Some Examples of Virtual Observatory Enabled Science

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Lecture 2

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What Are the Some Distinguishing Characteristics of the VO-Style Science?

- Data-intensive: use of massive (TB-scale and beyond) data sets
  - Poissonian errors not important, systematics dominate
- Data complexity, e.g., multi-wavelength and/or multi-scale and/or multi-epoch data sets, 100's or 1000's parameters per source, combining imaging, spectroscopy, etc.
  - Heterogeneity and visualization are key issues
- Computationally intensive
- Traditional solutions do not scale to the scope of new problems
  - Need new tools and algorithms
- Data and computing resources are generally geographically distributed
- Inherently cross-cutting in many ways…

Virtual Observatory Science Examples

- Combine the data from multi-TB, billion-object surveys in the optical, IR, radio, X-ray, etc., for:
  - Precision large scale structure in the universe
  - Precision structure of our Galaxy
- Discover rare and unusual (one-in-a-million or one-in-a-billion) types of sources
  - E.g., extremely distant or unusual quasars, brown dwarfs, etc.
- Probe the evolution of quasars discovered using different techniques (e.g., optical, radio, X-ray, etc.) over the cosmic time
- Match Peta-scale numerical simulations of star or galaxy formation with equally large and complex observations

… etc., etc.

Illustrative Example #1:

A Panchromatic Census of Active Galactic Nuclei (or: Supermassive Black Holes) in the Universe, and Their Evolution Over Cosmic Time

Why is this Important?

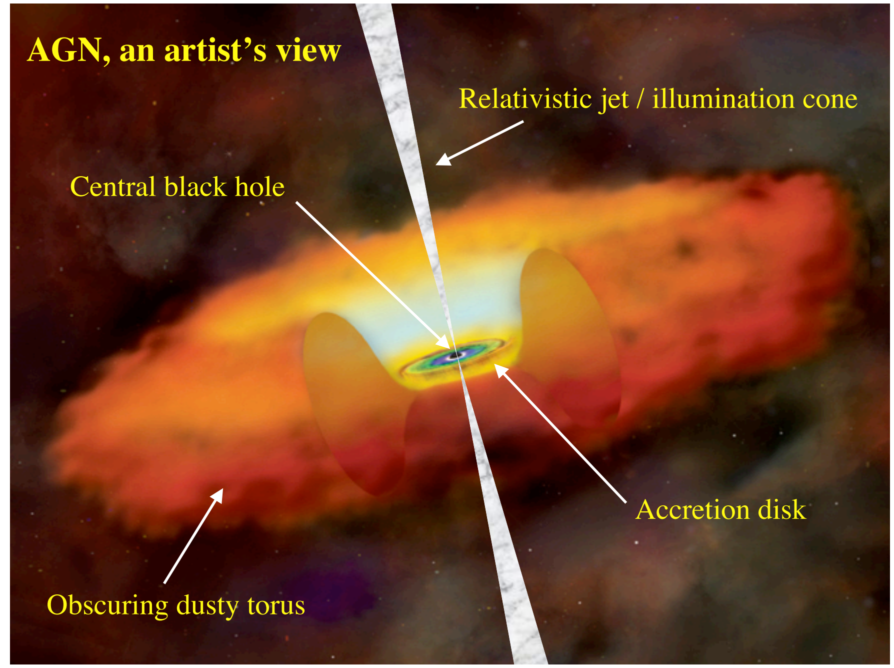
- AGN are one of the key constituents of the universe
- They are fundamentally related to galaxy formation and evolution
- They contain some very interesting relativistic physics

Why is it VO-Style?

- Each AGN discovery/study method has its own biases and selection effects; a panchromatic view would provide a more complete picture
- Large data sets are needed, as is their fusion

Quasars and AGN

- They are highly energetic manifestations in the nuclei of galaxies, believed to be powered by accretion onto massive black holes
- Empirical classification schemes and various types have been developed, on the basis of the spectra; but recently, various unification schemes have been developed to explain AGN as different appearances of the same underlying phenomenon
- Quasars/AGN are observed to evolve strongly in time, with the comoving densities of luminous ones increasing by ~ 10^3 from $z \sim 0$ to $z \sim 2$
- At z ~ 0, at least 30% of all galaxies show some sign of a nuclear activity (mostly low level); ~ 1% can be classified as Seyferts (moderately luminous), and ~ 10^{-6} contain luminous quasars
- However, we think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase



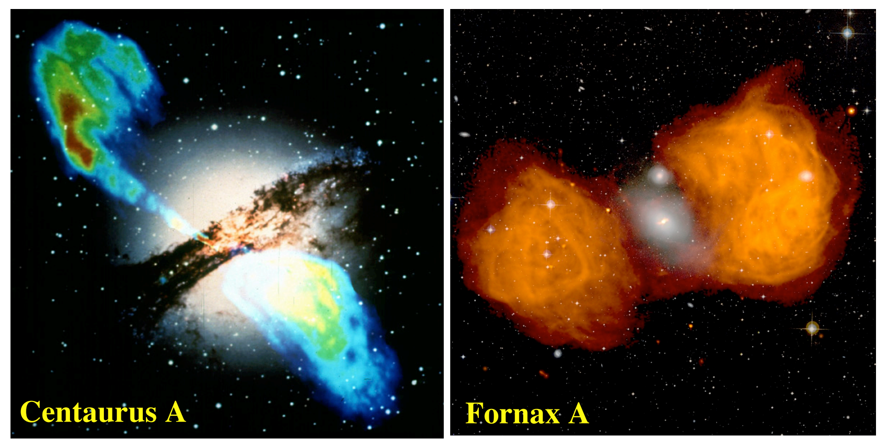
Observable Properties of AGN

- Energy emission over a broad range of frequencies, from radio to gamma rays
  - Nonthermal radio or X-ray emission is a good way to find AGN
  - Generally bluer spectra than stars: "UV excess"
  - Colors unlike those of stars, especially when modified by the intergalactic absorption
- Presence of strong, usually broad emission lines in their spectra
- Can reach large luminosities, up to ~ $10^{15}\, L_\odot$
- Strong variability at all time scales
  - Implies small physical size of the emission region
- Central engines unresolved
- Zero proper motions due to a large distances

All of these have been used to devise methods to discover AGN, and each method has its own limitations and selection effects

Radio Galaxies: Typical Examples

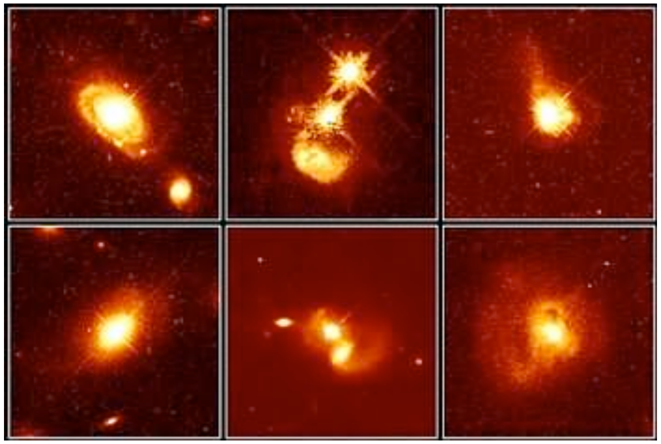
Radio overlayed on optical images



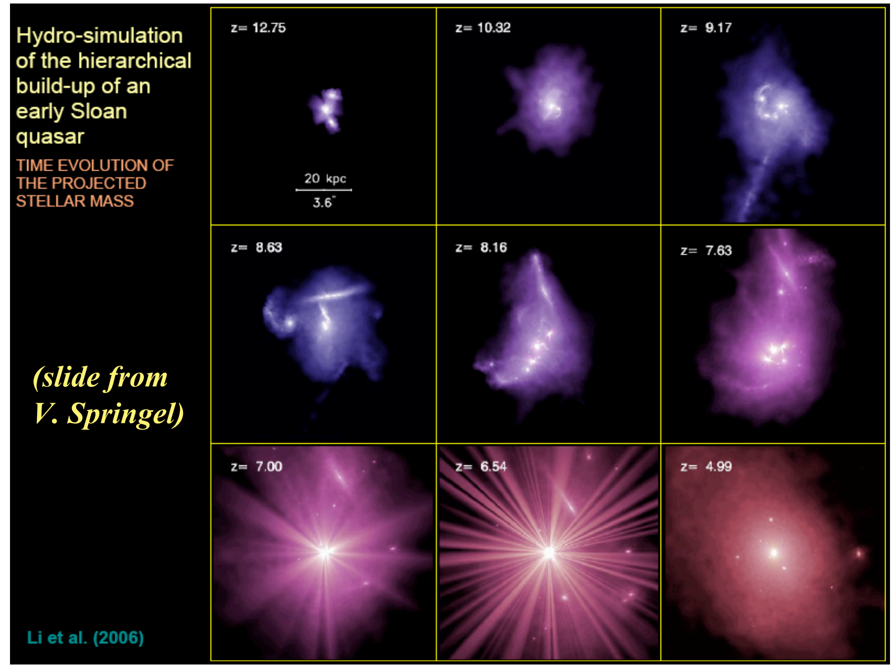
Energy stored in radio lobes can reach ~ 10^{60} - 10^{61} erg. If jet lifetime is ~ 10^8 yrs, the implied mechanical luminosities are ~ 10^{12} - 10^{13} $L_\odot$

What Makes Quasars "Quase" ?

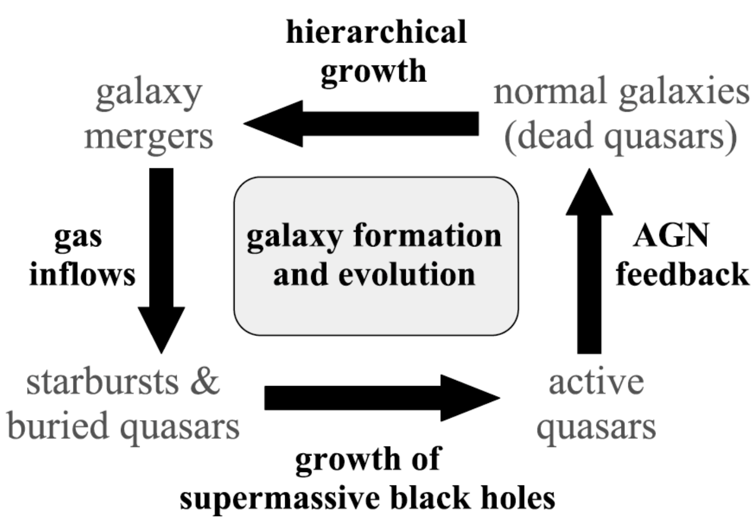
Dissipative galaxy interactions and mergers are believed to be fueling QSO activity - thus a QSO/galaxy evolutionary link



HST Images of QSO hosts



The Synergy of Galaxies and SMBHs

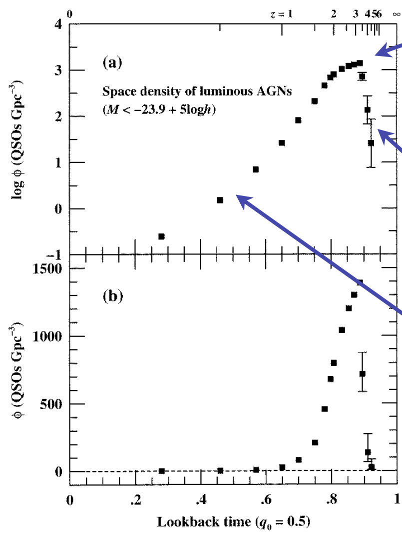


(from P. Hopkins)

Newly (re)ignited AGN can then regulate the growth and star formation in their hosts, through radiative and mechanical energy input feedback, and determine some of the fundamental properties of the host galaxies (and drive the observed correlations)

(Di Mateo, Springel, Hopkins, et al., and many others…)

The History of the Comoving Number Density of Quasars



The Peak of the Quasar Era at z ~ 2 - 3: The Maximum Merging Epoch?

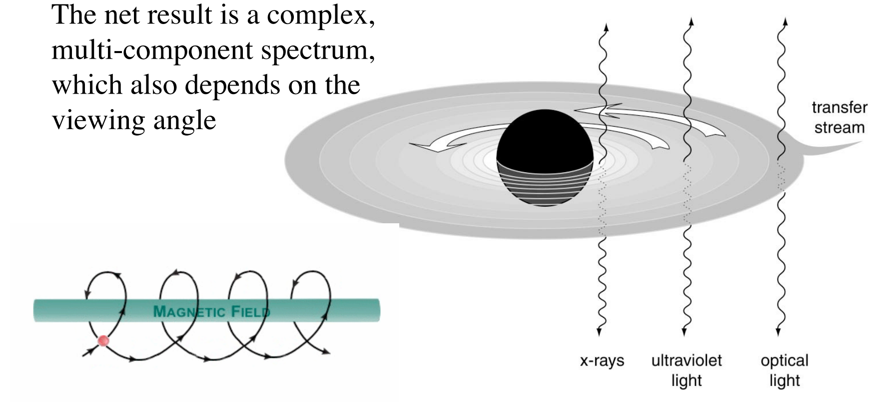
The Rise of Quasars: Initial Assembly of the Host Galaxies, Growth of the SMBHs

The Decline at Low *z*'s: Diminishing Fueling Events

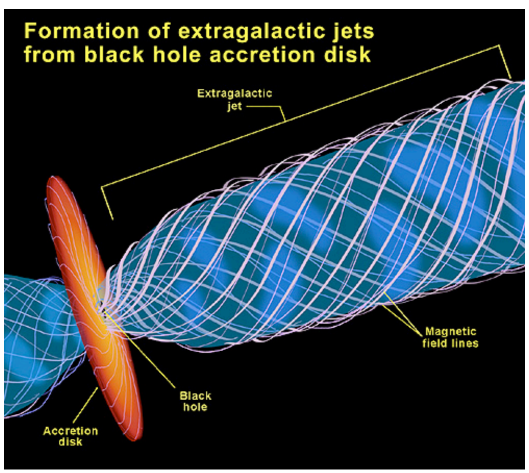
Energy Release From Central Engines

Some of it will emerge as a mix of ***thermal emission*** from various parts of the accretion disk; some emerges as a ***non-thermal synchrotron emission*** from particles accelerated by the magnetic fields embedded in the accretion disk or the BH itself

The net result is a complex, multi-component spectrum, which also depends on the viewing angle



AGN Jets: Accelerators in the Sky

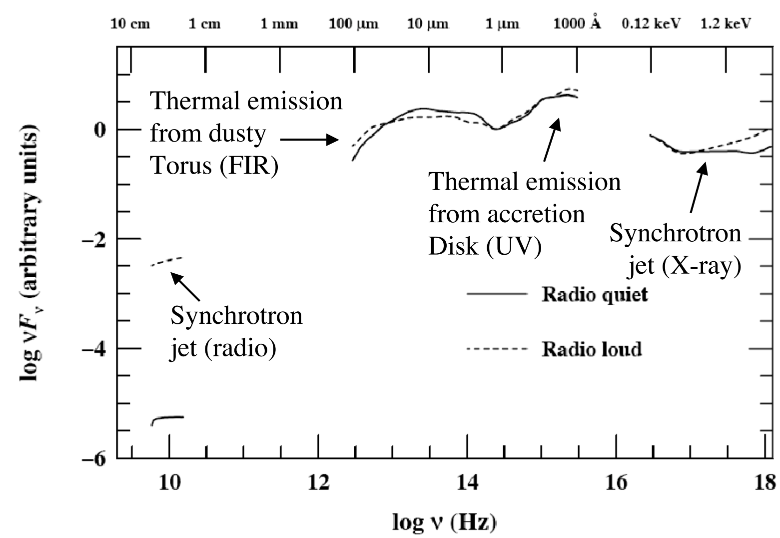


Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

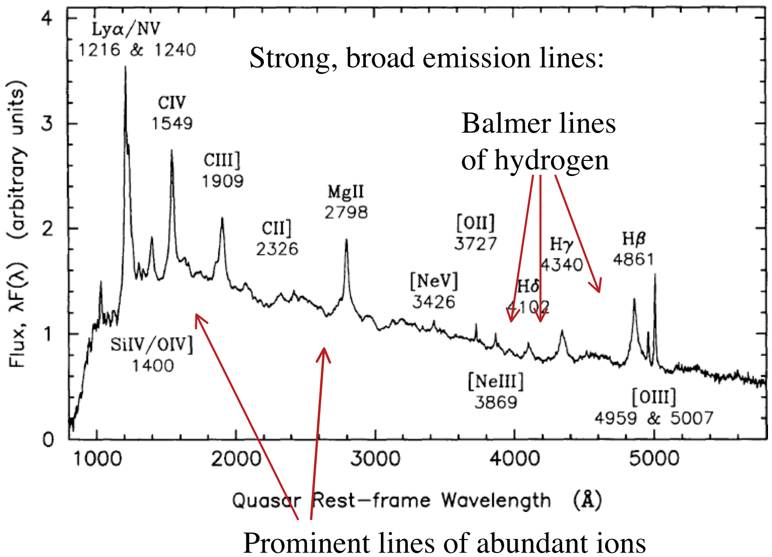
The spin turns the magnetic lines of force into well-defined and tightly wound funnels, along which charged particles are accelerated

This saps the rotational energy of the disk and/or the BH itself; aside from radiation, mechanical energy is carried by the jets to lobes

Explaining the Broad-Band Spectral Energy Distribution in AGN



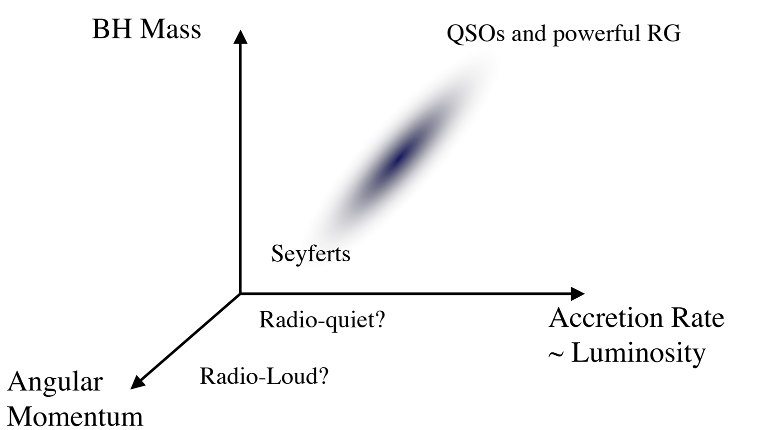
UV-Optical Spectra of Quasars



AGN Classification

- According to radio emission:
  - Radio loud: radio galaxies (RGs) and quasars; F-R types I and II
  - Radio quiet (but perhaps not entirely radio silent)
- According to optical spectrum:
  - Narrow-line RGs, Seyfert 2's; Liners
  - Broad line RGs, Seyfert 1's, quasars
- According to optical luminosity:
  - Seyfert to quasar sequence, range of radio powers, etc.
- Special types:
  - Blazars (aka BL Lac's) and optically violently variable (OVV) objects
- These classifications are largely parallel
- Some distinction may reflect real, internal physical differences, and some may be simply orientation effects
  - This is the central thesis of the AGN unification models

AGN: A Physical Classification



… but in addition, there will be some dependence on the viewing orientation

Quasar Surveys

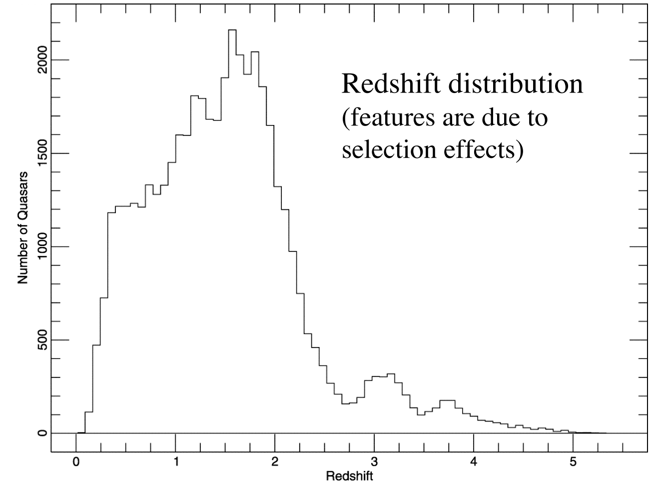
- In order to study QSOs (and other AGN), we first have to find them, in large numbers, and hopefully in a systematic fashion
  - This is especially important for studies of their evolution
- Recall that ***each discovery method has its own biases***
- Nowadays the most popular technique is to use colors to separate QSOs from normal stars
  - In optical, one can also use slitless spectroscopy, variability, and zero proper motions
- Sof X-ray (up to few keV) and optical selection find the same types of relatively unobscured objects; hard X-ray selection and FIR/sub-mm detect more obscured populations; radio finds both
- Next: multi-wavelength, survey cross-matching in the Virtual Observatory framework - will help with the selection effects

Quasar Surveys and Catalogs

- To date (~ 2007), there are ~ 100,000 QSOs catalogued, plus maybe ~ 500,000 color-selected QSO candidates
  - Most come from large systematic surveys, e.g., SDSS and 2QZ
  - Many smaller surveys in the past were done at Palomar, e.g., Palomar Green (PG), Palomar CCD (PC), Palomar Sky Survey (PSS), and now Palomar-Quest (PQ)
  - There were also many searches for emission line objects (some are AGN, some starformers), e.g., Mrk, UM, CSO, KISS, etc.
  - Older heterogeneous catalogs include Hewitt & Burbidge, and Veron & Veron-Cetty compilations
- There are now also > 10^5 X-ray sources catalogued (most are probably powered by AGN)
- There is also probably close to ~ 10^6 radio sources in various catalogs, and many (most?) of them are powered by AGN
  - Major radio surveys include: Parkes (PKS), Green Bank (GB), NRAO VLA Sky Survey (NVSS), Faint Images of Radio Sky at Twenty cm (FIRST), etc.

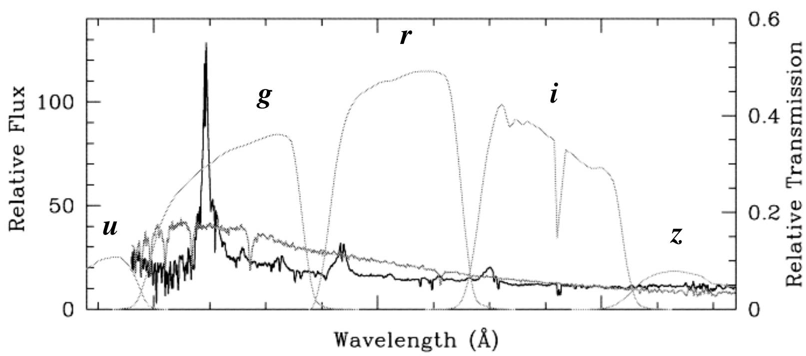
SDSS Quasar Survey

The largest QSO survey to date. Uses optical colors to select QSO candidates, reaching out to z ~ 6.4



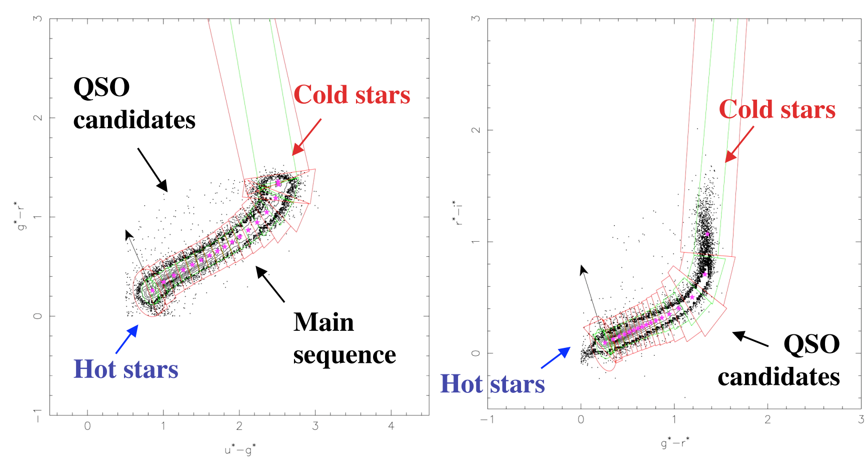
SDSS Quasar Survey

Ratios of fluxes in different survey filters (=colors) are in general different for QSOs and for stars - even though both look "stellar" on the images. The colors will change with redshift as different features (emission lines, continuum breaks) shift from one filter to another. For each redshift range, a different filter combination would be the optimal one for QSO selection



SDSS Quasar Survey

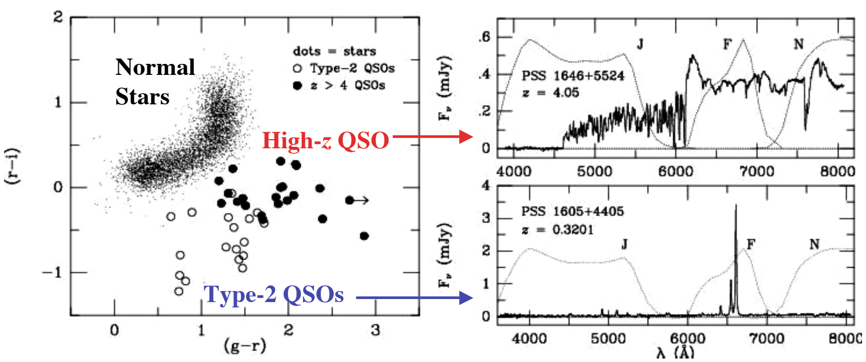
Examples of color selection of QSOs, as outliers away from the stellar locus

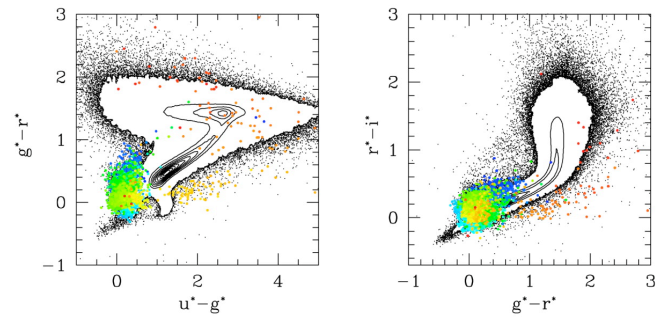


Using Colors to Find Quasars

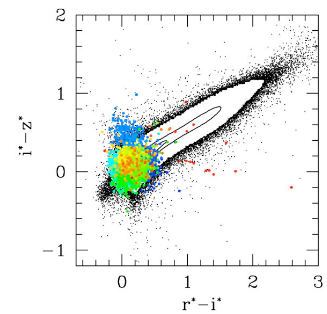
At $z > 3.5$ - 4, absorption by the intergalactic hydrogen makes QSOs very red in the blue part of the spectrum, while their retain their intrinsic blue colors in the red part of the spectrum …

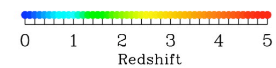
However, presence of strong emission lines can also affect colors





Black dots: stars and galaxies





Where the QSOs (colored dots) are as a function of redshift in each color space

What Should VO Survey for AGN Do?

- Do a multicolor selection using federated surveys from UV (e.g., GALEX), optical (SDSS, PQ,…), to NIR (2MASS, UKIDSS…)
  - Calibrate selection using spectroscopically confirmed samples
- X-ray source IDs
- Radio source IDs, as a function of radio morphology and spectral index
- Mid-IR and FIR selected samples from Spitzer, sub-mm obs., etc.

} Test for the extent and relative contribution of optically obscured QSO populations

- Federate all samples and evaluate various selection effects, as a function of redshift, luminosity, etc.
- Evaluate corrected comoving densities, luminosity functions, and obscured fractions as functions of redshift
- Correlate with large-scale environments using galaxy catalogs

Illustrative Example #2: Clusters of Galaxies, Their Evolution, and Cosmological Uses

Why is this Important?

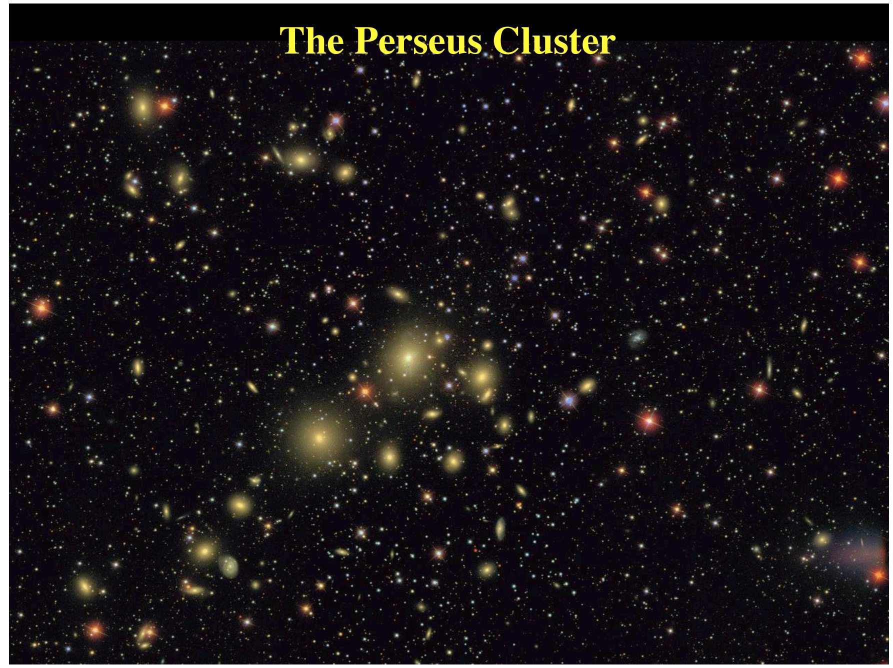
- Clusters are a major element of the large-scale structure of the universe, and the largest virialized structures
- They are fundamentally related to galaxy formation and evolution
- They can be used as cosmological probes

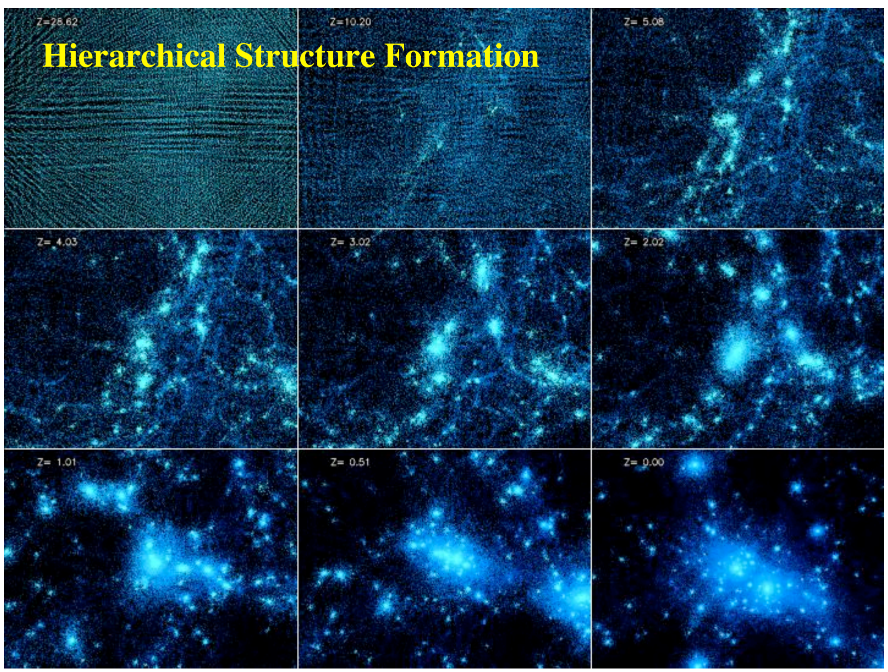
Why is it VO-Style?

- Each cluster discovery/study method has its own biases and selection effects; a panchromatic view would provide a more complete picture
- Large data sets are needed
- Compare with numerical simulations to gain physical insights

Clusters of Galaxies

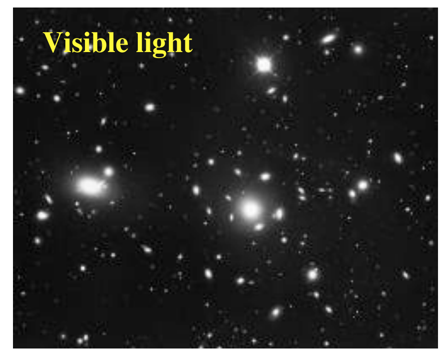
- Clusters are perhaps the most striking elements of the LSS
- Typically a few Mpc across, contain ~ 100 - 1000 luminous galaxies and many more dwarfs, masses ~ 10^{14} - 10^{15} $M_{\odot}$
- Gravitationally bound, but may not be fully virialized
- Filled with hot X-ray gas, mass of the gas may exceed the mass of stars in cluster galaxies
- Dark matter is the dominant mass component (~ 80 - 85%)
- Only ~ 10 - 20% of galaxies live in clusters, but it is hard to draw the line between groups and clusters, and at least ~50% of all galaxies are in clusters or groups
- Clusters have higher densities than groups, contain a majority of E's and S0's while groups are dominated by spirals
- Interesting galaxy evolution processes happen in clusters

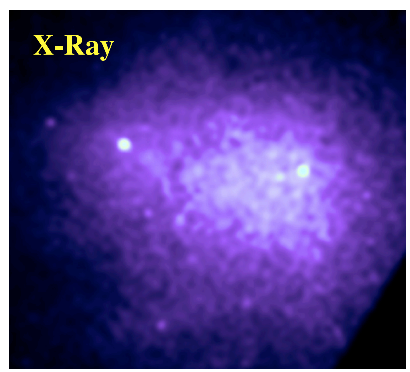


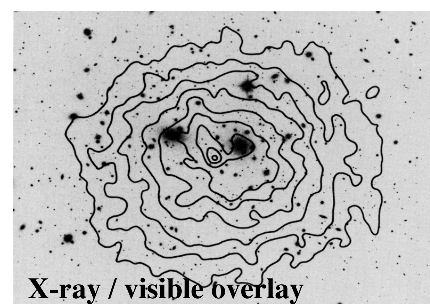


The Coma Cluster

- Nearest rich cluster, with >10,000 galaxies
- Distance ~ 90 Mpc
- Diameter ~ 4-5° on the sky, 6-8 Mpc







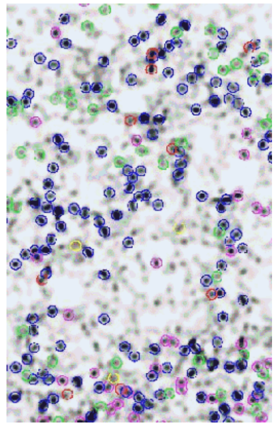
Surveys for Galaxy Clusters

Galaxy clusters contain galaxies, hot gas, and dark matter

Can survey for each of these components using observations in different wavebands:

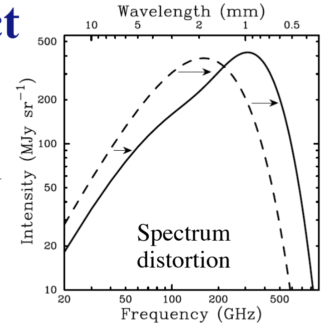
1. Optical

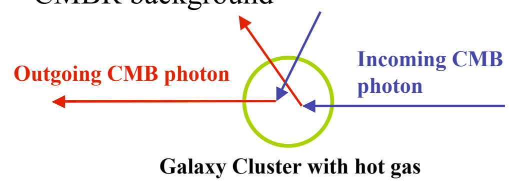
- Look for an overdensity of galaxies in patches on the sky
- Can use color information (clusters contain many red elliptical galaxies)
- At higher redshifts, use redder bands (IR)
- **Disadvantages:** vulnerable to projection effects, rich cluster in the optical may not have especially high mass

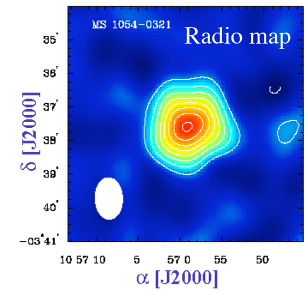


Synyaev-Zeldovich Effect

- Clusters of galaxies are filled with hot X-ray gas
- The electrons in the intracluster gas will scatter the background photons from the CMBR to higher energies and distort the blackbody spectrum
- This is detectable as a slight temperature dip or bump in the radio map of the cluster, against the uniform CMBR background







Surveys for Galaxy Clusters

2. X-Ray

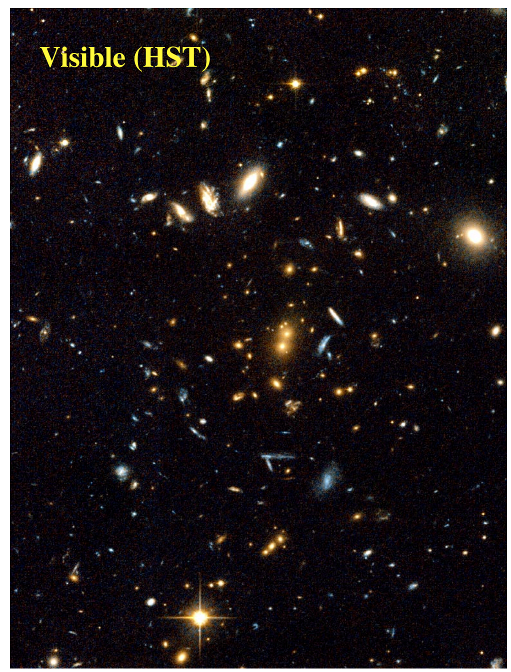
- Galaxy clusters contain hot gas, which radiates X-ray radiation due to bremsstrahlung
- Advantage: bremsstrahlung scales with density and temperature as $n^2T^{1/2}$ - i.e. *quadratically* in the density. ***Much less*** vulnerable to accidental line-of-sight projection effects
- **Disadvantage:** still not detecting clusters based on mass

3. Sunyaev-Zeldovich effect

- Distortion of the CMB due to photons scattering off electrons in the cluster. Mass weighted measure, but really detects hot gas, not dark matter, and subject to messy hydrodynamics

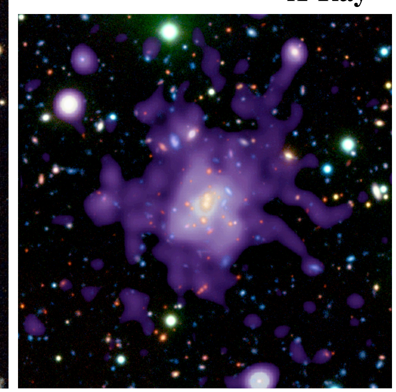
4. Weak Gravitational Lensing

- Selection based on mass. Difficult observationally



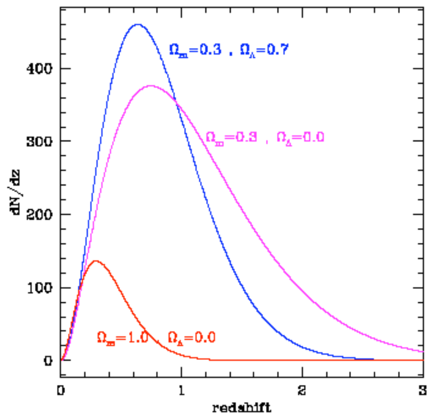
One of the most distant clusters now known, 1252-2927 (z = 1.24)

X-Ray



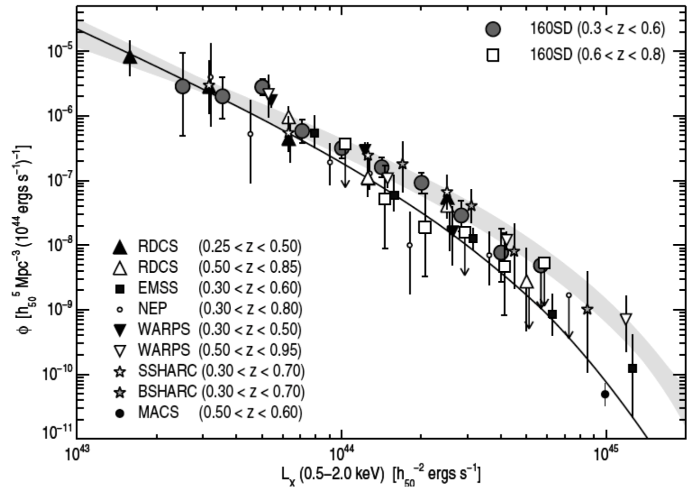
Clusters as Cosmological Probes

- Given the number density of nearby clusters, we can calculate how many distant clusters we expect to see
- In a high density universe, clusters are just forming now, and we don't expect to find any distant ones
- In a low density universe, clusters began forming long ago, and we expect to find many distant ones

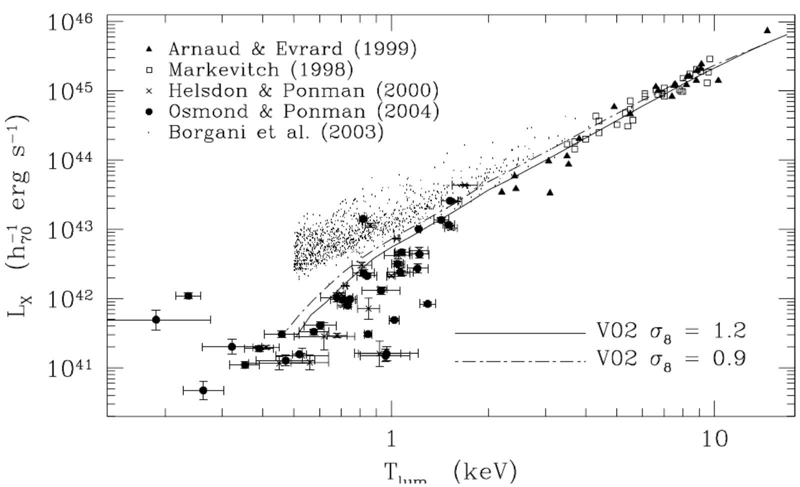


- Evolution of cluster abundances:
  - Structures grow more slowly in a low density universe, so we expect to see less evolution when we probe to large distances

Evolution of the Cluster X-Ray Luminosity Function



In the process, one also discovers various interesting correlations, which can provide new insights into cluster physics and evolution (and selection effects?)



What Should VO Cluster Survey Do?

- Discover samples of clusters using the variety of approaches:
  - Projected overdensities, using different algorithms: adaptive kernel, matched filters, Voronoi tesselation, red sequence, cut & enhance …
  - X-ray selection
  - S-Z effect (from CMBR obs.)
  - Bent radio sources
  - Weak lensing maps
- Federate overlapping samples and evaluate selection effects for each method, using a joint sample
- Interpret them as functions of cluster properties, e.g., richness, dynamical state, redshift, etc.
- Apply corrections and derive cluster luminosity and mass func's and their evolution is redshift
- Use for cosmological tests, and as a probe of cluster formation and evolution (compare with numerical simulations)

Illustrative Example #3:
A Multi-Dimensional Portrait of Our Galaxy

Why is this Important?

- Understanding our large-scale cosmic home: its structure, dynamics, chemical composition, star formation, etc.
- Fossil evidence of our Galaxy's formation and evolutionary processes, presumably applicable to all galaxies

Why is it VO-Style?

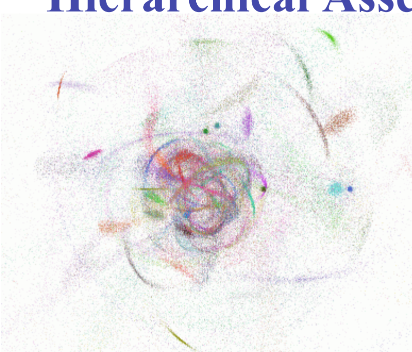
- It requires a very broad range of data sets and data types, and their fusion, including but not limited to:
  - Panoramic imaging: optical, NIR to study stars; multi-epoch to get the proper motions
  - Panoramic imaging: radio (continuum and 21 cm) and FIR (dust) to study the ISM and star formation
  - Spectroscopy: stars (radial velocities and chemical abundances) and gas (global kinematics, physical state)

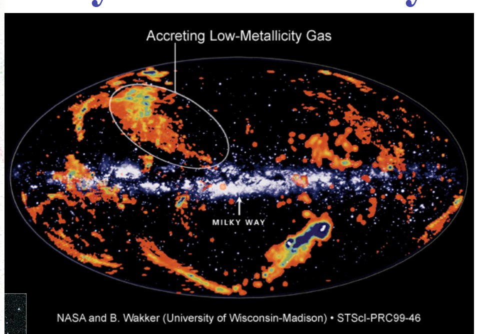
Constructing a Phase Space Portrait of the Milky Way

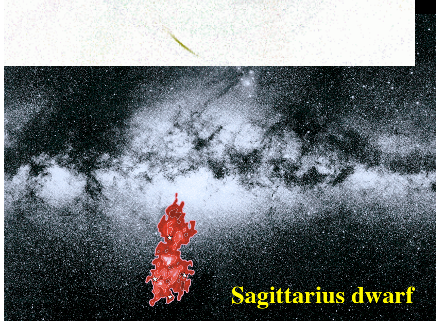
- Use stellar colors in the visible (e.g., SDSS) and IR (e.g., 2MASS) bands to simultaneously solve for stellar type and reddening, and thus absolute magnitude and distance ➙ 3-D distribution of stars
- Combine with FIR and molecular gas maps to derive the 3-D distribution of dust and cold gas
- Kinematics of disk gas from H I 21-cm line and molecular lines
- Stellar proper motions + radial velocities ➙ stellar kinematics
- Kinematics of the halo/infalling gas from absorption spectra
- Distribution of the dark matter from stellar and gas motions
- Separate different stellar population and kinematical components
- Correlate with chemical abundances from spectroscopy

➙ ***Kinematical and density structure of our Galaxy, its formation***

Hierarchical Assembly of Our Galaxy

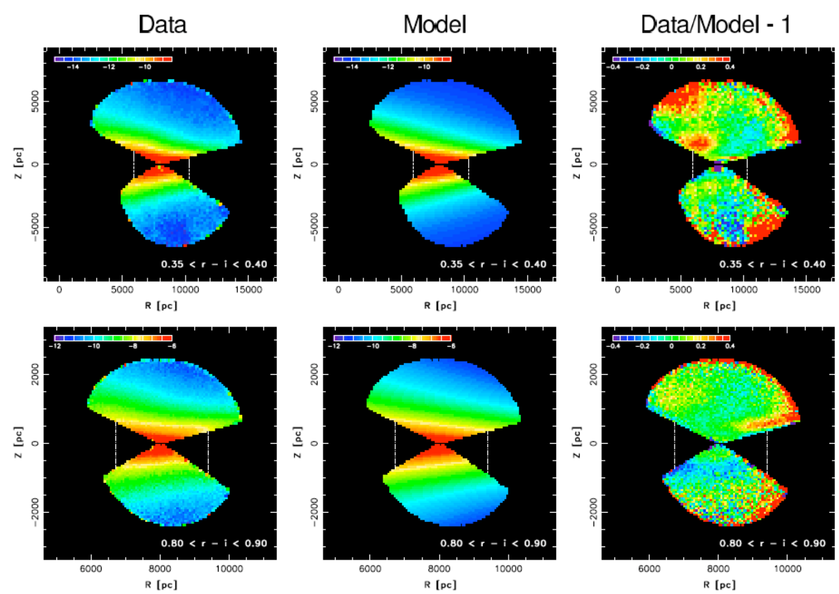






Disrupted dwarf satellites and stellar tidal streams provide a direct evidence for hierarchical assembly of the halo/spheroid. High-velocity H I clouds and the Magellanic Stream as well.

Evidence From SDSS Star Counts



Juric et al. 2006

Illustrative Example #4:

Astrophysical Foregrounds to Cosmic Microwave Background

Why is this Important?

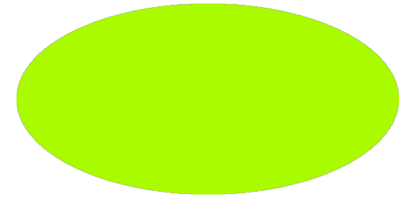
- One of the key cosmological and early-universe probes
- Foreground sources (compact and extended) distort the CMBR signal and inject energy to it
- Essential for inerpretation of data from WMAP, Planck, etc.

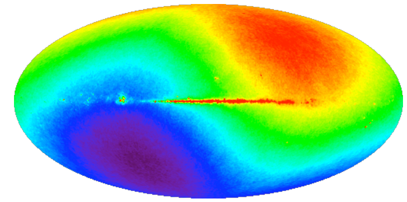
Why is it VO-Style?

- It requires large, complete samples of galaxies, clusters, AGN, diffuse emission in our own Galaxy (radio to FIR to X-ray), their fusion and detailed modeling in order to separate the cosmological signal from the foreground effects

Cosmology With CMBR

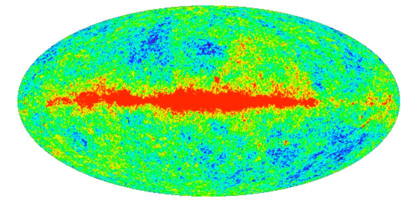
The CMBR sky from WMAP ➡

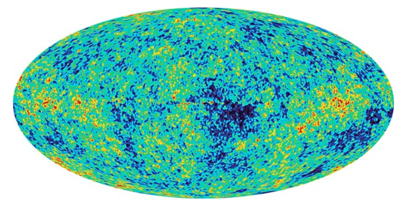




⬅ Enhance the contrast by 10^3

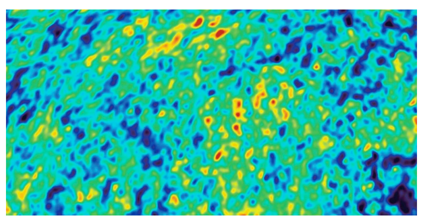
Remove the dipole and enhance the contrast to 10^5 ➡





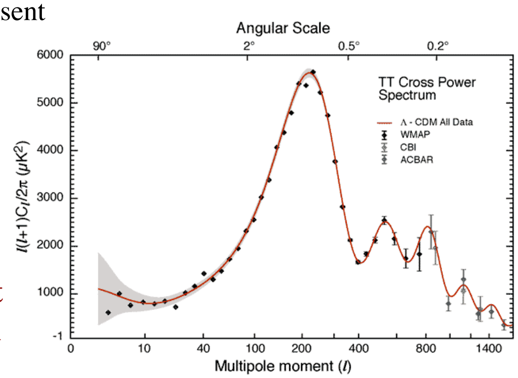
⬅ Remove the Galaxy, the contrast is 10^5 and see the primordial density fluctuations

A characteristic fluctuation scale exists of ~ 1 degree



This corresponds to the size of the particle horizon at the decoupling, and thus to the longest sound wavelength which can be present

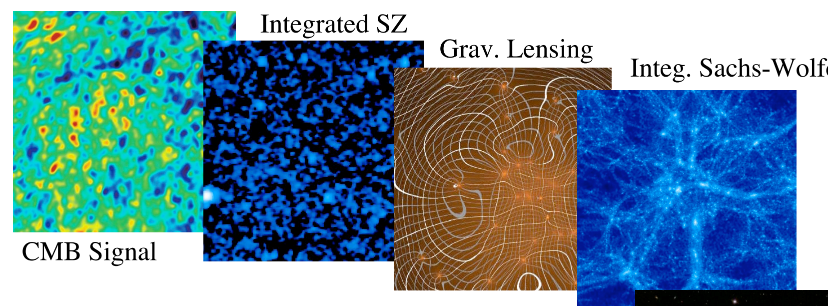
This is quantified as an angular fluctuation power spectrum:

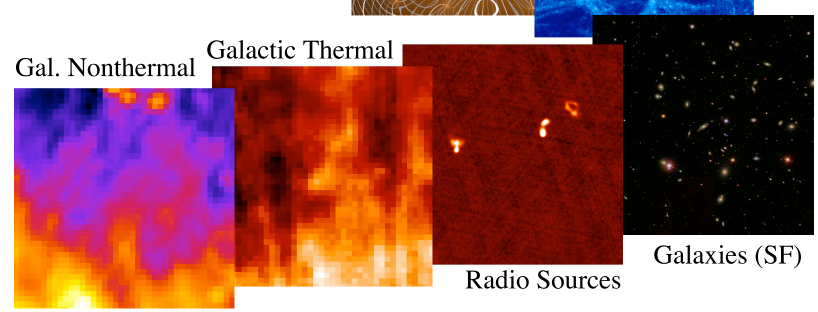


WMAP, angular power spectrum, Bennett et al. 2003

However, in order to get to the pure cosmological signal, one has to first understand and remove the various astrophysical foregrounds

Understanding the CMBR Foregrounds

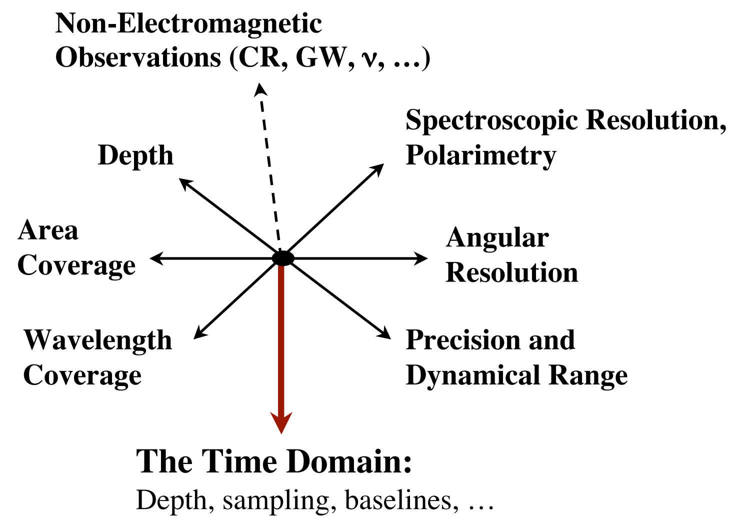




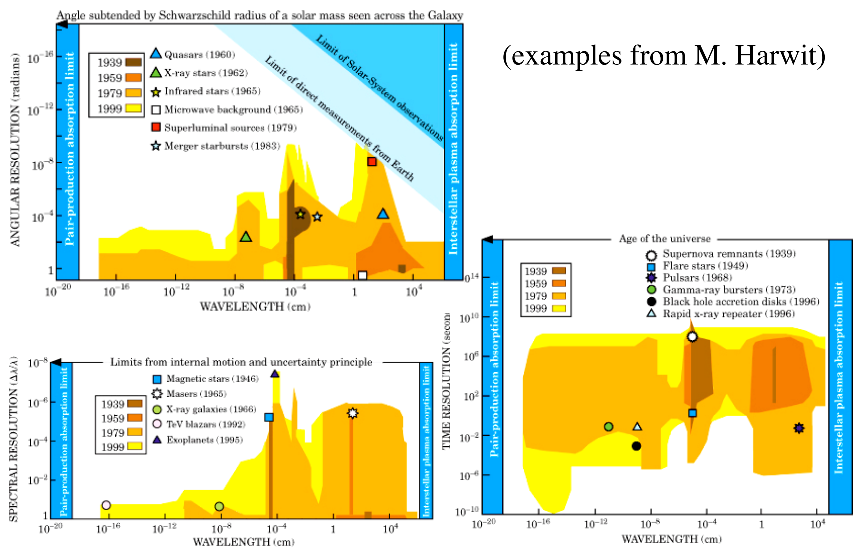
A Generic Example:
Exploration of Observable Parameter Space

- 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

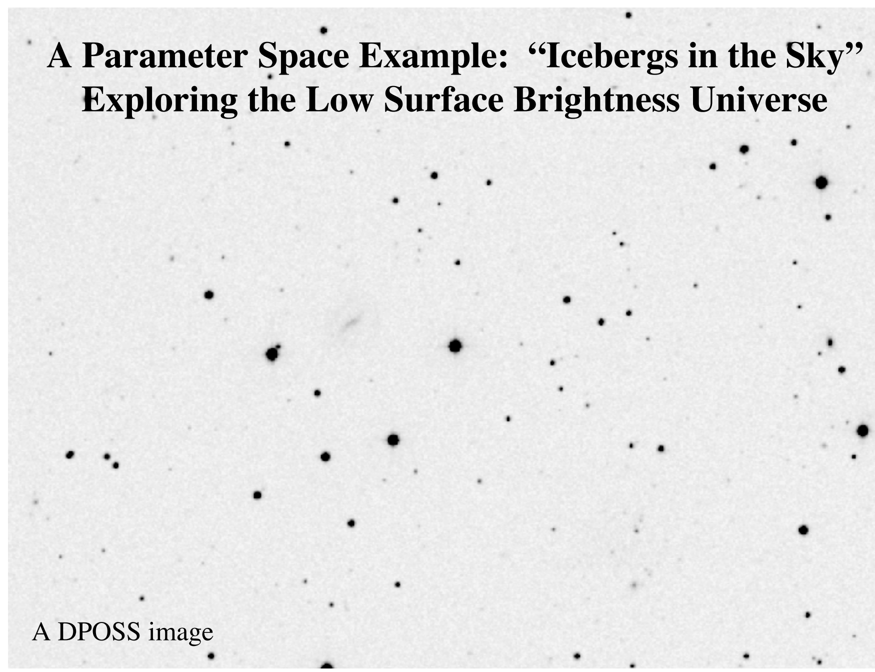


Covering the Observable Parameter Space

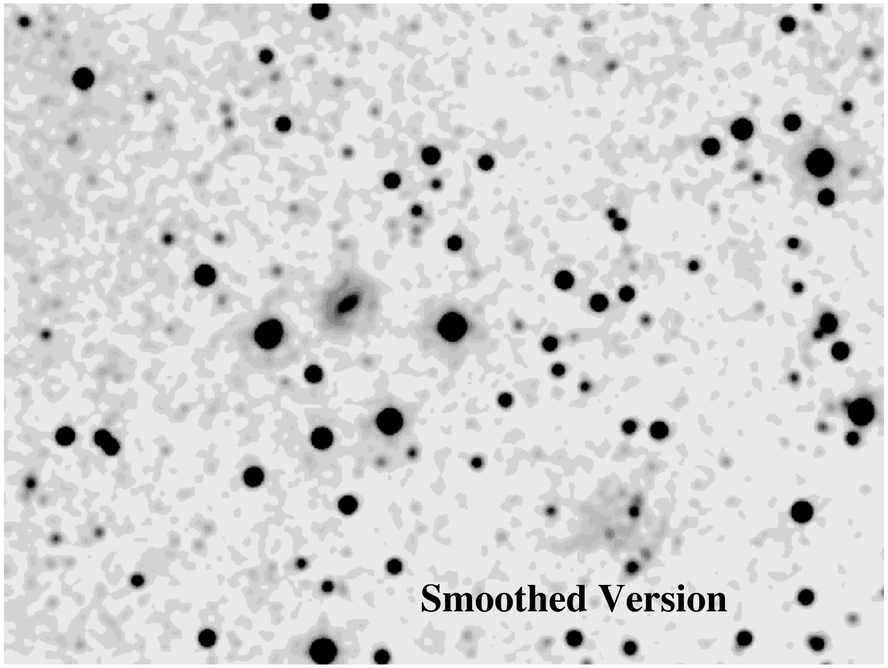


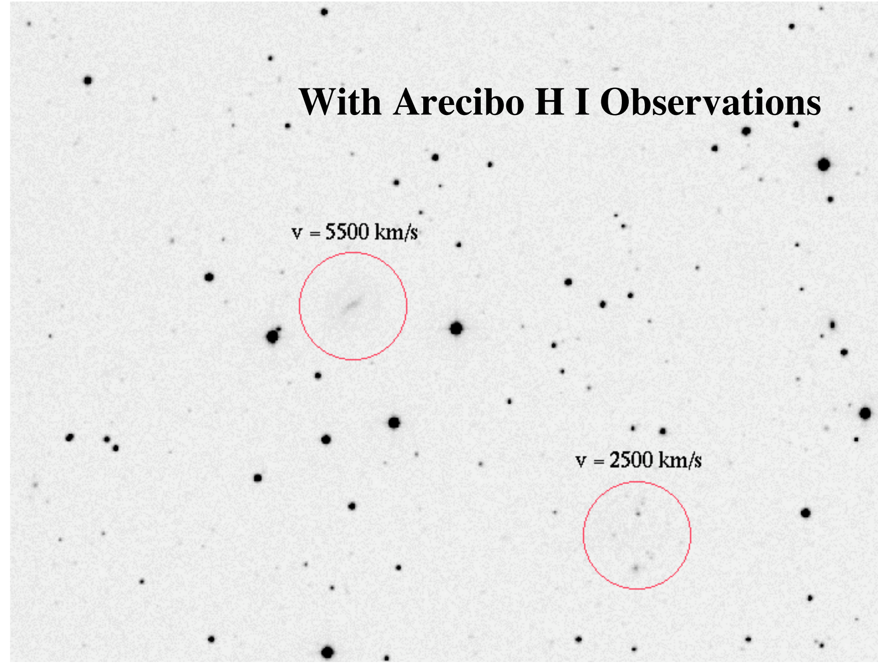
(examples from M. Harwit)

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

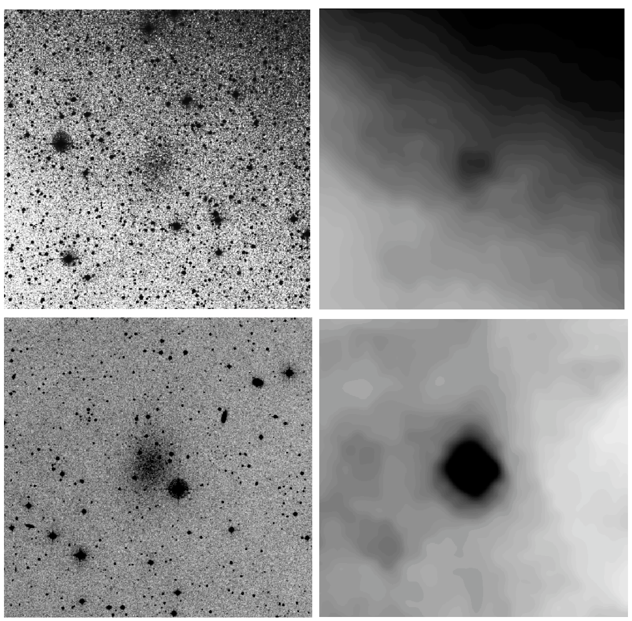


A DPOSS image





Background Enhancement Technique demonstrated on two known M31 dwarf spheroidals

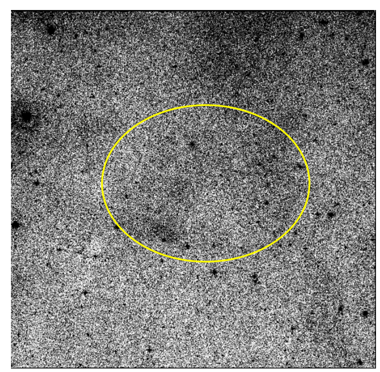


(Brunner et al.)

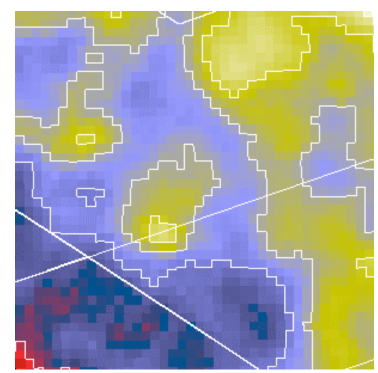
Exploring the Low Surface Brightness (Low Contrast) Universe

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

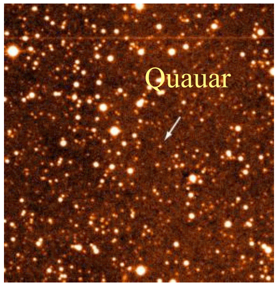
Rapid follow-up and multi-λ ➔ keys to understanding

Things That Move in Our Solar System

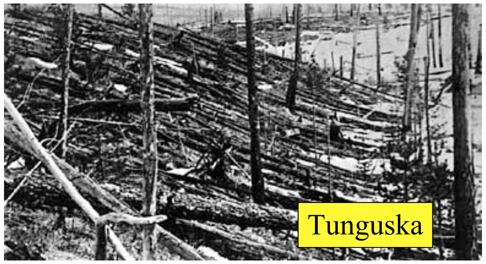
Dwarf planets and KBOs

M. Brown et al.

NEAT, Catalina, etc.



Killer Asteroids



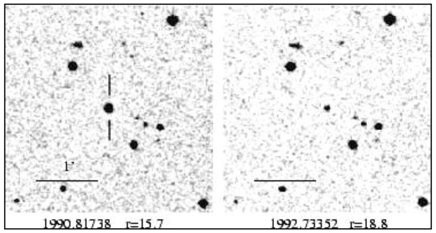
Donald Rumsfeld's Epistemology

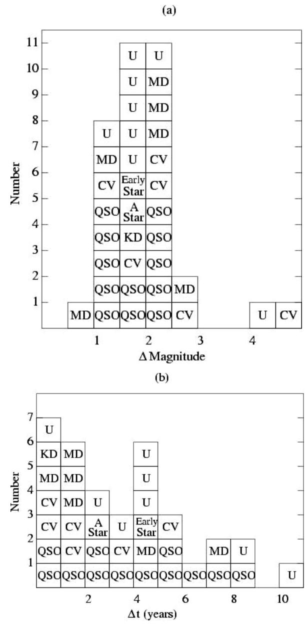
There are known knowns,
There are known unknowns, and
There are unknown unknowns

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?)

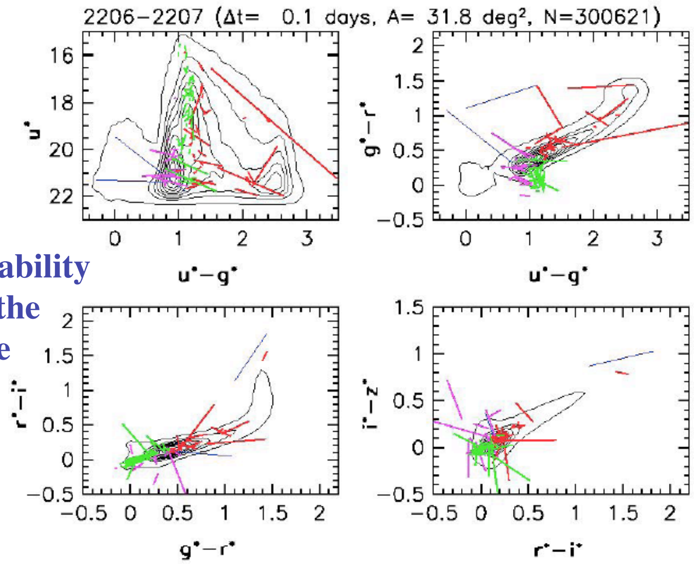
DPOSS Pilot Search for Highly Variable Objects
(using plate overlaps)





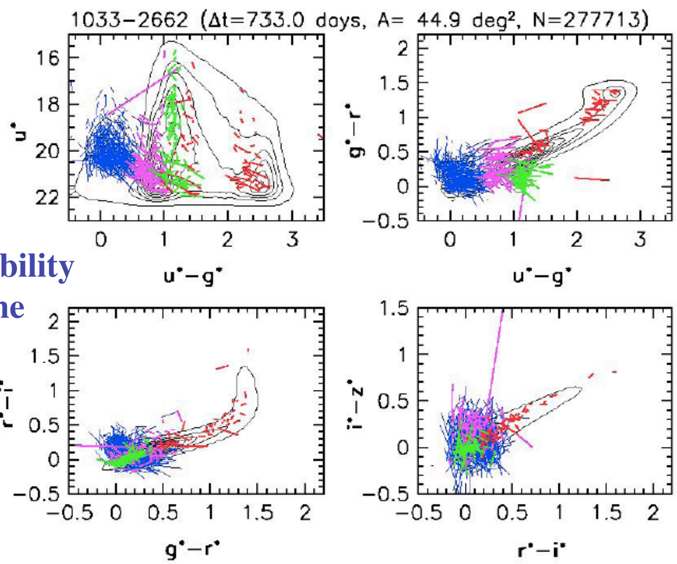
Spectroscopic IDs:
35% QSOs (1/2 radio loud)
18% CVs
18% M dwarfs
6% Earlier type stars
23% Unidentified (likely BL Lacs?)

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!

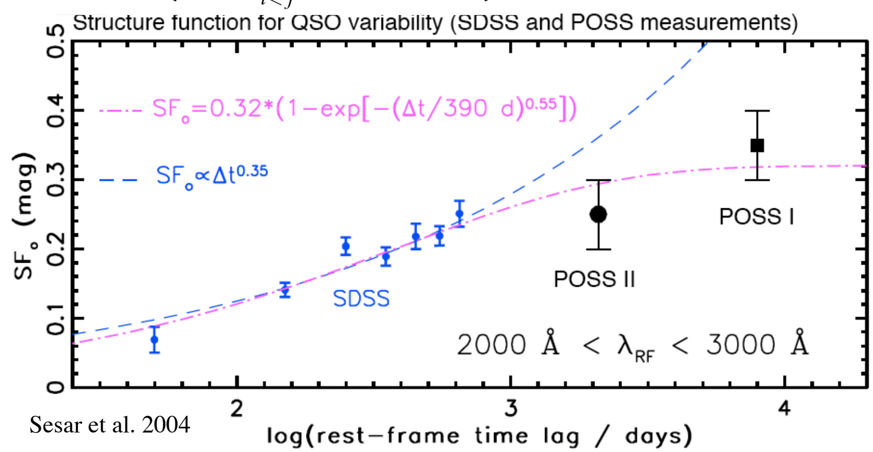


SDSS variability studies in the color space

Quasar Variability

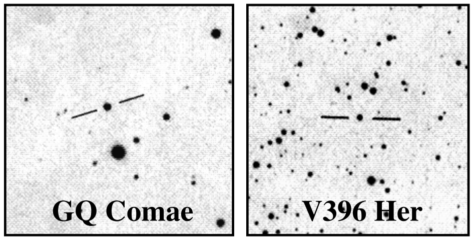
Typically quantified using the structure function,

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



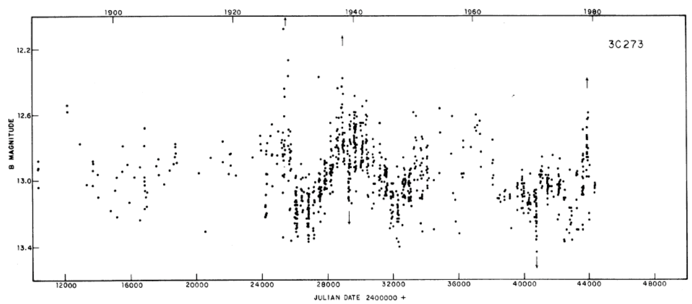
Sesar et al. 2004

How Quasars Were *Not* Discovered

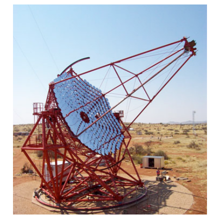


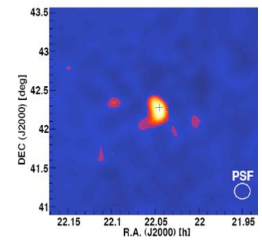
Noted as variable sources even in the 19th century, but … ***misclassified as variable stars***

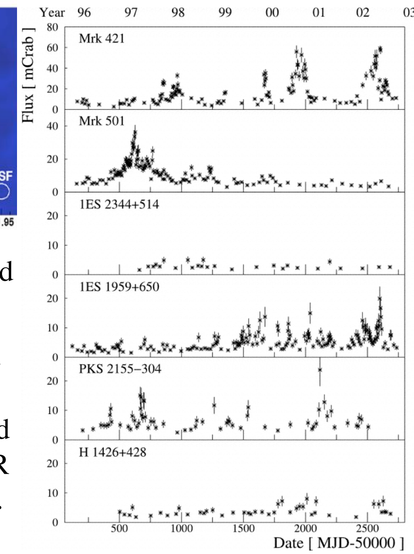
Historical (archival) lightcurve of 3C273, starting from the 1880's …



Beamed AGN: Blazars (Cosmic Accelerators)





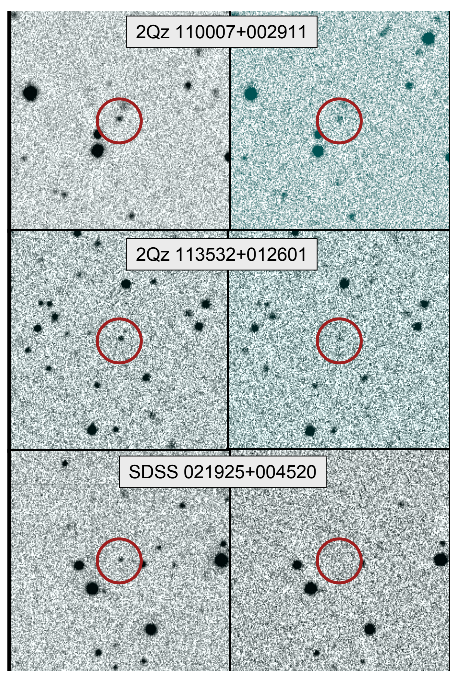


Presumed sources of TeV γ-rays and possibly some UHECRs

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

PQ Variability of AGN and Blazars

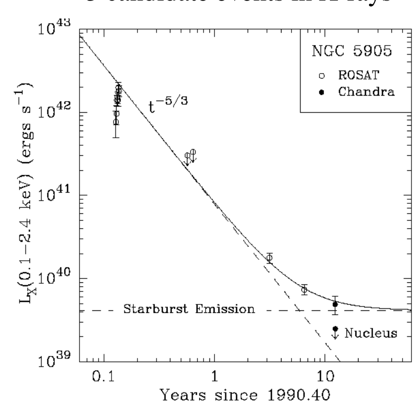
- Characterize the high-ampl. variability of known QSOs and especially Blazars
- Use to devise a pure optical variability (and color?) selection of Blazars
- Are we missing a population not found by the traditional radio or X-ray selection?
- A good multi-λ synergy with GLAST, TeV γ-ray, and UHECR surveys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



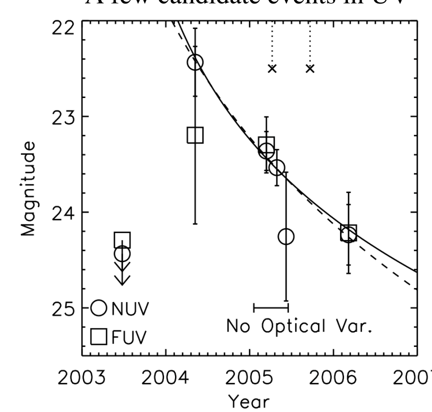
Accretion Flares From Otherwise Quiescent SMBHs

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

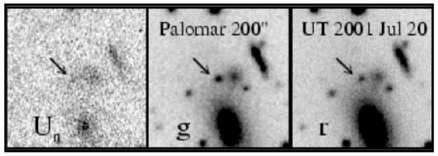
Komossa et al. (Rosat)
5 candidate events in X-rays

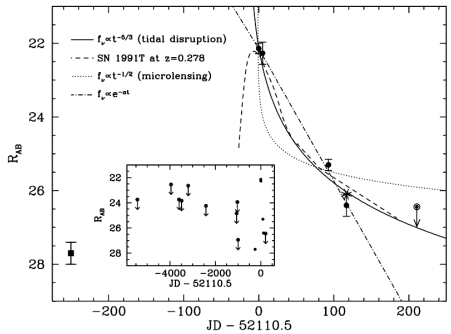


Gezari et al. (GALEX)
A few candidate events in UV



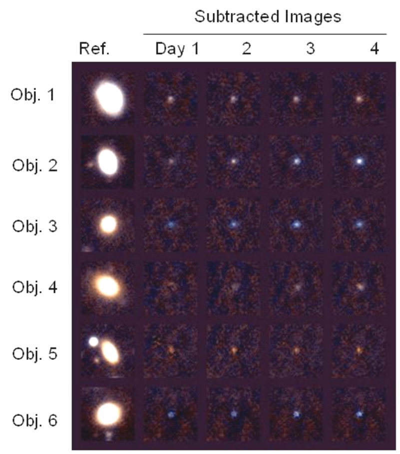
PALS-1 : A possible gravitationally magnified U-band dropout (z ~ 3.3?) behind Abell 267 (Stern et al.)





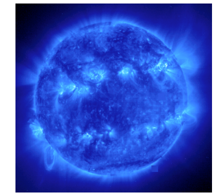
Variable sources in the centers of apparently normal galaxies at z ~ few tenths

(Totani et al., SUBARU)



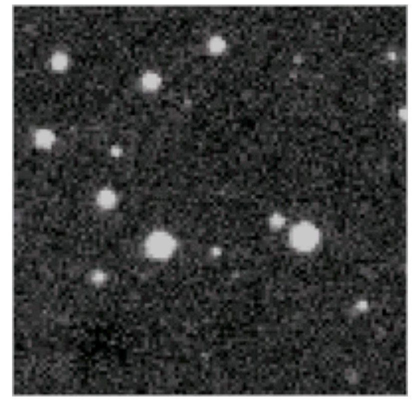
Flaring M Dwarfs

(a vermin of the synoptic sky surveys?)

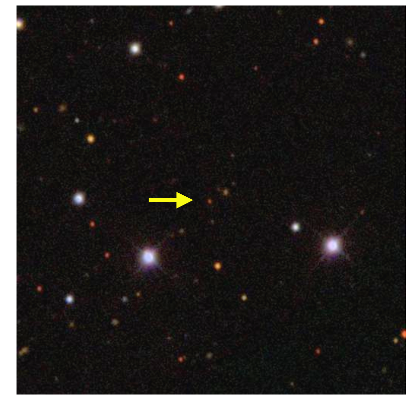


(just like the Solar flares, but much, much bigger)

Lynx OT (Catalina Sky Survey)



SDSS Counterpart

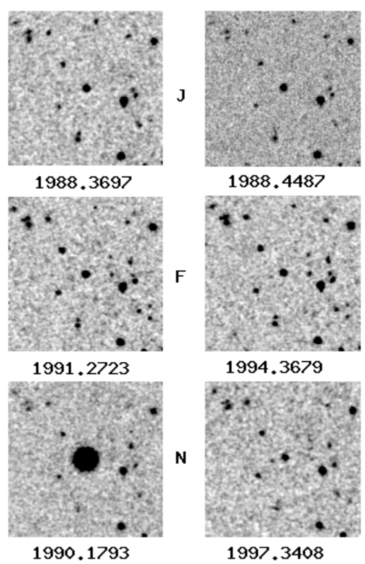


Megaflares From Normal (?) Stars

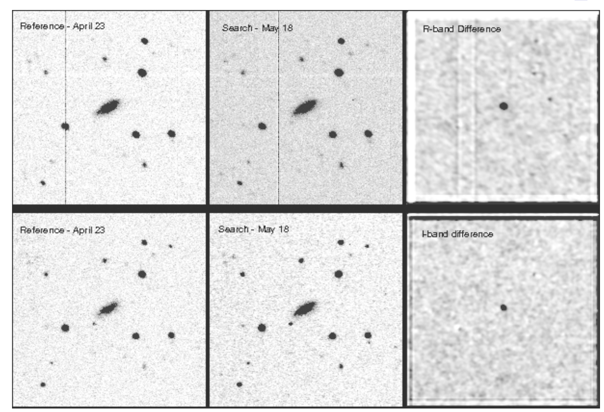
An example from DPOSS:
A normal, main-sequence star which underwent an outburst by a factor of > 300.

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

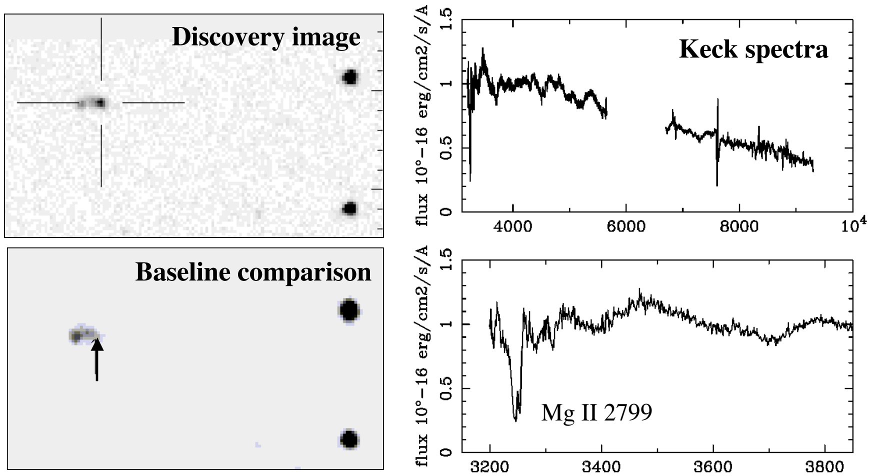
(Using the image subtraction technique)

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

Discoveries of Peculiar Supernovae

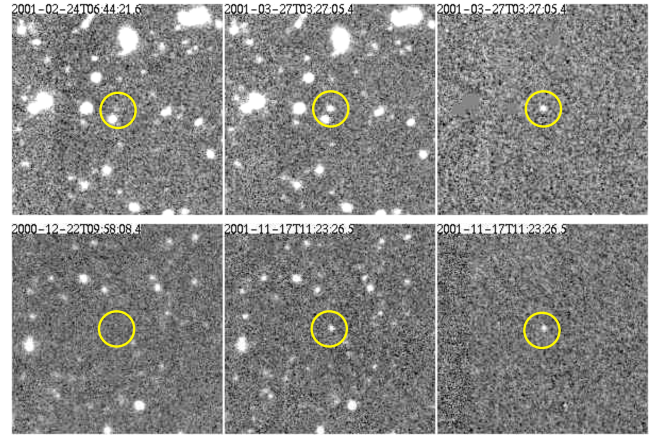
OT 060520:143933+054636, SNF discovery, Caltech follow-up

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!**

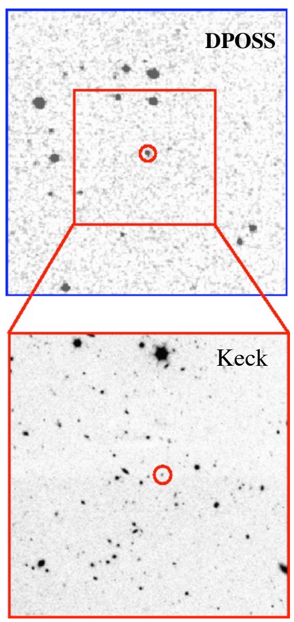
Optical Transients in DPOSS

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.

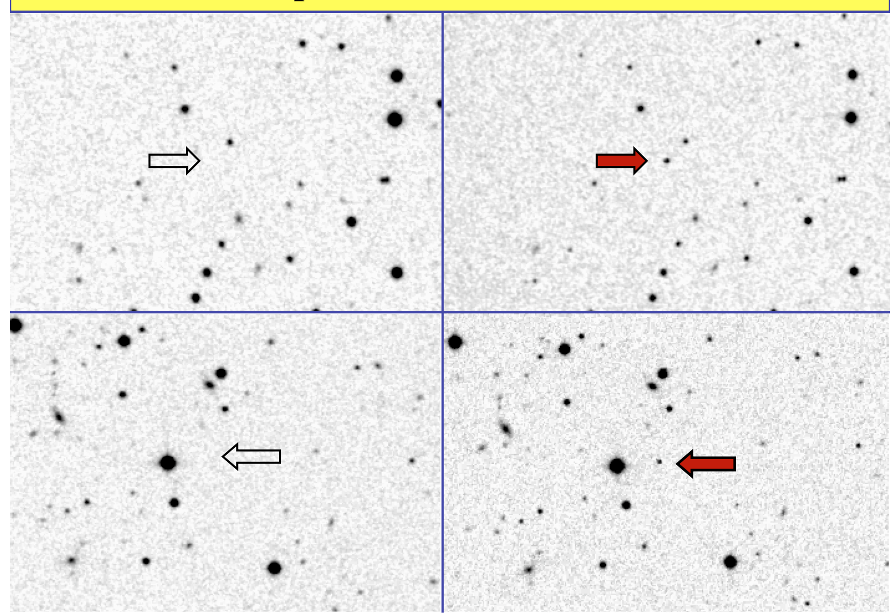
How many do we expect to see?

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

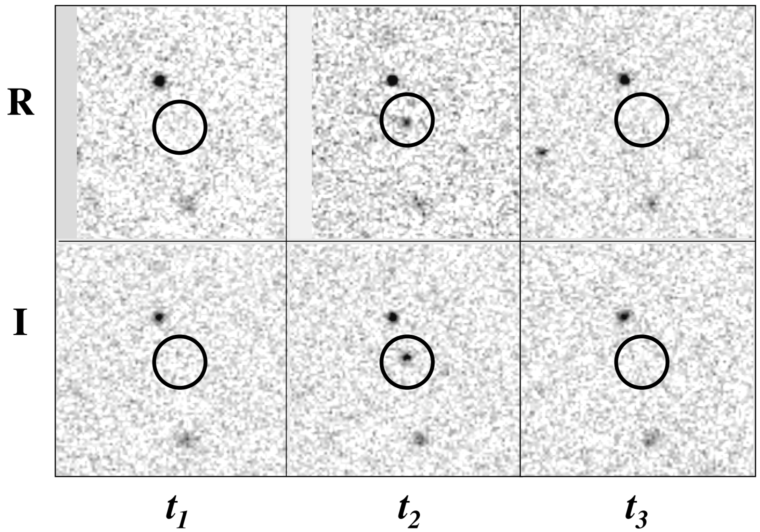
… But it could be something else entirely…



Examples of DPOSS Transients

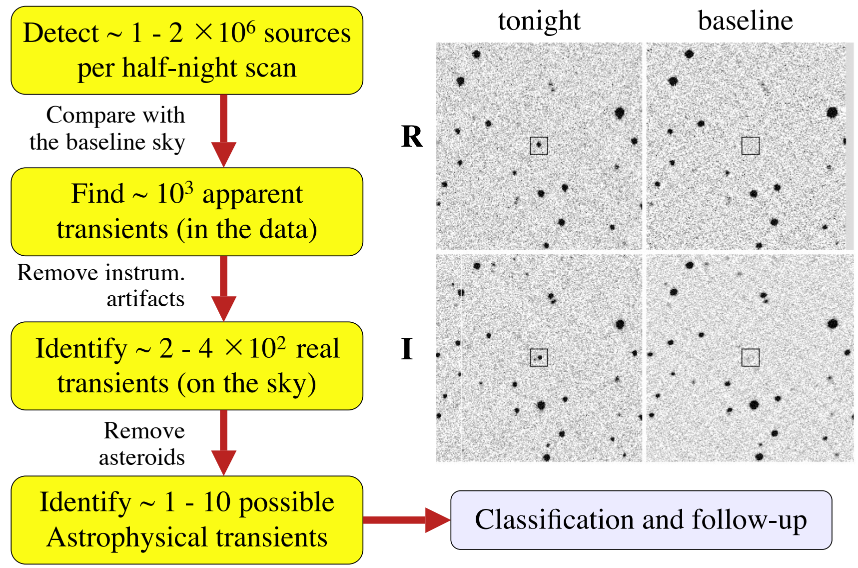


Unidentified Archival Transients in PQ

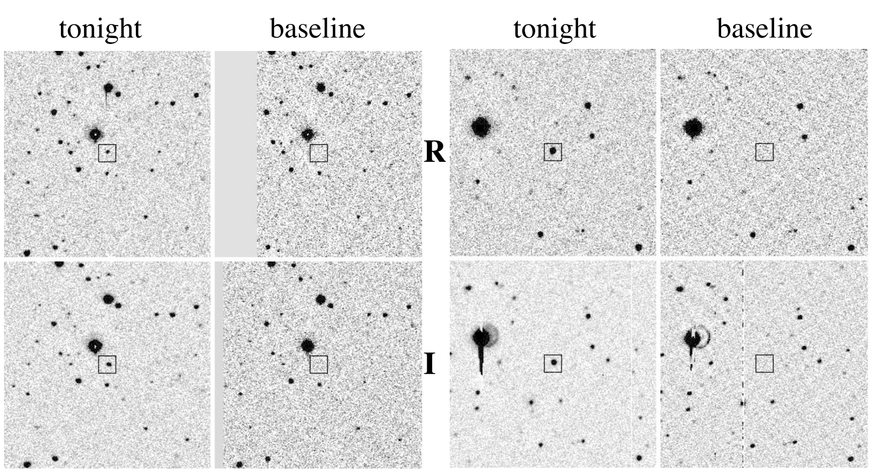


(A. Drake, A. Mahabal, et al.)

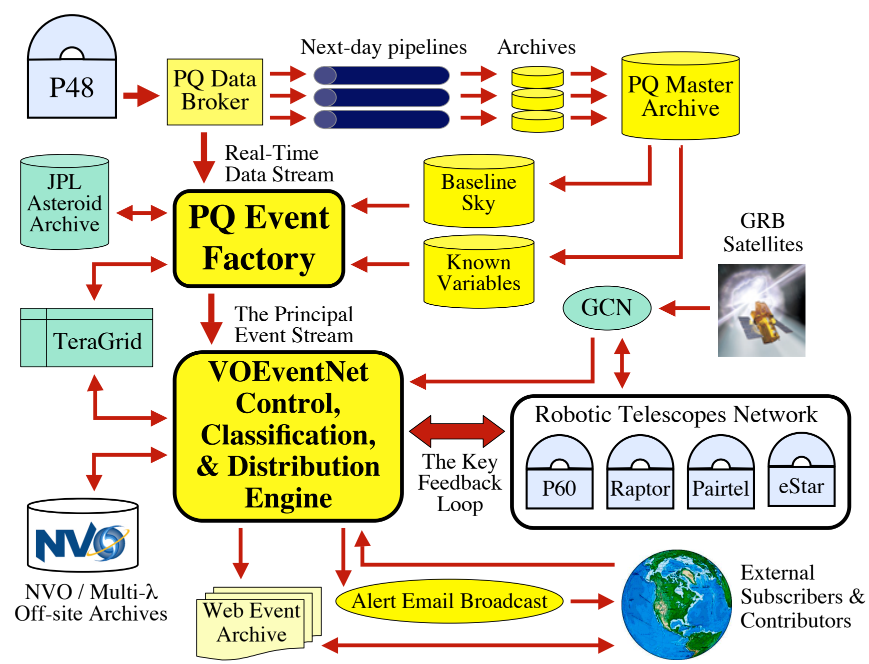
The Palomar-Quest Event Factory



Real-Time Discovery of Transients



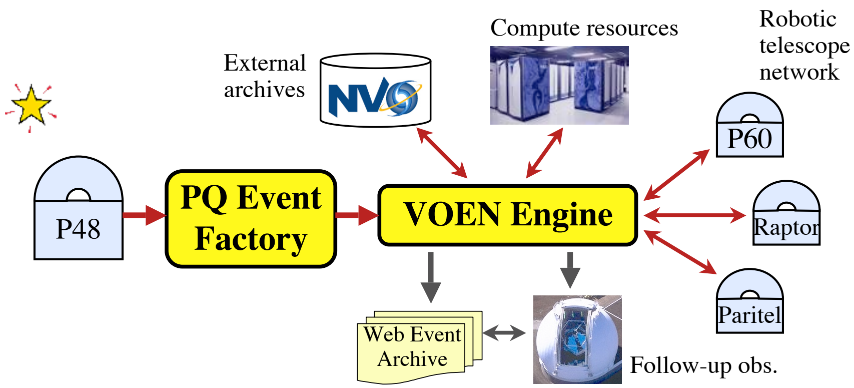
Examples of optical transients discovered in the real time in Sept.'06, using a prototype real-time pipeline



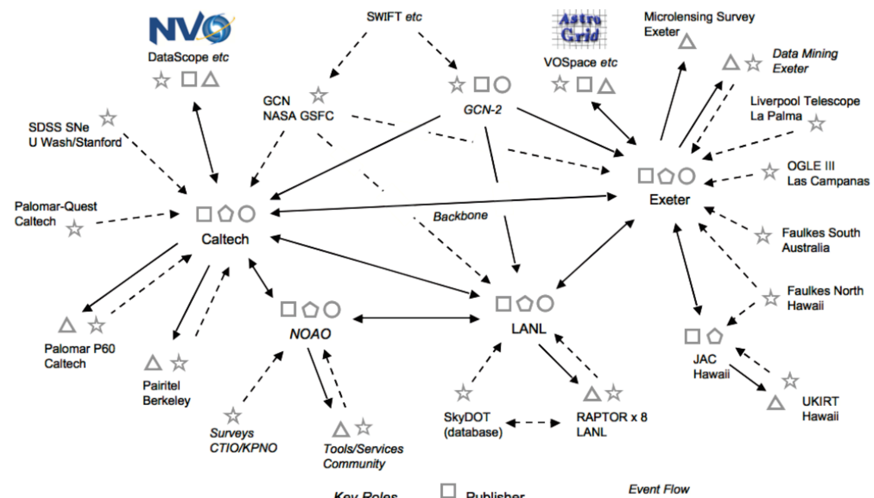
The VOEventNet Project

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

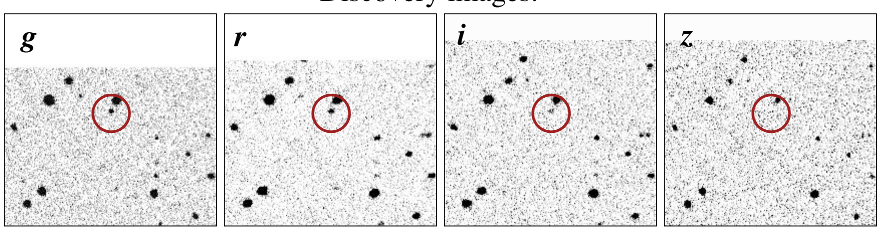


(from Seaman & Warner 2006)

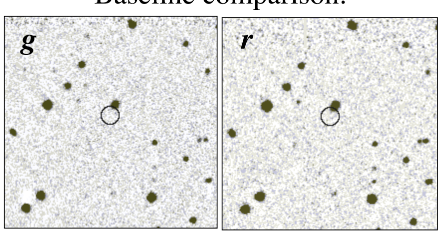
An Unidentified PQ Real-Time Event

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**

voeventnet.caltech.edu

- Home
- Project Description
- Personnel
- GCN VOEvents
- SDSS Supernovae
- ESSENCE Supernovae
- OGLE Microlensing
- PQ Transients
- Transients in the Griffith Park "Big Picture"
- IVOA VOEvent pages
- Search the Nexus
- Subscribe
- Wiki

VOEventNet: Real-Time Astronomy with a Rapid-Response Telescope Grid

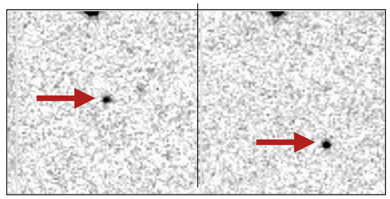
VOEvents from the Palomar Quest Transient Search

- This page is generated automatically as incoming PQ events are received and was last updated at
- Additional information about PQ Transients that are available **here** .
- Information on subscribing to receive PQ Transients and other VOEvents in **real time** is here:
- A near real time feed is available here: XML RSS
- This table contains information about Transients obtained from PQ (Table Help).

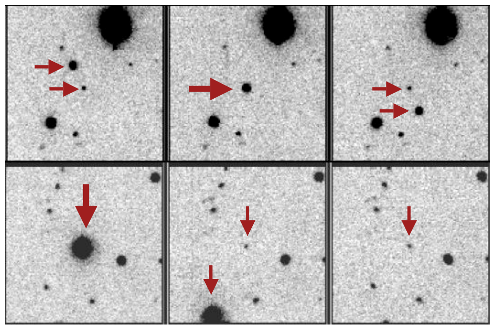
Palomar Quest Events					
ID	Alert Time (UT)	Event Time (UT)	RA (deg)	Dec (deg)	Error (
7052101243010670393	2007-05-21T08:43:11	2007-05-21T07:06:38	234.5119299	15.9229255	2.16
7052101243030690374	2007-05-21T08:43:09	2007-05-21T07:11:12	235.7001958	15.5061457	2.16
7052101233260390193	2007-05-21T08:43:07	2007-05-21T05:56:58	217.9791300	11.6790801	2.16
7052101243170240345	2007-05-21T08:43:06	2007-05-21T05:21:33	208.2908345	13.1145446	2.16
7052101243030690374	2007-05-21T07:26:34	2007-05-21T07:11:12	235.7001958	15.5061457	2.16
7052101243010670393	2007-05-21T07:16:57	2007-05-21T07:06:38	234.5119299	15.9229255	2.16
7052101243090550350	2007-05-21T06:47:02	2007-05-21T06:36:37	226.9676221	14.4591642	2.16
7052101233260390193	2007-05-21T06:36:53	2007-05-21T05:56:58	217.9791300	11.6790801	2.16

Asteroids: A Major Contaminant!

- We have many "transient" detections, but they are *mostly asteroids*
- We find **~ 1 - 3 asteroids / *deg²*** down to ~ 20 - 21 mag, per epoch



Sometimes as overlaps:



Mitigation:

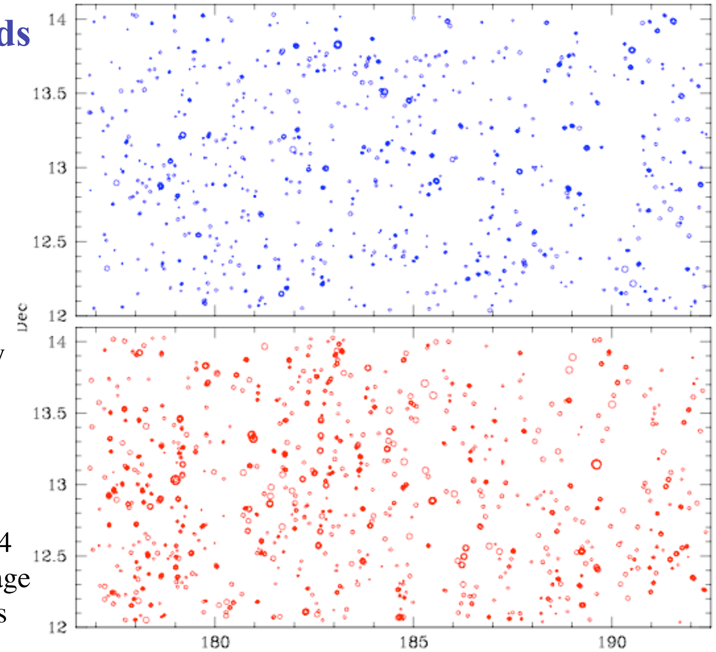
- Optimized cadence: scan and rescan the same night ~ 3 - 4^h apart
- Crossmatch to asteroid DB's (Horizons, IMCCE)
- Improved proper motions and colors

Asteroids in the BigPic area

New →

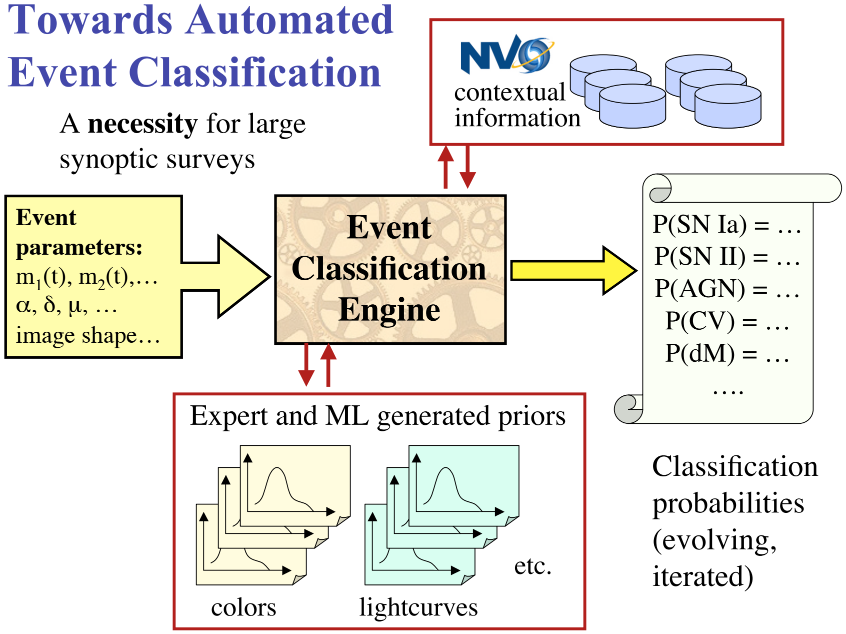
Previously known →

Area = 30.4 deg², average ~ 10 passes



Towards Automated Event Classification

A **necessity** for large synoptic surveys



Some Things We Have Learned

(from DPOSS, SDSS, DLS, PQ …)

- In a single-pass snapshot survey there are ~ 10^{-2} astrophysical transients/deg² 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.