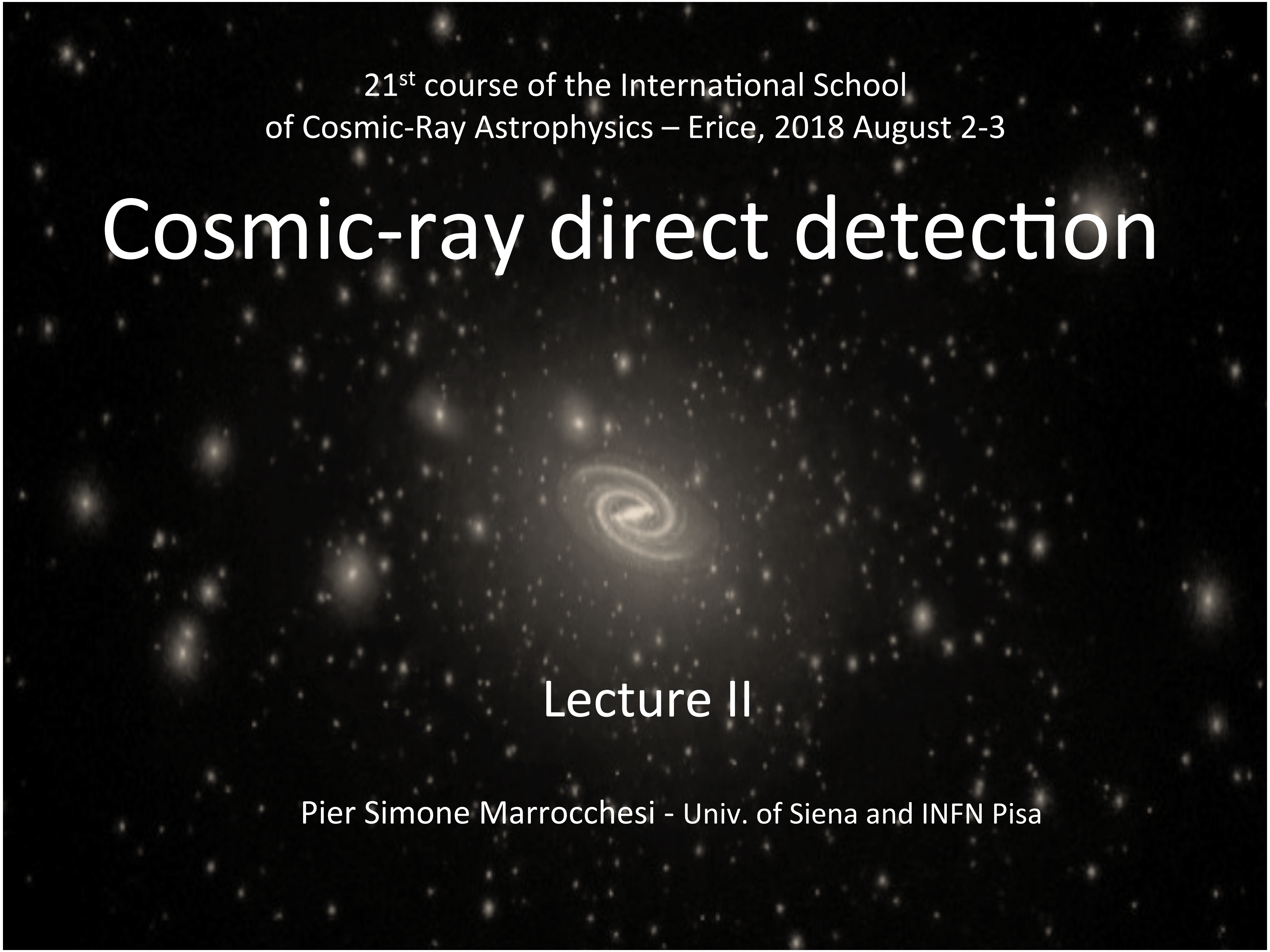


21st course of the International School
of Cosmic-Ray Astrophysics – Erice, 2018 August 2-3

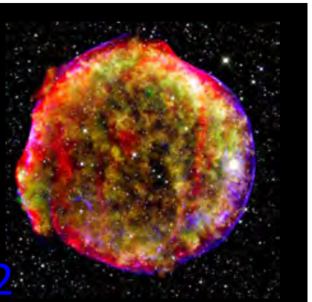
Cosmic-ray direct detection

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 Ratios
- Anti-protons
- Isotope flux ratios, propagation clocks, ultra-heavy nuclei
- A glimple to future direct measurements of VHE cosmic rays

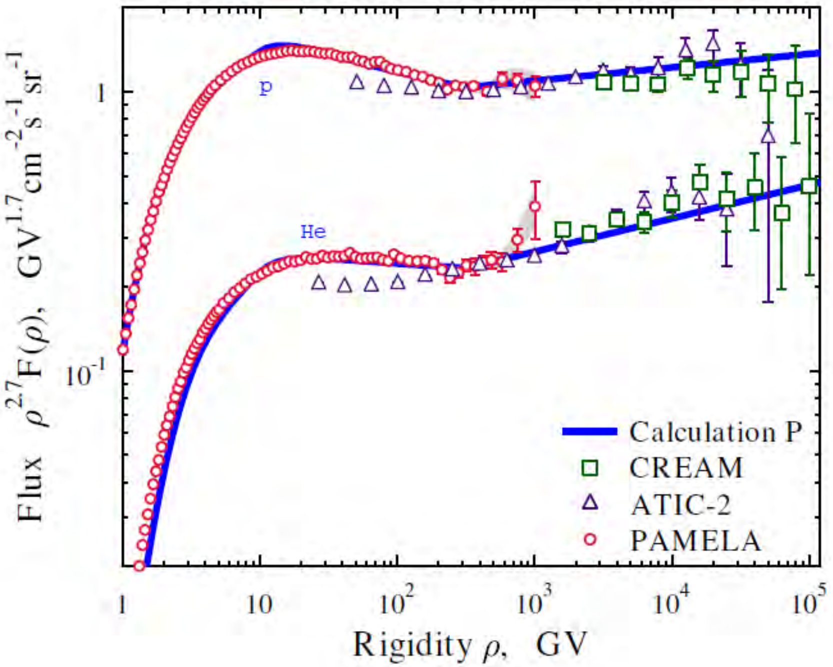

Tycho SN 1572

Charged cosmic-ray hadrons

energy spectra of primaries and secondaries

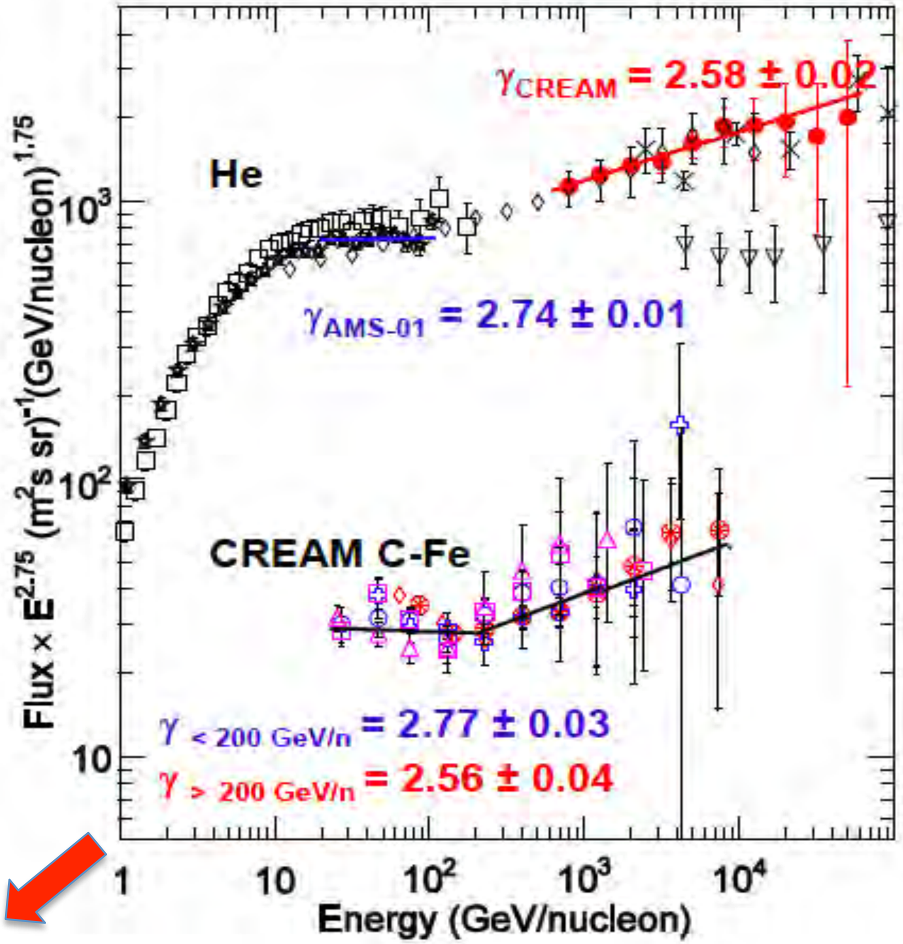
Direct measurements of proton and He spectra

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



A single power-law seems inadequate to fit the spectra

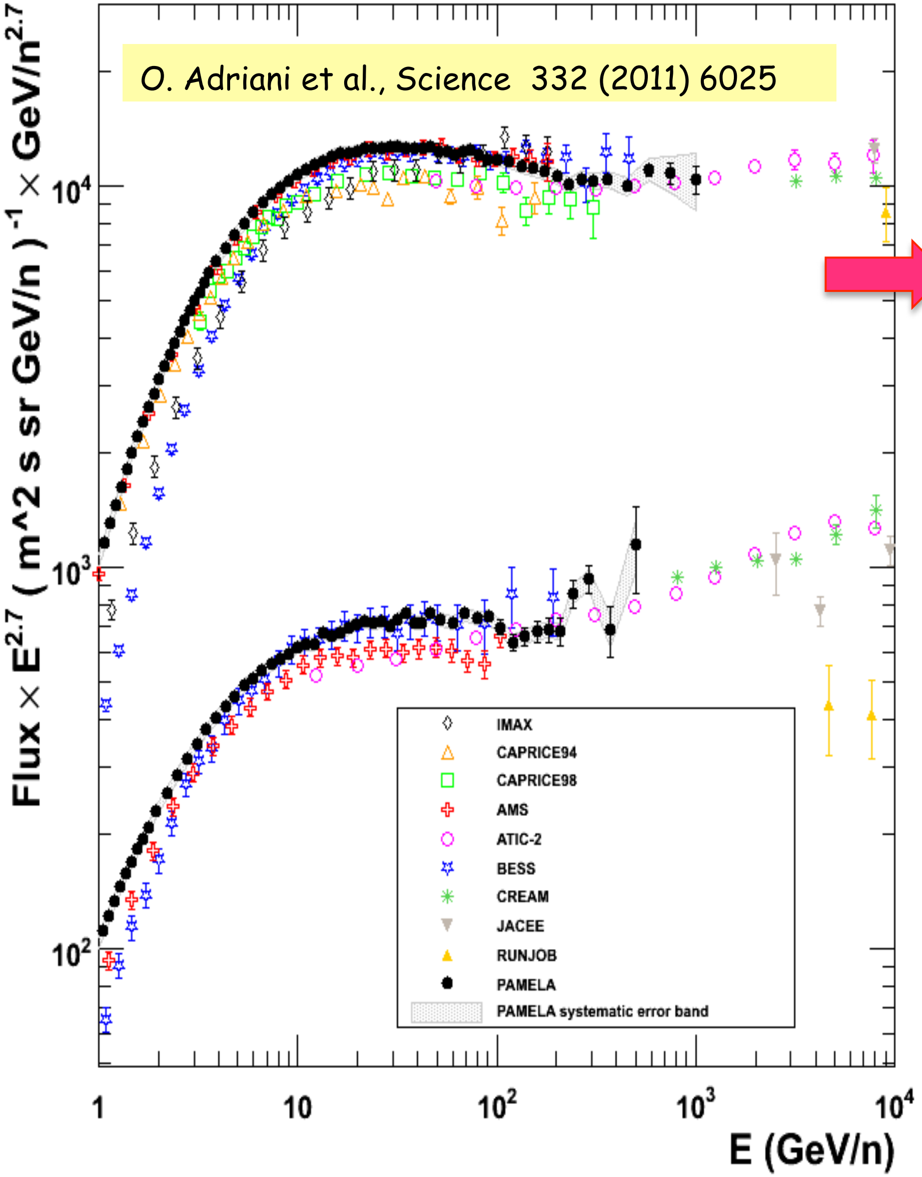
- ☐ **The break also appears in the spectra of NUCLEI measured by CREAM (2010) up to several TeV/n**



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

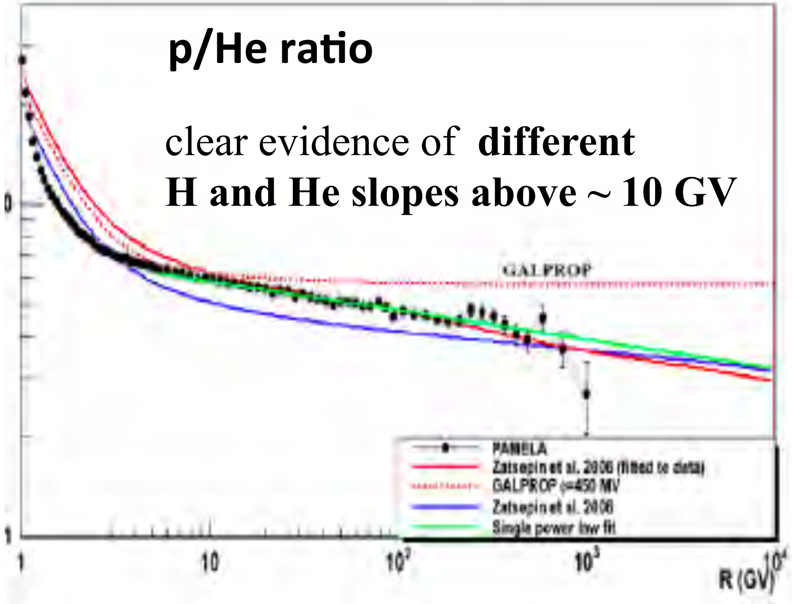
Ahn et al. ApJ 714, L89, 2010
Yoon et al. ApJ **728**, *122*, 2011

PAMELA (2011): 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

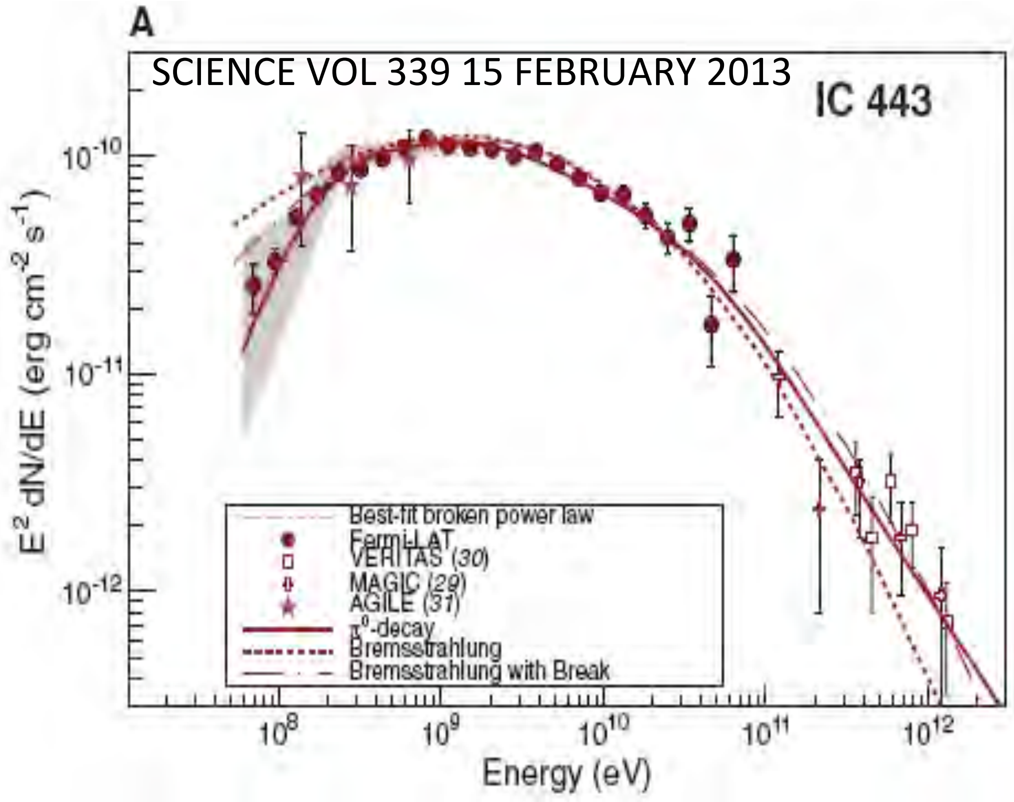


p/He ratio

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

2013: FERMI instrument detects the footprints of proton acceleration in SNRs

The identification of gamma rays from pion-decay has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering.


SCIENCE VOL 339 15 FEBRUARY 2013

"We detected the characteristic pion-decay feature in the gamma-ray spectra of two SNRs, IC 443 and W44, with the Fermi Large Area Telescope.

This detection provides direct evidence that cosmic-ray protons are accelerated in SNRs."

$p + p \rightarrow \pi_0$ + other products,
followed by $\pi_0 \rightarrow 2\gamma$,
each having an energy
of $m\pi_0 /2 = 67.5$ MeV

2015 Proton and He fluxes by AMS-02

PRL 114, 171103 (2015)

PRL 115, 211101 (2015)

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:

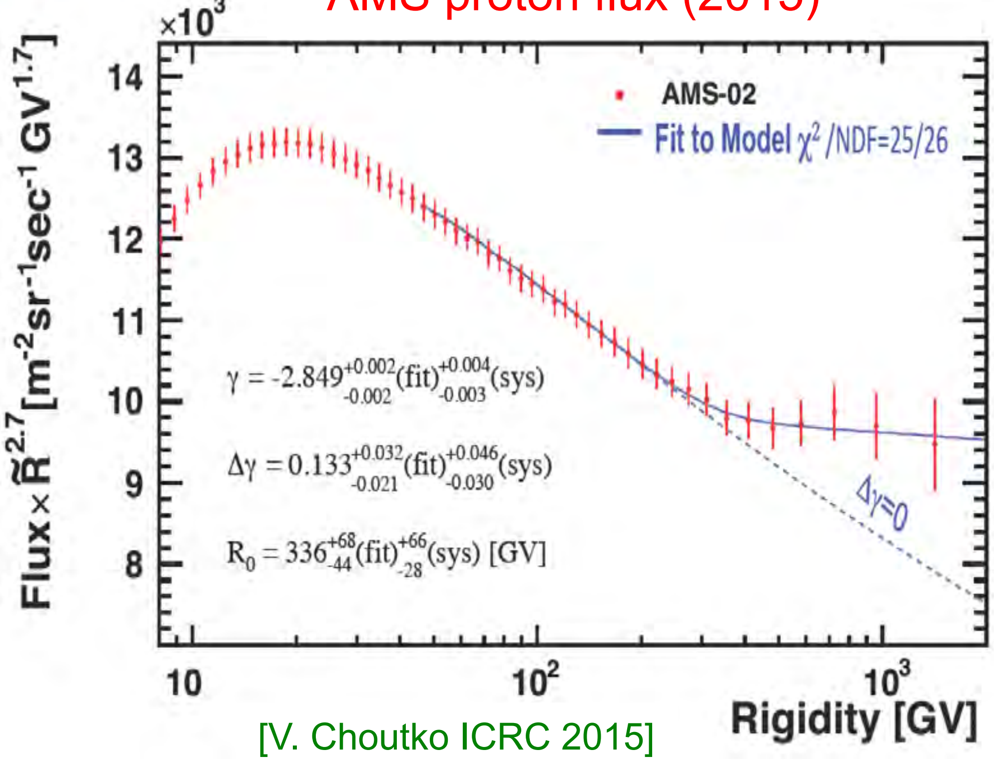
High statistics / High precision measurements

p: 300 million events

He: 50 million events

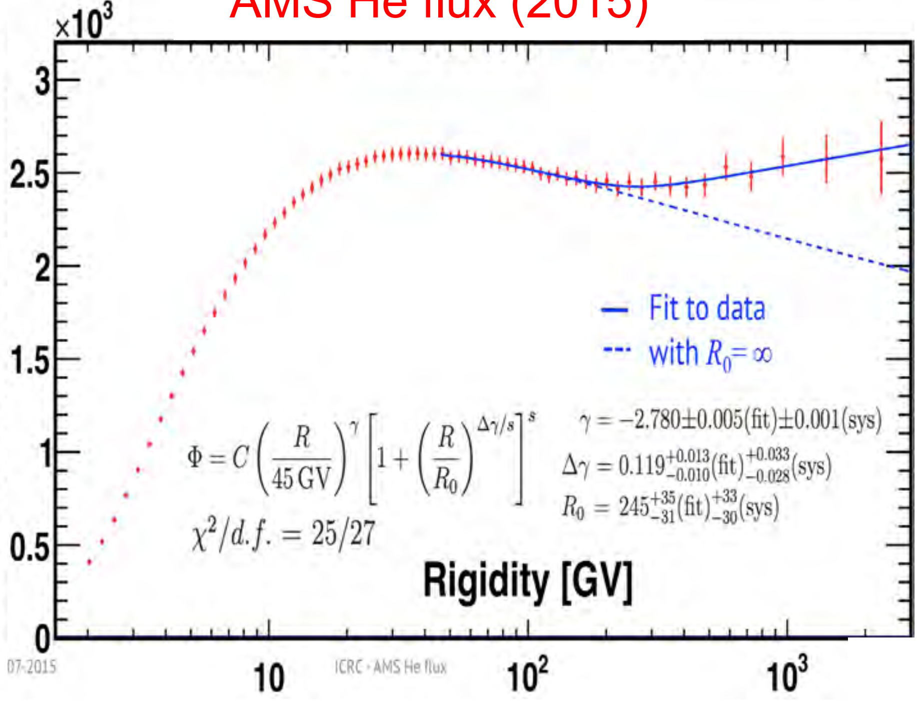
$$\Phi = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS proton flux (2015)



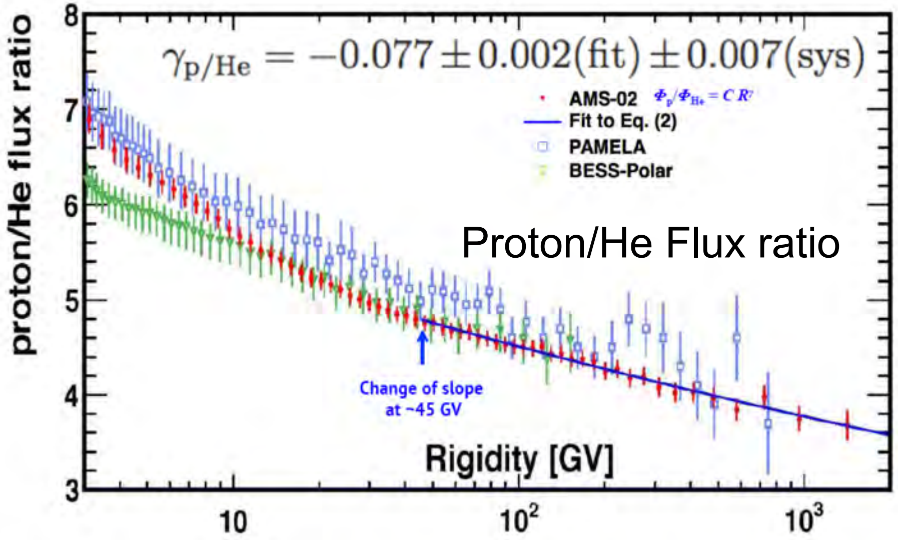
[V. Choutko ICRC 2015]

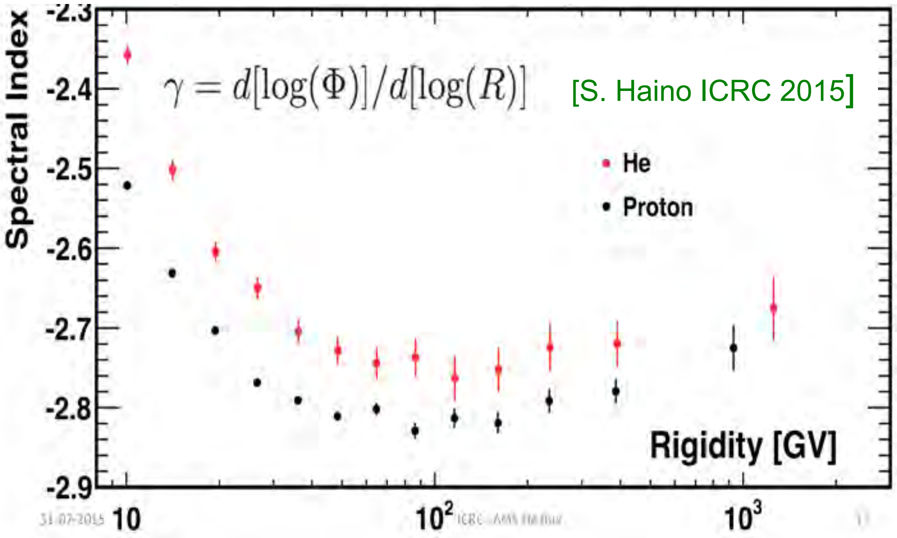
AMS He flux (2015)



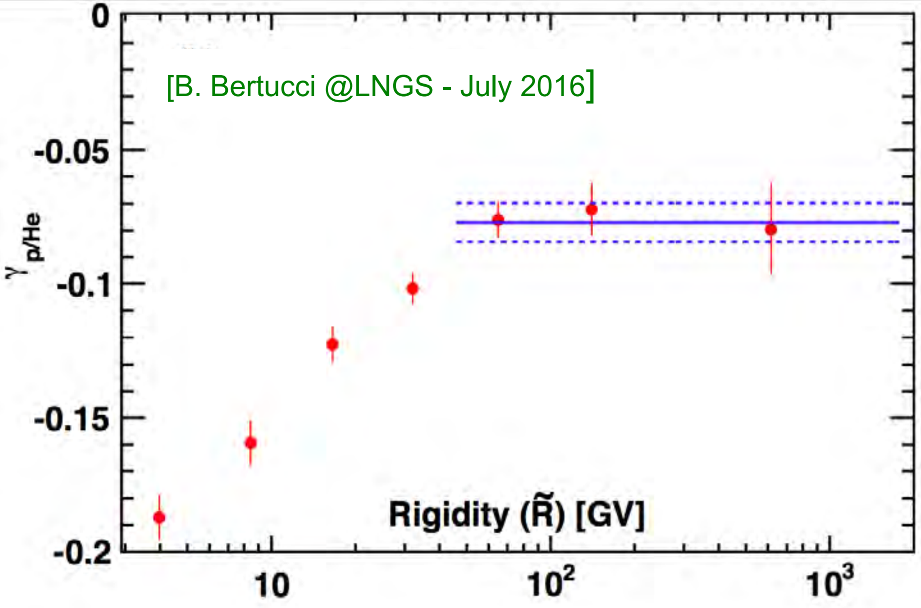
[S. Haino ICRC 2015]

AMS-02 (2015): spectral indices for p and He





[S. Haino ICRC 2015]



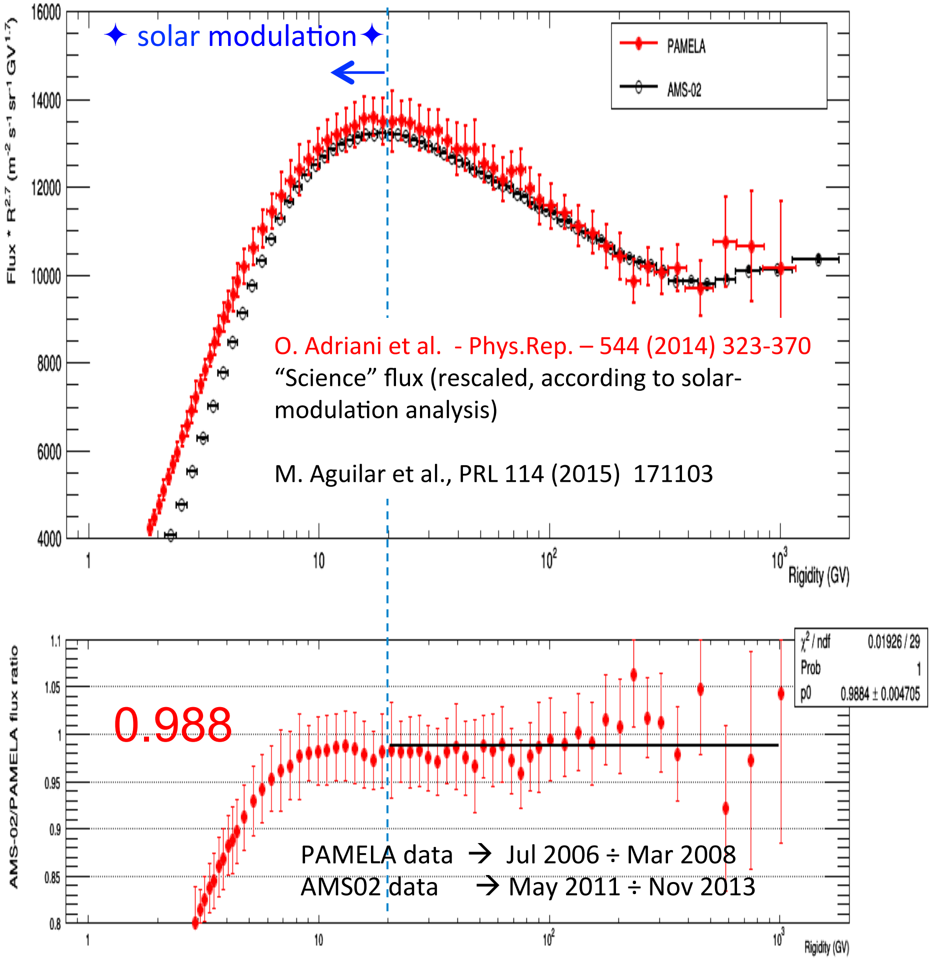
[B. Bertucci @LNGS - July 2016]

- 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 (2016) : 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



✦ solar modulation ✦

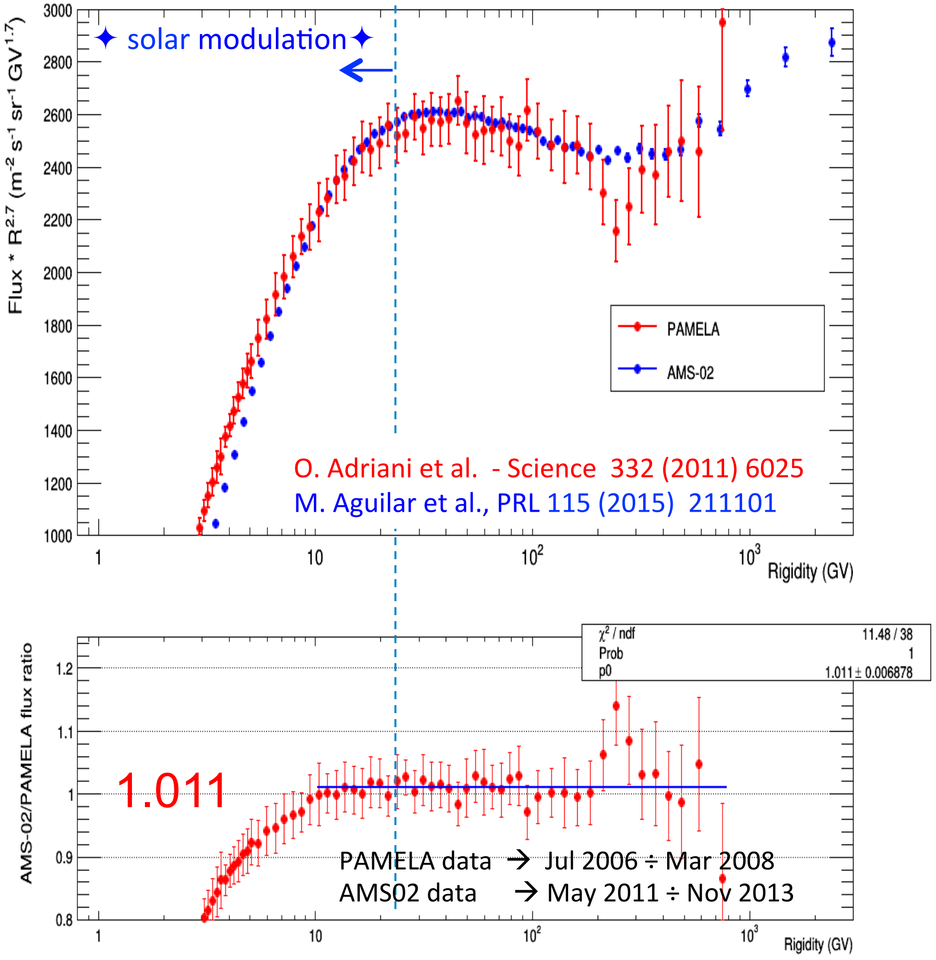
O. Adriani et al. - Phys.Rep. – 544 (2014) 323-370
“Science” flux (rescaled, according to solar-modulation analysis)

