AMS-02 in space

physics results
overview and challenges

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The AMS Project

Particle physics detector for high precision CR measurements at TeV energy

Physics goals

- ✓ **Antimatter search (|Z|>1 anti-nuclei)**
- ✓ **Dark Matter (light anti-matter & γ-rays)**
- ✓ **Exotic signals?**
- ✓ **GCR & γ-rays astrophysics**
- ✓ **Solar Physics (modulation & SEP)**
- ✓ **Magnetospheric physics**

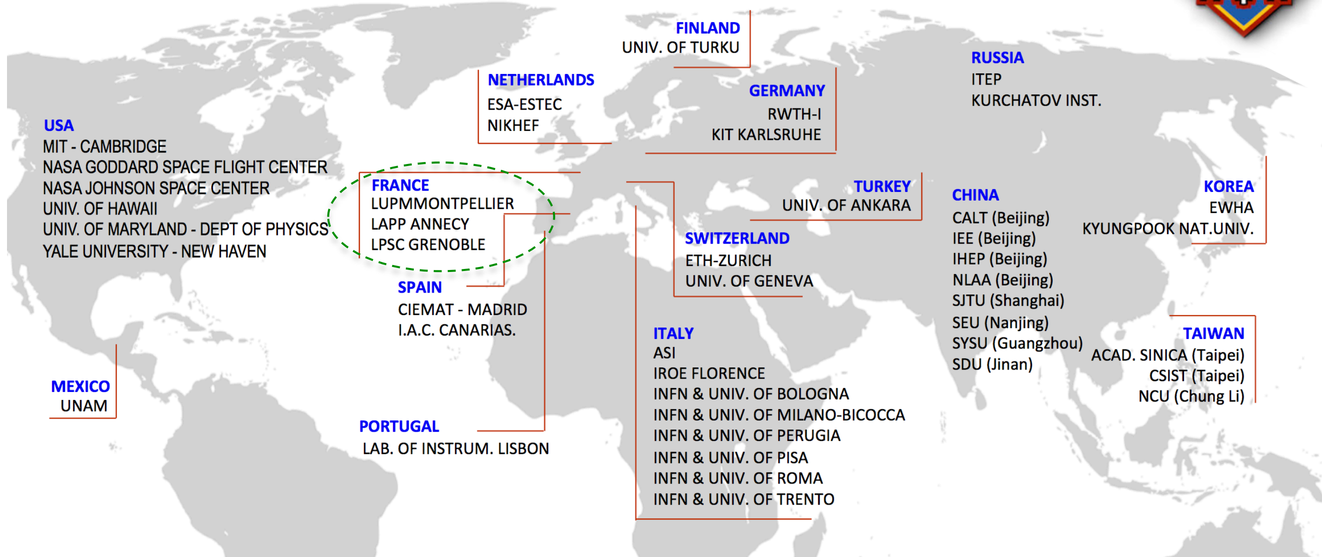
How it will fulfill these goals?

- **Large collaboration: 16 Countries, 60 Institutes and ~500+ Physicists**
- **Same concept (precision & capability) as the large state-of-the-art HEP detectors [but: fitting into the space shuttle & no human intervention after installation]**
- **Operation in space, ISS, at 400km, no backgrounds from atmospheric interactions [extensive multi-step space qualification tests]**
- **Collection power: geometrical factor (≈ 0.5 m2sr) X exposure time (= ISS lifetime) [extensive calibration campaigns on ground]**

The AMS Project

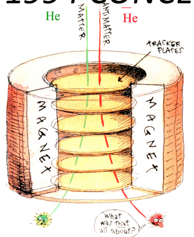
AMS Collaboration

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



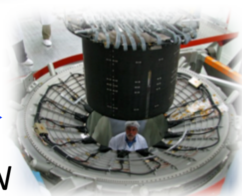
Project timeline

1994 CONCEPT

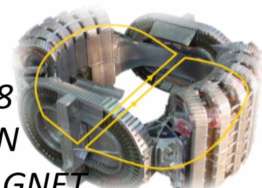


1997 AMS-01 PROTOTYPE

1998: STS-91



2000 @CERN AMS-02 CONSTRUCTION



2008 @CERN SC MAGNET BEAM TEST

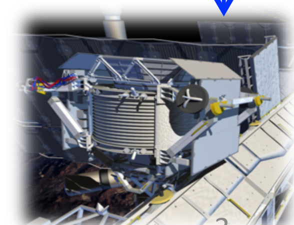
2010 TVT @ ESA (NL)

2010 @CERN SC -> PM NEW BEAM TEST

2011 @KSC INTEGRATION & CR-μ RUN

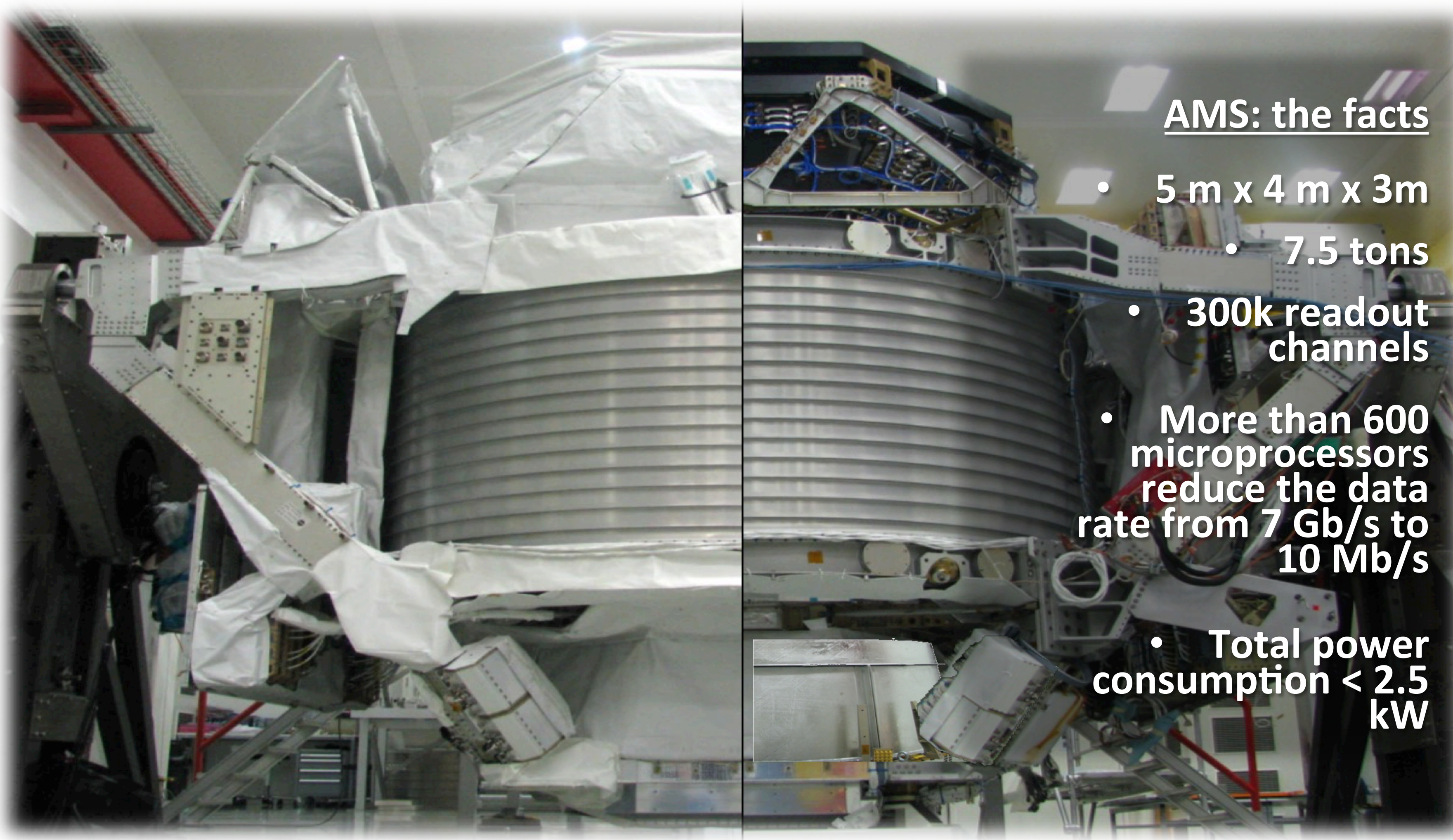
MAY 2011 STS-134 FLIGHT

ON THE ISS



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

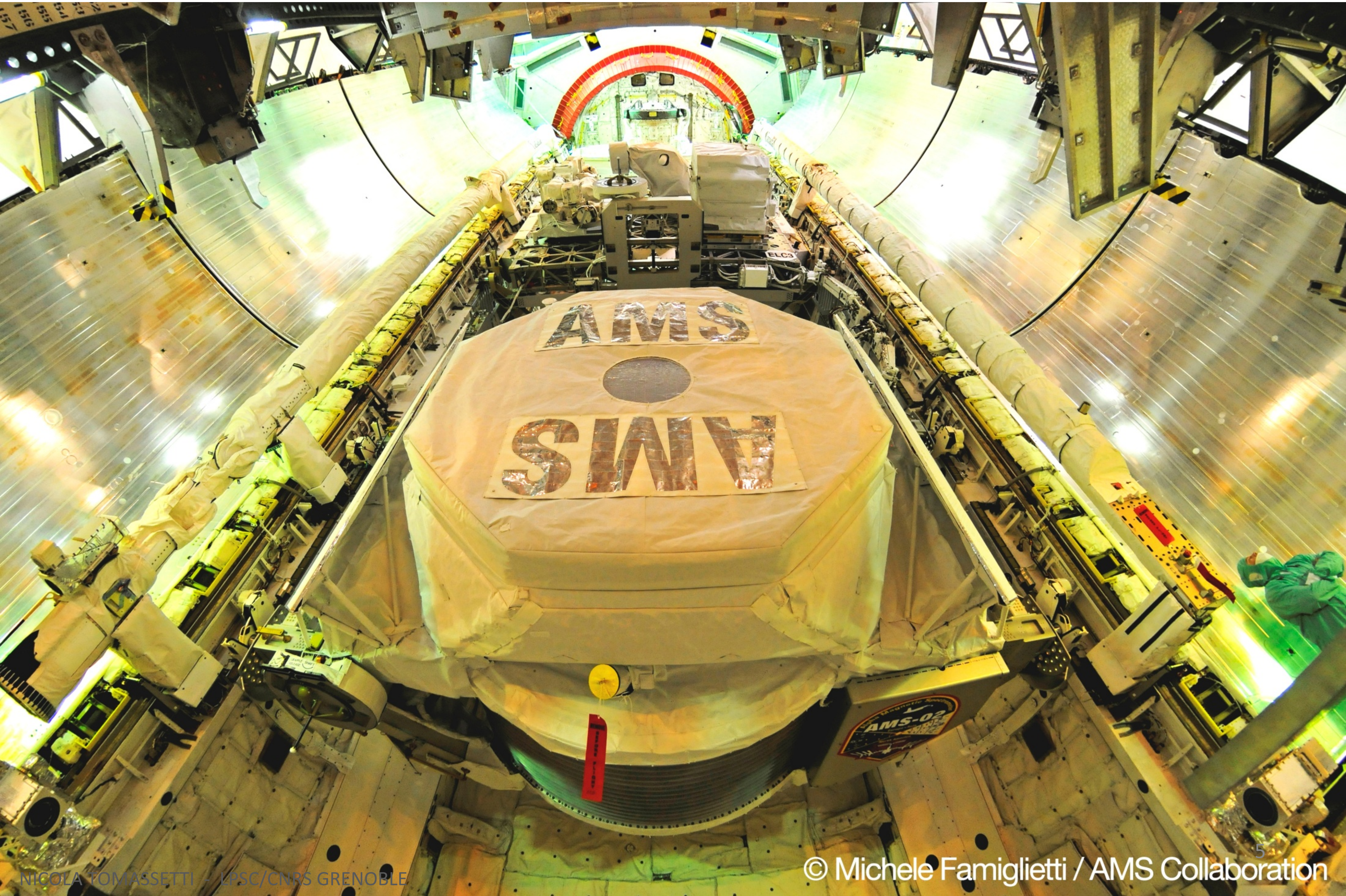
The Instrument – Pre-launch Integration



AMS: the facts

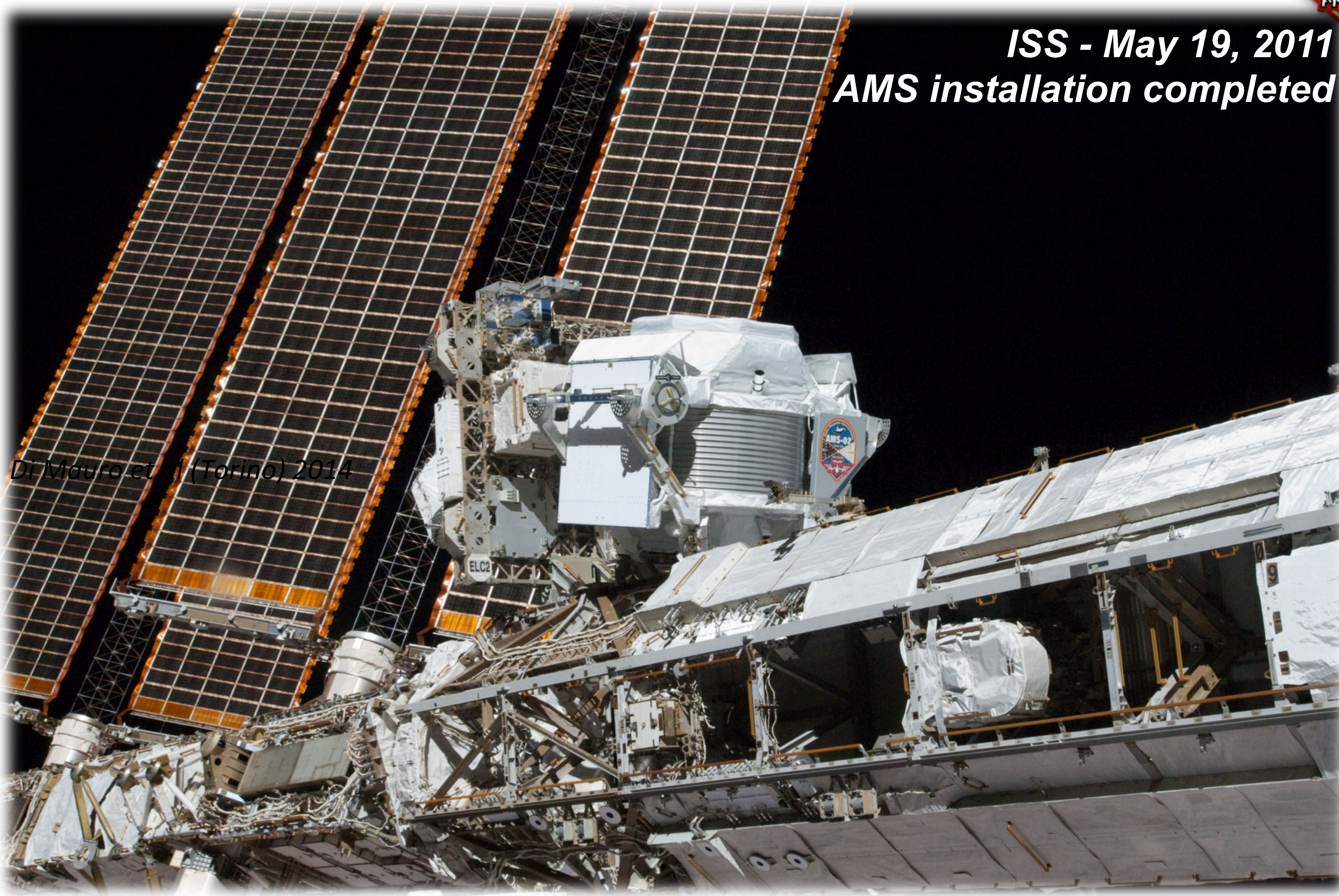
- 5 m x 4 m x 3m
- 7.5 tons
- 300k readout channels
- More than 600 microprocessors reduce the data rate from 7 Gb/s to 10 Mb/s
- Total power consumption < 2.5 kW

AMS-02 installed in Endeavour's Payload Bay



May 16th 1011: launch!

