

Blazar Variability & Variability Analysis with the Fermi/LAT

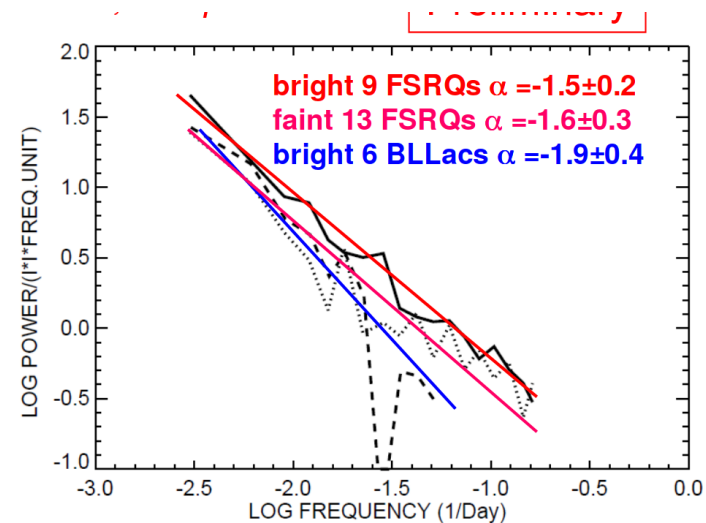
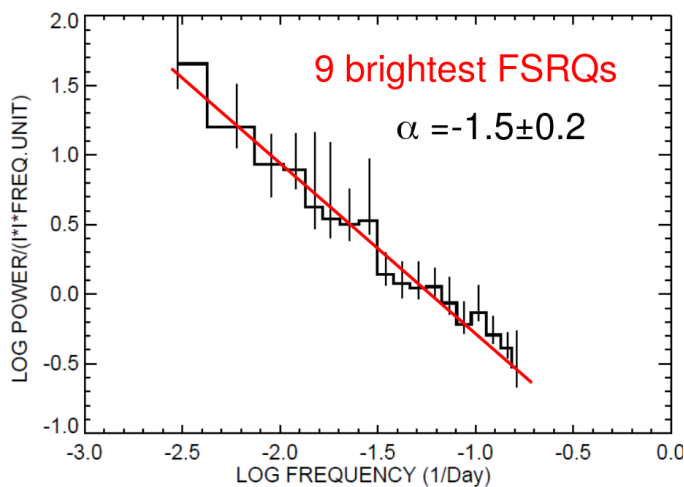
Eileen Meyer
University of Maryland Baltimore County
Fermi Summer School | Lewes, DE | 6 June 2018

Why Variability

- **To characterize the behavior of your source**
 - Periodicity
 - Shortest Timescale – constrains emission size through light-crossing time argument
 - Track flares/high flux states
- **To make sure your source is *not* variable!**
 - E.g., some models are incompatible: IC/CMB

Blazar Variability

- Blazars are highly variable at all wavelengths except very low-frequency radio where the lobe spectrum dominates (c.f Mary's talk)
- Variability is generally consistent with something between “pink noise” spectrum (roughly equal power per decade) and shot noise.

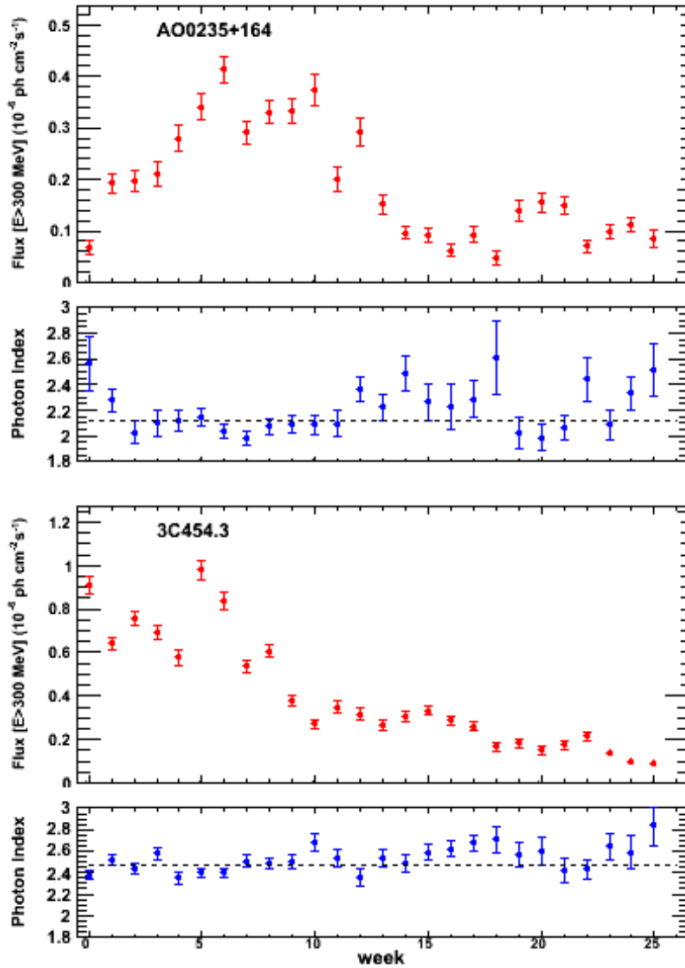


No significant difference in PSD shape between BLLacs and FSRQs but a tendency for the former to be slightly steeper. BLLacs have also a lower fractional variability.

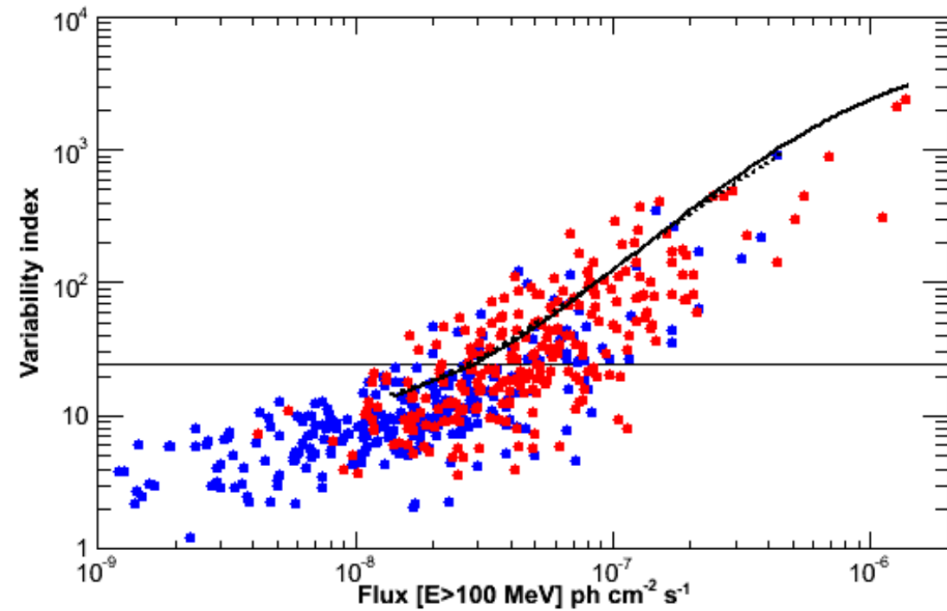
Variability index



Light curves



$$V = \sum_i \frac{(F_i - F_{av})^2}{\sigma_i^2 + (f_{rel} F_{av})^2}$$



[[Previous](#) | [Next](#) | [ADS](#)]

Fermi-LAT detection of a new gamma-ray source associated with the high-redshift FSRQ TXS 0552+398

ATel #11137; **R. Angioni (MPIfR-Bonn), C. C. Cheung (NRL) on behalf of the Fermi-LAT collaboration**
on 7 Jan 2018; 06:39 UT
Credential Certification: Sara Buson (sara.buson@gmail.com)

Subjects: Gamma Ray, AGN, Blazar

[Tweet](#) [Recommend 0](#)

The Large Area Telescope (LAT), one of two instruments on the Fermi Gamma-ray Space Telescope, has observed enhanced gamma-ray emission from a source positionally consistent with the Flat-Spectrum Radio Quasar (FSRQ) TXS 0552+398, also known as B2 0552+39A, with coordinates R.A. = 88.8783567 deg, Decl. = 39.8136569 deg (J2000; Jonhston et al. 1995 AJ, 110, 880), at redshift of $z=2.635$ (Wills & Wills 1976 ApJS, 31, 143). This source is not in any published LAT catalog and was not detected by AGILE or EGRET.

Preliminary analysis indicates that this source went into a high-flux state on 5 January 2018, with a daily averaged gamma-ray flux ($E>100\text{MeV}$) of $(1.3\pm 0.2) \times 10^{-6}$ photons $\text{cm}^{-2} \text{s}^{-1}$ and a single power-law photon index of 1.98 ± 0.12 (statistical uncertainty only).

Fermi has issued 100s of ATELS for flaring source, particularly blazars.

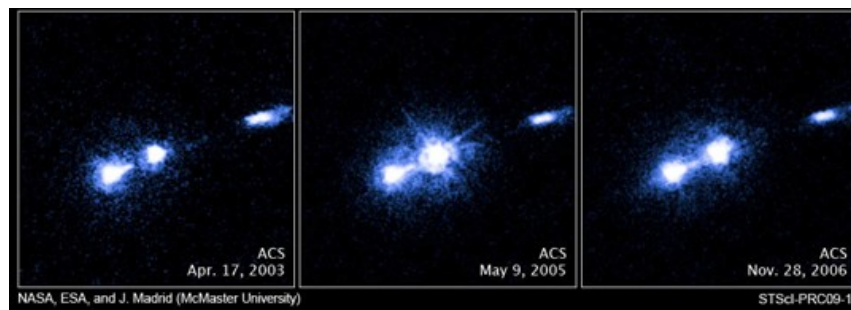
Enabled many multiwavelength campaigns and VHE follow-up with e.g., VERITAS, etc.

