The Crab Nebula as a standard candle in very high energy astrophysics[1]

Manuel Meyer, Dieter Horns, Hannes-Sebastian Zechlin

Institut für Experimentalphysik
Universität Hamburg

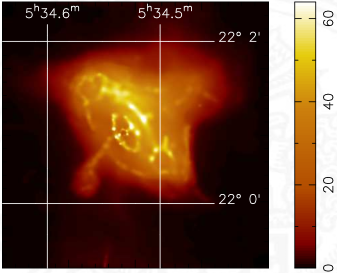
Astroteilchen Schule 2010, Obertrubach

Universität Hamburg

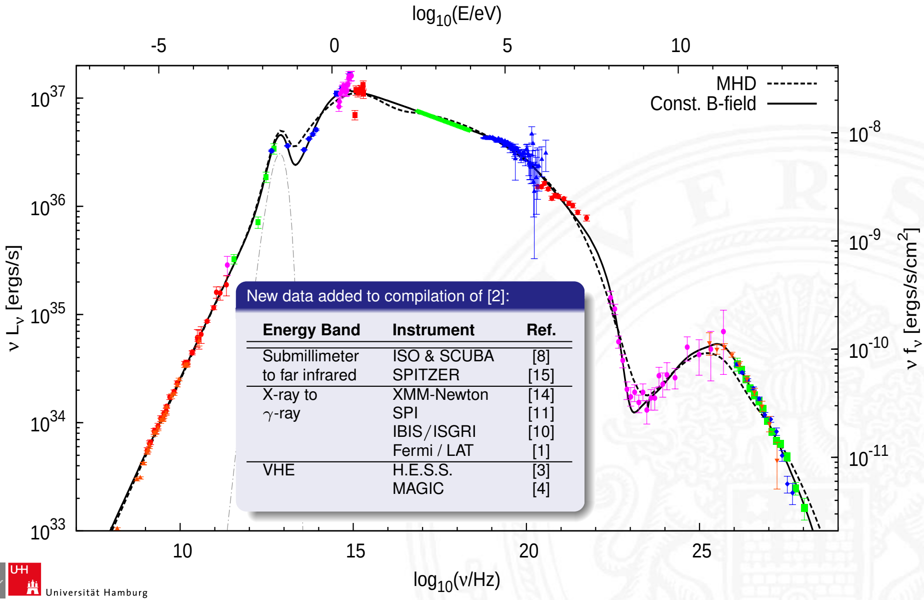
[1] ArXiv: 1008.4524 *accepted for publication in A&A*

The Crab Nebula

- Crab Nebula is part of a supernova remnant at a distance of $d \approx 2$ kpc
- Pulsar loses energy in form of a relativistic $e^+ + e^-$ plasma and magnetic field energy
- Assume that all particles are injected by the pulsar and expand into the plerion
- Relativistic wind terminates at a shockfront at $r_s = (0.14 \pm 0.01)$ pc $\Rightarrow$ particles accelerated up to PeV energies by 1$^{\text{st}}$ order Fermi acceleration
- Electrons in the nebula emit synchrotron radiation
- Photons are upscattered by the inverse Compton (IC) process



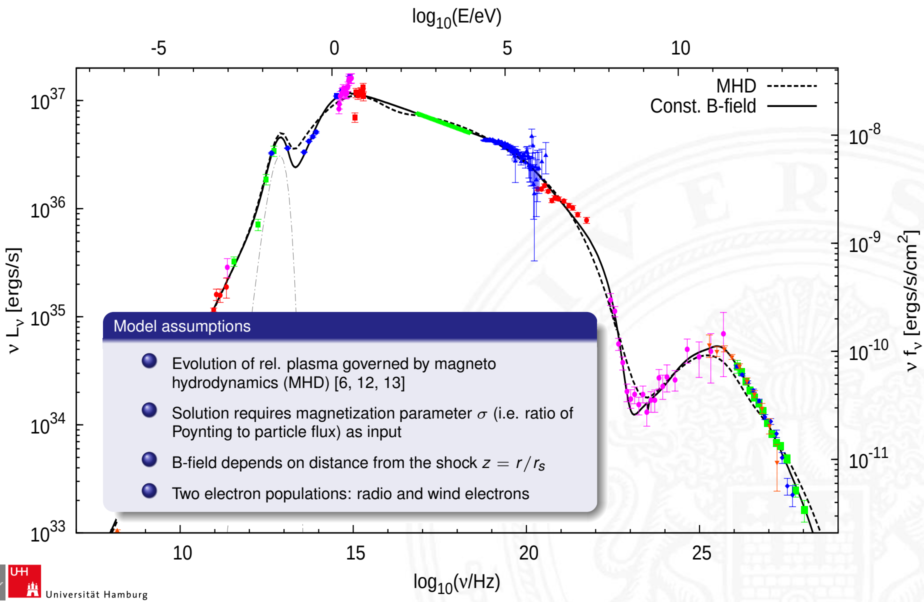
Spectral Energy Distribution (SED)