May 19th 2011: activation

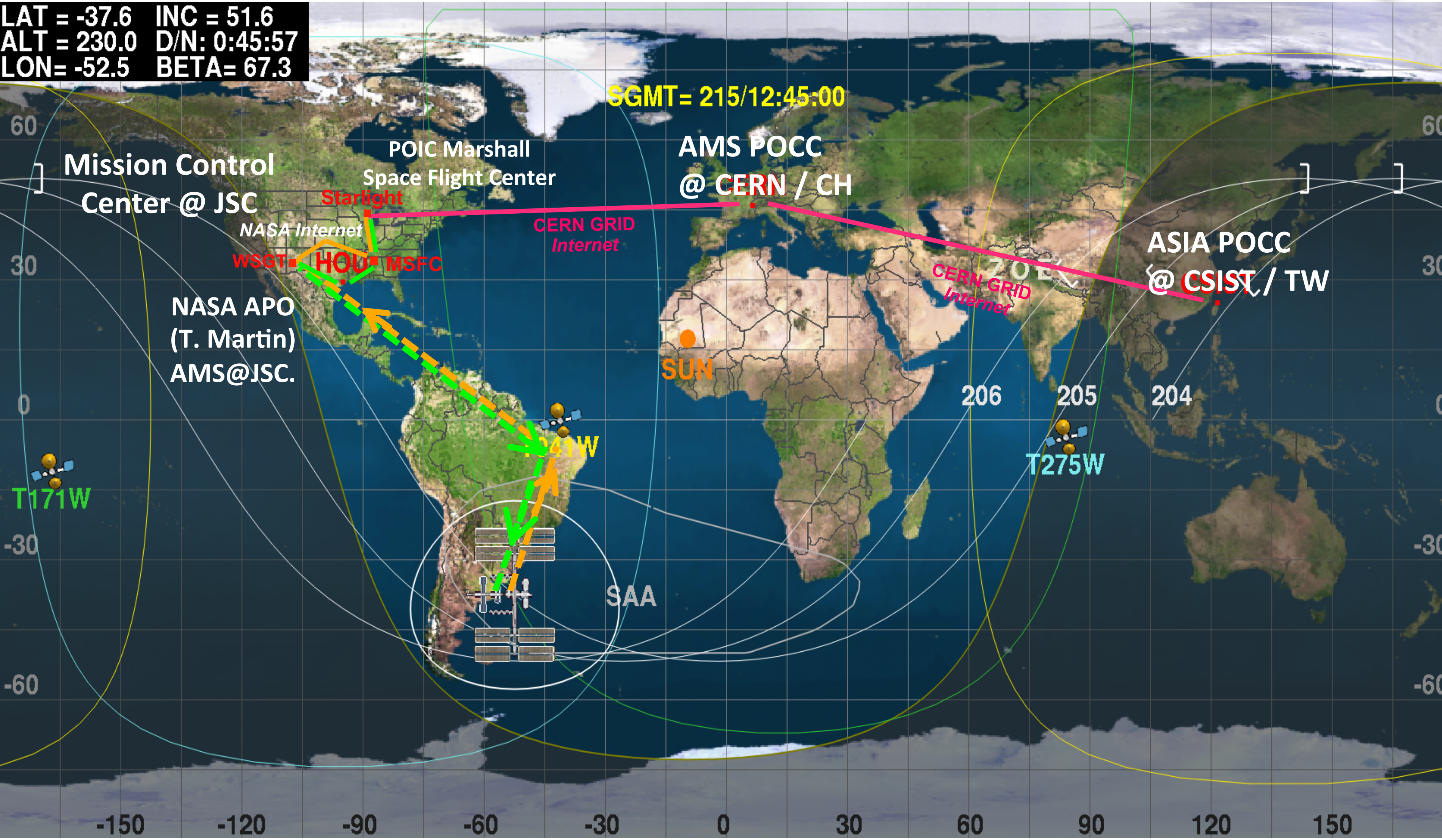


Di Mauro et al (Torino) 2014

Full time monitored

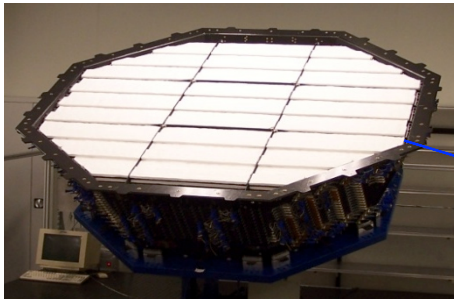
AMS POCC @CERN: Payload Operation Control Center

