Supernovae and the Era of Synoptic Surveys

Peter Nugent (LBNL/UCB)

Real-Time Decision Making Boot Camp
What is a Supernova?
(pl. supernovae)

- Bright and powerful explosion of a star.
- Biggest explosions in the Universe.
- Speeds of 10-20% the speed of light.
- Outshine galaxies made of hundreds of billions of stars.
- In ~1 month, emits as much energy as the Sun will over its 10 billion year lifetime.
What is a Supernova? (pl. supernovae)

• “Nova” is Latin for new.

• First used to describe “new” stars that suddenly appeared in the night sky. (The Chinese referred to them as “guest stars”.)

• The prefix “super” distinguishes them from “classical novae” which are fainter cousins of supernovae (but I won’t get into those in this talk).

• The term supernova was coined by Fritz Zwicky in 1926.

• Supernovae observations by humans have been recorded for the past 2000 years.
How Frequent are they?

• Somewhere in the universe there is a supernova exploding every second.

• In a galaxy like our Milky Way there is ~1 supernova per century.

• We find around 1-3 new supernova per night these days - most are very distant ~ 1 billion light years away.
Historical SNe (1006)

This is a SN remnant image with the Chandra X-ray satellite telescope.

It came from SN 1006, which was seen by ancient observers in Switzerland, Egypt, Iraq, China, Japan, and North America.

The SN cast shadows at night and was visible during the day for months.

Supernovae are the explosive deaths of some stars.
Historical SNe (1054)

The famous Crab nebula (using the Hubble Space Telescope).

A SNR of SN 1054, seen by Chinese, Japanese, Arab, and Native American astronomers.

Bright enough to see in daylight for 23 days and was visible in the night sky for 653 days.
Anasazi Indians living in Chaco Canyon, NM made this petroglyph in 1054.

The hand shows the relative size of the astronomical objects and the crescent moon shows the phase and position of the moon relative to the SN (the large star) on July 4, 1054.
Historical SNe (1572 - a Type Ia)

Danish observational astronomer Tycho Brahe discovered a SN by eye in 1572.
Historical SNe (1604)

German theoretical and observational astronomer Johannes Kepler, Brahe’s graduate student, discovered a SN by eye in 1604.
On Feb 24, 1987, in an extremely nearby dwarf galaxy, the Large Magellanic Cloud, SN 1987A exploded. It was only 170,000 ly away ($10^{18}$ miles), basically in our cosmic backyard. It has been observed from the time it exploded until today. Unfortunately, while it was visible for a short while with the naked eye, it was only up for folks in the southern hemisphere.
The ejecta of SN 1987A slamming into material released by the progenitor system ~20,000 years before the supernova exploded.
What are the Types of Supernovae?

Core collapse supernovae originate from the death of a star ~10 times the mass of our sun or greater.

Type II/Ib/Ic

The iron core can no longer resist the pressure, collapses, and the electrons and protons hook-up to make neutrons and neutrinos.
What are the Types of Supernovae?

A thermonuclear supernova, which we label a Type Ia.

Binary system perhaps with a main sequence star or red giant in which the white dwarf (which blows up) pulls hydrogen off the companion and burns it to carbon and oxygen.

As it approaches the Chandrasekhar limit, the carbon ignites in a runaway thermonuclear explosion.
What are the Types of Supernovae?

A double degenerate system - two white dwarfs.

How do we “know” this? We infer this from our observations since we see SNe Ia in old galaxies where no star is more and 2-3 times the mass of our sun, and the fact that we see neither hydrogen nor helium in the spectra of these supernovae.
We are star-stuff

Element Origins

Merging Neutron Stars
Dying Low Mass Stars
Exploding Massive Stars
Exploding White Dwarfs
Big Bang
Cosmic Ray Fission

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Binary Neutron Stars – Takes 2 SNe Explosions!
Over the past 15 years the observations of Type Ia supernovae at high redshift have shown that the universe is currently accelerating and that over 2/3 of it is in the form of "dark energy".

Cosmology

Einstein's Repulsive Idea

He invented antigravity in desperation and abandoned it first chance he got—but it may be the most powerful force in the universe.

Antigravity

Antigravity is the most powerful force on earth. The universe,
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 1995

RESULT: ~24 Type Ia supernovae discovered while still brightening, at new moon
Supernovae circa 1995

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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....
Cosmology

2011 Nobel Prize in Physics
Supernovae circa 1998

Per image we would have ~200 5-σ detections. We would require 2 independent detections.

Cuts were made based on shape, motion, etc., and a scanner would have to look at ~5 candidates per image.

