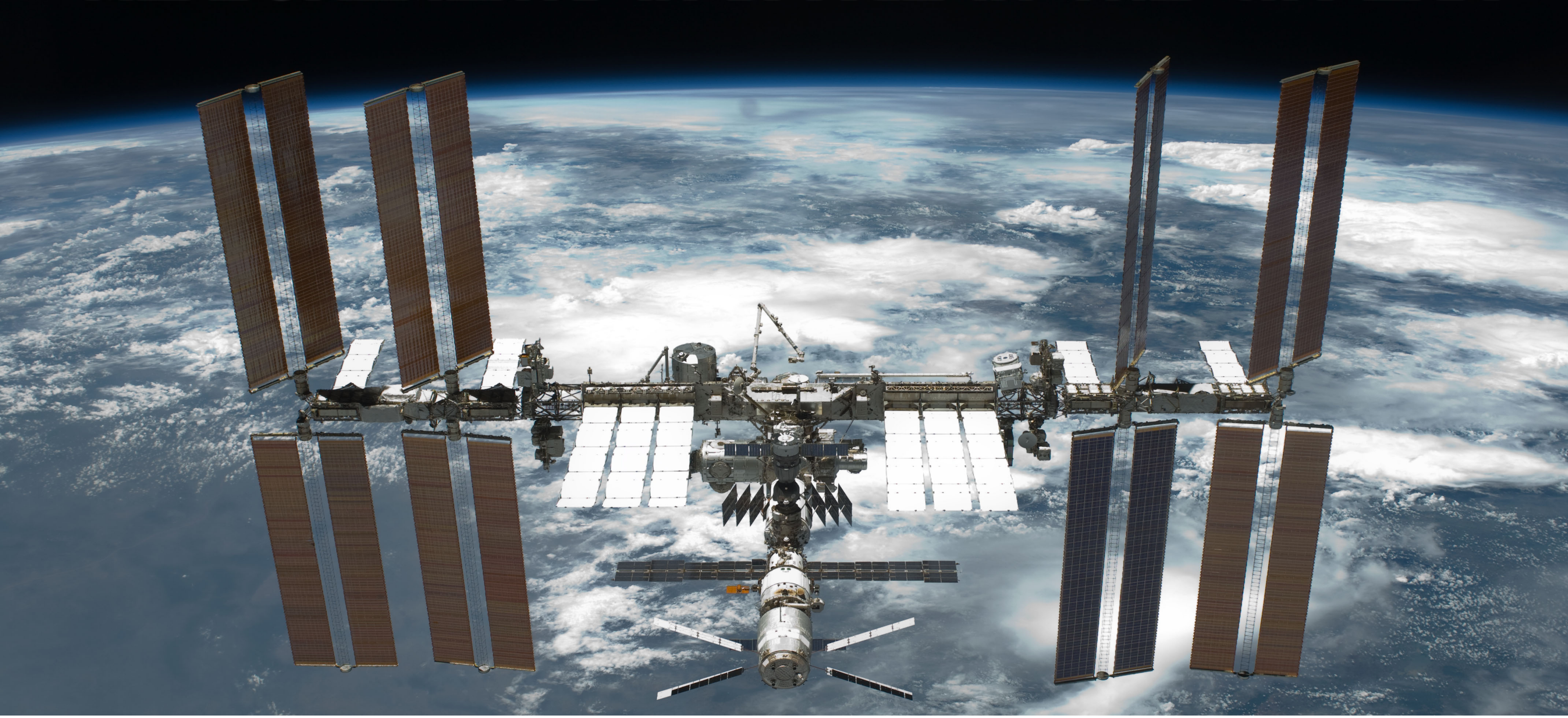
“Gamma Ray Astrophysics with CTA”
Sexten

# Direct (charged) cosmic ray measurements in space in the CTA era




**Matteo Duranti**

Istituto Nazionale Fisica Nucleare – Sezione di Perugia

# Outline

- (charged) cosmic rays
- experimental techniques and experiments
- important results
- new ideas to increase the statistical and energy range reach

# (Charged) Cosmic Rays

# What are the cosmic rays?

# What are the cosmic rays?

The origin of the super-powers of the
**Fantastic Four!**



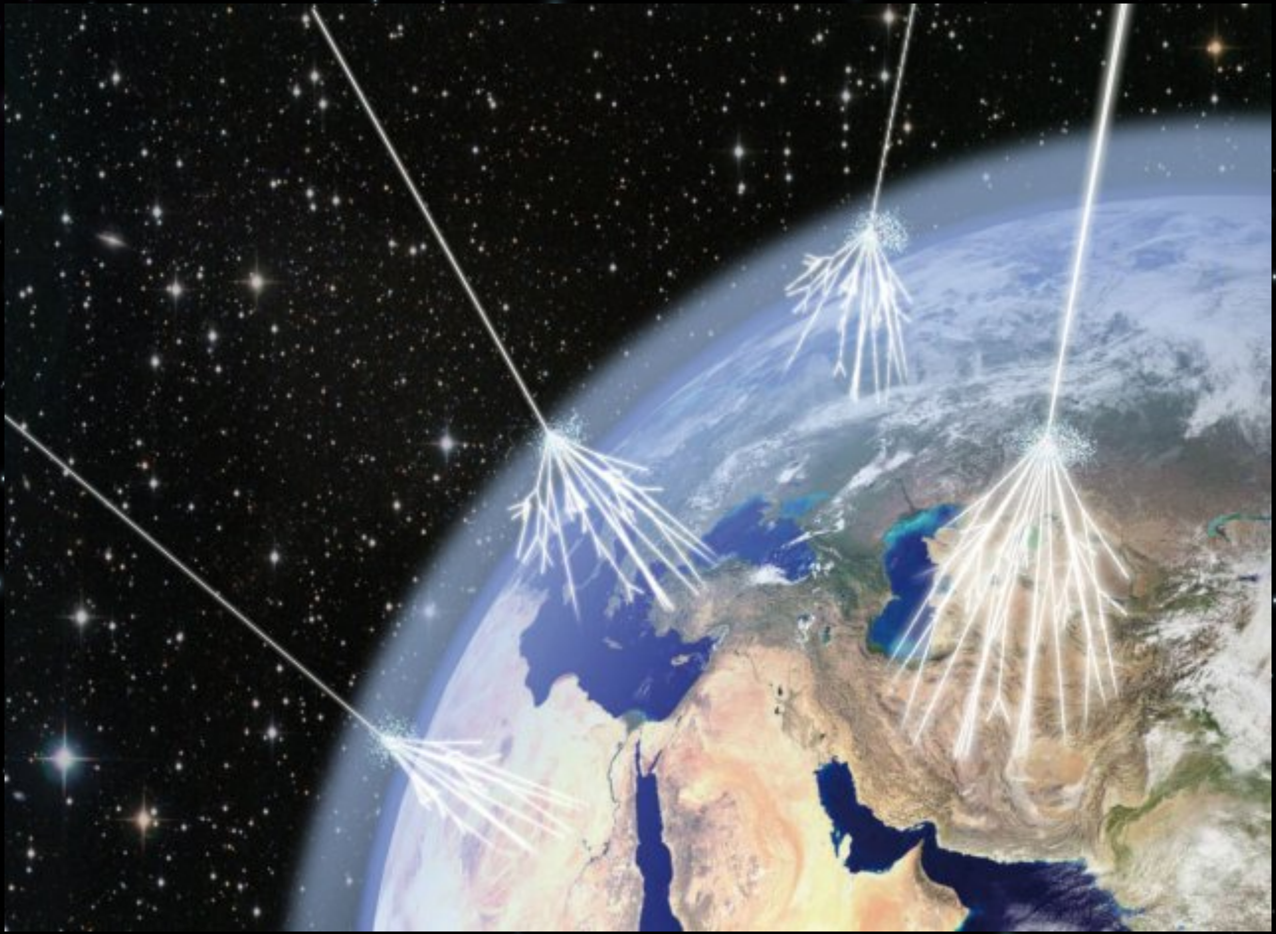
FROM FANTASTIC FOUR #1

# What are the cosmic rays?

One of the **Goldrake** weapons

also called ‘parallel disintegrators’!

# What are the cosmic rays?



The constituents of a flux incident the Earth

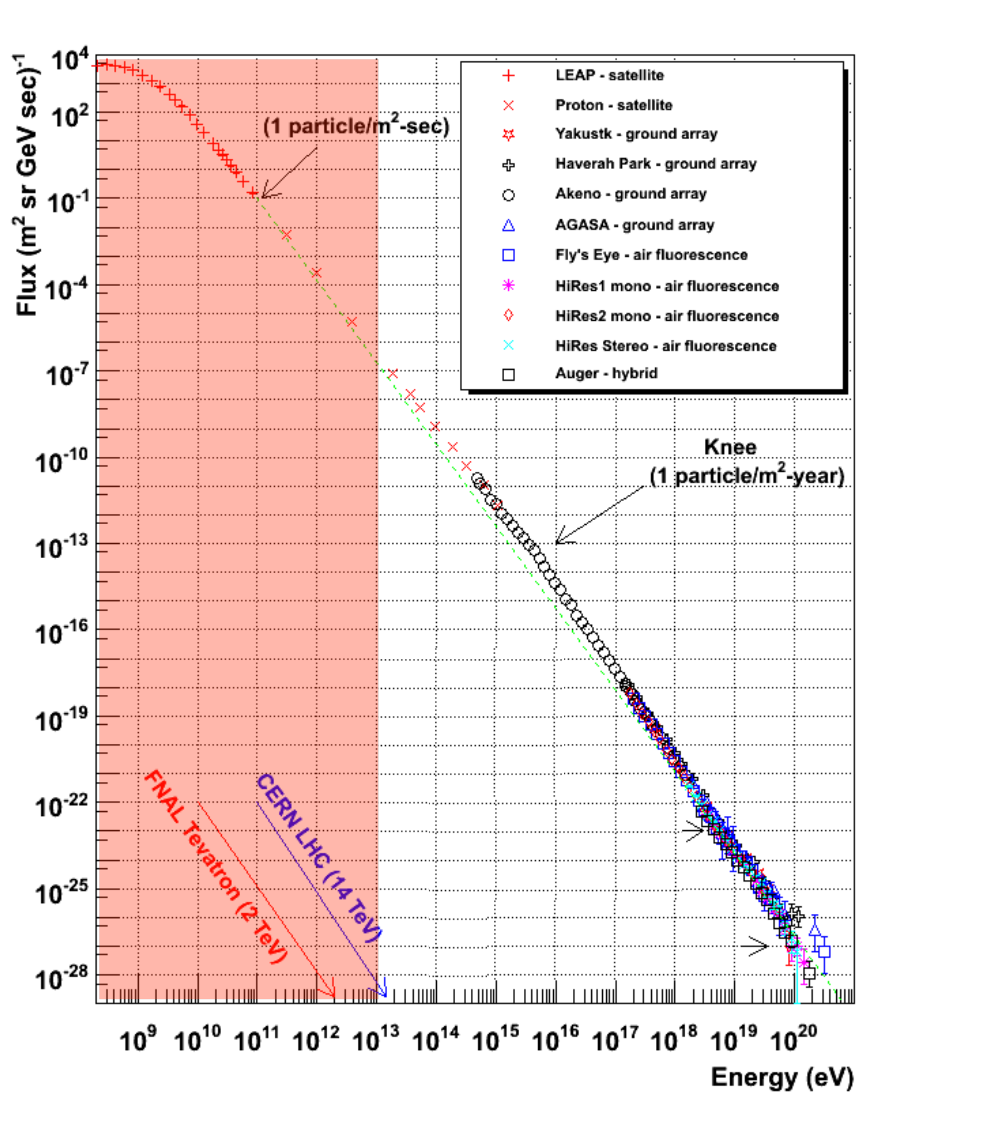
($1\ s^{-1}\ cm^{-2}$)

Thanks to the geo-magnetic field and the atmosphere, the great part doesn't reach the Earth

On the ground (mainly muons) the flux is

$1\ min^{-1}\ cm^{-2}$

# CR spectrum



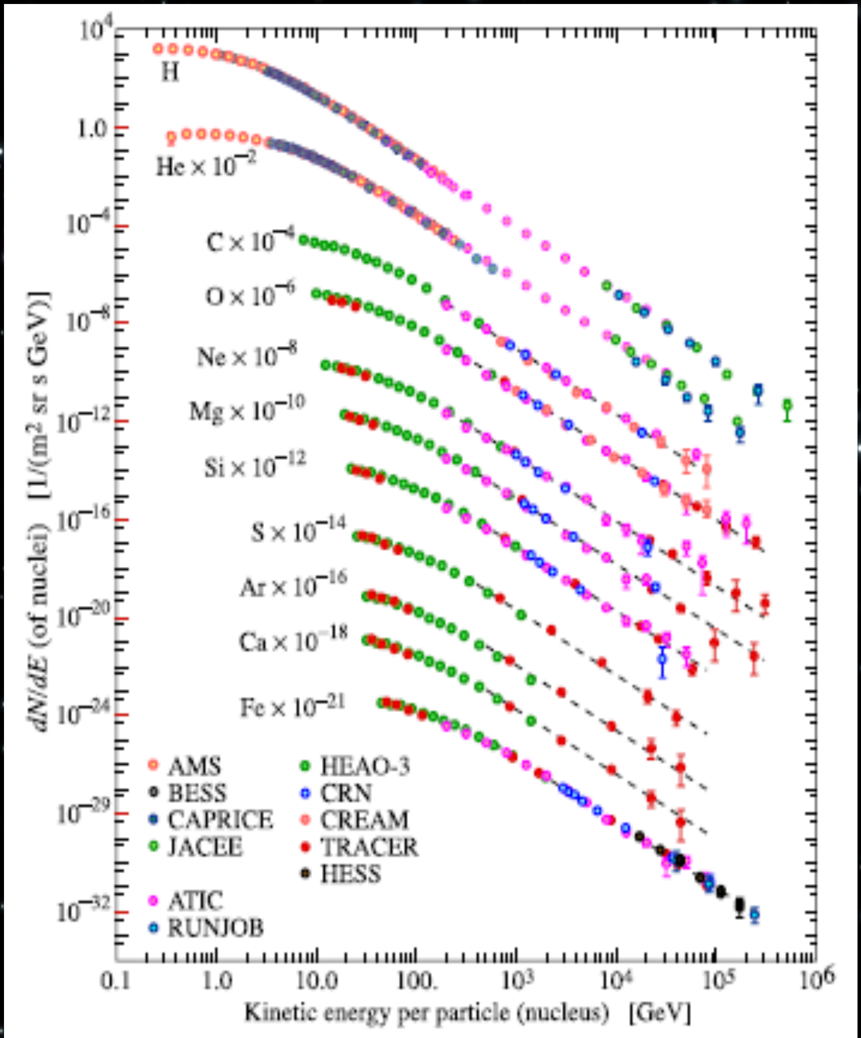

- Up to ~ $10^{20}$ eV;
- Energy density ≈ 1 eV / cm$^3$;
- Luminosity, L > $10^{40}$ erg/s;

$$\Phi(E)dE = kE^{-\gamma}dE$$

$\gamma \approx 2.6 - 2.7$

- energies much greater w.r.t. the ones reachable on ground;

# CR spectrum

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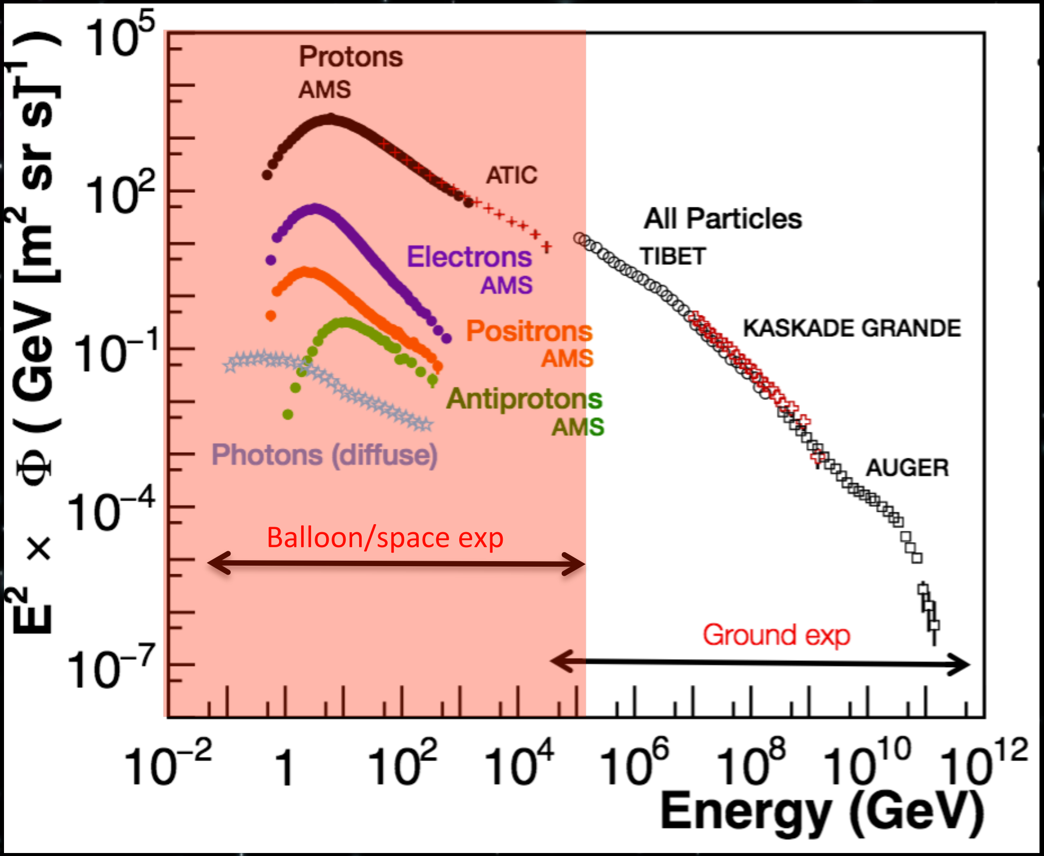
- to investigate the spectral and chemical composition accurate detector ('a la particle physics') are needed;

# CR spectrum

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$\gamma \approx 2.6 - 2.7$

- energies much greater w.r.t. the ones reachable on ground;
- to investigate the spectral and chemical composition accurate detector ('a la particle physics') are needed;
- to reach higher energies, bigger and bigger detectors are needed;

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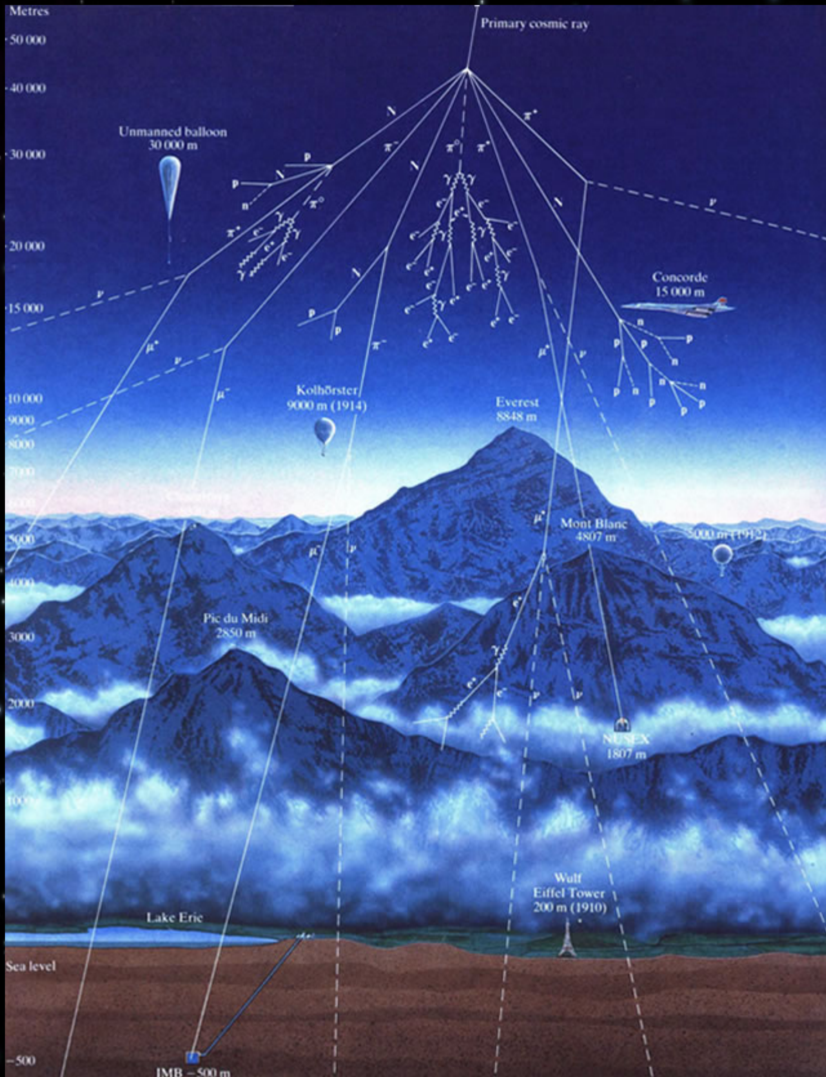
# Fasten your seatbelts!



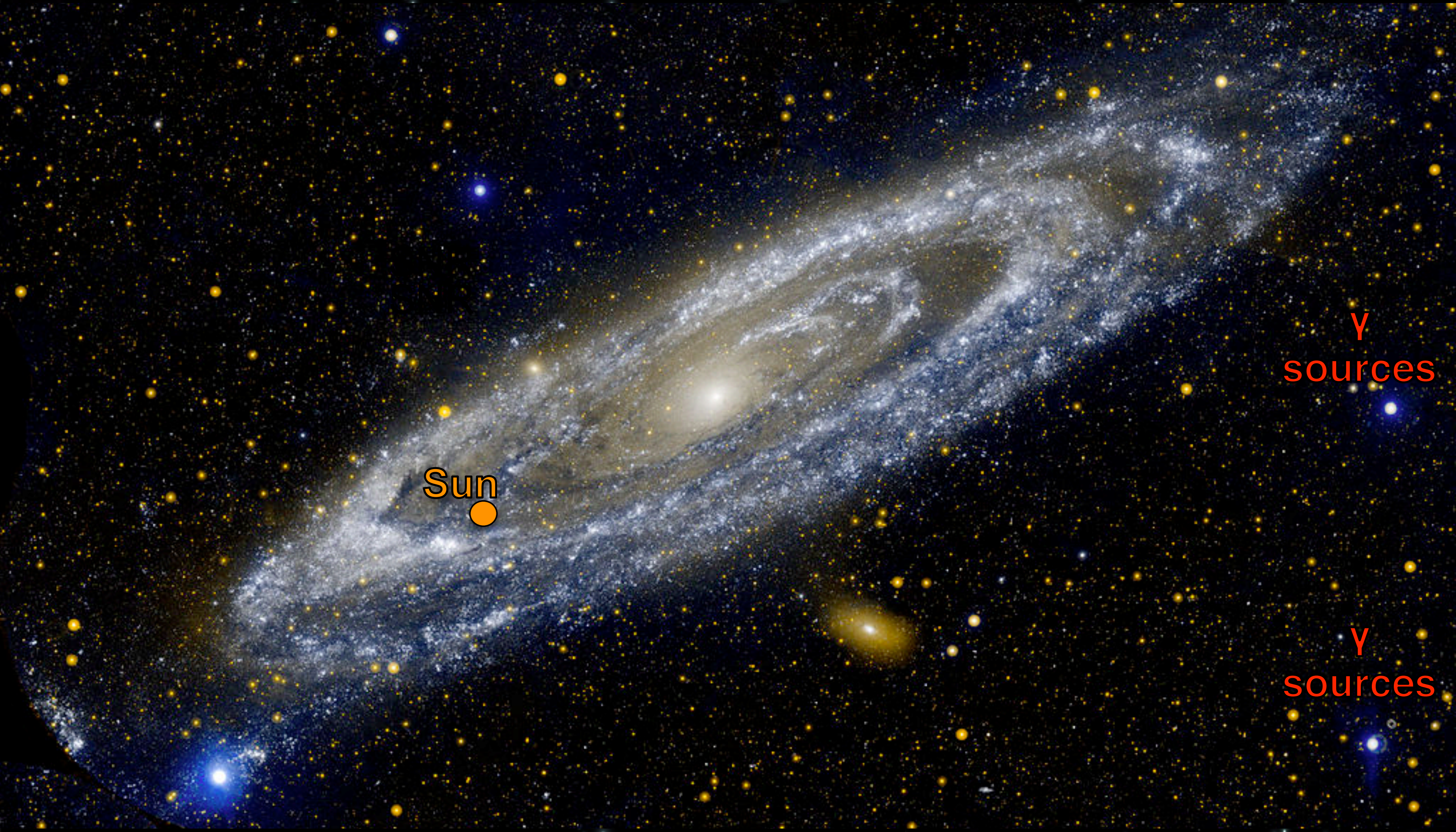

Most of CR's don't reach the Earth

Let's go 'above' the atmosphere (at least above the troposphere, in the stratosphere, reachable via a balloon flight)

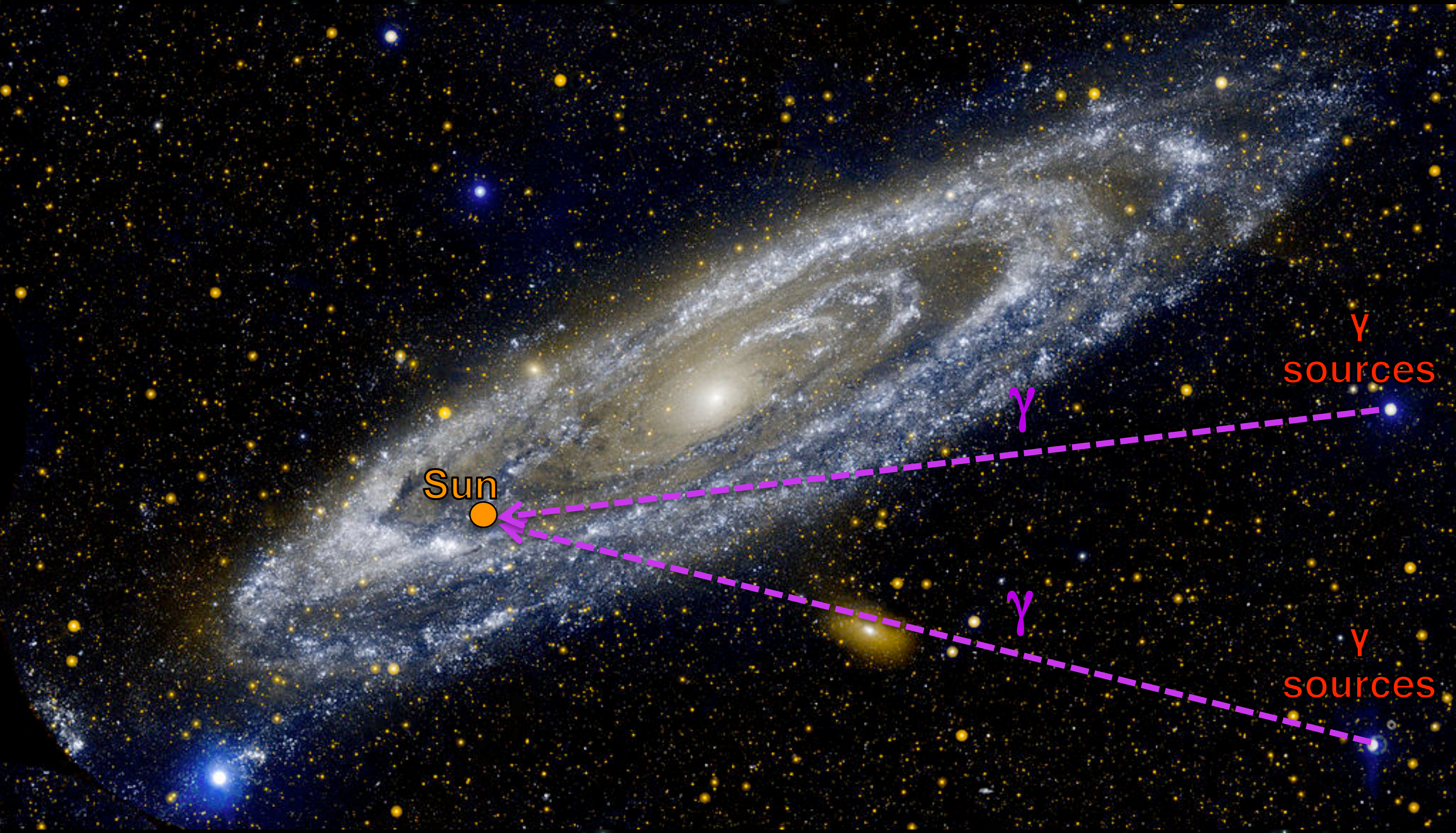
**Particle Physics in Space!**

# Cosmic Rays propagation

# Cosmic Rays propagation



# Cosmic Rays propagation



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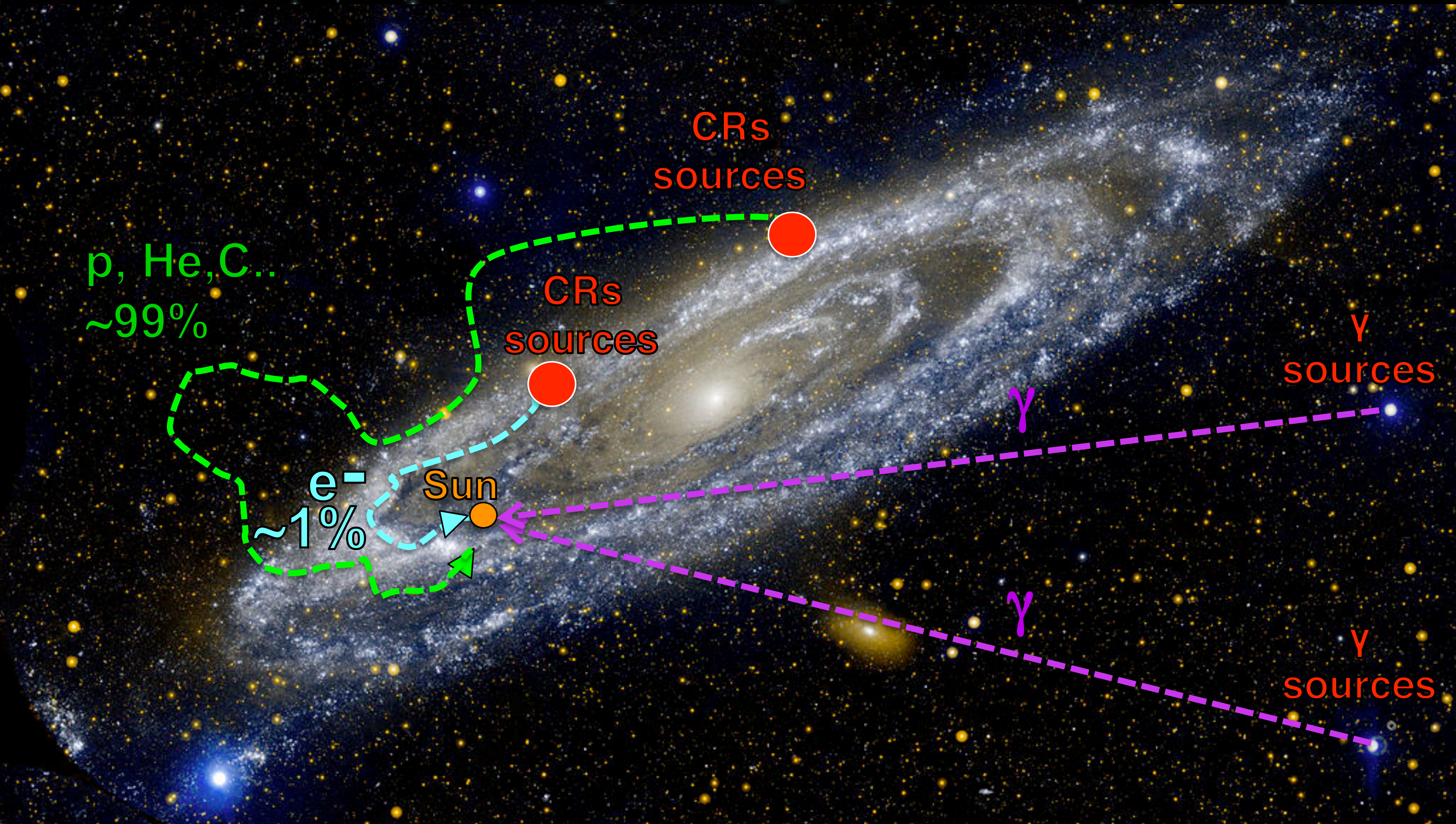
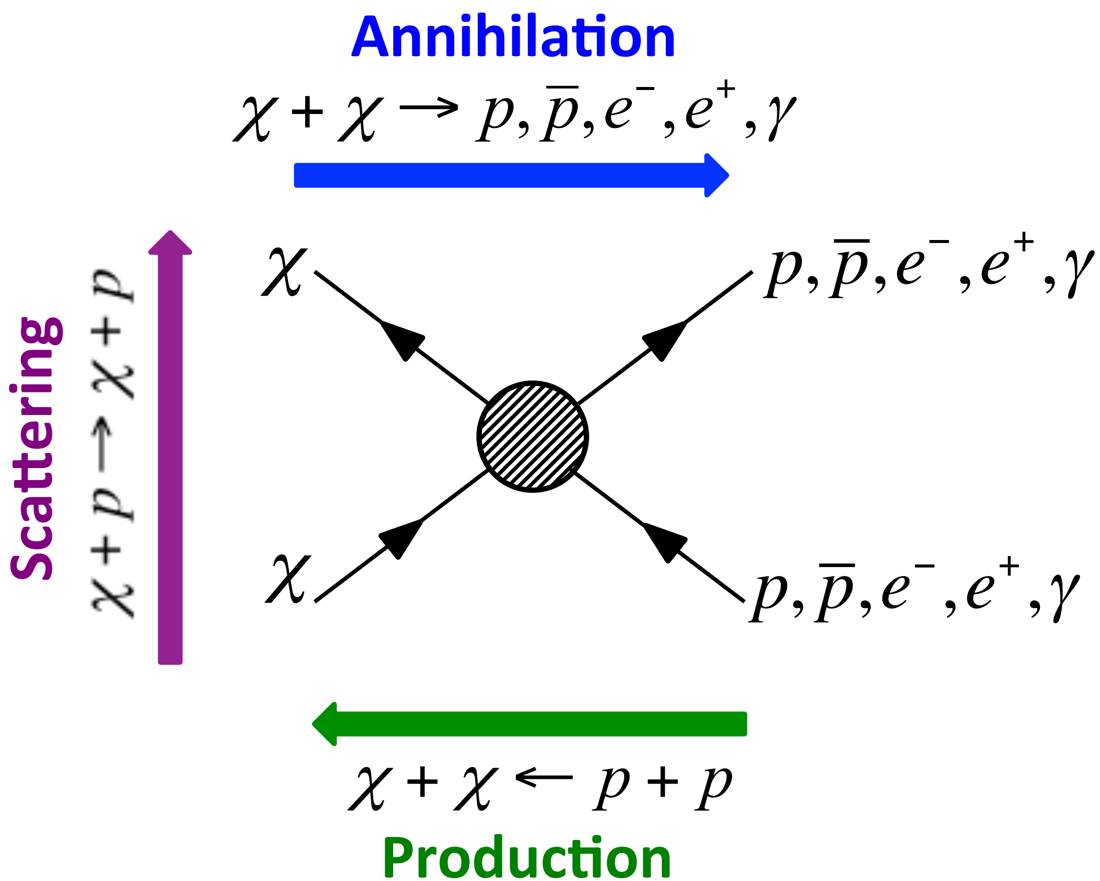