New data added to compilation of [2]:

Energy Band	Instrument	Ref.
Submillimeter to far infrared	ISO & SCUBA	[8]
	SPITZER	[15]
X-ray to γ-ray	XMM-Newton	[14]
	SPI	[11]
	IBIS / ISGRI	[10]
	Fermi / LAT	[1]
VHE	H.E.S.S.	[3]
	MAGIC	[4]

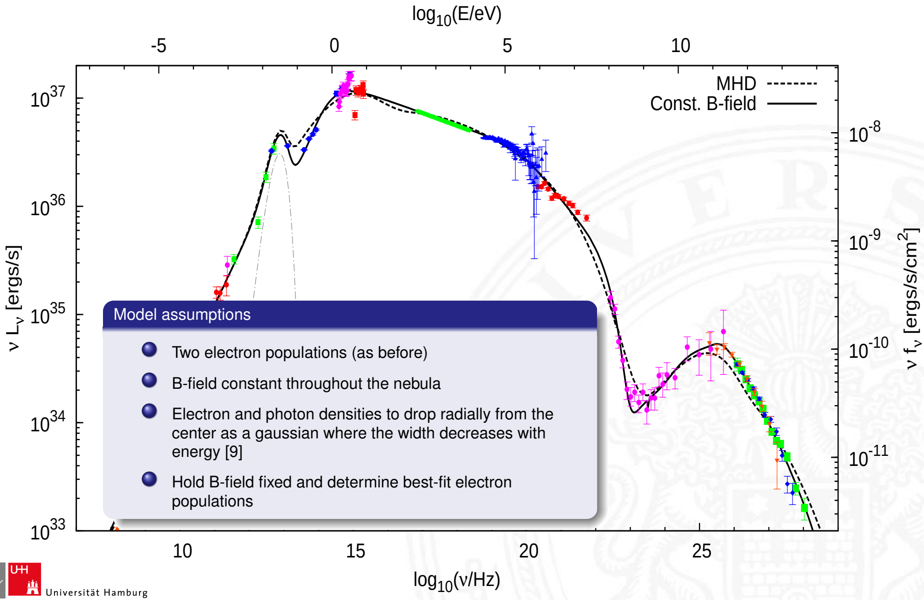
MHD flow model



Model assumptions

- Evolution of rel. plasma governed by magneto hydrodynamics (MHD) [6, 12, 13]
- Solution requires magnetization parameter σ (i.e. ratio of Poynting to particle flux) as input
- B-field depends on distance from the shock $z = r/r_s$
- Two electron populations: radio and wind electrons

