Exploring the Variable Sky with the Catalina Real-Time Transient Survey

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E. Beshore, S. Larson, et al. (UA/LPL),

and numerous collaborators world-wide

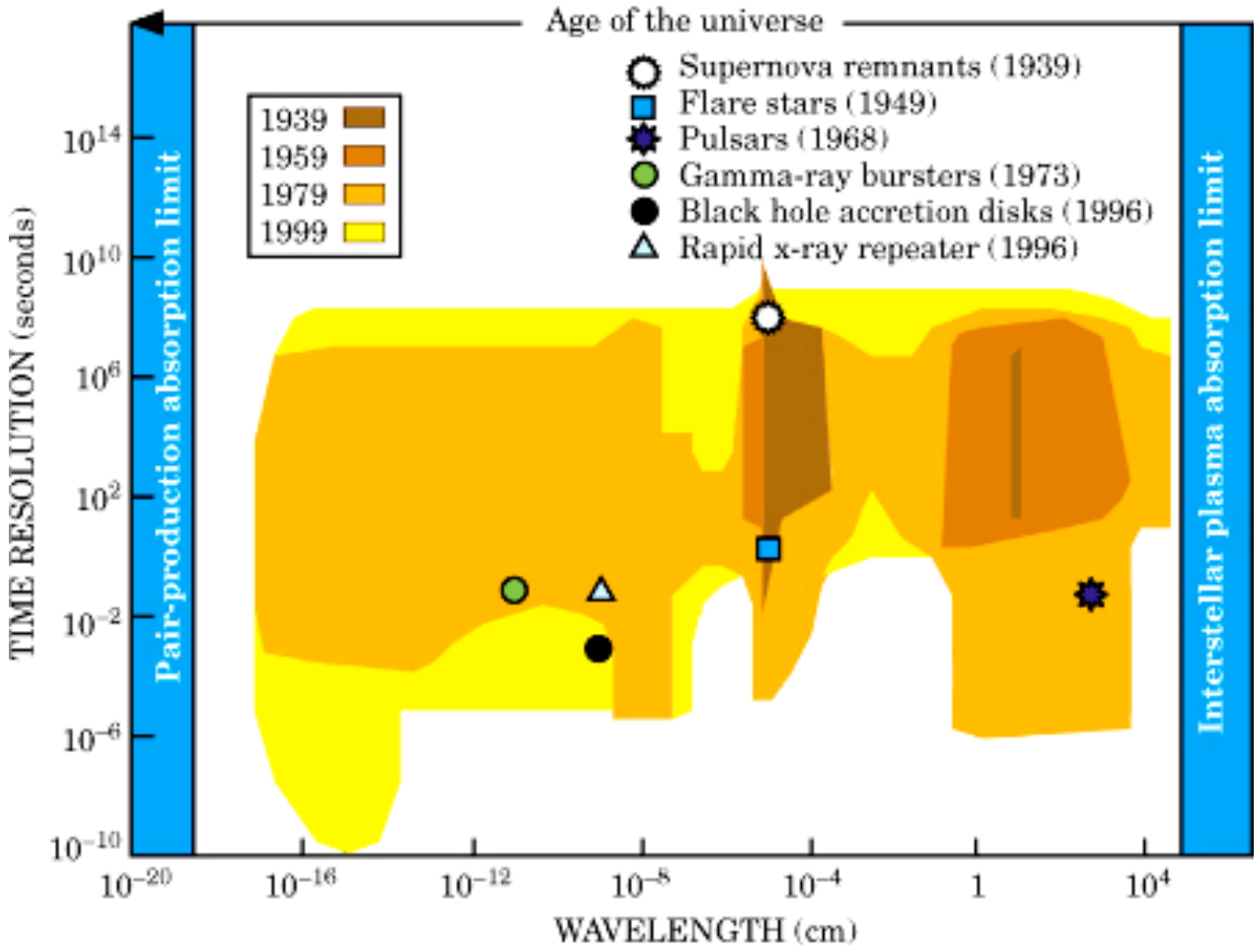
MAXI Workshop,
Tokyo, Dec. 2010

Expanding the Observable Parameter Space

Technology advances ➞ Expanded domain of measurements

➞ Discovery of new types of phenomena

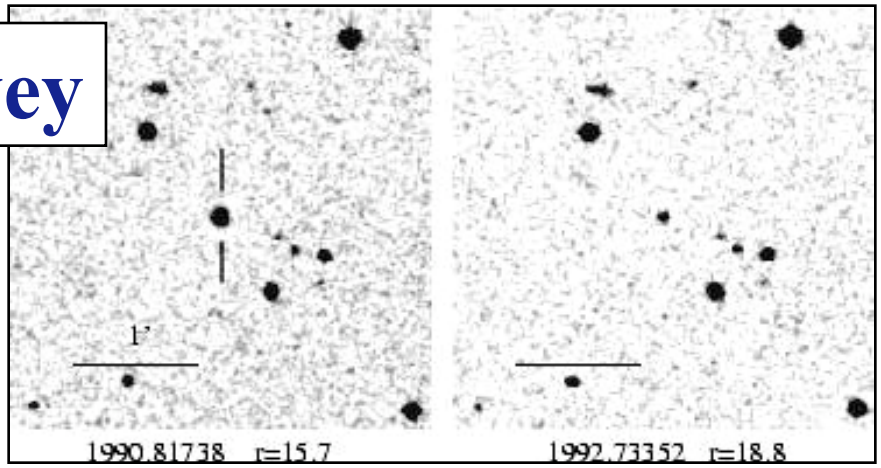
(M. Harwit)

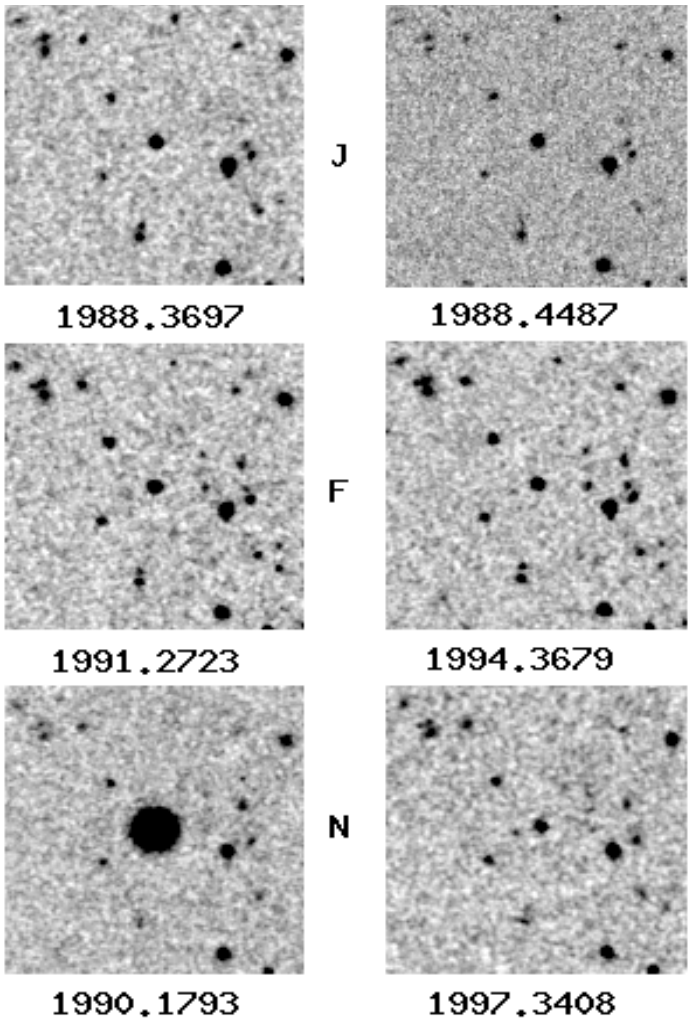


As we open up the time domain, we are bound to discover some new things!

DPOSS Plate Overlap Survey

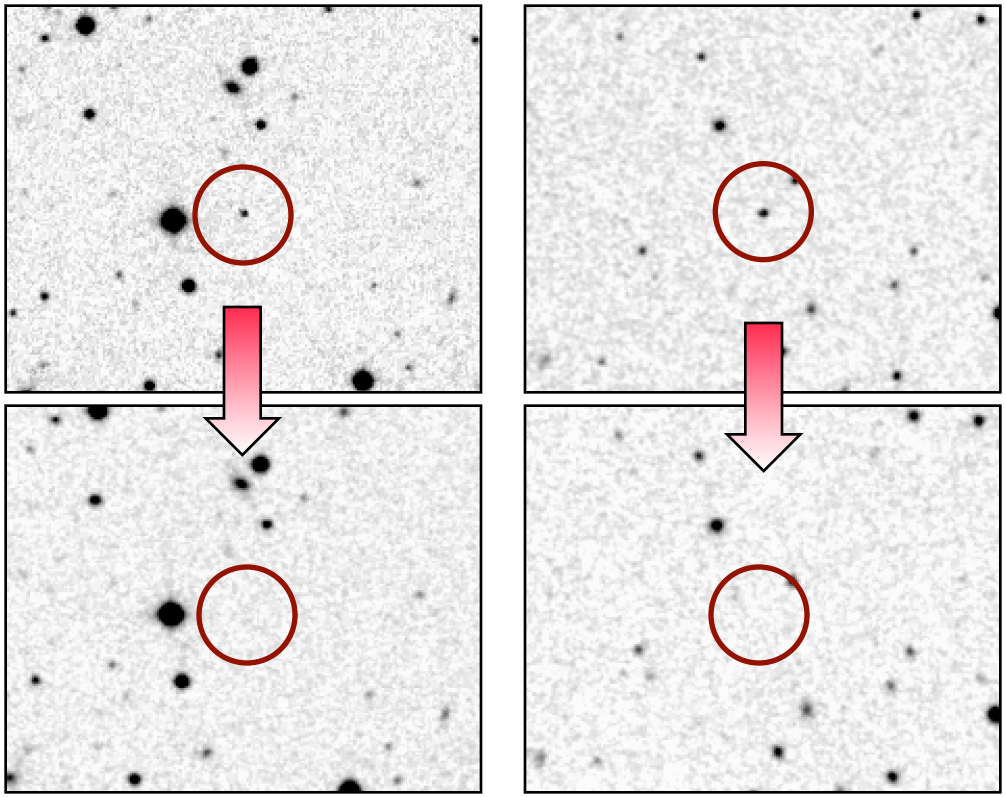
High-amplitude (non-OT) variables, mainly CVs and AGN, over the time baselines ~ a few years





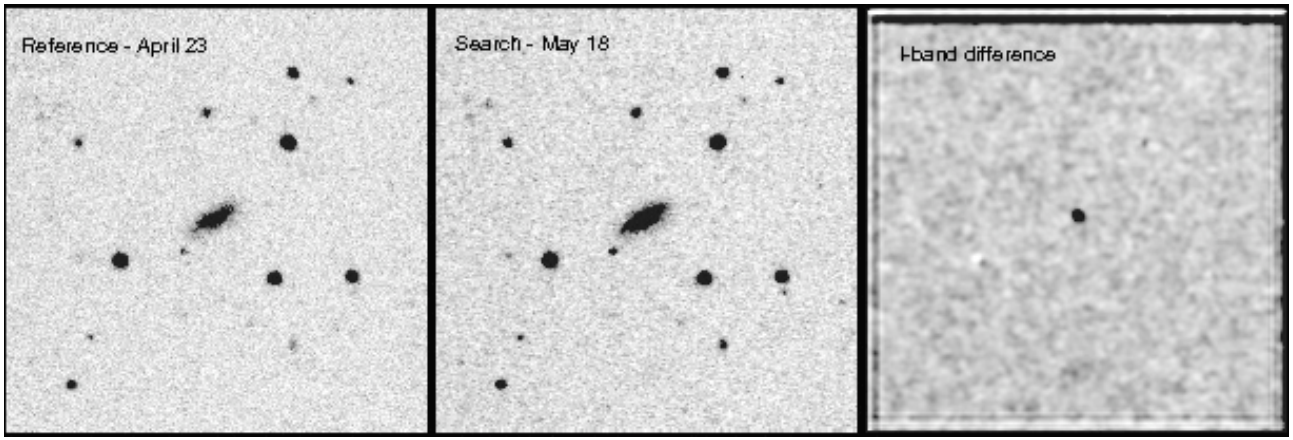
(Mahabal, Djorgovski, Granett 2001, 2003)

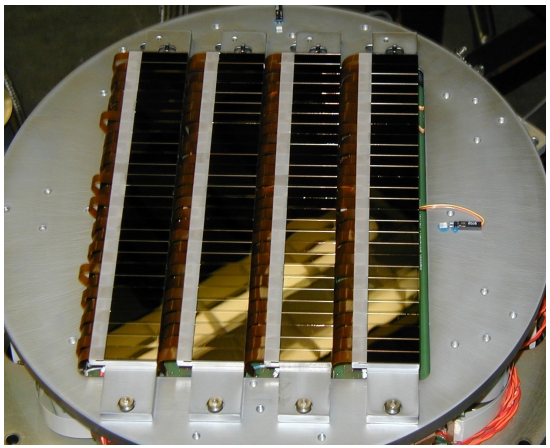
DPOSS Transients



The Palomar-Quest (PQ) Digital Synoptic Sky Survey

- Palomar 48-in. + 112-CCD, 161 Mpix camera
- A Caltech-Yale collab. Co-PIs: C. Baltay & SGD; plus other groups worldwide (LBL, etc.)
- Many passes with up to 4 filters (*UBRI/griz*), time baselines from minutes to years
- Collected > 50 TB of data
- Operated from Aug. 2003 through Sept. 2008
- ***Key goal: Exploration of the time domain***



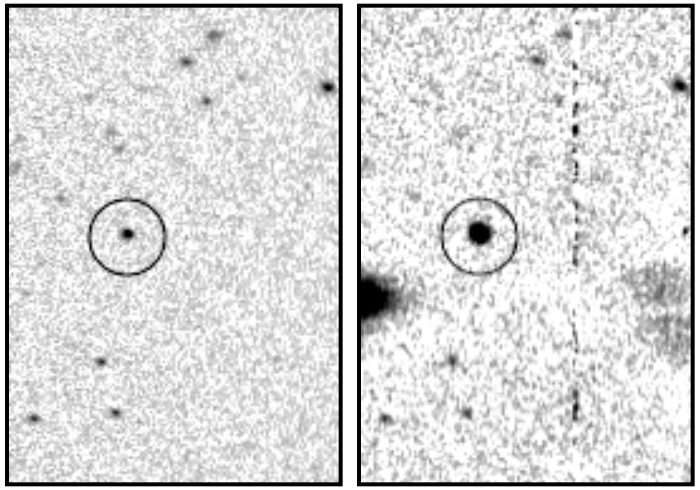


⇦ LBL SNF search (Nugent et al.)

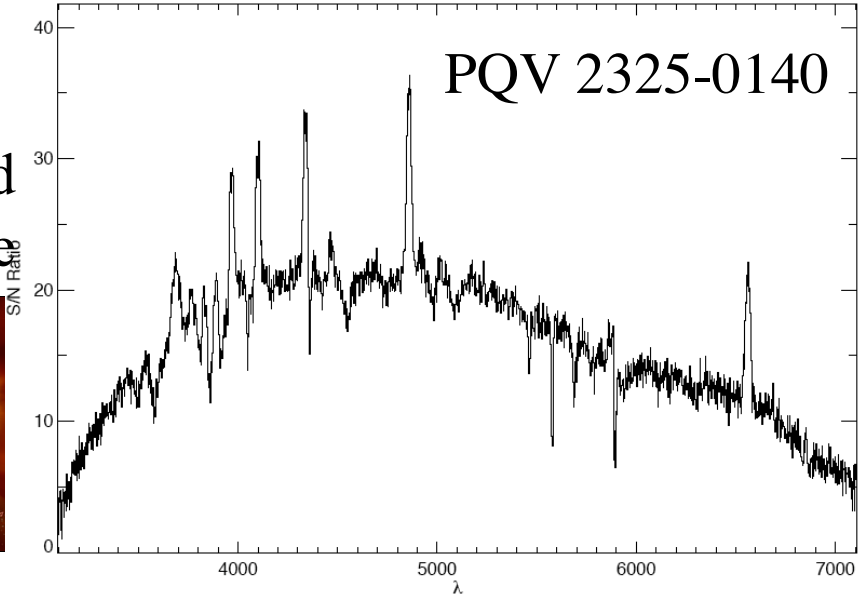
> 700 SNe discovered

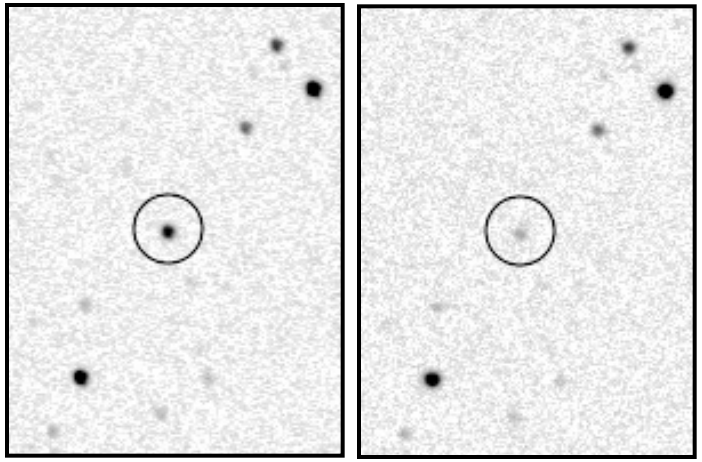
The Most Variable Sources on the Sky:

Selected in the Palomar-Quest Survey

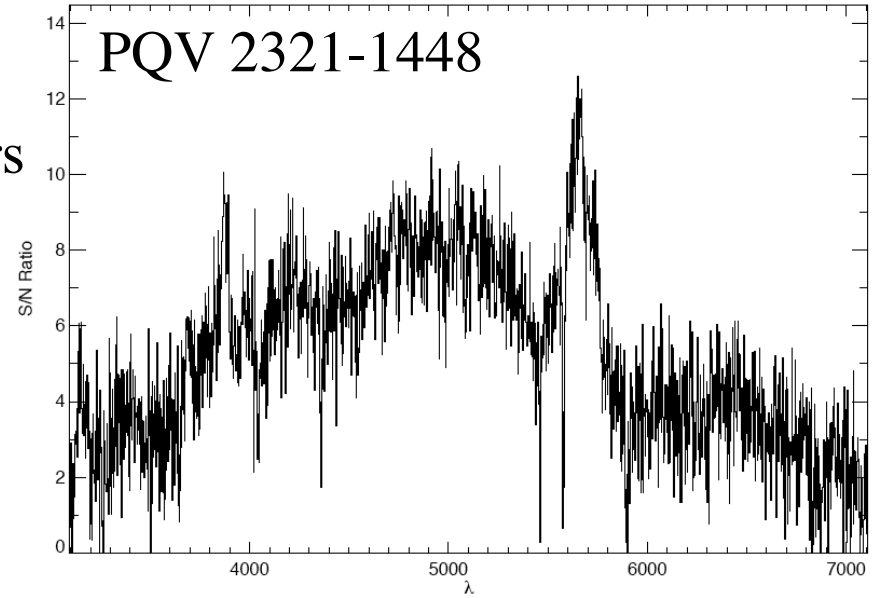


Cataclysmic Variables and Dwarf Novae





Blazars and OVV Quasars



The Palomar-Quest Event Factory

Sept. 2006

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

Compare with the baseline sky

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

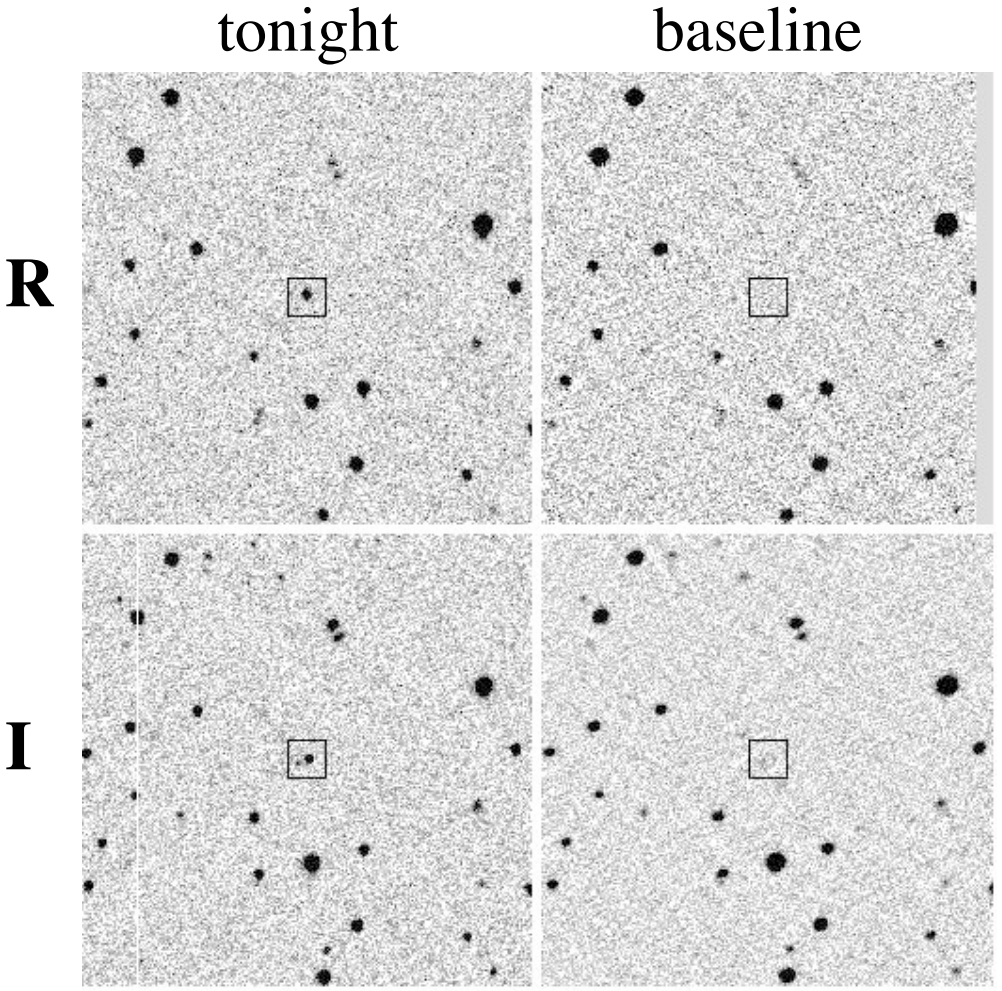
Remove instrum. artifacts

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

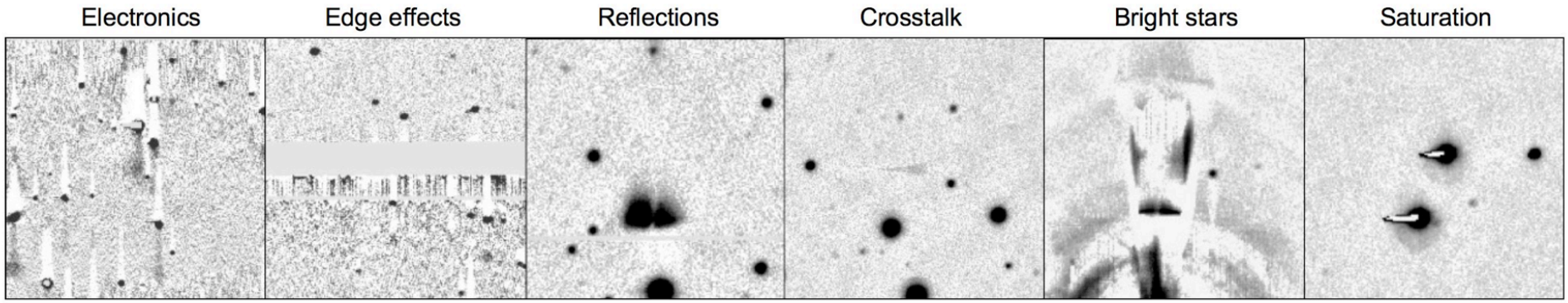
Remove asteroids

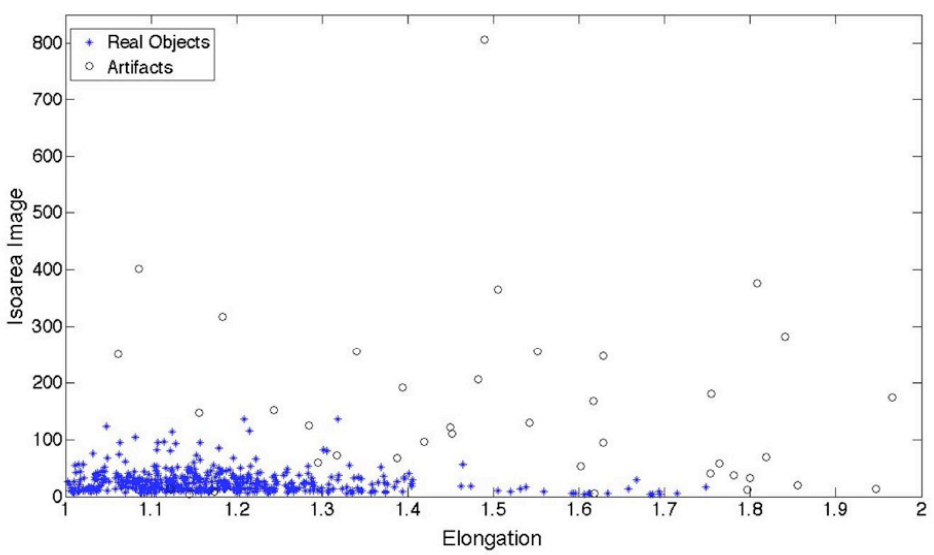
Identify ~ 1 - 10 possible Astrophysical transients

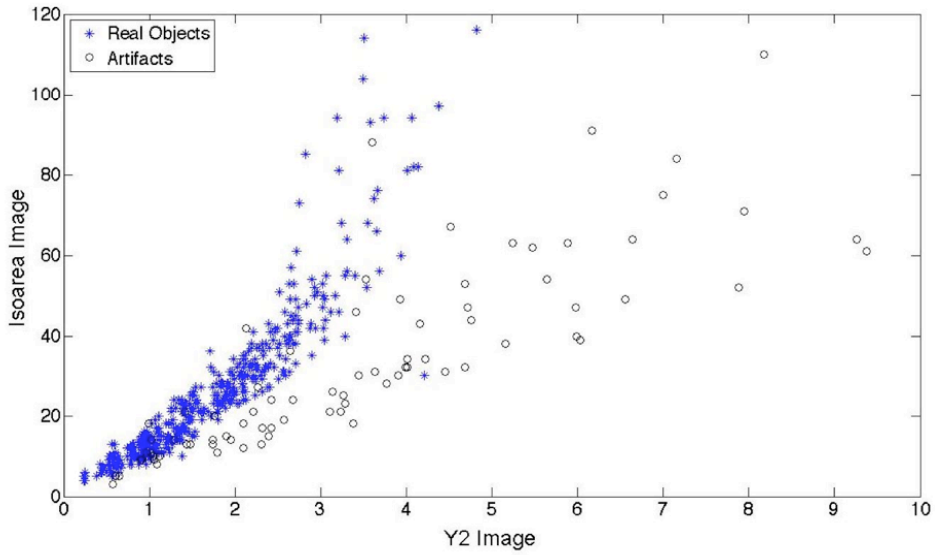
Classification and follow-up



Automated Filtering of Artifacts







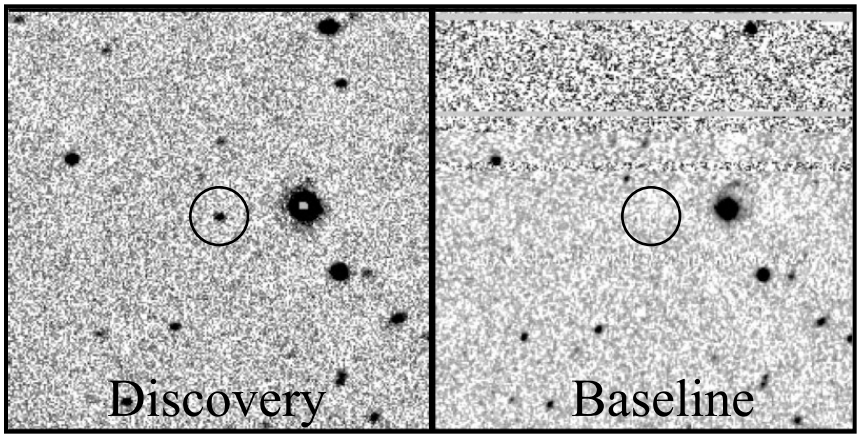
Automated classification and rejection of artifacts masquerading as transient events in the PQ survey pipeline, using a Multi-Layer Perceptron ANN *(Donalek et al.)*

Examples of PQ Real-Time Discoveries

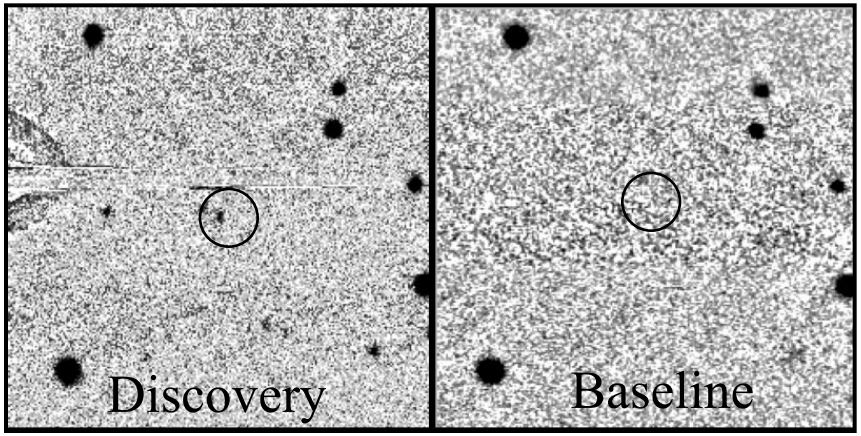
P200 spectroscopy sometimes within an hour of the initial detection

AGN

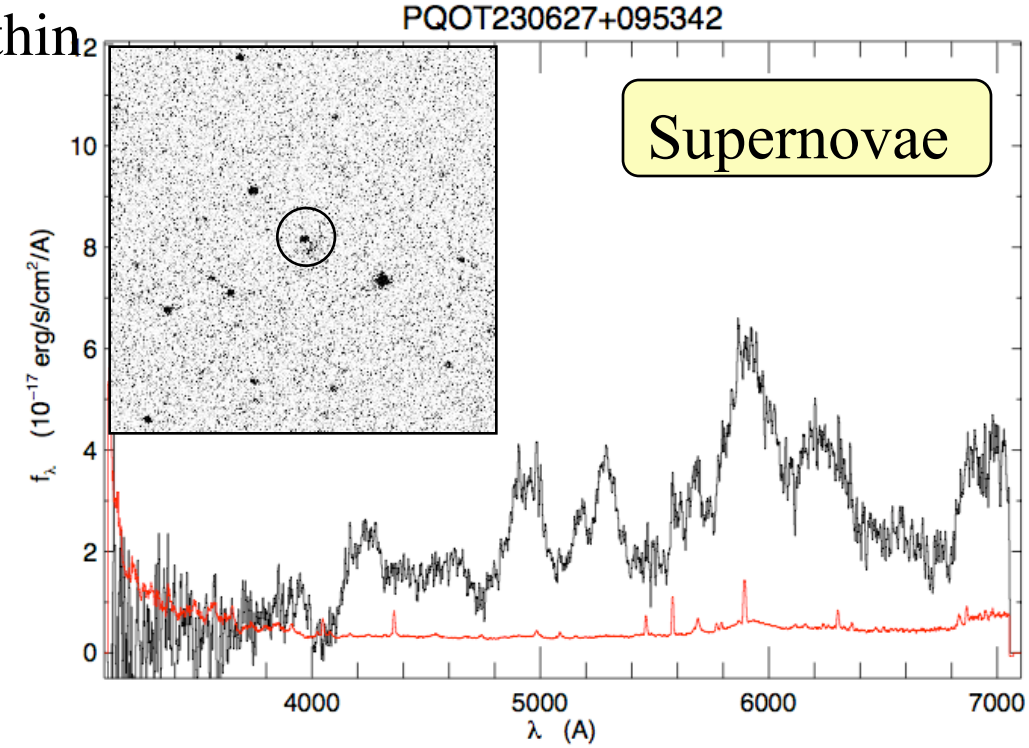
PQT 071010:034520-012111 Blazar



PQT 071011:031515-034914 QSO, z = 1.26

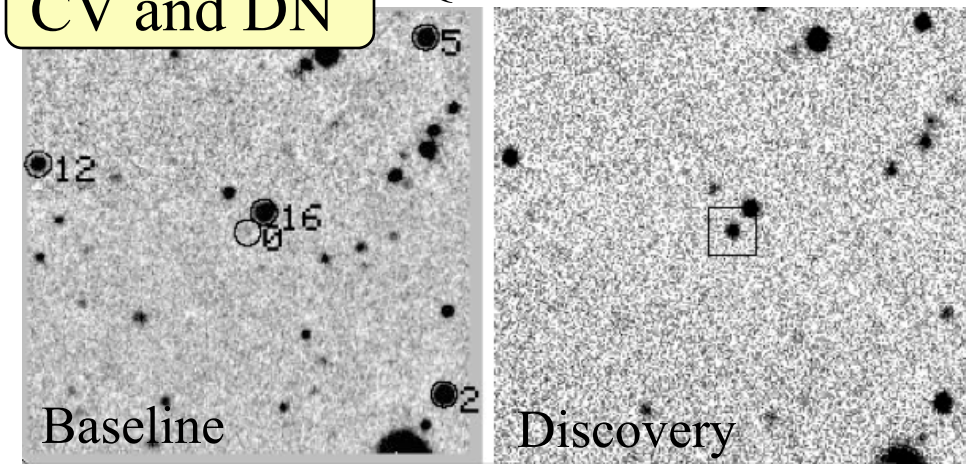


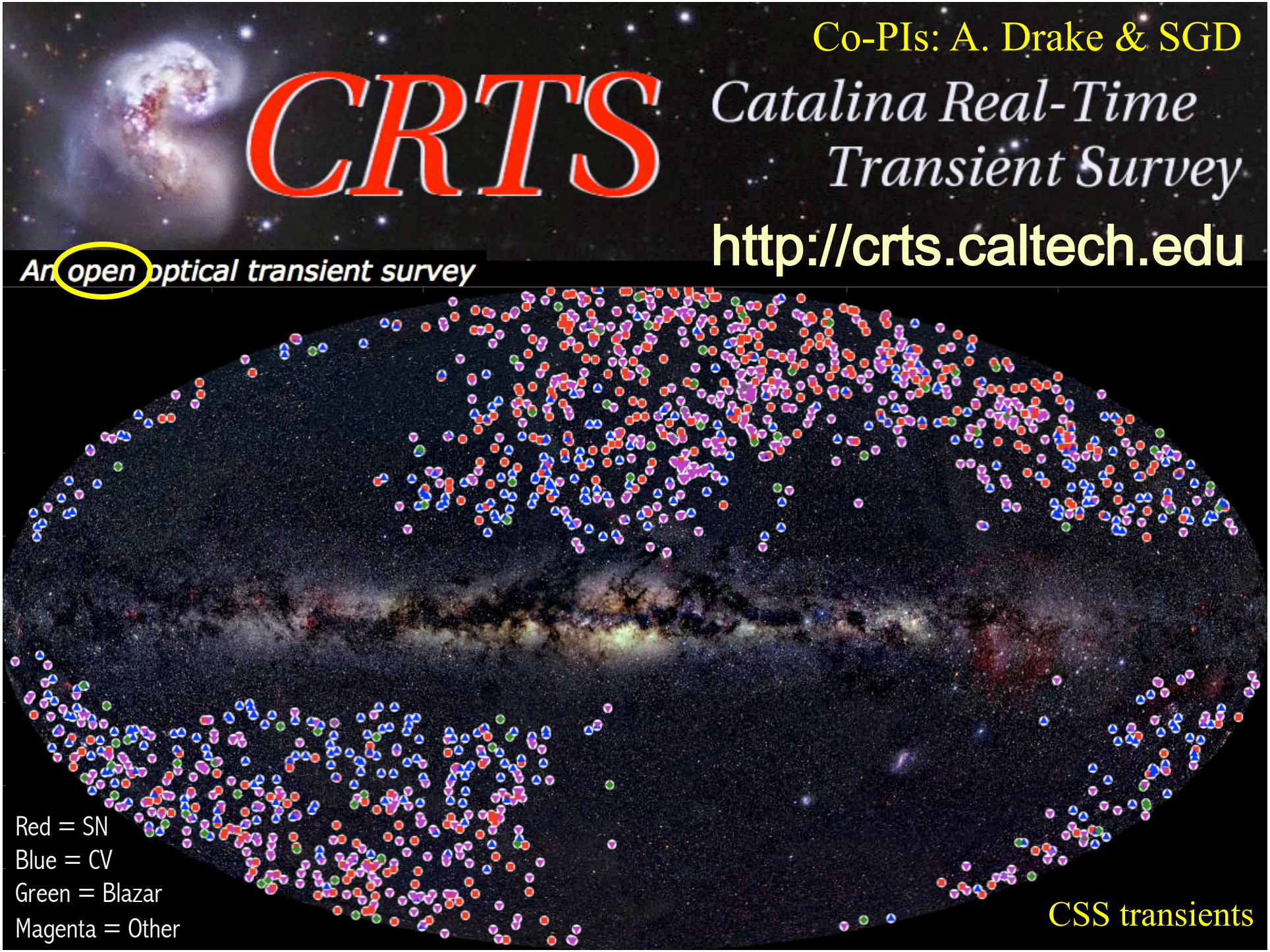
Supernovae



CV and DN

PQT 080119:091534+081356

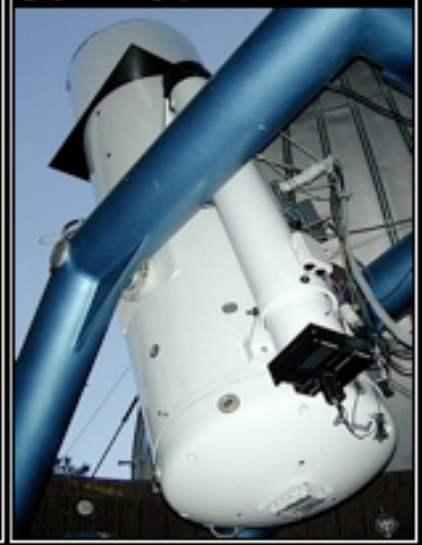



Co-PIs: A. Drake & SGD
CRTS
Catalina Real-Time Transient Survey
http://crts.caltech.edu
An open optical transient survey
Red = SN
Blue = CV
Green = Blazar
Magenta = Other
CSS transients

Catalina Sky Survey(s):

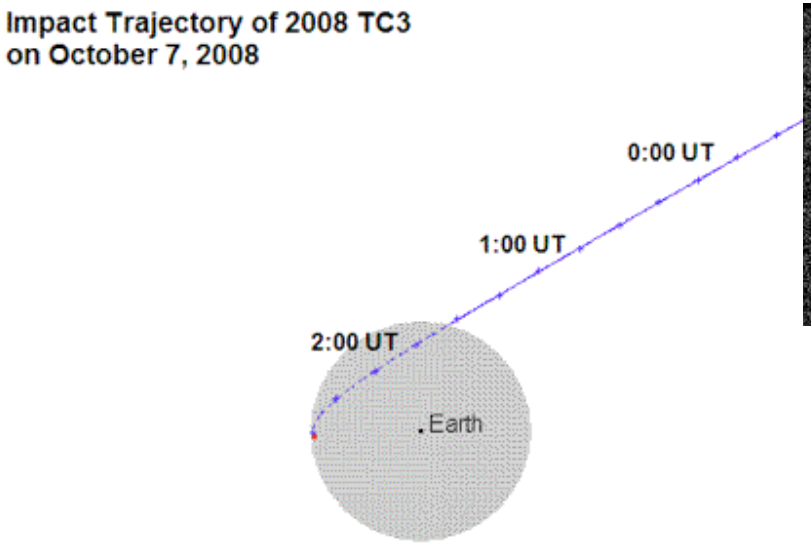
NEO survey Co-PI's:
E. Beshore & S. Larson (LPL)

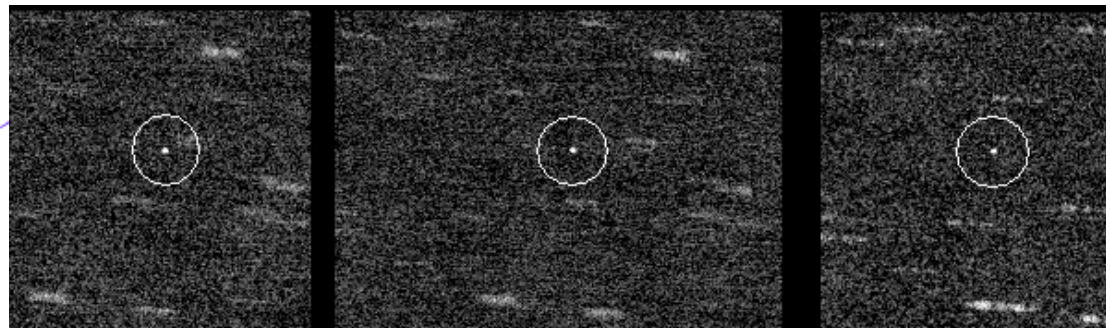
CRTS uses the data from all three Catalina NEO surveys, with a coverage of up to 2,500 deg^2 / night, and the total area coverage of ~ 30,000 deg^2

	MLS The Mt. Lemmon Survey 1.5m Cass	CSS Catalina Sky Survey 0.7m Schmidt	SSS Siding Springs Survey 0.5m Schmidt
			
Survey region (deg)	+/- 5 deg ecliptic	-25 < Dec < +70	-80 < Dec < -25
Field of View (square deg)	1.2	8.1	4.2
Mag limit (V)	21.5	19.5	19.0

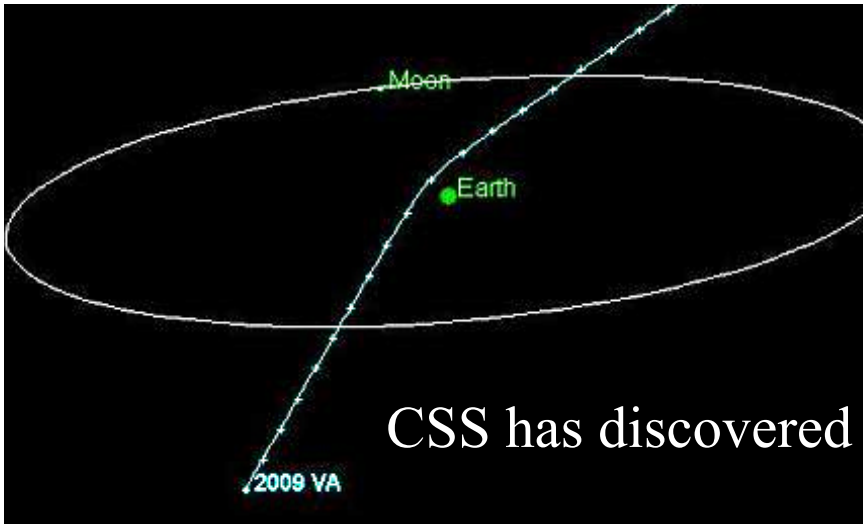
We are processing the Catalina data streams in real time to look for astrophysical transients

CSS Discoveries of Earth-Grazing Asteroids

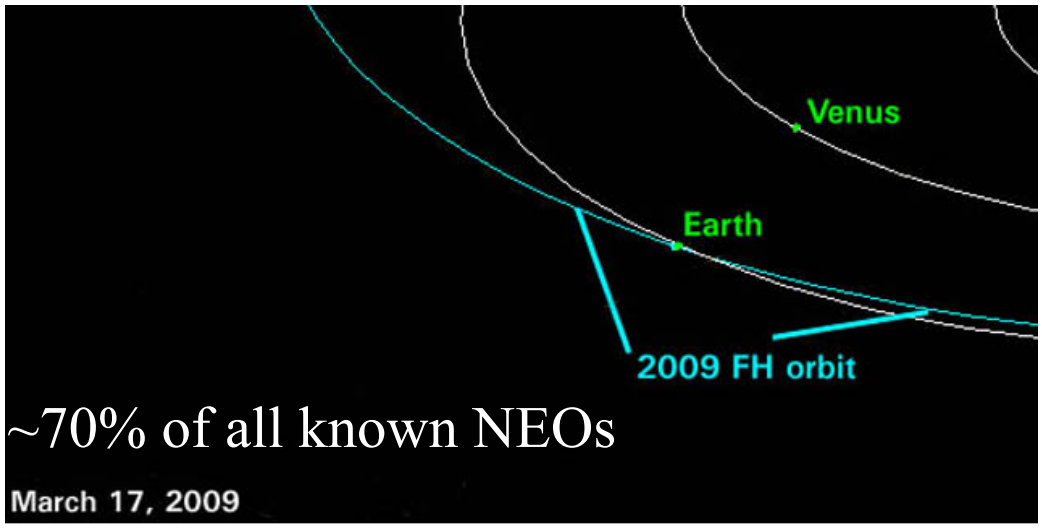




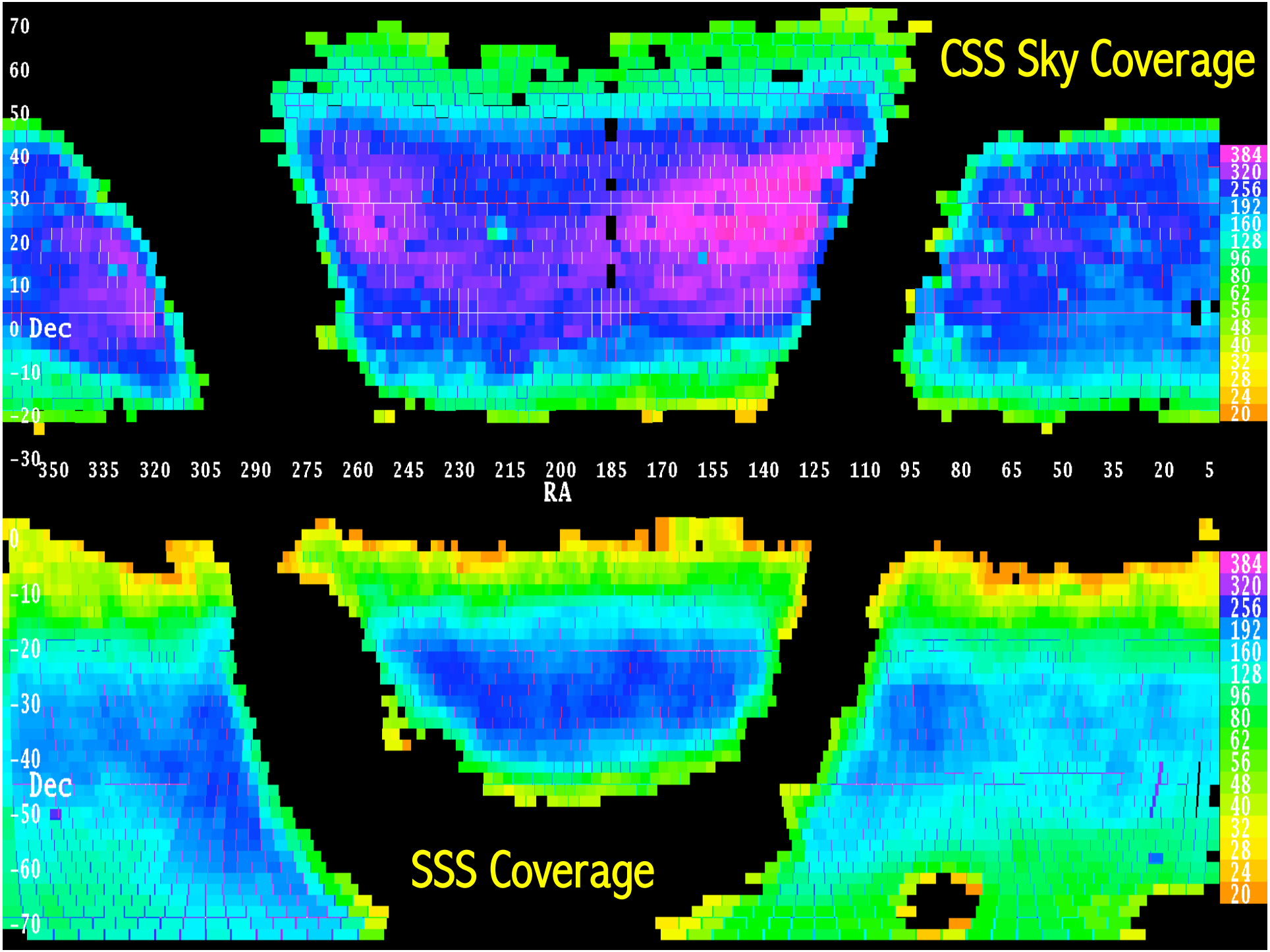
An extremely low cost
"sample return mission"



CSS has discovered



~70% of all known NEOs

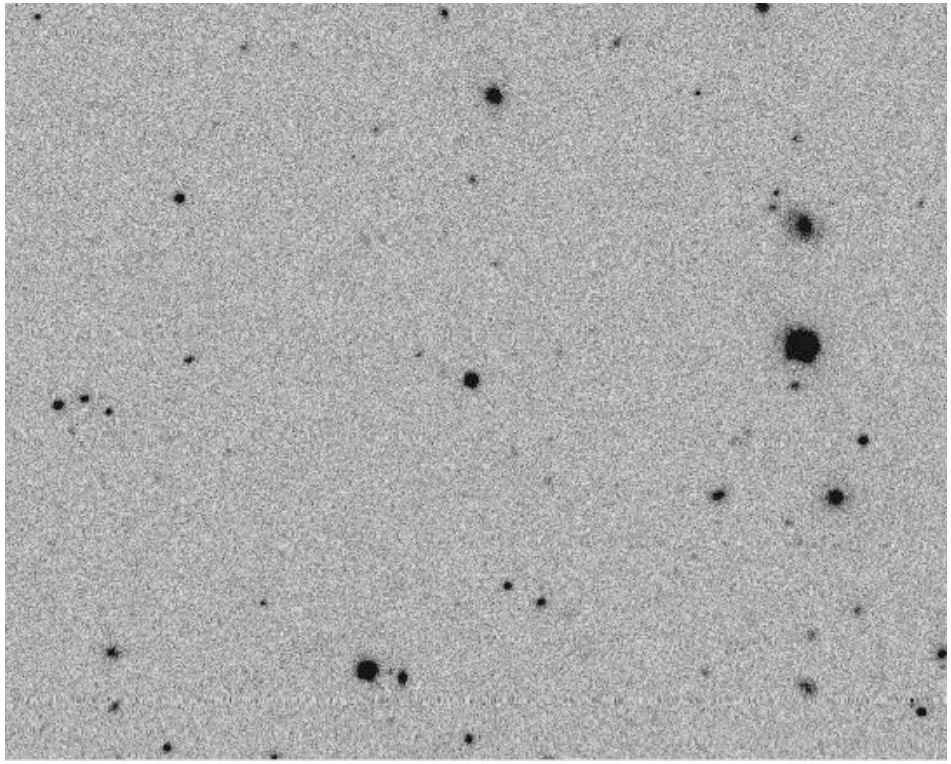

CSS Sky Coverage
70
60
50
40
30
20
10
0 Dec
-10
-20
-30
350 335 320 305 290 275 260 245 230 215 200 185 170 155 140 125 110 95 80 65 50 35 20 5
RA
384
320
256
192
160
128
96
80
62
56
48
40
32
28
24
20
0
-10
-20
-30
-40
Dec
-50
-60
-70
SSS Coverage
384
320
256
192
160
128
96
80
62
56
48
40
32
28
24
20

The Catalina Real-Time Transient Survey (CRTS)

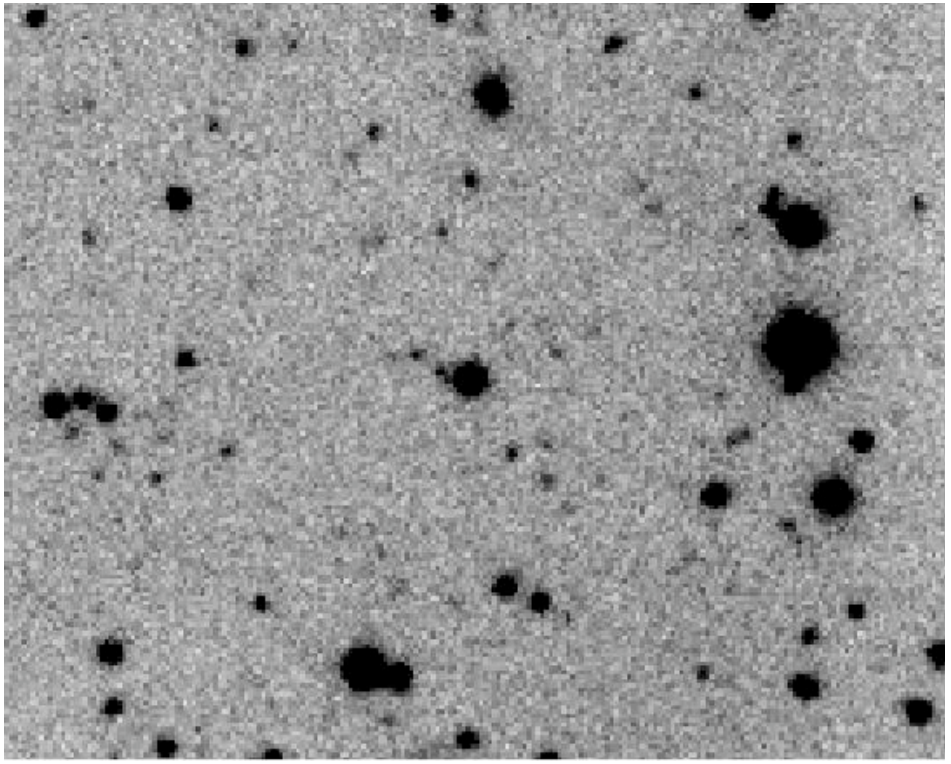
- Real-time processing, detection, and publishing of transients
  - Builds on the work started in the PQ survey (science & technology)
  - Added value for the data from the Catalina NEO surveys
  - Focus on astrophysical transients, ***a systematic exploration of the time domain***, and the computational infrastructure
  - Pilot project: late 2007 – 2008; full operations since 2009
  - Public outreach: Google's Sky, MSR's WWT, "Citizen Science"
  - Supported by the NSF, NASA, and private gifts
- It is ***a fully open survey***: all data are made public instantly, with no proprietary period at all
  - Benefits the entire community and maximizes the follow-up and the resulting science
  - A new "open data" sociology – the shifting focus from the ownership of data to the ownership of expertise

Coadded Images From MLS (1.5m)

SDSS



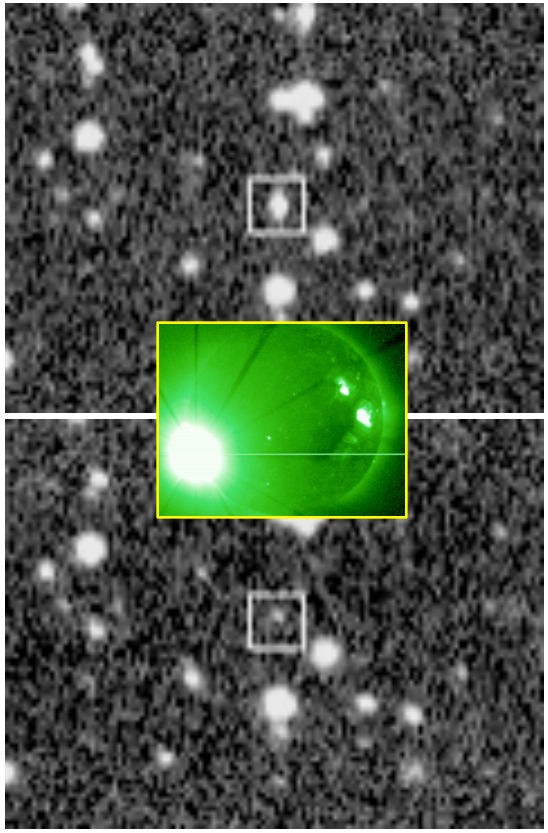
CRTS



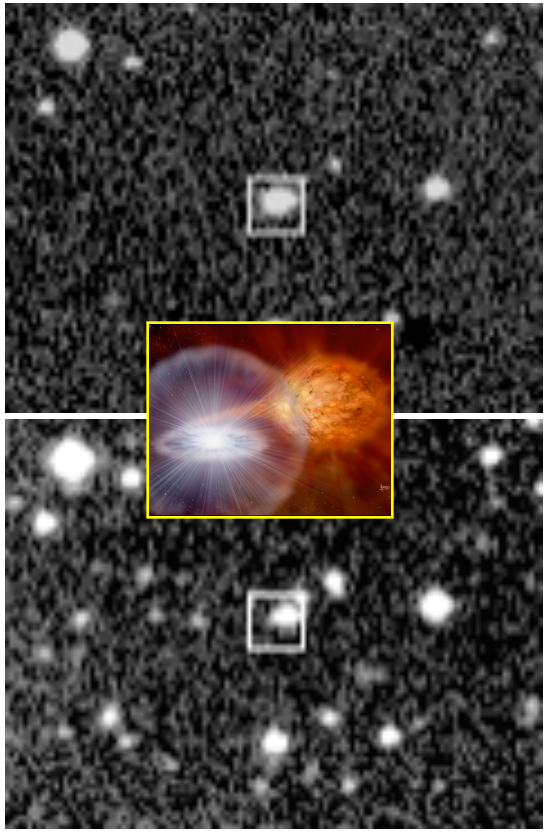
Combining the data from CRTS and PQ (DeepSky), we will have a reference sky coverage of ~ 3π sterad to the depth of $r > 23$ mag, and the light curves (detections or upper limits) for all detected sources

Examples of CRTS Transients

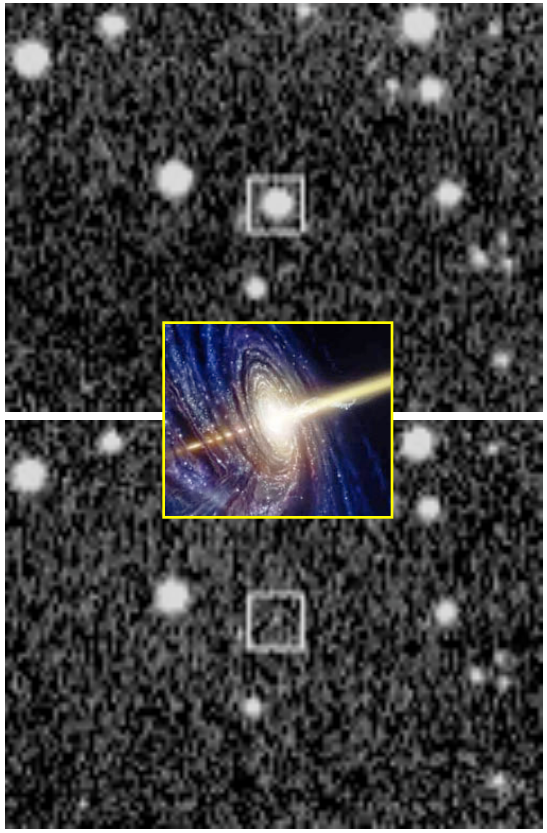
CSS090429:135125-075714
Flare star



CSS090429:101546+033311
Dwarf Nova



CSS090426:074240+544425
Blazar, 2EG J0744+5438



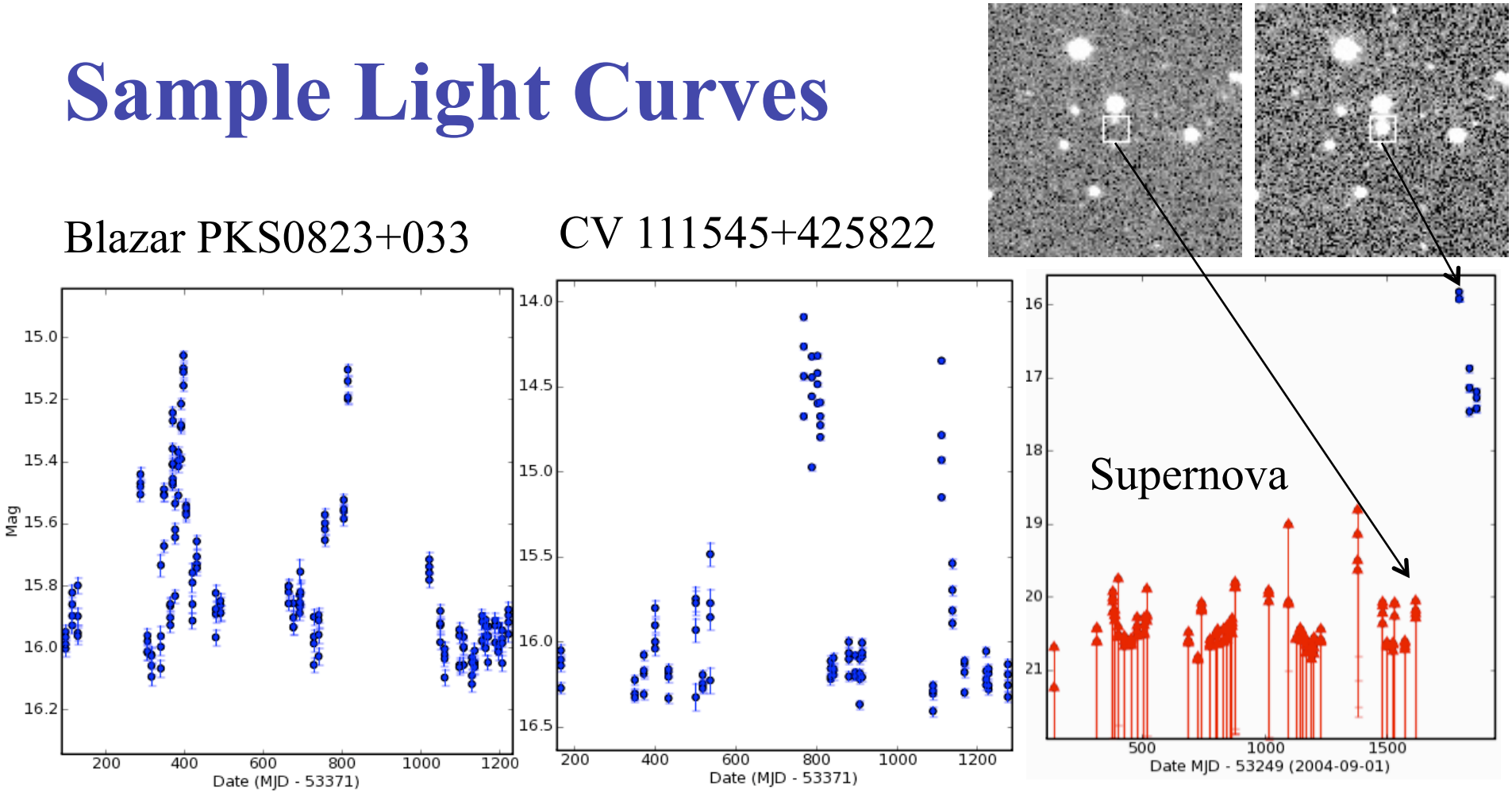
Vastly different physical phenomena, and yet they look the same!
Which ones are the most interesting and worthy of follow-up?

Rapid, automated transient classification is a critical need!

Sample Light Curves

Blazar PKS0823+033

CV 111545+425822



The plan is to produce light curves for every detected source in the survey (> 10^8 sources), make them publicly available, and mine that data set. Light curves are generated on demand for transient sources, blazars, etc.

CRTS Event Detections

Distinct Events Detection Statistics as of 30 Nov 2010 UT:

Telescope	All OTs	SNe	CV	Blazars	Ast/Flr	CV or SN	Other
CSS	1623	432	419	97	182	240	281
MLS	670	81	17	3	60	211	316
SSS	98	13	38	6	2	16	23
Total	2391	526	474	106	244	467	620

- Threshold set deliberately very high – only the most dramatic transients are pulled out in the real time
- About 1 strong transient per 10^6 source detections
- The rate of significant transients/variables is at least an order of magnitude higher
- Many events are re-detected repeatedly (not counted above)

Event Publishing / Dissemination

- Real time: VOEvents, Twitter, iApp (thousands of events)
  - Also on SkyAlert.org, feeds to the WWT, GoogleSky
- Next day: annotated tables on the CRTS website

CSS ID	RA (J2000)	Dec (J2000)	Date	Mag	CSS images	SDSS	Others	Followed	Last	LC	Classification
CSS091121:221159+263906	332.99697	26.65153	20091121	18.33	911211261084134848	no	34848	no	2009-11-21	34848	SN/Blazar mag 21
CSS091121:013728+253450	24.36768	25.58061	20091121	17.78	911211260084103595	no	03595	no	2009-11-21	03595	SN/CV
CSS091121:032627+070744	51.61364	7.12902	20091121	16.68	911211070194124436	no	24436	no	2009-11-21	24436	CV mag 21
CSS091121:033232+020439	53.13295	2.07747	20091121	16.93	911211010194134434	no	34434	no	2009-11-21	34434	CV mag 20
CSS091121:085600-051945	133.99922	-5.32906	20091121	18.17	911210040484107252	no	07252	no	2009-11-21	07252	SN CFHT mag 22 gal
CSS091120:100525+511639	151.35223	51.27742	20091120	18.80	911201520354108835	yes	08835	no	2009-11-20	08835	SN SDSS mag 21,9 gal
CSS091120:082908+482639	127.28503	48.44423	20091120	15.69	911201490314109371	yes	09371	no	2009-11-20	09371	CV/SN SDSS mag 21,6 gal?
CSS091120:004417+411854	11.07004	41.31494	20091120	17.00	911201400044145995	yes	45995	no	2009-11-20	45995	Nova M31 2009-11d
CSS091120:001019+410455	2.58044	41.08191	20091120	16.69	911201400014137919	no	37919	no	2009-11-20	37919	CV mag 20,0

- Days/weeks: ATel, CBET for selected transients (~ 200 so far)

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Present Time: 30 Nov 2010; 8:15 UT

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Flaring Blazars from CRTS

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e-mail: cbatiau@eps.harvard.edu (alternate cbat@i
URL http://www.cbat.eps.harvard.edu/index.html
Prepared using the Tamkin Foundation Computer Netw

SUPERNOVAE 2010jx, 2010jy, 2010jz, 2010ka, 2010kb
A. J. Drake, S. G. Djorgovski, A. Mahabal, M.
California Institute of Technology; T. A. Fatkhull
Moskvitin, V. V. Sokolov, and T. N. Sokolova, Spec
Observatory (SAO), Russian Academy of Sciences; J.
Observatories; M. Catelan, Pontificia Universidad

Real Time Event Publishing via *VOEvents* and *SkyAlert*

http://skyalert.org

PI: R. Williams

From the CRTS stream.
Catalina Real-time Transient Survey
Position is 115.98635,21.1753 ± 0.0012
This portfolio initiated 2009-11-11 08:35:18

See context in WorldWideTelescope

Basic event info

CRTS
911111210394136030
2009-11-11T11:34:58

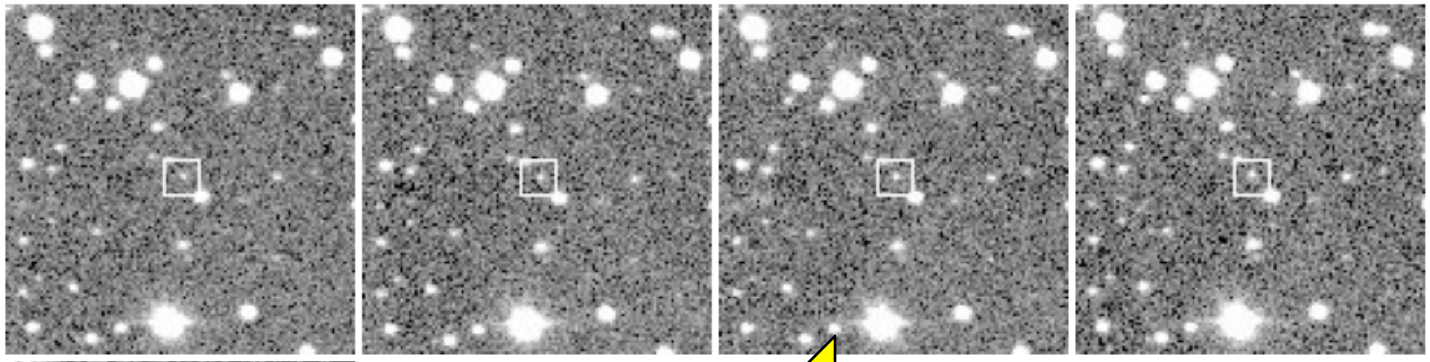
CRTSCircular
911111210394136030-2009-
2009-11-11T16:26:29

SDSS
observation
2009-11-11T16:35:19

CatalogArchives
observation
2009-11-11T16:35:26

CRTS (Catalina) Event identifier is 911111210394136030 or CSS091111:074357+211031

2455146.986330 | 2455146.975340 | 2455146.978970 | 2455146.982620



Reference

Finding Chart	Click here
Past CRTS images	Click here
Other images	Click here
Lightcurve	Click here
SDSS cutout	Click here
Position	(115.98635,21.1753)
Time	2009-1
Magnitude	18.559
Magnitude	18.673±01

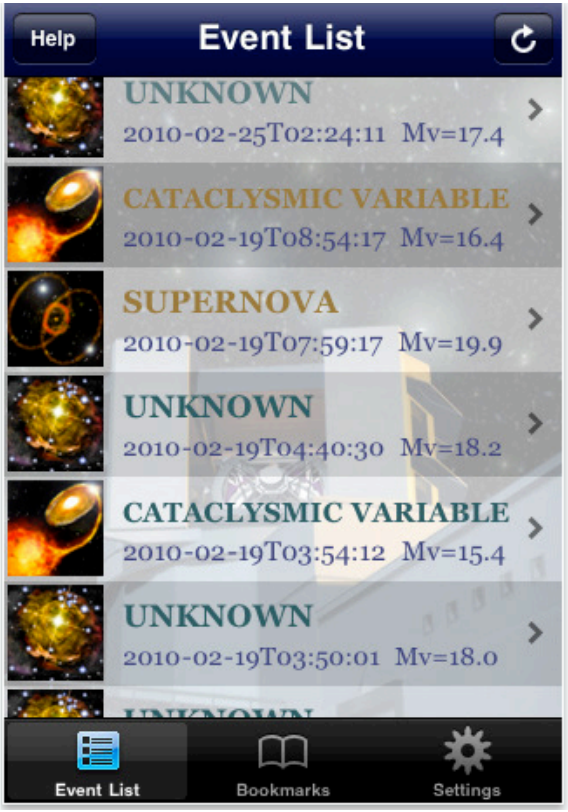
Linked VO/archival data for classif. and follow-up

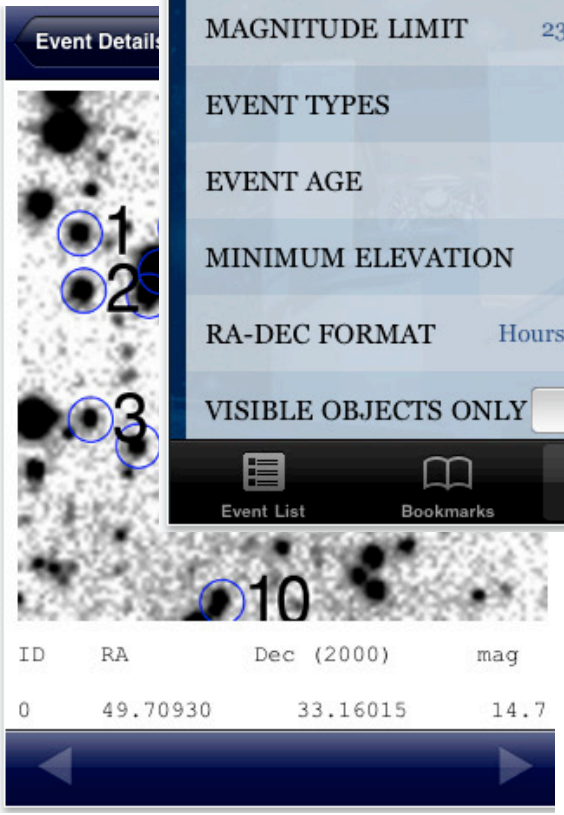
Dynamically growing portfolio

Subscribe to VOEvents via email, RSS, Atom feed, etc.

Twitter and iApp Event Distribution

A. Drake, R. Williams (CIT)
B. Truax (DLD, LLC)
J. Myers (LSST)





Automated Generation of Finding Charts for the Follow-Up Observing

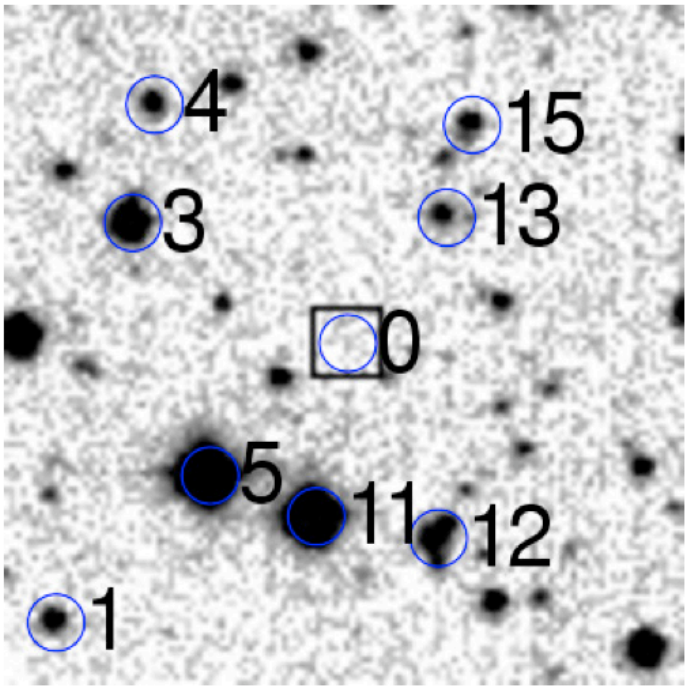
Transient CSS100320:135108+133407

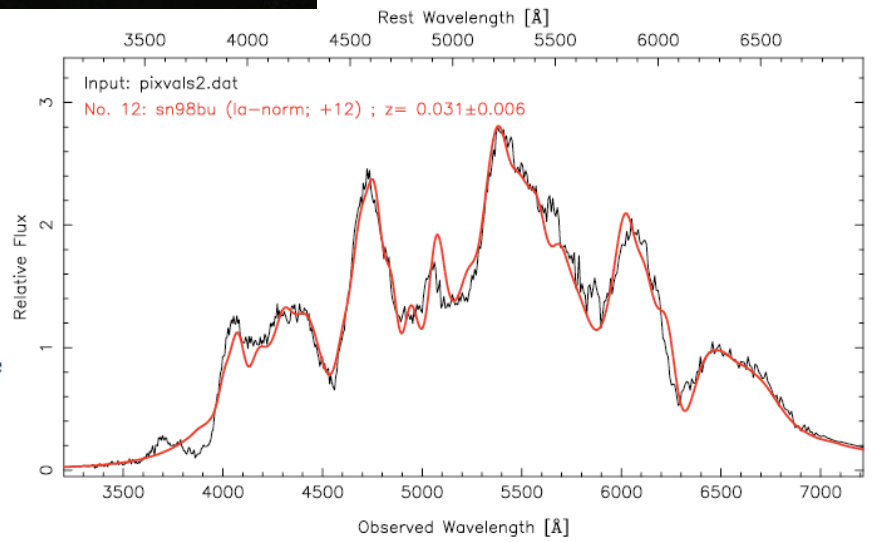
RA Dec (2000)
207.78253 13.56852

Rough Mag:
19.4

Discovery data
Current lightcurve
Pre and post-discovery CSS images
SDSS data
Images from other surveys
P60 Follow-up

Pre-discovery 5' Catalina Sky Survey coadd image (transient location marked with 0)
N is towards the top and E is to the left.





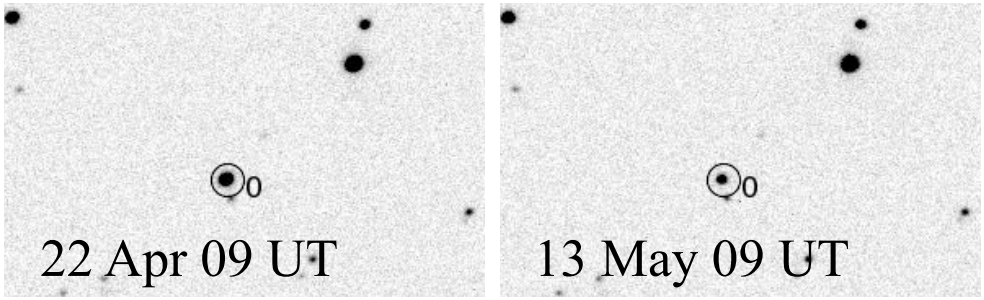
ID	RA	Dec (2000)	mag	delmag	delra (")	deldec
0	207.78253	13.56852	19.4	0.0	0.0	0.0
3	207.81002	13.58293	15.5	-3.9	96.2	51.9
4	207.80724	13.59740	18.4	-0.9	86.5	104.0
5	207.80025	13.55195	12.8	-6.6	62.0	-59.7
8	207.79109	13.56361	18.3	-1.0	30.0	-17.7

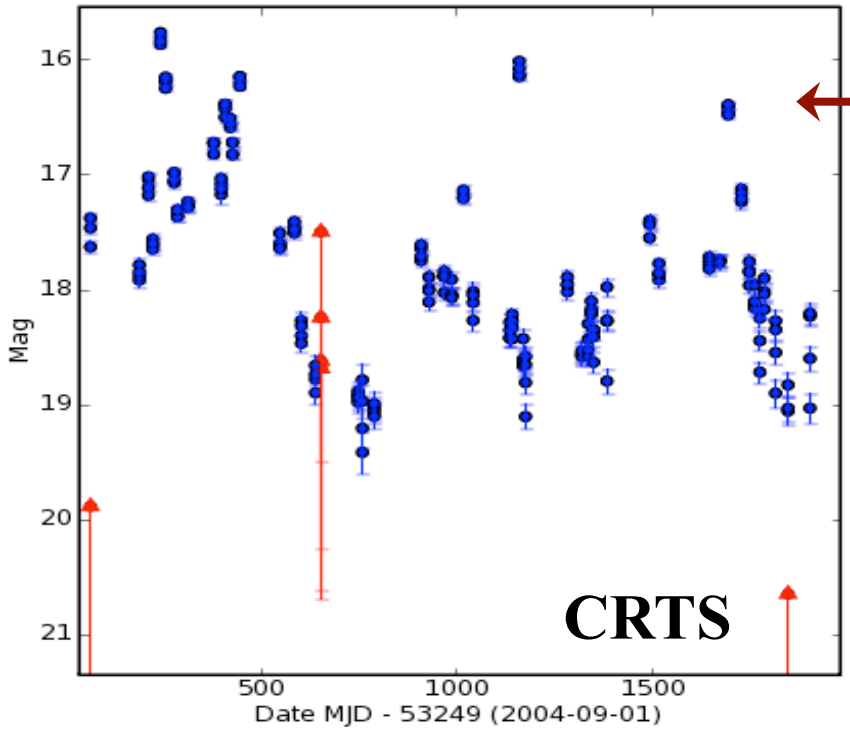
Follow-Up Observations:

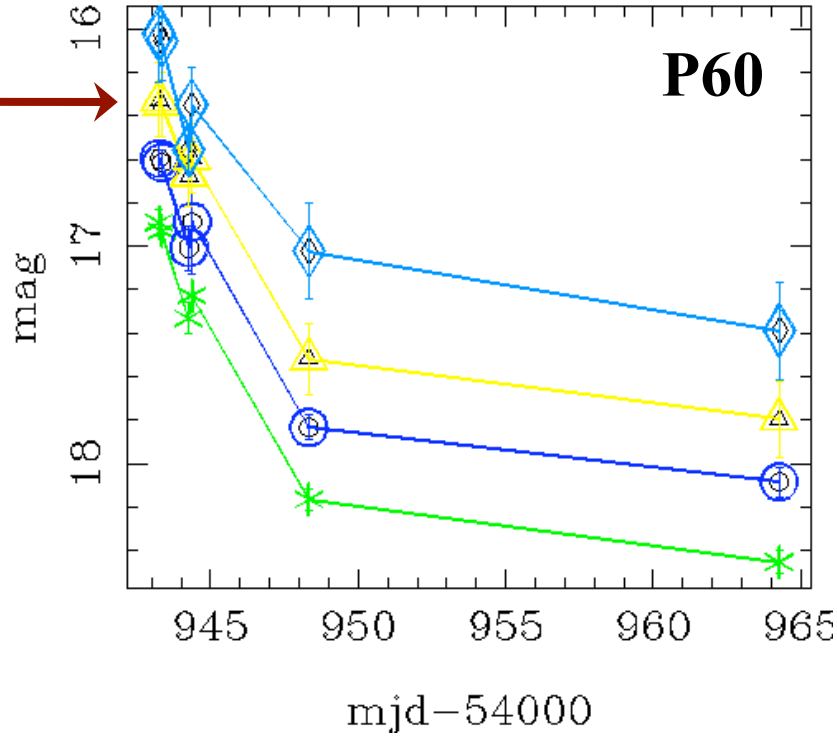
Lead: A. Mahabal

- Photometry (P60, NMSU, DAO, HTN, India, Mexico, etc.)
- Spectroscopy (Gemini N+S, Keck, P200, SMARTS, IGO, MDM)

CSS090421:174806+340401
A blazar, also monitored at OVRO in radio

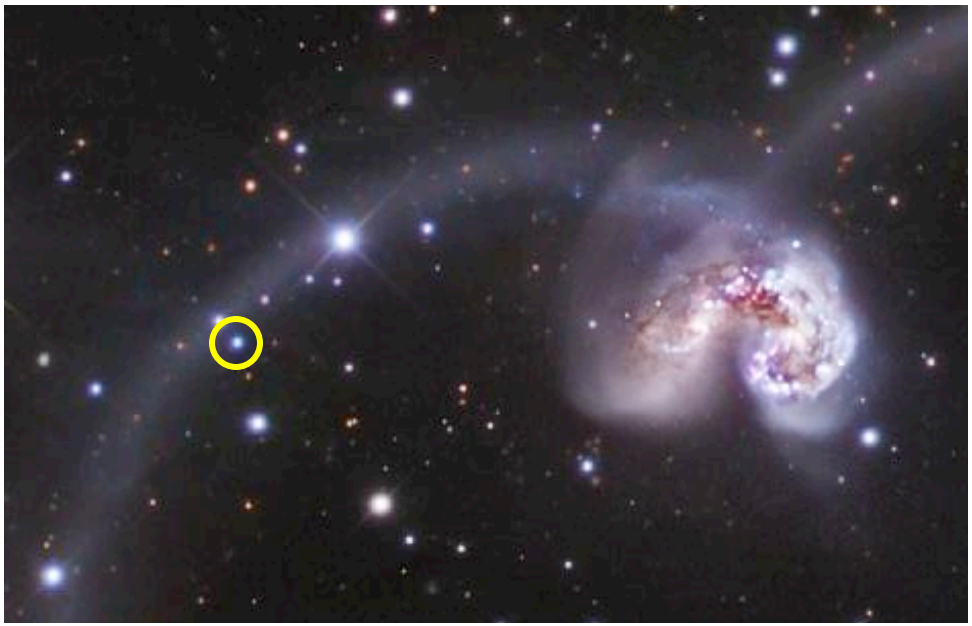


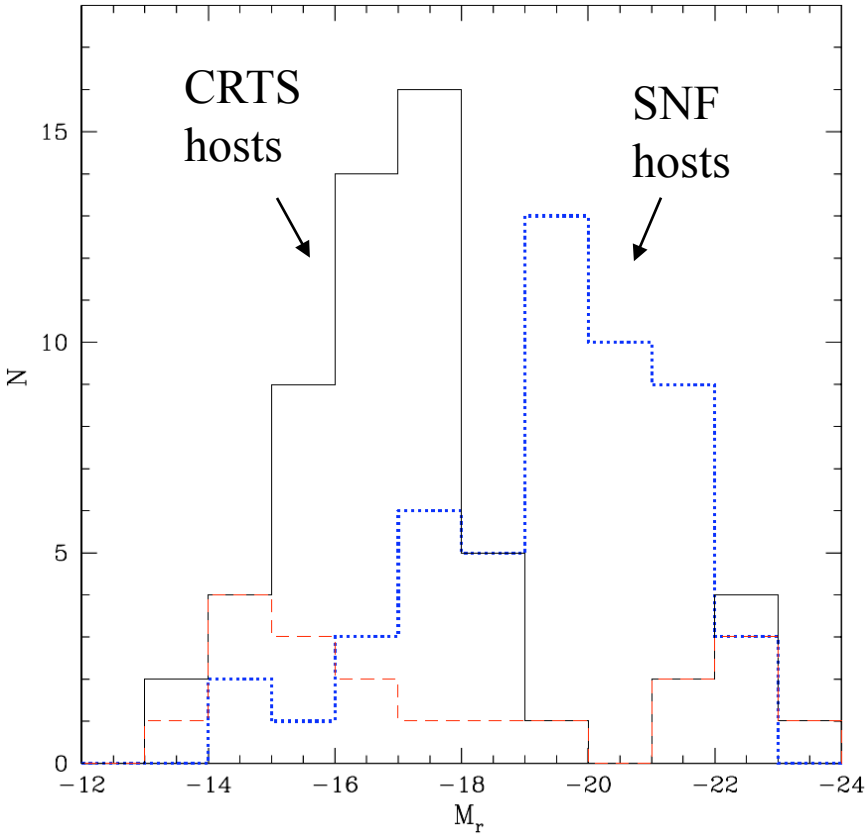




CRTS Supernova Discoveries

- More SNe published in 2009 than any other survey
- Extremely luminous and possible pair-production SNe (e.g., SN 2007bi, 2008fz, 2009jh)
- Extremely long time-scale SNe, e.g., 2008iy
- SNe associated with very faint host galaxies

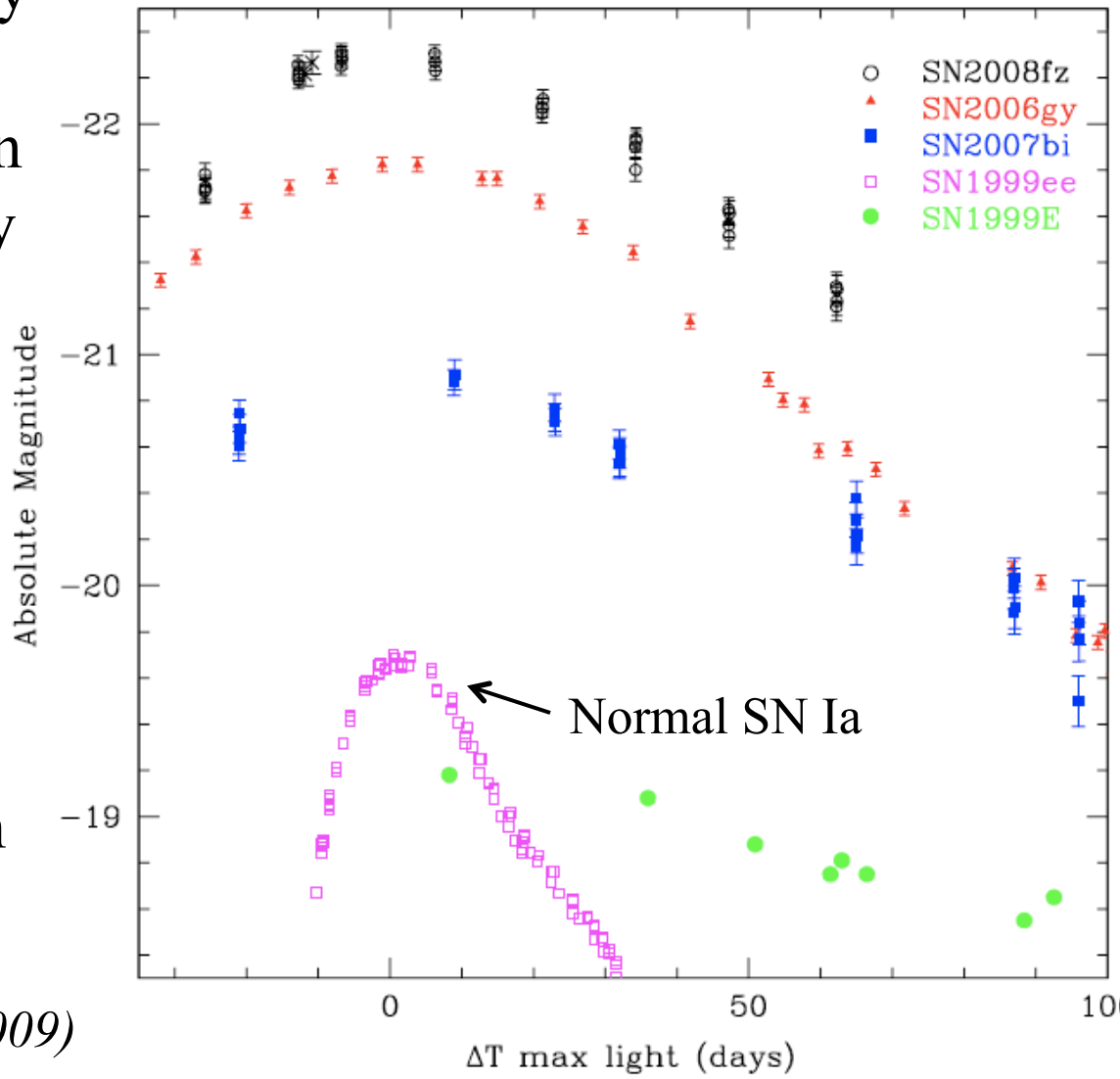




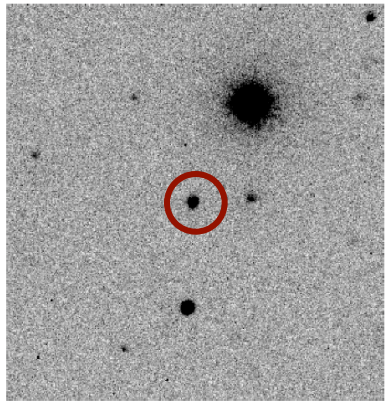
⇦ CSS 071218:120153-185822 = SN 2007sr: Ia in the Antennae merger

2008fz: The Most Luminous Supernova

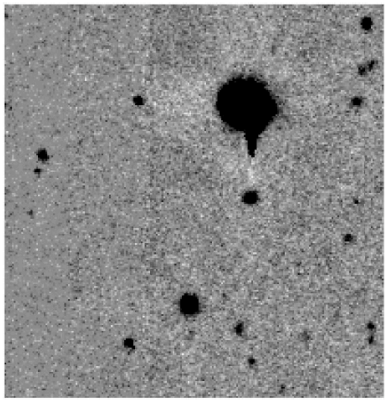
- Brightest type IIn known (5 times brighter than the Milky Way)
- Host galaxy > 50 times fainter than Milky Way
- A possible example of a pair-production SN?



Discovery



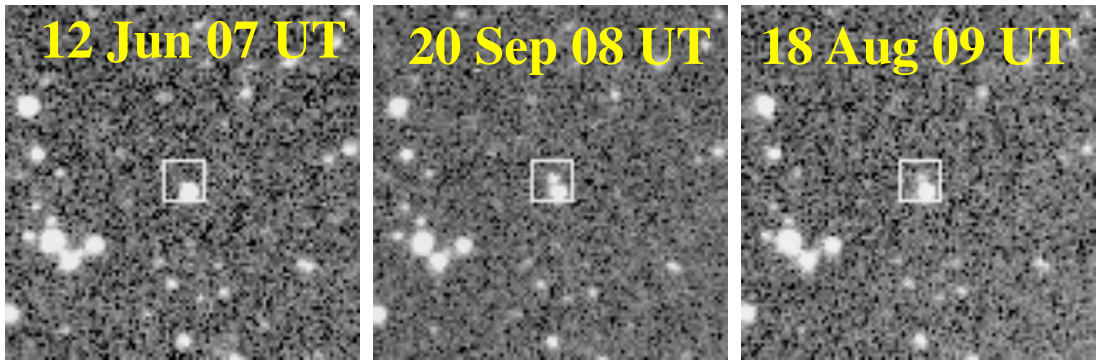
Comparison

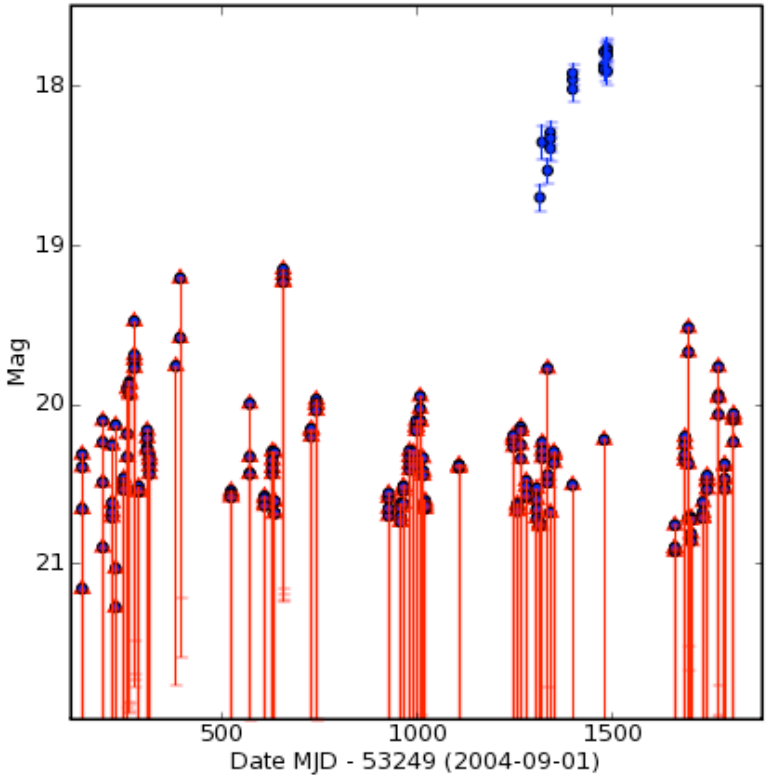


(Drake et al. 2009)

The Slow SN 2008iy

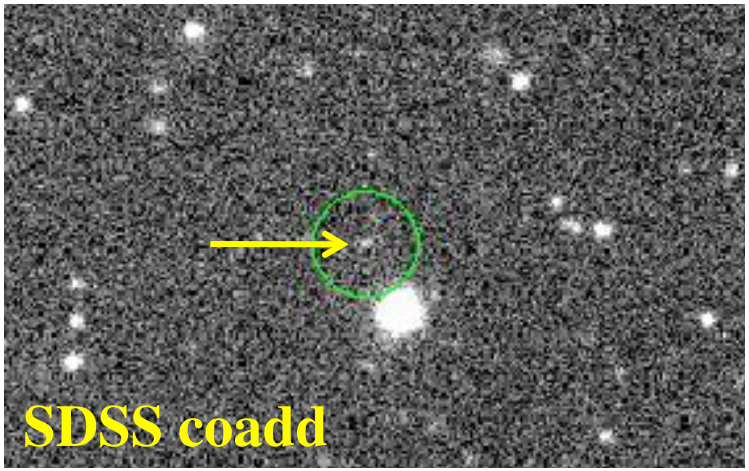
= CSS080928:160837+041627



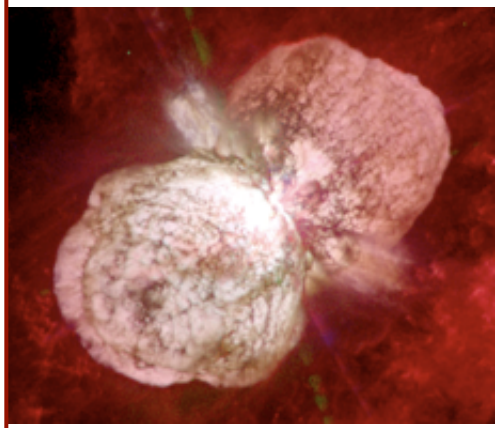


Longest-lasting type IIn at z = 0.041
it took **> 400 days** to reach the peak!

Host galaxy **> *500 times fainter*** than the Milky Way (M ≈ −13)



Possibly from an ~ η Carinae type progenitor: expanding SN interacts with the material from past outbursts

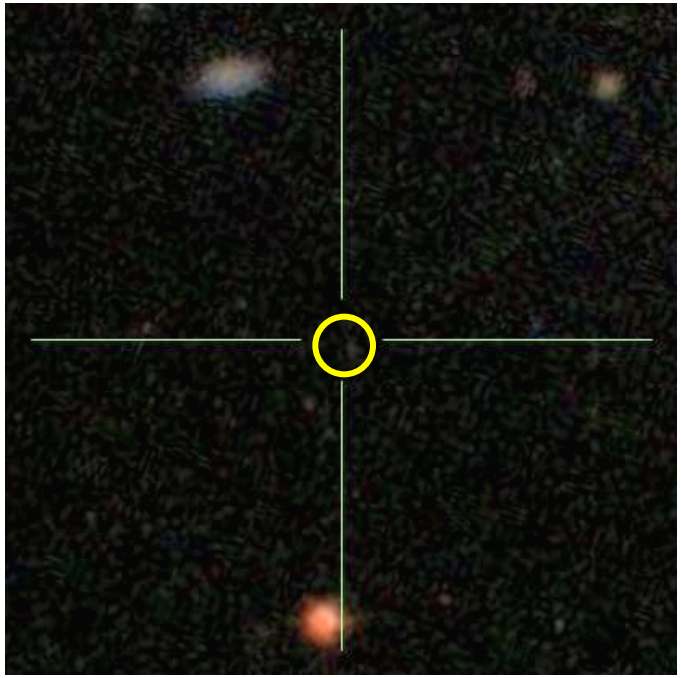


Luminous SNe in Underluminous Hosts

- A number of SNe discovered in extremely faint dwarf galaxy hosts (M ≈ –12 or –13), e.g., 2008fz, 2008iy, 2008hp, 2009aq, etc.

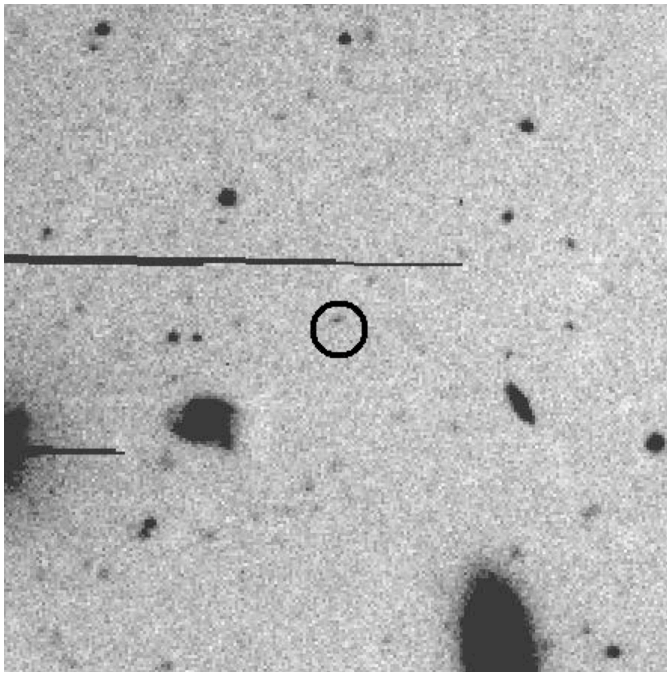
  ⇨ Huge specific SN rates (per unit stellar mass)

- Many are hyperluminous SNe ⇨ massive star progenitors?
- Low mass host ⇨ Low metallicity ⇨ Top-heavy IMF ??
- Possible connection with GRB hosts? Local Pop. III analogs?



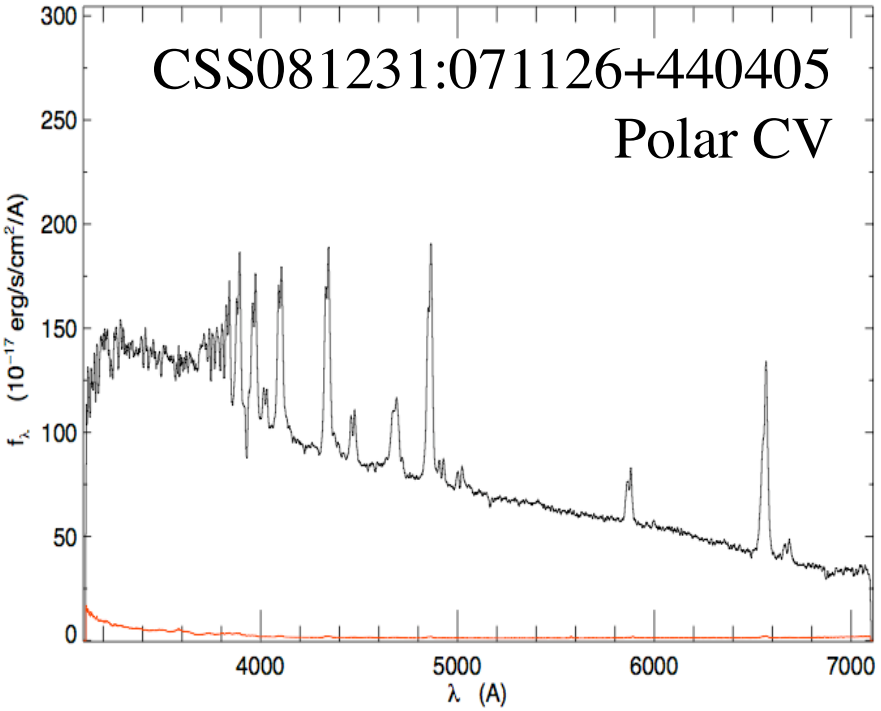
⇦ SN 2008hp
Host $M_r \approx$ –12.4

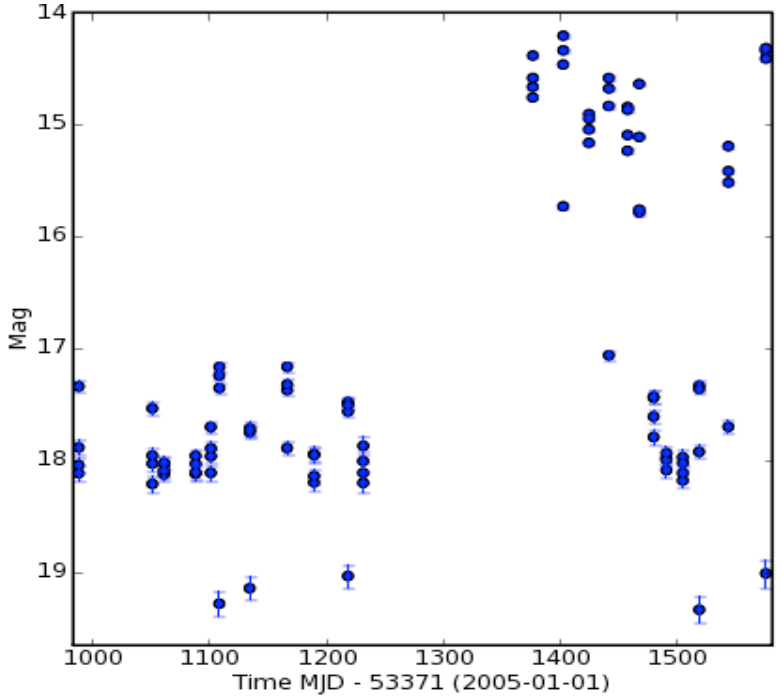
SN 2009aq ⇨
Host $M_r \approx$ –13



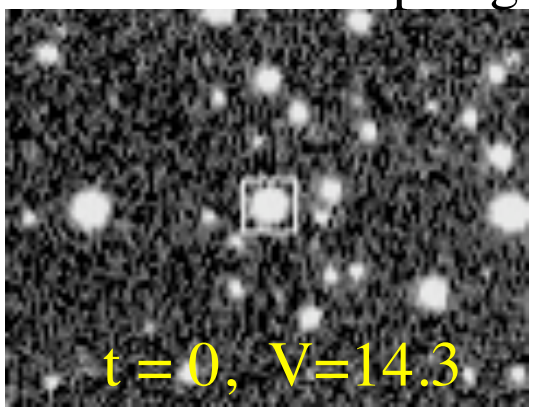
Cataclysmic Variables and Dwarf Novae

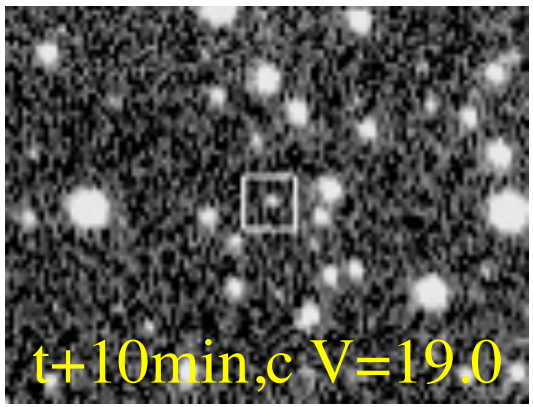
Over 500 detected so far, > 75% are new discoveries

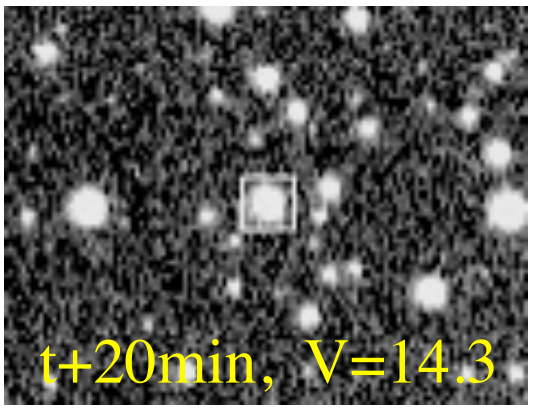




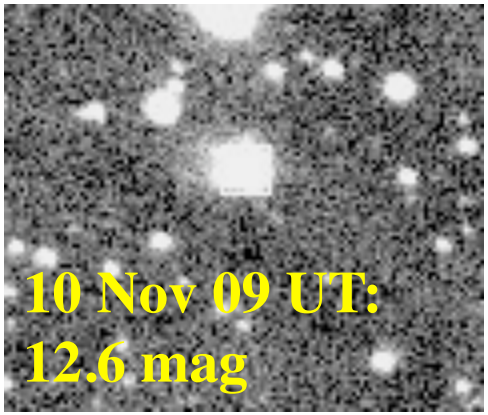
Eclipsing Polar CSS081231:071126+440405

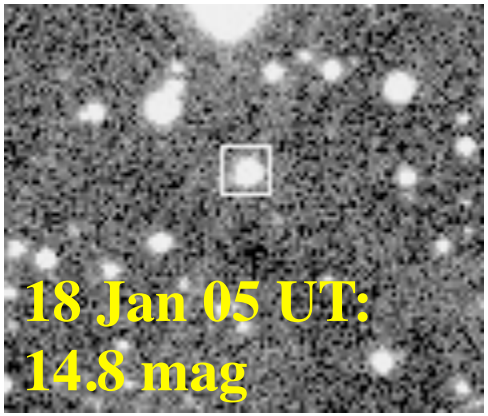


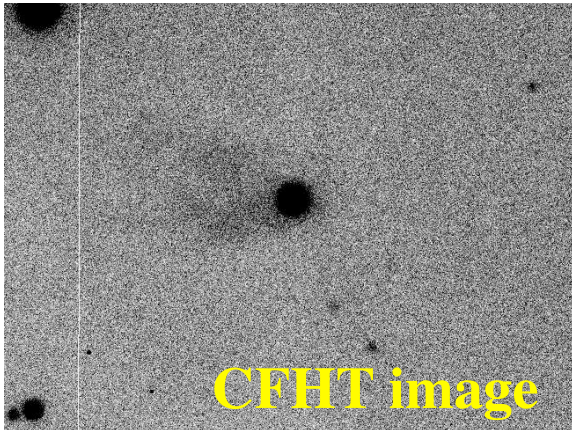


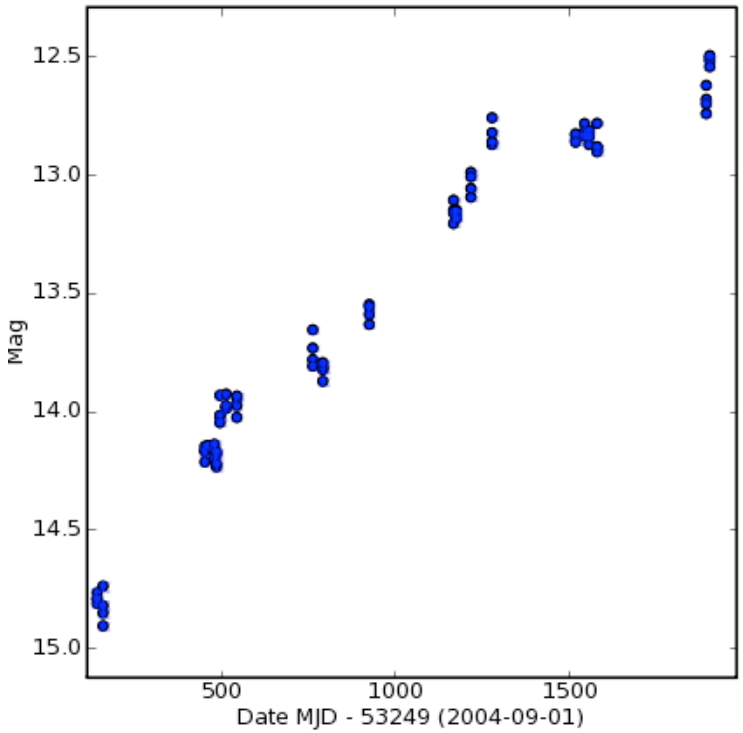


Discovery of a New FU Ori Object



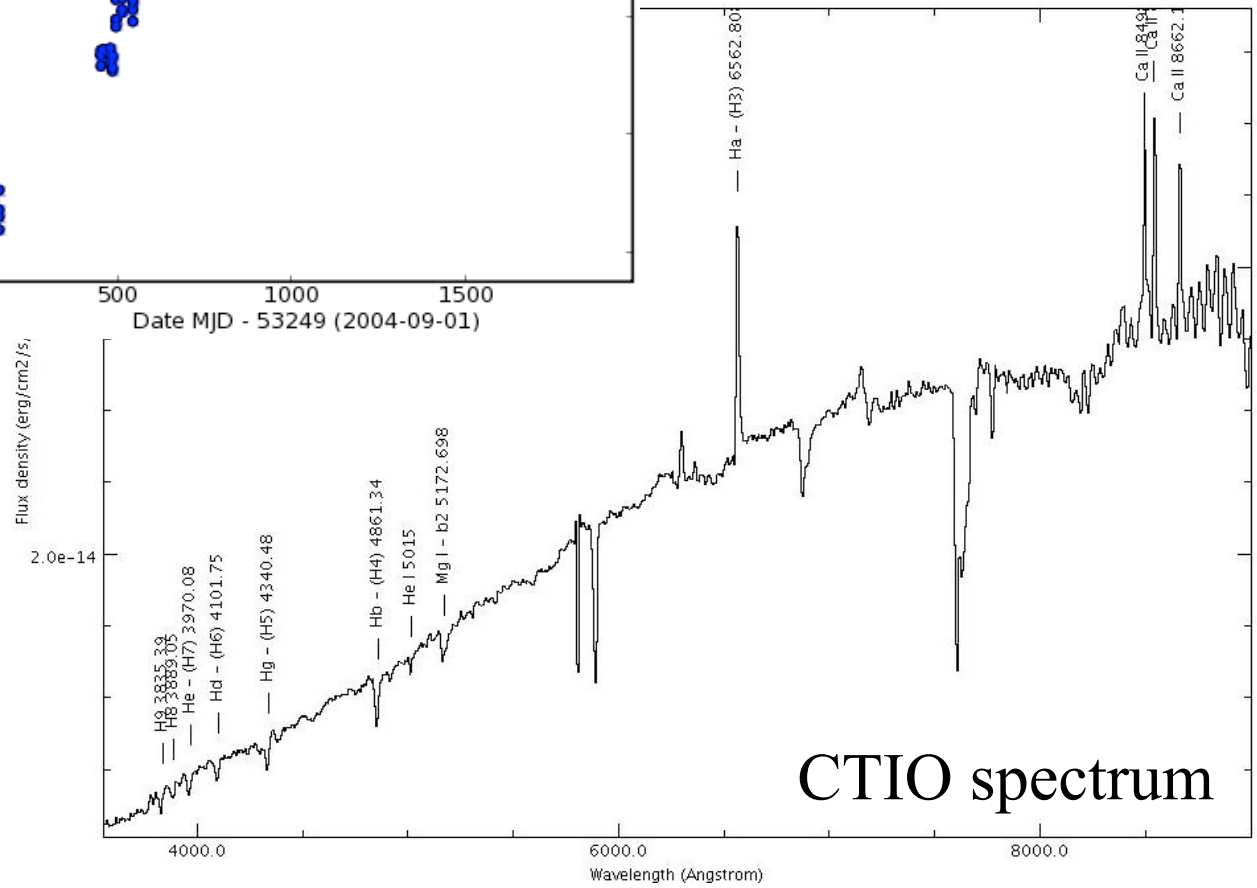






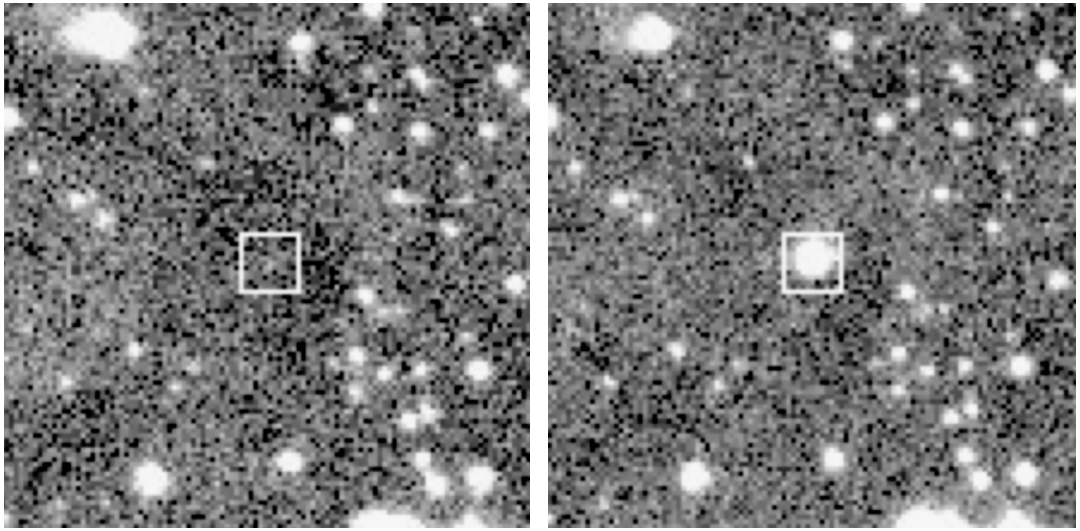
IRAS 06068–0641 =
CSS091110:060919–064155

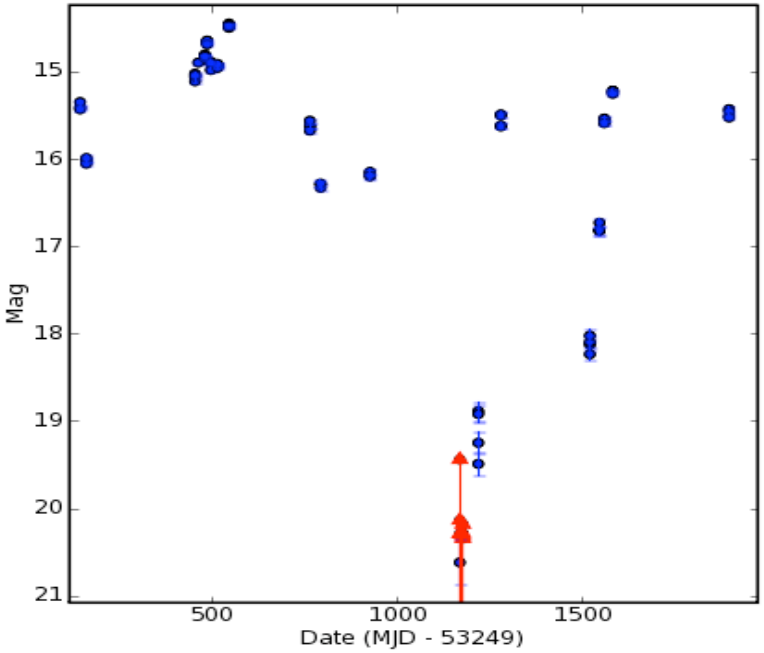
Wils et al. ATel 2307



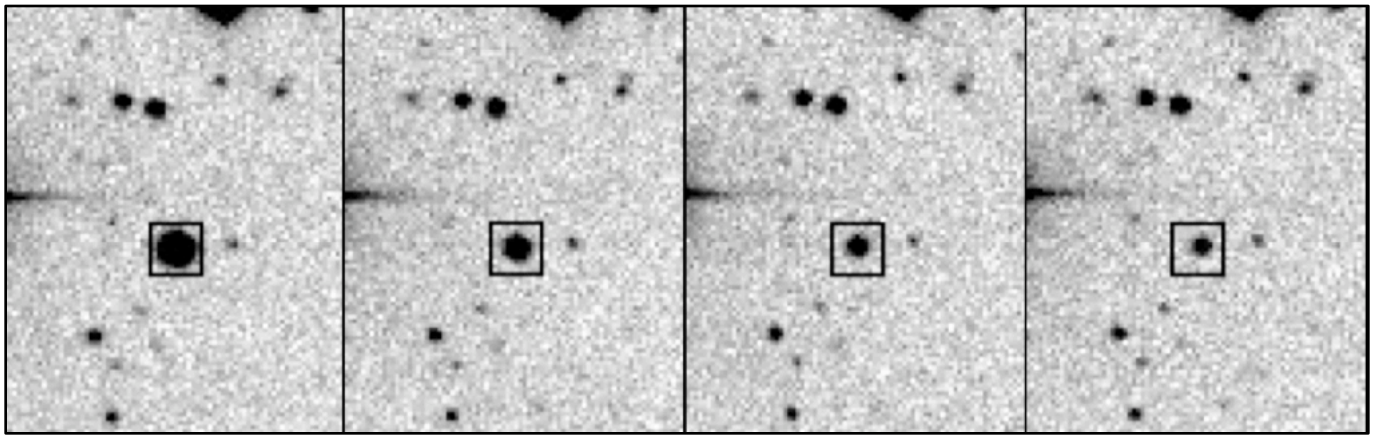
Unsettled Stars

IRAS 06068–0643 (UX Ori type) young star

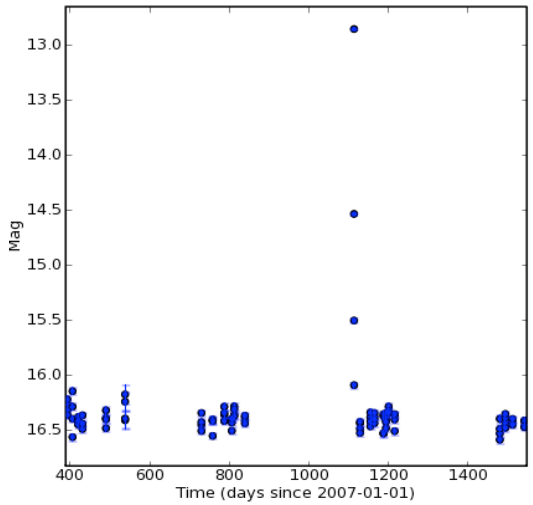




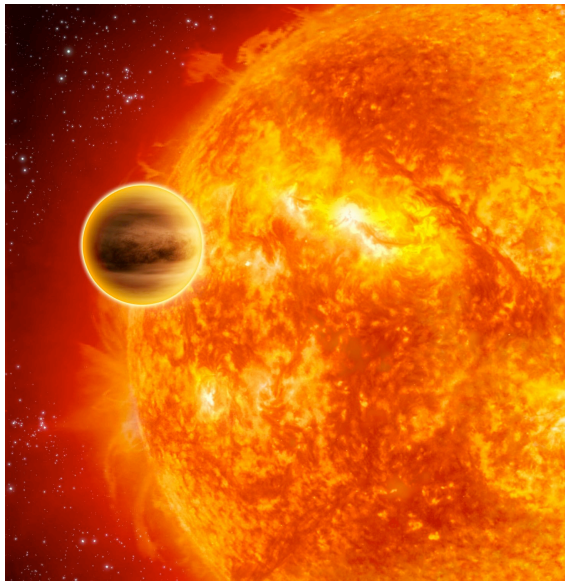
Fast transient (flaring dM), CSS080118:112149–131310
4 individual exposures, separated by 10 min



Light curve

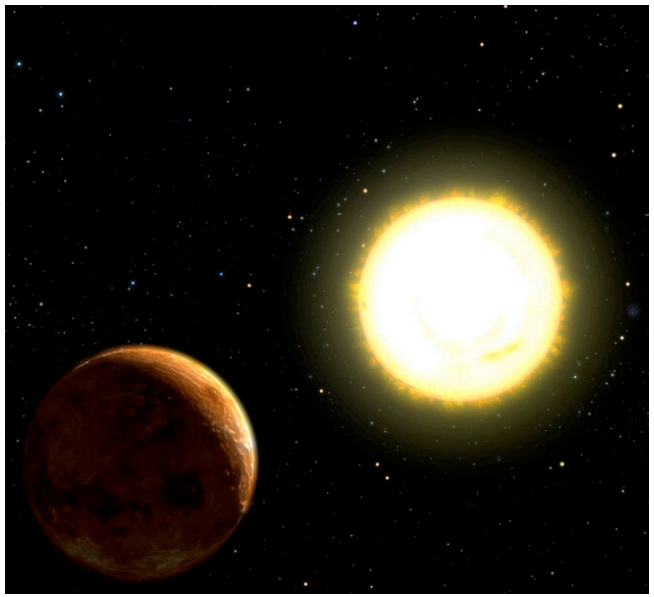


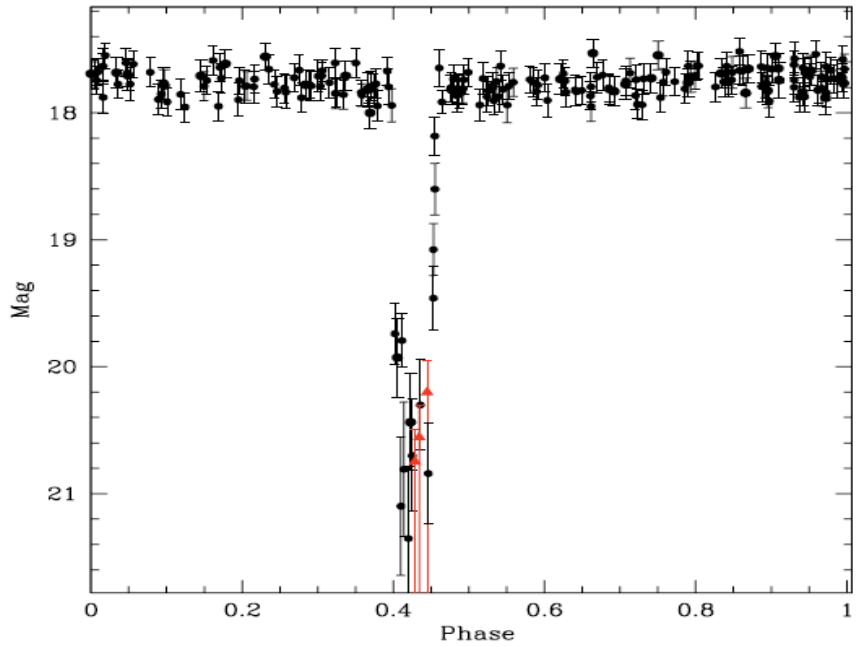
Eclipsing White Dwarfs: Planets?

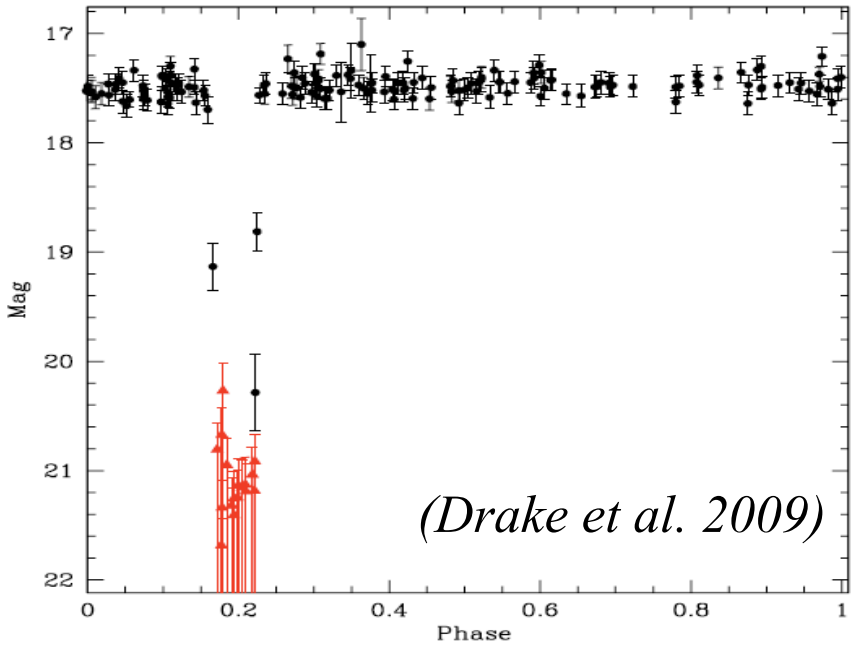


Earth-like planets cause ~ 10^{-4} eclipses for the main-sequence stars…

But it could be ~100% eclipses for the white dwarfs!

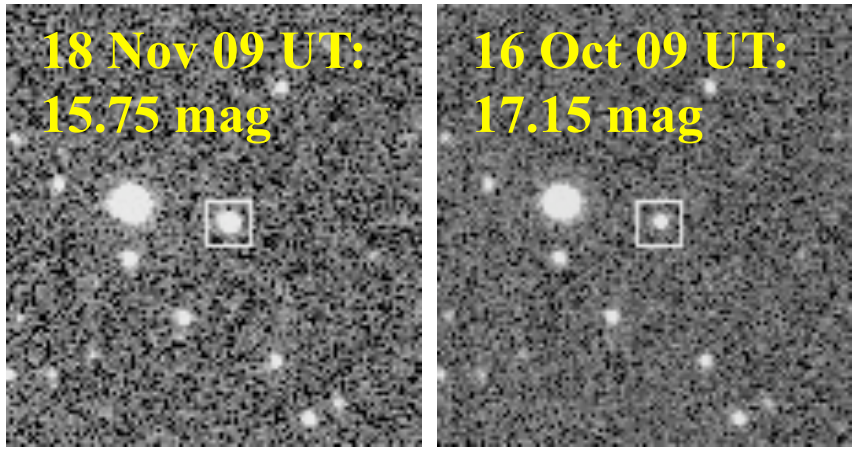


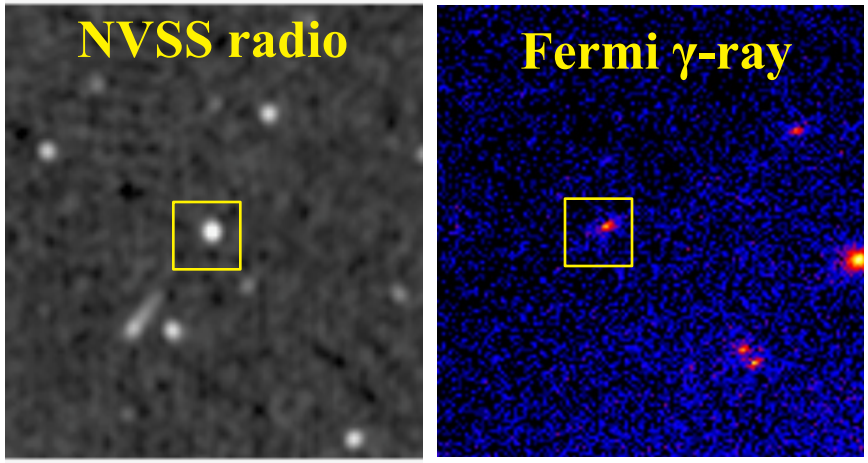


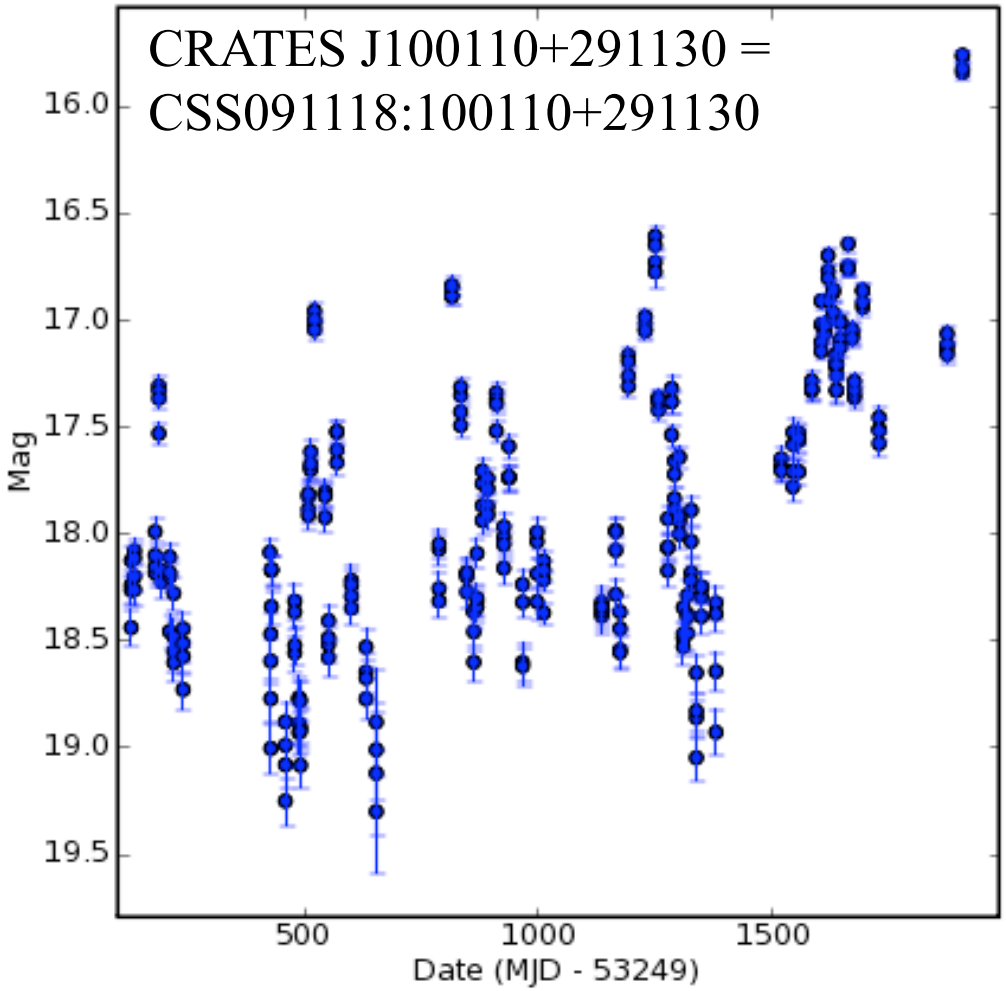


(Drake et al. 2009)

Flaring Blazars from CRTS

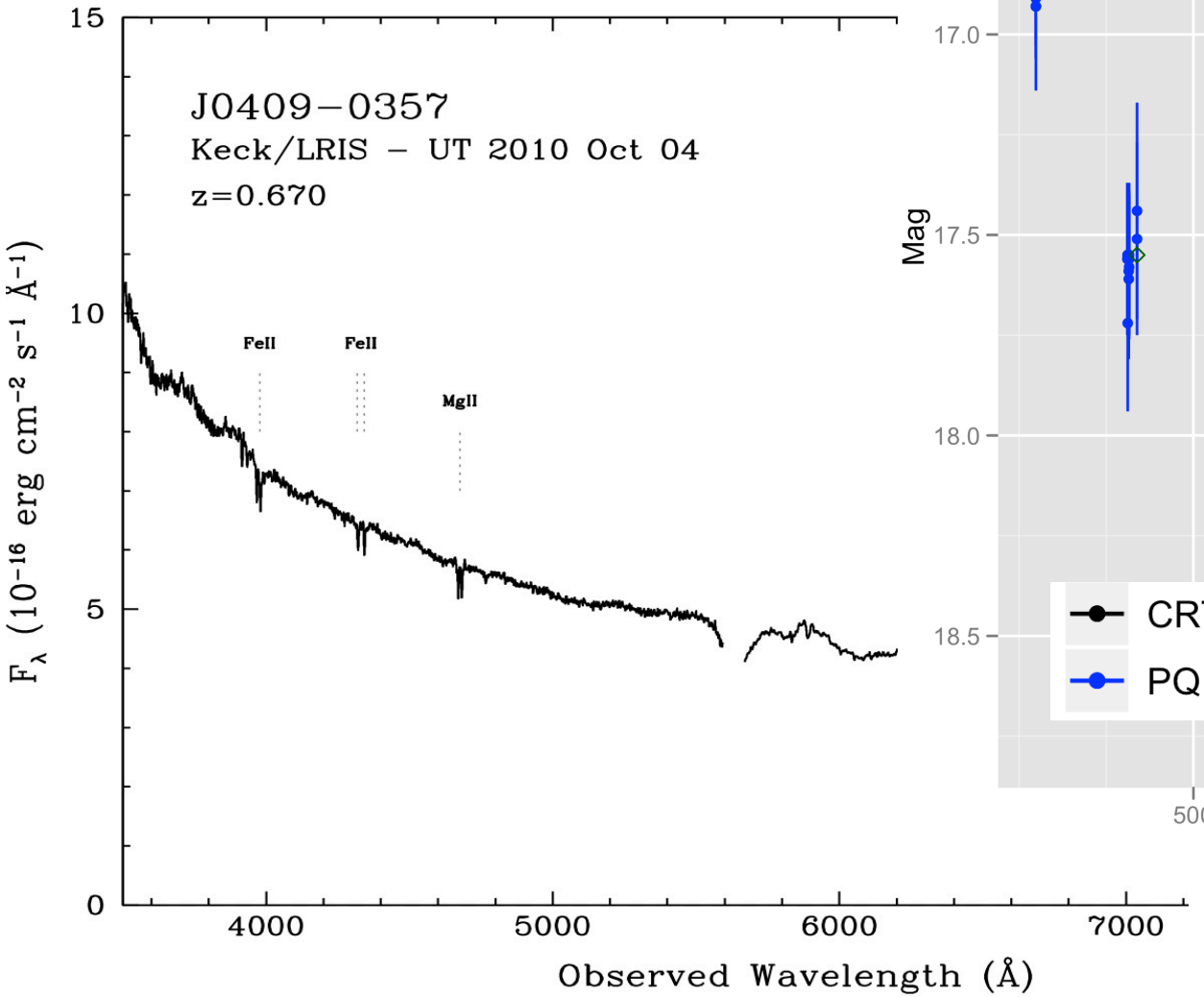


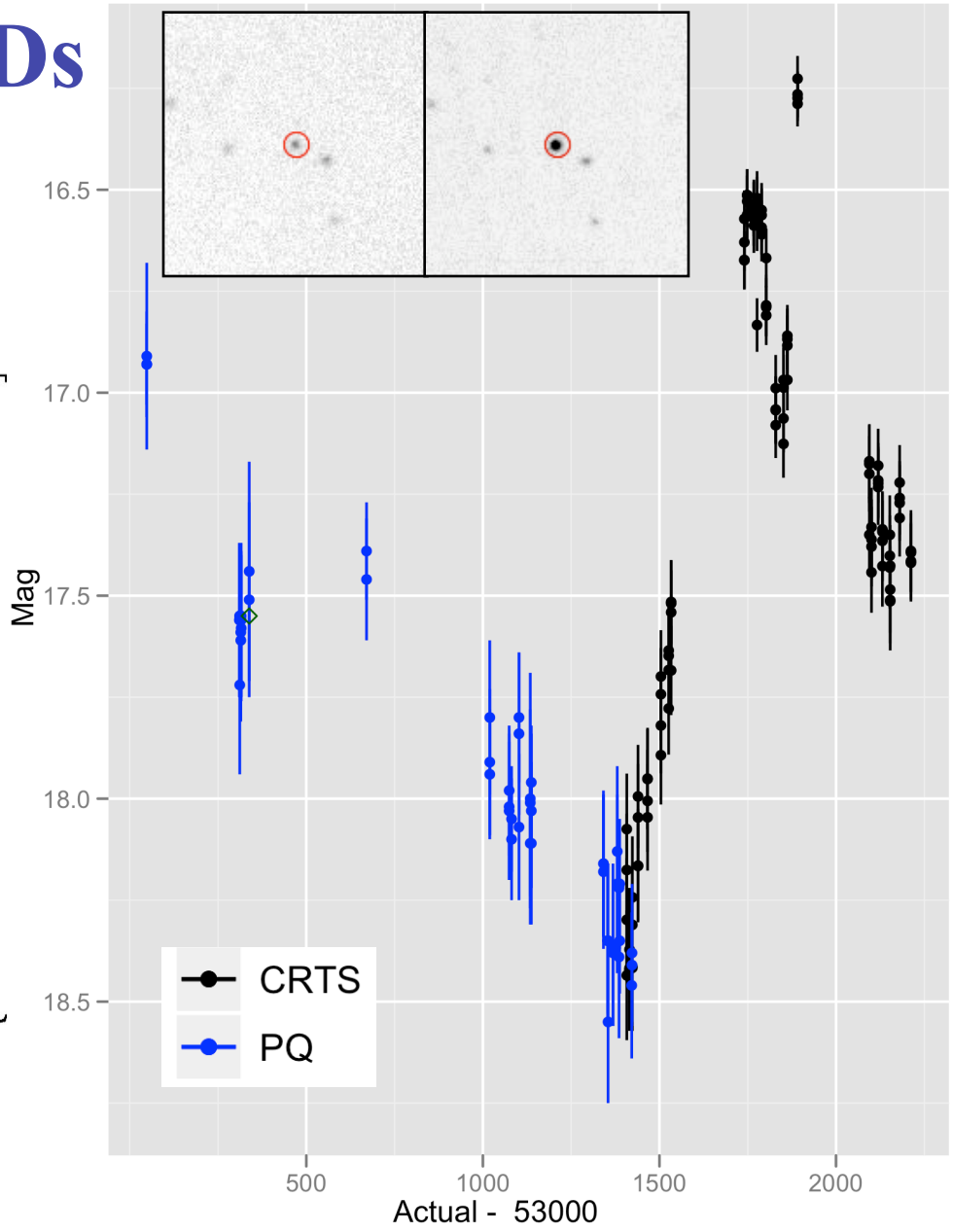




- Correlating blazar light curves from the visible, radio, and γ-rays, in order to constrain physical models
- Real-time correlated blazar flare discovery with CRTS+FGST

Variability-Selected IDs for the Unidentified Fermi LAT Sources

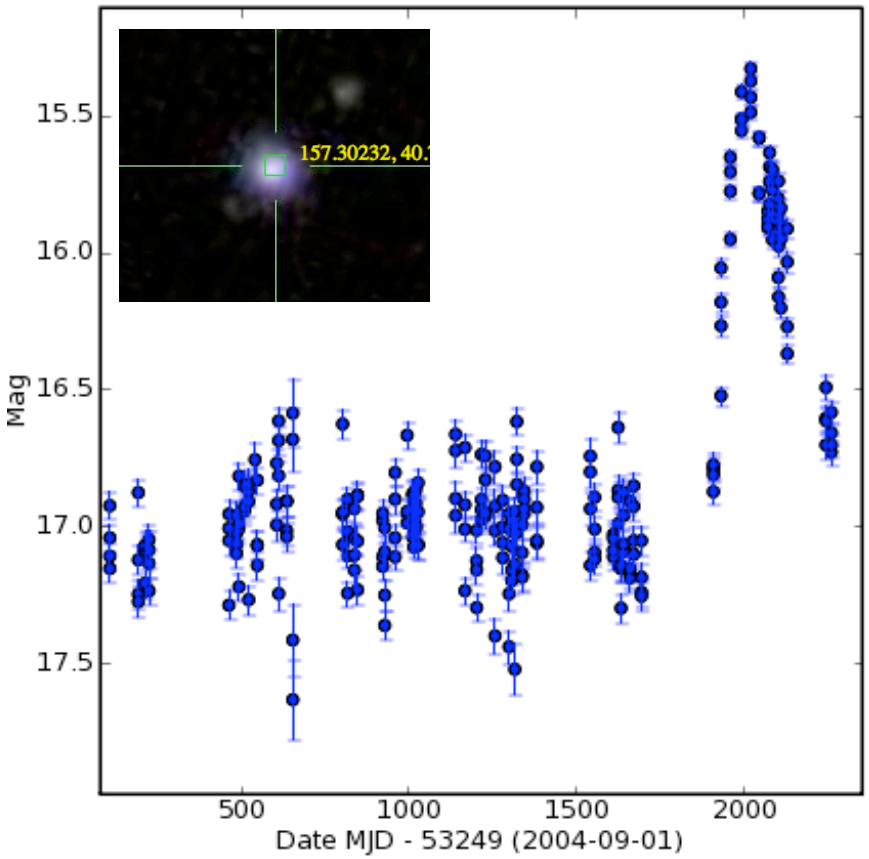


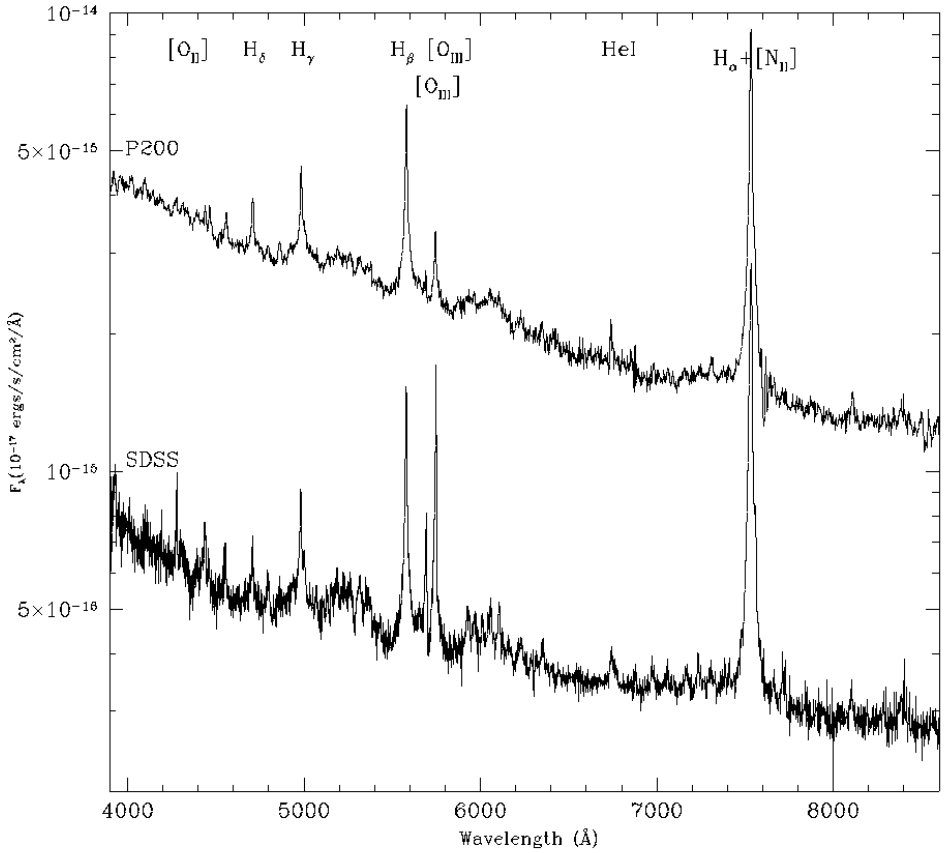


(Mahabal et al.)

The Mystery Event CSS100217:102913+404220

Drake et al. 2010, ATel 2544, and in prep.



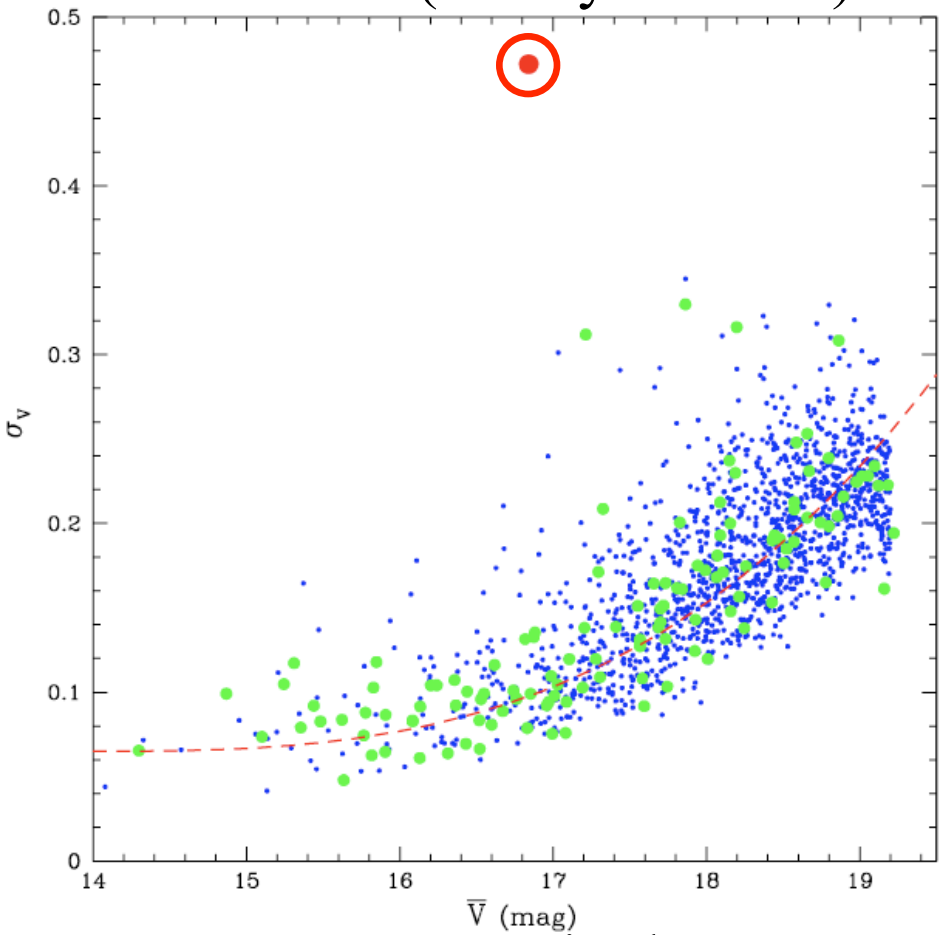


- Transient in a narrow-line Seyfert 1 (NLS1) galaxy at $z = 0.147$
- Peak $M_I \approx -23$ mag, integrated visible luminosity $> 6 \times 10^{51}$ erg
- *SWIFT* and *GALEX* ToO obs. exclude a "traditional" TDE

Could it be just an AGN variability? No.

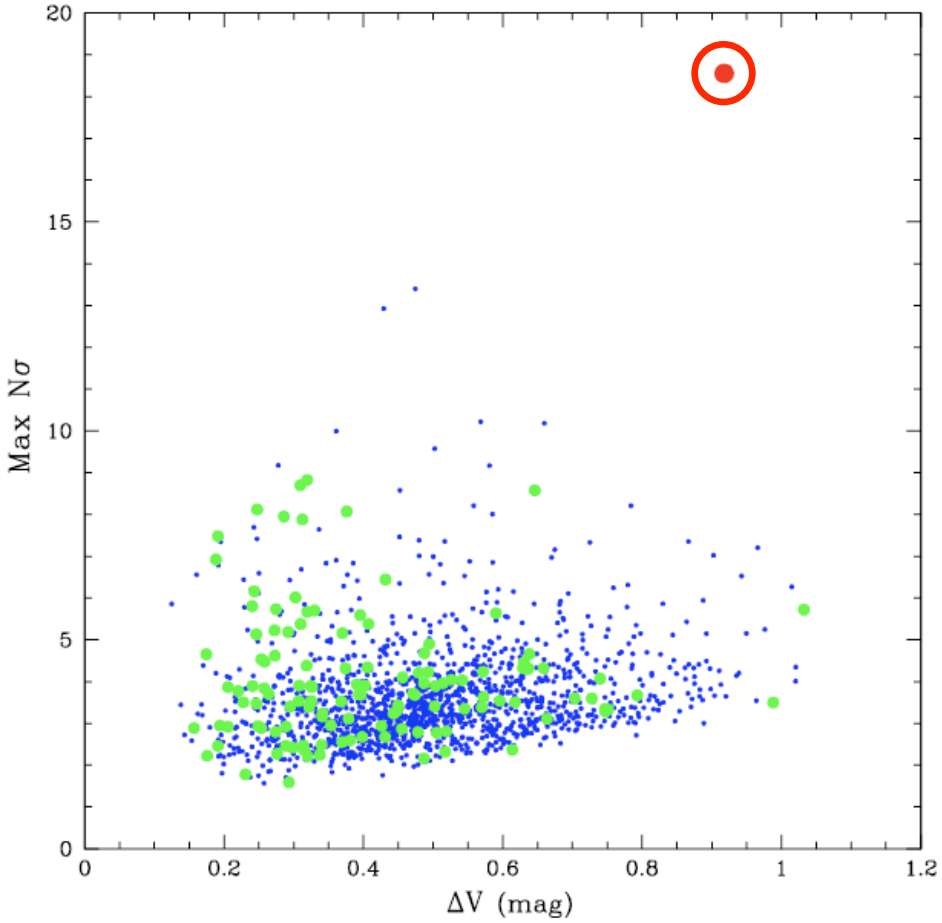
CSS100217 • Radio-loud NLS1 ▪ Radio-quiet NLS1

Variance (90 day window)



Mean magnitude

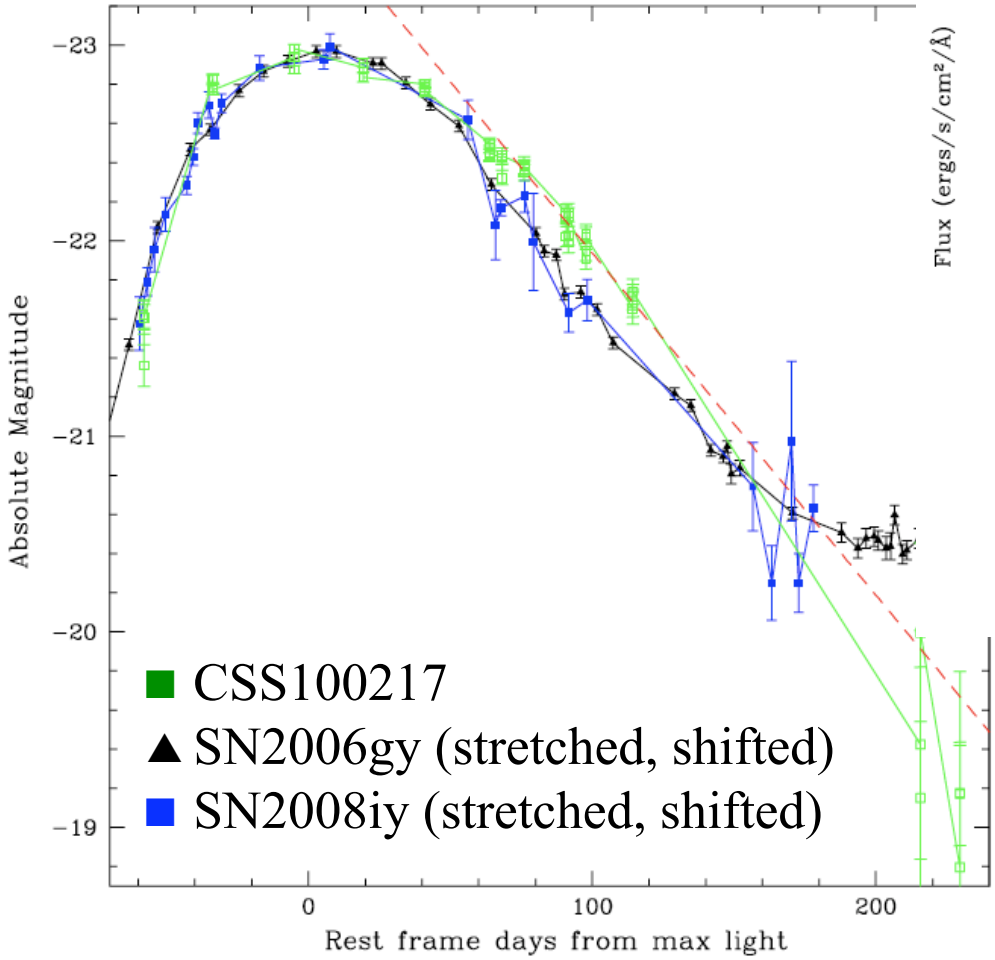
Maximum Nσ deviation

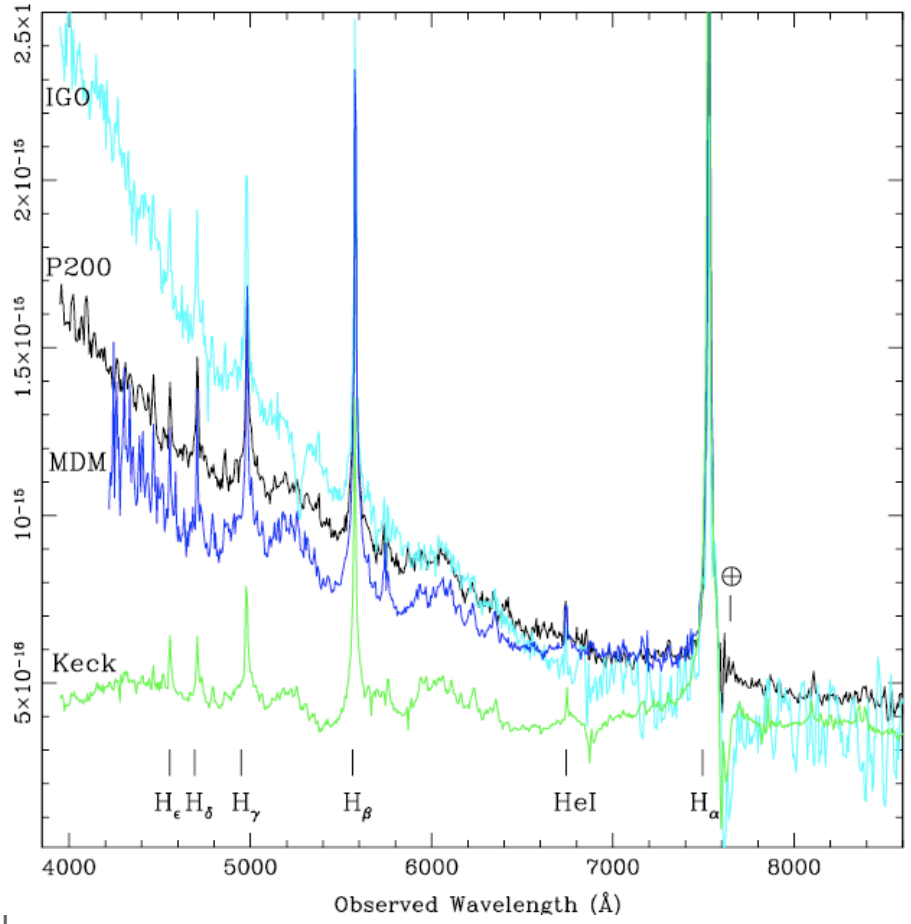


Maximum magnitude jump

Light curve and spectra typical of a SN IIn

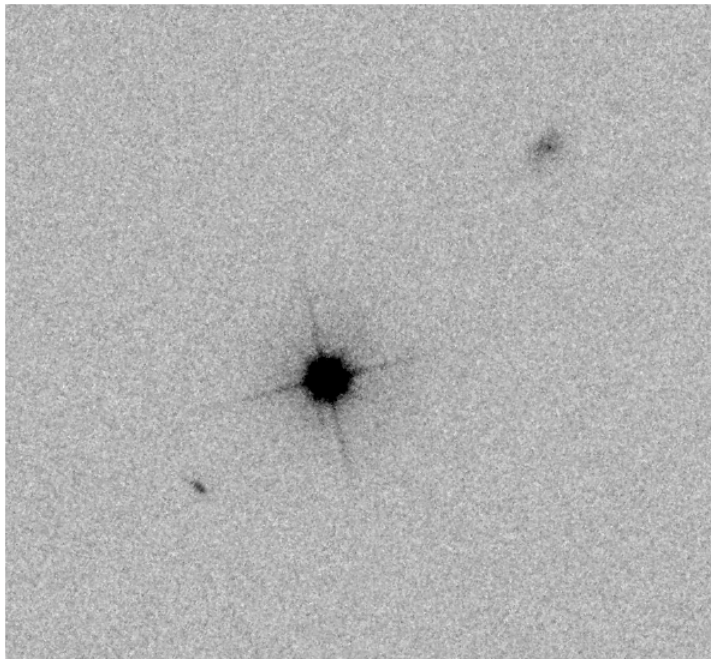
Evolving spectra ⇨
(host & AGN subtracted)





⇨ **The most luminous SN ever seen!**

The Nature of CSS100217



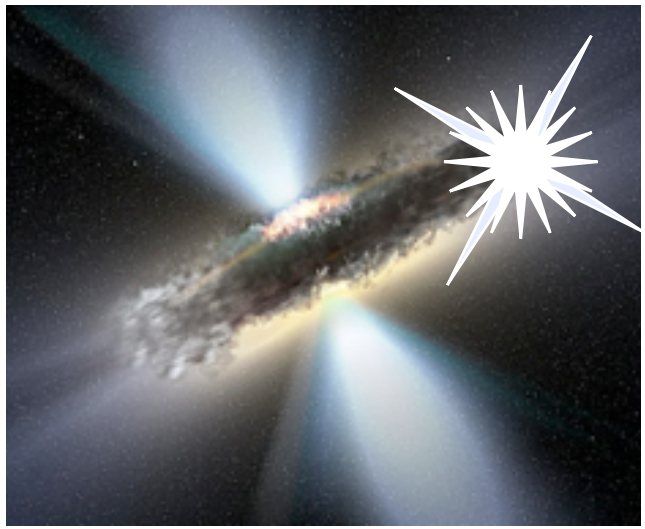
HST ToO and Keck AO+LGS imaging shows a single, unresolved point source

⇨The event occurred within ~ 150 pc from the AGN

No morphological indications of star forming regions outside of the unresolved nucleus

Vicinity of an AGN is not conducive to star formation, except…

… near the outer edge of the accretion disk, which is shielded from the UVX radiation, and should be violently unstable

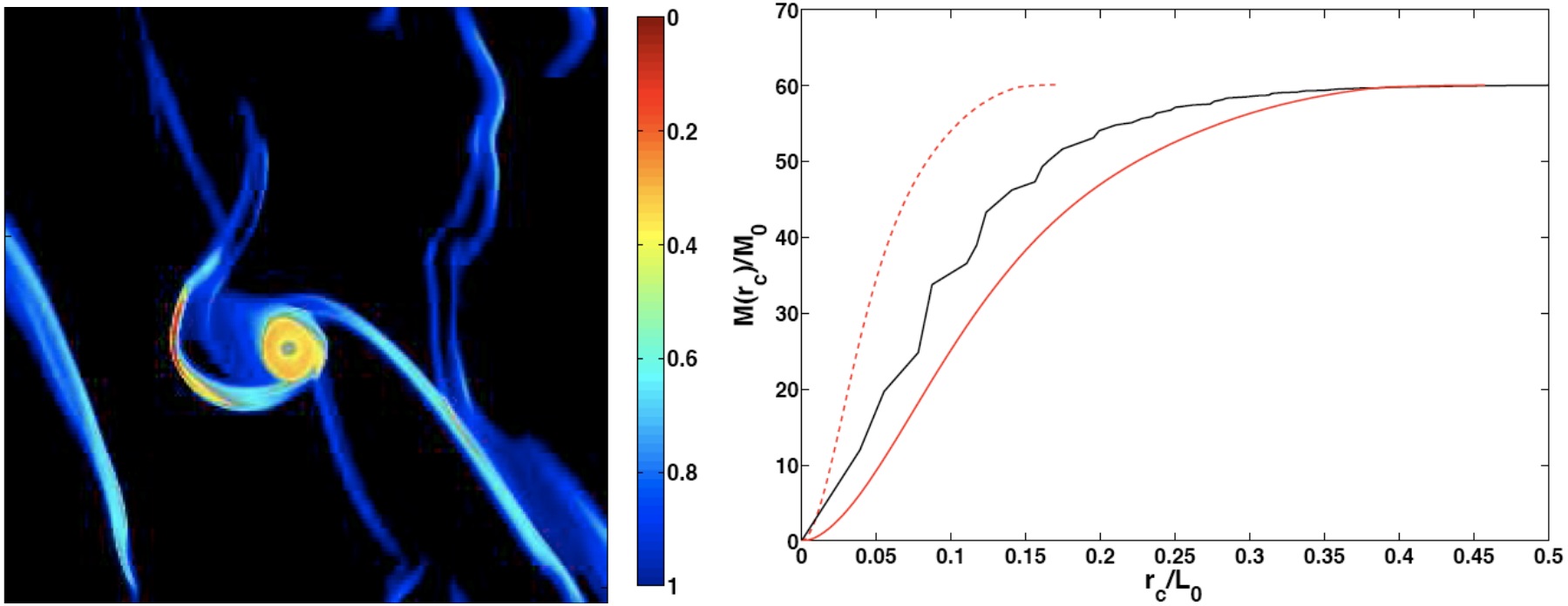


The first case of a SN from an AGN accretion disk?

Star Formation in AGN Accretion Disks

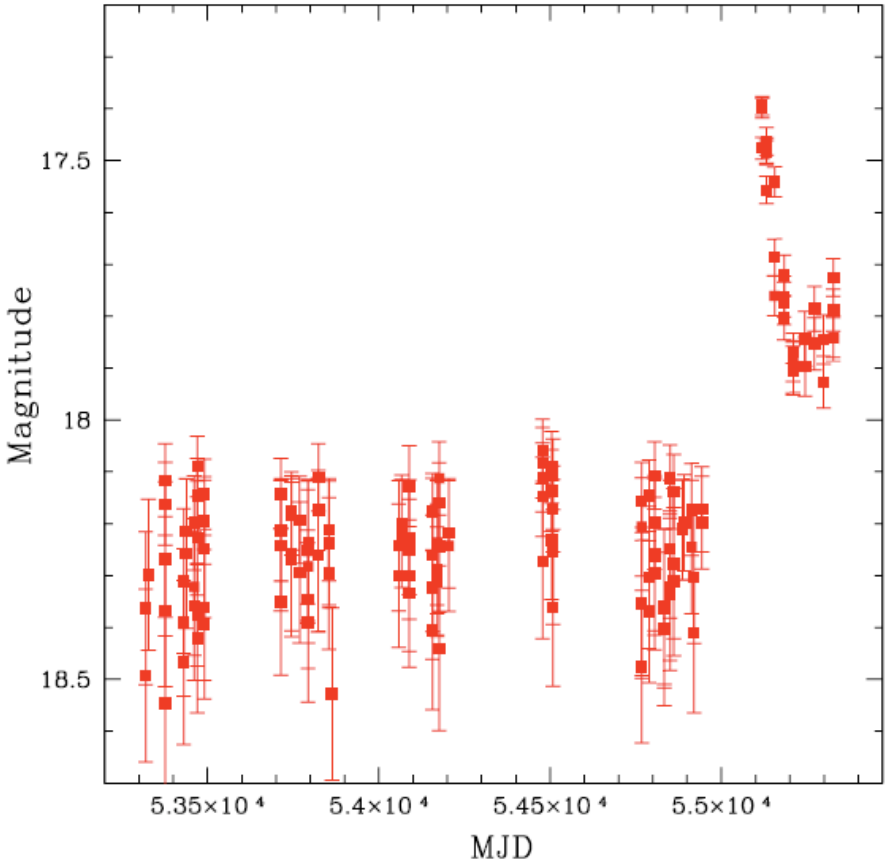
- Predicted by the theory: Shlosman & Begelman (1987, 1989)
  - Possible origin of the young stellar population in the Galactic center
- Supported by the modern numerical simulations (Goodman 2003, Goodman & Tan 2004, Jiang & Goodman 2010)
- Should be relatively common, but traditional SN searches discriminate against any AGN-associated events

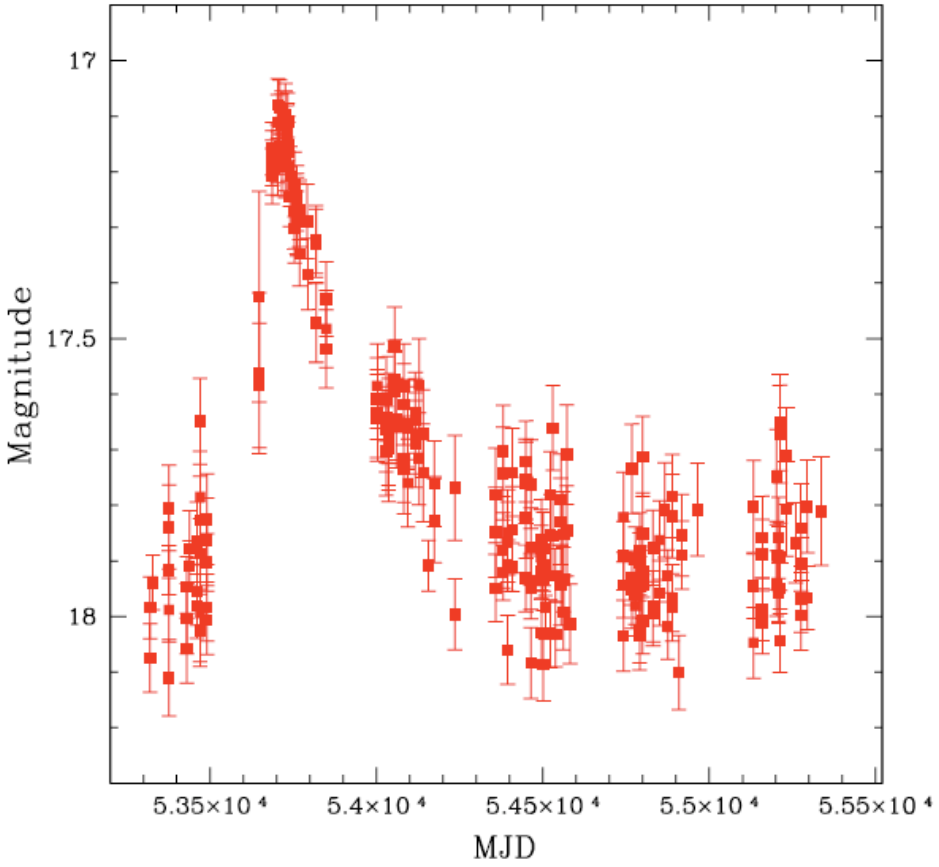
Formation of a ~ 60 $M_\odot$ star in a QSO accretion disk, from Jiang & Goodman 2010



There May Be More Like This

Possible SN events in low-*z* NLS1 galaxies





To be continued…

Summary

- Time domain astronomy is a vibrant research frontier, from Solar system to cosmology and extreme relativistic phenomena
  - Synoptic survey data streams feed a broad variety of studies
  - They are scientific and technological precursors / testbeds for the next generation of surveys, e.g., LSST, SKA
- Catalina Real-Time Sky Survey (CRTS) delivers a steady stream of publicly available transient events in real time
  - Exciting science, especially in the SN studies so far
  - Possible new class of transients: SNe from AGN accretion disks
  - Spectroscopic follow-up is a key bottleneck, and will get worse
  - Automated transient classification is a key challenge

We welcome new collaborations!