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

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### NEAT Search Facilities

<table>
<thead>
<tr>
<th>Site:</th>
<th>Haleakala</th>
<th>Palomar I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture:</td>
<td>1.2m</td>
<td>1.2m</td>
</tr>
<tr>
<td>Nights/Month:</td>
<td>18 dark/gray</td>
<td>16k × 24k</td>
</tr>
<tr>
<td>Imager Format:</td>
<td>4k × 4k</td>
<td>0.50”/pixel</td>
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<tr>
<td>Imager Scale:</td>
<td>1.33”/pixel</td>
<td>2.3° × 4.0°</td>
</tr>
<tr>
<td>Field of View:</td>
<td>1.1° × 3.4°</td>
<td></td>
</tr>
<tr>
<td>Filters:</td>
<td>open</td>
<td>4 fixed filters</td>
</tr>
<tr>
<td>Exposures:</td>
<td>1 sec</td>
<td>3 × 60 sec</td>
</tr>
<tr>
<td>Reader:</td>
<td>20 sec</td>
<td>TBD</td>
</tr>
<tr>
<td>Nigt:</td>
<td>600°</td>
<td>800°</td>
</tr>
<tr>
<td>Start:</td>
<td>Mar 2000</td>
<td>Feb 2001</td>
</tr>
<tr>
<td>Data (compressed):</td>
<td>12 Gbyte/night</td>
<td>17 Gbyte/night</td>
</tr>
</tbody>
</table>

**EVERY NIGHT!!!**

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

FEDEEx Networking: Do not underestimate the bandwidth of a station wagon filled with DAT tapes... achieved 200 kB/s
PTF/iPTF (2009-2017)

- 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 |

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HPWREN Network

155 Mbps from Palomar to UCSD, then $\infty$ via ESnet to NERSC ;-)
PTF Camera

92 Mpixels, 1” resolution, R=21 in 60s
# PTF Science

<table>
<thead>
<tr>
<th>PTF Key Projects</th>
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</thead>
<tbody>
<tr>
<td>Various SNe</td>
</tr>
<tr>
<td>Transients in nearby galaxies</td>
</tr>
<tr>
<td>RR Lyrae</td>
</tr>
<tr>
<td>CVs</td>
</tr>
<tr>
<td>AM CVn</td>
</tr>
<tr>
<td>Galactic dynamics</td>
</tr>
<tr>
<td>Flare stars</td>
</tr>
<tr>
<td>Nearby star kinematics</td>
</tr>
<tr>
<td>Type Ia Supernovae</td>
</tr>
<tr>
<td>Tidal events</td>
</tr>
</tbody>
</table>

The power of PTF resides in its diverse science goals and follow-up.

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Real-Time Decision Making Boot Camp
The power of PTF resides in its diverse science goals and follow-up.

Real-Time Decision Making Boot Camp
100 TBs of Reference Imaging

- Palomar 48" Telescope
- HPWREN Microwave Relay
- SDSC to ESNET
- NERSC Data Transfer Node
- Networking Data Transfer

Computing – I/O
- Astrometric Solution
- Image Processing / Detrending
- Image Subtraction
- Nightly Image Stacking

Reference Image Creation

Real-Time Trigger
- 40 Minutes

Heavy DB Access
- 500 GB/night

500 GB/night

1.5B objects in DB

Publish to Web

Outside Database for Triggers

Outside Telescope Follow-up

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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.

Real-Time Decision Making Boot Camp
PTF Database

<table>
<thead>
<tr>
<th></th>
<th>R-band</th>
<th>g-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>images</td>
<td>1.82M</td>
<td>305k</td>
</tr>
<tr>
<td>subtractions</td>
<td>1.52M</td>
<td>146k</td>
</tr>
<tr>
<td>references</td>
<td>29.2k</td>
<td>6.3k</td>
</tr>
<tr>
<td>Candidates</td>
<td>890M</td>
<td>197M</td>
</tr>
<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...

Data Transfer Nodes

2.5 MB/s

Observatory

250TB (185TB used)

Science Gateway Node 2

1 GB/s

Processing/db

12 MB/s

Subtractions

4 MB/s (crude)

Carver

Science Gateway Node 1

0.5 MB/s (full)

NERSC GLOBAL FILESYSTEM

One of 4 such pipelines running at NERSC.

PTF Classification

Real-Time Decision Making Boot Camp
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 is 30m.

