Gamma Ghosts and Gravitational Lensing

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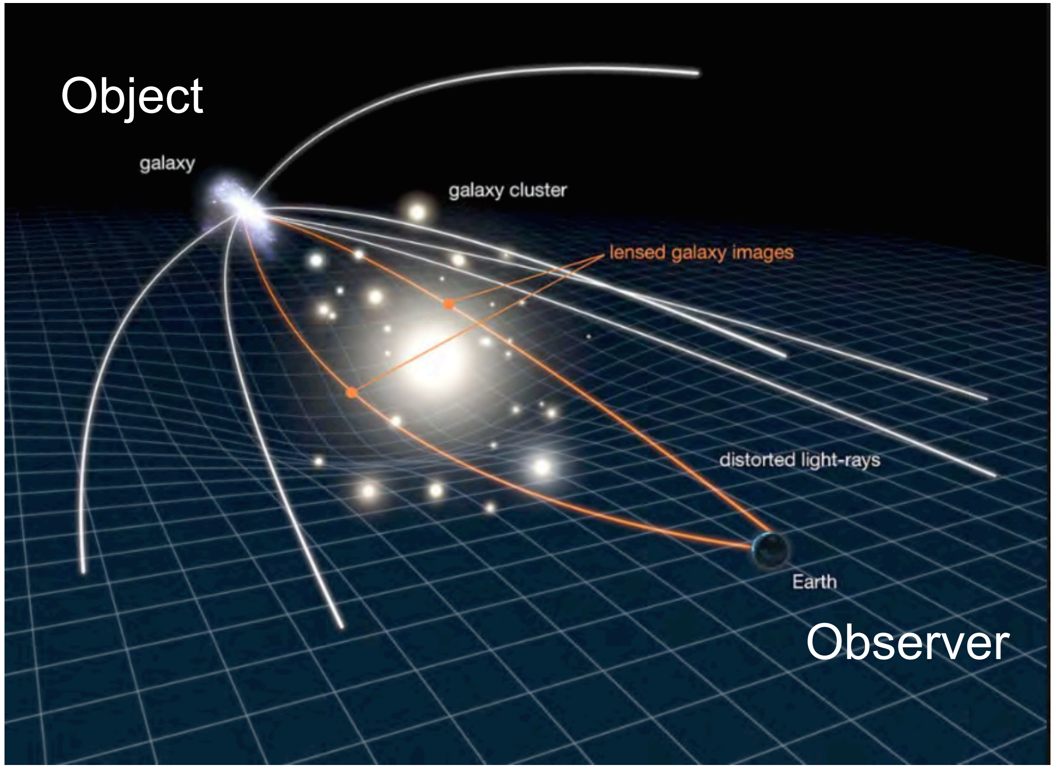
on behalf of the *Fermi* LAT collaboration

Outline

- **Gravitational lensing effect**
- **Lensed systems detected at gamma rays**
  - **PKS1830-211**
  - **B0218+35**
- **Summary**
- **Future Perspectives**



Gravitational Lensing effects

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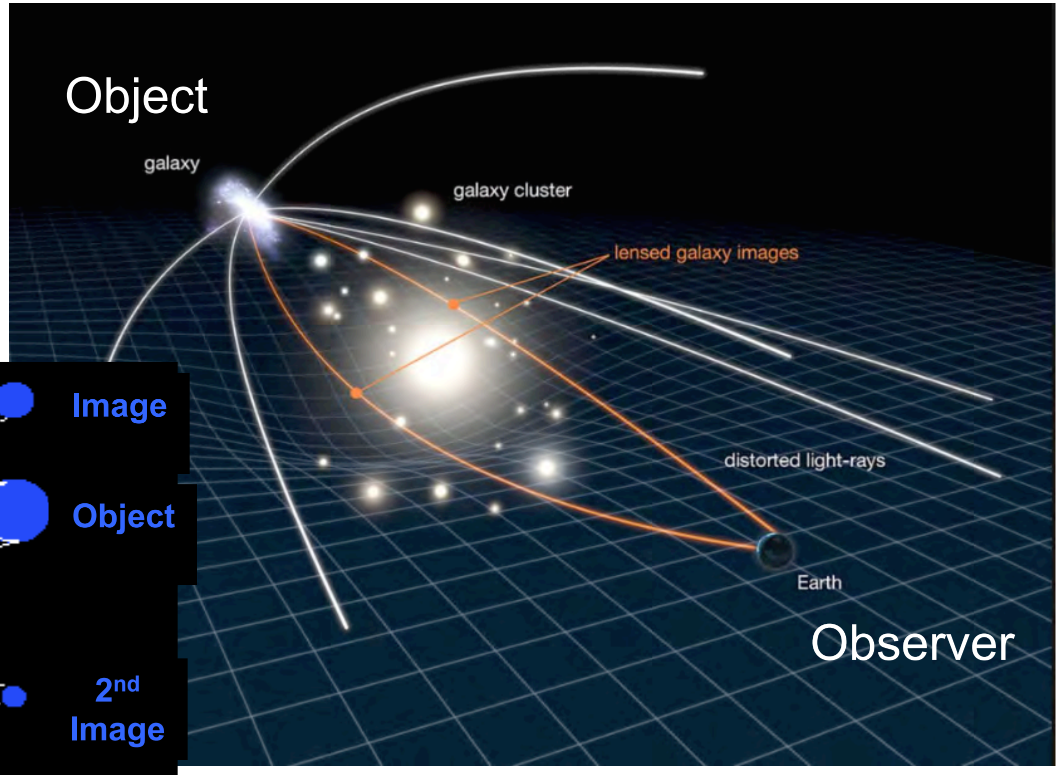
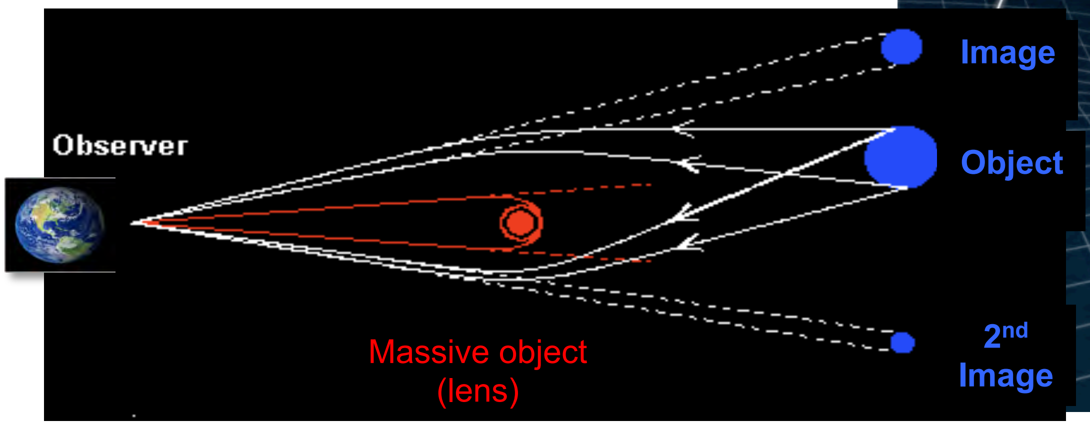
- Lensed systems detected at gamma rays
  - PKS1830-211
  - B0218+35
- Summary
- Future Perspectives

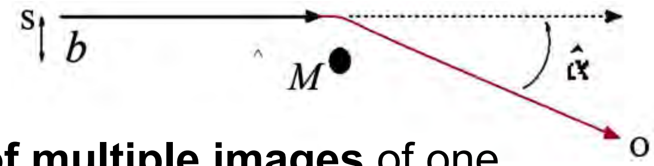




Gravitational Lensing: First Steps

General Relativity (Einstein 1915) predicts that a light ray which passes by a spherical body of mass M with impact parameter b, is deflected by the Einstein angle (provided b >> Schwarzschild radius R_s):

$$\hat{\alpha} = \frac{4GM}{c^2 b} = \frac{2R_s}{b}$$



• Einstein result confirmed by Dyson+ (1920)

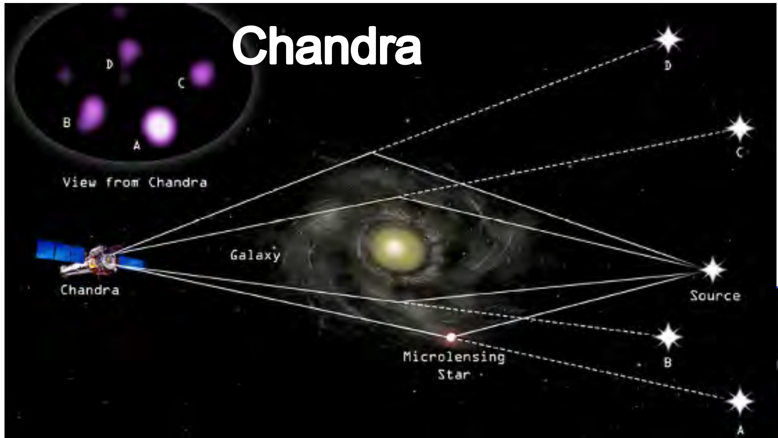
• Lodge (1919) invented the term "**gravitational lens**"

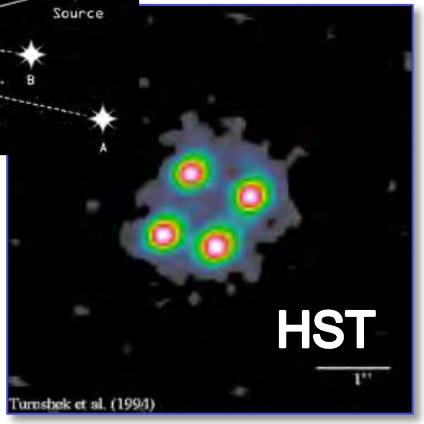
• Eddington (1920) showed the **possibility of observations of multiple images** of one lensed source; Chwolson (1924) found that **a lensed image may have a circular form (ring)**, when the source, lens and observer are on the same line; Tihov (1937) **magnification** of a lensed image; Zwicky (1937): gravitational lensing on massive extragalactic "nebulae" (present galaxies or galaxy clusters) much more effective than on stars; Zwicky (1937) probability that nebulae which act as gravitational lenses will become a certainty.

