Time-domain Gamma-ray Astrophysics

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Outline – Three Questions

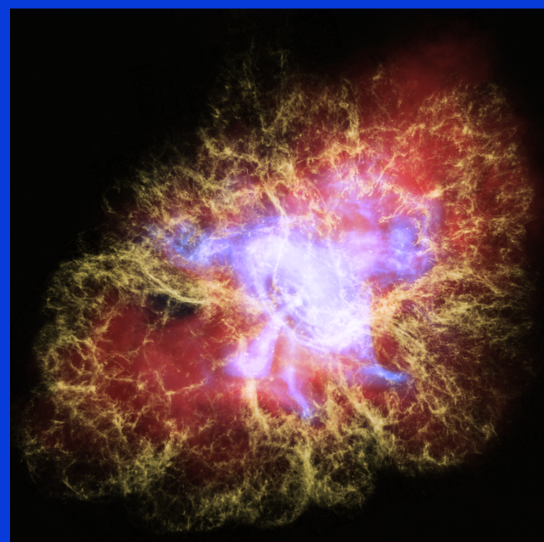
Why is time-domain astrophysics particularly important for gamma-ray studies?

How do we gamma-ray astrophysicists carry out time-domain studies?

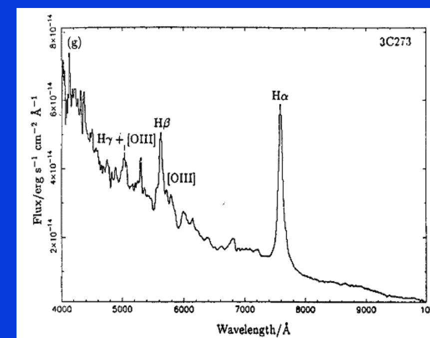
What are some ways to maximize the scientific return from time-domain gamma-ray astrophysics?

Why? Compare to traditional astrophysics

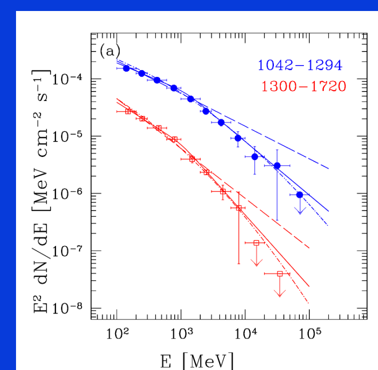
Imaging and spectroscopy are primary tools of traditional astrophysics, while gamma-ray studies are not particularly good at either one.



IR-Optical-X-ray image of the Crab Nebula.
Gamma rays can barely resolve the nebula as spatially extended.



3C273
Optical

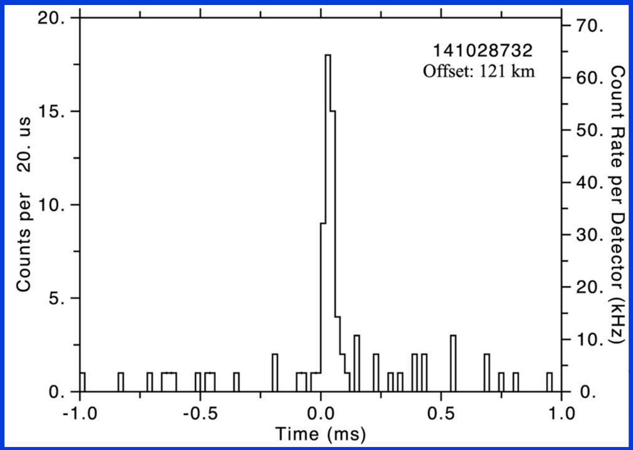


3C273
Gamma-ray

Gamma-ray spectra, except at the lowest gamma-ray energies, have only broad continuum features.

