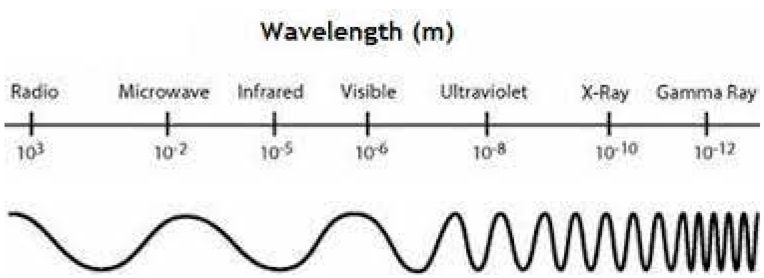
Joint-instrument analyses with Gammapy

Tim Unbehaun – High-energy astrophysics in the multi-messenger era 2023
Erlangen, 8. – 12. 5.2023

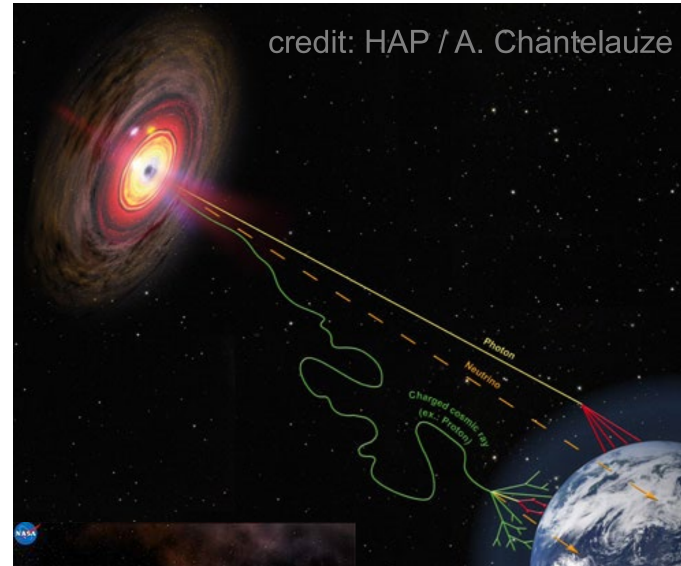
H.E.S.S.
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Motivation

- Use as much data as possible to answer physics questions
- Use large energy range
- Use different messenger particles
- Consistent analysis of the different data

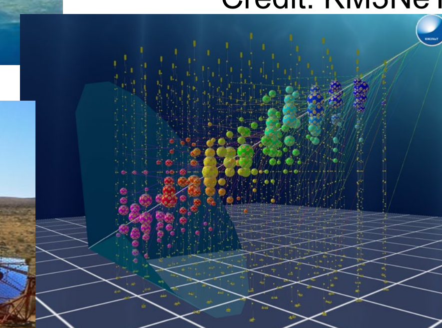


credit: labman.phys.utk.edu



credit: HAP / A. Chantelauze

Credit: NASA / Aurore Simonnet



Credit: KM3NeT

Credit: HESS Collaboration

3D analyses with Gammapy

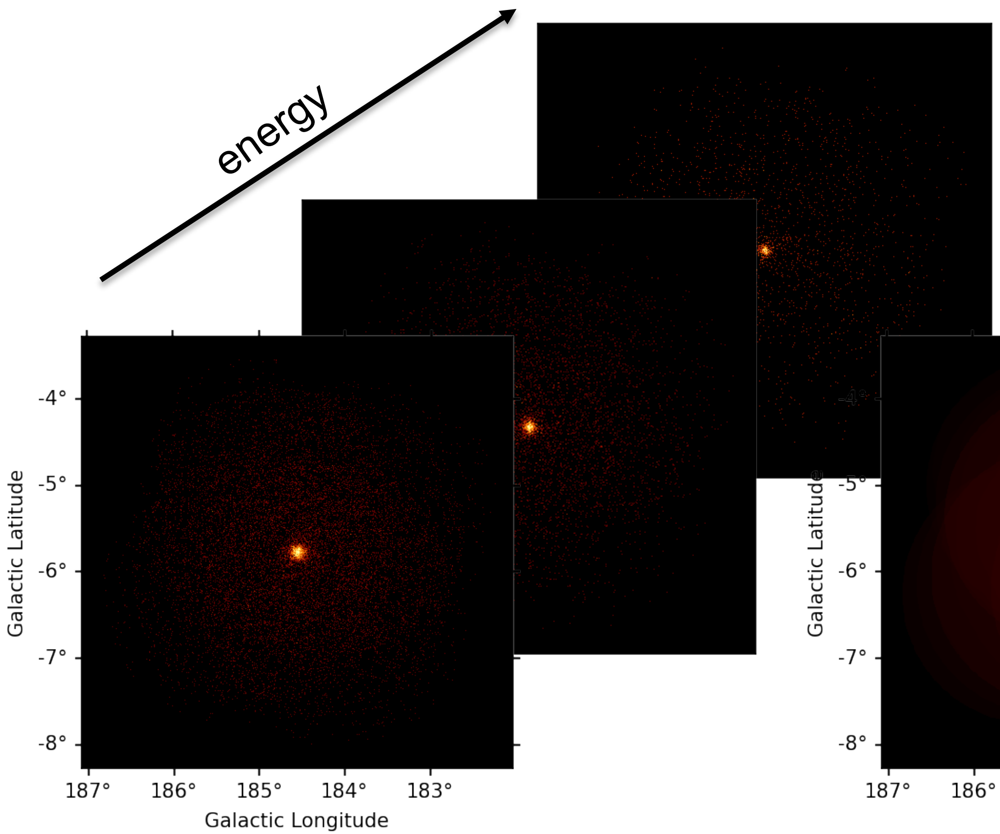
A **Python** package for **gamma-ray** astronomy

Gammapy is an open-source Python package for gamma-ray astronomy built on Numpy and Astropy.
It is a prototype for the Cherenkov Telescope Array (CTA) science tools, and can also be used to analyse data from existing gamma-ray telescopes.

