Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data

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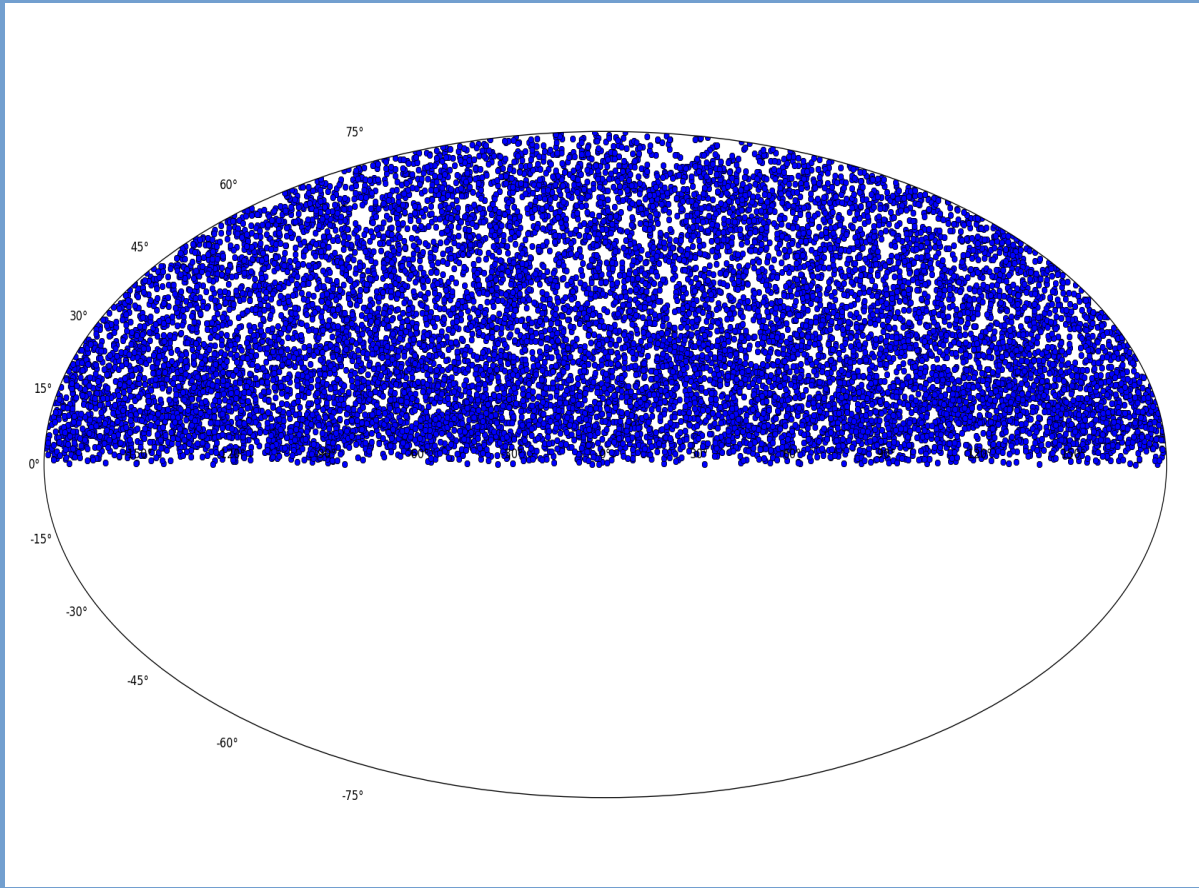
Fourth AMON Workshop
4 December 2015
Penn State

Background and Outline

- Two models for blazar emission: hadronic and leptonic
- Hadronic models robustly predict associated TeV neutrinos (proportional to TeV flux)
- AMANDA-II detected a neutrino from the vicinity of 1ES 1959+650 during a TeV orphan flare, though no association claimed, significance not quantifiable
- Neutrino observations of blazars should ultimately distinguish models:
  - Hadronic or leptonic for base emission?
  - Flares?
  - TeV orphan flares?

