Recent results from AMS-02 and their interpretation

Nicola Tomassetti
Perugia University & INFN

Searching for the sources of Galactic cosmic rays
December 11- 14| APC Paris, France

Meanwhile at POCC

Payload Operation Control Center
POCC – CERN, Genva

7.5 years of observation time

130+ Giga particles

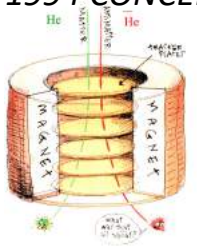
The AMS collaboration

AMS Collaboration

- *16 countries*
- *60+ institutes*
- *500+ physicists*
- *20 years*

Project timeline

1994 CONCEPT

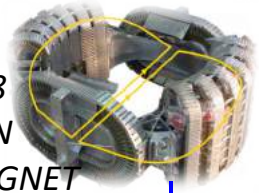


1997
AMS-01
PROTOTYPE

1998: STS-91

2000 @CERN
AMS-02 CONSTRUCTION

2008
@CERN
SC MAGNET
BEAM TEST



2010
TVT @ ESA (NL)

2010
@CERN
SC -> PM
NEW BEAM TEST

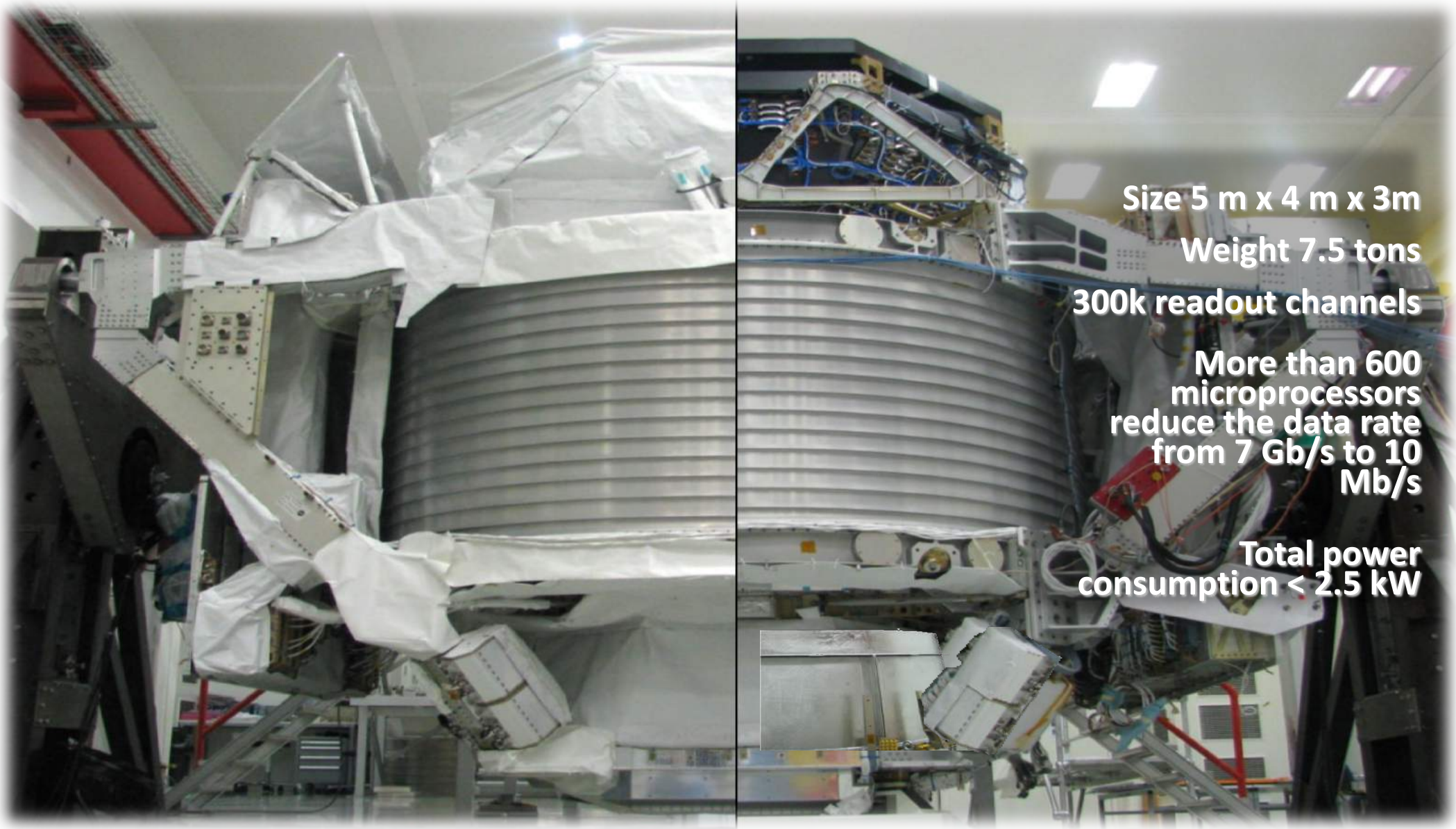
2011
@KSC
INTEGRATION & CR-μ RUN

MAY 2011
STS-134
FLIGHT

ON THE ISS

→ Steadily taking data on the ISS since May 19th 2011

The AMS instrument – Pre-launch Integration



AMS-02 installed in Endeavour's Payload Bay

May 16th 2011: launch

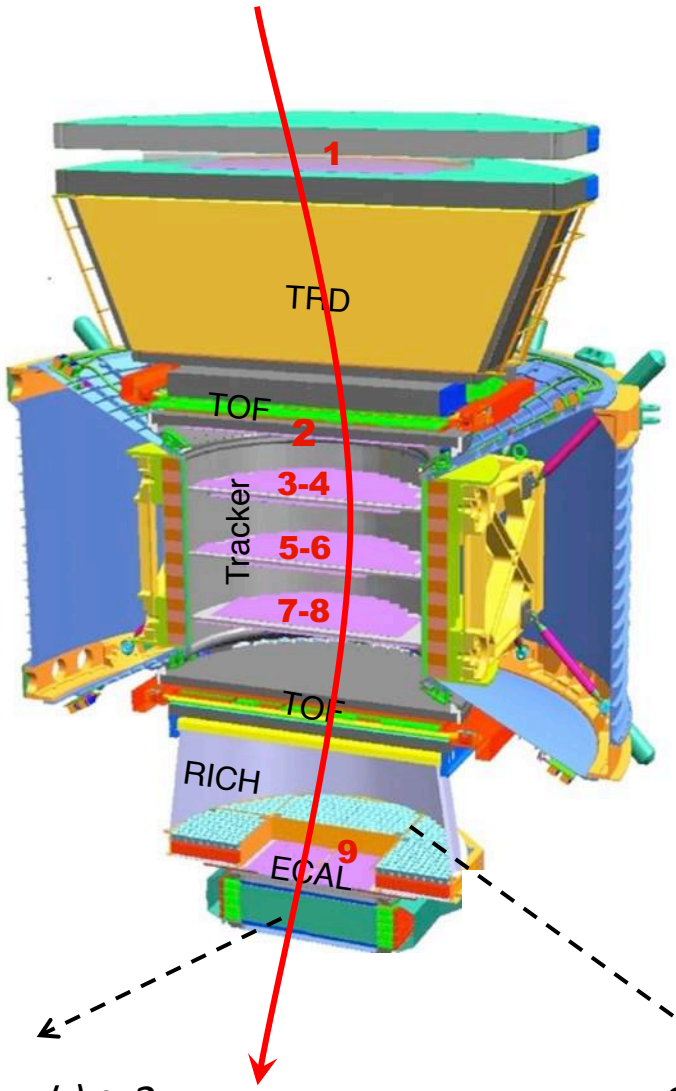
May 16, 2011 @ KSC, US
STS-134 / Endeavour on launchpad

May 19th 2011: activation

Di Mauro et al (Torino) 2014

Redundant energy measurements

TRD, $\gamma = E/M$
Leptons @10-300 GeV
Nuclei @1-20 TeV?



Tracker, R = p/Z
MDR ≈ 2TV (p); 3TV (He)

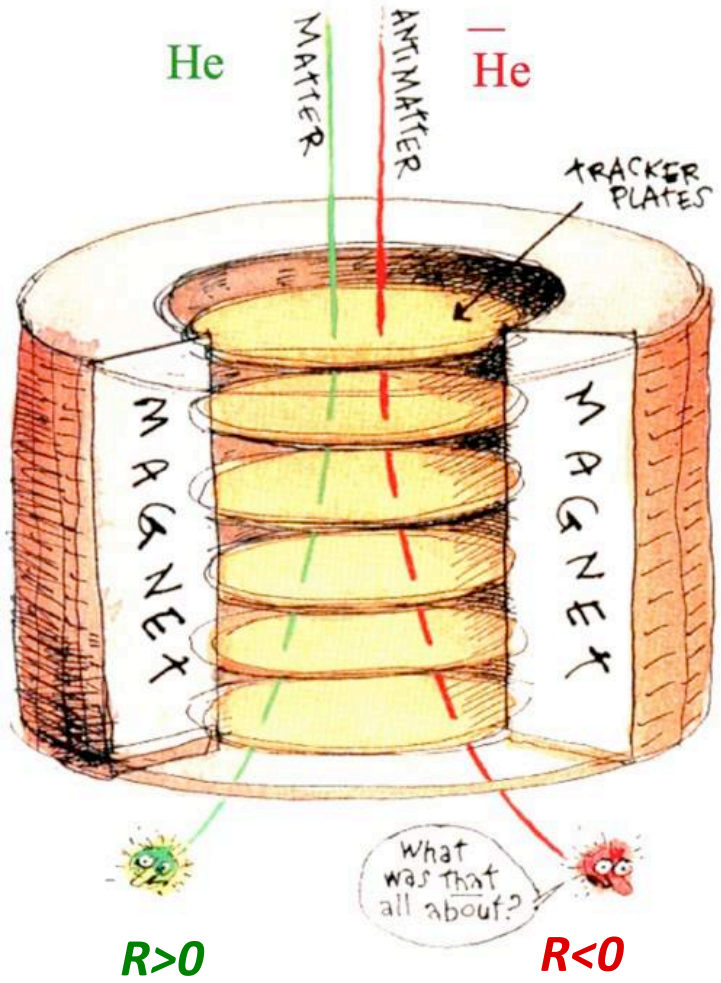
TOF, β
Δβ/β ≈ 1%

ECAL, E
ΔE/E (TeV e ±) ~ 2 %
ΔE/E (TeV p) ~ 50 %

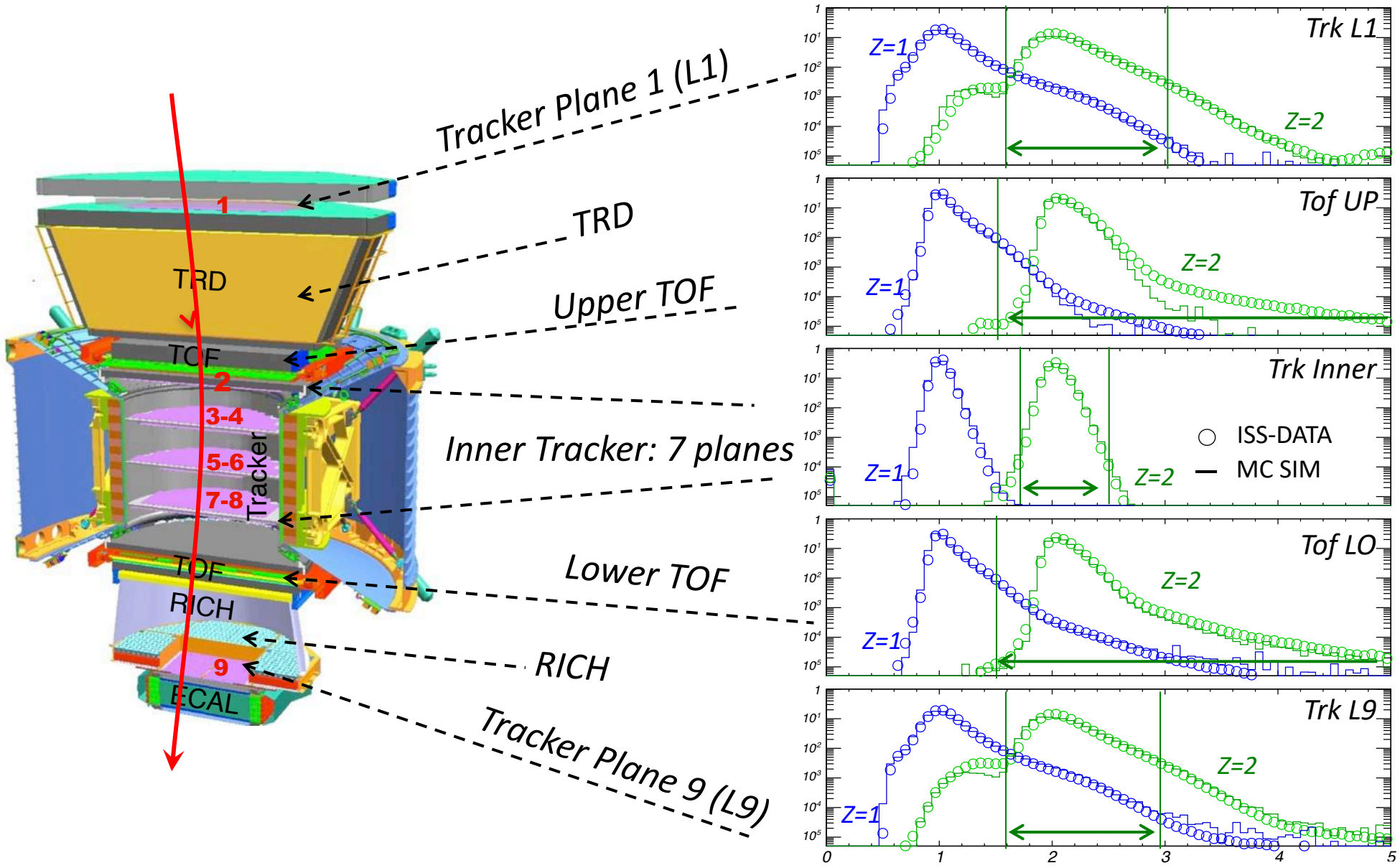
RICH, β
Δβ/β ≈ 0.05%

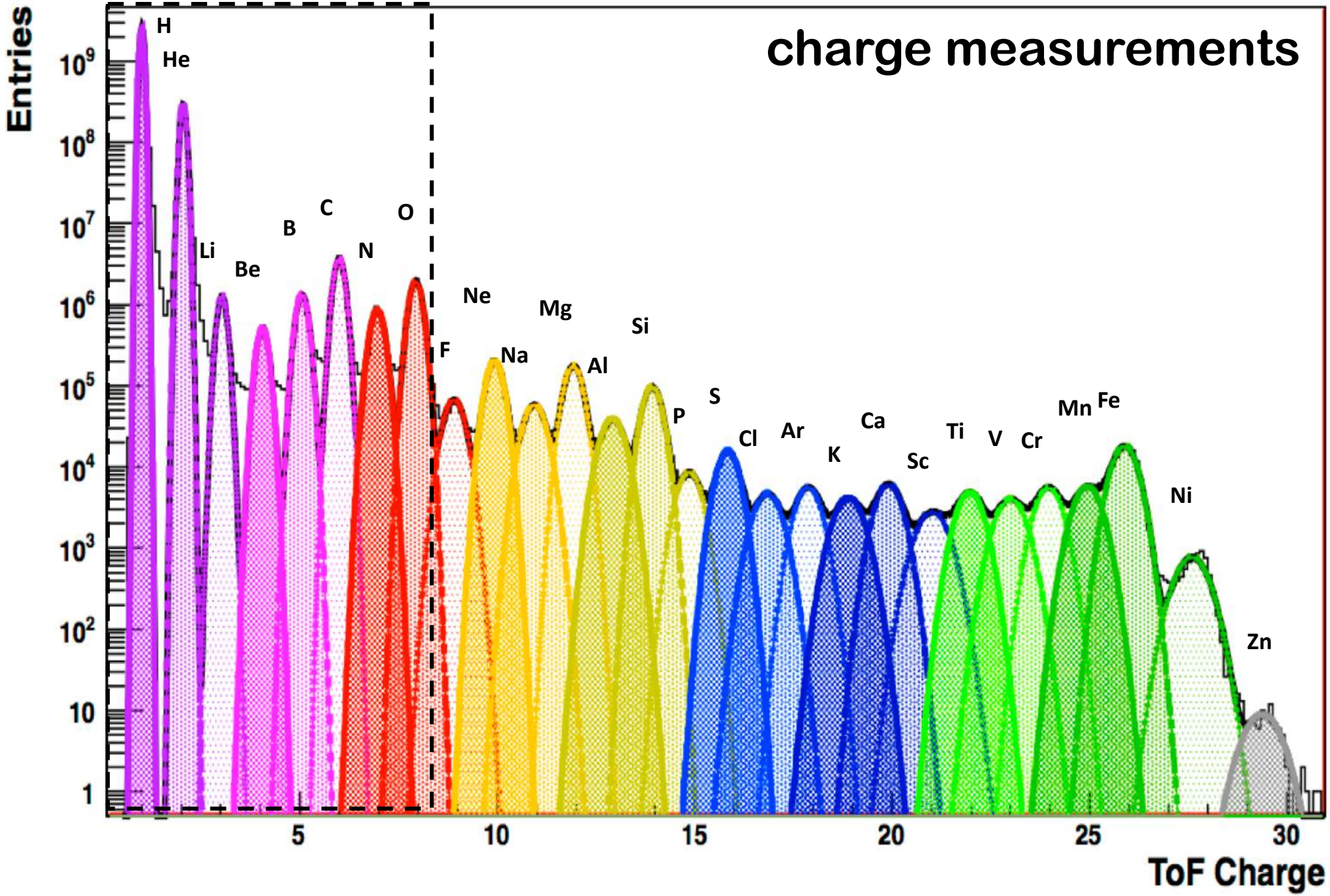
Geomagnetic cutoff, R
ΔR/R ≈ 10% up ~25 GV

