

# Supernovae and the Era of Synoptic Surveys

Peter Nugent (LBNL/UCB)

# 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.

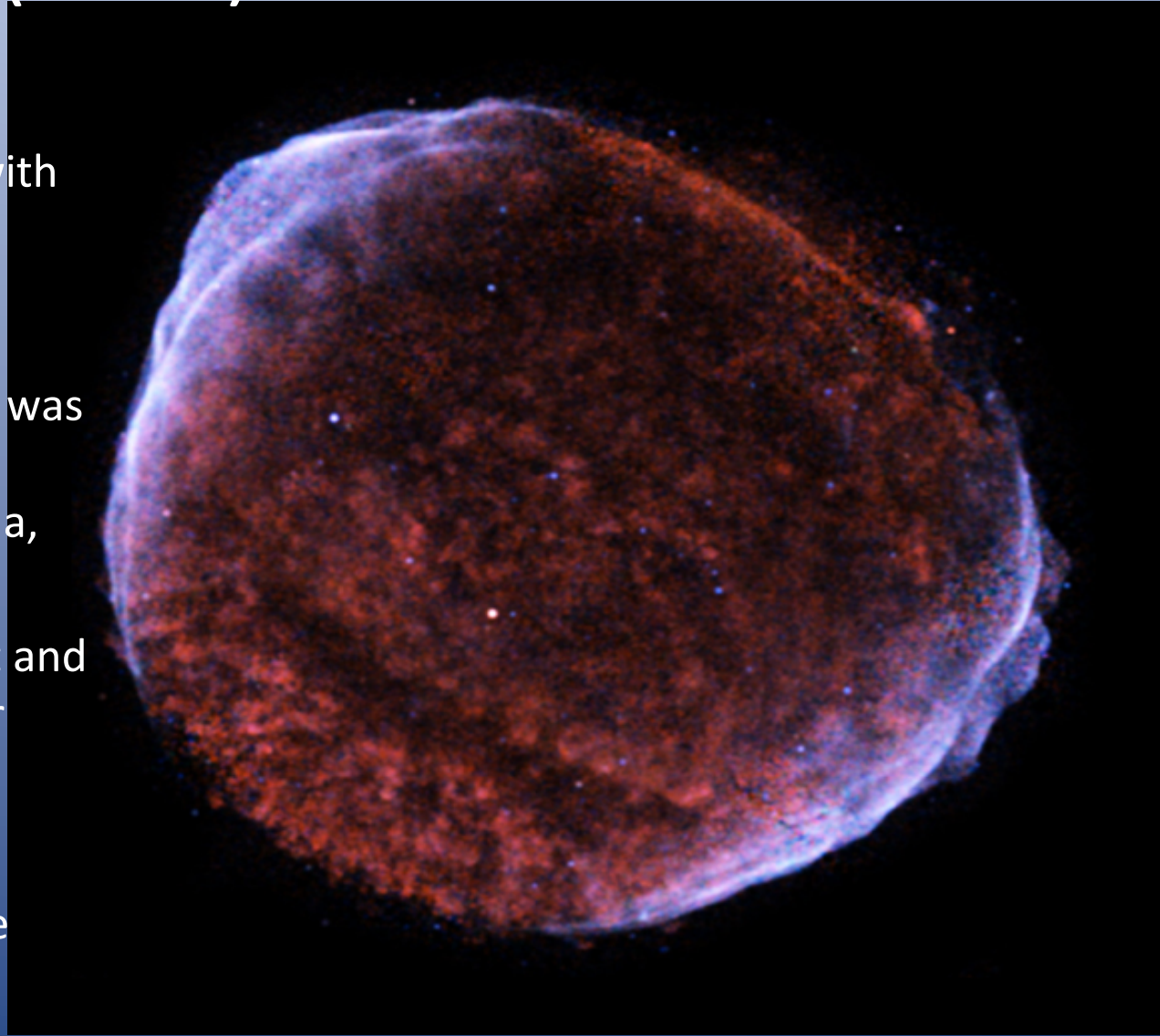
# Historical SNe (1006)

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.



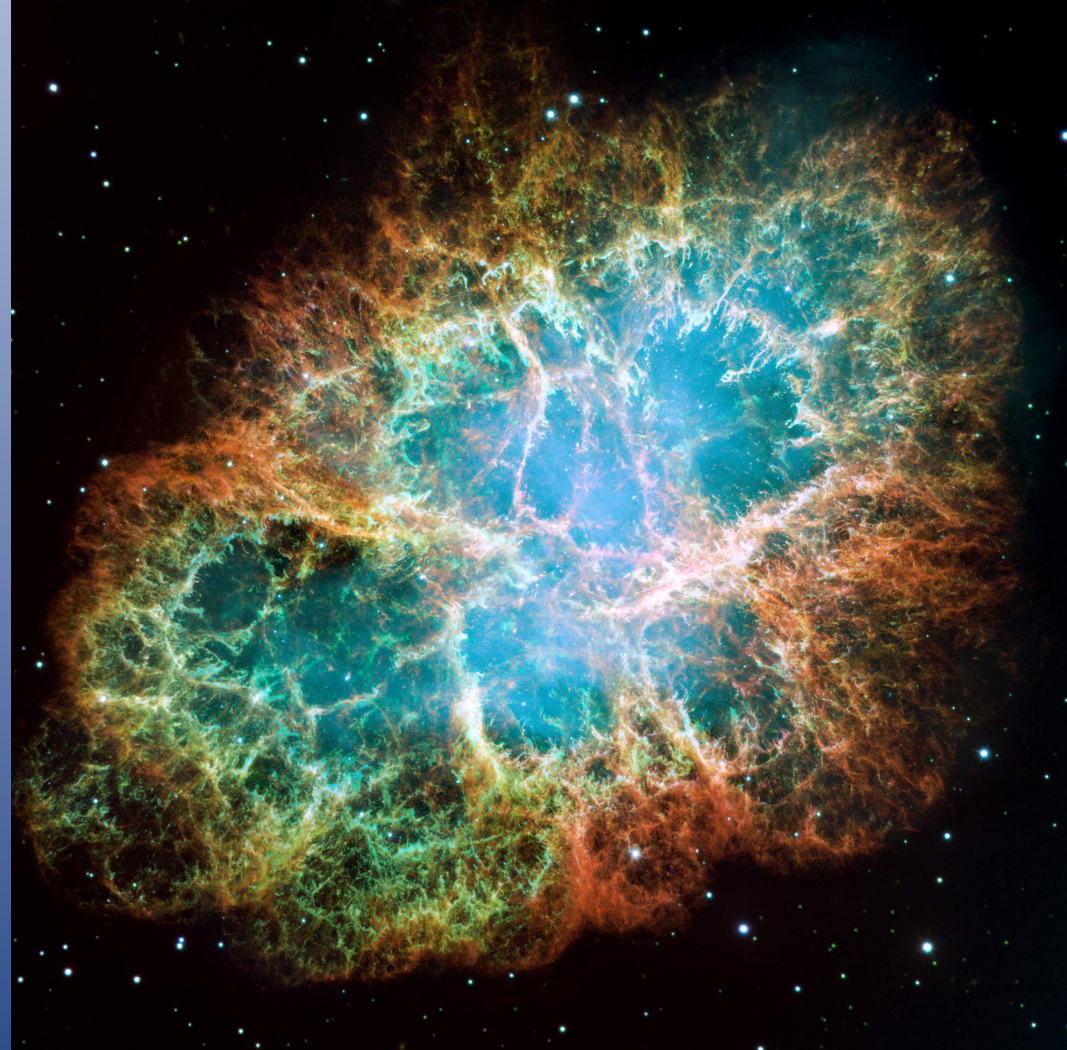


# Historical SNe (1054)

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)

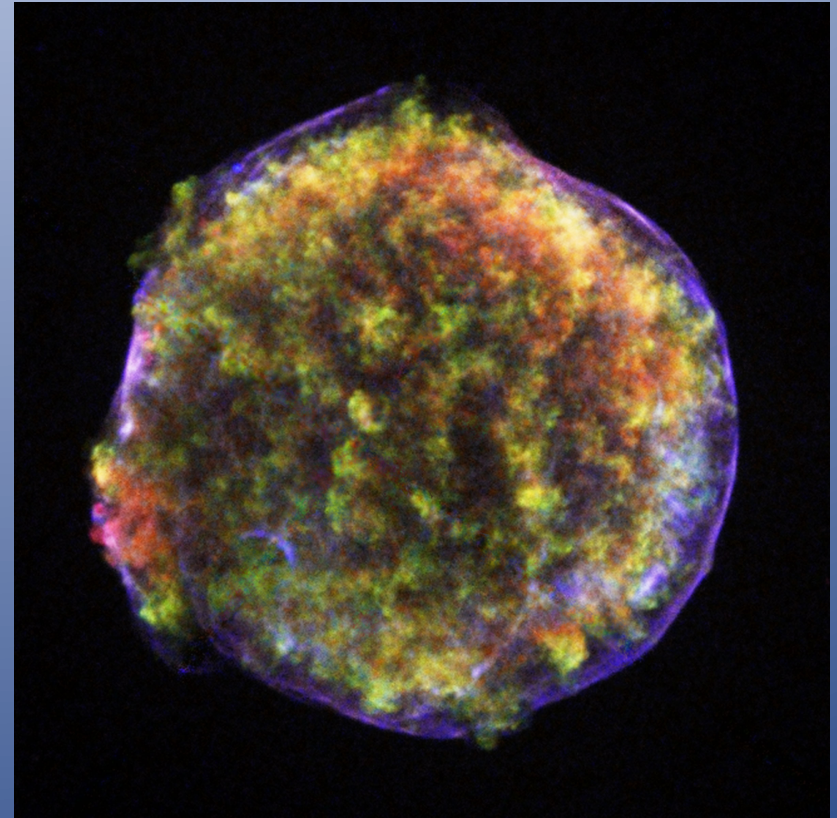
Anasazi Indians living in Chaco Canyon, NM made this petroglyph in 1054.



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.



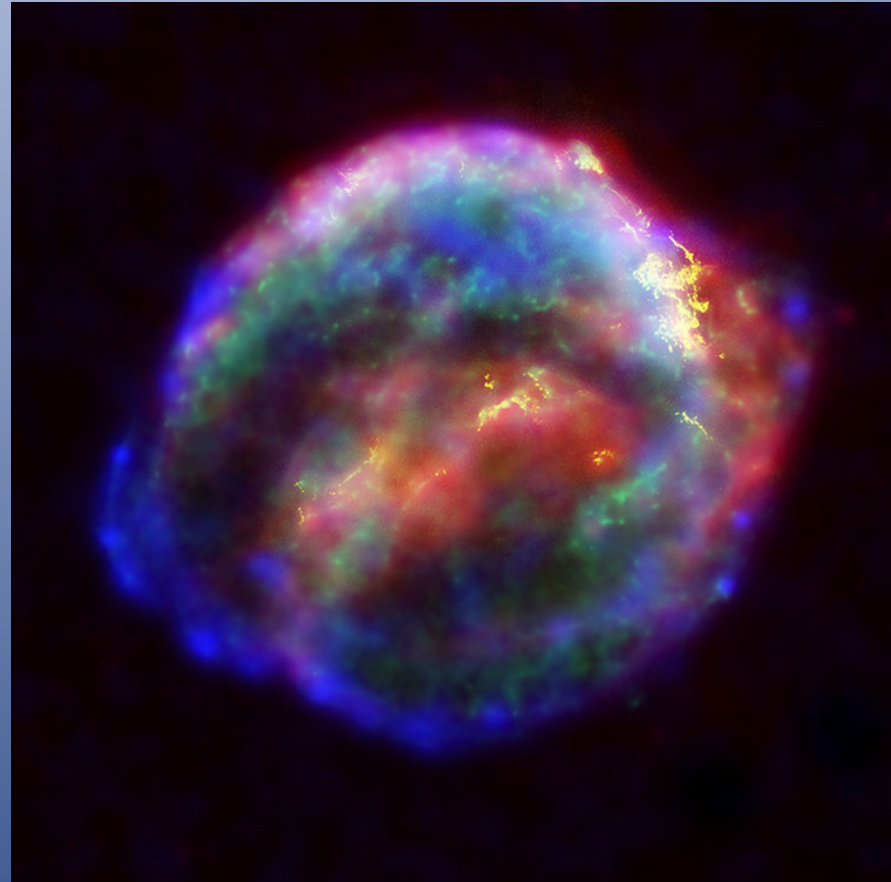
# Historical SNe (1572 - a Type Ia)



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.



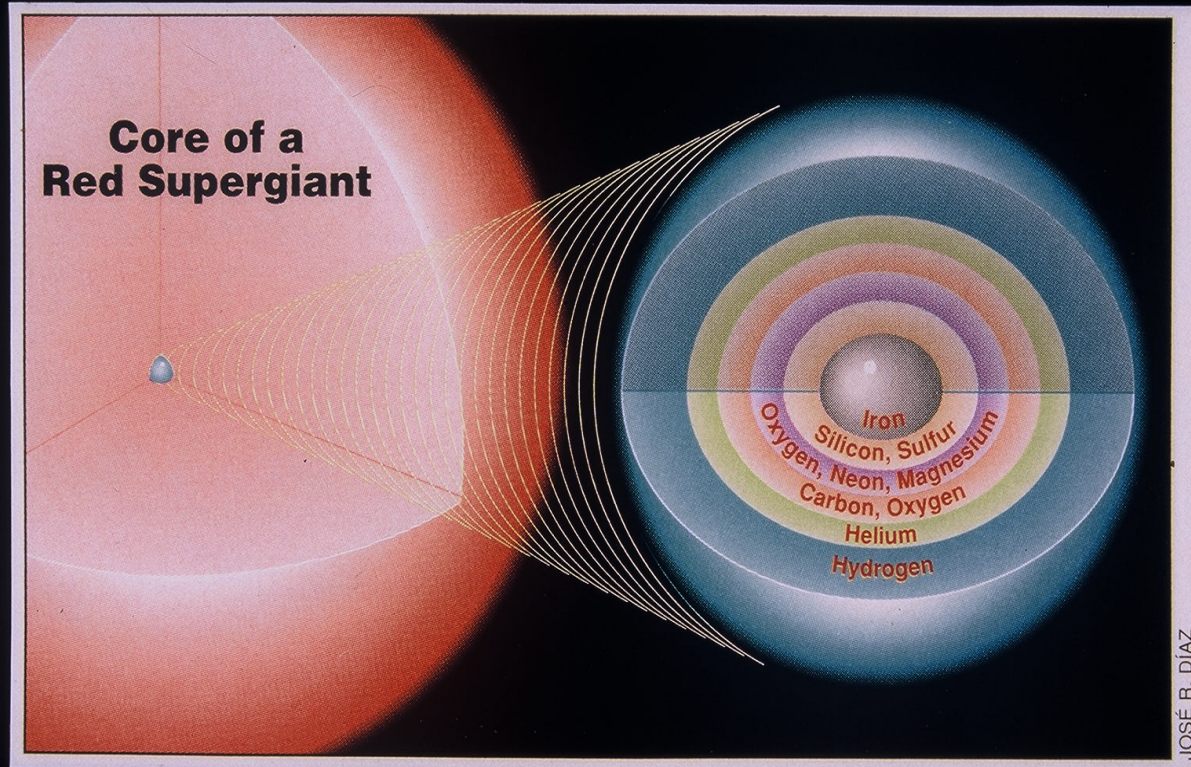
# SN 1987A



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?

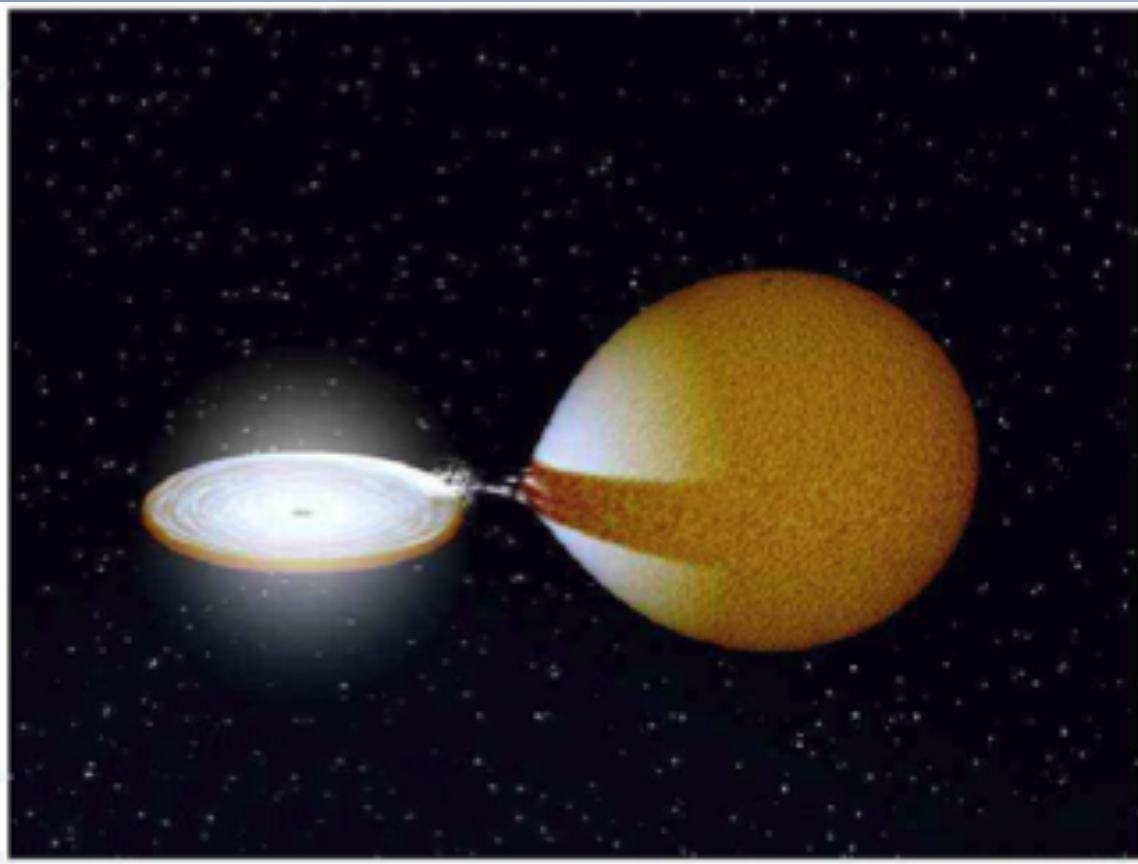


Core collapse supernovae originate from the death of a star  $\sim 10$  times the mass of our sun or greater.

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?

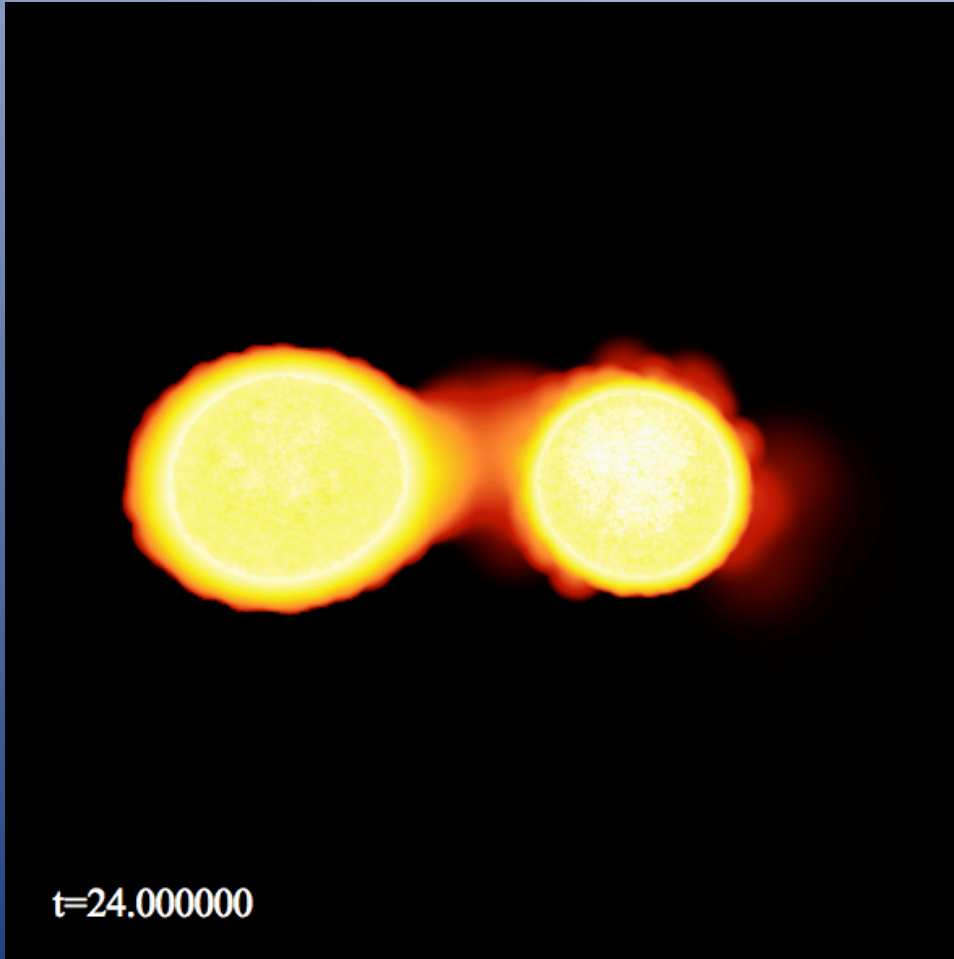


A thermonuclear supernova, which we label a Type Ia.