Open Question: Where is the gamma-ray emission coming from?

Why we care: We still lack a good understanding of how jets work, both in terms of how they are launched and particle content, and how/where particle acceleration takes place.

Case A: Location very close to the black hole b/c of very fast variability (assumes flaring region = whole jet cross-section)

Case B: Location beyond the inner broad line region and into the molecular torus or beyond (as far out as HST-1 in M87, 100 pc (projected) downstream)
- Argument based mainly on observations of gamma-ray flares coincident with 'ejections' from the VLBI core (Marscher+ 2010)



Case C: Maybe both? We see both 'orphan' gamma-ray flares and some accompanied by optical, radio emission – perhaps these occur in different environments...

Energy-Dependent Variability?

A METHOD FOR LOCALIZING ENERGY DISSIPATION IN BLAZARS USING *FERMI* VARIABILITY

AMANDA DOTSON¹, MARKOS GEORGANOPOULOS^{1,2}, DEMOSTHENES KAZANAS², AND ERIC S. PERLMAN³

¹ Department of Physics, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA; adot1@umbc.edu

² NASA Goddard Space Flight Center, Code 660, Greenbelt, MD 20771, USA

³ Department of Physics and Space Sciences, Florida Institute of Technology, 150 West University Boulevard, Melbourne, FL 32901, USA

Received 2012 July 31; accepted 2012 September 6; published 2012 September 21

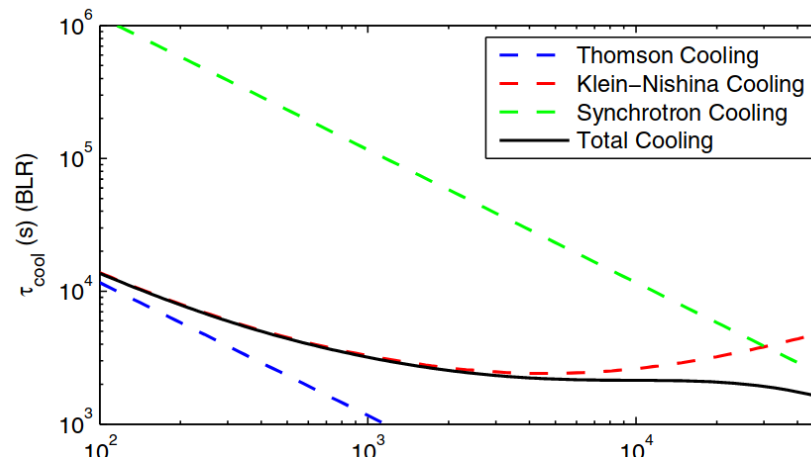
Simple Idea for locating the GEZ (Gamma-Ray Emission Zone):

- Gamma-ray Emission in blazars is due to Inverse Compton Emission (high-energy electrons upscattering a low-energy photon population)
- If the GEZ is in the **Broad Line Region (BLR)**, target photons are dominated by Lyman-alpha with typical energy $E = 3 \times 10^{-5} \Gamma$, Γ = jet Lorentz factor and E in units of $m_e c^2$.
- If the GEZ is in the **Molecular Torus (MT)**, target photons are infrared from warm/hot dust and $E \sim 5 \times 10^{-7}$ - about 2 order so magnitude lower

Energy-Dependent Variability?

The Cooling Time Argument:

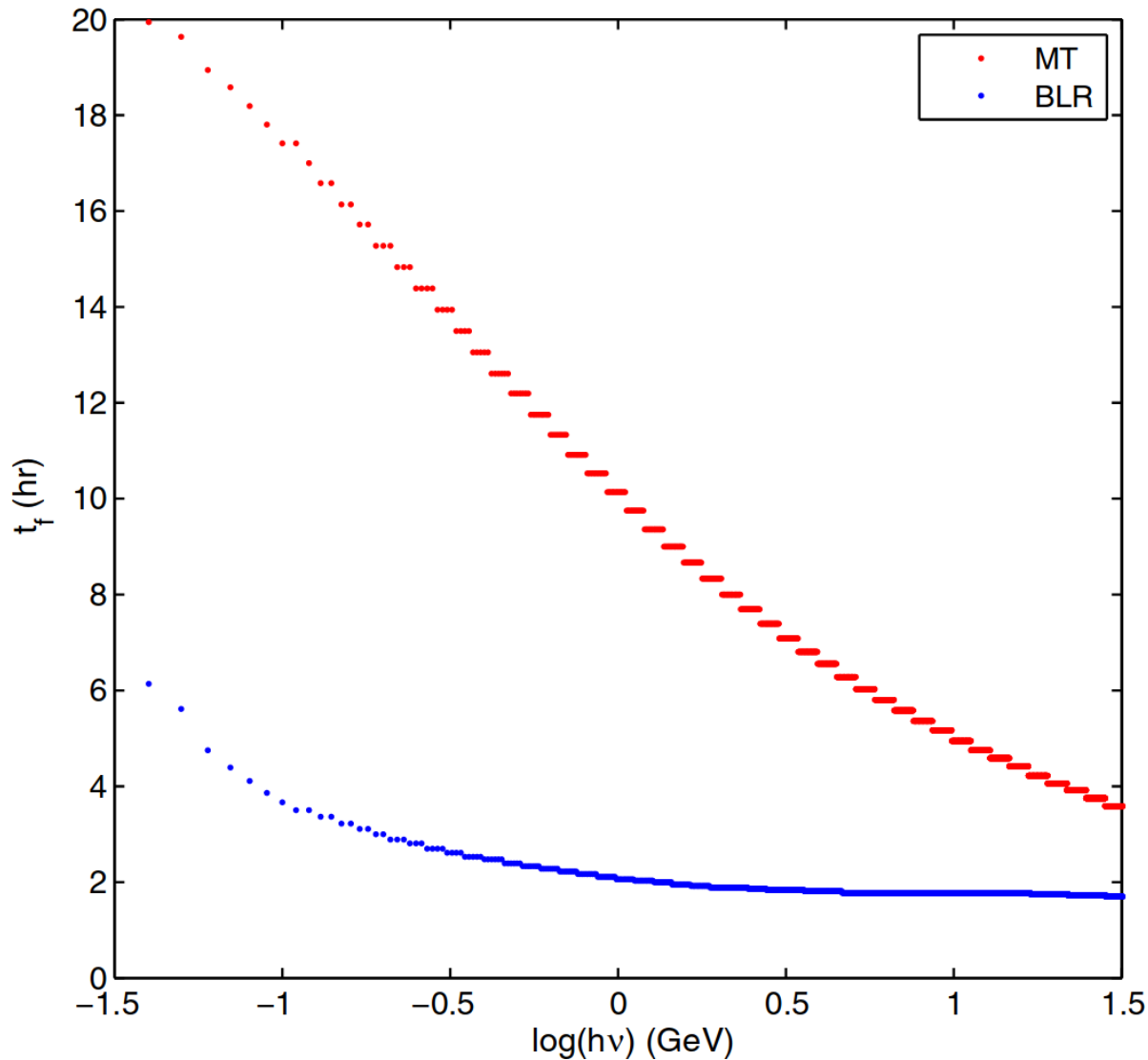
For this approach to work, IC cooling must dominate over synchrotron cooling. In powerful blazars the IC luminosity clearly dominates over the synchrotron luminosity by a factor of up to ~ 100 , so this is satisfied.



In the **Thomson Regime (which applies for the MT)**, the cooling rate for electrons goes as γ^2 .

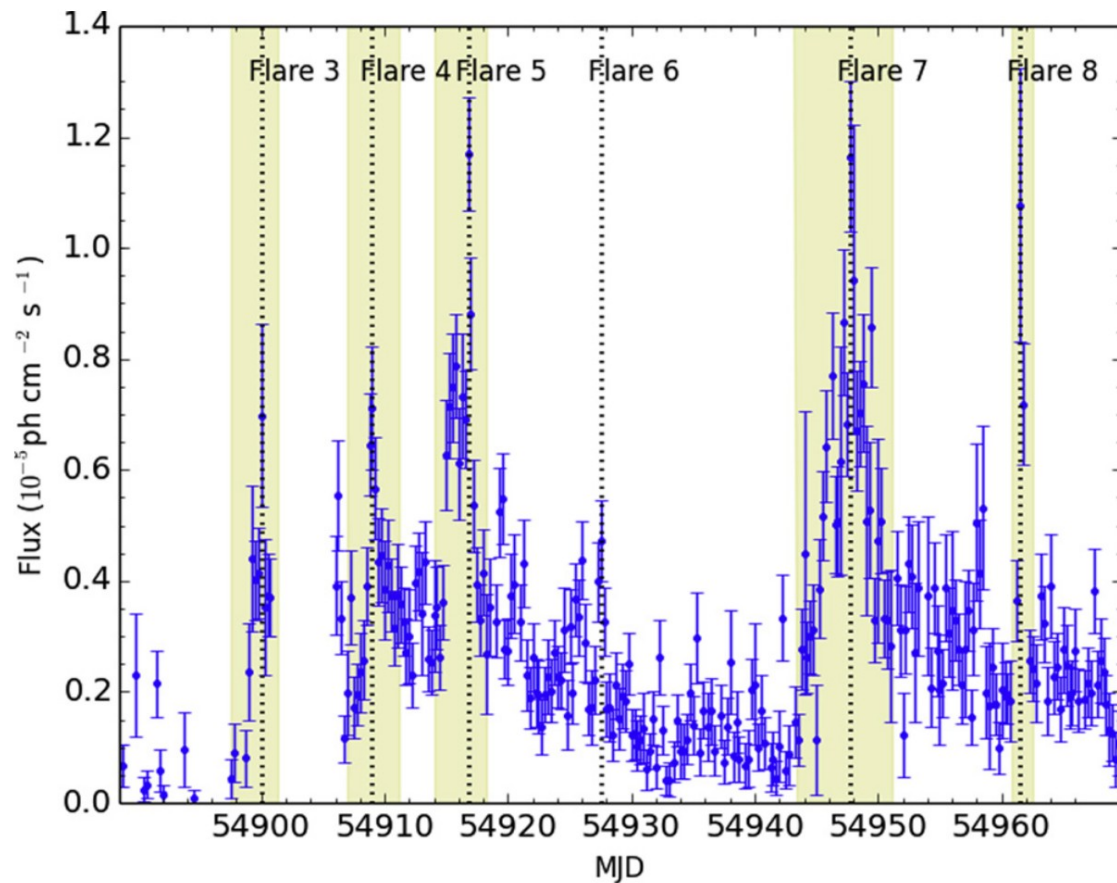
In the **Klein-Nishina Regime (which applies for the BLR)**, the cooling rate has a much slower energy-dependence and goes as $\ln(\gamma)$. (Blumenthal & Gould 1970).