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

0.988

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

He



✦ solar modulation ✦

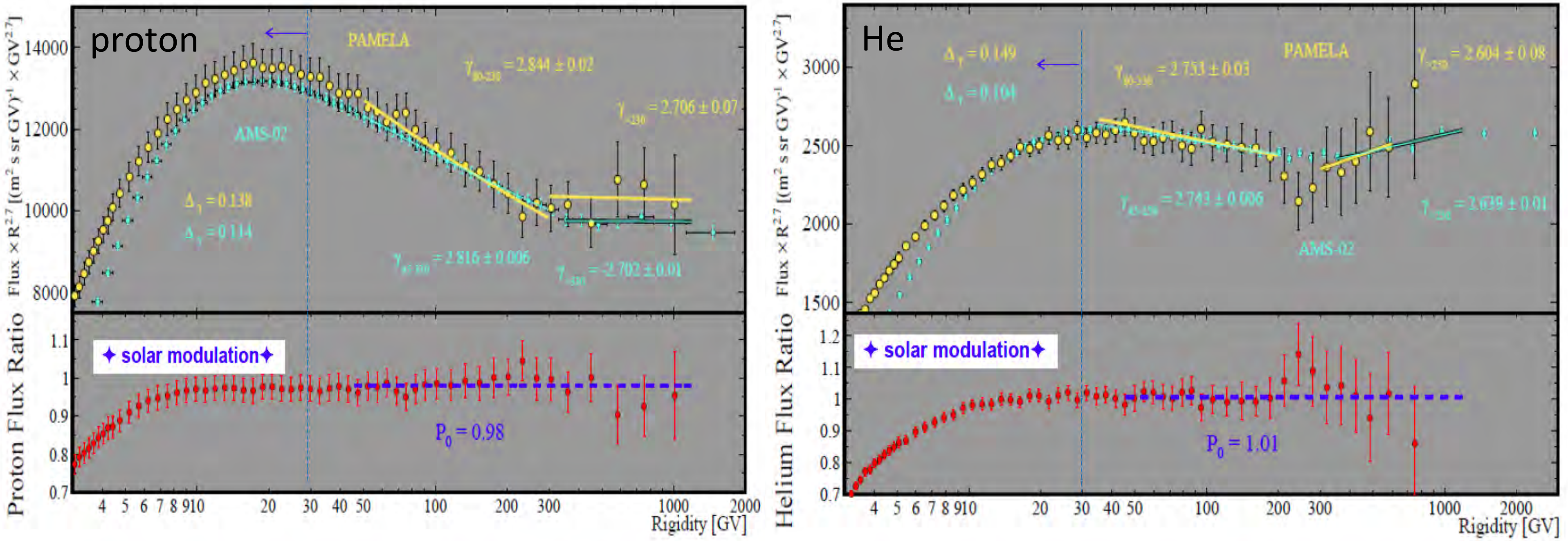
O. Adriani et al. - Science 332 (2011) 6025
M. Aguilar et al., PRL 115 (2015) 211101

1.011

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]

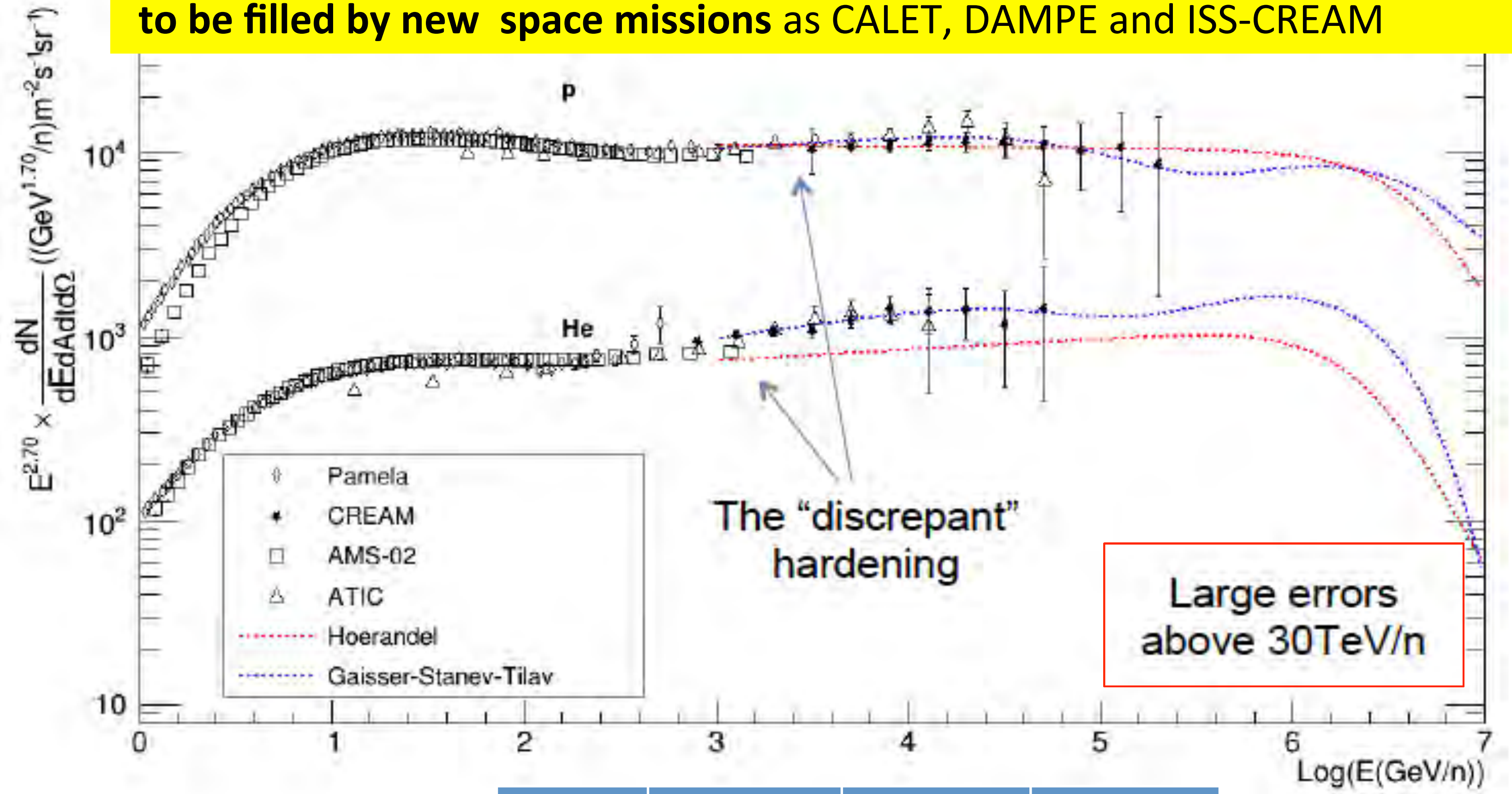
O. Adriani et al., Phys. Rep. 544 (2014) 323 ; M. Aguilar et al., PRL 114 (2015) 171103

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

The nergy gap above 2 TeV between PAMELA + AMS and CREAM data to be filled by new space missions as CALET, DAMPE and ISS-CREAM



The "discrepant" hardening

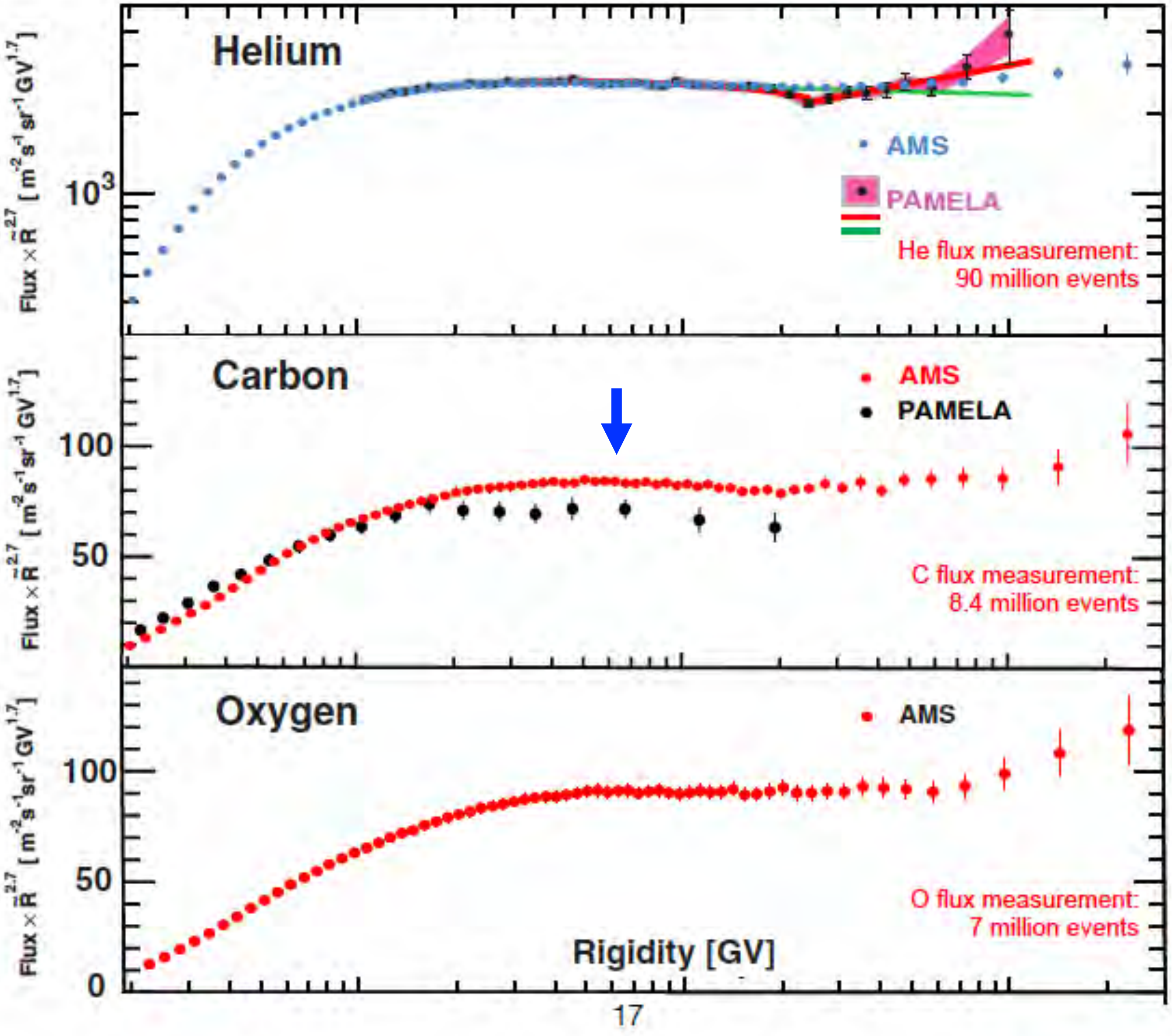
Large errors above 30TeV/n

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

Light nuclei: Primary fluxes vs Rigidity from PAMELA and AMS

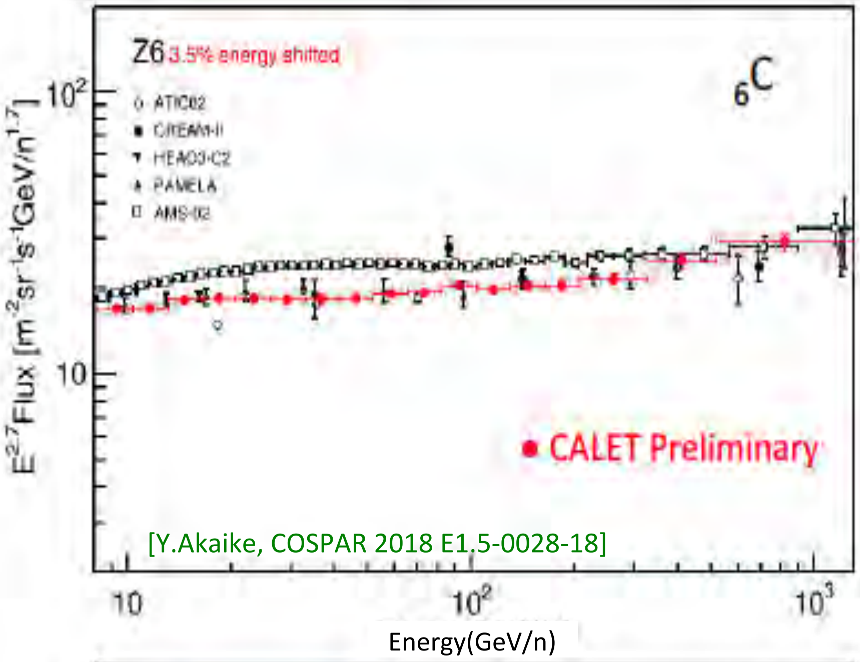


2018

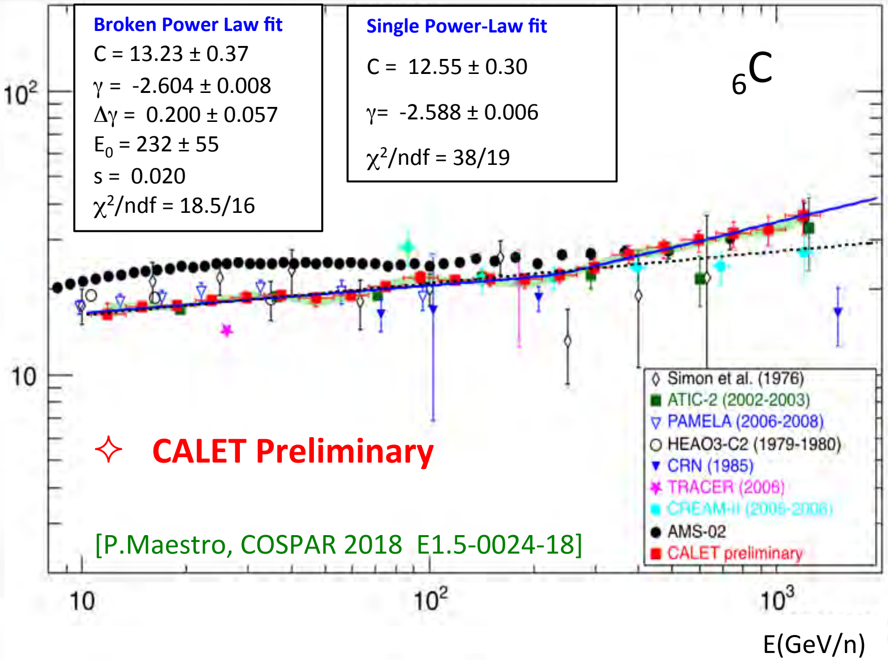
above 10 GV AMS **carbon** flux is ~15 % higher than PAMELA

no published data for **oxygen** flux by PAMELA

CALET (2018): Preliminary Energy spectra of C, O (2 independent analyses)



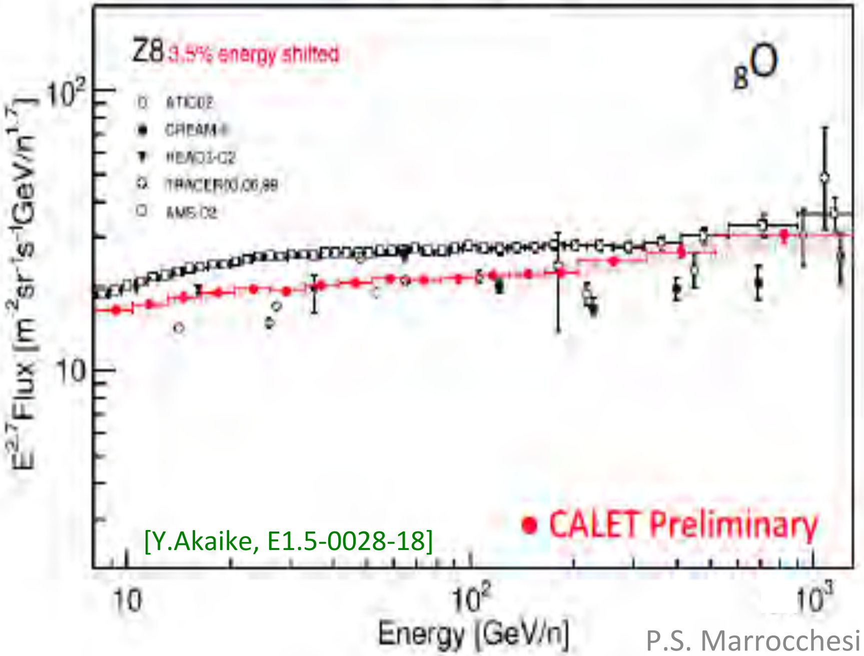
[Y.Akaike, COSPAR 2018 E1.5-0028-18]



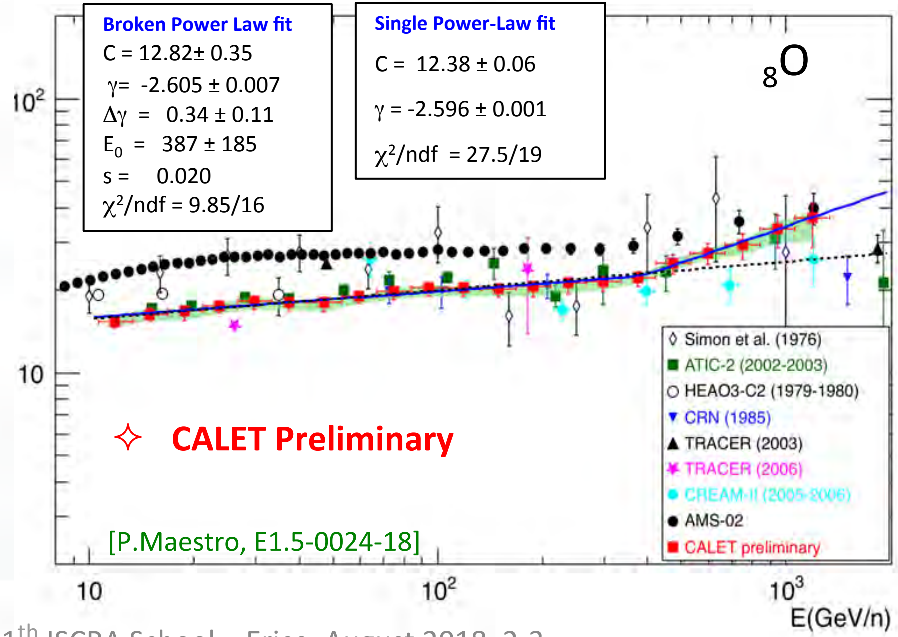
Broken Power Law fit
$C = 13.23 \pm 0.37$
$\gamma = -2.604 \pm 0.008$
$\Delta\gamma = 0.200 \pm 0.057$
$E_0 = 232 \pm 55$
$s = 0.020$
$\chi^2/ndf = 18.5/16$

Single Power-Law fit
$C = 12.55 \pm 0.30$
$\gamma = -2.588 \pm 0.006$
$\chi^2/ndf = 38/19$

[P.Maestro, COSPAR 2018 E1.5-0024-18]



[Y.Akaike, E1.5-0028-18]



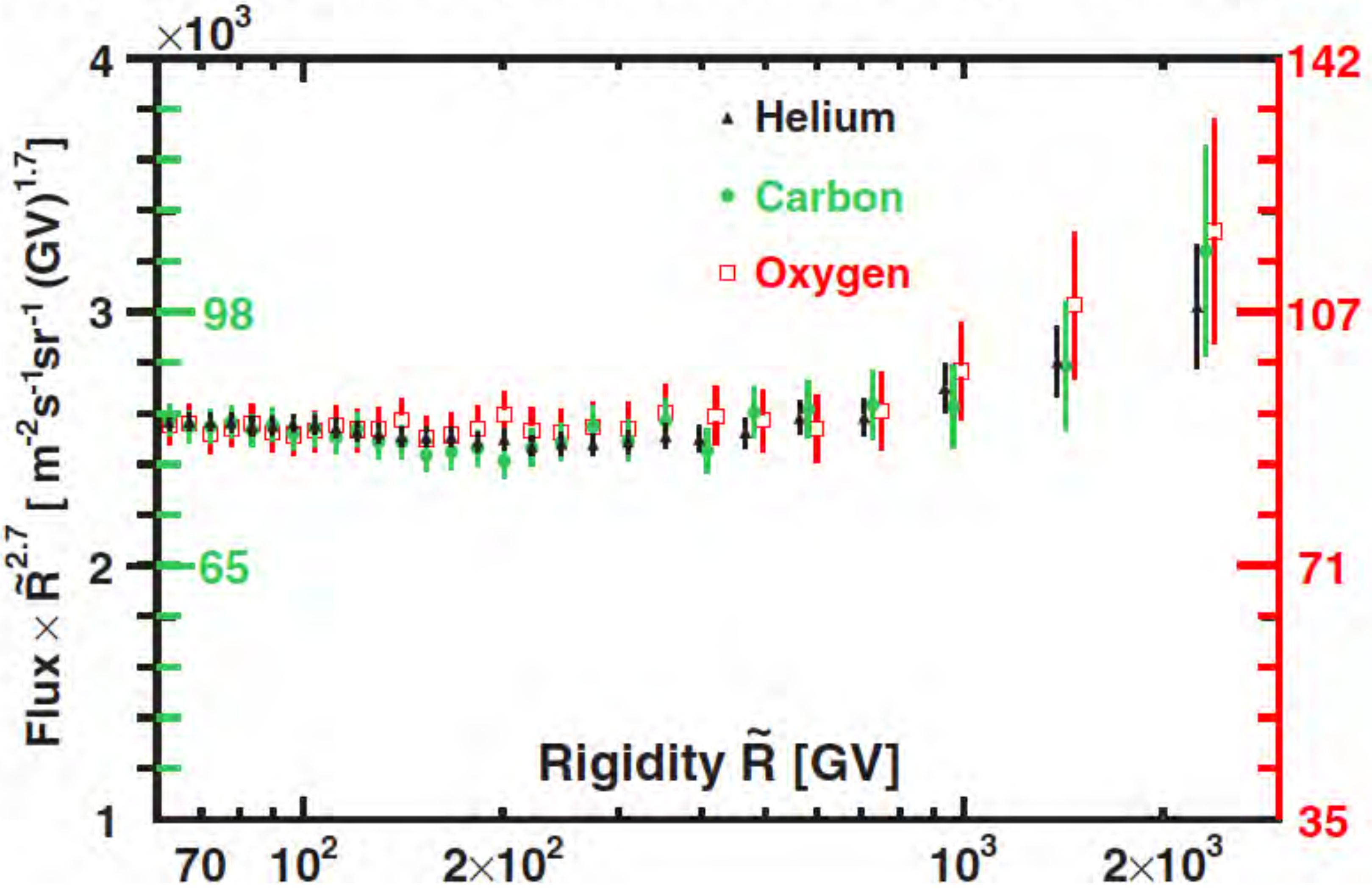
Broken Power Law fit
$C = 12.82 \pm 0.35$
$\gamma = -2.605 \pm 0.007$
$\Delta\gamma = 0.34 \pm 0.11$
$E_0 = 387 \pm 185$
$s = 0.020$
$\chi^2/ndf = 9.85/16$

Single Power-Law fit
$C = 12.38 \pm 0.06$
$\gamma = -2.596 \pm 0.001$
$\chi^2/ndf = 27.5/19$

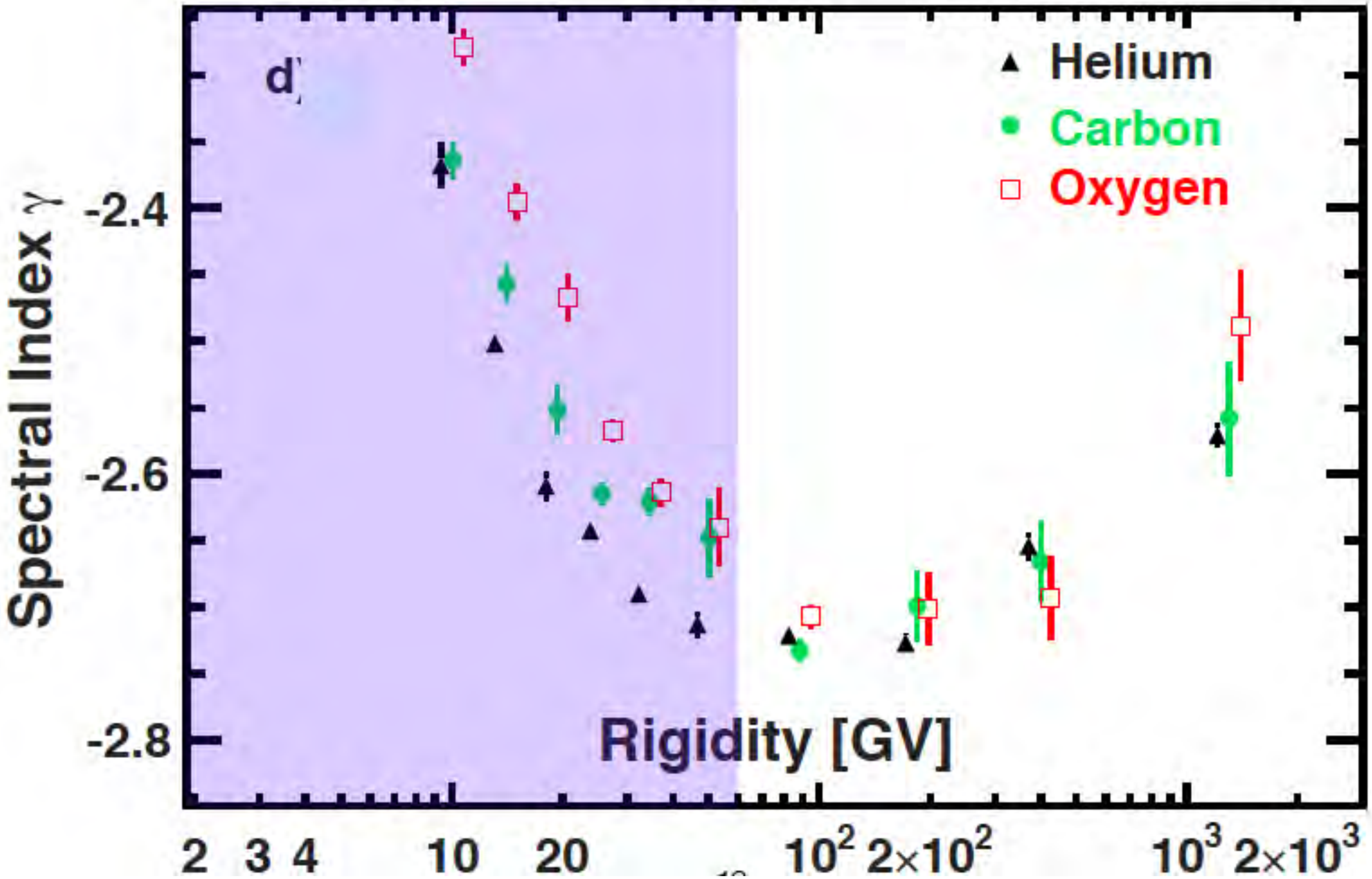
[P.Maestro, E1.5-0024-18]

Primary fluxes vs Rigidity from AMS

Remarkably, the 300GV hardening is a feature shared among all the heavier primaries.

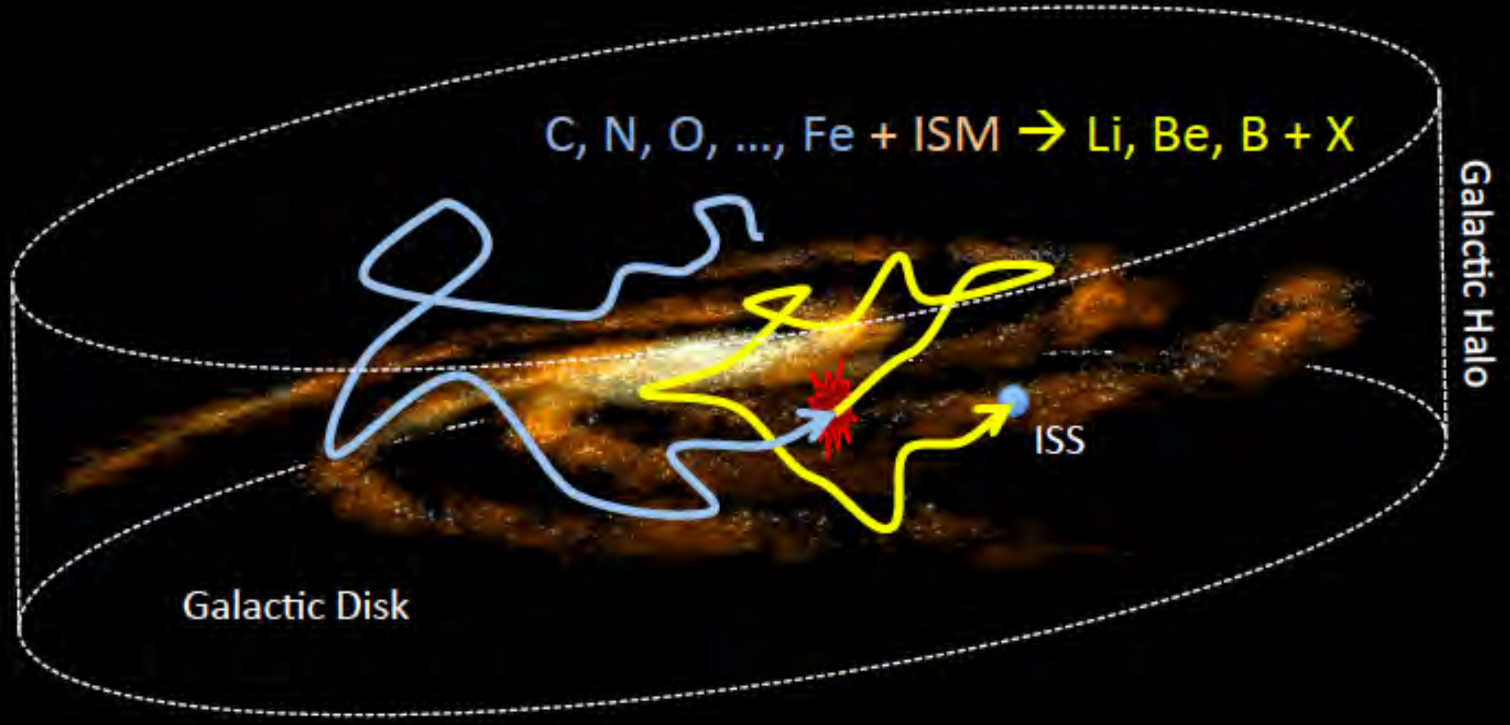


Primary fluxes: spectral index vs Rigidity from AMS



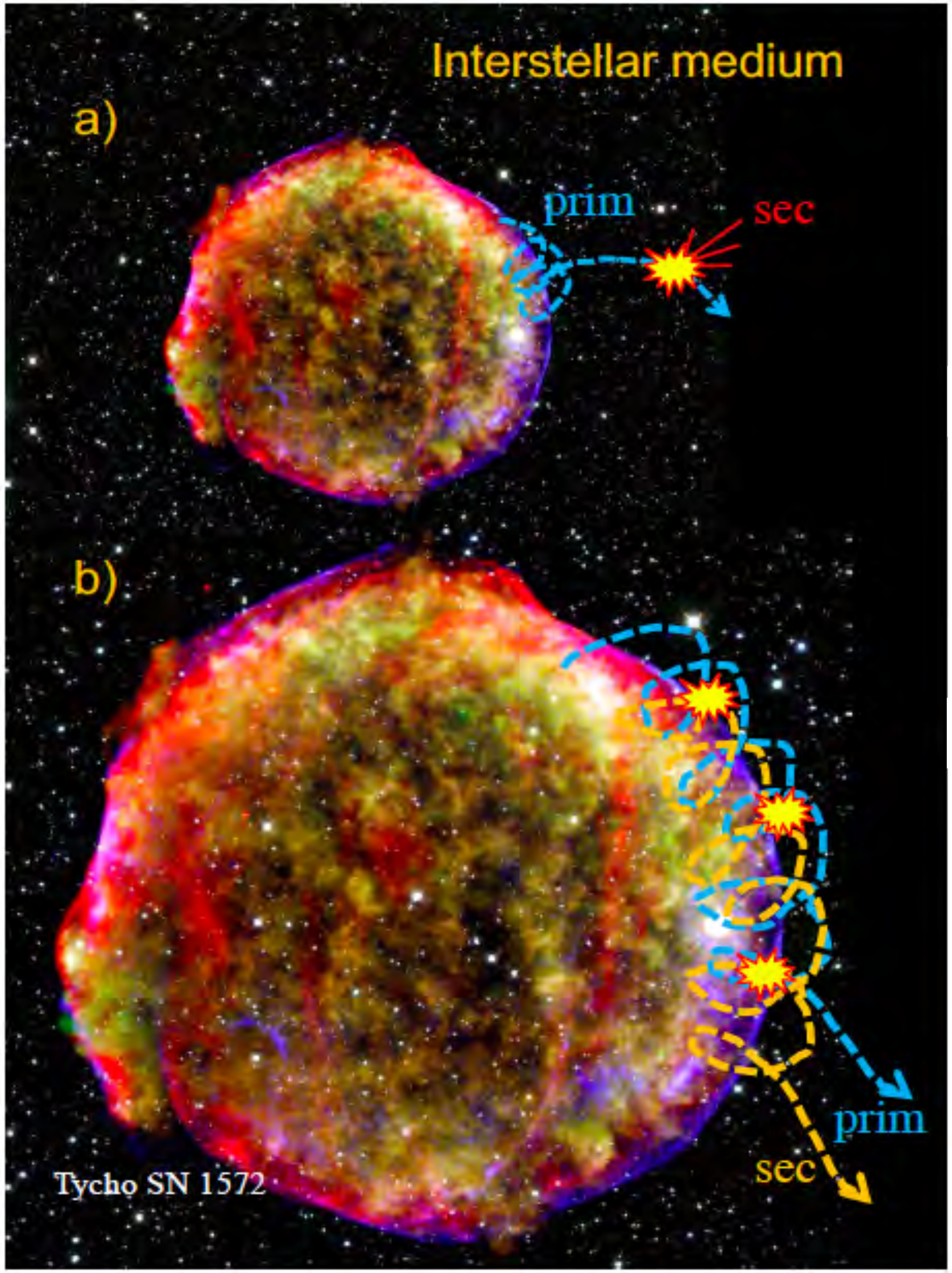
Secondary Nuclei in Cosmic Rays

Lithium, Beryllium and Boron are mostly to be produced purely from collision of cosmic rays, such as Carbon and Oxygen, with the interstellar medium (ISM).



