Gamma-ray Binaries: 1FGL J1018.6-5856, a Hunt for New Systems, Cyg X-3

Robin Corbet

(UMBC/NASA GSFC)

on behalf of the Fermi-LAT collaboration

Resources

1FGL J1018.6-5856:

Corbet, Cheung, Kerr, Fermi LAT Team, & M.J. Coe, F. Di Mille, P.G. Edwards, M.D. Filipovic, J.L. Payne, J. Stevens, M.A.P. Torres, 2012, Science, 335, 189

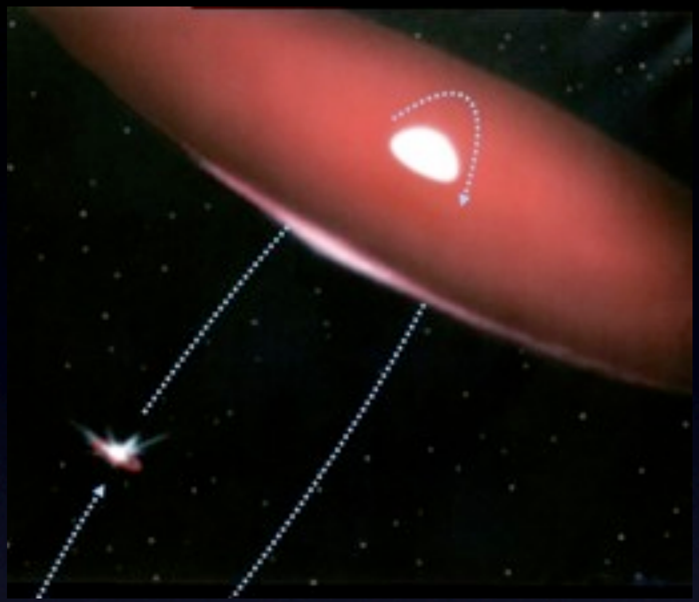
Cyg X-3:

Corbel et al. 2012, MNRAS, 421, 2947, Szostek et al., AAS, 2012: "Giant Radio Flare with Associated γ-ray Emission" (Corbel, Dubus, Szostek, Corbet, LAT Team, J. Tomsick et al.)

Zdziarski et al. 2012, MNRAS, 421, 2956, "Gamma-ray emitting Jet"

Many Cyg X-3 slides are thanks to Anna Szostek, Guillaume Dubus, and Stephane Corbel!

What Makes a Gamma-ray Binary?



- To make a gamma-ray binary you need:
  - Power source
  - Non-thermal mechanism. e.g. Fermi acceleration at shocks + inverse Compton scattering.
- The "conventional" mechanisms are:
  - Accreting microquasar with relativistic jets
  - Pulsar interacting with the wind of an O or B type companion. (Pulsar and stellar winds collide and form shocks.)

High-Mass X-ray Binary/Gamma-ray Binary Connection?

X-ray binaries may go through a gamma-ray binary phase early in their lives

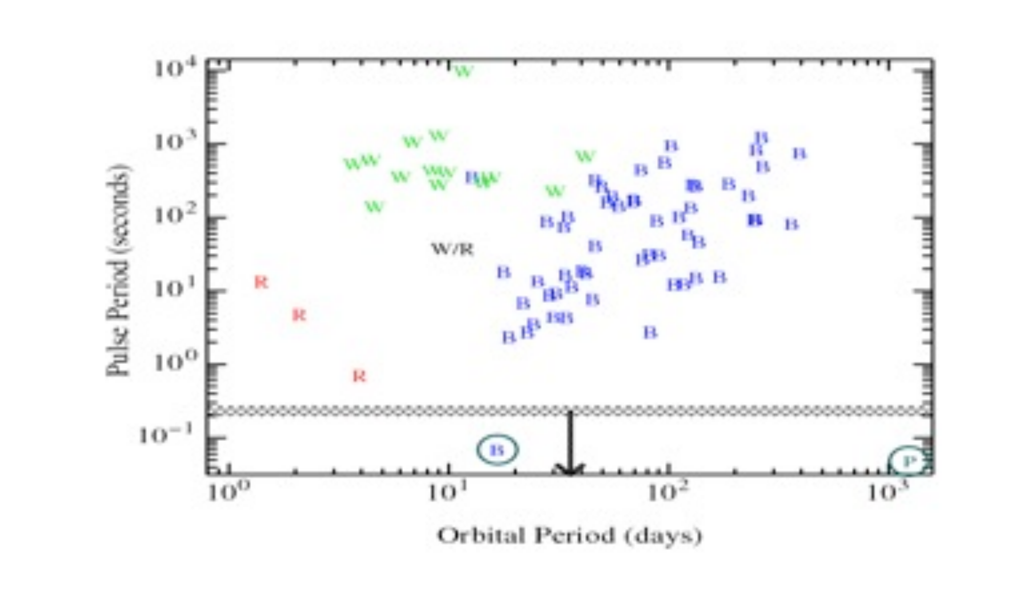
A newly born neutron star is expected to be rapidly rotating and highly magnetized.

Relativistic pulsar wind interacts with companion's wind and produces gamma-rays until neutron star has spun down (e.g. Dubus 2006).

Meurs & van den Heuvel (1989) predicted ~30 such systems in the Galaxy in this brief phase.

Pulsar wind pressure dominates for:

$$P_{spin} < 230\, B_{12}^{1/2}\, M_{15}^{-1/4}\ ms$$



Few Gamma-ray Binaries are Known

The Fermi LAT had previously detected only:

Cygnus X-3: transient *microquasar*, Wolf-Rayet (+ black hole?). 4.8 hr orbital period.

- LS I +61 303: Be star, *suspected pulsar companion*. 26.5 day period.
- PSR B1259-63: Be star, *definite 48ms pulsar companion*. 3.4 year period.
- LS 5039: O6.5V((f)) star, *suspected pulsar companion*. 3.9 days.
  - » These were all previously known, or at least suspected, gamma-ray binaries - even before Fermi.
  - » (Cyg X-1 & HESS J0632+057 not detected with LAT)

Either the mechanisms that make gamma-ray binaries occur infrequently, or else more systems (as predicted) remain to be discovered!

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The Fermi LAT

Fermi was launched on June 11, 2008

The primary instrument is the LAT: 100 MeV (or lower) to 300 GeV (and higher).

The LAT has several advantages over previous detectors:

- Instrument performance: Improved effective area, field of view, angular resolution.
- Observation mode: the LAT operates in sky survey mode almost all the time. The ***entire sky is observed every ~3 hours***. Can study binaries on wide range of timescales.

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The Hunt for New Binaries

- Known gamma-ray binaries show modulation on their orbital periods.
- Hope to find new binaries from the detection of periodic variability.
- Even with the improved sensitivity of the LAT, count rates are still low.
  - Even a "bright" source may only give ~20 photons/day.

Need highest possible signal-to-noise light curves and make sensitive period searches.

Optimizing Light Curves

There are two basic ways to make LAT light curves:

- Maximum likelihood fitting.
- Aperture photometry.

Likelihood fitting is slow, and is difficult/impossible if not many photons are present in a time bin.

Aperture photometry is non-optimal. Ignores source photons outside the aperture, includes background inside the aperture.

- Problem compounded by strong LAT PSF energy dependence.

Instead, use a "weighted photon/infinite aperture" technique. Sum the probabilities that each photon came from source of interest.

Can give a significant increase of Signal/Noise

Optimizing Power Spectra

To search for periodic modulation, use power spectra.

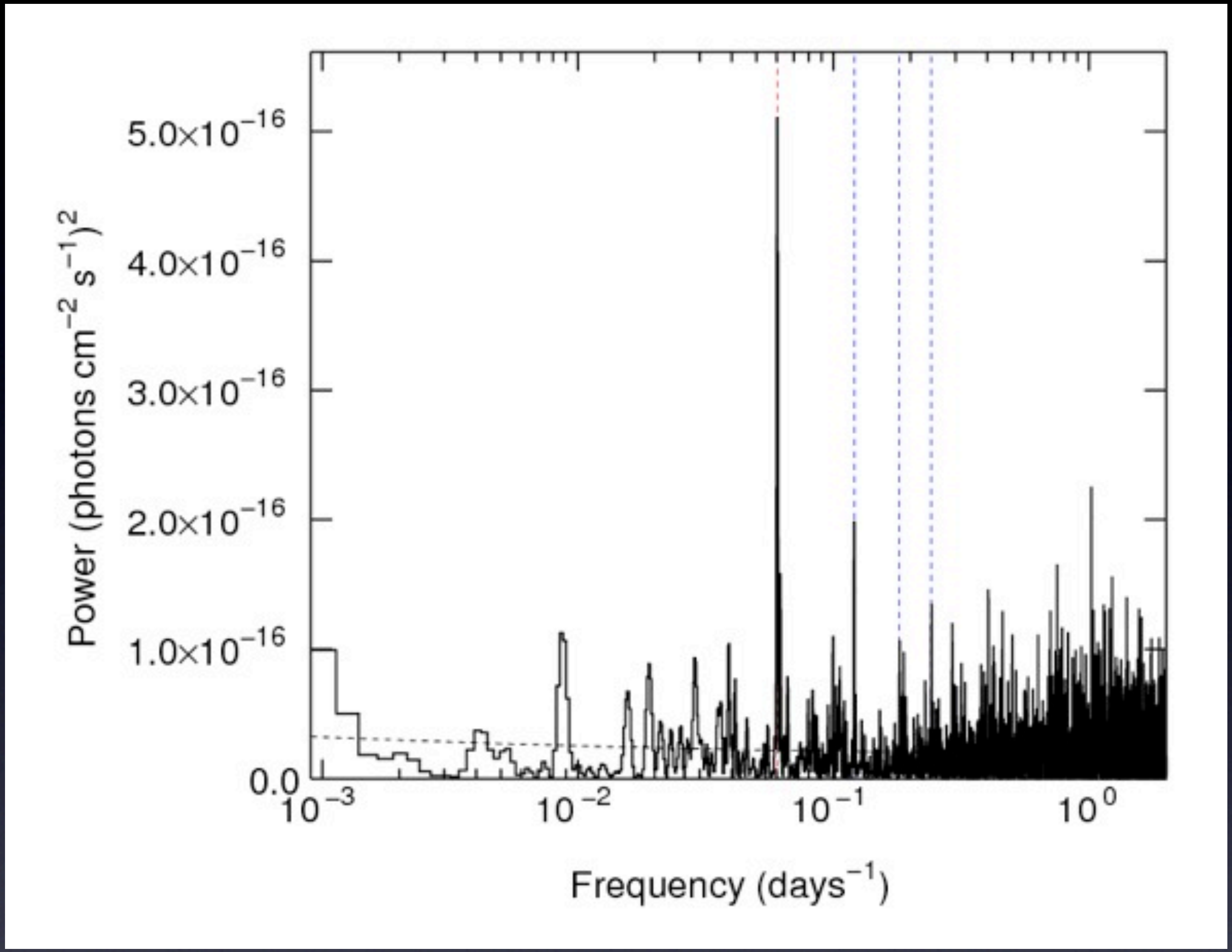
We want ability to search for short orbital periods, like Cyg X-3's 4.8 hour period.

- Short time bins are needed (e.g. < 1ks). Shorter than the LAT sky survey period of ~3 hours.
- This gives big variations in exposure.
- Use “exposure weighting” of each data point's contribution to the power spectrum.

The 1FGL Search

- Made weighted-photon light curves for all 1,451 1FGL (1st Fermi catalog) sources:
  - 3 degree radius aperture.
  - 600 s time bins (barycenter corrected).
  - 100 MeV to 200 GeV.
  - 752 days long (2.06 years) for initial search.
- Calculated exposure-weighted power spectra for all sources: 0.05 to 752 days.
- Easily detected LS I +61 303 and LS 5039, but not Cyg X-3. (To detect Cyg X-3 must only use data from active states.)
- And a candidate for a new binary...

A 16.6 Day Period in 1FGL J1018.6-5856



Probability of peak at 16.6 days arising by chance is $< 10^{-7}$.
Second (and possibly higher) harmonics of this period are also seen.
Modulation at 16.6 days is <u>not</u> seen in <u>any</u> other Fermi source.

