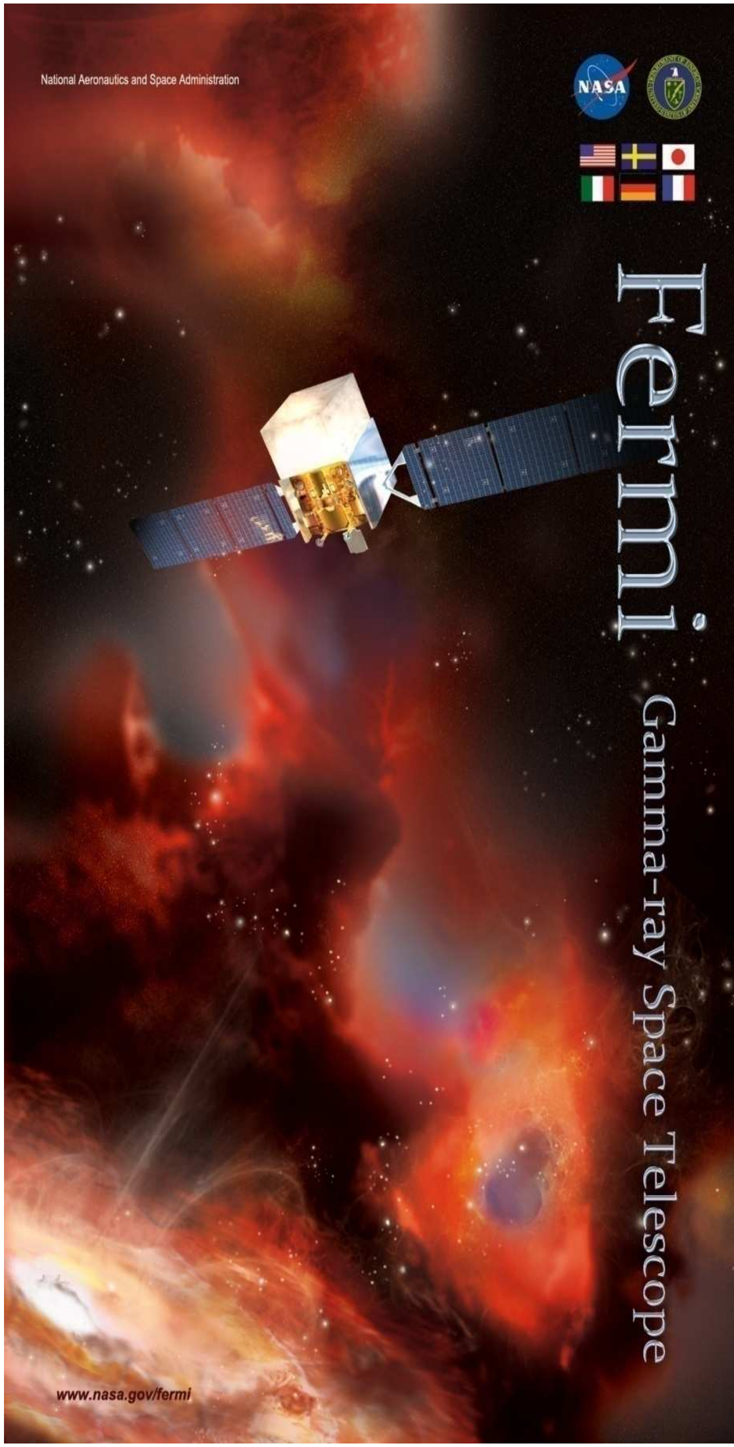

Long-Term Variability of Radio, Optical and Gamma-ray Emission of PG 1553+113 with the *Fermi* LAT

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Fifth International Fermi Symposium, October 20-24, 2014
Higashiyama Campus, Nagoya University, Nagoya, Japan

PG 1553+113: introduction

- PG 1553+113 (a.k.a. 1ES 1553+113)*, is an optically-selected BL Lac object reported in Green, Schmidt & Liebert 1986, ApJS, 61, 305. First citations of this blazar dates back to mid '80s (source seen by IRAS Neugebauer et al. 1986, ApJ 308, 815). BL Lac object classification (featureless optical spectrum, Miller & Green 1983, significant optical variability, Miller et al. 1988).
- PG 1553+113 is placed in the Serpens Caput constellation.
- The first fully source-dedicated paper is Falomo & Treves 1990, PASP, 102, 1120.
- The first radio catalogs including this source are the MIT-Green Bank 5 GHz survey catalog (MG or MG1) and the Texas survey of radio sources catalog (TXS).

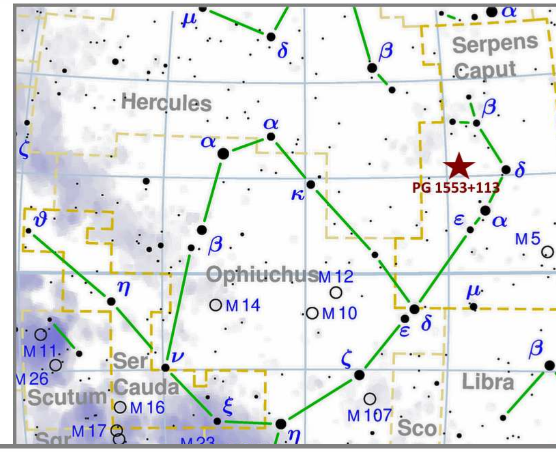

TABLE 5—*Continued*

R.A.(1950)	Dec.	Bpg	B lim	Comment	Class		B	U−B	B−V	v
15 52 08.5	+46 02 17	16.54	0.		sd					
15 52 19.2	+08 31 06	16.02	16.04	0.119	QSO					
15 52 52.8	+46 25 45	16.01	0.		sdOD	*				
15 53 08.7	+35 22 07	14.72	16.28		DA 3					14.71
15 53 20.9	+11 20 04	14.83	16.08		BLL					
15 53 21.3	−07 39 43	14.23	15.92		sdOB					14.94
15 53 33.3	+27 15 28	13.23	15.75		sdB		13.41	−0.84	−0.12	
										16.21
										16.82

