Precision Cosmic Ray Physics in Space-born Experiments

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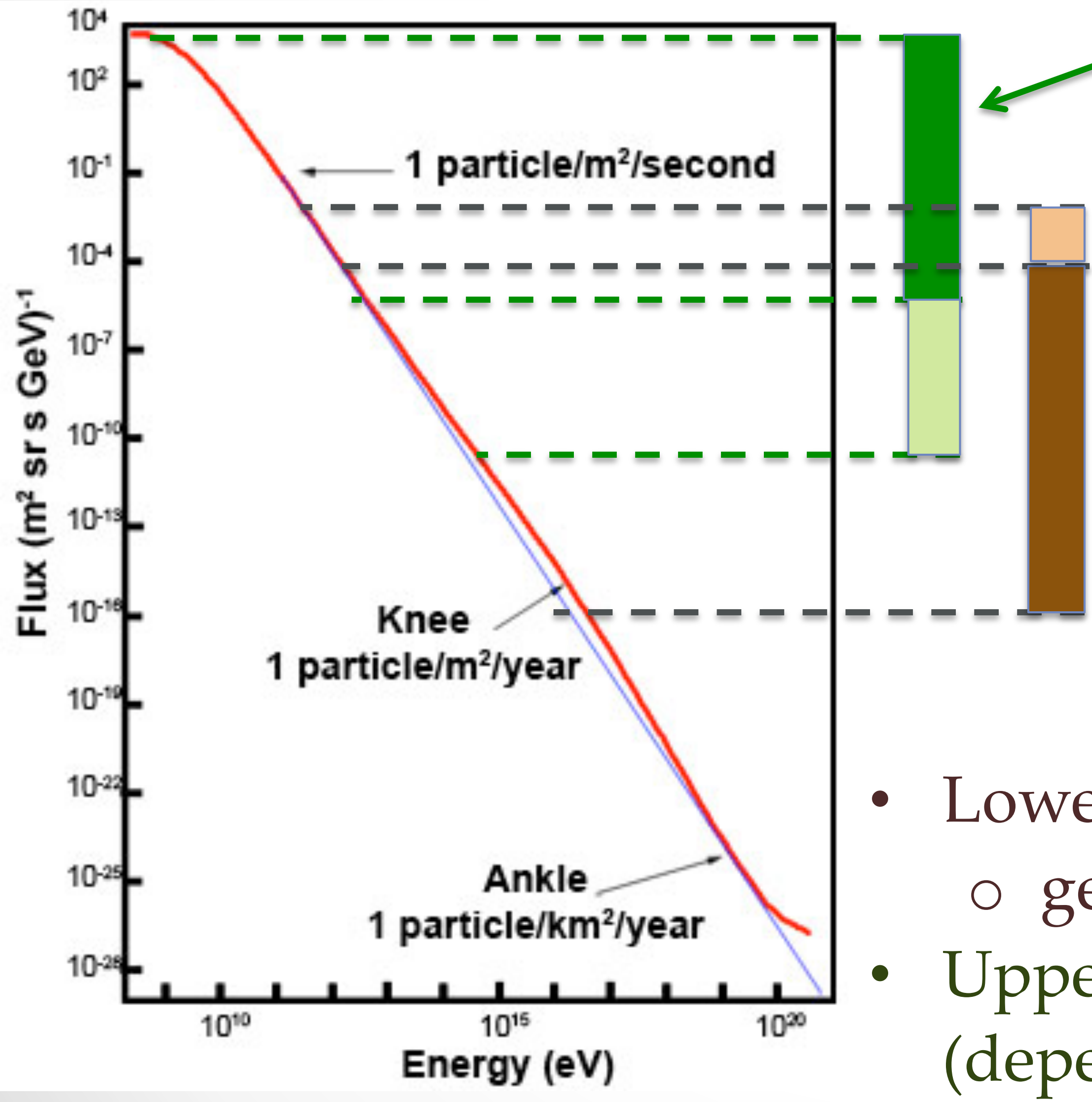
30 sep 2014

RICAP2014 @ Noto (Sicily, Italy)

Outline

1. Detectors for Space Experiments
   - Why
   - How
   - Where (that's easy: in space)
   - Calorimetric vs Magnetic vs Gamma detectors
2. Results from ongoing experiments:
   - PAMELA, AMS02
   - Photons → session of Thursday morning
3. Future Space Experiments
   - near term : 2015-2016
   - medium term : ≥2020

Charged Cosmic Rays



Space experiments

Cherenkov telescopes

- ◆ Dark color: current experiments
- ◆ Light color: future experiments

Space Experiments:

- Lower energy limit: ~1 GeV
  - o geomagnetic cutoff
- Upper energy limit: 1 TeV-1 PeV (depending on particle type)
  - o rapidly decreasing flux

Why Space Experiments

- *Sensitive to "primary" CR component* (i.e. before interacting with earth atmosphere)
- A *higher precision on energy and on chemical composition* can be reached, wrt ground exp.
- With magnet → *sensitivity to anti-particles*
- Compared to balloons: long period of continuos data taking → increased statistics, but also a better control of systematics

- Limited mass
- Limited geometrical acceptance
- Large cost

Space Detectors

- Space Detectors can be classified as:

1. Magnetic spectrometers (*à la* AMS02)
2. Pair-conversion telescopes (*à la* Fermi)
3. Cosmic Ray calorimeters (*à la* CREAM or ATIC, but also ISS-CREAM, CALET, DAMPE, ...), specialized on hadrons or on em-showers

with possible combinations of the different techniques

Spectrometers vs Calorimeters

- Spectrometers : momentum and charge sign
  - **access to anti-particles (positrons, antiprotons, ...)**
  - access to CR isotopical composition (in principle)
  - BUT... magnet is heavy (permanent) or hard to operate (superconducting) → some R&D in progress
- *Pair-conversion telescope : gamma physics*
  - **dedicated tracking stage (>1X_0) in which $\gamma \to e^+e^-$**
  - excellent Point Spread Function (PSF = angular resolution)
  - BUT ... adds some complexity: impact on Field Of View and Energy resolution
- Calorimeters : $e^{\pm}$, p, nuclei (Z measurement)
  - **maximum acceptance**
  - reach of high energies (~ PeV) for hadrons
  - precise (large statistics) measurement of e^++e^- flux

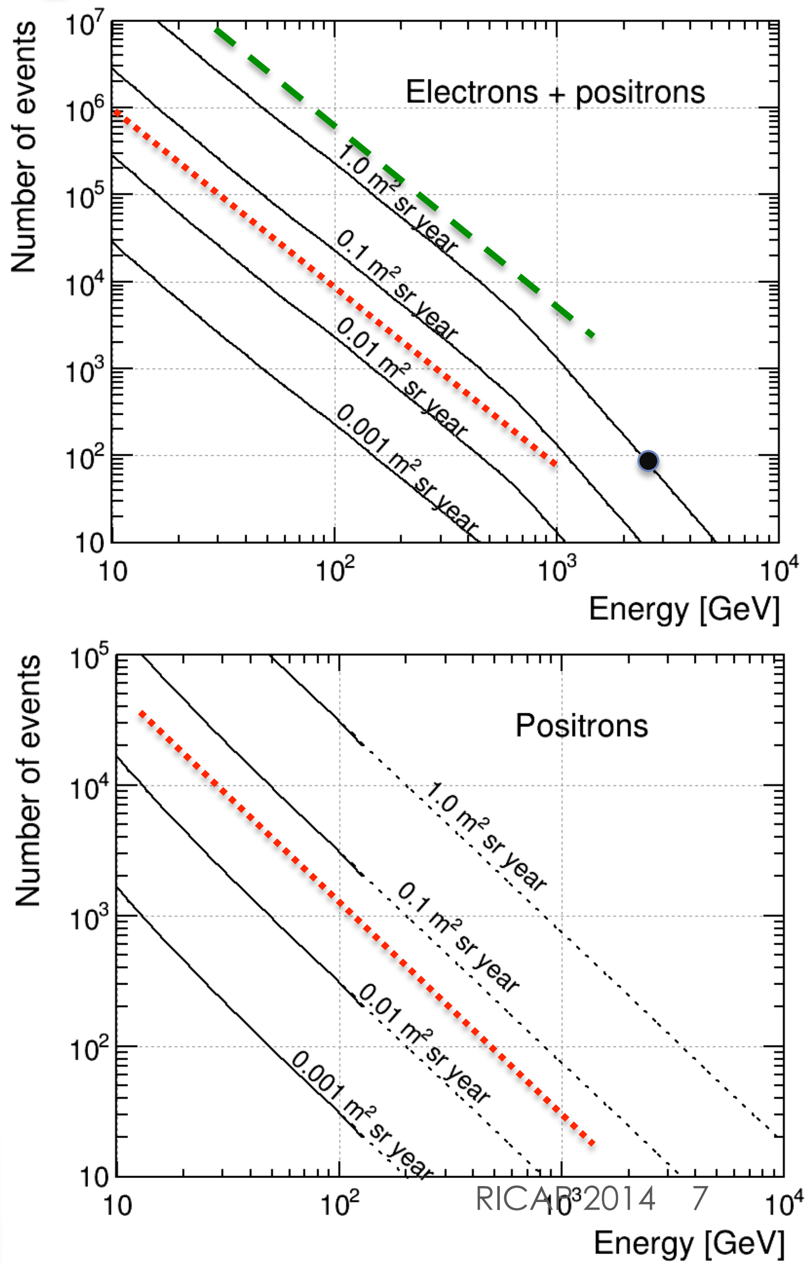
Statistics vs Acceptance

Geometrical Acceptance:

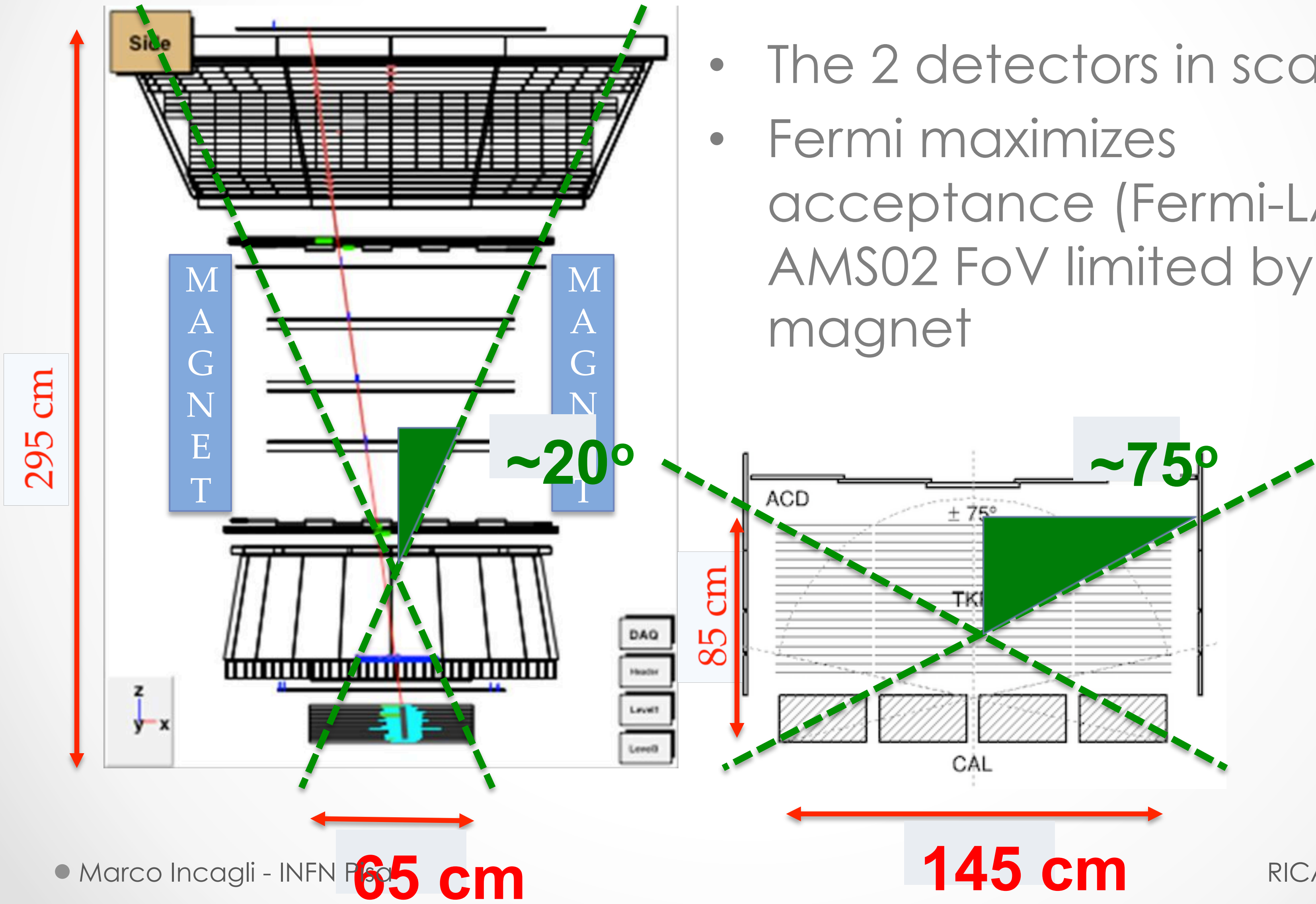
Fermi - - - -

AMS02 ....

- The CR flux rapidly decreases with energy (~E^{-3})
- For an Acceptance of ***1m² sr year*** → at most ***100 $e^{+}+e^{-}$ events*** per year are expected at ***E~2-3 TeV***
- A magnetic spectrometer is limited by the Field Of View (see next slide)



Comparison AMS02-Fermi



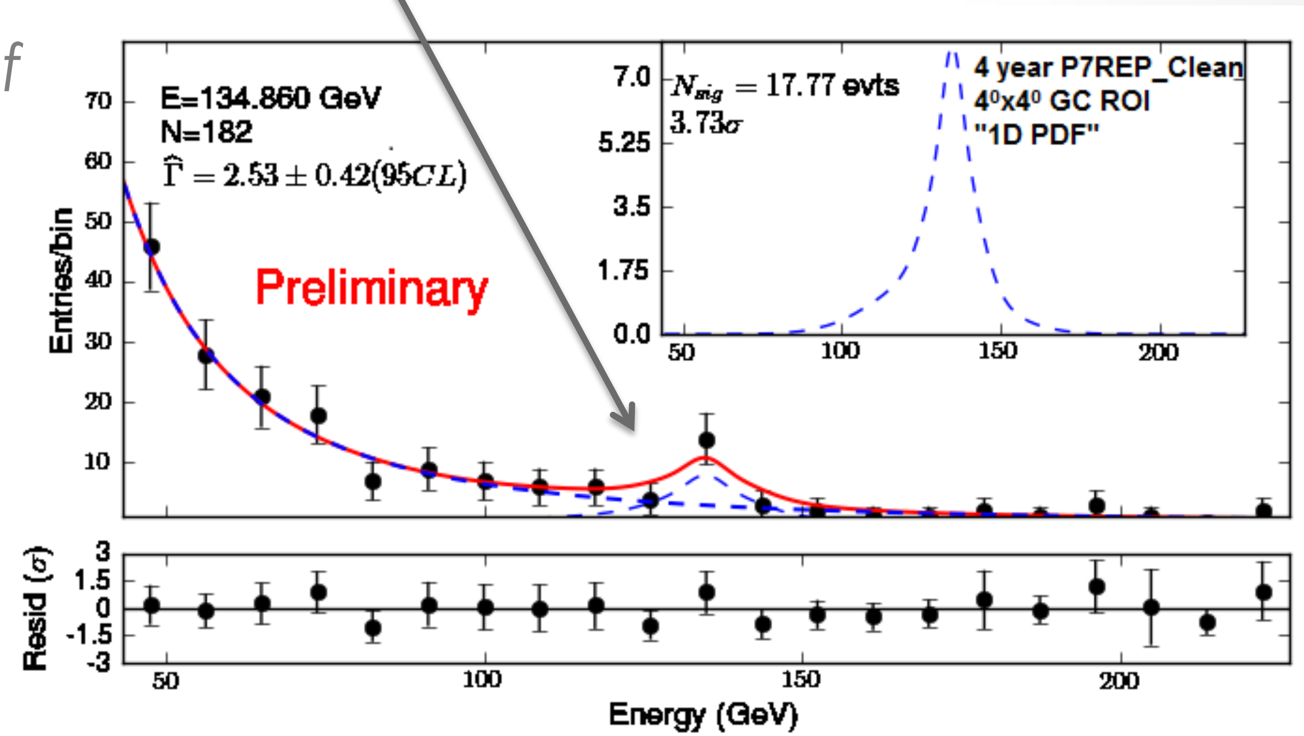
- The 2 detectors in scale
- Fermi maximizes acceptance (Fermi-LAT), AMS02 FoV limited by magnet

