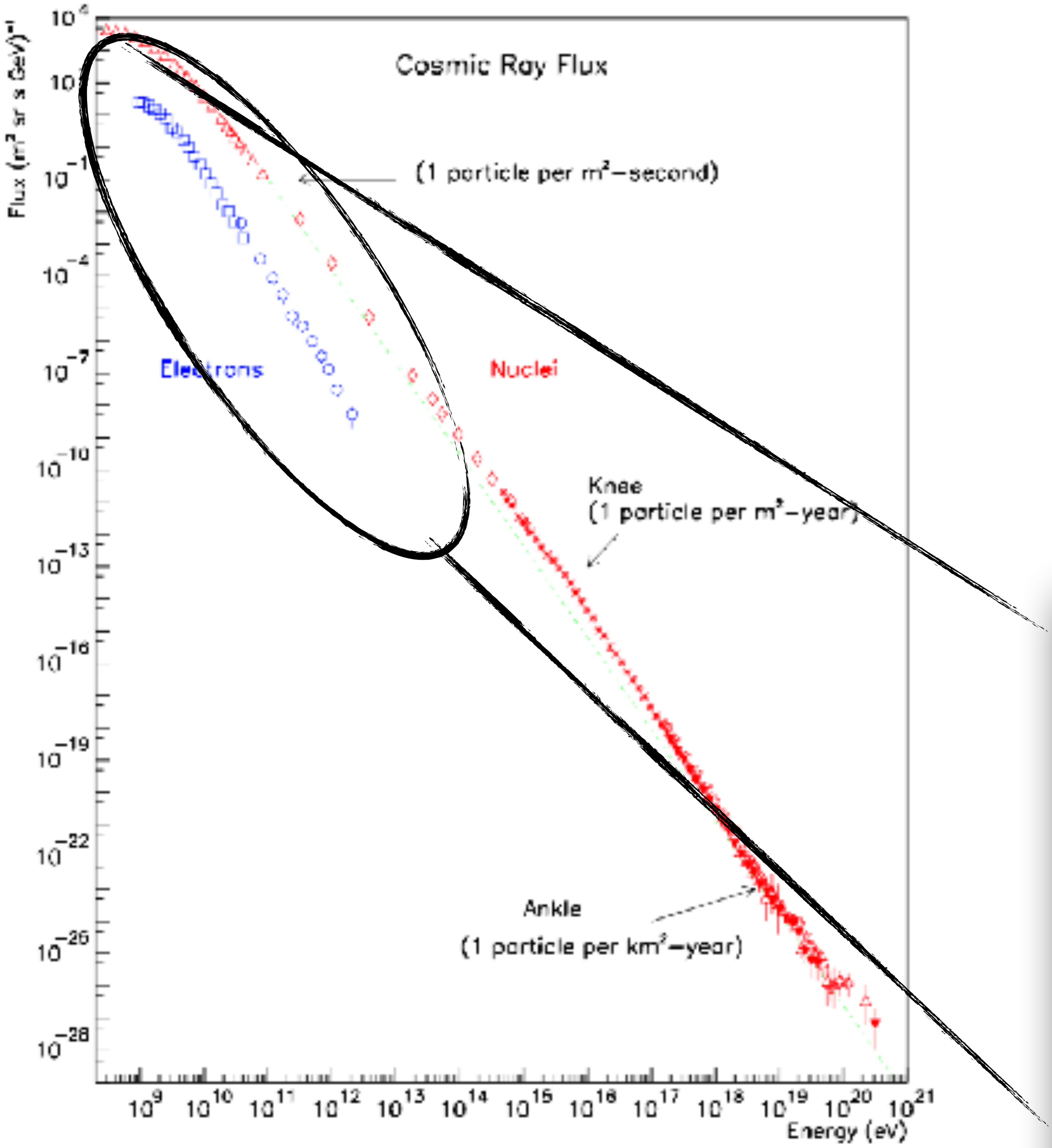
Rencontres du Vietnam 2018
Very High Energy Phenomena in the Universe
August 13-18 2018

The High-Energy End of the Cosmic-Ray $e^+ + e^-$ Spectrum

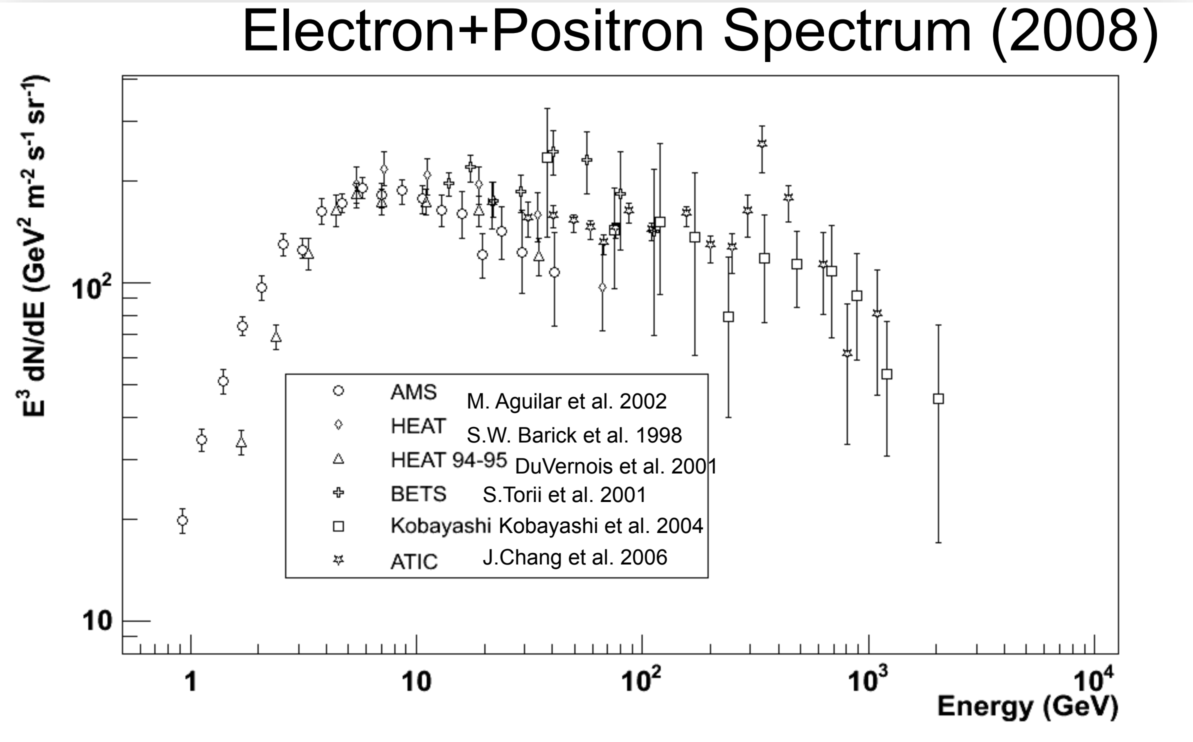
Kathrin Egberts
Potsdam University

The Spectrum of Cosmic-Ray Electrons + Positrons

- Steeper spectrum:
  $\Gamma_p \approx 2.7$ vs. $\Gamma_e \approx 3.0$ (below 1 TeV)
- Only small fraction of cosmic rays are electrons:
  - at 1 TeV ~0.5%
  - at 10 TeV ~0.01%
    → Very low fluxes at TeV energies



adopted from S. Swordy


Electron+Positron Spectrum (2008)

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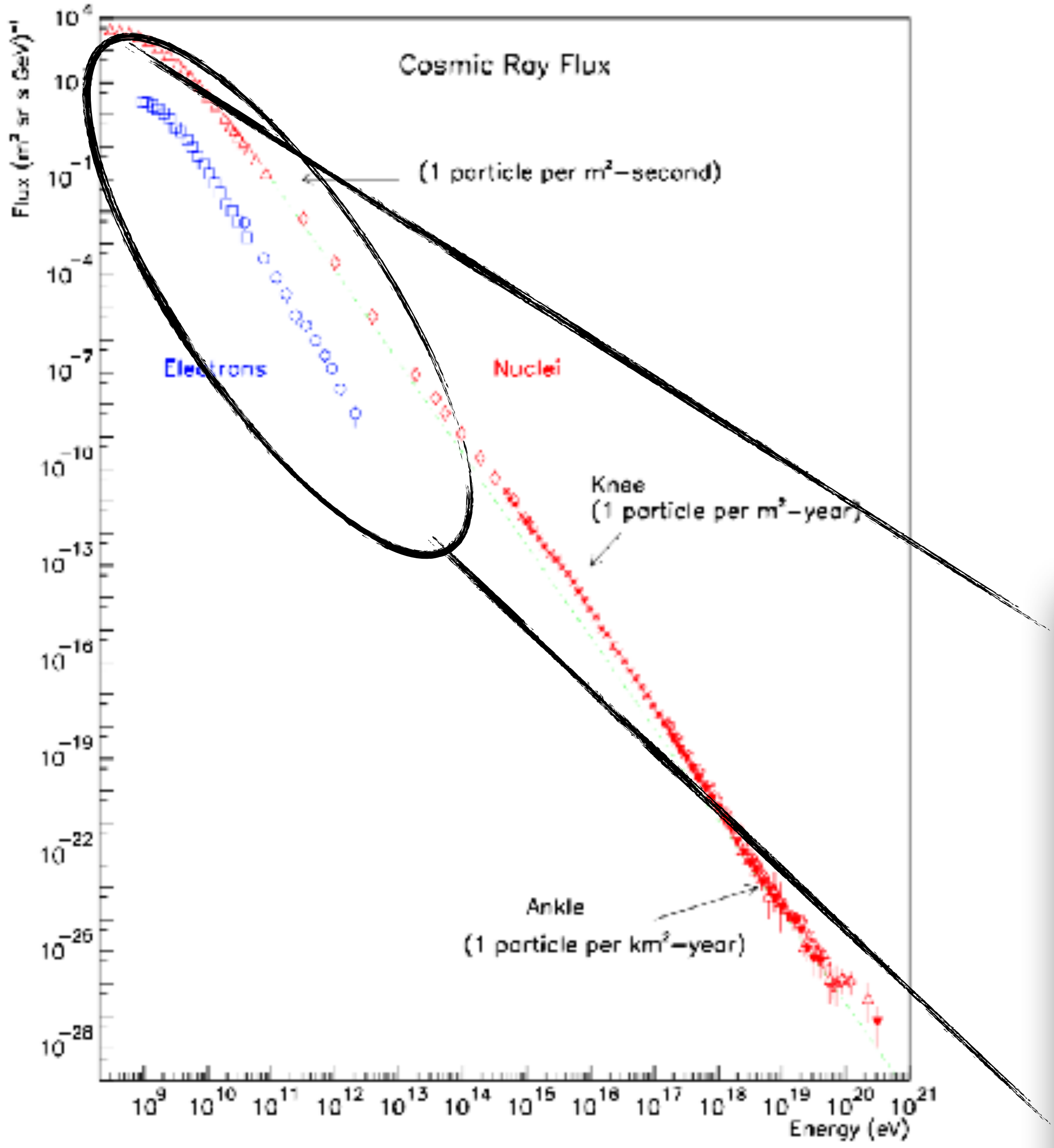