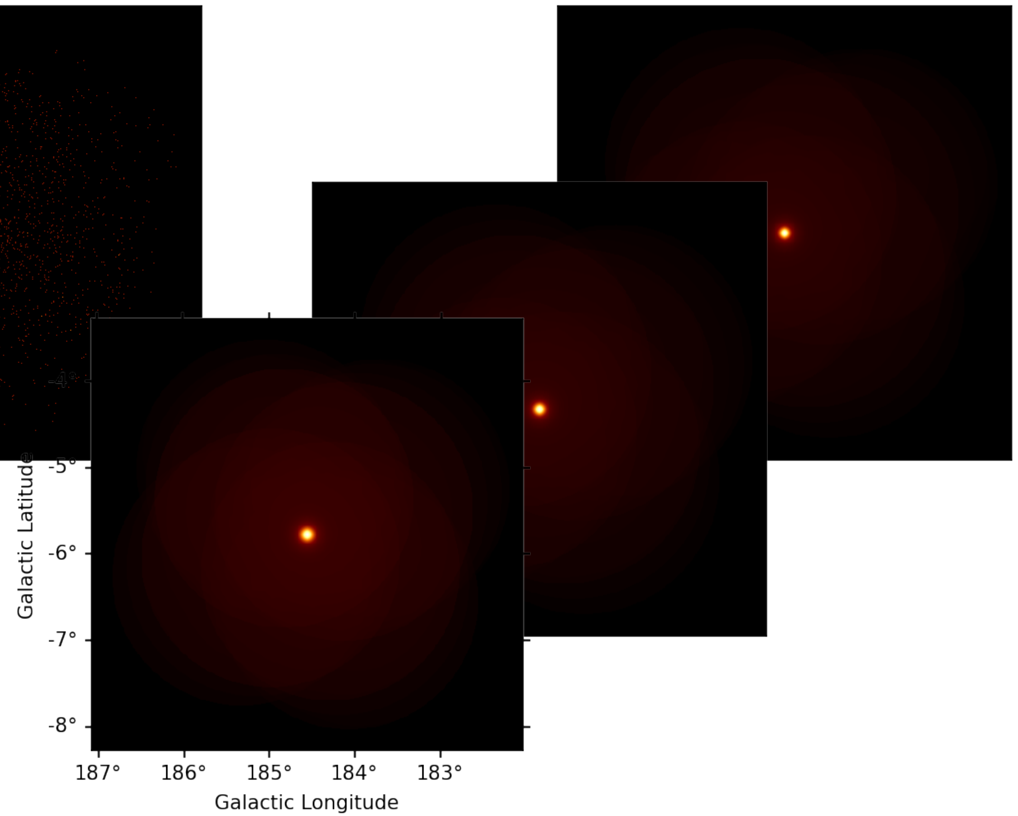
- Likelihood analysis in 3D (2 spatial, 1 energy)
- Combination of different data sets at likelihood level
  → can fit same physical model to data from different instruments
- Requirement: instrument data (DL3) in common format
  → can also include i.e neutrino data,
  although package is designed for γ-ray data analysis

3D analyses with Gammapy

Counts map:
each event is filled into a 3D Map



Predicted counts map:
from models and Instrument Response Functions



3D analyses with Gammapy

- Binned Likelihood fitting:
  - Poisson probability in pixel i to measure n counts given the model prediction $\nu(\xi)$ for parameters ξ

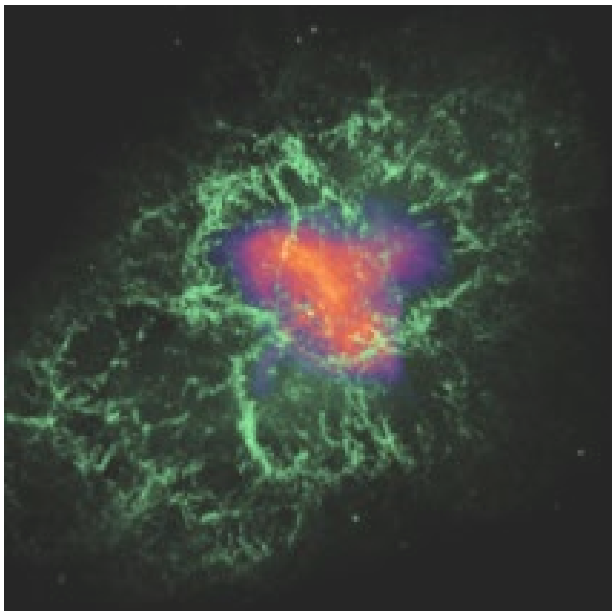
$$P\left(n_i \,\middle|\, \nu_i(\xi)\right) = \frac{\nu_i(\xi)^{n_i}}{n_i!} \times \exp(-\nu_i(\xi))$$

