

From Balloon Flights to Space Missions: The Evolution of Direct Cosmic-Ray Measurements

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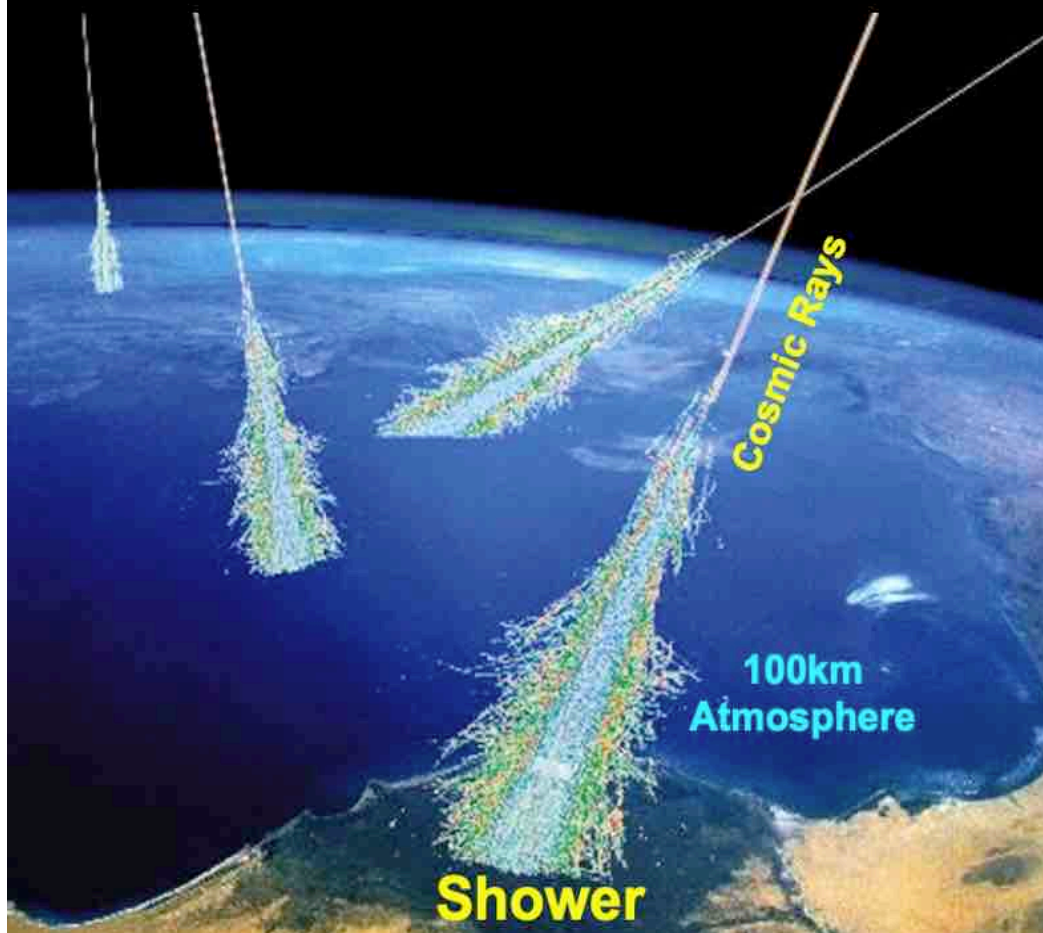
Overview



- A brief historical introduction
- Cosmic-ray direct detection: from balloons to space
- Electron and positron measurements
- Spectral structures in the energy spectra of p, He, and heavier nuclei
- Flux ratios of secondaries/primaries, primaries/primaries
- A glimpse to future direct measurements of VHE cosmic rays

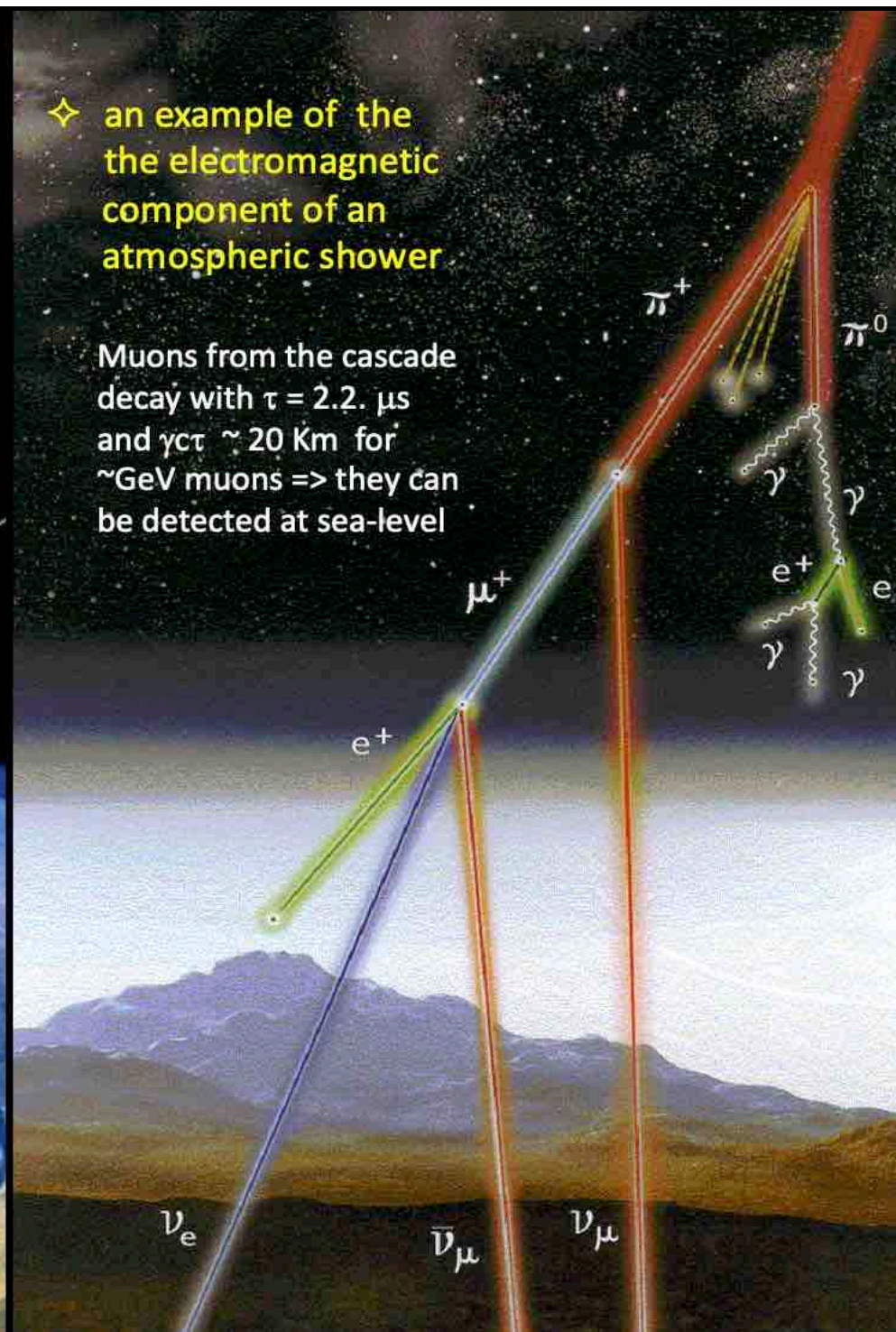
GENERATION OF SHOWERS IN THE ATMOSPHERE

- ✧ hadronic showers generated by cosmic rays impinging on top of the atmosphere



- ✧ an example of the the electromagnetic component of an atmospheric shower

Muons from the cascade decay with $\tau = 2.2 \mu\text{s}$ and $\gamma\tau \sim 20 \text{ Km}$ for $\sim \text{GeV}$ muons \Rightarrow they can be detected at sea-level



COSMIC RAYS: DIRECT AND INDIRECT MEASUREMENTS

- **SPACE-BORNE**

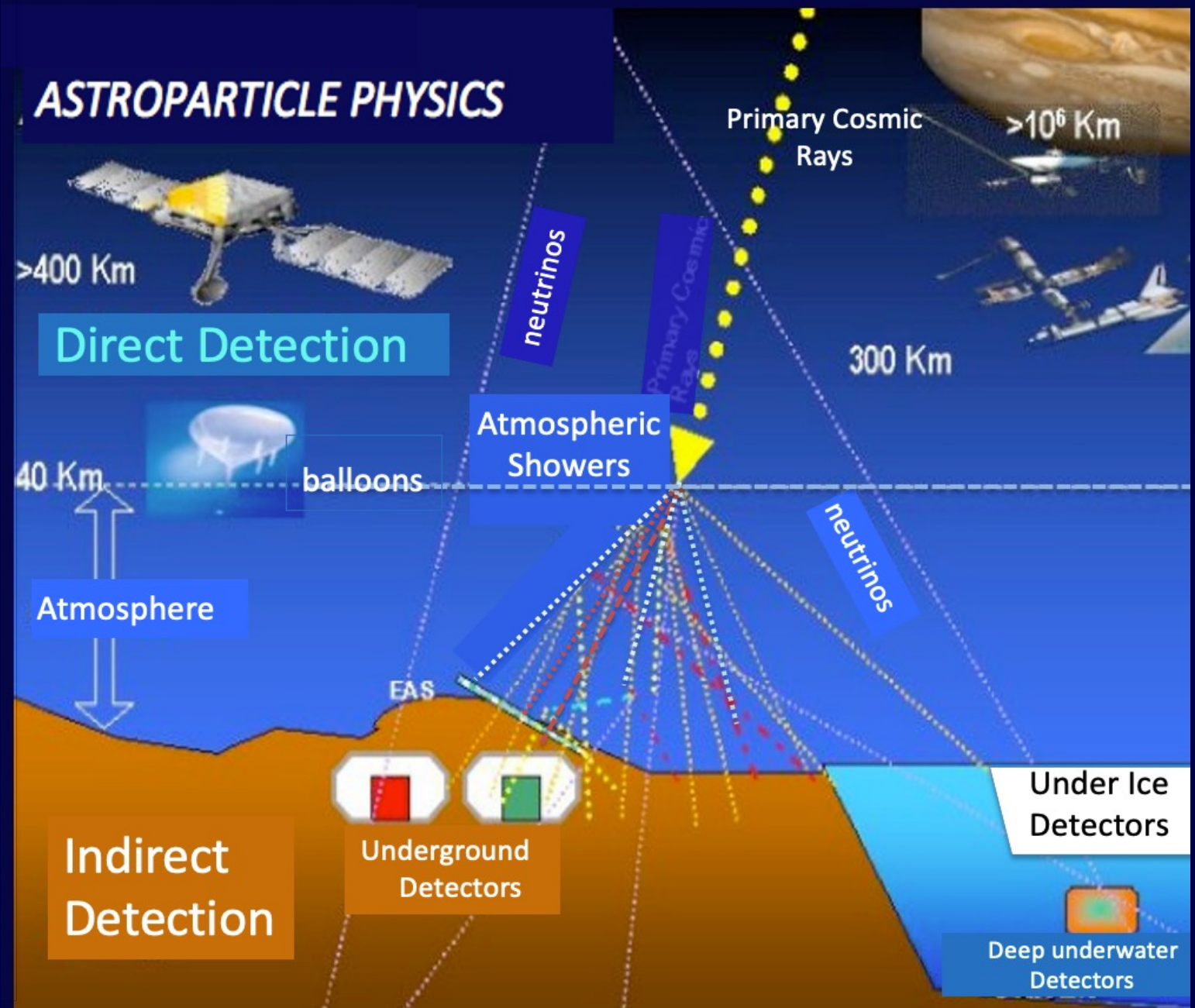
- free-flyers
- International Space Station (ISS)

- **BALLOON-BORNE**

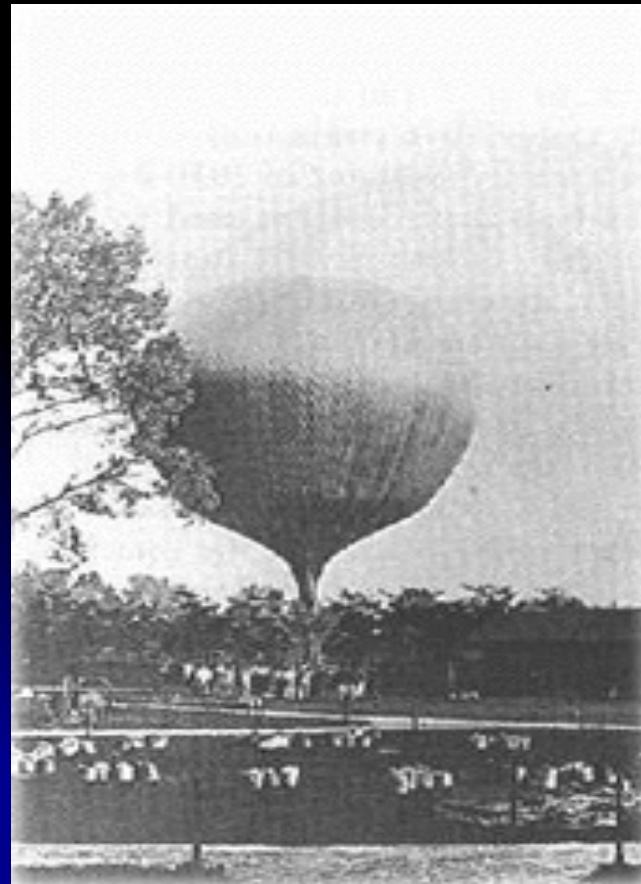
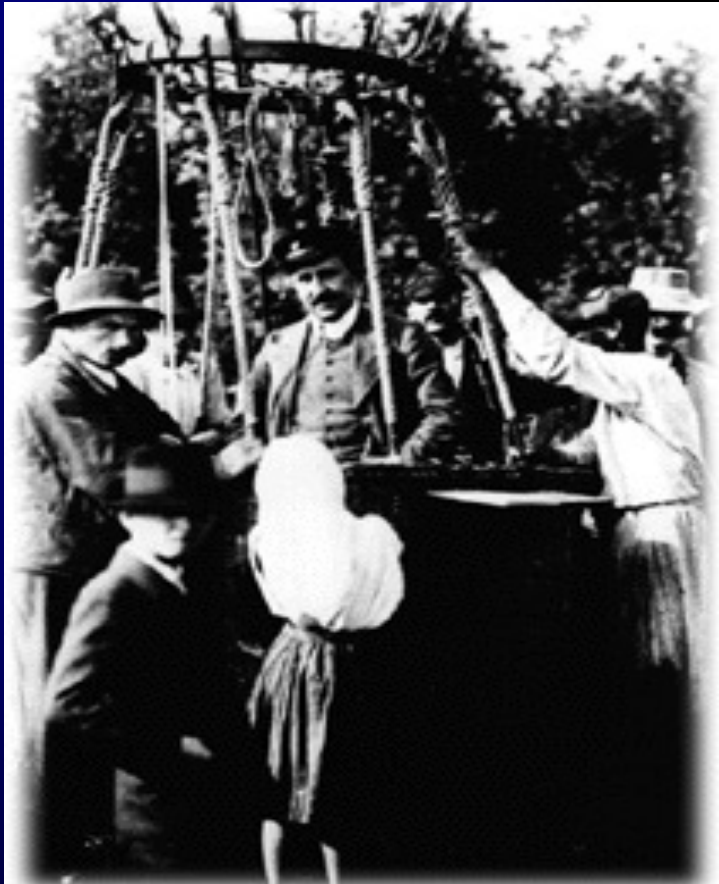
- Long Duration (LDB)
- Ultra Long (ULDB)

- **GROUND-BASED**

- Air Cherenkov
- Extensive Air Shower
- Under-ground
- Under-water
- Under-ice

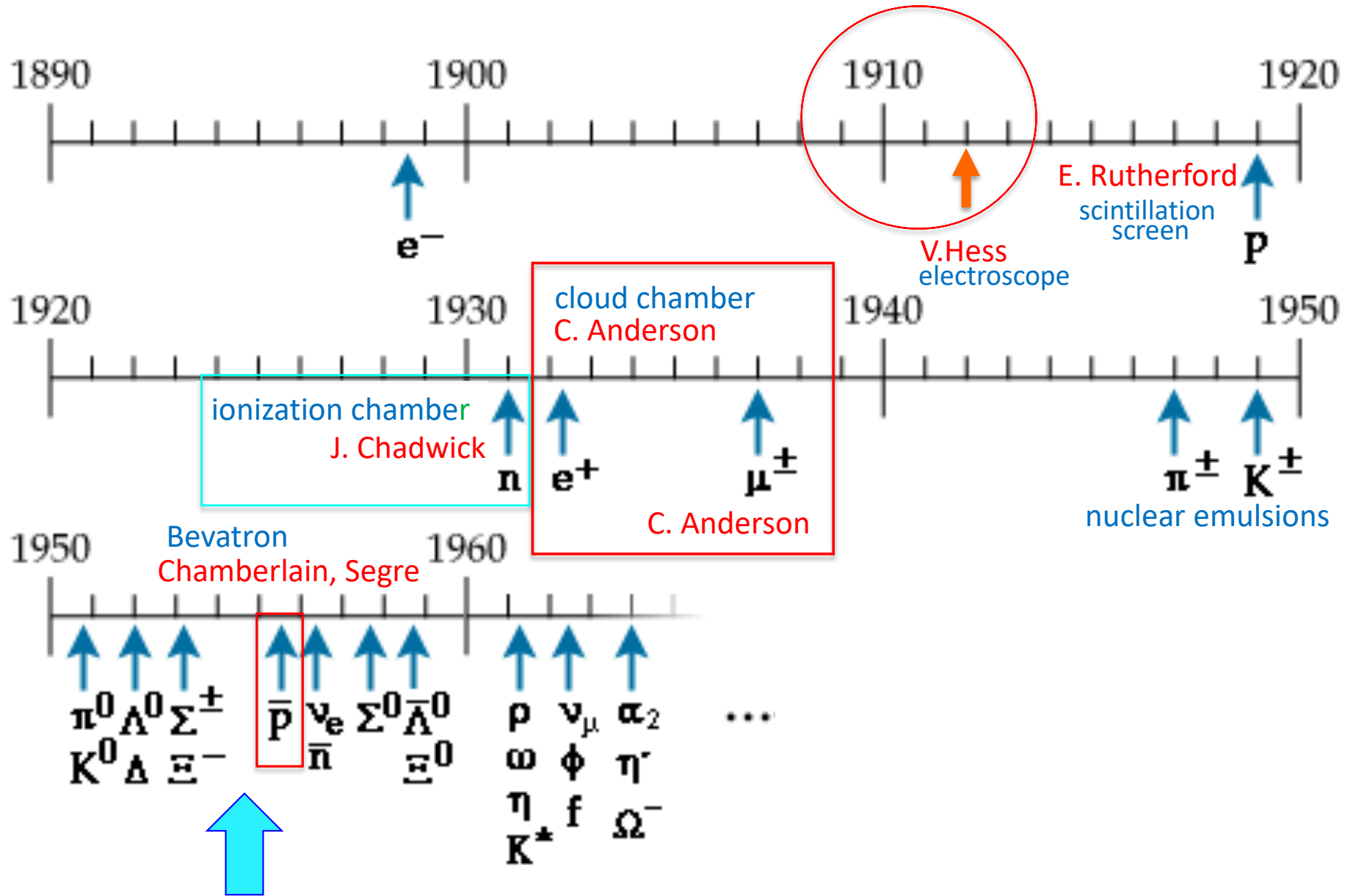


It all started with balloons !



In 1912 the Austrian physicist Victor Hess carried out measurements, at different altitudes in the atmosphere, of the intensity of the mysterious ionizing radiation that had been observed at sea level. Taking serious risks (no oxygen mask), he reached an altitude ~ 6500 m aboard a balloon and measured an INCREASE of the radiation flux with altitude: just the OPPOSITE of what the current expectations were at the time !

Particle Physics was born MUCH LATER than the discovery of COSMIC RAYS



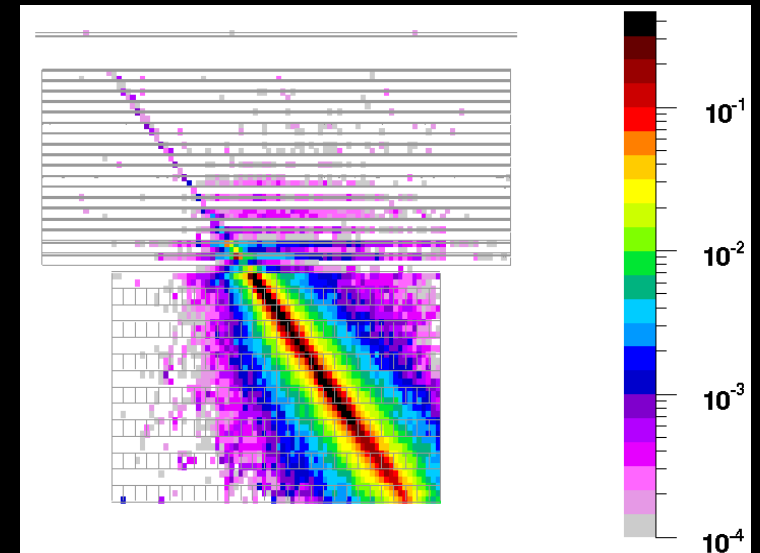
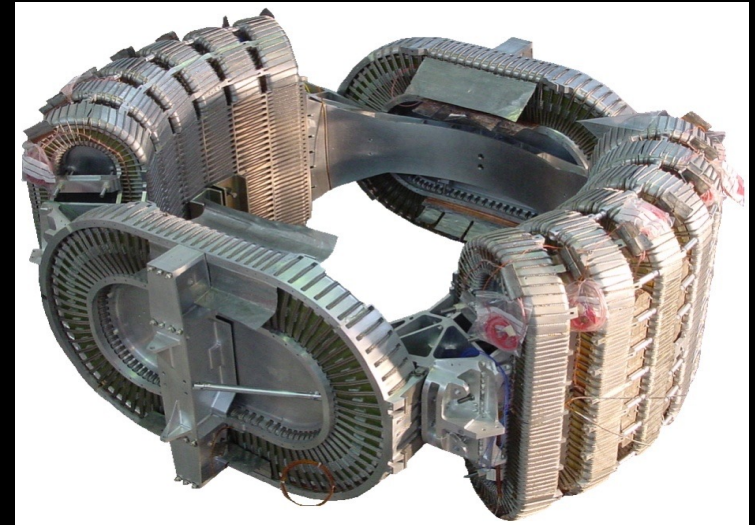
First experiments at particle accelerators

Direct measurements of cosmic rays

7

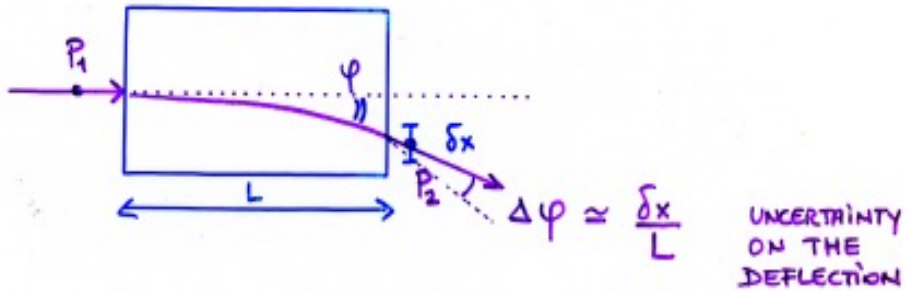
Two broad classes of instruments providing:

- measurement of **momentum**:
 - **Magnetic spectrometers**: magnet + tracker
 - permanent magnetization
 - super-conducting coils
 - Earth magnetic field (at low rigidity)
- **Separation between positive and negative charges**
- measurement of **energy**:
 - **Calorimeters** (homogeneous / sampling)
 - Transition Radiation Detectors (TRDs)
- **No sign-of-charge discrimination**



Example 1. (over simplified)

- One point P_1 known with infinite precision before the magnet
- One point P_2 measured with (point resolution) accuracy δx after the magnet



- The uncertainty on the transverse momentum comes from the uncertainty on the deflection

$$\delta\left(\frac{1}{p}\right) = \delta\left(\frac{\varphi}{L}\right) = \frac{\delta\varphi}{L} = \frac{\delta x}{L^2}$$

Then:

$$\frac{\delta p_T}{p_T^2} \approx \frac{1}{0.3 B} \frac{\delta x}{L^2}$$

$$\frac{\delta p_T}{p_T} \approx \left(\frac{p_T}{0.3}\right) \frac{\delta x}{BL^2}$$

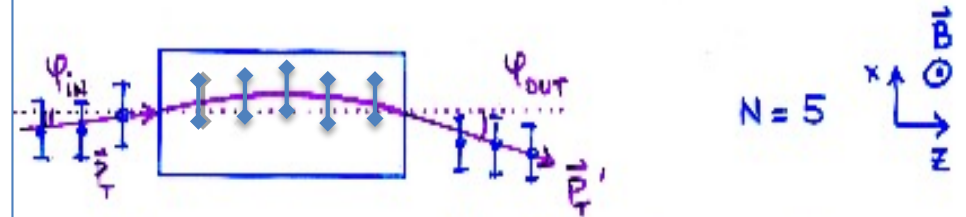
important scale factor

B (Tesla)
 p_T (GeV/c)
 L (m)



Example 2. (neglecting MS)

- NO MULTIPLE SCATTERING
- TRACKING SYSTEM WITH $N+1$ MEASUREMENTS WITH ACCURACY δx



• IN THIS CASE: $\frac{p_T' - p_T}{p_T} = \frac{L}{p} = \sin\varphi_{out} - \sin\varphi_{in}$

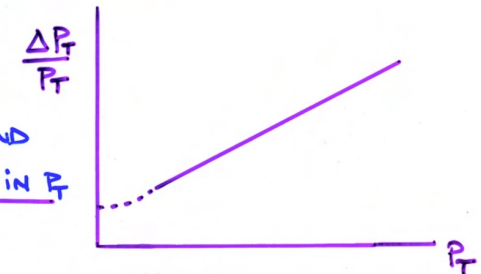
• THE p_T RELATIVE ERROR: $\frac{\delta p_T}{p_T} \approx \frac{p_T \delta x}{0.3 BL^2} \sqrt{A_N}$

WHERE A_N IS A STATISTICAL FACTOR THAT DEPENDS ON: [Gluckstern, NIM 24, 381 (1963)]

- THE NUMBER $N+1$ OF INDEPENDENT MEASUREMENTS
- THE GEOMETRY OF THE "TRACKING SYSTEM"

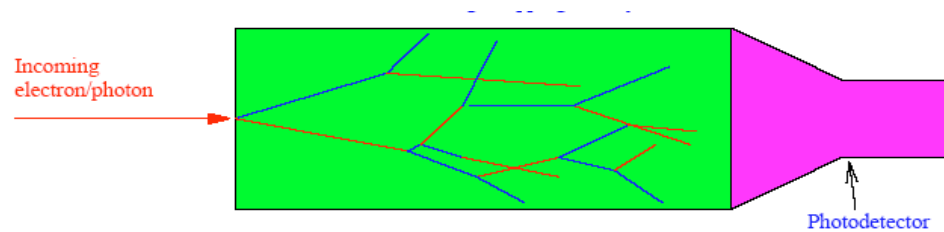
- THESE RESULTS HOLD WHEN THE CONTRIBUTION OF THE MULTIPLE SCATTERING (MS) IN THE MATERIAL TRAVERSED BY THE PARTICLE IS NEGLECTIBLE

- AT LOW p_T THIS IS NO LONGER TRUE AND $\frac{\Delta p_T}{p_T}$ IS NOT LINEAR IN p_T



Homogeneous calorimeters:

absorber is the active medium for detection



Absorber detector

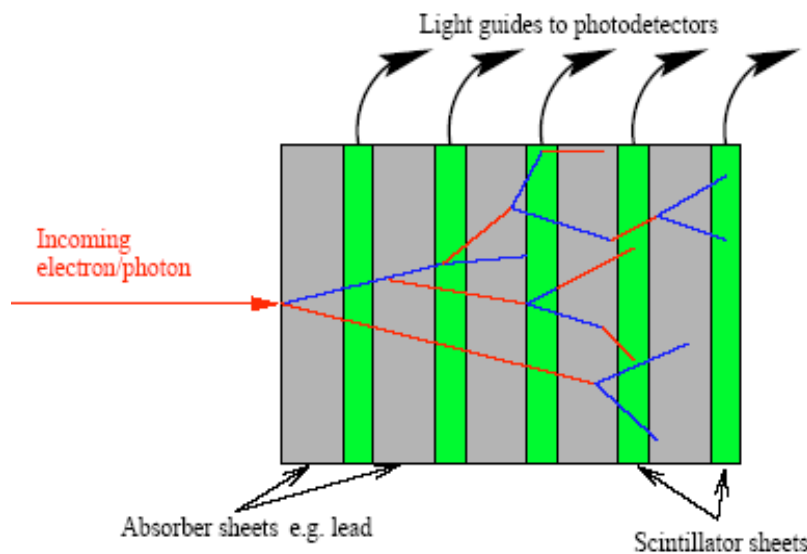
e.g.: BGO, CsI crystals, Lead Glass etc...



crystal calorimeters
are more expensive

Sampling calorimeters:

alternate structure absorber + active medium



Absorber

Pb, Tungsten, Uranium, etc...

