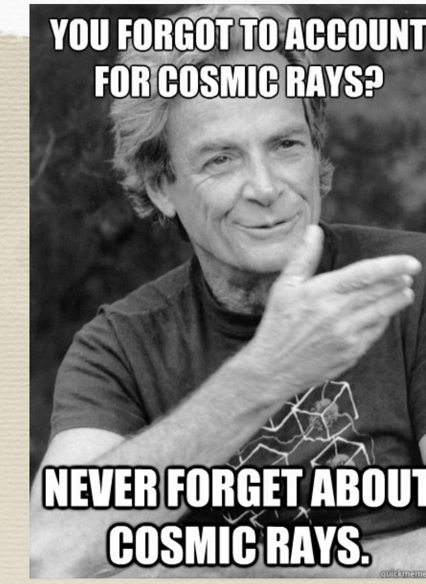
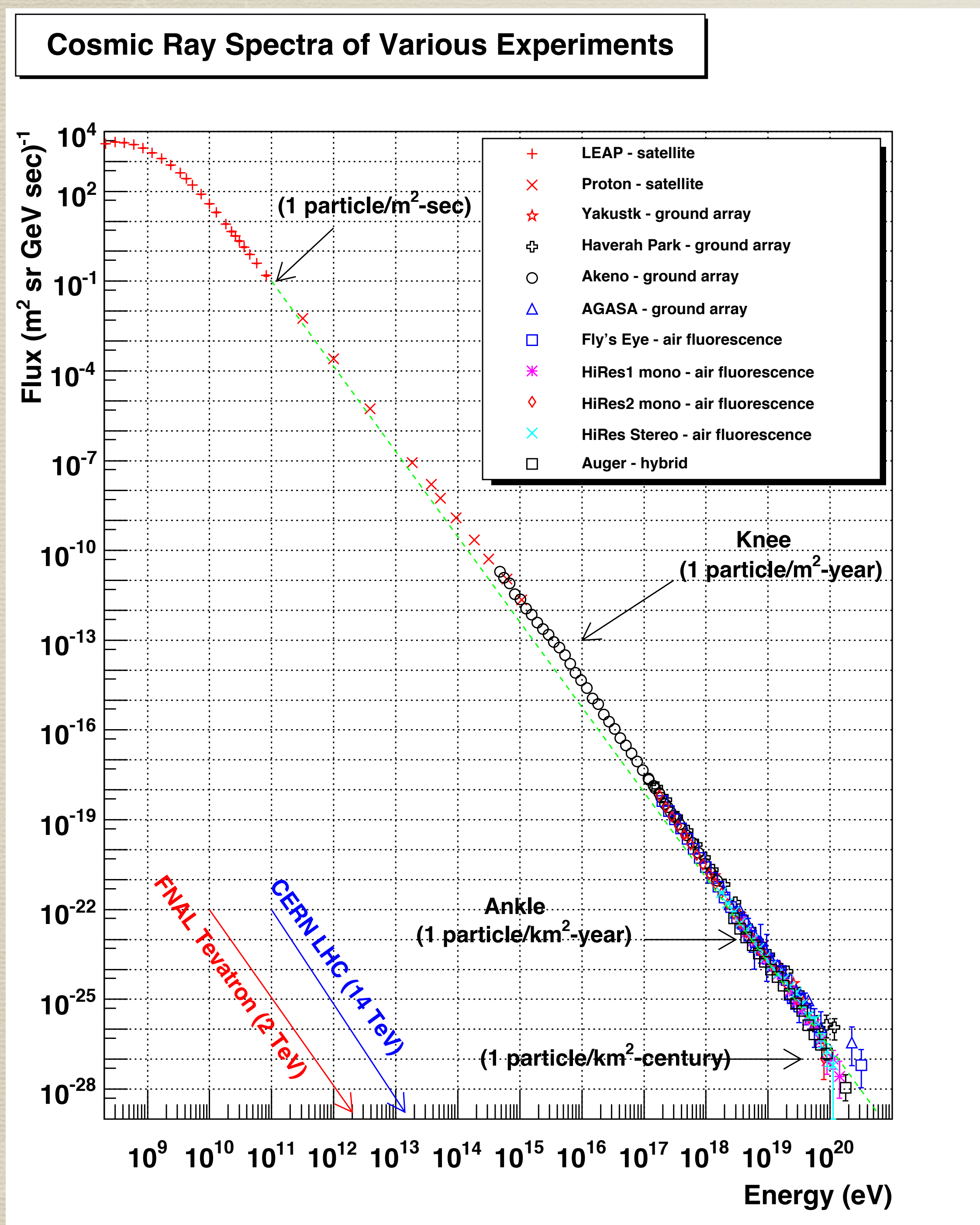
High energy cosmic ray electrons with CTA

Rubén López-Coto - INFN Padova
F2F INFN meeting - Padova - 18/11/19

Funded by H2020 Marie Sklodowska
Curie FELLINI - Grant 754496

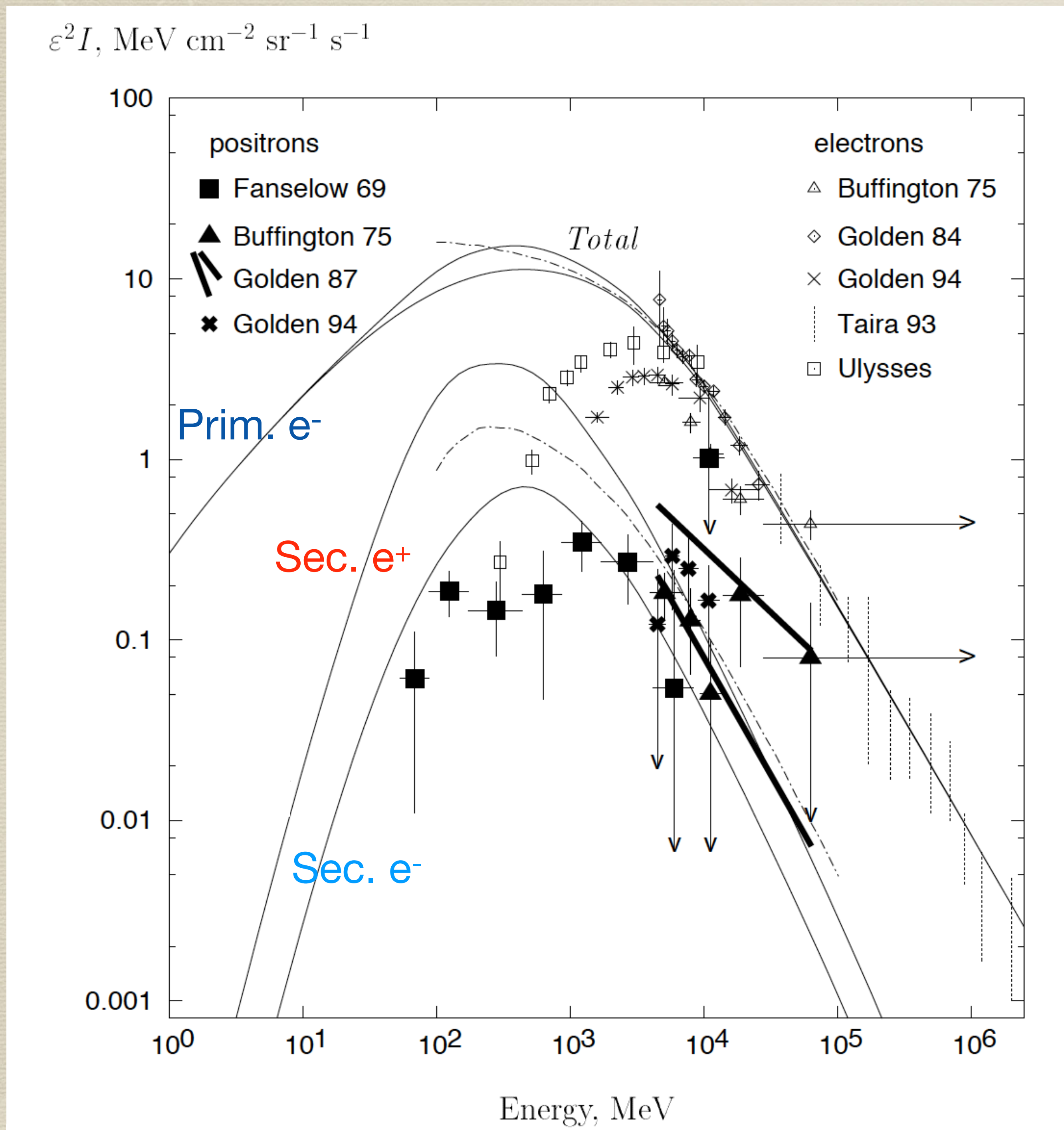
Spectrum and composition





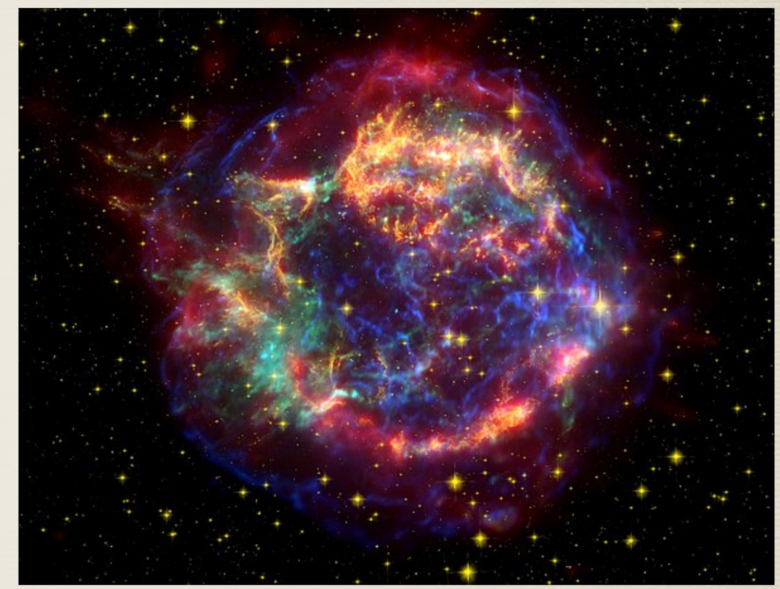
- Spectrum and composition measured by **satellites**, **balloons** and **extended air shower arrays**.
- Different origin:
  - Solar (E<1 GeV)
  - Galactic (1 GeV < E < ~PeV)
  - Extragalactic (E > PeV)
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, neutrinos…

Positrons and Electrons



Moskalenko & Strong, 1998

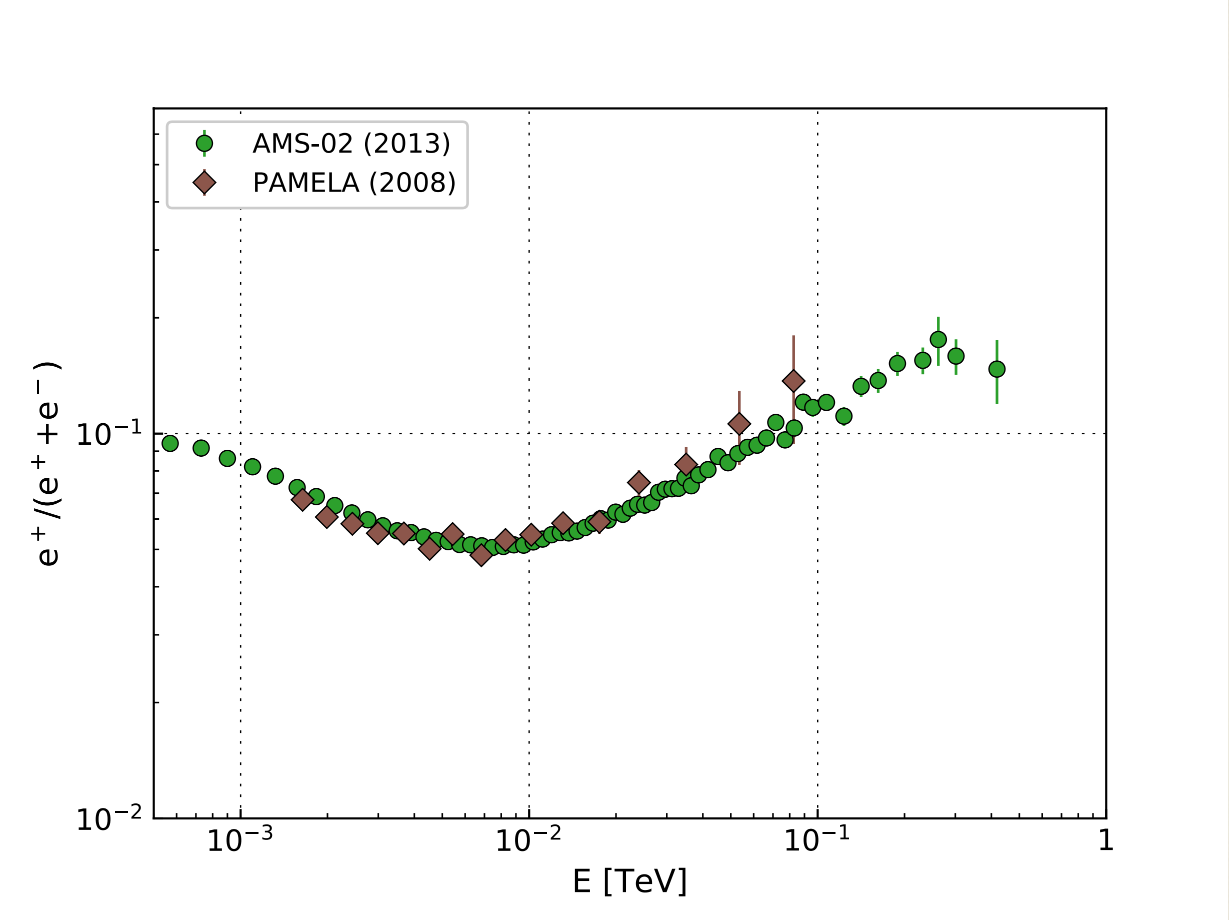
Primary electrons are produced in astronomical sources such as Supernova Remnants



Secondary electrons and positrons are produced in cosmic ray collisions with ISM particles