C, N, O, …, Fe + ISM → Li, Be, B + X

The study of the secondary species is important for the understanding of the origin and propagation of cosmic rays.



Production of secondaries in SNR shock

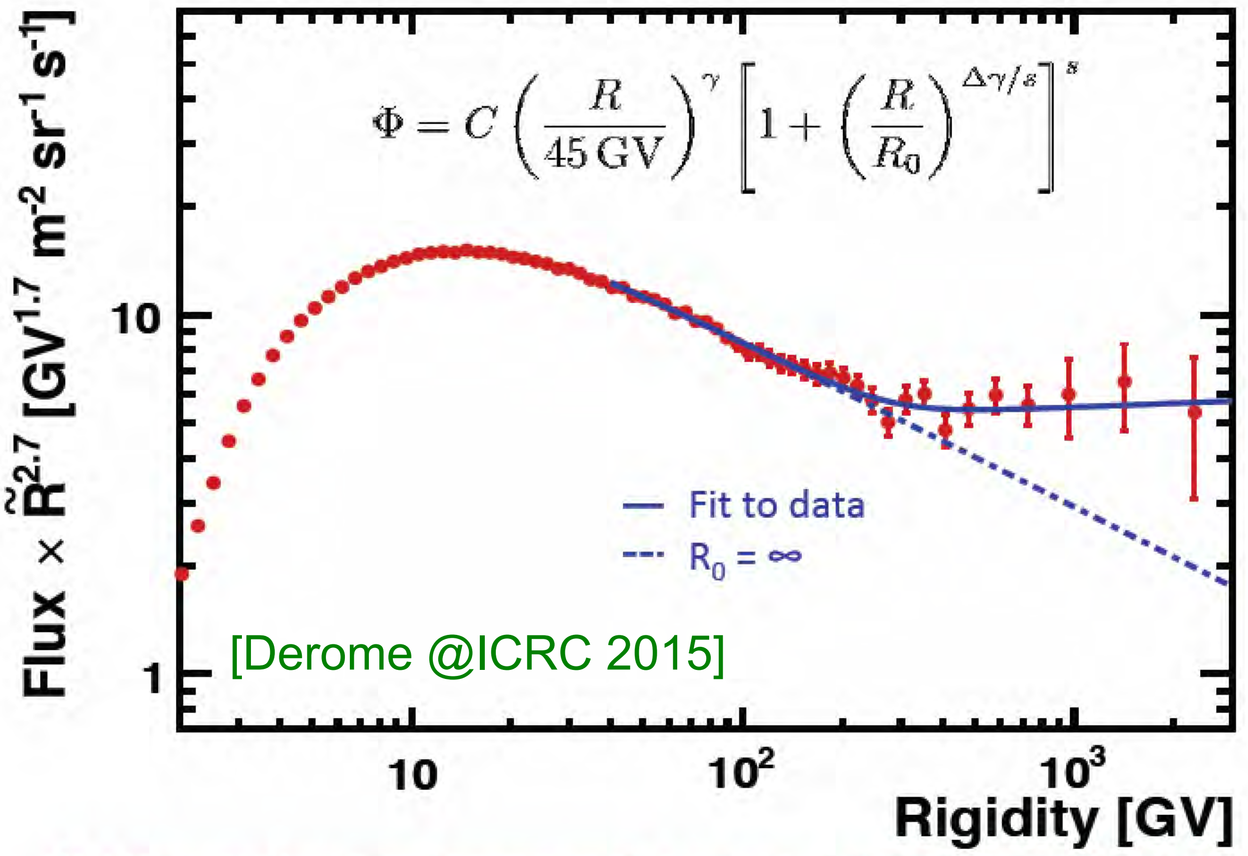
(a) In the "standard" scenario, secondary species are produced in the interstellar medium – softer spectrum at all energies

(b) In the SNR scenario, some proportion of secondary species is produced in the shock and then accelerated together with primary species – harder spectrum at high energies

[I. Mosklenko, 2018]

2015: Lithium flux from AMS-02 shows a hardening !

- measured in the rigidity range 2 GV – 3 TV



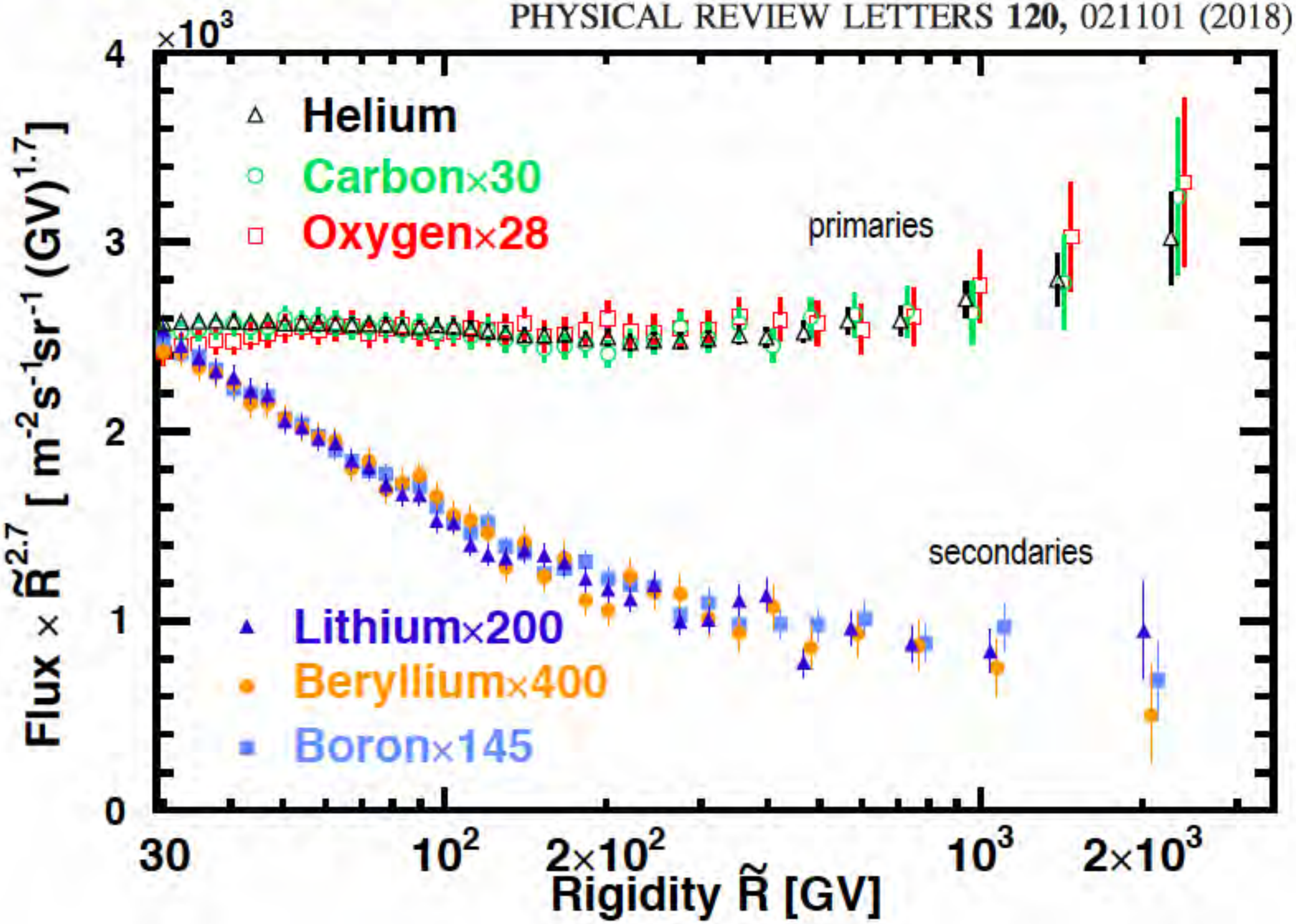
[Derome @ICRC 2015]

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

2018

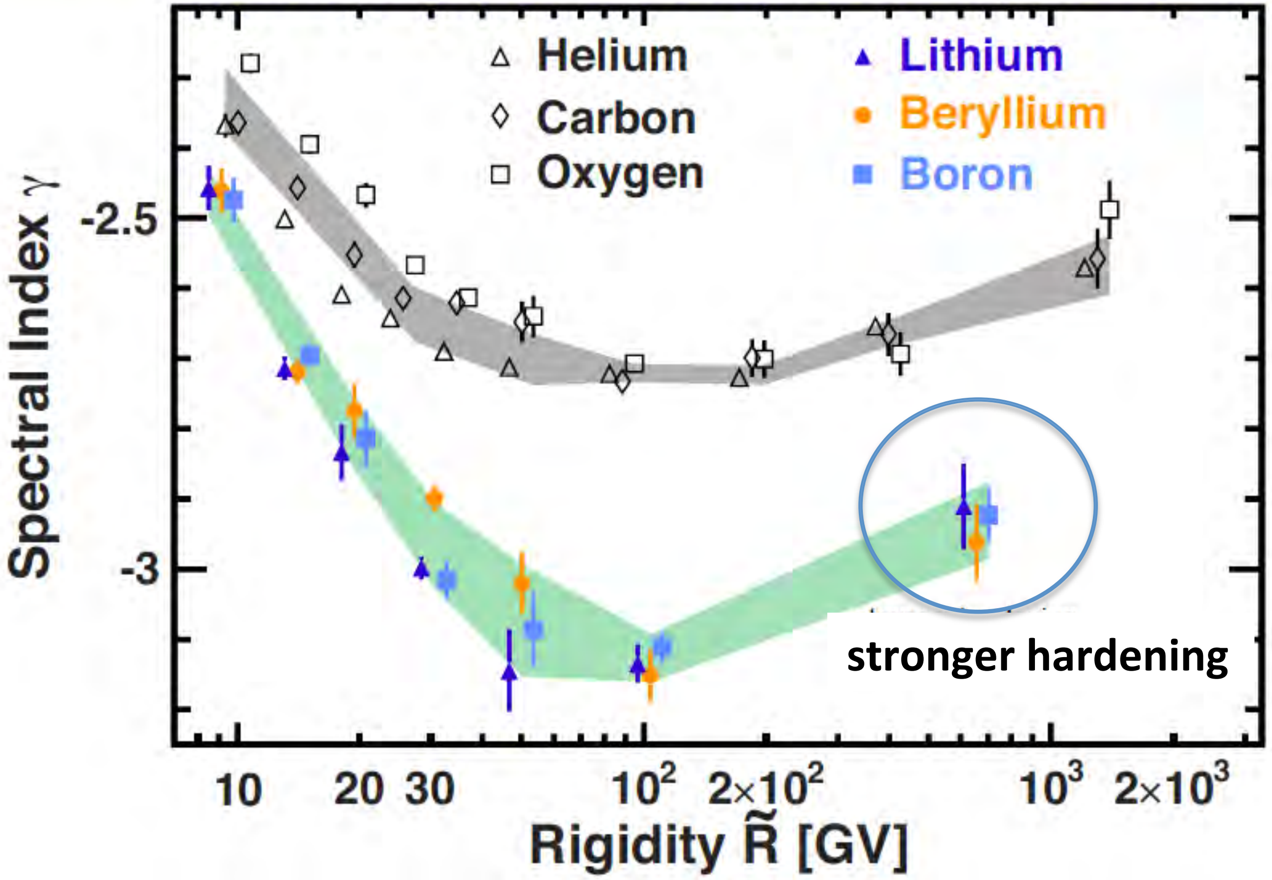
Primary and Secondary Cosmic Ray Fluxes

PHYSICAL REVIEW LETTERS **120,** 021101 (2018)



Primary and Secondary Cosmic Ray Spectral Indices

Deviate from single power law above 200 GV. Secondary hardening is stronger.



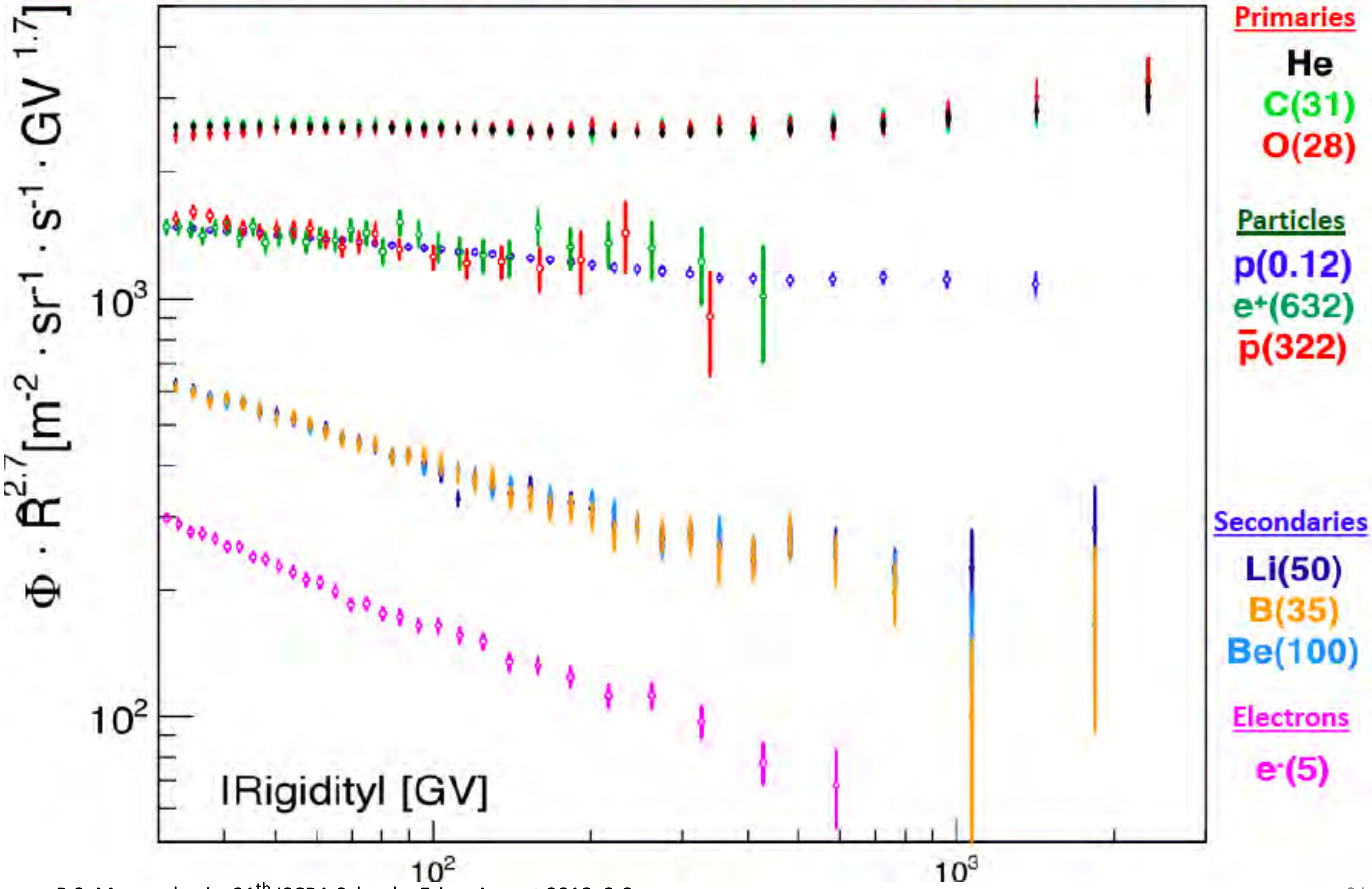
stronger hardening

If secondaries have a similar hardening to the one of the primaries, then hardening can be related to properties of the **injected spectra at their sources**.

If the secondary hardening is stronger than primaries one, than the hardening can be related **propagation properties**.

Summary of AMS results on Cosmic Ray Fluxes

High energy cosmic ray fluxes have 4 classes of rigidity dependence.



The CR hadronic sector puzzle (*observations*)

Emerging picture from current observations:

① unexpected pattern from primaries: He, C, and O fluxes share the same energy dependence, showing a change of spectral index at rigidity R ~300 GV (approx.)

② hardening of secondaries seems to be steeper than primaries

③ violation of universality of spectral indices: protons spectrum is softer by $\Delta\gamma \sim 0.1$

④ positron spectral index energy dependence similar to proton and anti-proton

WANTED: precision measurements of p, He and light nuclei in the multi-TeV energy range

- position of spectral breaks and $\Delta\gamma$ for each species
- differential measurements of spectral $d\gamma/dE$ + extension to higher energy
- exploration of energies above 100 TeV

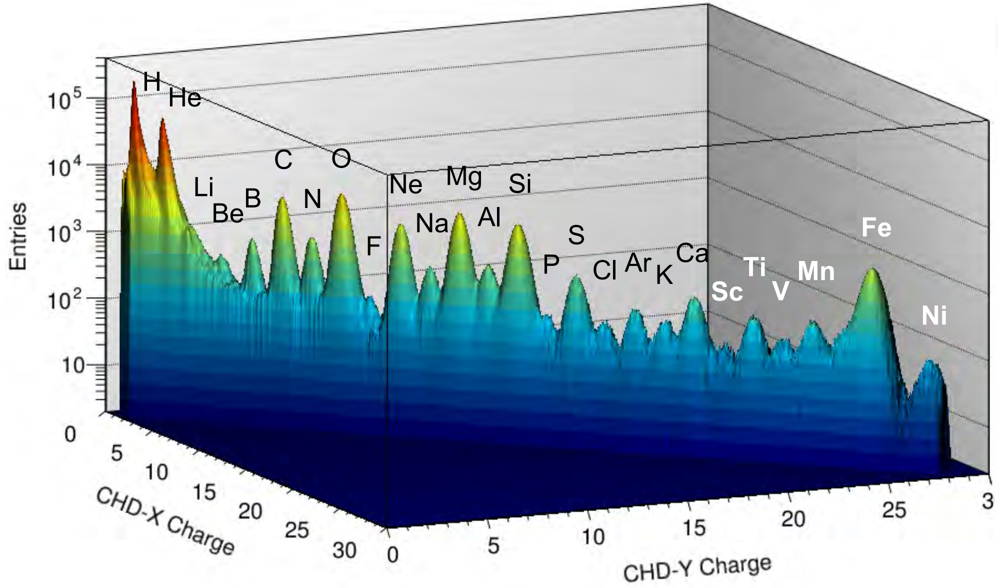
Above Oxygen: CALET Preliminary Fluxes of primaries (2018)

Flux measurement:

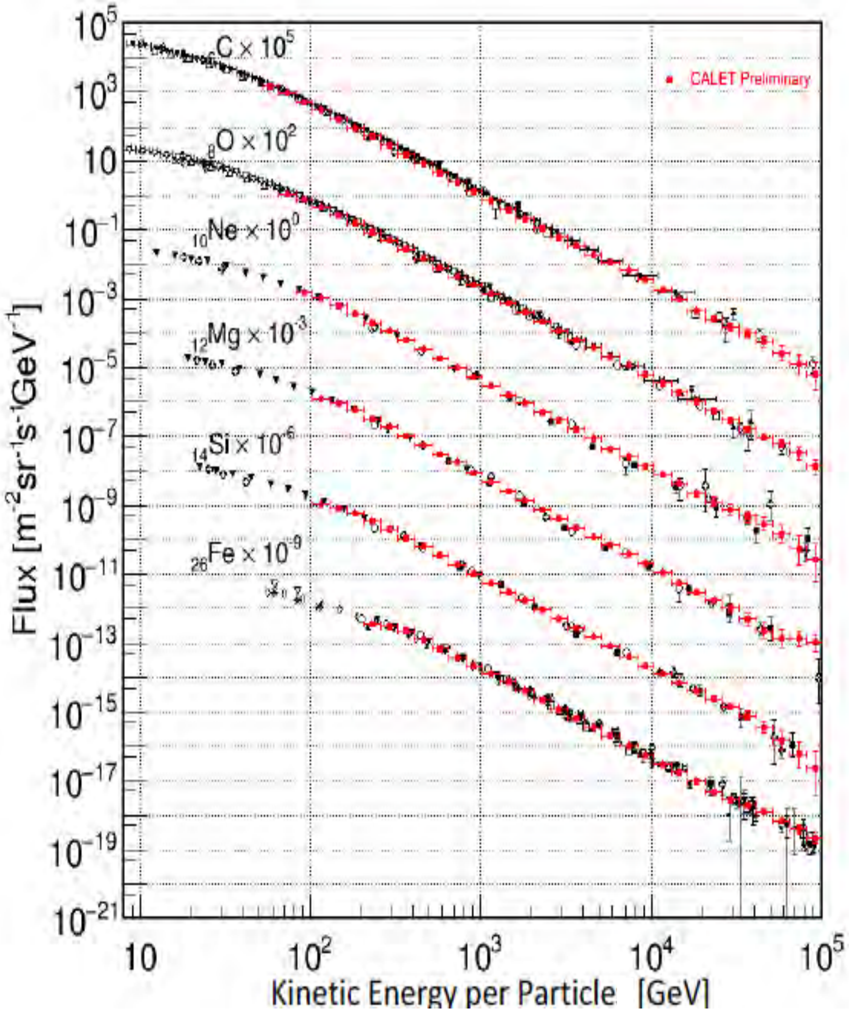
$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

N(E): Events in unfolded energy bin
$S\Omega$: Geometrical acceptance
T : Live time
$\varepsilon(E)$: Efficiency
ΔE : Energy bin width

Observation period:
2015.10.13 – 2017.10.31 (750 days)
Selected events: ~13 million

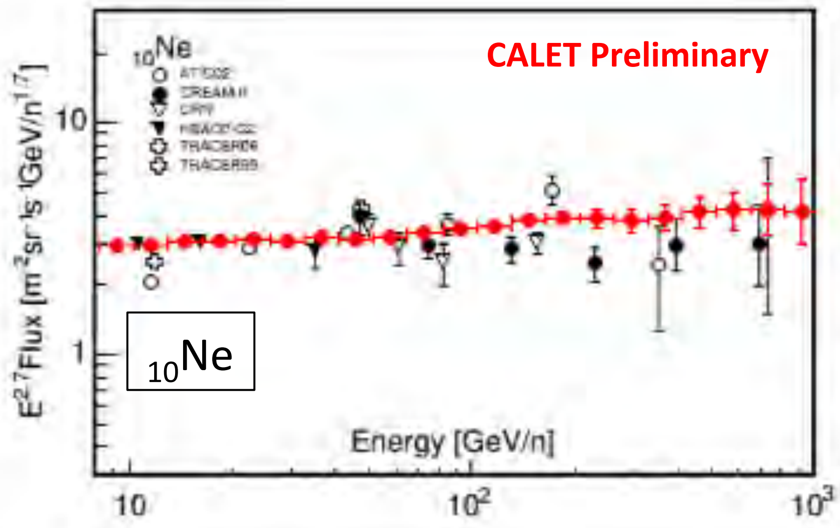


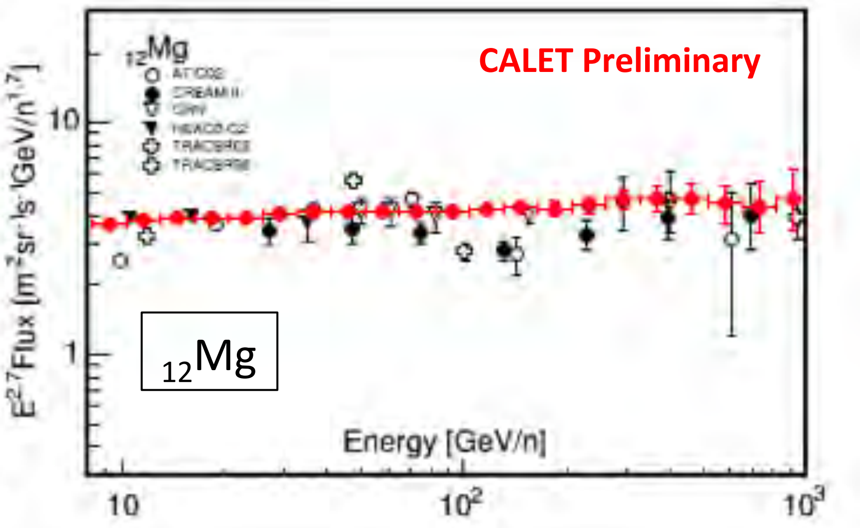
[Y.Akaike, E1.5-0028-18]

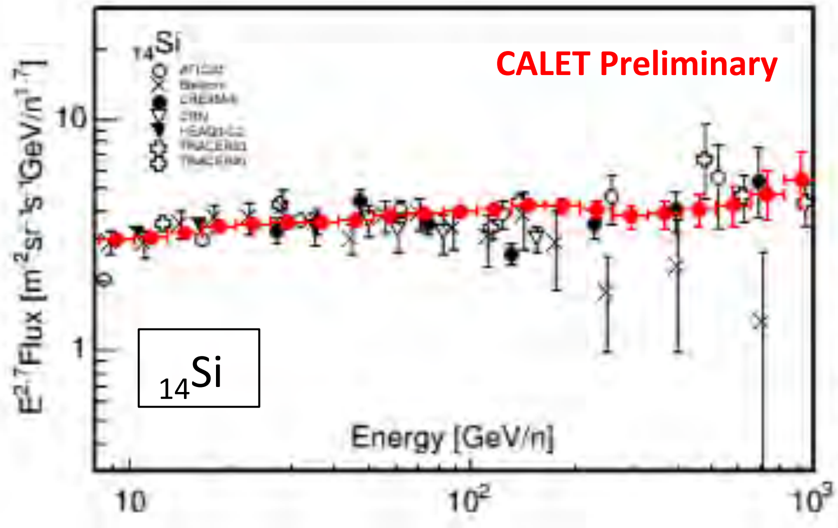


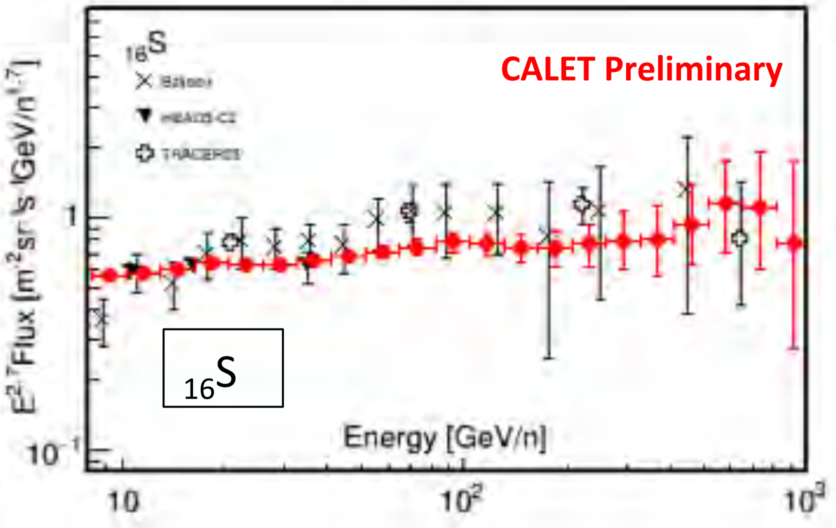
CALET: Preliminary Spectra of Nuclei with **Even** Atomic Number (Z = 10 ÷16)

[Y.Akaike, COSPAR 2018 E1.5-0028-18]



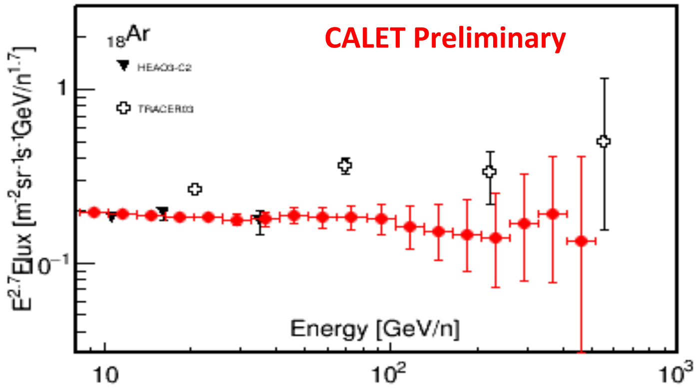


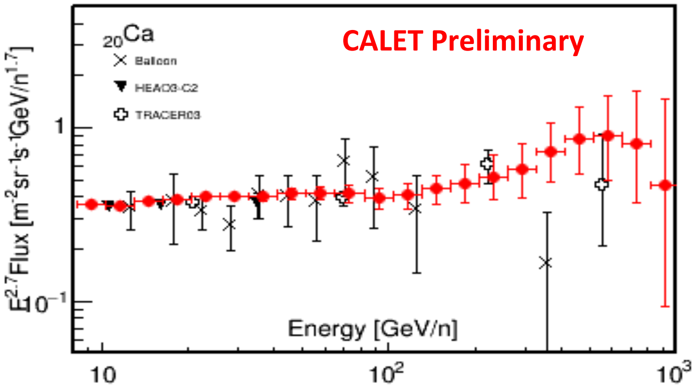




CALET: Preliminary Spectra of Nuclei with **Even** Atomic Number (Z = 18 ÷28)