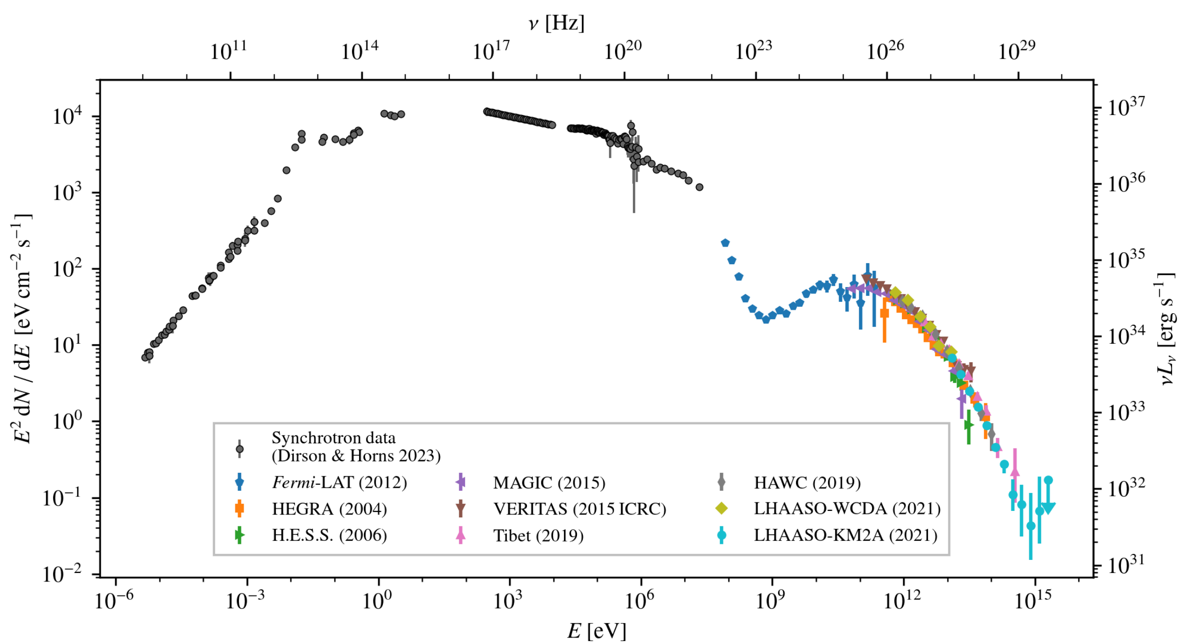
  - LogLikelihood:

$$-\ln \mathcal{L}(\xi) = -\sum_{i=1}^{N} \ln\left[\frac{\nu_i(\xi)^{n_i}}{n_i!} \times \exp(-\nu_i(\xi))\right]$$

  - Minimizing $\mathrm{TS} \equiv -2 \ln \mathcal{L}$ maximizes the Likelihood

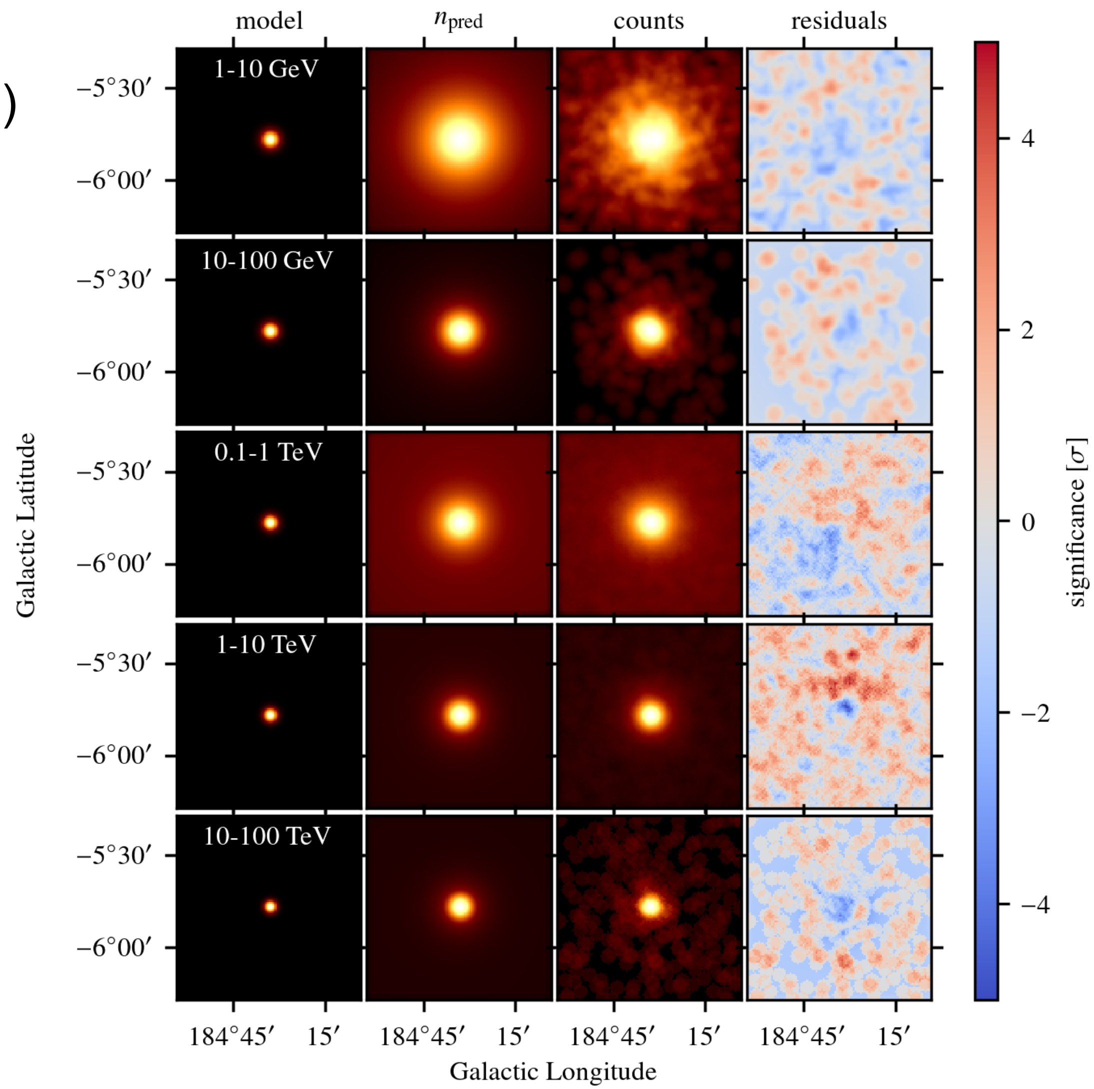
Combined Fermi + HESS analysis on the Crab nebula