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

1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U													

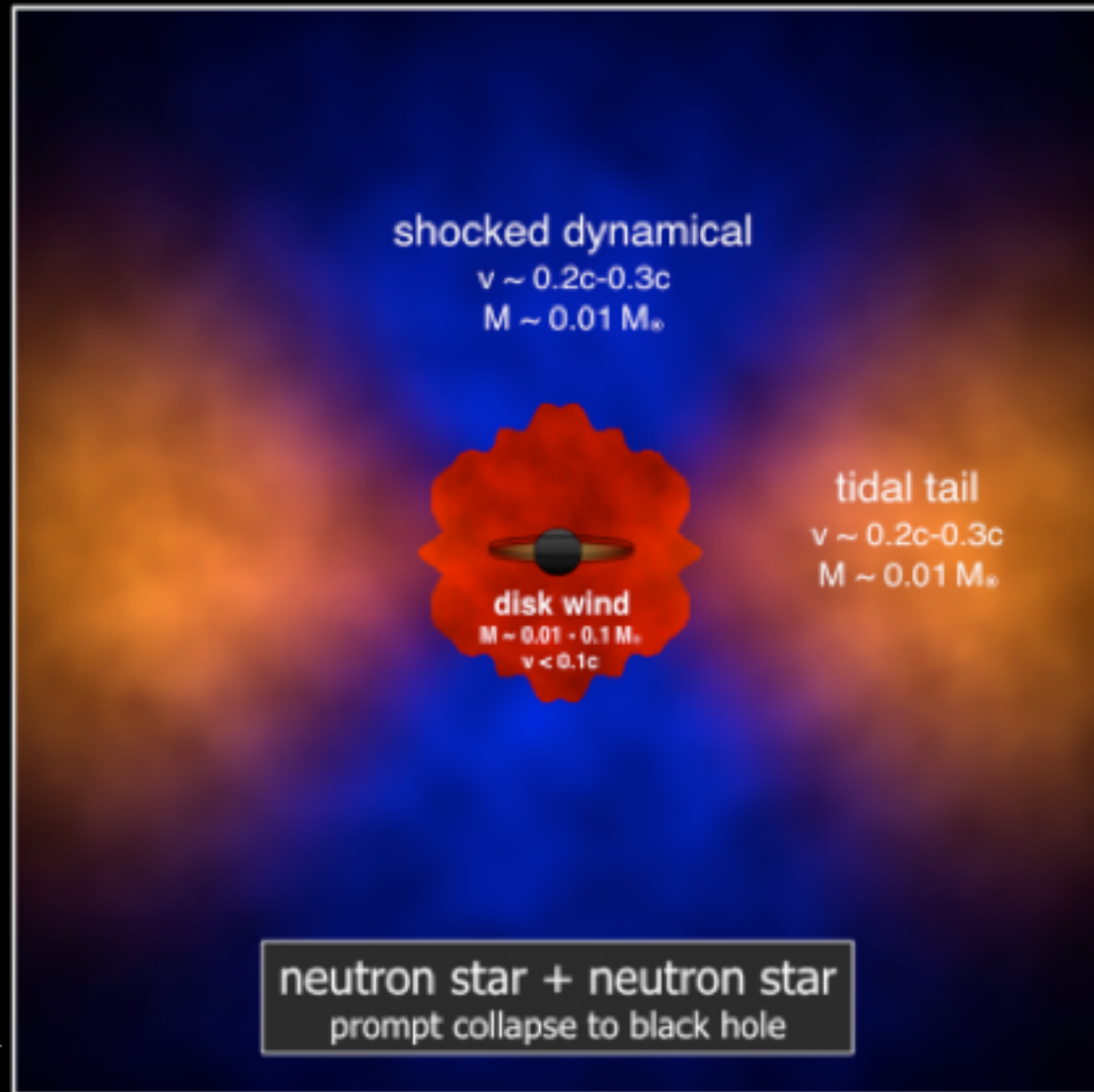
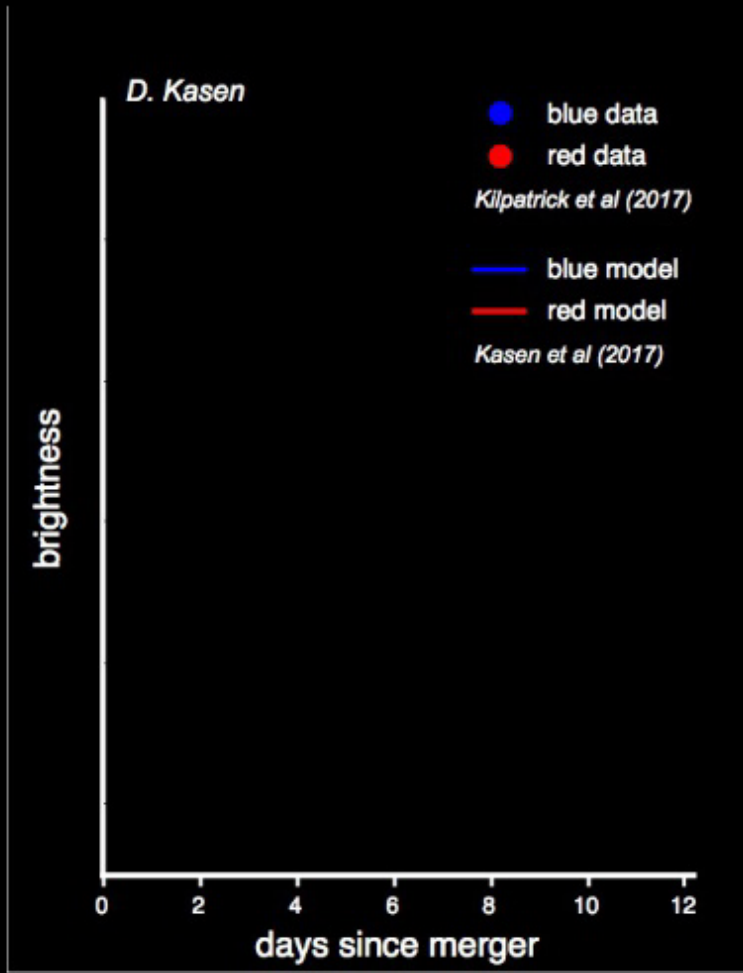
**Merging Neutron Stars**  
**Dying Low Mass Stars**

**Exploding Massive Stars**  
**Exploding White Dwarfs**

**Big Bang**  
**Cosmic Ray Fission**

Based on graphic created by Jennifer Johnson

# 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".

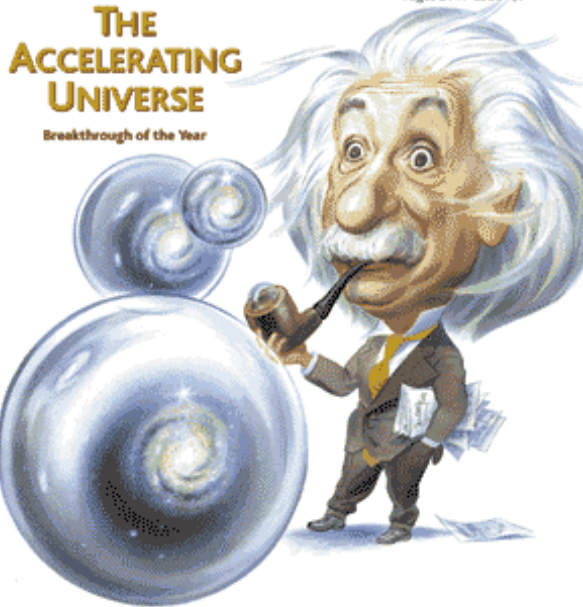
## Science

18 December 1998

Vol. 282 No. 5397  
Pages 2141-2336 57

### THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

# 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

By MICHAEL D. LEONICK

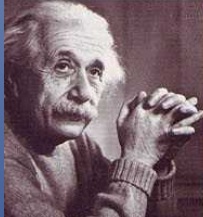
**ALBERT EINSTEIN NEVER DID LIKE THE idea of antigravity. It wasn't that he had a problem with far-fetched notions. After all, his special and general relativity theories made the astonishing assertion that time, space and matter could be squeezed and stretched like so much India rubber. The trouble was that some sort of antigravity force—Einstein called it the "cosmological term"—was required to make the predictions of general relativity**

#### 1 GRAVITY

● **WHAT IT IS:** An attractive force that pulls matter together like a rubber band

● **HOW IT OPERATES:** Gravity weakens over distance; when the distance between two galaxies doubles, the force between them is one-fourth as strong

● **WHAT THAT MEANS:** As the universe expands, gravity is less and less effective at slowing the expansion



THINK: Diagram by Jon Luttick

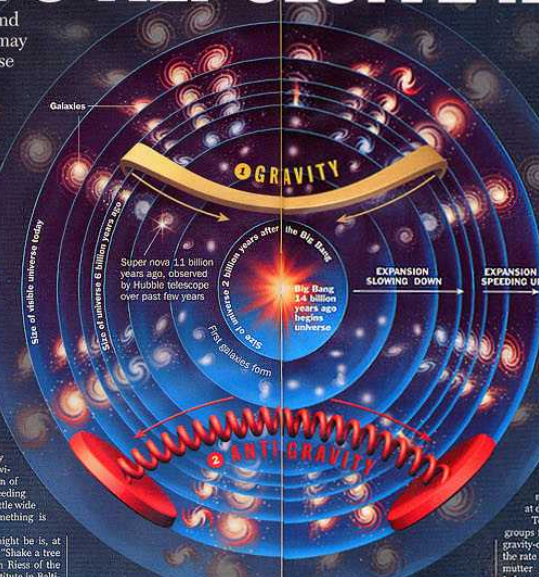
and study a distant supernova—an exploding star—astronomers from two rival research teams have jointly gathered the strongest evidence yet that the expansion of the universe is actually speeding up, like a rocket with its throttle wide open. And that means something is pushing it.

What that something might be is, at this point, anybody's guess. "Shake a teeny bit of theorists," says Adam Riess of the Space Telescope Science Institute in Baltimore, Md., leader of the collaboration, "and 20 ideas will fall out." For now, the unknown force is simply being called "dark energy," to emphasize its mysterious nature.

But its existence is becoming hard to dispute. The first hint came a couple of

years ago, when two independent teams of astronomers tried to calibrate the cosmic expansion using Type Ia supernovae, a kind of exploding star whose intrinsic brightness

SPACE



#### 2 ANTIGRAVITY (dark energy)

● **WHAT IT IS:** A property of empty space that exerts an outward force like a compressed spring at every point in space

● **HOW IT OPERATES:** A given volume of space always has the same amount of dark energy, so when the distance between two galaxies doubles, the force pushing them away from each other is twice as strong

● **WHAT THAT MEANS:** As the universe expands, the volume of space increases, which means more dark energy. By now, 14 billion years after the Big Bang, antigravity has overwhelmed gravity, so the expansion will get faster and faster

In cosmic history its light was emitted. Then, by measuring how fast each supernova is moving away from Earth in the overall ballooning of the universe, it can be determined what the expansion rate was at different times in the past.

To everyone's astonishment, both groups found that instead of the gradual, gravity-driven slowdown they expected, the rate was getting faster. Says Saul Perlmutter of Lawrence Berkeley National Laboratory in California, who leads one of the groups: "We spent at least a year struggling to understand what we were seeing." In the end, both groups decided that dark energy, functioning as a kind of antigravity, was their best guess.

Critics argued that there might be a

more conventional explanation, such as intergalactic dust, which could contaminate the brightness measurements. But the new observations seem to have closed that loophole. The newly identified supernovae went off about 11 billion years ago—about 50% further back in time than the previous record holder. "If the dust were there," says Lawrence Berkeley astrophysicist Kater Nagai, a member of Perlmutter's team and Riess's collaborator on the new research, "the supernovae would have been much dimmer than it was."

The new supernova's remoteness was even more important for another reason. "If dark energy is really the explanation for what we see," says Riess, a member of the rival team, "then its effect should have been weaker in the early universe." That's because while the force of gravity between galaxies falls as they move farther apart, dark energy is a property of space and gets stronger as the universe expands. Shortly after the Big Bang, when the universe took up relatively little space, there wasn't much dark energy. Now much bigger, the modern universe has more space and thus more energy to shove galaxies apart. Sure enough, this distant supernova shows that the expansion was slower long ago.

While the new observations go a long way toward confirming that dark energy is real, astronomers would love to see a few more distant supernovae, just to be sure. Unfortunately, that won't be happening soon. The Hubble pictures that Riess and Nagai analyzed were all taken purely by chance, while the telescope was looking for other things. Aiming at distant galaxies in hopes a supernova will go off is an inefficient use of the telescope's valuable time. The best bet would be a satellite devoted to such a project—and indeed, Perlmutter and others are working on that idea, although it will take years to get off the ground.

If space really does reebee with dark energy, the fate of the universe, a matter of longstanding debate, will be clear. With more dark energy today than yesterday, and more of the stuff tomorrow than today, the cosmos should fly apart faster and faster as time goes by. There will be no Big Crunch, as some have predicted, with billions of galaxies falling in on one another in a fiery apocalypse. Tens of billions of years from now, our Milky Way galaxy will find itself alone in empty space, with its nearest neighbors too far away to see. In the end, the stars will simply wink out—and the universe will end not with a bang but with the meekest of whimpers.

TIME, APRIL 16, 2001

TIME, APRIL 16, 2001

# Supernovae circa 1998

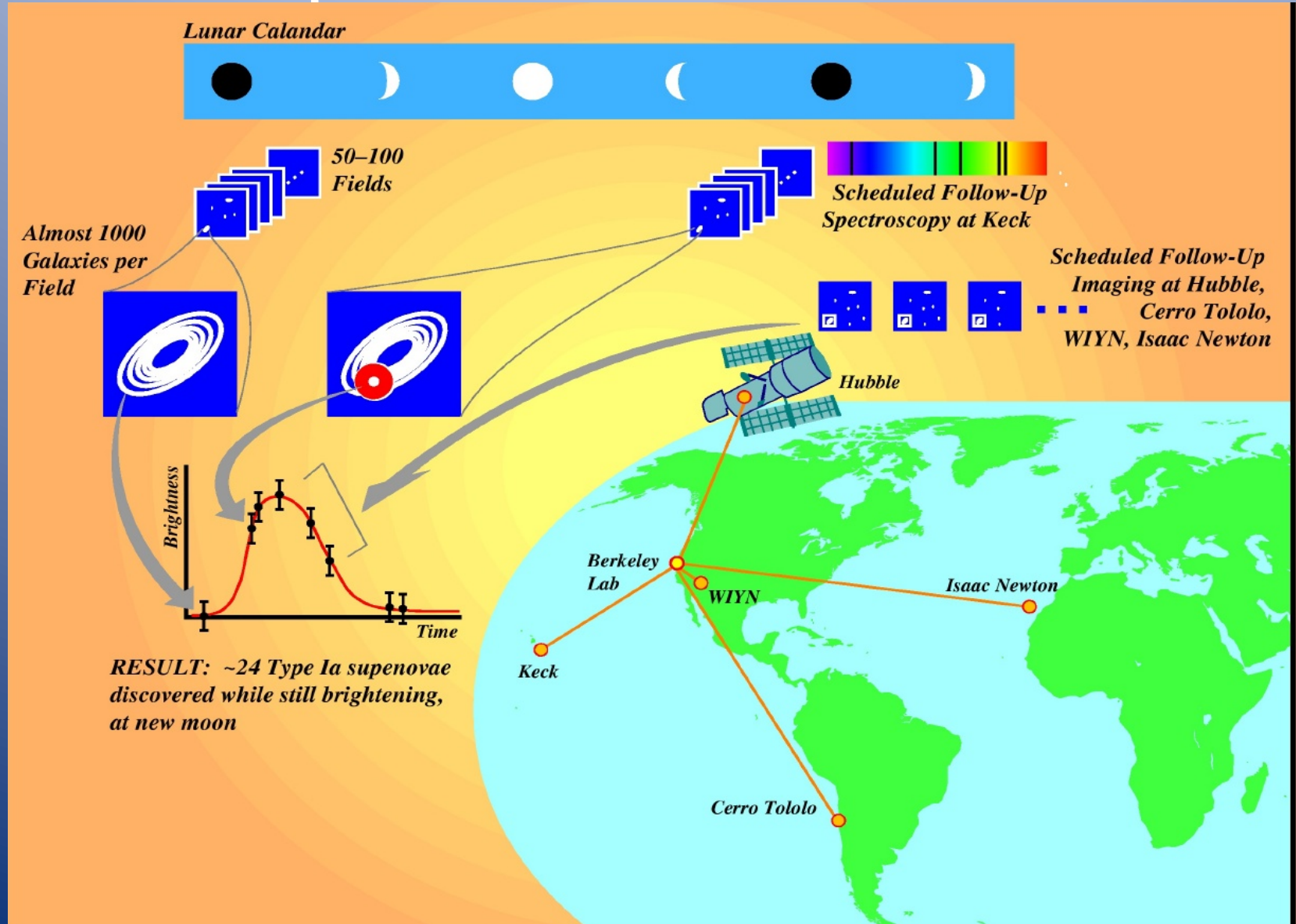
The 4-m Victor Blanco telescope was equipped with 1 (and then 4) 2kX2k ccd's. Exposures were typically 5-10 min long.

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...