Full time monitored

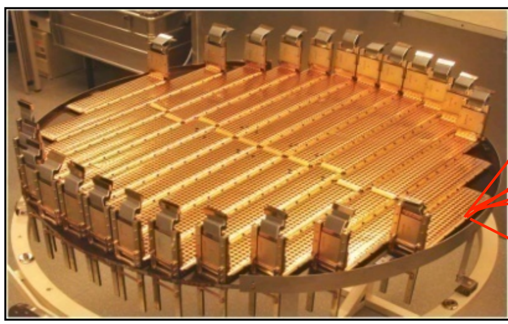


The AMS-02 instrument

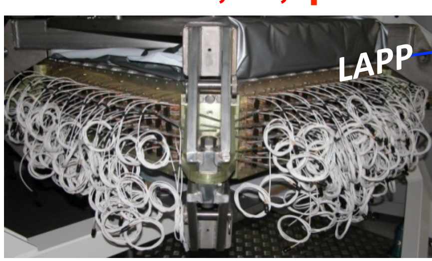
TRD
Identify e+, e-



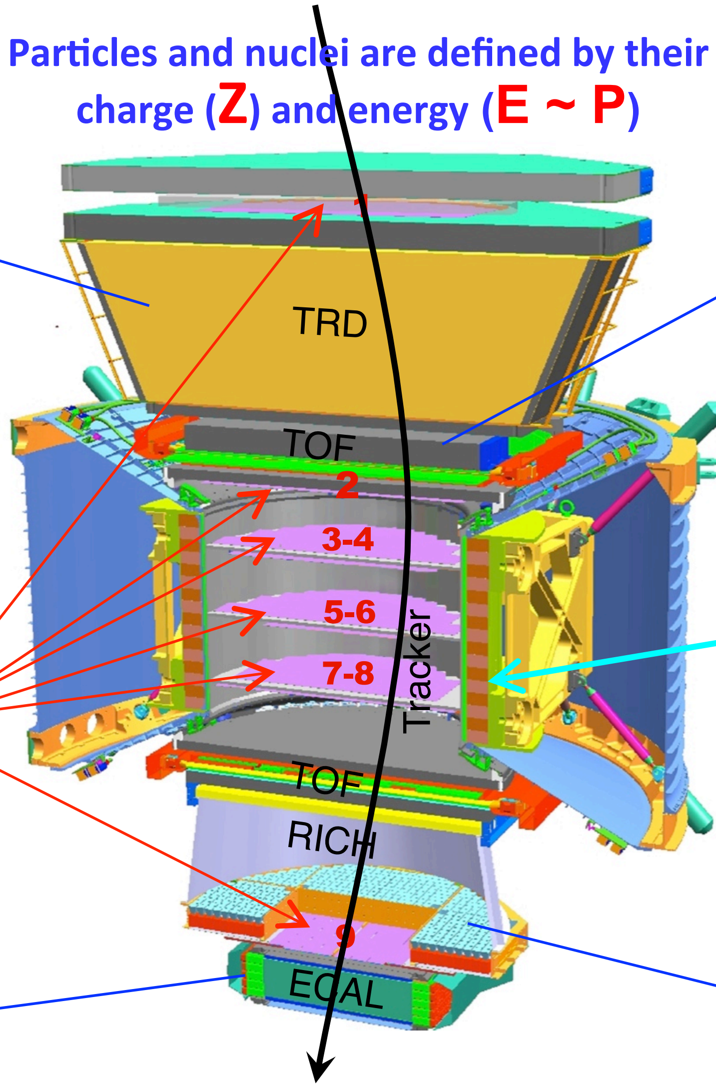
Silicon Tracker
Z, P



ECAL
E of e+, e-, γ

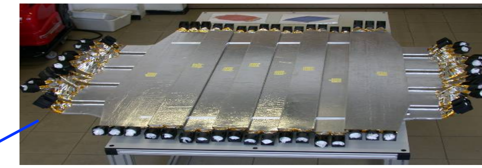


Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

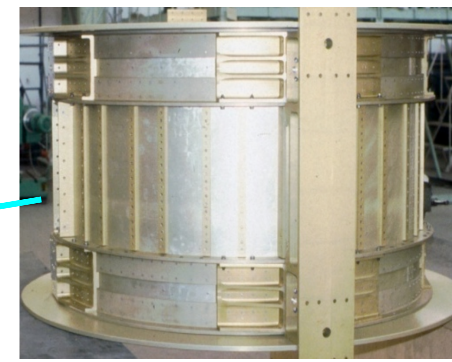


Z, P are measured independently from Tracker, RICH, TOF and ECAL

TOF
Z, E

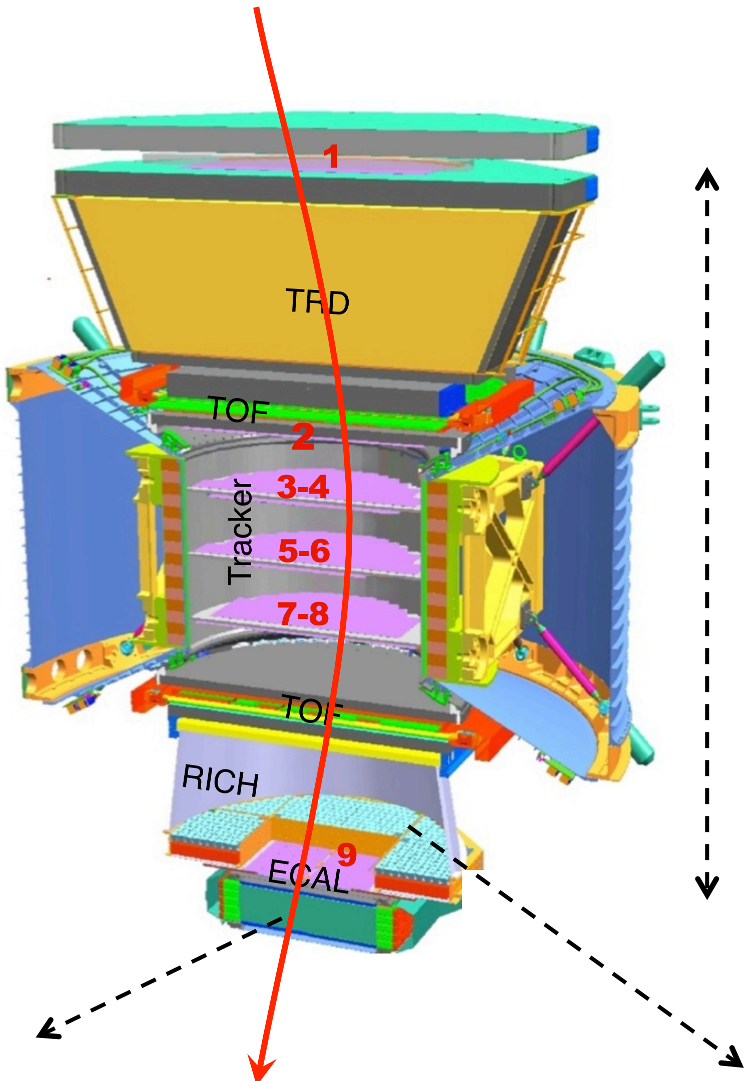


Magnet
±Z



RICH
Z, E

Multiple measurements of energy



Tracker, R = p/Z
MDR ≈ 2TV

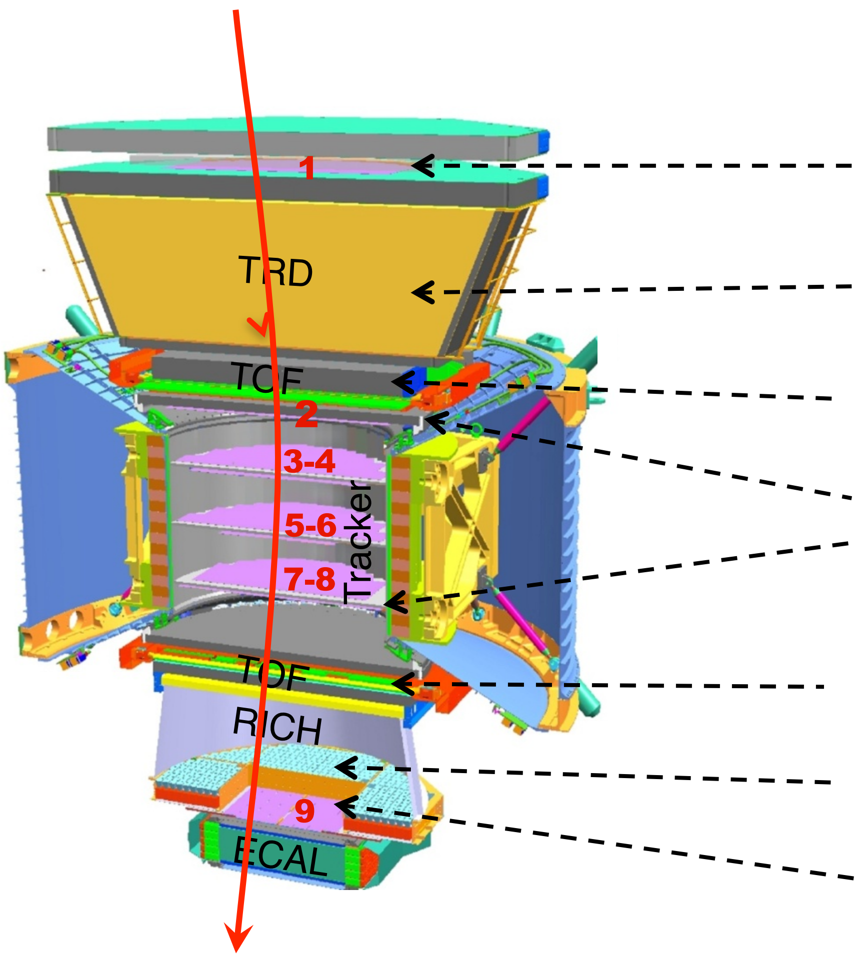
***TOF**, β*
Δβ/β ≈ 1%

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

***RICH**, β*
Δβ/β ≈ 0.05%

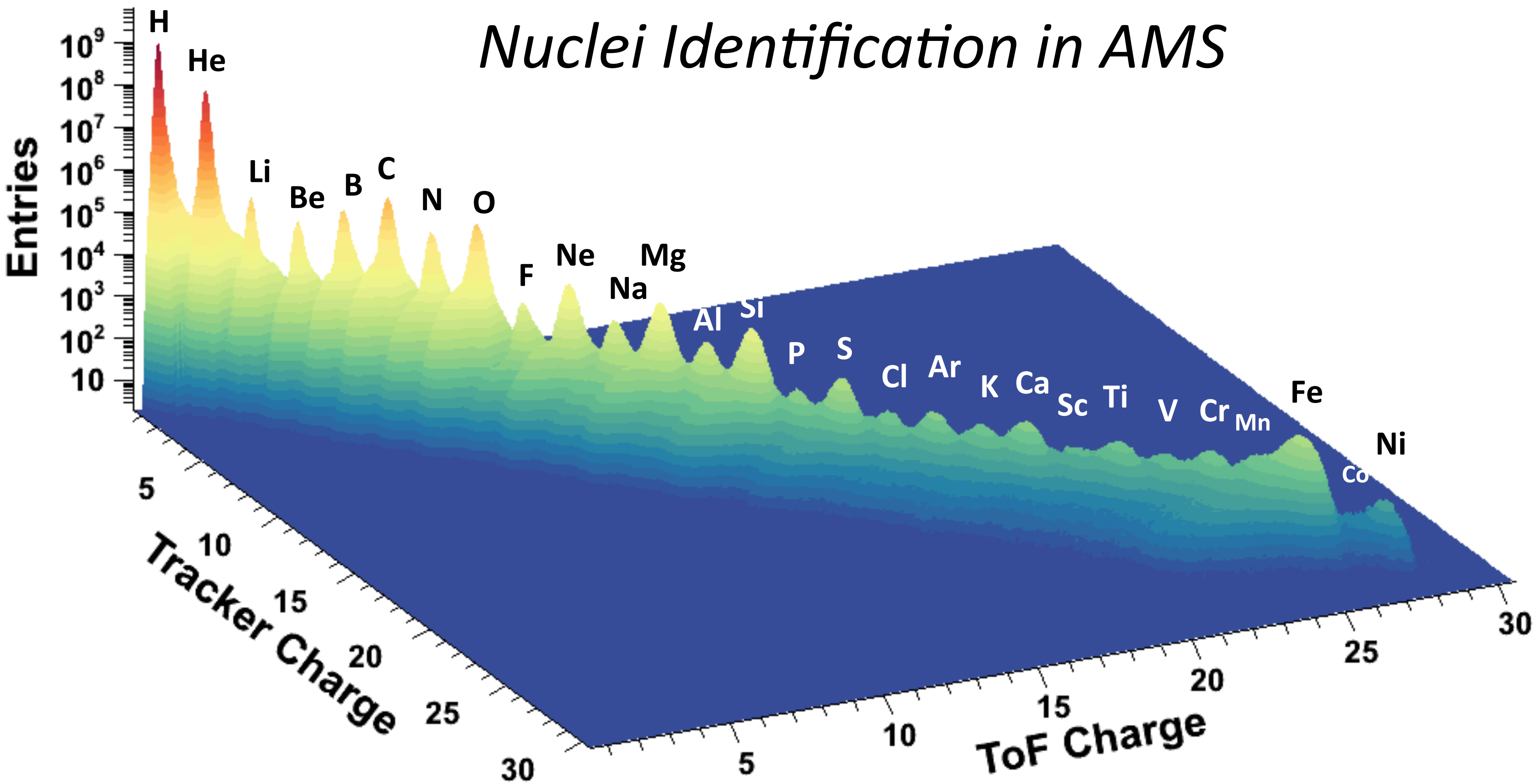
Geomagnetic cutoff
ΔR/R ≈ 10% up ~25 GV

Multiple measurements of charge



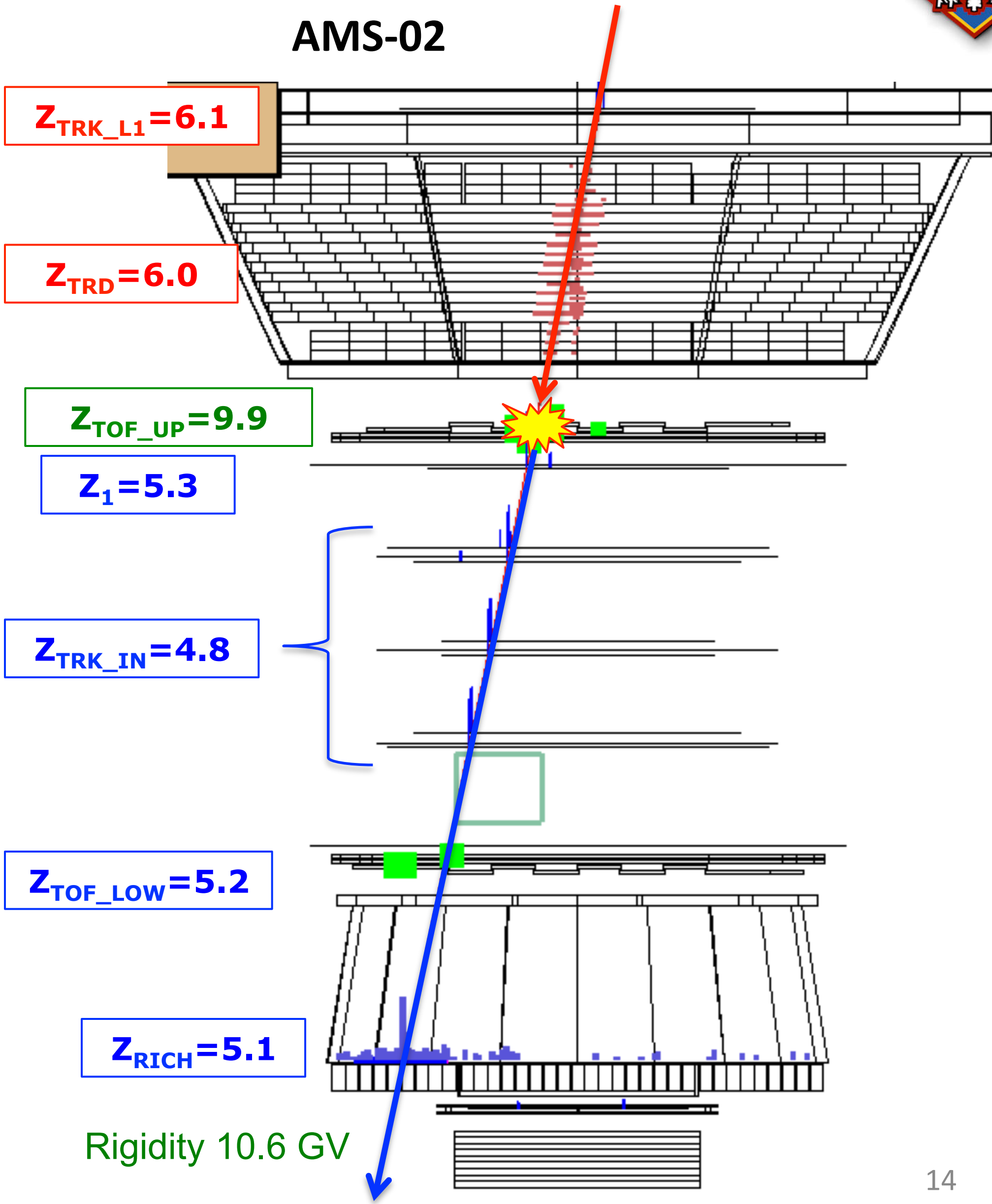
	ΔZ (carbon)
Tracker Plane 1 (L1)	*0.30*
TRD	*0.33*
Upper TOF (1 counter)	*0.16*
Inner Tracker (L2-L8)	*0.12*
Lower TOF (1 counter)	*0.16*
RICH	*0.32*
Tracker Plane 9 (L9)	*0.30*

Multiple measurements of charge



AMS-02 : Evidence of fragmentation Carbon → Boron

Carbon → Boron in Upper TOF



Optimized for high-Z measurements

-Large dinamical range: Z~ 1 - 30

-Many layers of active material.

-Many independent evaluations of Z.

Dedicated Trigger for Z>1:

-4/4 TOF planes fired

-Multiple TOF hits allowed

-NACC <5

Minimum bias trigger:

-1/100 prescaling!!

-3/4 TOF fired

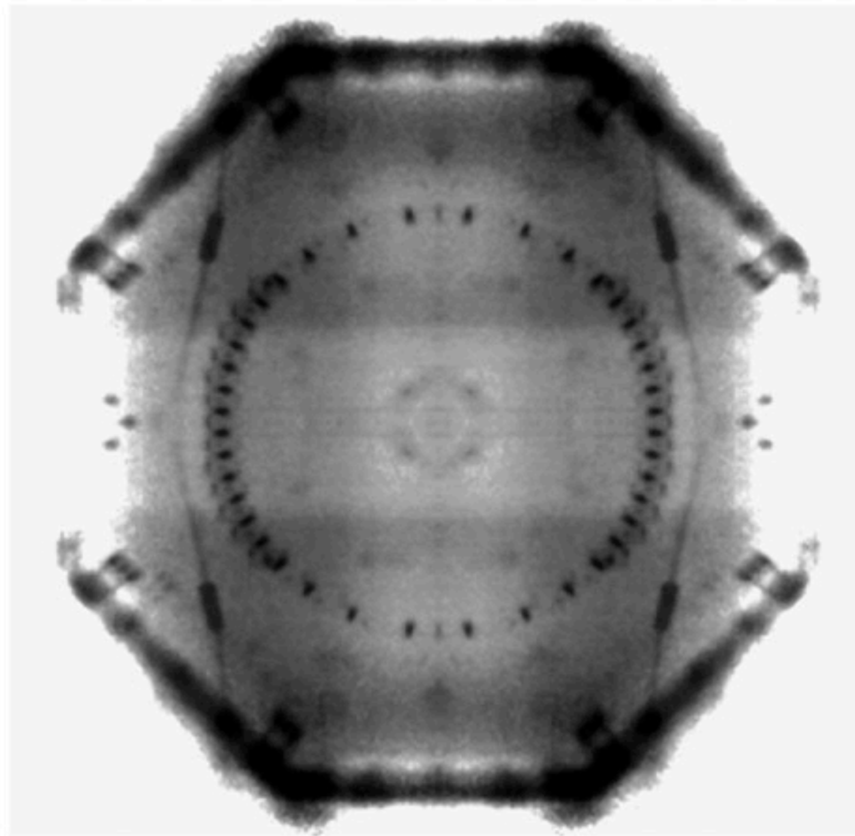
-No conditions on NACC

AMS-02 : Evidence of fragmentation He absorption in TOI

AMS Hadronic Tomography

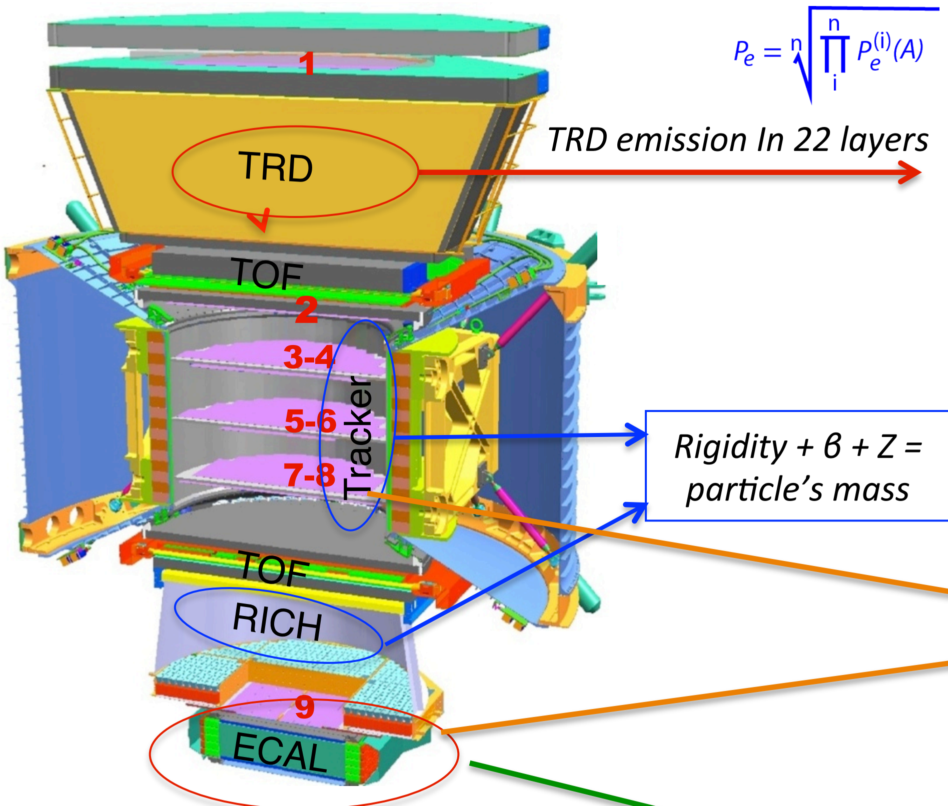
with the cosmic-ray p/He ratio

Exposure Time:	May 20 2011 – May 20 2012
Number of Protons:	3,676,863,217
Number of Helium nuclei:	620,303,906
Rigidity range:	2 GV – 2000 GV
Tomographic plane:	Z = +165 cm
XY pixel area:	1 cm^2

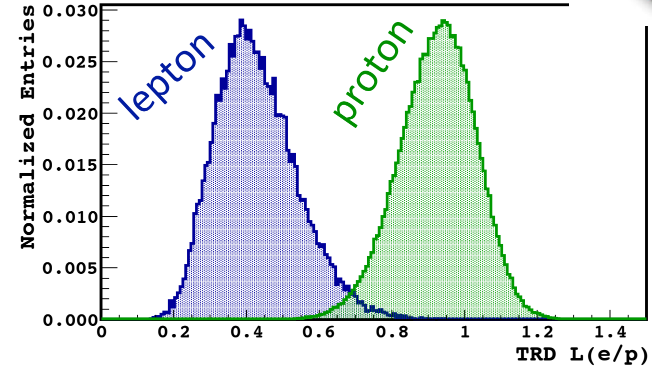


Tomographic reconstruction of the AMS top-of-instrument material obtained using the Proton-to-Helium flux ratio. Tiny differences in the interaction cross-section of proton and He are used to trace the material inhomogenities. Several detector elements such as screws, electronics boards, and mechanical interfaces are clearly recognizable.