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 61:305–352, 1986 June
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THE PALOMAR-GREEN CATALOG OF ULTRAVIOLET-EXCESS STELLAR OBJECTS

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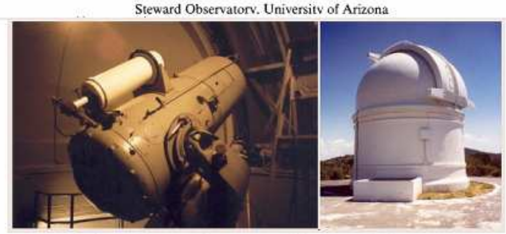

Palomar 18 inch (46 cm) Schmidt telescope

* Note:
- PG: Palomar-Green Bright Quasar Catalog + Palomar-Green catalog of ultraviolet-excess stellar objects (1976-1986). → The PG name origin.
- IRAS: Quasars measured by the Infrared Astronomical Satellite (1986). → IRAS B1553+113
- MG (MG1): The MIT-Green Bank (MG) 5 GHz survey (1986). → MG 1555+1110 / MG1 J155545+1110
- TXS: Texas Survey of Radio Sources (1974-1983). → TXS 1553+113
- 1ES: Einstein IPC Slew Survey Source Catalogue (1992). → The 1ES name origin.
- RX: ROSAT X-Ray source list (>1992). → RX J1555.7+1111

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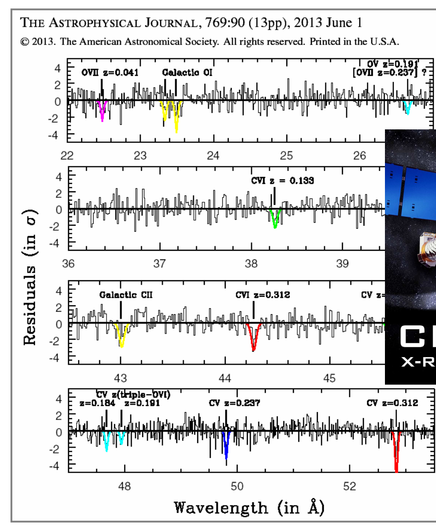
The first and a recent X-ray observation

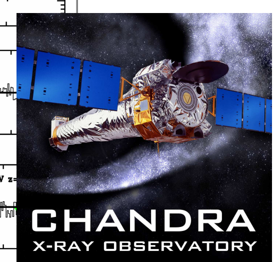
- The X-ray counterpart is discovered by the Einstein Observatory (1ES catalog, source appeared in #10608 observation of Einstein satellite, 1981 March 12, 3.352 ksec, count rate 1.27 cts/s), putting it among the brightest BL Lac objects in the X-ray band.

- Chandra observed warm-hot intergalactic medium (WHIM) toward PG 1553+113 (Nicastro et al. 2013, ApJ, 769, 90). A total of 11 possible X-ray absorption lines (8 lines may be imprinted by intervening absorbers, high-ionization counterparts of FUV H I and/or O VI intergalactic medium, 5 of these identified as C V and C VI K_alpha absorbers belonging to 3 WHIM systems at z_X=0.312, z_X=0.237, and z_X=0.133).

REDSHIFT:

- Limits to the PG 1553+113 redshift value based on indirect measurements (Sbarufatti et al. 2005, 2006). Most recent redshift lower limit estimated using the host galaxy as a standard candle: z>0.24 or z>0.31 (Shaw et al., 2013, ApJ, 764 135). Limit z>0.4 was set in Danforth et al. 2010, ApJ, 720, 976, based on intervening Ly-alpha absorbers. Upper limit set at z<0.58 based on the non-detection of any Ly-beta absorbers at z>0.4.





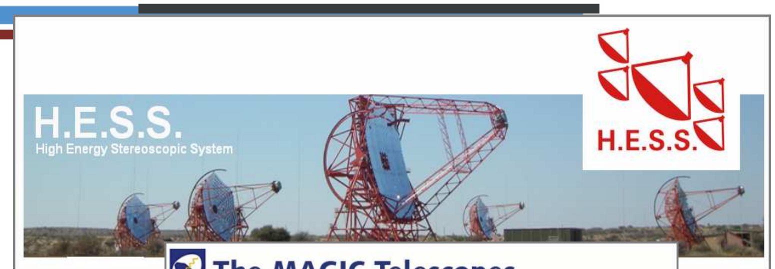
PG 1553+113: VHE gamma-rays

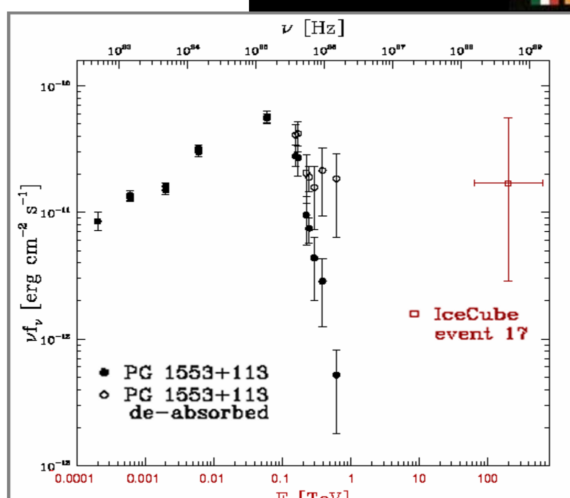
- VHE (E>100GeV) gamma-ray emission from PG 1553+113 discovered independently and almost simultaneously by H.E.S.S. (Aharonian et al. 2006, A&A, 448, L19), and by MAGIC (Albert et al. 2007, ApJL., 654, L119, Aleksic et al. 2012 ApJ, 748, 46).