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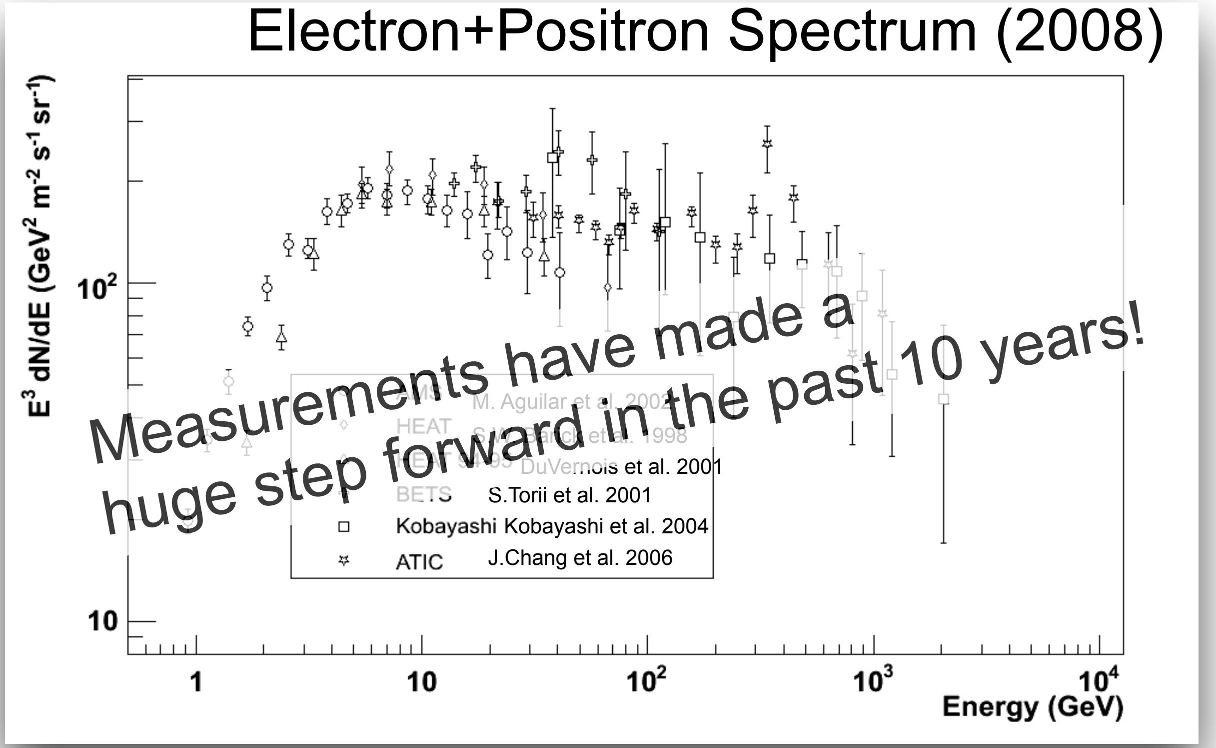


Electron+Positron Spectrum (2008)

Measurements have made a huge step forward in the past 10 years!

Production Sites

- Primary e^-: Fermi acceleration in SNRs
- Primary $e^\pm$: production in strong mag fields of pulsars, acceleration in relativistic shocks of PWNe
- Secondary $e^\pm$: production in interactions of nucleonic CRs with ISM

Propagation

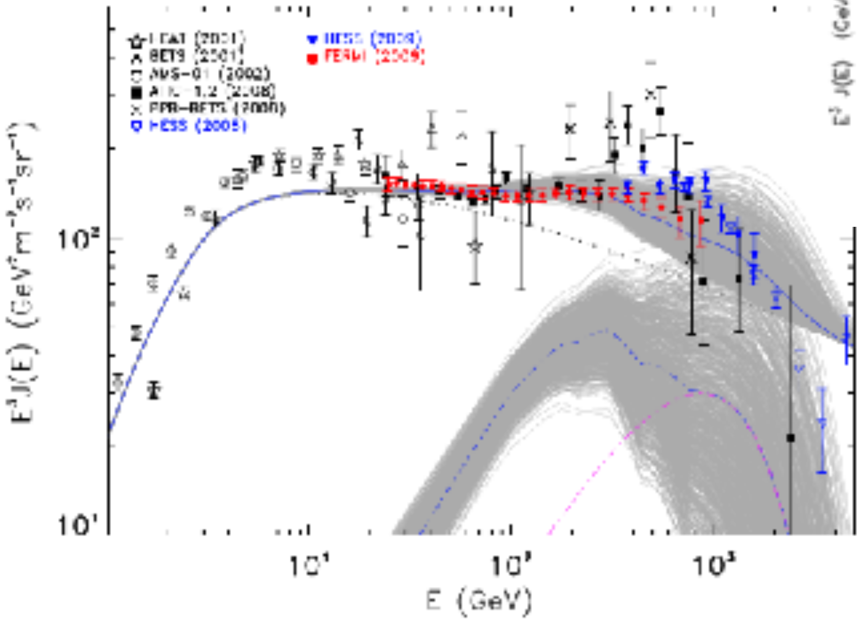
- Above few GeV mostly diffusion in interstellar magnetic field inhomogeneities
- Energy loss by inverse Compton scattering and synchrotron radiation
  - TeV $e^\pm$ must have been injected not much longer than $\sim 10^5$ yr ago
  - Propagation distance:
    $\sim \sqrt{D}\, T_{\mathrm{cool}} \sim$ 100-500 pc for TeV $e^\pm$
    (assuming reasonable diffusion coefficient D)

$$t \sim\ 5 \times 10^5 \left(\frac{\mathrm{TeV}}{E_{e^\pm}}\right)\ \mathrm{yr}$$

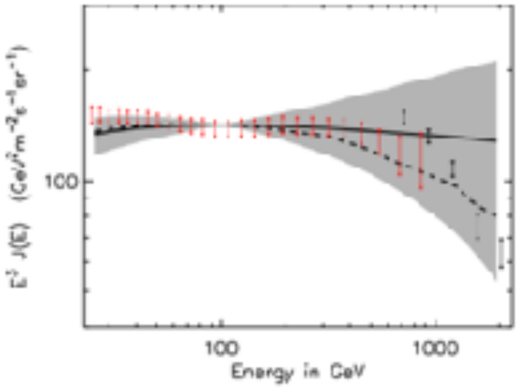
Only limited number of nearby accelerators can contribute to the overall spectrum!

- Sources are discrete,
  potential to see direct imprint of local accelerators on the electron spectrum
- Identifying local sources:
  - Uncertainties in distance estimates
  - Surveys using el.-mag. radiation: bias due to different propagation of photons and CRs
  - → Hard to determine the true distribution of sources

ATNF pulsars with random parameter variation



Stochastic source distribution



Grasso et al., Astropart. Phys. 32, 2 (2009)

- Shape of the spectrum very sensitive to both, propagation characteristics and source properties: distribution and number of sources in our Galactic neighbourhood, their individual properties (e.g. confinement/release times)

Cosmic-Ray Electron Measurements at TeV Energies

Measurements need:

→ High statistics, exposure = A_{eff} × FoV × T_{obs}

large effective areas

large field of view

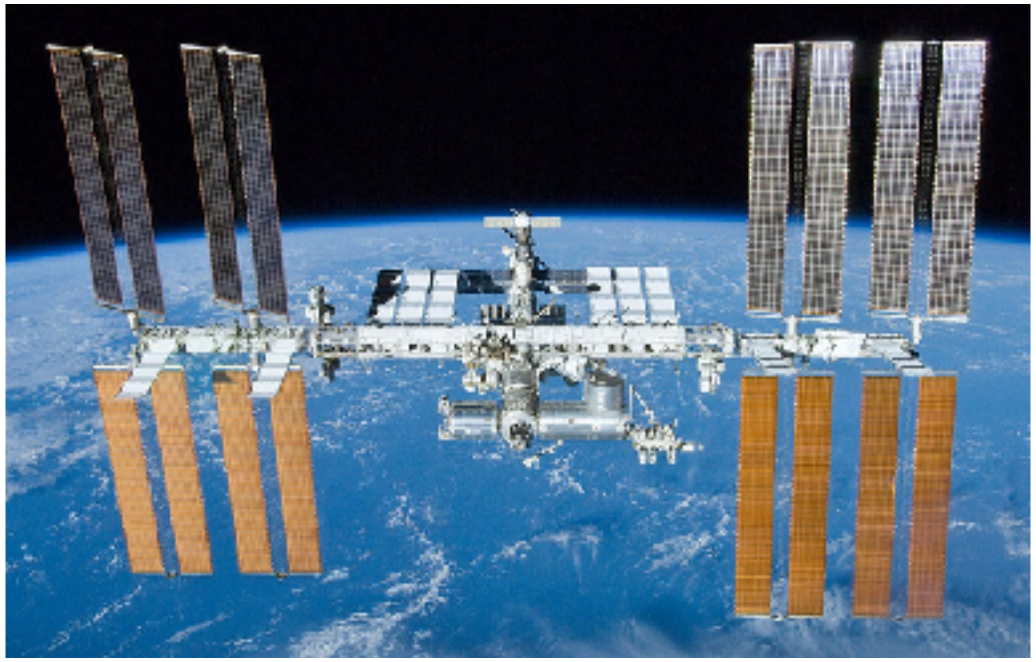
long observation times

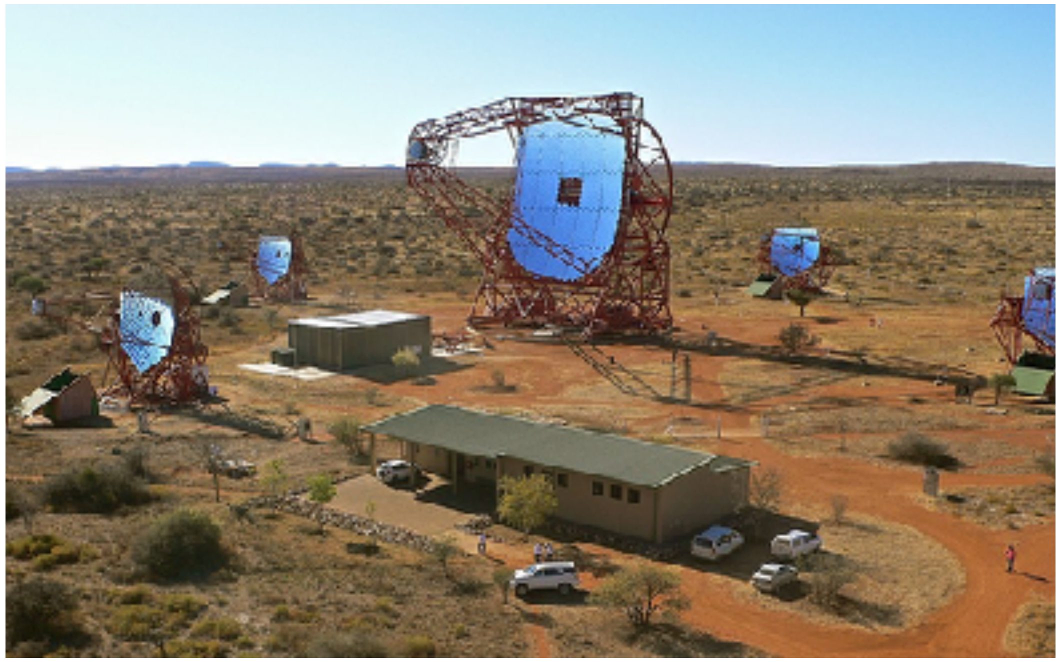
→ Deep calorimeters for TeV energy reconstruction