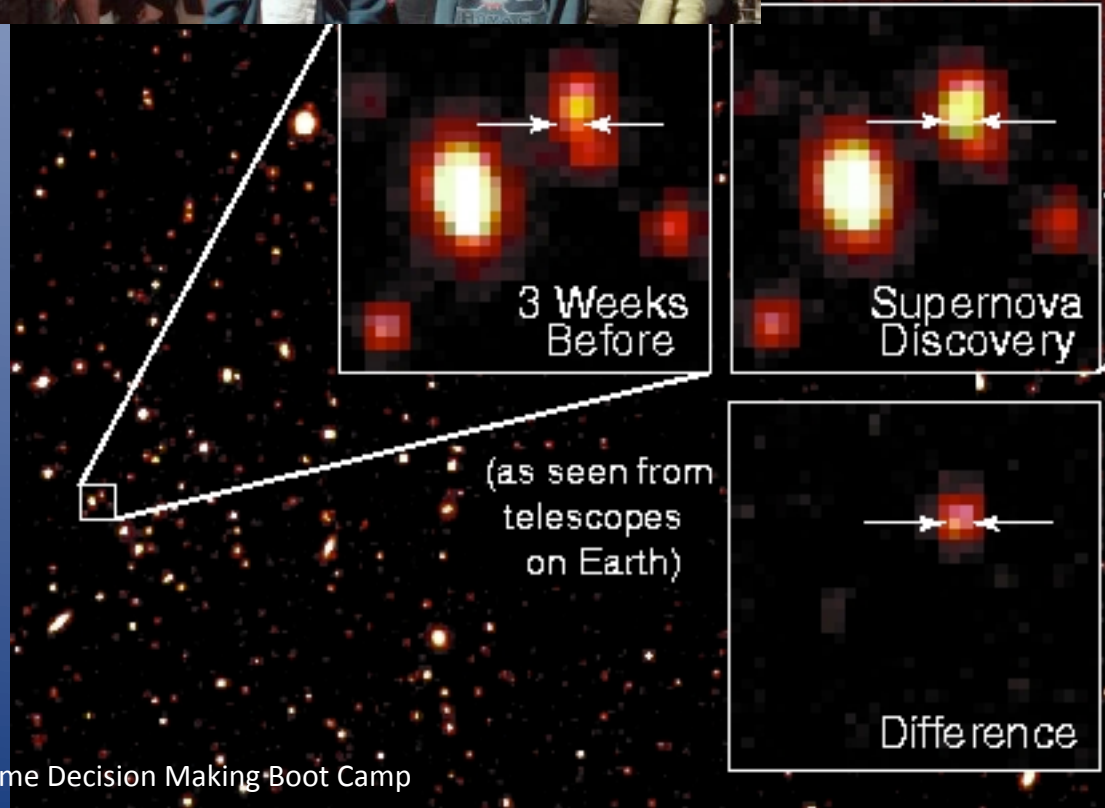




# Supernovae circa 1995



# Supernovae circa 1995

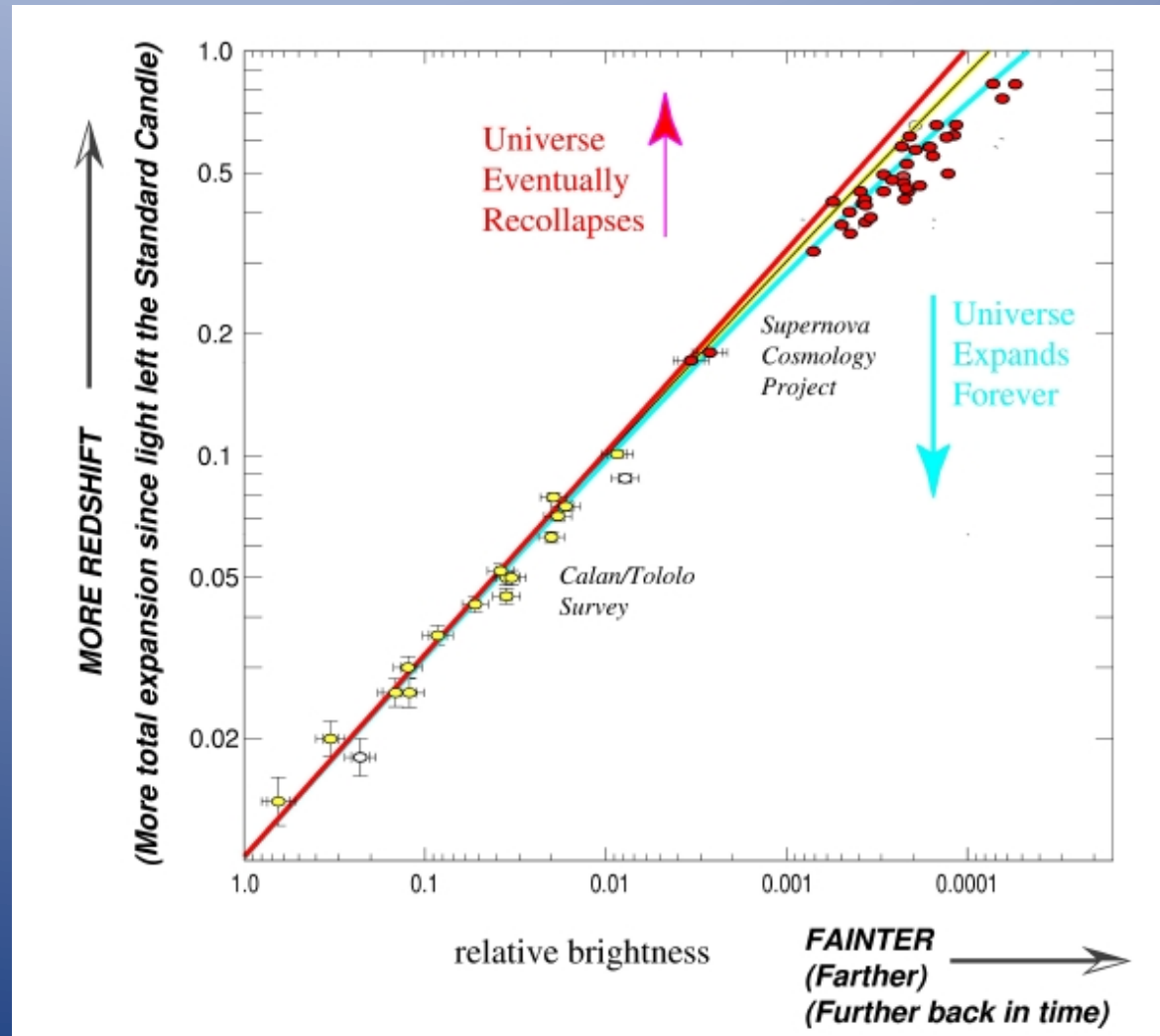




# Supernovae circa 1998

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....



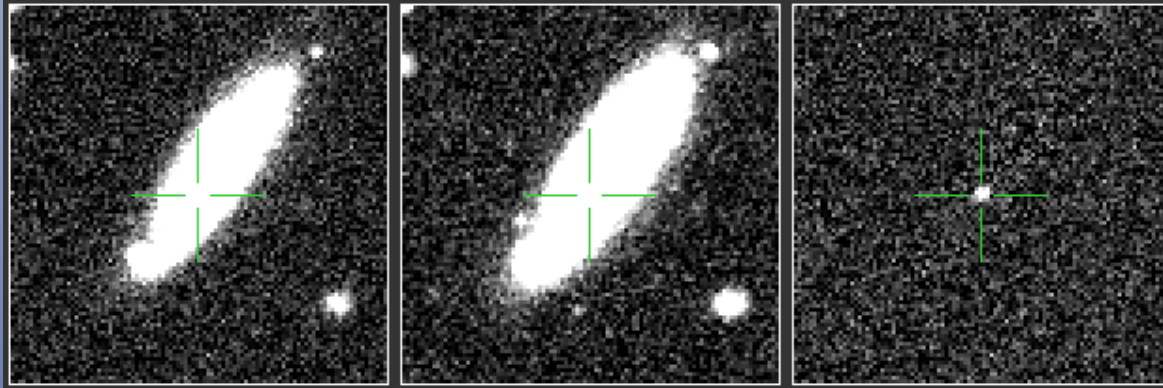
# Cosmology

2011 Nobel Prize in Physics



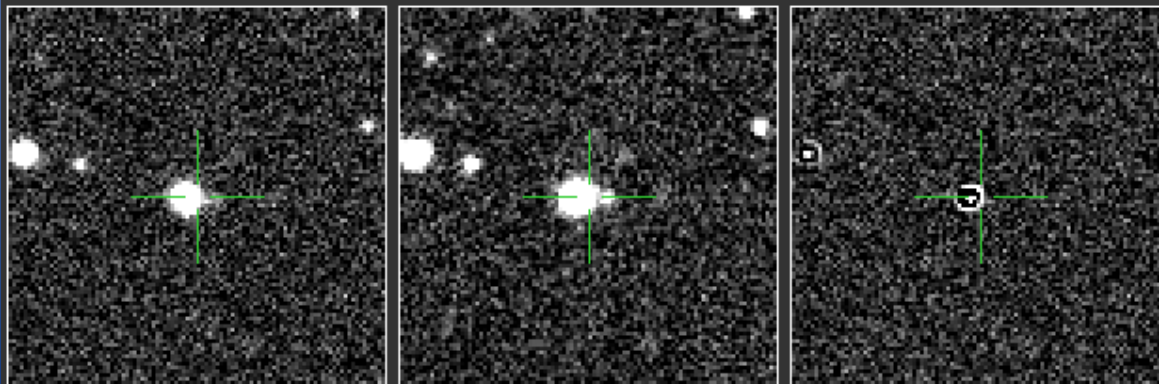
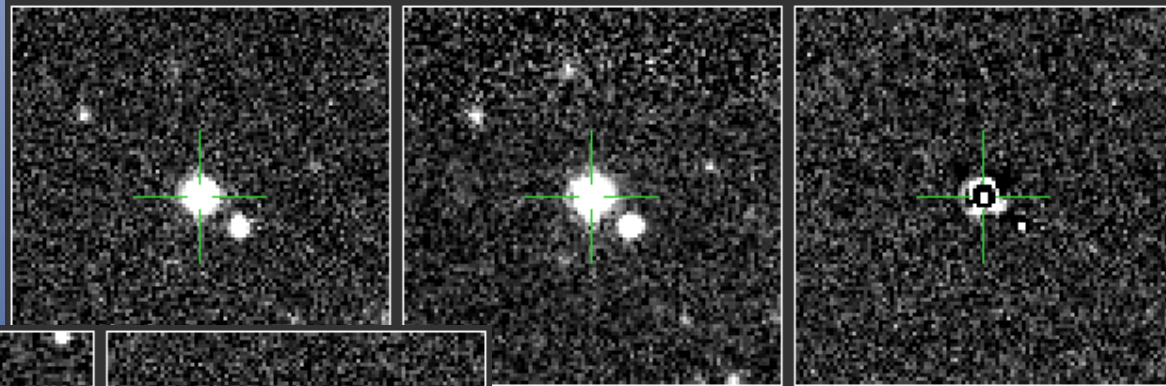


# Supernovae circa 1998



Per image we would have  $\sim 200$   $5\text{-}\sigma$  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  $\sim 5$  candidates per image.

# Supernovae circa 2000

Pain begins....

## *NEAT Search Facilities*

Site:	Haleakala	Palomar I	Palomar II
Aperture:	1.2m	1.2m	1.5m
Nights/Month:	18 dark/gray	10 dark/gray	10 dark/gray
Imager Format:	4k × 4k	16k × 16k	16k × 24k
Imager Scale:	1.33"/pixel	0.50"/pixel	0.50"/pixel
Field of View:	1.1° × 3.4°	1.1° × 3.4°	2.3° × 4.0°
Filters:	open	open	4 fixed filters
Exposures:	3 × 60 sec	3 × 60 sec	TBD
Readout:	20 sec	20 sec	TBD
Night Area:	600□°	800□°	(2000 □°)
Start:	Mar 2000	Feb 2001	~Dec 2001
Data (Compressed):	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 13<sup>th</sup>, 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



P48:  
Discovery Engine

P60:  
Followup

Instrumentation, system  
design, first results

Law, Kulkarni, Dekany et al. 2009 PASP 121 1395L

Science plans

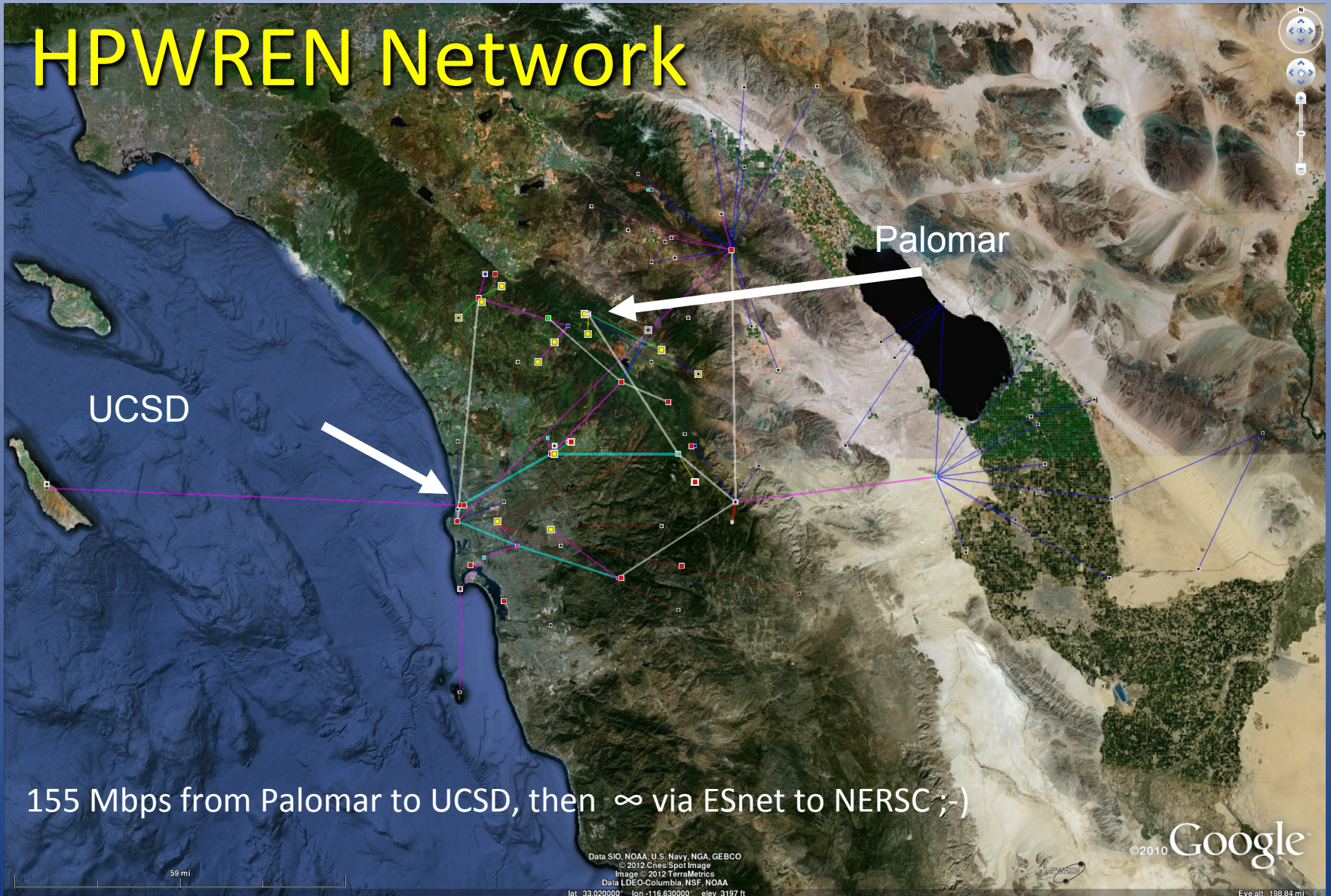
Rau, Kulkarni, Law et al. 2009 PASP 121 1334R

2010 survey status

Law et al. 2010 SPIE 7735  
Real-Time Decision Making Boot Camp

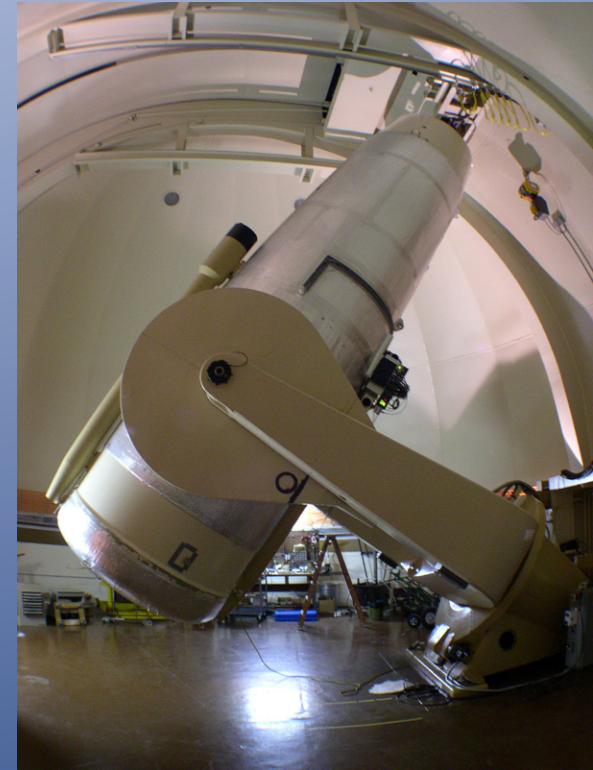
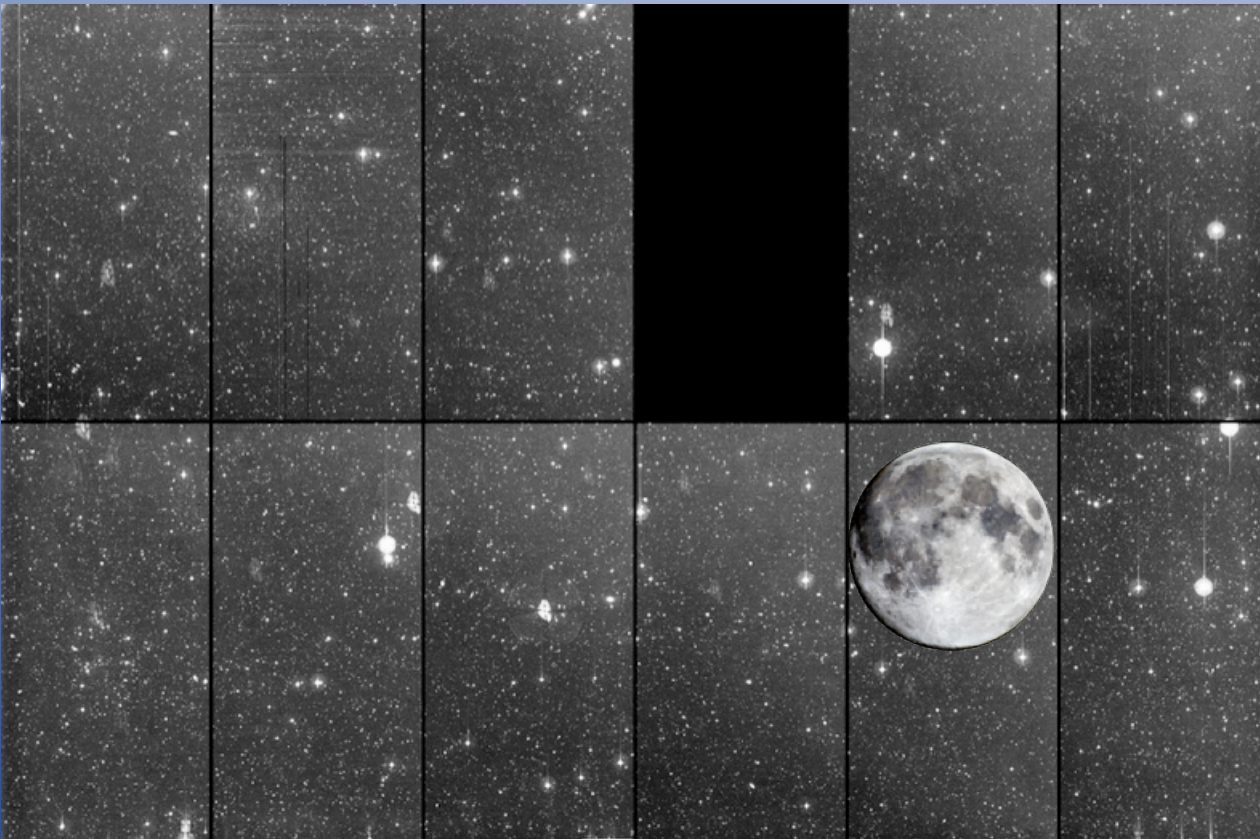


# HPWREN Network





# PTF Camera



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

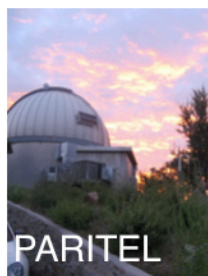
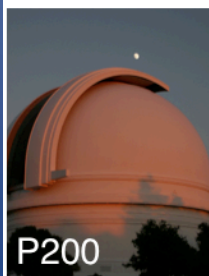
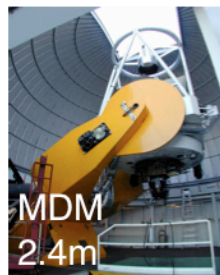
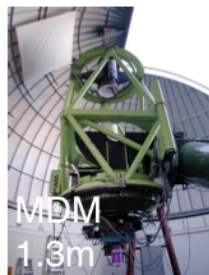
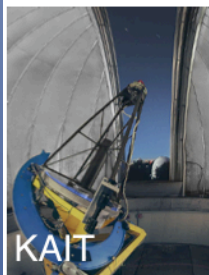
# PTF Science