# The quest for dark matter



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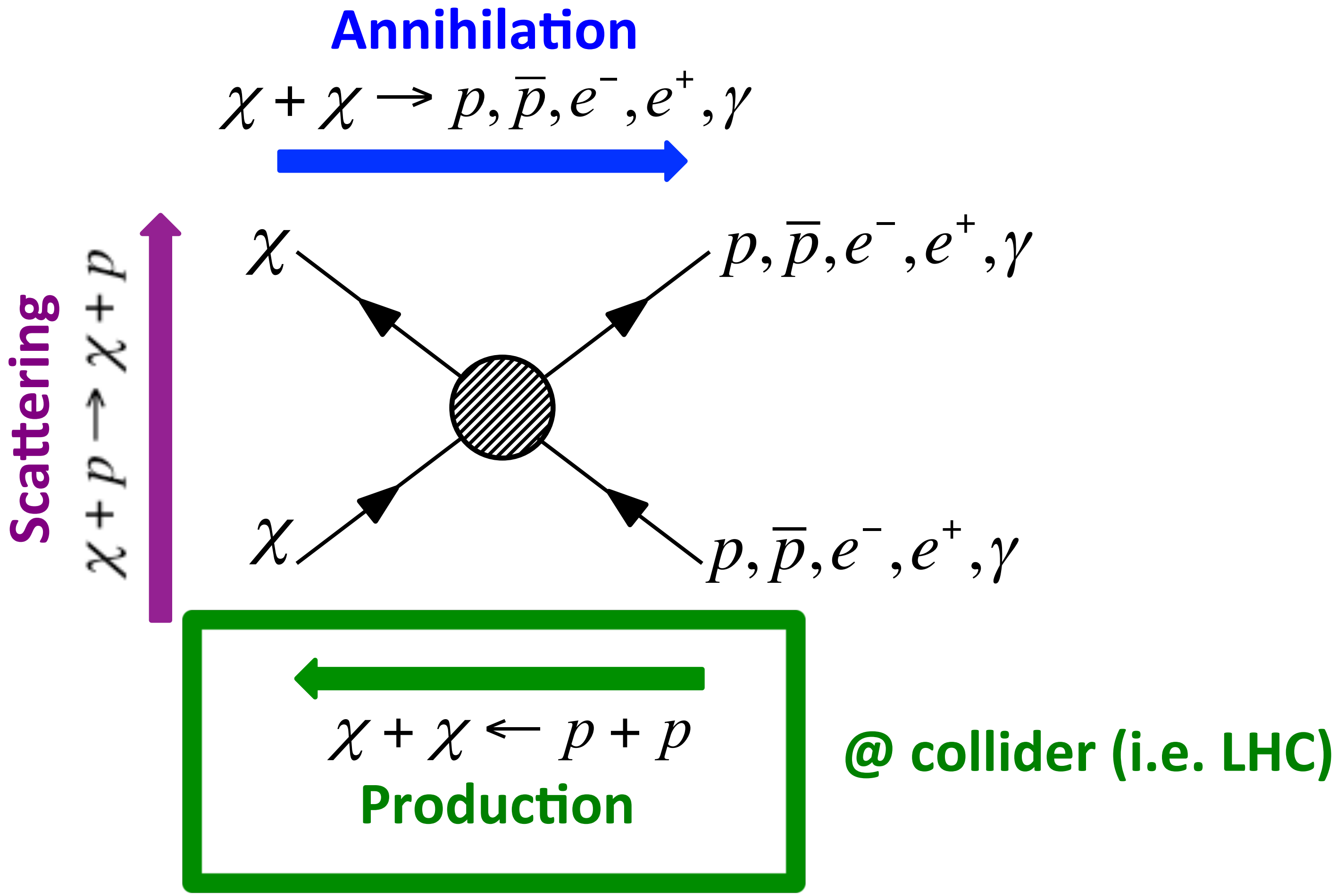

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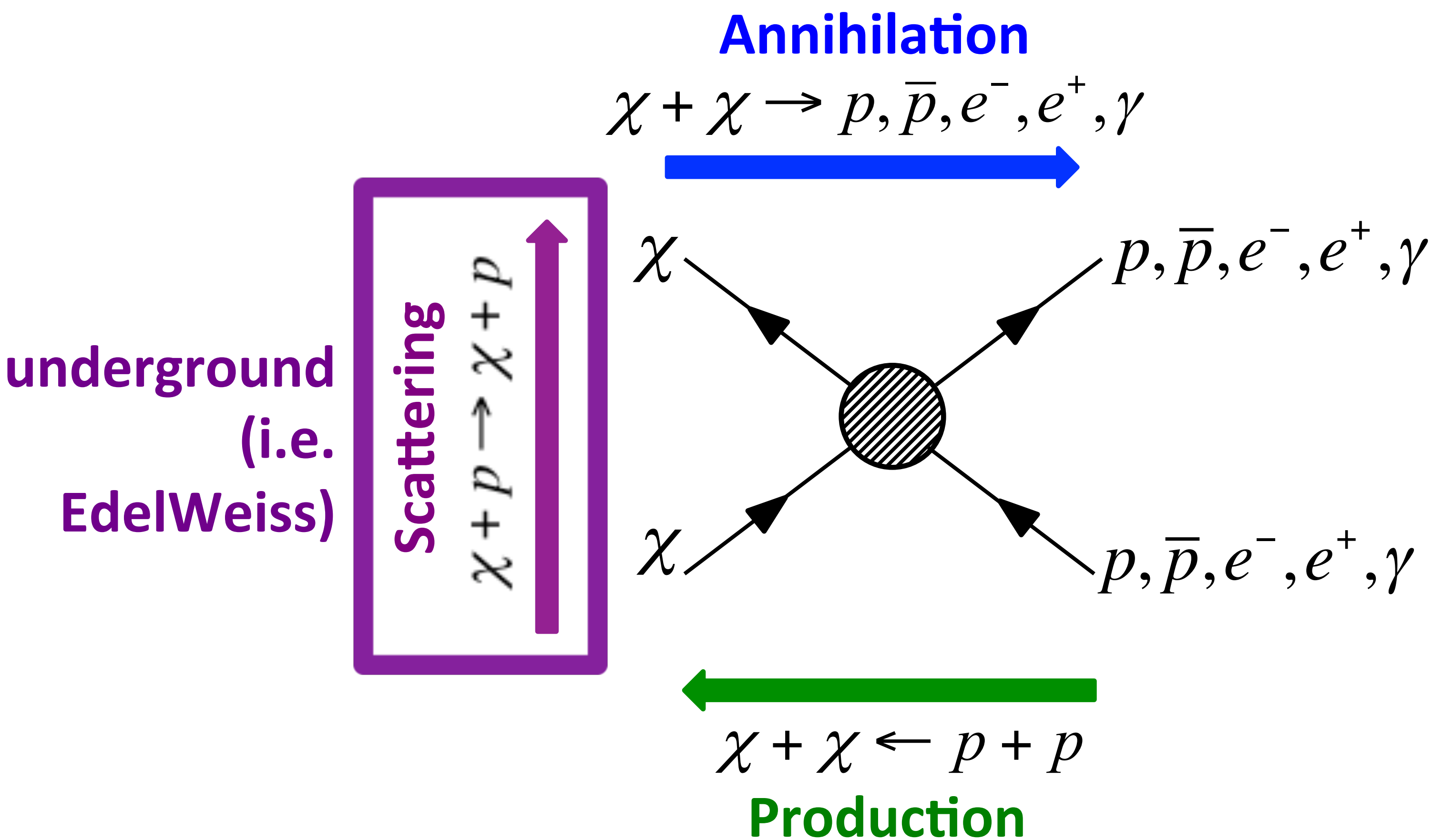

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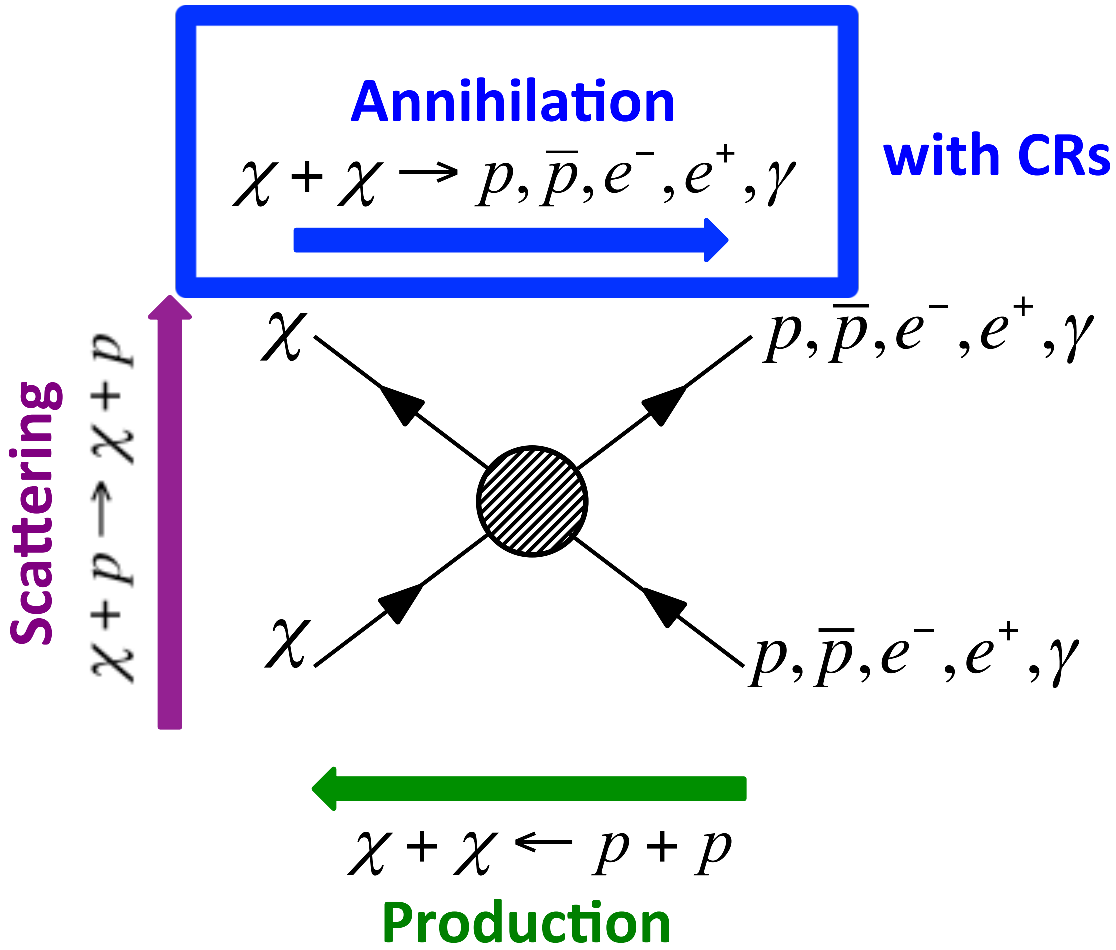

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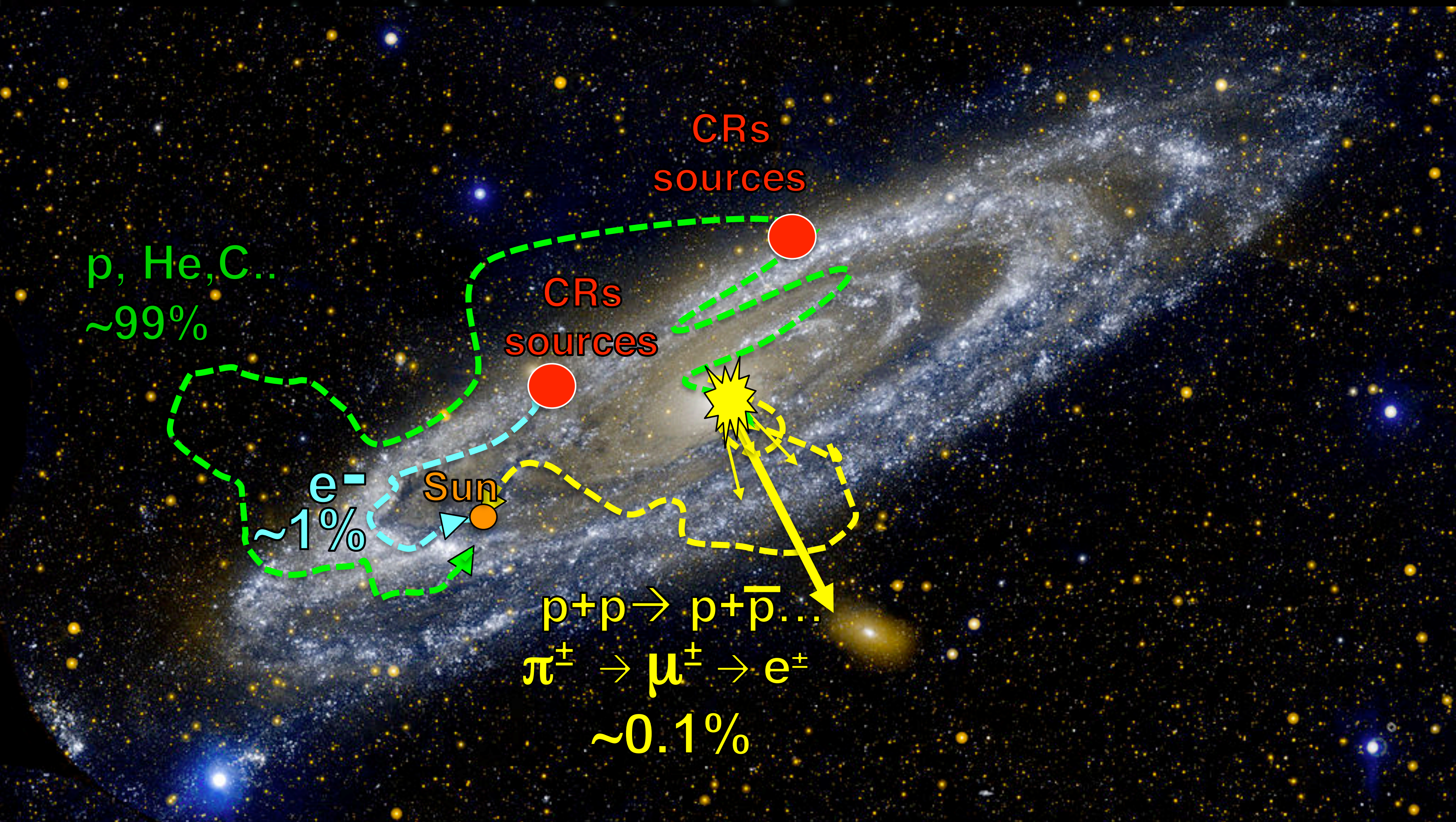
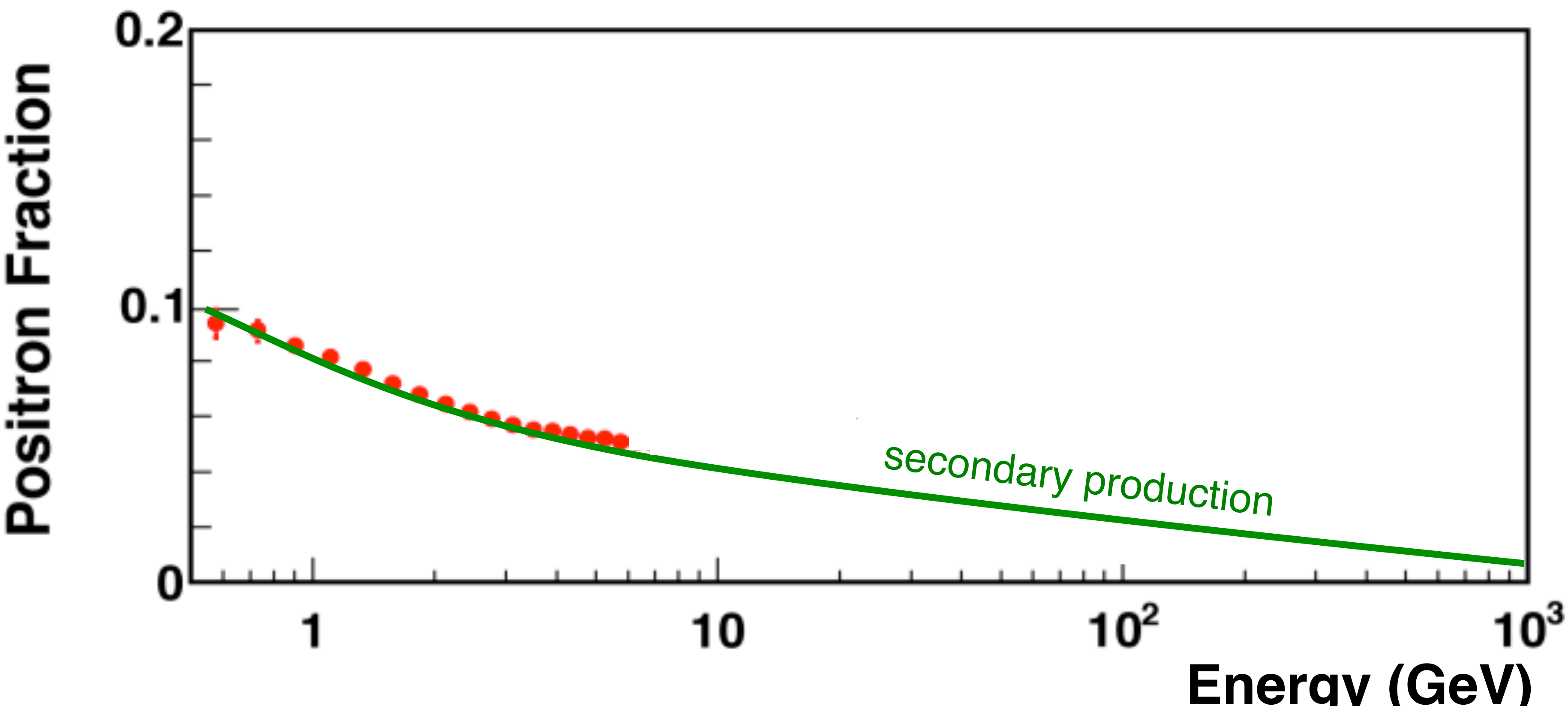
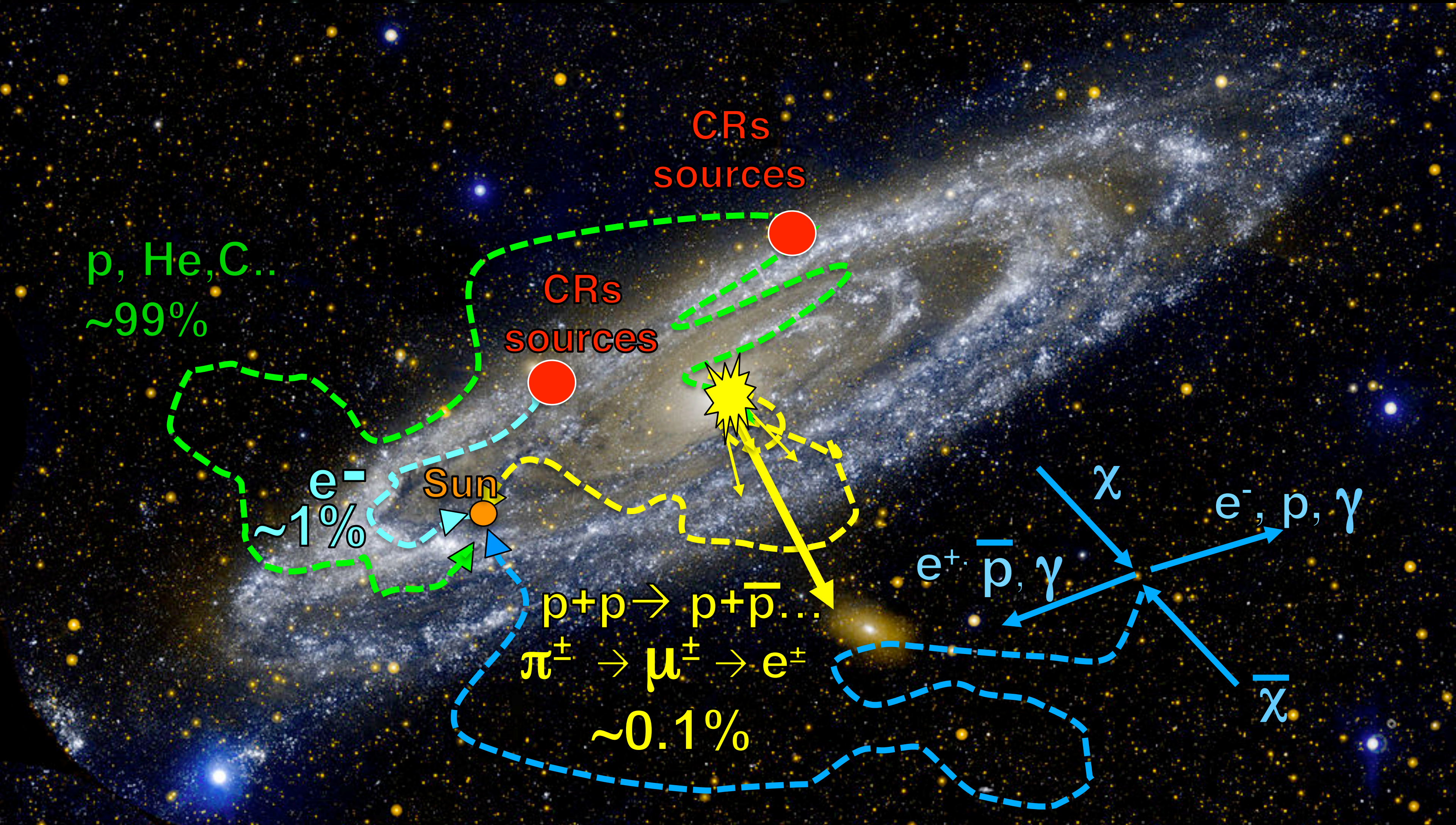
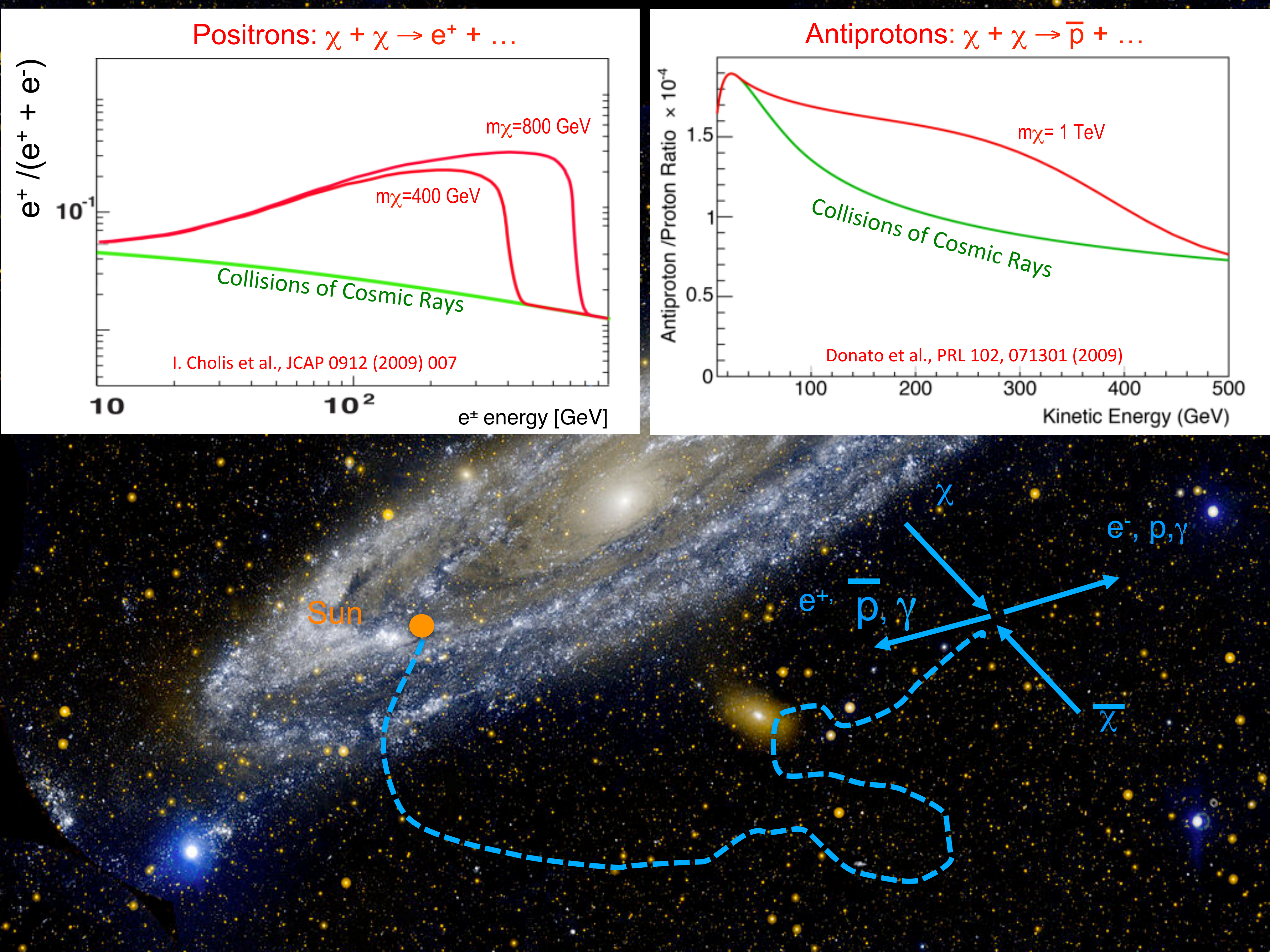


# Anti-matter flux

Even if “not-interesting” to search for primordial Anti-matter, the Z=1 Anti-matter, being rare, is the key in the ***indirect*** search for Dark Matter

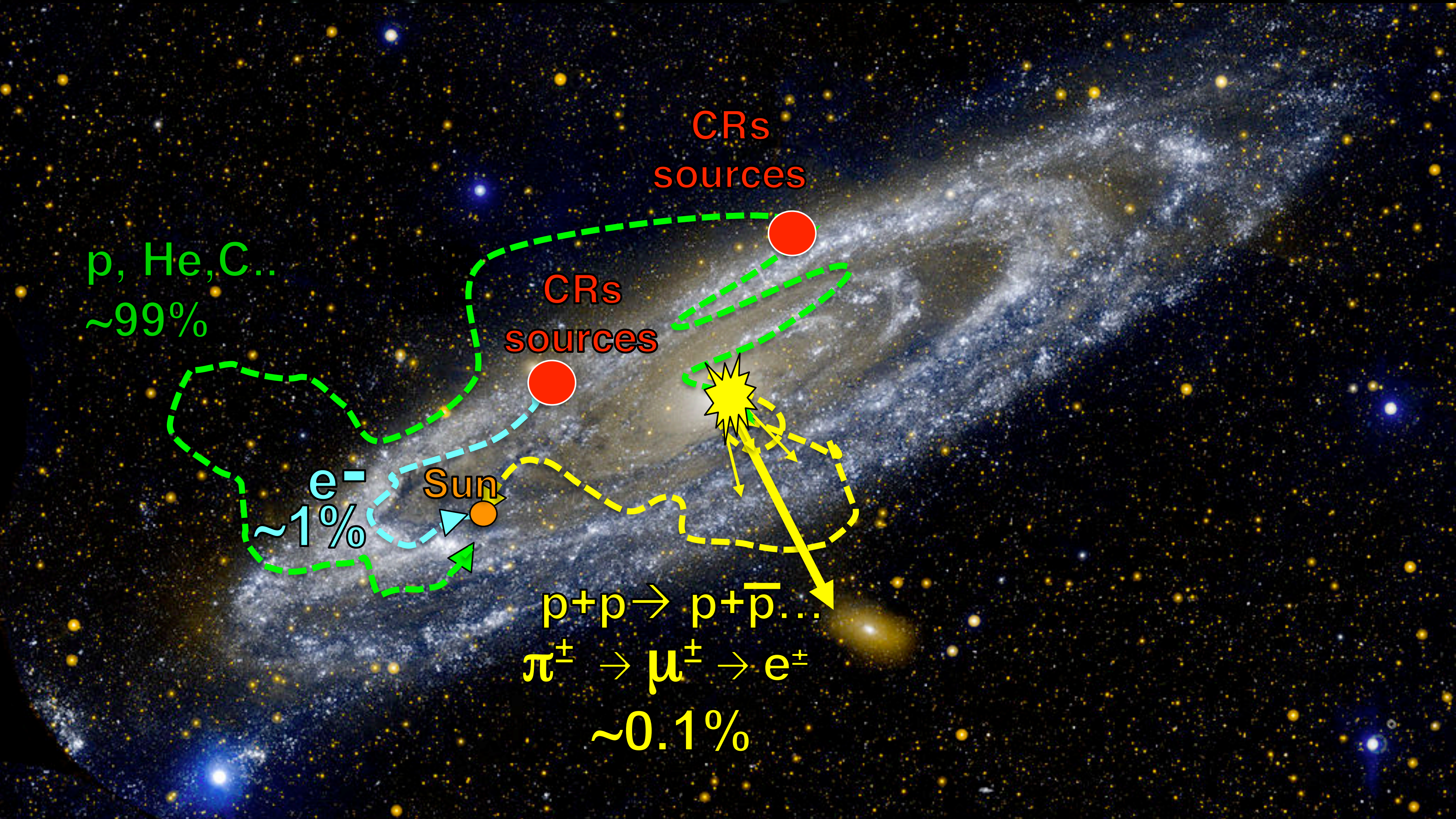



CRs
sources
CRs
sources
p, He,C..
~99%
e-
~1%
Sun
p+p→ p+p̄...
π± → μ± → e±
~0.1%
χ
e-, p, γ
e+, p̄, γ
χ̄