Fermi + HESS on the Crab

- One 3D analysis over the whole Inverse Compton (IC) energy range (1 GeV – 100 TeV)
- Consistent analysis between Fermi and HESS (proof of concept)
- Modelling of the SED
- Measuring the extension and its energy dependency

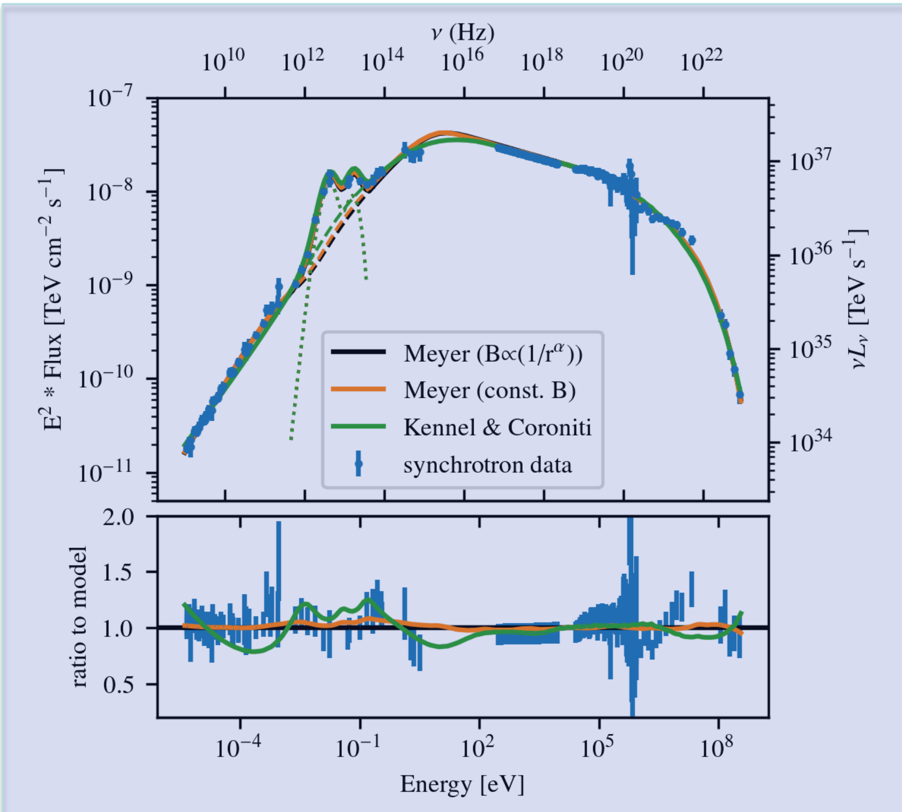


Fermi + HESS on the Crab

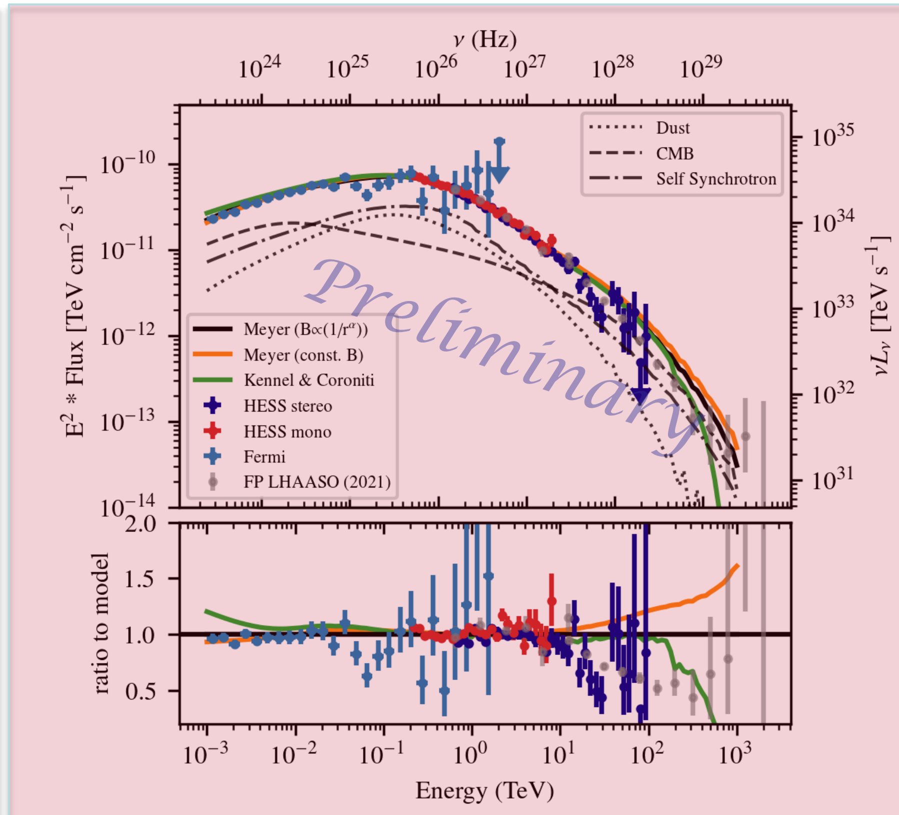
- Fitting 3 Self-Synchrotron Compton models to the data
- Adding the χ²-value of the synchrotron component to the TS-value of the IC Fit