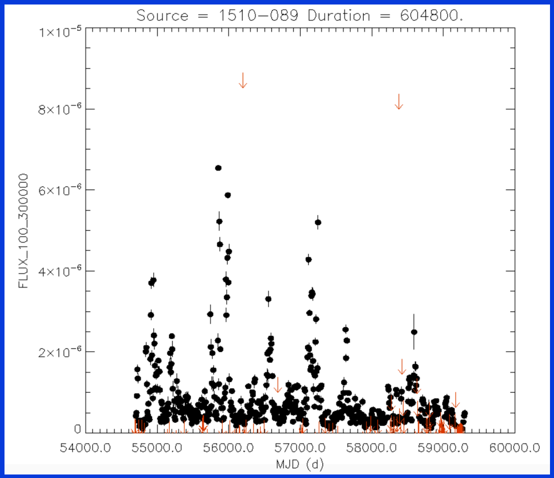
Why? The gamma-ray sky is dynamic

A significant fraction of all gamma-ray sources are variable (more than half if transients are included). Timing studies therefore represent opportunities for discovery.



Terrestrial Gamma-ray Flash

Timing of individual gamma rays with microsecond accuracy enables measurement of very rapid events.



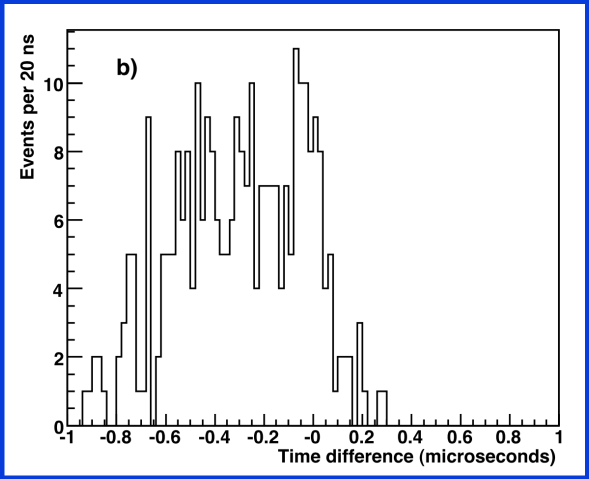
Multi-year light curve of a blazar.

Nearly continuous monitoring of the gamma-ray sky allows an unbiased tracking of source behavior.

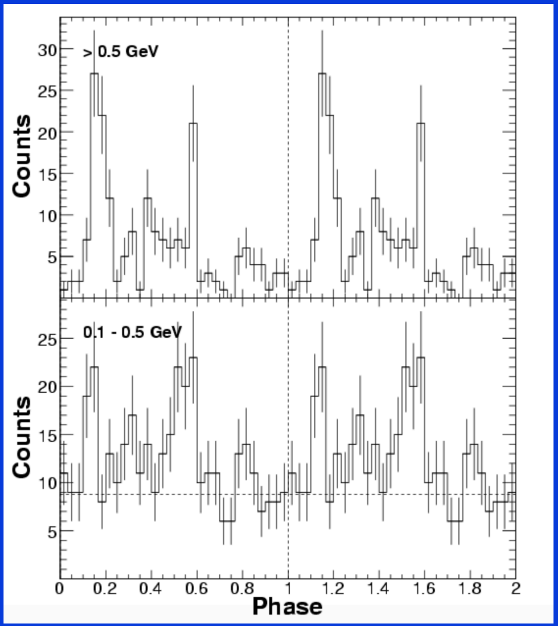
How? First, timing must be accurate

Maintaining absolute timing on a satellite is non-trivial. Various satellites have experienced problems with this.

We tend to wave our hands and say, “GPS”, but the GPS information still has to be attached to the data correctly.



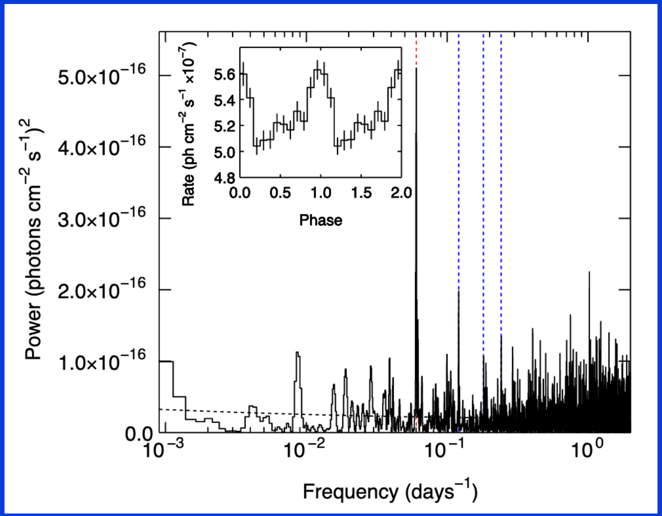
Fermi-LAT ground test comparing onboard times with an independent GPS system.