Charge-sign separation



Reduntant charge measurements

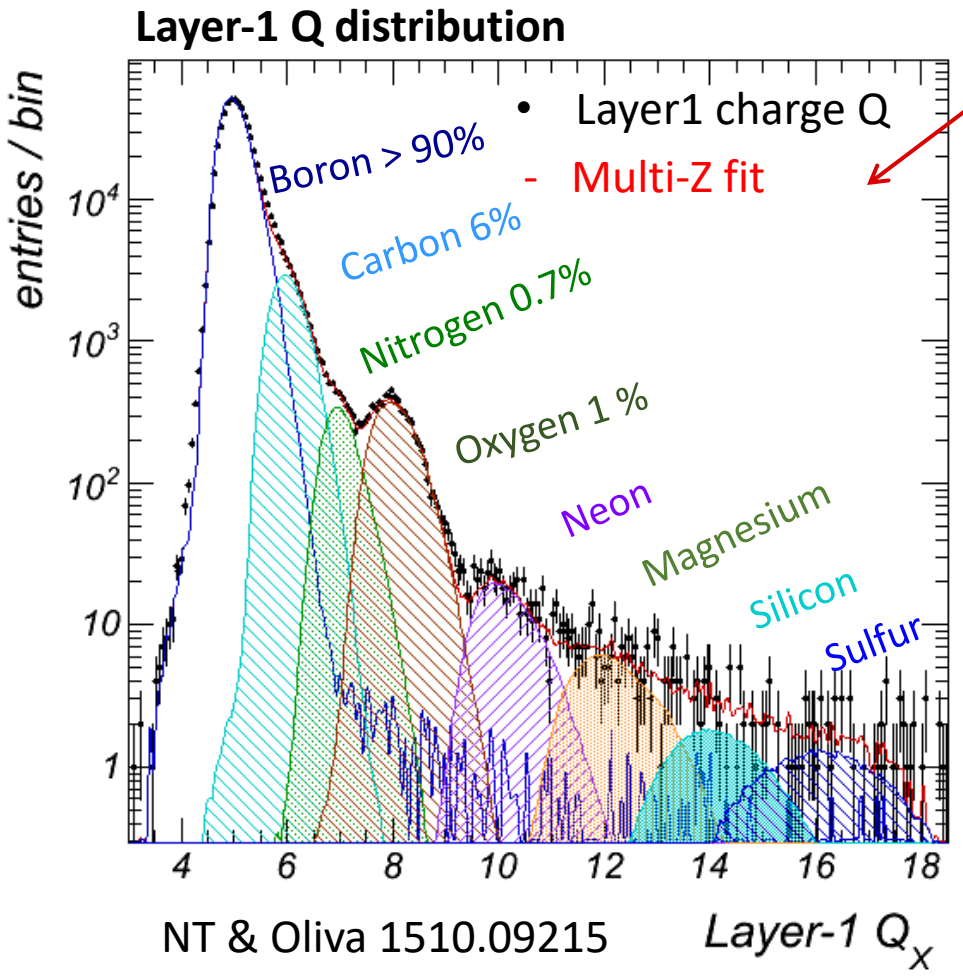



charge measurements
Entries
ToF Charge
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Ni
Zn
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
5
10
15
20
25
30

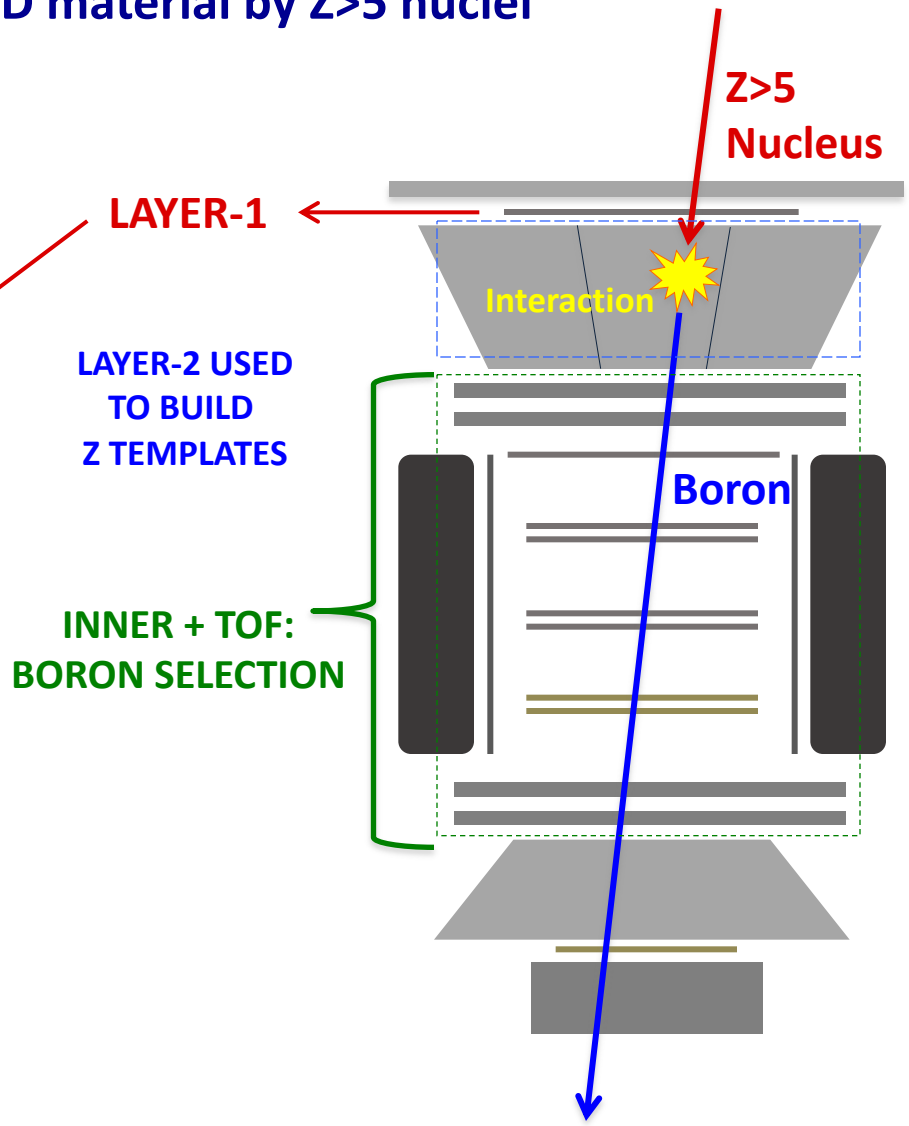
Top-of-Instrument fragmentation

Study of fragmentation processes appearing at different levels in the detector.

Example: secondary production of Boron in TRD material by Z>5 nuclei



NT & Oliva 1510.09215

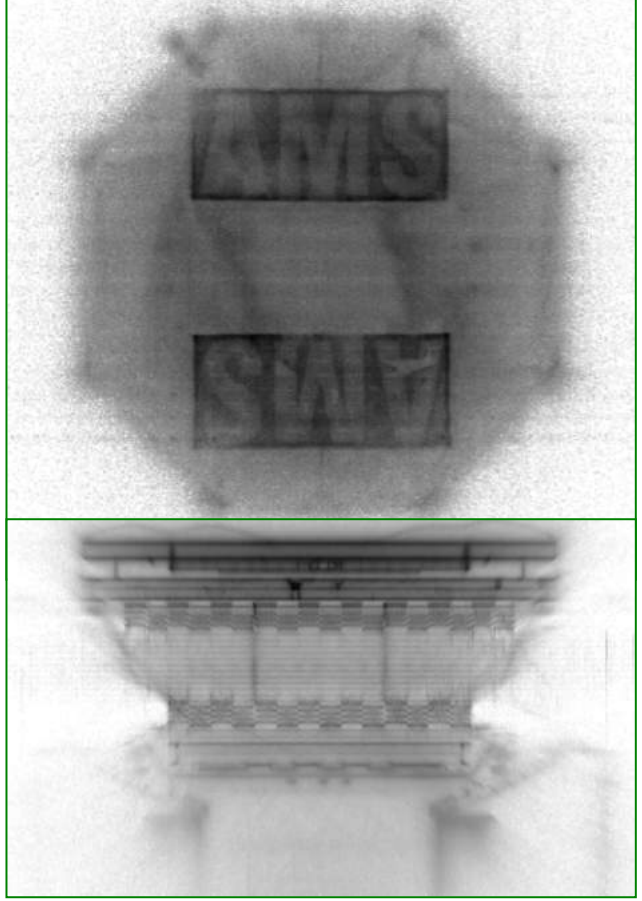


Top-of-Instrument fragmentation

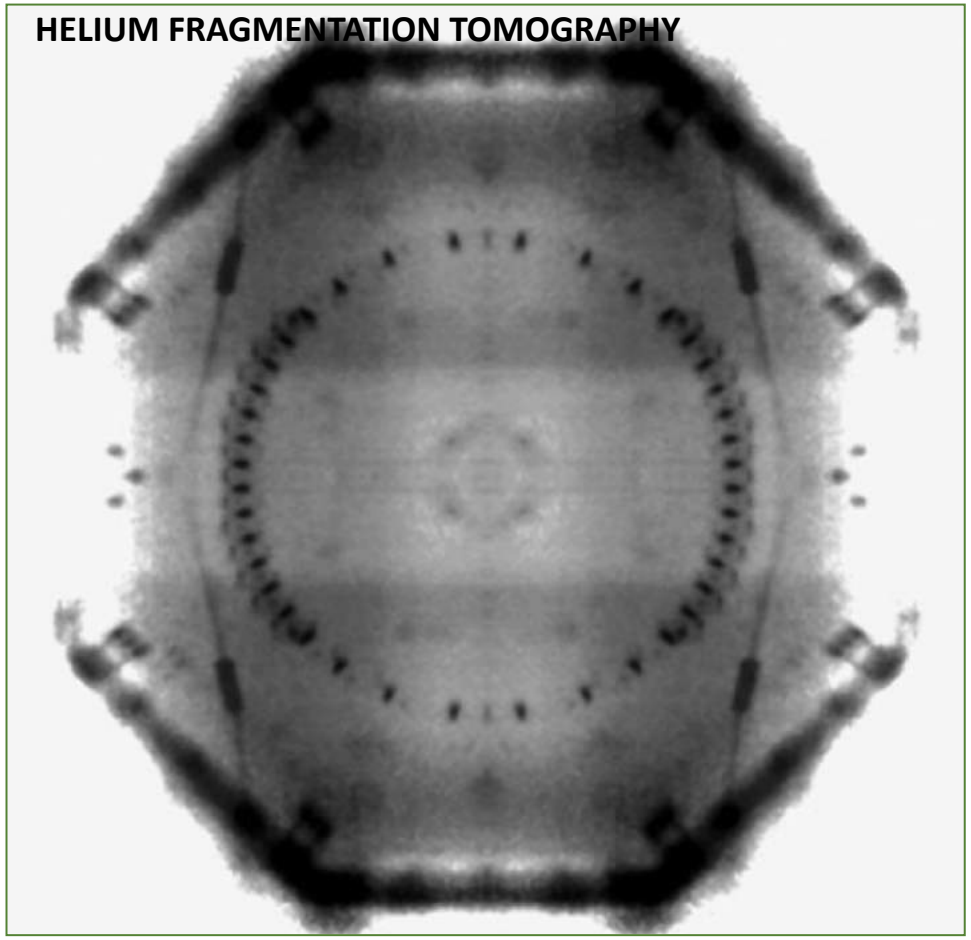
3D HADRON TOMOGRAPHY FROM PARTICLE INTERACTIONS IN THE MATERIAL

AMS ON ISS - PHOTO

TRACK VERTICE TOMOGRAPHY



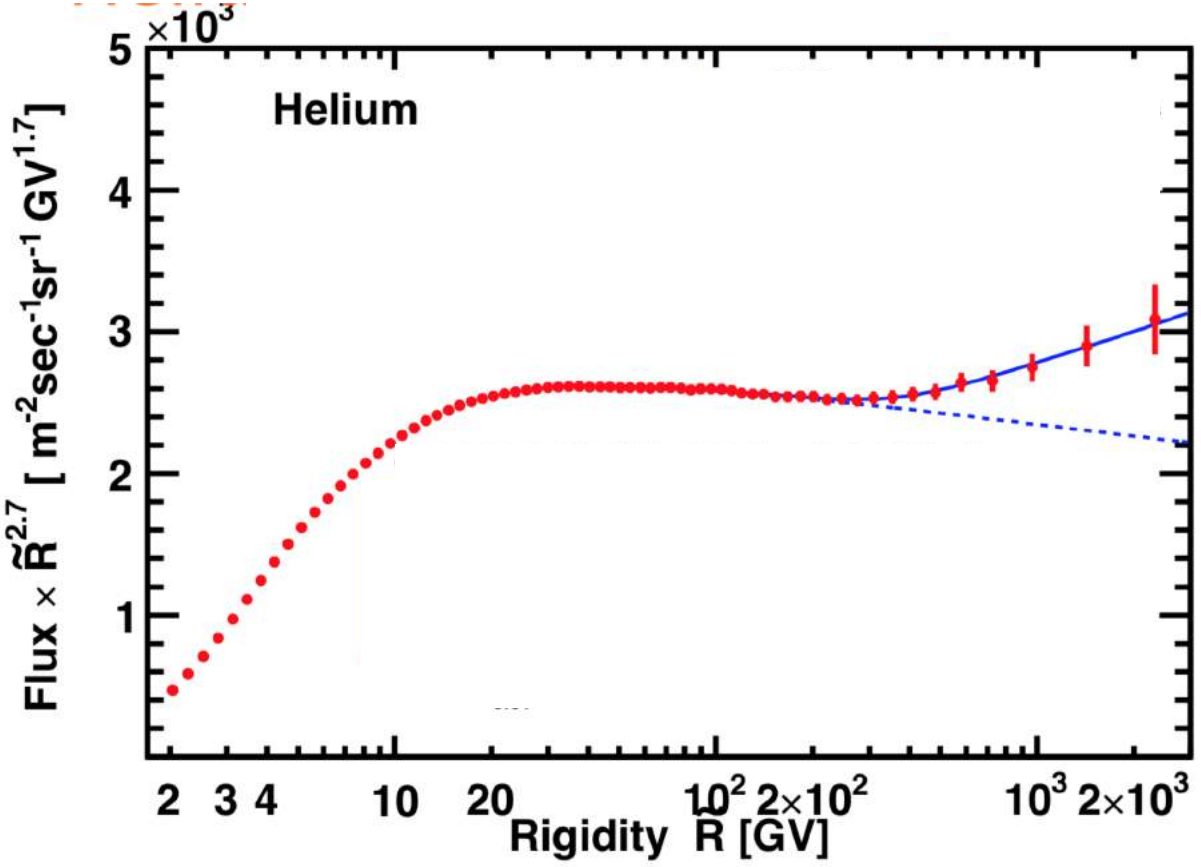
HELIUM FRAGMENTATION TOMOGRAPHY



Proton and helium fluxes

- Re-analysis of data ongoing
- Larger statistics, strong improvement of systematic errors
➢ Different slopes. Common value for critical rigidity R0