Now forced to be reduced to < 15min due to following discoveries:
Due to the X-SWAP project (Extreme-Scale Scientific Workflow Analysis and Prediction), funded through the ASCR LAB-1088 call (Analytical Modeling for Extreme-Scale Computing Environments), we have been able to understand and eliminate a lot of our inefficiencies and decrease the turn-around by an order of magnitude!

Better use of the Lustre filesystem (for everything), better use of OpenMP in all codes, reserved nodes, etc.
iPTF 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!
Instrumented Pipeline with 39 Checkpoints

Covers everything from:

• Pulling the data from the telescope
• I/O on scratch
• Subtraction software
• Running ML algorithms
• Loading the db with discoveries
• Performing difficult geometric queries to match with known stars, asteroids, previous discoveries, etc.
• Copying data from scratch to project
For 8 hours every night, we now know more about the NERSC center than they do in real-time.

Given 3000 images per night with 39 checkpoints for each, we are monitoring some aspect of NERSC or ESnet every quarter second.
Decent correlation between number of objects and the total time for our queries with some scatter likely due to overlapping queries.
I/O time on Cori

Now exploring relationship between nightly conditions and the bulk of the data through ML.

While getting a hold of the outliers via NERSC system information.
PTF/iPTF Sky Coverage

The Final Tally:

- 3015 Spectroscopically typed supernovae
  (Ia: 2060 | II: 693 | Ib: 45 | Ic: 60 | Ib/c: 15 | Ic-BL: 35 | SLSNe: 48)
- $10^5$ Galactic Transients
- $10^4$ Transients in M31

190 publications, 7 in *Nature* and 3 in *Science* since 2009
Pre-Outbursts


Possible Explanation: 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.
Overcoming wide & fast: iPTF13bxl in 71 deg²!

Singer et al. 2013

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The second Fermi afterglow: iPTF13dsw at z=1.87!

Overcoming Wide, Fast & Faint

Pinpointing the afterglow amidst 30,000 candidates

Kasliwal et al. 2013b
IPN found a GRB (localization ~200-300 sq. deg.)
~15 min before first detection...
Flash Spectroscopy

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

![Flash Spectroscopy Diagram]

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Flash Spectroscopy

![Graph showing spectroscopy data with various wavelengths and flux values.]

- SN 2013cu, 15.5 hours
- NOT, 3.09 days
- HET, 3.23 days
- Keck I, 6.45 days

**Real-Time Decision Making Boot Camp**
Flash Spectroscopy

Scaled Flux [$\text{erg s}^{-1} \text{cm}^{-2} \text{Ang}^{-1}$]

- SN2013cu (IIb)
- SN 1993J (IIb)
- SN 2011dh (IIb)
- SN2004et (II-P)

Rest Wavelength [Ang]

He I

Fe II

H

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g-band run:

• ~500 sq. deg. hit twice during the night subtractions - rest went to new references

• 50-50 split between Dynamic and SN cadence

• 10 new transients found that night

• Pipeline was slow, running 6 hrs behind normal due to catching up from a kernel “update” on the NERSC machines.

• An IP address at Caltech had just been changed, thus we could only save things by hand....
11klx - JSB @ UT 19:48
- response “I see your $20 and raise you $100”

11kly - PEN @ UT 19:50
“Hi all,
M101 has given birth to 11kly
Check it out, alert the troops!!!”
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 (rcthomas@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 closest Type Ia supernova in the last 25 years and the 5th brightest supernova of any type in the last century. It was found by the Palomar Transient Factory, which processes its data at NERSC.

It was caught 11 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.
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

Gravitational Wave Trigger GW150914


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GW150914

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.
Pipeline...

Observatory

Data Transfer Nodes

2.5 MB/s

Processing/db

Science Gateway Node 2

12 MB/s

Subtractions

Graphical representation of data transfer and processing nodes:

- Data Transfer Nodes
- Science Gateway Node 2
- Subtractions
- Carver

NERSC GLOBAL FILESYSTEM
250TB (185TB used)

Science Gateway Node 1

PTF Classification

4 MB/s (crude)

0.5 MB/s (full)

Real-Time Decision Making Boot Camp

Trigger new subtractions: output now greater than input ~ 1 TB/night

Science Gateway Node 2

Processing/db

1 GB/s
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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<tbody>
<tr>
<td>Active Area</td>
<td>7.26 deg$^2$</td>
<td>47 deg$^2$</td>
</tr>
<tr>
<td>Overhead Time</td>
<td>46 sec</td>
<td>&lt;15 sec</td>
</tr>
<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 deg$^2$/hour

⇒ $3\pi$ 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???
Future w/ ZTF

Like taking a hit from a firehose.

Be careful what you wish for...