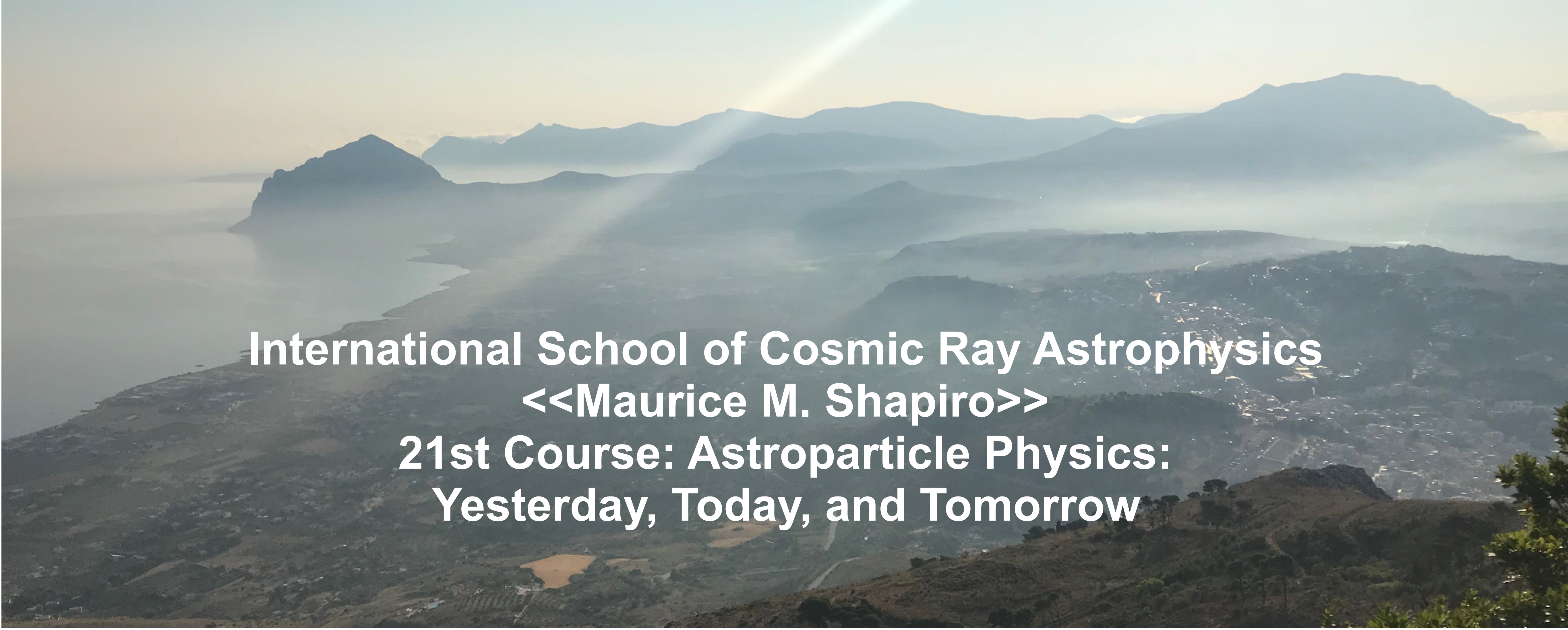


International School of Cosmic Ray Astrophysics
<<Maurice M. Shapiro>>
21st Course: Astroparticle Physics:
Yesterday, Today, and Tomorrow

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

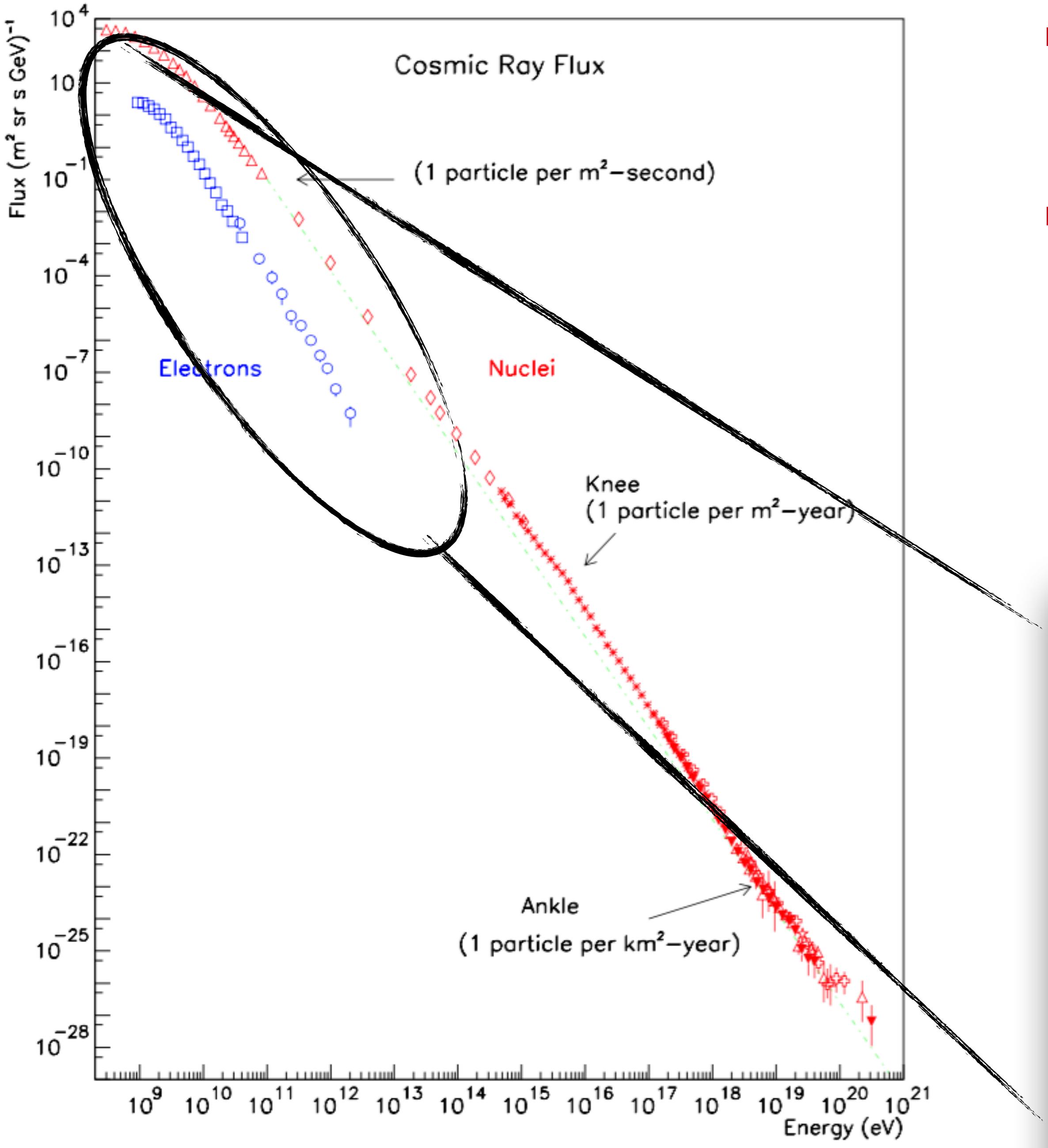
WORLD FEDERATION OF SCIENTISTS
Founded in Erice
Beijing Geneva Moscow New York

