Some Examples of Virtual Observatory Enabled Science

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Lecture 2 - Part 2

Inaugural BRAVO Lecture Series,
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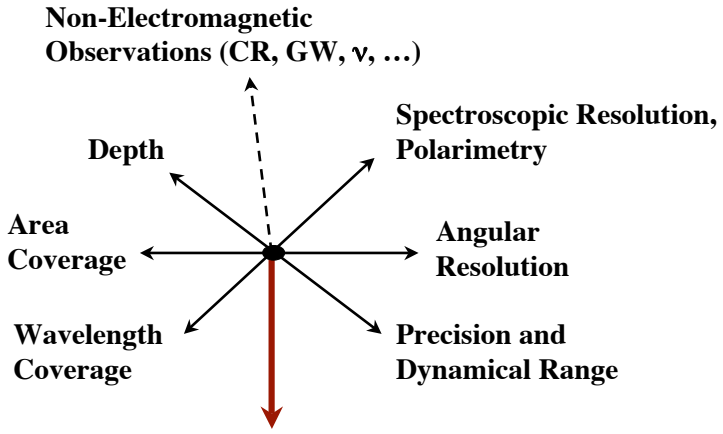
A Generic Example:
Exploration of Observable Parameter Space

- A purely general approach to a systematic exploration of the universe
- Every astrophysical observation (or even a survey) carves out a specific slice in the parameter space, and is thereby limited
- Usually, new discoveries are made when some new portion of the observable parameter space opens up (e.g., a new wavelength range - but it could be improved resolution, etc.)
- Once sources are identified and catalogued in some survey or a federation thereof, they form data vectors in a highly multidimensional parameter space:
  - Sources of different types (e.g., stars, galaxies, quasars…) form clusters and correlations in this parameter space
  - Outliers may represent rare, unusual, or even new types of objects

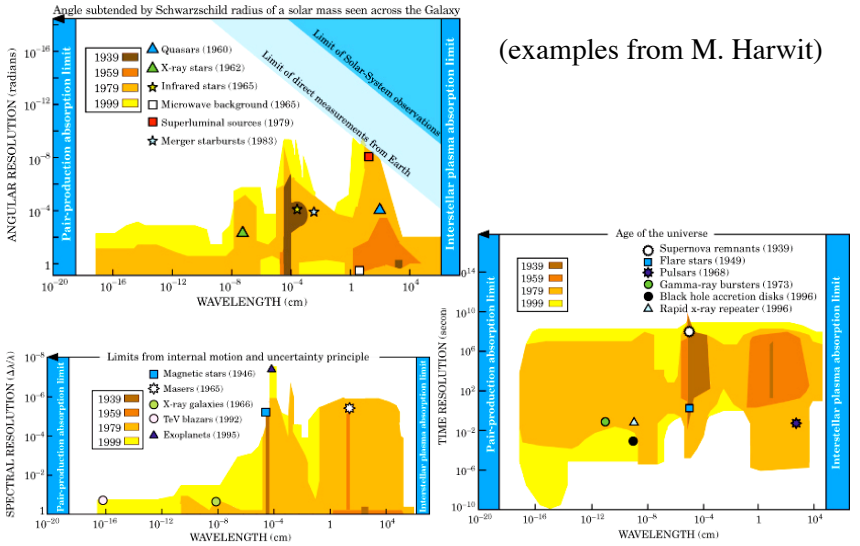
The Observable Parameter Space



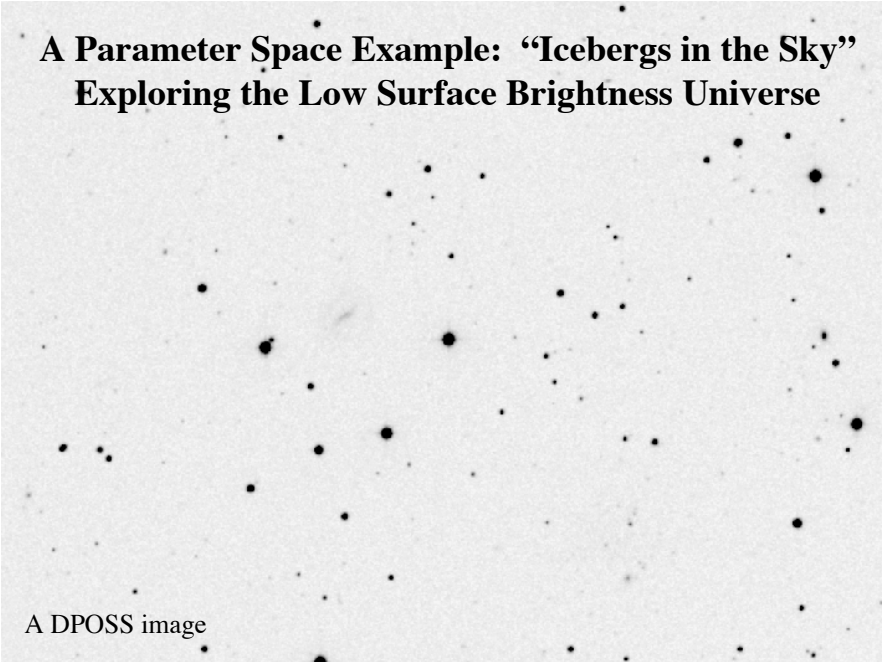
The Time Domain:
Depth, sampling, baselines, …

Covering the Observable Parameter Space

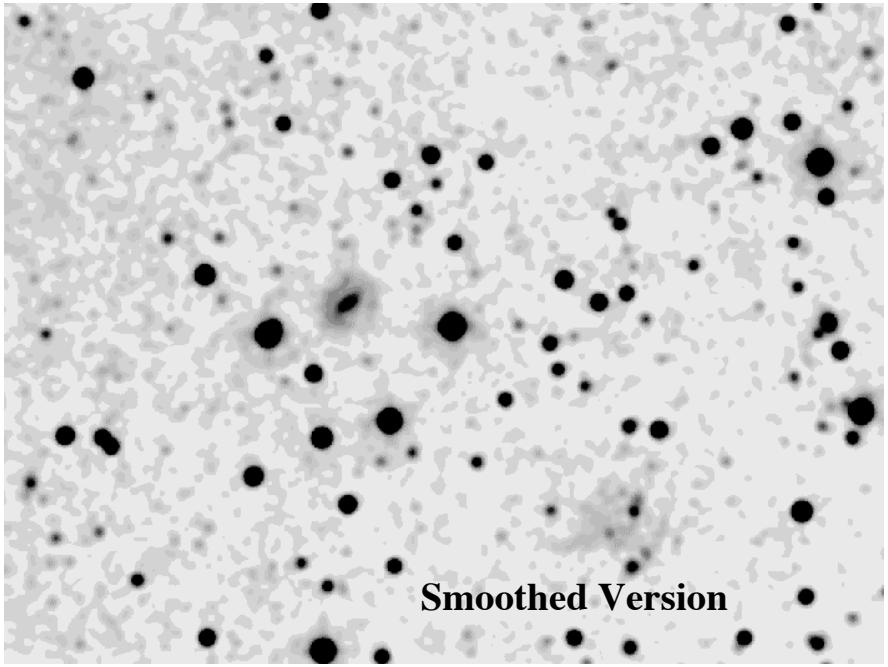
(examples from M. Harwit)



