An Optical 10-Year Data Archive for *Fermi* and the Masses

(Full Spectropolarimetric & Spectrophotometric Monitoring of γ-ray –Bright Blazars)

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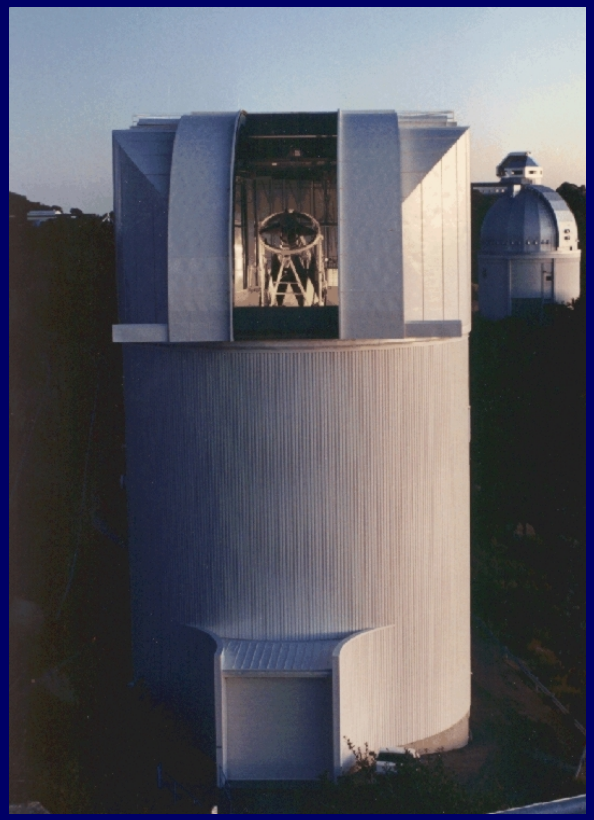
The Optical Monitoring Program at Steward Observatory (2008-2018)

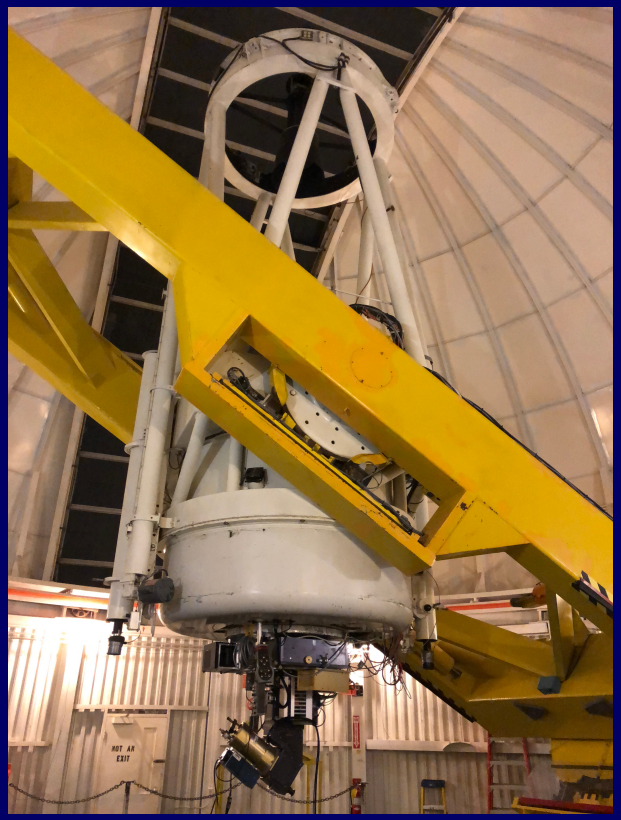
- **Goal – Provide the AGN research community with accurate & *public* spectropolarimetric & spectrophotometric monitoring data that *completely* characterizes the optical emission of γ-ray-bright blazars that *Fermi* can detect within one or a few days.**
- **Priority was placed on *polarimetry*, as it yields direct information on the magnetic field of the nonthermal emission region(s).**
- **Since γ-ray and optical variability is significant on short time scales, the optical monitoring was nightly. For blazars showing significant γ-ray/optical activity, multiple optical measurements were made during the night if possible.**
- **~Week-long observing campaigns were scheduled every month (excluding August) to keep track of the longer-term trends of the sample.**

The equipment used for the monitoring:

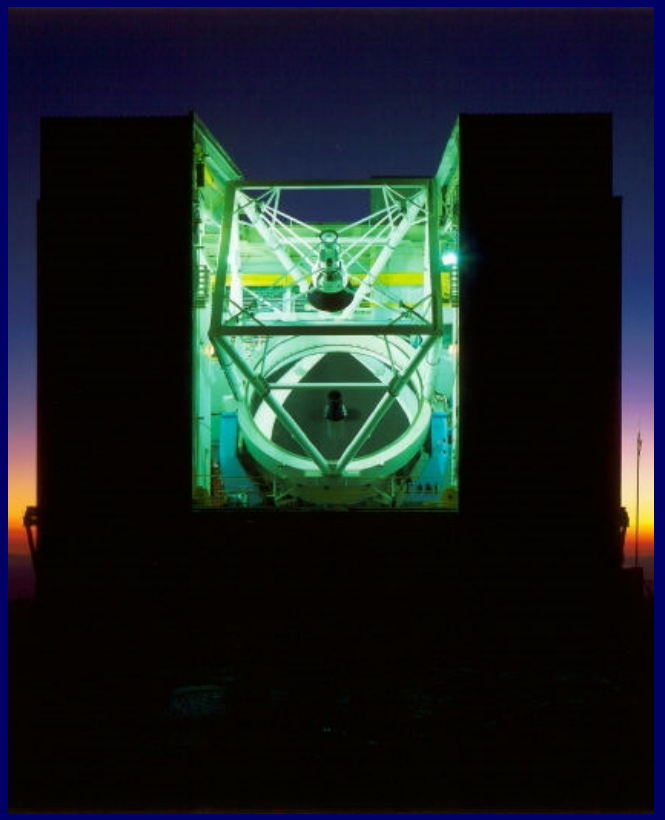
Telescopes –



Bok 2.3m Telescope, Kitt Peak, AZ (elev.=2071m)

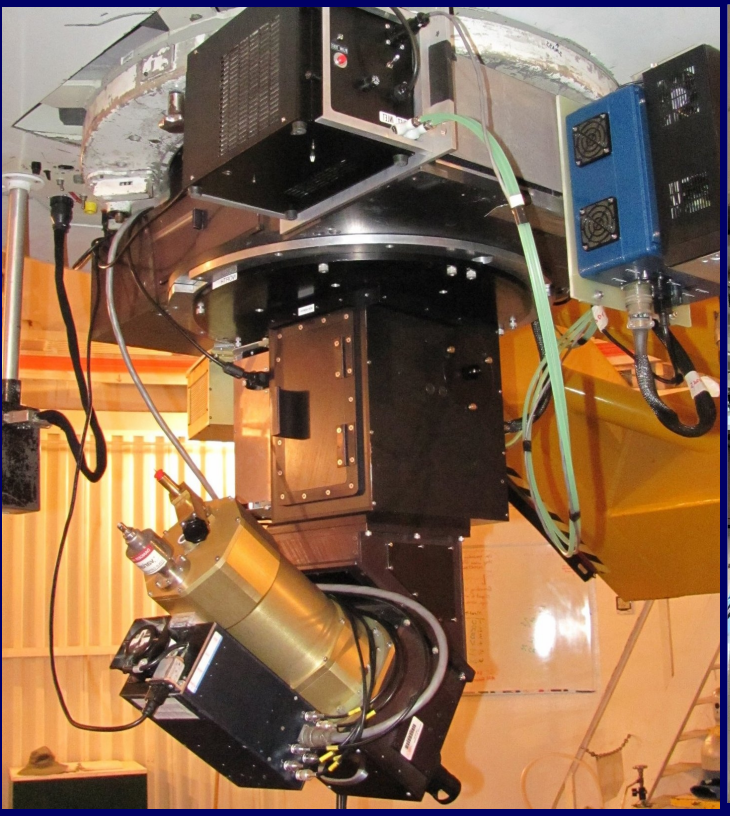


Kuiper 1.54m Telescope, Mt. Bigelow, AZ (elev.=2510m)