Universität Potsdam

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

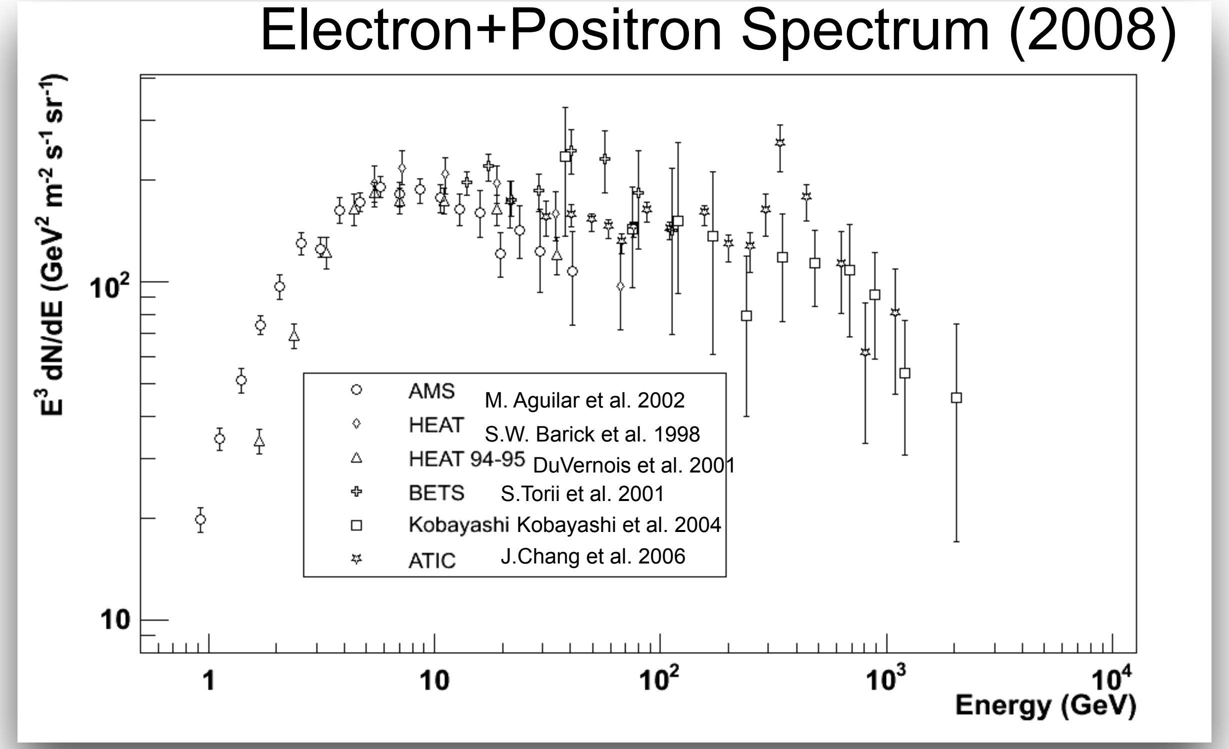
Kathrin Egberts
Potsdam University

Cosmic-Ray Electrons + Positrons

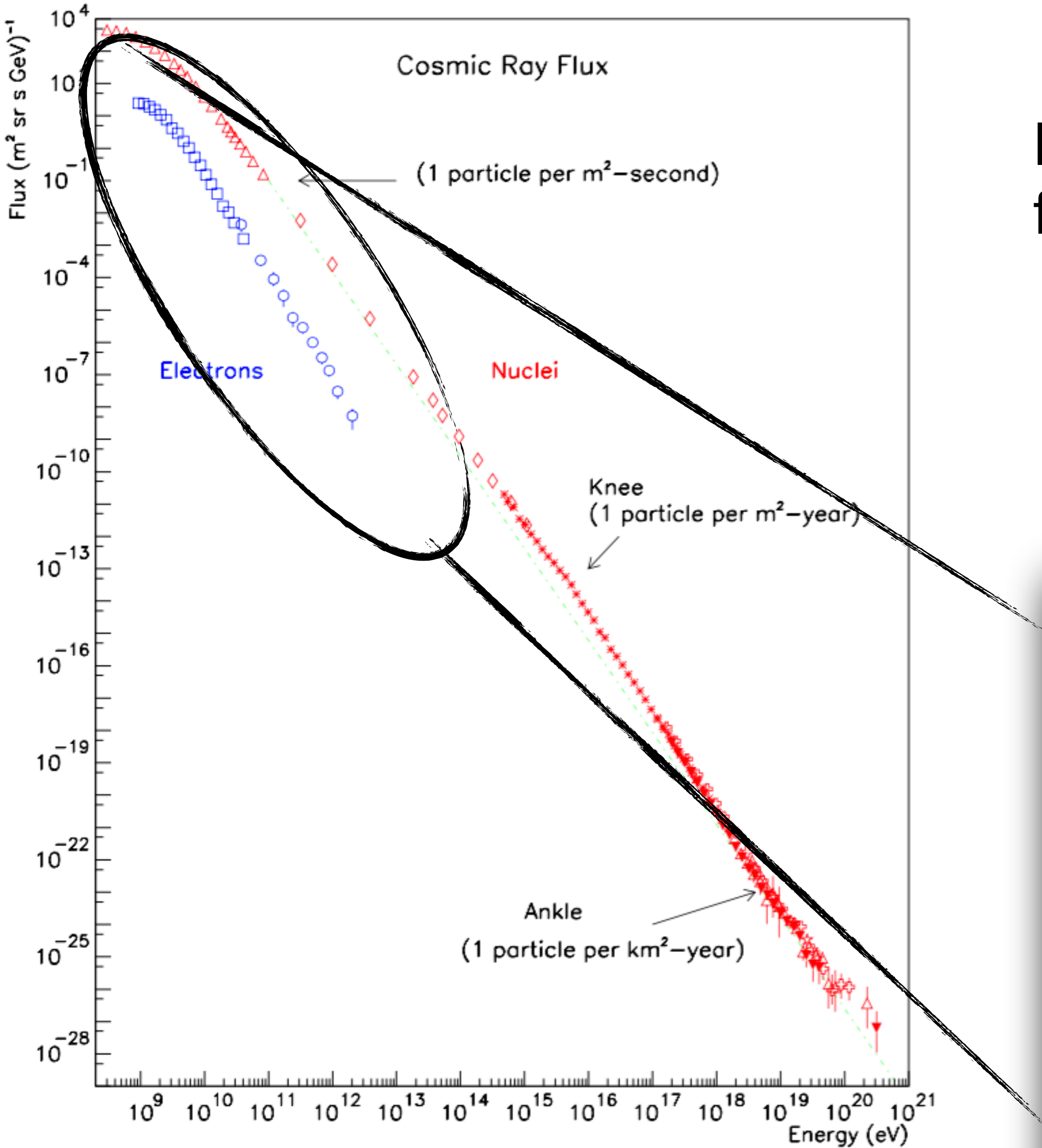


adopted from S. Swordy

- 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



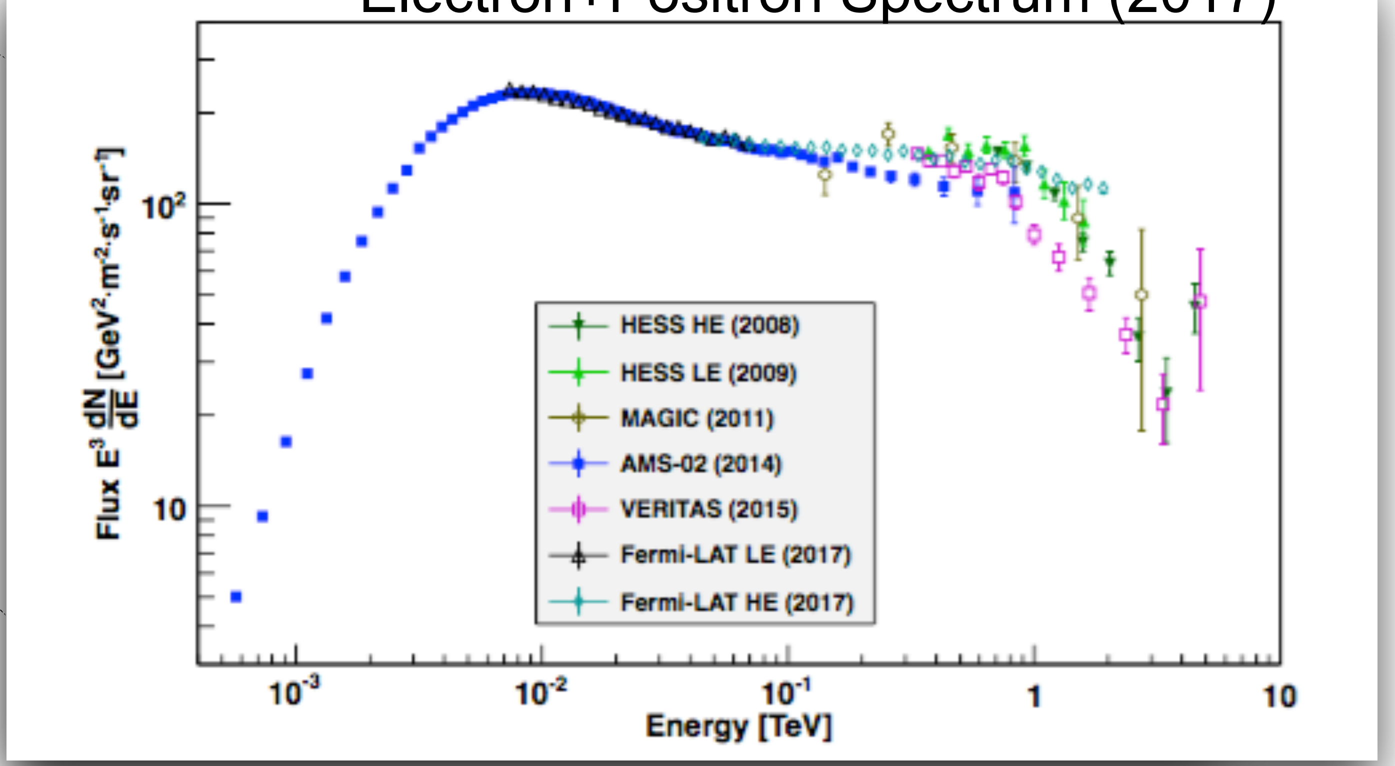
Cosmic-Ray Electrons + Positrons



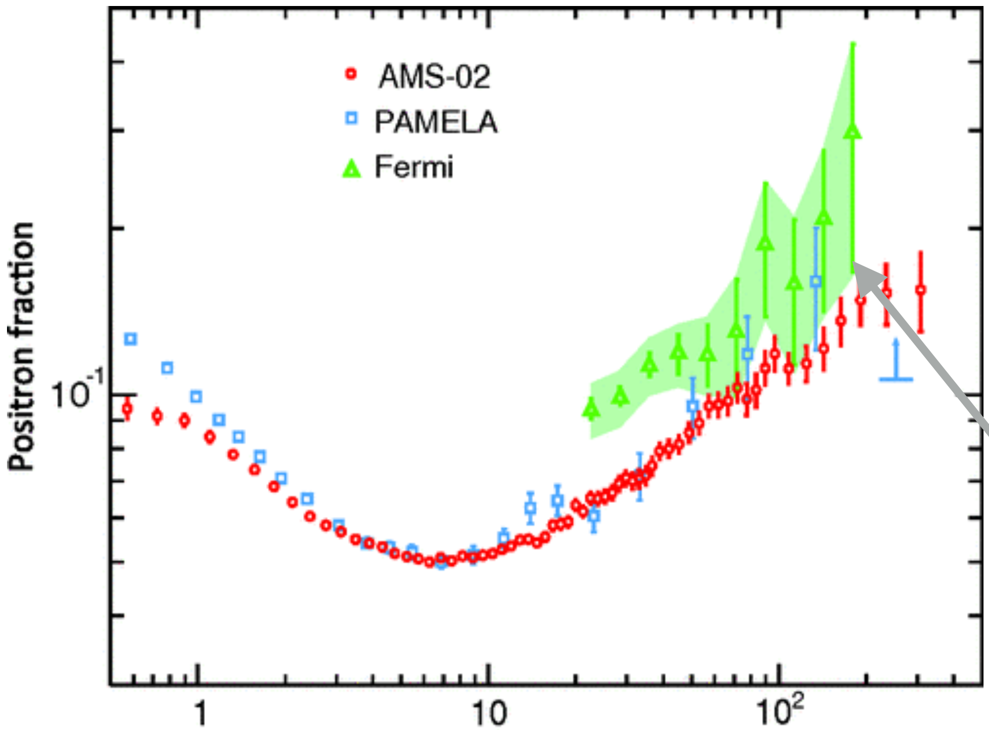
adopted from S. Swordy

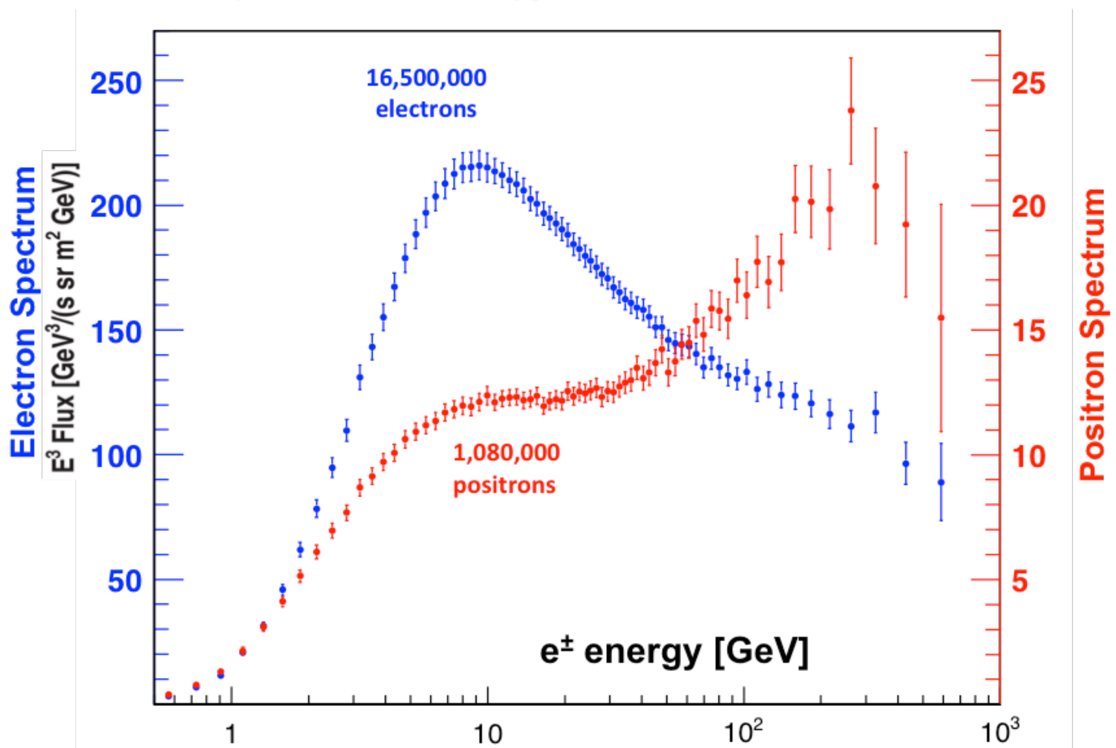
Measurements have made a huge step forward in the past 10 years!

Electron+Positron Spectrum (2017)



Cosmic-Ray Electrons + Positrons



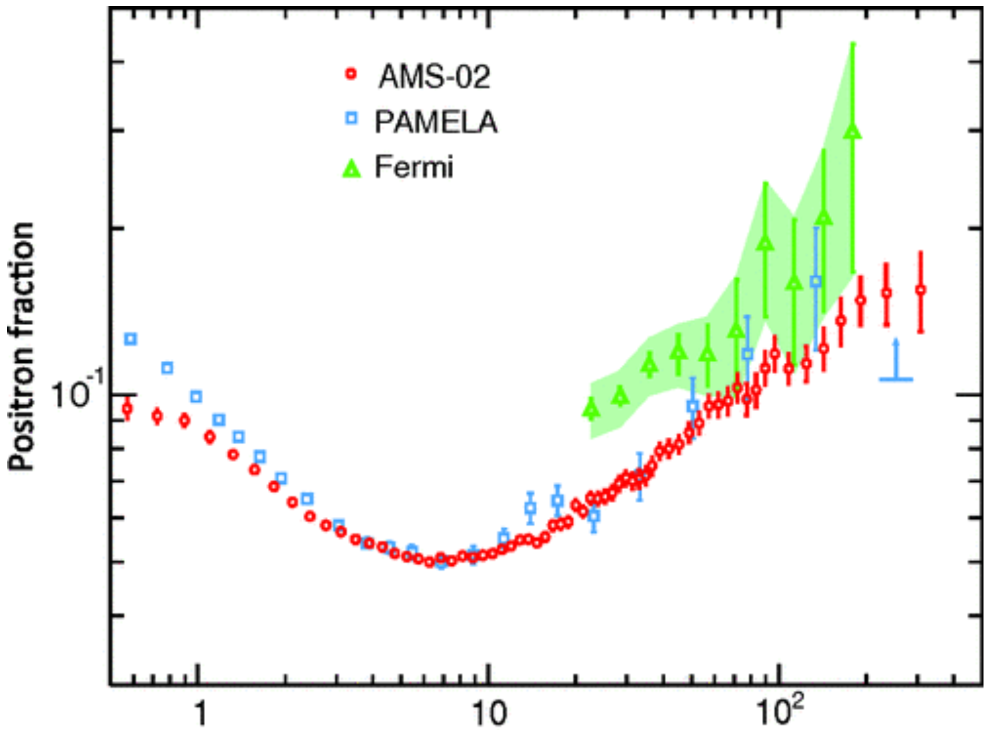


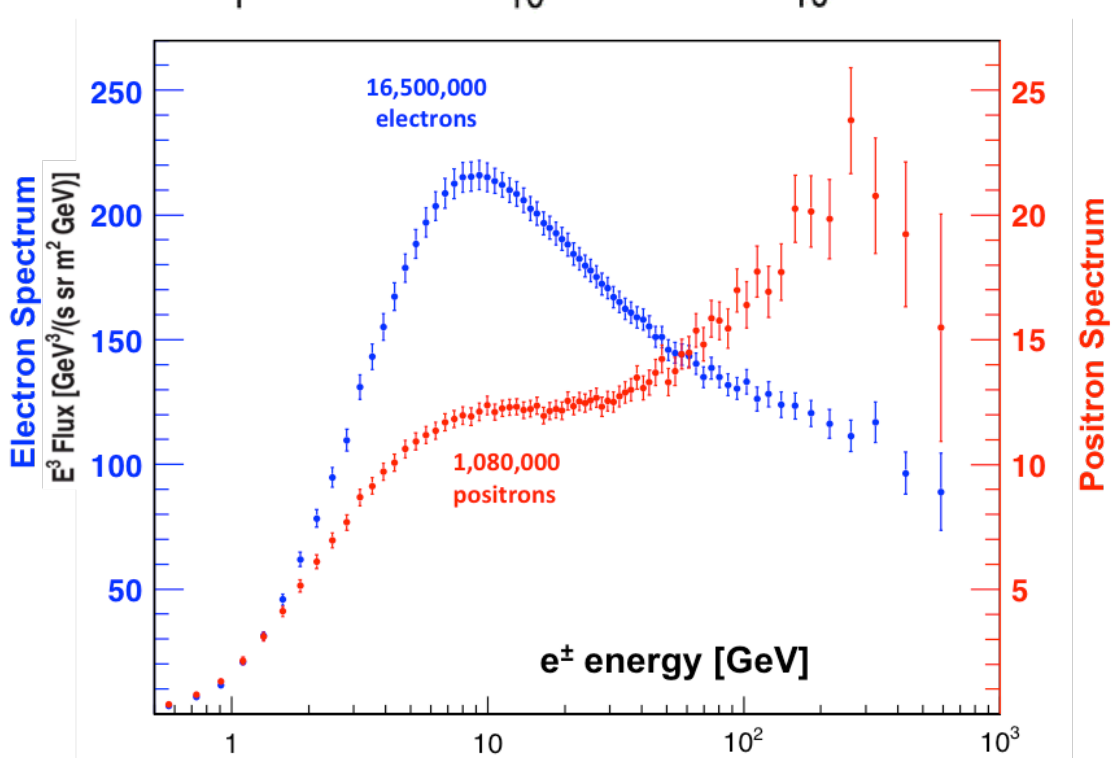
- Further observables, using magnetic fields:
  separation of e^- + e^+
- Either as positron fraction $e^+/(e^- + e^+)$ (cancellation of systematics!)
  or as e^- spectrum and e^+ spectrum