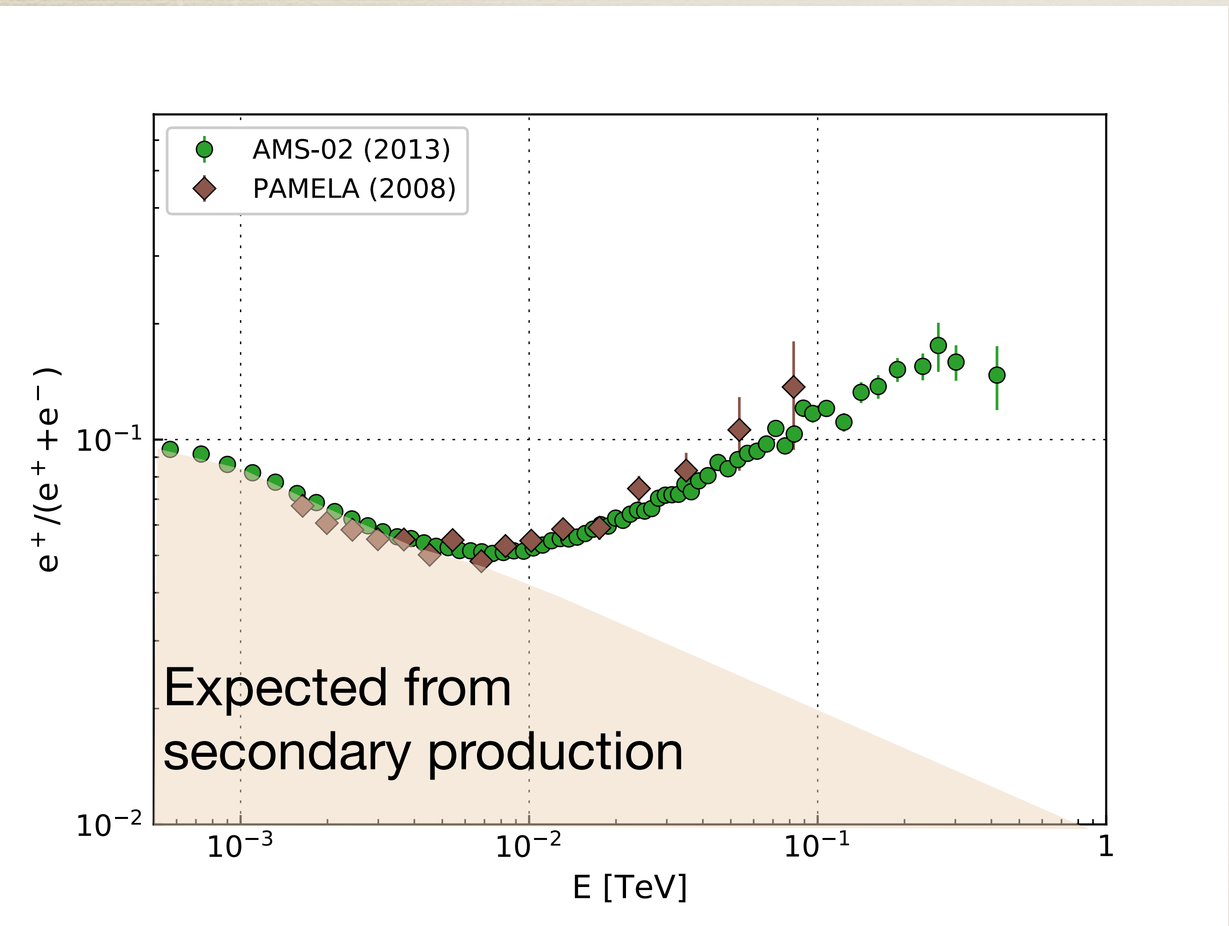
Rubén López-Coto - 25/06/19

Positron Fraction



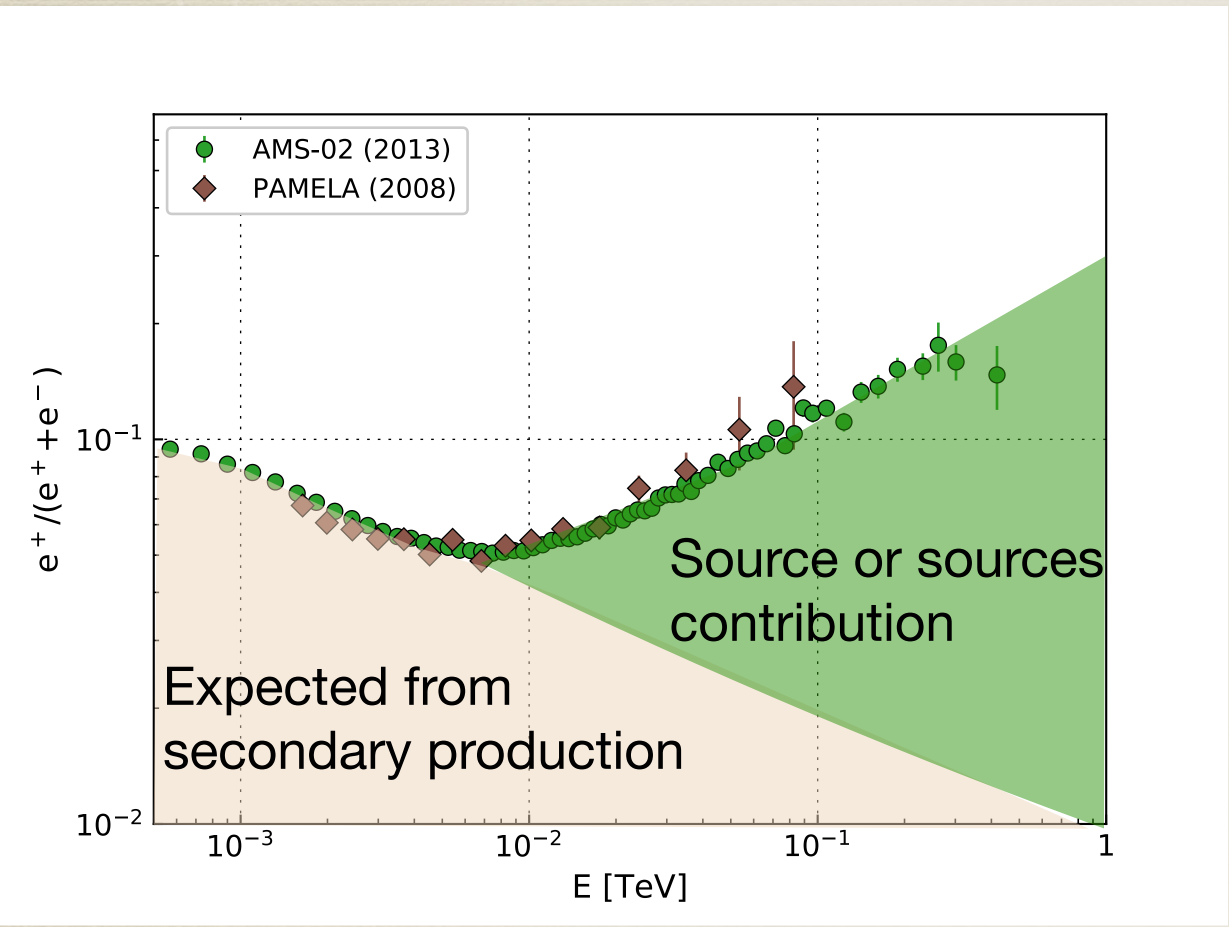
- The positron fraction is expected to decrease with Energy

Positron Fraction



- The positron fraction is expected to decrease with Energy
    - This is the case for energies below a few GeV

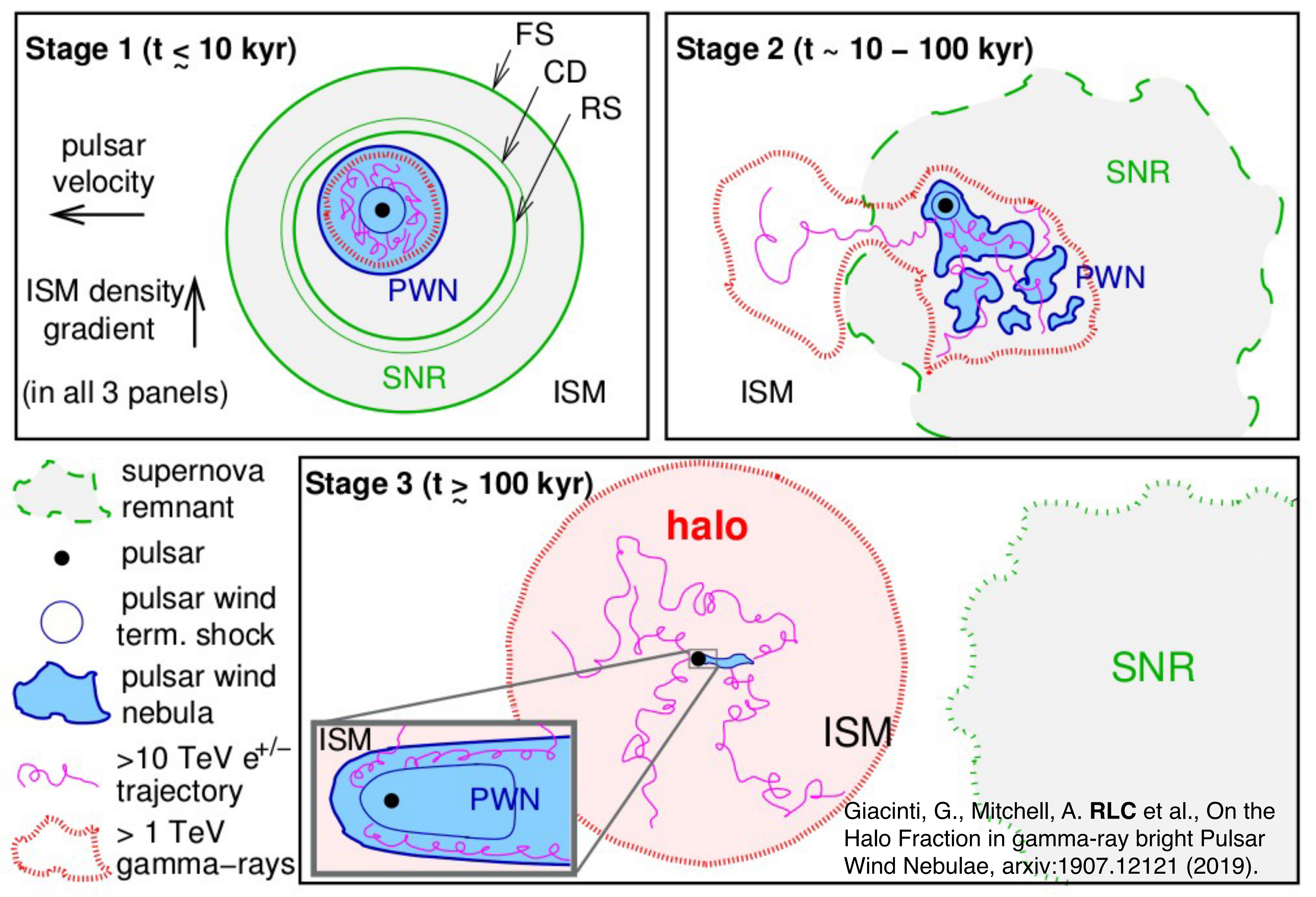
Positron Fraction



- The positron fraction is expected to decrease with Energy
  - This is the case for energies below a few GeV
- At higher energies the positron fraction increases -> There has to be a source injecting them
- If we take the diffusion coefficient derived from the ratio between secondary to primary cosmic ray species, the highest energy electrons and positrons should come from a source with:
  - **Age**: 0.1-1 Myr old
  - **Distance**: < 1 kpc away

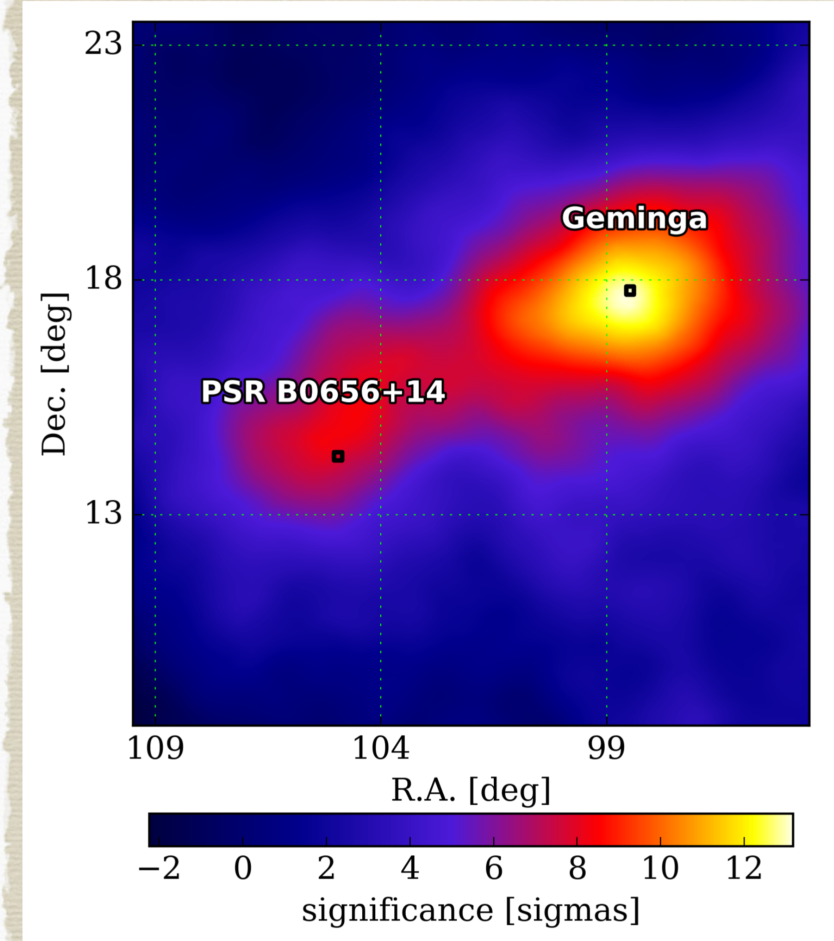
Study of the local positron contribution of TeV halos

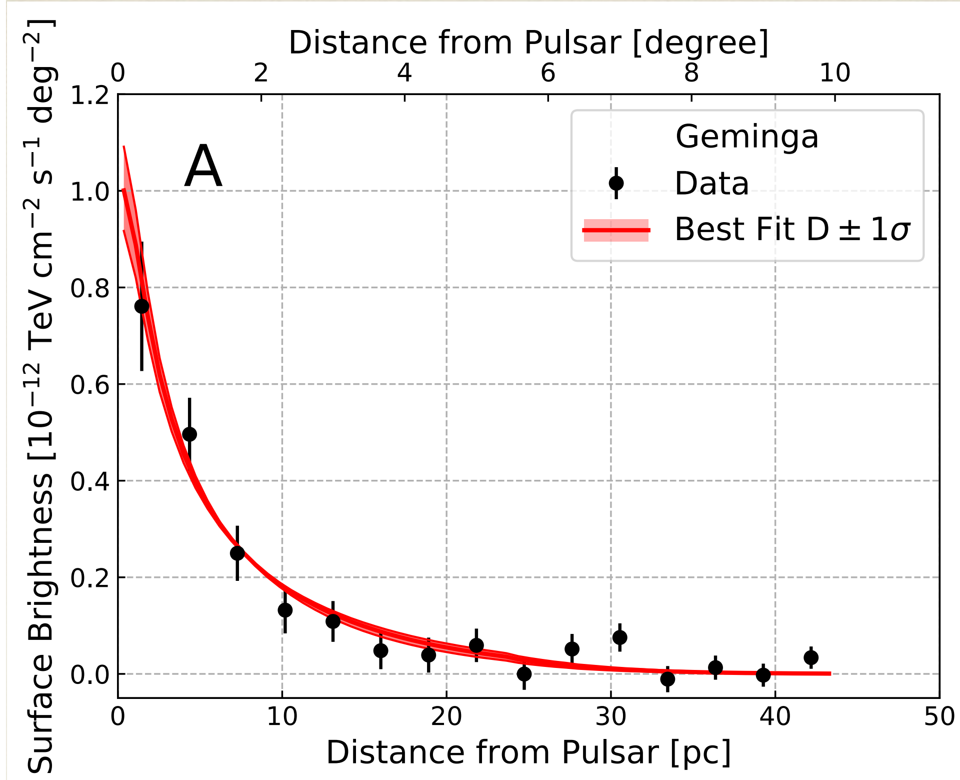
Definition of TeV halos

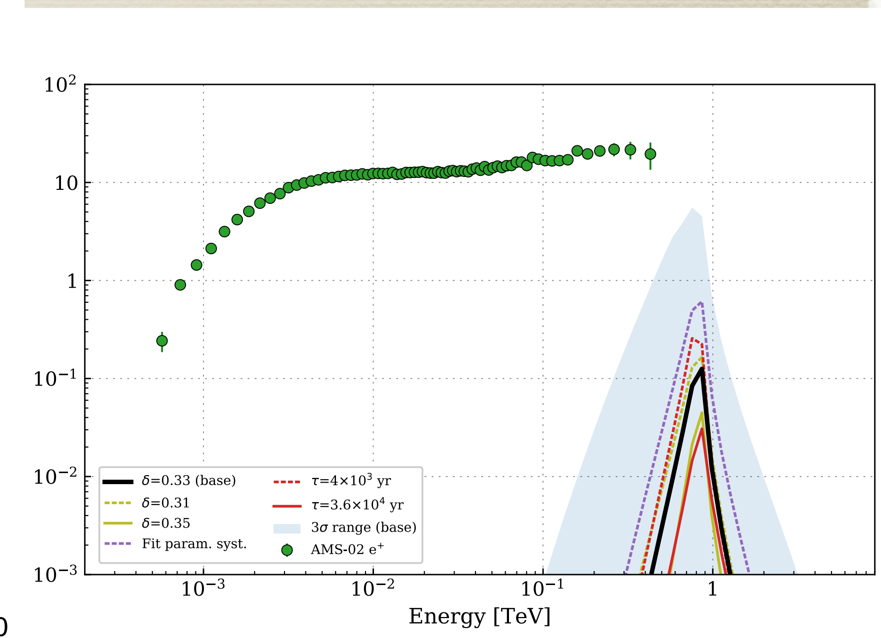


Giacinti, G., Mitchell, A. **RLC** et al., On the Halo Fraction in gamma-ray bright Pulsar Wind Nebulae, arxiv:1907.12121 (2019).