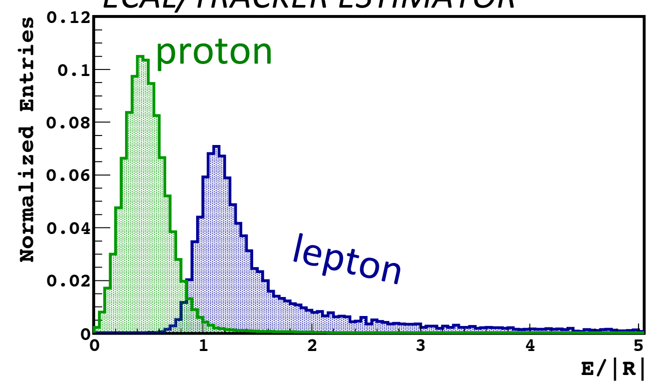
Multiple lepton/hadron separation



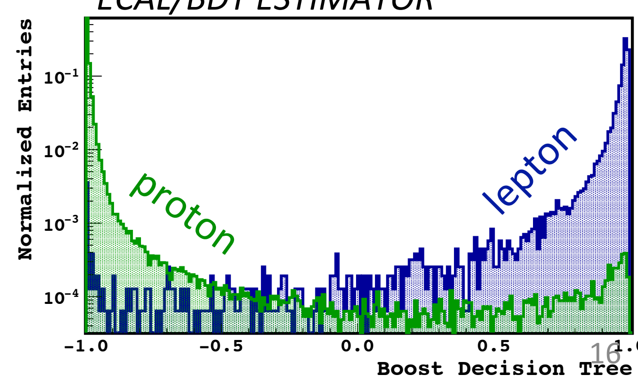
TRD ESTIMATOR



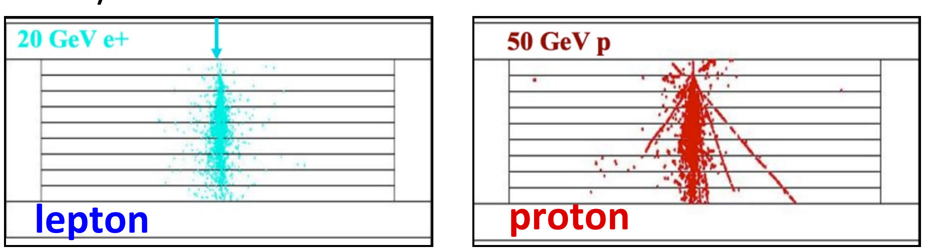
ECAL/TRACKER ESTIMATOR



ECAL/BDT ESTIMATOR



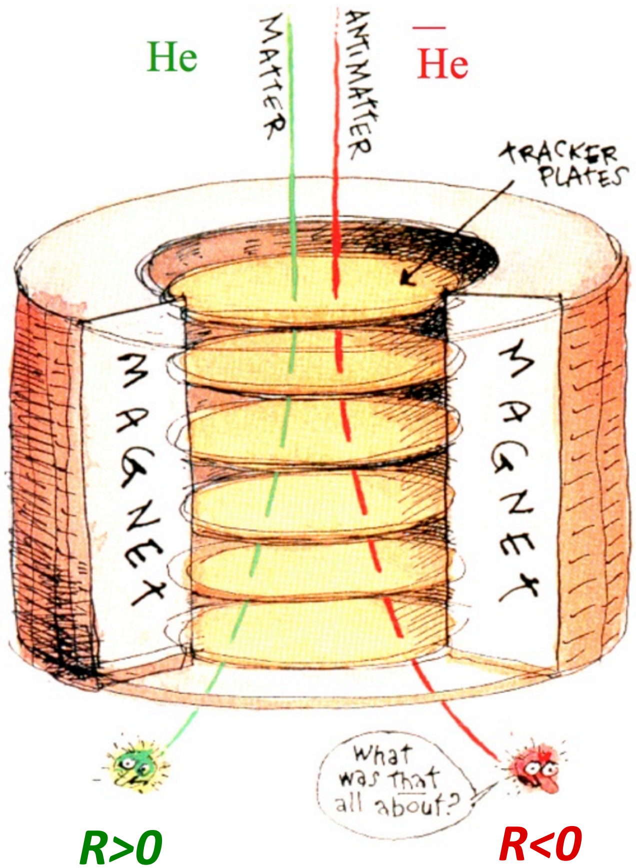
ECAL/BDT DISCRIMINATION ON SHOWER TOPOLOGY



No redundancy for particle sign

Matter-antimatter distinction: only from the track curvature

***Charge confusion*: probabilty to get the wrong particle sign**



Sources of charge confusion:

- Interactions & sec production
- Track mis-reconstruction
- Finite momentum resolution

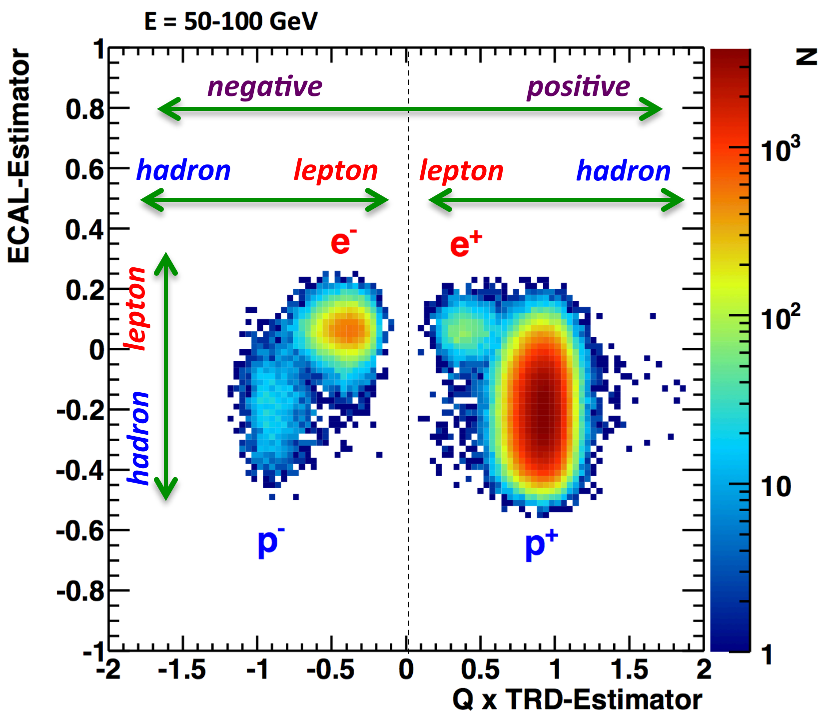
Charge confusion probability estimators have been developed for leptons and hadrons, with the help of beam test data and MC simulation

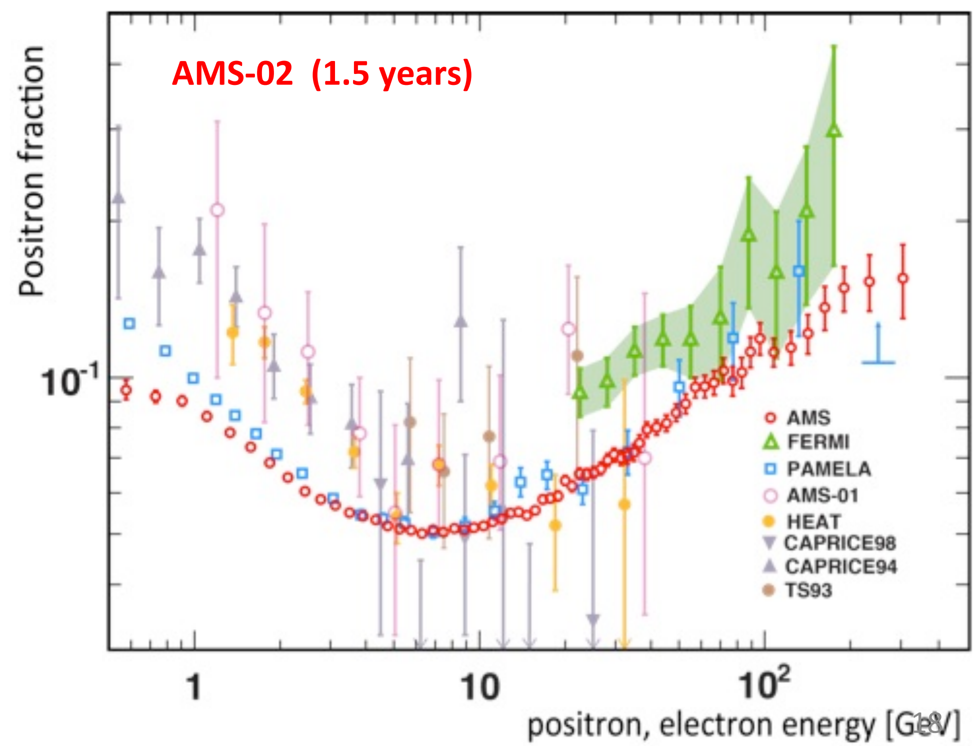
Positron fraction results

Positron fraction measured between 0.5 to 350 GeV of energy

- ✓ *1.5 years of data. 74,000 events.*
- ✓ *72 events in the last energy bin*
- ✓ *No fine structure in the spectra.*
- ✓ *Persistent rise up ~ 200 GeV*

The e+ secondary production is expected to decrease monotonically, while results indicate a persistent rise. The positron fraction increases steadily from 10 to 250 GeV.



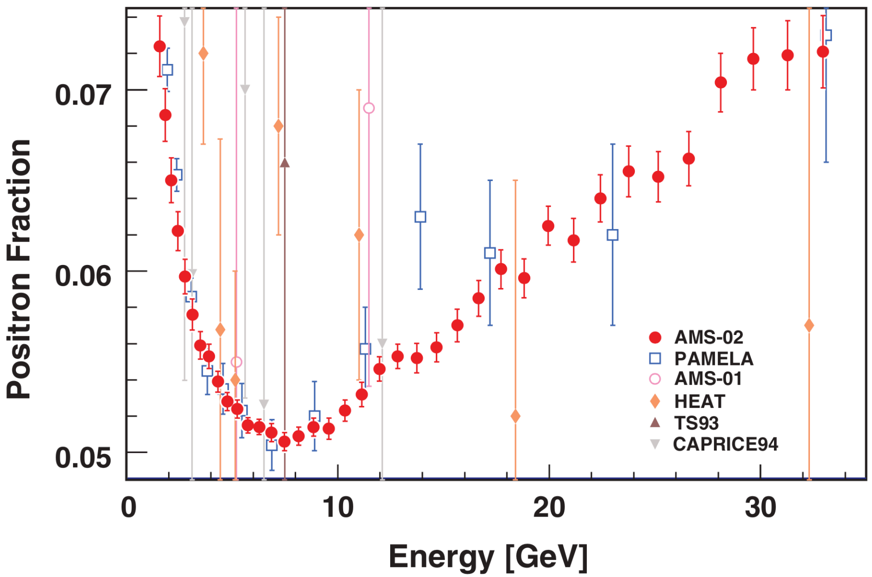


Positron fraction at high energy

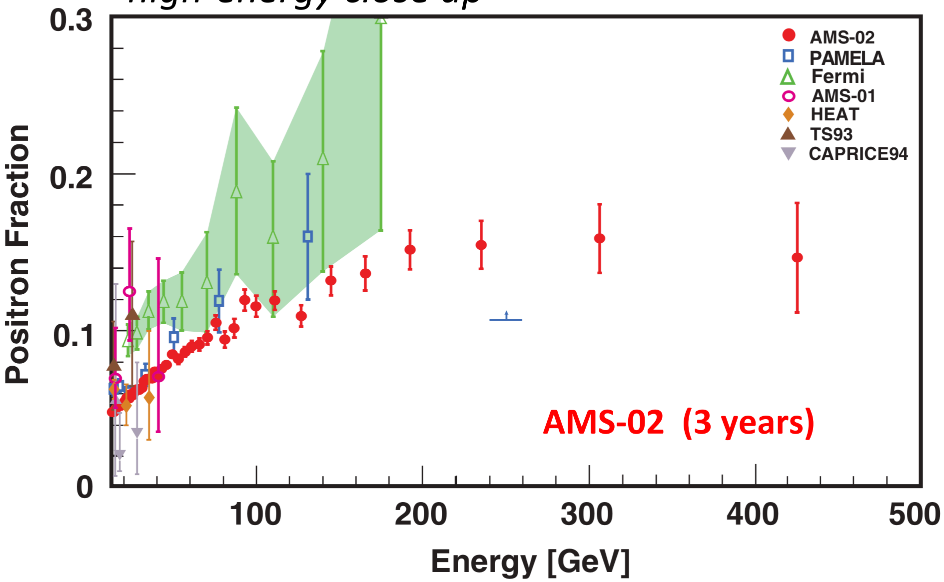
September 2014 – Positron fraction from 0.5 to 500 GeV. With 3yrs data