→ Excellent electron-hadron separation capabilities

Cosmic-Ray Electron Measurements at TeV Energies

Direct Measurements or Indirect Measurements





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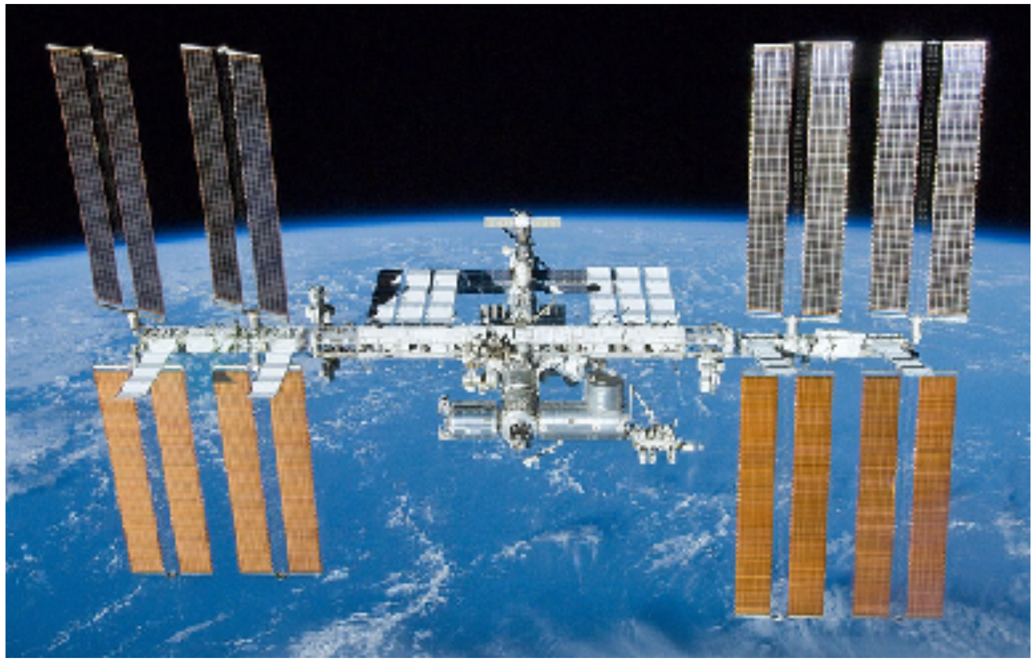
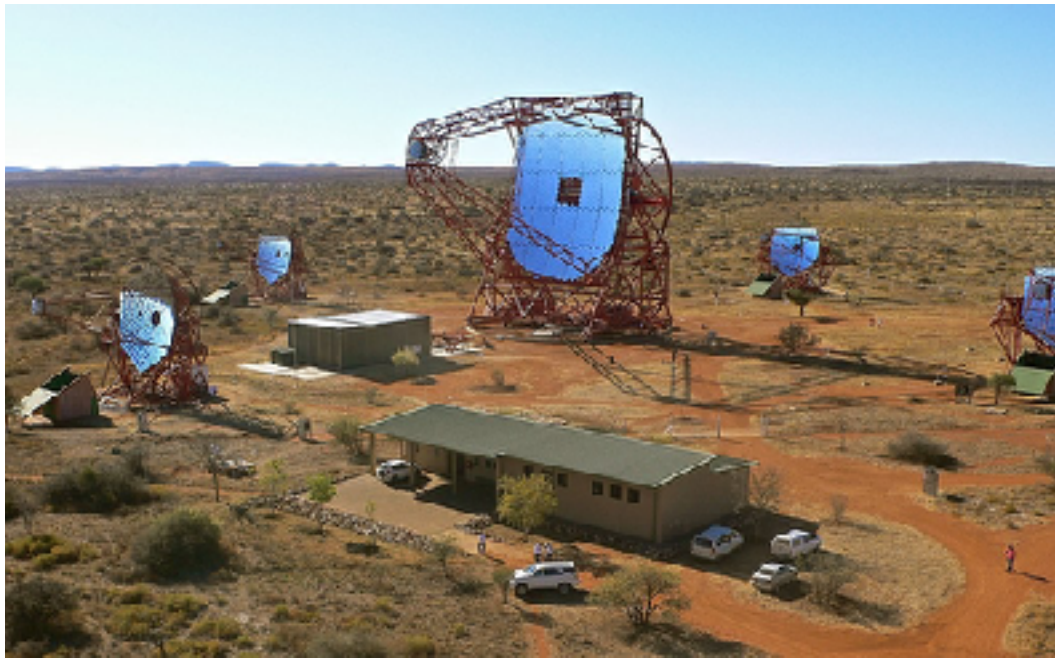




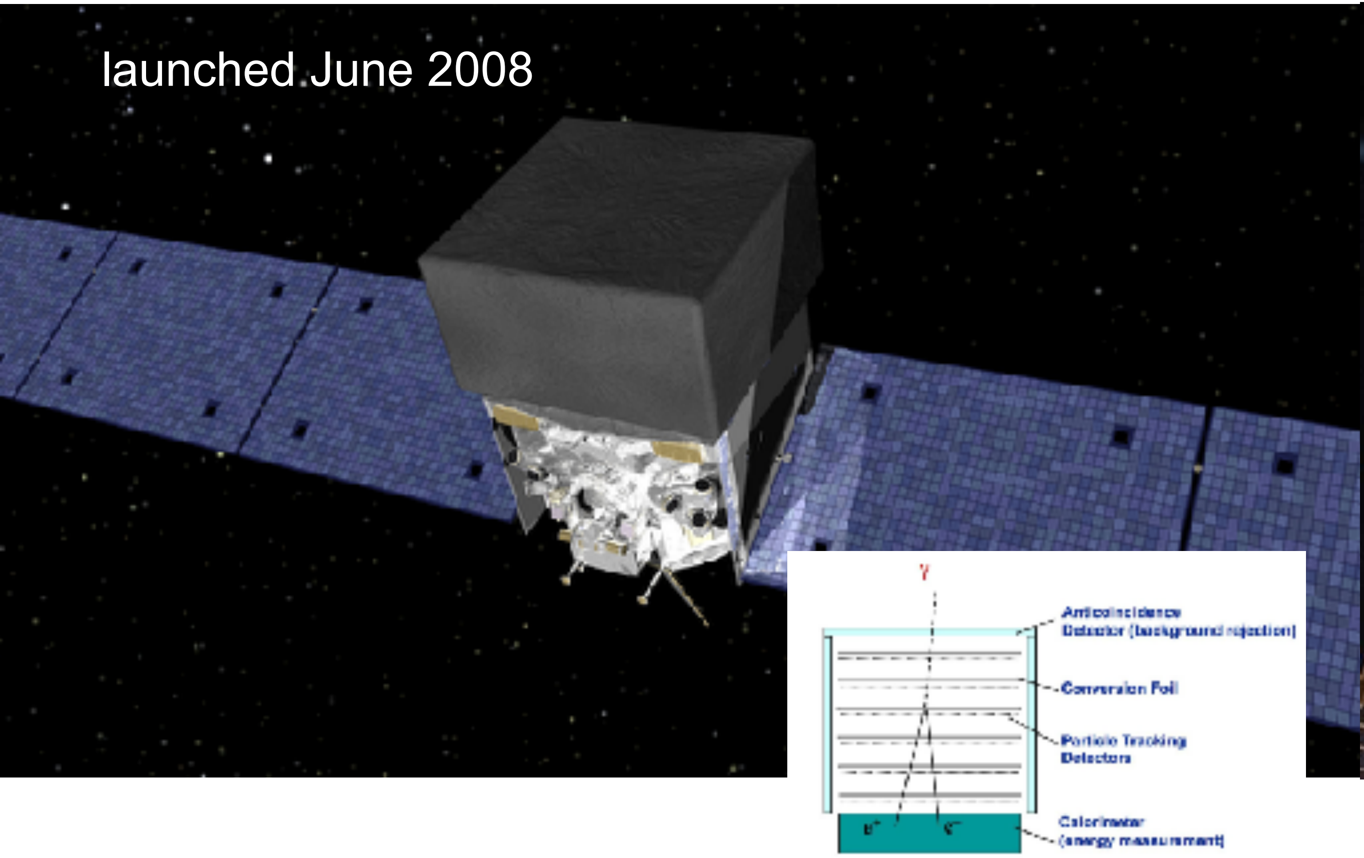
Measurements need:

→ High statistics, exposure = $A_{eff} \times FoV \times T_{obs}$

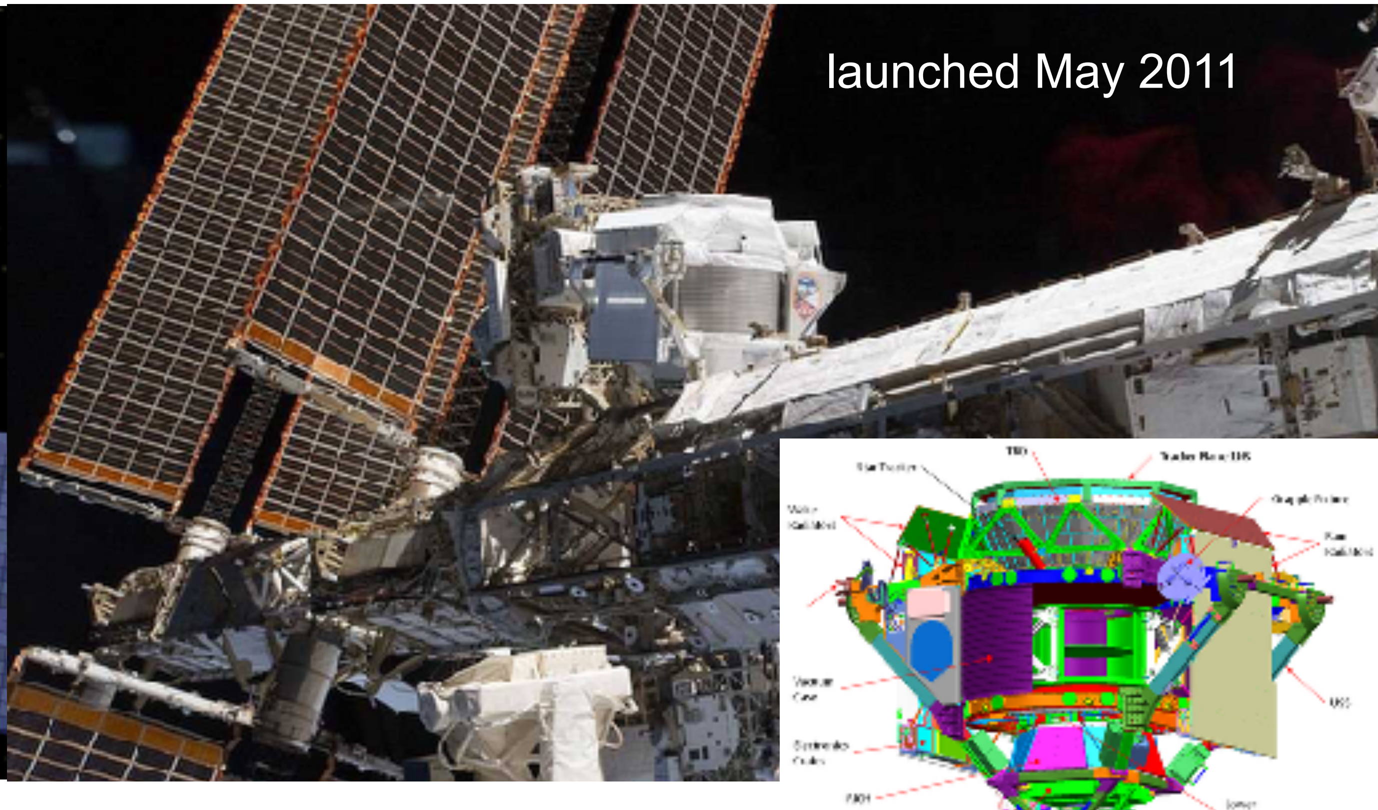
✗	large effective areas	✓
✓	large field of view	✗
✓	long observation times	✗
✗	→ Deep calorimeters for TeV energy reconstruction	✓
✓	→ Excellent electron-hadron separation capabilities	✗