TeV halos







HAWC Coll., Science, 358, 911 (2017)

- Proposal for CTA Data Challenge 2:
  - Introduce the model of the two sources seen by HAWC
  - Total flux and angular profile

All-electron spectrum

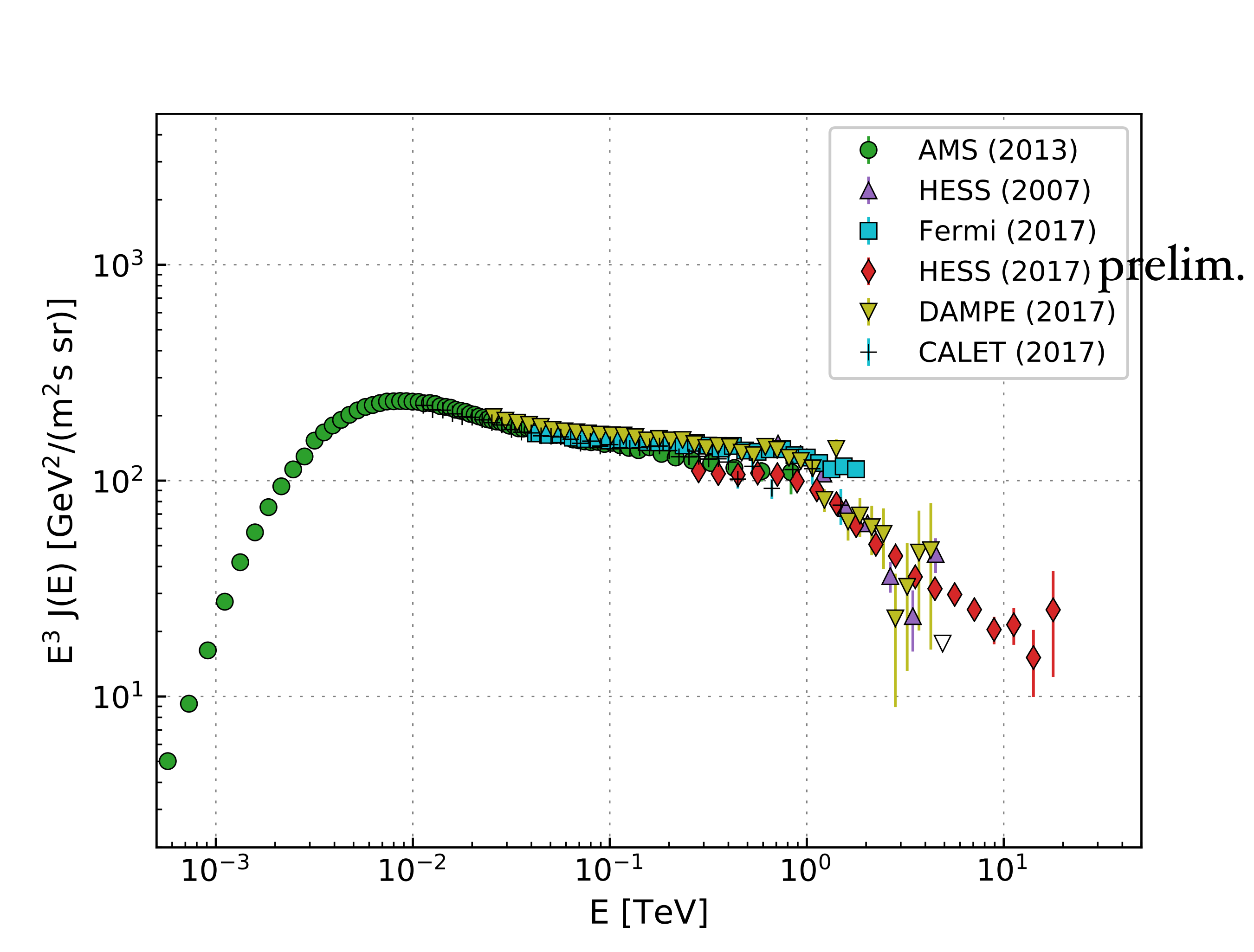
Latest all-e measurement

Used to measure cosmic ray propagation -> short cooling times

For a 1 TeV electron lifetime is only ~10^5 years

Reaching up to 20 TeV energies implies a lifetime of < 10^4 years ——> very local (order of 100 pc) sources

Compare with the ~10^8 year lifetime of hadronic cosmic rays, where only ionization and hadronic interactions are the only important loss mechanisms



Very High Energy cosmic ray electrons can only originate from nearby sources

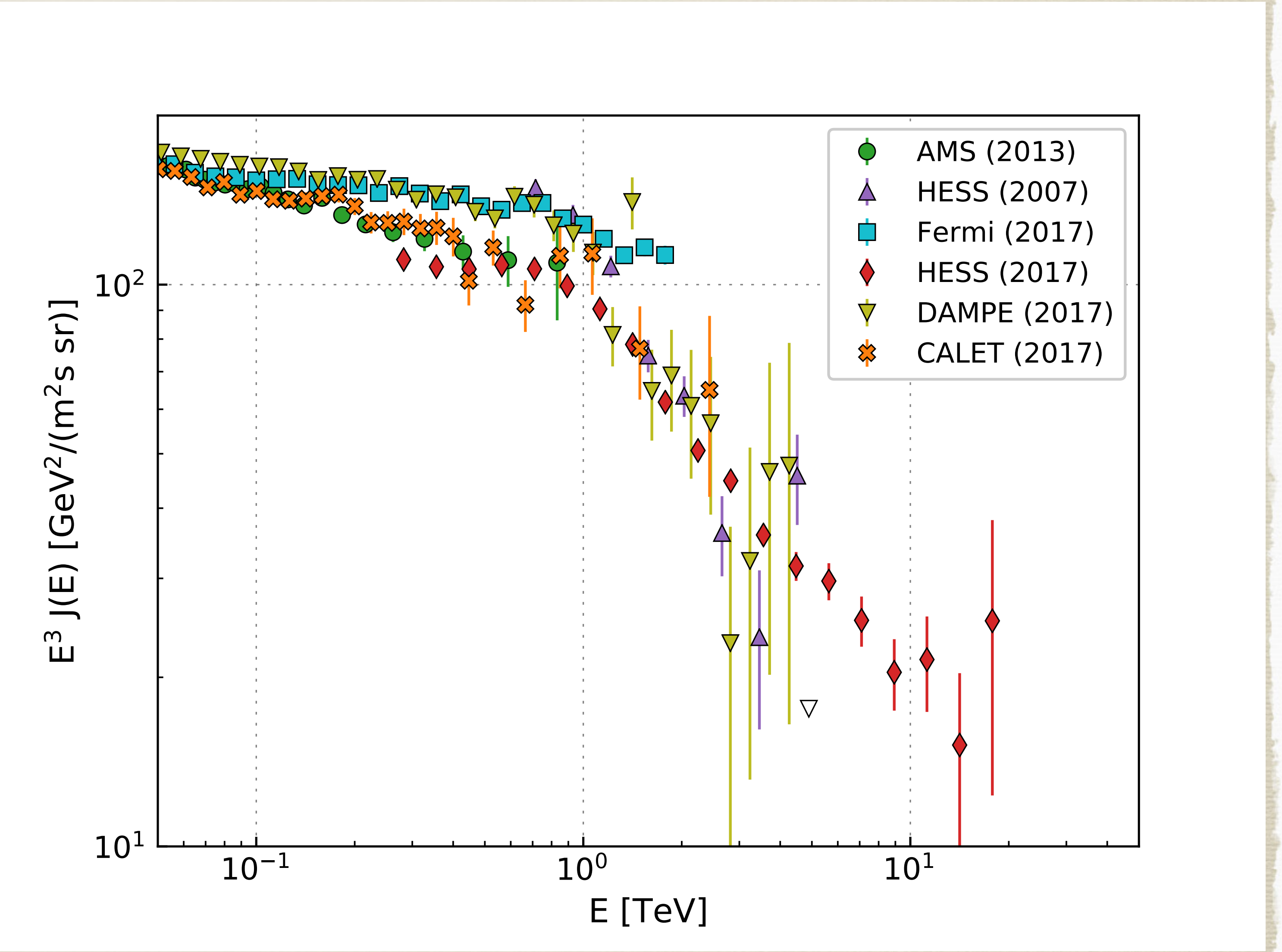
The cosmic ray energy spectrum is very dependent on the local source distribution

Current VHE measurements

- Currently, there are several satellites/ground instruments that have performed the all-electrons measurement

- The highest energies are specially interesting because they are proving local sources

- IACTs have great potential for measuring the all-electron spectrum
  - CTA will be the only instrument to be able to measure >10 TeV all-electron spectrum with high statistics

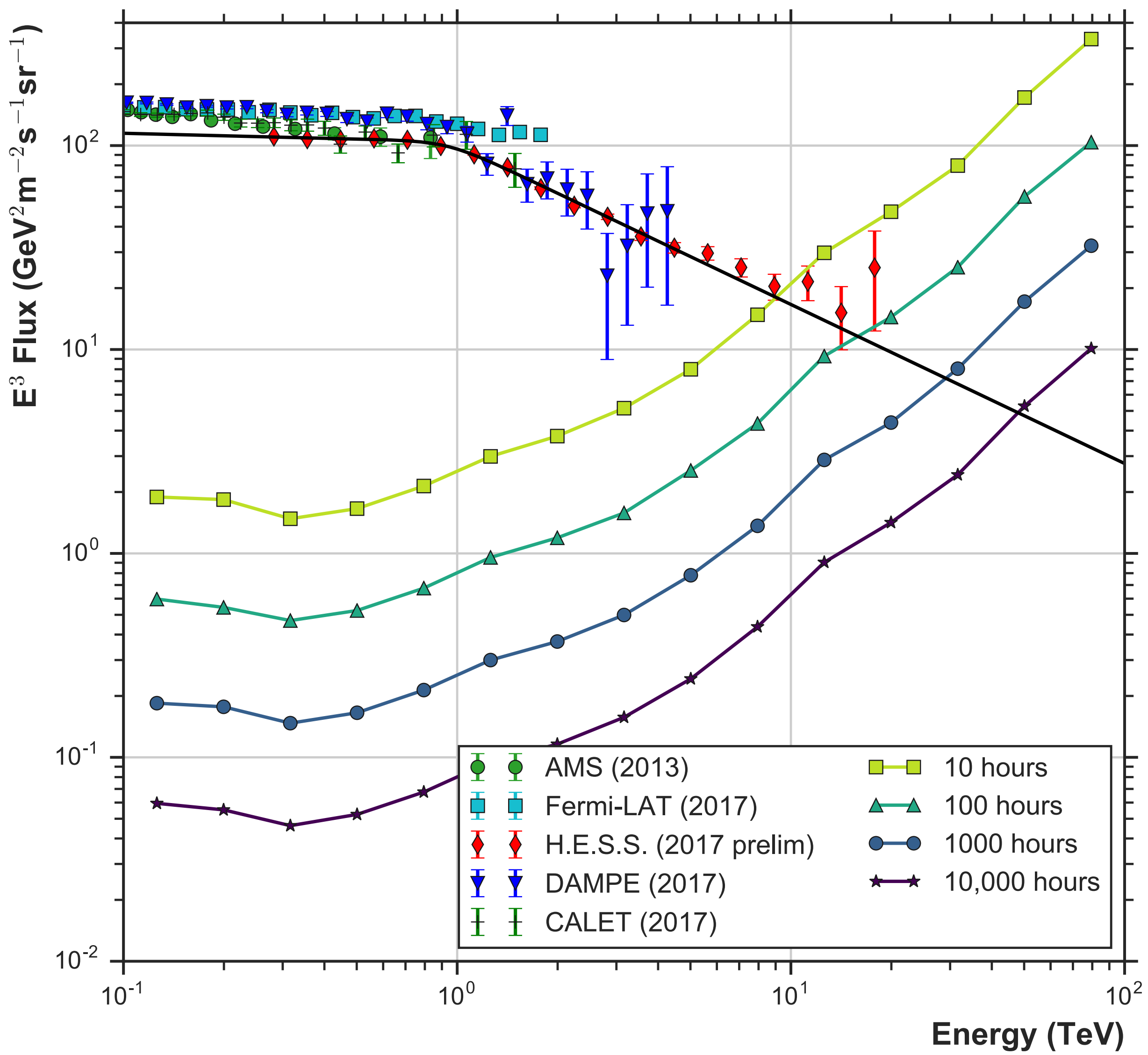


What do we want to test?

- Understanding the low energy spectral behaviour would certainly be useful (see incompatibility between Fermi/DAMPE and AMS/CALET)
  - This is likely impossible to quantify as the dominant effects here are systematics (hadronic interaction, weather effects etc)
- The most interesting part of the spectrum we can investigate is surely the highest energy points
- However the predictions of the high energy behaviour for a given source type is highly model-dependent
- Most of the model input remains pretty much unknown (diffusion coefficient/energy dependence, source spectrum etc)
- Would like to avoid tying the predictions to a model and attack this problem from a purely experimental standpoint

How sensitive is CTA to deviations in the high energy spectrum from the power-law seen by HESS?

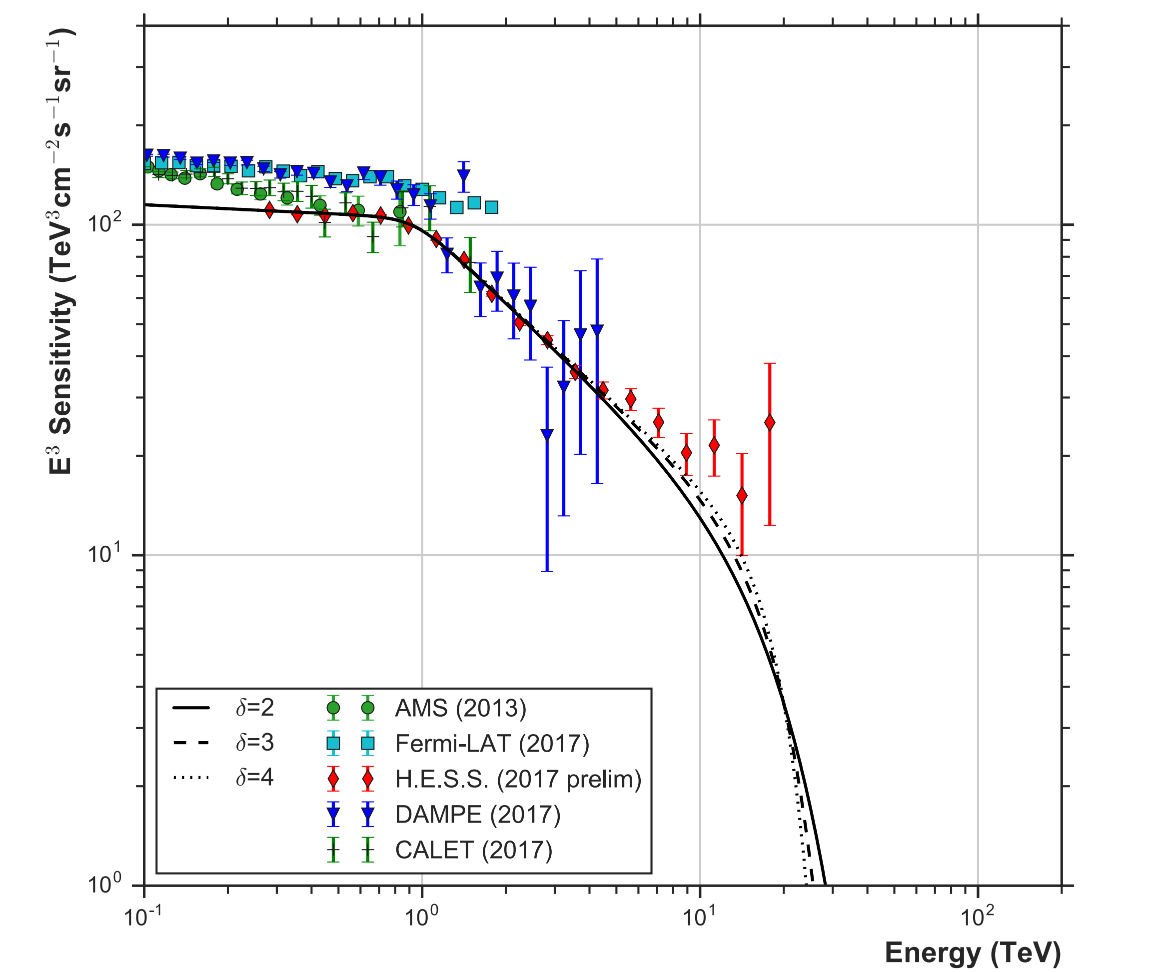
Sensitivity



Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation

- Sensitivity derived for different observation times
- For a 3 sigma measurement of the spectrum at different energies.
- We can see that with 100 hours we are already able to perform a >3-sigma measurement at 20 TeV
- But we we would like to evaluate the sensitivity to detect features in the spectra