- New high-energy data (3 yrs statistics) released. 0.5 GeV – 500 GeV
- The Positron fraction above ~200 GeV *does not increase anymore*

low-energy close up



high-energy close up

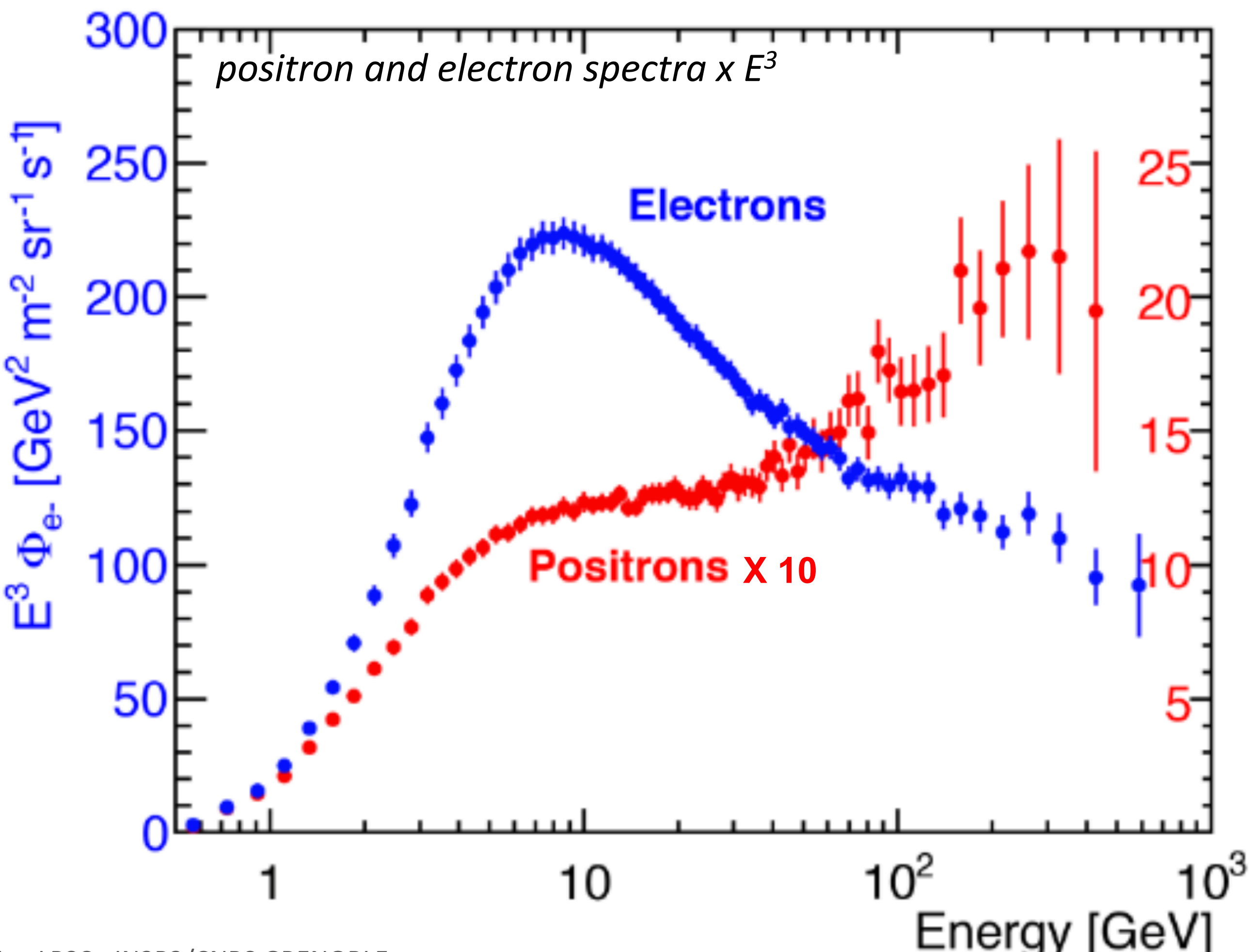


Lepton fluxes: e^+, e^-, and "*all electron*"

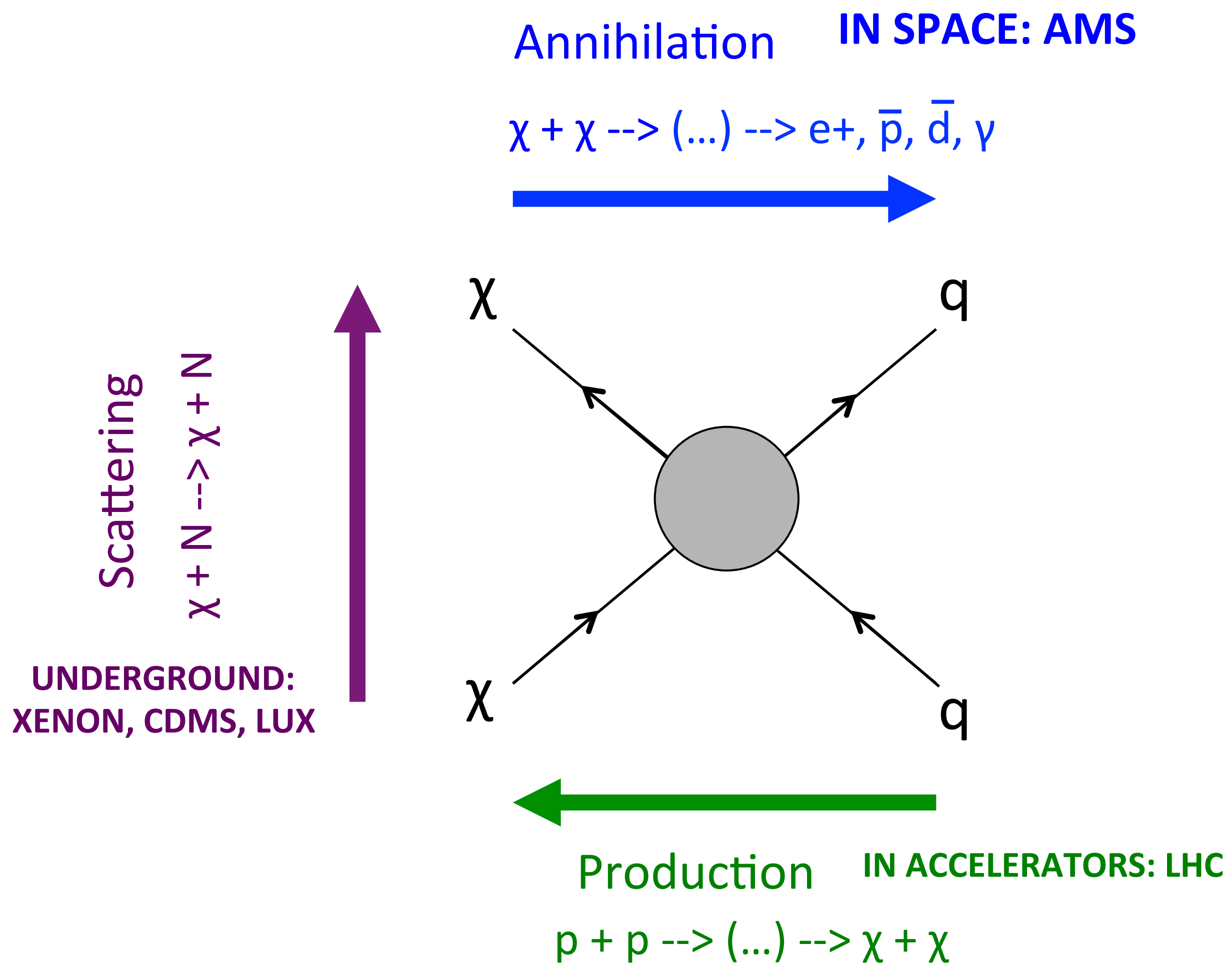
September 2014 – New publication: positron fraction in 0.5 - 500 GeV

October 2014 – New publication: electron and positron fluxes up to 700 GeV

November 2014 – New publication: electron + positron total flux up to 1 TeV

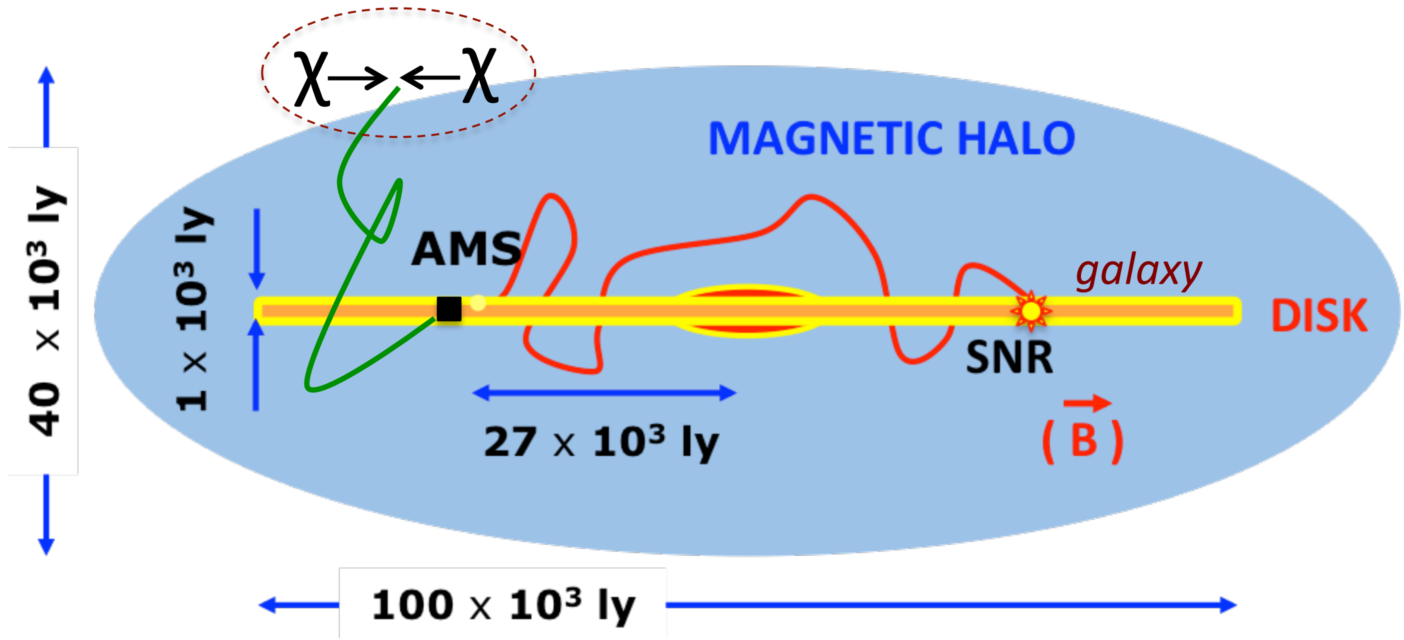


Search for dark matter



Dark matter and CR propagation physics

- ✓ *Background* from cosmic-ray sources (SNR) - No anti-matter expected
- ✓ *Background* from p+ISM collisions on disc: highly dependent on CR propagation
- ✓ *Signal* from DM annihilation χ + χ --> (...) --> antimatter

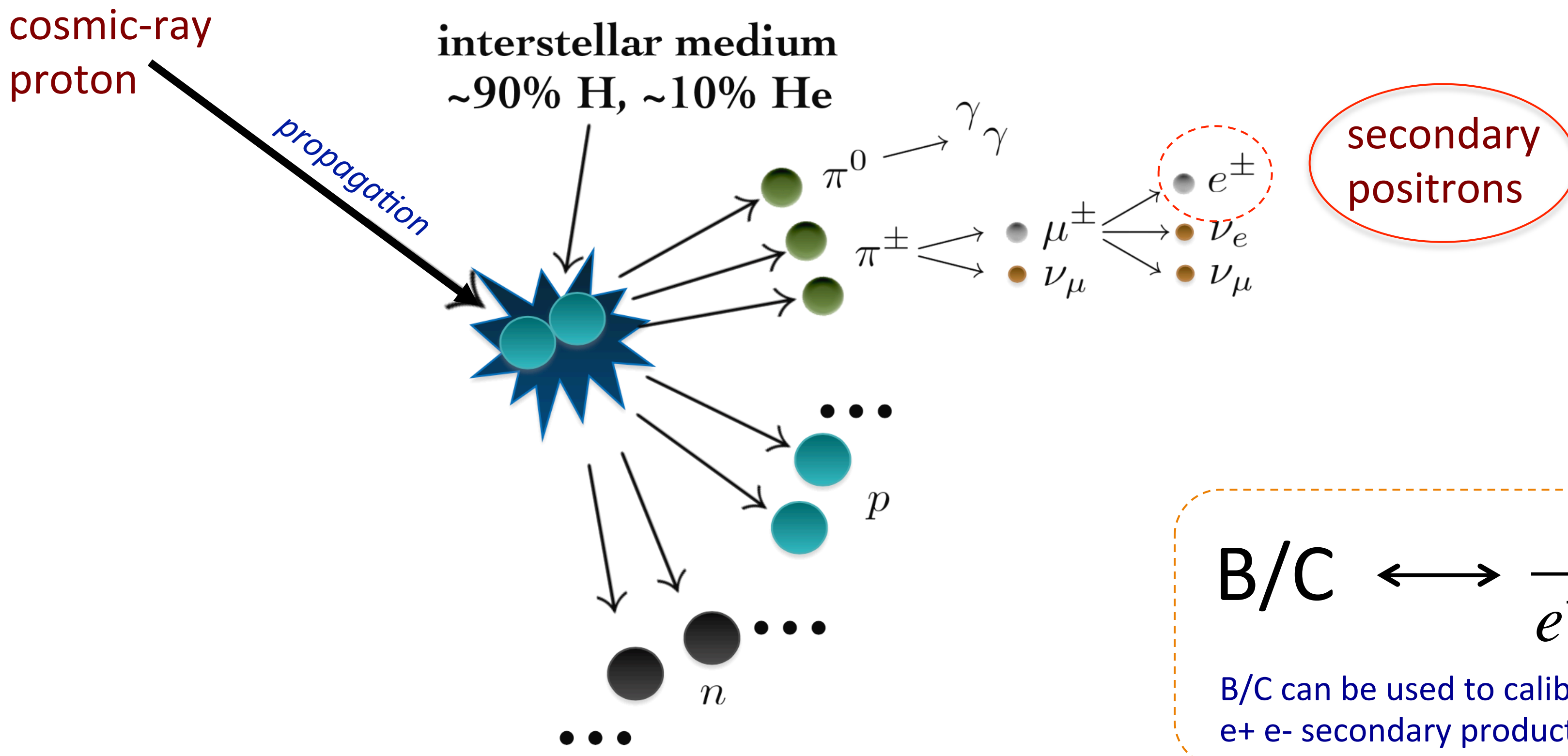


DISC
- *Sources (SNRs)*
- *Intestellar matter (ISM)*

MAGNETIC HALO
- *Turbulent B-field. Zero matter.*
- *Energy dependent CR diffusion*