• Gravitational lensing theory developed by Klimov (1963), Liebes (1964), Refsdal (1964), Ingel' (1974); **First discovery (Walsh et al. 1979): "twin" quasar TXS 0957+561** (SBS 0957+561, z=1.4141); quasars ideal sources for search strong gravitational macrolensing; Byalko (1969): microlensing and calculations of light curves; microlensing event observations from 1991 (Alcock 1993, Aubourg 1993 in LMC and Galactic Halo).

• Mysterious 'Giant arcs' in A370,Cl224. Paczynski suggests lensing. Fort 1987 confirm. Spectroscopy. **Clusters are more massive than expected**.

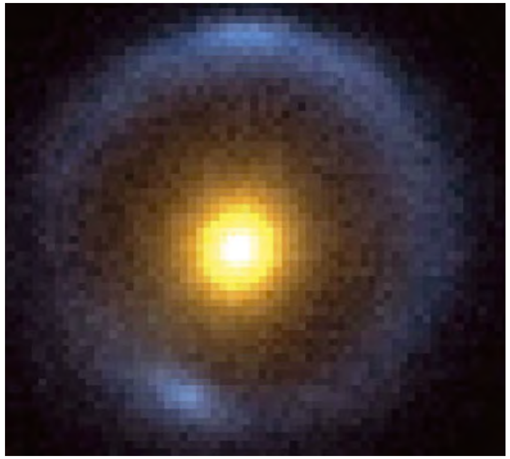
Picturesque Gravitational Lenses



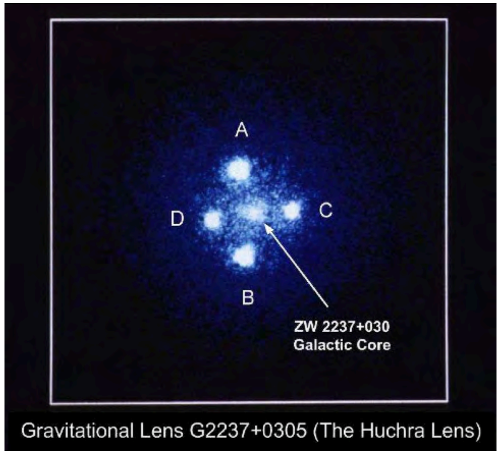


The Cloverleaf Quasar
(H 1413+117, z=2.5582)

Einstein Ring
the gravitational lens system
TXS 1938+666 (z=0.8809, 1'' diameter)



Einstein Cross quasar [HB89] 2237+030
(z= 1.695, lensed into four images by a z=0.04 galaxy)

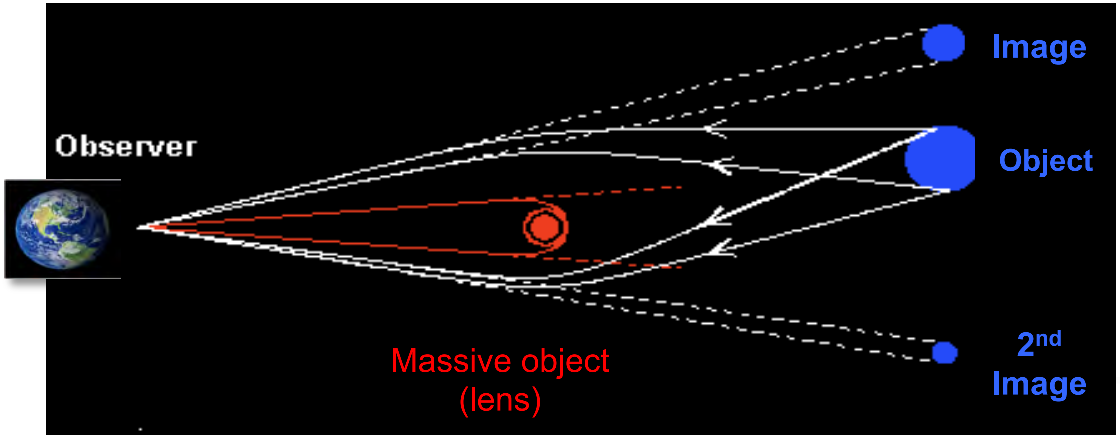


Gravitational Lens G2237+0305 (The Huchra Lens)

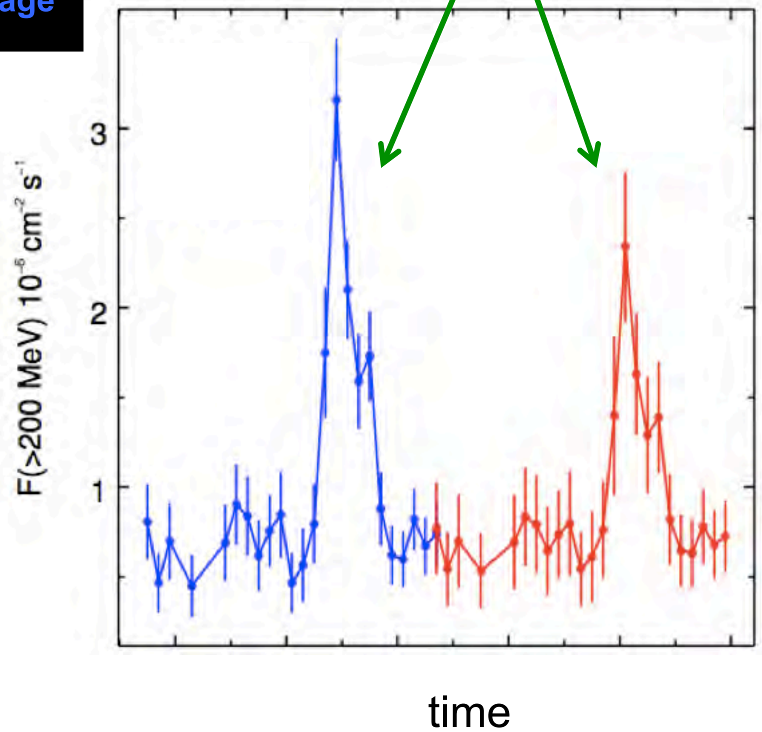
Observational Point of View

- **STRONG LENSING:** easily visible distortions of light, Einstein Rings, arcs and multiple images
- **WEAK LENSING: distortions of background sources are much smaller**, **detected** by analyzing large numbers of sources to find coherent distortions of only a few percent, **only in a statistical way** (example weak lensing in cluster Abell 1703). Many distorted images of galaxies → reconstruct the mass (dark matter too) distribution in the lens.
- **MICROLENSING**: **no distortion in shape**, amount of light received from a background object changes over time, **strong lensing in which the image separation is unresolved**, a single star can lead to images split into micro-images separated by mas (example is microlensing on planets). Smooth, symmetric flux magnification curve as a lens star moves between a source star and an observatory on Earth. Short spike in magnification is caused by a planet orbiting.

