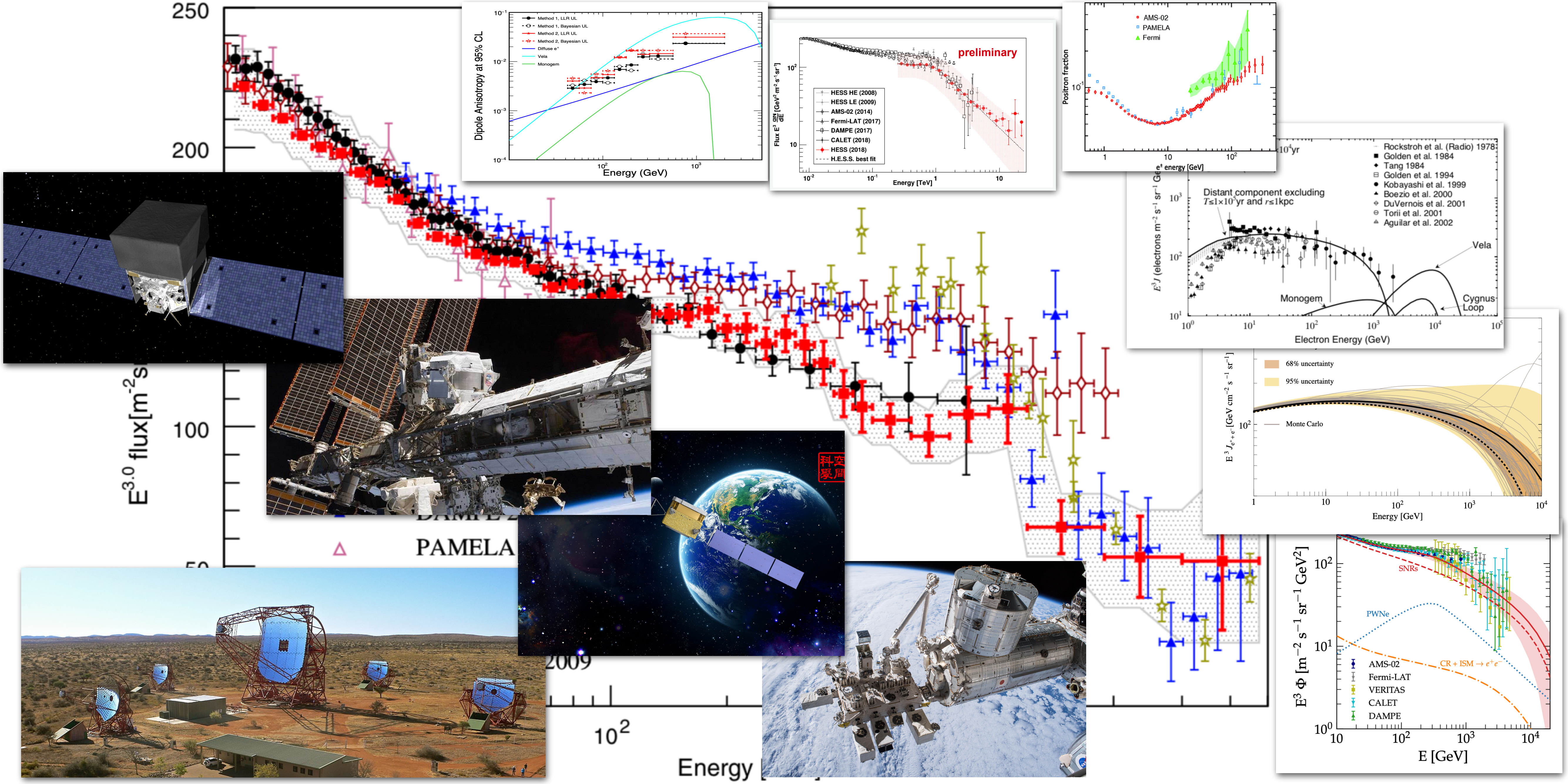
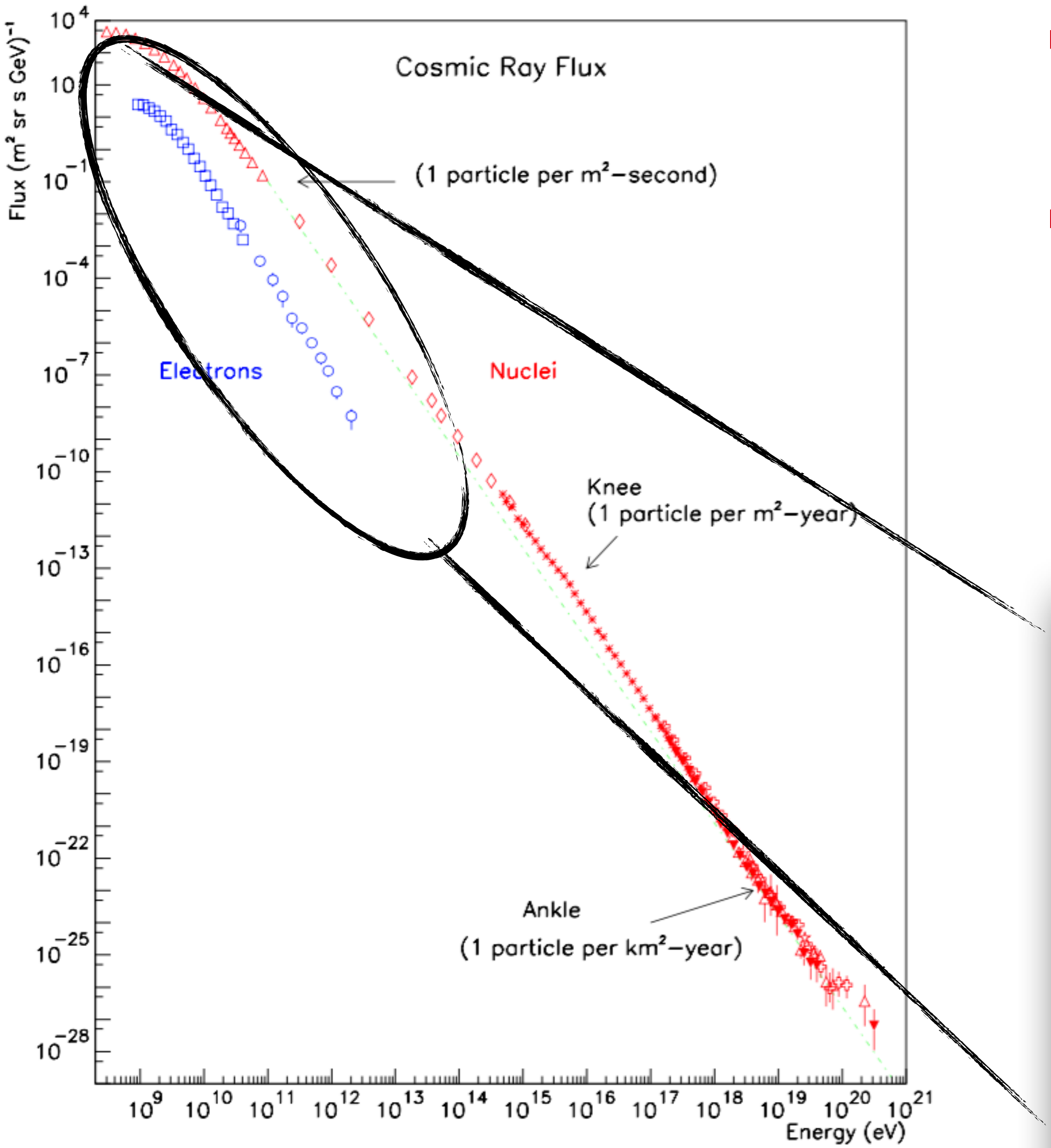


VHE Cosmic-Ray Electrons Observation and Theory

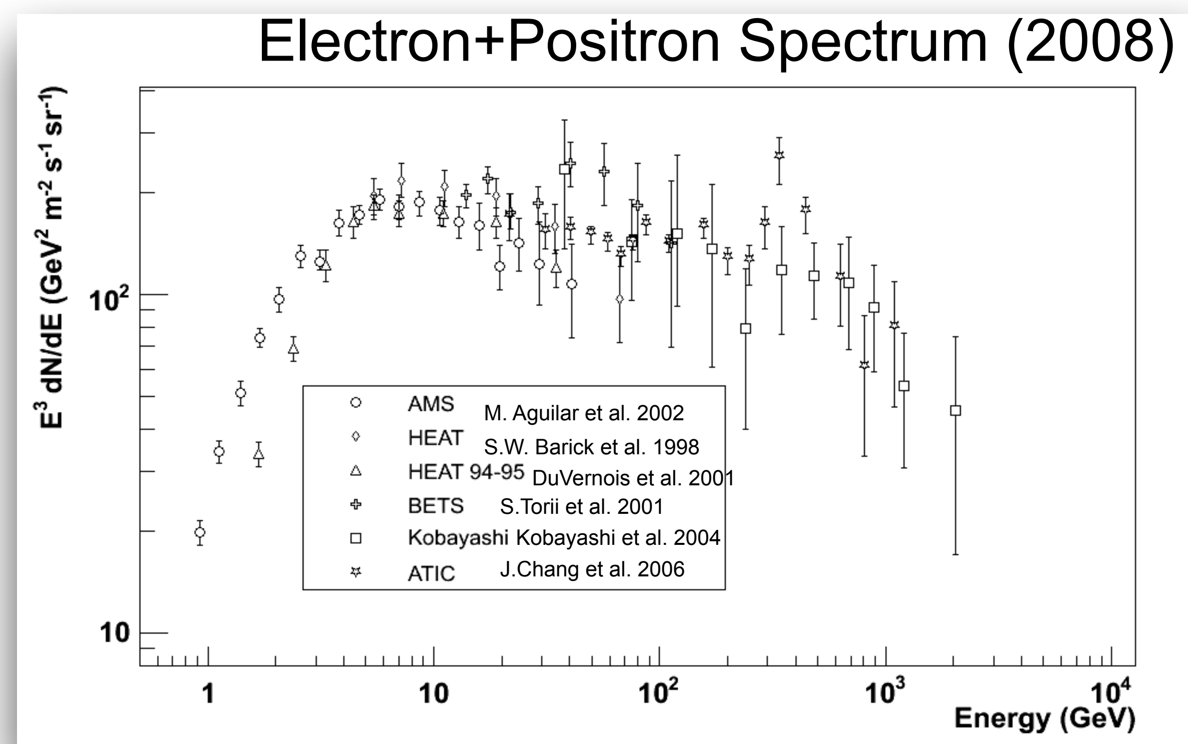
Kathrin Egberts
University of Potsdam

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



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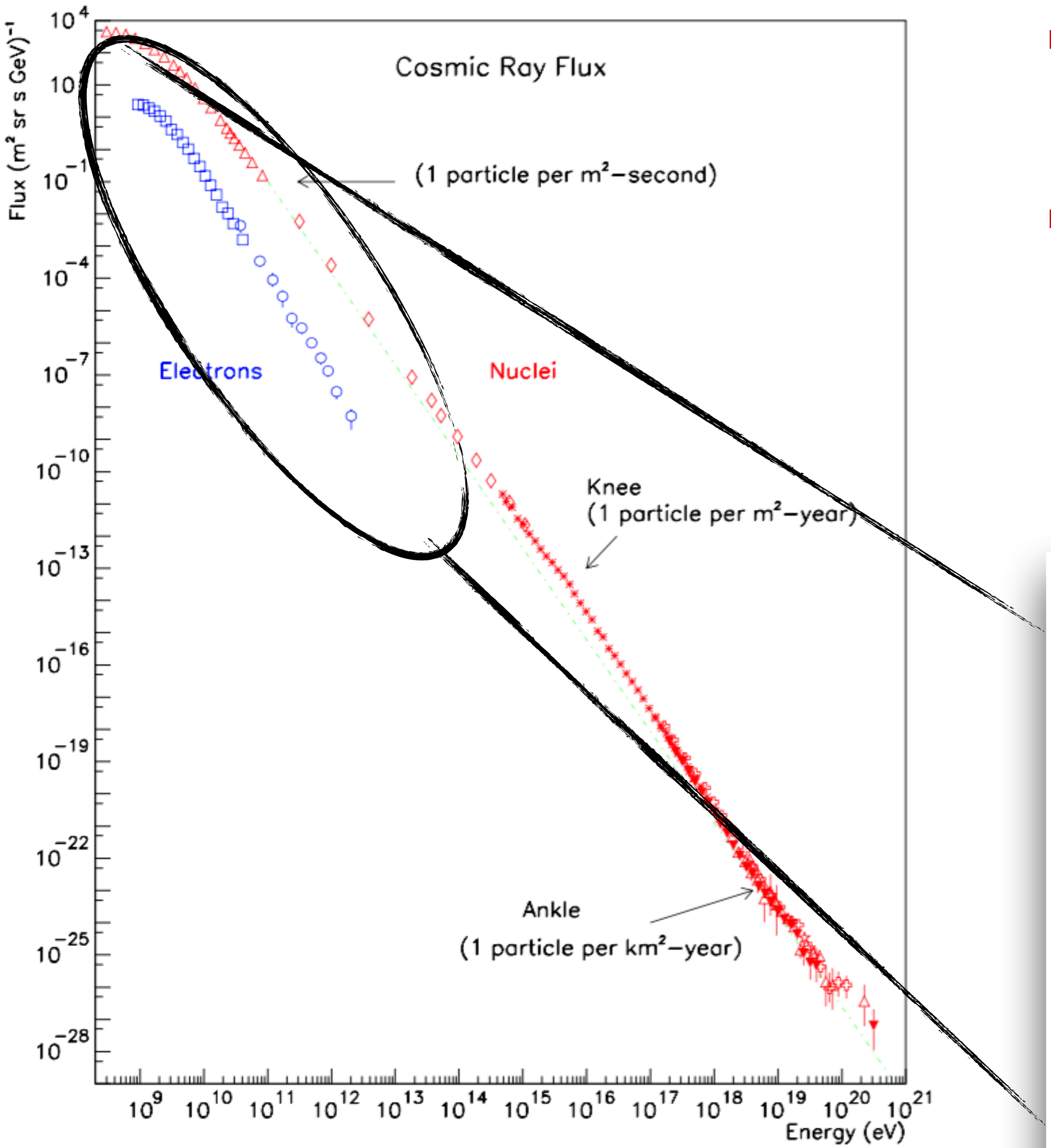