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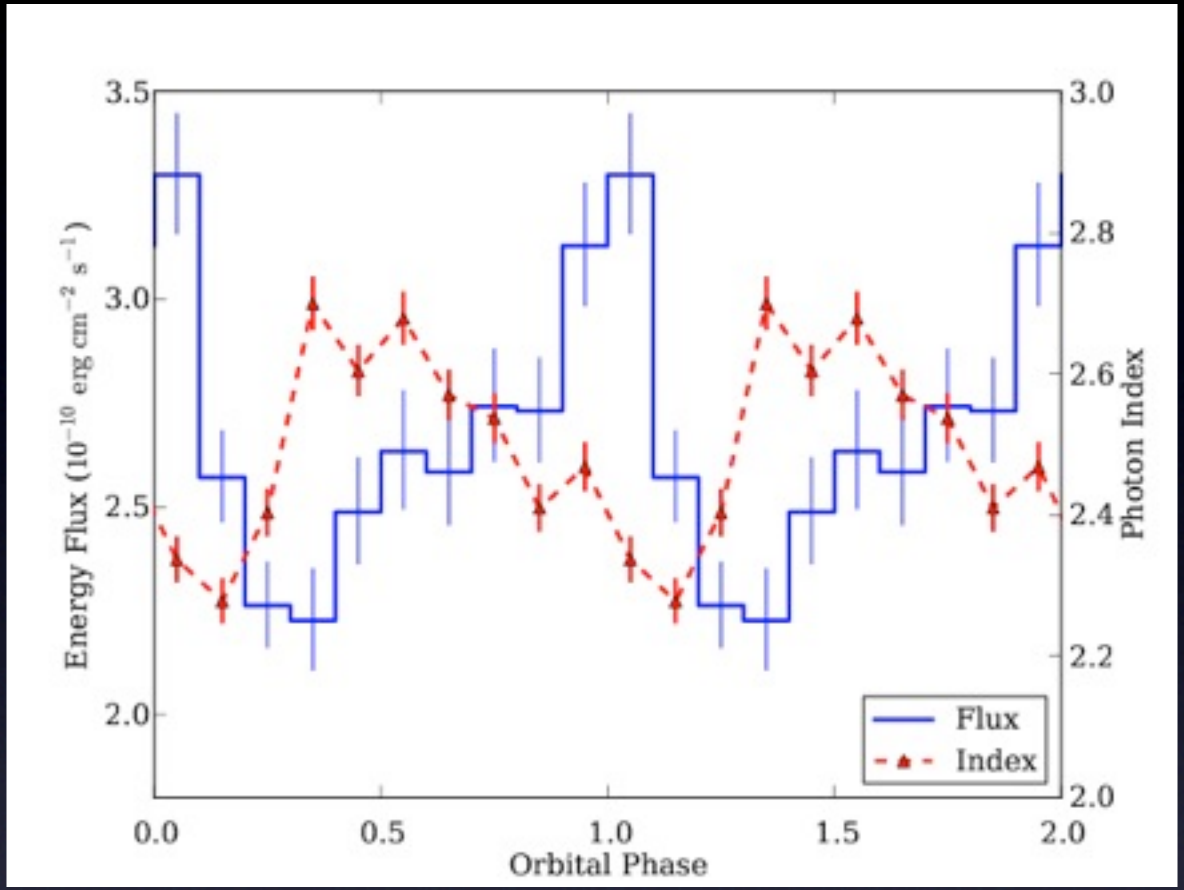
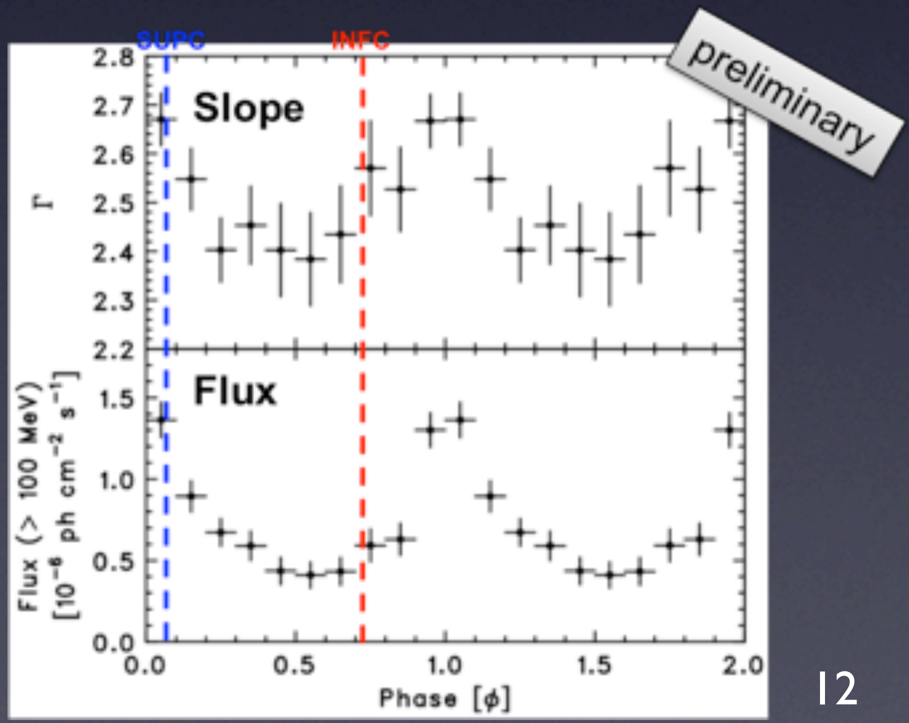
Flux/Spectral variability on 16.6 day period

- Gamma-ray spectrum is also modulated on the 16.6 day period. (Harder when bright.)
- *Qualitatively* similar to LS 5039 (3.9 day period), but <u>not</u> LS I +61 303.
- Except... LS 5039 is softer when bright.



LS 5039
(Hadasch et al)



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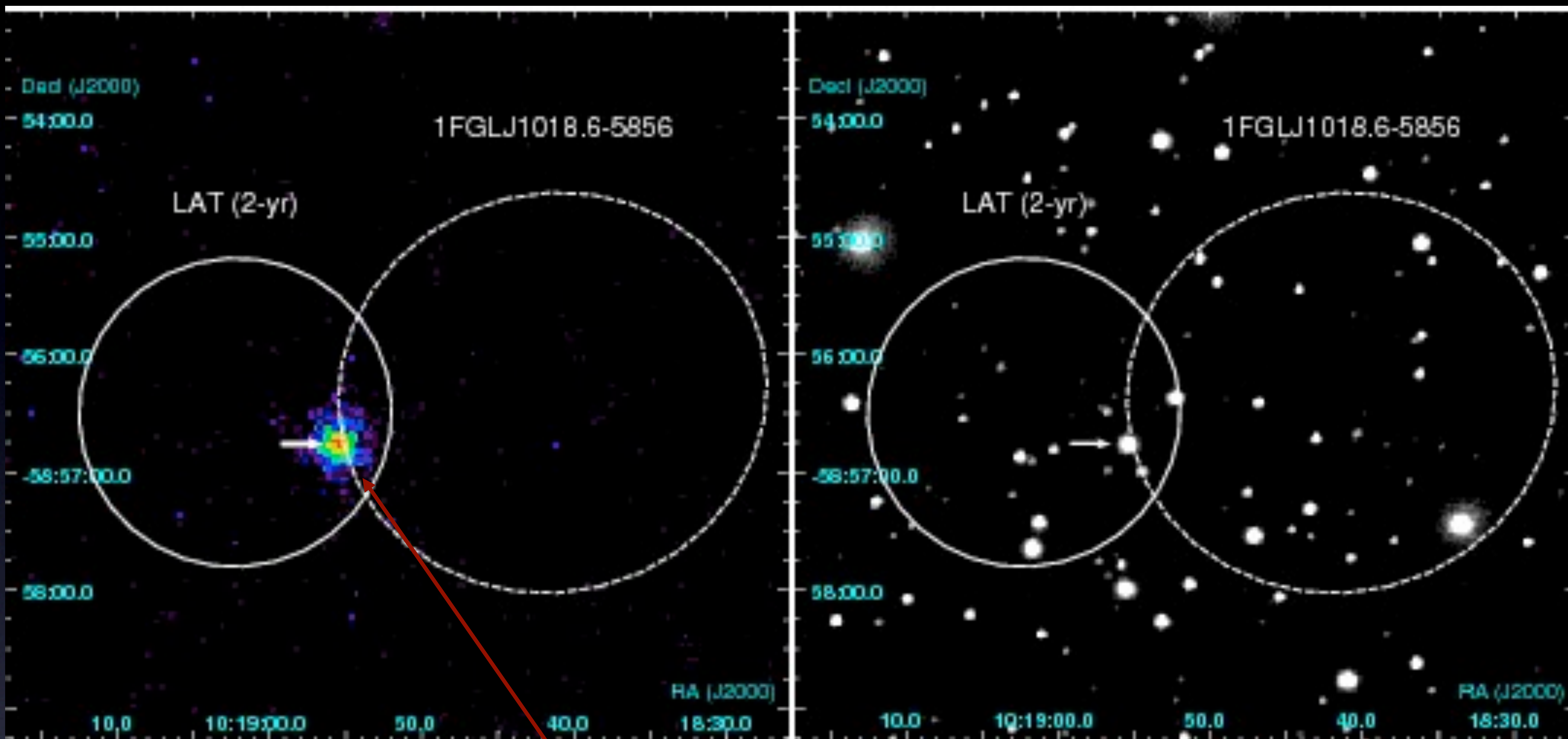
X-ray & Optical Counterparts



Swift XRT
(X-ray)

Swift UVOT
(UV/optical)

A prominent X-ray source is present at the edge of the LAT error circles.
Optical source seen at X-ray position.

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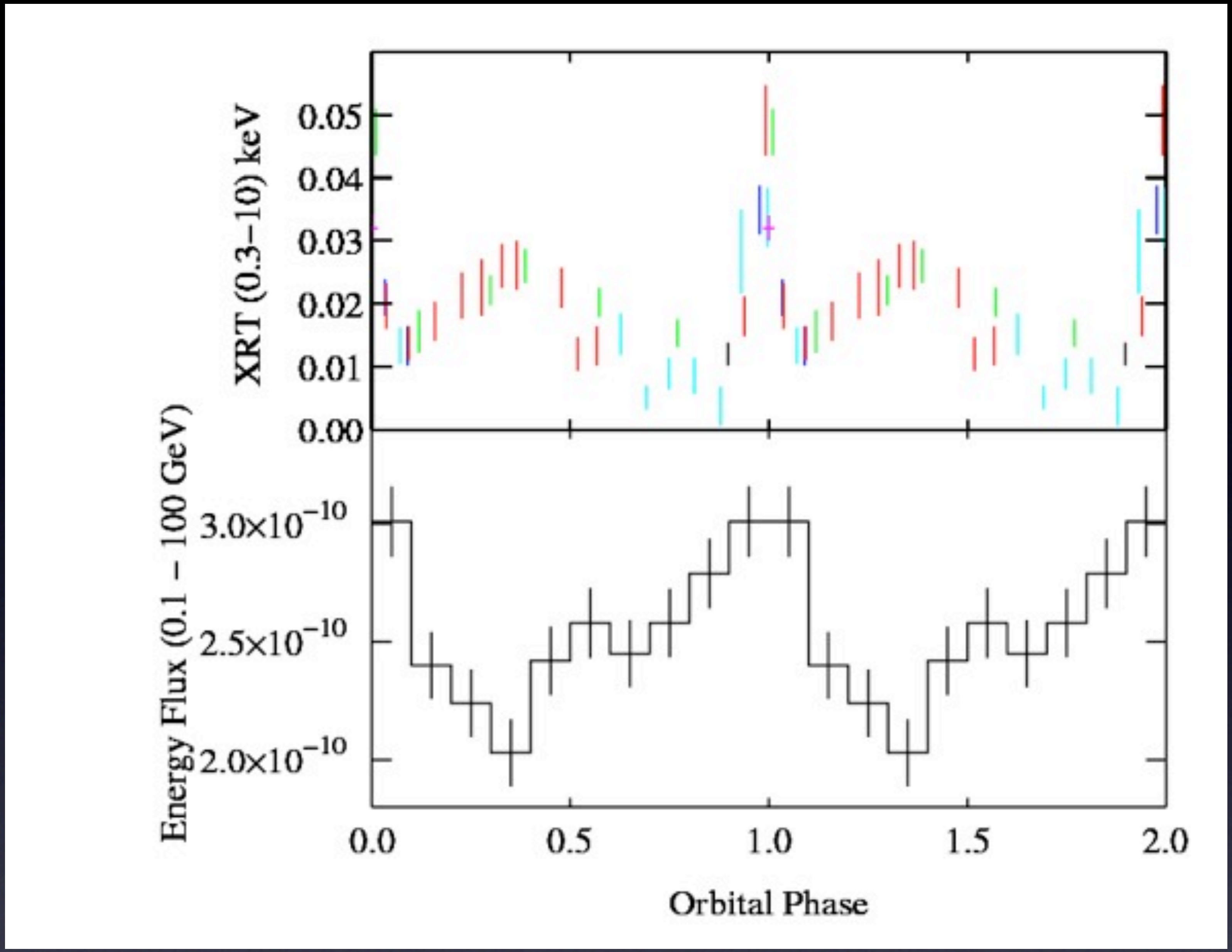
Large X-ray variability (Swift XRT)