The IceCube 40-String Search

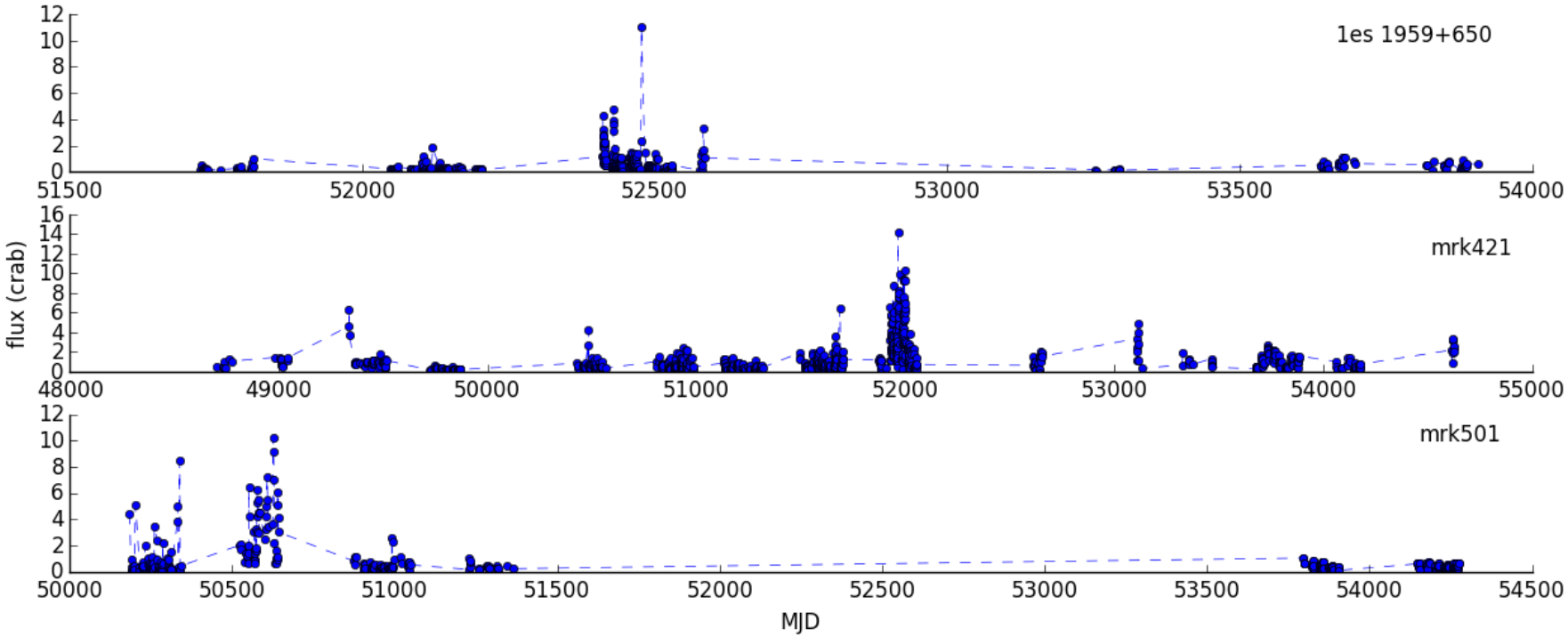
- Collected between April 2008 and May 2009
- Public since 2011
- Detected 12876 upgoing neutrino events (atmospheric/cosmic ray air shower dominated)
- IceCube team analysis revealed no point sources (IceCube+11)
- Blazars are not steady sources...



Every neutrino detected by IceCube in its 40 string configuration, plotted in a mollweide projection.