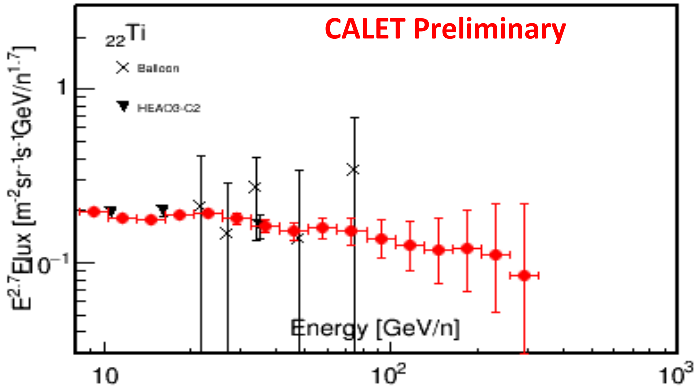
$_{18}$Ar

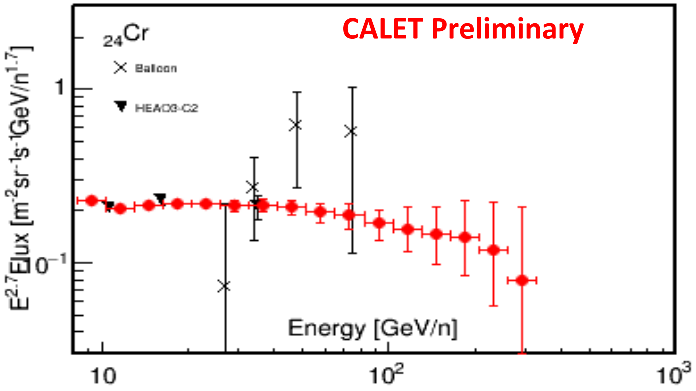




$_{20}$Ca

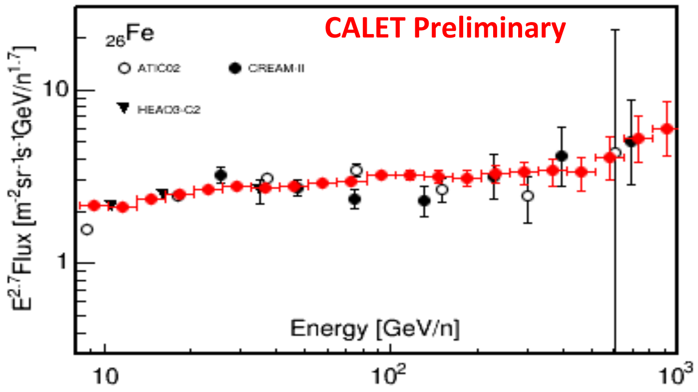
$_{22}$Ti

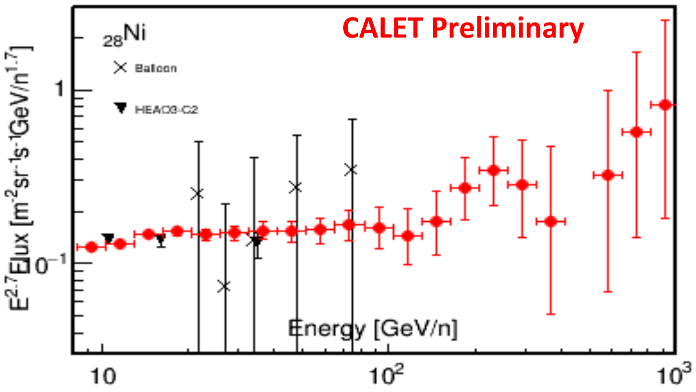




$_{24}$Cr

$_{26}$Fe





$_{28}$Ni

Let’s take a short break from CR spectra ...

and go back to an interesting instrumentation technique based on

TRANSITION RADIATION detection

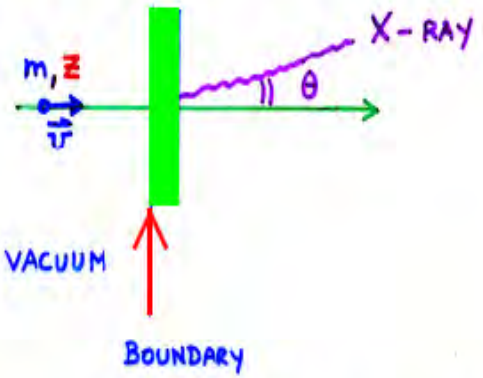
which is quite effective to separate electrons from hadrons at high energies

and has been used in balloon experiments (e.g.: TRACER) as well as

in space experiments (e.g.: AMS-02)

Transition Radiation Detectors (TRD)

- AT THE BOUNDARY BETWEEN TWO MEDIA OF DIFFERENT REFRACTION **indices** n_1, n_2 LIGHT IS EMITTED (MOSTLY IN THE X-RAY REGION) IN A CONE OF SEMIAPERTURE θ :

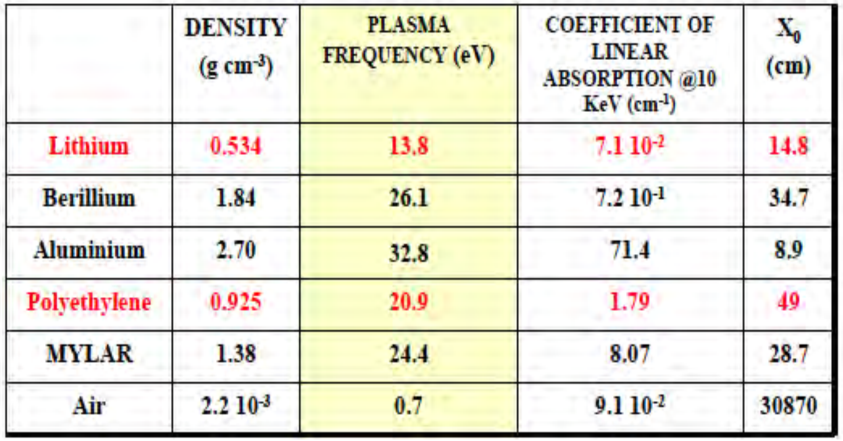


$$\theta \sim \frac{1}{\gamma}$$

- THE SPECTRUM IS GOVERNED BY A SCALE SET BY $\hbar\omega_p$ WHERE ω_p = PLASMA FREQUENCY
- $E_p = \hbar\omega_p$ IS PROPORTIONAL TO $\sqrt{N_e} = \sqrt{\rho \frac{Z}{A} N_A}$ THE ELECTRON DENSITY IN THE MEDIUM
- TYPICAL VALUES $E_p \sim 20$ eV (e.g.: STYRENE)

The phenomenon was first predicted by two Russian physicists, Ginzburg and Frank, in 1945 (J. Phys.9 (1945) 353)

More than 20 years later, the first TR detector was exploited successfully in a HEP experiment at the CERN-ISR thanks to Garibyan who found in 1958 that ultra relativistic particles (γ>>1) emit TR in the X-band and that the radiated energy is proportional to the particle's Lorentz factor γ (i.e. the particle's energy).



	DENSITY ($g\ cm^{-3}$)	PLASMA FREQUENCY (eV)	COEFFICIENT OF LINEAR ABSORPTION @10 KeV (cm^{-1})	X_0 (cm)
Lithium	0.534	13.8	7.1 10^{-2}	14.8
Berillium	1.84	26.1	7.2 10^{-1}	34.7
Aluminium	2.70	32.8	71.4	8.9
Polyethylene	0.925	20.9	1.79	49
MYLAR	1.38	24.4	8.07	28.7
Air	2.2 10^{-3}	0.7	9.1 10^{-2}	30870

Transition Radiation Spectrum

- Transition radiation (TR) depends on:

– particle's energy and Z^2

– plasma frequencies of media ω_1 and ω_2

Photon yield

$$\langle N(\omega > 0.15\gamma\omega_1)\rangle \cong 0.5\, z^2 \alpha$$

TR has very **low intensity** ($\approx \alpha \approx 1/137$)

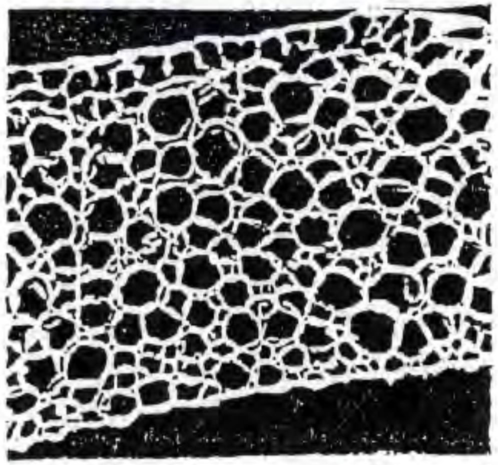
$\Rightarrow$ need many radiators

Low Z radiators are better :

- Absorption ~ Z^4 (photoelectric effect)
- Plasma freq ~ $Z^{1/2}$ (Tot. energy)

- Radiator's length should be of the order of formation length(*), and is proportional to γ_{th}

TRD Radiators



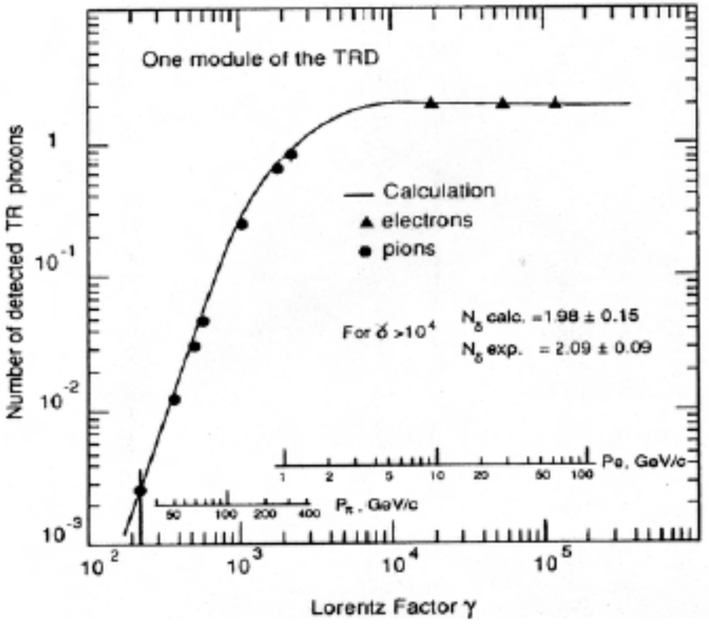
Microphotograph of polyethylene foam, 0.059 g/cm^3

Ideal radiator: material with high density of electrons (high ω_p) and low Z (small X-ray absorption $\propto Z^5$)

(*) the *formation length* is related to the destructive interference from radiation emitted on different surfaces

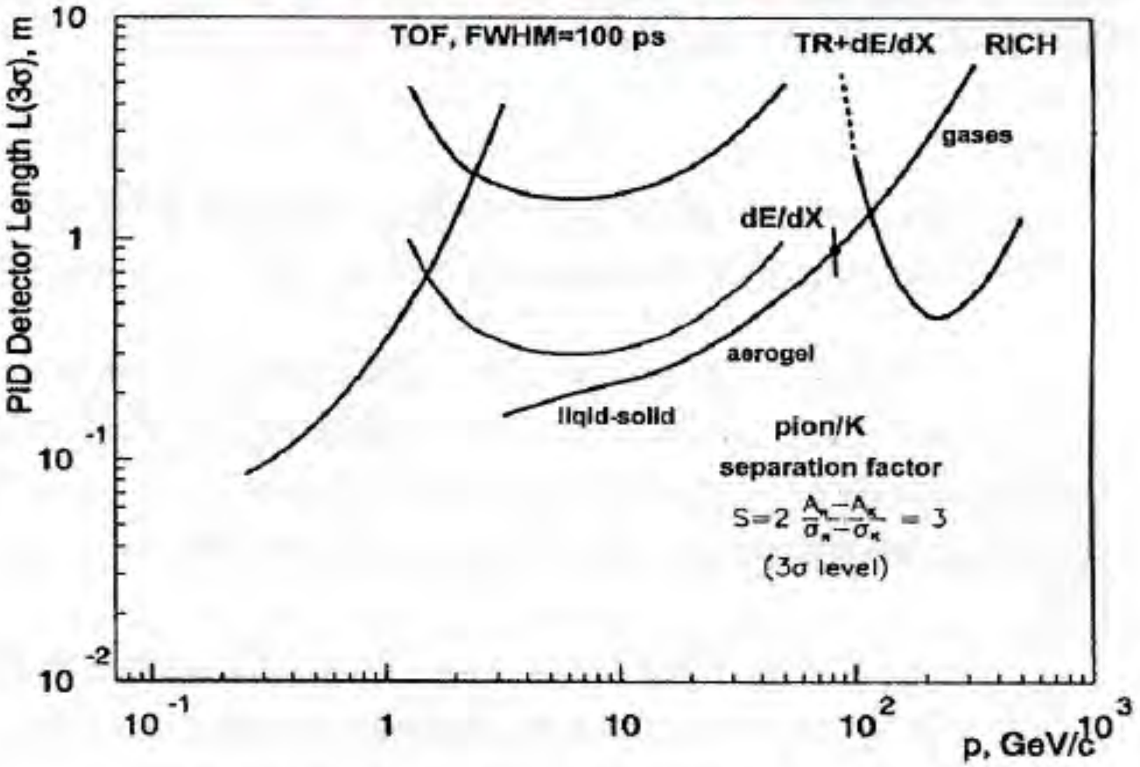
Cosmic-Ray Energy measurement with TR

- Measurements of high energy cosmic rays require:
  - large area detectors
  - light-weight detectors (for balloon and/or space-borne instruments)
- TRD satisfy requirements but TR yield is too low except for heavier nuclei ($Z \geq 3$)
- TR scales as $\mathbf{Z^2}$ with particle's charge Z
  => Particle IDentification (PID)
- **TR threshold** is typically
  between γ = 500 and 10^3
- **TR saturation** is typical onset
  at $\gamma \sim 10^4$ (possibly 10^5)



[TRD-1] B. Dolgoshein "Transition radiation Detectors" Nucl. Inst. Meth. A433, 533, 1999
[TRD-2] S.P.Wakely, 2002, Astroparticle Physics 18, 67

PID with TR vs others



Pion–kaon separation by different PID methods: the length of the detectors needed for 3 sigma separation.

While other **Particle IDentification** methods (e.g.: energy loss by ionization, ToF and Cherenkov radiaton) depend on the particle velocity, thereby representing only moderate identification possibilities for ultra relativistic particles (β -> 1),

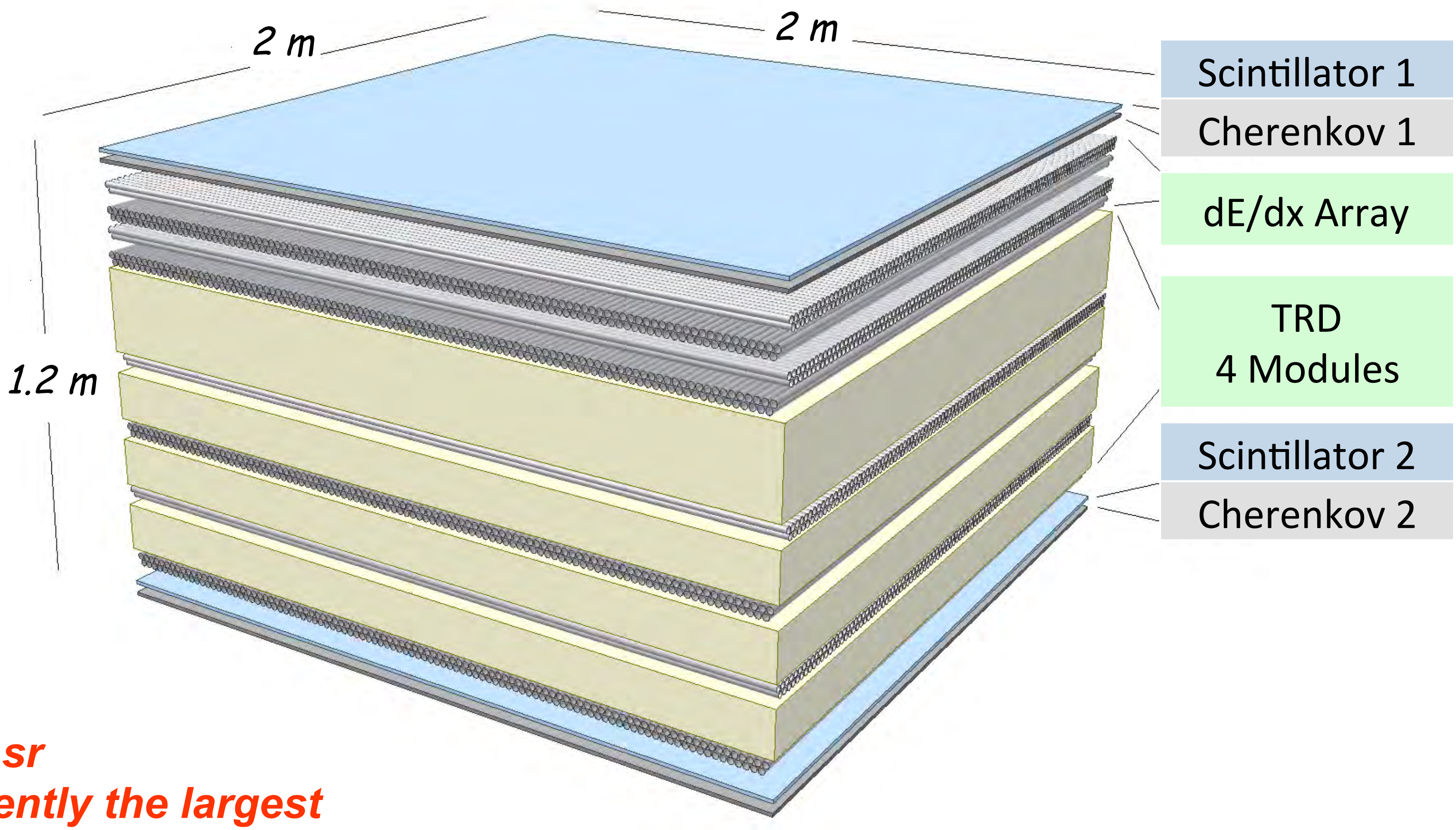
the γ**-dependent** effect of TR is extremely valuable for PID at very high energies.

TRACER

Transition Radiation Array for Cosmic Energetic Radiation

2 flights:
ANTARCTICA 2003 (14 days)
SWEDEN to CANADA 2006 (5 days)

TRACER (detector concept)



5 m^2 sr
Currently the largest balloon-borne cosmic-ray detector

1600 proportional tubes, 2 cm diam., 200 cm long

TRACER Detector response

Electromagnetic processes are used to determine Z and E of the CR nuclei:

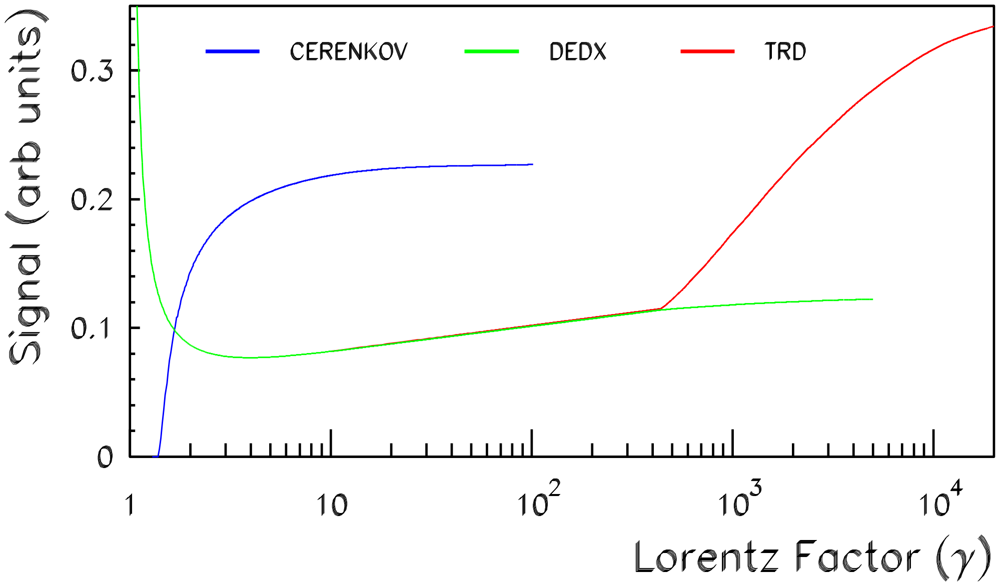
- *Acrylic Cherenkov Counter **(γ < 10)***
- *Specific Ionization in Gas **(4 < γ < 1000)***
- *Transition Radiation Detector **(γ > 400)***

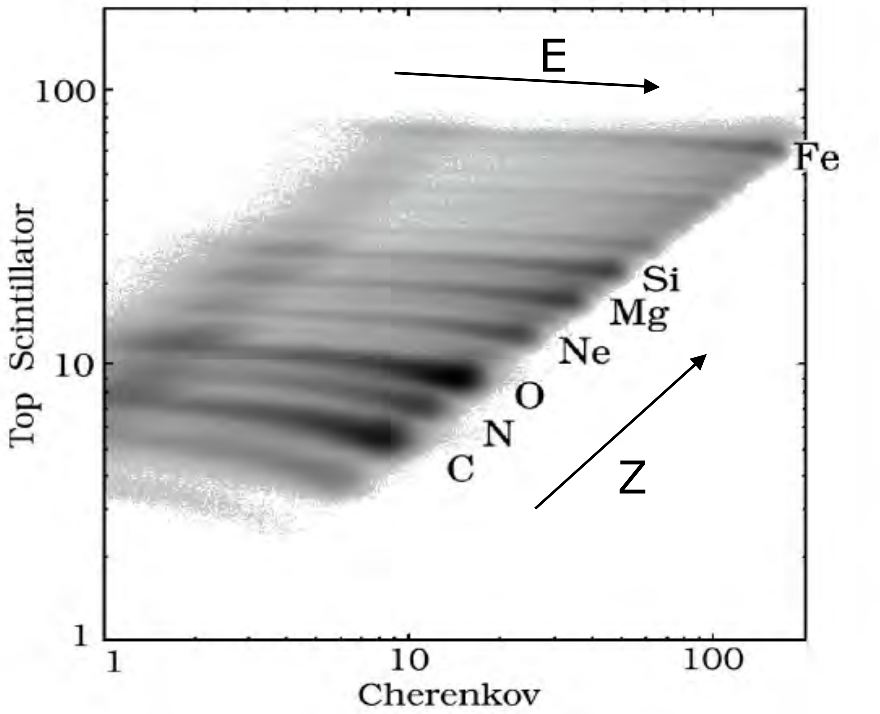
Energy range: 10^9 - 10^{13} eV/amu

Charge resolution   O: 0.3 e

$\Delta E/E$ < 10% (CER, TRD); 40-90% (dE/dx)

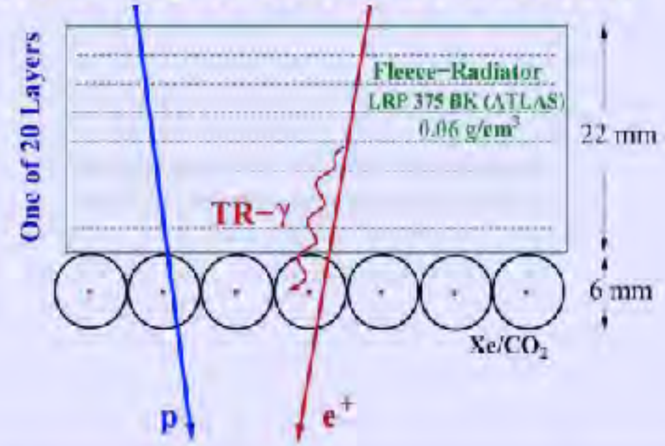
(CER+Scint.) **Fe: 0.5 e**

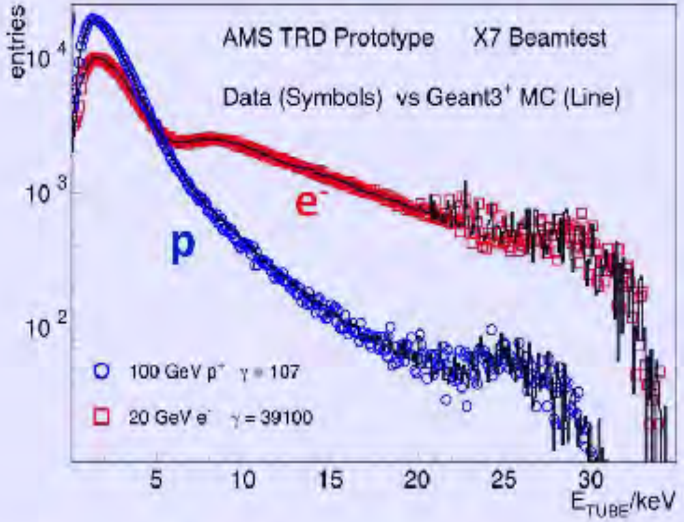




AMS Antiproton/electron identification with TRD

Identifies nuclei by dE/dX and e± by transition radiation

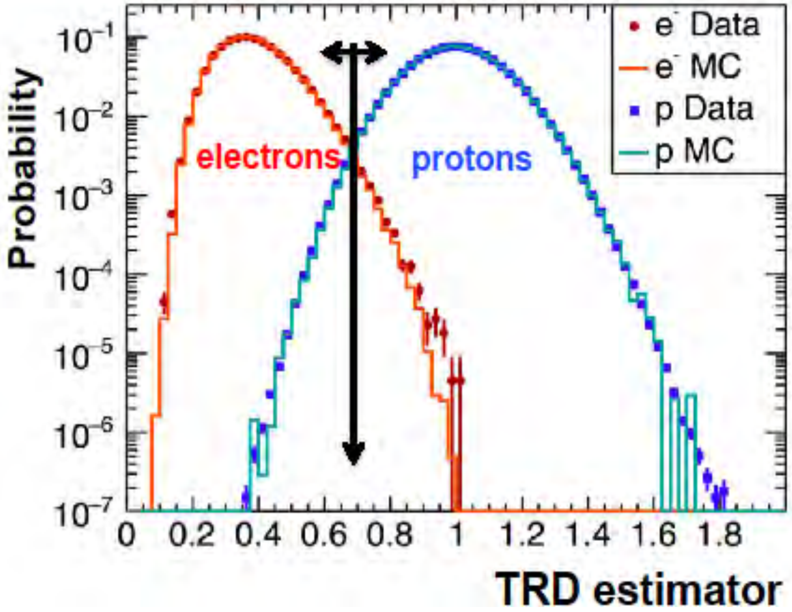


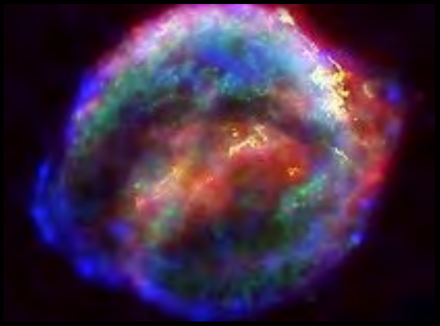


N = 20 layers

$$P_p = \sqrt[n]{\prod_{i}^{n} P_p^{(i)}(A)} \qquad P_e = \sqrt[n]{\prod_{i}^{n} P_e^{(i)}(A)}$$

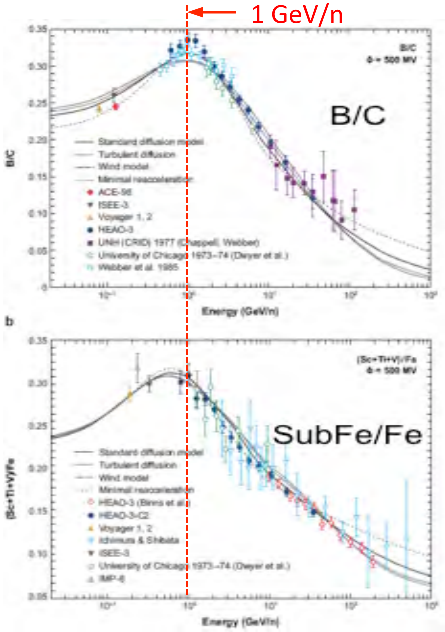
TRD estimator = -ln($P_e/(P_e+P_p)$)

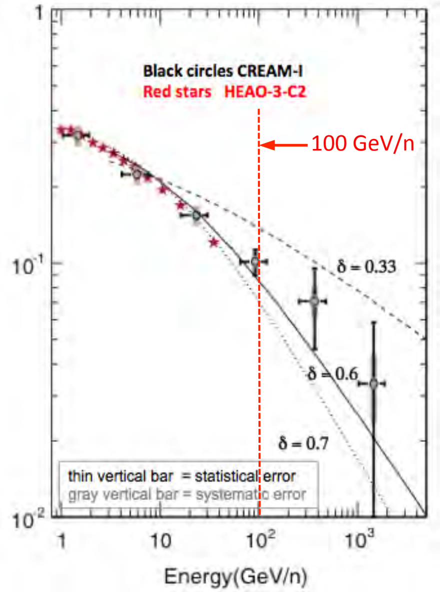



SN 1604

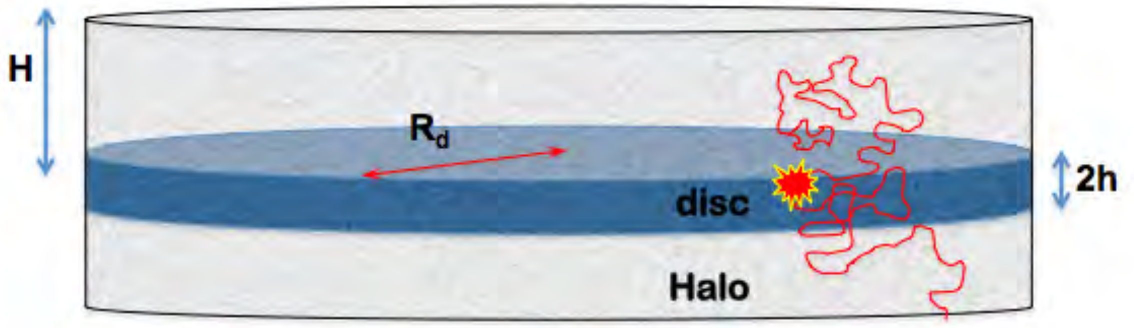
Secondary-to-Primary Ratios

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 $E^{-\delta}$



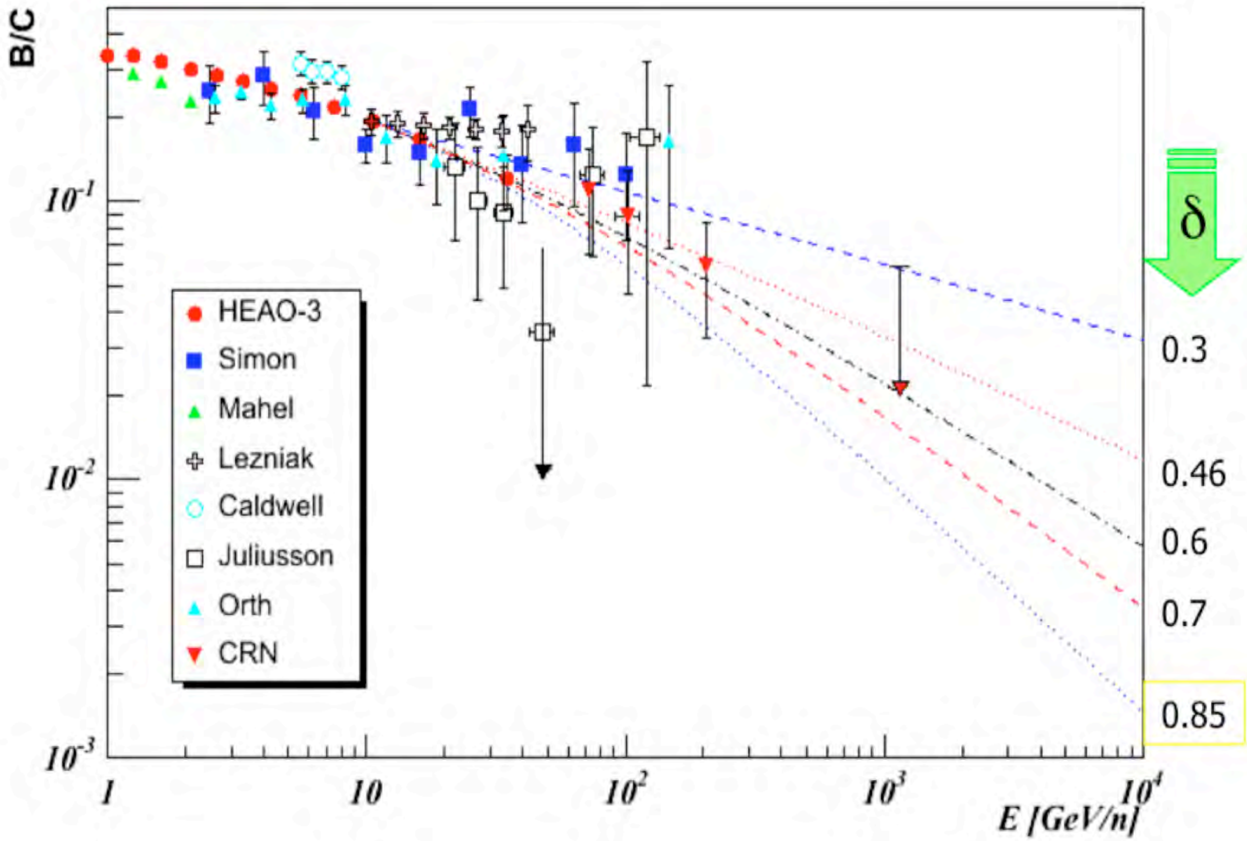
PRIMARY COSMIC RAY SPECTRUM AT EARTH

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

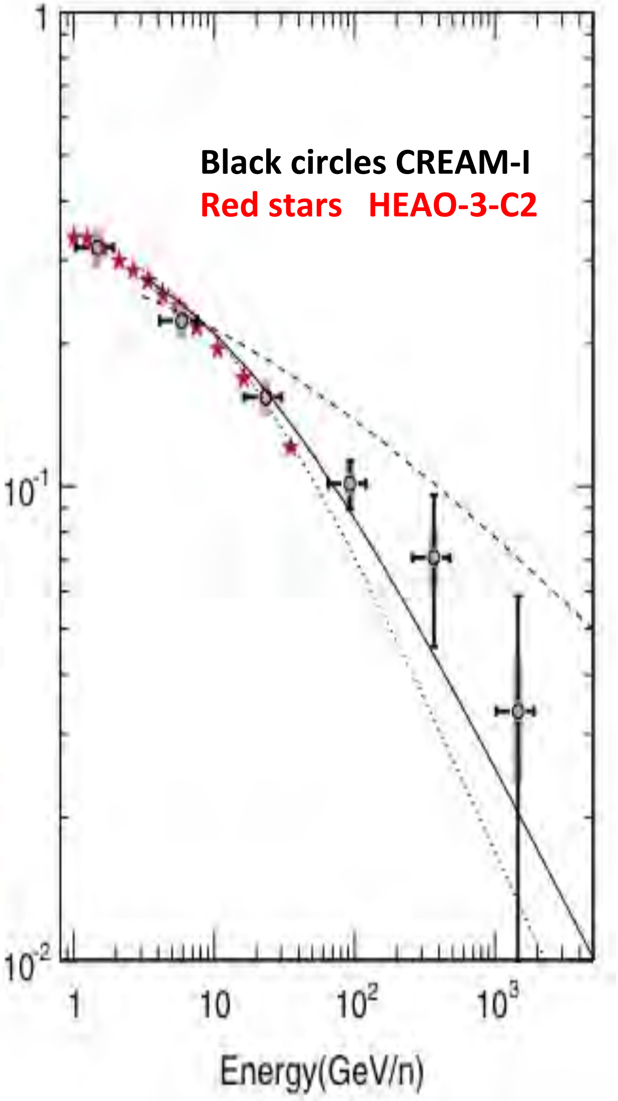
- **BUT** the diffusion coefficient might also depend on position and have a **tensor** character