- Different colors (top panel) show X-ray data from different 16.6 day cycles.
- Flare-like behavior near phase 0, coinciding with gamma-ray maximum.
- X-ray modulation also has a quasi-sinusoidal component with peak at phase ~0.4

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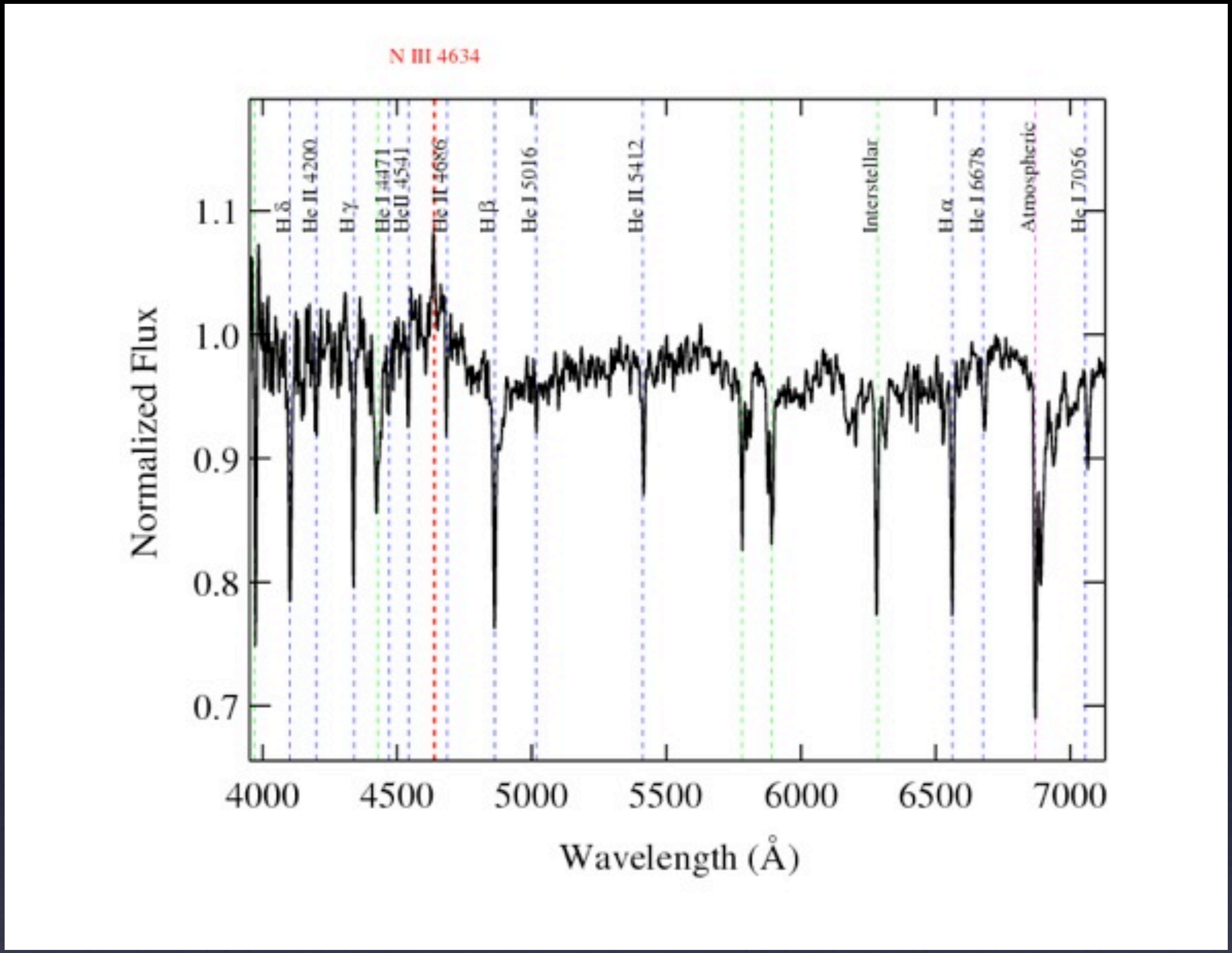
Optical Spectrum

- H, He I/II lines indicate early spectral type.
- He II 4686Å absorption ⇒ main sequence.
- He II/I ratio ⇒ ~O6
- NIII emission ⇒ O6V((f)).
- Spectral type is almost identical to LS 5039.

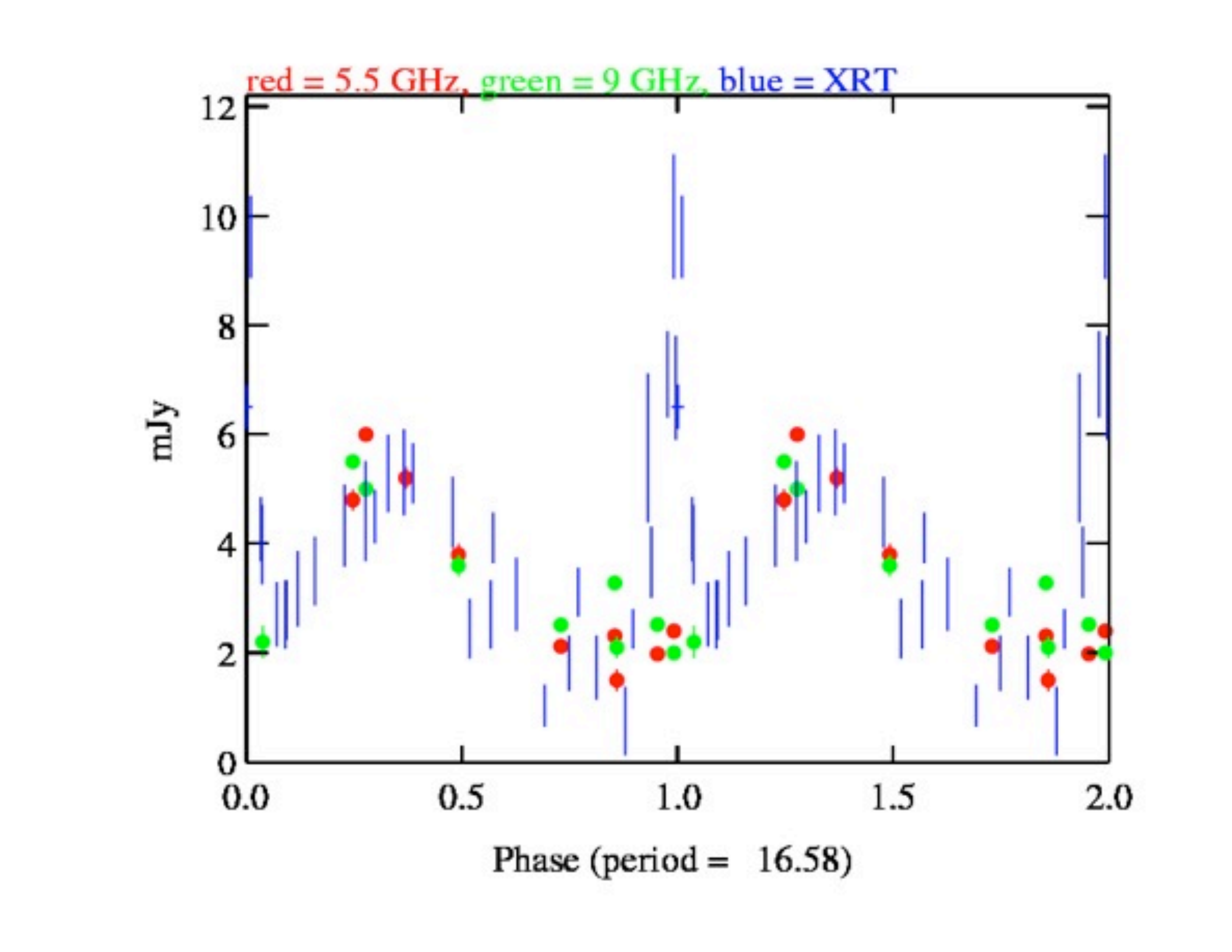


SAAO 1.9m telescope

Interstellar absorption lines ⇒ E(B-V) ~1.25.

V ~12.6 (ASAS Catalogue)
Distance ~5 kpc (± 2kpc)

Variable Radio Counterpart



(ATCA Radio data)

The radio flux appears to be modulated on the orbital period.
But, <u>no</u> increase at phase 0.
Radio flux may be following sine wave component of X-ray flux.

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TeV Counterpart to 1FGL J1018.6?

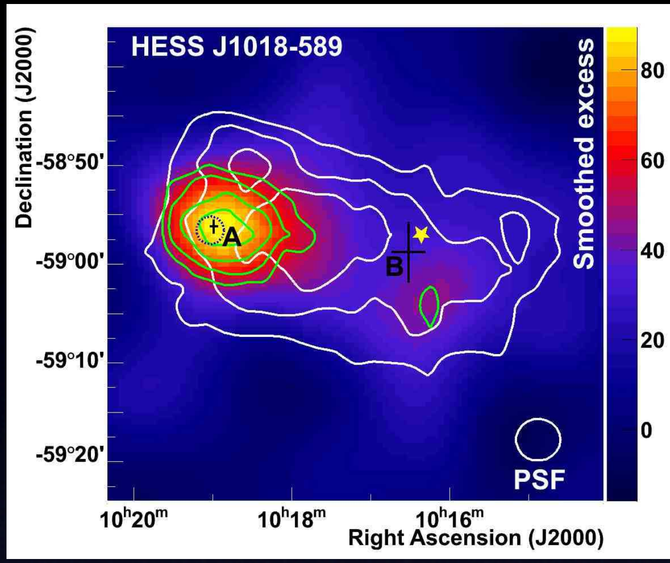
The H.E.S.S. team (2012) report discovery of HESS J1018-589.

Positionally coincident with SNR G284.3–1.8 and 1FGL J1018.6– 5856 (diffuse extension towards PSR J1016–5857).

TeV emission is seen (at least sometimes) from LS 5039 and LS I +61 303,

Is this the TeV counterpart of 1FGL J1018.6??

Temporal variability in the TeV source would confirm association.



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1FGL J1018.6-5856 Overview

- 1FGL J1018.6-5856 is a new gamma-ray binary with X-ray, optical, and radio counterparts.
- We don't definitely know what is driving the gamma-ray emission.
  - J1018.6 may contain a rapidly rotating pulsar interacting with the wind of an O star.
  - But other explanations might be possible. e.g. magnetar model proposed for LS I + 61 303 (Torres+ 2012).

Continued Observations of 1FGL J1018.6-5856

Several multi-wavelength programs will provide more information on 1FGL J1018.6-5856

- X-rays: Swift monitoring (Donato/Cheung)
  - Long term variability. Repeatability of orbital modulation.
- X-rays: Suzaku phase constrained (Tanaka et al.)
  - Emission mechanisms.
- Radio: ATCA (Edwards et al.)
  - Orbital modulation of radio flux. Long term variability.
- Optical: Radial velocity measurements (Romani et al.)
  - Determine system geometry, constraints on nature of compact object (neutron star vs. black hole).
- Optical: photometry (McSwain et al.)
  - System geometry and constraints on compact object.

