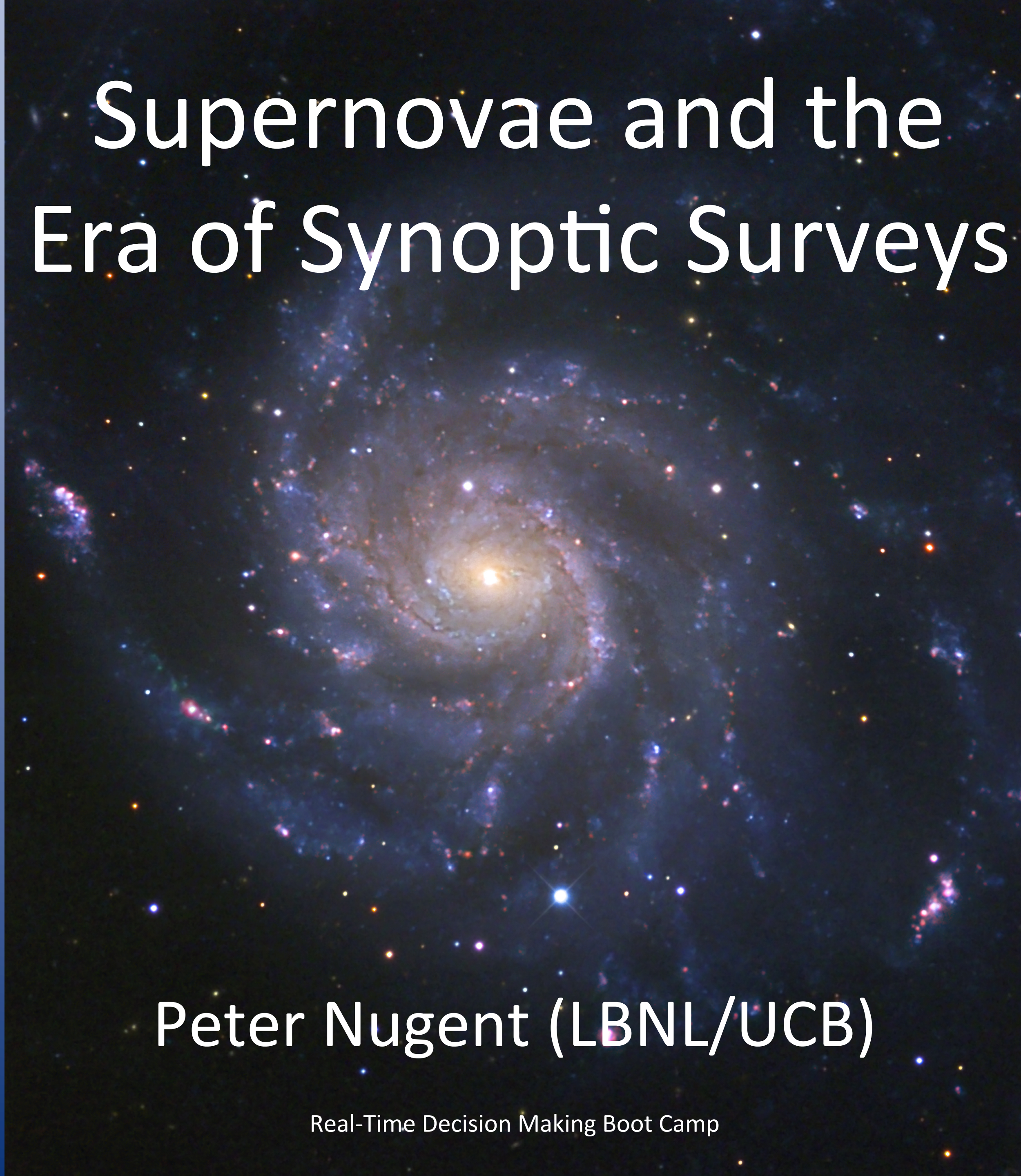
Supernovae and the Era of Synoptic Surveys



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.

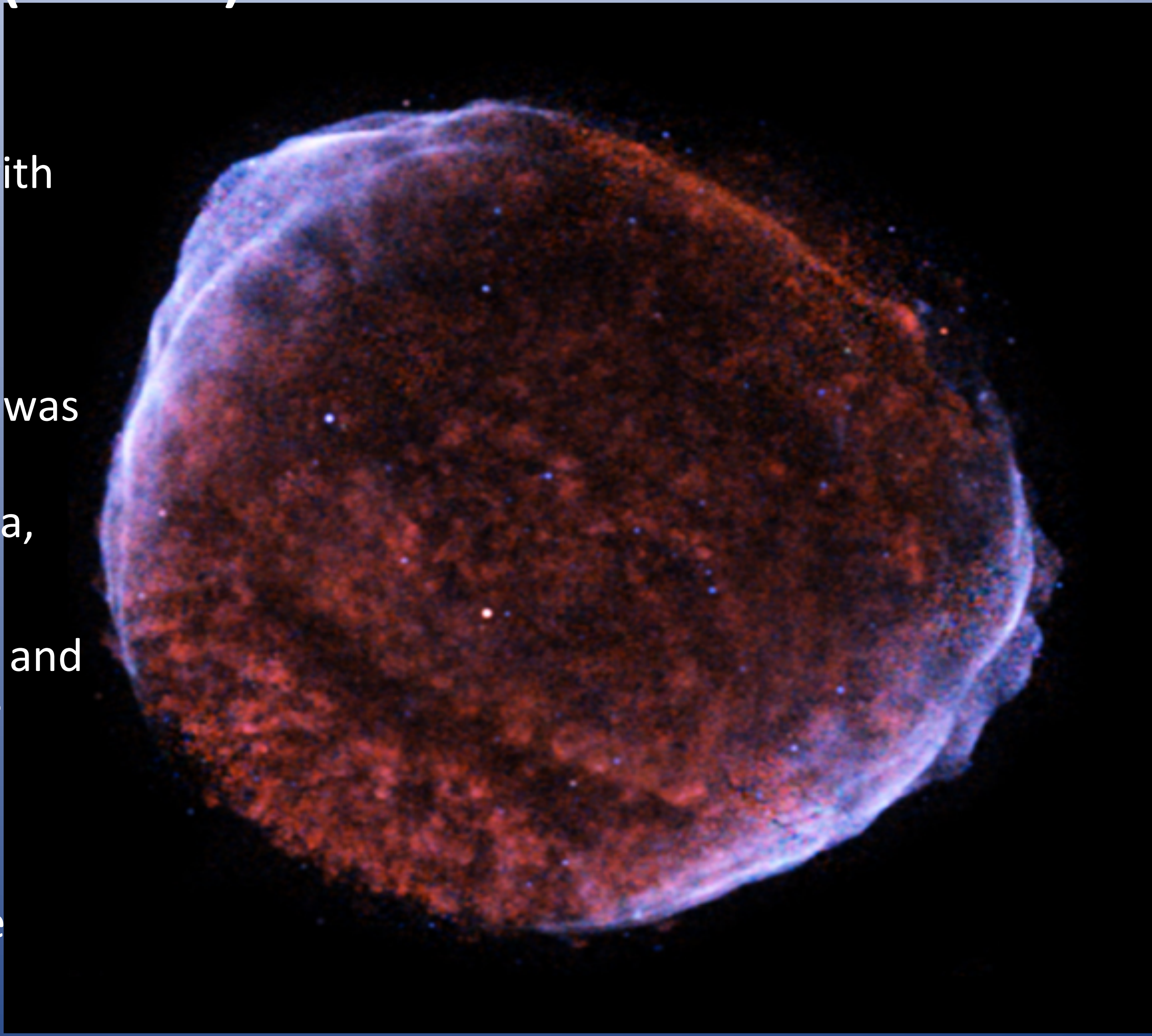
Historical SNe (1006)

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.

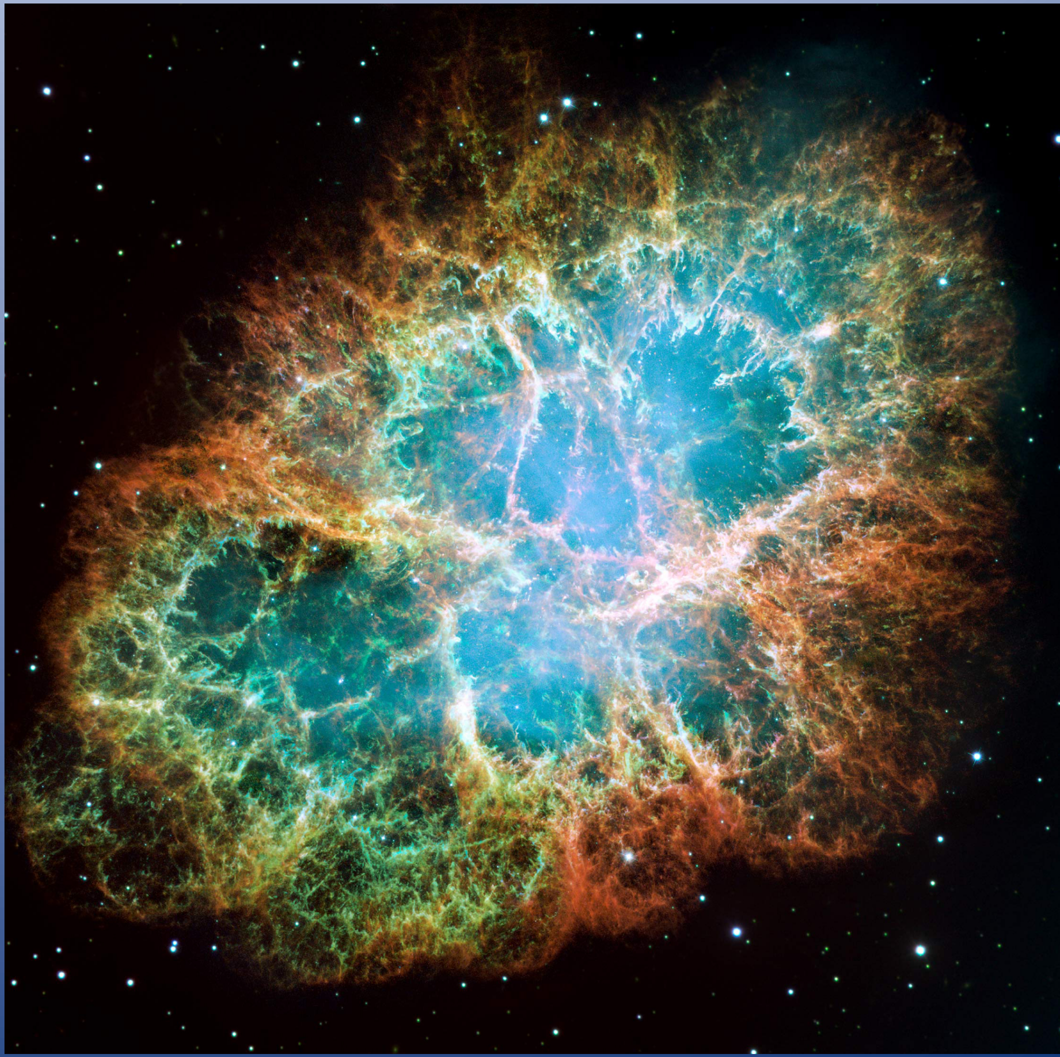


Historical SNe (1054)

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.

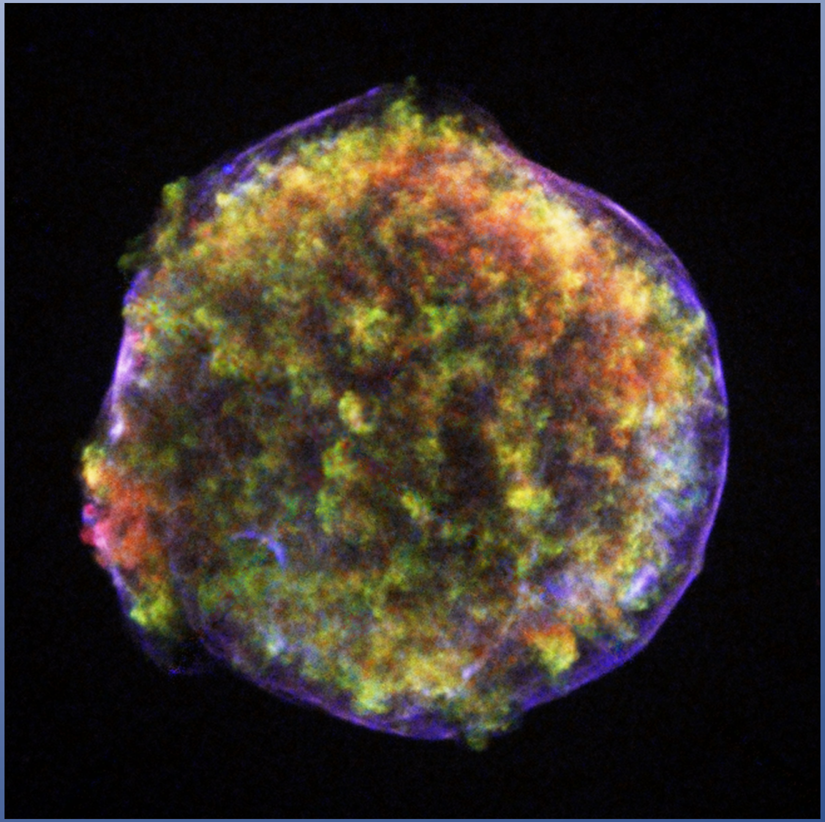


Historical SNe (1054)

Anasazi Indians living in Chaco Canyon, NM made this petroglyph in 1054.

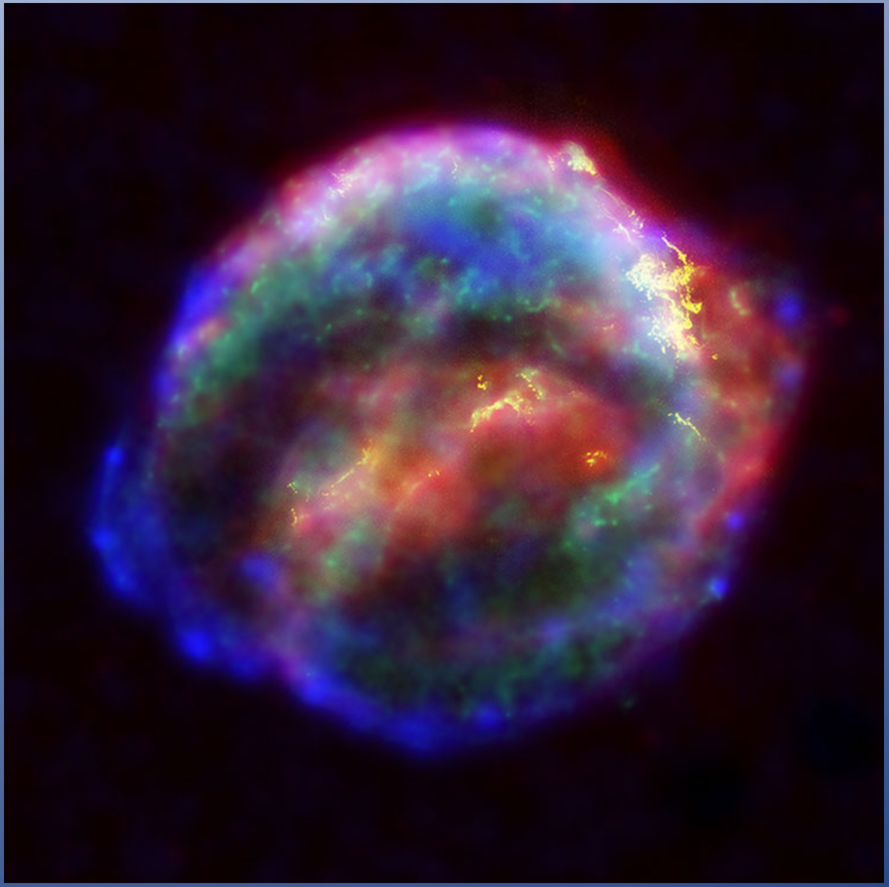
The hand shows the relative size of the astronomical objects and the crescent moon shows the phase and position of the moon relative to the SN (the large star) on July 4, 1054.

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.

SN 1987A

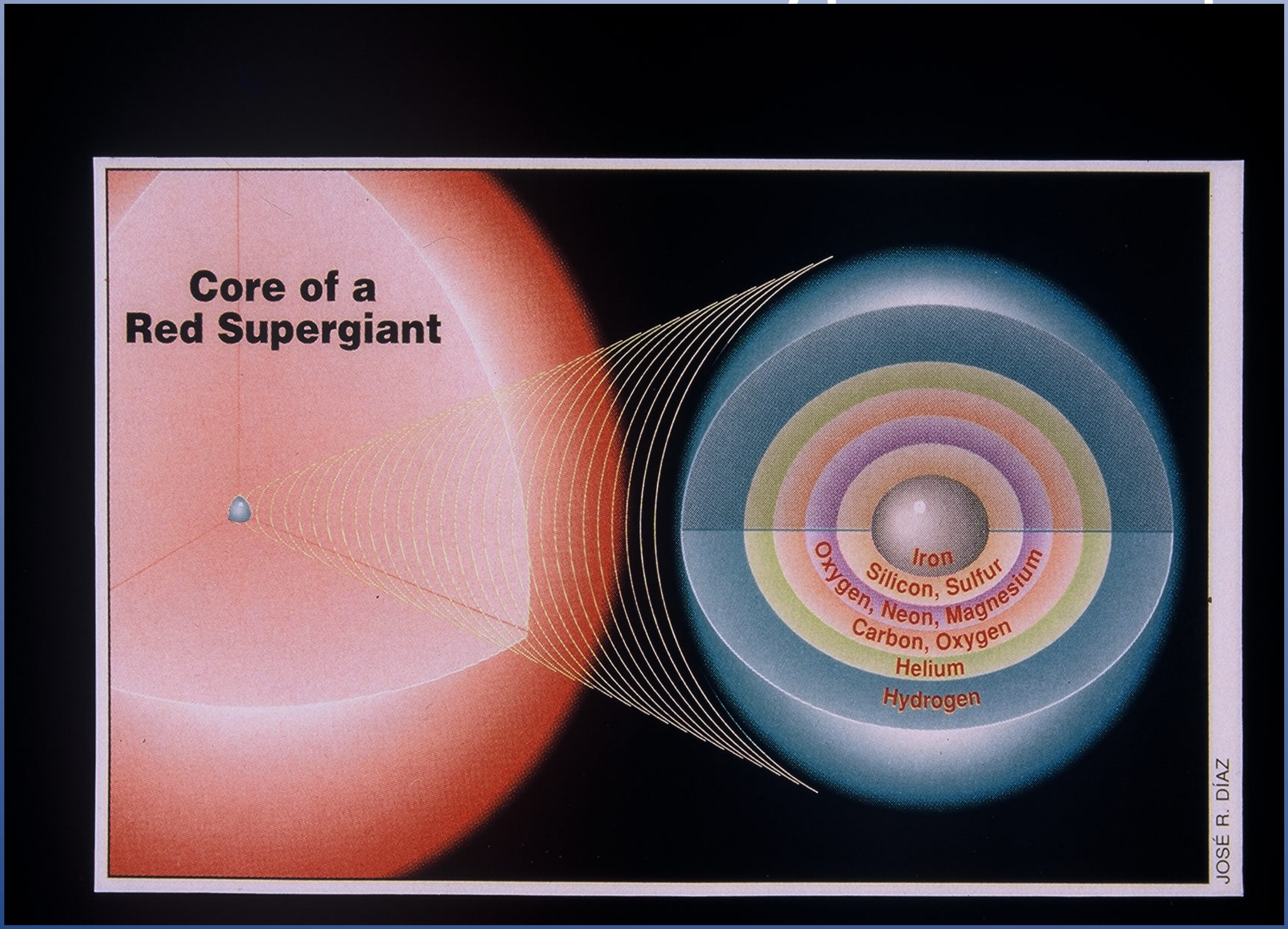
On Feb 24, 1987, in an extremely nearby dwarf galaxy, the Large Magellanic Cloud, SN 1987A exploded.

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.

SN 1987A

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?

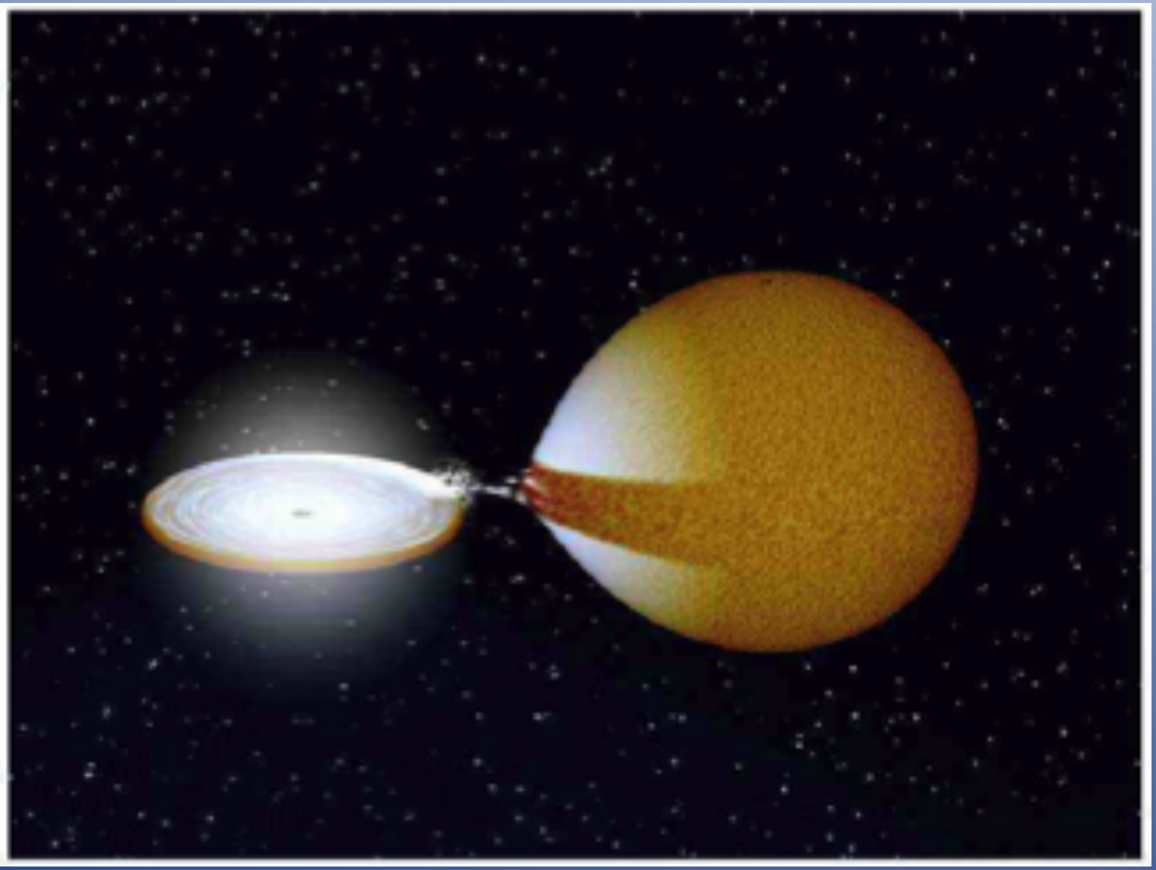


Core collapse supernovae originate from the death of a star ~10 times the mass of our sun or greater.

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?