Gravitationally effects at gamma rays



Expected to have the same variability pattern



Gamma rays (Fermi-LAT) can not resolve the two images but can **estimate the time delay** between components of lensed variable source

Gamma-ray flares of Lensed Blazars

PKS1830-211

ATel #2943

Fermi LAT detection of an intense GeV flare from the high-redshift and gravitationally lensed blazar PKS 1830-211

ATel #2943; *S. Ciprini (Perugia Univ. / ASI-INAF, Italy), on behalf of the Fermi Large Area Telescope Collaboration*
on 15 Oct 2010; 16:52 UT
Distributed as an Instant Email Notice Request For Obser
Credential Certification: Stefano Ciprini (stefano.ciprini@p

Subjects: Gamma Ray, >GeV, Request for Obs

Referred to by ATel #: 2950, 4158

ATel #4158

Fermi LAT detection of renewed GeV gamma-ray activity from the gravitationally lensed blazar PKS 1830-211

ATel #4158; *Stefano Ciprini (ASI Science Data Center and INAF Rome, Italy), on behalf of the Fermi Large Area Telescope Collaboration*
on 7 Jun 2012; 21:53 UT
Credential Certification: Stefano Ciprini (stefano.ciprini@asdc.asi.it)

Subjects: Gamma Ray, >GeV, Request for Observations, AGN, Blazar, Quasar

B0218+35

ATel #4343

Fermi LAT detection of a GeV flare from the gravitationally lensed blazar S3 0218+35

ATel #4343; *S. Ciprini (ASI ASDC & INAF OAR, Rome), on behalf of the Fermi Large Area Telescope Collaboration*
on 28 Aug 2012; 20:45 UT
Credential Certification: Stefano Ciprini (stefan

Subjects: Gamma Ray, >GeV, Request f

ATel #4361

Fermi LAT Detection of Gamma-ray Flaring from Gravitationally Lensed Blazar B0218+35

ATel #4361; *M. Giroletti (INAF-IRA Bologna), M. Orienti (Univ. Bologna, INAF-IRA Bologna), C. C. Cheung (NRL/NRL) on behalf of the Fermi Large Are Collaboration*
on 8 Sep 2012; 09:10 UT
Credential Certification: Marcello Giroletti (giroletti@ira.inaf...

Subjects: Gamma Ray, >GeV, Request for O

ATel #4371

Fermi LAT detection of a potential echo gamma-ray flare from gravitational lens S3 0218+35

ATel #4371; *M. Giroletti (INAF-IRA Bologna), M. Orienti (Univ. Bologna, INAF-IRA Bologna), C. C. Cheung (NRC/NRL); on behalf of the Fermi Large Area Telescope Collaboration*
on 11 Sep 2012; 20:42 UT
Credential Certification: Teddy Cheung (ccheung@

Subjects: Gamma Ray, >GeV, AGN, Blazar

ATel #4411

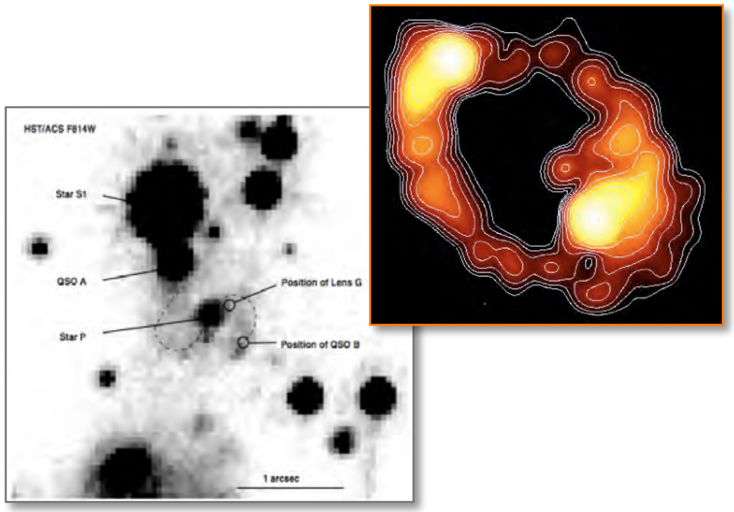
Fermi LAT Detection of New Gamma-ray Flaring from Gravitationally Lensed Blazar S3 0218+35 and Scheduled Fermi Pointed Observations from 2012 September 24 - October 1

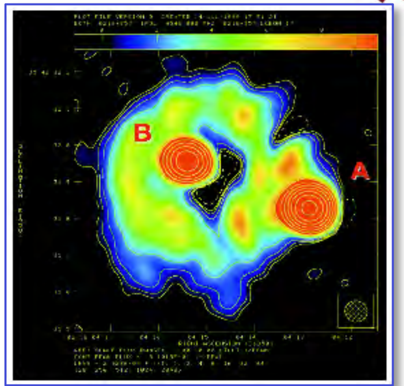
ATel #4411; *C. C. Cheung (NRC/NRL), R. Ojha (NASA/GSFC), M. Orienti (Univ. Bologna, INAF-IRA Bologna), D. L. Wood (Praxis/NRL); on behalf of the Fermi Large Area Telescope Collaboration*
on 22 Sep 2012; 03:01 UT
Credential Certification: Teddy Cheung (ccheung@milkyway.gsfc.nasa.gov)

Subjects: Gamma Ray, >GeV, AGN, Blazar

PKS1830-211 – B0218+357

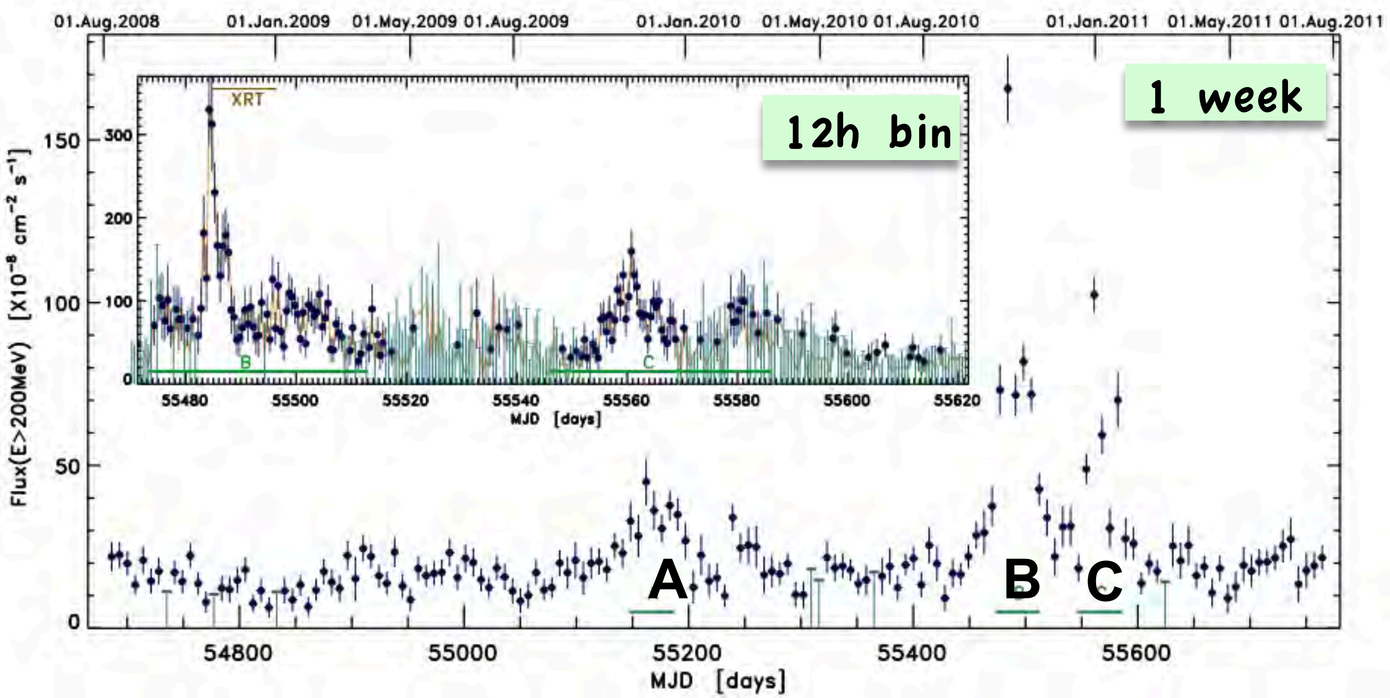
- FSRQ at z=2.507;
- lens separation of 0.98”; Einstein ring
  - Lensing galaxy z=0.886
  - Intervening galaxy z=0.19
- Radio delays claimed: 26+/-5 days, 24+/-5 days
- magnification ratio ~1.5





- z = 0.944
- Smallest separation lens from CLASS survey (0.335”); Einstein ring
  – Lensing galaxy z = 0.6847
- Delay 10.5 +/- 0.4 day (95% CL, Biggs et al. 1999)
- Associated with LAT gamma-ray source (2FGLJ0221.0+3555)