Continued Search for More Binaries

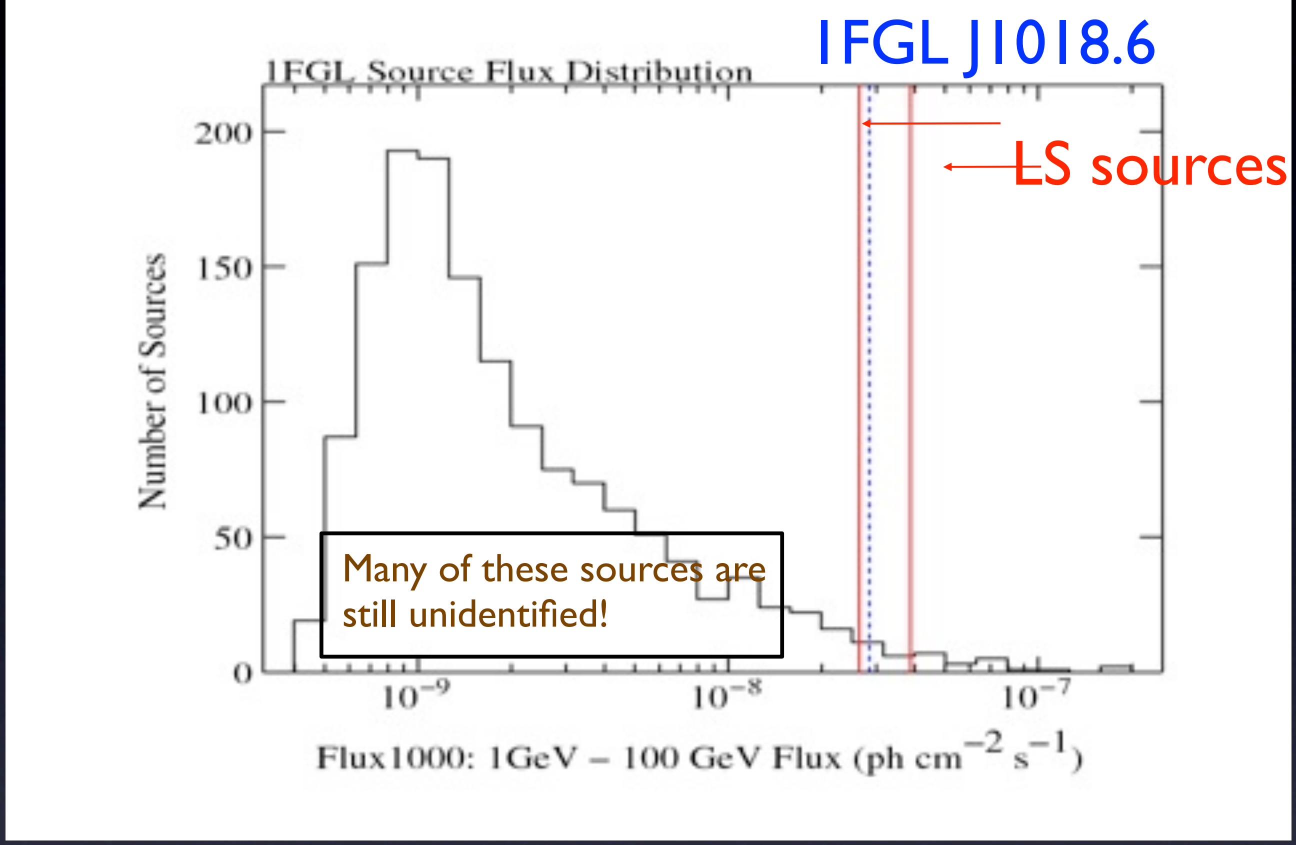
- So far, we've only found binary periods in bright sources.

- LAT binary search sensitivity is continually improving as more data accumulates. (Noise ∝ 1/Time)

- "Pass 7" LAT data enhanced the soft response.

- 2FGL catalog increased number of sources, and more accurately parameterized known sources. (Important for weighting.)

- Continue to perform periodicity searches on all cataloged sources, hoping to find more binaries!



Evolutionary models predict we should see more binaries in the "iceberg" of sources...

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The Gamma-ray Flares of Cyg X-3

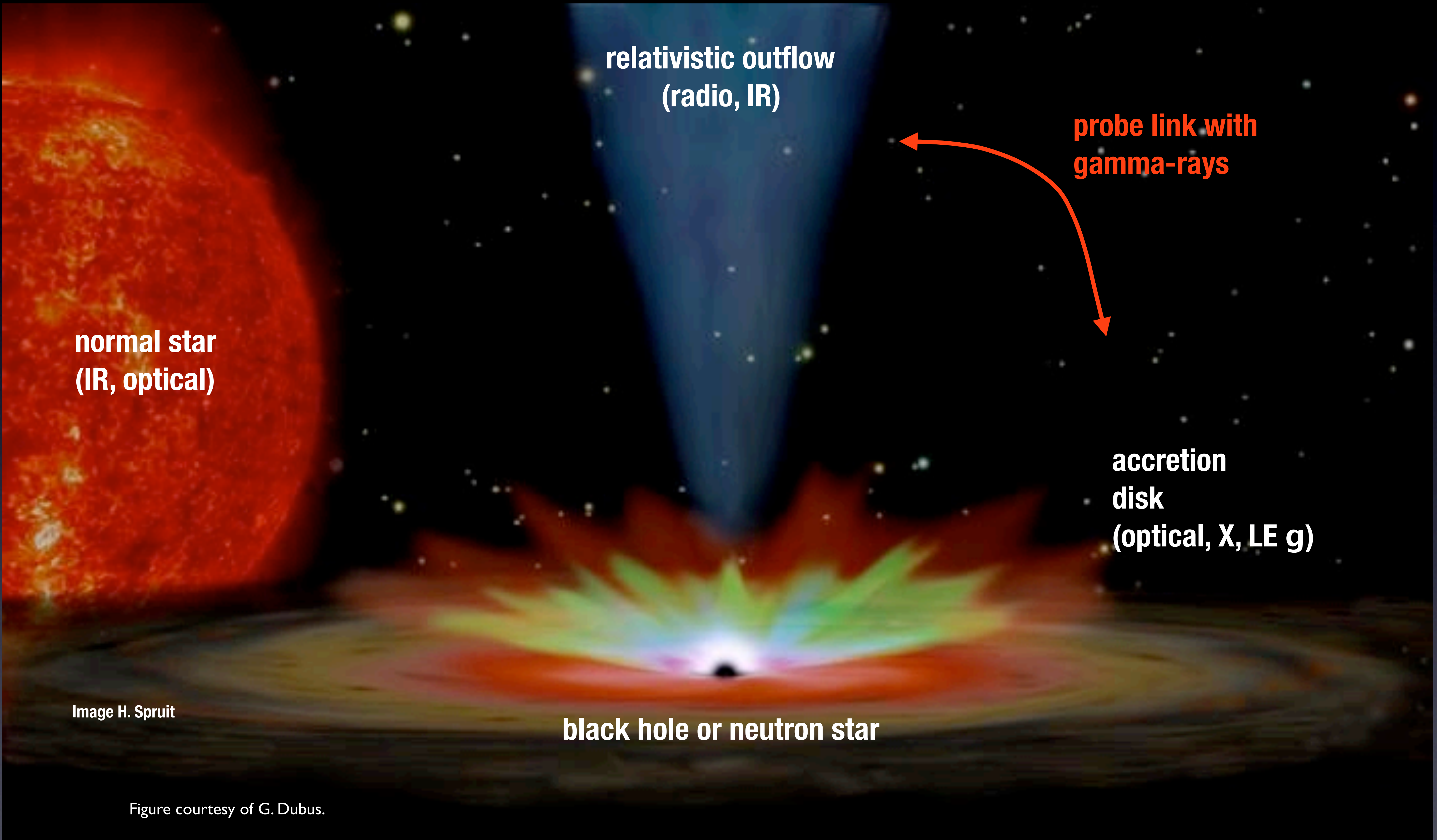

Figure courtesy of G. Dubus.

Cygnus X-3

Bright X-ray binary with Wolf-Rayet primary.

Short orbital period: 4.8 hours.

Black hole candidate.

Radio outbursts common and relativistic jets are produced:

⇒ Cyg X-3 is a "microquasar".

Highly unusual source - perhaps unique in the Galaxy?

The only accretion-powered gamma-ray binary known.

Some prefer to describe Cyg X-3 as a "gamma-ray emitting X-ray binary" because $L_x > L_\gamma$.

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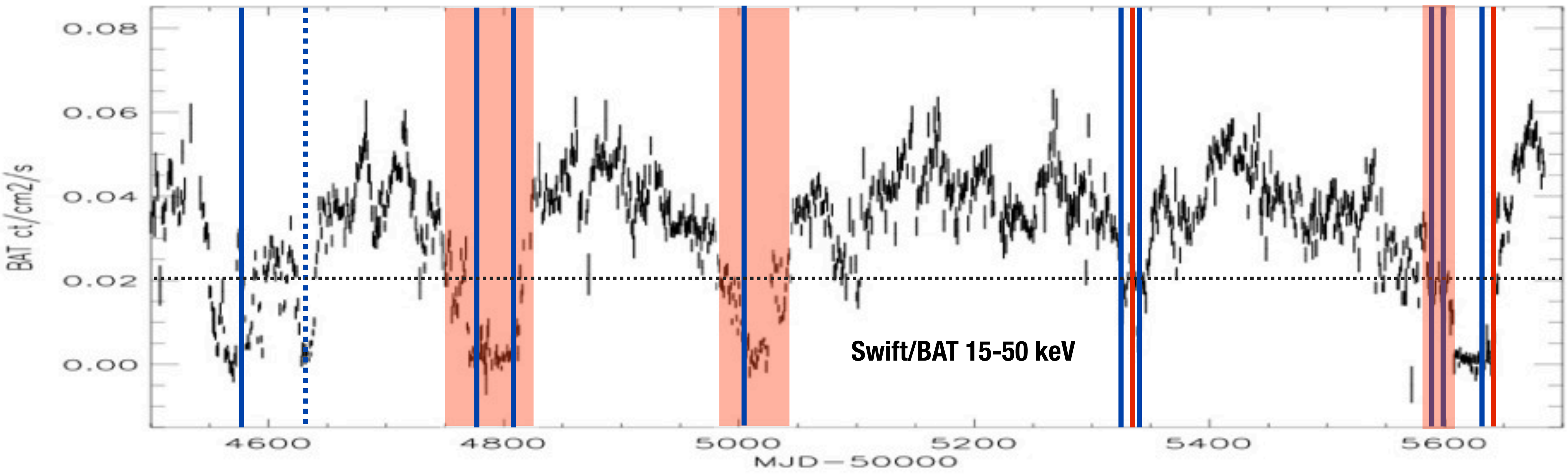
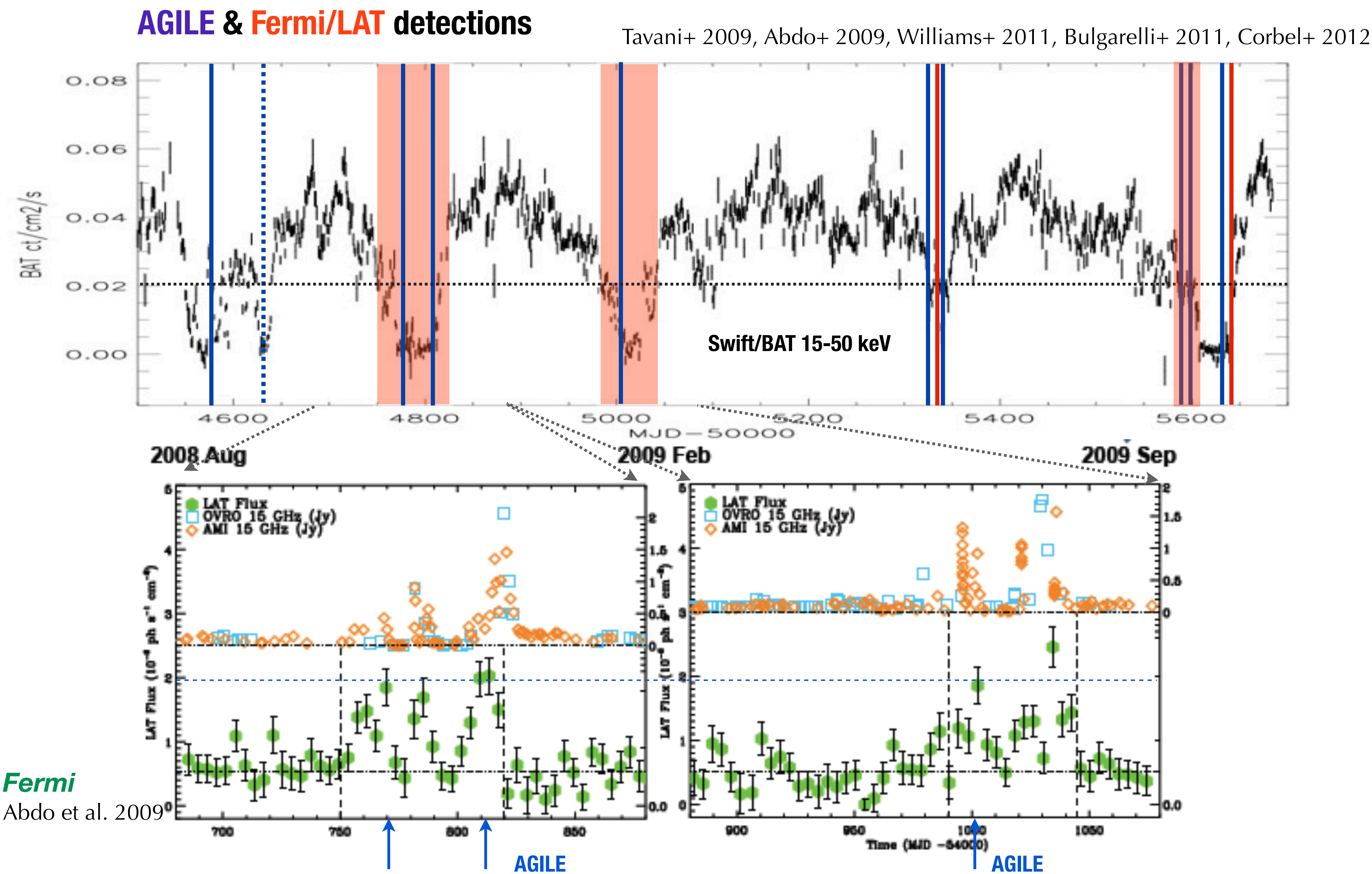
Cyg X-3: a microquasar in γ-rays