Direct Measurements

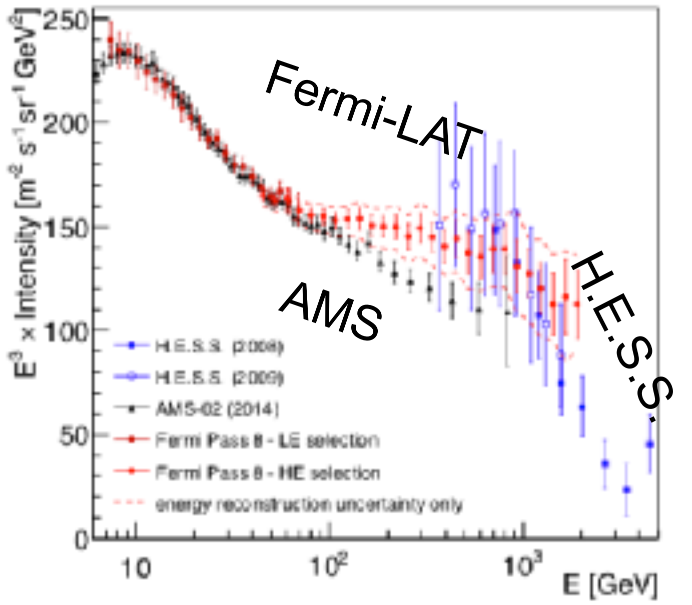
Fermi-Lare Area Telescope (Fermi-LAT)


launched June 2008

Alpha Magnetic Spectrometer (AMS)


launched May 2011

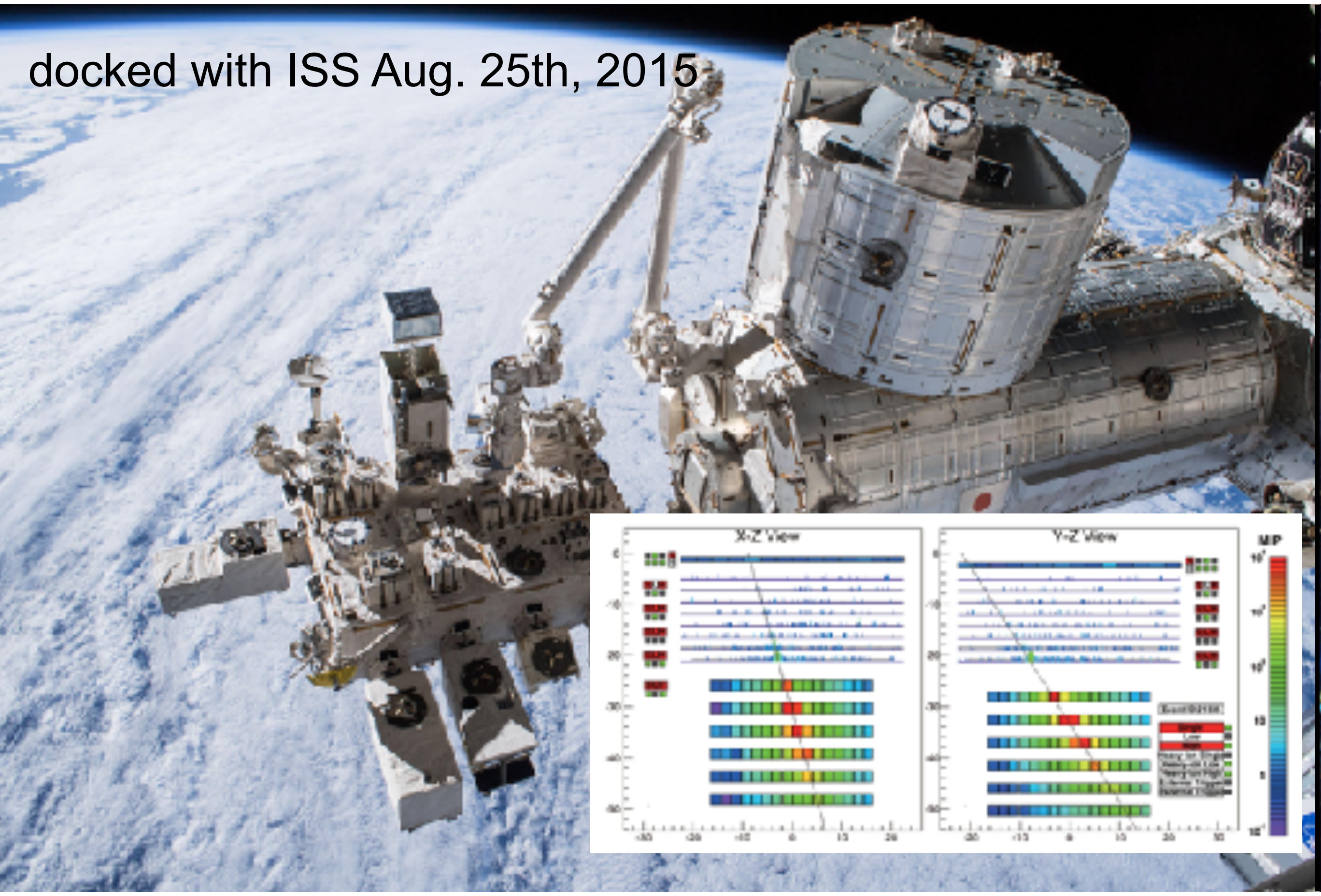
- High-statistics precision measurements from ~GeV up to ~ TeV
- Excellent agreement at energies below 100 GeV
- Divergence at higher energies



Fermi-LAT Coll, Phys. Rev. D 95, 082007 (2017)

A New Generation of Space-Born Experiments

CALorimetric Electron Telescope (CALET)