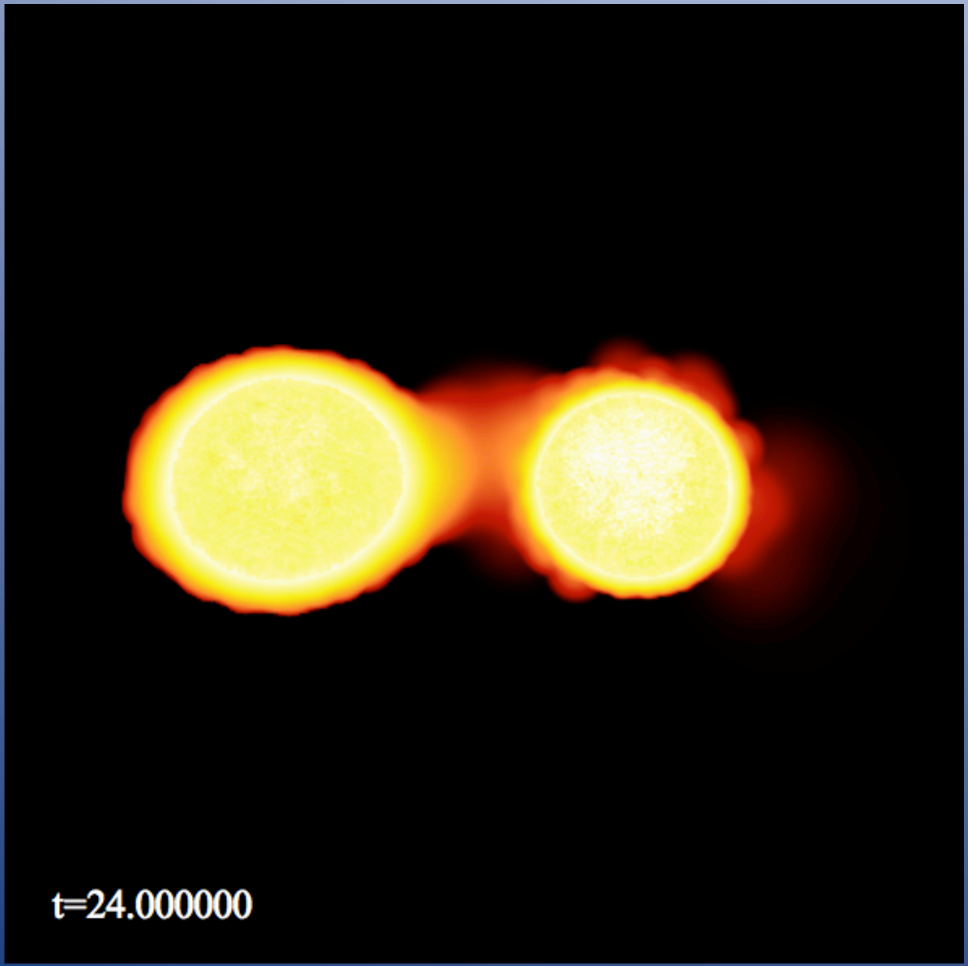


A thermonuclear supernova, which we label a Type Ia.

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.

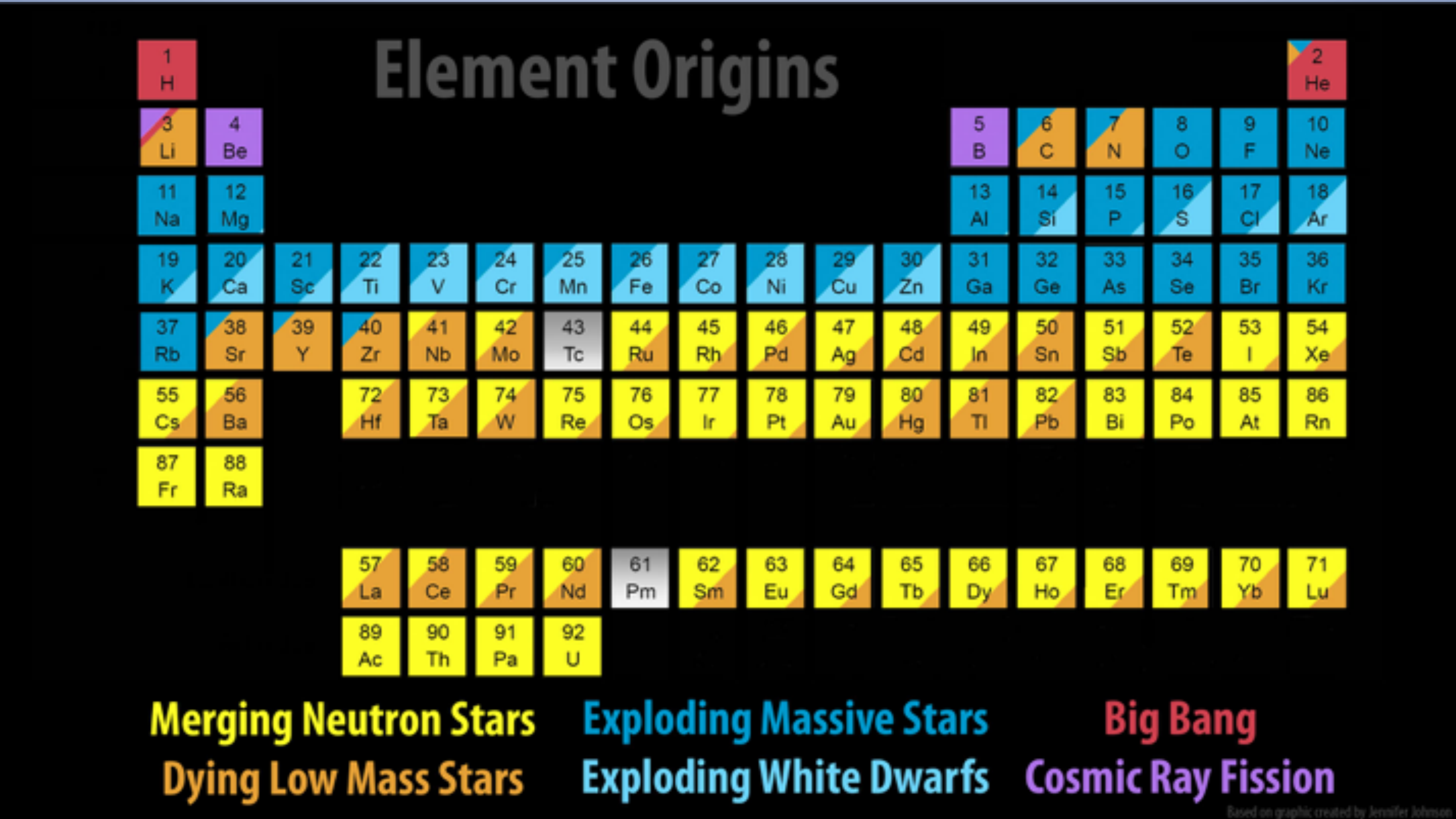
What are the Types of Supernovae?



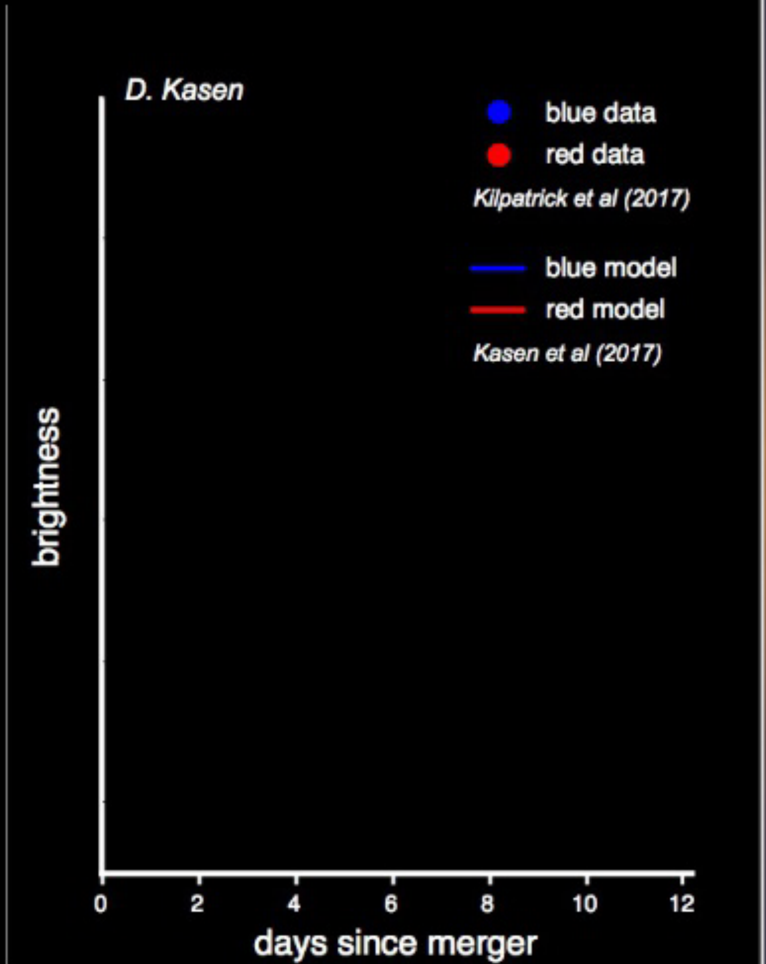
A double degenerate system - two white dwarfs.

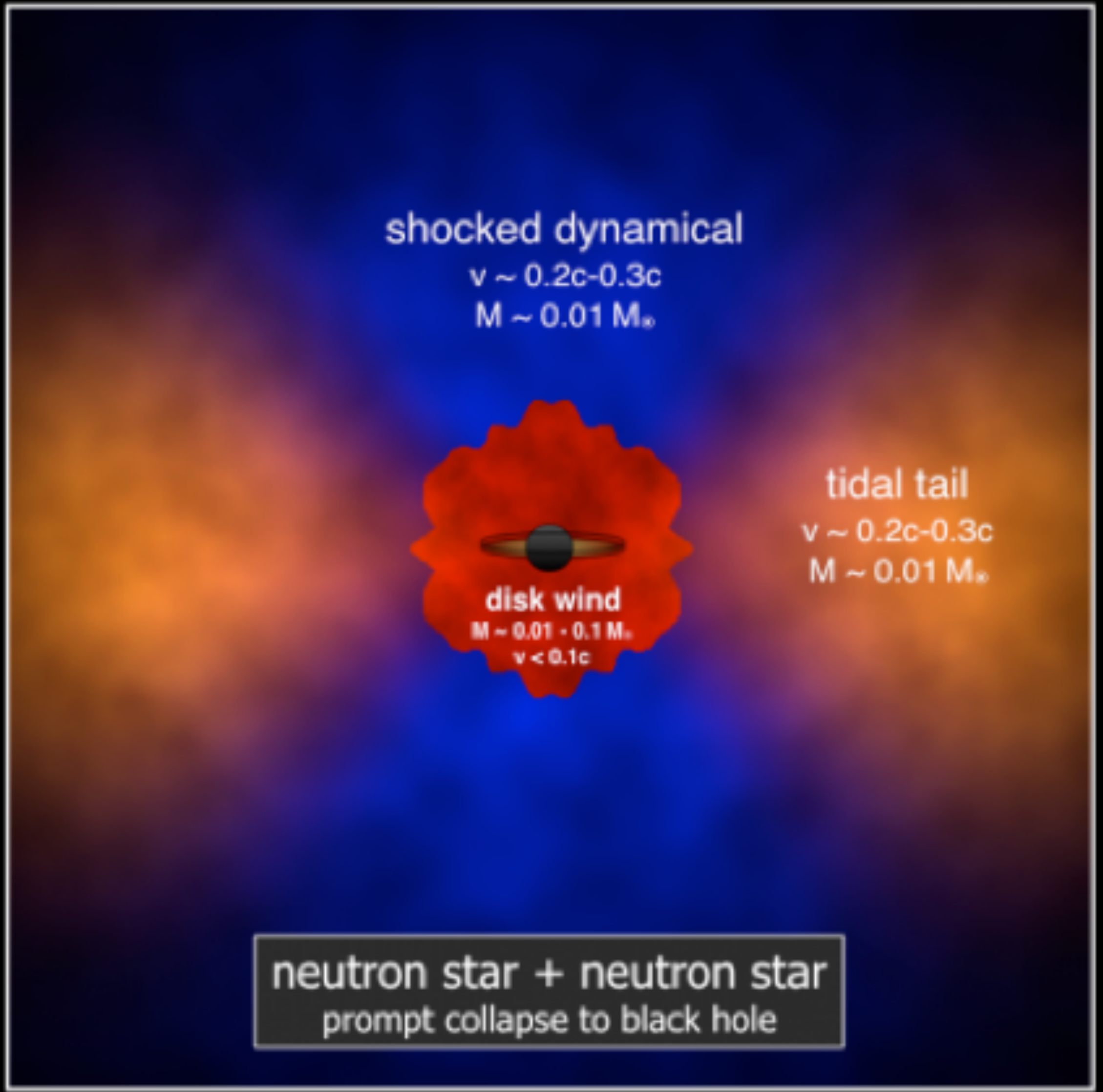
How do we "know" this? We infer this from our observations since we see SNe Ia in old galaxies where no star is more and 2-3 times the mass of our sun, and the fact that we see neither hydrogen nor helium in the spectra of these supernovae.

We are star-stuff



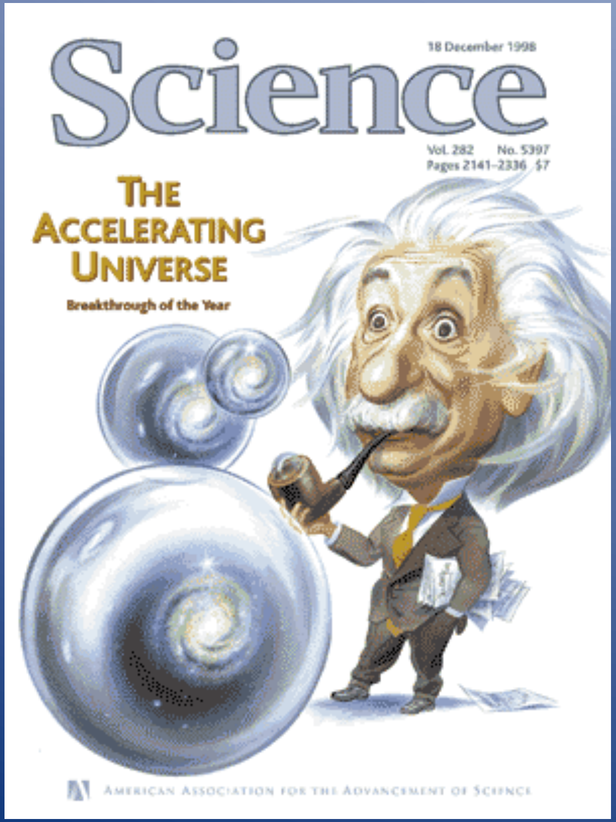
Binary Neutron Stars – Takes 2 SNe Explosions!

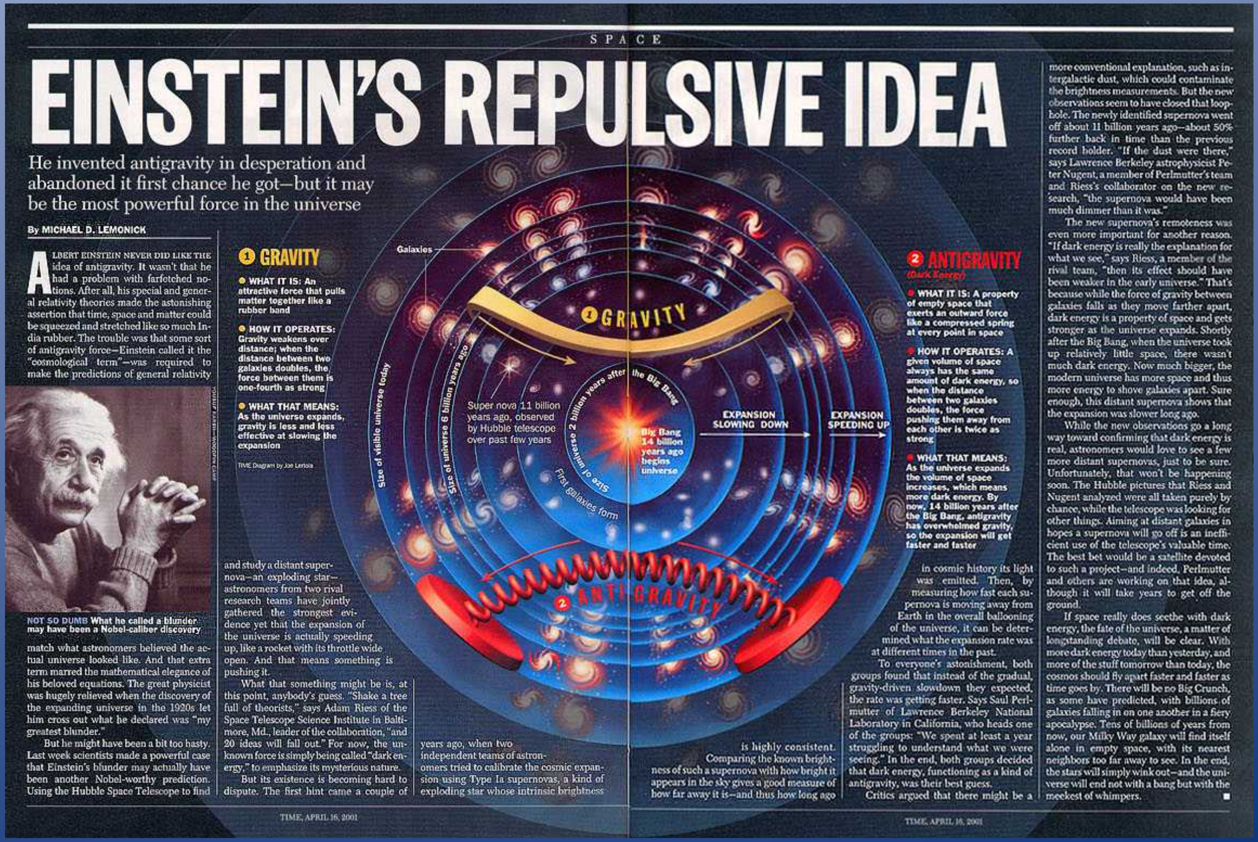




Cosmology

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".



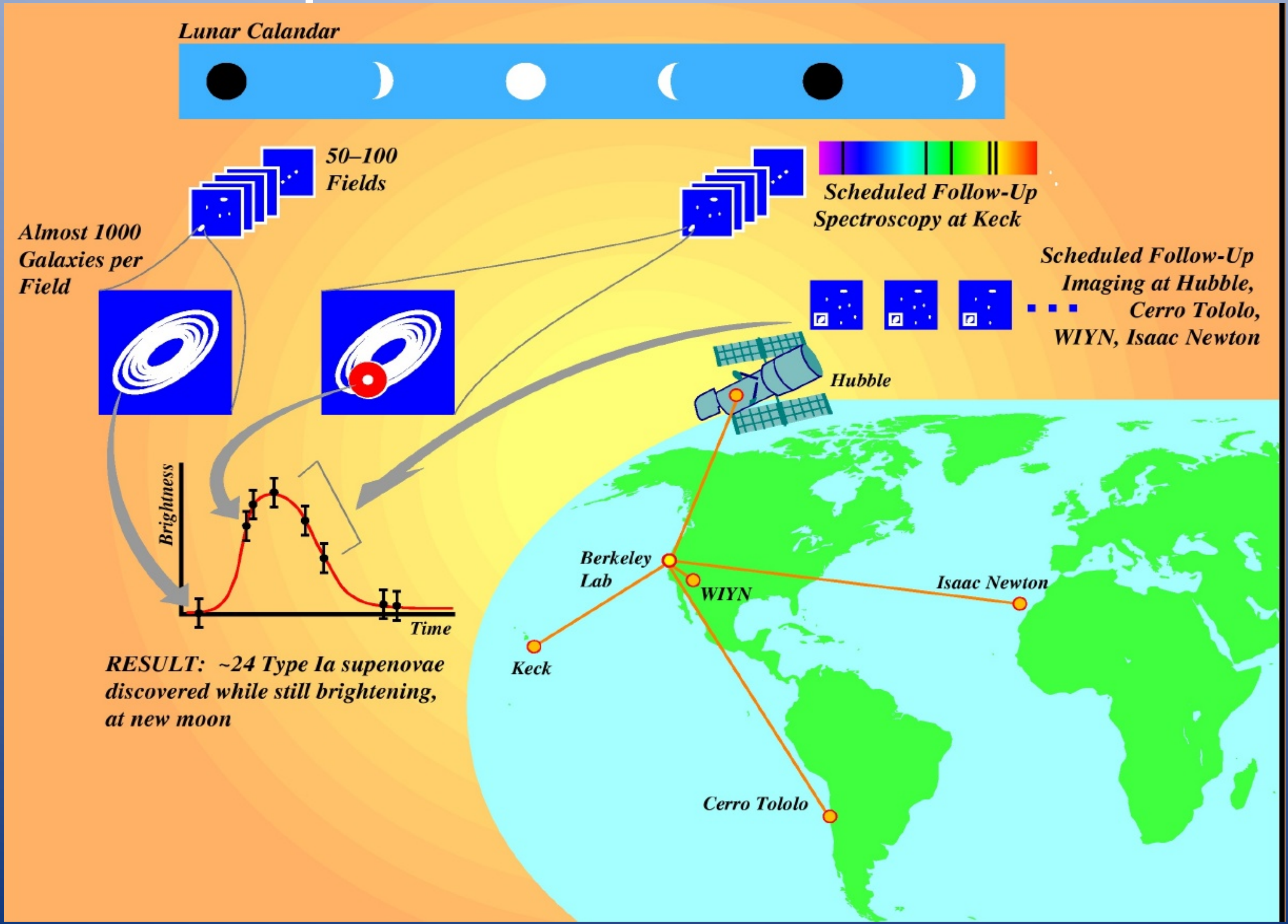


Supernovae circa 1998

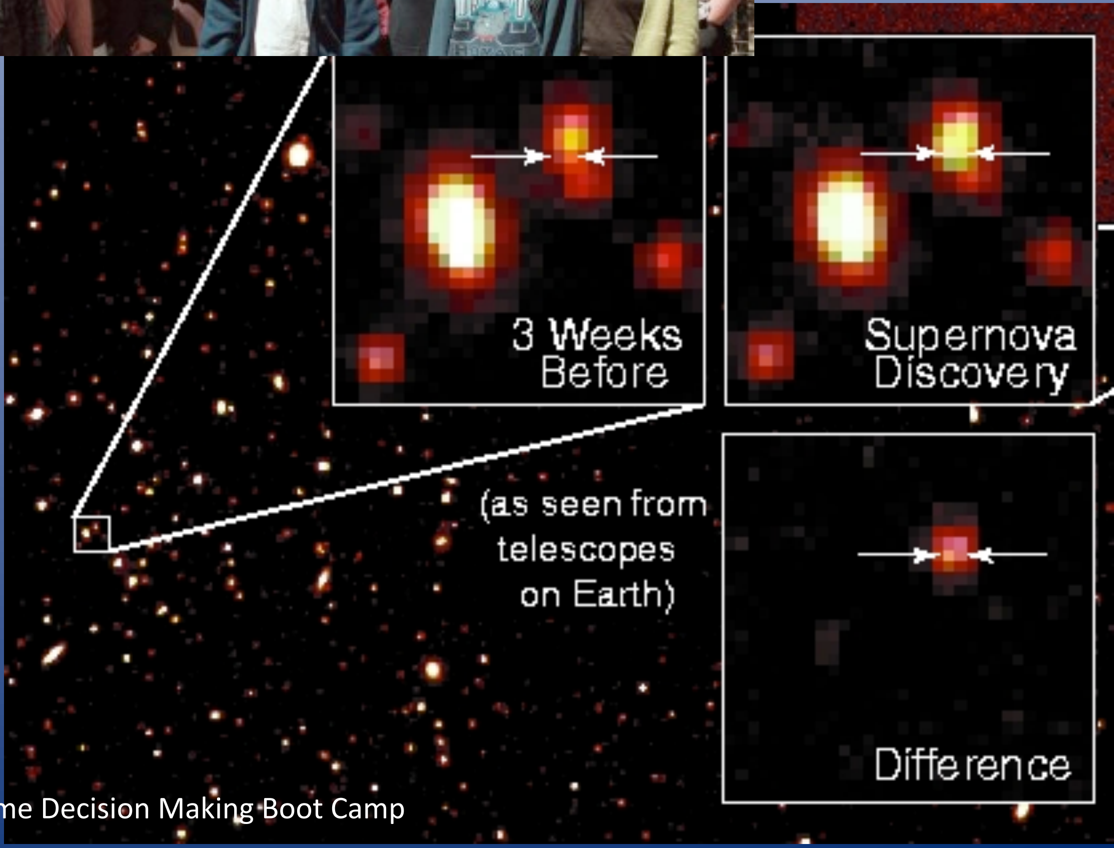
The 4-m Victor Blanco telescope was equipped with 1 (and then 4) 2kX2k ccd's. Exposures were typically 5-10 min long.