A Parameter Space Example: "Icebergs in the Sky" Exploring the Low Surface Brightness Universe

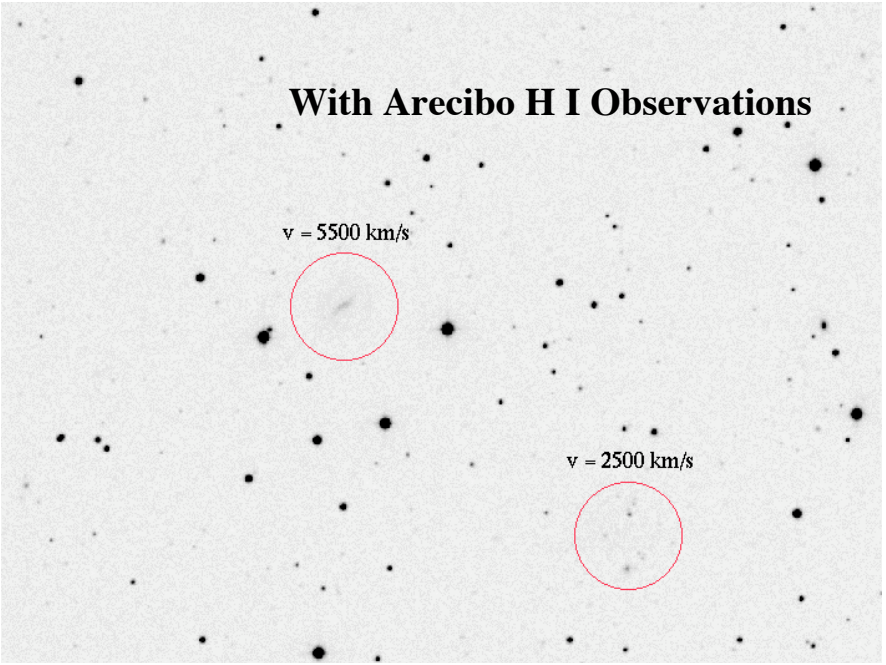


A DPOSS image

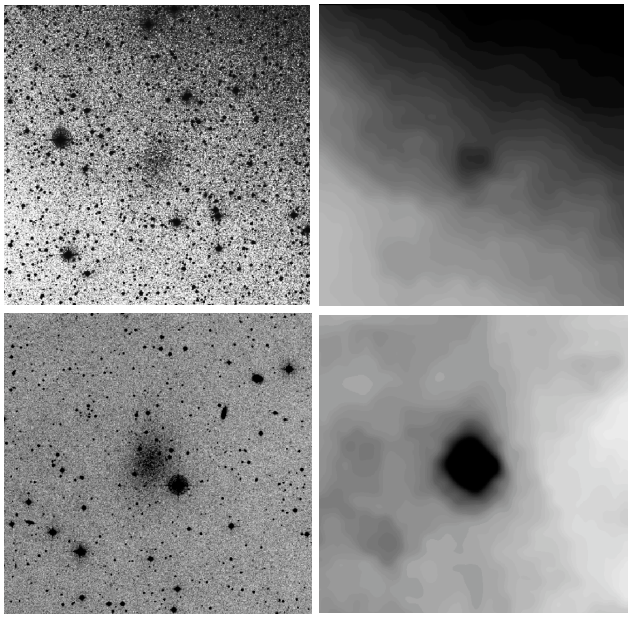


Smoothed Version

With Arecibo H I Observations



Background Enhancement Technique demonstrated on two known M31 dwarf spheroidals

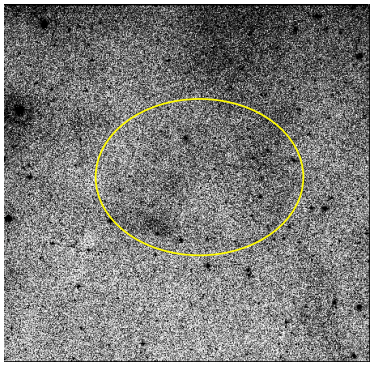


(Brunner et al.)

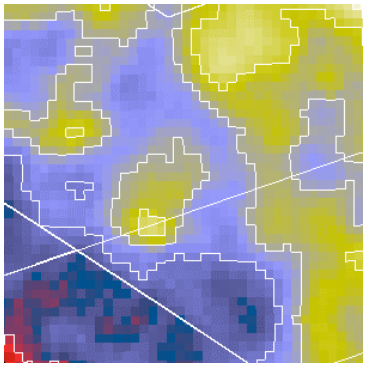
Exploring the Low Surface Brightness (Low Contrast) Universe

Comparison between HI, Hα, and 100μ Diffuse Emission

DPOSS red image



IRAS 100 Micron Image



Brunner et al.

Time Domain Astrophysics

- **Moving objects:** Solar system, Galactic structure, exoplanets
- **Variability** < Intrinsic; Modulation along the LOS: microlensing, ISS, eclipses, variable extinction …

Physical causes of intrinsic variability:

- Evolution (structural changes etc.), generally long time scales
- Internal processes, e.g., turbulence inside stars
- Accretion / collapse, protostars to CVs to GRBs to QSOs
- Thermonuclear explosions
- Magnetic field reconnections, e.g., stellar flares
- Line of sight changes (rotation, jet wiggles…)

Variability is known on time scales from ms to 10^{10} yr

Synoptic, panoramic surveys ➔ event discovery

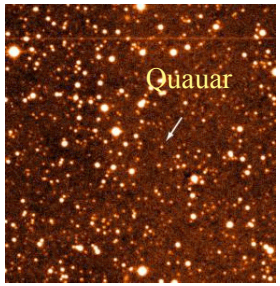
Rapid follow-up and multi-λ ➔ keys to understanding

Things That Move in Our Solar System

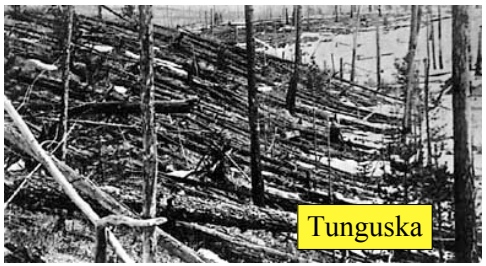
Dwarf planets and KBOs

M. Brown et al.

NEAT, Catalina, etc.