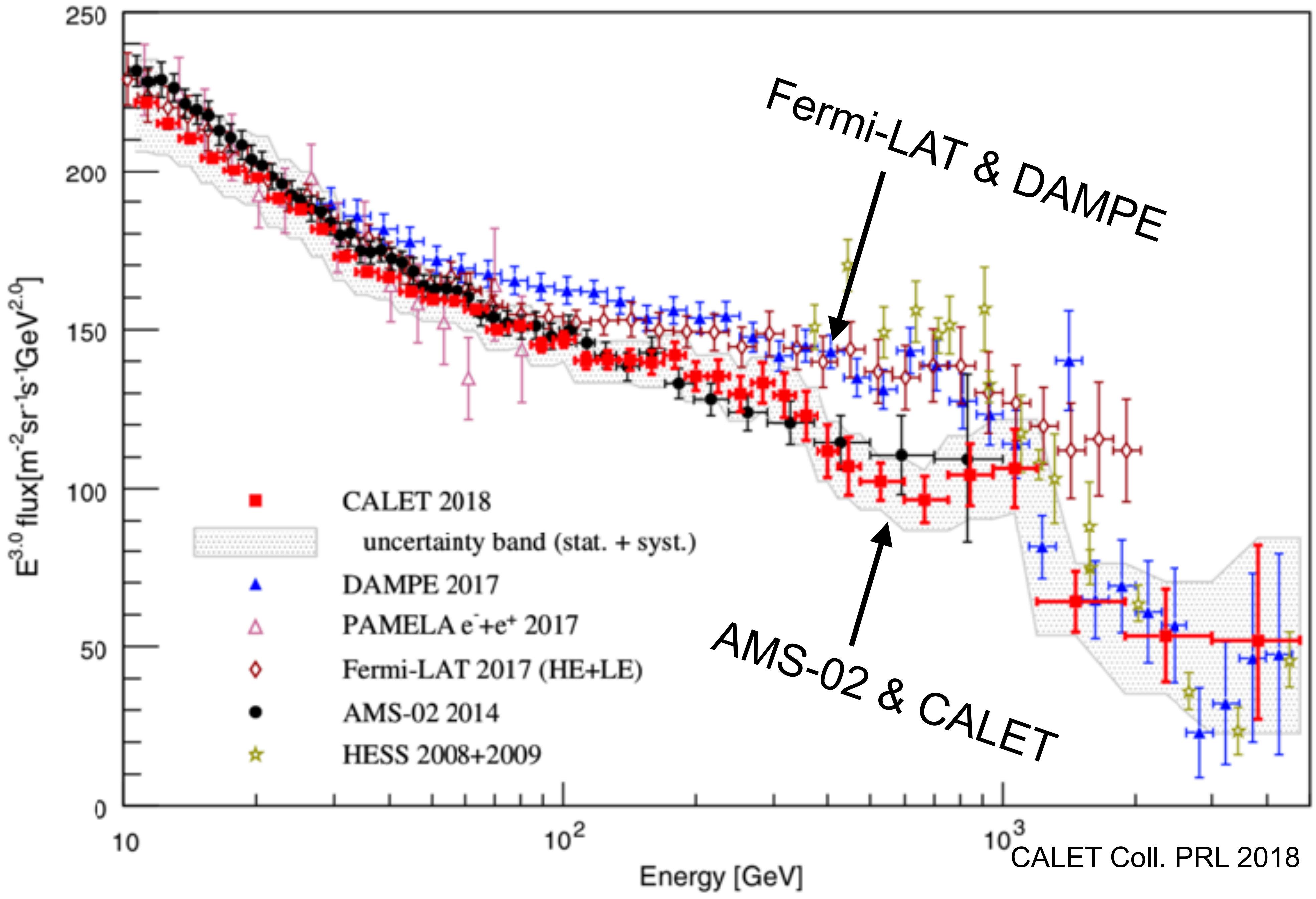


docked with ISS Aug. 25th, 2015

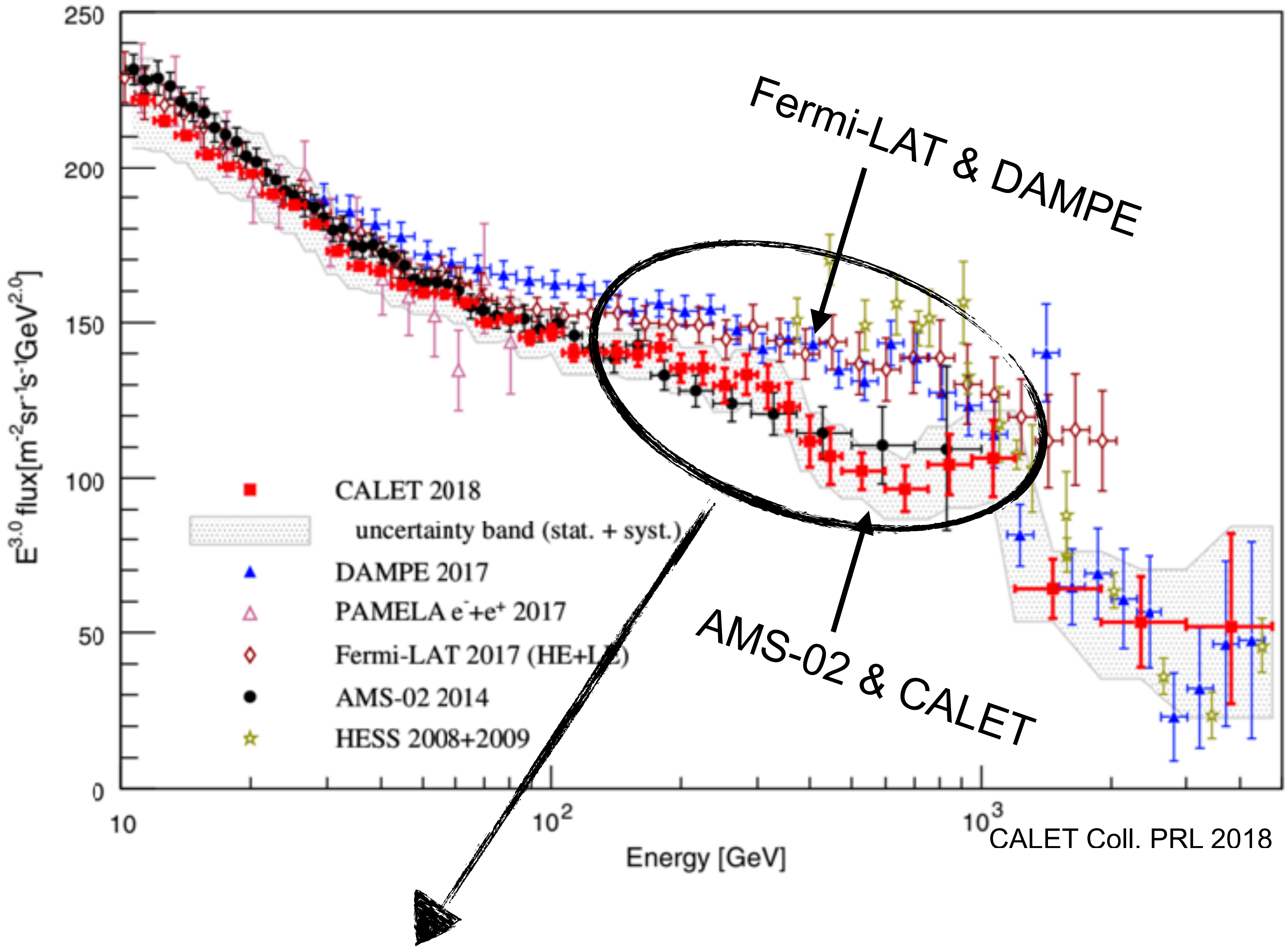
DArk Matter Particle Explorer (DAMPE)

launched on Dec. 17th, 2015

- Deep calorimeters: 30 X_0 / 32 X_0 (*cf*. AMS-02 17 X_0, Fermi-LAT 8.6 X_0)
- Proton contamination $\lesssim$5% at 1 TeV
- Energy resolution ~few %



CALET Coll. PRL 2018

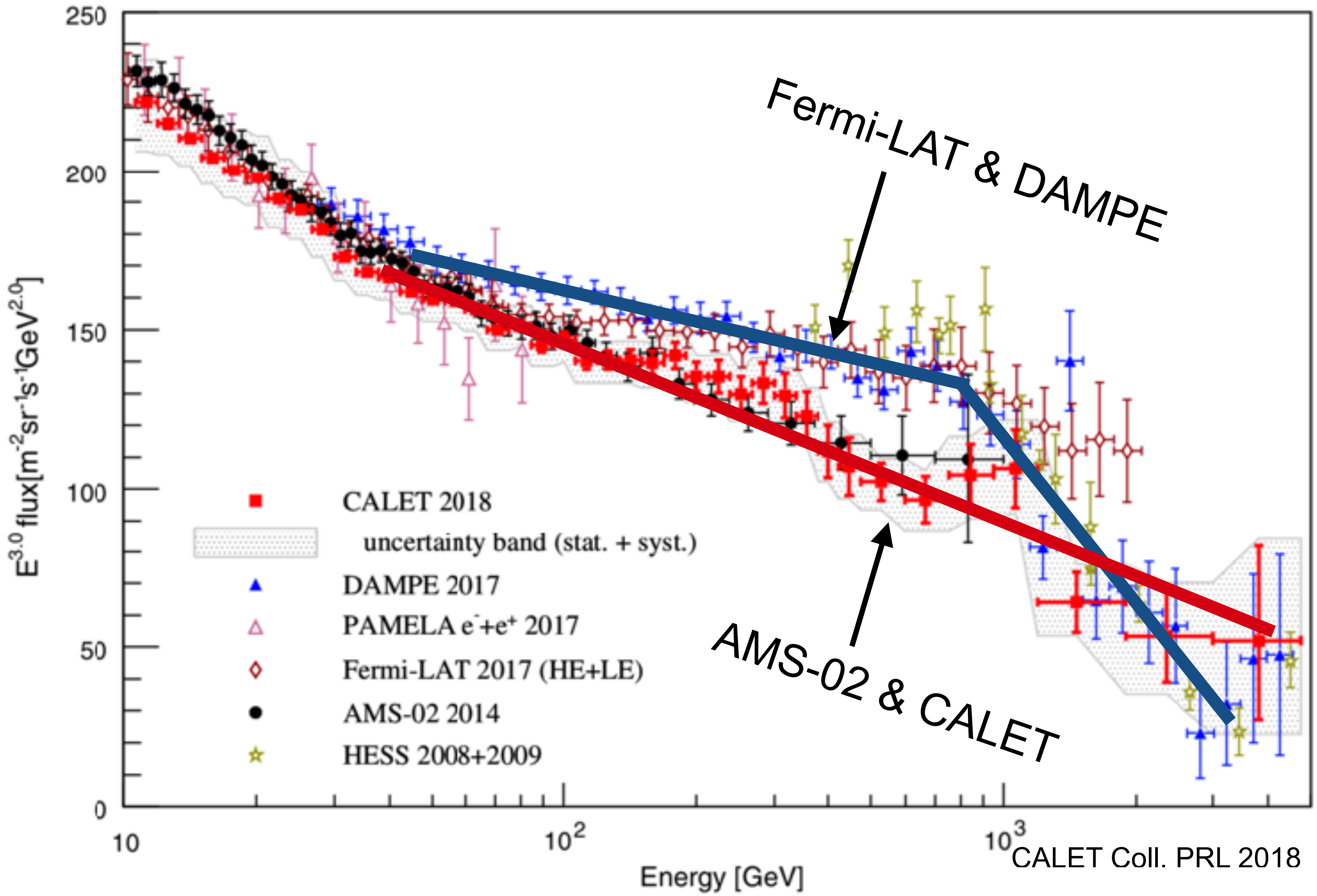


Fermi-LAT & DAMPE

AMS-02 & CALET

CALET Coll. PRL 2018

Unaccounted systematics? clearly energy dependent - agreement at low and at high energies - interesting to note the agreement between each two measurements



CALET Coll. PRL 2018

Is there a break in the spectrum? - Fitting a smoothly broken power-law:

DAMPE

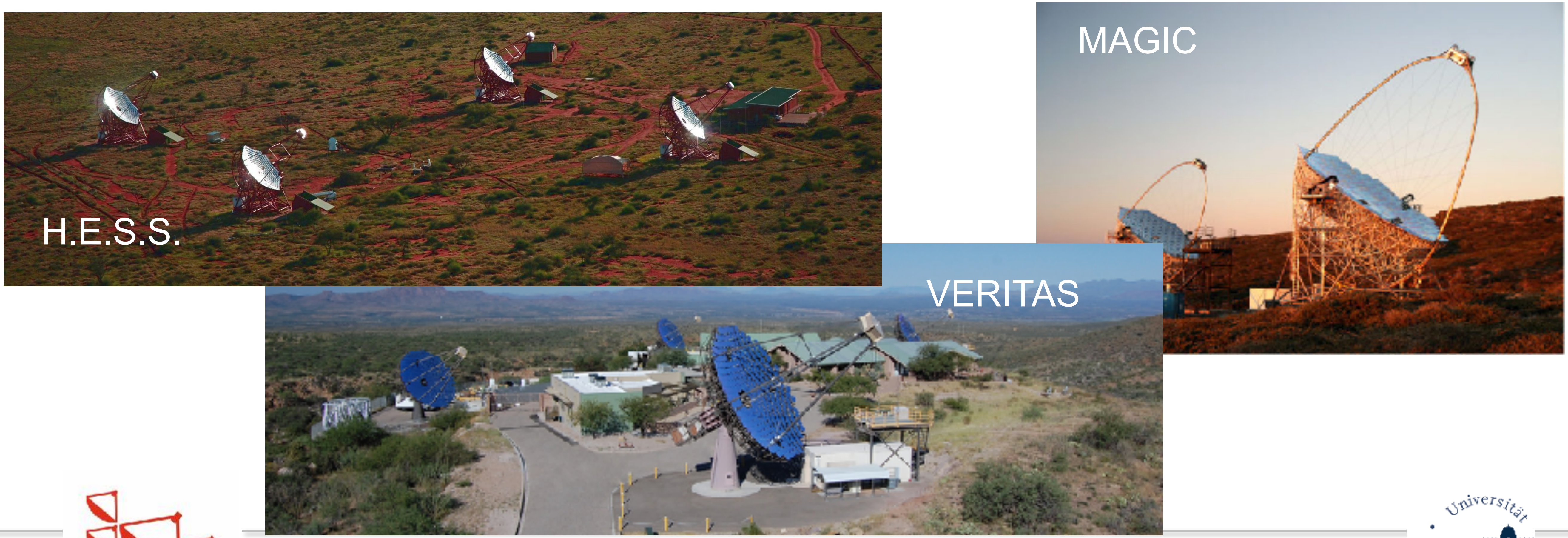
- $\Gamma = 3.09 \pm 0.01 \rightarrow 3.92 \pm 0.20$,
  $E_b = 914 \pm 98$ GeV
- χ^2/ndof = 23.3/18,
  pure power-law: χ^2/ndof = 70.2/20

CALET

- $\Gamma = 3.15 \pm 0.02 \rightarrow 3.81 \pm 0.32$,
  if fixing $E_b = 914$ GeV
- χ^2/ndof = 17/25,
  pure power-law: χ^2/ndof = 26.5/26