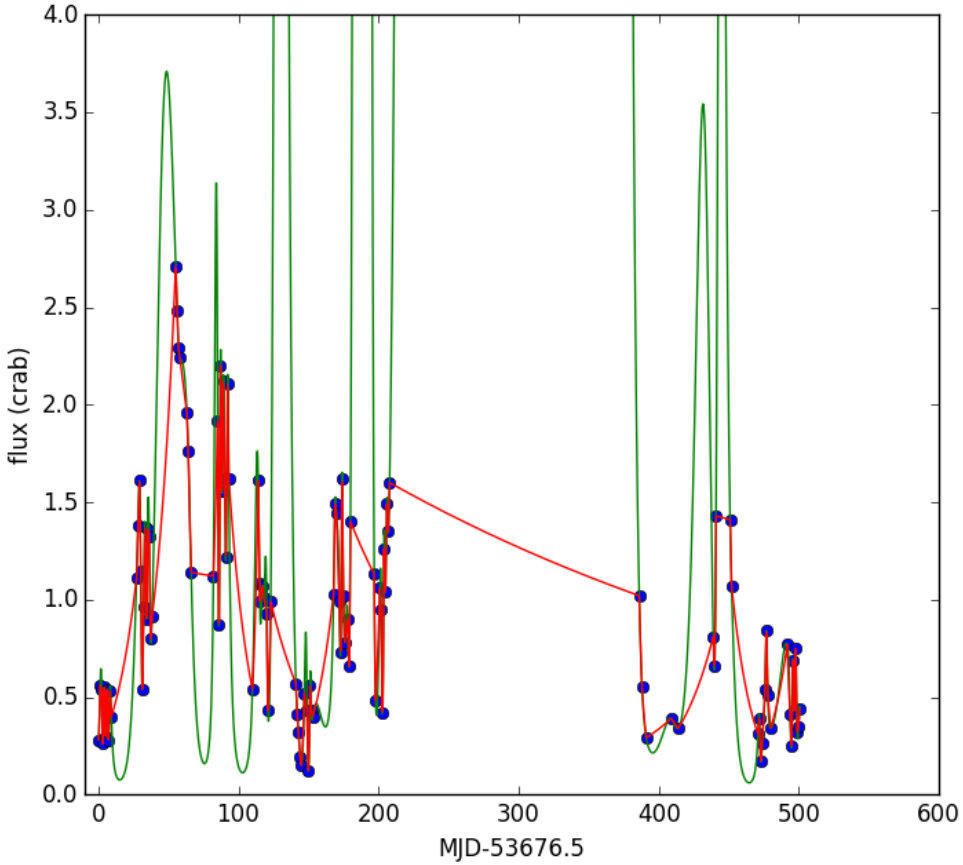
Blazar Light Curves

- VERITAS TeV blazar monitoring over IC40
- Data are not public (VERITAS collaborative project)
- We will illustrate the approach here using public data



TeV gamma ray light curves for three blazars. These graphs compile public data from several observatories, including VERITAS. The data was obtained at http://astro.desy.de/gamma_astronomy/magic/projects/light_curve_archive/index_eng.html