Distinguish between options

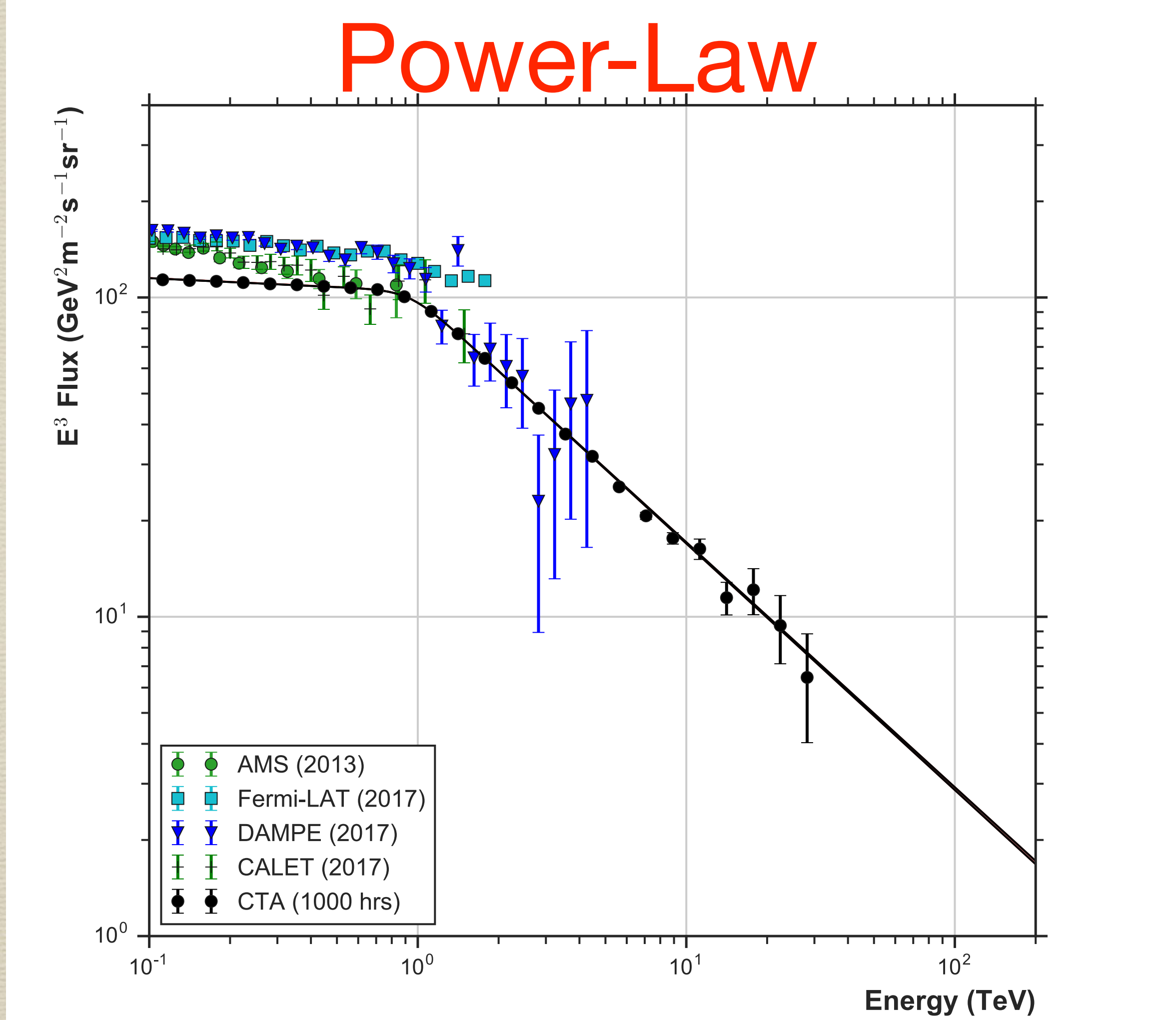


Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation

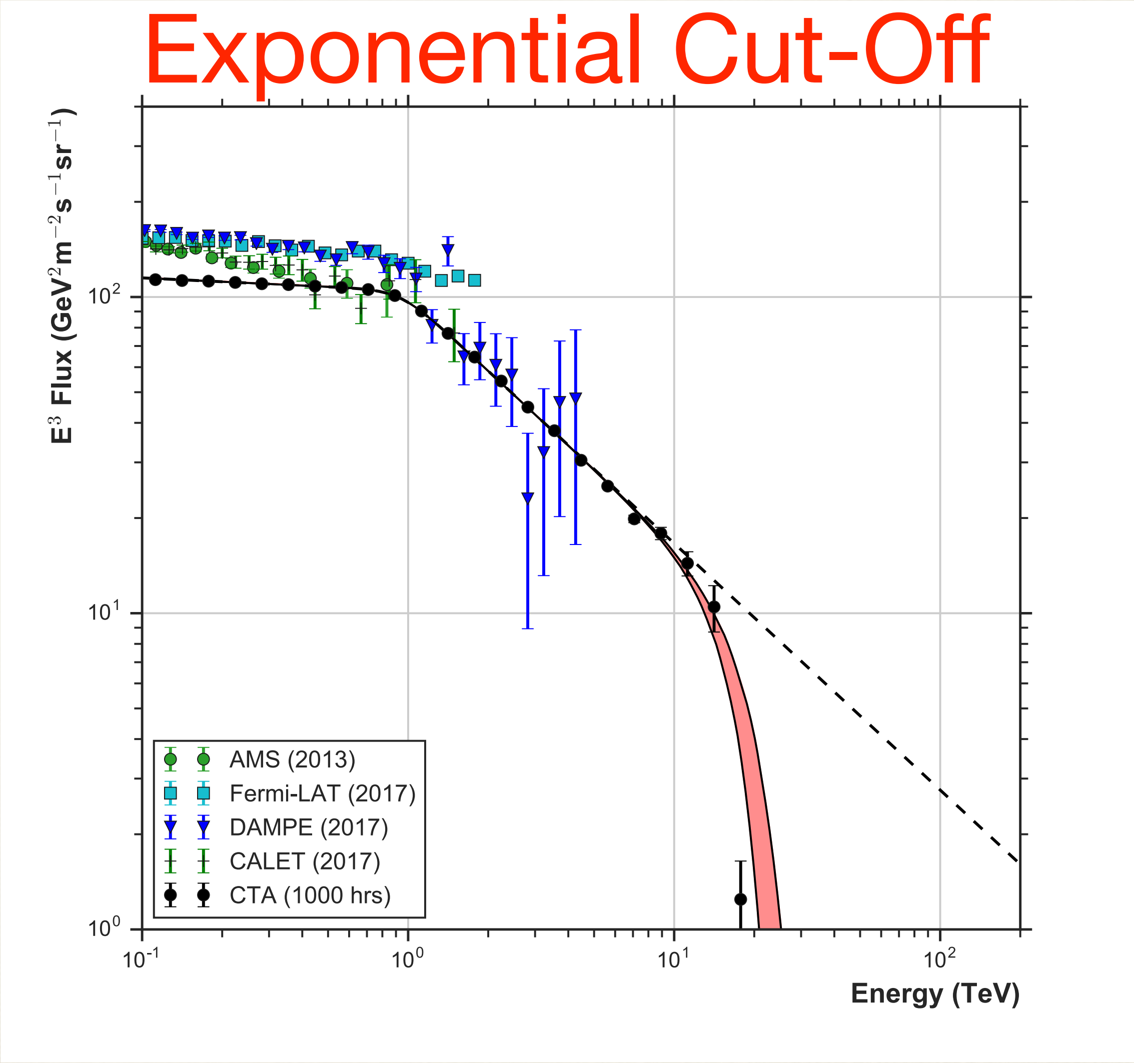
- If there is a cut-off of the form:
- $E^{-\Gamma} * \exp(E/E_{cut})^{\delta}$
  - with E_{cut} = 20 TeV
  - δ = 2, 3, 4 (Solid, Dashed, Dotted)
- This is the form the cut-off would have, played with previous measurements.

CTA measurement of different spectral shapes

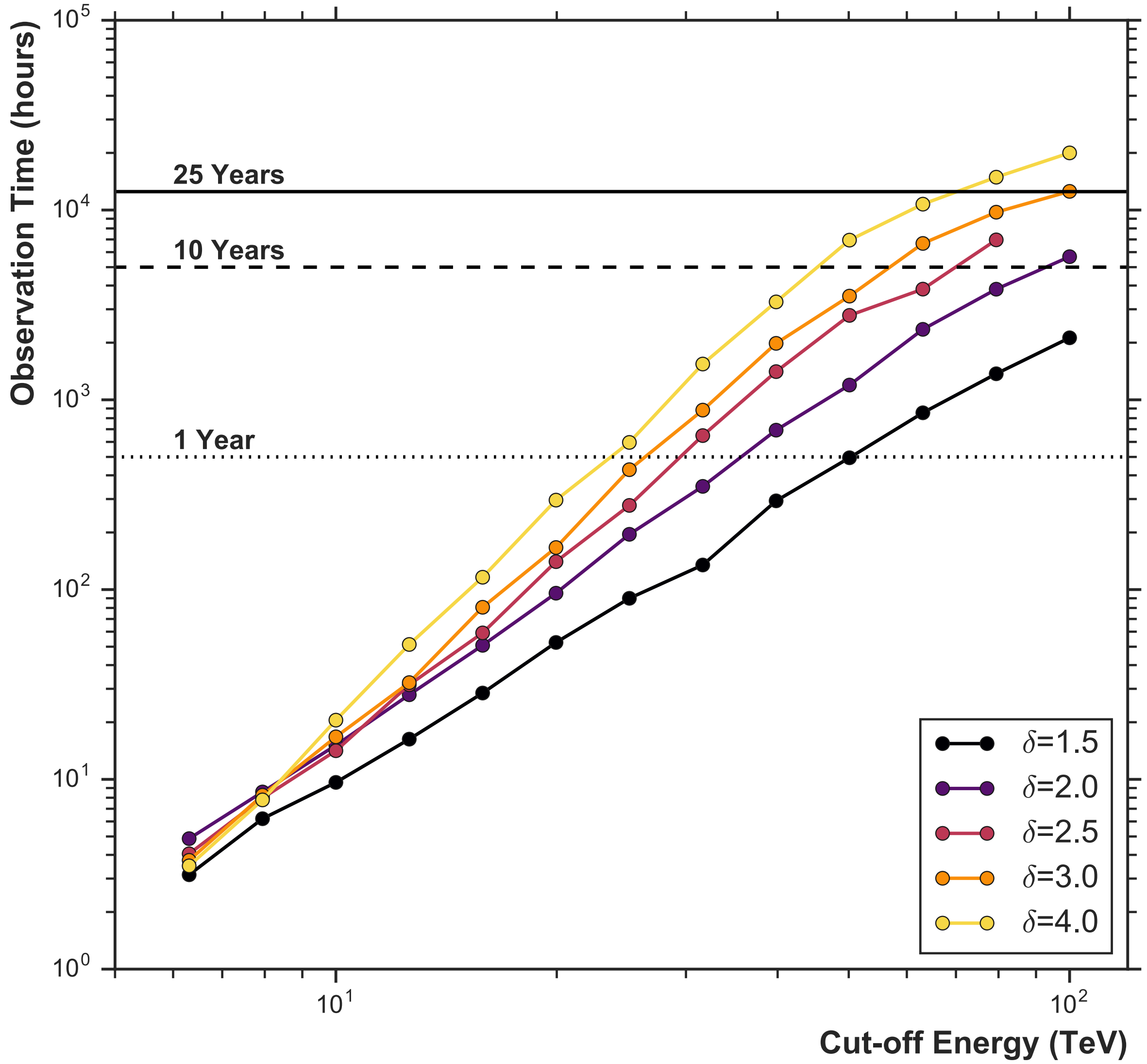
- Considering 1000 hours of observation and a cut-off at 20 TeV



Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation



CTA sensitivity for a cut-off

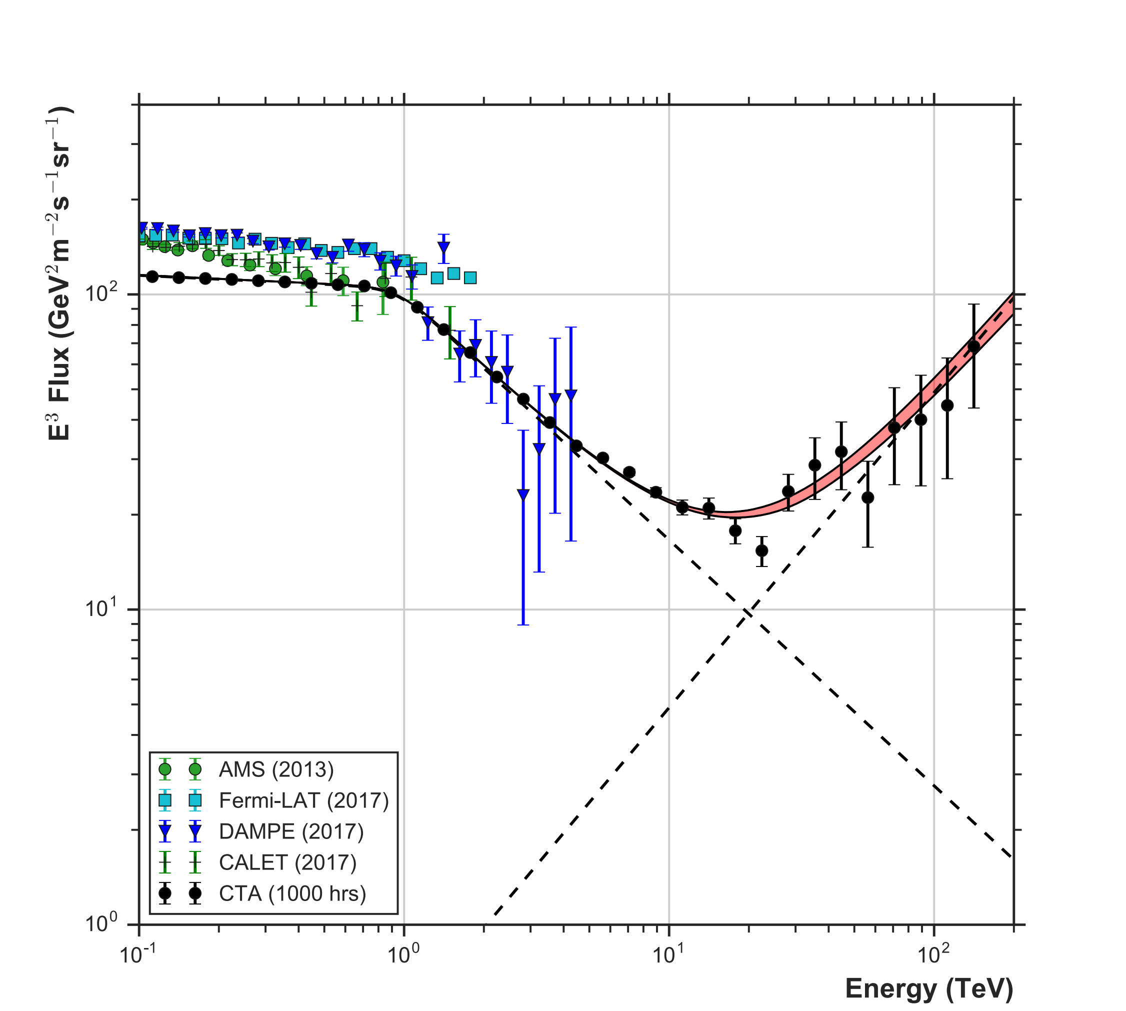


Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation

- For different exponents for the cut-off, we evaluate CTA sensitivity to detect the cut-off at 3 sigma level
- For reasonable amount of time after several years of CTA operation, we would be able to measure a cut-off up to tens of TeV