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



PRL 2017

Carbon and Oxygen fluxes

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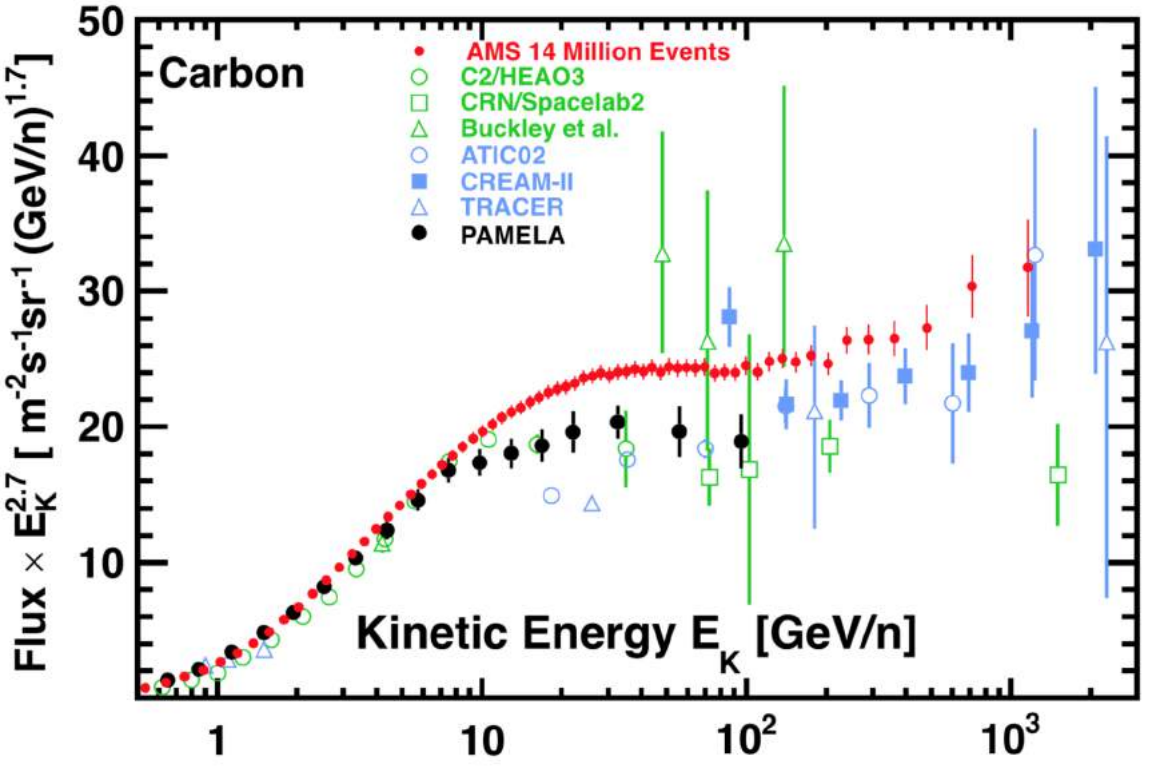
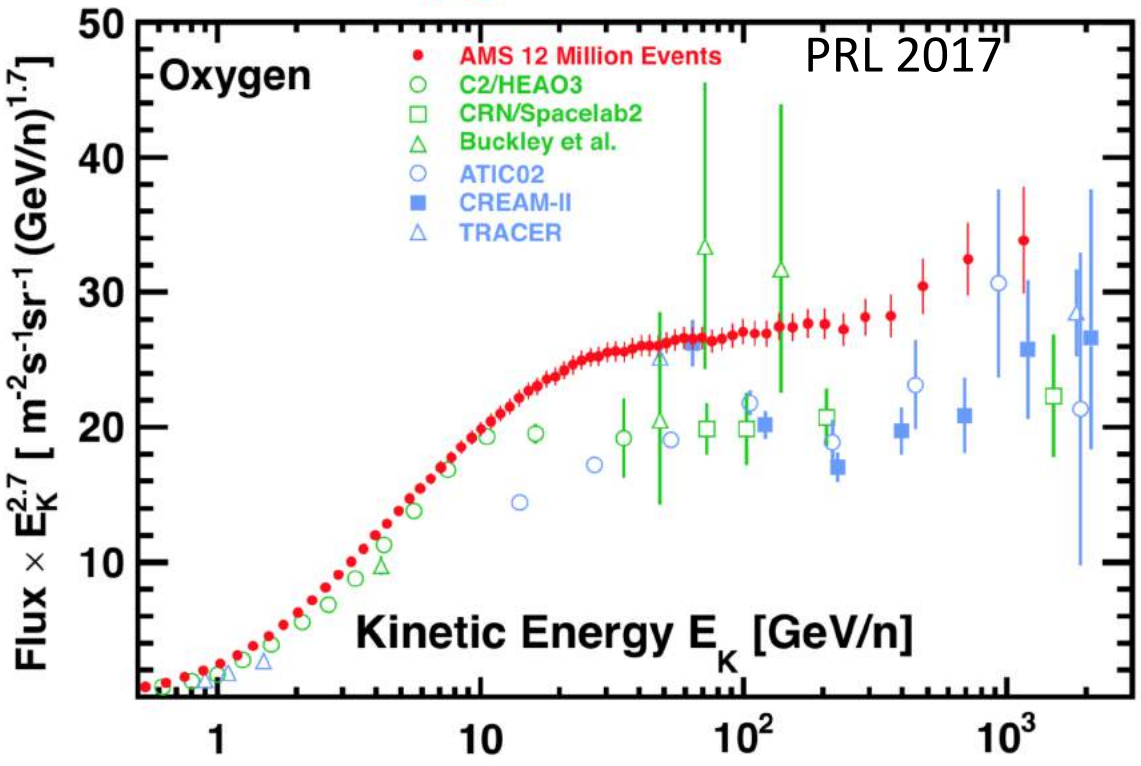
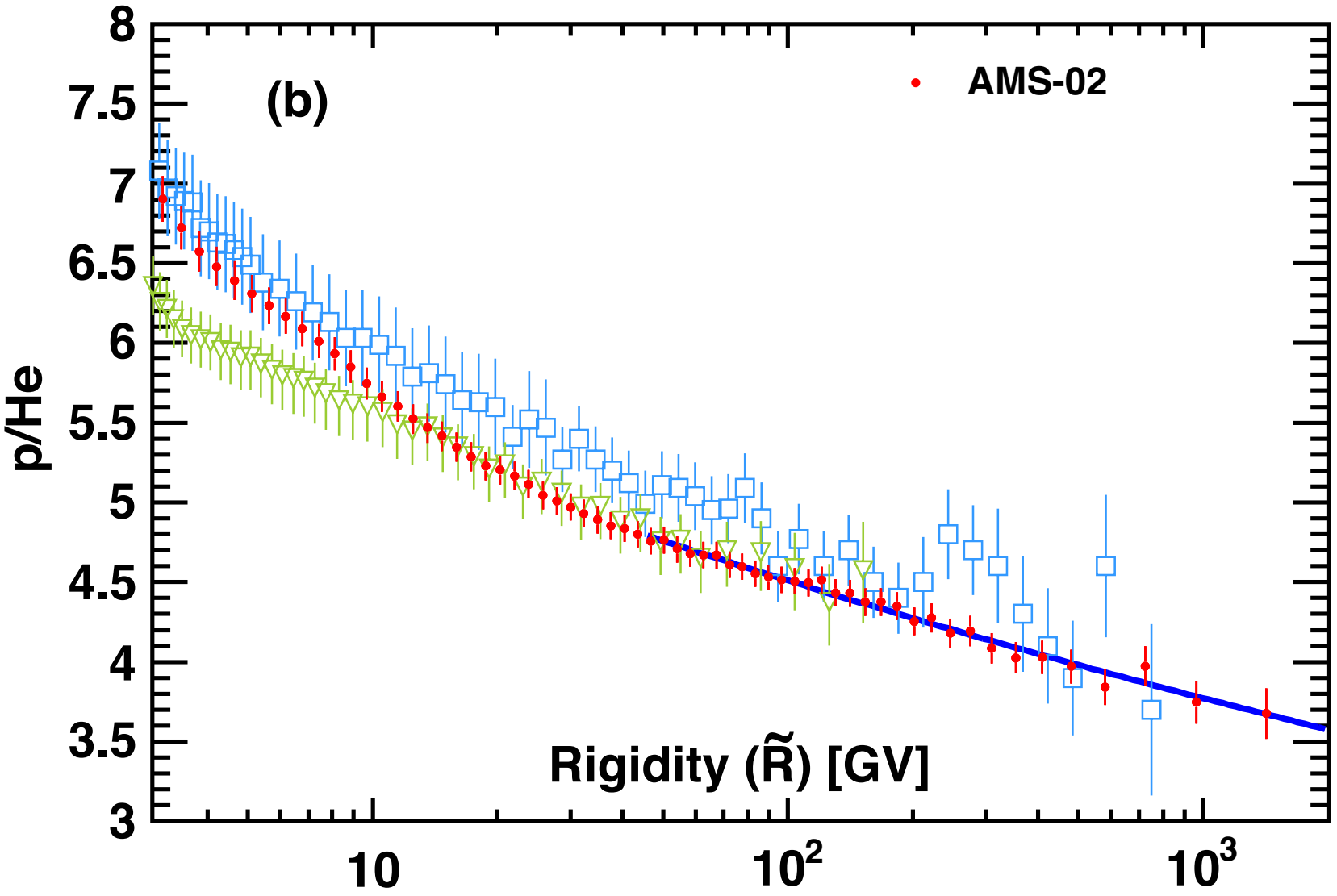




p/He ratio

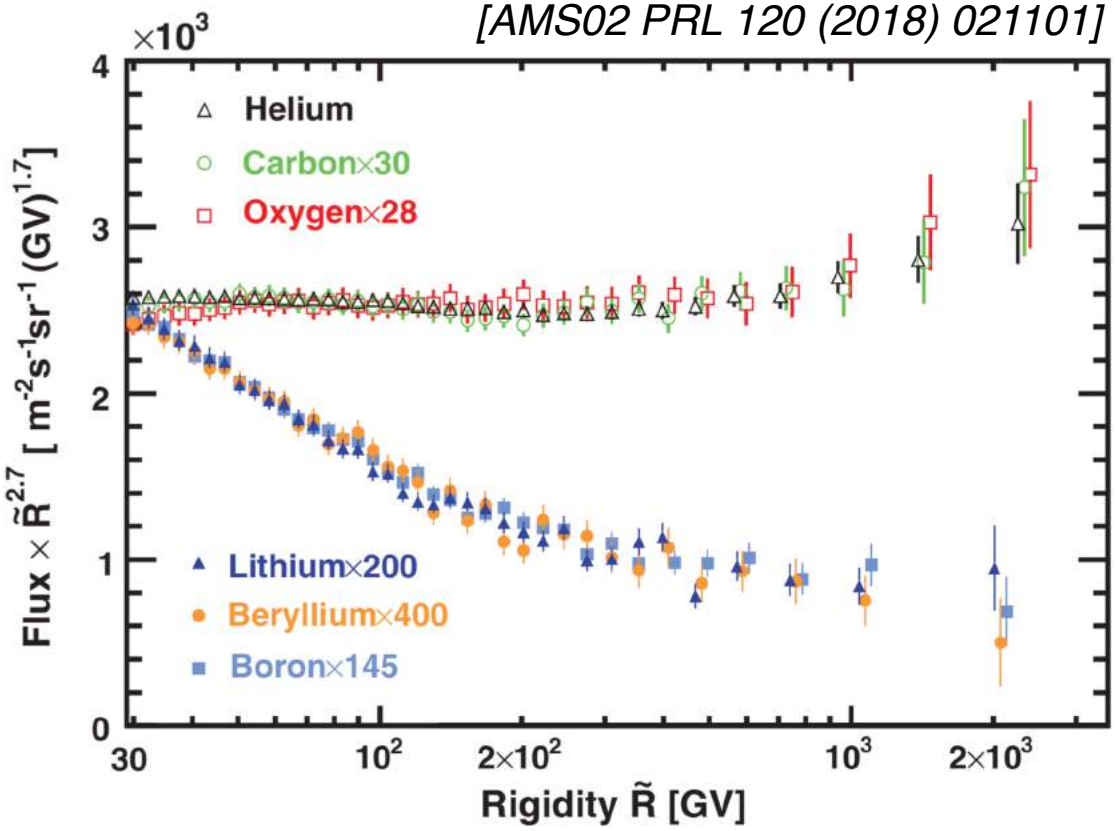


2.5 years of data [PRL 115 (2015) 211101]

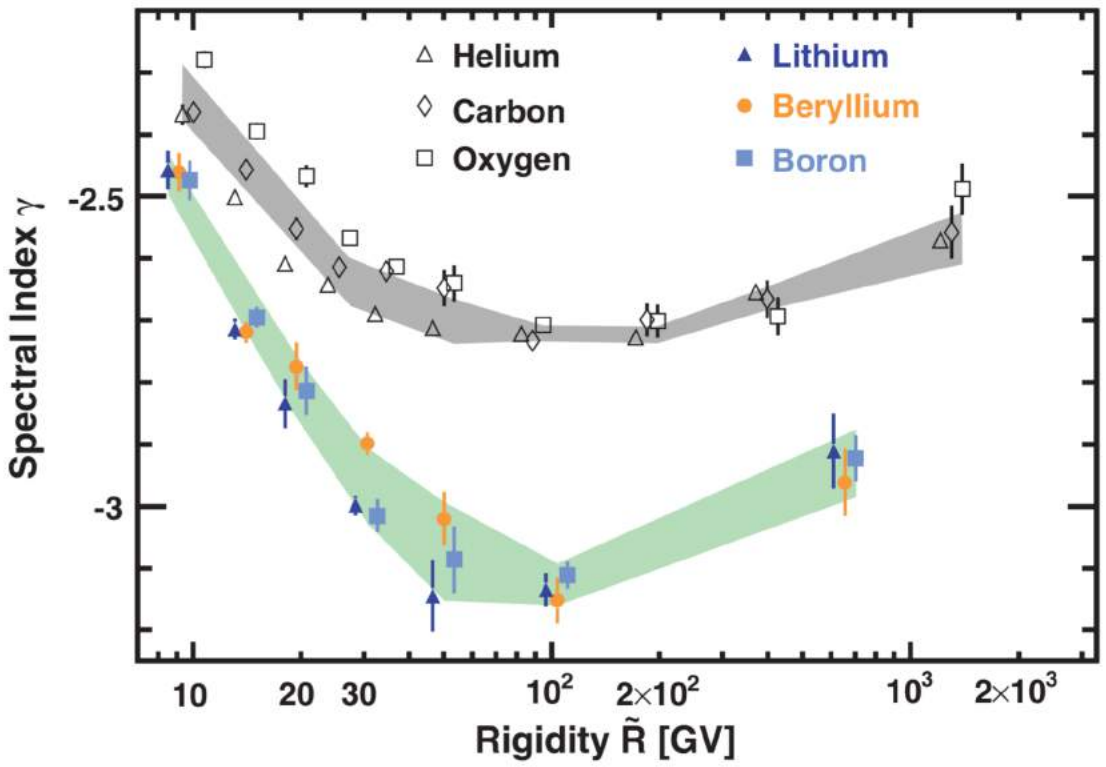
Lithium, Beryllium, and Boron

- ✓ Two groups: Li-Be-B vs He-C-O
- ✓ Spectral hardening at R~O(300 GV)
- ✓ Different changes of slopes Li-Be-B > He-C-O

[AMS02 PRL 120 (2018) 021101]



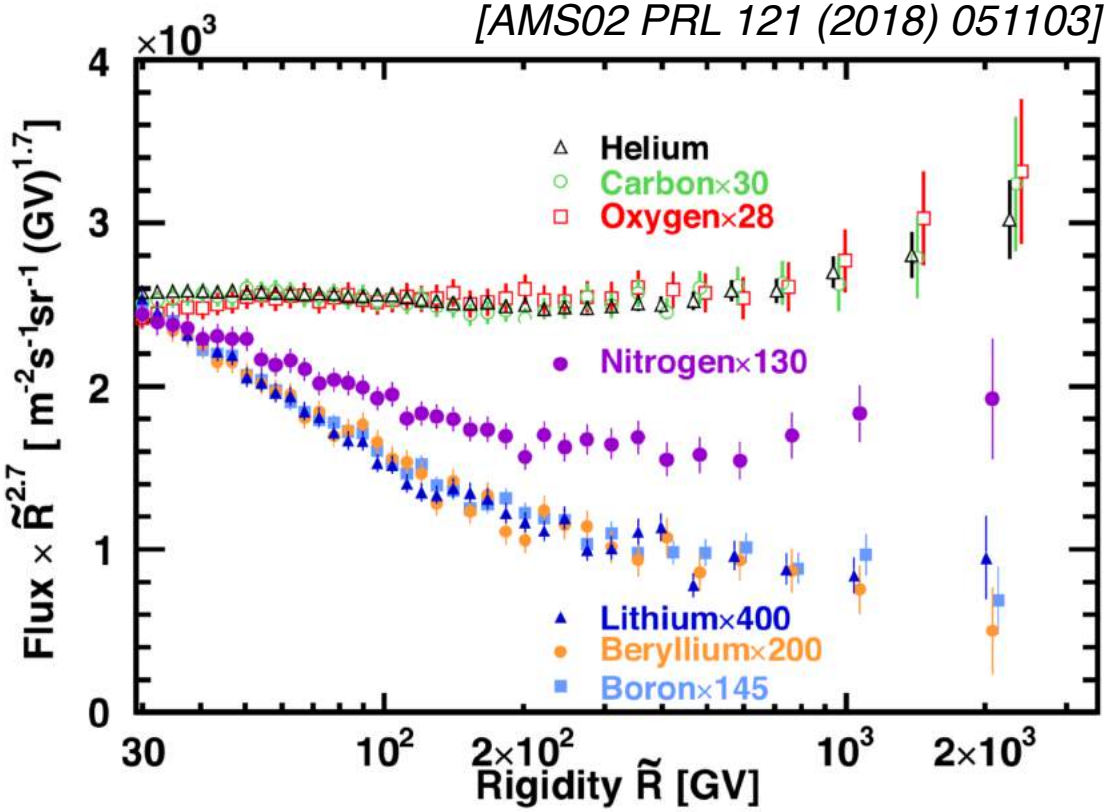
$$\gamma(R) \equiv dlog[\Phi(\mathrm{R})]/dlog[\mathrm{R}]$$



Lithium, Beryllium, and Boron, and Nitrogen

- ✓ Two groups: Li-Be-B vs He-C-O
- ✓ Spectral hardening at R~O(300 GV)
- ✓ Different changes of slopes Li-Be-B > He-C-O

[AMS02 PRL 121 (2018) 051103]



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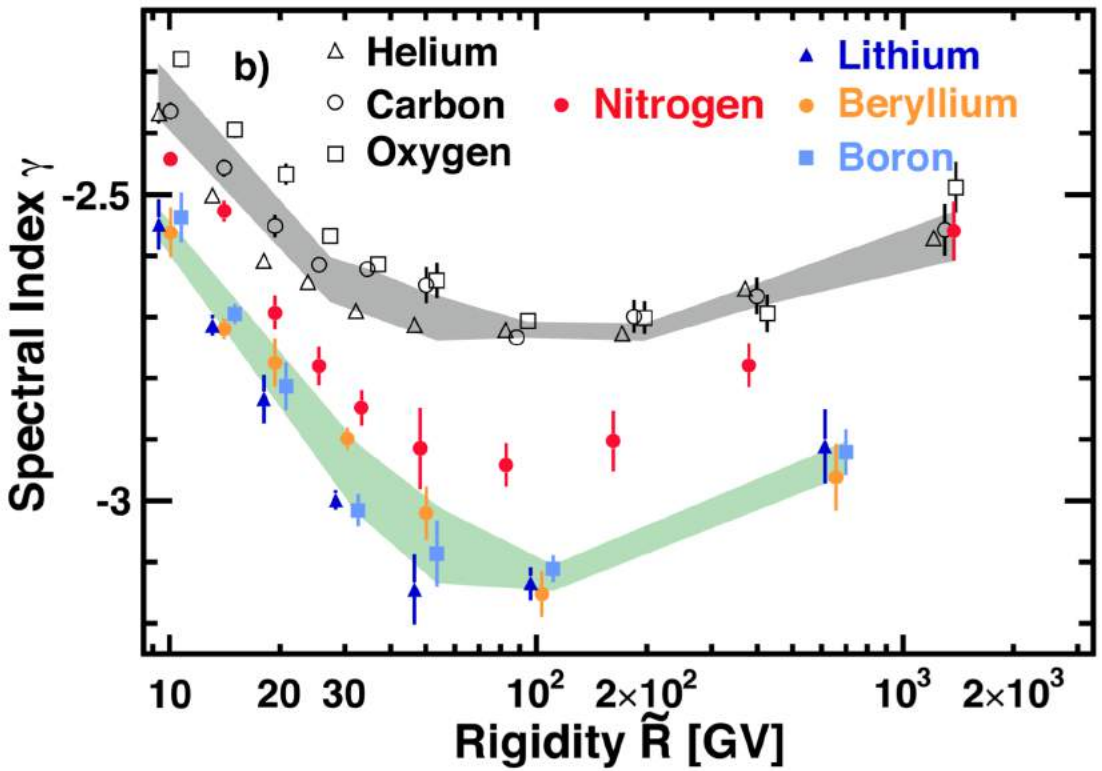