- MAGIC observed enhanced VHE gamma-ray activity (ATel#3977, ATel#4069, Aleksic et al. 2014, MNRAS submitted, arXiv:1408.1975 in PG 1553+113.

- The EBL imprint on the VHE gamma-ray spectrum can be used to set upper limits on the redshift of the source (see Sanchez et al. 2014, POSTER at this SYMPOSIUM).

- Recent discovery of HE neutrinos of astrophysical origin (up the PeV) by IceCube. The TeV BL Lac object PG 1553+113 is a plausible gamma-ray counterpart (SED and position within the, large, error region) with the IceCube event ID 17 (Padovani & Resconi 2014, MNRAS, 443, 474).





Adapted from Padovani & Resconi 2014.

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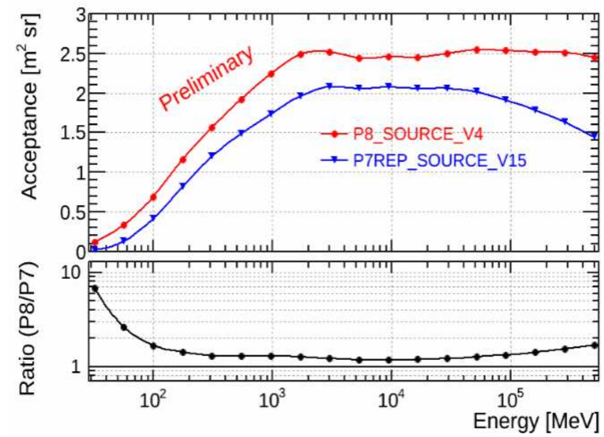
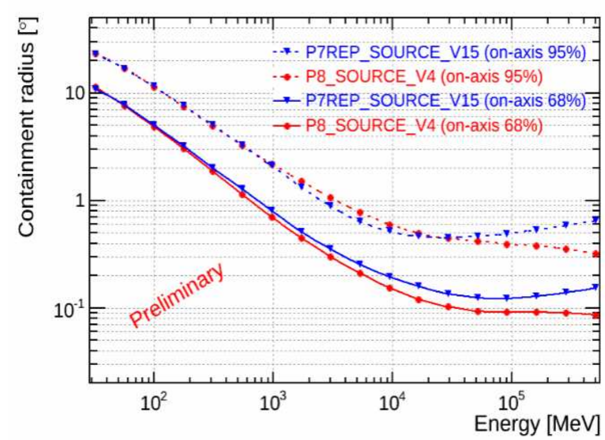
PG 1553+113 and *Fermi* LAT

❑ PG 1553+113 was detected in gamma-rays (E>100MeV) by the *Fermi* Large Area Telescope (LAT). 2FGL Catalog designation is: 2FGL J1555.7+1111, Nolan et al. 2012, ApJS, 199, 31). Details on the first 200 days of observations are in Abdo et. al. 2010, ApJ, 708, 1310. The gamma-ray GeV energy spectrum can be well fitted by a power-law with a hard spectral photon index of 1.67+/-0.02 and F(E>100MeV)=(5.7+/-0.2)X10^-9 ph cm^-2 s^-1. The source has found variable in GeV gamma-rays based on 1-month bin light curves (Nolan et al. 2012, ApJS, 199, 31).



❑ LAT Pass 8 analysis represents a new analysis strategy for the reconstruction and selection of the LAT events, developed by the *Fermi* LAT Collaboration. Pass 8 analysis and data allow to achieve a larger effective area both at low (<100 MeV) and high energy, and a sharper Point Spread Function than before. These features are fundamental to improve the detailed study of gamma-ray sources like PG 1553+113, both in the spectral and the temporal domain.

