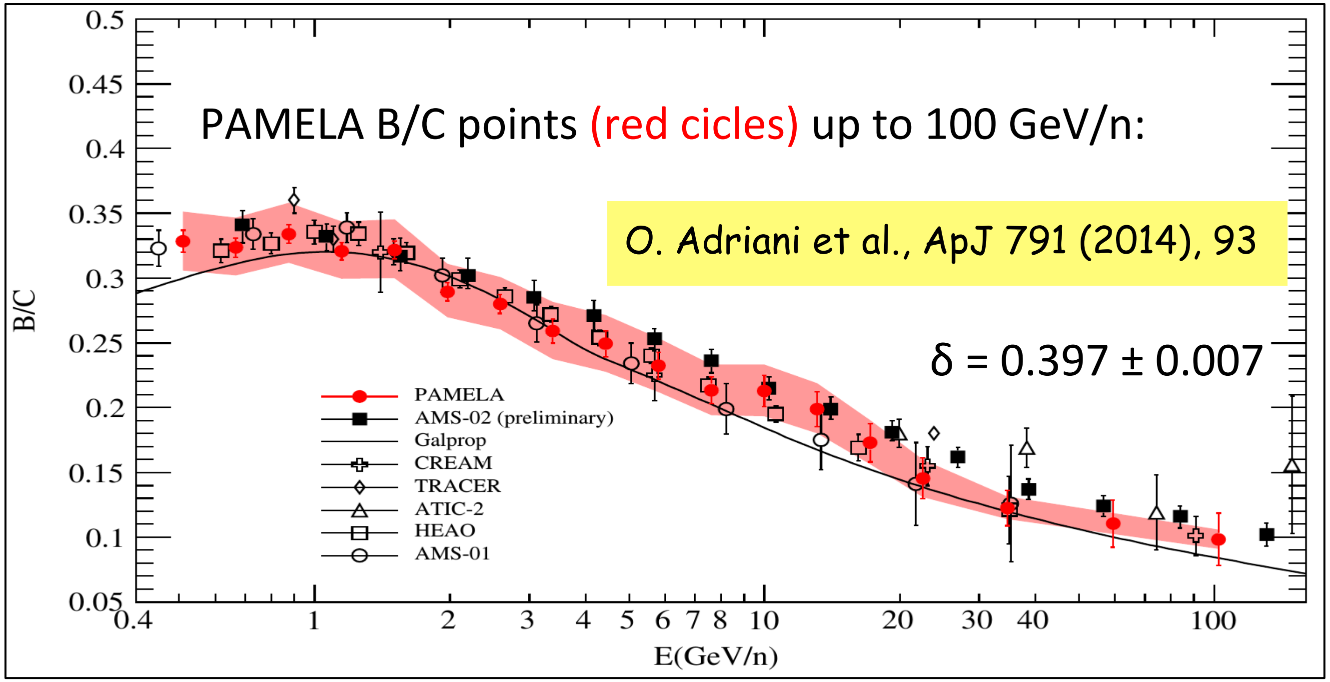
Black circles CREAM-I

Red stars HEAO-3-C2

thin vertical bar = statistical error

gray vertical bar = systematic error

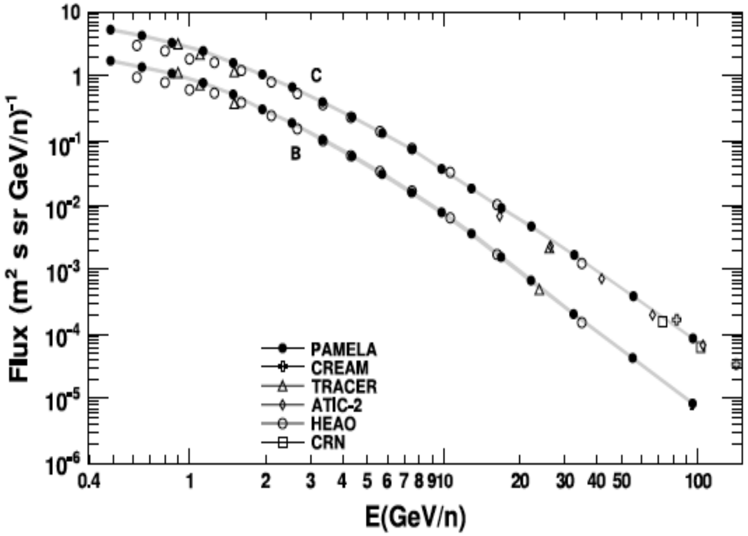
PAMELA: Boron and Carbon fluxes and B/C to 100 GeV/n



PAMELA B/C points (red cicles) up to 100 GeV/n:

O. Adriani et al., ApJ 791 (2014), 93

δ = 0.397 ± 0.007

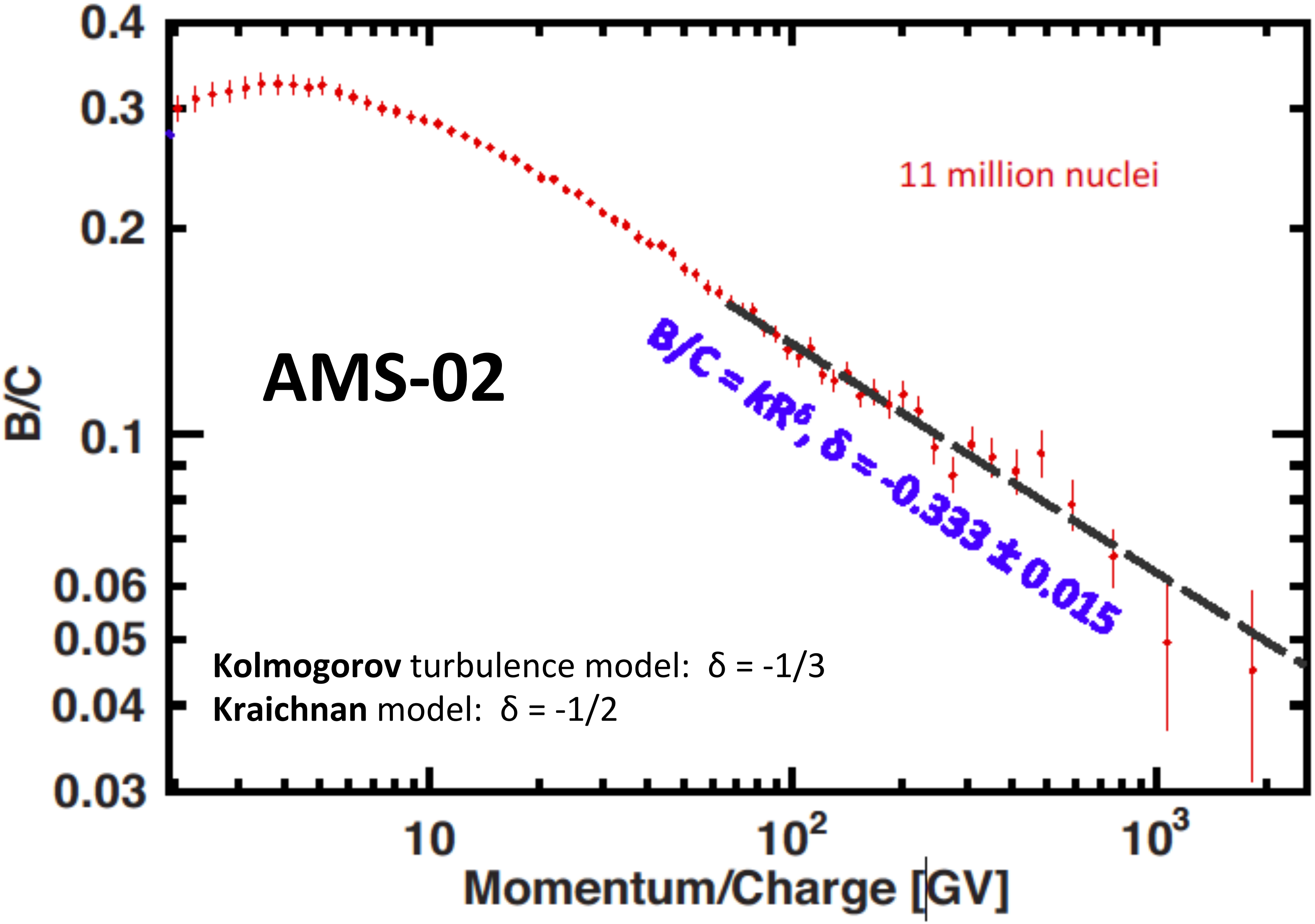


B and C differential fluxes to 100 GeV/n

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

SPL fit above 20 GeV/n
$\gamma_B = 3.01 \pm 0.13$
$\gamma_C = 2.72 \pm 0.06$

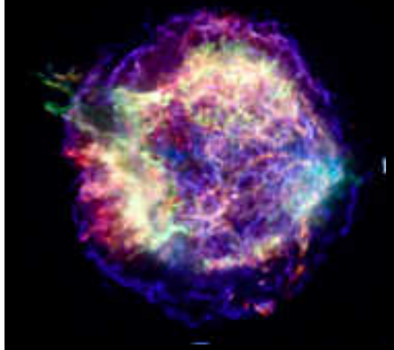
B/C measurement by AMS-02



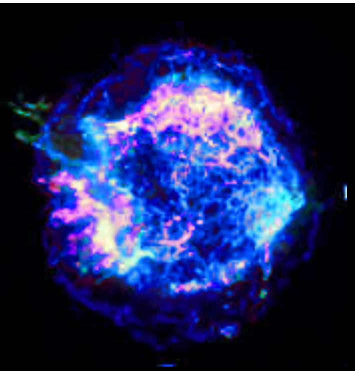
Kolmogorov turbulence model: δ = -1/3

Kraichnan model: δ = -1/2

M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 231101 (2016)



Matter



Anti-Matter ?

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

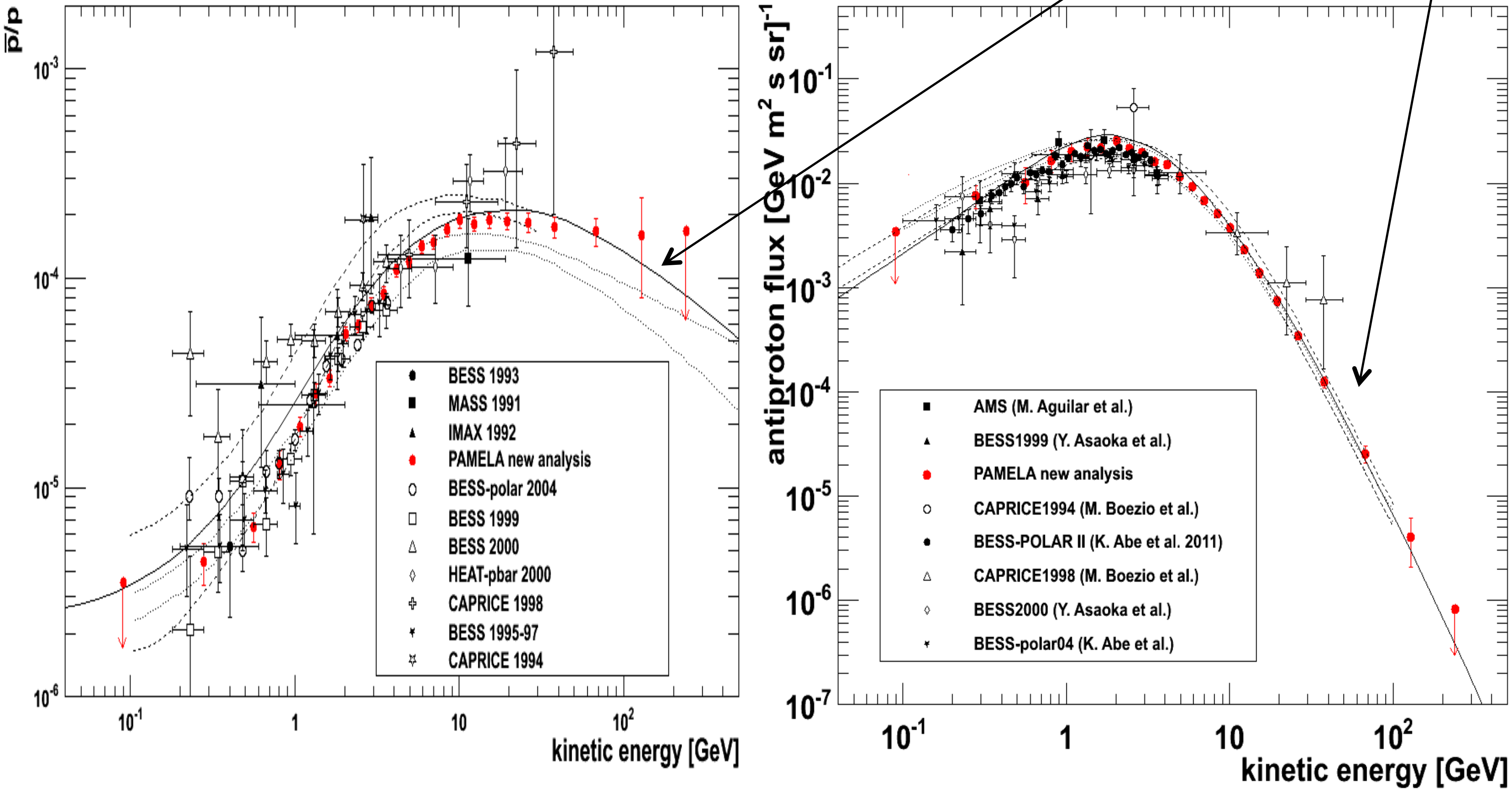
PAMELA Antiparticle Results: Antiprotons

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*

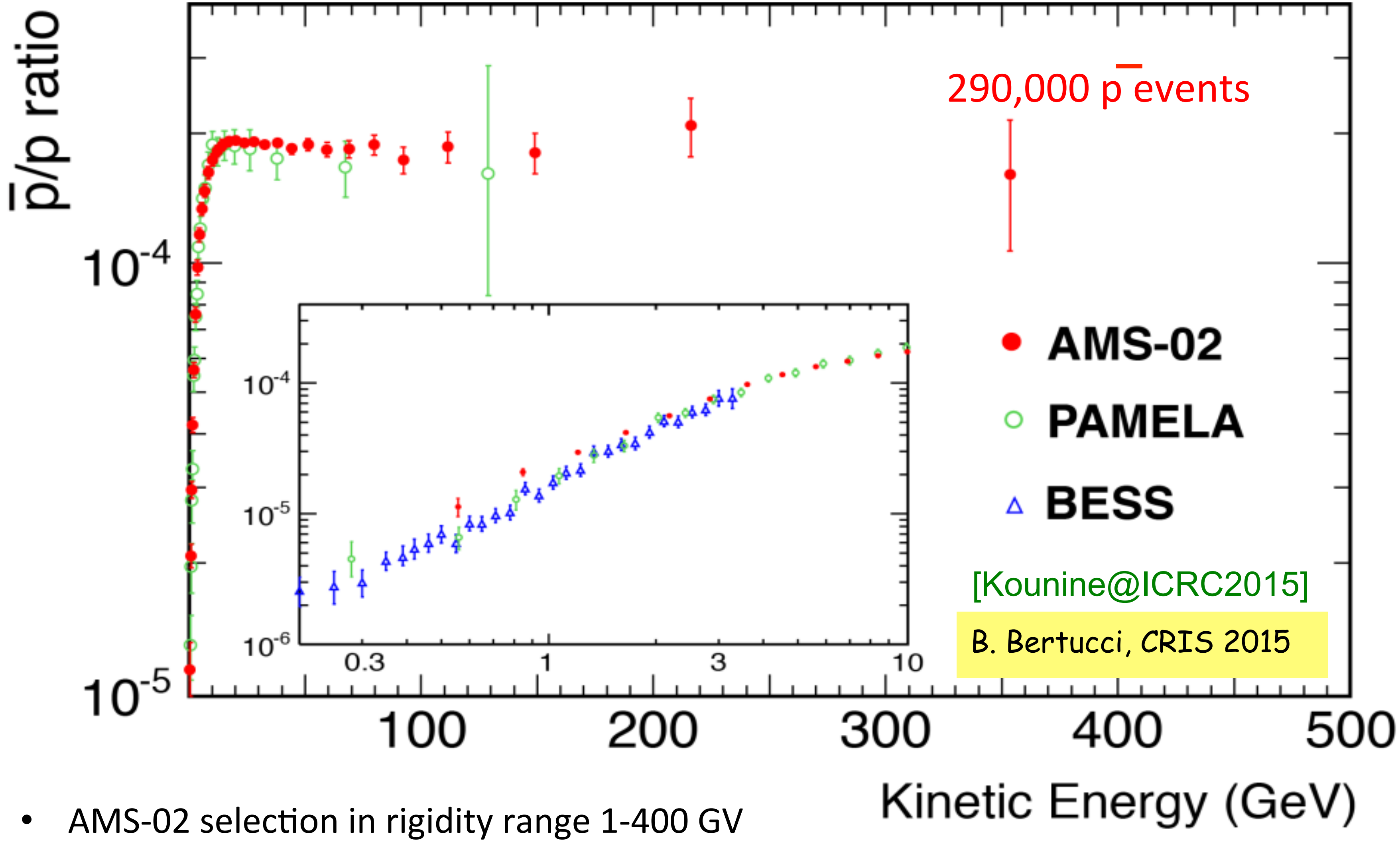
-Pamela first measurement to 180 GeV
 extended to ~350 GeV

Secondary production calculations



anti-proton/proton ratio

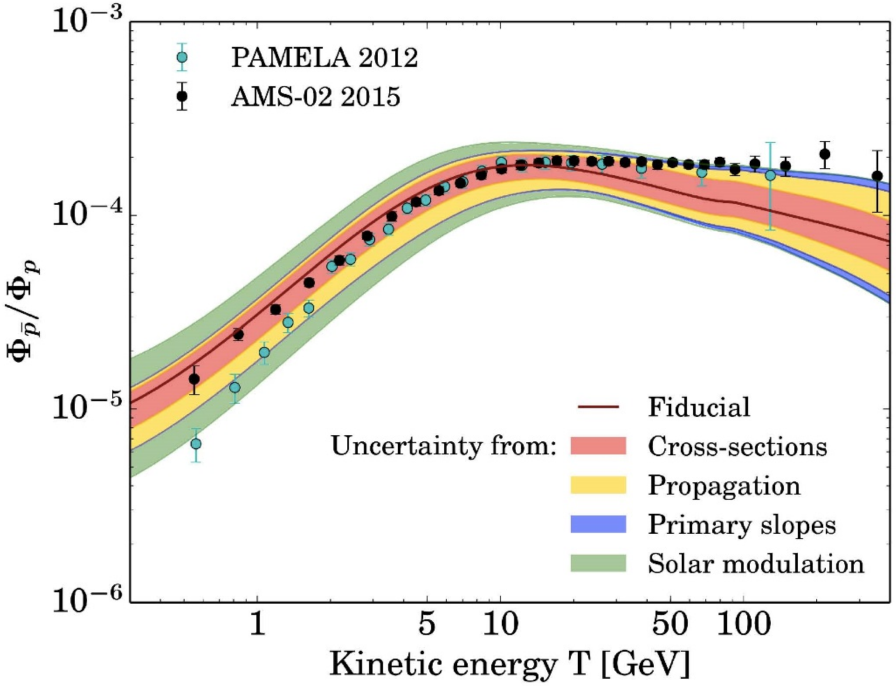
AMS-02 vs PAMELA & BESS



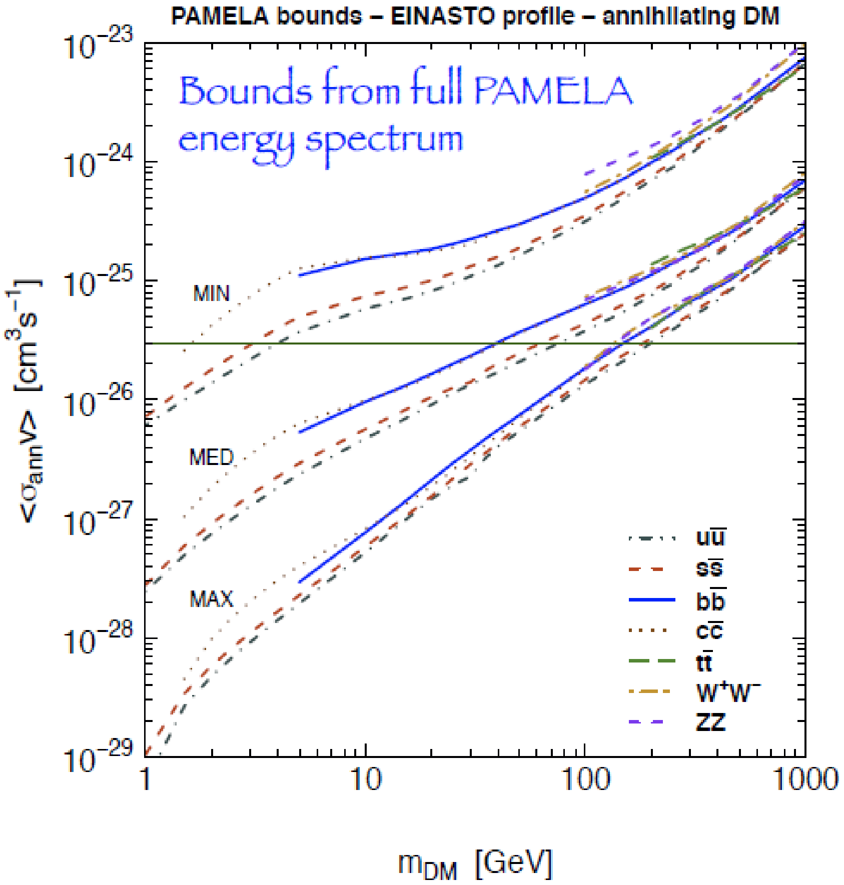
- AMS-02 selection in rigidity range 1-400 GV
- PAMELA data from 60 MeV to 350 GeV

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.