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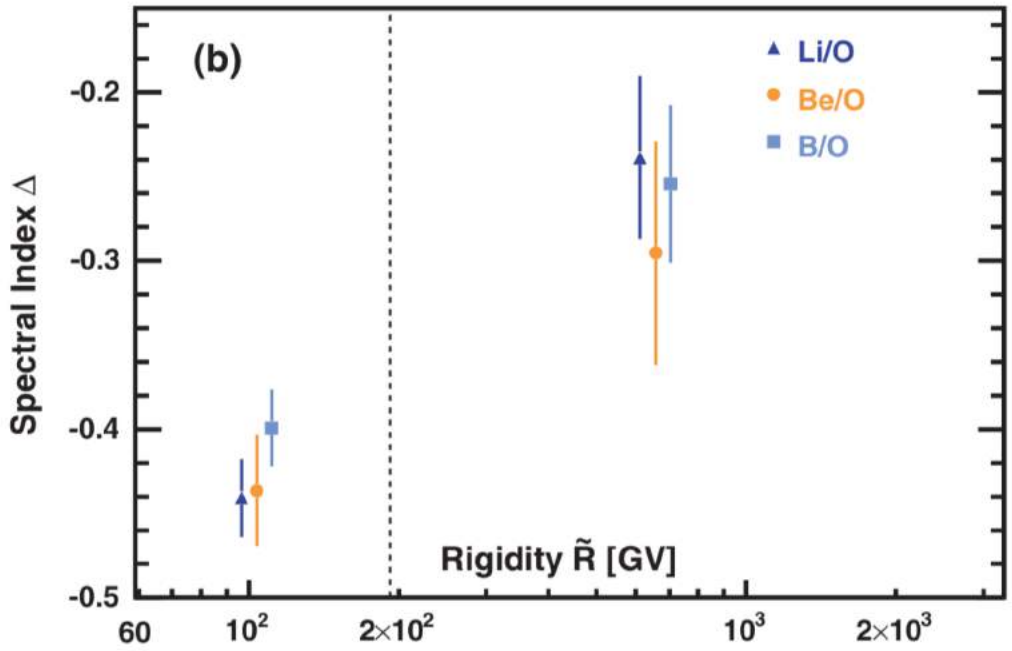
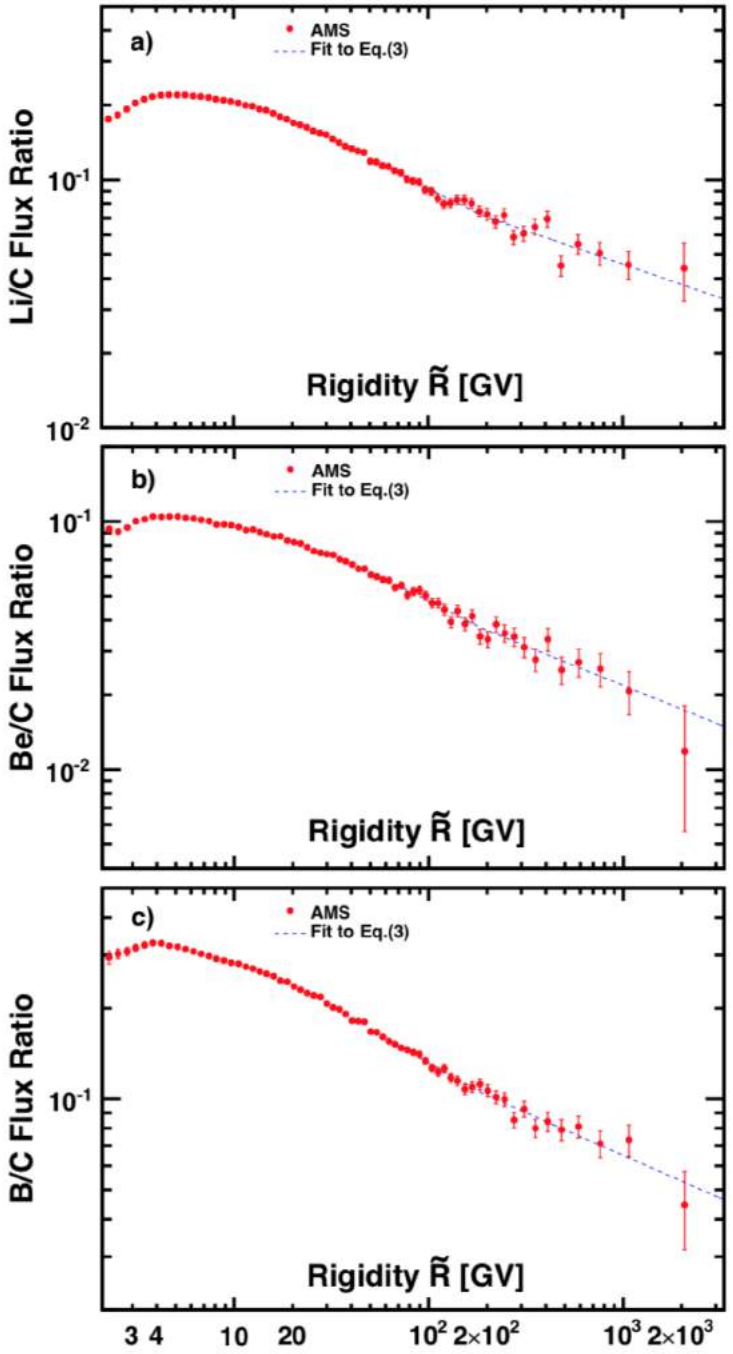
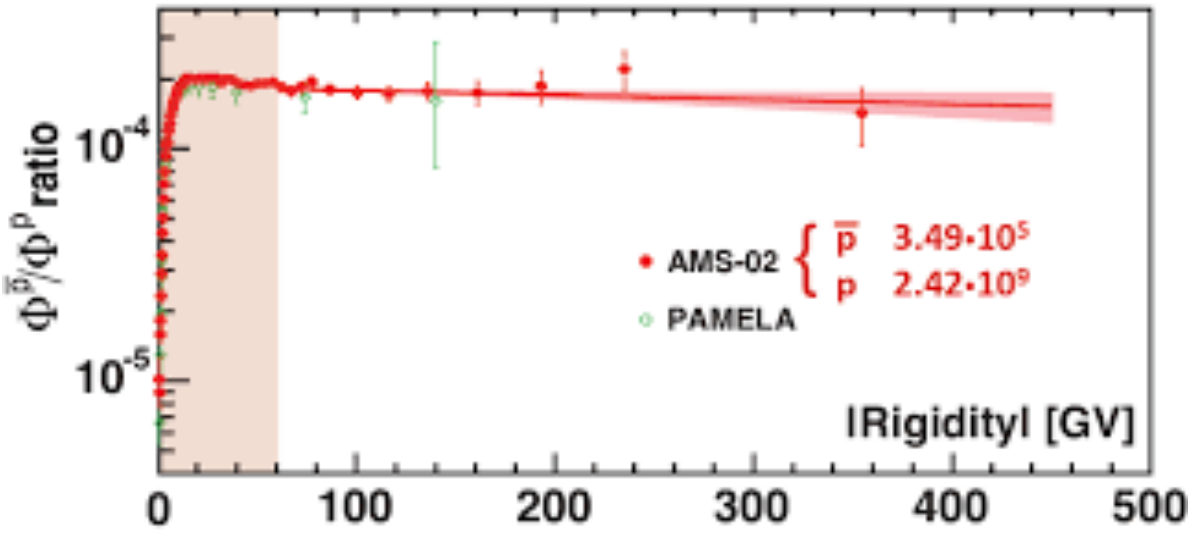


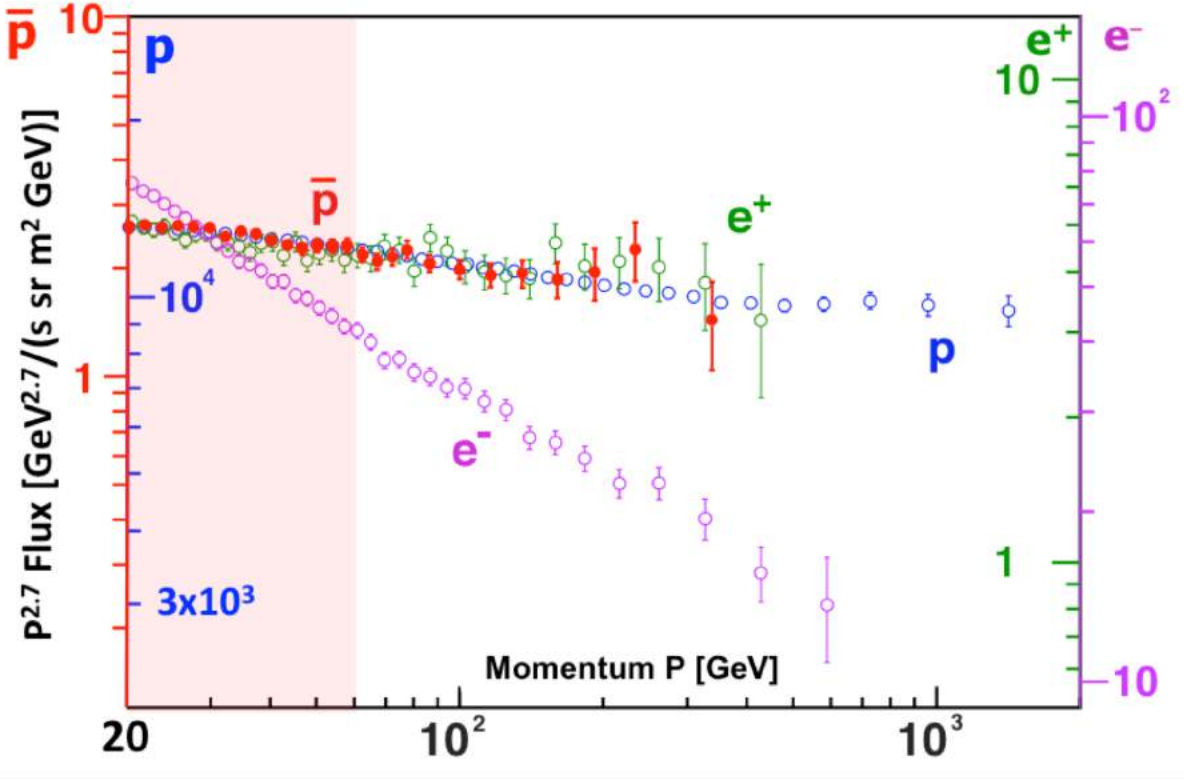


Antiproton flux and $\bar{p}/p$ ratio

- ✓ $\bar{p}/p$ expectation: high-energy decrease [B/C-like]
- ✓ $\bar{p}/p$ observation: at R>50 GV, the ratio is constant

AMS-02, PRL 115 (2016) 211101





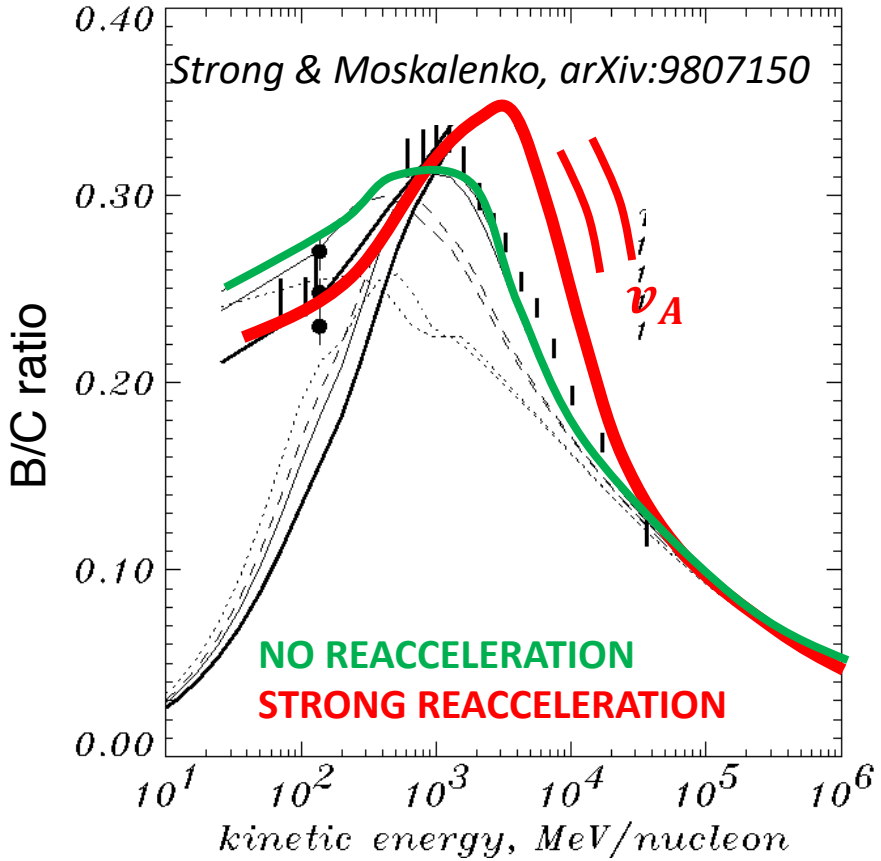
Behind the spectra: conventional approach

- Use <u>breaks in injection spectra</u>: high-rigidity break at R~350 GV
- Set <u>strong diffusive reacceleration</u> with $v_A \approx 30 - 40\ km\ s^{-1}$
- Use proton injection steeper than that of Z>1 elements
- **At tension with antiprotons**

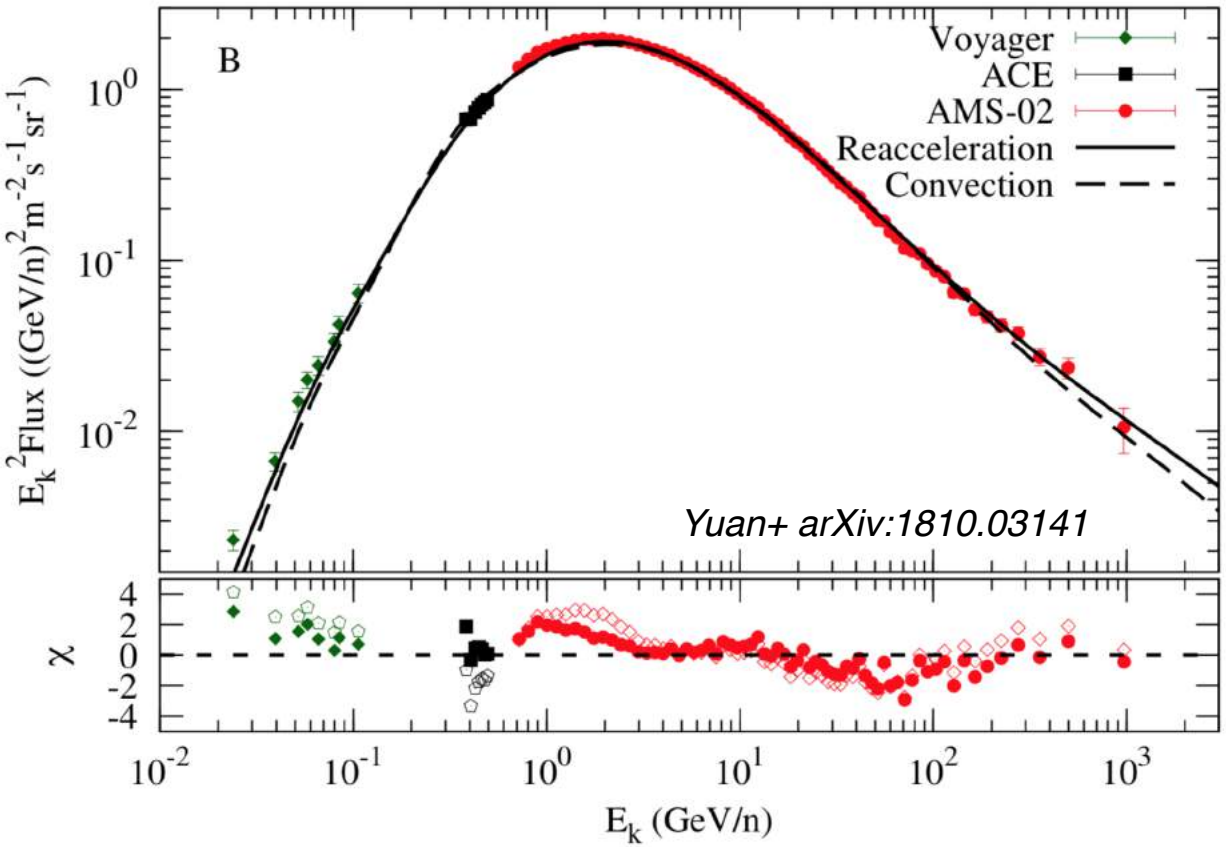
$$v_A \gg \sqrt{\frac{B^2}{4\pi\rho}} \approx 6\ km\ s^{-1}$$

