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.

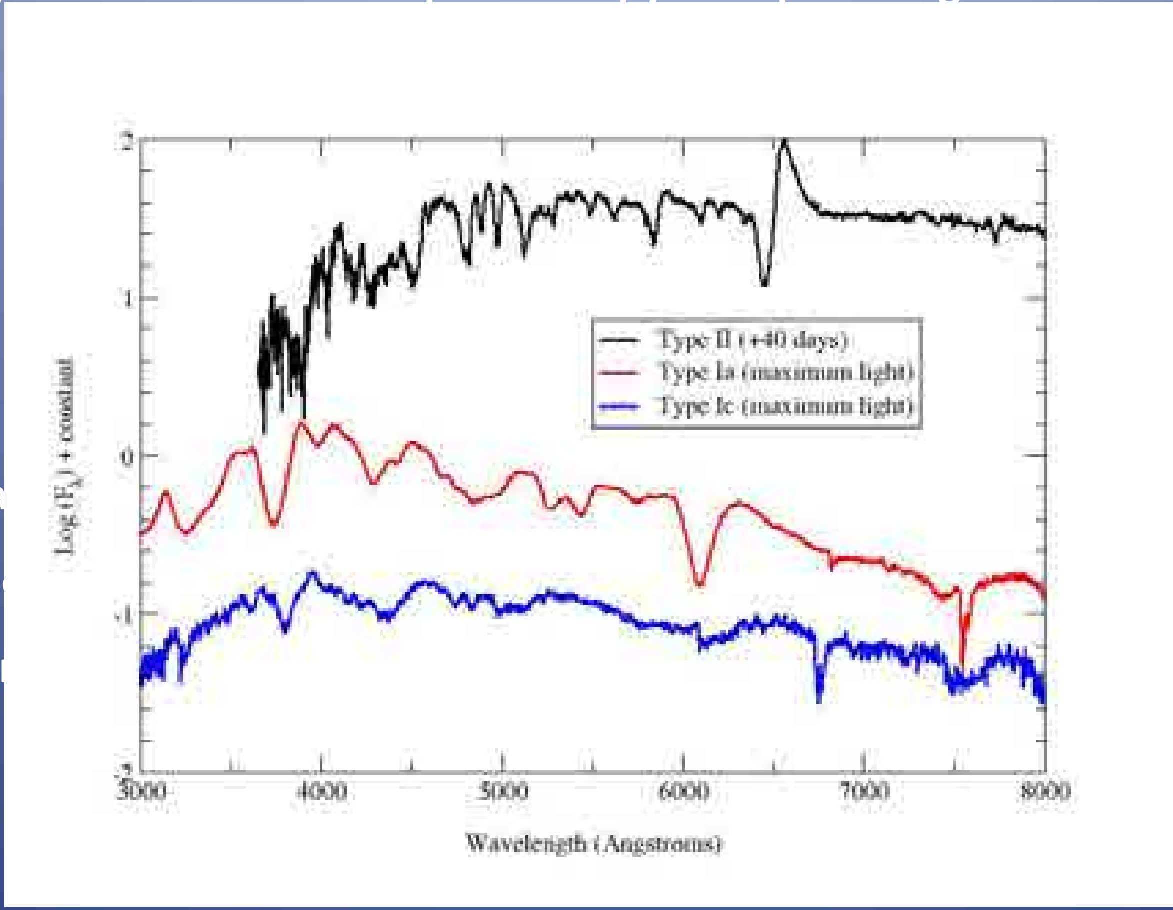
Historically, until 1989, the main goal was an effort to better understand the physics behind these events.