Energy-Dependent Variability



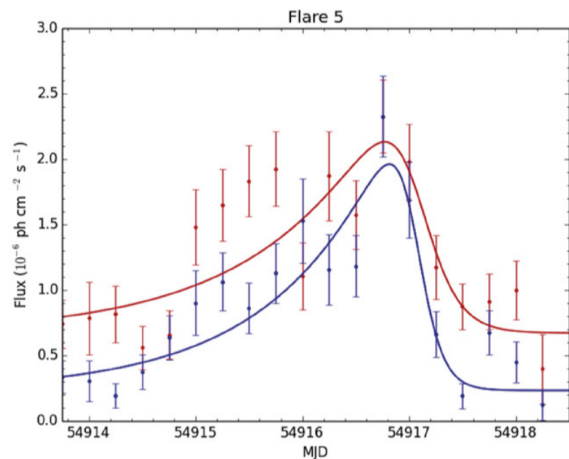
← From Dotson et al 2012 theory paper, showing strong energy-dependence of Fermi flare decay timescale for MT flares, Versus nearly energy-independent flares in the BLR.

Energy-Dependent Variability

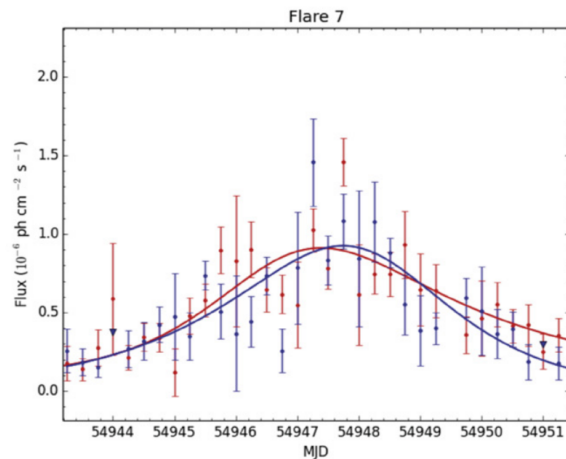


Application to several flares seen by Fermi/LAT in PKS 1510-089 in 2009 (Dotson et al. 2015)