Killer Asteroids



Donald Rumsfeld's Epistemology

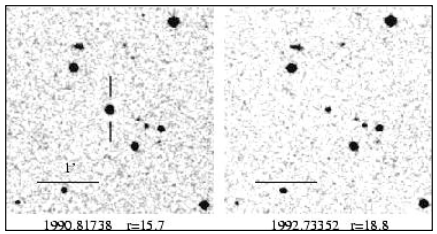
There are known knowns,
There are known unknowns, and
There are unknown unknowns

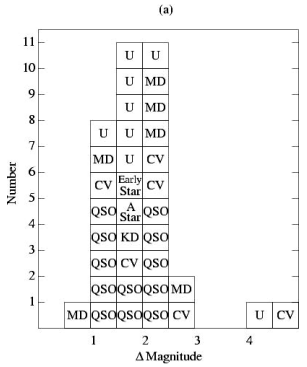
Intrinsically Variable Phenomena

- Things we know about:
  - **Stars:** oscillations, noise, activity cycles, atmospheric phenomena (flares, etc.), eclipses, explosions (SNe, GRBs), accretion (CVs, novae), spinning beams (pulsars, SS 433, …)
  - **AGN:** accretion power spectrum, beaming phenomena
- Things we see, but don't really understand:
  - Faint fast transients
  - Archival optical transients (OT)
  - Megaflares on normal stars
- Things we expect to see, and maybe we do:
  - Breakout shocks of Type II SNe
  - SMBH loss cone accretion events
  - BH mergers (LIGO, LISA?), QSO formation…?
- Things as yet unknown and/or unexpected:
  - Manifestations of ETCs? (SETF?)

DPOSS Pilot Search for Highly Variable Objects

(using plate overlaps)

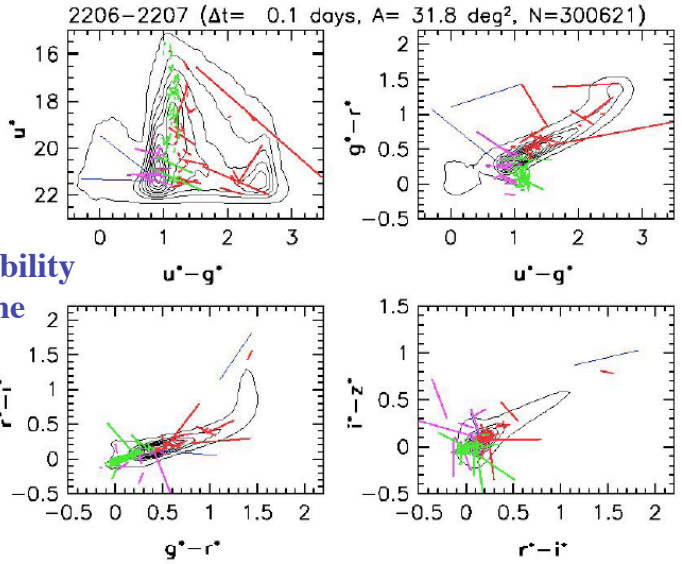




Spectroscopic IDs:

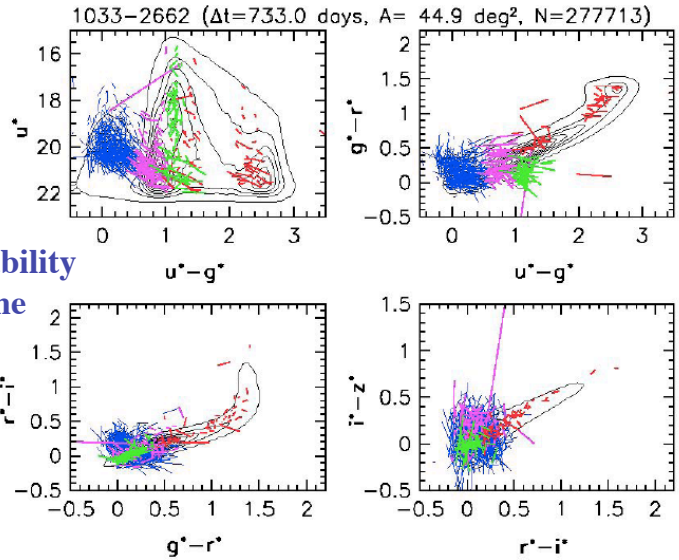
35% QSOs (1/2 radio loud)
18% CVs
18% M dwarfs
6% Earlier type stars
23% Unidentified (likely BL Lacs?)

Scans 3 hours apart (note the absence of low-z QSOs):



SDSS variability studies in the color space

$\Delta t \sim 2$ years. QSOs dominate the variable sample!

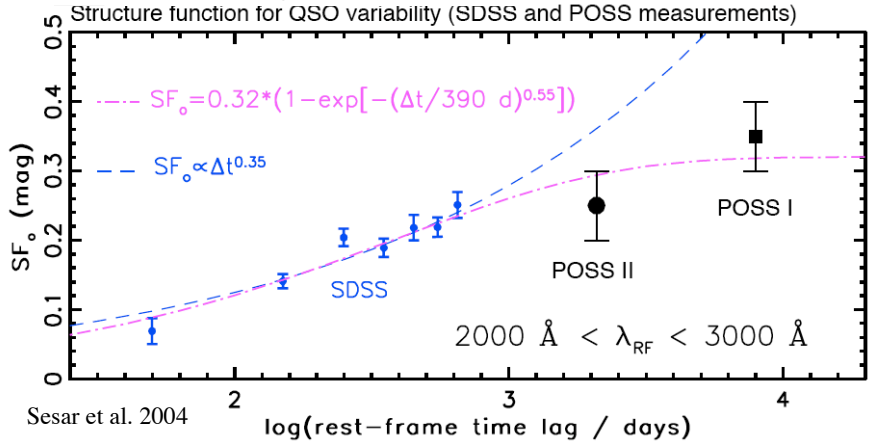


SDSS variability studies in the color space

Quasar Variability

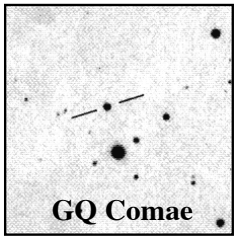
Typically quantified using the structure function,

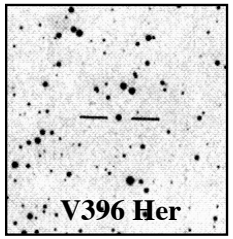
$$S(\tau) = \left\{ \frac{1}{N(\tau)} \sum_{i<j} [m(i) - m(j)]^2 \right\}^{1/2} \quad \text{where} \quad \tau = t_j - t_i$$