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



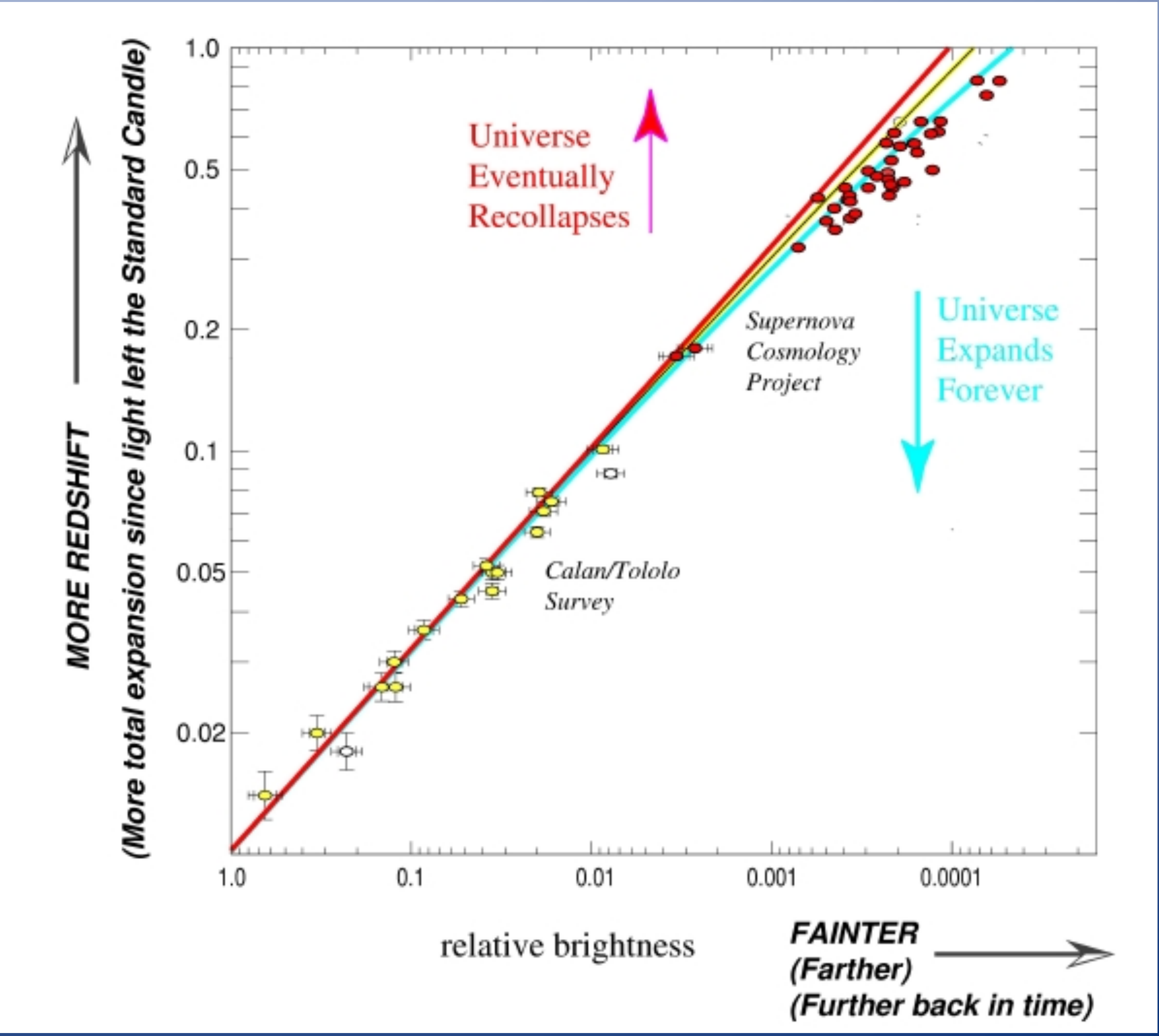
Supernovae circa 1995



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.

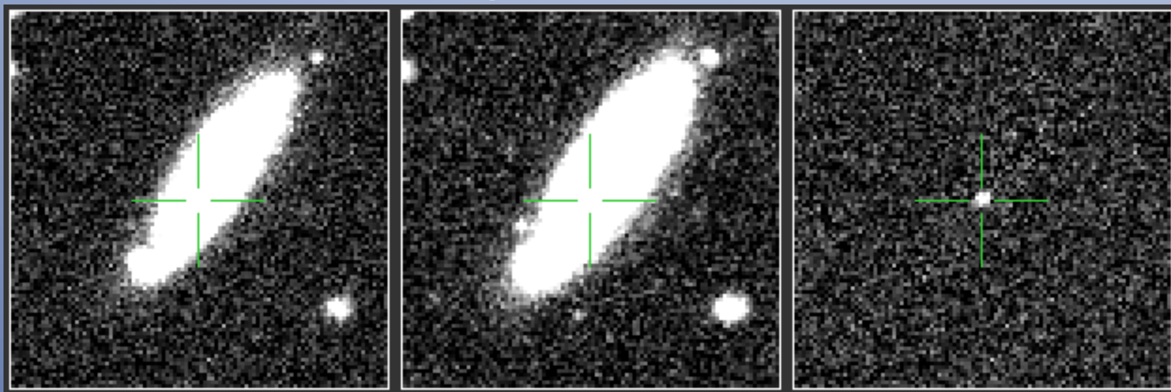
Turns out it is easier to find them at high redshift than low redshift....



Cosmology

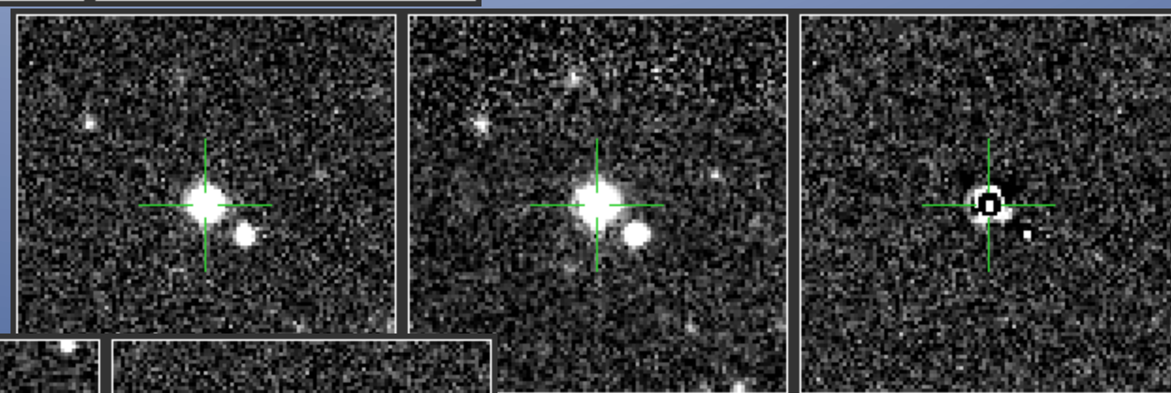
2011 Nobel Prize in Physics

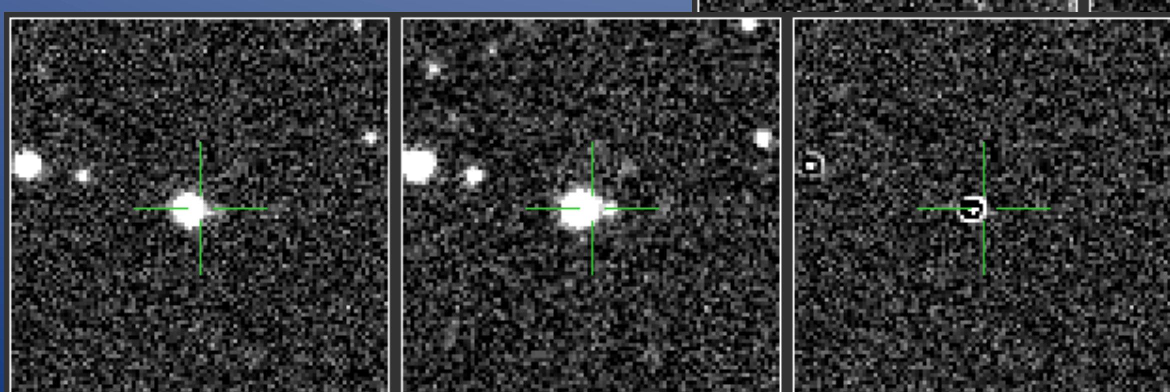
Supernovae circa 1998



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

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





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

Supernovae circa 2000

Pain begins.....

NEAT Search Facilities

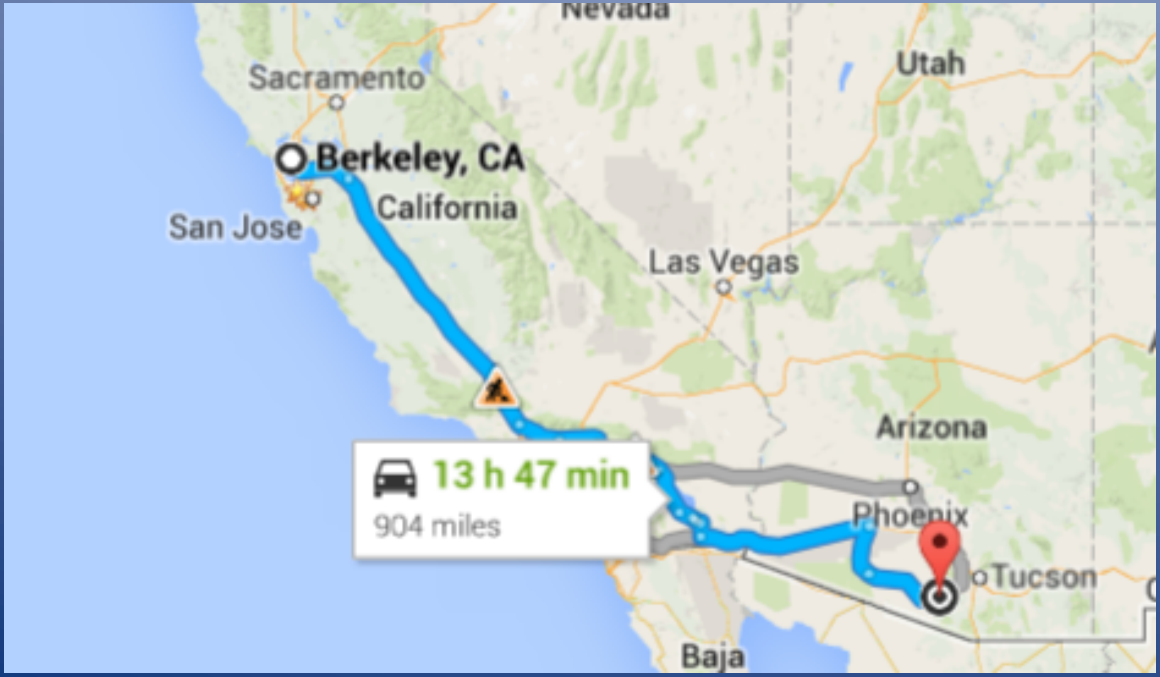
Site:	Haleakala	Palomar I	[illegible]
Aperture:	1.2m	1.2[illegible]	[illegible]m
Nights/Month:	18 dark/gray	18 [illegible]	[illegible] dark/gray
Imager Format:	4k × 4k	[illegible]	16k × 24k
Imager Scale:	1.33″/[illegible]	[illegible]/pixel	0.50″/pixel
Field of View:	[illegible]	[illegible].1°×3.4°	2.3°×4.0°
Filters:	[illegible]	open	4 fixed filters
Exposures:	[illegible] sec	3×60 sec	TBD
Reado[illegible]	20 sec	20 sec	TBD
Nig[illegible]	600□°	800□°	(2000 □°)
Start[illegible]	Mar 2000	Feb 2001	~Dec 2001
Data ([illegible]ompressed):	12 Gbyte/night	17 Gbyte/night	(28 Gbyte/night)

~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/iPTF (2009-2017)

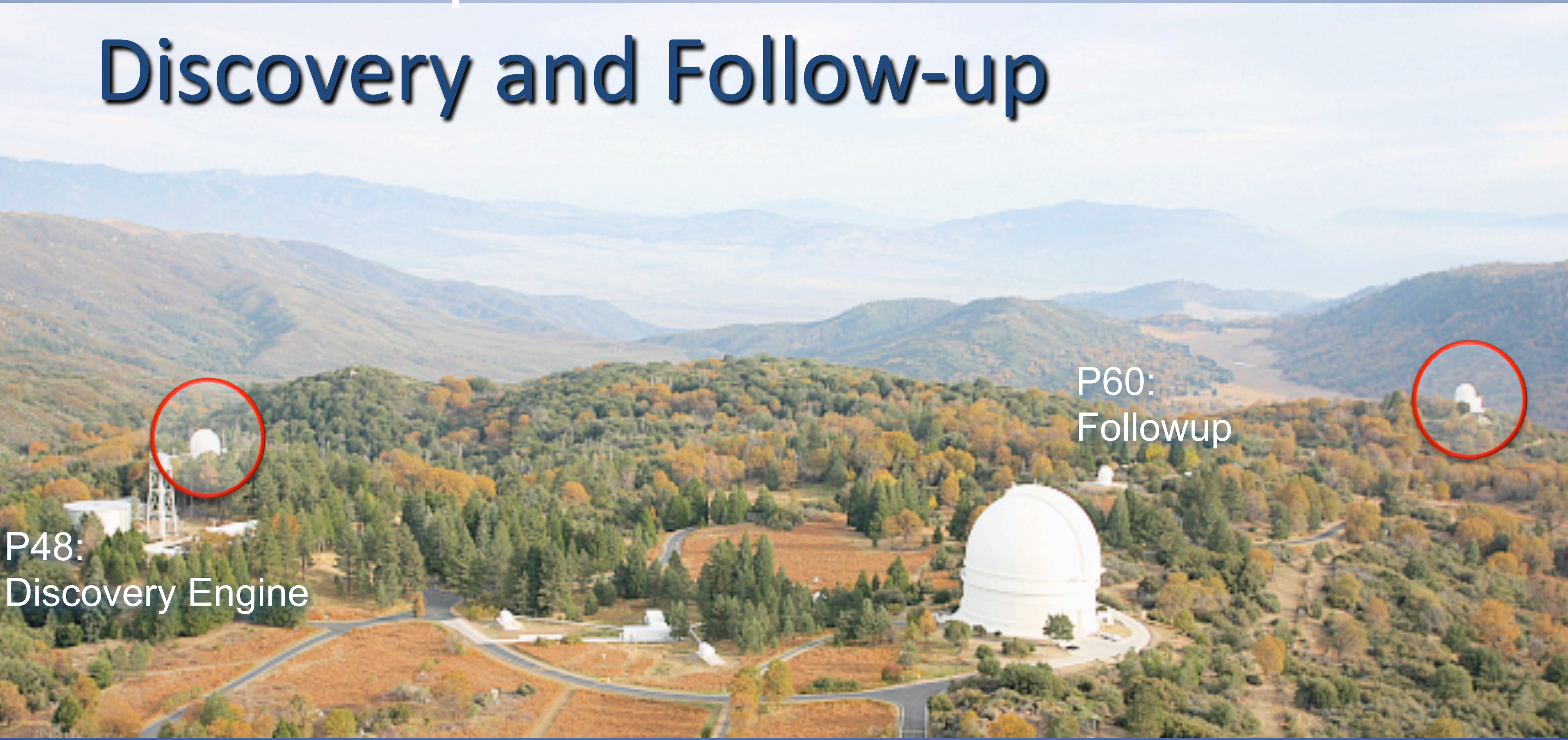
- CFH12k camera on the Palomar Oschin Schmidt telescope
  - 7.8 sq deg field of view, 1" pixels
  - 60s exposures with 15-20s readout in r, g and H-alpha
  - First light Nov. 24, 2008.
  - First useful science images on Jan 13th, 2009.

- 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.

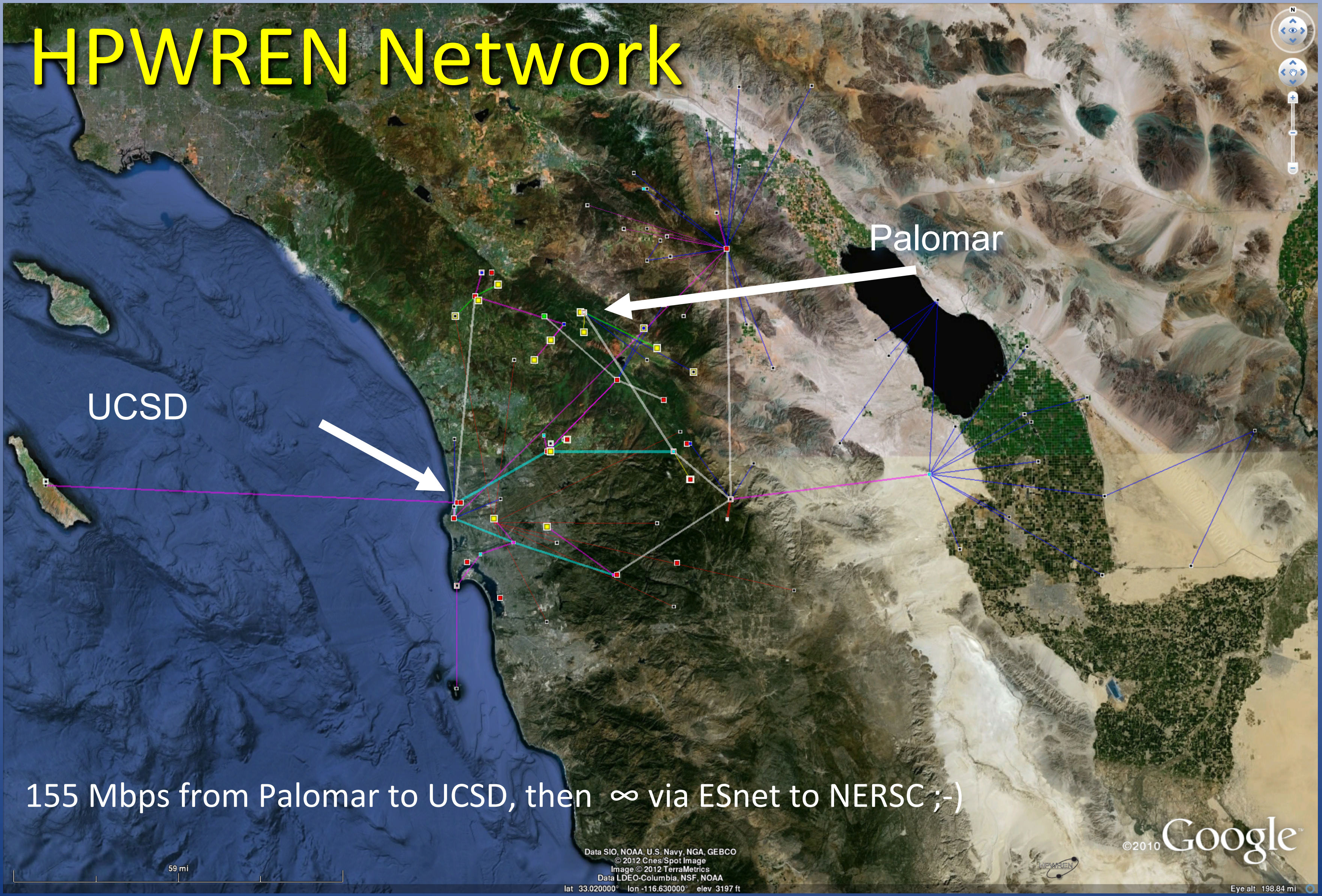
Supernovae circa 2009

Discovery and Follow-up



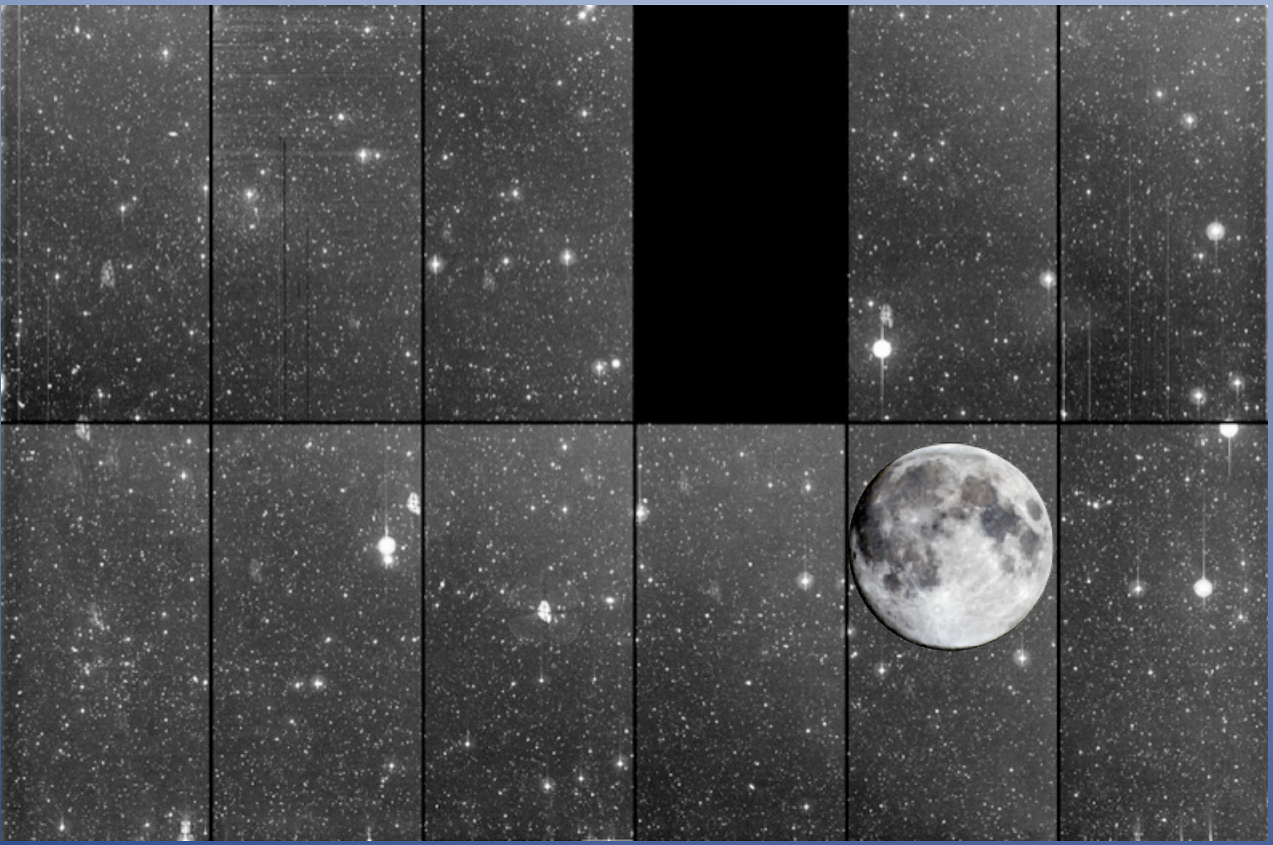
Instrumentation, system design, first results	Law, Kulkarni, Dekany et al. 2009 PASP 121 1395L
Science plans	Rau, Kulkarni, Law et al. 2009 PASP 121 1334R
2010 survey status	Law et al. 2010 SPIE 7735