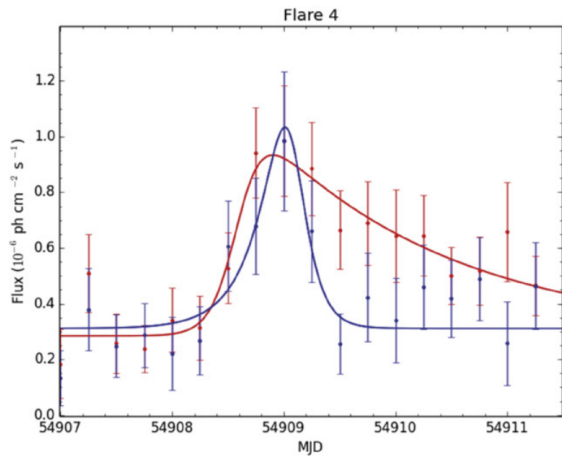
Energy-Dependent Variability



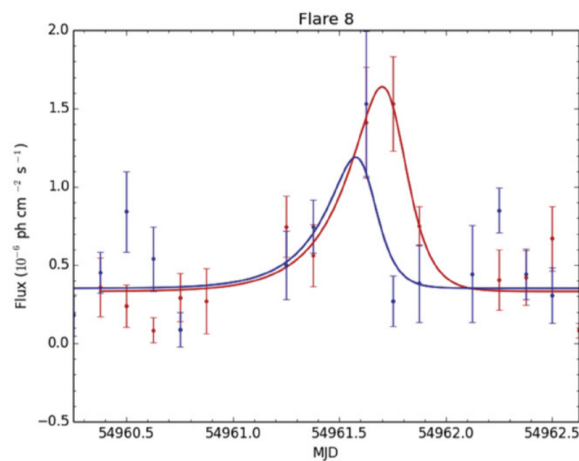
(c) Flare 5



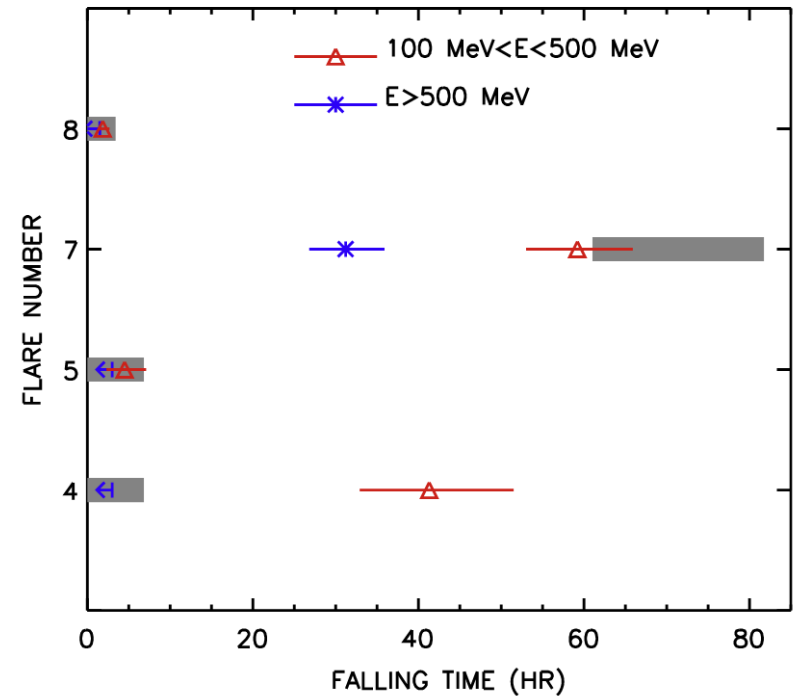
(d) Flare 7



(b) Flare 4

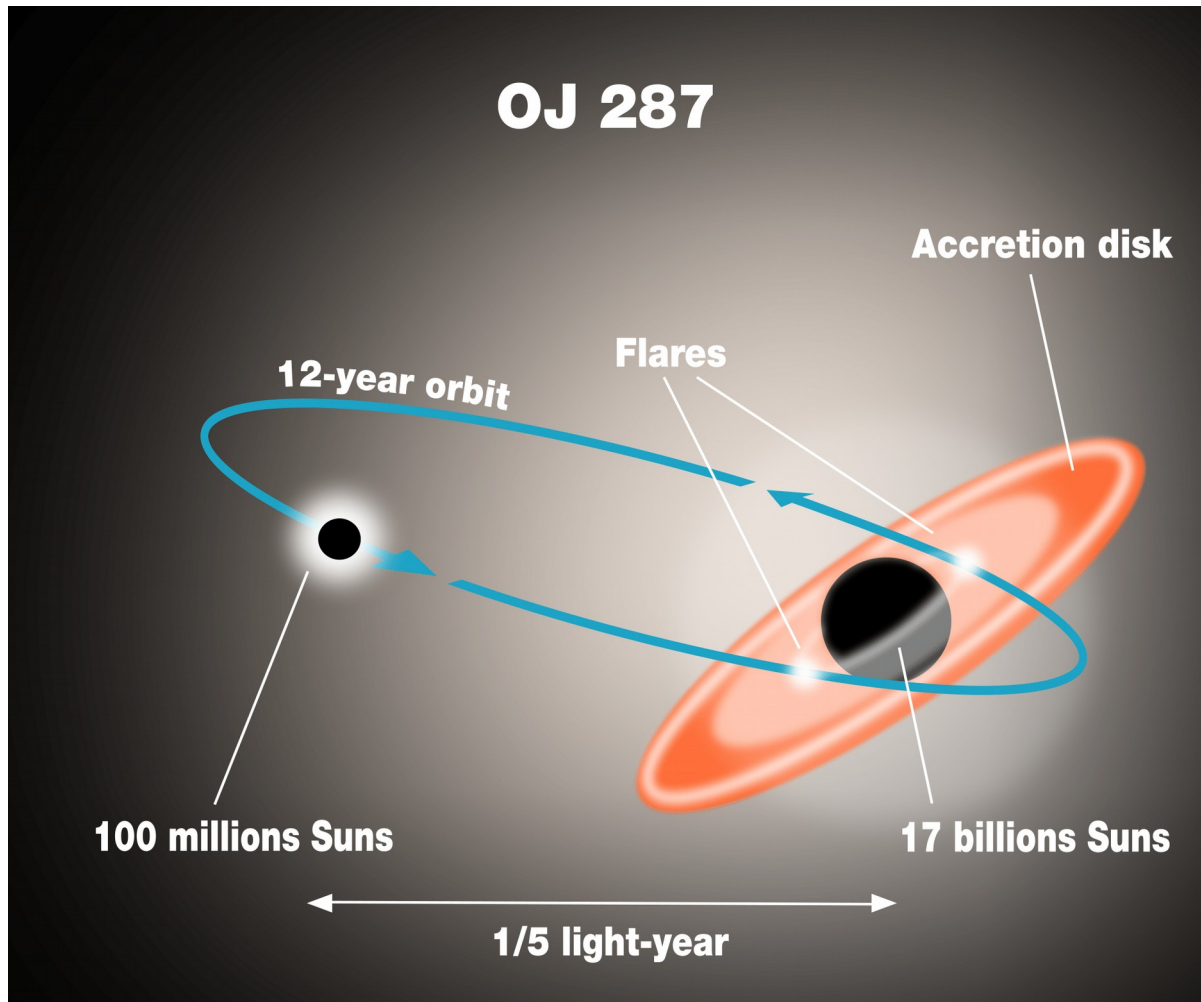


(e) Flare 8



Some flares show clear separation, others show none - multiple sites?

OJ 287



OJ 287 is very likely a binary black hole with a 12-year orbit.

Flares occur in the IR/optical when the smaller companion impacts the accretion disk.

Flares have been predicted & later validated by observations (most recently in 2015).

Fermi has detected shorter timescale variability from this source as well as flux enhancement during the most recent flare.

Periodic Signatures?

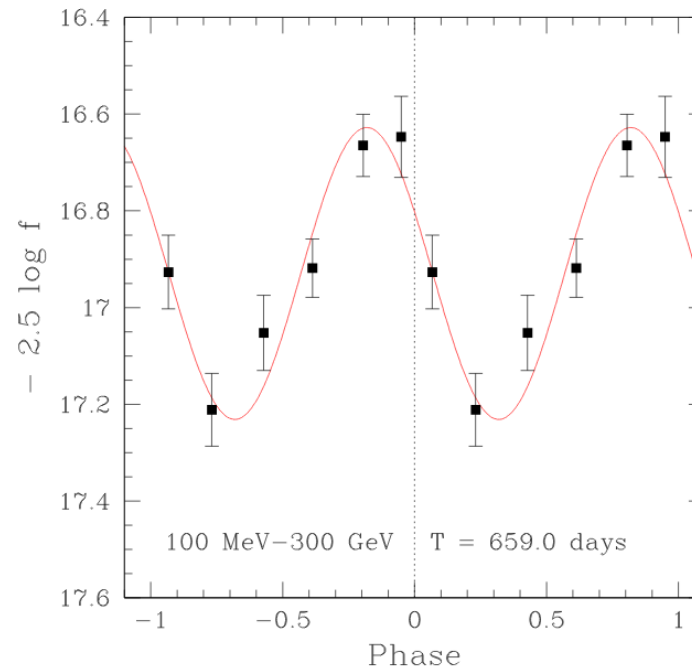
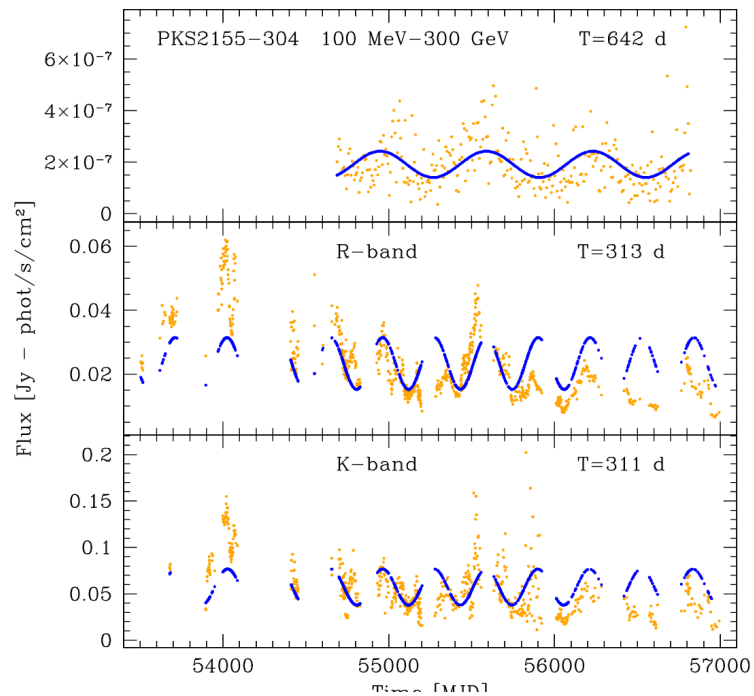
QUASI-PERIODICITIES AT YEAR-LIKE TIMESCALES IN BLAZARS

A. Sandrinelli^{1,2}, S. Covino², M. Dotti^{3,4}, and A. Treves^{1,2,5,6}

Published 2016 February 9 • © 2016. The American Astronomical Society. All rights reserved.

[The Astronomical Journal](#), [Volume 151](#), [Number 3](#)

doi:10.1088/1538-3801/151/3/034001



LAT Photometry*

- **LAT light curves can be obtained in two basic ways:**
 - Likelihood analysis
 - Aperture photometry
- **Likelihood analysis** has the potential for greater sensitivity and absolute flux measurements.
- **Aperture photometry** is easier, faster, and has the benefit of model independence.

* AP slides adapted from Robin Corbet's presentation. See also Corbet (2007)

Aperture Photometry

- **Literally, measuring the light that comes in through an aperture**
 - Originally done with optical telescopes using a mask of metal with a hole in it.
 - The amount of PSF that is outside the aperture can be accounted for in this case.
- **With Fermi, we use a software-defined aperture (an ROI).**

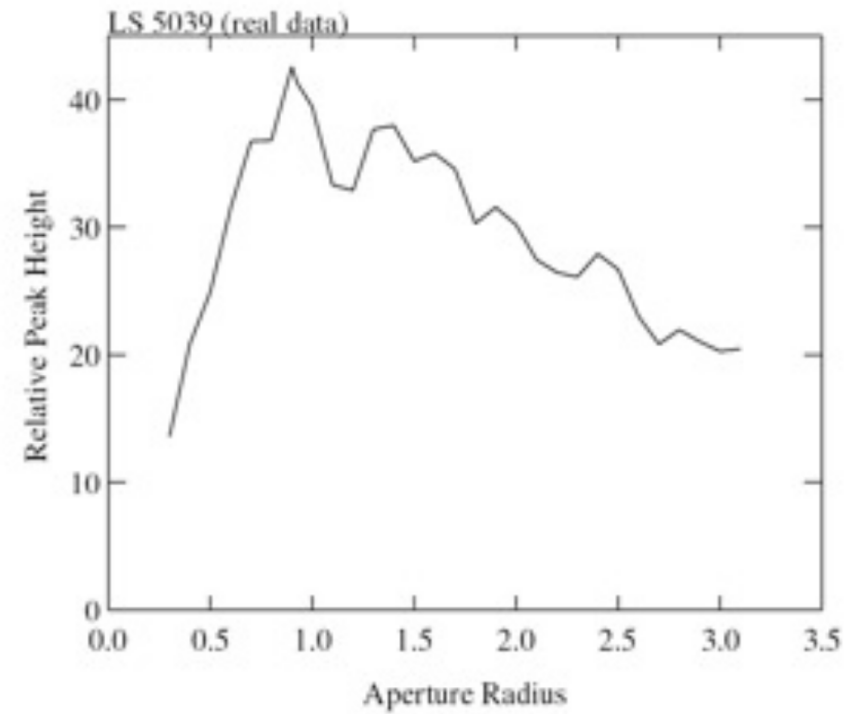
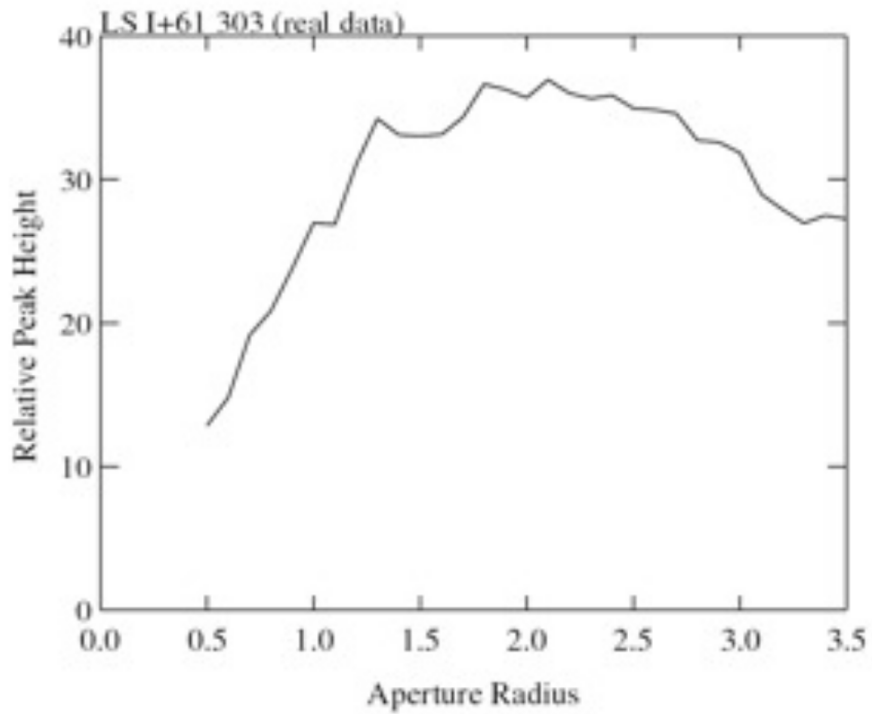
Aperture Photometry: Caveats