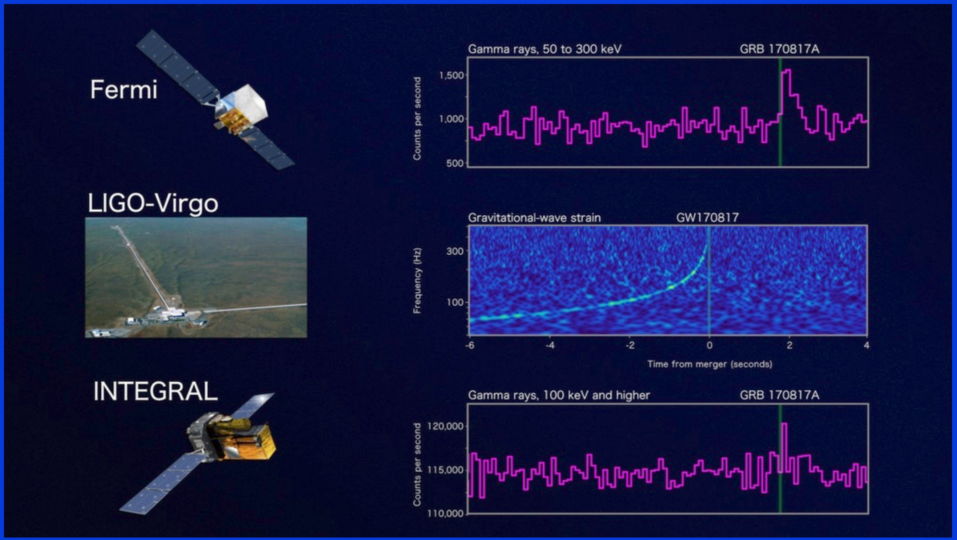
Fermi-LAT light curve for the 4.8 ms pulsar PSR J0030+0451. The bin width is 160 microseconds, showing clock stability over months.

How? Using timing for source identification

Periodicity is a certain way to identify the nature of a gamma-ray source. Variability correlated with changes seen by other instruments is also a solid source identifier.



Power spectrum and gamma-ray light curve of 1FGL J1018.6-5856, showing the 16.6-day period that identifies it as a binary system.

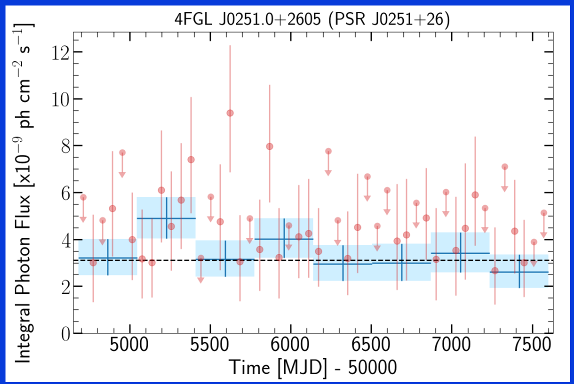


GW170817/GRB 170817A neutron star merger event.

How? Using timing for source identification

A less obvious way of using gamma-ray timing information is the search for new pulsars.

With a few exceptions, gamma-ray pulsars do not show long-term variability, so lack of variability (coupled with spectral information) can direct radio astronomers in pulsar searches, or the gamma-ray data themselves can be used for periodicity searches.