6.5m MMT, Mt. Hopkins, AZ (elev.=2606m)

“SPOL” CCD Spectropolarimeter was used for ALL observations.



Portable **dual-beam polarimetry by G. D. Schmidt and H. S. Stockman (telescope+instrument total throughput ~ 30%; very low (<0.05%) instrumental polarization; first light in 1991)**

Examples of individual observations with SPOL:

Blue spectra:

- 320 s total exposure time (R ~ 13.0) at 1.54m Kuiper telescope; P = 2%

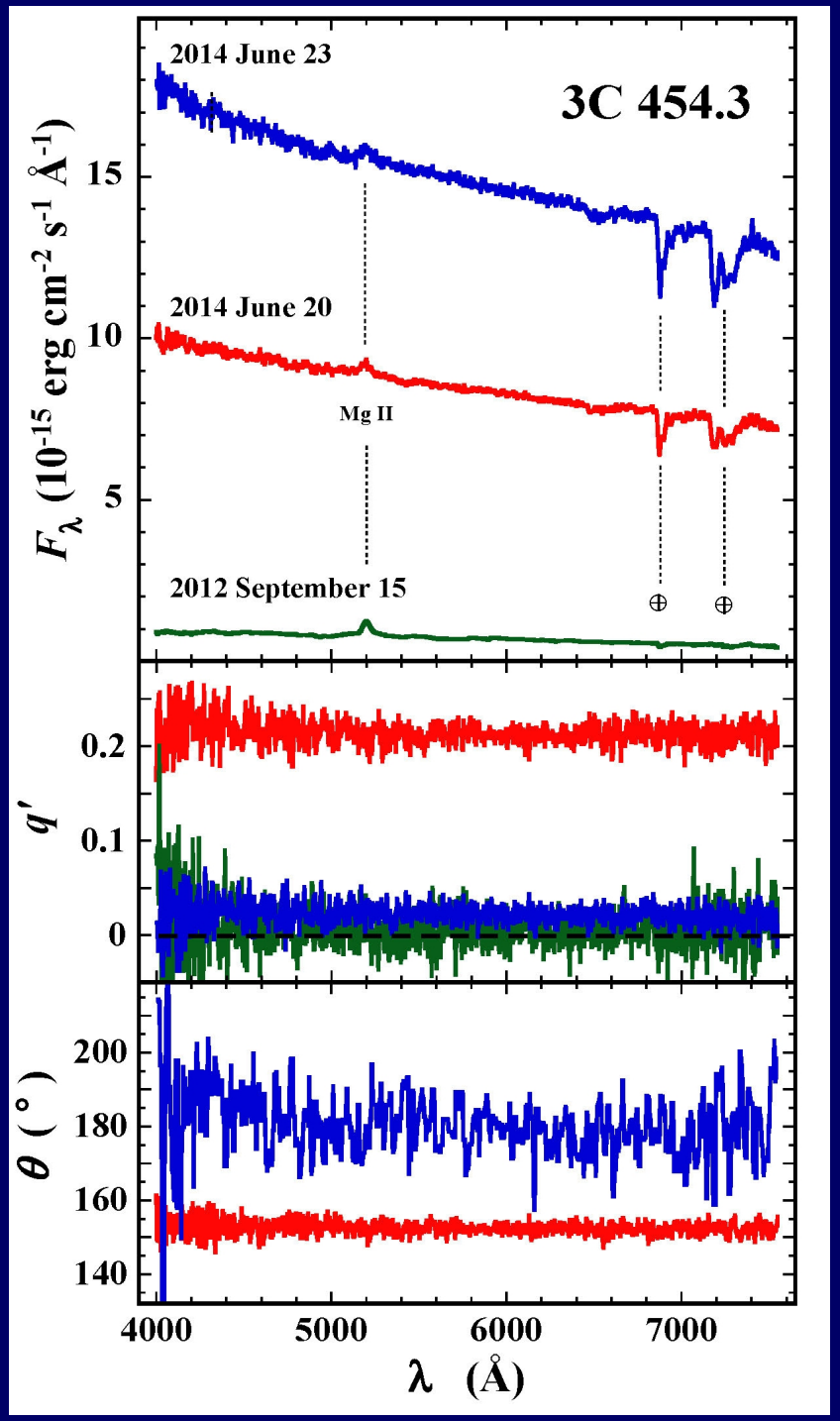
Red spectra:

- 480 s total exposure time at Kuiper telescope (R ~ 13.6); P = 21%

Green spectra:

- 1440 s total exposure time at 2.3m Bok telescope (R ~ 16.3); P ~ 0.6%

σ(P) < 0.1% if data binned by 2000 Å (5000-7000 Å).



The scale of the program (how *hard* did we work?)

- 112 monthly optical campaigns completed from 2008 Oct − 2018 July
- Obtained data on 836 nights (*Fermi* "nights" = 3586)
  - 454 nights with the Kuiper 1.54m Telescope
  - 357 nights with the Bok 2.3m Telescope
  - (25) nights with the 6.5m MMT

- 12,747 polarization measurements
- Roughly 10,000 differential photometry measurements in both *V* and *R* bands
  - 80% of the time when polarimetry acquired, photometry was also possible
- Over 12,000 Stokes *I*, *Q*, & *U* spectra available
  - Spectra span 4000–7550 Å; $\lambda/\Delta\lambda \sim 350$

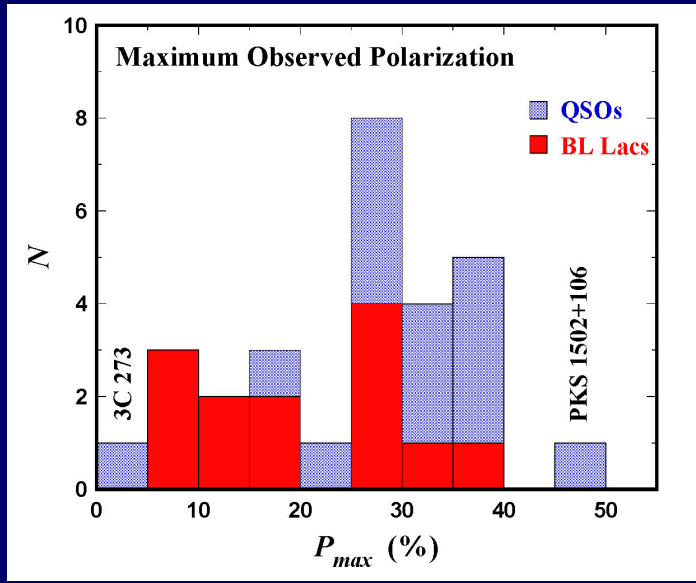
- Data are public at http://james.as.arizona.edu/~psmith/Fermi

