Searching for Variability of the Crab Nebula Flux at TeV Energies using MAGIC Very Large Zenith Angle Observations

36th International Cosmic Ray Conference
July 29th, 2019

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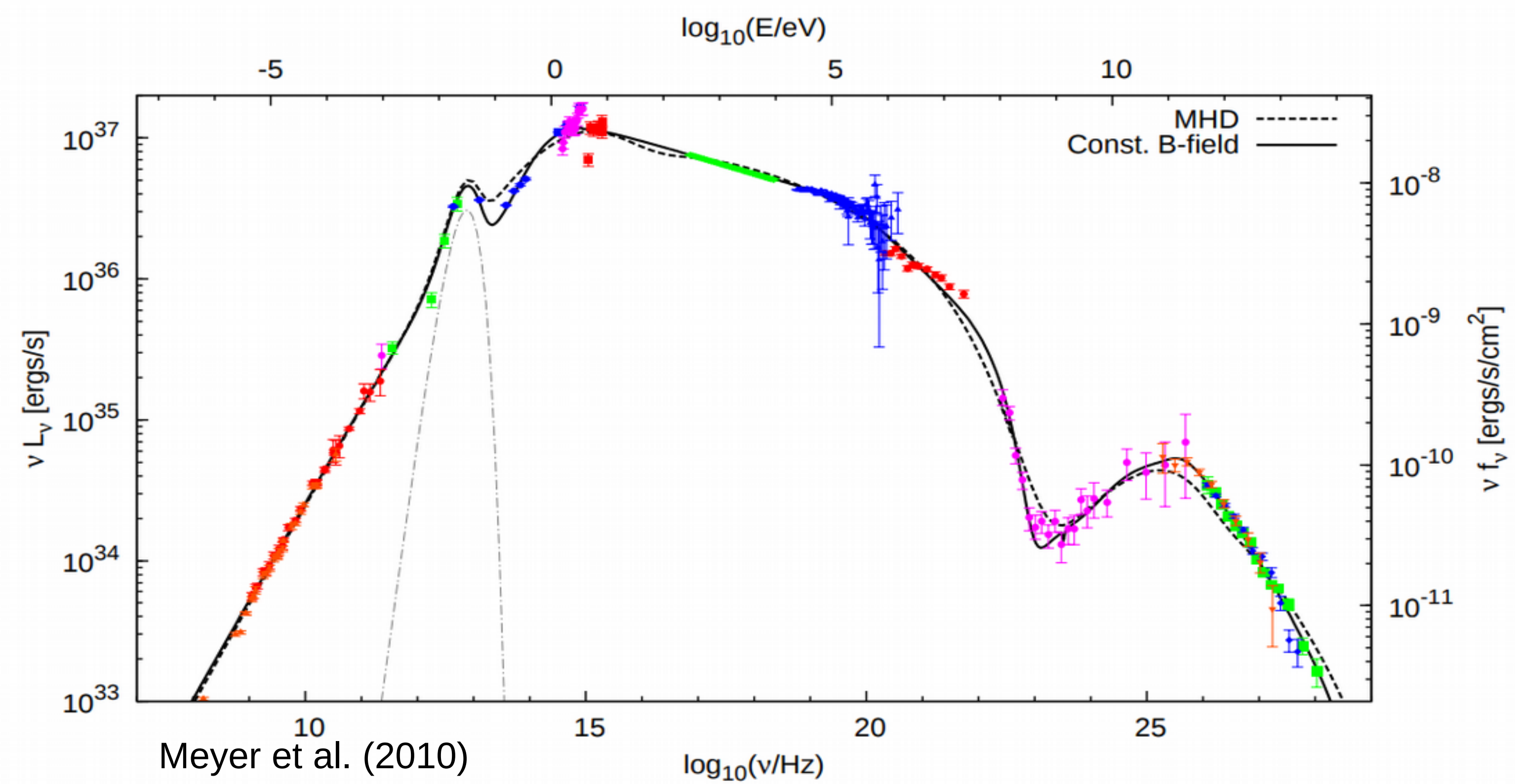
The Crab Nebula

The Crab Nebula

- Pulsar wind nebula
- SED well described by one-zone synchrotron – SSC model

- Brightest persistent source in gamma rays
- ‘Standard Candle’ of VHE gamma-ray astronomy



Meyer et al. (2010)

Why search for variability?

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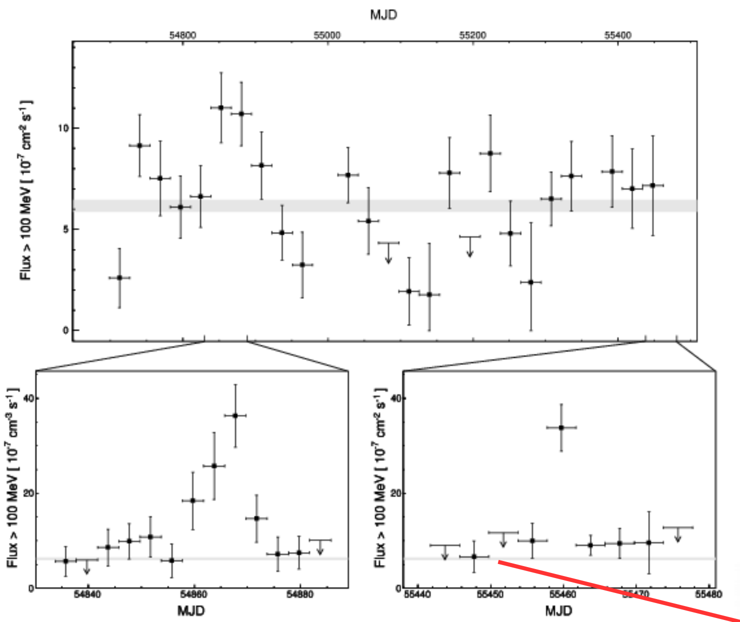
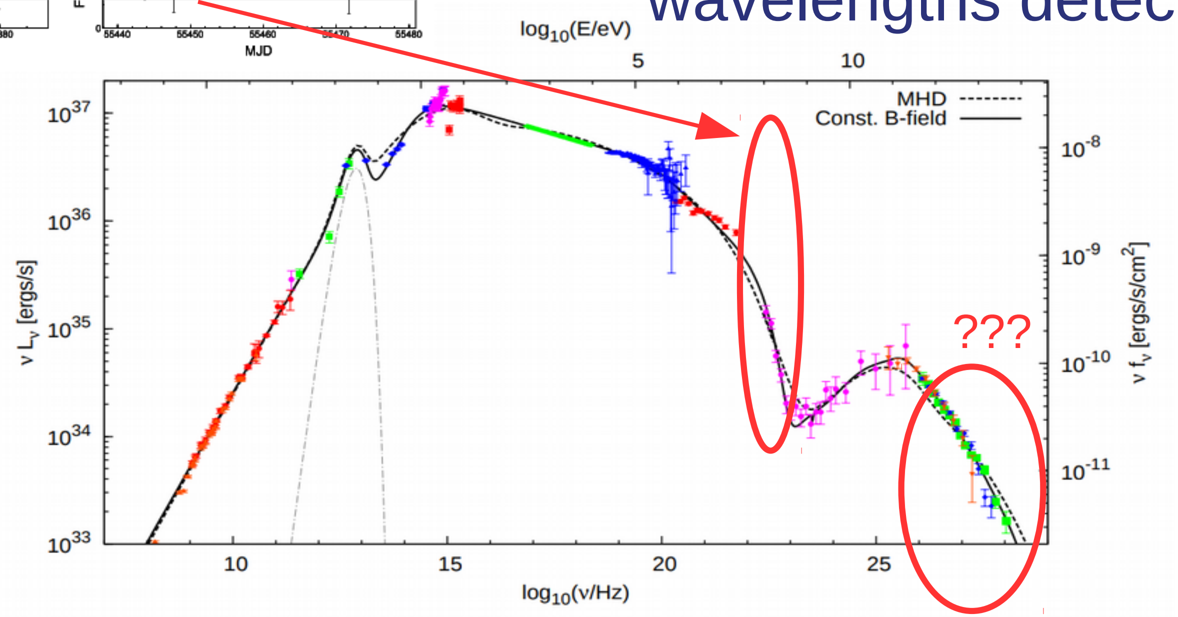
- Observation of flares for first time in 2010 by AGILE & Fermi-LAT (Tavani et al., Abdo et al., 2011)
- Since then ~1 flare per year
- Origin not fully understood
- No counterpart at other wavelengths detected



(Abdo et al. 2011)



Meyer et al. (2010)

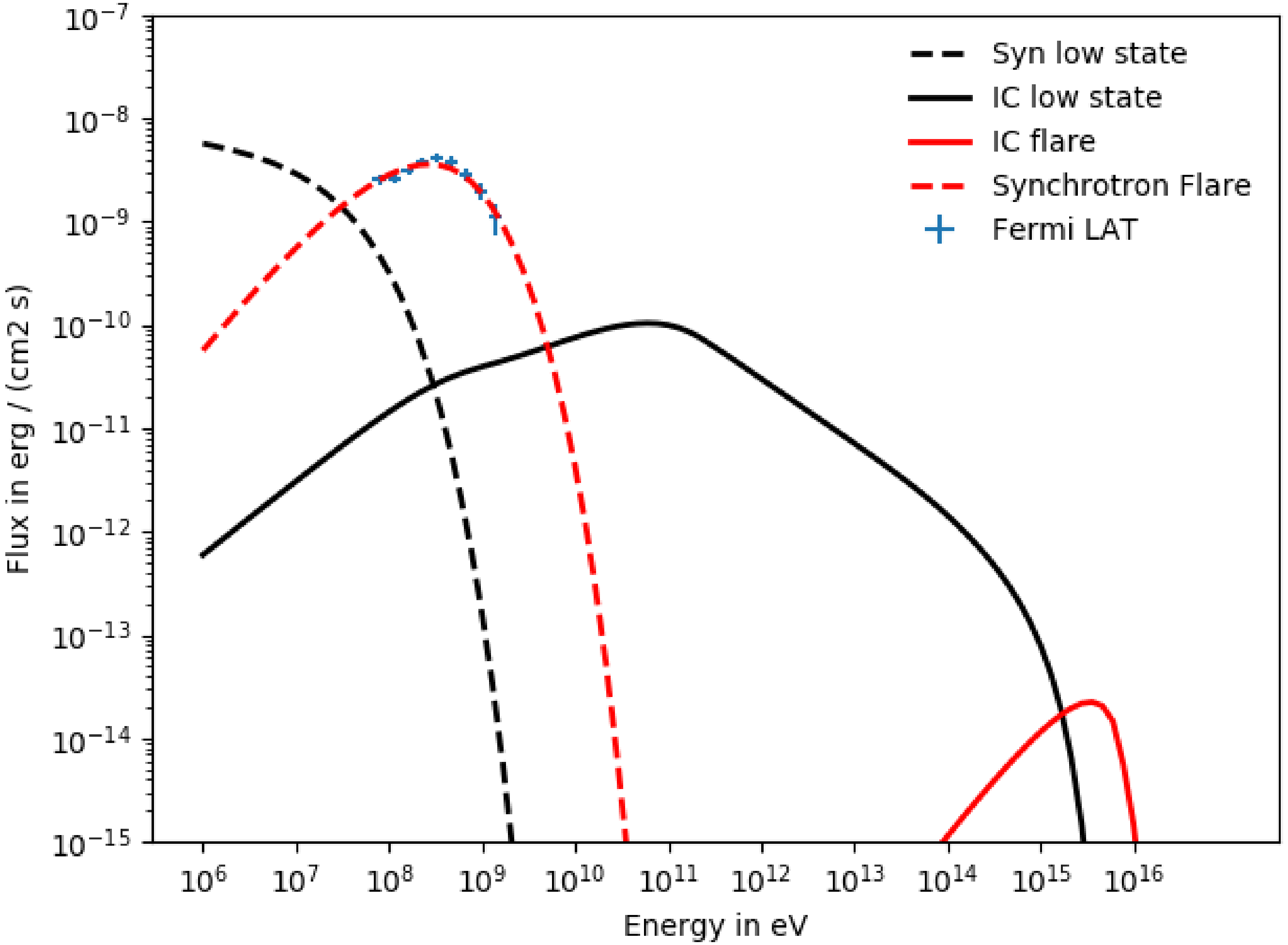
Flares in the Crab Nebula

Brightest Fermi flare:
April 2011
(arxiv:1112.1979)

Using *naima*-package:
Fermi-LAT data approximated by introducing additional e⁻-population

With standard Crab nebula parameters:
B ≈ 125 µG
R ≈ 2 pc

Inverse Compton component around ~PeV

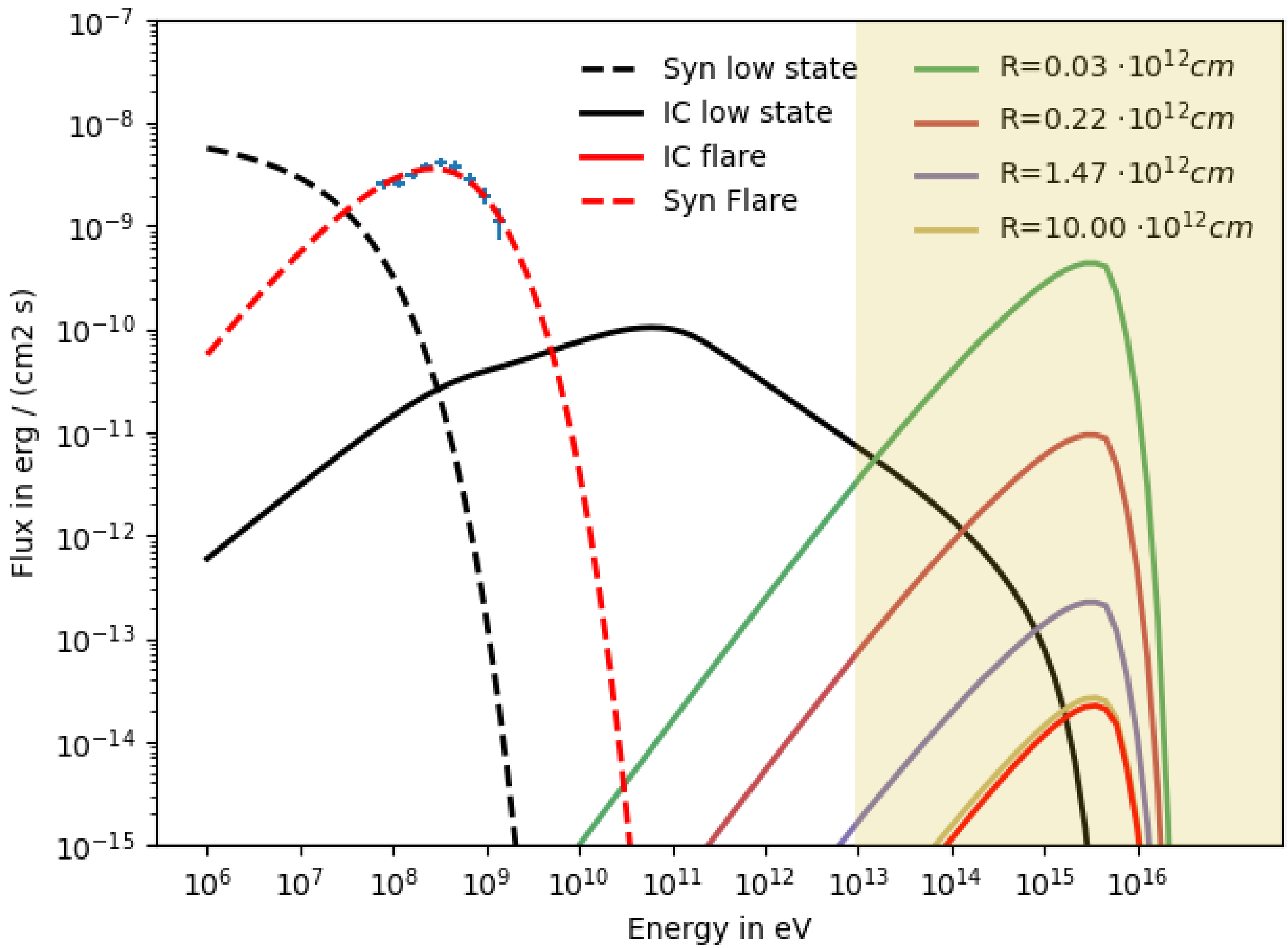


Flares in the Crab Nebula

Standard Crab nebula parameters:
$B_{Crab} \approx 125\ \mu G$
$R_{Crab} \approx 2$ pc

Short timescale of flares
→ emission region << R_{Crab}
$R_{flare} \sim 10^{-4}$pc $\sim 10^{14}$ cm
(plus locally strongly enhanced magnetic fields, Doppler boosting)

IC counterpart would appear in very high TeV energies



Difficulty: For low state Crab at 10 TeV <10 Events per hour per $1km^2$ expected (at 300 GeV ~ 1 Event per second)

The MAGIC Telescopes

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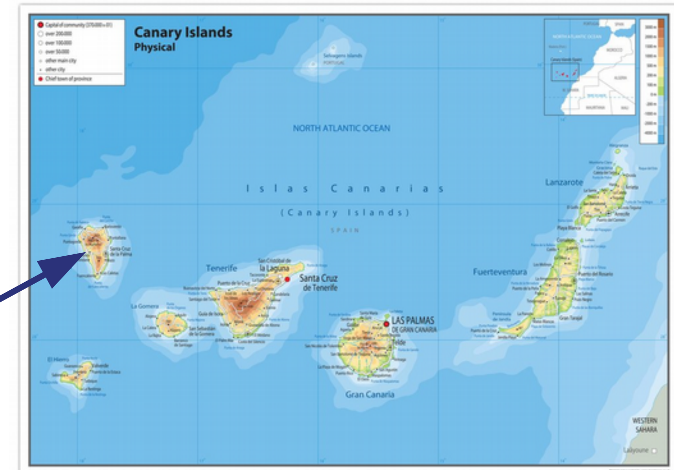
- Two Imaging Air Cherenkov Telescopes (IACTs) working in stereoscopic mode
- Located at Roque de los Muchachos Observatory on La Palma at 2200m a.s.l.

MAGIC 1 **Counting House** **MAGIC 2**



- Energy range from 30 GeV to 100 TeV
- Energy resolution between 15% and 25%
- Field of view 3.5°
- Sensitivity of ~0.5% Crab Nebula Flux in 50hrs above ~400GeV
- Typical effective area: $10^3 - 10^5$ m^2

VLZA Observations with the MAGIC Telescopes

VLZA = **V**ery **L**arge **Z**enith **A**ngles: 70° - 80°

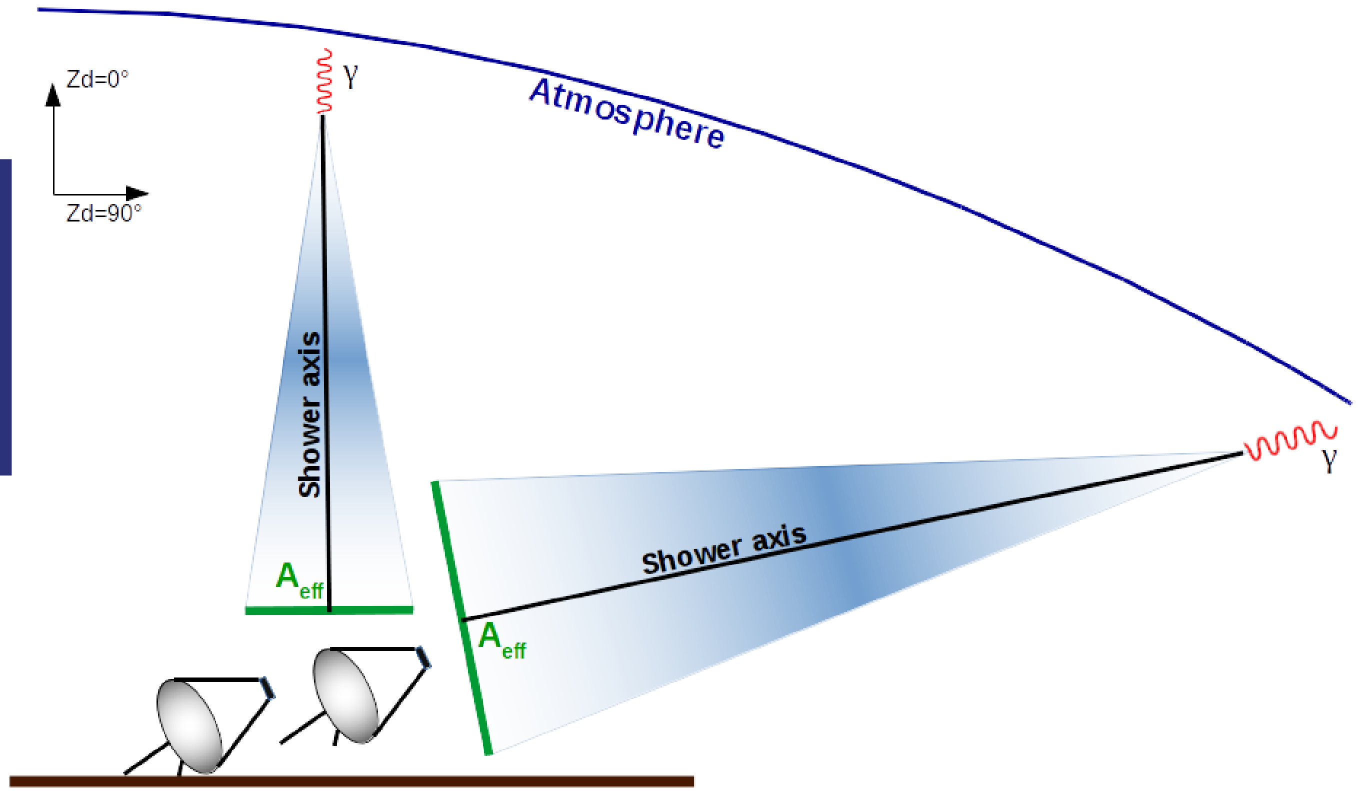
A new efficient tool to study the highest energy gamma rays

Larger distance from the air shower → boost in effective area to > 1km²

See also:

Crab spectrum at ~100 TeV
Michele Peresano
Presentation, GAI9d
July 30th
PoS(ICRC2019)759

VLZA-technique
Martin Will
Poster, Session 3, #86
July 30th & 31st
PoS(ICRC2019)828

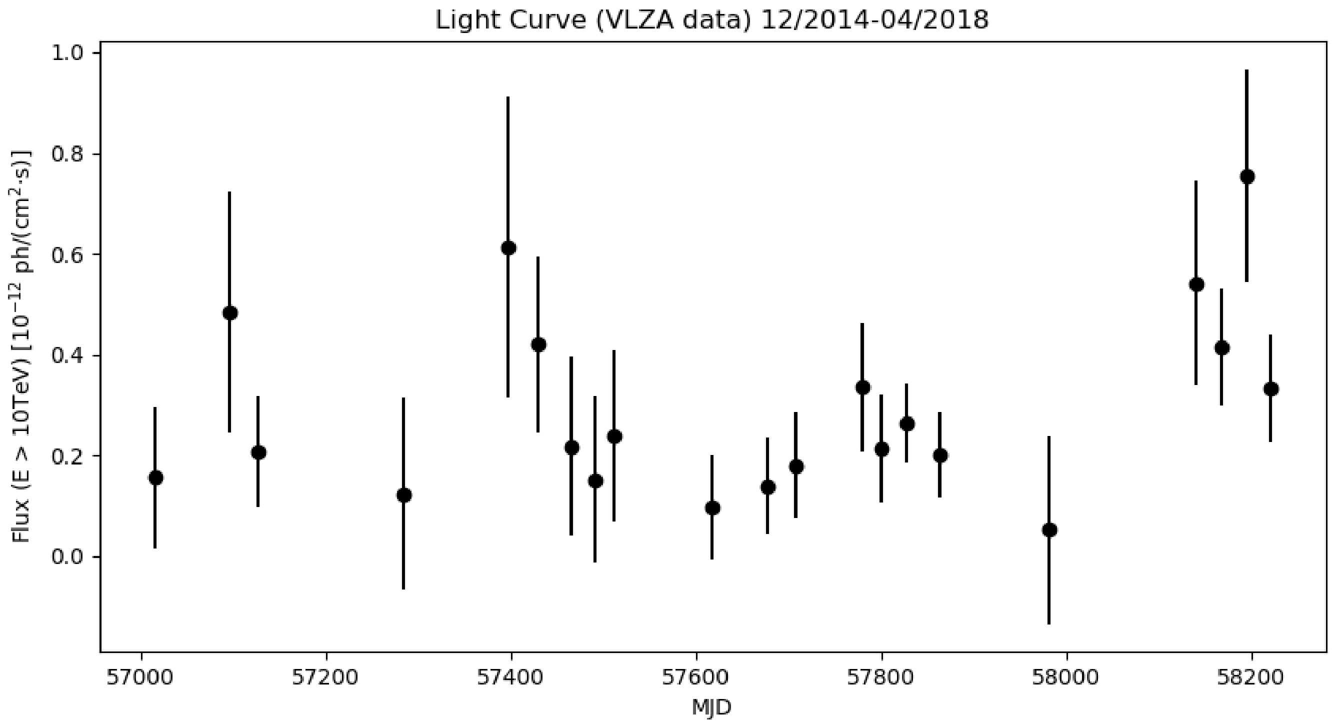


Multi-year Light Curve

- Data taken between December 2014 and April 2018
- Zenith Angles: 70° - 80°
- ~ 50 hours of good quality data

Light Curve:

- Energy threshold: 10 TeV
- Monthly bins



Multi-year Light Curve

Light Curve:

- Energy threshold: 10 TeV
- Monthly bins

Fit:

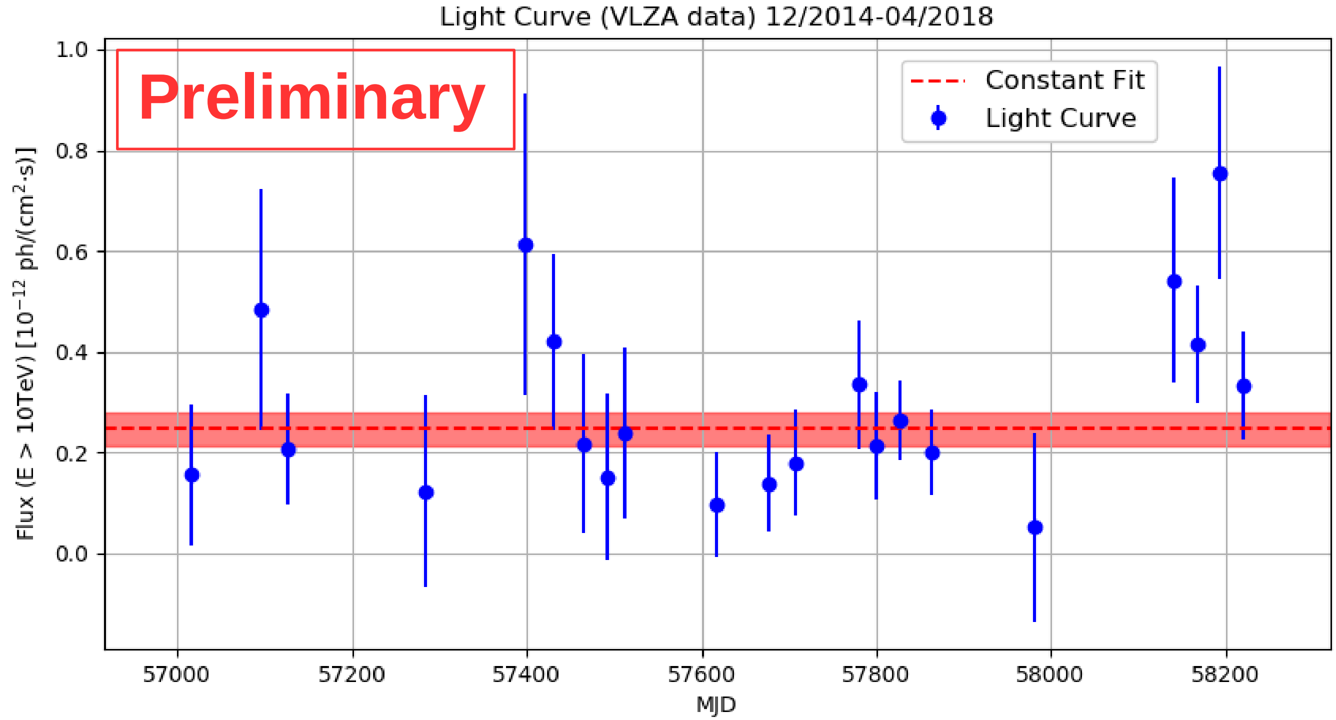
- $F_{fit} = (0.25 \pm 0.03) \cdot 10^{-12}\ cm^{-2}\ s^{-1}$
- p = 0.99 $\quad X^2/Ndf = 21.27/20$

Constant Fit:

- Poisson statistics
- Maximum likelihood

Goodness of Fit:

- Simulation of equivalent LCs
- Compute logL for each
- P-value from CDF of simulated logL-values



Data in good agreement with a constant fit → No evidence for variability

Upper Limits on Variability

Common quantification of variability:

- Fractional Variation

$$F_{var} = \frac{\sqrt{\sigma^2 - \delta^2}}{\langle f \rangle}$$

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (f_i - \langle f \rangle)^2$$

Mean squared deviation from fit

$$\delta^2 = \frac{1}{N} \sum_{i=1}^{N} \delta_i^2$$

Mean squared uncertainty of data (only statistical here)

$$\langle f \rangle$$

Fitted flux

- Same set of simulated light curves as for goodness of fit estimation
- Calculate F_{var} for each
- From cumulative distribution obtain upper limits

99.7% upper limit for variability above 10 TeV: F_{var} = 1.86 (preliminary)

Sensitivity to fluctuations

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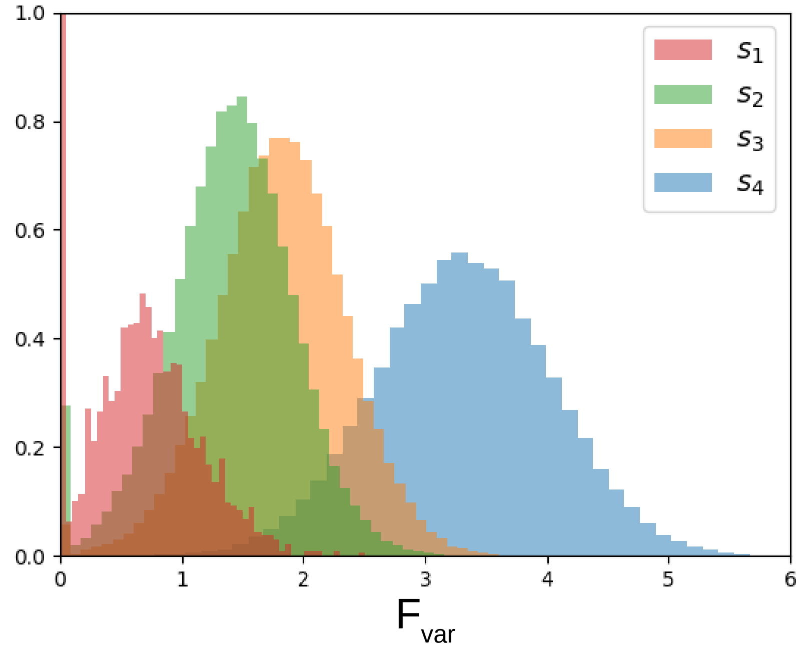
Which scale of fluctuations in the Crab nebula flux could we detect ?

- Simulations of light curves as before, but allowing flux to fluctuate within certain range [-s, s]
  - $f = f_{fit} + \Delta f \cdot f_{fit}$, where Δf drawn from uniform distribution between $[\max(-1,-s), s]$
- Produce distribution of fractional variation F_{var}
- Repeat for different scales
- Calculate probability for F_{var} distribution to overlap with F_{var} distribution from constant flux assumption



$P_{overlap} \leq 0.3\%$ for $s \geq 2.25$

Sensitive to fluctuations on top of Crab nebula flux above 10 TeV within at least $2.25 \cdot f_{fit} = 0.56 \cdot 10^{-12}\ cm^{-2}\ s^{-1}$ (preliminary)

Sensitivity to fluctuations

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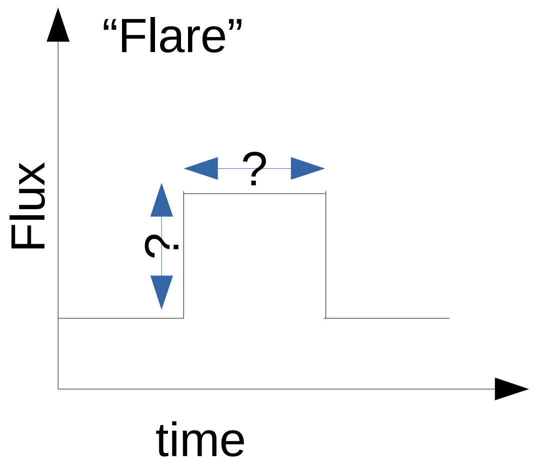
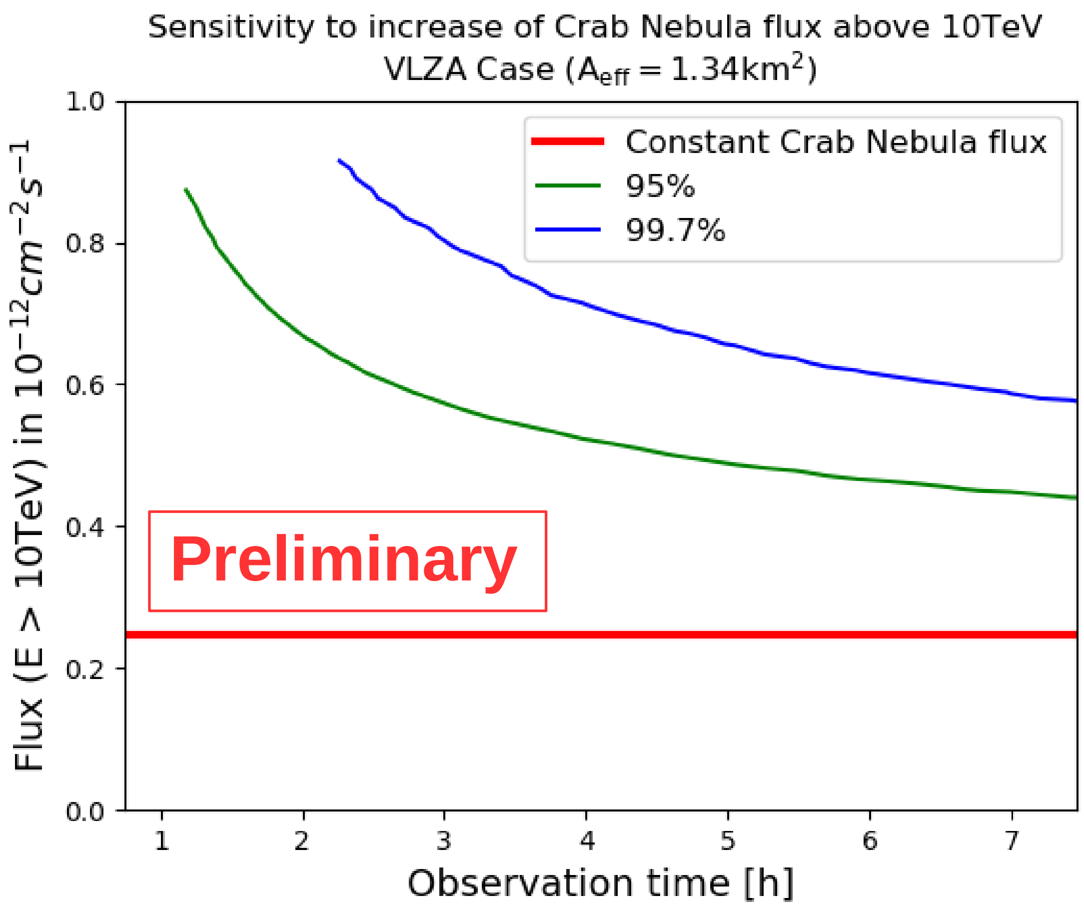
Which scale of flux increase could we detect within a given time?



Compare distribution of expected number of On-source counts for certain flux increase to expectation for nominal flux above 10 TeV

→ For different flux increases
→ For different exposures



Note: 1h per night at VLZA
→ 5 nights for 5 hours of observation time

Summary & Outlook

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- VLZA observations open window for MAGIC towards the highest TeV energies
- Technique and analysis well under control
- No variability found in 3.5 year light curve
  → Crab is still our “standard candle”
- Sensitive to overall fluctuations of within $2.25 \cdot F_{crab}$
- Sensitive to flares with factor ~3 flux increase in < 4 hours

- Still exploring possibilities of improving VLZA analysis to increase sensitivity
- Large and interesting data set → room for more detailed studies
- Will keep monitoring Crab nebula at VLZA
- Hope for Crab to be nice to us and bless us with a BIG flare!