$$TS_{tot} = -2\ln\mathcal{L}_{tot} = -2\ln\mathcal{L}_{IC} + \chi^2_{SYN}$$

1D flux points -- Synchrotron

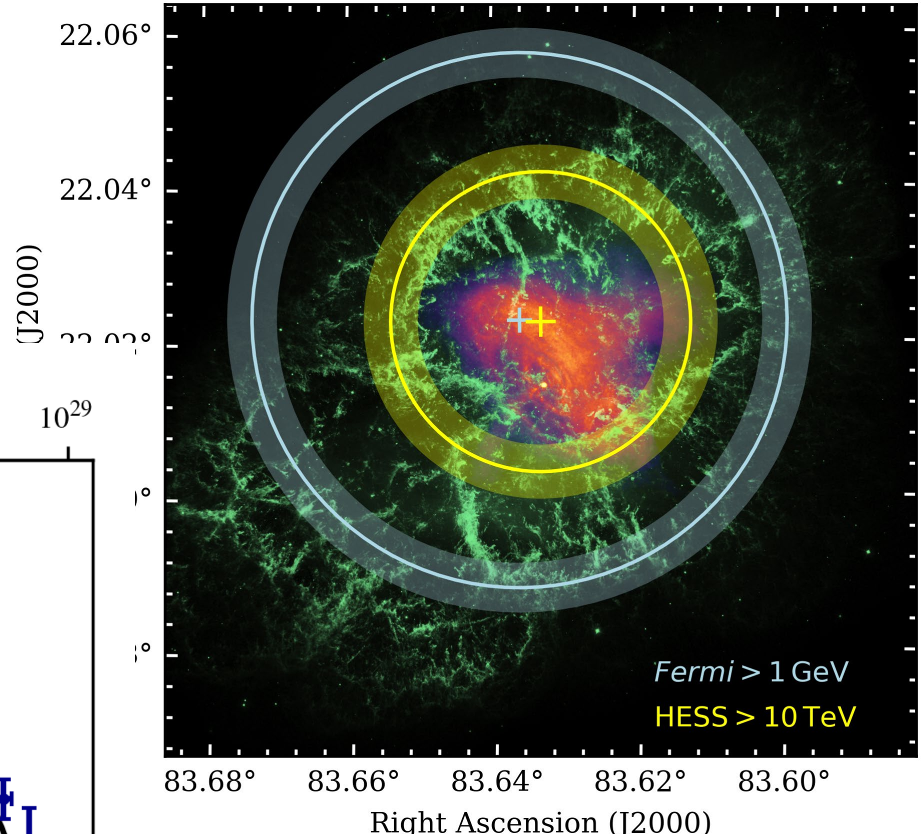


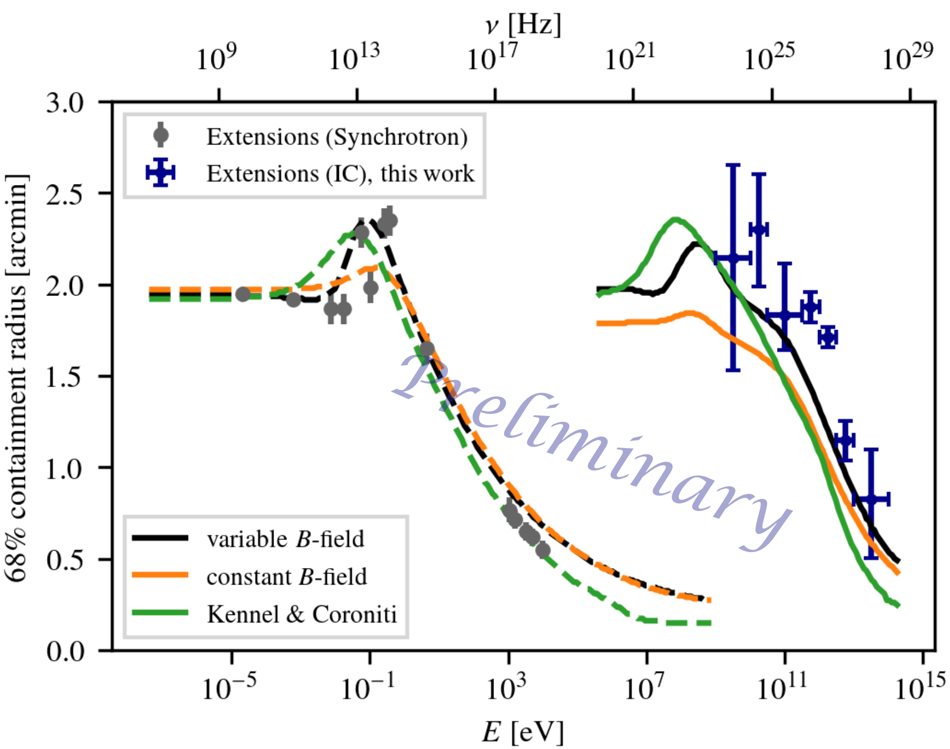
Inverse Comptron -- 3D data sets



Fermi + HESS on the Crab

- Measuring the extension in energy intervals
- Compare the IC extensions to the synchrotron extensions