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 $\frac{1}{2}$ sky survey

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

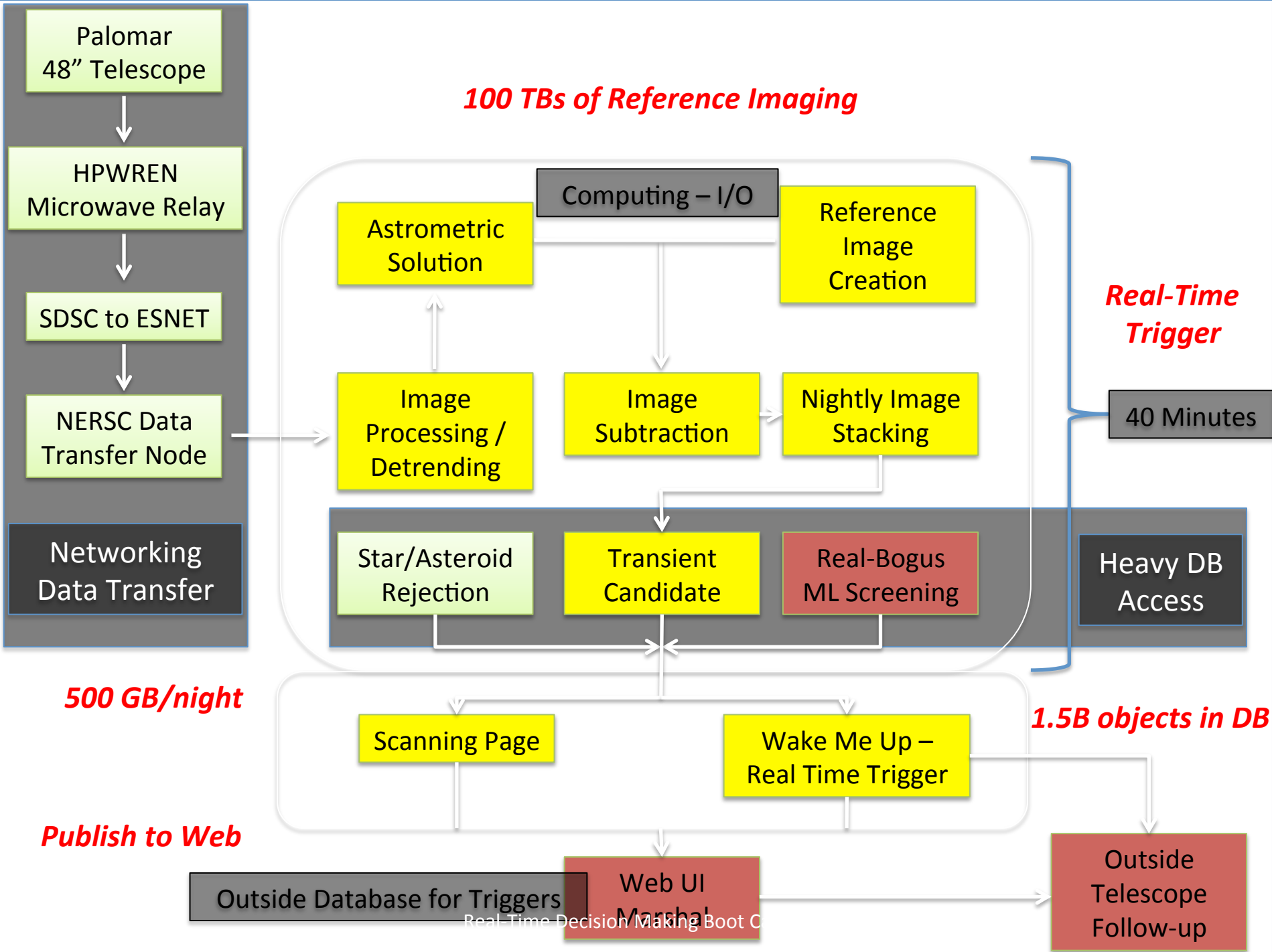
# PTF Science

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

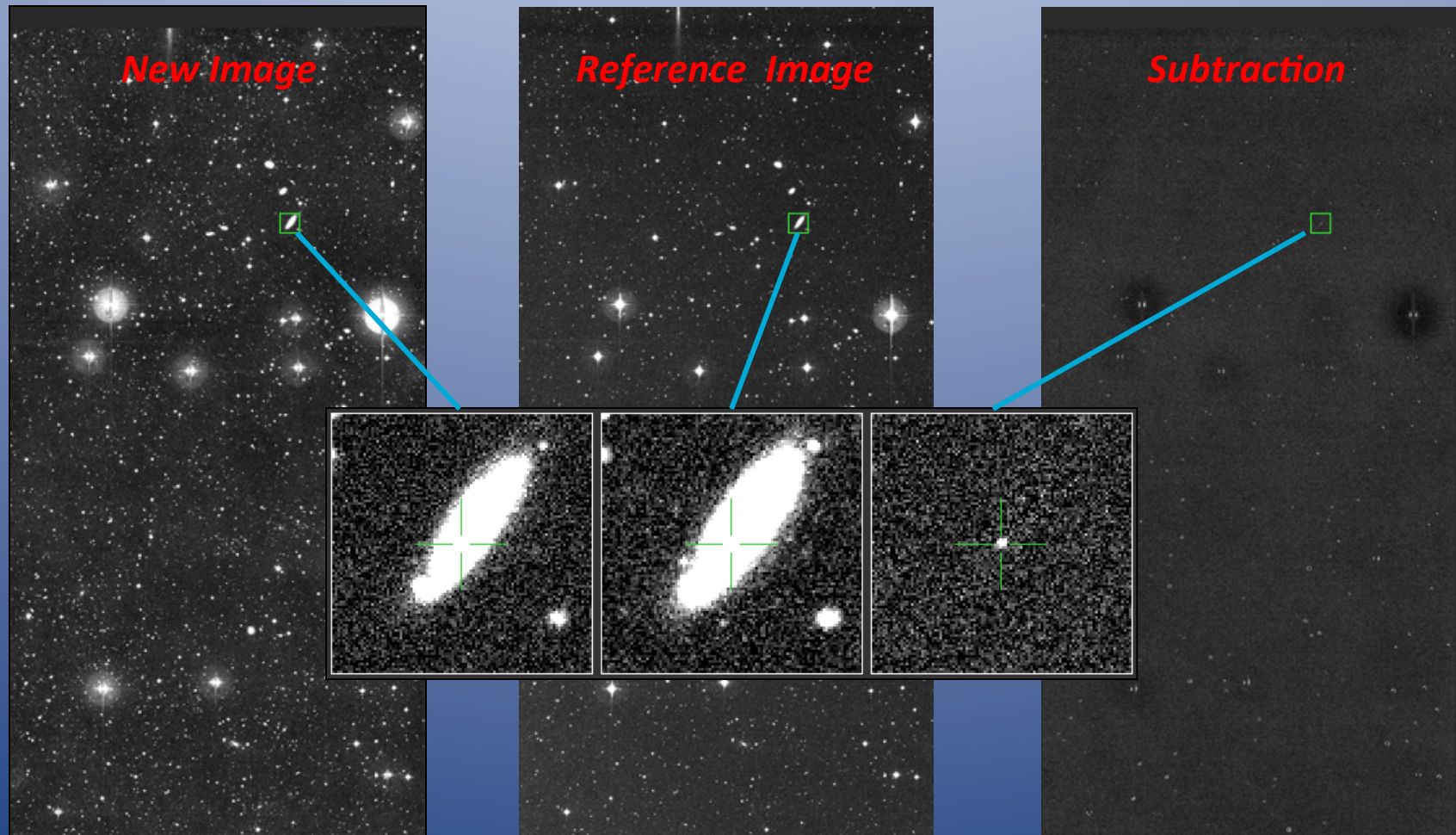


The power of PTF resides in its diverse science goals and follow-up.





# 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.

# 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

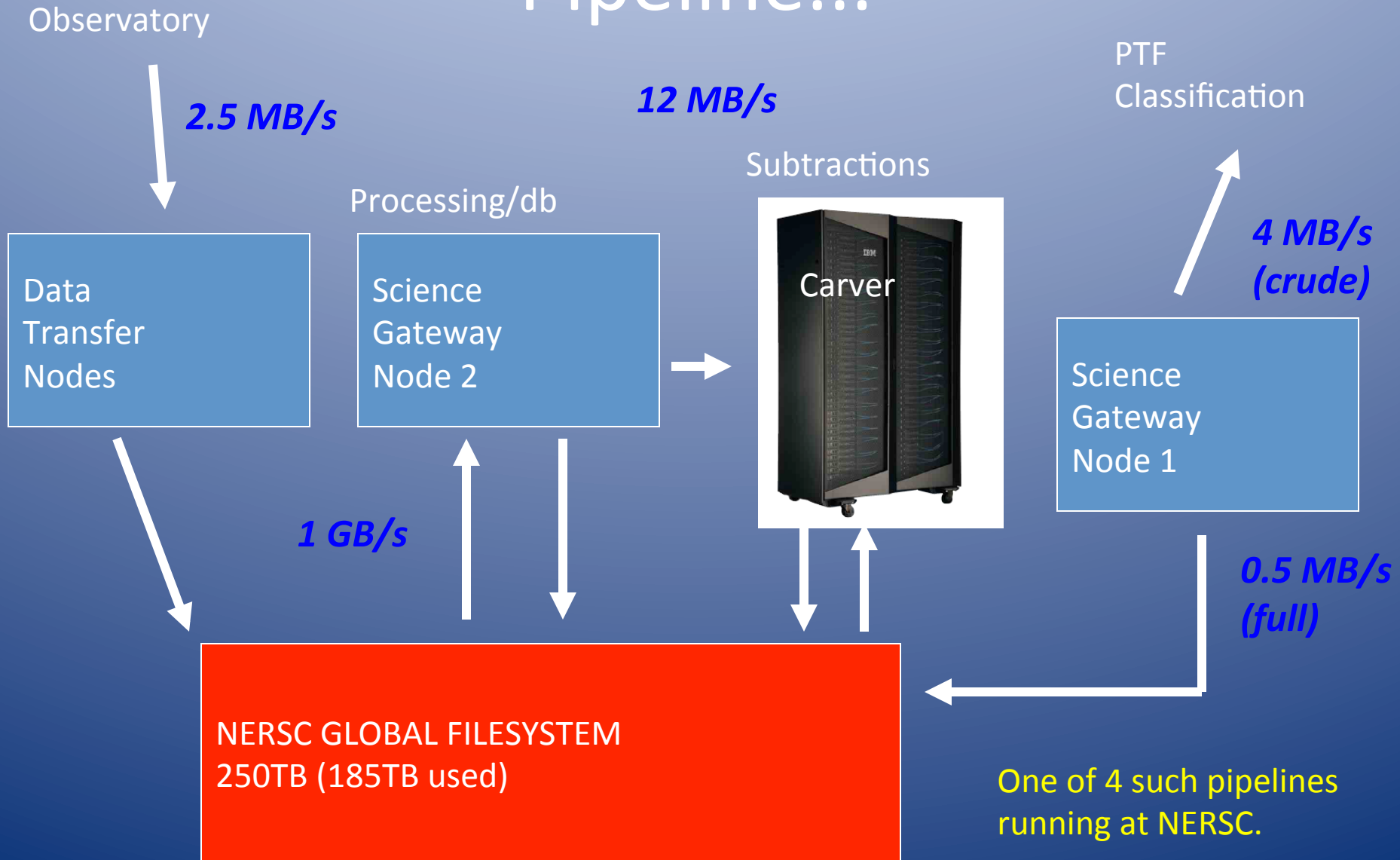
All in 851 nights.

An image is an individual chip (~0.7 sq. deg.)

The database is now 1 TB.

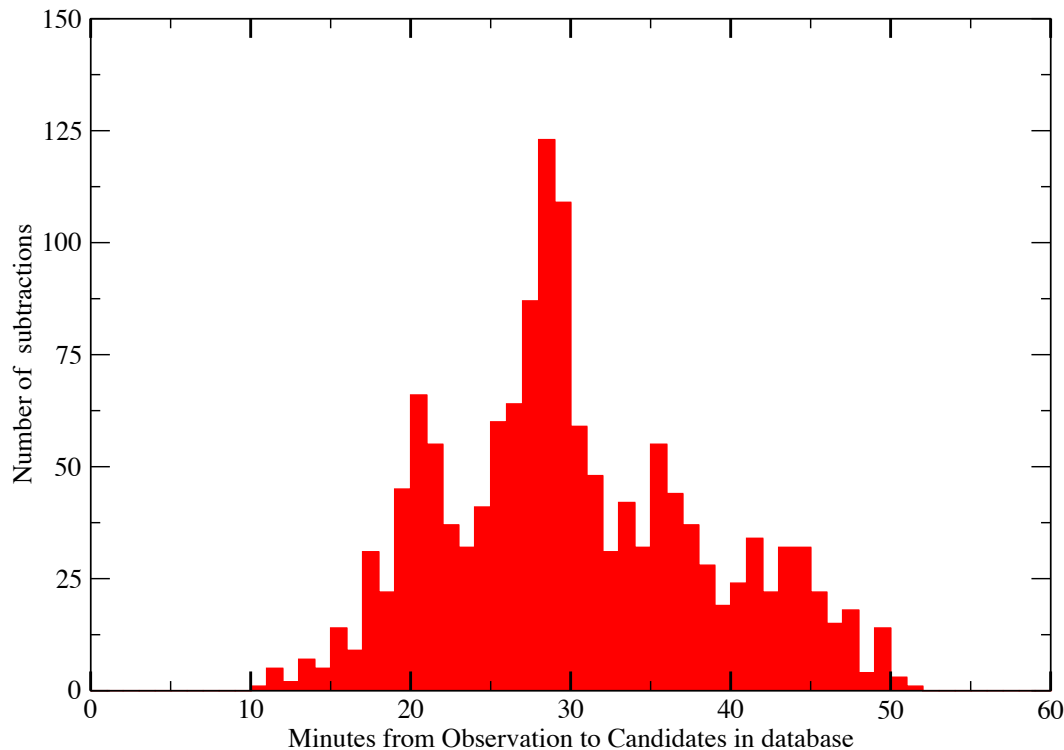


# Pipeline...



# Turn-around

## Typical night: 2012-07-06



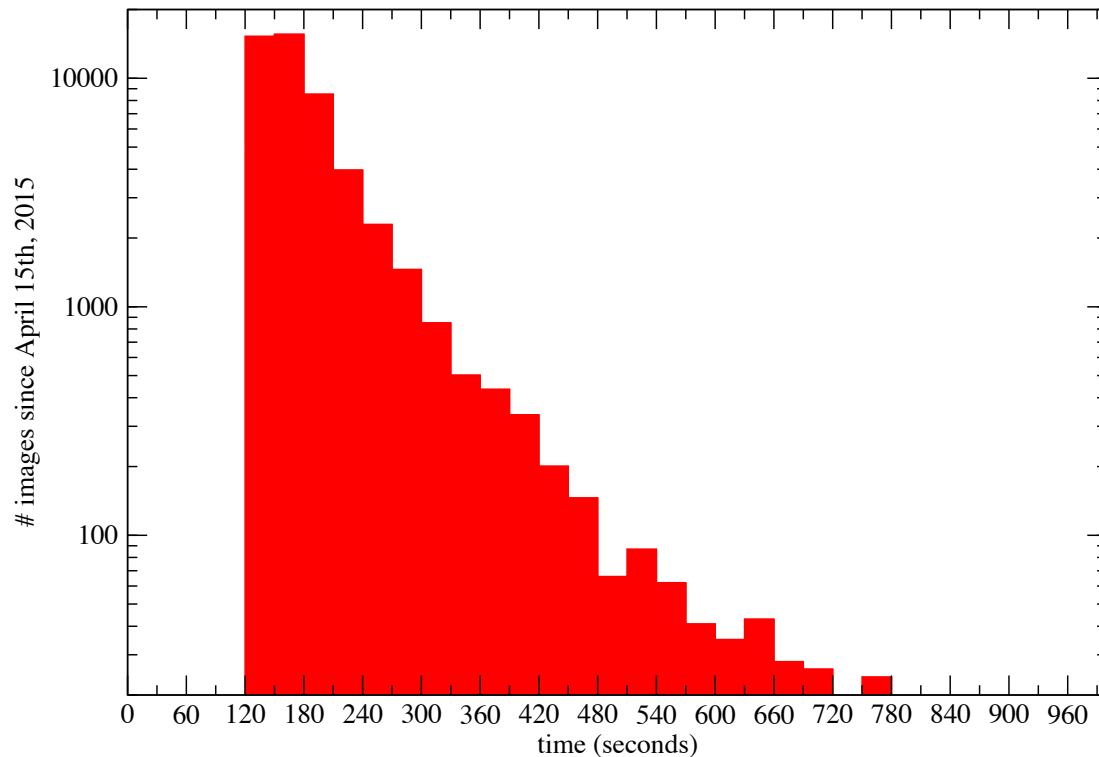
What does “real-time” subtractions really mean?

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 < 1 hr 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!

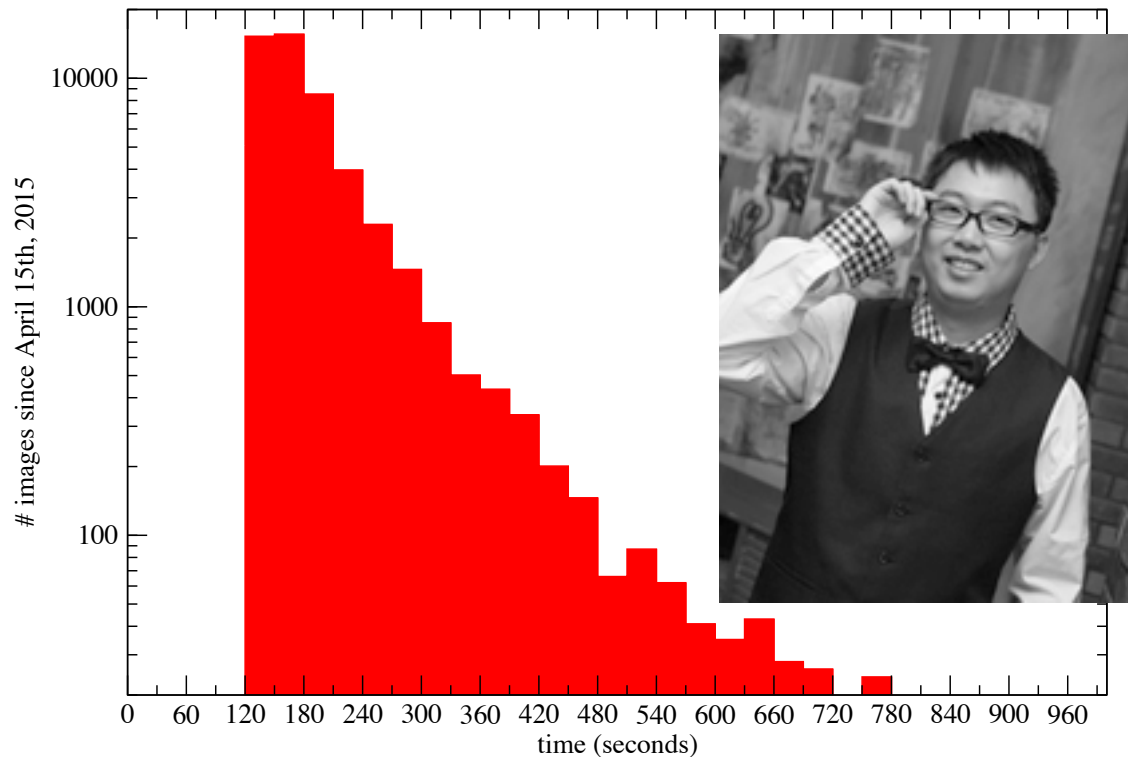
Better use of the Lustre filesystem (for everything), better use of OpenMP in all codes, reserved nodes, etc.



# iPTF turn-around

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



Yi Cao's Caltech thesis May 3, 2016.

Became an eScience Postdoctoral Fellow

at University of Washington → Google!