Sesar et al. 2004

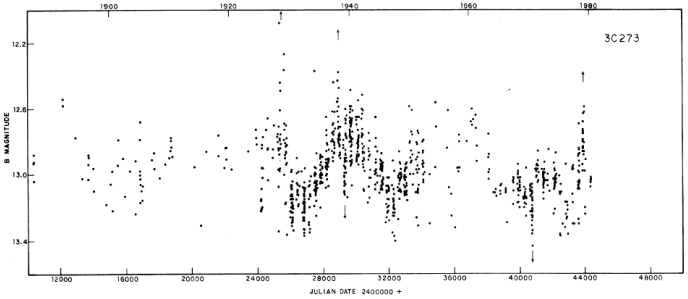
How Quasars Were *Not* Discovered



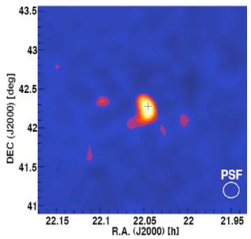


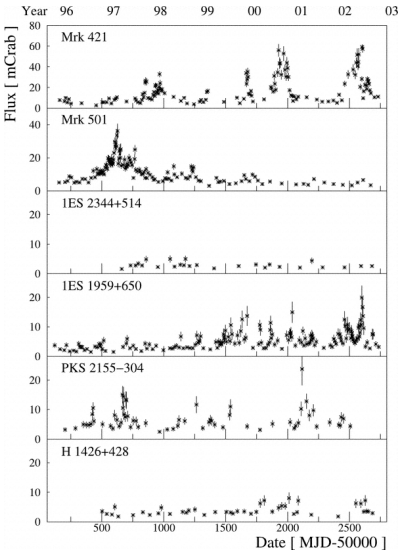
Noted as variable sources even in the 19th century, but … ***misclassified as variable stars***

Historical (archival) lightcurve of 3C273, starting from the 1880's …



Beamed AGN: Blazars (Cosmic Accelerators)



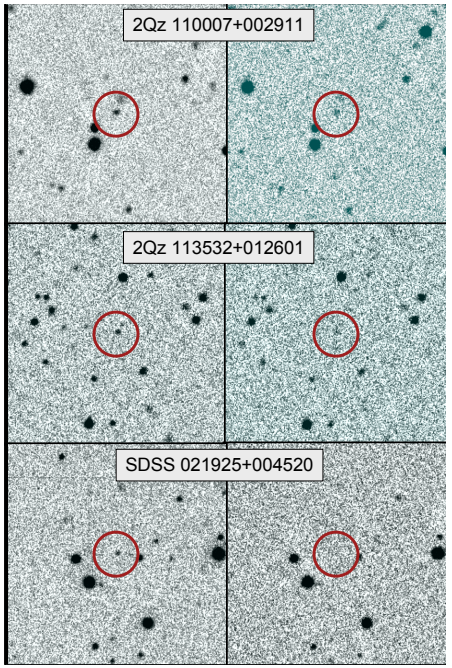


Presumed sources of TeV γ-rays and possibly some UHECRs

Important for the GLAST mission, and ground-based TeV and UHECR experiments (e.g. Auger)

PQ Variability of AGN and Blazars

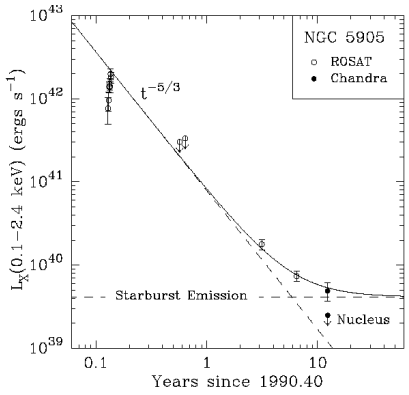
- Characterize the high-ampl. variability of known QSOs and especially Blazars
- Use to devise a pure optical variability (and color?) selection of Blazars
- Are we missing a population not found by the traditional radio or X-ray selection?
- A good multi-λ synergy with GLAST, TeV γ-ray, and UHECR surveys and experiments



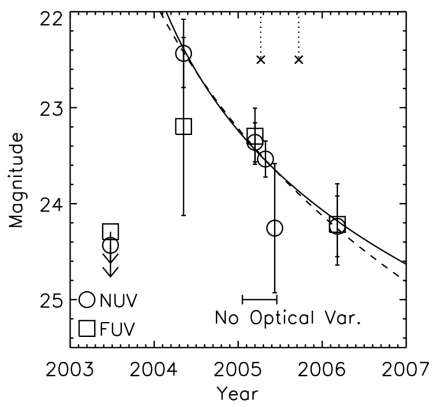
Accretion Flares From Otherwise Quiescent SMBHs

Tidal disruption of passing-by stars, and fallback.
Expected rate ~ 10^{-4} /galaxy/yr, L_{peak} ~ 10^{44} erg/s

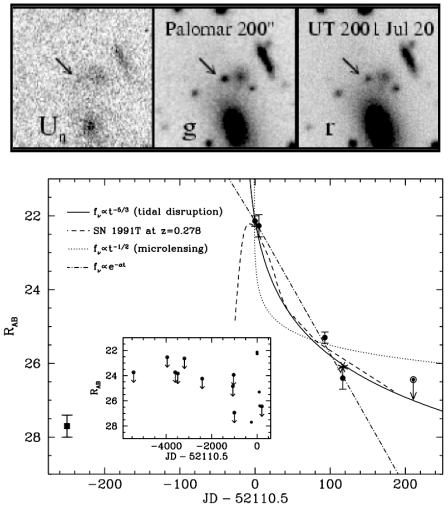
Komossa et al. (Rosat)
5 candidate events in X-rays



Gezari et al. (GALEX)
A few candidate events in UV

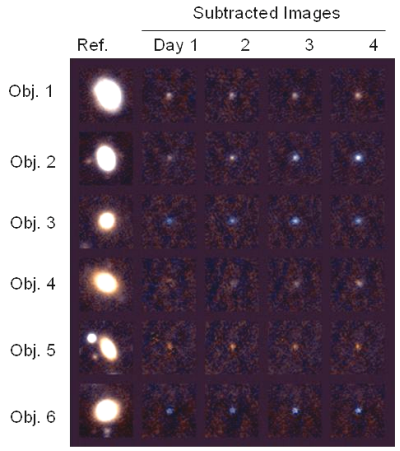


PALS-1 : A possible gravitationally magnified U-band dropout (z ~ 3.3?) behind Abell 267 (Stern et al.)

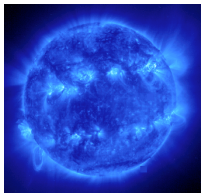


Variable sources in the centers of apparently normal galaxies at z ~ few tenths

(Totani et al., SUBARU)

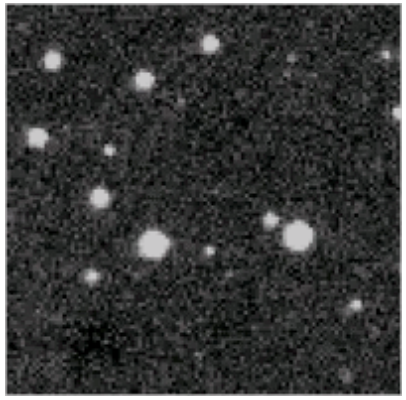


Flaring M Dwarfs
(a vermin of the synoptic sky surveys?)

