The Palomar Transient Factory and the Discovery of Incredibly Young Supernovae

Peter Nugent (LBNL/UCB)
Why search for supernovae?

Unless you get very lucky (repeatedly), dedicated searching is the only way to guarantee enough objects to study the death states of stars.

Historically, until 1989, the main goal was an effort to better understand the physics behind these events.

- Nuclear physics in extreme environments
- Radiation transport with important relativistic terms
- Shock physics
- Metal enrichment of ISM, stellar formation, feedback...

Presently, for better or worse, supernova searches are dominated by the lofty goals of cosmology.
Classification

They are primarily classified based on spectroscopy near peak brightness and subsequently on their photometric evolution.

- **Type IIP** - Plateau lightcurve
- **Type IIL** - Linear lightcurve
- **Type IIn** - narrow H lines
- **Type Ia** - Strong Si II and S II lines
- **Type Ib** - Weak Si II and He I lines
- **Type Ic** - Weak Si II (GRB-SNe)

[Graph showing different types of lightcurves and spectral features]
How hard are they to find?

Rates:

Typically you have about 1 SN/MW-like galaxy/century.

Or in other words about 1 core-collapse SN per year within 7 Mpc and 1 Type Ia SN within 15 Mpc.

Given that the faintest SNe are around $M_V = -14$, to survey this volume completely for all types of supernovae one has to conduct a survey of the entire sky every week to an apparent magnitude of 17, what a 0.5-m telescope can do in 30s under an average sky conditions...covering the northern and southern hemispheres this would take 4 telescopes and perfect weather.
So what do astronomers do?

They cheat...

- Go for more volume by only going after the brightest SNe.
- Look less frequently, thus they go after the SNe that are brighter for a longer amount of time.
- Target specific galaxies so as to fill up their field of view with as much mass as possible.
Steady up to 1990...

- SNLS + SNf (100/yr)
- SNf and SDSS
- High-Z Searches
- KAIT
- Calán-Tololo Search
- Zwicky + Amateurs
SN 1987A and 1988U

IMHO these two supernova, coupled with one paper, were responsible for the massive upswing in dedicated supernova searches.

SN 1987A greatly expanded the number of astronomers and physicists studying supernovae. Thus after the hoopla died down on this one, there was a demand for more.

SN 1988U (Noergaard-Nielsen, et al.) was the first SN Ia discovered at an appreciable redshift for cosmology beyond $H_0$. 
Phillips (1993)

The “Phillips’ relationship” for Type Ia supernovae - broader lightcurves mean brighter supernovae - opened the door to precision cosmology. One could now measure distances to SNe Ia to 7%!

Well gee... given how bright they are and how well I can measure distances to them. “Please TAC of telescope X, give me ungodly amounts of time to measure the cosmological parameters from supernovae.” And it was done... triggering searches at both high and low redshift.
Calán-Tololo Survey

- Started in 1990 using the Curtis Schmidt telescope at CTIO with the goal of getting a sufficient sample of low redshift SNe (both Ia’s and II’s) in the smooth Hubble flow to measure $H_0$ and peculiar velocities.

- 5X5 degree field of view - still the largest to date (ZTF will be next)!

- Used photographic plates with 15min exposures of 60 fields over 3-5 moonless nights - limiting magnitude of 17-19

- Searched with a monthly cadence, blinking!!!

- Found 40+ SNe in 3 years.
Supernovae circa 1995

Result: ~24 Type Ia supernovae discovered while still brightening at new moon.

Almost 1000 galaxies per field

50–100 fields

Scheduled follow-up spectroscopy at Keck

Scheduled follow-up imaging at Hubble, Cerro Tololo, WIYN, Isaac Newton
Supernovae circa 1998

The 4-m Victor Blanco telescope was equipped with 1 (and then 4) 2kX2k ccd’s. Exposures were typically 5-10 min long.