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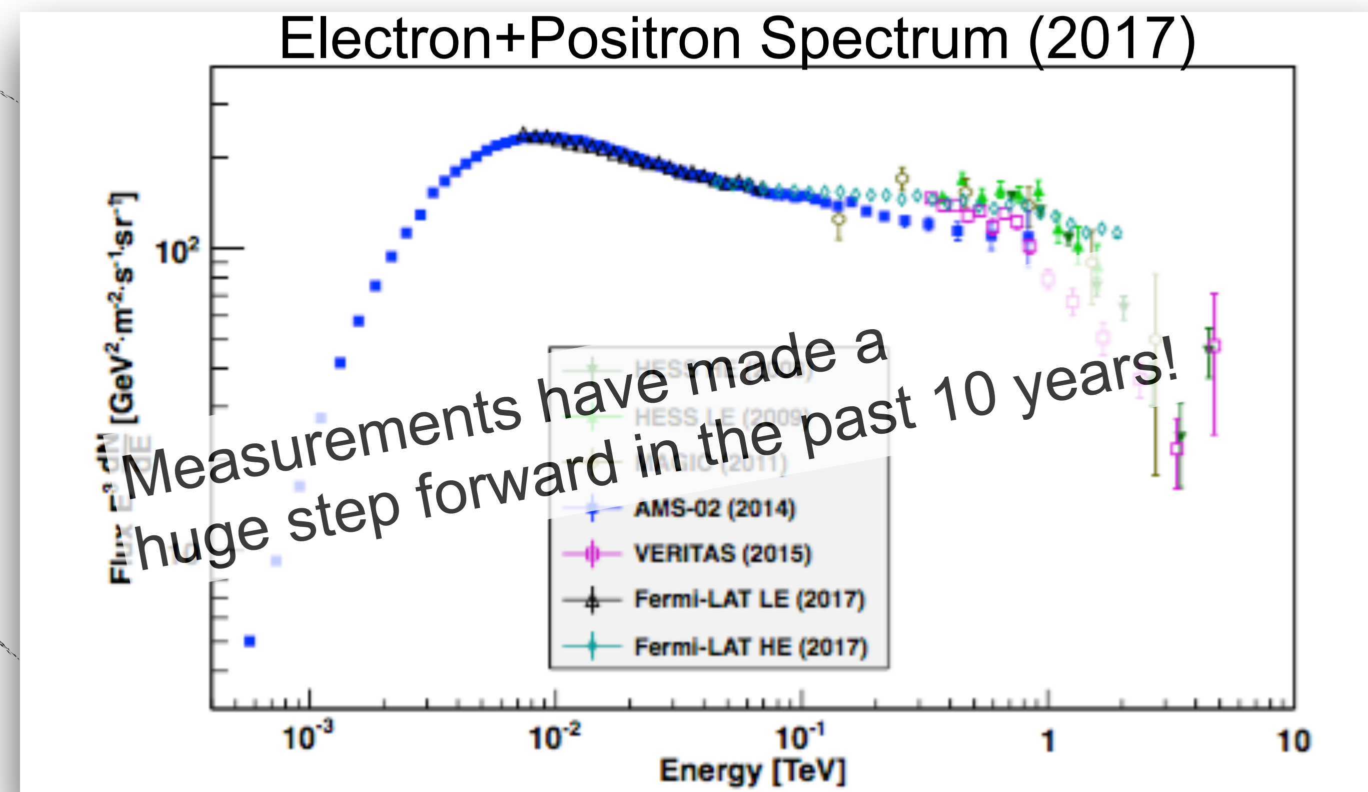


Measurements have made a huge step forward in the past 10 years!

VHE Measurements of Cosmic-Ray Electrons

Measurements need:

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

large effective areas

large field of view

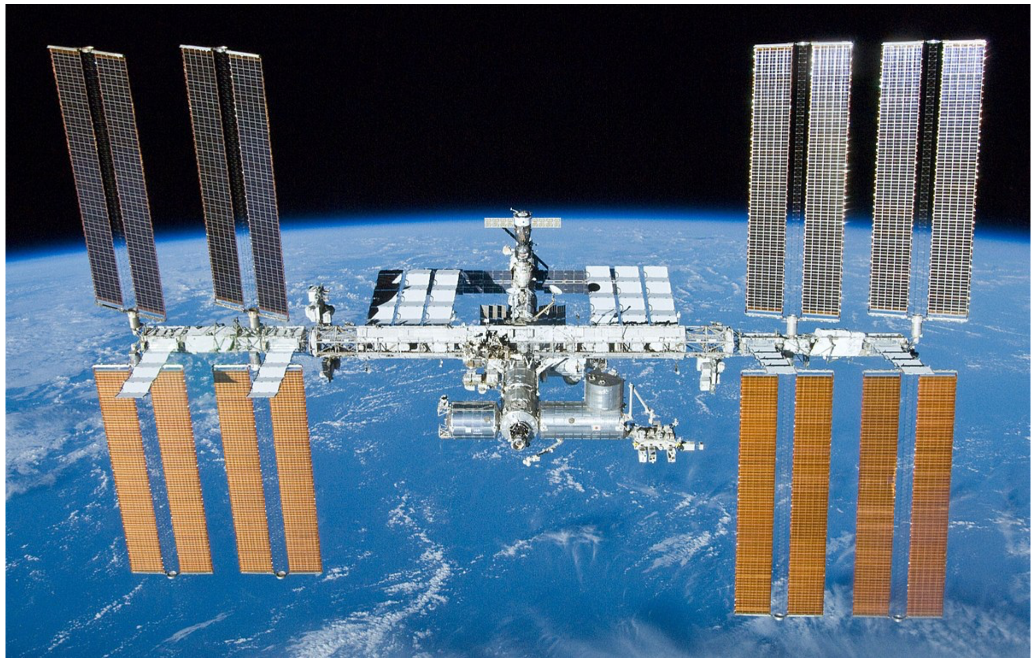
long observation times

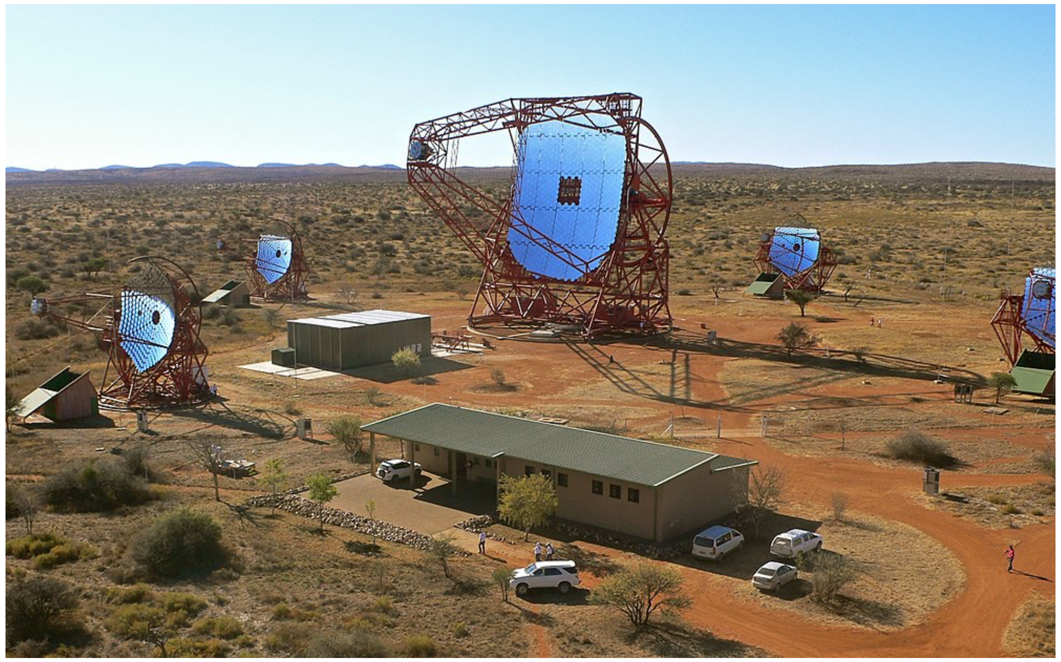
→ Deep calorimeters for TeV energy reconstruction

→ Excellent electron-hadron separation capabilities

VHE Measurements of Cosmic-Ray Electrons

Direct Measurements or Indirect Measurements





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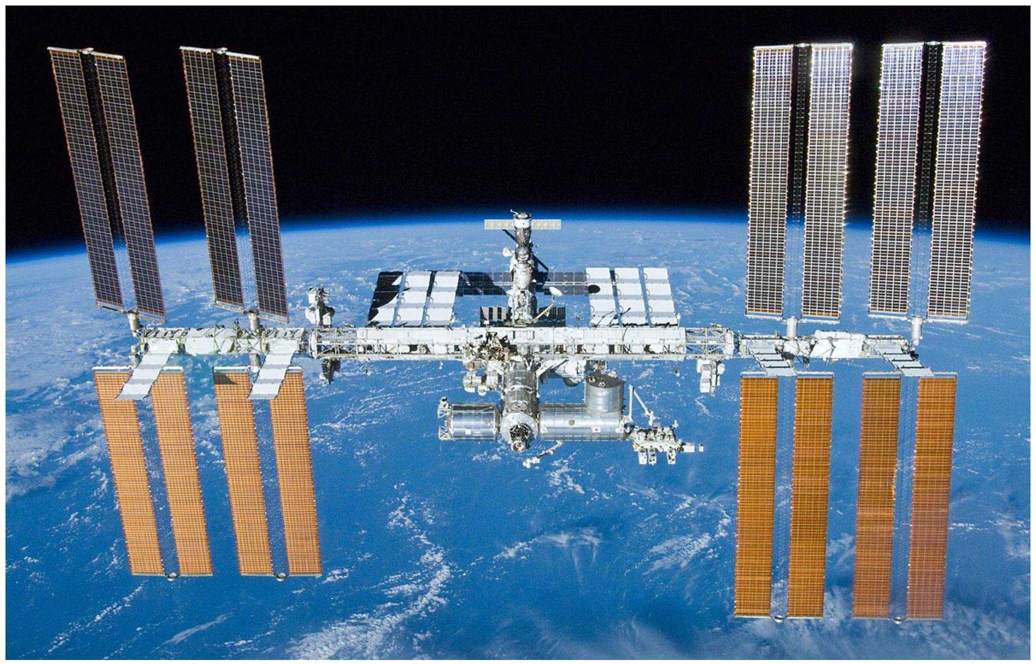
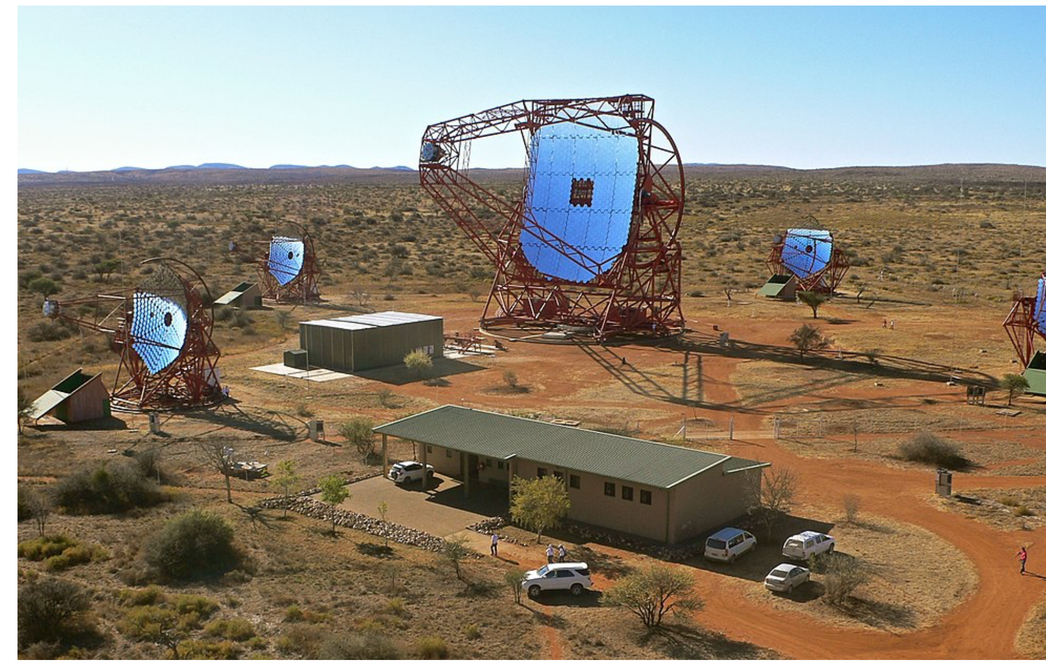
		

