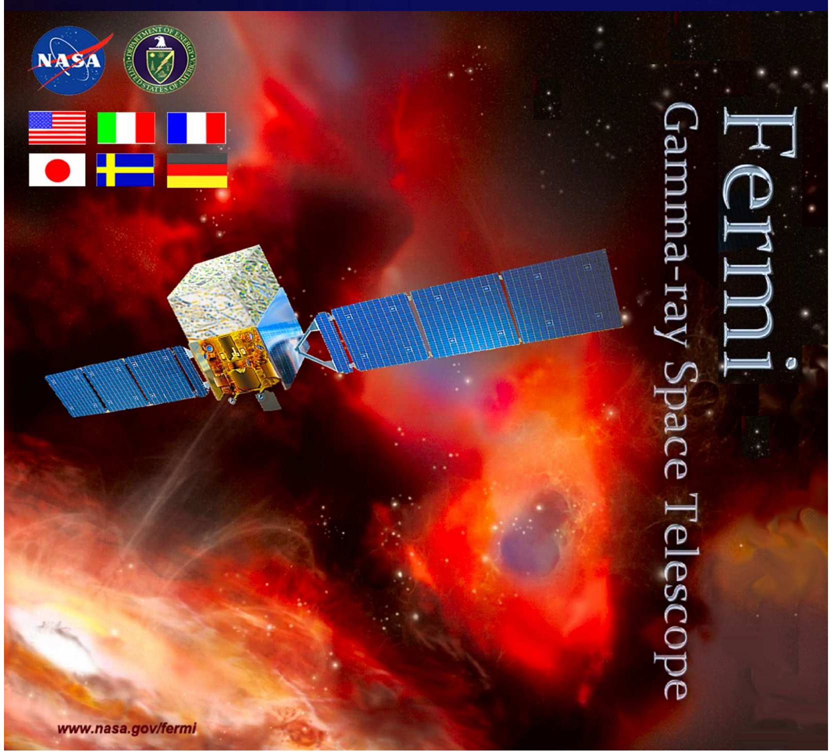

10-year Fermi LAT observations of PG 1553+113: confirmation of a nearly periodic gamma-ray flux modulation

Stefano Ciprini[1,2,3],
Sara Cutini[2], Stefan Larsson[4,5]

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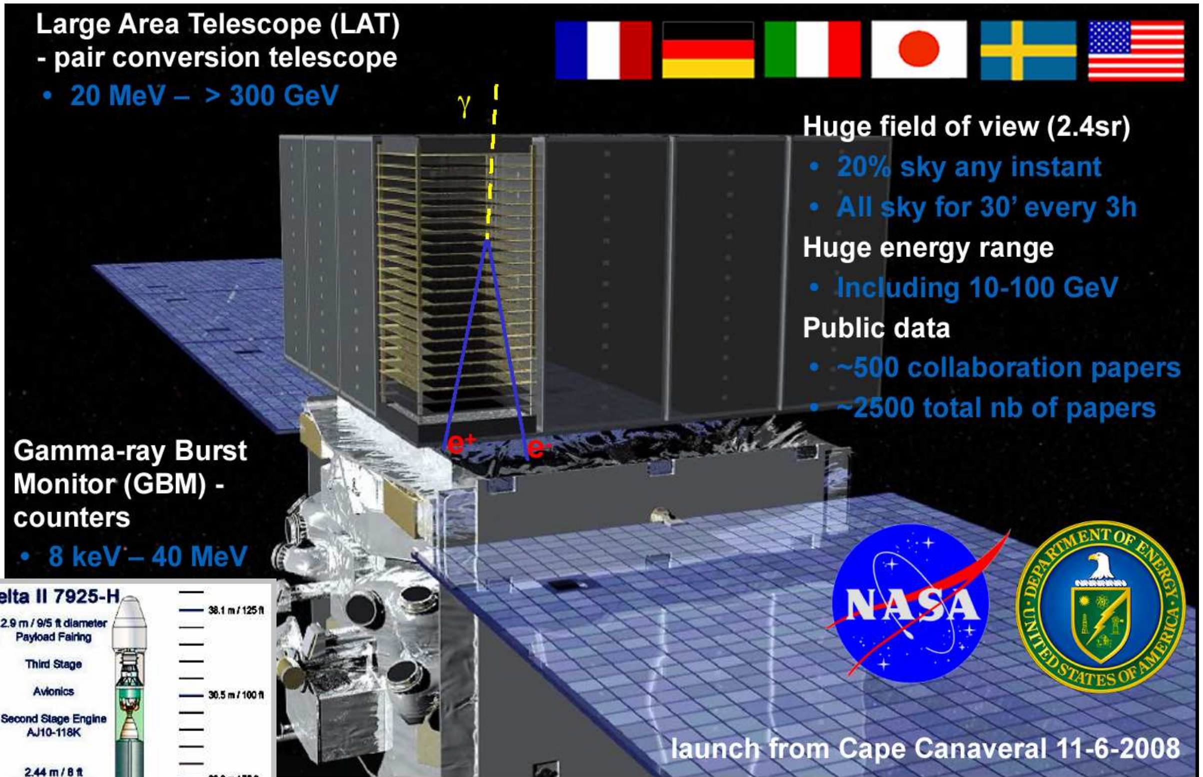
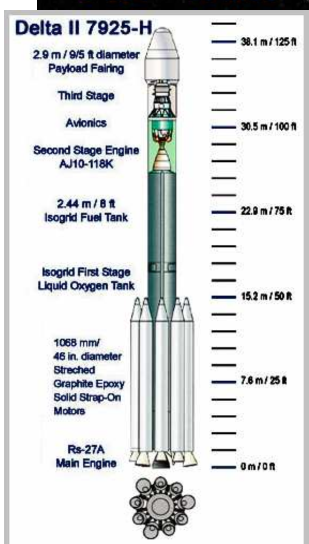
4. KTH Royal Institute of Technology, Stockholm, Sweden
5. Dalarna University, Falun, Sweden

on behalf of the Fermi Large Area Telescope Collaboration

8th International Fermi Symposium
“Celebrating 10 Years of Fermi”,
October 14-19, 2018, Baltimore, MD, USA

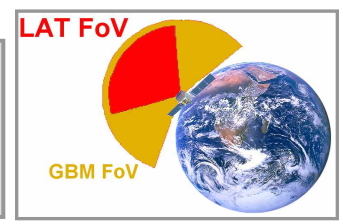
10 years of *Fermi* Gamma-ray Space Telescope





- ❑ Gamma-rays cover a huge swath of the e.m. spectrum
- ❑ The gamma-ray sky is relatively poorly studied
- ❑ HE (GeV) gamma-rays probe the non-thermal universe
- ❑ Extreme environments hosting powerful cosmic particle acceleration
- ❑ Galactic/Extragalactic multimessen. physics, transients, variability
- ❑ More: dark matter, Solar sci., TGFs…
- ❑ Enhanced multi-messenger/multi-wavelength opportunities.
- ❑ Fermi unique all-sky monitor in a broad energy range (unique survey at GeV photon energy band).

Celebrating 10 Years of Fermi
June 11, 2018



❑ **Launched** 11 june 2008, Delta II Rocket, circular orbit, 565km altitude, 25.6 deg inclination.
Operations. Primary mode: all-sky survey with scan of the entire sky for 30min every 3 hours. Autonomous Repoint Request (ARR). Target of Opportunity (ToO). Huge field of view (2.4sr).

- **Large effective area**
- **Good angular resolution**
- **Huge energy range**
- **Wide field of view**

Mission to study cosmic particle accelerators in energy, time, sky position/distribution, distance

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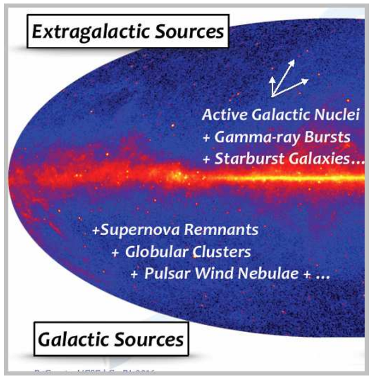
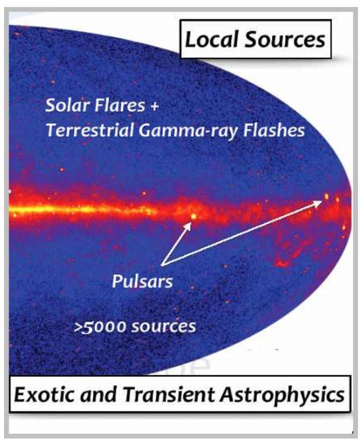
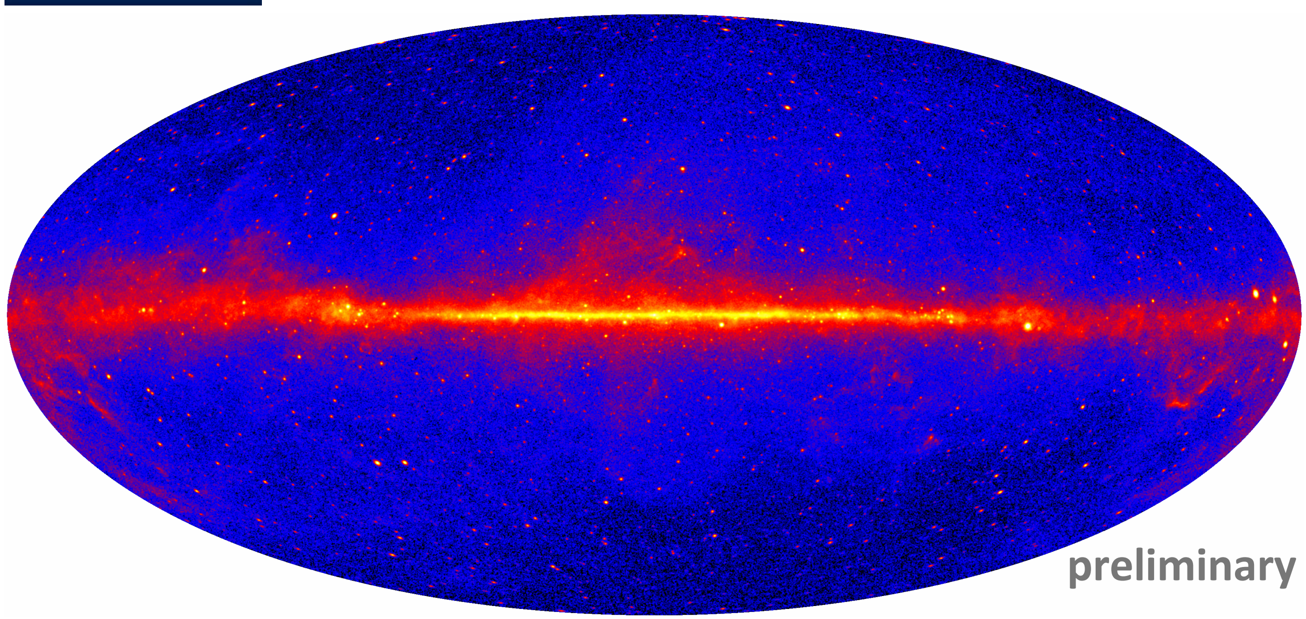
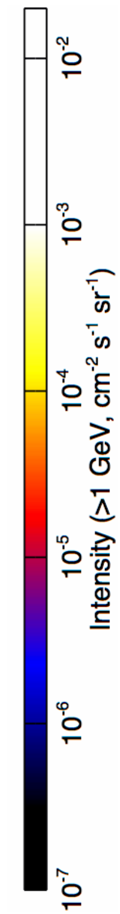
10-year E>1 GeV gamma-ray sky



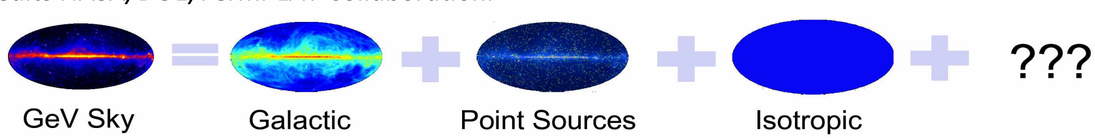


All-sky SURVEY:
uniformity, sensitivity depth, diffuse emission science, populations studies, serendipity, variability monitor, transients search, cross-correlation, cross-match, time domain science, multifrequency astronomy, multi-messenger astroparticle physics





10-year (August 4, 2008 - August 4, 2018) gamma-ray intensity all-sky image obtained by the Fermi LAT.
Pass 8 Source class PSF3 event type data, intensity units, E>1 GeV, 100 deg zenith angle limit, Galactic coordinates, Hammer-Aitoff projection and logarithmic scaling. *Credits NASA/DOE/Fermi-LAT Collaboration.*



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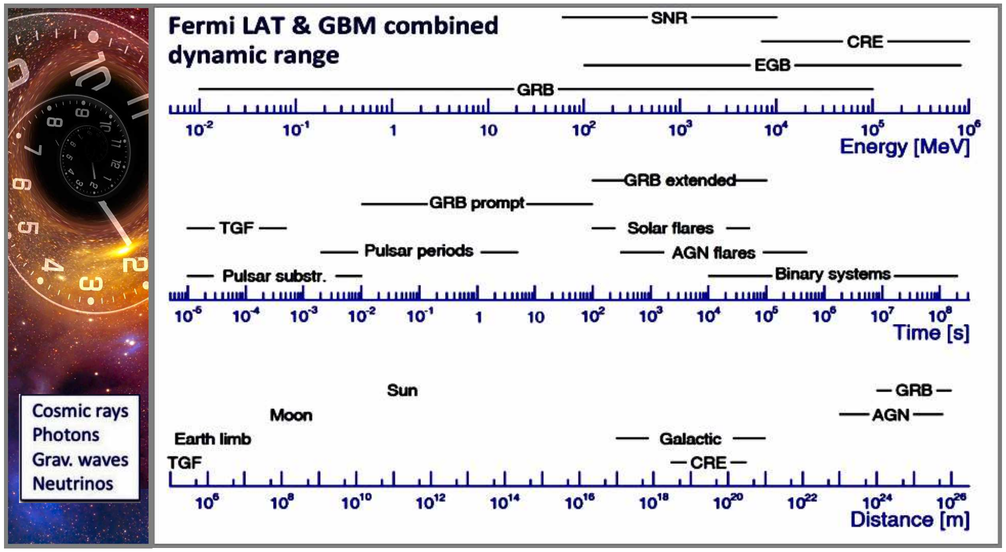
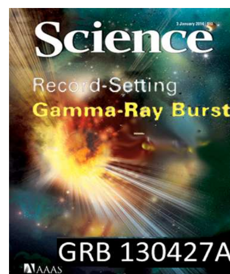
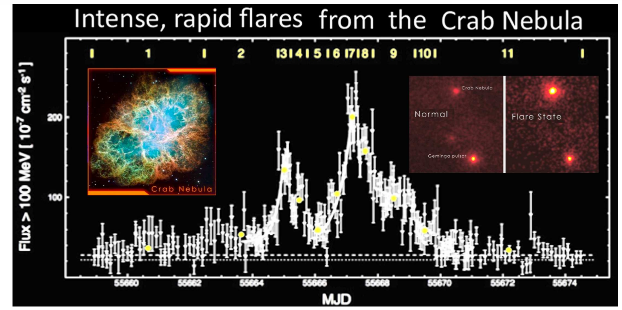
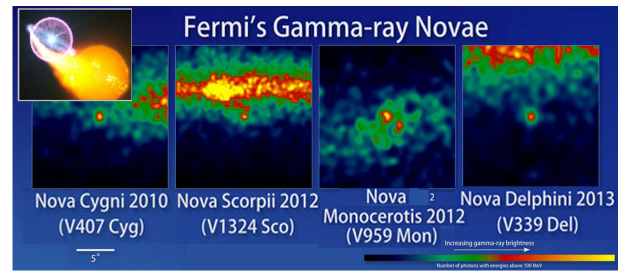
Fermi: all-sky survey & time-domain monitor

ALL-SKY + ALL-TIMES (spatial SURVEY + TIME-DOMAIN monitor + depth in z)
mission for the HE Universe, exploring gamma-ray timescales from millisec to years.