Real-Time Decision Making Boot Camp

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

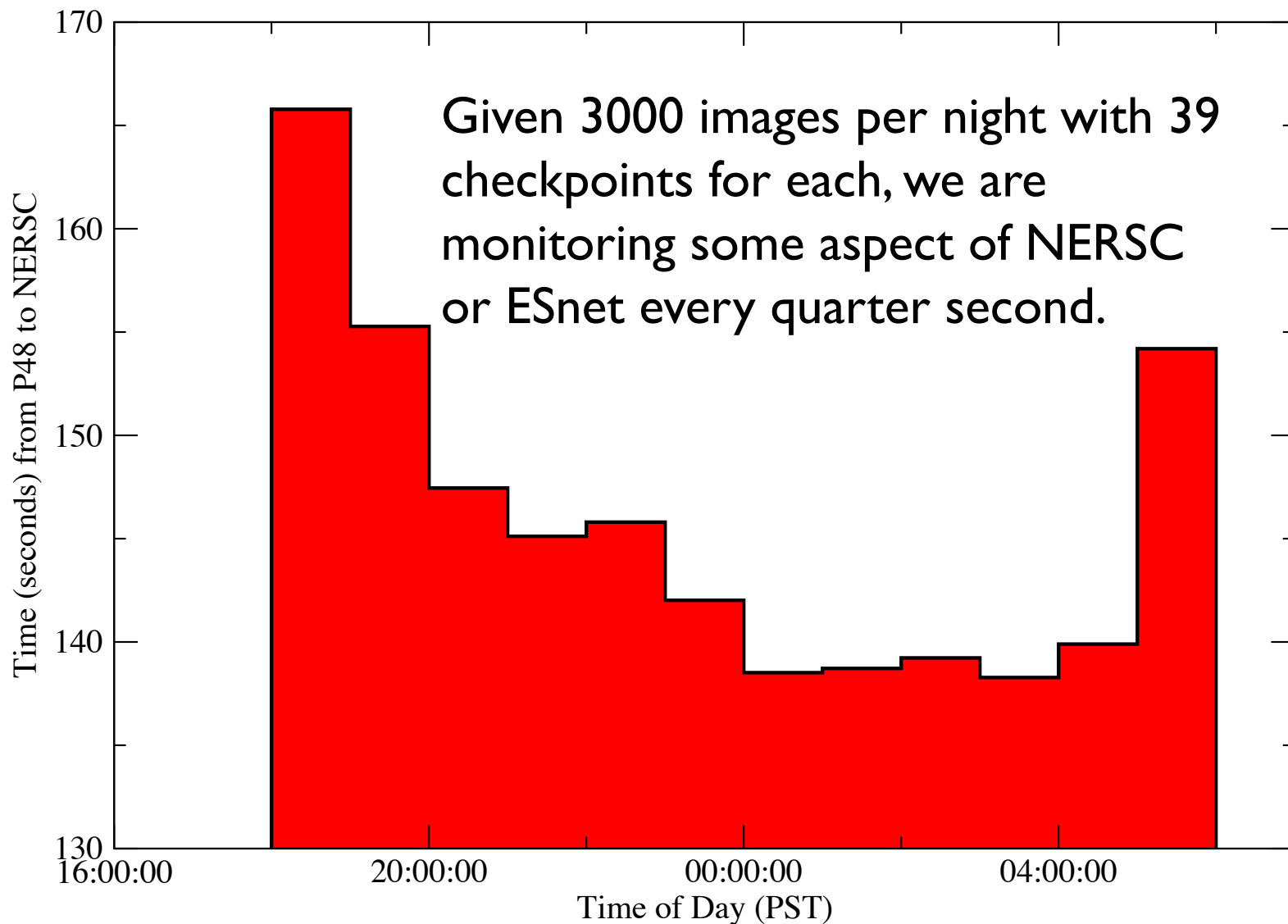
# Instrumented Pipeline with 39 Checkpoints

Covers everything from:

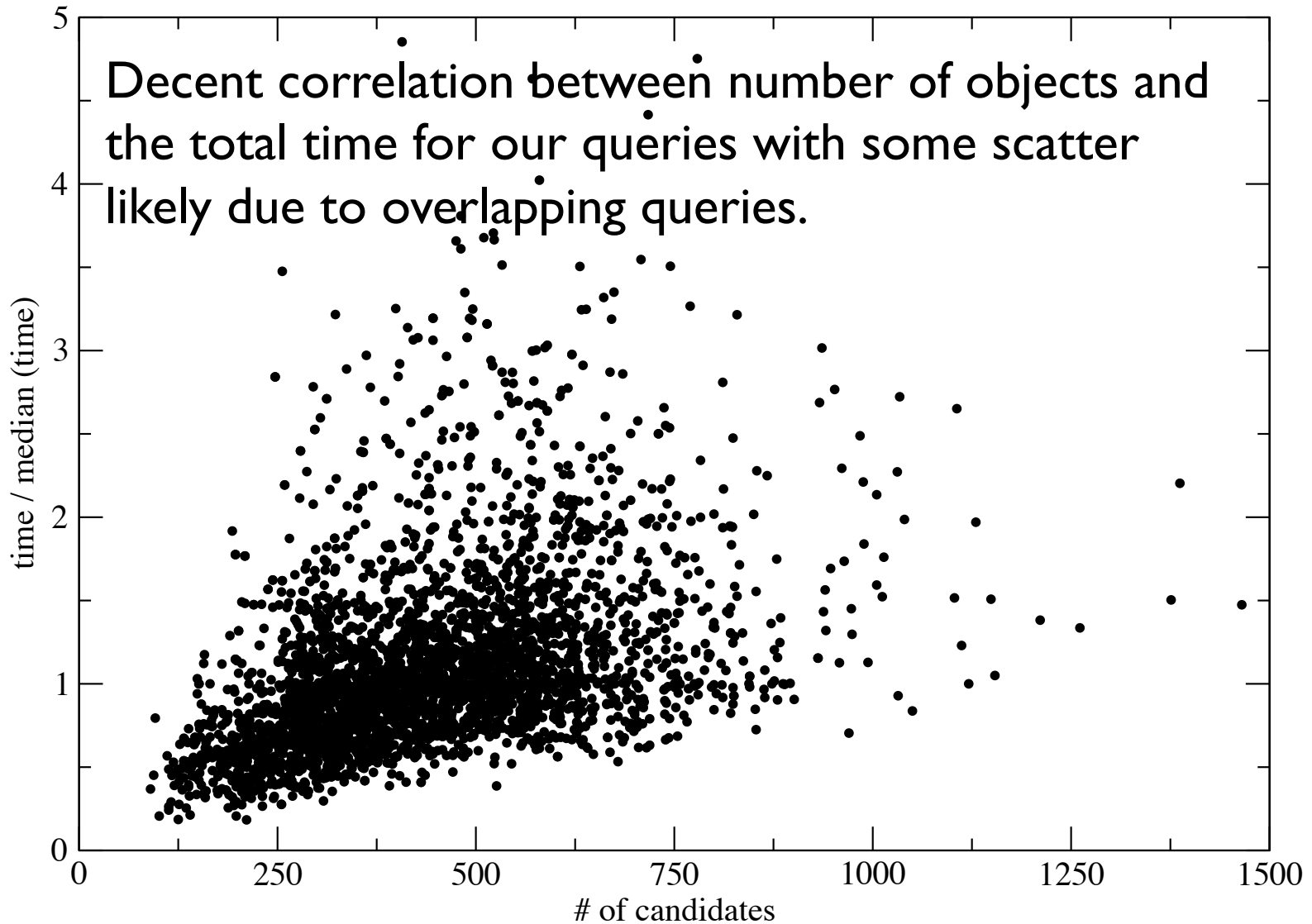
- Pulling the data from the telescope
- I/O on scratch
- Subtraction software
- Running ML algorithms
- Loading the db with discoveries
- Performing difficult geometric queries to match with known stars, asteroids, previous discoveries, etc.
- Copying data from scratch to project



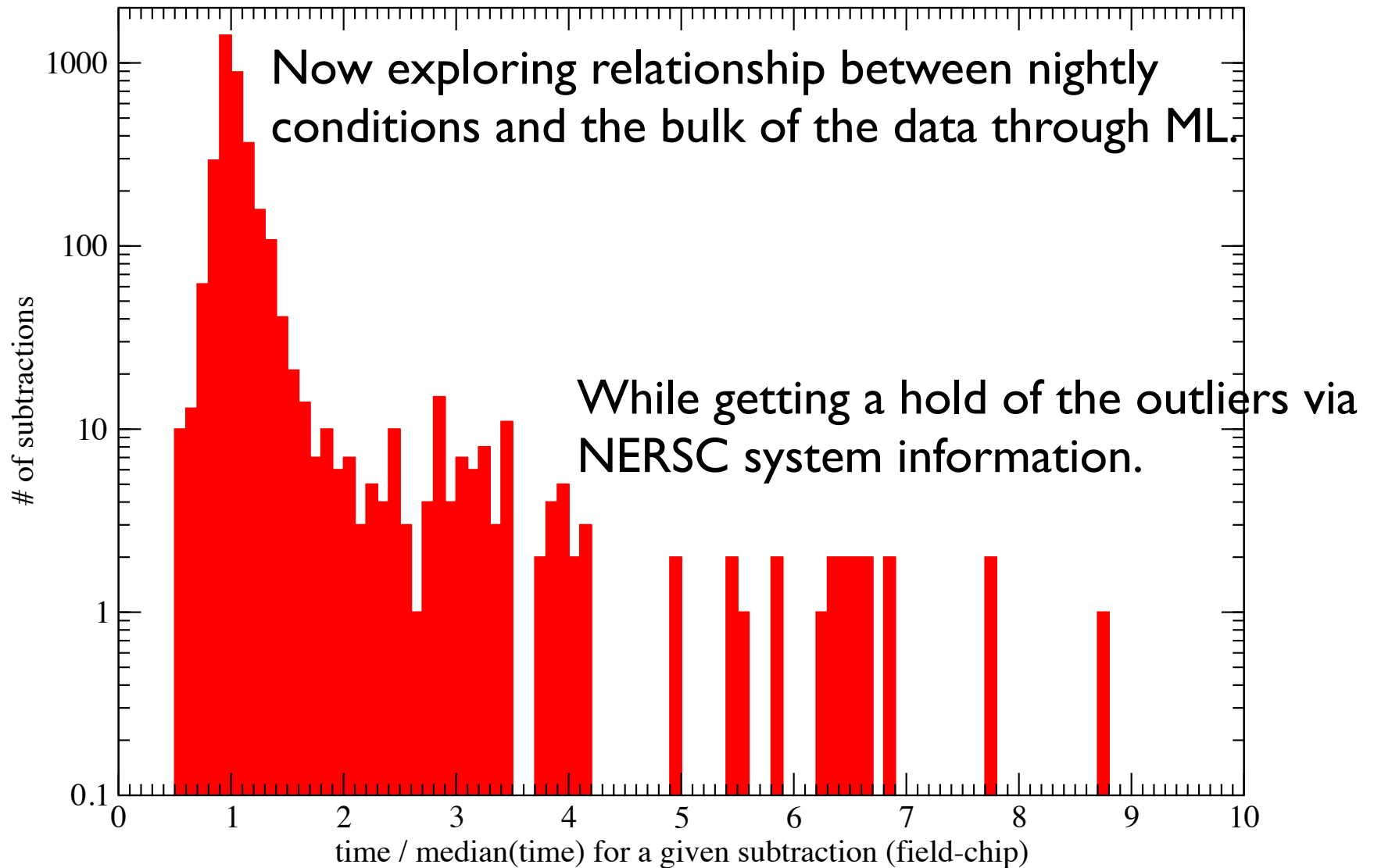
For 8 hours every night, we now know more about the NERSC center than they do in real-time.



## DB Access



# I/O time on Cori



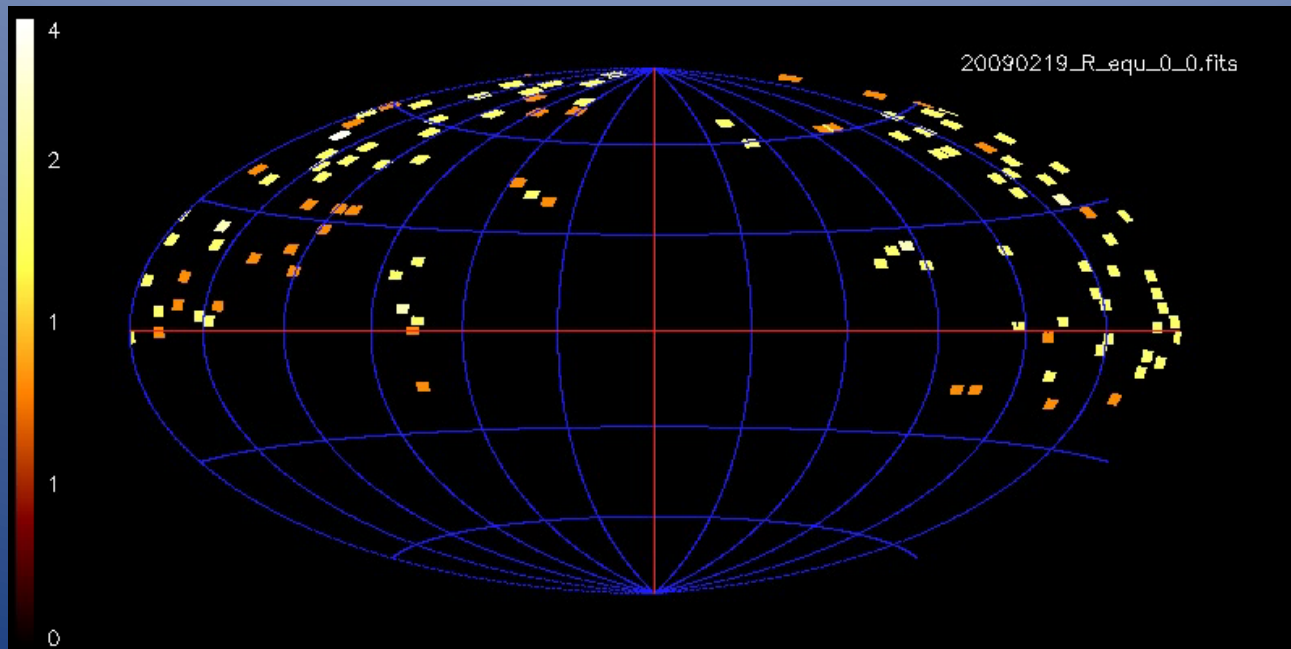


# PTF / iPTF Sky Coverage

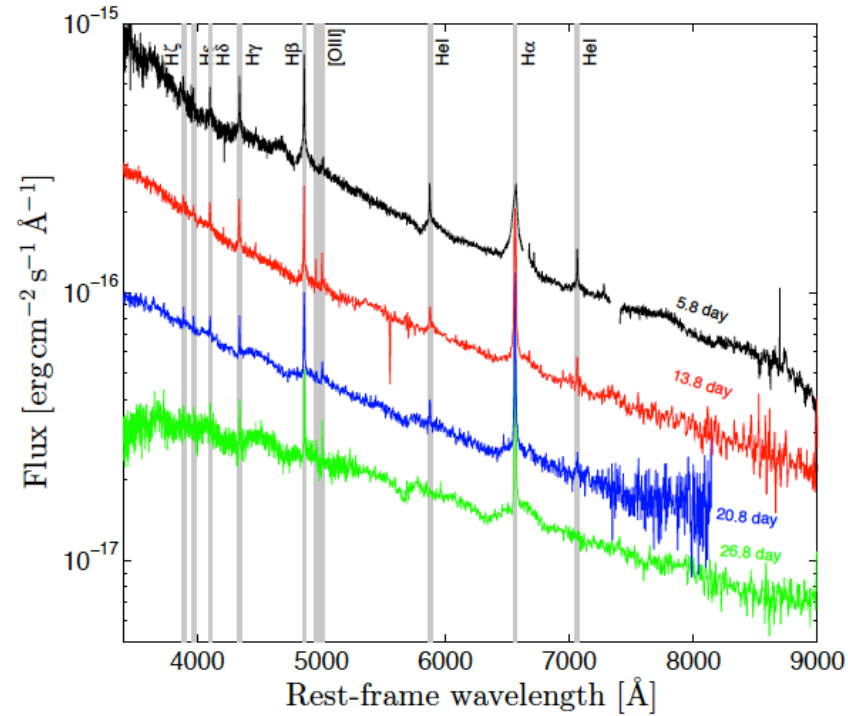
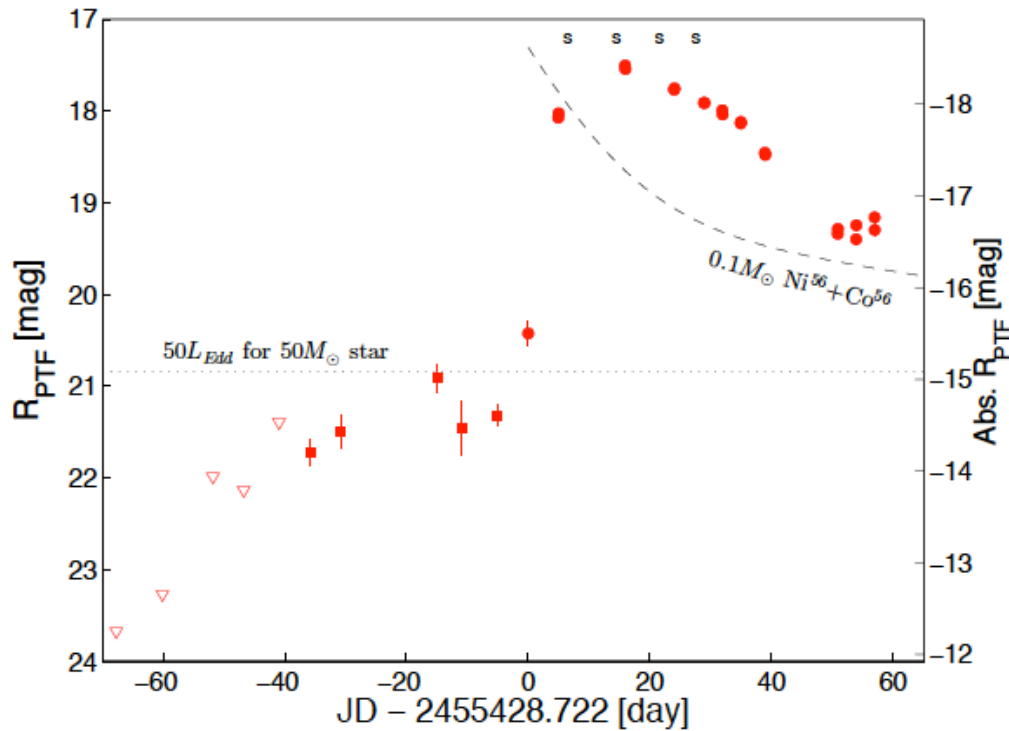
The Final Tally:

- 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



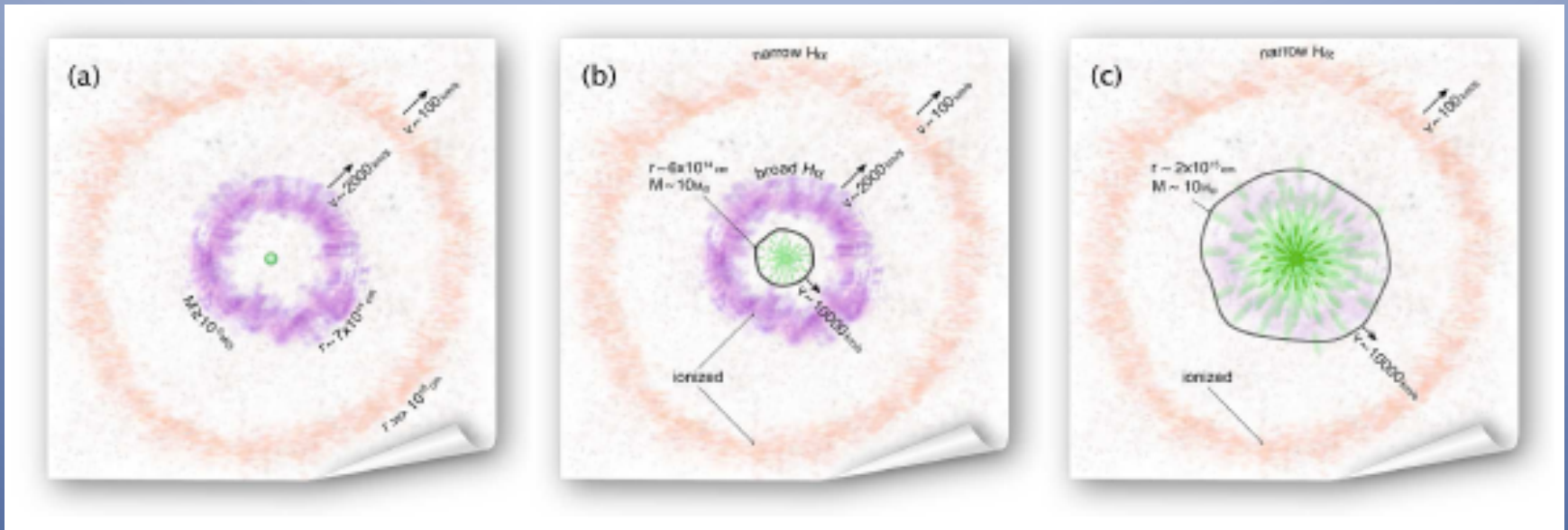
# Pre-Outbursts



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



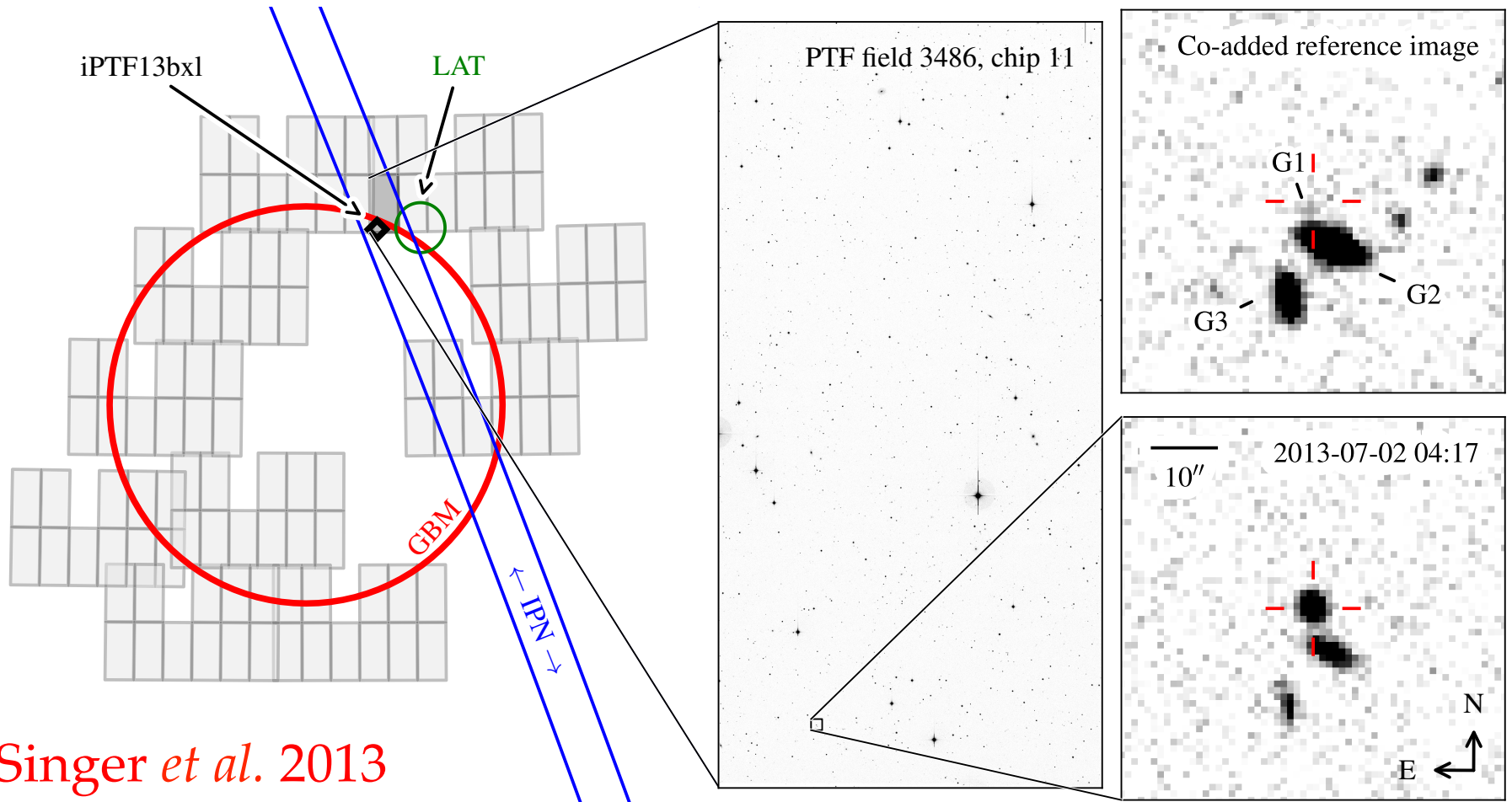
(a)  $10^{-2} M_{\odot}$  ejected one month earlier during pre-outburst  $\sim 2000 \text{ km/s}$

(b) At day  $\sim 5$ , the SN shock front (grey line at  $10^4 \text{ km/s}$ ) 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.



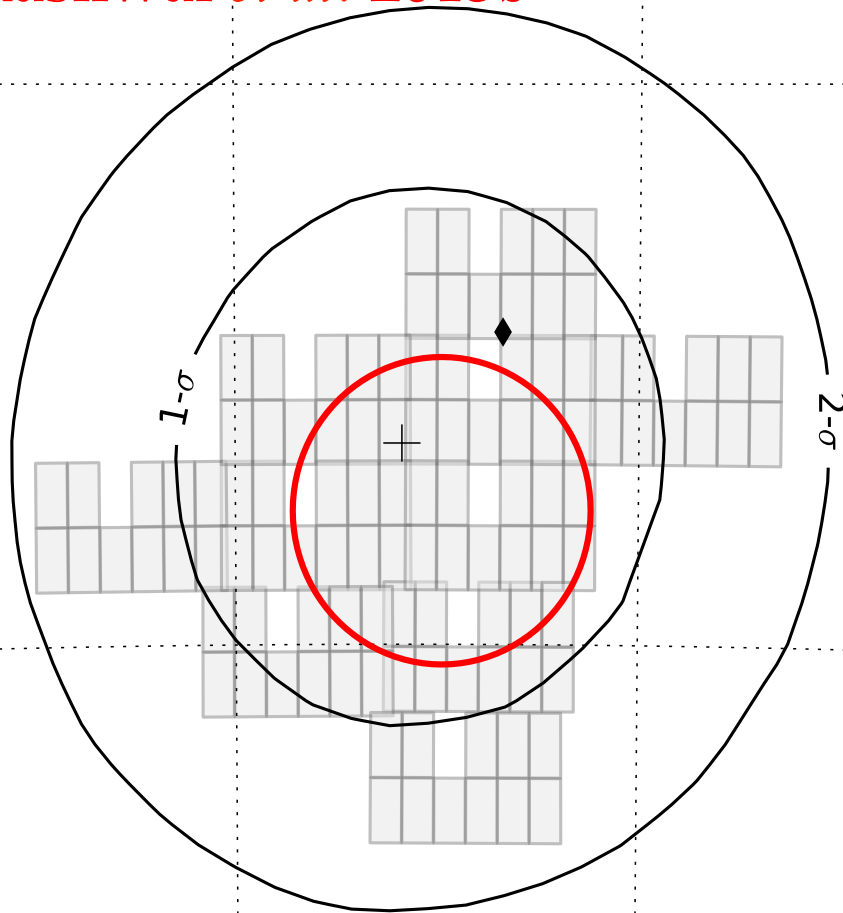
# Overcoming wide & fast: iPTF13bxi in 71 deg<sup>2</sup>!



*Singer et al. 2013*

# The second Fermi afterglow: iPTF13dsw at $z=1.87$ !

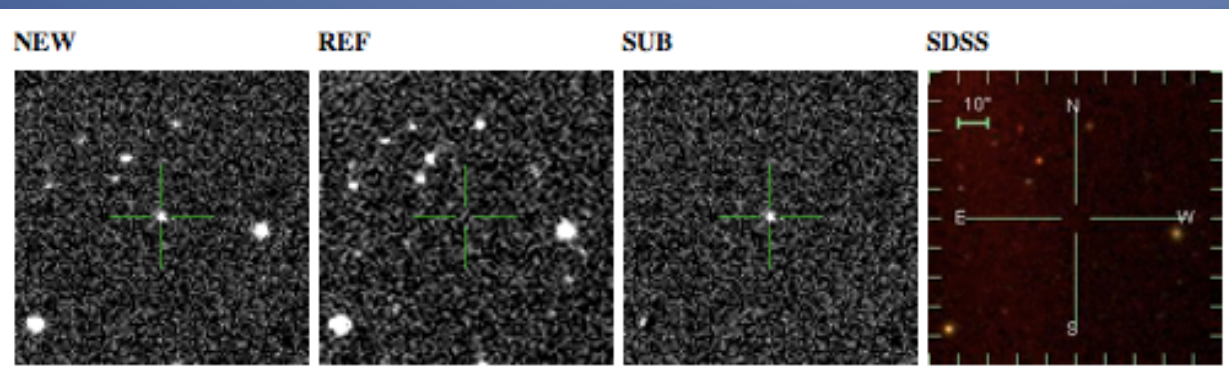
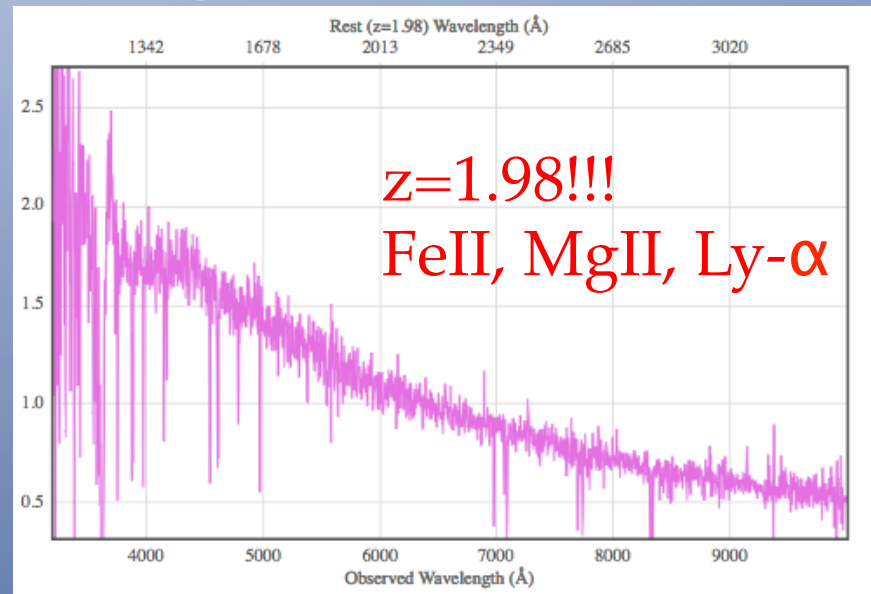
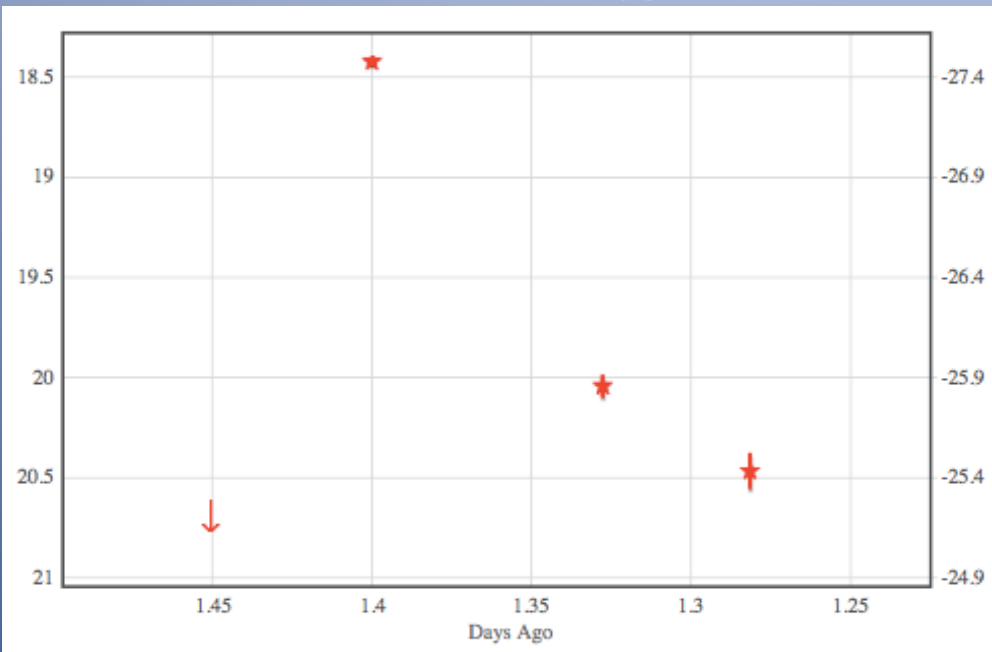
Kasliwal *et al.* 2013b



Overcoming  
Wide, Fast & Faint

Pinpointing the afterglow  
amidst 30,000 candidates

# Orphan Afterglow

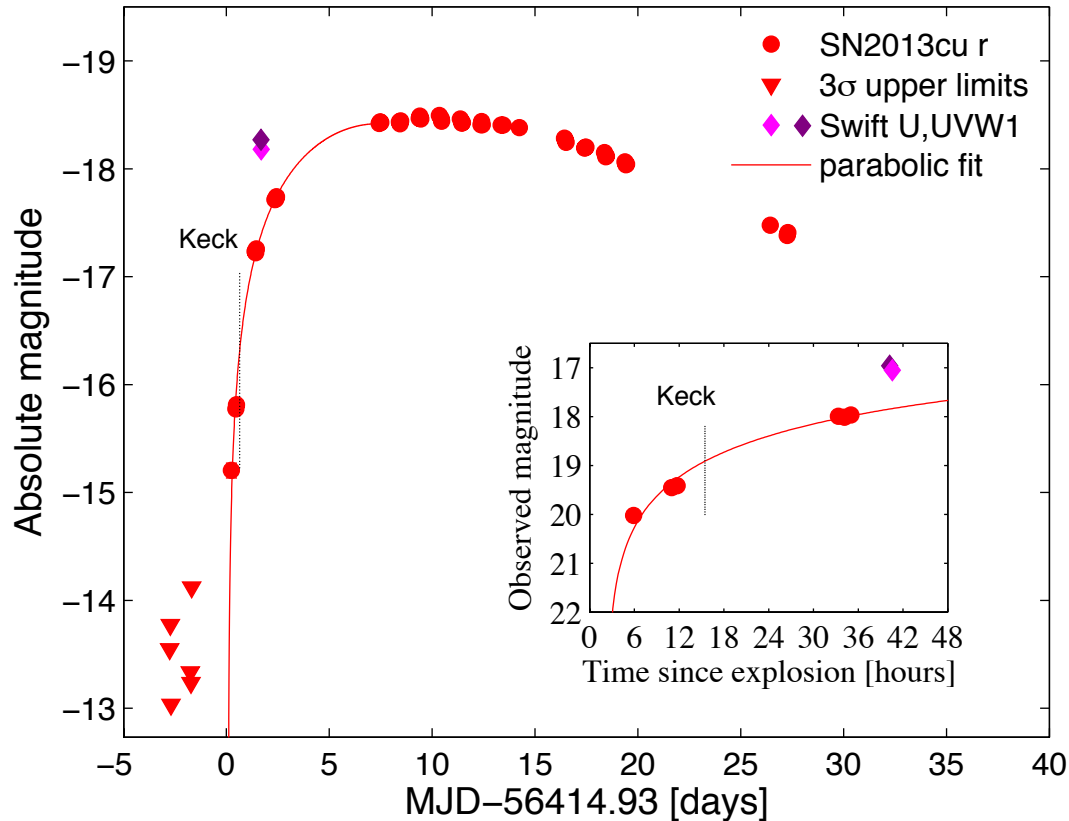


iPTF14yb  
Cenko et al. 2014

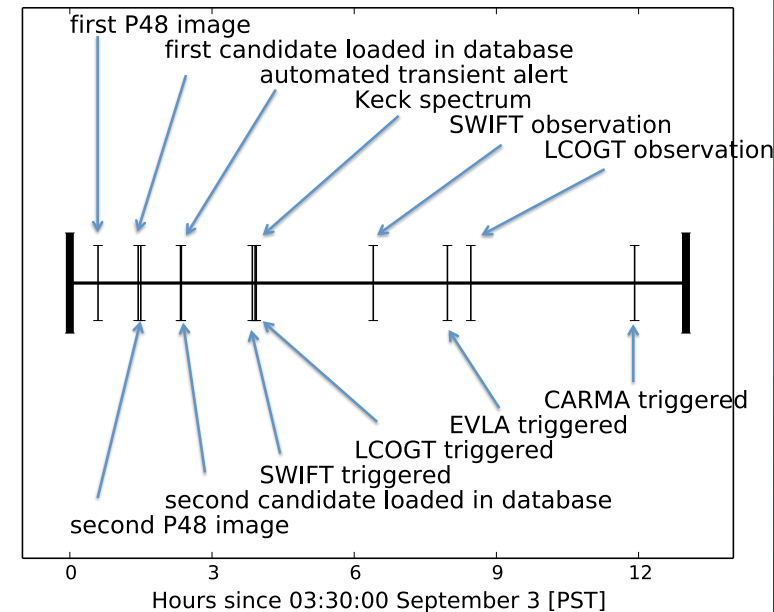
IPN found a GRB (localization  $\sim 200$ - $300$  sq. deg.)  
 $\sim 15$  min before first detection....