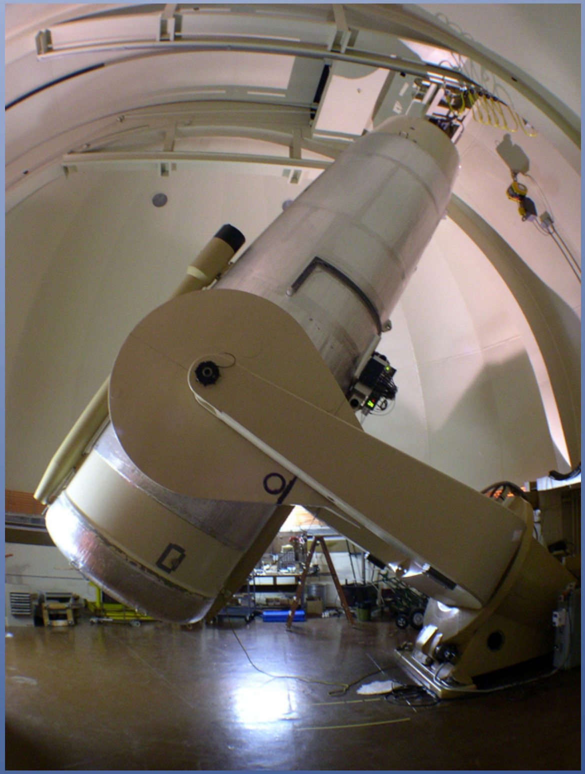
HPWREN Network



155 Mbps from Palomar to UCSD, then ∞ via ESnet to NERSC ;-)

PTF Camera





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

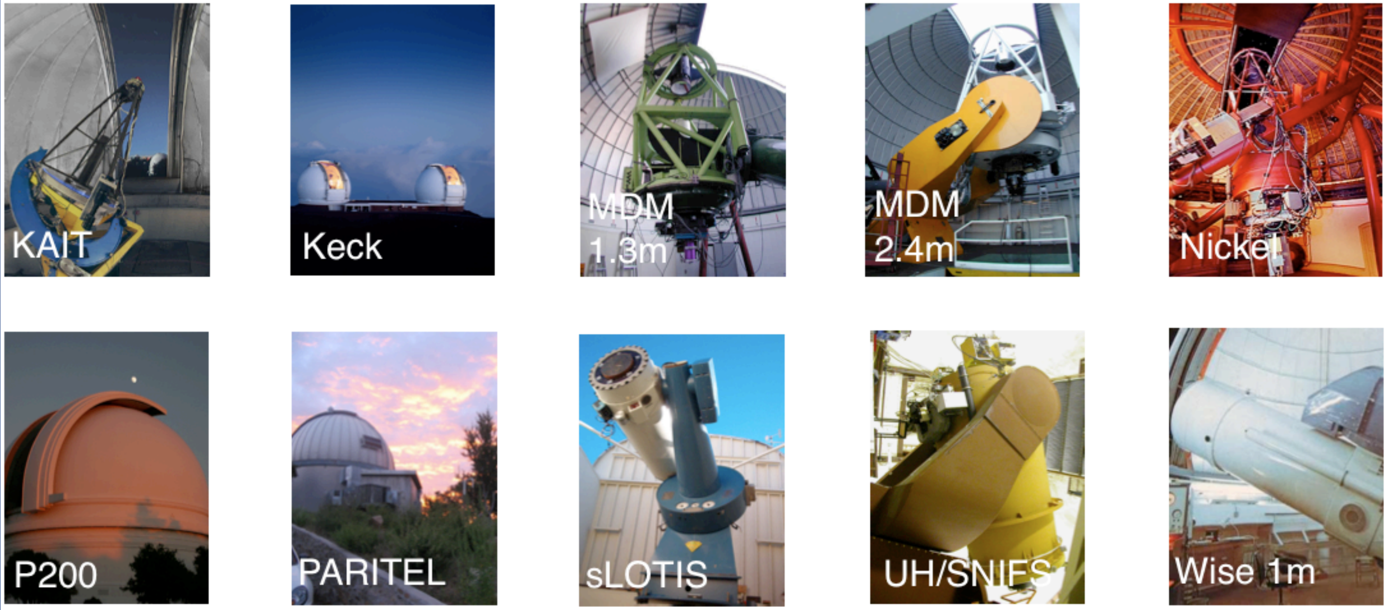
PTF Science

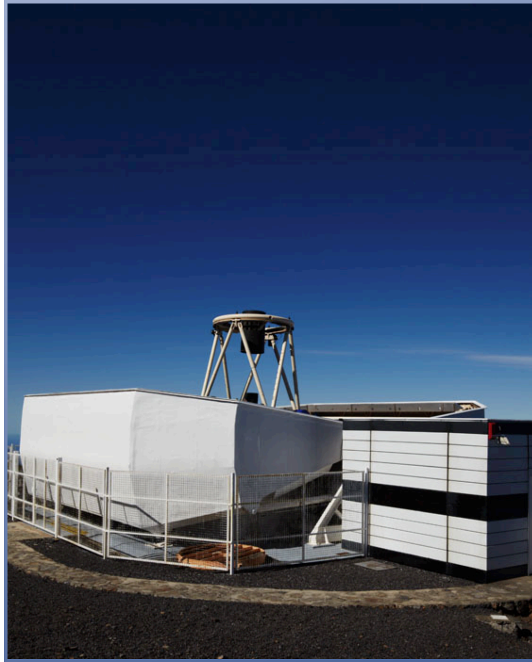
PTF Key Projects	
Various SNe	Dwarf novae
Transients in nearby galaxies	Core collapse SNe
RR Lyrae	Solar system objects
CVs	AGN
AM CVn	Blazars
Galactic dynamics	LIGO & Neutrino transients
Flare stars	Hostless transients
Nearby star kinematics	Orphan GRB afterglows
Type Ia Supernovae	Eclipsing stars and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

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

PTF Science

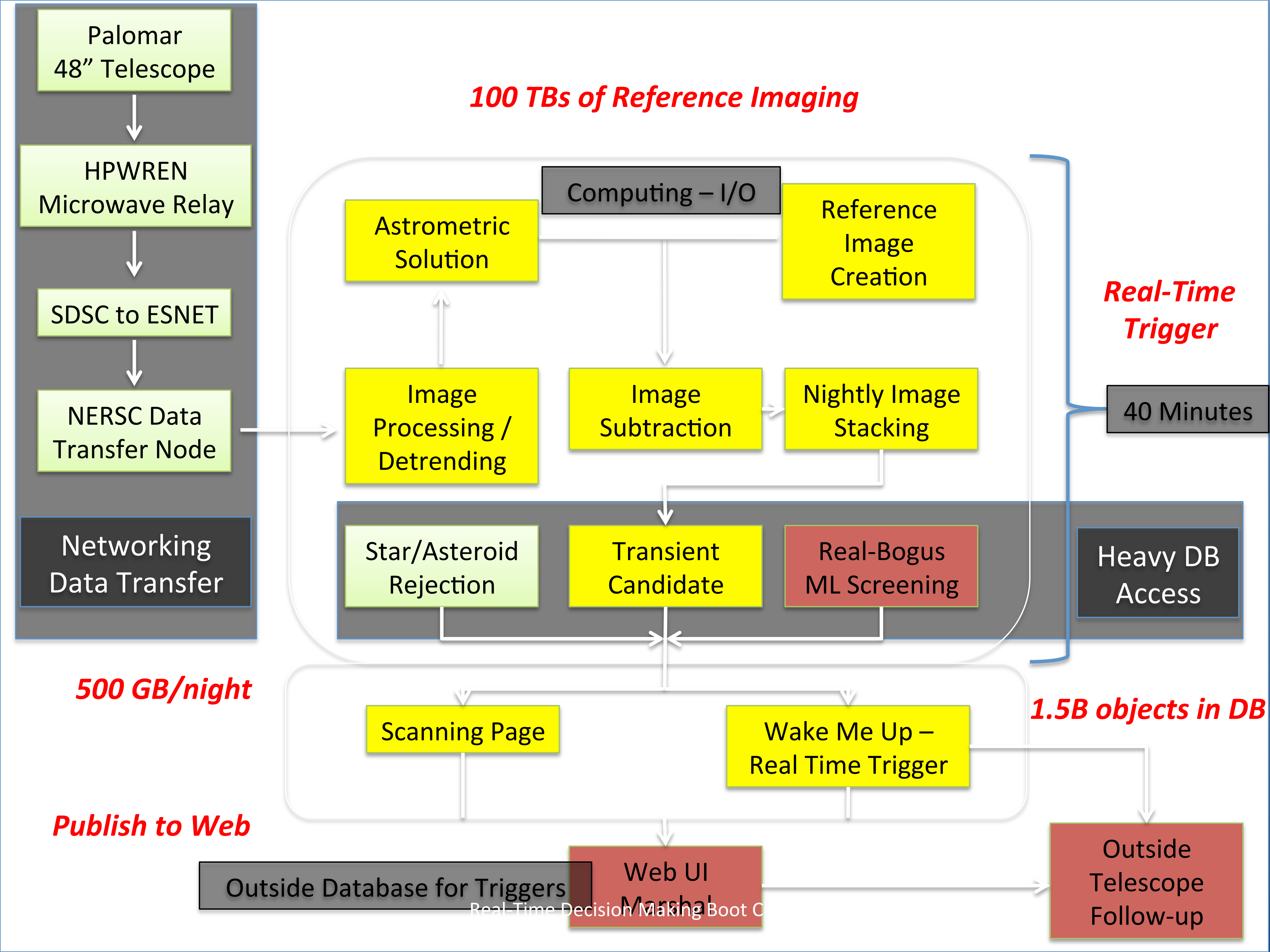
▼ ▶ Detected transients will be followed up using a wide variety of optical and IR, photometric and spectroscopic followup facilities.





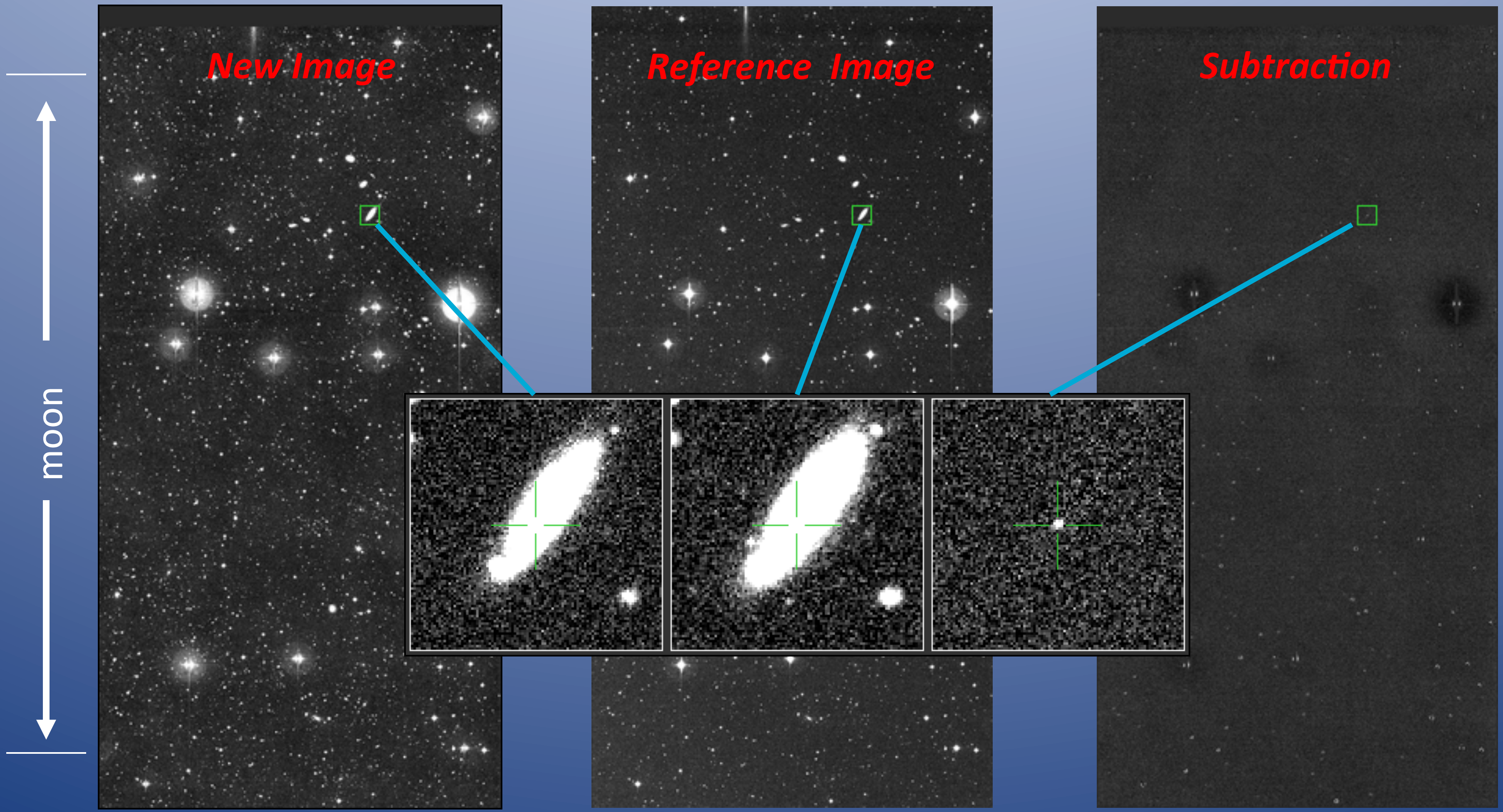
Liverpool Telescope

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



Palomar
48” Telescope
HPWREN
Microwave Relay
SDSC to ESNET
NERSC Data
Transfer Node
Networking
Data Transfer
100 TBs of Reference Imaging
Computing – I/O
Astrometric
Solution
Reference
Image
Creation
Real-Time
Trigger
Image
Processing /
Detrending
Image
Subtraction
Nightly Image
Stacking
40 Minutes
Star/Asteroid
Rejection
Transient
Candidate
Real-Bogus
ML Screening
Heavy DB
Access
500 GB/night
1.5B objects in DB
Scanning Page
Wake Me Up –
Real Time Trigger
Publish to Web
Outside Database for Triggers
Web UI
Marshal
Outside
Telescope
Follow-up

Real or Bogus – Machine Learning Analysis



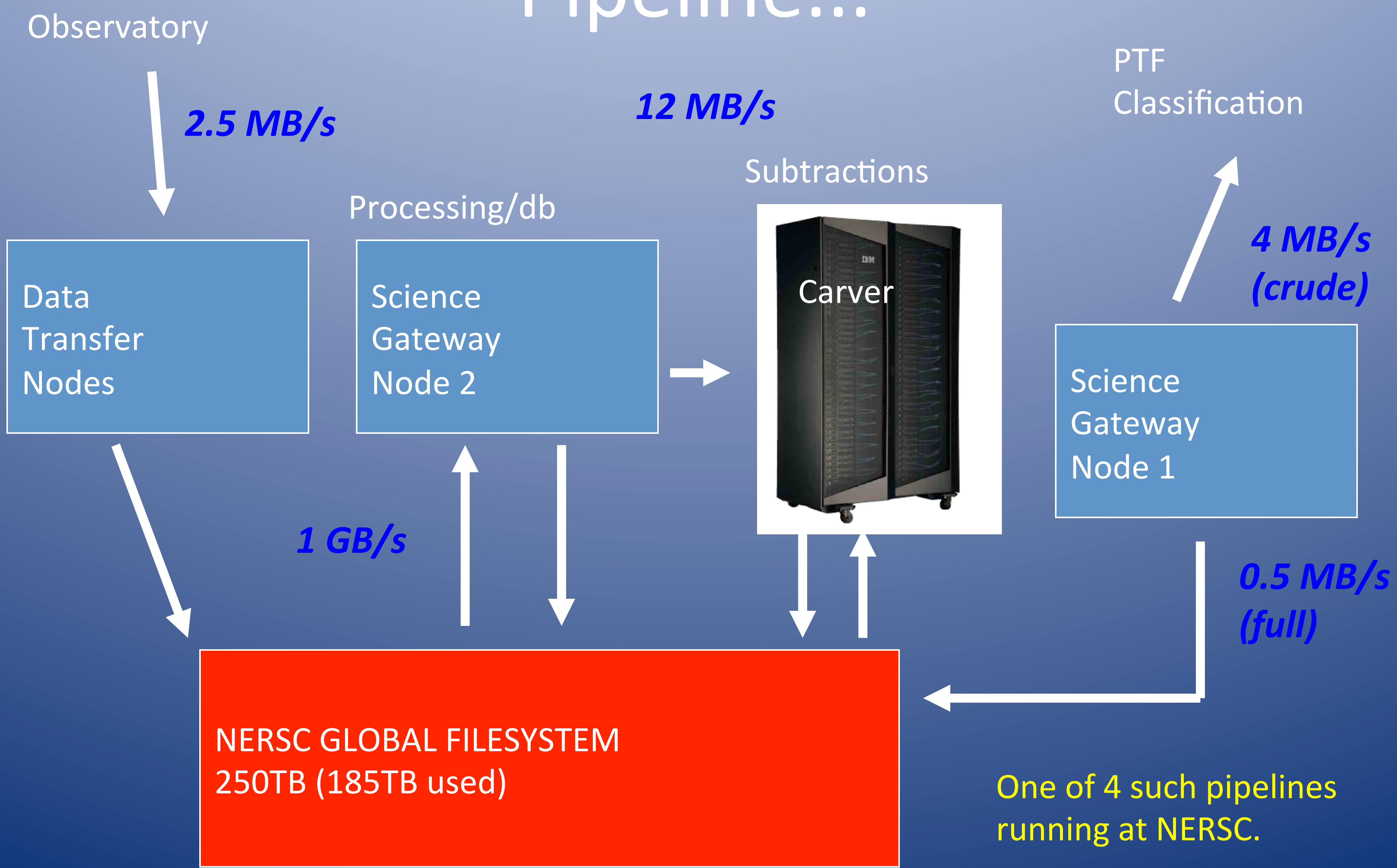
4096 X 2048 CCD images - over 3000 per night – producing 1.5M bogus detections, 50k known astrophysical objects and only 1-2 new astrophysical transients of interest every night. Machine learning is used to wade through this sea of garbage.

PTF Database

	R-band	g-band
images	1.82M	305k
subtractions	1.52M	146k
references	29.2k	6.3k
Candidates	890M	197M
Transients	42945	3120

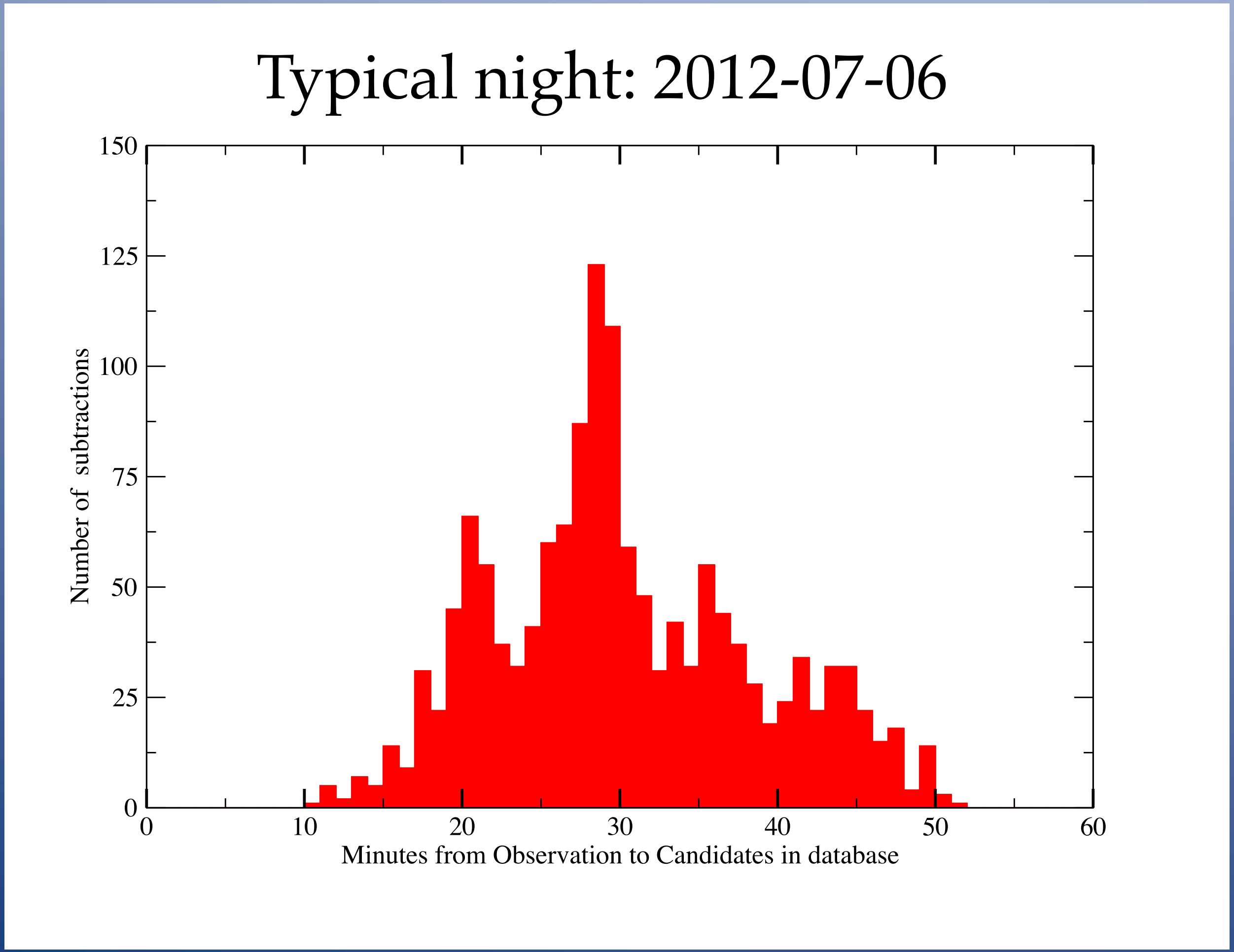
All in 851 nights.
An image is an individual chip (~0.7 sq. deg.)
The database is now 1 TB.

Pipeline...



Observatory
2.5 MB/s
12 MB/s
PTF Classification
Subtractions
Processing/db
Data Transfer Nodes
Science Gateway Node 2
Carver
4 MB/s (crude)
Science Gateway Node 1
1 GB/s
0.5 MB/s (full)
NERSC GLOBAL FILESYSTEM
250TB (185TB used)
One of 4 such pipelines running at NERSC.

