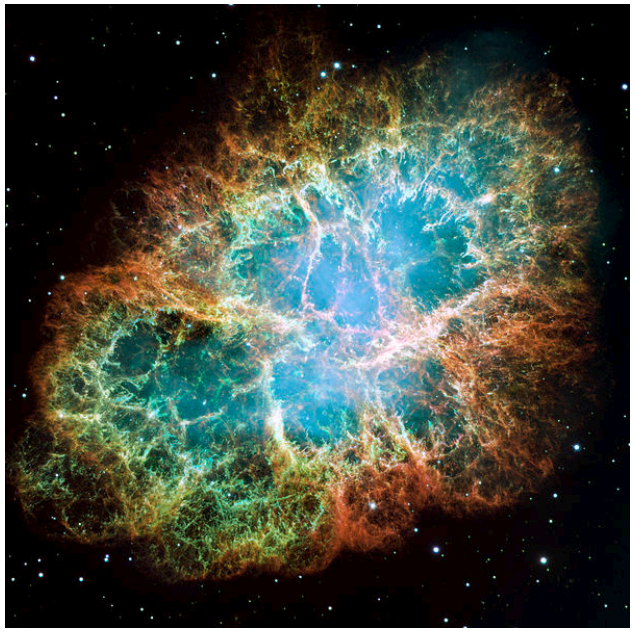
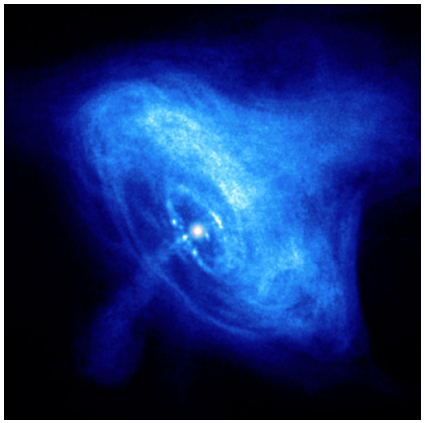
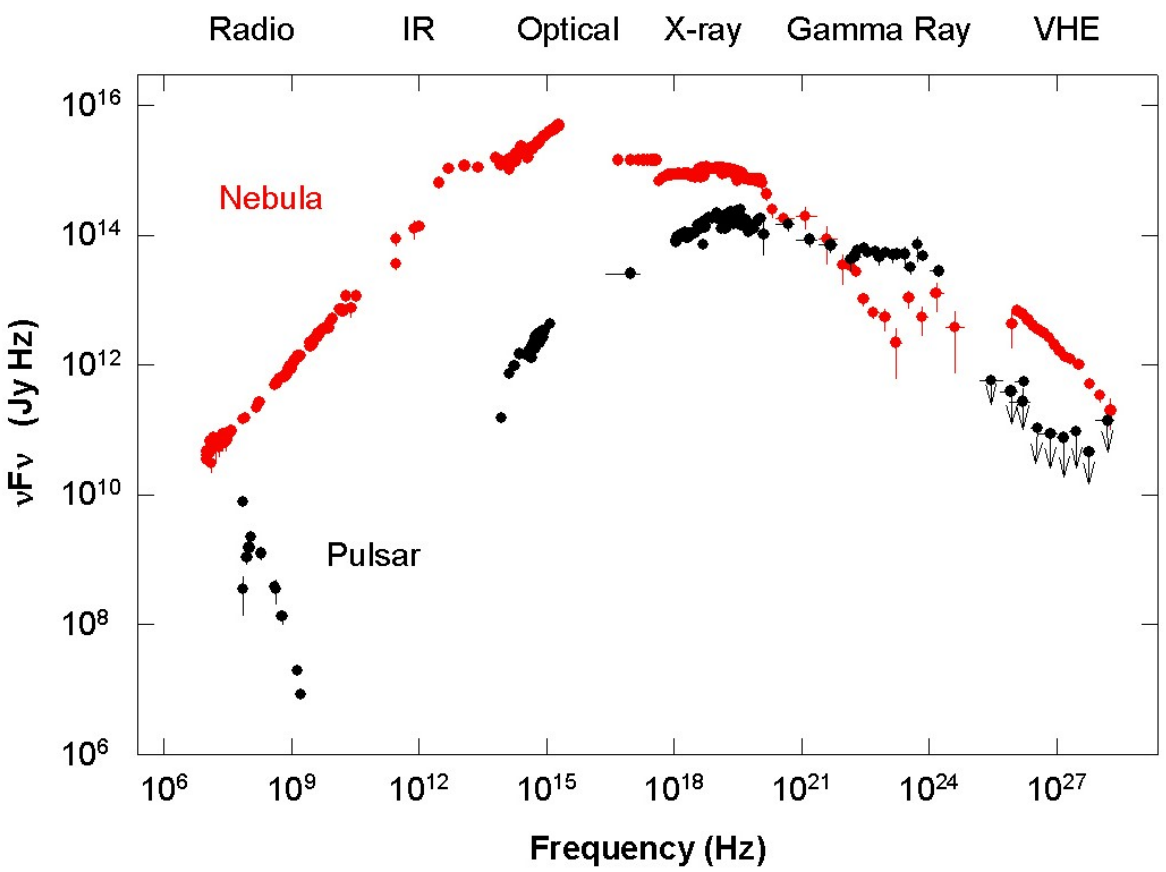
Analysis Topics: The Crab

Liz Hays
NASA GSFC

Why the Crab?



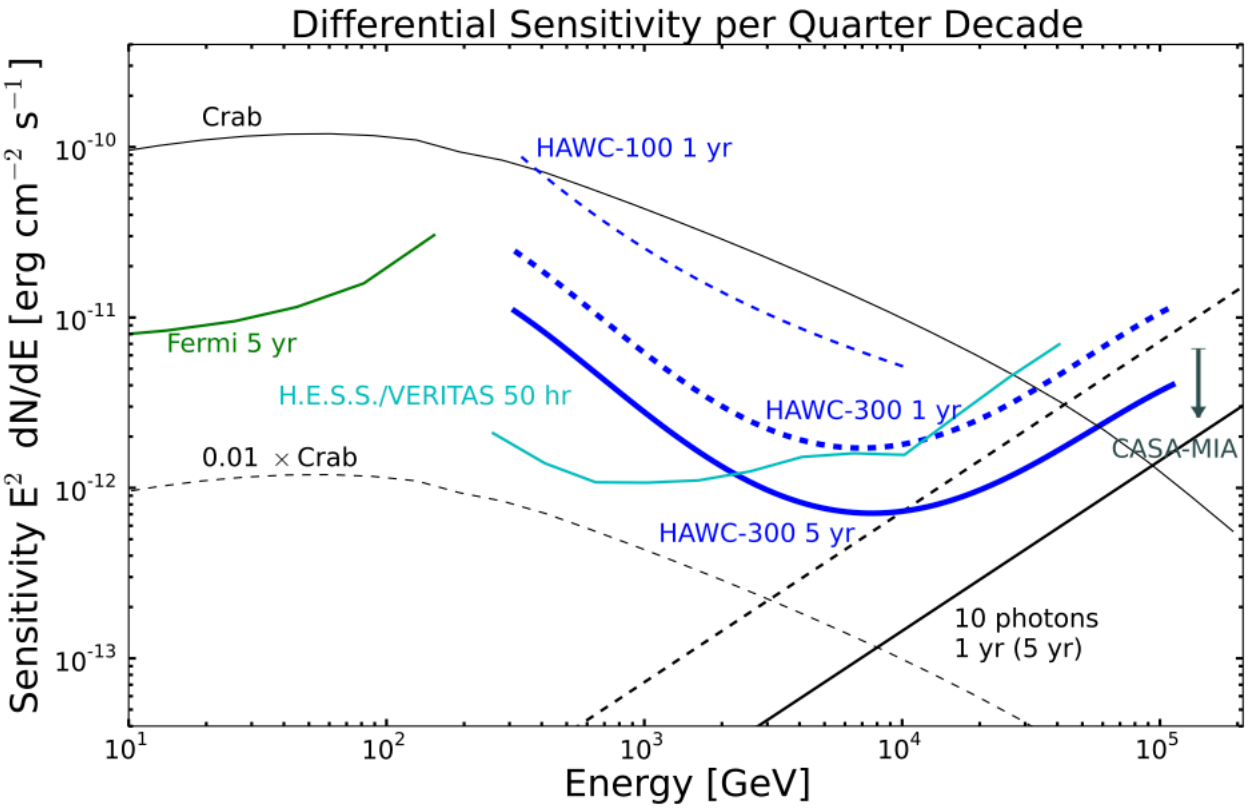




Spectrum from D. Thompson, compiled ~2006

>5500 references for Crab Nebula in ADS

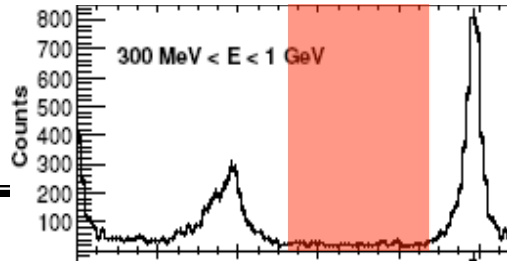
Why the Crab? Because we can!



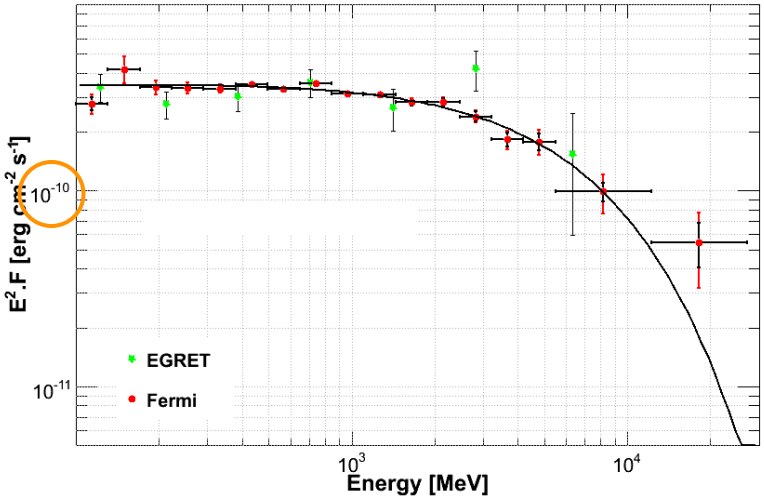
Abeysekara et al. (HAWC Collaboration) 2013, APh, 50, 26

Plus, it continues to push the limits of our astrophysical understanding…

The GeV Picture



Pulsar 100 MeV to 20 GeV

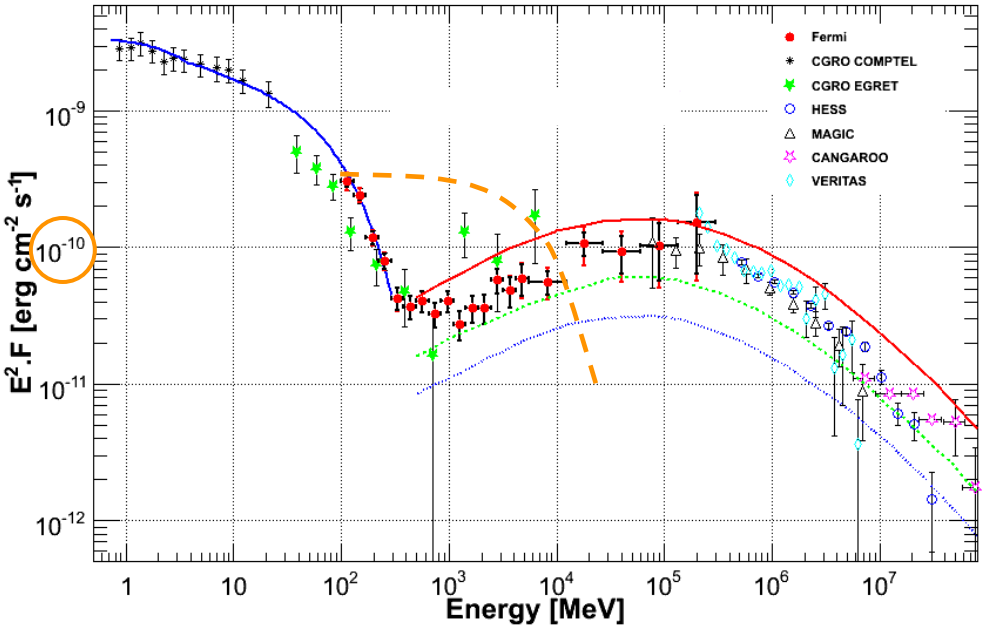


Hyper-exponential cutoff excluded in phase-averaged spectrum.

WARNING: Phase matters!

Also see later slide on how this is NOT an expo cutoff…

Nebula from MeV to TeV

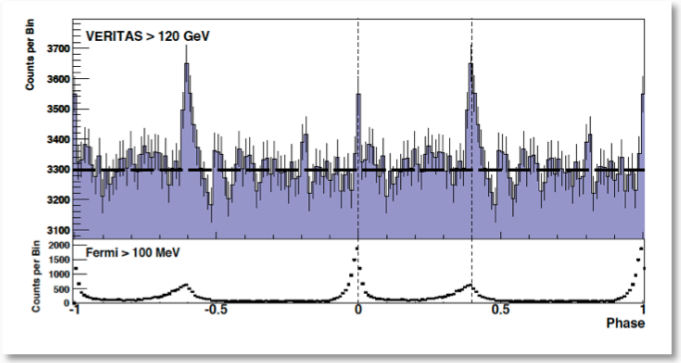


2 components: Synchrotron + Inverse Compton extending to multi-TeV.

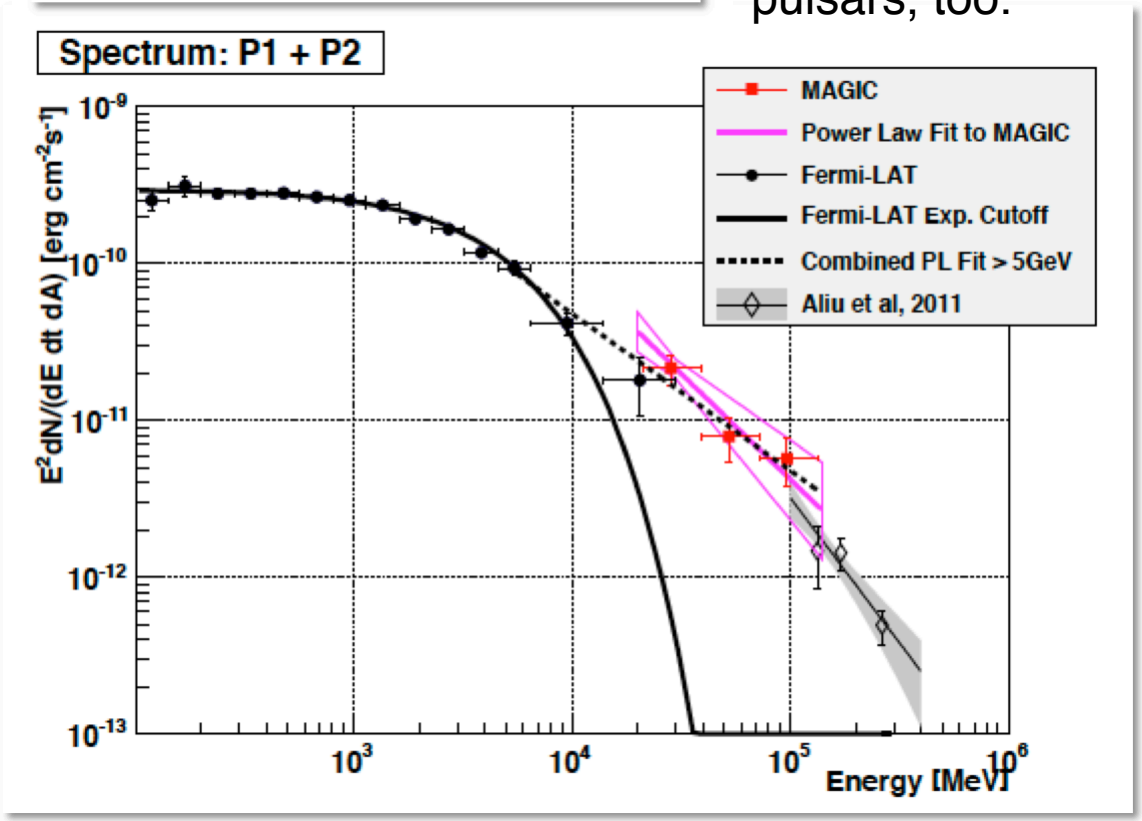
Mean B field in nebula 100 to 200 μG.

Abdo et al. 2010, ApJ, 708, 1254

Sub-TeV Pulsations: Beyond theory



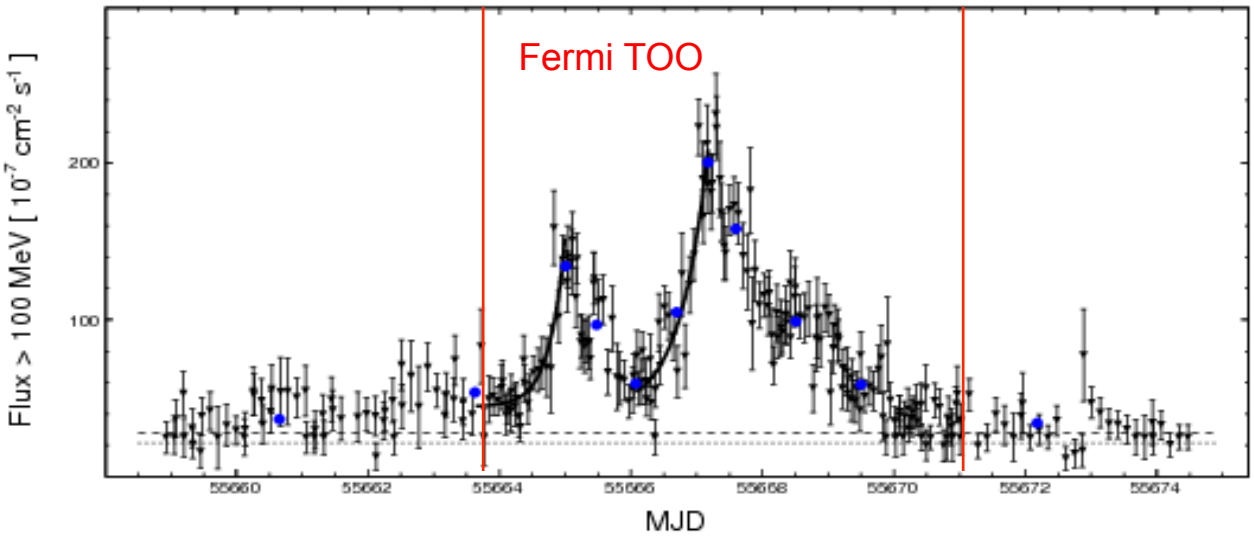
High energy pulsar “tail” and overlap measurements with ground-based observations constrain the neglected component (IC?). Really interesting to further constrain shape and to try to see this in other pulsars, too.



Aliu et al. et al. 2011

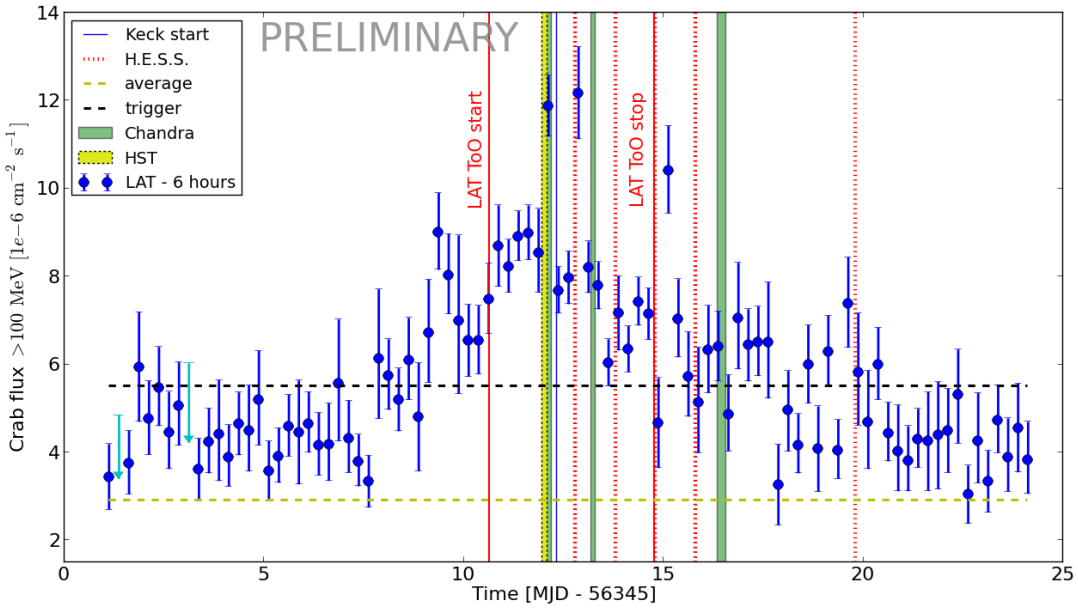
Aleksic et al. 2011

Extreme Variability: beyond expectation



Buehler, R. et al. 2012, ApJ, 749, 26

Crab flux doubles as quickly as 5-8 hrs with surprisingly high energy photon emission.



Meyer, M. et al. 2013, ApJL

A Basic Analysis

1. Select data (photons and time intervals)
- Some room for creativity

2. Calculate exposure (account for response)
- Creativity not usually advisable. ☺

3. Estimate flux and spectral shape (maximum likelihood fit of model to the data)
- Most of the artistry is here in the model choices

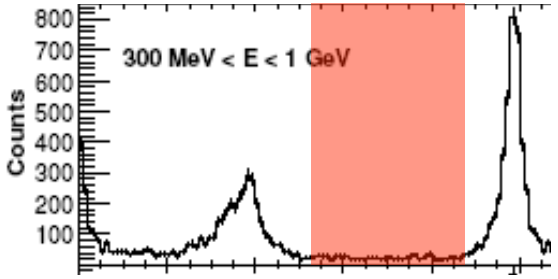
Analysis Challenges: Spatial confusion

Basic Crab Analysis Tool Kit:

"Waiter, there's a pulsar in my nebula!"

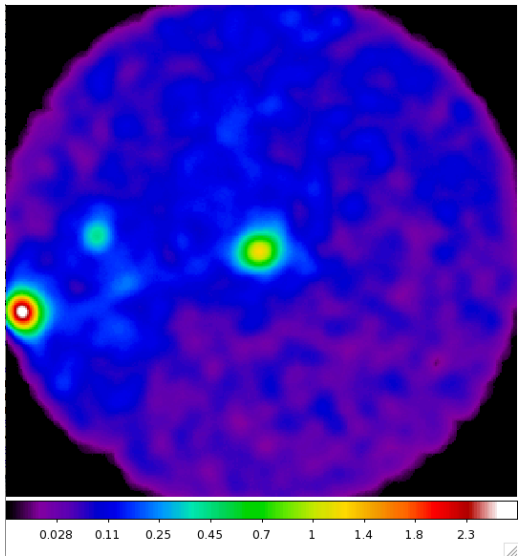
Pulsar gating

- Tag photons in relation to pulsar phase and remove photons associated with peak of the pulsed signal.
- Reduces pulsed signal, but also reduces exposure.
- Requires good, continuous timing solution covering the data set.

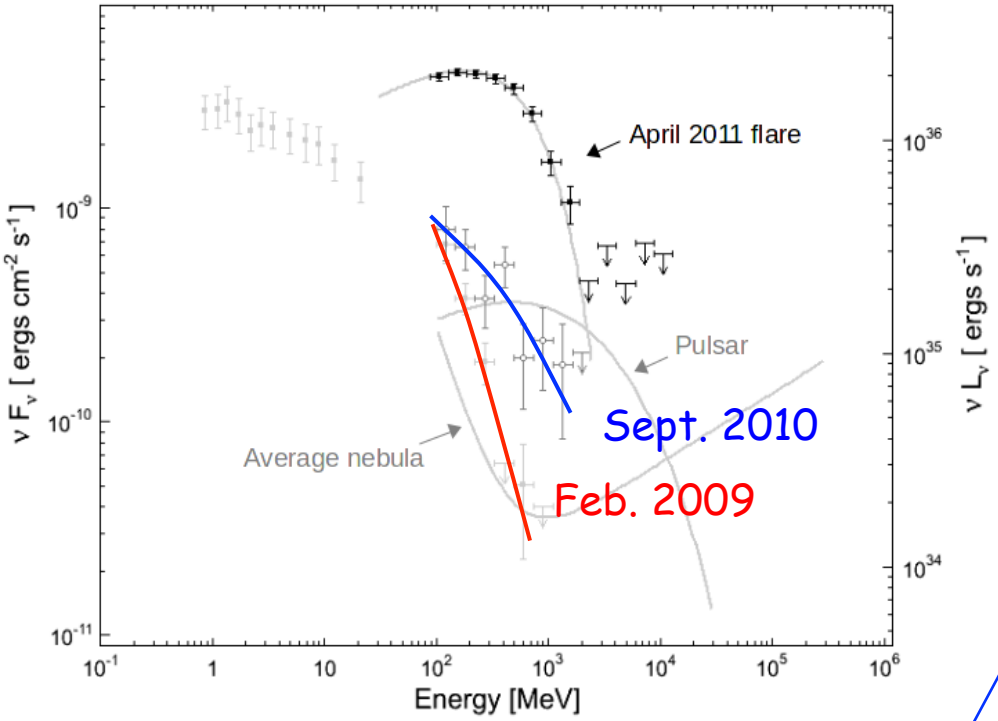


Regional sky model

- Energy-dependent confusion – spatial separation depends on the PSF, which depends on E. For the Crab, this is mainly a nuisance in muddying the measurements at low energy. Same goes for confusion with the Galactic diffuse emission.
- Requires a good model of the surrounding sky. Bright neighbors and Galactic diffuse emission important for most time scales



Analysis Challenges : Spectral confusion



Component modeling in the likelihood spectral/spatial model

1. Pulsar spectral shape
2. Synchrotron nebula spectral shape
3. IC nebula spectral shape
4. Flare spectral shape

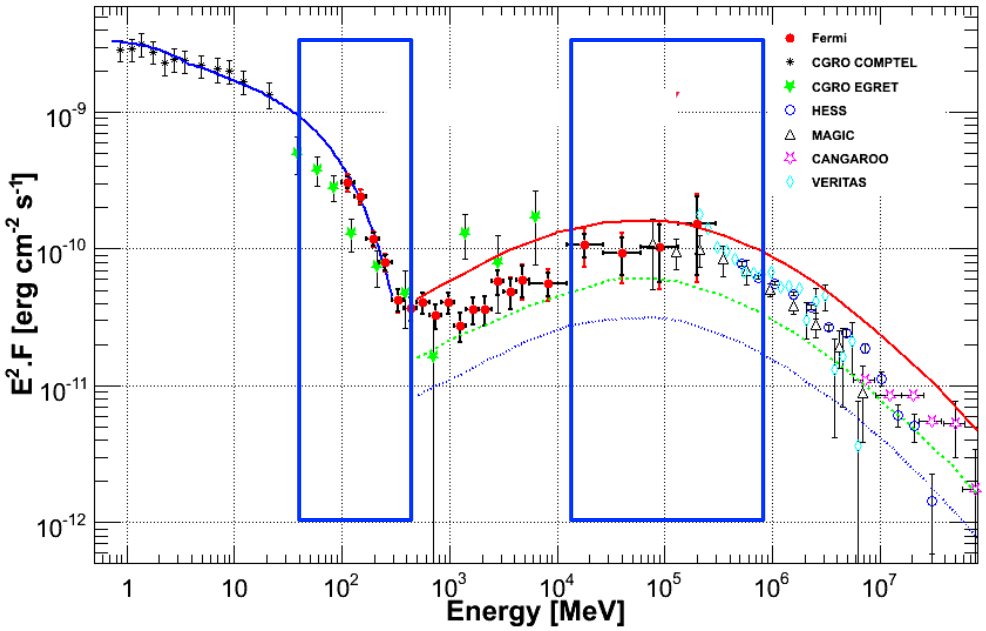
Fixed parameters

Using longer interval

Free parameters

Note that all variation is forced into the variable component (and will be considered in the error estimate) unless a background component is also left free to absorb fluctuations in CR rate.

Analysis Challenges: Steep spectrum/hard spectrum



Pushing the energy range is interesting and challenging!

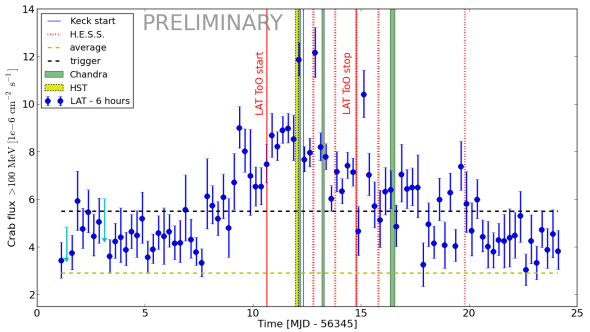
Statistics limited above 10 GeV, but overlap with VHE continues to improve.

One of the steepest spectrum objects observed with LAT. Paired with rapidly changing effective area makes energy dispersion and systematics an important consideration. Plus, GBM and others show that the soft gamma-ray nebula emission varies gradually.

Note for the future: LAT data reconstructed using Pass 8 will help in both regimes.

Analysis Challenges: Rapid variability

Crab Variability Analysis Tool Kit:



Different regime!
Forget pulsar gating and detailed modeling.

Data Selection

Zenith cut for photons and ROI-based timing cut to correct exposure
No rocking angle cut! Simply remove data when Earth is impacting your source to preserve coverage.

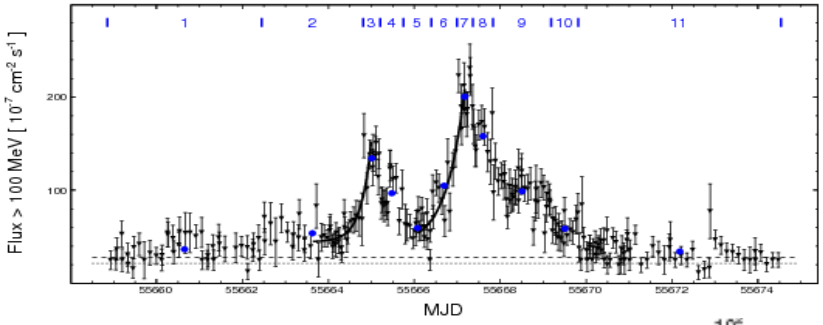
Binning

LAT can only view sources when unocculted. Maximum continuous coverage ~20 min in a 3 hour period (closer to 30-40 of 95 min. for TOO).
Bayesian blocks are useful for assigning periods with significant change in flux level.

Systematics

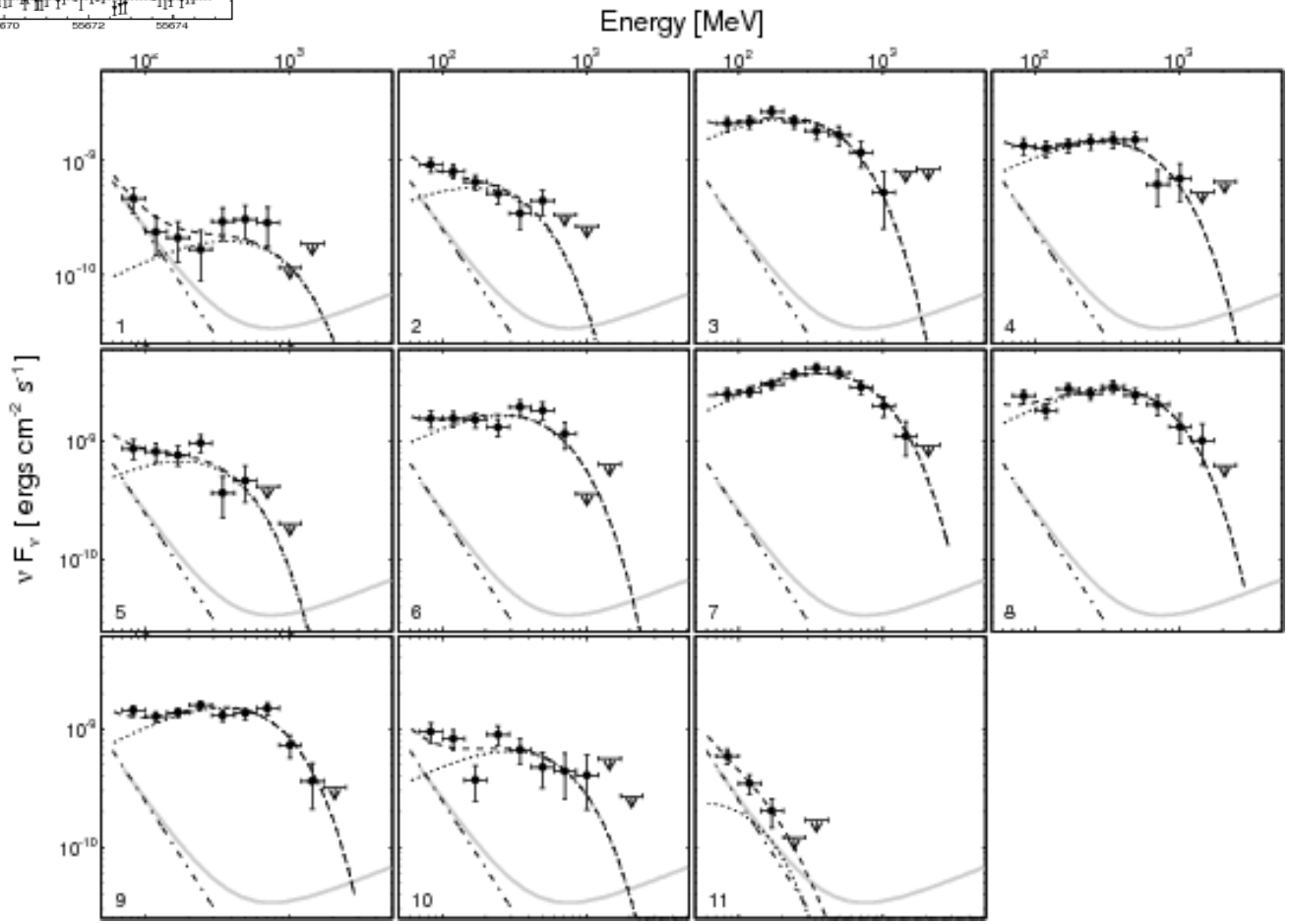
Some don't average out on short timescales for bright sources, e.g. FOV effects and TOOs cause sources to spend a high fraction of time in the same part of the instrument. For the Crab, using a theta-dependent PSF reduces false variation.

Spectral variation throughout flare



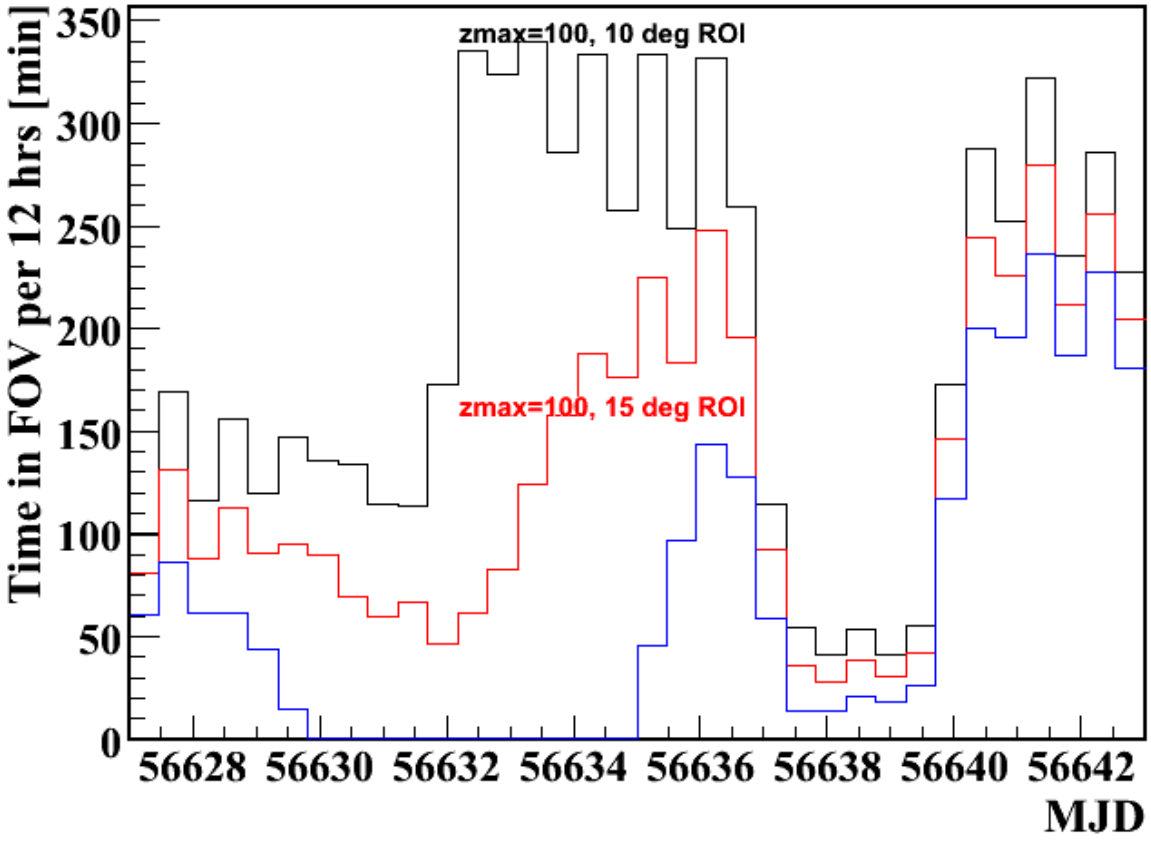
Bin intervals for spectral analysis defined using Bayesian blocks.

Tracks evolution of the shape of the flare component, power-law with exponential cutoff. Lower lines indicate average nebula spectrum.



Caveat for lightcurve comparisons

Selections matter for detailed lightcurve comparisons!



Example for a TOO on a source in the continuous viewing zone (close to orbital pole).

Notes on Crab Flare TOO process

Alerts and real time efforts:
LAT is always looking back in time. Data hits the public server in under 10 hours on average. (Not feasible to look onboard for beyond burst time scales and loose selections.)

1. Identify “flare”. Crab passes semi-arbitrary threshold. Currently ~2x the average flux for the combined pulsar + nebula.
- Trigger MW observations depending on approved proposals.
2. Submit Fermi TOO request.
3. Emit ATel.
4. Monitor and update MW observers. Additional Atel if there is a signficant new event or behavior.

Less formal approaches: Rolf and myself are always open to discussions of the work, what is going on with the Crab, and collaborative suggestions. If you’re curious, ask!

Summary

- Crab is an exceptional gamma-ray source and contains great science for overlap studies
- Analysis in LAT is challenging, but many tools and techniques available
- Discussion Questions
  - How far can we push overlap studies for pulsar and nebula in the near-term?
  - How to better organize ongoing flare monitoring and follow-up from TeV perspective? What information is most useful when a flare happens?
  - Considerations for timing studies between instruments with different energy passes and observations cadences? Variability appears to occur over a range of scales. What is energy dependence?
  - What are challenges for longer-term variability studies with TeV instruments?