- 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



Type IIP - Pla

Type IIL - Lin

Type IIn - na

S II lines

He I lines

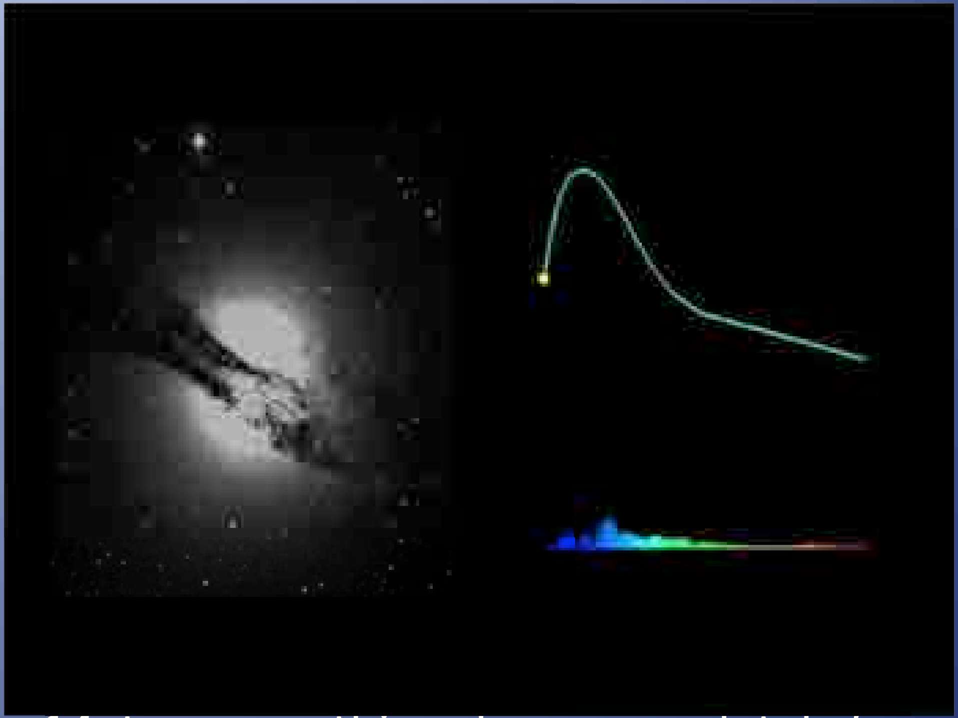
-SNe)

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.



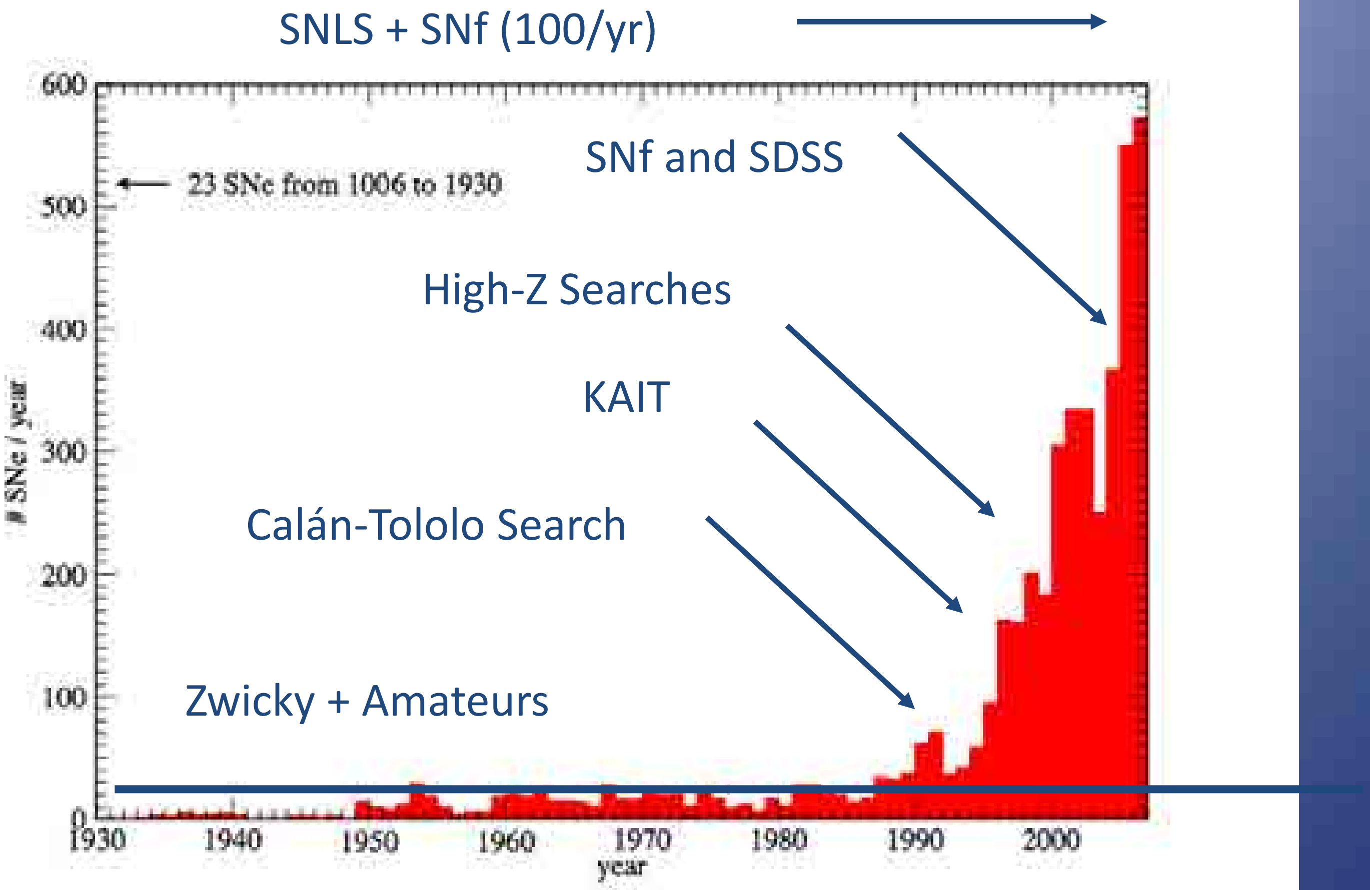
Given that the faintest SNe are around M_V = -14, to survey this volume completely for all types of supernovae one has to conduct a survey of the entire sky every week to an apparent magnitude of 17, what a 0.5-m telescope can do in 30s under an average sky conditions…covering the northern and southern 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…