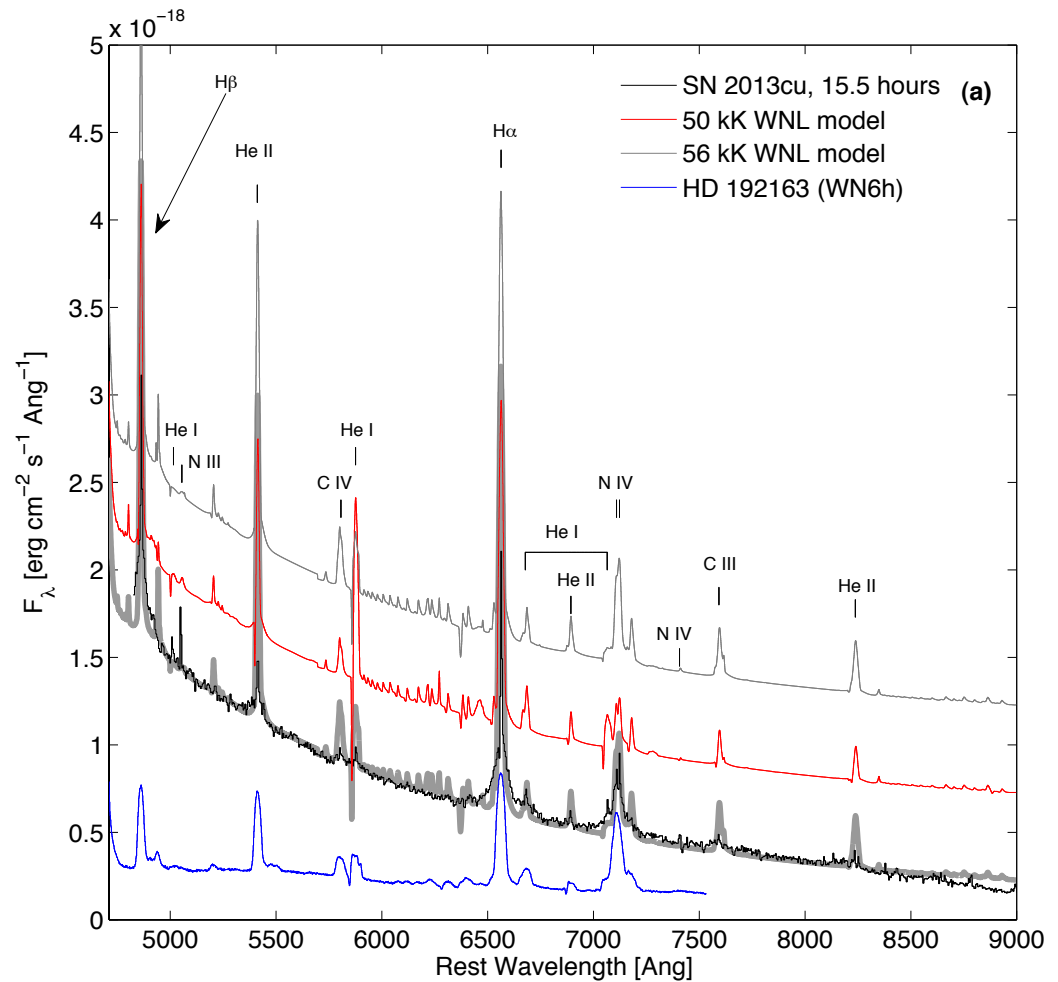
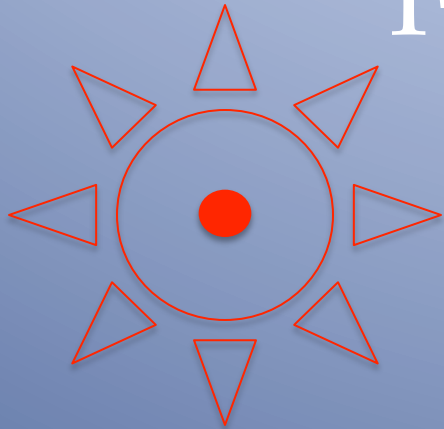
# Flash Spectroscopy



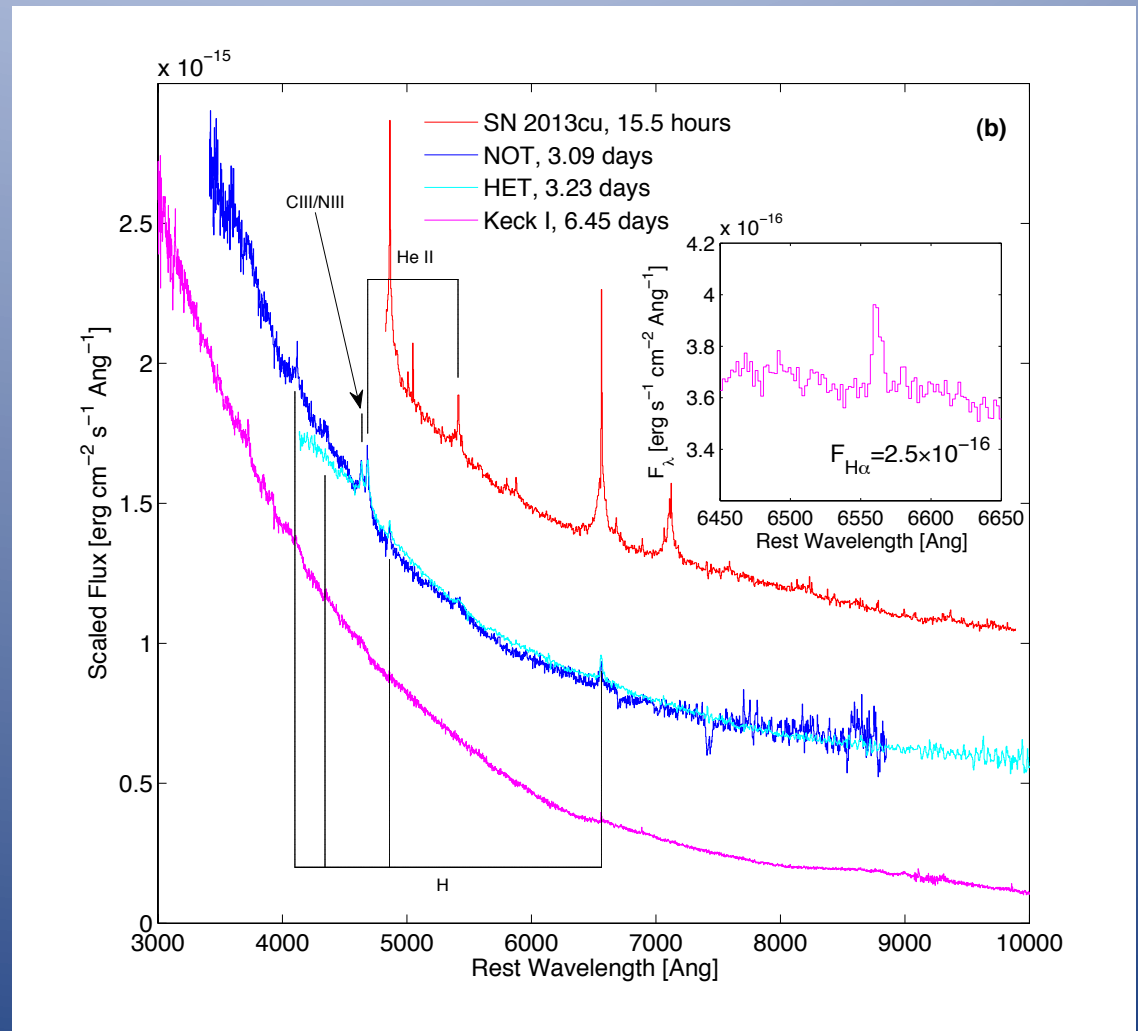
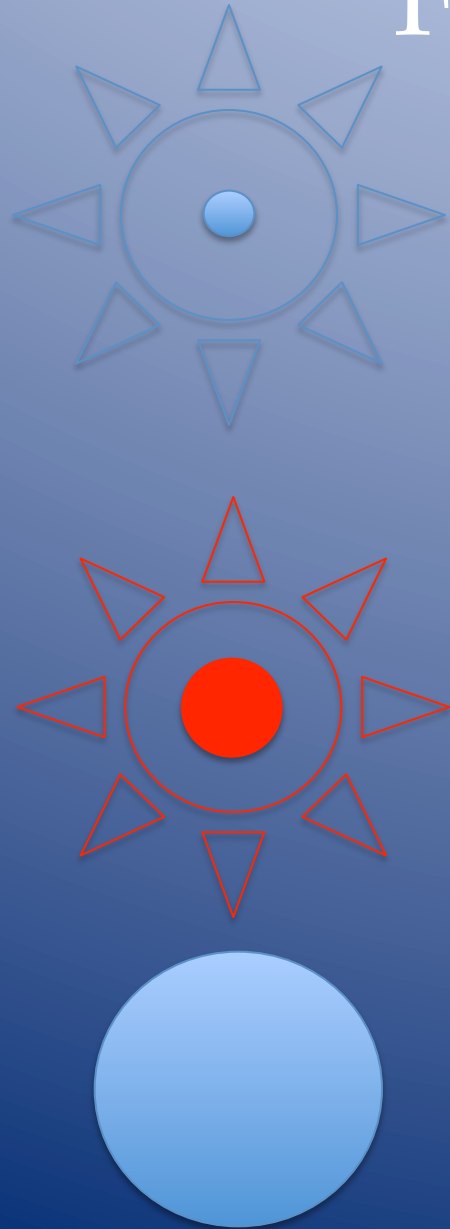
SN2013cu (iPTF13ast)  
Gal-Yam et al. (2014) *Nature*



# Flash Spectroscopy

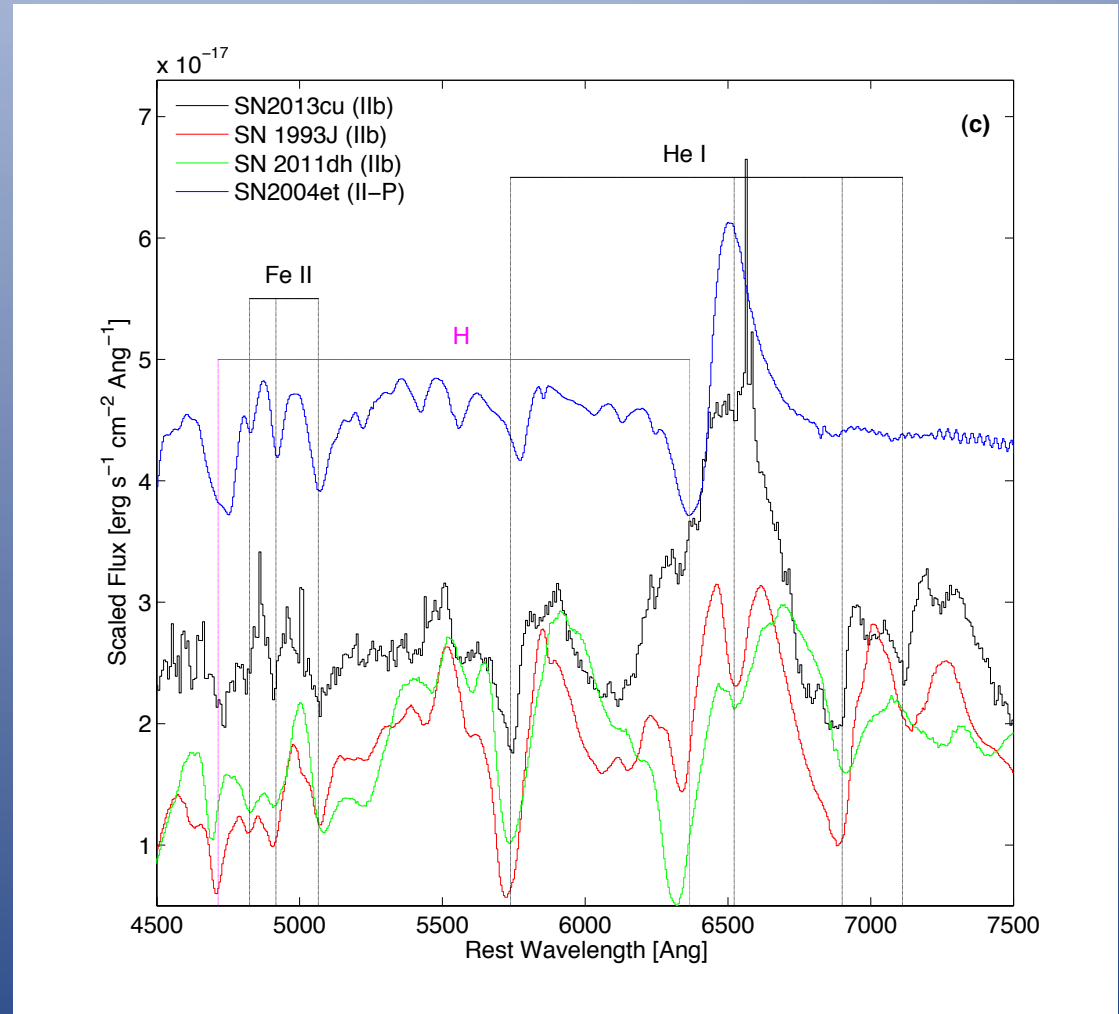


# Flash Spectroscopy





# Flash Spectroscopy

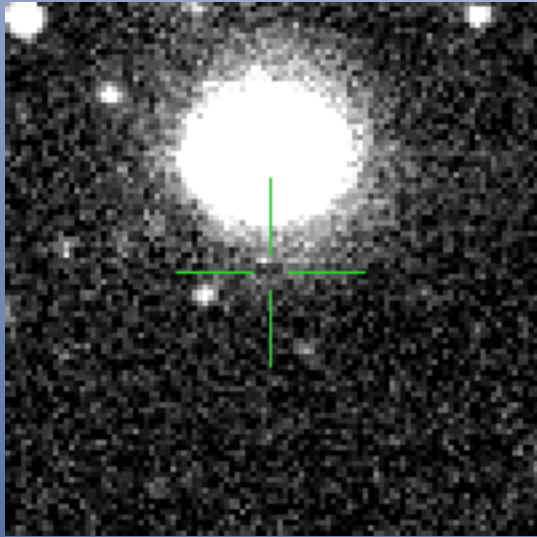


# August 24, 2011

g-band run:

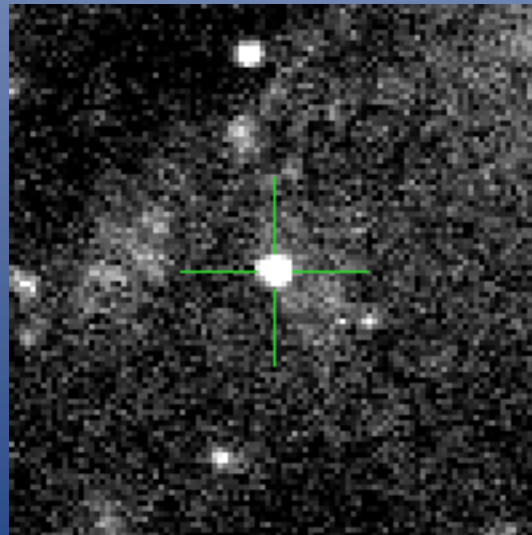
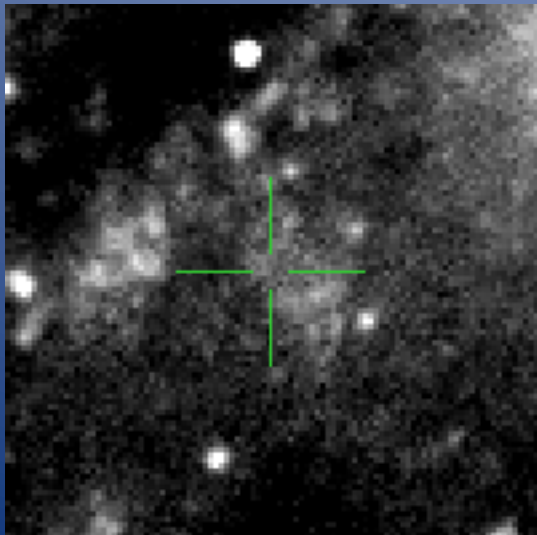
- ~500 sq. deg. hit twice during the night subtractions - rest went to new references
- 50-50 split between Dynamic and SN cadence
- 10 new transients found that night
- Pipeline was slow, running 6 hrs behind normal due to catching up from a kernel “update” on the NERSC machines.
- An IP address at 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

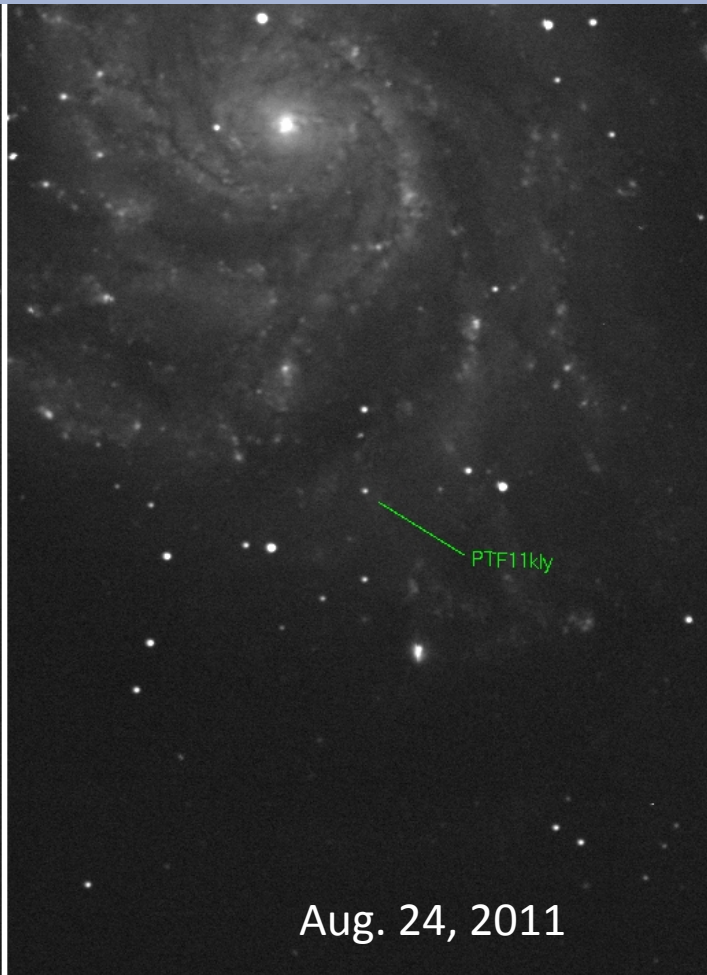
"Hi all,

M101 has given birth to 11kly

Check it out, alert the troops!!!"



# PTF11kly (SN 2011fe)



Caught at magnitude  $\sim 17.4$ ,  $\sim 100,000$  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.

2E+04

4E+04

6E+04

# 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)*

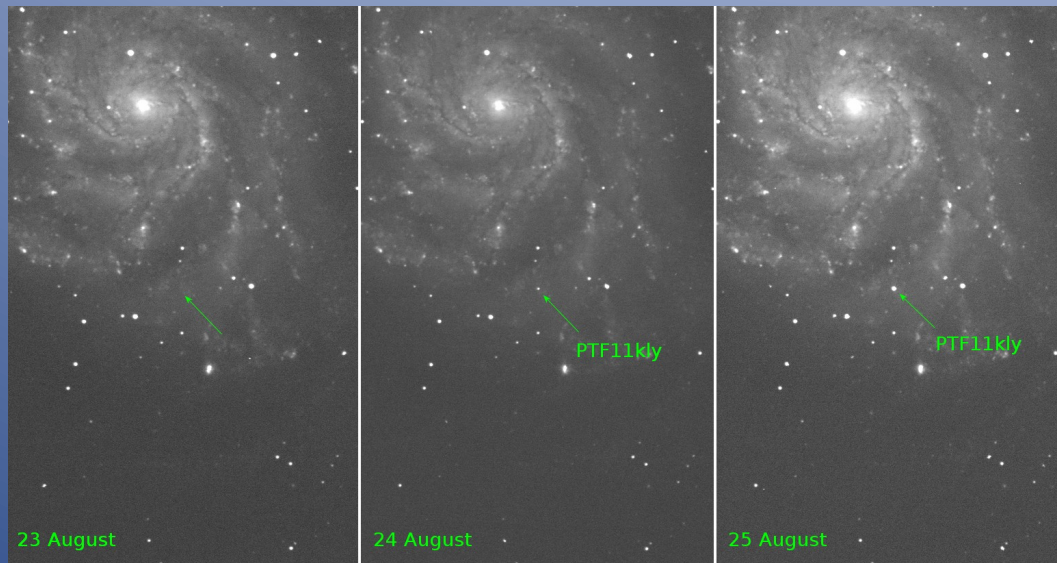
Subjects: Optical, Supernovae

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 5<sup>th</sup> 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.