Flares of Lensed Blazar PKS1830-211



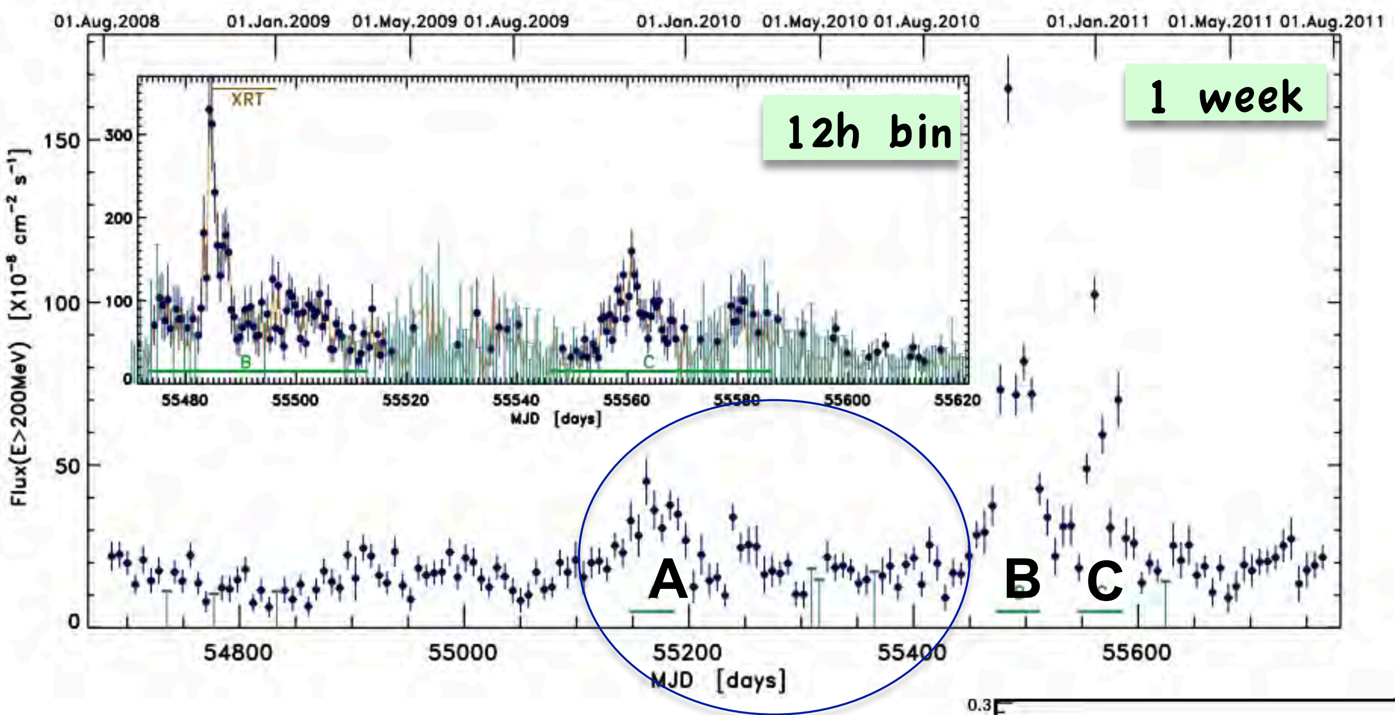
PKS 1830-211:

✓ the third most distant object detected in flaring activity by the LAT

✓ among the brightest high-z Fermi blazars with an averaged apparent isotropic gamma-ray luminosity about 10^{49} erg s^{-1}

✓ peak flux F(0.2-100GeV) of 2010 October 14-15 was about $3x10^{-6}$ ph cm^{-2} s^{-1} (factor 17 greater than the average 3-year flux).

Flare A (PKS1830-211)



Gamma-ray lensing delay claimed:
27.1+/-0.6 days (Barnacka et al. 2011)

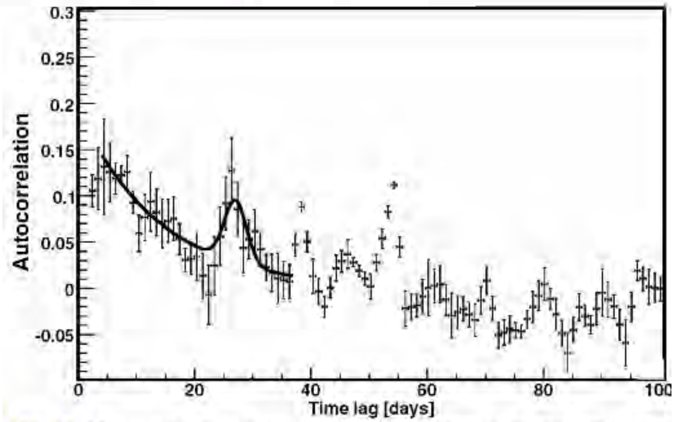
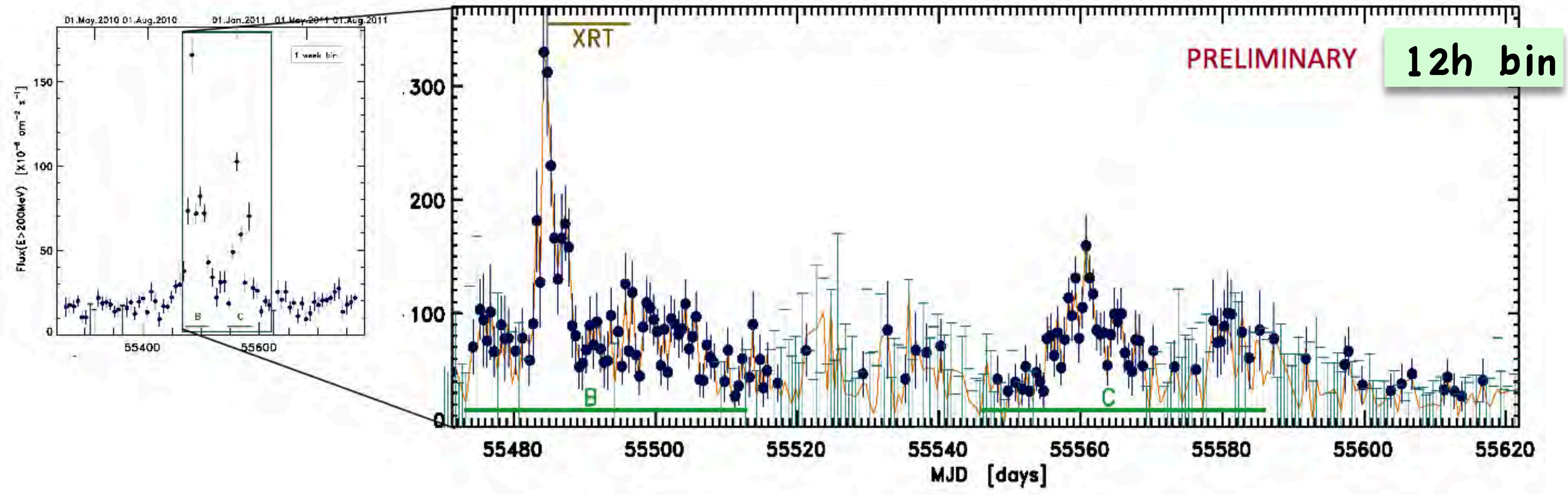


Fig. 7. Measured autocorrelation function of PKS 1830-211. The solid line is a fit to an exponential plus Gaussian profile.

Flare B (PKS1830-211)



• 150-day range (2010 October 2 to 2011, March 1) flux light curve extracted with 12-hour bins and containing the "B" and "C" intervals when the main outburst of 2010 Oct. and the second largest, and double-peaked, flare of 2010 Dec.-2011 Jan. occurred.

• 12 hours are about 8 Fermi orbits exposures from bin to bin are roughly the same.

• 2010 Oct. outburst is characterized by a rapid increase of a factor of about 2.6 in flux in 12 hours between 2010 Oct.14 and 15, and a F_{peak}(>200MeV) = (330 +/- 42)X10^{-8} phot/cm^2/s , yet taking about 48 hours to fall, resulting in an asymmetric temporal shape. The total peak lasts about 2.5 days, and seems to be followed by another weaker peak also lasting 2.5 days.

No clear evidence of time-delayed events produced by lensing in PKS1830-211

- A clear evidence **lensing-induced following-up flares is ruled out**. **No delayed gamma-ray flares** from the second lens image for both the ``B" outburst and the ``C" second brightest flare found. Gtlike flux (bin x bin spectral fit) light curve (12-hour, 2-day and 1-week binnings over 3 years) extracted using the same event class (Pass-6) and analyzed with different methods (**PDS, DACF, WT**). Minor variability on longer timescales (weeks/months) also found.

- Time delay of 26^{+5}_{-4} days (Lovell98), 24^{+5}_{-4} days (Wiklind01), main outburst peak of 2010 Oct. 14-15 showed no delayed event. The same for the 44±9 days time delay (VanOmmen95). Magnification ratio in radio bands is 1.5.

- Barnacka et al. (2011) claimed a **27.1±0.6 days time delayed signal** (using 2-day bin flux **LC extracted through "aperture photometry"** which differs from that used by the Fermi collaboration (maximum likelihood analysis).

- **Signal feature at 53.4-day timescale**: precession period of the spacecraft orbit **systematics by effective area** variation not completely taken into account in Pass-6 data and IRFs. Incidentally the 27.1±0.5 day delay claimed is the first harmonic of that.