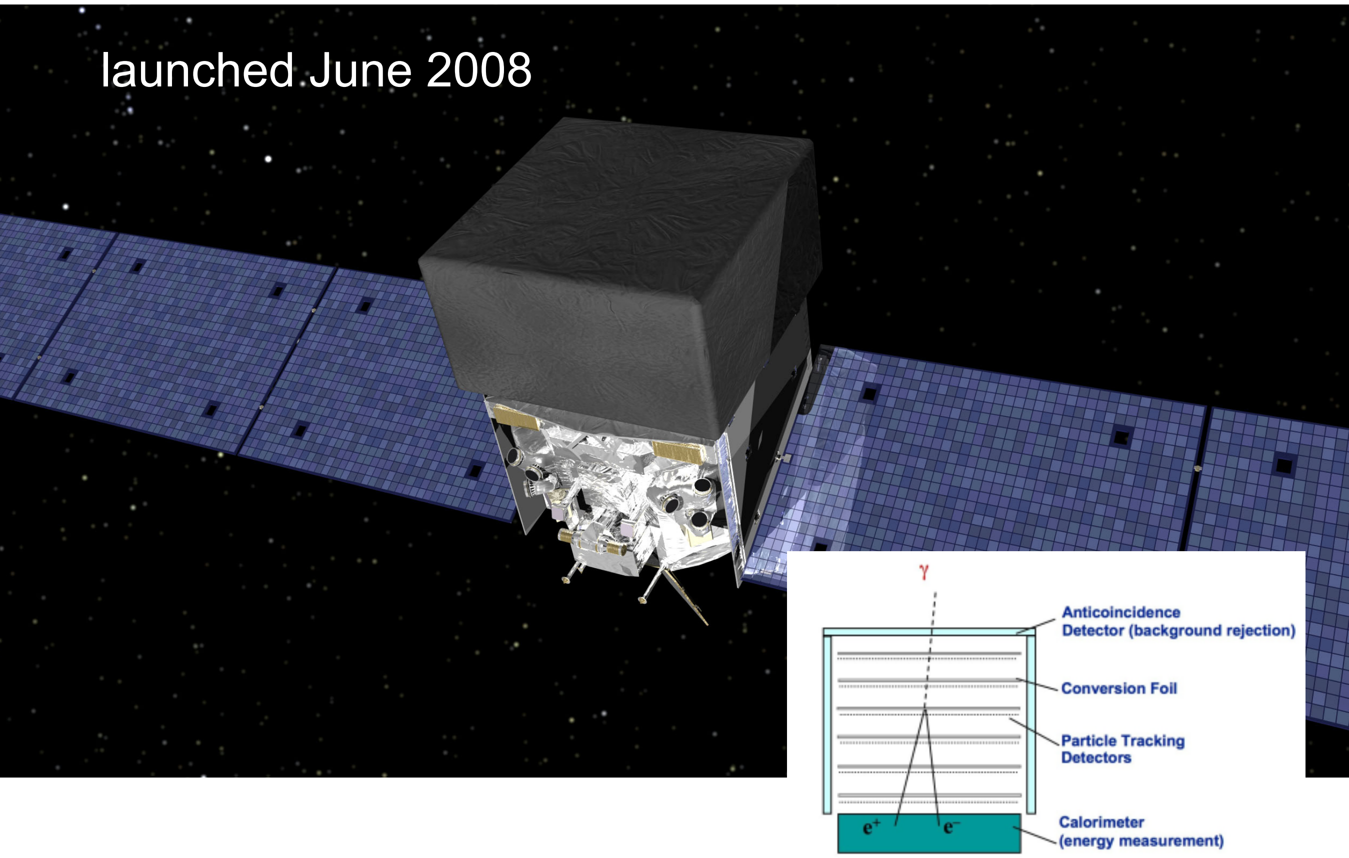
Measurements need:

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

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

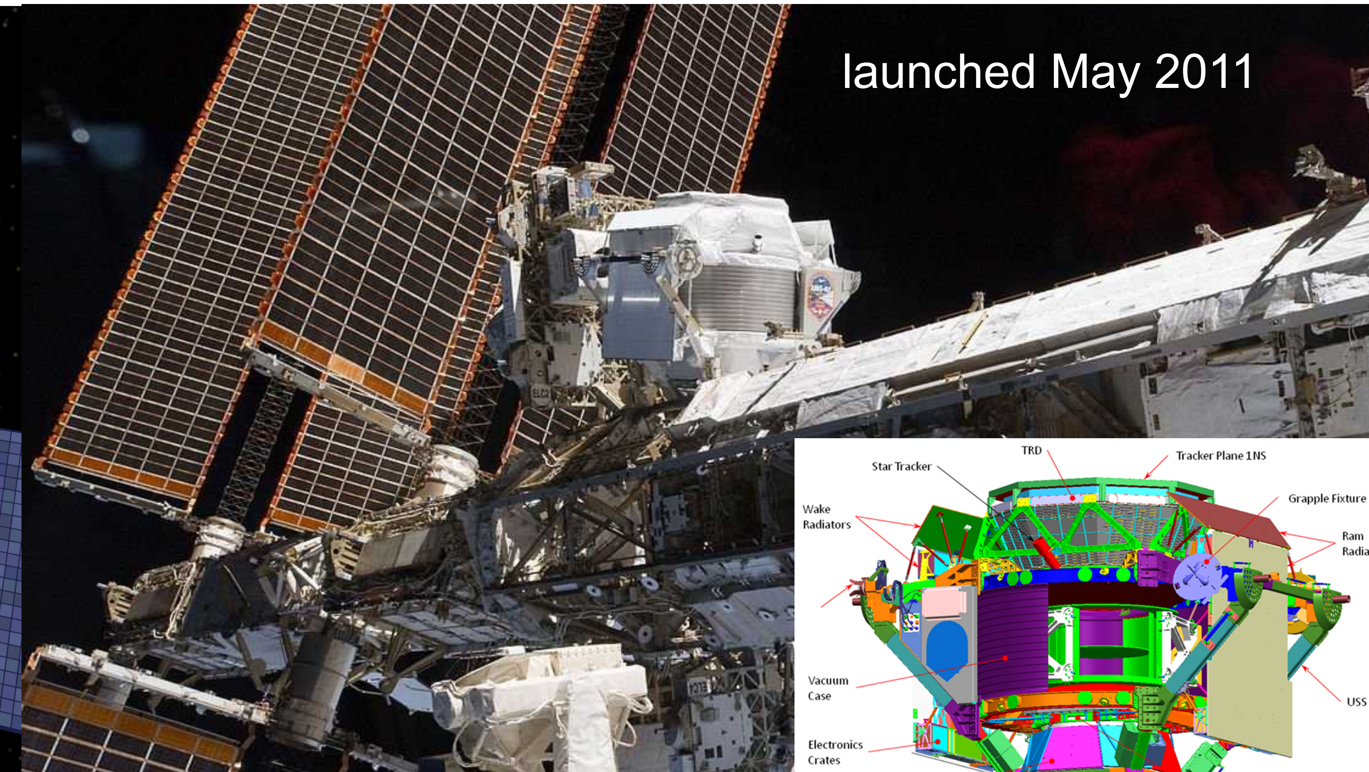
Direct Measurements

Fermi-Lare Area Telescope (Fermi-LAT)

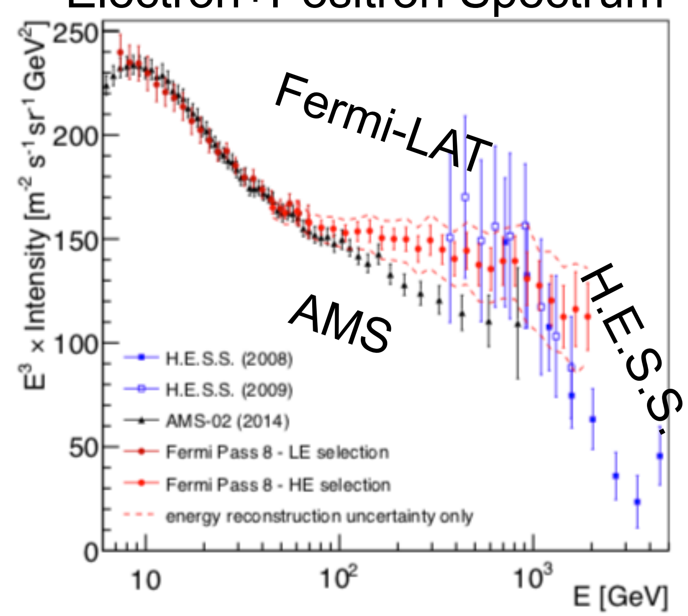


- High-statistics precision measurements from ~GeV up to ~ TeV
- Excellent agreement at energies below 100 GeV
- Divergence at higher energies

Alpha Magnetic Spectrometer (AMS)



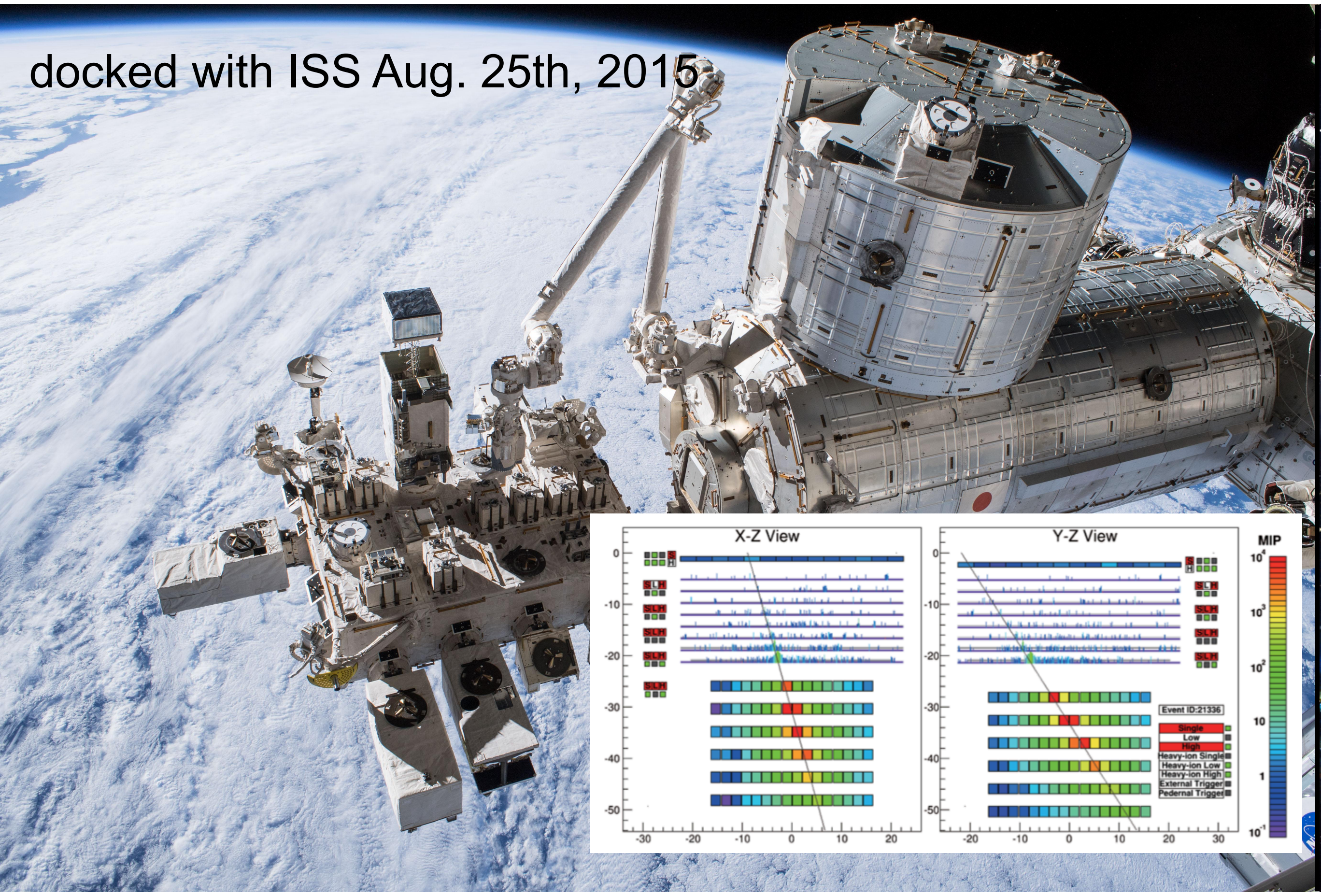
Electron+Positron Spectrum



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

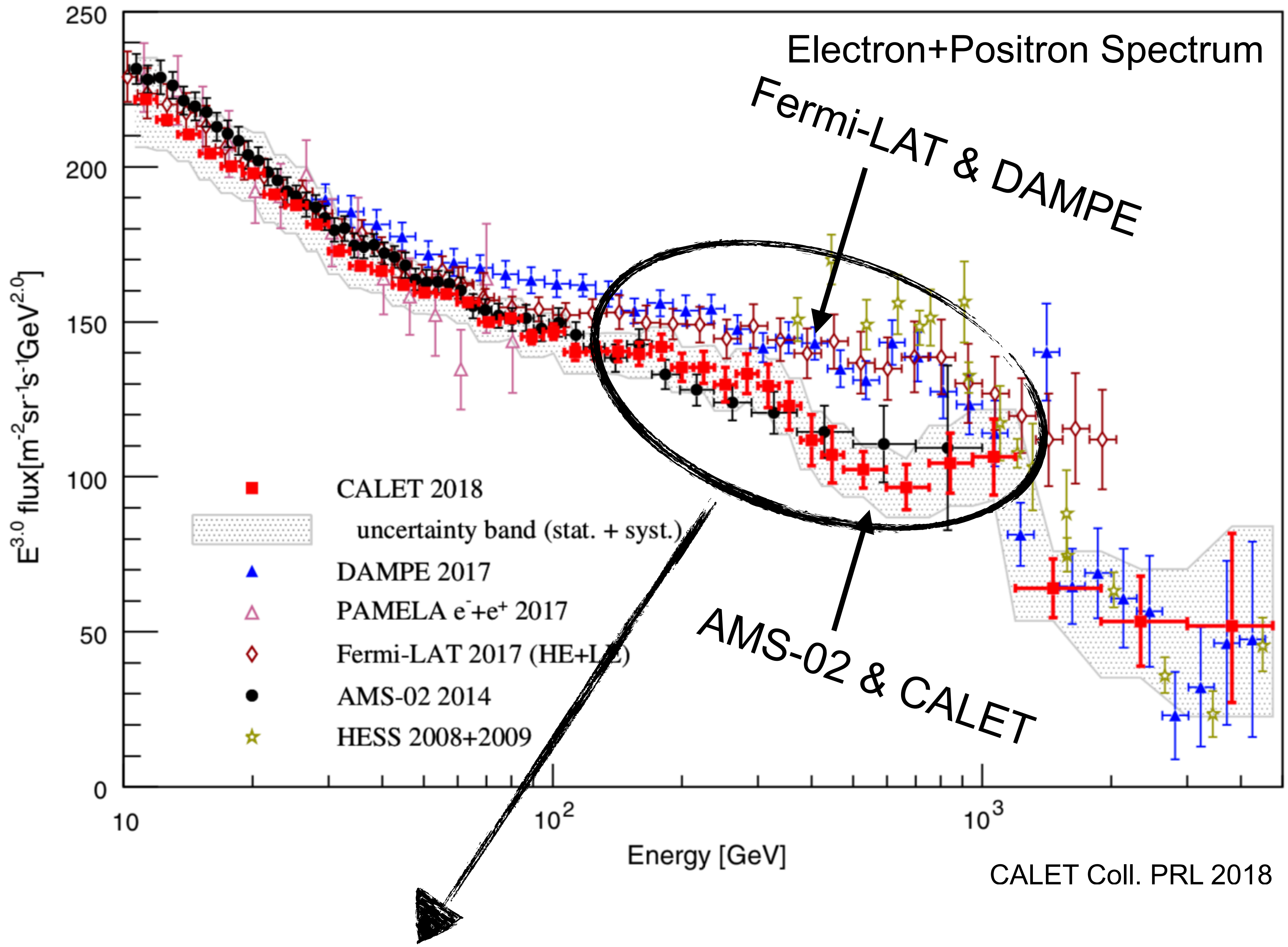
A New Generation of Space-Born Experiments