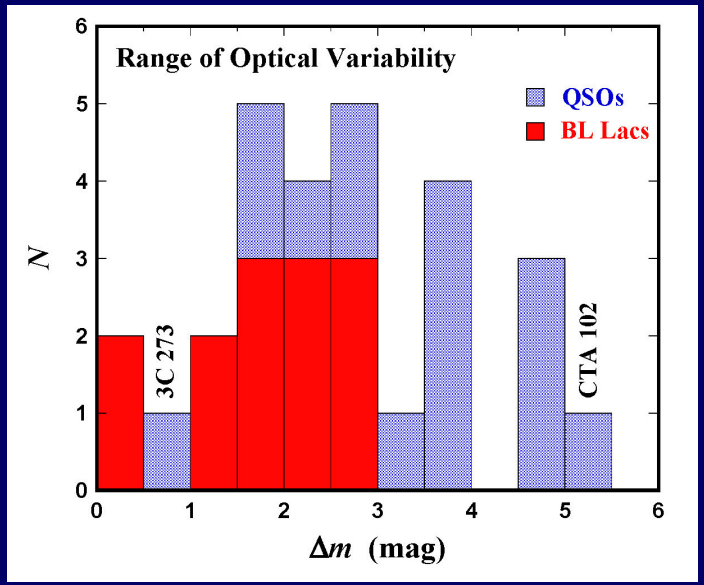
The Blazar Sample

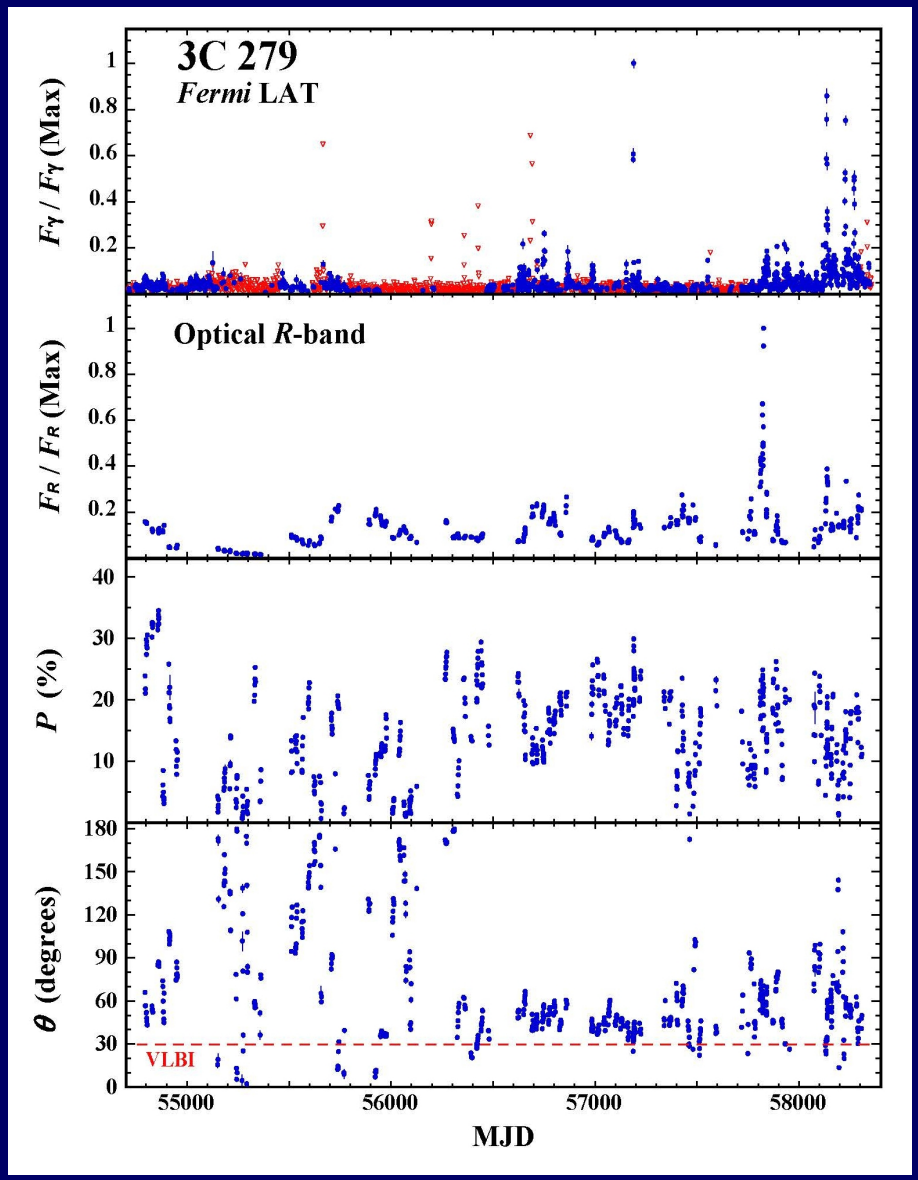
- **80 blazars were observed. (although 28 observed on <10 nights)**
- **Core sample (*least biased*):**
  - **28 objects observed on every night possible regardless of optical or γ-ray activity.**
  - **All objects observed on over 100 nights (most > 300 nights) spanning >1100 days (most > 3000 days)**
  - **Includes favorites like, e.g., 3C279, 3C454.3, BL Lac, Mrk421, OJ287, …**
- **Generally optically fainter blazars while in optical/γ-ray outburst (more deficient in optical measurements when faint)**
- **Objects added to the observing list when the LAT started to detect them daily, or objects dropped because of persistent inactivity in γ-rays and/or impossibly faint optical flux levels.**
  - **e.g., PKS0736+01, 4C28.07, H1426+428, BZU J0742+5444**
- **ToO observations generally initiated by *Fermi*, TeV, or neutrino detection-related ATELs.**
  - **e.g., PKS1441+252, *TXS0506+056***