Additional component

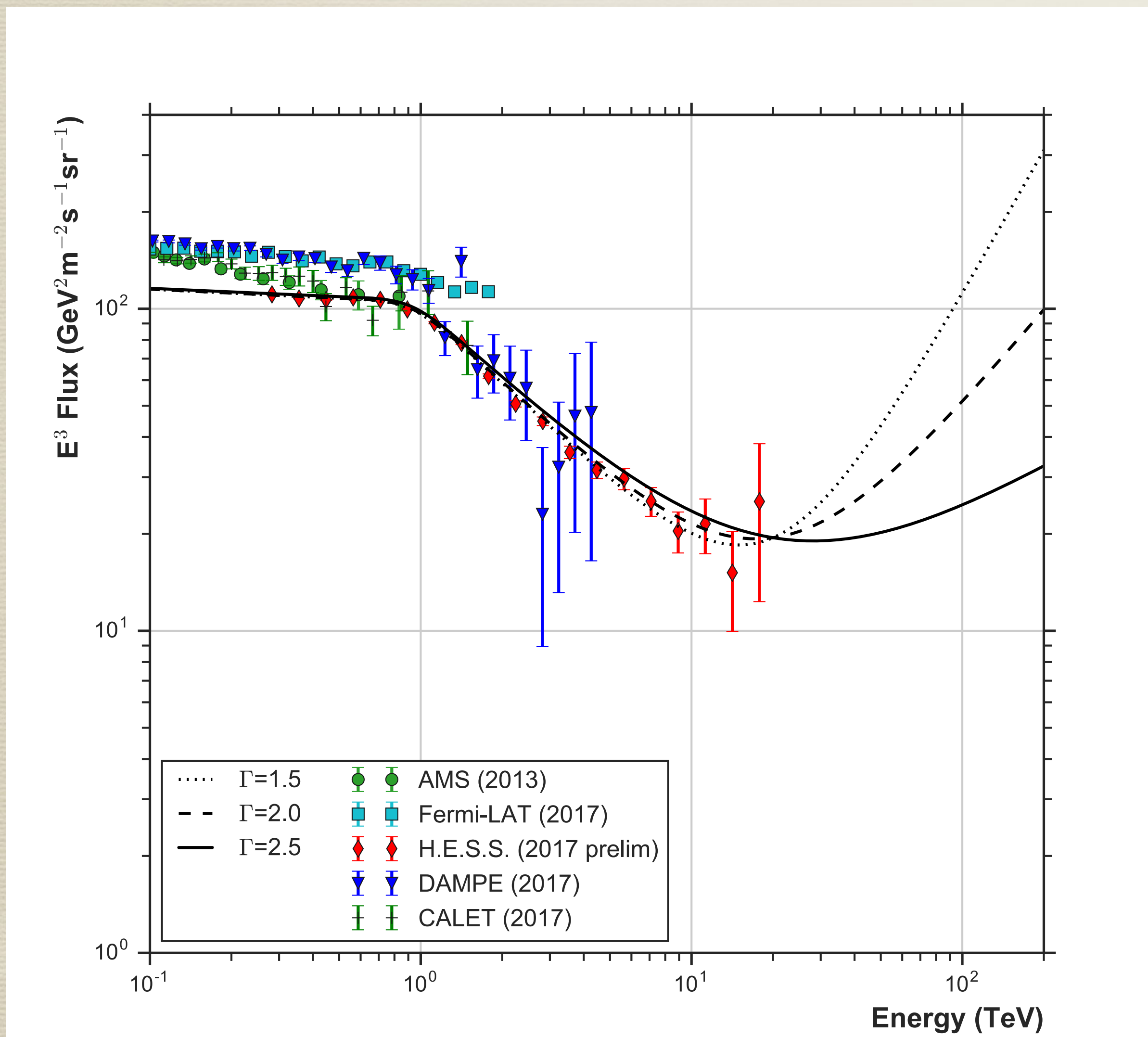
- Local source providing an additional component in the spectrum
- Additional component with spectrum E^{-2} and equal contribution at 20 TeV than HESS spectrum
- The band corresponds to different realizations of this spectra



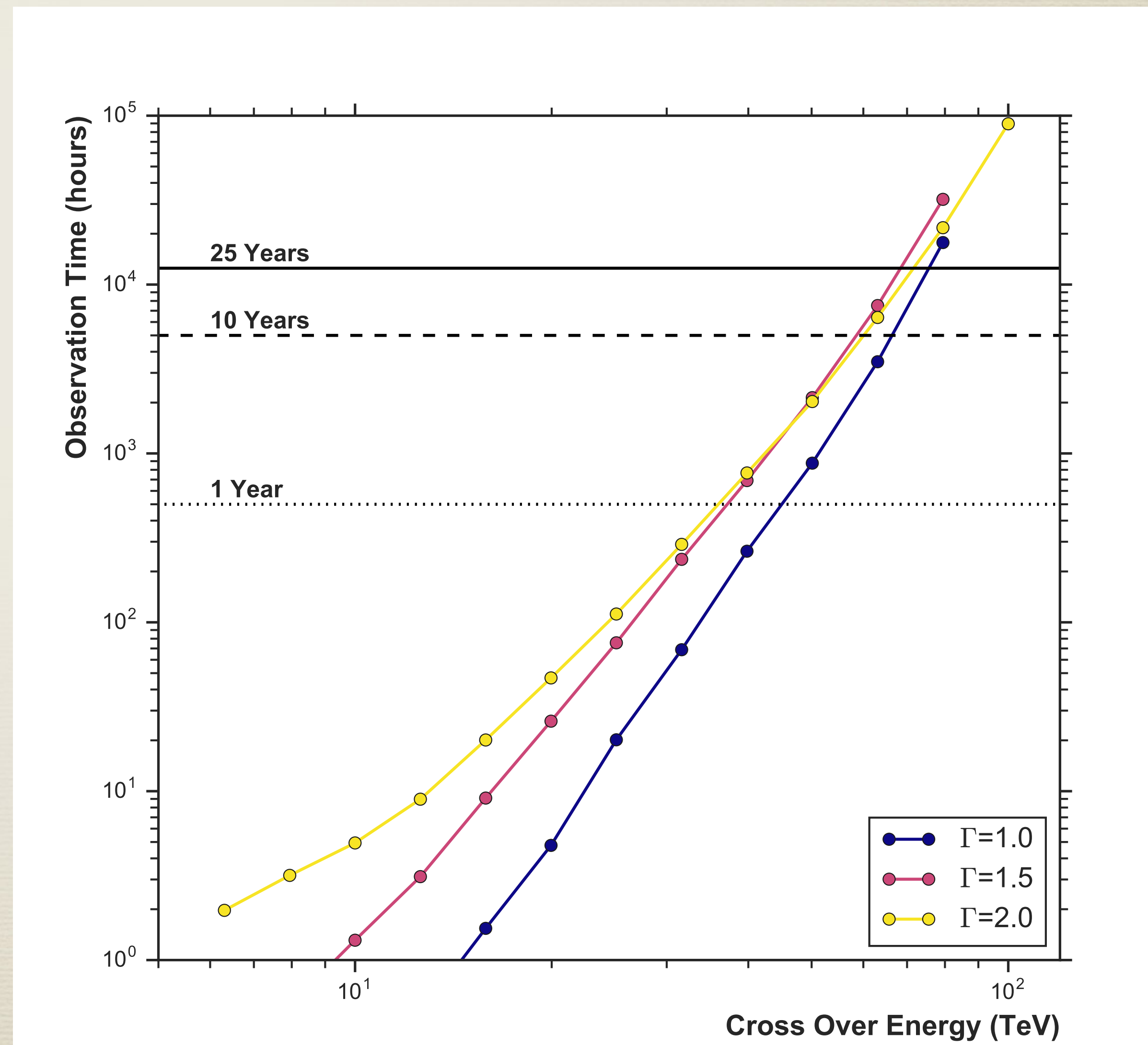
Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation

Sensitivity for an additional source

- Additional component with different spectral indices and equal contribution at 20 TeV than HESS preliminary spectrum.
- Good sensitivity up to tens of TeV



Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation



Parsons, Schoorlemmer, RLC, Kerszberg for the CTA Consortium, in preparation

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Summary

- Positrons are very important to determine cosmic ray propagation parameters
  - The lower energy ones (<1 GeV) are of secondary origin
  - The higher energy ones (> 1 GeV) are of primary origin
  - Unfortunately, not distinguishable with IACTs

- All-electron spectrum measured by satellites and IACTs
  - Only ATIC sees a bump at ~600 GeV
  - Only DAMPE sees a line-like feature at 1.4 TeV
  - Only Fermi does not see a break at ~900 GeV

- CTA will be the only facility that will be able to provide a high statistical measurement of the all-electron spectrum at E > 10 TeV

BACKUP

Properties of the source term

- Life-time of electrons propagating in the ISM
  $t_{COOL}(E) = 3 \times 10^8 (E/GeV)^{-1}$ yr

- Diffusion coefficient and diffusion radius for electrons:
  $D_{diff}(E) = D_0(1+ E/E^*)^{\delta}$ cm^2
  $r_{diff}(E) = 2 \, sqrt(D_{diff}(E) \, t(E))$

- If we take the diffusion coefficient derived from the ratio between secondary to primary cosmic ray species, the highest energy electrons and positrons should come from a source with:
  - **Age**: 0.1-1 Myr old
  - **Distance**: < 1 kpc away

- Possible sources:
  - Pulsars/PWNe (Aharonian et al. (1995), Yüksel et al. (2009),…)
  - Dark matter (zillions of papers…)
  - Microquasar jets (Gupta & Torres 2014)
  - Different assumptions about secondary production (no source)