SN 1987A and 1988U

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

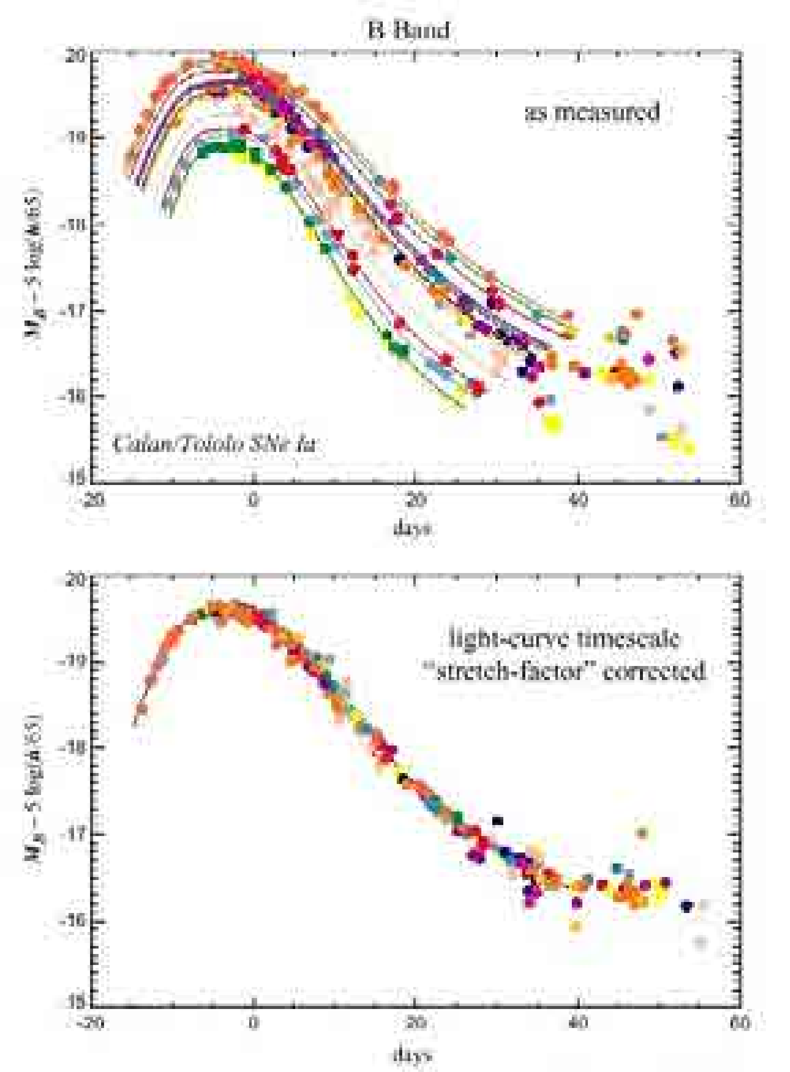
SN 1987A greatly expanded the number of astronomers and physicists studying supernovae. Thus after the hoopla died down on this one, there was a demand for more.

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%!