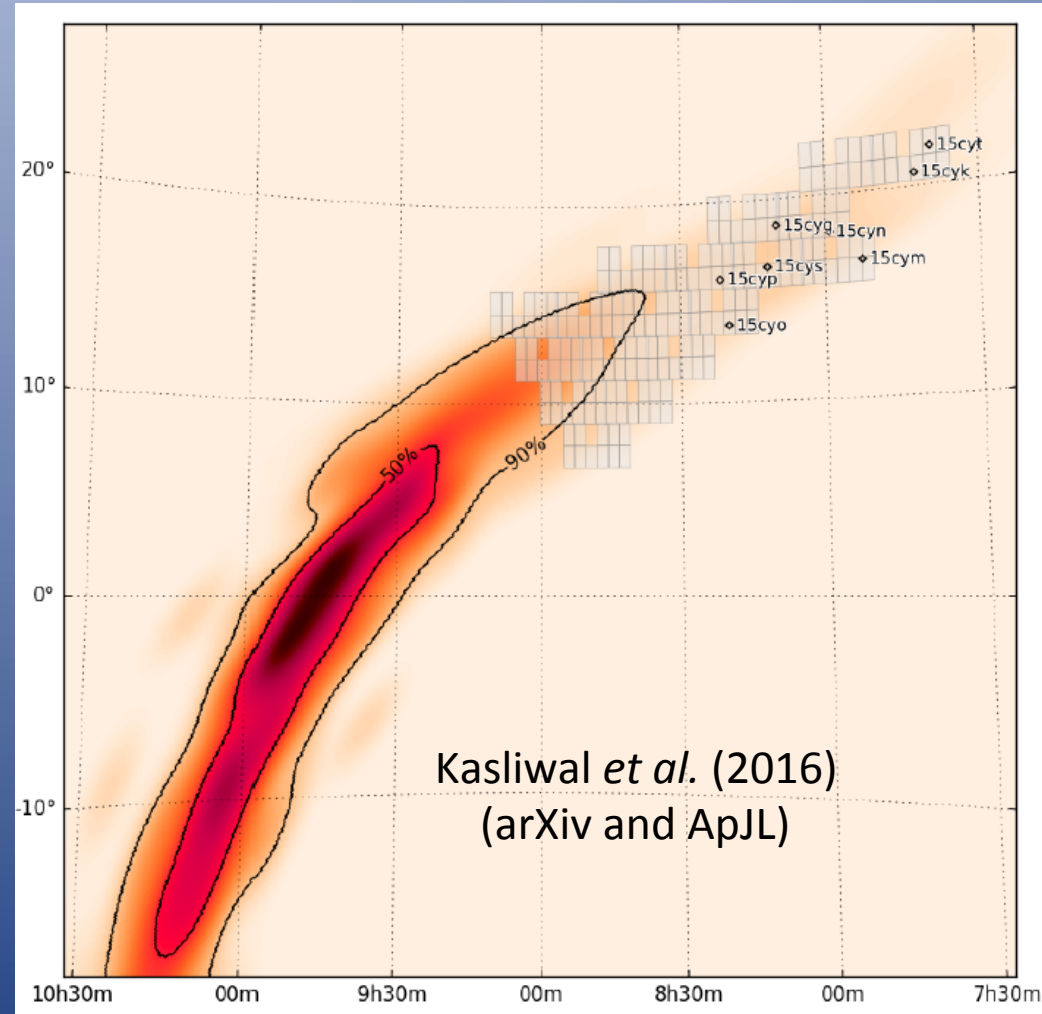
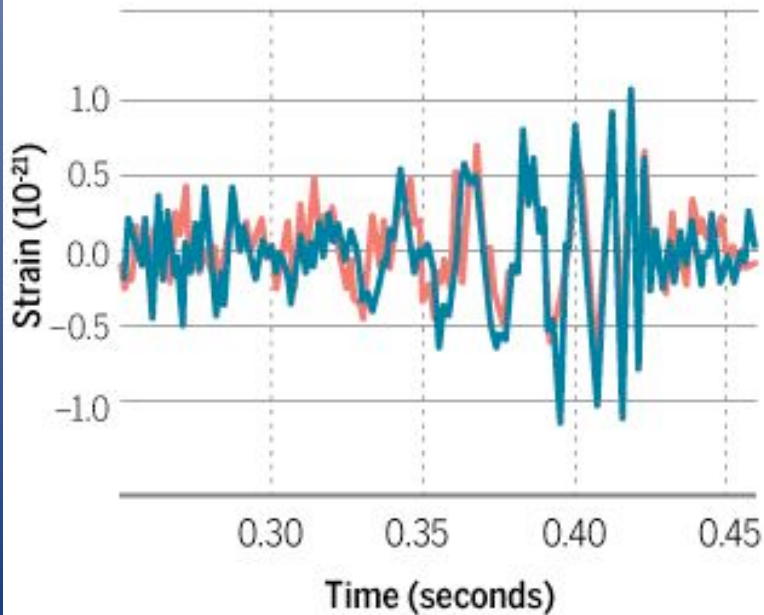
# Gravitational Wave Trigger

## GW150914

### Signals in synchrony

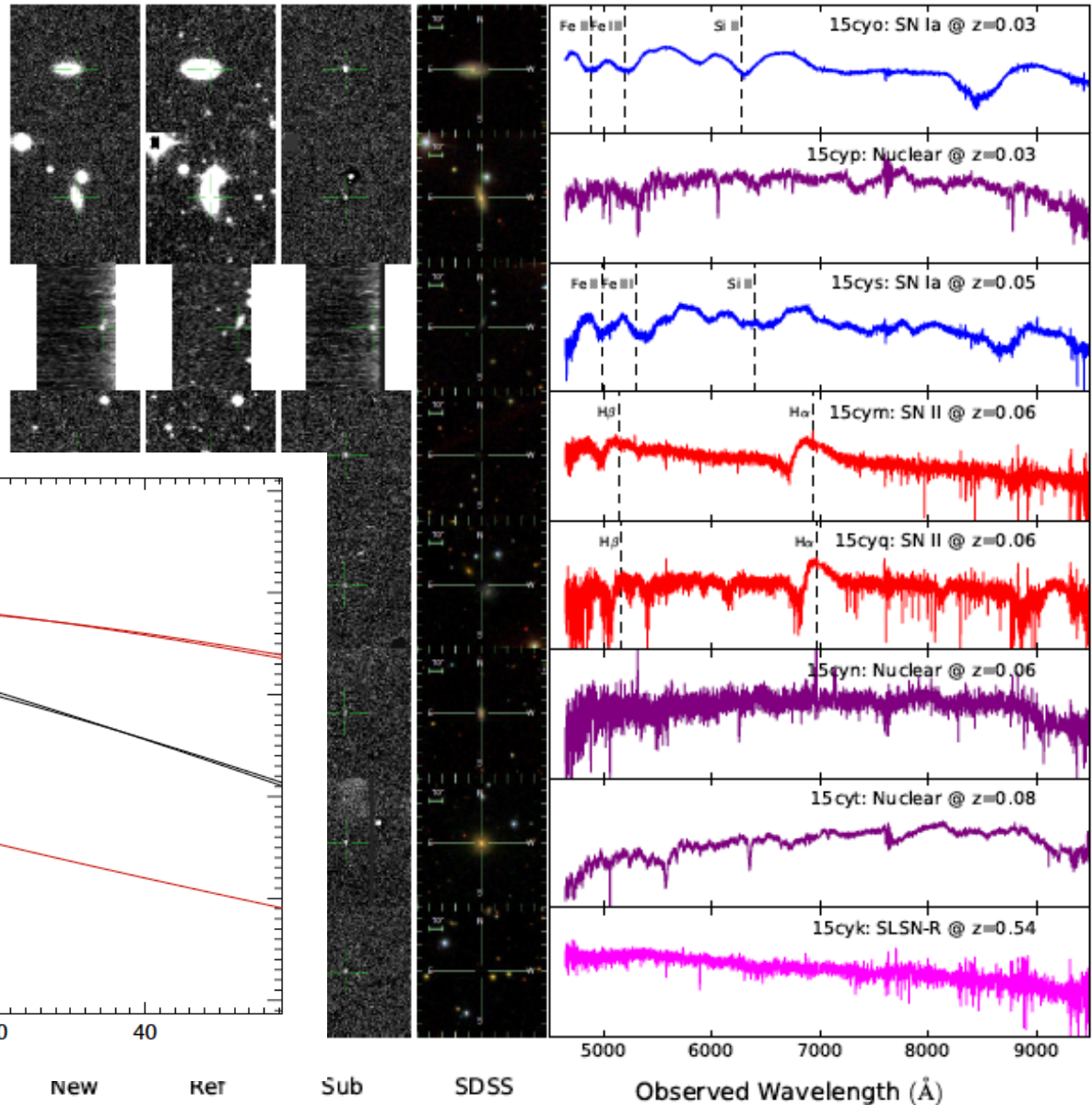
When shifted by 0.007 seconds, the signal from LIGO's observatory in Washington (red) neatly matches the signal from the one in Louisiana (blue).

● LIGO Hanford data (shifted) ● LIGO Livingston data

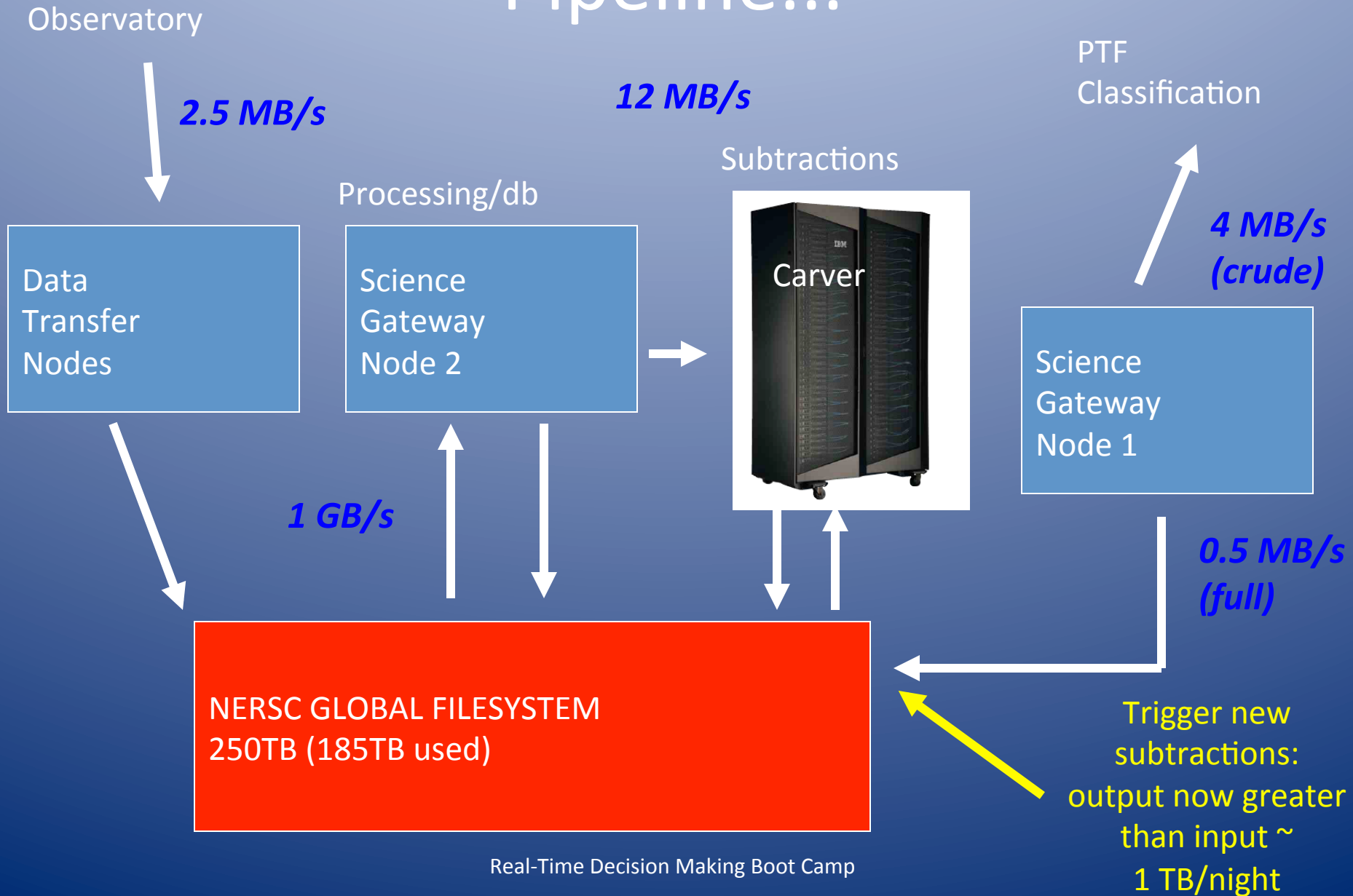


# GW150914

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...





# Zwicky Transient Facility



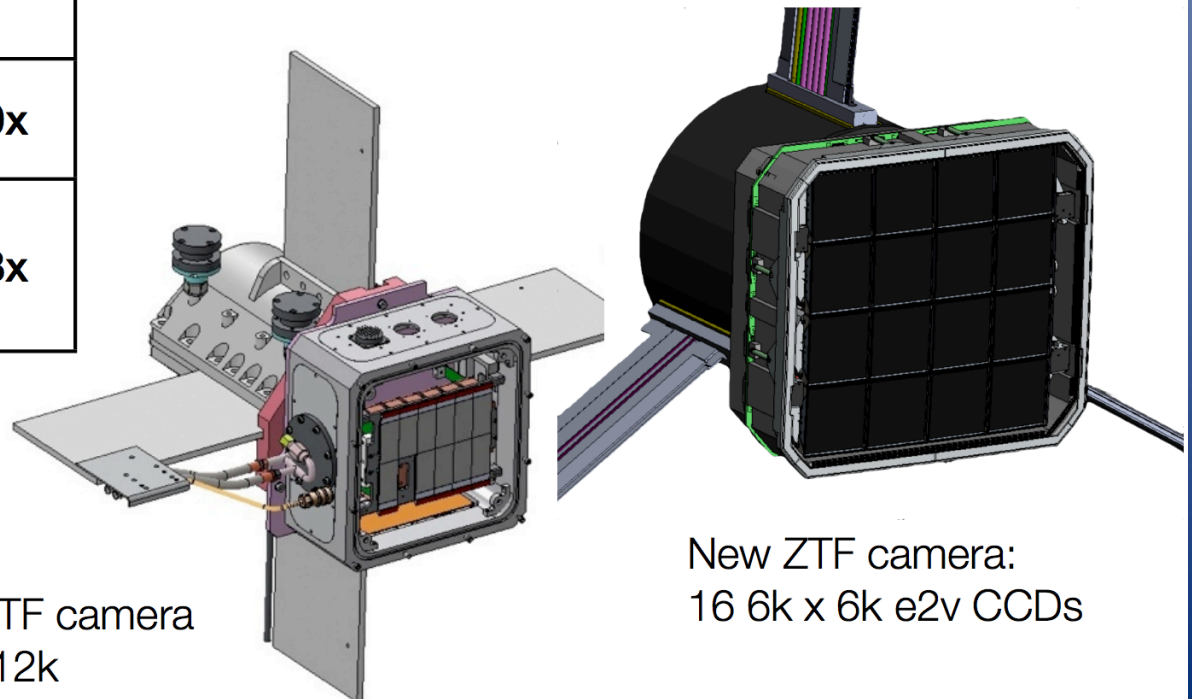
# ZTF will survey an order of magnitude faster than PTF.

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

**3750 deg<sup>2</sup>/hour**

⇒ 3π survey in 8 hours

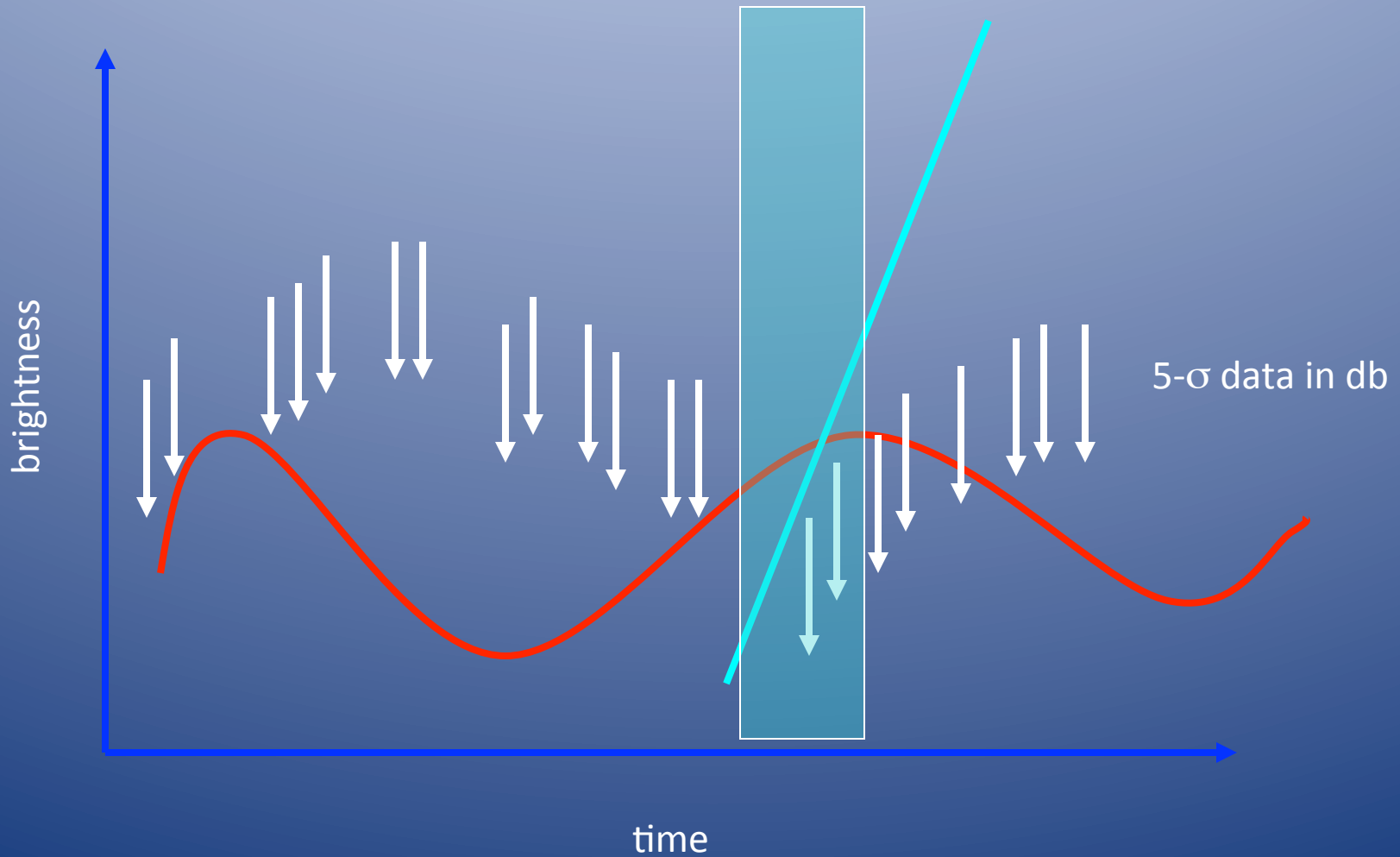
**>250 observations/field/year**  
for uniform survey



Existing PTF camera  
MOSAIC 12k

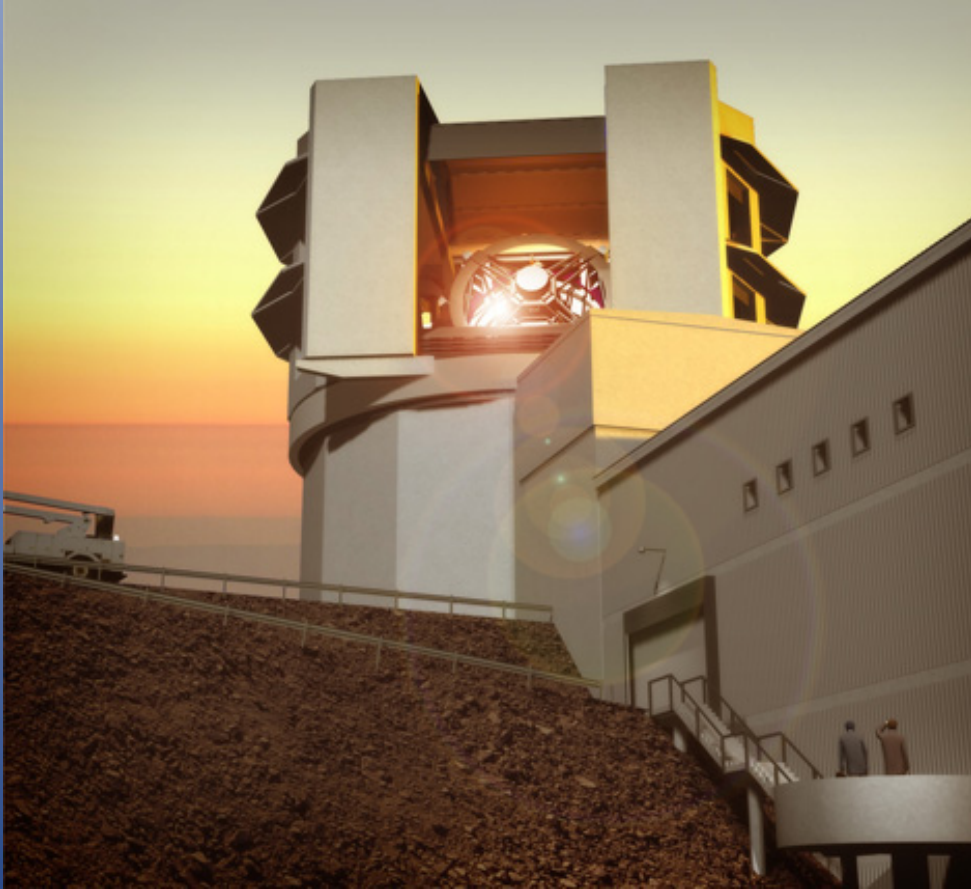
New ZTF camera:  
16 6k x 6k e2v CCDs

# 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...

