Mining the sky in real time

Fast optical transients
and
robotic telescope networks

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Discovery space for explosive transients

○ Includes:

- Established classes (solid)
- Emerging classes (vertical hatch)
- Objects predicted by extension of known facts (horizontal hatch)
- Theoretically predicted objects (open)

○ Spans many orders of magnitude luminosity and time-scale (decay by ~2 mag)

○ Has room for surprises!

○ Small telescopes are useful

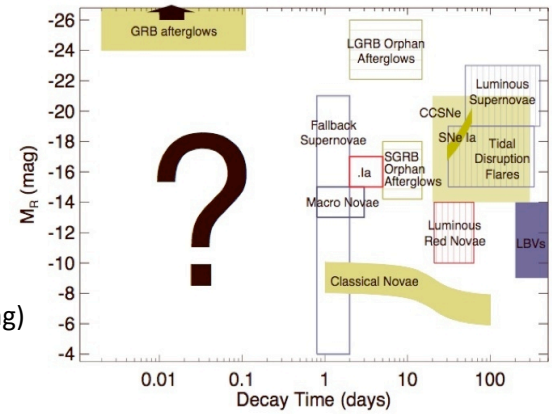


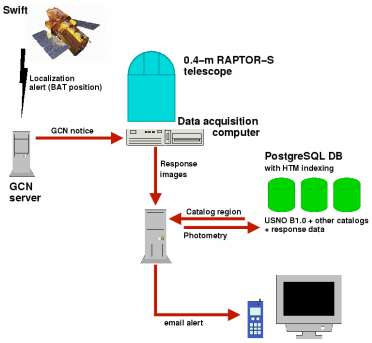
Fig. by A. Rau

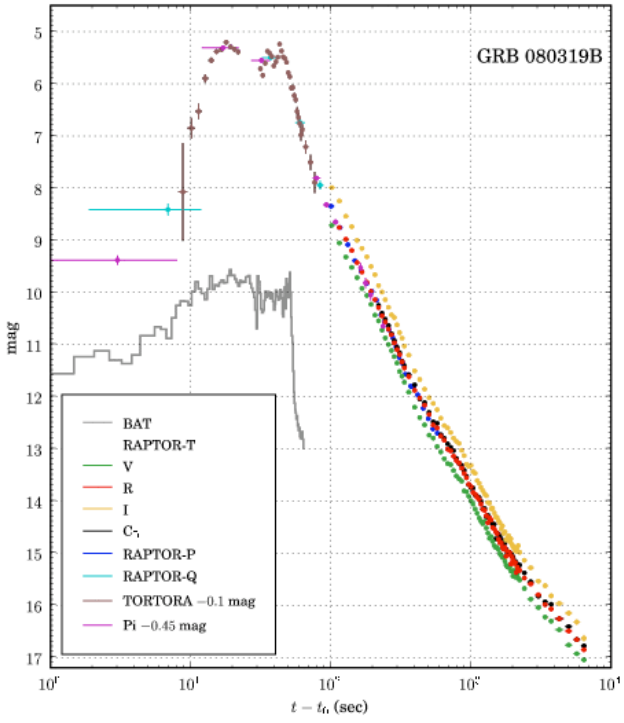
Similar diversity of persistent sources with unusual states:
rapid flaring in M-dwarfs, CV outbursts, compact binaries, Blazar flares

Finding transients and taking a closer look

- High energy sky is relatively empty: variable sources stand out, but localizations are poor (e.g. GRB follow-up)
- In the optical must find needles in hay stacks: efficient creation and searching of large spatio-temporal DBs, optimizing event selection algorithms (e.g. microlensing searches)
- Learning more before it disappears forever: real-time data processing, rapid response, robotic instruments and autonomous operation, optimizing alert content, context gathering for triage and command generation, messaging systems, standard protocols

Grand Challege: make it all work together





GRB 080319B

naked eye burst
from z ~ 0.9 !