Boron to Carbon ratio vs. Energy/nucleon

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

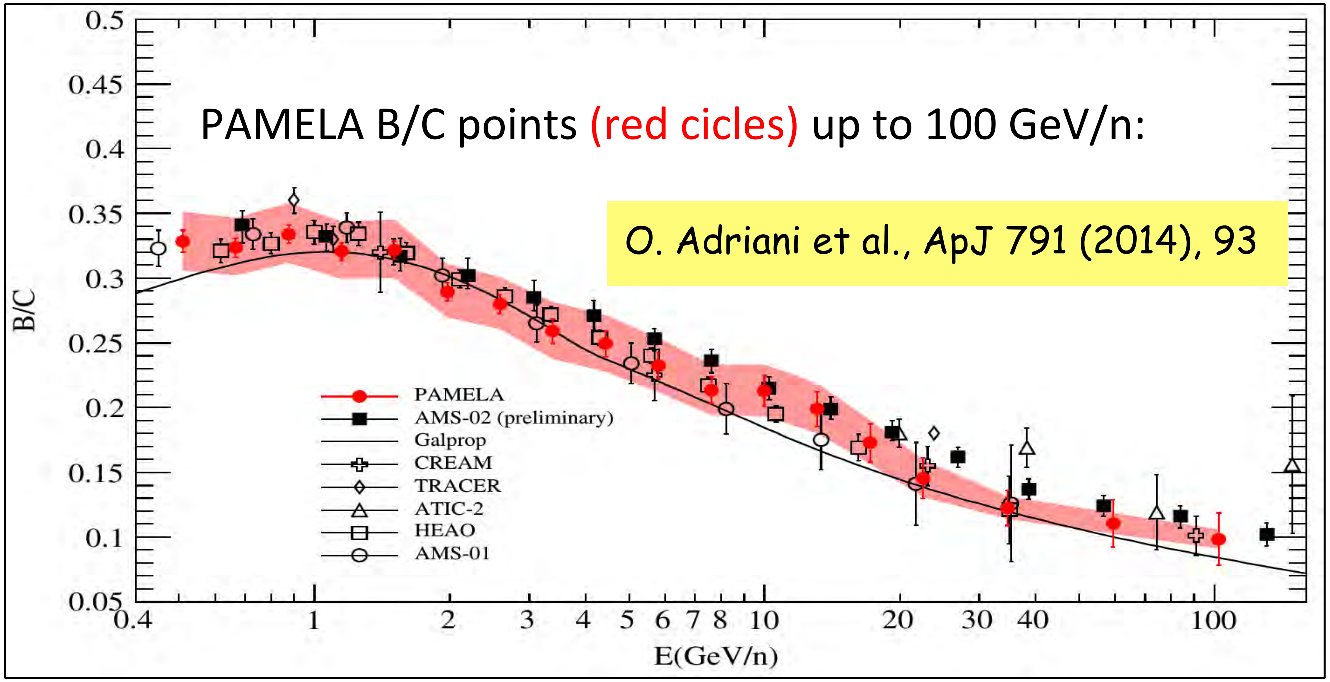


above 100 GeV/n with CREAM



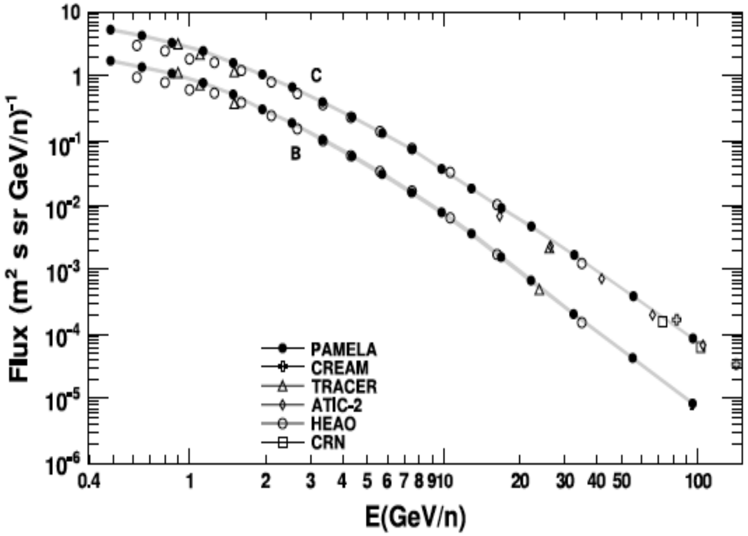
Black circles CREAM-I
Red stars HEAO-3-C2

PAMELA (2014): Boron and Carbon fluxes and B/C to 100 GeV/n



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

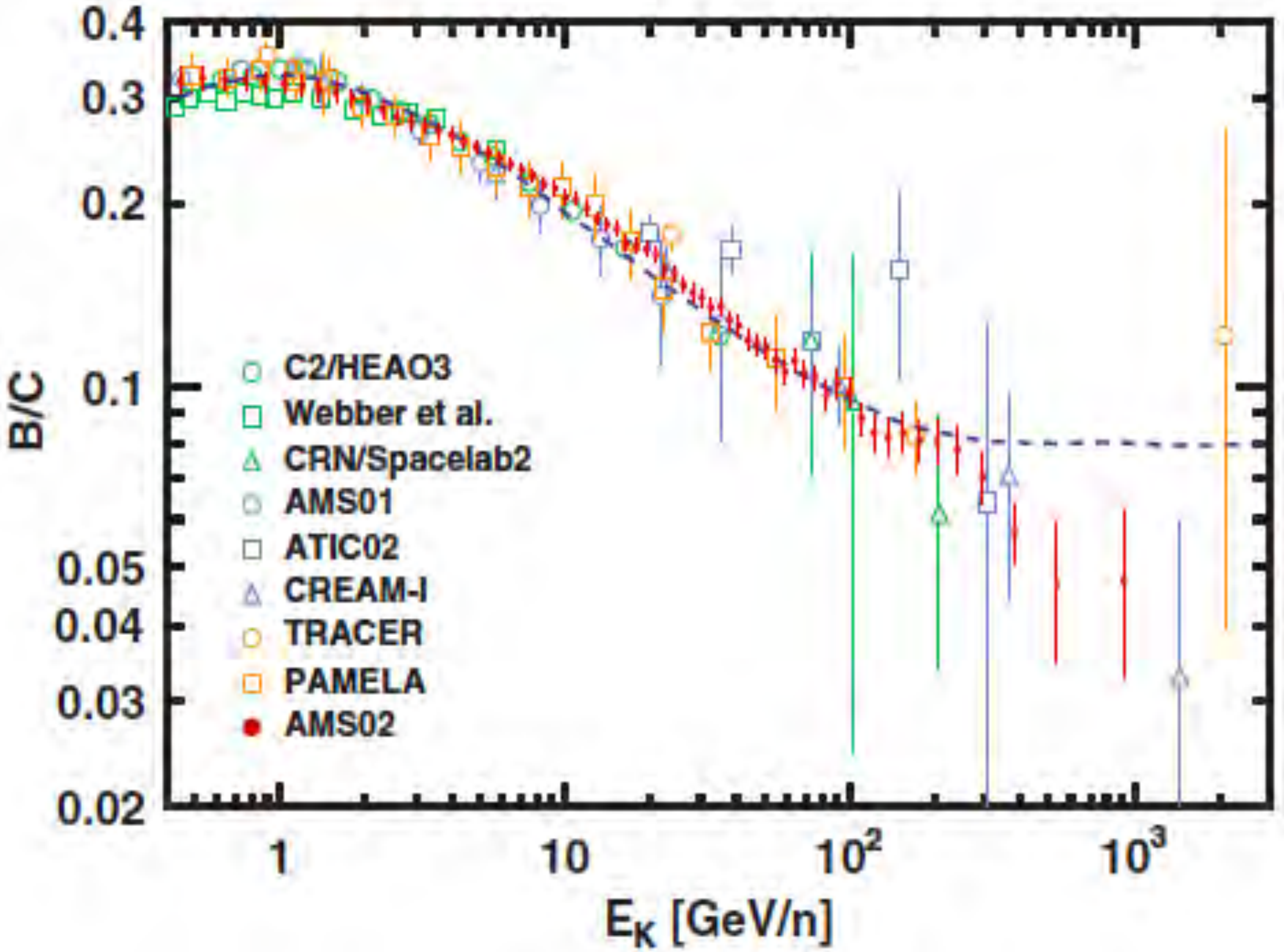
O. Adriani et al., ApJ 791 (2014), 93



B and C differential fluxes to 100 GeV/n

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

B/C measurements (AMS-02 red points)

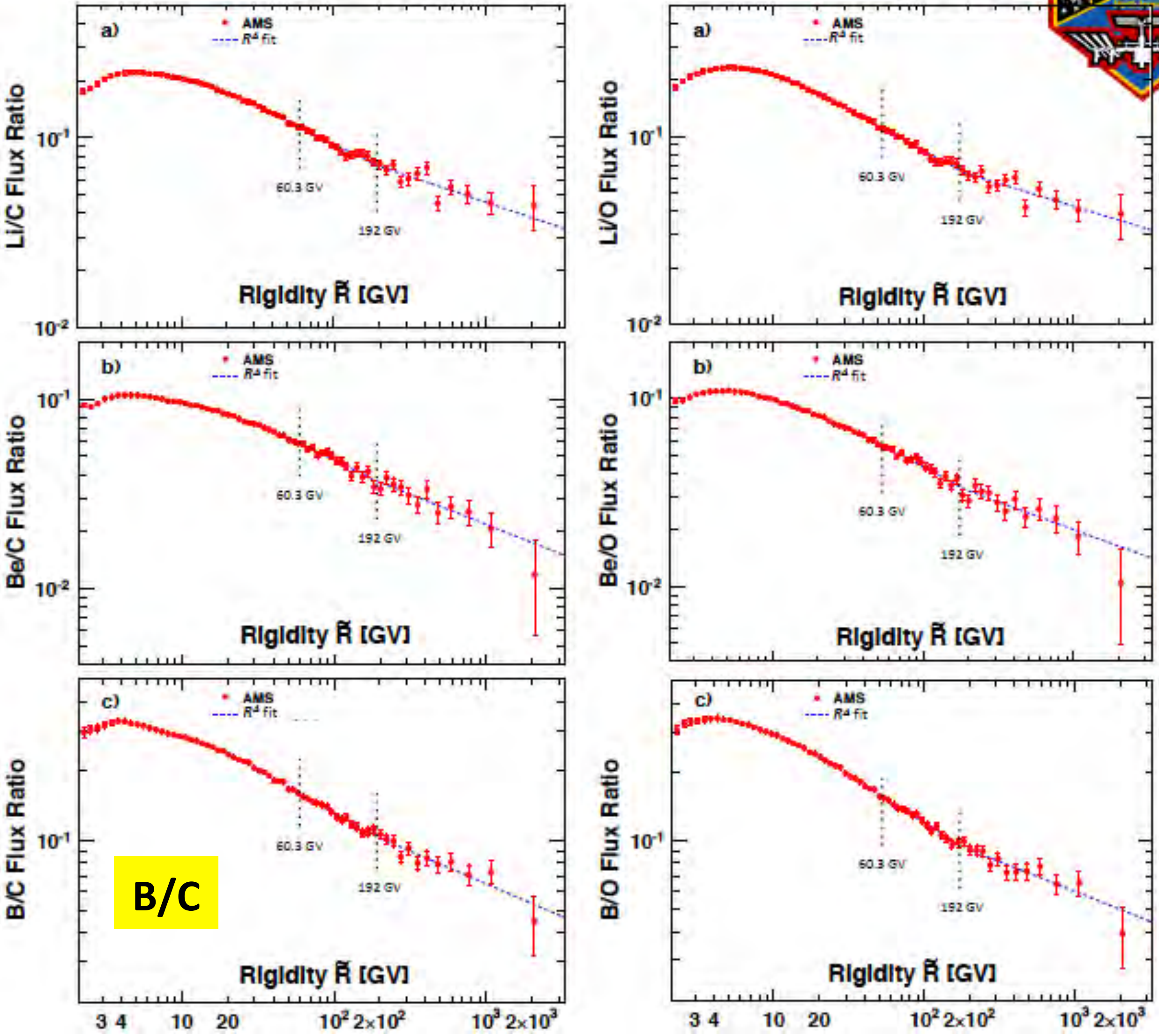


Secondary/Primary vs rigidity

Li/C, Be/C, B/C, Li/O, Be/O, B/O
[2 GV, 3 TV] 5 years AMS 2011-16

To investigate the rigidity dependence and the origin of the spectral hardening at high rigidity :

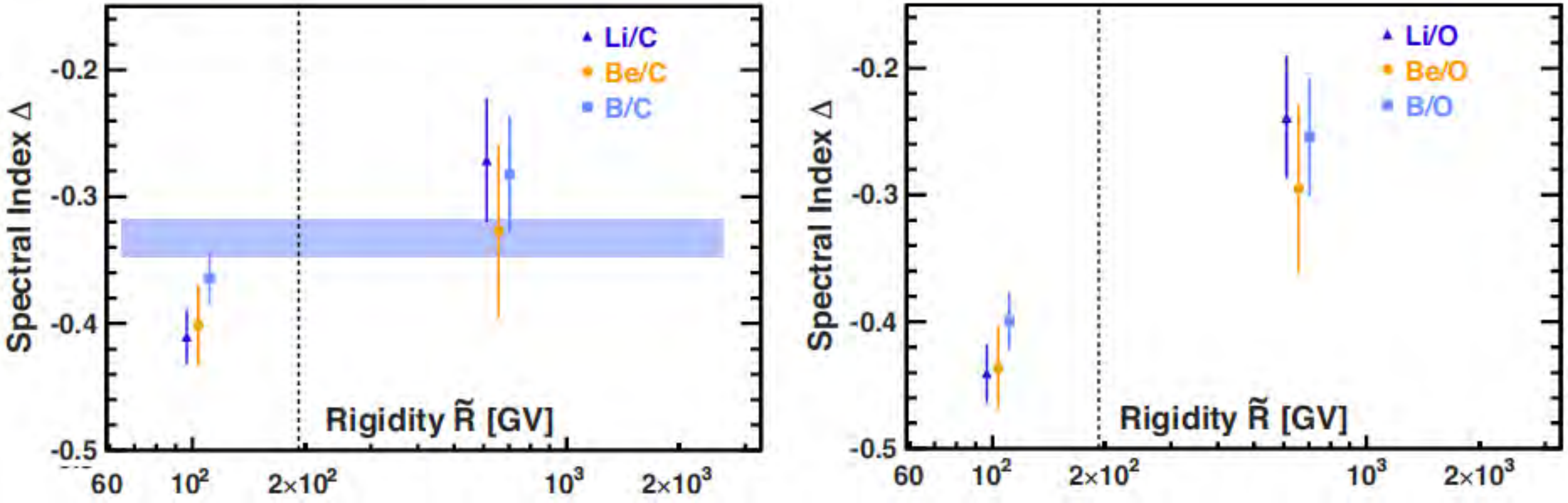
R^{Δ} fits for two rigidity intervals:
[60.3 GV–192 GV] and [192 GV–3300 GV]



[L.Derome, 2018]

Secondary/Primary vs rigidity

R^{Δ} fits for two rigidity intervals [60.3 GV–192 GV] and [192 GV–3300 GV] of Li/C, Be/C, B/C and Li/O, Be/O, B/O:



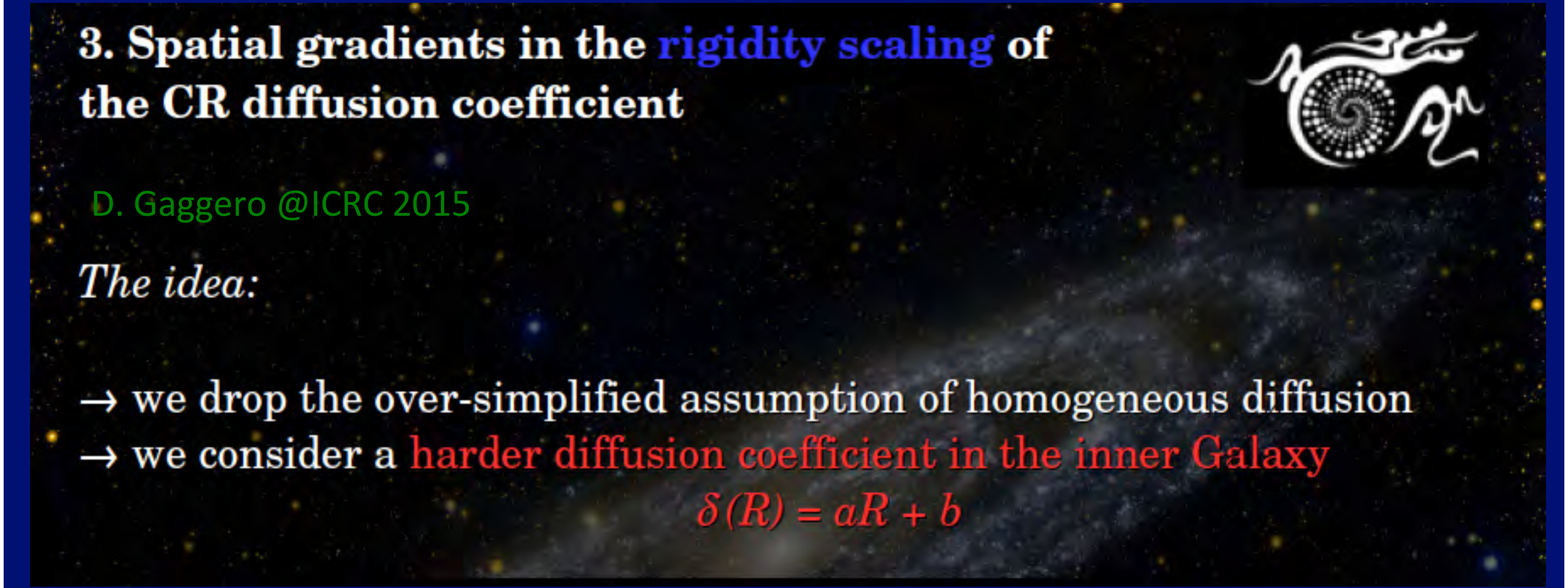
→ Indications for a hardening on the ratio (average 0.13±0.03)

→ Support the interpretation of the hardening in terms of a change in the propagation properties in the Galaxy.

[L.Derome, 2018]

◆ 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:

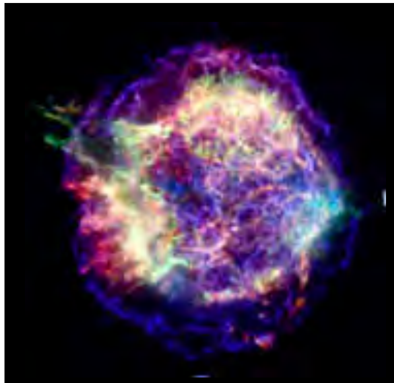
→ we drop the over-simplified assumption of homogeneous diffusion
→ we consider a harder diffusion coefficient in the inner Galaxy

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

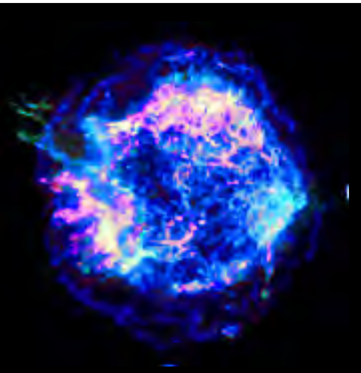
physical interpretation:

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

(see Blasi 2013. Tomassetti 2014)



Matter



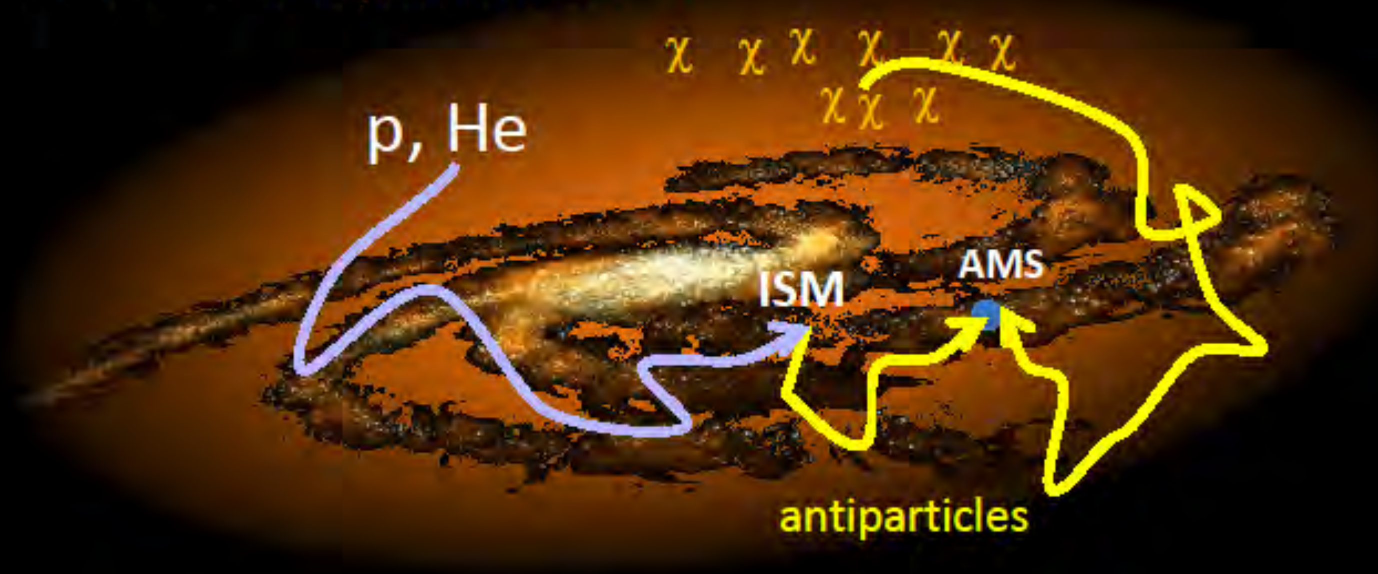
Anti-Matter ?

- Energy spectra of anti-protons
- Anti-p/p ratio

Antiparticles in Cosmic Rays and Dark Matter

The collision of cosmic rays with **interstellar medium (ISM)** produces **antiparticles (e^+, $\bar{p}$, $\bar{D}$, ...)**

p, He + ISM → antiparticles + ...



The collision of dark matter particles will produce additional antiparticles

$\chi + \chi \rightarrow$ antiparticles + ...

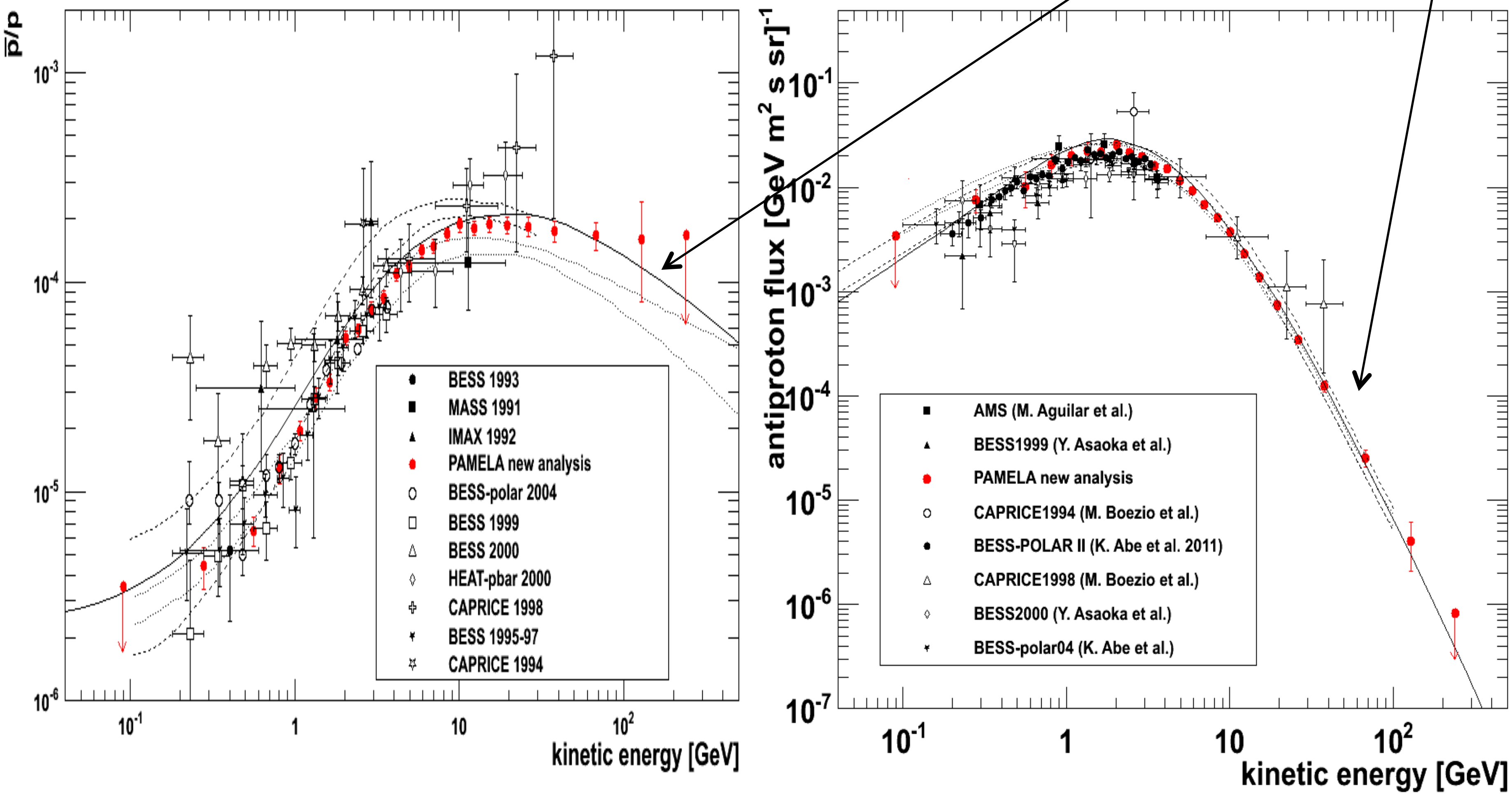
PAMELA Antiparticle Results: Antiprotons

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

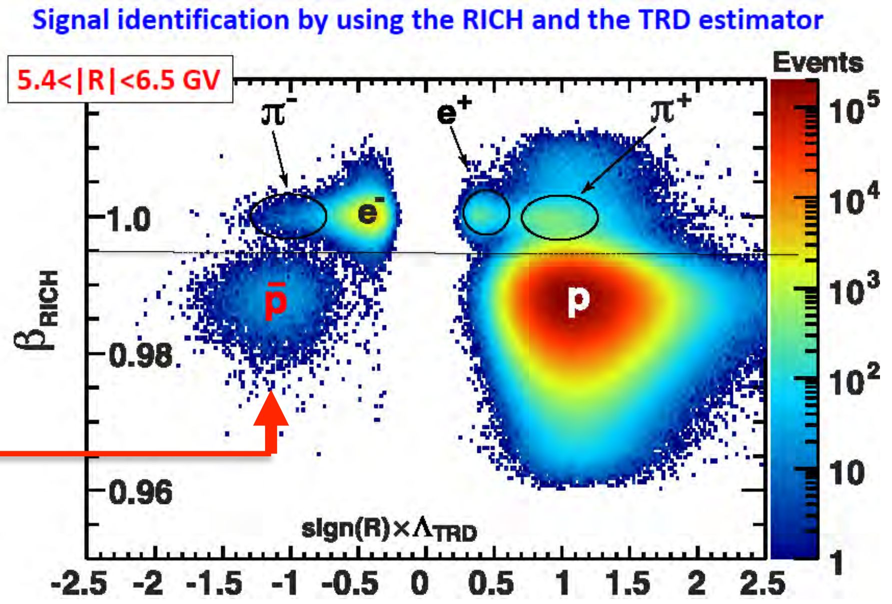
- spectrum shape consistent with a *pure secondary production*