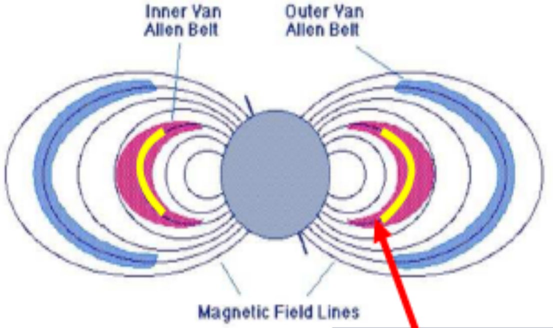
for a review see for instance:

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



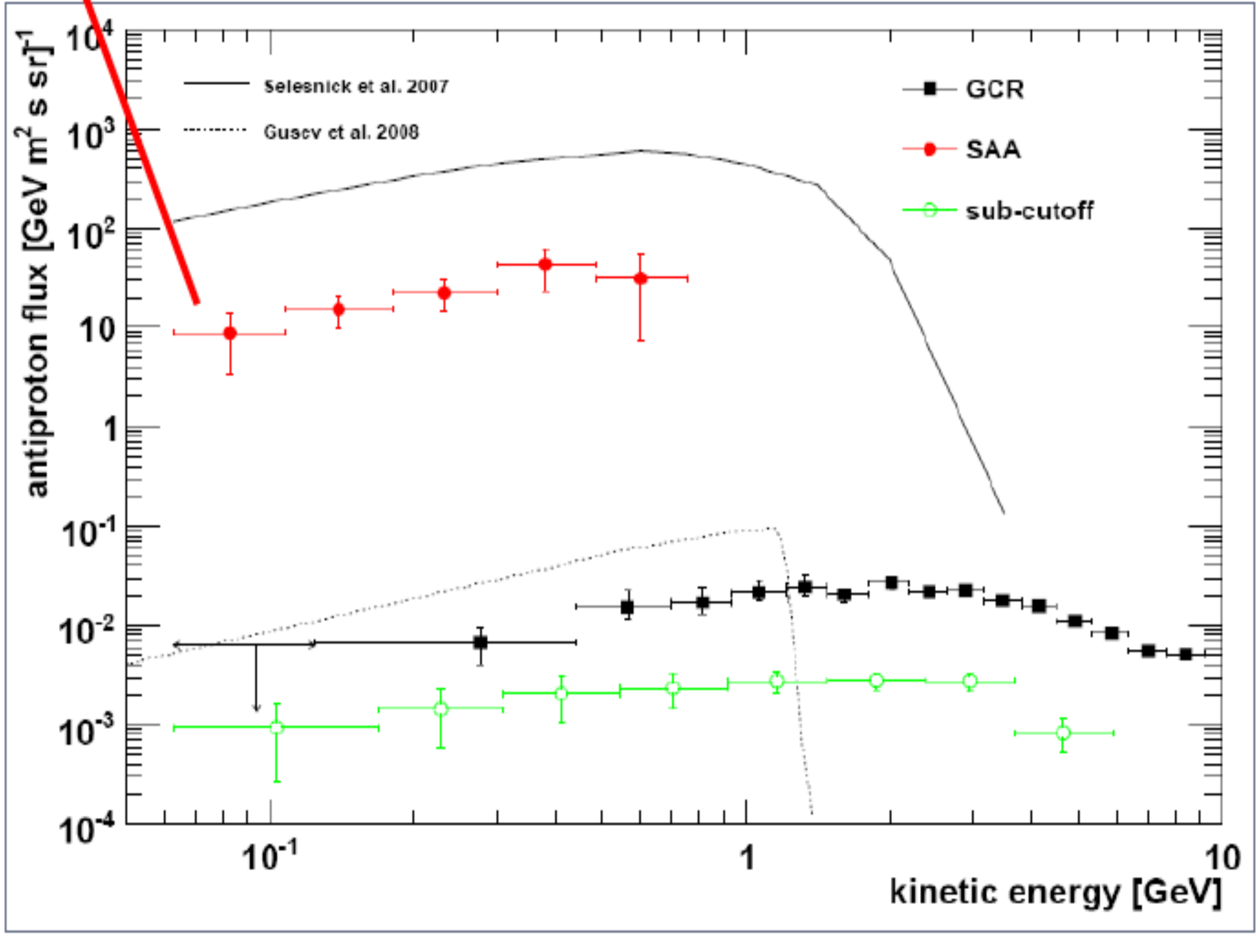
PAMELA: Geomagnetically trapped anti-protons

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**

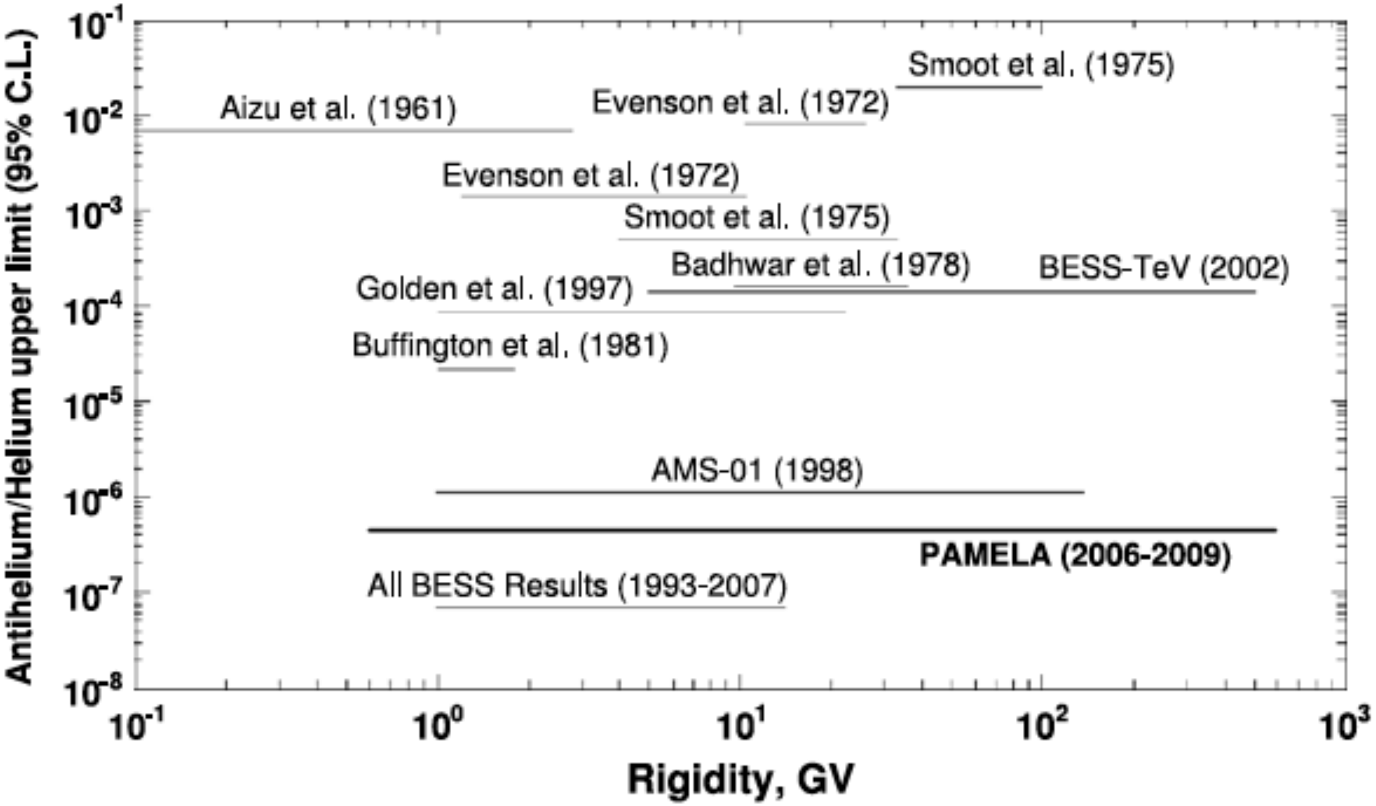
p-bar flux exceeds GRC flux by **3 orders of magnitude,** as expected by models



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

Anti-matter limits

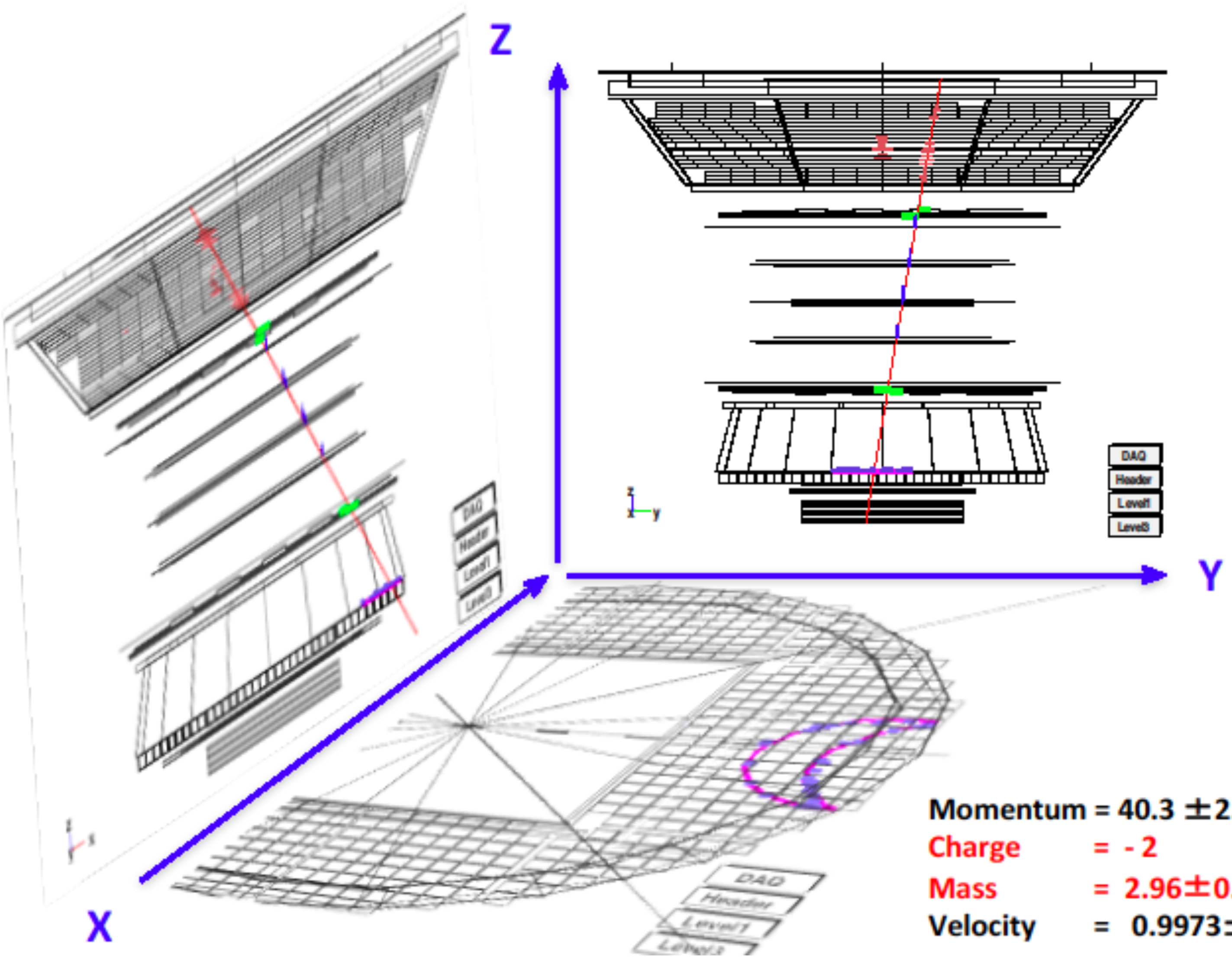
[Physics Reports 544 (2014) 323–370]



AMS-02

[S.C.C.Ting @CERN, Dec 2016]

An anti-Helium candidate:



Momentum = 40.3 ±2.9 GeV/c

Charge = - 2

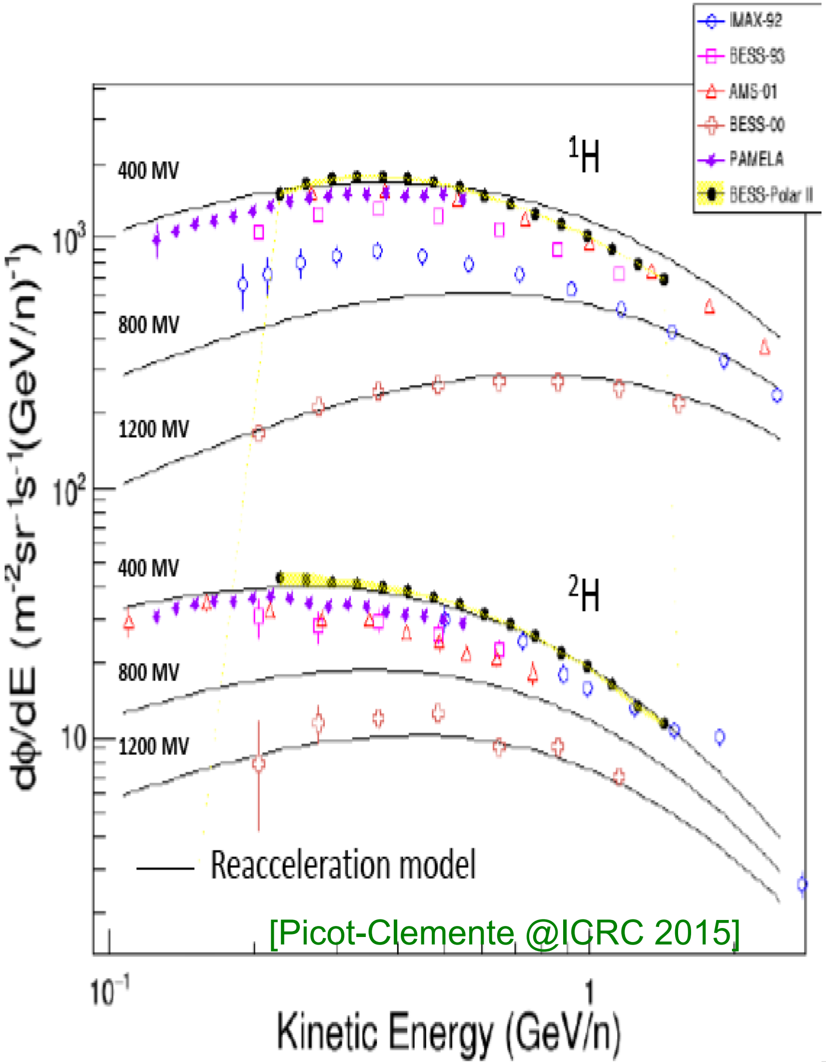
Mass = 2.96±0.33 GeV/c^2

Velocity = 0.9973±0.0005 c

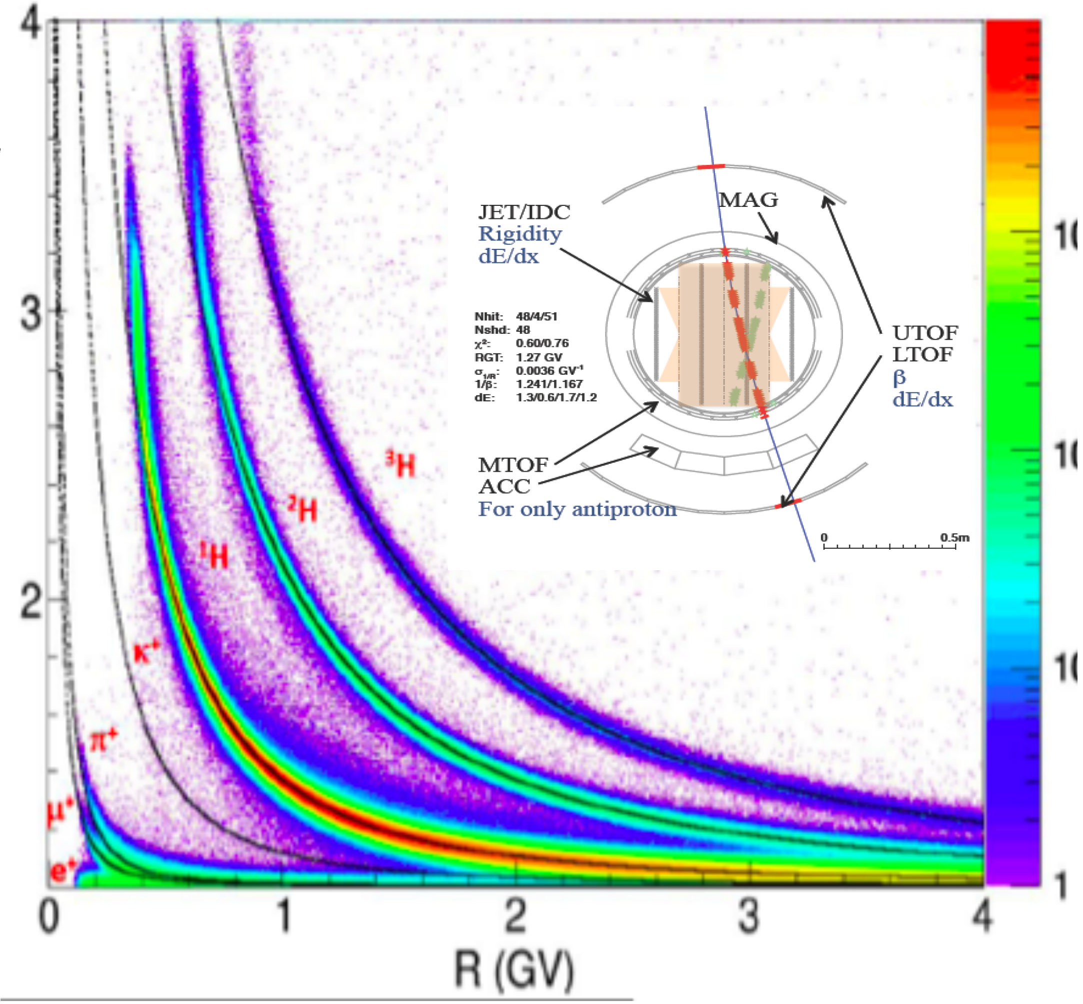
Cosmic-Ray Isotopes

- 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)

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

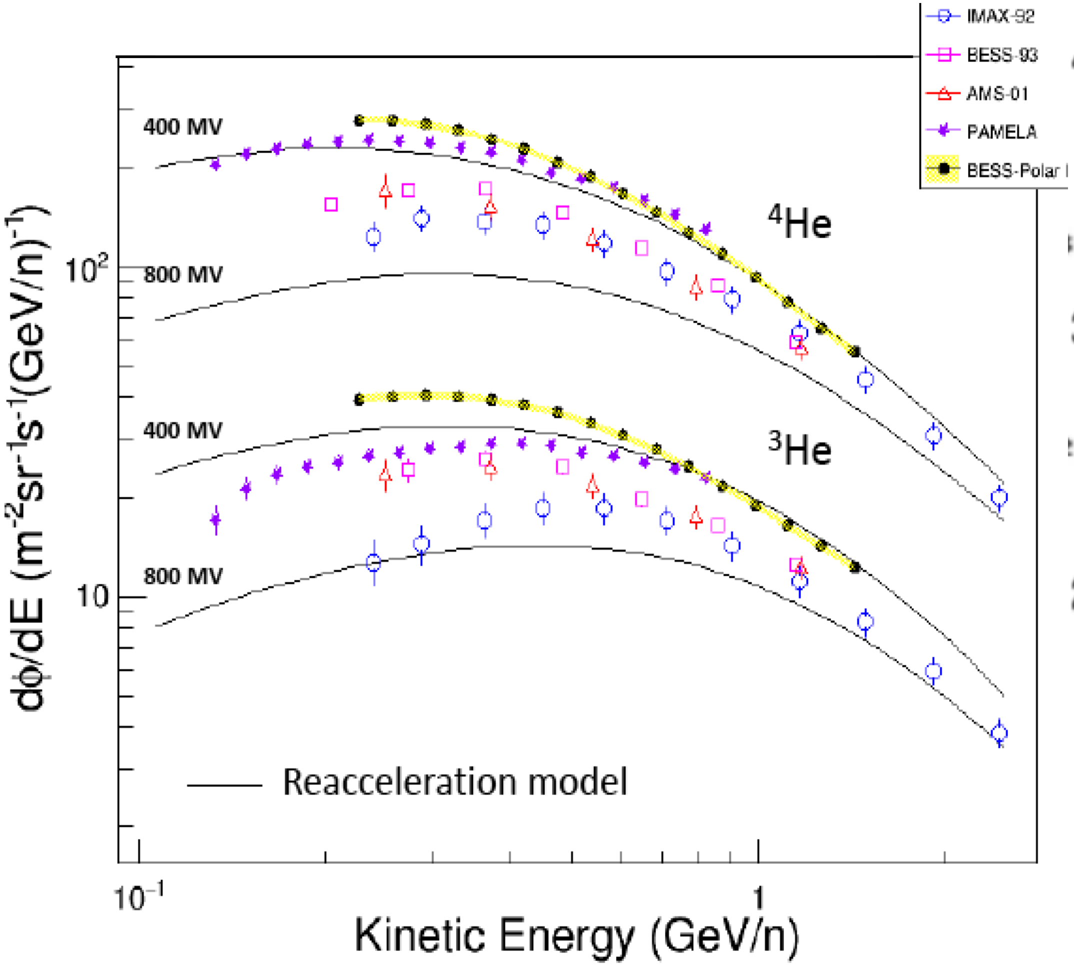


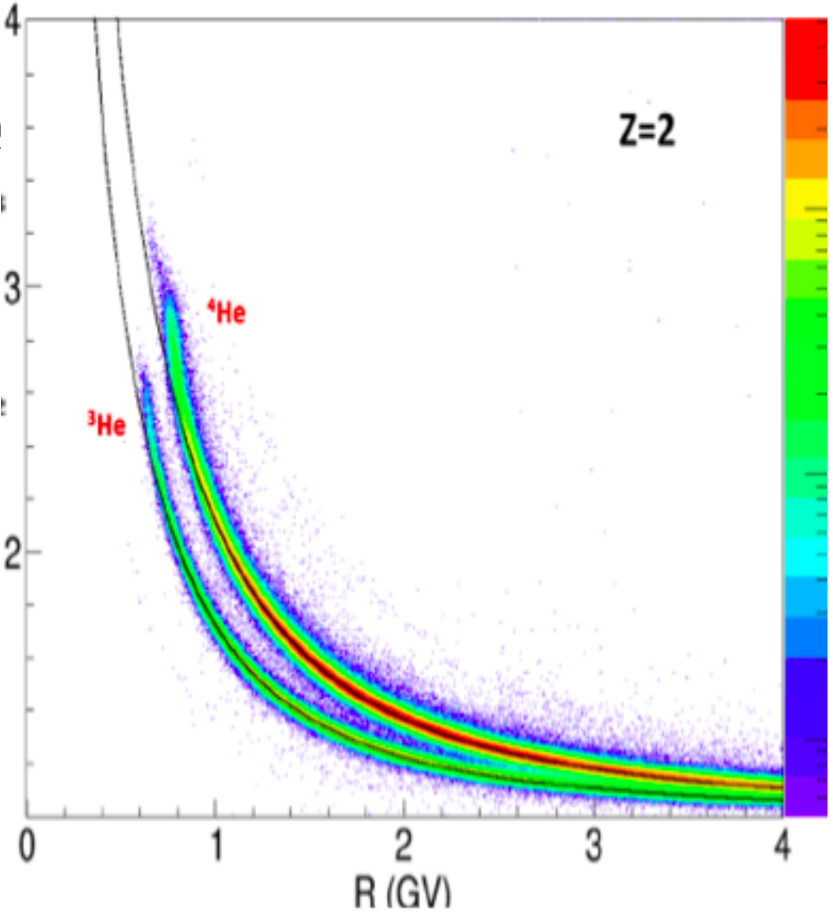
[Picot-Clemente @ICRC 2015]



- 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.