AGILE & Fermi/LAT detections

Tavani+ 2009, Abdo+ 2009, Williams+ 2011, Bulgarelli+ 2011, Corbel+ 2012



Cyg X-3: a microquasar in γ-rays



Fermi
Abdo et al. 2009

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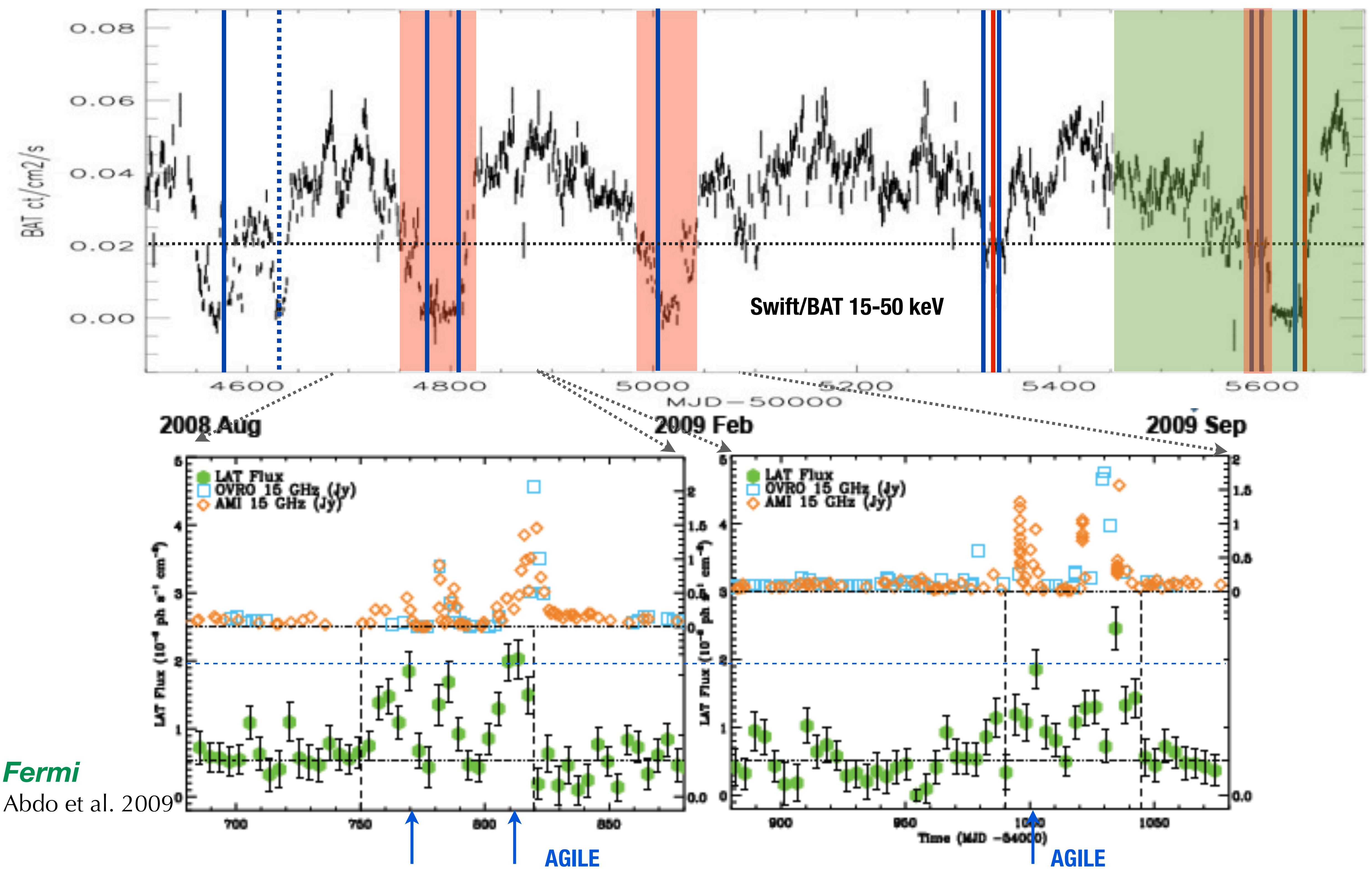
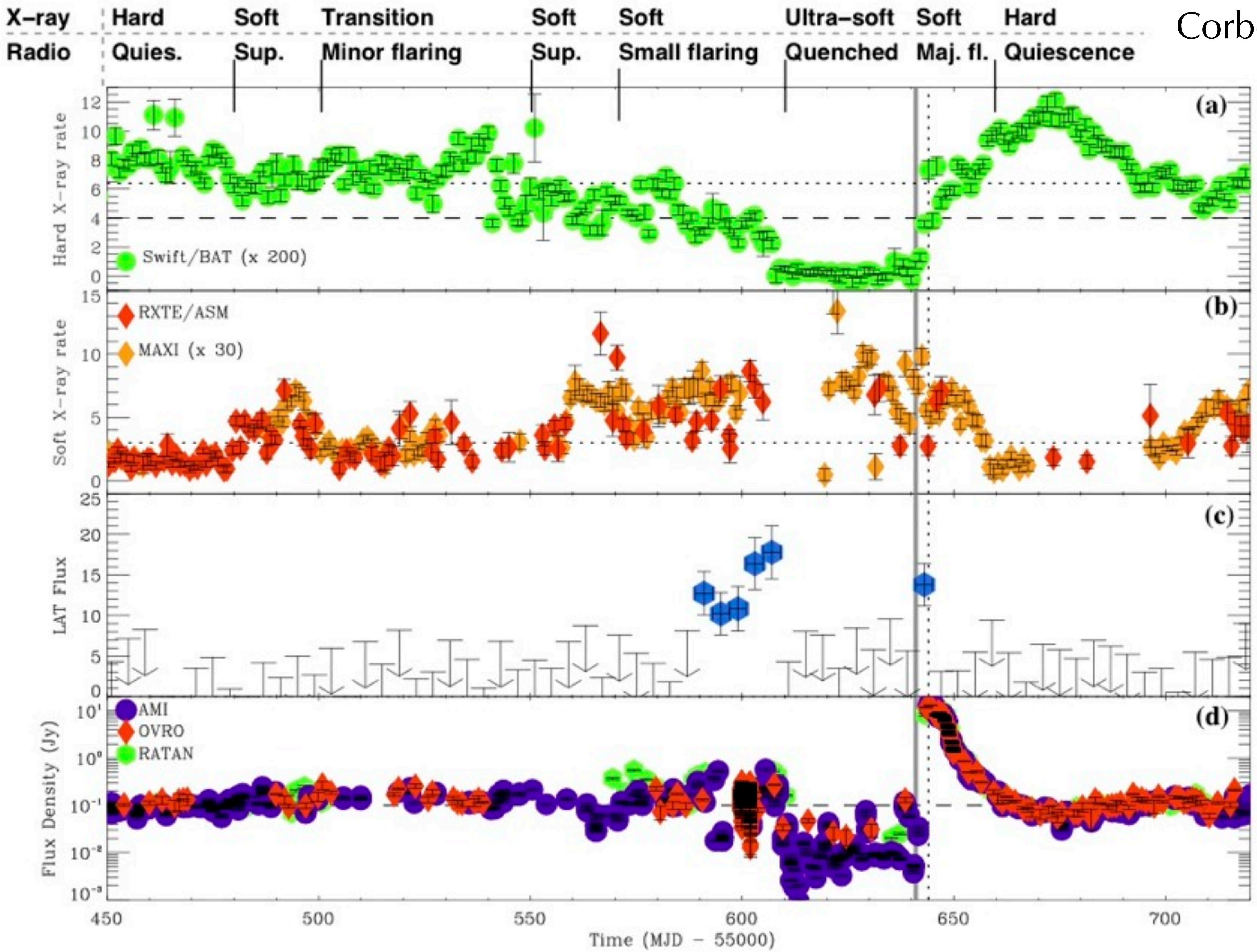


Fermi
Abdo et al. 2009

Major radio flare, March 21, 2011

Corbel+ 2012

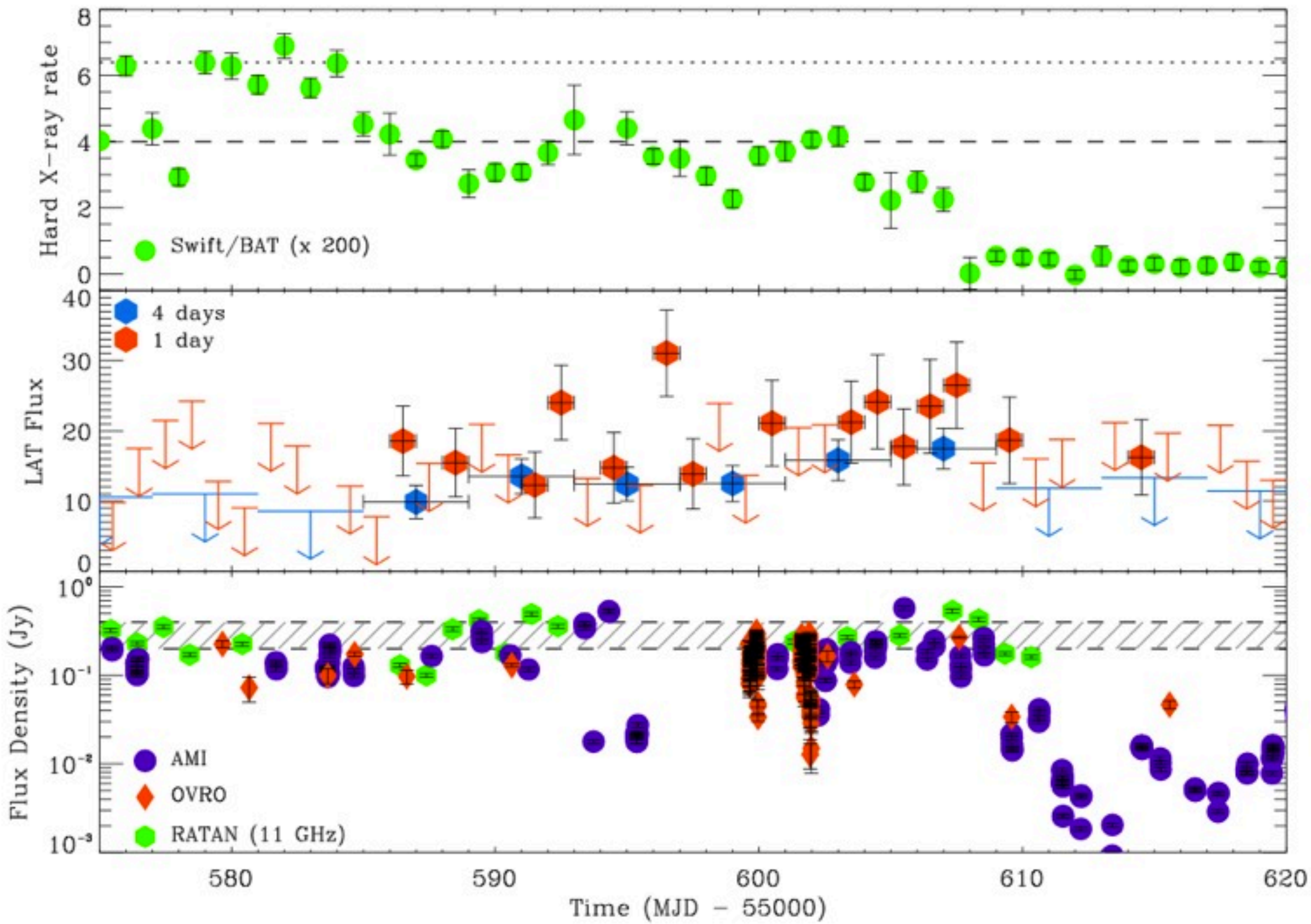


Accretion

non-thermal / thermal

Ejection

Gamma-ray activity in period 1 (2011)