Detector

e.g.: scintillators, SciFibers, silicon pads, MWPC, etc...

cost effective

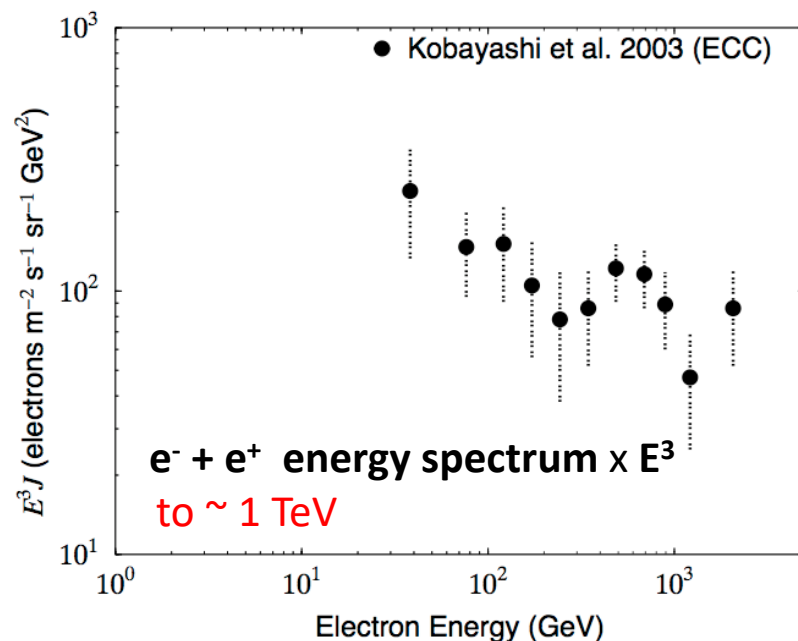
- Shower sampled by layers of **active media (low-Z)** alternated with **dense (high-Z)** passive absorbers
- Only a fraction of the shower energy is collected by the active media
- Energy resolution affected by fluctuations in energy deposited in the active layers: **sampling fluctuations**

The early days of cosmic-ray balloons

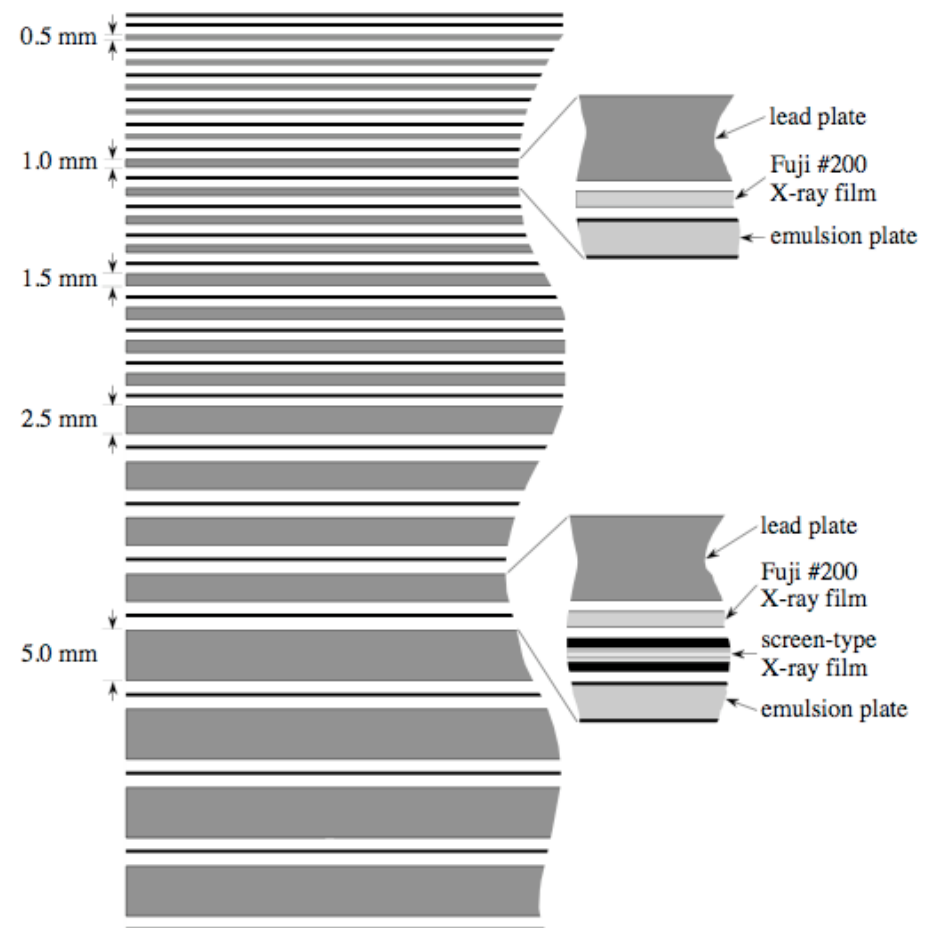


Passive imaging instruments

- 13 Balloon flights in 1968-2001
 - From Sanriku, Japan, etc.
- Exposure time = 270hr
- Altitude = $\sim 4\text{-}9 \text{ g/cm}^2$
- $S\Omega = \sim 3.8 \times 10^3 \text{ cm}^2 \text{ sr}$
- $e^- + e^+$ (no separation)

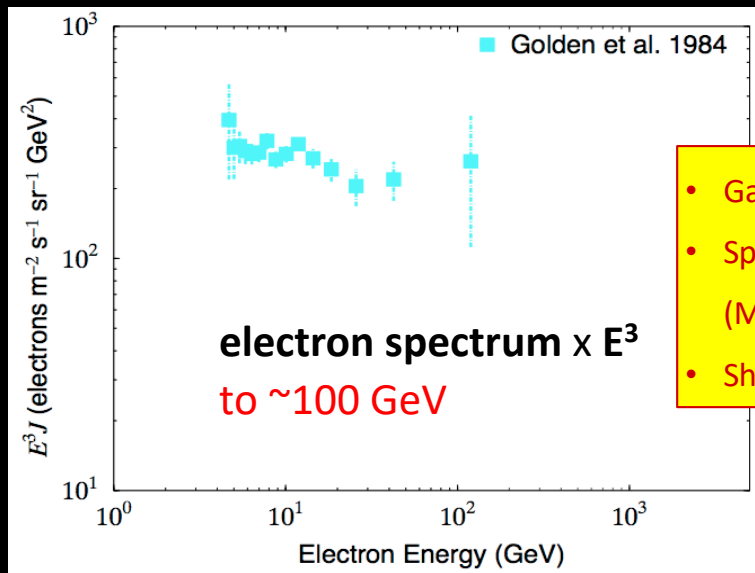


Emulsion Chambers

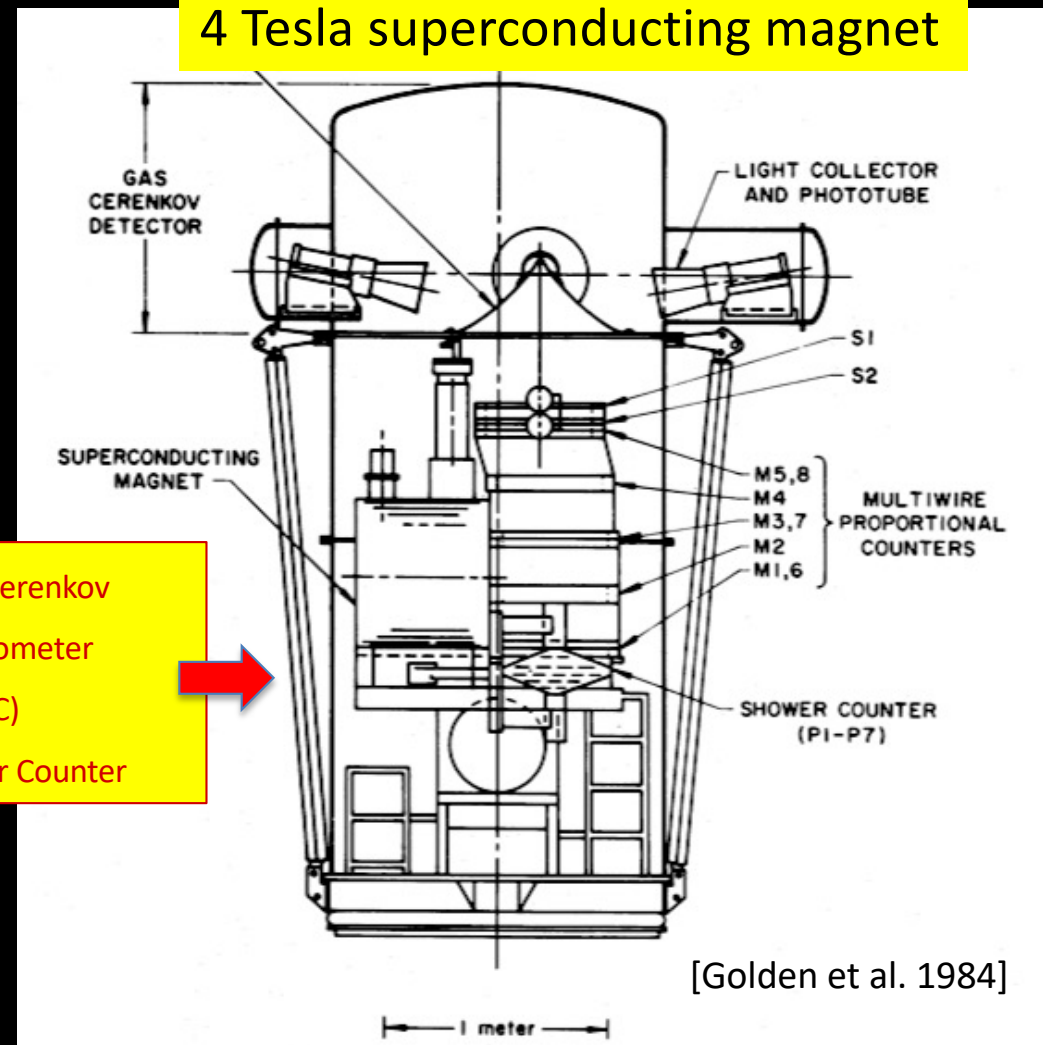


Golden's balloon-borne superconducting magnetic spectrometer

- Balloon flight in **1976** from Palestine, U.S.A.
- Exposure time = **19hr**
- **Altitude: $\sim 5.8 \text{ g/cm}^2$**
- **$S\Omega = 324 \text{ cm}^2\text{sr}$**
- e^- (separated from e^+)

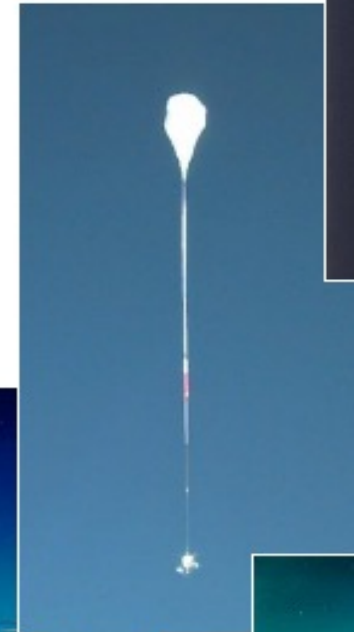
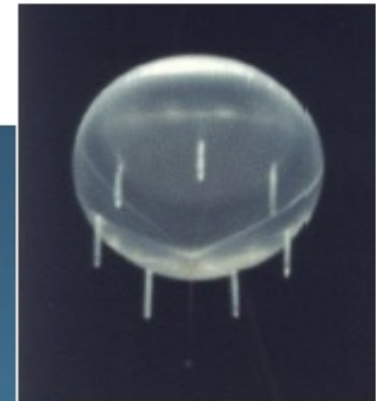


- Gas Cherenkov
- Spectrometer (MWPC)
- Shower Counter



Balloons in the '90s

- ▶ Extensive campaign of **daily balloon flights** operated by several groups
 - ▶ **Wizard** (MASS, TS, CAPRICE) **large Italian contribution**
 - ▶ **BESS**
 - ▶ Others (HEAT, IMAX...)
- ▶ **Main instrument characteristics**
 - ▶ Superconducting magnets ($\sim 1T$ field)
 - ▶ MWPC & drift chamber tracking systems ($O(100\mu m)$ resolution)
 - ▶ MDR $\sim 100 \div 300$ GV

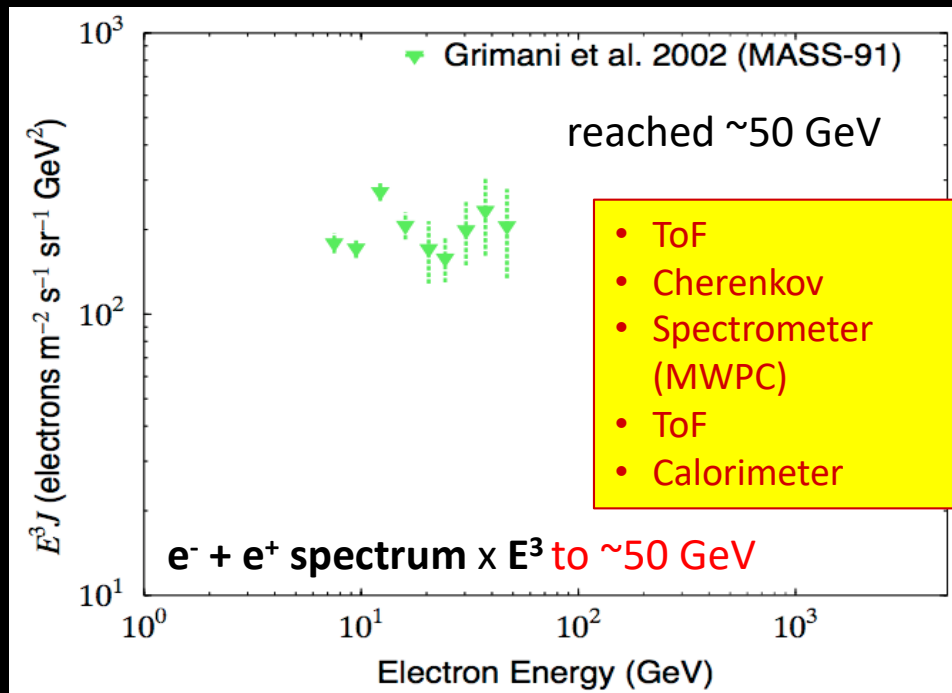


courtesy of
E. Vannuccini
ISSS-2017

Balloon-borne magnetic spectrometers

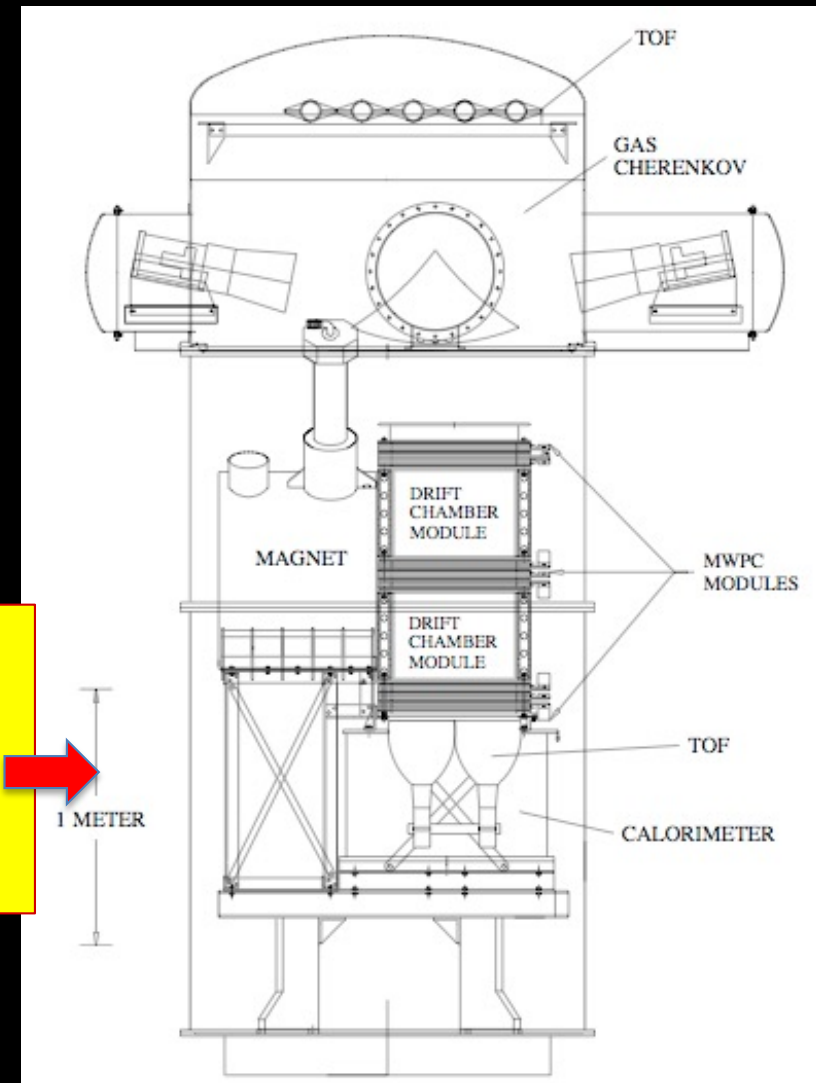
MASS-91

- Balloon flight in **1991**
- From Fort Sumner, U.S.A.
- Exposure time = **~10hr**
- Altitude = **~5.8 g/cm²**
- **$S\Omega = 182 \text{ cm}^2\text{sr}$**



- ToF
- Cherenkov
- Spectrometer (MWPC)
- ToF
- Calorimeter

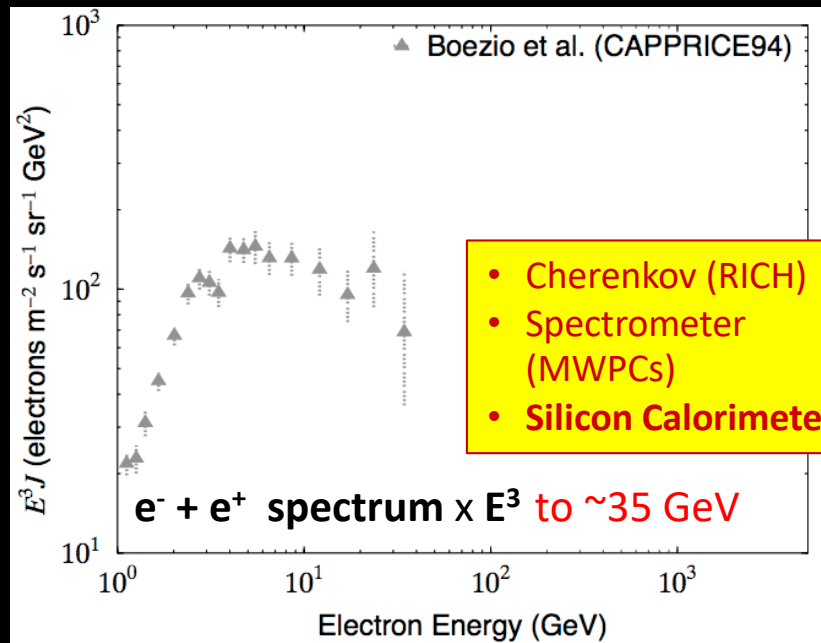
2.2 Tesla superconducting magnet



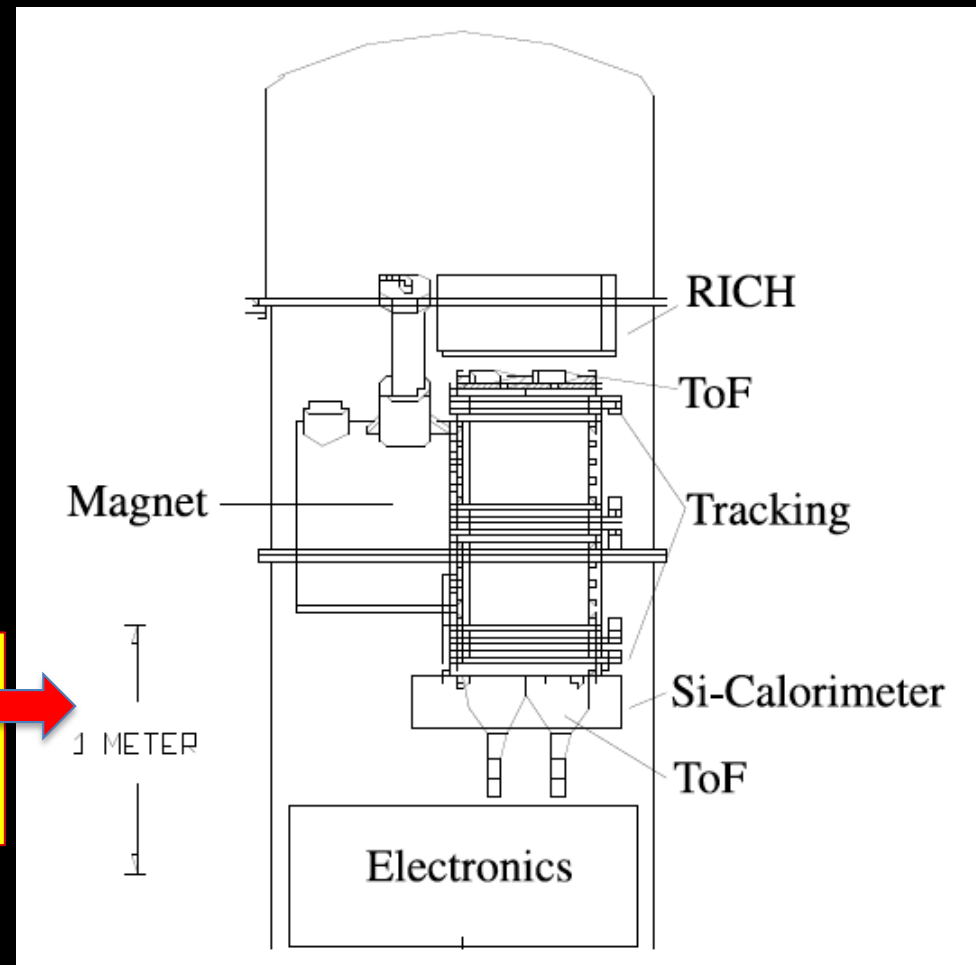
Balloon-borne magnetic spectrometers

CAPRICE94

- Balloon flight in **1994**
 - From Lynn Lake, Canada
- Exposure time = **~18hr**
- Altitude = **~3.9 g/cm²**
- **$S\Omega = \sim 170 \text{ cm}^2\text{sr}$**
- **e⁻, e⁺ (separated)**



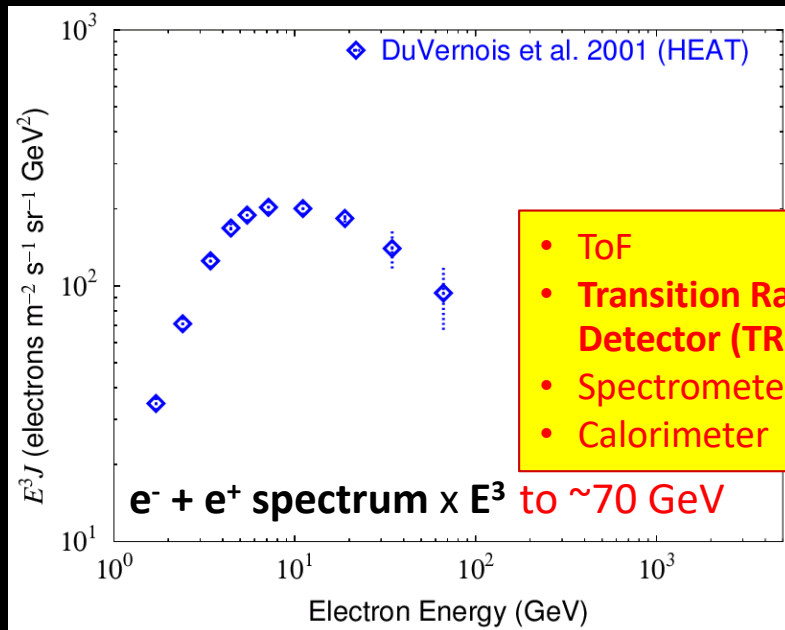
4 Tesla superconducting magnet



Balloon-borne magnetic spectrometers

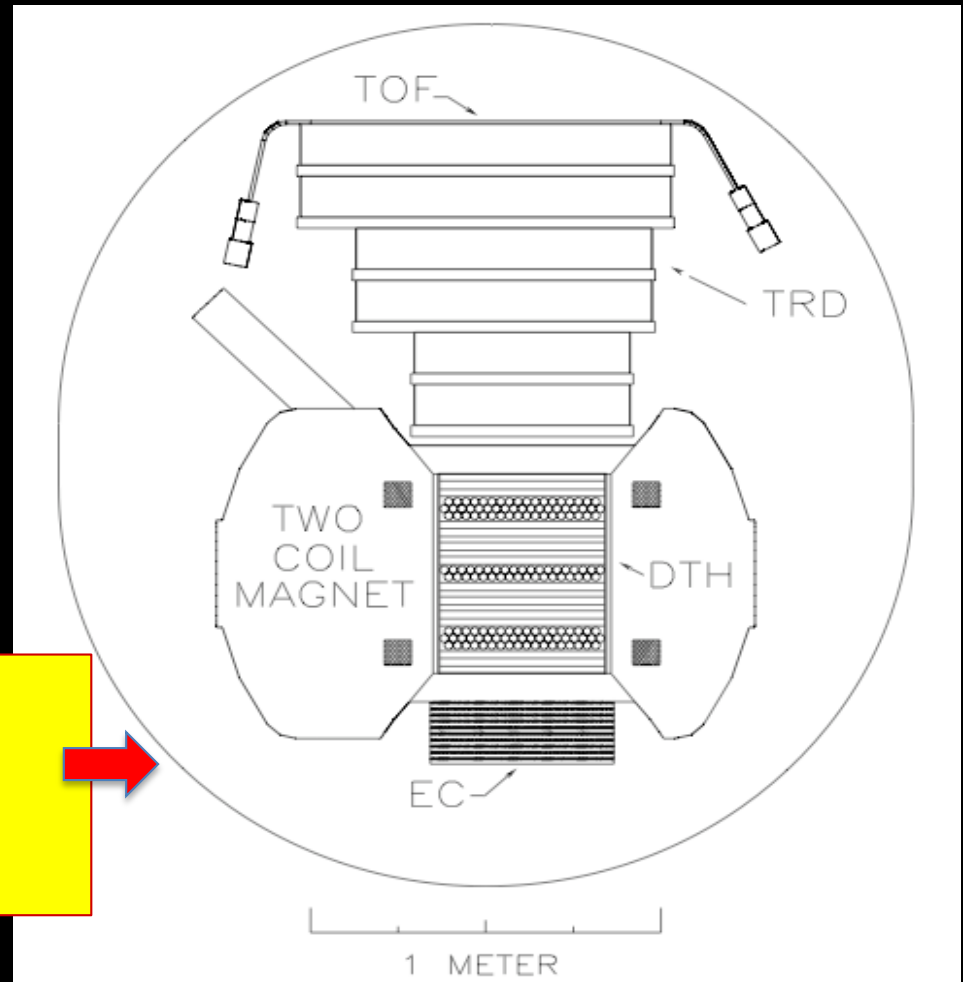
HEAT (1994-95)

- Launches from Fort Sumner, Lynn Lake
- Exposure time = 55hr
- Altitude = 5~6 g/cm²
- $S\Omega = 495 \text{ cm}^2\text{sr}$
- e⁻, e⁺ (separated)



- ToF
- Transition Radiation Detector (TRD)
- Spectrometer
- Calorimeter

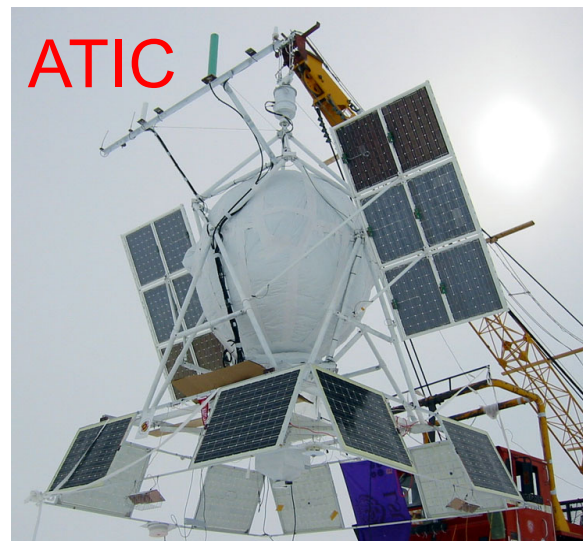
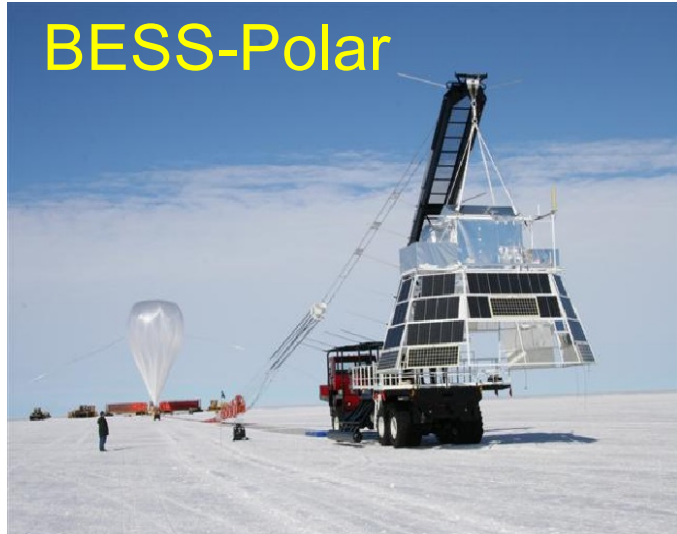
1 Tesla superconducting magnet



Scientific ballooning: the new generation



Long Duration Balloon (LDB) experiments



and others...