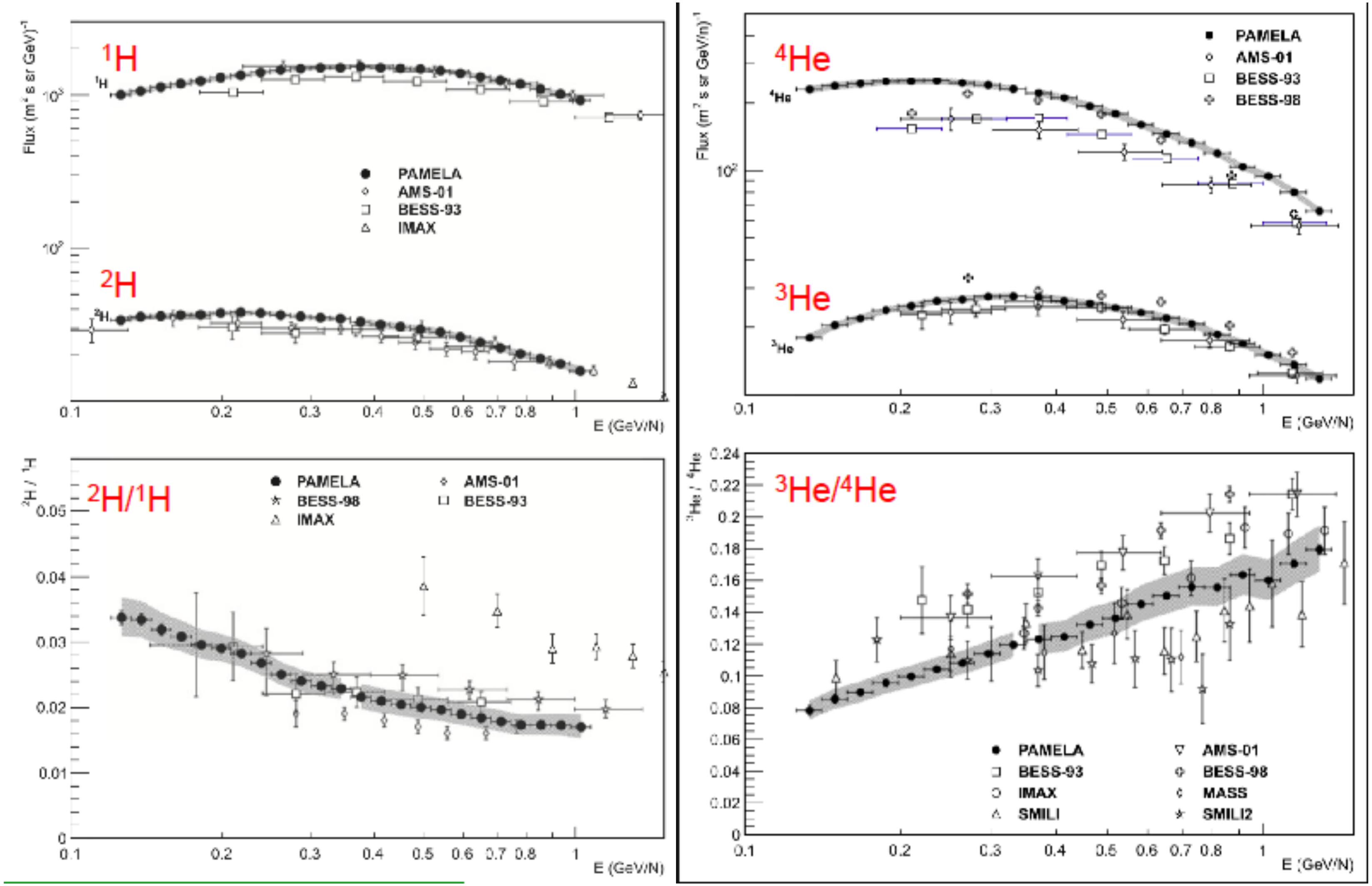
^{3}He, ^{4}He Isotope separation with BESS-Polar II





- 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

H and He isotopes from PAMELA

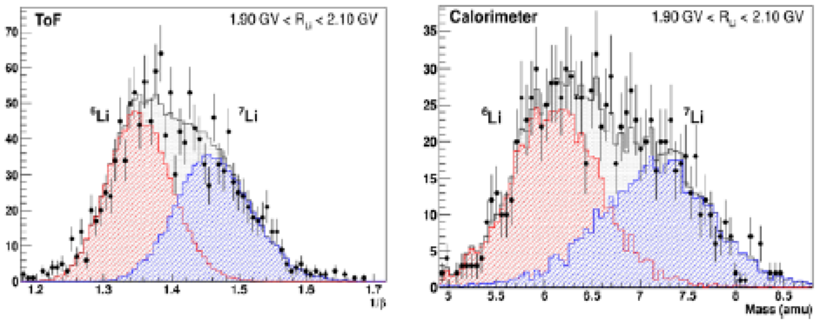


[Adriani et al., ApJ 818:68 (2016)]

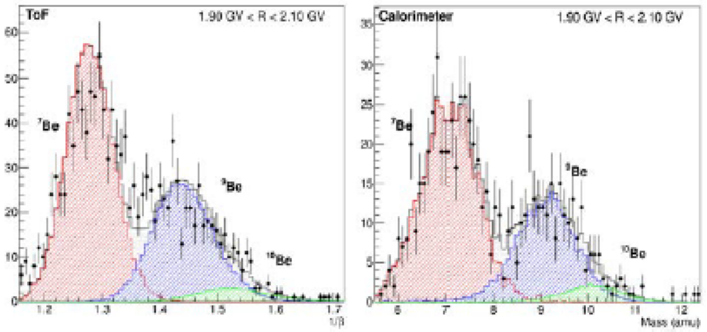
Lithium and Beryllium Isotopes

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

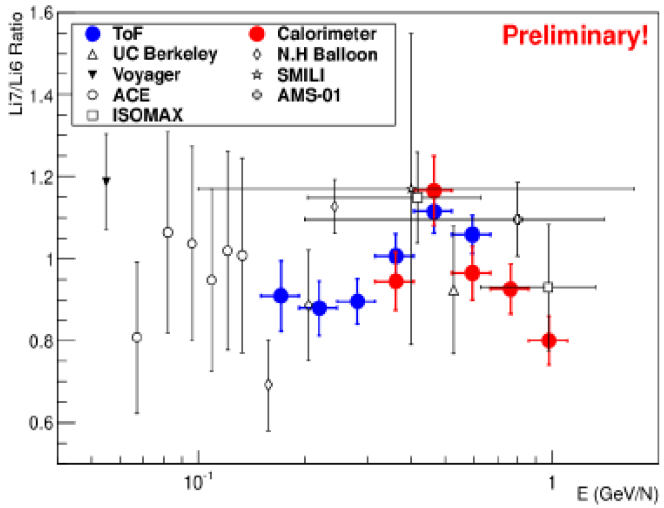
Lithium



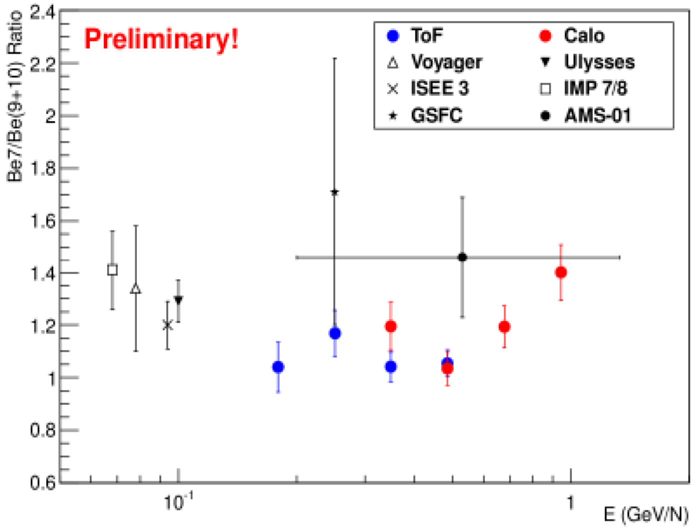
Beryllium



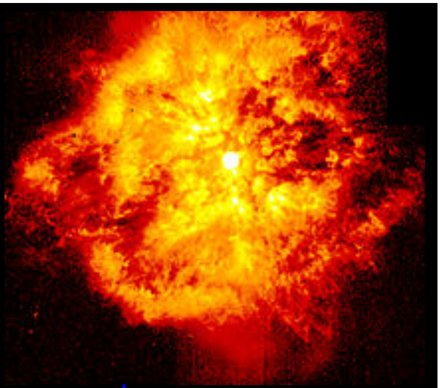
Ratio ^{7}Li / ^{6}Li



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



[Menn @ICRC 2015]



Nebula around
Wolf–Rayet star WR124

Ultra Heavy CR

Trans-Iron elements and “propagation clocks” (ACE/CRIS, Super-TIGER)

Measurement of the Relative Abundances of the Ultra-Heavy Galactic Cosmic-Rays ($30 \leq Z \leq 40$) with TIGER

Trans-
Iron
Galactic
Element
Recorder

Washington University in St. Louis
B.F. Rauch, W.R. Binns, J.R. Cummings, M.H. Israel, J.T. Link, L.M. Scott

California Institute of Technology
S. Geier, R.A. Mewaldt, S.M Schindler, E.C. Stone

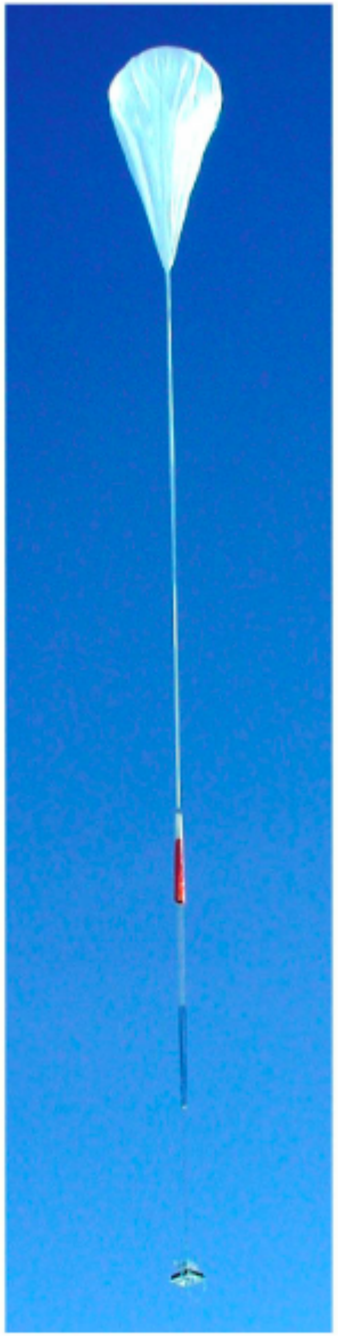
Goddard Space Flight Center
L.M. Barbier, E.R. Christian, J.W. Mitchell, G.A. de Nolfo, R.E. Streitmatter

University of Minnesota
C.J. Waddington

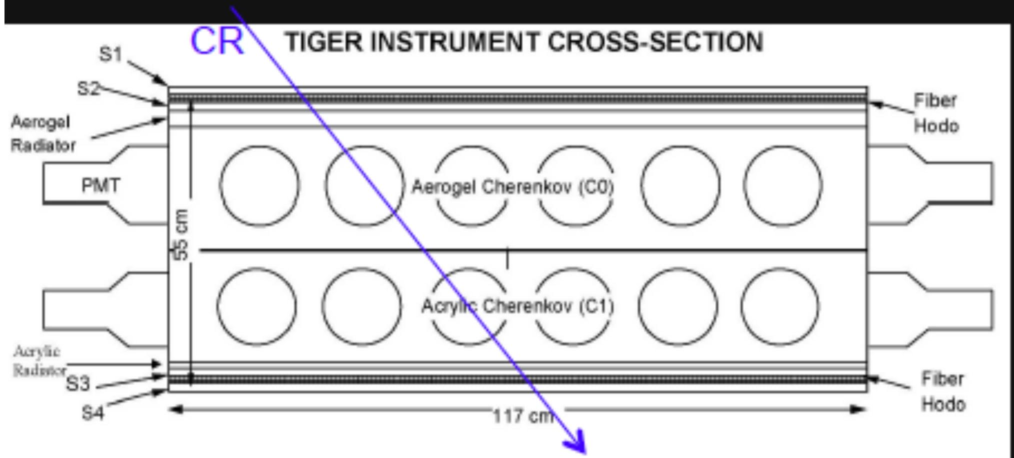
2 antarctic flights

Dec. 2001 - Jan. 2002 32 days

Dec. 2003 - Jan. 2004 18 days



TIGER Instrument



TIGER is composed of plastic scintillators, Cherenkov detectors with two different indices of refraction, and a scintillation fiber hodoscope.

- Measure elemental abundances of nuclei with $10 \leq Z \leq 40$
- TIGER is a 1 m^2 electronic instrument measuring the elemental composition of the rare GCR's heavier than iron.

Scintillator ~ dE/dx ~ (Z^2/β^2)x(logarithmic increase w. energy)

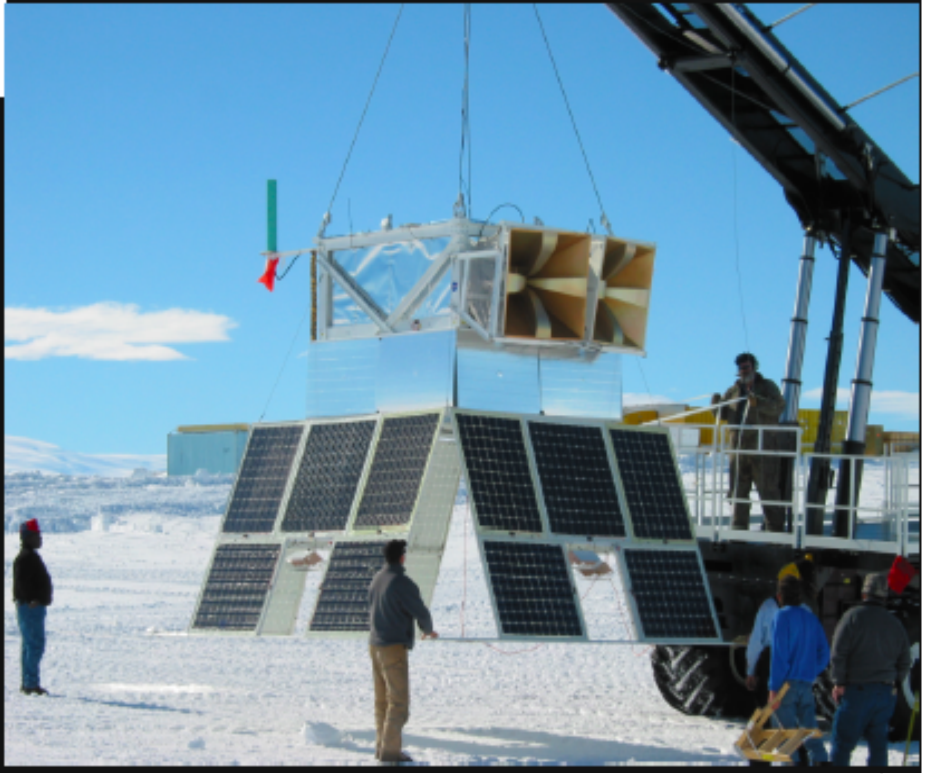
Cherenkov ~ $Z^2(1-1/n^2\beta^2)$

Acrylic n = 1.5 → threshold 325 MeV/nuc

Aerogel n = 1.04 → threshold 2.5 GeV/nuc

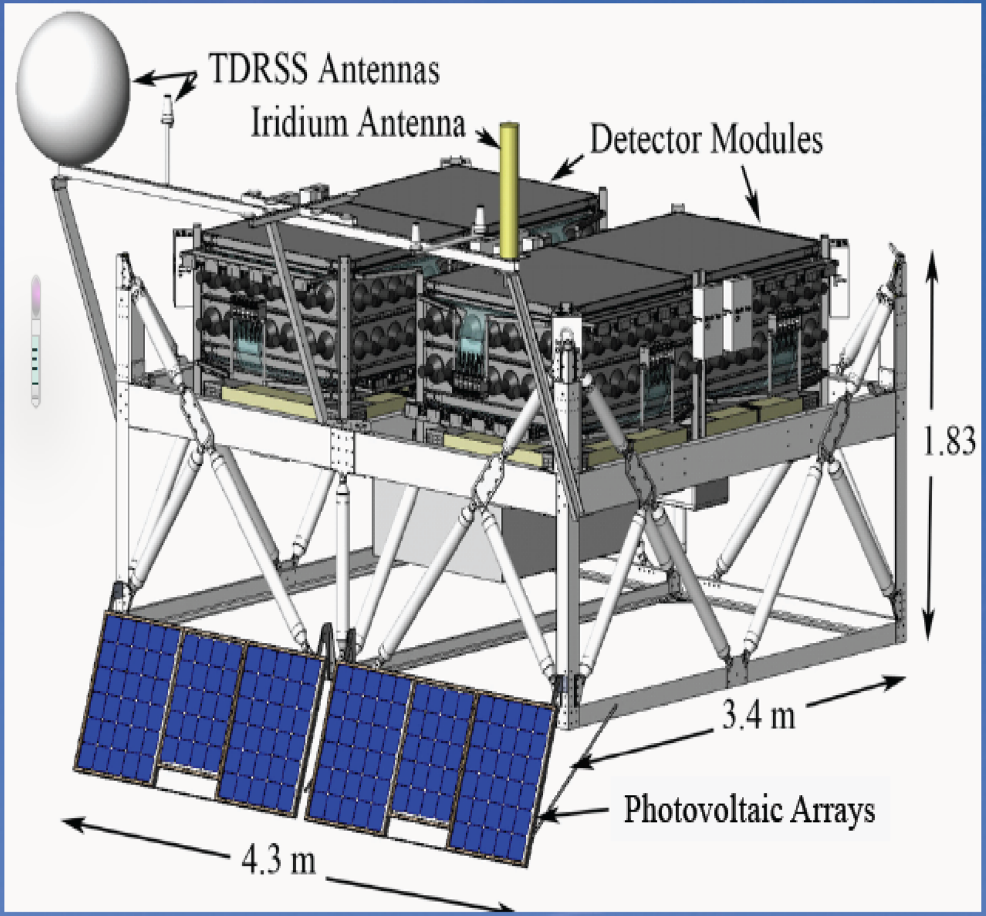
Between 325 MeV/nuc and 2.5 GeV/nuc determine charge and energy from Scintillator and Acrylic Cherenkov.

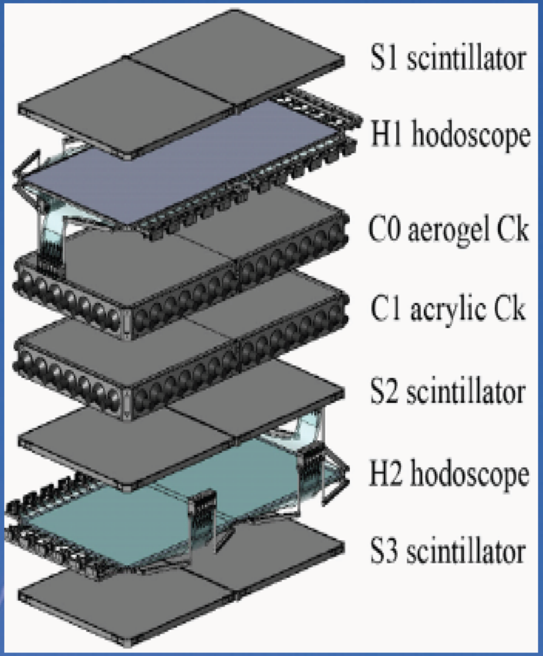
Above 2.5 GeV/nuc determine charge from the two Cherenkov (and from Scintillaor and Aerogel Cherenkov.



Super-TIGER (Trans-Iron Galactic Element Recorder)

Antarctic flight in 2012-13: 55 days





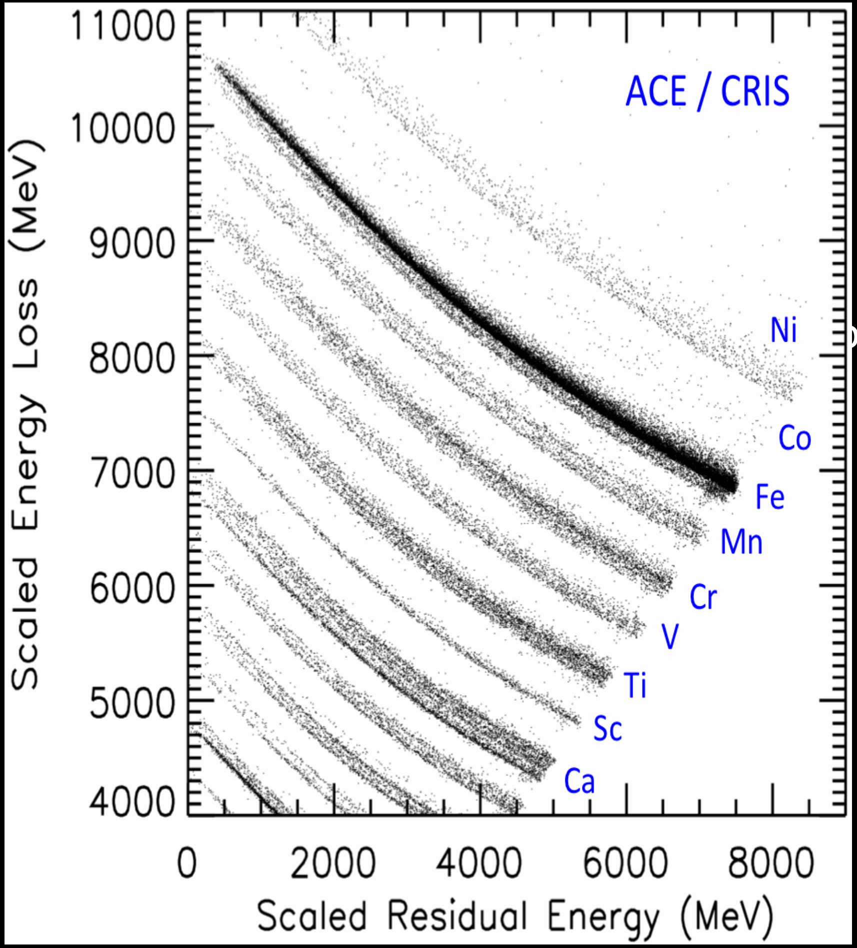
- Two identical modules
- Each module consists of
  - Scintillating fiber hodoscopes (H1, H2)
  - Three scintillator detectors (S1, S2, S3)
  - Aerogel Cherenkov detector (C0)
  - Acrylic Cherenkov detector (C1)

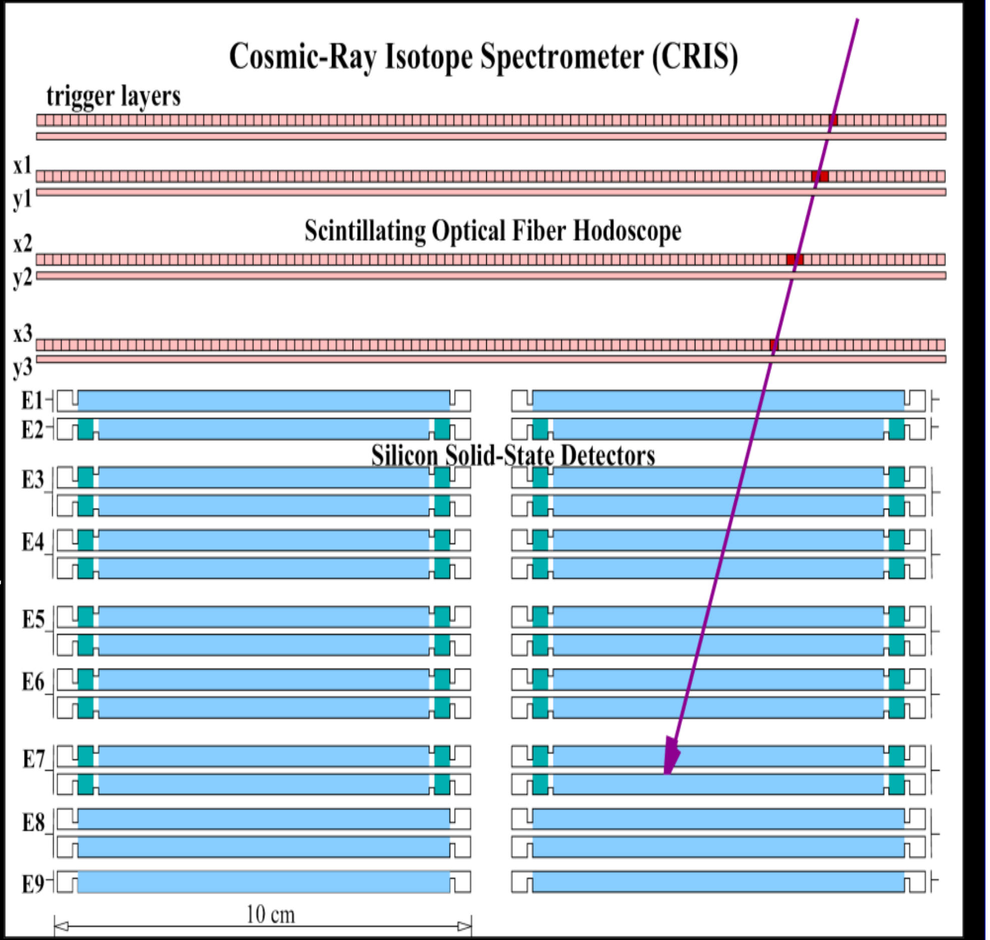
Acceptance ~8.3 m^2sr

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!

