CRIS 2016
10th Cosmic Ray International Seminar

Direct CR Measurements

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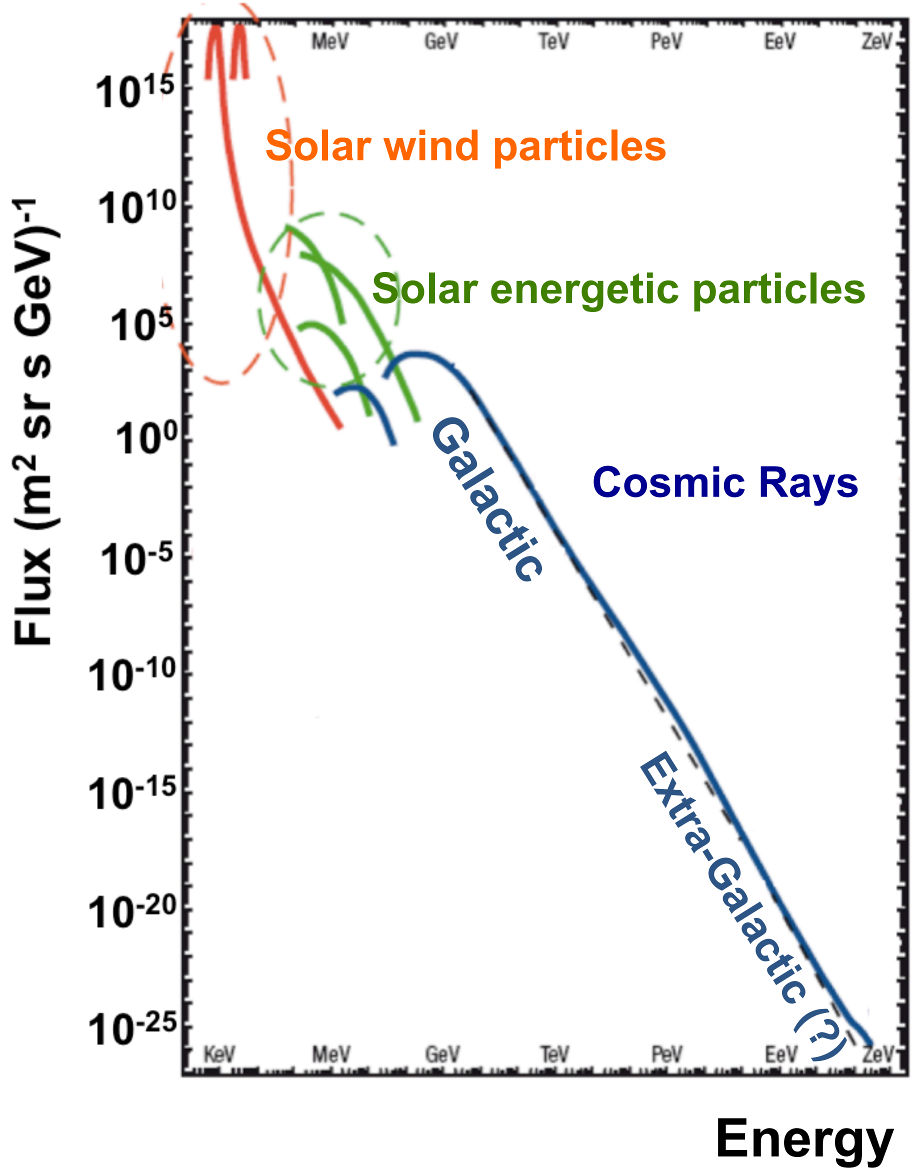
University & INFN Perugia

The CR spectrum: the overall picture



The CR spectrum: the overall picture

Direct measurements:

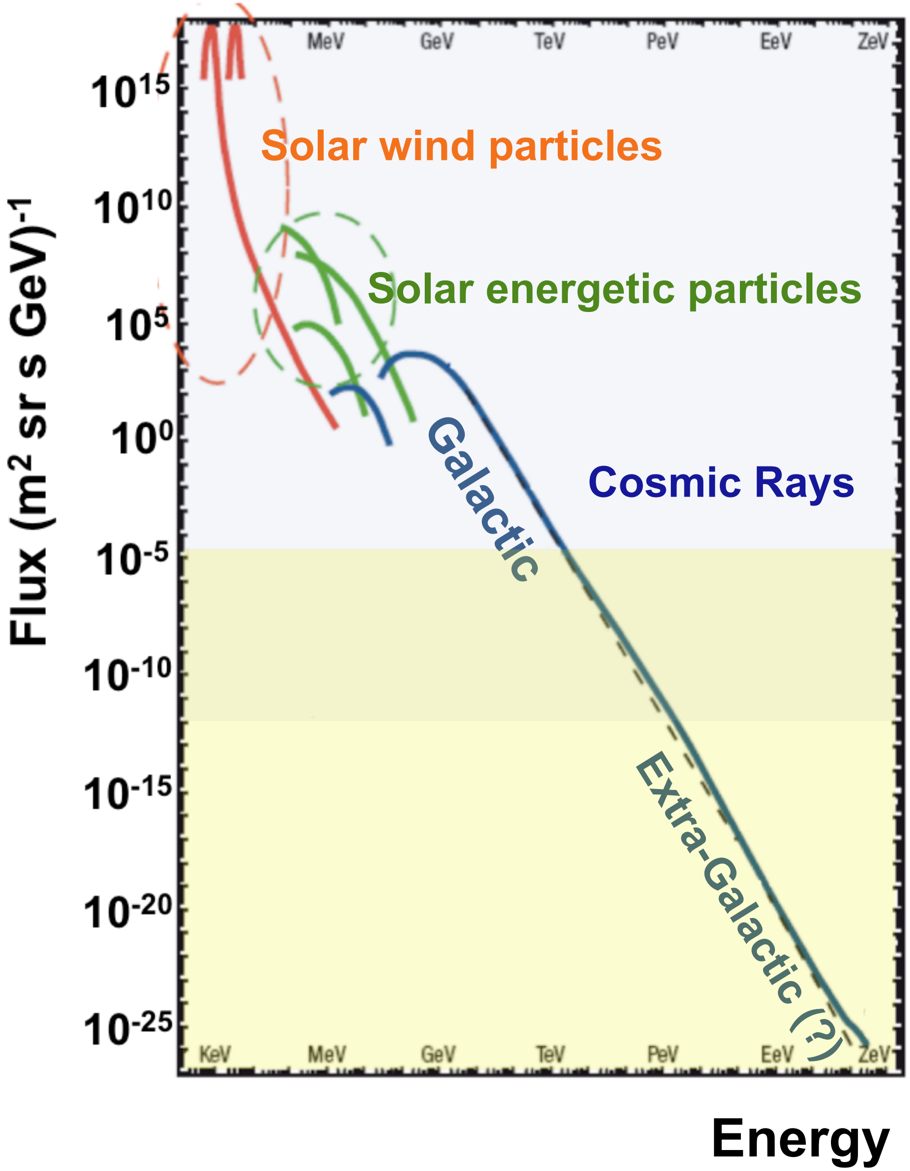
☺ Particle identification/Energy calibration, anti-matter

☹ Space: Weight/Size constraints limit the energy range (< PeV)

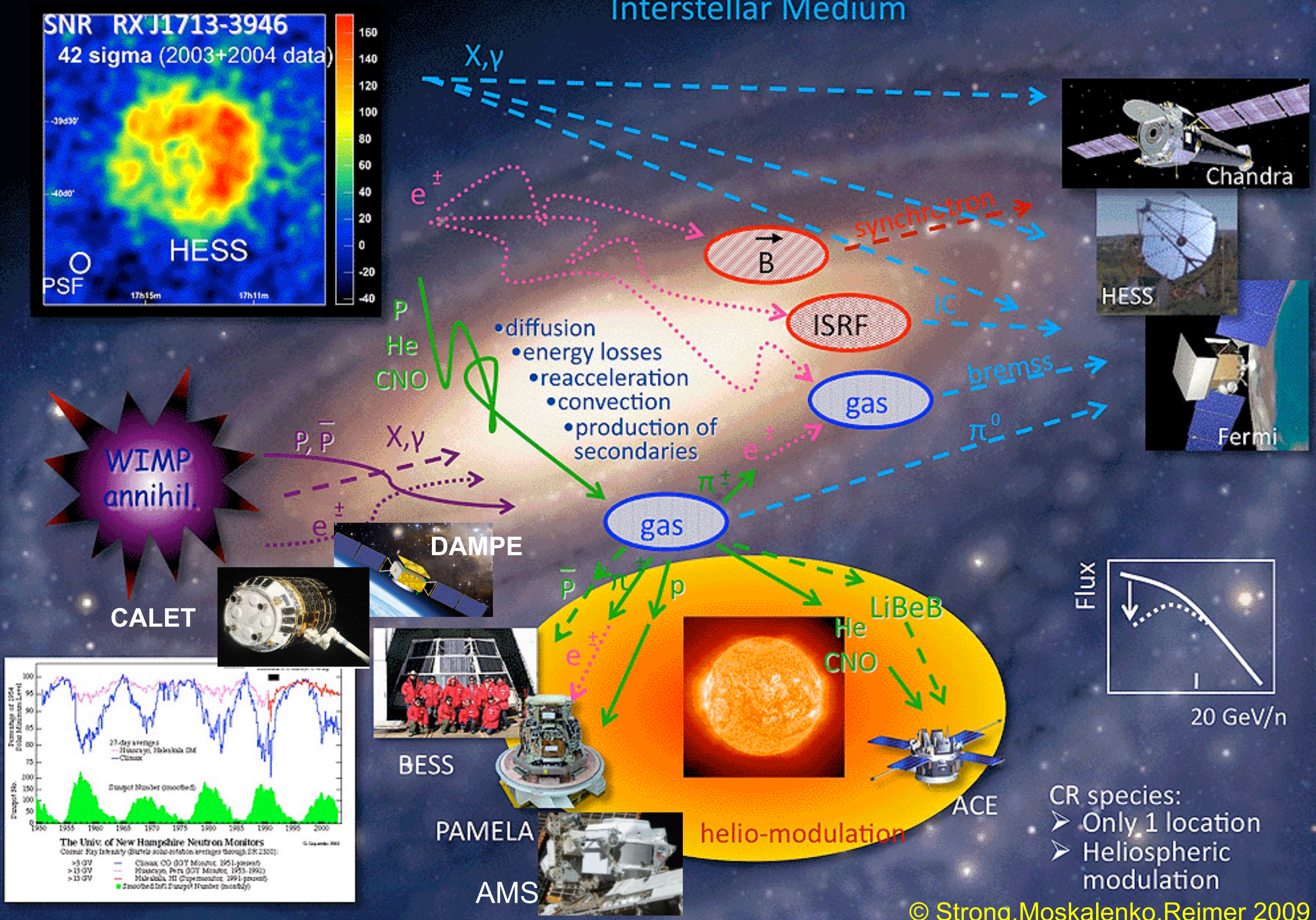
Indirect measurements:

☺ Ground: Extended energy range (>PeV)

☹ Pid/Energy : dependence on modelling of atmospheric interactions

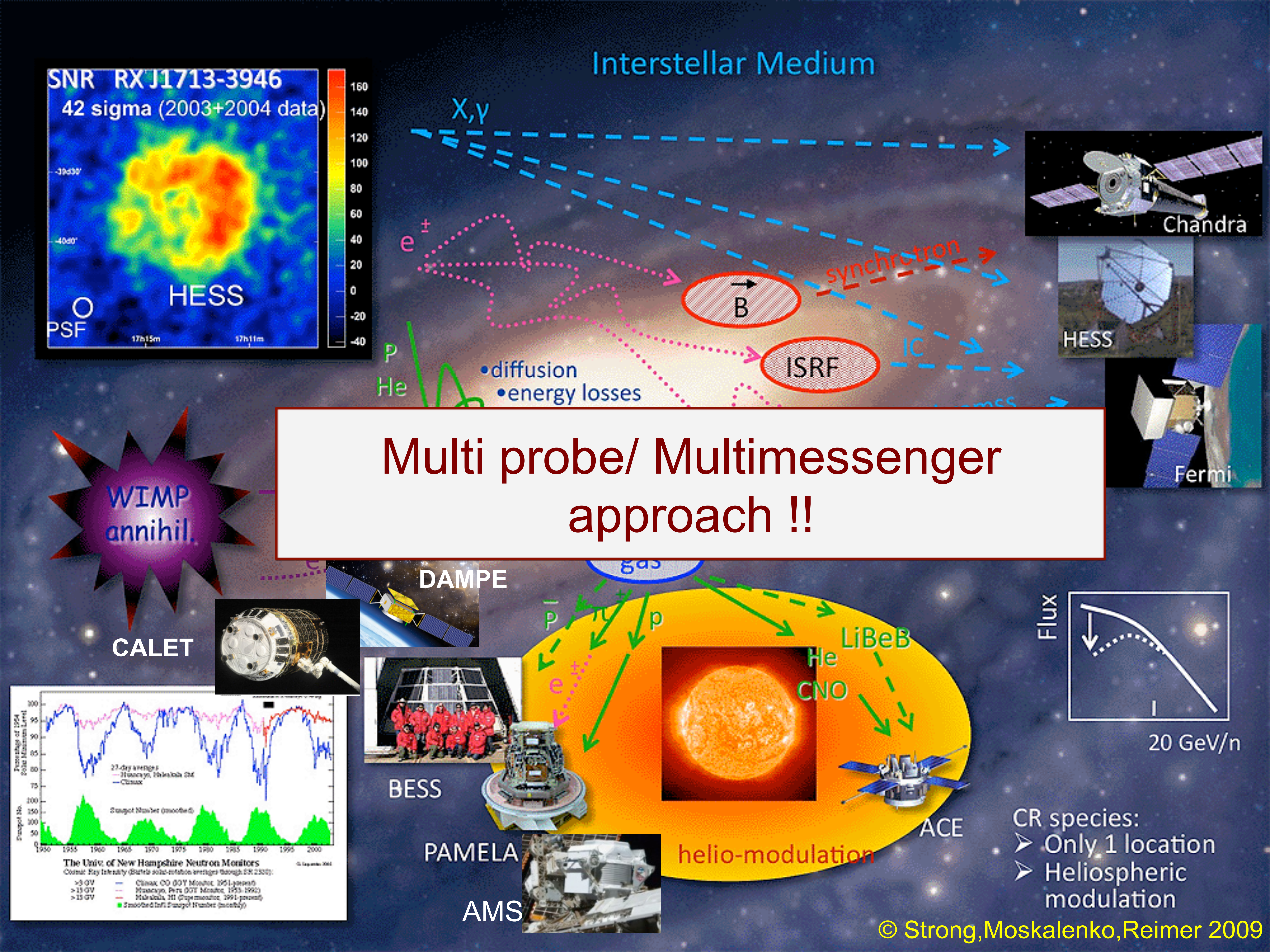


Interstellar Medium

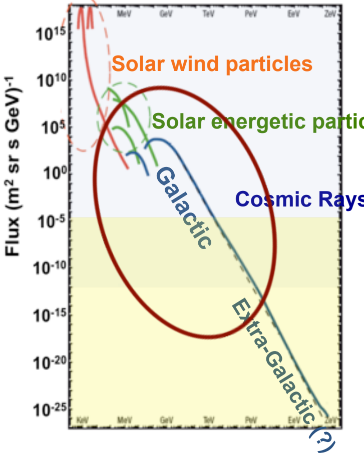


CR species:
- Only 1 location
- Heliospheric modulation

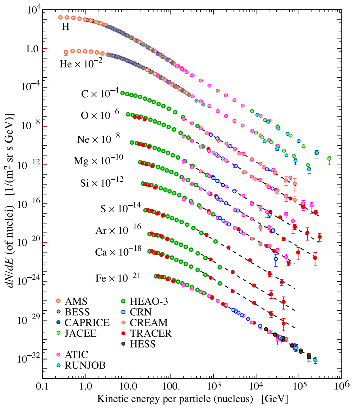
Multi probe/ Multimessenger approach !!

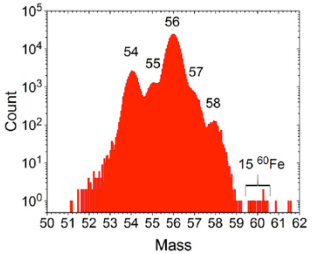


The measurements

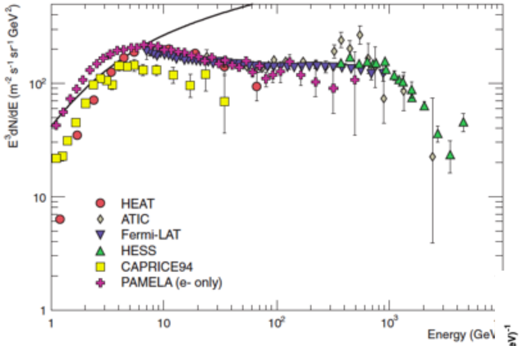


Chemical composition

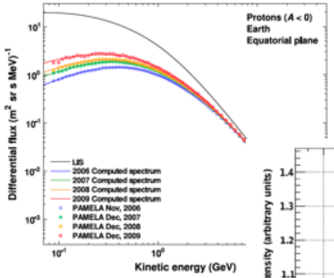


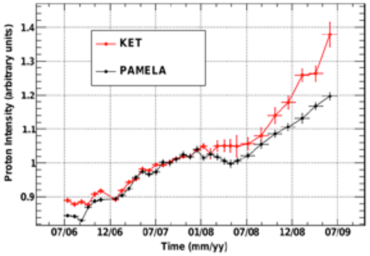


The electron component



Earth & Sun



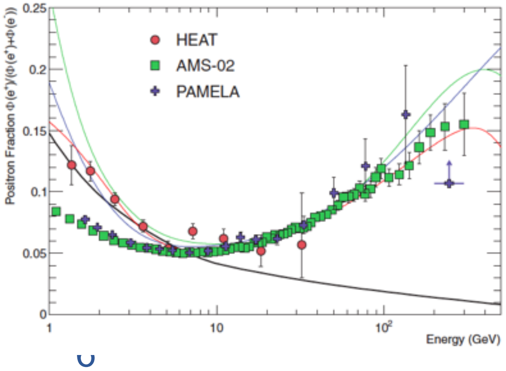


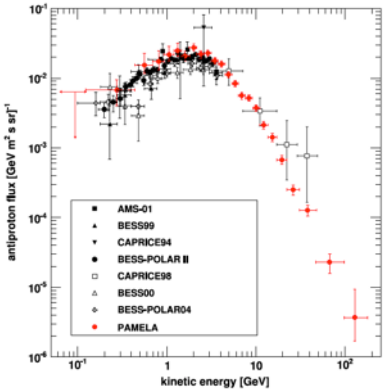
Sources

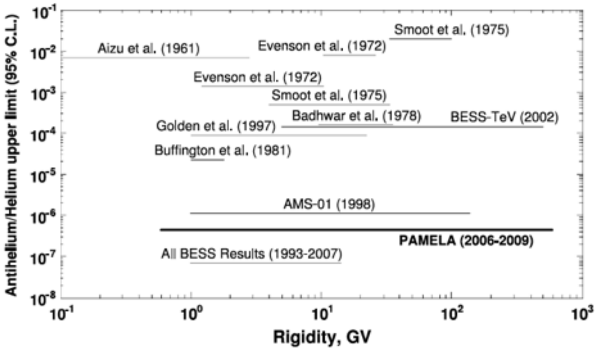
Propagation

ISM

New Physics?

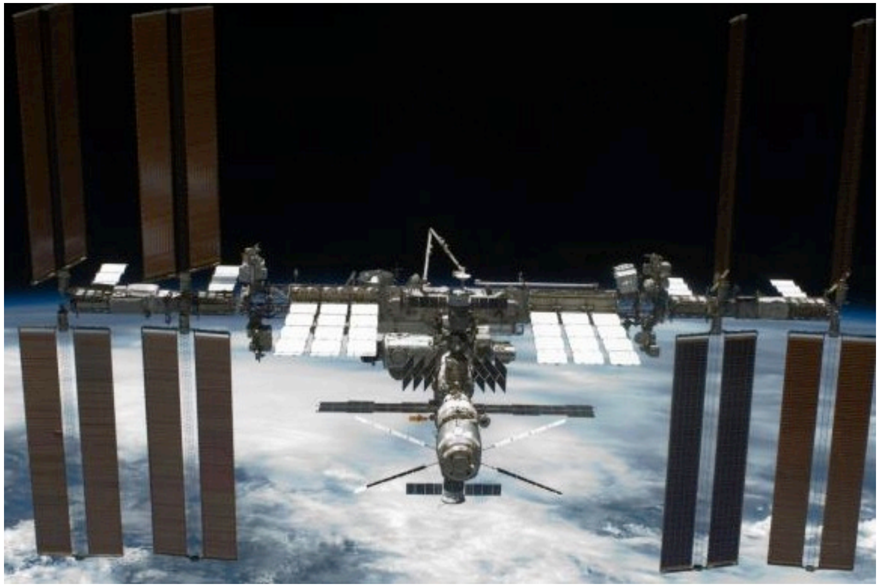






Anti-matter

The experimental challenge



DIRECT ≠ EASY **!**

No atmosphere: Stratospheric Balloons
Space

Limits on size and time: Detector design focused on specific measurements

Stratospheric Balloons: from few hrs to months

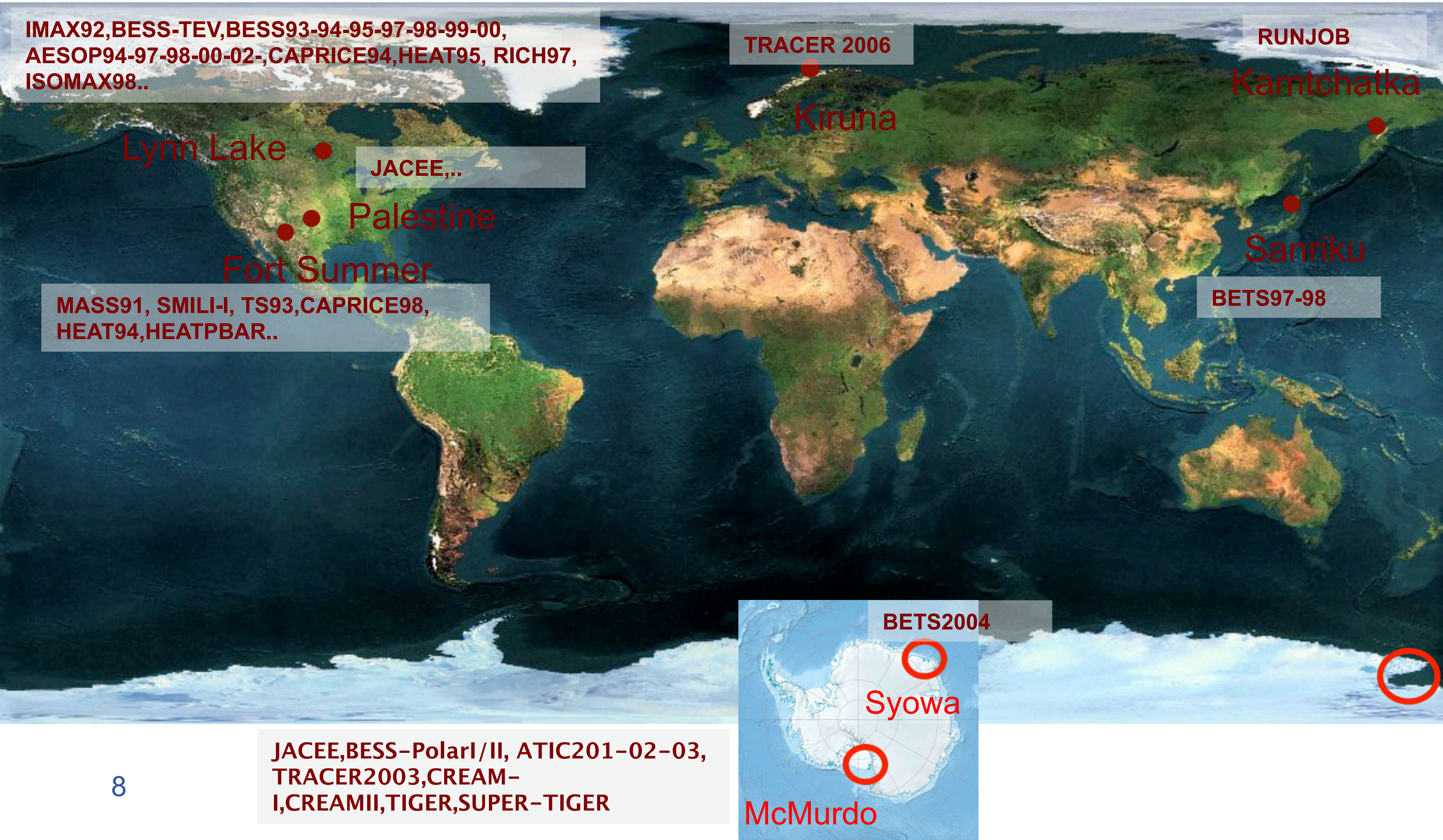
Magnetic Spectrometers

…

BESS/POLAR/TEV (9 Flights)
WIZARD (6,Flights)
HEAT/PBAR (4,Flights)

Calorimetry, TRD +..

RUNJOB (62 day, 10 Flights)
TRACER (18 days, 3 Flights)
CREAM (161 days,6 Flights)
ATIC (53 days, 3 Flights)
TIGER/S-TIGER (2/55 days)



IMAX92,BESS-TEV,BESS93-94-95-97-98-99-00, AESOP94-97-98-00-02-,CAPRICE94,HEAT95, RICH97, ISOMAX98..

JACEE,..

MASS91, SMILI-I, TS93,CAPRICE98, HEAT94,HEATPBAR..

TRACER 2006

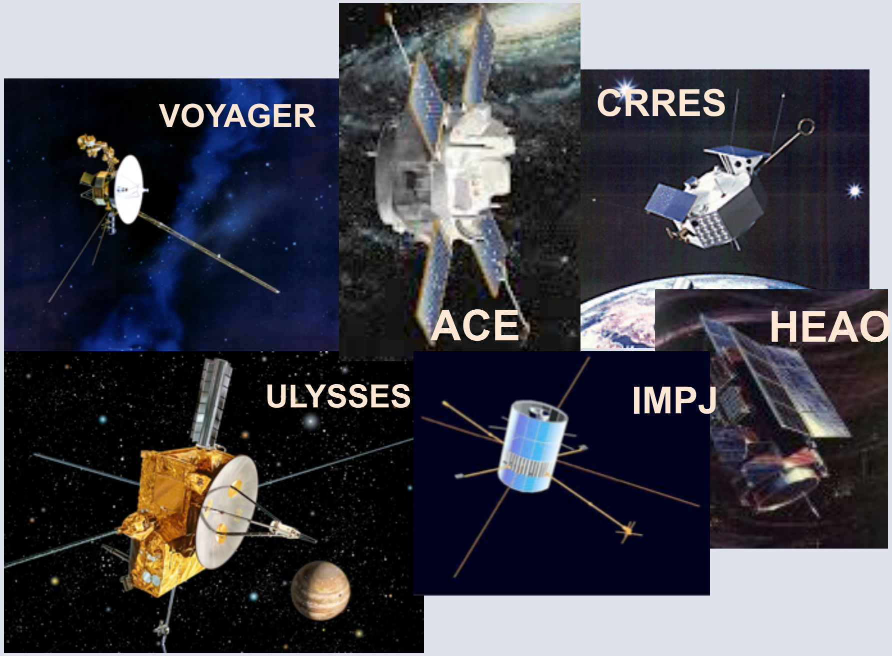
RUNJOB

BETS97-98

BETS2004

JACEE,BESS-PolarI/II, ATIC201-02-03, TRACER2003,CREAM-I,CREAMII,TIGER,SUPER-TIGER

Space:



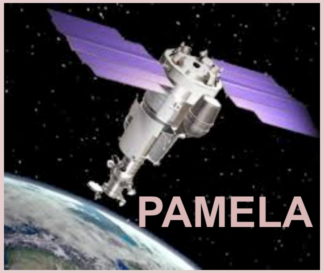
Long missions (years)
Small payloads
Low energies..