Interpolation

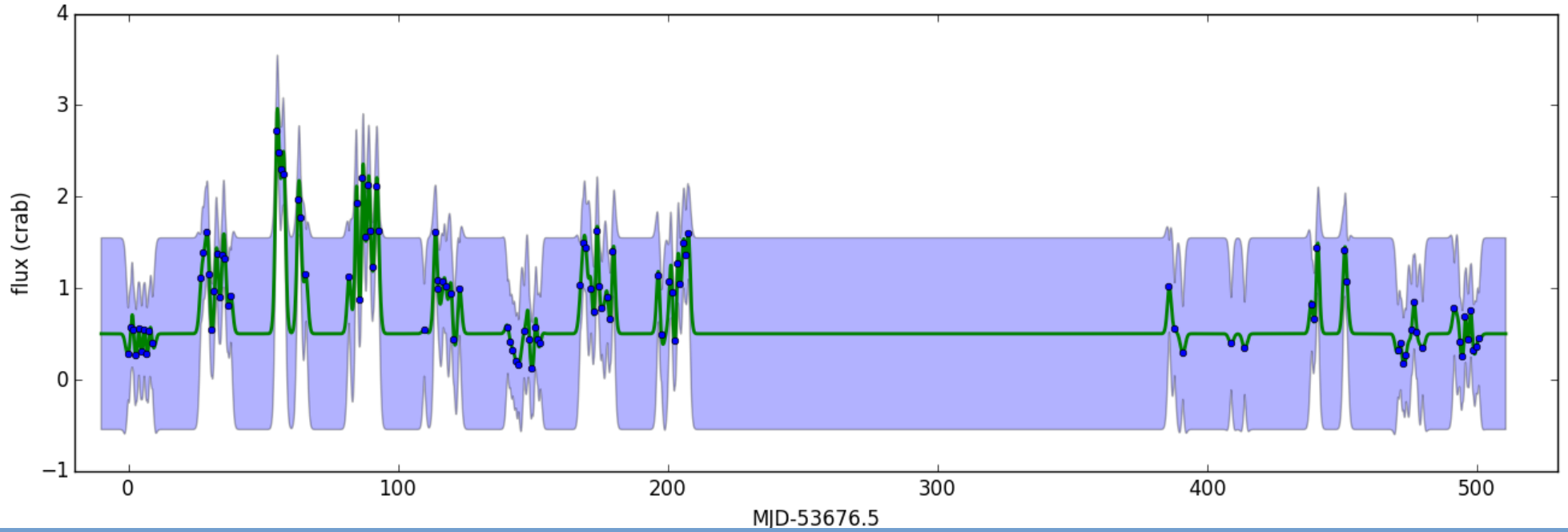


A linear (red) and spline (green) interpolations for Mrk 421 VERITAS public data

- Idea: Leverage TeV data, integrate on each blazar only when it is TeV-bright
- Requires defining temporal periods of interest for each blazar
- Linear interpolation: Simple but unphysical, esp. with long gaps
- Spline fitting: Poorly motivated, range violations common

Interpolation via the Gaussian Process Regression (GPR)

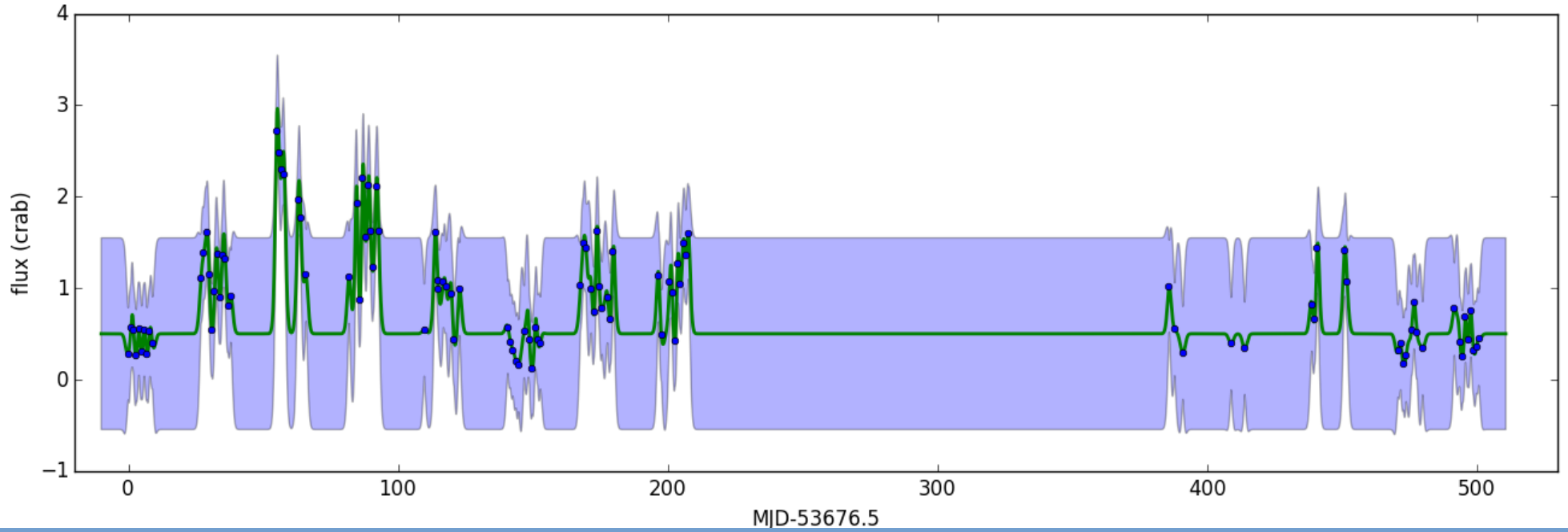
- GPR: assume data can be reproduced as normally distributed samples from a process with stationary mean and covariance
  - First pass: Analyze data to determine mean and covariance
  - Second pass: Predict function values at arbitrary intermediate points (with confidence regions)