Turn-around



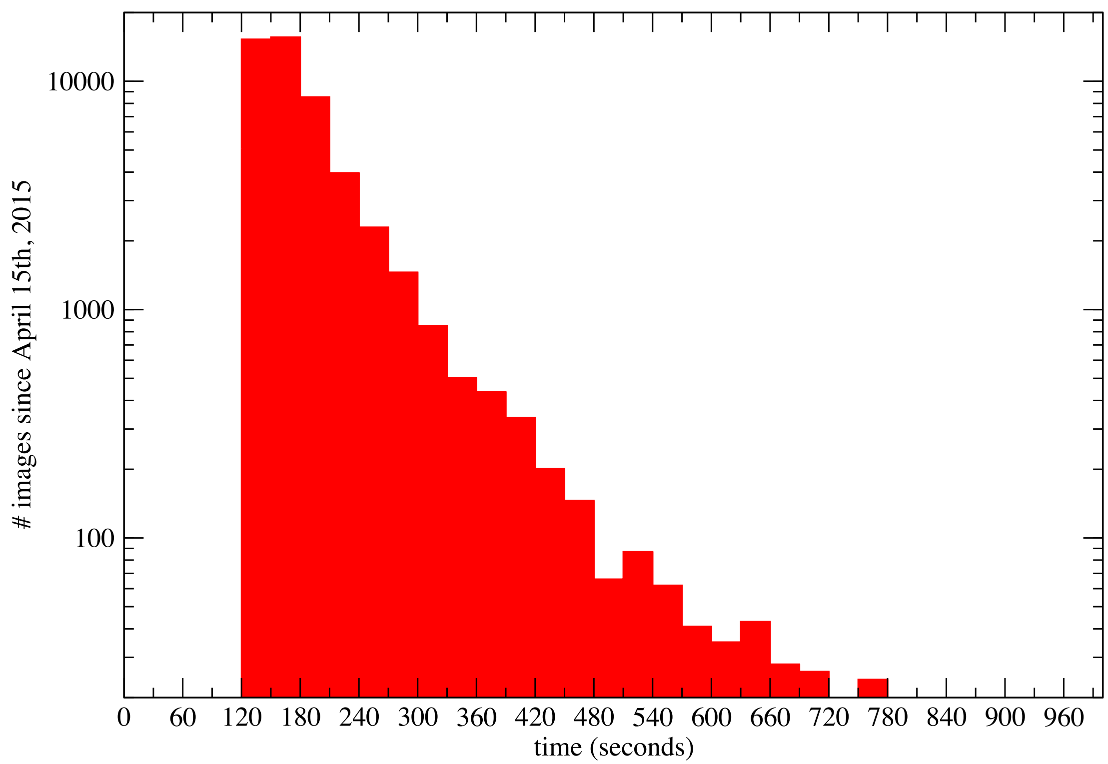
What does "real-time" subtractions really mean?

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:

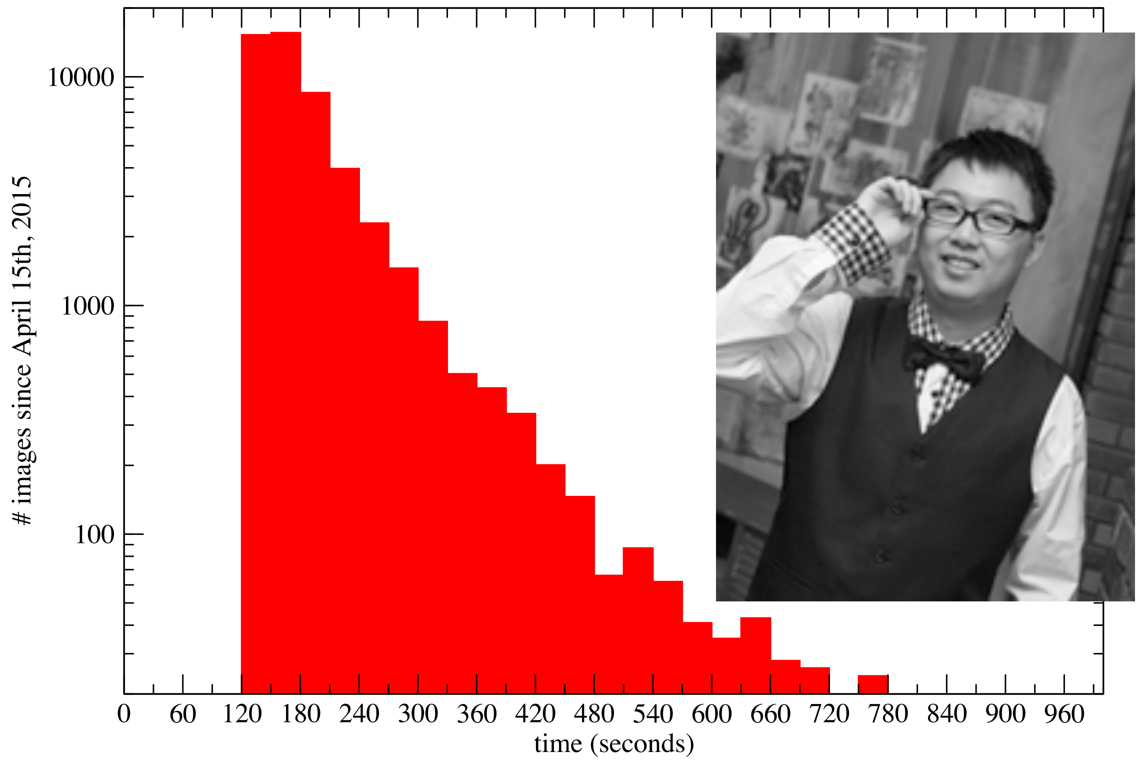
iPTF turn-around



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



Yi Cao's Caltech thesis May 3, 2016.
Became an eScience Postdoctoral Fellow at University of Washington → Google!

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

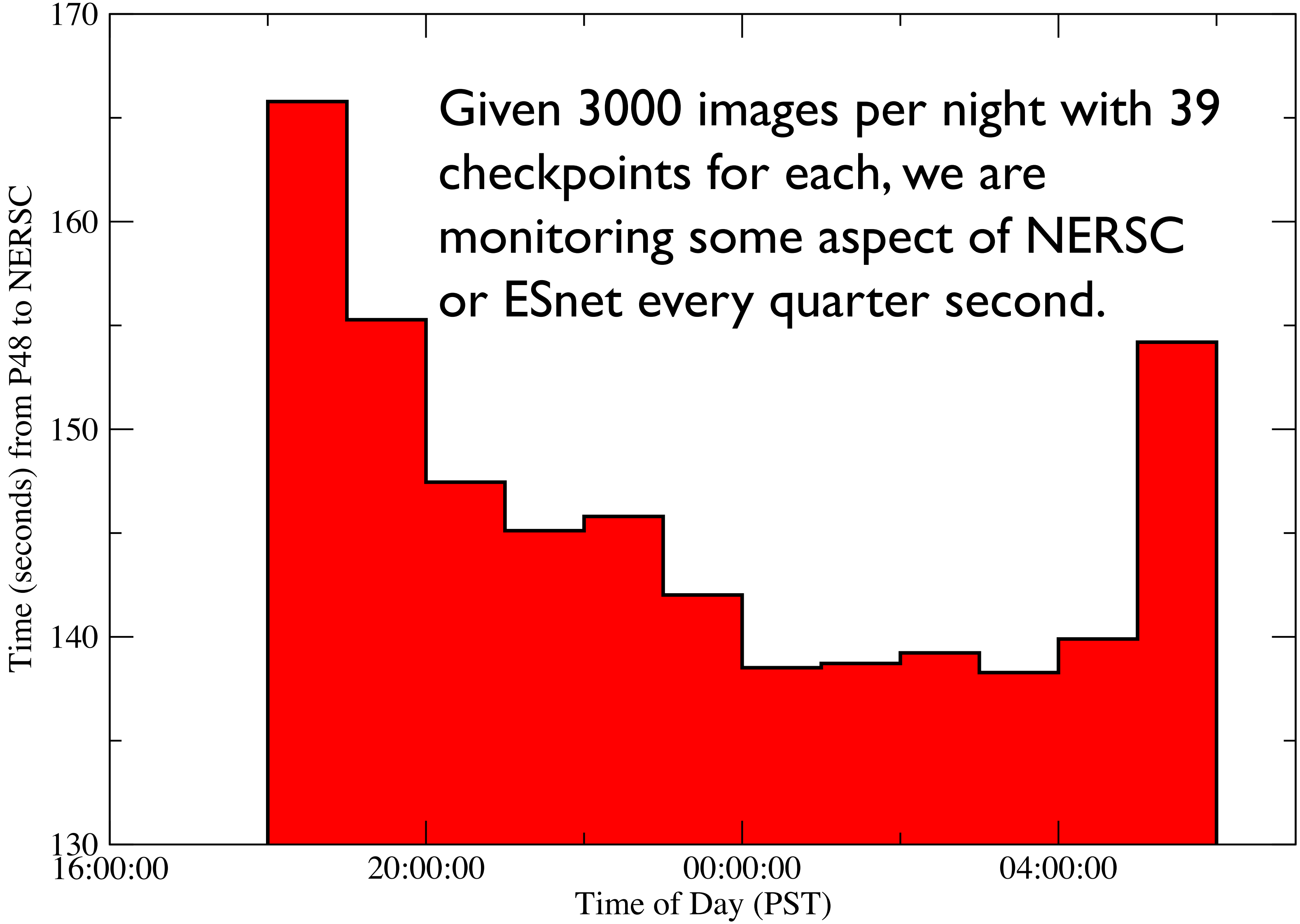
Typical turnaround is now < 5 minutes for 95% of the data!

Instrumented Pipeline with 39 Checkpoints

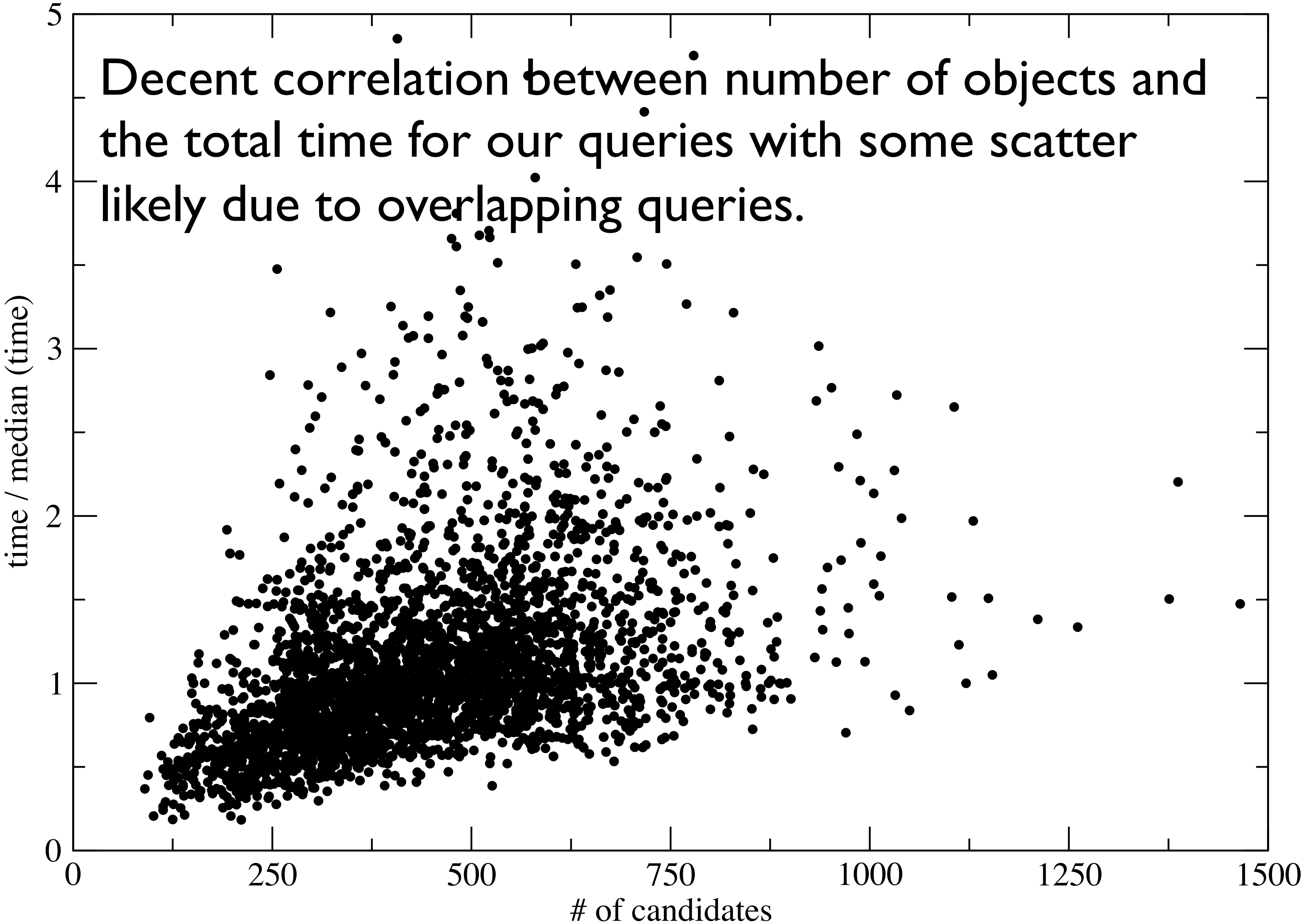
Covers everything from:

- Pulling the data from the telescope
- I/O on scracth
- 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

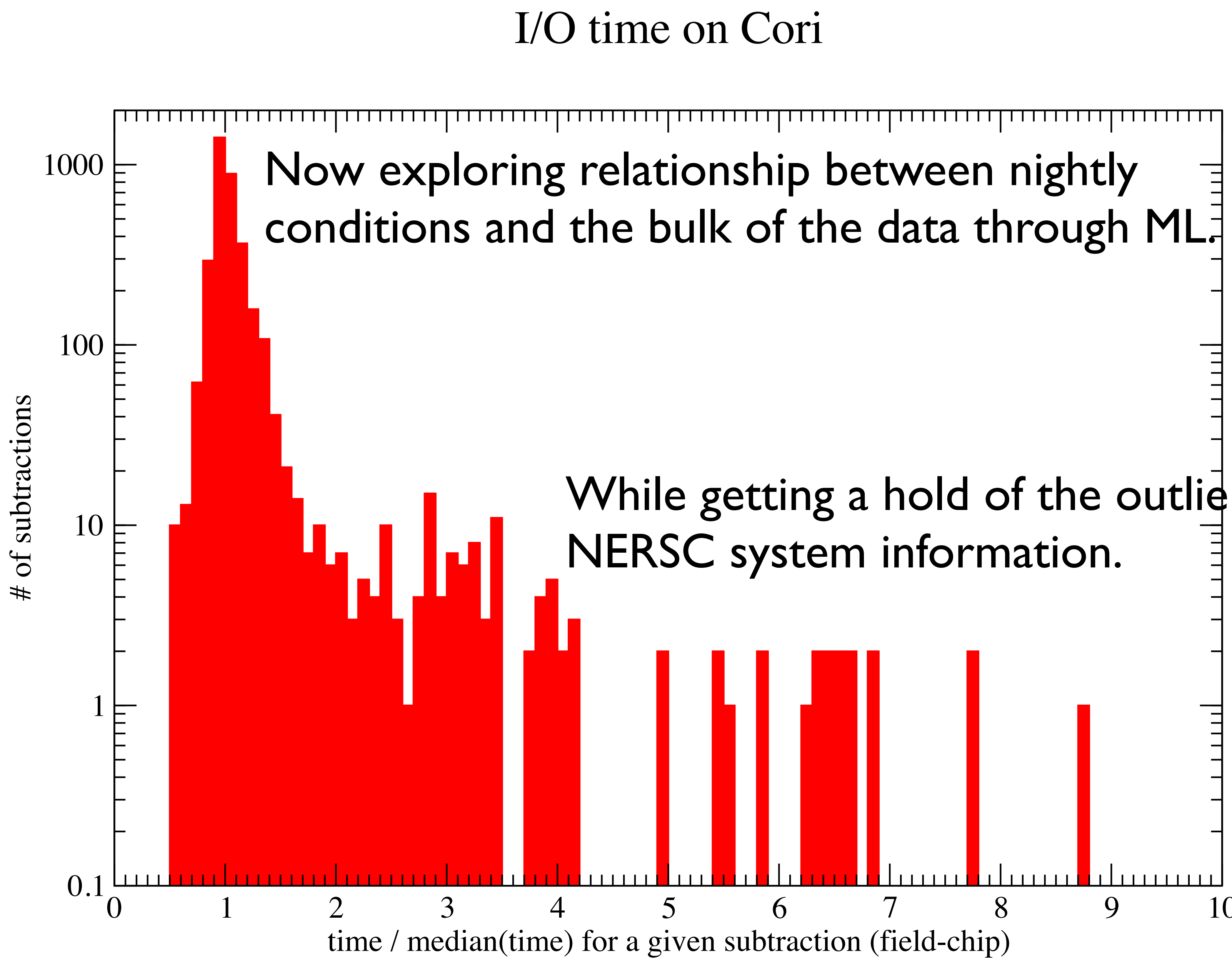
For 8 hours every night, we now know more about the NERSC center than they do in real-time.



DB Access



Decent correlation between number of objects and the total time for our queries with some scatter likely due to overlapping queries.



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

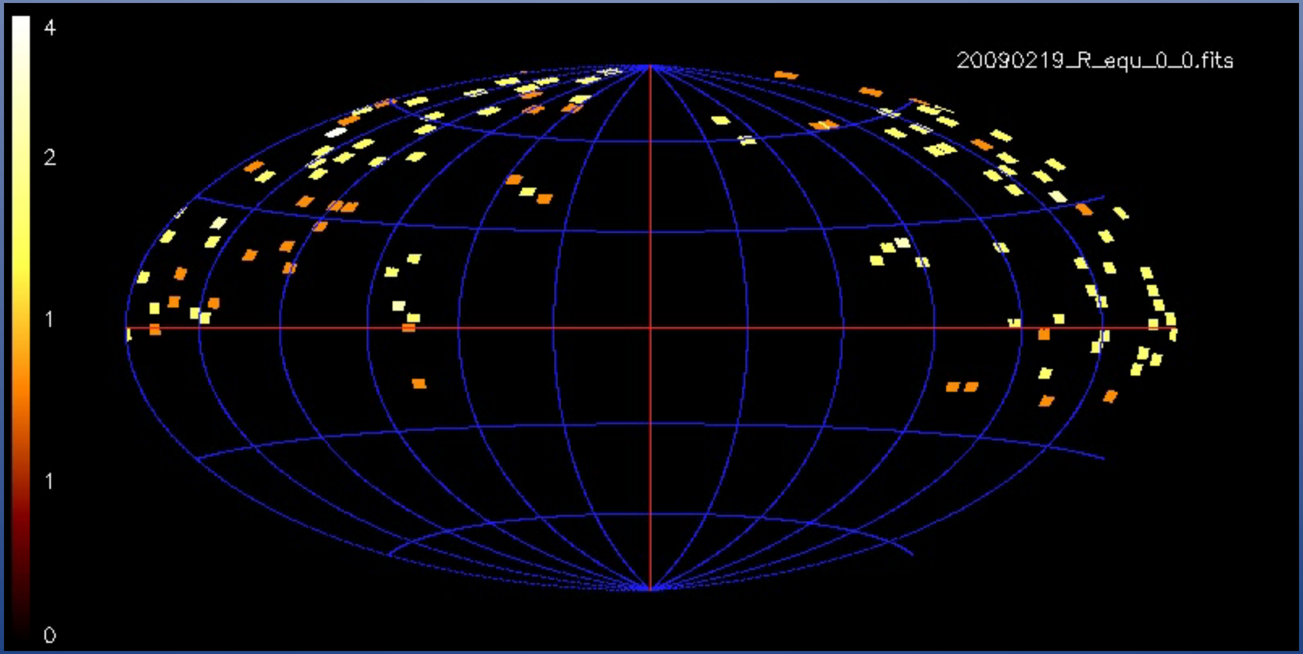
The Final Tally:

- 3015 Spectroscopically typed supernovae

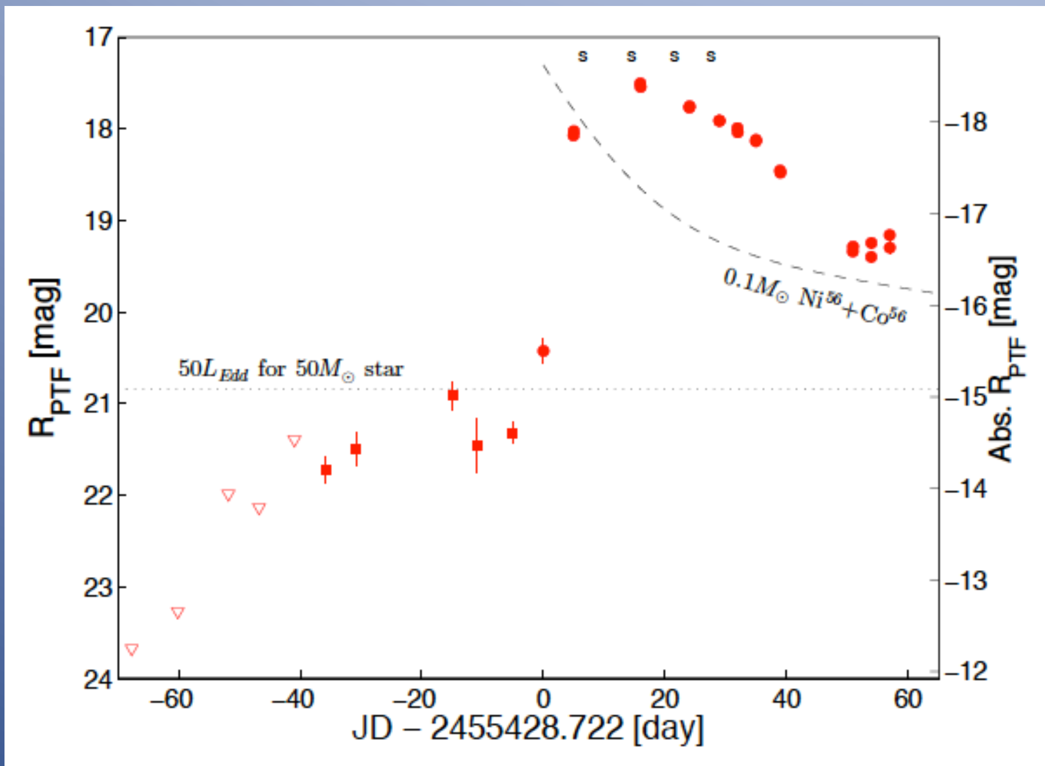
(Ia: 2060 | II: 693 | Ib: 45 | Ic: 60 | Ib/c: 15 | Ic-BL: 35 | SLSNe: 48)

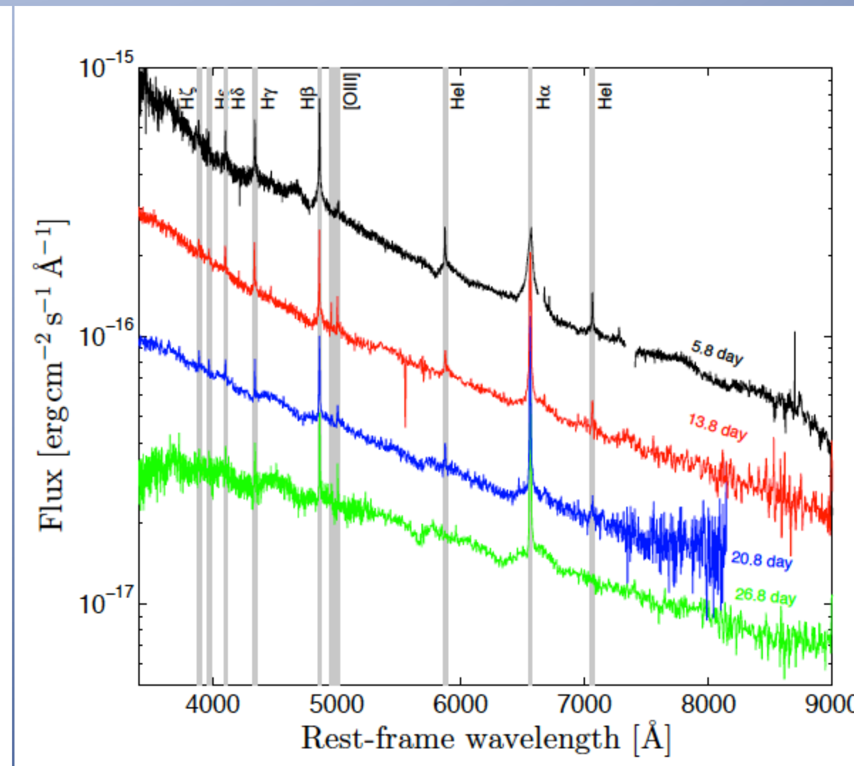
- 10^5 Galactic Transients
- 10^4 Transients in M31

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



Pre-Outbursts

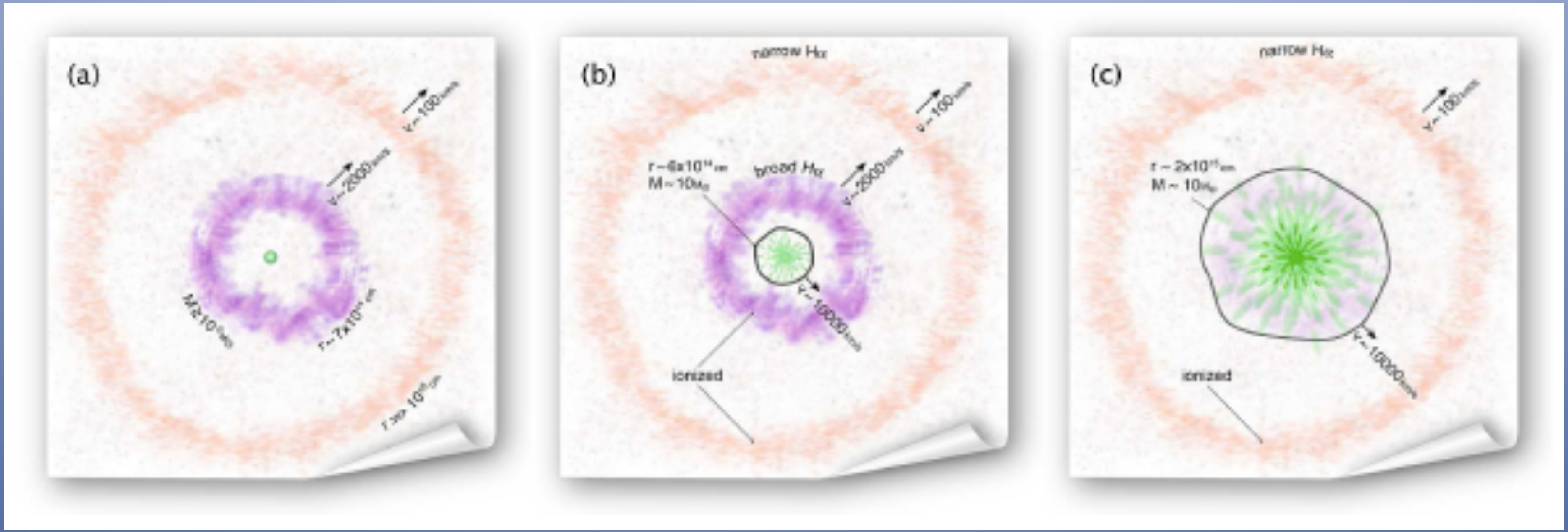




SN 2010mc - Ofek et al. (2013) *Nature &* SN 2011ht – Fraser et al. (2013) *ApJ*

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.