Fermi-LAT: measurement using Earth shadow, which is offset in opposite directions for opposite charges due to Earth magnetic field

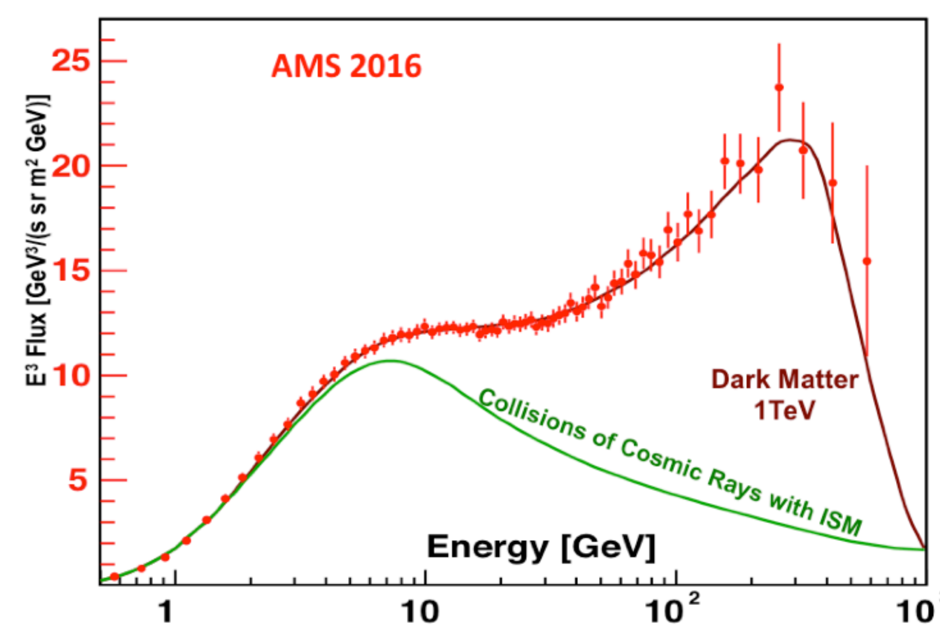
AMS press release Dec 2016

“Anomalous” Positron Fraction?





- Positrons assumed to be produced only as secondaries:
  CR + ISM → π → μ± → e±
- Expectation of a falling positron fraction with energy (to follow B/C ratio)
- Rise suggests a primary component: Dark matter?



AMS press release Dec 2016

Or Rather Astrophysical Phenomena?

- Radioactive decays in SNRs

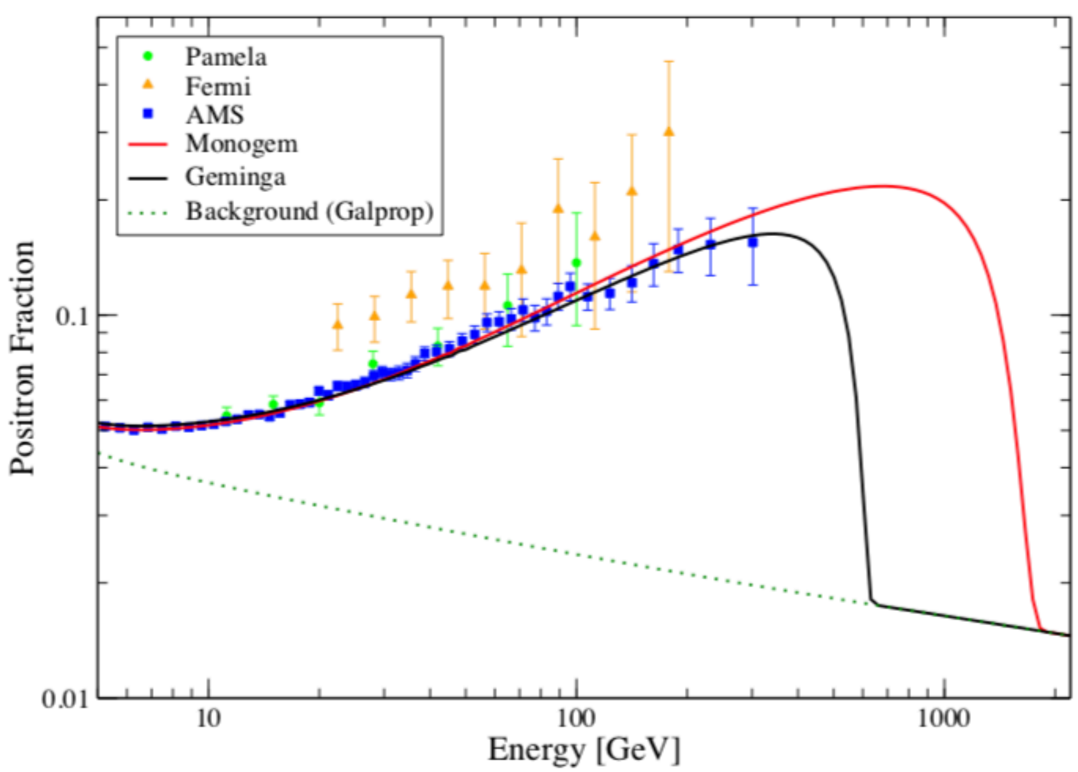
$$^{56}Ni \Rightarrow ^{56}Co \Rightarrow ^{56}Fe + e^{+} + \gamma$$

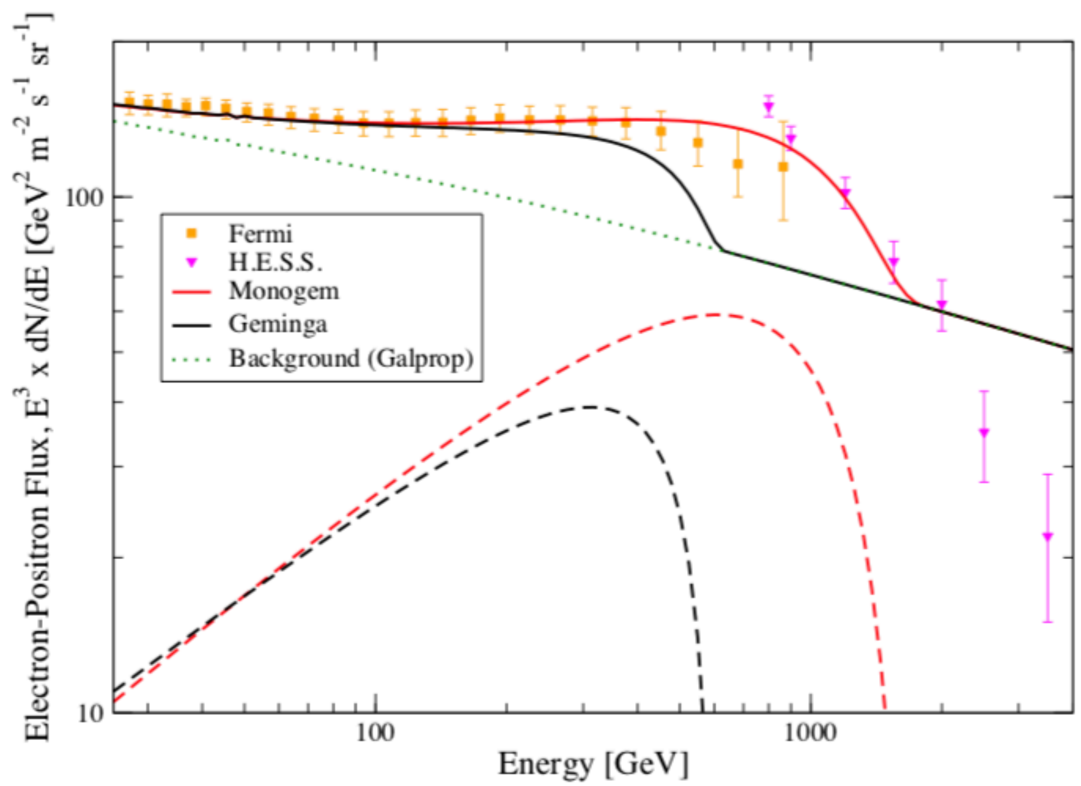
$$^{44}Ti \Rightarrow ^{44}Sc + e^{-} \Rightarrow ^{44}Ca + e^{+} + e^{-}$$

$T_{1/2,\, Ni}$ = 6.1 days, $T_{1/2,\, Co}$ = 77 days

$T_{1/2,\, NiTi}$ = 63 years

- Pulsars





Linden, Profumo, Astrophys. J. 2013

Cosmic-Ray Electrons at TeV energies

- Severe energy losses of TeV electrons by inverse Compton and synchrotron radiation (small masses!)
- Energy loss prop to E^2 (in Thomson limit): $dE/dt = -b\,E^2$
- $\rightarrow$ the maximum energy an electron can have after time t is $E_{max} = 1/bt$

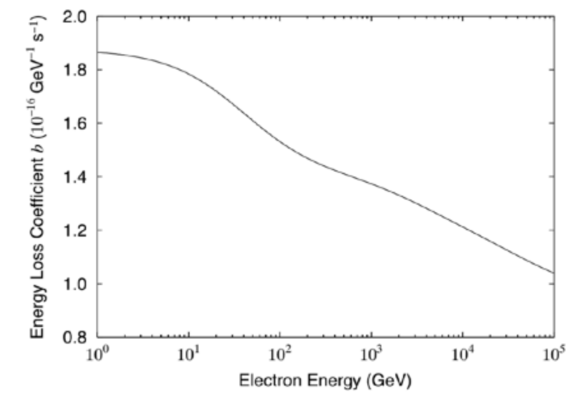


Fig. 1.— Energy loss coefficient of cosmic-ray electrons in the Galaxy with energy. The magnetic field is assumed to be $B_\perp = 5\mu$G.

Kobayashi et al., ApJ 601 340-351 (2004)

- Cooling time: $t_{cool} = E/\dot{E} \sim 1/E$

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

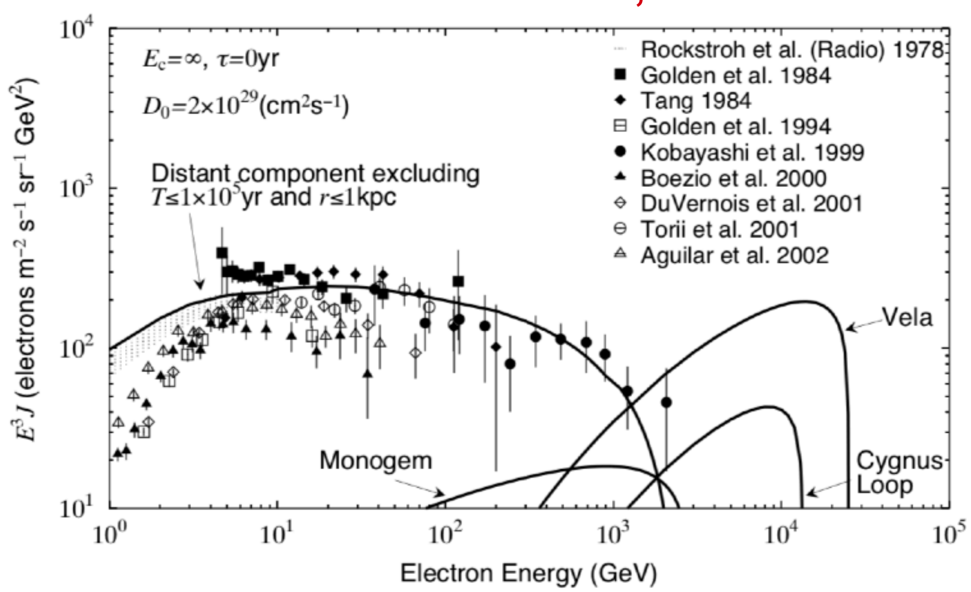
  TeV $e^\pm$ must have been injected not much longer than ~10^5 yr ago

- Propagation distance: ~ $\sqrt{D\,T_{cool}}$ ~ 100-500 pc for TeV $e^\pm$ (assuming reasonable diffusion coefficient D)

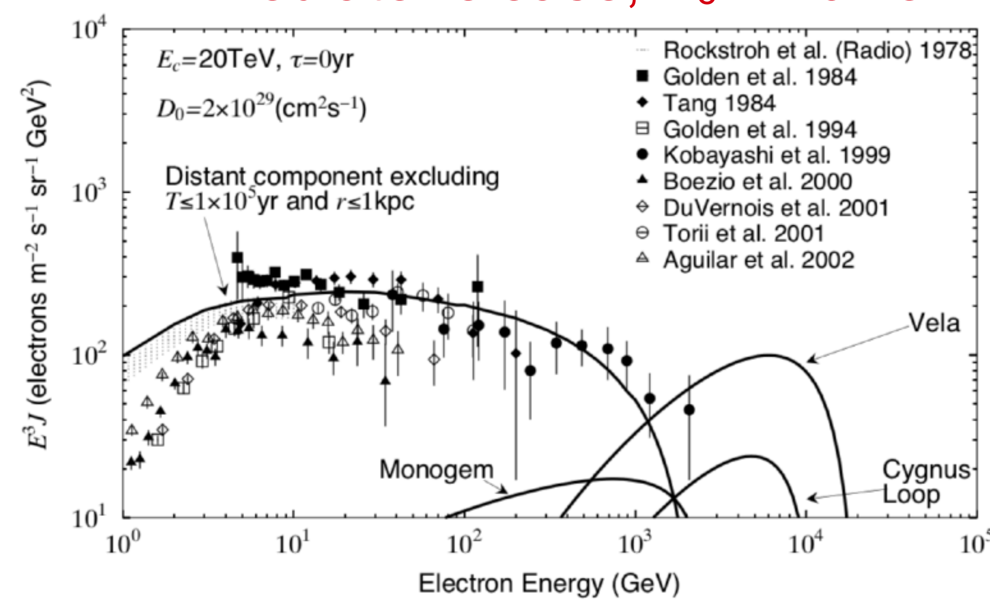
Only limited number of nearby accelerators can contribute to the overall spectrum!