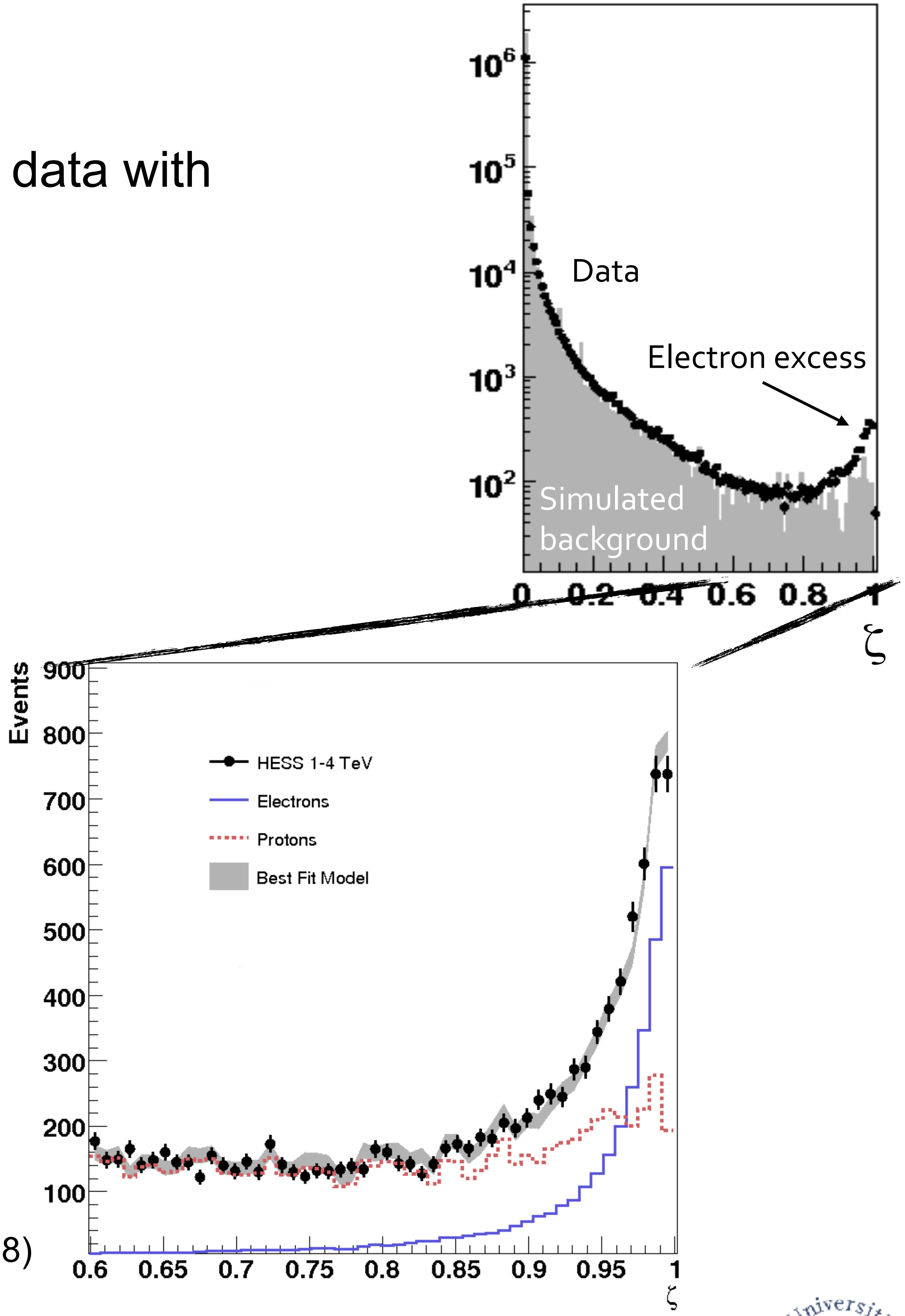
Measurements with Imaging Atmospheric Cherenkov Telescopes

- Designed for TeV gamma-ray measurements
- No charge separation: only inclusive spectrum of $e^+ + e^-$
- Main challenge: background subtraction
  - Gamma-rays (mostly) localised sources, which allows for background measurement in field of view
  - For isotropic electrons need to find alternative solutions



First Ground-Based Measurement of CR Electrons

- Nucleonic background determined by fitting the data with simulations (electrons and protons)
- Fit performed in a discriminator distribution (analysis tailored for this use case)



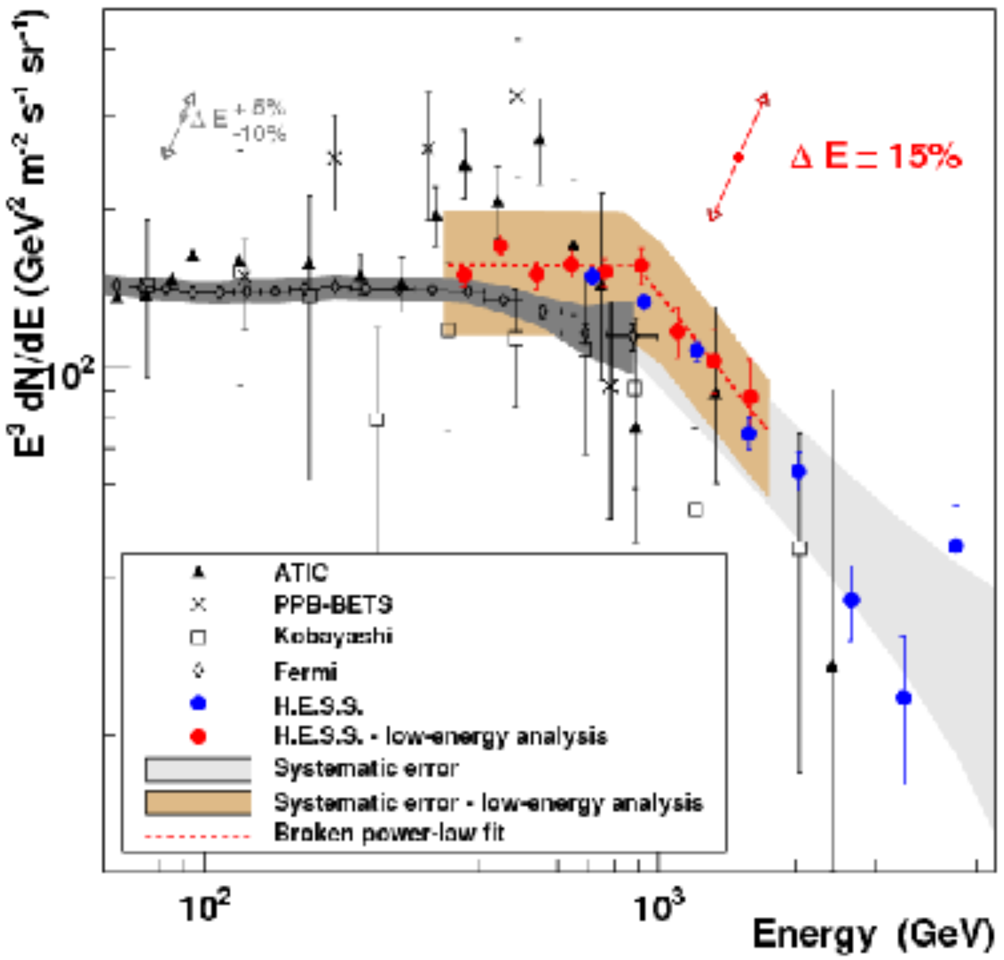
Drawback:

- Proton simulations much less accurate than electron (electromagnetic) ones
- Introduces dependence on hadronic models used (SIBYLL, with QGSJET cross check)

Aharonian et al., PRL **101**, 261104 (2008)

First Ground-Based Measurement of CR Electrons

- Measurement by H.E.S.S. in 2008/2009, followed by VERITAS and MAGIC
- Discovery of break at 1 TeV
- Measurement dominated by systematic uncertainties due to
  - hadronic interaction model
  - atmospheric uncertainties
- Beyond 6 TeV issues with the systematics

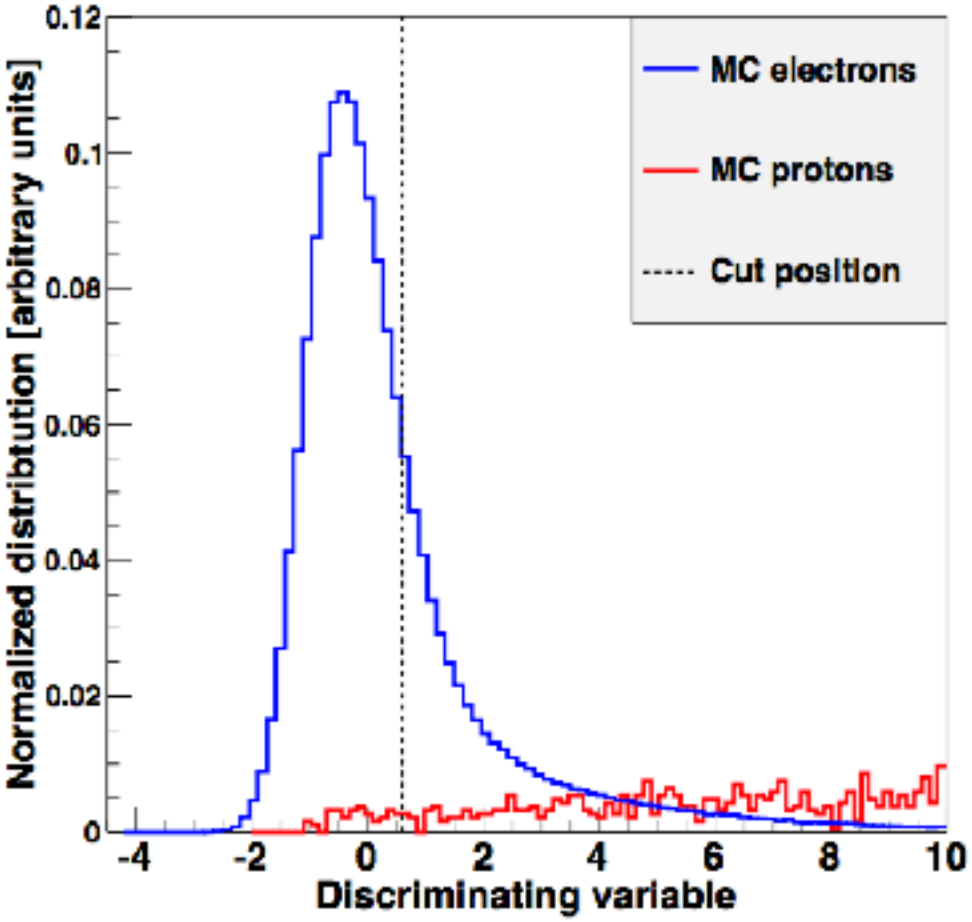


Aharonian et al., A&A 508, 561–564 (2009)