Positrons: χ + χ → e⁺ + …
e⁺ /(e⁺ + e⁻)
10⁻¹
mχ=800 GeV
mχ=400 GeV
Collisions of Cosmic Rays
I. Cholis et al., JCAP 0912 (2009) 007
10
10²
e± energy [GeV]
Antiprotons: χ + χ → p̄ + …
Antiproton /Proton Ratio × 10⁻⁴
0
0.5
1
1.5
mχ= 1 TeV
Collisions of Cosmic Rays
Donato et al., PRL 102, 071301 (2009)
100
200
300
400
500
Kinetic Energy (GeV)
Sun
χ
e⁻, p, γ
e⁺, p̄, γ
χ̄

# Cosmic Rays propagation



# From sources to us

Transport inside the galaxy:

$$\frac{dN_i}{dt} = D\nabla^2 N_i + \frac{\partial}{\partial E}[b\,N_i] + Q_i - \frac{N_i}{\tau_i} + \sum_{j>i}\frac{P_{ij}}{\tau_j}N_i$$

Diffusion in the galaxy volume → Motion in the galactic magnetic field

Energy losses →
- Ionization
- Bremsstrahlung
- **Synchrotron radiation**
- **Inverse Compton effect**

Sources → SNR at least up to sub-PeV energies

Decay and secondary production → Interaction with the ISM (i.e. spallation) and decay into/from another specie

**Important for $e^{+/-}$ that are probes for “close” phenomena**

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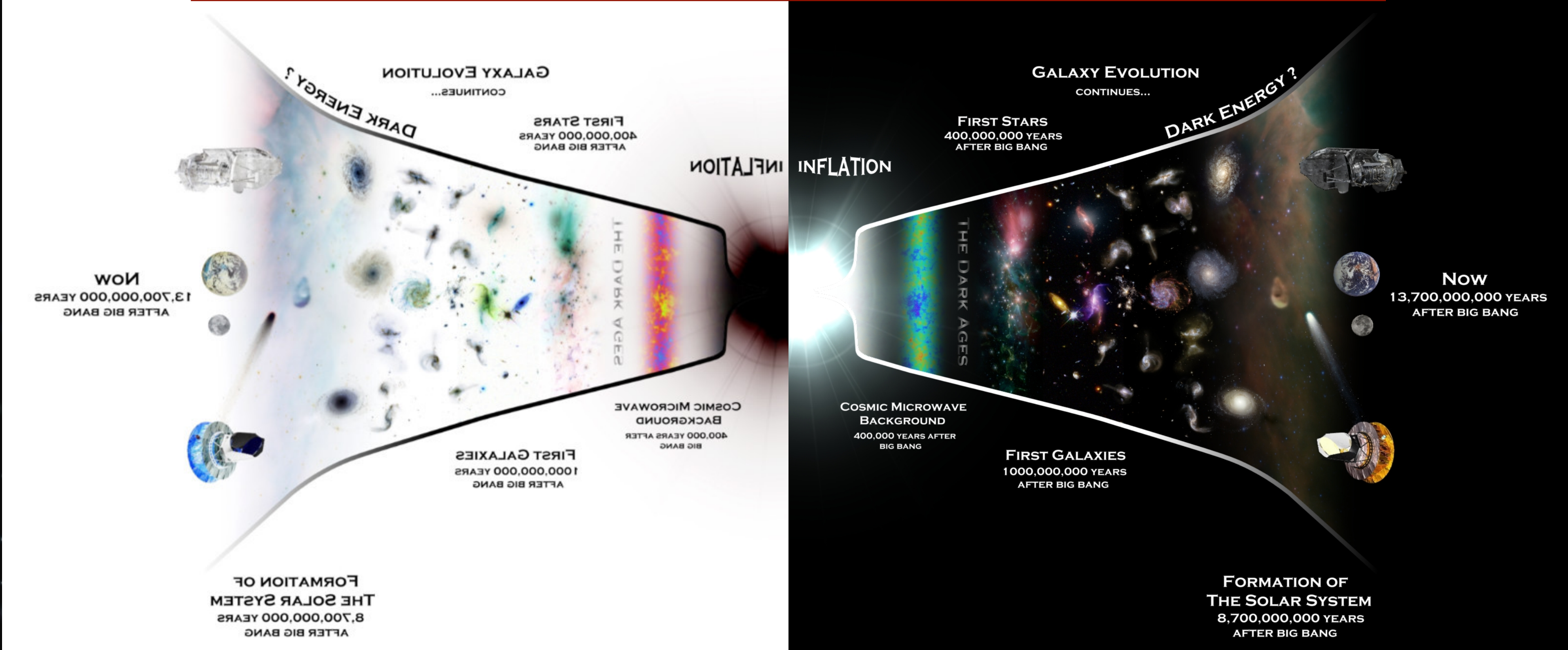
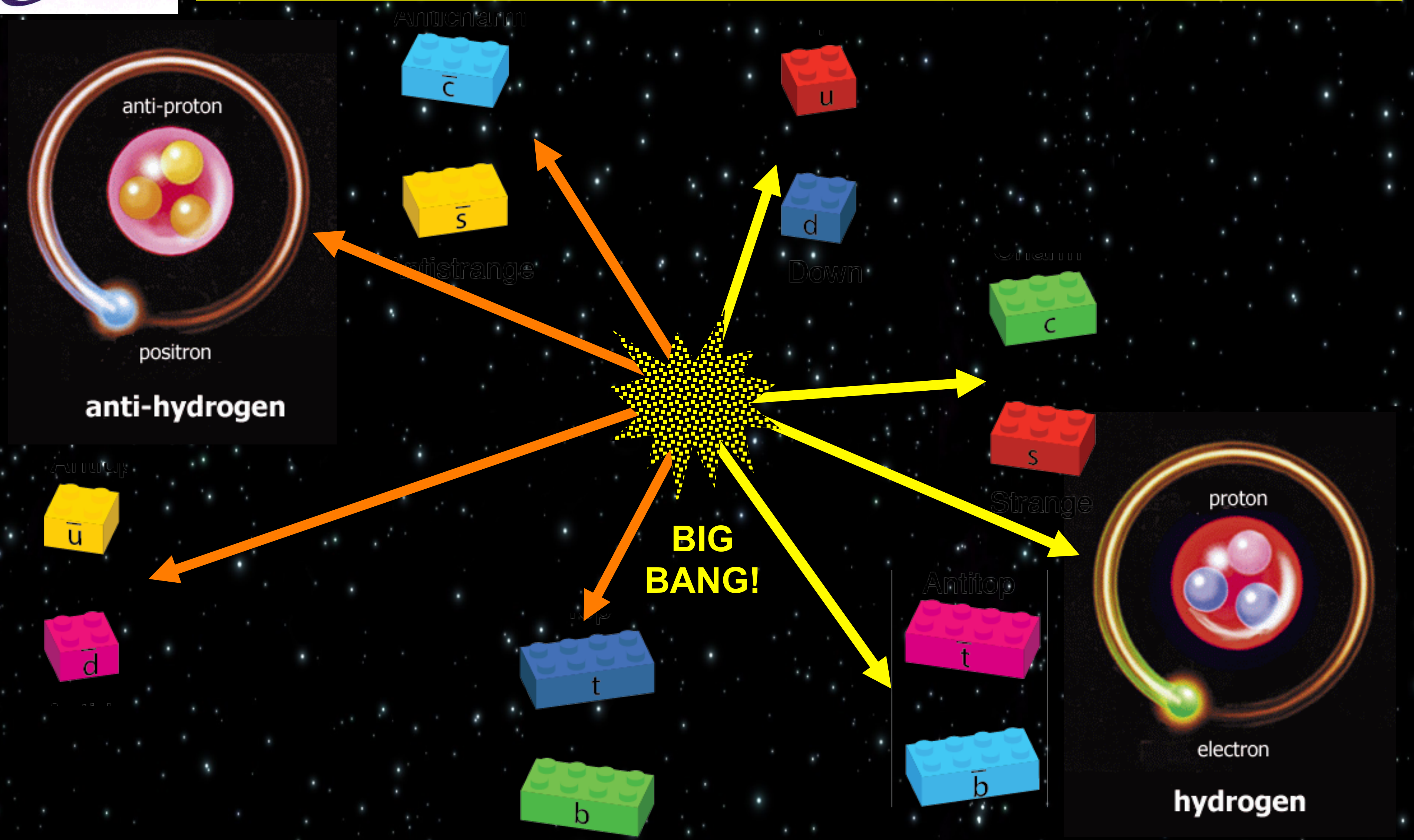
# Primordial matter and anti-matter

## Dirac's Nobel speech

*"We must regard it rather as an accident that the Earth [...] contains a preponderance of negative electrons and positive protons. It is quite possible that for some stars it is the other way about."*



# Primordial matter and anti-matter



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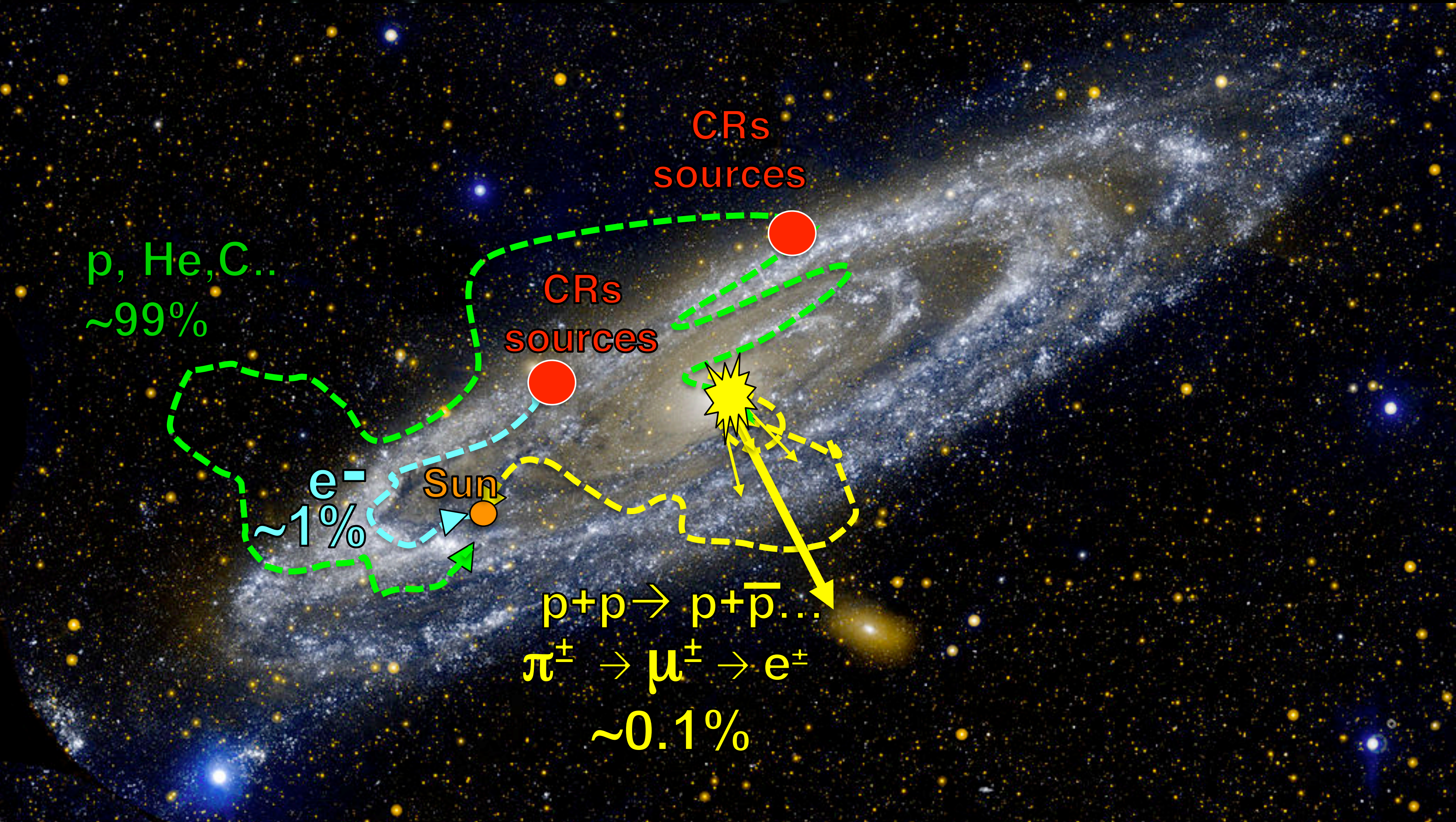
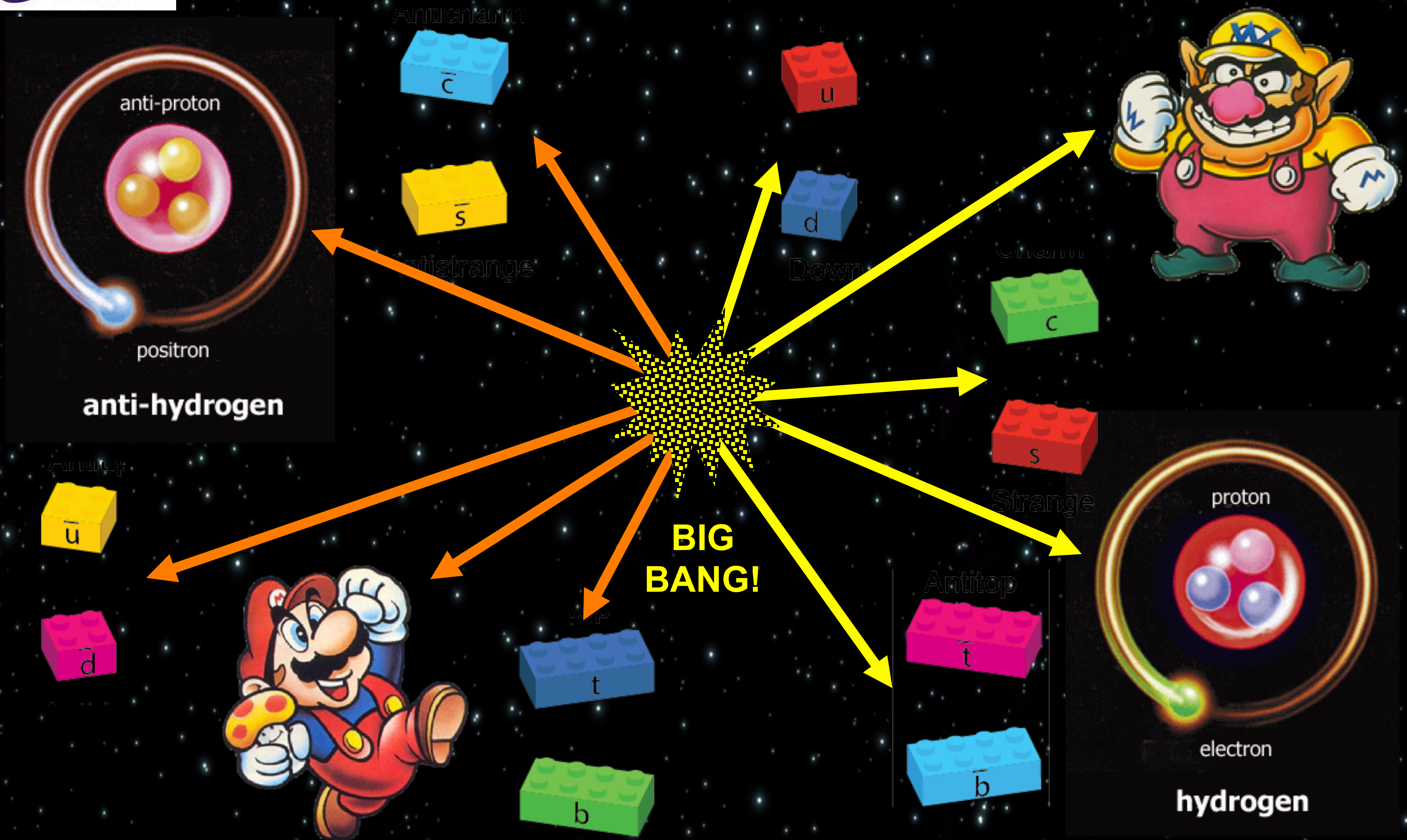
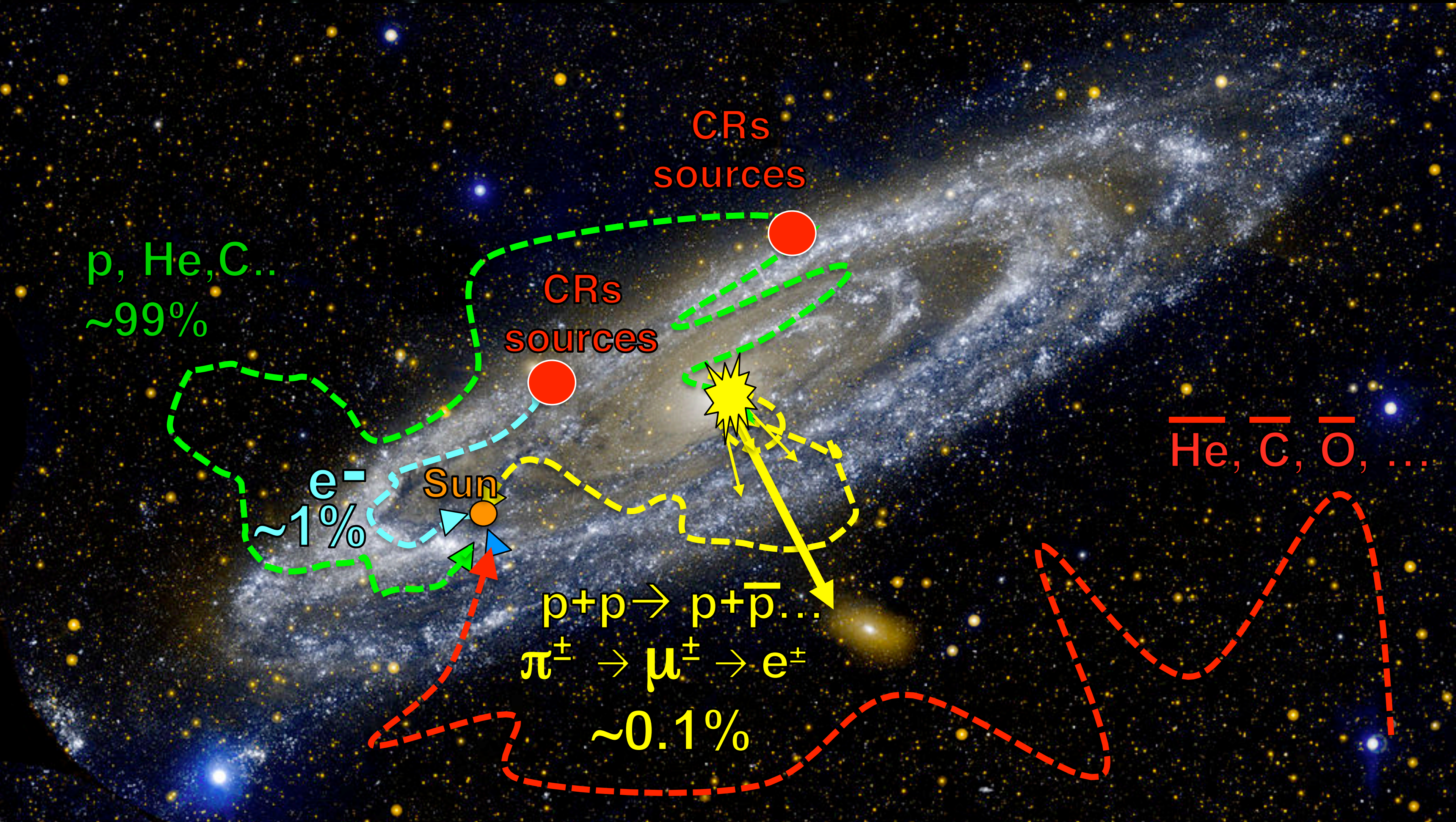


# Primordial matter and anti-matter



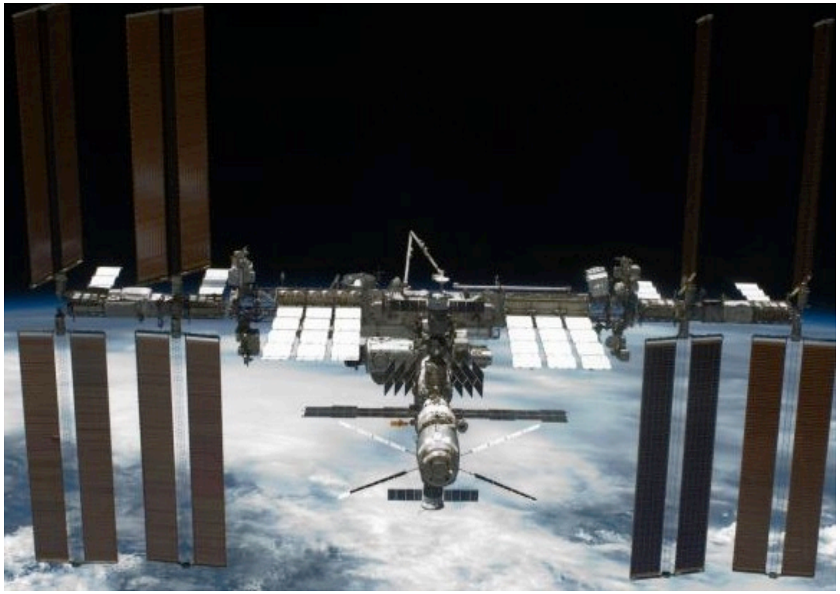
# Primordial anti-matter



# Experimental Techniques and Experiments

# The experimental challenge

## DIRECT ≠ EASY !



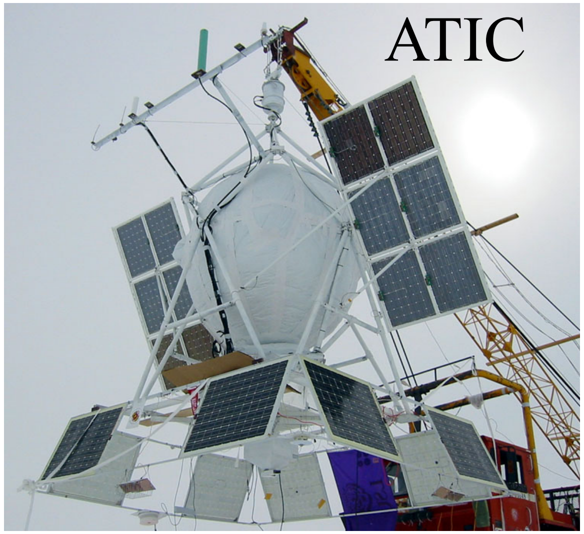
Particle identification ⇒ HEP detectors:
magnetic spectrometers (+/-)
calorimeters, TRD.. (e/p, nuclei)

No atmosphere ⇒
- Stratospheric Balloons
- Space

# Direct measurements: balloons


**Cosmic Ray Energetics and Mass (CREAM)**

- 966 kg
- Flights: 2004 and 2005 (70 days) and 2007 (29 days), …
- ISS-CREAM soon on the ISS




**Advanced Thin Ionization Calorimeter (ATIC)**

- 1636 kg
- Flights: 2000, 2002 (30 days), last in 2007 (14.5 days)

# Direct measurements: balloons


**Transition Radiation Array for Cosmic Energetic Radiation (TRACER)**

- 1614 kg
- Flights: 2003, 2006 (14 days)


**Trans-Iron Galactic Element Recorder (TIGER)**

- 700 kg
- Flights in 2001and 2003 (50 days)
- Super-TIGER working since 2013

# Direct measurements: balloons

**Balloon-borne Experiment with Superconducting Spectrometer (BESS)**

- 890 kg
- Voli: from 1993 to 2004 (BESS-Polar)



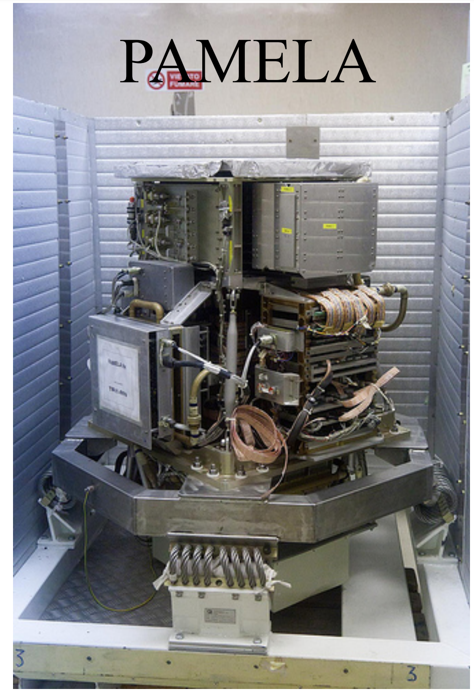
**Cosmic AntiParticle Ring Imaging Cherenkov Experiment (CAPRICE)**

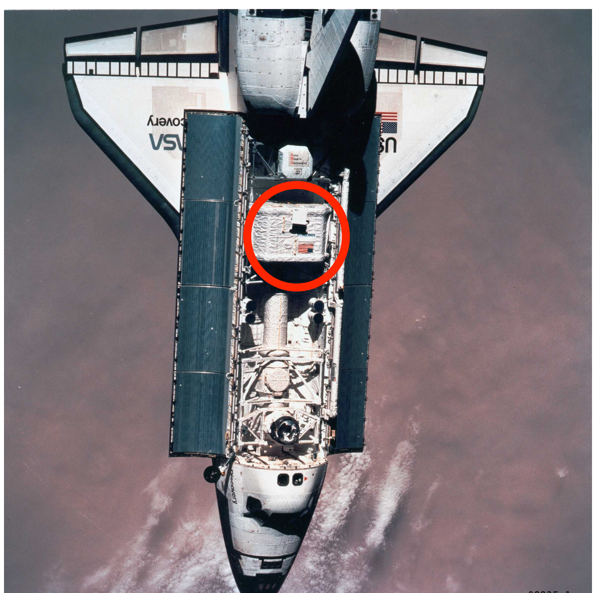
- 3500 kg
- Flights in 1994, 1997 and 1998

# Direct measurements: space!

**Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA)**

- 470 Kg
- In orbit since 15 June 2006



**Alpha Magnetic Spectrometer - 01 (AMS-01)**

- Same orbit of the ISS and of AMS-02
- 10 days of mission on board the Space Shuttle Discovery mission STS-91

# Particle-matter interactions

1. **Ionizations** (interaction with atomic electrons)

2. **Photon radiation** (Bremmstrahlung in the Coulumbian field of the nuclei) **and pair-production** (production of electron-positron pairs in the matter)

3. **Transition radiation** (production of radiation at the interfaces between two refractive indeces, proportional to $\gamma$ → important for light particles)

4. **Cherenkov effect** (particle travelling in a medium with a speed greater than the speed of light in that medium)

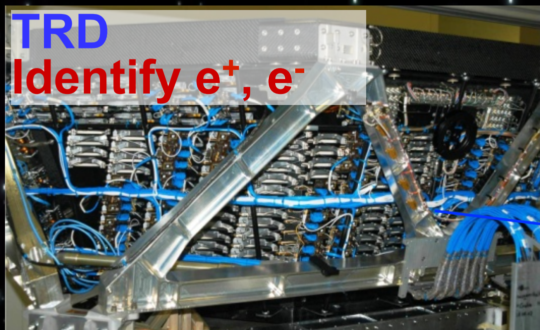
# Particle-matter interactions

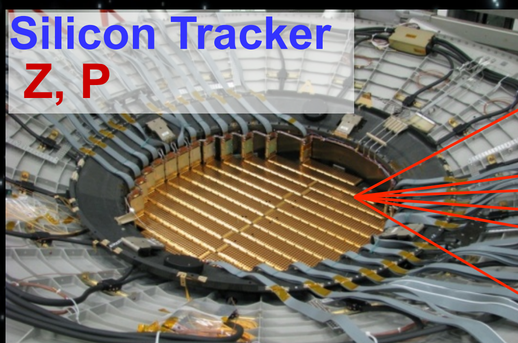
1. **Time of flight (measurement of the travel time between (at least) two points)**
2. **Mass spectrometetry (measurement of the bent trajectory of a charged particle in a magnetic field)**
3. **Calorimetry (counting of the particles in the shower created by the destructive interation of a particle with matter)**
4. **Cherenkov rings (measurement of the velocity of a particle by the measurement of the radius of the Cherenkv cone)**
5. **TR detectors (measurement of the $\gamma$ by the energy deposit in TR photons)**

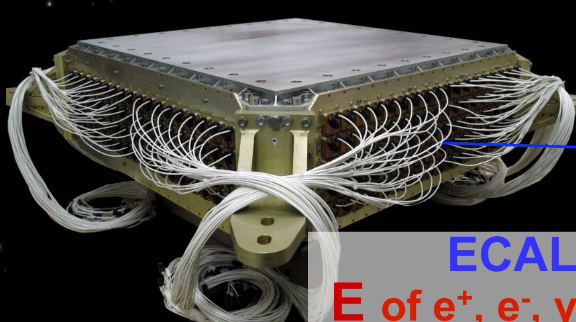
Alpha Magnetic Spetrometer, AMS-02, on the ISS