In the last two decades, direct measurements of VHE cosmic rays have been performed by several instruments flown on NASA Long-Duration Balloons. They are **active** instruments with **hundreds of electronics channels** that usually relay data to ground stations via satellite link (e.g. TRDSS in Antarctica).

BESS-Polar Program

Status of the BESS-Polar I Flight

Observation Time: 8.5 days

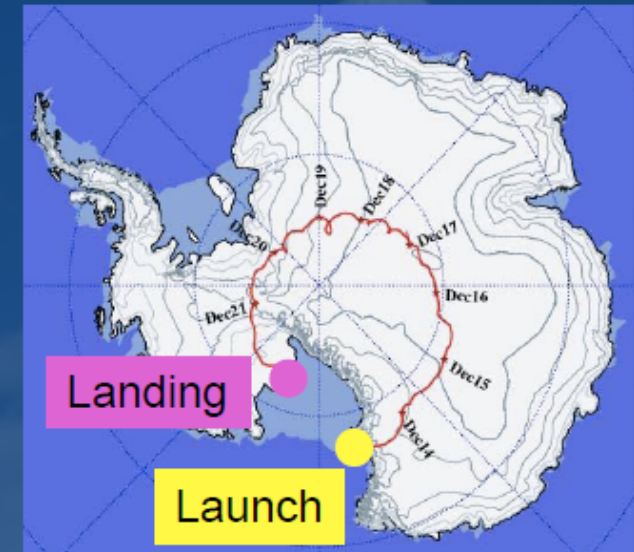
Float Time: 8.5 days (12/13/2004-12/21/2004)

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

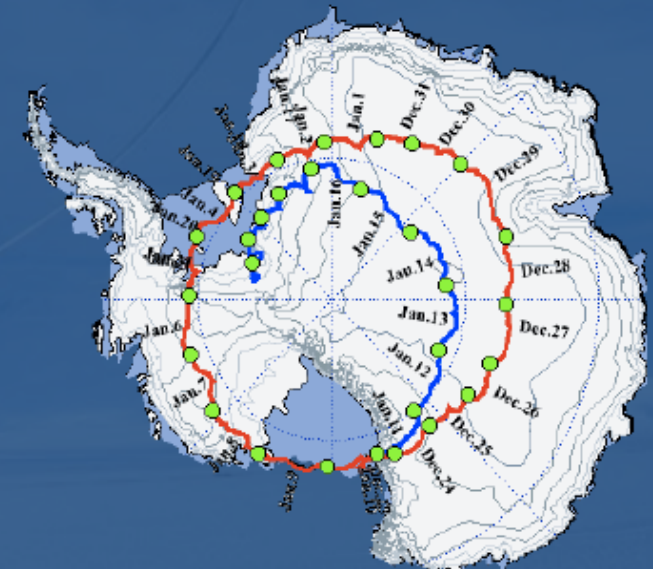
Float Time: 29.5 days (12/23/2007-01/21/2008)

Events recorded: > 4.7×10^9

Data volume: ~ 13.5 terabytes

Data recovery: **completed** Feb 3, 2008

Payload recovery: **completed** Jan 16, 2010

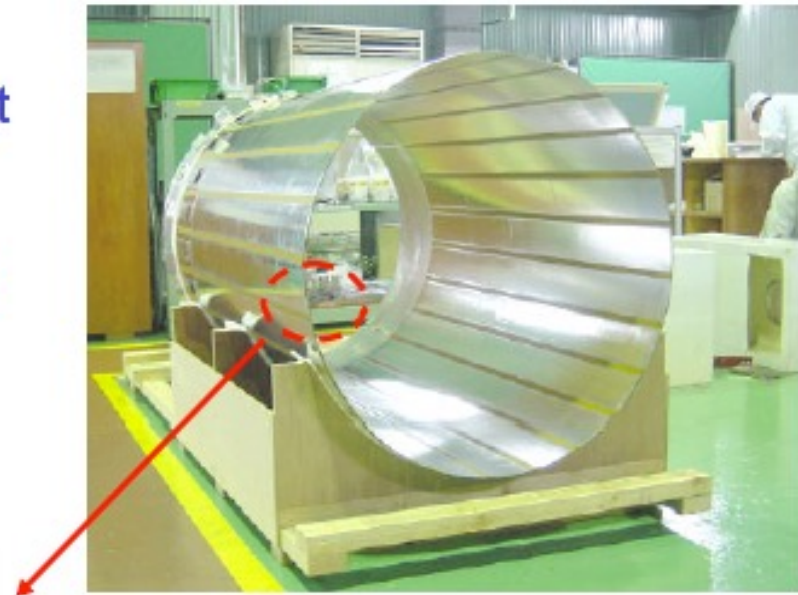


Magnet

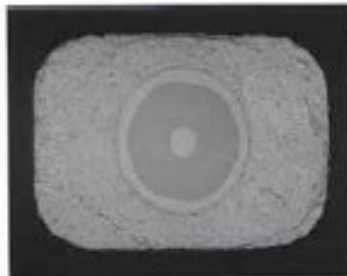
Newly developed ultra-thin superconducting solenoidal magnet

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/cm²** (half of previous **BESS**).



Previous BESS
(4 layers)



BESS-Polar
(2 layers)

very important technological achievement !

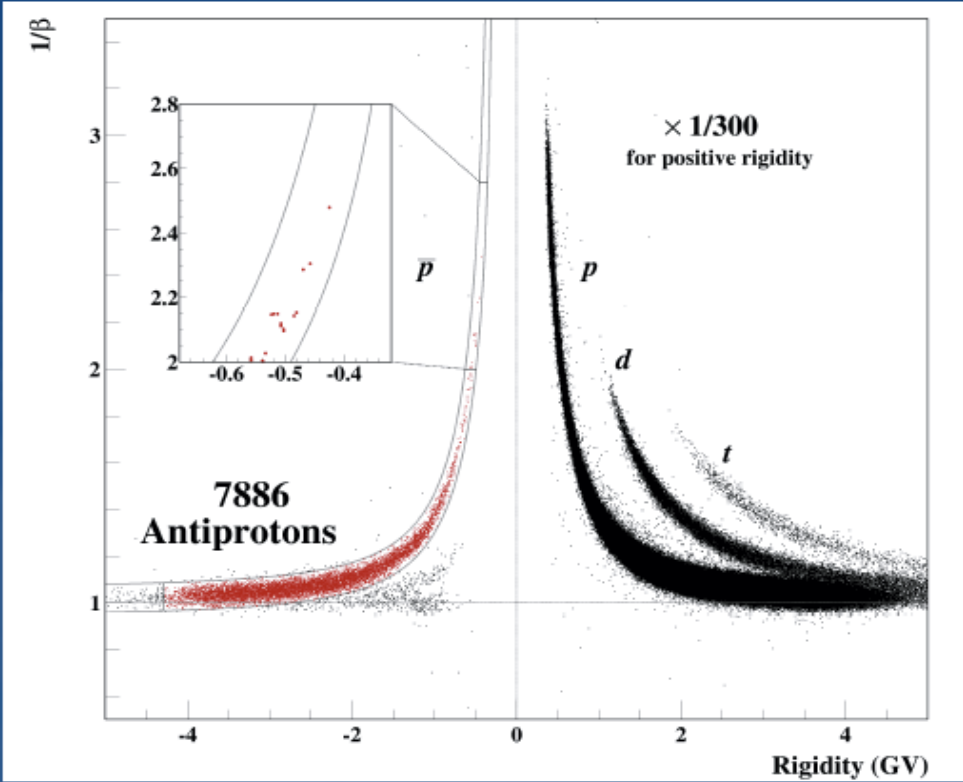
- Flying a **super-conducting** magnet on a balloon or in space *for a significant amount of time* is a considerable technical challenge

An example: the complexity of the **cryostat** of the BESS-Polar II balloon experiment

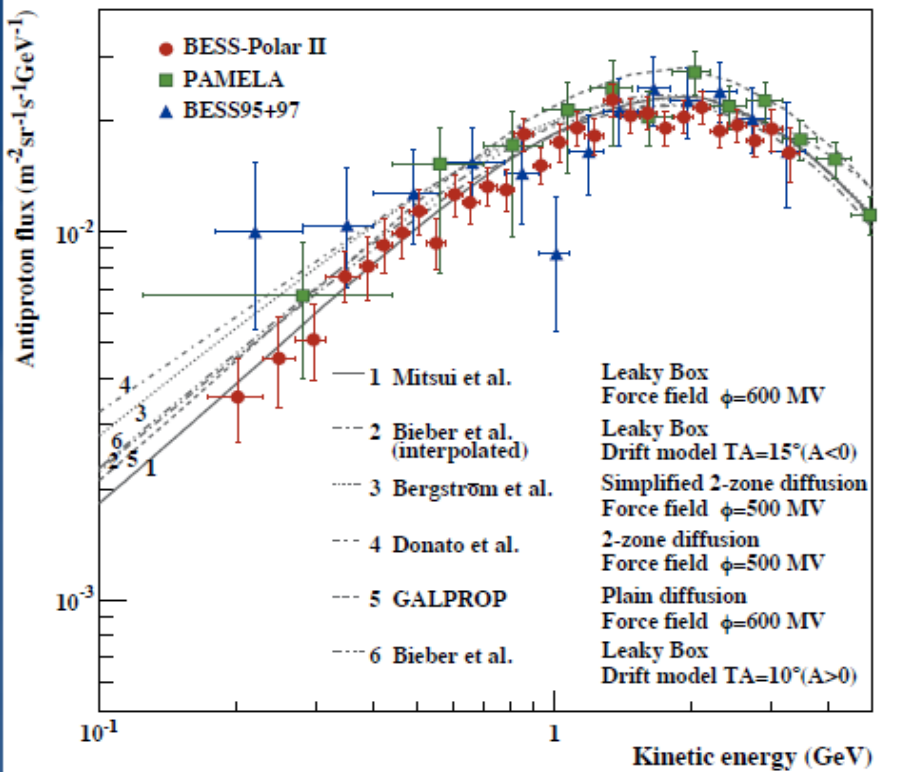


Antiproton Measurement

BESS-Polar II Z=1 Particle Id



Antiproton Spectrum



- MDR 240 GV, TOF 120 ps, ACC rejection 6100
- 7886 Antiprotons ~10-20 times previous Solar minimum dataset

- BESS-Polar II and PAMELA spectra agree in shape but differ ~14% in absolute flux
- Both agree in shape with secondary

TRACER

Transition Radiation Array
for Cosmic Energetic Radiation

VERY LARGE: 2m x 2m x 1.2m

2 flights:

ANTARCTICA 2003 (14 days)

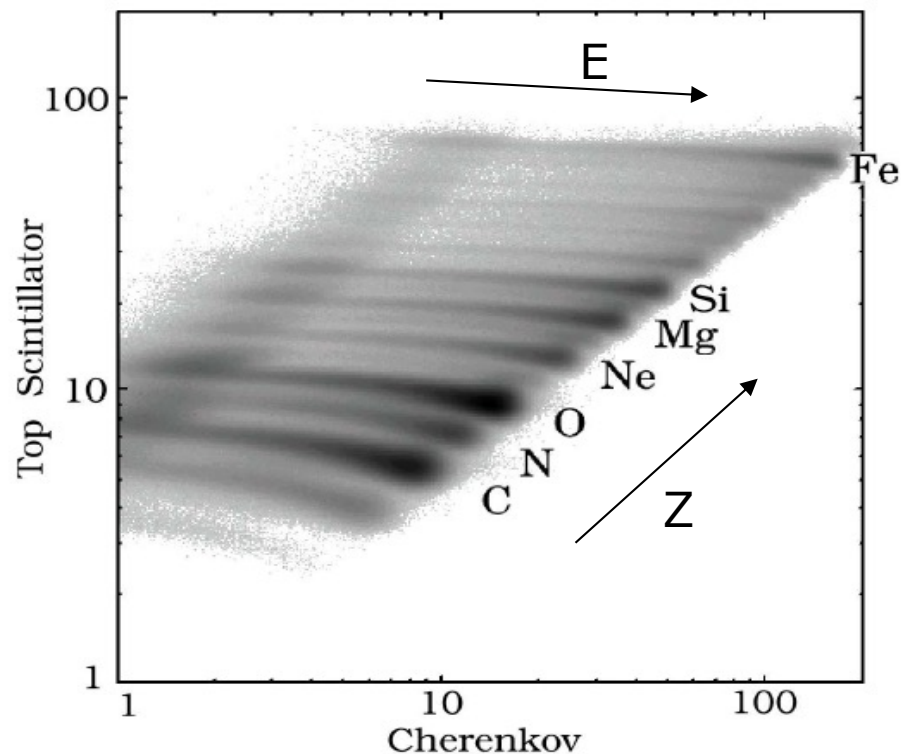
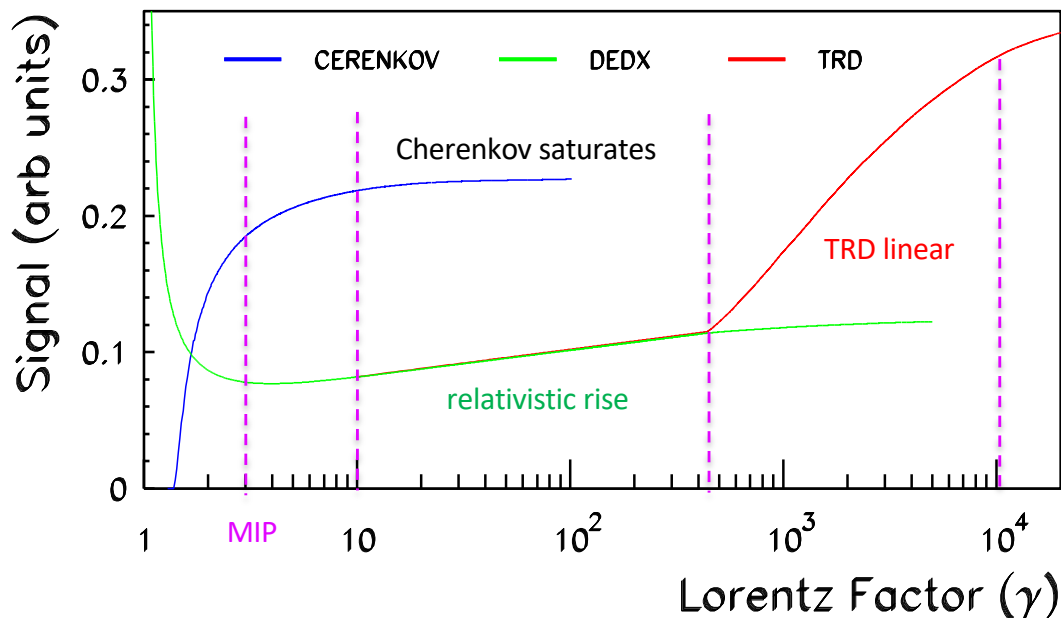
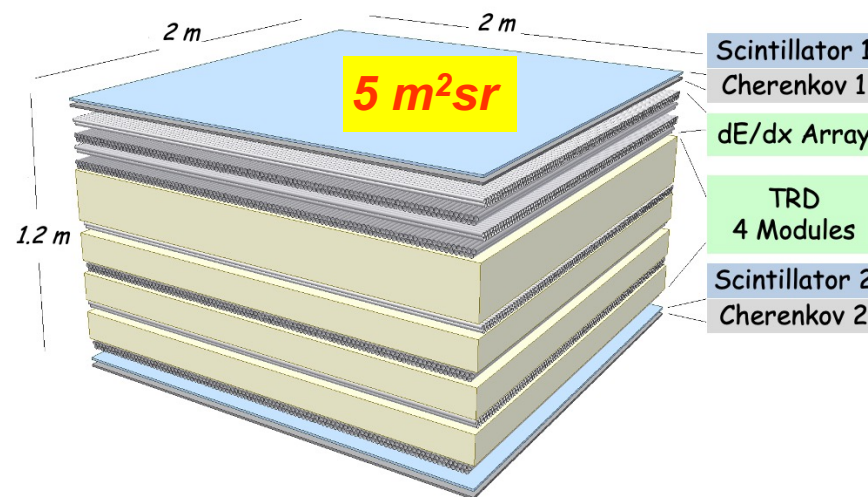
SWEDEN to CANADA 2006 (5 days)



TRACER Instrument

Measure Z, E via electromagnetic processes:

- **Acrylic Cherenkov Counter ($\gamma < 10$)**
- **Specific Ionization in Gas ($4 < \gamma < 1000$)**
1600 proportional tubes, 2 cm diam., 2 m long
- **Transition Radiation Detector ($\gamma > 400$)**
- **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**



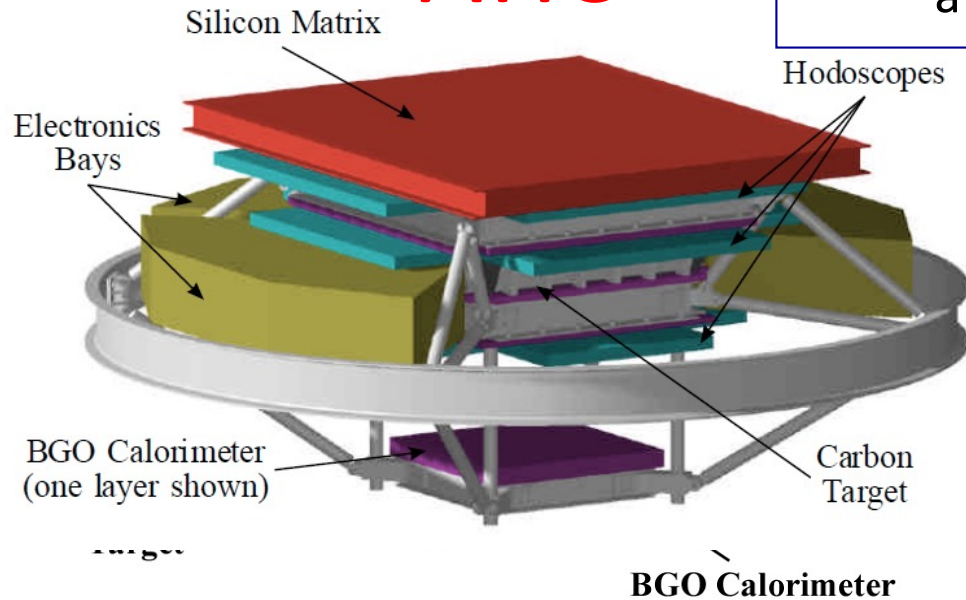
Scientific ballooning from Antarctica

Mount Erebus
(active volcano)

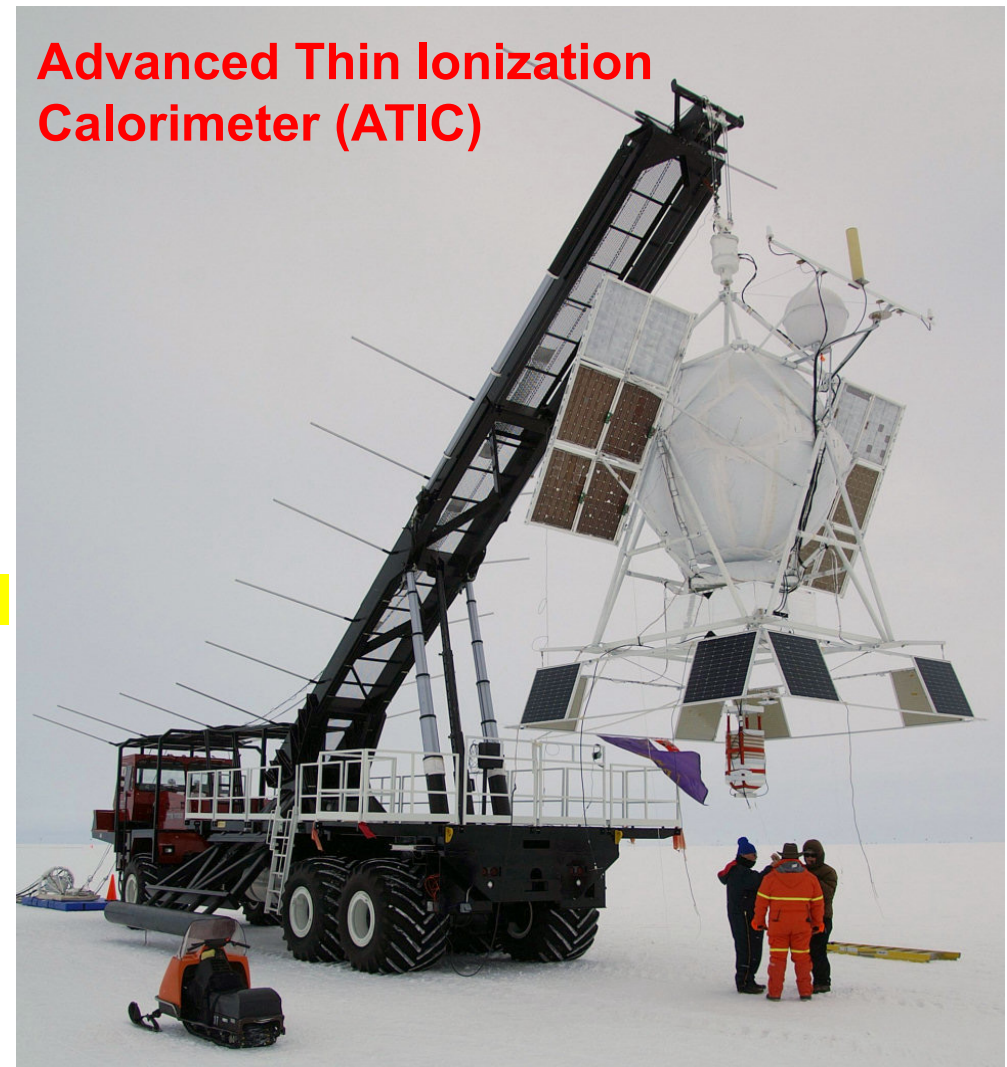
Mc Murdo - Antarctica

ATIC

Balloon-borne **calorimetric** experiment with a large number of electronics channels



Advanced Thin Ionization Calorimeter (ATIC)



3 successful antarctic flights: **2000, 2002, 2007**
(~57 days in total)

Si-Matrix: 4480 pixels (each 2 cm x 1.5 cm) to measure GCR charge in presence of backscattered shower particles.

Plastic scintillator hodoscope, embedded in Carbon target, provides event trigger, charge and particle tracking.

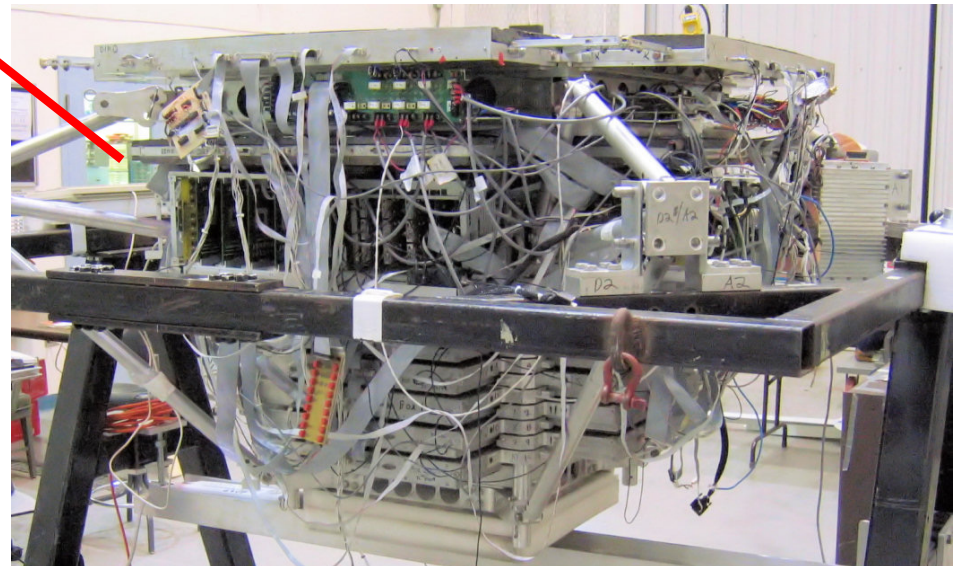
Calorimeter: 10 layers BGO crystals, 40 per layer. Total depth $22 X_0$, 1.14λ . Measure the electromagnetic core of the nuclear shower.

Geometrical factor: $0.45 \text{ m}^2 \text{ sr}$ (calorimeter top) to $0.24 \text{ m}^2 \text{ sr}$ (calorimeter bottom)

Advanced Thin Ionization Calorimeter (ATIC)



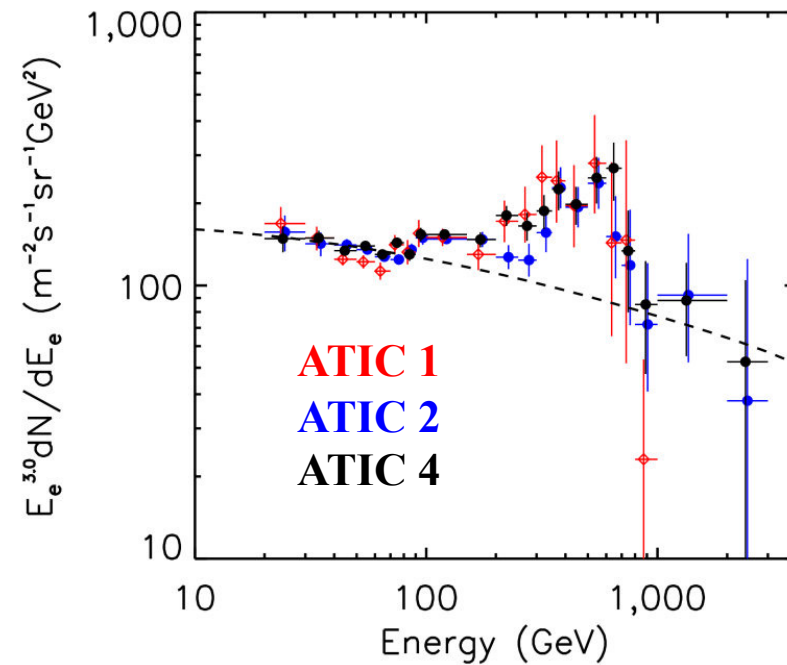
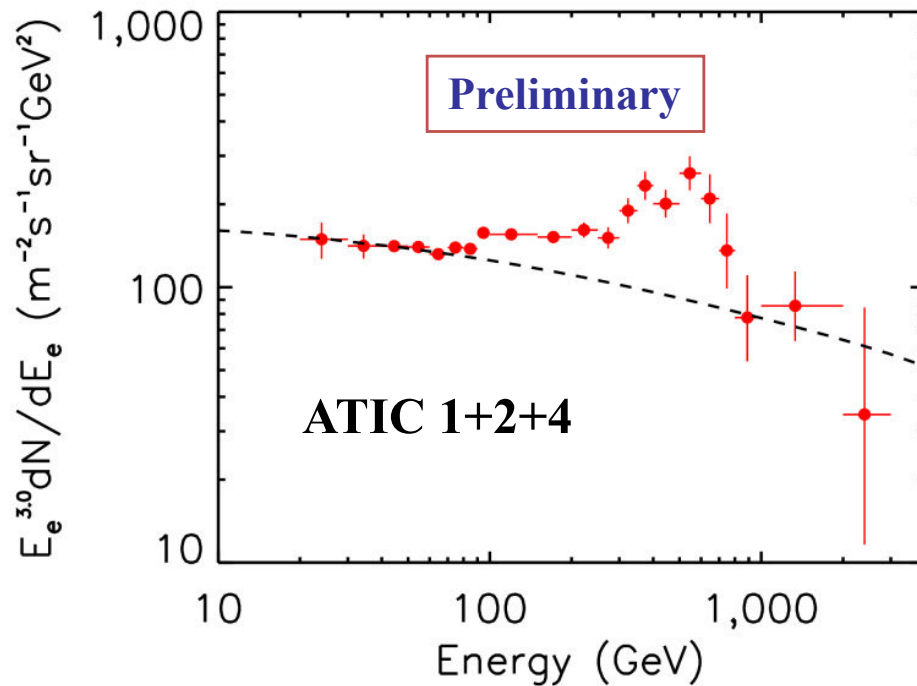
- **Carbon Target**, placed **upstream the ionization calorimeter**, thick enough (30cm, $0.75 \lambda_I$) to induce proton interactions.
- However it is "thin" ($1.5 X_0$) in terms of electromagnetic interactions.