Strong power requirement
Drury & Strong 1608.04227

Effect of reacceleration on Sec/Pri ratios



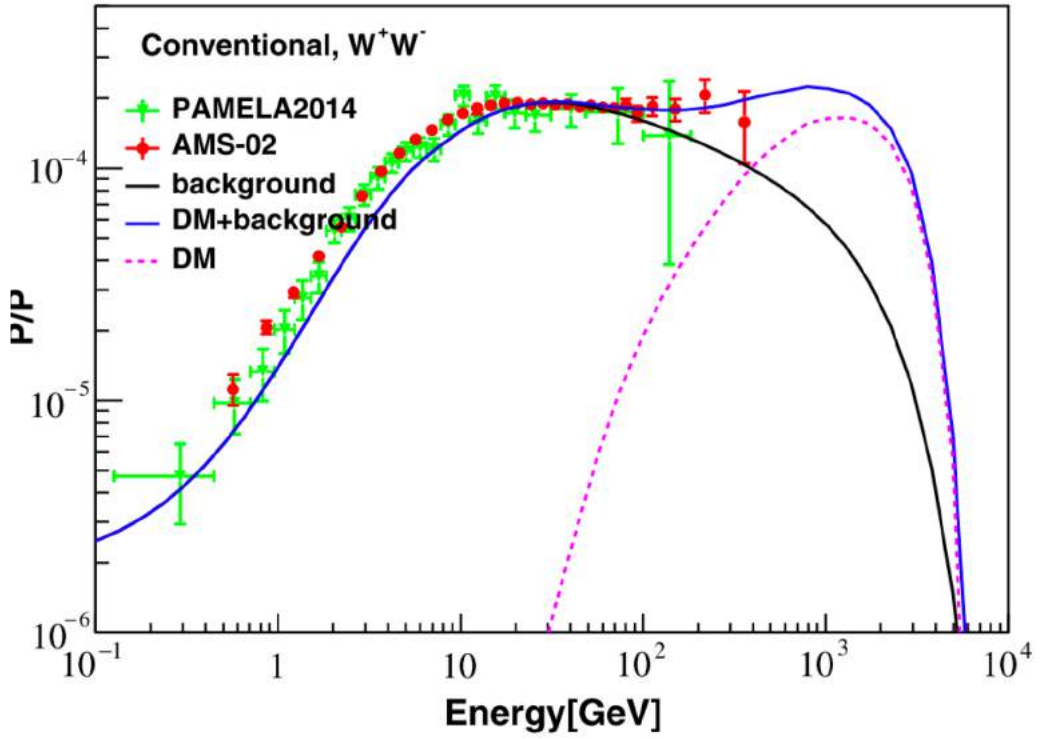
Diffusive-reacceleration model fit to the AMS-02 boron flux



Behind the spectra: conventional approach

- Use breaks in injection spectra: high-rigidity break at R~350 GV — Jin+ 1504.04604
- Set strong diffusive reacceleration with $v_A \approx 30 - 40\ km\ s^{-1}$ — Jin+ 1701.02213
- Use proton injection steeper than that of Z>1 elements
- **At tension with antiprotons**

Tension with antiprotons: @100+ GeV



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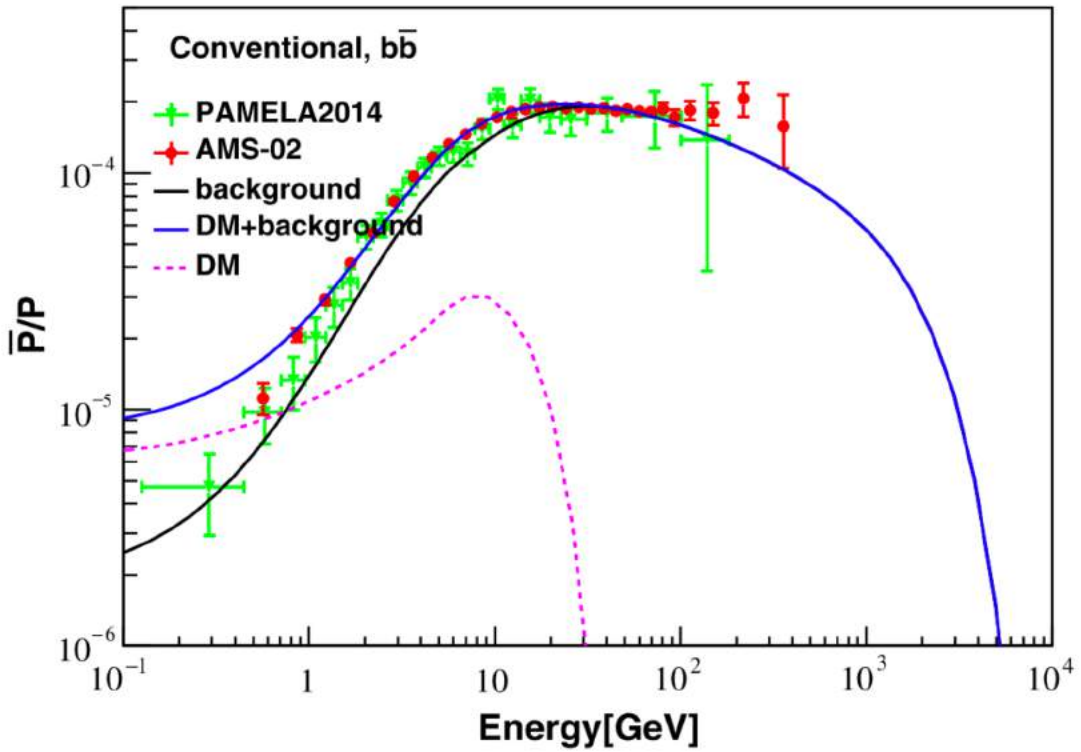

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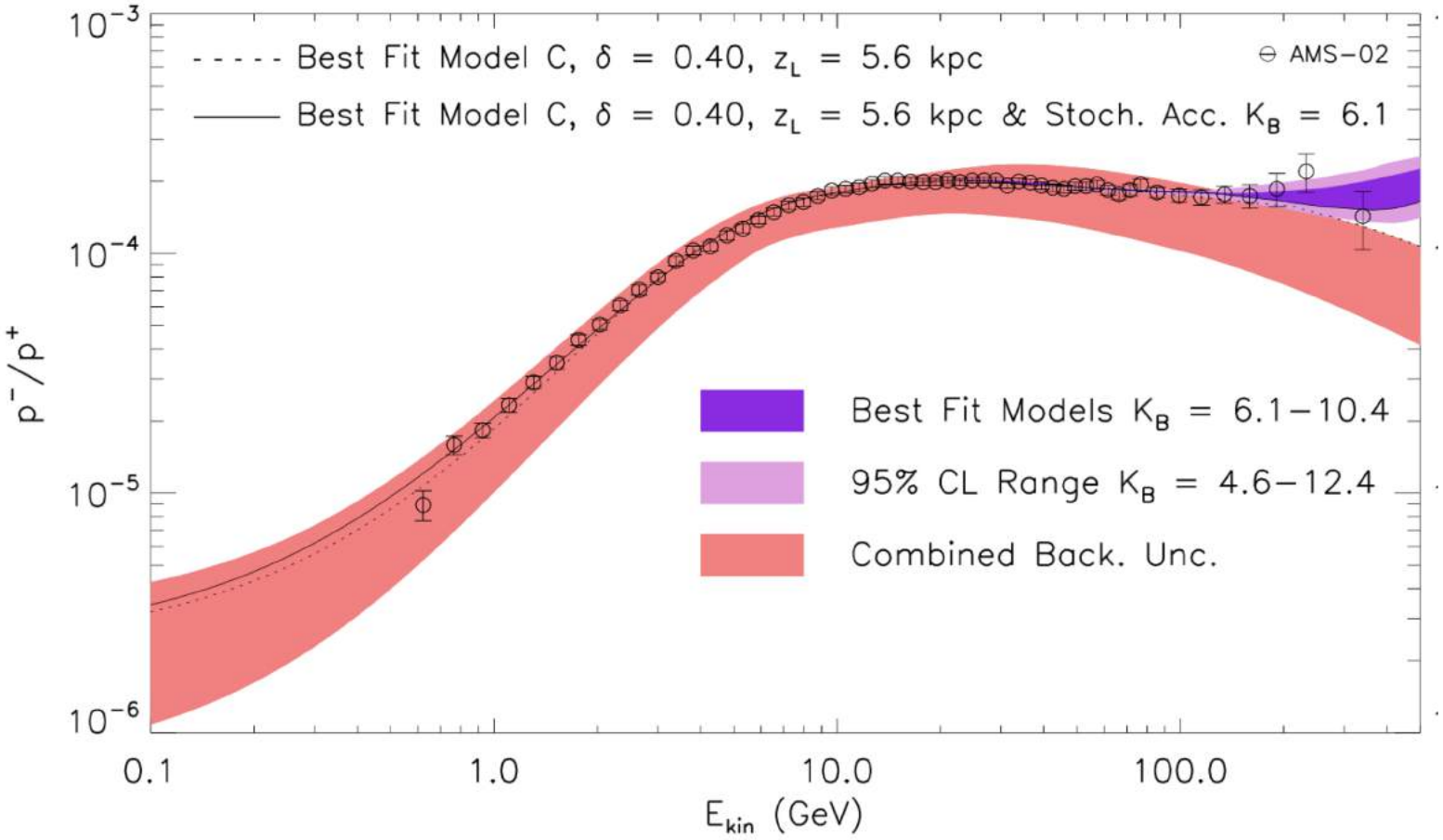
- **Add shock accelerated antiprotons?**

Cholis & Hooper 2017 [1701.04406]



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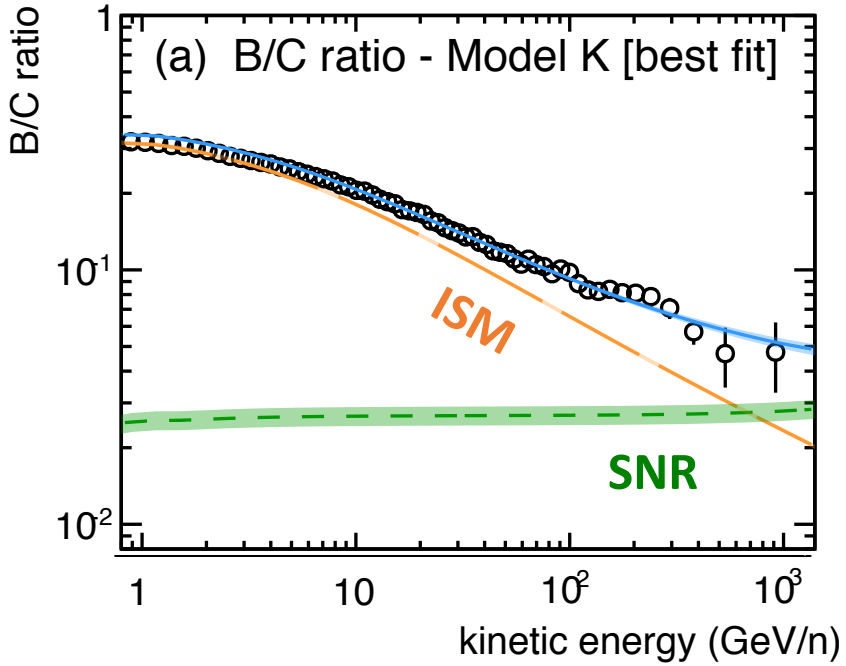
- **Add shock accelerated antiprotons?**

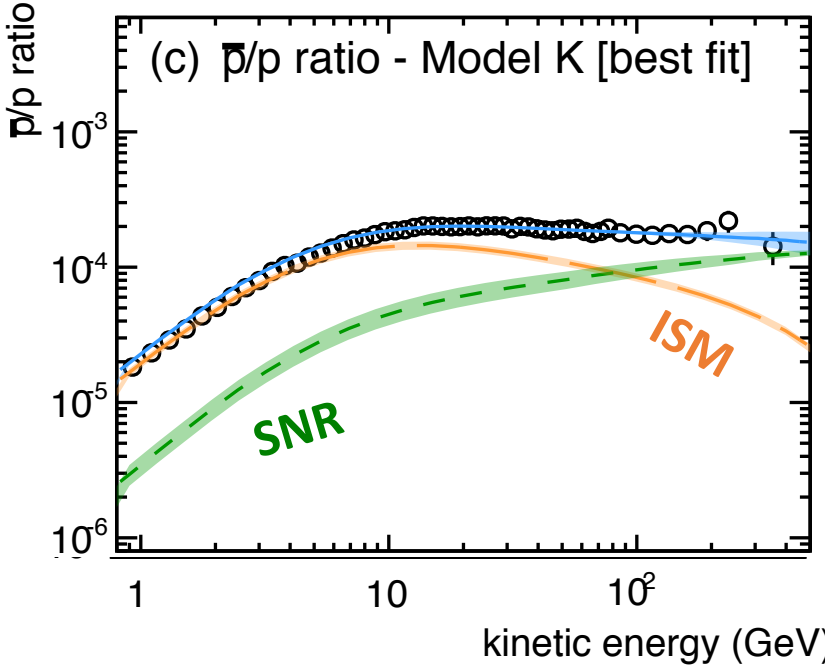
→ **At tension with shock accelerated boron**

NT & Oliva [1707.06915]