Pre-Outbursts

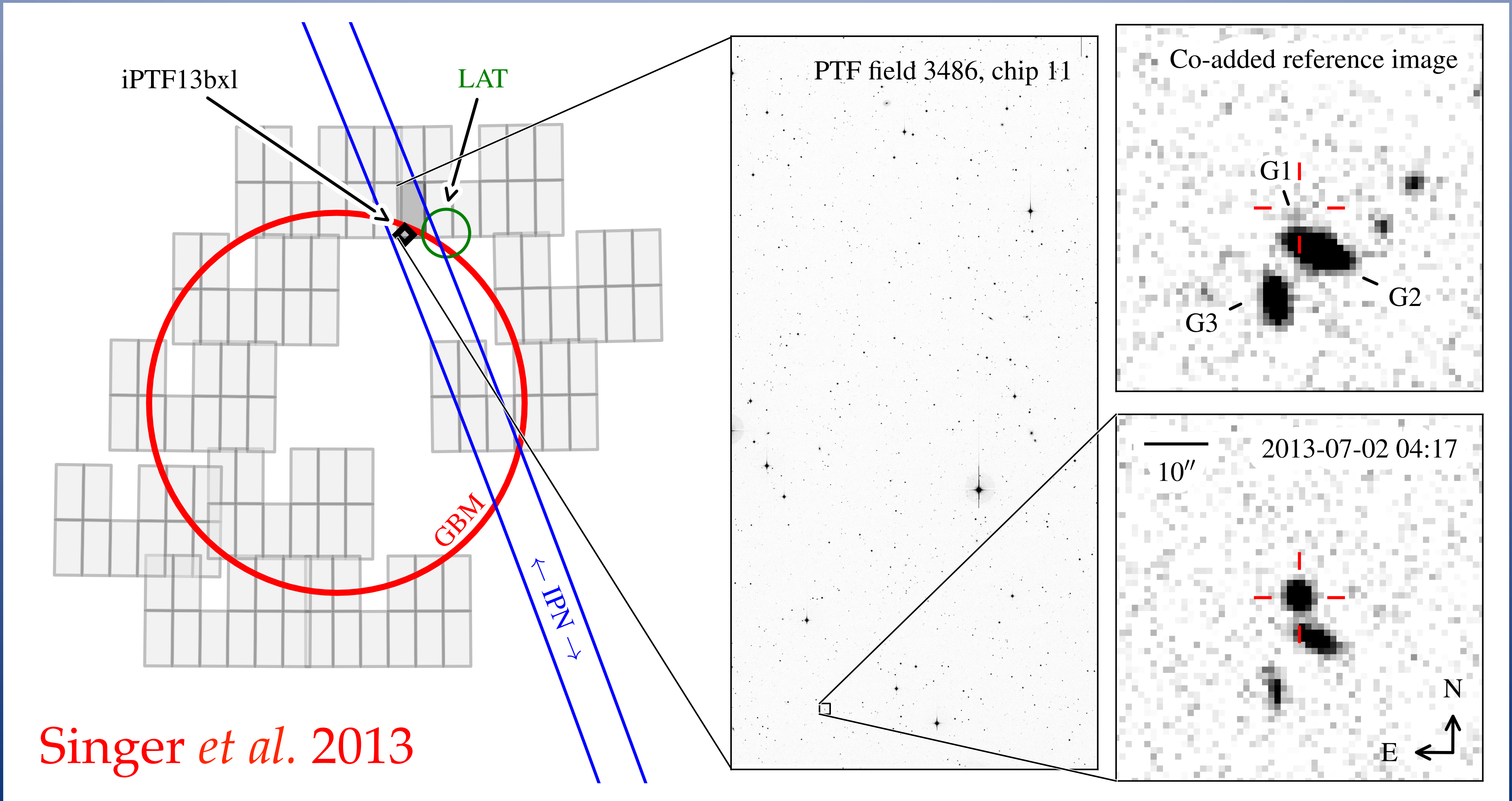


(a) 10^{-2} $M_{\odot}$ ejected one month earlier during pre-outburst ~2000 km/s

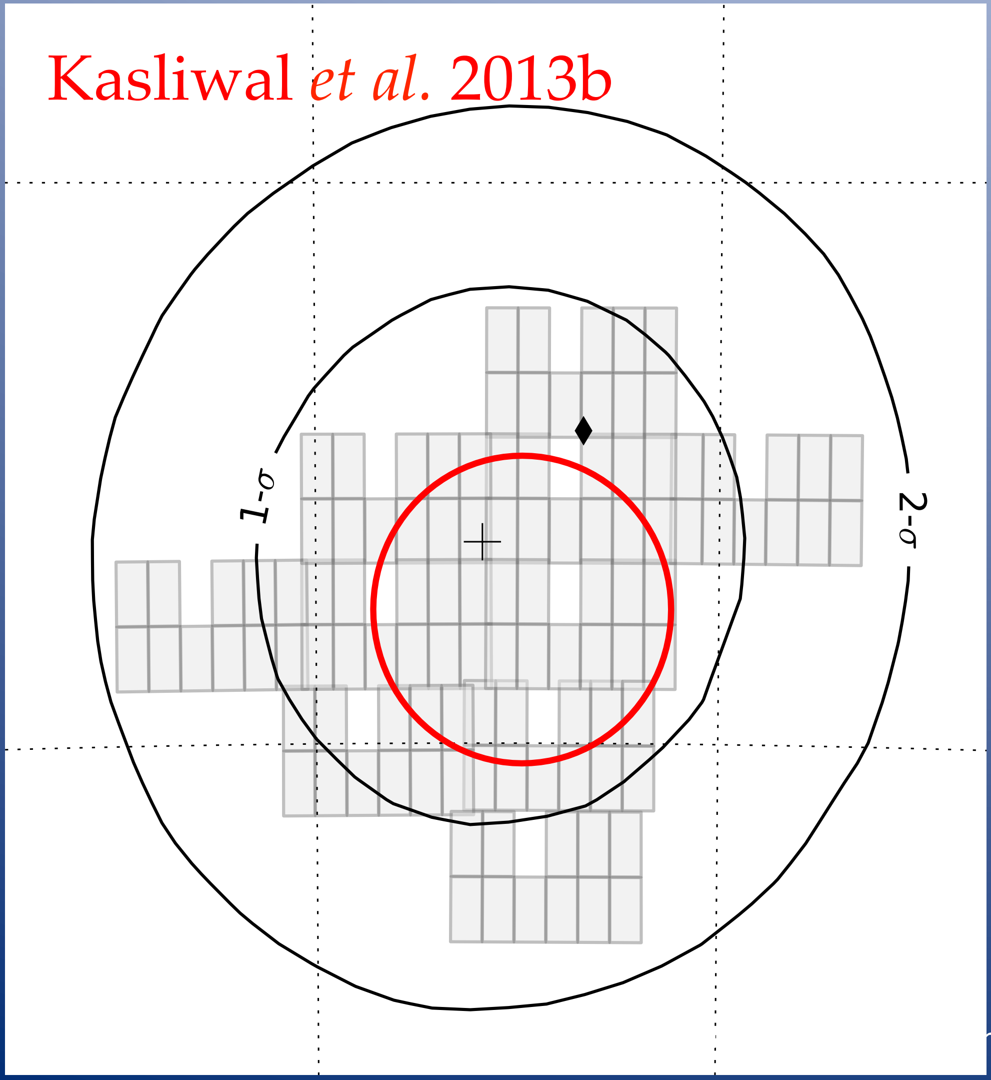
(b) At day ~ 5, the SN shock front (grey line at 10^4 km/s) is ionising the inner and outer shells which produce the broad and narrow H emission seen in the early-time spectra.

(c) At day ~ 20, the SN shock engulfs the inner shell, and the intermediate width Hα vanishes and narrower features appear: pre-pre-outbursts.

Overcoming wide & fast: iPTF13bxl in 71 deg^2!



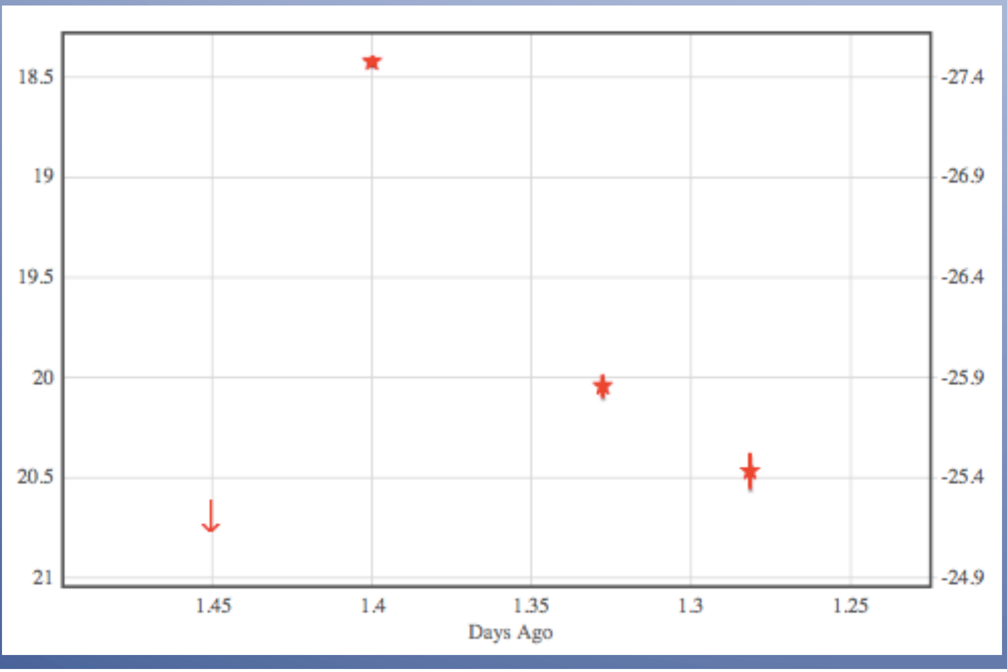
The second Fermi afterglow: iPTF13dsw at z=1.87!