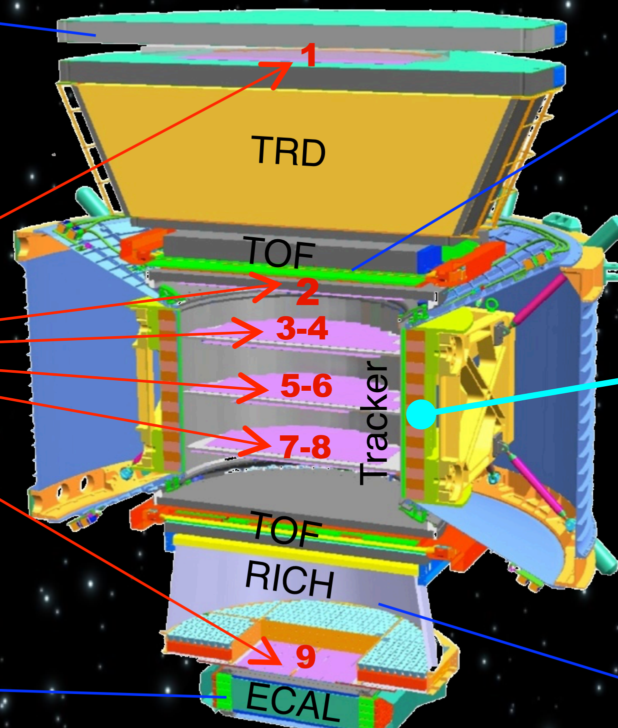
# The AMS-02 detector

*Z, P independently measured by Tracker, RICH, TOF and ECAL*

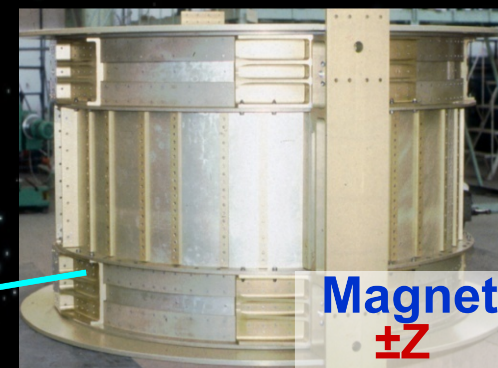


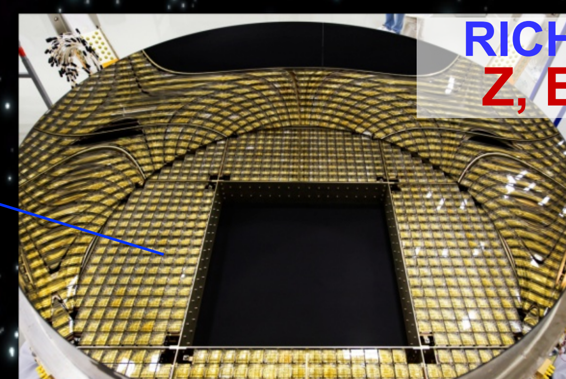



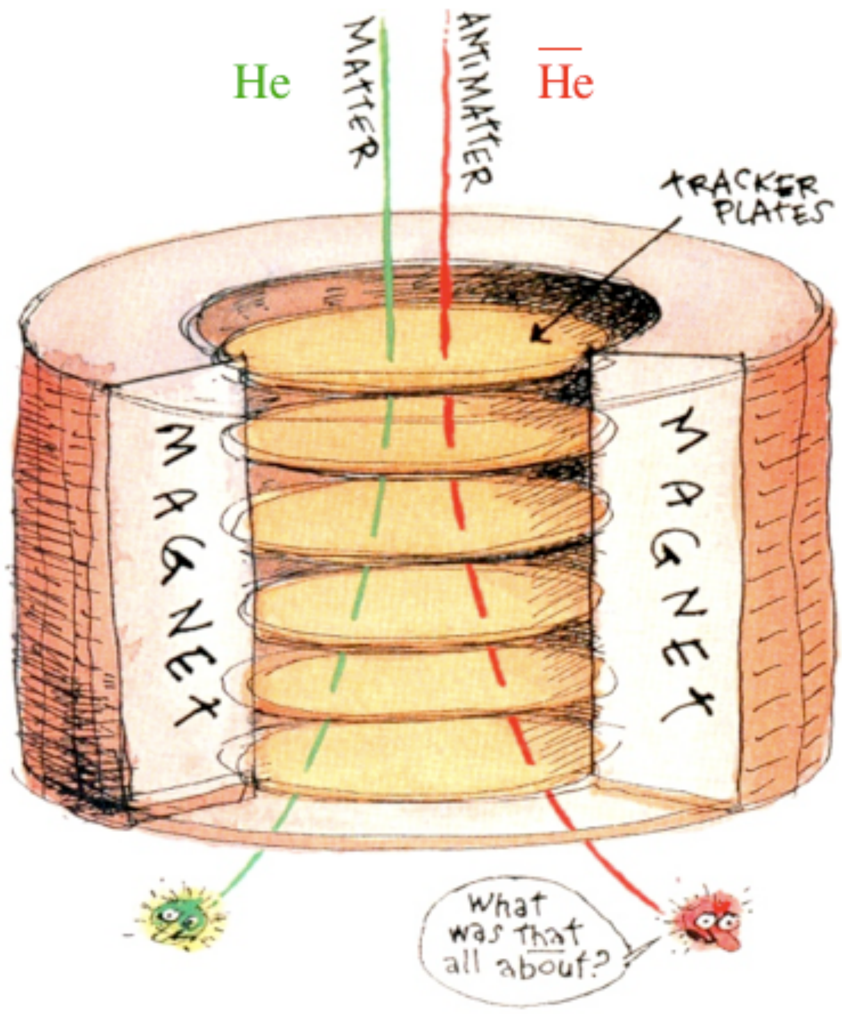



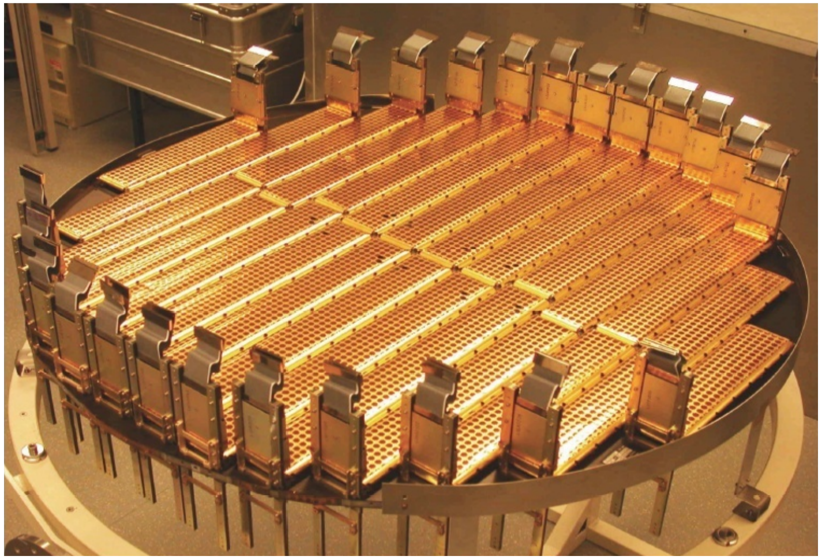


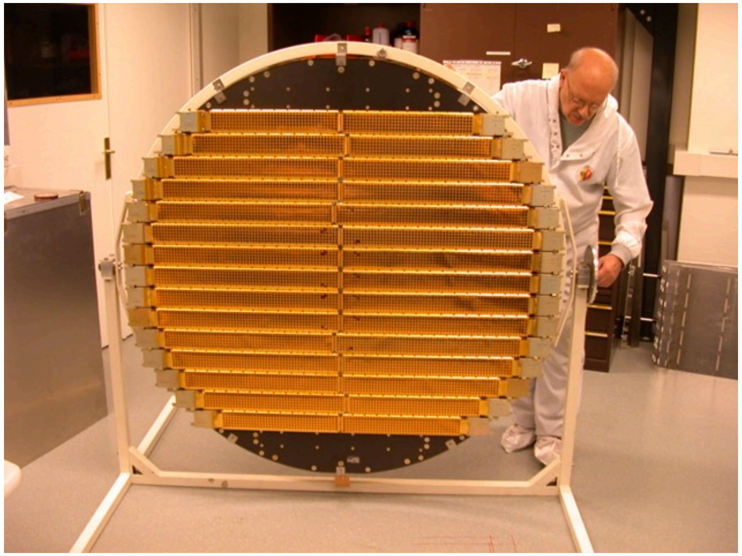


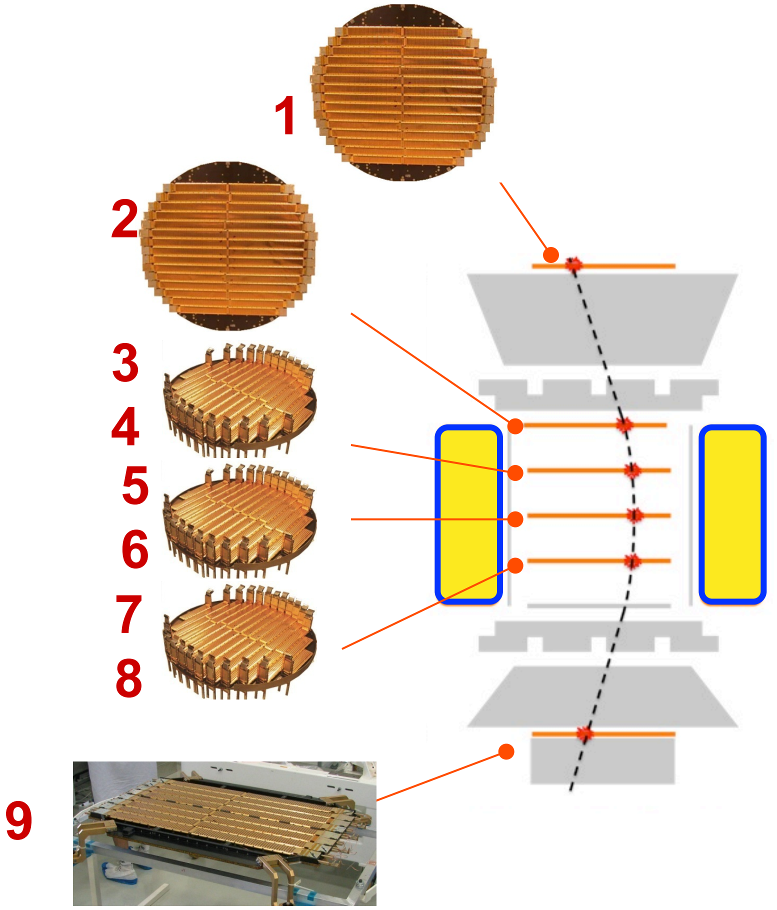
# Magnetic spectrometry





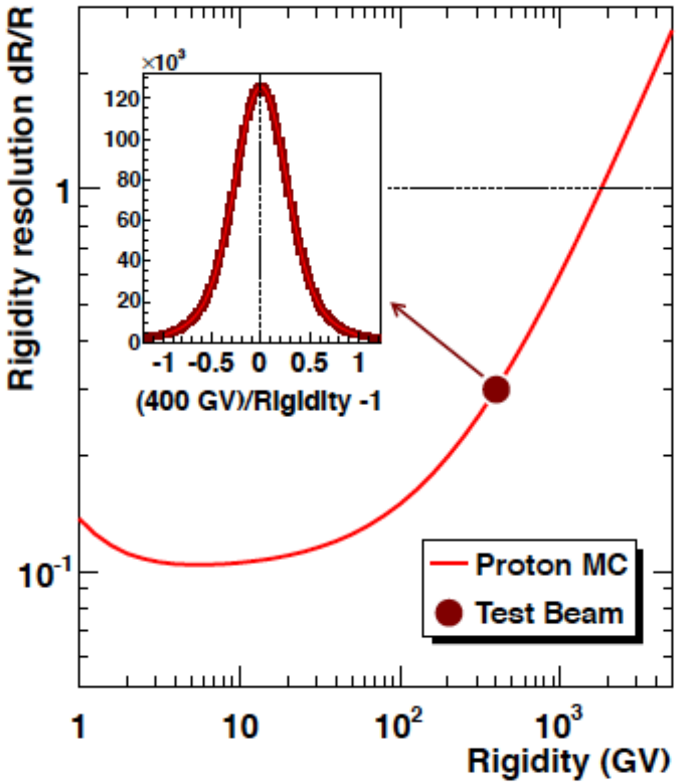
# AMS-02 silicon tracker




Coordinate resolution 10 μm

→ 20–UV Lasers to monitor inner tracker alignment

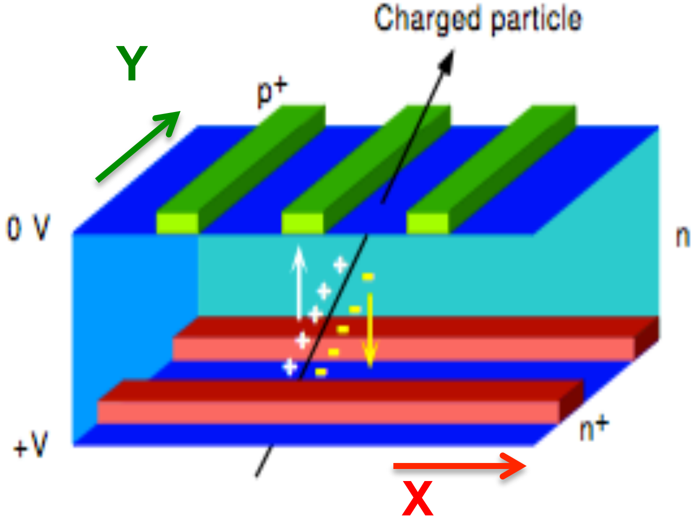
→ Cosmic rays to monitor outer tracker alignment




9 layers of double sided silicon microstrip detectors

192 ladders / 2598 sensors/ 200k readout channels

# Charge measurement from energy deposit in AMS-02




Ionization Energy Loss $\propto Z^2$

$$\text{Cluster Amplitude} = \sum_{strips} S_i \propto Z^2$$

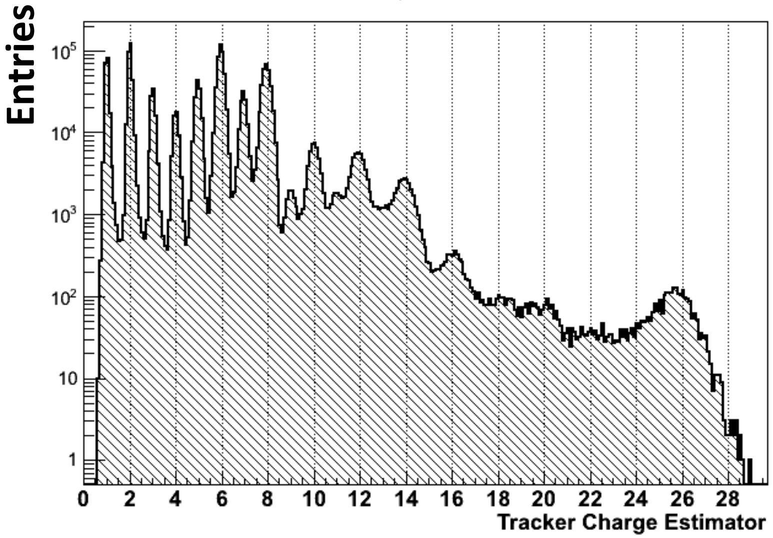
Signal Usually Collected by Number of Adjacent Strips (Cluster)

9 planes → up to 18 measurements

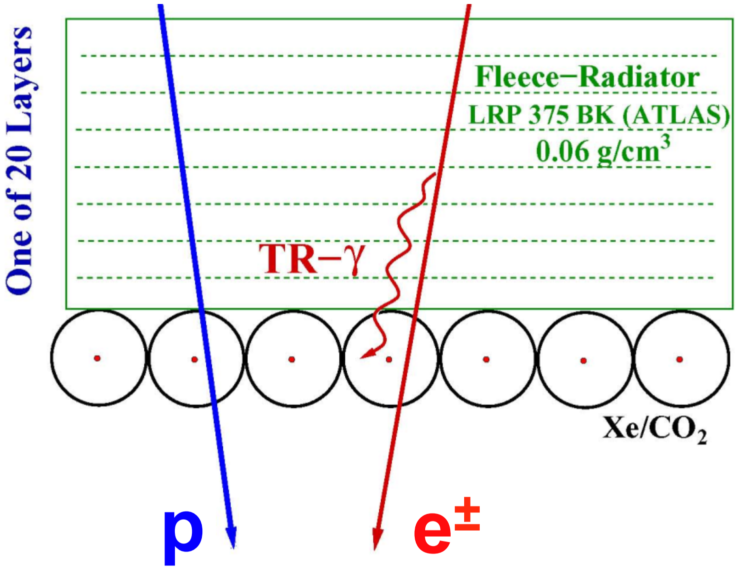
**Thanks to several energy deposits in silicon and the High Dynamic Range of the Front End electronics, the Silicon Tracker has a very accurate charge resolution**

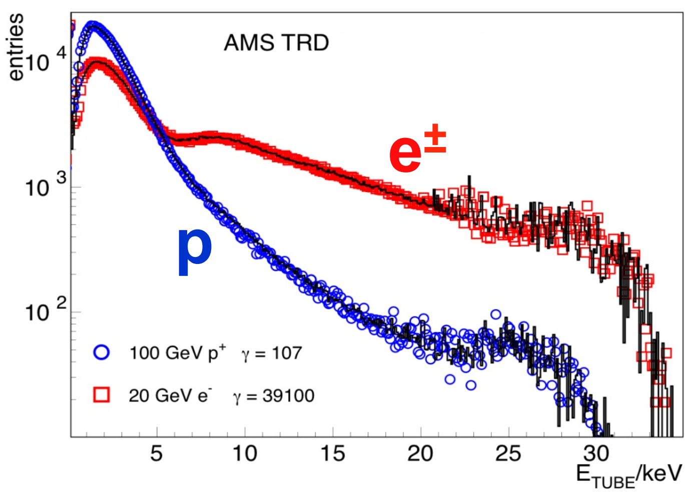
**→ ~ 0.1 c.u.**

**Abundances not corrected for detector efficiencies, H and He prescaled**

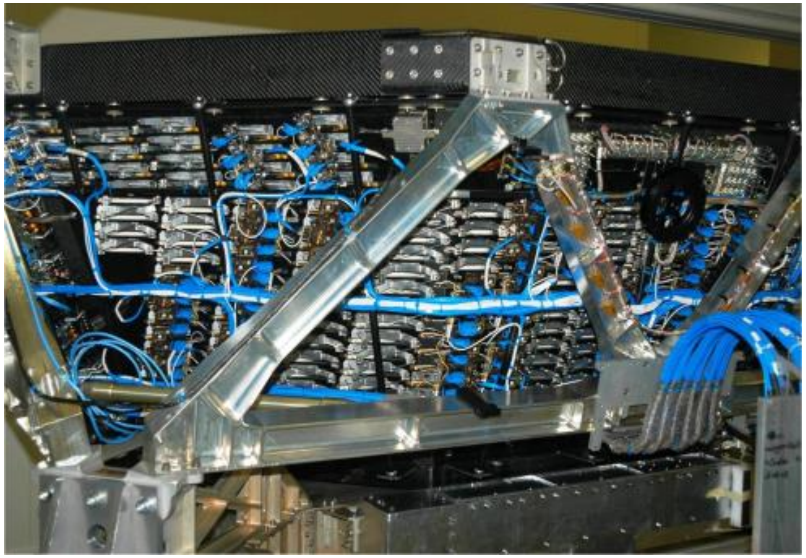


# AMS-02 Transition Radiation Detector (TRD)



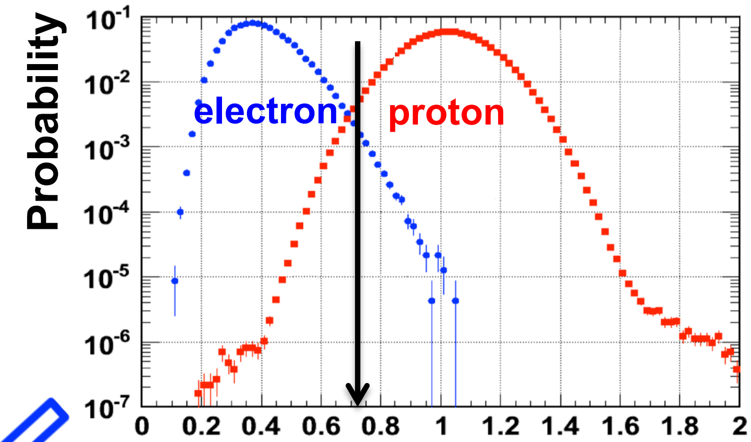

**20 layers of fleece-radiator + straw-tubes to detect the TR X-rays**



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

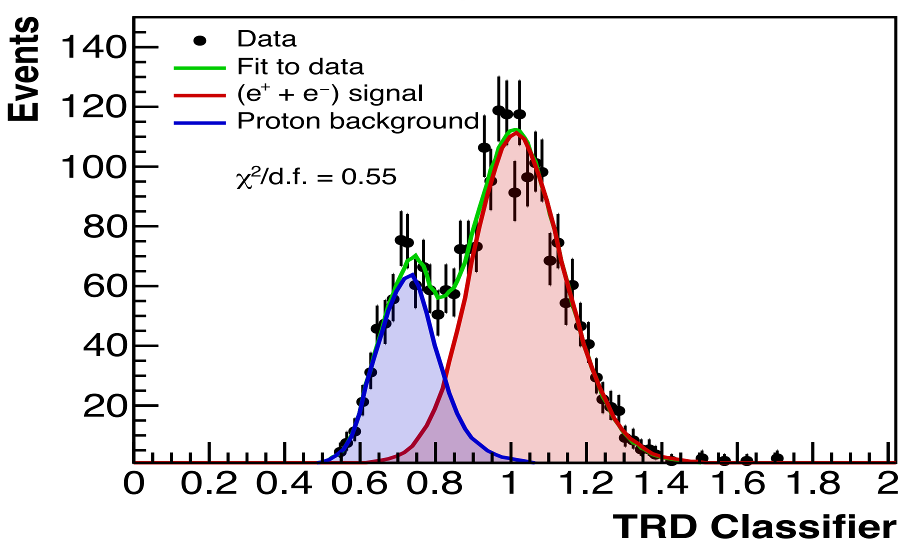
$$P_p = \sqrt[n]{\prod_{i}^{n} P_p^{(i)}(A)}$$

# AMS-02 TRD e/p separation

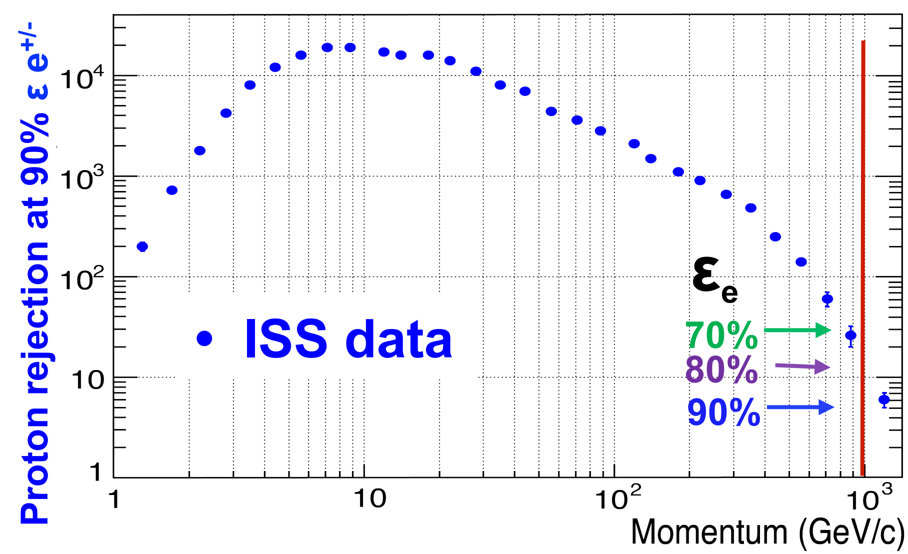



$$\text{TRD estimator} = -\ln(P_e/(P_e+P_p))$$

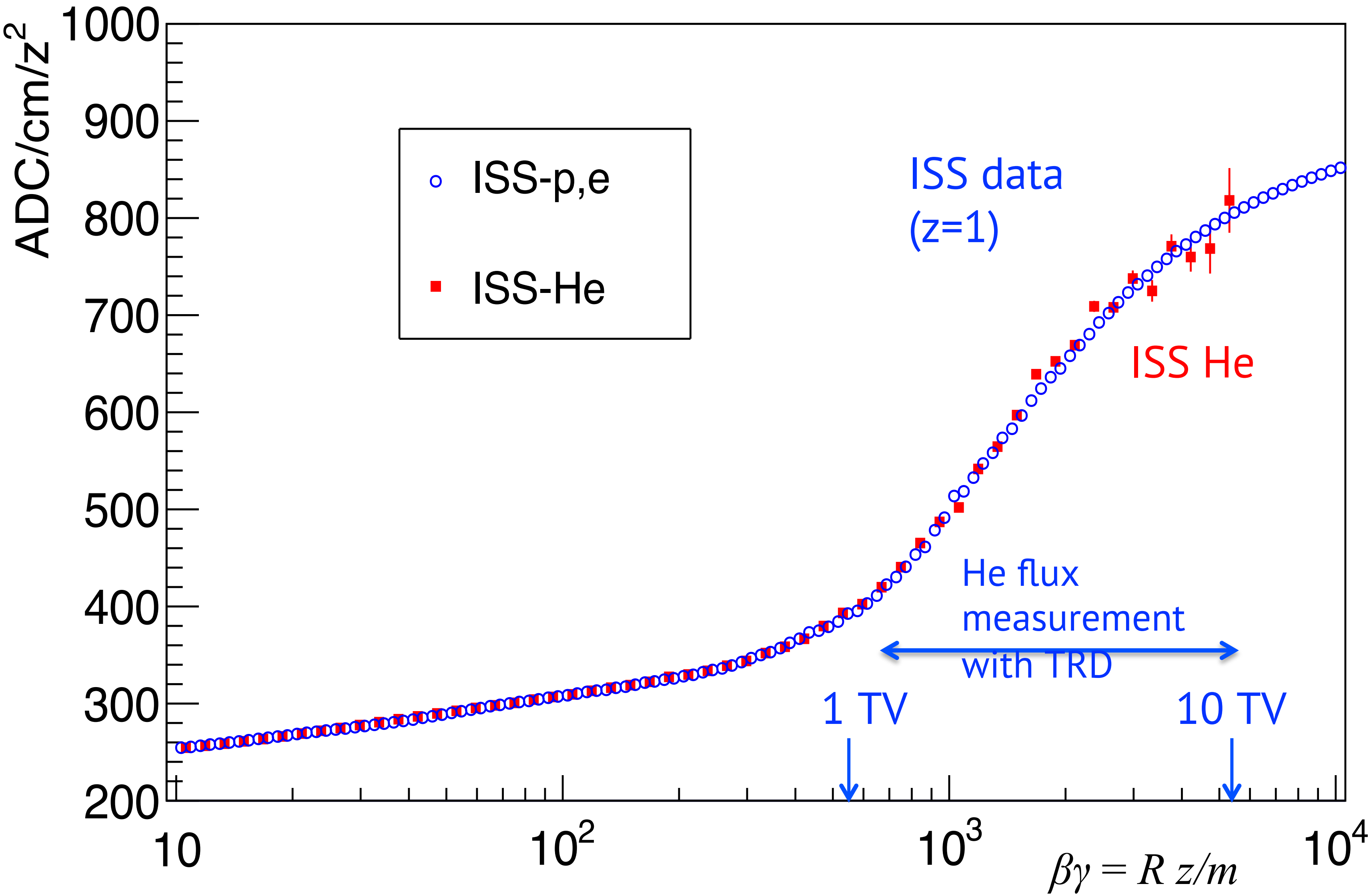
FIT



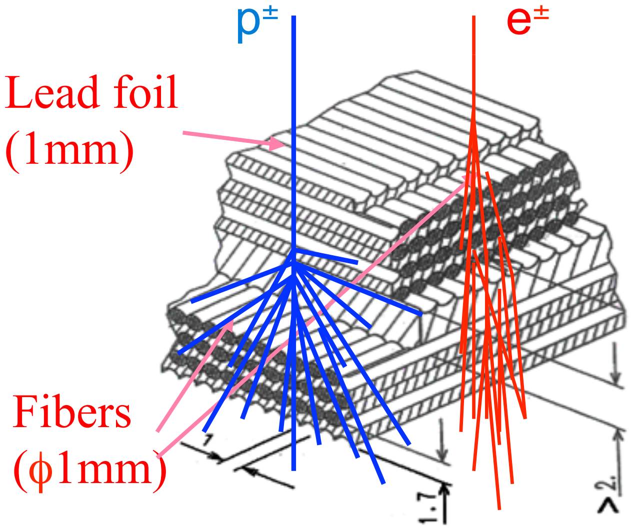

CUT



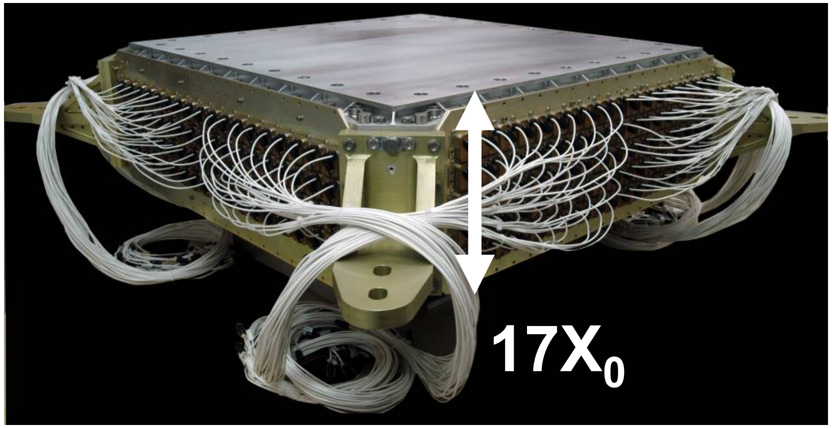
# Transtion Radiation to measure the "energy"



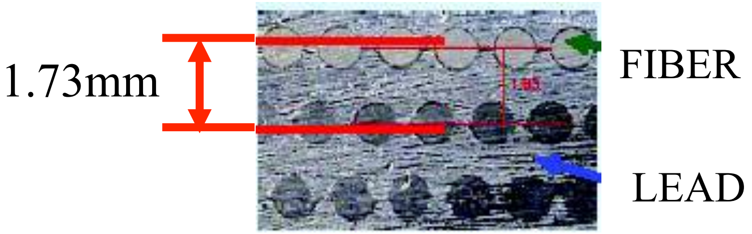
# AMS-02 Electromagnetic CALorimeter (ECAL)