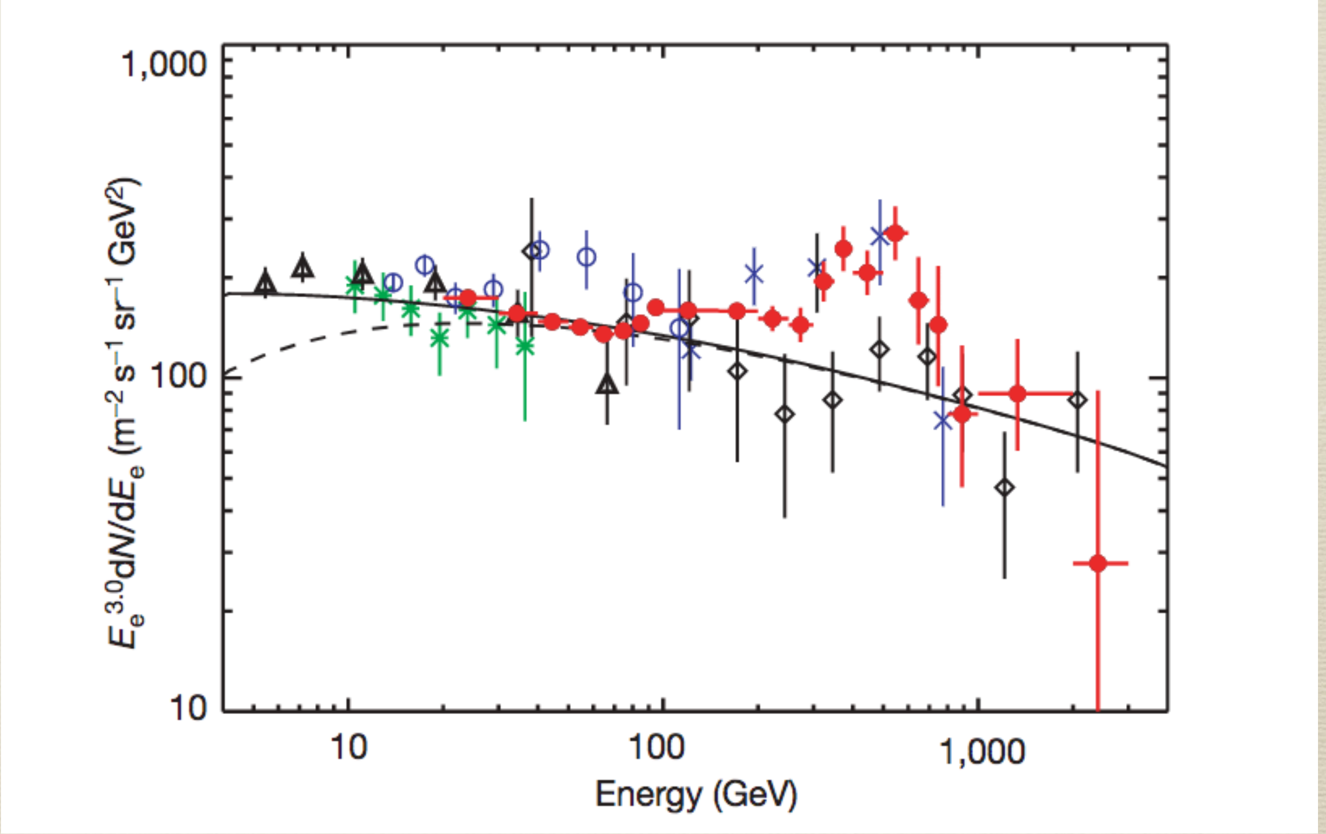
Cosmic ray electrons: ATIC

nature
International journal of science

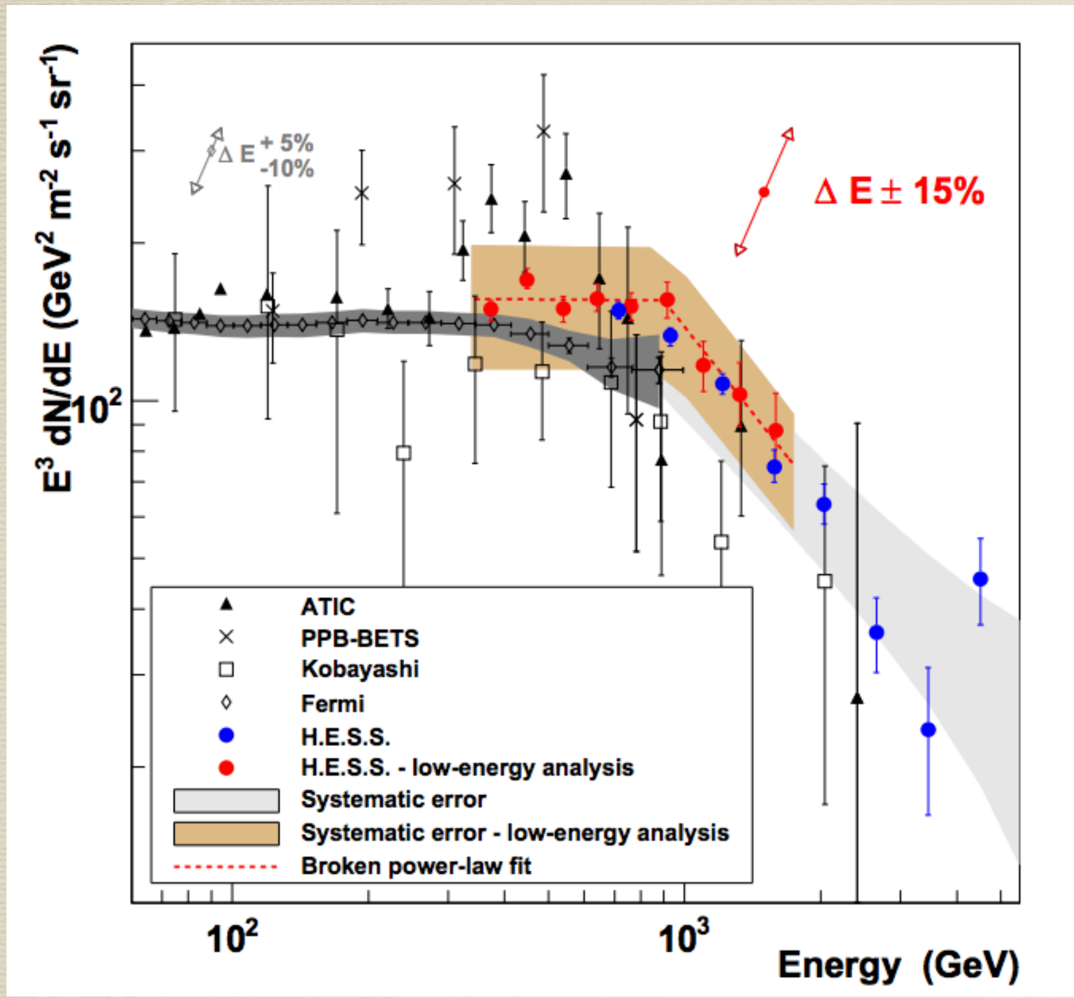
Letter | Published: 20 November 2008

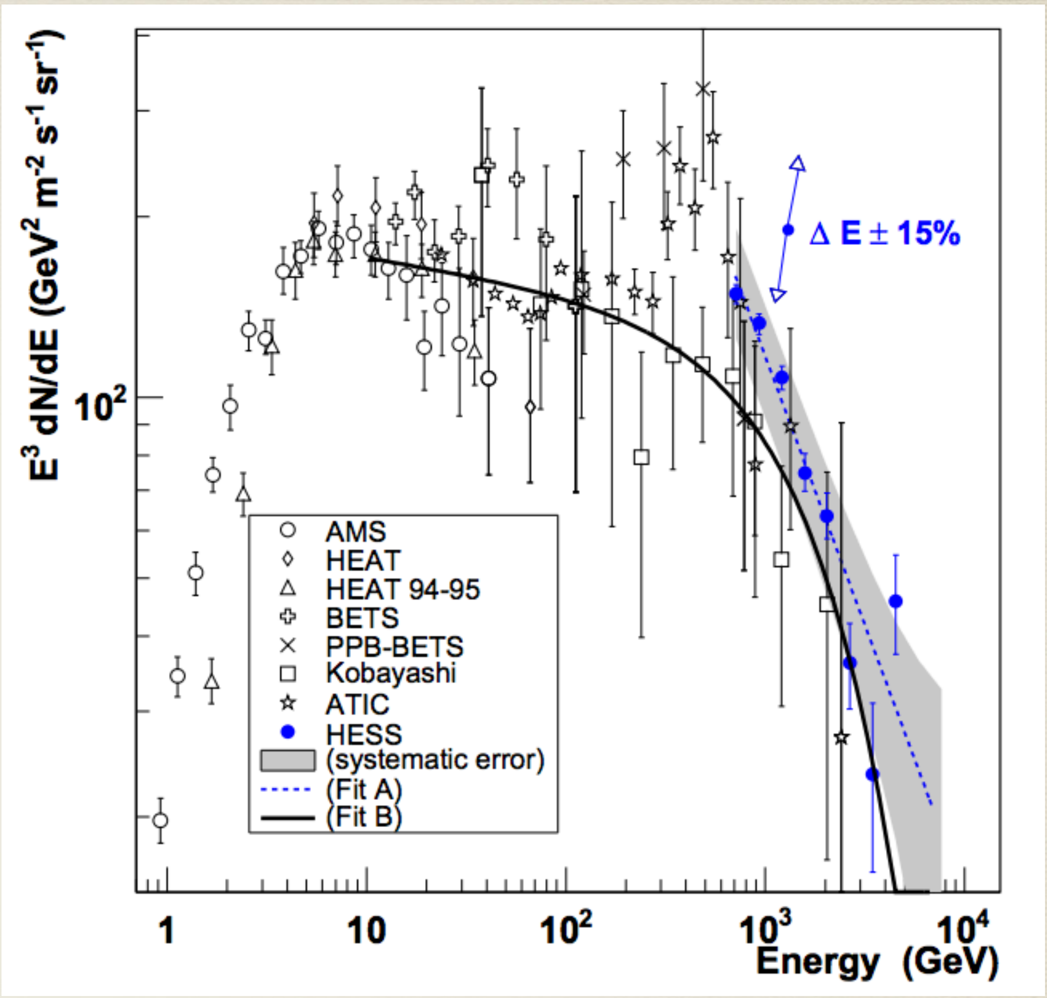
An excess of cosmic ray electrons at energies of 300–800 GeV

- ATIC also performed a measurement in 2008, this time of an excess of cosmic ray electrons+positrons



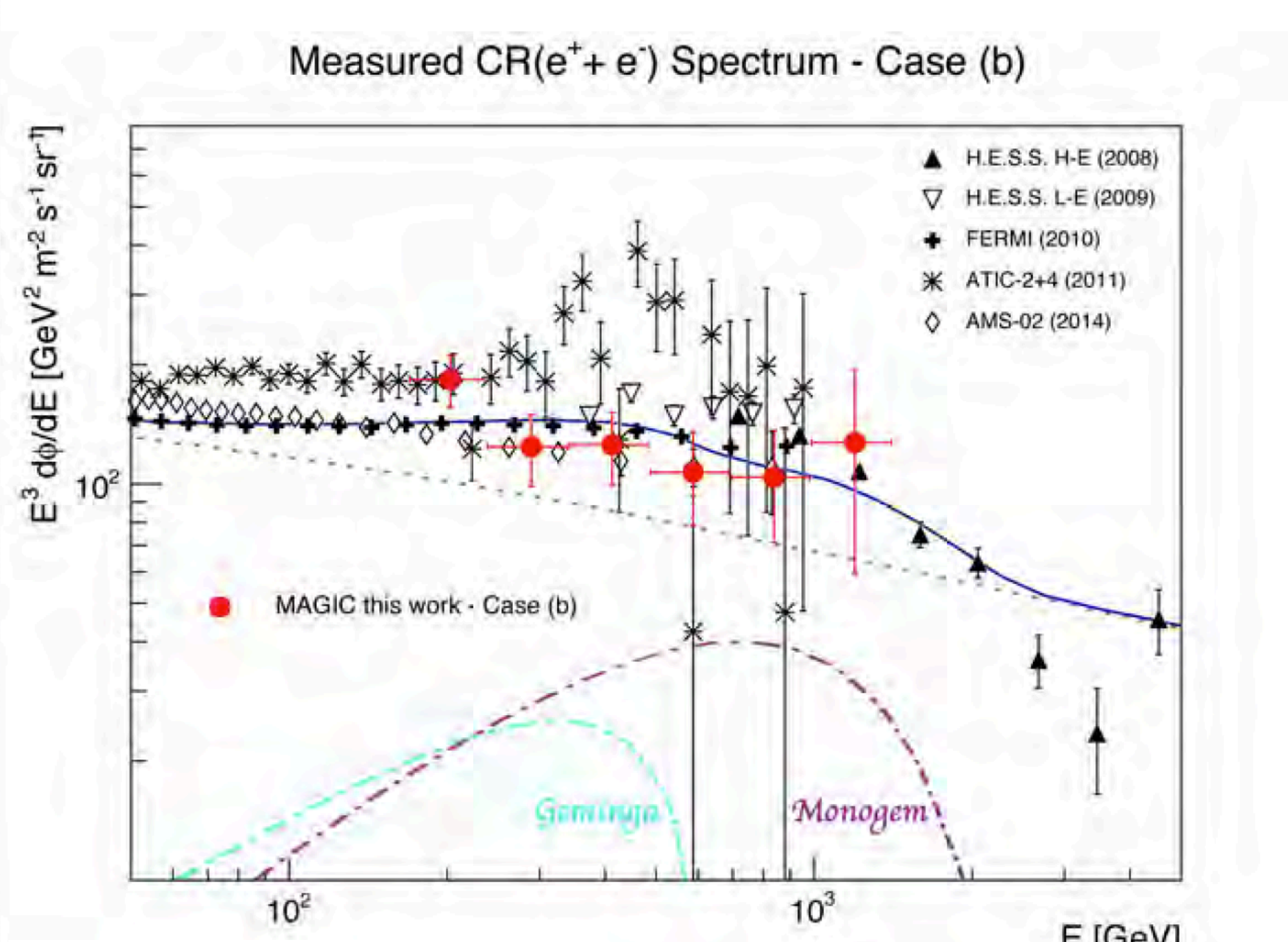
HESS



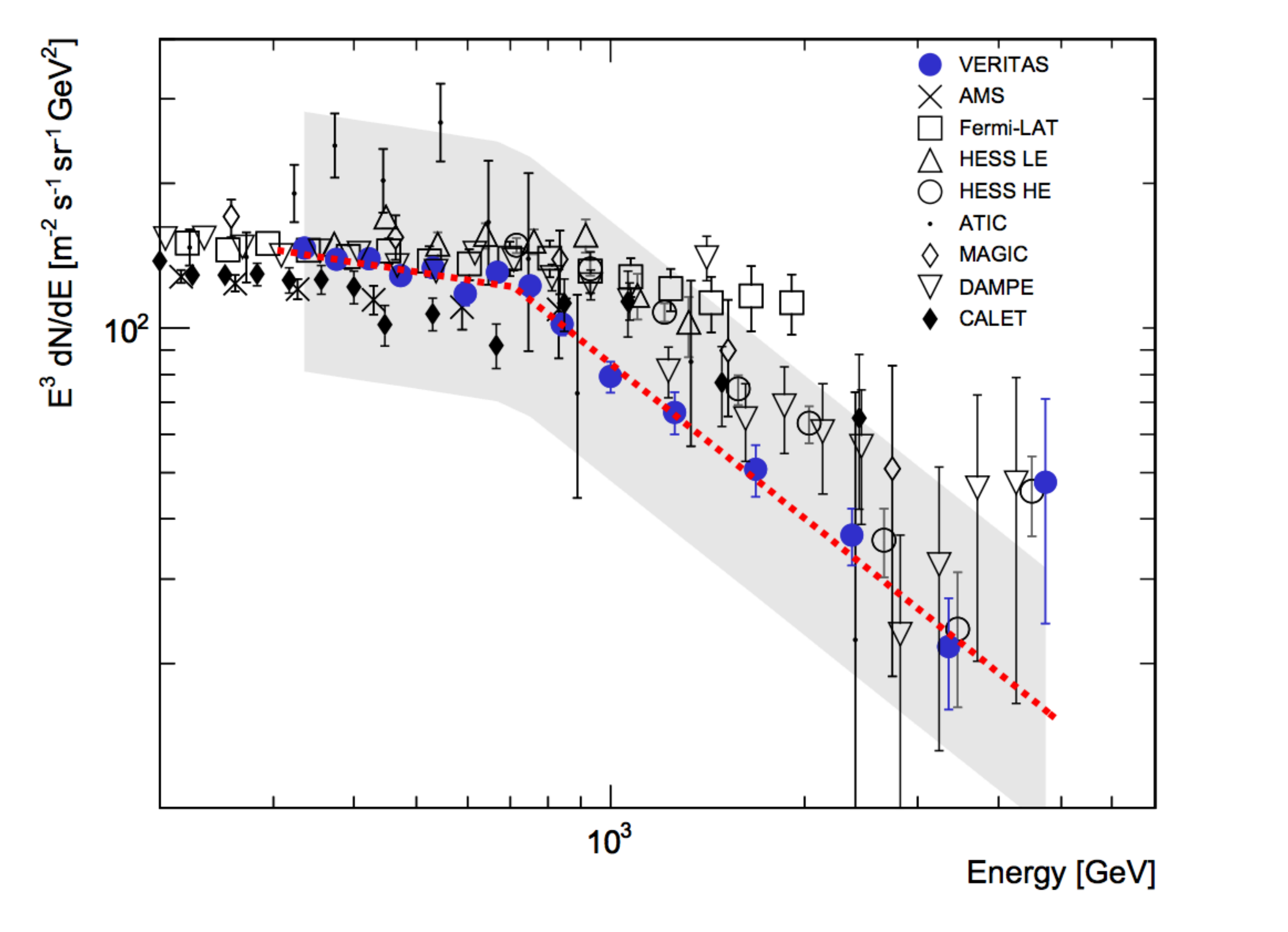


- HESS measured the spectrum
  - Up to higher energies than ATIC and found a break at ~900 GeV
  - In the same energy range and found a result compatible within systematics and statistical uncertainties with ATIC, but without finding any peak in the spectrum

MAGIC VERITAS



Palatiello, M., PhD Thesis (2015)



- Confirm HESS measurement of a non significant peak at ~600 GeV
- Confirm the break in the spectrum (VERITAS)

Fermi-LAT

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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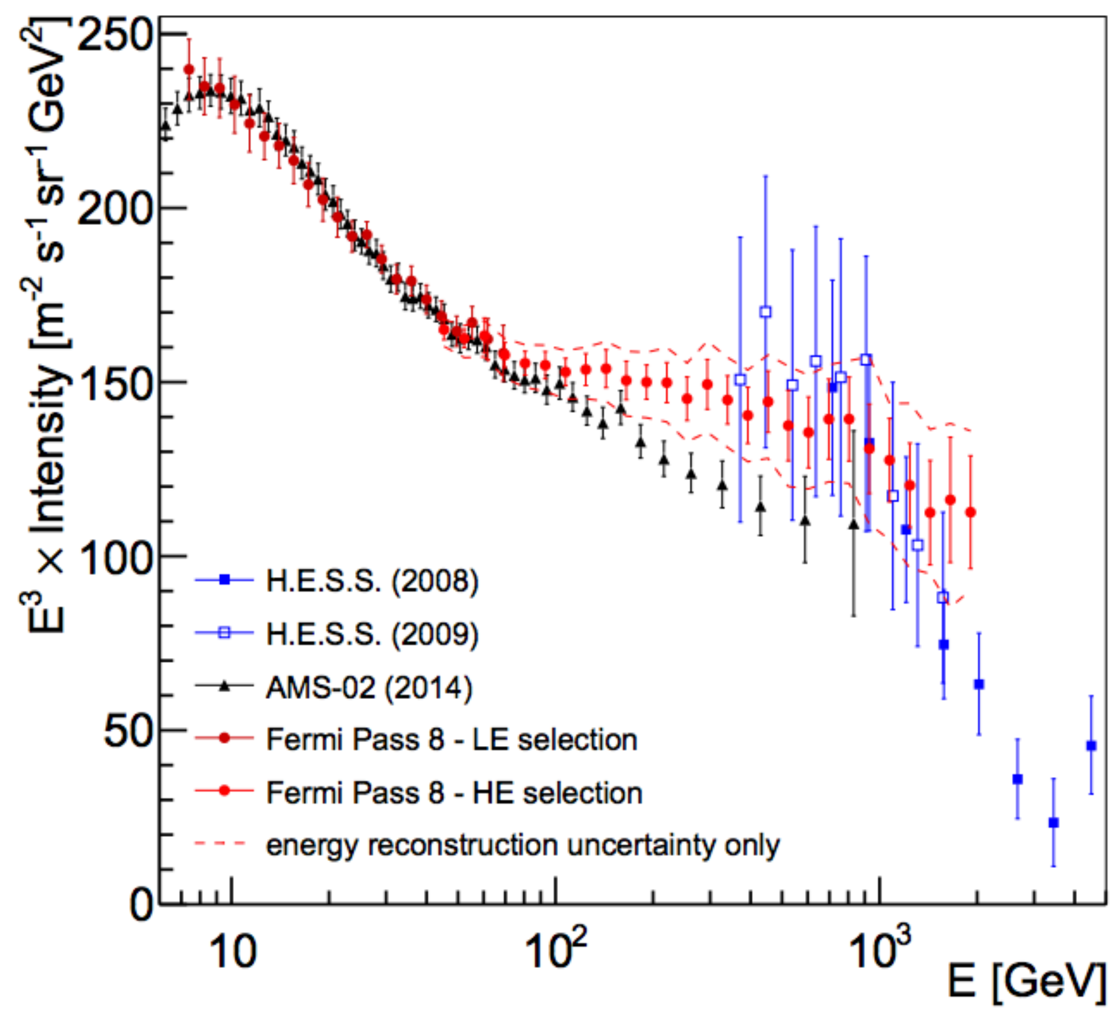
Cosmic-ray electron-positron spectrum from 7 GeV to 2 TeV with the Fermi Large Area Telescope

S. Abdollahi *et al.* (The Fermi-LAT Collaboration)
Phys. Rev. D **95**, 082007 – Published 21 April 2017



- Although a gamma-ray satellite, Fermi can also measure electrons and positrons
- The spectrum measured does not show a break at ~1 TeV