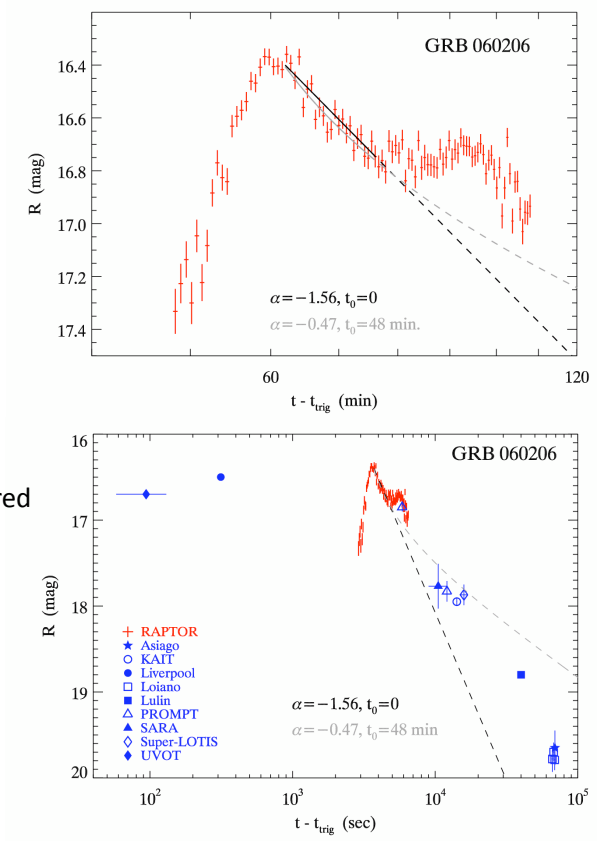
GRB 060206

Found autonomously in triggered data (cell phone alert when still rising)

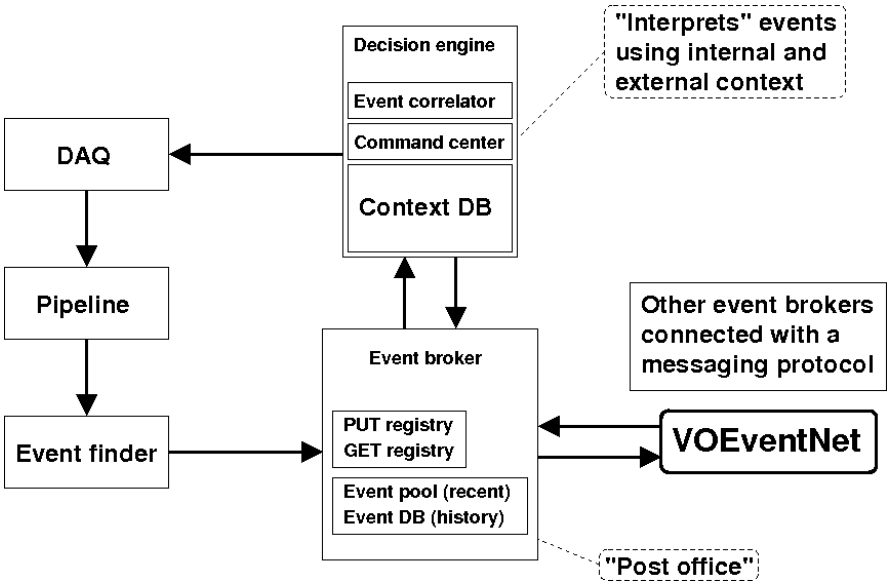
Second bright optical peak ~1 hour after the GRB