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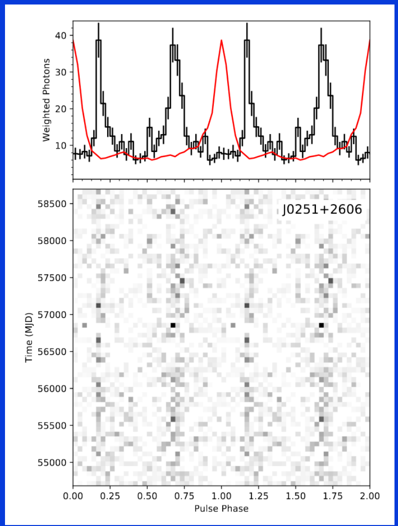
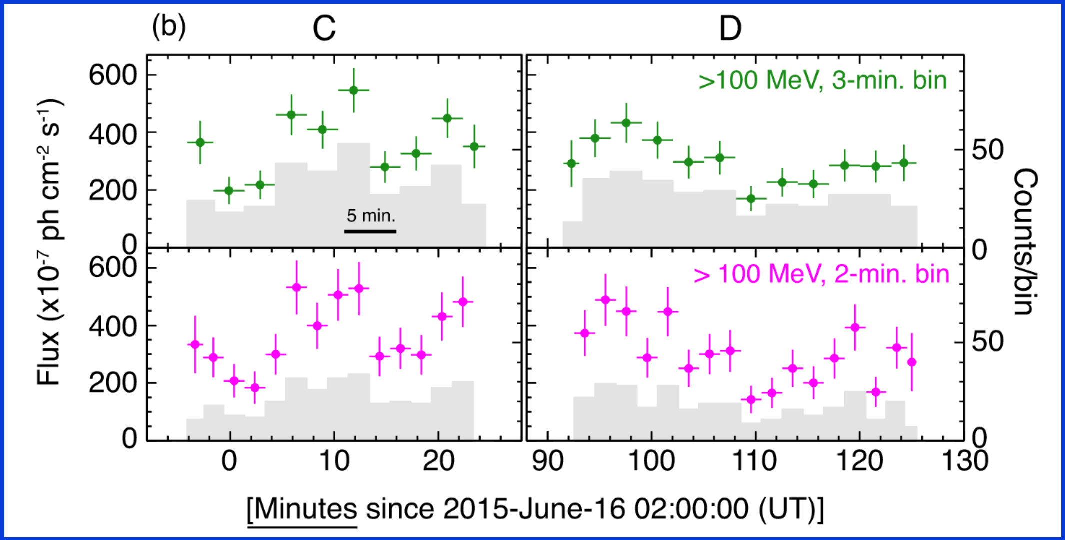


PSR J0251+2606, an eclipsing black widow pulsar.
Gamma-ray data in black; radio data in red.

How? Timing to determine source properties

Probably the most familiar use of time-domain studies for active galactic nuclei (AGN) is that the variability time scale constrains the size of the emitting region to be smaller than the light-crossing time.

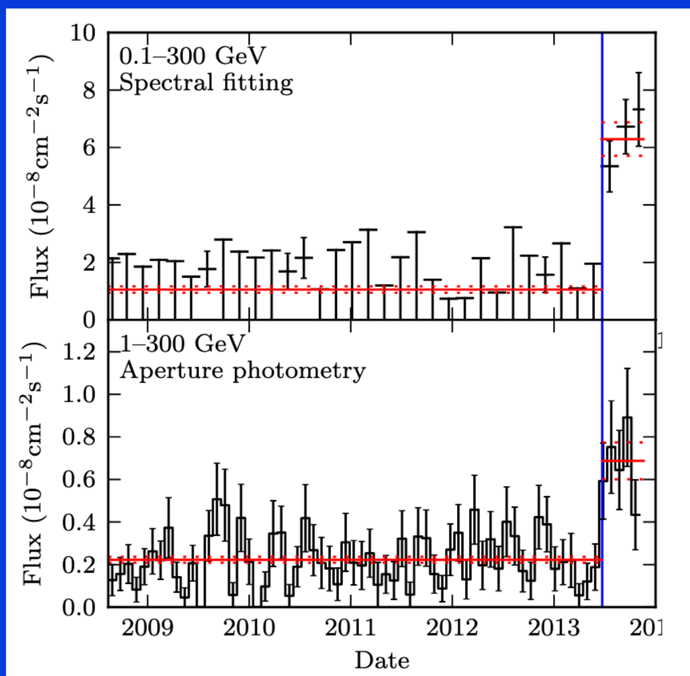


Minute-scale gamma-ray flux variations during a large flare of 3C279 imply a very compact emitting region (~ 100 Schwarzschild radii).

Caution: AGN modeling is a complex field, and this type of constraint must be considered in light of other observational and theoretical factors.