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 %



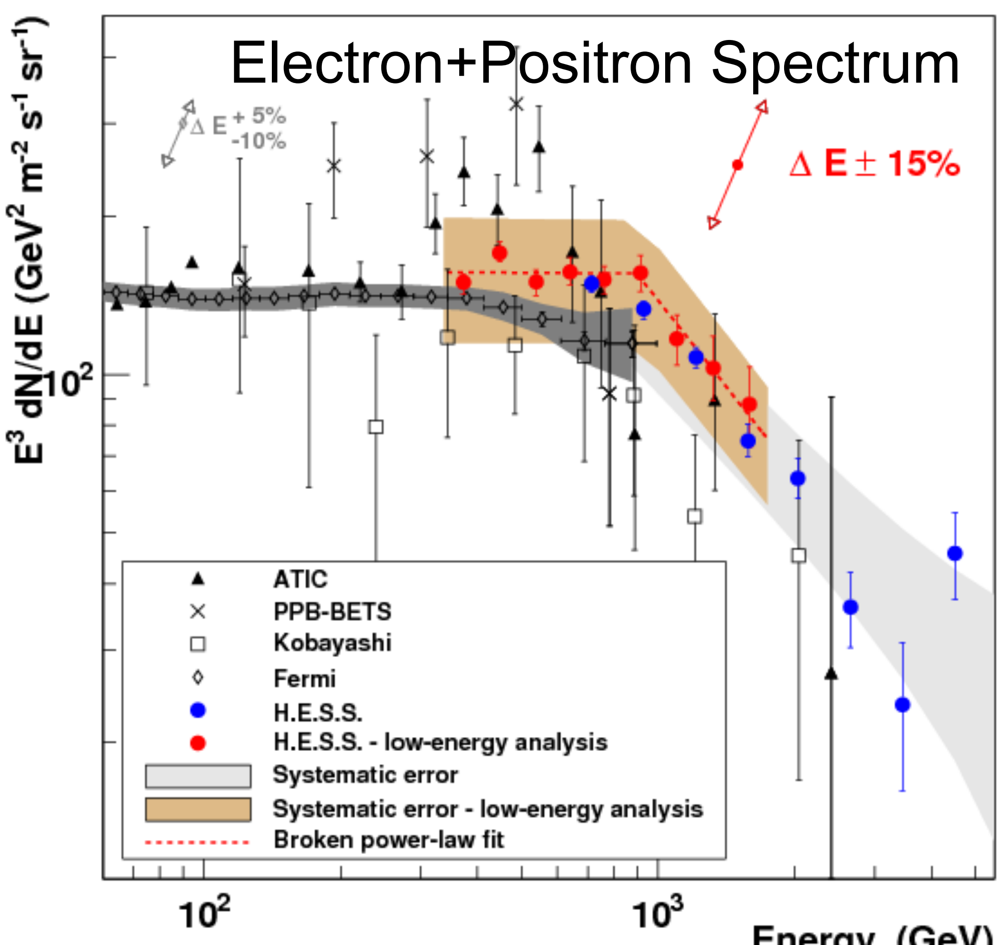
Unaccounted systematics? clearly energy dependent - agreement at low and at high energies - interesting to note the agreement between each two measurements

Measurements with Imaging Atmospheric Cherenkov Telescopes

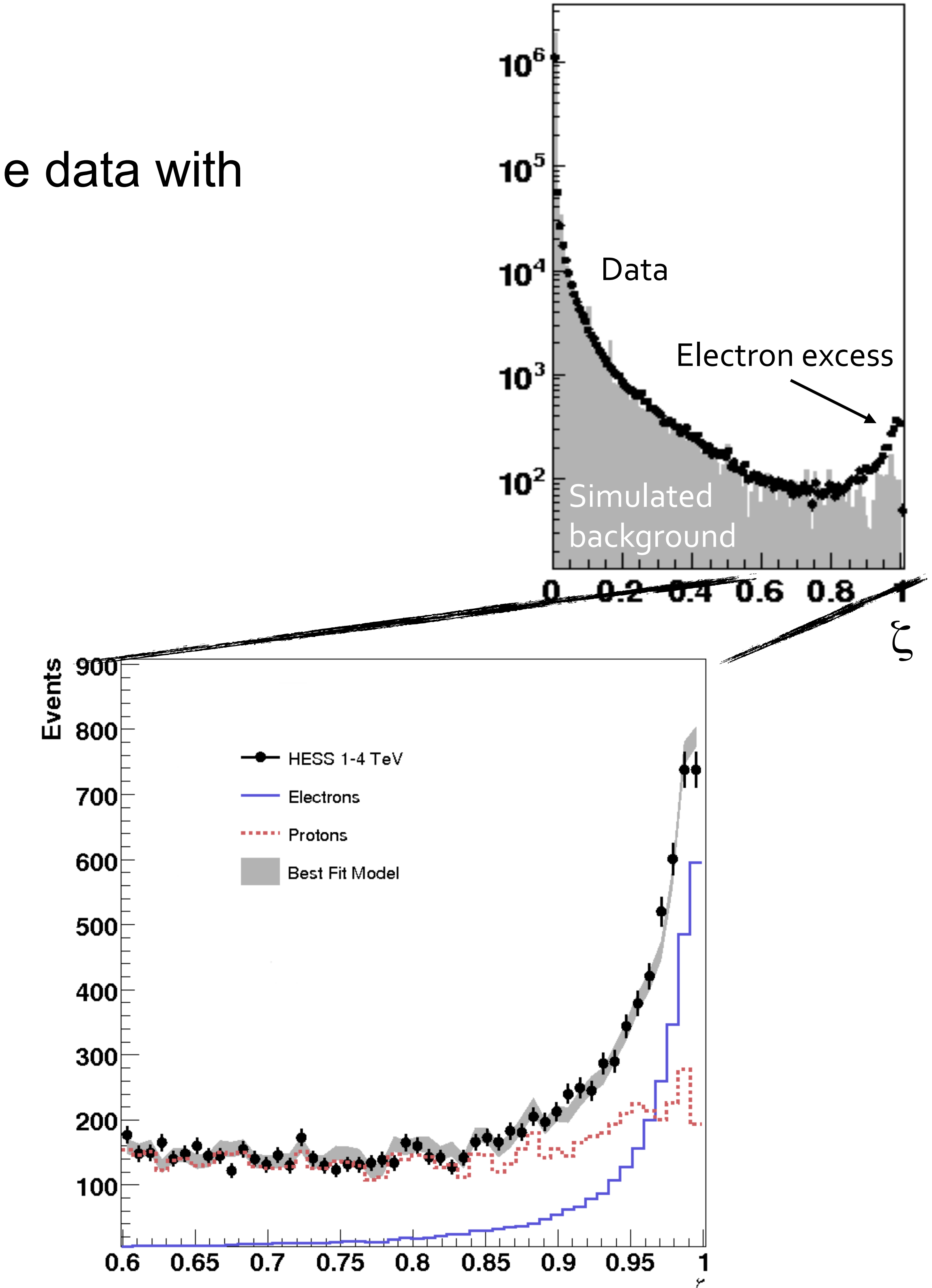
- Designed for TeV gamma-ray measurements
- No charge separation: only inclusive spectrum of $e^+ + e^-$
- Main challenge: background subtraction
  - Gamma-rays (mostly) localised sources, which allows for background measurement in field of view
  - For isotropic electrons need to find alternative solutions

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

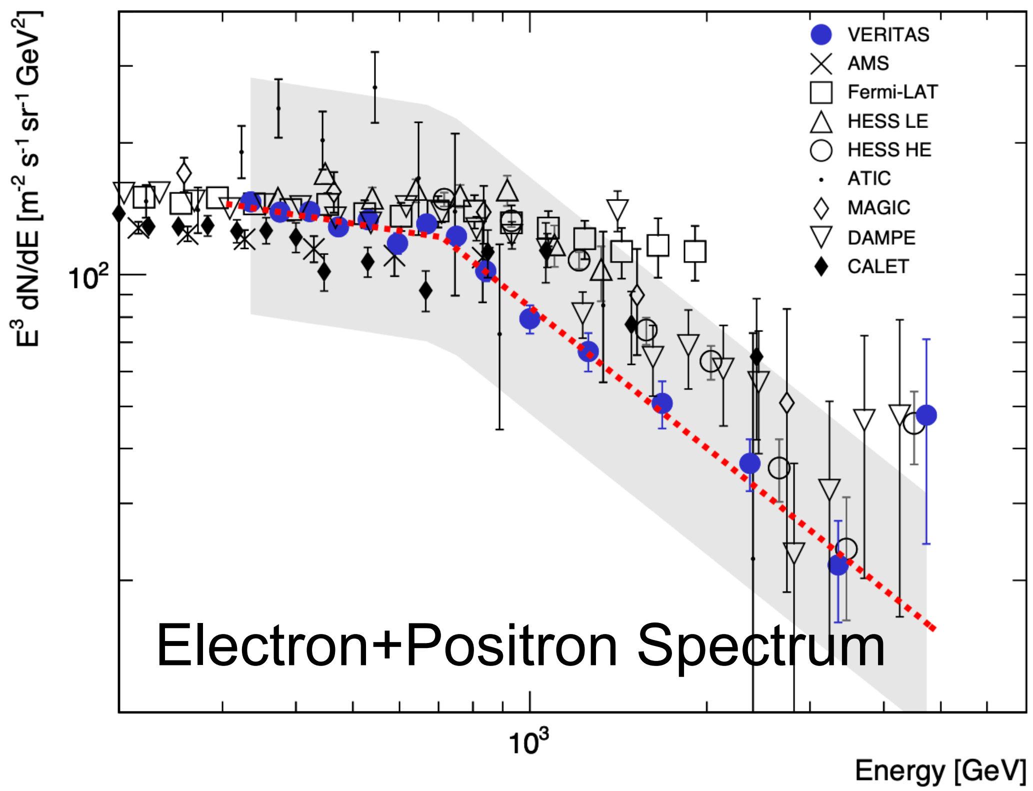


Aharonian et al., A&A 508, 561–564 (2009)

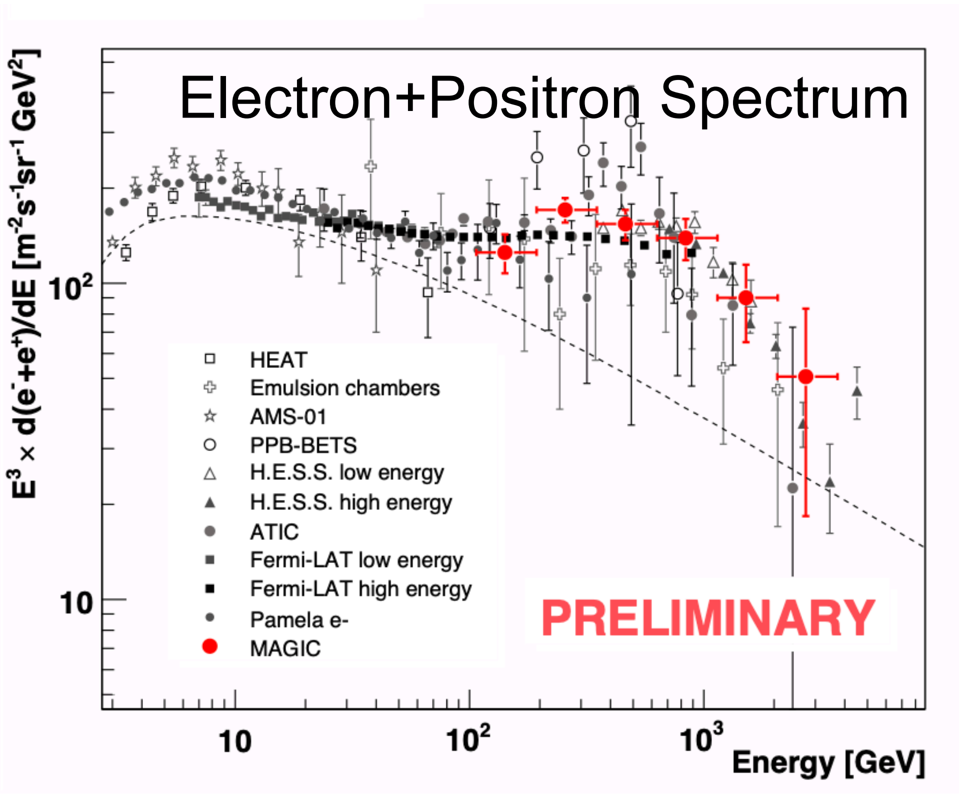


Aharonian et al., PRL **101**, 261104 (2008)