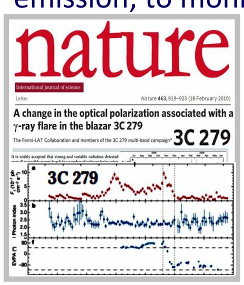


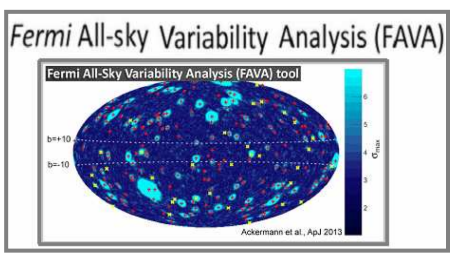


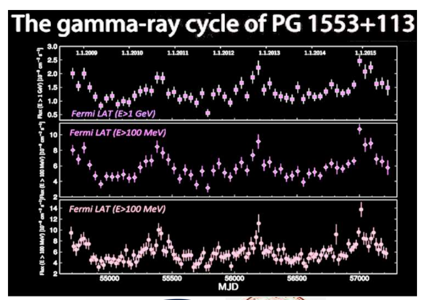


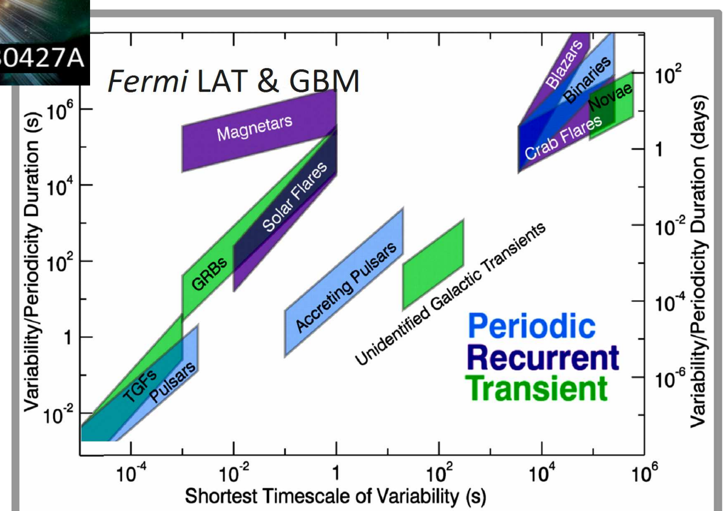


- Fermi LAT+GBM wide FoV and continuous survey → excellent to "catch" GRBs, AGN/blazars flares, glitches, galactic transients, novae, SNs, solar flares, TGFs; to search for neutrinos ,UHECRs, gravitational waves e.m. counterparts, DM non-steady emission; to monitor the variable HE sky (SERENDIPITY).









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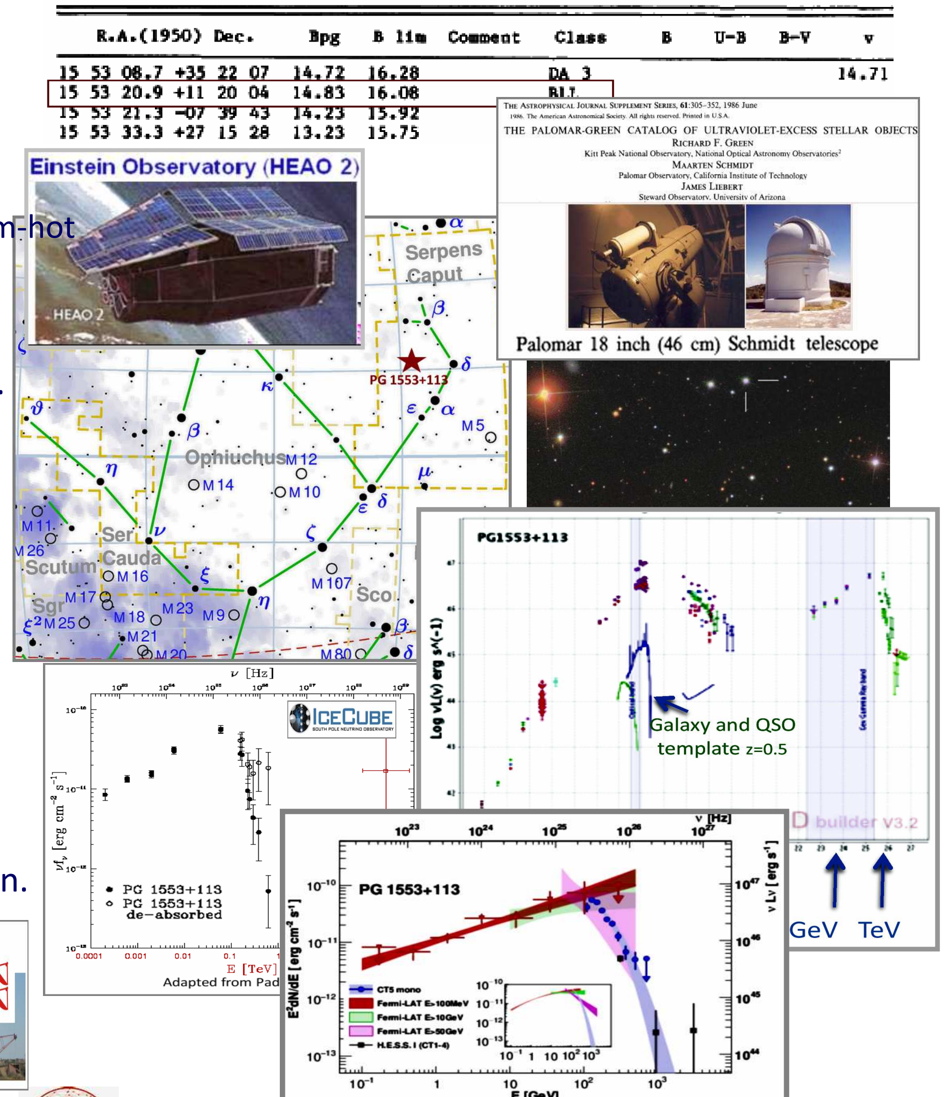
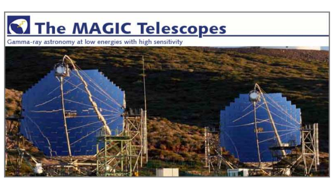
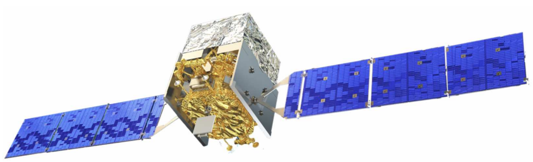
The blazar PG 1553+113 (a.k.a. 1ES 1553+113)

- ❑ PG 1553+113 (a.k.a. 1ES 1553+113): optically/X-ray selected BL Lac object (Green+ 1986; Falomo & Treves 1990).
- ❑ X-ray counterpart discovered by the Einstein Observatory (1ES catalog, in 1981 March 12, 3.3ksec, 1.27 cts/s). Observations by XMM, Chandra, Suzaku, Swift, etc. Chandra. Warm-hot intergal. medium (Nicastro+ 2013).
- ❑ Redshift constraints: $0.39 < z < 0.62$ (Danforth+ 2010, Aliu+ 2015). Further estimation z=0.49+/-0.04 (Abramowski+ 2015).
- ❑ VHE (E>100GeV) gamma-ray emission discovered independently by H.E.S.S. (Aharonian+ 2006), and by MAGIC (Albert+ 2007; Aleksic+ 2012).
- ❑ PG 1553+113 plausible counterpart with IceCube event ID 17 (Padovani & Resconi 2014).
- ❑ Fermi LAT 3FGL catalog (3FGL 1555.7+1111): power-law, hard spectral photon index (1.604+/-0.025) and F(E>100MeV) =(1.32+/-0.03)X10^-8 ph cm^-2 s^-1). Variable source.
- ❑ Many spectral/SED studies (LAT data + MAGIC /H.E.S.S./VERITAS data). Dominant non-thermal in-jet emission.





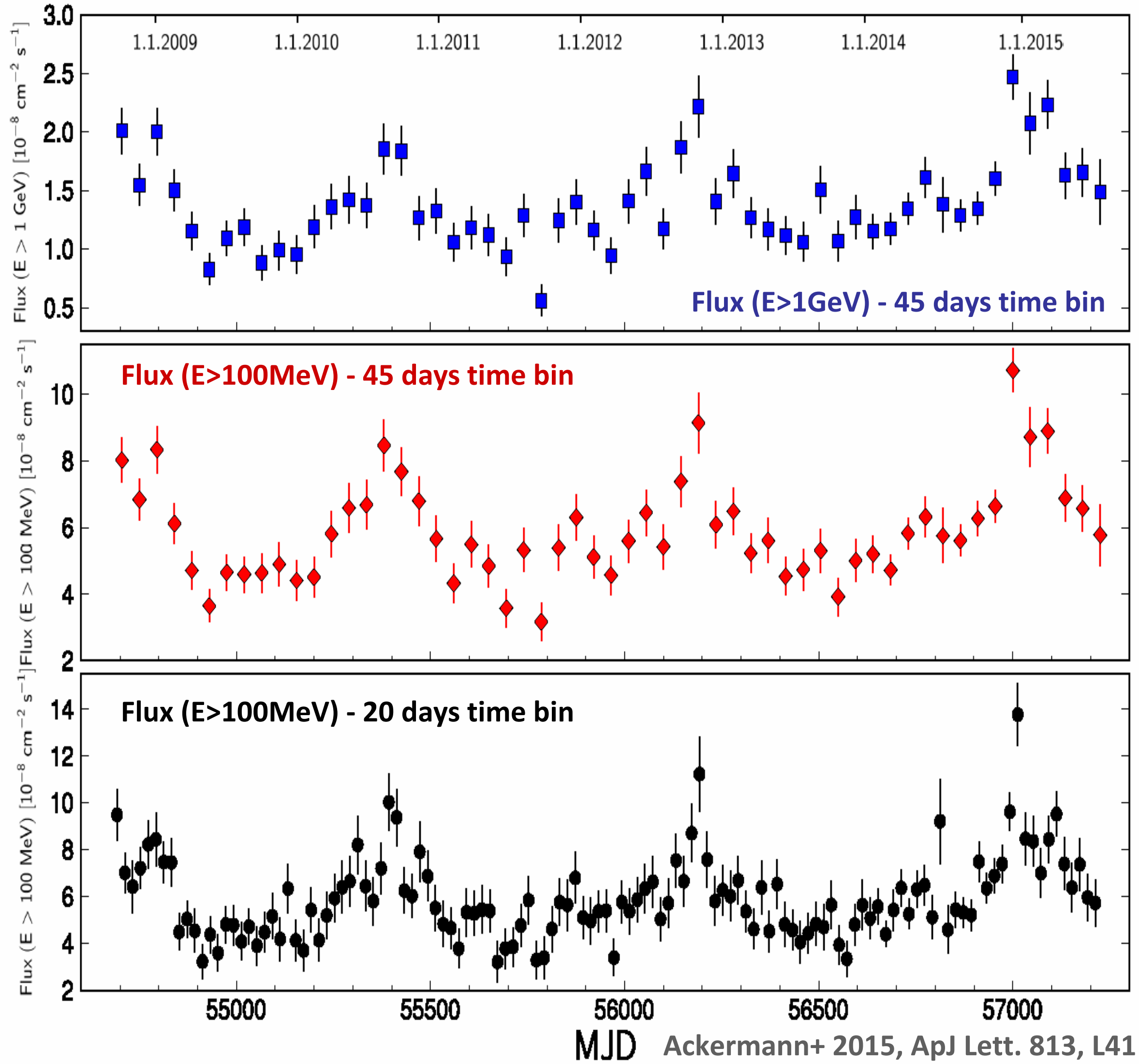
Recap: the 6.9-year Fermi LAT gamma-ray light curves



- ❑ [Ackermann+ 2015, ApJ L., LAT paper]: *Fermi* LAT gamma-ray flux (E>100MeV and E>1GeV) light curves of PG 1553+113 based on Pass 8 dataset up to July 19, 2015, produced in regular/large-size time bins of 45-day and 20-day bins.

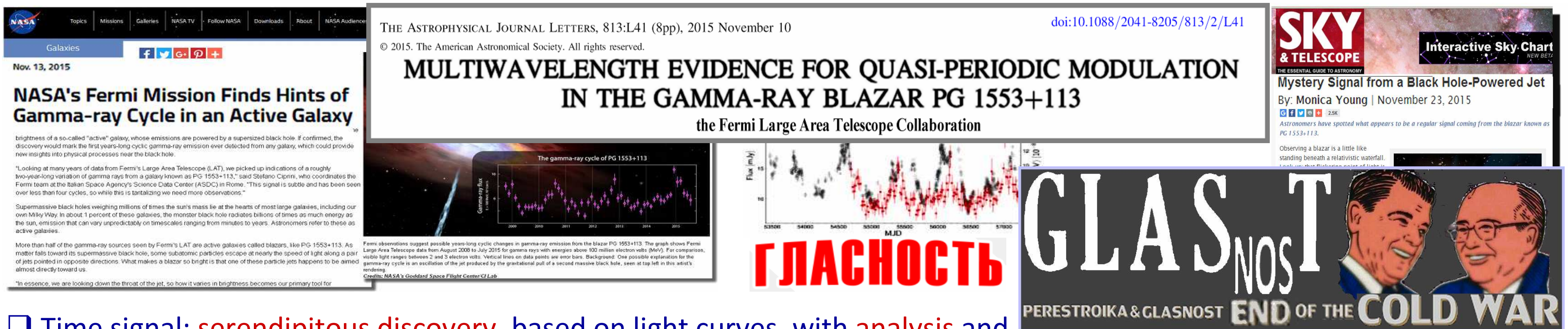
- ❑ A long-term oscillating trend visually evident. Sinusoidal modulation (using magnitude log-flux scale). Quasi regular periodicity in 3.5 cycles. Significance still marginal against red-noise but strengthened by MW cross-correlations. Similar oscillatory trend in optical data.

➔ Deterministic prediction (valid in long-lived coherence hypothesis): next quasi-periodic GeV peaks were foreseen around 2017 and 2019.



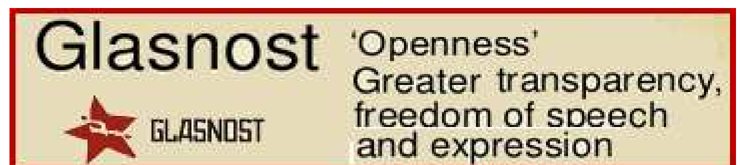
Ackermann+ 2015, ApJ Lett. 813, L41

"Glasnost" recap on the discovery and the 2015 paper



❑ Time signal: serendipitous discovery, based on light curves, with analysis and research led by **Sara Cutini** (INFN Perugia, was SSDC) that saw in 2014 the gamma-ray long-term oscillation using large time bins in LAT data, and by **S. Ciprini** (INFN TorVergata+Perugia & SSDC) with first variability timing analysis, discussion and paper handling.
→ First joint (shy) talk based on Pass7 data on Sept. 2014 at LAT Coll. Meeting in Montpellier, France.

