Cross Calibration of Imaging Air Cherenkov Telescopes with Fermi

A model for the emission of the Crab is derived by comparing it to Fermi measurements. It is used for a cross calibration of air shower experiments that eliminates the uncertainties on the global energy scales.

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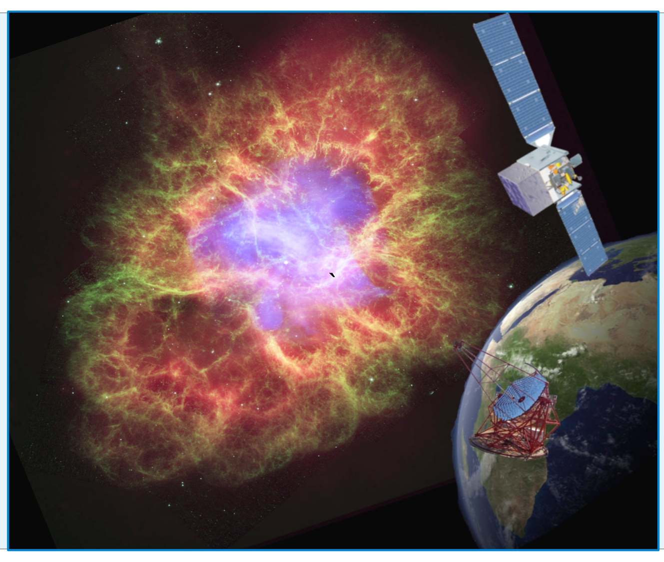
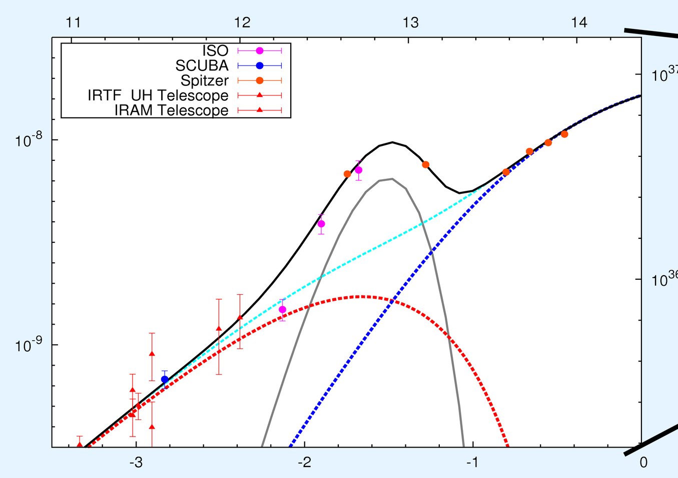


Abstract

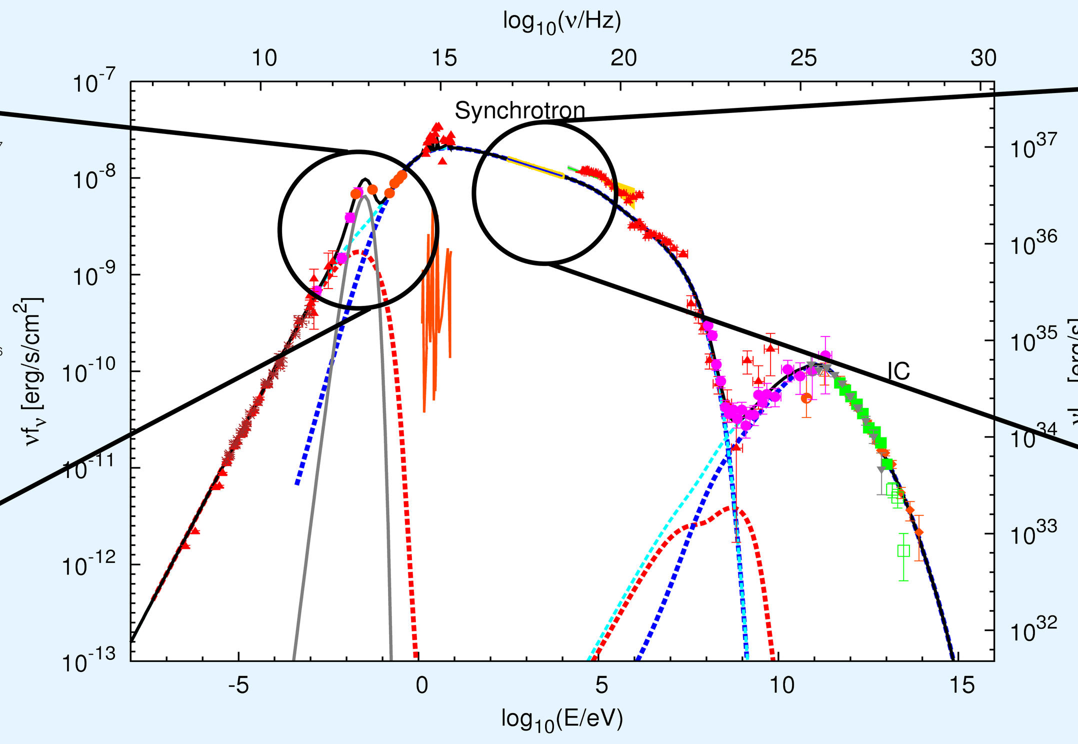
An updated model for the synchrotron and inverse Compton emission from a population of high energy electrons of the Crab nebula is used to reproduce the measured spectral energy distribution from radio to high energy γ-rays. By comparing the predicted inverse Compton component with recent Fermi measurements of the nebula's emission, it is possible to determine the average magnetic field in the nebula and to derive the underlying electron energy distribution. The model calculation can then be used to cross calibrate the Fermi observations with ground-based air shower measurements. The resulting energy calibration factors are derived and can be used for combining broad energy measurements taken with Fermi in conjunction with ground based measurements.