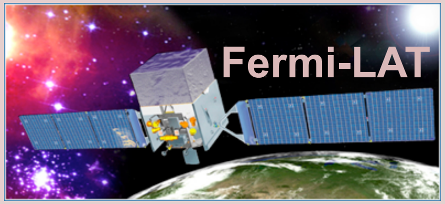
IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads

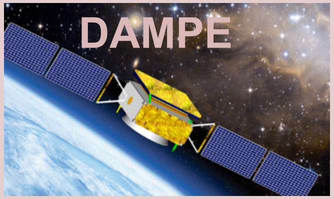
CRN on Challenger
(3.5 days 1985)

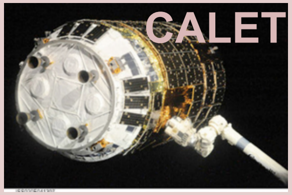
AMS-01 on Discovery
(8 days, 1998)

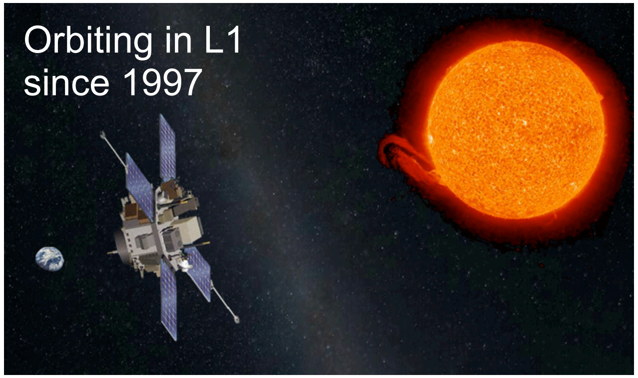




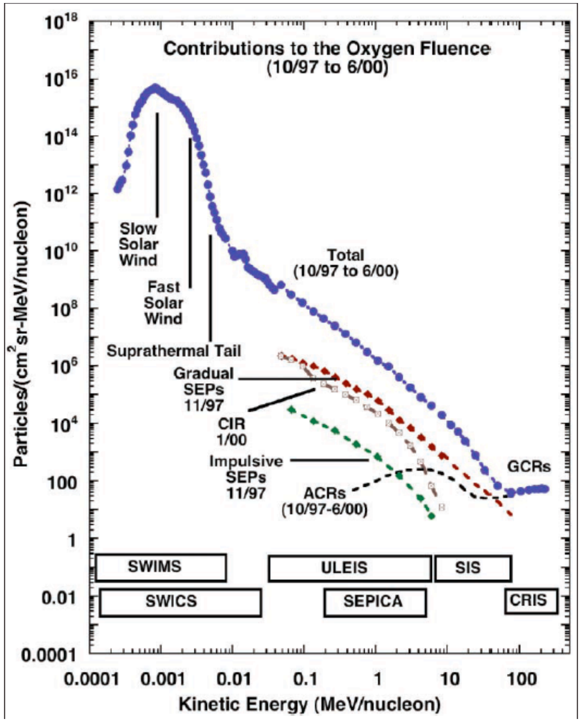
Long missions
Large payloads







Orbiting in L1
since 1997

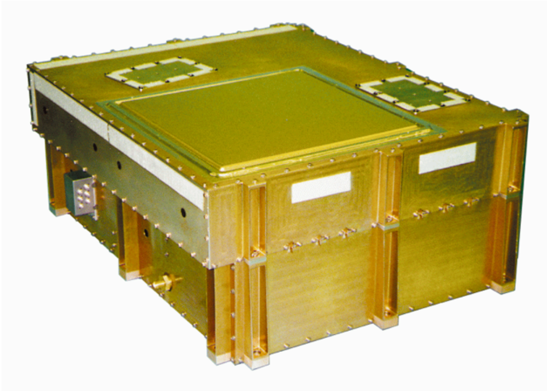


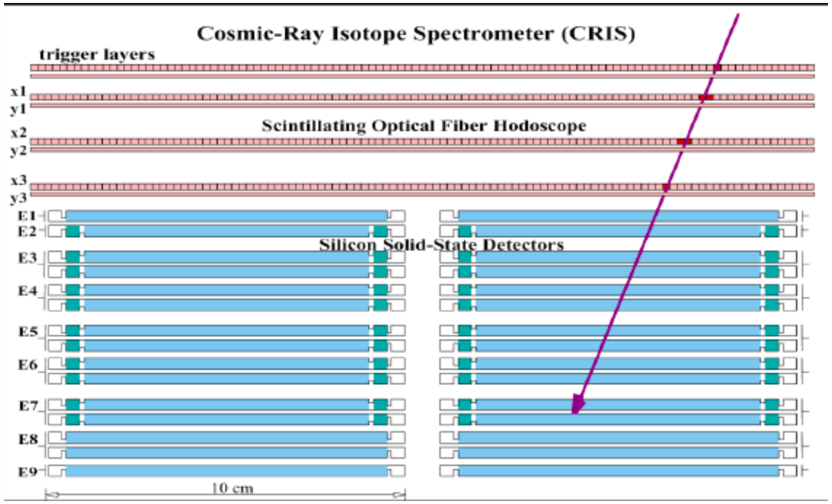
ACE/CRIS
&
Super Tiger

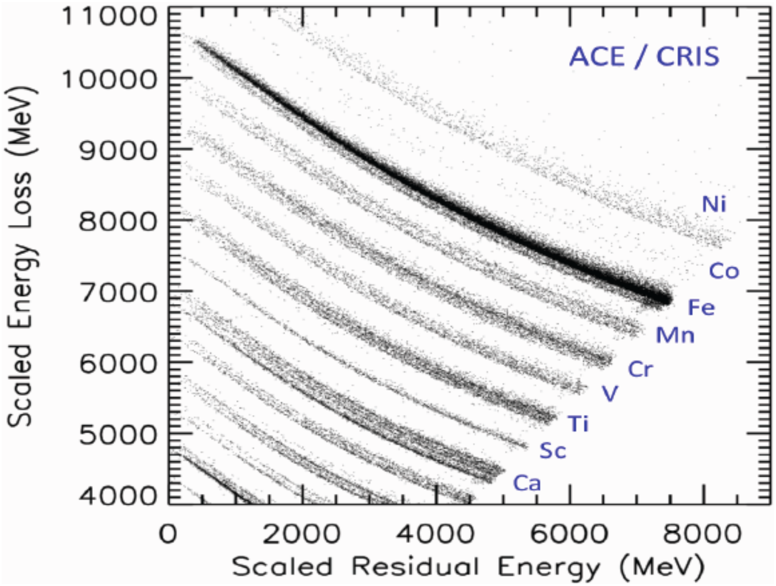
(or David and Goliath..)

ACE/Cosmic Ray Isotope Spectrometer (CRIS)

A ≈ 250 cm^2 sr instrument flying on the Advanced Composition Explorer since 1997 → ≈ 0.5 m^2 sr yr



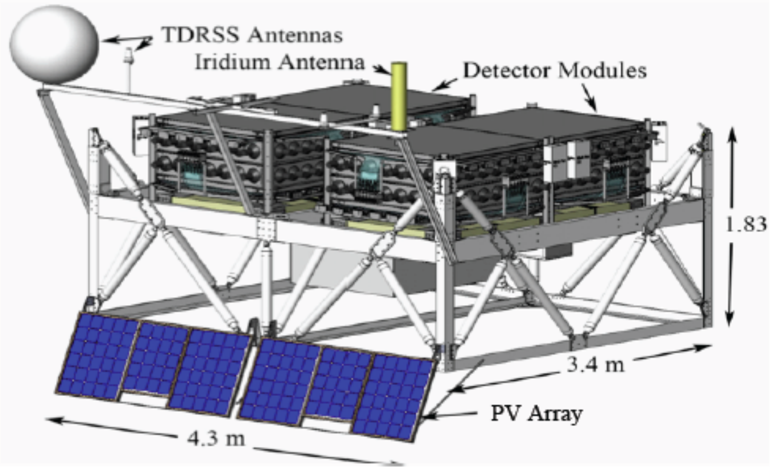


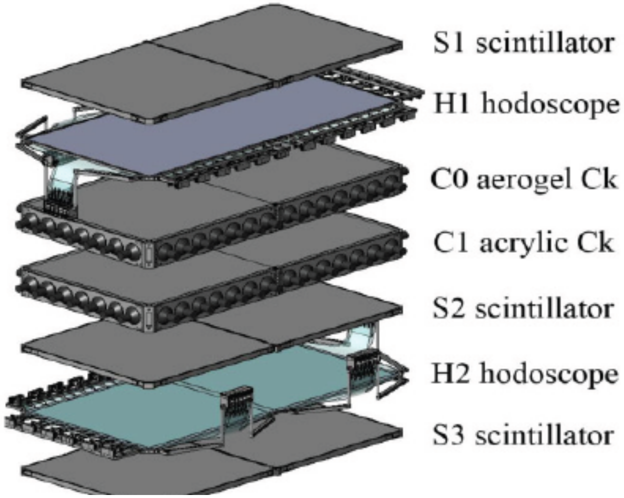


CRIS measures dE/dx and total energy of cosmic rays stopping in a stack of silicon solid-state detectors to determine the particles’ charge & mass.

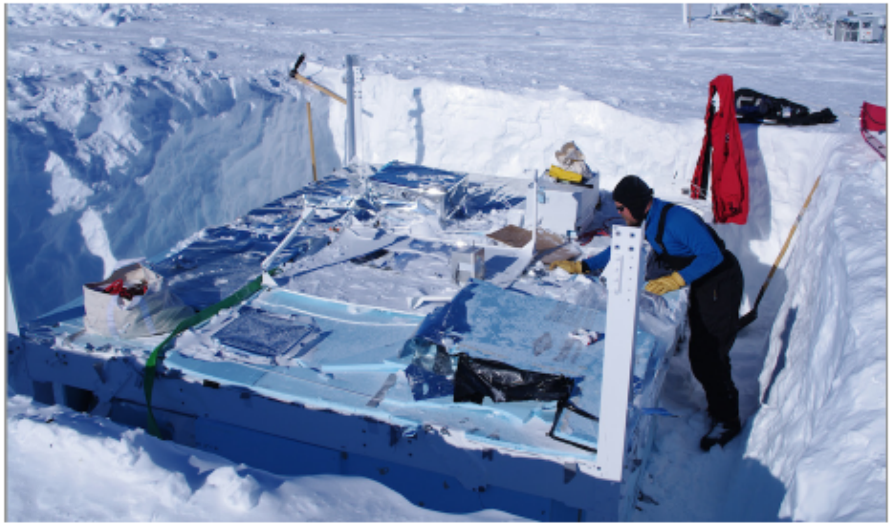
Super-TIGER : **T**rans-**I**ron **G**alactic **E**lement **R**ecorder

a balloon borne detector in polar flight for 55 days
Acceptance ≈ 8m^{2}sr : total exposure ≈ 1m^2 sr yr
E>0.8 GeV/nucleon



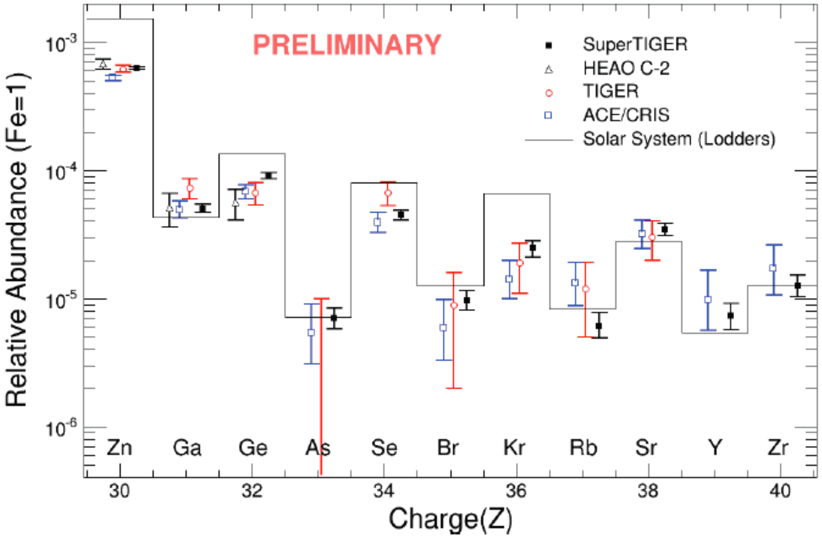


>2 years to recover it
...buried under 2 meters
of snow...

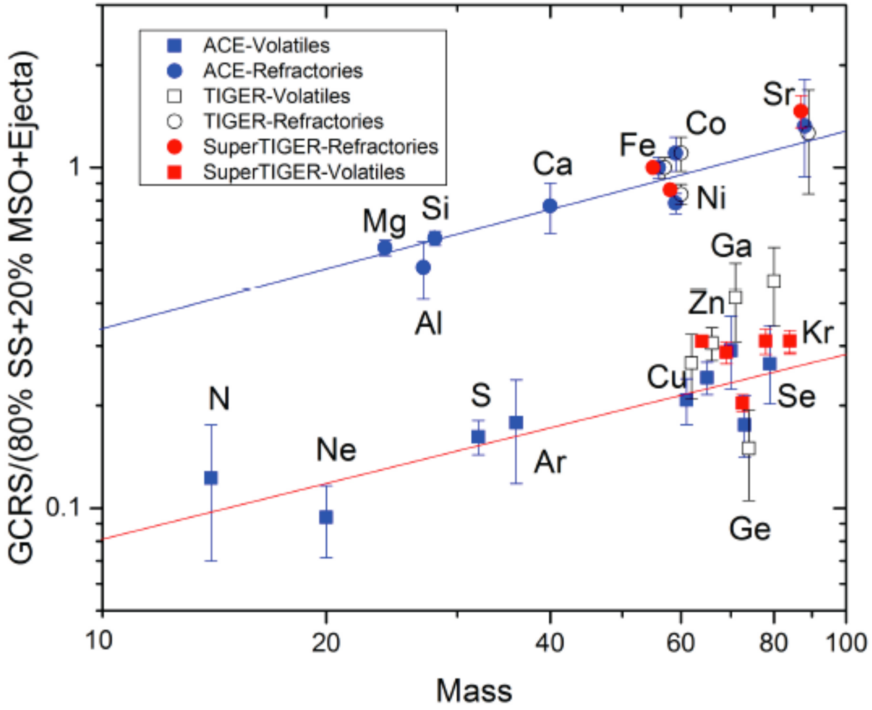


Question:
What is the source of the material that is accelerated and the mechanism for injecting that material into the cosmic-ray accelerator?

Stellar atmospheres (most abundant Low FIP vs High FIP abundances) vs interstellar dust (refractories & volatiles)



Elemental composition relative to Fe...

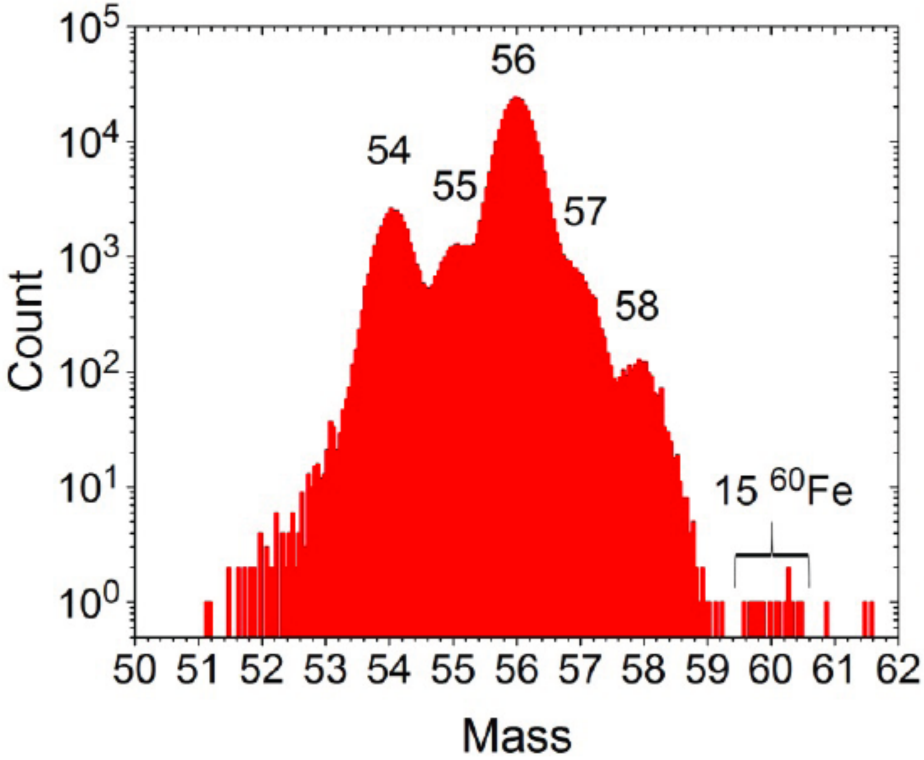


Elemental ratios wrt to a:
20% massive stars /ejecta 80% SS
refractory elements are accelerated most efficiently...

More info from radioactive Fe isotopes measurement in CRIS;

295 K of ^{56}Fe
15 ^{60}Fe (half-life 2.62 Myr)

^{60}Fe/^{56} Fe :
near earth = (4.4±1.6) 10^{-5}
@ acceleration (0.8±0.3)10^{-4}



≤ 10 Myr between nucleosynthesis & acceleration
> 10^5 yr from the lack of ^{59}Ni in CR

CRs are not accelerated by the same SN in which are synthetized but must take place in regions, like OB associations, where two nearby supernovae in few Myr.

Anti-matter?

Z>1
positrons (and electrons)
anti-protons

Baryogenesis: a long standing question..

"..*We must regard it as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons*.."
P.Dirac, Nobel Lecture 1933

Sakharov way to an asymmetric universe...

Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe
A. D. Sakharov, 1967 (Pis'ma Zh. Eksp. Teor. Fis. 5, 32-35, JETP Lett 5, 24-27)

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (**C asymmetry**).

In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (**baryonic asymmetry**).

We wish to point out a possible explanation of C asymmetry in the hot model of the expanding universe by making use of effects **of CP invariance violation** [2].
…

The quest for primordial antimatter

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

1) β is constant and the universe is 100% matter dominated
2) The universe is globally baryo-symmetric

Thus, we have ruled out a B = 0 universe with domains smaller than a size comparable to that of the visible universe. It follows that the detection of Z > 1 antinuclei among cosmic rays would shatter our current understanding of cosmology, or reveal something unforeseen in the realm of astrophysical objects.

Cohen, De Rujula, Glashow Astrophys.J.495:539-549,1998

3) The universe has non-vanishing average baryonic charge, but β is not spatially constant....in other words there could be lumps of antimatter in a matter dominated universe.

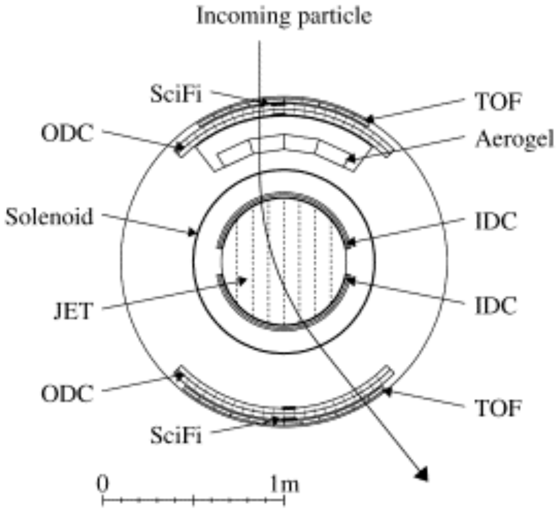
→ **Anti-nuclei from anti-stars**

$$\frac{N_{\bar{S}}}{N_S} \lesssim \left(\frac{\overline{\mathrm{He}}}{\mathrm{He}}\right)_{\mathrm{ES}}$$

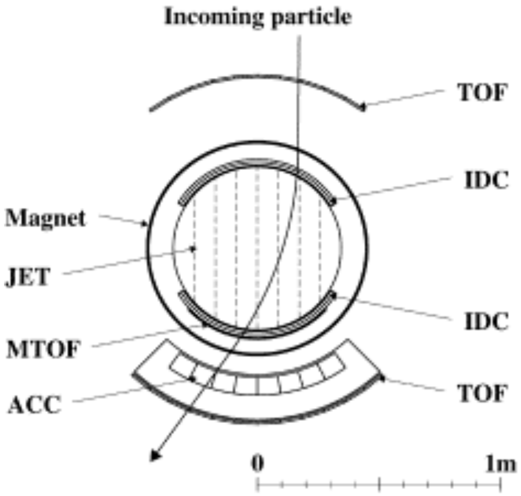
C.Bambi, A.D. Dolgov, Nuclear Phys. B 784 (2007) 132-150

Balloon borne Experiment with Superconducting Spectrometer BESS: 9 flights between 1993 and 2004

- large solenoidal thin-wall superconducting magnet: 0.3 m^{2}sr, 0.8 T
- a time-of-flight system of scintillation counter hodoscopes
- inner drift chambers (IDC)
- a jet-type drift particle-tracking chamber
- outer drift chambers / aerogel Cherenkov counter depending on the configuration

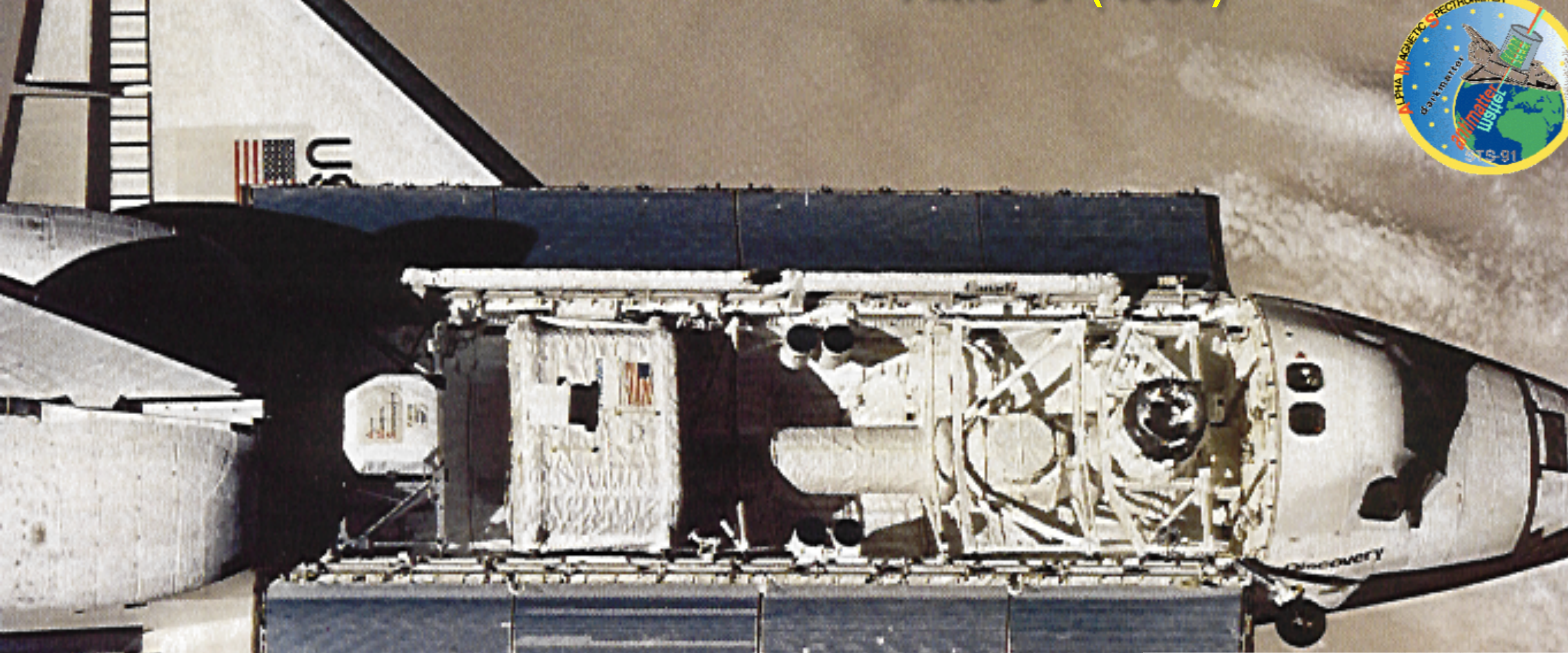


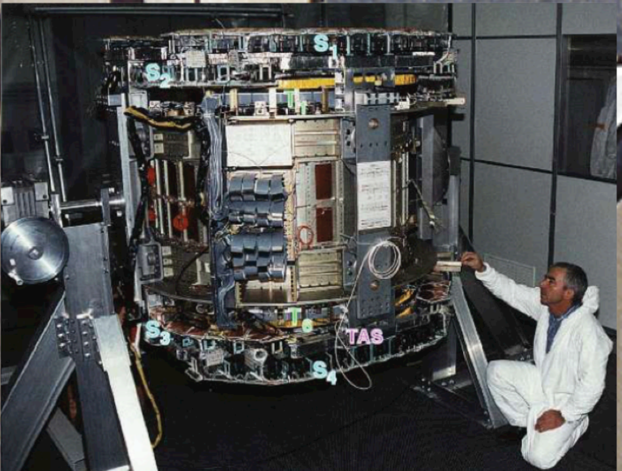
BESS-TeV
MDR 1.4 TV

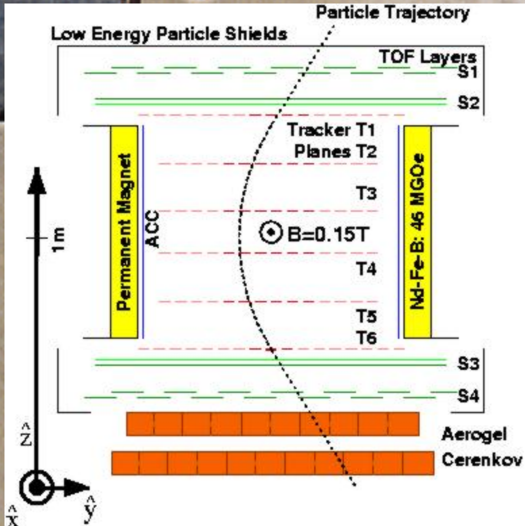


BESS-Polar
MDR 240 GV

Alpha Magnetic Spectrometer on STS-91
AMS-01 (1998)



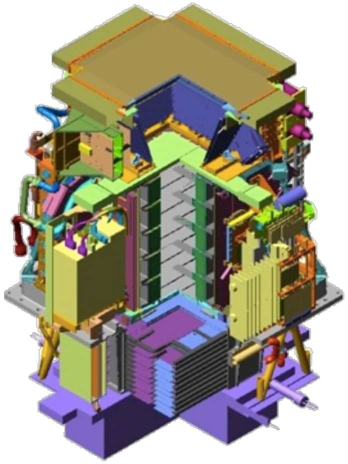


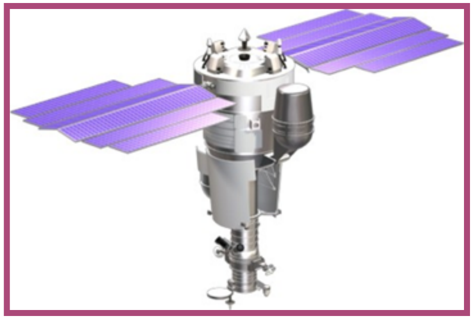


Payload for **M**atter/Antimatter **E**xploration and **L**ight nuclei **A**strophysics - **PAMELA**

→ Launched on 15th June 2006
→ PAMELA in continuous data-taking mode for 10 years

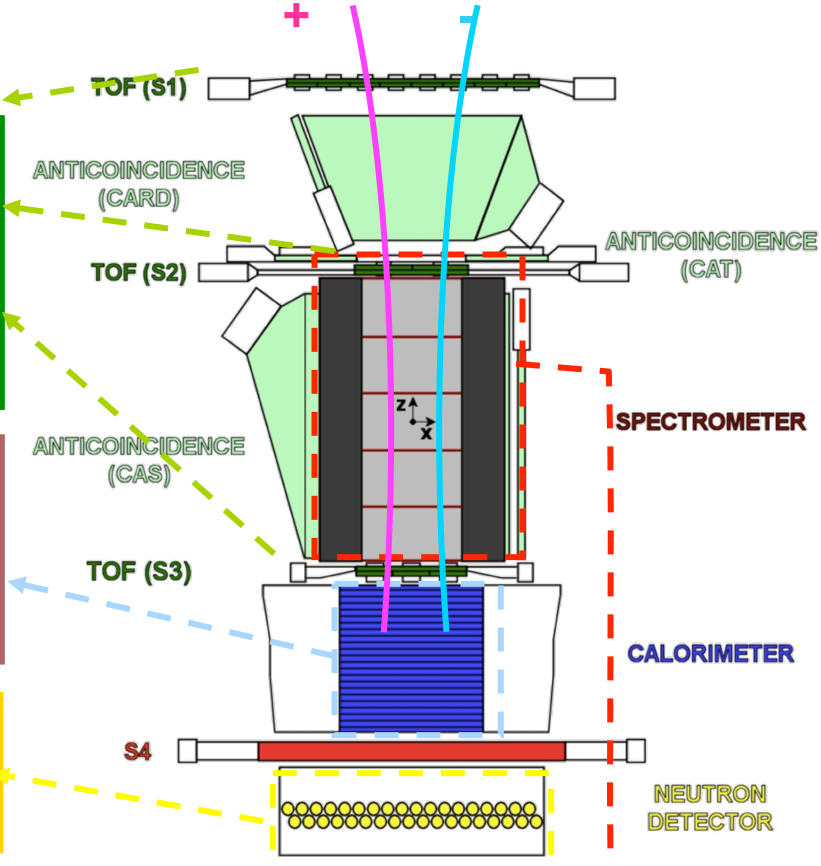

Launch from Baykonur





- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~70^o (⇒ low energy)
  - altitude ~ 360-600 km (elliptical)
  - active life >3 years (⇒ high statistics)