Example: Sensitivity to Gamma line

- Annihilation of a Dark Matter particle in a photon pair results in a distinct "line" in the photon spectrum
- The "*Quality of the line*" is:

$$Q = \frac{n_s}{\sqrt{n_b}}$$

- The term n_b is proportional to the Energy Resolution ΔE



- Both n_s and n_b are proportional to the Geometrical
- Acceptance *A*

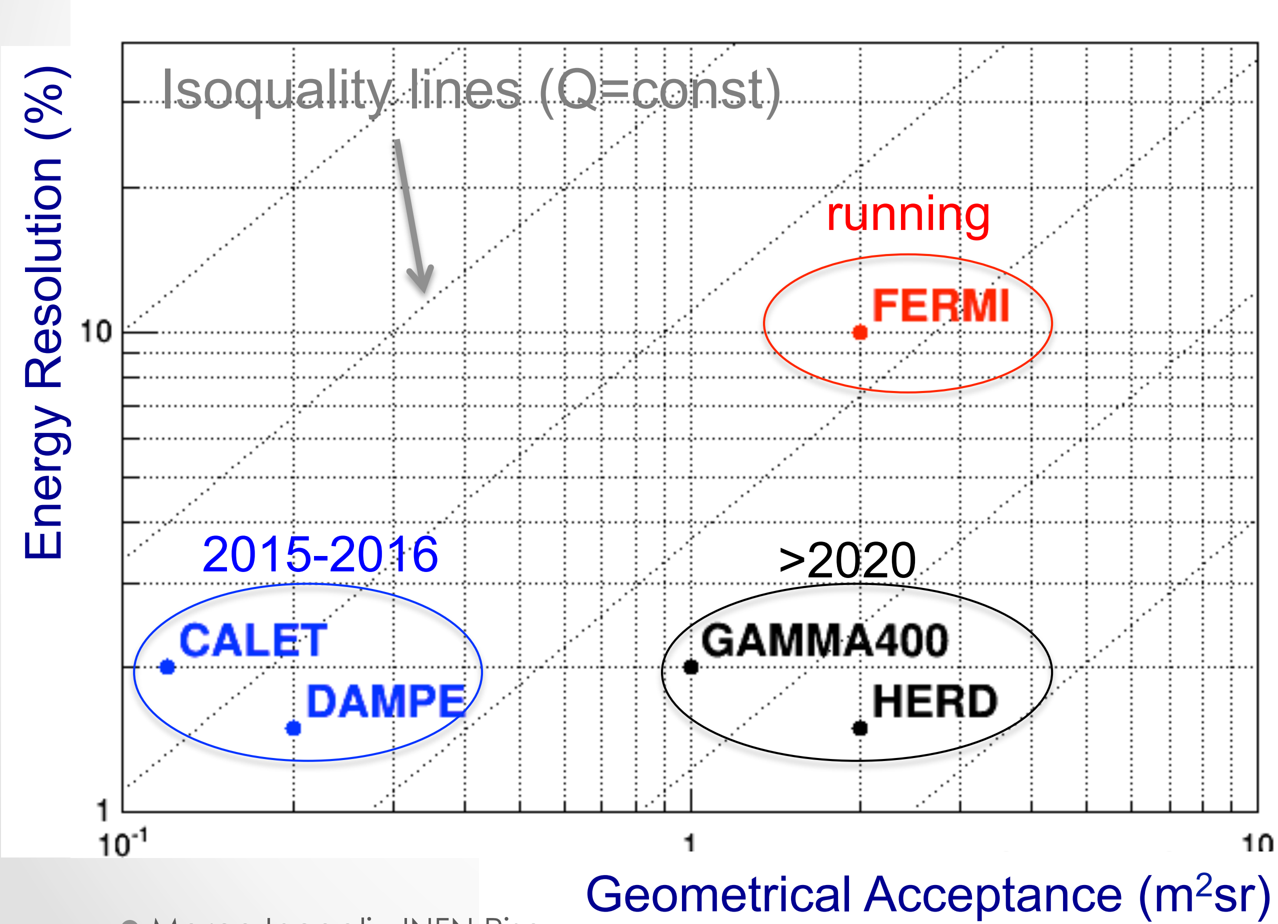
Sensitivity to Gamma line

$$Q = \frac{n_s}{\sqrt{n_b}} \propto \sqrt{\frac{A}{\Delta E/E}}$$

Acceptance

Energy Resolution

L. Baldini, 2014



The message:

energy resolution is good ... if you are not trading too much acceptance for it!

NOTE: the parameters used for future detectors should only be taken as ***order of magnitude***!

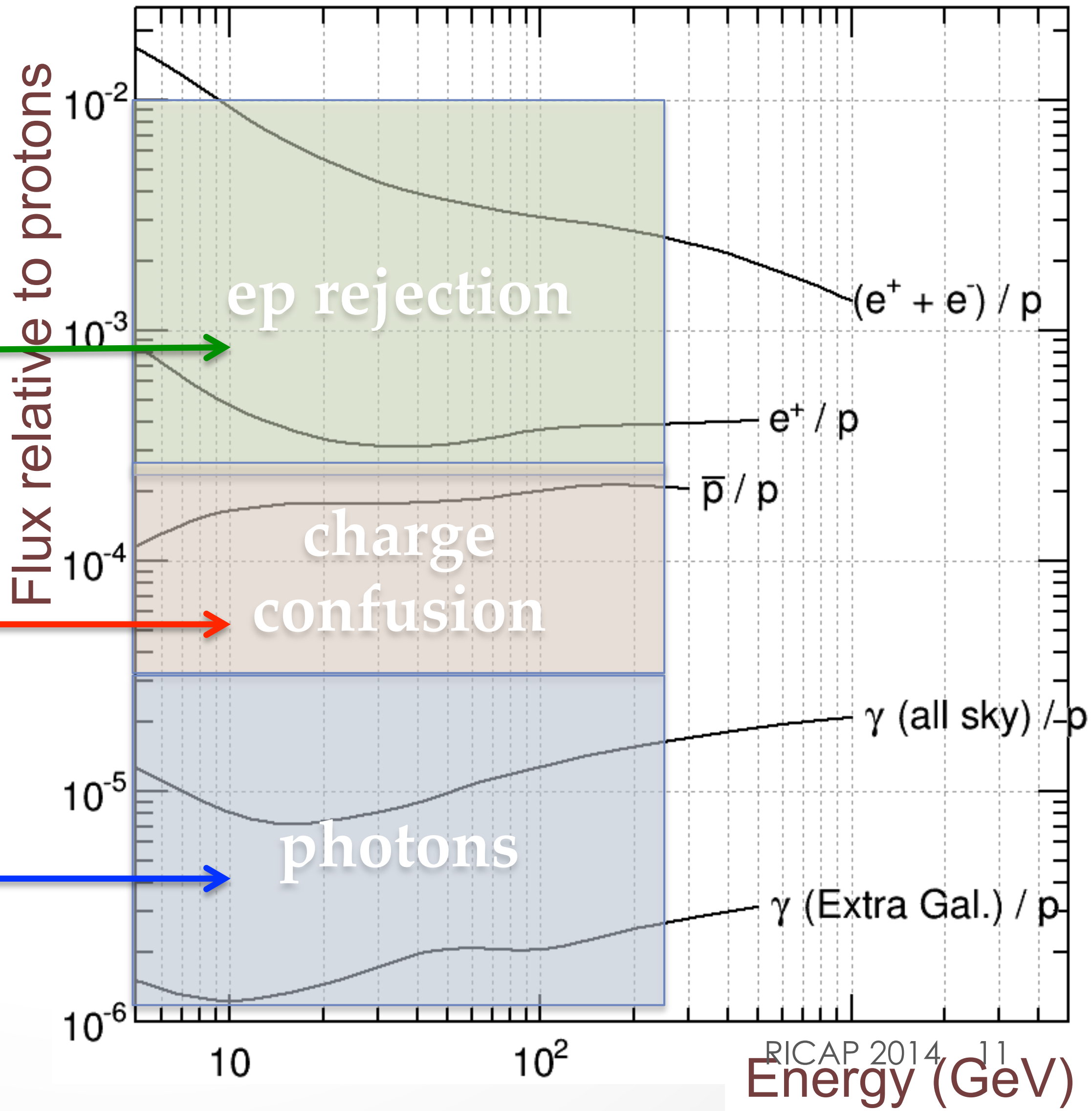
The issue of background

- But statistics is not the whole story!

✧ electrons (positrons) suffer from a proton background of 10^2 (10^4) times higher

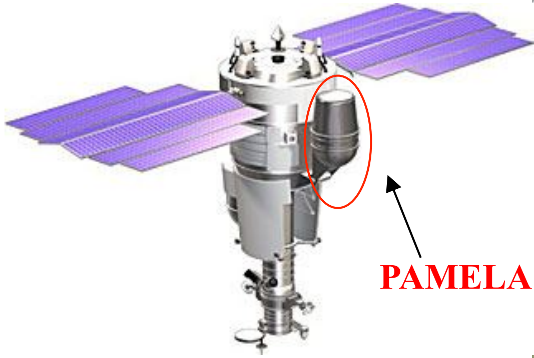
✧ proton background in anti-protons is ~10^4

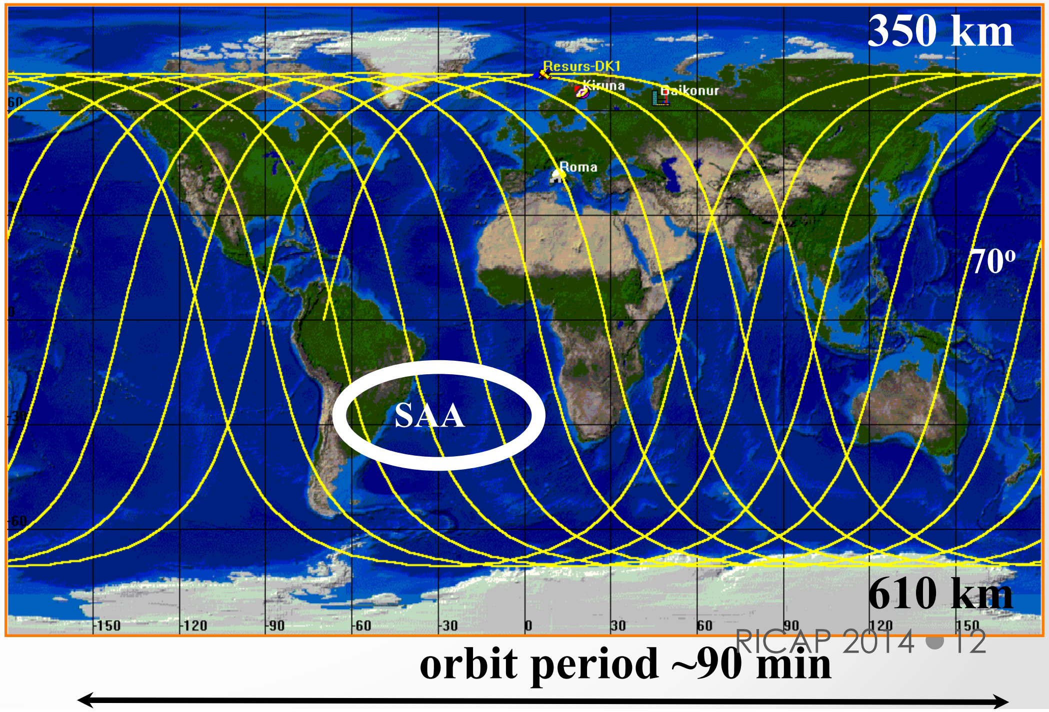
✧ (diffuse) photons need rejection power of ~10^6



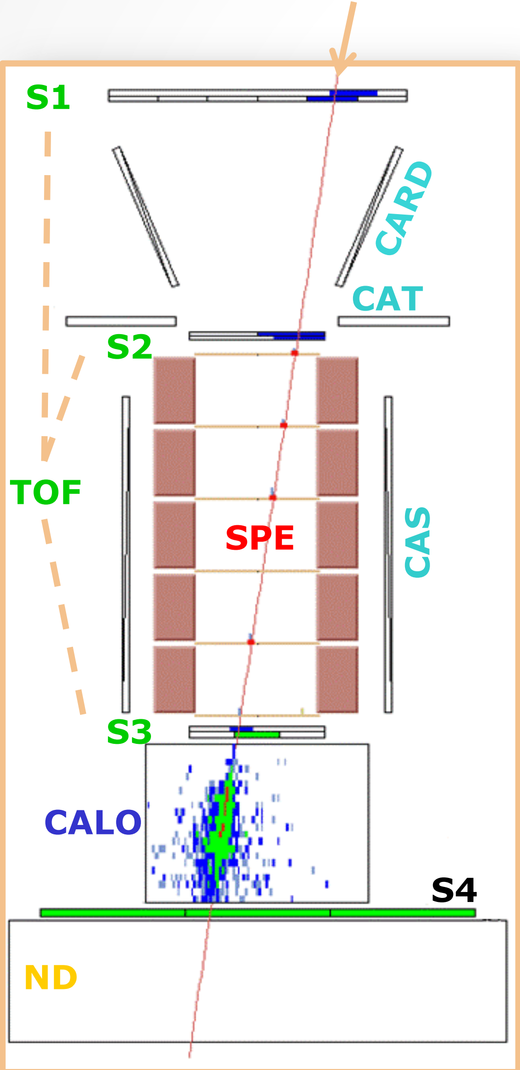
The first large scale space experiment: PAMELA

- PAMELA on board of Russian satellite **Resurs DK1**
- Launched on June 2006
- M ~ 470 kg
- A ~ 0.0024 m^2 sr

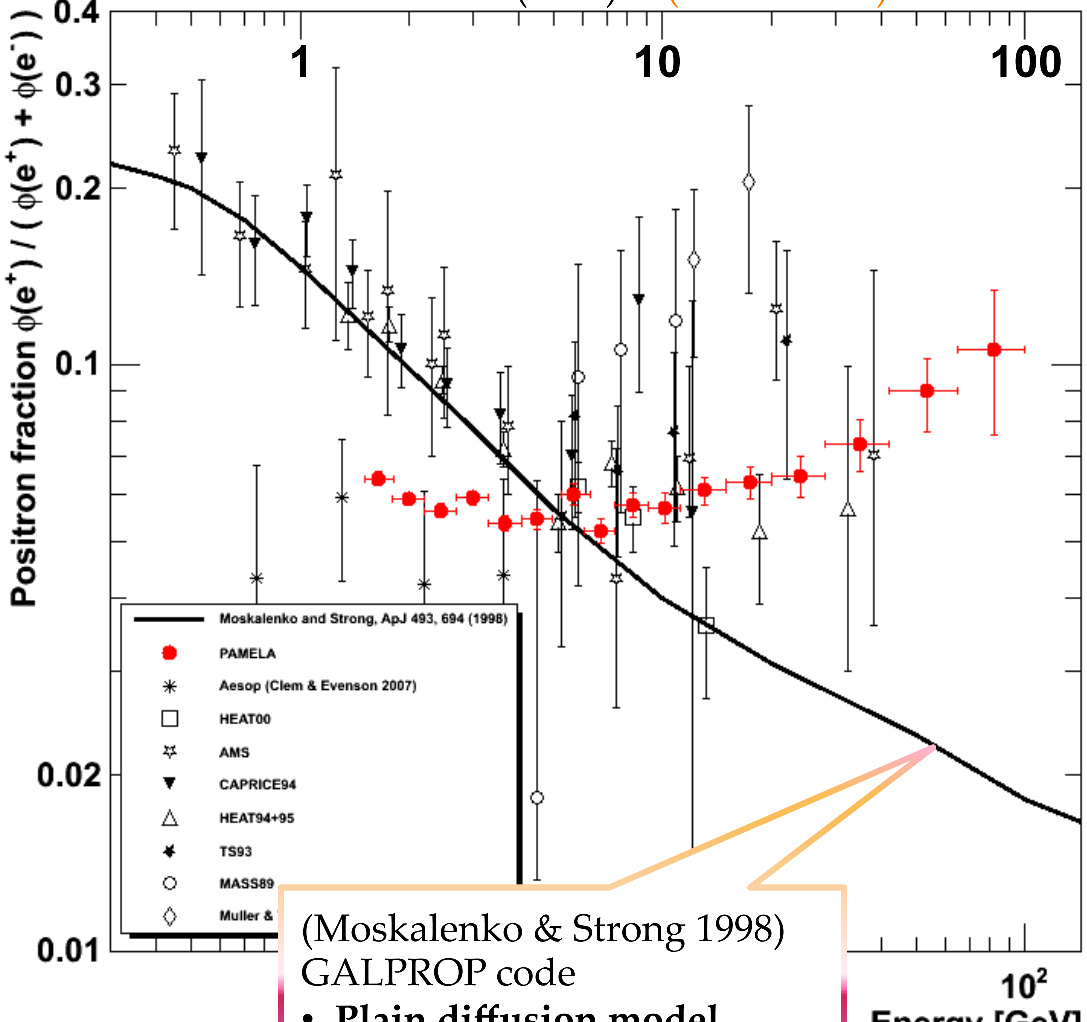




Fraction of positrons = $e^+/(e^++e^-)$



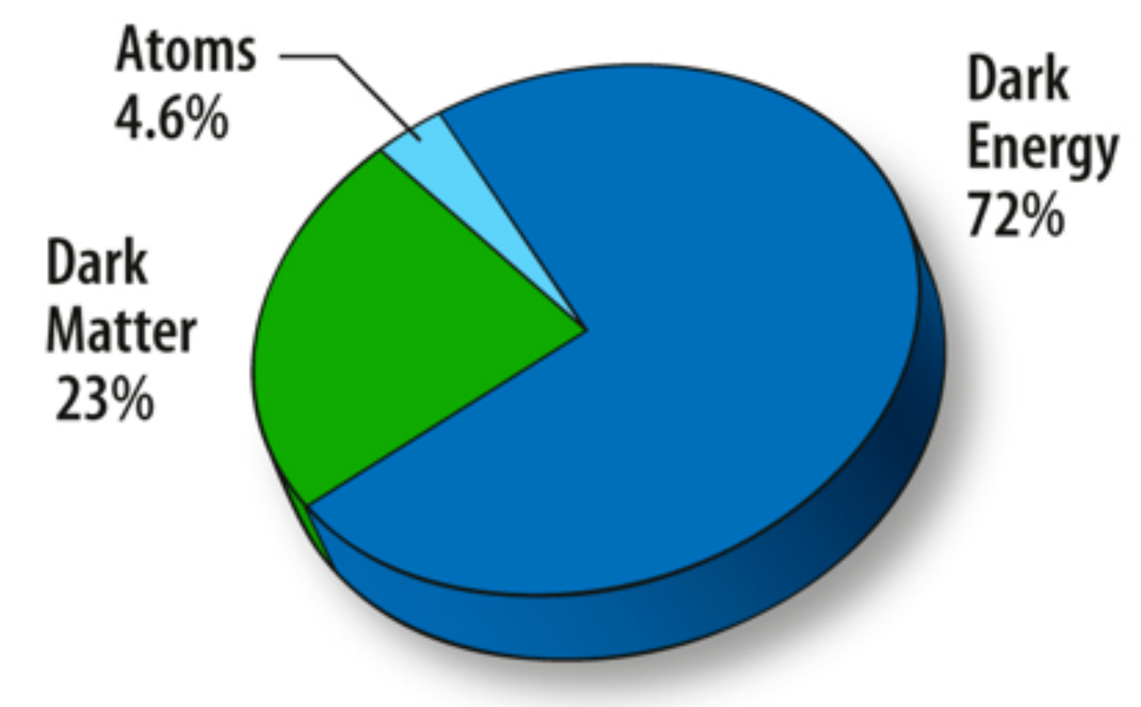
Adriani et al. – Nature 458 (2009) 607
Adriani et al. –AP 34 (2010) 1 (new results)



(Moskalenko & Strong 1998)
GALPROP code

- **Plain diffusion model**
- Interstellar spectra

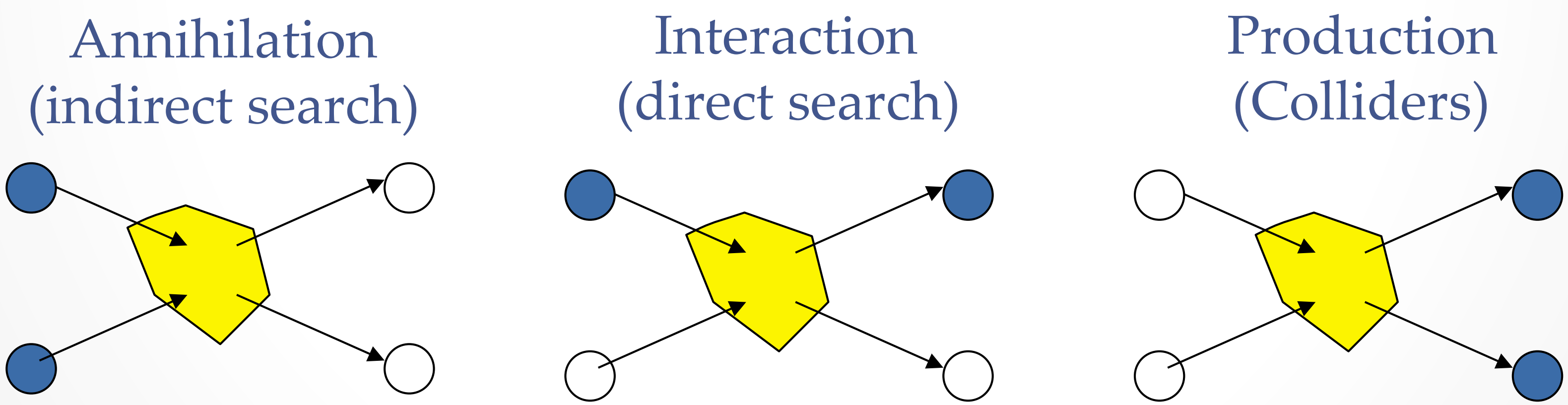
Excess of positrons as signal of Dark Matter?