❑ Soon fundamental contribution by our friend **S. Larsson** (KTH Royal Inst. Tech. Stockholm & Dalarna U.): complementary and also critical cross-check variability timing analysis and cross correlation analysis.

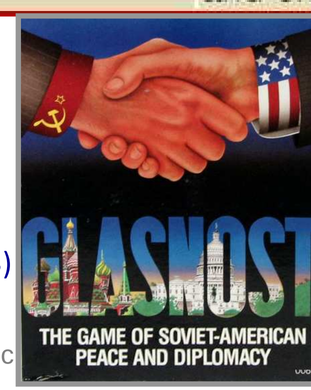


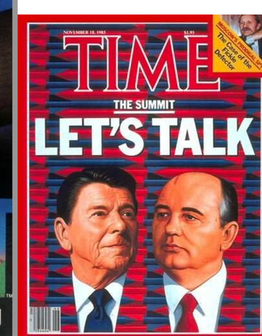
❑ Main contribute in the paper then by **D.J. Thompson** (NASA GSFC).

❑ Contributions to parts of analysis also by **R. Corbet** and **W. Max-Moerbeck**.

❑ Discussion contributions by many. External multifrequency data contributors. **E. Lindfors**, **T. Readhead** leaders for optical/radio data, **M. Perri** leader for Swift XRT and UVOT data).

❑ Target initially triggered by **A. Stamerra** (now MAGIC co-spokeperson), that asked to Sara Cutini in 2014 to produce LAT SEDs data for high/low states of a few MAGIC TeV blazars (also PG 1553+113)
→ serendipitous discovery during the work for identification of high/low states.





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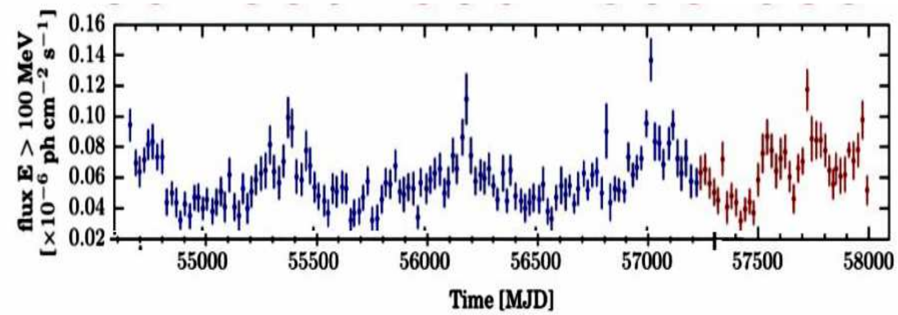
LAT ApJ 2015 paper: follow-up interest and papers

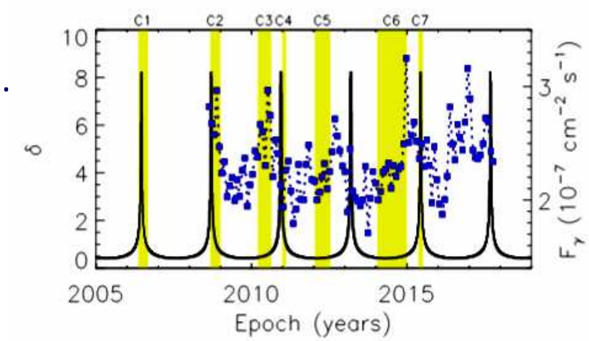
Interest by the external scientific community in this [Ackermann+ 2015, ApJ] LAT paper → follow-up works & tests/models all in the binary SMBH scenario and addition of a 1 or 2 year data baseline.



Examples:

- ❑ [Tavani+ 2018]:

2016-2017 data added and claim for a Jan. 2017 new gamma-ray peak fitting the 2.2-year modulation. Binary SMBHs dynamics (about 10^8 and 10^7 Msun. BH masses). Periodic stresses of the main BH jet triggering MHD-kinetic tearing instabilities. Magnetic reconnections and acceleration of electrons producing synchrotron emission and inverse Compton emission in GeV gamma rays.



- ❑ [Caproni+ 2017]:

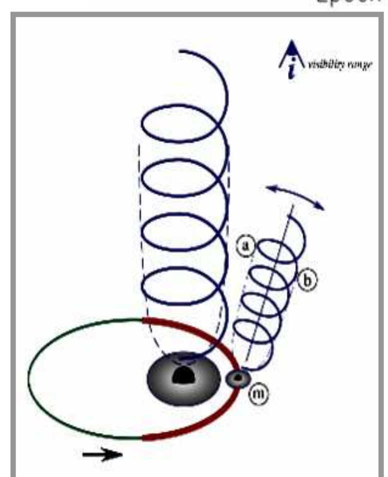
Binary SMBH model with main relativistic jet that is steadily precessing in time.

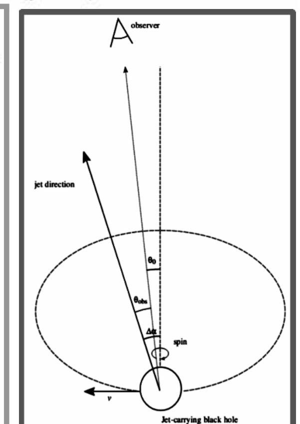
- ❑ [Sandrinelli+ 2018]:

Binary SMBH model & relativistic jet instabilities both probable. Binary SMBHs model in tension with very low freq. gravitational wave background currently measured by Pulsar Timing Arrays. General difficulties in associating quasi-periodicities of BL Lac objects to binary SMBH systems.

- ❑ [Sobacchi+ 2017]:

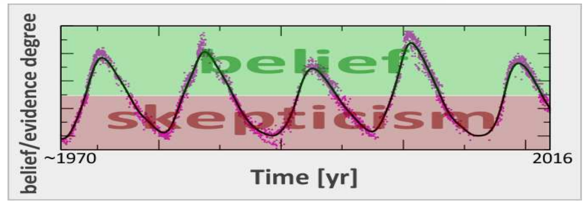
Binary SMBH model with an imprint of the secondary SMBH orbital speed on its jet. Jet preferably carried by (secondary) SMBH.





Blazars quasi-periodic claims and red-noise

❑ Periodicity (optical/radio long-term light curves) of AGN is a controversial astronomical topic. Skepticism dominating but many papers on periodicity published! Some recurrent "periodical" enthusiasm/claims since '70s.



Periodicity → binaries
- Sillanpää+1988
- Lehto&Valtonen 1996
- Raiteri+2001
- Fan et al. 2002
- Rieger 2004
- Liu et al. 2006
- Valtonen et al. 2008
- Sandrinelli et al. 2014
- Graham+2015
- Ackermann et al. 2015
- Valtonen et al. 2016

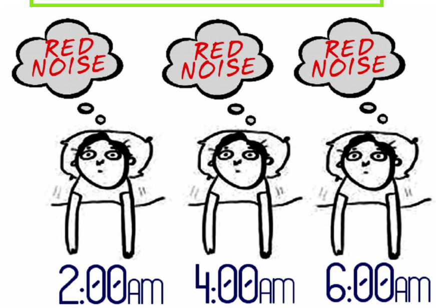
❑ Red-noise problem. The period significance is difficult to assess given the usually limited light curves duration.

❑ Random and relatively enhanced low-frequency fluctuations (red/Brownian noise) over intervals comparable to the time series sample length, hinders the evaluation of significance.

→Essentially stochastic low-frequency variability can build red noise, miming misinterpreted periodicities.

(*"...one swallow, i.e. 2,3 periodic oscillations, does not a summer make or periodicity ! "*)

❑ Blazar luminosities over 3,4 orders of magnitude. Periodicities have similar multi-year time scales (1-25 years). → puzzling (real?). But no way to investigate >30-year timescale periods.



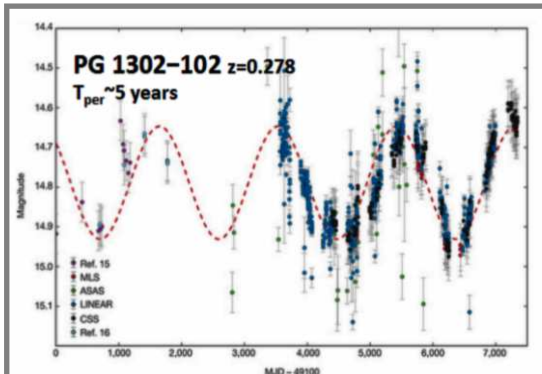
red-noise keeps you awake during the night !

OTHER CAVEATS:
- single band light curves (too strong claims on 1 band)

→ Multifreq. quasi-periodicity + cross-correlat. help!

→Helical pc-scale radio-jet patterns + polarization help!.

- Preferred portions of light curve data ("cherry pick").
- Periods intrinsically "transient" (only 2,3 cycles).
- Data gaps and sparse time series handling problem.
- Data quality/significance for AGN light curves lower than those for QPOs of X-ray binaries.

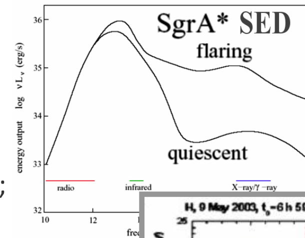


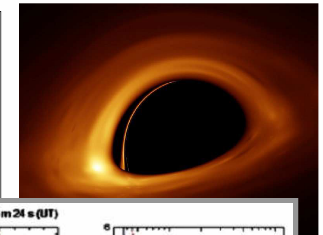
Graham et al. 2015, Nature 518

Binary SHBH 0.01 parsec (2X10^4 AU) separation

One example: 20-min QPO in Sgr A* vs red-noise

❑ Claims for near-IR and X-ray wavelengths quasi-periodic oscillation (QPO) signal with 20-minute period reported in light curves of Sgr A* since 2003 (hot spots Keplerian orbits at ISCO, rotational modulations of accretion instabilities).





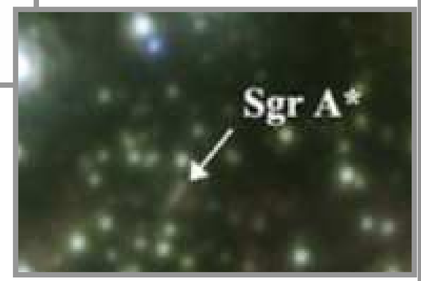

nature
International journal of science
Letter | Published: 30 October 2003

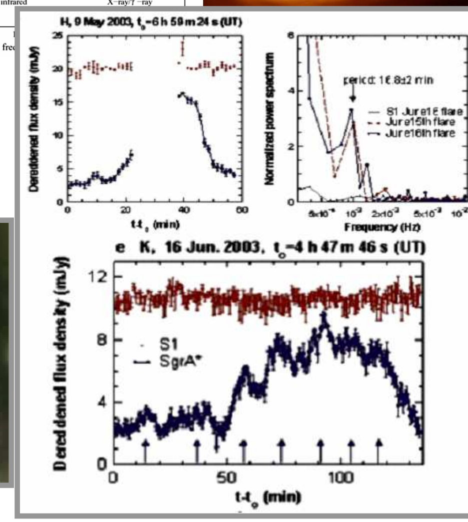
Near-infrared flares from accreting gas around the supermassive black hole at the Galactic Centre

R. Genzel, R. Schödel, T. Ott, A. Eckart, T. Alexander, F. Lacombe, D. Rouan & B. Aschenbach

Nature **425**, 934–937 (30 October 2003)

Genzel+ 2003;
Aschenbach+ 2004;
Eckart+ 2006;
Meyer+ 2006;
Trippe+ 2007;
Falanga+ 2007;
...etc.

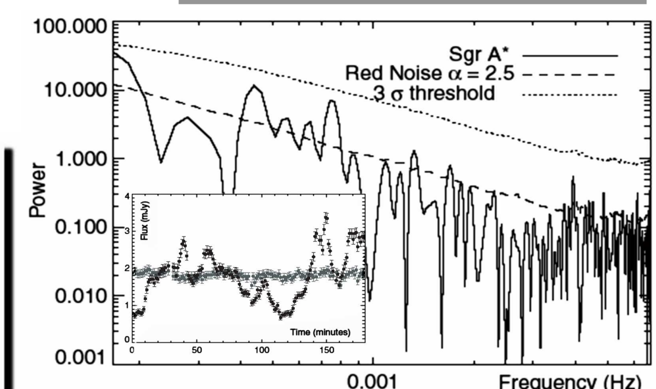


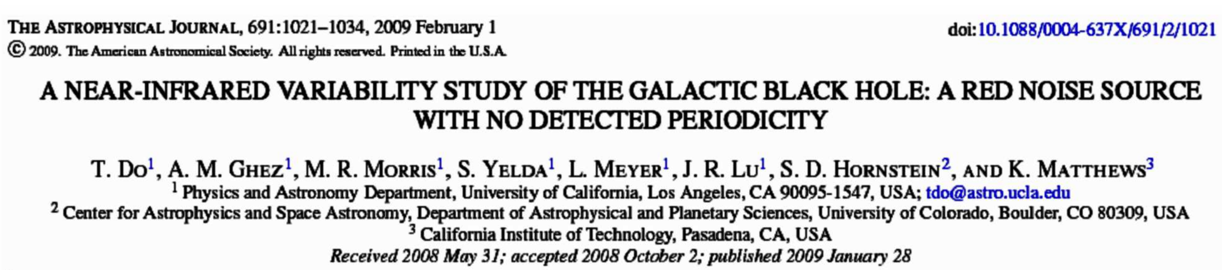


❑ Sgr A* near-IR periodicity disproved six years later: relatively short observation time baselines; only a few clamined-period oscillations; low amplitude oscillations; not rigorous assessment of statistical significance.

→ Oscillations entirely consistent with models based on correlated noise (power density spectra, PDS, 1/f^a with slopes a between 2.0 and 3.0) .

→ i.e. realizations purely ascribed to RED NOISE).