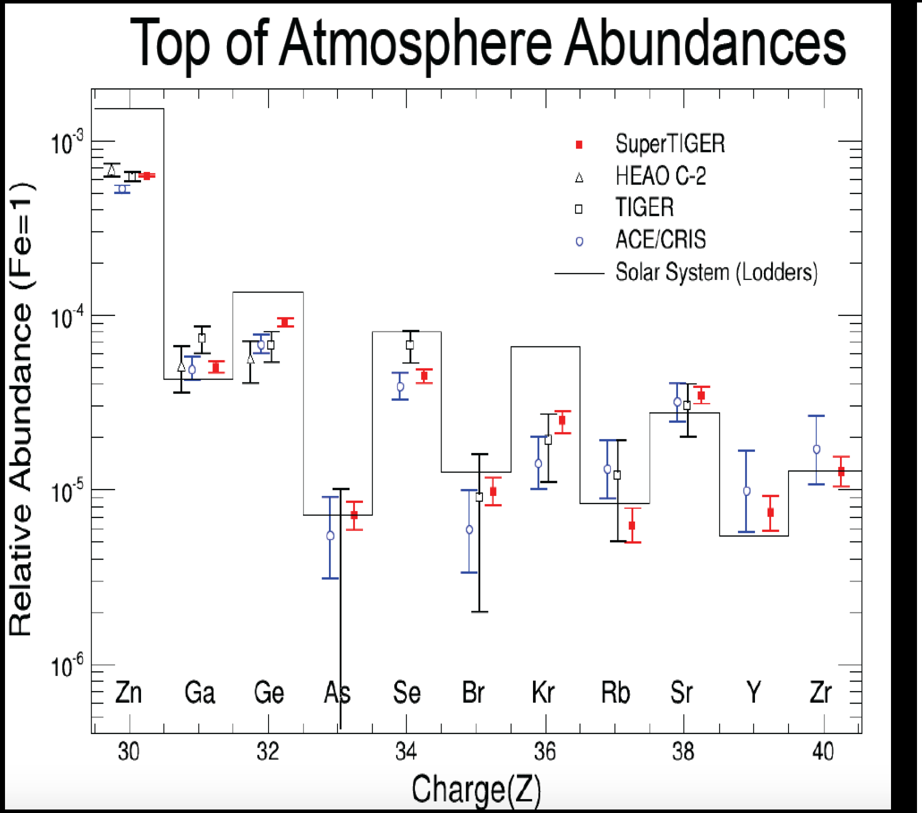


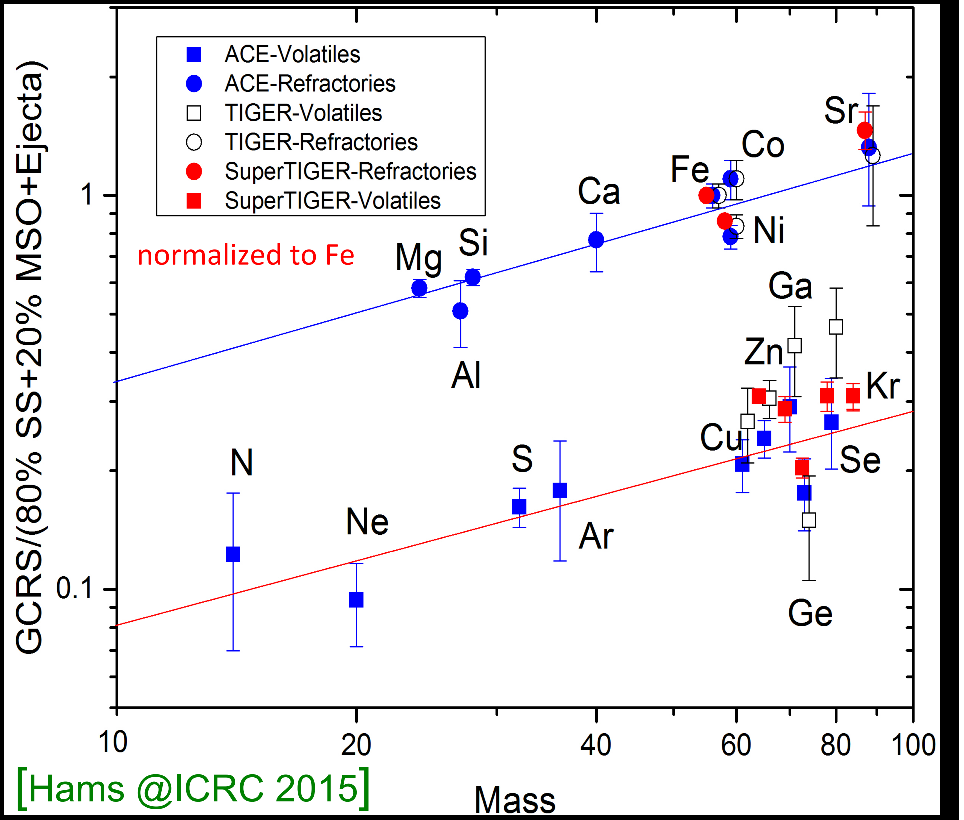


CRIS determines the charge and mass of cosmic rays stopping in a stack of silicon detectors using the dE/dx vs E technique

ACE energy range: 150-600 MeV/n

Ultra Heavy Nuclei





[Hams @ICRC 2015]

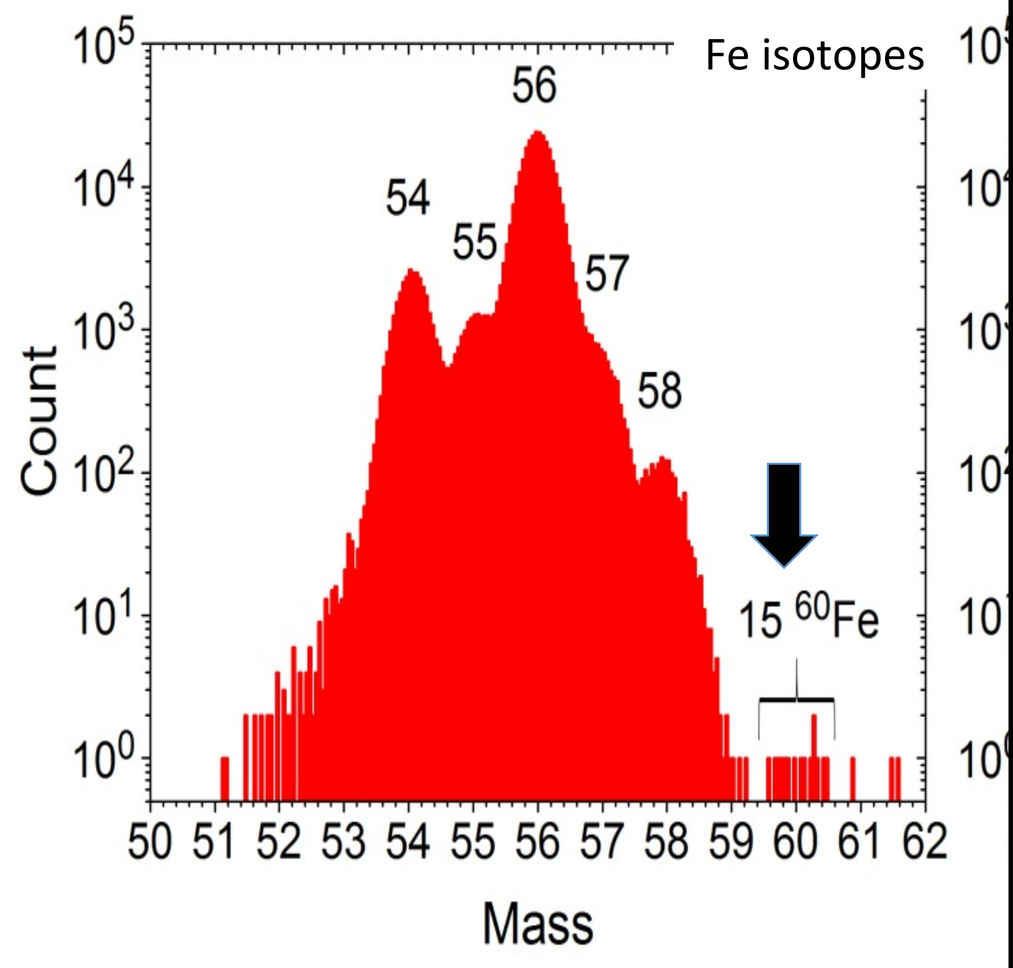
- Refractory elements (those likely found in interstellar grains) more effectively accelerated (enhanced by a factor ~4) compared with volatile elements.

- 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 observed are almost all primaries

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

[M.H.Israel @ICRC 2015]

Also:

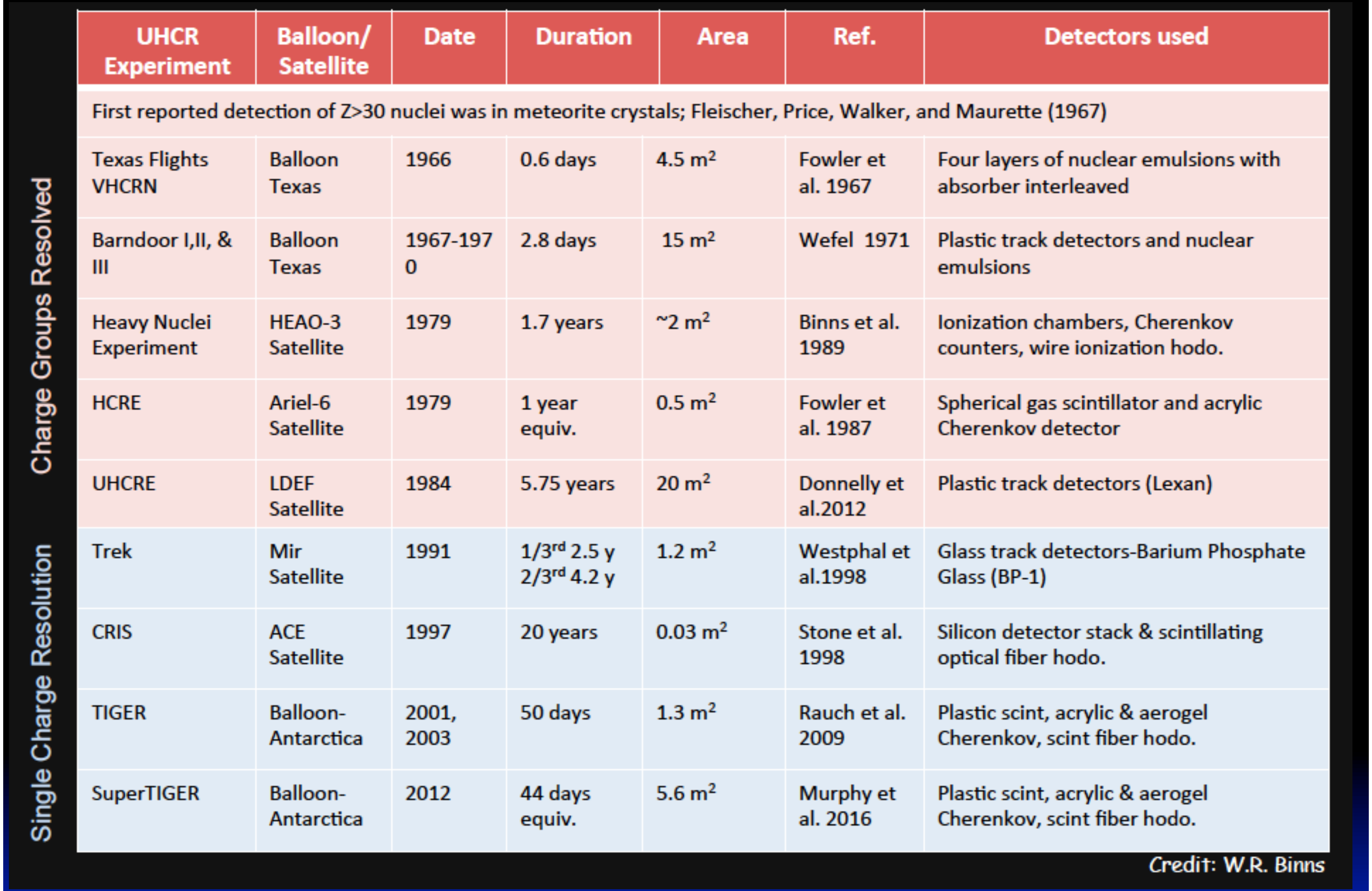
^{59}Ni + e- → ^{59}Co + ν with $t_{1/2} = 7.6 \times 10^4$ yr

No ^{59}Ni are observed.

This implies that CR acceleration must have occurred not earlier than ~10^5 years after nucleosynthesis.

- 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.

Ultra Heavy Cosmic Rays (UHCR) detection



	UHCR Experiment	Balloon/ Satellite	Date	Duration	Area	Ref.	Detectors used
	First reported detection of Z>30 nuclei was in meteorite crystals; Fleischer, Price, Walker, and Maurette (1967)						
Charge Groups Resolved	Texas Flights VHCRN	Balloon Texas	1966	0.6 days	4.5 m^2	Fowler et al. 1967	Four layers of nuclear emulsions with absorber interleaved
	Barndoor I,II, & III	Balloon Texas	1967-1970	2.8 days	15 m^2	Wefel 1971	Plastic track detectors and nuclear emulsions
	Heavy Nuclei Experiment	HEAO-3 Satellite	1979	1.7 years	~2 m^2	Binns et al. 1989	Ionization chambers, Cherenkov counters, wire ionization hodo.
	HCRE	Ariel-6 Satellite	1979	1 year equiv.	0.5 m^2	Fowler et al. 1987	Spherical gas scintillator and acrylic Cherenkov detector
	UHCRE	LDEF Satellite	1984	5.75 years	20 m^2	Donnelly et al.2012	Plastic track detectors (Lexan)
Single Charge Resolution	Trek	Mir Satellite	1991	1/3rd 2.5 y 2/3rd 4.2 y	1.2 m^2	Westphal et al.1998	Glass track detectors-Barium Phosphate Glass (BP-1)
	CRIS	ACE Satellite	1997	20 years	0.03 m^2	Stone et al. 1998	Silicon detector stack & scintillating optical fiber hodo.
	TIGER	Balloon-Antarctica	2001, 2003	50 days	1.3 m^2	Rauch et al. 2009	Plastic scint, acrylic & aerogel Cherenkov, scint fiber hodo.
	SuperTIGER	Balloon-Antarctica	2012	44 days equiv.	5.6 m^2	Murphy et al. 2016	Plastic scint, acrylic & aerogel Cherenkov, scint fiber hodo.

Credit: W.R. Binns

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:

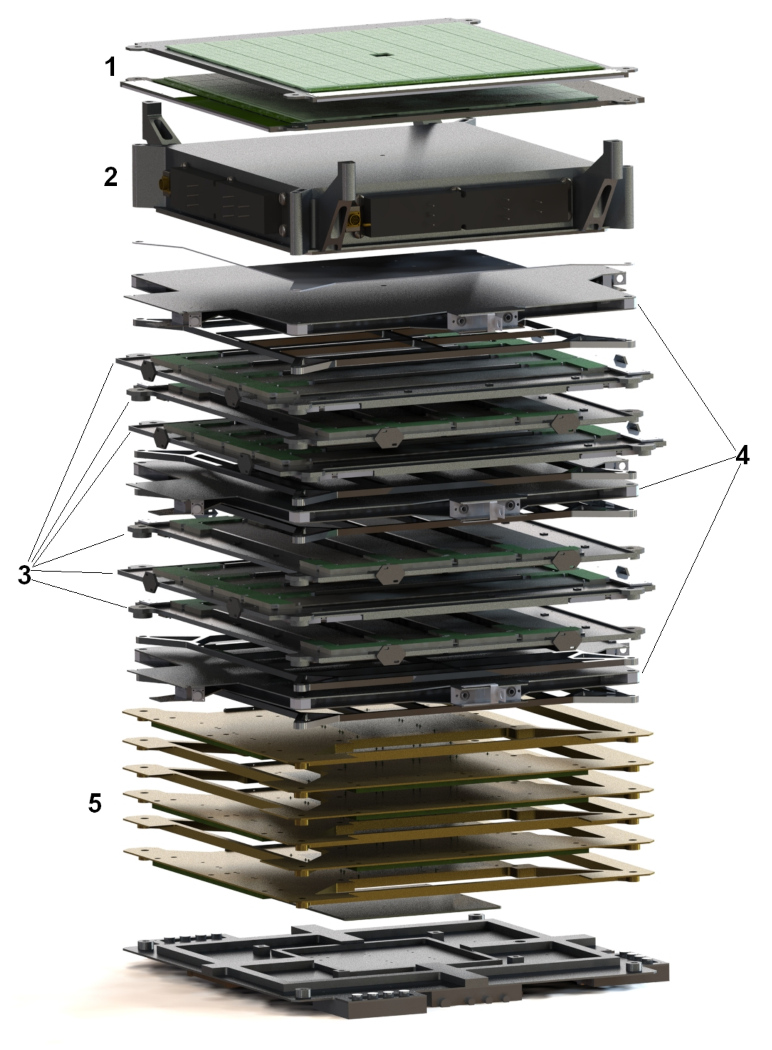
  HERD, GAMMA-400, GAPS, CSES, HELIX, HNX, ...

Experiment	e^+ | e^- (present data)	e^++e^- (Energy range)	CR nuclei (Energy range)	charge Z	Gamma-ray	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

NUCLEON

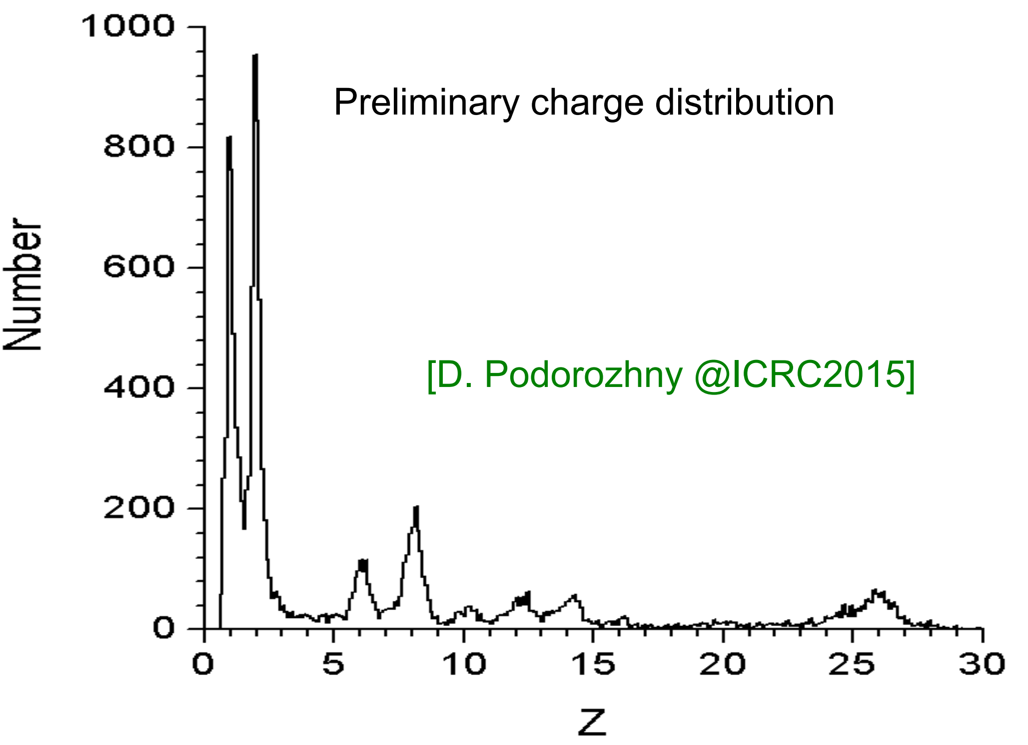
- Launched on Dec. 26th 2014 on Resurs-P satellite
- uses the Kinematical Method (KLEM) to estimate the energy

> 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)