- We know that Dark Matter exists, but:
  - What is DM made of?
  - What is the energy scale of DM?

WIMP Dark Matter

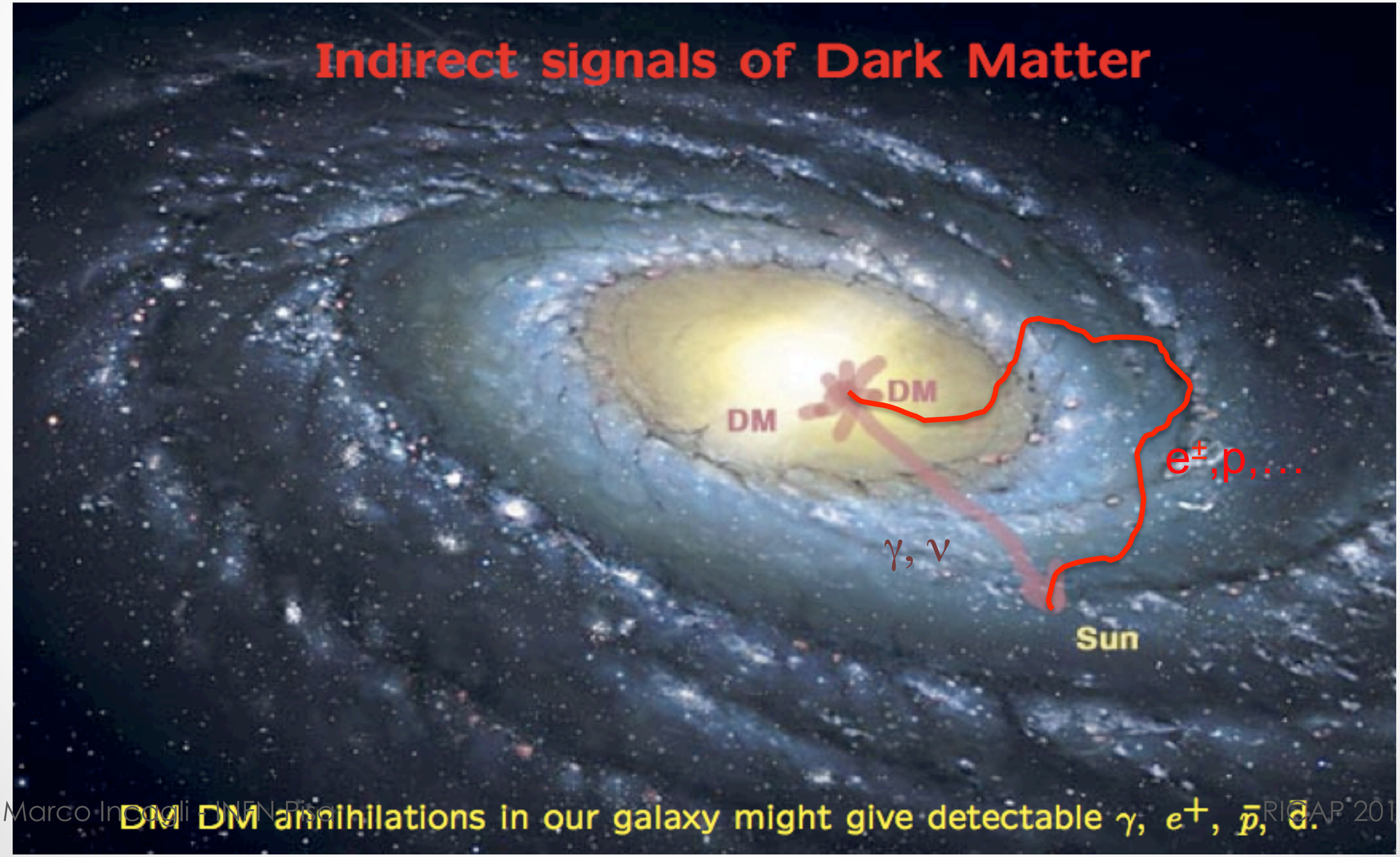
- Many solutions for DM, but the WIMPs (=Weakly Interacting Massive Particles) are special: singular coincidence between the parameters of the Standard Model and of the Cosmological Model to provide valid DM candidates at the electroweak scale (~TeV) with a cross section $\langle\sigma v\rangle \sim 3*10^{-26}\,cm^3s^{-1}$



● = DM (Dark Matter) ○ = SM (Standard Model)

Indirect search

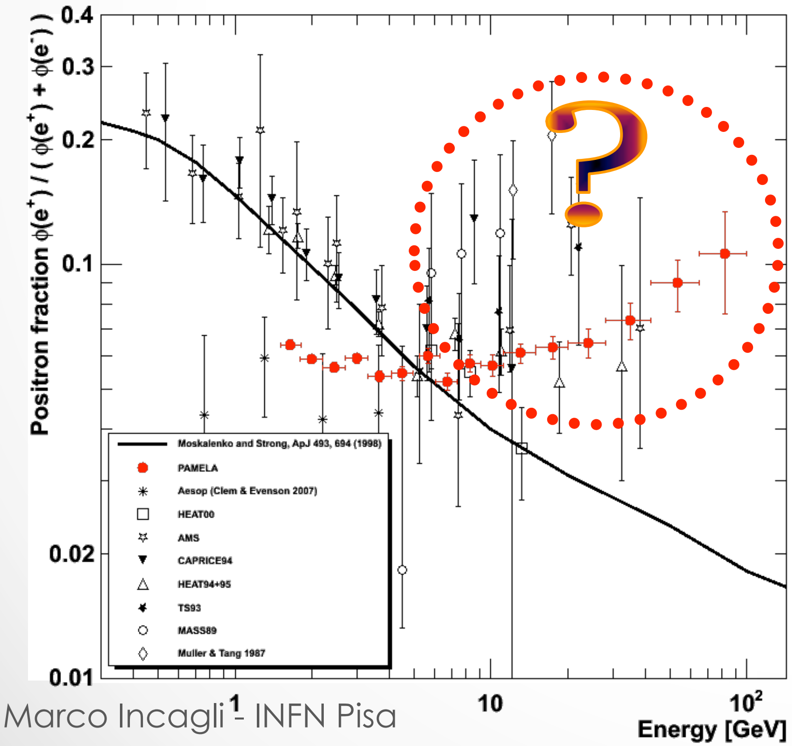
- If DM particles annihilate, an excess of (anti)particles wrt to standard production could be observed



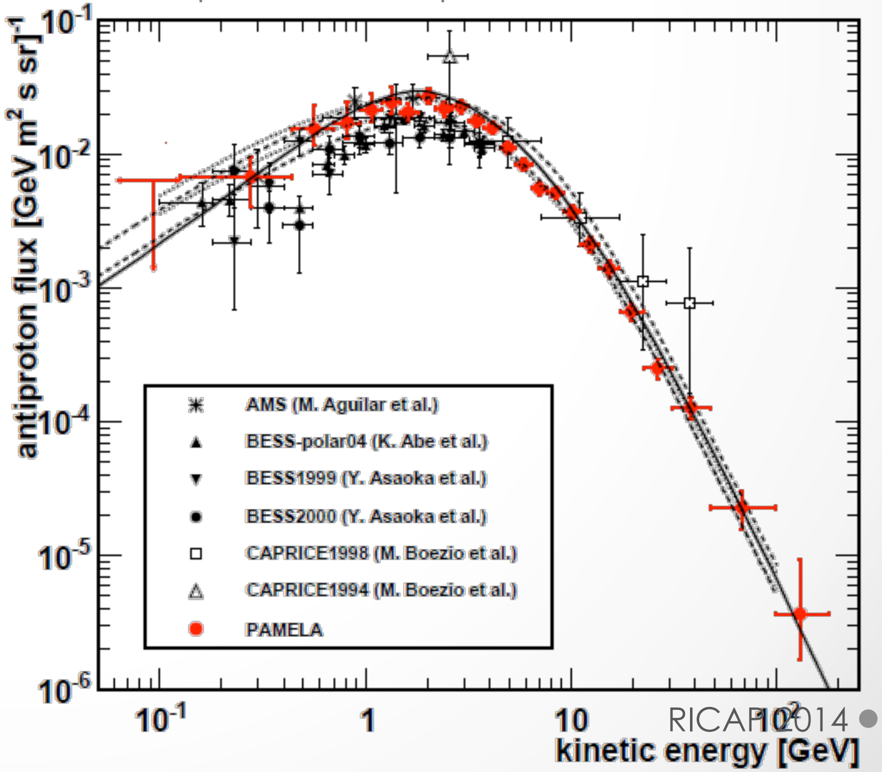
Positrons and anti-protons

- If the positron excess was due to *a "well-behaving" DM particle*, a similar effect should be seen in antiprotons
- Not observed by PAMELA → importance of measuring multiple channels

- Positrons
- → Evidence for an excess



- Antiprotons
- → Consistent with pure secondary production up to 180 GeV



- Excitement after PAMELA positron excess damped by
  - Absence (up to ~180 GeV) of similar excess in anti-protons → ad hoc theories (leptophilic DM)
  - Magnitude of the effect → need of important Boost Factors

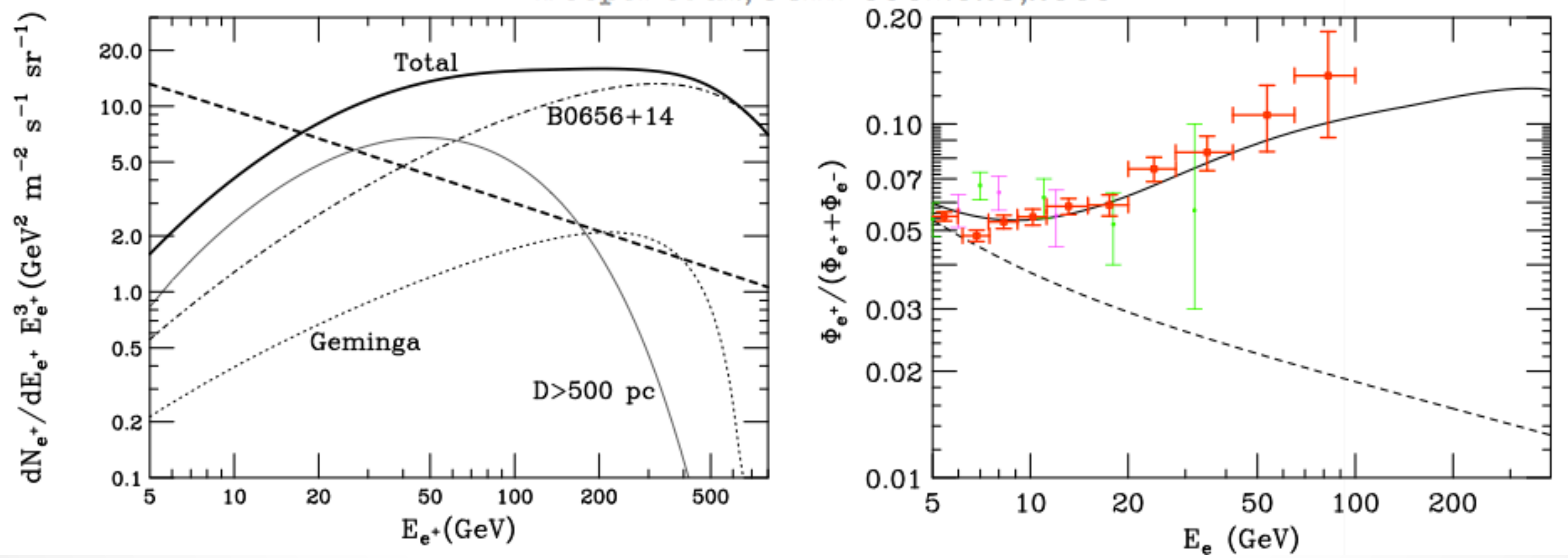
(more details during specific talks on friday morning)

- Alternative explanations of the positron excess based on Standard Cosmology:
  - Pulsars
  - Acceleration of secondaries in shock waves

Pulsars

- Neutron stars with magnetic axis at an angle wrt rotation axis
- Dipole emission with photons converting to e^+e^- pair (no protons/anti-protons emitted)

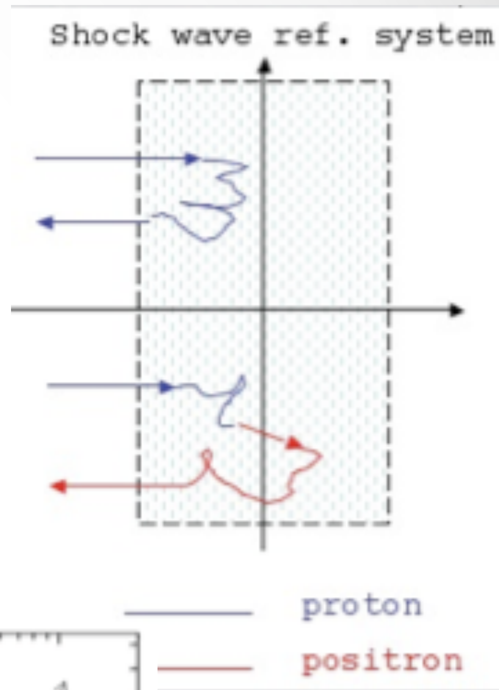
Hooper *et al.*, JCAP 0901:025,2009

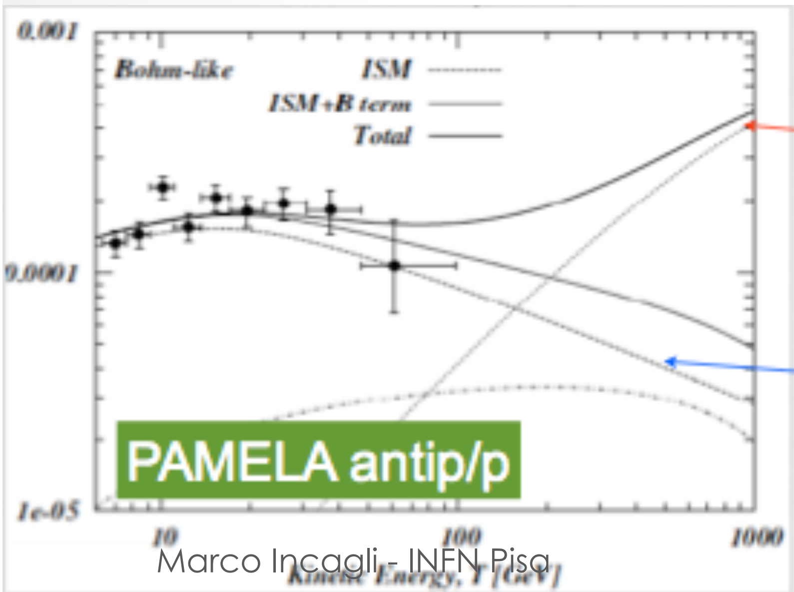


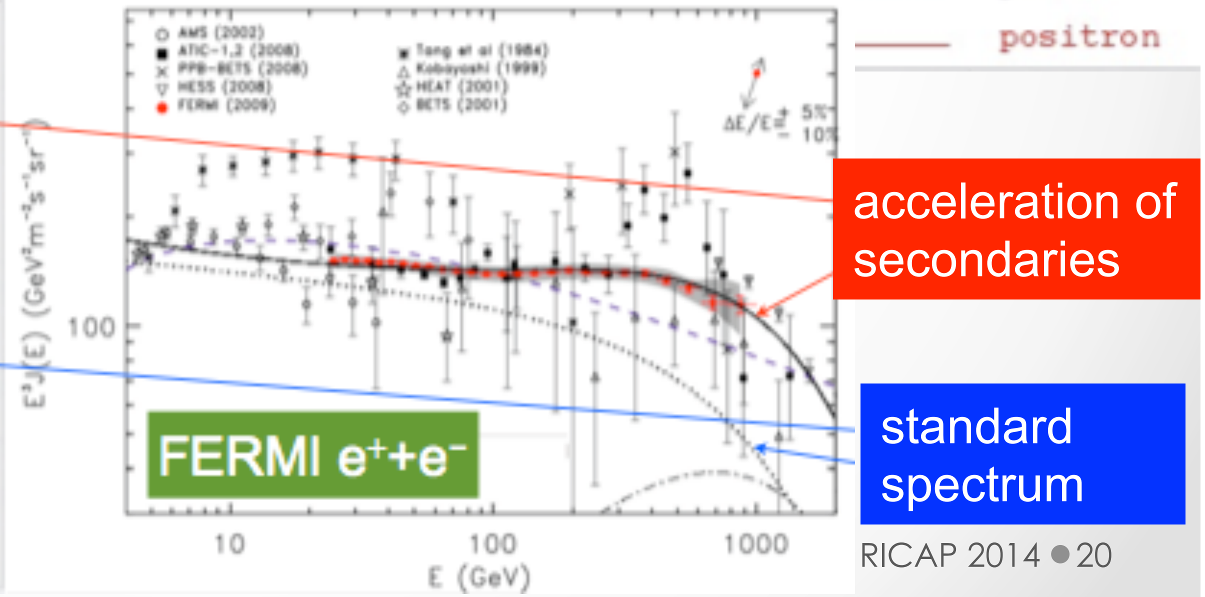
- Positron fraction can be reproduced with an energy cutoff at ~600GeV and production efficiency ~10 %