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

Secondary production calculations

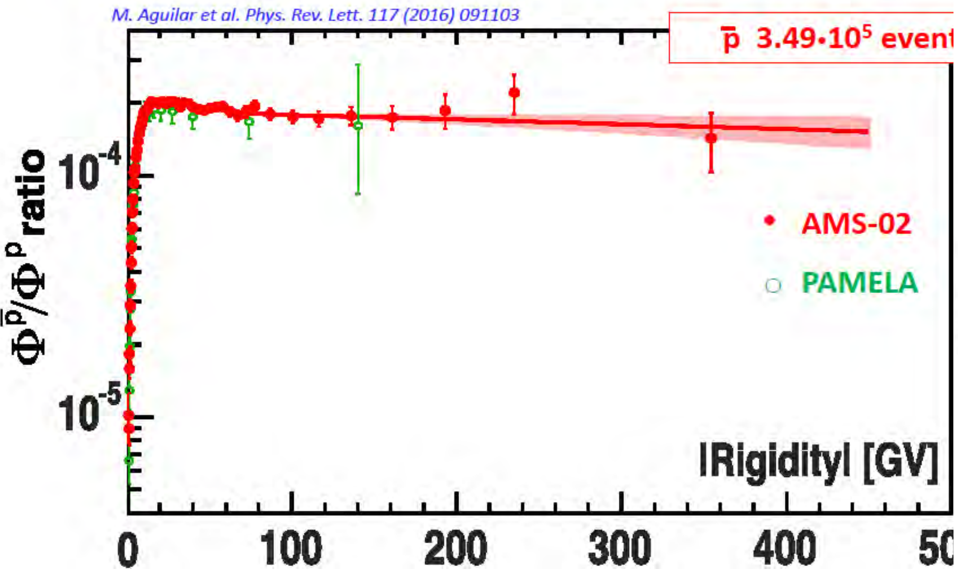


Anti-protons in AMS


Signal identification by using the RICH and the TRD estimator

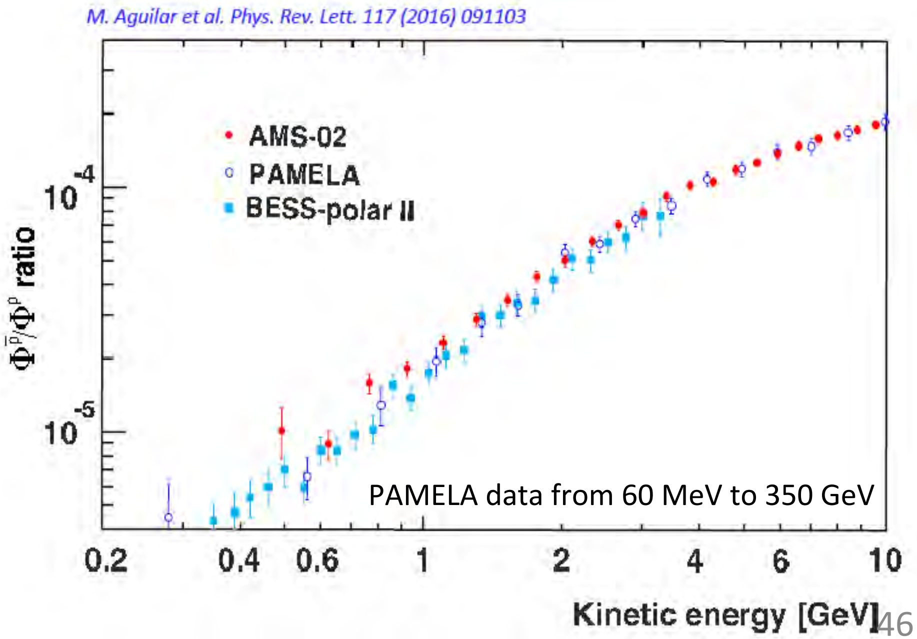
Antiproton-to-Proton Flux Ratio

Show no rigidity dependence above 60 GV


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

$\bar{p}$ 3.49·10^5 event

Antiproton-to-Proton Flux Ratio


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

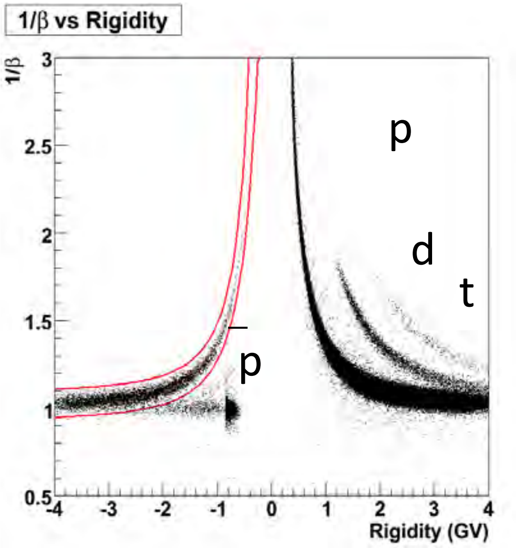
PAMELA data from 60 MeV to 350 GeV

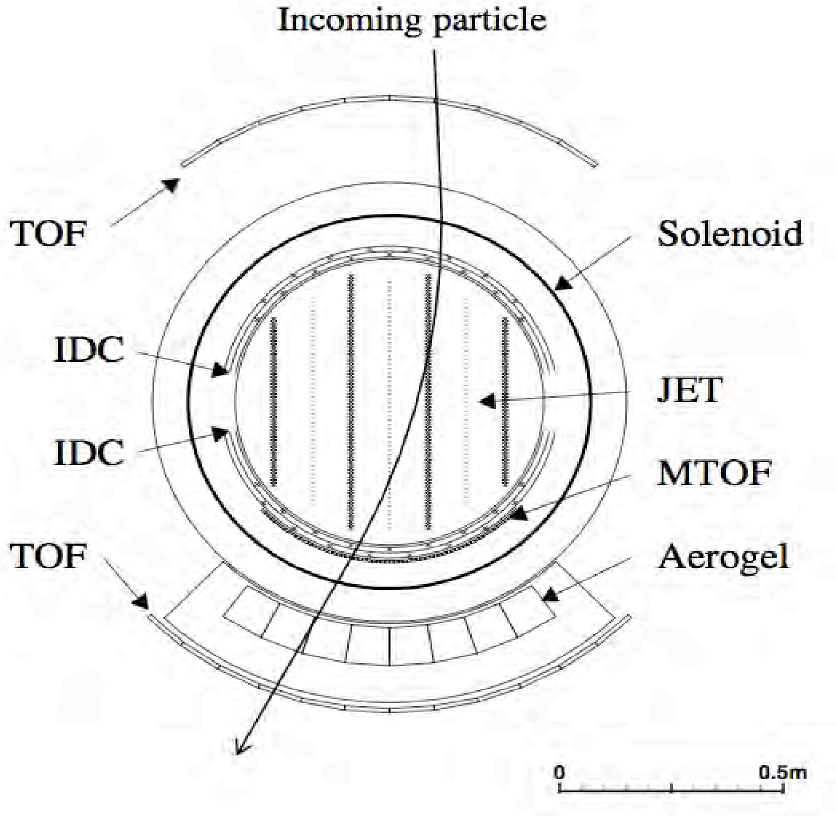
Baloon-borne Experiment with a Superconducting Spectrometer

BESS main goals: study of low-energy antiprotons and anti-matter searches

- Original instrument was flown 9 times between 1993 and 2002.
- BESS-Polar instrument flew from Antarctica in 2004 (8.5 days) and 2007 (24.5 days).
- Measures charge, charge-sign, momentum velocity and mass of the particles
- “JET” drift chamber with 52 points on trace, σ ~100 μm MDR 240 GV
- Time-of-flight system (TOF)
- Silica-aerogel Cherenkov detector

BESS-Polar





Magnet

Newly developed ultra-thin superconducting solenoidal magnet

Produce a uniform magnetic field of **0.8 T** in the tracking region.

Using high-strength aluminum stabilized superconductor.

Inner cryostat wall material is reduced to **2.5g/cm^2 (half of previous BESS).**

Previous BESS (4 layers)

BESS-Polar (2 layers)

Makoto Sasaki, Antideuteron 2014, UCLA

BESS-Polar Program

Status of the BESS-Polar I Flight

Observation Time: 8.5 days

Float Time: 8.5 days (12/13/2004-12/21/2004)

Events recorded: > 0.9×10^9

Data volume: ~ 2.1 terabytes
Data recovery: **completed** 2004
Payload recovery: **completed** 2004

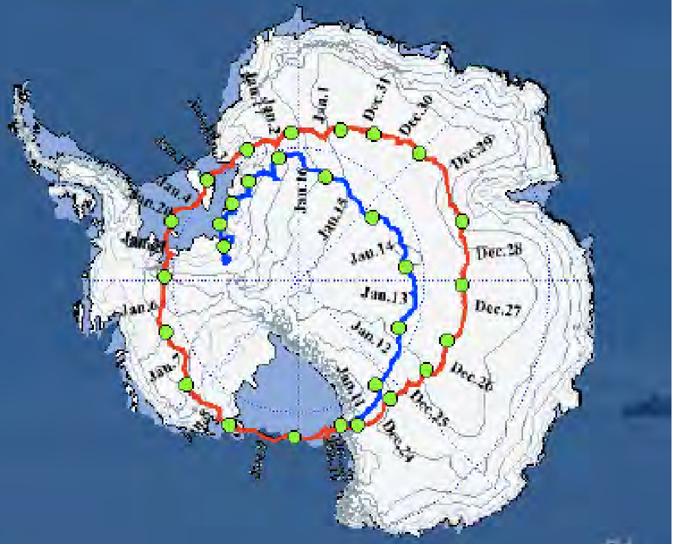
Status of the BESS-Polar II Flight

Observation Time: 24.5 days

Float Time: 29.5 days (12/23/2007-01/21/2008)

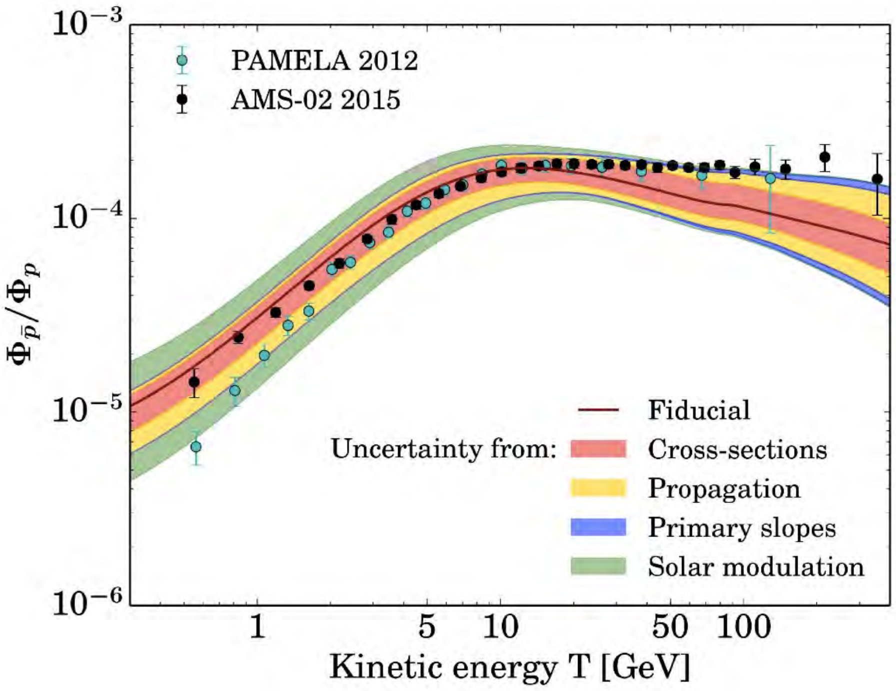
Events recorded: > 4.7×10^9

Data volume: ~ 13.5 terabytes
Data recovery: **completed** Feb 3, 2008
Payload recovery: **completed** Jan 16, 2010

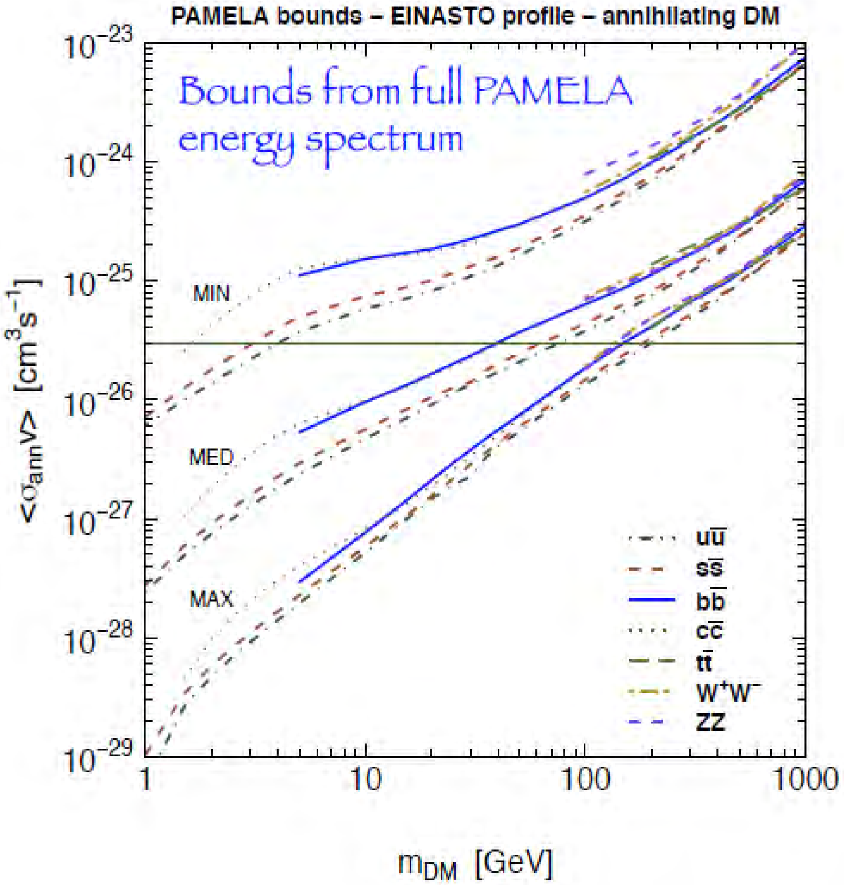


Cosmic-Ray Antiprotons and DM limits

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 *could 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:

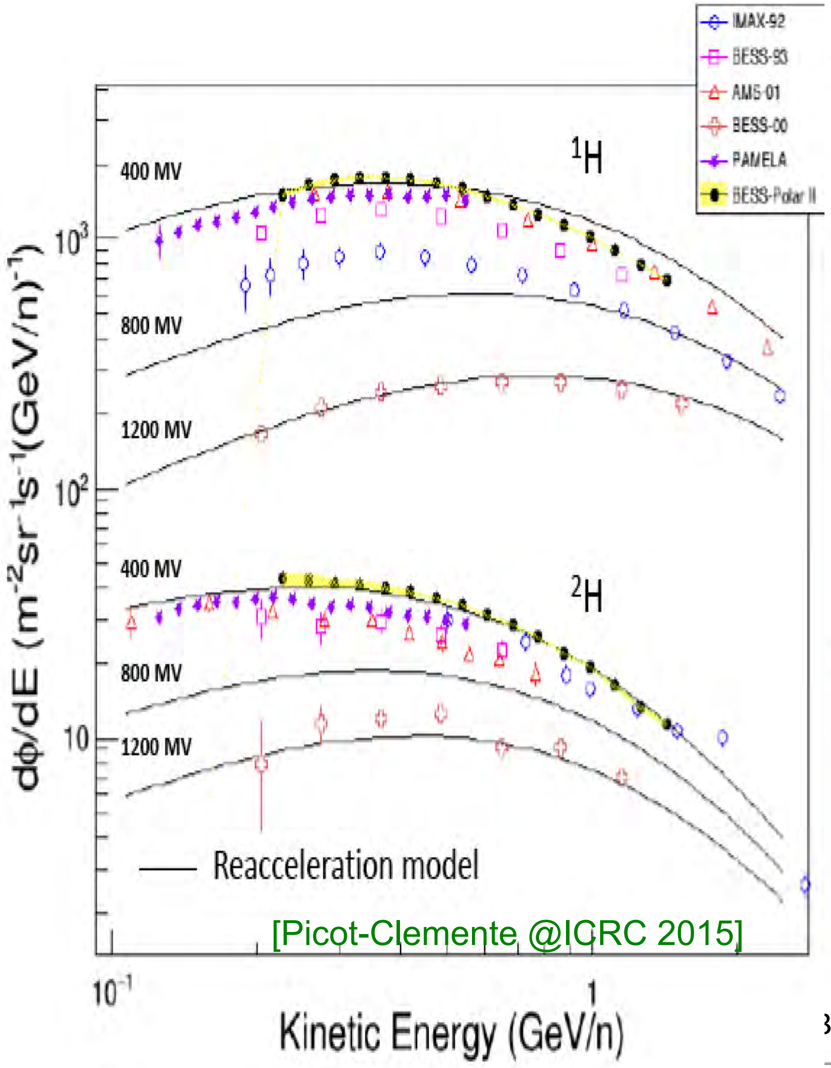
- PAMELA and AMS data are consistent with BESS measurements below 4 GeV

Nebula around
Wolf–Rayet star WR124

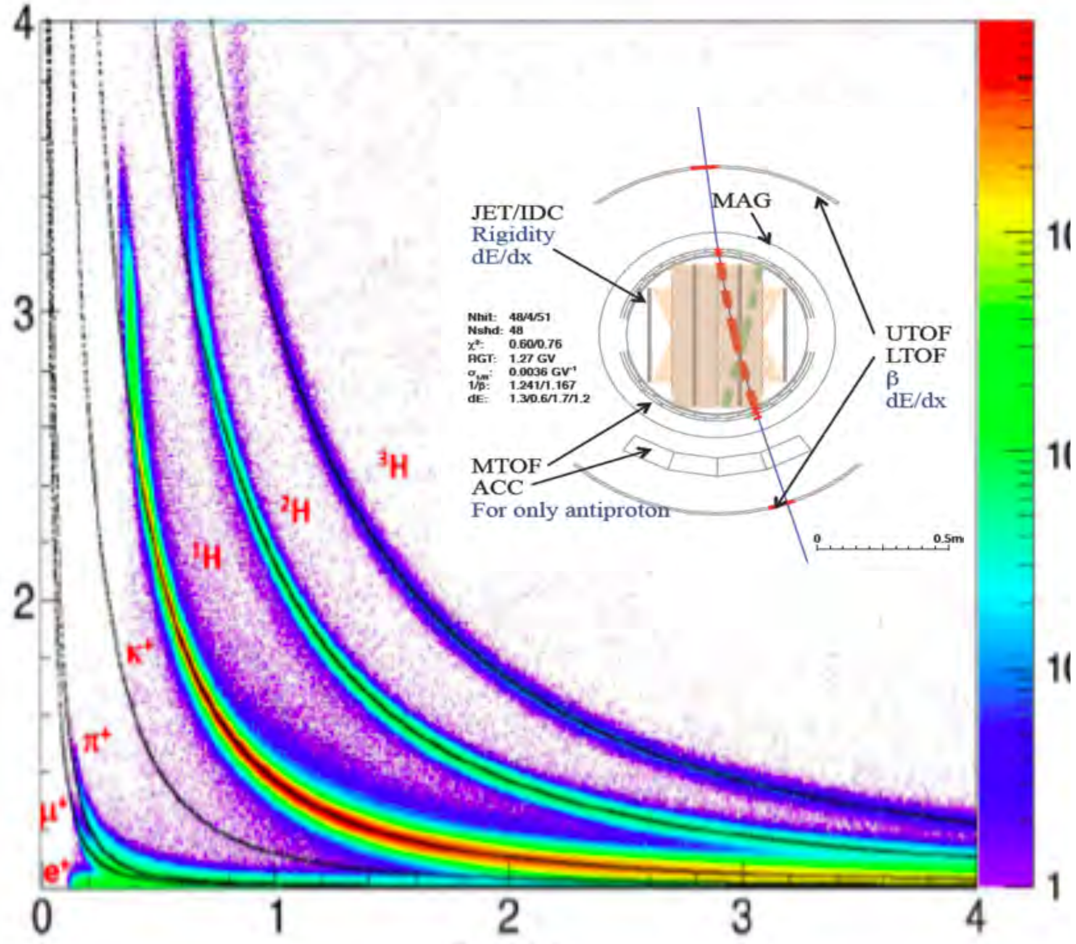
Cosmic-Ray Isotopes

- Isotope flux ratios like $^2H/^1H$ and $^3He/^4He$ 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

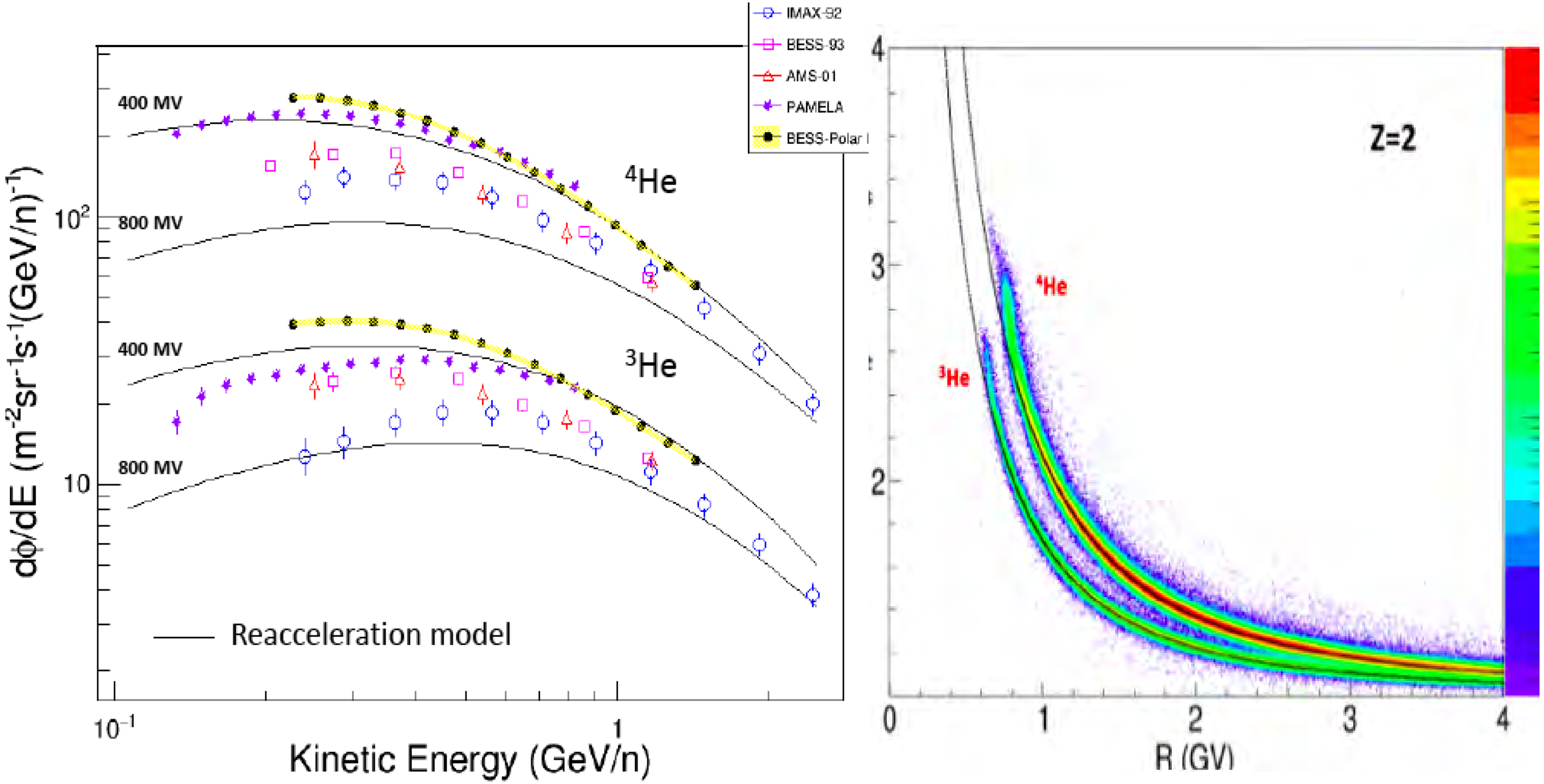


[Picot-Clemente @ICRC 2015]



^{3}He/^{4}He are complementary to B/C measurements in constraining propagation models as ^{2}H and ^{3}He are mostly secondaries.

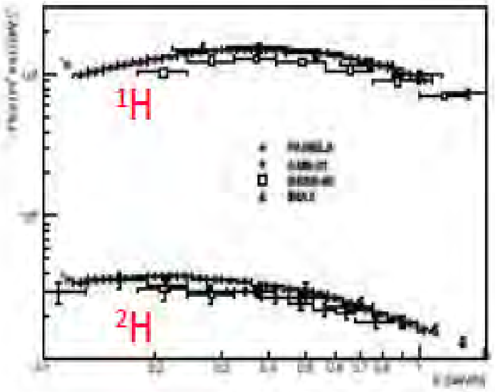
^{3}He, ^{4}He Isotope separation with BESS-Polar II

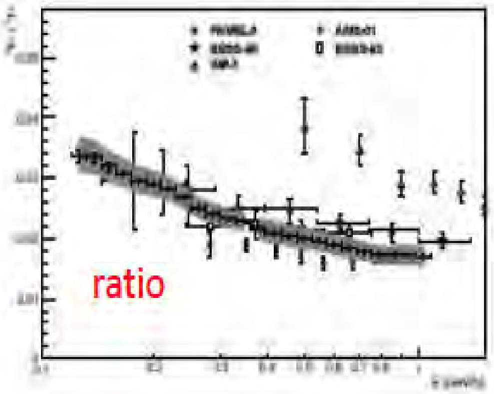


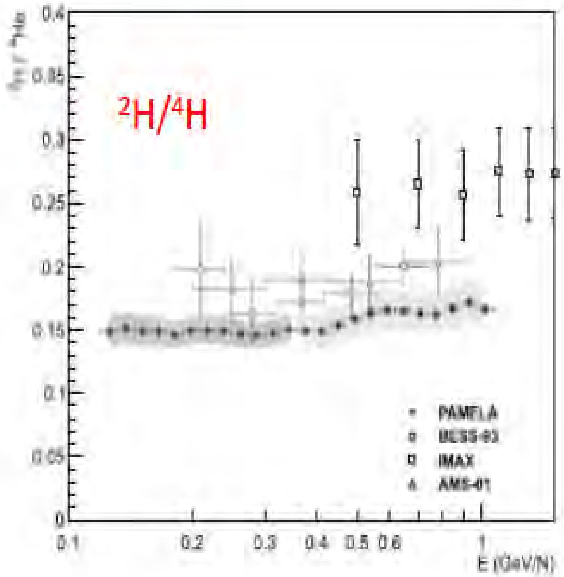
- Bess-Polar II data during solar minimum: in agreement with solar modulation expectations
- Data fitted using Reacceleration Model with ϕ ~400 MV
- Fluxes agree with PAMELA, with the exception of ^{3}He
- Bess Polar ^{3}He/^{4}He comparison vs Pamela may clarify this issue

Hydrogen and Helium Isotopes

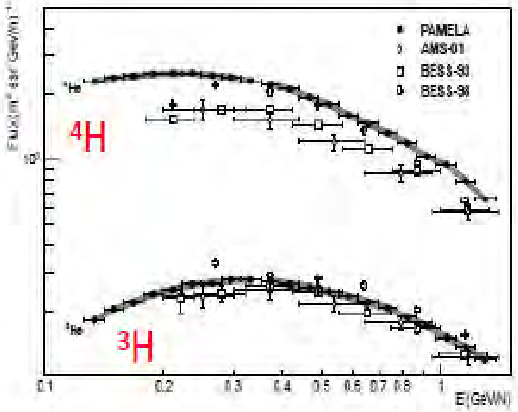
from PAMELA

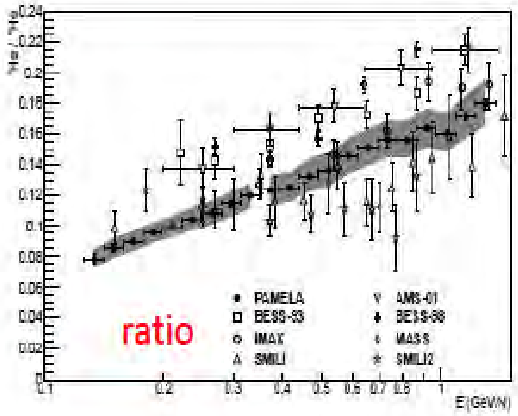






Pamela coll. APJ 818,1,68 (2016)

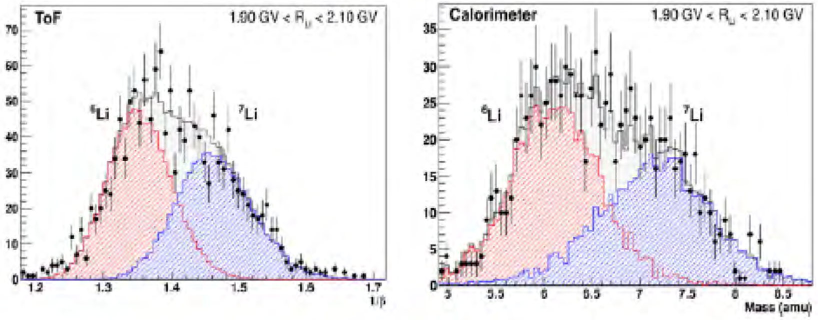




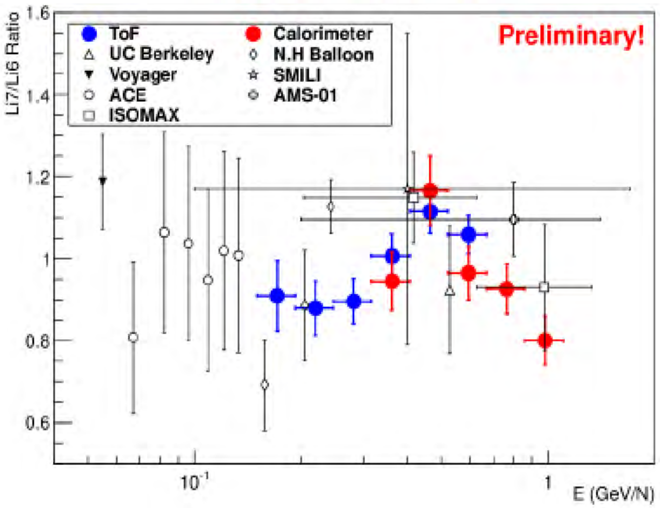
Lithium and Beryllium Isotopes

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

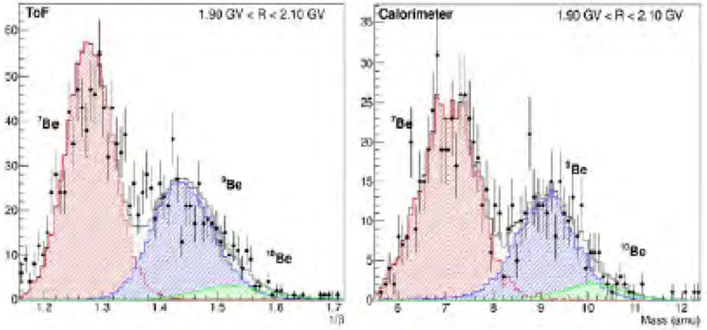
Lithium



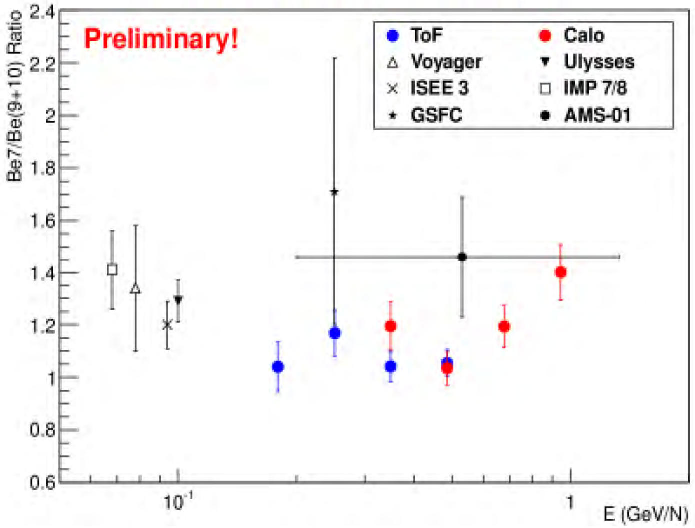
Ratio ^{7}Li / ^{6}Li



Beryllium



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

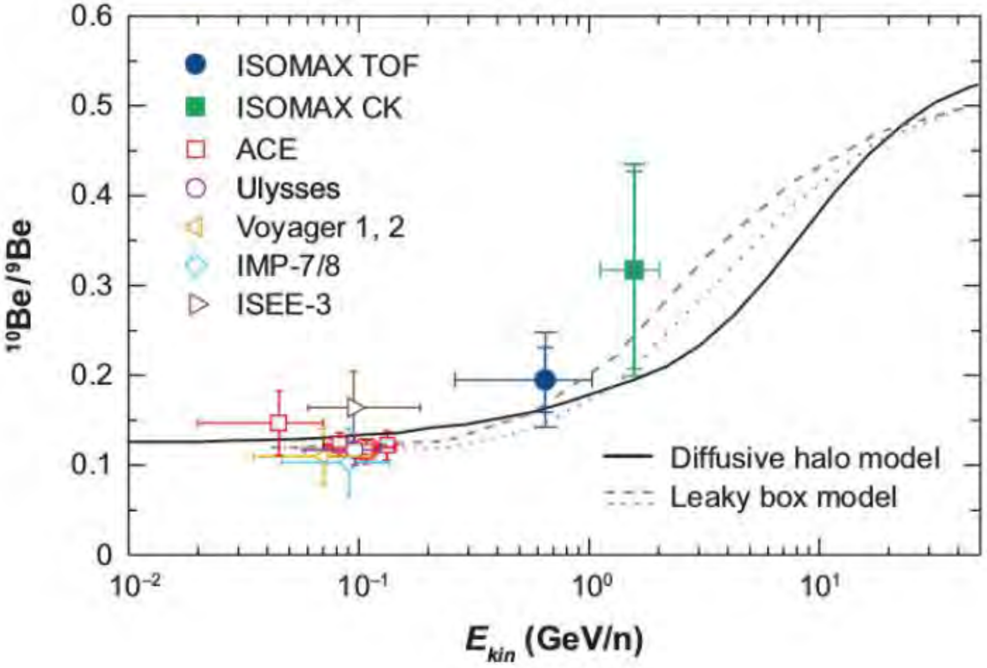


[Menn @ICRC 2015]

Secondary-to-Primary ratios of unstable cosmic isotopes

The main unstable secondary cosmic nuclei that live long enough to be useful probes of cosmic ray propagation are ^{10}Be, ^{14}C, ^{26}Al and ^{54}Mn. Among them, ^{10}Be is the longest lived and best measured in the low energy region.