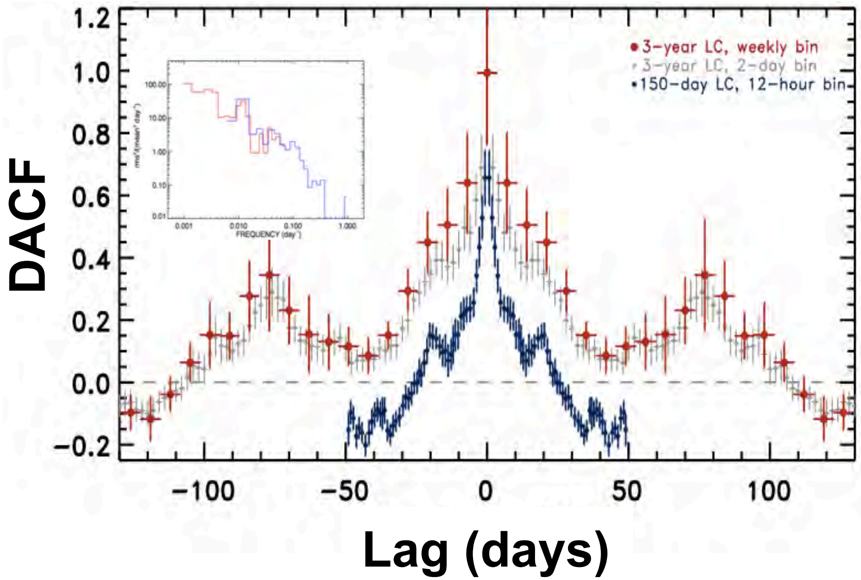
No clear evidence of time-delayed events produced by lensing in PKS1830-211

No evident sign of delayed gamma-ray flares caused by lens

(The Fermi-LAT coll., submitted)

Delayed flare does not exist in gamma rays or magnification ratio in gamma rays is much smaller, or there is a time or energy variable magnification ratio too given by the complex lens system and ambient.

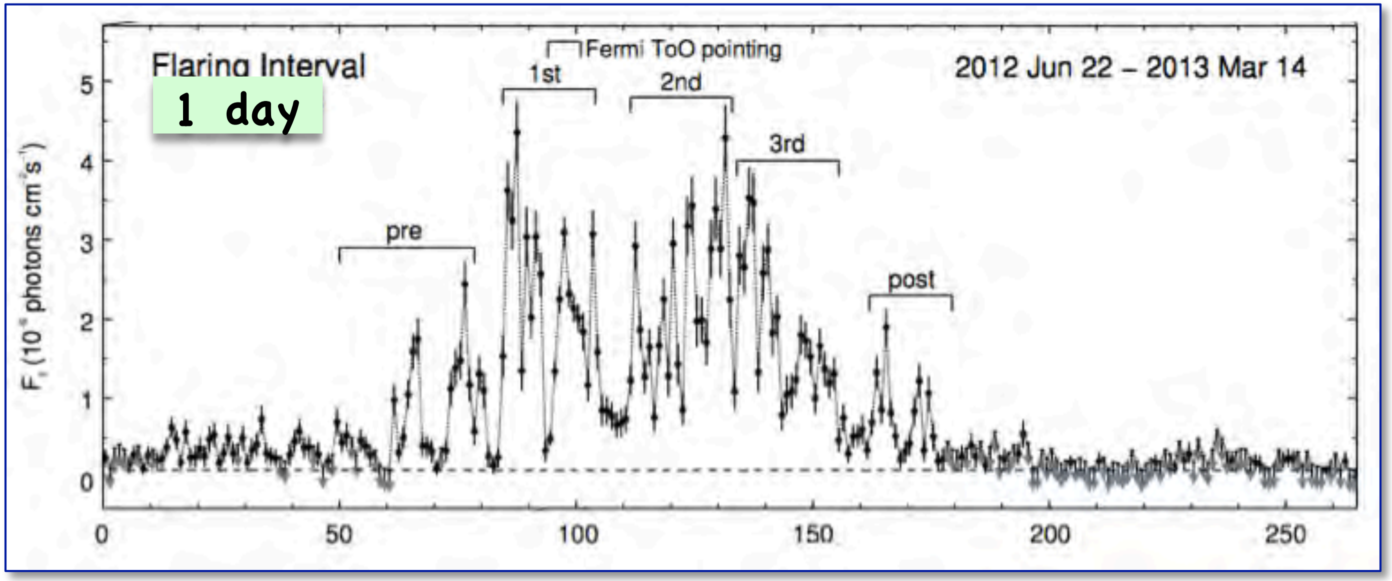
Preliminary



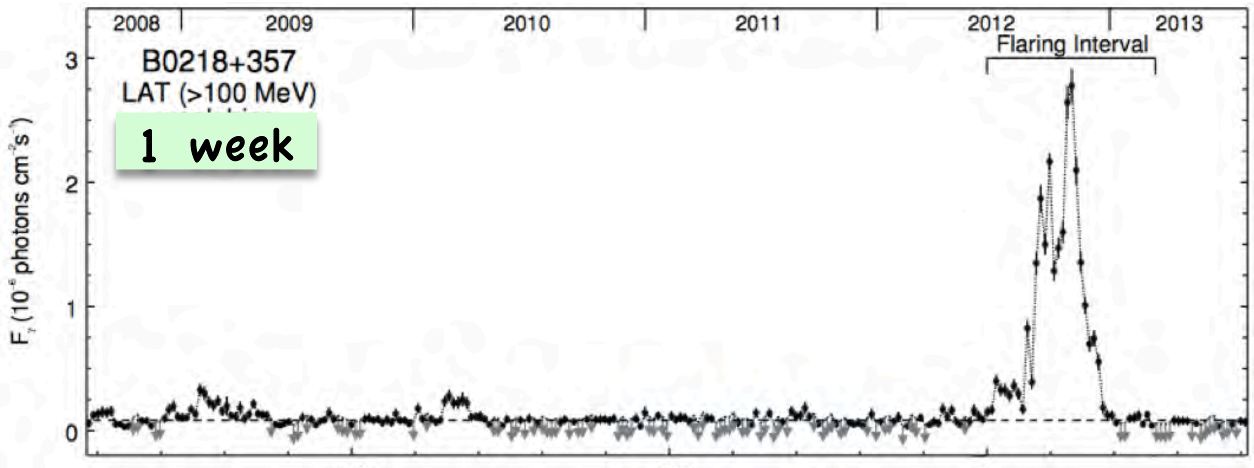
To be noted:

- Different spatial origin of the emission at different wavelengths
- Magnification ratio different for radio and gamma-ray emission
- Lower limit of ~6 in the gamma-ray flux ratio → upper limit on the size of the gamma-ray emitting region (in agreement with SED modeling)
- ALMA remarkable frequency-dependent behavior of the flux ratio of the two images (Marti-Vidal et al. 2013)