Method & Results Confirmed by Other IACTs

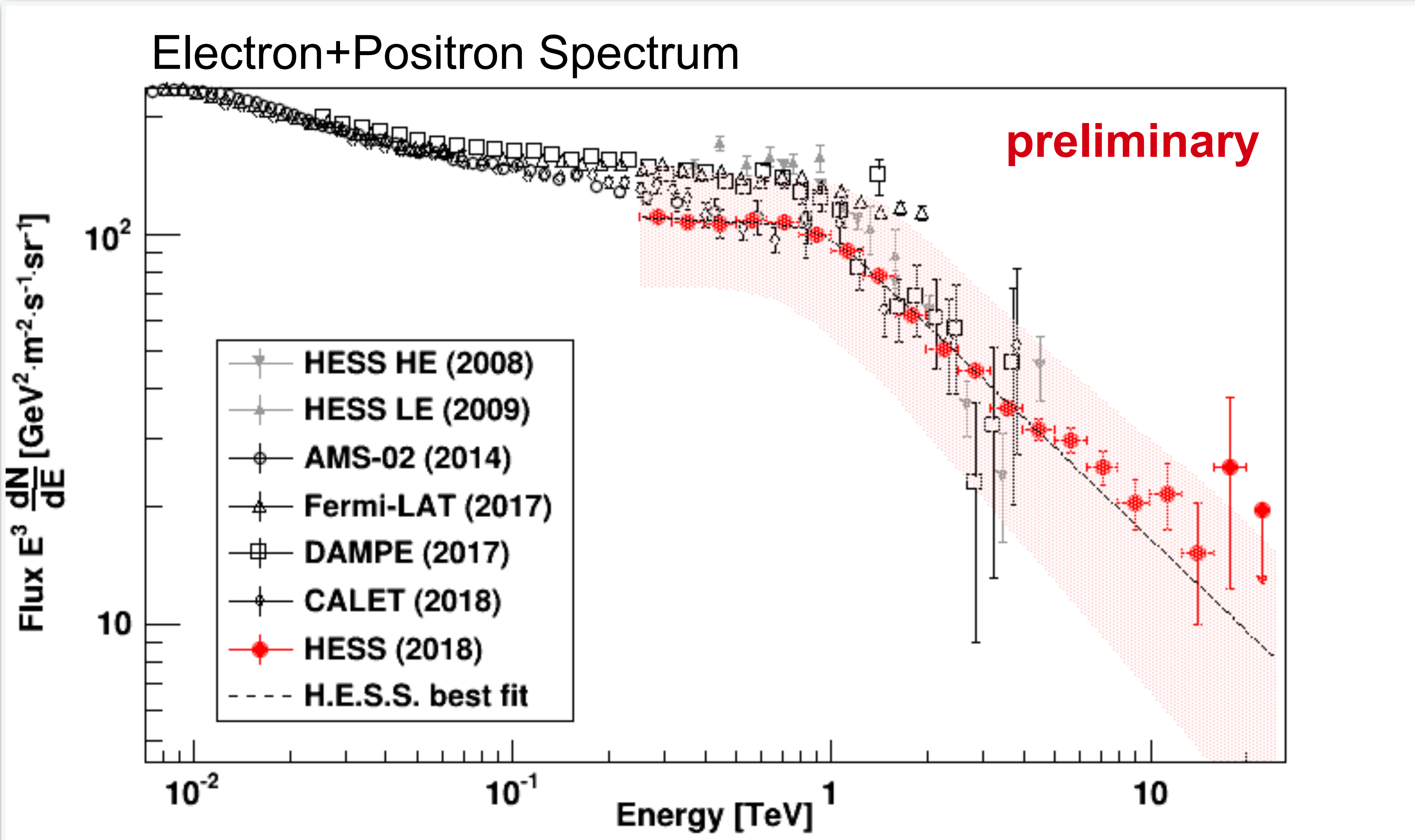


Veritas PRD 2018

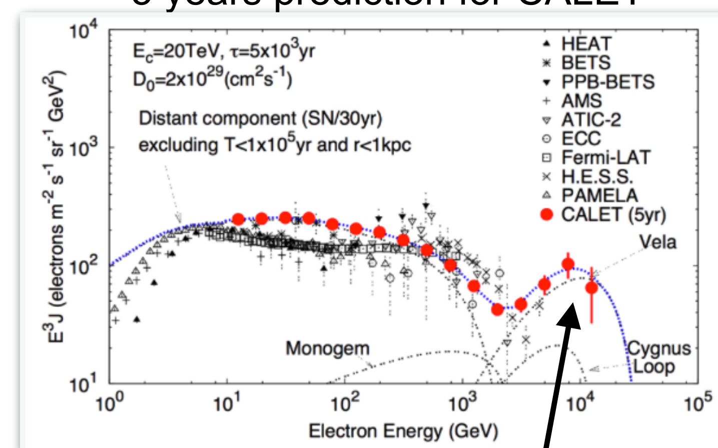


MAGIC ICRC 2011

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



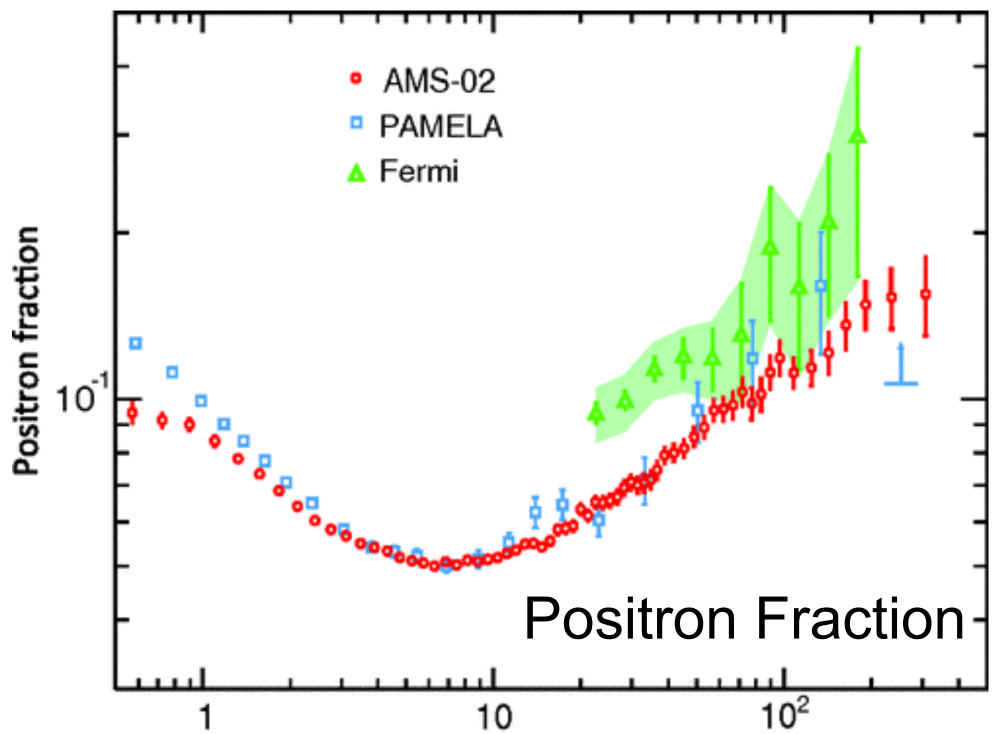
5 years prediction for CALET

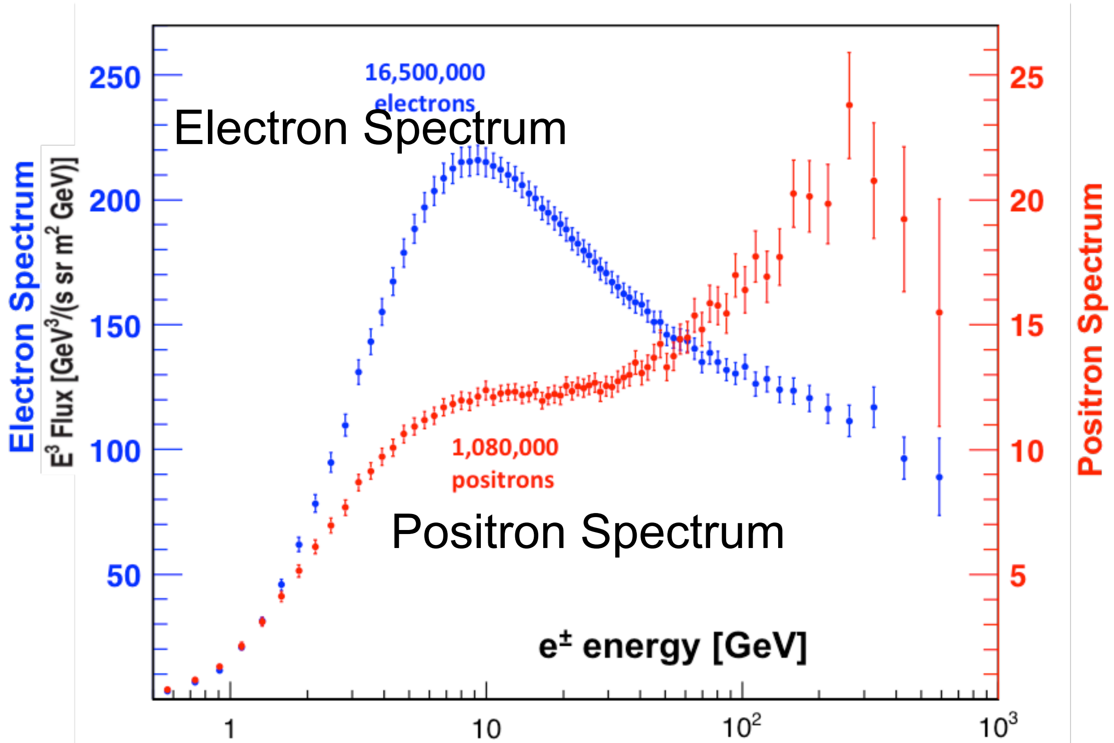


~ factor 5 higher flux

- Increased data set by factor of 5 (239h →1186h) & a hard cut without BG modelling
- Result preliminary and unpublished
- Indication of a continuously falling spectrum up to 20 TeV
- Demonstration of the potential of IACTs for the measurement of CR electrons

Other Observables





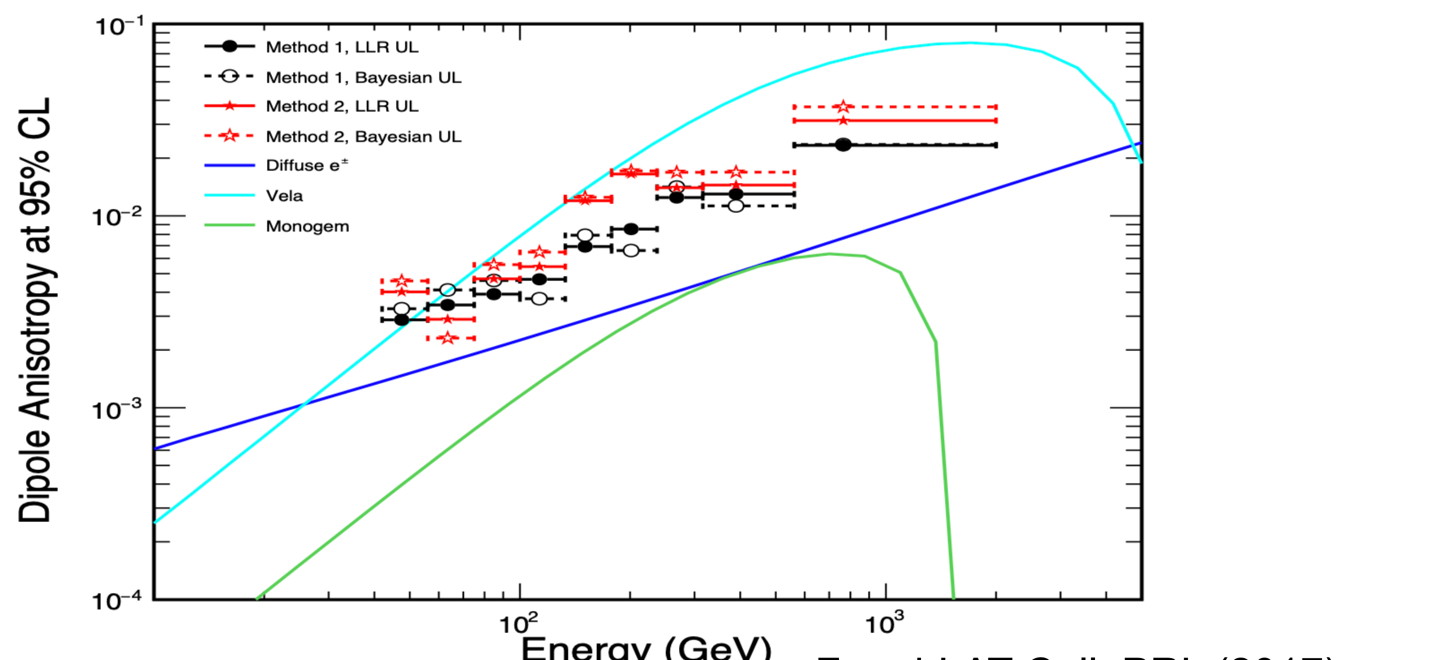
AMS press release Dec 2016

Charge separation:

- Positron flux only ~10% of the electrons with a spectrum significantly harder than electron one
- Data available only for E < 1 TeV
- Suggests a primary component in positrons

Anisotropy:

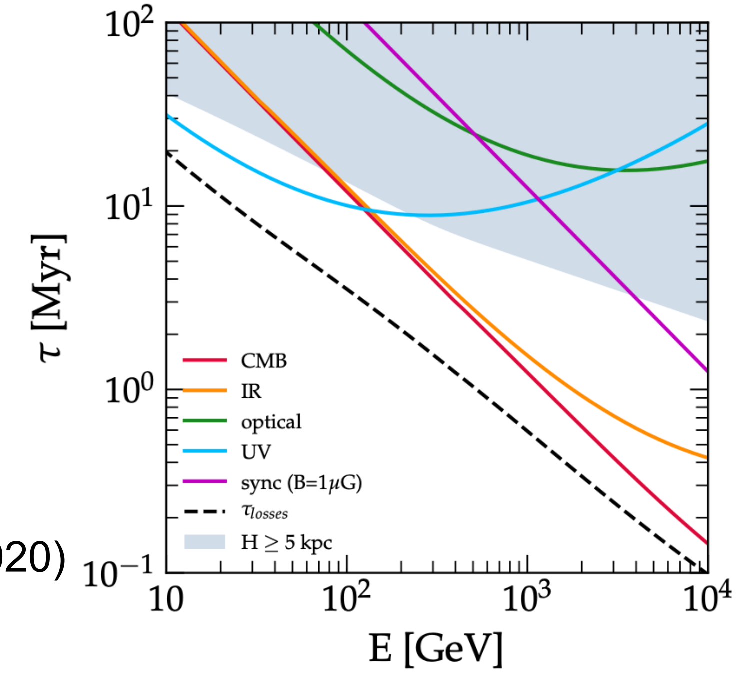
- Limits on dipole anisotropy currently at <% level
- Distinction of dark-matter vs local-source scenarios?