GPR on Mrk 421 VERITAS public data (ML in green, 90%-c.i. in blue)

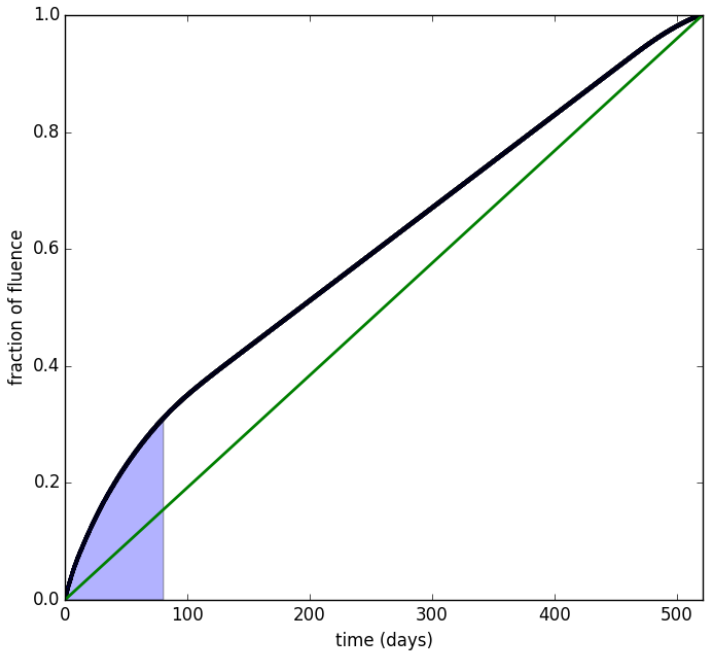
Interpolation via the Gaussian Process Regression (GPR)

- Beyond a few correlation lengths, the GPR reverts to the mean function for its max likelihood, and to the data range for confidence intervals
  - Work in log space to reduce heteroskedasticity
  - Force the mean function to the blazar baseline flux
- Use the Python package pyGPs and work only with ML light curve



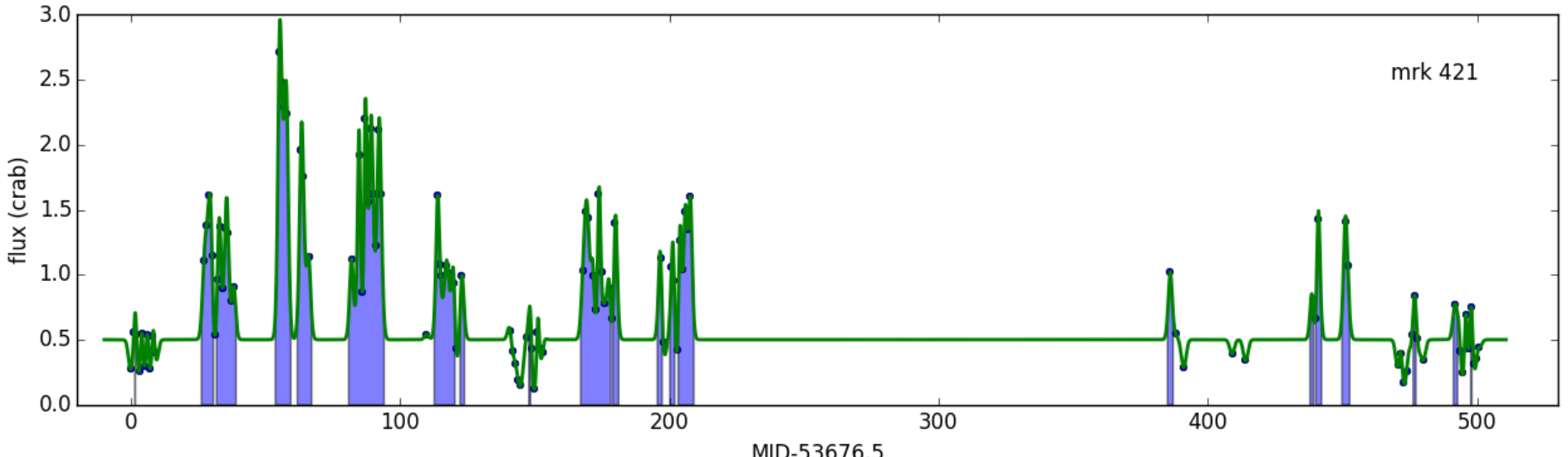
GPR on Mrk 421 VERITAS public data (ML in green, 90%-c.i. in blue)