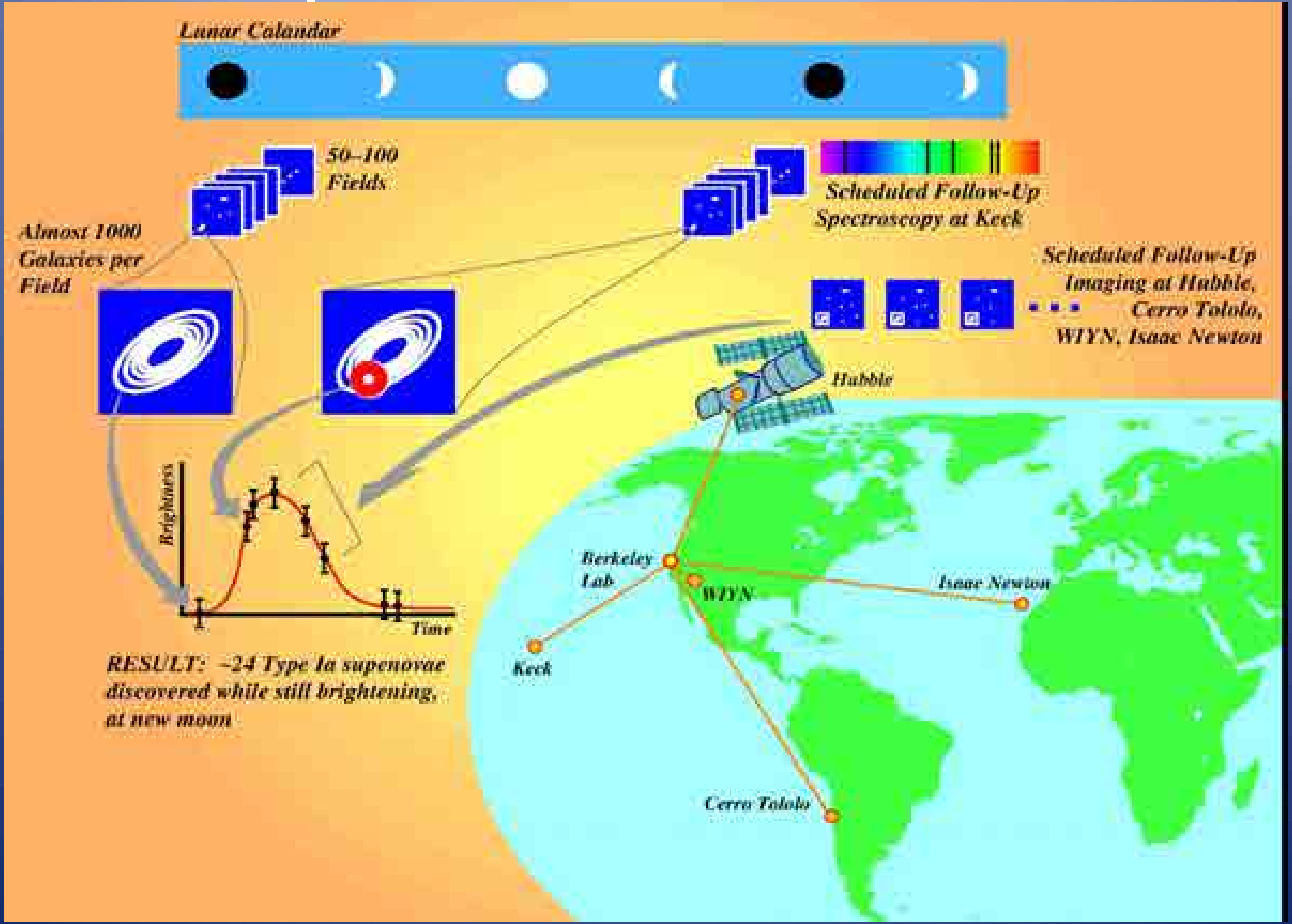
Well gee… given how bright they are and how well I can measure distances to them. “Please TAC of telescope X, give me ungodly amounts of time to measure the cosmological parameters from supernovae.” And it was done… triggering searches at both high and low redshift.