The ATIC “bump” PUZZLE

All three ATIC flights are consistent

from: Joachim Isbert RICAP 2009



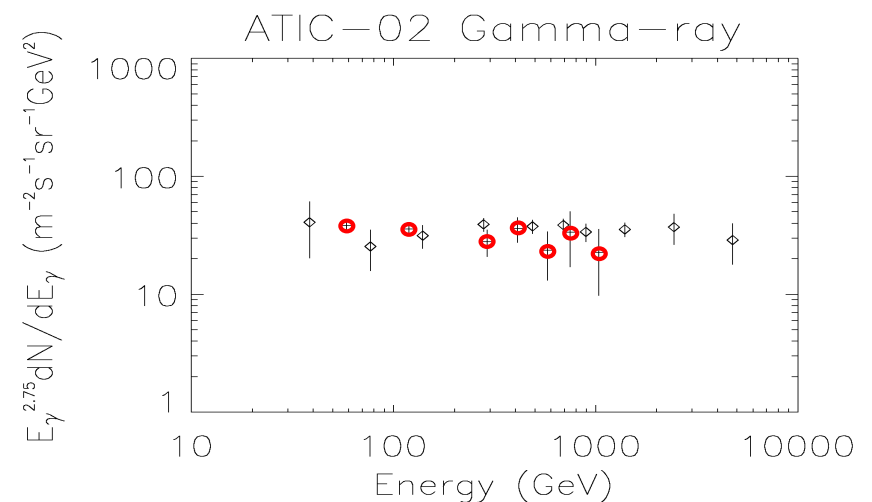
A “Bump” in electron+positron spectrum

was seen in all three flights above 100 GeV.

Significance for ATIC1+2+4 was 5.1 sigma

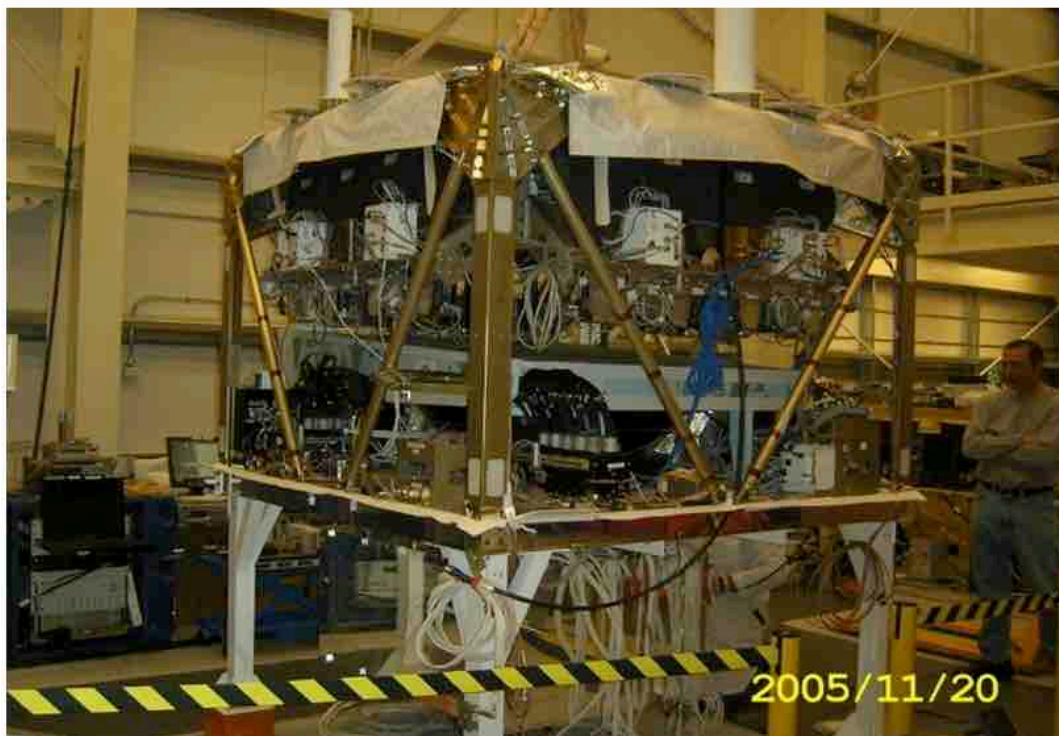
ATIC - atmospheric Gamma-rays:
check using the same electron selection

→ NO BUMP seen in γ -rays

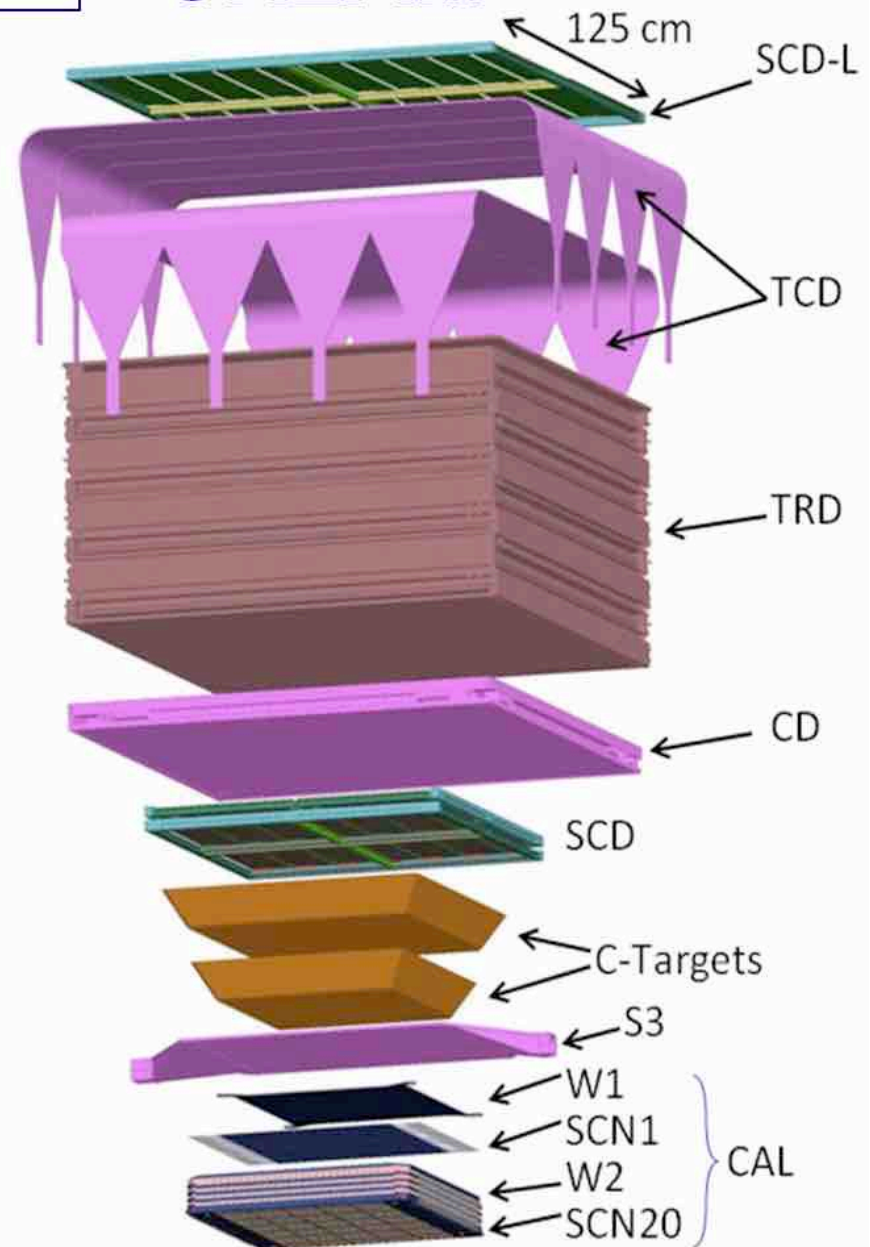


Balloon-borne calorimetric experiments

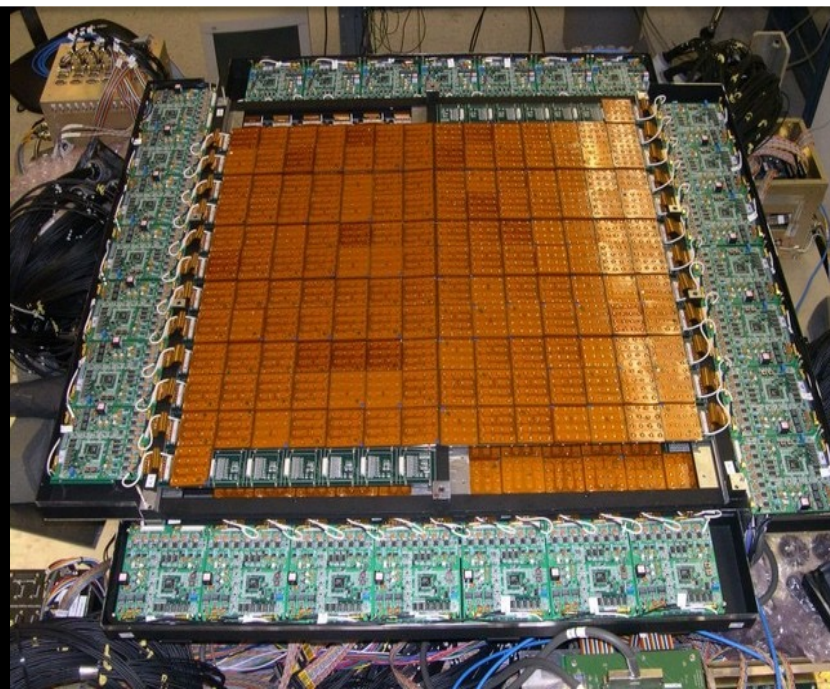
- 3 independent charge measurements
 - Timing-based Charge Detector (TCD)
 - Pixelated Silicon Detector (SCD)
 - Cerenkov counter (CD) and Camera (w/o TRD)
- 2 independent energy measurements + tracking
 - Transition Radiation Detector ($Z > 3$)
 - Tungsten Sci-Fi calorimeter ($Z \geq 1$)
- GF $\sim 0.3 \text{ m}^2 \text{ sr}$ for $Z=1,2$; $\sim 1.3 \text{ m}^2 \text{ sr}$ for $Z>3$



CREAM



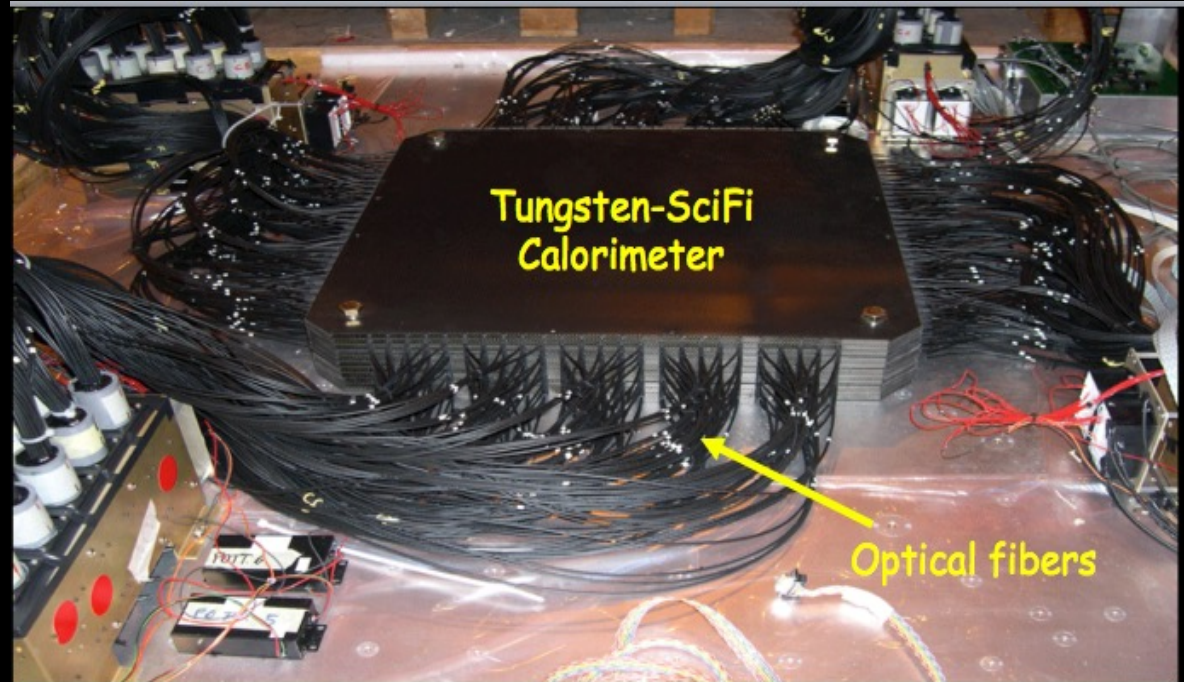
Exploded view: configuration with TRD



Silicon Charge Detector (SCD)

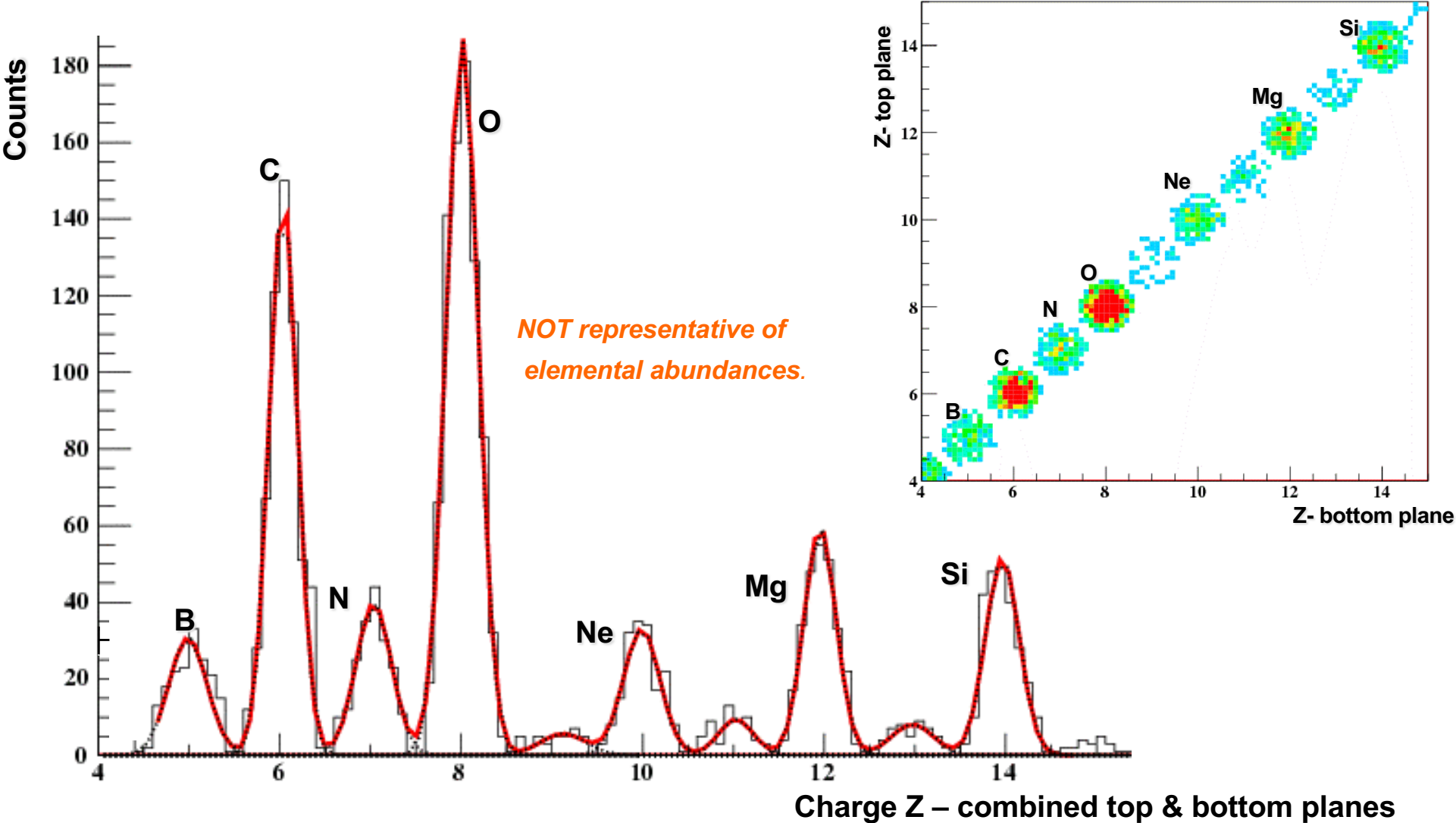
- particle-ID by charge measurement from $Z = 1$ to $Z \sim 33$ ($\sigma \sim 0.1 - 0.2 e$)
- **2 layers** of sensors
- pixel size $\sim 2.1 \text{ cm}^2$
- **16 pixels per sensor**
- 380 mm thick Si sensor
- depletion at 70 V
- Active area per layer $\sim 0.52 \text{ m}^2$
- 2496 chans/layer were readout

Tungsten Scintillating-Fibers Sampling Calorimeter



Preceded by a graphite target ($\sim 0.5 \lambda_{\text{INT}}$) to induce an hadronic interaction
 Active area $50 \times 50 \text{ cm}^2$: **2560** channels (3 gain ranges) readout by **40 HPDs**
 Longitudinal sampling : 3.5 mm Tungsten ($1 X_0$) + 0.5 mm SciFi ribbons
 Total of 20 layers ($20 X_0 \sim 0.7 \lambda_{\text{INT}}$) : **alternate x-y views**
 Transverse granularity : scintillating fiber ribbons $1 \text{ cm} \sim 1$ Moliere radius

Charge measurement with SCD



Excellent charge resolution: $\sim 0.2 e$ from C to Si

Flight I: Dec 2004 - Jan 05

- **42 days** - Balloon Record at that time
- (54 days by ULDB, now 55 days by Super-TIGER in 2013)
- ~ 40 million Hi-Z Triggers



CREAM

Recovery operations



From balloon flights to space

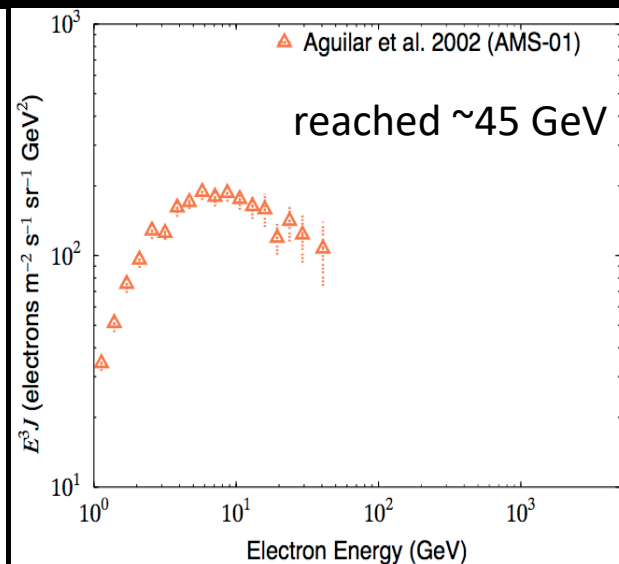
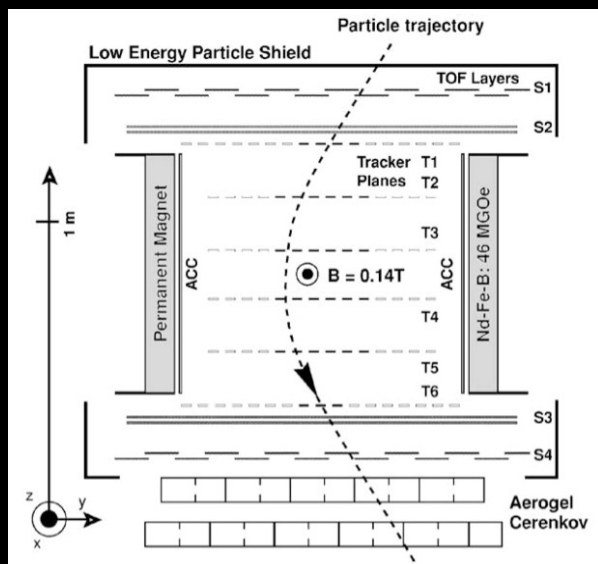
Today direct measurements of CR fluxes are mostly carried out by experiments in space that can provide a much **LARGER EXPOSURE** (e.g.: PAMELA, AMS, FERMI, CALET, DAMPE)



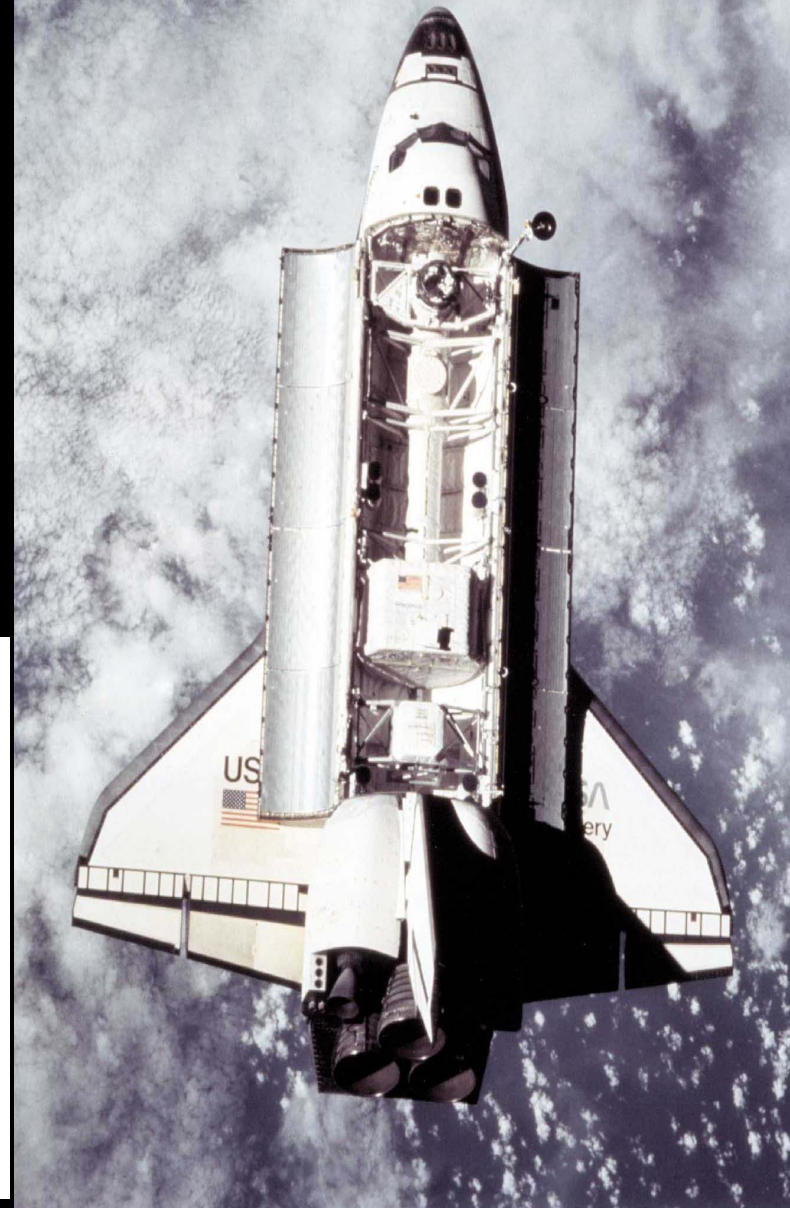
Space-borne magnetic spectrometer

AMS-01 (1998)

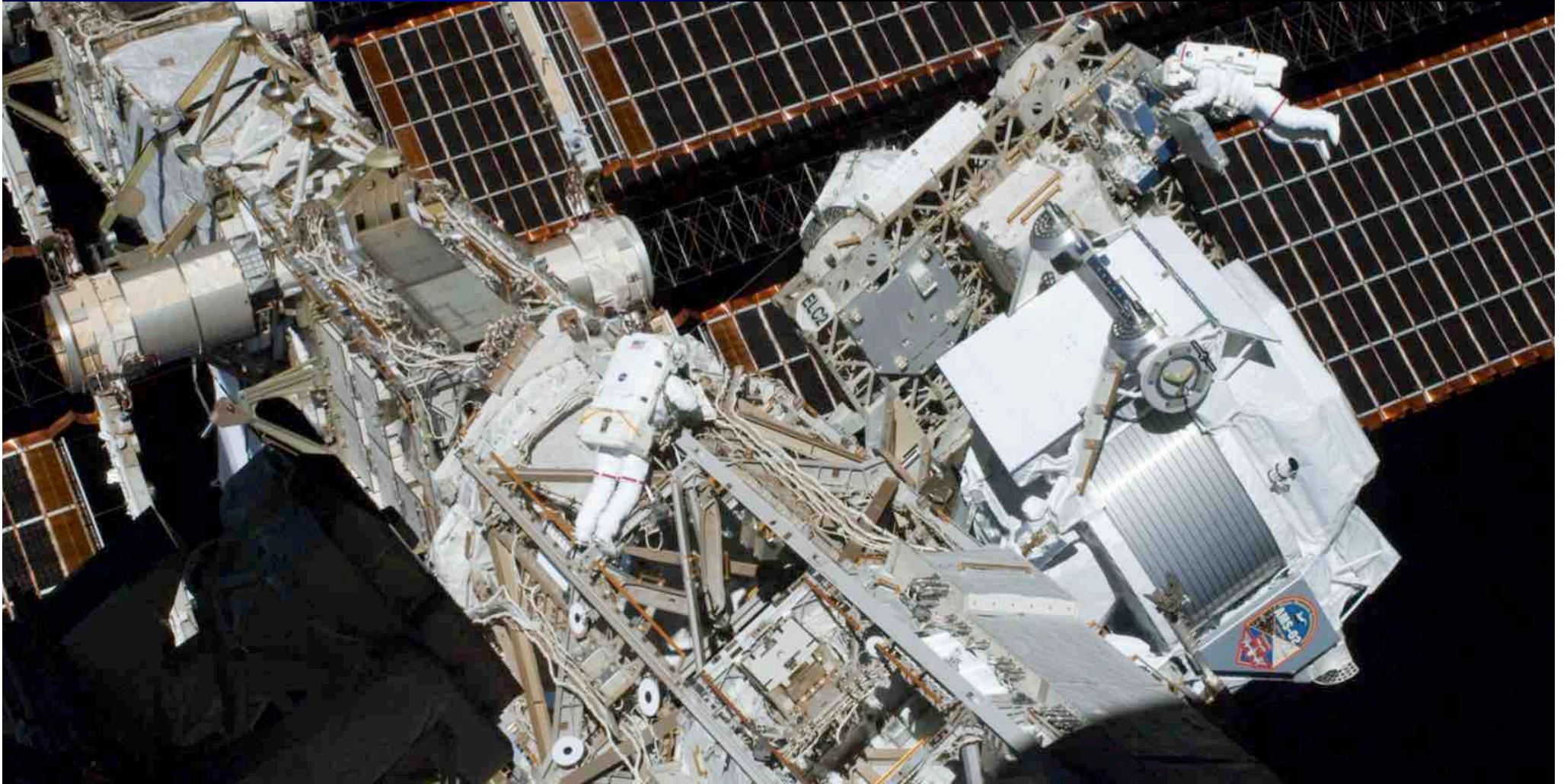
- Space shuttle Discovery
- Exposure time = $\sim 1800\text{hr}$
- Altitude: 320-390km
- $S\Omega = \sim 1.0 \times 10^3 \text{ cm}^2\text{sr}$
- e^- , e^+ (separated)



0.14 T permanent magnet



The era of cosmic-ray precision measurements



PAMELA

launched in **2006**

0.4 Tesla permanent magnet



GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

Elliptical orbit 350 – 610 km
70° inclination
in operation at 560 km

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 X_0 , 0.6 λ_I)

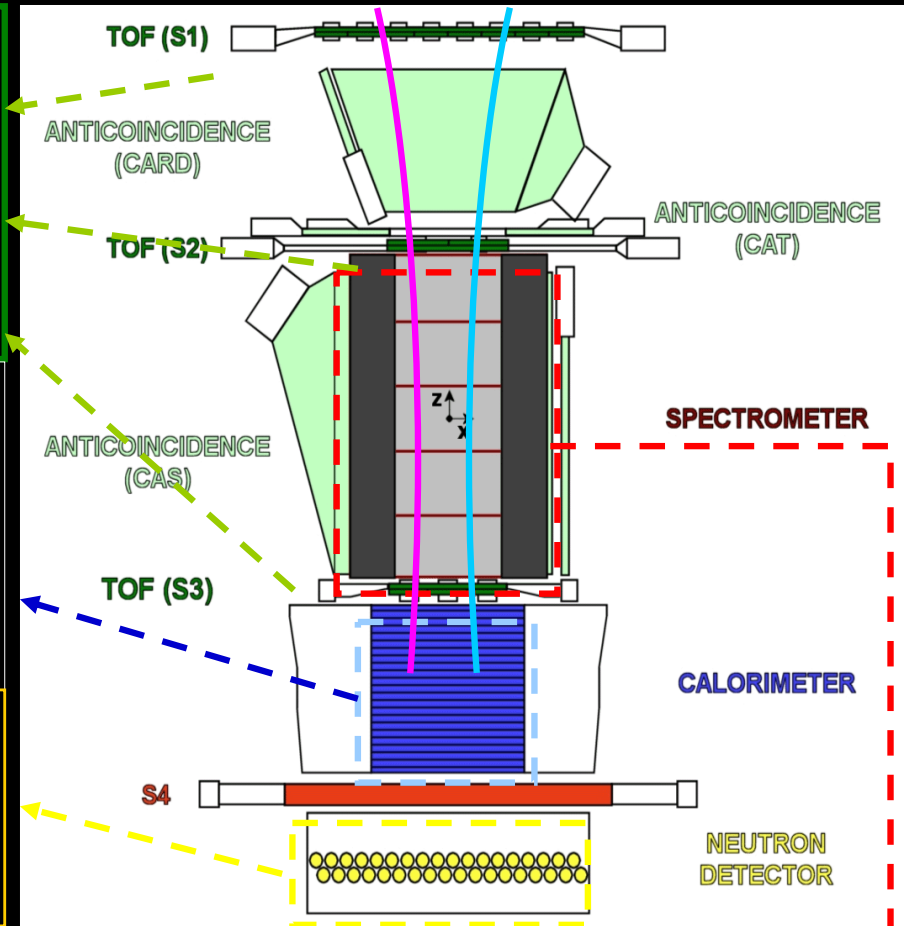
- Discrimination e^+ / p , anti- p/e^- (shower topology)
- Direct E measurement for e^-