Selecting Times of Interest



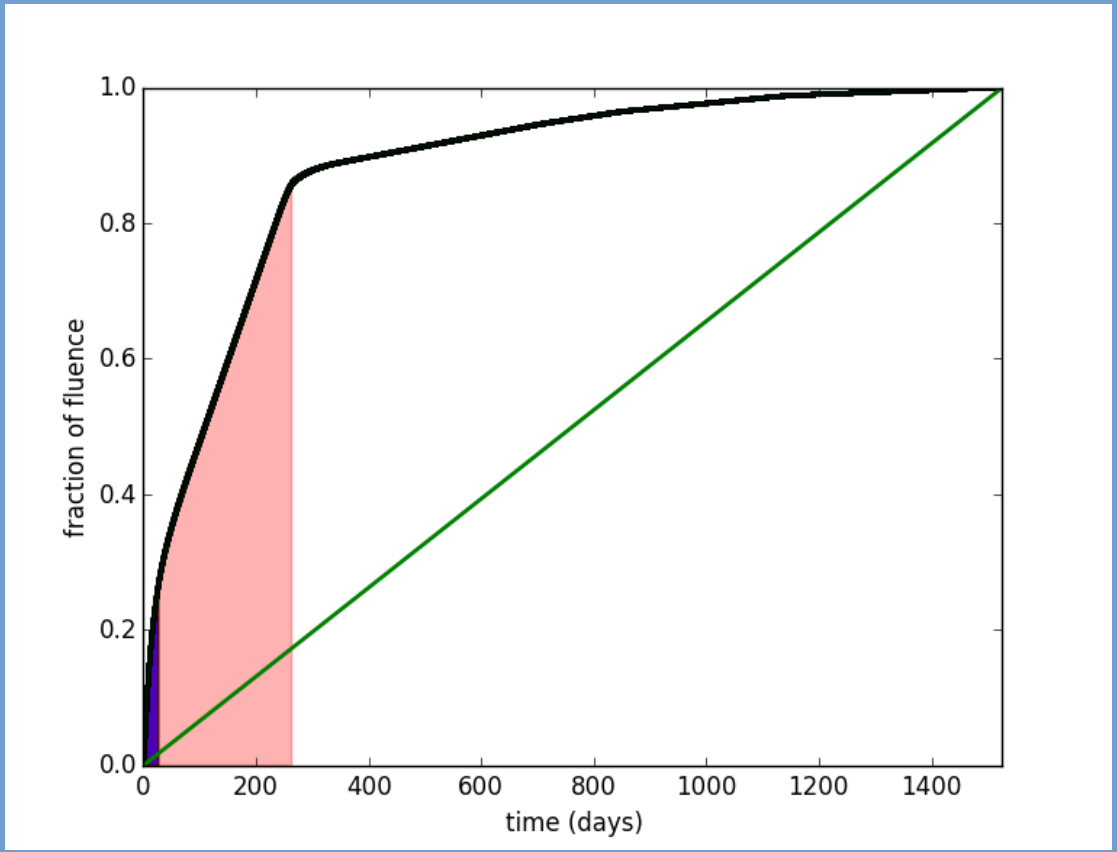
- Work with complete ML light curve for each blazar (spanning IC40)
- Select the brightest fraction of points
- Maximize ratio of TeV fluence to number of neutrinos needed to give a 3σ excess over atmospheric background

Fraction of fluence vs. time for Mrk 421 (left). The green line shows constant fluence. Optimization selected the brightest 80 days, shaded to the left, and also shown below.