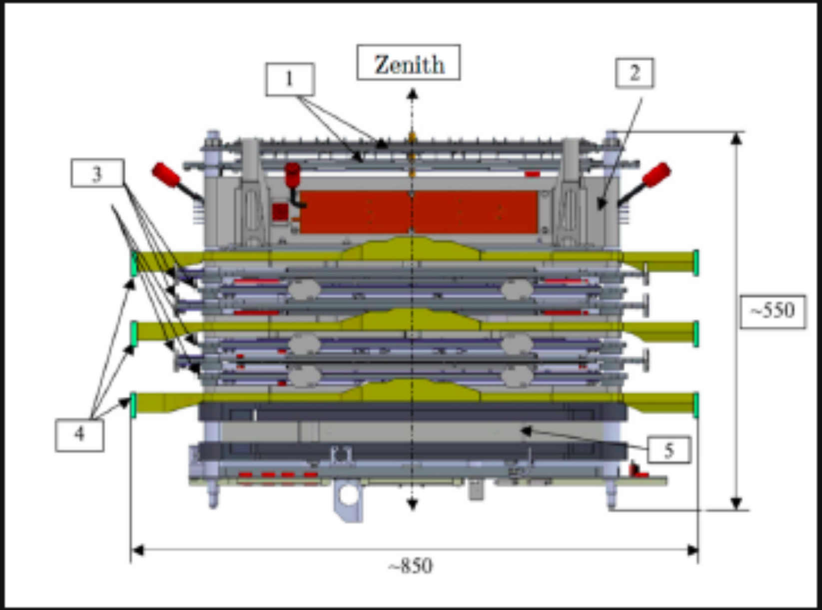
Total: 10604 channels depth ~16 X_0



[D. Podorozhny @ICRC2015]

NUCLEON

Launched on Dec. 26th 2014 on Resurs-P satellite

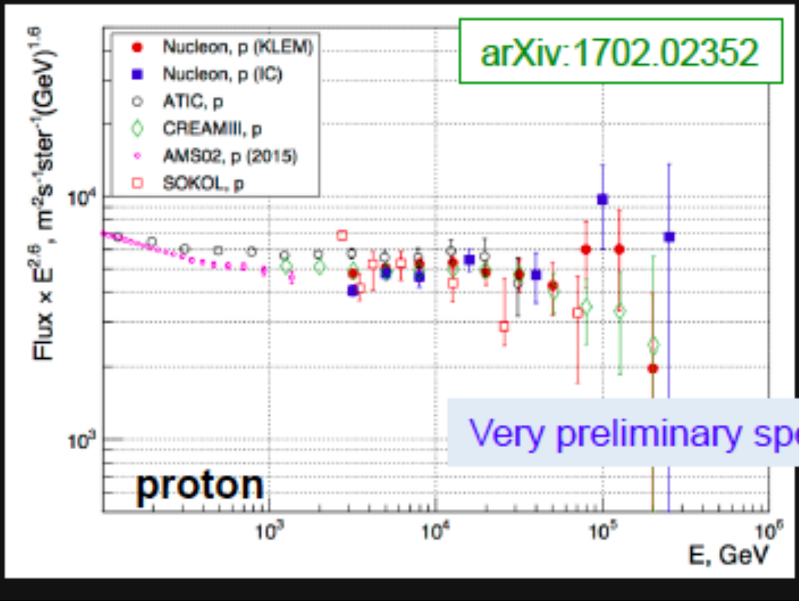


The instrument includes:

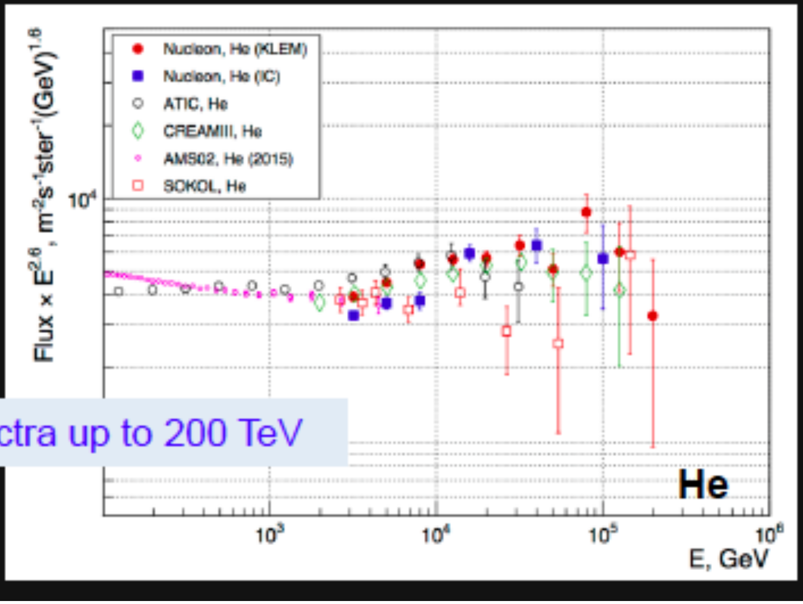
1) 4 Si pad detectors (to measure CR charge)
2) carbon target
3) Si microstrip/W tracker (0.5x0.5 m^2) ➔ **KLEM**
4) Scintillator trigger system
5) Si/W calorimeter (0.25x0.25 m^2)

Total: 10604 channels depth ~16 X_0

Kinematic Lightweight Energy Method (KLEM) based on measurements of spatial density of secondary particles in hadronic shower.

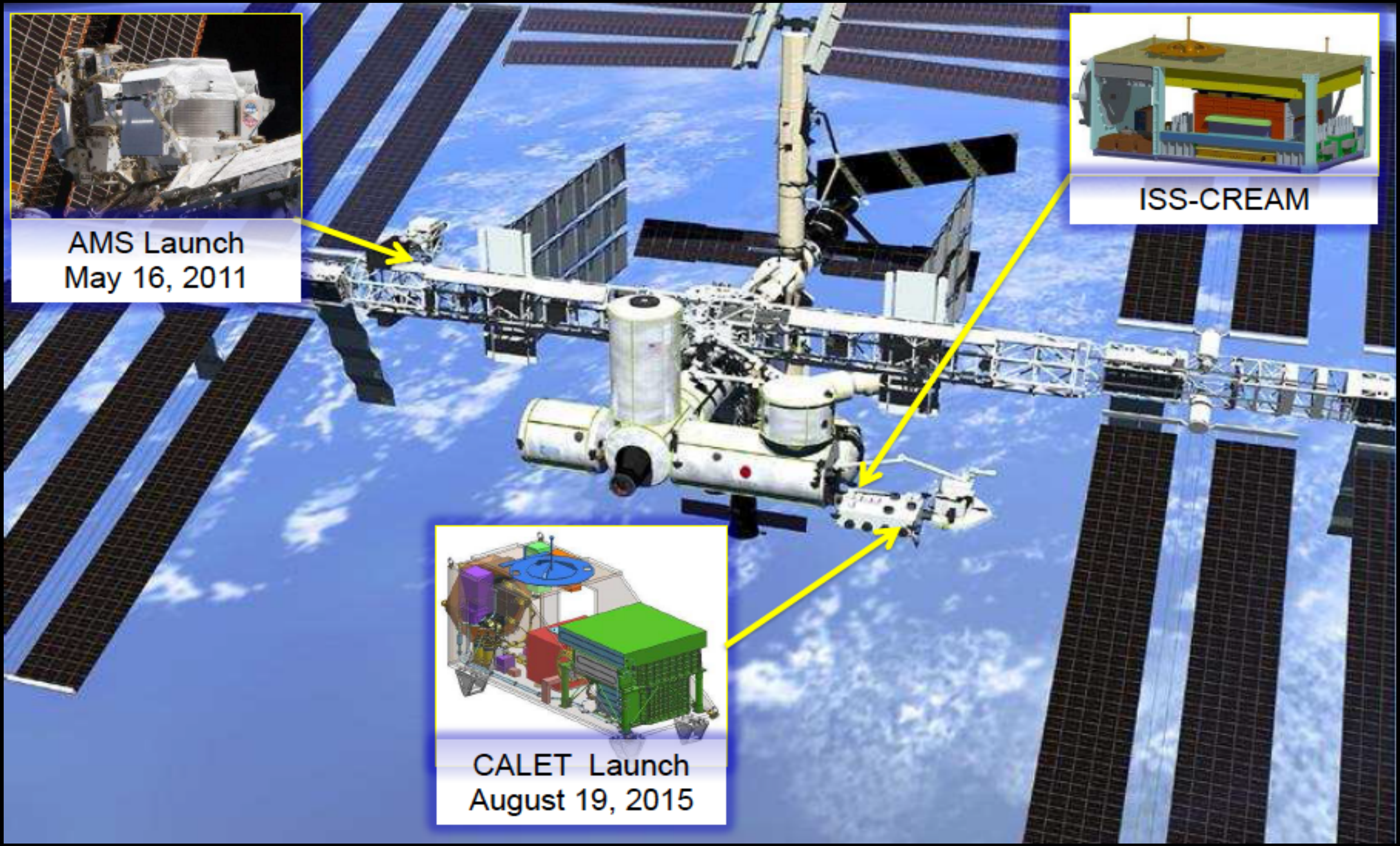


arXiv:1702.02352



Very preliminary spectra up to 200 TeV

ISS: a cosmic-ray observatory in Low Earth Orbit



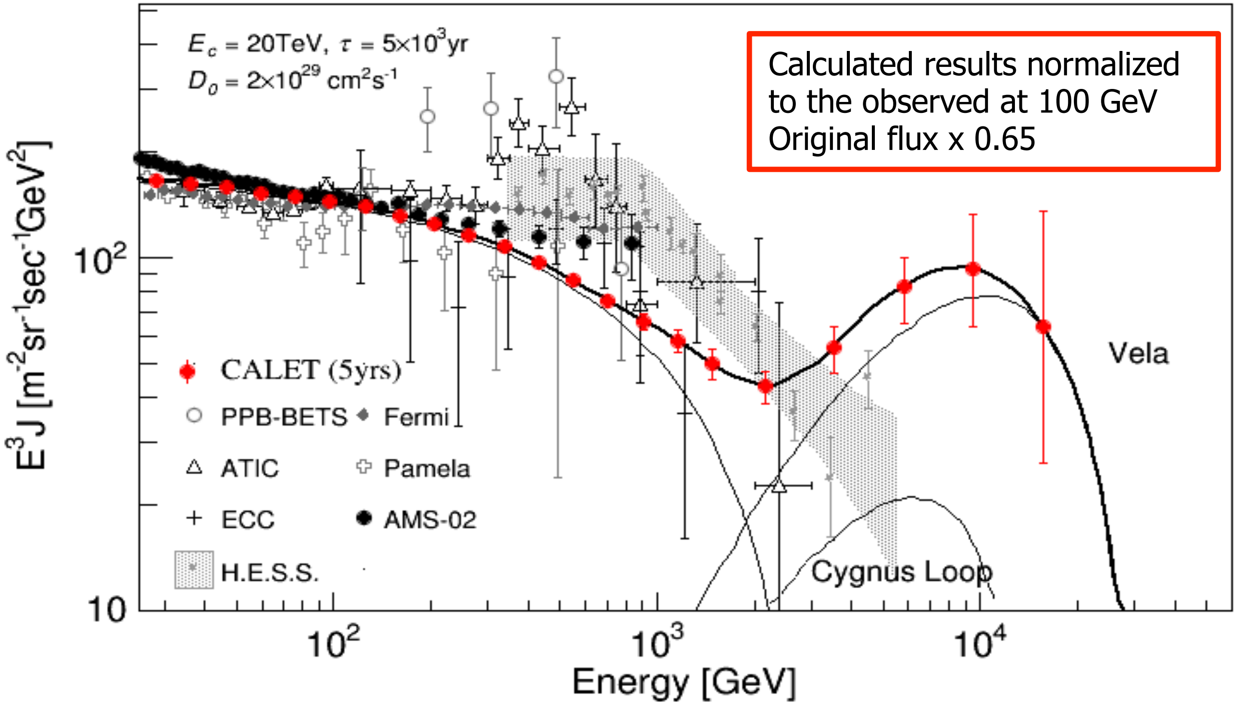
New experiments: CALET Identification of Electron Sources

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)

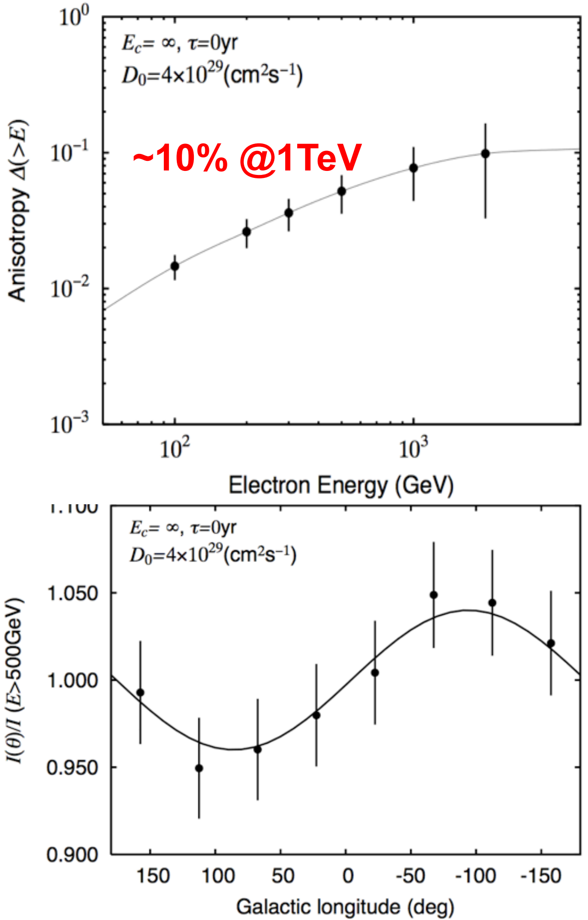
Expected flux
for 5 year mission

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

Expected Anisotropy
from Vela SNR



Calculated results normalized to the observed at 100 GeV Original flux x 0.65



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

CALET instrument overview

Geometric Factor :

1200 $cm^2 sr$ for electrons, light nuclei

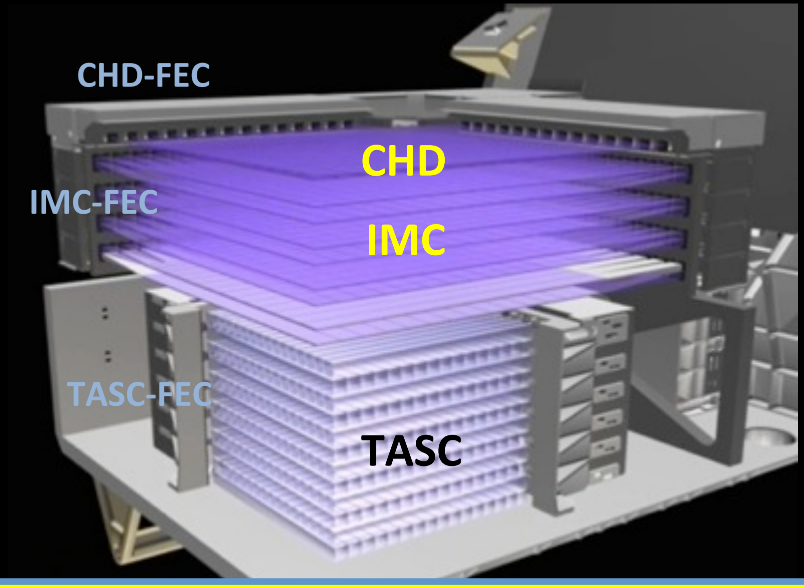
1000 $cm^2 sr$ for gamma-rays

4000 $cm^2 sr$ 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

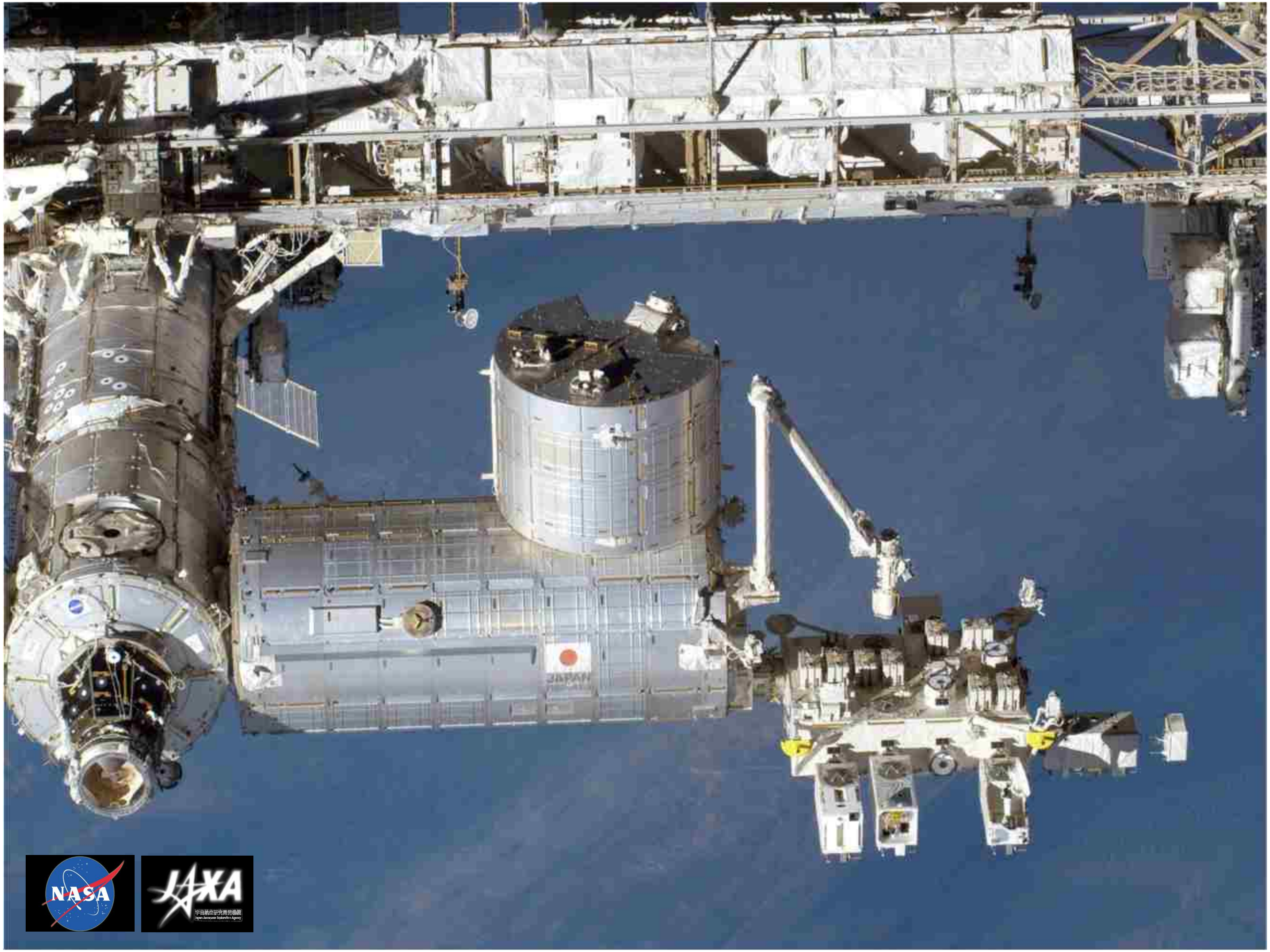


CALET: a unique set of key instruments.

- ☐ **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


JAPAN
NASA
JAXA

CALET on the ISS explores the Multi-TeV region

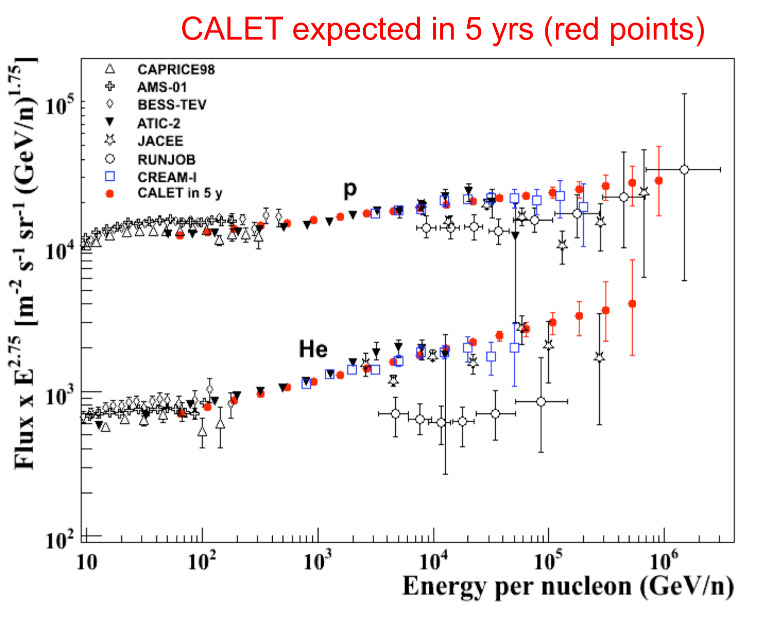
Elemental spectra

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

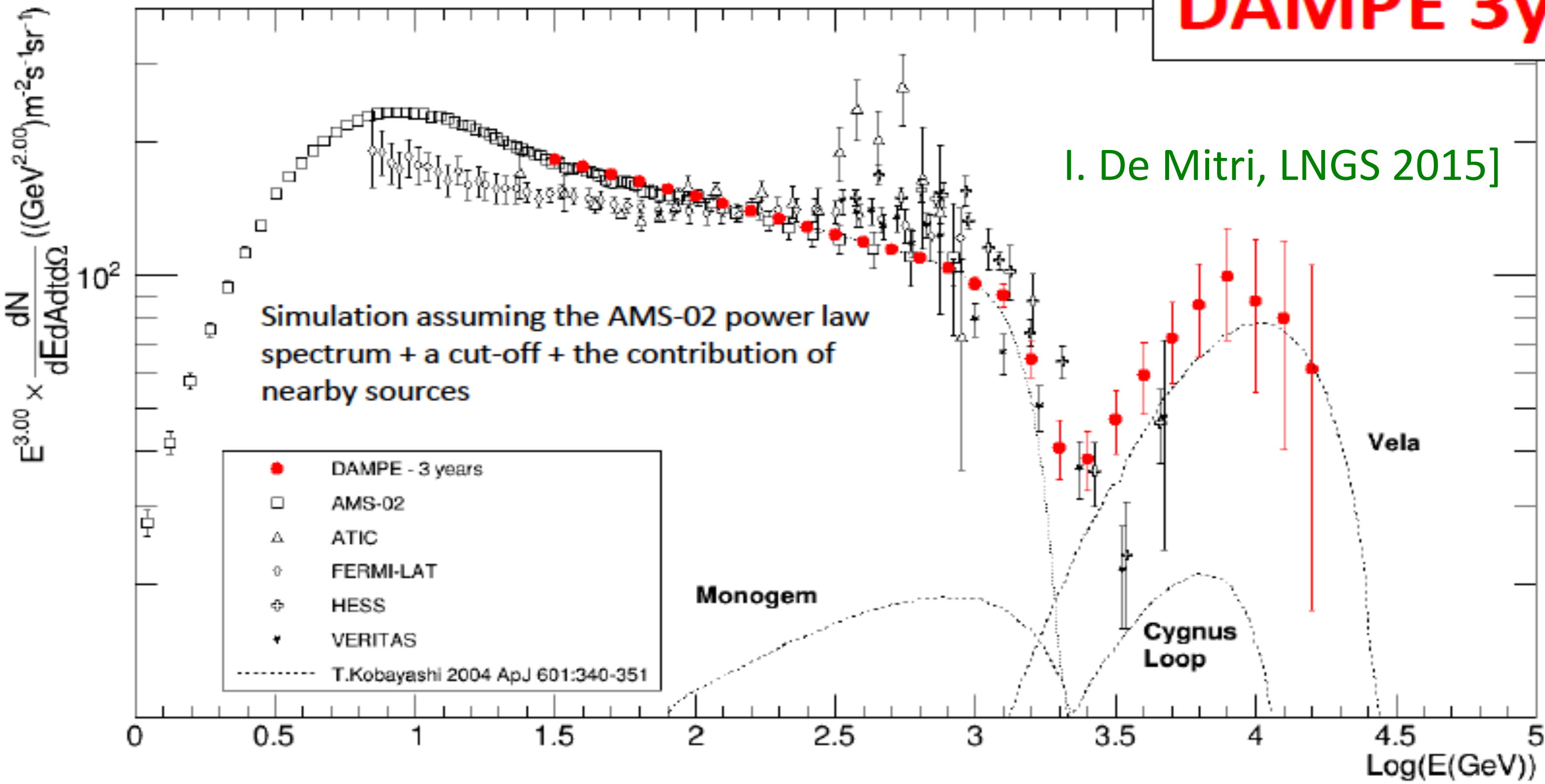

CALET expected in 5 yrs (red points)