Considering nearby and recent SNRs:

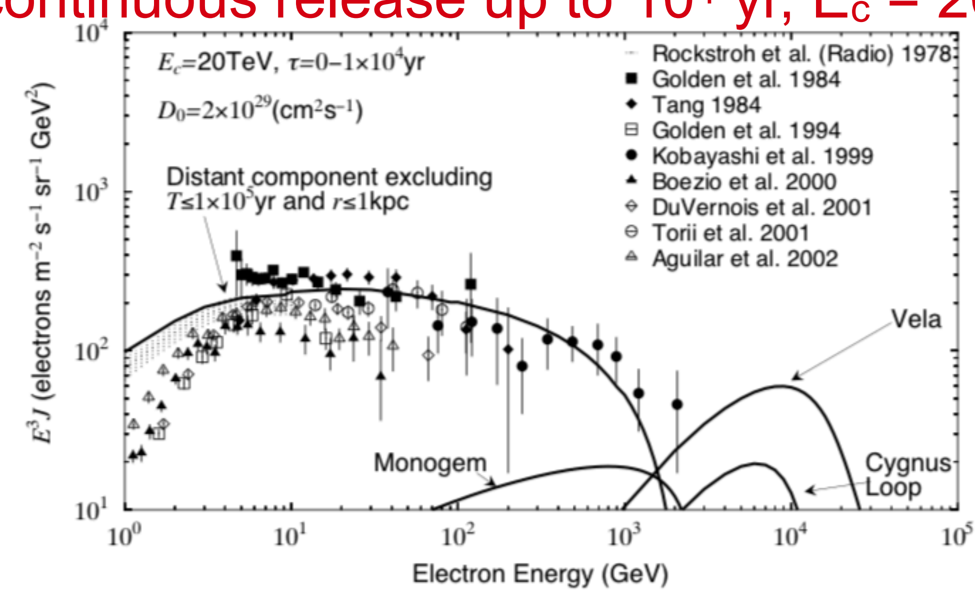
immediate release, no cutoff



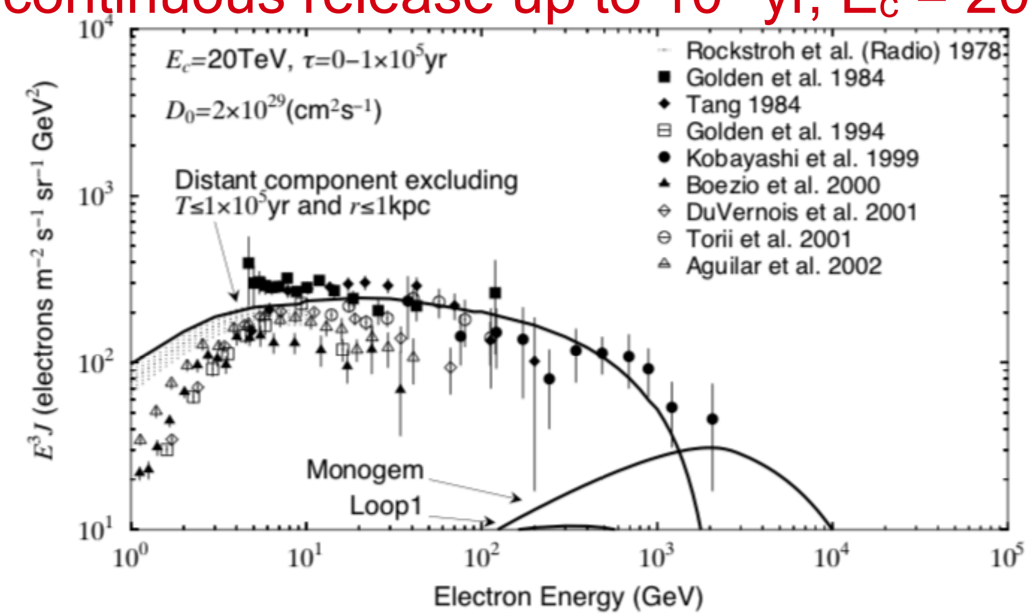
immediate release, E_c = 20 TeV



continuous release up to 10^4 yr, E_c = 20 TeV



continuous release up to 10^5 yr, E_c = 20 TeV

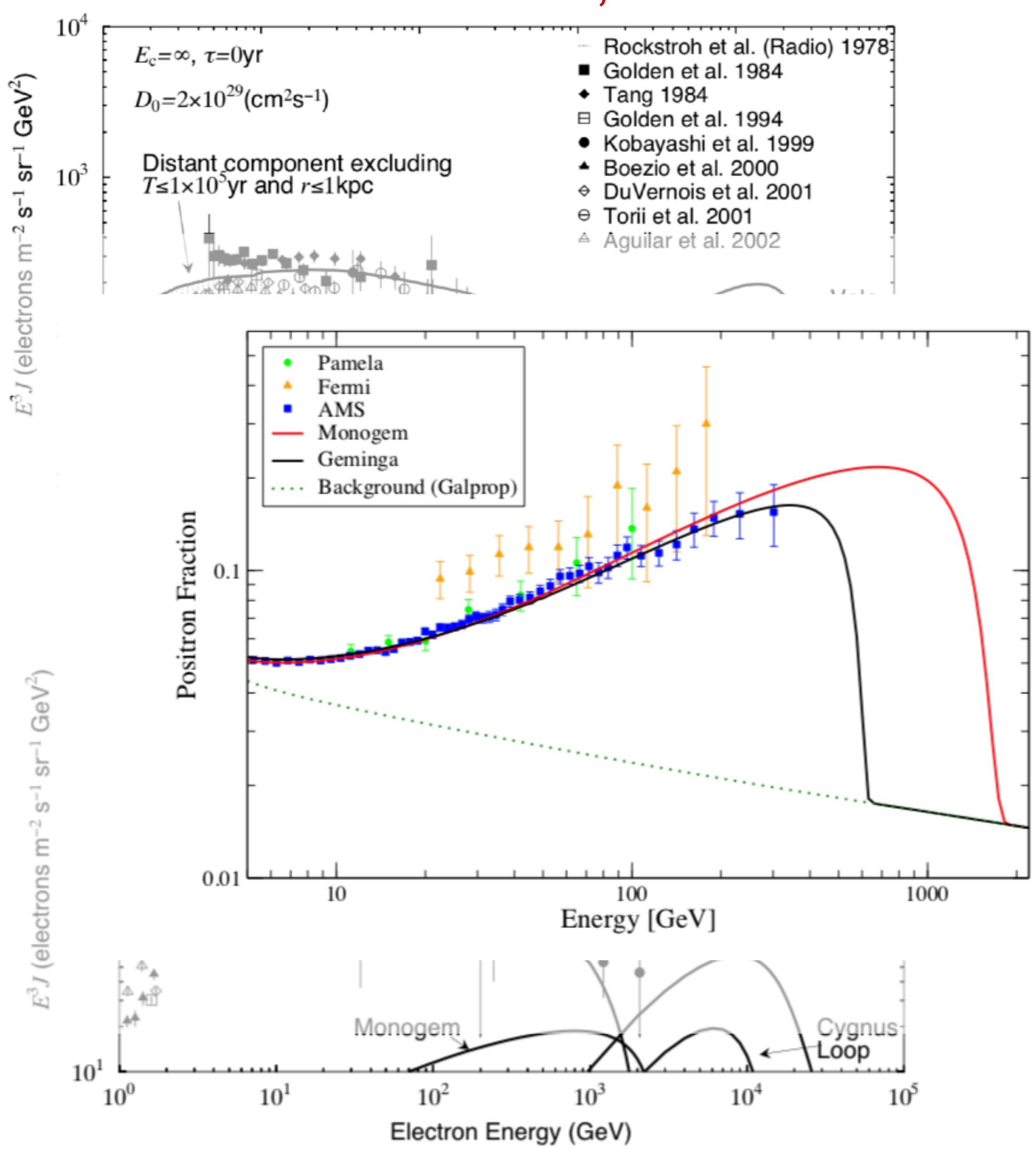


Kobayashi et al., ApJ 601 340-351 (2004)

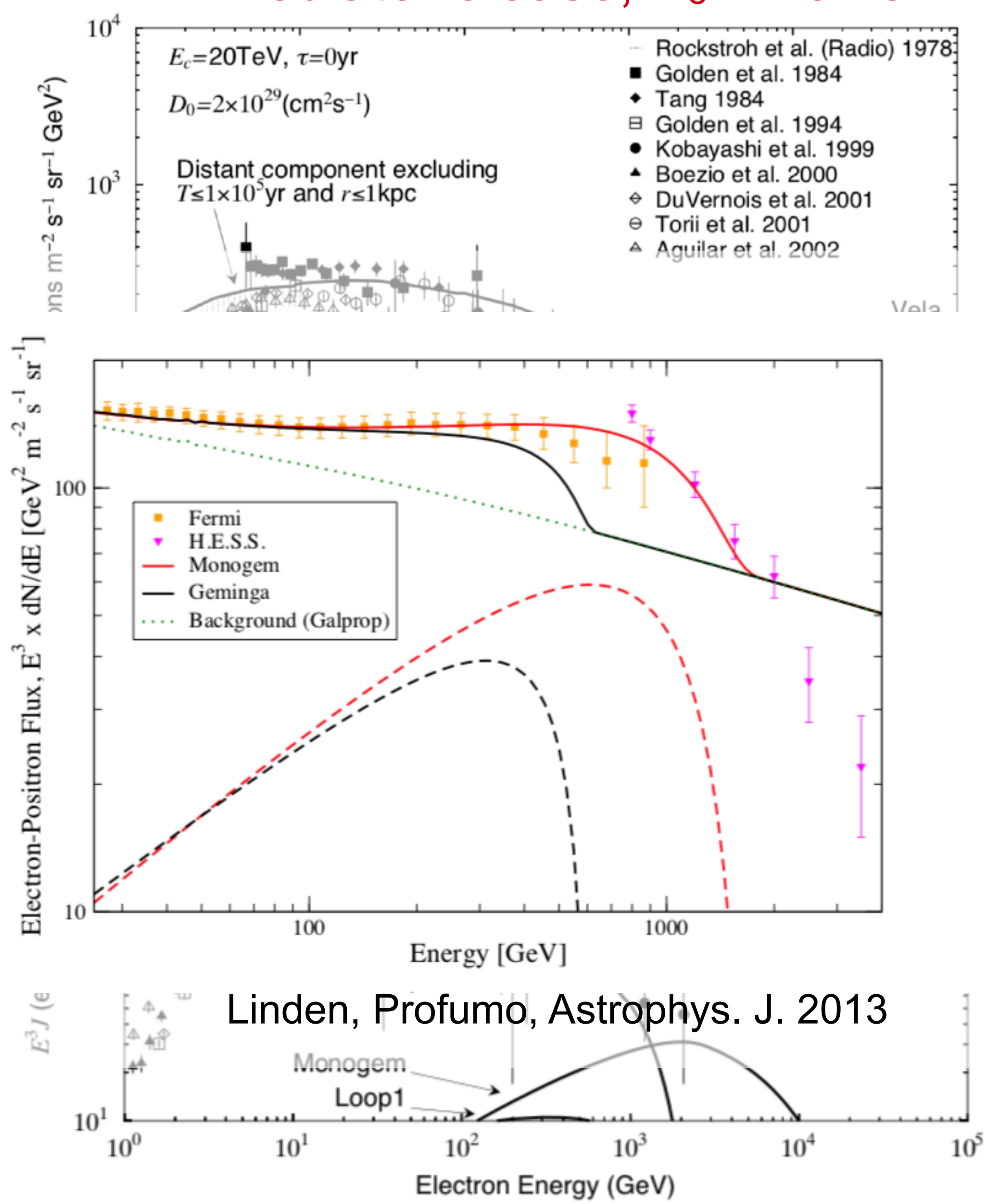
Only limited number of nearby accelerators can contribute to the overall spectrum!