Neutron detector

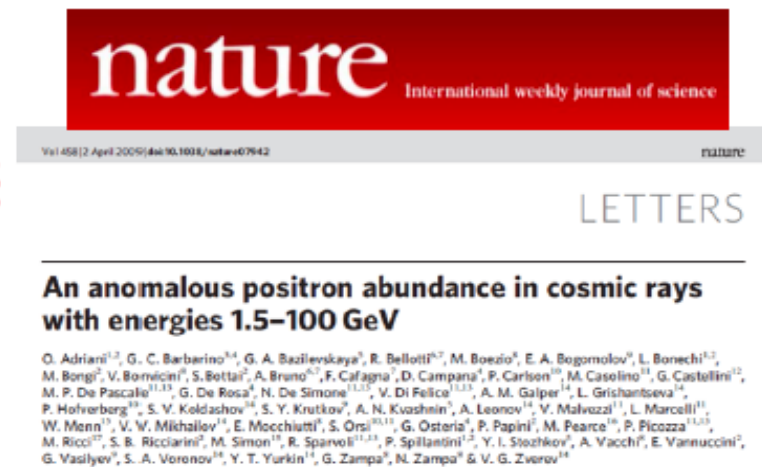
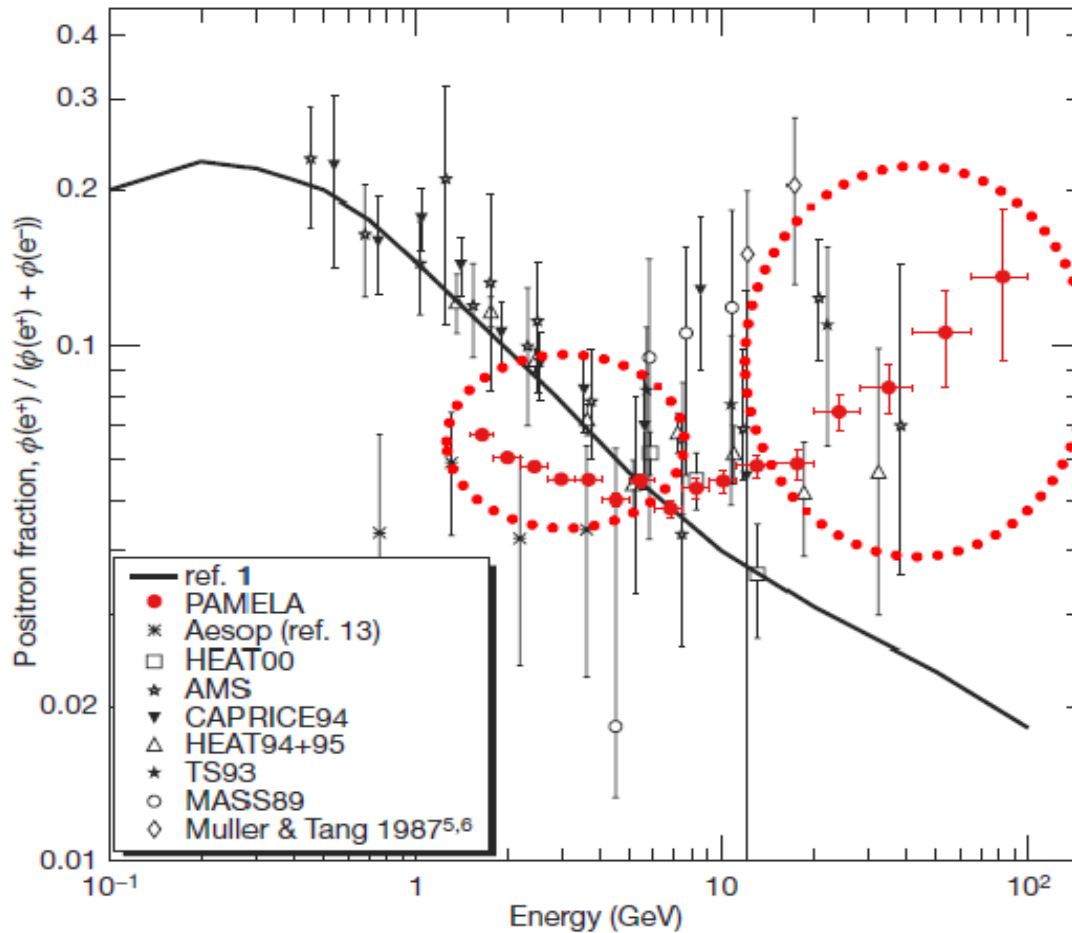
- ^3He tubes + polyethylene moderator:
- High-energy e/h discrimination

microstrip silicon tracking system + permanent magnet

- provides:
- *Magnetic rigidity* $\rightarrow R = pc/Ze$
 - *Charge sign*
 - *Charge value from dE/dx*



PAMELA: first unambiguous evidence of the rise of the positron fraction above 10 GeV

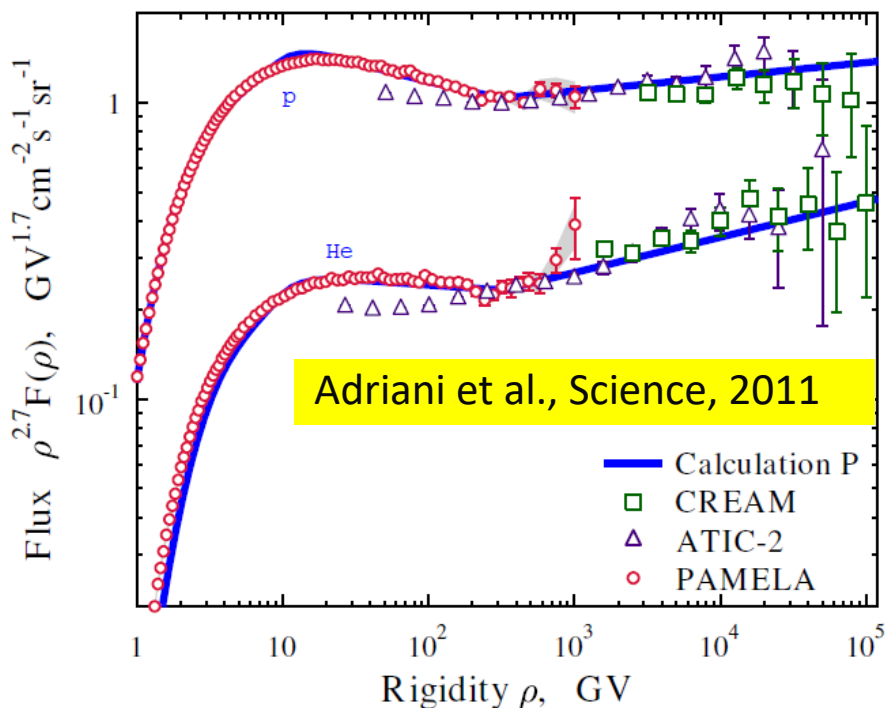


August 2009

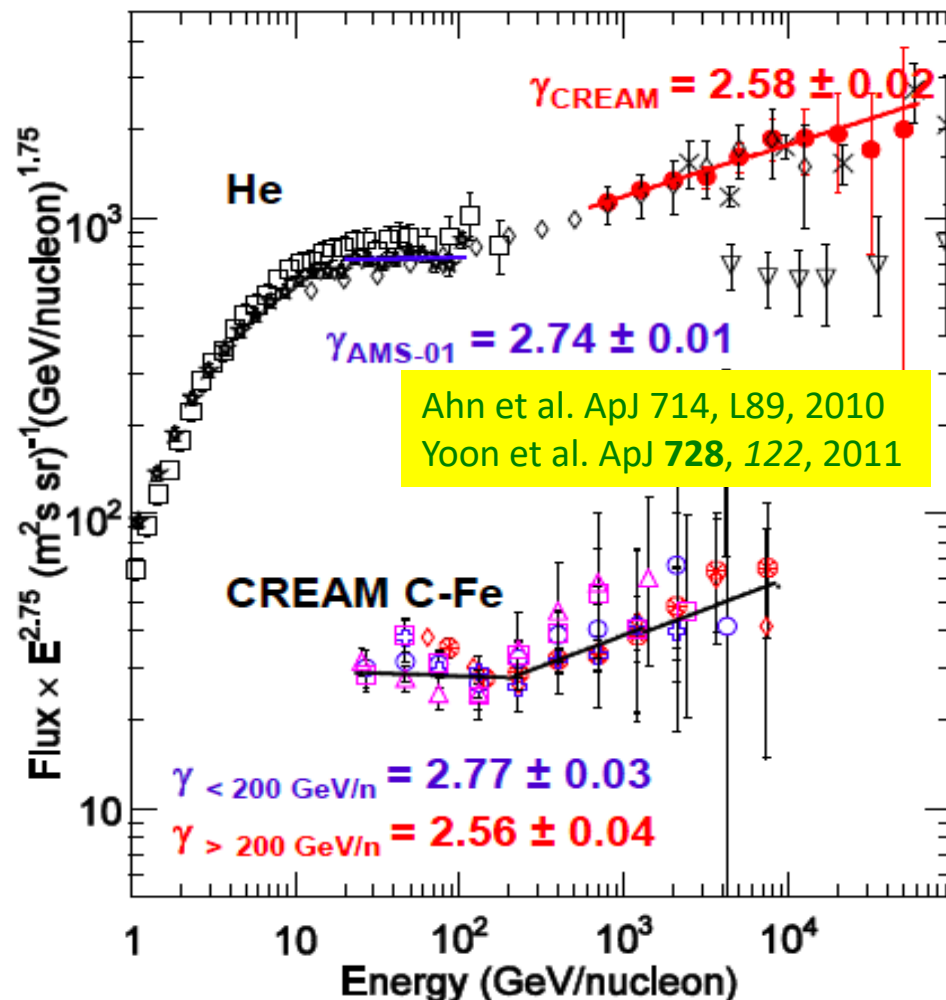
First hints of deviations from power-law spectra

- ❑ PAMELA detected a spectral break in PROTON and HE spectra at $R \sim 240$ GV

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



A single power-law seems inadequate to fit the spectra



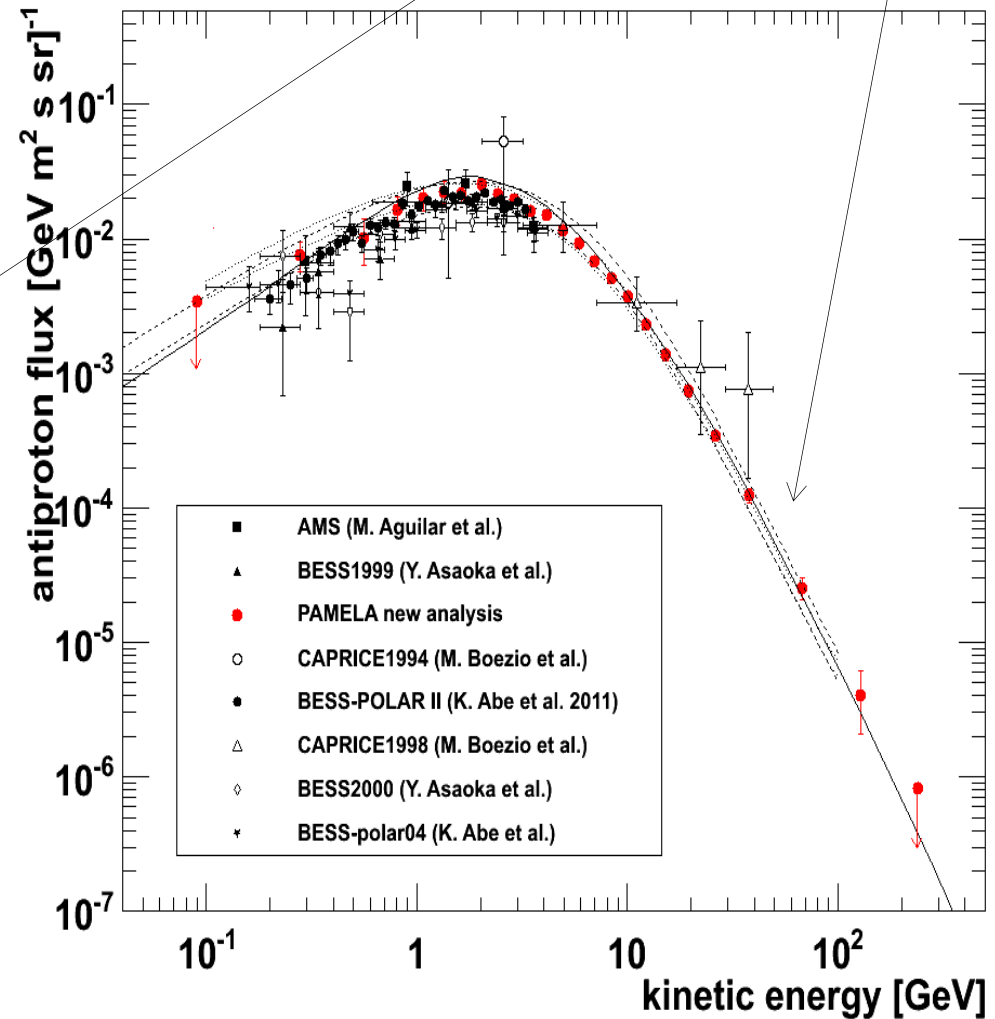
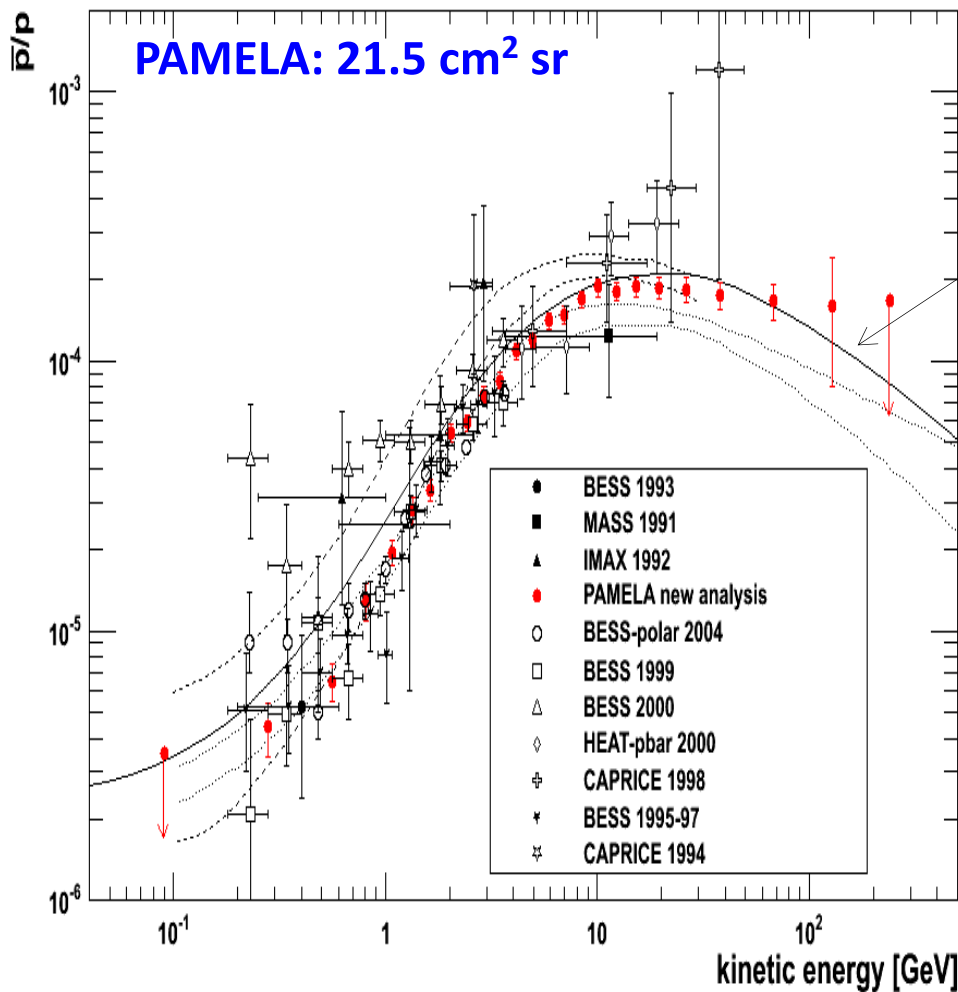
The slope of $Z > 2$ NUCLEI at high energy looks similar to He and different from protons

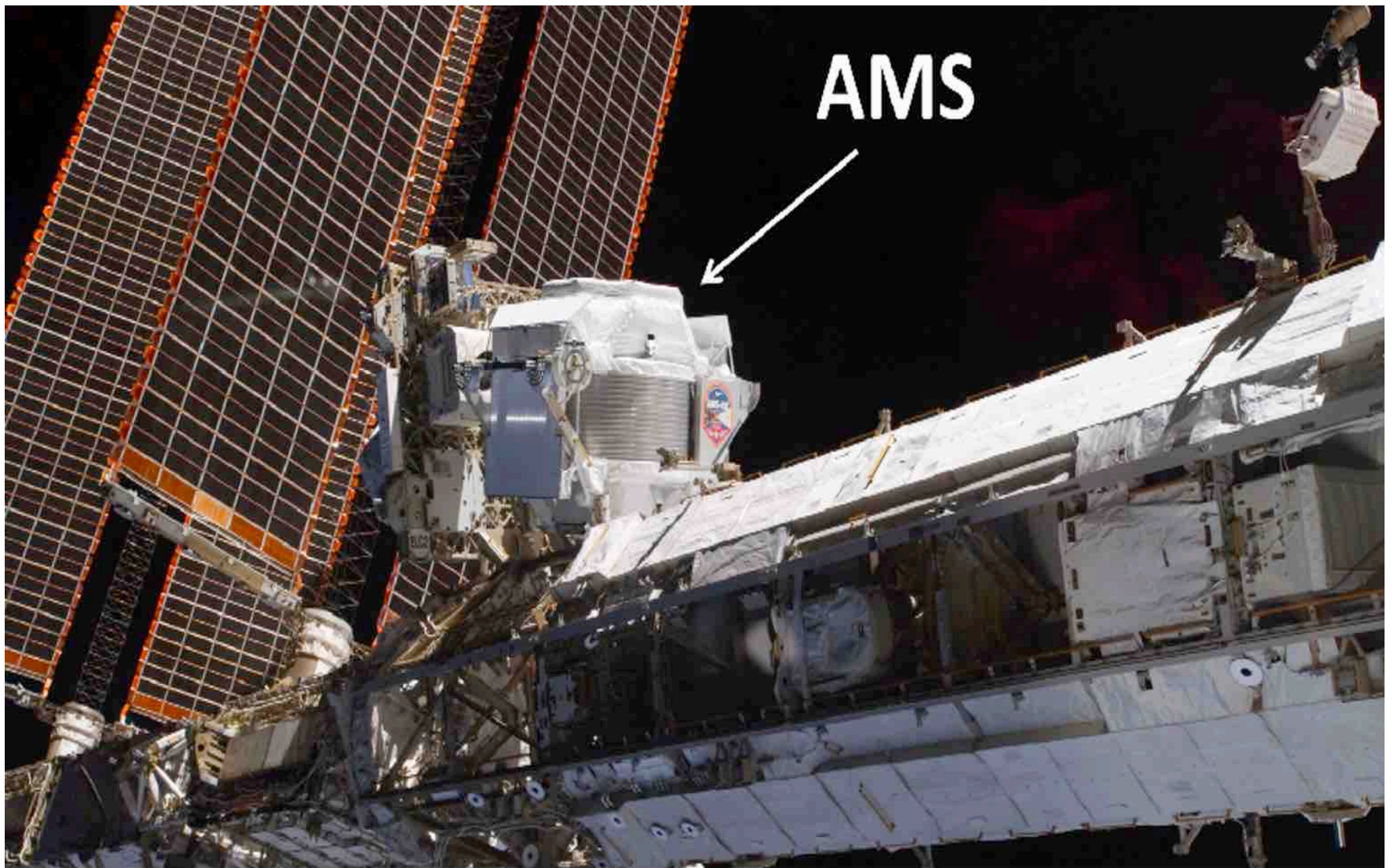
PAMELA - Antiprotons

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





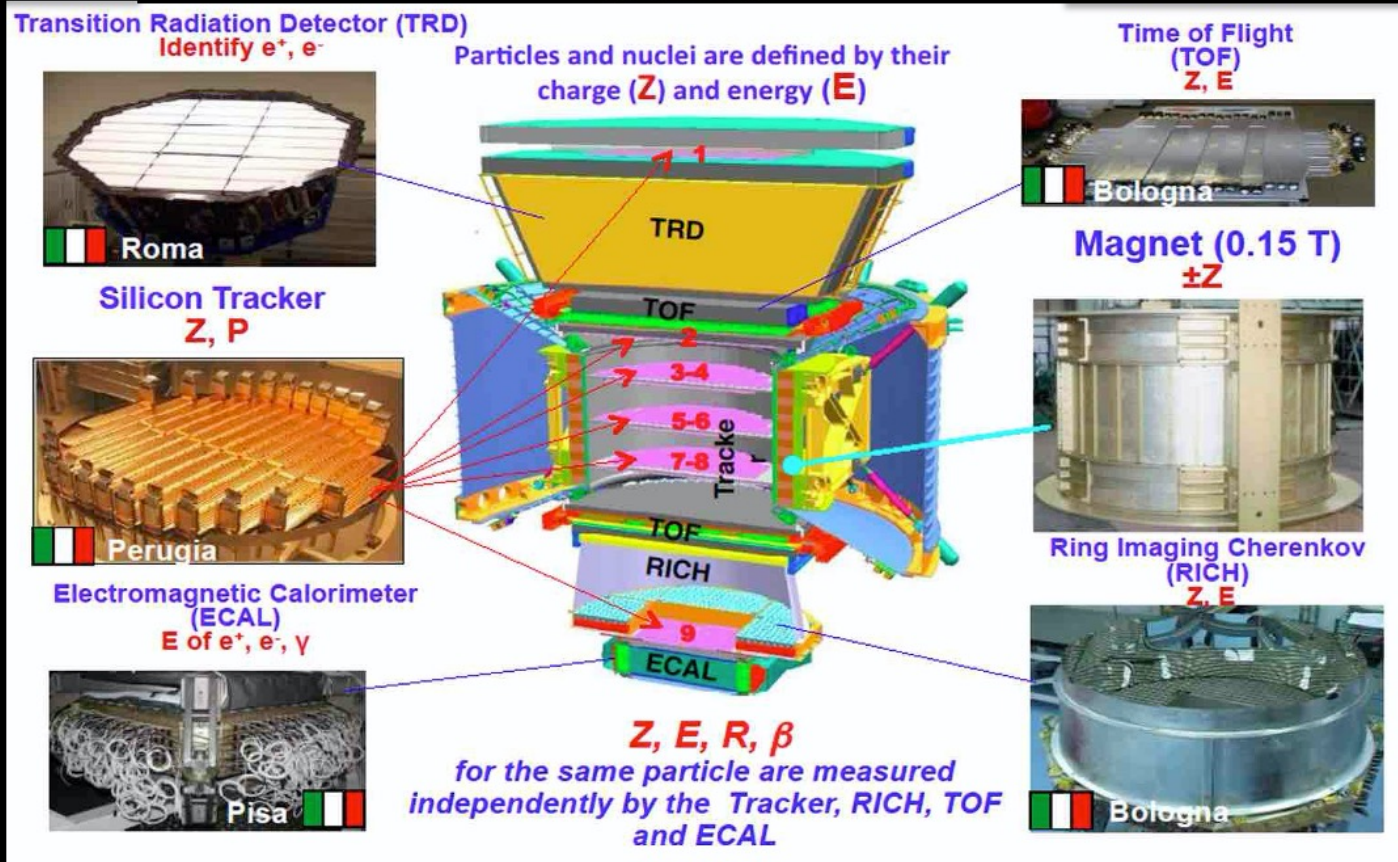
ALPHA Magnetic Spectrometer (AMS) on the ISS - launched in 2011

AMS-02



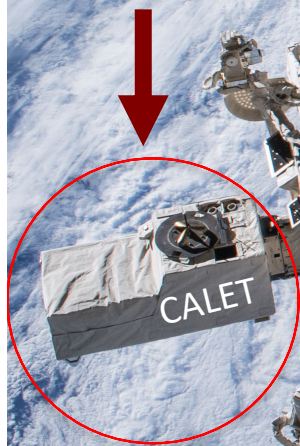
size: 5m x 4m x 3m
mass: 7.5 tons
power: 2.5 kW

PERMANENT MAGNET 0.15 T



CALET

Calorimetric Electron Telescope



Geometric Factor :

1040 cm²sr for electron, proton

4000 cm²sr for ultra-heavy nuclei

• $\Delta E/E$:

~2% (>10 GeV) for e, gamma

~30-35 % for protons, nuclei

• e/p separation : $\sim 10^{-5}$

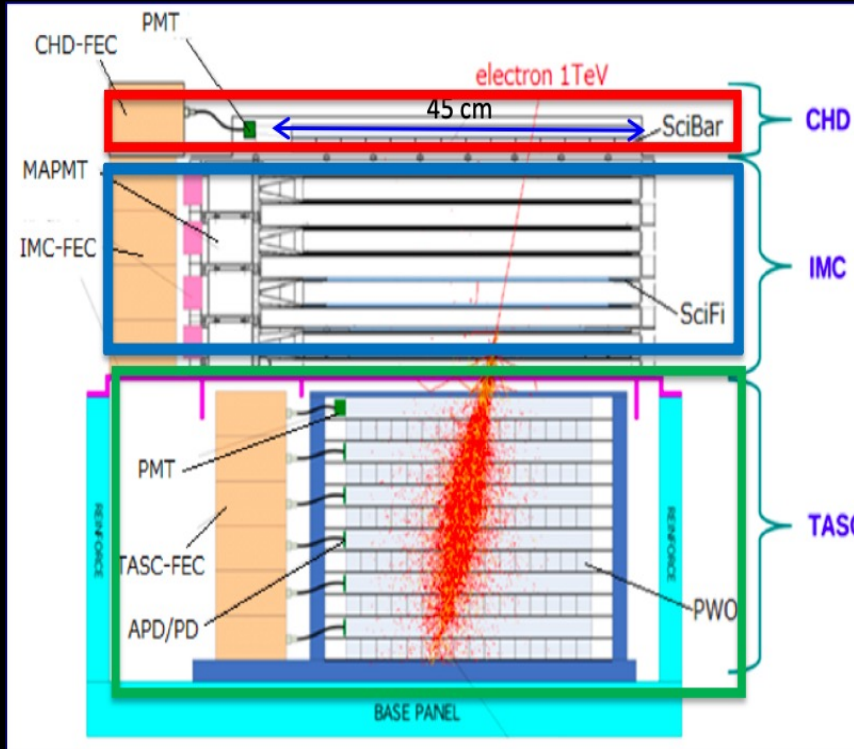
• **Charge resolution** : 0.15 - 0.3 e

• **Charge range**: up to Z = 40

• **Angular resolution** : 0.2° for $\gamma > \sim 50$ GeV

CALorimetric Electron Telescope (CALET)

Field of view: ~ 45 degrees (from the zenith) - Geometrical Factor: $\sim 1,040 \text{ cm}^2\text{sr}$ (for electrons) - Thickness: $30 X_0$, $1.3 \lambda_I$



CHD – Charge Detector

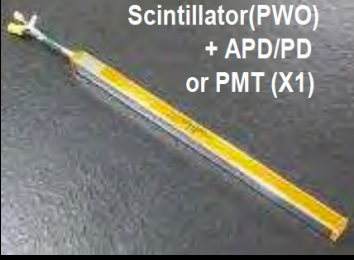
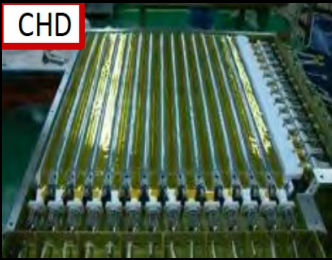
- 2 layers x 14 plastic scintillating paddles
- **single element charge ID** from p to Fe and above ($Z = 40$)
- charge resolution $\sim 0.1-0.3 e$

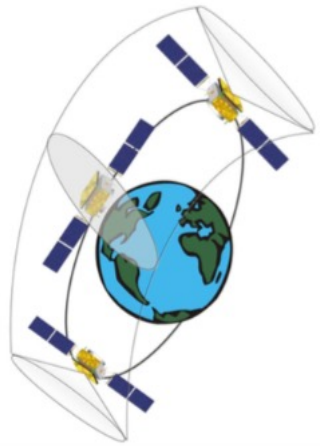
IMC – Imaging Calorimeter

- Scifi. + tungsten absorbers: $3 X_0$
- $8 \times 2 \times 448$ plastic scintillating fibers (1mm) **readout individually**
- **tracking** ($\sim 0.1^\circ$ angular resolution) + **Shower imaging**