Flares of Lensed Blazar B0218+35

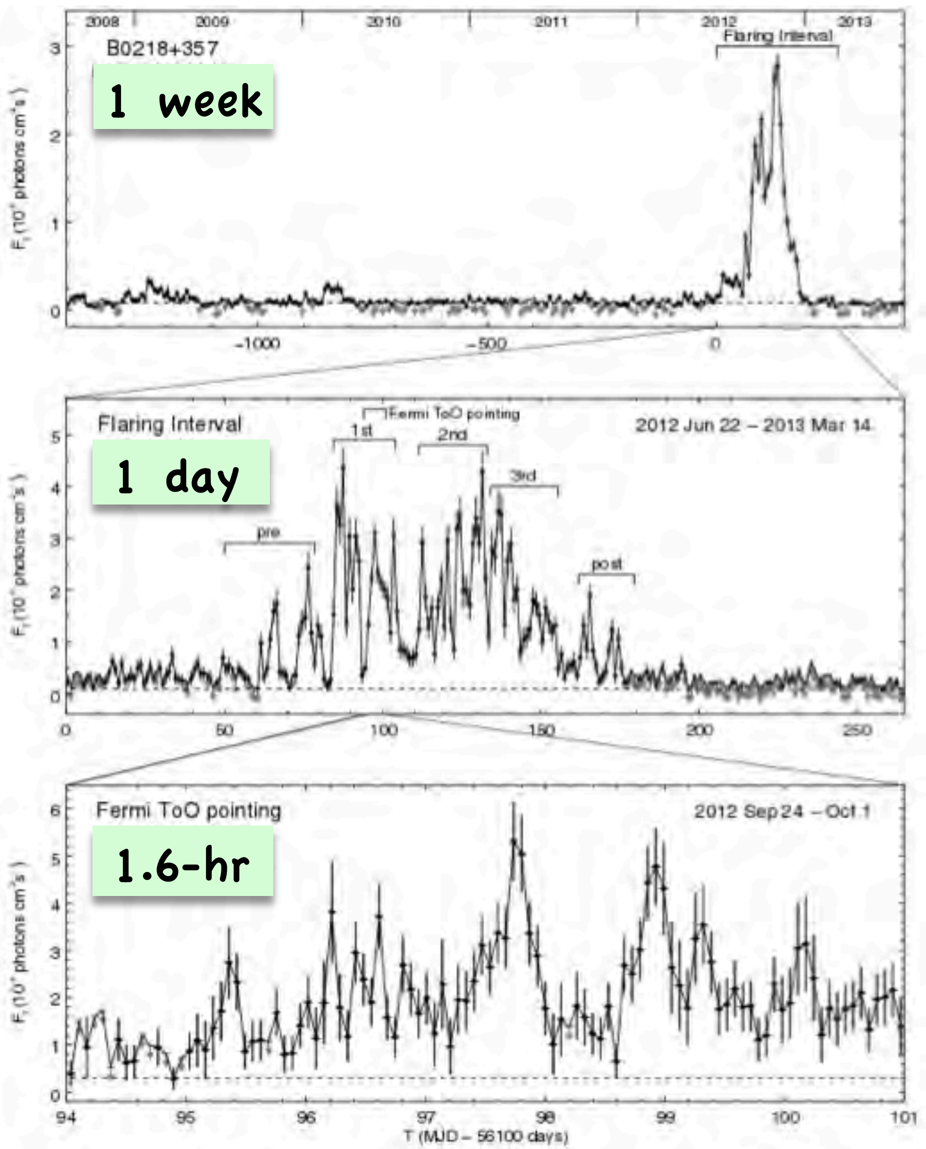


150 days



5 years

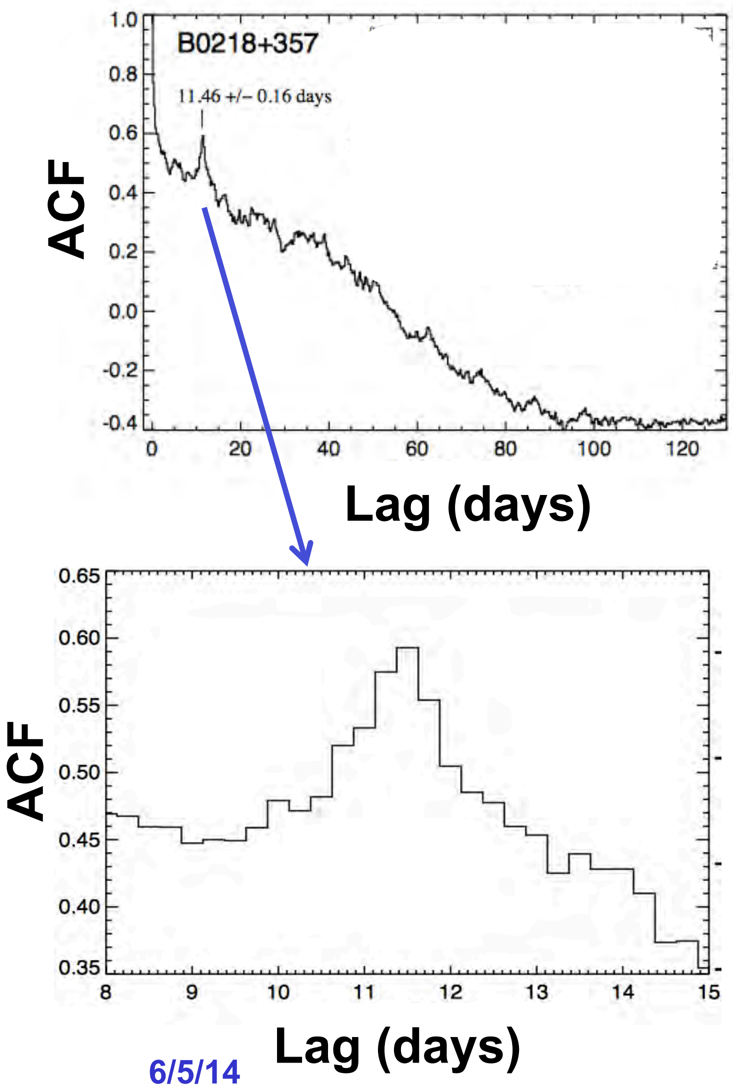
Flares of Lensed Blazar B0218+35

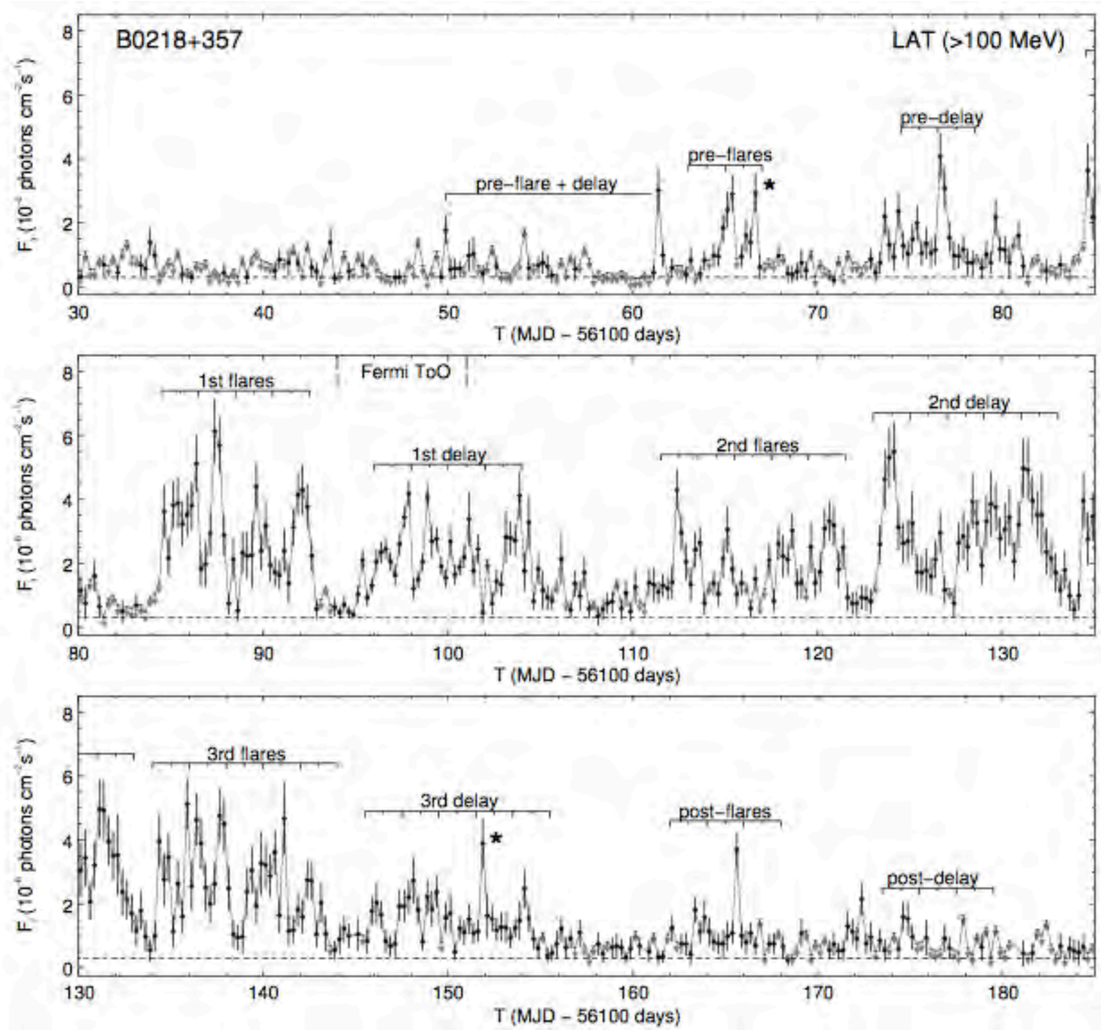


- Beginning around 2012 July, the Fermi LAT observed increased gamma-ray activity from the radio double-imaged gravitationally lensed blazar B0218+35
- FA **ATel issued** at the end of Aug 2012.
- A **simpler strong gravitational lens** more promising for time delayed event identification in gamma rays
- Sustained and bright gamma-ray flaring activity in late Aug.2012 through Sept.2012. Unique opportunity to identify and measure the expected gravitationally lensed delayed flare emission for the first time in gamma rays
- **LAT pointed observations** for the anticipated delayed emission epoch. Brightest flares with peaks ~60x its nominal flux at the end of September 2012.
- **Constrain the gamma-ray magnification ratio between the images**.