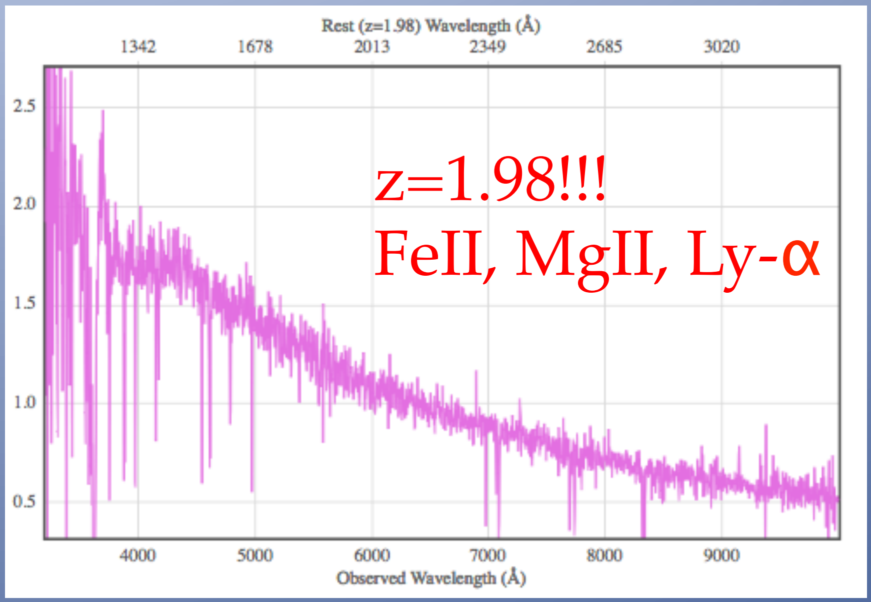


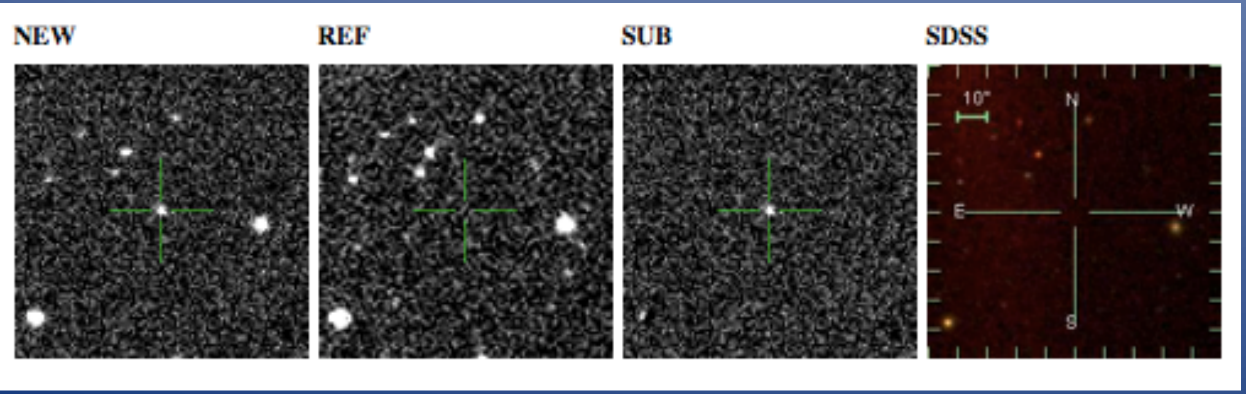
Overcoming
Wide, Fast & Faint

Pinpointing the afterglow amidst 30,000 candidates

Orphan Afterglow



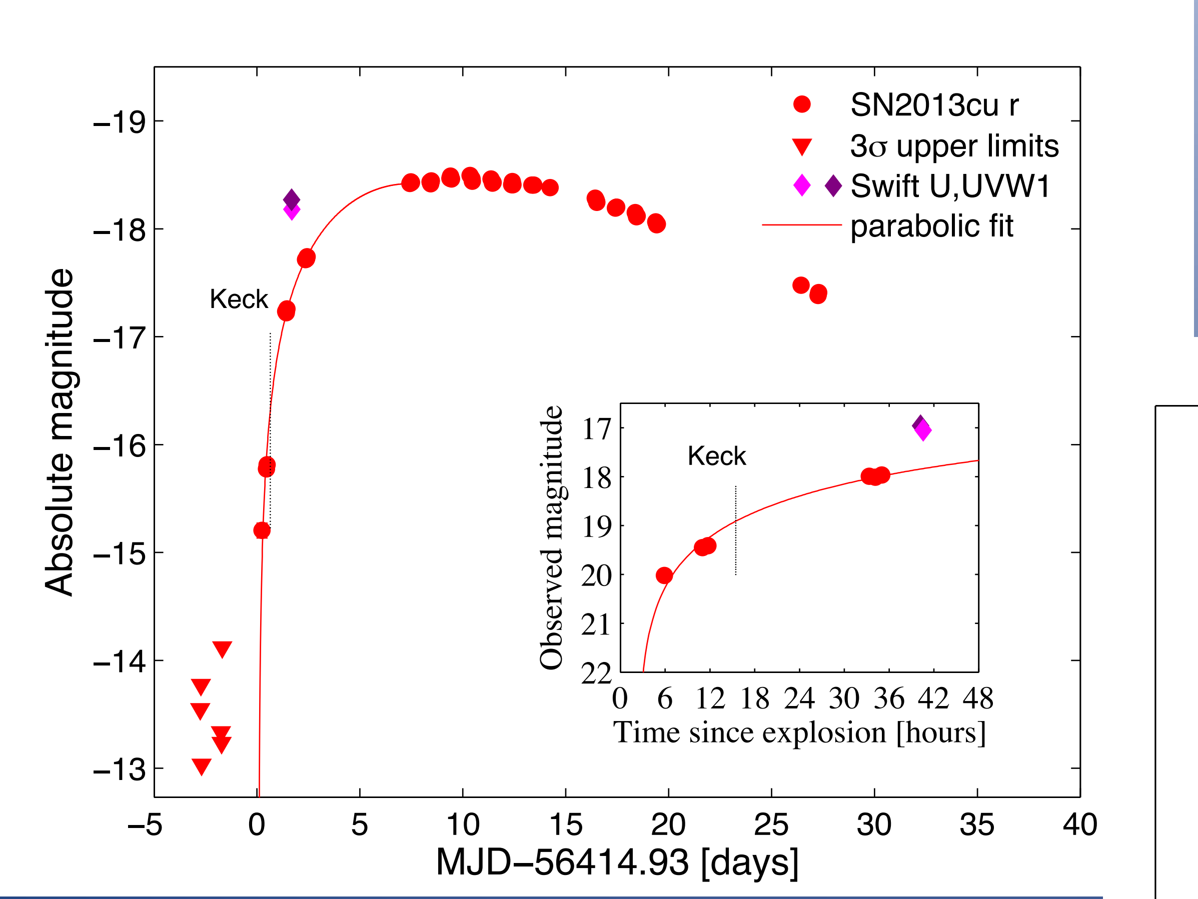




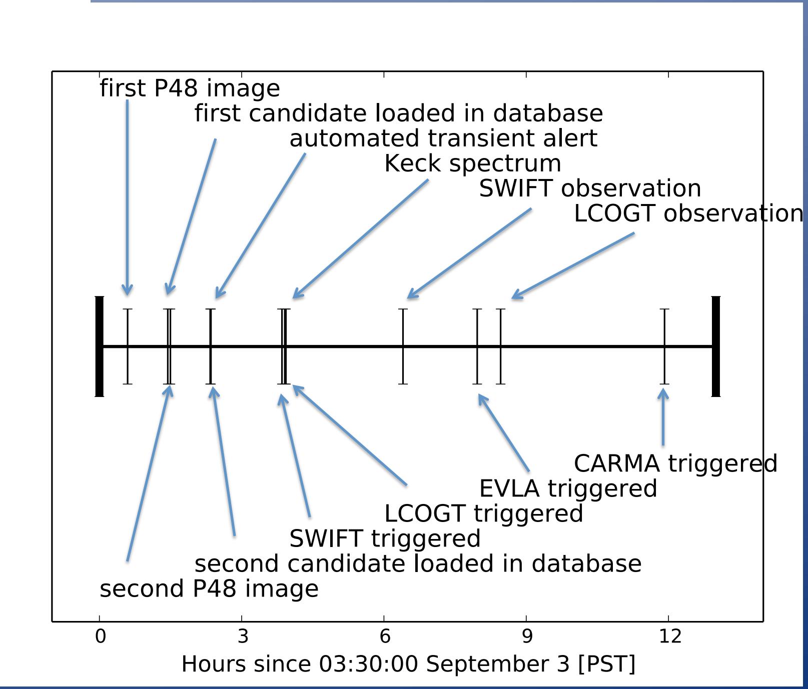
iPTF14yb
Cenko et al. 2014

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

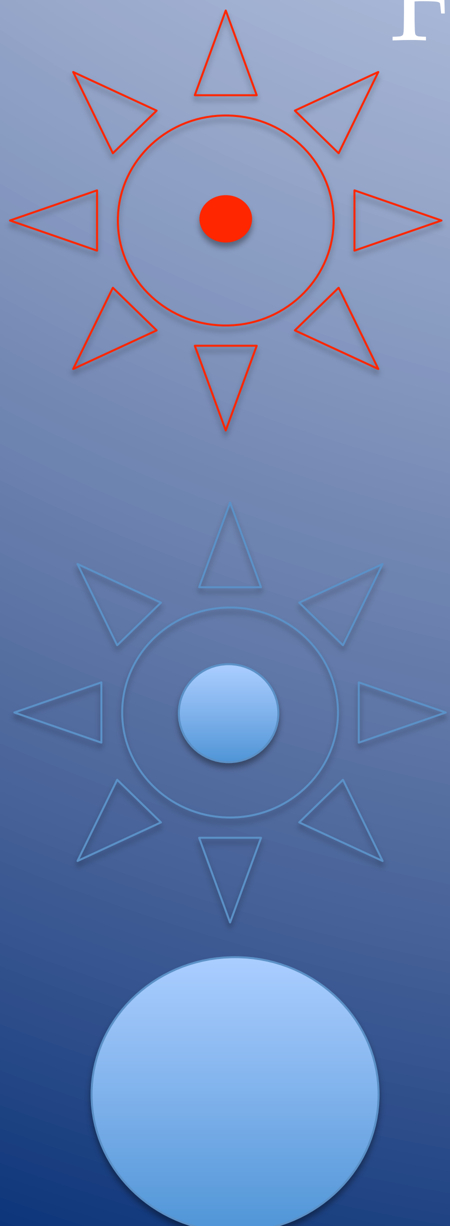
Flash Spectroscopy

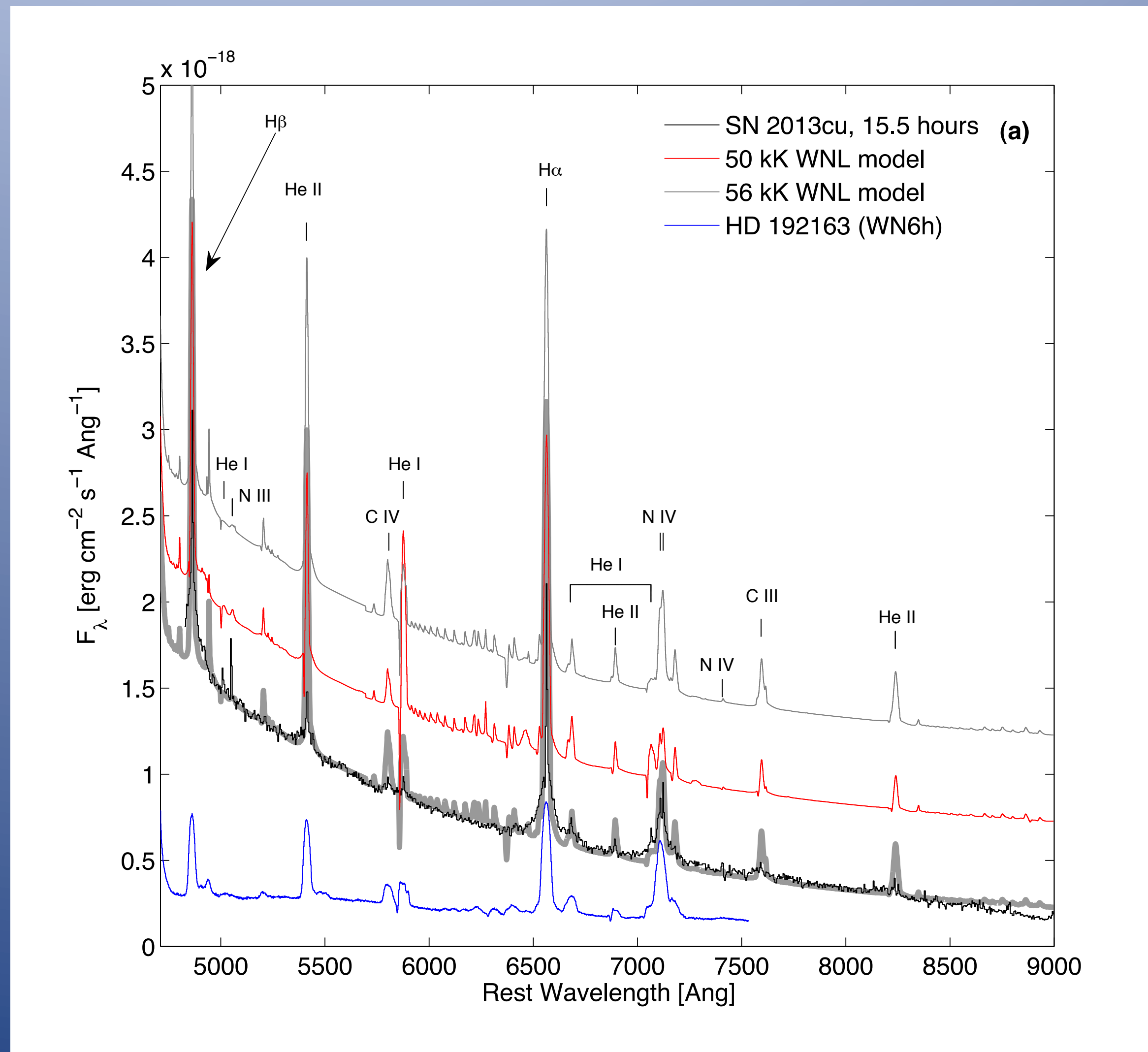


SN2013cu (iPTF13ast)
Gal-Yam et al. (2014) *Nature*

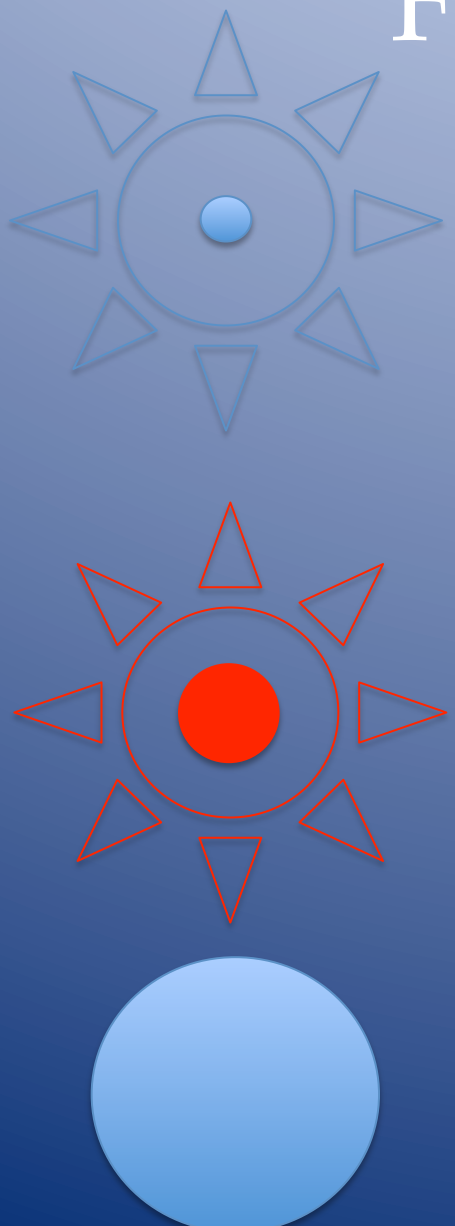


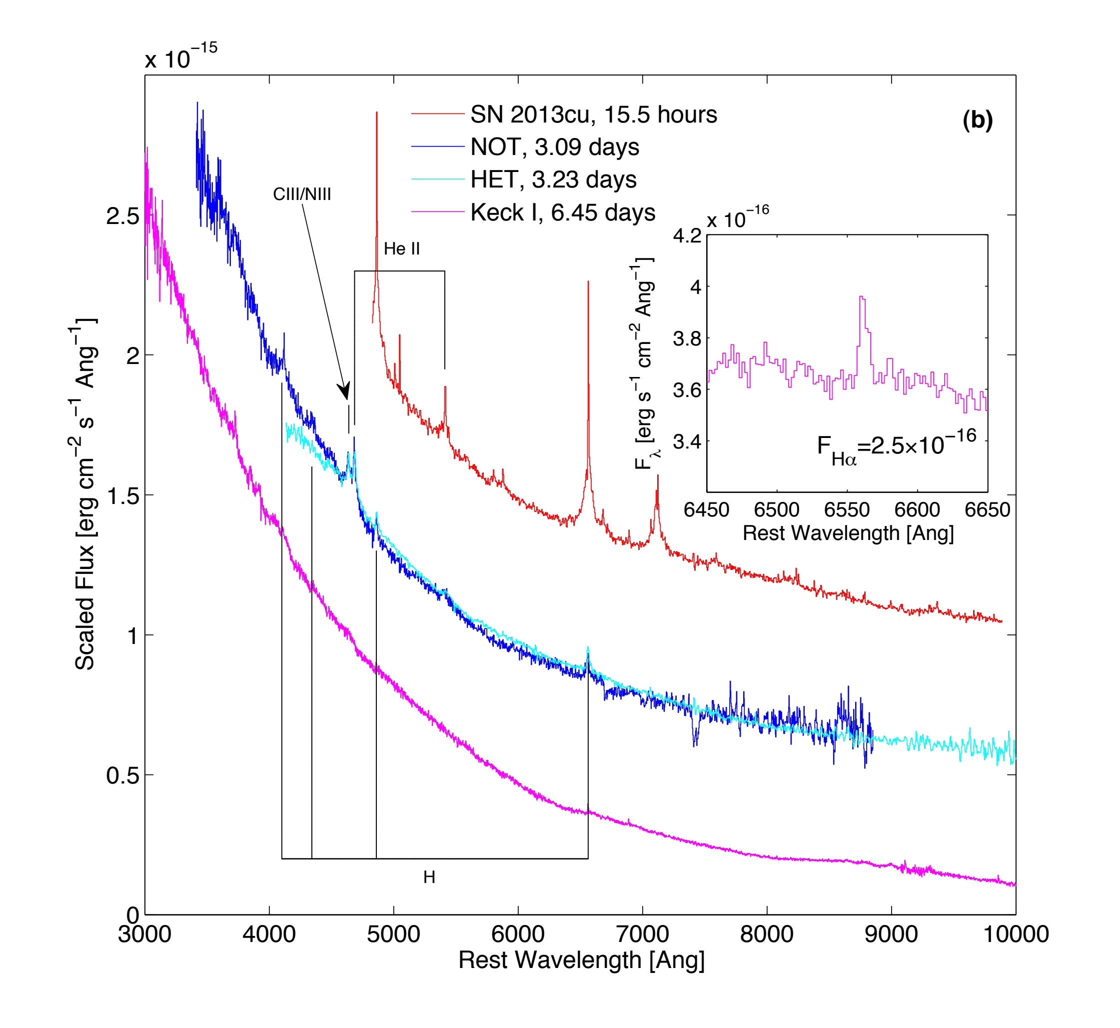
Flash Spectroscopy



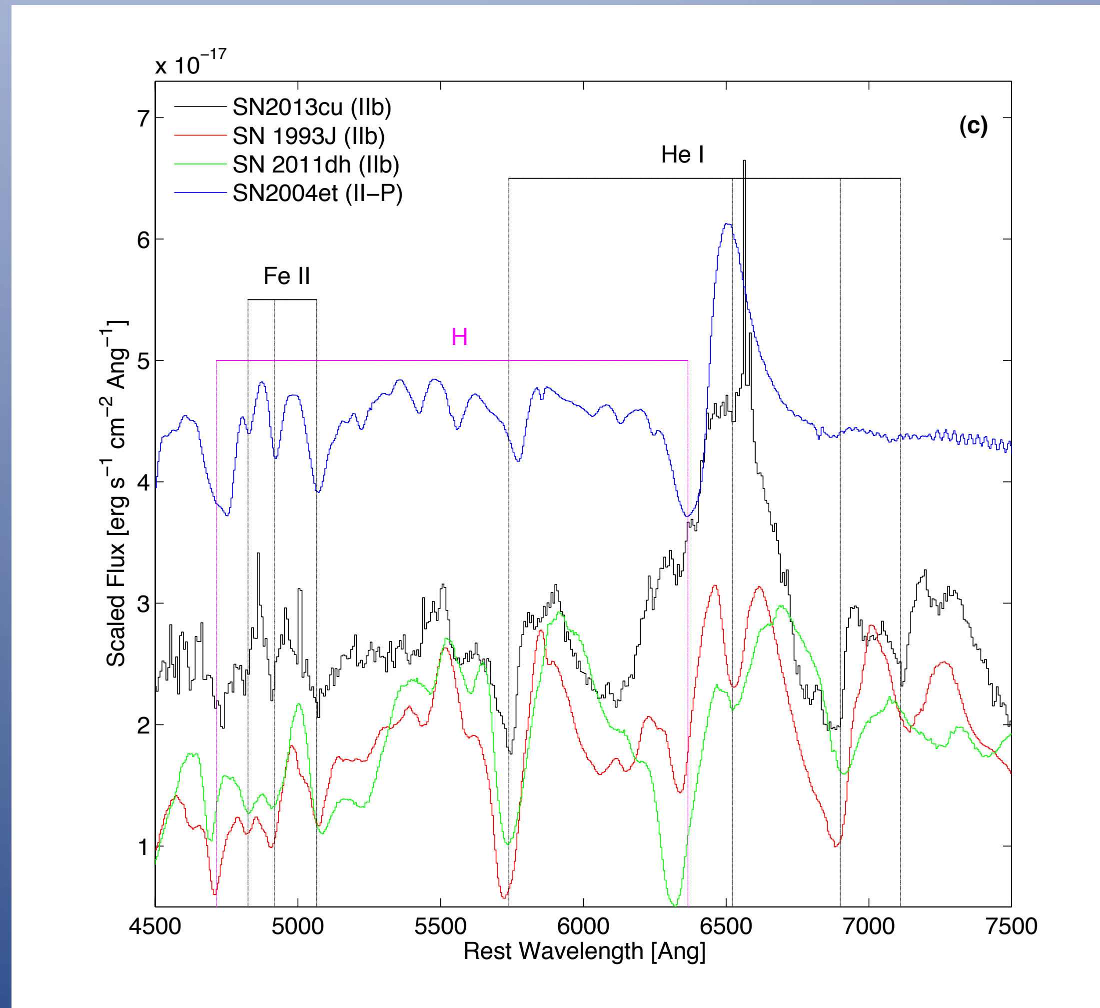


Flash Spectroscopy





Flash Spectroscopy



August 24, 2011

g-band run:

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

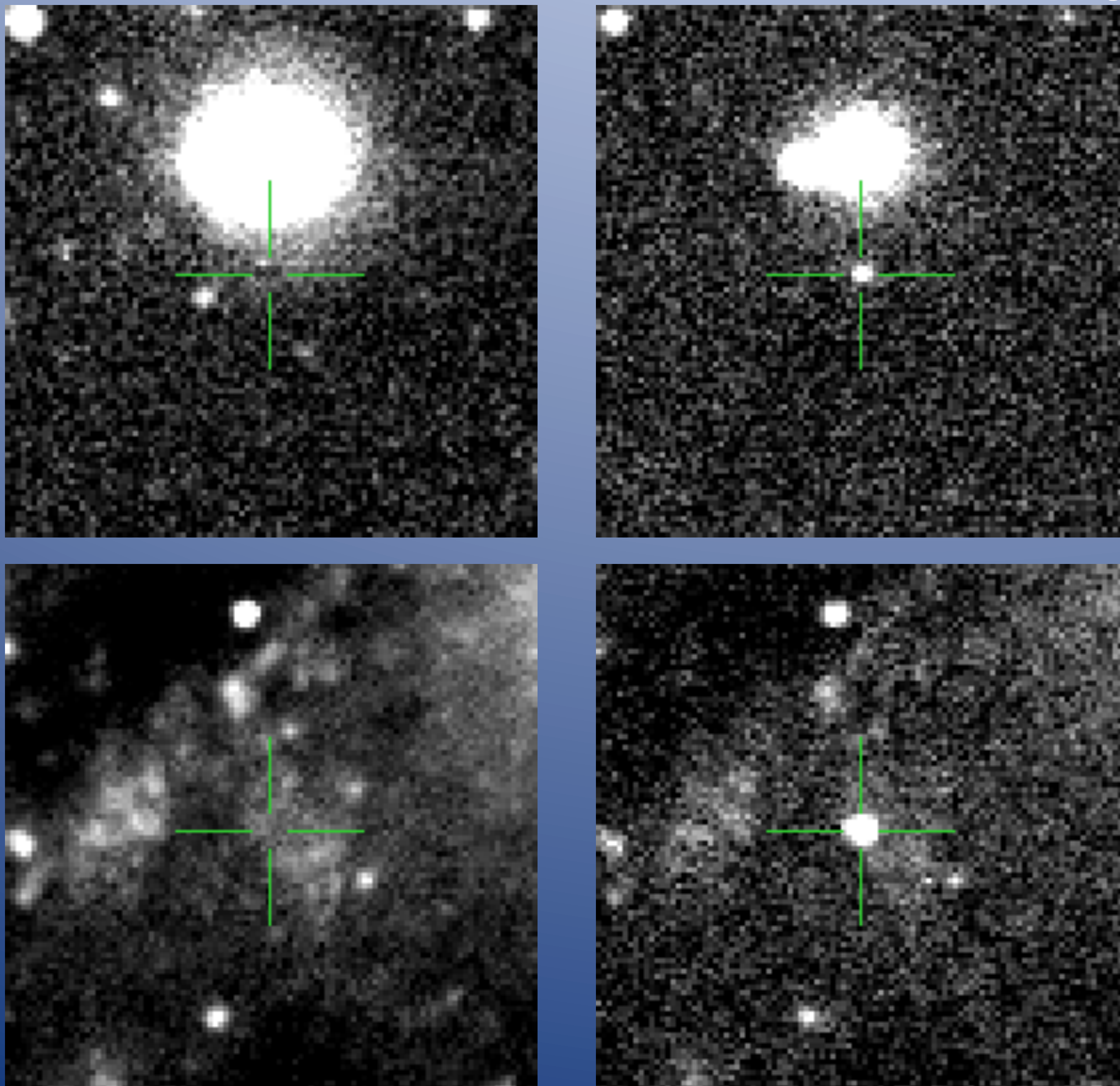
• 50-50 split between Dynamic and SN cadence

• 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....

Discovery



11klx - JSB @ UT 19:48

- response “I see your $20 and raise you $100”

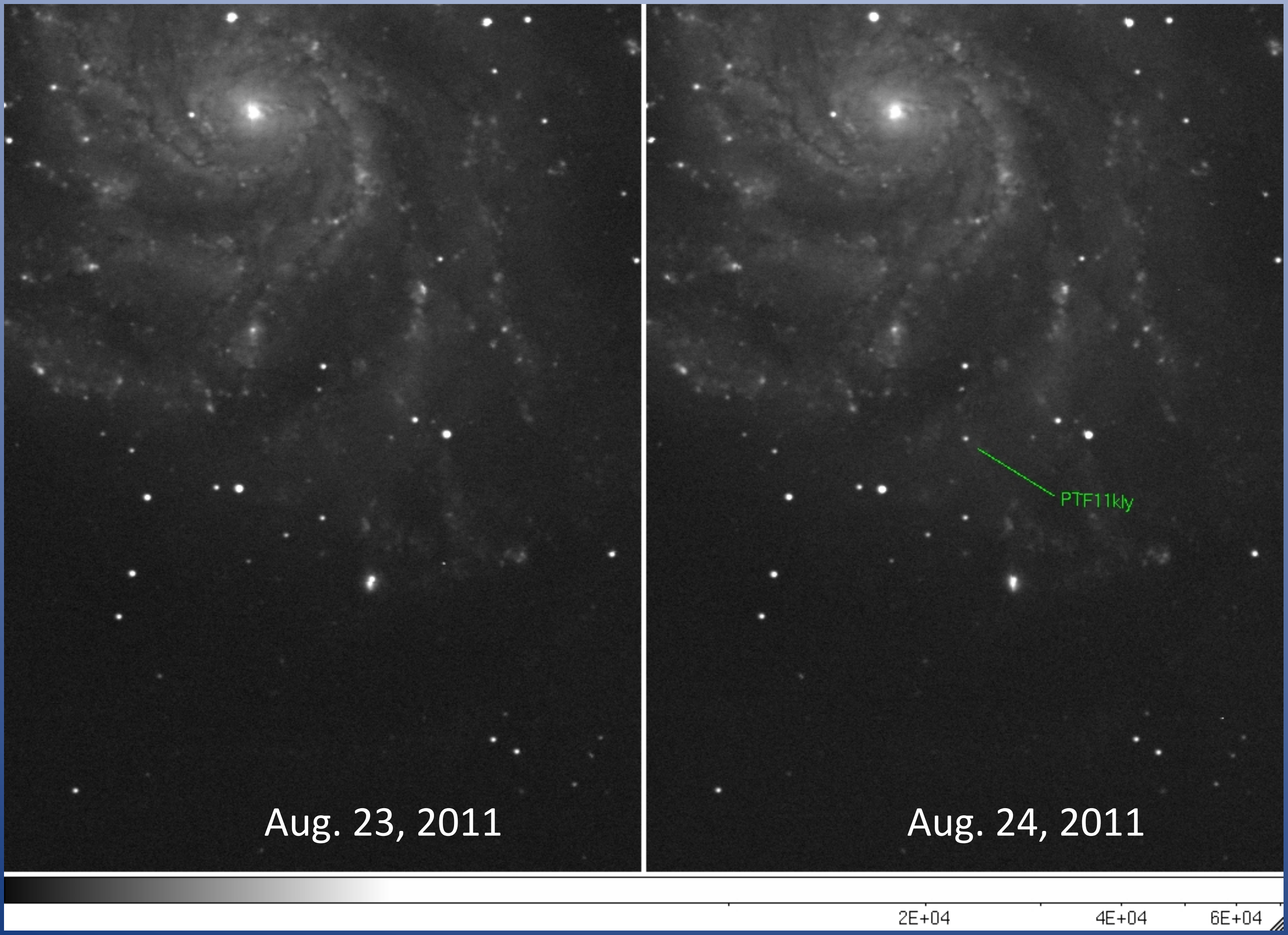
11kly - PEN @ UT 19:50

“Hi all,

M101 has given birth to 11kly

Check it out, alert the troops!!!”

PTF11kly (SN 2011fe)



Caught at magnitude ~17.4, ~100,000 times fainter than the eye can see.

20% rise between first 2 detections separated by 1hr

~1/1000 as bright as the SN reached at peak brightness.

Discovery

Young Type Ia Supernova PTF11kly in M101

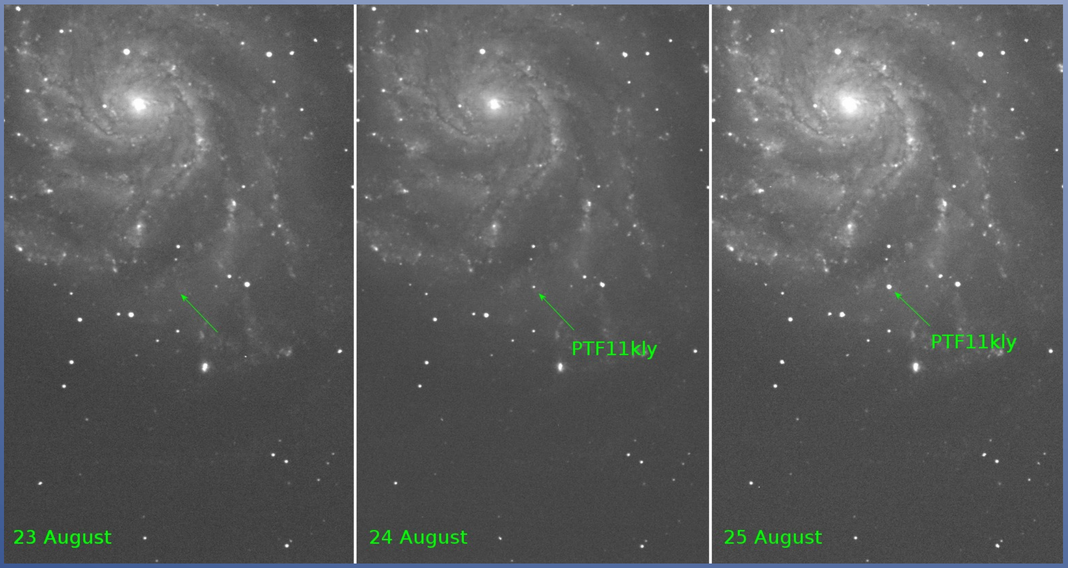
ATel #3581; ***Peter Nugent (LBL/UCB), Mark Sullivan (Oxford), David Bersier (Liverpool John Moores), D.A. Howell (LCOGT/UCSB), Rollin Thomas (LBL), Phil James (Liverpool John Moores)***
on ***24 Aug 2011; 23:47 UT***
Distributed as an Instant Email Notice Supernovae
Credential Certification: R. C. Thomas (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.

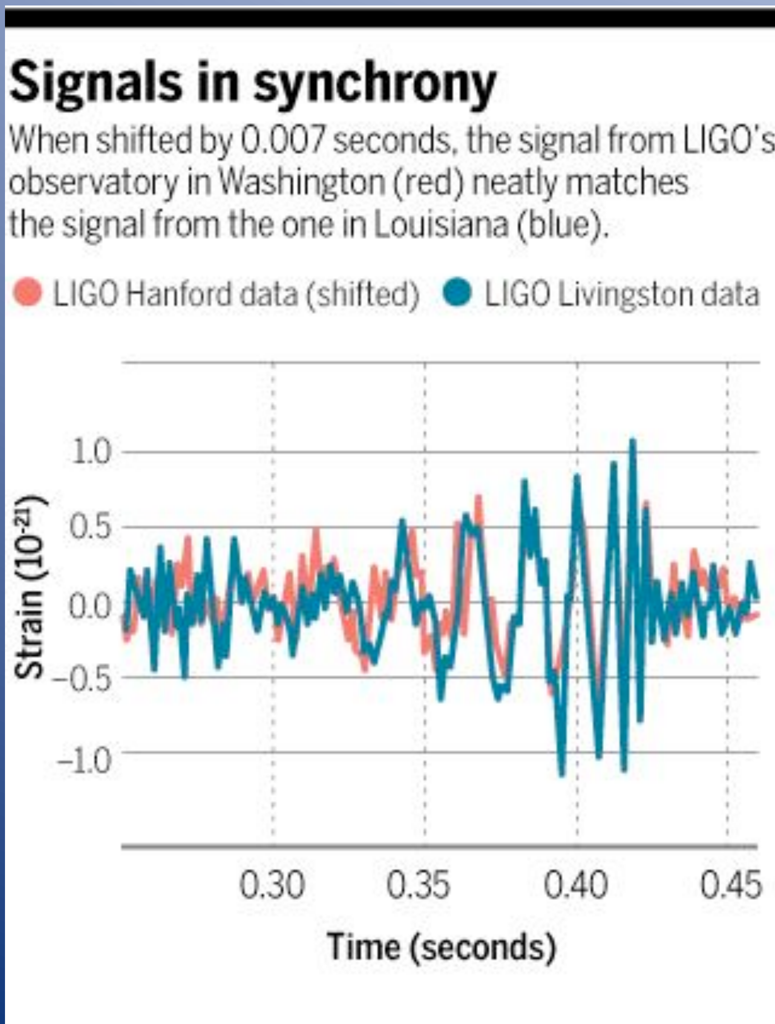
SN 2011fe is the closest Type Ia supernova in the last 25 years and the 5th brightest supernova of any type in the last century. It was found by the Palomar Transient Factory, which processes its data at NERSC.