Very little gamma-ray emission compared to optical flux

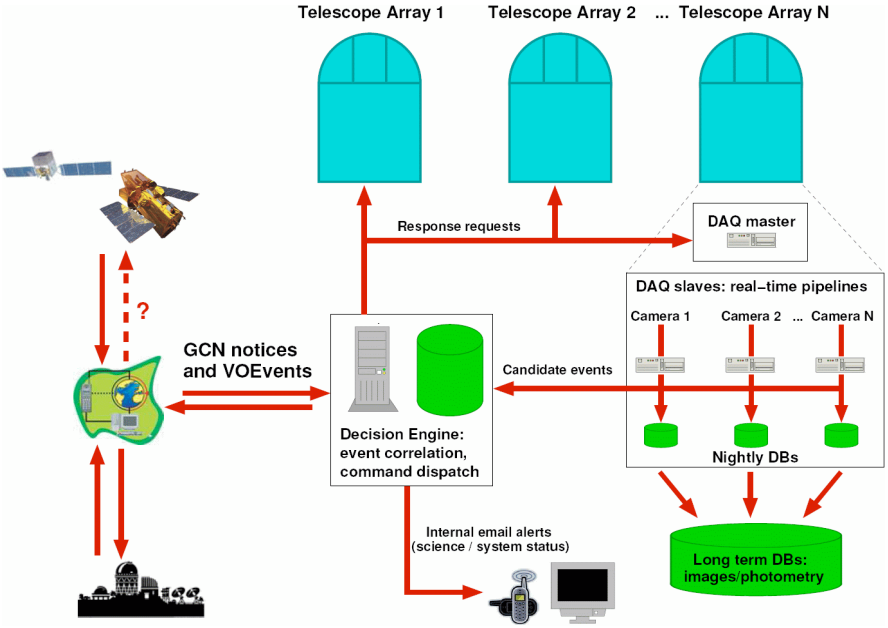
Existence proof for untriggered optical searches



Emerging system architecture

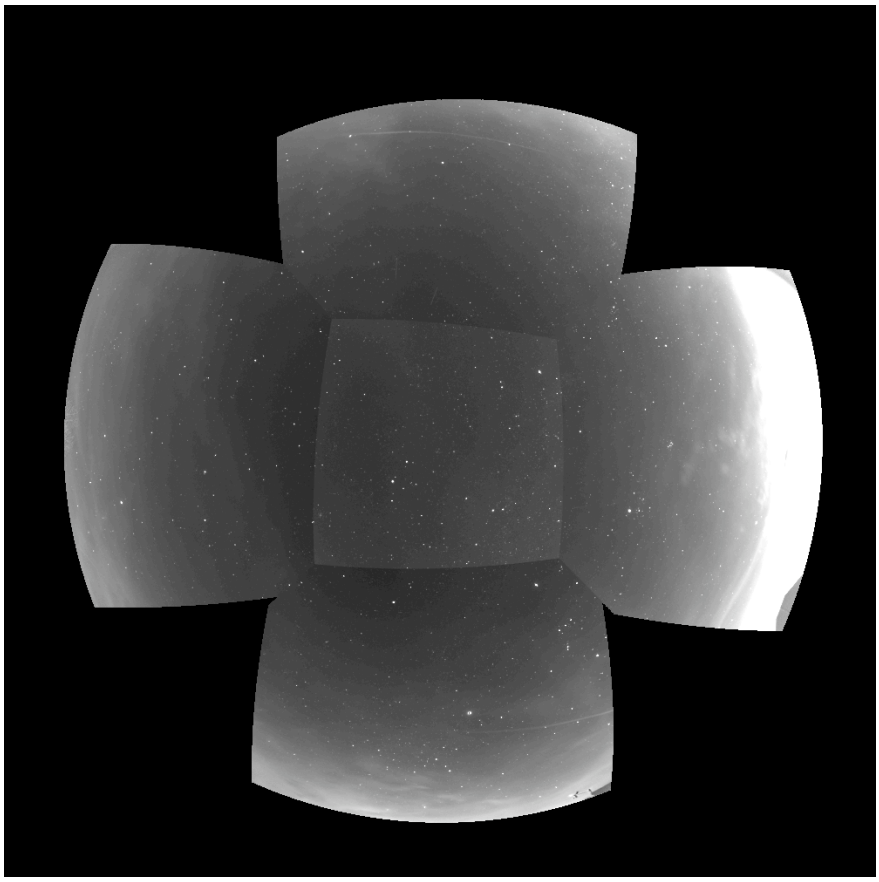


RAPTOR telescope network



RQD2 all sky monitor

- Bottom of the food chain, but easy to replicate
- ~11-12 mag limit (unfiltered)
- Single air-conditioned package for DAQ and pipeline computing