Updated SED of the Crab Nebula

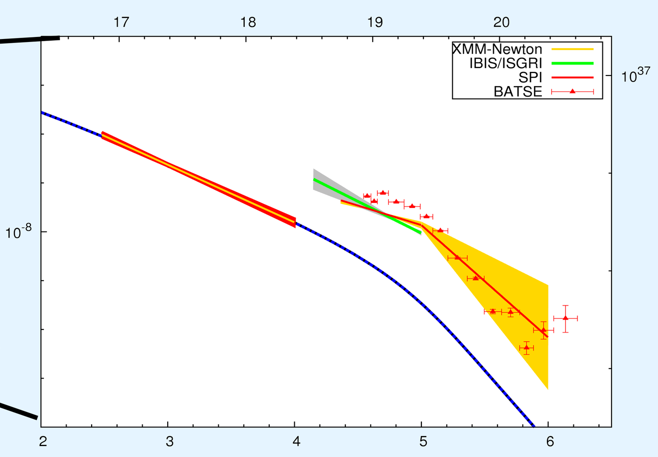
- SED of Aharonian et al. (2004) is updated with a new electron spectrum and new data of different measurements in the following energy bands:
  - *Spitzer*[1], *ISO and Scuba*[2]: FIR, sub mm
  - *XMM-Newton*[3], *SPI, IBIS / ISGRI*[4]: X-ray
  - *FERMI*[5]: γ-ray
- Model to calculate the SED is based on the work by Hillas et al. (1998) with the following improvements:
  - New electron spectrum (two populations)
  - Full treatment of synchrotron emission[6]
  - Additional seed photon field due to optical line emission of the filaments



Sub-mm and FIR energies. The dust component in the Crab is modelled with a graybody with T = 93 K. The red and blue dashed curves show the synchrotron contri-butions from the two electron populations. The *Spitzer* points fit the continuum of the wind electrons well.



Broadband SED of the Crab nebula.



SED at X-ray energies. The underlying electron spectrum $dN_{el}/d\gamma$ is fixed so that the XMM-Newton power law is reproduced.

[1]Temim et al. (2006)
[2]Green et al. (2004)
[3]Kirsch et al. (2005)
[4]Jourdain & Roques (2009)
[5]Fermi Collaboration (2009)
[6]Blumenthal & Gould (1970)

Electron Spectrum for <B> = 122 μG

[1] Atoyan (1999)
[2] e.g. Marsden et al. (1984)

Radio Electrons:

0 → 1: Low energy cut-off for $\gamma \leq 20$: $\frac{dN_{el}}{d\gamma} = 0$ (1)

1: radio electrons, source unknown, maybe *relic electrons*[1]?