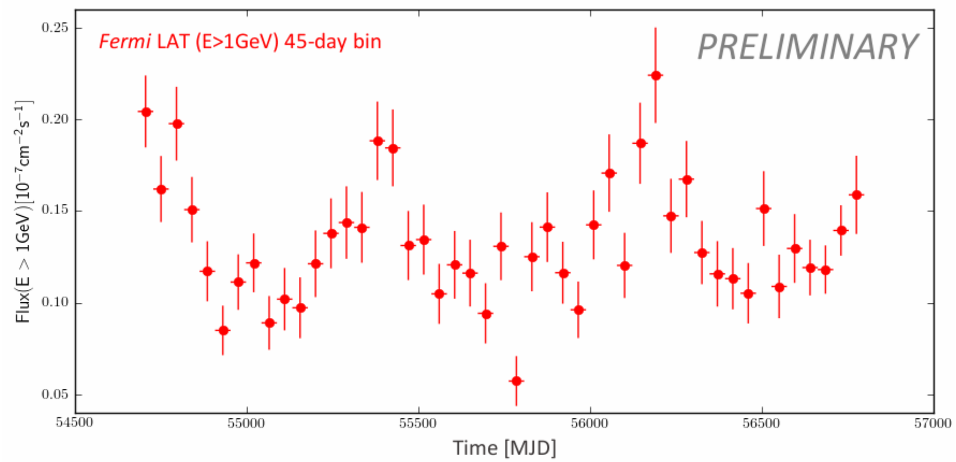


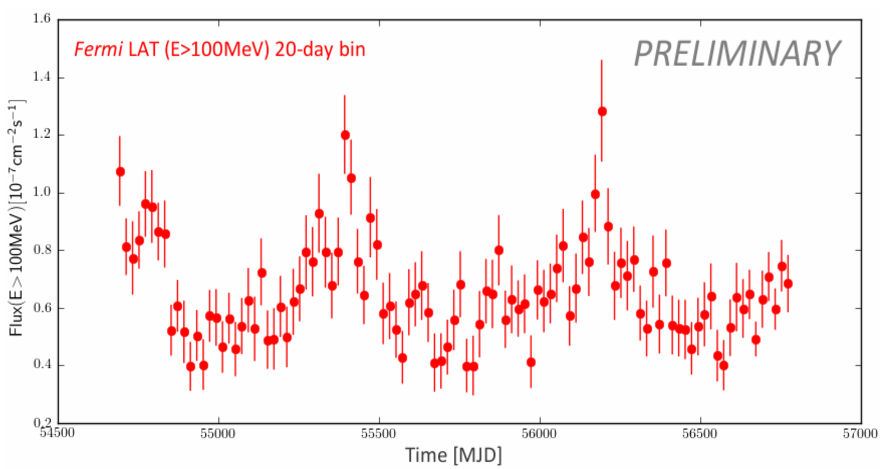
❑ *Fermi* LAT light curves of PG 1553+113 presented in the following slides are based on LAT Pass 8 dataset up to April 30, 2014 (Pass full reprocessing in completion). We selected gamma rays from 100 MeV to 300 GeV belonging to the Pass 8 SOURCE event class, with P8_V4 Instrument Response Functions, in a Region of Interest of 10° centered on the source. A maximum likelihood fit using the tool GTlike, unbinned, included in the *Fermi* Science tools is used in each time bin (regular bin sizes) of the light curve using a power law model.

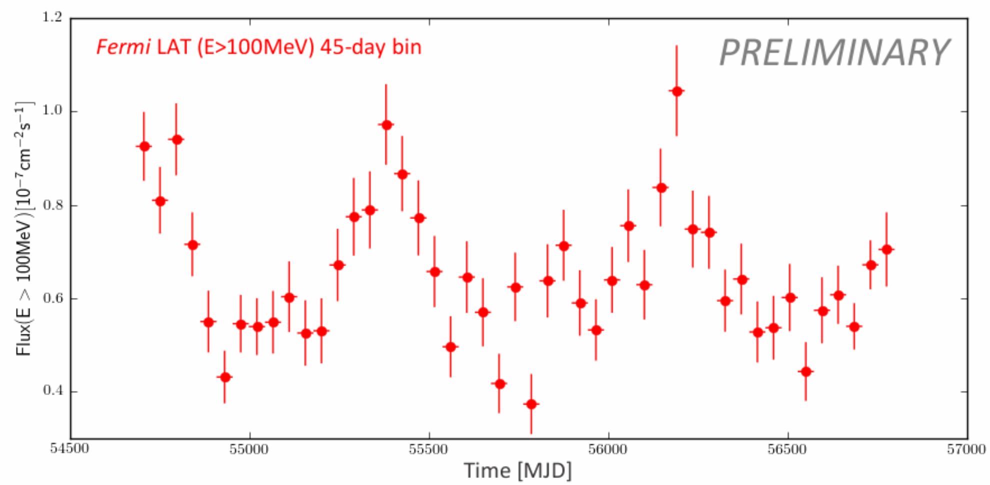
LAT Pass 8 gamma-ray light curves

- *Fermi* LAT gamma-ray flux (E>100MeV) light curves of PG 1553+113 based on Pass 8 dataset up to April 30, 2014, produced in regular time bins of 45-day and 20-day size.

- A long-term oscillating trend is visually evident from these LAT gamma-ray light curves.