Raptor-K wide field survey

- 16-camera system covering 1000 sq. deg to 16.5 mag (unfiltered)
- Co-existing on a fast slewing mount
- A “circuit survey” looping over 5-10 tiles covering most useful sky
- Generates 134 MB of pixel data every ~30 seconds, or 0.5-1.0 TB per week
- Software automatically reduces data on-the-fly in ~4 seconds
- Anomaly detection constantly runs on up to ~500,000 light curves (circular buffers in RAM)
- Events reported/response initiated in real time
- Raptor-K had the first light

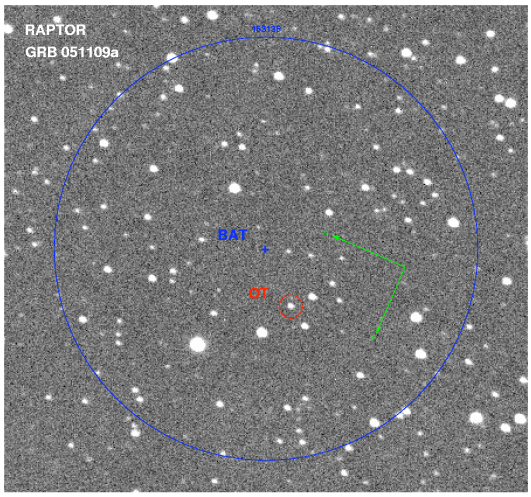
Next generation response

- Four 0.4-m f/10 telescopes on a fast-slewing mount
- Points anywhere on the sky in less than 10 sec
- Strictly simultaneous light curves in V, R, I, clear
- Mag limit R_c~19 for 60-second exposures

- 0.5-m telescope
- EMCCD can run at 1Hz or higher cadence with very little read noise
- plans for a polarimeter

Current trends

- One transient at a time ➔ many (>~10^4 per night for LSST): need scoring of interesting objects and better follow-up strategies
- Single trigger source/follow-up path ➔ multiple feedback loops: (weaker distinction between survey and follow-up, replaced by co-observing)
- Dedicated filtering of one type of object ➔ full classification of data
- Higher data rates, more complex, more structured data: e.g. multi-color GRB light curves



Event/Alert life cycle

- What is an event?
- What to alert?
- What about retractions?
- How to break the classification degeneracy?
- How to select the best feature spaces?
- How to fuse diverse data? (~100 posible features most of which will be missing)

Interpretation of transients is an incremental/iterative process

Scenario 1:

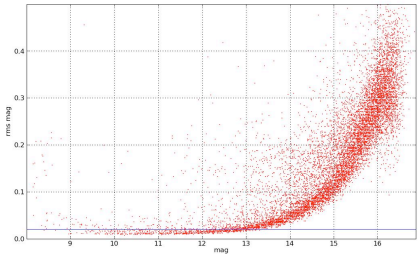
- Initial Swift/BAT position: few arc min error box
- Variable optical counterpart
- XRT position
- One or more confirmations of OT

- Fermi cross-ids are much more ambiguous: ~1-10 deg position error

Scenario 2:

- GW detections of SMBH mergers from LISA: evolving 3-D error box
- Decreasing number of candidate EM counterparts as the position error shrinks from ~1 arc deg to ~1 arc min

Data level event selection



- Sliding window determined by available (N = few x 10 epochs for every source)
- Consider residuals on top of a baseline (running mean)
- Anomaly score for residuals based on density estimate (Parzen windows) using stars of similar brightness
- For each lag (up to 1, 2, 3, ... , N frames back) the total score is the product of scores for all relevant epochs normalized to a median residual (threshold is a vector with values for all lags)
- Variable objects tested for trending behavior
- Object states: init|const|+|-|+/-
- Report selected state changes to the next level
- Computationally intensive, but relatively free of assumptions about the form of the error distribution and variability pattern

Science level event cross-correlation

- Input events are continually assigned and reassigned to ”sources”
- Each source of a given type has a set of "facts” + a history of states and alerts
- Cross-correlate Raptor events with GCN localizations (each with finite extent)
- Extract event “context”: (instr/obj id, position error box, time interval) ➔ set of relevant source ids
- Reinterpret (possibly split/merge sources) using additional info from existing catalogs ➔ still very primitive
- Report state changes and "facts"