We could transfer all the data up on a 56k-baud connection during the night and it would be subtracted within a few hours of dawn – when the connection was good. Often the astronomer would make it back to Berkeley with the tapes before all the data was in...
Supernovae circa 1998

Per image we would have \( \sim200 \) 5-\( \sigma \) detections. We would require 2 independent detections.

Cuts were made based on shape, motion, etc., and a scanner would have to look at \( \sim5 \) candidates per image.

Typically only 50-200 images taken per night - 4 sq. deg. of sky.
Supernovae circa 1998

The Calan/Tololo Survey by Hamuy et al. pinned the low-z part of the Hubble diagram, while the work of Riess et al. and Perlmutter et al. got the high-z end.

Turns out it is easier to find them at high redshift than low redshift.... 29 low-z SNe Ia would make it to a Hubble diagram. It was, for nearly 20 years, the defining set of low-redshift SNe Ia in anchoring the Hubble diagram.
SN Searches 2000+

SHOES – Supernova for H0 and the Equation of State

IPMU Colloquium
Suzuki et al. (2012), the Union 2.1 sample, now has 117 SNe Ia with $0.03 < z < 0.10$, defined as the smooth Hubble flow. Below the lower redshift peculiar velocities dominate and above this redshift the uncertainties in the cosmological parameters cause a departure from the linear Hubble law.

There is a strong desire to improve the low-redshift sample, as well as the high-redshift one, in order to reduce systematics which dominate these Hubble diagrams. Also, some folks are interested in other types of supernovae....
KAIT sits atop Mt. Hamilton, just above the city of San Jose. It is a fully roboticized telescope, with a limiting magnitude of 19 and keeps a cadence of 1 to 5 days on a list of 500 galaxies/night. Many of the SNe Ia from Hicken et al (2009) and Contreras et al. (2010) came from this survey.
KAIT/IAUC Biases

More than half the SNe Ia will suffer from uncertainties due to peculiar velocity errors which are at or above current systematic limits.

E/S0’s are overrepresented in the RC3 catalog (where most of these searches obtain the lists of hosts to look for SNe) by 1-2 orders of magnitude.
This is a 1 sq degree cut out of the Coma Cluster.
The KAIT fov is shown for comparison.
SNfactory Search

Near Earth Asteroid Tracking

Palomar QUEST

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### Supernovae circa 2000

Pain begins.....

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## NEAT Search Facilities

<table>
<thead>
<tr>
<th>Site:</th>
<th>Haleakala</th>
<th>Palomar I</th>
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<tbody>
<tr>
<td>Aperture:</td>
<td>1.2m</td>
<td>1.2m</td>
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<tr>
<td>Nights/Month:</td>
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<td>18 dark/gray</td>
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<tr>
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<tr>
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<td>0.50”/pixel</td>
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<tr>
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<td>Readout:</td>
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<tr>
<td>Nig.:</td>
<td>600°</td>
<td>(2000 °)</td>
</tr>
<tr>
<td>Data (compressed):</td>
<td>12 Gbyte/night</td>
<td>17 Gbyte/night</td>
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<tr>
<td></td>
<td></td>
<td>(28 Gbyte/night)</td>
</tr>
</tbody>
</table>

~1000 sq. deg. – 250 X increase in scale per night EVERY NIGHT !!!
Supernovae circa 2000

FEDEx Networking: Do not underestimate the bandwidth of a station wagon filled with DAT tapes... achieved 200 kB/s
PTF (2009-2012)  
(& now iPTF from 2013 to 2016)

- CFH12k camera on the Palomar Oschin Schmidt telescope
  - 7.8 sq deg field of view, 1” pixels
  - 60s exposures with 15-20s readout in r, g and H-alpha
  - First light Nov. 24, 2008.
  - First useful science images on Jan 13th, 2009.