The detector



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

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e^+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
36 He^3 counters :
- High-energy e/h discrimination

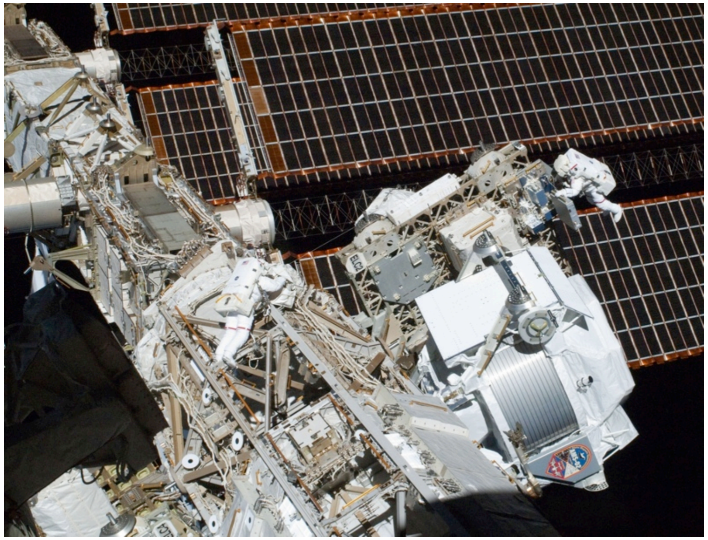
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze MDR≈1(0.25) TV
- *Charge sign*
- *Charge value from dE/dx*

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

Alpha Magnetic Spectrometer on the ISS: AMS-02

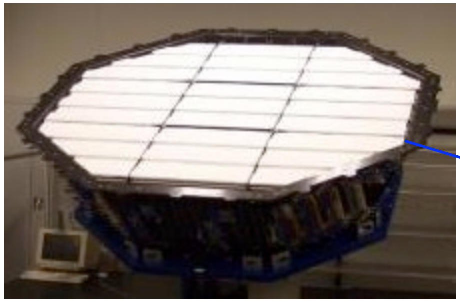
- → Launched on May 16, 2011
- → Installed on ISS May 19, 2011
- → AMS-02 foreseen to operate for the entire ISS lifetime

5m x 4m x 3m
7.5 tons
GF ≈ 0.5 m^2sr



AMS-02: the detector

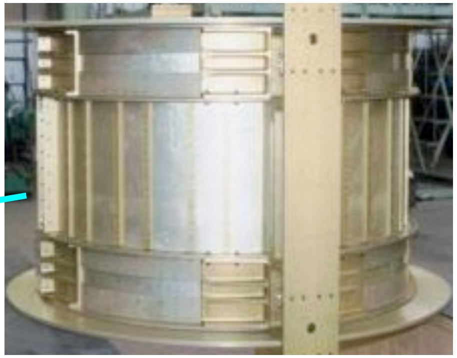
Transition Radiation Detector
Identify electrons



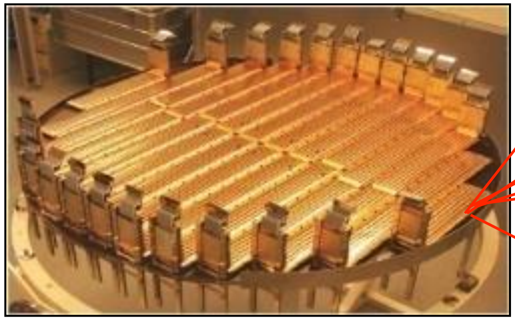
Particles are defined by their charge (Z) and energy (E) or momentum (P)

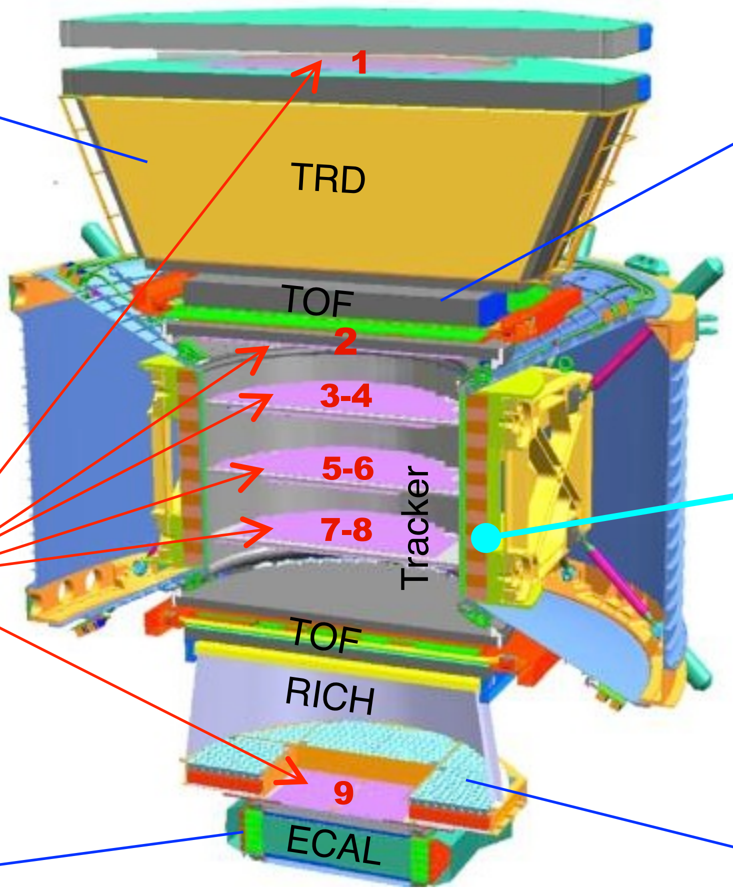
Time of Flight
Z, E

Magnet
±Z



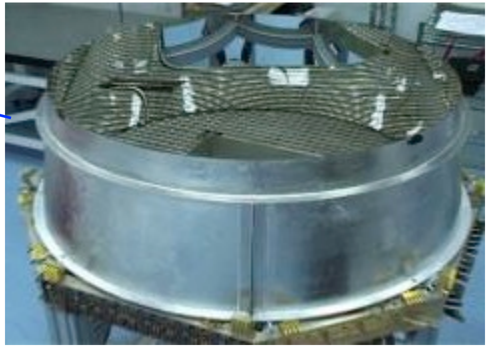
Silicon Tracker
Z, P





Electromagnetic Calorimeter
E of electrons

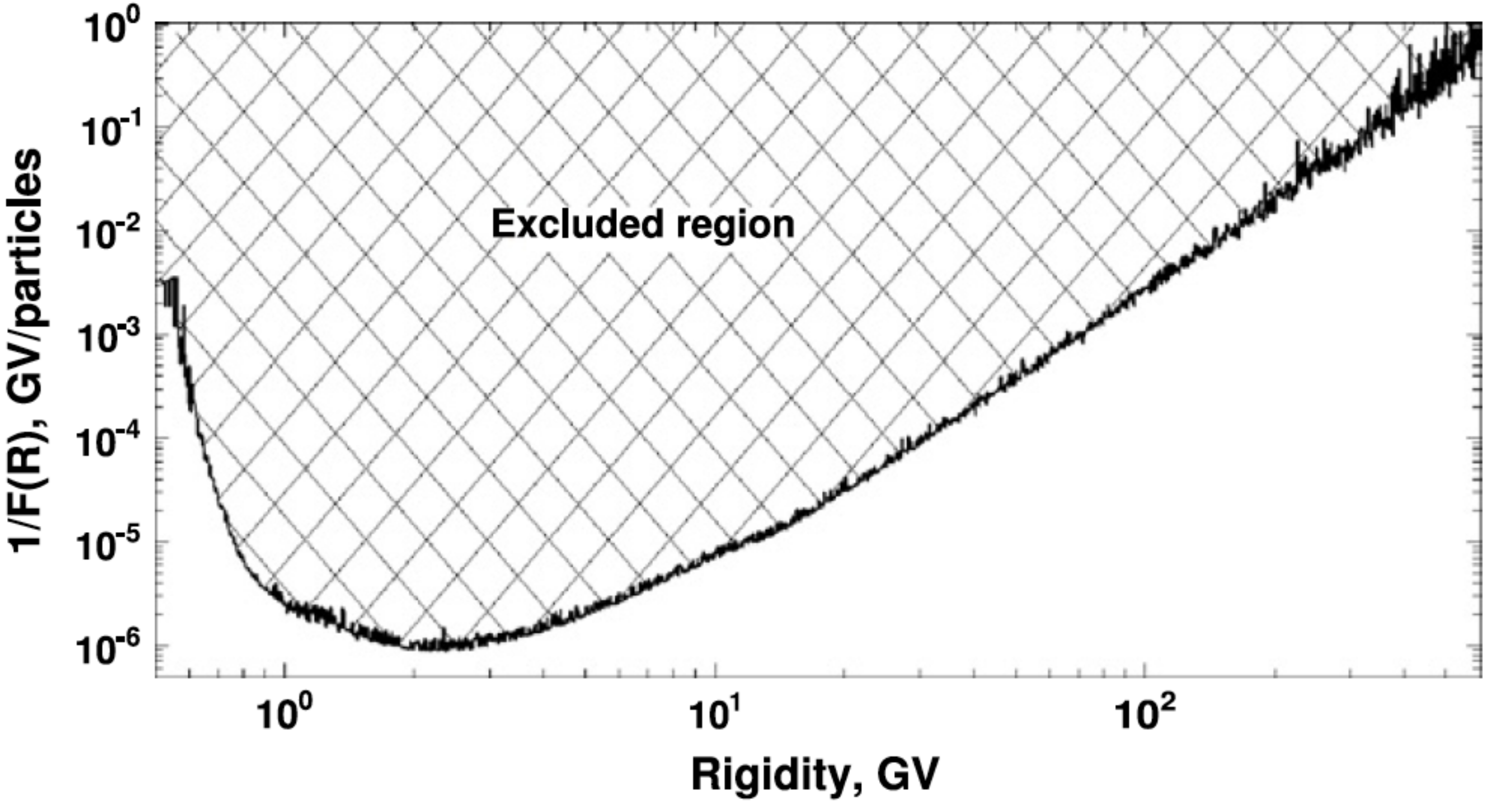
Ring Imaging Cherenkov
Z, E



The Charge and Energy (momentum) are measured independently by many detectors

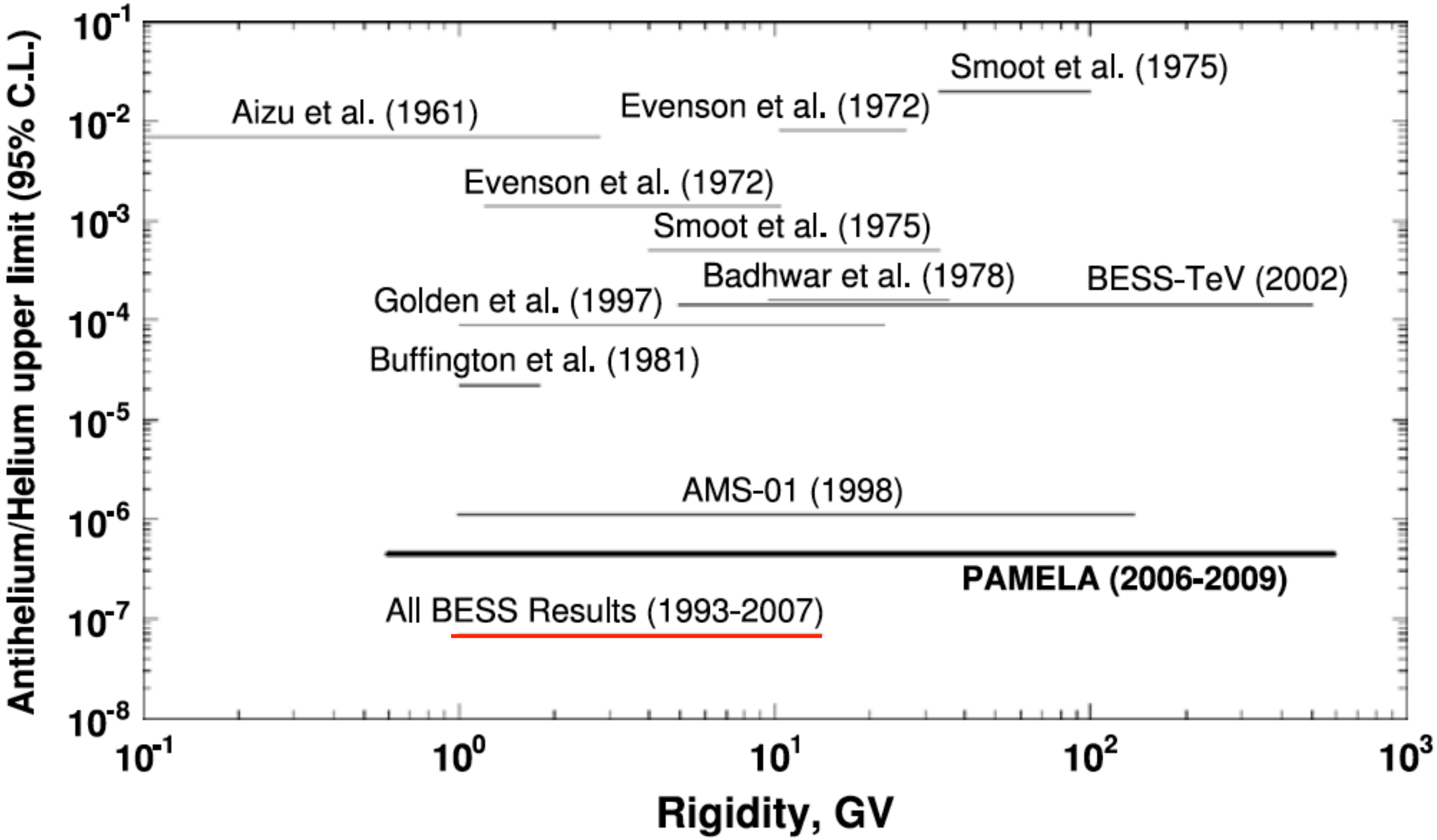
Anti-He/He

differential upper limit with 6.3 M He events collected in PAMELA



$$\frac{N_{\overline{\mathrm{He}}}(R_i; R_f)}{N_{\mathrm{He}}(R_i; R_f)} < \frac{3}{\int_{R_i}^{R_f} F(R)dR} = \frac{3}{\int_{R_i}^{R_f} \frac{dN'_{\mathrm{He}}(R)}{dR} dR} \cdot \frac{\epsilon_{\mathrm{He}}(R_i; R_f)}{\epsilon_{\overline{\mathrm{He}}}(R_i; R_f)},$$

Anti-He/He



Waiting for AMS-02 ......

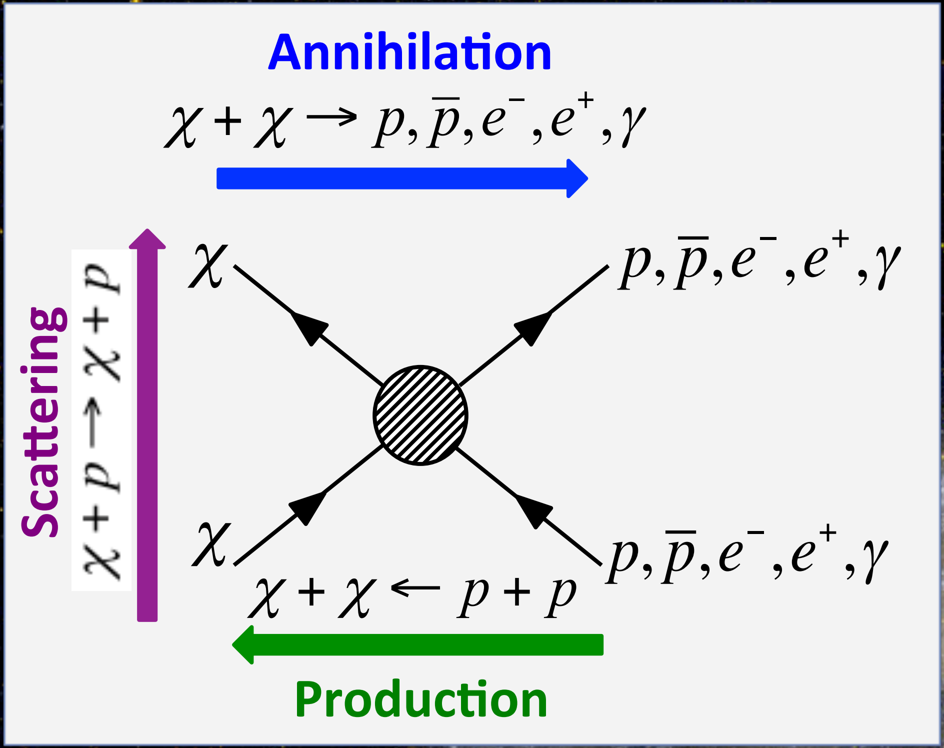
Anti-matter?

Z>1 Anti-matter

positrons (and electrons)

anti-protons

The quest for Dark Matter



Annihilation

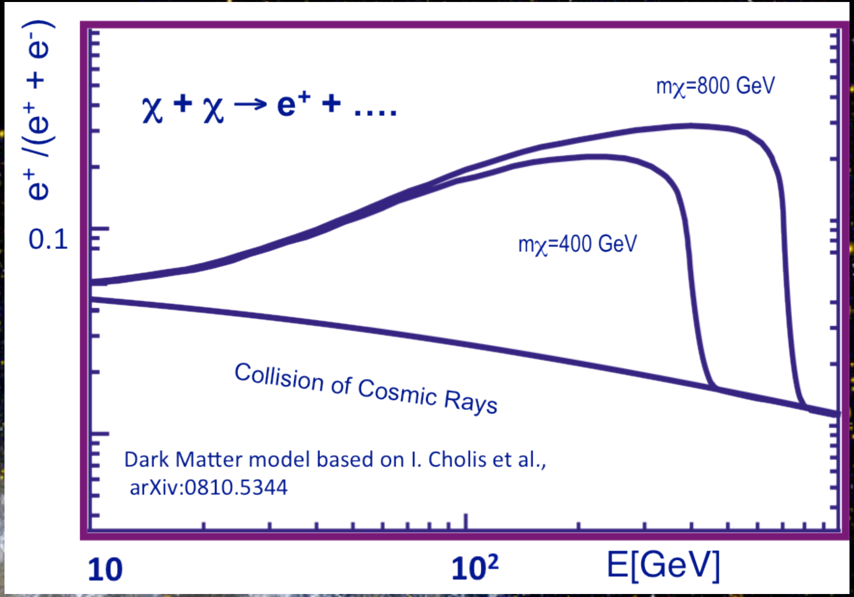
$\chi + \chi \rightarrow p, \bar{p}, e^-, e^+, \gamma$

Scattering

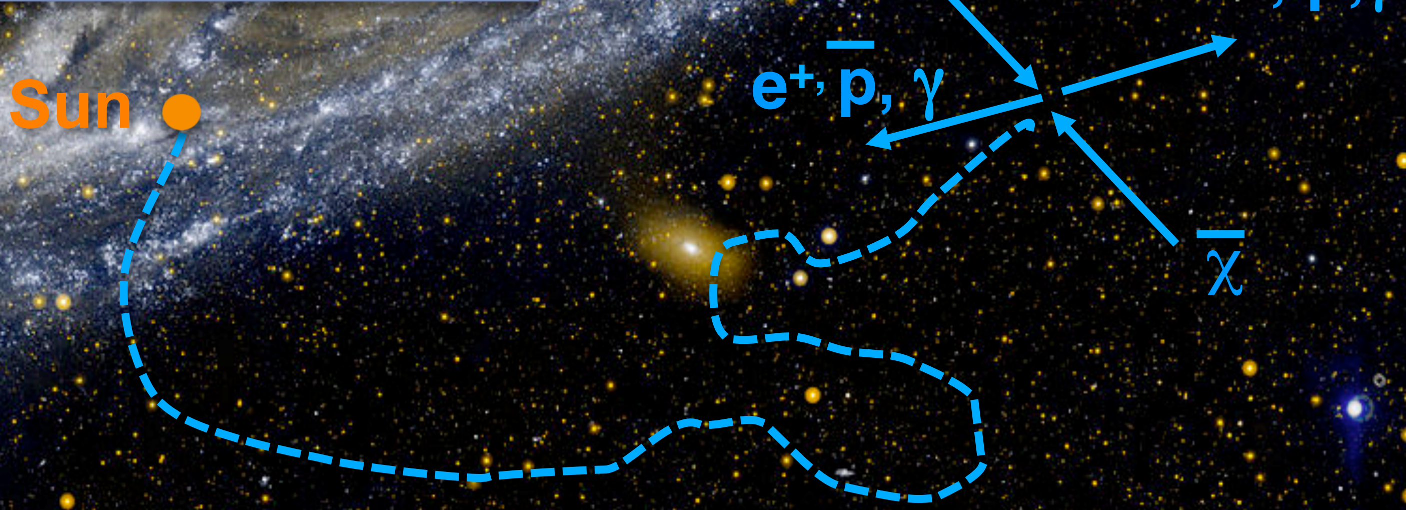
$\chi + p \rightarrow \chi + p$

$\chi + \chi \leftarrow p + p$

Production

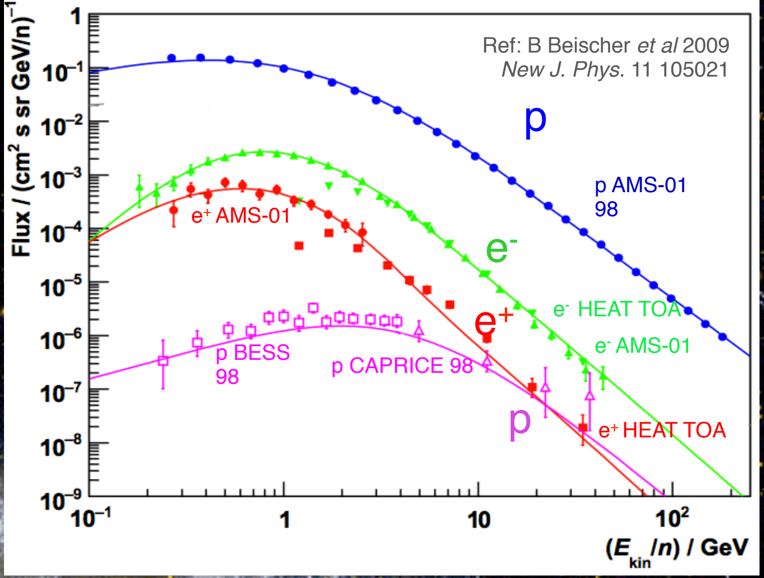


Dark Matter model based on I. Cholis et al., arXiv:0810.5344

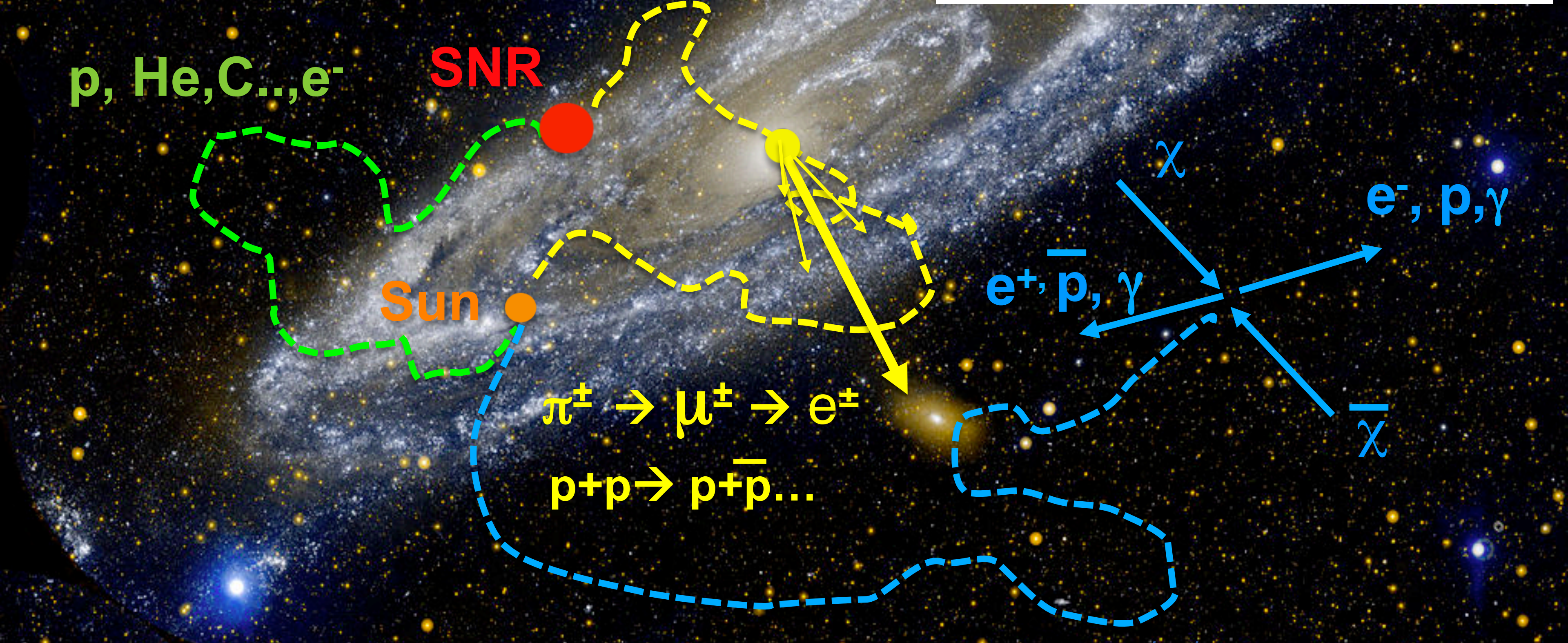


The Cosmic Background:

Origin, propagation and production of CRs and their secondaries



Ref: B Beischer *et al* 2009 *New J. Phys.* 11 105021



p, He,C..,e^-

SNR

Sun

$\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$

$p+p \rightarrow p+\bar{p}\ldots$

χ

e^-, p, γ

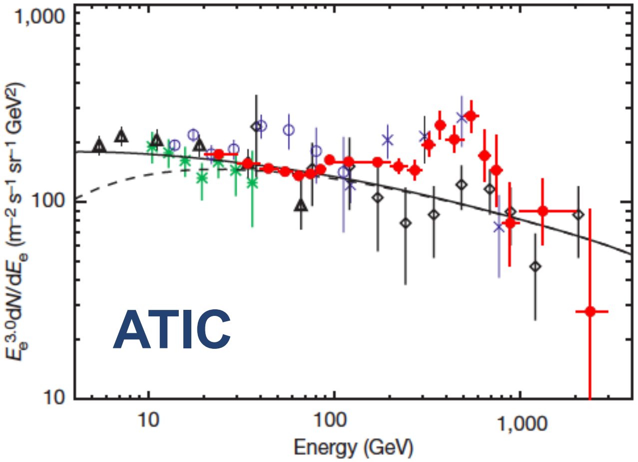
$e^+, \bar{p}, \gamma$

$\bar{\chi}$

2008-2009: the e^+/e^- puzzle

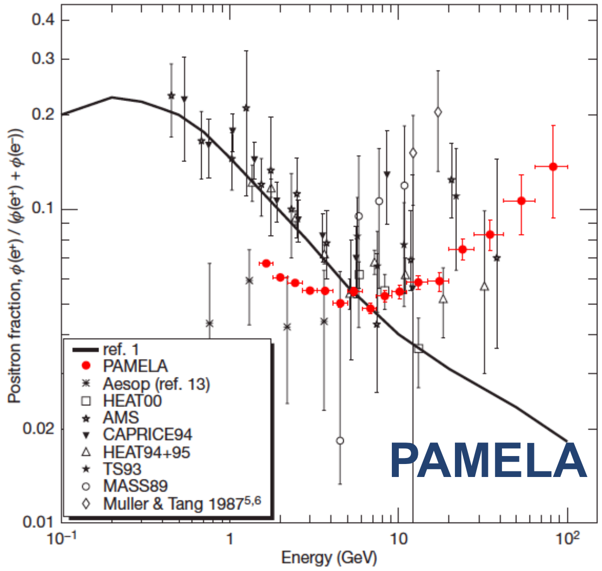
An excess of cosmic ray electrons at energies of 300–800 GeV