Considering nearby and recent SNRs: + Pulsars/Pulsar Wind Nebulae!

immediate release, no cutoff



immediate release, E_c = 20 TeV

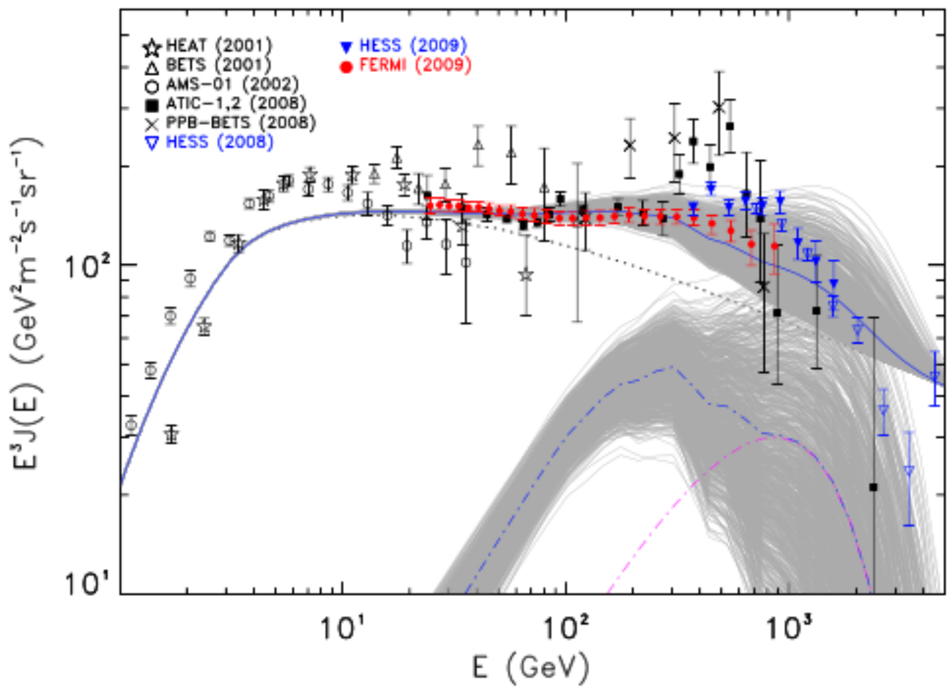


Linden, Profumo, Astrophys. J. 2013

Kobayashi et al., ApJ 601 340-351 (2004)

Is that all?

- All sources considered? selection biases
- Uncertainties in distance estimates
- Surveys using el.-mag. radiation: bias due to different propagation of photons and CRs
- Difficult to determine the complete real distribution of sources



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

→ Stochastic source distribution

Cosmic-Ray Electrons at TeV energies: Conclusions

- Low predictive power of what is happening at TeV energies
- Sources are discrete, potential to see direct imprint of local accelerators on the electron spectrum
- Shape of the spectrum very sensitive to exact distribution of sources in our Galactic neighbourhood and their properties

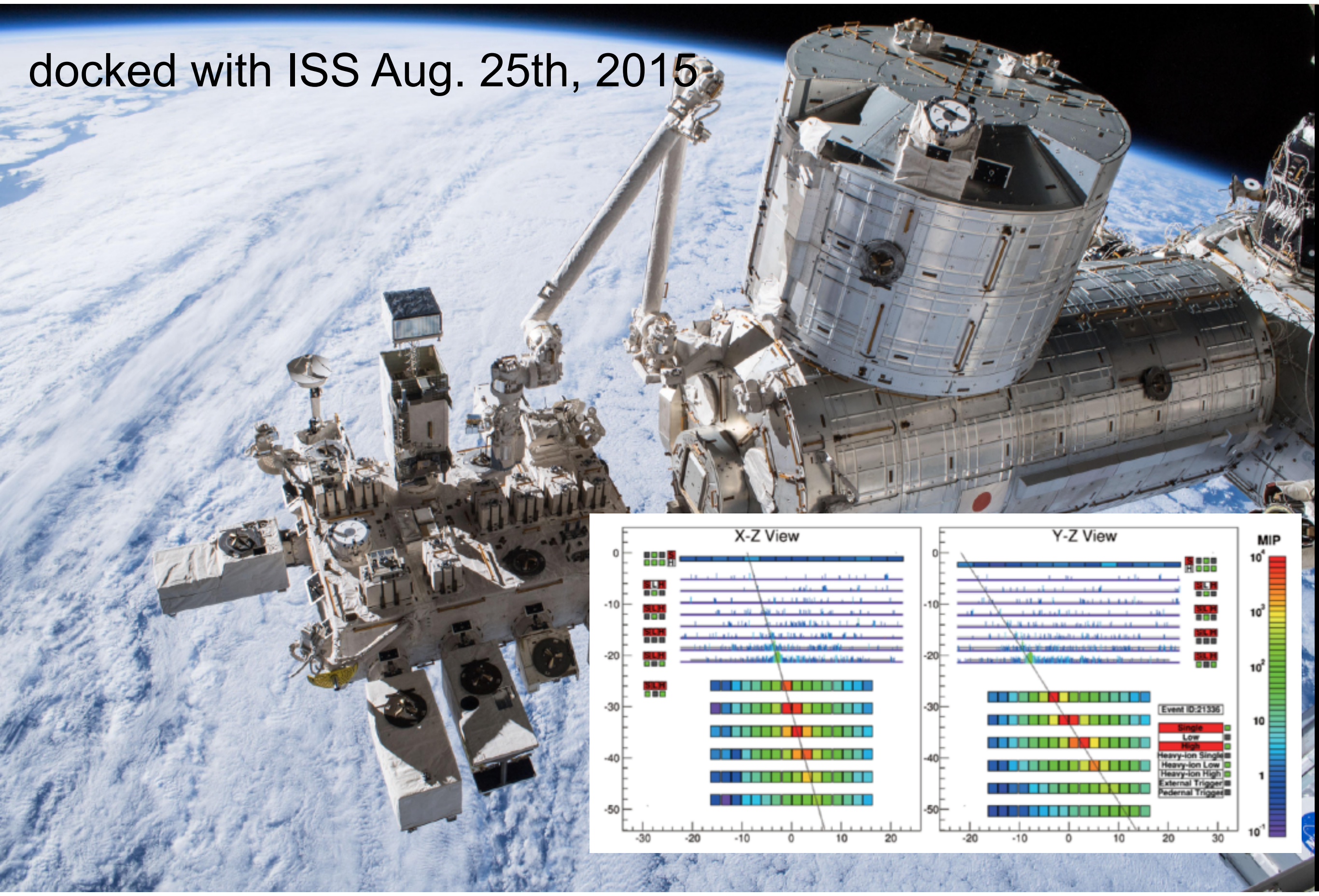
Cosmic-Ray Electron Measurements at TeV Energies

Measurements need

- High statistics: large effective areas and field of view and long observation times
  - exposure = $A_{eff} \times FoV \times T_{obs}$
- Deep calorimeters for TeV energy reconstruction
- Excellent electron-hadron separation capabilities

A New Generation of Space-Born Experiments

CALorimetric Electron Telescope (CALET)

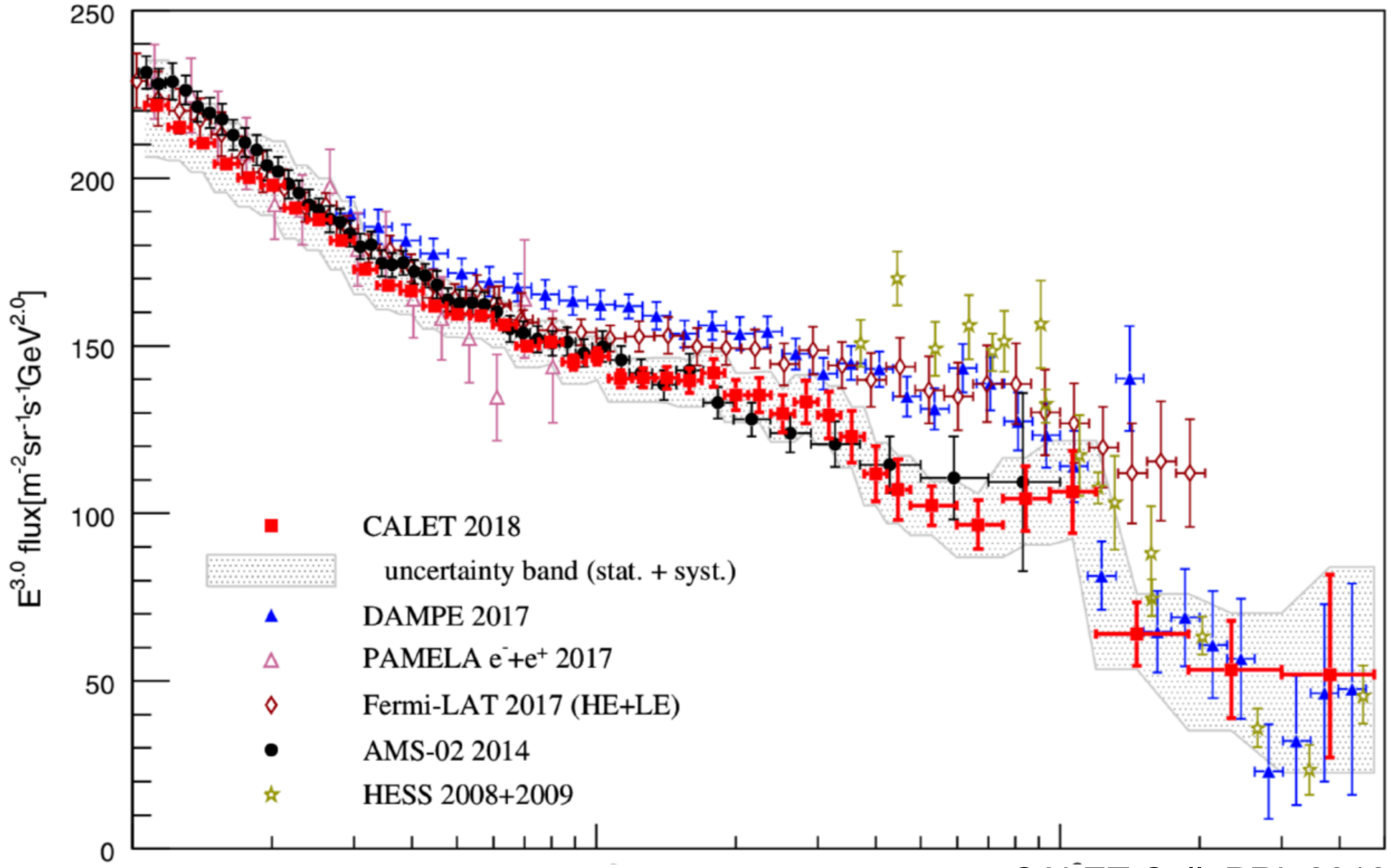


DArk Matter Particle Explorer (DAMPE)

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

A New Generation of Space-Born Experiments

CALorimetric Electron Telescope (CALET) **DArk Matter Particle Explorer (DAMPE)**