Fermi-LAT Coll, PRL (2017)

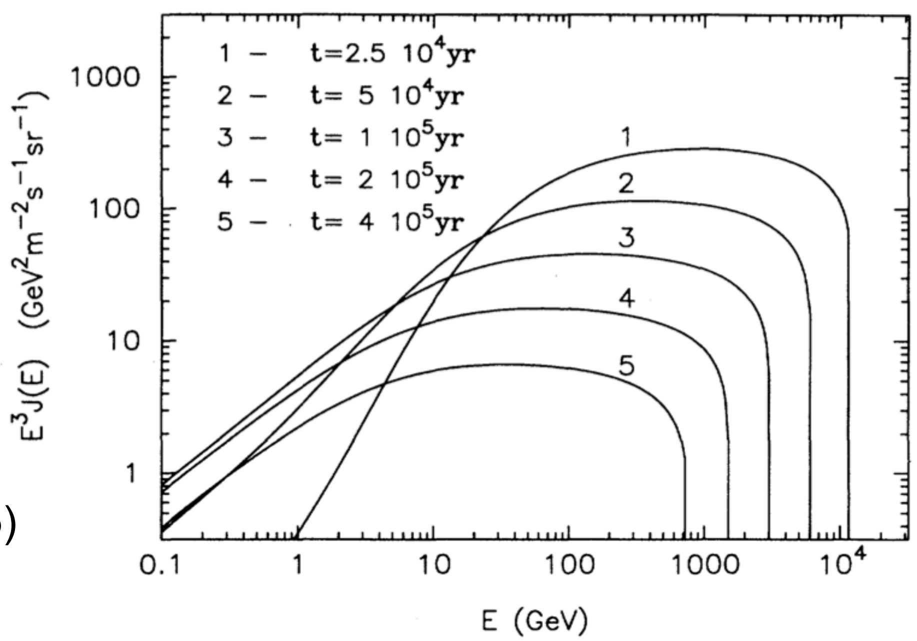
What is there to learn from VHE Electrons?

- Small electron masses make radiative losses much stronger than for nucleonic CaRs: bremsstrahlung, inverse Compton scattering, and synchrotron radiation
- Energy loss prop to E^2 (in Thomson limit):
  $dE/dt = -b\,E^2$
  → most pronounced effects at high energies
- → the maximum energy an electron can have after time t is $E_{max} = 1/bt$



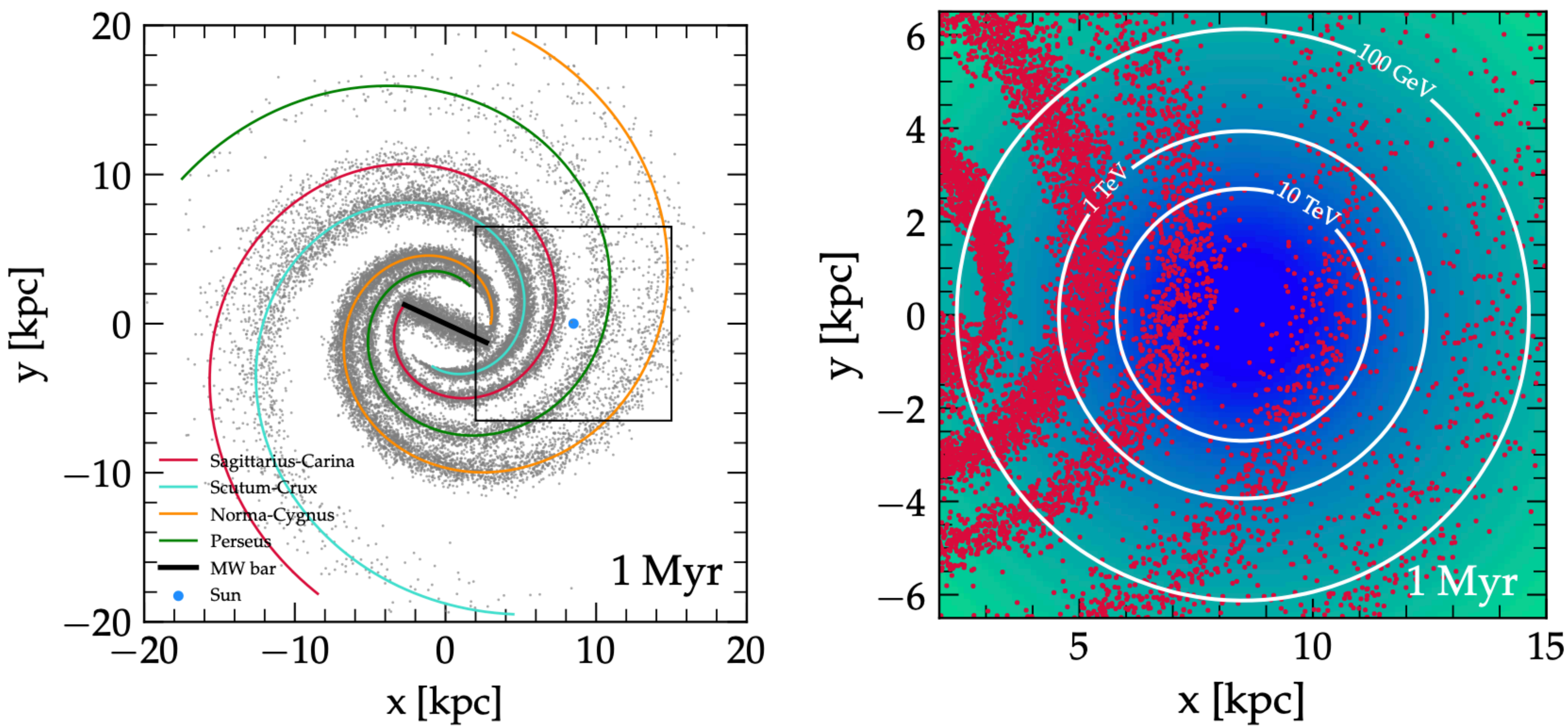
Evoli, Amato, Blasi, Aloisio (2020)

- Cooling time: $T_{cool} = E/\dot{E} \sim 1/E$
  TeV $e^{\pm}$ must have been injected not much longer than $\sim 10^5$ yr ago
- Propagation distance $\sim \sqrt{D\,T_{cool}}$
  → spectrum sensitive to local sources
  → complementarity to CR nuclei
  → note dependance on diffusion coefficient



Atoyan, Aharonian, Völk (1995)

Distances to be probed by energetic electrons



Evoli, Amato, Blasi, Aloisio (2020)

Production Sites

- Fermi acceleration in SNRs: primary p and e^- (+ e^+ from p interactions inside the remnant or from radioactive decay)
- Production in strong mag fields of pulsars and acceleration in shocks of PWNe: primary $e^\pm$
- Production in interactions of nucleonic CRs with ISM: secondary $e^\pm$

needed for positron fraction

Propagation

- Above few GeV mostly diffusion in interstellar magnetic field inhomogeneities
- Solve diffusion equation at position of Earth

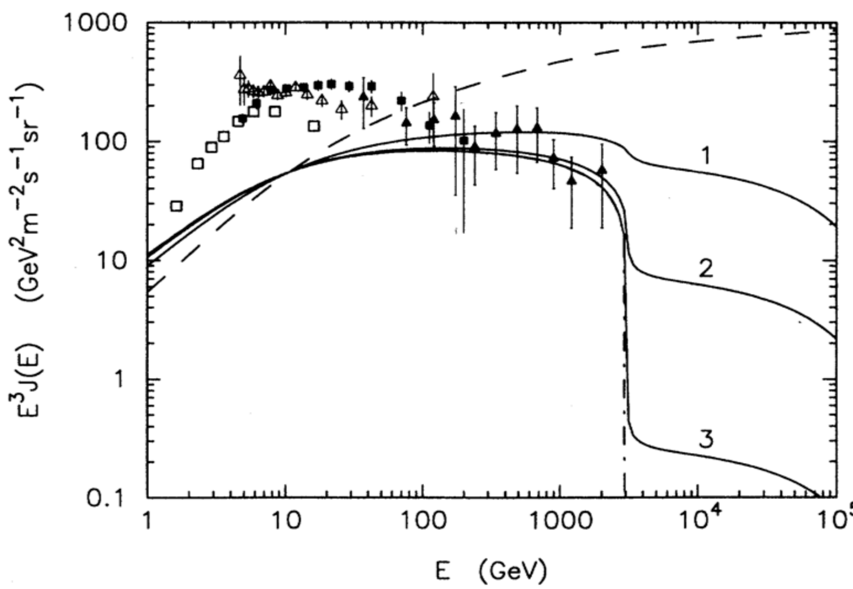
$$\frac{\partial}{\partial t} n_e(t, E, \boldsymbol{r}) = D(E)\nabla^2 n_e(t, E, \boldsymbol{r}) - \frac{\partial}{\partial E}\left[b(E) n_e(t, E, \boldsymbol{r})\right] + \mathcal{Q}(t, E, \boldsymbol{r})$$

Two Approaches

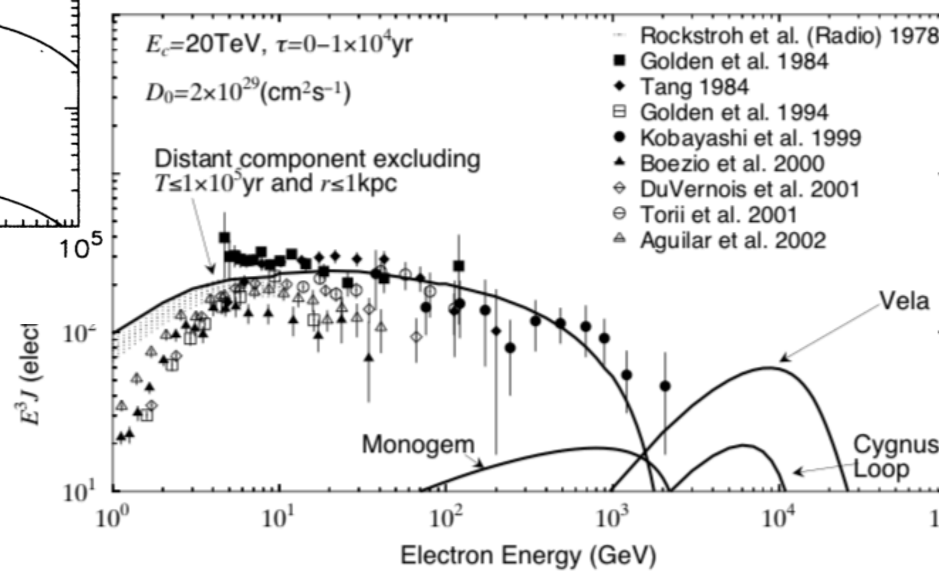
1. Modelling the spectrum in terms of known local sources
2. Modelling the spectrum in terms of a stochastic distribution of sources