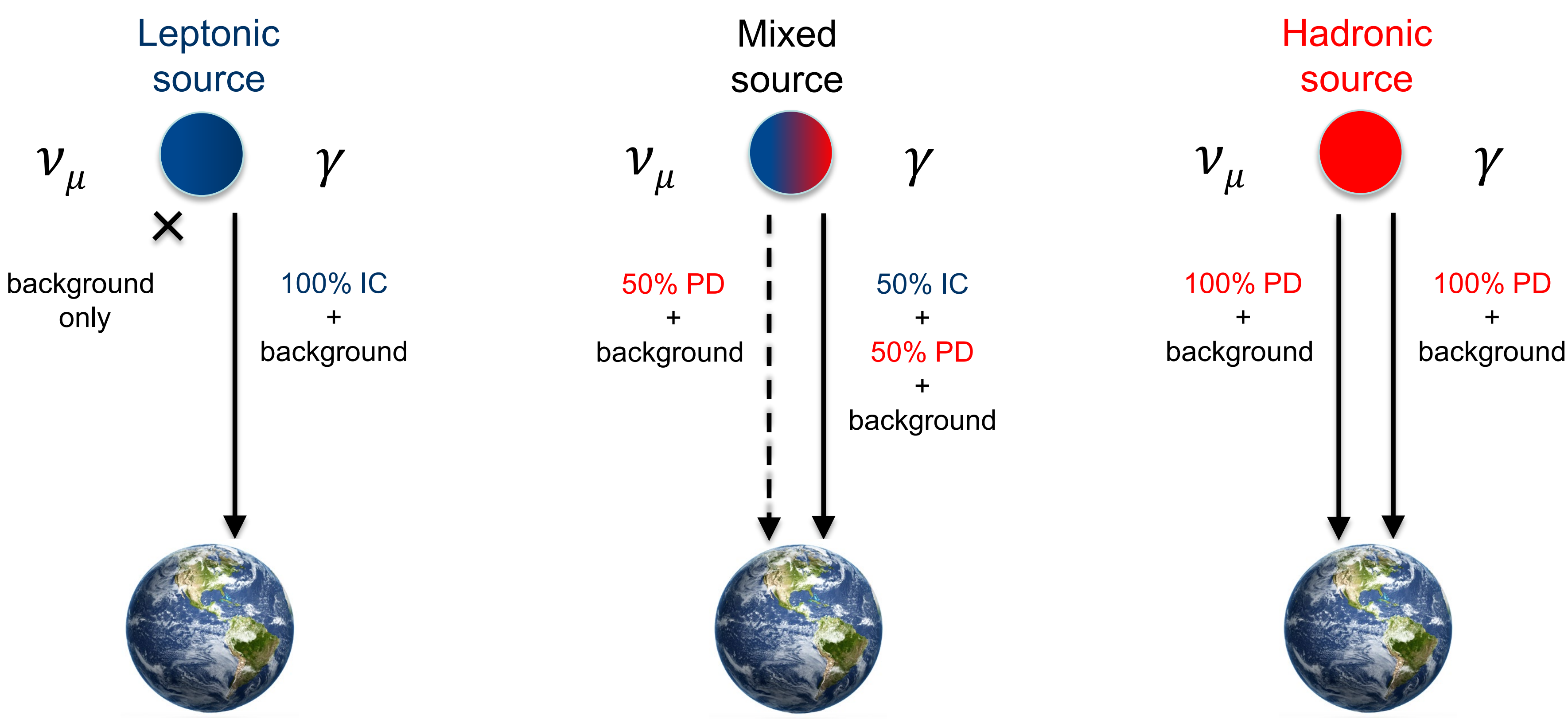
Combined CTA + KM3NeT analysis

“Are there Galactic gamma-ray sources for which the combined analysis of data from KM3NeT and CTA would help us to discriminate between hadronic and leptonic emission scenarios?“

Motivation

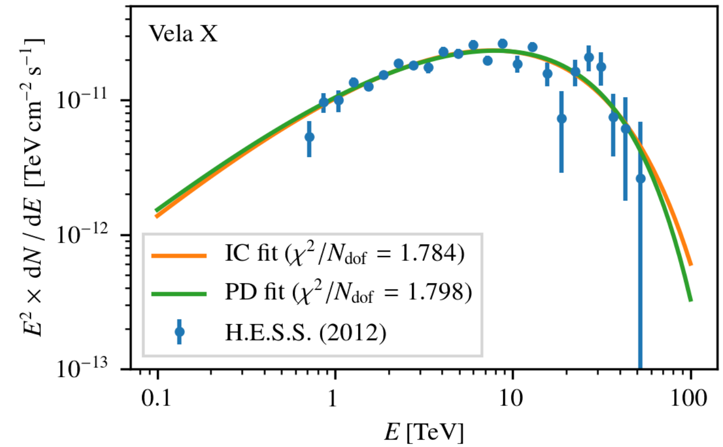
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Differentiating between leptonic and hadronic emission scenarios