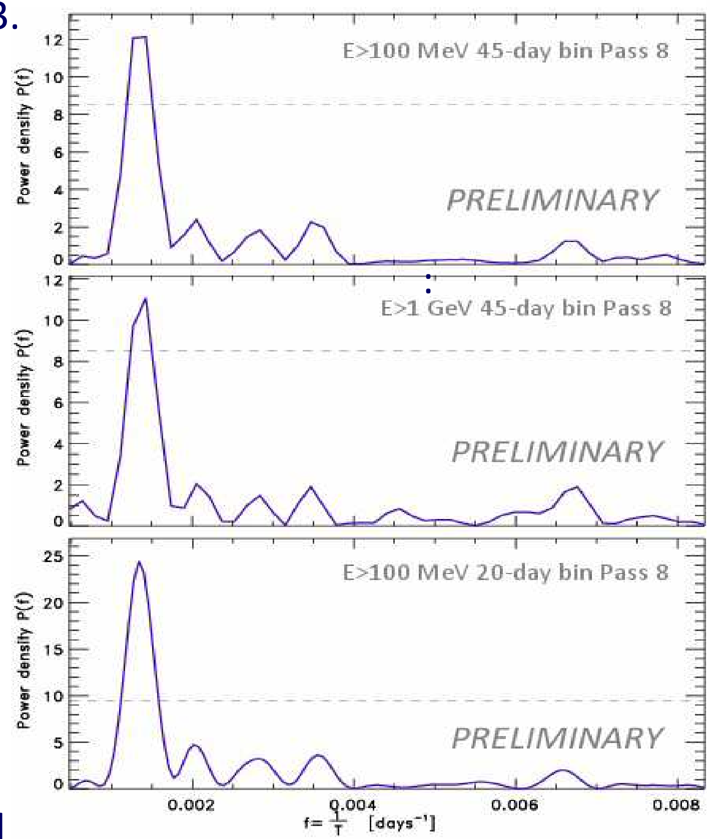




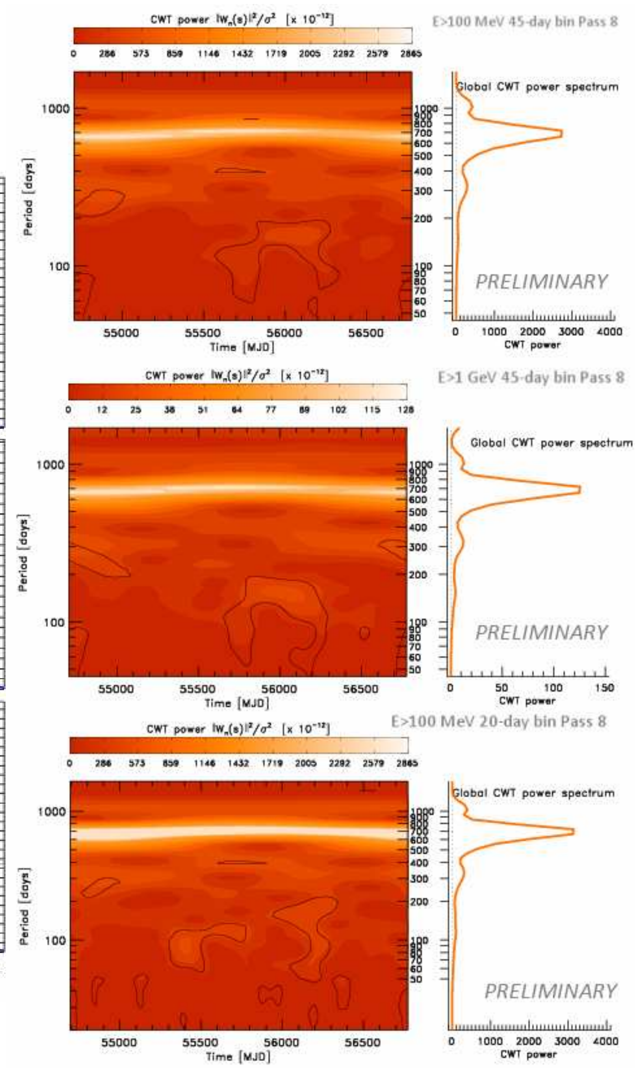
LAT gamma-ray light curves: periodogram and wavelet analysis

❑ Both the Fourier transform power spectrum in the Periodogram technique and the Wavelet transform power spectrum are used to analyze our preliminary LAT gamma-ray flux light curves of PG 1553+113.

❑ Figures on the left report the Lomb-Scargle periodograms of the Pass 8 light curves presented in the previous slide. Dashed line is the 1% false alarm probability level.



❑ Figures on the right report the Morlet-mother wavelet 2D local power spectrum “scalogram” and the global (averaged) wavelet power spectrum.



❑ A peak of power is found for a characteristic timescale of 720+/-60 days. Work in progress.

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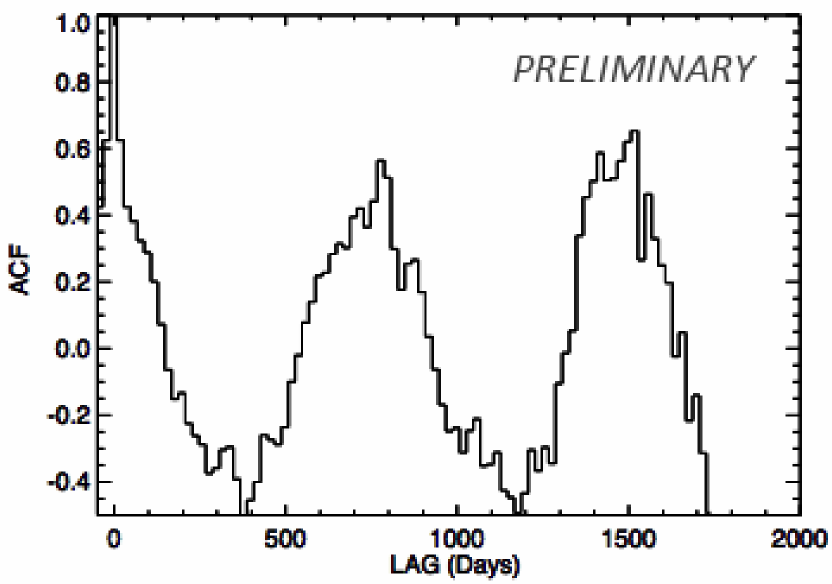
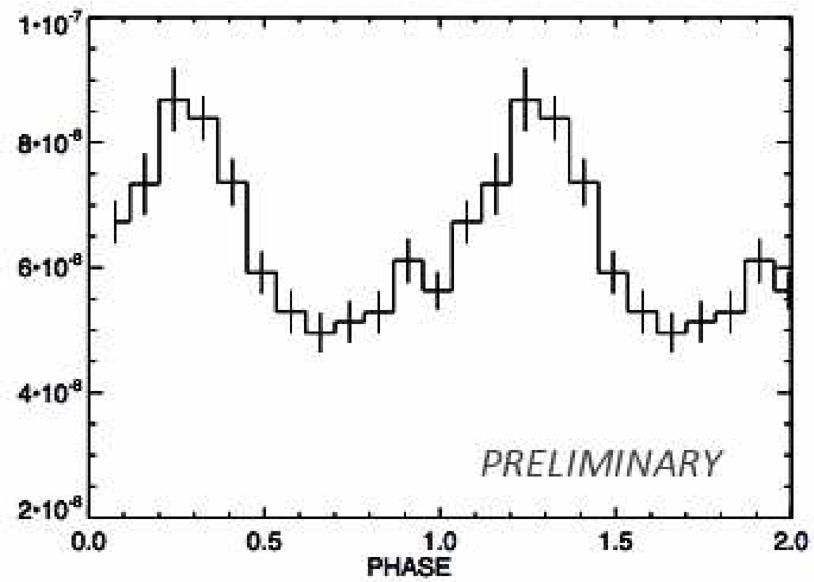
LAT gamma-ray light curves: autocorrelation and epoch-folding analysis