Dark matter and CR propagation physics

Secondary e+ production



$$B/C \longleftrightarrow \frac{e^+}{e^+ + e^-}$$

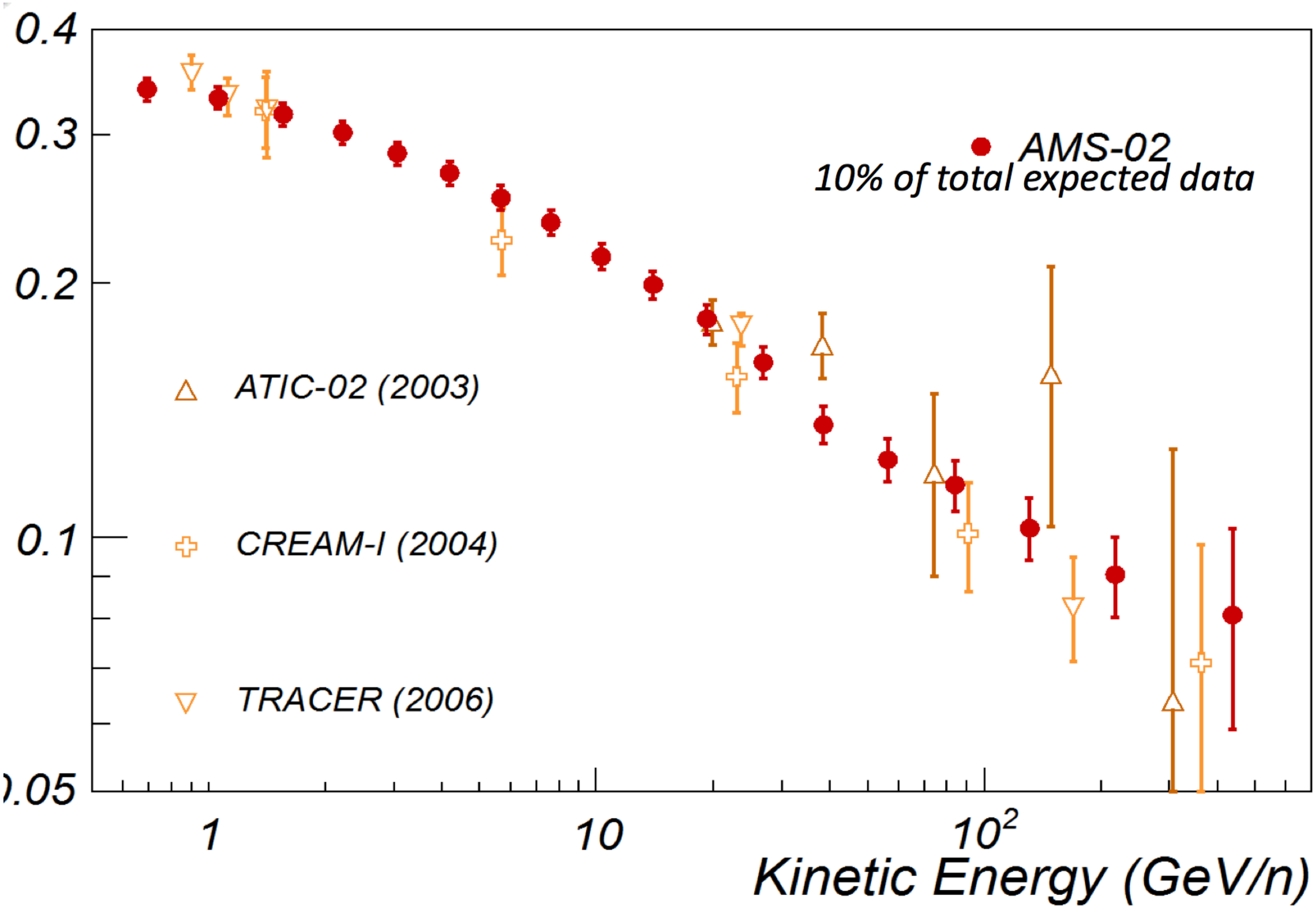
B/C can be used to calibrated
e+ e- secondary production

Secondary nuclei production

CNO… Fe + ISM → Li, Be, **B**
B, Be + ISM → **Li**, Be
Be +ISM → **Li**

secondary
Li-Be-B

Secondary-to-Primary: the B/C ratio



Positron excess: sources of HE positrons

- Dark Matter particles
- Astrophysical sources (SNR/PWN)
- CR collisions with ISM

$\chi + \chi$ --> (...) --> e+

e+ e- provided by annihilation of WIMP particles of ~ TeV mass

PWN *e+ e- pair production Inside Pulsar Wind Nebulae*

SNR *e+e- production from p+p collisions inside shells of Supernova Remants*

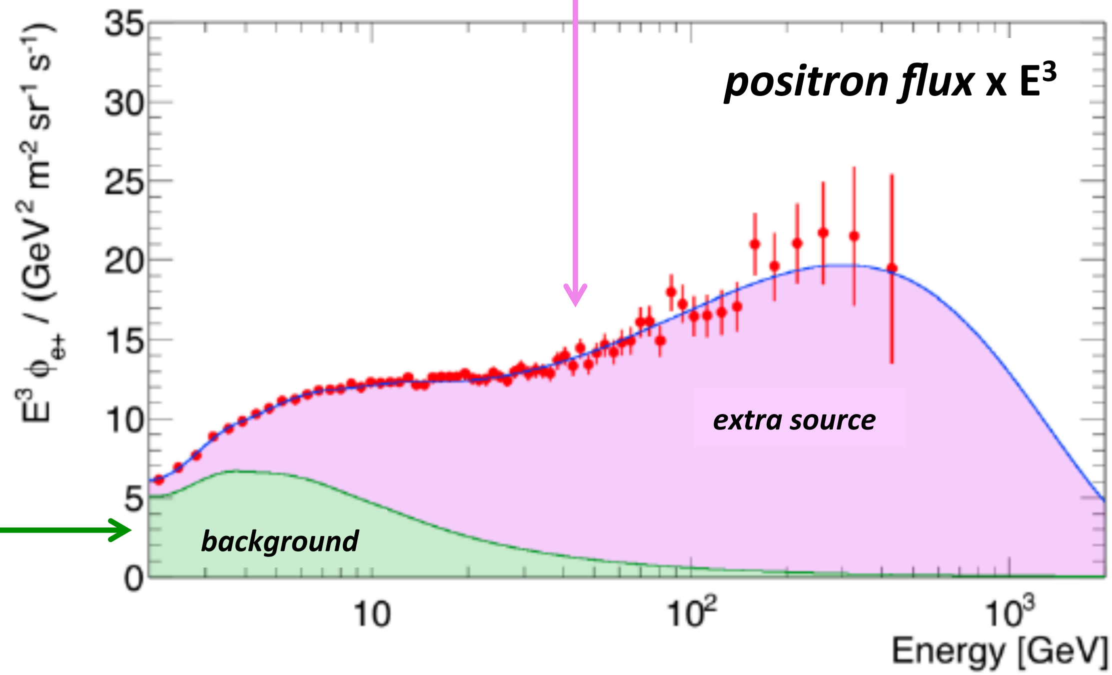
our understanding of secondary production and CR propagation is totally wrong… ?

Positron excess: sources of HE positrons

***Standard** prediction: of e+ from p+ISM collisions*
→Cannot account for the observed positron data
→Background for new physics/astrophysicssignals

- Dark Matter particles
- Astrophysical sources (SNR/PWN)
- ✓ CR collisions with ISM

our understanding



PWN-scenario: high-energy e+ e- from pulsar

- ✓ **SNRs: accelerate electron and nuclei**
- ✓ **Nuclei + ISM collisions -> e+ & e- secondary production**
- ✓ **PWNe: primary e+ and e-**

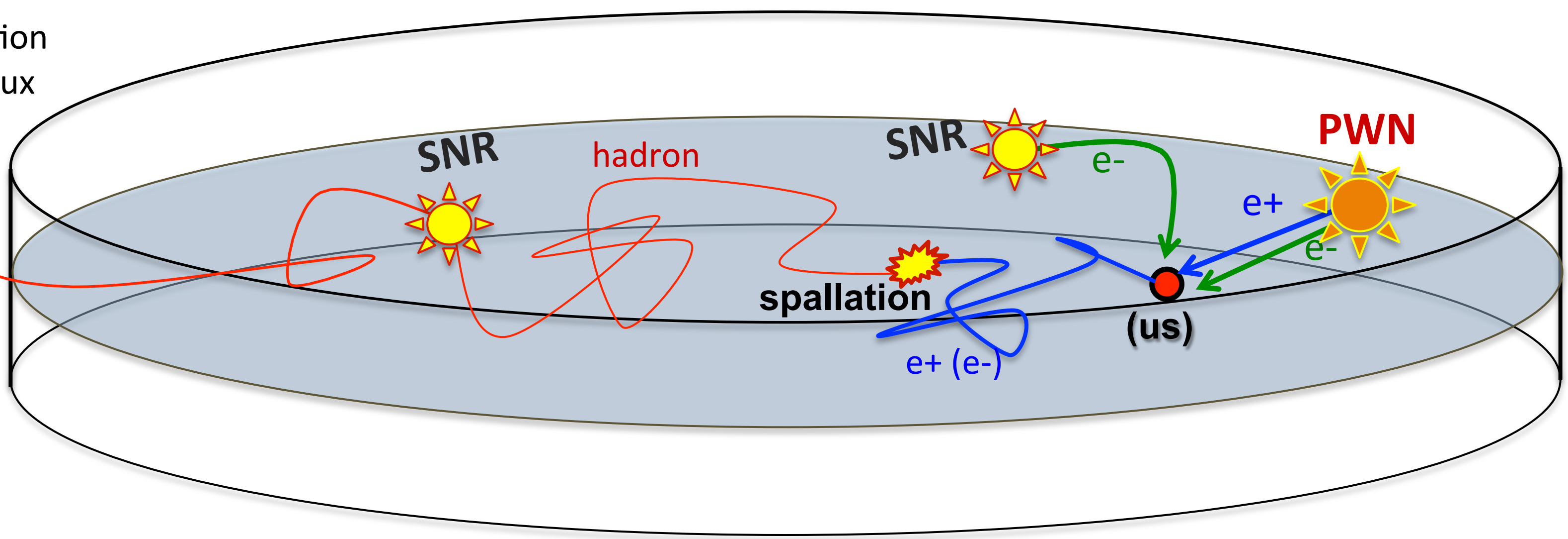
Rotation-powered neutron stars radiate energy by producing e+e- pairs, injected in ISM when out of PWN

PWN are *additional* source for e+ e- (to the usual sources SNR & ISM)

Nearby source contribute at high-energy: d(E>100 GeV) ~ few kpc

Signatures in

- Electron flux
- Positron flux
- Positron fraction
- All-electron flux



PWN-scenario: high-energy e+ e- from pulsar

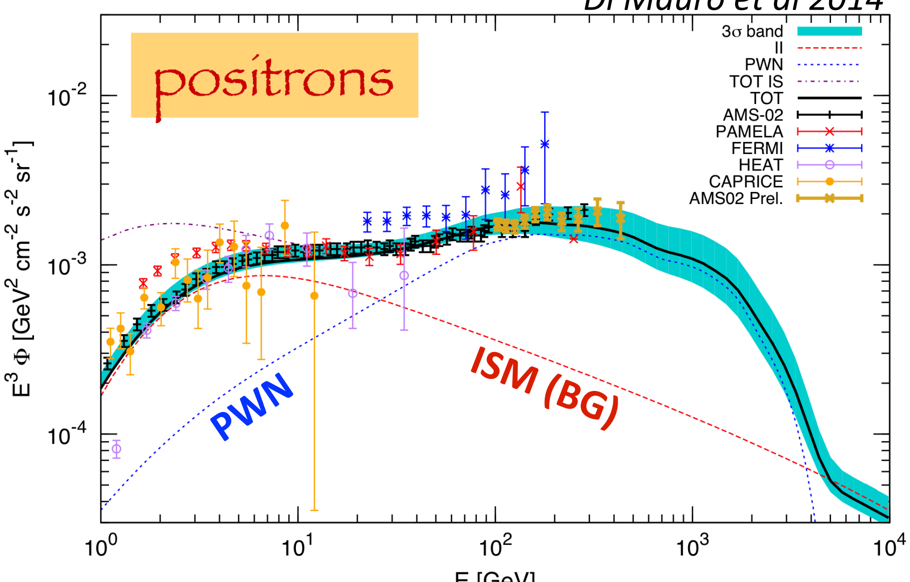
- ✓ **SNRs [nearby & d>3kpc]: e-** [Green+Ensemble | γ=2 / E_{Cut}~2TeV]
- ✓ **p-He + ISM: secondary e+ and e-** [From p/He spectra & propagation]
- ✓ **PWNe: primary e+ and e-** [(ATNF) / E_{MAX} ~ 1 – 10 TeV]

All observables
- Electron flux
- Positron flux
- Positron fraction
- All-electron flux