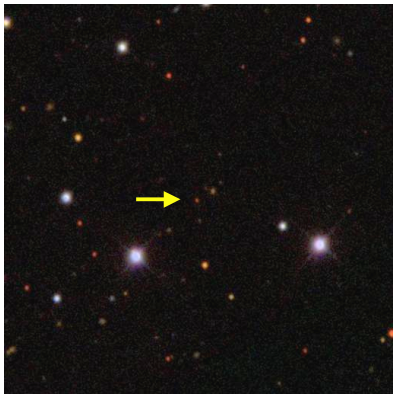


(just like the Solar flares, but much, much bigger)

Lynx OT (Catalina Sky Survey)



SDSS Counterpart

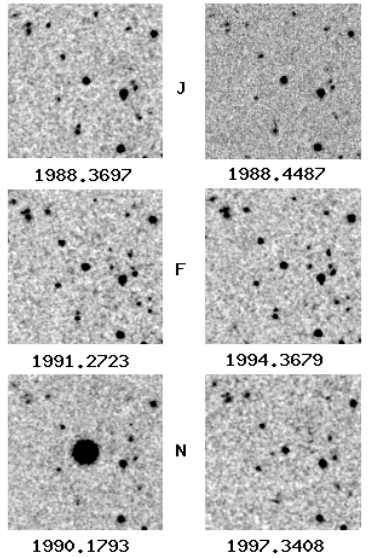


Megaflares From Normal (?) Stars

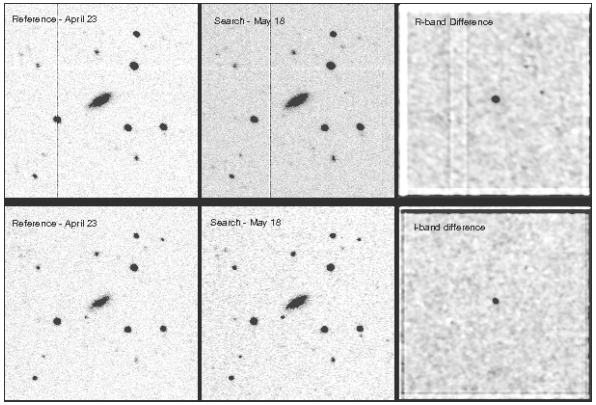
An example from DPOSS:
A normal, main-sequence star which underwent an outburst by a factor of > 300.

There is some anecdotal evidence for such **megaflares** in normal stars (Schaefer).

The cause(s), duration, and frequency of these outbursts is currently **unknown**.



PQ Search for Low-z Supernovae



In collaboration with R. Ellis, S.R. Kulkarni, A. Gal-Yam, and the LBL SN Factory

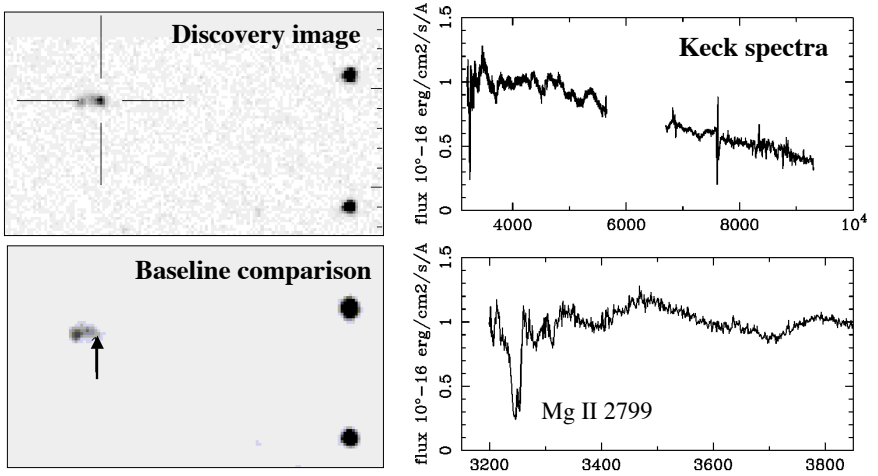
(Using the image subtraction technique)

- Calibration of the SN Ia Hubble diagram
- New standard candles from SN II
- Endpoints of massive star evolution

Discoveries of Peculiar Supernovae

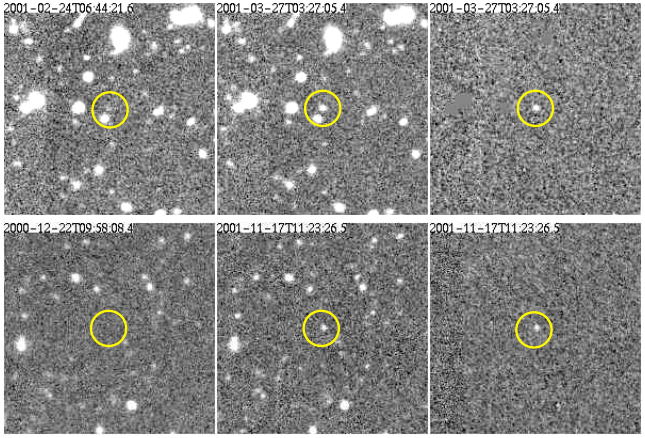
OT 060520:143933+054636, SNF discovery, Caltech follow-up

Peculiar SN Ib, similar to 1984L? *A. Mahabal et al., ATEL 827*



Faint, Fast Transients From DLS

(Tyson, Becker, et al.)



Some are flaring M-stars, some are extragalactic, …

➔ **A heterogeneous population!**

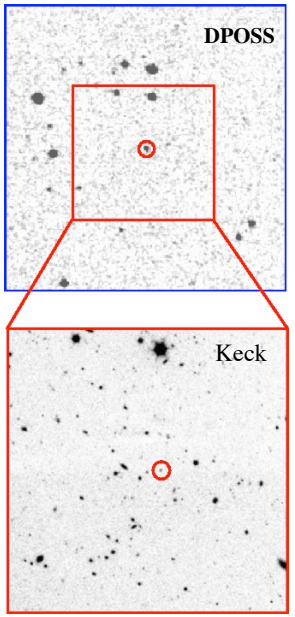
Optical Transients in DPOSS

A possible **orphan afterglow** ➔ discovered serendipitously in DPOSS: an 18th mag transient associated with a 24.5 mag galaxy. At $z_{est} \sim 1$, the observed brightness is ~ 100 times that of a SN at the peak.

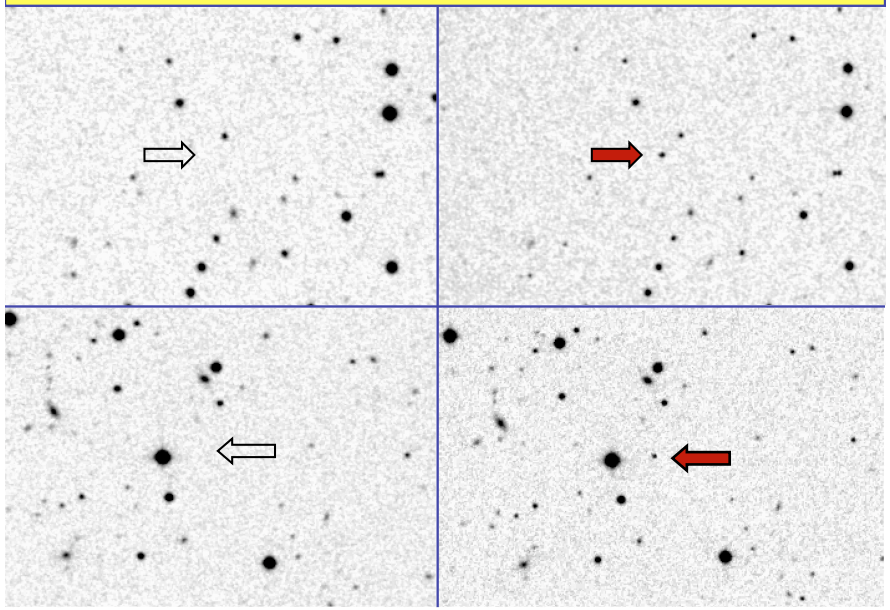
How many do we expect to see?

Depending on the beaming factors, there should be ~ 10 afterglows down to R ~ 20 mag per all-sky snapshot.

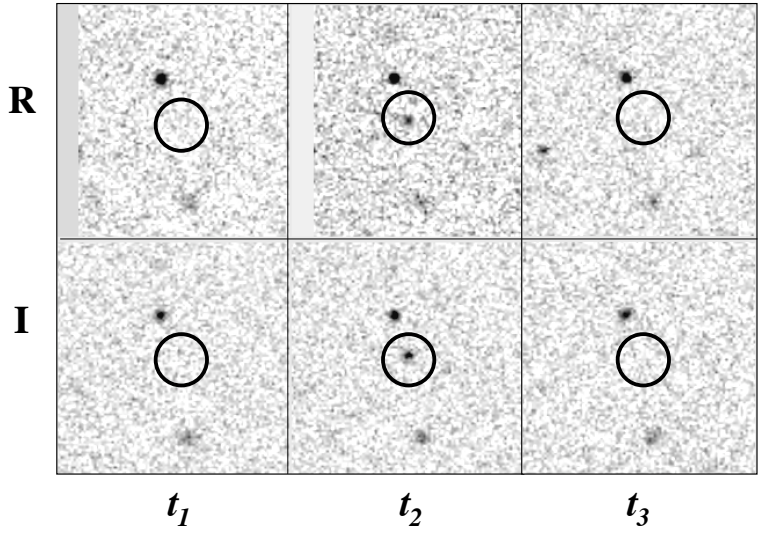
… But it could be something else entirely…



Examples of DPOSS Transients



Unidentified Archival Transients in PQ



(A. Drake, A. Mahabal, et al.)

The Palomar-Quest Event Factory

Detect ~ 1 - 2 $\times 10^6$ sources per half-night scan

Compare with the baseline sky

Find ~ 10^3 apparent transients (in the data)

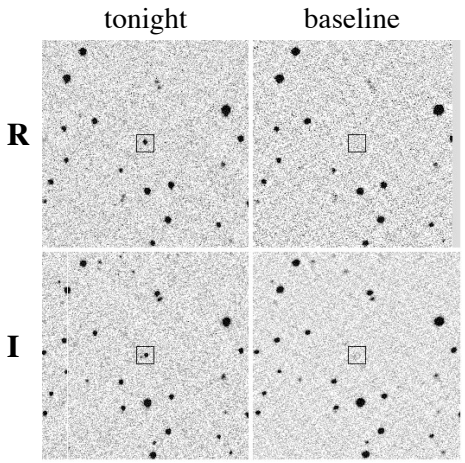
Remove instrum. artifacts

Identify ~ 2 - 4 $\times 10^2$ real transients (on the sky)

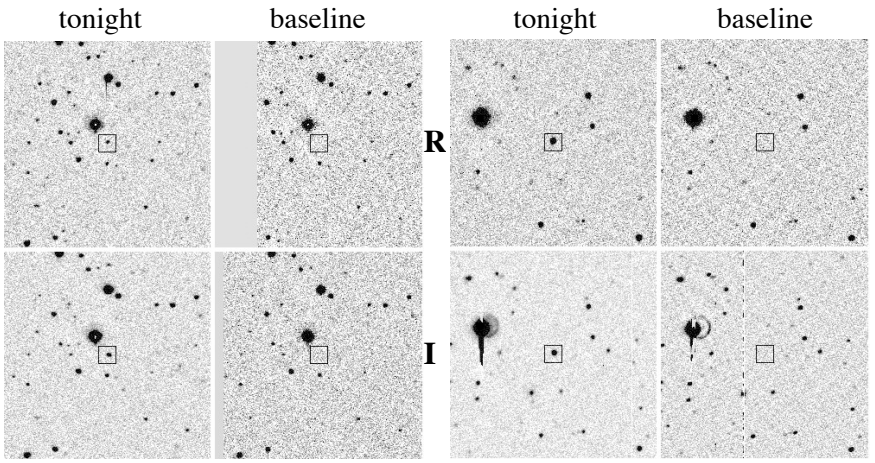
Remove asteroids

Identify ~ 1 - 10 possible Astrophysical transients

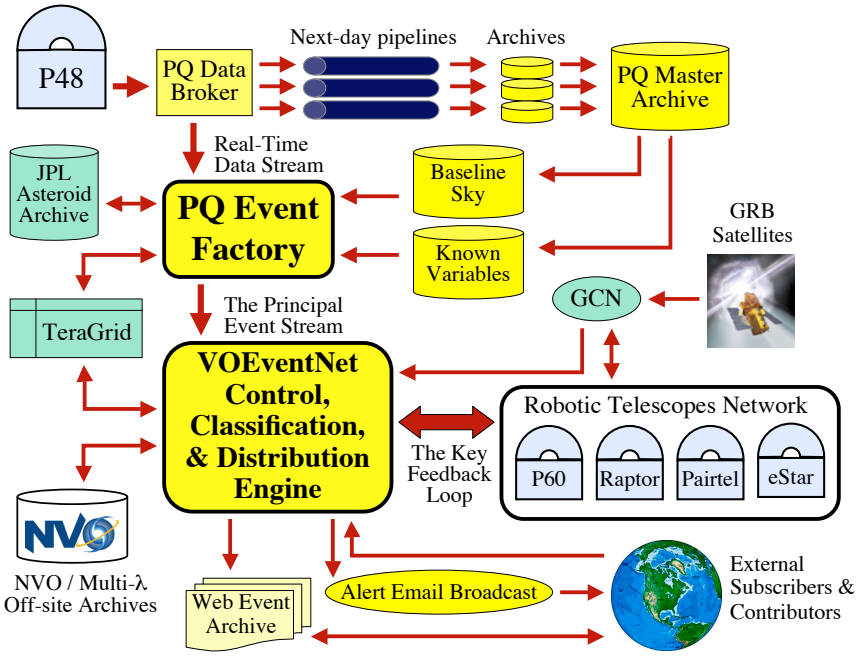
→ Classification and follow-up



Real-Time Discovery of Transients



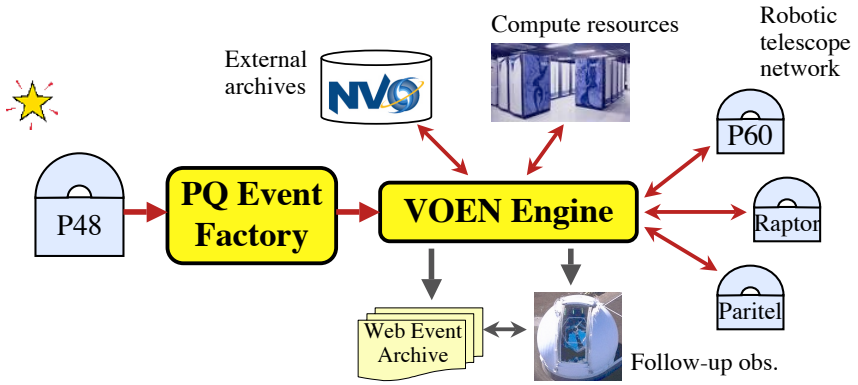
Examples of optical transients discovered in the real time in Sept.'06, using a prototype real-time pipeline



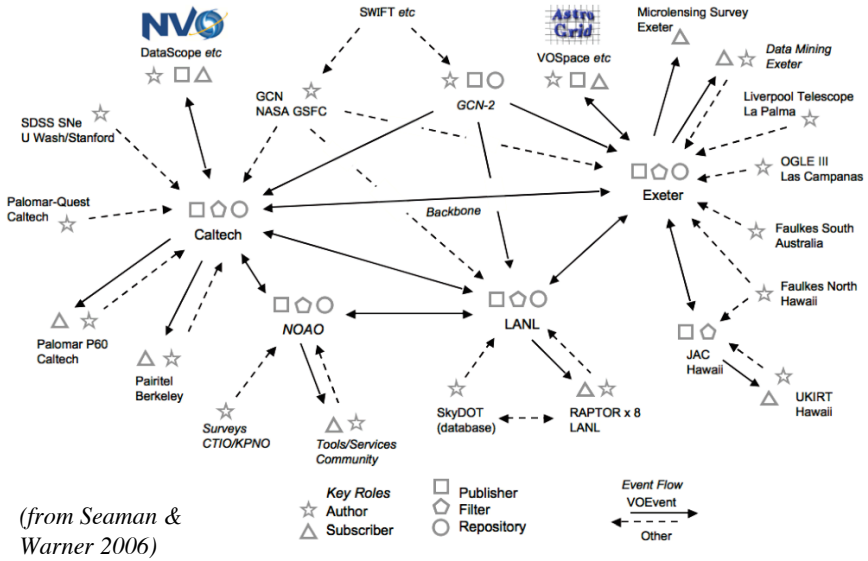
The VOEventNet Project

PI: R. Williams

- A telescope sensor network with a feedback
- Scientific measurements spawning other measurements and data analysis in the real time
- Please see **http://voeventnet.org**



The Emerging Global VOEvent Network

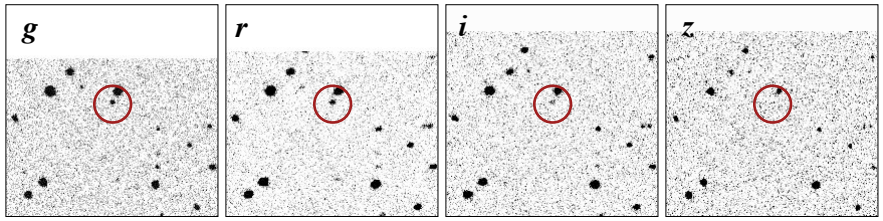


(from Seaman & Warner 2006)

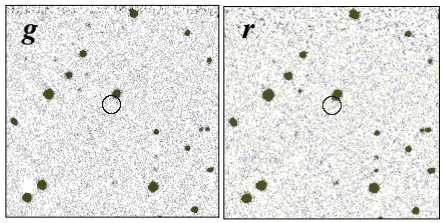
An Unidentified PQ Real-Time Event

PQOT 070519:143933+054636 *A. Drake et al., ATel 1083*

Discovery images:



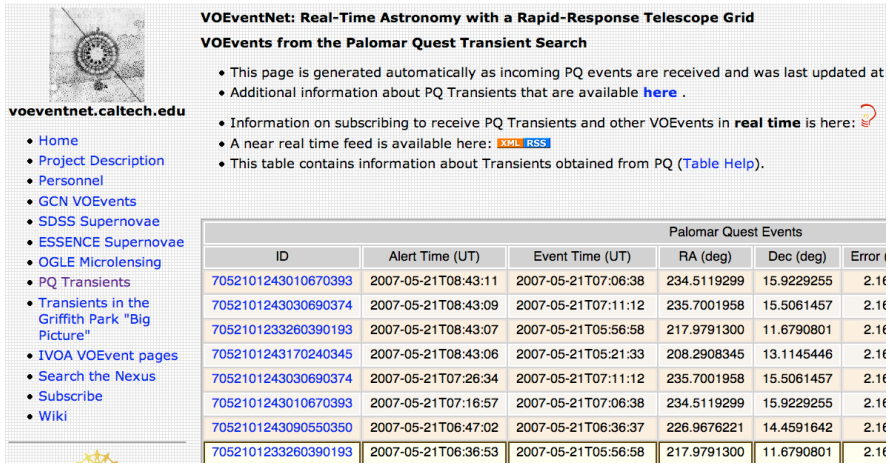
Baseline comparison:



- Initially very blue, but getting redder rapidly
- Slow fading, 0.3 - 0.4 mag/day, reached plateau
- Possible SN ?
- Followed up by *SWIFT* (*ATel 1088*) - no X-ray detection

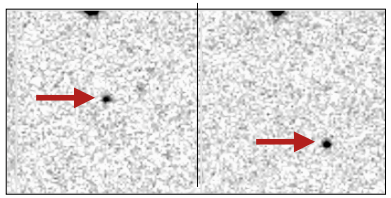
Real-Time Event Publishing & Distribution With VOEventNet

R. Williams, A. Drake, M. Graham, et al. **http://voeventnet.caltech.edu**

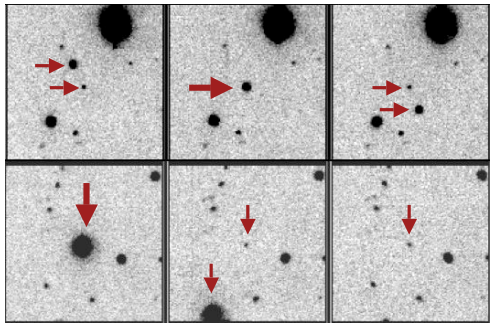


Asteroids: A Major Contaminant!