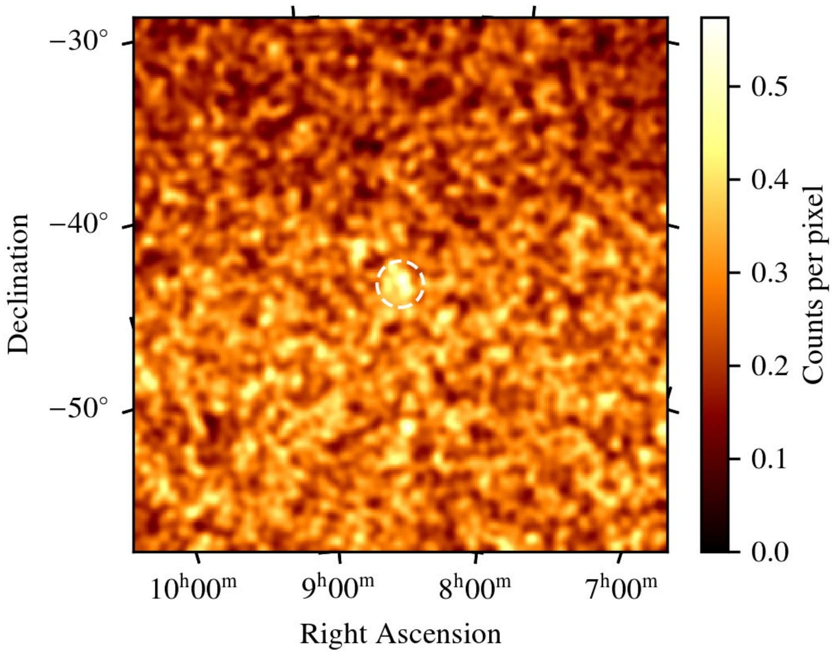


Generation of KM3NeT data sets

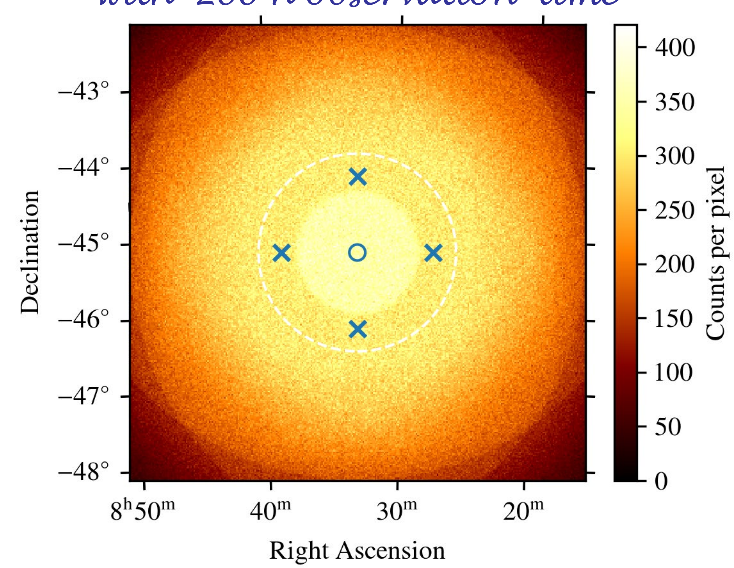
- gamma-ray spectra are very similar
- Need to include neutrino information