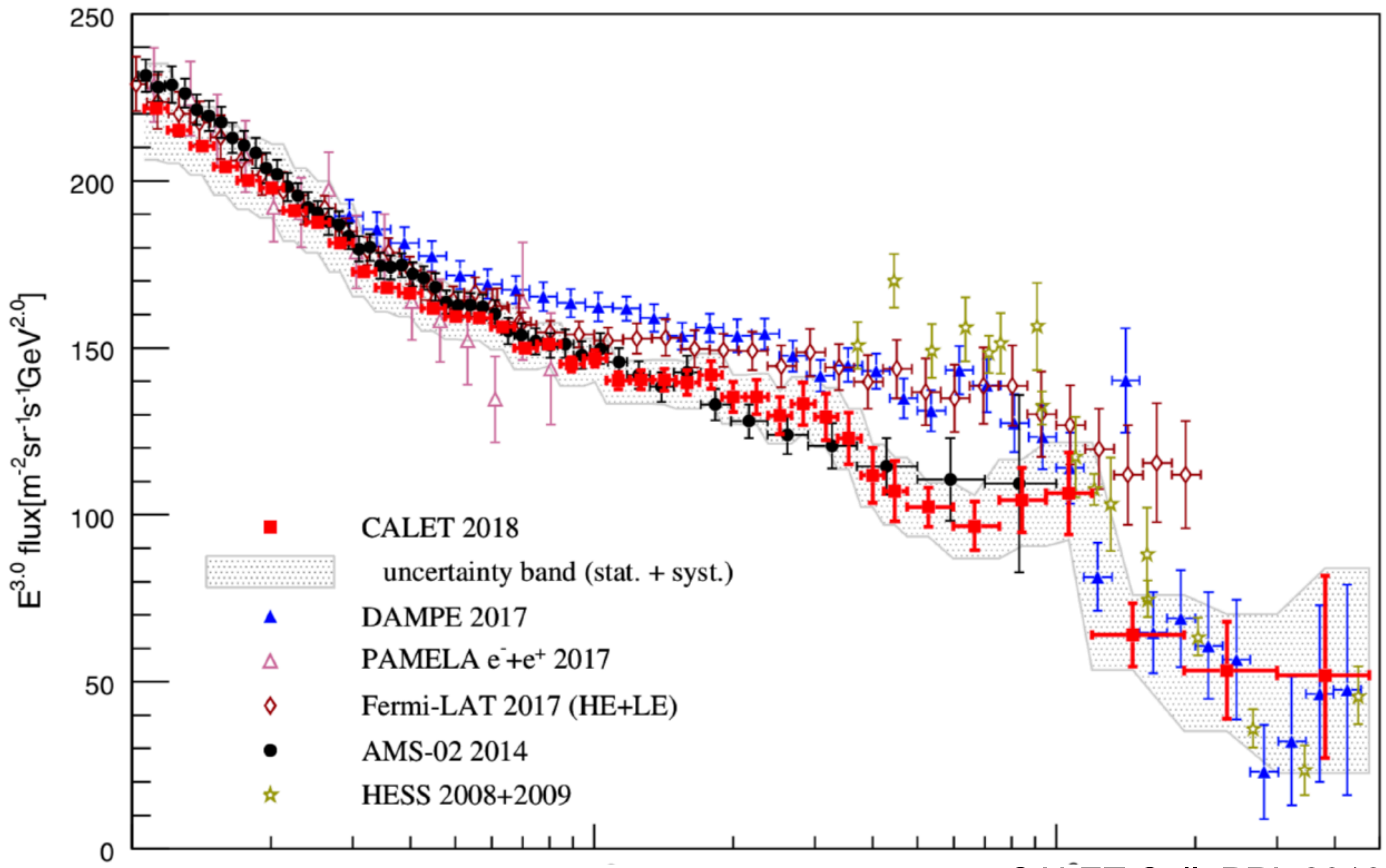
CALET Coll, PRL 2018

- Below 50 GeV agreement between Fermi, AMS, DAMPE, CALET
- At ~50 GeV diverging hardening, which splits the data into two groups: AMS&CALET, Fermi&DAMPE
- AMS&DAMPE observe a dip in the spectrum between 300 GeV to 1 TeV
- Beyond 1 TeV agreement between DAMPE and CALET (poor statistics)

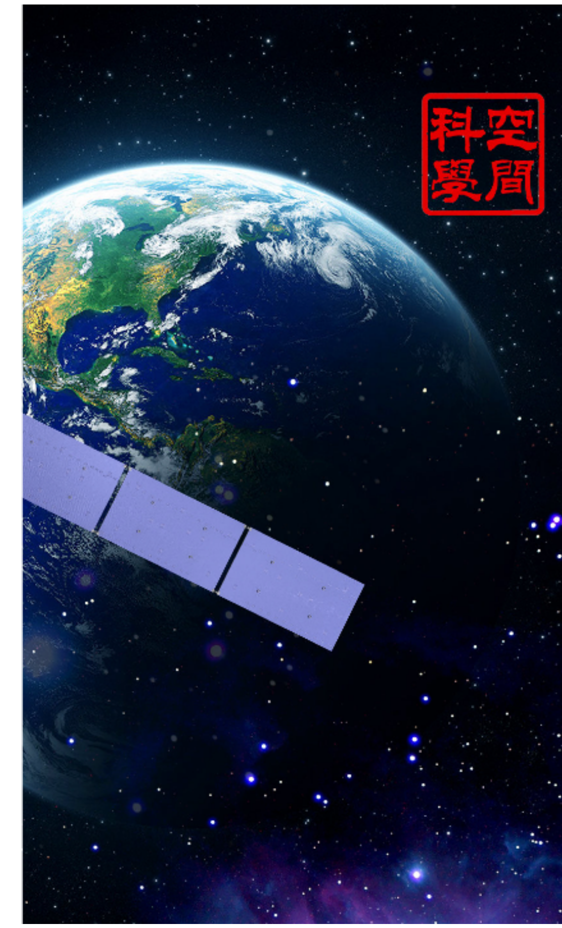
A New Generation of Space-Born Experiments

CALorimetric Electron Telescope (CALET)

DArk Matter Particle Explorer (DAMPE)



CALET Coll, PRL 2018



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

- Γ = 3.15 ± 0.02 → 3.81 ± 0.32, if fixing E_b = 914 GeV
- χ^2/ndof = 17/25, pure power-law: χ^2/ndof = 26.5/26

- Γ = 3.09 ± 0.01 → 3.92 ± 0.20, E_b = 914 ± 98 GeV
- χ^2/ndof = 23.3/18, pure power-law: χ^2/ndof = 70.2/20

Ground-Based Measurements

- Imaging atmospheric Cherenkov telescopes (IACTs) designed for TeV gamma-ray measurements
- Gamma-rays and electrons both produce el.-mag. air showers
- But: gamma-rays are (mostly) localised sources, which allows for simple background subtraction!
  - need to find alternative mechanisms

	IACTs	Satellite
A_{eff}	10^5 m^2	1 m^2
Ω	10 deg^2	10^4 deg^2
T_{obs}	10^3 h/year	10^4 h/year

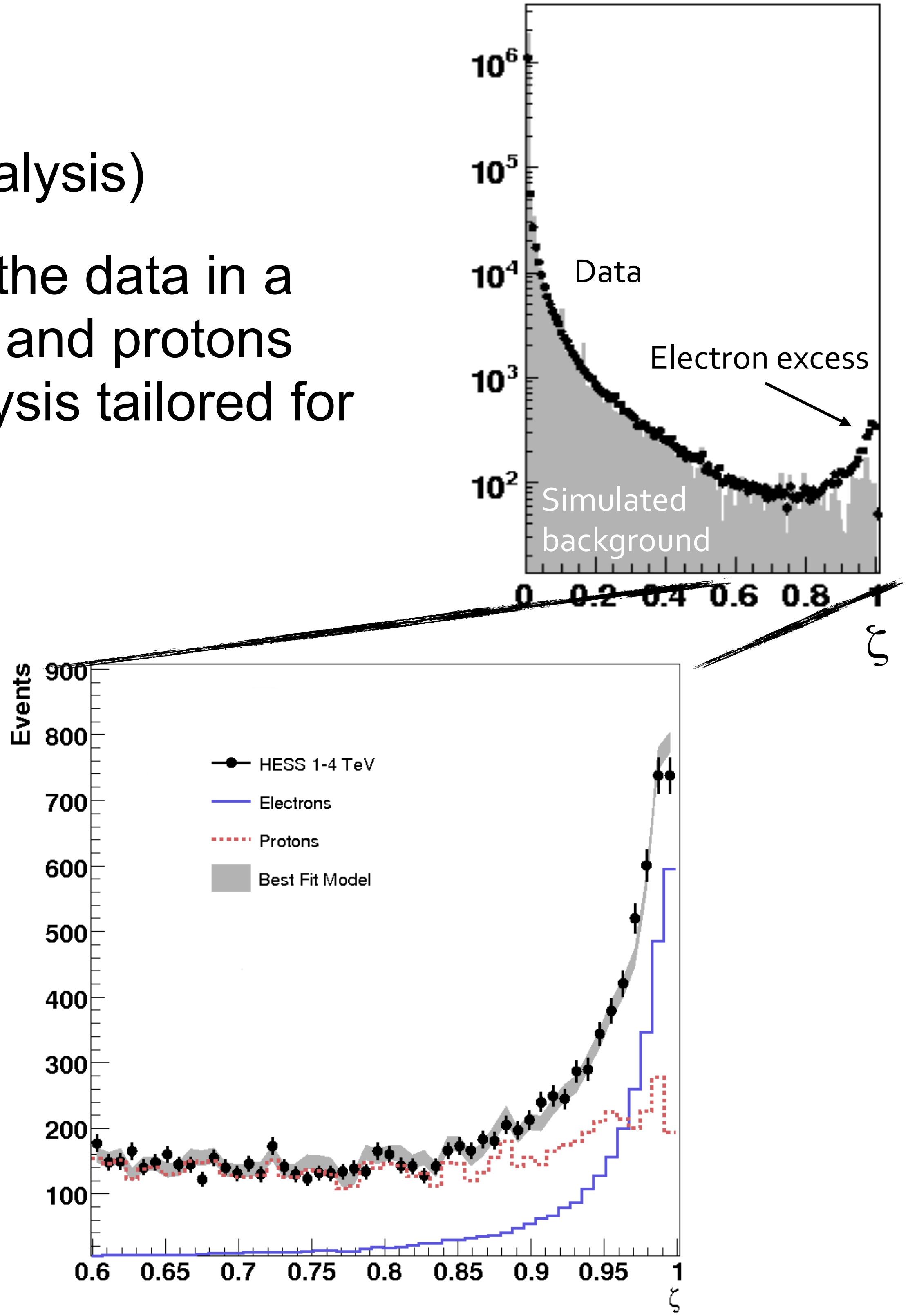
High Energy Stereoscopic System (H.E.S.S.)

Electron Measurement from 2008/2009

- Livetime: 239 h (77 h for the low-energy analysis)
- Hadronic background determined by fitting the data in a discriminator distribution with MC electrons and protons (discriminator: Random Forest output, analysis tailored for this use case)

Drawback:

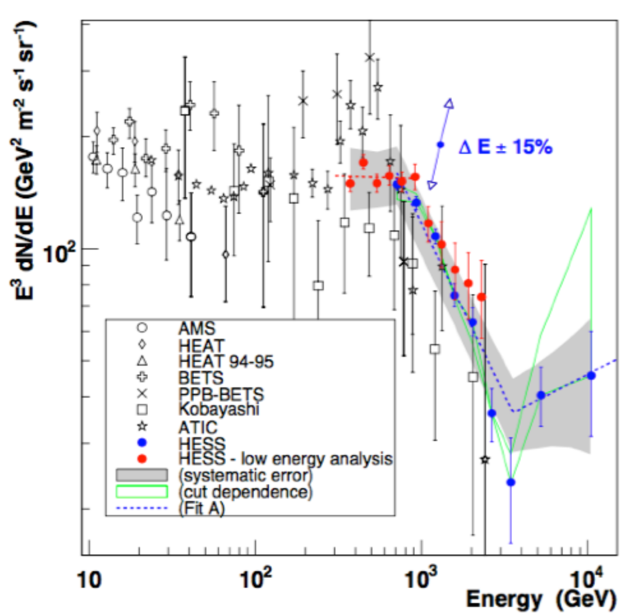
- Proton simulations much less accurate than electron (electromagnetic) ones
- Introduces dependence on hadronic models used (SIBYLL, with QGSJET cross check)

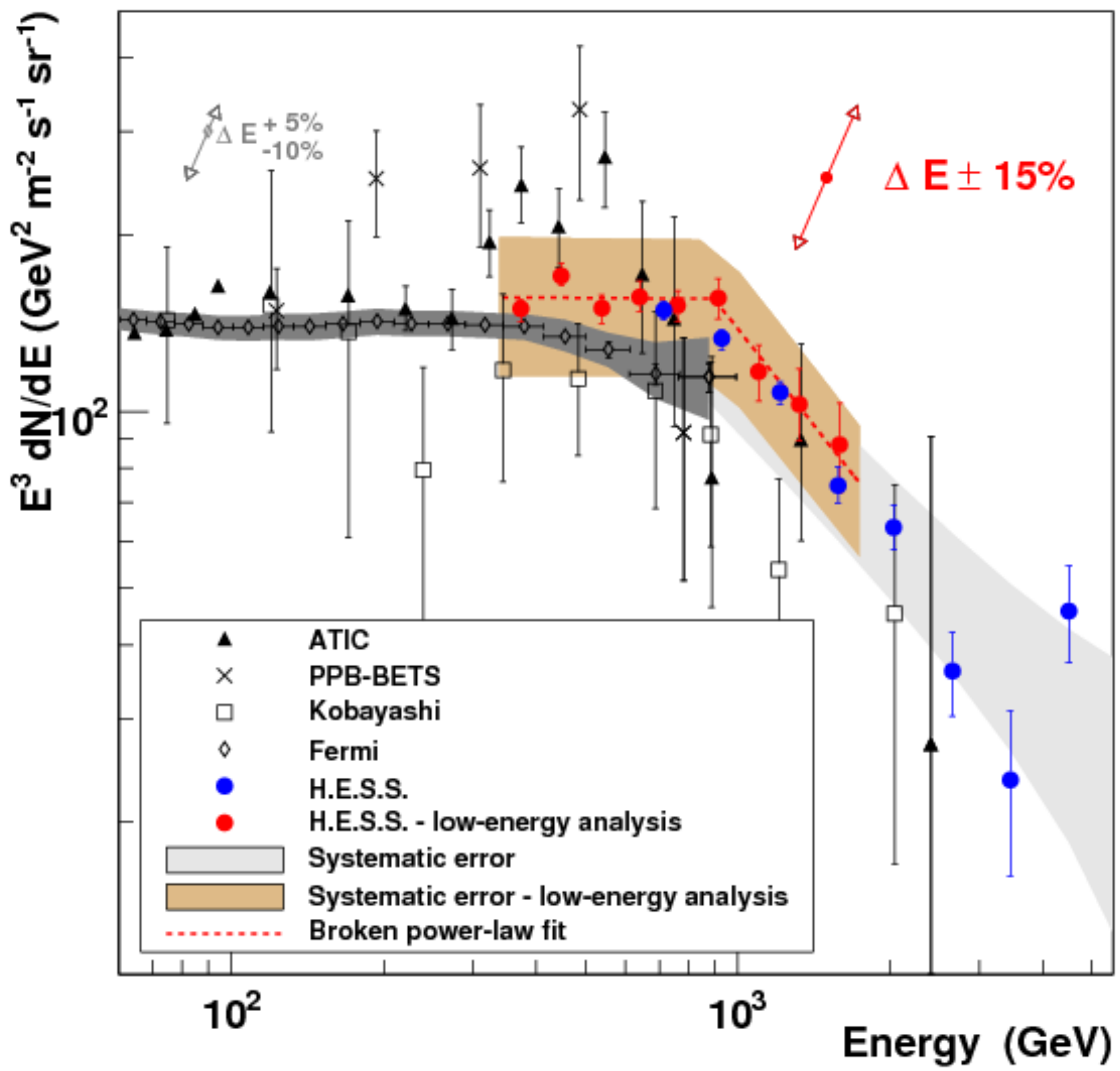


Aharonian et al., PRL **101**, 261104 (2008)