- **The flux you measure in the aperture is from both source + background (I.e, tails of nearby sources)**
 - Background is particularly strong in the galactic plane
- **Smaller Aperture = less background, but also less source**
- **Larger Aperture = more source, but now more background**
 - Most Analyses seem to do well with 1 degree ROI

Aperture Photometry

- **Optimizing your Aperture Size:**

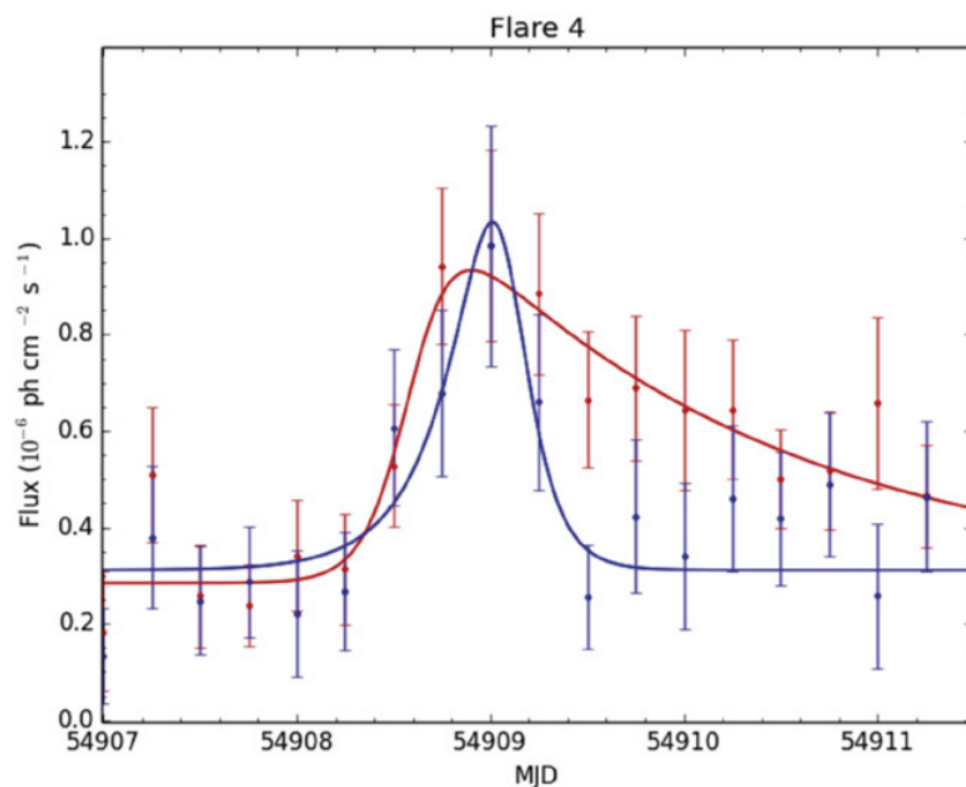
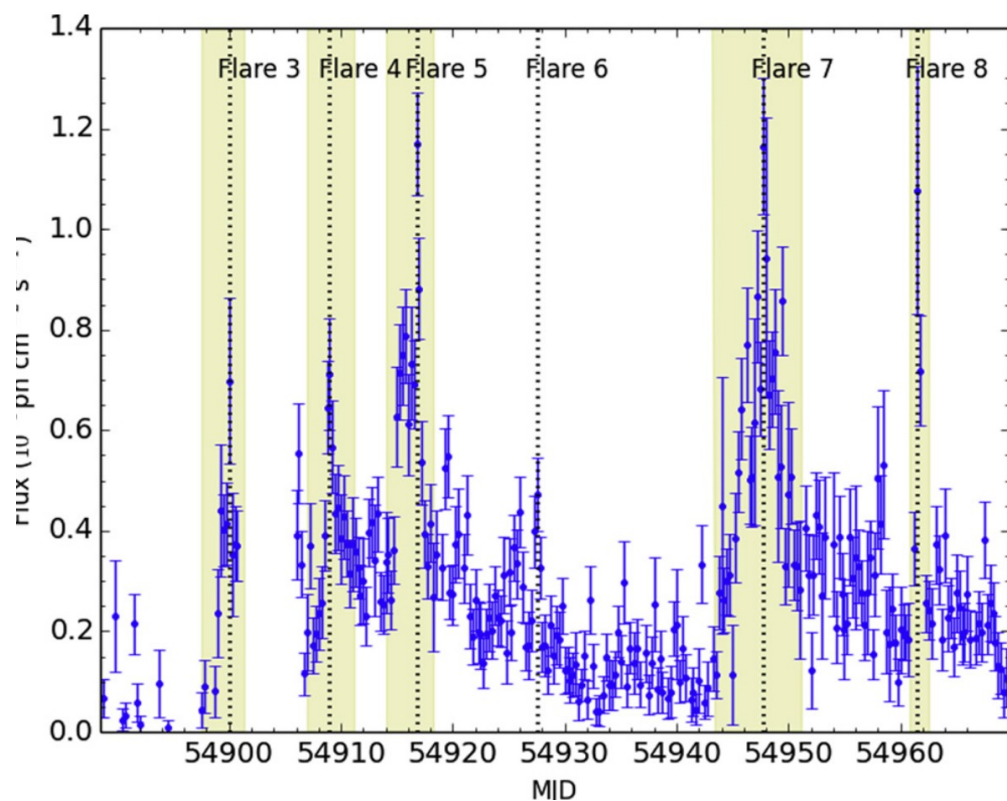
- In the Optical/X-ray this is more straightforward, since PSF size depends only weakly on Energy – not true with LAT!
- Optimize S/N ratio:
 - $S/N = S/(S+B)^{1/2}$ (S = source B = background)
- Choosing an Aperture is complicated by:
 - Energy Dependence of the PSF
 - Background is very energy-dependent!
- Optimum Aperture and Energy range varies from source to source



Two microquasars, looking at S/N ratio with different Aperture Radii

Aperture Photometry Demo

- **PKS 1510-089, the flaring blazar from Dotson (2015) study.**



Aperture Photometry Demo

- **Get photons from the LAT Photon Server**
 - Energy: 100 - 100000 MeV
 - MJD 54907-54912 (convert to MET with xtime)
 - RA/Dec = 228.2105538, -9.0999522, **1 deg ROI**
- **gtselect (first set of steps for low energy = 100-500 MeV)**

```
meyer-> gtselect
Input FT1 file[full_range_gti.fits]
Output FT1 file[pks1510_1deg_lowE.fits]
RA for new search center (degrees) (0:360) [228.2105538]
Dec for new search center (degrees) (-90:90) [-9.0999522]
radius of new search region (degrees) (0:180) [1]
start time (MET in s) (0:) [259351202]
end time (MET in s) (0:) [259372802]
lower energy limit (MeV) (0:) [100]
upper energy limit (MeV) (0:) [500]
maximum zenith angle value (degrees) (0:180) [90]
Done.
```

Aperture Photometry Demo

- **gtmktime**

- Here we use a more restrictive cut to avoid times when the sun is near (generally a good idea although it's not important here). See:
- https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/aperture_photometry.html

```
meyer-> gtmktime
Spacecraft data file[sc.fits]
Filter expression[(DATA_QUAL==1) && ABS(ROCK_ANGLE)<90 && (LAT_CONFIG==1) && (angsep(RA_ZENITH,DEC_ZENITH,228.2105538,-9.0999522)+1<105) && (angsep(228.2105538,-9.0999522,RA_SUN,DEC_SUN)>5+1) &&(angsep(228.2105538,-9.0999522,RA_SCZ,DEC_SCZ)<180)]
Apply ROI-based zenith angle cut[yes]
Event data file[pks1510_1deg_lowE.fits]
Output event file name[pks1510_1deg_lowE_gti.fits]
```

Aperture Photometry Demo

- **gtbin**

- Just chopping up the event file into bins
- Here we use 6 hour time bins (21600 sec)

```
meyer-> gtbin
This is gtbin version ScienceTools-v11r5p3-fssc-20170716
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [LC]
Event data file name[pks1510_1deg_lowE_gti.fits]
Output file name[lc_1510_lowE.fits]
Spacecraft data file name[sc.fits]
Algorithm for defining time bins (FILE|LIN|SNR) [LIN]
Start value for first time bin in MET[258940802]
Stop value for last time bin in MET[259372802]
Width of linearly uniform time bins in seconds[21600]
```

Aperture Photometry Demo

- **gtexposure**

- Takes lightcurve we just produced as input
- Calculates the Fermi effective area for each time bin so we can convert from counts to flux

```
meyer-> gtexposure  
Light curve file[lc_1510_highE.fits] lc_1510_lowE.fits  
Spacecraft file[sc.fits]  
Response functions[P8R2_SOURCE_V6]  
Source model XML file[none]  
Photon index for spectral weighting[-2]
```

Aperture Photometry Demo

- **gtbary**

- Optional, but we will do it here as part of the demo
- Most important for short-timescale variability
- 'corrects' the incoming photon arrival times for the fact that Fermi is not sitting in an inertial frame but is in fact orbiting the Earth, which orbits the sun, etc.

```
meyer-> gtbary tcorrect=BARY
This is gtbary version ScienceTools-v11r5p3-fssc-20170716
Event data file name[lc_1510_lowE.fits]
Spacecraft data file name[sc.fits]
Output event data file name[lc_1510_lowE_bary.fits]
Right Ascension to be used for barycenter corrections (degrees)[228.2105538]
Declination to be used for barycenter corrections (degrees)[-9.0999522]
```


Aperture Photometry Demo

• A little arithmetic and plotting...