How? Timing to determine source properties

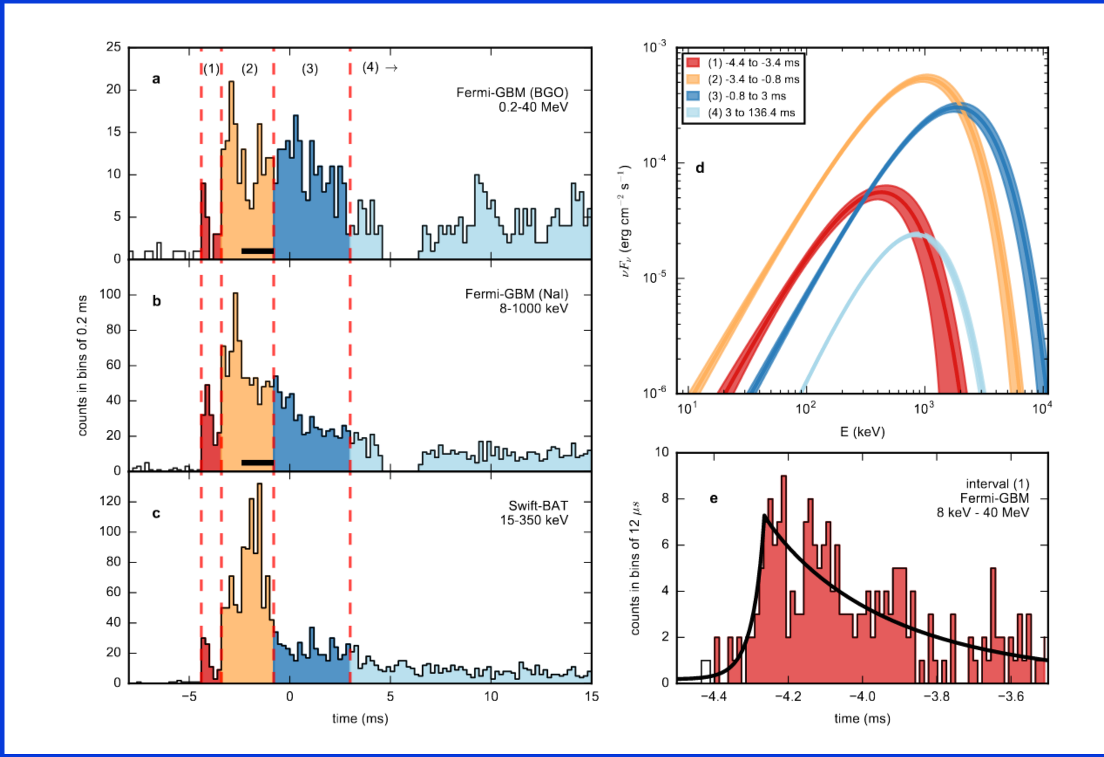
A change in gamma-ray flux has been associated with transitions between a Low Mass X-ray Binary and a millisecond pulsar.



PSR J1023+0038 (2FGL J1023.6+0040) was a bright millisecond radio pulsar until mid-2013, at which time its radio pulsations vanished and its gamma-ray flux increased by a factor of five.
A transition in the other direction, with pulsations appearing and the gamma-ray flux decreasing, was seen in PSR J1227−4853 (3FGL J1227.9−485).

How? Timing to determine source properties

Temporal and Spectral Variability of GRB 200415A indicated that this short burst (140 ms duration) likely originated from a magnetar in galaxy NGC 253.



What can be done to maximize the scientific return from gamma-ray time-domain astrophysics?

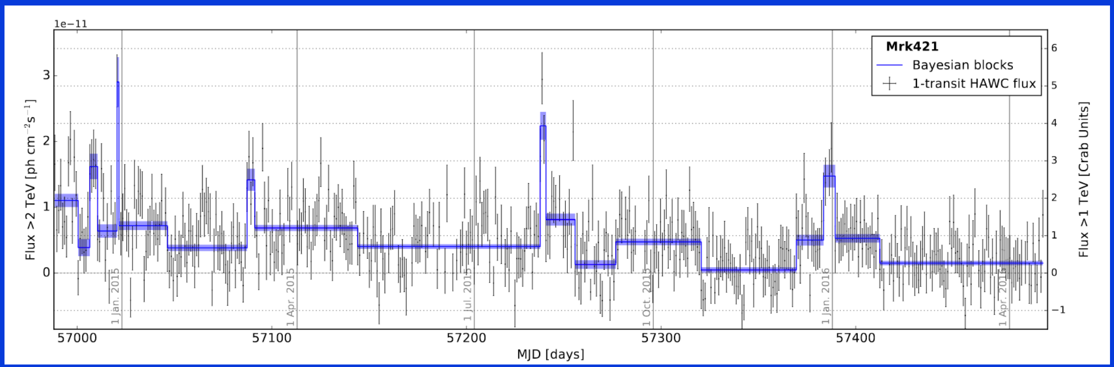
Here are a few suggestions in two areas:

1. **Expand the use of quantitative analysis of gamma-ray time features.**

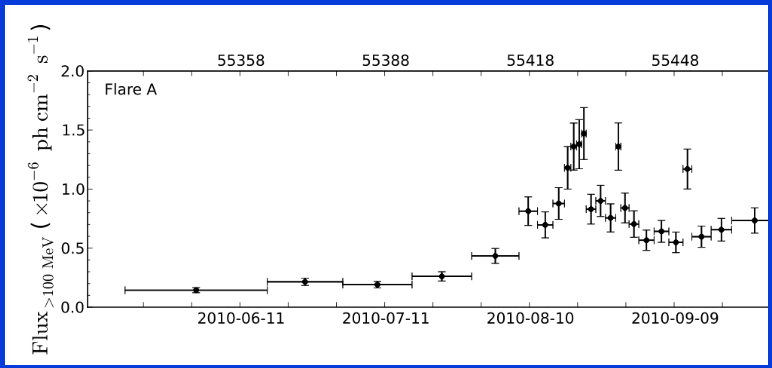
2. **Improve information sharing with multiwavelength/multimessenger colleagues.**

What about identifying gamma-ray time features?

One constraint that affects many gamma-ray time analyses is limited photon counting statistics. The resulting uncertainties can challenge the separation of real variability from statistical fluctuations. The tendency has been to divide data sets “by eye.” There are quantitative ways to handle this issue:



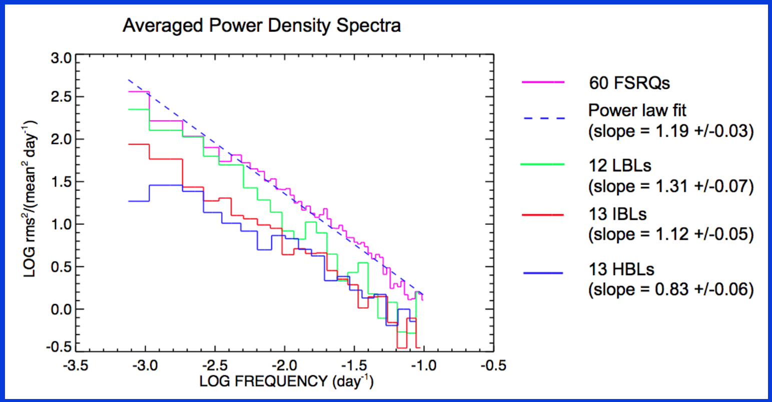
Jeff Scargle developed the Bayesian Block method of identifying significant changes in data without relying on binning. https://arxiv.org/abs/1207.5578



A complementary approach is adaptive binning, developed by Benoit Lott and colleagues https://arxiv.org/pdf/1201.4851.pdf

What about characterizing gamma-ray time features?

The broad range of variability time scales for gamma-ray sources offers many opportunities for quantitative analysis of the data. Here are some:



Power Density Spectra characterize variability on different time scales.

Periodicity searches invoke a wide variety of methods. Here are some:

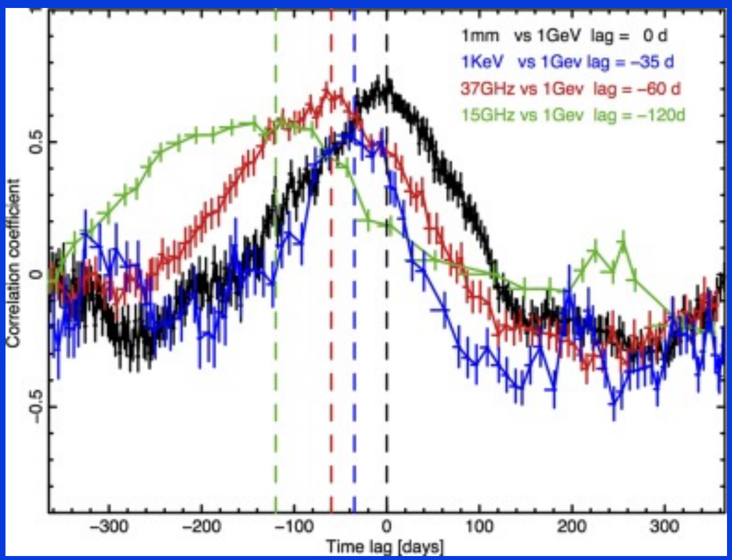
Lomb-Scargle periodogram
Discrete Fourier Transform
Continuous Wavelet Transform
REDFIT
Phase dispersion minimization

https://arxiv.org/pdf/2002.00805.pdf

For descriptions of these and others

What can improve multiwavelength/multimessenger time-domain studies?

One goal is to compare variability patterns. Differences (or lack of those) shed light on where and how the radiation is produced.



Discrete Cross Correlation Function for 3C454.3

Analysis tools like the Discrete Cross Correlation Function can extract the needed information – but only if simultaneous (or at least contemporaneous) data are available. Resources to monitor all the interesting sources all the time just do not exist.

The challenge is often collecting the required data, and that means the problem is COMMUNICATION.

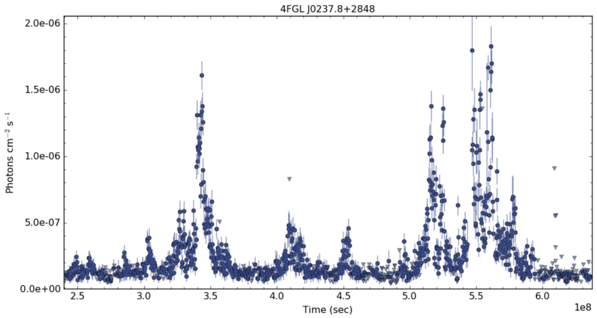
What can sharing of monitoring data do to help?

A number of groups across the electromagnetic spectrum have already made monitoring data available for quite a few sources – Examples include OVRO, MOJAVE, Catalina Sky Survey, SMARTS, Swift, Fermi. We should be encouraging programs like this. For included sources, data are readily available when interesting events occur.

Links to many of these resources are publicly available at
https://confluence.slac.stanford.edu/display/GLAMCOG/Fermi+LAT+Multiwavelength+Coordinating+Group
OR
https://fermi.gsfc.nasa.gov/ssc/observations/multi/programs.html

For blazars, one particularly useful link is the one by Matt Lister that lists which observatories are monitoring which blazars: http://www.physics.purdue.edu/astro/MOJAVE/blazarlist.html

Coming Soon (now in beta testing): A regularly updated library of Fermi-LAT light curves for all variable sources, with time scales down to 3 days. Thanks to Dan Kocevski and colleagues.