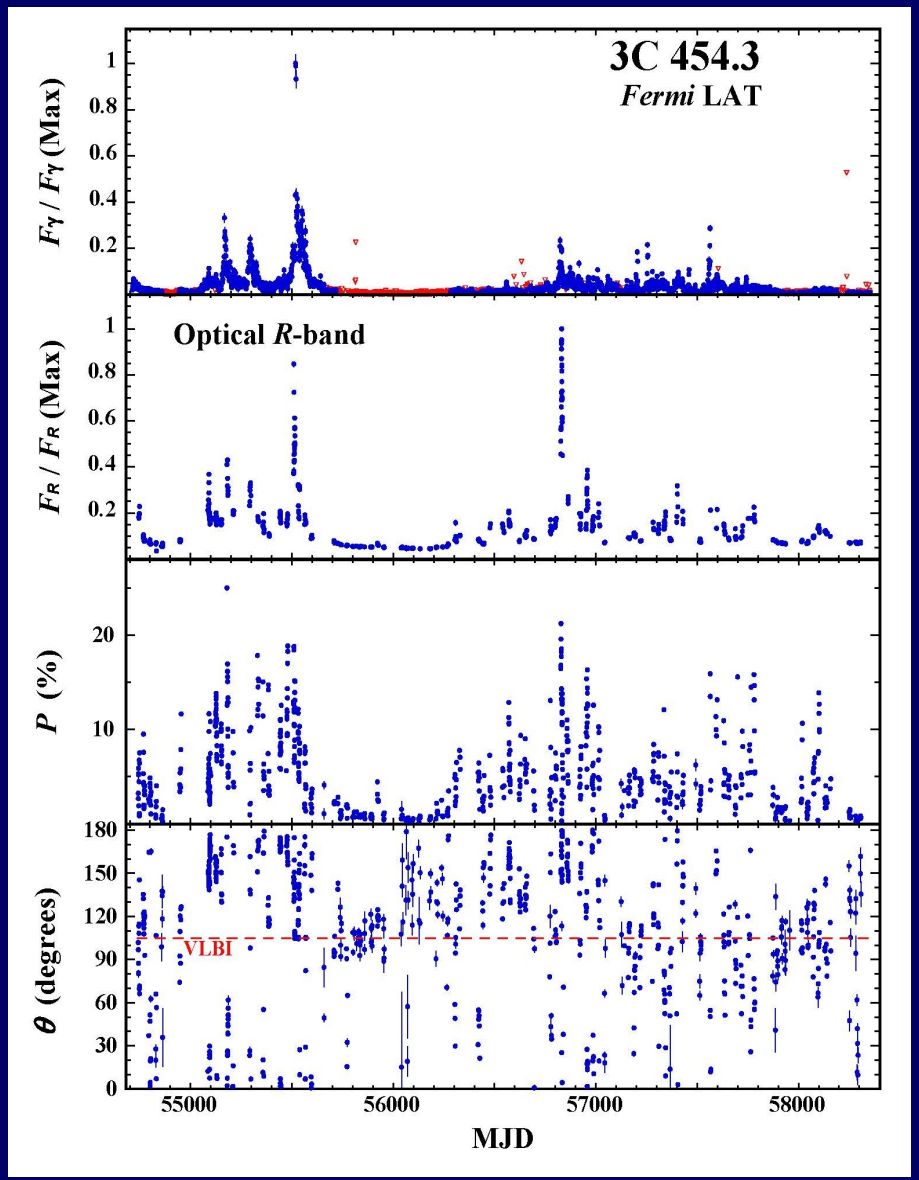
Basic Statistics for the "Core" Sample

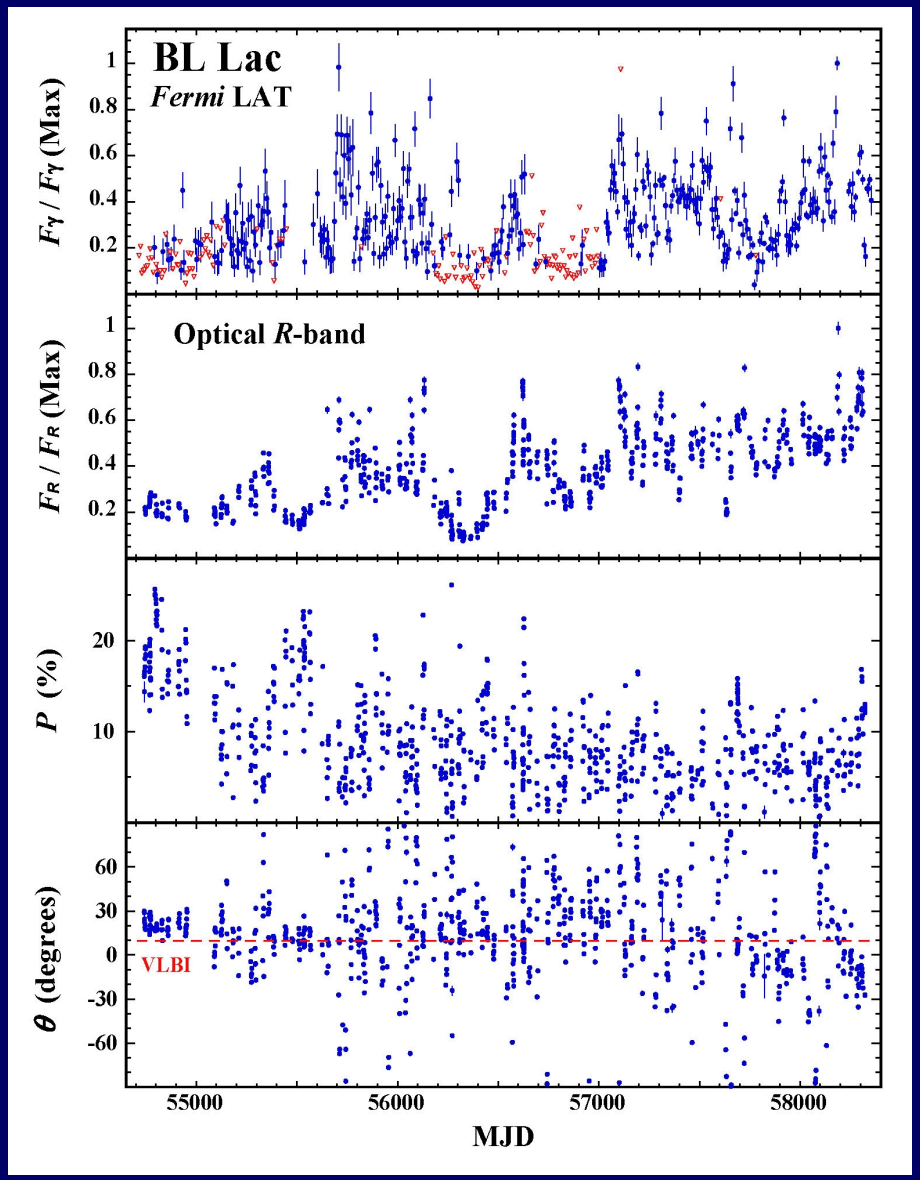
- Maximum level of polarization (P_{max})
  - 1/28 with $P_{max} > 40\%$ (PKS1502+106: did this *twice* ~9 yrs. apart)
  - BL Lacs with $P_{max} < 10\%$ have strong starlight contributions from host galaxy
  - Optical light from 3C273 dominated by isotropic "QSO" emission.
- Minimum level of polarization
  - 14/28 with $P < 0.5\%$
  - 27/28 with $P < 1\%$
  - S3 1227+25 had minimum P of ~2%
- Range of Flux Variability
  - 1/28 with $\Delta m > 5$ (CTA 102: $\Delta m \sim 5.5$)
  - Majority of strong emission-line blazars have $\Delta m > 3$
  - Variability of all BL Lacs < 3 mag
  - Least variable BL Lacs muted by host galaxies.