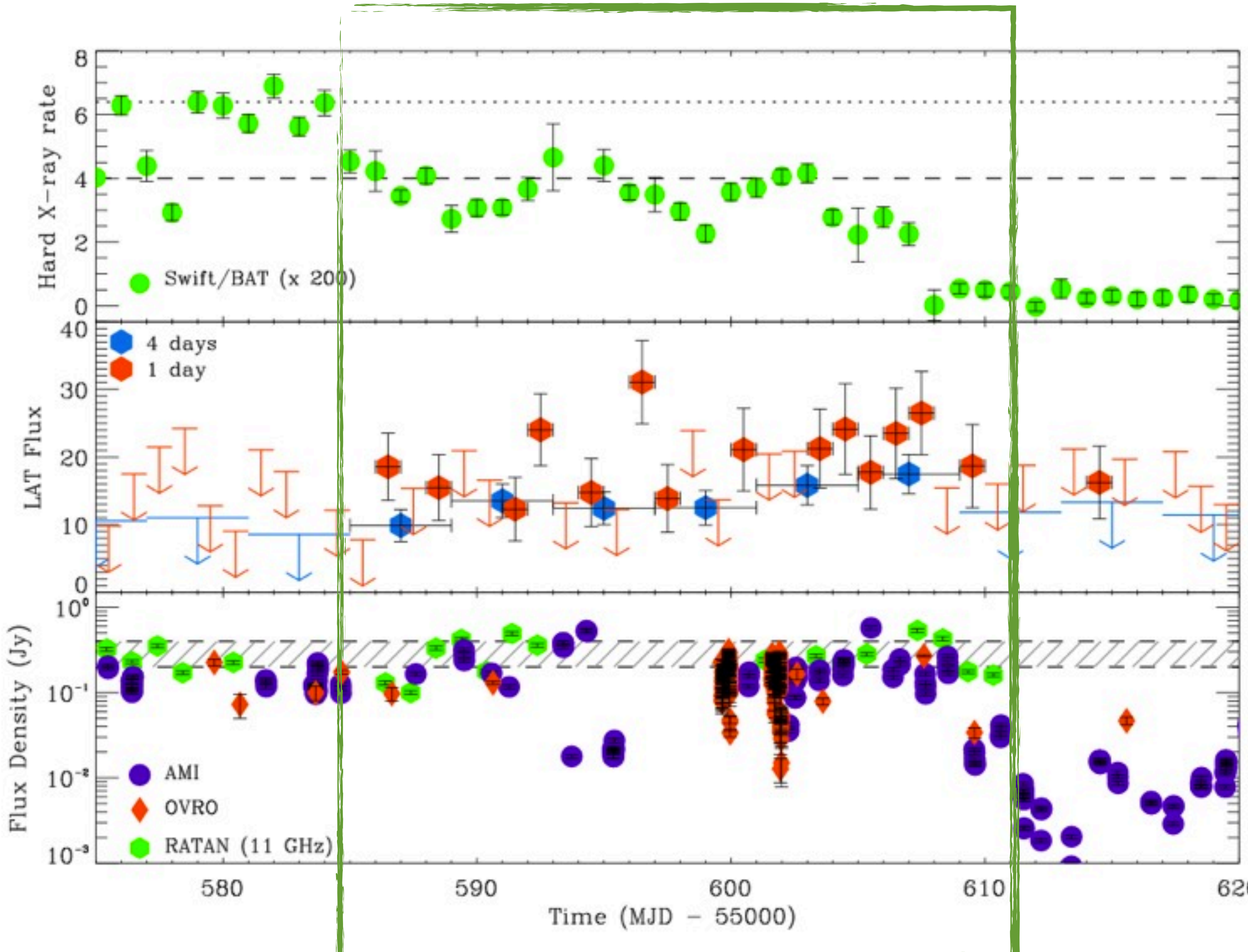


X-ray
15-50 keV

gamma-ray
>100 MeV

radio
11 & 15 GHz

Gamma-ray activity in period 1 (2011)



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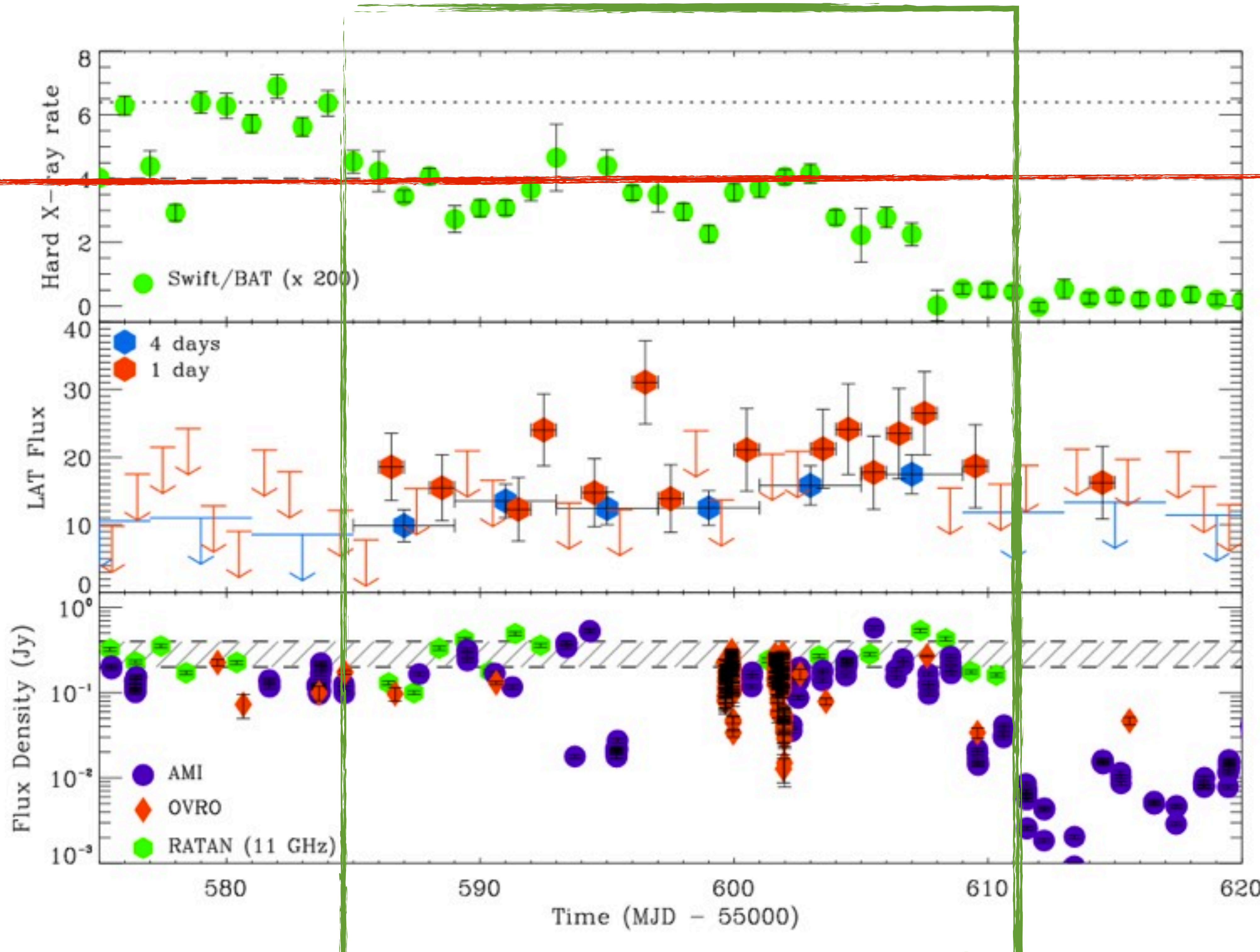