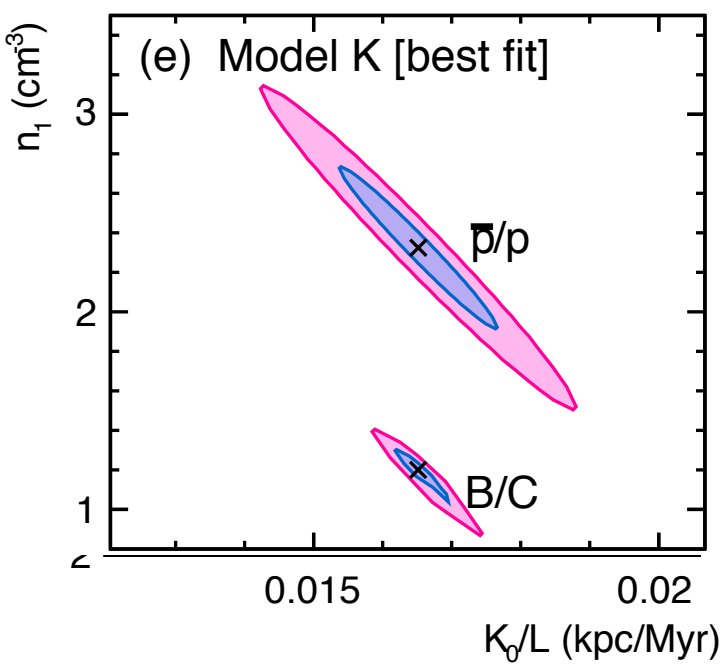
B/C driven fit



pbar/p driven fit

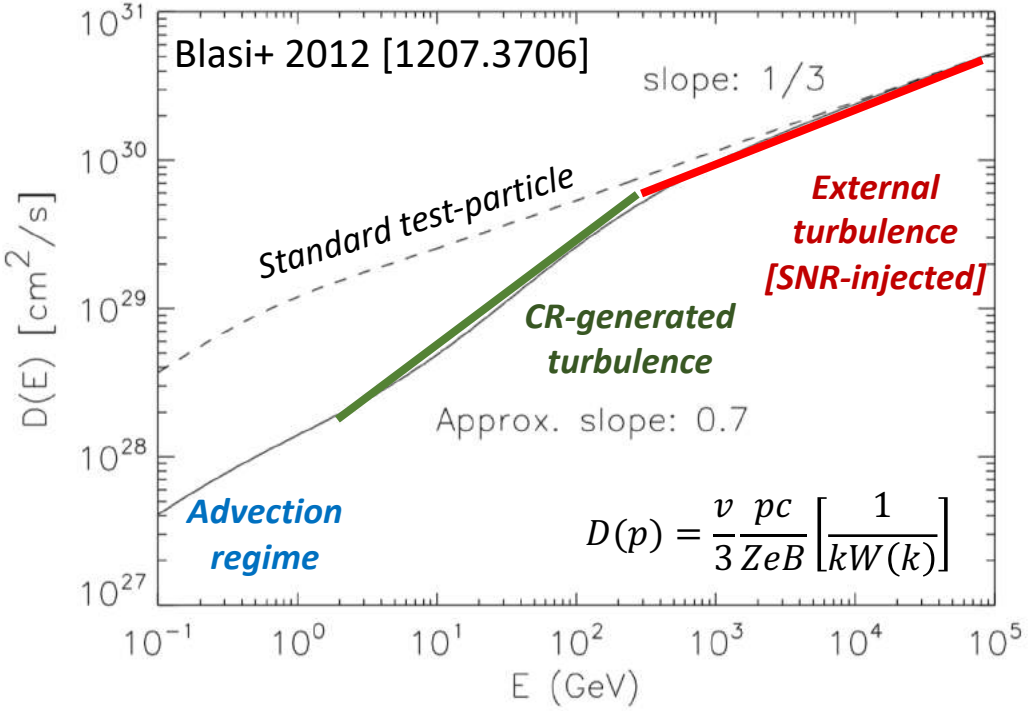


key parameters

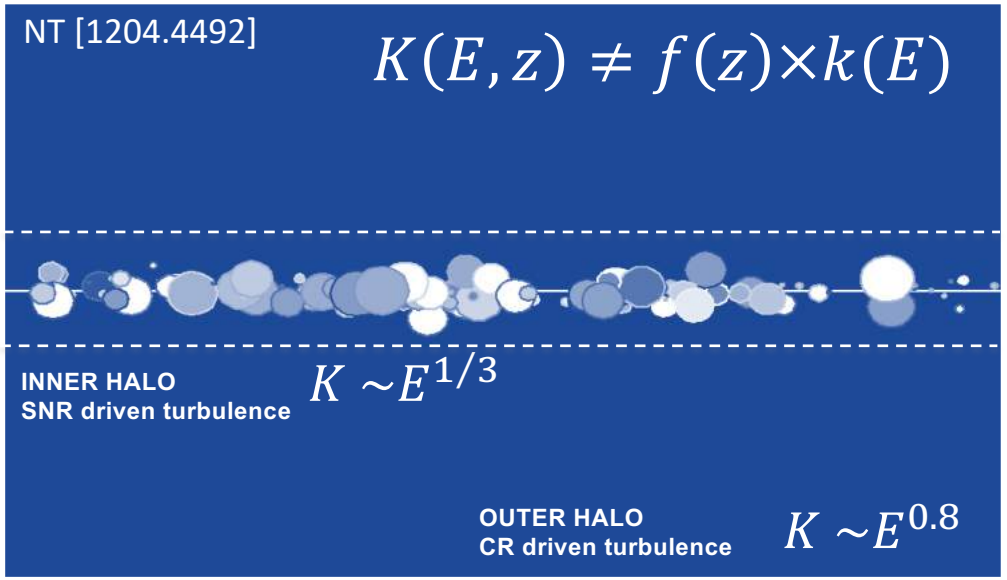


Behind the spectra: revisited CR transport

Drop linearity: *Non-linear CR transport*



Drop homogenity: *Non-separable CR diffusion*

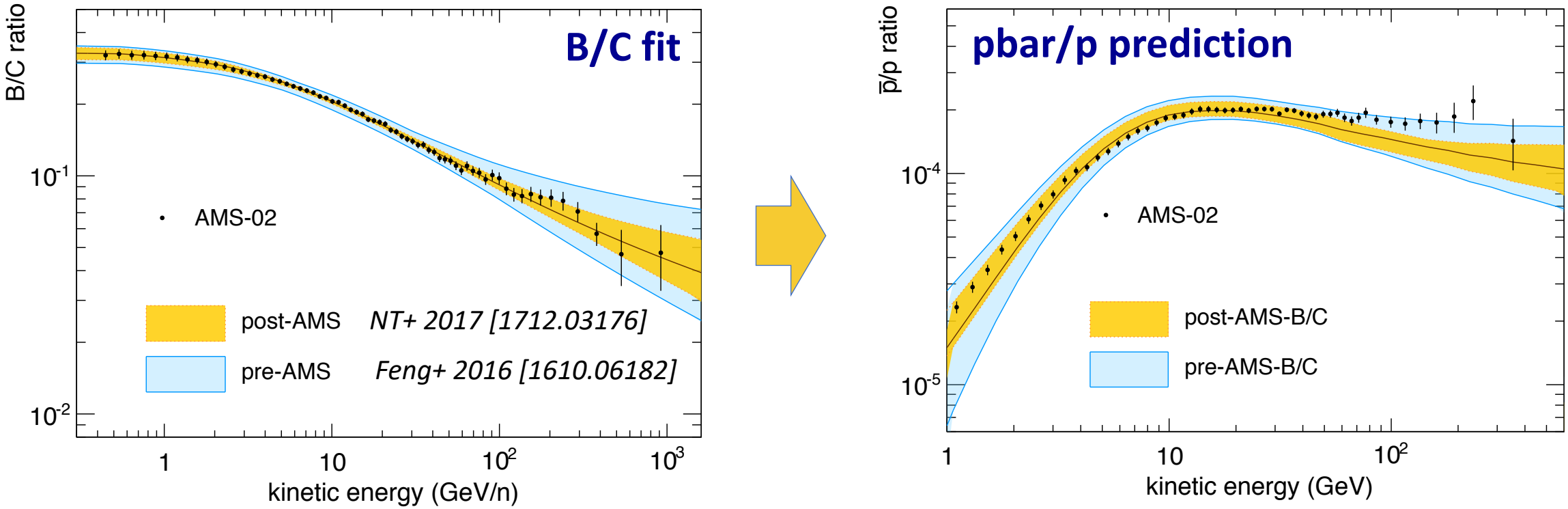


- **Universal change of slopes for all elements (pri, sec, sec/pri ratios)**
- **Harder antiparticle spectra (but not as hard as e^+ or $\bar{p}$)**

Behind the spectra: revisited CR transport

Secondary antiprotons from B/C driven THM global fit

Global Bayesian analysis



Cross section uncertainties: estimated from LHC data and MC generators

Astrophysical uncertainties: estimated by MCMC including correlations and degeneracies

Behind the spectra: the effects of a local source

Nearby source appearing in the CR flux

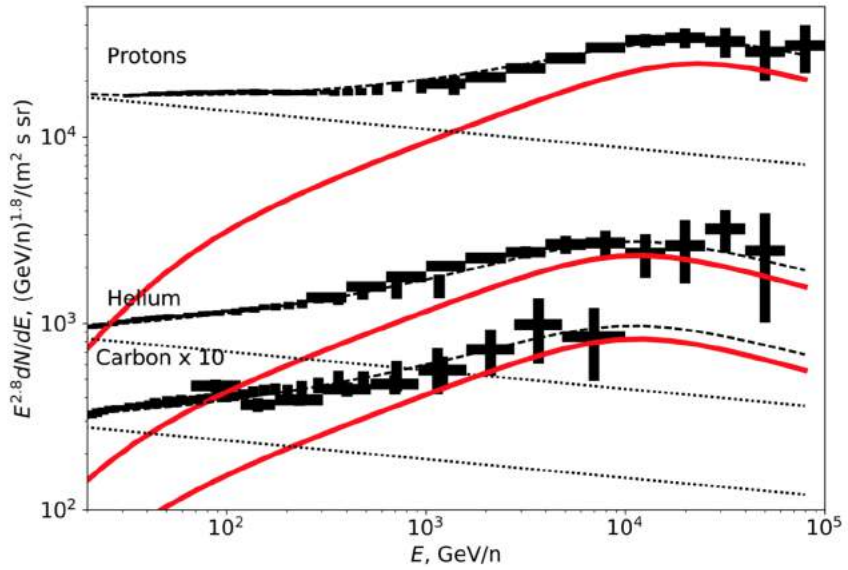
✓ **Evidences for nearby SN explosion(s)**

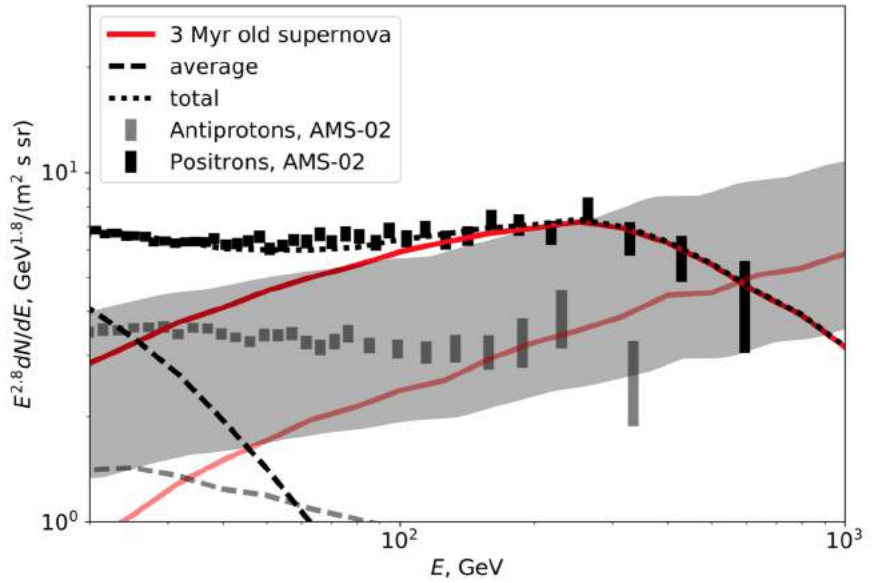
Abundances of ^{60}Fe isotopes (Binns+ 2016, Science 352, 677)
Sco-Cen OB: T~3 Myr, d~100 kpc, E~2x10^{50} erg

✓ **Many features explained**

➢ **Poor predictivity**

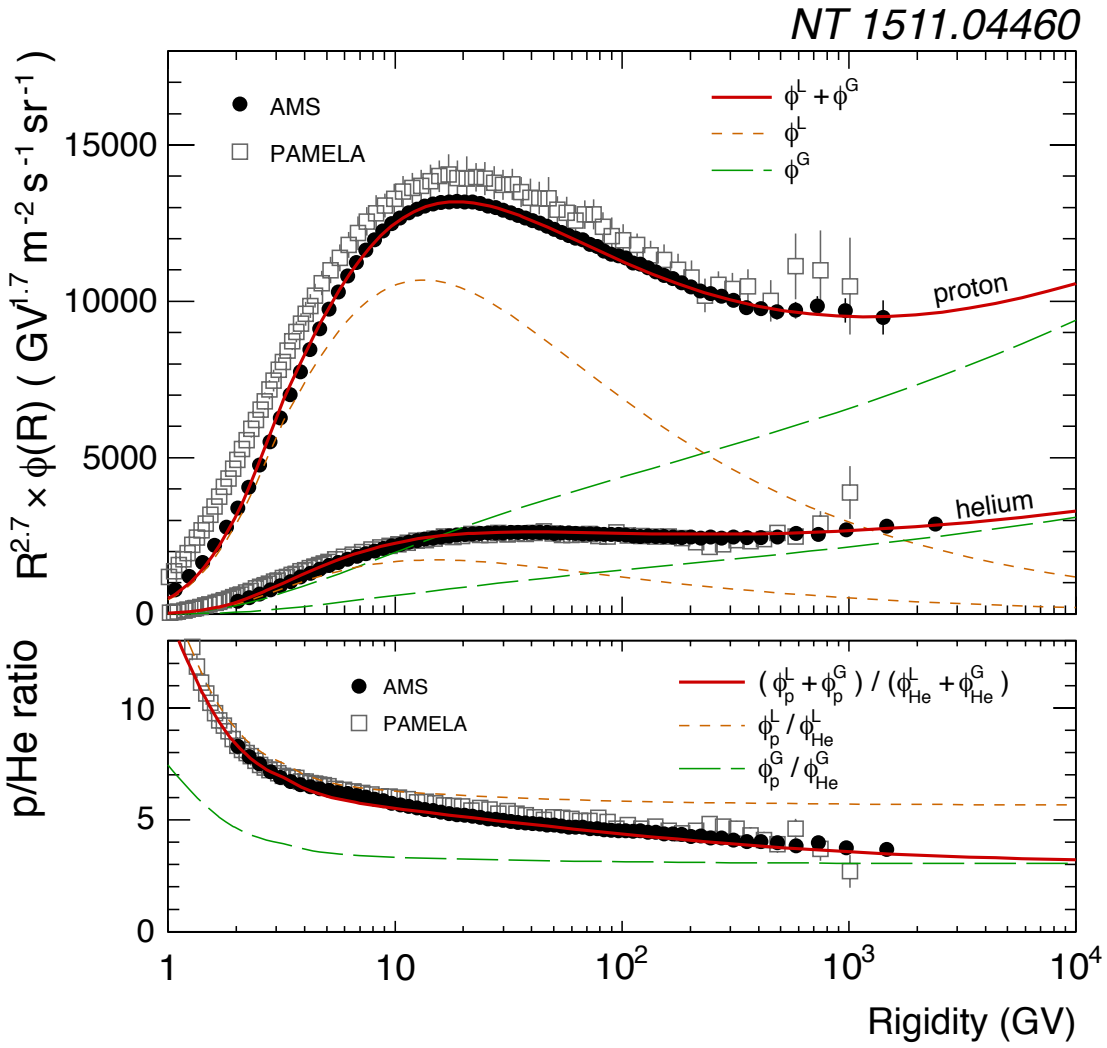
Kachelriess+ PRD arXiv:1710.02321



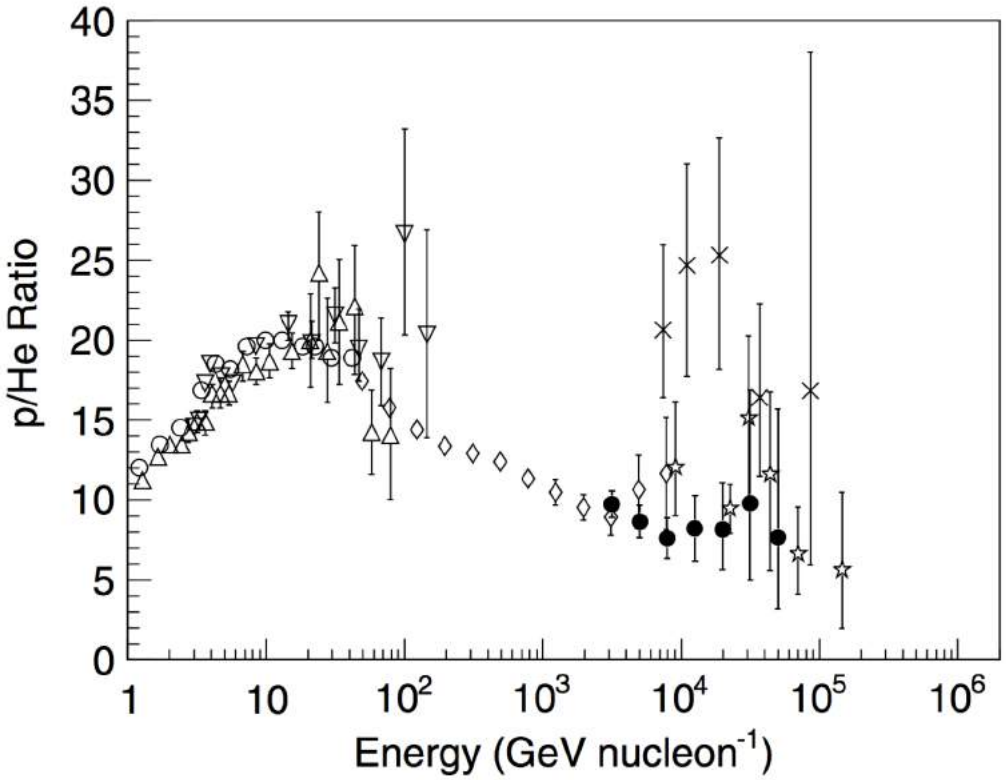


Behind the spectra: the effects of a local source

Two classes of accelerator + fluctuations in composition → p/He ratio



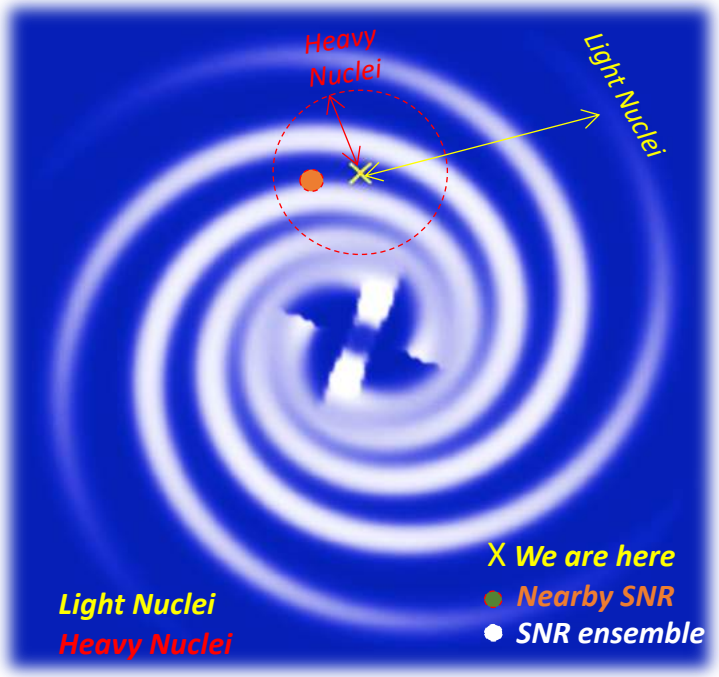
$$p/He = \frac{\phi_p^L + \phi_p^G}{\phi_{He}^L + \phi_{He}^G}$$



Possible signature: multi-TeV flattening of the p/He ratio

Behind the spectra: the effects of a local source

Nearby source appearing in the CR flux



Milky Way model, Ahlers 0909.4060

Energy and mass dependences

$$\tau^{sp} = (n\, v\, \sigma^{sp})^{-1} \propto A^{-2/3}$$

$$K(R) \propto R^{\delta}$$

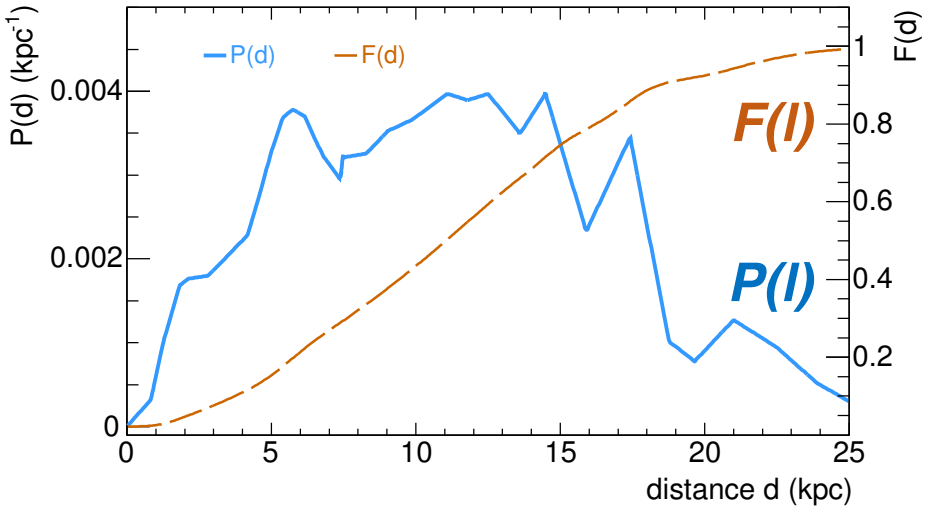
Spallation-limited diffusion distance

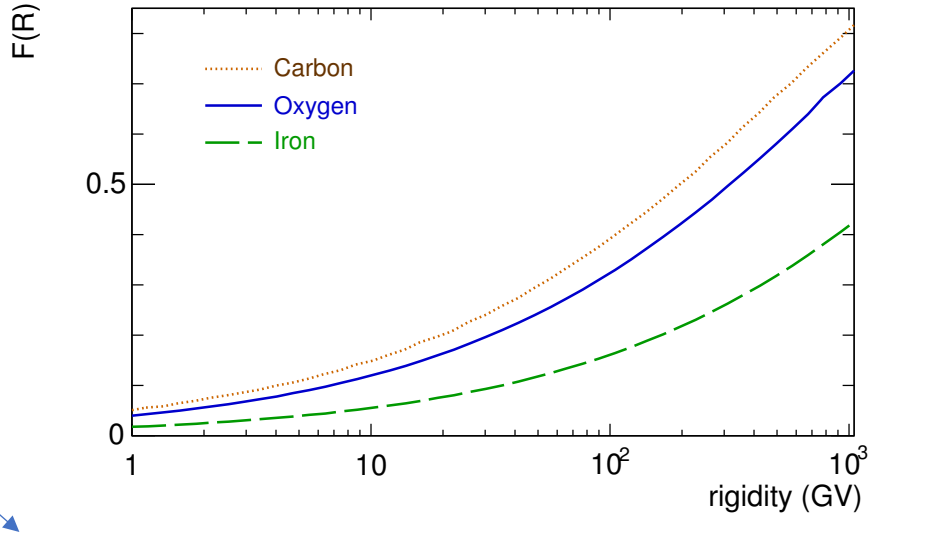
$$\lambda^{sp} \approx \sqrt{K\, \tau^{sp}} \propto A^{-1/3} R^{\delta/2}$$