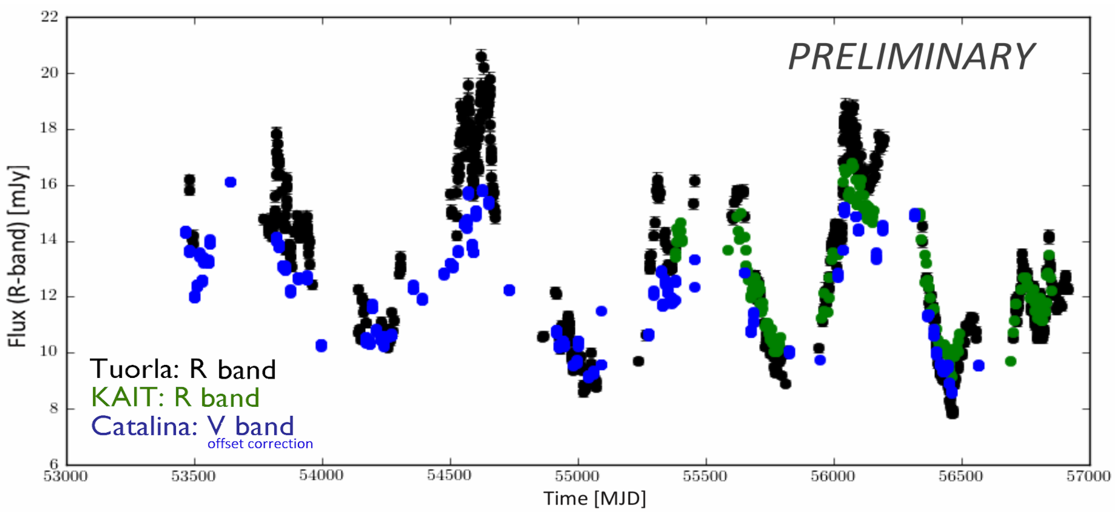
- ❑ Autocorrelation analysis and epoch folding on trial period are also performed on the same LAT gamma-ray light curves.
- ❑ Also with autocorrelation method a peak of power is evident around 750 days.
- ❑ The epoch folding techniques found a characteristic timescale of 737+/-14 days (uncertainty associated with measurement errors and sampling).
- ❑ The LAT light curve can be modeled based on this scale as a periodic modulation. The pulse shape estimated by epoch folding is reported in the right plot.

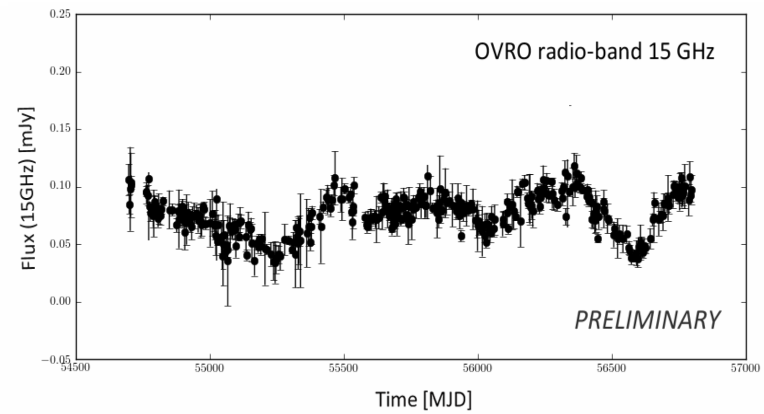




Long-term 15 GHz and optical flux light curves

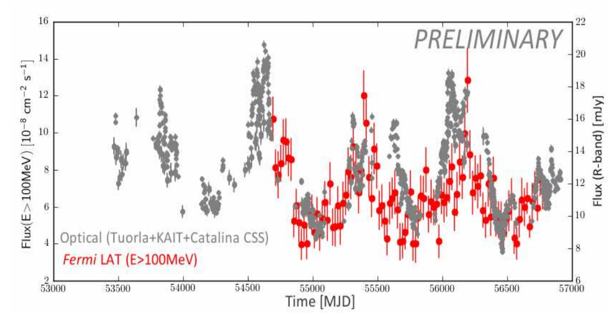
❑ Flux light curves of PG 1553+113 are assembled at optical (R band) and radio (15 GHz) band. At optical band mainly thanks to the Tuorla monitoring program (Takalo et al. 2008, AIP Conf. Proc. 1085, 705; Lindfors et al 2008, AIP Conf. Proc. 1085, 715, unpublished data) with Katzman Automatic Imaging Telescope (KAIT) monitoring data and Catalina Sky Survey (CSS) data added. At 15 GHz thanks to the 40m Owens Valley Radio Observatory (OVRO) with blazar monitoring program supporting *Fermi* (Richards et al. 2011, ApJS, 194, 29).





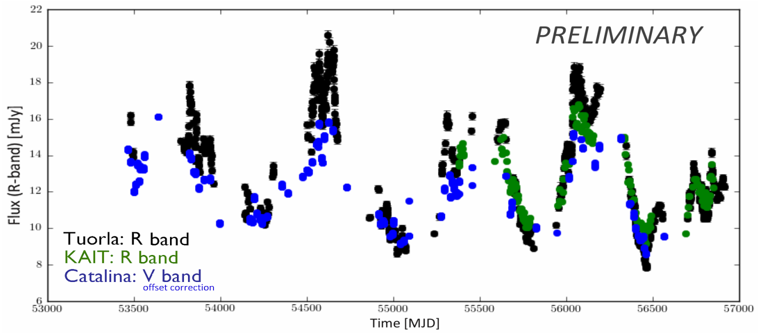
❑ 10 years (2004-2014) of long-term light curve (Tuorla optical monitoring program, unpublished data). Data are collected from several telescopes participating to the Tuorla monitoring program (users.utu.fi/kani/1m) : 1) Tuorla Observatory telescope, Finland; 2) KVA observatory on La Palma, Canary islands, Spain; 3) Searchlight Observatory Network telescope, San Pedro de Atacama, Chile; 4) Searchlight Observatory Network telescope, New Mexico, USA; 5) Belogradchik telescope, Bulgaria.