Optimization with the Proprietary VERITAS Data

- Markarian 421 bright intervals dominate the optimization
- So we have split our analysis in two:
  1. Mrk 421 bright intervals only
  2. All other blazar bright intervals (distinct optimization)



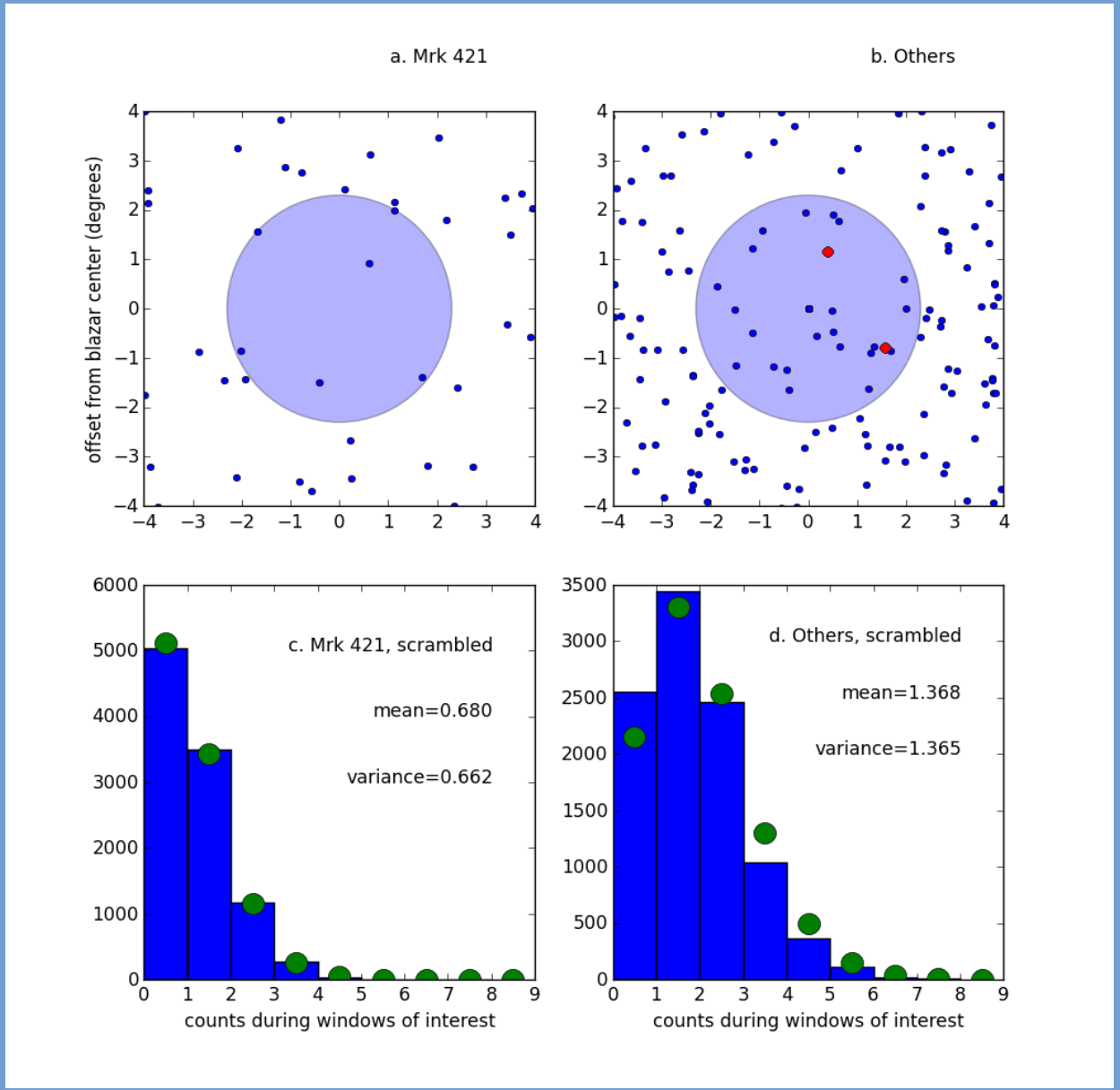
Fraction of fluence vs time for the six blazars. Points from Markarian 421 are shaded red. The blue shading indicates the optimal cut while the green line shows constant fluence.