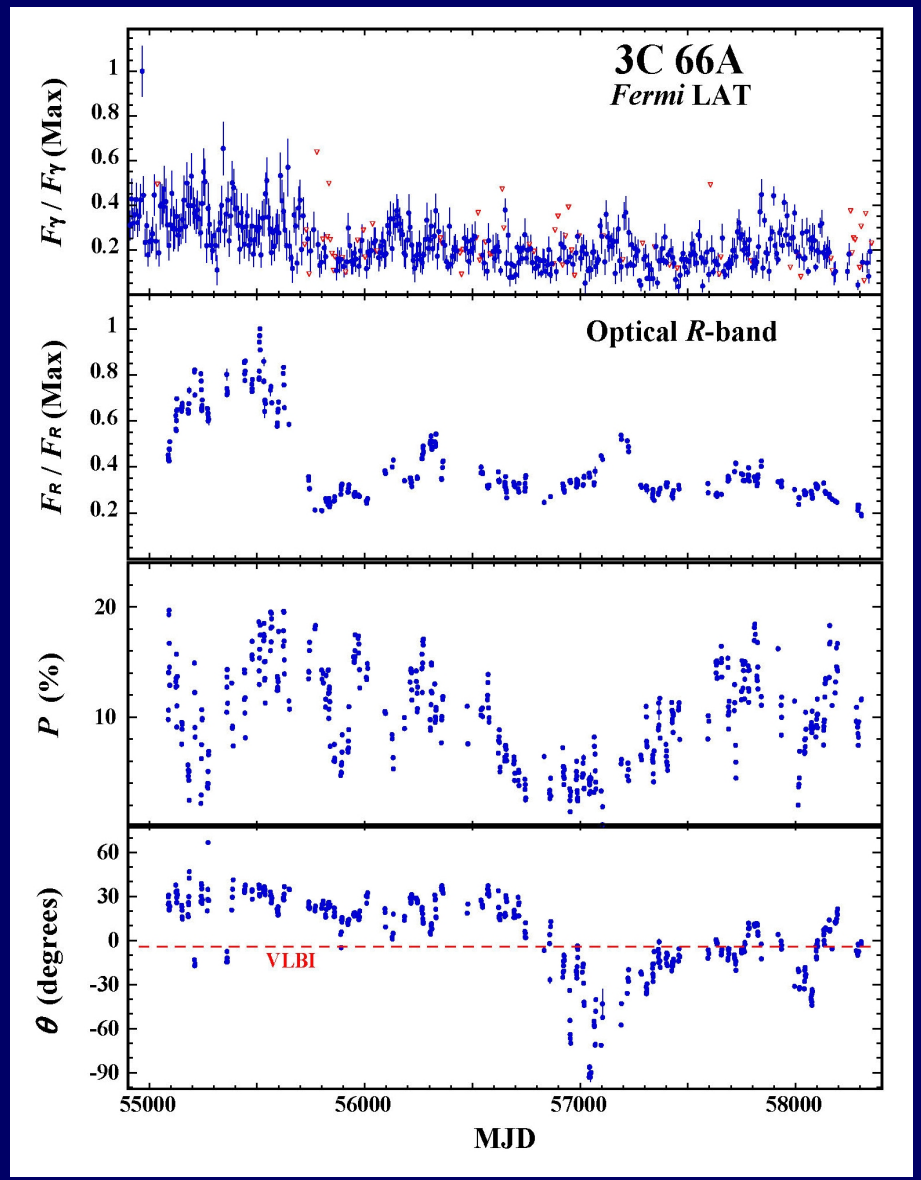


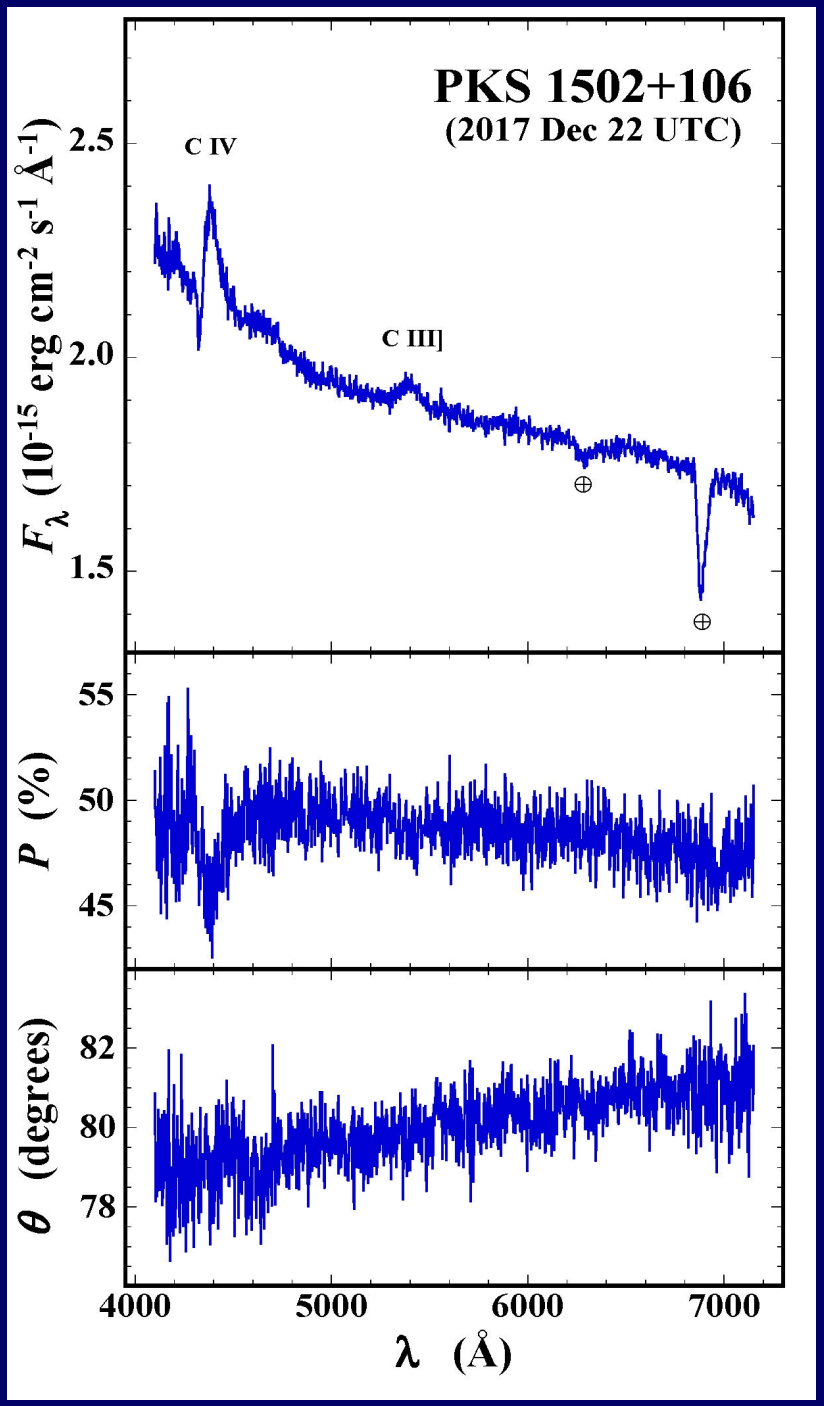


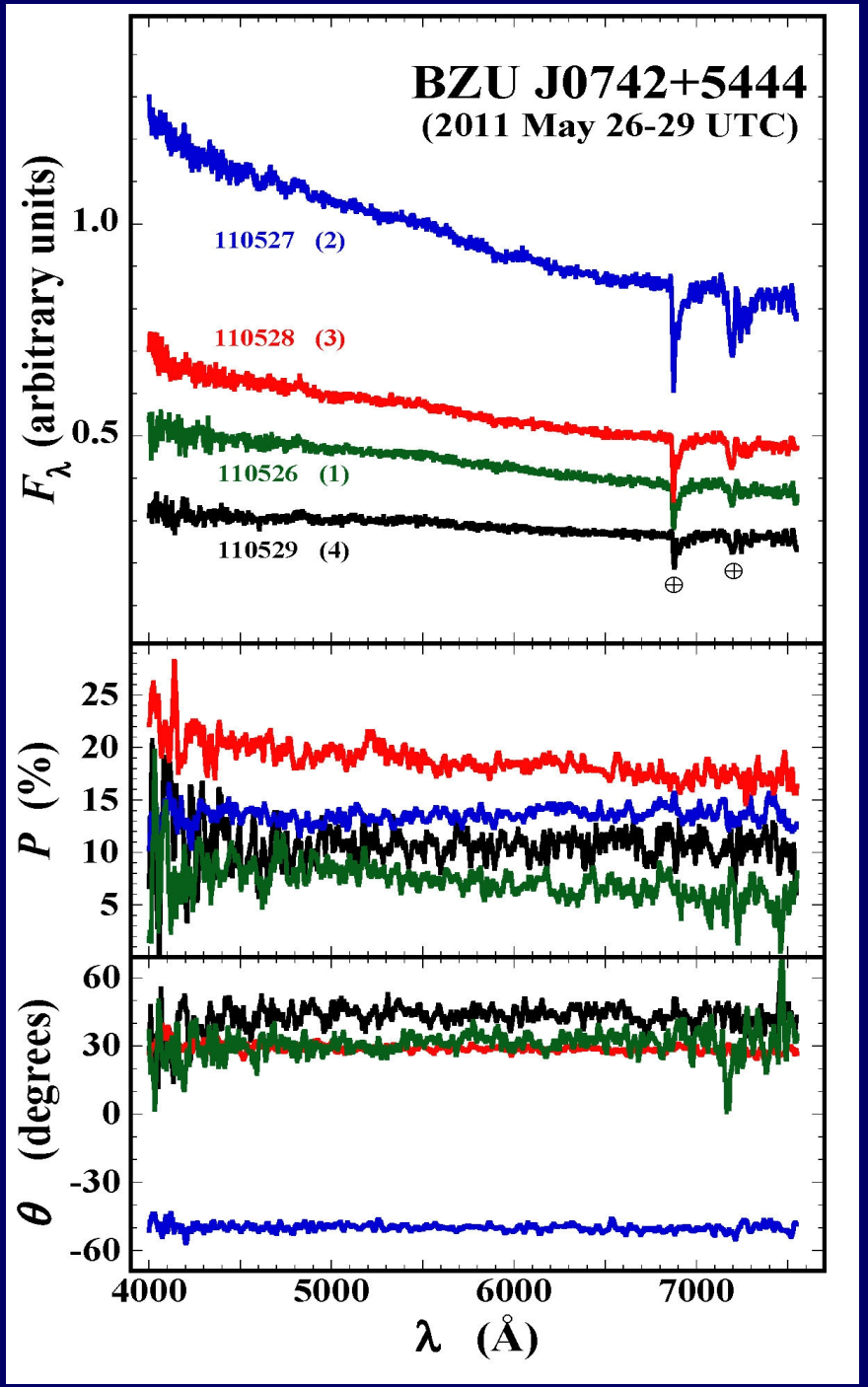

3C 279
Fermi LAT
Fγ / Fγ (Max)
Optical R-band