Acceleration of secondaries

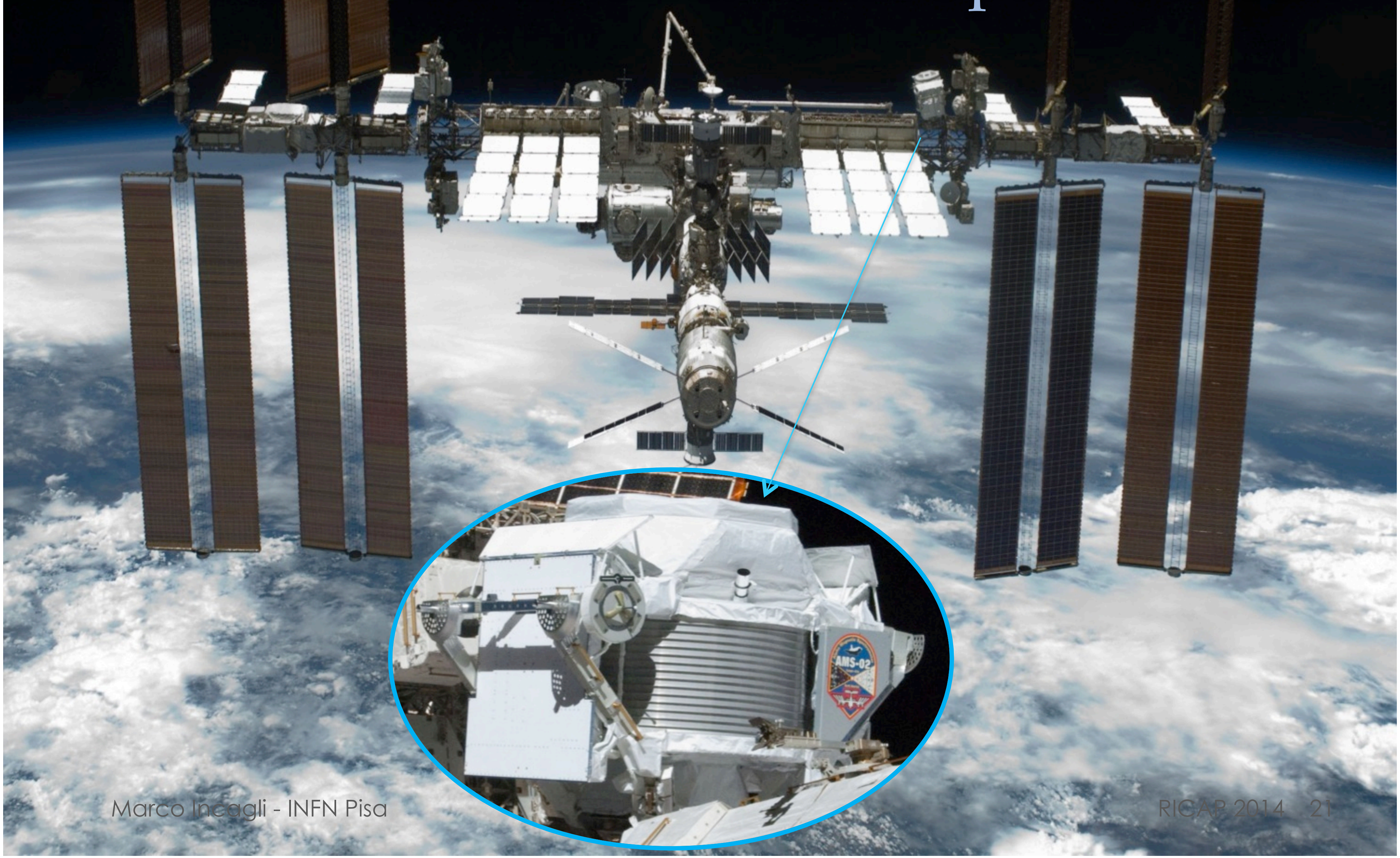
- **Fermi mechanism** : cosmic rays are accelarated in interactions with supernovae shock waves
- **Acceleration of secondaries** (*Blasi et al. PRL103 (2009) 051104*) : secondaries are produced *inside* the acceleration region
- This mechanism predicts an *excess in positrons but also in the anti-p/p and in B/C ratios*





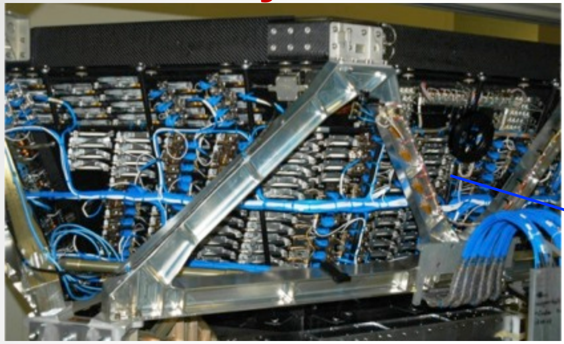


Need more precise measurements: AMS02 on the International Space Station

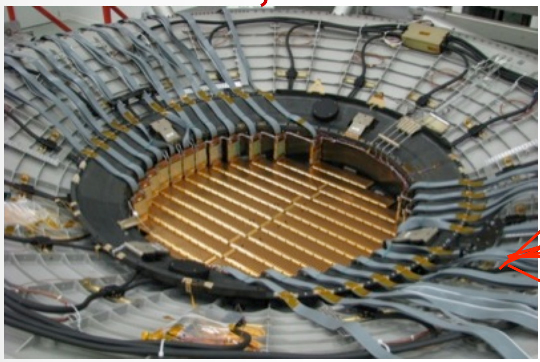


AMS02: a particle physics experiment in space

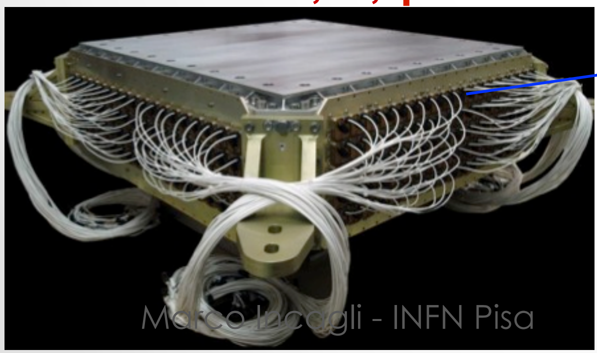
TRD
Identify e^+, e^-

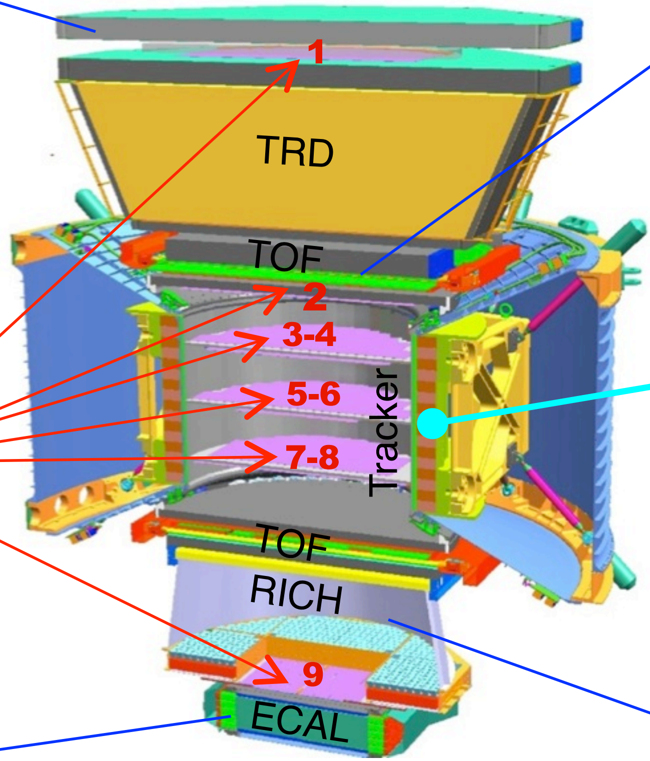


Silicon Tracker
Z, P



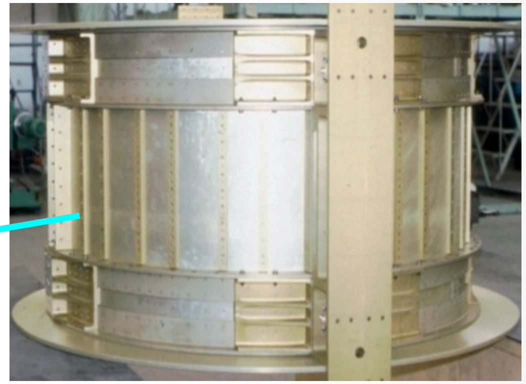
ECAL
E of e^+, e^-, γ





TOF
Z, E

Magnet
±Z

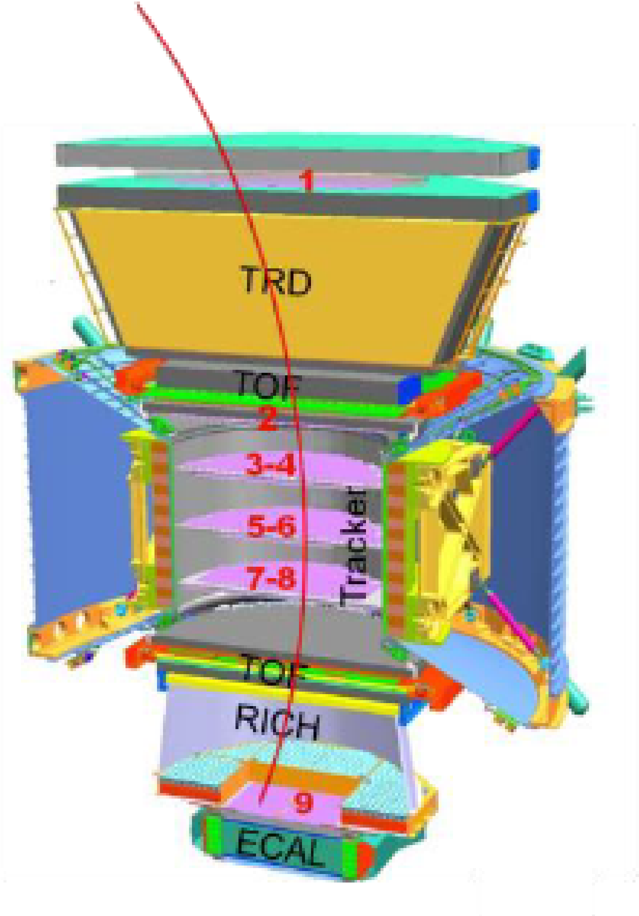


RICH
Z, E

Z, p (E) are measured by Tracker, RICH, TOF, ECAL
→ keyword: redundancy!

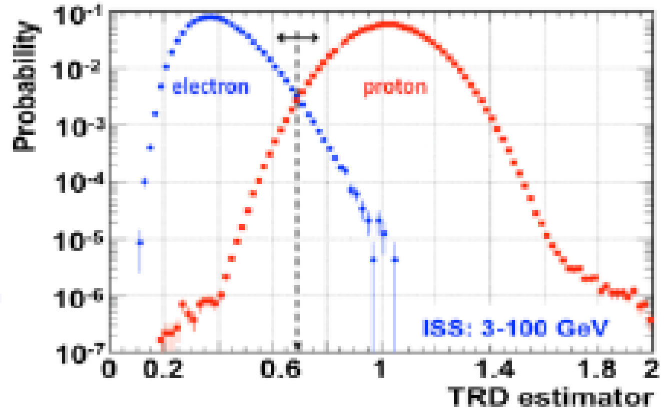
Electrons and positrons

Details on analysis in the talks of C.Pizzolotto and J.Bazo



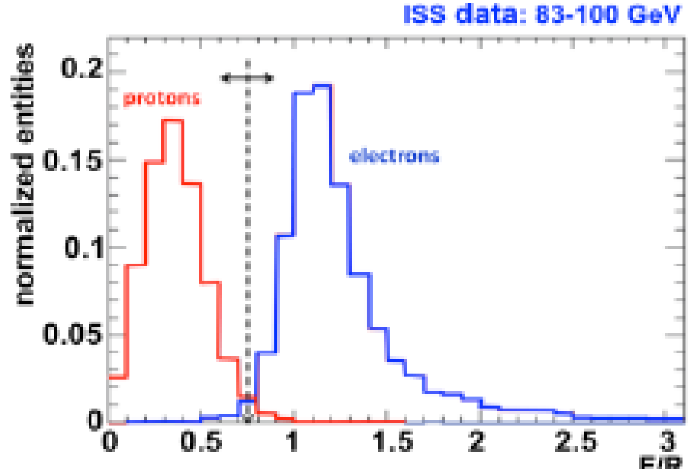
TRD

(transition radiation)



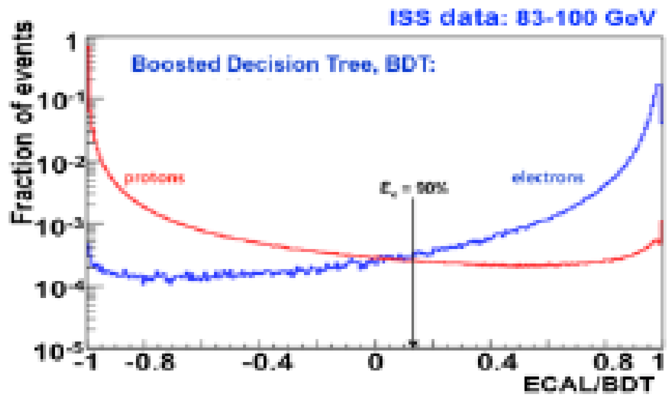
ECAL/Tracker

(E/p matching)



ECAL

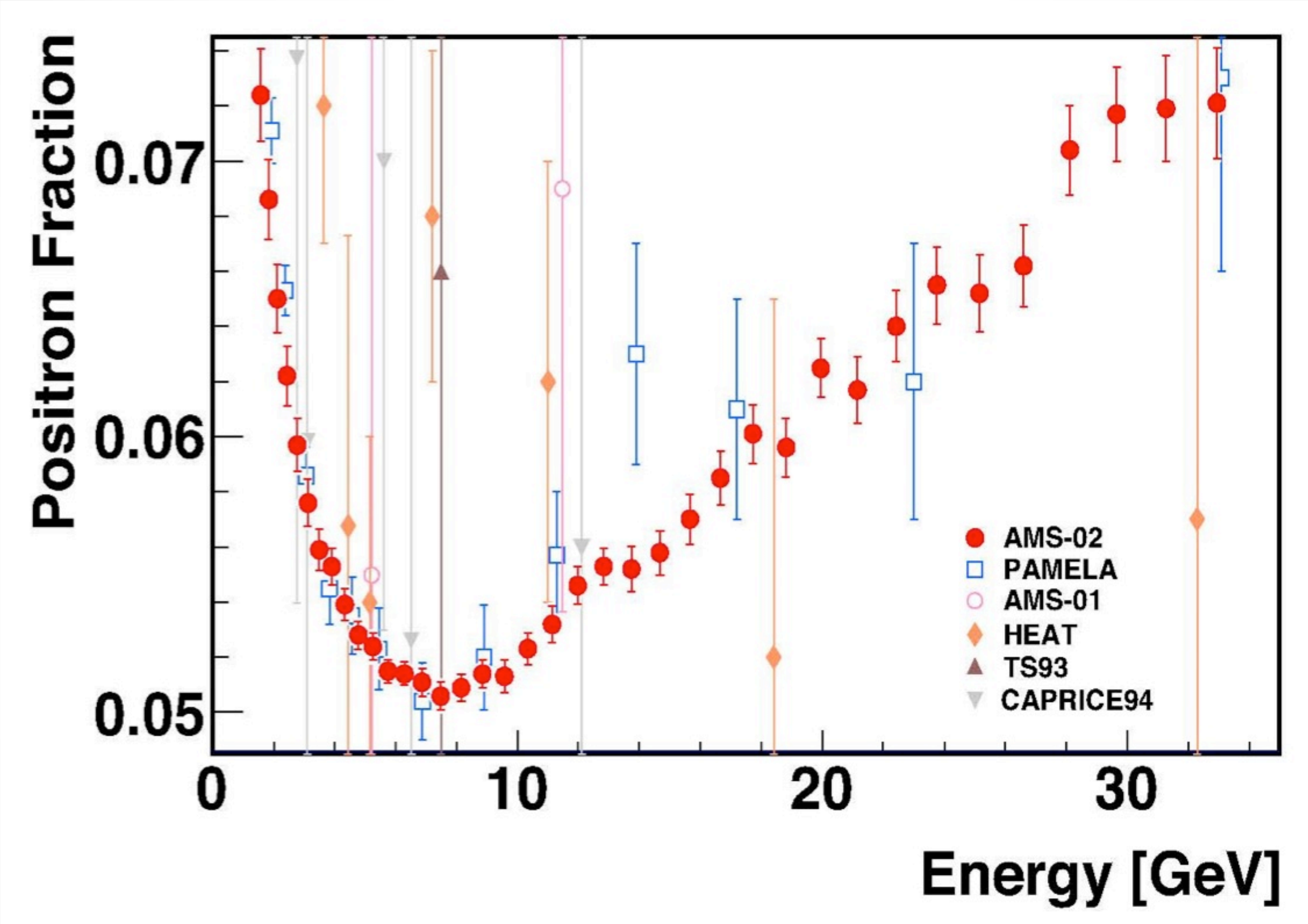
(shower shape)