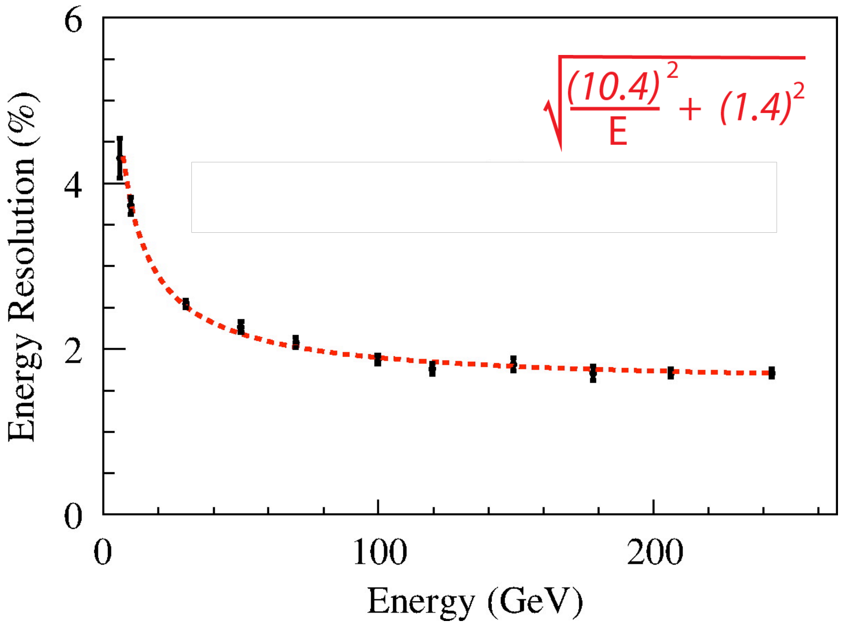



**50,000 fibers, ϕ = 1 mm**
**distributed uniformly Inside 600 kg of lead**

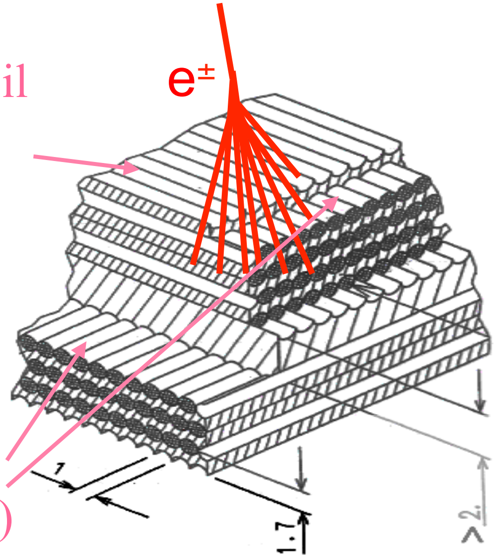


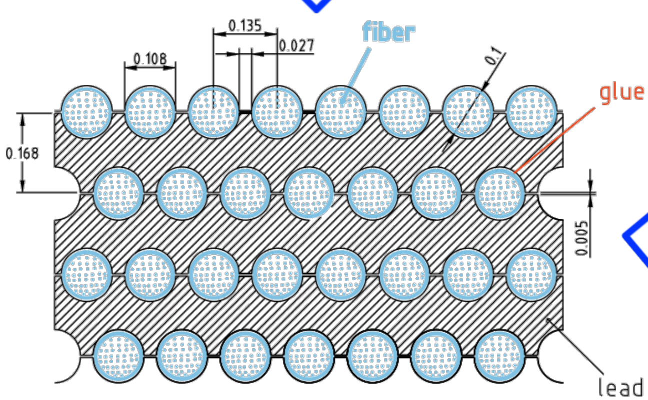

**A precision, 3-D measurement of the directions and energies of gammas and electrons up to 1 TeV**



# AMS-02 ECAL segmentation



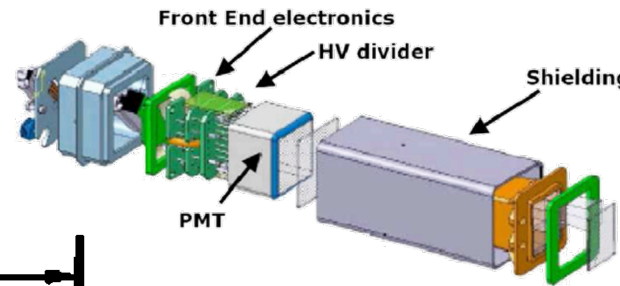



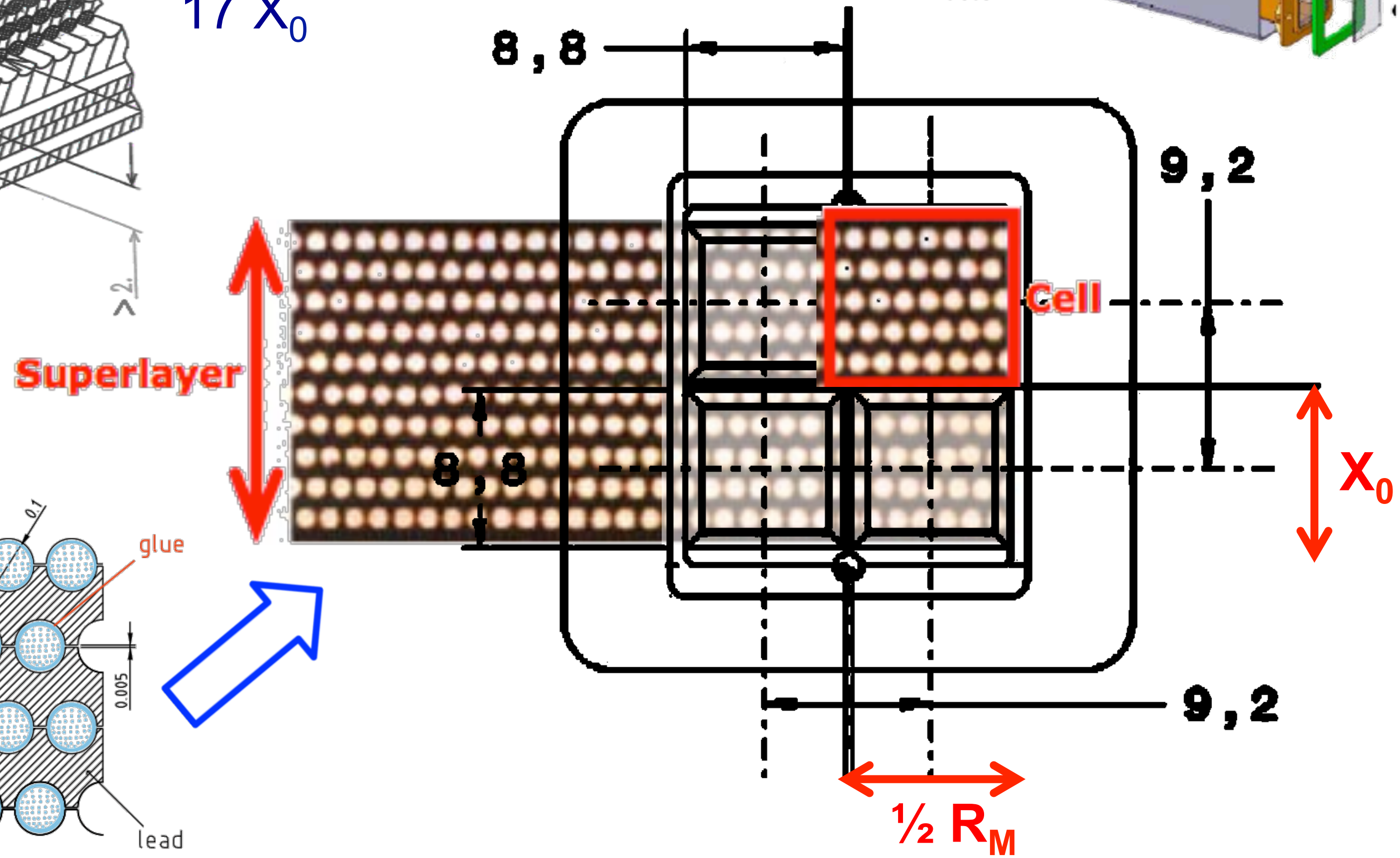

AMS ECAL:

18 layers

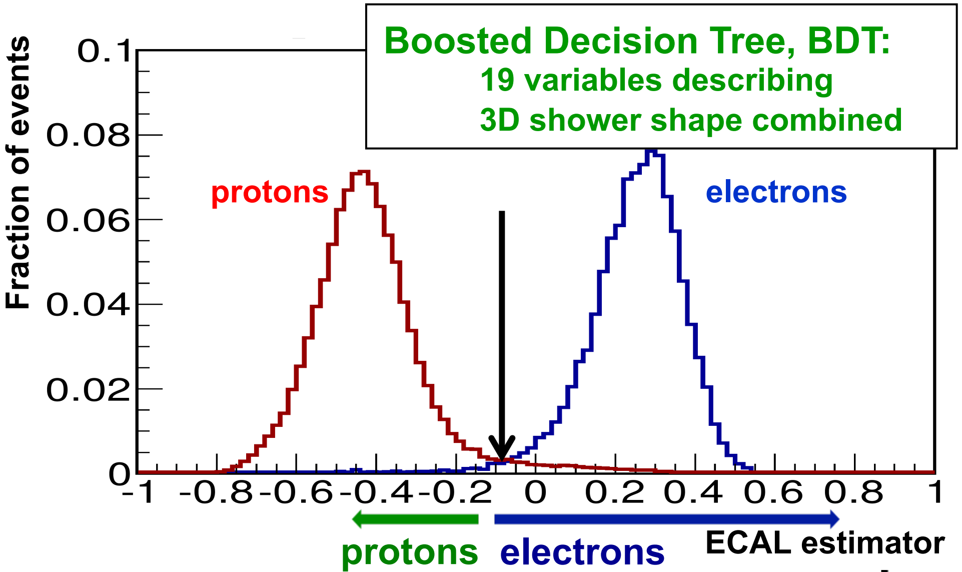
9 super-layers

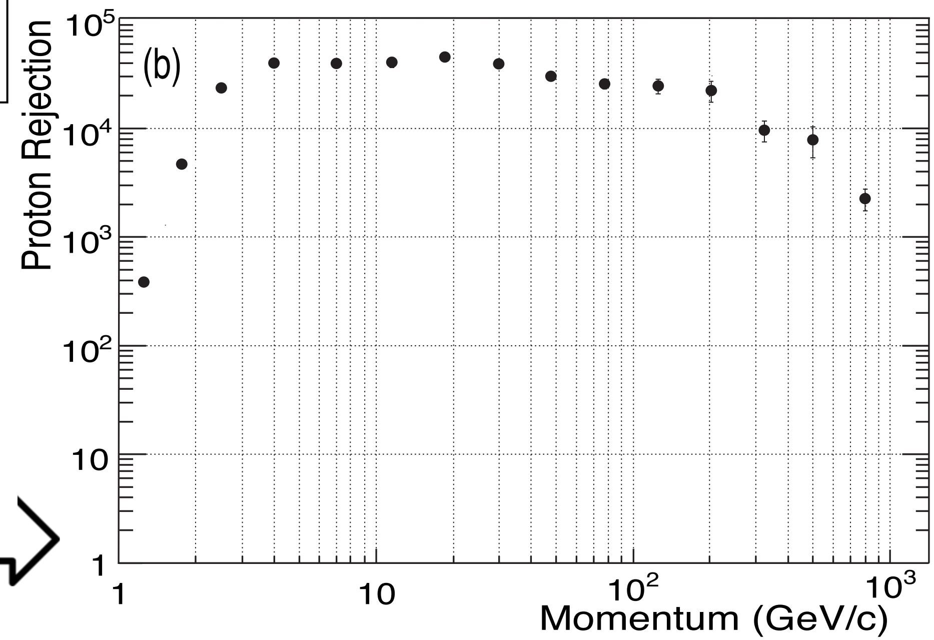
17 $X_0$

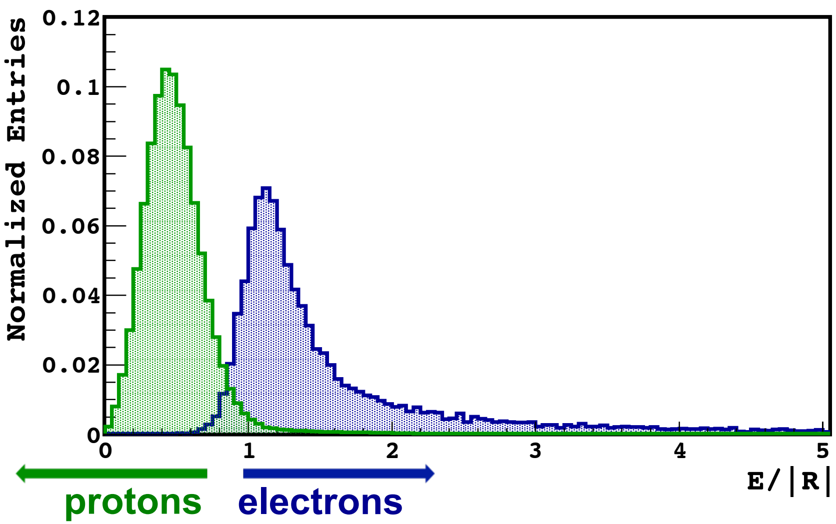


# AMS-02 ECAL e/p separation



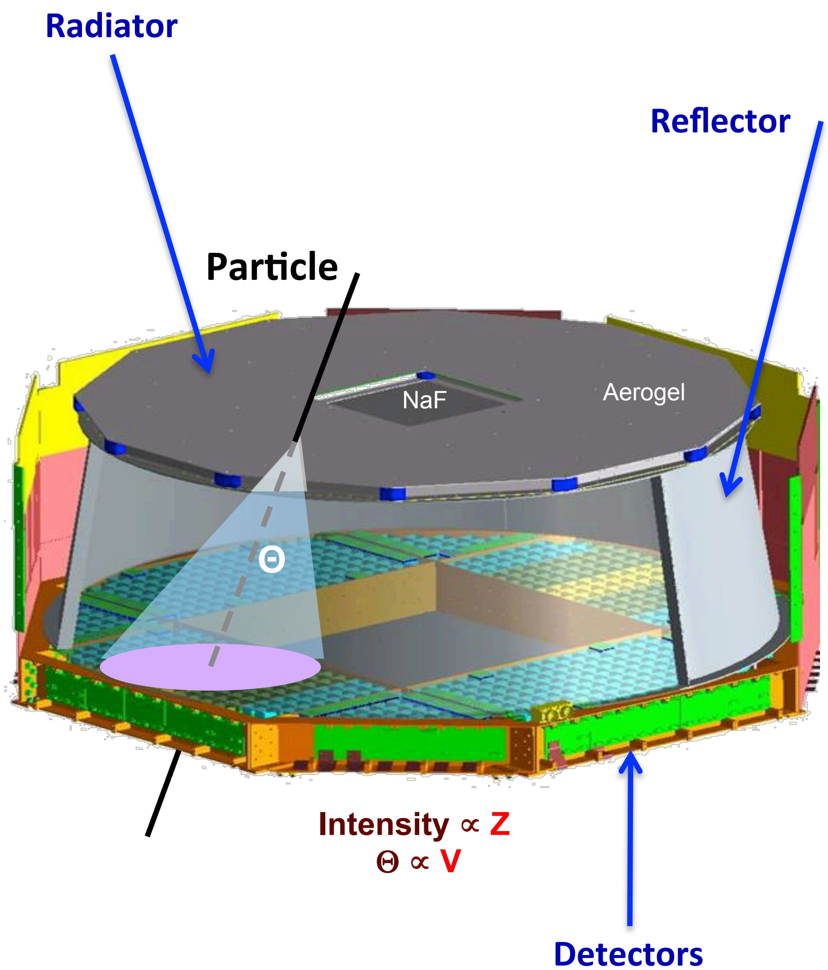



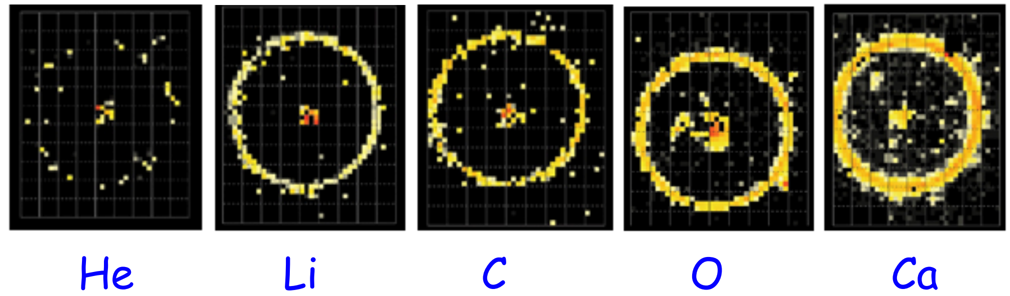



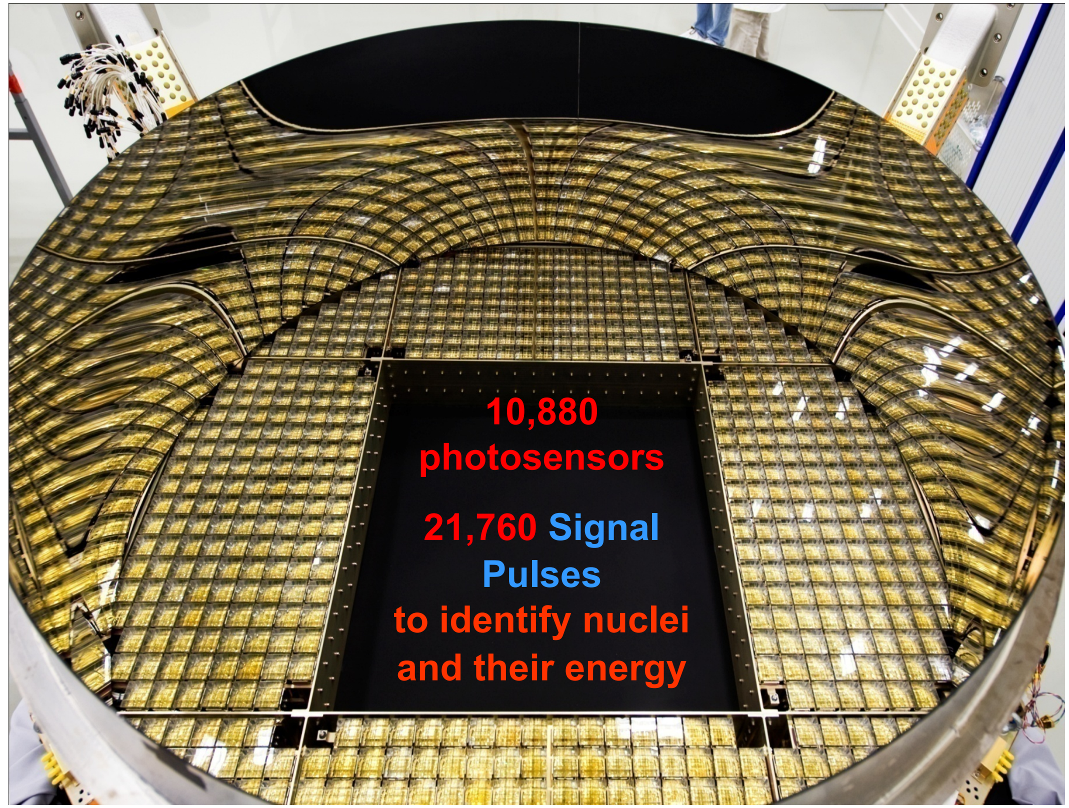

**The Calorimeter thanks to its shower shape imaging capabilities can discriminate very sensibly eletromagnetic from hadronic showers**

**Combining the ECAL energy information with the Tracker Rigidity (E/R) the e/p rejection can be furtherly increased**

# AMS-02 Ring Imaging CHerenkov

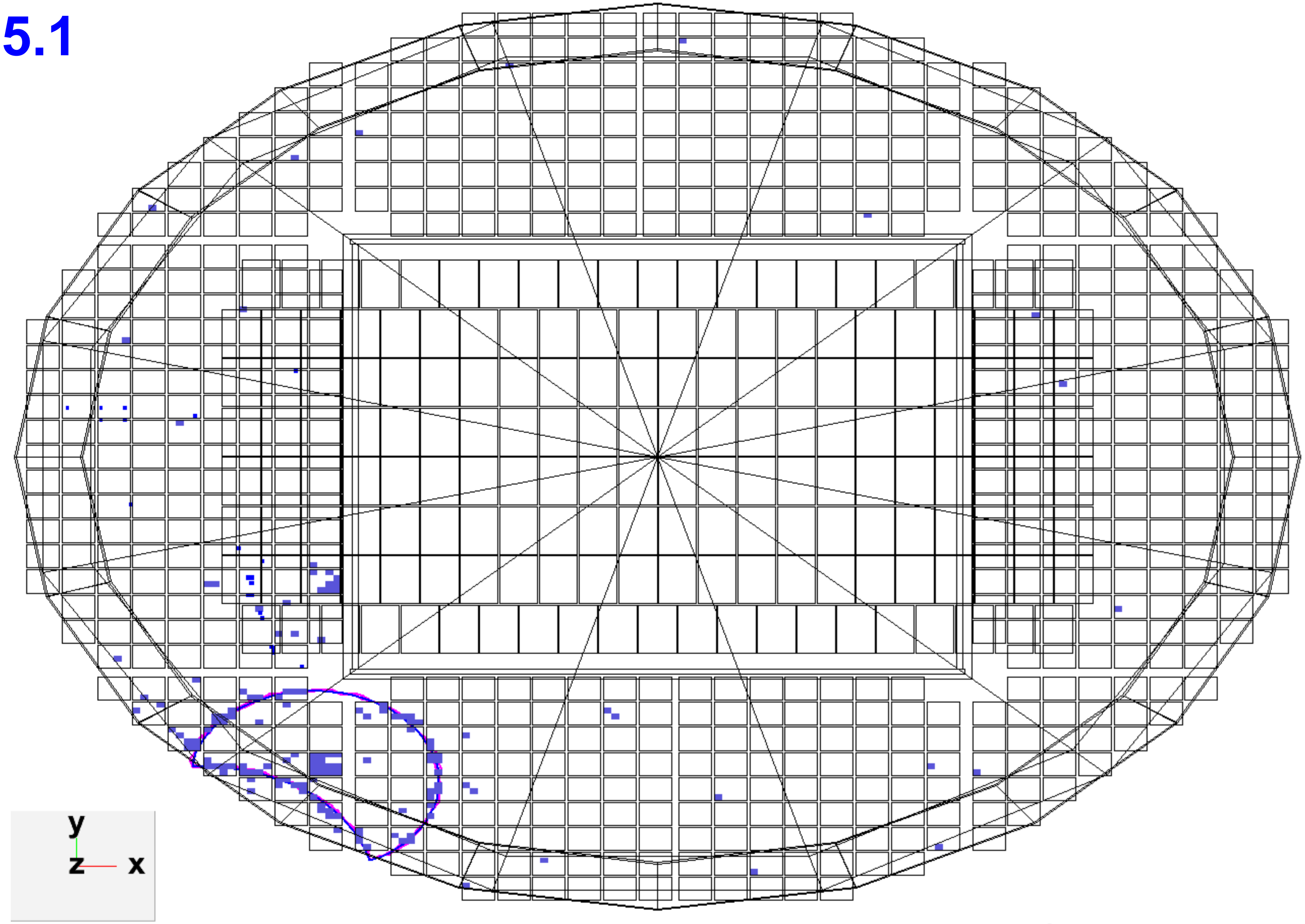


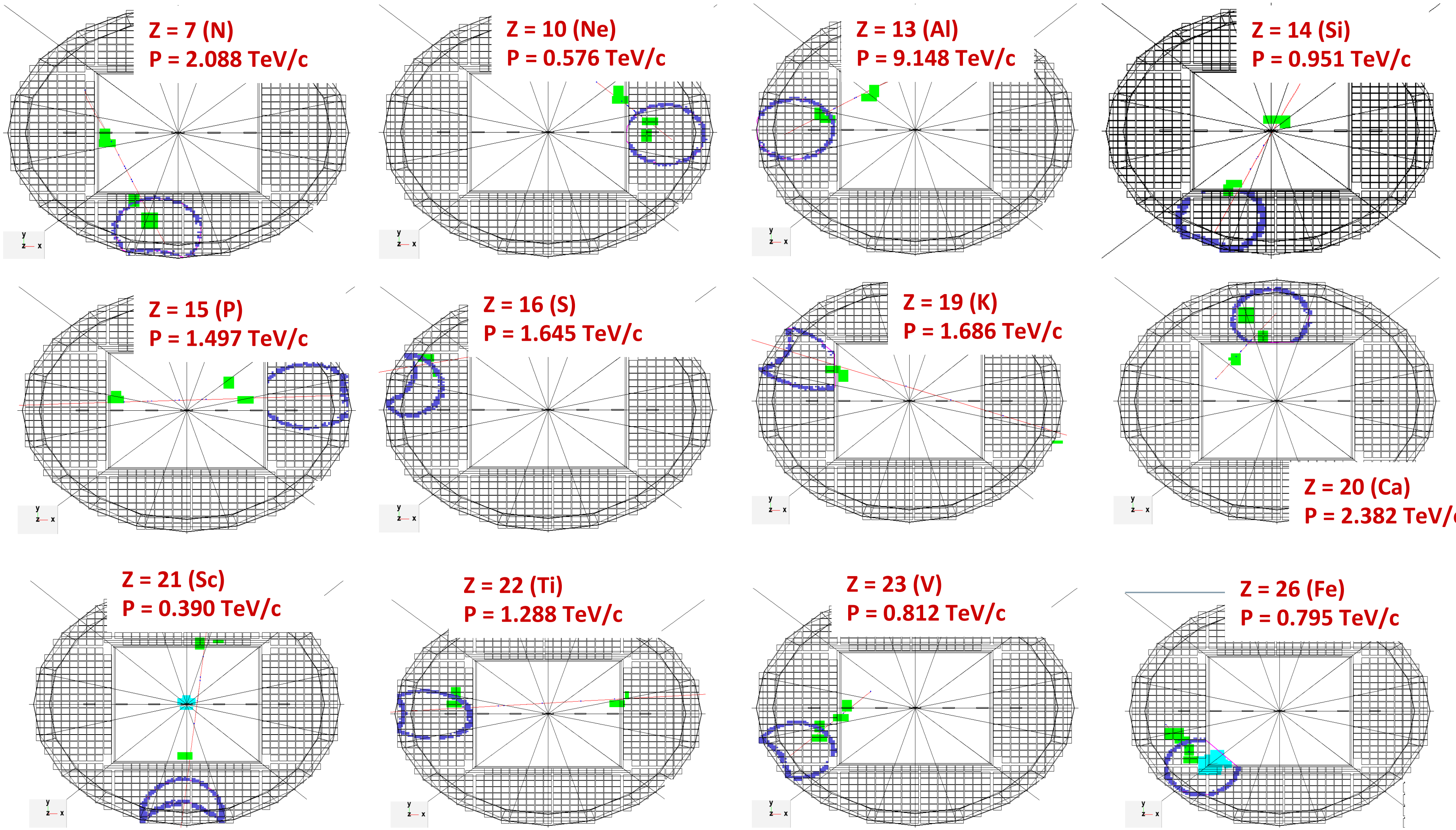



# An AMS-02 RICH ion ring

$Z_{RICH}$= 5.1

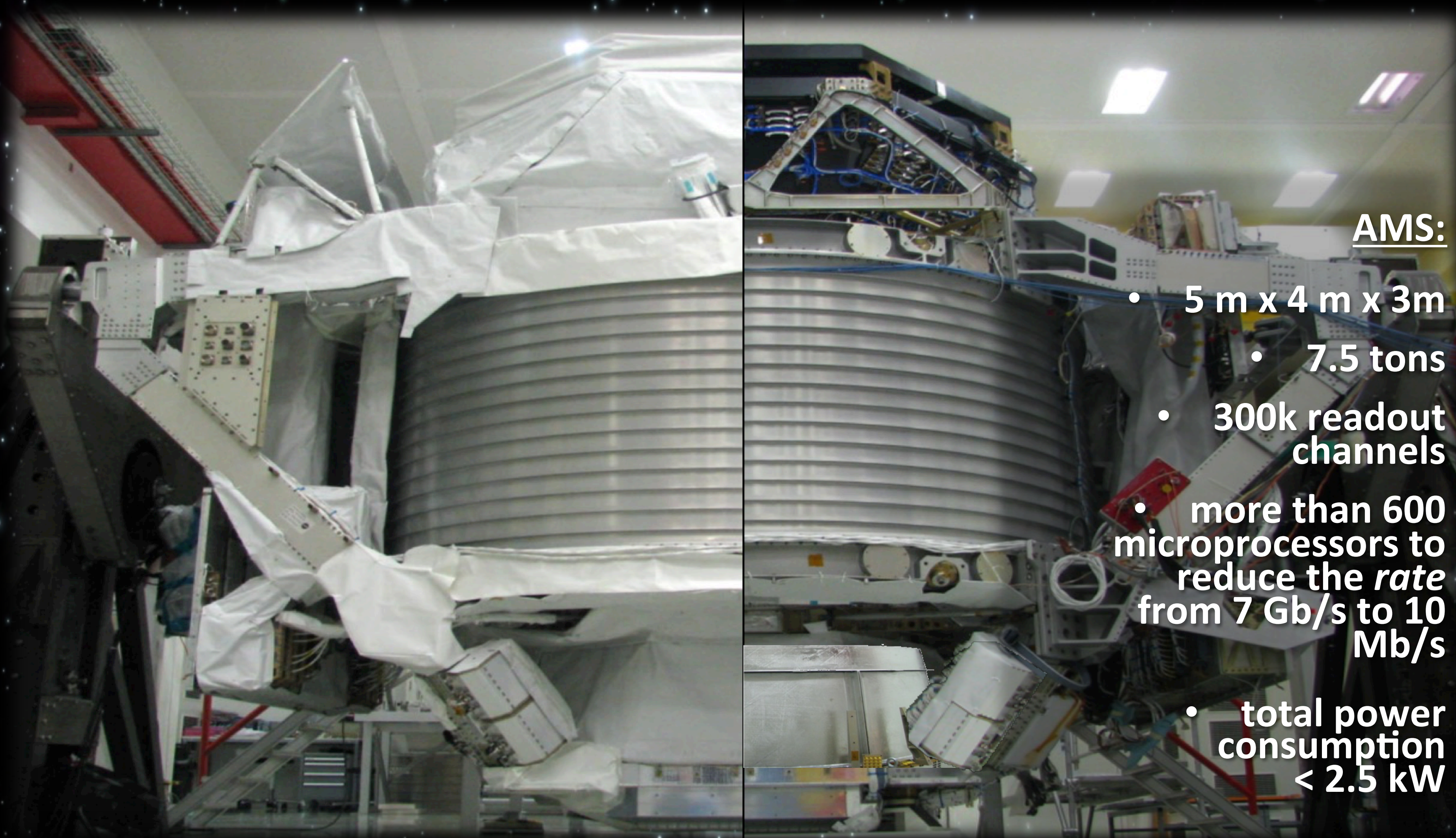


# Up to iron…



Z = 7 (N)
P = 2.088 TeV/c
Z = 10 (Ne)
P = 0.576 TeV/c
Z = 13 (Al)
P = 9.148 TeV/c
Z = 14 (Si)
P = 0.951 TeV/c
Z = 15 (P)
P = 1.497 TeV/c
Z = 16 (S)
P = 1.645 TeV/c
Z = 19 (K)
P = 1.686 TeV/c
Z = 20 (Ca)
P = 2.382 TeV/c
Z = 21 (Sc)
P = 0.390 TeV/c
Z = 22 (Ti)
P = 1.288 TeV/c
Z = 23 (V)
P = 0.812 TeV/c
Z = 26 (Fe)
P = 0.795 TeV/c

# AMS-02 assembled



**AMS:**

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

# Required “performances”

- performance a la ‘particle physics’:
  - high resolution measurements of momentum, velocity, charge and energy
- characteristics to properly work in the space environment:
  - Vibration (6.8 G rms) and acceleration (17 G)
  - Temperature variation (day/night $\Delta T$ = 100°C)
  - Vacuum ($10^{-10}$ Torr)
  - Orbital debris and micrometeorites
  - Radiation (Single Event Effect)
- limitation in weight (7 ton), power (~2KW), bandwidth (10Mpbs) and maintenance
- compliant with Electromagnetic Interference and Electromagnetic Compatibility specs

# AMS in the Shuttle (Endeavour, STS-134)


STOP
CAUTION
VACUATION INSTRUCTIONS

# AMS-02 launch (KSC, Florida)

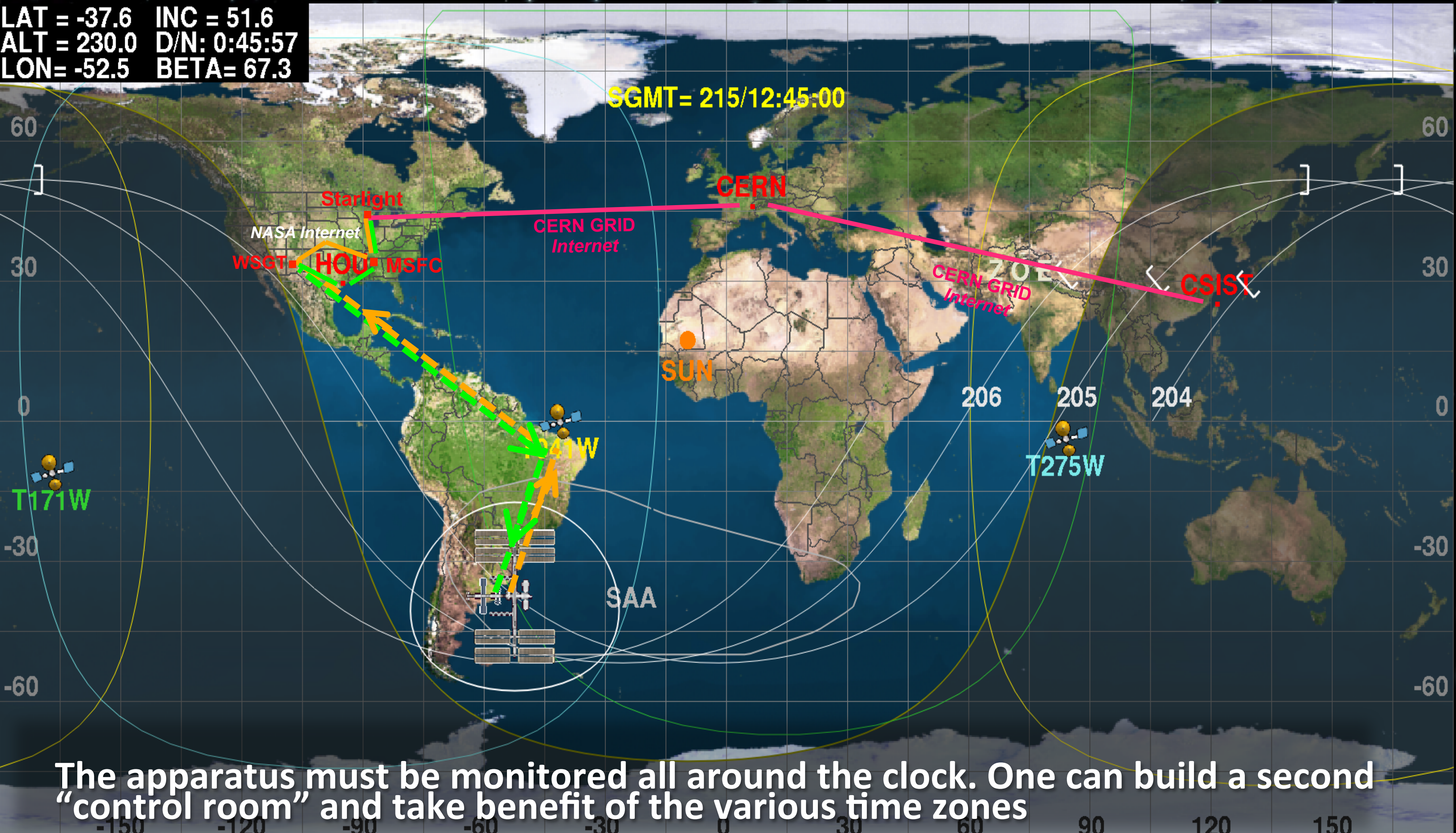
16th May, 2011, 08:56 AM

Total weight: 2008 t
AMS weight: 7.5 t

# AMS-02 on the International Space Station

May 19$^{th}$, 2011: AMS installation completed!