Electron Measurement from 2008/2009

- Measurement dominated by systematic uncertainties due to
  - hadronic interaction model
  - atmospheric uncertainties
- Beyond 6 TeV systematics no longer under control

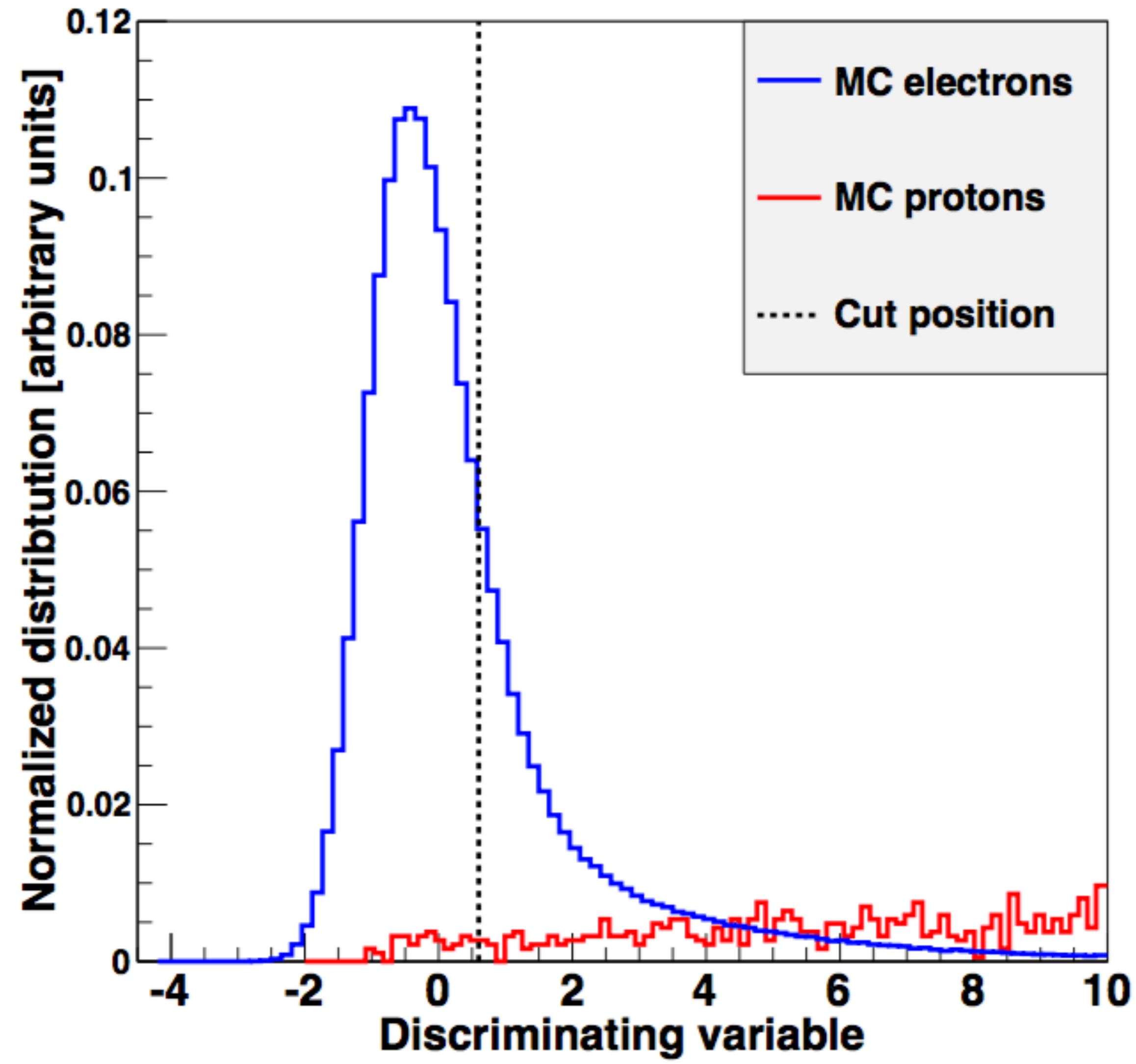




Aharonian et al., A&A 508, 561–564 (2009)

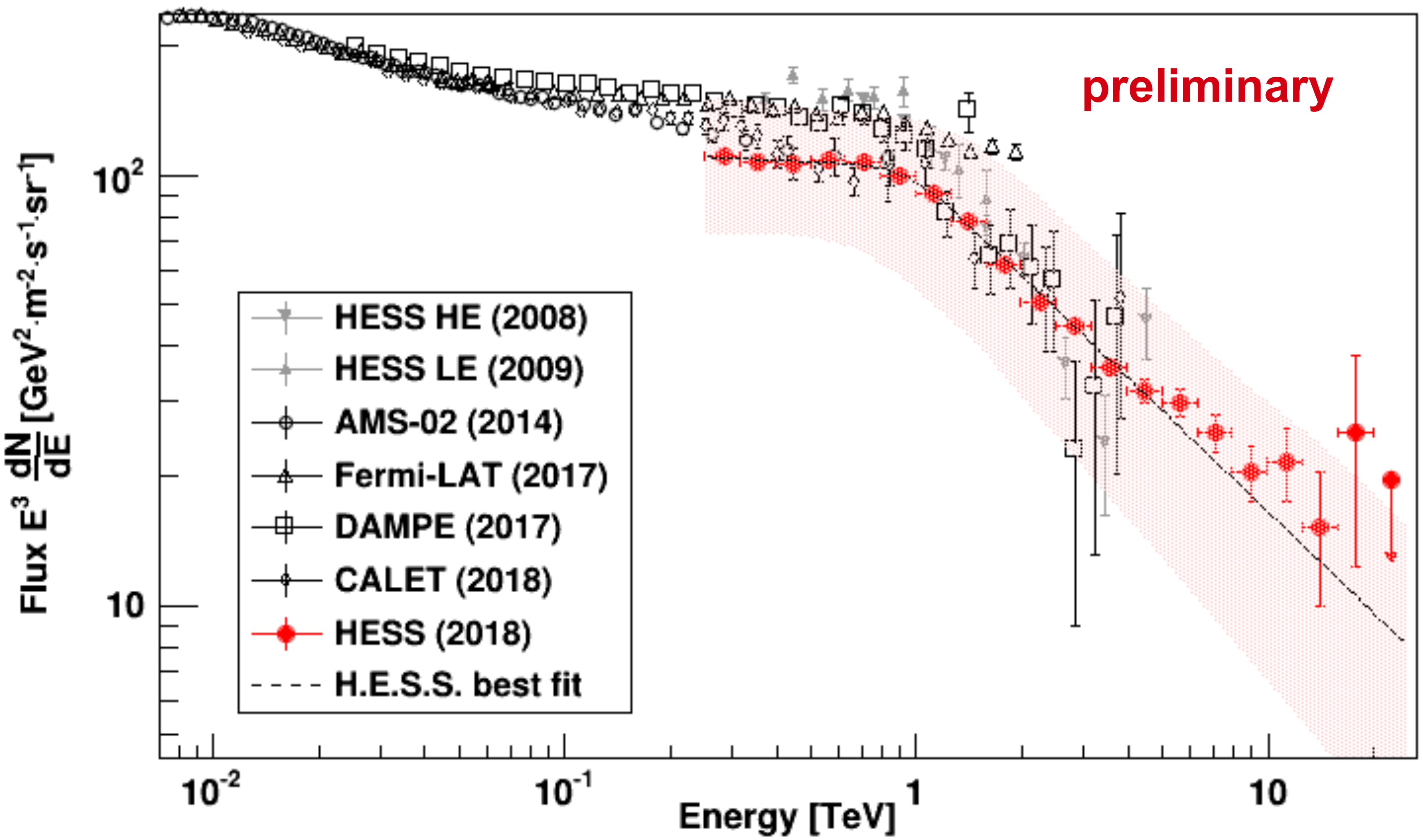
How to Improve: Data Set and Analysis Technique

- Increased data set by factor of 5: 239 h →1186 hours
- Improvements in the analysis methods yield a very powerful hadron rejection:
  - Log-likelihood comparison between recorded images and pre-calculated templates
  - 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



- 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

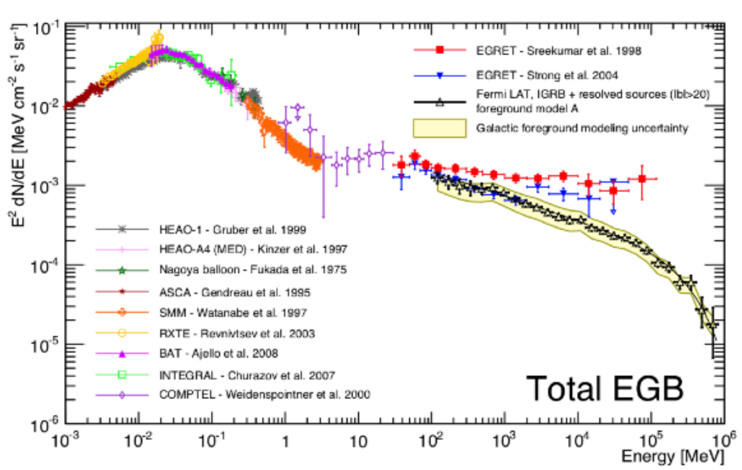
- Cosmic-ray hadrons:
  - A hard cut on the goodness eliminates most of the background
  - Using MC simulations, the residual background can be estimated to be ≲15%

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

Universität Potsdam

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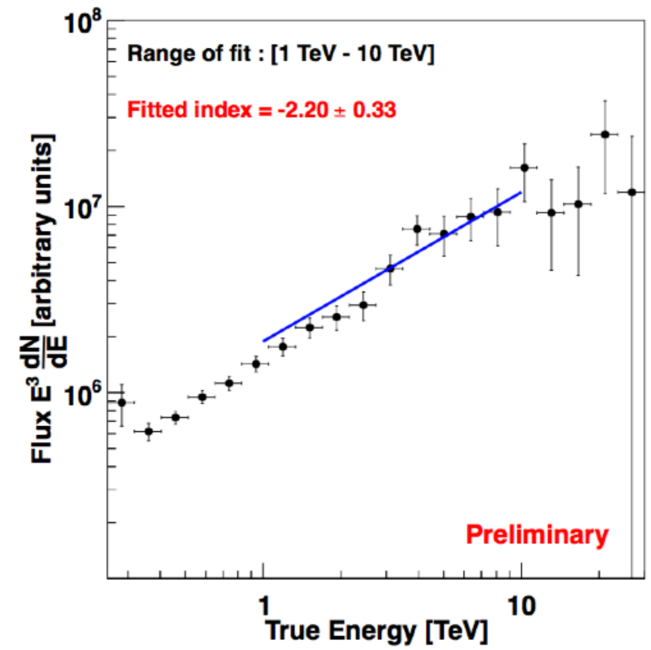

Injection of **MC protons** with simulated spectral index of -2.8 reconstructed using **electrons** acceptance.