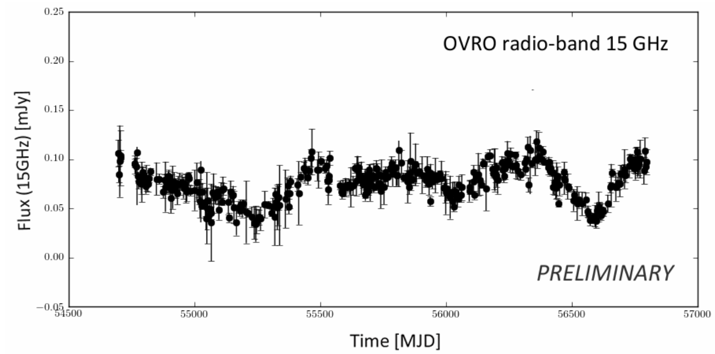
OBSERVERS: R. Bachev, A. Berdyugin, S. Ciprini, A. Halkola, C. Harlingten, T. Hovatta, V. Kadenius, P. Kehusmaa, E. Lindfors, K. Nilsson, P. Nurmi, A. Oksanen, L. Ostorero, M. Pasanen, R. Reinthal, J.Saarinen, J. Sainio, A. Somero, A. Strigachev, L. O. Takalo, T. Tuominen, C. Villforth, T. Vornanen.

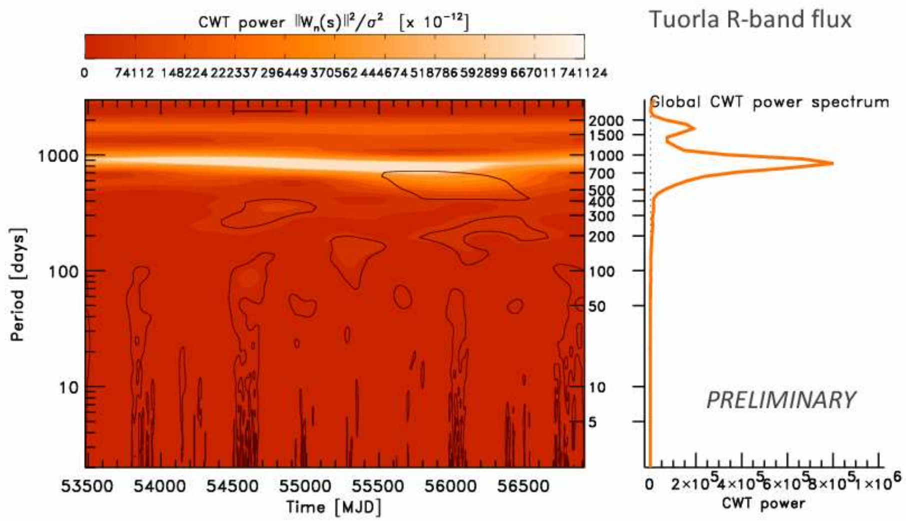


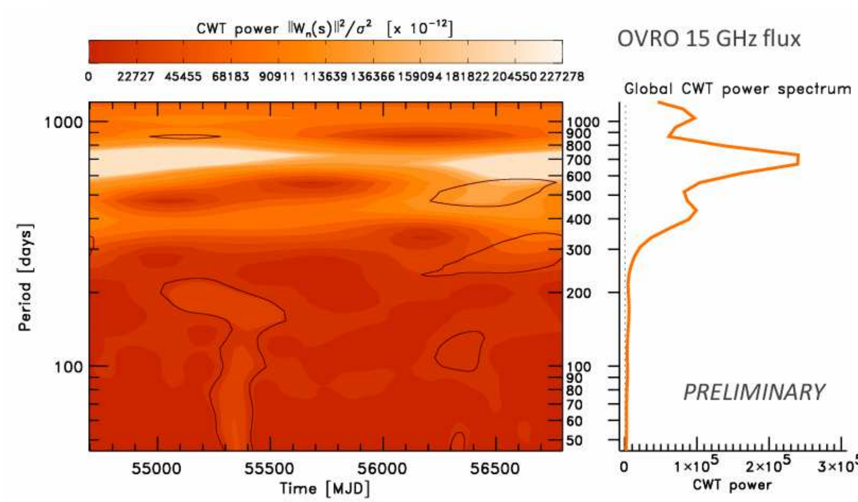
Tuorla and OVRO light curves: wavelet analysis

- Morlet-mother wavelet 2D local power spectrum “scalogram” and the global (averaged) wavelet power spectrum is evaluated also for the 10-years R-band optical flux (Tuorla) light curve and the radio 15 GHz flux (OVRO) light curve. Wavelet power spectrum peaks are evident also in these light curves (at characteristic timescale of 840+/-70 days in the optical band, and a characteristic timescale of 730+/-60 days in the radio band) . Work in progress.