TASC – Total Absorption Calorimeter

- $6 \times 2 \times 16$ lead tungstate (PbWO_4) logs: $27 X_0$, $1.2 \lambda_I$
- **energy resolution:** $\sim 2\%$ ($>10\text{GeV}$) for e, γ
 $\sim 30-35\%$ for p, nuclei
- **e/p separation:** $\sim 10^{-5}$
- **angular resolution:** 0.2° for γ -rays $> \sim 50 \text{ GeV}$





- Altitude: ~ 500 km
- Inclination: ~ 97°
- Period: ~ 95 minutes
- Orbit: sun-synchronous

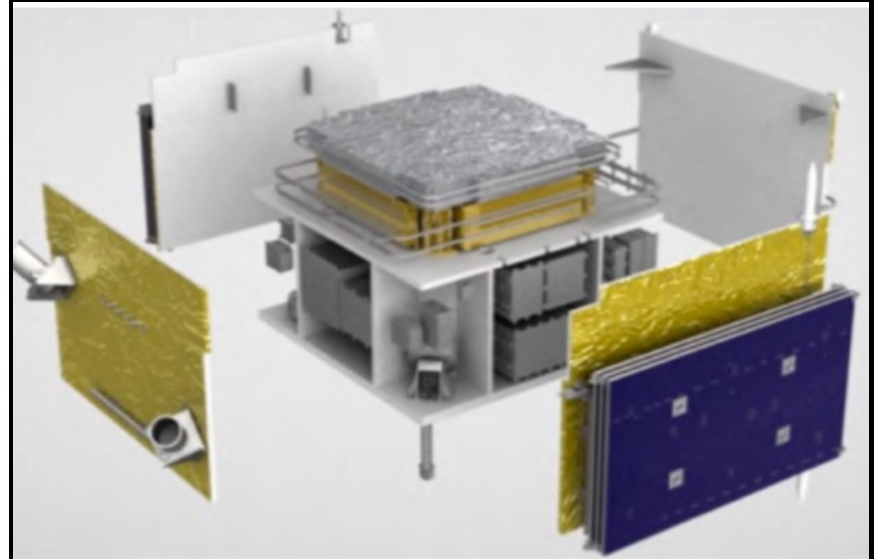
17th Dec. 2015
@Jiuquan

DAMPE



“Wukong” 悟空

Dark Matter Explorer Satellite

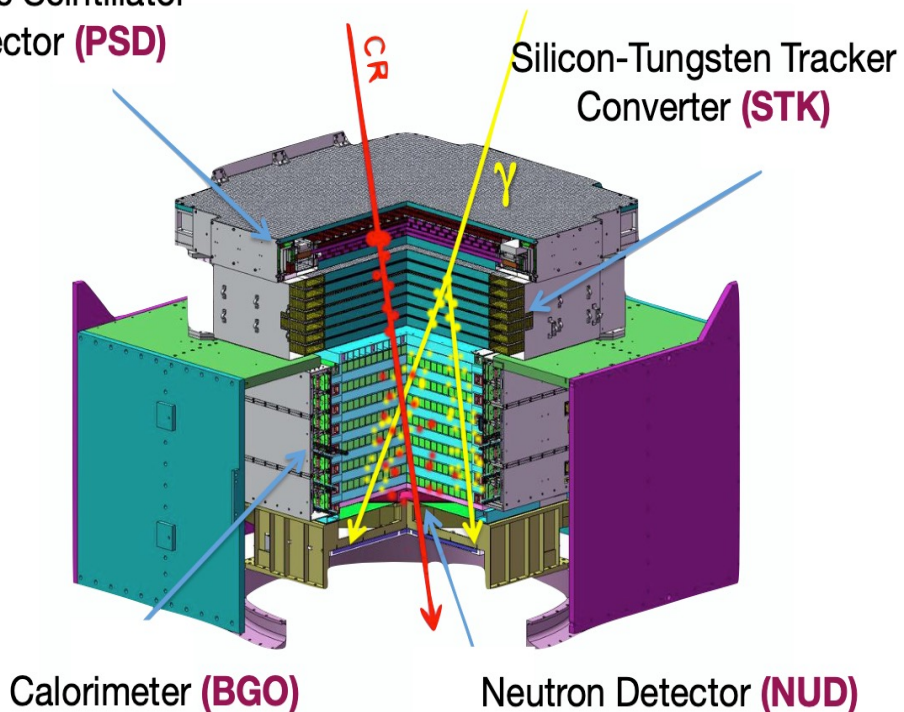


- sun-synchronous orbit
- altitude 498 km
- inclination angle ~97°
- average orbital period ~ 95 minutes

weight: 1.4 ton
power: ~ 400 W

DARk Matter Particle Explorer (DAMPE)

Plastic Scintillator
Detector (PSD)



Silicon-Tungsten Tracker
Converter (STK)

PSD

- Charge identification to $Z=28$
- gamma-ray anticoincidence

STK

- position resolution $\sim 50\mu\text{m}$
- γ angular resolution $0.5^\circ - 0.1^\circ$ (GeV – TeV)
- Absolute Charge (Z) identification

BGO Calorimeter

- $32 X_0 - 1.6 \lambda$
- e/γ detection up to 10 TeV
- p / ions up to 50 GeV – 500 TeV

NUD

additional e/p rejection capability

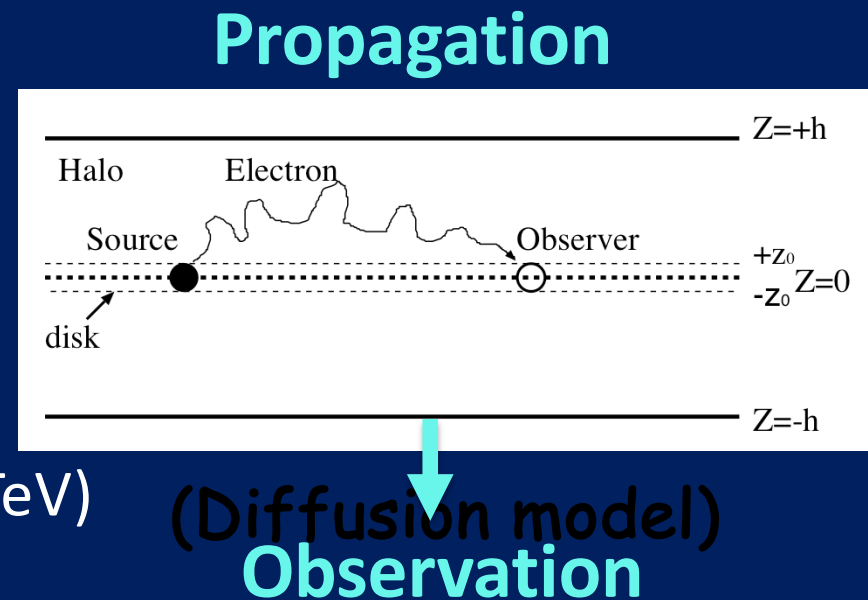
Launched on December 2015

Cosmic-ray electrons in the Galaxy

- **Energy losses:**
 - Inverse Compton scattering with interstellar photons
 - Synchrotron radiation in the interstellar magnetic field ($B \sim 6 \mu\text{G}$) $\Rightarrow dE/dt = -bE^2$

- Life time:
 $T = 1/(bE) \approx 2.5 \times 10^5 \text{ yr}/E(\text{TeV})$

- **Propagation distance in the Galaxy:**
 $R = (2DT)^{1/2} \approx 0.4 \div 0.8 \text{ kpc} (@E=1\text{TeV})$



Energy losses \rightarrow Observable sources of TeV electrons:

- located at a distance $< 1 \text{ kpc}$
- age $< 10^5 \text{ yr}$

\rightarrow **Softening of the spectrum is expected above 1 TeV**

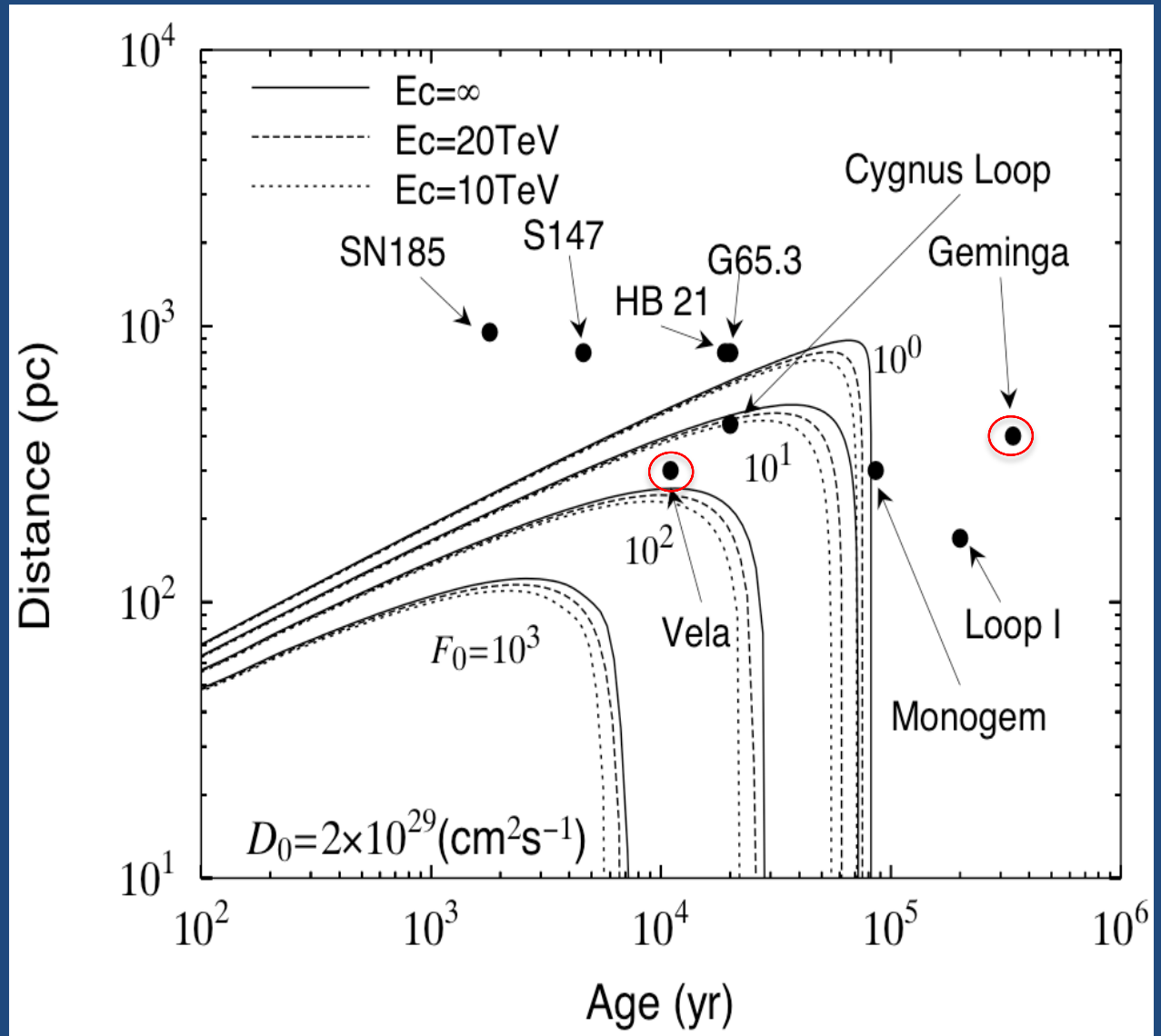
Known Nearby SNRs

Contour of electron flux
distance vs. age ($E=3\text{TeV}$)

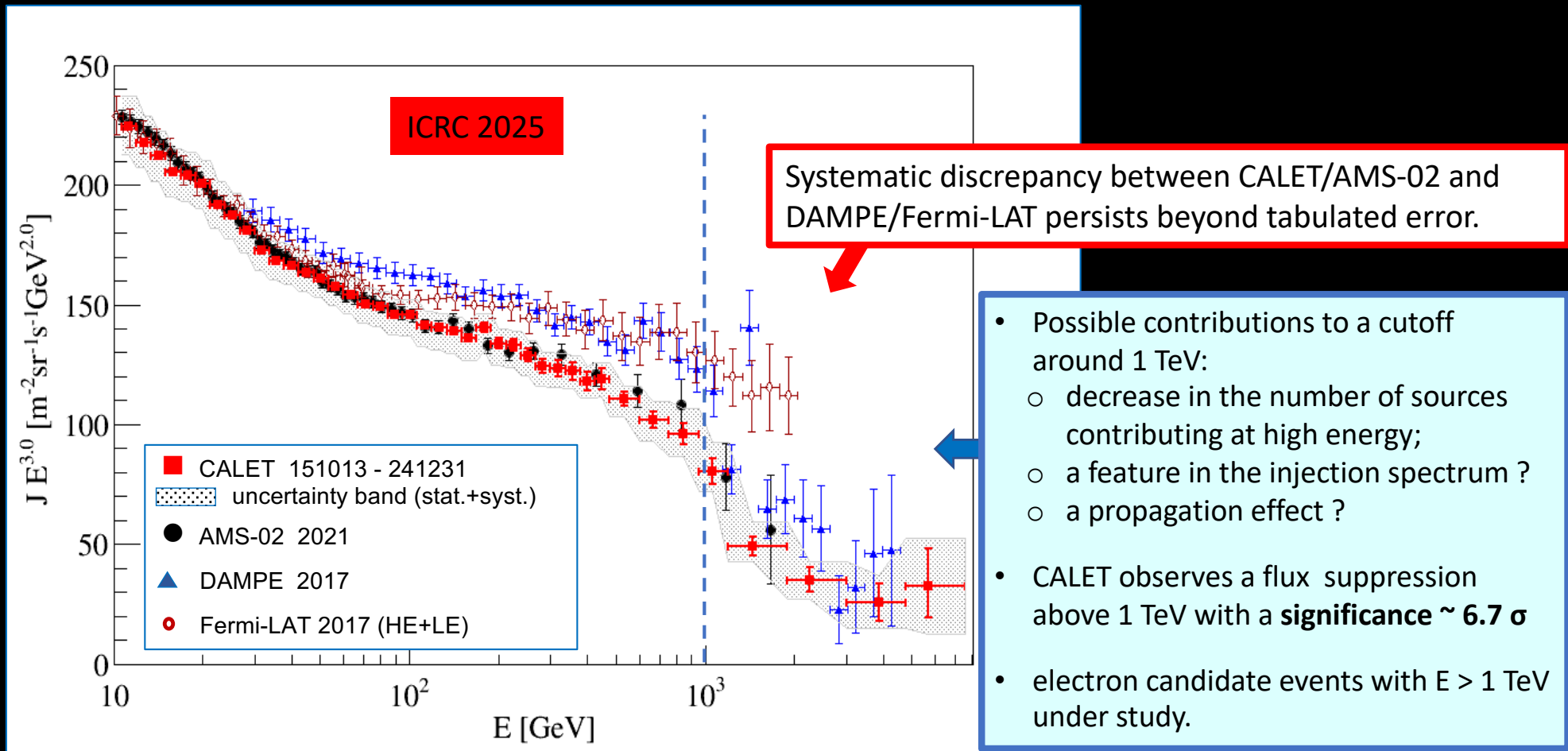
SNR	R(kpc)	T(yr)
SN185	0.95	1.8×10^3
S147	0.80	4.6×10^3
HB 21	0.80	1.9×10^4
G65.3+5.7	0.80	2.0×10^4
Cygnus Loop	0.44	2.0×10^4
Vela	0.30	1.1×10^4
Monogem	0.30	8.6×10^4
Loop1	0.17	2.0×10^5
Geminga	0.4	3.4×10^5



Vela is "young" and closeby



BREAK in the electron (+positron) spectrum around 1 TeV



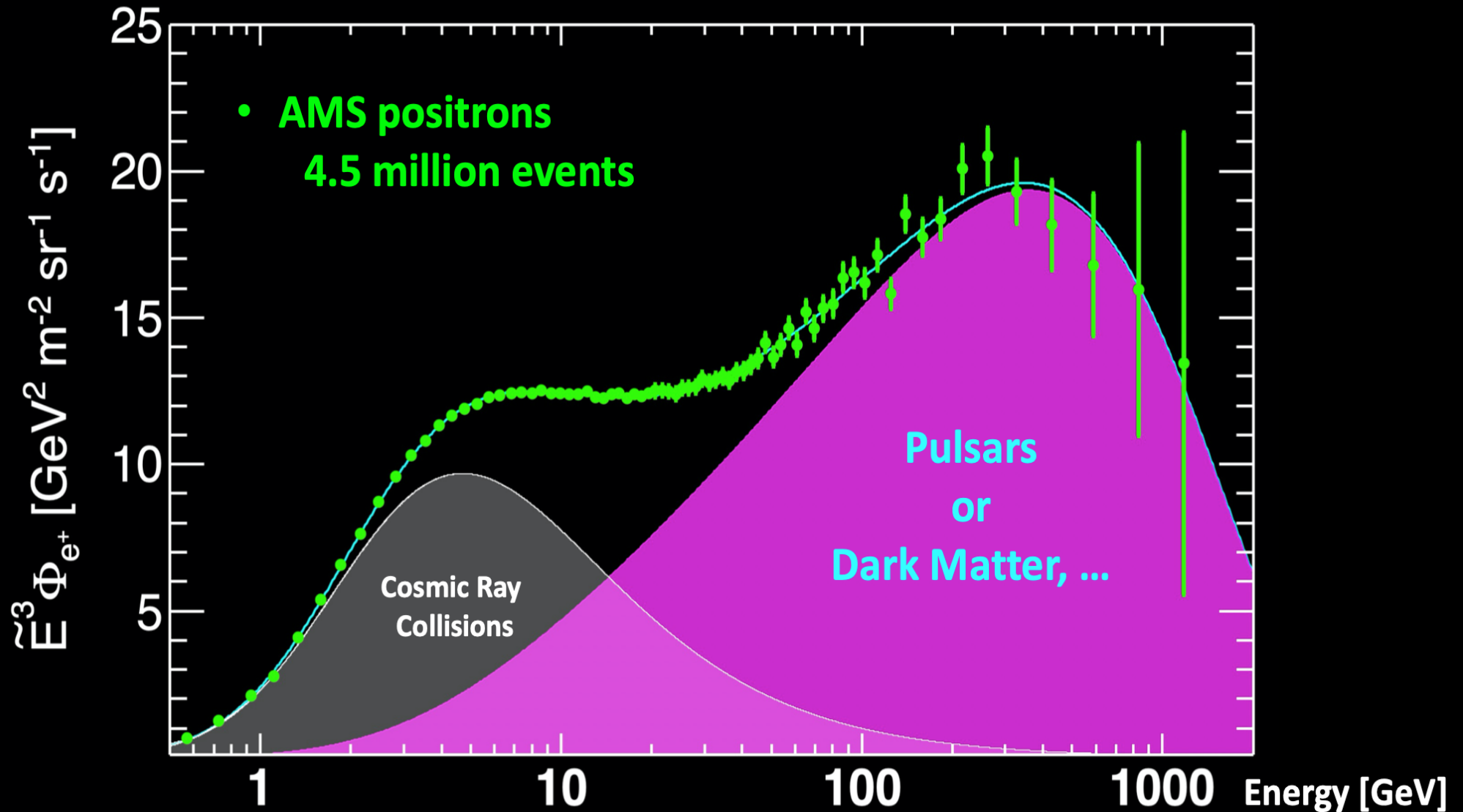
- The data are consistent with a **broken power law**: an exponential cutoff is excluded at $> 5\sigma$
- the origin of the break is most likely a feature in the injection spectrum, not propagation [Morlino & Celli, MNRAS, 508 (2021)]

The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter with a cutoff energy

Empirical model: $\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2} \left[C_d (\hat{E}/E_1)^{\gamma_d} + C_s (\hat{E}/E_2)^{\gamma_s} \exp(-\hat{E}/E_s) \right]$

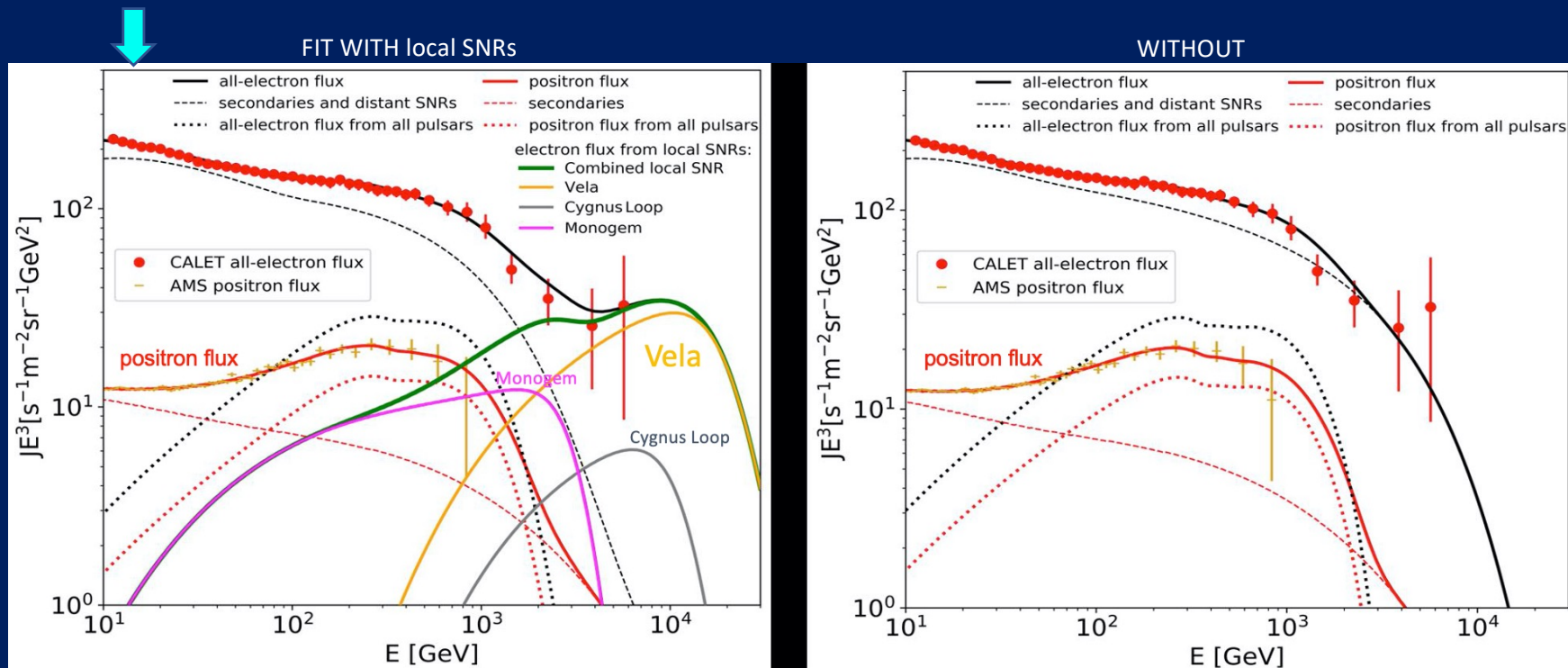
$\chi^2/\text{dof} = 40/66$

Solar Collisions Pulsars or Dark Matter



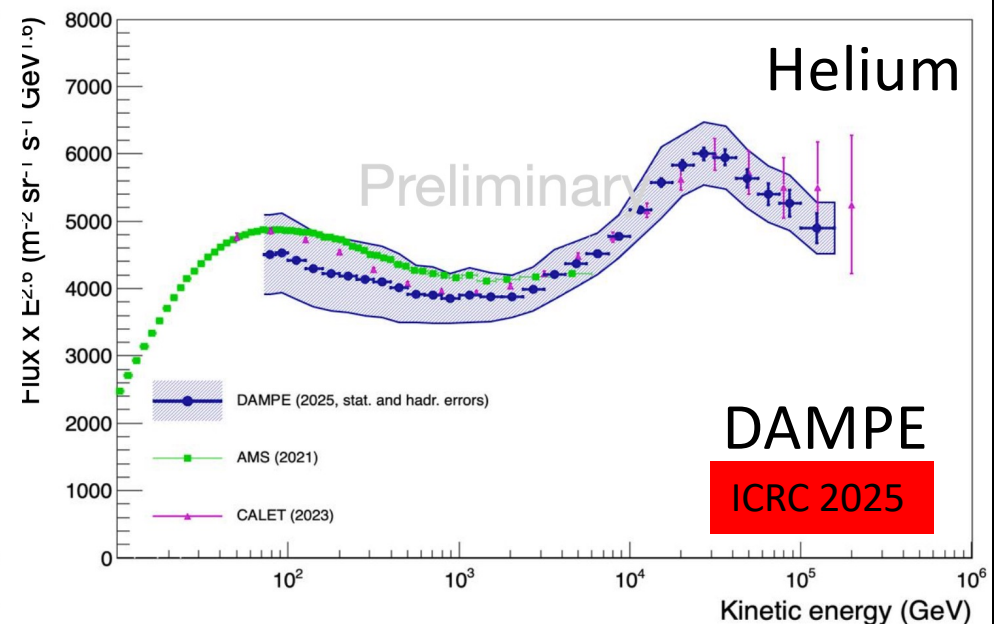
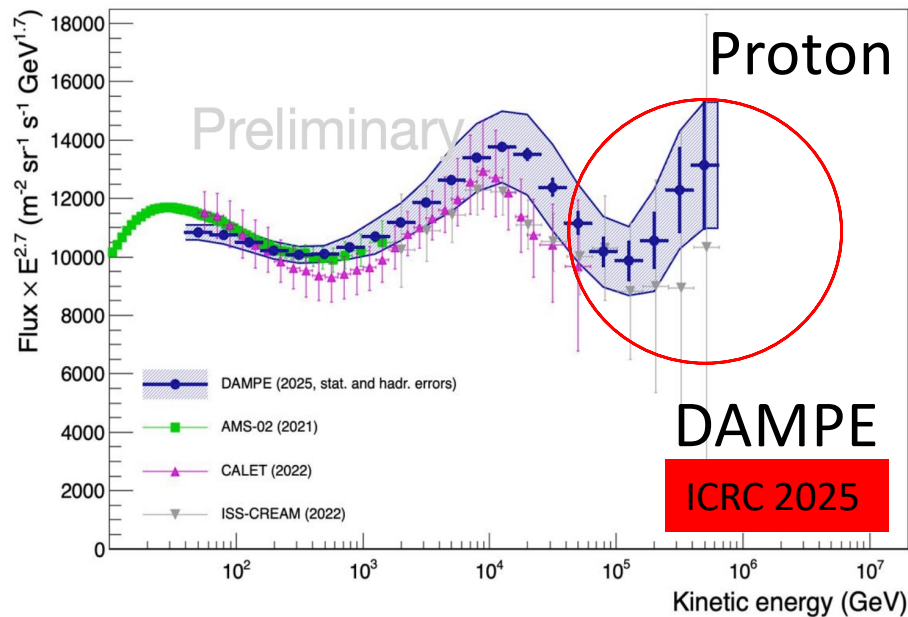
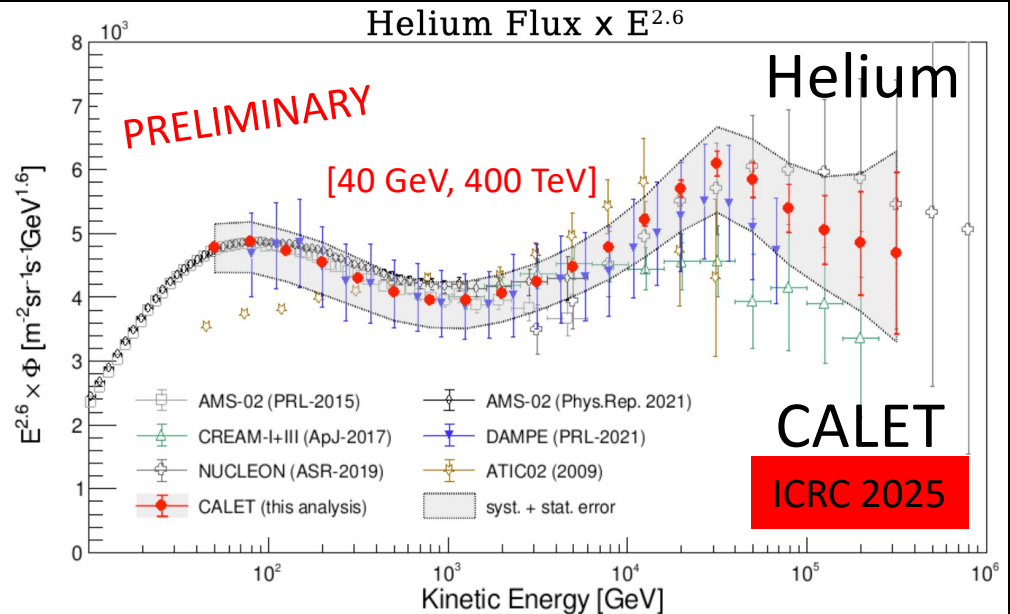
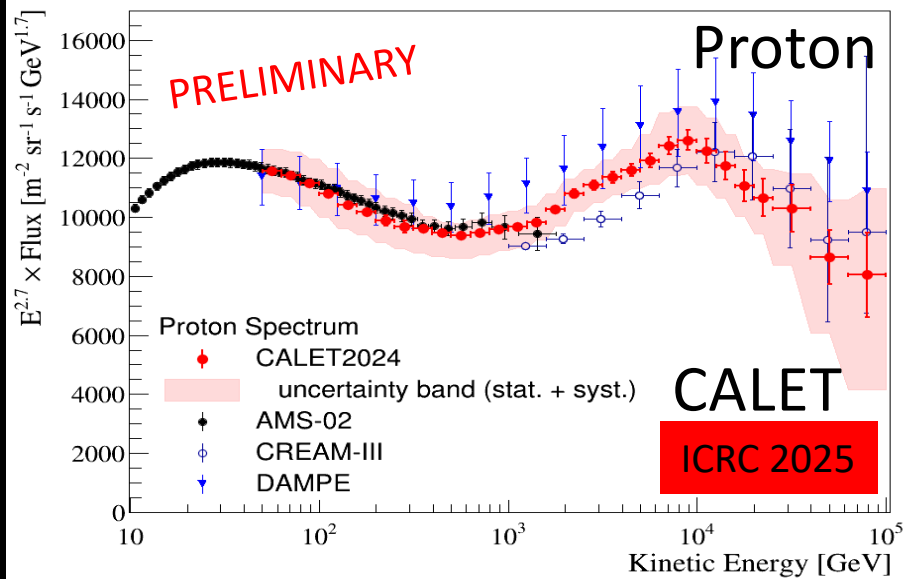