FR / FR (Max)
P (%)
θ (degrees)
VLBI
MJD

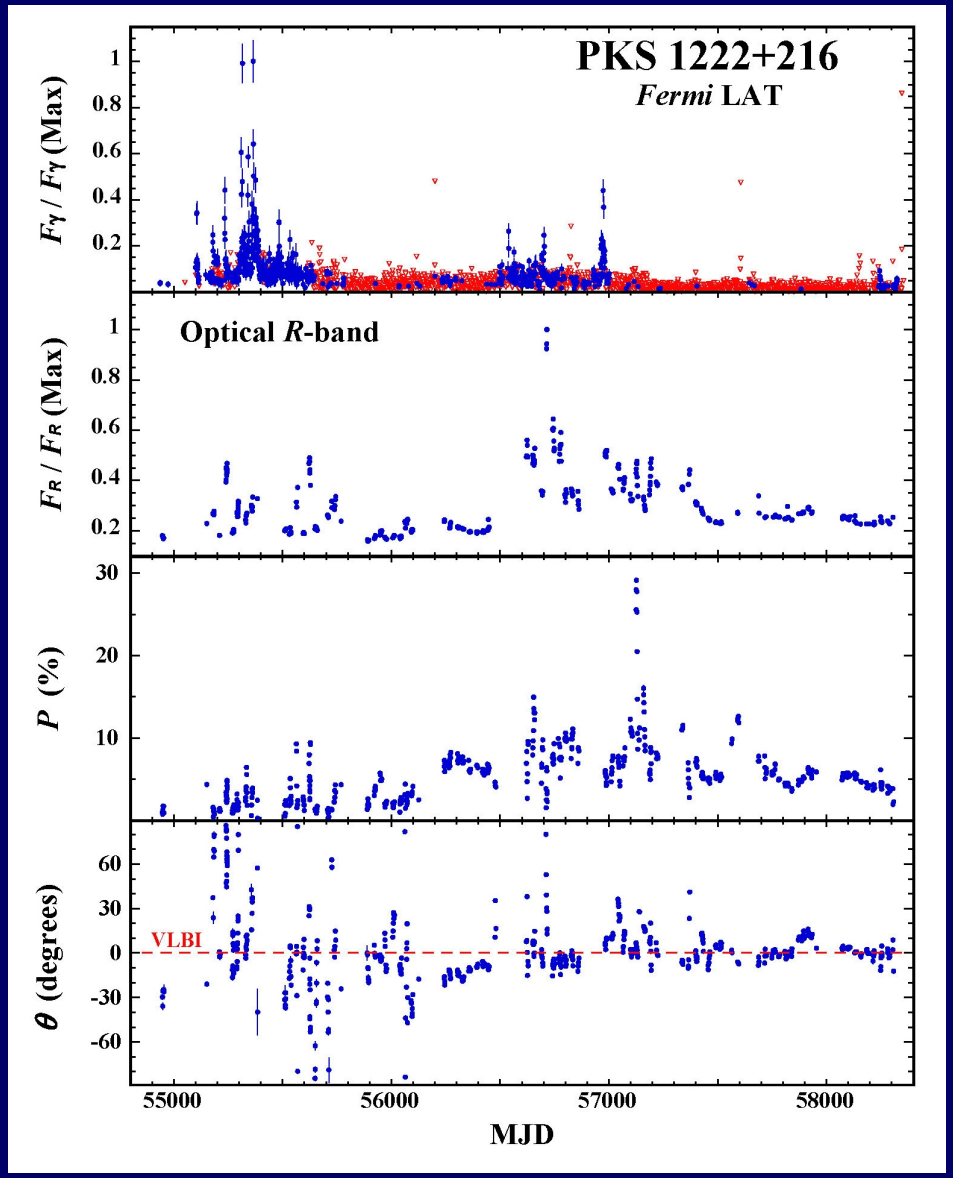

3C 454.3
Fermi LAT
Fγ / Fγ (Max)
Optical R-band
FR / FR (Max)
P (%)
θ (degrees)
VLBI
MJD