1. Use ftcalc:

```
ftcalc lc_1510_lowE_bary.fits lc_1510_lowE_rate.fits RATE 'counts/exposure'  
ftcalc lc_1510_lowE_rate.fits lc_1510_lowE_rate_error.fits RATE_ERROR 'error/exposure'
```

2. open the rate_error.fits file with utility 'fv' and save table as a comma-separated text file [NOT a csv] (renamed lc_1510_lowE_rate_error_t1.txt)

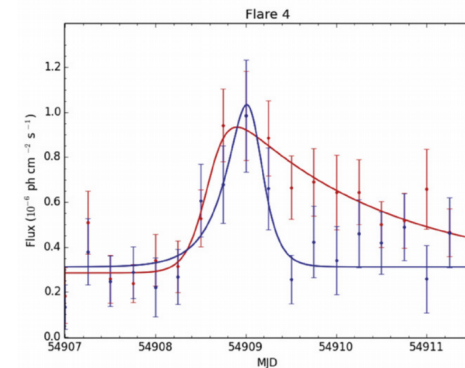
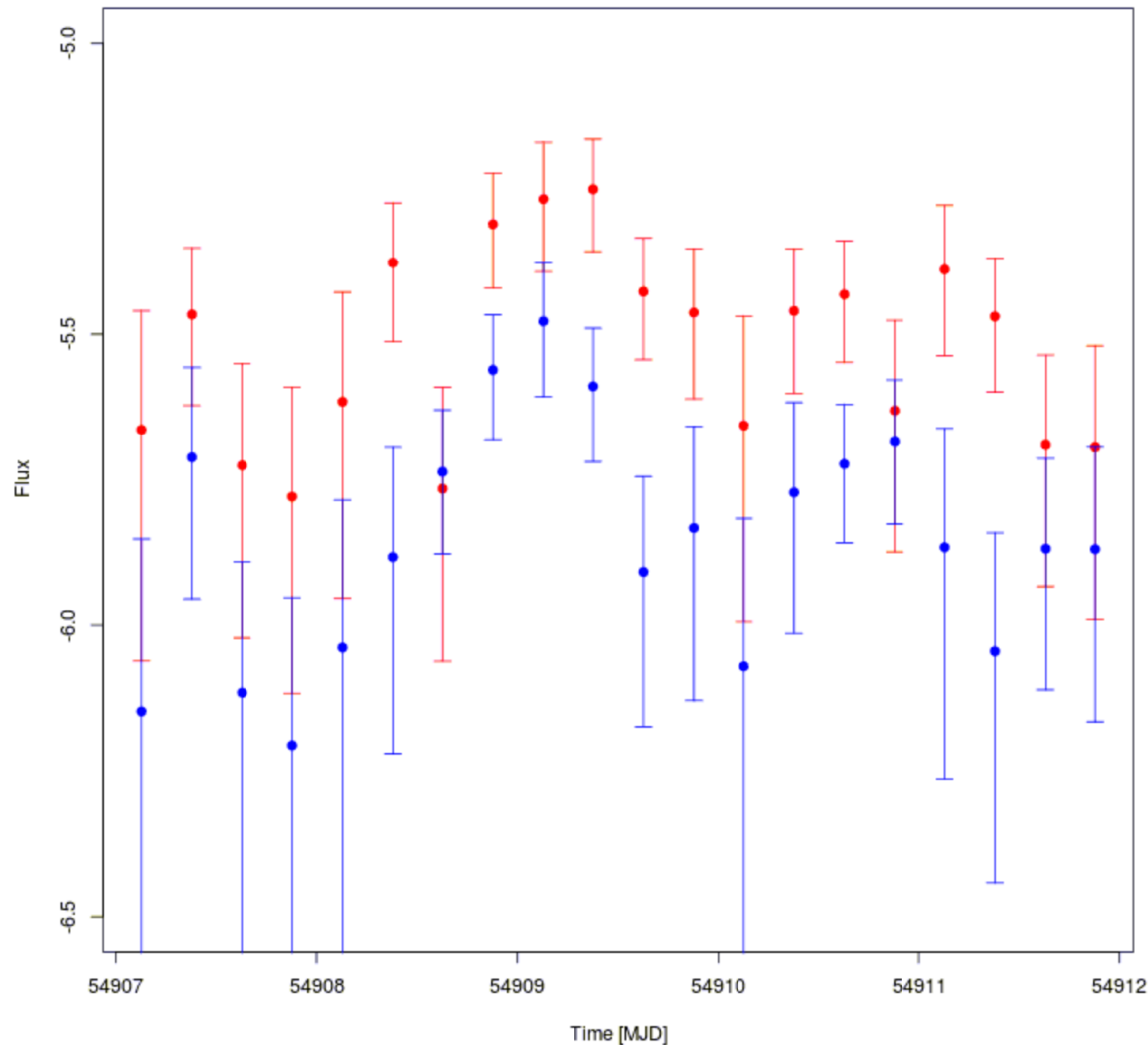
3. use a perl or similar script to rationalize the output:
./fixtable.pl lc_1510_lowE_rate_error_t1.txt > lowE.txt

4. Plot with R:

```
t<- read.table("lowE.txt")  
library(gplots)  
time = (t$V1-258940802)/86400 + 54907  
plotCI(time,t$V2,li=t$V4,ui=t$V3,col="red",gap=0,pch=19,ylim=c(-6.5,-5),ylab="Flux",xlab="Time [MJD]")
```

```
t<- read.table("highE.txt")  
time = (t$V1-258940802)/86400 + 54907  
off=0.6  
plotCI(time,t$V2+off,li=t$V4+off,ui=t$V3+off,col="blue",gap=0,pch=19,add=TRUE)
```

Aperture Photometry Demo



(b) Flare 4

← More or less matches the much more accurate/time-consuming likelihood result from Dotson (2015). Peak of the flare just after MJD 54909 matches ... faster fall-time of the high-energy component is harder to see, but probably there. (note high-E is arbitrarily scaled up here.)

But WAIT, there's MORE!

- If you really want a 'quick look', your best bet may be to use **FAVA**
 - FAVA=Fermi All-Sky Variability Analysis
 - <https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/>

NASA National Aeronautics and Space Administration
Goddard Space Flight Center

FSSC • HEASARC • Sciences and Exploration

Fermi All-sky Variability Analysis (FAVA)

Light Curve Generator

RA:

Dec:

FAVA Analysis Overview

Weeks Analyzed	506
FAVA Detections (>6 σ)	5041
Associated Detections	4399
Unassociated Detections	642

FAVA Resources

- [FAVA Weekly Flare List](#)
- [FAVA Light Curve Generator](#)
- [1st FAVA Catalog](#)
- [2nd FAVA Catalog](#)
- [About FAVA](#)

Weekly FAVA Runs

FAVA

- **Photometric Variability Analysis**
- **Covers the Entire Sky with 0.5 degree binning**
- **Time binning is weekly (this is good for certain types of sources, like blazars, but may not be good for yours!)**
- **Not much spectral information:**
 - Low-Energy Binned Analysis (100-800 MeV)
 - High-Energy Unbinned Analysis (> 800 MeV)

- **Analysis Method:**

- Is model-independent
- Takes the most recent catalog values (Averaged over 4 years for 3FGL) to estimate the expected flux from a sky pixel in 1 week (with some smoothing)
- Integrates over Energy and incidence angle
- Result is a measure of deviation from expectation which is converted into a # of sigma.
- Catalog sources are those with > 6 sigma deviation

- **Flares are followed up with likelihood analysis**

- 5x5 degree TS Map is generated
- Localization is at the 0.1 degree level (95% CI)
-

Getting LightCurve

- Just type in your RA/Dec:



National Aeronautics and Space Administration
Goddard Space Flight Center

FSSC • HEASARC • Sciences and Explo



Fermi All-sky Variability Analysis (FAVA) - Light Curve Generator

Coordinate Input

RA:

Dec:

Light Curve Information

Coordinates

RA: 228.2105538°

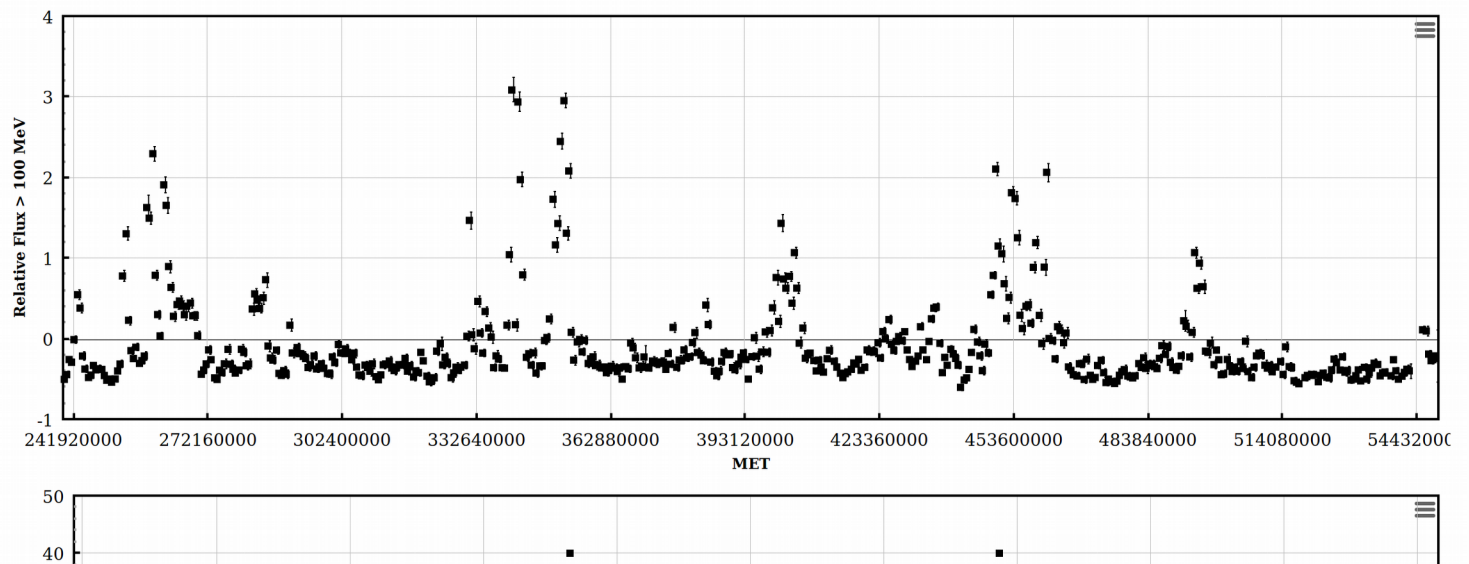
Dec: -9.0999522°

Galactic l: 351.2893°

Galactic b: 40.1387°

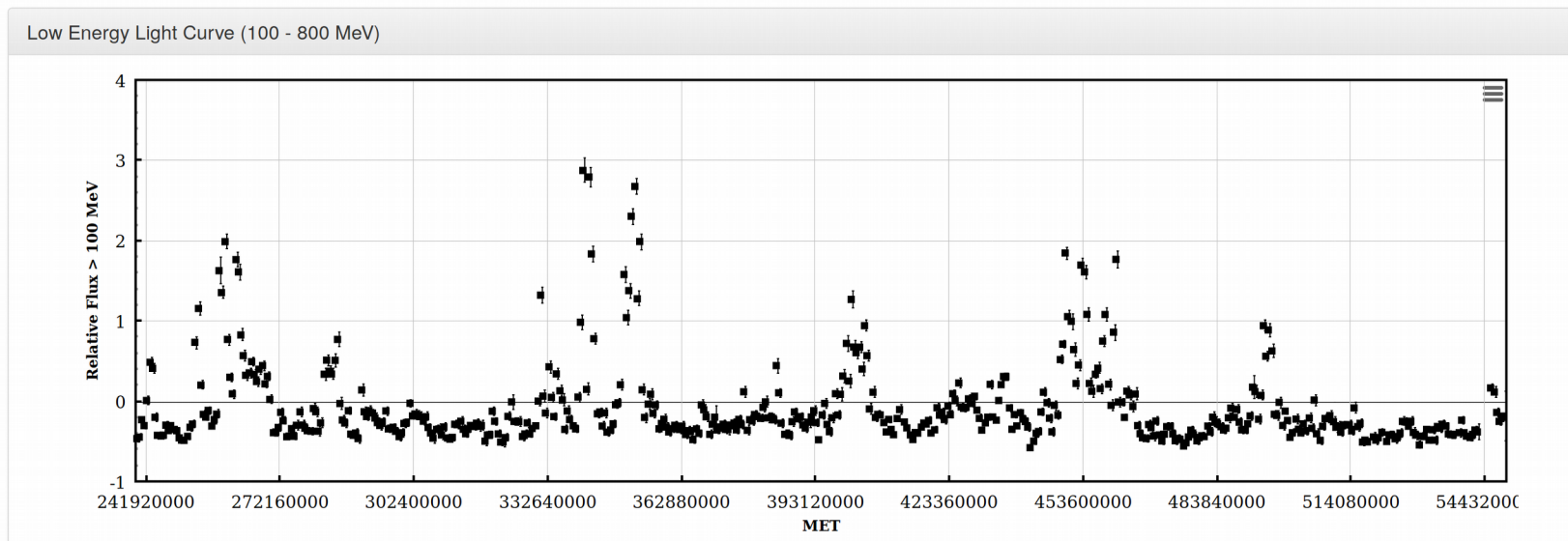
Low Energy Analysis

Low Energy Light Curve (100 - 800 MeV)



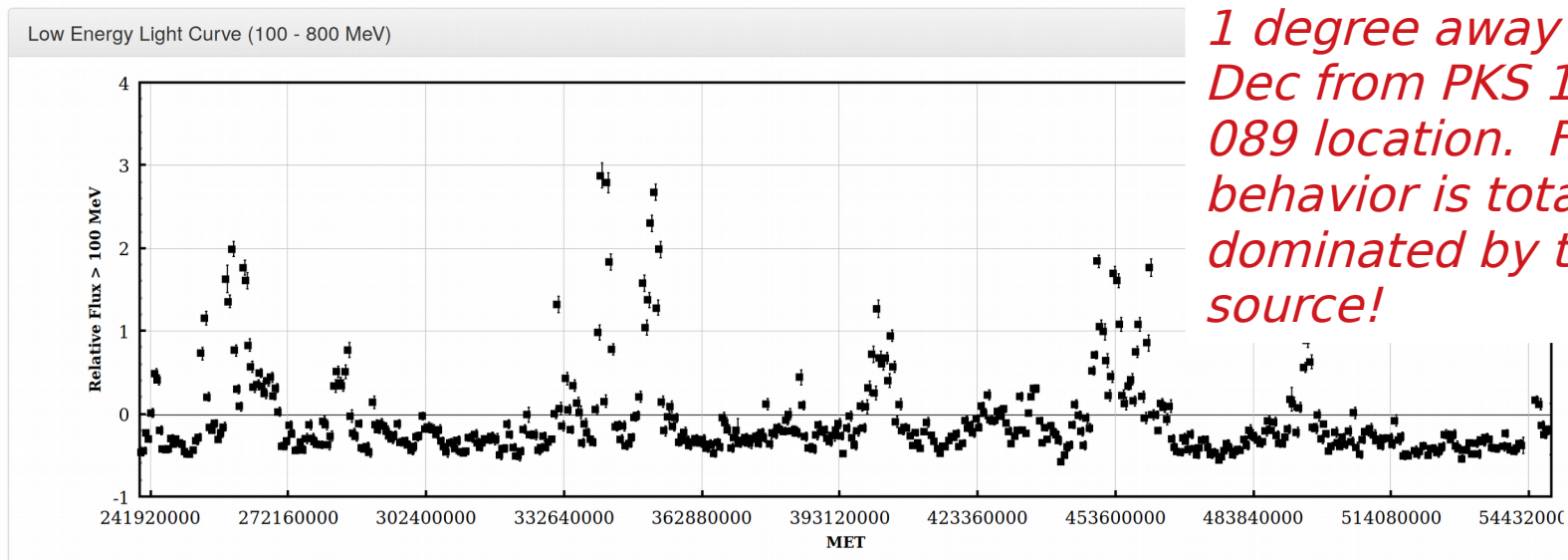
CAVEAT

- Keep in mind this is a photometric analysis, which has certain drawbacks
- Most serious is that major flares can 'spill over' into neighboring areas.
- *If you think you have a flaring source, double-check the more precise follow-up location of that flare!*



CAVEAT

- Keep in mind this is a photometric analysis, which has certain drawbacks
- Most serious is that major flares can 'spill over' into neighboring areas.
- *If you think you have a flaring source, double-check the more precise follow-up location of that flare!*



This lightcurve is from 1 degree away in RA/Dec from PKS 1510-089 location. Flaring behavior is totally dominated by that source!

Likelihood Method

- **Probably the best for most science cases**
- **Considerably more sensitive and accurate**
- **Demo: Flare 4 of PKS 1510-089, again**
 - We will do an unbinned analysis because of the very short timescales (6 hours)
 - Side Note: general rule of thumb for our group is to switch to binned only for timescales of 0.5-1 year or longer (assuming using full energy range). However unbinned can be appropriate for long time ranges if you are only focused on high-energies (because the total photons go down dramatically with Energy).

Likelihood Lightcurve Demo

- **I have provided simple lightcurve scripts using the python fermi tools (not fermipy).**
 - One is for binned, one for unbinned
 - Each set has two parts: a “setup” script and a “run” script. Setup runs all the tools up to but not including the final likelihood
 - Each set takes a config file.
 - Feel free to take these scripts and adapt them. There are some “hard-coded” choices you will probably want to check or change!