- Gamma-rays:
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  - Exclusion of gamma-ray sources and Galactic plane reduces contamination significantly - remaining: high-latitude Galactic diffuse and extragalactic gamma-ray background (EGB)

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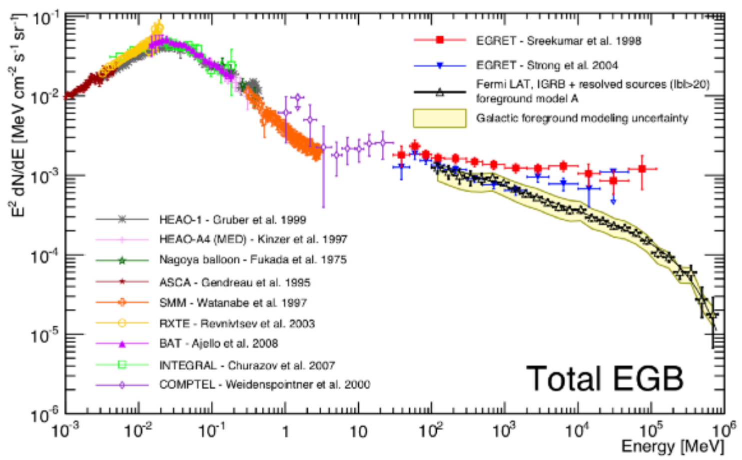
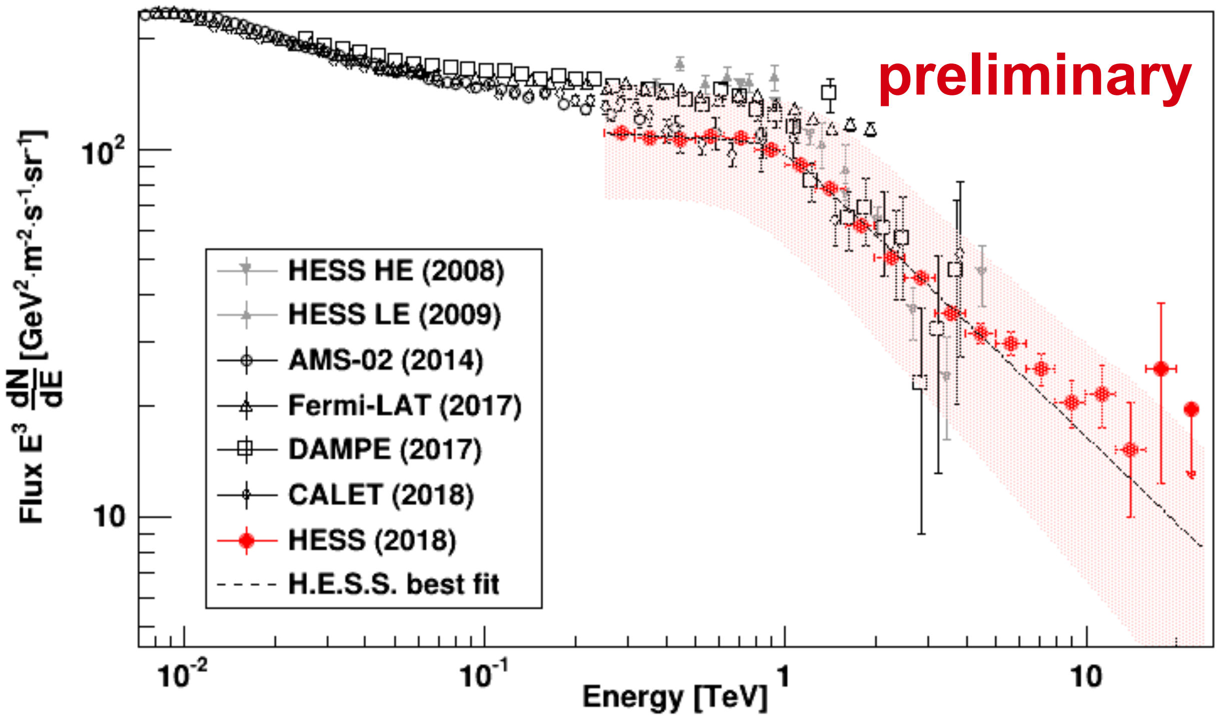


M. Ackermann et al. 2015 ApJ 799 86

Investigation of Systematics

- Drastically reduced due to avoidance of hadronic models
- Stability thoroughly checked, studies included:
  - Test on event selection cuts
  - Dependency on zenith angle
  - Dependency on atmos. conditions
  - Dependency over the years
- Always present: energy scale uncertainty of ΔE/E~15%
- → Mostly *normalisation* uncertainty



Fitting a smoothly broken power-law:

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

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

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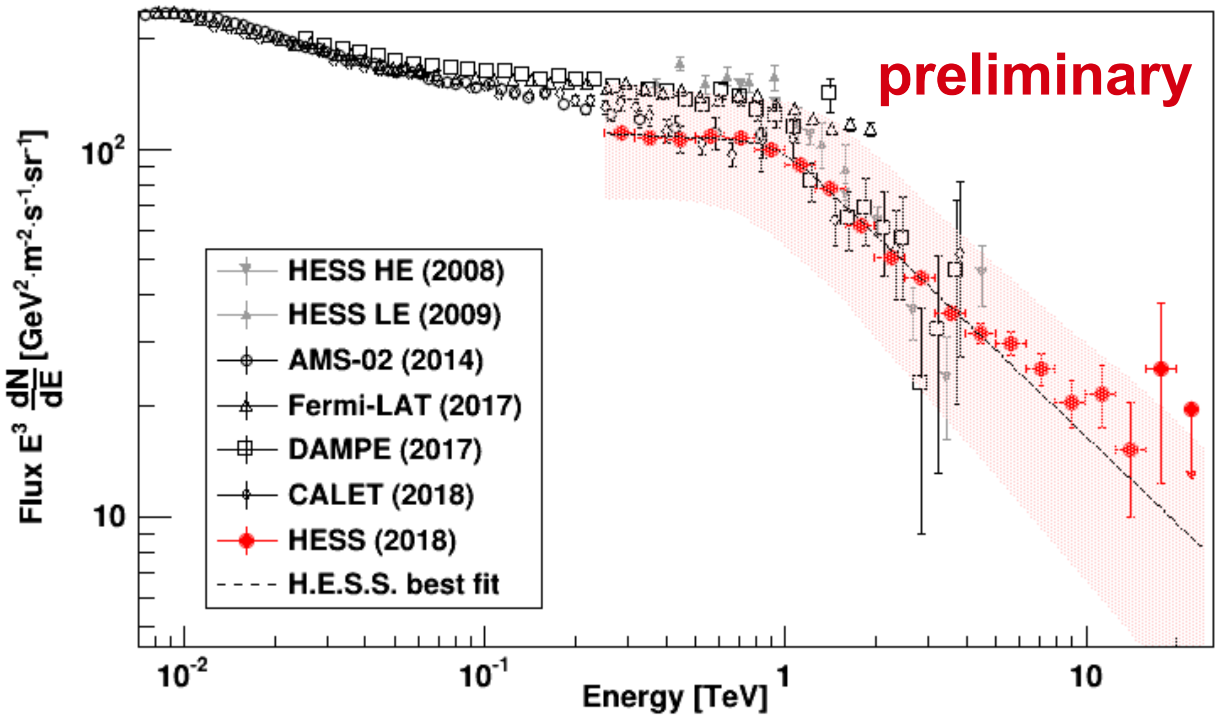

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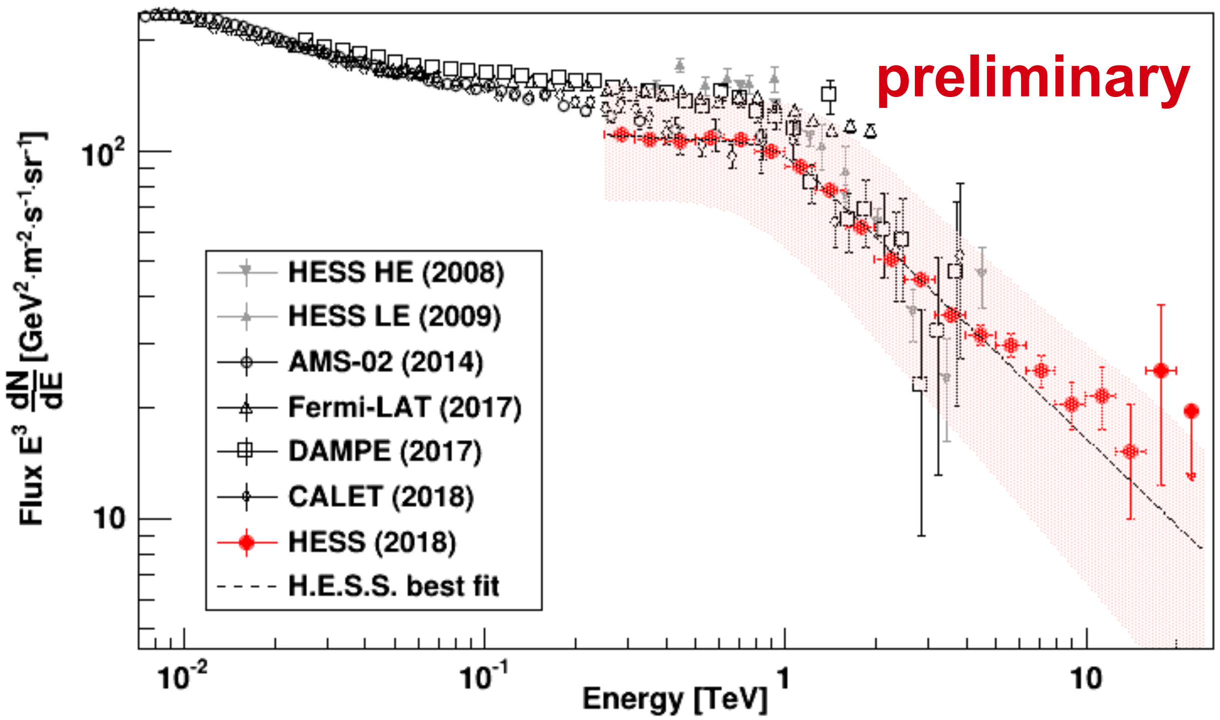
$$\alpha = 0.12 \pm 0.01\ \text{(stat)}\ ^{+0.19}_{-0.05}\ \text{(sys)}$$

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

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

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

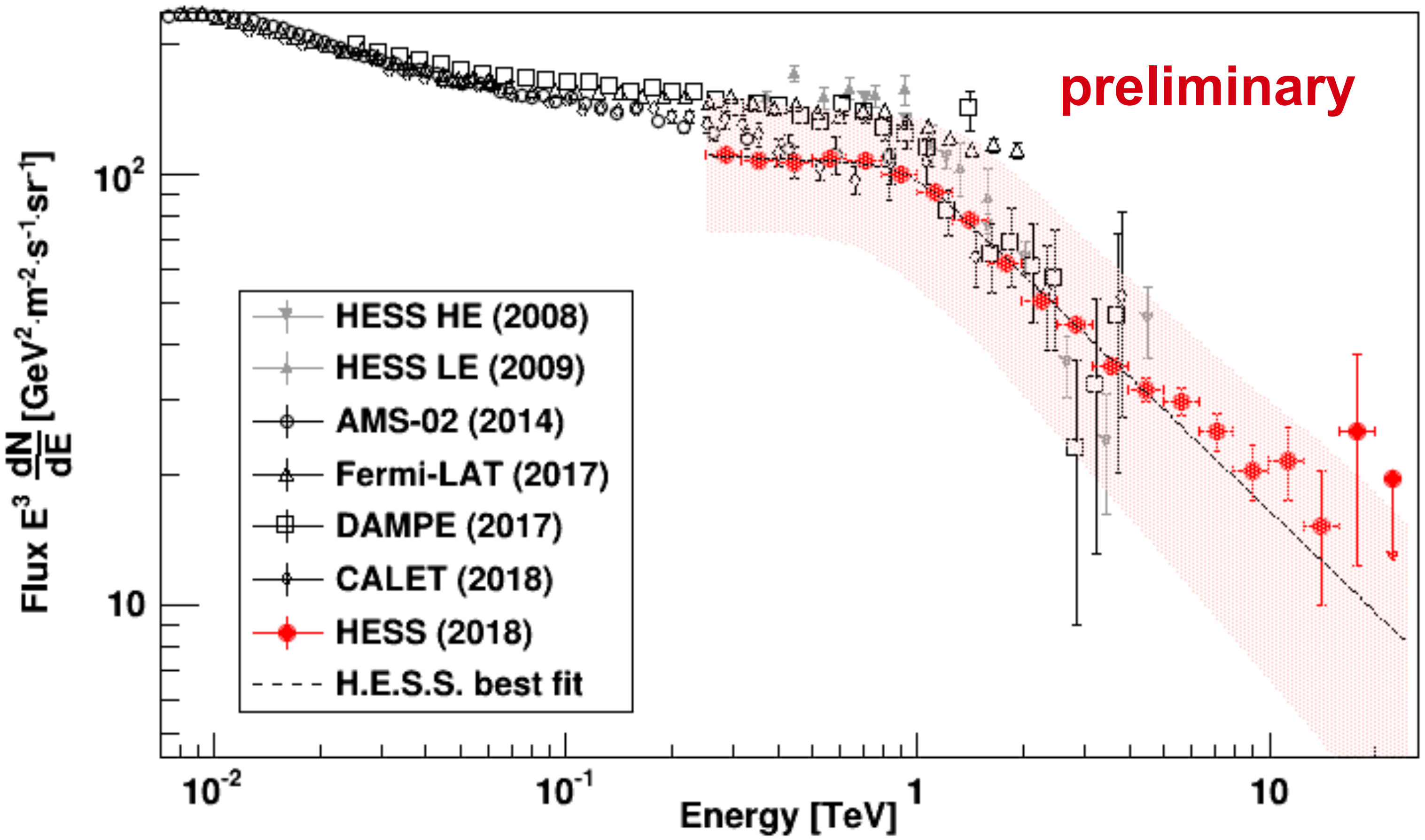
- There are no features of local accelerators in the spectrum
  - Very existence of TeV electrons points to an accelerator within ~1 kpc
  - Spectrum constrains local source models
- No features of dark matter
  - Energy resolution ~15%
- Nature of the break at 1 TeV?
  - cutoff of the accelerator?
  - propagation effect?



- Do we see the “end of the cosmic-ray electron spectrum”?

(and what about the secondaries?)

Summary



- Although CR e± are only a small fraction of CRs, they provide complementary information, probing our local neighbourhood
- Measurements are challenging because of low fluxes and large background
- New space-born instruments start to probe the energy regime beyond 1 TeV, while ground-based measurements now extend to 20 TeV
- Approaching the end of the CR e± spectrum - still awaiting full scientific exploitation