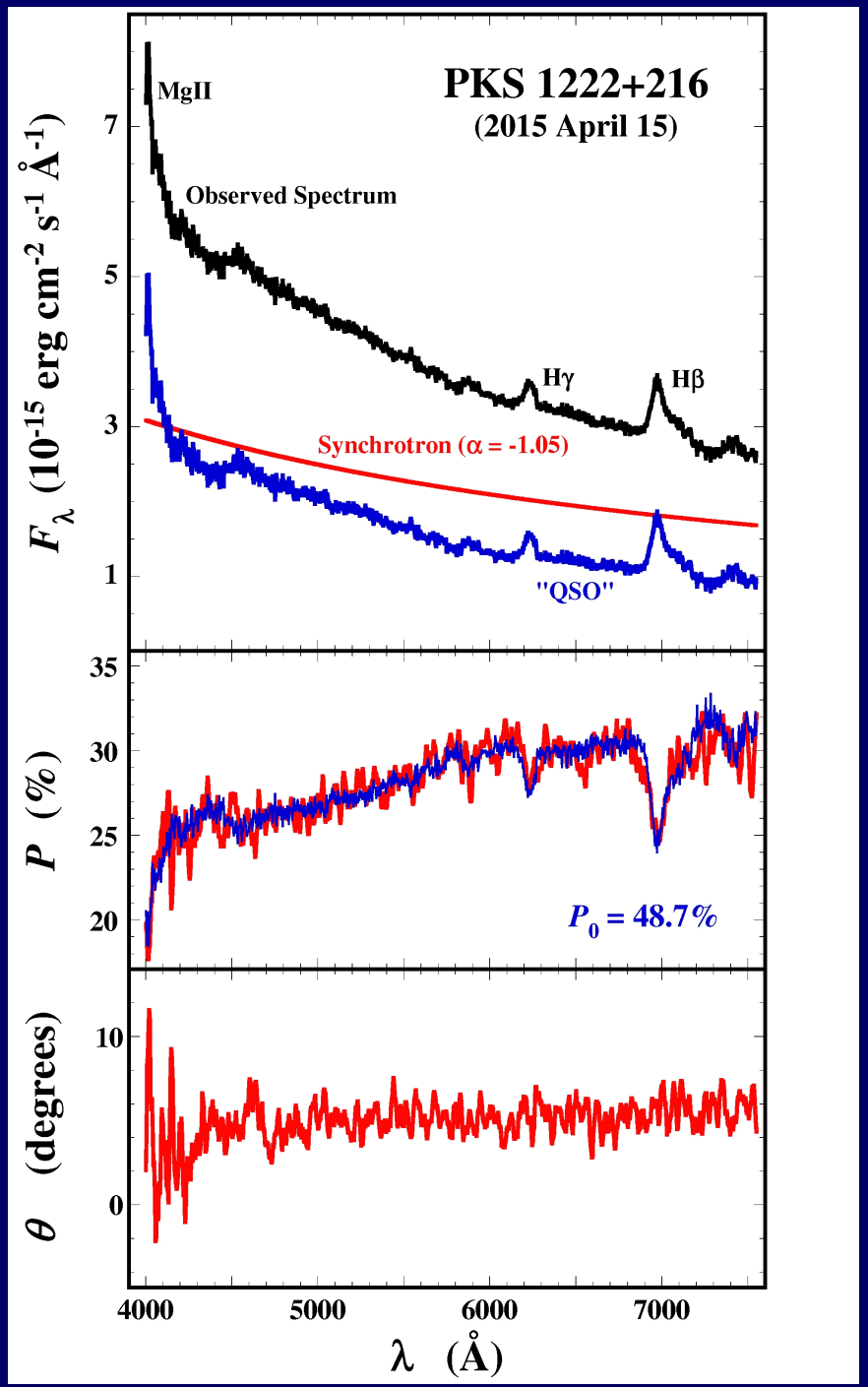

BL Lac
Fermi LAT
Fγ / Fγ (Max)
Optical R-band
FR / FR (Max)
P (%)
θ (degrees)
VLBI
MJD


3C 66A
Fermi LAT
Fγ / Fγ (Max)
Optical R-band
FR / FR (Max)
P (%)
θ (degrees)
VLBI
MJD


PKS 1502+106
(2017 Dec 22 UTC)
C IV
C III]
F_λ (10^{-15} erg cm^{-2} s^{-1} Å^{-1})
2.5
2.0
1.5
⊕
⊕
P (%)
55
50
45
θ (degrees)
82
80
78
4000
5000
6000
7000
λ (Å)


BZU J0742+5444
(2011 May 26-29 UTC)
F_λ (arbitrary units)
1.0
0.5
110527 (2)
110528 (3)
110526 (1)
110529 (4)
⊕
⊕
P (%)
25
20
15
10
5
θ (degrees)
60
30
0
-30
-60
4000
5000
6000
7000
λ (Å)