The Astrophysical Journal, 691:1021–1034, 2009 February 1 doi:10.1088/0004-637X/691/2/1021

A NEAR-INFRARED VARIABILITY STUDY OF THE GALACTIC BLACK HOLE: A RED NOISE SOURCE WITH NO DETECTED PERIODICITY

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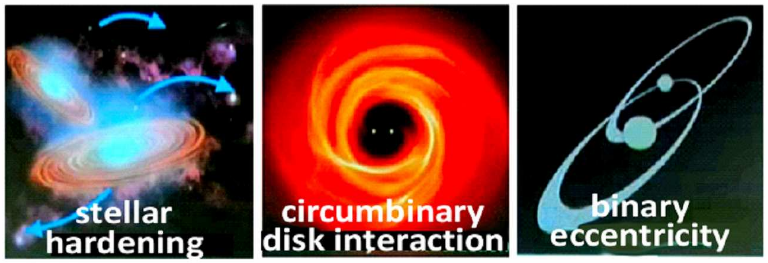
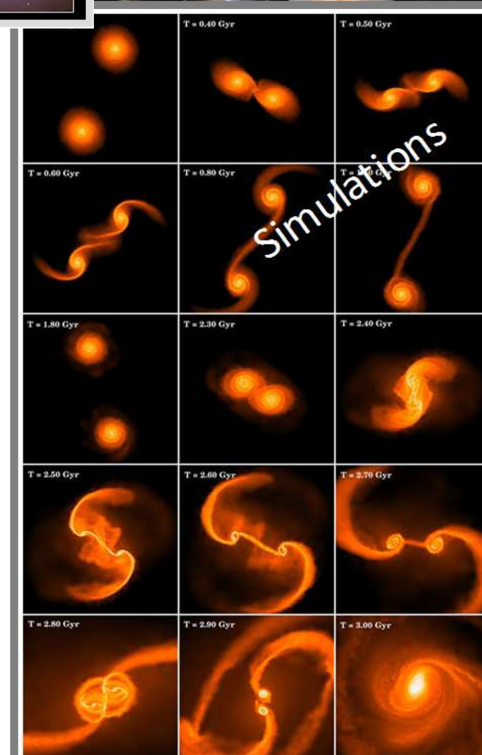
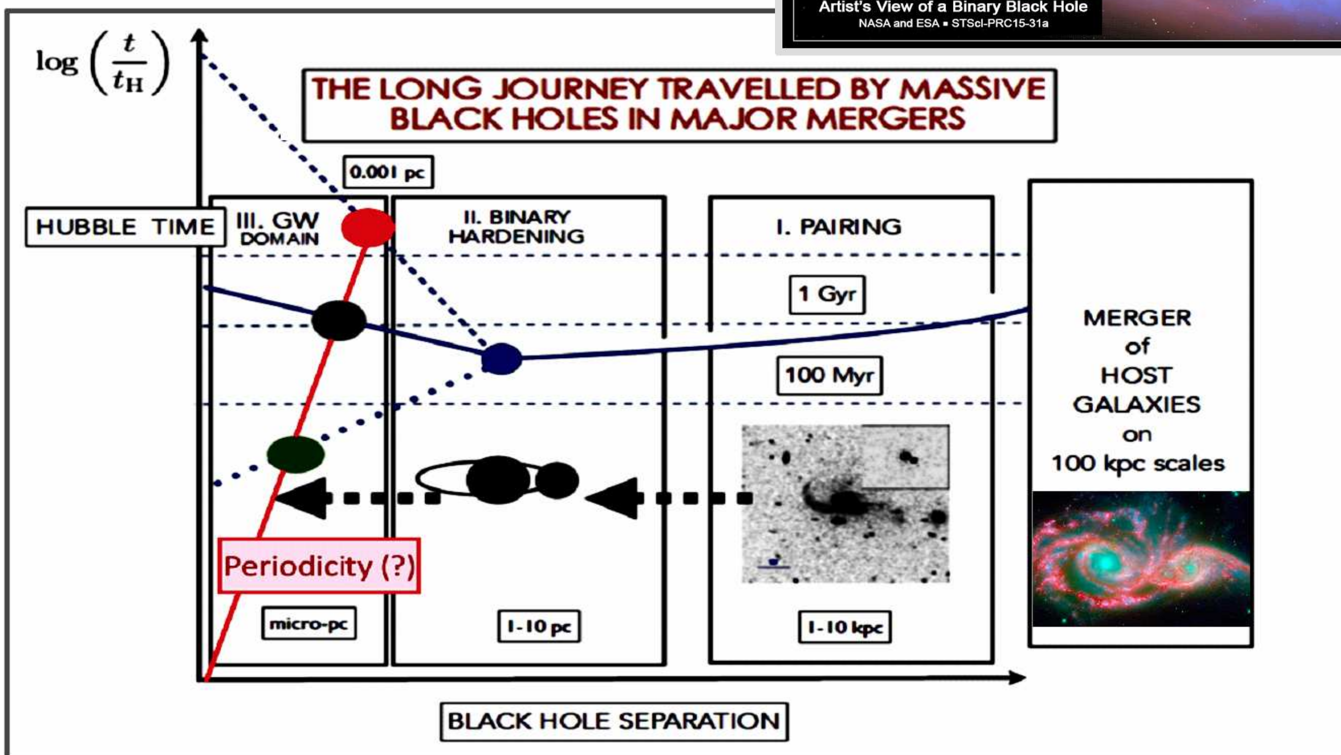
[1] Physics and Astronomy Department, University of California, Los Angeles, CA 90095-1547, USA; tdo@astro.ucla.edu
[2] Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309, USA
[3] California Institute of Technology, Pasadena, CA, USA
Received 2008 May 31; accepted 2008 October 2; published 2009 January 28

Periodicities by binary supermassive black holes ?







Supermassive BHs binaries in AGN

r/pc: 1000 — 100 — 10 — 1 — 0.1 — 0.01

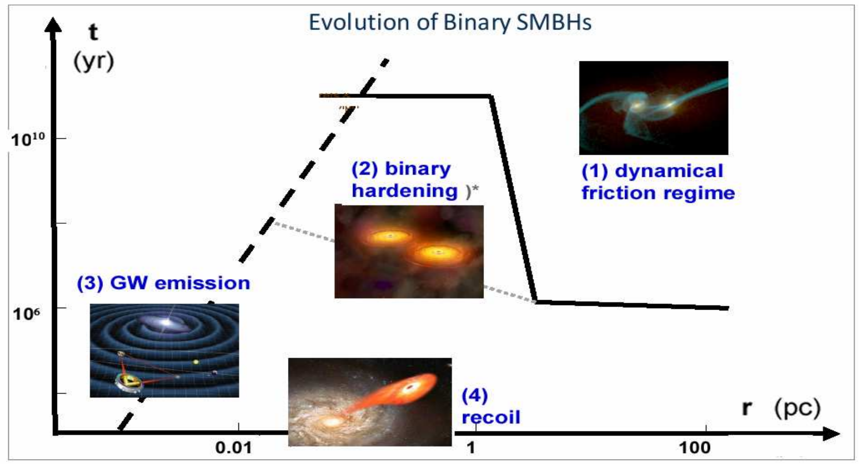
Observational evidence for SMBH pairs and gravitationally bound binary systems:

- ❑ quasar pairs, AGN in clusters of galaxies
- ❑ pairs of active galaxies, interacting galaxies in early phase of interaction/merging (double-peaked narrow optical emission lines, if both galaxies have NLR)
- ❑ SMBH pairs in "single" galaxies and advanced mergers, kpc/100-pc scales (ex.: two accreting SMBHs spatially resolved, often heavily obscured --> X-ray/radio observations)
- ❑ spatially unresolved binary-SMBHs candidates (1. pseudo/quasi/semi-periodic signals in radio/opt flux light curves; 2. pc-scale spatial radio-structures distorted/helical-patterns in jets; 3. double-peaked broad lines)
- ❑ a few post-merger candidates (X-shaped radio sources, galaxies with central light deficits, double-double radio sources, recoiling SMBHs)

Nature Vol. 287 25 September 1980 307

Massive black hole binaries in active galactic nuclei

M. C. Begelman*, R. D. Blandford† & M. J. Rees‡

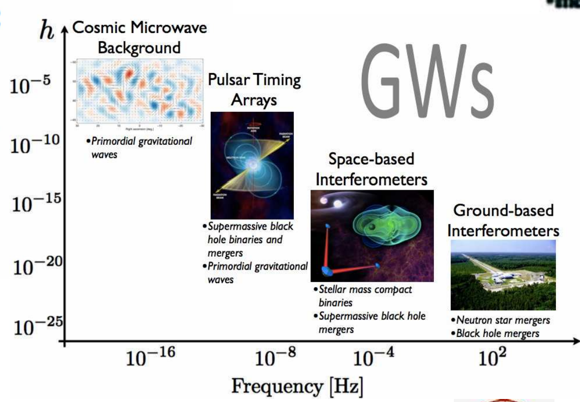


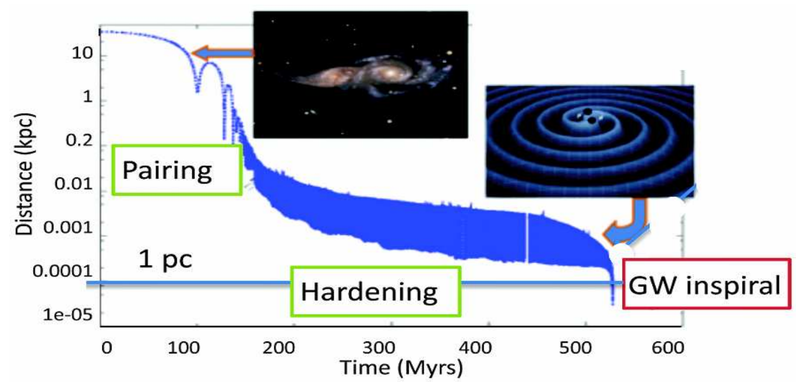
[Credits S. Komossa 2014]

- Galaxy mergers. Sites of major BH growth & feedback processes.
- Coalescing binary SMBHs. GWs and e.m. radiation powerful emission
- GW recoil. SMBHs oscillate about galaxy cores or even escape.

$$t_{merge}(a) = 5.8 \times 10^6 \left[\frac{a}{0.01\,\mathrm{pc}}\right]^4 \left[\frac{10^8 M_\odot}{m_1}\right]^3 \frac{m_1^2}{m_2(m_1+m_2)}\ \mathrm{yr}$$

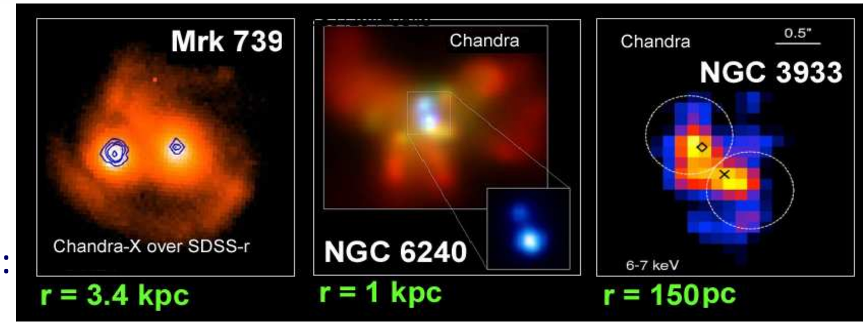
GWs





Obs. evidence for SMBHs pairs (less for binaries)

Pair of accreting SMBH in "single" galaxies (spatially resolved 10-pc to 100-pc): NGC 6240; 4C+37.11 , NGC 3933, LBQS 0103-2753, Mkn 739, ESO 509-IG 066, etc.

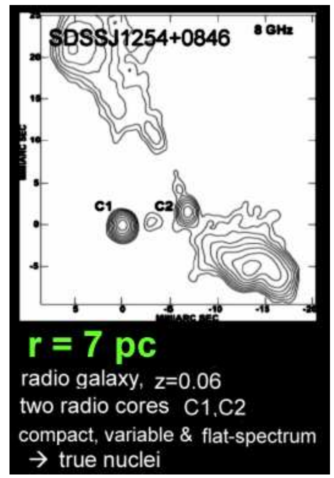


Spatially unresolved (close if <0.1pc) binary SMBHs:

❑ 1) from claims of quasi-periodic variability signatures (years): OJ 287, PG 1302-102, 3C 345, PSO J334.2028+01.4075, AO 0235+16, 3C 273, TXS 0059+581, S5 0716+71, BL Lac, 3C 66A, (skepticism here).

❑ 2) also from short-term optical/X-ray/TeV blazar light curves (weeks) as "transient periods" (super-skepticism here!).

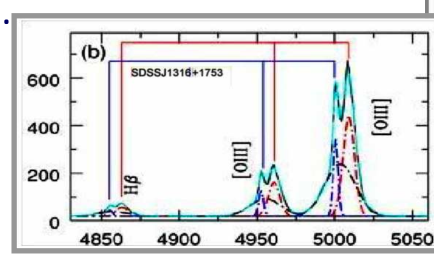
❑ 3) from observed helical distorted radio jets (jet-emitting 2ndary SMBH orbiting primary, precession, jet reorientation in radio X-shapes): 3C 345, NRAO 530, 3C 120, 3C 66B, Mkn 501, …



name	periods P_{obs}	$(m+M)/10^8 M_\odot$
Mkn 501	23.6 d (X-ray)	(2-7)
	~ 23 d (TeV)	
	10.06 yr (optical)	
BL Lac	13.97 yr (optical)	(2-4)
	~ 4 yr (radio)	
3C 273	13.65 yr (optical)	(6-10)
	8.55 yr (radio)	
OJ 287	11.86 yr (optical)	6.2
	~ 12 yr (infrared)	
	~ 1.66 yr (radio)	
	~ 40 d (optical)	
3C66A	4.52 yr (optical)	≥1
	65 d (optical)	
0235+16	2.95 yr (optical)?	≥1
	8.2 yr (optical)?	
	5.7 yr (radio)	

Rieger 2008, 2007

❑ 4) from observed double-peaked broad lines: SDSS J0927+2943, SDSS J1316-1753, SDSS J150243.1+111557, PG 1302-102 (non-double but asymmetric). Small fraction of all "double-peakers" are good. Only a few real "detections".

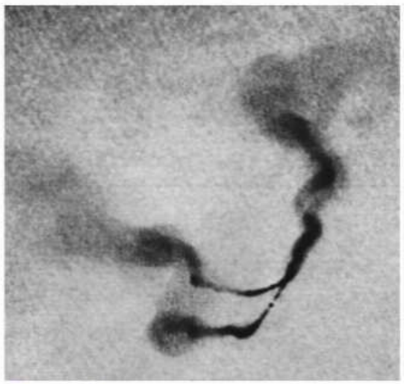


❑ 5) other evidences: some candidate TDEs (SDSS J120136.02+300305.5), recoils (anisotropic emission of GWs from coalescing binary SMBHs leads to recoil of the newly formed single SMBH) and more exotic ones.

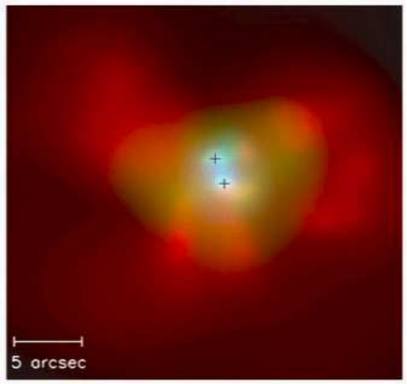
Obs. evidence for SMBHs pairs (less for binaries)

Many binary binary SMBHs candidates but few non-controversial confirmations! Why so few ?

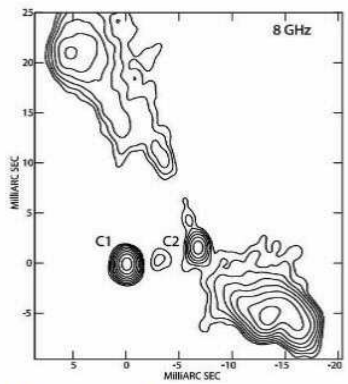
- ❑Large distances (difficult to resolve). Perhaps obscured. Need to distinguish other phenomena (in-jet knots, lensing). In close binaries methods require at least one SMBH to be active (many may not be active).
- ❑ Great challenge: identify inactive binary SMBHs. The most abundant but also the most difficult to identify.
- ❑ Binary SMBHs may form quiescently either in gas-poor or minor galaxy mergers without AGN activity.