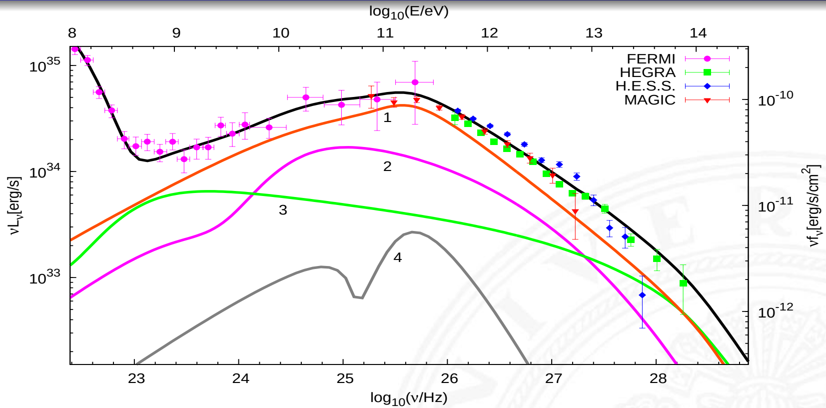
Const. B-field model



Model assumptions

- Two electron populations (as before)
- B-field constant throughout the nebula
- Electron and photon densities to drop radially from the center as a gaussian where the width decreases with energy [9]
- Hold B-field fixed and determine best-fit electron populations

Modeling of the SED: Const. B-field model – IC part



Seed photon fields

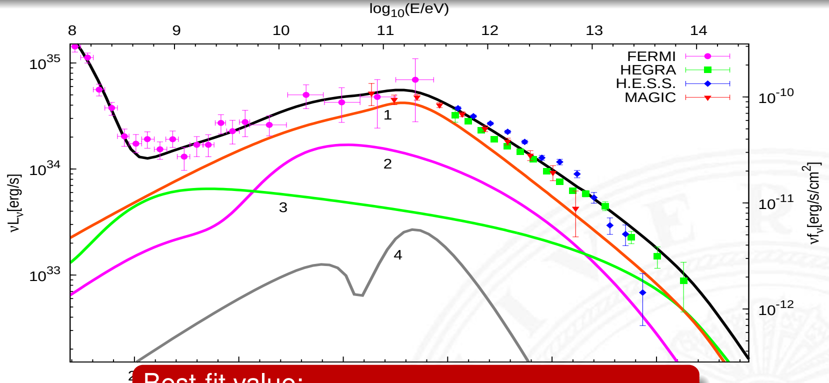
1. Synchrotron
2. Thermal Dust
3. Cosmic microwave background
4. Emission from filaments

Determination of B-field

- Synchrotron emission fixed, calculate IC emission
- Calculate χ^2 of model and Fermi/LAT measurements
- Increase B-field, start from last slide

Universität Hamburg

Modeling of the SED: Const. B-field model – IC part



Seed photon fields

1. Synchrotron
2. Thermal Dust
3. Cosmic micro
4. Emission fron

Best-fit value:

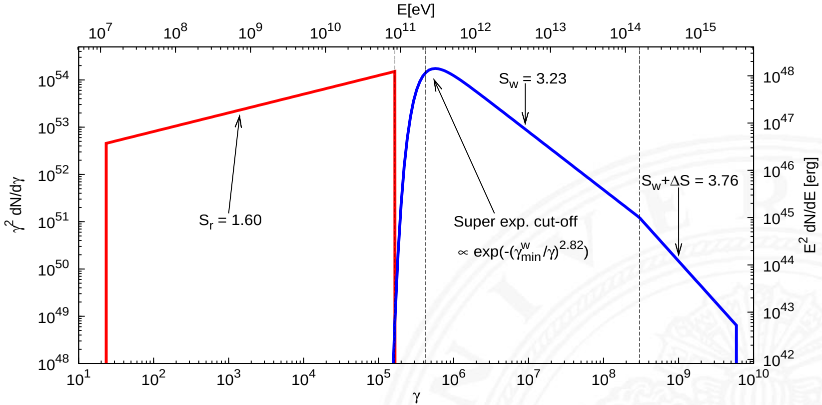
$$B = \left(124 \pm 6\,(\text{stat.})\,^{+15}_{-6}\,(\text{sys.})\right)\ \mu\text{G}$$

- Value smaller than previously assumed ($\approx 300\ \mu$G)
- Value further away from equipartition

nission
surements

Universität Hamburg

B-field model – Best-fit Electron spectra



- The electron populations are modeled with powerlaws: $dN_{el}/d\gamma = N_0\gamma^{-S}$
- Powerlaw index of radio electrons cannot be explained by Fermi acceleration
- Radio electrons injected in an early rapid spin down phase of the pulsar? [5] Acceleration of electrons in Wisps? [e.g. 7]
- Wind electrons constantly injected at the shock and cooled due to synchrotron radiation