Flares of Lensed Blazar B0218+35

Structured gamma-ray light curve





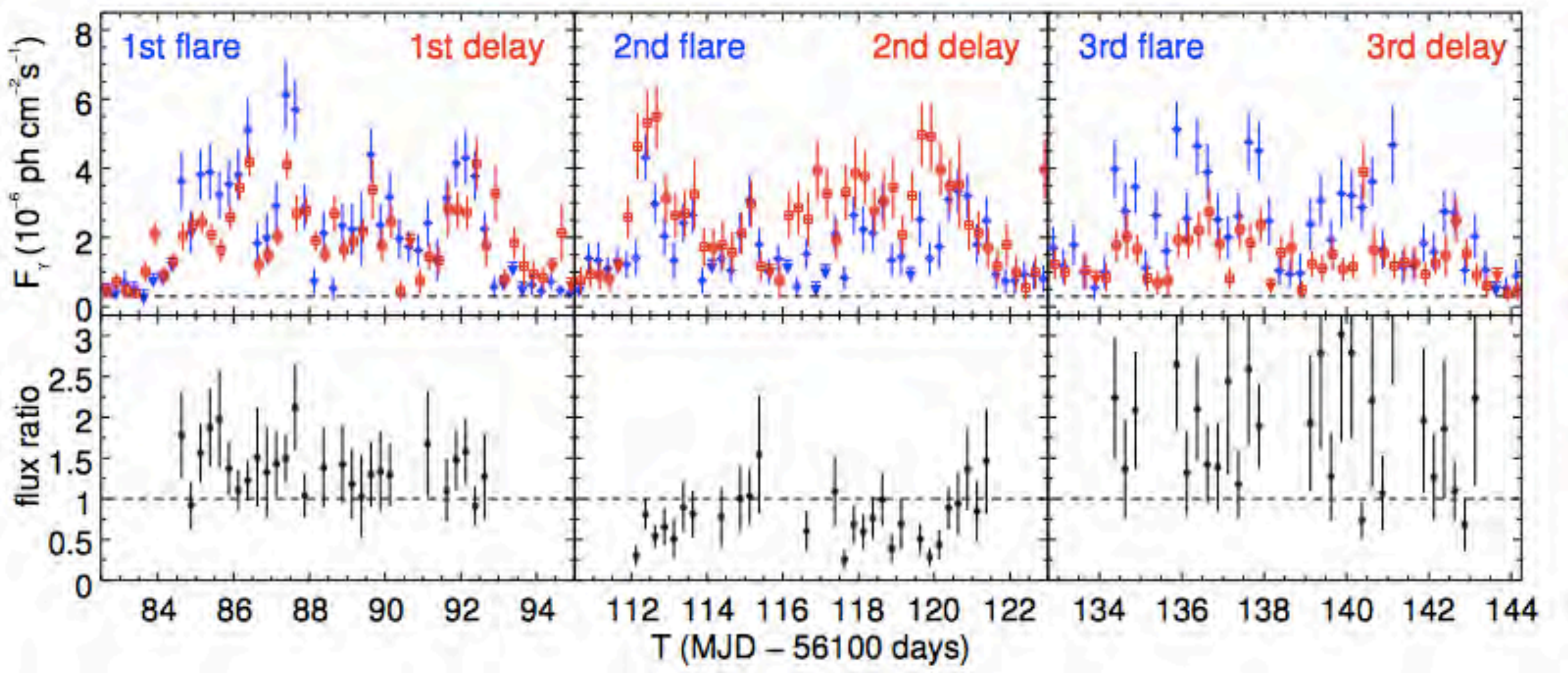
First gamma-ray delay measurement

B0218+35

Delay estimated = 11.46 +/- 0.16 days
Flux ratio = 1.16 +/- 0.07
Magnification ratio = 1.32 +/- 0.09

Cheung+ 2014, ApJL, 782, L14

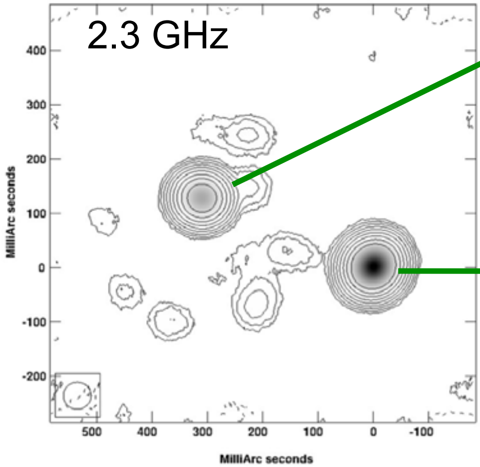
Flare emission divided by the observed flux ratio of 1.16 and shifted by +11.46 days to match the delayed emission

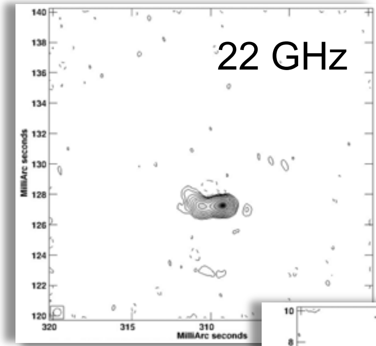


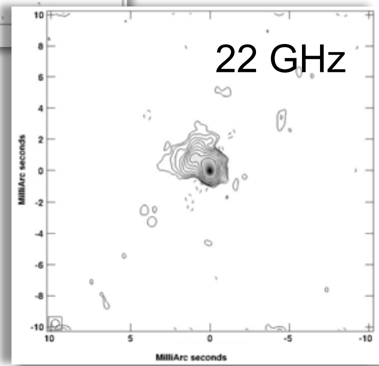
Radio Light Curve: stable emission

Observations (~60 days) at 2.3, 8.4 and 22 GHz simultaneous to gammma-ray flares:
→ **No evidence for radio flare**

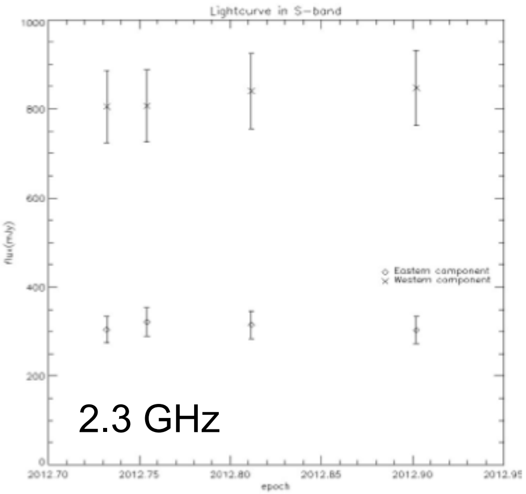
Opacity?
The flare may originate in the core region near the central black hole. While the core region is transparent to the gamma radiation, it is optically thick to the radio emission due to synchrotron self-absorption.

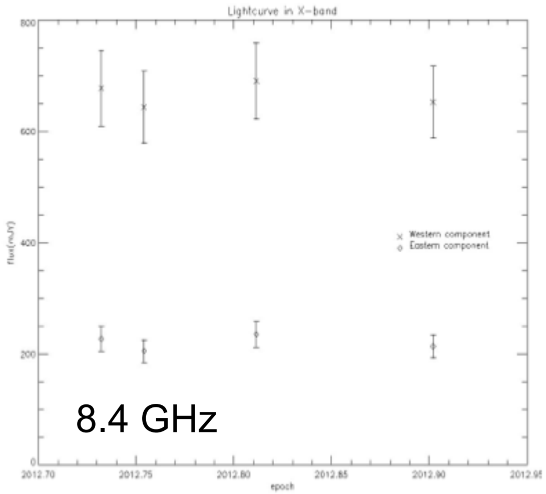


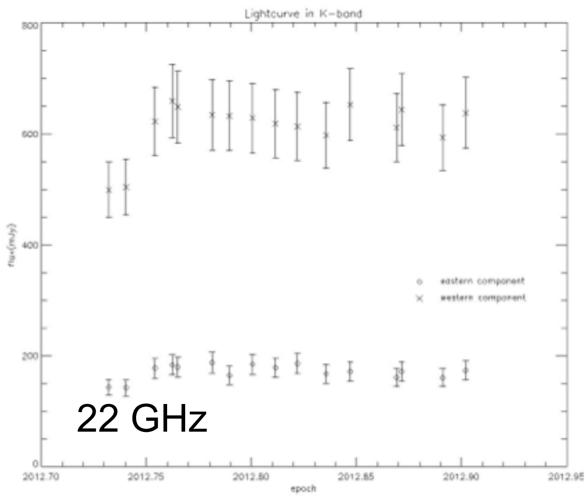




Spingola+2014 in prep.







Summary

P
K
S

1
8
3
0
-
2
1
1

- A gravitationally lensed bright gamma-ray blazar. Contrary to previous published claims we find **no substantial evidence for a time delayed** event from the second lens image in the LAT gamma-ray light curves (the expected delay of about 27 days with a flux magnification ratio of about 1.5 was not detected by the LAT).
- The flux ratio between the images at gamma rays must be significantly greater than 6. Magnification ratio could be different for radio and gamma-ray emission.
- Although macrolensing is achromatic, different magnification ratios are found in other lensed quasars (Blackburne06, Chen11), caused by microlensing substructure and complex multi-lensing system like PKS 1830-211 should be.