DAMPE

nature
International journal of science

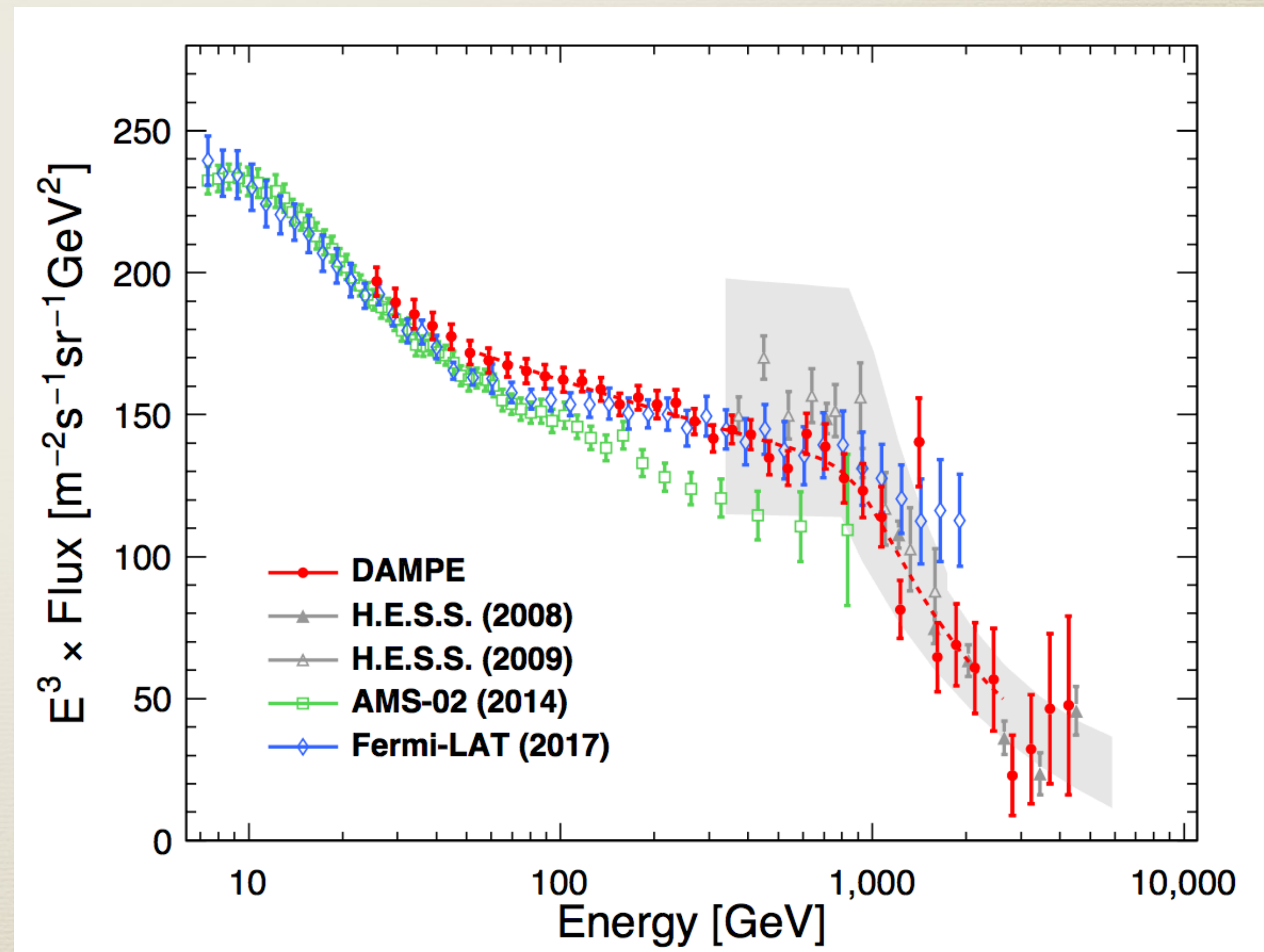
Letter | Published: 29 November 2017

Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons

DAMPE Collaboration

Nature **552**, 63–66 (07 December 2017) | Download Citation

- Confirmation of IACT measurements
- Flux compatible with Fermi
- Fluctuation at 1.4 TeV that was suggested by several authors as a Dark Matter signature



CALET

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Energy Spectrum of Cosmic-Ray Electron and Positron from 10 GeV to 3 TeV Observed with the Calorimetric Electron Telescope on the International Space Station

O. Adriani *et al.* (CALET Collaboration)
Phys. Rev. Lett. **119**, 181101 – Published 1 November 2017

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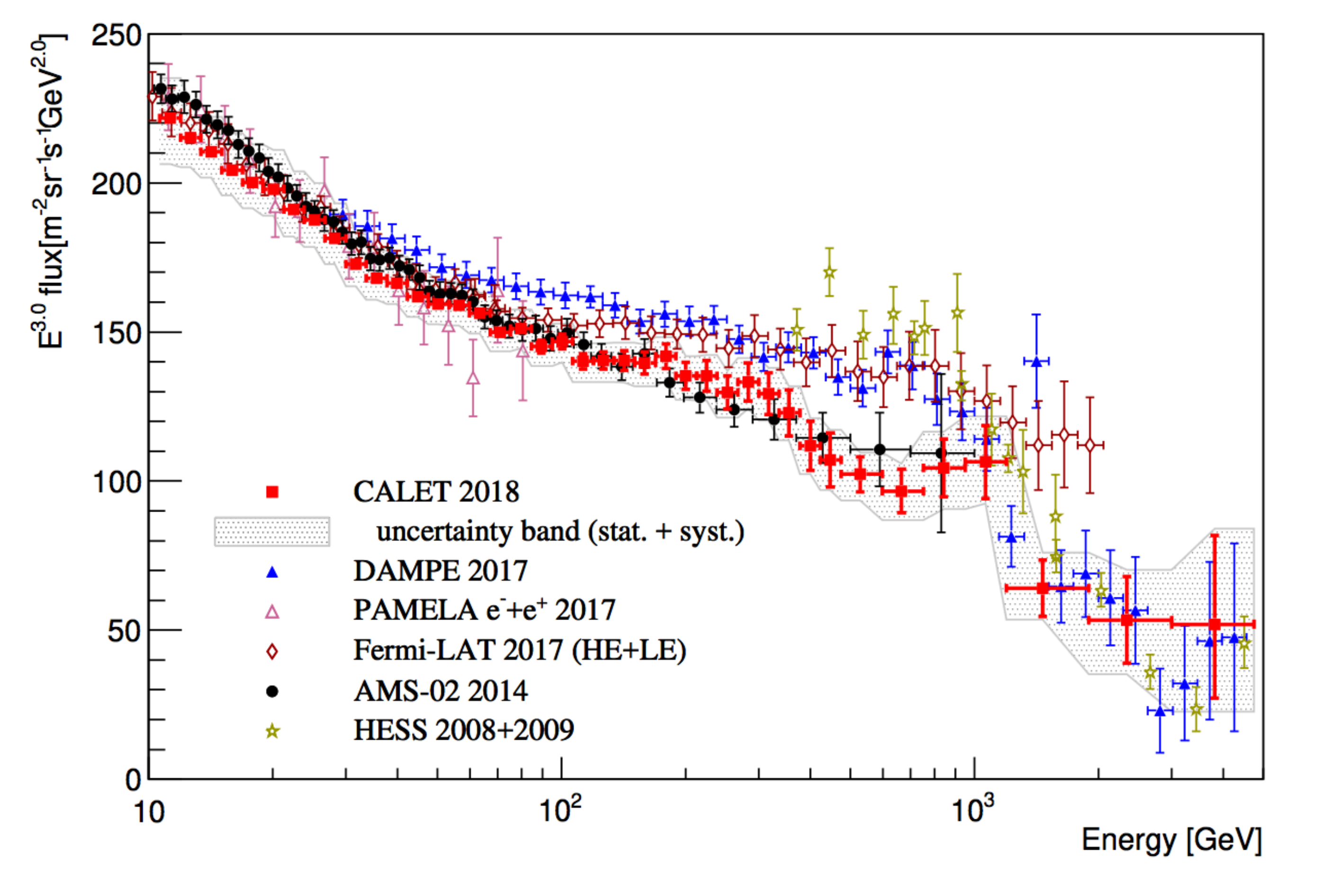
Extended Measurement of the Cosmic-Ray Electron and Positron Spectrum from 11 GeV to 4.8 TeV with the Calorimetric Electron Telescope on the International Space Station

O. Adriani *et al.* (CALET Collaboration)
Phys. Rev. Lett. **120**, 261102 – Published 25 June 2018



- Also found a break in the spectrum
- No line-like feature at 1.4 TeV

AMS

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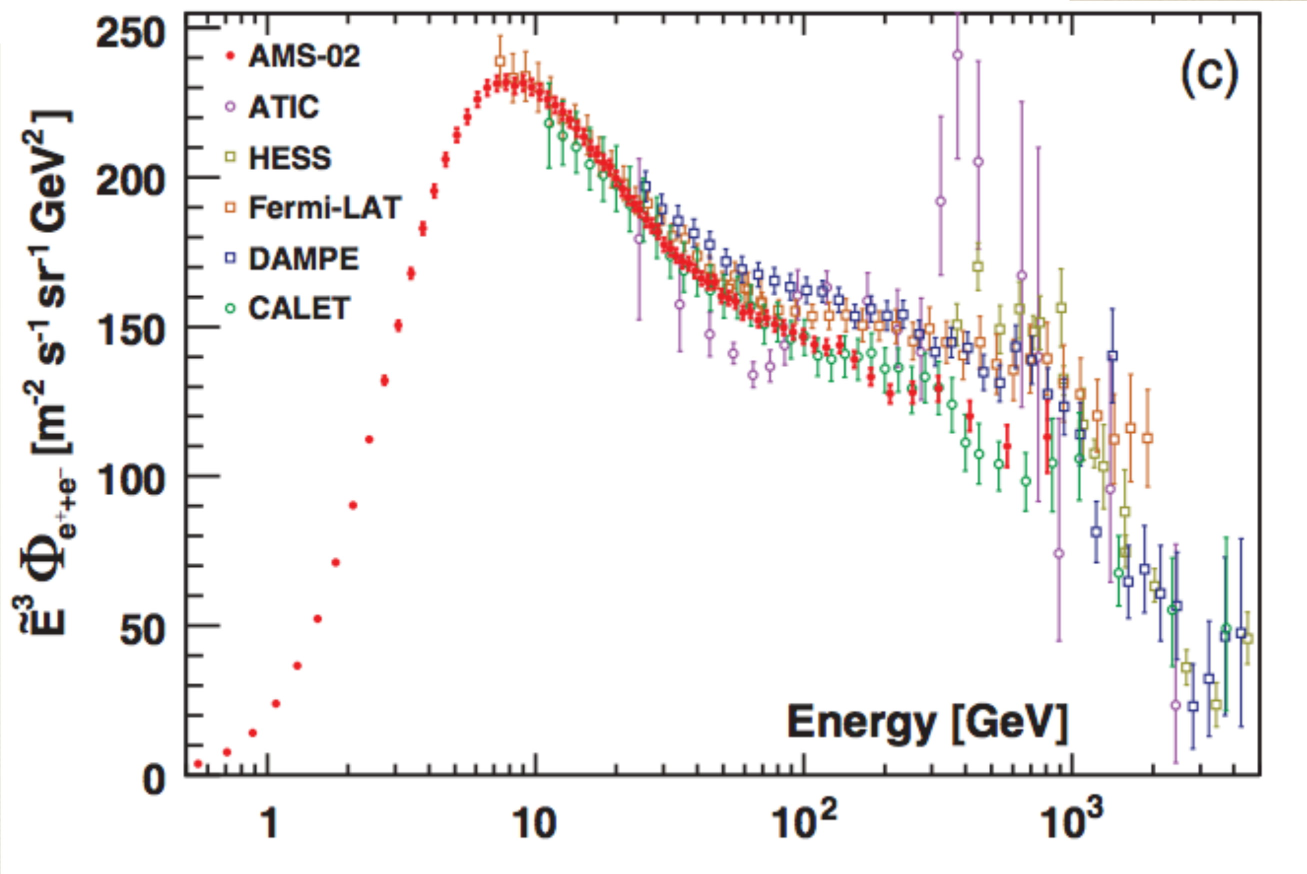
Open Access

Towards Understanding the Origin of Cosmic-Ray Electrons

M. Aguilar *et al.* (AMS Collaboration)

Phys. Rev. Lett. **122**, 101101 – Published 13 March 2019

- Similar spectrum to the CALET one
- Does not reach high enough energies to give a statement about the break