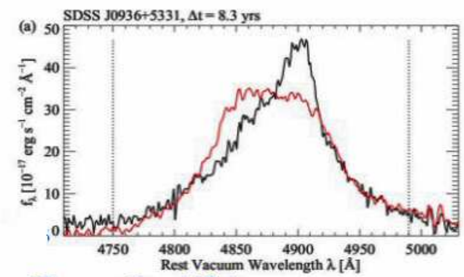
Dual jets (3C 75, a~7kpc)
[Owen+ 1985]



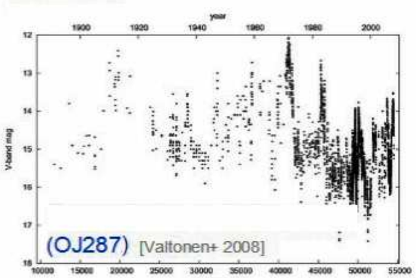
Dual X-ray sources
(NGC 6240, a ~ 1.5 kpc) [Komossa+ 2003]

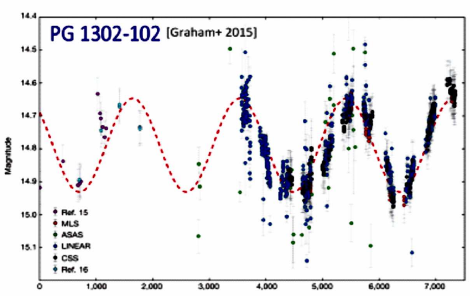


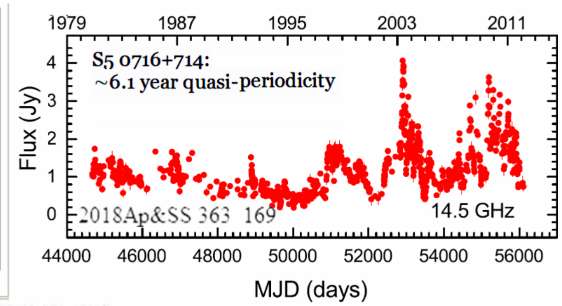
Binary radio sources
(0402+379, a ~ 7pc) [Owen+ 1985]



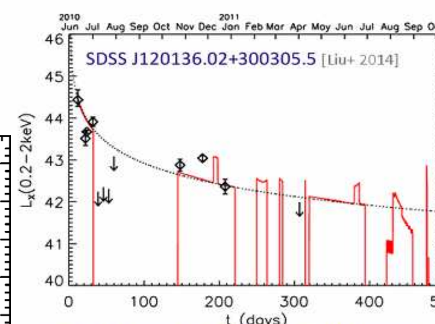
Kinematic shift in multi-epoch observations
[Liu+ 2013]





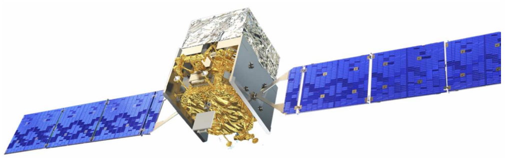


Quasi periodicity in light curves (still controversial topic)



TDE events and dips in X-ray light curves

The new 9.5-year LAT gamma-ray flux light curves

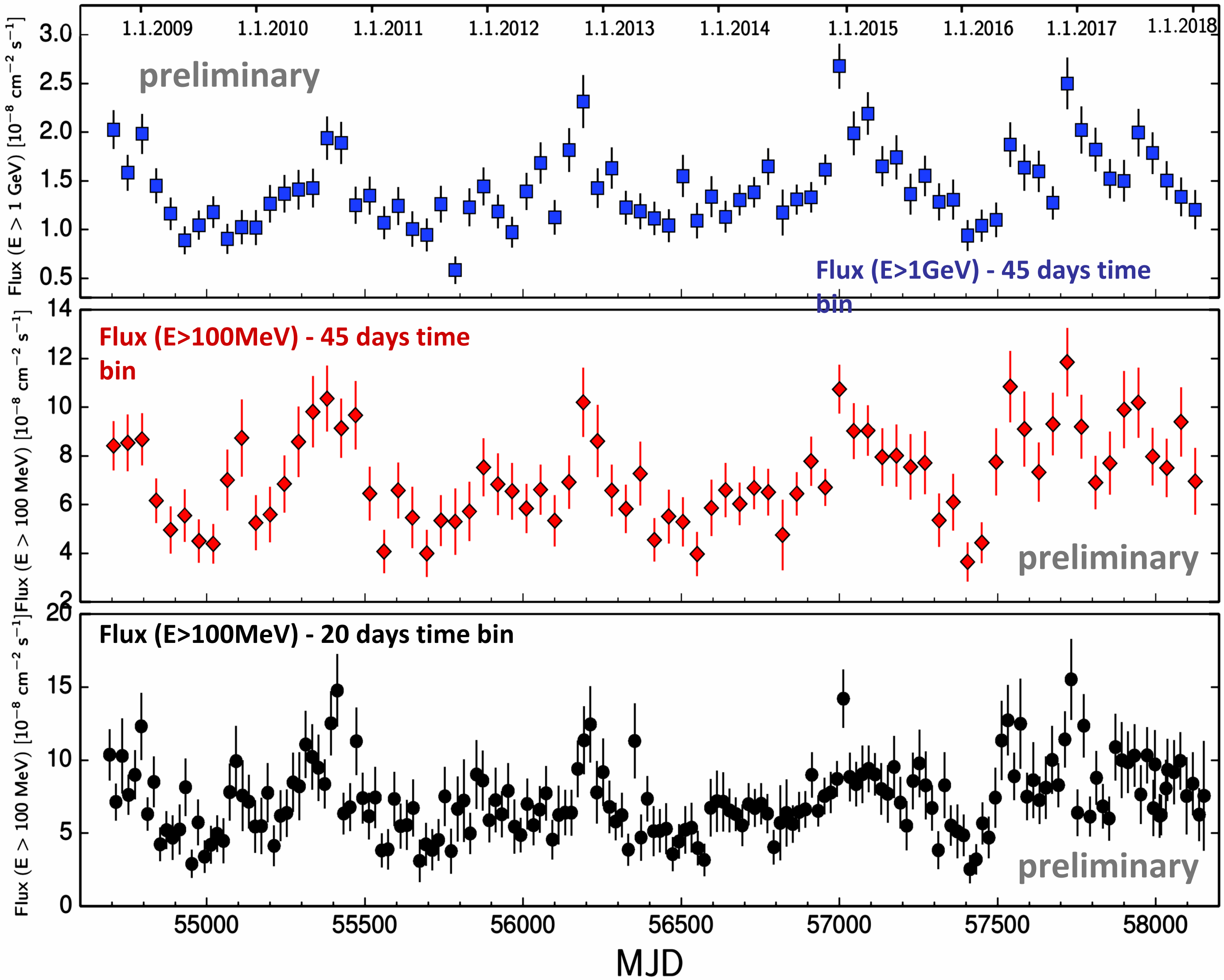


❑ *Fermi* LAT gamma-ray flux (E>100MeV and E>1GeV) light curves (lc) of PG 1553+113 Pass 8 dataset up to Jan. 2018 (full 10-year baseline in the paper in preparation).

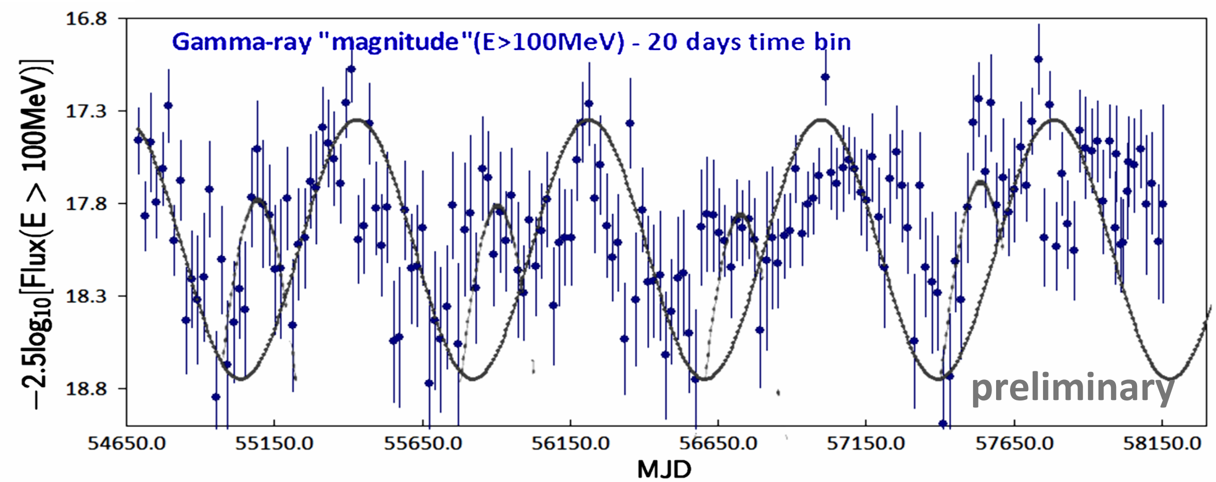
❑ Regular/large-size time bins of 45-day and 20-day bin size. Temporal analysis cross-checks on adaptive bin and aperture photometry lcs.

❑ Long-term oscillating trend visually evident but a more noisy appearance. Predicted oscillation maximum is observed.

→ Periodicity in 4.5 cycles.



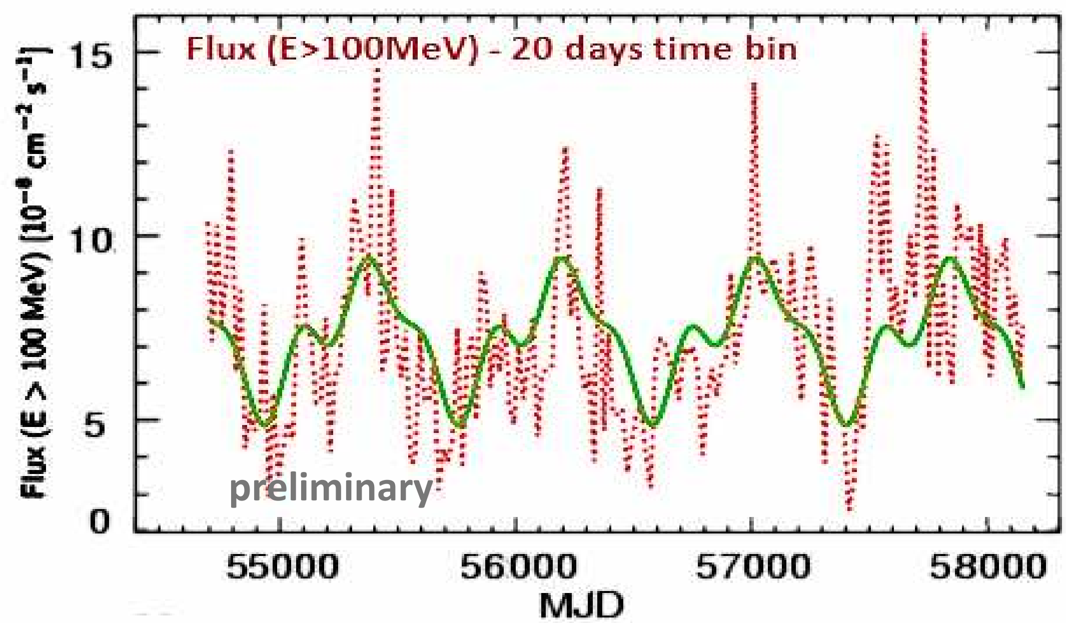
The new 9.5-year LAT gamma-ray light curves

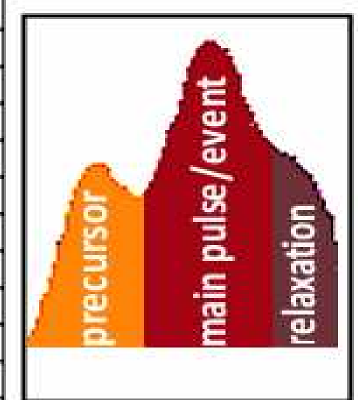


- 9.5-year LAT gamma-ray flux light curve of PG1553+113 (E>100MeV 20-day bin) reported in log10 Y-scale ("magnitude"). A strict single-pulse sinusoidal curve (P=2.18y) curve is superposed.

- 9.5-year LAT gamma-ray flux (E>100MeV 20-day bin) light curve of PG 1553+113.

The light curve is fitted (green curve) with a coherent pulse consisting of 4 Fourier components.

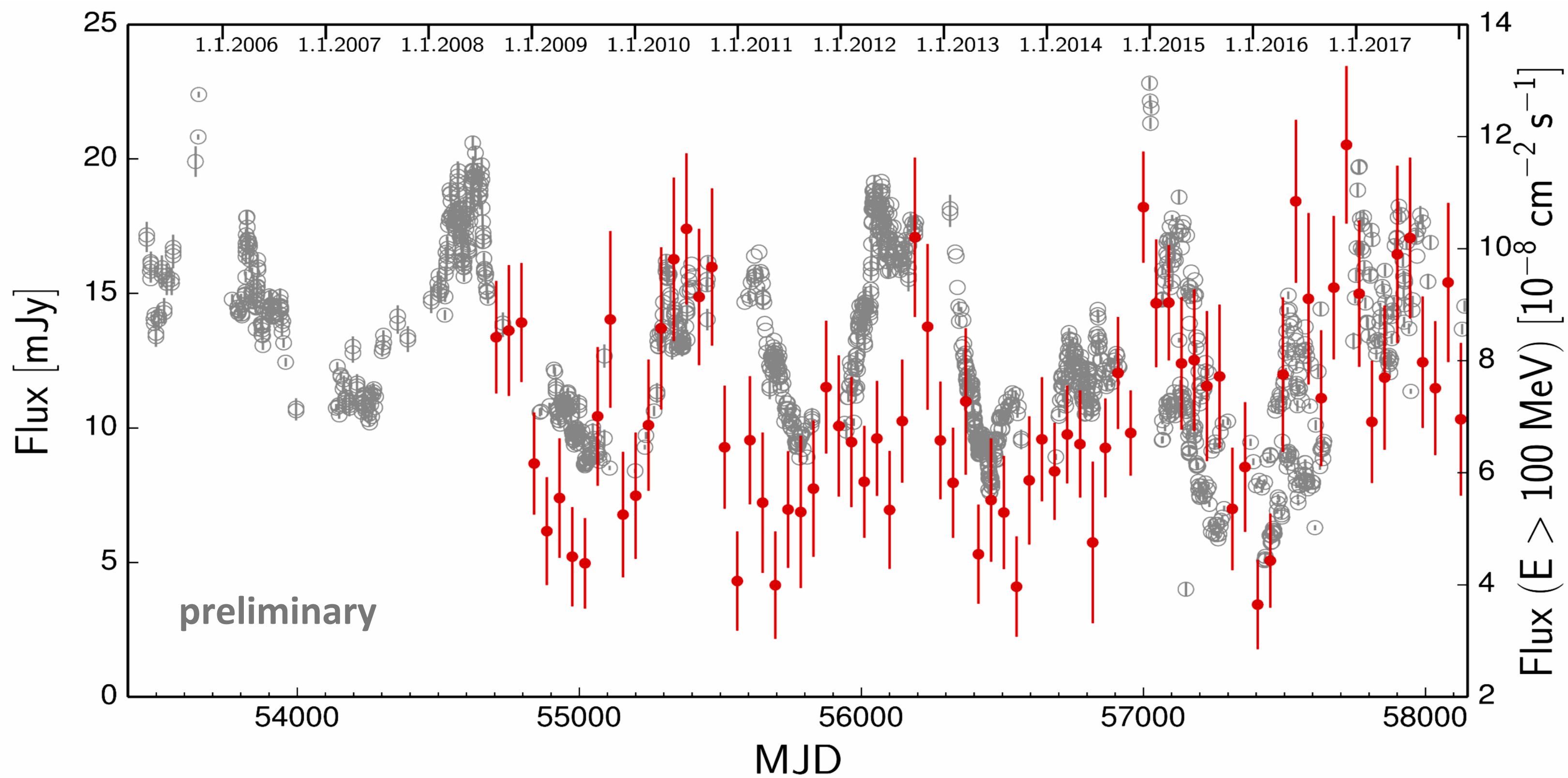




Gamma-ray overlapped optical light curves

- 9.5-year LAT gamma-ray flux (E>100MeV 20-day bin) light curve of PG 1553+113 (red datapoints).
- 12.5-year optical (R-band) light curve of PG 1553+113 (grey datapoints).