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

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

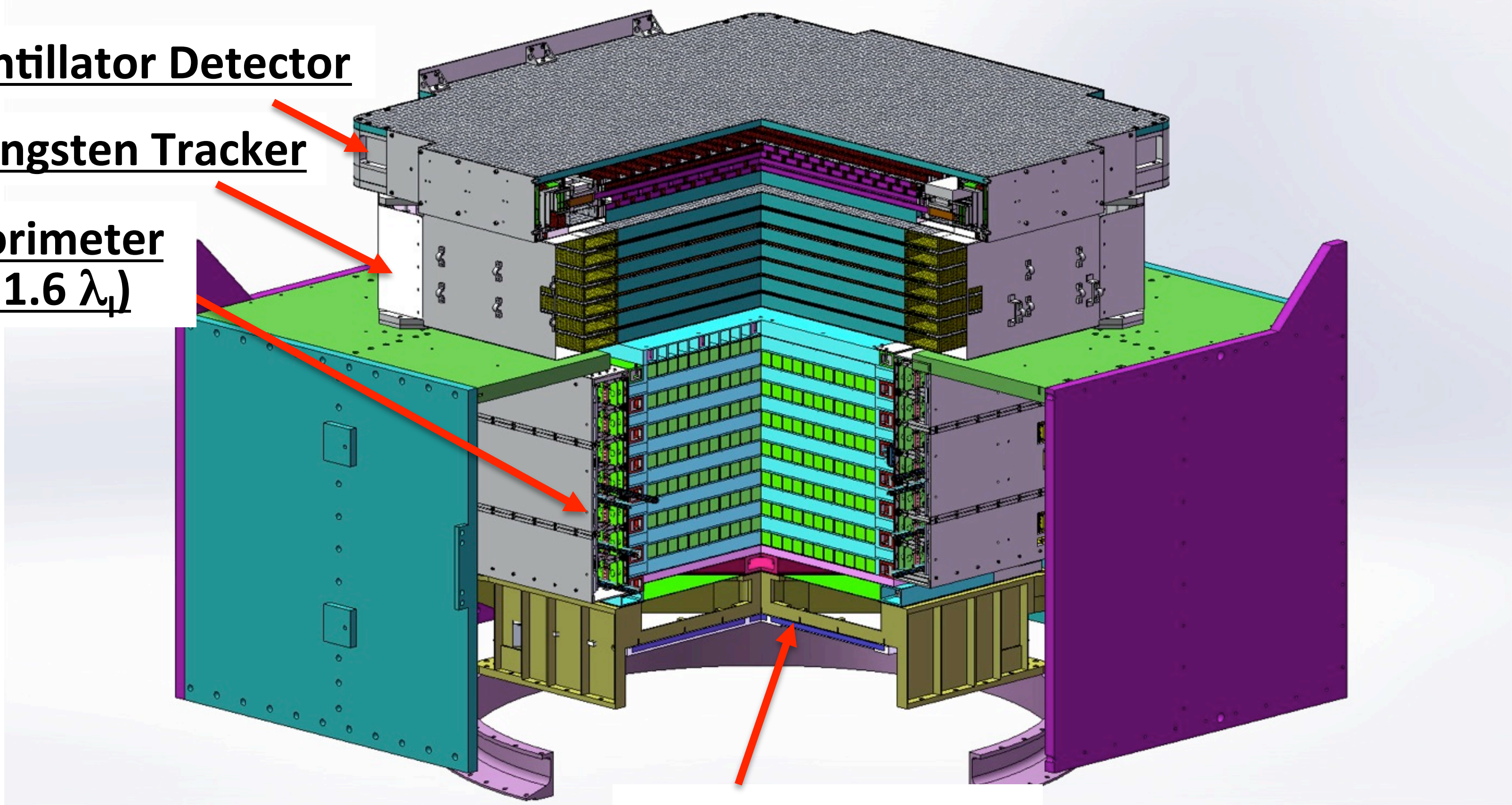


DAMPE 3yrs

I. De Mitri, LNGS 2015]

Simulation assuming the AMS-02 power law spectrum + a cut-off + the contribution of nearby sources

The DAMPE Detector



Plastic Scintillator Detector

Silicon-Tungsten Tracker

BGO Calorimeter
(31 X_0, 1.6 λ_I)

Neutron Detector

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

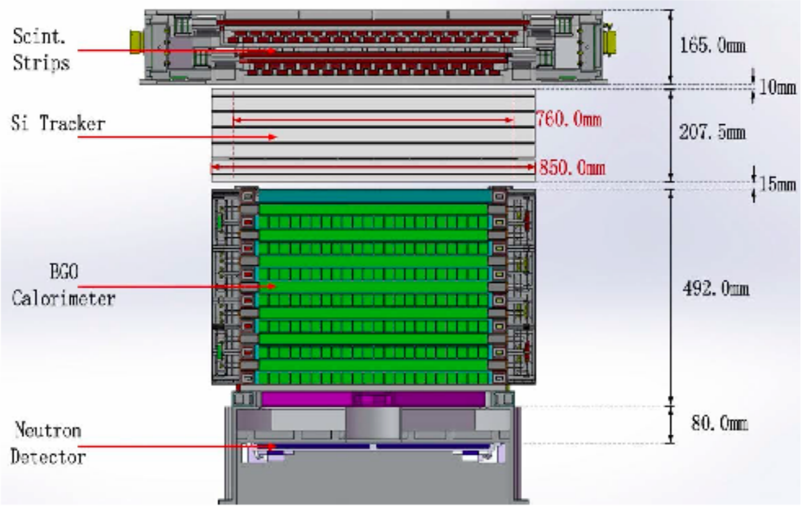
high energy gamma-ray, electron and CR telescope

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**

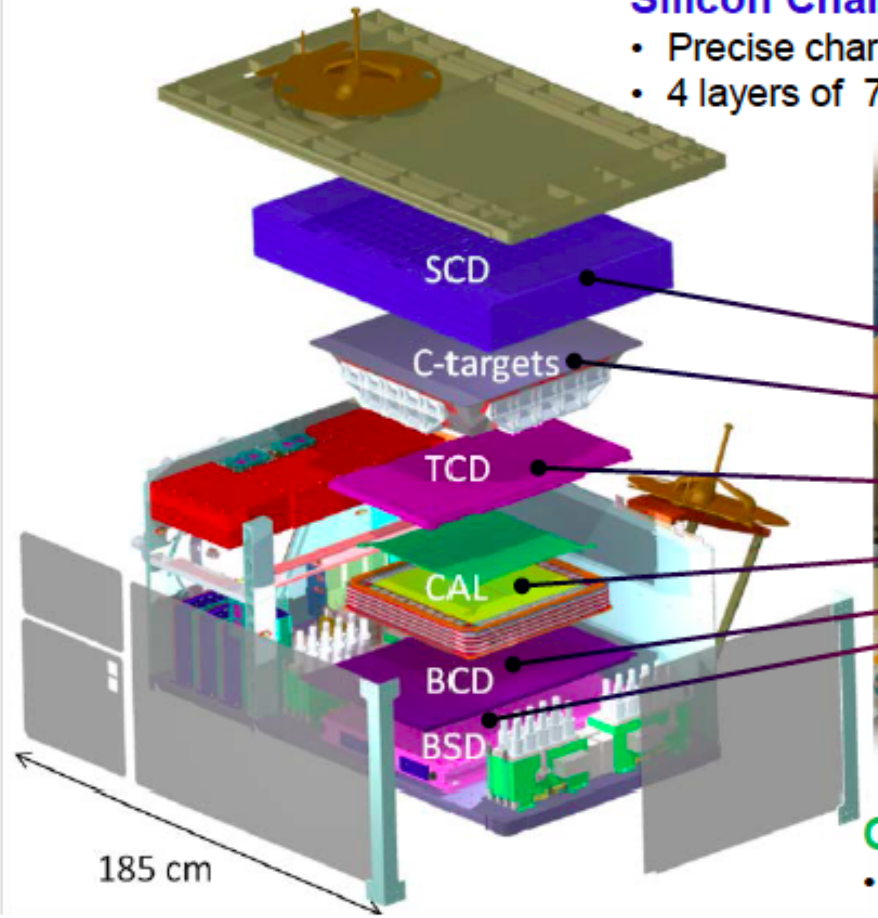
ISS-CREAM Instrument

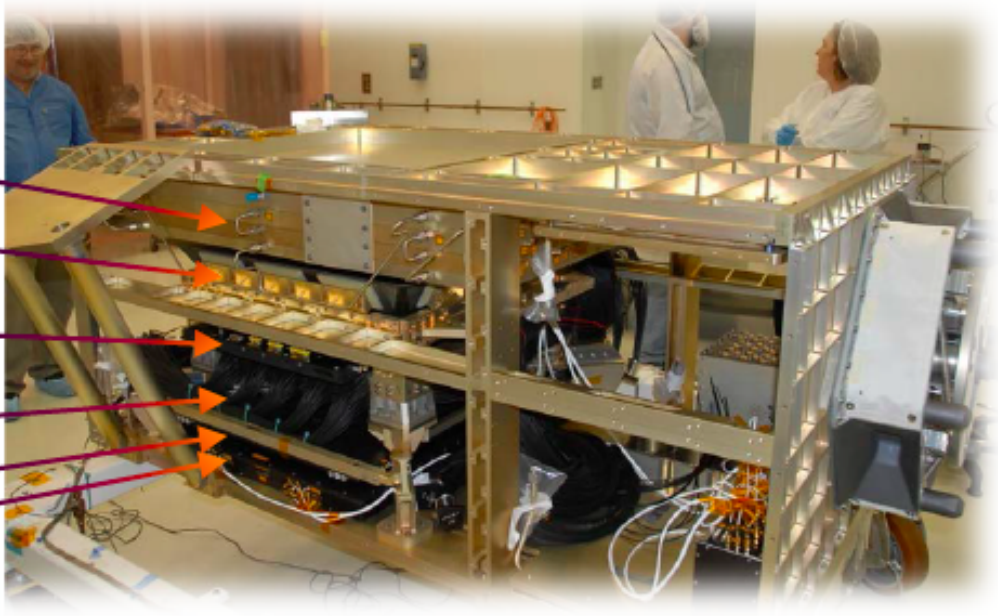
[Seo@Vulcano 2016]

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)

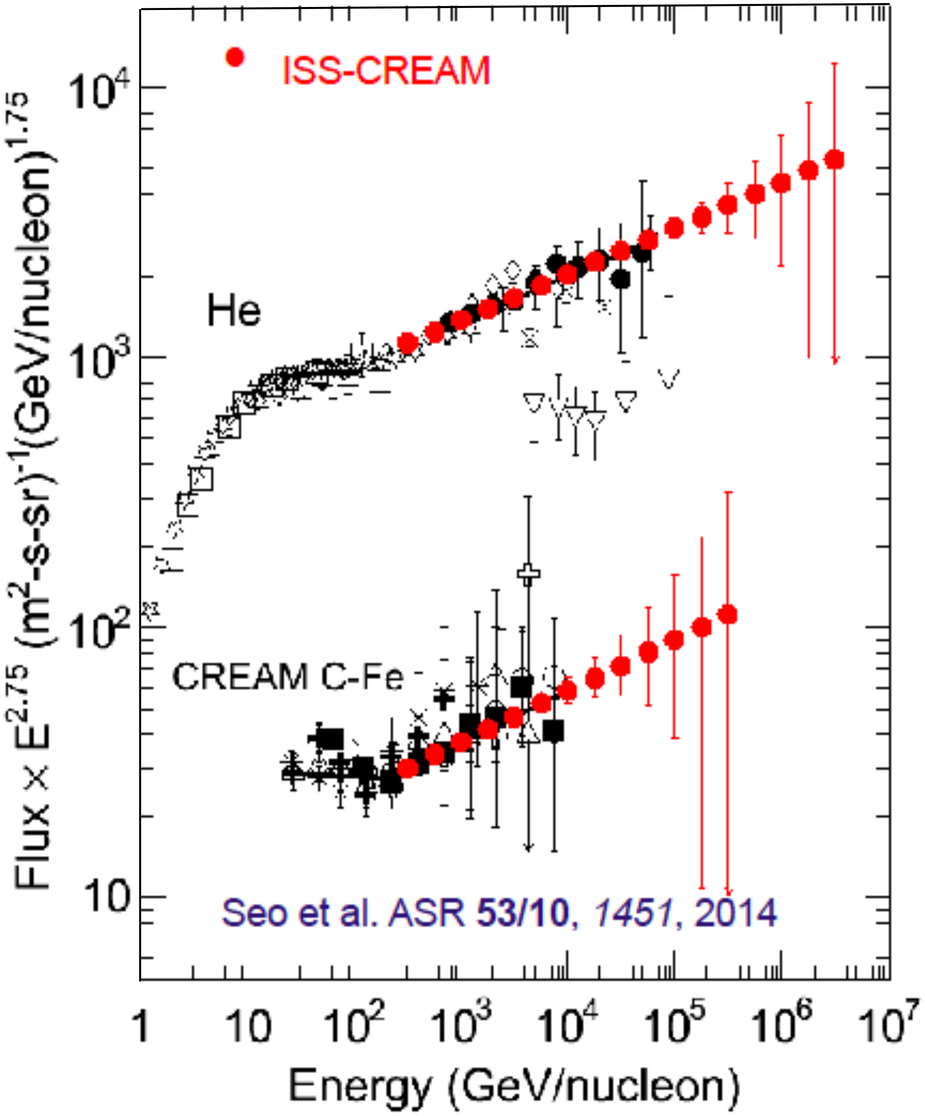
- Plastic scintillator instrumented with an array of 20 x 20 photodiodes for e/p separation.
- Independent trigger.

ISS-CREAM takes the next major step

Increases the exposure by an order of magnitude!

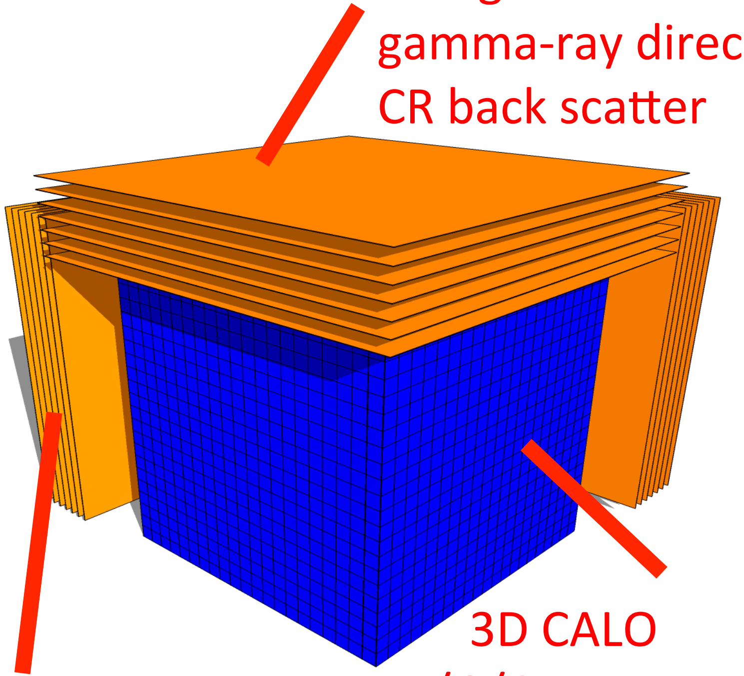
- The ISS-CREAM space mission can take the next major step to 10^{15} eV, and beyond, limited only by statistics.
- The 3-year goal, 1-year minimum exposure would greatly reduce the statistical uncertainties and extend CREAM measurements to energies beyond any reach possible with balloon flights.

[E.S.Seo @Vulcano 2016]



HERD Design： 3D Calo & 5-Side Sensitive

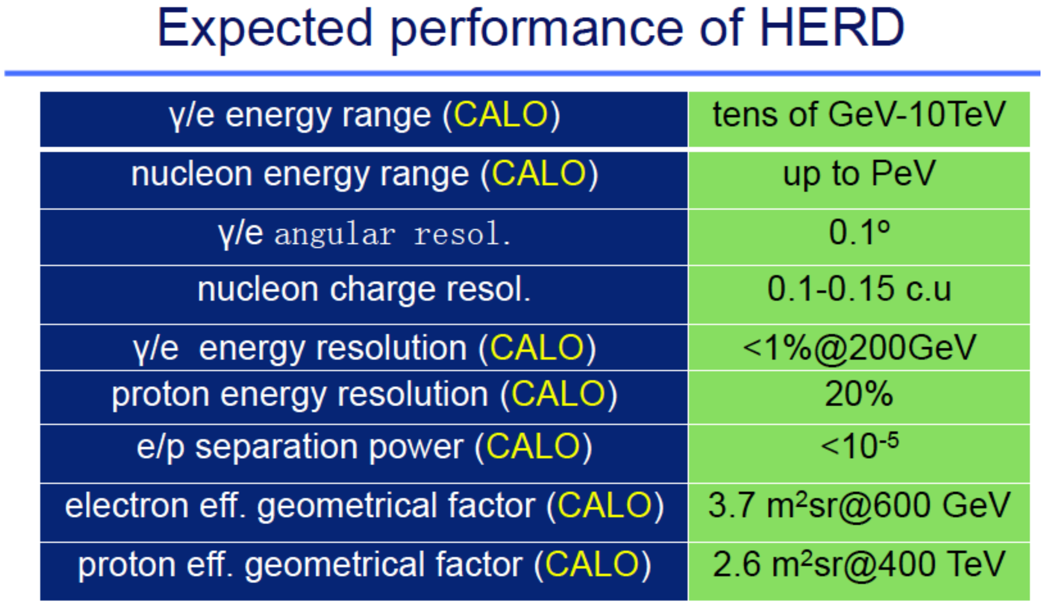
About a factor 10 increase in statistics respect to existing experiments with a weight 2.3 T ~1/3 AMS



STK(W+SSD)
Charge
gamma-ray direction
CR back scatter

3D CALO
e/G/CR energy
e/p discrimination

STK(W+SSD)

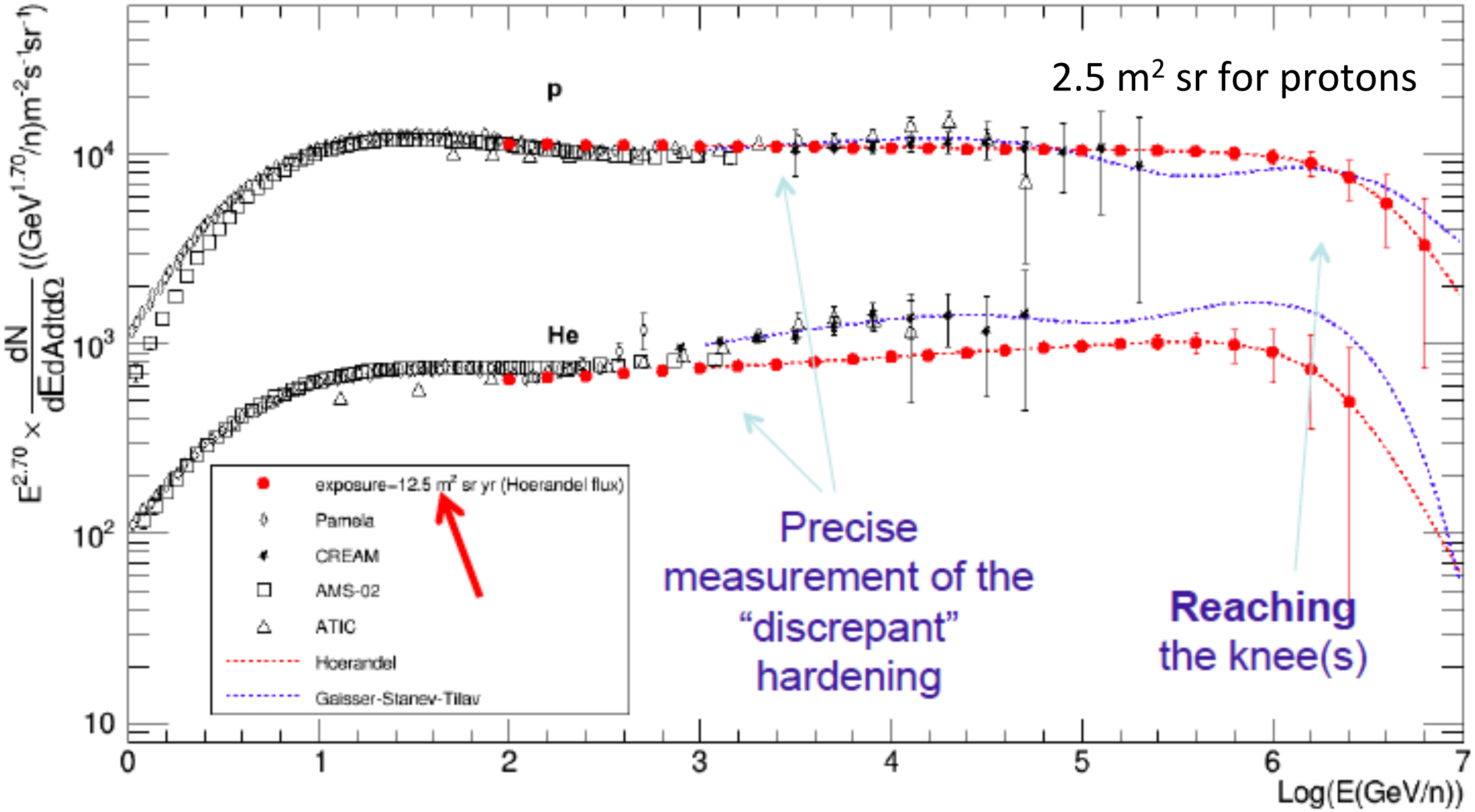


Expected performance of HERD

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

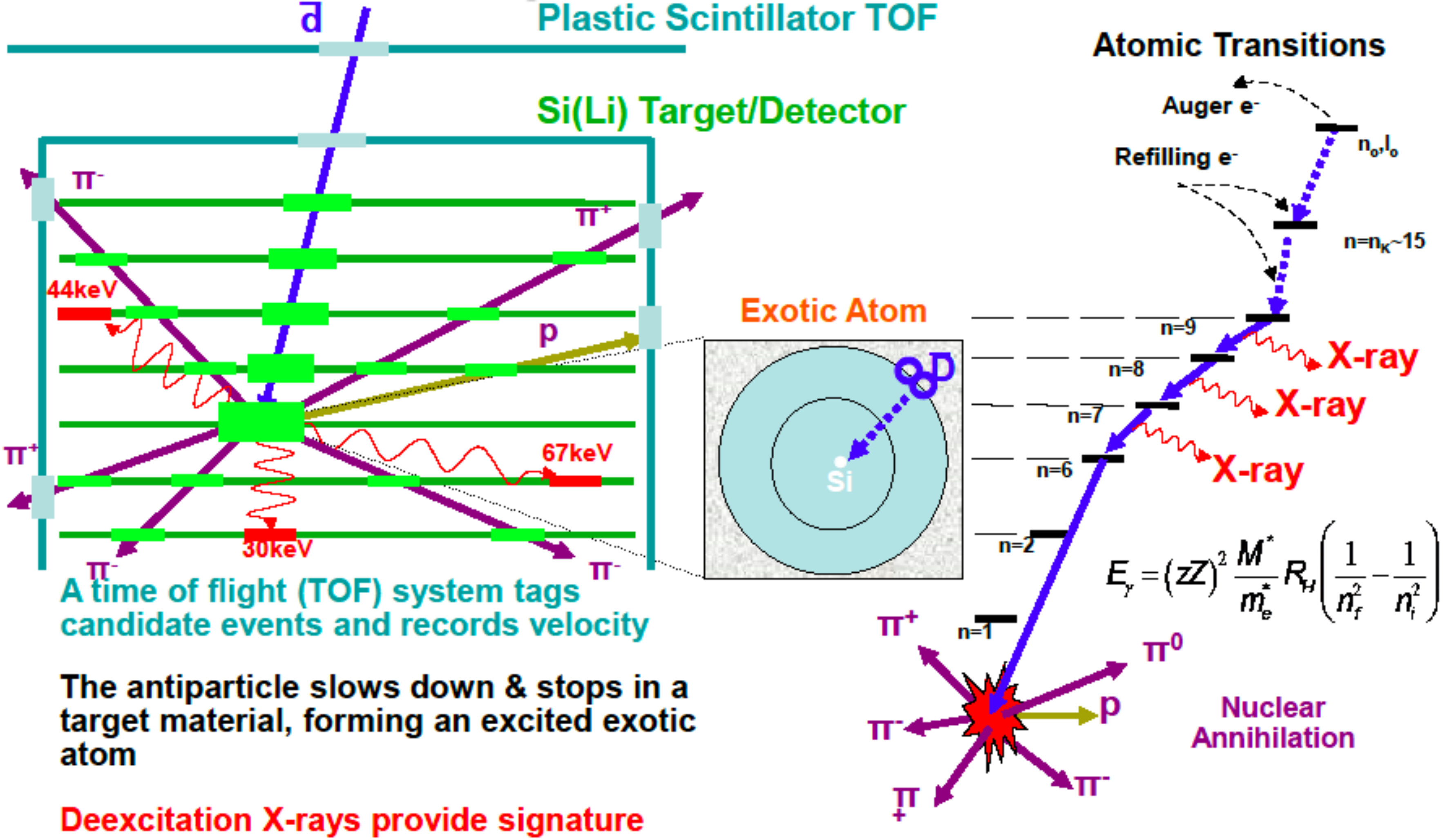


2.5 m^2 sr for protons

Precise measurement of the “discrepant” hardening

Reaching the knee(s)