- 2 Cadences (Mar. - Nov.) 2009-2011
  - Nightly (35% of time) on nearby galaxies and clusters (g/r)
  - Every 3 nights (65% of time) on SDSS fields with minimum coverage of 2500 sq deg. (r) to 20th mag 10-sigma
  - H-alpha during bright time (full +/-2 days)

Nov-Feb, minute cadences on select fields.
### Supernovae circa 2009

#### Discovery and Follow-up

| Instrumentation, system design, first results | Law, Kulkarni, Dekany et al. 2009 PASP 121 1395L |
| Science plans | Rau, Kulkarni, Law et al. 2009 PASP 121 1334R |
| 2010 survey status | Law et al. 2010 SPIE 7735 IPMU Colloquium |
155 Mbps from Palomar to UCSD, then ∞ via ESnet to NERSC ;-)

HPWREN Network

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PTF Camera

92 Mpixels, 1” resolution, R=21 in 60s
The power of PTF resides in its diverse science goals and follow-up.

<table>
<thead>
<tr>
<th>PTF Key Projects</th>
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<tbody>
<tr>
<td>Various SNe</td>
<td>Dwarf novae</td>
</tr>
<tr>
<td>Transients in nearby galaxies</td>
<td>Core collapse SNe</td>
</tr>
<tr>
<td>RR Lyrae</td>
<td>Solar system objects</td>
</tr>
<tr>
<td>CVs</td>
<td>AGN</td>
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<tr>
<td>AM CVn</td>
<td>Blazars</td>
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<tr>
<td>Galactic dynamics</td>
<td>LIGO &amp; Neutrino transients</td>
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<td>Flare stars</td>
<td>Hostless transients</td>
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<tr>
<td>Nearby star kinematics</td>
<td>Orphan GRB afterglows</td>
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<tr>
<td>Type Ia Supernovae</td>
<td>Eclipsing stars and planets</td>
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<tr>
<td>Tidal events</td>
<td>H-alpha ½ sky survey</td>
</tr>
</tbody>
</table>

PTF Science
The power of PTF resides in its diverse science goals and follow-up.
Real or Bogus – Machine Learning Analysis

4096 X 2048 CCD images - over 3000 per night – producing 1.5M bogus detections, 50k known astrophysical objects and only 1-2 new astrophysical transients of interest every night. Machine learning is used to wade through this sea of garbage.

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User Interface

ML for determining if Real or Artifact

Using machine learning for discovery in synoptic survey imaging data

Henrik Brink,¹* Joseph W. Richards,¹,² Dovi Poznanski,³ Joshua S. Bloom,¹ John Rice,² Sahand Negahban⁴ and Martin Wainwright²,⁴

In 2010, to support the SN Ia program in PTF and a WHT spectroscopy run, I spent a week with the folks at Oxford setting up the db and giving them training sets of good and bad candidates. They did the rest… 1200 members of galaxy zoo screened all the candidates between Aug 1 and Aug 12 in 3 hrs. The top 50 hits were all SNe/variable stars and they found 3 before we did. They scanned ~25,000 objects - 3 objects/min. They routinely did ~250 nightly and we had 15,000 users at peak.

http://supernova.galaxyzoo.org is was up and running to help us scan.
Citizen Scientists

Just 4 simple questions and the candidates can be classified. Typically one could do this in no more than 10 seconds per candidate.

1. **Q:** Is there a candidate centered in the crosshairs of the right-hand image?
   - No (-1)
   - Yes

2. **Q:** Has the candidate itself subtracted correctly?
   - No (-1)
   - Yes

3. **Q:** What is wrong with the subtraction?
   - No candidate
   - Not all pixels positive
   - Poor subtraction

4. **Q:** What is wrong with the candidate?
   - Not circular - too small
   - Not circular - elongated
   - Not circular - distorted
   - Not circular - diffuse

5. **Q:** Is the candidate star-like and approximately circular?
   - No (-1)
   - Yes (+1)

6. **Q:** Is the candidate centred in a circular host galaxy?
   - No (+2)
   - Yes

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A random forest was trained to generate real-bogus scores.
Removing the Humans

Machine-learned, immediate classification out-performs crowdsourced SN discovery by ML Zoo.