Collected from: Tuorla+KVA monitor program data + Catalina CSS archive data + KAIT monitor data + Swift UVOT data. Swift dedicated program on PG 1553+113 since 2015.



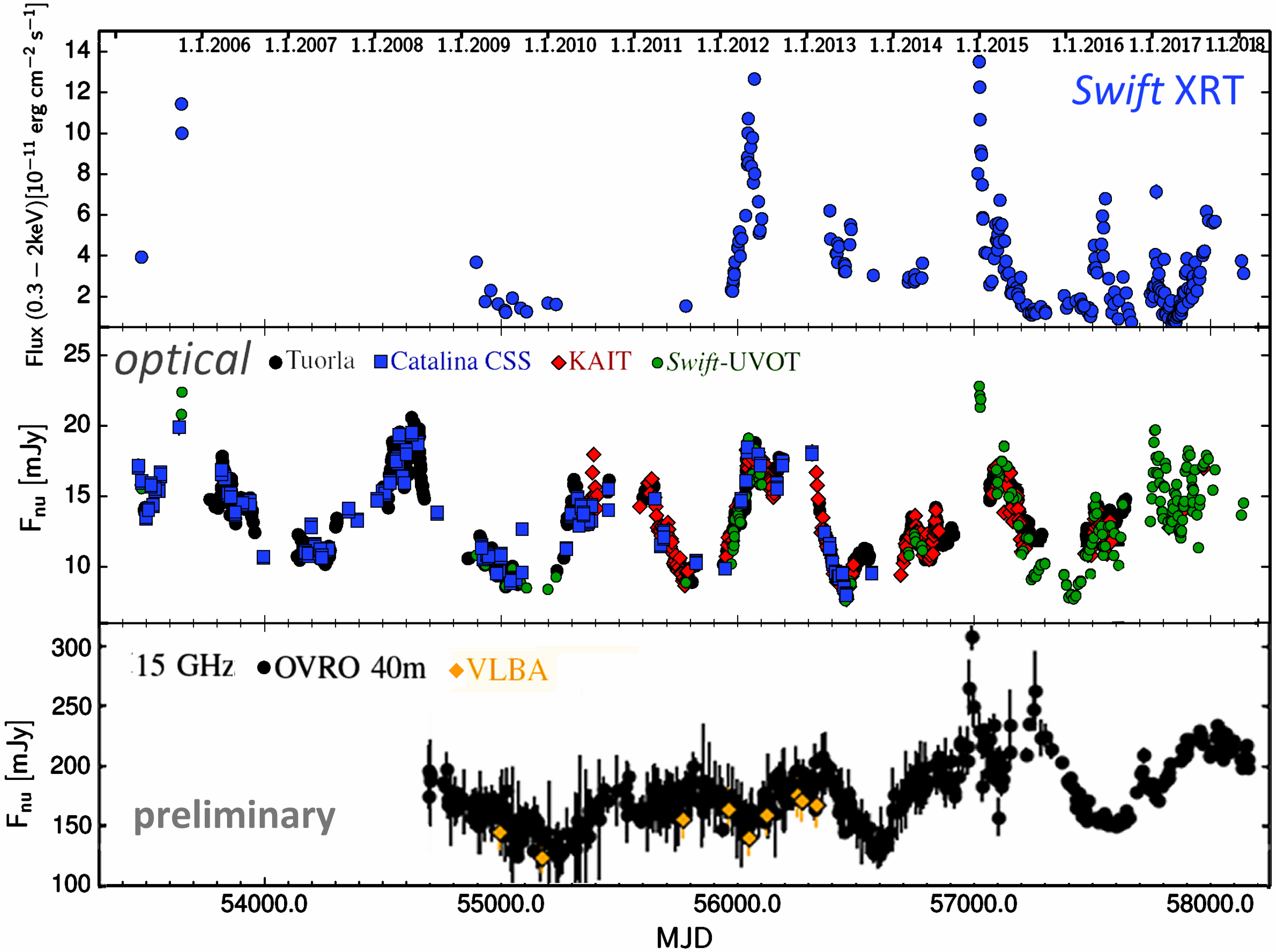
Radio/optical/X-ray light curves

Multifrequency flux light curves built at: X-ray, optical (R and V bands) and radio (15 GHz) band.

➔X-ray data obtained with Swift-XRT (thanks to past MW campaigns and dedicated follow-up program on PG 1553+113 started on Dec.2014).

➔ Long-term Rossi-XTE (ASM) and Swift-BAT also under re-analysis (but poor statistics and noisy).

➔ Optical band is assembled with Tuorla monitoring program, with Katzman Automatic Imaging Telescope (KAIT) monitoring data Catalina Sky Survey (CSS) data and a dedicated follow-up program of *Swift*-UVOT.



➔ Radio band at 15 GHz is assembled with 40m Owens Valley Radio Observatory (OVRO) with blazar monitoring program supporting *Fermi* (Richards+ 2011) and Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE, Lister+ 2009)

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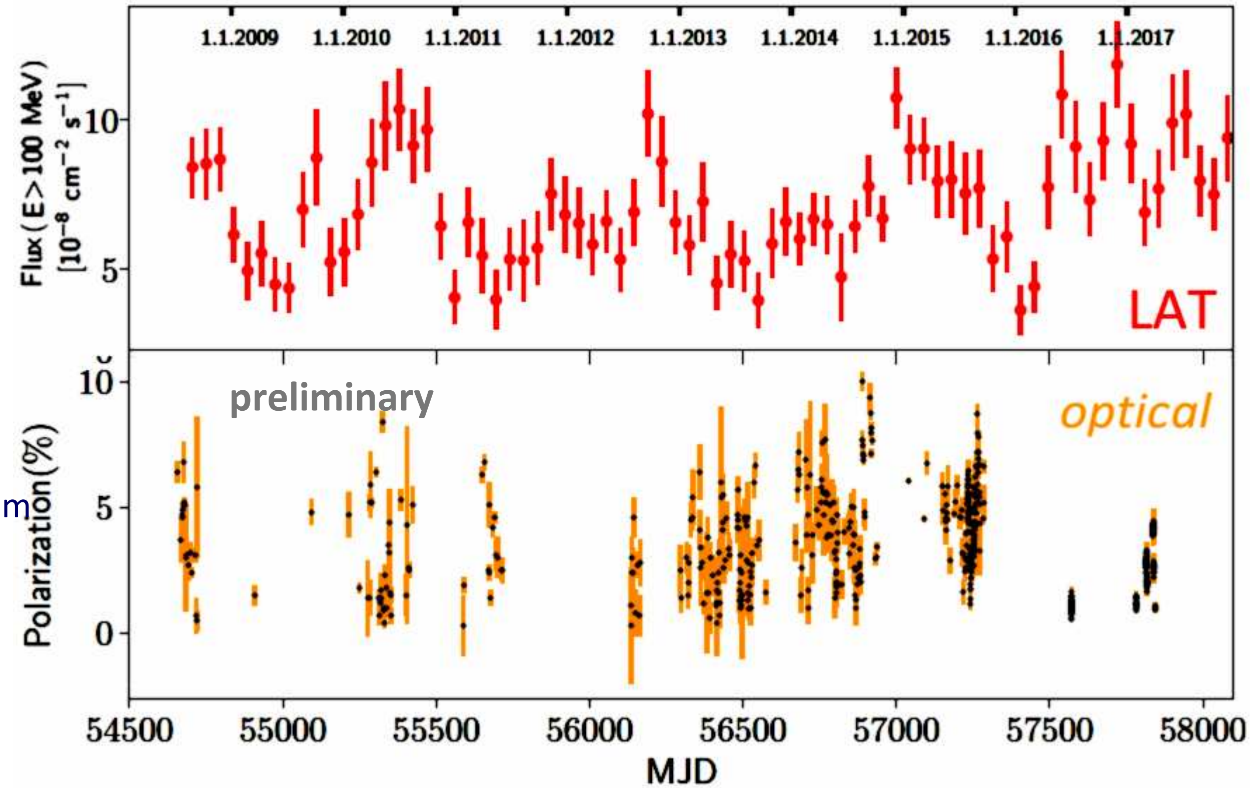
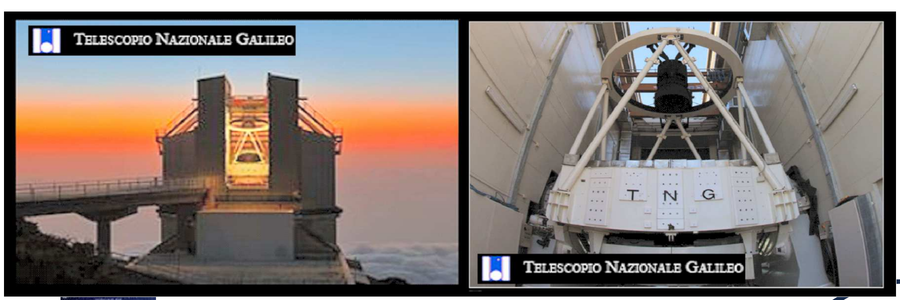
Optical polarization degree light curve

- LAT 45-day bin gamma-ray (E>100 MeV) flux light curve compared to 10-year optical polarization data.
- Optical polarization degree data collected mainly from KANATA telescope, Japan.
- Some data added from Raiteri+ 2016 (Crimean Obs. in Russia, Lulin Obs. in Taiwan, Skinakas Obs. in Crete Greece, St. Petersburg obs. in Russia).
- More (short term) data from our program at the Italian 3.6m INAF-TNG telescope in La Palma, Canary Islands (DOLORES and PAOLO instruments).
- Preliminary, optical polarization degree appear related to short term, erratic in-jet, optical flaring activity.





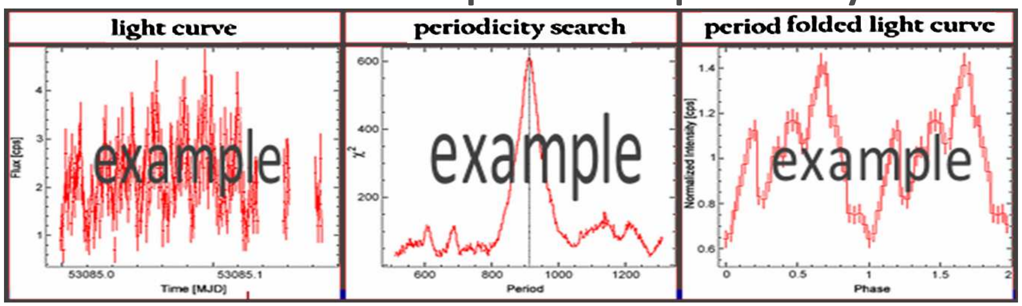
Higashi-Hiroshima Observatory

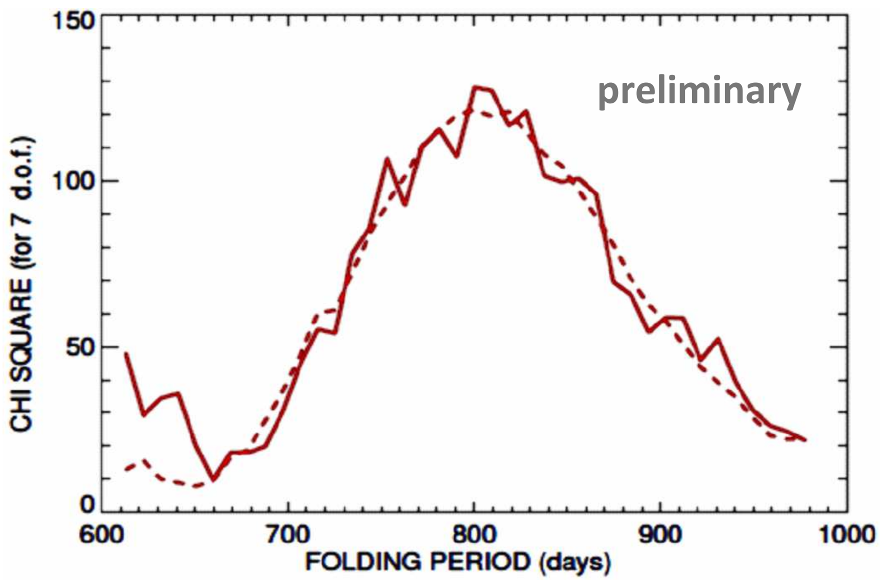
KANATA optical and NIR telescope

KANATA 1.5-m Optical and Near-Infrared telescope

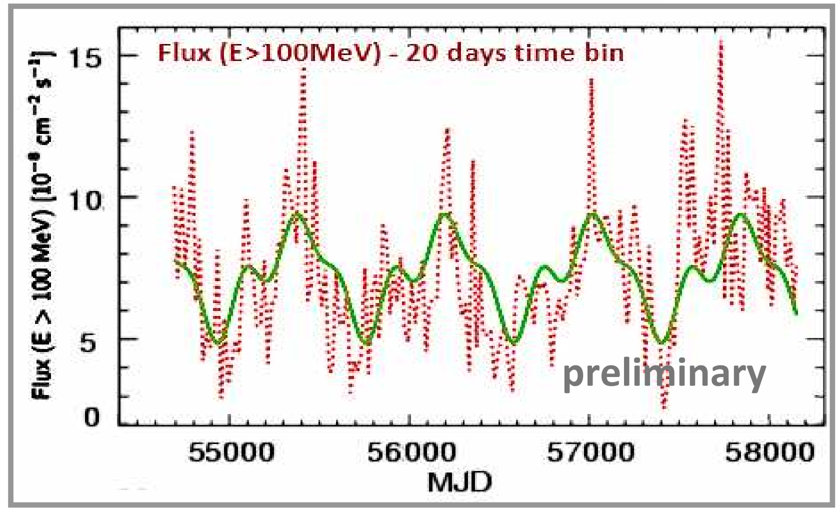
Temporal variability analysis: epoch folding

A classical 3-step "how-to" periodicity:





Epoch folded light curve (flux E>100 MeV 20-day bin)



Pulse shape analysis (flux E>100 MeV 20-day bin)

❑ 1) The epoch folding / pulse shape analysis.

- The driving method in presence of a mostly regular sampling and coherent sinusoidal oscillations.
- Analysis based on period-folded and pulse shape light curve (4 Fourier components).
- Power is confirmed at a gamma-ray characteristic periodical timescale of 2.2+/-0.2 years in all the 9.5-year LAT gamma-ray light curves.

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Temporal variability analysis: further methods

- 2) FSSC at GSFC web: direct discrete Fourier transform and power density spectra (PDS) using a gross 30-day bin aperture photometry technique, confirms the same 2.2-year timescale.

- 3) Lomb-Scargle algorithm PDS periodogram (LSP), also compared to the wavelet epoch-average spectrum.