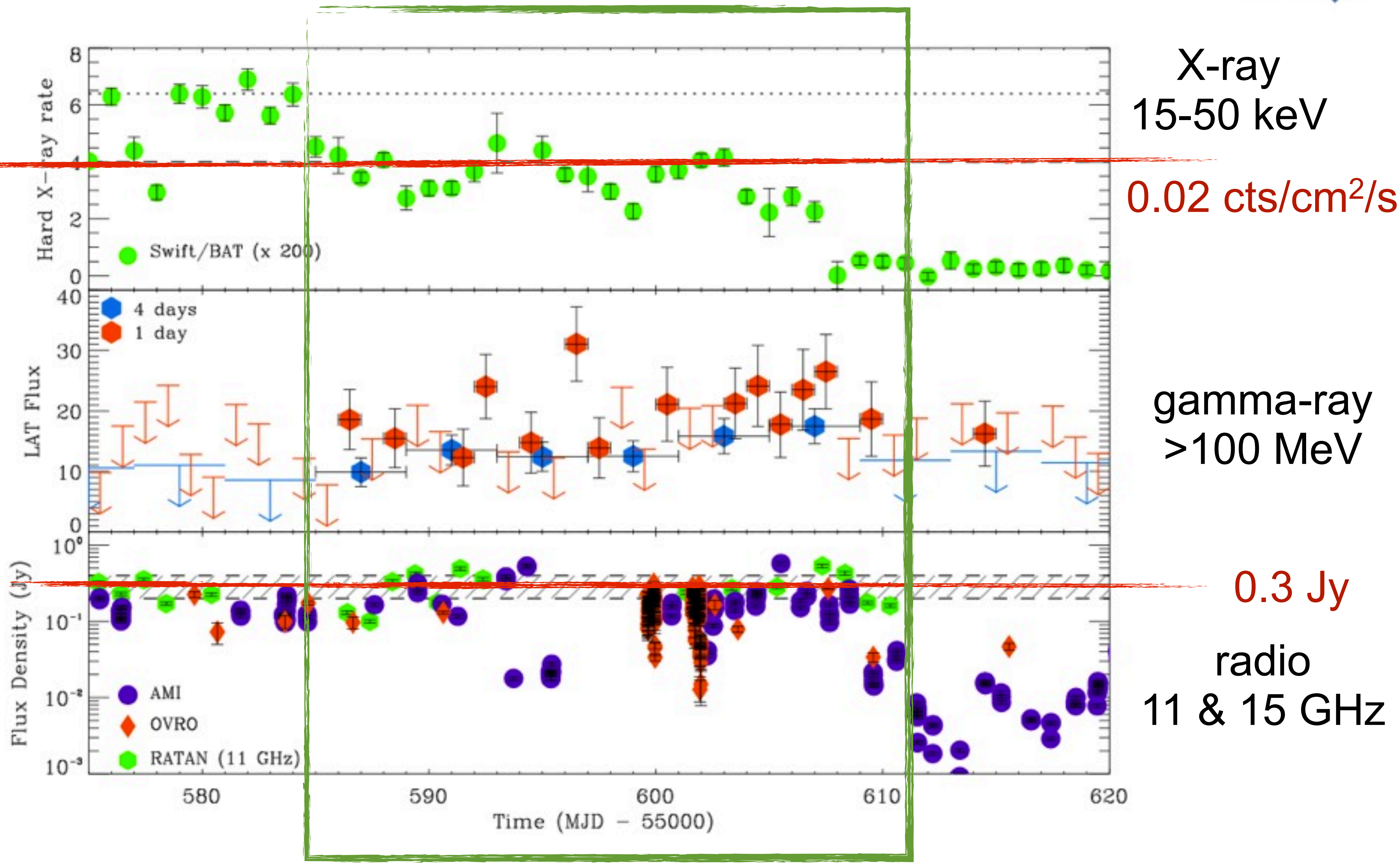
X-ray
15-50 keV

0.02 cts/cm^2/s

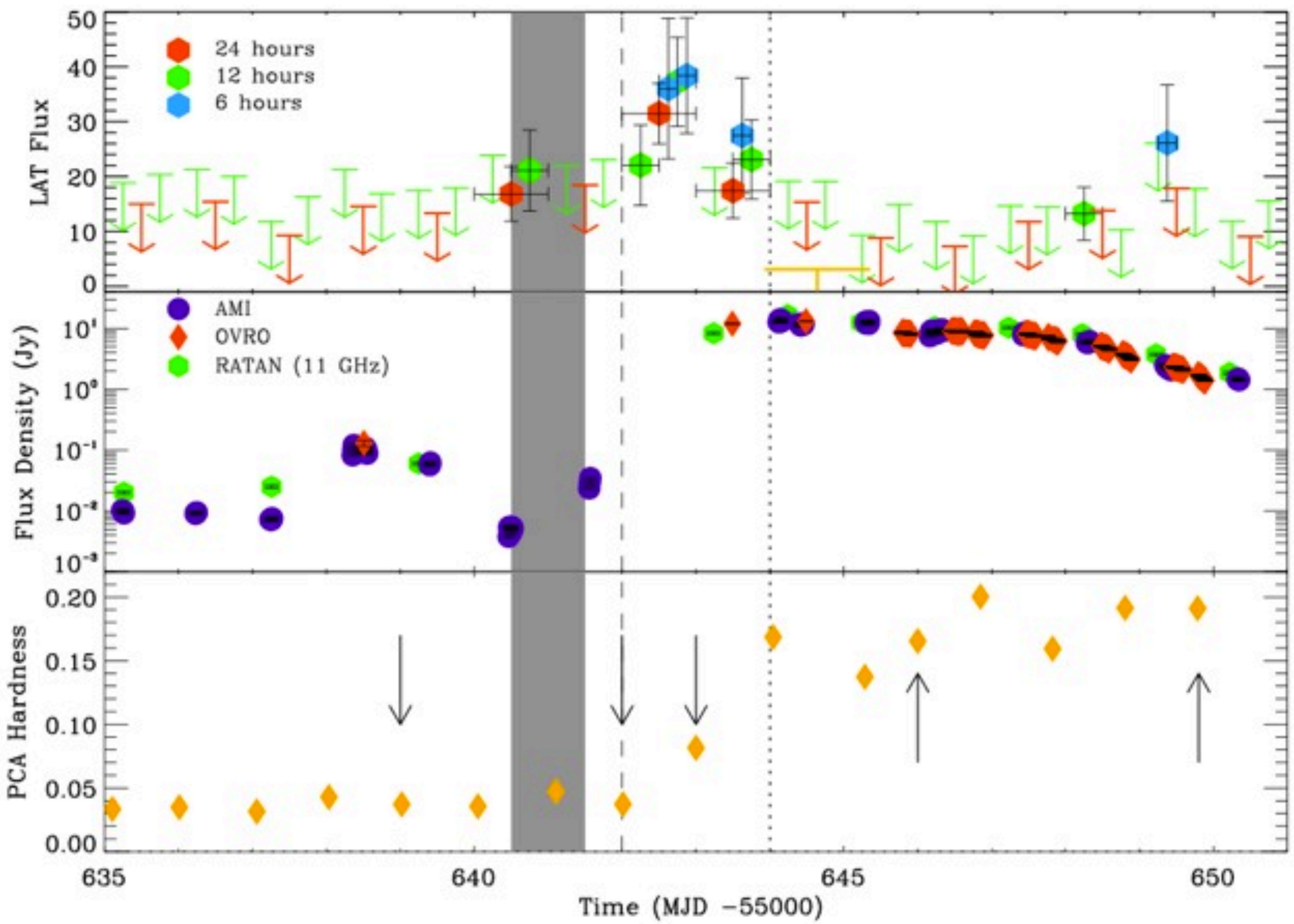
gamma-ray
>100 MeV

radio
11 & 15 GHz

Gamma-ray activity in period 1 (2011)



Relation between flare onset and gamma-ray trigger in period 2 (2011)



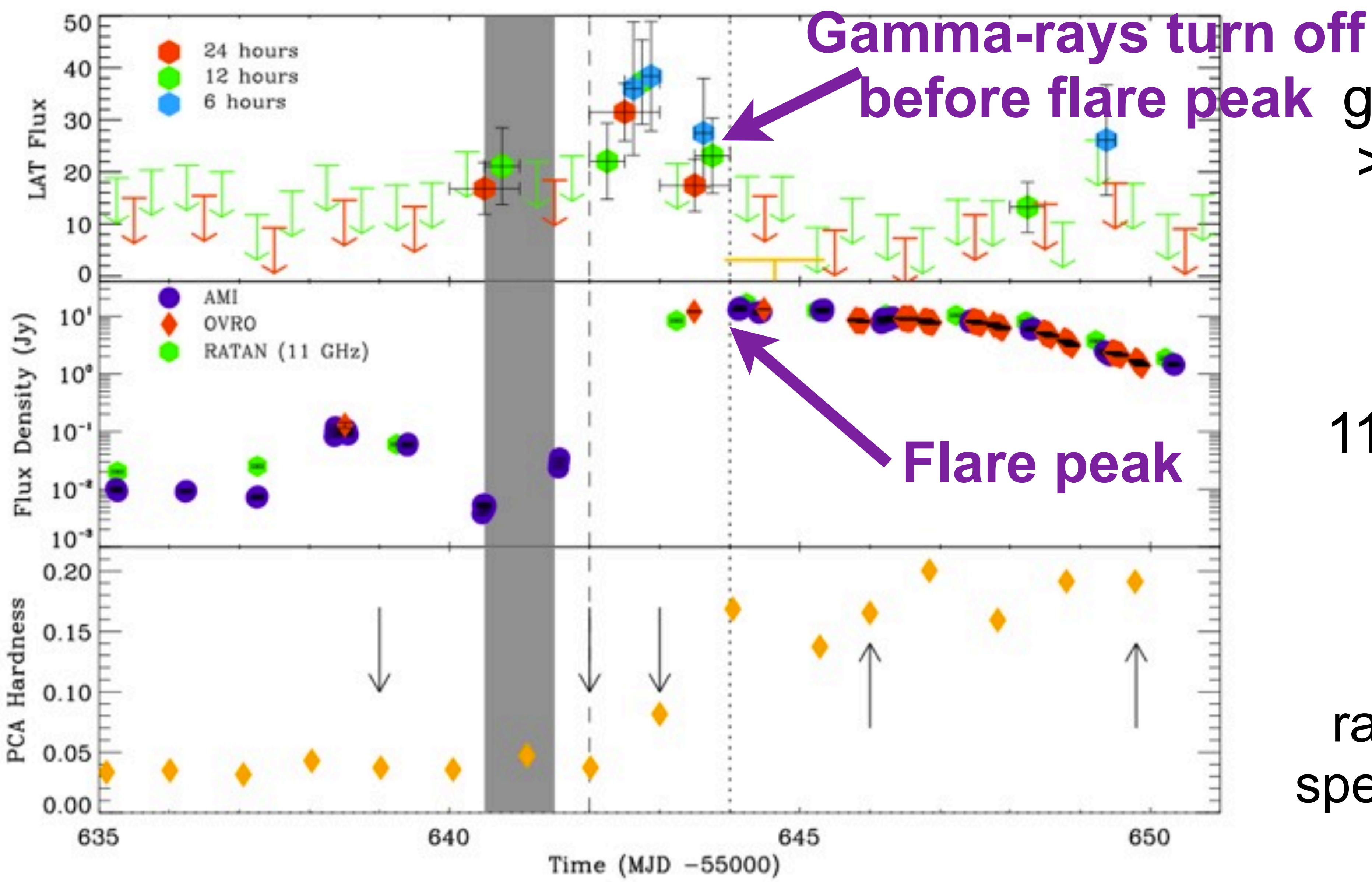
gamma-ray >100 MeV

radio 11 & 15 GHz

X-ray hardness ratio & RXTE spectra (arrows)

Simultaneous rise
radio + non-thermal X-ray + gamma-ray

Relation between flare onset and gamma-ray trigger in period 2 (2011)



gamma-ray >100 MeV

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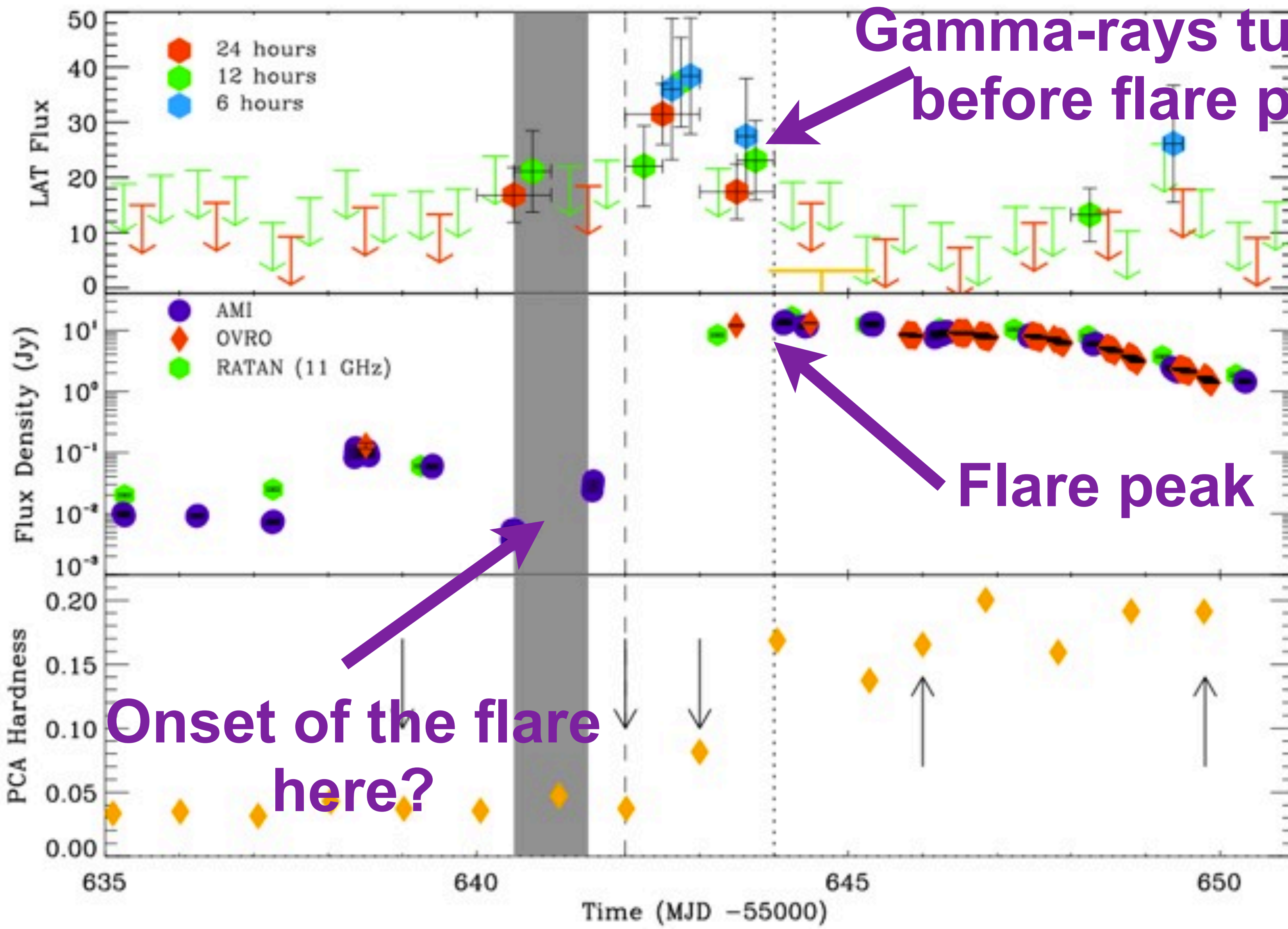

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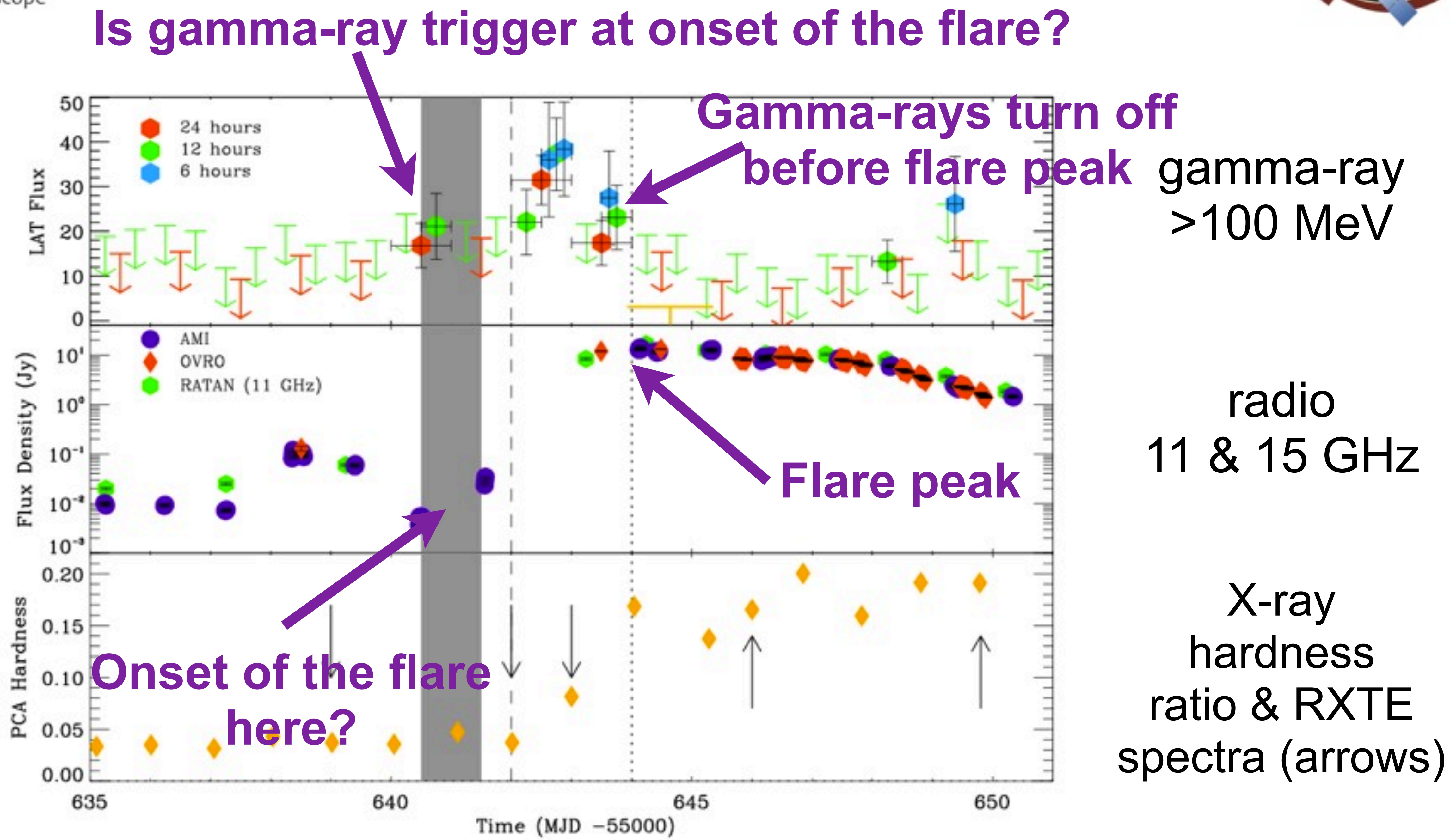