- In the TeV region and above, nearby accelerators could leave **observable features in the spectrum**
- In the study below (H. Motz et al.) the all-electron spectrum is modeled as combination of:
 - e^- and e^+ fluxes from pulsars (black dotted line)
 - + secondaries and distant SNRs (black dashed line)
- Tentative spectral fit in 11 GeV to 4.8 TeV including pulsars and possible VELA SNR contribution

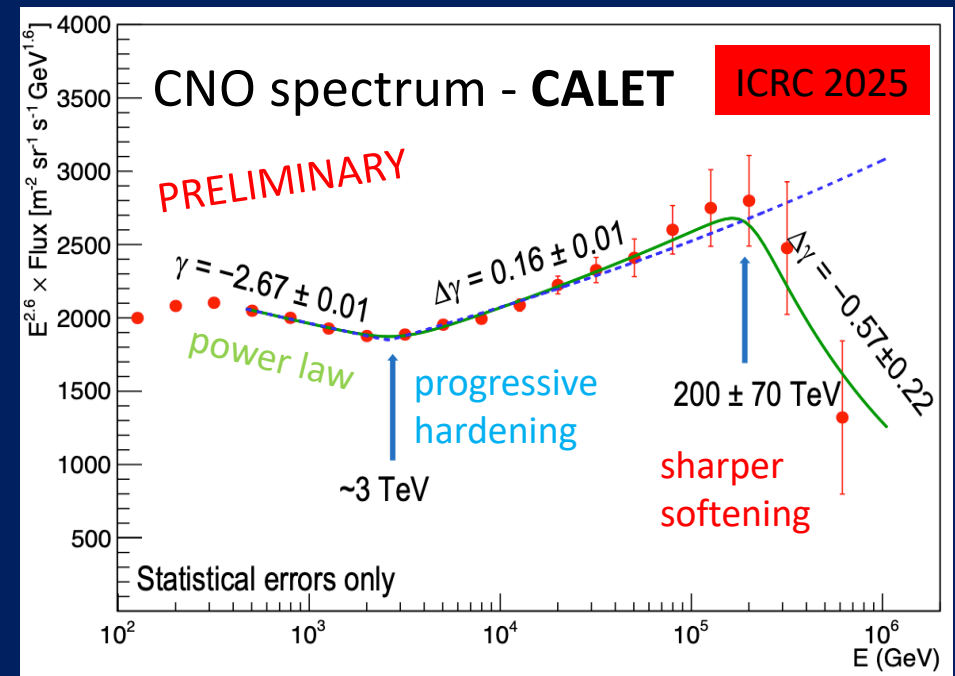
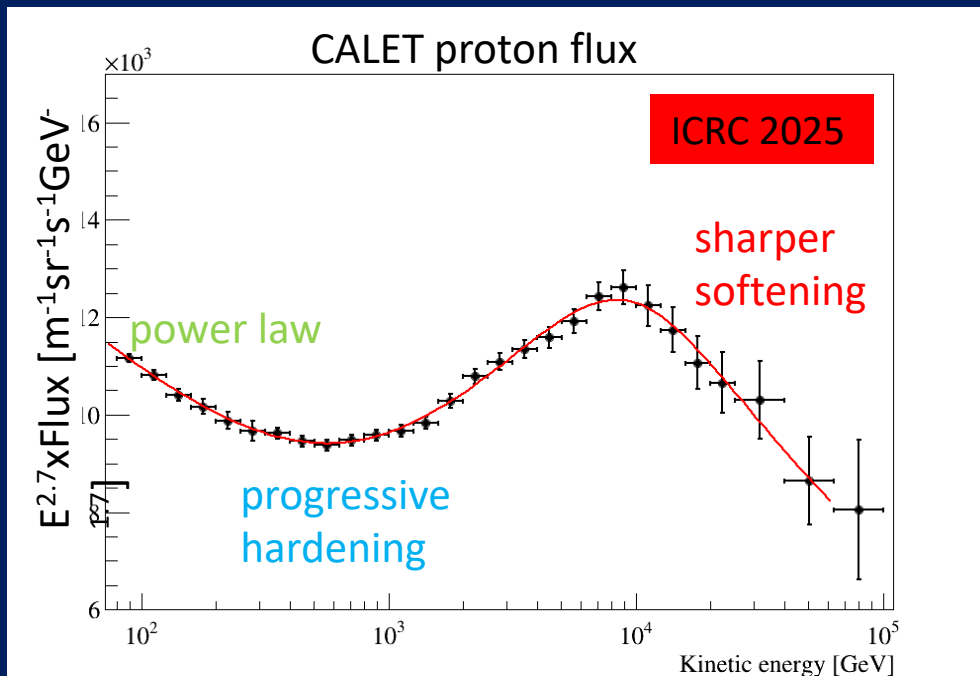


- Fits **with and without** nearby sources give similar $\chi^2/d.o.f$, but sources inclusion provides better spectral agreement in the TeV region

BUMPS in proton and Helium spectra



Spectral anomalies (Broken Power Laws)

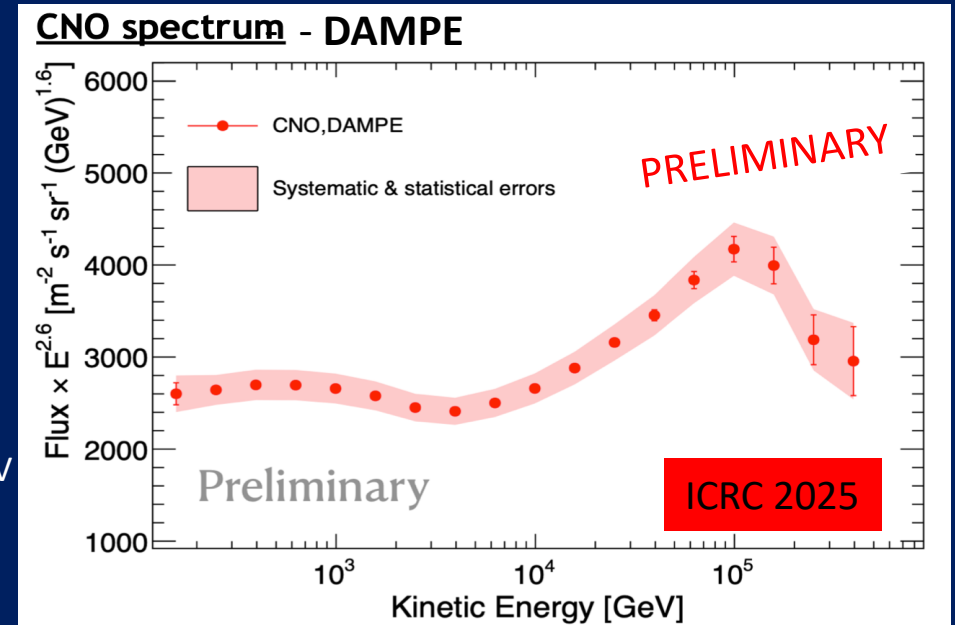


Fitting function (Double Broken Power Law):

$$\Phi = E^{2.7} \times C \times \underbrace{\left(\frac{E}{1\text{GeV}}\right)^\gamma}_{\text{Low energy}} \times \underbrace{\left(1 + \left(\frac{E}{E_0}\right)^s\right)^{\frac{\Delta\gamma}{s}}}_{\text{hardening}} \times \underbrace{\left(1 + \left(\frac{E}{E_1}\right)^{s_1}\right)^{\frac{\Delta\gamma_1}{s_1}}}_{\text{softening}}$$

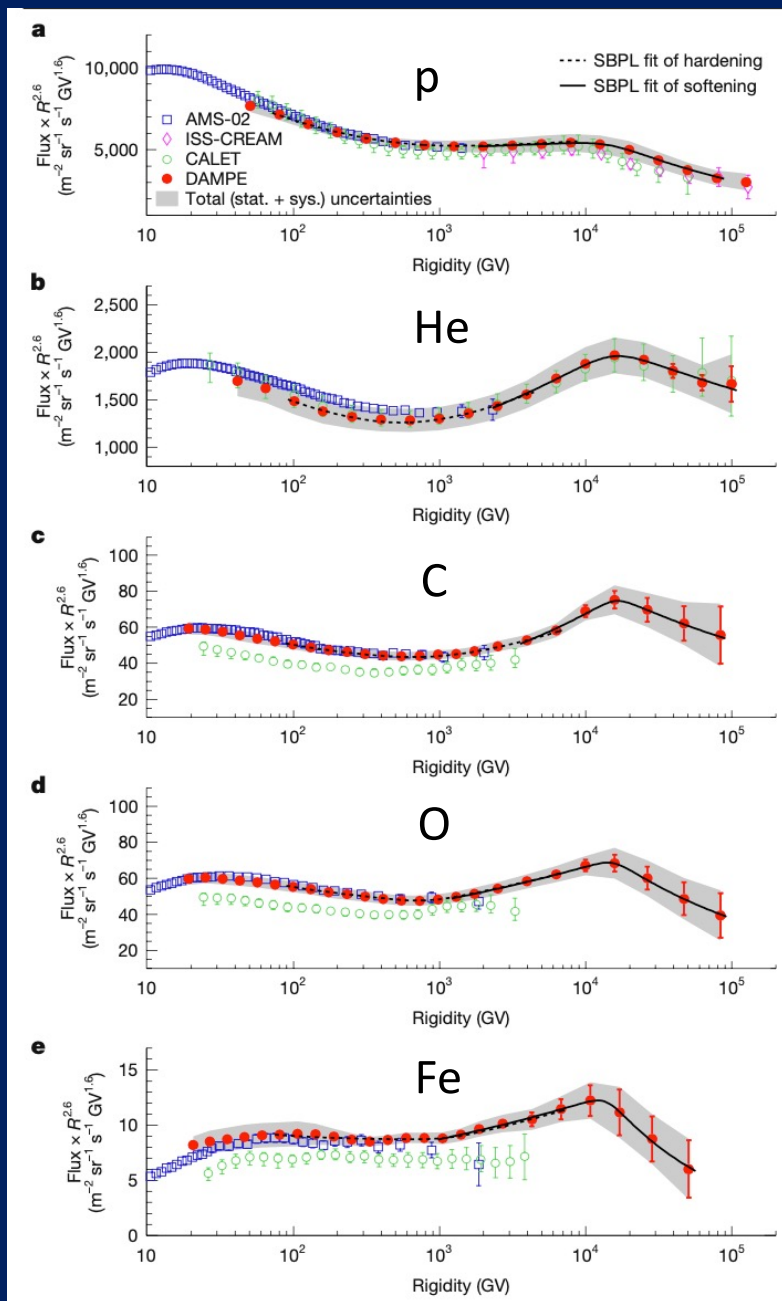
OBSERVED SPECTRAL FEATURES in p, He, CNO

- progressive **hardening** (not a sharp break) above a few hundred GV
- spectral **softening** at rigidities $> \sim 10\text{-}20 \text{ TV}$
- fit parameters s, s_1 describe the sharpness of transition



Spectral anomalies (Broken Power Laws)

CNO spectrum - CALET



- OBSERVED UNIVERSALITY IN SPECTRAL FEATURES of p, He, C, O, Fe RIGIDITY SPECTRA

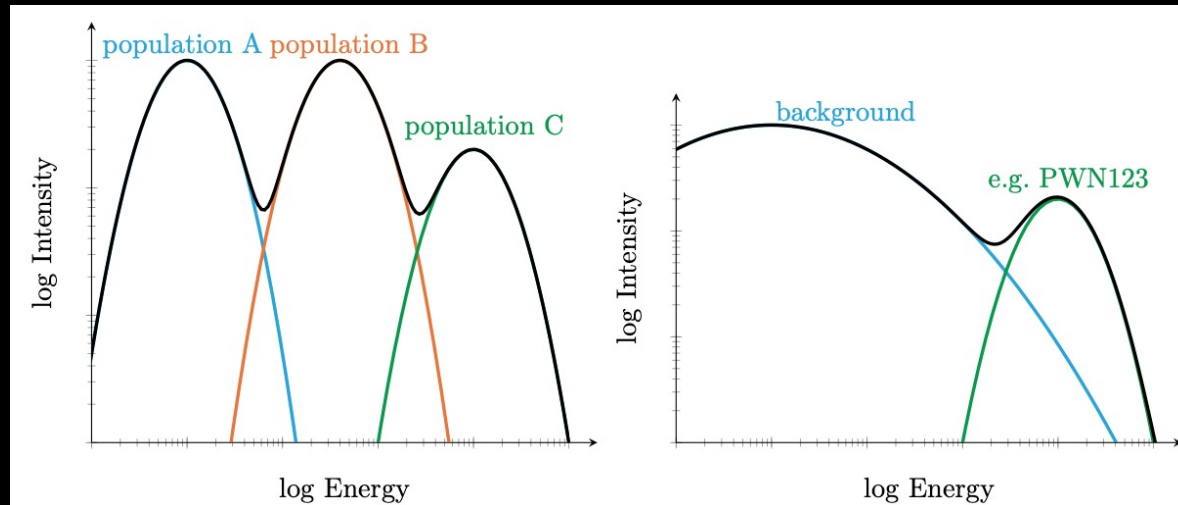
recent paper of DAMPE Collaboration

"Charge-dependent spectral softenings of primary cosmic rays below the knee"

Nature volume 653, pages 52–55 (2026)

Why "bumps" show up in the spectra ?

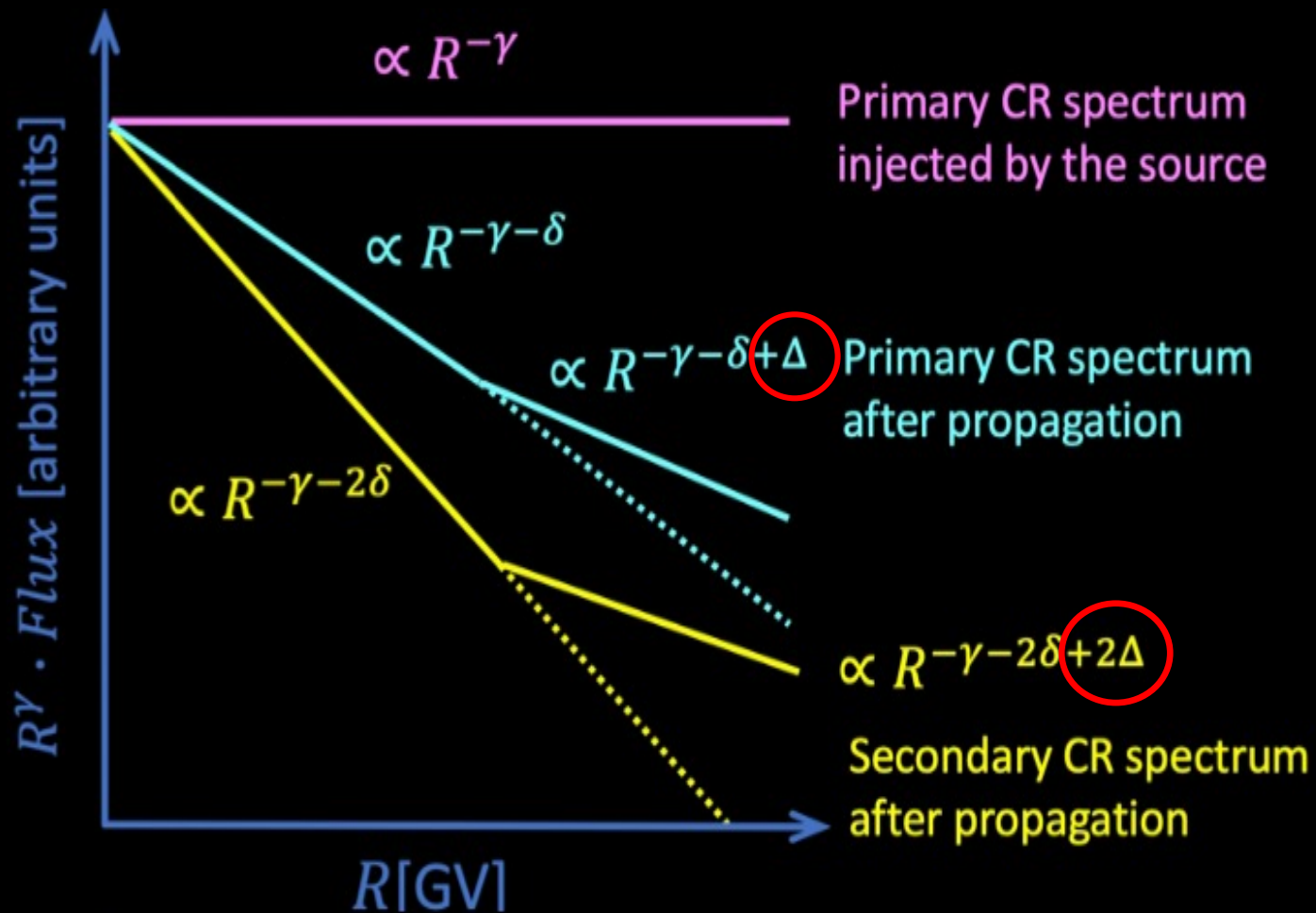
- Is it a "source effect" ?
 - • Different populations of sources
 - • Hard spectra, different cut-off energies



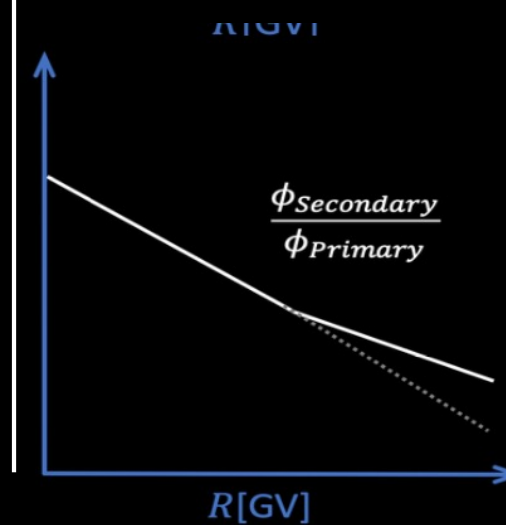
[P. Mertsch, ICRC 2025]

- Is it related to propagation ? (see next slide)

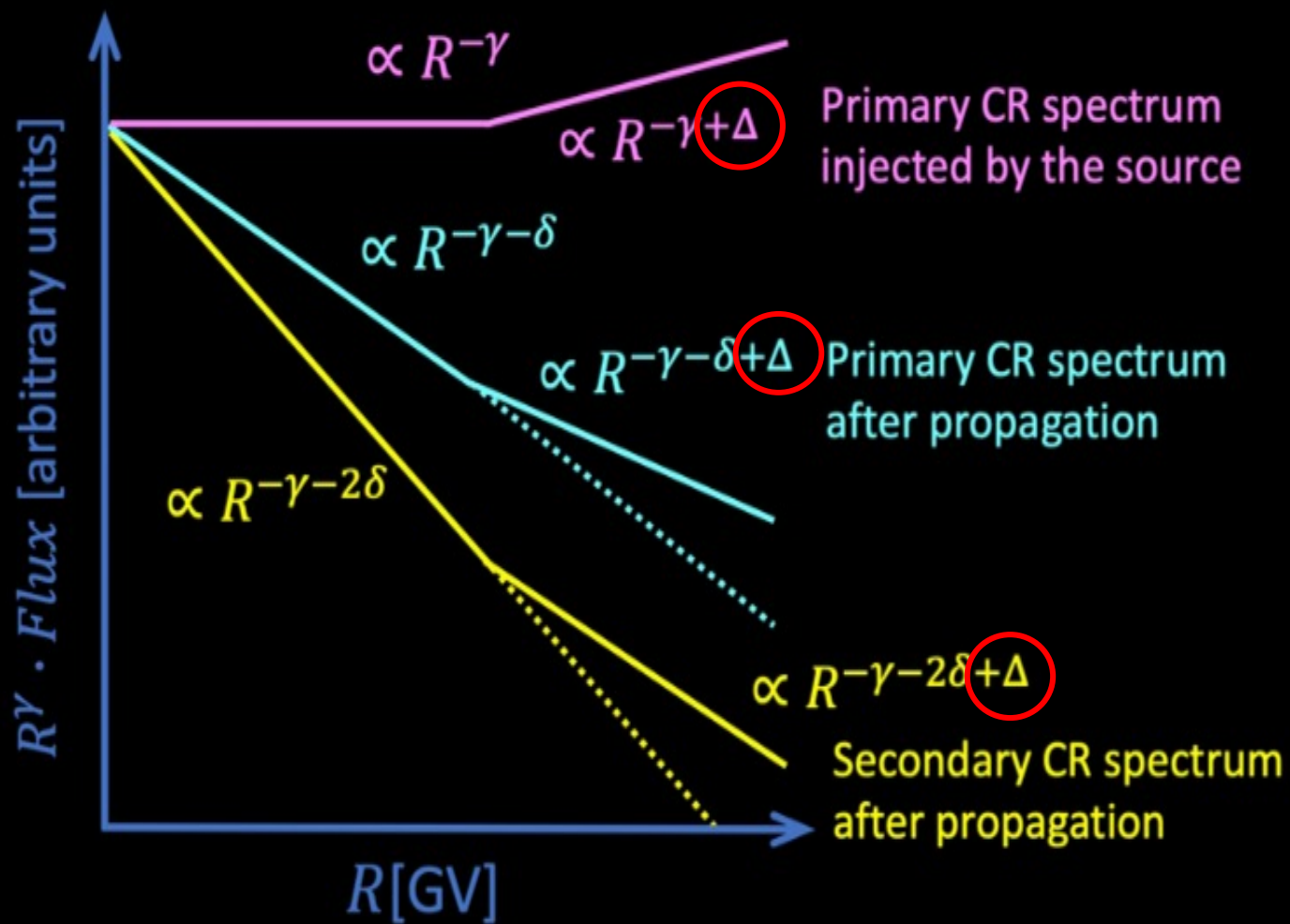
- Flux ratios are a powerful tool to remove degeneracy



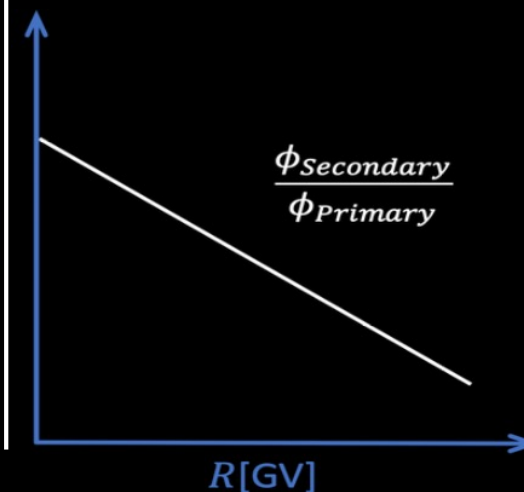
Hypothesis 1: **hardening Δ** is a pure **propagation effect**



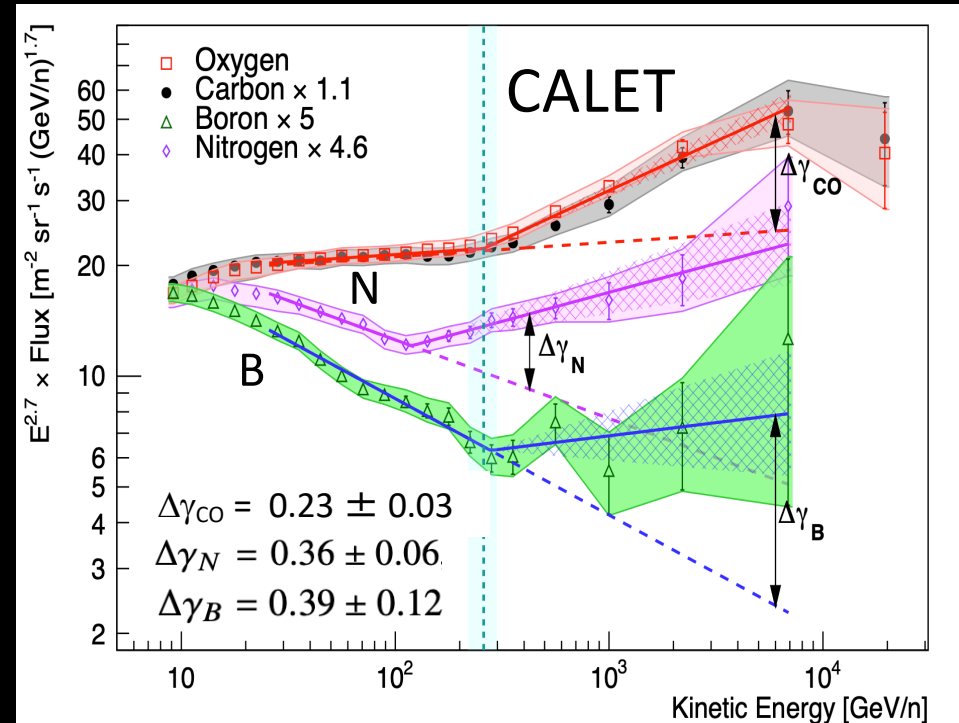
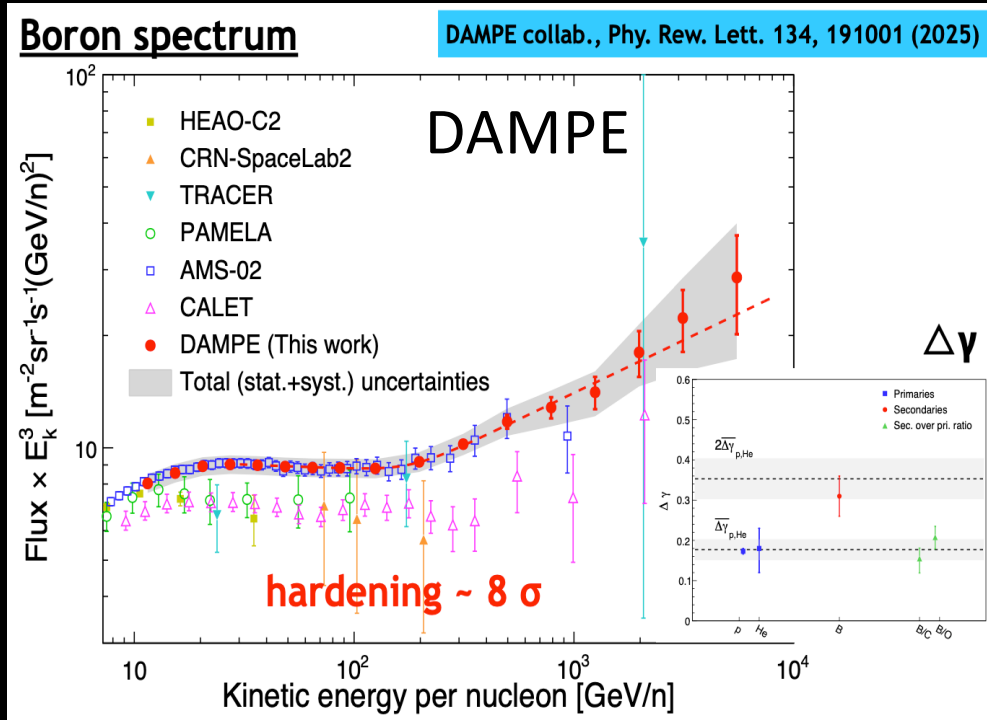
- Flux ratios are a powerful tool to remove degeneracy



Hypothesis 2:
hardening Δ is due to
source(s) spectra



Boron hardens almost twice as p, He, C, O



⇒ **A spectral hardening of Boron flux at $\sim 200 \text{ GeV}/n$ is observed by DAMPE (significance 8σ) and CALET (significance 2.5σ)**