Comparison of the models

Common features

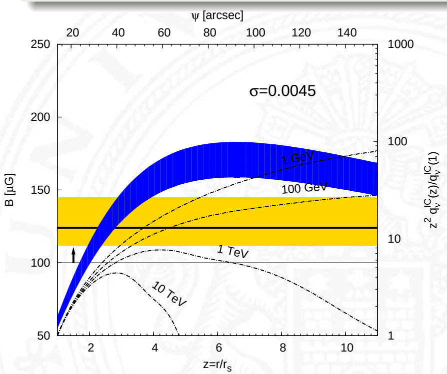
- Very high energy (and gamma-ray) observations not included in the fit – allows for comparison between theory and experiment
- Two distinct electron populations have to be invoked

MHD flow model

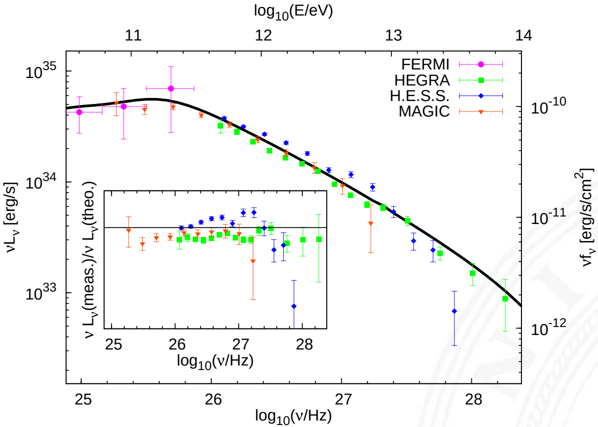
- More physical description of the evolution of injected particles and the B-field in the nebula
- Note: first time that shock radius of $r_s = 0.14$ pc was used
- Overall shape of SED reproduced
- 7 free parameters
- Data not fitted well in detail:
- $\chi^2/\mathrm{d.o.f.} = 397.02/222 \approx 1.79$

Const. B-field model

- Simplified approach to describe emission from the nebula
- 12 free parameters
- Describes data remarkably well:
- $\chi^2/\mathrm{d.o.f.} = 214.5/217 \approx 0.99$
- $\chi^2(B)/\mathrm{d.o.f.} = 6.37/13 \approx 0.49$



Cross Calibration of IACTs with Fermi/LAT



IACT:	HEGRA	H.E.S.S	MAGIC
Scalingfactor s	1.042	0.961	1.003
$\pm\Delta s_{\mathrm{stat}}$	0.005	0.004	0.01

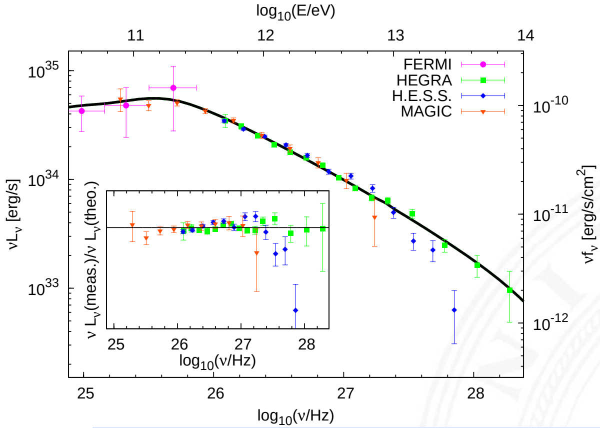
- IACTs should measure the same flux
- Differences due to systematic errors in energy calibration
- Introduce the scaling parameter s and fit data points to IC model
- Determine s via χ^2 minimization

$$\mathbf{E}' = \mathbf{s} \times \mathbf{E}$$

Energy scale fixed to Fermi/LAT's scale $\Rightarrow$ profit from energy calibration

Universität Hamburg

Cross Calibration of IACTs with Fermi/LAT



IACT:	HEGRA	H.E.S.S	MAGIC
Scalingfactor s $\pm\Delta s_{\mathrm{stat}}$	1.042 0.005	0.961 0.004	1.003 0.01