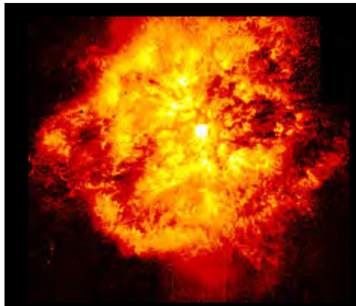
The radioactive isotope ^{10}Be which decays to the stable isotope ^{9}Be with ∼1.39 x 10^6 years half-life is considered as a "cosmic propagation clock". The ^{10}Be/^{9}Be ratio can provide a measurement of the **confinement time** of cosmic-ray particles in the galaxy and crucial information to verify models of propagation.



^{10}Be/^{9}Be

as measured by ISOMAX, ACE, Ulysses, Voyager, IMP and ISEE up to ~ 2 GeV/n.

Requires the accurate measurement of momentum, velocity and charge. (i.e.: magnetic spetrometer, Cherenkov, charge identification)

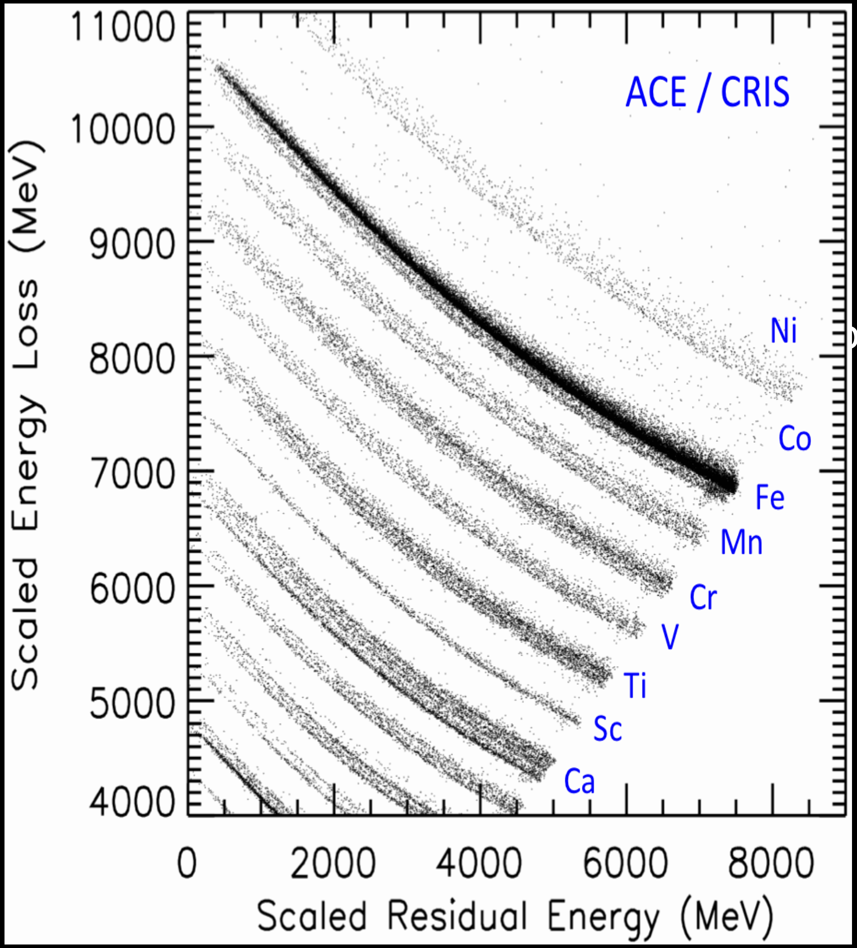


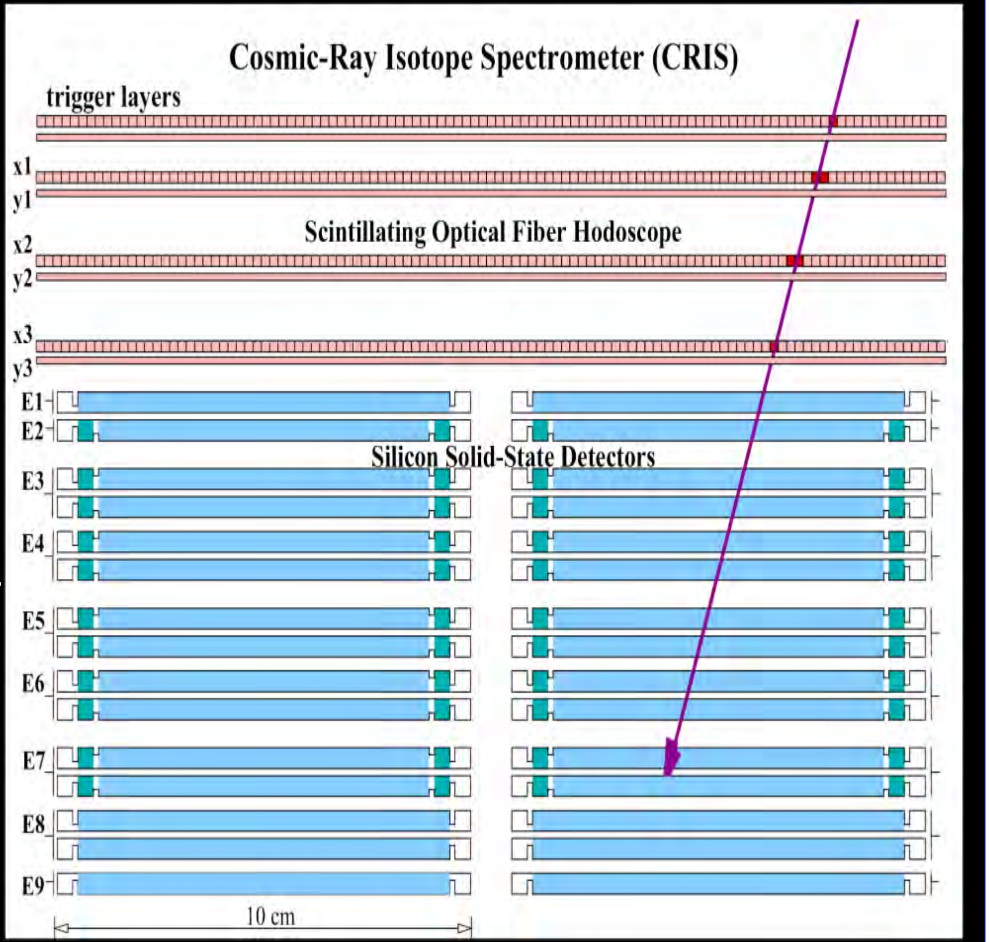
Nebula around
Wolf–Rayet star WR124

Trans-Iron elements and “propagation clocks”

Cosmic-Ray Isotope Spectrometer (CRIS)

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



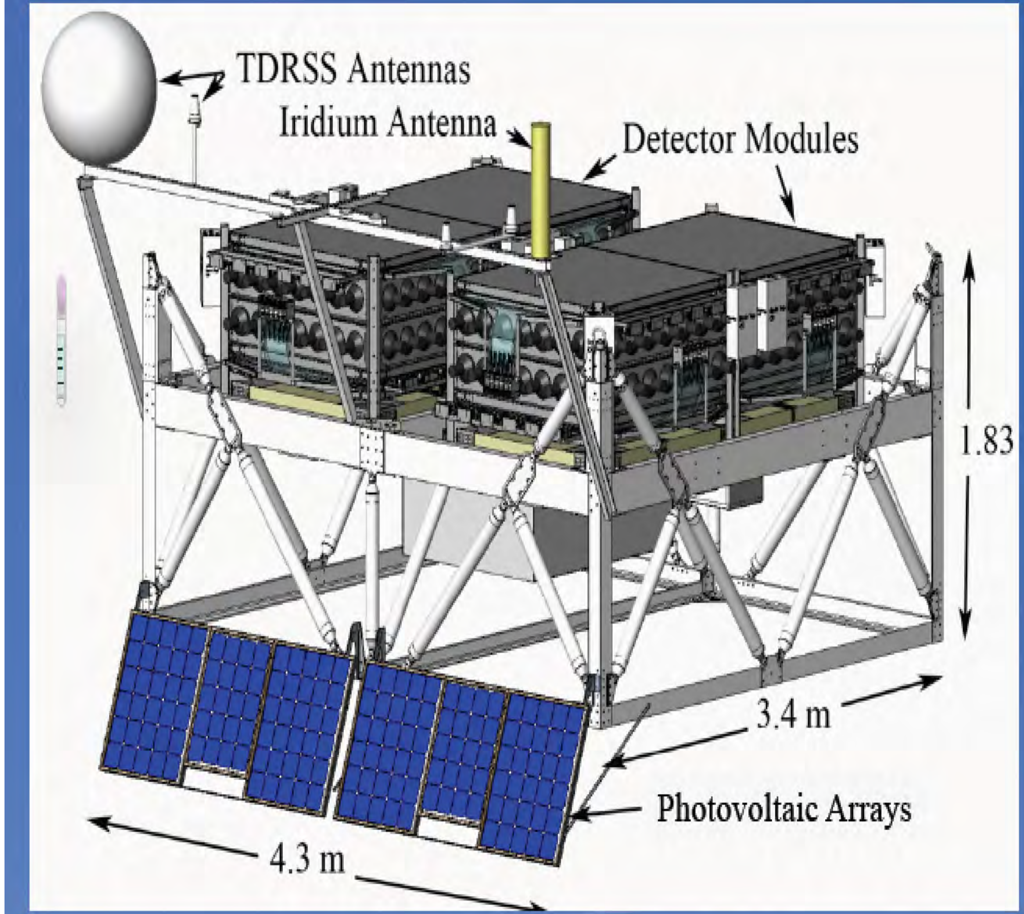


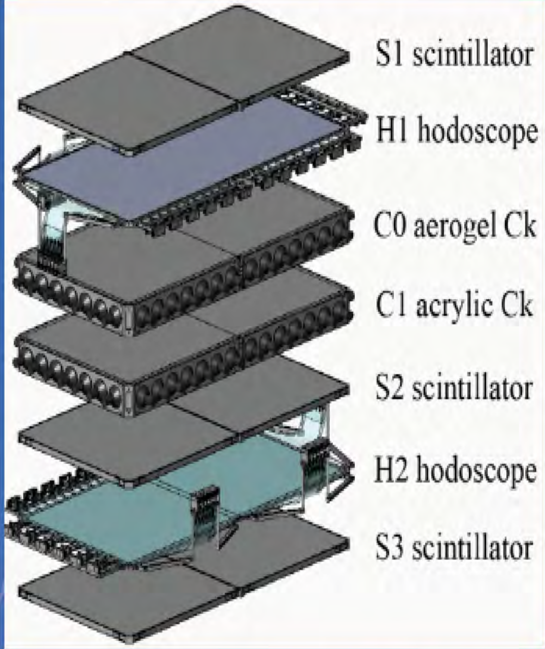
CRIS determines the charge and mass of cosmic rays stopping in a stack of silicon detectors using the dE/dx vs E technique

ACE energy range: 150-600 MeV/n

Super-TIGER (Trans-Iron Galactic Element Recorder)

Antarctic flight in 2012-13: 55 days



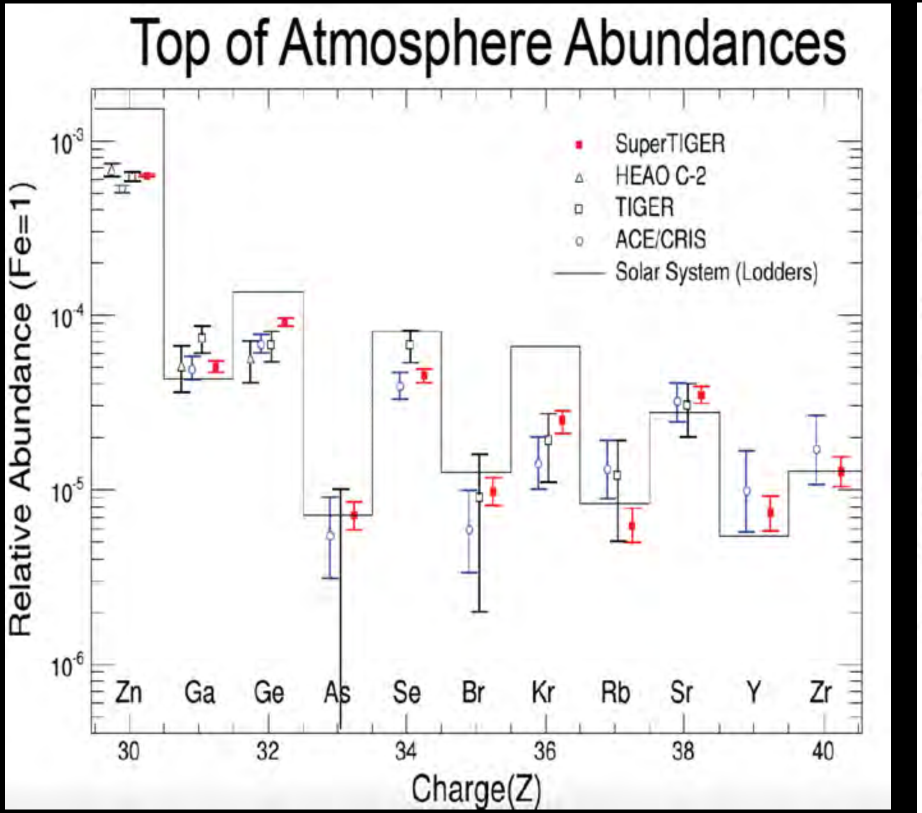


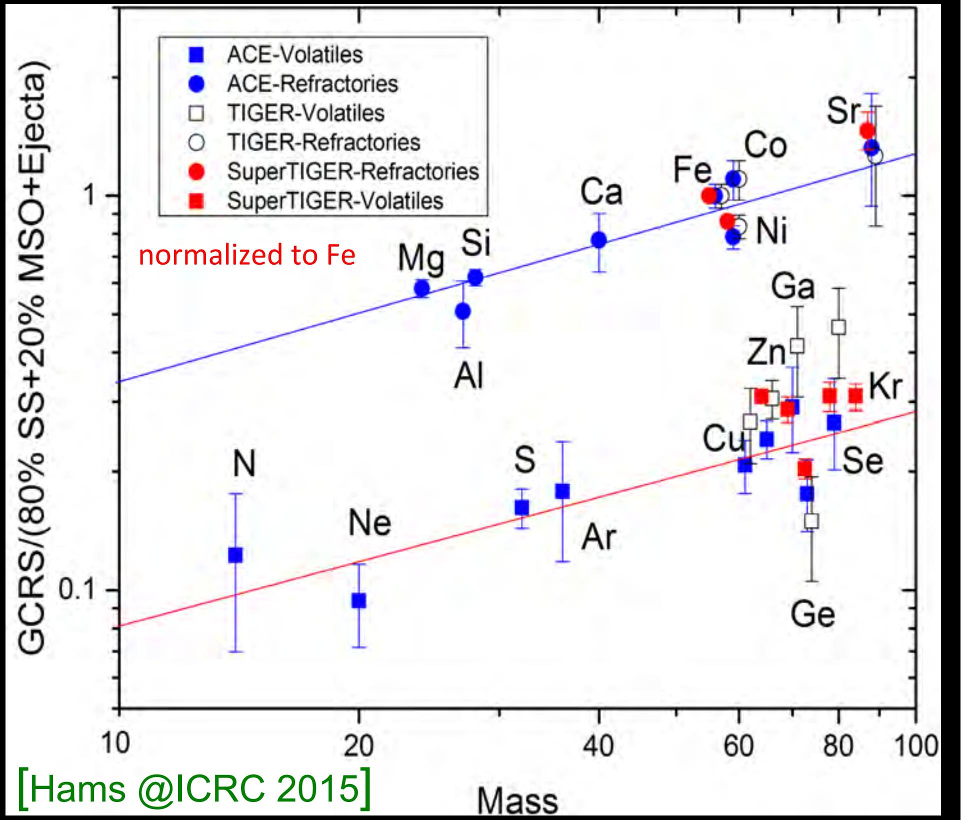
- Two identical modules
- Each module consists of
  - Scintillating fiber hodoscopes (H1, H2)
  - Three scintillator detectors (S1, S2, S3)
  - Aerogel Cherenkov detector (C0)
  - Acrylic Cherenkov detector (C1)

Acceptance ~8.3 m^{2}sr

TIGER & SuperTIGER energy range 0.8-10 GeV/n

Ultra Heavy Nuclei





[Hams @ICRC 2015]

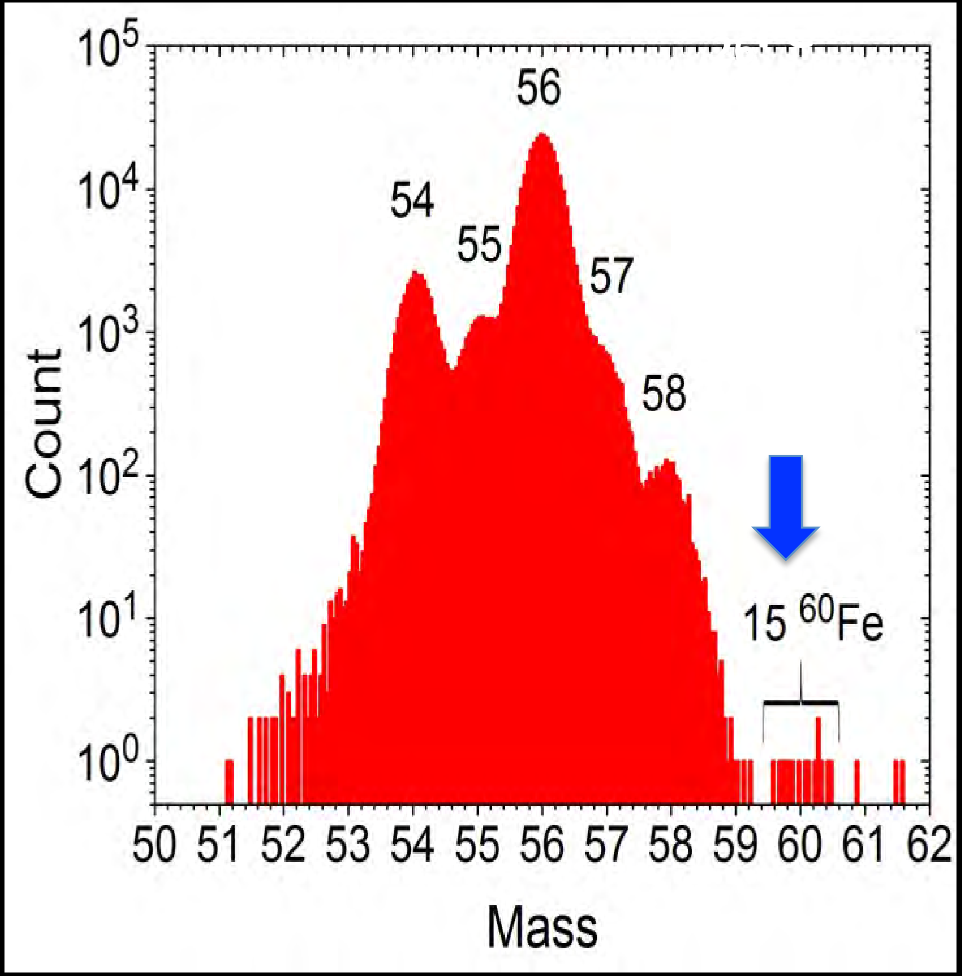
- Refractory elements (those likely found in interstellar grains) more effectively accelerated (enhanced by a factor ~4) compared with volatile elements.

- 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.Israel @ICRC 2015]

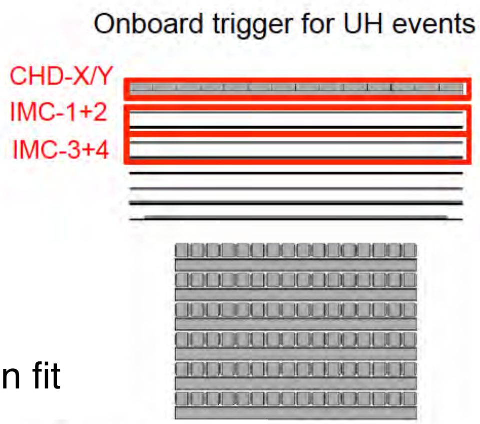
- CR acceleration occurs within several Myr of nucleosynthesis.
- Combined with lack of ^{59}Ni ➔ ~10^5 years < *T* < ~several x 10^6 years
- Supports the idea of OB associations as CR acceleration sites.

CALET Preliminary: Ultra Heavy Nuclei $26 < Z \leq 40$

- CALET measures the relative abundances of ultra heavy nuclei through $_{40}$Zr

CALET has a special UH CR trigger utilizing the CHD and the top 4 layers of the IMC that:

- has an expanded geometry factor of ~4000 cm^{2}sr
- has a very high duty cycle due to low event rate

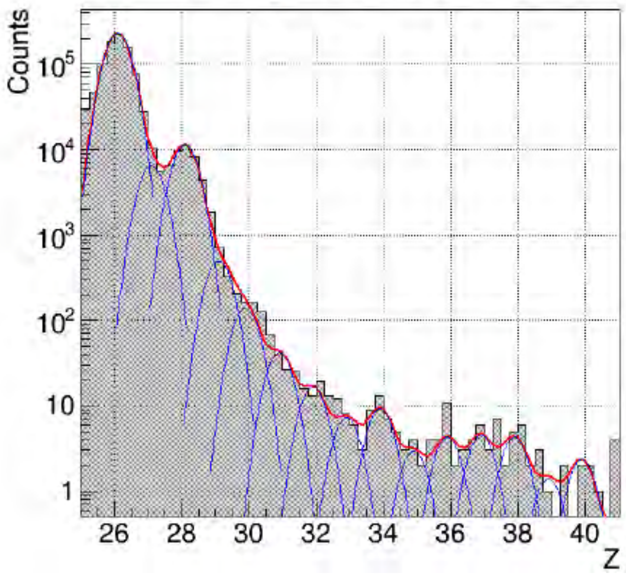

Onboard trigger for UH events

Data analysis

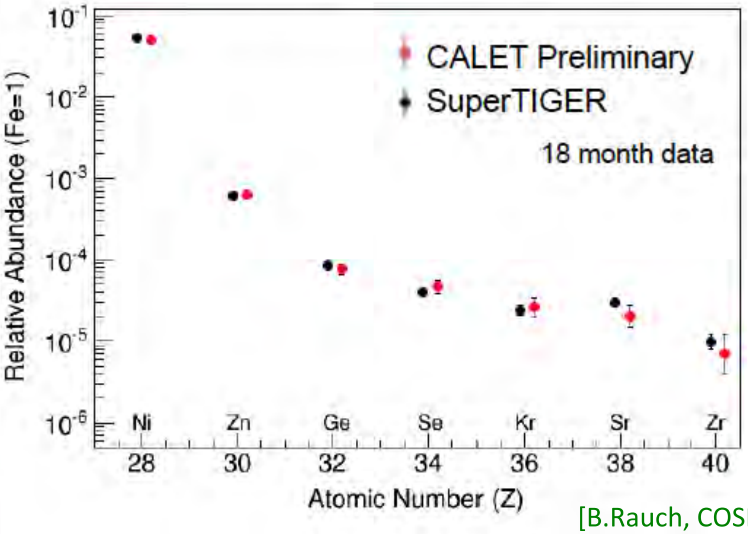
☐ Event Selection: Vertical cutoff rigidity > 4GV & Zenith Angle < 60 degrees

☐ Contamination from neighboring charge are determined by multiple-Gaussian fit

Charge distribution



Relative abundance (Fe=1)



[B.Rauch, COSPAR 2018 E1.5-0029-18]

Present and future missions for direct measurements of VHE cosmic-rays

- Space missions in flight at present:

  PAMELA(*), FERMI, AMS-02, NUCLEON, CALET, DAMPE, ISS-CREAM

- Proposed balloon or space missions:

  HERD, GAMMA-400, GAPS, HELIX, HNX, …

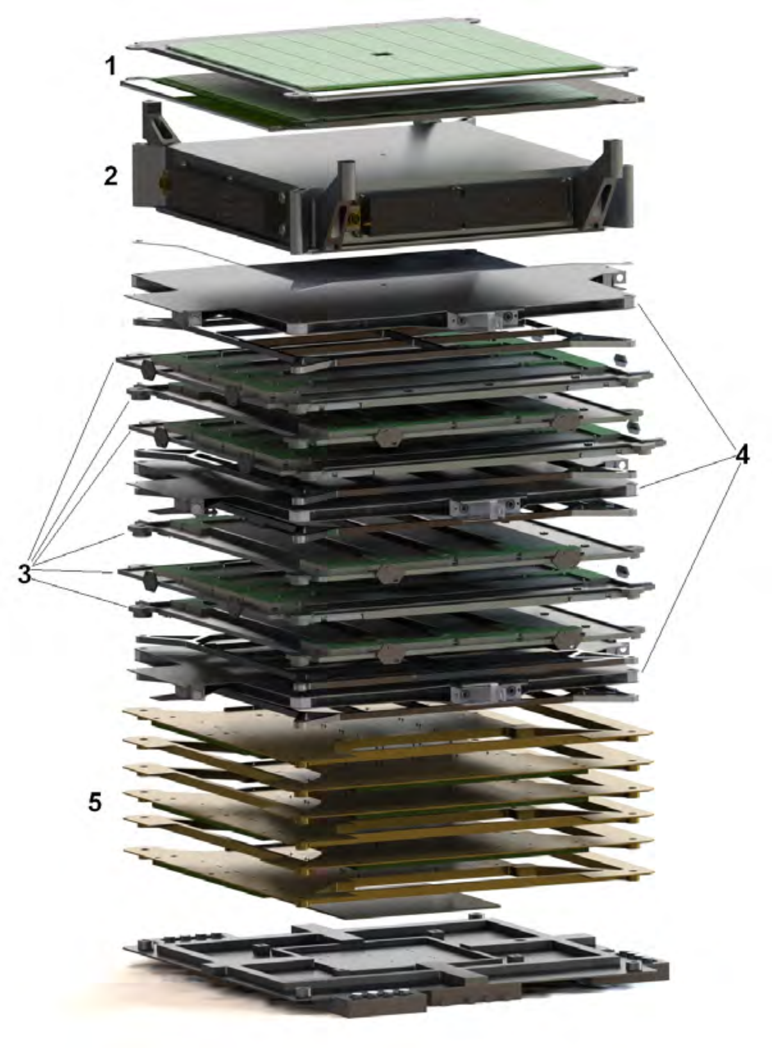
(*) scientific operations have been discontinued

Experiment	e^+ | 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 Aug 14
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

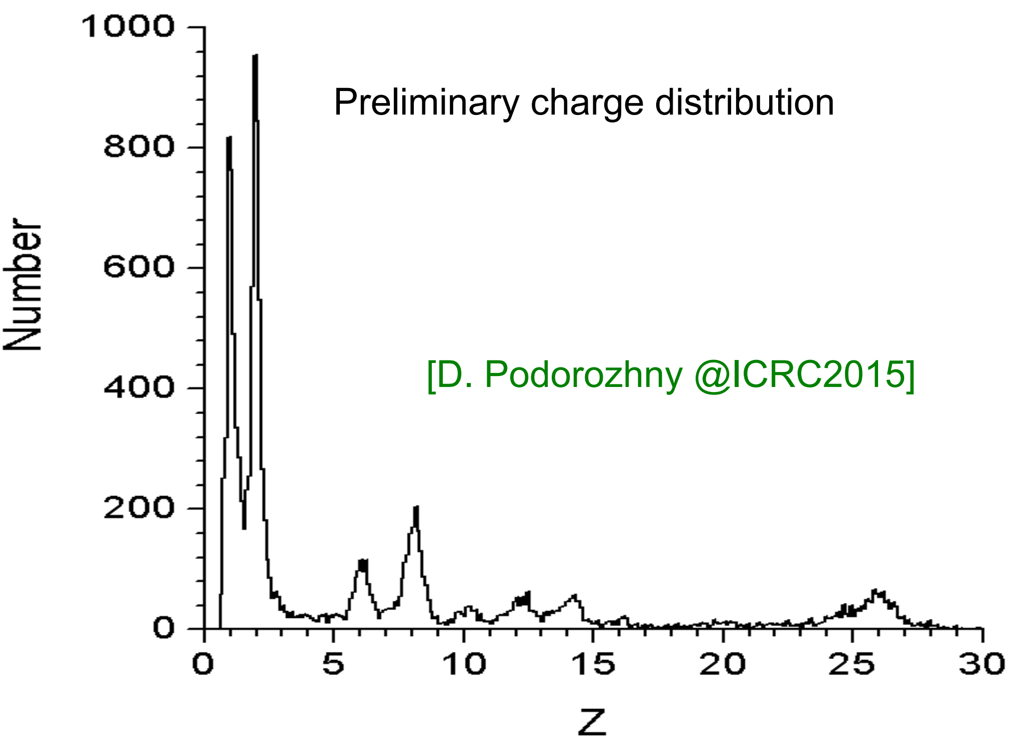
- Launched on Dec. 26th 2014 on Resurs-P satellite
- uses the Kinematical Method (KLEM) to estimate the energy

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

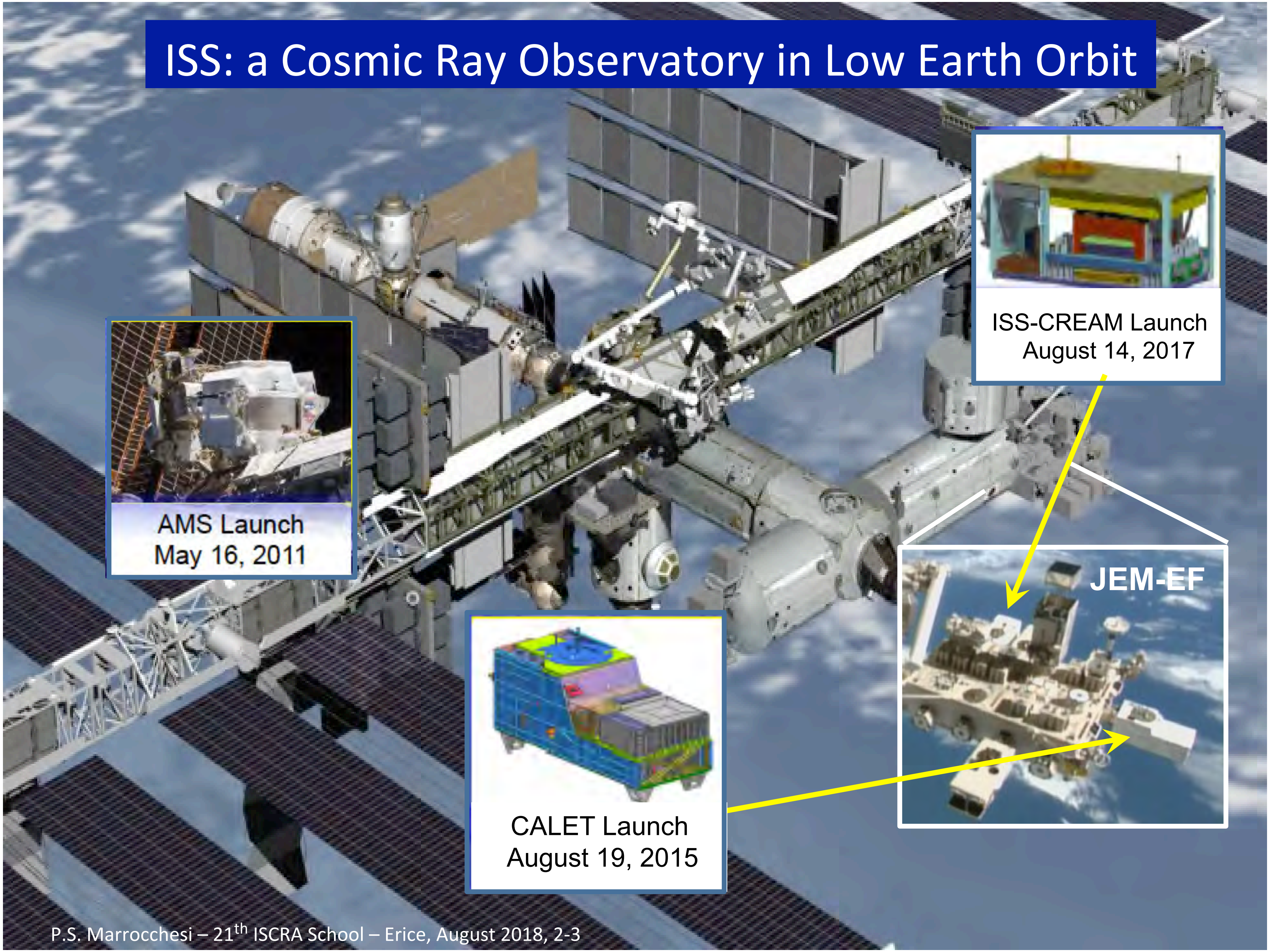


- charge measurement: 4 Si pad detectors
- carbon target to induce hadronic interaction
- Si microstrip/W (0.50x0.50 m^2) → tracking → KLEM
- Si/W calorimeter (0.25x0.25 m^2)