Likelihood Lightcurve Demo

- **First, get photon and SC file from server**
 - We use a 15 degree ROI
 - Energies from 100-100,000 MeV
 - Same Timerange/RA/Dec as prev example
- **Equivalently, make a selection from the Fermi weekly files**
 - Our group keeps a mirror of the entire Fermi archive locally – you can automate this with scripts that download new files each week
 - See: https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/LAT_weekly_allsky.html
- **For this demo, our starting photon file is called 'pks1510_binned_filtered.fits'**

Likelihood Lightcurve Demo

- **You will also need:**

- A model xml file. We will include (fixed) sources up to 25 degrees away using the -ER flag
- Please read the help file for the make3FGLxml.py script carefully. There are a lot of options!!
- You will also need a copy (or softlinks) of:
 - gll_iem_v06.fits
 - gll_psc_v16.fit
 - iso_P8_R2SOURCE_V6_v06.txt

```
meyer-> python make3FGLxml.py gll_psc_v16.fit pks1510_binned_filtered.fits -o pks1510_input_model.xml -G $FERMI_DIR/refdata/fermi/galdiffuse/gll_iem_v06.fits -g gll_iem_v06 -I $FERMI_DIR/refdata/fermi/galdiffuse/iso_P8R2_SOURCE_V6_v06.txt -i iso_P8R2_SOURCE_V6_v06 -N -r 15 -R 15 -ER 10 -s 20 -p TRUE
This is make3FGLxml version 01r01.
The default diffuse model files and names are for pass 8 and assume you have v10rxxpxx of the Fermi Science Tools or higher.
Creating file and adding sources from 3FGL
Added 58 point sources, note that any extended sources in ROI were modeled as point sources because psForce option was set to True
```

Likelihood Lightcurve Demo

- **Setup:**

- First, setup your Fermi tools environment
- Create a new directory within your working space called 'bins'
- Make sure your events file, spacecraft file, and xml model file are in the working directory.
- Run the setup script with 'config' option to get empty config file:

```
python lc_setup_unbinned.py config
```

Output file is 'lc_tools.cfg'. Edit this.

```
model_file----->
fglname----->
events_file----->
spacecraft_file---->
ev_class----->
ev_type----->
ra----->
dec----->
radius----->
zmax----->
tmin----->
tmax----->
emin----->
emax----->
bin_size----->
```

```
model_file----->pks1510_output.xml
fglname----->J1512.8-0906
events_file----->pks1510_binned_filtered.fits
spacecraft_file---->sc.fits
ev_class----->128
ev_type----->3
ra----->228.2105538
dec----->-9.0999522
radius----->15
zmax----->90
tmin----->258940802
tmax----->259372802
emin----->500
emax----->100000
bin_size----->21600
base----->pks1510[~]
```

Likelihood Lightcurve Demo

- **Run setup:**

- `python lc_setup_unbinned.py 1`

- Output is fairly verbose. Check for errors!

```
changing to directory bins/bin13

time -p /opt/ScienceTools-v10r0p5-fssc-20150518-x86_64-unknown-linux-gnu-libc2.19-0/x86_64-unknown-linux-gnu-libc2.19-0/bin/gtselect infile=pks1510_binned_filtered.fits outfile=pks1510_filtered.fits ra=228.2105538 dec=-9.0999522 rad=15.0 tmin=259200002.0 tmax=259221602.0 emin=100.0 emax=500.0 zmin=0.0 zmax=90.0 evclass=128 evclsmin=0 evclsmax=10 evtype=3 convtype=-1 phasemin=0.0 phasemax=1.0 evtble="EVENTS" chatter=2 clobber=yes debug=no gui=no mode="ql"
Done.
real 0.10
user 0.08
sys 0.01
time -p /opt/ScienceTools-v10r0p5-fssc-20150518-x86_64-unknown-linux-gnu-libc2.19-0/x86_64-unknown-linux-gnu-libc2.19-0/bin/gtmktime scfile=sc.fits sctable="SC_DATA" filter="(DATA_QUAL>0)&&(LAT_CONFIG==1)" roicut=yes evfile=pks1510_filtered.fits evtble="EVENTS" outfile="pks1510_filtered_gti.fits" apply_filter=yes overwrite=no header_obstimes=yes tstart=0.0 tstop=0.0 gtifile="default" chatter=2 clobber=yes debug=no gui=no mode="ql"
real 3.17
user 2.60
sys 0.56
time -p /opt/ScienceTools-v10r0p5-fssc-20150518-x86_64-unknown-linux-gnu-libc2.19-0/x86_64-unknown-linux-gnu-libc2.19-0/bin/gtlcube evfile="pks1510_filtered_gti.fits" evtble="EVENTS" scfile=sc.fits sctable="SC_DATA" outfile=pks1510_ltcube.fits dcostheta=0.025 binsz=1.0 phibins=0 tmin=0.0 tmax=0.0 file_version="1" zmin=0.0 zmax=90.0 chatter=2 clobber=yes debug=no gui=no mode="ql"
Working on file sc.fits
.....!
real 1.65
user 1.38
sys 0.27
```

Likelihood Lightcurve Demo

- **Run likelihoods**

- You really may want to change the default settings (minimizer, tolerance, etc)

```
python lc_run_unbinned.py 1 20
```

- The two arguments (1,20) are the starting and stopping bins.
- This can be useful if one bin (say, #7) is failing and kicking you out of the lightcurve script. You can pick up the rest of the bins with input

```
python lc_run_unbinned.py 8 20
```

- When this happens usually you need to go in by hand to see what's going on in bin 7 - sometimes model file needs adjusting.

Likelihood Lightcurve Demo

- **Watch the output:**

```
Minuit did successfully converge.  
# of function calls: 215  
minimum function Value: 436.5757693709  
minimum edm: 0.01187727228846
```

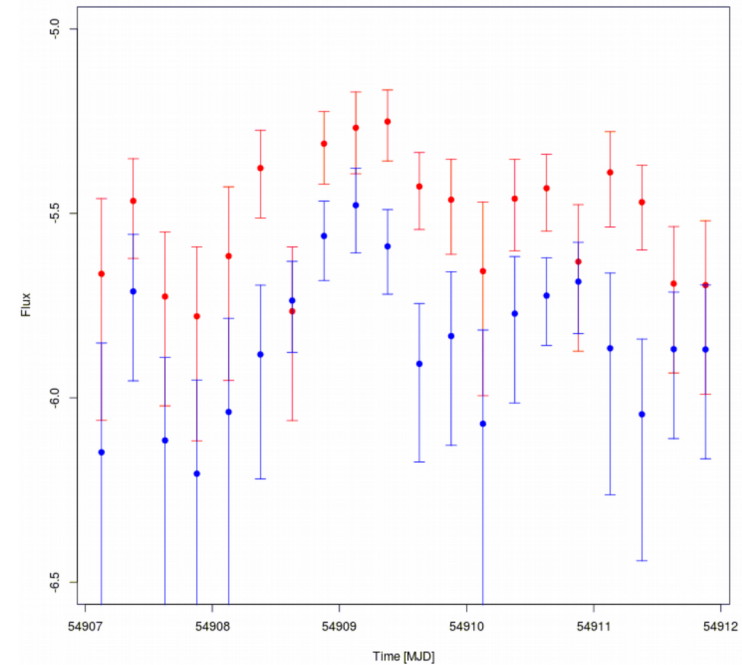
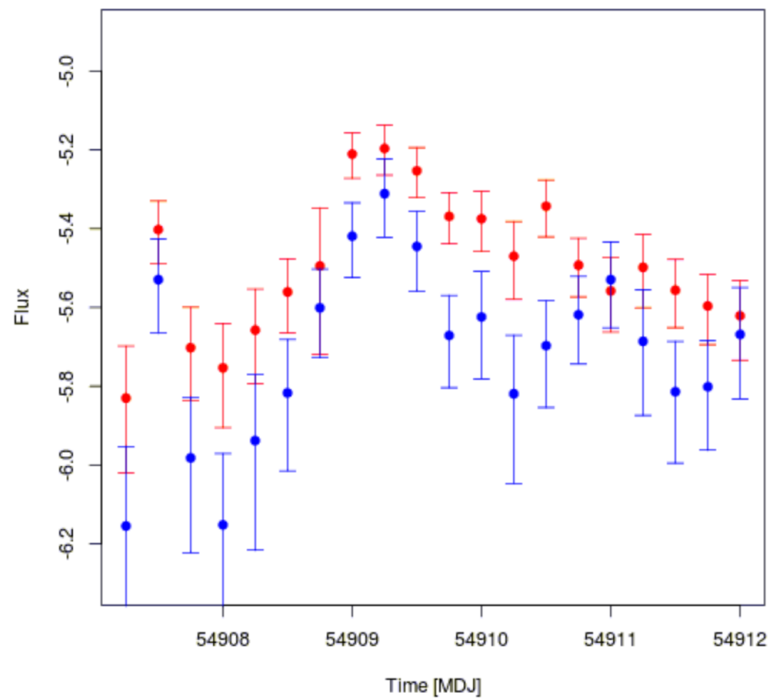
```
fit_status=0  
Source detected as TS=41.6812641427, Flux = 3.40117012048e-06+/-1.0706585763e-06
```

Each time bin gets its own directory within 'bins'. So there is bins/bin01, bins/bin02, etc.

Within each directory there is a file called 'results.txt' which contains the TS of your source, the flux and error, and the fit status (non-zero == bad!)

Likelihood Lightcurve Demo

Results! Likelihood on Left, note much smaller error bars than AP method on right. However, the essential behavior of the flare is similar.



- **Obtain the scripts here:**

- http://astro.umbc.edu/~meyer/uploadbin/fermi_summer_2018/scripts/

- Note: these scripts could easily be adapted to bin in energy rather than time.

- **A few final thoughts**

- Be careful with your time bins. You may want to consider using equal-GTI time rather than equal “real” time, because Fermi won’t necessarily have the same exposure in the same real time.
 - Don’t go below 3 or 6 hour time bins unless you know what you are doing! This is roughly the timescale for Fermi to scan the whole sky – below this, you will need Fermi to be in staring mode on your source to get better time-resolution, or you will need to accept gaps in your lightcurve [care is needed!]

- **The same cautions as with my previous lecture: make sure all sources are accounted for in your ROI! I did not do it in the demo because of short timeframe, but if you are doing a 10-year lightcurve, your initial step should be to localize all new sources and use a TS map to make sure none are missing! (see Lecture from Saturday).**