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

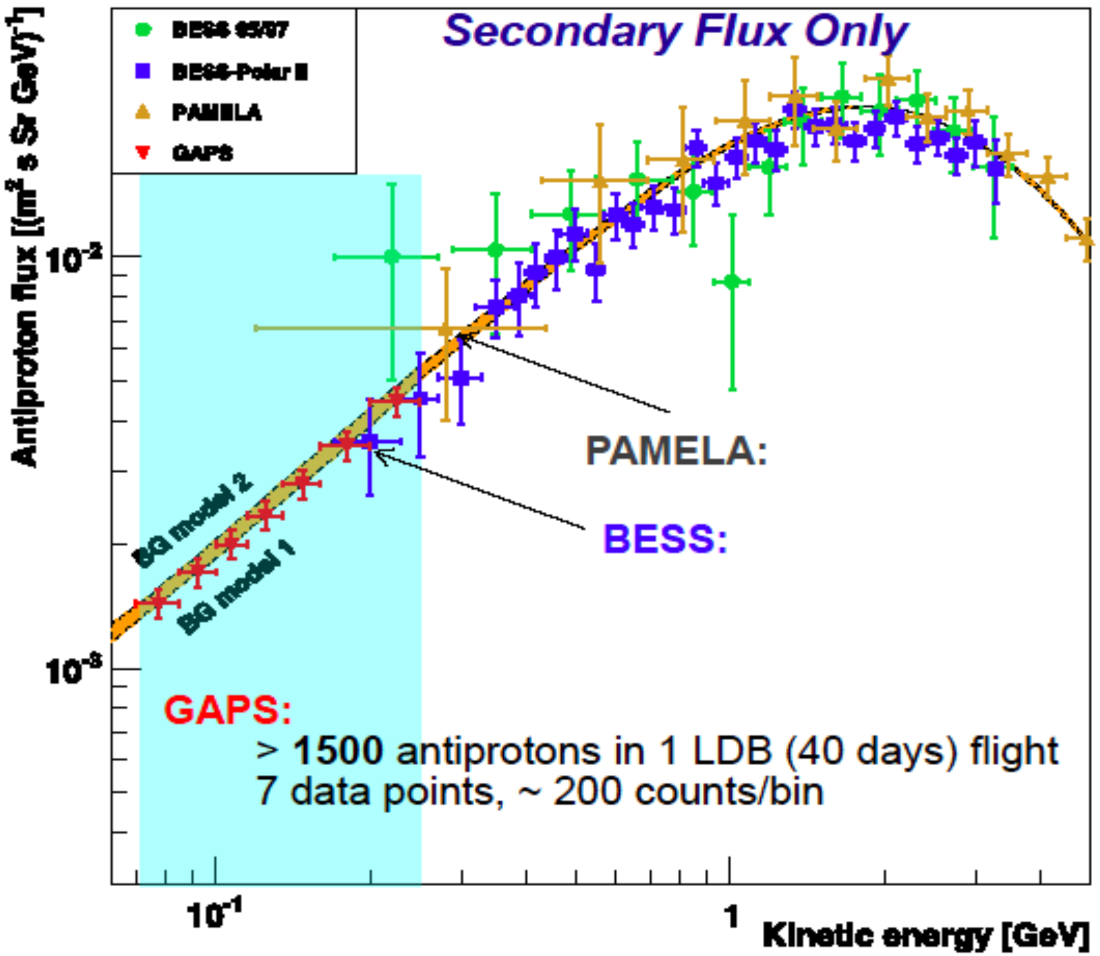
The antiparticle slows down & stops in a target material, forming an excited exotic atom

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

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

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

Secondary flux

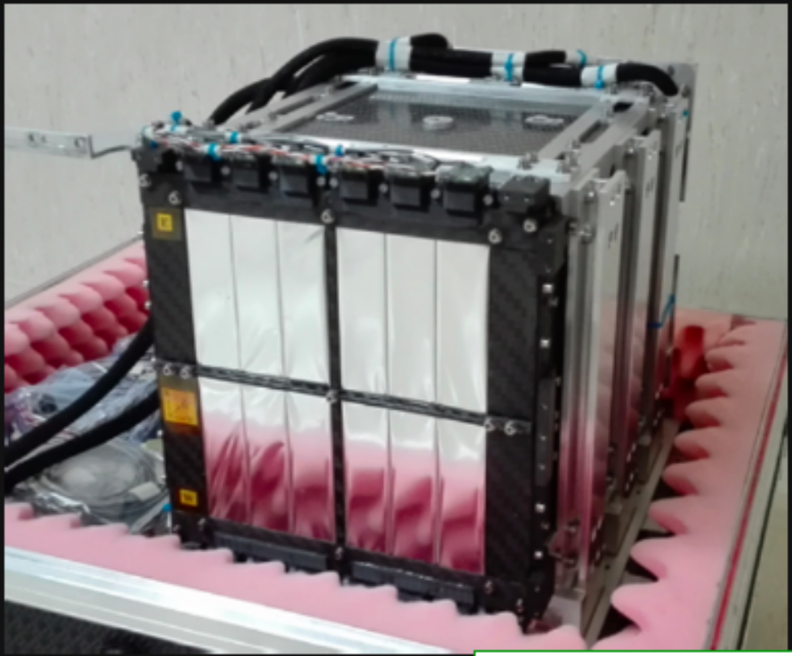
- constrained by B/C ratio

M. Hailey, Dark Matter 2014, UCLA

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

The HEPD on CSES satellite

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].

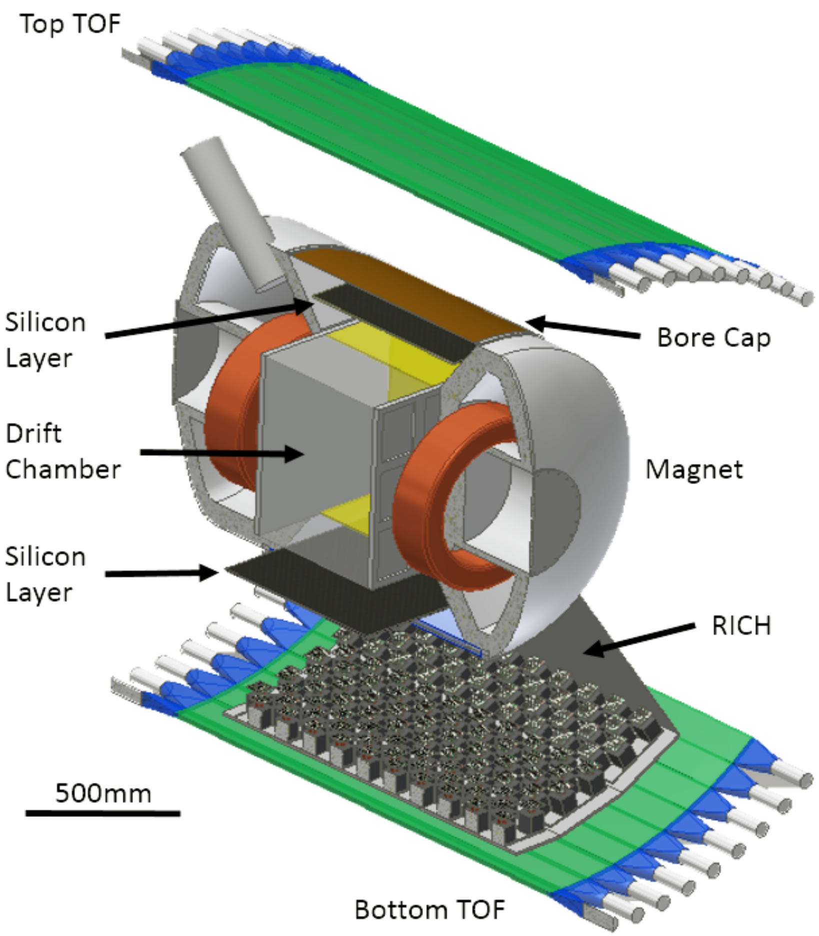


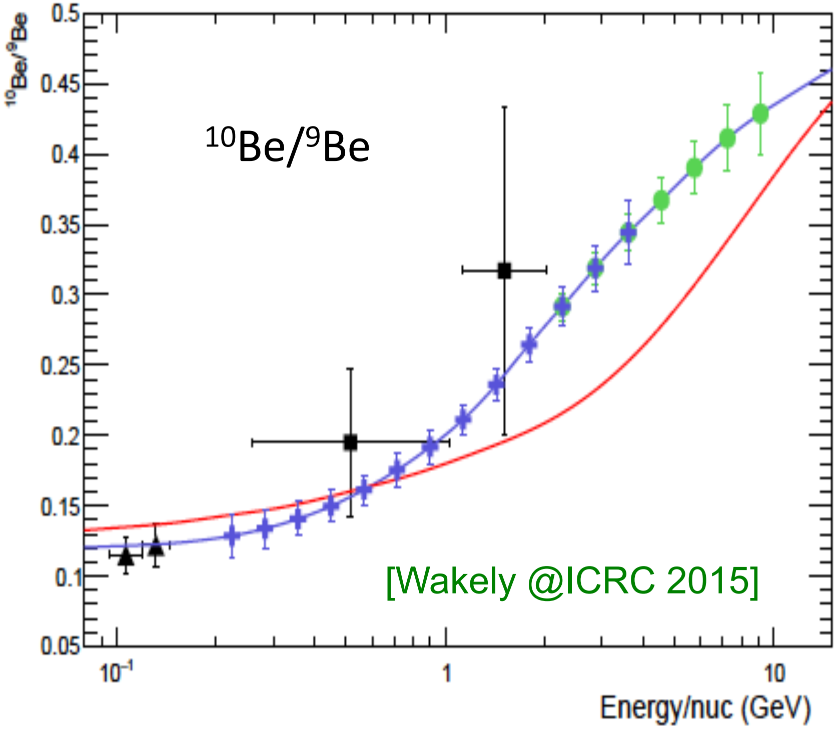
Sparvoli @ LNGS Jul. 2016

HEPD specs	
Energy range electrons:	3 MeV~100 MeV
Energy range protons:	30 MeV~200 MeV
Angular resolution	<8° @ 5 MeV
Energy resolution	<10% @ 5 MeV
Particle Identification	> 90 %
Mass (including electronics)	≤ 35 kg
Power consumption	≤ 38W

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

HELIX: High Energy Light Isotope (balloon) Experiment





[Wakely @ICRC 2015]

- 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^{2}sr 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

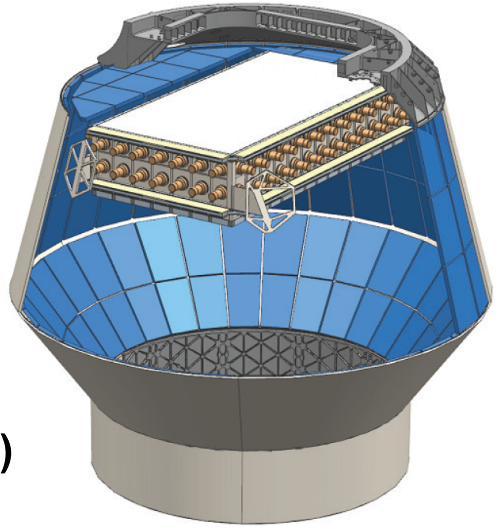
- **HNX uses two complementary instruments to span a huge range in atomic number $6 \le Z \le 96$ and measure Actinides (Th,U,Pu) clocks**

  –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]

Summary

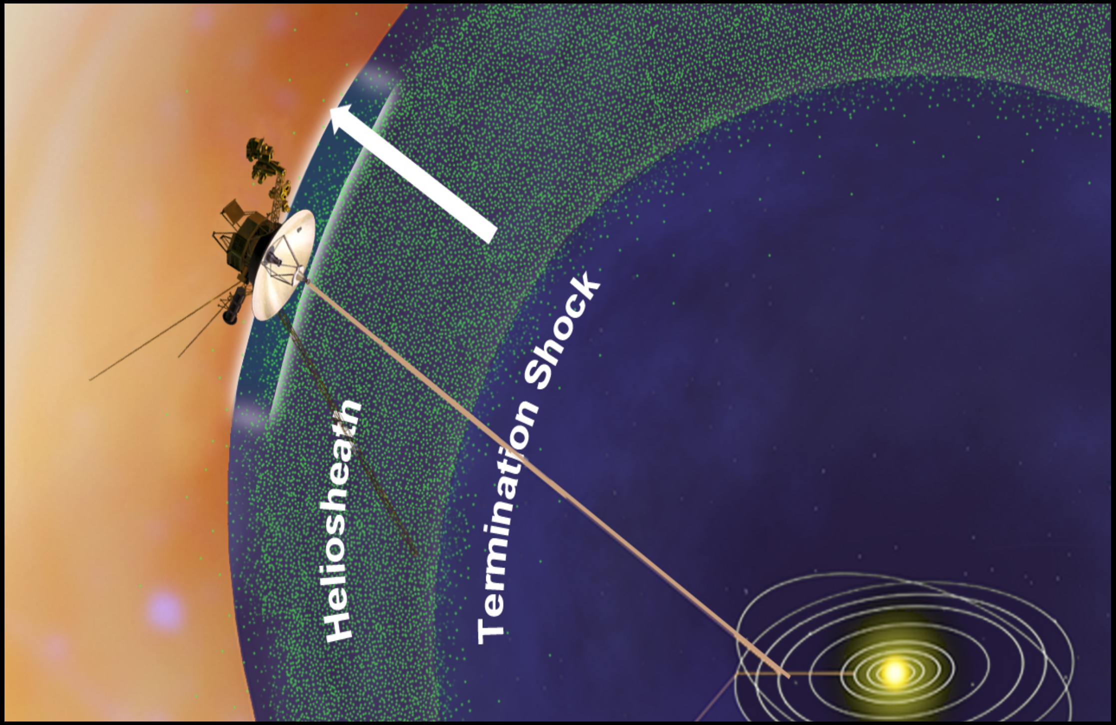
- Present observations
  - Discrepancy of electron fluxes by factors 2~3 among experiments
  - Few observations above 100 GeV region

- Requirements for future observations:
  - Accurate measurements of the electron spectrum with:
    - Large statistics
    - High proton rejection
  - Observations at higher energy (above 1TeV)

- Expected outcome
  - Acceleration mechanisms and propagation characteristics of cosmic rays
  - Identification of specific cosmic-ray sources

Low energy CR and solar modulation

In August 2012, Voyager 1 entered the LISM

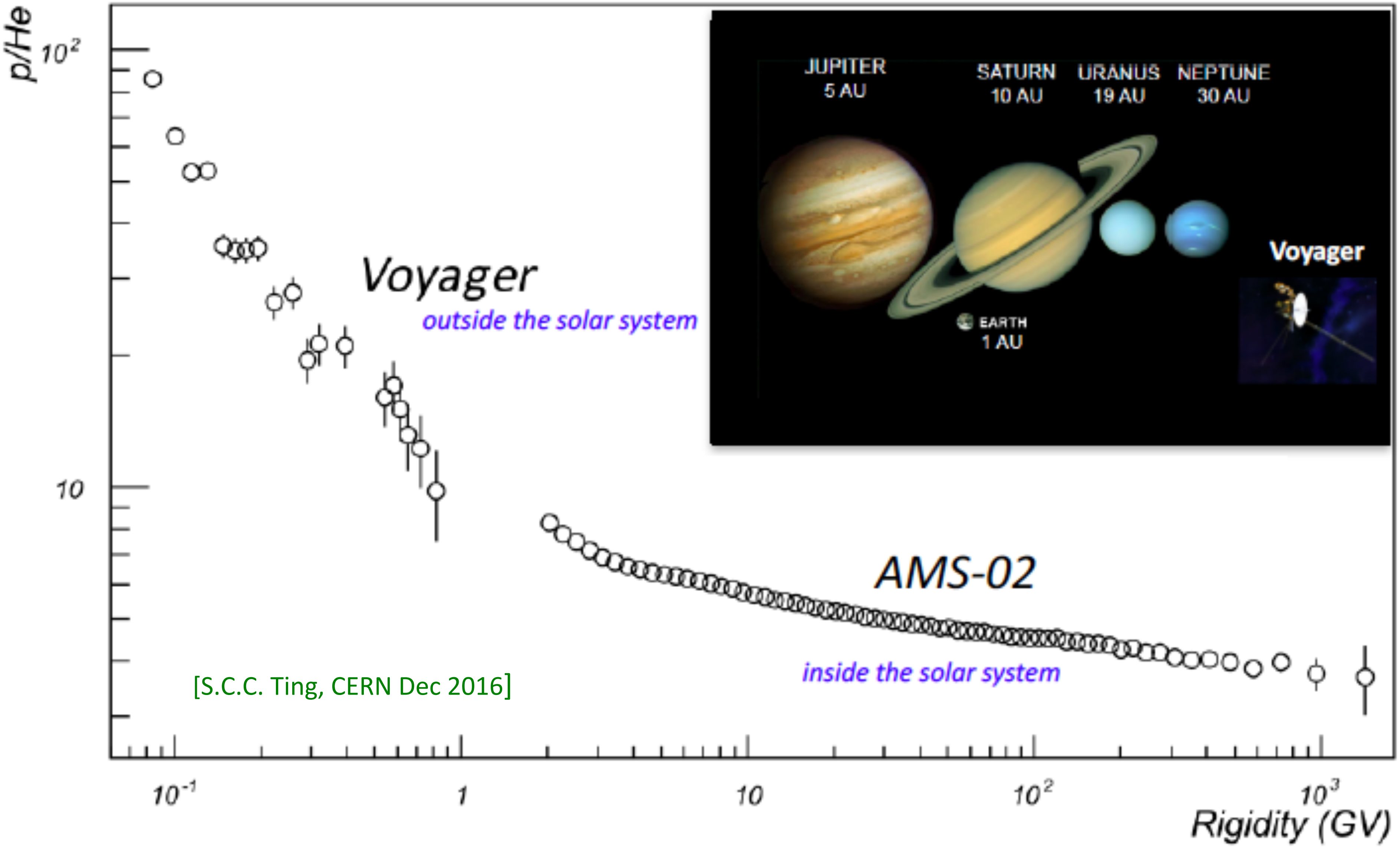


Energetic charged particles underwent dramatic changes past the heliopause:

- heliospheric ions disappeared completely as a result of their escape into interstellar space
- an increase in galactic cosmic rays followed by a ~ constant intensity for the next two years,