Room for Improvement:
Data Set and Analysis Technique

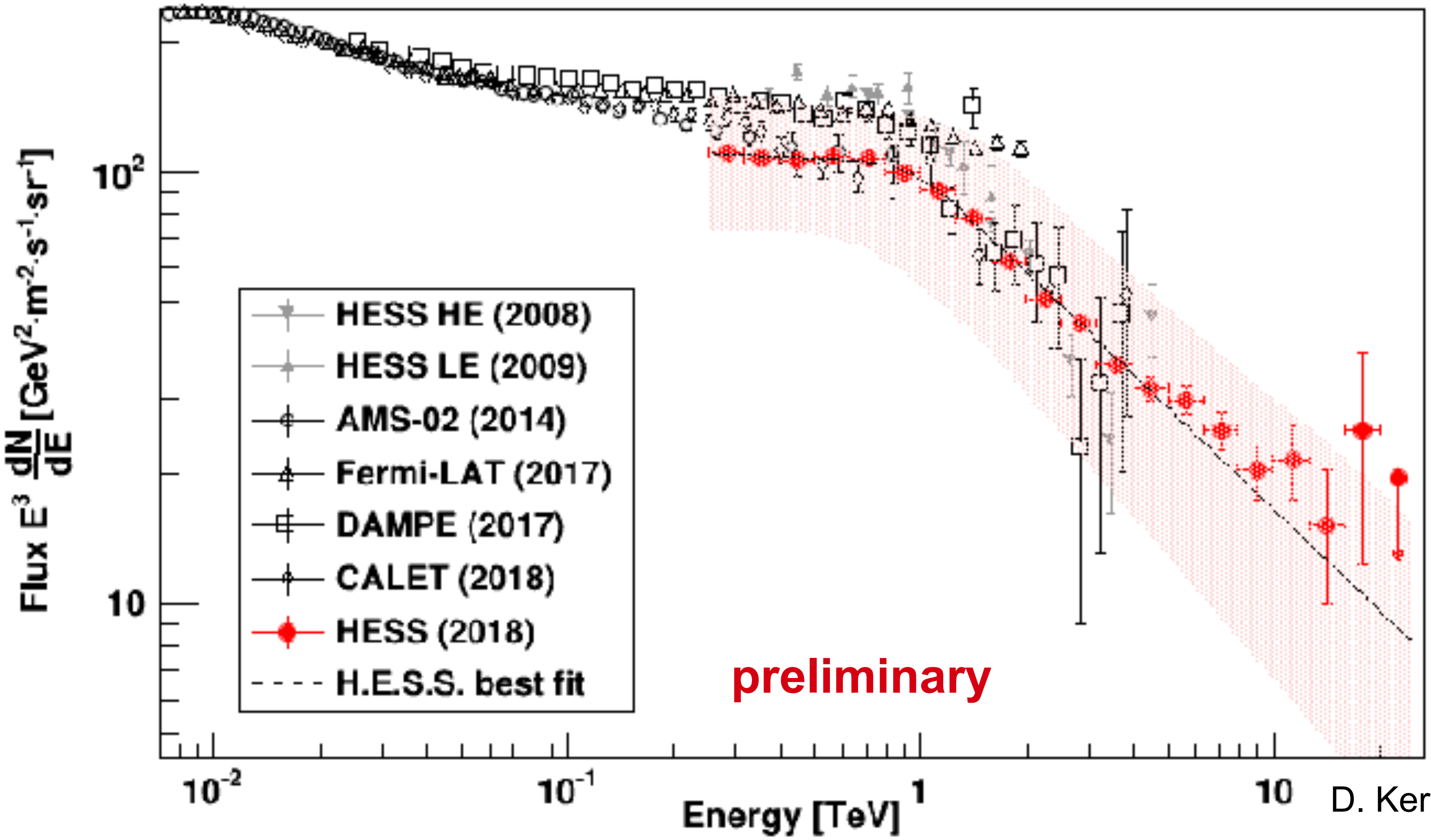
- Between 2008 and 2018: drastically increased data set - 239 h → 1186 hours
- Improvements in the analysis methods yielding a very powerful hadron rejection:
  - Log-likelihood comparison between recorded images and pre-calculated templates from semi-analytical shower model
  - Discrimination based on goodness of fit

→ standard H.E.S.S. analysis



M. de Naurois & L. Rolland,
Astropart. Phys., 32 (2009), 231-252

The New H.E.S.S. Cosmic-Ray Electron Spectrum

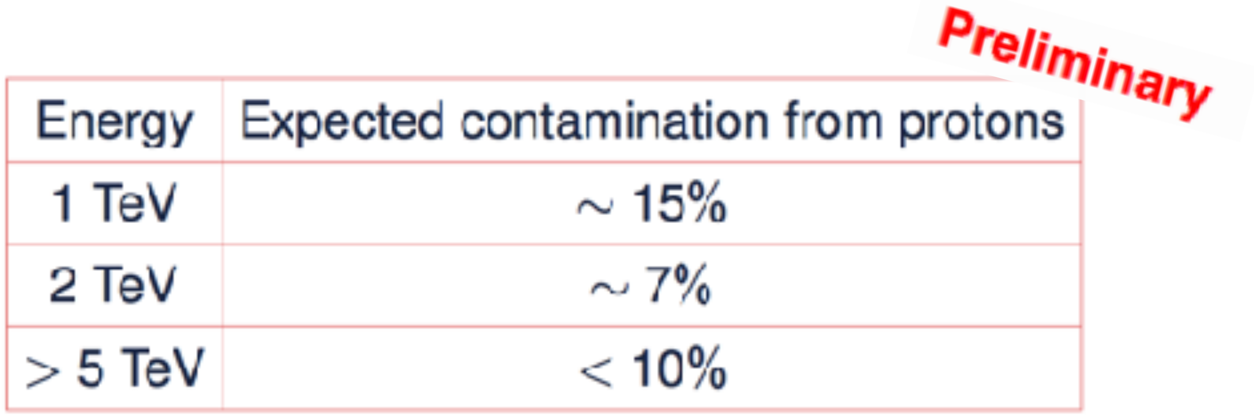


D. Kerszberg, ICRC2017

- Broken power-law spectrum without any apparent structure up to 20 TeV
- Consistent with previous H.E.S.S. measurements, confirmation of the sharp break at around 1 TeV

Background Contamination

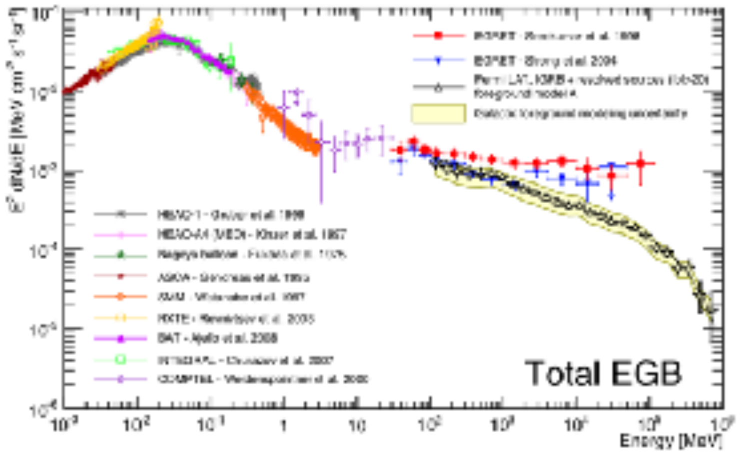
- Cosmic-ray hadrons:
  - A hard cut on the classification variable eliminates most of the background
  - Using MC simulations, the residual background can be estimated to be ≲15%



Preliminary

Energy	Expected contamination from protons
1 TeV	$\sim 15\%$
2 TeV	$\sim 7\%$
> 5 TeV	$< 10\%$

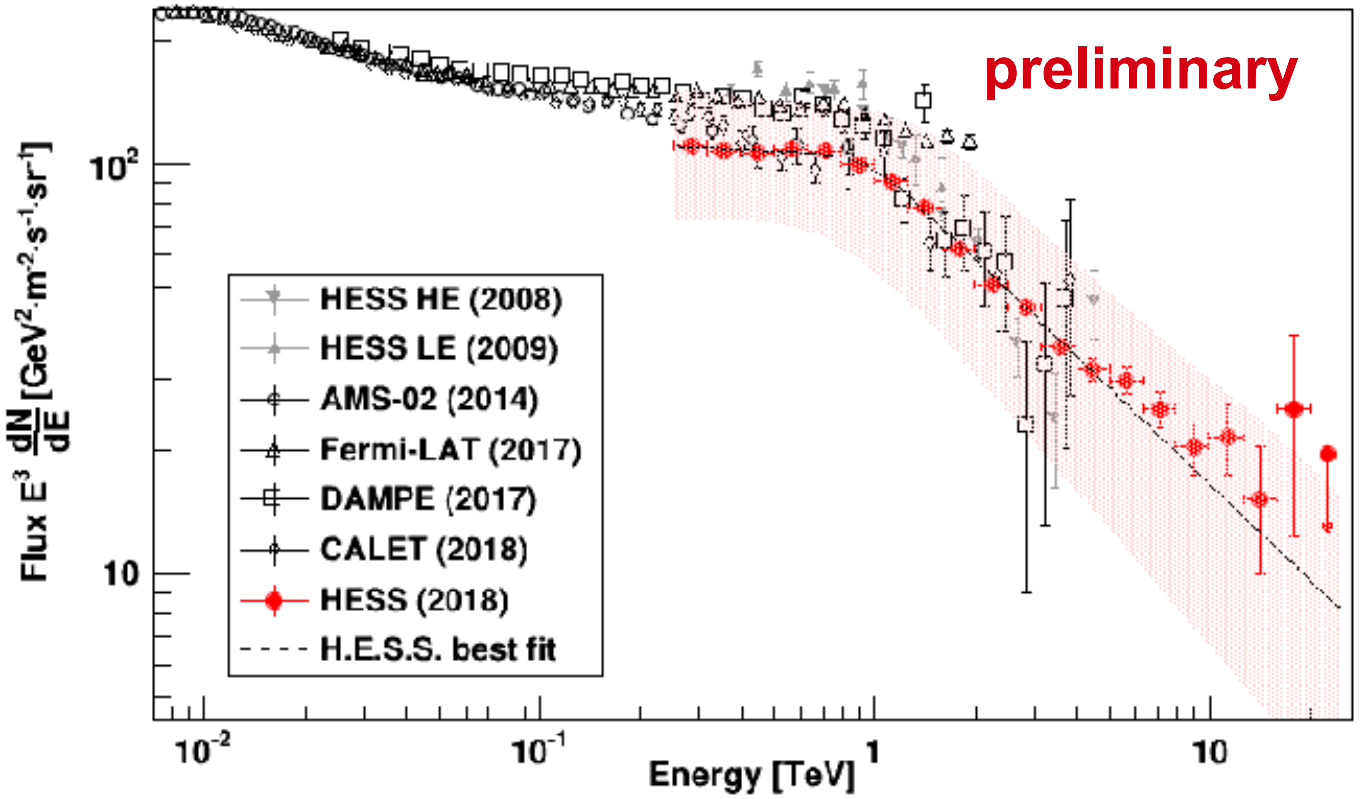
- Gamma-rays:
  - Air showers very similar to CR electron ones, discrimination challenging
  - Exclusion of gamma-ray sources and Galactic plane reduces contamination significantly - remaining: high-latitude Galactic diffuse and extragalactic gamma-ray background (EGB)
    → EGB is 0.1% of the electron flux at 1 TeV



M. Ackermann et al. 2015 ApJ 799 86

Investigation of Systematics

- Drastically reduced due to avoidance of hadronic models
- Stability thoroughly checked, studies included:
  - Event selection cuts
  - Zenith angles
  - Atmos. conditions
  - Yearly variations
- Always present: energy scale uncertainty of ΔE/E~15%
- → Mostly *normalisation* uncertainty
- Due to normalisation uncertainty, H.E.S.S. data are consistent with both, AMS & CALET and Fermi & DAMPE



Fitting a smoothly broken power-law:

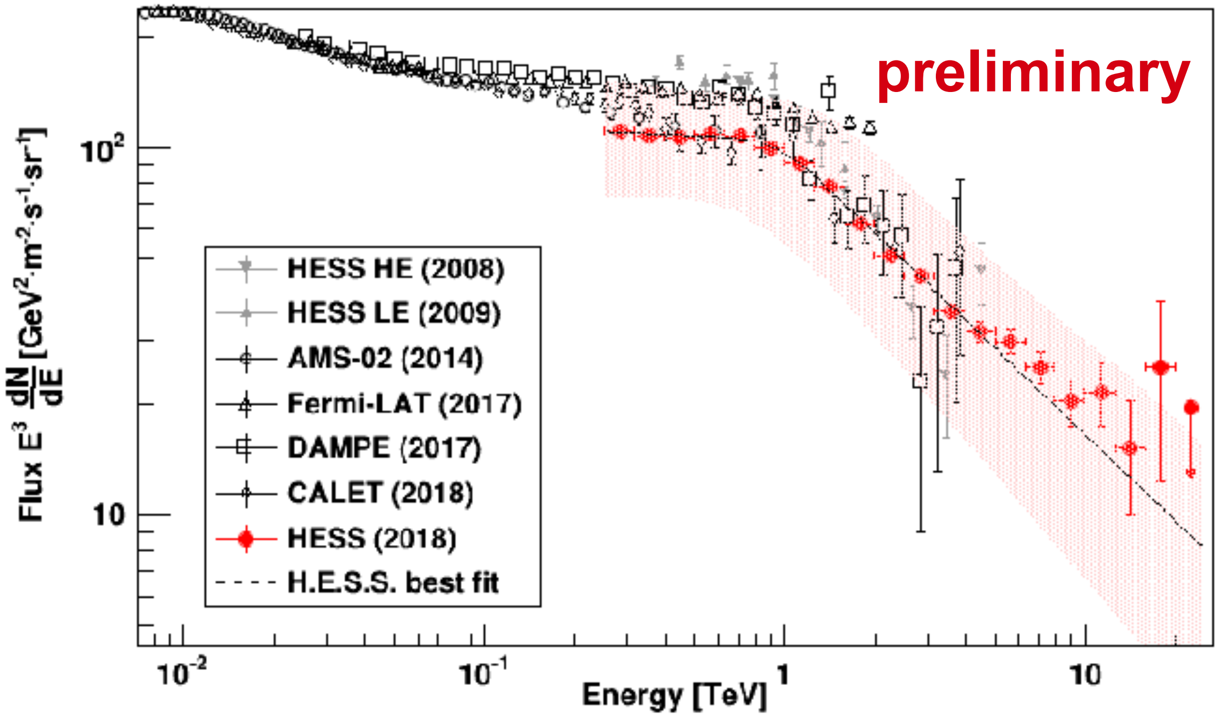
$$E^3 \frac{dN}{dE} = N_0 \left(\frac{E}{(1\ \mathrm{TeV})}\right)^{3-\Gamma_1} \left(1+\left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_1-\Gamma_2)\alpha}$$

$$\begin{aligned}
\Gamma_1 &= 3.04 \pm 0.01\ (\mathrm{stat})\ {}^{+0.10}_{-0.18}\ (\mathrm{sys}) \\
\Gamma_2 &= 3.78 \pm 0.02\ (\mathrm{stat})\ {}^{+0.17}_{-0.06}\ (\mathrm{sys}) \\
E_b &= 0.94 \pm 0.02\ (\mathrm{stat})\ {}^{+0.29}_{-0.26}\ (\mathrm{sys})\ \mathrm{TeV} \\
N_0 &= 104 \pm 1\ (\mathrm{stat})\ {}^{+27}_{-16}\ (\mathrm{sys})\ \mathrm{GeV}^2\cdot\mathrm{m}^{-2}\cdot\mathrm{sr}^{-1}\cdot\mathrm{s}^{-1} \\
\alpha &= 0.12 \pm 0.01\ (\mathrm{stat})\ {}^{+0.19}_{-0.05}\ (\mathrm{sys})
\end{aligned}$$

What is there to learn from the high-energy CR e$^-$ + e$^+$?

High-energy spectrum of CR e$^-$ + e$^+$ is featureless power-law with a break at ~1 TeV

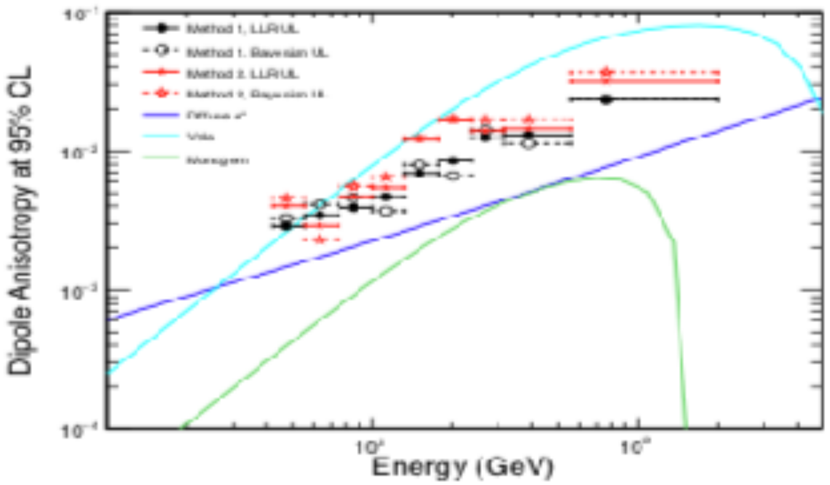
- There are no features of local accelerators in the spectrum
  - Very existence of TeV electrons points to an accelerator within ~1 kpc
  - Constraint to local source models
- No apparent features of dark matter
- Nature of the break at 1 TeV?
  - Related to the accelerator?
  - Propagation effect?



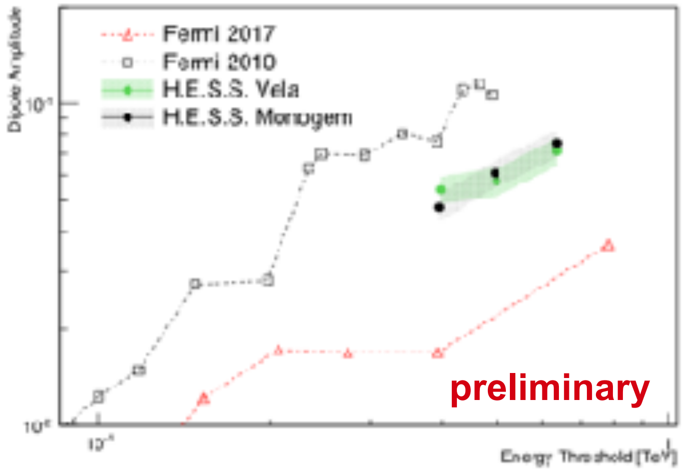
- Do we see the "end of the cosmic-ray electron spectrum"? Or what room is there for continuation of the spectrum? And what about the secondaries?

Another Observable: Anisotropy

- Expected at VHE energies due to limited number of sources, increasing with energy
- Might be especially interesting to differentiate dark matter scenarios

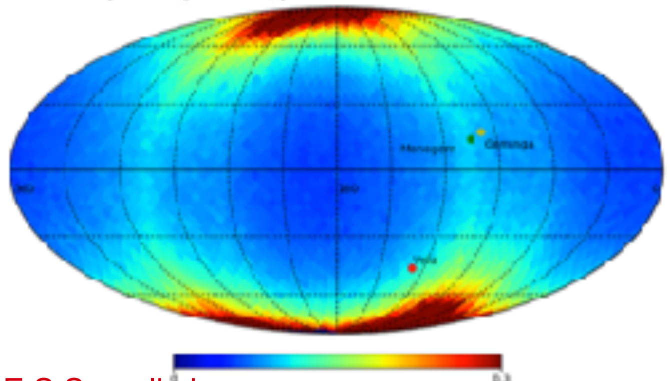


Fermi-LAT Collaboration, PRL 118, 091103 (2017)



M. Kraus, ICRC2017

upper limits sky map
for dipole anisotropy >0.4 TeV

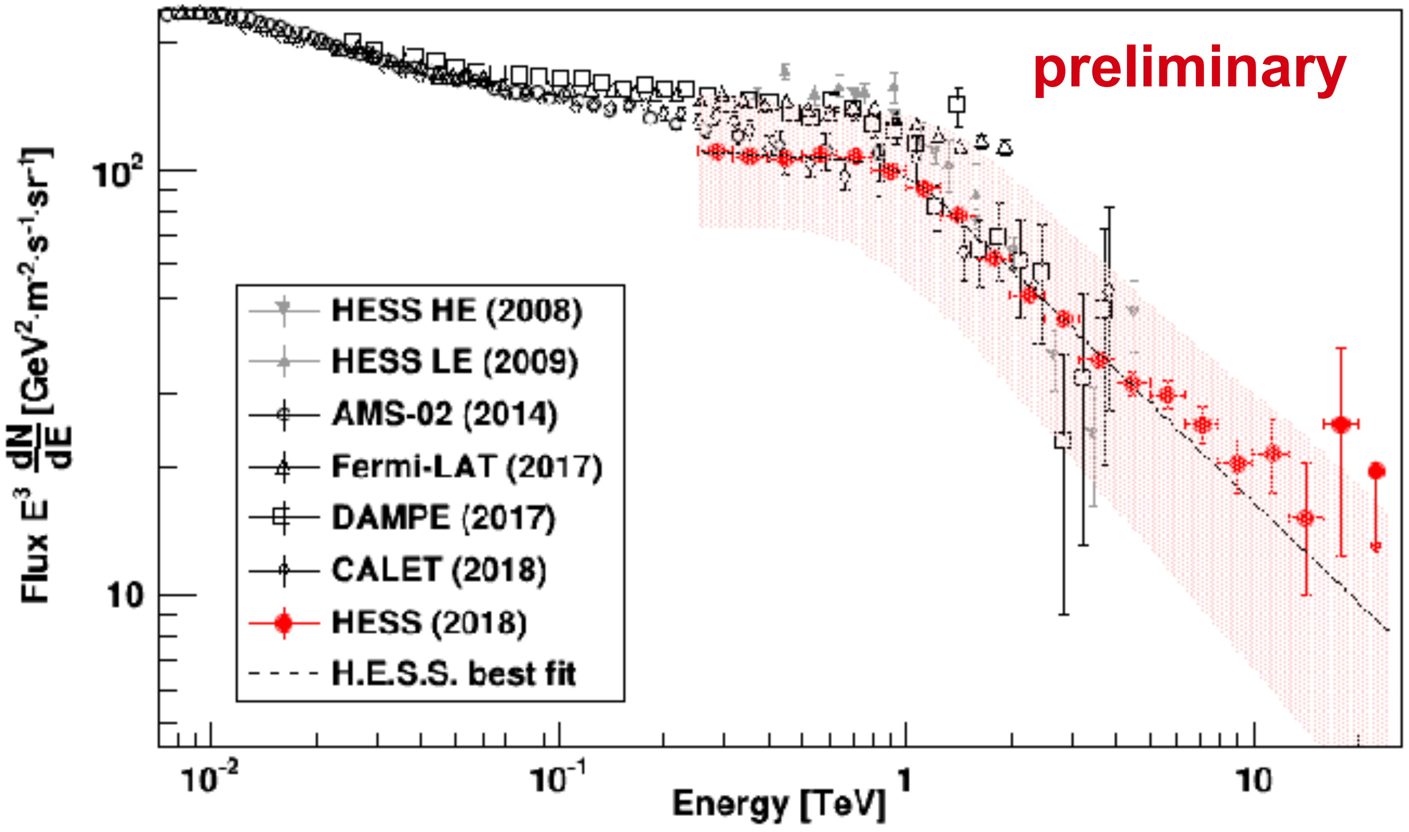


H.E.S.S. preliminary

no sensitivity at the poles!

- Upper limits on dipole anisotropy by e.g. AMS (up to 100 GeV), Fermi-LAT (up to ~1 TeV)
- Challenging for ground-based instruments
  - pointed observations/
    sensitivity based on pointing pattern
  - normalisation uncertainty due to systematics

Summary & Conclusion



- Recent measurements made a giant step in both, accuracy and energy coverage
- Despite some discrepancy between measurements yet to be resolved, the data seems to indicate that the one major feature of the CR e^- + e^+ spectrum is a break at ~1 TeV
- We are approaching the end of the CR e^- + e^+ spectrum
  - measurements still awaiting full scientific exploitation