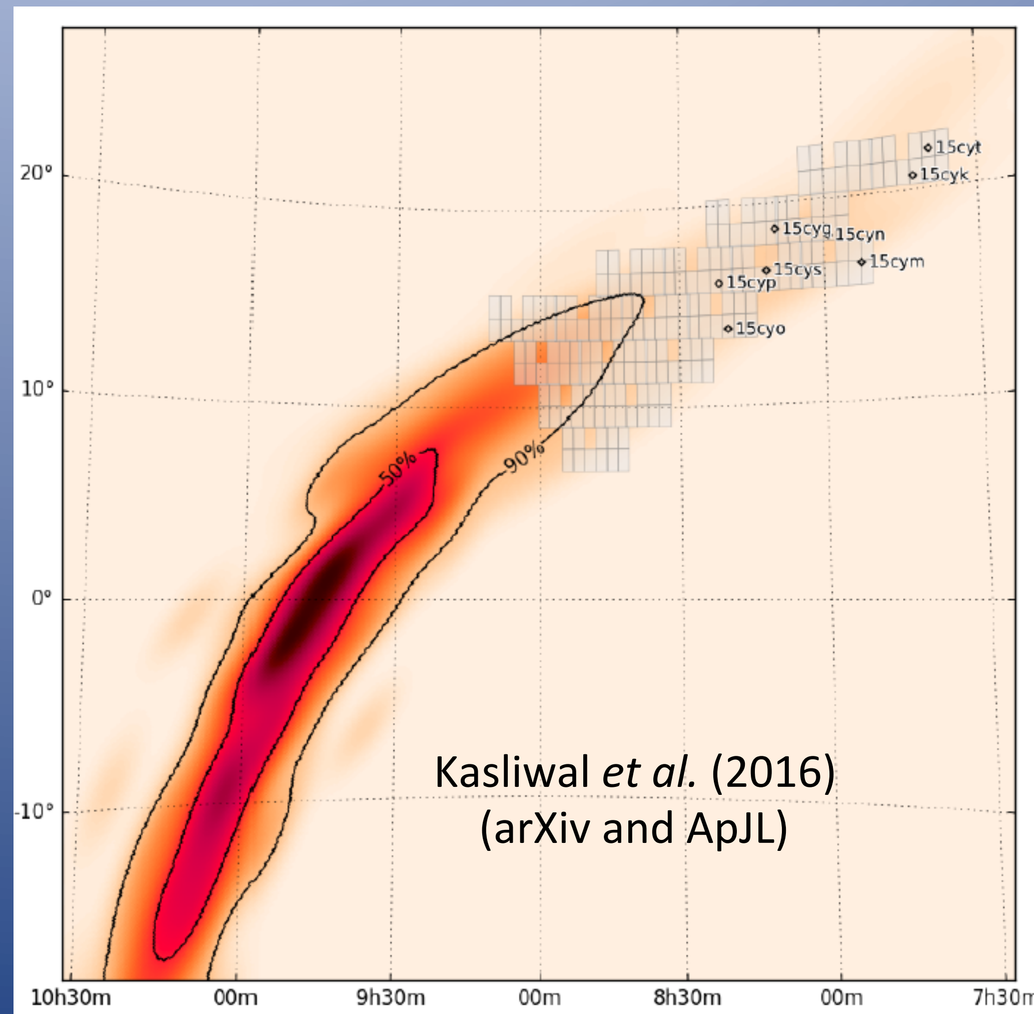


It was caught 11 hours after explosion, and has been followed by almost every professional telescope on earth and in space – could be seen in binoculars.

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.

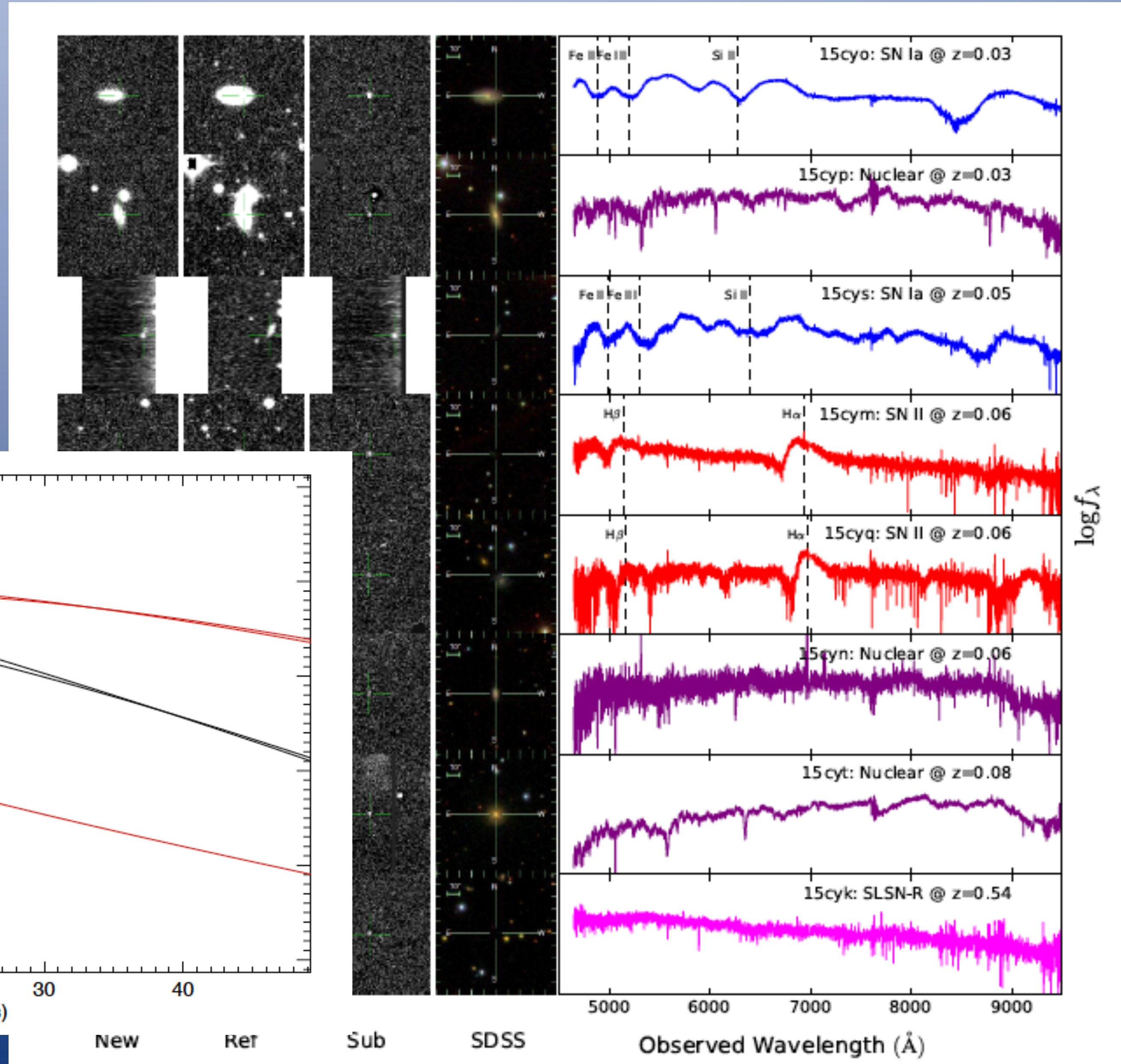
Gravitational Wave Trigger GW150914

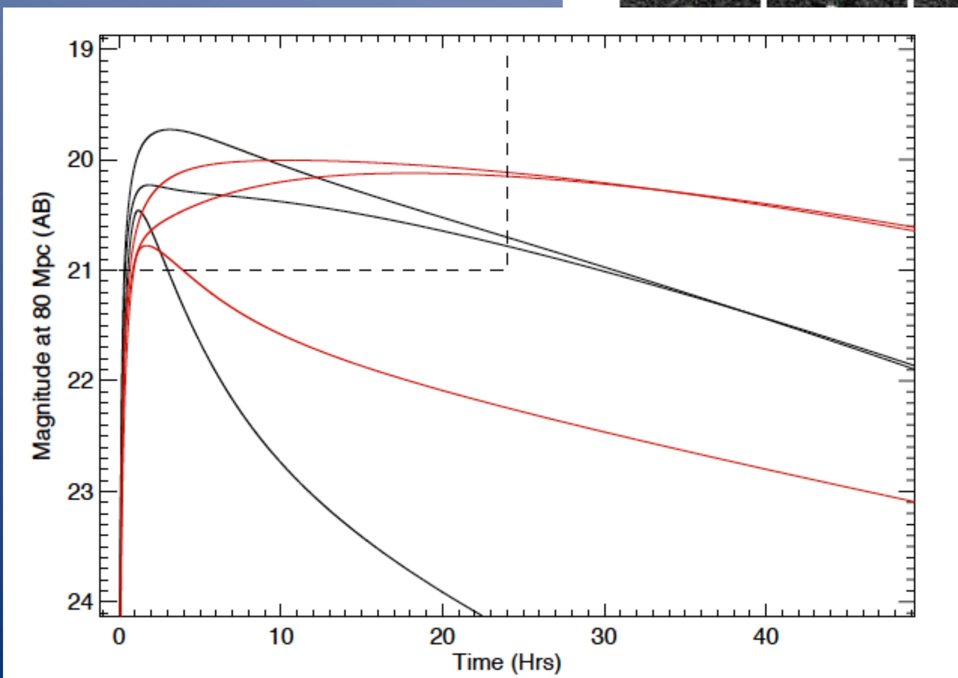




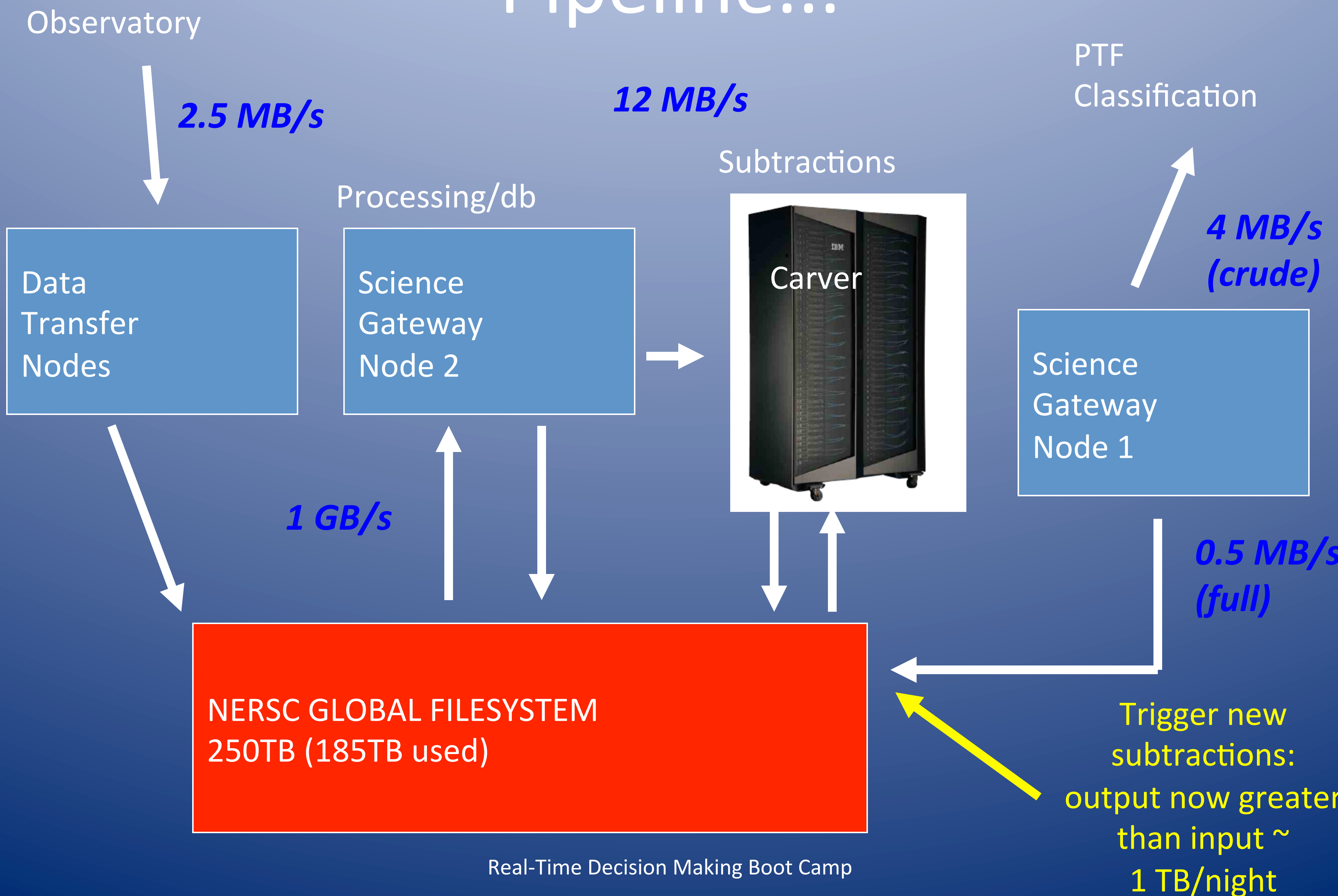
GW150914

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
2.5 MB/s
12 MB/s
PTF
Classification
Subtractions
Processing/db
4 MB/s
(crude)
Data
Transfer
Nodes
Science
Gateway
Node 2
Carver
Science
Gateway
Node 1
1 GB/s
0.5 MB/s
(full)
NERSC GLOBAL FILESYSTEM
250TB (185TB used)
Trigger new
subtractions:
output now greater
than input ~
1 TB/night

Zwicky Transient Facility

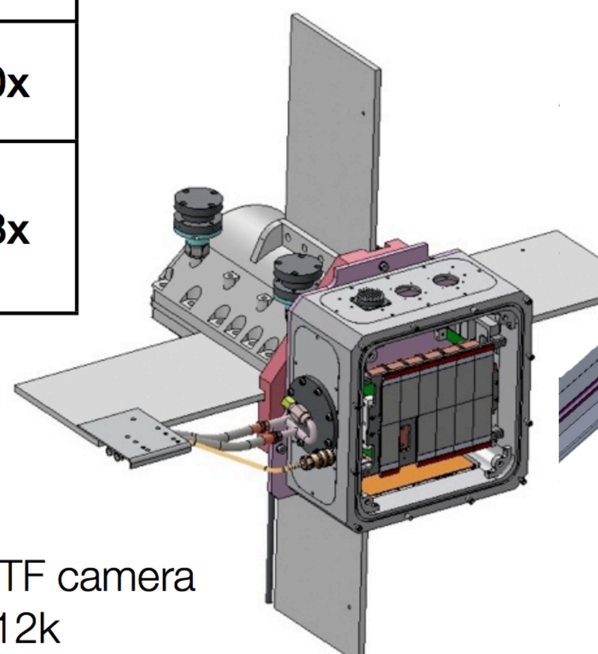
ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**15.0x**
Relative Volumetric Survey Rate	1x	**12.3x**

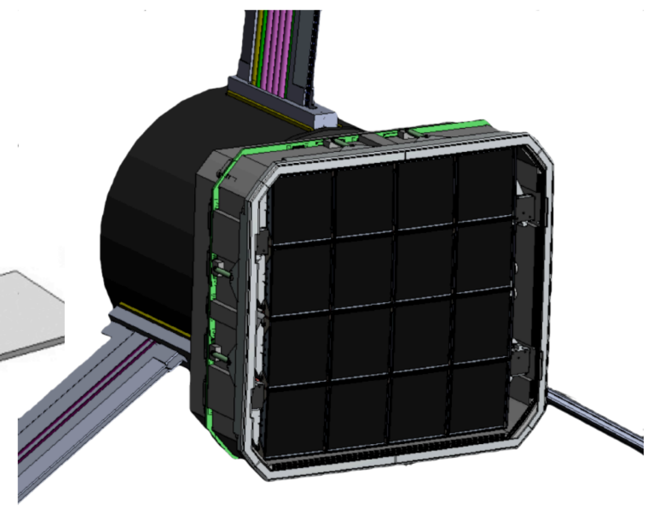
3750 deg^2/hour

⇒ 3π survey in 8 hours

>250 observations/field/year
for uniform survey

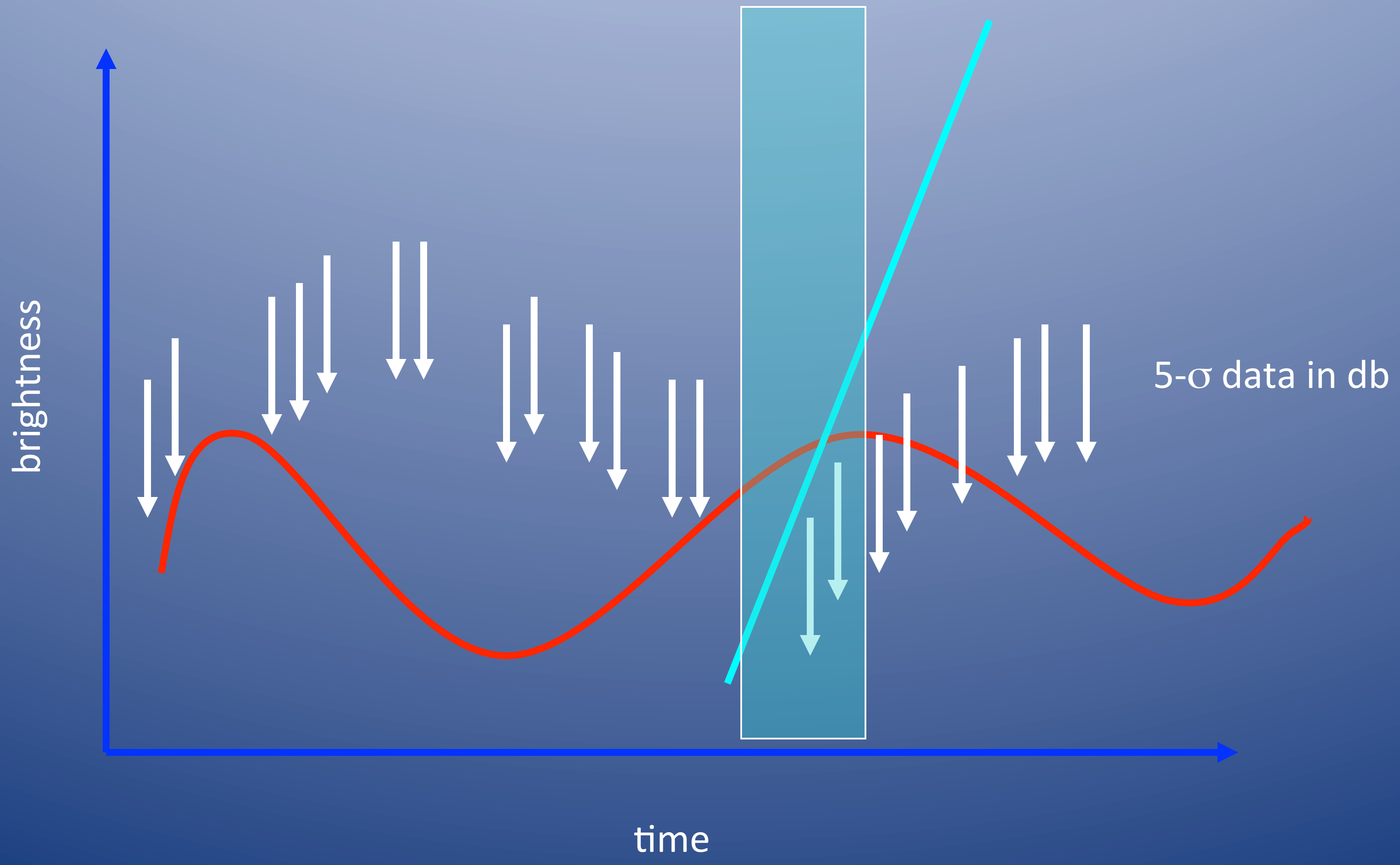


Existing PTF camera
MOSAIC 12k

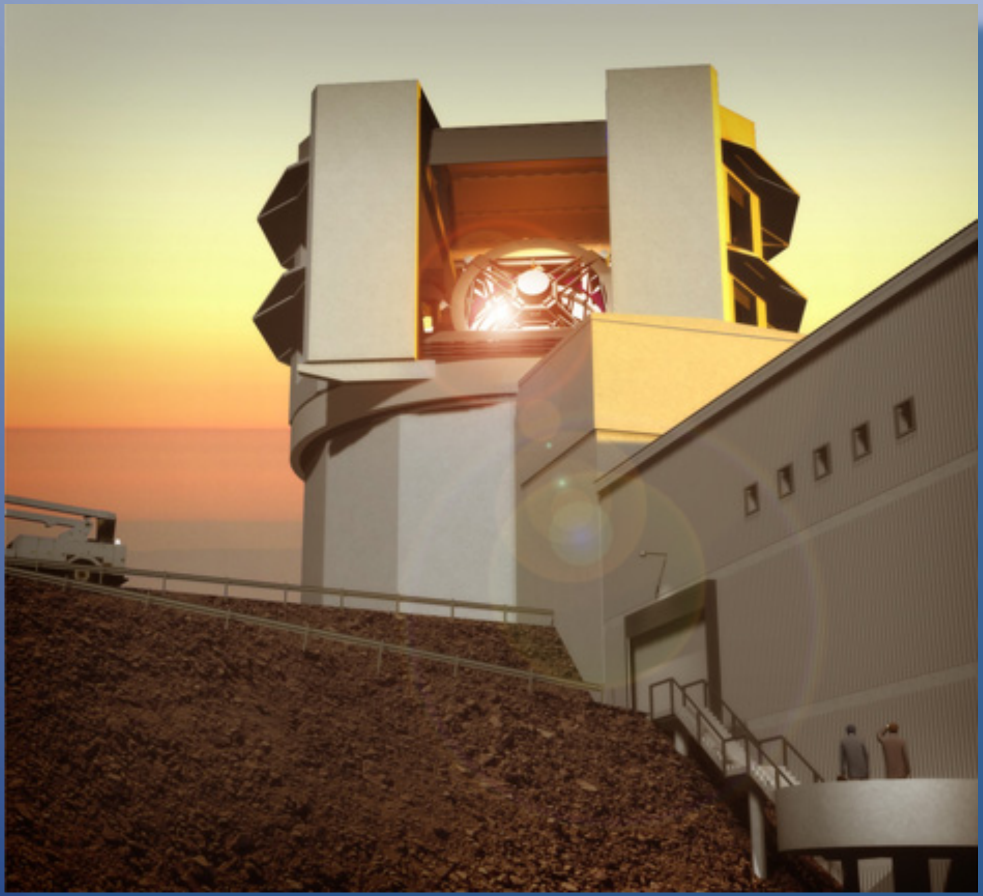


New ZTF camera:
16 6k x 6k e2v CCDs

Bottlenecks…crude *vs*. real



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...