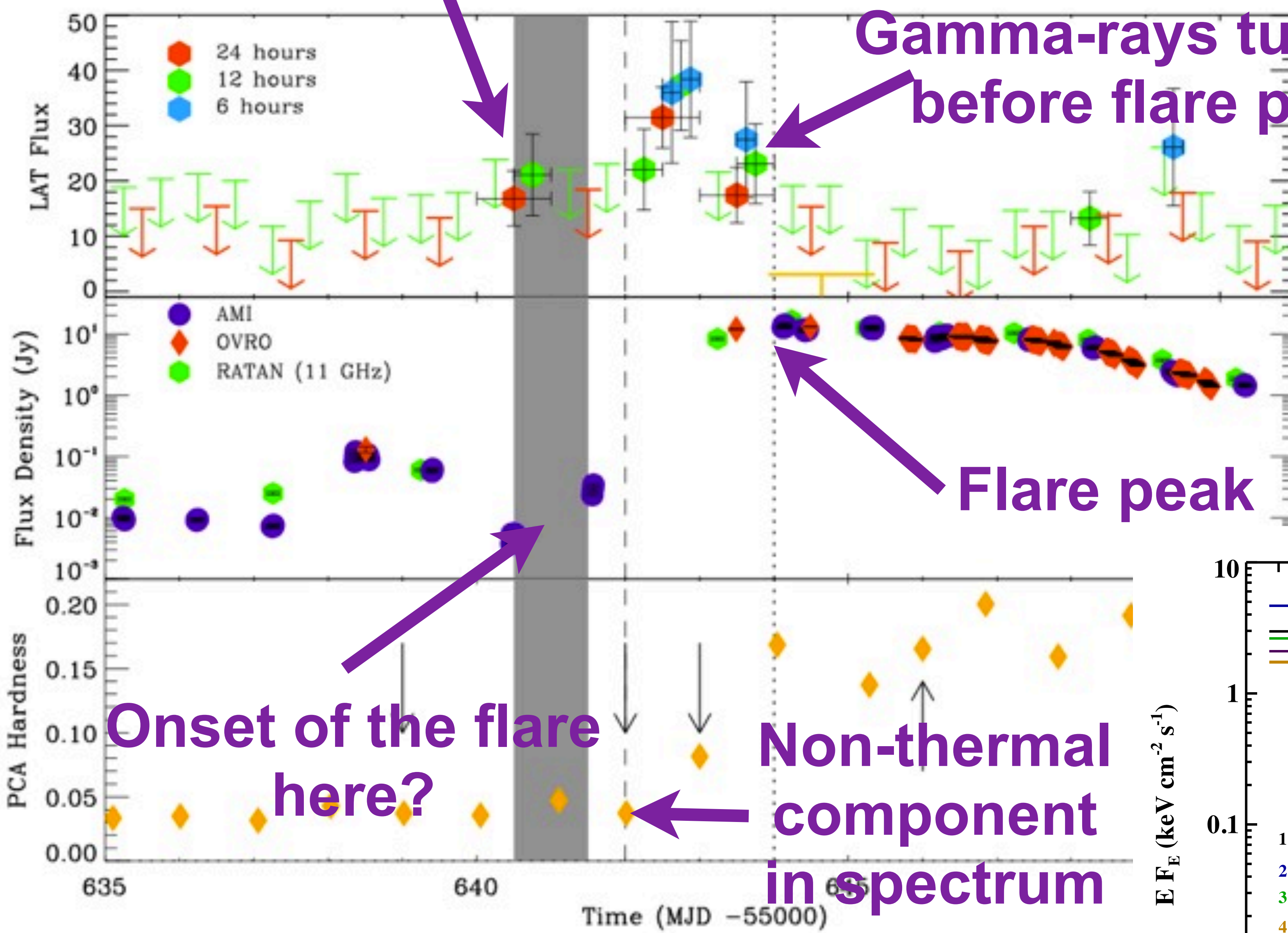
Simultaneous rise
radio + non-thermal X-ray + gamma-ray

Relation between flare onset and gamma-ray trigger in period 2 (2011)

Is gamma-ray trigger at onset of the flare?

Gamma-rays turn off before flare peak

gamma-ray >100 MeV

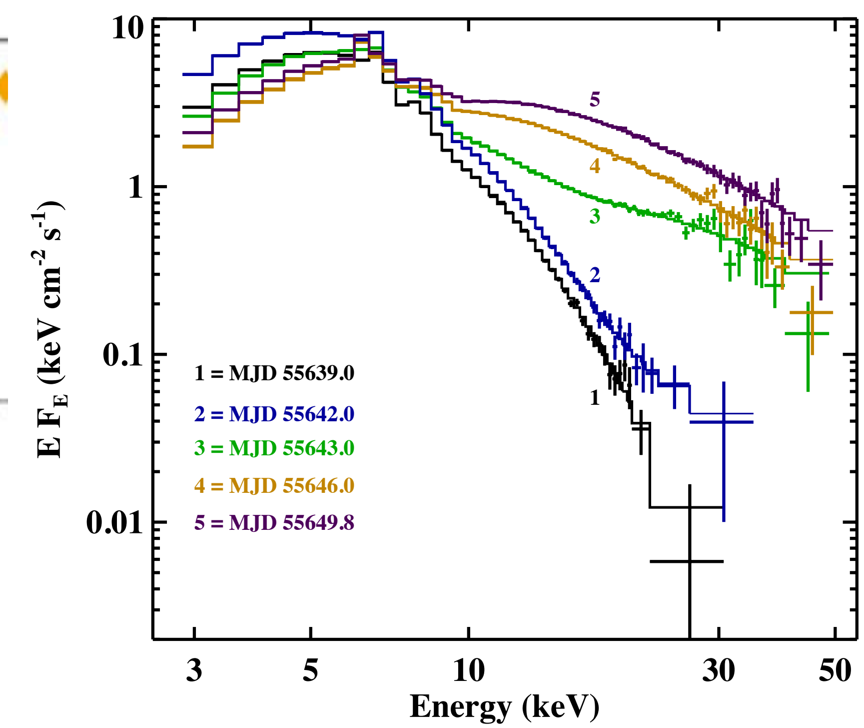


radio 11 & 15 GHz

Flare peak

Onset of the flare here?

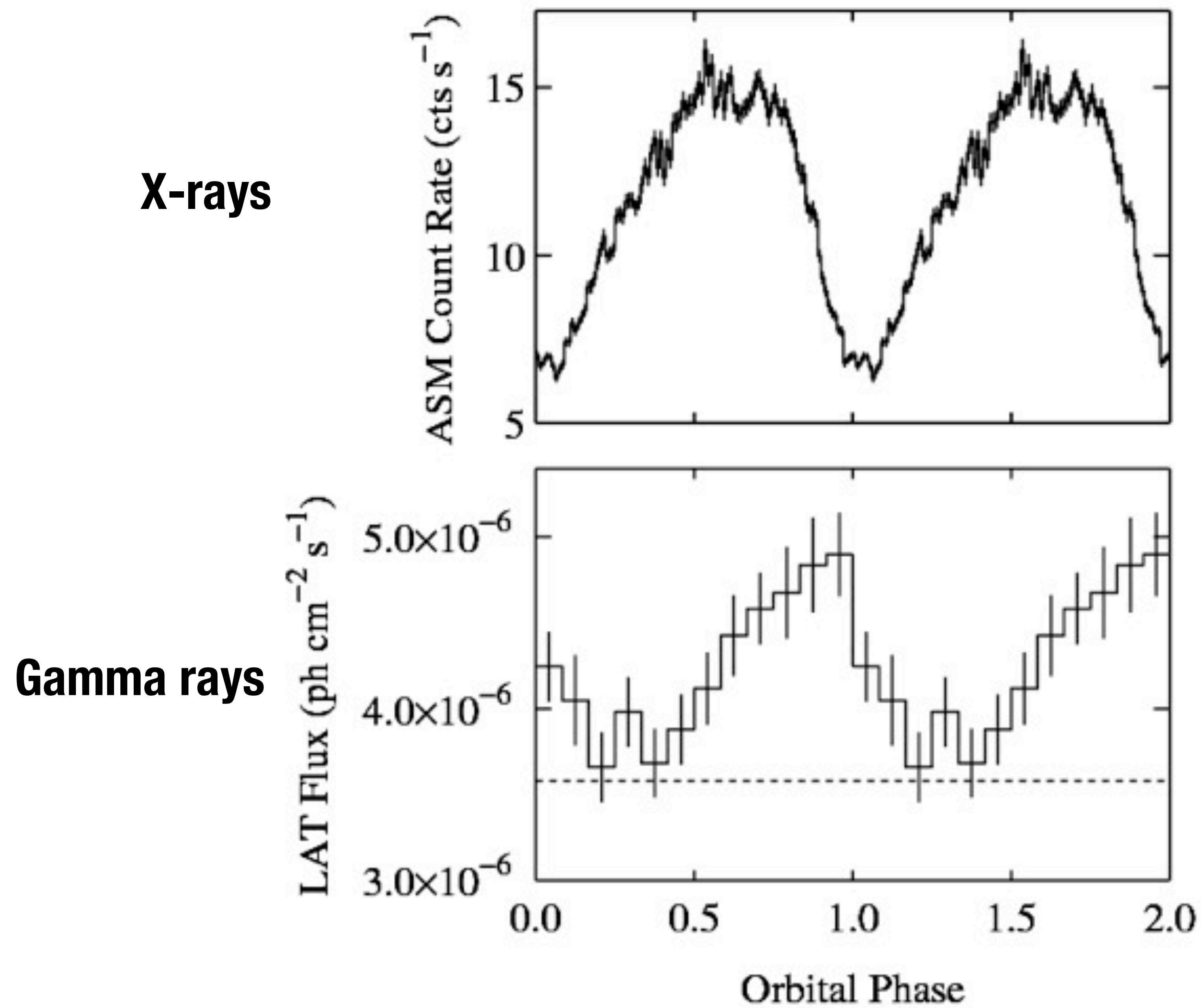
Non-thermal component in spectrum



Simultaneous rise radio + non-thermal X-ray + gamma-ray

Orbital Modulation in Cyg X-3

- During the first two outbursts from Cyg X-3 (2008, 2009) modulation of LAT flux on the orbital period was clearly detected.
- Modulation also detected in 2011 outburst. But investigation hampered by short duration.
- Analysis being undertaken using Pass 7 with improved soft response...



Possible scenario

(7-12 Jan 2012, 219th AAS, Texas, Anna Szostek et al.)

• Shock forms at various distances along the jet (Lindfors et al. 2007; Miller-Jones et al. 2009)

• Transition **IN**/**OUT** of the ultrasoft X-ray state signal a **decrease**/**increase** in jet efficiency with non-thermal region moving **CLOSER**/ **FURTHER** from the compact object

• Gamma-ray emission is most efficient at “sweet-spot” bounded by strong pair production on thermal X-rays and declining seed photon density for inverse Compton scattering (Cerutti et al. 2011; Sitarek & Bednarek 2011)

• Detections prior to and after the quenched state when shock moves through this region