→ *Fraction of SNRs contributing to the CR flux as function of rigidity R*

$$F(R) = \int_0^{\lambda^{sp}(R)} P(l)\, dl$$

[NT1509.05774]





PDF of SNRs at distance *d* [Ahlers+ 0909.4060]

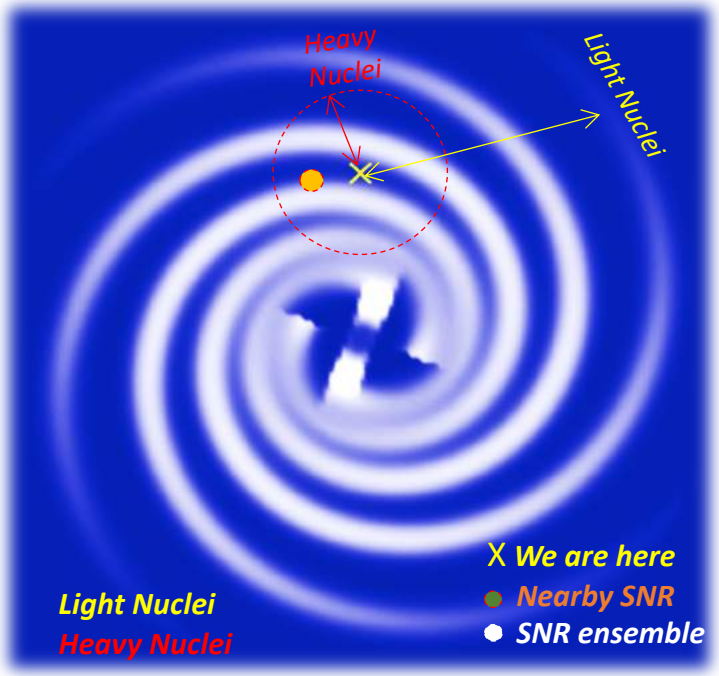
✓ *Elemental and rigidity dependent*

✓ *Low-energy reduction of SNR-ensemble component*

Behind the spectra: the effects of a local source

[NT1509.05774]

Nearby source appearing in the CR flux



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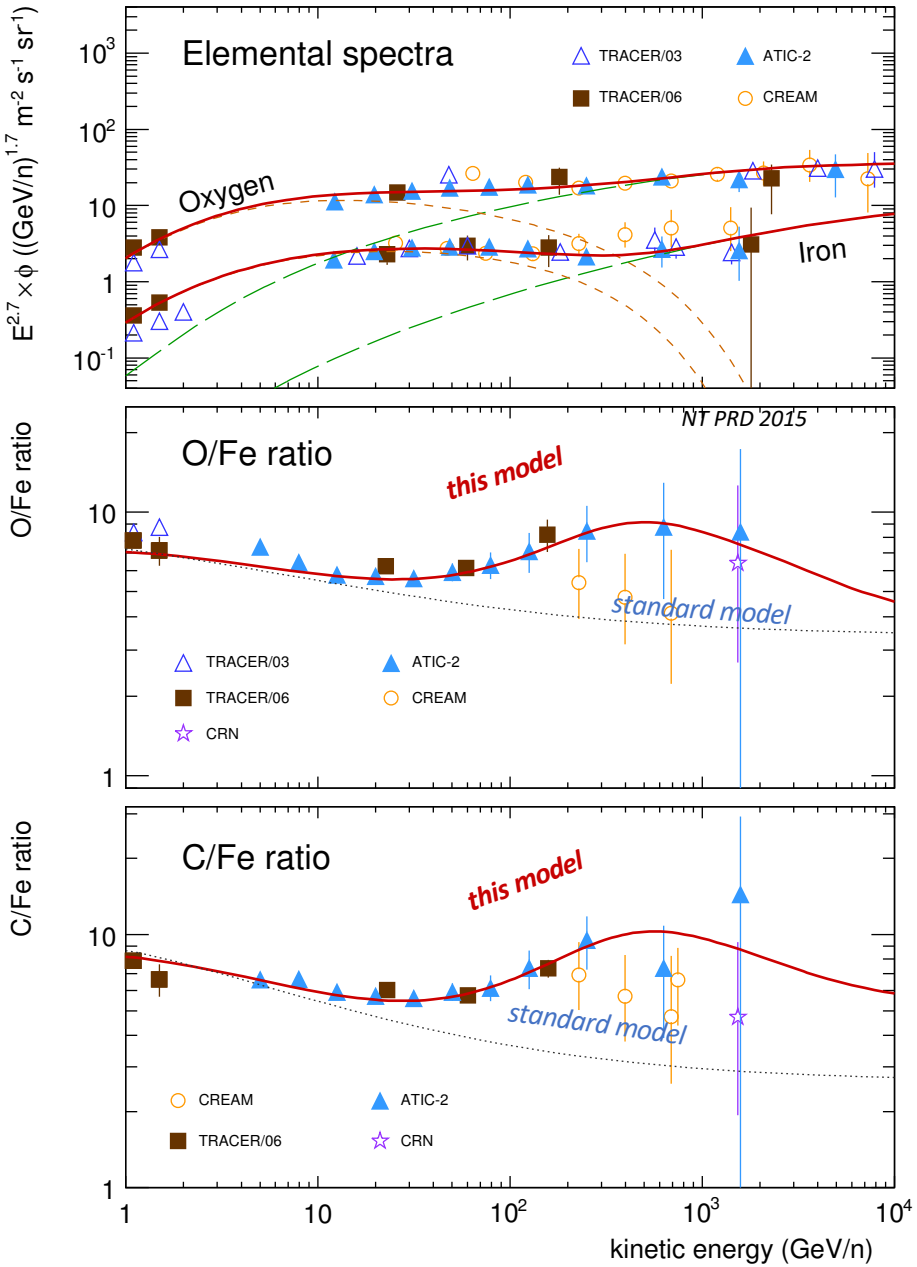


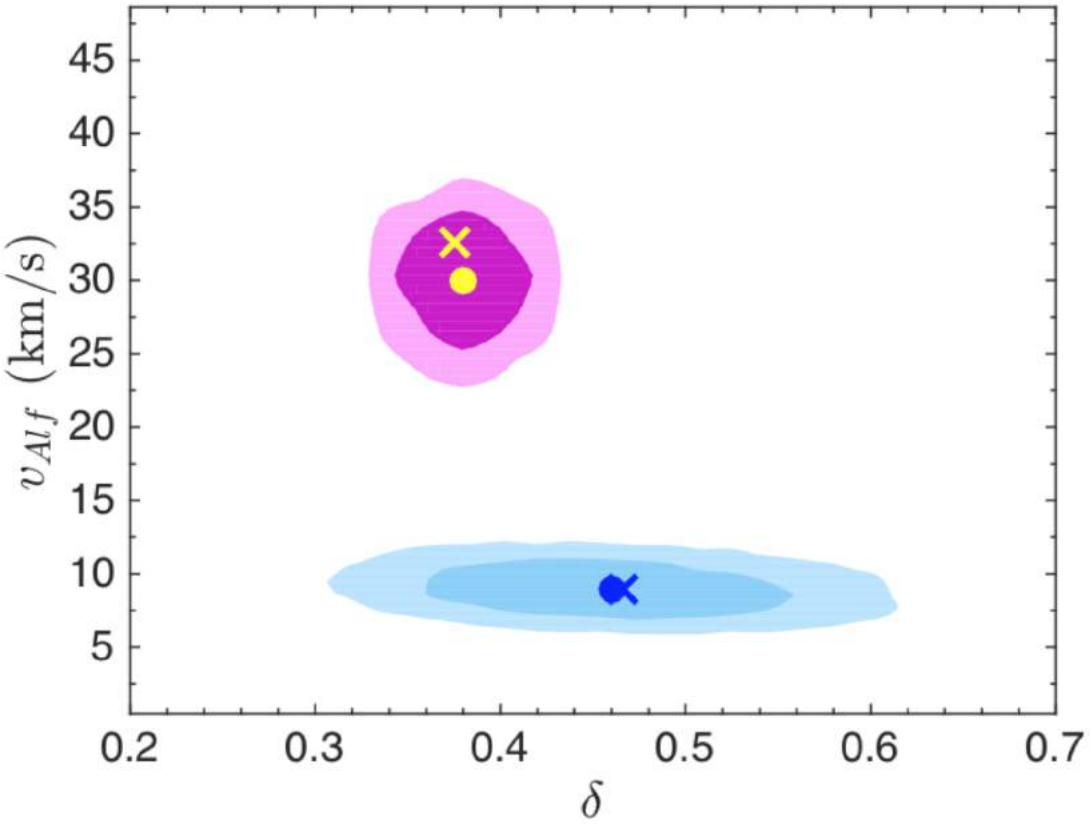
- ✓ ***Atic data: upturn in light/heavy ratios [Panov+ 2014]***
- ✓ ***Signature of local SNR in C/Fe and O/Fe ratios***

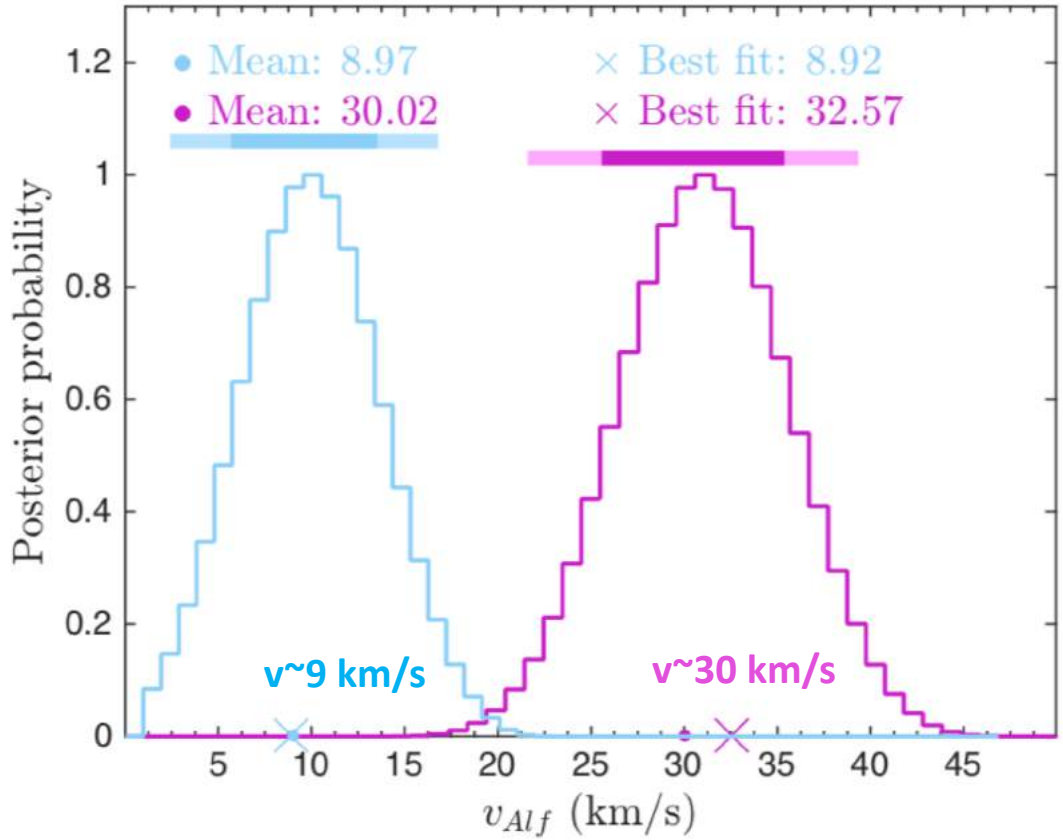
Light VS Mid CR elements puzzle

Jóhannesson+ arXiv:1602.02243

BAYESIAN ANALYSIS OF CR PROPAGATION: EVIDENCE AGAINST HOMOGENEOUS DIFFUSION ?

- **Mid: Boron to Silicon [*B/C* driven]**
- **Light: ^{2}H-^{3}He-$\overline{p}$ [$\overline{p}/p$ driven]**



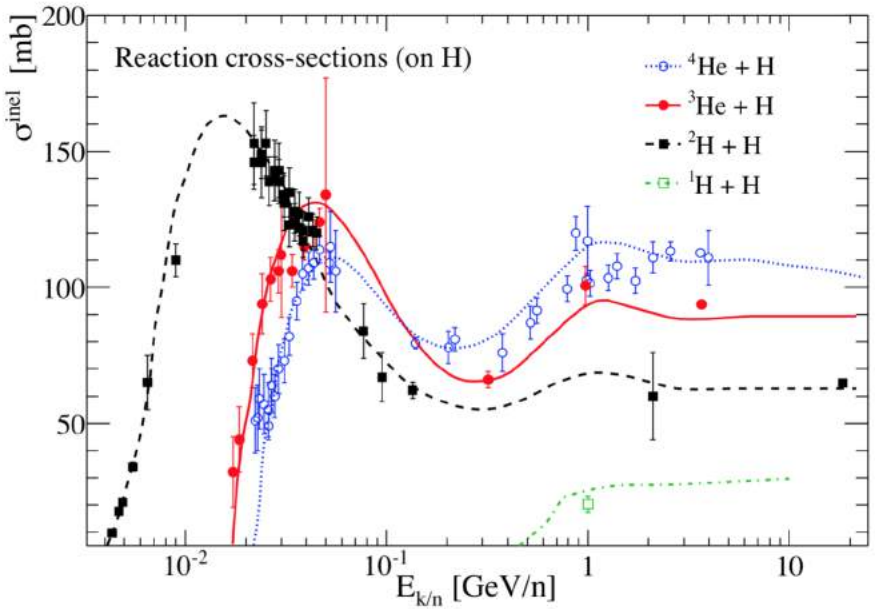


The cosmic-ray "quartet" -> B/C-free test for CR propagation

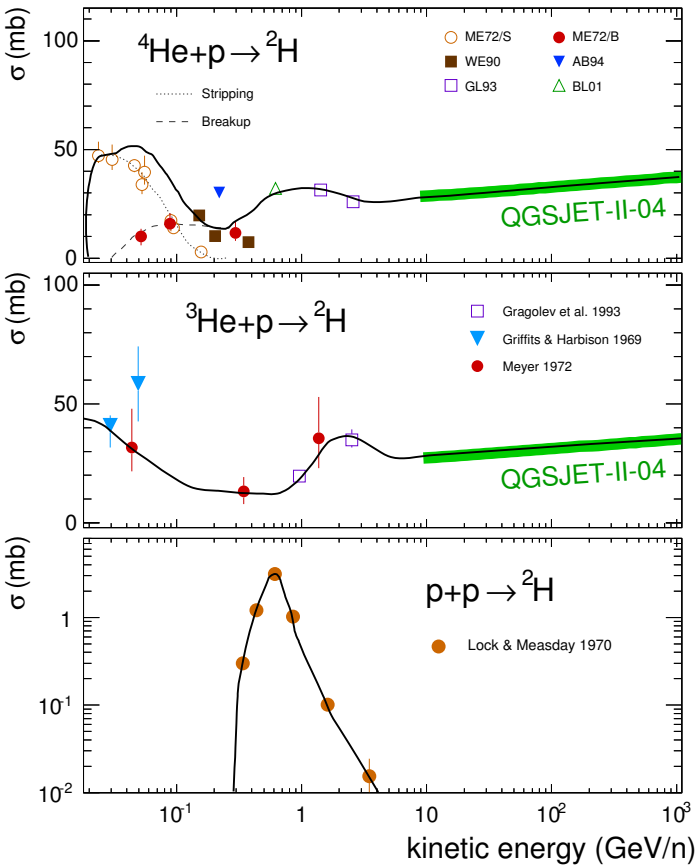
- ✓ **Better diagnostic for antiprotons**
  - Similar progenitors (p, He fragmentation off ISM)
  - Similar propagation histories (probe similar regions of the Galaxy)
- ✓ **Known production cross-sections**
- ➢ **Scarce cosmic-ray data**