Simulated data set for KM3NeT with 10 yr observation time

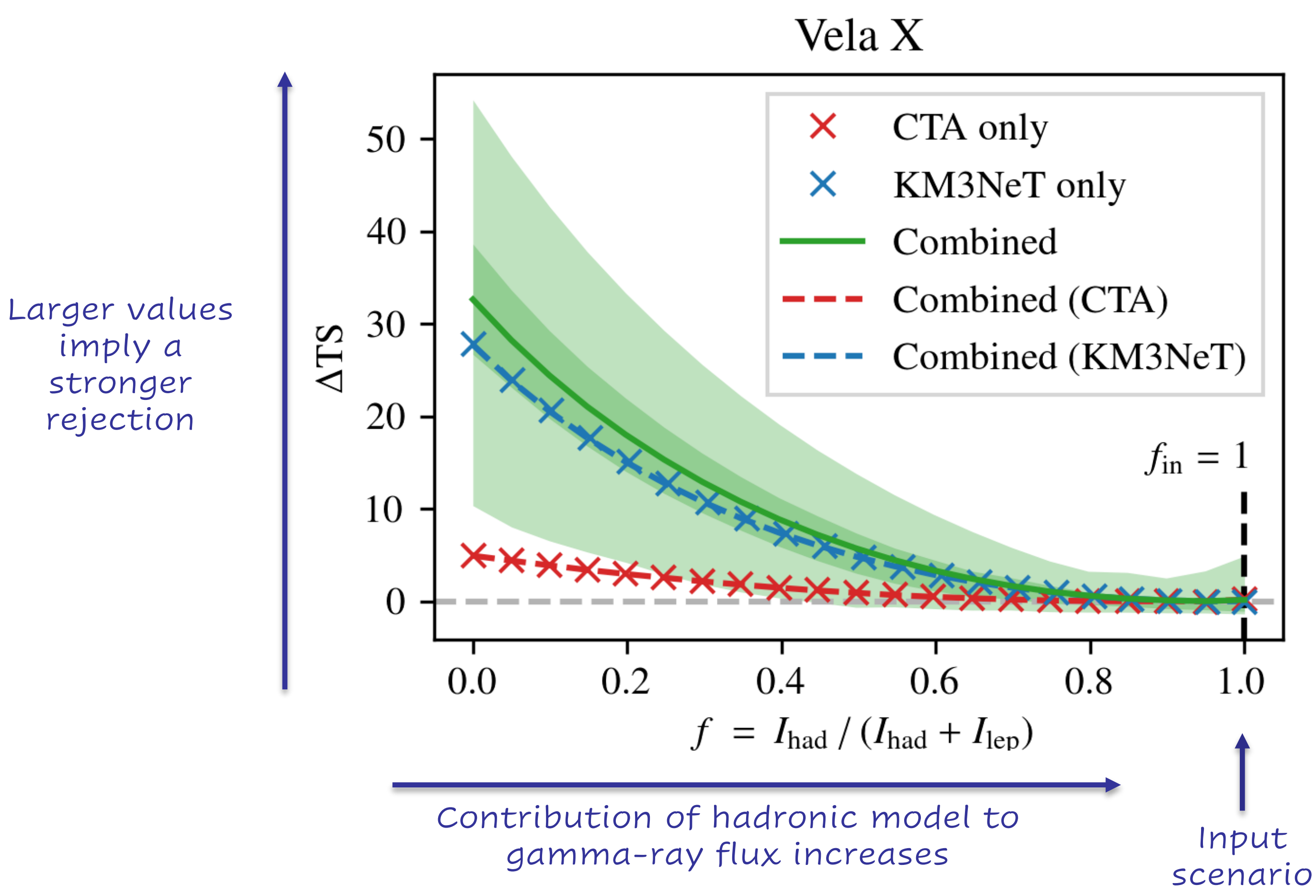


Simulated data set for CTA with 200 h observation time



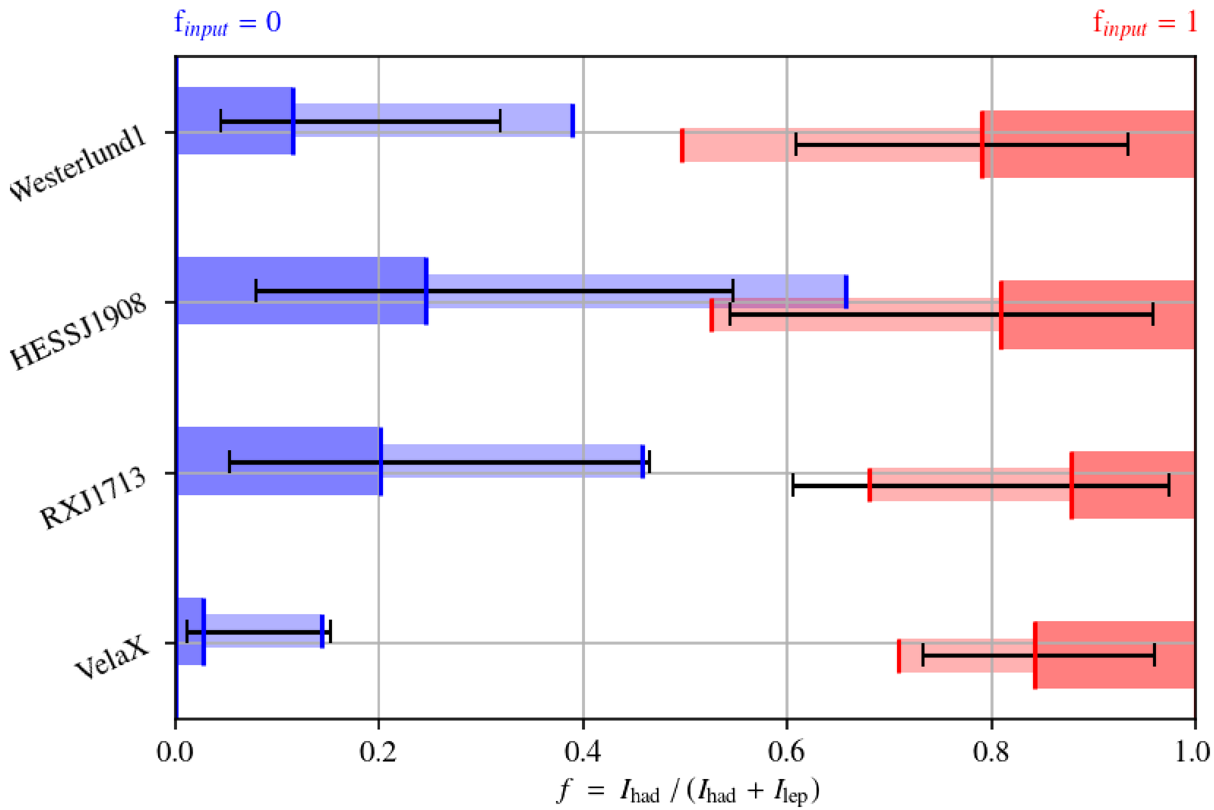
Limits on the hadronic contribution

- Perform *likelihood-profile* scans of the hadronic contribution *f*



Limits on the hadronic contribution

- Distribution of the best-fit values together with the average uncertainty



ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Summary

- Combined likelihood fit of Fermi + HESS data / CTA + KM3NeT data
  - Extended gamma-ray energy range
  - Combination of gamma-ray and neutrino data
- Flexible analysis framework of GAMMAPY
  - Fit customized physical models to the data
  - Include prior terms on parameters

Thanks for your attention!

Bundesministerium
für Bildung
und Forschung

FAU
FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG