Six Years of Observations of The Crab Nebula With VERITAS
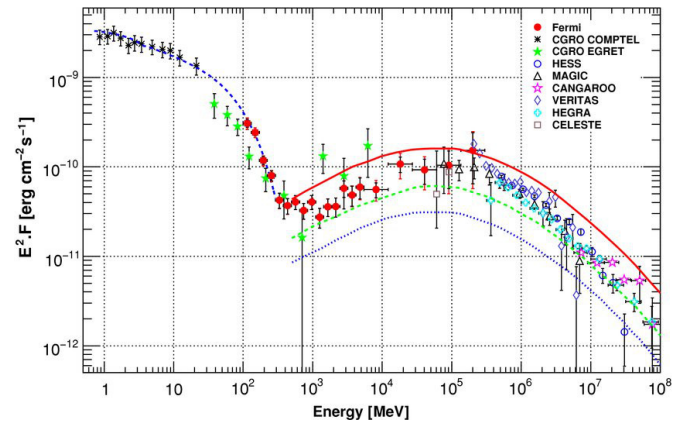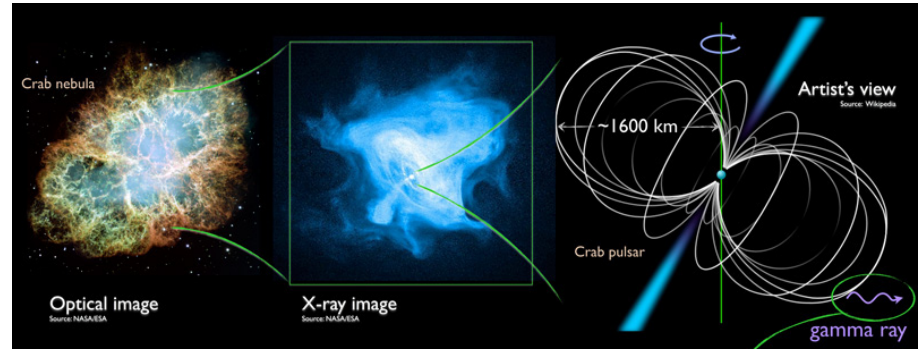
Kevin Meagher
For The VERITAS Collaboration

The Crab Nebula

- Pulsar Wind Nebula powered by Crab Pulsar
- Remnant of a supernova which occurred in AD 1054
- Distance (2.0±0.2) kpc
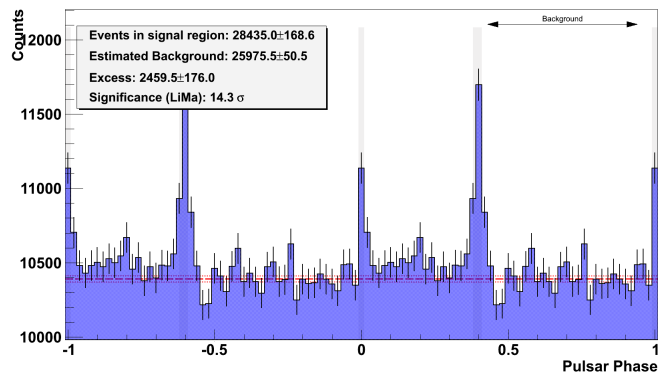- VHE emission believed to be inverse Compton upscattering of synchrotron photons

VERITAS Gamma-Ray Telescope

- Energy Range: 85 GeV to >30TeV
- Energy Resolution: 15-25%
- Sensitivity: 1% Crab in ~25hr
- Angular Resolution: R68 < 0.1 deg at 1 TeV
- Pointing Accuracy: Error < 50 arcsec
- located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona

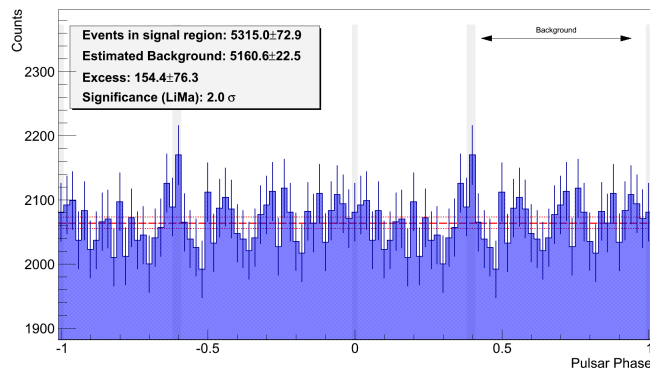# Crab Pulsar Observation with VERITAS
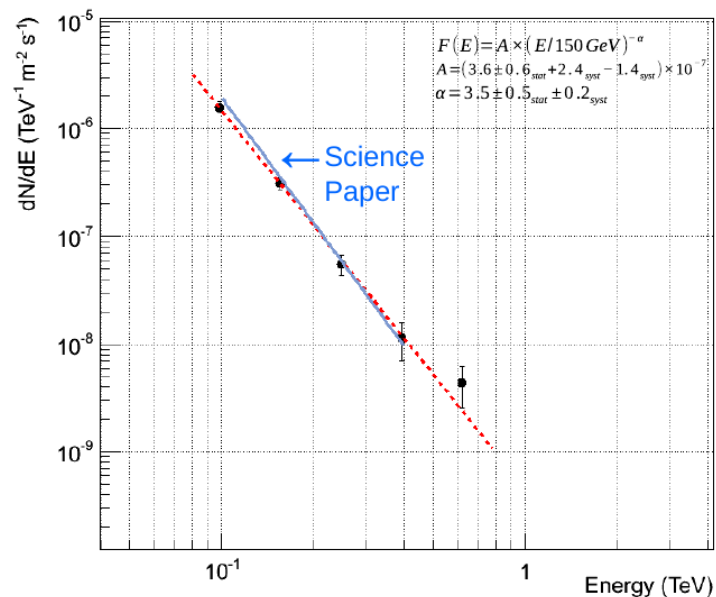
Board #74, 30/7/2015 at 15:30

PSRB0531+21 Phaseogram with all energies

Events in signal region: 28435.0±168.6
Estimated Background: 25975.5±50.5
Excess: 2459.5±176.0
Significance (LiMa): 14.3 σ

~200 hours of Crab data

PSRB0531+21 Phaseogram with energies > 400 GeV

Events in signal region: 5315.0±72.9
Estimated Background: 5160.6±22.5
Excess: 154.4±76.3
Significance (LiMa): 2.0 σ

$$F(E) = A \times (E/150\,GeV)^{-\alpha}$$
$$A = (3.6 \pm 0.6_{stat} + 2.4_{syst} - 1.4_{syst}) \times 10^{-7}$$
$$\alpha = 3.5 \pm 0.5_{stat} \pm 0.2_{syst}$$

← Science Paper
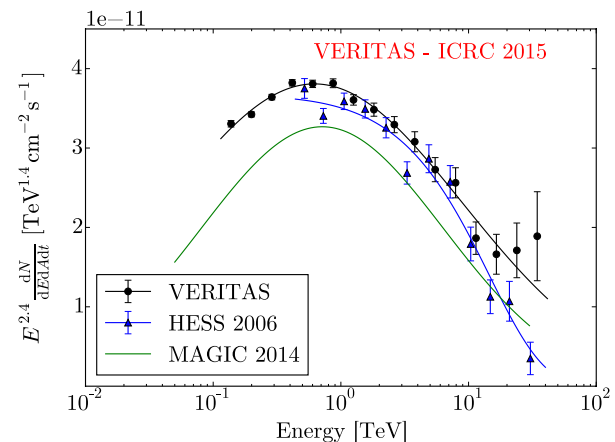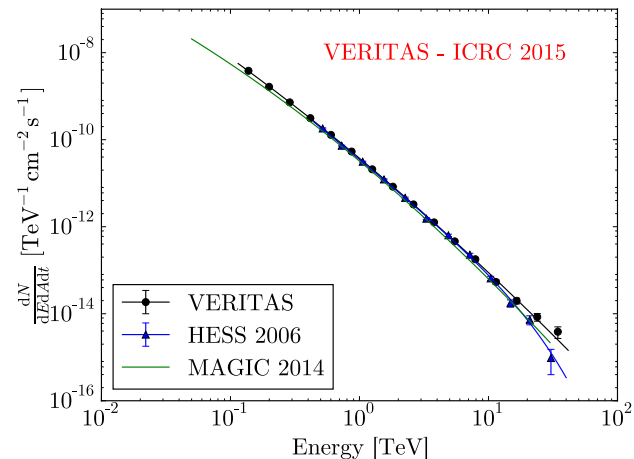
Spectrum

- Well fit by curved power law (also known as log parabola)
- Fit from 115 GeV to 42 TeV
- Chi2/dof = 12.9/13
- Dominant systematic error: energy ~15%
- Consistent within systematic errors with published HESS and MAGIC spectra
- Work is still ongoing to simulate VERITAS' analog electronics for   events >10TeV
- Fit Parameters:

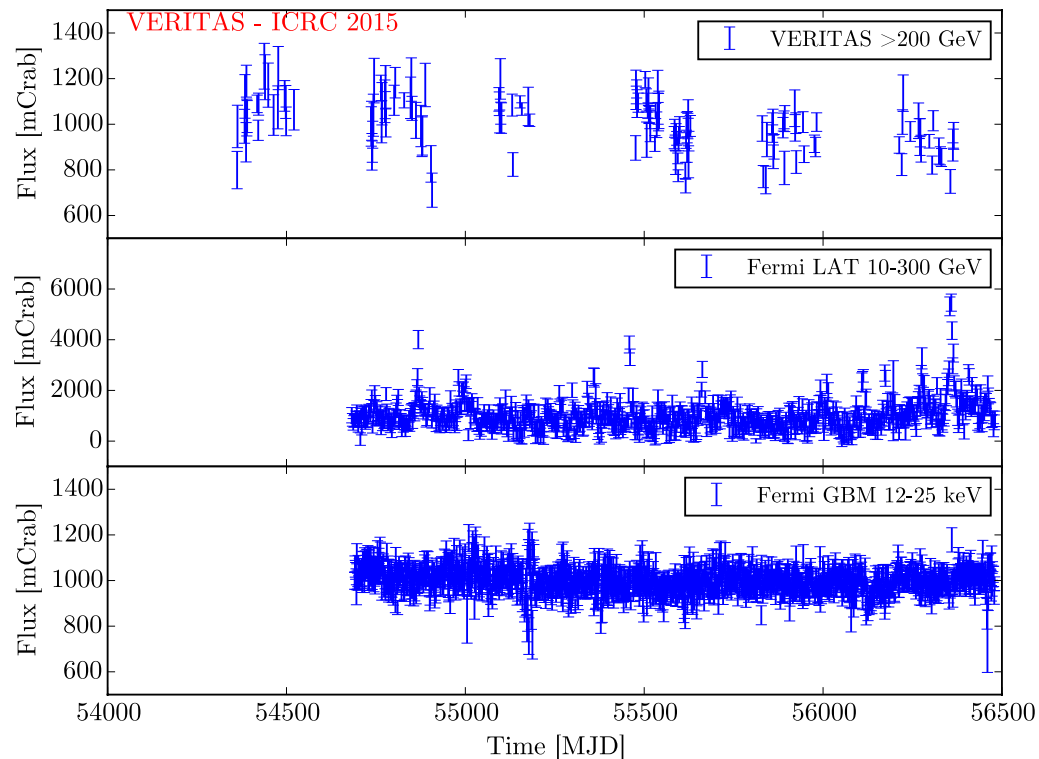 $F(1\ \text{TeV}) = (3.75 \pm 0.03)10^{-11}\ \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$
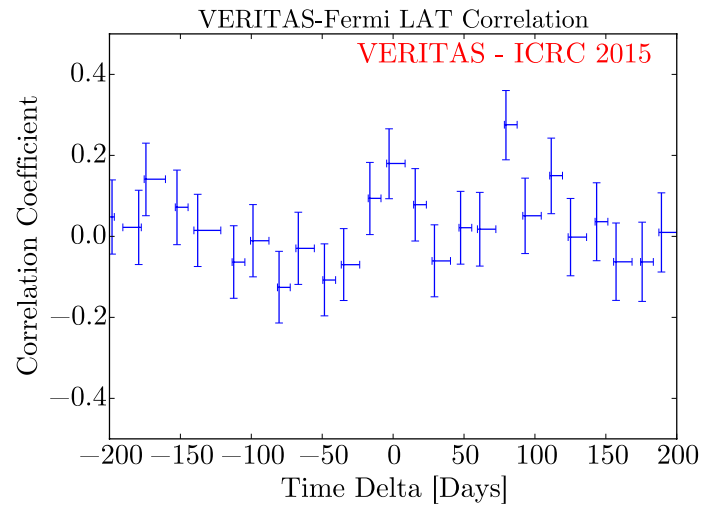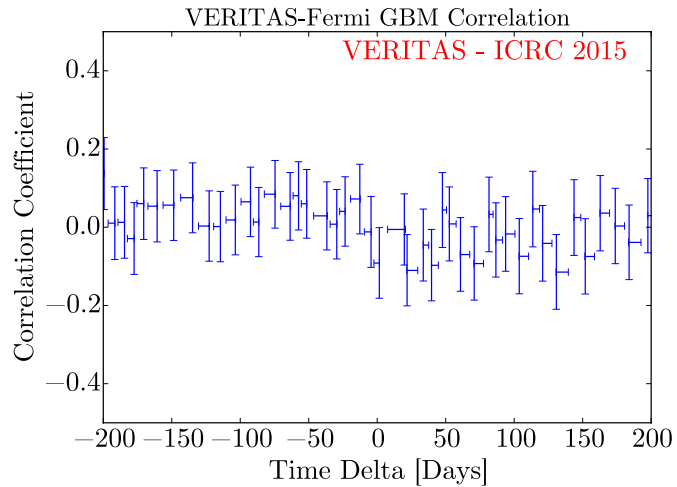
  $\alpha = -2.47 \pm 0.006$

  $\beta = -0.16 \pm 0.01.$

Variability of the Crab Nebula

- 10-100 MeV the Crab Nebula is known to flare
- 10 -100 KeV the Crab is variable decreasing its output by ~10%
- Uncertainty in VERITAS time series are dominated by weather related systematics.

VERITAS-Fermi GBM Correlation / VERITAS-Fermi LAT Correlation

- Use z-transformed discrete correlation function (ZDCF) to measure correlation [arXiv:1302.1508]
- Correlation coefficient calculated for every time delta:
  0=not correlated, 1=complete correlation, -1 = anti-correlation
- No time scale has a statistically significant non-zero coefficient -> no evidence of correlation

K. Meagher, ICRC 2015

Measuring the Extent of the Crab Nebula

- A source with a small extension will cause a subtle broadening of the observed spatial distribution of gamma-rays.
- The extension of the Crab Nebula is predicted to be around 1.5 arcmin [de Jager and Harding ApJ 396, 161 1992]
- A 1.5 arcsecond source will broaden VERITAS's point source by about 5%
- Systematic uncertainties in VERITAS' simulation ~10% effect
- Sources observed in the North from the VERITAS site such as Mrk421 and Mrk501 are excluded because of geomagnetic effect (~5%)
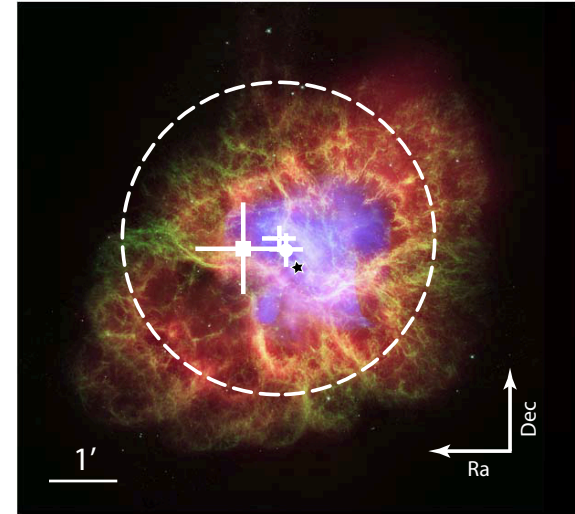

Current MAGIC limits:
2.2 arcmin >500 GeV
ApJ 674 1037 (2008)

VER J0521+211

- Assumed to be a point source for the purpose of comparing with the Crab Nebula, closest blazar to the Crab: 3°
- Brightest blazar in the VHE band seen to the south when viewed from VERITAS' location
- Due to its proximity to the Crab, it is observed with with similar azimuth and elevation profile as the Crab
- Highly variable flux: averages ~25% Crab
- Detected by VERITAS before the PMT upgrade with a significance of 15σ and spectral index Γ=3.44 [ApJ 776, 69, (2013)]
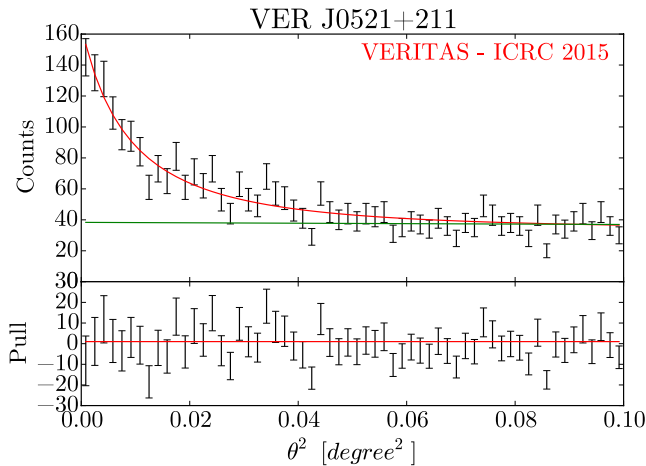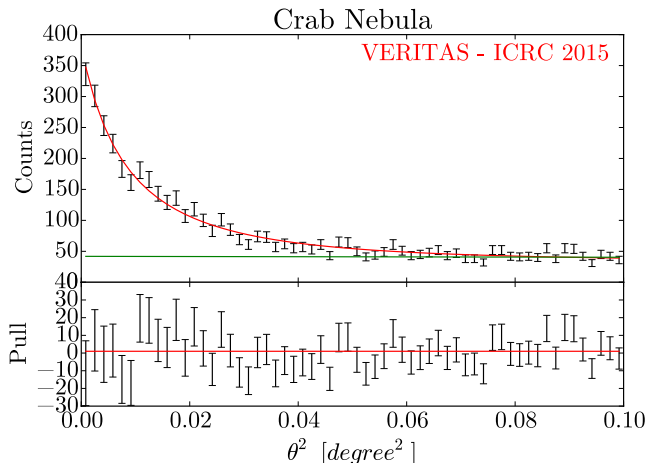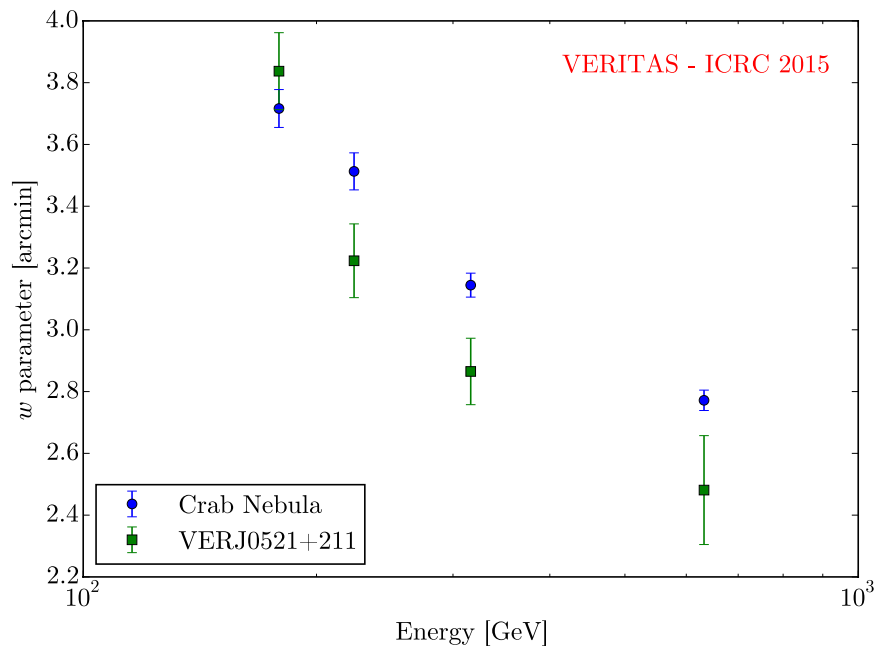- Observations post upgrade have significance of 63σ
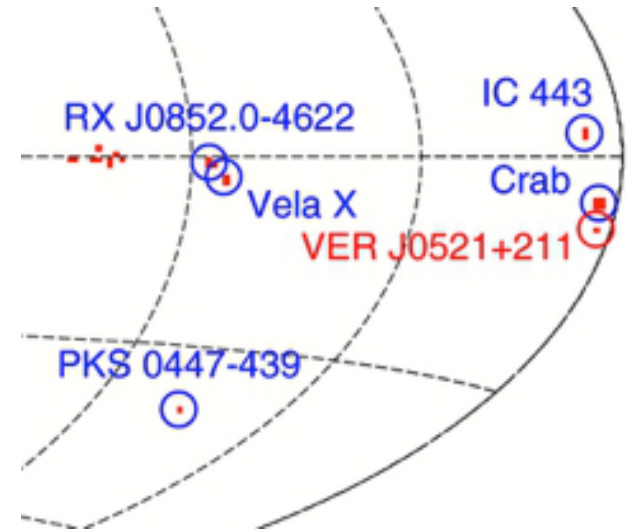
Maximum Likelihood Fit

- A one dimensional fit is performed on θ^2 distribution for parameter w

$$S(\theta^2 ; w) = \frac{2N}{\pi w} \text{sech}\left(\frac{\sqrt{\theta^2}}{w}\right)$$

- w denotes 55.1% confinement.
- θ^2 distribution is well described by hyperbolic secant function
- Fit includes background and uses number of signal events as a nuisance parameter

- Fits are performed in several energy bins
- No compelling evidence of an extent is observed
- Setting exact limits is still a work in progress

Conclusions

- Spectrum has been measured and is consistent within quoted systematic error with other instruments
- Variability was investigated by looking for correlation between the TeV flux measured by VERITAS and the flux at other wavelengths. No evidence of a correlation was observed.
- The extension of the nebula was measured using VER J0521+211 as a template for the point spread function, no compelling evidence of an extension was observed

[Backup Slides]

Maximum Likelihood Method

- Assume source distribution is radial hyperbolic secant function with free width parameter w

$$S(\theta^2 \;;w) = \frac{2N}{\pi w}\mathrm{sech}\left(\frac{\sqrt{\theta^2}}{w}\right)$$

- Assume background is a linear function of θ^2
- Do a two dimensional fit with n and w as free parameters

$$f(n_{sig},w) = -2\sum_{\theta^2}\log\left[\frac{n_{sig}}{n_{total}}S(\theta^2 \;;w) + \left(1 - \frac{n_{sig}}{n_{total}}\right)B(\theta^2 \;)\right]$$

Background

- All data was taken with source 0.5° from center of the camera
- Background data from far side of camera used to estimate the shape of the background
- Events scrambled about the center of the camera and θ^2 distribution measured
- Background well fit by linear function
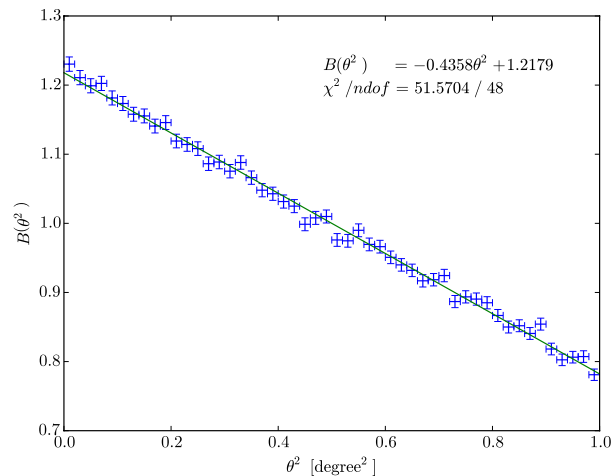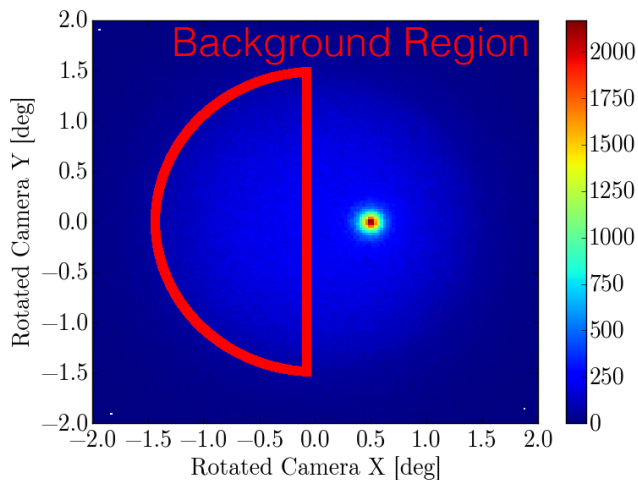
- Exposure time:
- 2007-2009 Before relocation of T1:   25hr
- 2009-2012:   77 hr
- 2012-2013 After camera PMT upgrade 25hr