- IACTs should measure the same flux
- Differences due to systematic errors in energy calibration
- Introduce the scaling parameter s and fit data points to IC model
- Determine s via χ^2 minimization

$$\mathbf{E}' = \mathbf{s} \times \mathbf{E}$$

Energy scale fixed to Fermi/LAT's scale $\Rightarrow$ profit from energy calibration

Summary and Outlook

Summary

- Crab Nebula has been observed in every accessible wavelength ⇒ ideal candidate for spectral modeling
- Two models for the SED presented:
  - Const. B-field model: accurate description of the SED
  - MHD flow model: more physical approach worse description
- Const. B-field model can be used for a cross calibration between IACTs and Fermi/LAT

Outlook

- **MHD flow model**:
  - Extend model: incorporate asymmetric particle flow with varying σ
  - Particles at different energies “feel” different magnetic field ⇒ possible to measure σ
- **Cross calibration**:
  - Useful for any multiwavelength observations with Fermi/LAT and ground based air shower experiments
  - E.g. Dark Matter searches, observations of the galactic center, etc.

References I

[1] A. A. (Fermi Collaboration) Abdo et al. Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20GeV to 1TeV with the Fermi Large Area Telescope. *Physical Review Letters*, 102(18):181101–+, May 2009.

[2] F. (HEGRA Collaboration) Aharonian et al. The Crab Nebula and Pulsar between 500 GeV and 80 TeV: Observations with the HEGRA Stereoscopic Air Cerenkov Telescopes. *Astrophys. J.*, 614:897–913, October 2004.

[3] F. (H.E.S.S. Collaboration) Aharonian et al. Observations of the Crab nebula with HESS. *Astron. Astrophys.*, 457:899–915, October 2006.

[4] J. (MAGIC Collaboration) Albert et al. VHE γ-Ray Observation of the Crab Nebula and its Pulsar with the MAGIC Telescope. *Astrophys. J.*, 674:1037–1055, February 2008.

[5] A. M. Atoyan. Radio spectrum of the Crab nebula as an evidence for fast initial spin of its pulsar. *Astron. Astrophys.*, 346:L49–L52, June 1999.

[6] A. M. Atoyan and F. A. Aharonian. On the mechanisms of gamma radiation in the Crab Nebula. *Mon. Not. R. Astron. Soc.*, 278:525–541, January 1996.

[7] M. F. Bietenholz, J. J. Hester, D. A. Frail, and N. Bartel. The Crab Nebula's Wisps in Radio and Optical. *Astrophys. J.*, 615:794–804, November 2004.

[8] D. A. Green, R. J. Tuffs, and C. C. Popescu. Far-infrared and submillimetre observations of the Crab nebula. *Mon. Not. R. Astron. Soc.*, 355:1315–1326, December 2004.

References II

[9] A. M. Hillas, C. W. Akerlof, et al. The Spectrum of TeV Gamma Rays from the Crab Nebula. *Astrophys. J.*, 503:744–+, August 1998.

[10] E. Jourdain, D. Götz, N. J. Westergaard, L. Natalucci, and J. P. Roques. INTEGRAL Cross-calibration Status: Crab observations between 3 keV and 1 MeV. In *Proceedings of the 7th INTEGRAL Workshop*, 2008.

[11] E. Jourdain and J. P. Roques. The High-Energy Emission of the Crab Nebula from 20 keV TO 6 MeV with Integral SPI. *Astrophys. J.*, 704:17–24, October 2009.

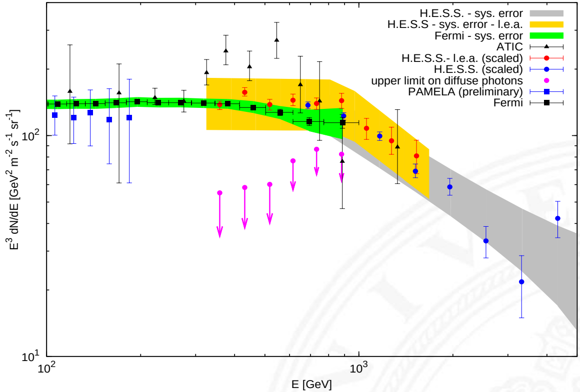
[12] C. F. Kennel and F. V. Coroniti. Confinement of the Crab pulsar's wind by its supernova remnant. *Astrophys. J.*, 283:694–709, August 1984.