Vol 456|20 November 2008|**doi:10.1038/nature07477**



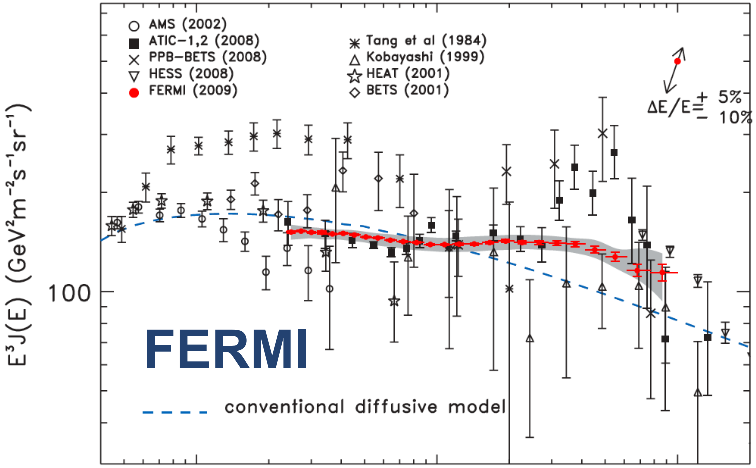
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

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



Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope

PRL **102,** 181101 (2009)

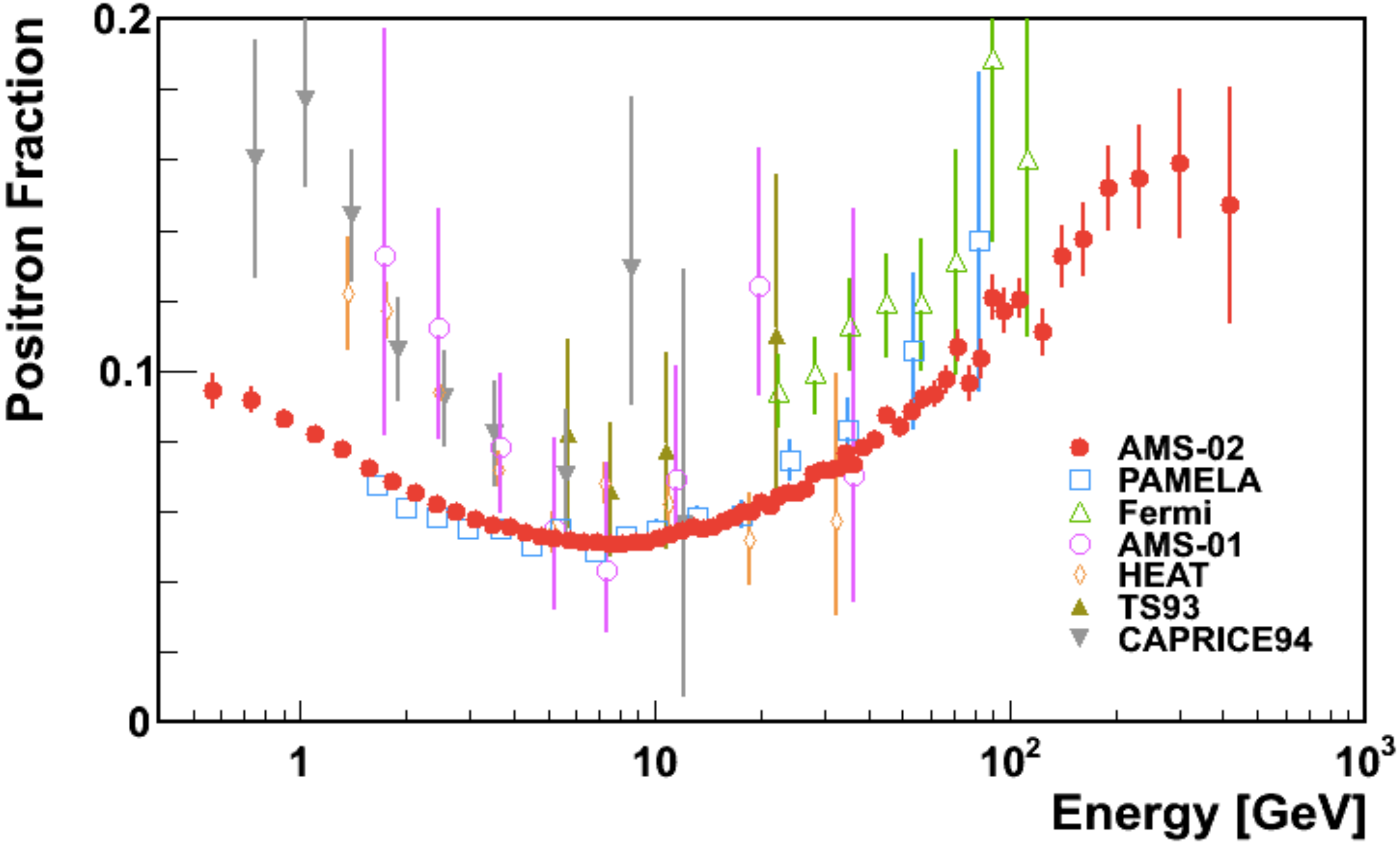


The actual status (not the end of the story)

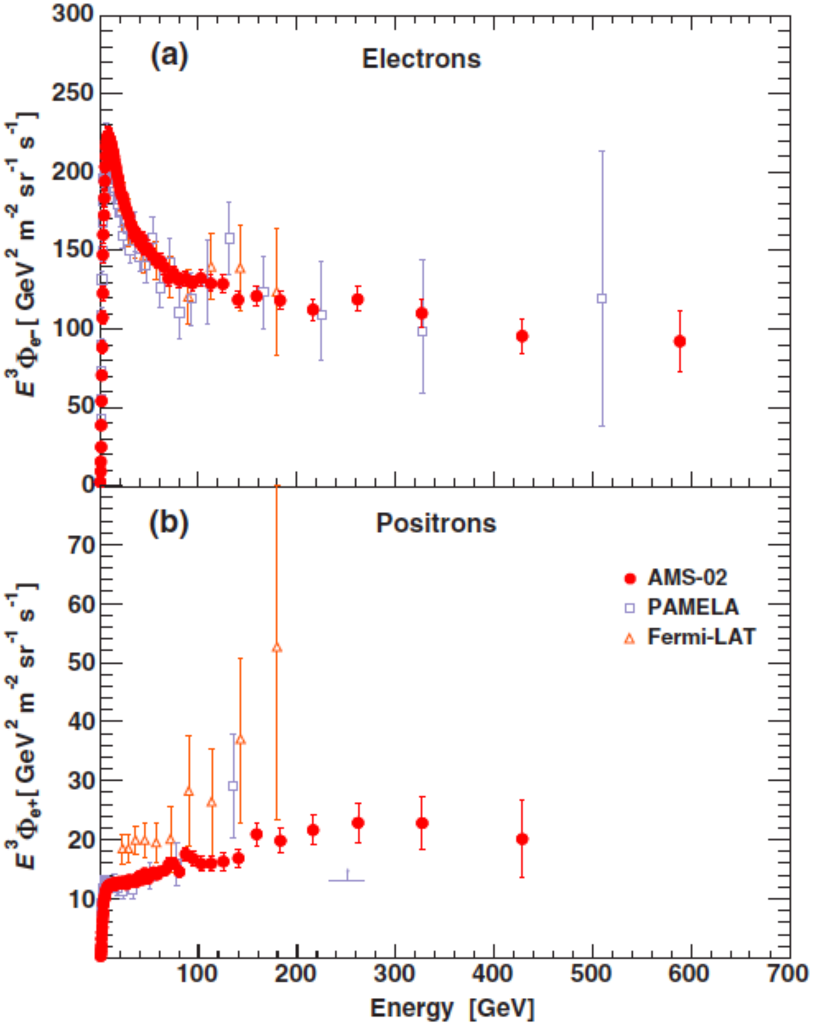
PRL **113,** 121101 (2014)   PHYSICAL REVIEW LETTERS   week ending
19 SEPTEMBER 2014

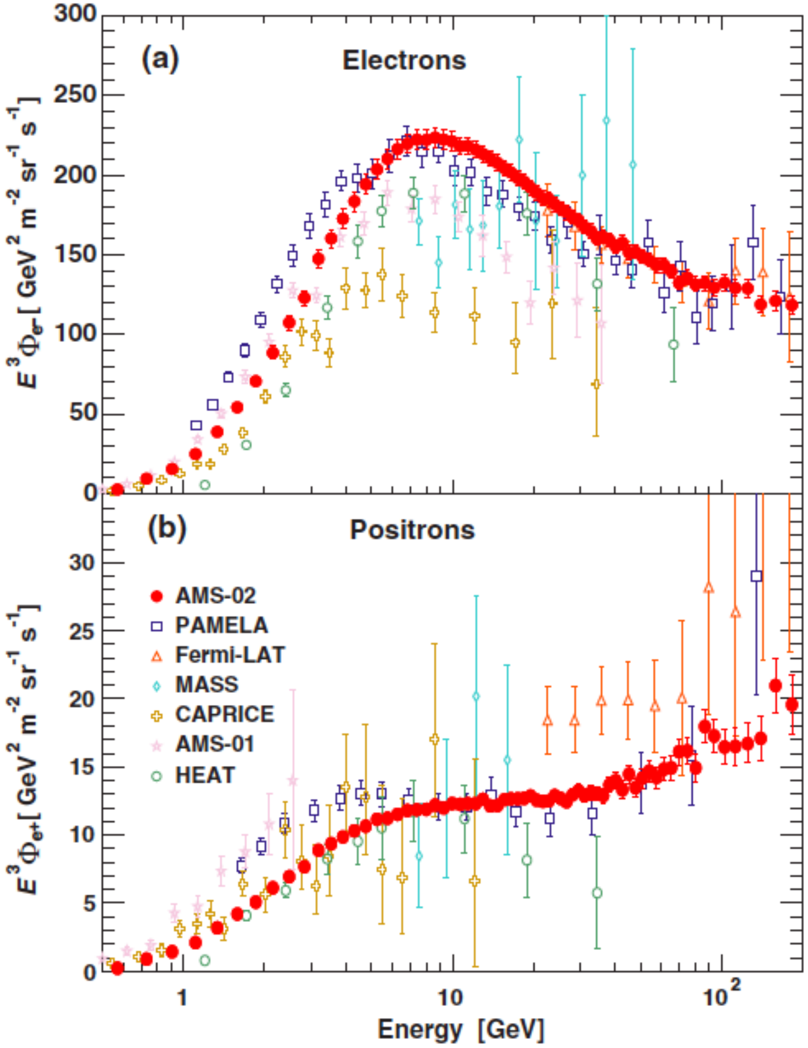
High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station

10.9 million e+ and e- events

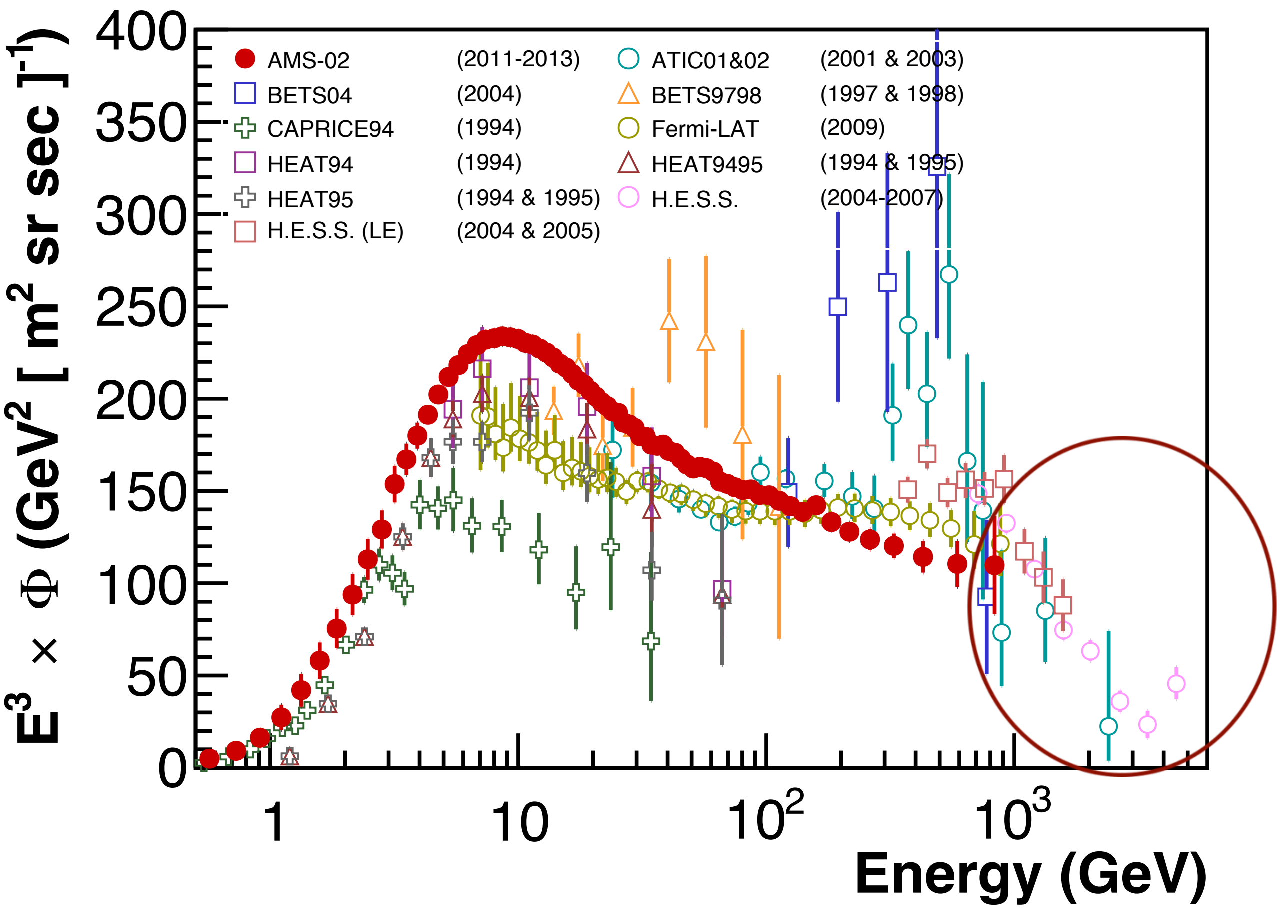


e+/e- fluxes


(a)
Electrons
(b)
Positrons
AMS-02
PAMELA
Fermi-LAT
$E^3\Phi_{e-}$[GeV^2 m^{-2} sr^{-1} s^{-1}]
$E^3\Phi_{e+}$[GeV^2 m^{-2} sr^{-1} s^{-1}]
0
50
100
150
200
250
300
10
20
30
40
50
60
70
100
200
300
400
500
600
700
Energy [GeV]


(a)
Electrons
(b)
Positrons
AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT
$E^3\Phi_{e-}$[GeV^2 m^{-2} sr^{-1} s^{-1}]
$E^3\Phi_{e+}$[GeV^2 m^{-2} sr^{-1} s^{-1}]
0
50
100
150
200
250
300
0
5
10
15
20
25
30
1
10
10^2
Energy [GeV]

$e^+ + e^-$ fluxes



Waiting for new results from:

- + Fermi
- + AMS
- + CALET
- + DAMPE

Anti-protons?

Z>1 Anti-matter

positrons (and electrons)

anti-protons

Anti-proton/proton : the early times (1984)

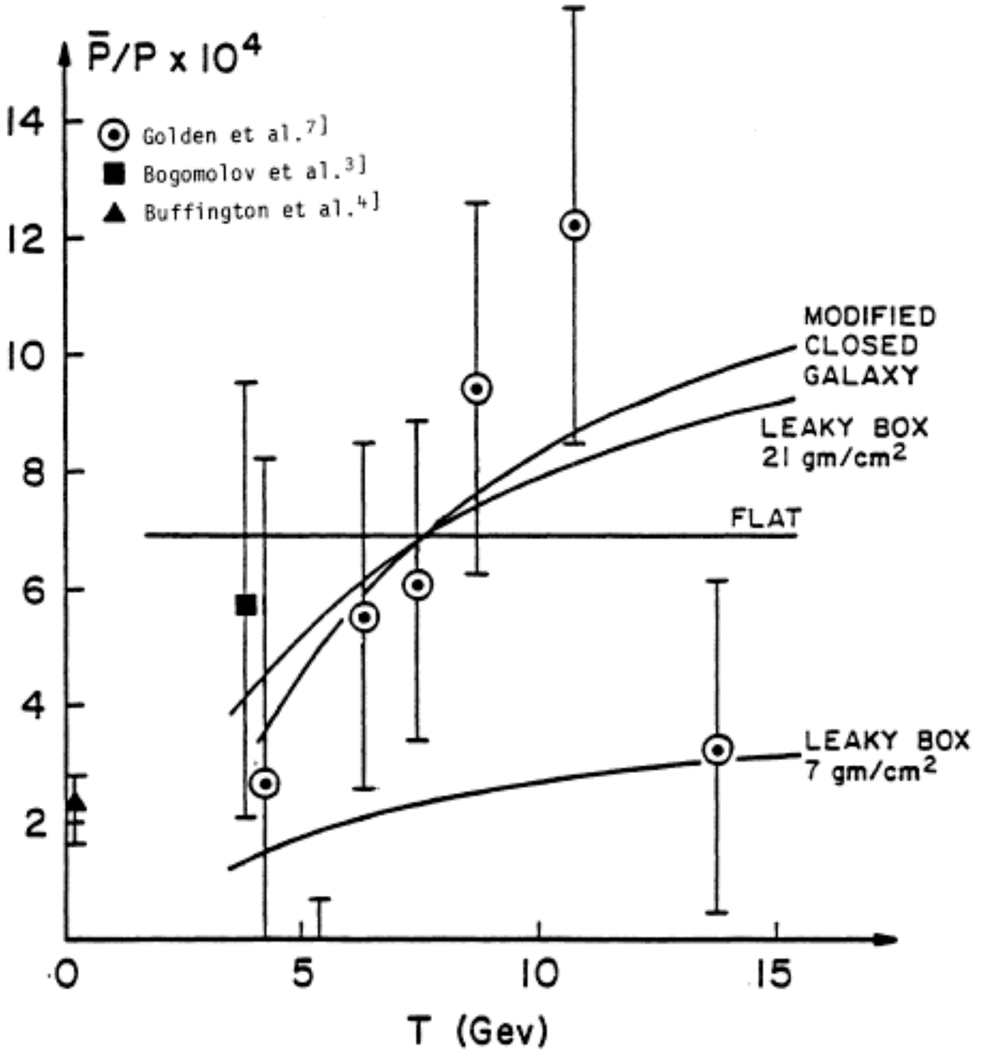
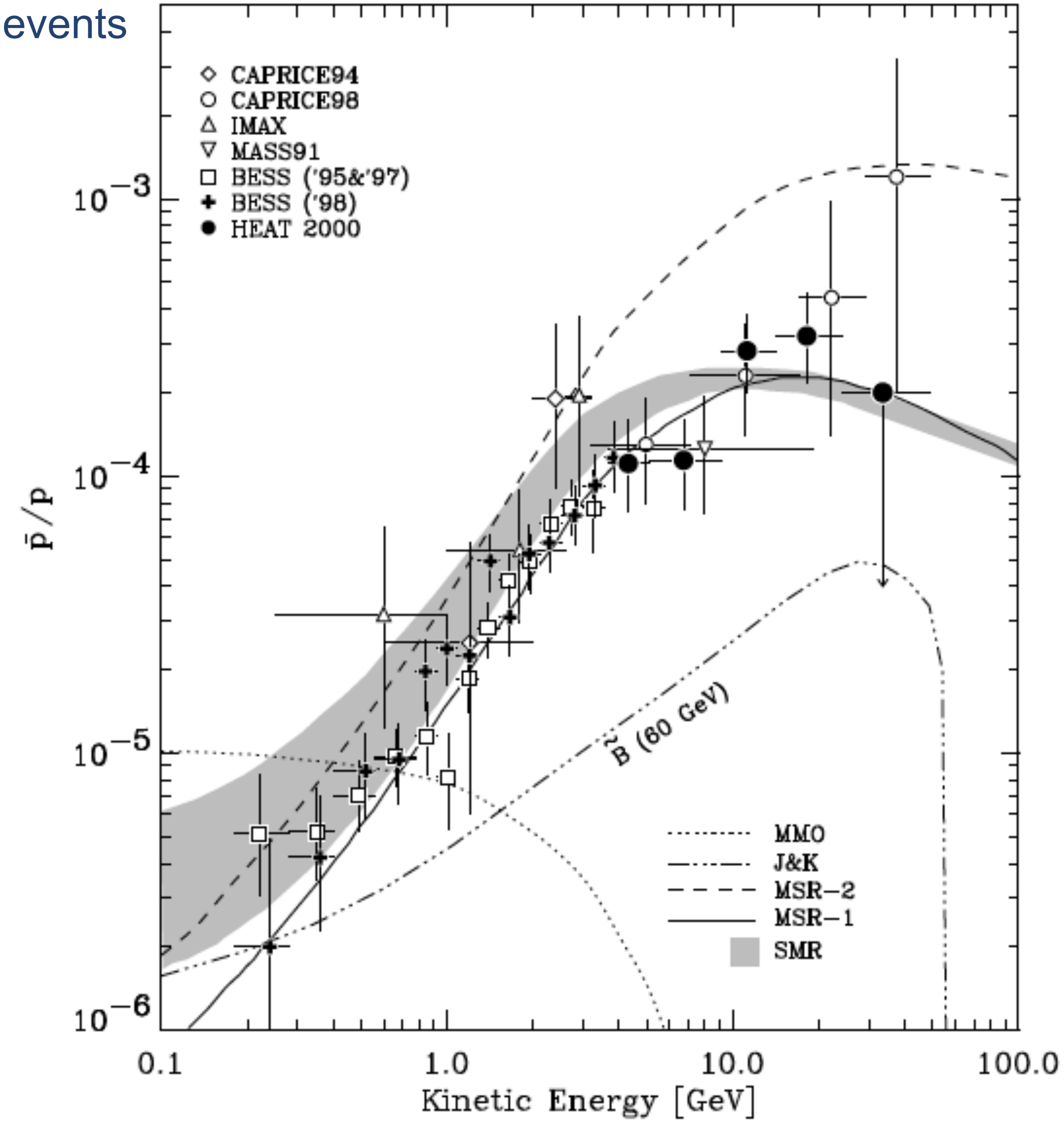