Geometric acceptance:

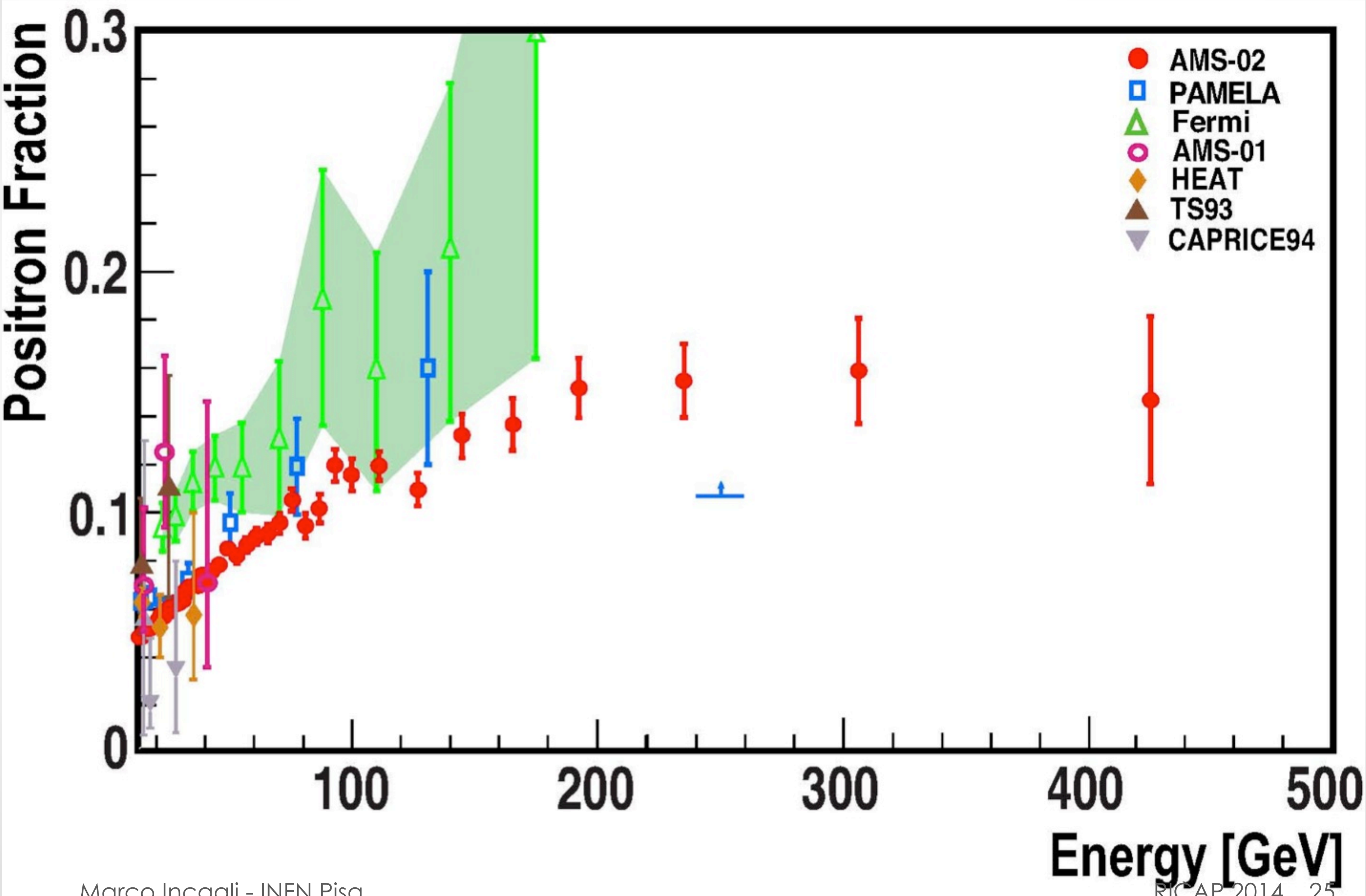
A ~ 550cm^{2}sr (= 0.055m^{2}sr)

Positron fraction E<35GeV

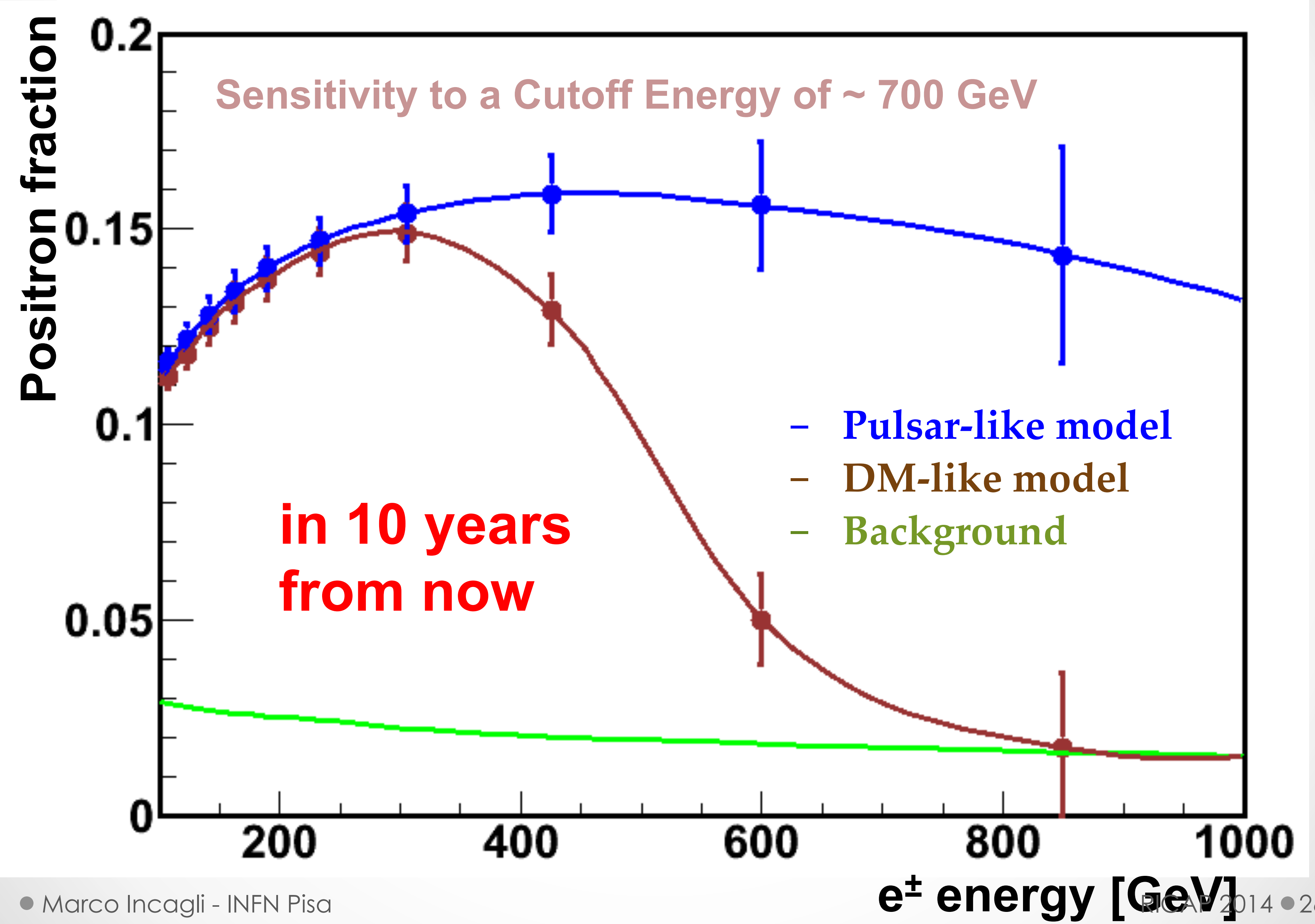


Minimum at $E = 8\ GeV$

High energy behavior E>15GeV



Projected AMS sensitivity on positron fraction



The flux measurement

- AMS02 has measured
  - e^+ flux up to 500 GeV
  - e^- flux up to 700 GeV
  - $e^+ + e^-$ flux up to 1000 GeV
- More ingredients are needed wrt positron fraction:

$$\Phi(E) = \frac{N(E, E+\Delta E)}{\Delta E \Delta T_{\text{exp}} A_{\text{eff}} \varepsilon_{\text{trig}}}$$

Φ = Absolute differential flux ($m^{-2}\, sr^{-1}\, GeV^{-1}$)

N = Number of observed events

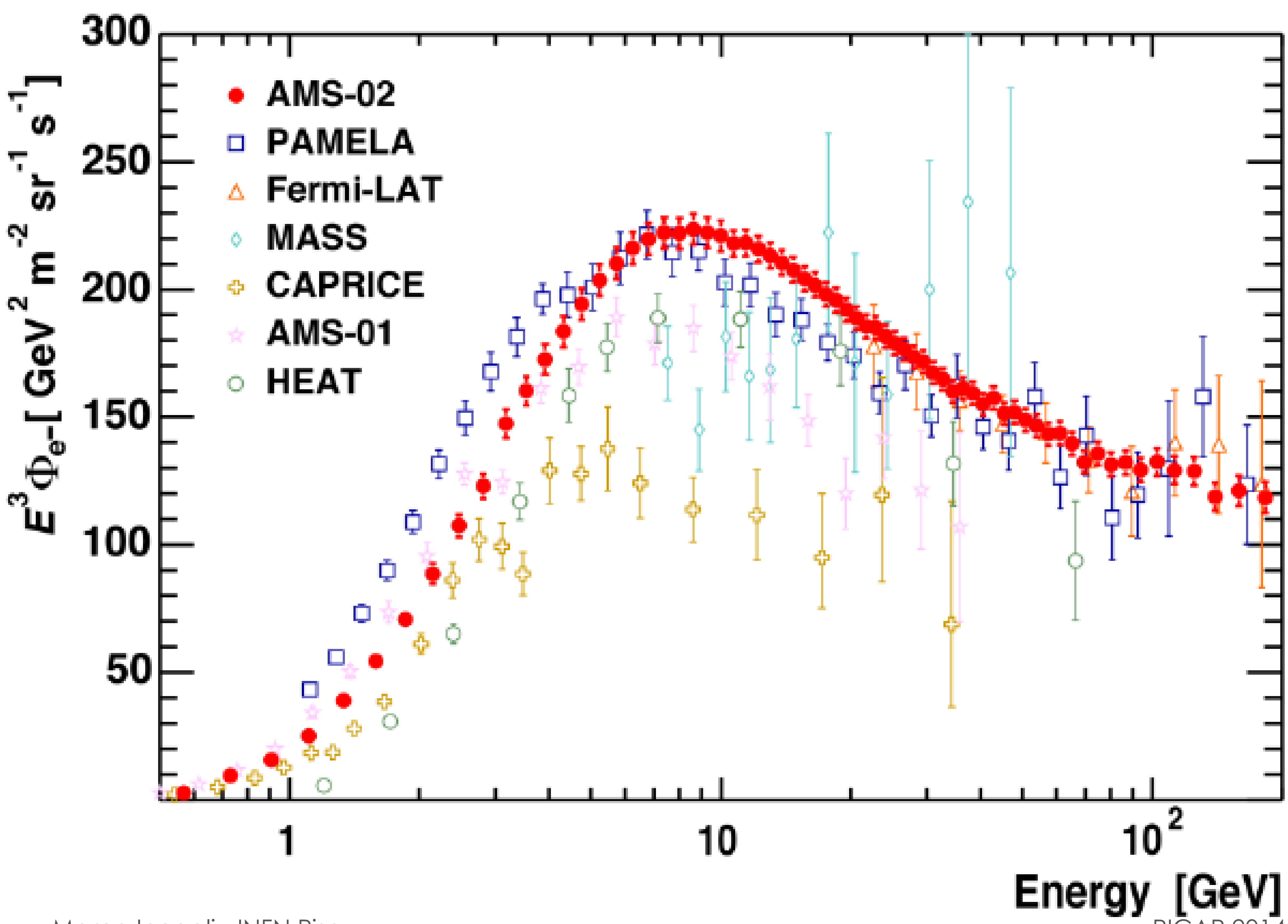
ΔT_{exp} = Exposure time (sec)

A_{eff} = effective acceptance ($m^2 sr$)

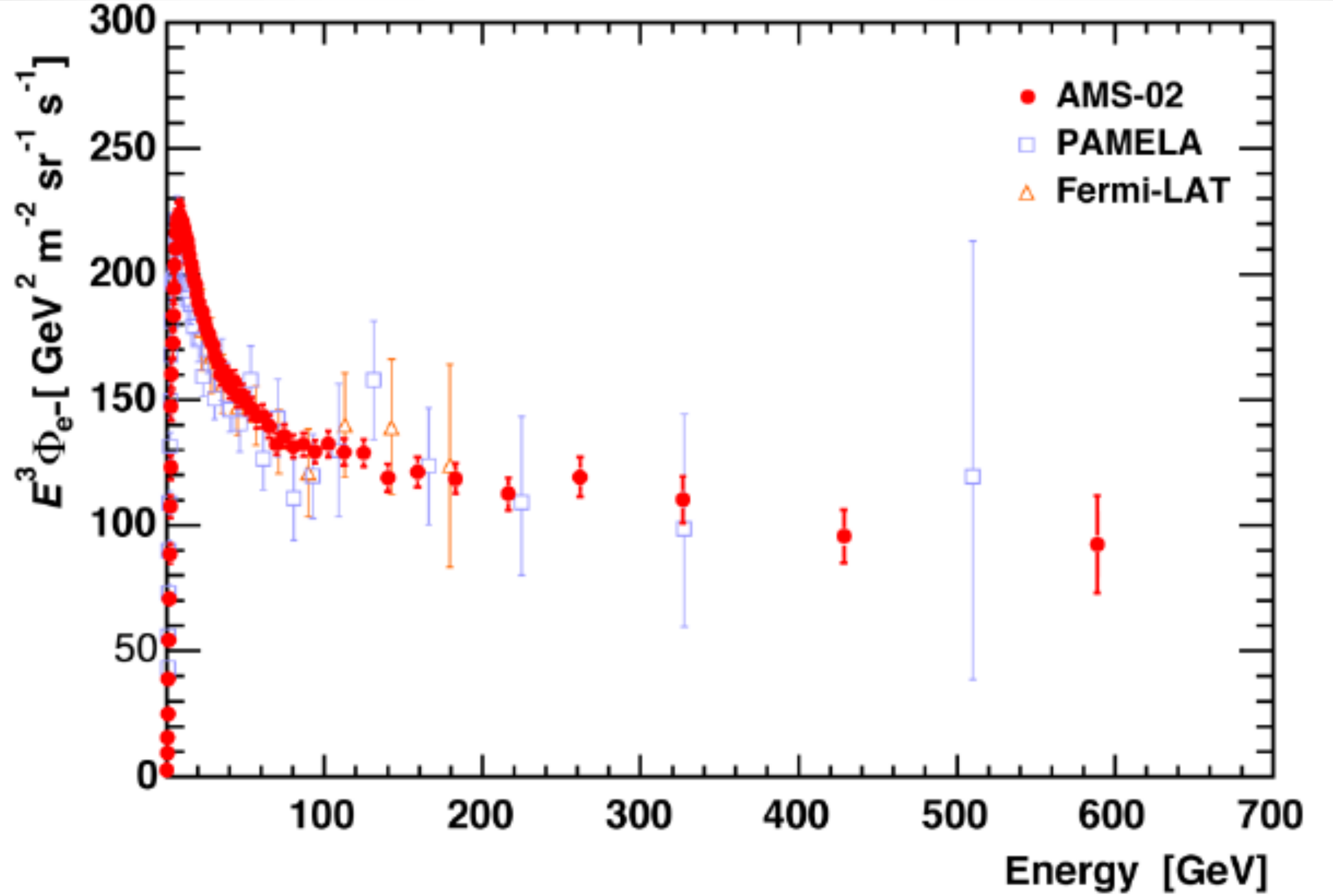
ε_{trig} = trigger efficiency

} **new ingredients** (ΔT_{exp}, A_{eff}, ε_{trig})

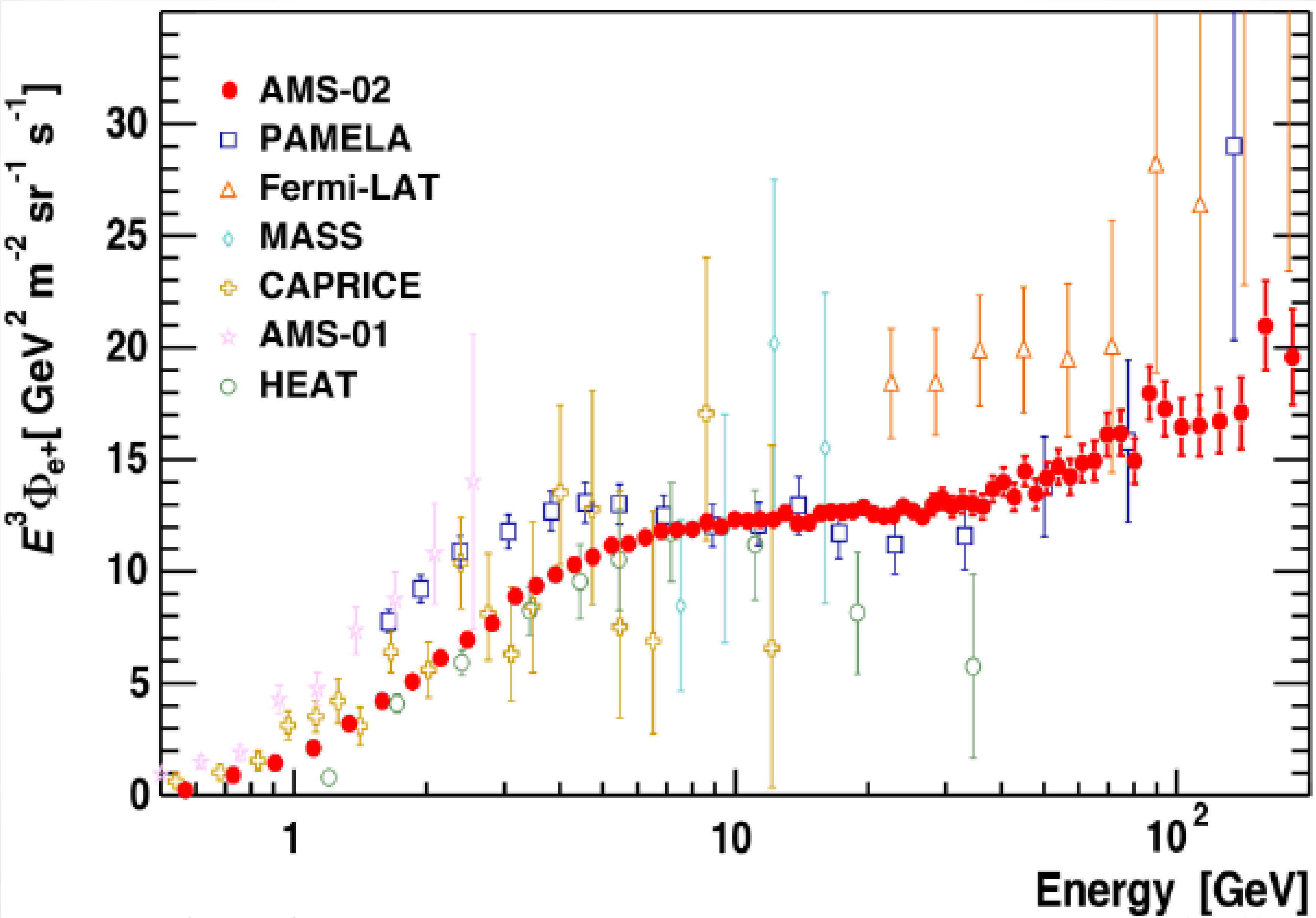
Electron flux – E<200GeV



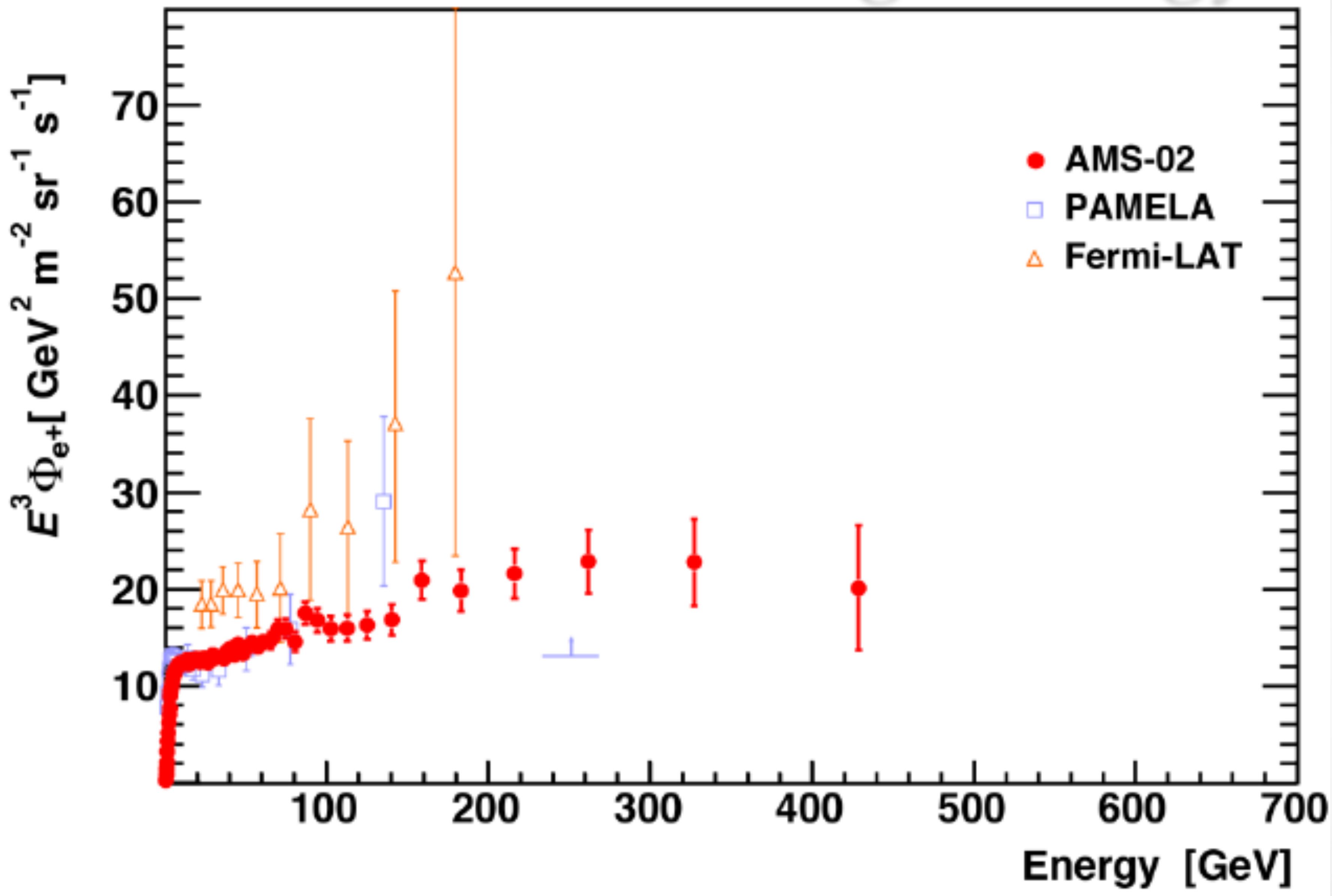
Electron flux – high energy

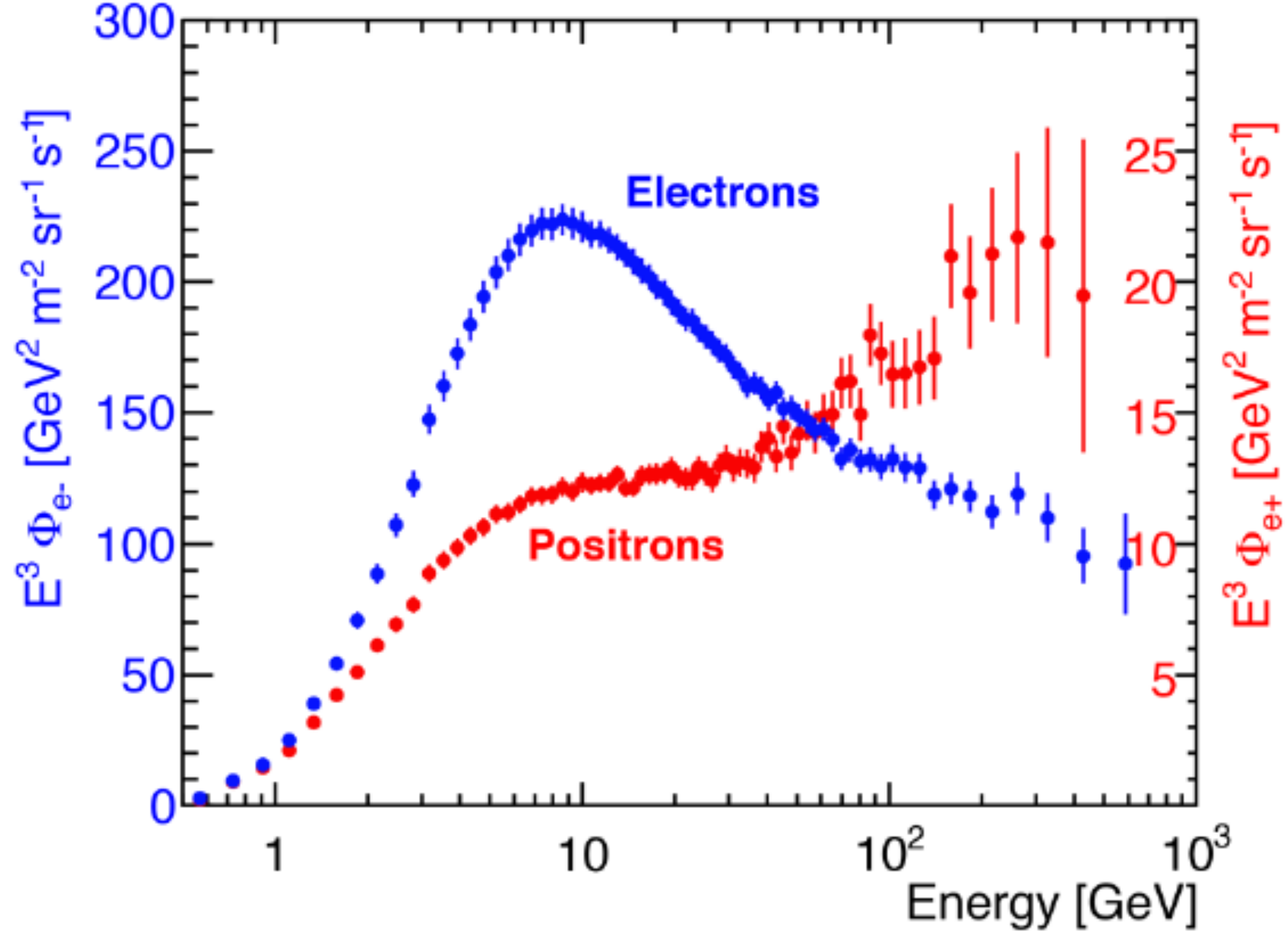


Positron flux – E<200GeV



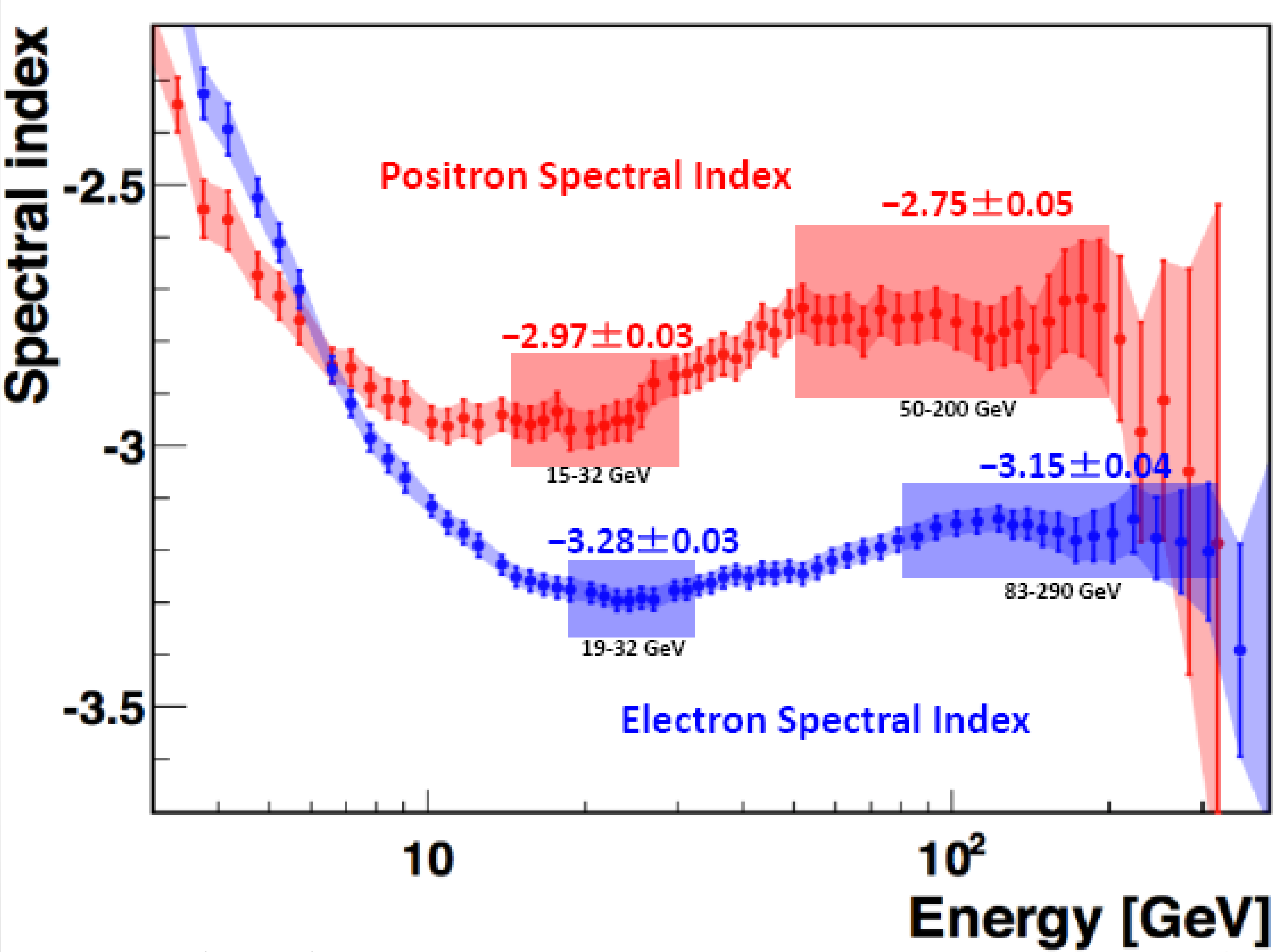
Positron flux – high energy





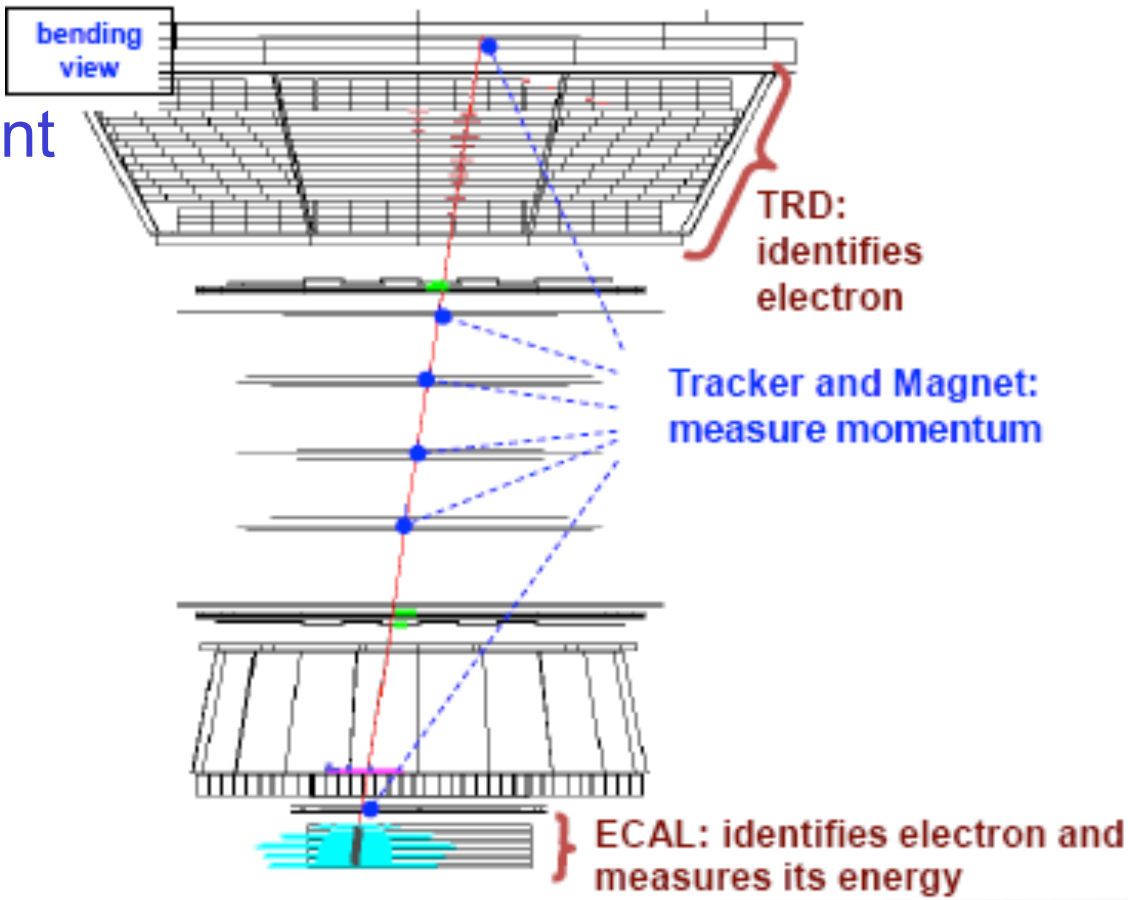
Conclusion: The electron flux and the positron flux are different in their magnitude and energy dependence.

Positron vs Electron index

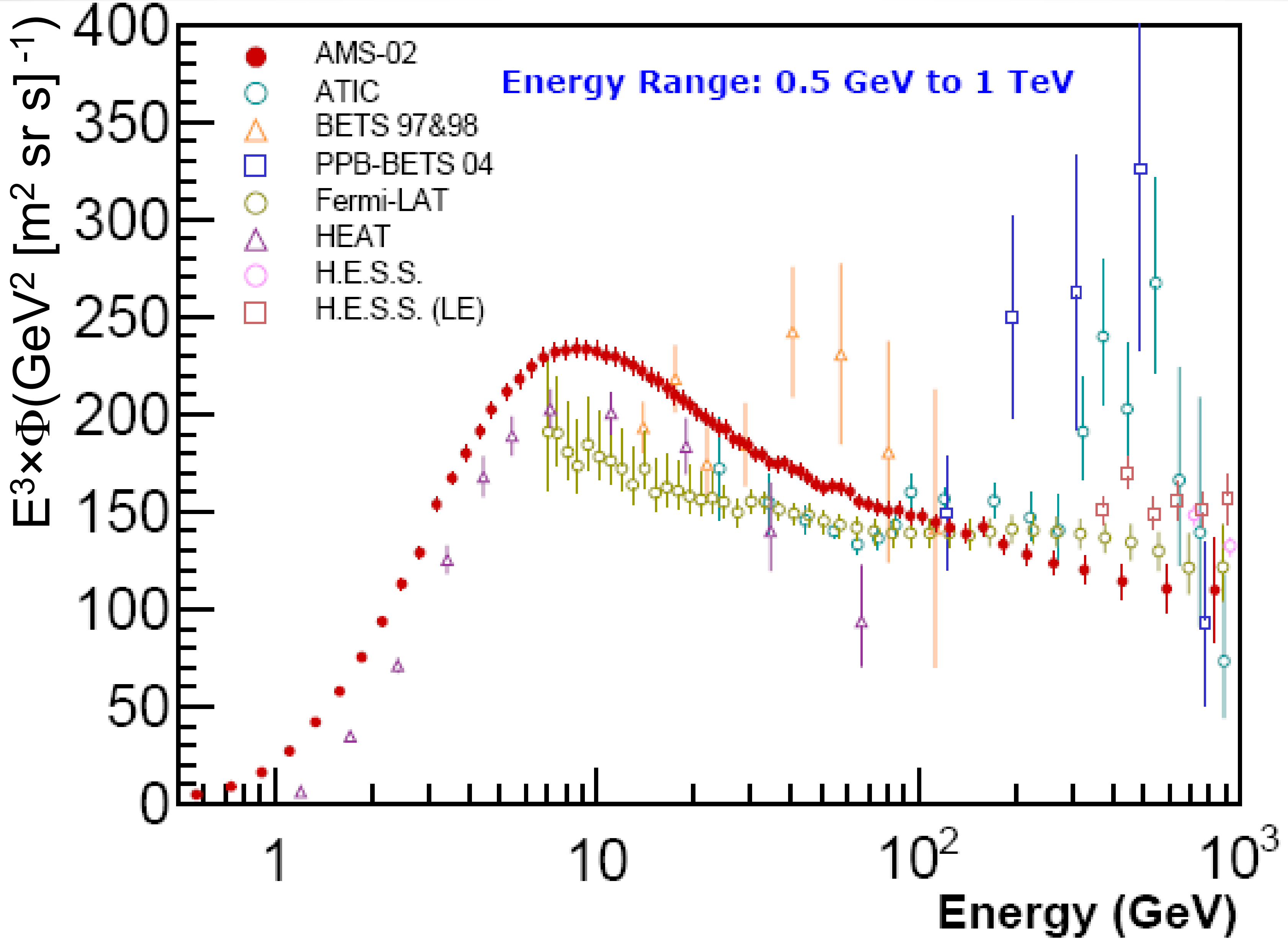


Combined $e^+ + e^-$ flux

- Calorimetric measurement
- TRD provides additional ep separation power
- No charge sign identification required → no charge confusion effects
- Can push the flux measurement to higher energies (up to 1 TeV)



Combined $e^+ + e^-$ flux

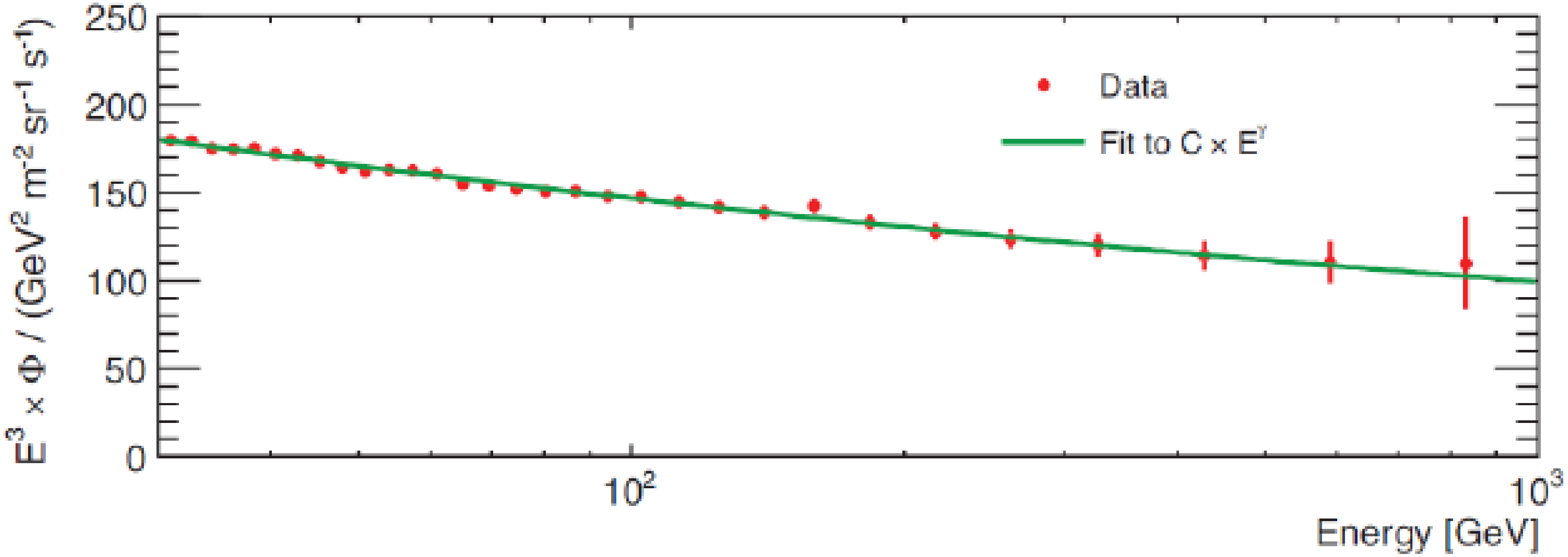


The flux is smooth and reveals new and distinct information.

$$\Phi(e^{+}+e^{-}) = C\,E^{\gamma}$$

$\gamma = -3.170 \pm 0.008$ (stat + syst.) ± 0.008 (energy scale)

$E > 30$ GeV



The flux is consistent with a single power law above 30 GeV

Minimal Model:

Diffuse Flux / Source Flux

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

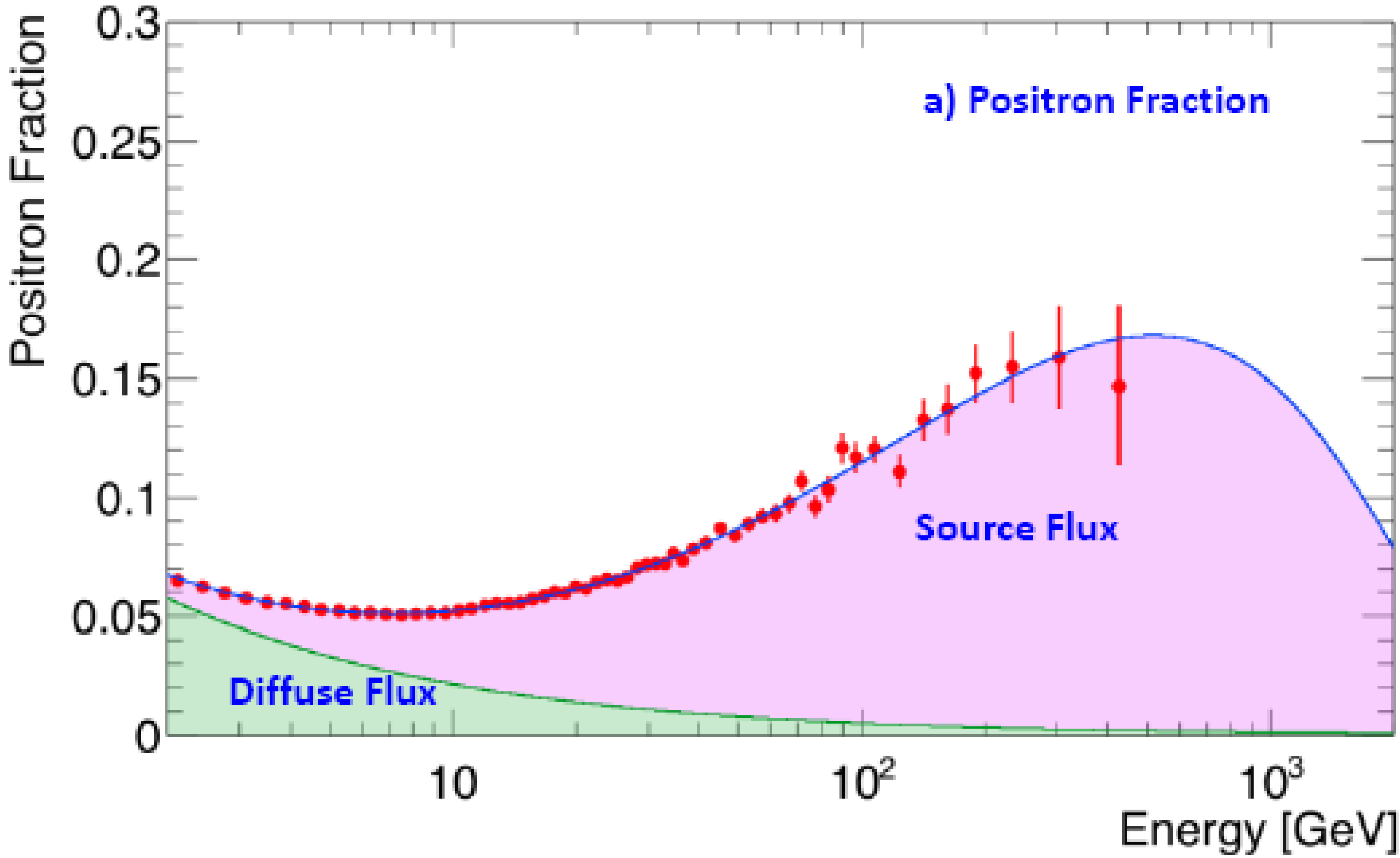
$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Fit to a) Positron Fraction from 2 GeV determines the relations:

$\gamma_{e-} - \gamma_{e+} = -0.63 \pm 0.06$, $\gamma_{e-} - \gamma_s = 0.66 \pm 0.05$,

$C_{e+} / C_{e-} = 0.095 \pm 0.003$, $C_s / C_{e-} = 0.008 \pm 0.001$

$1/E_s = 1.3 \pm 0.6\ \mathrm{TeV}^{-1}$



Minimal Model:

Diffuse Flux / Source Flux

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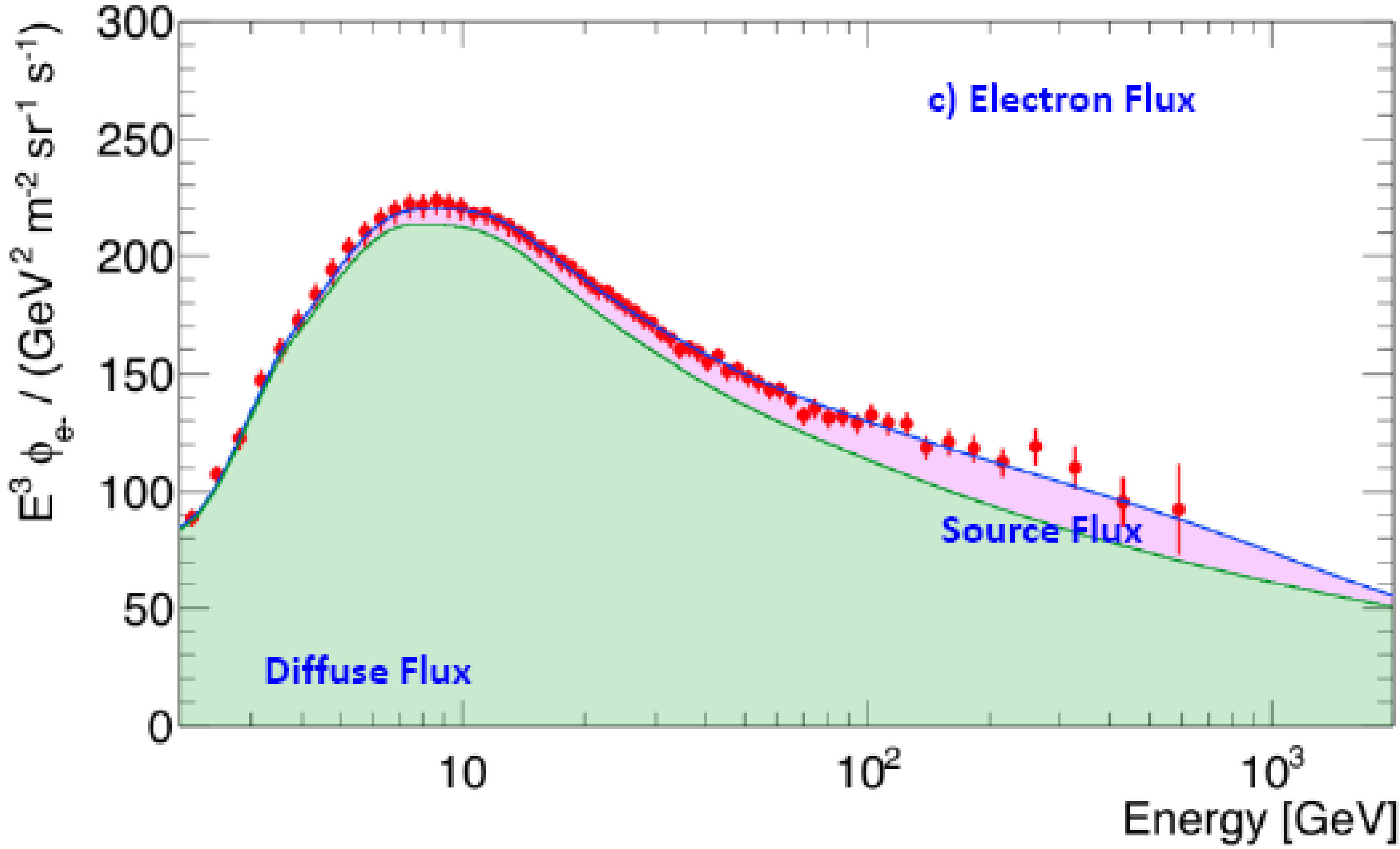
$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Prediction from fit it to a) Positron Fraction and b) Electron + Positron Flux



Minimal Model:

Diffuse Flux | Source Flux

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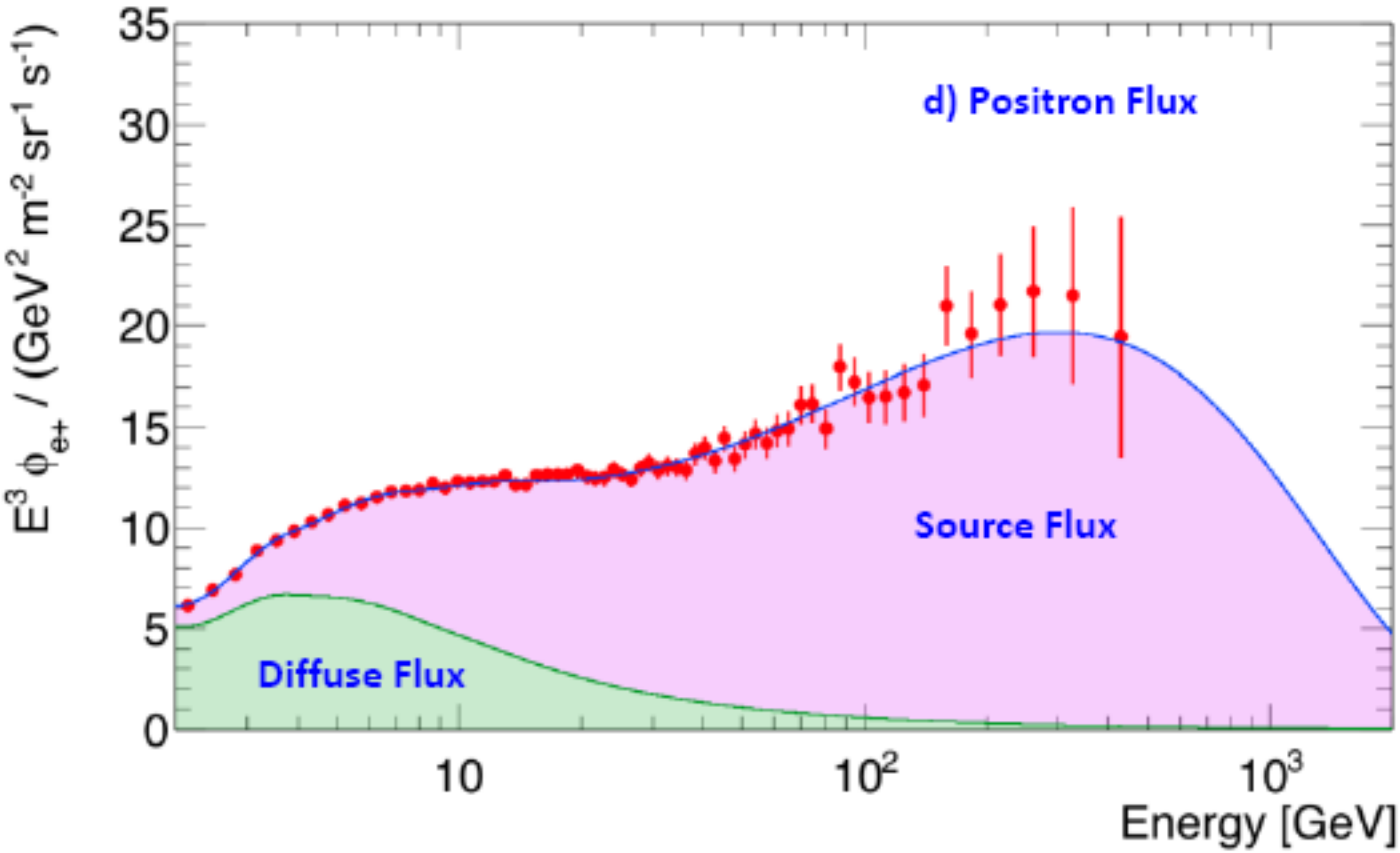

Minimal Model:

Diffuse Flux — Source Flux

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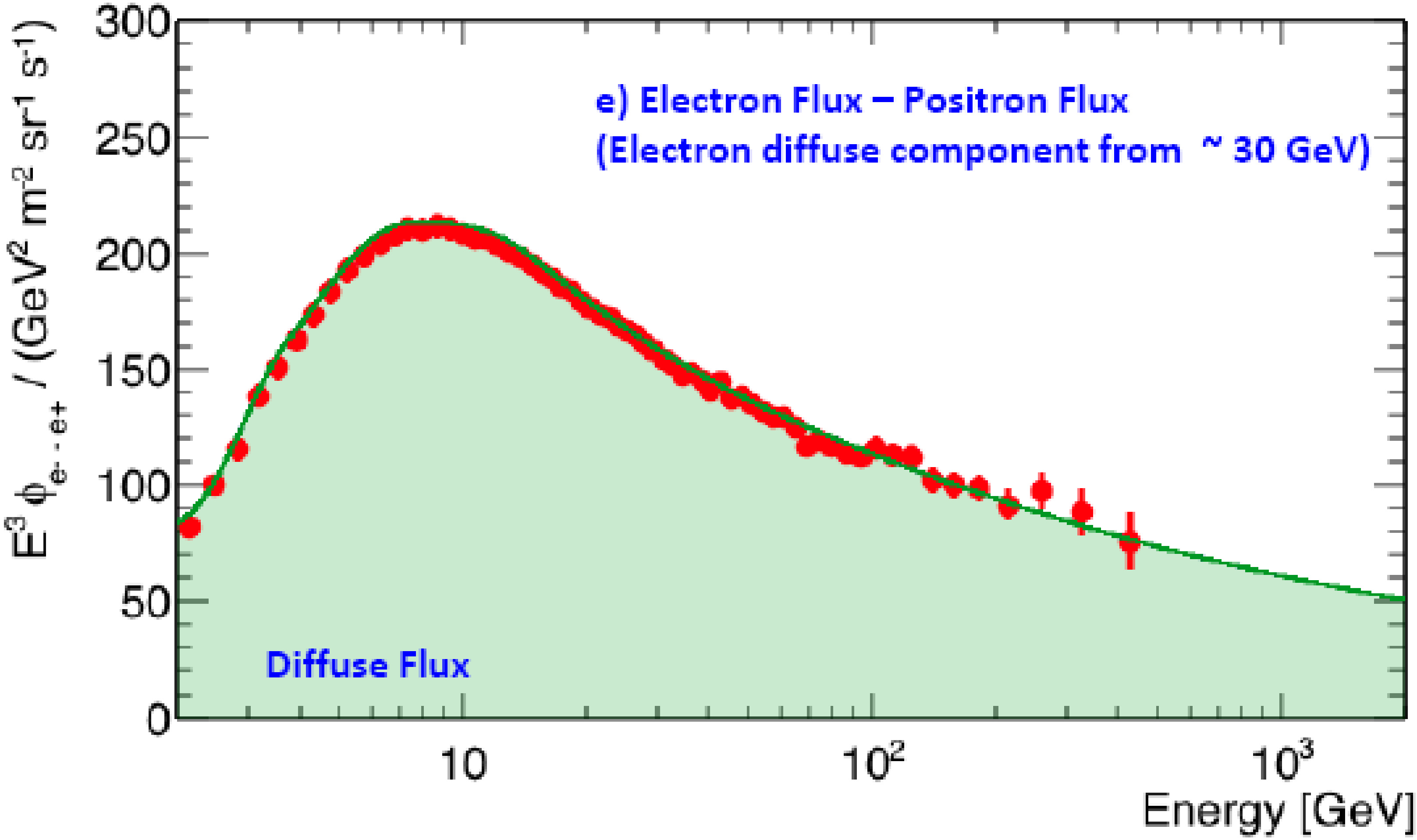
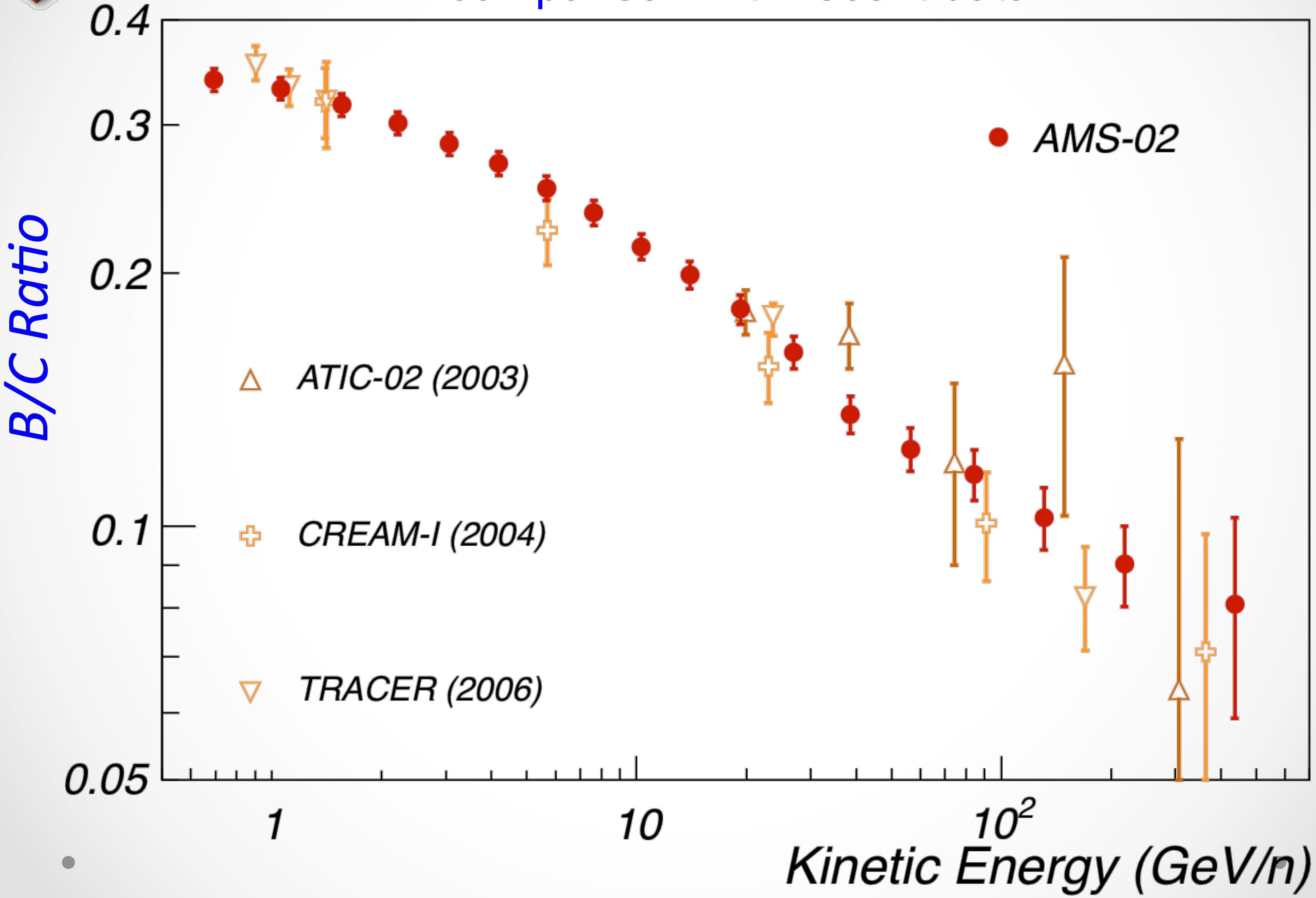


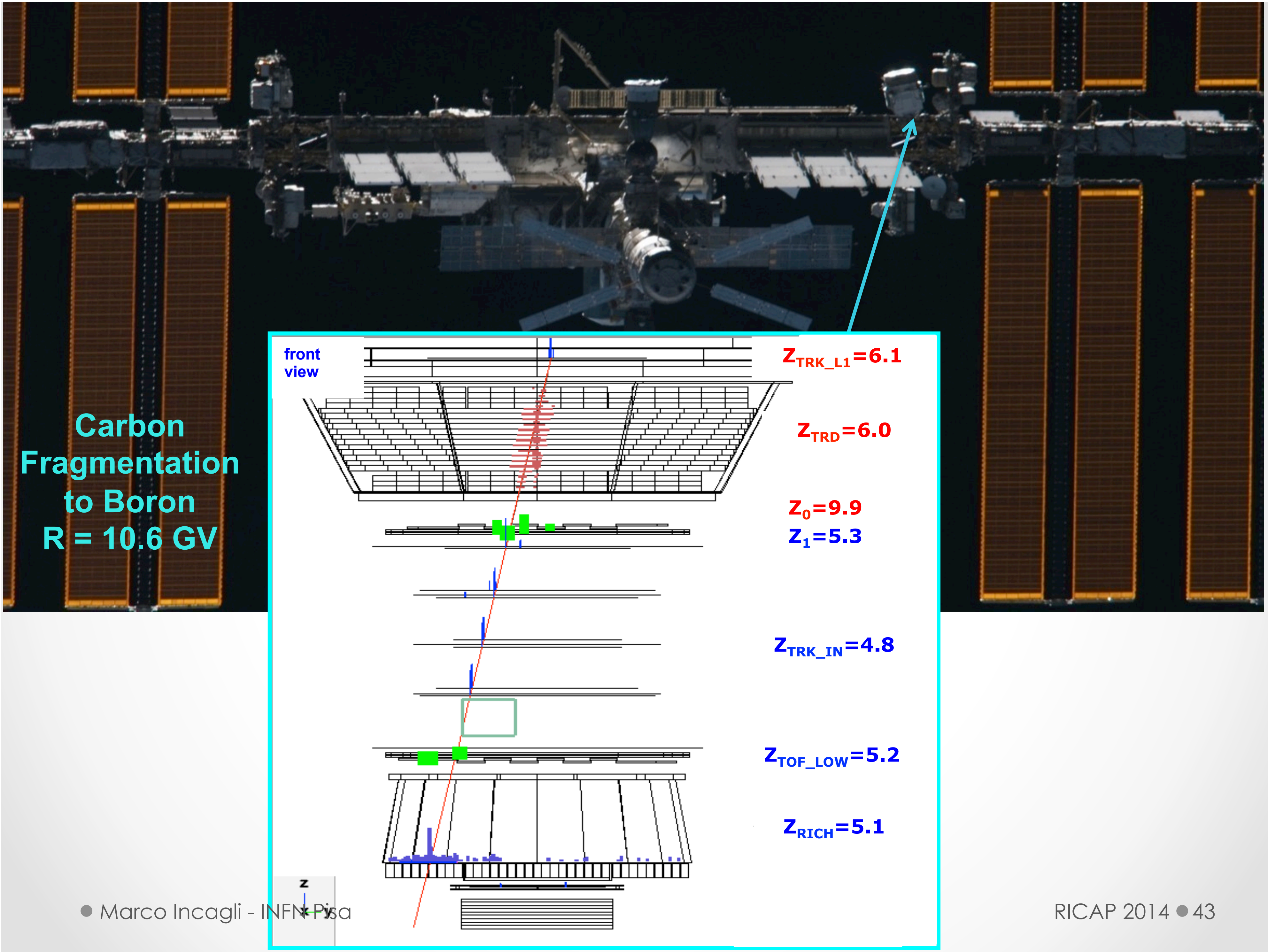
AMS02 results

- What have we learned from AMS02?
  - ... let the theorists do their homework!
  - More analyses are coming:
    - proton and helium flux
    - B/C, C/O and B, C, O fluxes
    - anti-protons
    - light nuclei and Nitrogen (Li, Be, N)
    - photons
    - heavier nuclei
    - isotopes ($^{3}He/^{4}He$, $^{10}Be/^{9}Be$)
    - anti-D
    - anti-He
    - ...

Boron-to-Carbon ratio (preliminary)

comparison with recent data

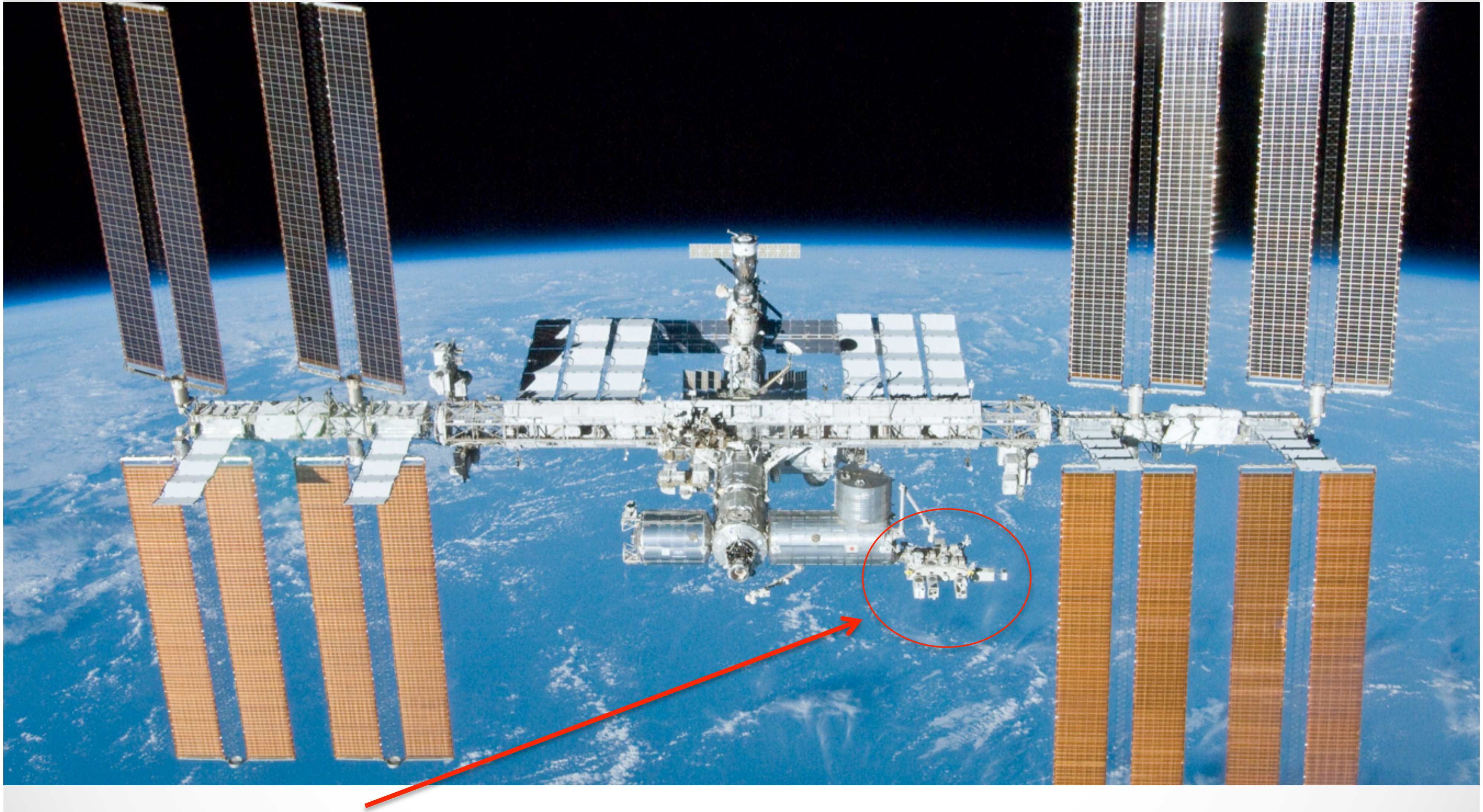



Carbon Fragmentation to Boron
R = 10.6 GV
front view
$Z_{TRK\_L1}=6.1$
$Z_{TRD}=6.0$
$Z_0=9.9$
$Z_1=5.3$
$Z_{TRK\_IN}=4.8$
$Z_{TOF\_LOW}=5.2$
$Z_{RICH}=5.1$
z

Future Cosmic Rays experiments in Space

Short term: 2015/16

- Experiments foreseen for the nearest future:
  - ISS CREAM
    - Japanese module of ISS
    - physics of nuclei in E = 10 GeV – 100 TeV
  - CALET
    - Japanese module of ISS
    - electrons/photons in E = 5 GeV – 10 TeV
  - DAMPE
    - chinese satellite
    - electrons/photons in E = 10 GeV – 10 TeV
- All these detectors are of *calorimetric type*



- The "terrace" of the Japanese KIBO module where CALET and ISS-CREAM will be installed

ISS-CREAM

- CREAM balloon detector, with (major) modifications
- Core of the instrument:
  - calorimeter (0.5 λ_{int}) with *carbon target in front for hadron energy measurement*
  - Silicon layers for charge (Z) measurement
- launch: 2016
- physics goal:
  - cosmic ray composition (Z=1-26) in the energy range 10^{10}-10^{14} eV
  - determination of parameters for CR propagation
  - not a *DM-search experiment*

CALET

- Instrument:
  - calorimeter with 30 X_0
  - geometric acceptance 0.11 m^2sr (2-3 × AMS02)
- launch: 2015
- main physics goal:
  - electron(e^++e^-) spectrum 1 GeV – 20 TeV
  - gamma spectrum 4 GeV – 10 TeV

- Extend the spectrum of all electrons (e^++e^-) wrt AMS02 and Fermi
- Some hope for gamma-line search (acceptance?)

DAMPE

- instrument:
  - calorimeter with $31X_0$
  - geometrical acceptance = 0.2-0.3 m^2 sr
- launch: second half 2016
- main physics goals:
  - electron/gamma spectrum 5 GeV – 10 TeV

- large overlap with the physics of CALET

Personal comments

- CALET, DAMPE (focused on electrons/photons):
  - limited increase in acceptance wrt AMS02, with similar energy resolution
  - improved energy resolution wrt FERMI, but smaller acceptance (factor 5-10)
- ISS-CREAM (focused on nuclei):
  - characterized by a passive carbon target on top of the calorimeter → access to hadron energy

- (In My Humble Opinion) none of them is a real breakthrough, or a "*next generation*" space experiment, although interesting information will be collected

medium term projects (≥ 2020)

- GAMMA400
  - on a russian satellite at h~150,000 km
  - Gamma ray telescope (converter-tracker) possibly with a high acceptance calorimeter (A≥1 m^2sr calocube technique)
- Experiment on board of Chinese Space Station
  - calorimetric option: HERD
    - some activity on detector design already started (calocube technique approved)
  - magnetic spectrometer option: AMS03
    - conceptual design, only

Conclusions

- Space experiments have made possible a new era of Precision Measurements of CRs
- (Probably) the best way to study the DM-WIMP region (M_χ = 10 GeV – 10 TeV) ...
- ... BUT not very encouraging results so far!
- *Calorimetric detectors* maximize the Geometrical Acceptance → best way to study the properties of charged Cosmic Rays (nuclei) up to the knee
- ... BUT no access to anti-particles!
- Experiments foreseen in the near future (2015-2016)
- More ambitious programs for >2020