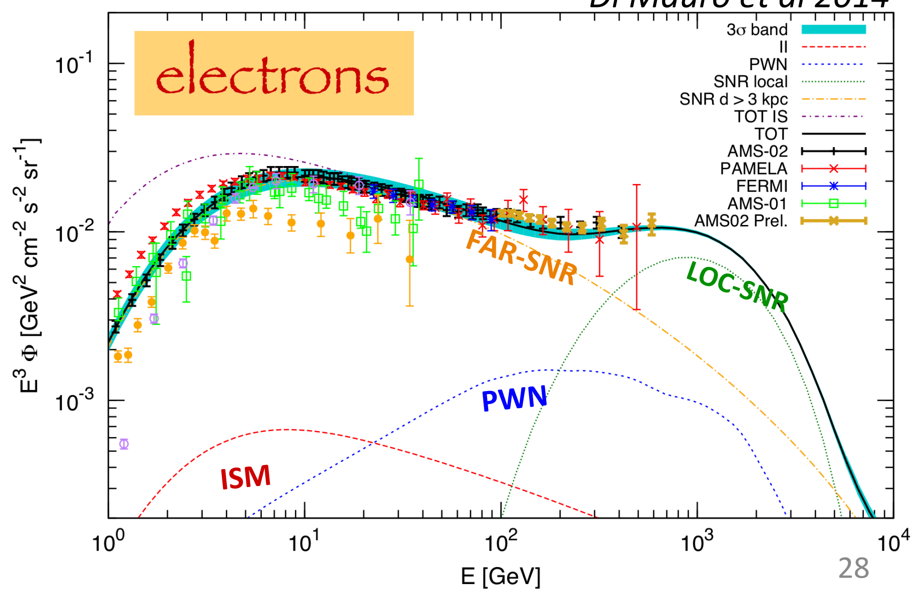
Excellent fits to all channes

- ✓ All ATNF / Single-PWN / Powerful-PWNe
- ✓ Dependence on Emax = 1 – 10 TeV

Di Mauro et al 2014



Di Mauro et al 2014



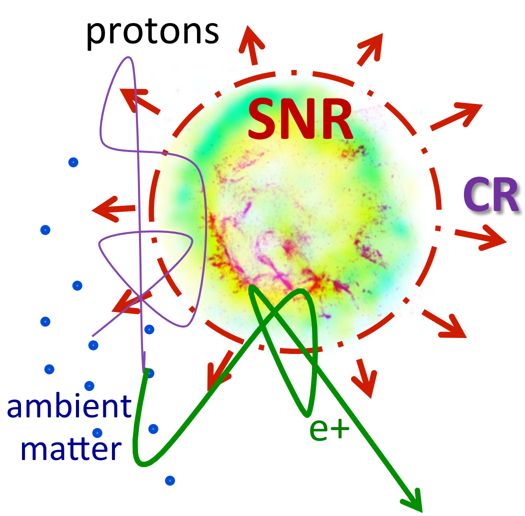
SNR-Scenario: e+ e- from hadronic production in SNRs

- ✓ **SNRs: electron, hadrons, and e+ from collisions**
- ✓ **hadrons+ ISM collisions: secondary e+ and e-**
- ✓ ~~**PWNe: primary e+ and e-**~~

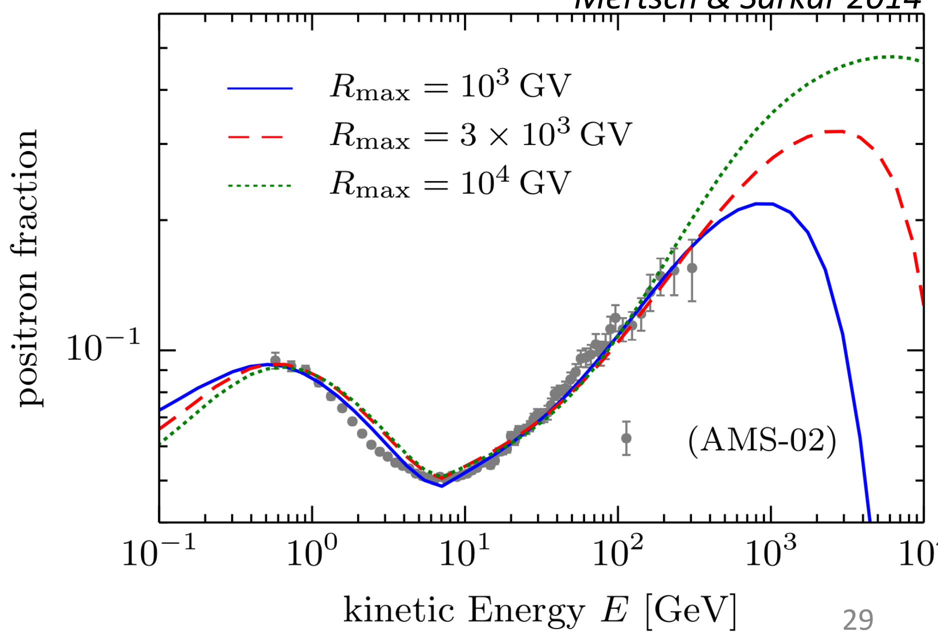
All needed ingredients are already there

→ **This effect *must* exist, but it's strength is not predicted a priory**
→ **Require damped B field and low shock speed -> typical of OLD SNR**

→ **Rising positron fraction at source**
→ **Expected Signature in nuclear channels**



Mertsch & Sarkar 2014



Hadronic production in SNRs: antiproton/proton ratio

The same mechanism must happen with **antiprotons**

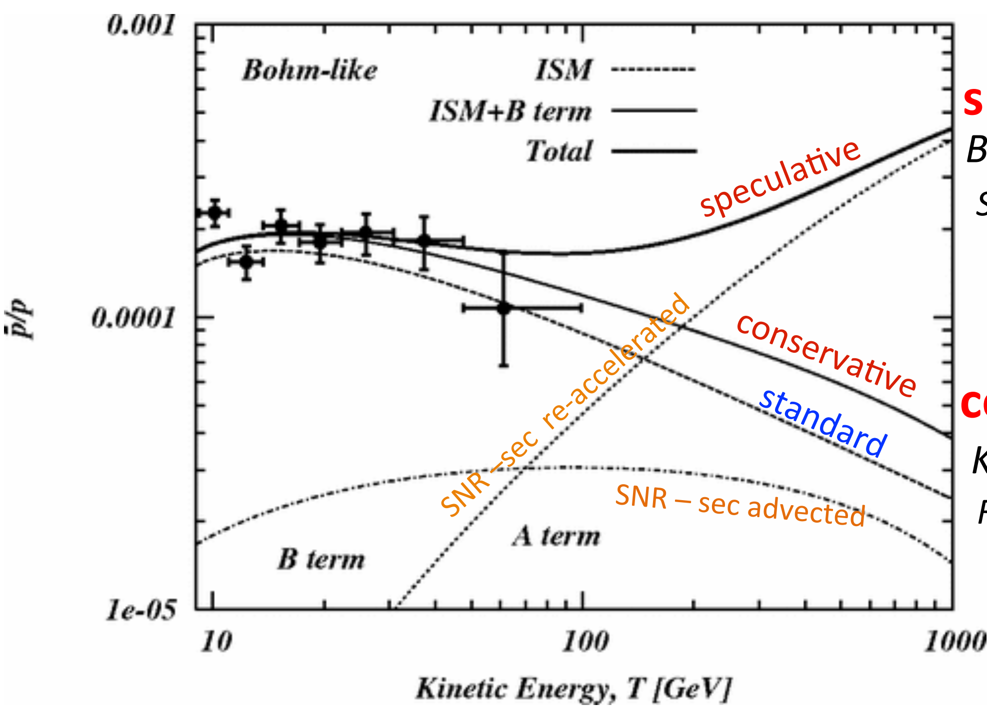
→ At ~100 GeV/n, pbar production in SNRs can overtake the spectrum.

- Advected pbars: slight pbar/p flattening – plausible.
- Re-accelerated pbars: pbar/p rise at HE – to match the positron fraction

→ *To be tested by AMS-02*

→ **Rising positron fraction at source**

→ **Signature in hadron channels**



speculative

Blasi & Serpico 2009

SNR parameters to match the positron fraction

conservative

Kachelriess et al 2011

Reasonably expected for a tiptycal SNR

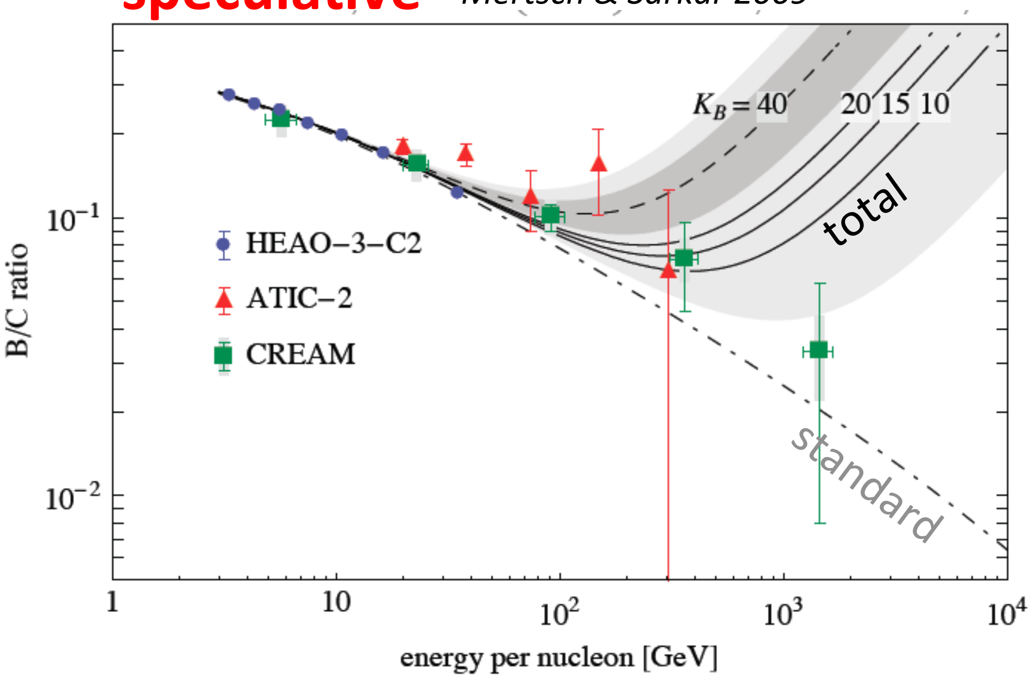
Hadronic production in SNRs: test with B/C ratio

The same mechanism must happen with CR nuclei.

→ At ~100 GeV/n, the B/C ratio must eventually rise.

- Advected nuclei: B/C flattening: plausible.
- Re-accelerated nuclei: B/C rise at HE, to match the positron fraction

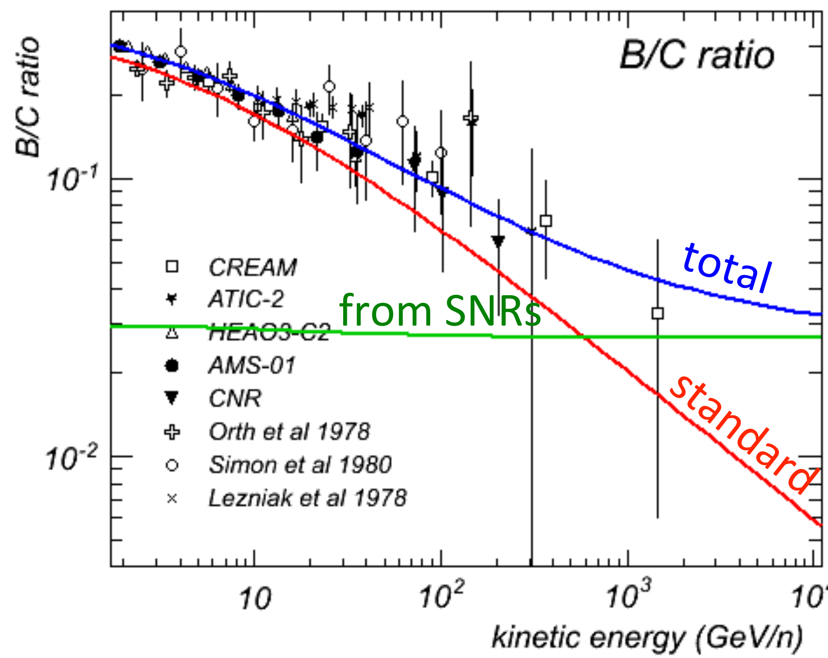
speculative *Mertsch & Sarkar 2009*



✓ **Can explain the rise in positron fraction**

X **Not observed by new B/C data from AMS**

conservative *NT & Donato 2012*

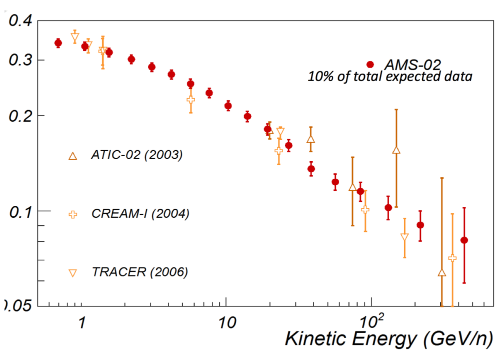


✓ **No match to e+, but guaranteed effect.**

✓ **Impact on propagation parameters**

Explaination for the positron excess: simple chart

Scenario \ signature in…	positron fraction	antiproton/ proton ratio	B/C ratio
DM scenario	Yes	Yes?	No
PWN Scenario	Yes	No	No
SNR Scenario	Yes	Yes	Yes