# In orbit @ 400 km from ground



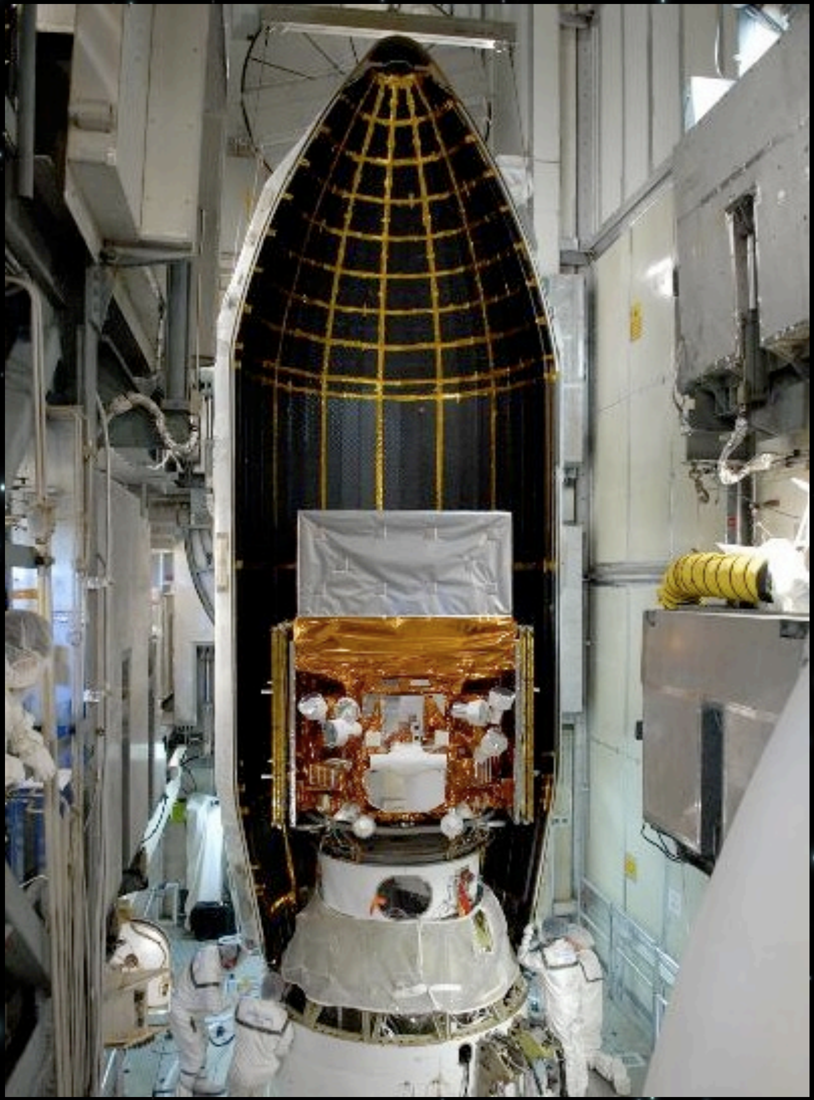

The apparatus must be monitored all around the clock. One can build a second "control room" and take benefit of the various time zones

# Payload Operation Control Center (POCC) @ CERN

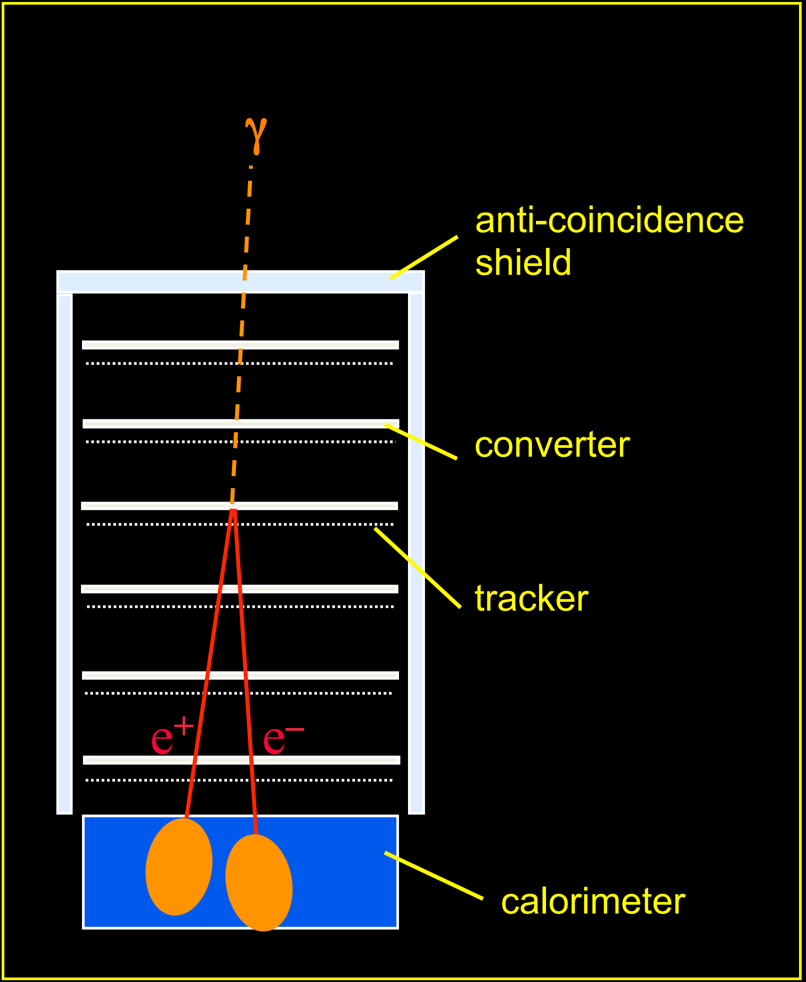
**"In the POCC there's no night and day, no Sunday or Summer, no Christmas nor Easter, no Technical Stop or Long Shutdown. The detector must be monitor 24h, 365d" S. Ting**

# Fermi-LAT

Large Area Space Telescope
Sodium Iodide Detectors (NaI)
Gamma-ray Large Area Space Telescope (GLAST)
Integrated on the Space Craft at Spectrum Astro Space Systems
December 2006

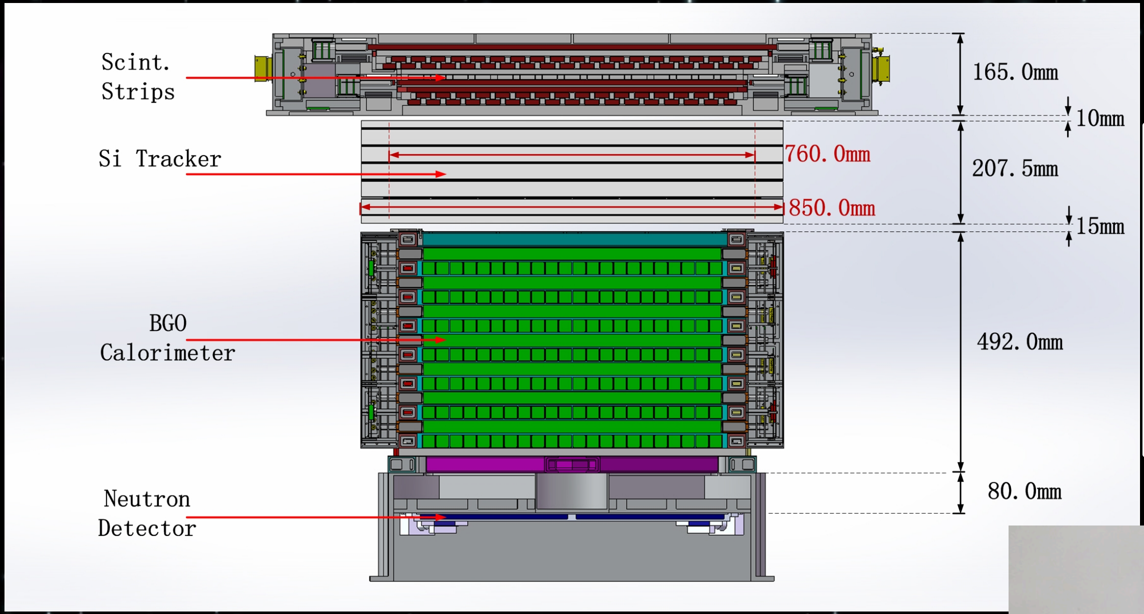



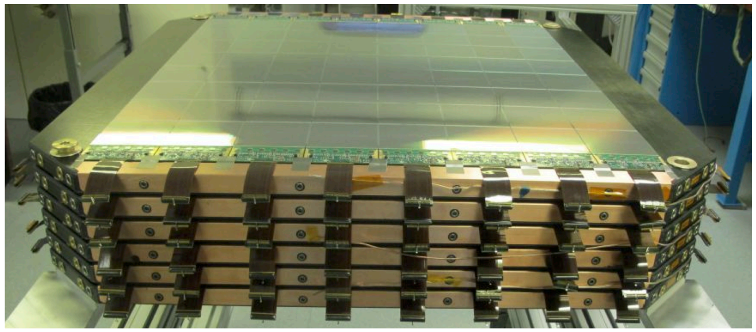
# Schematic layout

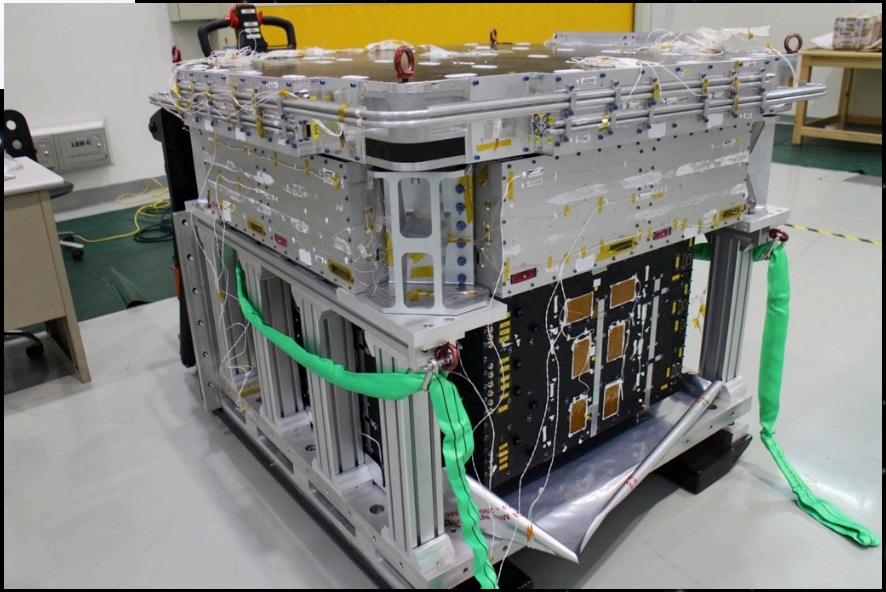



- Measurement:
  - Direction
  - Energy
  - Time
- Aanti-coincidencd shield
  - Identify charged particles
- Converter
  - Enhance the photon conversion into $e^{-}$-$e^{+}$ pairs
- Tracker
  - Measure the electron-positron trajectories and hence the photon direction
- Calorimeter
  - Measure the energy of the two electromagnetic particles
- Count rate (GBM)

# DAMPE



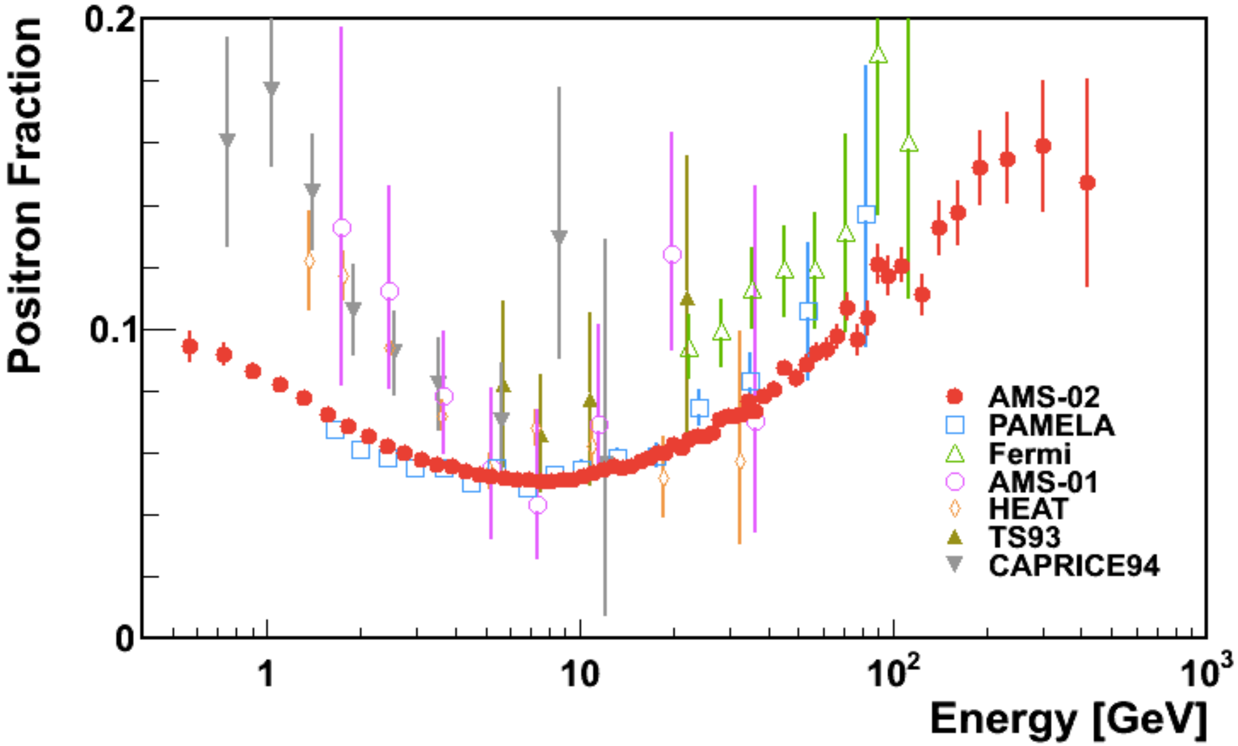





- Scintillators, Silicon tracker, BGO calorimeter, neutron detector
- γ-ray telescope + deep calorimeter
  - Silicon tracker/converter + imaging BGO calorimeter
    → Total ~33 $X_0$

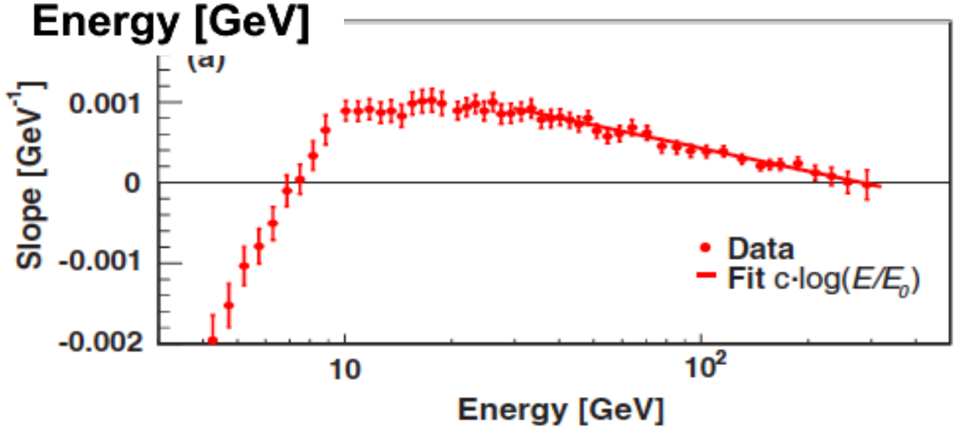
## Important results

# Positron fraction




- ✓ No evidence of structures
- ✓ Steady increase up to ~ 275 GeV
- ✓ Well described by a power law + cut-off term, common for $e^+/e^-$

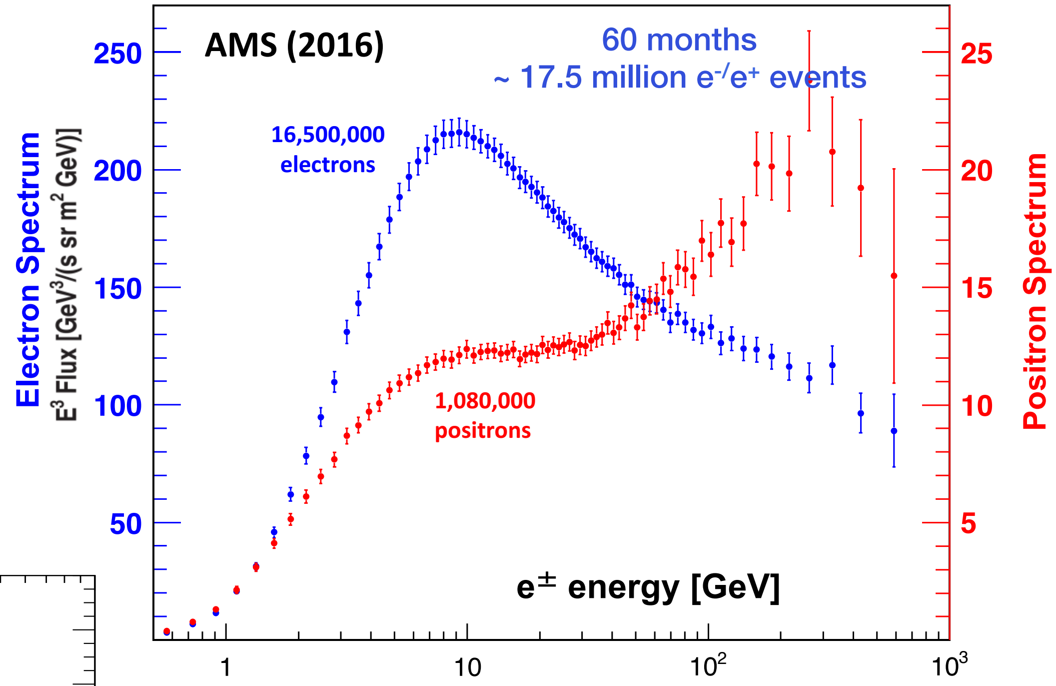
- Unexpected raise "discovered" by PAMELA
- Confirmed by FERMI and AMS-02
- Measured with high accuracy by AMS-02

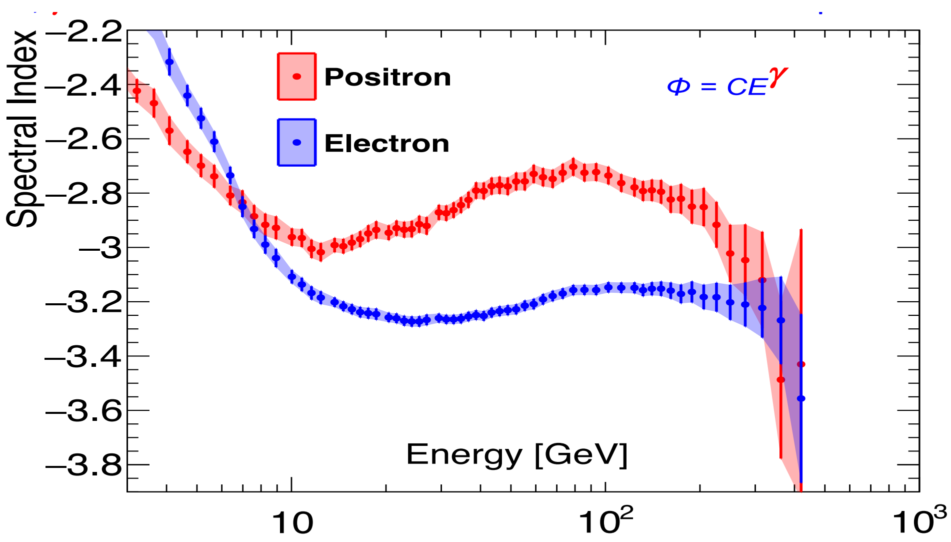


# Positron and electron fluxes (AMS preliminary)

AMS-02 preliminary results
(Please refer to the forthcoming AMS publication in PRL)

Electrons and Positrons
[0.5 – 700] GeV



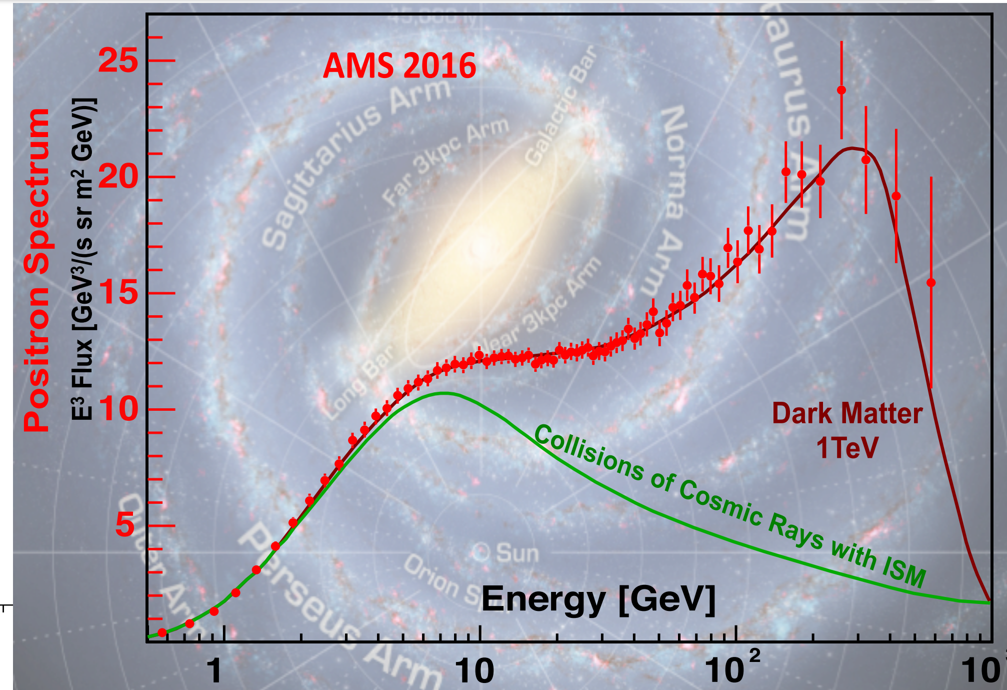



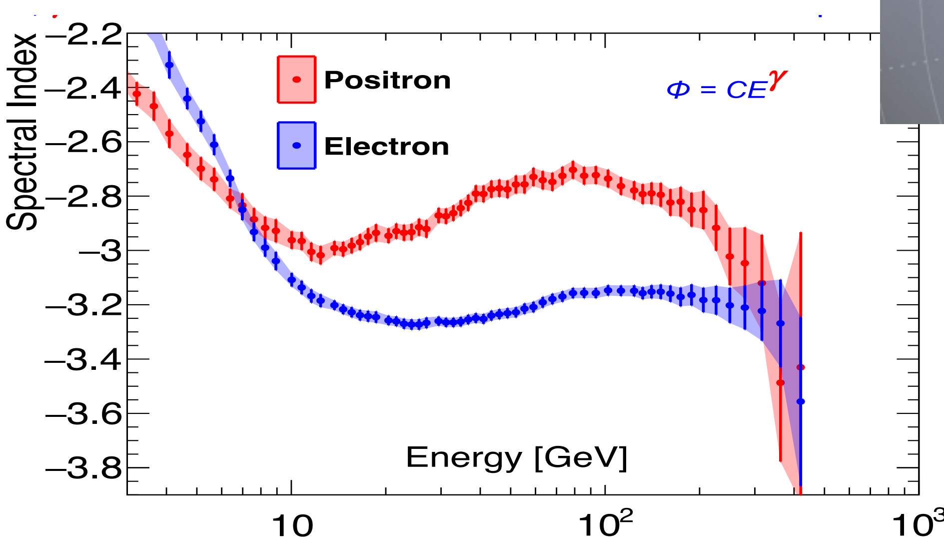

The two fluxes of $e^+$ and $e^-$ are significantly different in absolute value and energy dependence

The positron "raise" is due to an **excess of positrons**, not to a lack of electrons

AMS-02 preliminary results
(Please refer to the forthcoming AMS publication in PRL)

Electrons and Positrons
[0.5 – 700] GeV

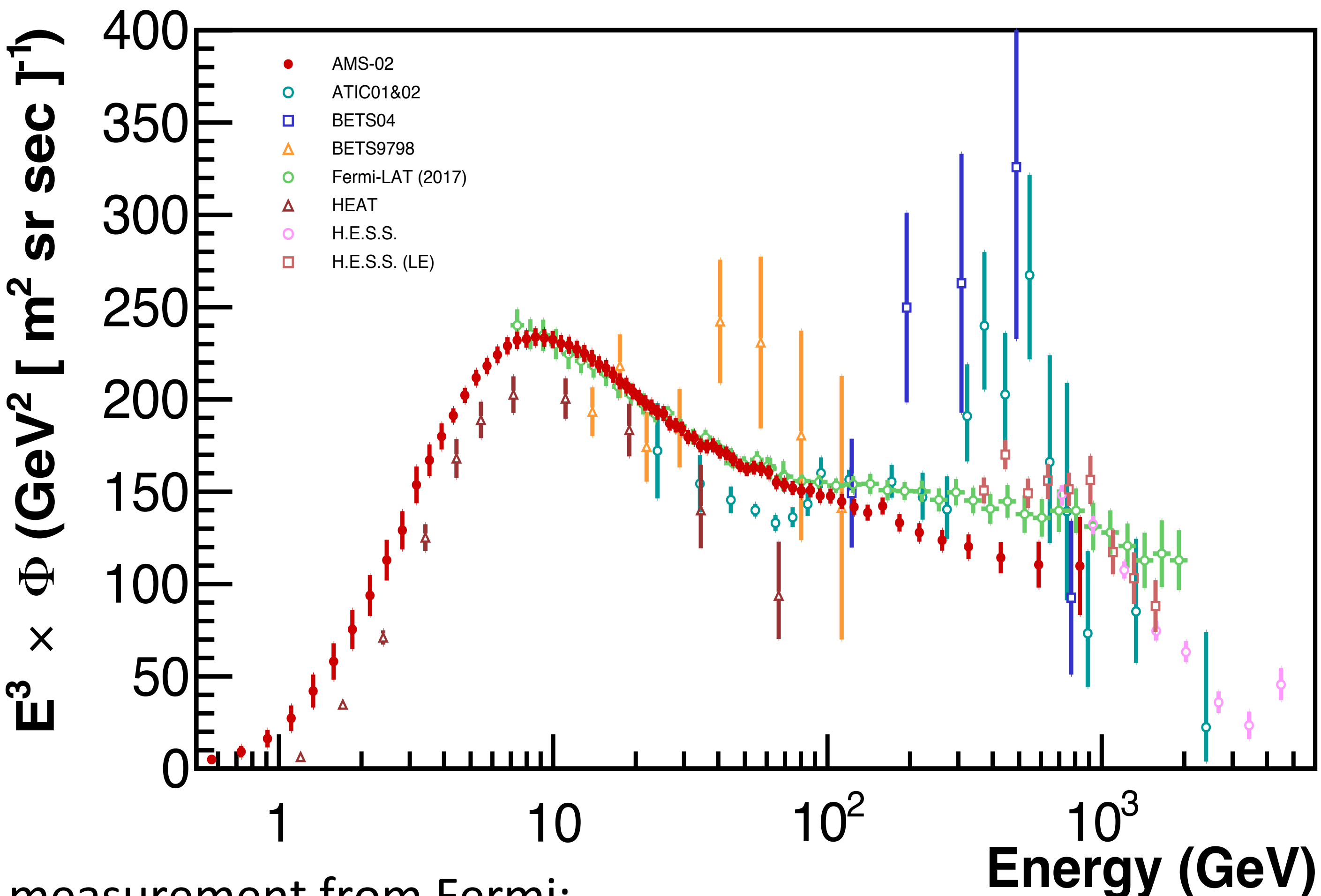



The two fluxes of $e^+$ and $e^-$ are significantly different in absolute value and energy dependence

The positron "raise" is due to an **excess of positrons**, not to a lack of electrons

# Electron + Positron flux

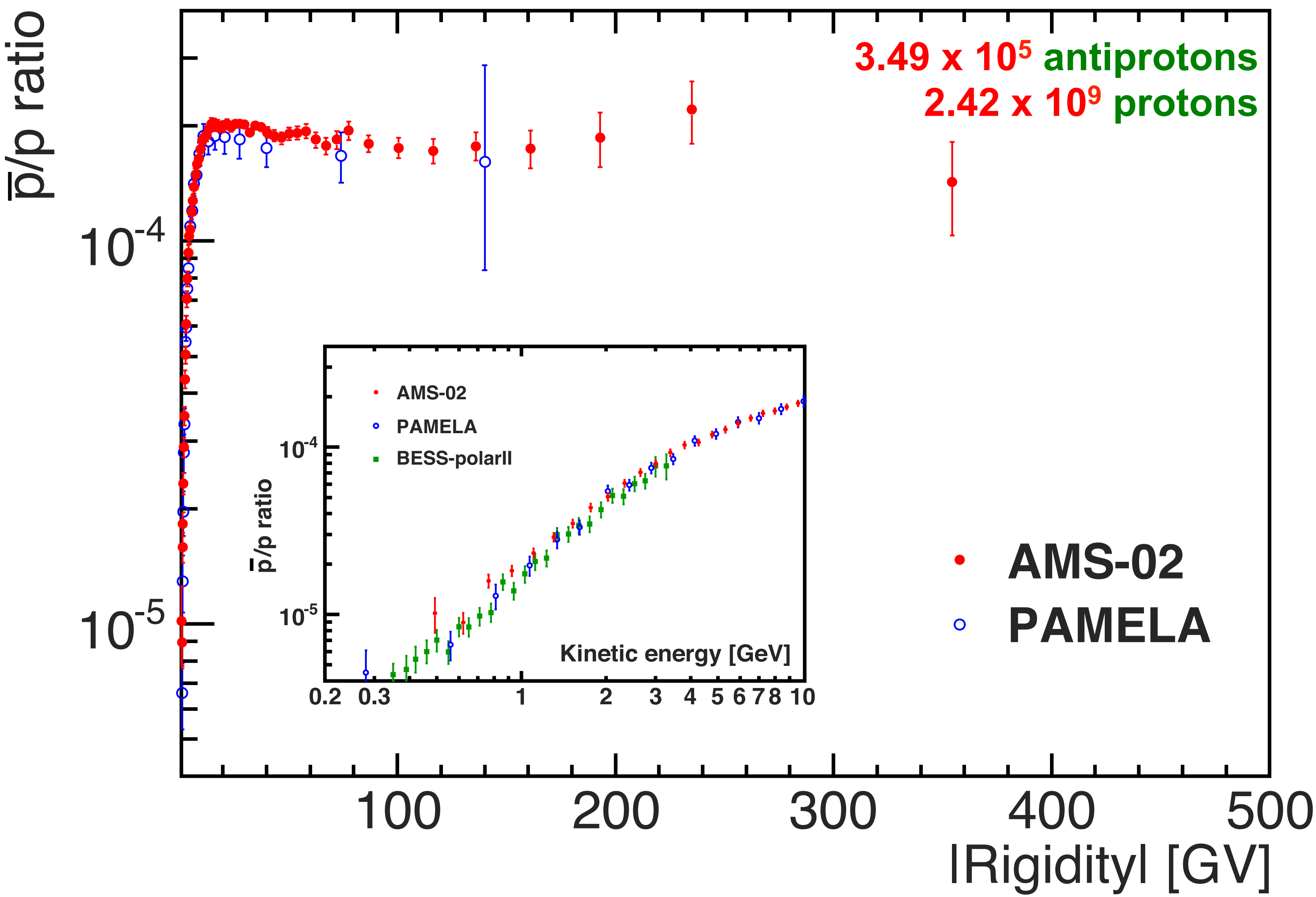



New measurement from Fermi:

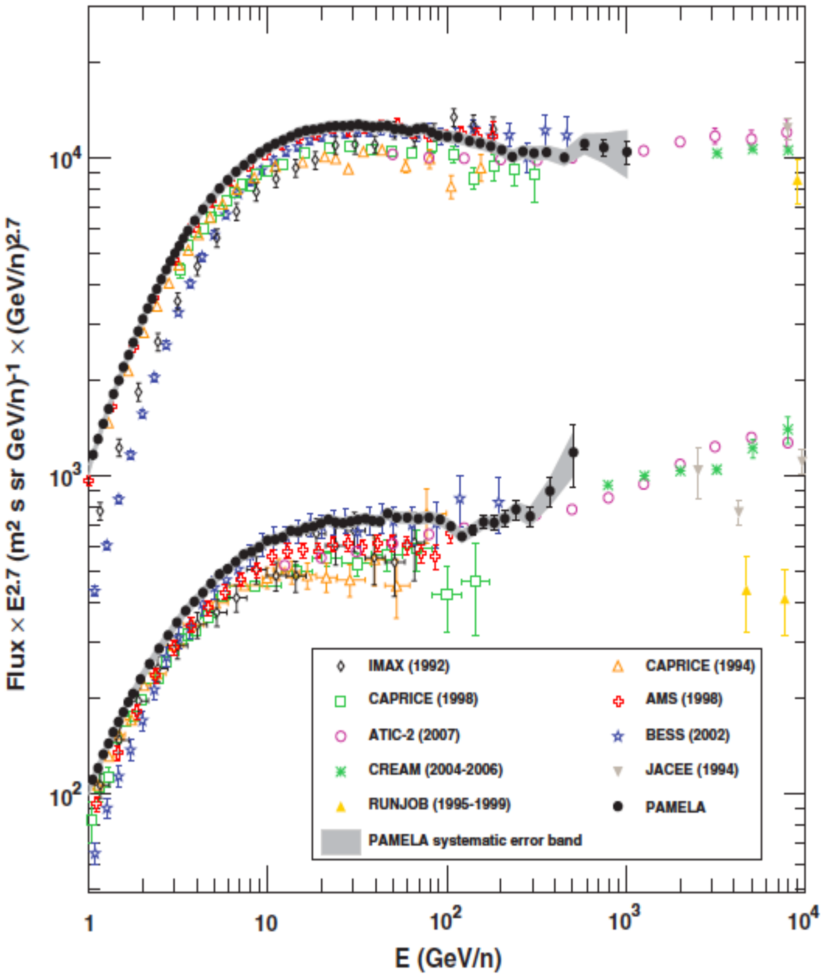
→ The "ATIC peak" has been ruled out

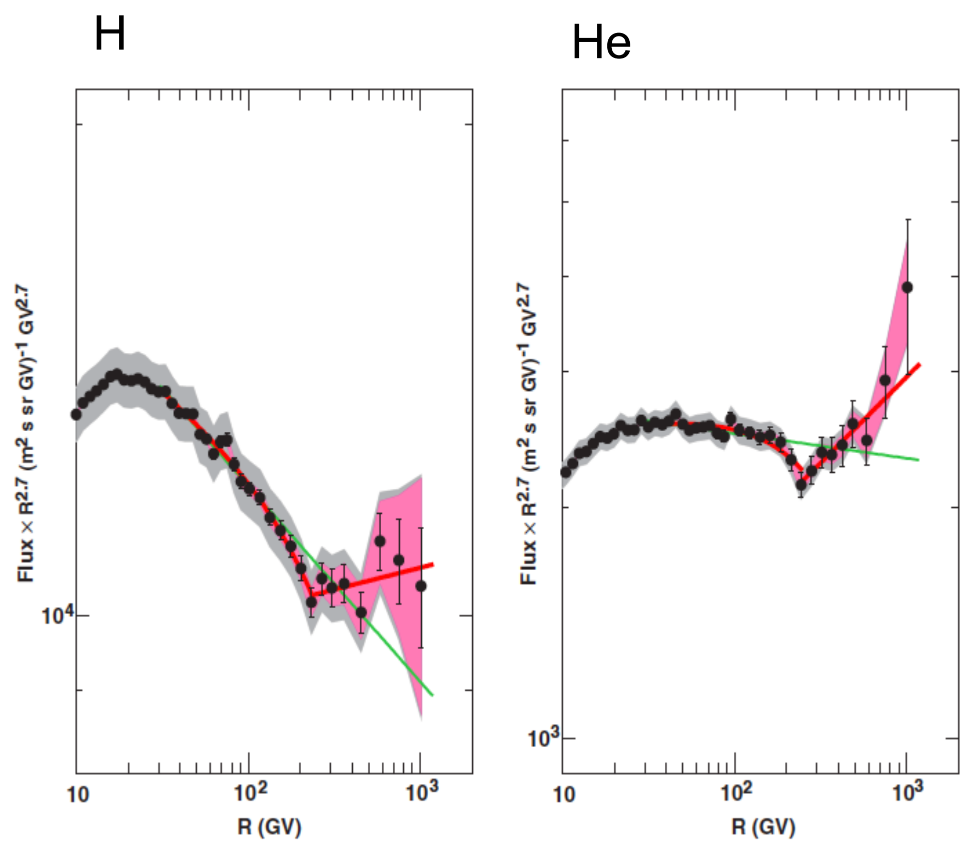
→ New measurements expected by AMS, DAMPE, CALET …

# Anti-proton/proton ratio



# Proton and Helium (PAMELA)



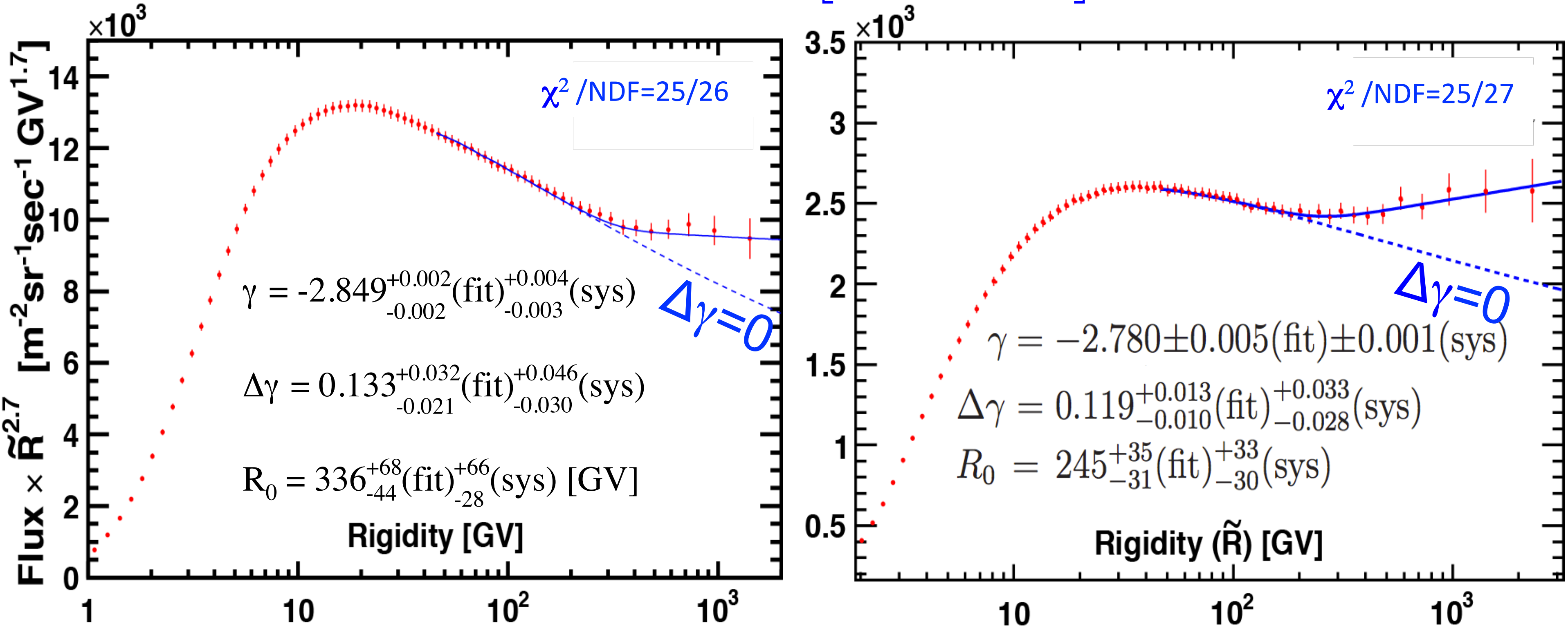




**PAMELA H and He: 10 GV-1.2 TV**
**Science, 2011**

# Proton and Helium (AMS)

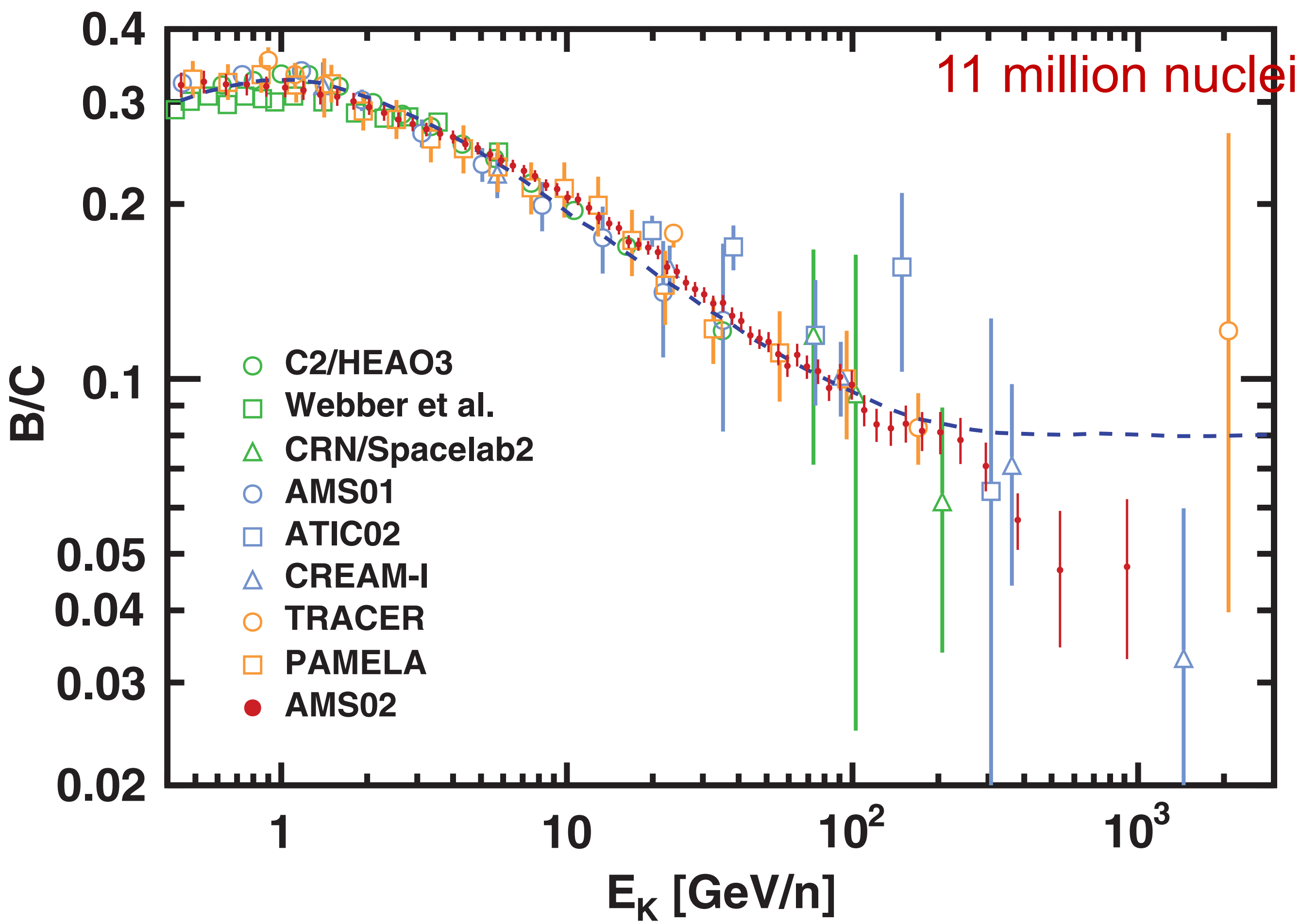
Two power-laws $R^{\gamma}, R^{\gamma+1}$ with a transition rigidity $R_0$ and a *smoothness* parameters: this well describe the experimental data:

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



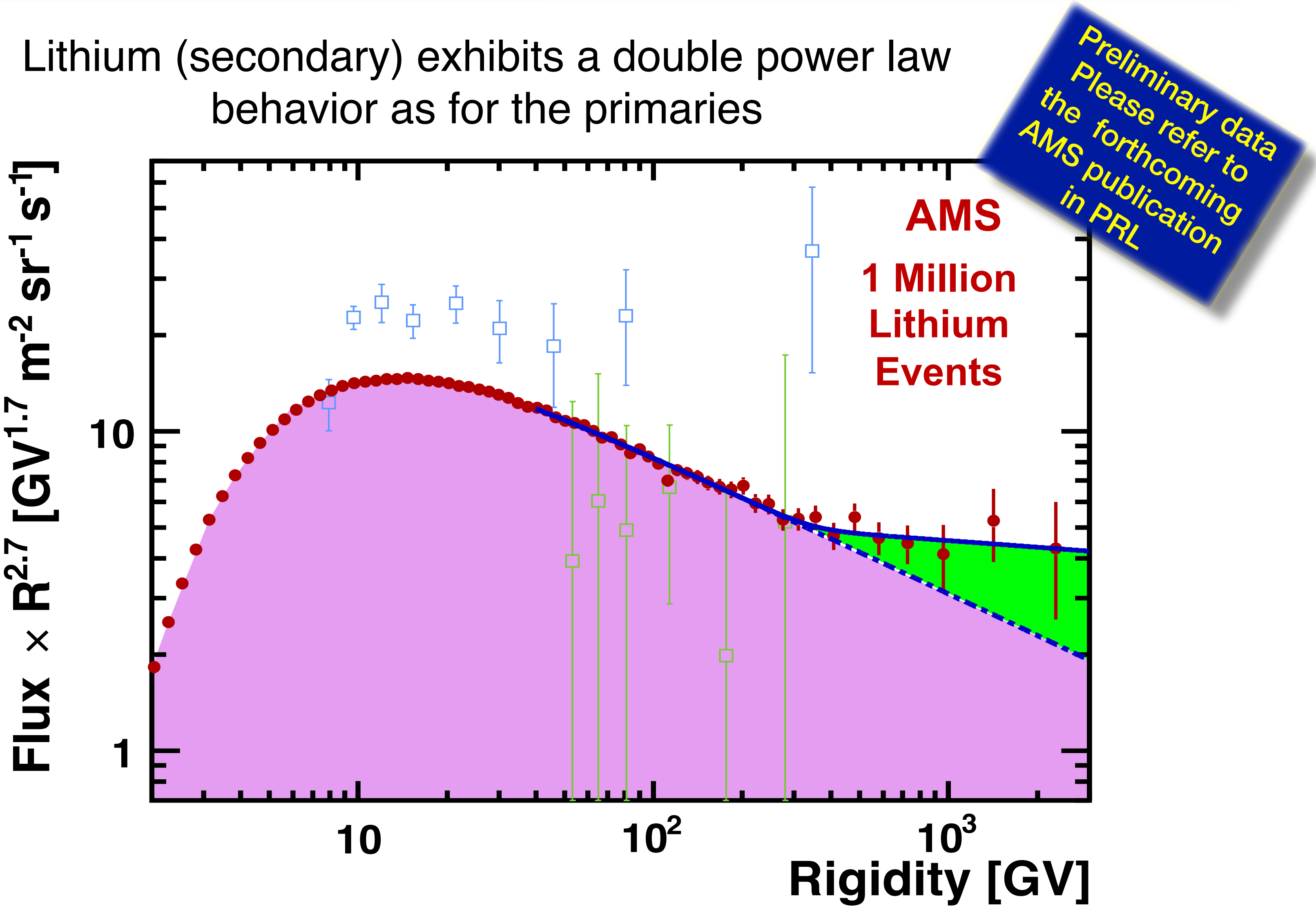
# Secondary CRs: Boron to Carbon flux ratio (AMS)

The flux ratio between primaries (C) and secondaries (B) provides information on propagation and the ISM:



# Other secondaries: Lithium (AMS)

Lithium (secondary) exhibits a double power law behavior as for the primaries

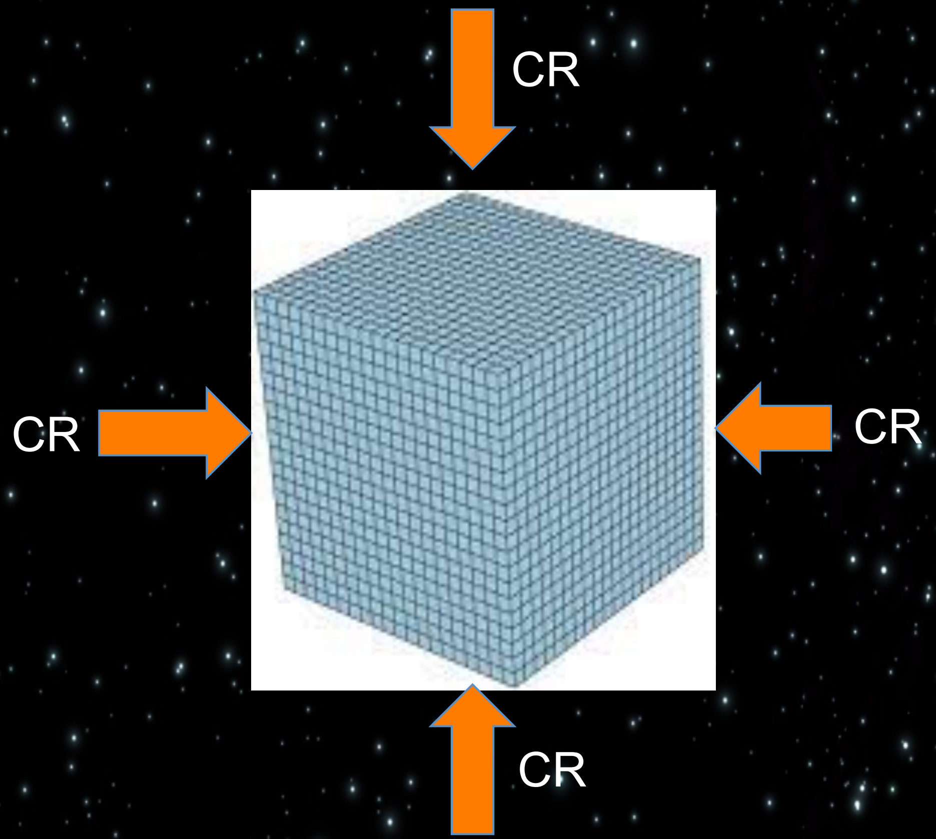


New ideas to increase the statistical and energy reach

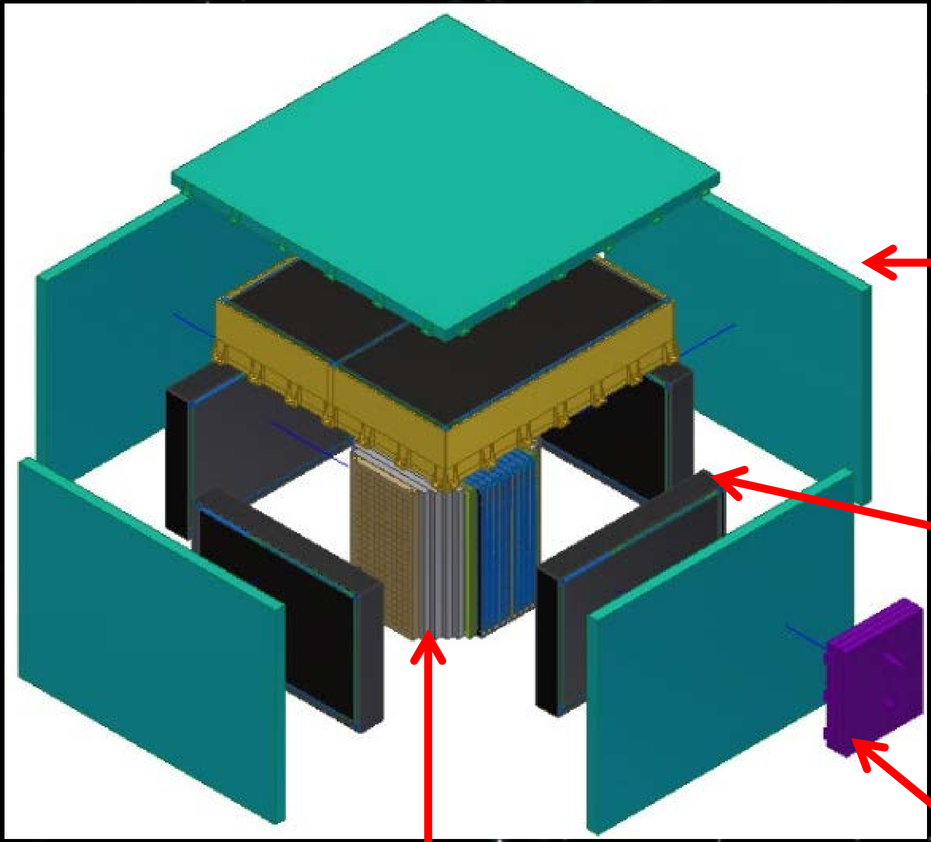
# Calo-Cube

- 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



# HERD layout



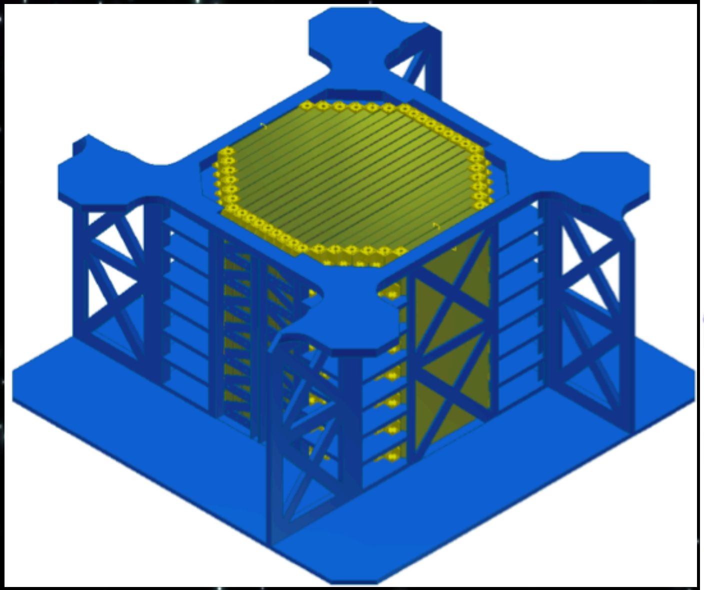
PSD, five sides
LE Gamma identification
Charge

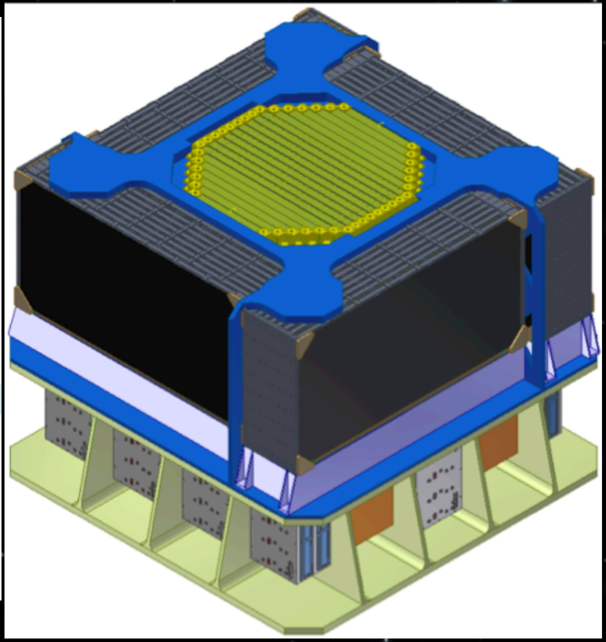
STK(SSD),five sides
Charge
Trajectory
Gamma tracking

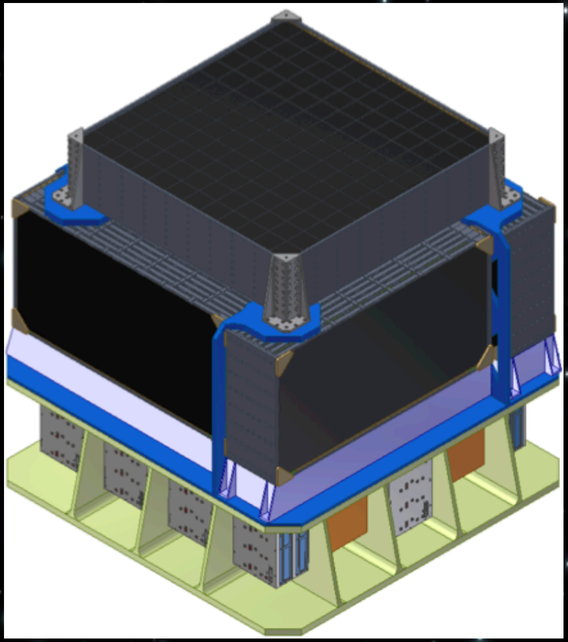
TRD
TeV proton calibration

CALO, 3-d
e/G/CR energy
e/p discrimination

# HERD layout

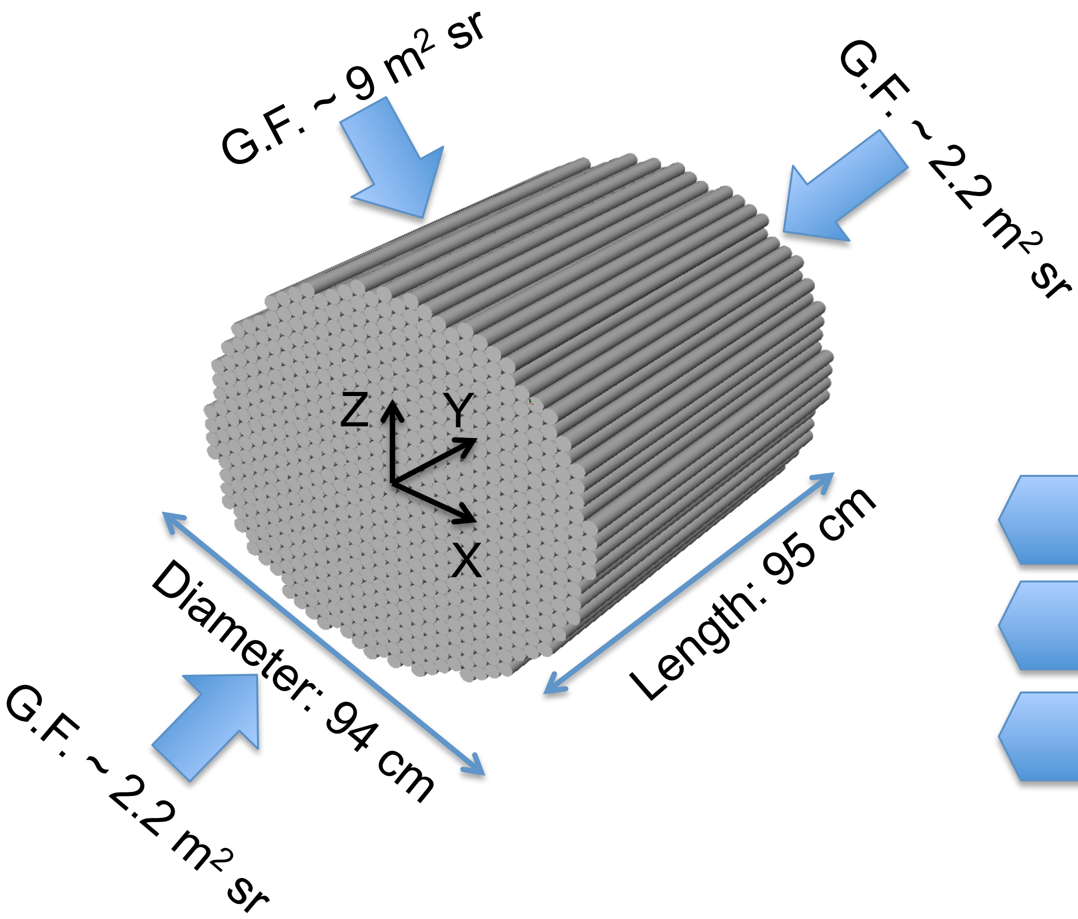


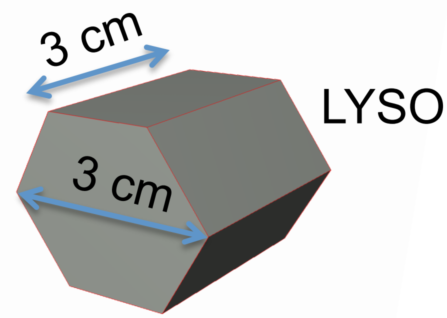




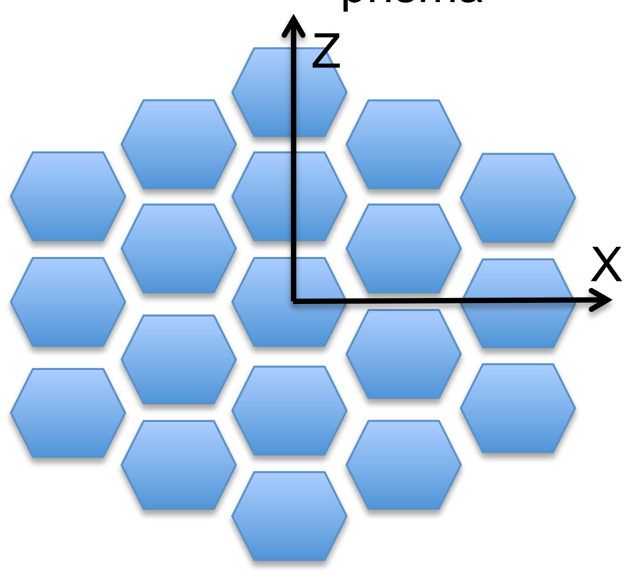
# ALADINO - Calorimeter

Weight~(2000+300) kg
N. crystals: ~20.000



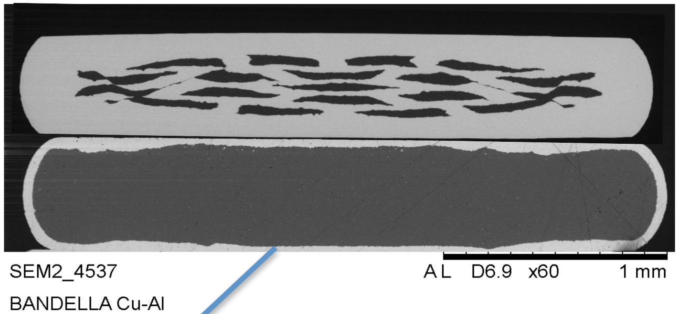



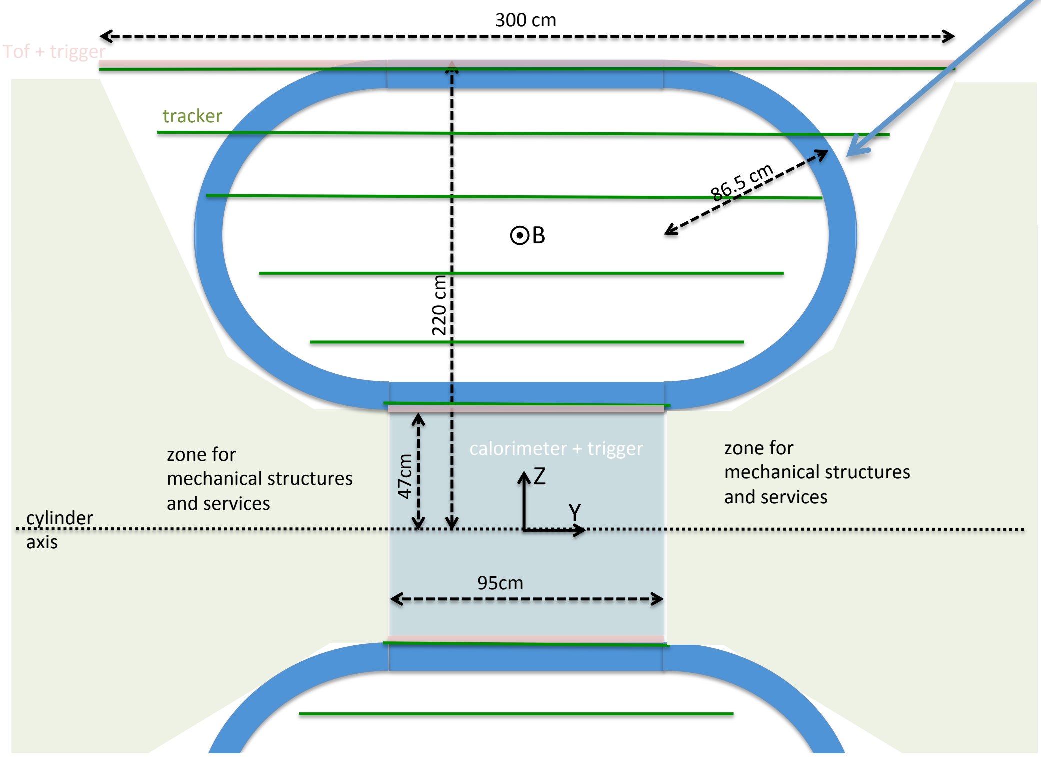

Basic crystal: hexagonal base prisma

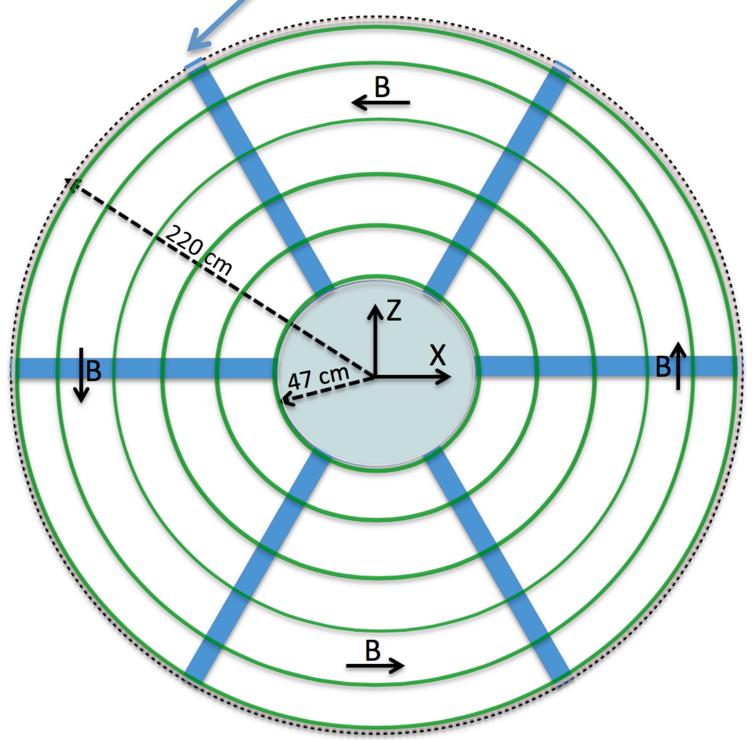


# ALADINO - Magnet

Benefit from the R&D of high temperature superconducting magnets ($MgB_2$) for space applications (T ≈ 10÷20 °K)