For the first time, GCR were measured in their unmodulated state

Proton to Helium Flux Ratio

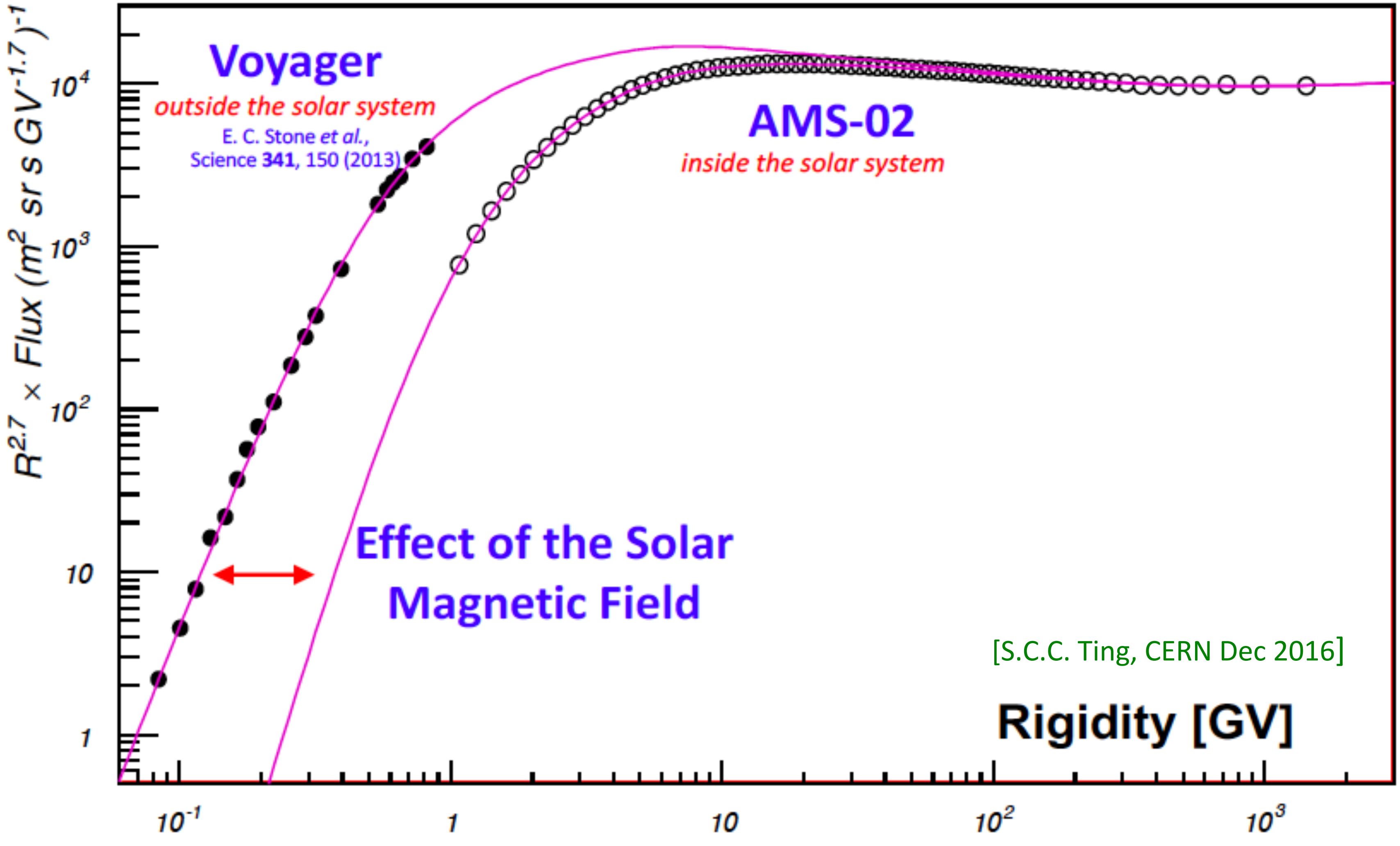


[S.C.C. Ting, CERN Dec 2016]

The p/He ratio is independent of solar activity

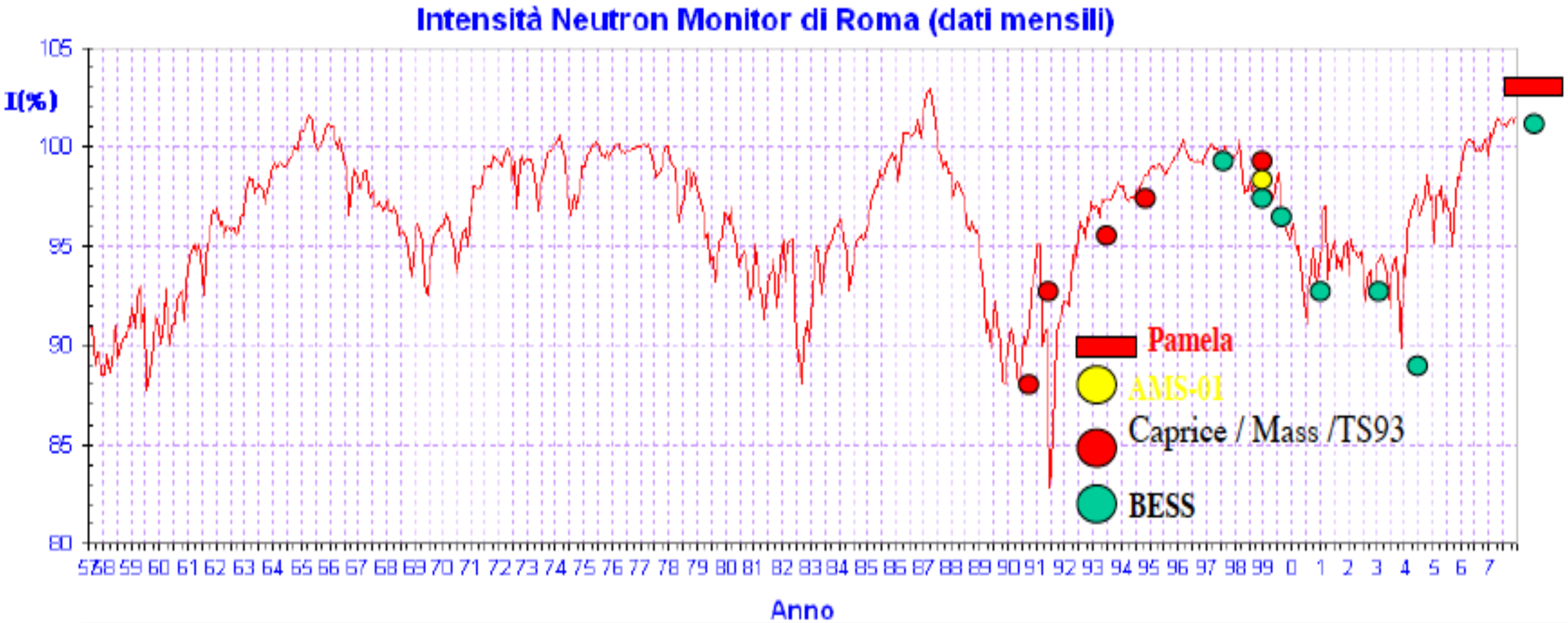
Understanding of the Solar Magnetic Field:

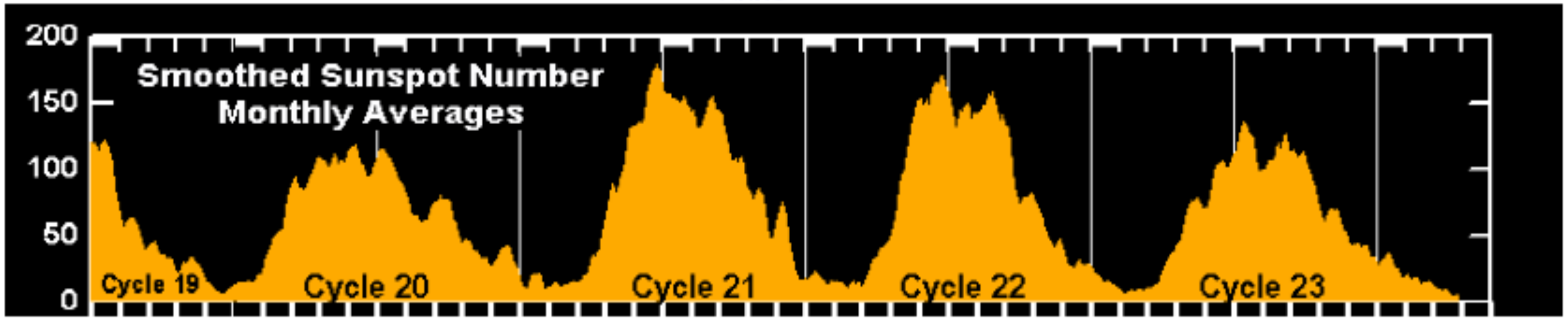
The proton flux and the effect of the solar magnetic field



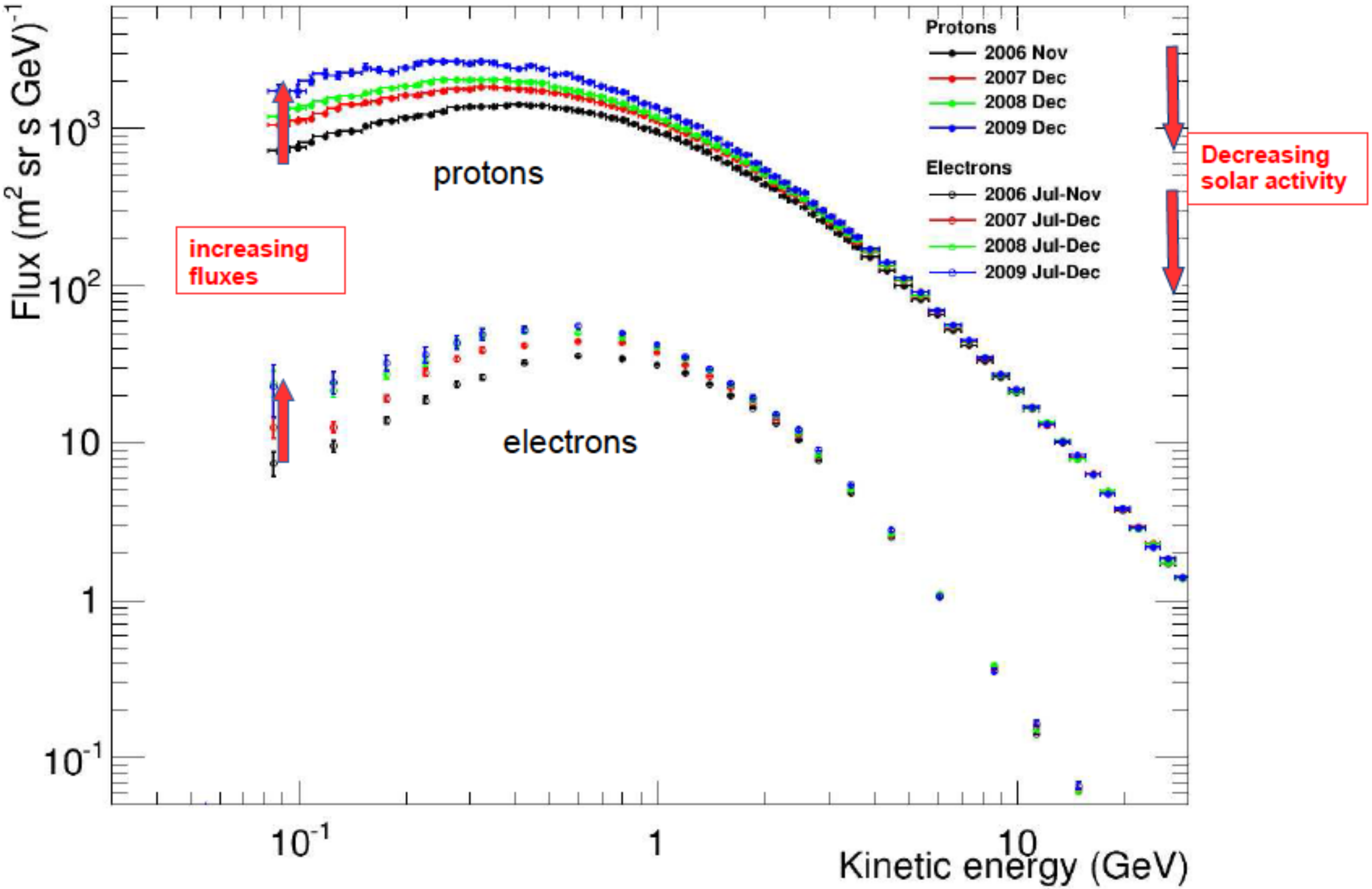
C. Corti *et al.*, ApJ **829**, 8 (2016)

Solar Modulation of Galactic Cosmic Rays



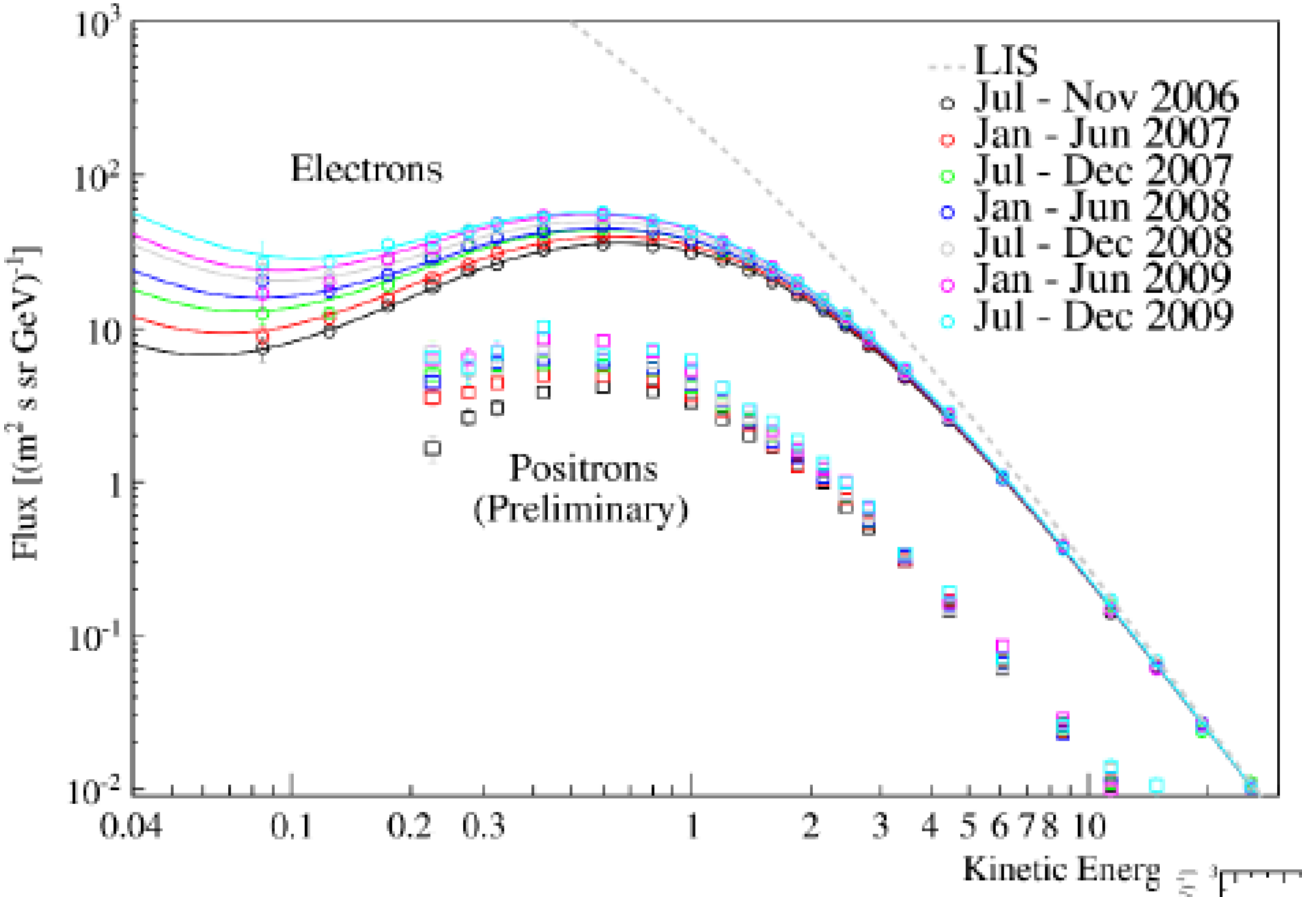


Solar modulation in the heliosphere



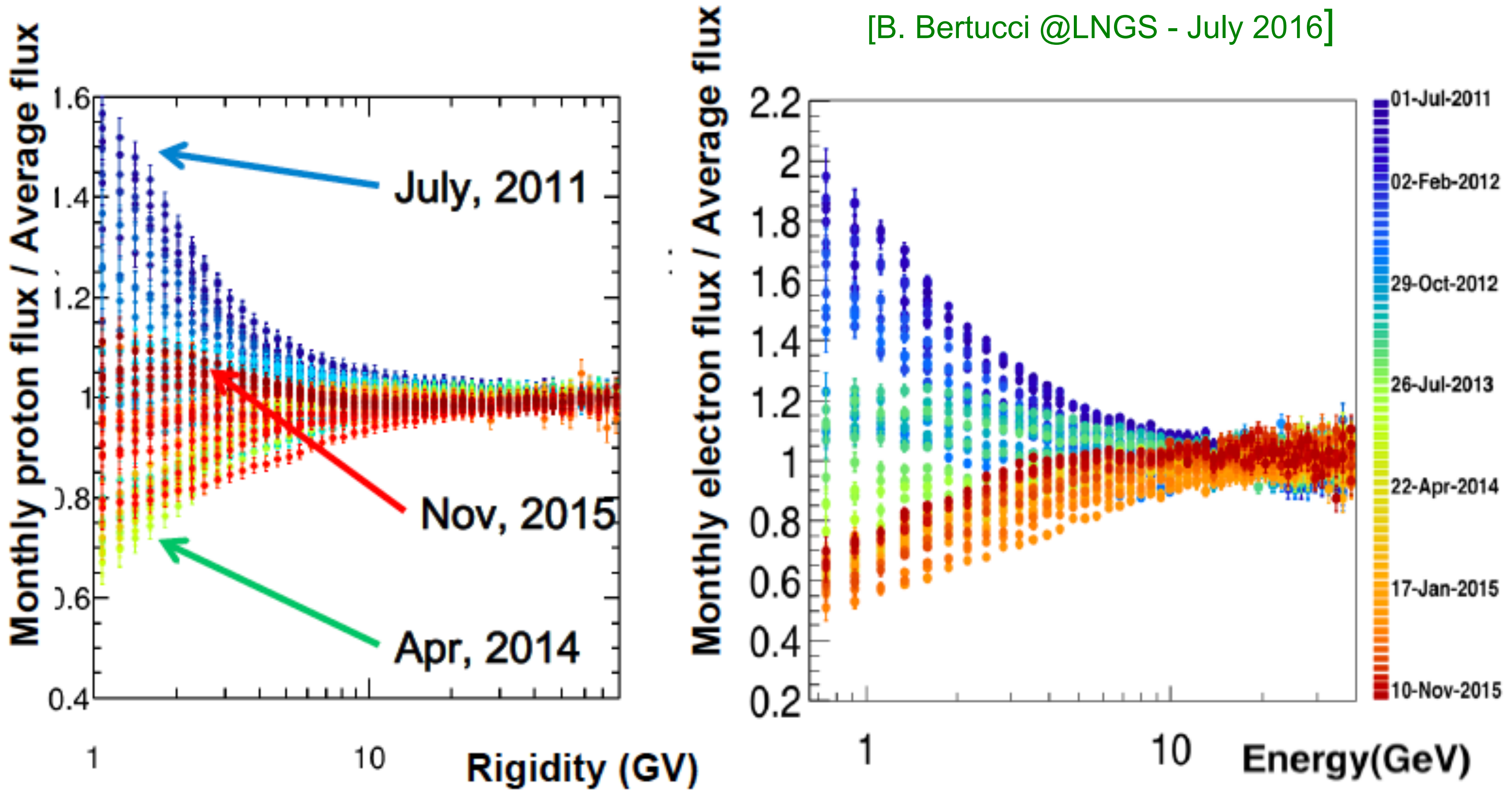
O. Adriani et al., ApJ 765 (2013), 91;
M. S. Potgieter et al., Sol. Phys. (2014), 289

PAMELA: solar modulation of CR charged leptons over the last solar minimum



Boezio @ICRC 2015]

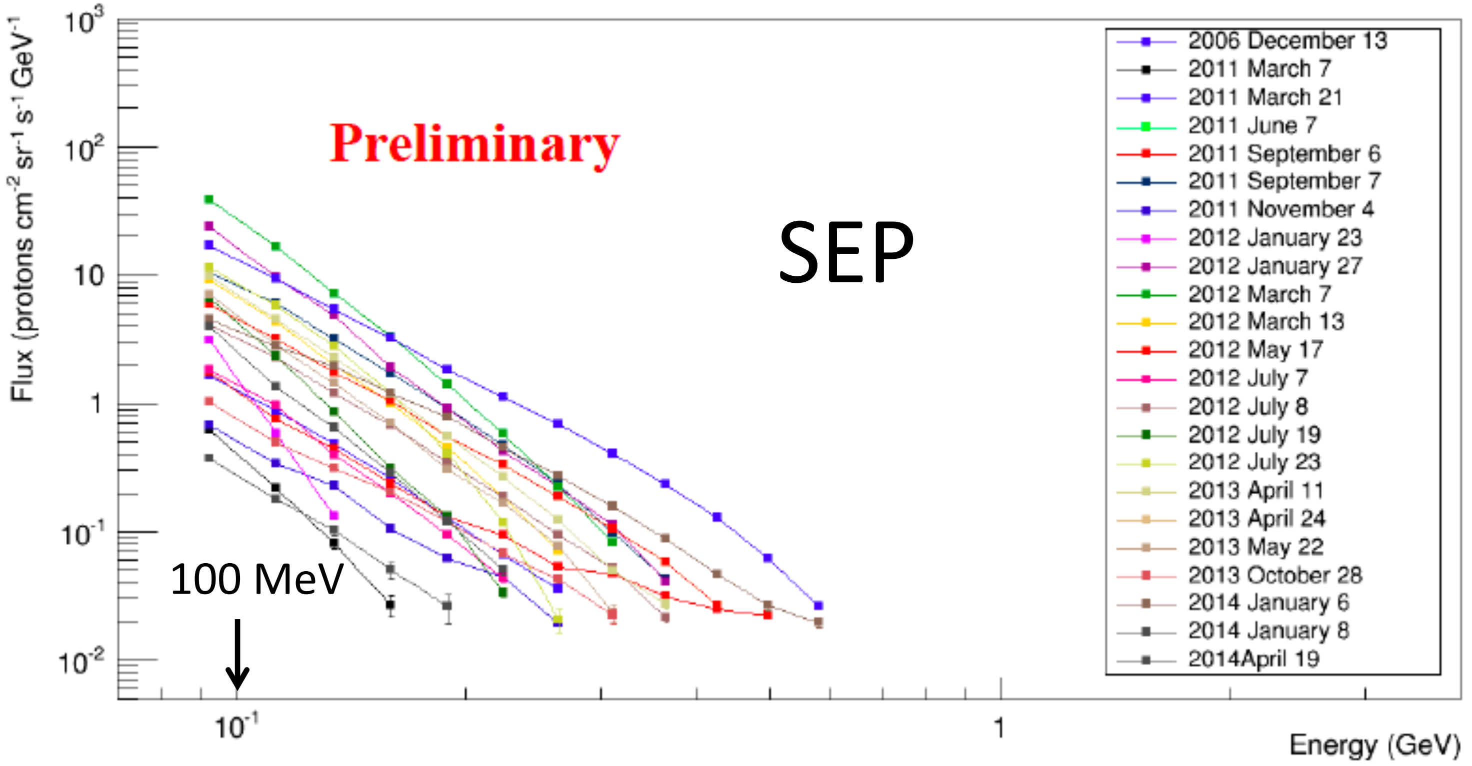
Solar effects & flux time dependence as measured by AMS-02



[B. Bertucci @LNGS - July 2016]

Time variation of proton and electron fluxes from mid-2011 to end 2015. Reported is the monthly flux with respect to average flux over ≈4 years.

Preliminary PAMELA Solar Energetic Proton Spectra



Adriani et al., ApJ 742 102, 2011
Adriani et al., ApJL 801 (2015) L3