While a great way to start our project, and an excellent form of public outreach, it was no longer necessary.
PTF Database

<table>
<thead>
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<th>R-band</th>
<th>g-band</th>
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<tr>
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<td>29.2k</td>
<td>6.3k</td>
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<tr>
<td>Candidates</td>
<td>890M</td>
<td>197M</td>
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<tr>
<td>Transients</td>
<td>42945</td>
<td>3120</td>
</tr>
</tbody>
</table>

All in 851 nights.
An image is an individual chip (~0.7 sq. deg.)
The database is now 1 TB.
Pipeline...

Observatory → Data Transfer Nodes

2.5 MB/s → Processing/db → Science Gateway Node 2

1 GB/s → Subtractions → Carver

12 MB/s → PTF Classification → Science Gateway Node 1

4 MB/s (crude)

0.5 MB/s (full)

NERSC GLOBAL FILESYSTEM - 250TB

One of 4 such pipelines running at NERSC.

IPMU Colloquium
Palomar 48” Telescope

HPWREN Microwave Relay

SDSC to ESNET

NERSC Data Transfer Node

Networking Data Transfer

100 TBs of Reference Imaging

Astrometric Solution

Image Processing / Detrending

Star/Asteroid Rejection

Transmit Candidate

Real-Bogus ML Screening

Image Subtraction

Nightly Image Stacking

Computing – I/O

Reference Image Creation

500 GB/night

Publish to Web

Outside Database for Triggers

Web UI Marshal

Outside Telescope Follow-up

Scanning Page

Wake Me Up – Real Time Trigger

Real-Time Trigger

40 Minutes

Heavy DB Access

1.5B objects in DB

Publish to Web
What does “real-time” subtractions really mean?

For 95% of the nights all images are processed, subtractions are run, candidates are put into the database and the local universe script is run in < 1hr after observation.

Median turn-around was 30m.

Science demands this be quicker...
New Turn-around

We made major changes to the old pipeline.

- Pipeline completely instrumented for timings.
- Identified and fixed python load time on Edison (15min to 5 sec).
- Moved all I/O in processing to Lustre /scratch filesystem
- Now optimizing db access

Typical turnaround is now < 5 minutes for 95% of the data.
PTF Sky Coverage

To date:
• 2655 Spectroscopically typed supernovae
• $10^5$ Galactic Transients
• $10^4$ Transients in M31

115 publications, 6 in *Nature* and 2 in *Science* since 2009
Pre-Outbursts


Possible Explanation for this Type II-n supernova: Super-Eddington fusion luminosities, shortly prior to core collapse, drive convective motions that in turn excite gravity waves that propagate toward the stellar surface and eject substantial mass.

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(a) $10^{-2} M_\odot$ ejected one month earlier during pre-outburst $\sim 2000$ km/s

(b) At day $\sim 5$, the SN shock front (grey line at $10^4$ km/s) is ionising the inner and outer shells which produce the broad and narrow H emission seen in the early-time spectra.

(c) At day $\sim 20$, the SN shock engulfs the inner shell, and the intermediate-width H $\alpha$ vanishes and narrower features appear: pre-pre-outbursts.

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Overcoming wide & fast: iPTF13bxl in 71 deg²!

Singer et al. 2013
The second Fermi afterglow: iPTF13dsw at z=1.87!

Kasliwal et al. 2013b

Overcoming Wide, Fast & Faint

Pinpointing the afterglow amidst 30,000 candidates
Orphan Afterglow

IPN found a GRB (localization ~200-300 sq. deg.) ~15 min before first detection.....

iPTF14yb
Cenko et al. 2014

z=1.98!!!
Fell, MgII, Ly-α

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Flash Spectroscopy

SN2013cu (iPTF13ast)
Gal-Yam et al. (2014) Nature

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Flash Spectroscopy

(a) SN 2013cu, 15.5 hours
- 50 kK WNL model
- 56 kK WNL model
- HD 192163 (WN6h)
Flash Spectroscopy

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PTF11kly (SN 2011fe)

Caught at magnitude $\sim 17.4$, $\sim 100,000$ times fainter than the eye can see.

20% rise between first 2 detections separated by 1hr

$\sim 1/1000$ as bright as the SN reached at peak brightness.
Young Type Ia Supernova PTF11kly in M101

ATEl #3581; Peter Nugent (LBL/UCB), Mark Sullivan (Oxford), David Bersier (Liverpool John Moores), D.A. Howell (LCOGT/UCSB), Rollin Thomas (LBL), Phil James (Liverpool John Moores)

on 24 Aug 2011; 23:47 UT

Distributed as an Instant Email Notice Supernovae
Credential Certification: R. C. Thomas (rcthomason.lbl.gov)

Subjects: Optical, Supernovae

Referred to by ATEL #: 3582, 3583, 3584, 3588, 3589, 3590, 3592, 3594, 3597, 3598, 3602, 3605, 3607, 3620, 3623, 3642

The Type Ia supernova science working group of the Palomar Transient Factory (ATEL #1964) reports the discovery of the Type Ia supernova PTF11kly at RA=14:03:05.81, Dec=+54:16:25.4 (J2000) in the host galaxy M101. The supernova was discovered on Aug. 24 UT when it was at magnitude 17.2 in g-band (calibrated with respect to the USNO catalog). There was nothing at this location on Aug 23 UT to a limiting magnitude of 20.6. A preliminary spectrum obtained Aug 24 UT with FRODOSPEC on the Liverpool Telescope indicates that PTF11kly is probably a very young Type Ia supernova: Broad absorption lines (particularly Ca II IR triplet) are visible. The presence of an H-alpha feature is confidently rejected. STIS/UV spectroscopic observations on the Hubble Space Telescope are being triggered by the ToO program "Towards a Physical Understanding of the Diversity of Type Ia Supernovae" (PI: R. Ellis). Given that the supernova should brighten by 6 magnitudes, the strong age constraint, and the fact that the supernova will soon be behind the sun, we strongly encourage additional follow-up of this source at all wavelengths.
SN 2011fe is the 2nd closest Type Ia supernova in the last 25 years and the 5th brightest supernova of any type in the last century.

It was caught hours after explosion, and has been followed by almost every professional telescope on earth and in space – could be seen in binoculars.

These observations have led to the best constraints to-date for the progenitors of these supernova, and have added several new wrinkles on how these runaway thermonuclear explosions take place.

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PTF11kly/SN2011fe

DM = 29.04 ± 0.23
Shroppe, Stanek 11
Keck/NIRC2/H-band
Aug 26, 2011 (t₀+3day)
HST/ACS/F814W (~I band) Nov 11, 2002

Keck/NIRCam/H-band Aug 26, 2011 (t₀+3day)
$1\sigma = 21$ mas
(nearest star is $\sim 9\sigma$ away)

$2'' \times 2''$

HST/ACS/F814W ($\sim$I band) Keck/NIRC2/H-band
Nov 11, 2002
Aug 26, 2011 ($t_0 + 3$ day)
Constraints on the progenitor system.

Basically all we can have are a double degenerate system or a low mass main sequence companion.

Li et al., Nature (2011)
LT, Lick & Keck HIRES spectra.

No dust along the line of sight.

OI line suffers geometrical dilution in 8hrs...

Nugent et al., Nature (2011)
SYNAPPS spectrum synthesis fits on NERSC’s Hopper commenced 1 hour after first spectrum was reduced.

Rollin Thomas finished analysis 30 hours after SN was first detected!
So similar to the maximum light spectrum abundance-wise that it is clear there is a lot of mixing in the SN explosion.
SN 2011fe was caught within 11 hrs +/- 20 min. of explosion following $t^2$ fireball law. From homologous expansion and:

$$L = 4\pi R^2 \sigma T^4$$

First spectra came in ~24 hr later.

Peaked @ mag 9.9, making it the 5th brightest SN in last 100 years.
Temperature is cold (UV deficit) and roughly constant for the first few days after explosion... then it starts getting hot.
Why follow $t^2$ law? 
Pure Luck!

Ni$_{56}$ in outer layers, photosphere does not drop much in velocity space, temp constant - leads to luminosity increasing like surface area.

Nugent et al., Nature (2011)
Collisions & Shocks

Kasen (2010)

Doesn’t matter if it is the shock coming off the surface of the WD or collision in the progenitor system – you can constrain either.
Assuming supernova energetics, a shock is produced that cools adiabatically and has a luminosity and temperature which is dependent on the initial radius of the system.
Open University observations on Mallorca only 4hrs after explosion.

Fakes put in assuming 4000K and 7000K blackbodies.

Constrains limiting magnitude to 19.0-19.5 in g-band

Constrains the explosion radius to $R < 0.02 R_\odot$

Mixing to the outer layers of Ni$^{56}$ or some other radioactive source is the only way to explain the early lightcurve – $M_\odot < 0.1$

Likely had a “dark day” (or at least a few hours) – a phrase I overheard David Branch say 20 some years ago...
But there could be a “dark day”.... adds more time and a possible cool down phase.

Constraints on the shock assuming it happened following the $t^2$ fireball law.

Constrains the explosion radius to $R < 0.04 \, R_\odot$

Piro & Nakar (2013)
Limits the progenitor to a WD or NS.

Companion from a WD+WD merger?

0.4 $R_\odot$ at as the detonation makes its way out...

Pakmor et al., (2012)
Firth *et al.* (2015)
Fireball model is incorrect and there is either a range in Ni$^{56}$ in the outer layers of the SN Ia or interaction powering the early rise.
Interestingly, not a normal SN Ia, a low-velocity one like SN 2002es or SN 2005hk

PTF14atg

UV Luminosity $\sim 3 \times 10^{41}$ ergs/s

Companion at 70-90 $R_\odot$ away
Gravitational Wave Trigger GW150914

Signals in synchrony

When shifted by 0.007 seconds, the signal from LIGO’s observatory in Washington (red) neatly matches the signal from the one in Louisiana (blue).

- LIGO Hanford data (shifted)
- LIGO Livingston data


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Going to have to be able to sift through a lot of stuff, and react quickly with follow-up, to get on the optical companion for a GW trigger.
Zwicky Transient Facility
ZTF will survey an order of magnitude faster than PTF.

<table>
<thead>
<tr>
<th></th>
<th>PTF</th>
<th>ZTF</th>
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</thead>
<tbody>
<tr>
<td>Active Area</td>
<td>7.26 deg²</td>
<td>47 deg²</td>
</tr>
<tr>
<td>Overhead Time</td>
<td>46 sec</td>
<td>&lt;15 sec</td>
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<tr>
<td>Optimal Exposure Time</td>
<td>60 sec</td>
<td>30 sec</td>
</tr>
<tr>
<td>Relative Areal Survey Rate</td>
<td>1x</td>
<td>15.0x</td>
</tr>
<tr>
<td>Relative Volumetric Survey Rate</td>
<td>1x</td>
<td>12.3x</td>
</tr>
</tbody>
</table>

3750 deg²/hour
⇒ 3π survey in 8 hours

>250 observations/field/year for uniform survey

Existing PTF camera: MOSAIC 12k

New ZTF camera: 16 6k x 6k e2v CCDs
Future

LSST - 15TB data/night
Only one 30-m telescope

*How many triggers can we handle??*

Intelligent Optical Network Infrastructure
Bottlenecks...crude vs. real

5-σ data in db
Future w/ LSST... gets complicated

• We will need to be able to provide historical LSST data at the drop of a hat so folks can perform their own studies on new transients immediately.

• We will need to be able to query existing databases OTF to understand host galaxies, variable stars, etc. at other wavelengths and spectroscopically.

• These will likely be run by many people, completely automated and at cross-purposes.

The future is now, forget LSST....