The CR quartet
^{1}H-^{2}H-^{3}He-^{4}He

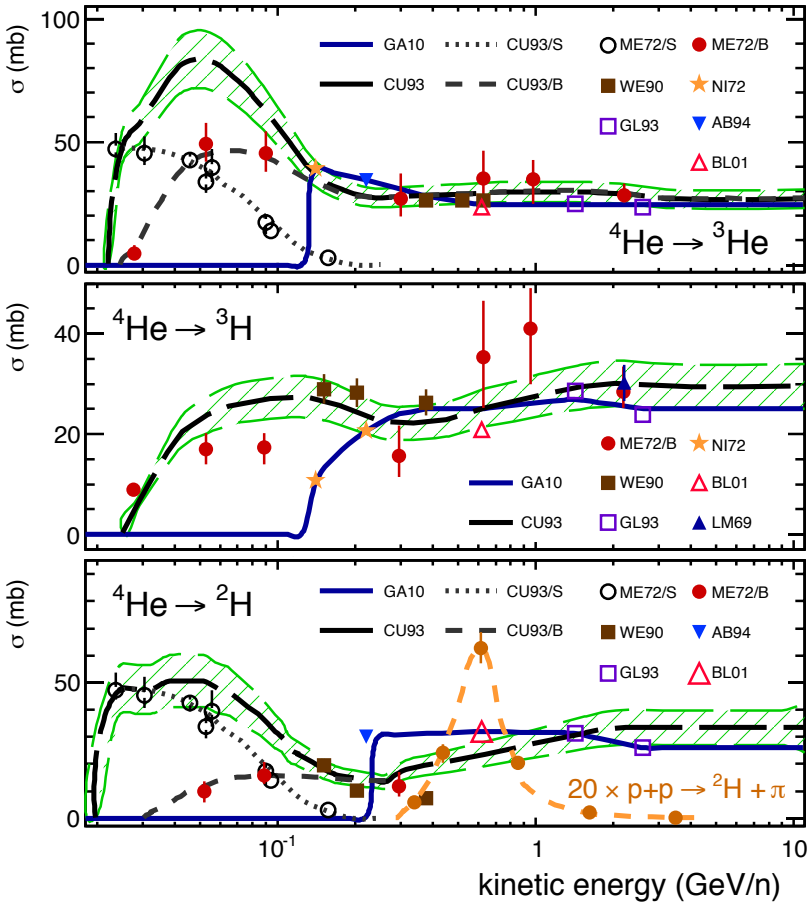
[Coste+ 1108.4349, large XS compilation]



[NT & Feng 1612.05651]



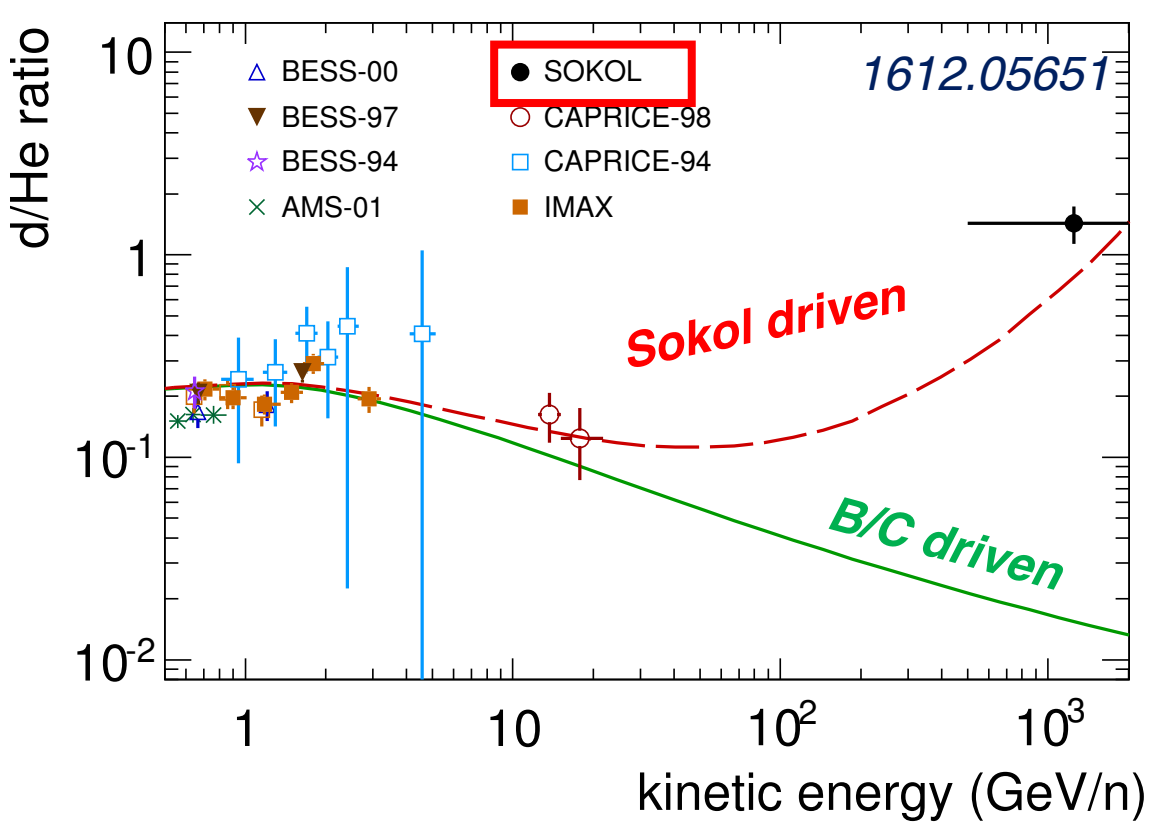
[NT 1210.7355]

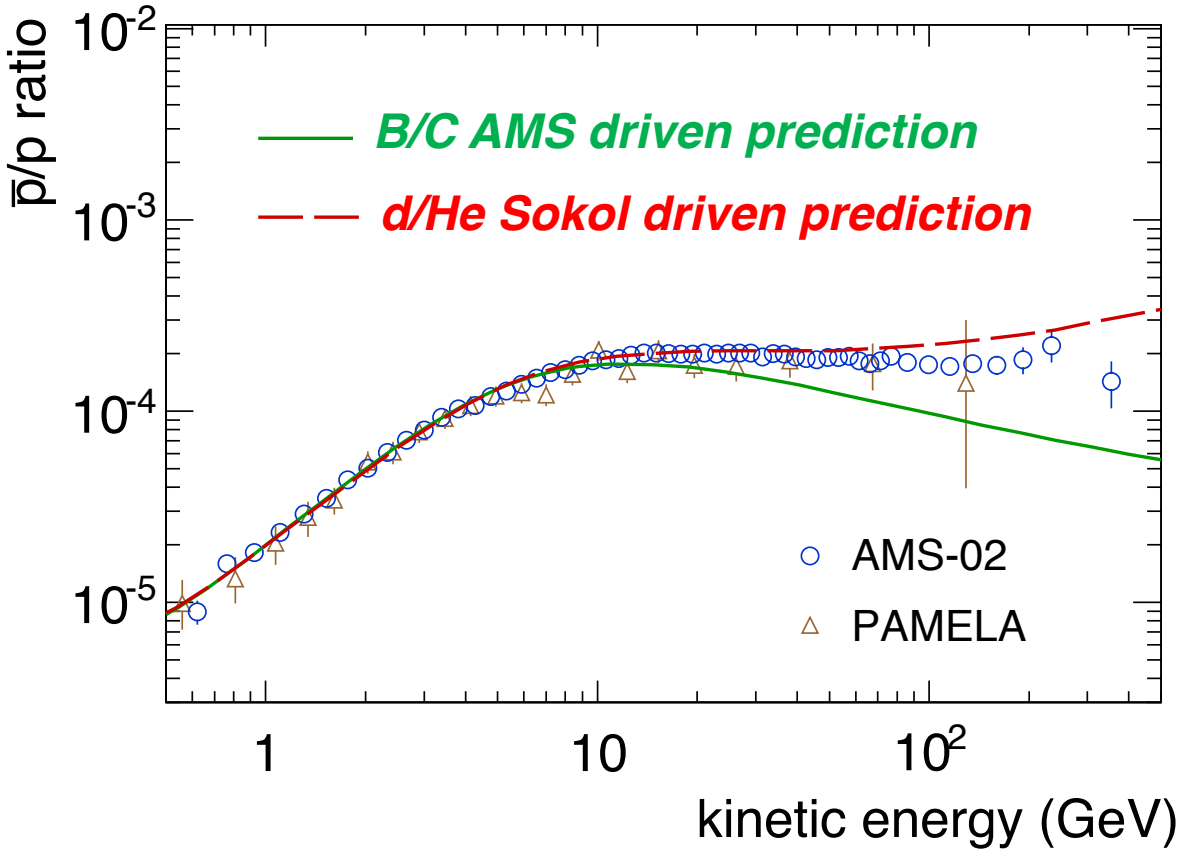


The cosmic-ray "quartet" -> B/C-free test for CR propagation

Example: deuteron/helium ratio

NT & Feng 2017: the curios case of HE deuterons in CRs [1612.05651]
Sokol datum: Turundaevskiy & Podorozhnyi ASR 59, 496-501 (2017)

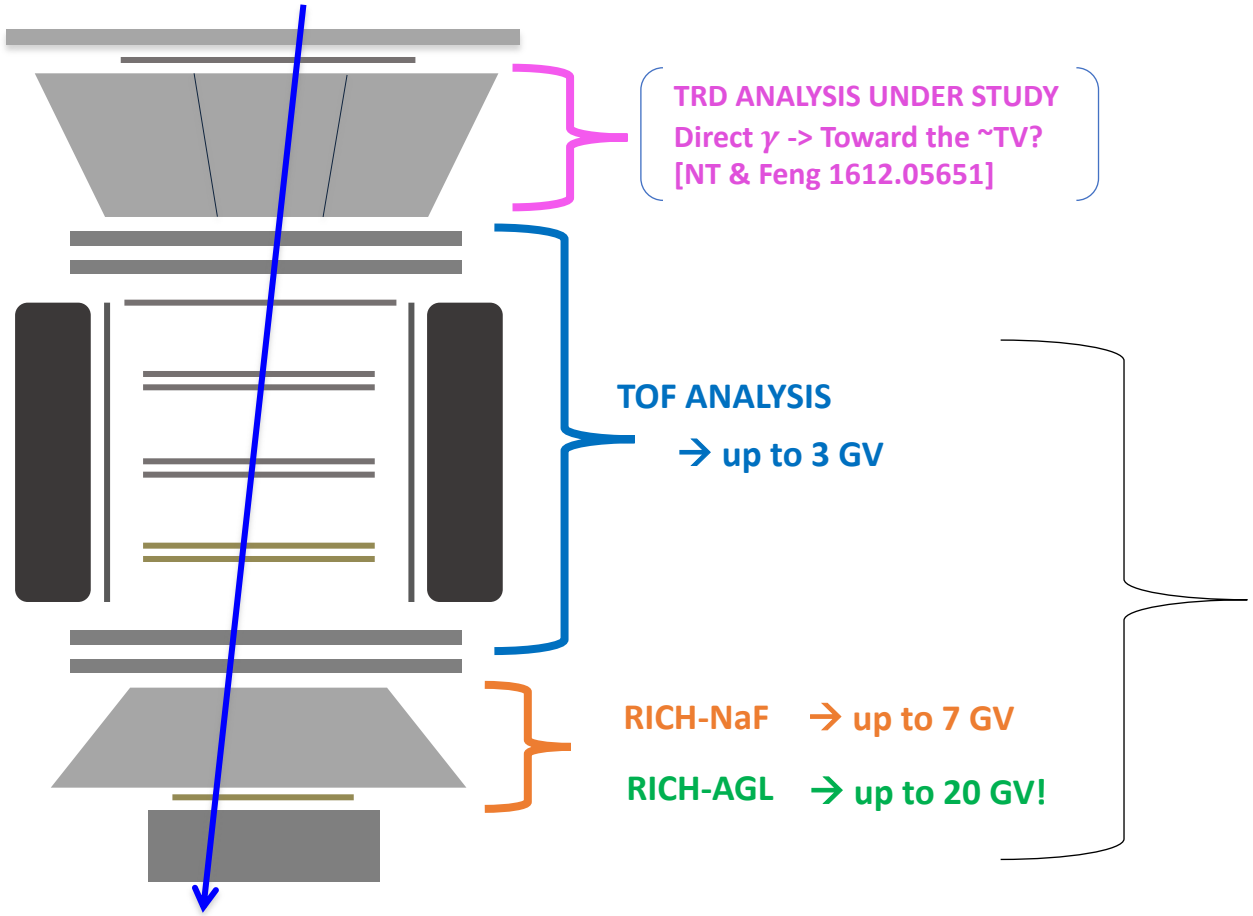


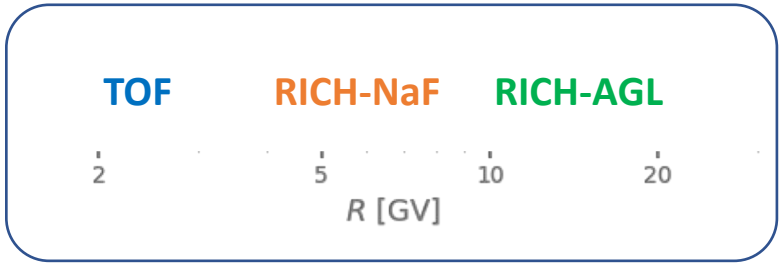


The cosmic-ray “quartet” -> B/C-free test for CR propagation

AMS-02 mass measurement from R, Z, γ

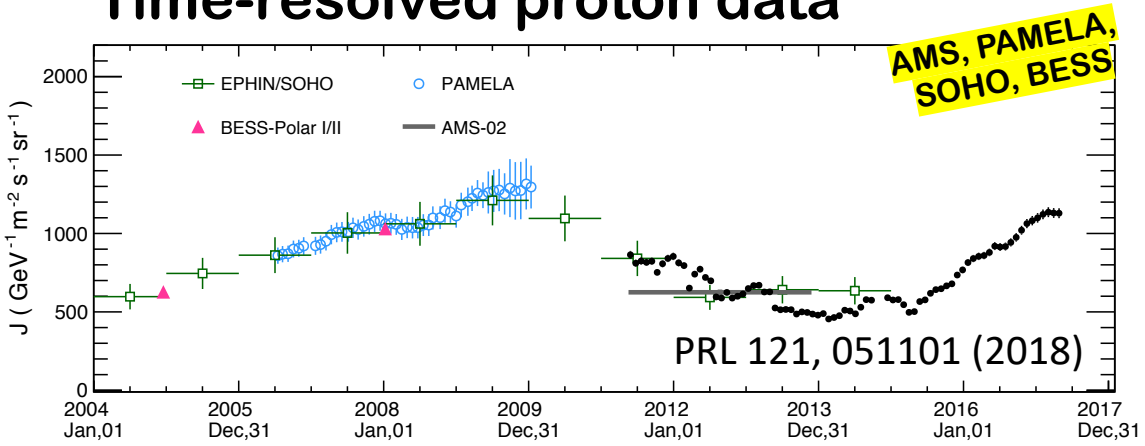
$$M = \frac{RZ}{\gamma\beta} \Rightarrow \left(\frac{\delta M}{M}\right)^2 = \left(\frac{\delta R}{R}\right)^2 + \gamma^4 \left(\frac{\delta \beta}{\beta}\right)^2$$

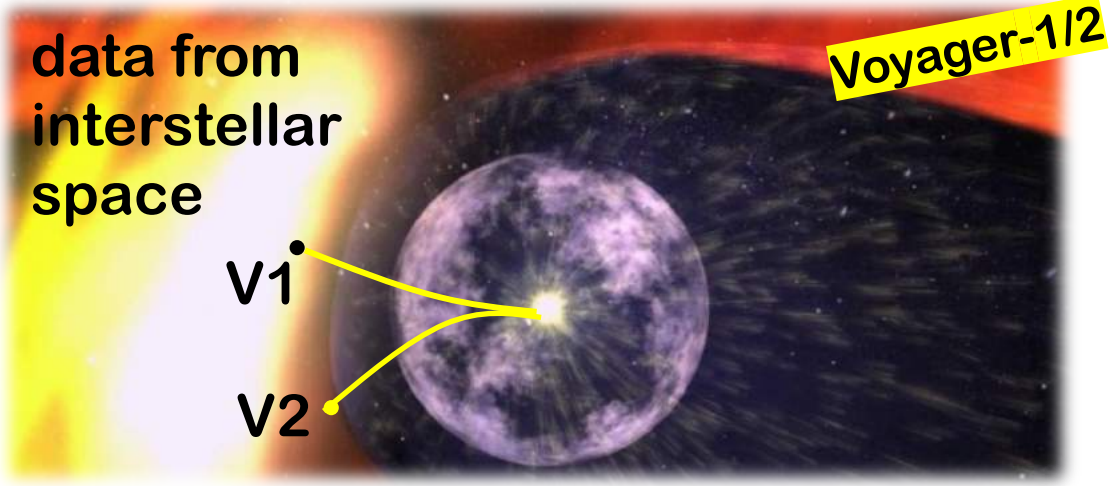




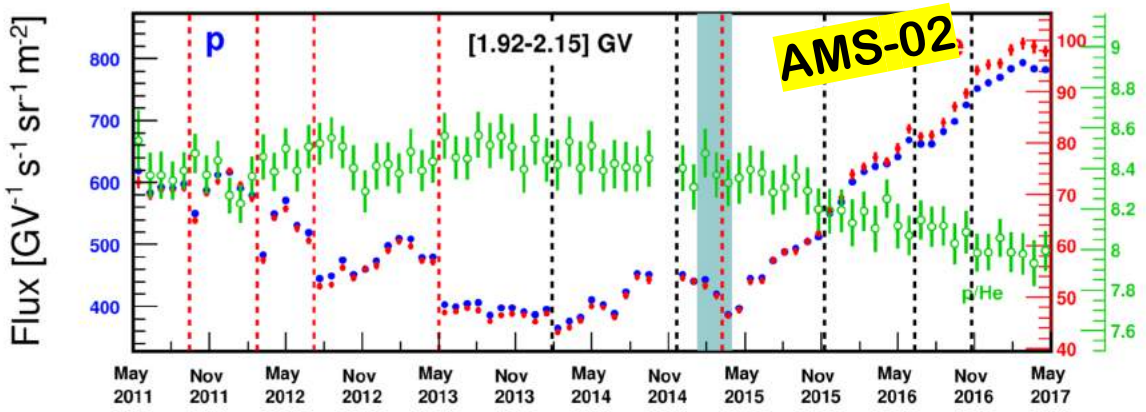
solar modulation: observational milestones

Time-resolved proton data





Long-term behavior of the p/He ratio



Time dependence of antimatter