1. Modelling with single (known) local sources

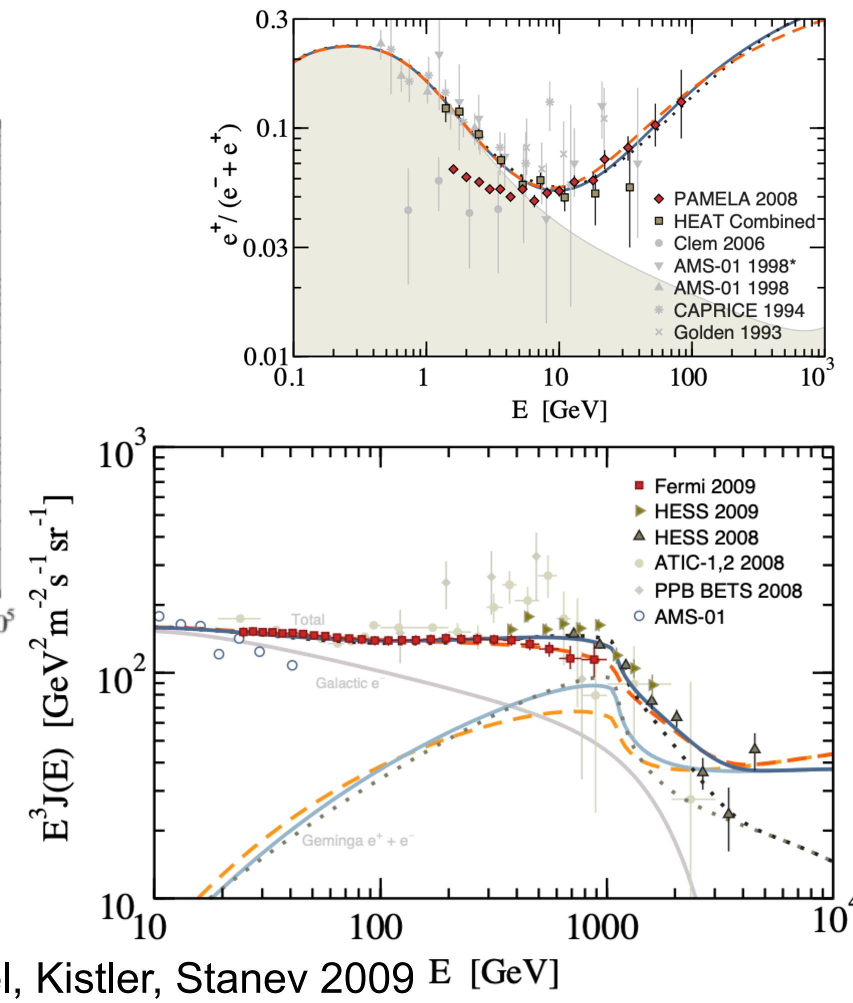
impossible to give an overview over all work conducted in this context, apologies to everybody I fail to mention



Atoyan, Aharonian, Völk PRD (1995)



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



Yüksel, Kistler, Stanev 2009

Some pronounced features of isolated sources possible, but strongly dependent on the choice of parameters

e.g. diffusion coefficient, release time, continuous vs burst-like injection, energy spectrum and max energy of electrons…

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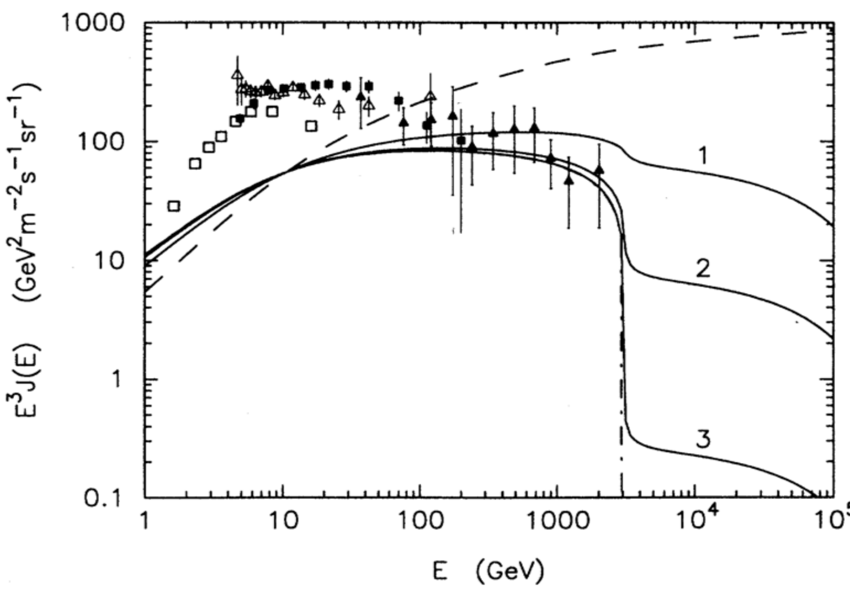

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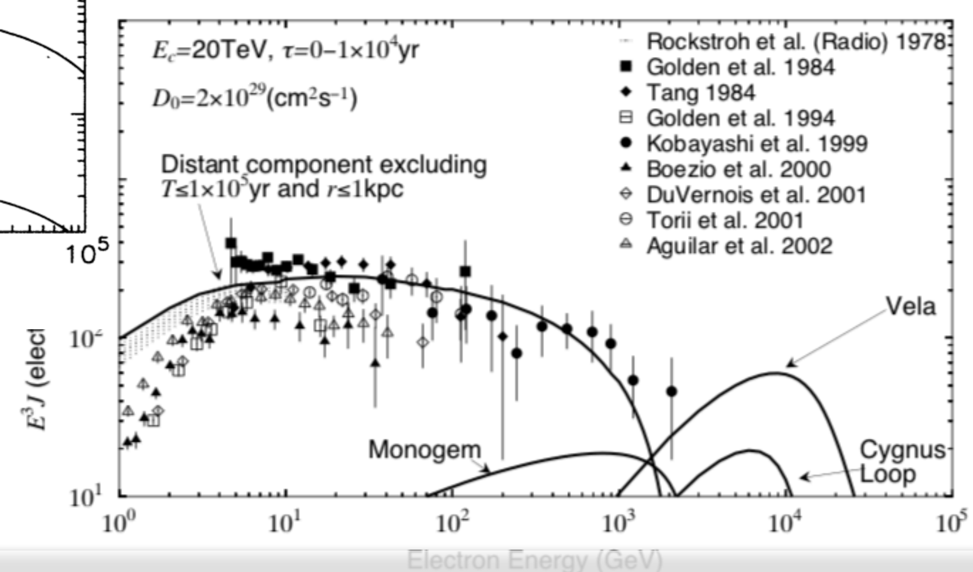
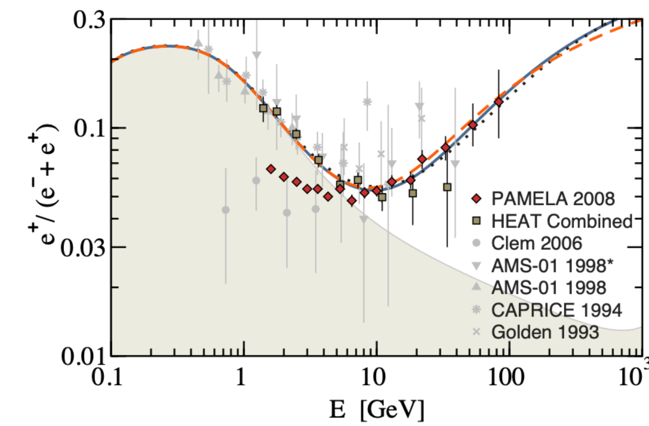
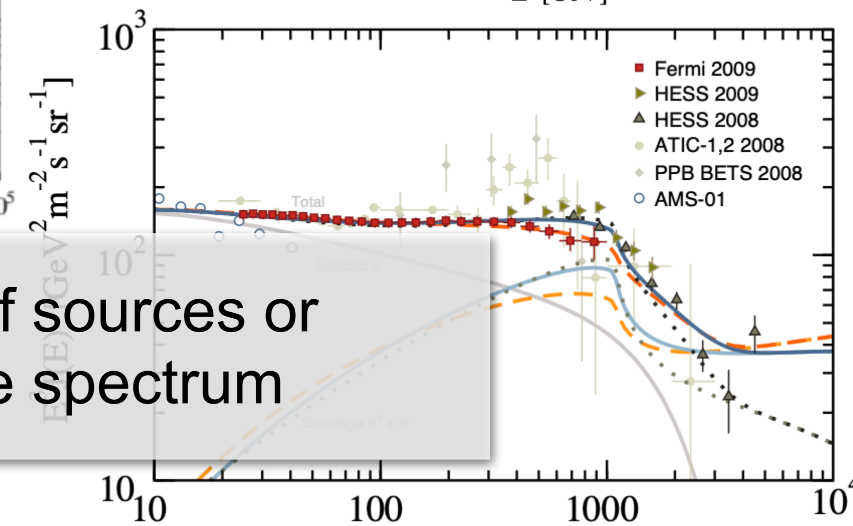






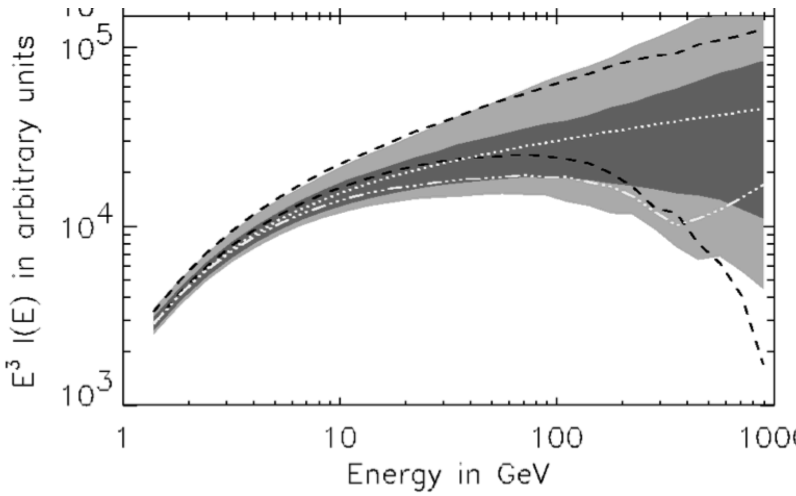
Yüksel, Kistler, Stanev 2009

Method of choice for characterisation of sources or interpretation of distinct features in the spectrum

Some pronounced features of isolated sources possible, but strongly dependent on the choice of parameters

e.g. diffusion coefficient, release time, continuous vs burst-like injection, energy spectrum and max energy of electrons…

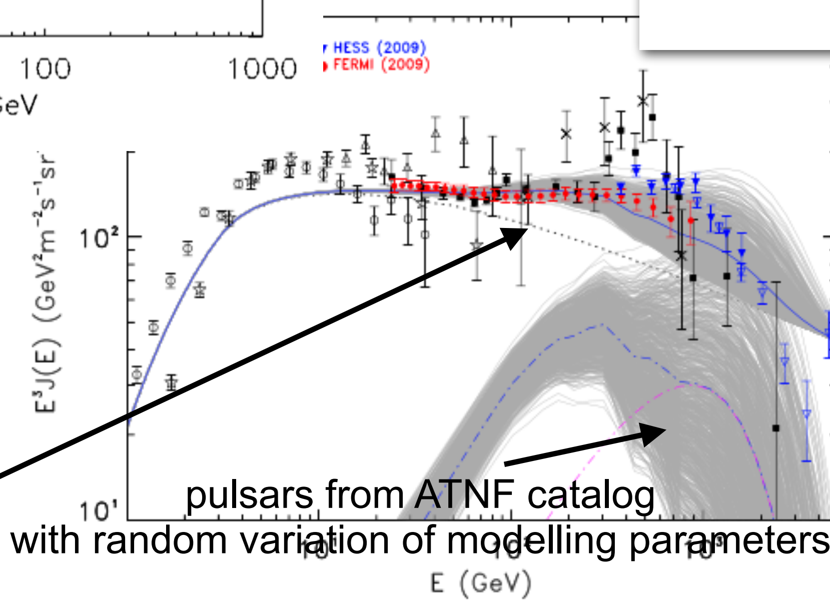
2. Modelling with a stochastic distribution of sources



Pohl, Esposito (1998)

Motivation: Avoiding bias in the source selection

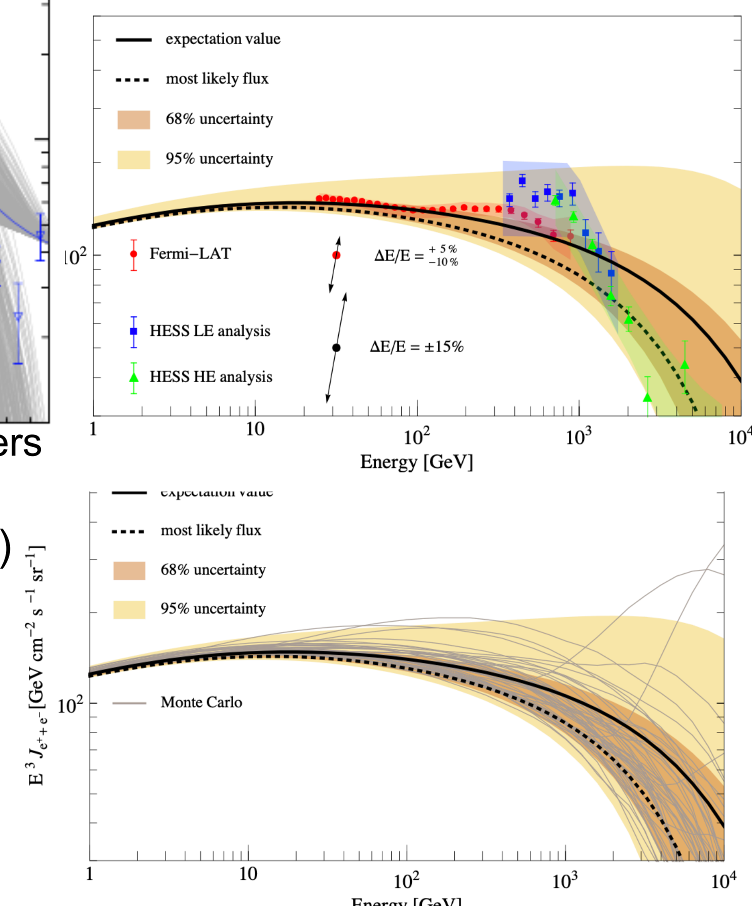
- Catalogs incomplete
- Different propagation of photons and CRs
- Uncertainties in distance and age estimates