Lomb-Scargle periodogram

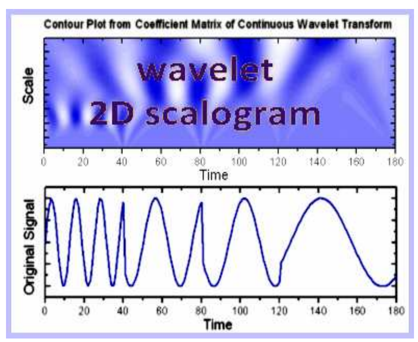
frequency spectrum estimation method
Nicholas R. Lomb and Jeffrey D. Scargle

time delay parameter $\tan 2\omega\tau = \dfrac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$

periodogram $$P_x(\omega) = \frac{1}{2}\left(\frac{\left[\sum_j X_j \cos\omega(t_j-\tau)\right]^2}{\sum_j \cos^2\omega(t_j-\tau)} + \frac{\left[\sum_j X_j \sin\omega(t_j-\tau)\right]^2}{\sum_j \sin^2\omega(t_j-\tau)} \right)$$

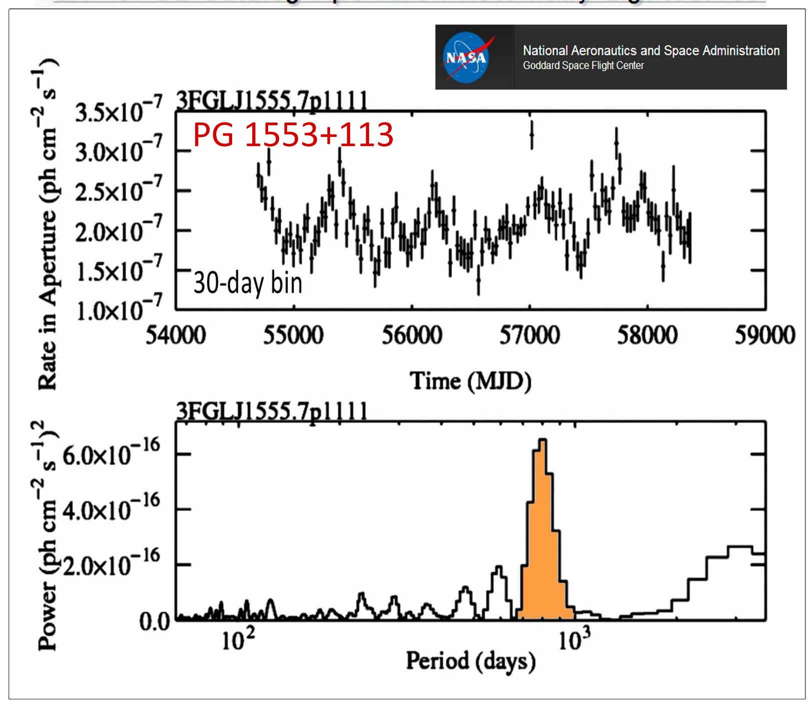
- 4) More methods (also for cross-check): discrete autocorrelation function DACF, structure function SF, phase dispersion minimization PDM, etc.)

- 5) Continuous Wavelet Transform (Morlet-mother waveform). Coherent gamma-ray signal peak along all the light curve epochs.



- 6) Two approaches for signal significance estimation against the red-noise. (quantitative analysis in progress on the 10 year dataset, for the paper).

LAT 3FGL Catalog Aperture Photometry Lightcurves



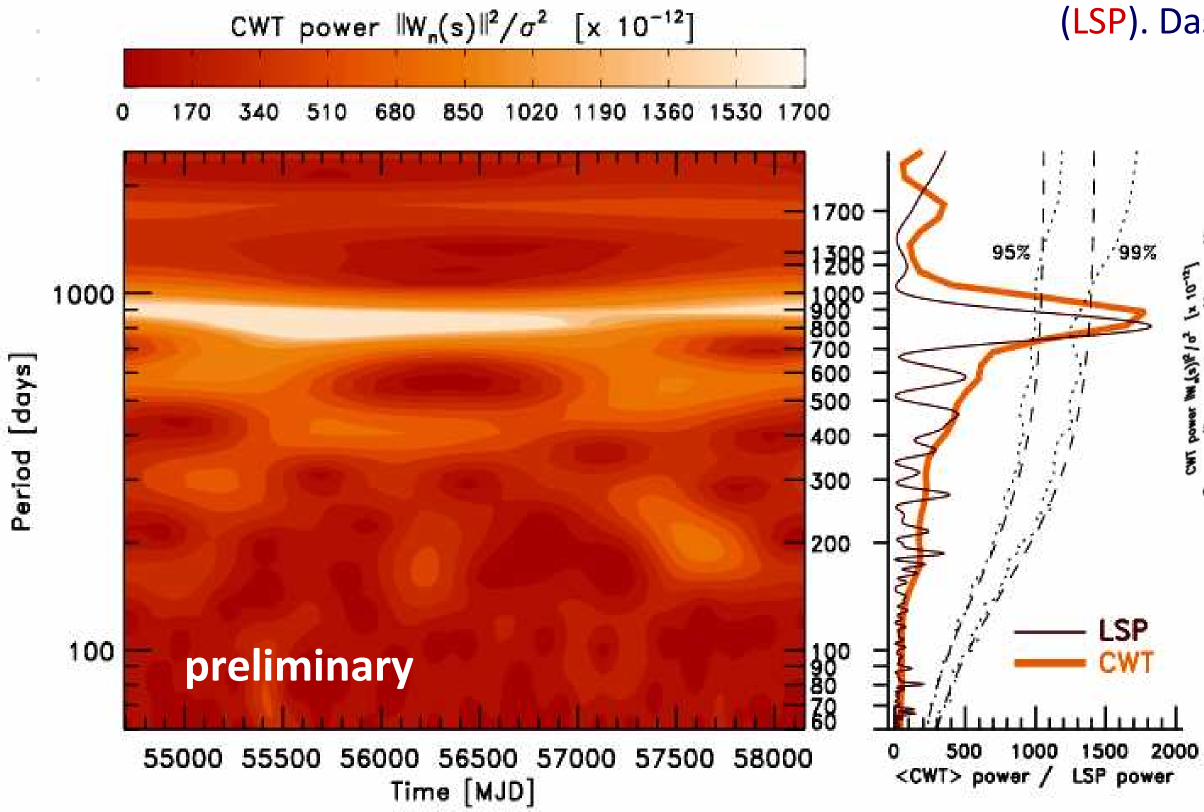
Public discrete FFT PDS using aperture photometry counts and exposure weighted light curve at FSSC-GSFC website (suitable for quicklook inspection of gross features). Not suitable for scientific analysis and publications (not background subtracted, contaminated by nearby sources photons in the aperture).

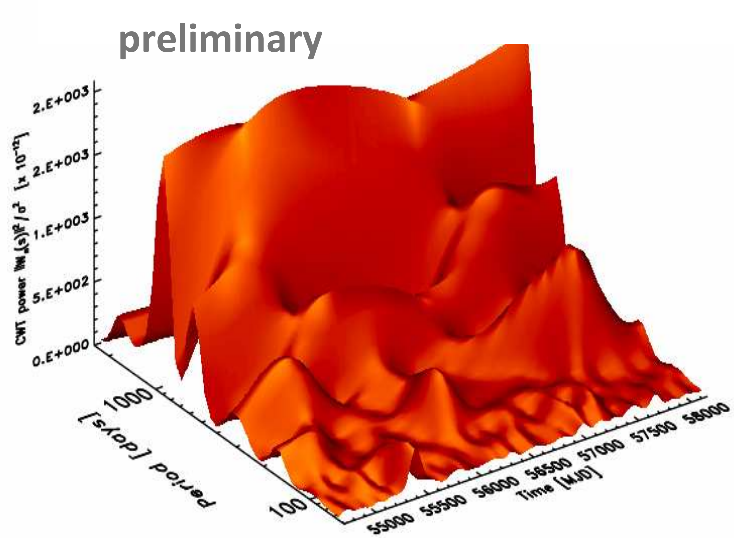
Credits [Robin Corbet, NASA GSFC]

Gamma-ray light curve: wavelets and LSP

❑ 2D plane contour plot of the continuous wavelet transform (CWT, i.e. a 2D power density spectrum), a.k.a. wavelet scalogram, of the 9.5-year, 20-day bin, LAT gamma-ray (E>100 MeV) light curve of PG 1553+113.

❑ Morlet mother function (filled color contour). The right side panel shows the 1D smoothed (all-time-epoch-averaged) power spectrum of the CWT scalogram. A signal power peak is in agreement with the 2.2 year value found with epoch fold/pulse shape analysis. This right side panel also include the Lomb-scargle Periodogram (LSP). Dashed lines depict increasing levels of confidence against red noise.





The same CWT scalogram in a 3D surface representation.

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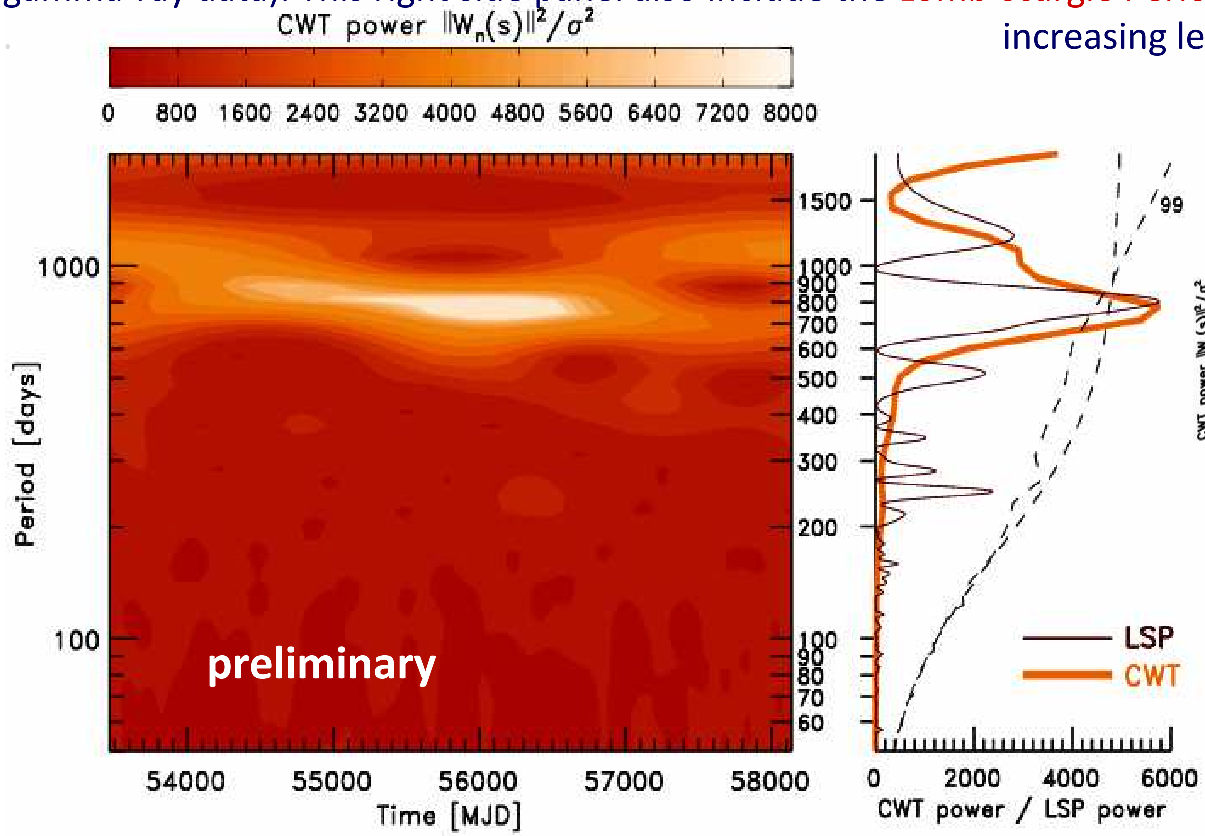
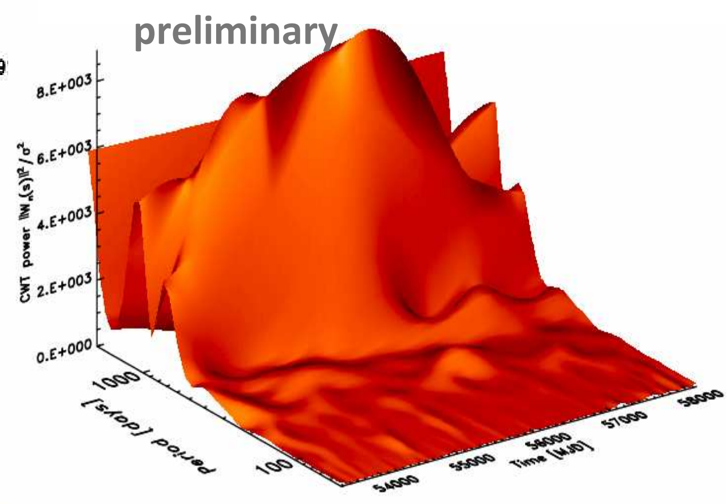
Optical lc wavelet and LSP analysis

- 2D plane contour plot of the continuous wavelet transform (CWT, i.e. a 2D power density spectrum), a.k.a. wavelet scalogram, of the about 13-year, optical, unevenly sampled, light curve of PG 1553+113.
- Morlet mother function (filled color contour). The right side panel shows the 1D smoothed (all-time-epoch-averaged) power spectrum of the CWT scalogram. A signal power peak is at 2.2-year value (the same of the gamma-ray data). This right side panel also include the Lomb-scargle Periodogram (LSP). Dashed lines depict increasing levels of confidence against red noise.





The same CWT scalogram in a 3D surface representation.

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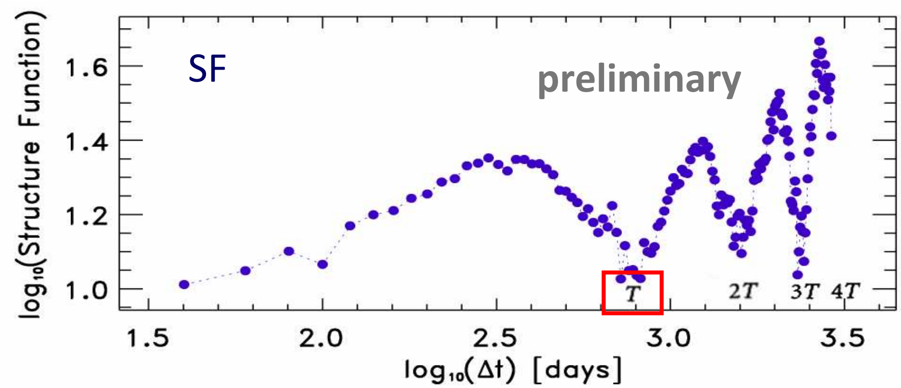
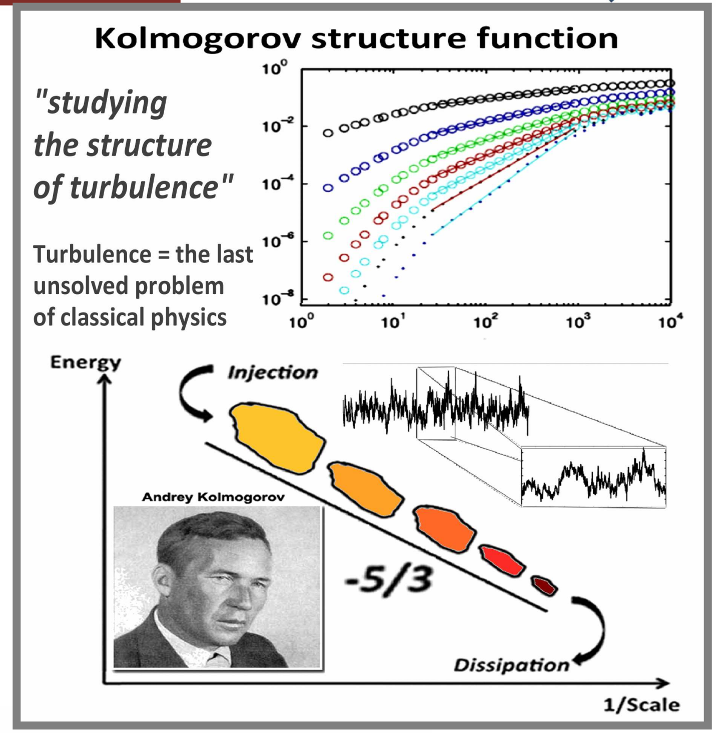
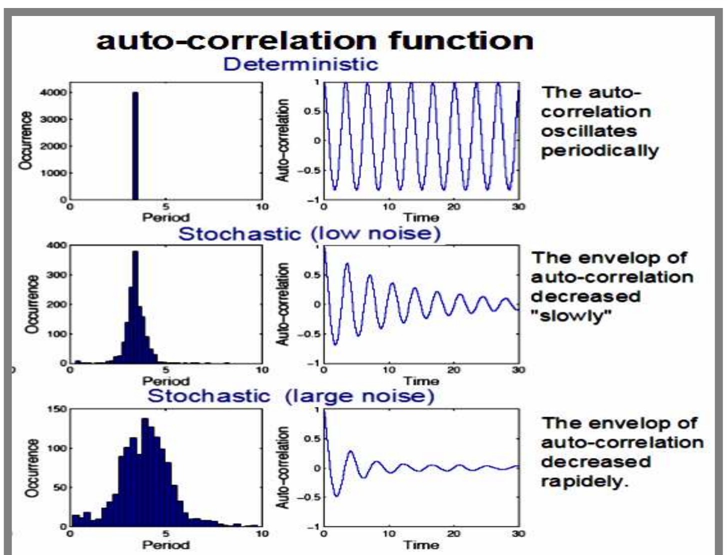
Structure Function and Discr. AutoCorr. Function