Total: 10604 channels depth ~16 X_0



ISS: a Cosmic Ray Observatory in Low Earth Orbit


AMS Launch
May 16, 2011

ISS-CREAM Launch
August 14, 2017

CALET Launch
August 19, 2015

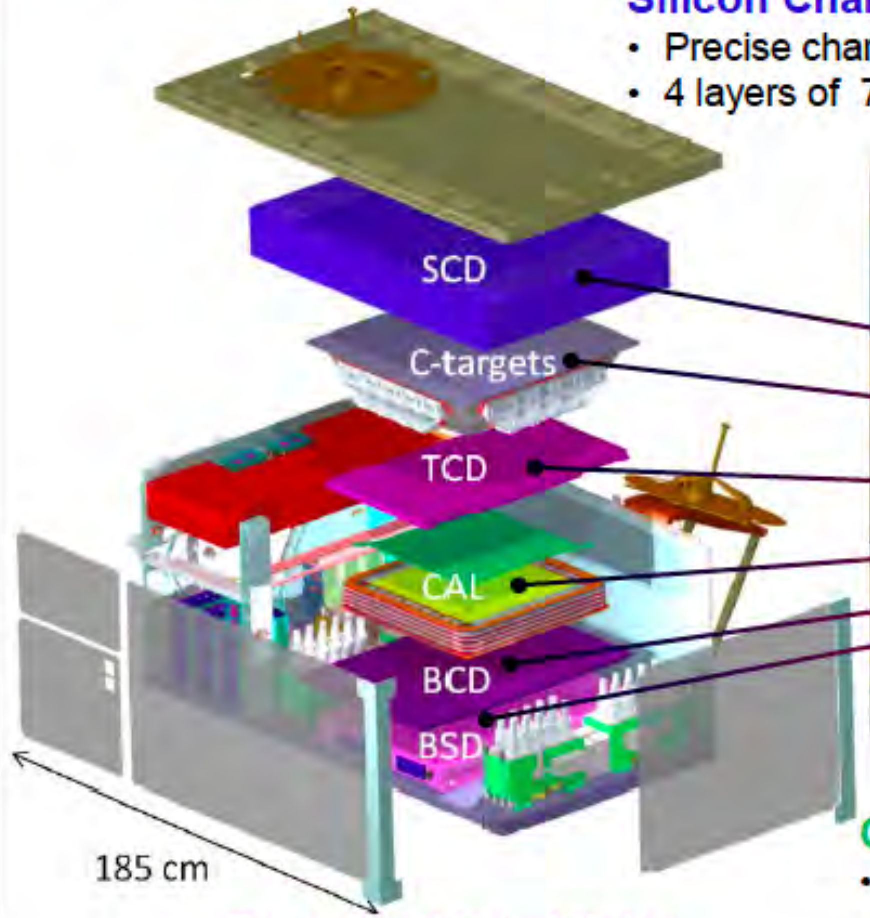
ISS-CREAM Instrument

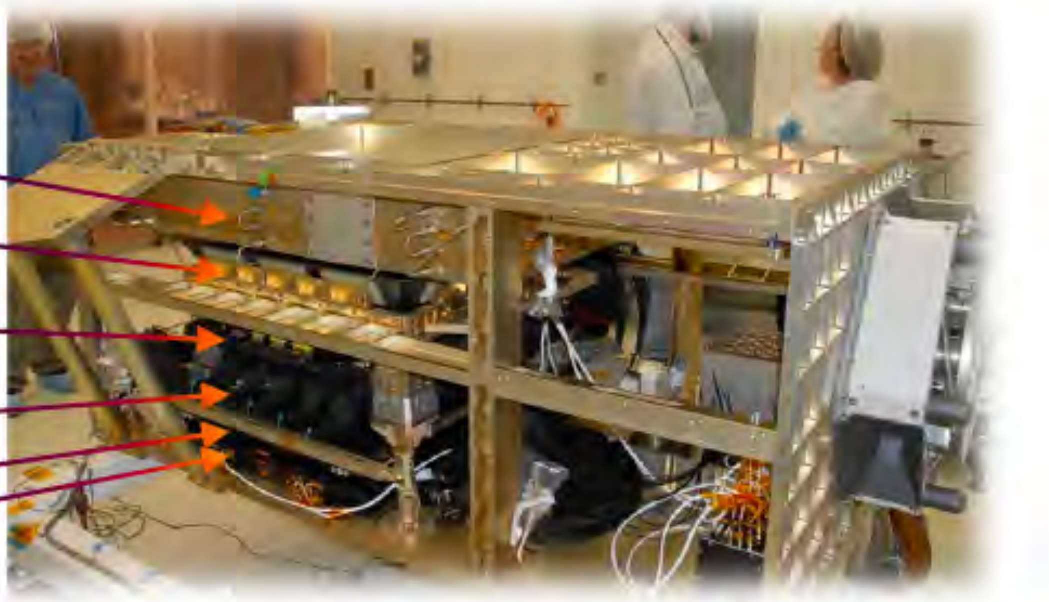
[Seo@Vulcano 2016]

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.

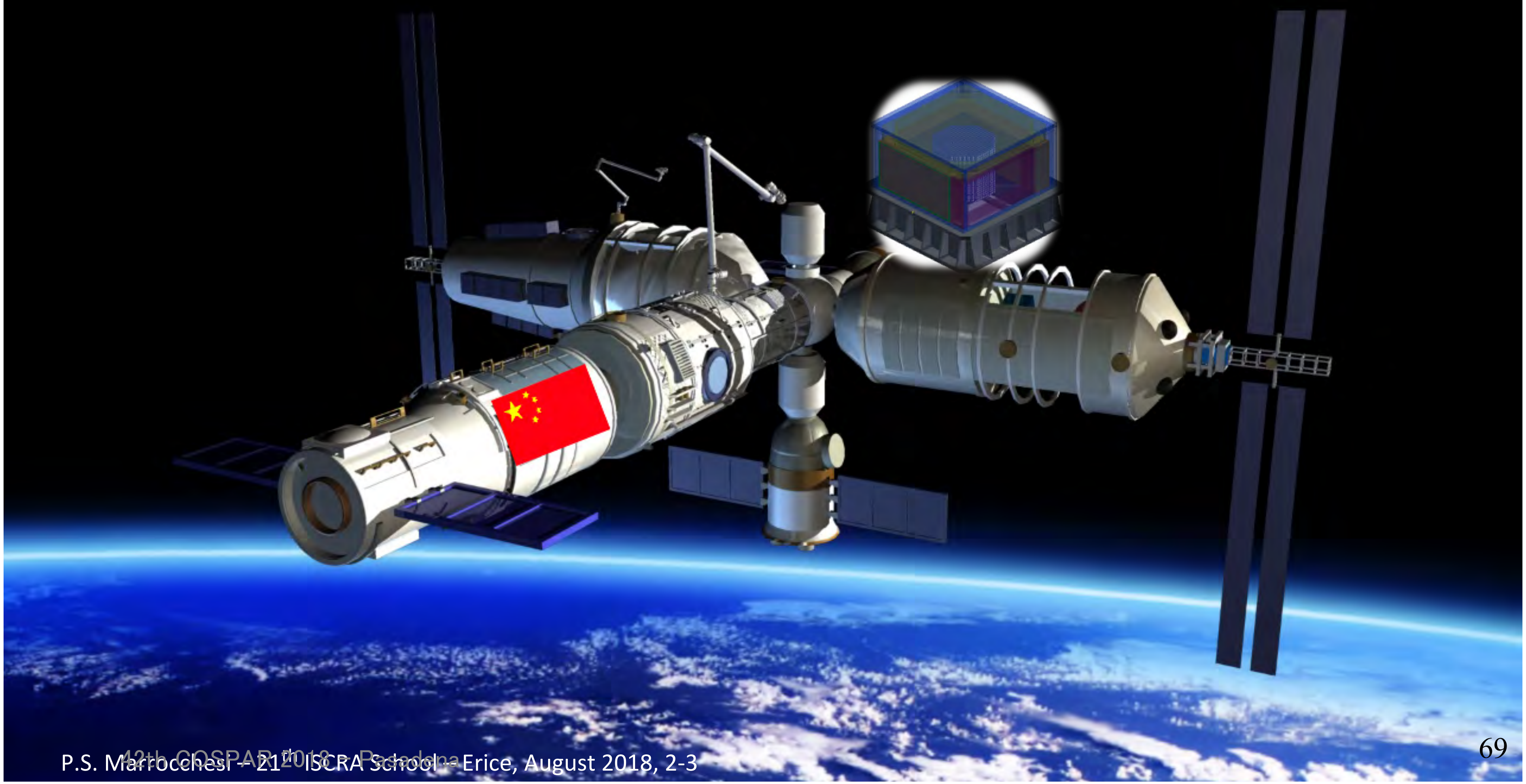
Calorimeter (CAL)

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

Top/Bottom Counting Detector (T/BCD)

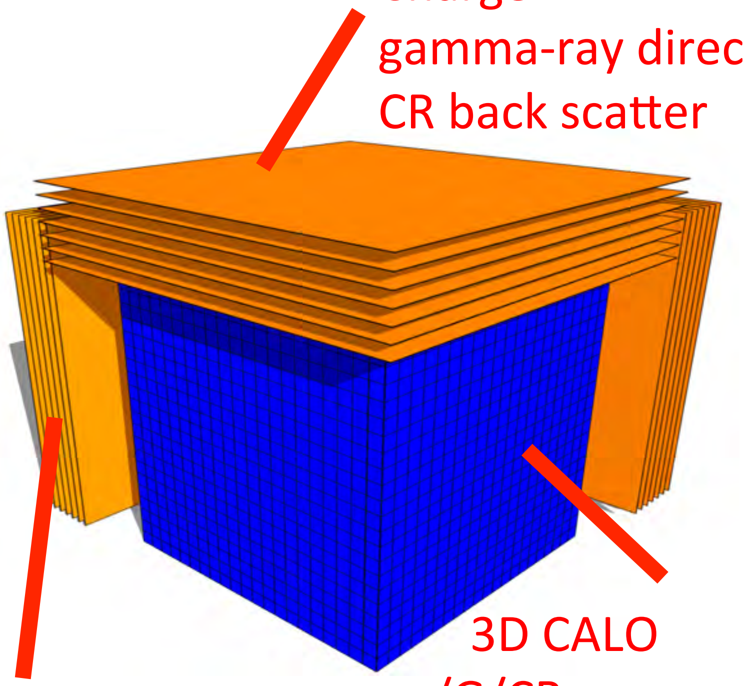
- Plastic scintillator instrumented with an array of 20 x 20 photodiodes for e/p separation.
- Independent trigger.

The High Energy cosmic-Radiation Detection (**HERD**) Facility aboard China's Future Space Station



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

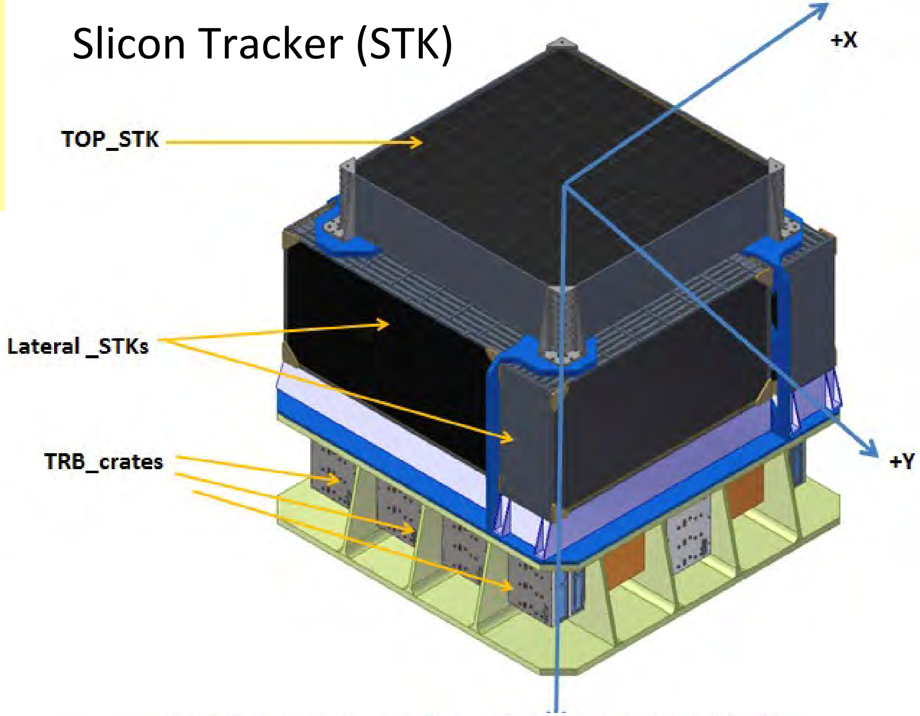


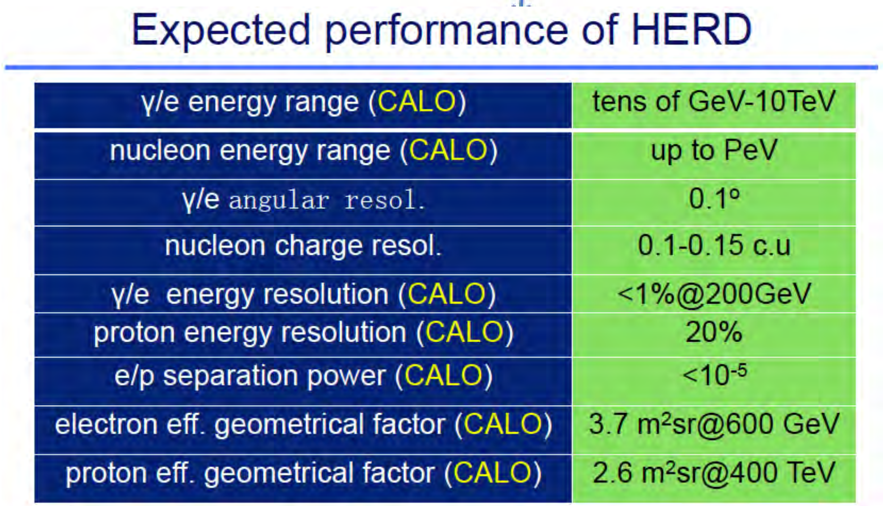
STK(W+SSD)
Charge
gamma-ray direction
CR back scatter

STK(W+SSD)

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

Slicon Tracker (STK)



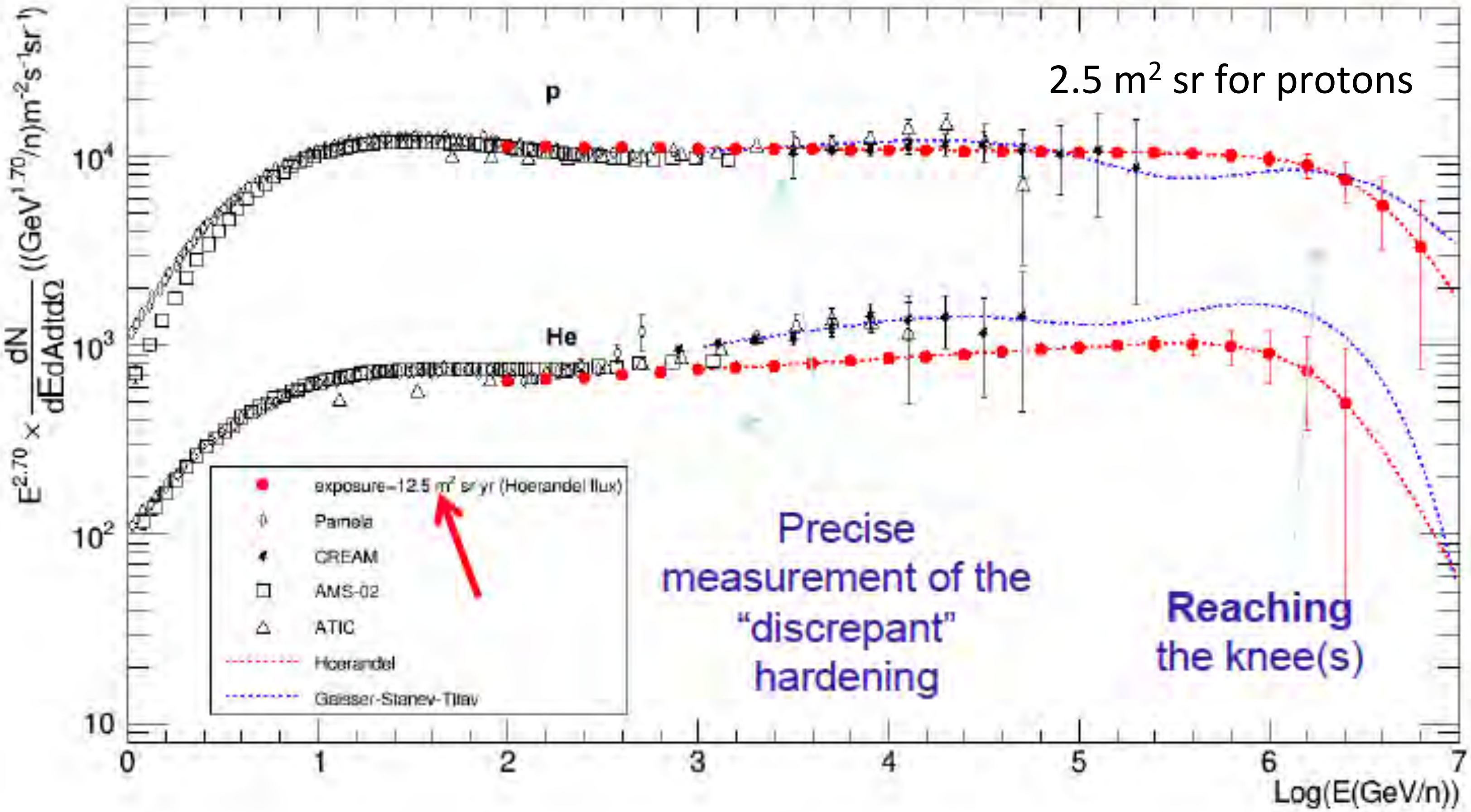


Expected performance of HERD

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

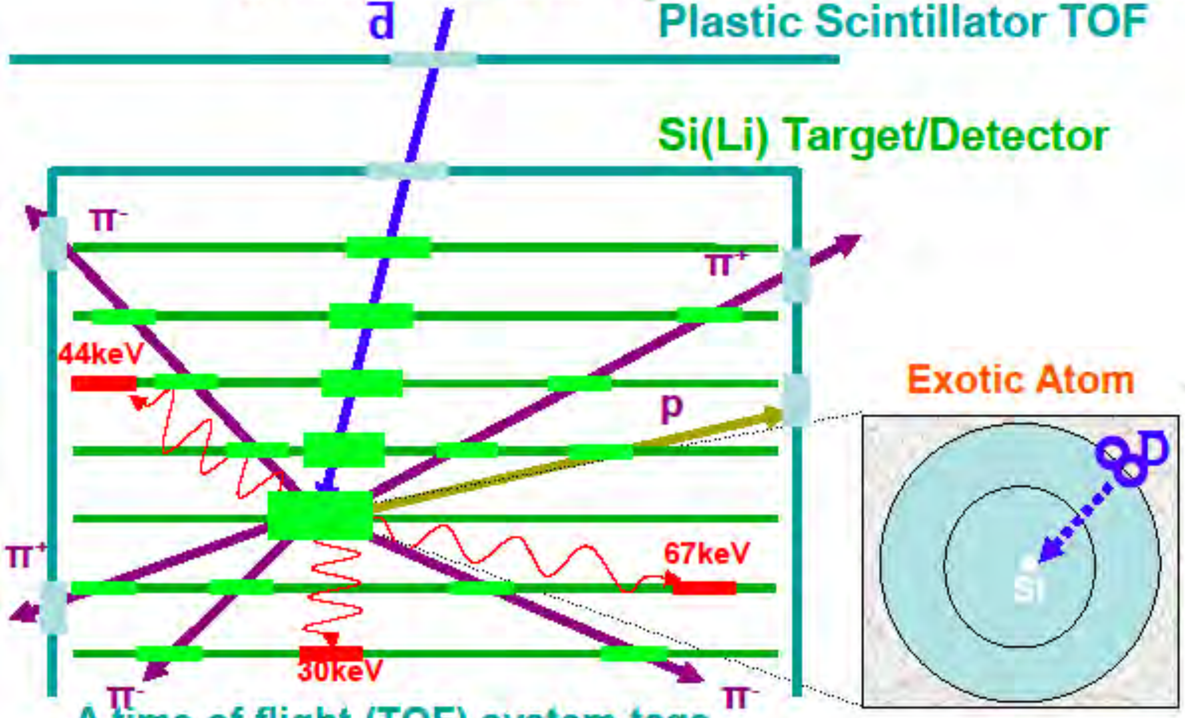


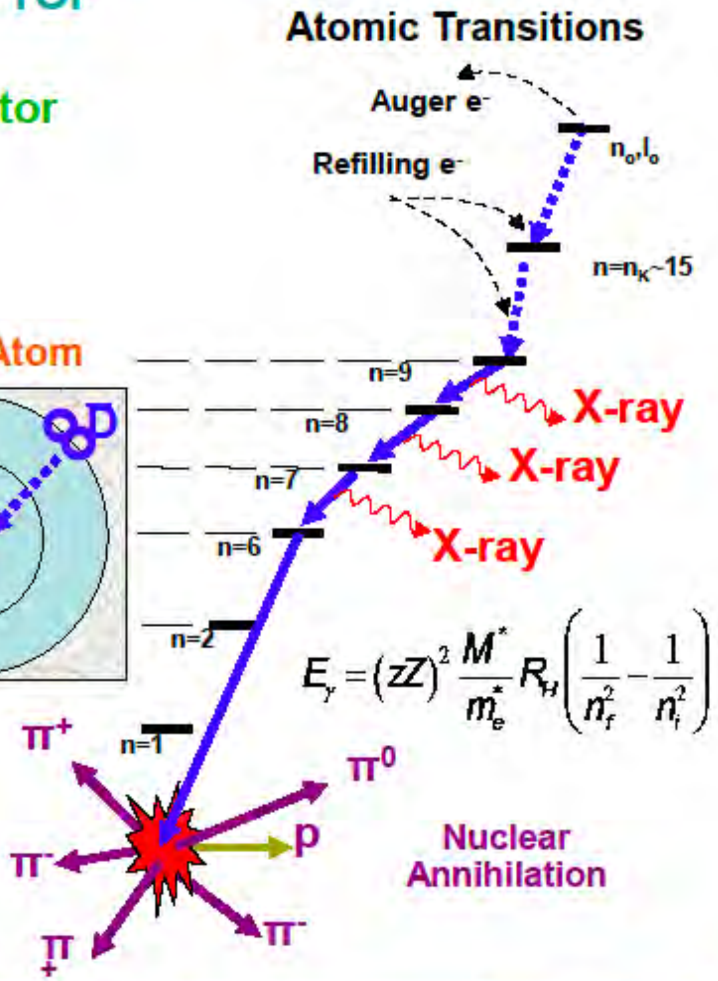
2.5 m^2 sr for protons

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

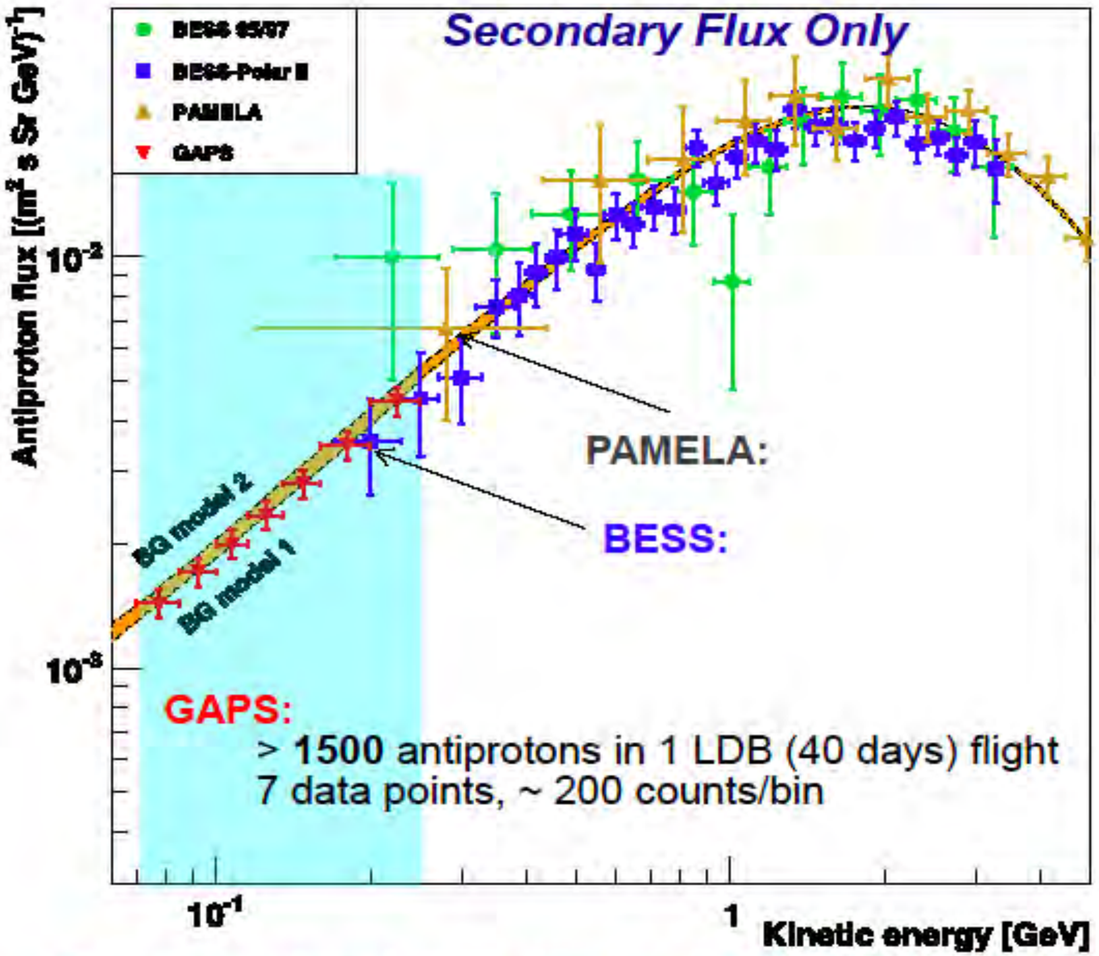
The antiparticle slows down & stops in a target material, forming an excited exotic atom

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



GAPS:
> 1500 antiprotons in 1 LDB (40 days) flight
7 data points, ~ 200 counts/bin

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

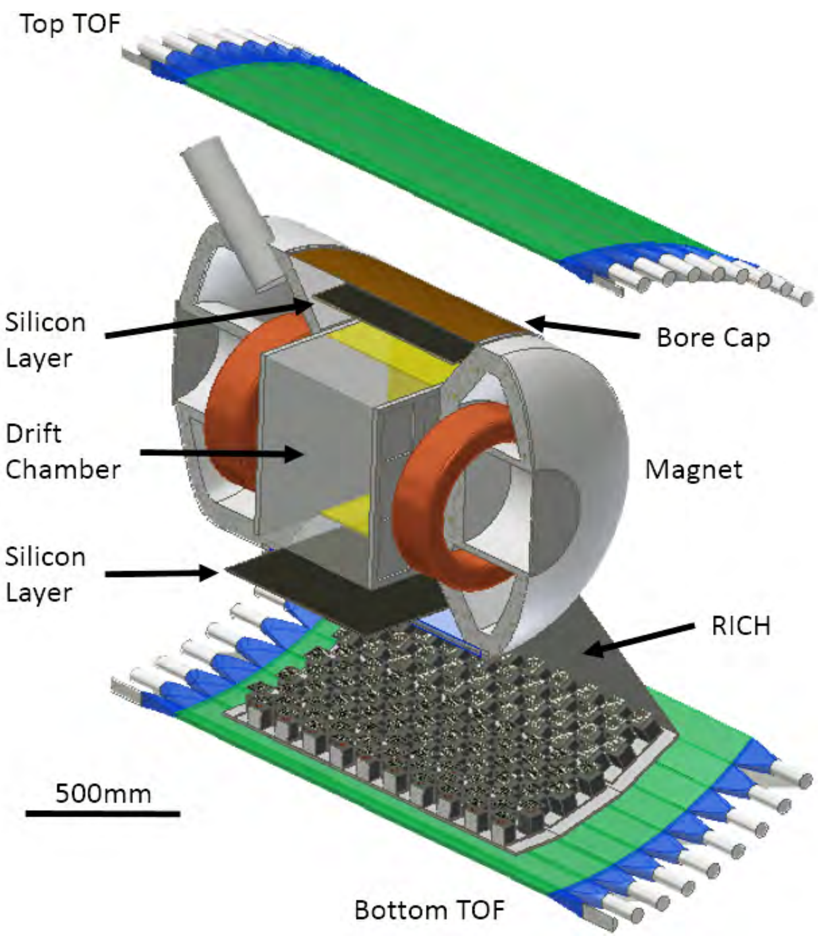
Secondary flux

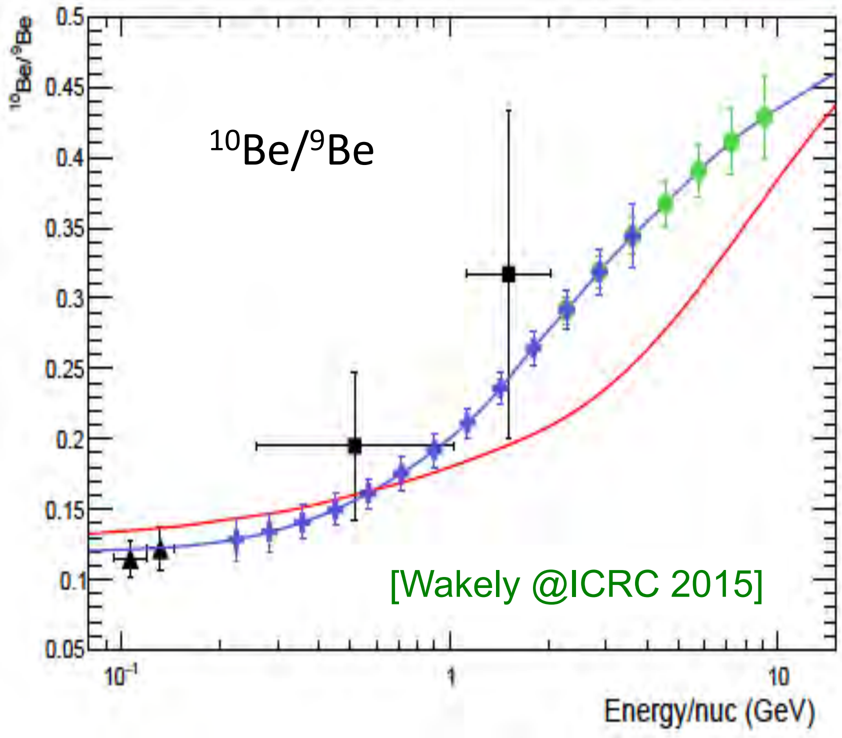
- constrained by B/C ratio

M. Hailey, Dark Matter 2014, UCLA

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

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)