Figure 1. Antiproton Observations and Predictions

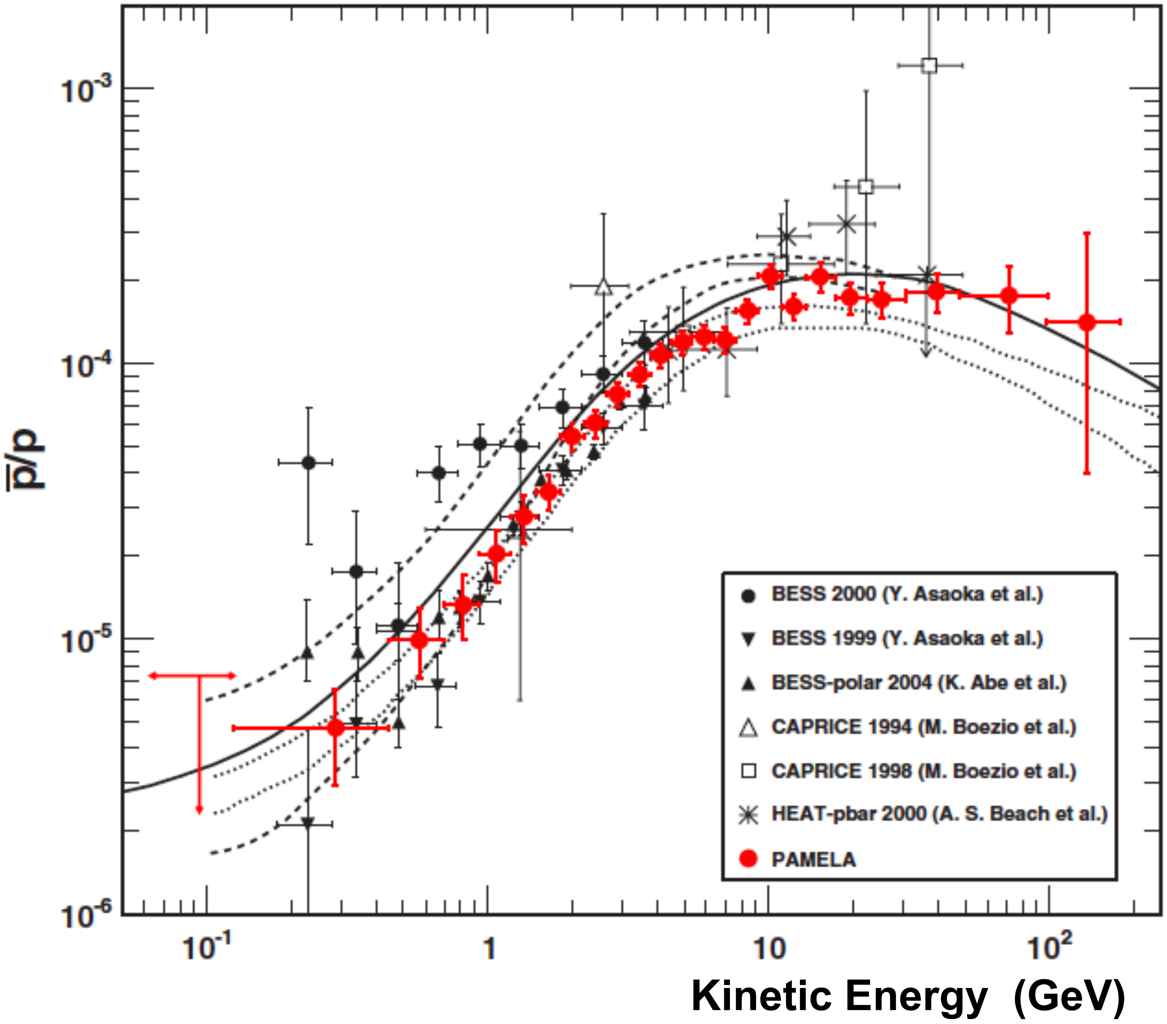
Anti-proton/proton : 2001

HEAT ≈ 70 events
CAPRICE ≈ 31 events

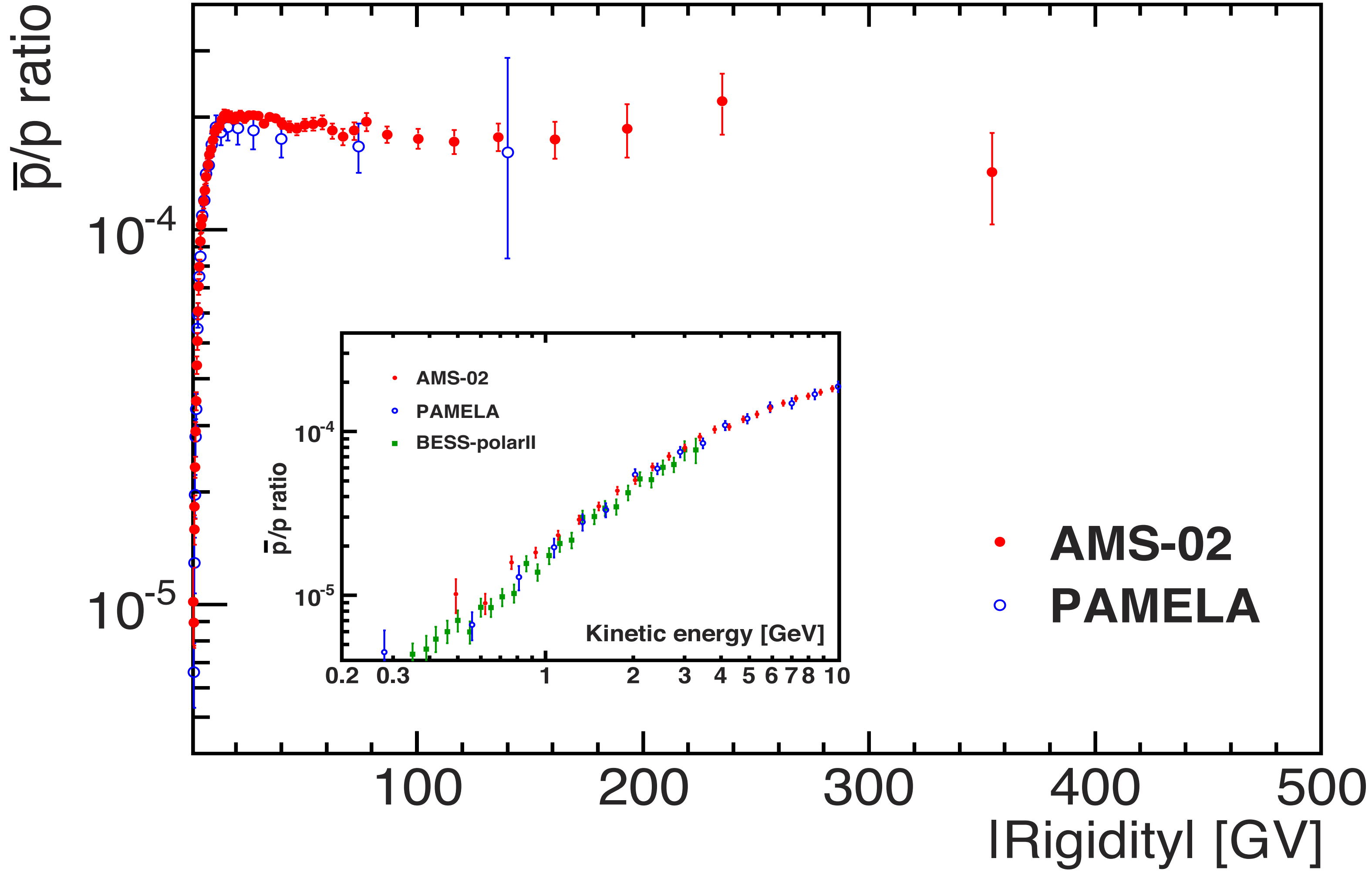


Anti-proton/proton : 2010

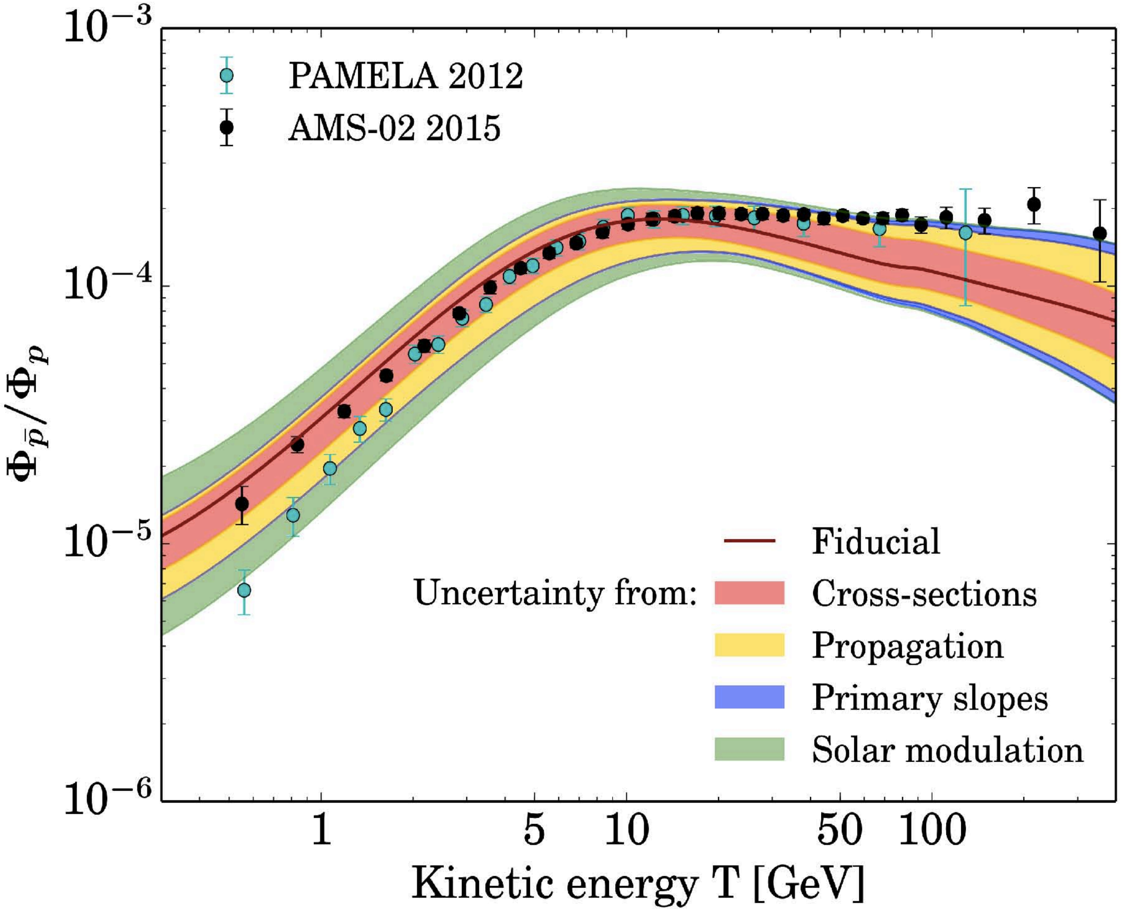
BESS-POLAR (2004) ≈ 1520 event < 4.2 GeV
PAMELA (2006-2009) ≈ 1500 events



Anti-protons: 2016

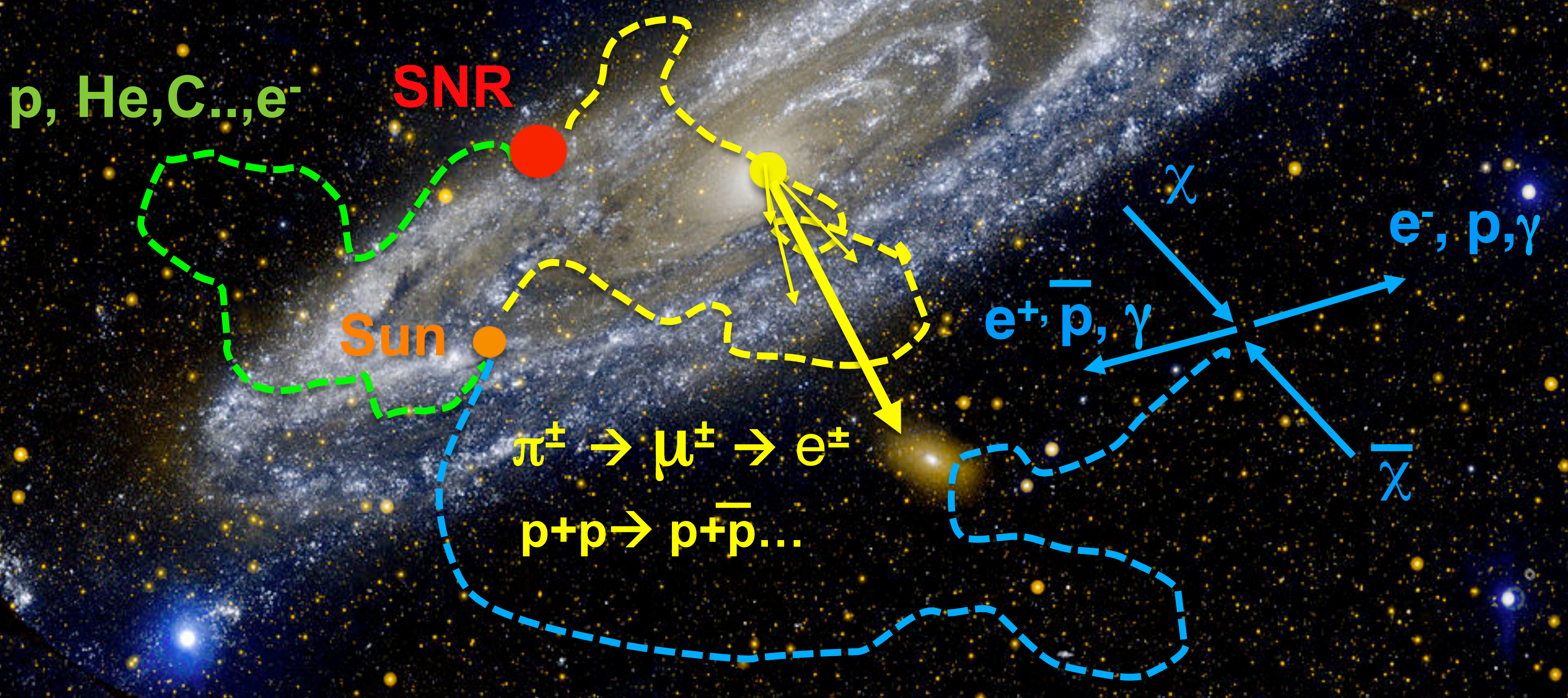


The accuracy of the latest measurement challenges current knowledge of cosmic background !



The Cosmic Ray background..

- ✓ Origin, acceleration
- ✓ propagation & ISM
- ✓ the Sun/Earth effects...



p, He,C..,e^-

SNR

Sun

$\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$

$p+p \rightarrow p+\bar{p}$…

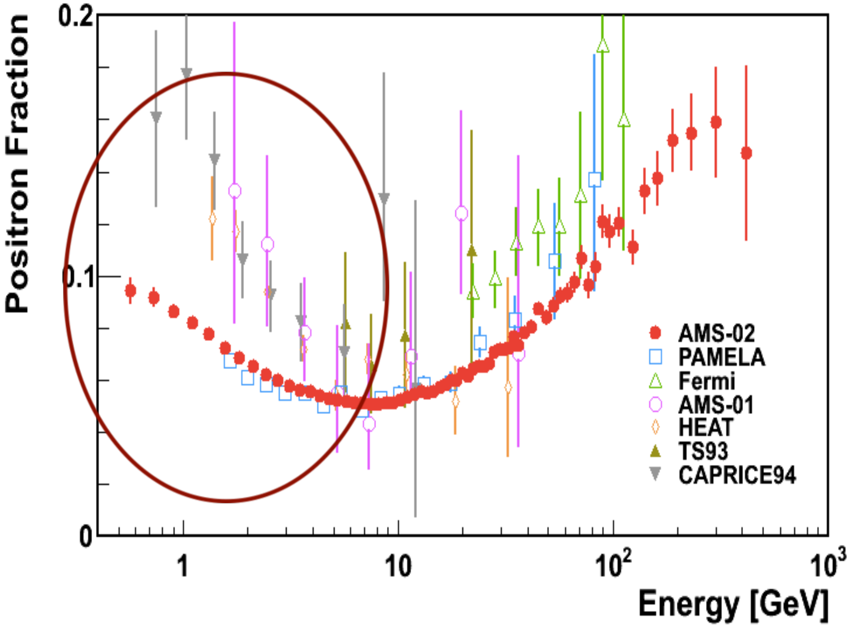
χ

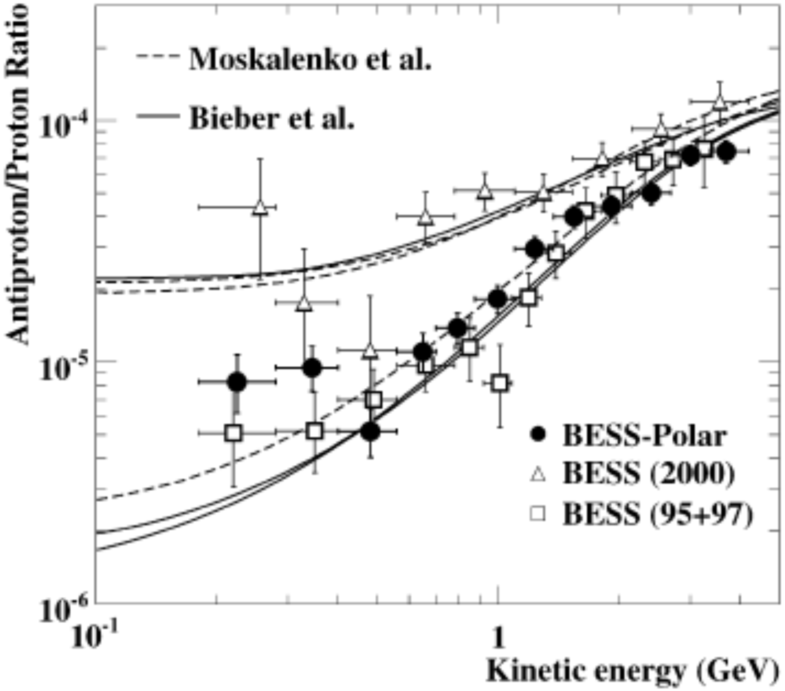
e^-, p, γ

$e^+, \bar{p}, \gamma$

$\bar{\chi}$

Solar effects on CR

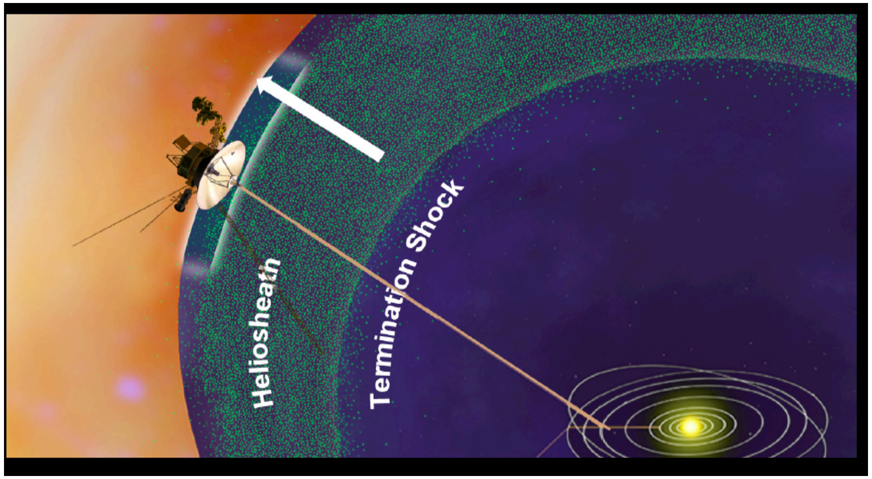


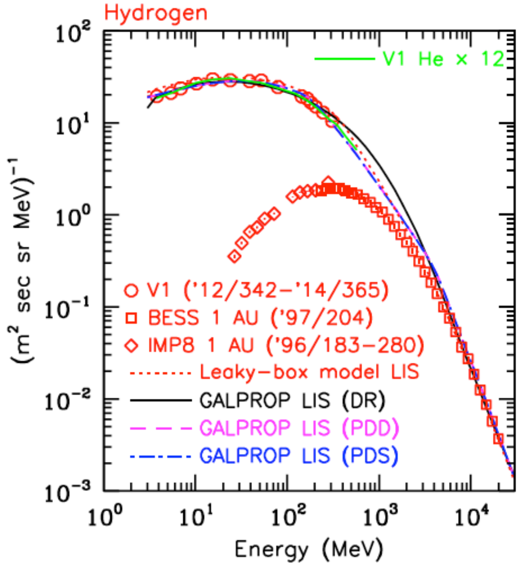


A long journey in planetary mission,
(jupiter, saturn, titan), heliosphere and interstellar space..

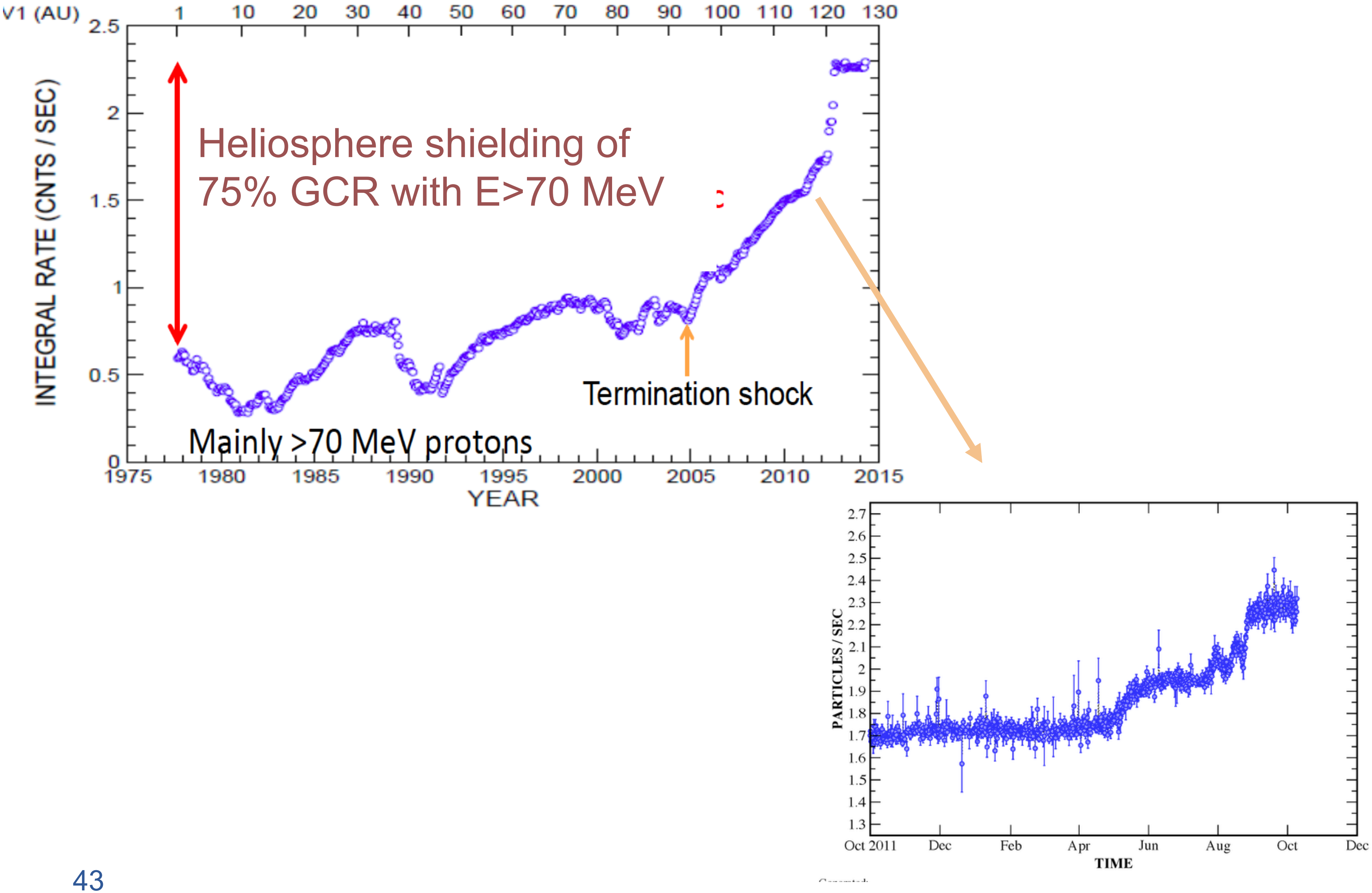
In orbit from Sept.5 1977 :
38 years ..9 months..and still counting (up to 2025...)
@ 121 a.u. out from heliospheric effects !

Voyager-1
&
the (un) modulated CR spectrum





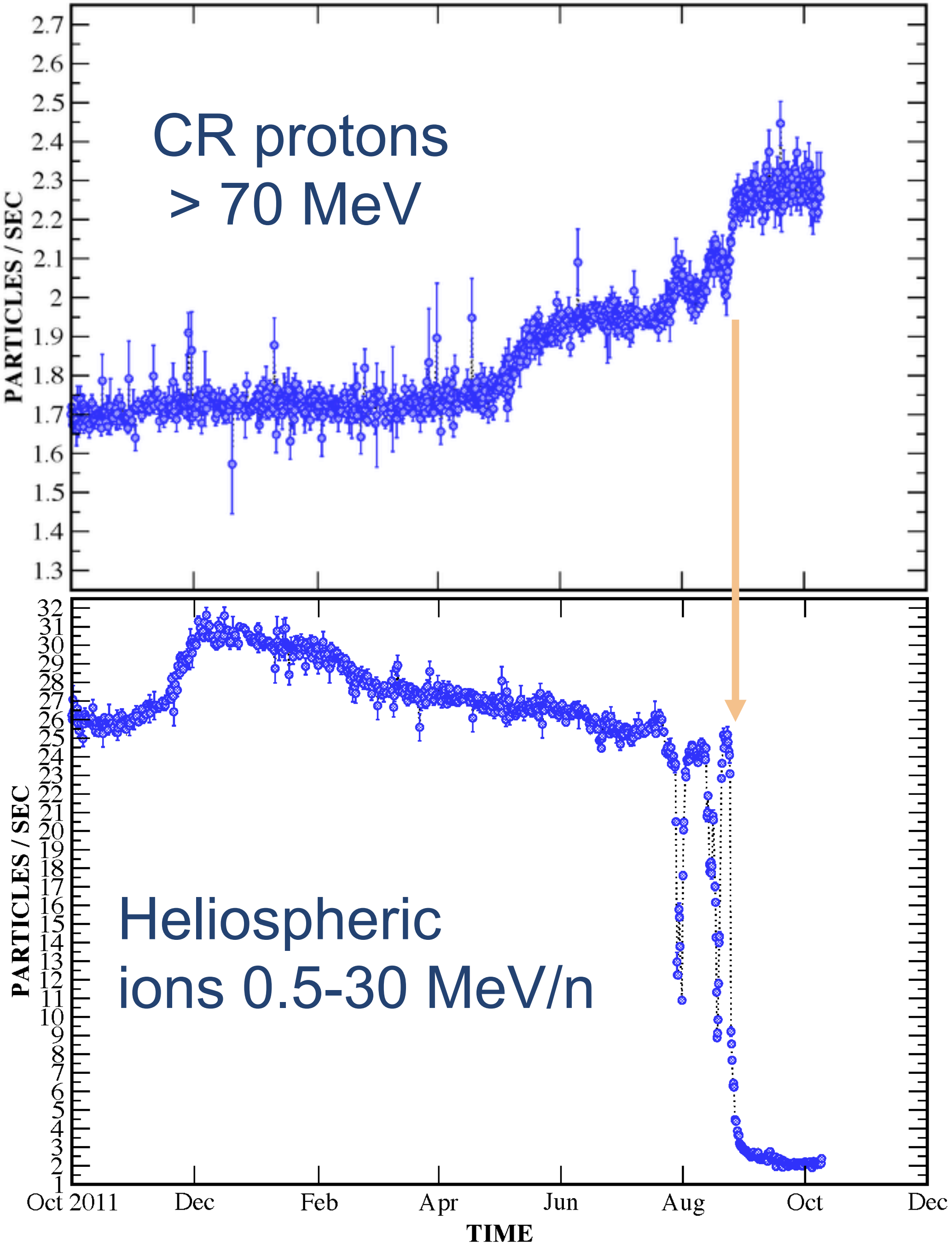
First observation of CR in the LISM !



Heliosphere shielding of 75% GCR with E>70 MeV

Termination shock

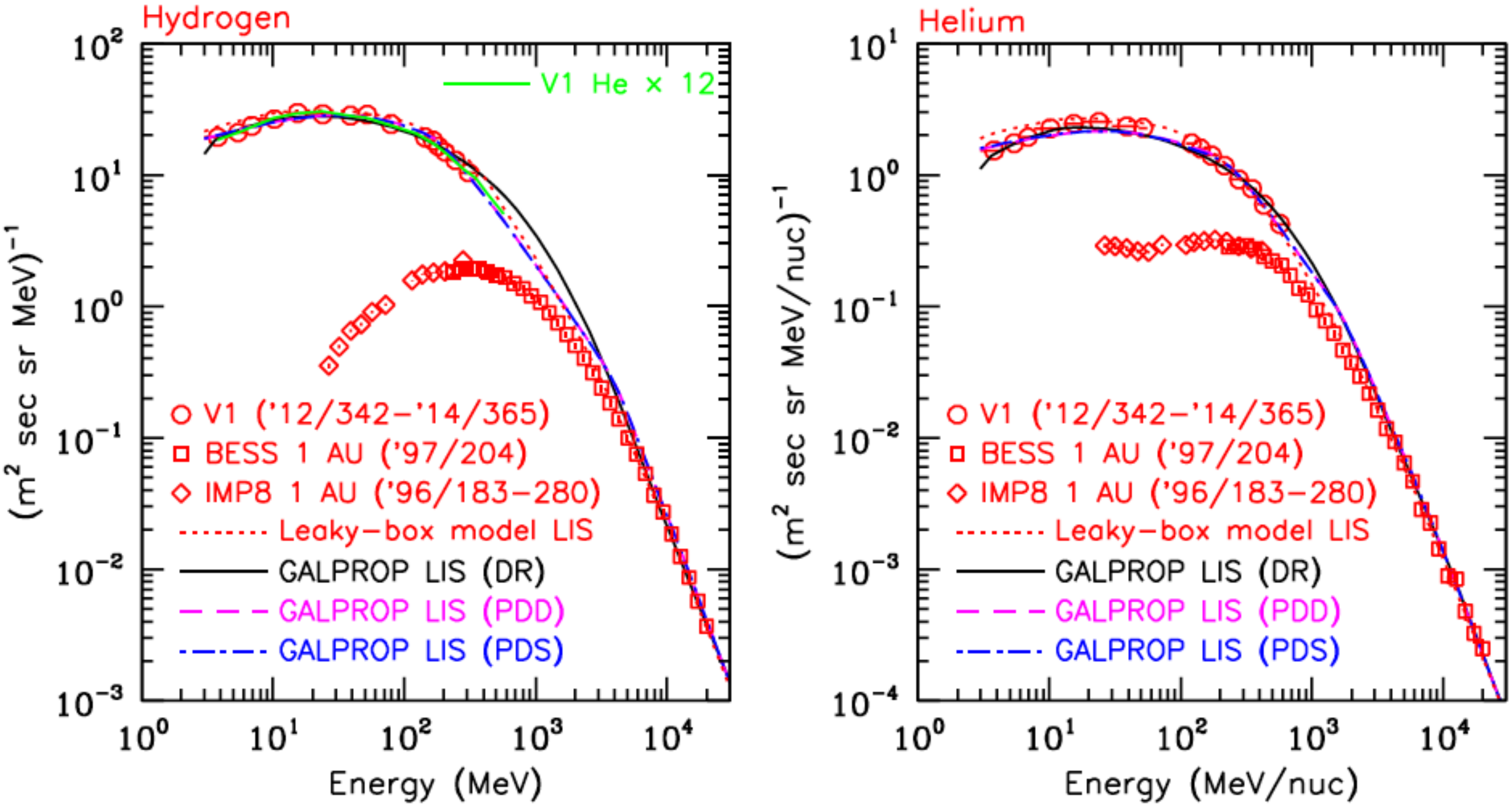
Mainly >70 MeV protons



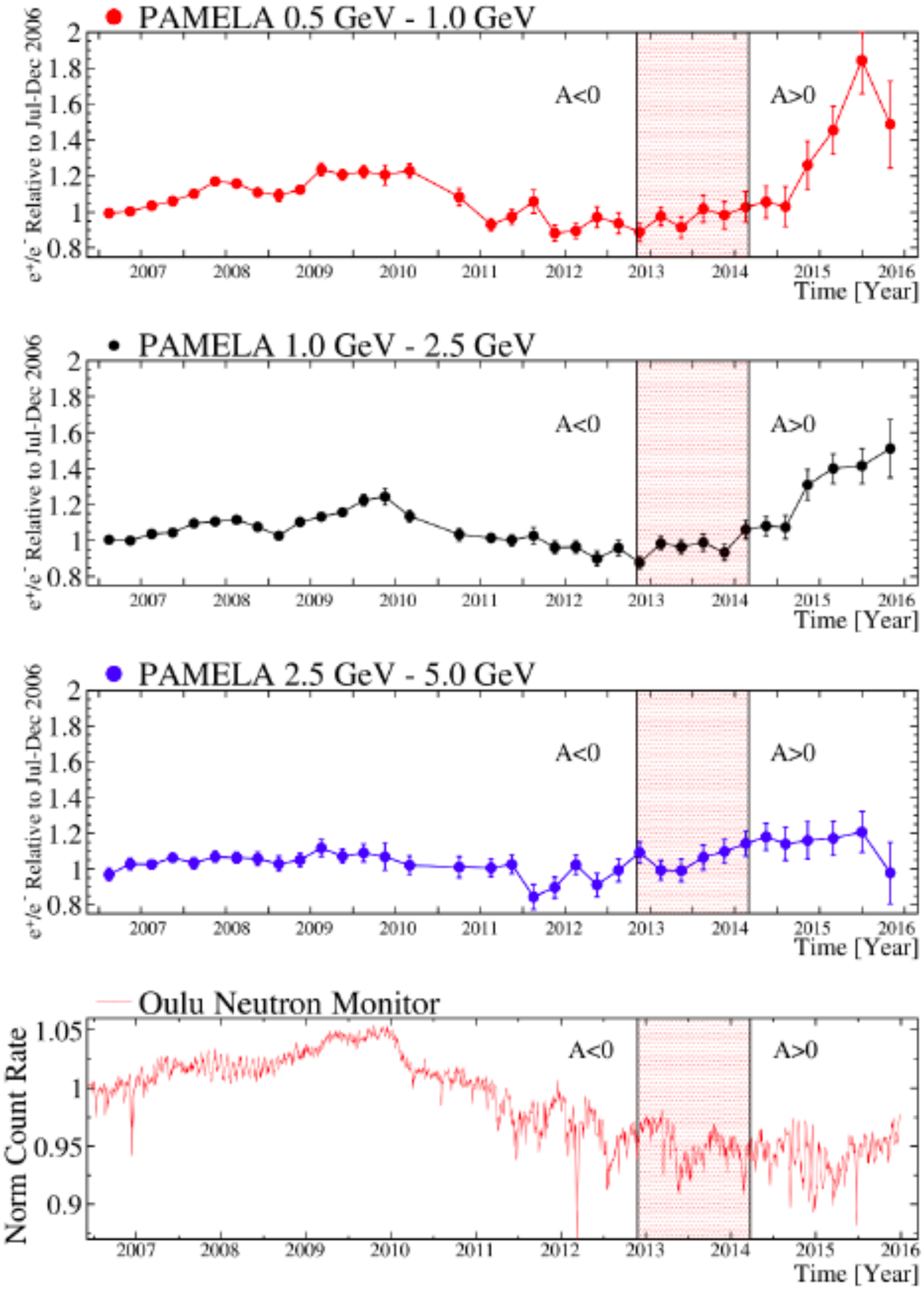
CR protons
> 70 MeV

Heliospheric
ions 0.5-30 MeV/n

From the modulated to the unmodulated spectrum...