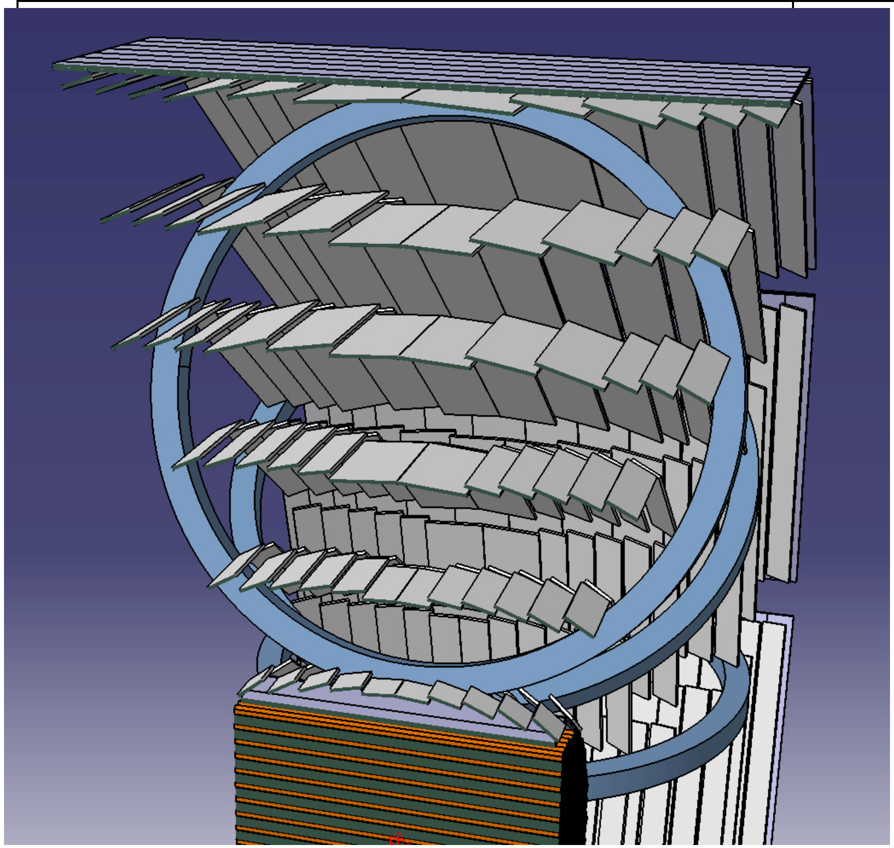


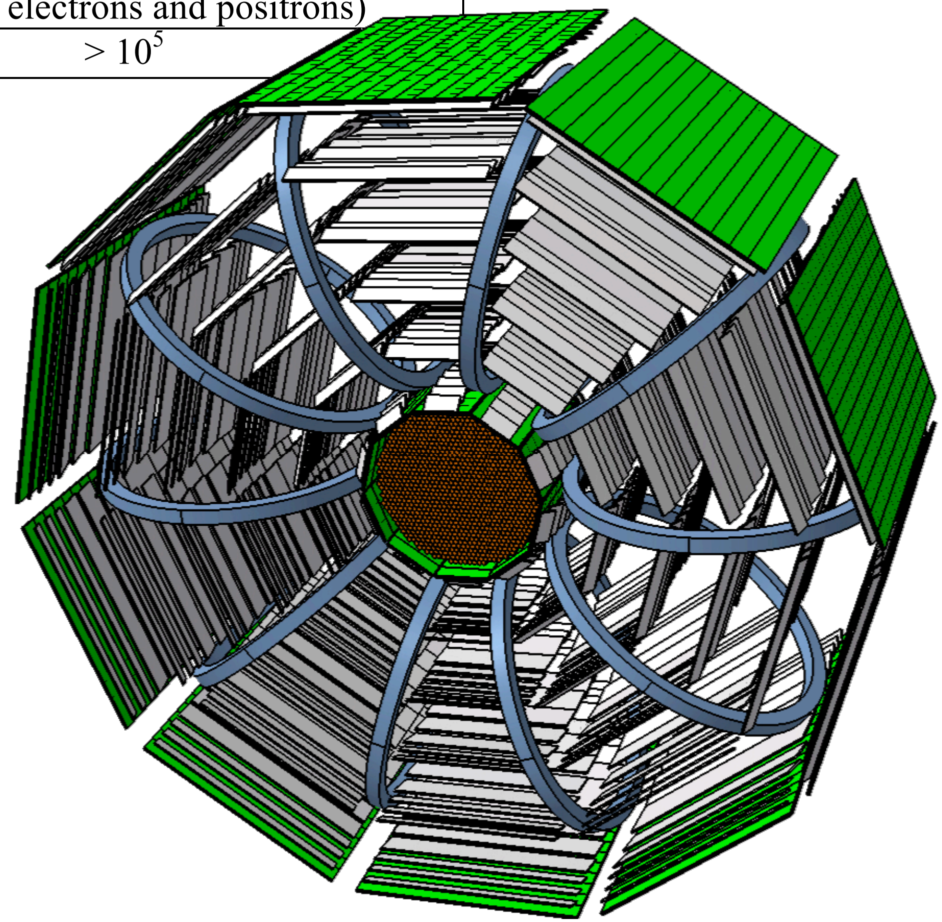



# ALADINO

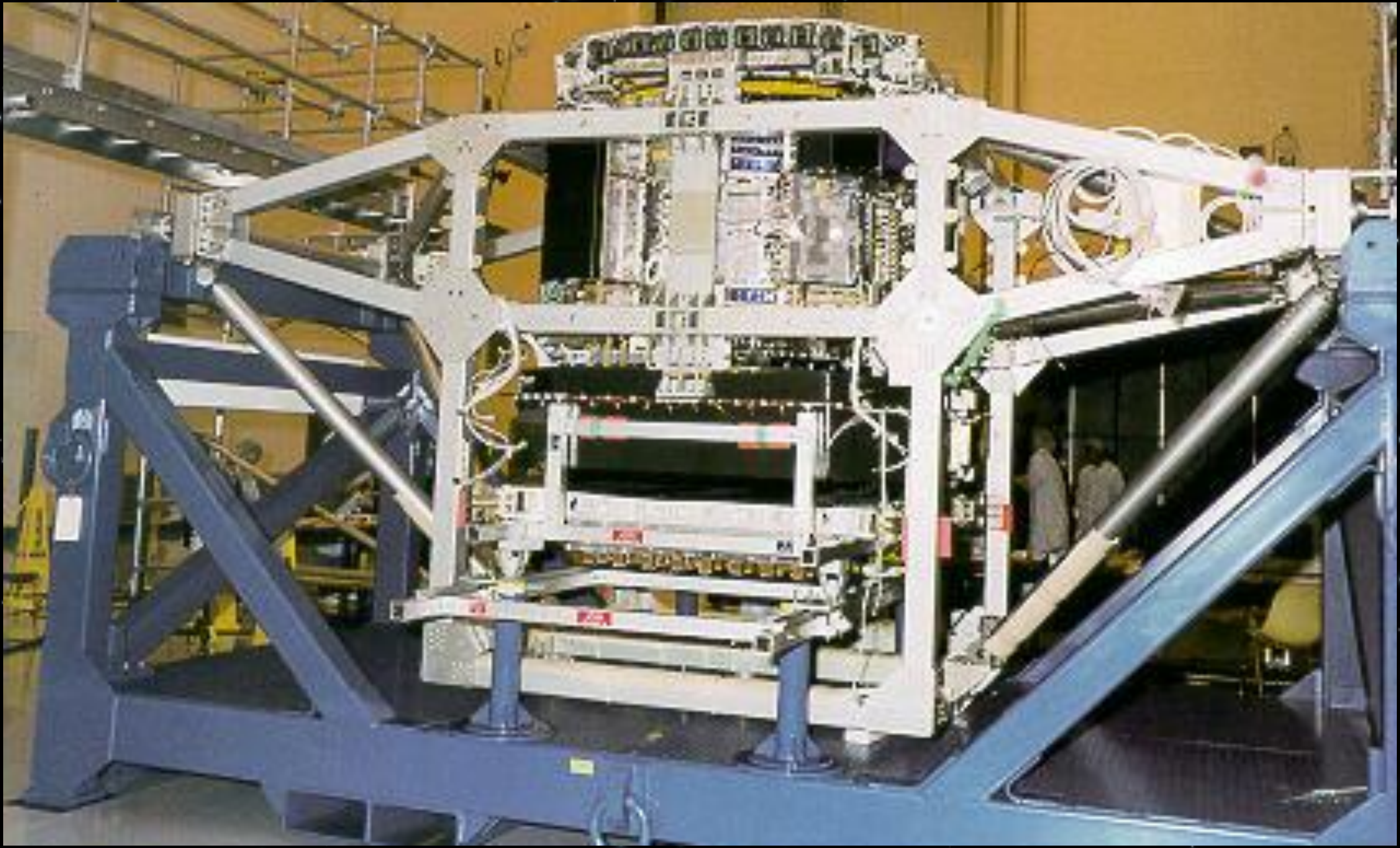
| | |
|---|---|
| Calorimeter acceptance | ~ 9 $m^2$ sr |
| Spectrometer acceptance | ~ 3 $m^2$ sr |
| Spectrometer Maximum Detectable Rigidity | > 20 TV |
| Calorimeter energy resolution | 24% ÷ 35% (for nuclei)<br>2% (for electrons and positrons) |
| Calorimeter e/p rejection power | > $10^5$ |





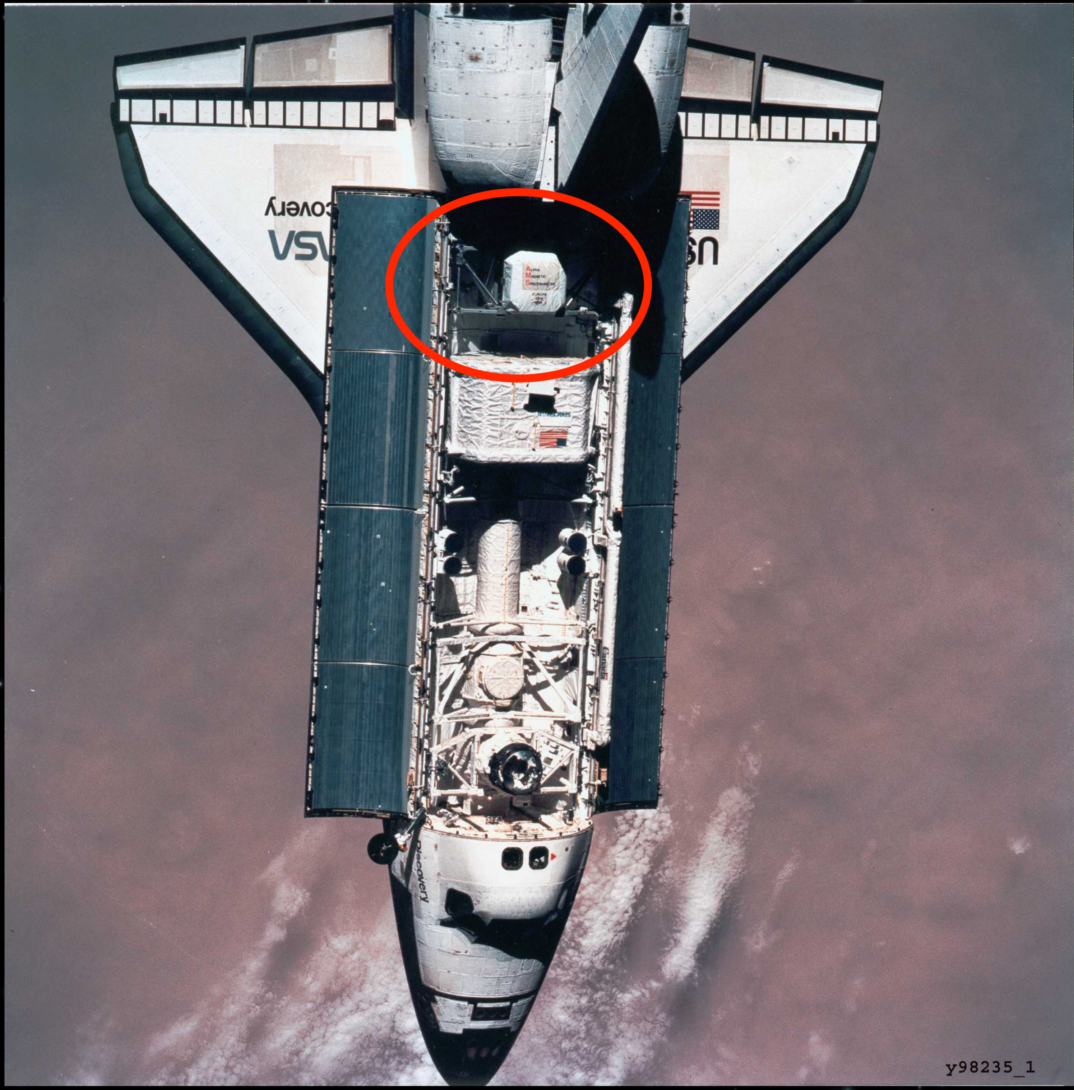

Endeavour
NASA
United States
KELLY
JOHNSON
CHAMITOFF
FINCKE
STS
134
AMS
FEUSTEL
VITTORI
STS-134/ULF6
Alpha Magnetic Spectrometer Team
28 February 2011
Kennedy Space Center
STORRM
OBSS
STS-134
ULF6
STP-H3
MISSE-8
Critical Spares
AMS-02
ELC3

# 1998: prototipo di AMS @ KSC (Florida)



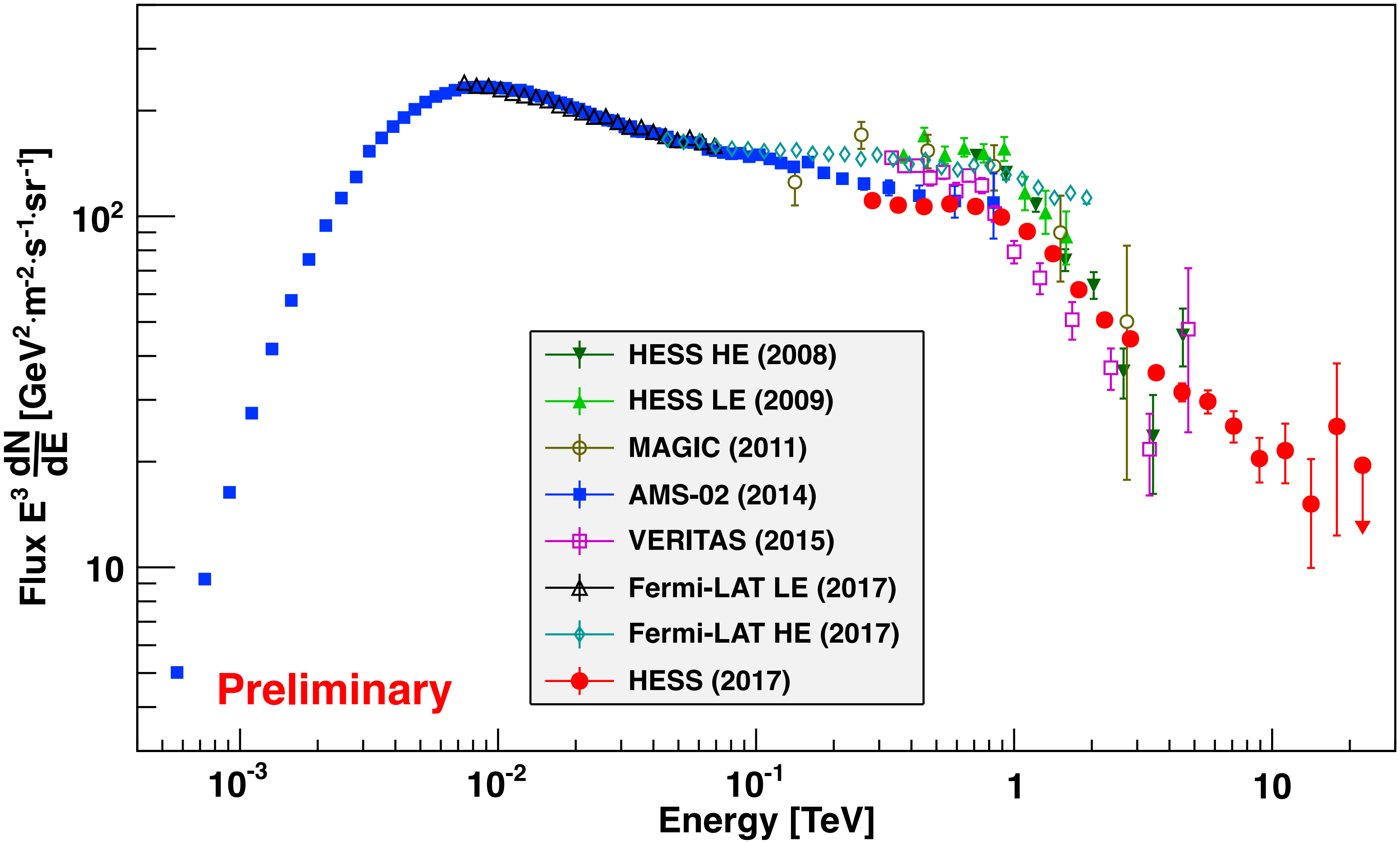
# 2 – 12 Giugno 1998: AMS-01 sul Discovery STS91

- 10 giorni di presa dati in orbita:
  - 400 Km di altitudine
  - latitudini <51.7°
  - tutte le longitudini
- $10^8$ eventi acquisiti
- risultati di fisica
(Phys. Rep. 366 (2002) 331)
  - misure di precisione dei flussi primari
  - rivelazione di particelle secondarie (quasi-trapped)
  - limite sull'antimateria a$10^{-6}$



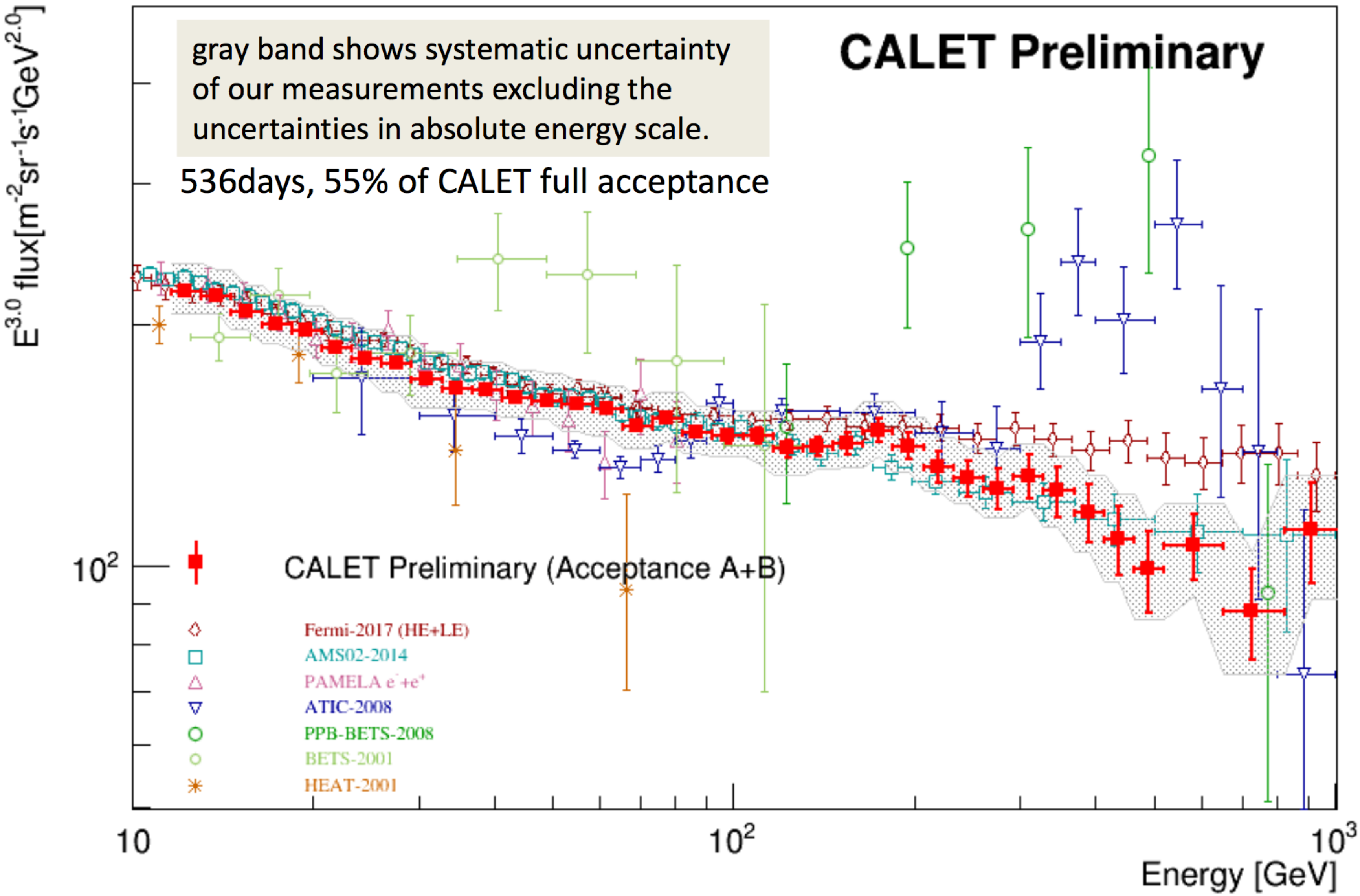
# Una nuova collaborazione che inizia…

# New H.E.S.S. cosmic-ray electron spectrum



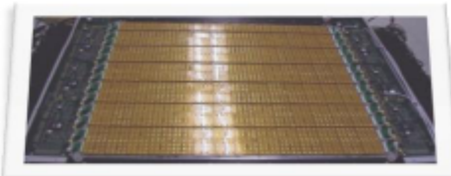
# Total Electron Spectrum up to 1TeV

Energy scale is determined by absolute calibration using cutoff rigidity (difference from MIP calibration is +3.5%)



# ISS-CREAM Instrument

Ahn et al., NIM A, **579**, 1034, 2007; Anderson et al., Hyun et al., & Seo et al. 33rd ICRC, 2013

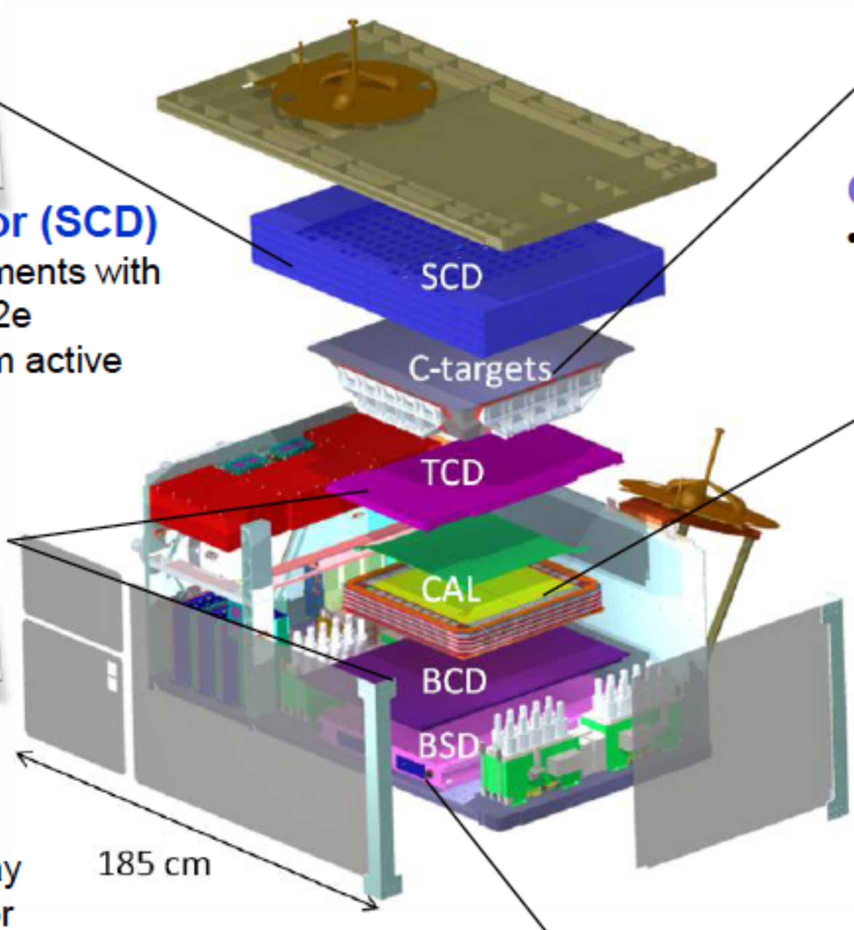


## Silicon Charge Detector (SCD)

- Precise charge measurements with charge resolution of ~ 0.2e
- 4 layers of 79 cm x 79 cm active area (2.12 $cm^2$ pixels)

## Top/Bottom Counting Detector (T/BCD)

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

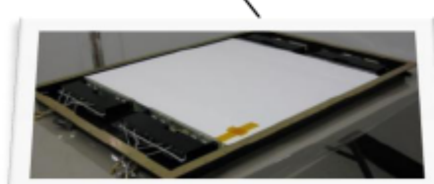



## Carbon Targets

- Induces hadronic interactions

## Calorimeter

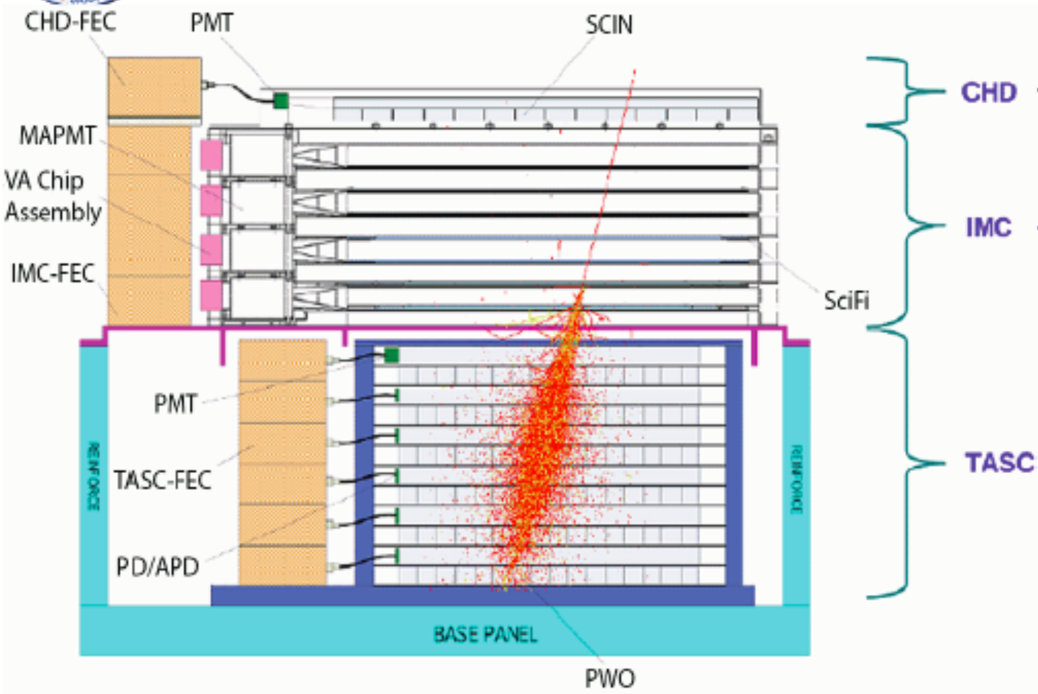
- 20 layers of alternating tungsten plates and scintillating fibers
- Determines energy
- Provides tracking and trigger



## Boronated Scintillator Detector (BSD)

- Additional e/p separation by detection of thermal neutrons

# 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, Particle ID |
| Sensor (+ Absorber) | **Plastic Scintillator : 2 layers**<br>**Unit Size: 32mm x 10mm x 450mm** | SciFi : 16 layers<br>Unit size: 1mm² x 448 mm<br>Total thickness of Tungsten: 3 $X_0$ | PWO log: 12 layers<br>Unit size: 19mm x 20mm x 326mm<br>Total Thickness of PWO: 27 $X_0$ |
| Readout | **PMT+CSA** | 64 -anode PMT+ ASIC | APD/PD+CSA<br>PMT+CSA ( for Trigger) |