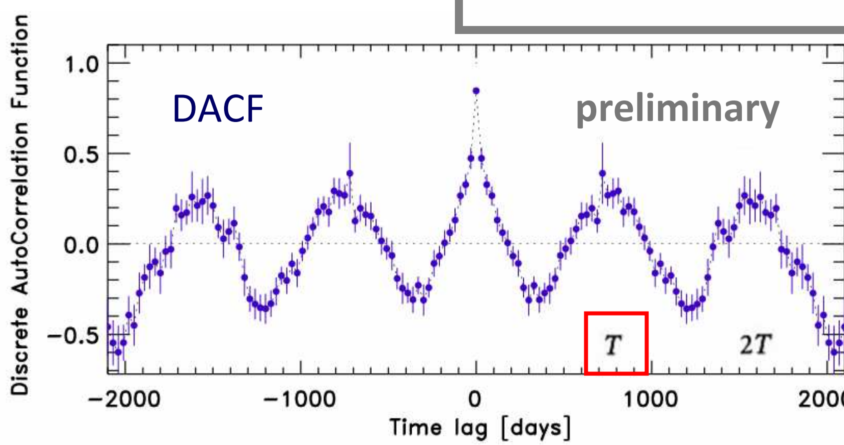
- Cross checks with further analysis methods and functions of the LAT 20-day bin, gamma-ray (E>100 MeV) light curve of PG 1553+113 are consistent with quasi-periodicity signal of T=2.2 years period.

1st order Structure Function (SF) plot









Discrete Auto-Correlation function (DACF) plot

PG 1553+113: cross-correlation analysis

Cross-correlation analysis. Important diagnostic for multifrequency periodicity analysis in AGNs/blazars.

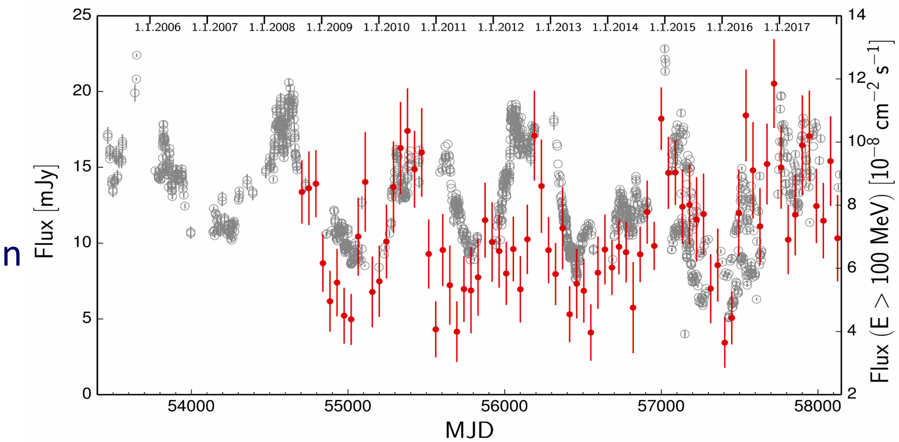
❑ Optical-gamma-ray cross-correlation (unbinned unevenly-sampled and large-gapped optical light curve opposed vs the uninterrupted and regular 45-day bin (E>1GeV) LAT gamma-ray light curve) supports the periodicity because:

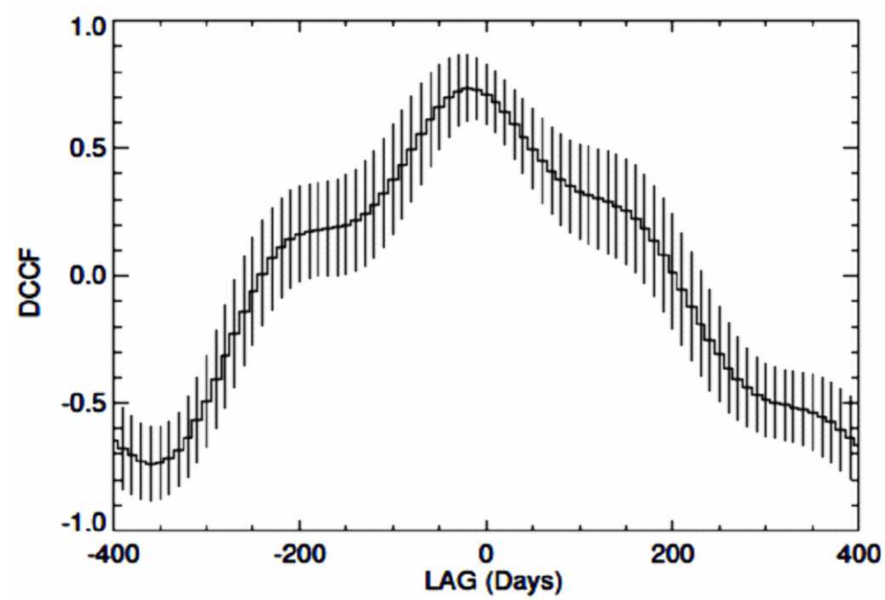
1) the optical covers additional time epochs, a bit more backwards in time

2) the optical-gamma energy bands can be described with similar periodicity plus erratic faster variations (in-jet flaring plus usual blazar variability and/or measurements noise). But optical/gamma noise and sampling different → found similar quasi periodicity strengthen its reality.

❑ Significance of the gamma-ray-optical cross-correlation preliminary estimated to be >95%.

Strong cross-correlation with time lag consistent with zero lag (-16+/-27 days) → strengthens the fact the periodicity is real and possibly coherent.





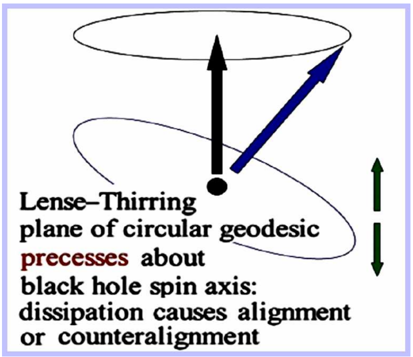
Open astrophysical scenarios

❑ Jet wobbling/precession/rotation/nutation on parsec scales (…but 2-years is a too short timescale?). Non-ballistic (→components) helical motion travel time effects can lead to observed time shortening effects.

❑ Curvature and helical-like structure of the relativistic jet, and/or of the radiating in-jet components. Such features can results in differential Doppler beaming magnification changing periodically, with oscillations of the angle of sight and the observed radiation boosting. A whole jet structure/geometry and/or in-jet localized components.

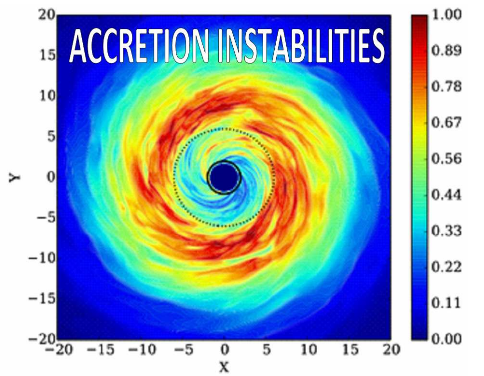
❑ Alternatively disc-jet connection and symbiosis with induced quasi-periodical triggers and ejections.

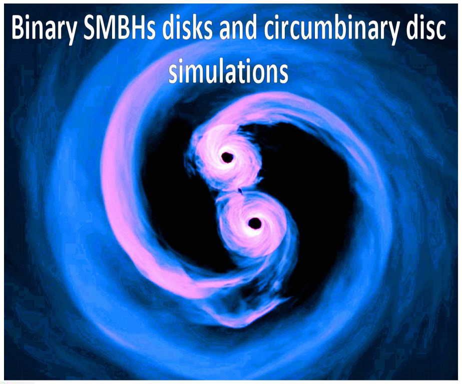
- Warped disks; accretion perturbations; periodically intermittent supply of plasma in the jet funnel; MHD/magneto-rotational instabilities in relativistic magnetized accretion disks, MHD stresses with magnetic reconnection (intrinsic to material of accretion disk or jet itself).
- These can be well consinstent with tidal/efficiency/ perturbations and MHD-tearing instabilities given by a close BH companion, i.e. a sub-parsec (<10^18 cm) binary, gravitationally bound, supermassive black hole system (SMBHs).

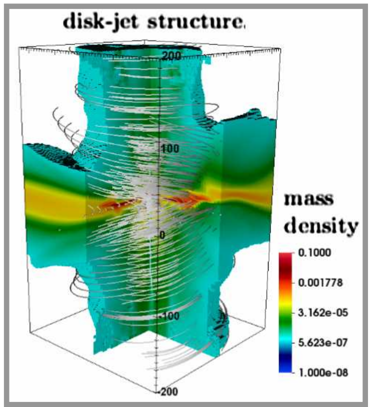


❑ Physical origin of jet wobbling is in changes in direction at the jet nozzle:

- by accretion disk precession, Lense-Thirring (rotational dragging in GR) precession, orbital Keplerian motion of the accretion system with jet nutation (rocking, nodding) in a binary SMBHs scenario,
- by periodic perturbations, warps, stresses to accretion disc again in a binary SMBHs scenario.





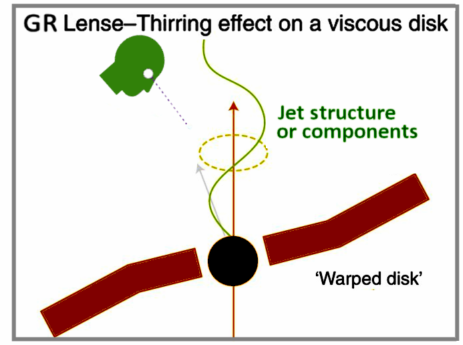


Open astrophysical scenarios

❑ Pulsational accretion flow instabilities, approximating periodic behavior, are able to explain periodic modulations in the energy outflow efficiency.
Magnetically arrested and magnetically dominated accretion flows (MDAFs) could be suitable regimes for radiatively inefficient of TeV BL Lac objects like PG 1553+113 (Fragile & Meier 2009), characterized by advection-dominated accretion flows and subluminal, turbulent, and peculiar radio kinematics.

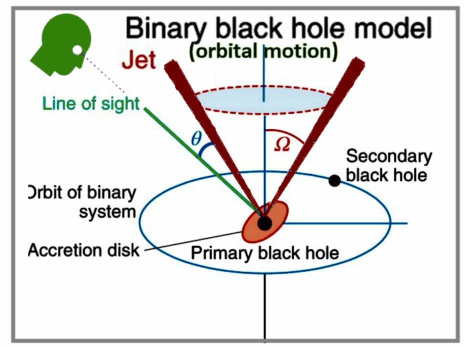
❑ Similar mechanims to low-frequency QPO of Galactic high-mass binaries (Fender & Belloni 2004, King et al. 2013). PG 1553+113 has a low accretion rate. QPO Lense-Thirring precession requires inner accretion flow forms a geometrically thick torus rather than a standard thin disk as the latter warps (Bardeen-Petterson effect) rather than precesses (Ingram et al. 2009). ADAF-disks anyway can give precessing jets.

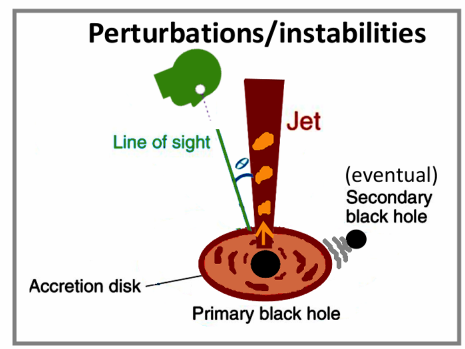
❑ Lense-Thirring precession could affect the jet direction, giving the QPO.



❑ Binary, gravitationally bound, SMBH system (total mass of 1.6X10^8 Msun, milliparsec separation, early inspiral nano-Hz gravitational-wave driven regime. Keplerian binary orbital motion with periodic accretion perturbations or jet nutation.

- Disk evolution accelerated onto a binary SMBH system, as shown by simulations. Probability of observing such a GW-driven milli-pc system (mass ratios 0.1–0.01, and lifetime 10^5−10^6 years) might be small.
- About current PTAs nano-Hz GW detection limits we would better aim to have millisec pulsars timing constrains/detections from Square Kilometer Array.
- Event Horizon Telescope, EHT, (too distant ?); LISA (too very-low frequency GWs ?).





Conclusions

❑ Interest and several follow-up papers (with LAT public data) by the scientific community external to the *Fermi* LAT collaboration for the [Ackermann+ 2015] LAT paper. Interpretations based on the, tantalizing, binary supermassive black hole (SMBH) scenario.

❑ 9.5 year *Fermi*-LAT Pass 8 data here presented, 10-year data paper in preparation: → deterministic prediction (valid in long-lived coherence hypothesis) is observed and confirmed, with increased significance.

❑ Recent gamma-ray oscillation peak, even if noisier and broader, confirms the 2.2 year gamma-ray period → 4.5 flux modulation cycles observed. Different time-series analyses all agree with this period timescale.

❑ Gamma-ray period also confirmed by 12.5-yar optical data (more than 6 cycles seen). Additional support from X-ray and radio data.

❑ Significant optical-gamma-ray cross-correlation (unbinned, unevenly-sampled, gapped, optical light curve and continuous regular-monitored LAT GeV gamma-ray light curves). The found similar periodicity strengthen the reality of the observed periodic flux oscillation.

❑ This is the first confirmed periodicity in an high-energy blazar/AGN in more than one single energy band.

❑ Model interpretation in progress, but the sub-parsec separation gravitationally bound, binary SMBH system (total mass of 1.6X10^8 Msun) in an early inspiral gravitational-wave (nano-Hz) regime can be reasonable. Perspective for GW pulsar timing detection with SKA. Some interest also for EHT and LISA.

❑ *Fermi* mission opening a further window for exciting science (long-term time-domain science, binary SMBH science): → further 10 years of Fermi all-survey (monitor) needed to see more periodic gamma-ray blazars (longer multi-years periods, >3,4 cycles needed against chances of pure red noise realizations).

❑ 2-decades observations important also for PG 1553+113 (9 cycles, if coherence will continue) and possible drifts by GW energy losses, allowing constraints on SMBH binary dynamics in strong-field GR.