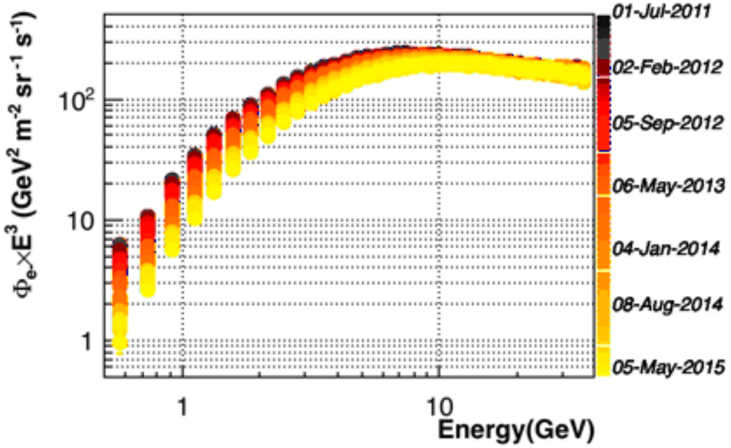
H/He ≈ 12 , flat with energy : shape not due to solar modulation but to ionization losses : V-1 is not near the source !

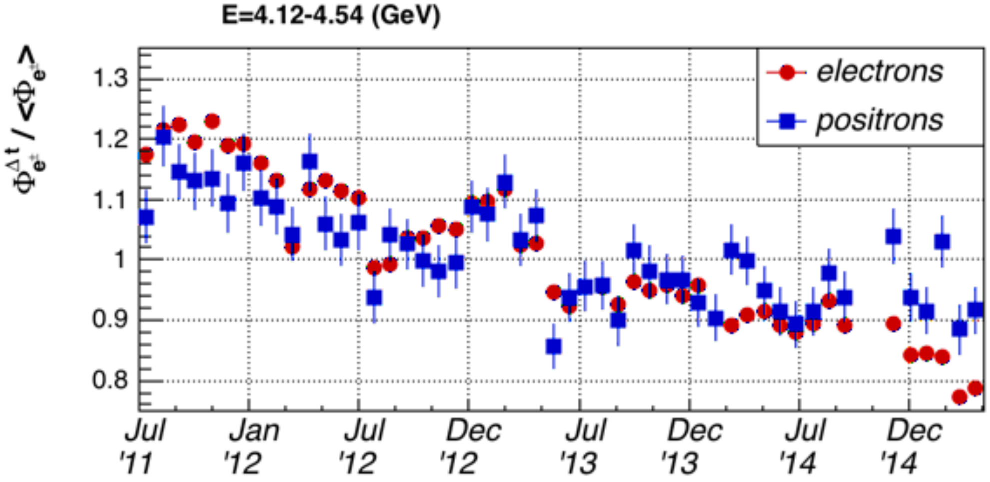


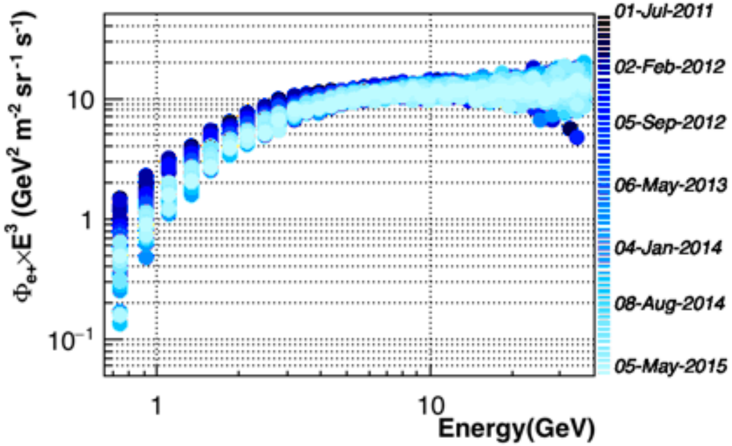
Time dependance of the electron and positron fluxes

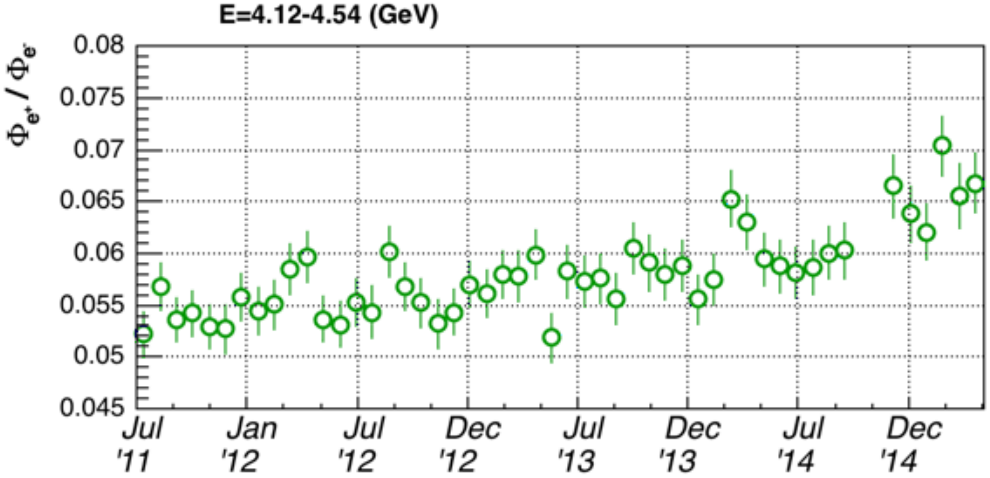
O. Adriani et al., to appear in PRL
(Editors' suggestion)

Solar effects on CR...







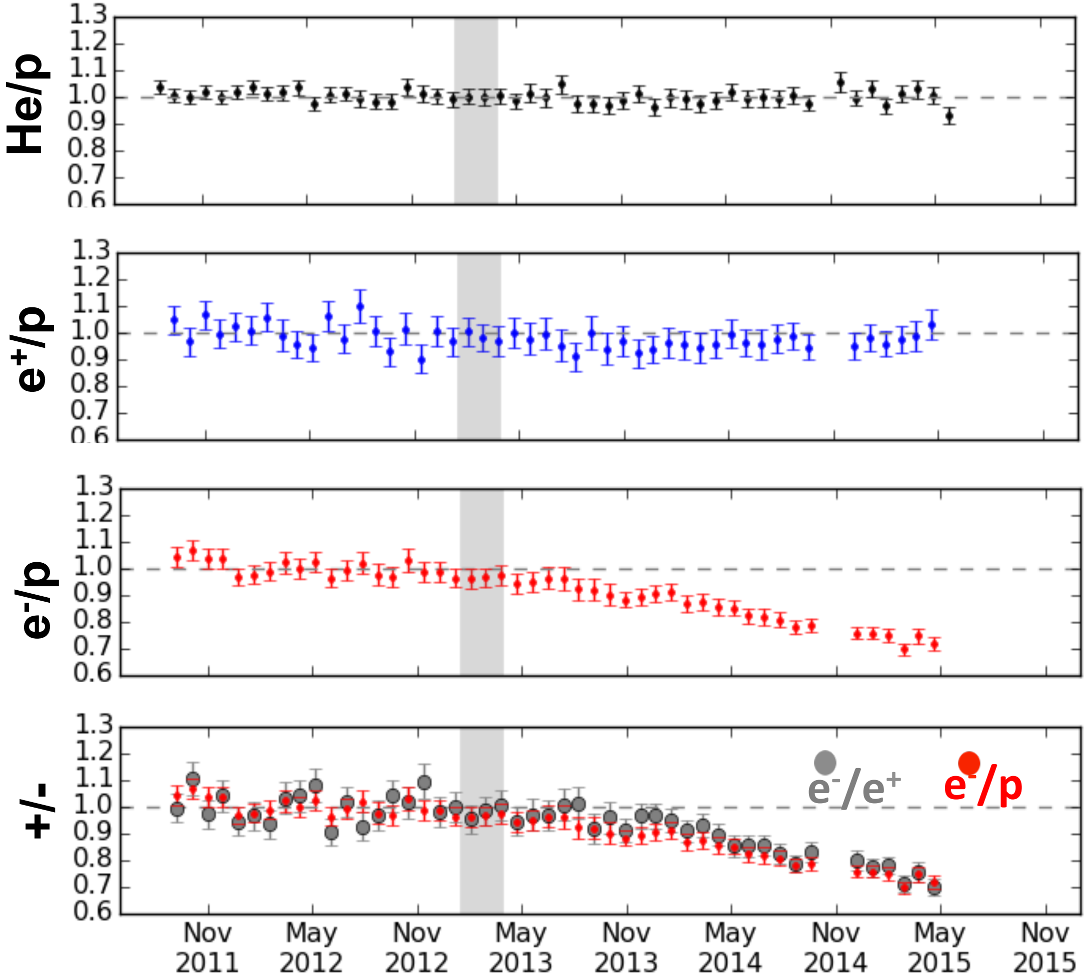


Solar effects on CR...

2 GeV

Different species, same sign of charge

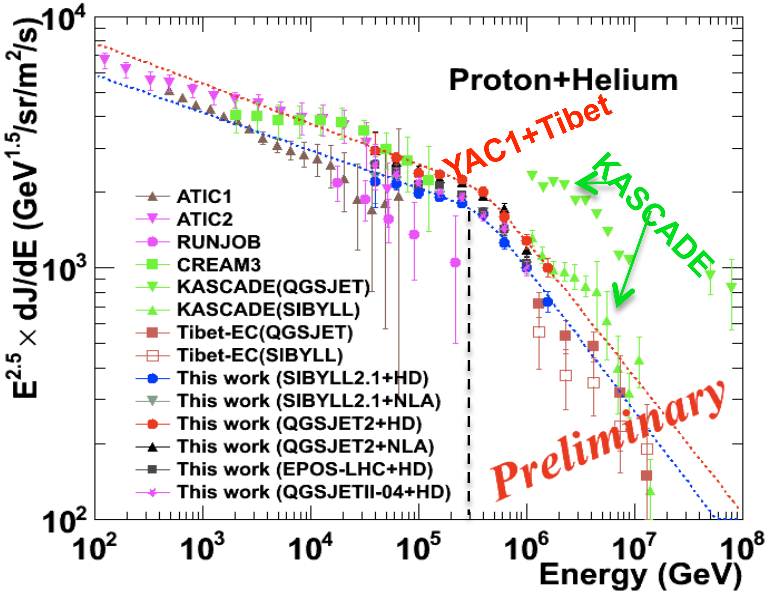
Different species, different sign of the charge

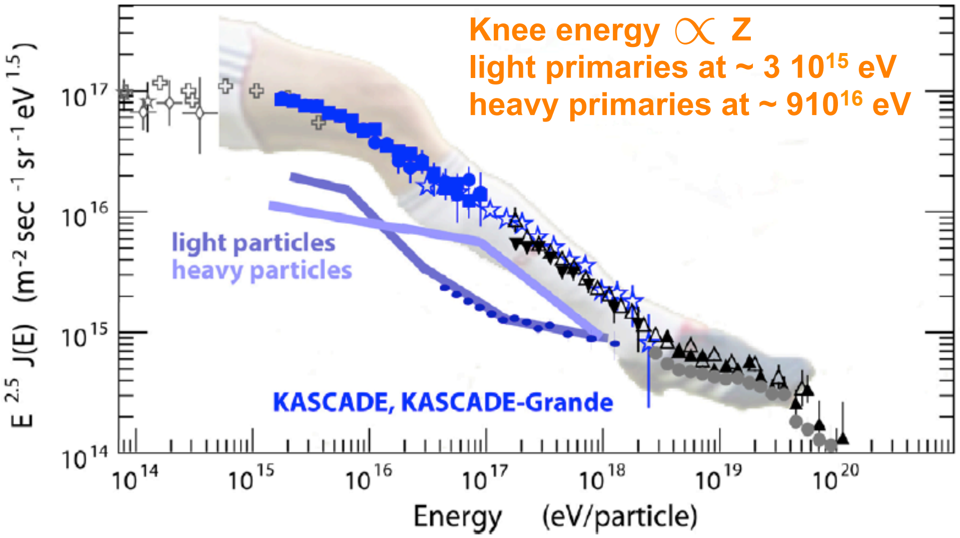


Spectral features & composition ....

Spectral features & composition

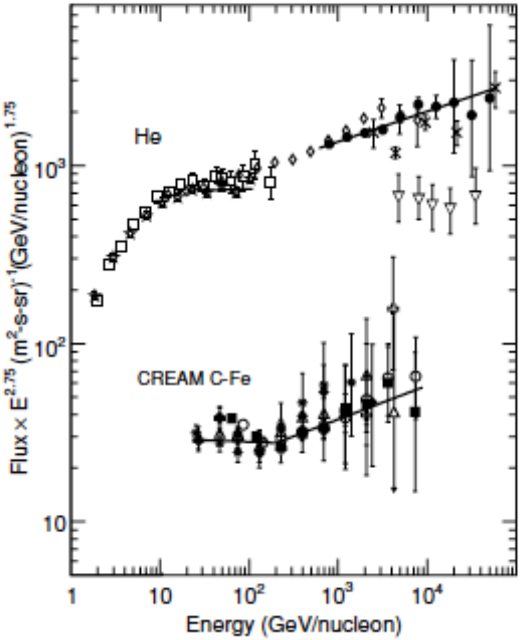
- Accelerators?
- Galactic vs extra-galactic
- features in the propagation...

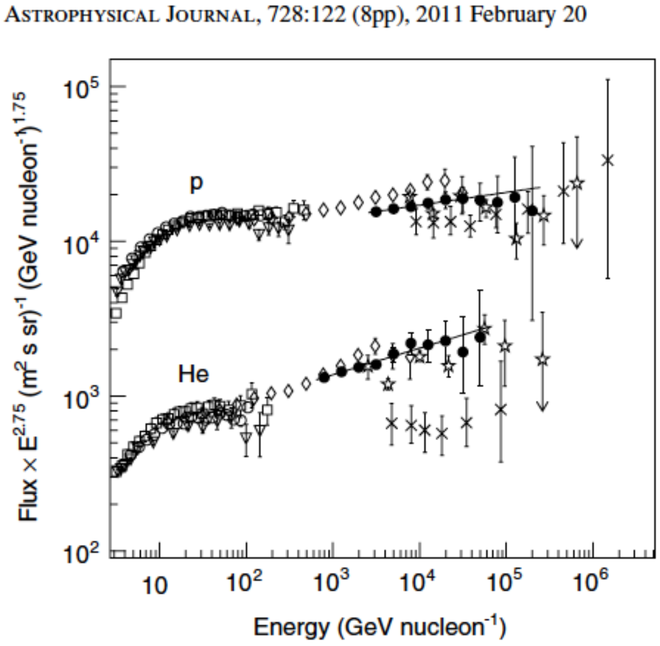




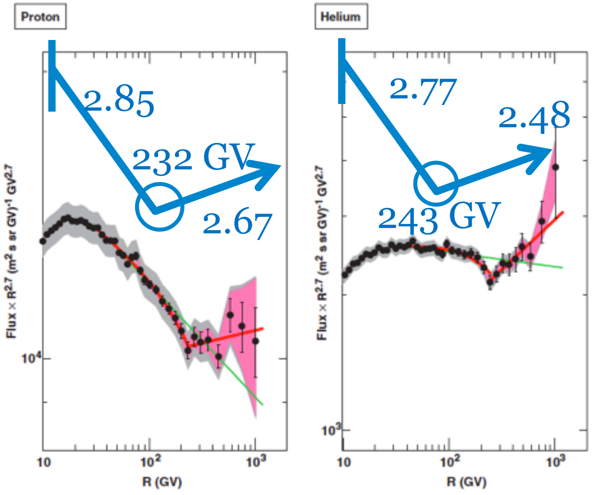
Knee energy $\propto$ Z
light primaries at ~ 3 10^{15} eV
heavy primaries at ~ $9 10^{16}$ eV

Spectral features & composition





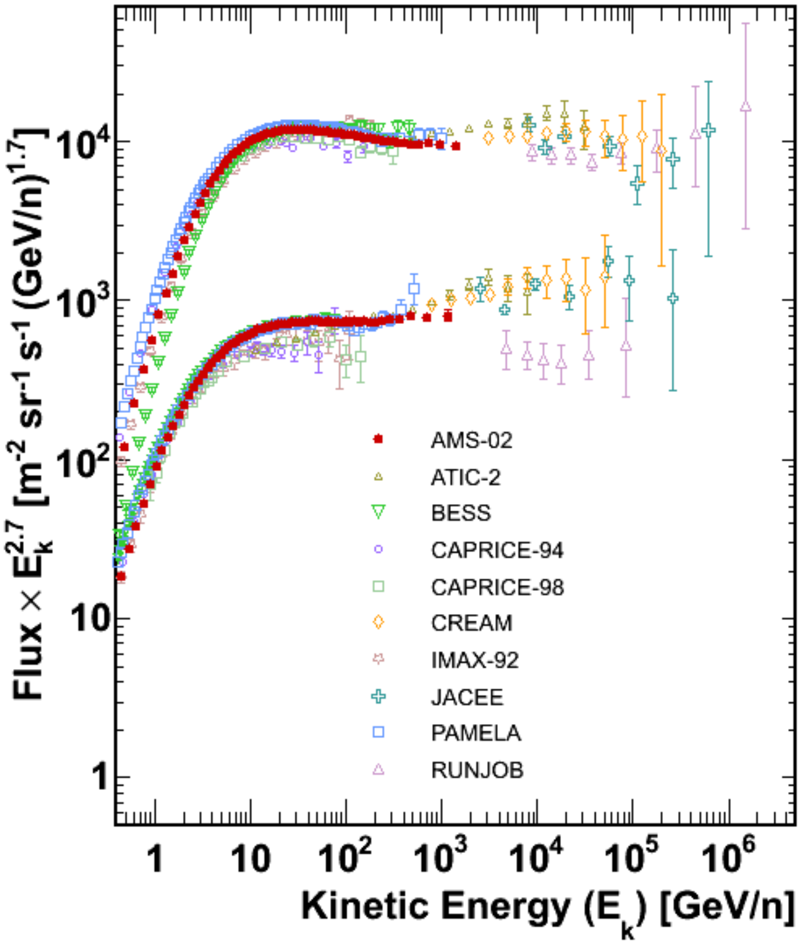
CREAM, APJ 2010, 2011

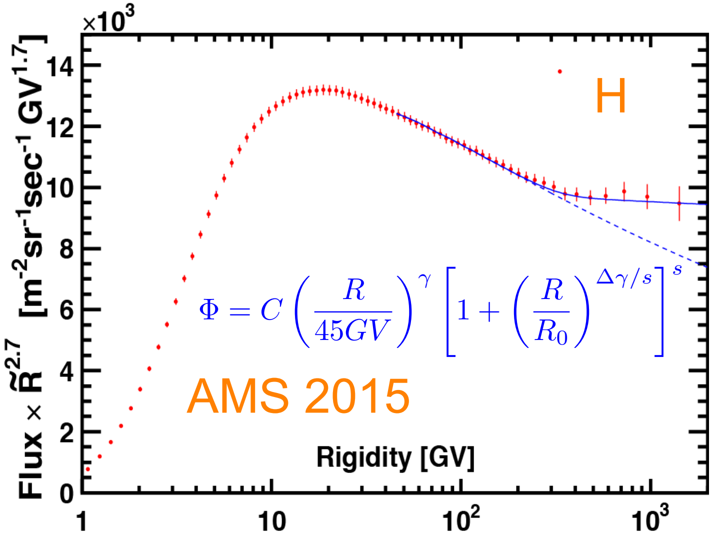


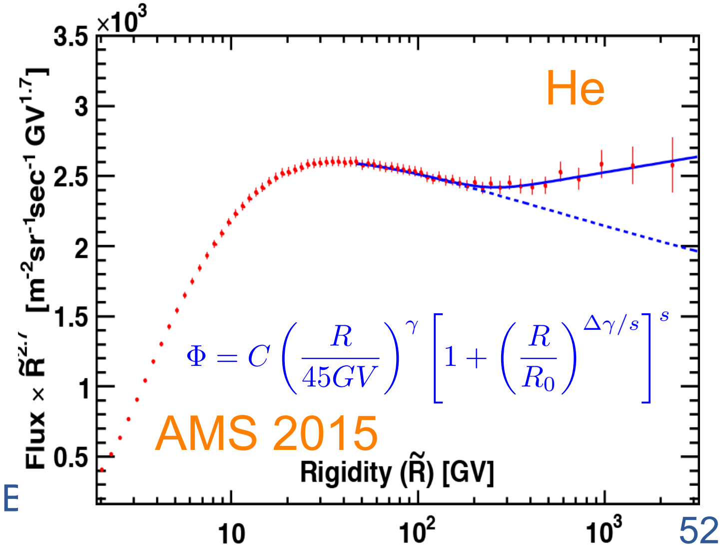
PAMELA, Science 2011

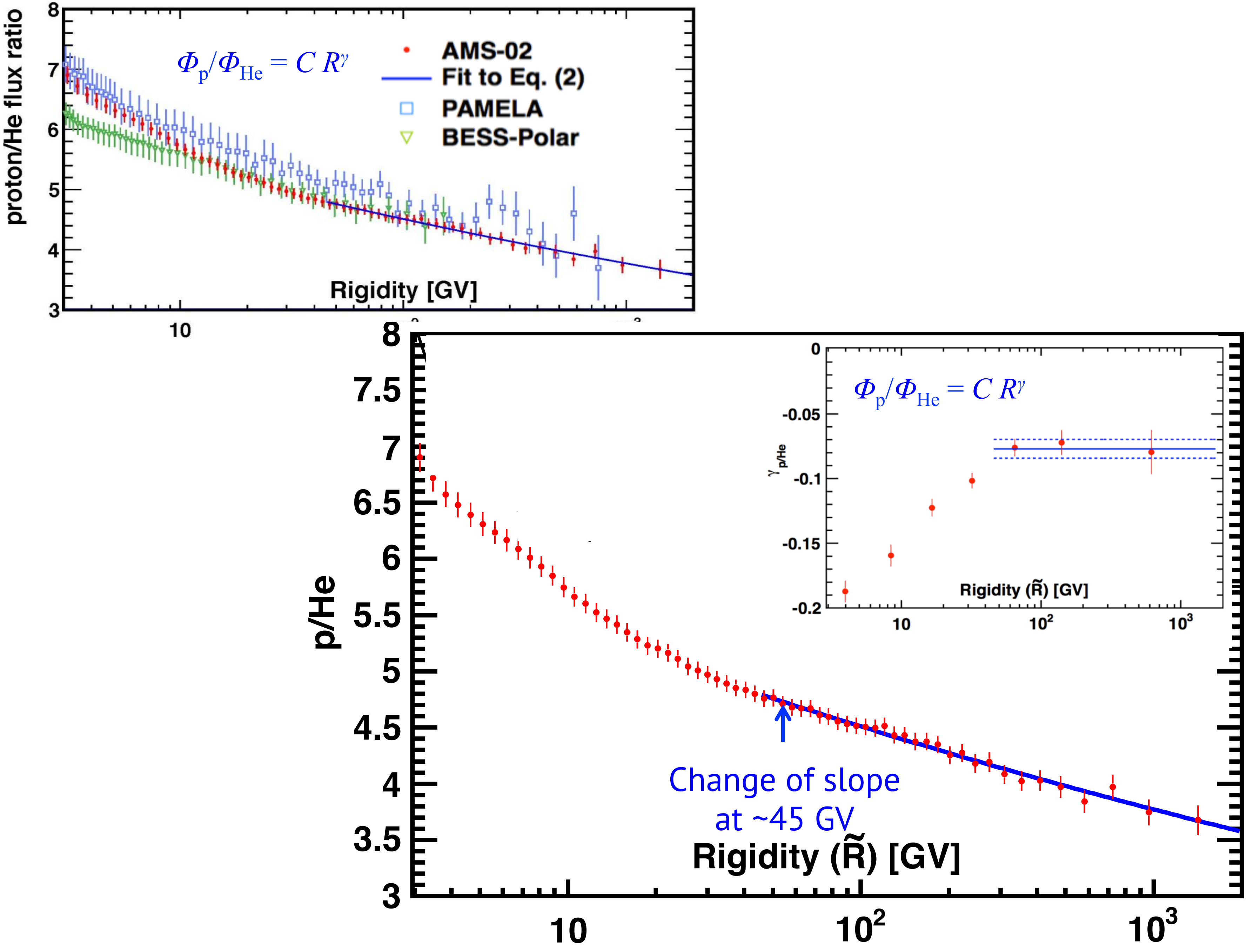
Breaks occur also at “low” energies…

AMS-02 :
the smooth change of spectral index









Change of slope at ~45 GV

What about origin of spectral hardening?

Related to acceleration mechanisms at source?

- distributed acceleration by multiple sources at the origin ?
- non linear DSA ?
- reacceleration by weak shocks in the Galaxy?

Propagations effects?
e.g. space and energy dependent diffusion coefficients?

Effect of nearby young CR sources?

What about origin of spectral hardening?

Related to acceleration mechanisms at source?

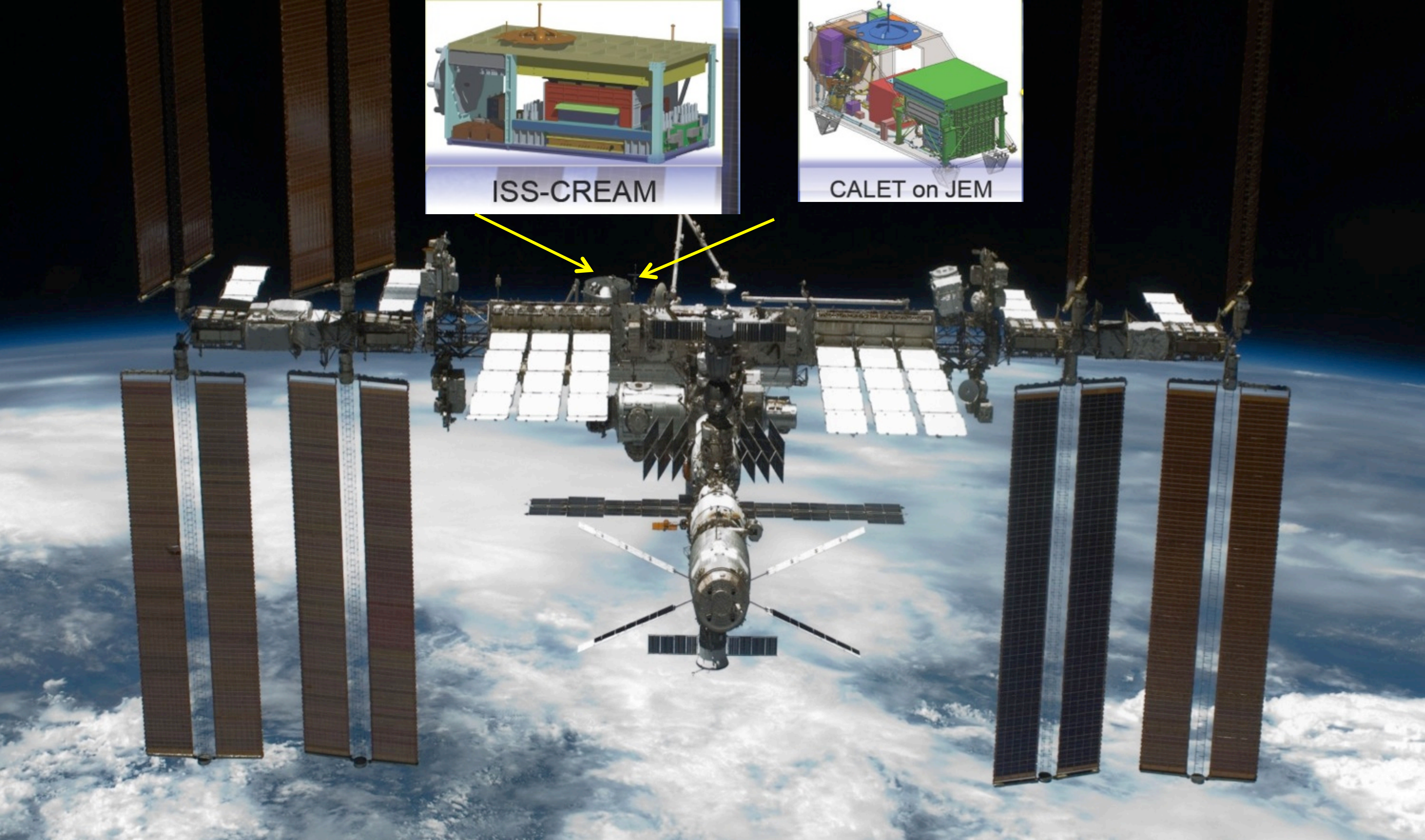
- distributed acceleration by multiple sources at the origin ?
- non linear DSA?
- reacceleration by weak shocks in the Galaxy?