- We have many "transient" detections, but they are *mostly asteroids*
- We find **~ 1 - 3 asteroids / *deg*^{2}** down to ~ 20 - 21 mag, per epoch



Sometimes as overlaps:



Mitigation:

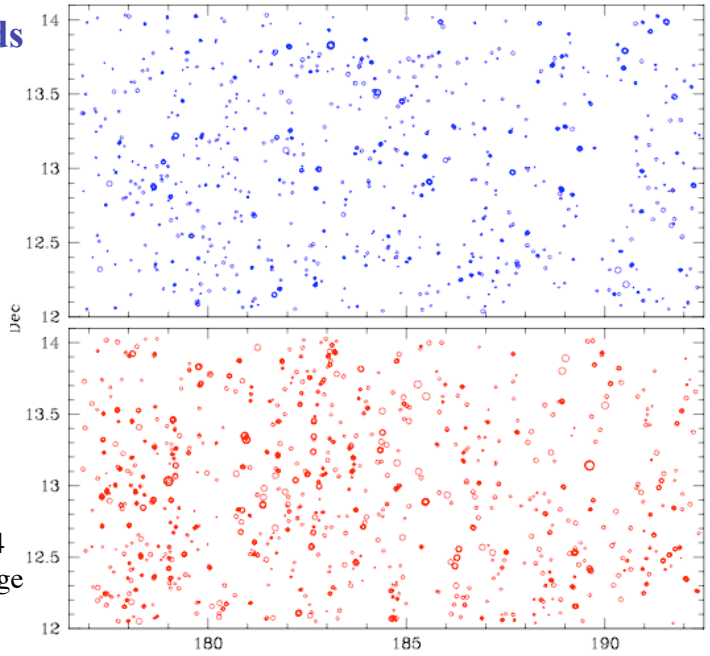
- Optimized cadence: scan and rescan the same night ~ 3 - 4^h apart
- Crossmatch to asteroid DB's (Horizons, IMCCE)
- Improved proper motions and colors

Asteroids in the BigPic area

New →

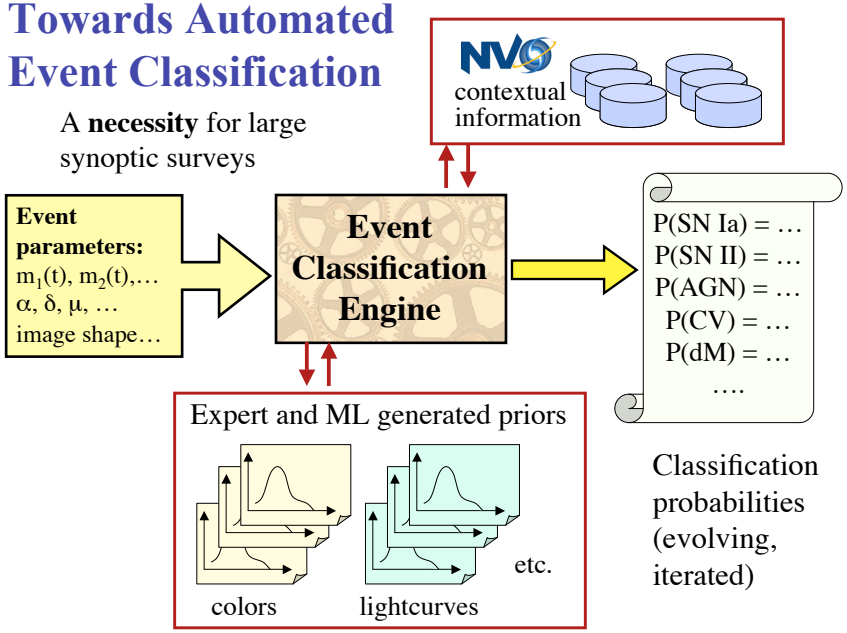
Previously known →

Area = 30.4 deg^2, average ~ 10 passes



Towards Automated Event Classification

A **necessity** for large synoptic surveys



Classification probabilities (evolving, iterated)

Some Things We Have Learned

(from DPOSS, SDSS, DLS, PQ …)

- In a single-pass snapshot survey there are ~ 10^{-2} astrophysical transients/deg^2 down to ~ 21 mag at high Galactic latitudes
- Most of the transients and variables are known types of objects; stars dominate on short time scales (~ minutes to months), AGN on longer time scales (~ years and beyond)
- Populations of as yet unidentified transients do exist; some may be new types of objects or phenomena
  - *Real-time follow-up is necessary* in order to understand them
- The quality of the ***baseline/fiducial sky*** is a key issue
  - It must be deep, clean, complete, and wavelength-matched
  - Generating a standard, dynamically evolving, annotated, multi-λ, baseline sky may be a good community (VO) project; we are developing a prototype from PQ

Some Thoughts on Time Domain Astronomy

- Scientific motivation and opportunities
  - A *very rich variety of astrophysical phenomena*: from asteroids to cosmology, extrasolar planets to extreme relativistic physics
  - Time domain can provide unique new insights
  - **Time domain astronomy ≠ small (telescope) science**
    Rather, it is intrinsically optimal for telescope systems
- Distinguish general surveys vs. dedicated experiments
  - The same synoptic survey data streams can (and do) serve multiple scientific goals
  - The same infrastructure can serve multiple follow-up needs
- Event discovery is just a start: 99% of the astrophysics is in the follow-up, and mostly in optical spectroscopy
  - **Spectroscopic follow-up will be a key bottleneck for any synoptic sky survey!**

This is a *Rapidly Evolving Field!*

- Now: data streams of **~ 0.1 TB / night, ~ 10 - 10^2 transients / night** (SDSS, PQ, various SN surveys, asteroid surveys)
- Forthcoming on a time scale ~ 1 - 5 years:
  ~ 1 TB / night, ~10^4 transients / night
  (PanSTARRS, Skymapper, VISTA, VST…)
- Forthcoming in ~ 5 - 10 years: LSST, **~ 30 TB / night, ~ 10^5 - 10^6 transients / night**

} **A major, qualitative change!**

Time-Domain Astronomy is the VO "Killer App"

Synoptic, panoramic surveys ➞ Event discovery

Rapid follow-up and multi-λ ➞ Keys to understanding

Massive data streams + rapid, automated response

➞ No humans in the loop (need machine intelligence)

What Are the Implied Technological and Methodological Needs?

- Data discovery and access mechanisms
- Data federation in both catalog and image domains
- Manipulation tools for combined data sets
- On-demand source re-extraction from panoramic imagery
- Clustering analysis tools in the catalog domain
- Visualization, visualization, visualization!
- Statistical analysis tools
- Methods to compare data and numerical simulations
- Automated robotic telescope and software systems for time domain exploration, event publishing mechanisms

… etc., etc.