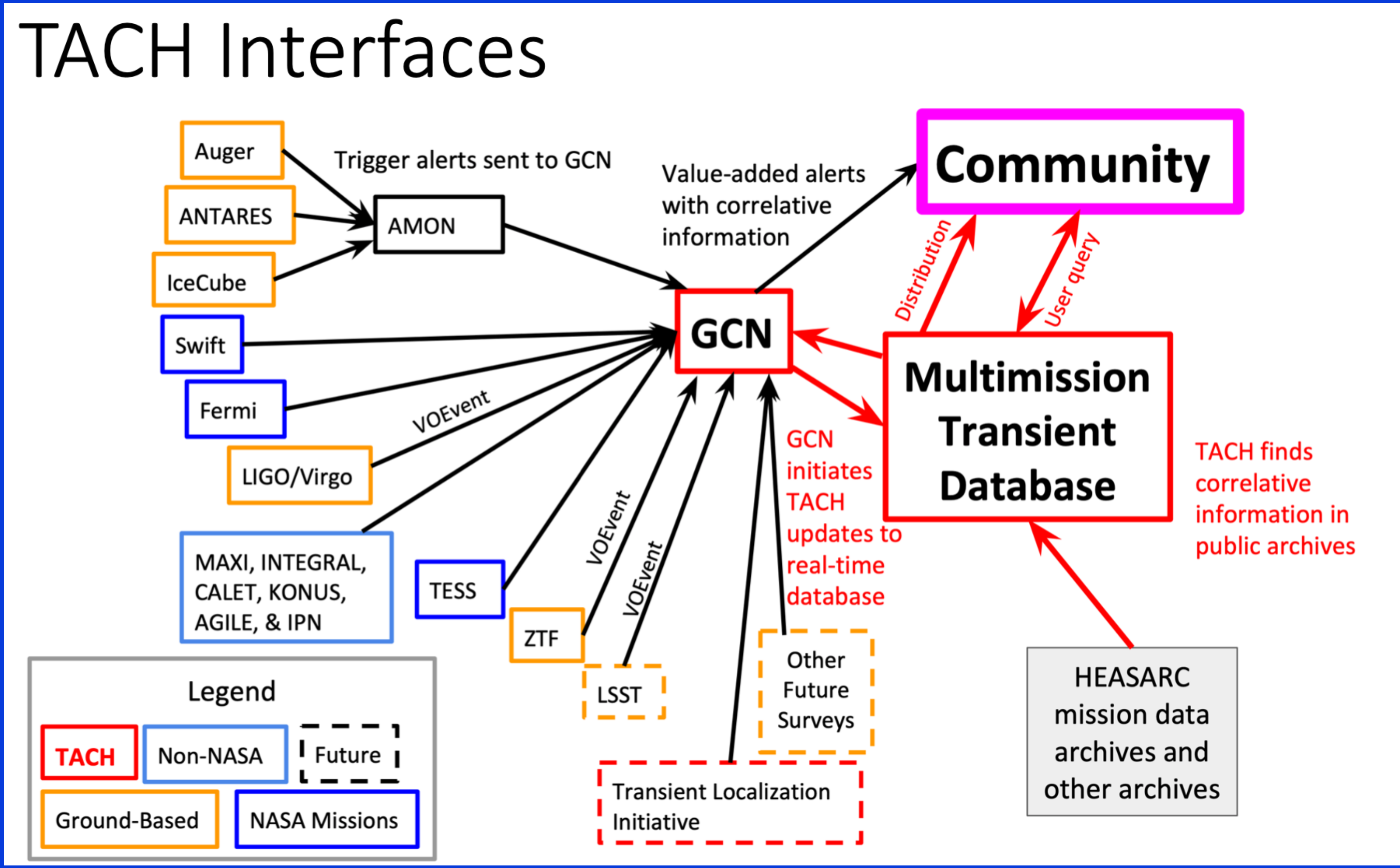
What can improve sharing of interesting events?

Rapid multiwavelength/multimessenger response to astrophysical events of interest is critical. Traditional methods have included word of mouth, e-mail, and Astronomer's Telegrams. The gamma-ray burst community has led the way, and the Gamma-ray Coordinates Network (GCN) has become a key to speedy dissemination of information. Scott Barthelmy deserves a lot of credit for keeping GCN going during the pandemic and for expanding its use to transients other than bursts.

With the emergence of observatories like the Zwicky Transient Facility and the Vera Rubin Observatory (LSST), which can generate vast numbers of transient notices, new systems of data sharing have become essential. Brokers are needed to manage the data streams (see https://www.lsst.org/scientists/alert-brokers for information) and distribute information. Merging those with existing systems is a challenge.

Two data management systems that are under development are outlined on the following slides, courtesy of Judy Racusin.

What can the Time-domain Astronomy Coordination Hub (TACH) do?



What can SCiMMA: Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics do?

- Developing cyberinfrastructure for the astronomy community
- Includes:
  - Infrastructure for astronomy alerts, influenced by Kafka usage by large ground-based optical surveys (ZTF, VRO)
  - Common IAM platform using federated identities (InCommon, CILogon), universities and other institutions act as IdPs
  - Alerts and IAM are not yet integrated, but may be in the future
- National Science Foundation funded project

Summary

The dynamic gamma-ray sky makes time-domain astrophysics particularly relevant for gamma rays.

Good gamma-ray timing enables source identification, periodicity searches, and correlation studies with other observations.

Modern analysis methods and enhanced data-sharing techniques offer opportunities for improved gamma-ray time-domain studies.