Propagations effects?
e.g. space and energy dependent diffusion coefficients?

Effect of nearby young CR sources?

Future promises more & more fun:
precise data also on other primary/secondary species are coming;

- AMS released just a small part of his data...and will continue to run as the ISS will be operational (Oliva, later on)
- DAMPE (Bernardini, later on)
- HERD (Ambrosi, later on)



Cosmic Ray Observatory on ISS

CALET is taking data on the ISS !

① **August 19th**: After a successful launch of the Japanese H2-B rocket by the Japan Aerospace Exploration Agency (JAXA) at 20:50:49 (local time), CALET started its journey from Tanegashima Space Center to the ISS.

② **August 24th:**

The HTV-5 Transfer Vehicle（HTV-5) is grabbed by the ISS robotic arm.

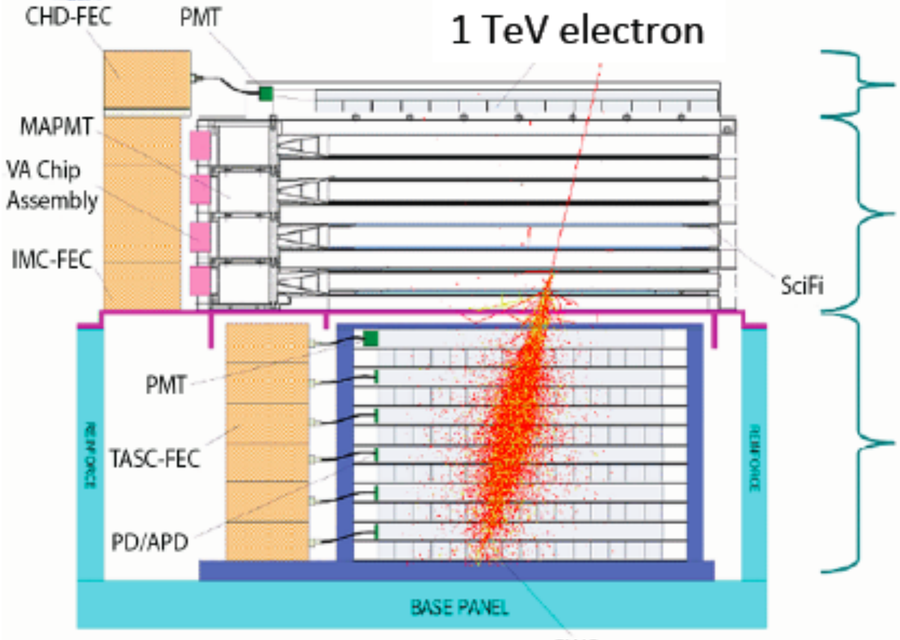
③ **August 24th:**

The HTV-5 docks to the ISS at 6:28 (EDT).

④ **August 25th:**

CALET is emplaced on port #9 of the JEM-EF and data communication with the payload is established.

CALorimetric Electron Telescope (CALET): INSTRUMENT OVERVIEW



CHD - **CHarge Detector (CHD)**

(Charge Measurement Z=1-40)

IMC - **Imaging Calorimeter (IMC)**

(Particle ID, Direction)

Total Thickness of Tungsten (W): **$3\ X_0$, $0.1\ \lambda_I$**

Layer Number of Scifi Belts: 8 Layers × 2(X,Y)

TASC - **Total Absorption Calorimeter (TASC)**

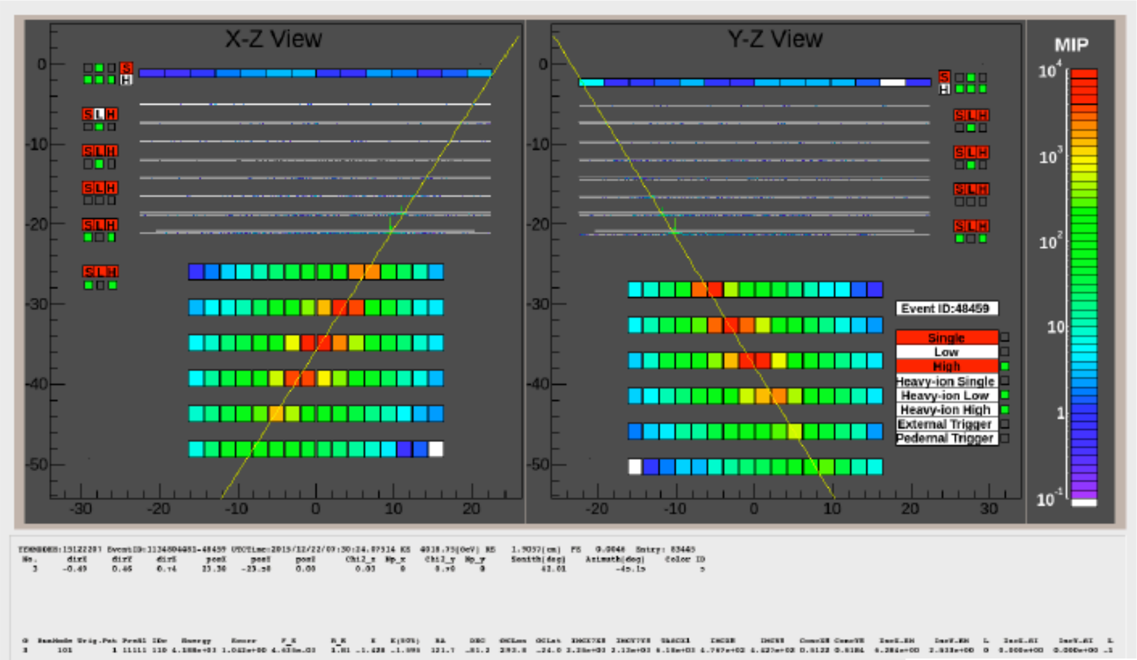
(Energy Measurement, Particle ID)

PWO 20mm x 20mm x 320mm

Total Depth of PWO: **$27\ X_0$** (24 cm), **$1.2\ \lambda_I$**

	CHD **(Charge Detector)**	**IMC** **(Imaging Calorimeter)**	**TASC** **(Total Absorption Calorimeter)**
Function	**Charge Measurement (Z = 1 - 40)**	**Arrival Direction, Particle ID**	**Energy Measurement, PID**
Sensor (+ Absorber)	**Plastic Scintillators: 2 layers** **Unit Size: 32mm x 10mm x 450mm**	Scintillating Fibers: 16 layers single readout: **1mm^2** x 448 mm Total thickness of Tungsten: $3\ X_0$	PWO logs: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: 27 X_0
Readout	**PMT+CSA**	64-anode MAPMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)

CALET & e±



EntryNum 83445

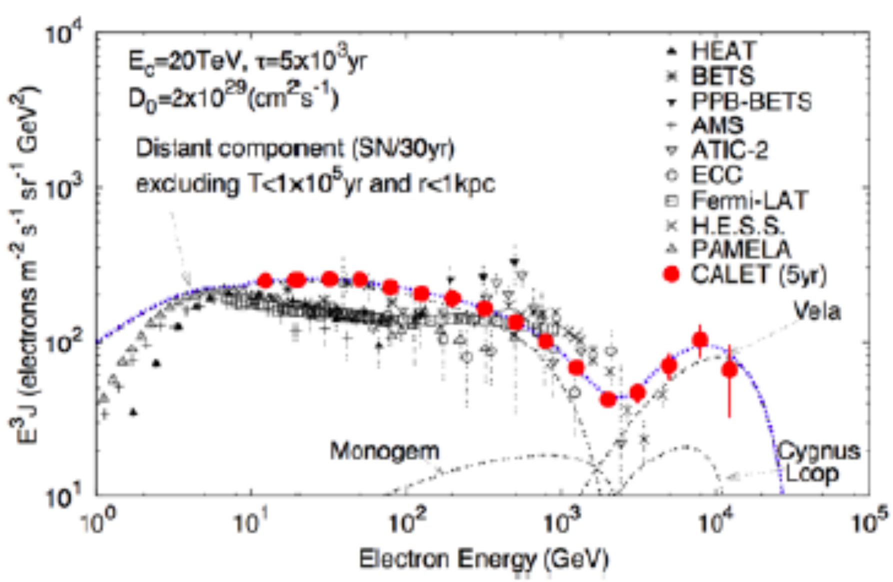
MDCTime 1134804481

EventID 48459

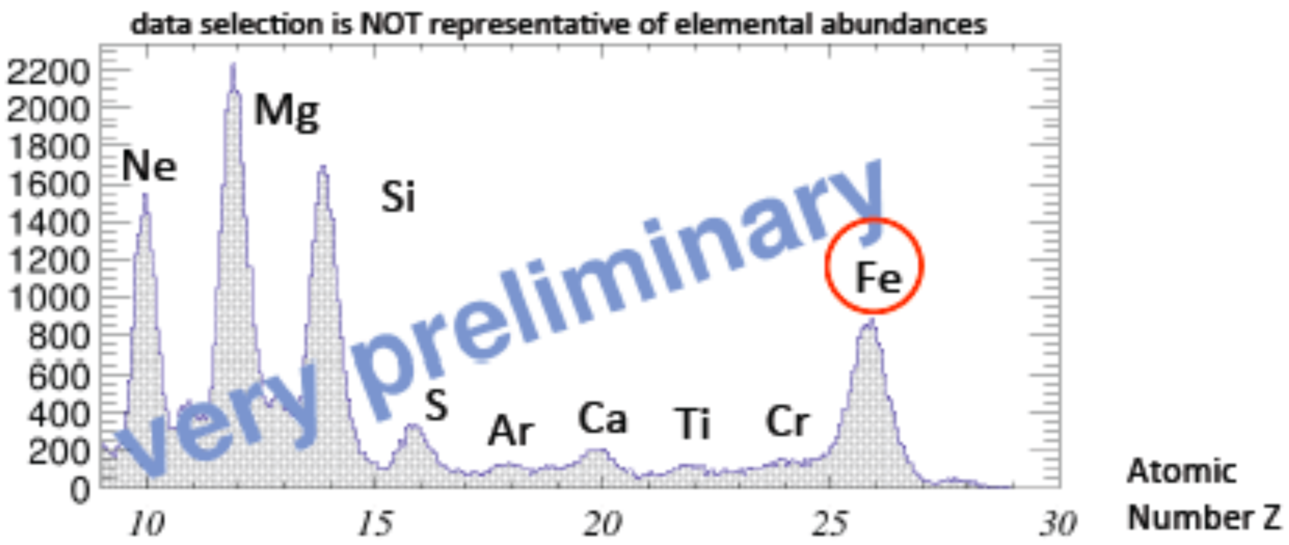
Tracking ☑

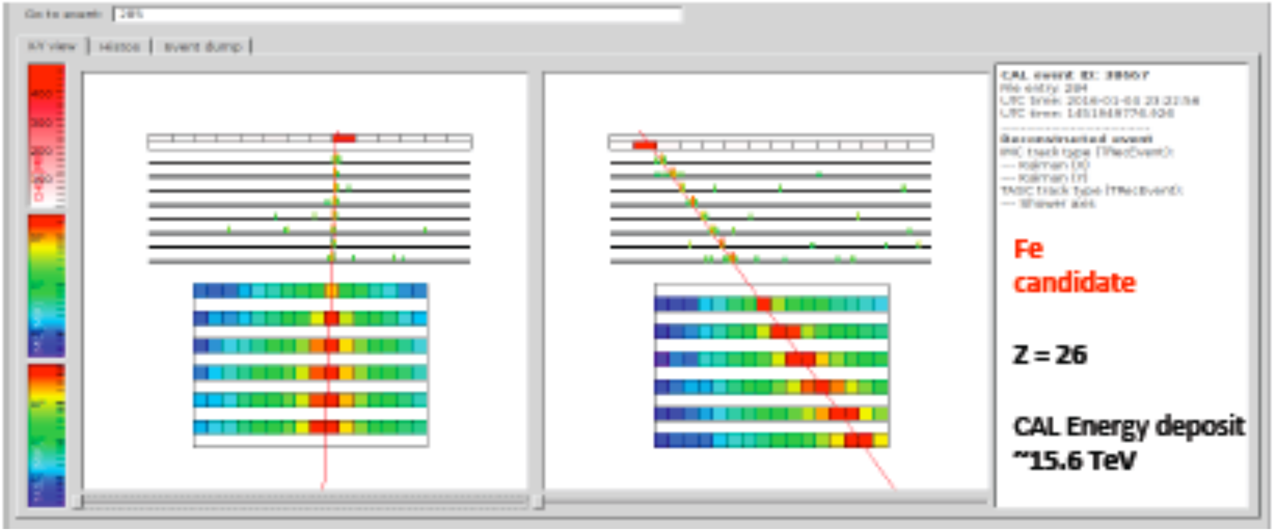
Prescaling 0

Energy Itgl



CALET & Nuclei



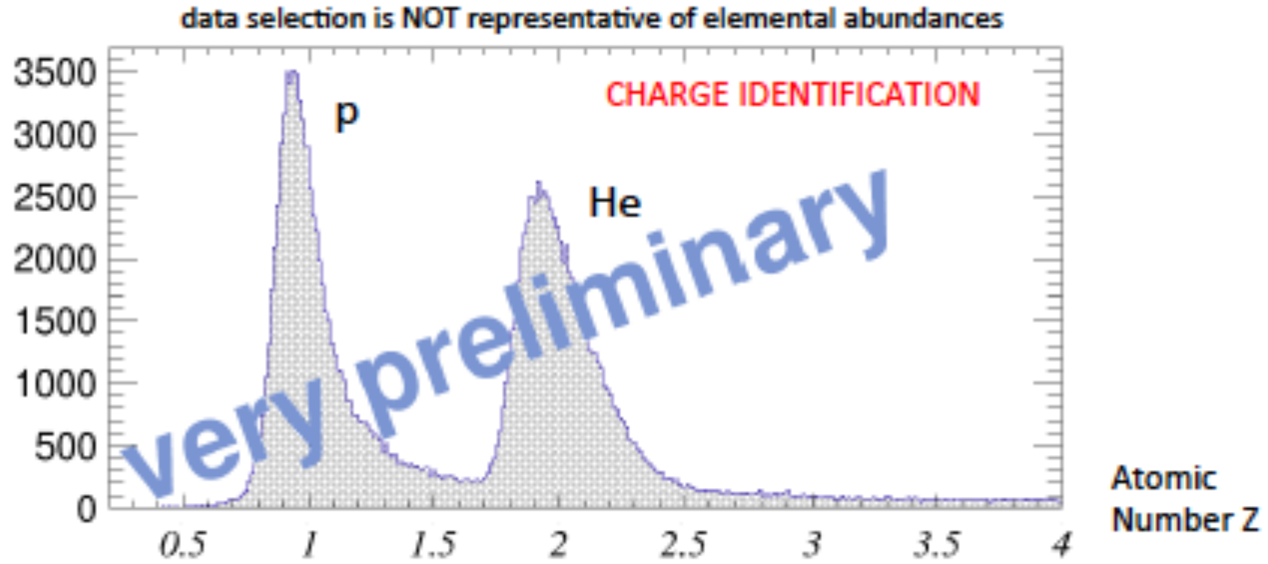


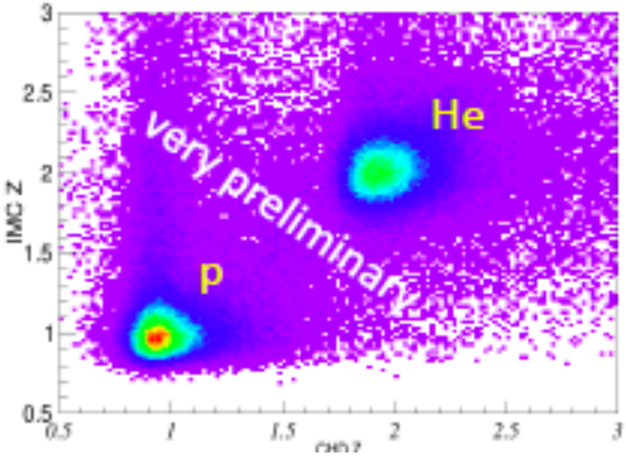
Fe candidate

Z = 26

CAL Energy deposit ~15.6 TeV

CALET & Nuclei

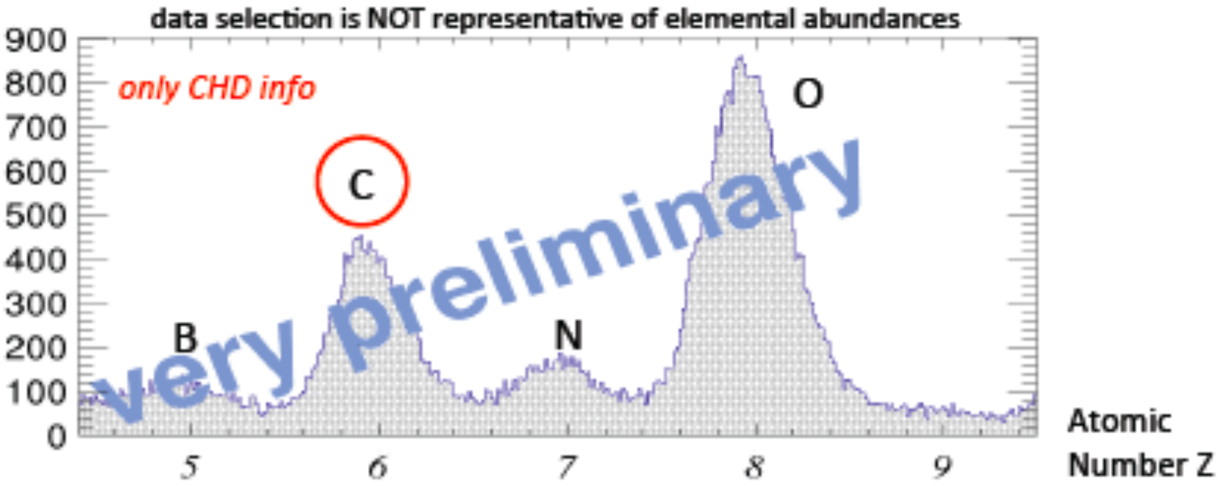


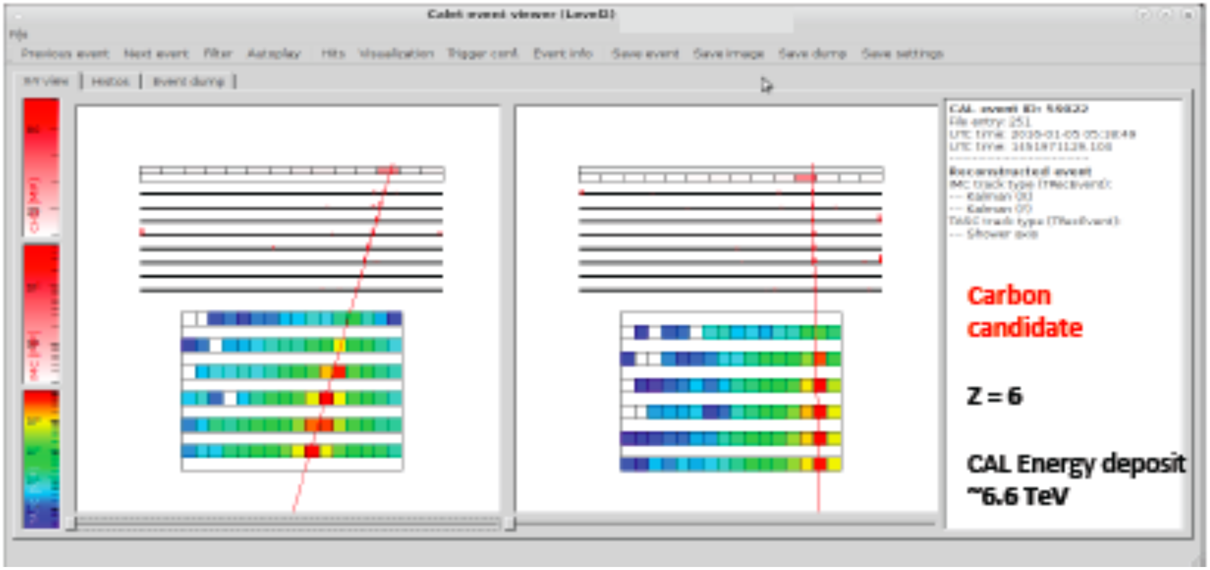


Using multiple dE/dx measurements from the IMC scintillating fibers (upstream the interaction point), a complementary charge measurement from IMC is plotted vs the CHD charge assignment (abscissa).

A clear separation between p and He can be seen from preliminary data analysis.

CALET & Nuclei



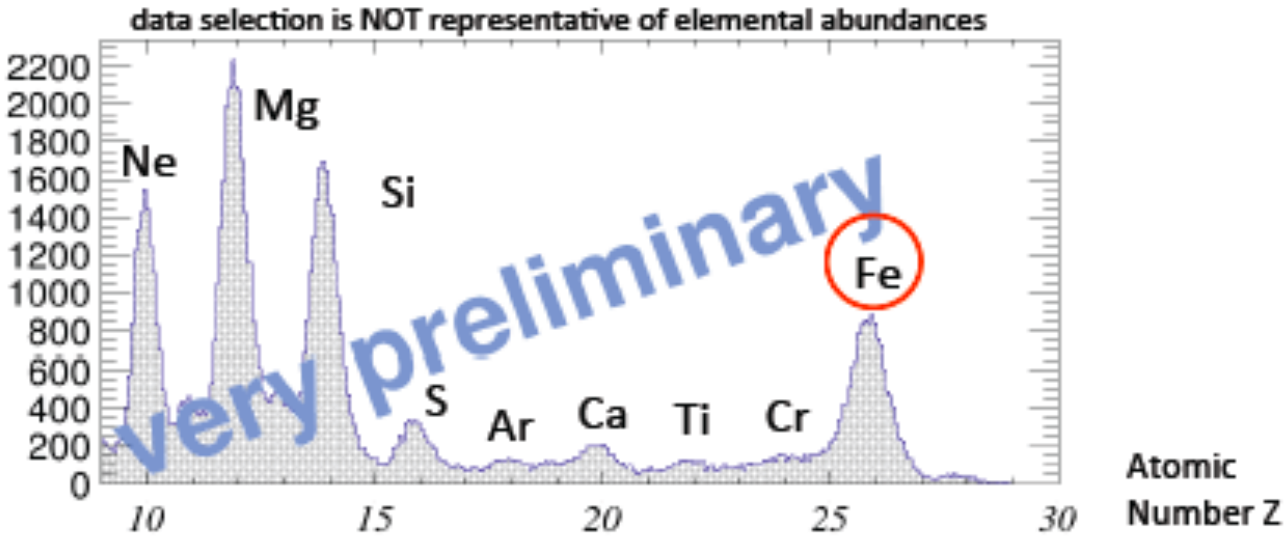


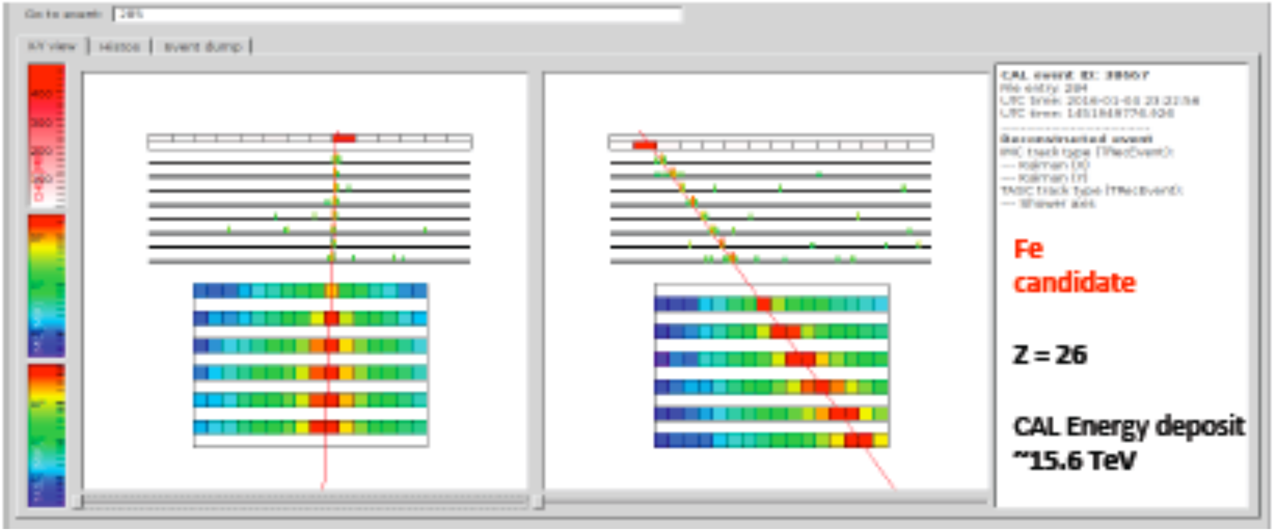
Carbon candidate

Z = 6

CAL Energy deposit ~6.6 TeV

CALET & Nuclei



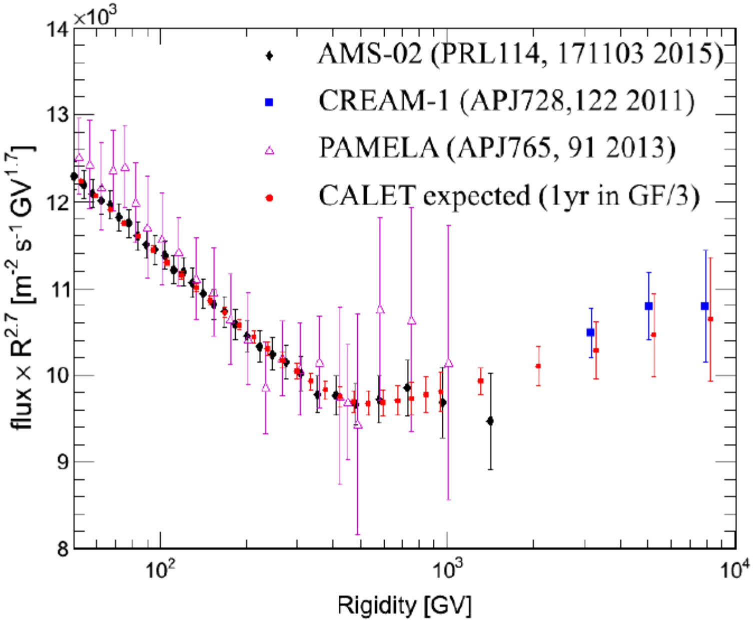


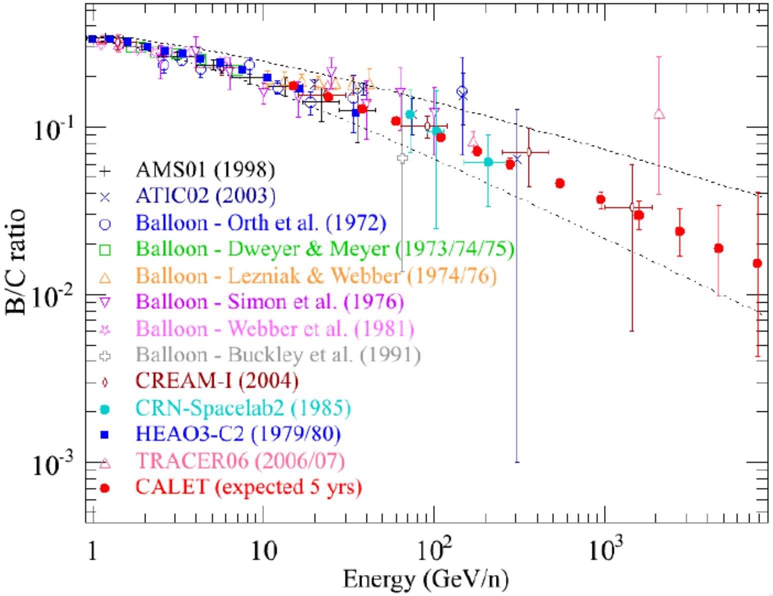
Fe candidate

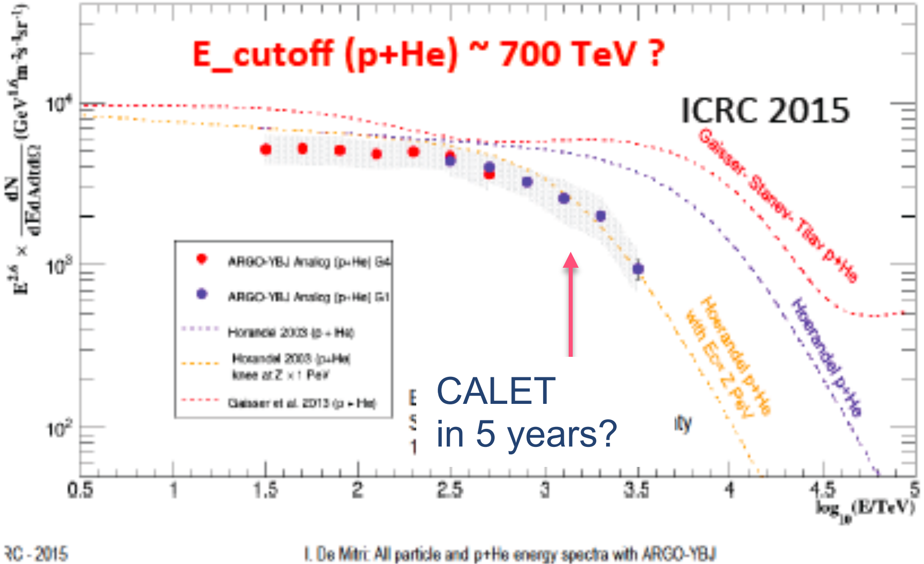
Z = 26

CAL Energy deposit ~15.6 TeV

CALET & CR ...