1 → 2: Synchrotron cooling for radio electrons sets in ⇒ $\Delta\Gamma = 1$. For $t_{age} = 955$ yr this yields an upper limit on the average *B*-field since a cooling break $< 8 \cdot 10^4$ is not compatible with the radio data.

$$\langle B \rangle < 180 \left(\frac{\gamma}{8 \cdot 10^4}\right)^{-1/2} \left(\frac{t_{sy}}{955\mathrm{yr}}\right)^{-1/2} \mu\mathrm{G}$$

Wind Electrons:

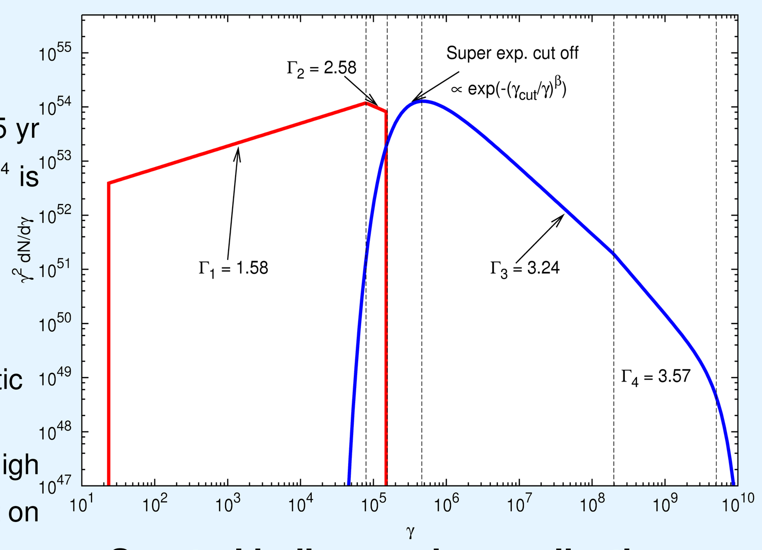
3: Wind electrons are continuously injected and undergo ultra-relativistic 1[st] order Fermi acceleration with synchrotron cooling ⇒ Γ = 2.24 + 1 = 3.24

3 → 4: Break at $\gamma_0 = 2 \cdot 10^8$ possibly due to Kolmogorov-type diffusion of high energy electrons. With $r_{diff} < r_{nebula} \approx 2$ pc and $t_{esc} = t_{age}$ yields an upper limit on the diffusion coefficient:

$$D_0 = \frac{r^2_{diff}}{\sqrt{2}t} \leq 1.3 \cdot 10^{27}\,\mathrm{cm^2 s^{-1}}$$

where $D(\gamma) \propto D_0(\gamma/\gamma_0)^\delta$, $\delta \approx 0.3$

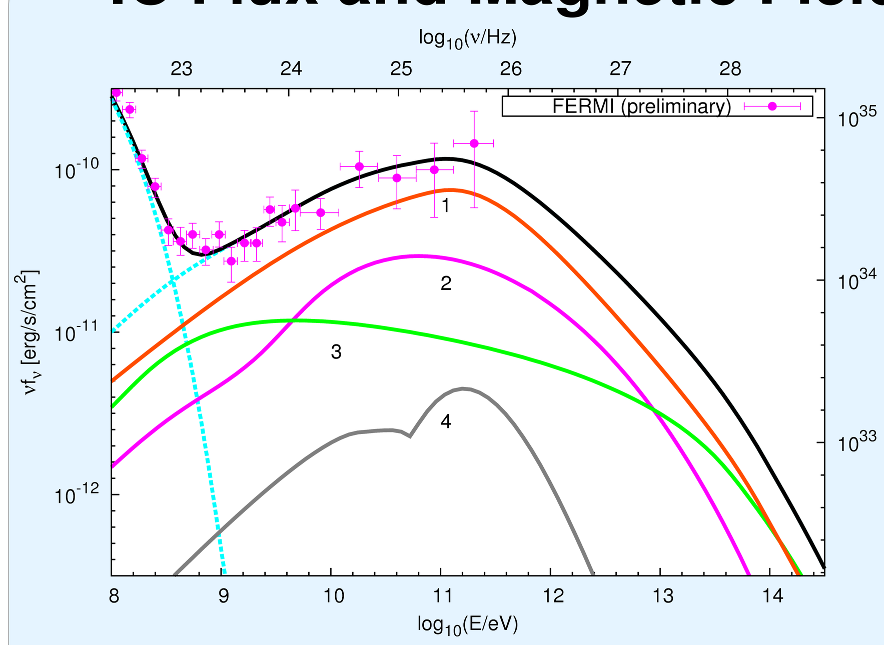
4 → ∞: Super exponential cut-off for $\gamma_{cut} = 4.5 \cdot 10^9$ with β= 2.5: $\frac{dN_{el}}{d\gamma} \propto \left(\frac{\gamma}{\gamma_{break}}\right)^{-\Gamma} e^{-\left(\frac{\gamma}{\gamma_{cut}}\right)^\beta}$

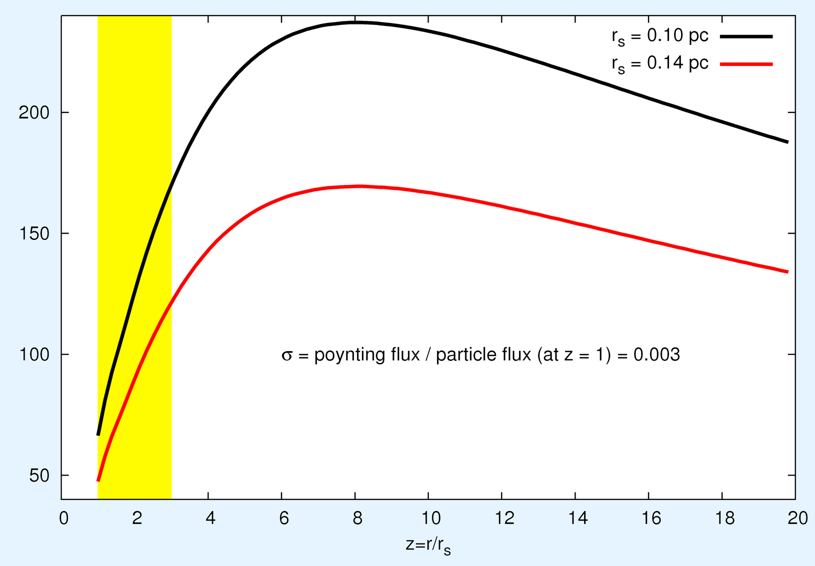


Spectral indices and normalisations are well constrained due to the high number of observations.

IC Flux and Magnetic Field

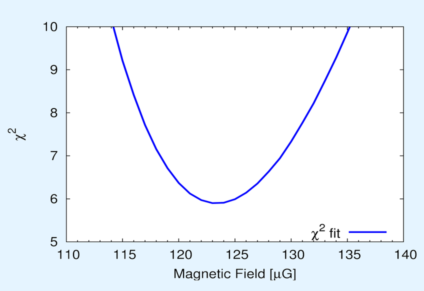
[1]Fermi Collaboration (2009)
[2]Weisskopf et al. (2000)
[3]Rees & Gunn (1974)
[4]Kennel & Coroniti (1984)





Seed Photon fields contributing to the inverse Compton flux:

1) Synchrotron Radiation
2) Emission from thermal dust
3) CMB
4) Optical line emission



The Magnetic Field:

- Magnetic Field is varied until IC flux fits the Fermi data points[1]
- $dN_{el}/d\gamma$ is varied accordingly to keep observed synchrotron flux constant

$$\langle B \rangle = \left(122\,^{+5}_{-4}\,(\mathrm{stat.})\,^{+12}_{-4}\,(\mathrm{sys.})\right)\,\mu\mathrm{G}$$

Discussion of the Magnetic Field:

- Chandra observations[2] indicate that the shock front is at a distance r_s = 0.14 pc from the pulsar (not 0.10 pc as commonly assumed)[3]
- MHD calculations[4] yield an equipartition field of $B \leq 160$ μG
- VHE emitting electrons reside between $1 \leq r/r_s \leq 3$ (yellow region in plot)

⇒ average *B*-field in this region agrees well with the derived value

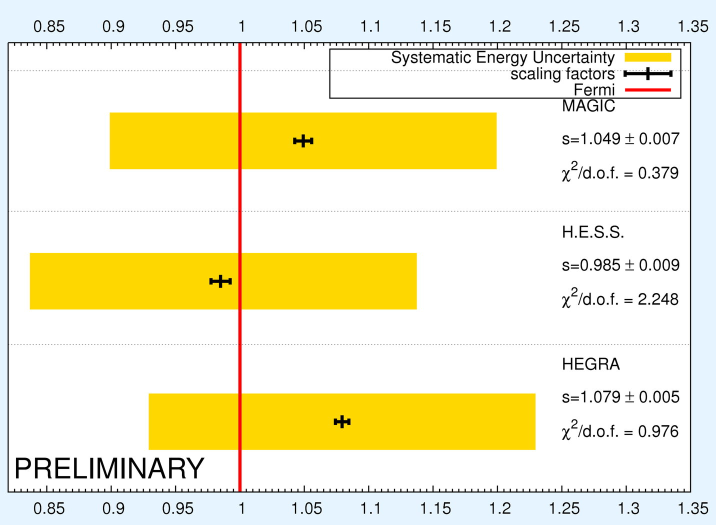
Cross Calibration of IACTs & Fermi

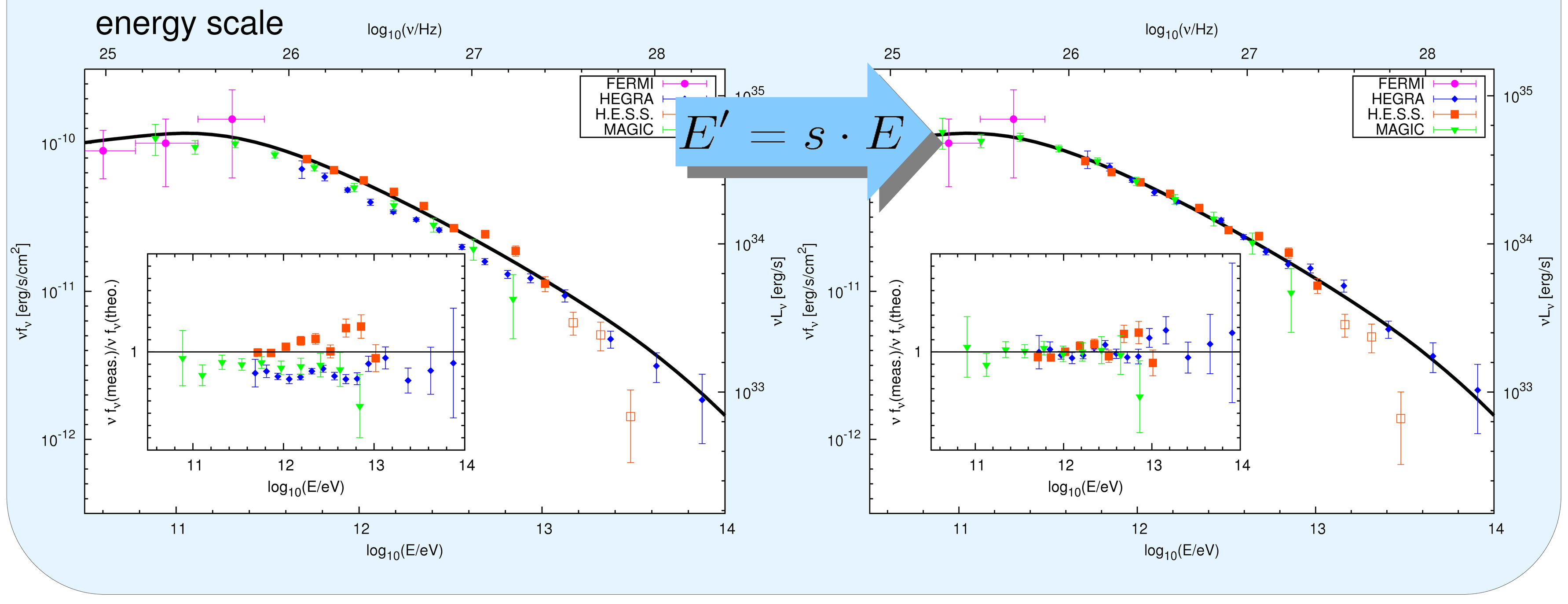
- In theory, all IACTs should measure the same flux from the nebula (neglecting secular decline <1%p.a.)
- Differences are due to systematic uncertainties in the overall energy calibration
- Introduce scaling factor *s* to fix the IACT data points to the model
- Energy calibration uncertainties:

IACTs: $\Delta E \approx \pm 15\%$

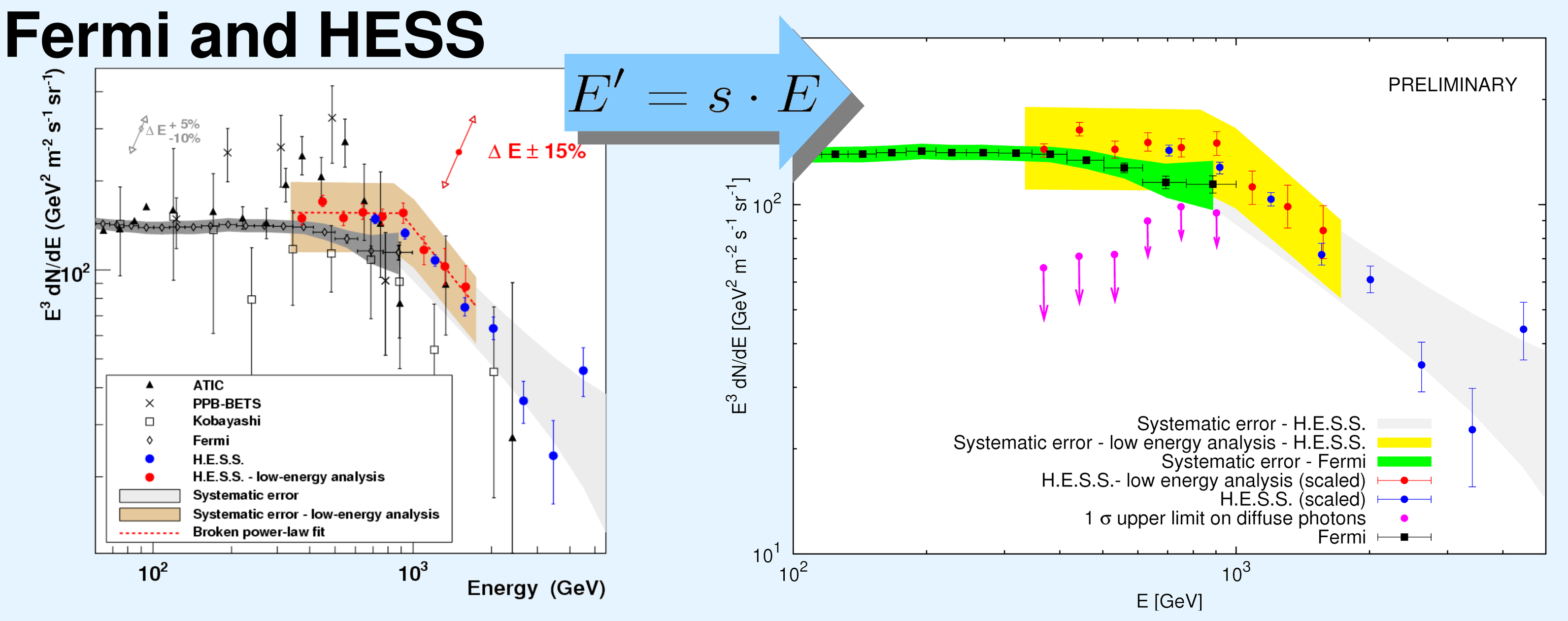
Fermi: $\Delta E = ^{+5\%}_{-10\%}$

⇒ Use Fermi (beam line calibration) to fix global energy scale





Application of Cross Calibration to Electron Data of Fermi and HESS



Cross Calibration can be used to derive upper limits on the diffuse γ-ray background:

⇒Major uncertainties on energy calibration of IACTs now eliminated

⇒Upper limits for diffuse γ-ray background were derived by taking the maximum (within the systematic uncertainties) difference between the H.E.S.S. and Fermi flux

⇒After scaling: ATIC peak unlikely

Aharonian et al. (2009)
Abdo et al. (2009)

Summary

- An updated SED and electron spectrum have been derived and the *B*-field has been fixed to measurements by Fermi
- The model makes it possible to calculate energy scaling factors for ground based air shower experiments
- All scaling factors lie within 15%, i.e. in the claimed systematic energy uncertainties of the instruments

Outlook

- Cross Calibration for other bright steady or pulsed sources (e.g. Crab Pulsar, Galactic Center, Pulsar Wind Nebulae...)
- Establish Crab Nebula as a “true” standard candle for γ-ray astronomy
- Application for Extragalactic Background Light constraints, Dark Matter searches, electron spectrum, etc.

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