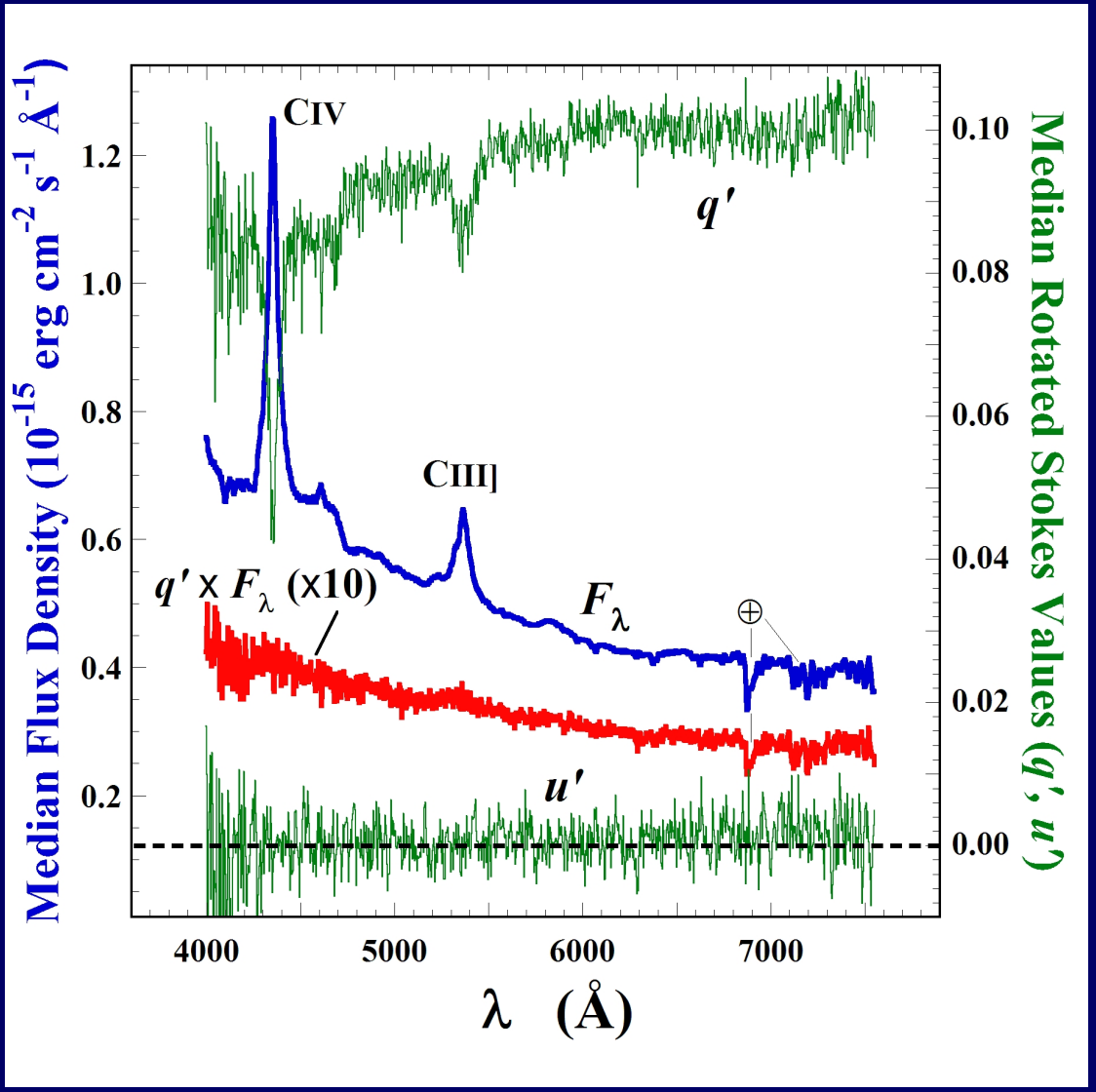

PKS 1222+216
Fermi LAT
Fγ / Fγ (Max)
Optical R-band
FR / FR (Max)
P (%)
θ (degrees)
VLBI
MJD


PKS 1222+216
(2015 April 15)
MgII
Observed Spectrum
Hγ
Hβ
Synchrotron (α = -1.05)
"QSO"
Fλ (10-15 erg cm-2 s-1 Å-1)
P (%)
P0 = 48.7%
θ (degrees)
λ (Å)

B2 1633+382 (4C 38.41; z = 1.814; see Raiteri *et al.* 2012)

- The effect on the polarization spectrum by (presumably) unbeamed and unpolarized emission has been traced for objects down to a rest wavelength of ~1400 Å.

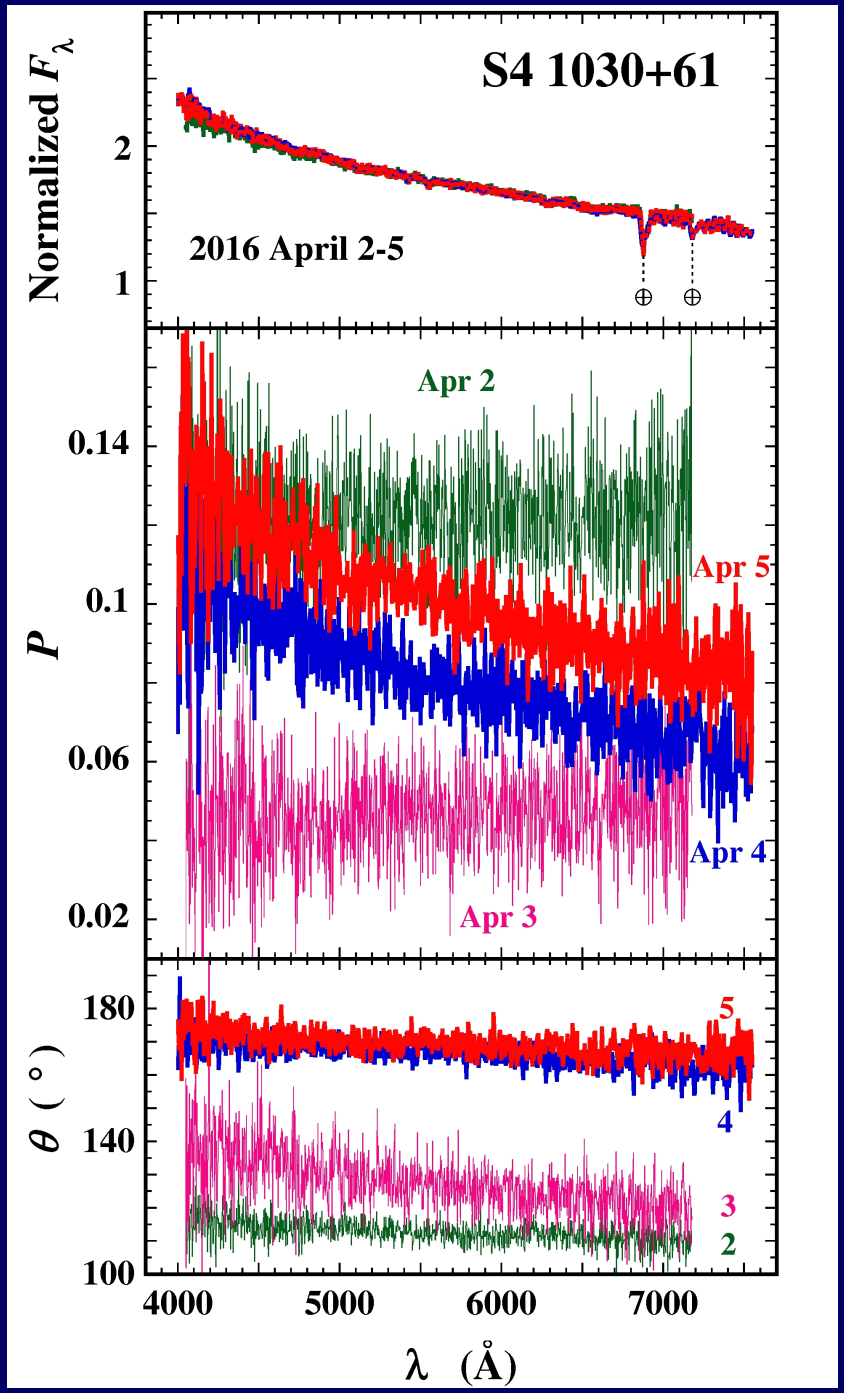
- Observations of blazars with strong emission lines are consistent with their optical-UV continuum emission coming from a combination of polarized synchrotron light from the jet and a "normal" (unpolarized) QSO.



Episodes of Variable λ-dependent Polarization:

- Although relatively rare, these events give insights into the evolution of the synchrotron emission region that the flux spectrum and its variations do not.

- This example from S4 1030+61 shows that dramatic, daily changes can occur in the polarization spectrum without any change in the shape of the non-thermal flux spectrum.



Acknowledgments

- **Steward Observatory and its TAC for making the huge investment of telescope time needed for success.**
- **The Steward Observatory staff (until 2016 led by the late Robert L. Peterson) for keeping the Bok and Kuiper telescopes in top operating form.**
- **The *Fermi* Guest Investigator Program for realizing the unique opportunity enabled by *Fermi* for multi-wavelength studies of AGNs.**
- **The *Fermi* project for designing and operating a mission that is ideal for the study of very challenging questions raised by blazars.**
- **Researchers that have used these optical data in their work.**

Reminder: Before (and probably after) formal publication of the data archive, you can find all of these data at

http://james.as.arizona.edu/~psmith/Fermi