[13] C. F. Kennel and F. V. Coroniti. Magnetohydrodynamic model of Crab nebula radiation. *Astrophys. J.*, 283:710–730, August 1984.

[14] M. G. Kirsch, U. G. Briel, et al. Crab: the standard x-ray candle with all (modern) x-ray satellites. In O. H. W. Siegmund, editor, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 5898 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 22–33, August 2005.

[15] T. Temim, R. D. Gehrz, C. E. Woodward, T. L. Roellig, N. Smith, L. Rudnick, E. F. Polomski, K. Davidson, L. Yuen, and T. Onaka. Spitzer Space Telescope Infrared Imaging and Spectroscopy of the Crab Nebula. *Astron. J.*, 132:1610–1623, October 2006.

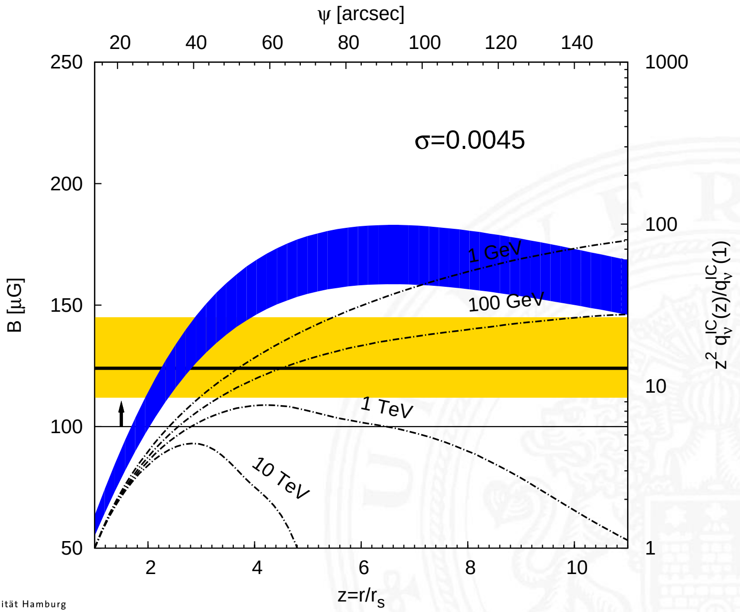
Application of Cross Calibration: diffuse γ-background



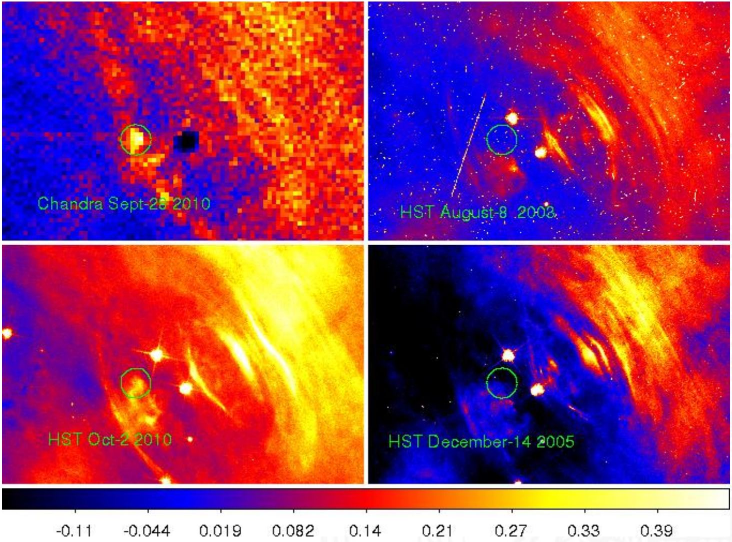
- Cross calibration can be used if measurements overlap in energy
- Adjusts measurements to common energyscale, reduces systematic uncertainties
- Example: measurement of $e^+ + e^-$ spectrum by Fermi/LAT and H.E.S.S.
- Allows for the determination of upper limit of diffuse γ-ray background

Universität Hamburg

B-field in the different models



Flare of the Crab Nebula



Universität Hamburg