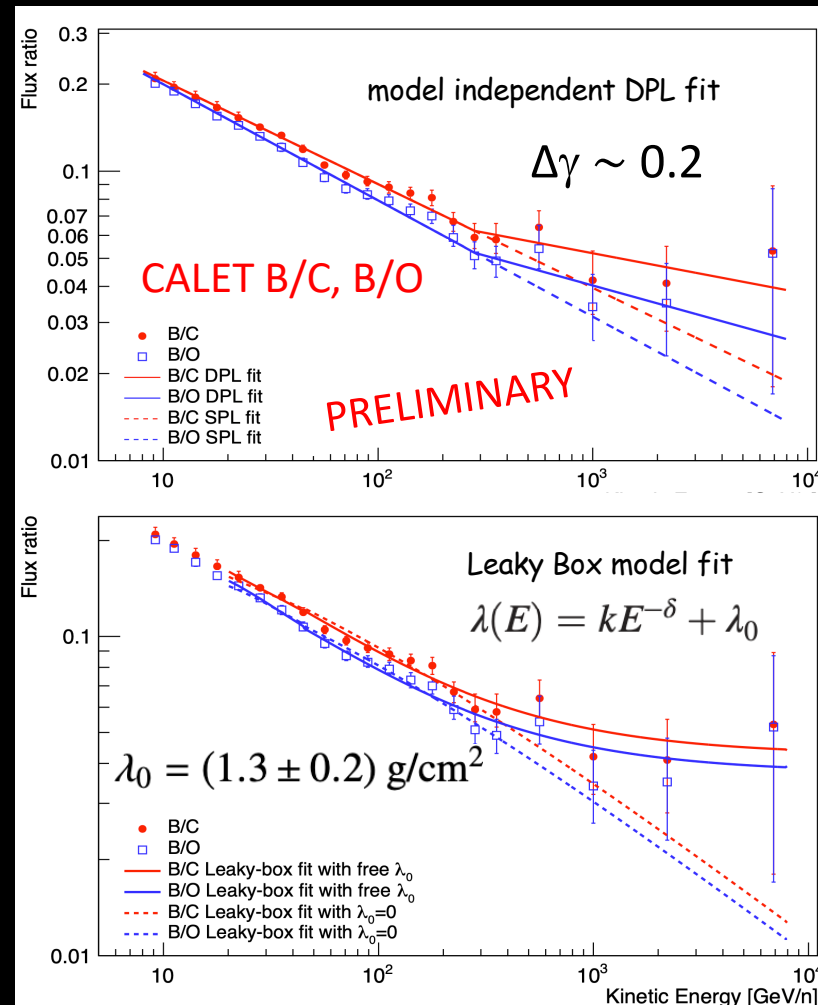
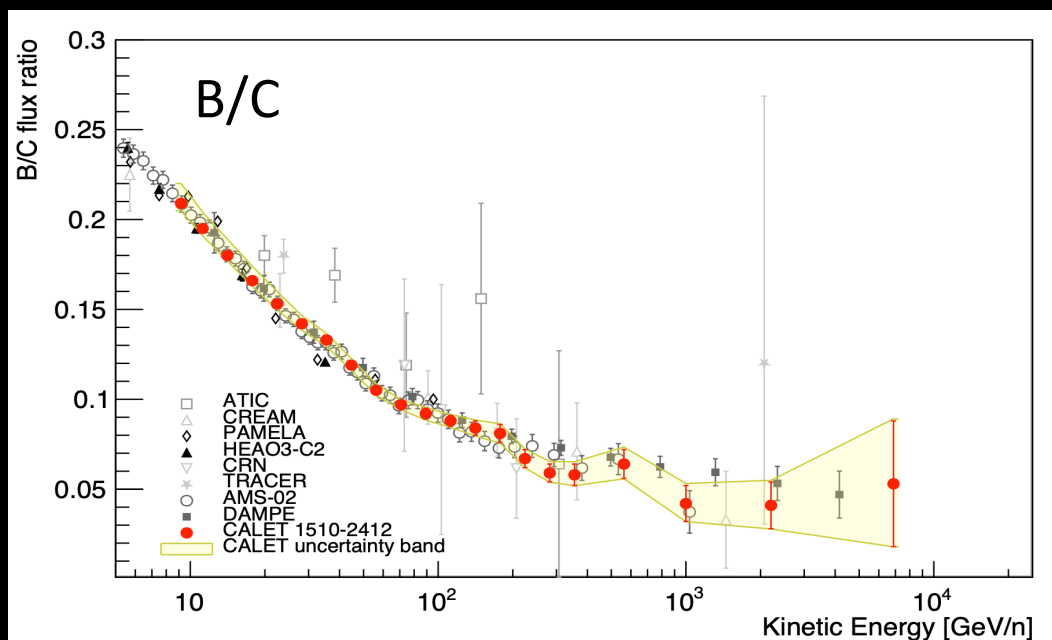
This is consistent with the hypothesis that hardening could be dominated by **propagation effects**

B/C and B/O ratios

ICRC 2025



talk: CRD 308

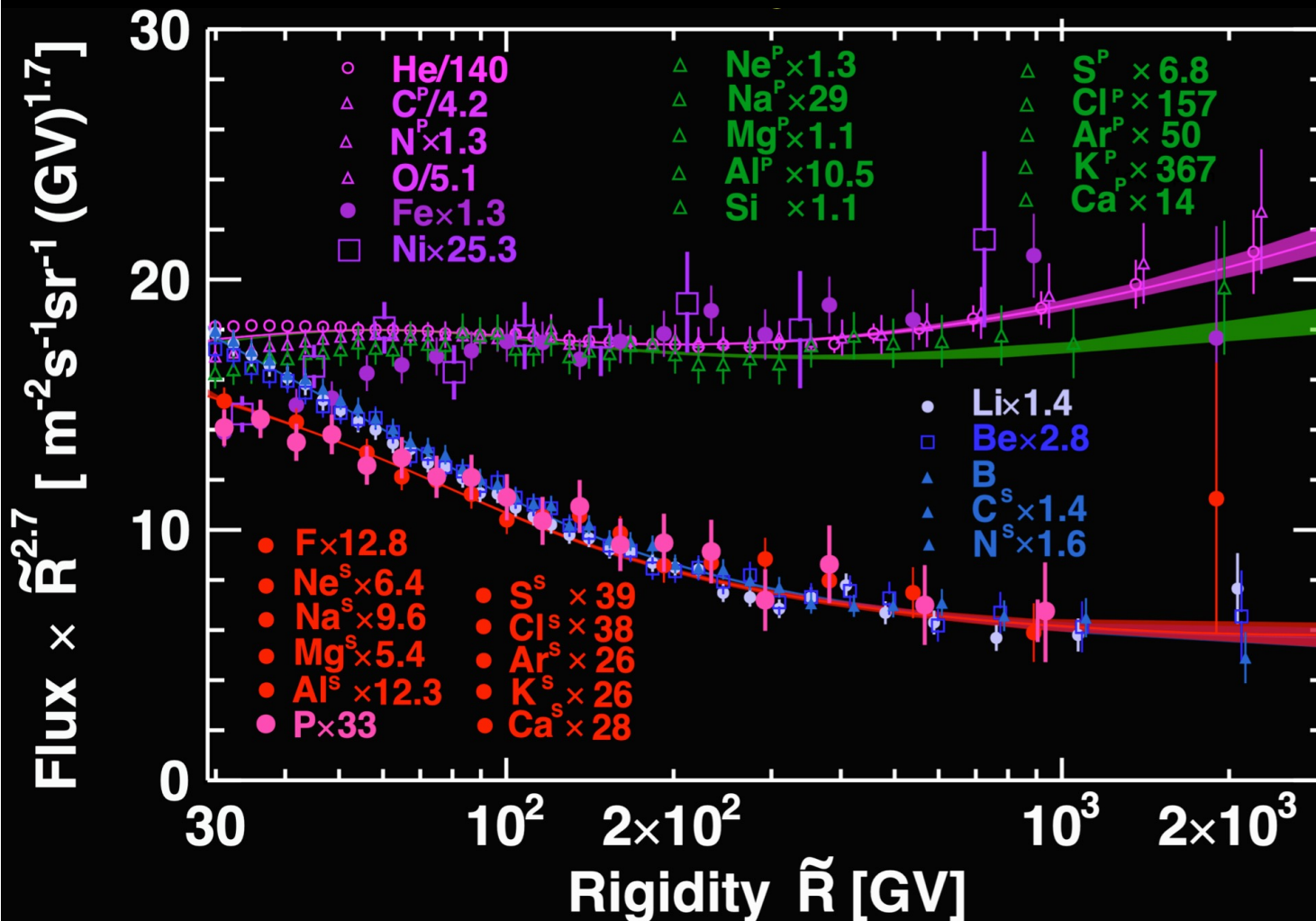


Observation of a deviation of B/C and B/O from a PL:

- from a model independent DPL fit
- from a Leaky Box model fit => non-zero residual path length λ_0 with a statistical significance $> 5\sigma$

The apparent flattening at TeV/n energies might be due to a break in the spectral index δ of the diffusion coefficient or the presence of source grammage.

from E. Robyn for the AMS-02 Collaboration



Primaries

two main classes:

He – C – O – Fe
Ne – Mg – Si – S

Secondaries:

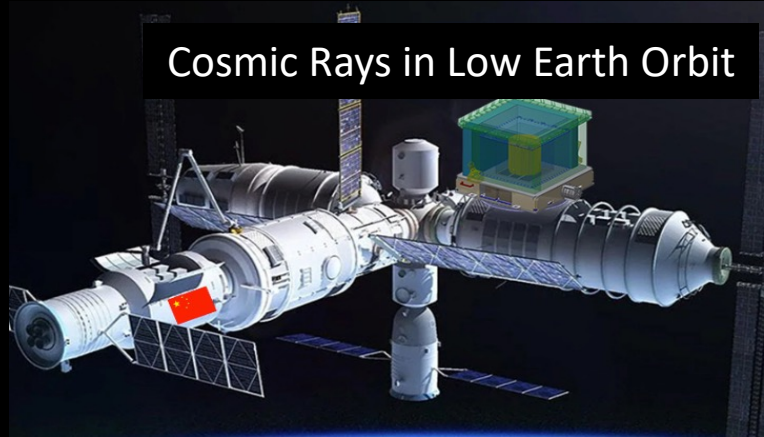
- Li, Be and B fluxes exhibit an identical rigidity dependence above 30 GV.
- F-P fluxes show a distinct rigidity dependence compared to Li-Be-B.

- Maximum Detectable Rigidity (MDR) limits AMS-02 spectra to a few TV
- Some primaries found to have a secondary component (e.g. C)

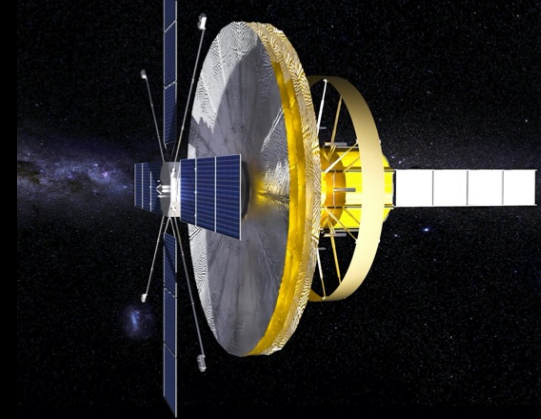
Direct Detection of cosmic rays

Main instruments in Low Earth Orbit at present (or recent past)

Experiment	e^\pm (present data)	e^+e^- (Energy range)	CR nuclei (Energy range)	charge Z	Gamma-ray	Site	Launch	Status
PAMELA	spectrometer	1-700 GeV (3 TeV with calorimeter)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006	ended
FERMI	no magnet	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008	operative
AMS-02	spectrometer	$e^+ < 2$ TeV $e^- < 3$ TeV (after upgrade)	1 GV-3 TV	1-28	1 GeV-1 TeV (calorimeter)	ISS	2011	operative
NUCLEON	no magnet	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014	ended
CALET	no magnet	1 GeV-20 TeV (extendable -> 20TeV)	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015	operative
DAMPE	no magnet	10 GeV-20 TeV	50 GeV-1 PeV	1-20	5 GeV-10 TeV	SAT	2015	operative
ISS-CREAM	no magnet	100 GeV-10 TeV	1 TeV-1 PeV	1-28	-	ISS	2017	ended



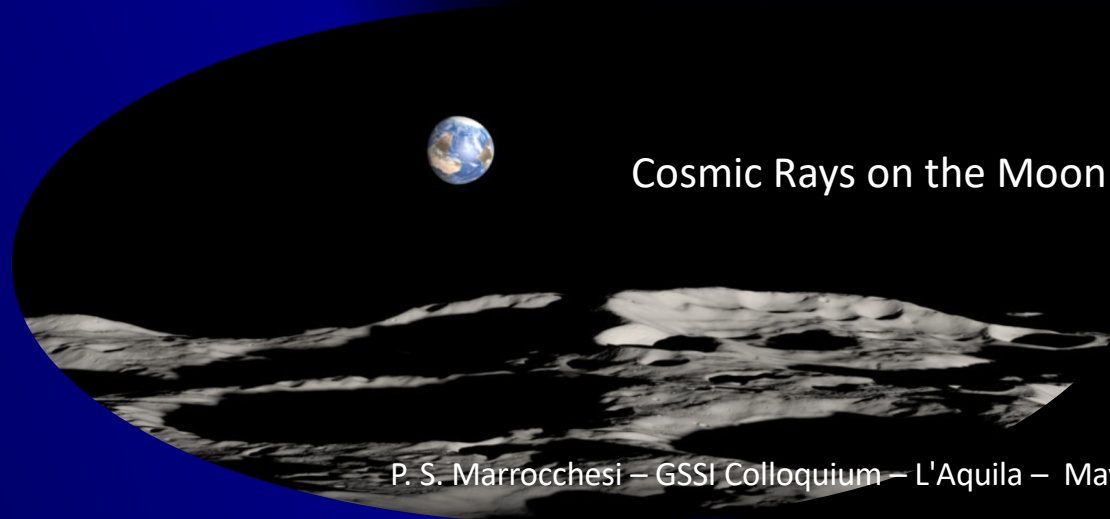
Cosmic Rays at Lagrangian Point L2 ?



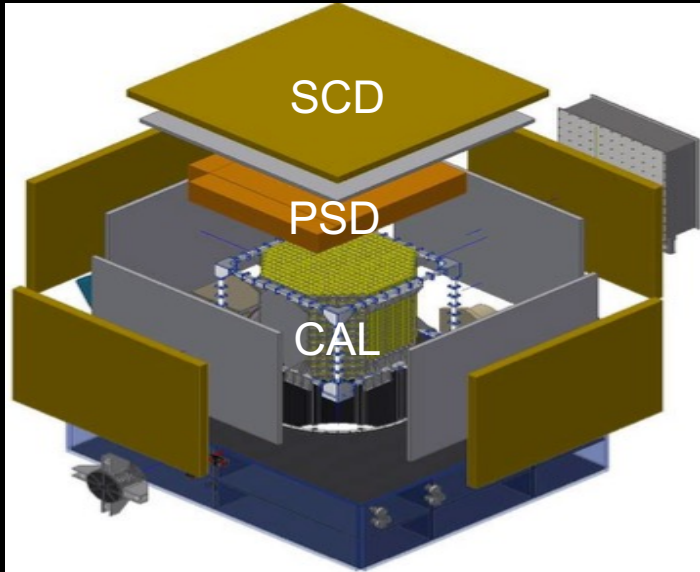
A glimpse into the future



Ultra Long Duration Balloons (ULDB)

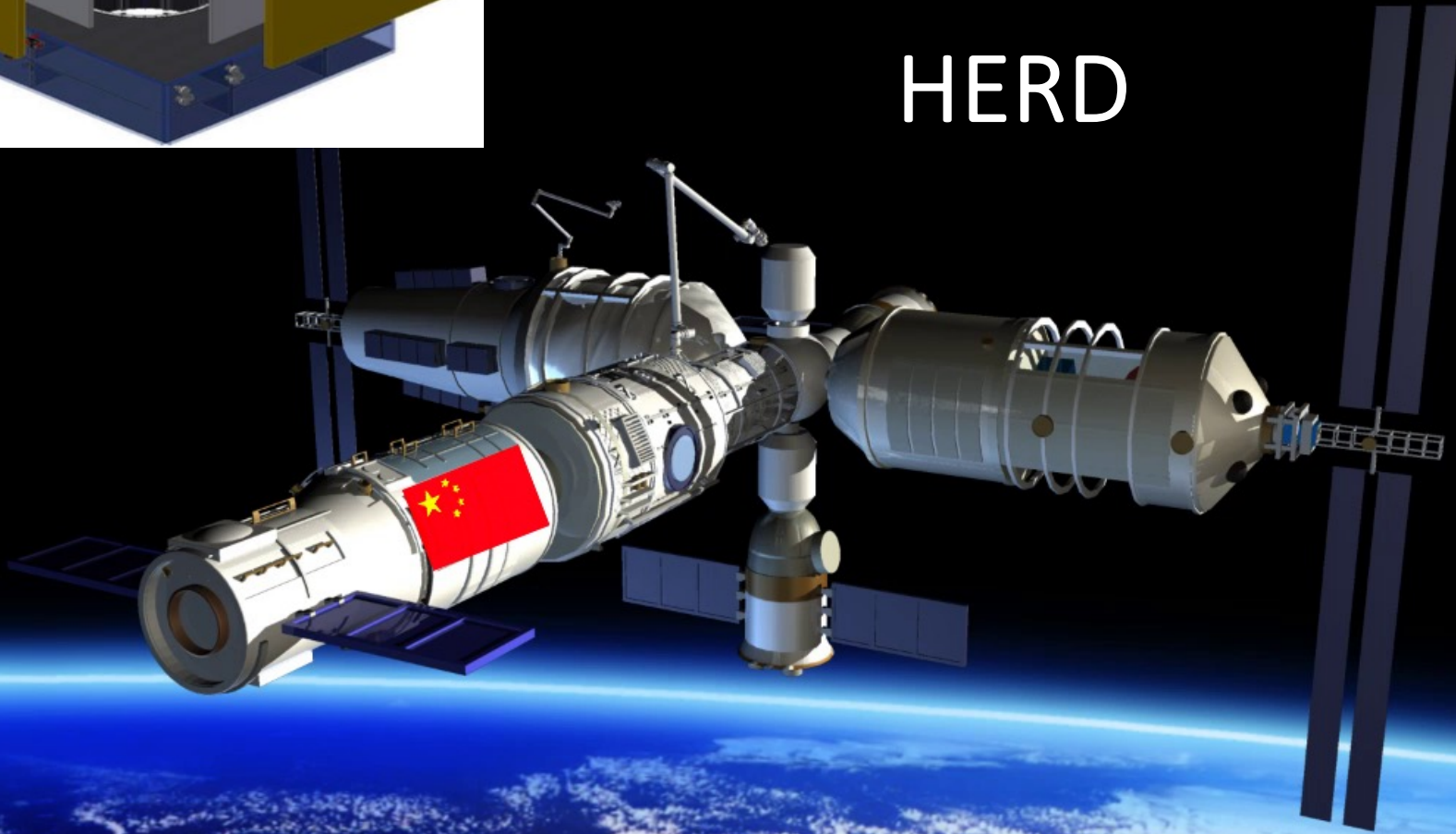


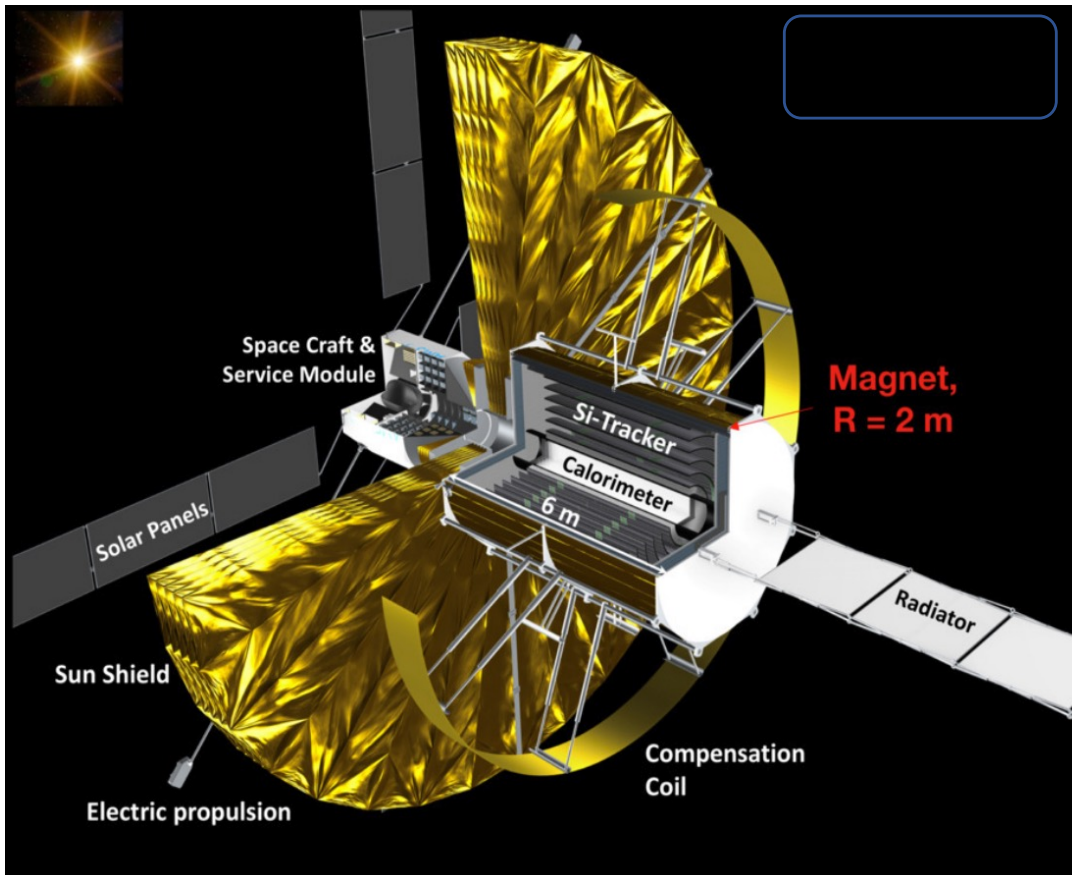
Cosmic Rays on the Moon ?



The High Energy cosmic-Radiation
Detection Facility aboard
China's Space Station

HERD





AMS-100

Acceptance 20-30 m^2sr (nominal 100 m^2sr)

MDR = 80 -100 TV

depth: 70 X_0

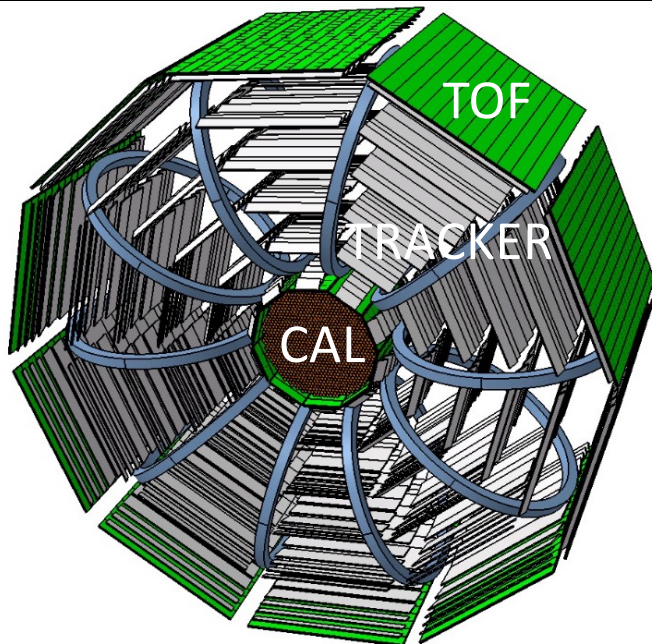
Weight ~ 40 t

4.0 λ

Power: 15 KW

SUPERCONDUCTING SOLENOID: 1 Tesla

site: [Lagrangian Point L2](#)



Antimatter Large Acceptance Detector In Orbit (ALADInO)

Acceptance (calorimeter) 9 m^2sr

depth: 61 X_0

(spectrometer + calorimeter) 3 m^2sr

3.5 λ

MDR = 20 TV

Weight ~ 6 t

Power: 4kW

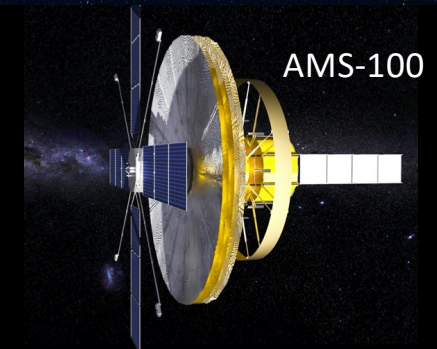
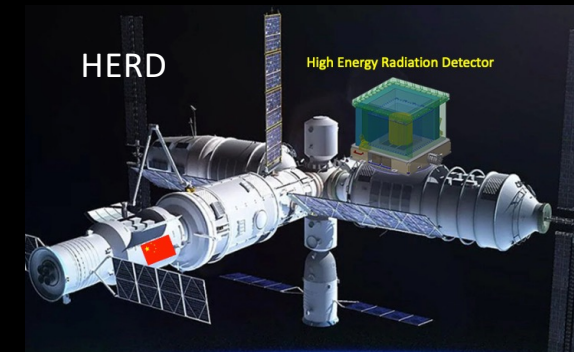
TOROIDAL MAGNET

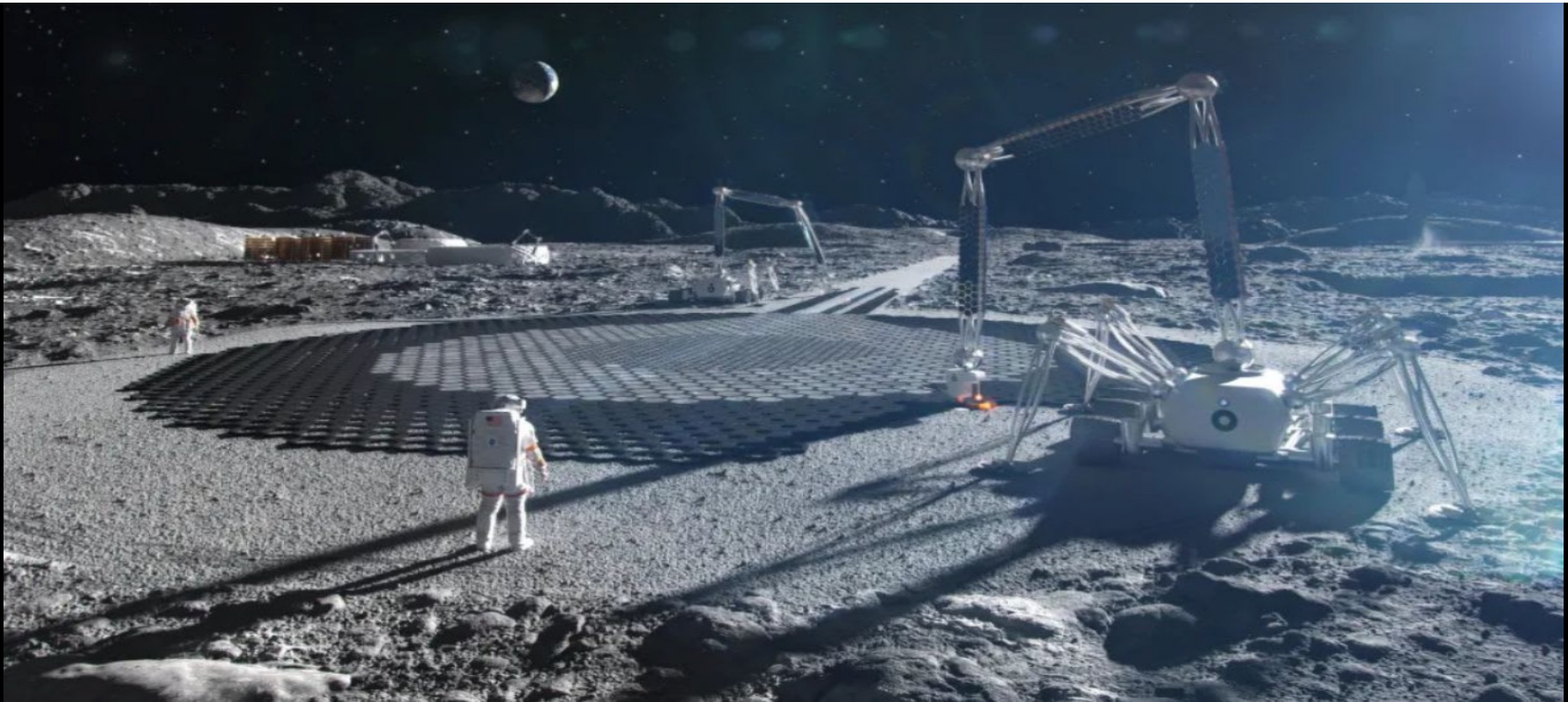
site: [Lagrangian Point L2](#)

NEXT GENERATION OF DIRECT MEASUREMENTS

- A new generation of LARGE and VERY LARGE space instruments are under study
- They are facing formidable challenges in terms of payload size, weight, power, and cost

Item	HERD (LEO)	ALADINO (L2)	AMS-100 (L2)
calorimeter depth for electrons	55 X_0	61 X_0	70 X_0
calorimeter depth for protons	3 λ_I	3.5 λ_I	4 λ_I
MDR	N/A	20 TV	100 TV
Acceptance (spectrometer + calorimeter)	N/A	~ 3 m ² sr	~ 20-30 m ² sr
Acceptance (calorimeter)	~ 2-3 m ² sr	~ 9 m ² sr	~ 20-30 m ² sr
# of channels	300 k	2.5 M	8 M
Mass	~ 4,000 kg	~ 6,000 kg	~ 40,000 kg
Power Consumption	~ 1.4 kW	~ 4 kW	~ 15 kW





A Cosmic Ray Observatory at the South Pole of the Moon ?



MOONRAY site at Lunar South Pole (AI artist's view)



*Thank you
for your
attention !*