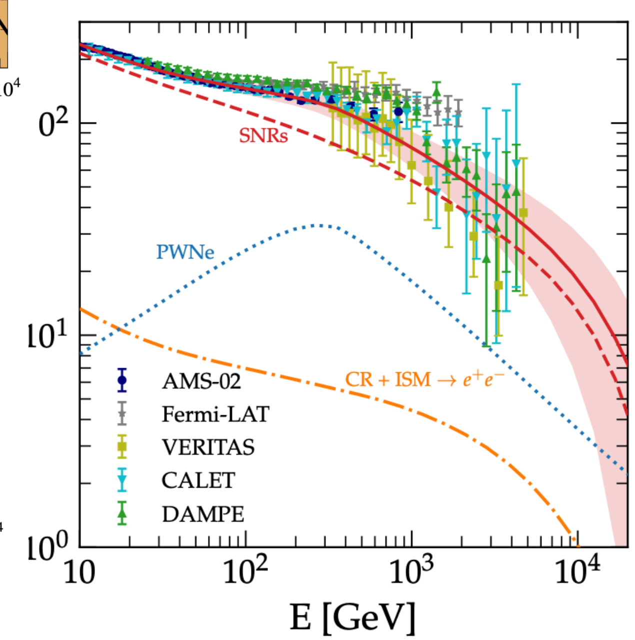
continuous distribution of distant sources

pulsars from ATNF catalog with random variation of modelling parameters

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



Mertsch (2011)



Evoli, Amato, Blasi, Aloisio (2020)

- Large scatter in possible realisations approaching the TeV regime, visualising the low predictive power at TeV energies
- Most simulations exhibit a propagation cut-off at a few TeV

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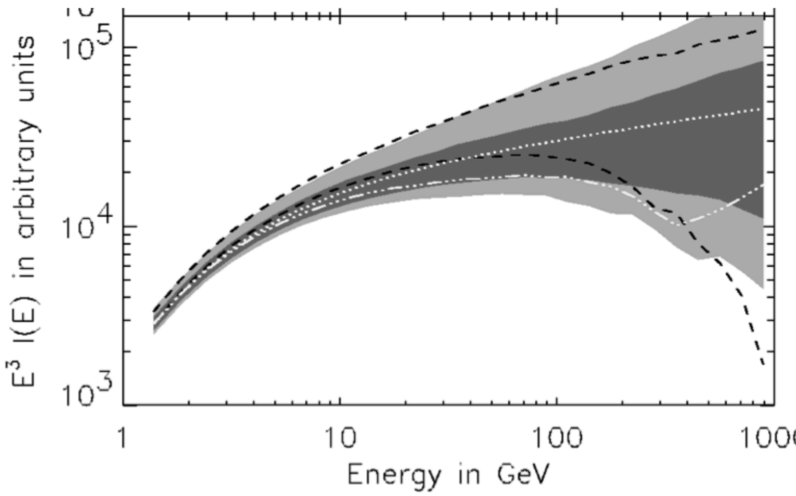

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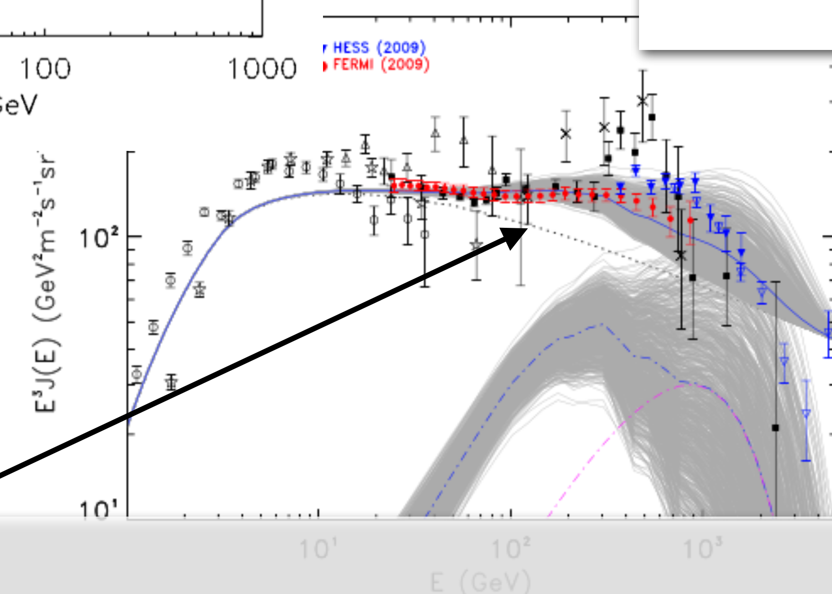

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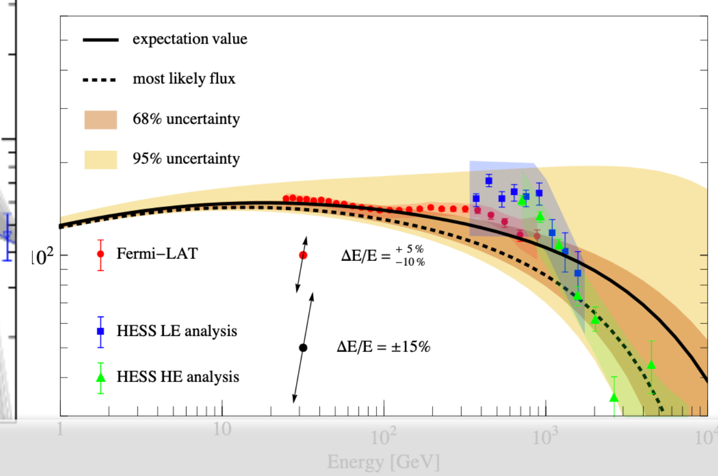
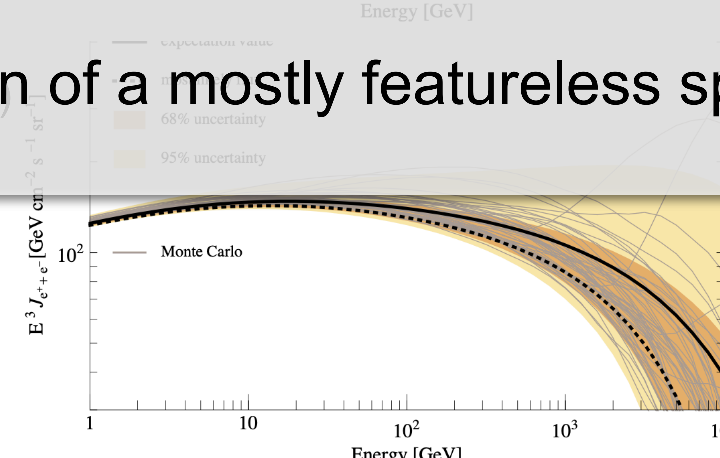
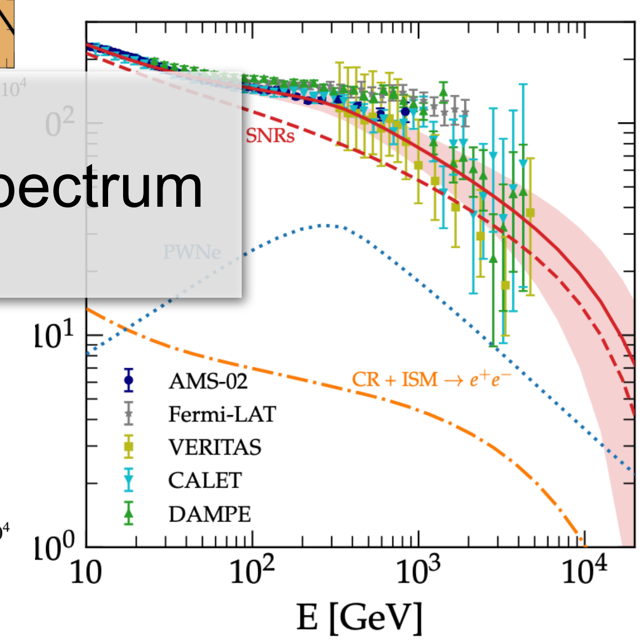




Mertsch (2011)



Evoli, Amato, Blasi, Aloisio (2020)

Method of choice for description of a mostly featureless spectrum

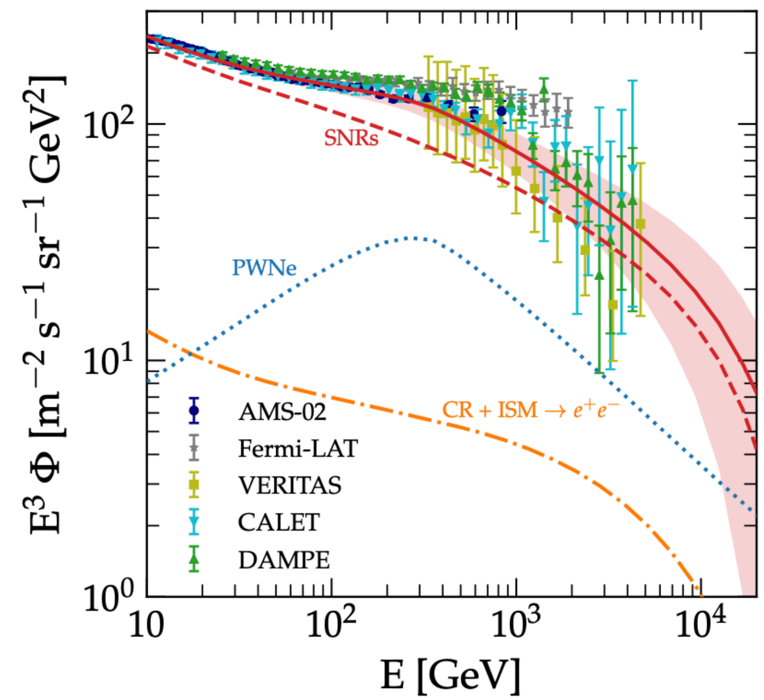
- Large scatter in possible realisations approaching the TeV regime, visualising the low predictive power at TeV energies
- Most simulations exhibit a propagation cut-off at a few TeV

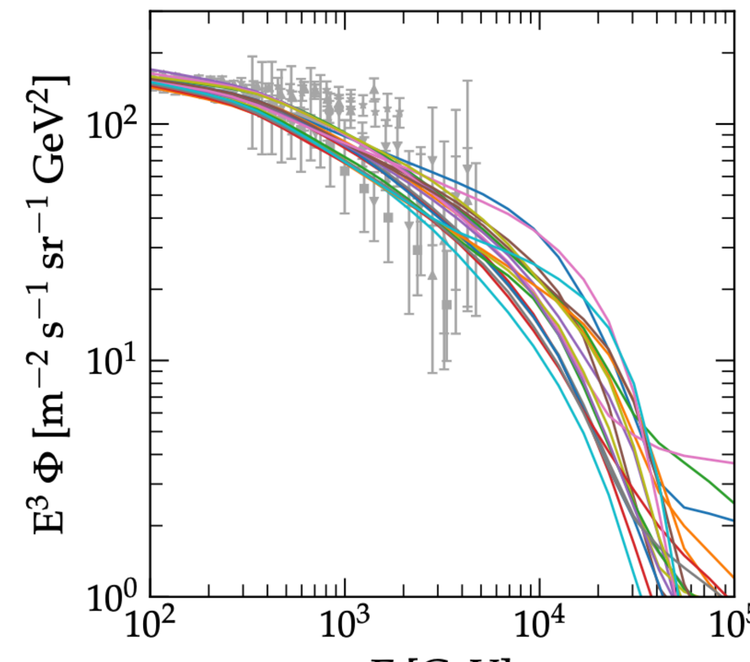
2nd Approach with Modified Diffusion Coefficient

D adjusted to describe breaks in AMS p, He spectra:

Evoli, Aloisio, Blasi (2019)

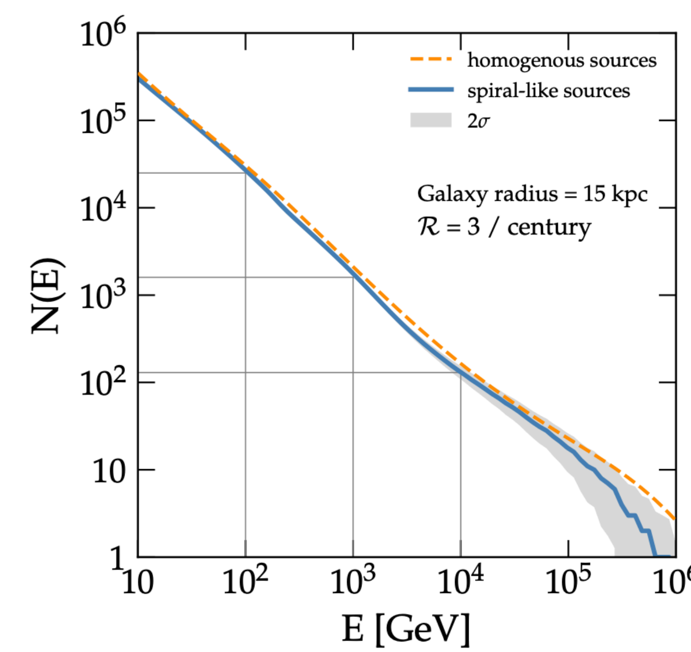
$$D(E) = 2v_A H + D_0 \left(\frac{E}{\mathrm{GeV}}\right)^{\delta} \left[1 + \left(\frac{E}{E_b}\right)^{\Delta\delta/s}\right]^{-s}$$





Evoli, Amato, Blasi, Aloisio (2020)

- Considerably larger number of sources contributing at VHE: few sources dominate at ~10 TeV, with order 100 contributing
- Consequently less pronounced features, pushes most interesting region of spectrum to beyond 10 TeV (c.f. featureless H.E.S.S. spectrum >1 TeV)
- Large number of sources reduces expectations for anisotropy



Demonstrates impact on parameter choices

Conclusions

- 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 (possibly a propagation effect)

- Low predictive power of what is happening at TeV energies
- Sources are discrete, potential to see direct imprint of local accelerators
- Shape of the spectrum very sensitive to both, propagation characteristics and source properties
- Number of sources contributing to multi-TeV energies might be larger than previously thought, spectrum extending to higher energies
- For reaching the end of the cosmic-ray electron spectrum we need to push further, which will require ground-based instruments