B
0
2
1
8
+
3
5

- **Multiple radio delays** published for this system with independent datasets & analysis methods giving: 12 +/- 3 day (Corbett et al. 1996) 10.5 +/- 0.4 day (Biggs et al. 1999), 10.1 (+1.5/-1.6) day (Cohen et al. 2000); reanalysis of Cohen + data: 9.9 (+4.0/-0.9) or 11.8 (+/- 2.3) day (Eulaers & Magain 2011).
- **Independent gamma-ray measurement of gravitational lens delay**.
- In radio, image A (brighter) leads image B (fainter) with A/B flux ratio ~3.7.
- In gamma-rays the observed flux ratio is smaller A/B ~1.2 .
- **Stable radio emission during gamma-ray flares.**

Future Perspectives

- Just under about 30 known lenses from JVAS/CLASS flat-spectrum radio source survey (16,500 objects). A fraction (~1/2) are doubles. **Delays from radio measured for ~5 with varying uncertainty.**
- Gamma-ray flares more pronounced with 1-day flares of ~4-10x common (compare to few-10% increases in radio). **LAT can provide independent and new delay measurements.**
- **LAT can discover new gravitational lens via gamma-ray temporal analysis**
  - **smaller separation ones than resolvable in CLASS 0.2” finding images**
  - **yet unidentified southern hemisphere sources**
  - **maybe radio-faint objects in unidentified (different magnification ratios at radio and gamma-rays)?**
- Strong gravitational lensing suggested as a tool to constrain the internal structure of blazar jets (Barnacka 2014)

- **Near future for Fermi, major upgrades:**
  - Pass 8: larger acceptance, better Point Spread Function at high energies and a wider energy range
  - will provide a dramatic improvement in capability for time-domain high-energy astronomy

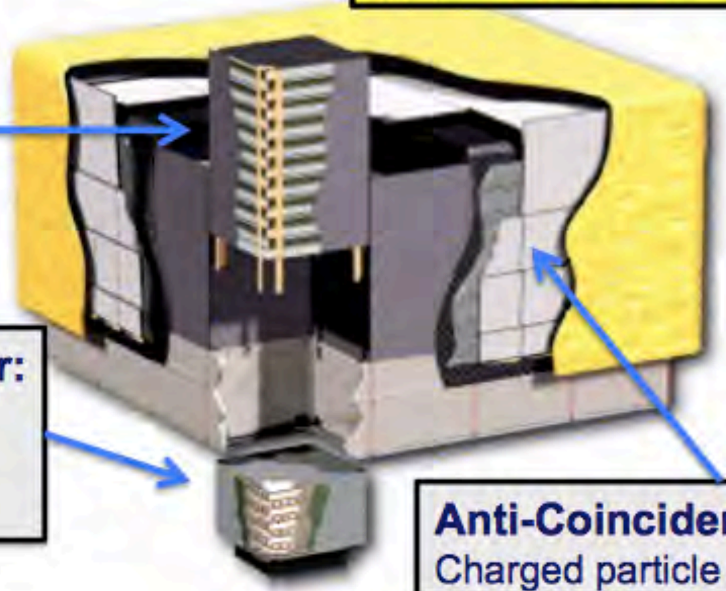
Back up

The Fermi Telescope

GBM (not pictured):
Covers entire un-occulted sky
from 8 keV to 30 MeV

***Fermi*-LAT Collaboration:**
~400 Scientific Members,
NASA / DOE & International
Contributions

Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM v. hadron separation



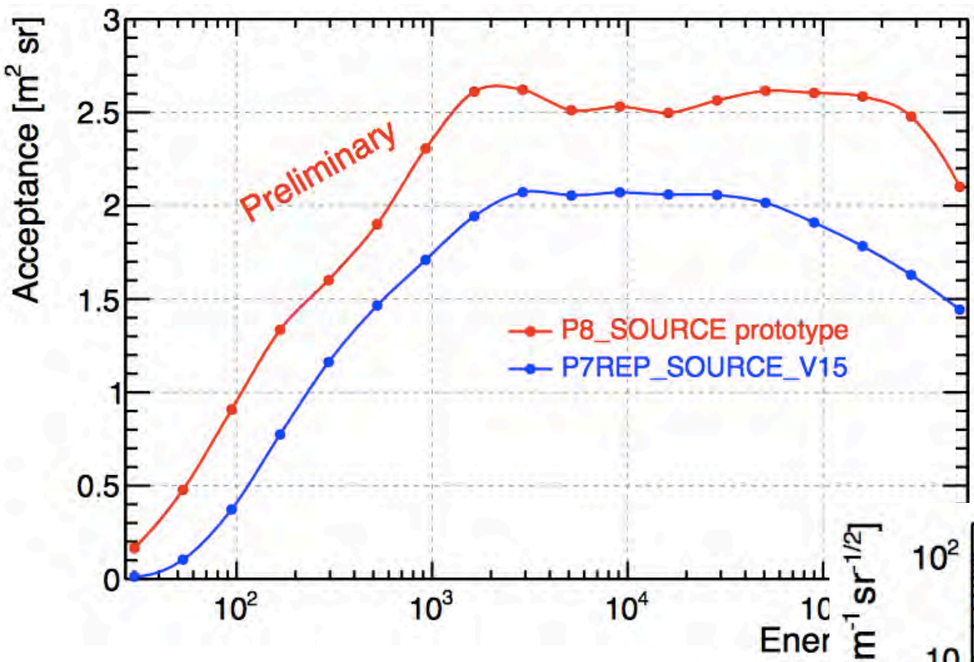
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

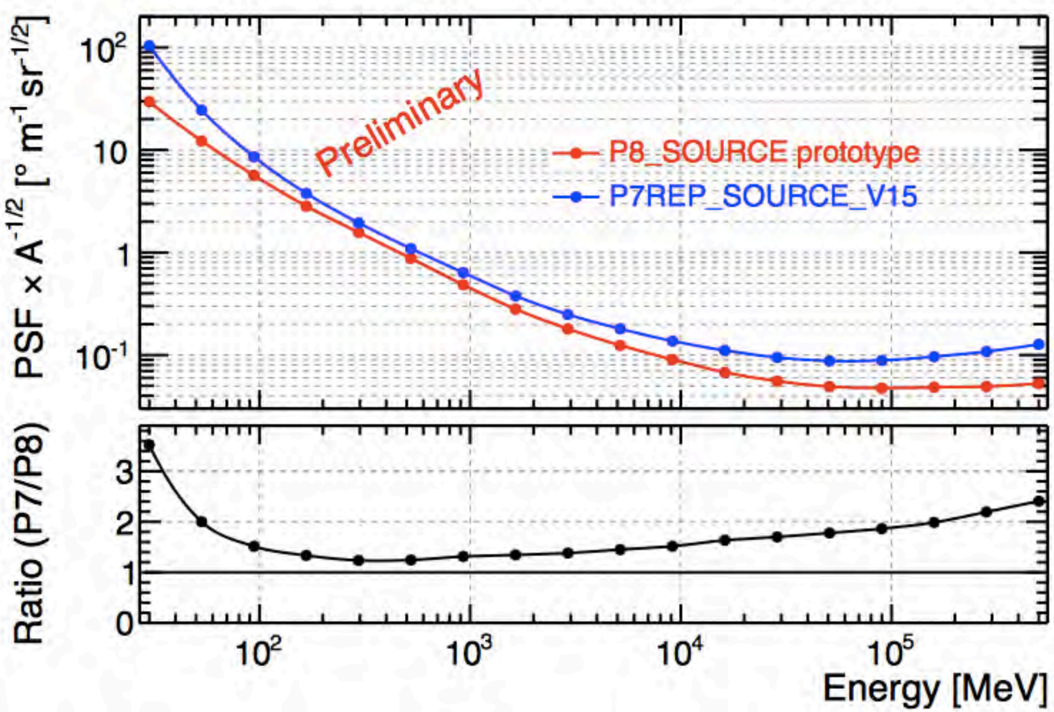
Sky Survey:
With 2.4 sr field-of-view LAT
sees whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz
to 300-500 Hz

Pass 8



Acceptance [m² sr]
Preliminary
P8_SOURCE prototype
P7REP_SOURCE_V15
Ener



PSF × A^-1/2 [° m^-1 sr^-1/2]
Preliminary
P8_SOURCE prototype
P7REP_SOURCE_V15
Ratio (P7/P8)
Energy [MeV]

PKS1830-211: the Blazar Itself

- Peculiarly asymmetric peak (fast rise, slower decay) for the gamma-ray outburst with a rise of a factor 2.6 in flux in 12h. Asymmetry of the main outburst might imply particle acceleration and cooling times that are greater than the light crossing time, or be evidence for a dominant contribution by EC radiation. A 2.5-day flux peak timescale appears to characterize the main outburst and the 2011 January second brightest flare.
- PDS spectrum has power law index 1.2, behavior closer to flickering fluctuations.
- ToO Swift observations. Hard X-ray spectrum (ph.index 1.2), no evidence for variability. No correlated X-ray and gamma-ray variability is somewhat typical for FSRQs.
- Mechanism producing gamma-ray flare not influenced the X-ray spectrum. The hard and soft X-rays are thought to be a combination of the contributions from SSC and EC processes.
- SED modeling: gamma-rays originate primarily from dust-torus EC process. Energy dissipation occurred far from the BLR.
- The gamma-ray behavior over the first 3 years of Fermi LAT operations can be attributed to intrinsic variability within the source, with no evident events caused by strong (macro) gravitational lensing.