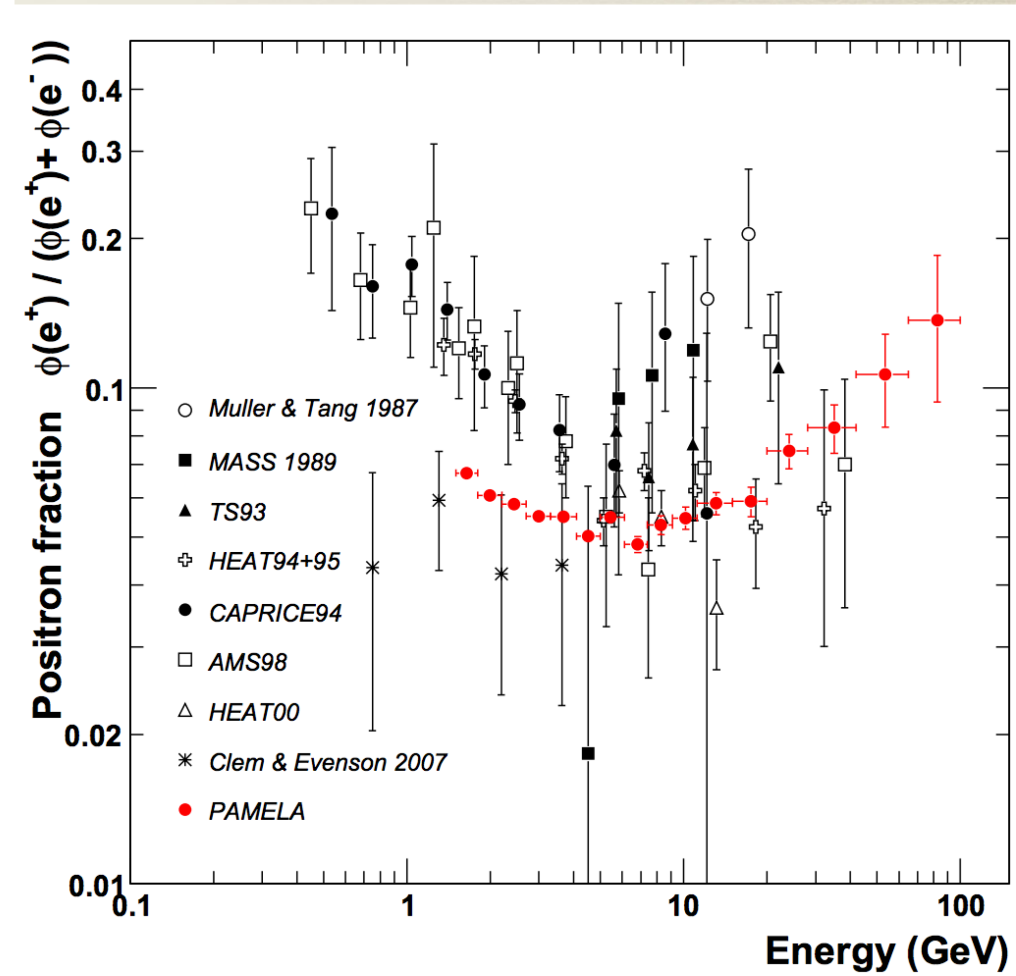
Positron Fraction: PAMELA

nature
International journal of science

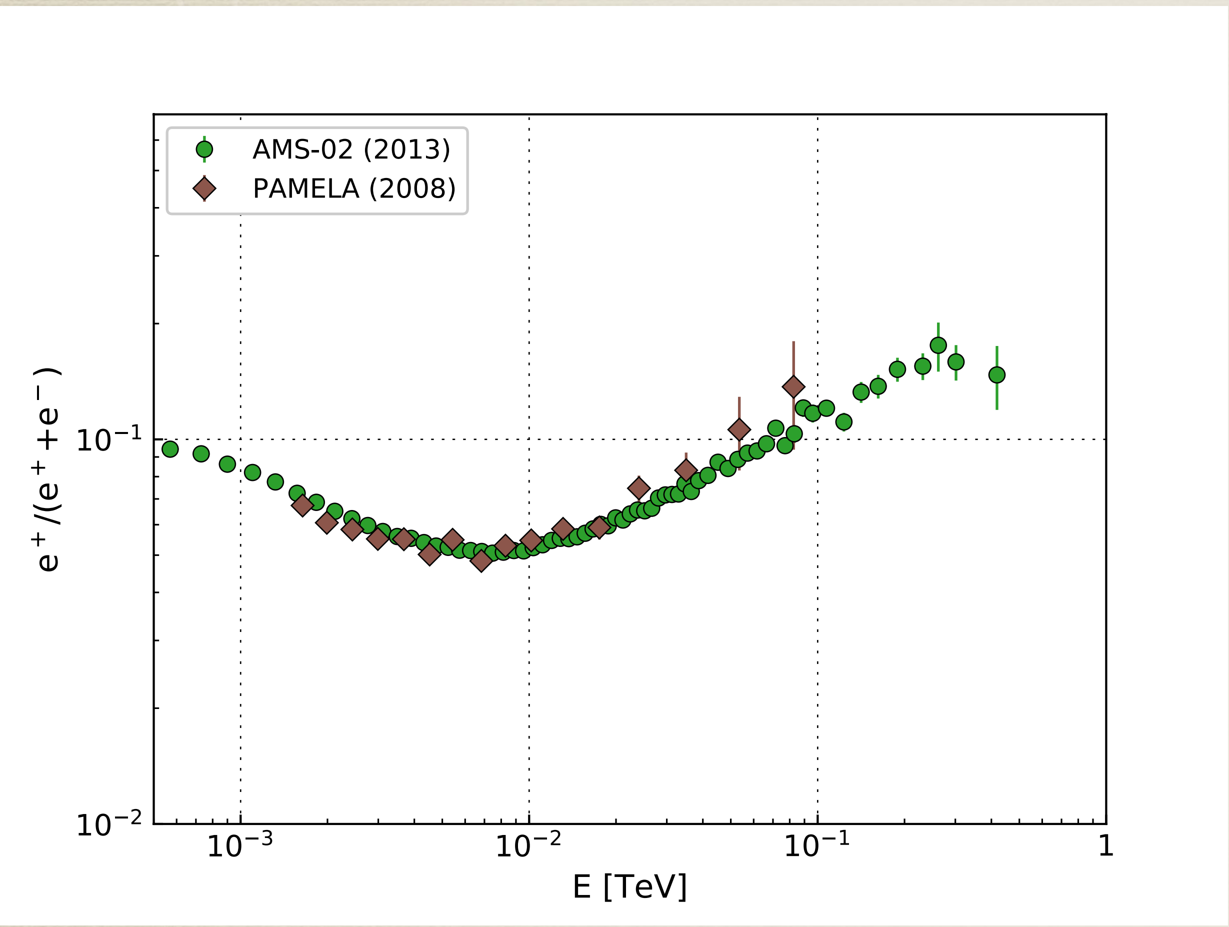
Letter | Published: 02 April 2009

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

In 2009, PAMELA measured an anomalous positron abundance

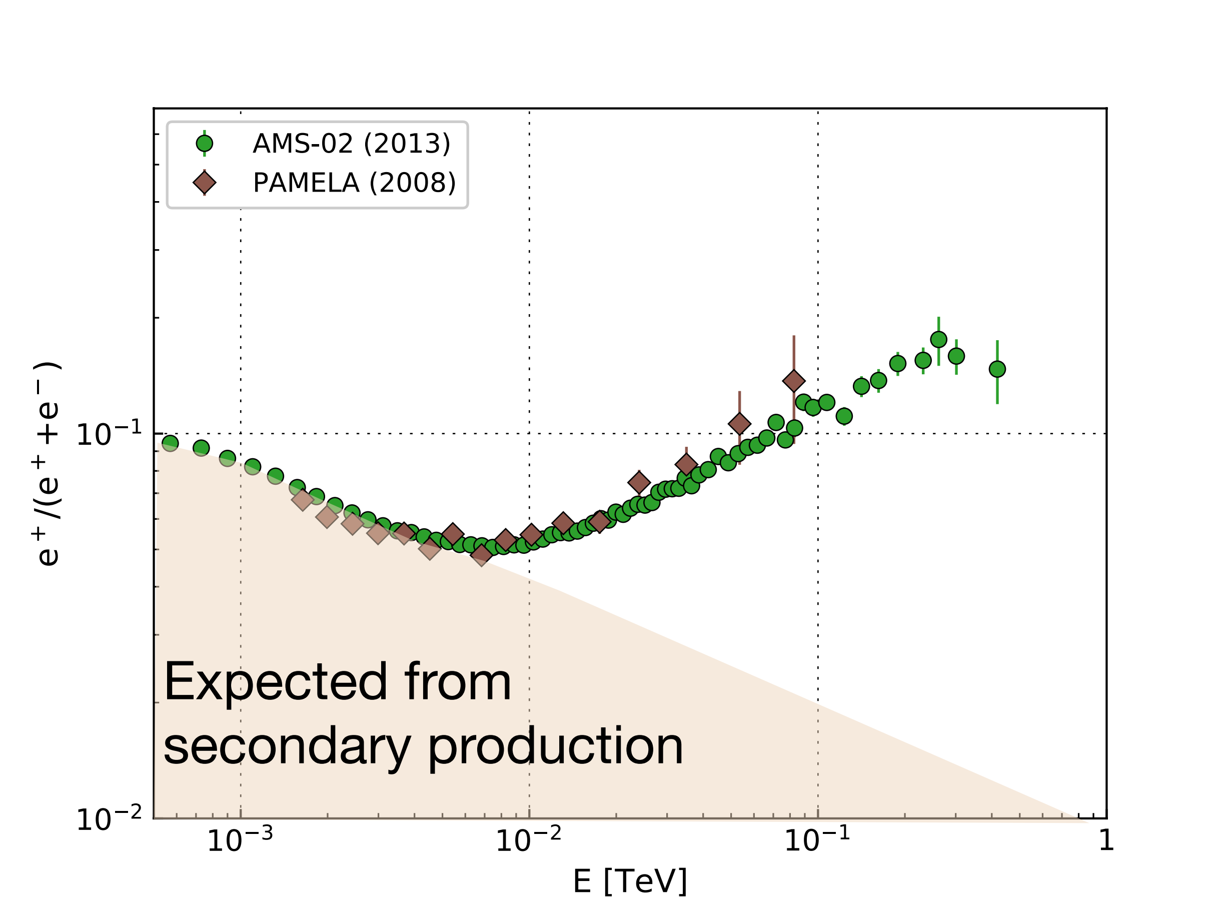


Positron Fraction



- The positron fraction is expected to decrease with Energy

Positron Fraction



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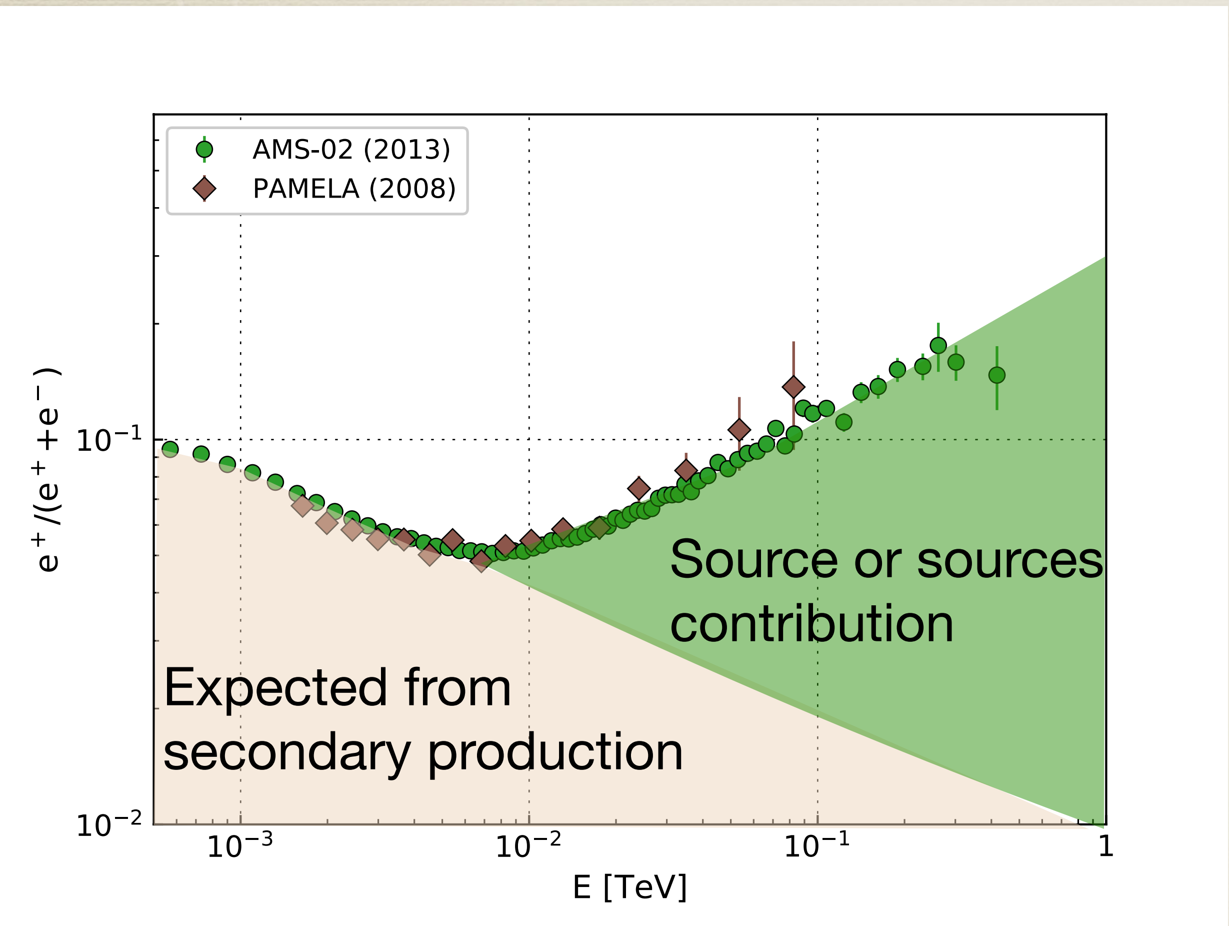
  - This is the case for energies below a few GeV

Positron Fraction



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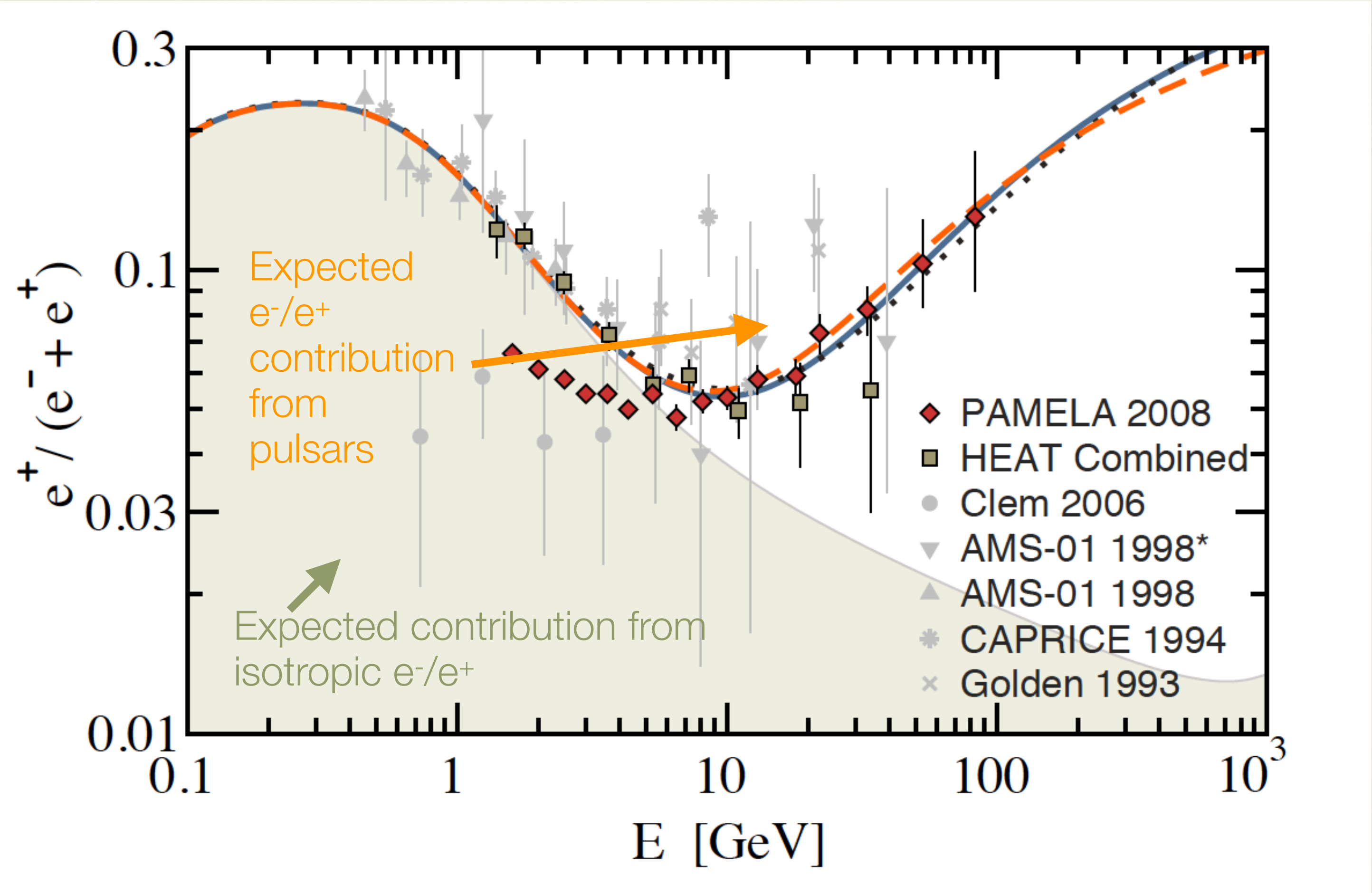
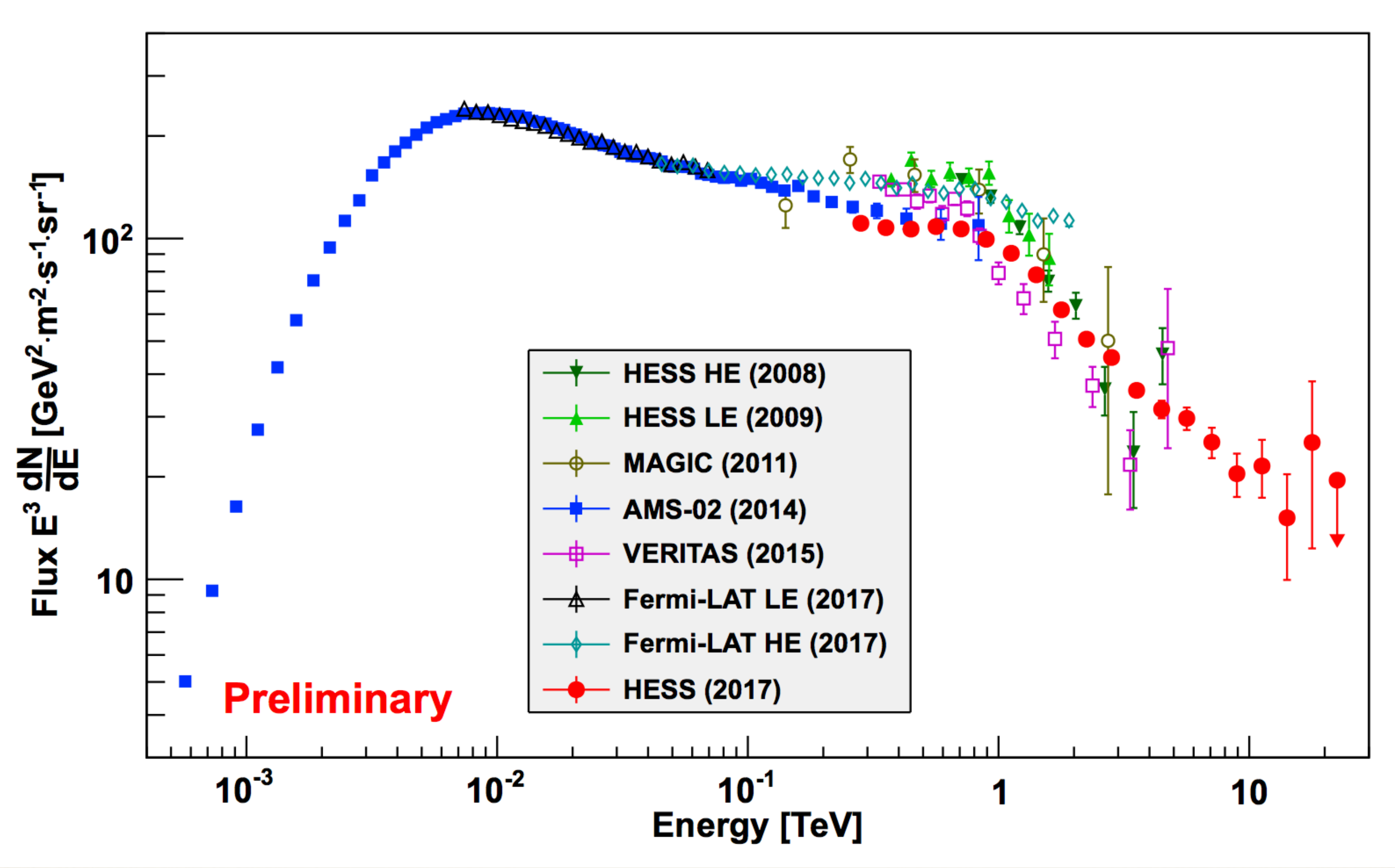
Pulsars as sources of the positron excess



Yuksel et al. (2009)

- Possible sources:
  - Pulsars/PWNe (Aharonian et al. (1995), Yüksel et al. (2009), …)
  - Dark matter (zillions of papers…)
  - Microquasar jets (Gupta & Torres 2014)
  - Different assumptions about secondary production (no source)

Latest all-e measurement



- Presented at ICRC 2017
- Extends the spectrum up to ~20 TeV
- Confirms the break at ~900 GeV
- Featureless power-law for higher energies