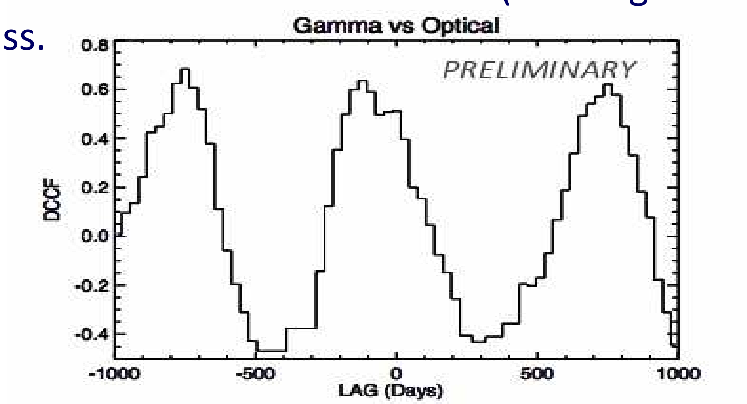


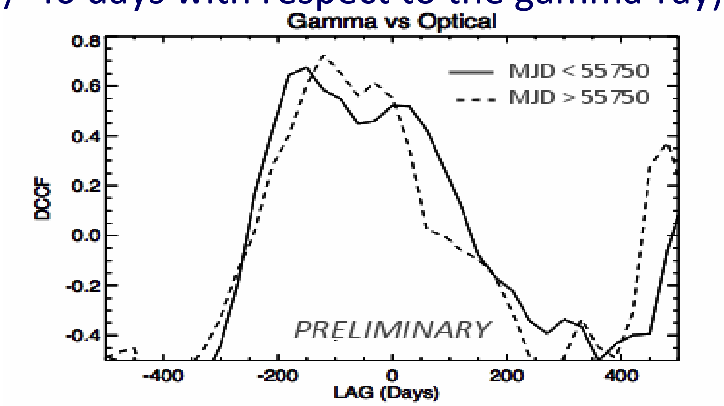


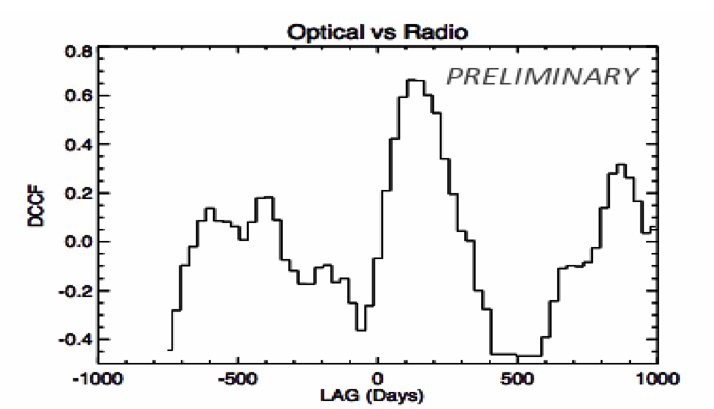


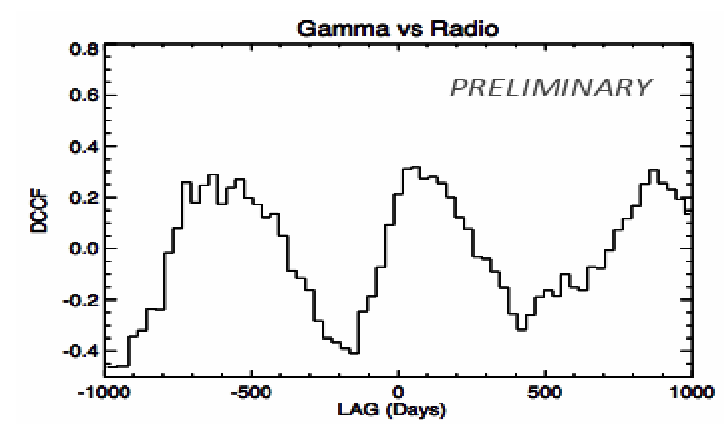
Gamma-ray vs optical/radio cross correlation analysis

❑ Cross Correlation Function of gamma-ray LAT vs optical light curves. A second Cross Correlation Function plot of gamma-ray LAT vs optical light curves is produced dividing the light curves in two segments (MJD<55750 solid line, and MJD>55750 dashed line). There are time lags. First results suggest a leading by the optical flux variations, then the gamma-ray flux (with lag of 91+/-24 days with respect to the optical) and then the radio-band flux (with lag of 85+/-40 days with respect to the gamma-ray). Work in progress.









Conclusions

- Our study represents a first hint for a regular cyclic behavior (timescale of about 2 years) discovered in a gamma-ray emitting blazar. This is referred to about a 6-year time range of *Fermi* LAT continuous monitoring and is made possible thanks to the new PASS 8 data analysis. The analysis is ongoing refining the LAT light curve extraction, checking nearby sources in the RoI and systematics.

- In the past long-term radio band and optical band flux monitor of blazars has provided claims for periodicity on blazars (for example is sources like AO 0235+164, OJ 287, 3C 273, 3C 66A, BL Lac, W Com). Characteristic timescales or periods are from about 1.5 years to about 24 years.
  This topic is still highly debated.

- Our investigations are ongoing, but regular long-term oscillations with a rough 2-year characteristic time-scale are also discovered at optical band (Tuorla, KAIT, CSS) and radio (15 GHz, OVRO) band in PG 1553+113. A preliminary cross-correlation analysis agrees with this result. There are evidences for gamma-ray-optical/radio time lags with the optical flux variations leading. The analysis using the optical data suffers of long seasonal gaps in the data. We are still working on the analysis.

- Speculations and hypotheses on models explaining the data are still to be addressed based on results of our analysis.

- The *Fermi* mission is again opening a further window for exciting science. The long-term variability analysis at high-energy gamma rays is now opening in the time-domain astronomy framework, thanks to the continuous all-sky survey (i.e. regular time monitor) *Fermi* is performing.