CALET
in 5 years?

Conclusions

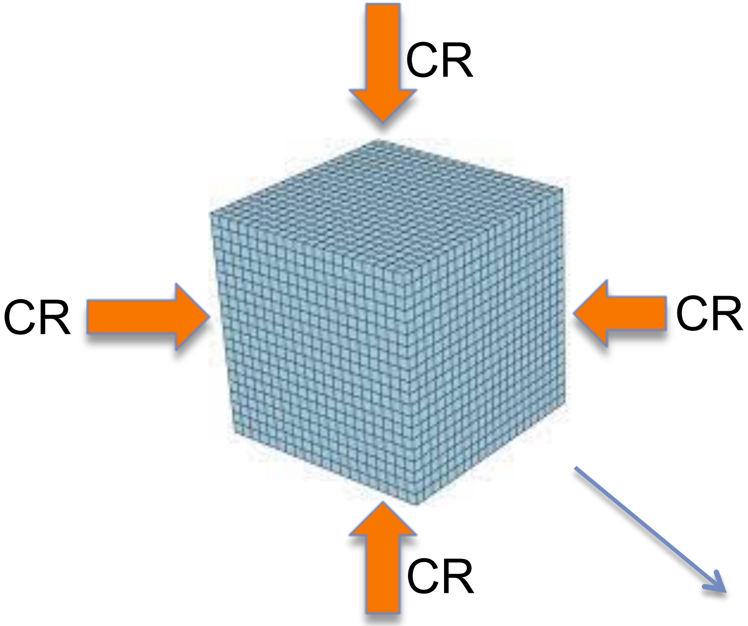
- ✓ Stratospheric balloon program relevant for specific measurements (GAPS for anti-d ?..)
- ✓ Space is giving an important contribution to direct CR measurements…
  - ✓ PAMELA did a great job…
  - ✓ AMS-02 is starting to release impressive results..and more will come in the next future
  - ✓ CALET and DAMPE just launched...

- ✓ in 10 years large acceptance space based calorimetric experiments insuring good overlap with ground based (indirect) measurements. Up to knee ?

- ✓ Anti-matters matters ! A long term plan is needed (and is starting..) for a new antimatter large acceptance detector in orbit ..

CaloCube (INFN gruppo V)

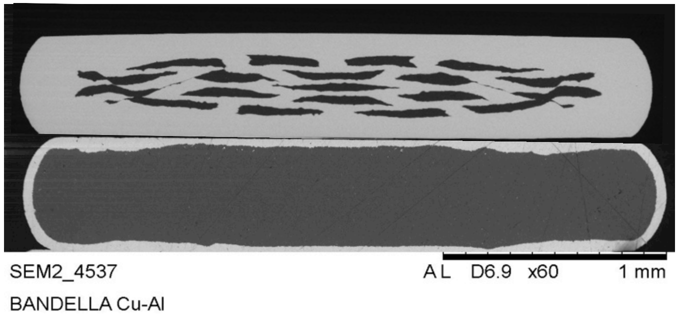
- Exploit the CR isotropy to maximize the effective geometrical factor, by using all the surface of the detector (aiming to reach $\Omega = 4\pi$)
- The calorimeter should be highly isotropic and homogeneous



Assumption for the next slides:
2000 kg for the calorimeter
2000 kg for the magnetic material

SR2S (INFN and UE)

- R&D of high temperature superconducting magnets (MgB$_2$) for space applications (T ≈ 10÷20 °K)



Materials percentages:

titanium: 40%

alluminium: 50%

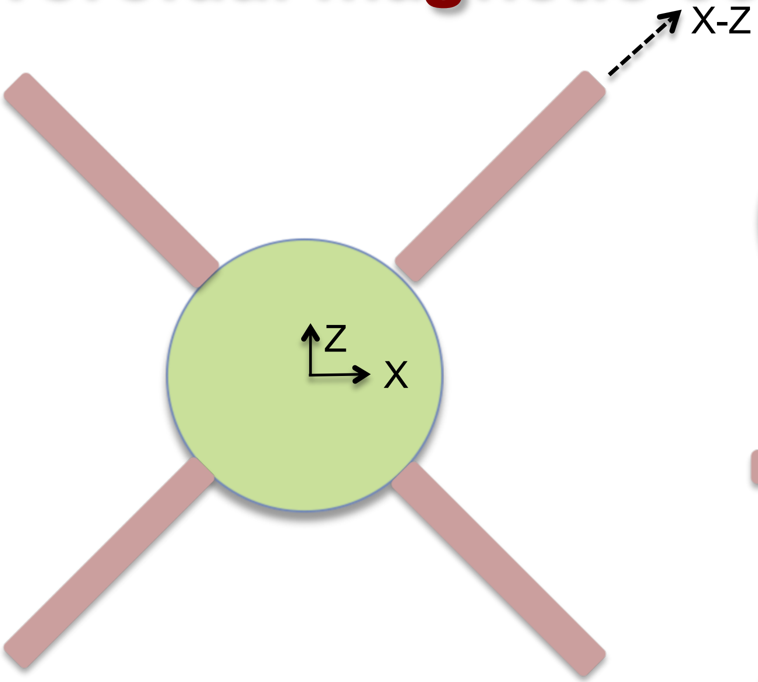
MgB$_2$: 10%

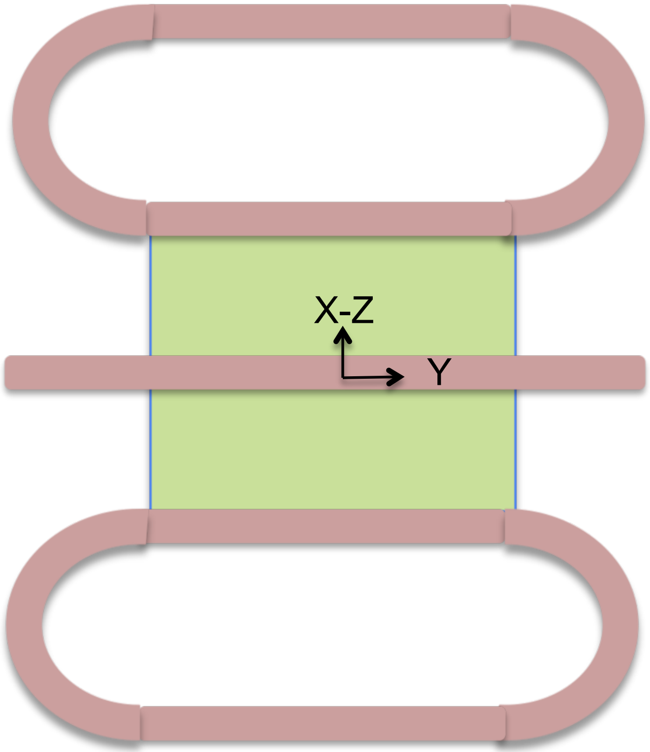
Quite small density: ≈ 3.4 g/cm^3

A novel idea for a next generation cosmic ray experiment in space

Work and slides by
Paolo Papini, thanks!

Toroidal magnetic configuration





The magnetic system should be optimized taking into account the relationship btw maximum current density and maximum B field

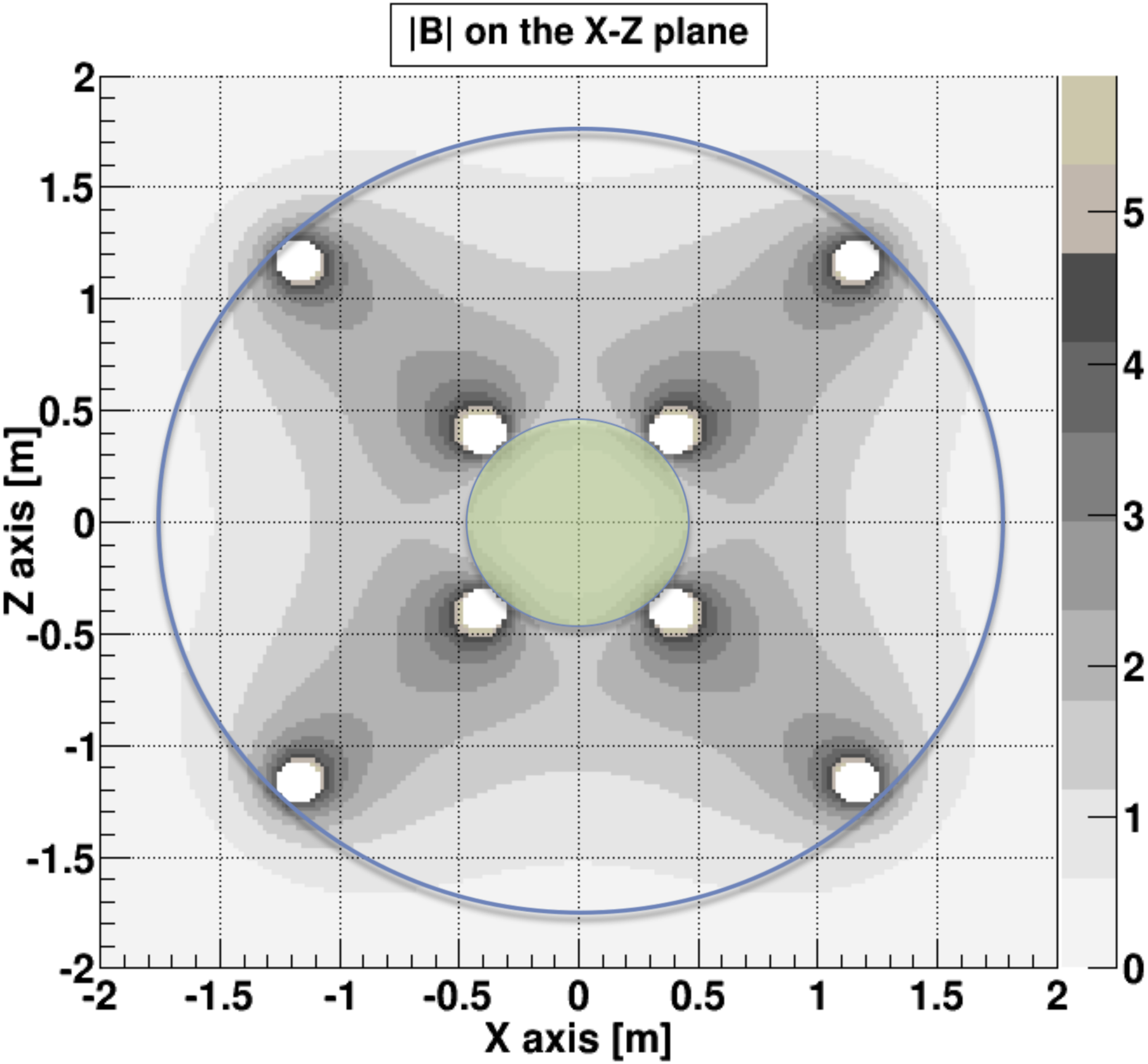
Calorimeter diameter: 93.35 cm
Calorimeter length: 96.8 cm
External diameter: 350 cm
Weight of the magnetic material: 2000 kg
Current density: 83.6 A/mm^2
Number of coils: 4

→

Coils diameter: 18.65 cm
Maximum field: 6.9 T

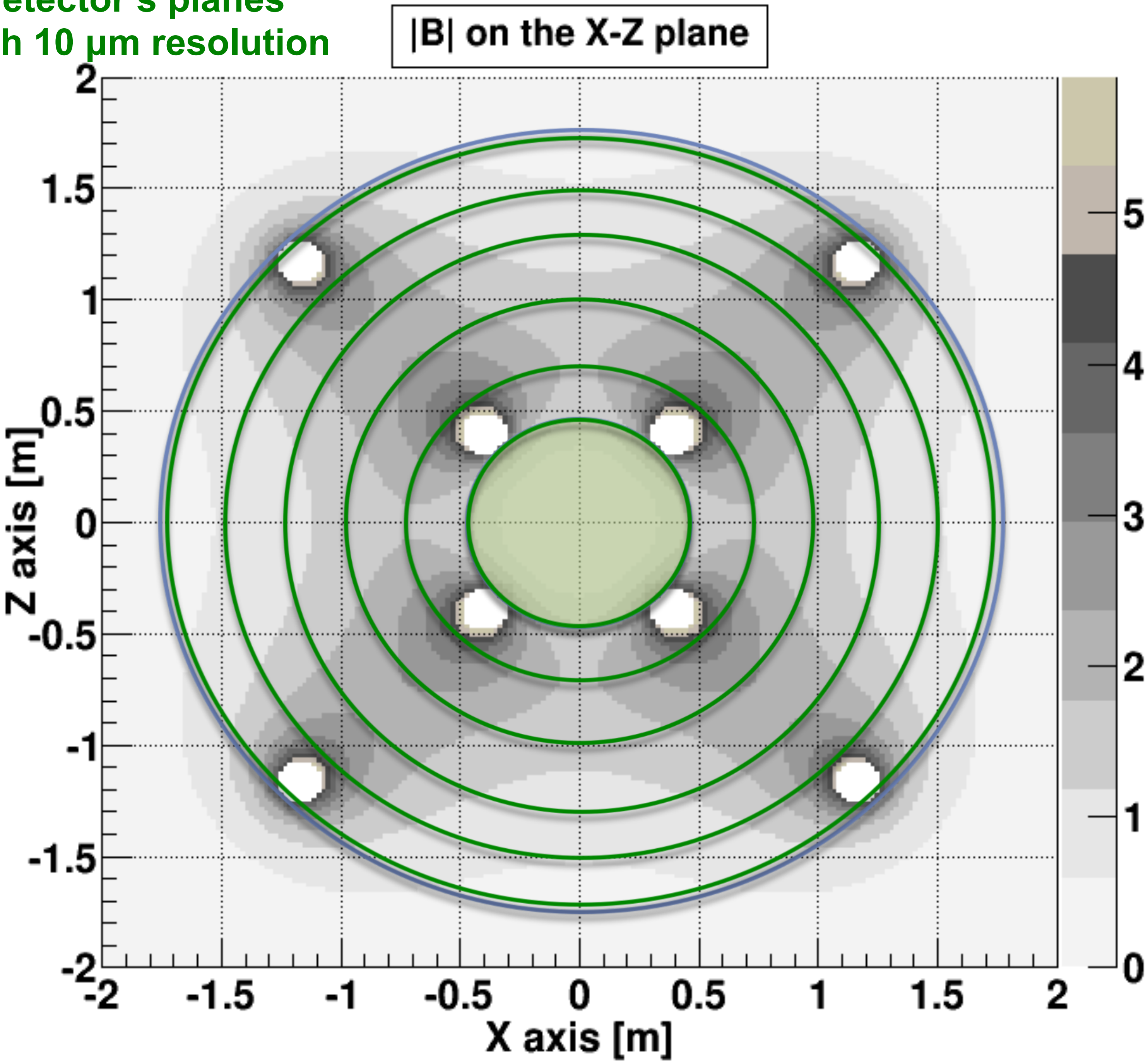
Advantages of the toroidal configuration:

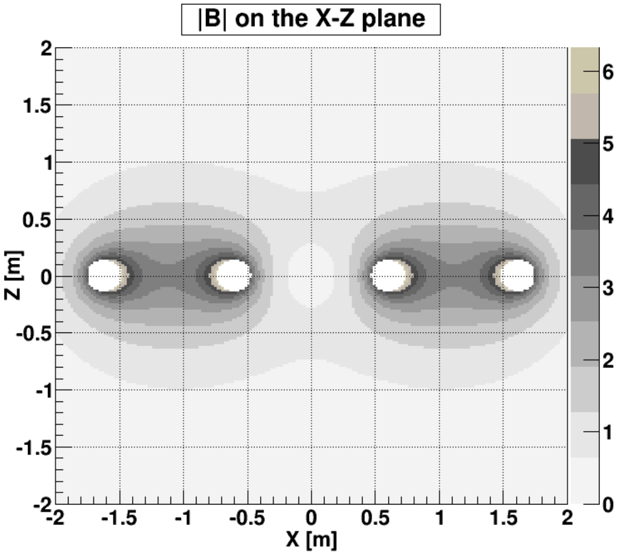
- Null Magnetic Moment
- Compensation coils not necessary



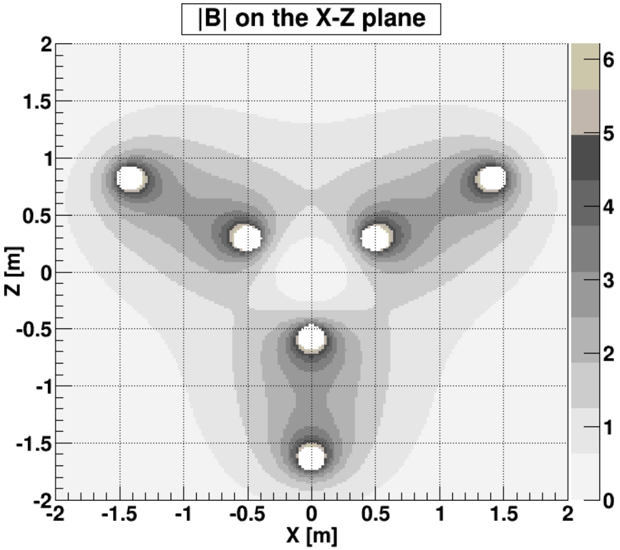
|B| on the X-Z plane
Z axis [m]
X axis [m]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
5
4
3
2
1
0

6 detector's planes with 10 μm resolution

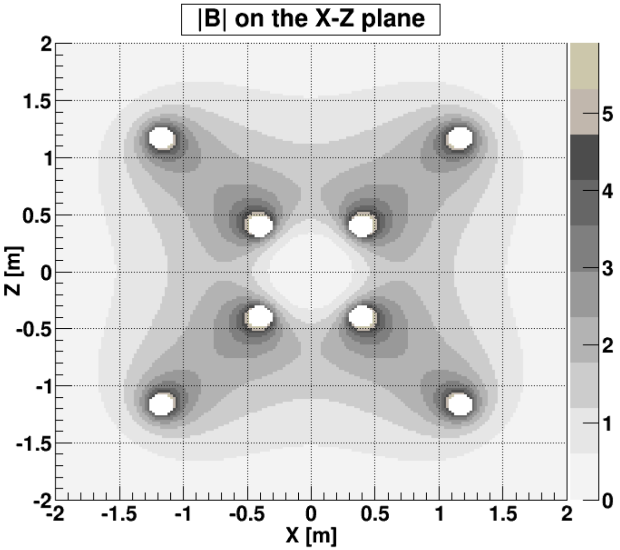




2 spire

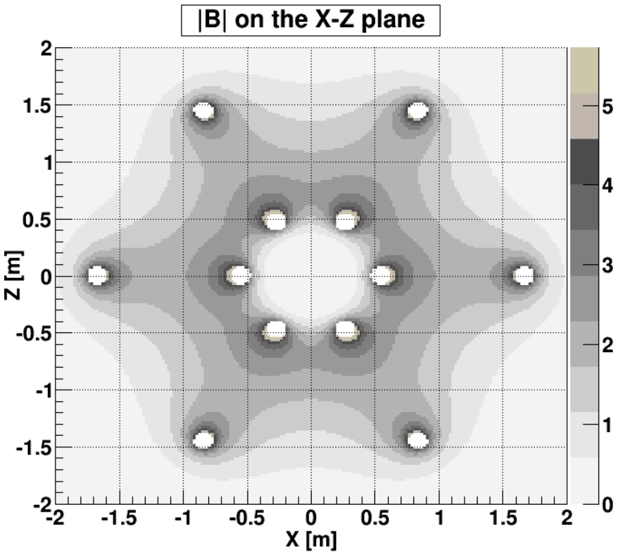


3 spire

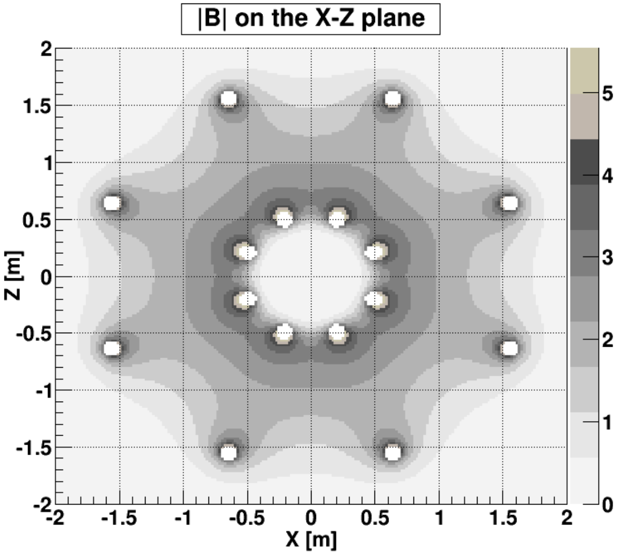


4 spire

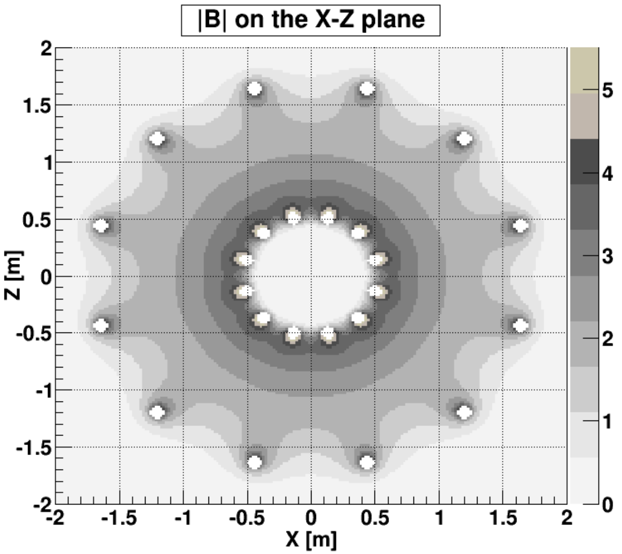
The number of coils can be optimized



6 spire

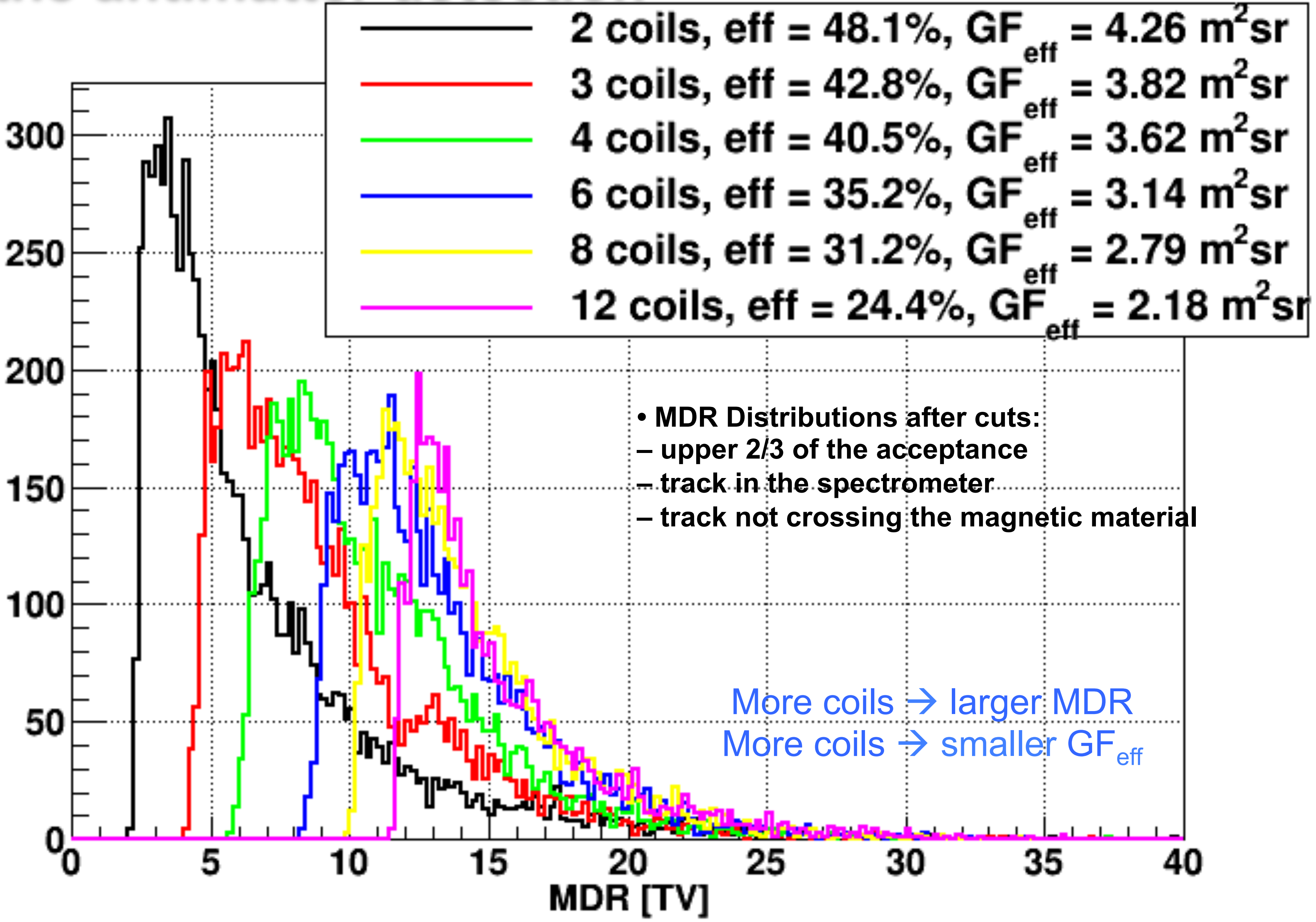


8 spire



12 spire

MDR: a way to estimate the performance in the antimatter detection



- MDR Distributions after cuts:
  - upper 2/3 of the acceptance
  - track in the spectrometer
  - track not crossing the magnetic material

More coils → larger MDR

More coils → smaller GF$_{eff}$