Test Analyses on Scrambled Data

Results of scrambled data runs

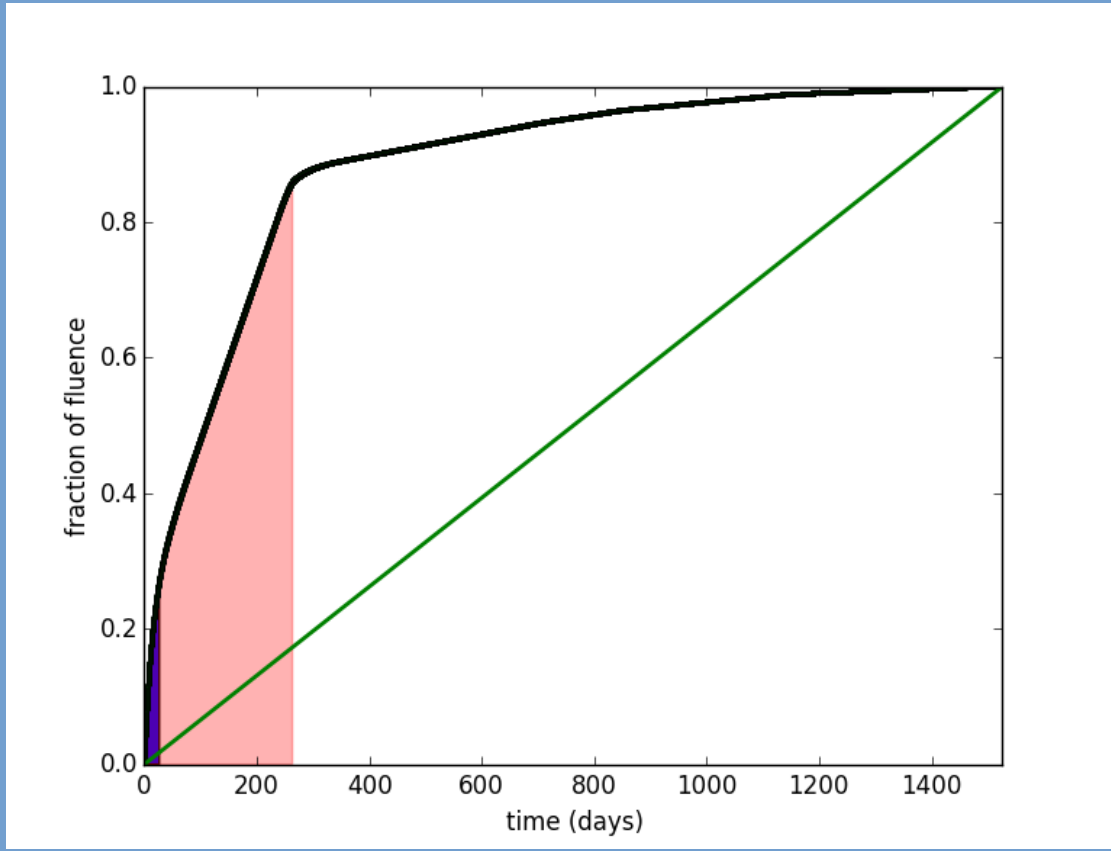
Top: distribution for a random single run. Red points were found during times of interest.

Bottom: distribution of neutrinos found during times of interest from the 10000 scrambled runs.



Conclusions

- Periods of interest from VERITAS data for IC40 have been defined
- Scrambled data sets confirm Poisson behavior
- Waiting for collaborator approval before applying to unscrambled data



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Future Work

- Flux-sensitive point source search protocol has been defined, can easily be extended to include IC59
- Numerous projects provide regular monitoring of Mrk 421 (HAWC, Swift/BAT, FACT, etc)
- Can adapt search process for real time analysis
- Mrk-421 project with similar TeV selection and x-ray data from Swift (isolate orphan flares)