e+ excess observed & established

Unclear. Need AMS-02 data at above 100 GeV

No evidence of rise observed up to ~500 GeV

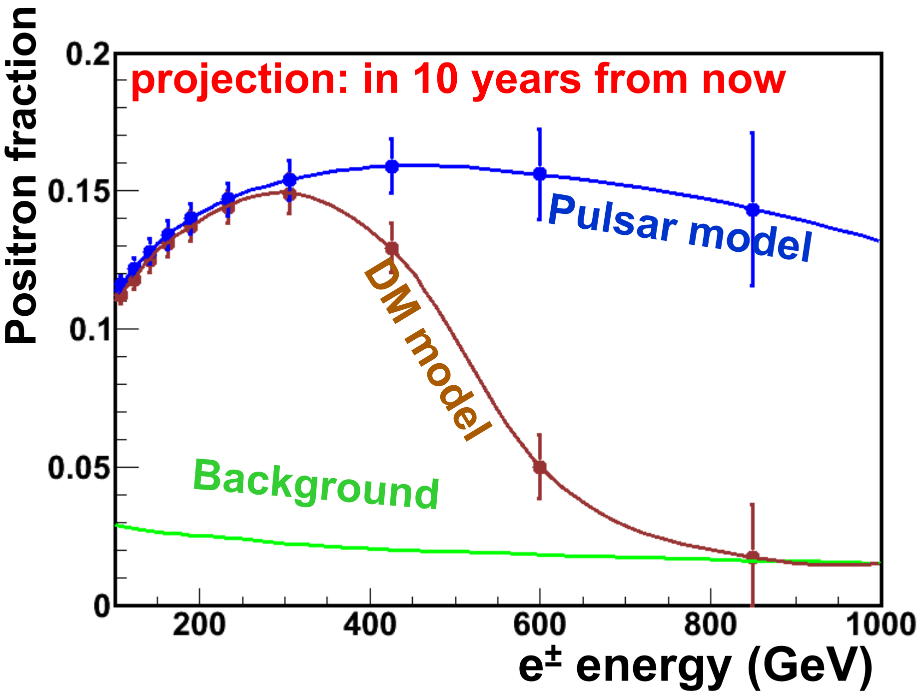
Perspective for the DM search

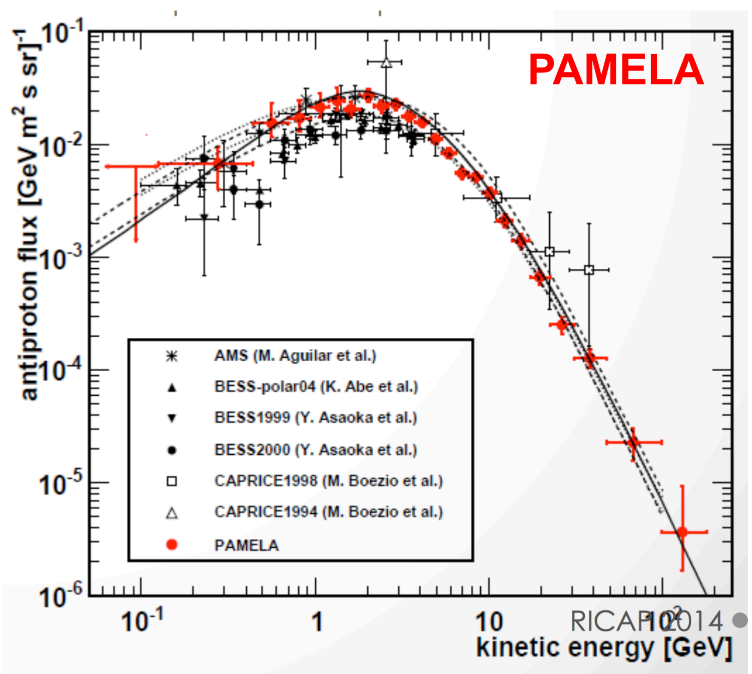
Lepton data at TeV energy

- Discrimination DM/Astro scenarios
- Long observation time
- Model unknown, parameter degeneracy

Anti-proton/proton ratio above ~100 GeV

- Expected signature from DM
- Present data consistent with background
- BG uncertainty (propagation &cross-sections)





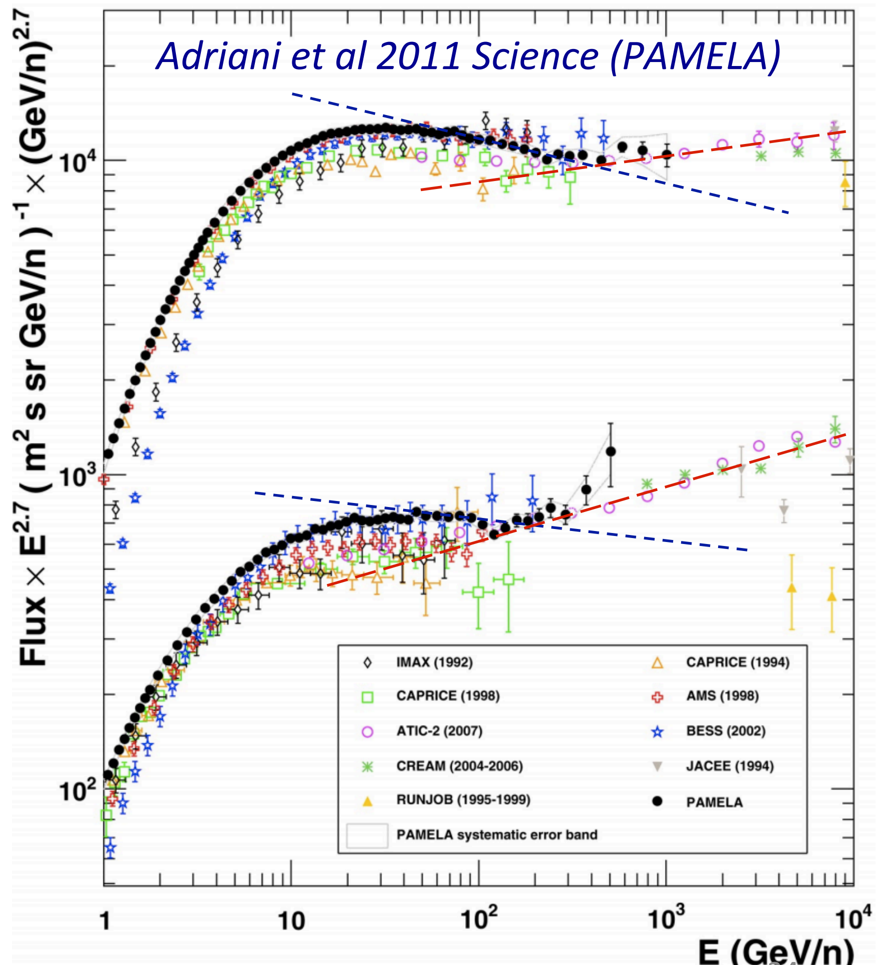
Cosmic-Ray Hadron Fluxes: another anomaly

Proton and Helium spectra at high energies are revealing interesting spectral features that may offer a clue to the origin of the observed cosmic rays

"These data challenge the current paradigm of cosmic-ray acceleration in supernova remnants followed by diffusive propagation in the Galaxy".

- *HE Hardening: Spectra at >1 TeV are remarkably harder than those at ~100 GeV*
- *p/He anomaly: Helium energy spectrum seems harder than that of the Hydrogen.*
- Sharp break? Sharp transition located at 300 GV, as claimed by PAMELA data 2011.

Ongoing data analysis. To be released soon.



Spectral features in H and He

Very basic predictions (E~ 10 GeV – 100 TeV)

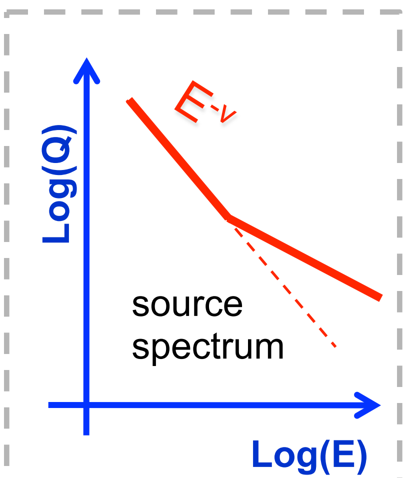
$$Q(E) \approx E^{-\alpha}$$ **DSA@SNRs: power-law source spectra (α~ 2.0 – 2.2)**

$$K(E) \approx E^{\delta}$$ **QLT: power-law diffusion regime (δ~ 0.3 - 0.6)**

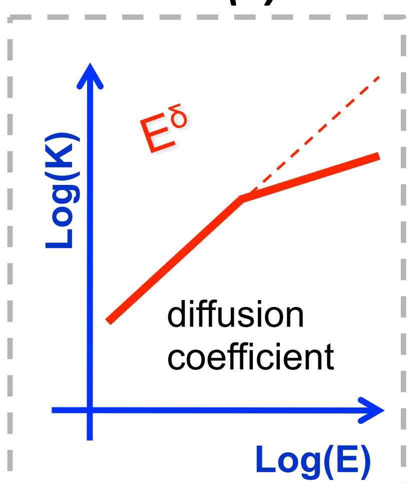
$$\phi(E) \sim Q/K \approx E^{-(\nu+\delta)}$$ **Expected CR spectra at Earth (E>>GeV; no int)**

Possible Explanaition for the change in slope of (E):

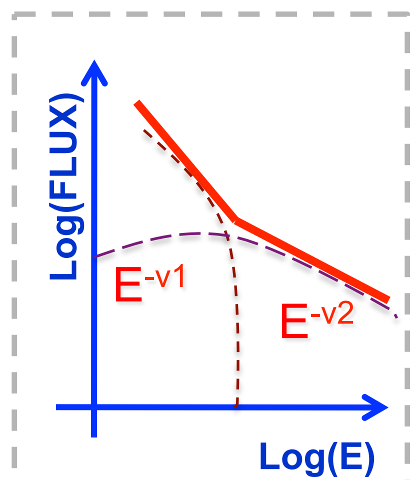
Break in Q(E)



Break in K(E)



Multi - sources



- *Inhomogeneus diffusion*
- *Reacceleration at weak shocks*
- *Dispersion of spectral indices*
- *...*

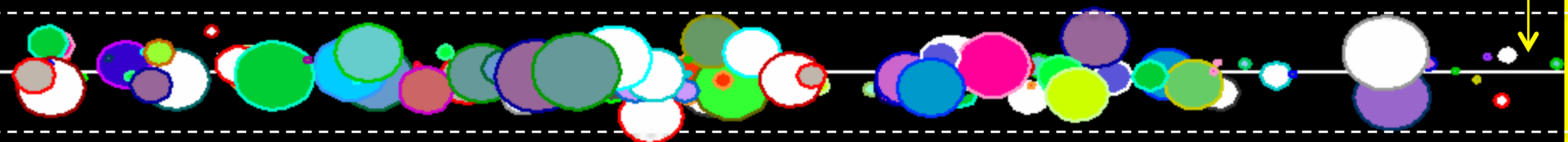
The Diffusive Halo

$$w(\kappa)d\kappa \sim \kappa^{-2+\delta}d\kappa$$

L ~ 5 kpc

INNER HALO
SNRs are the source of turbulent motion

- → large irregularities
- → small wave numbers
- → soft turbulence spectrum
- → slow diffusivity (small δ)



OUTER HALO
No SNRs! Turbulence is driven by CRs themselves.

→ steeper diffusivity (large δ)

set full screen to see the animation

Diffusive origin of CR spectral hardening

NT astro-ph/1204.4492

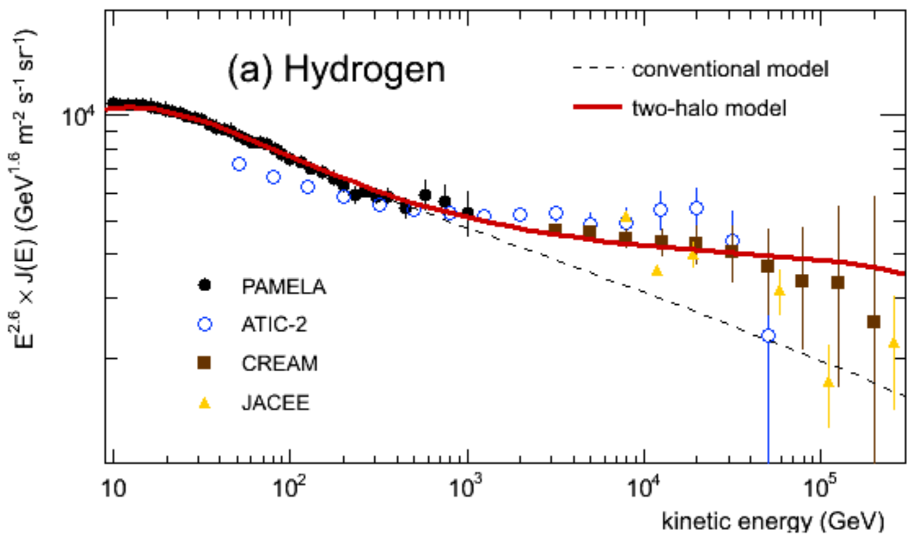
Basic idea: the diffusion coefficient is NOT separable into space and energy

$$K(z,R) \neq f(z)\cdot k(R)$$

→ **deviation from power-law** $\phi(E) \neq Q/K$

- Disk: SNR-induced turbulence.
- Halo: CR-induced turbulence.

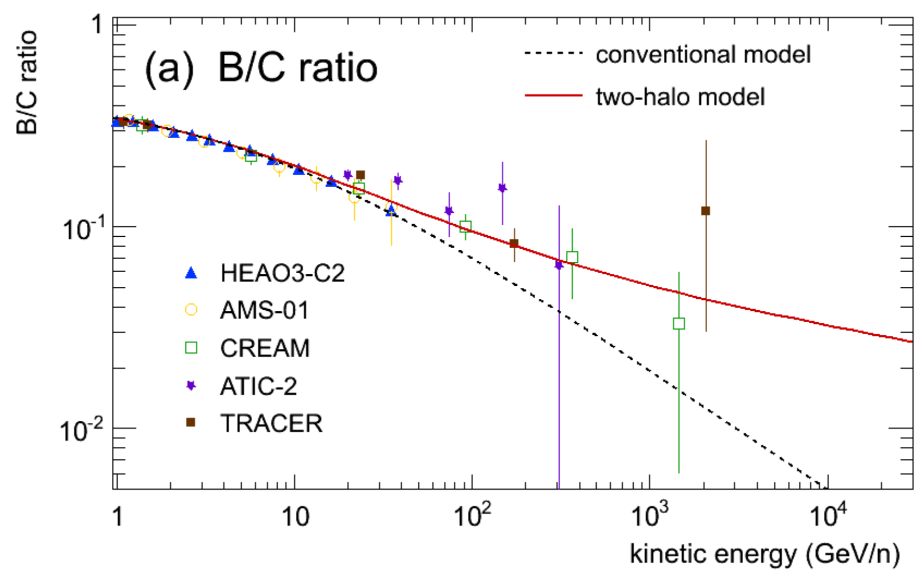
→ Different diffusivity in d*isk and halo*



Model predictions:

✓ **Proton & nuclei hardening above ~300 GV**

✓ ***B/C ratio flattening at ~50 GeV/n***



Additional benefits:

✓ **Lower anisotropy at high-energy**

✓ ***Harder source spectra, close to 2.0***

To be tested soon by AMS-02

Conclusions

AMS fundamental science experiment in the International Space Station

Dark Matter search is central to the AMS Physics Program

- **Potential to shed a light on the nature of the Dark Matter**
- **Positron fraction up to 500 GeV with ~3 years of time exposure**
- **Search for anomalies in the anti-proton spectrum at high energy**
- **CR spectra measurements of proton and light nuclei**

Data taking ongoing. Extensive data analysis ongoing.

~1300 days of mission. 60 Giga-particles collected

2014: lepton data released

Positron fraction at high energy

Electron & Positron spectra

All-electron energy spectrum

2015: hadrons and nuclei

Proton and Helium spectra at TeV

Nuclei: B/C ratio and C/O ratio

Antimatter: antiproton/proton ratio