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

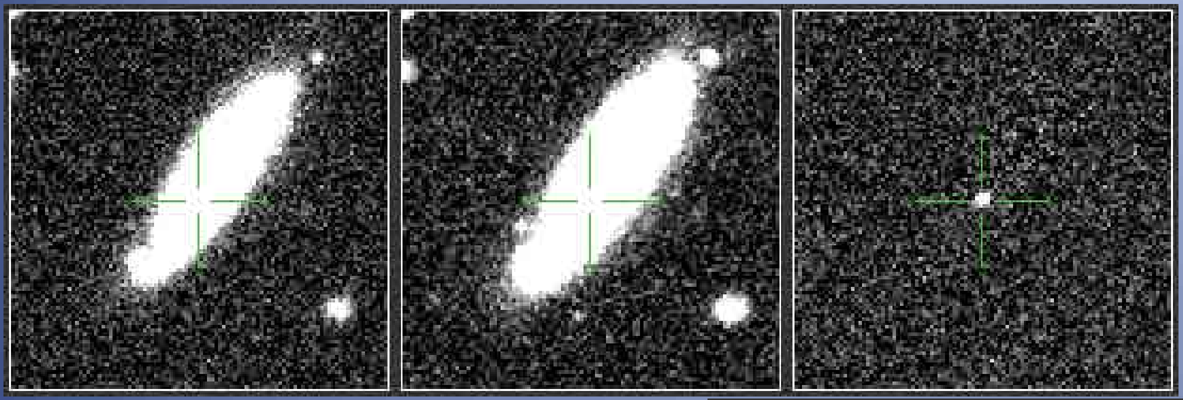


Supernovae circa 1998

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

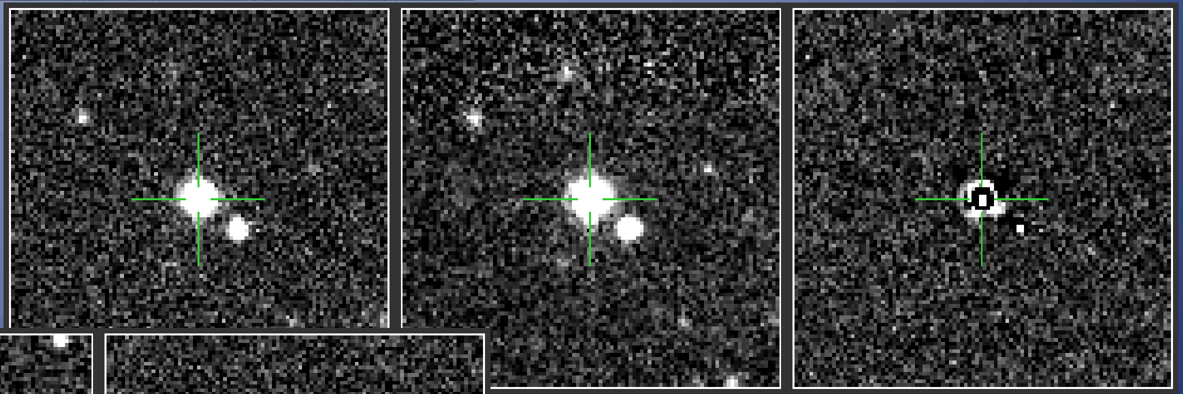
We could transfer all the data up on a 56k-baud connection during the night and it would be subtracted within a few hours of dawn – when the connection was good. Often the astronomer would make it back to Berkeley with the tapes before all the data was in...

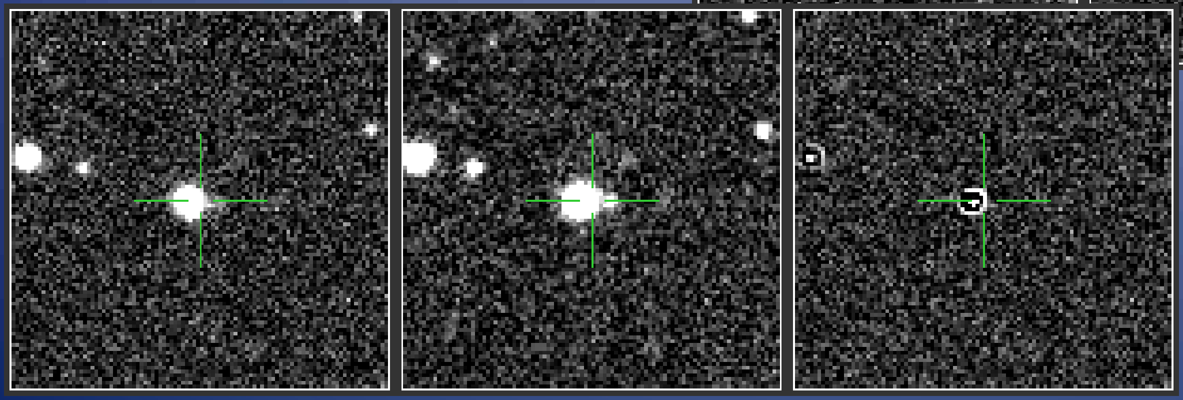
Supernovae circa 1998



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

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



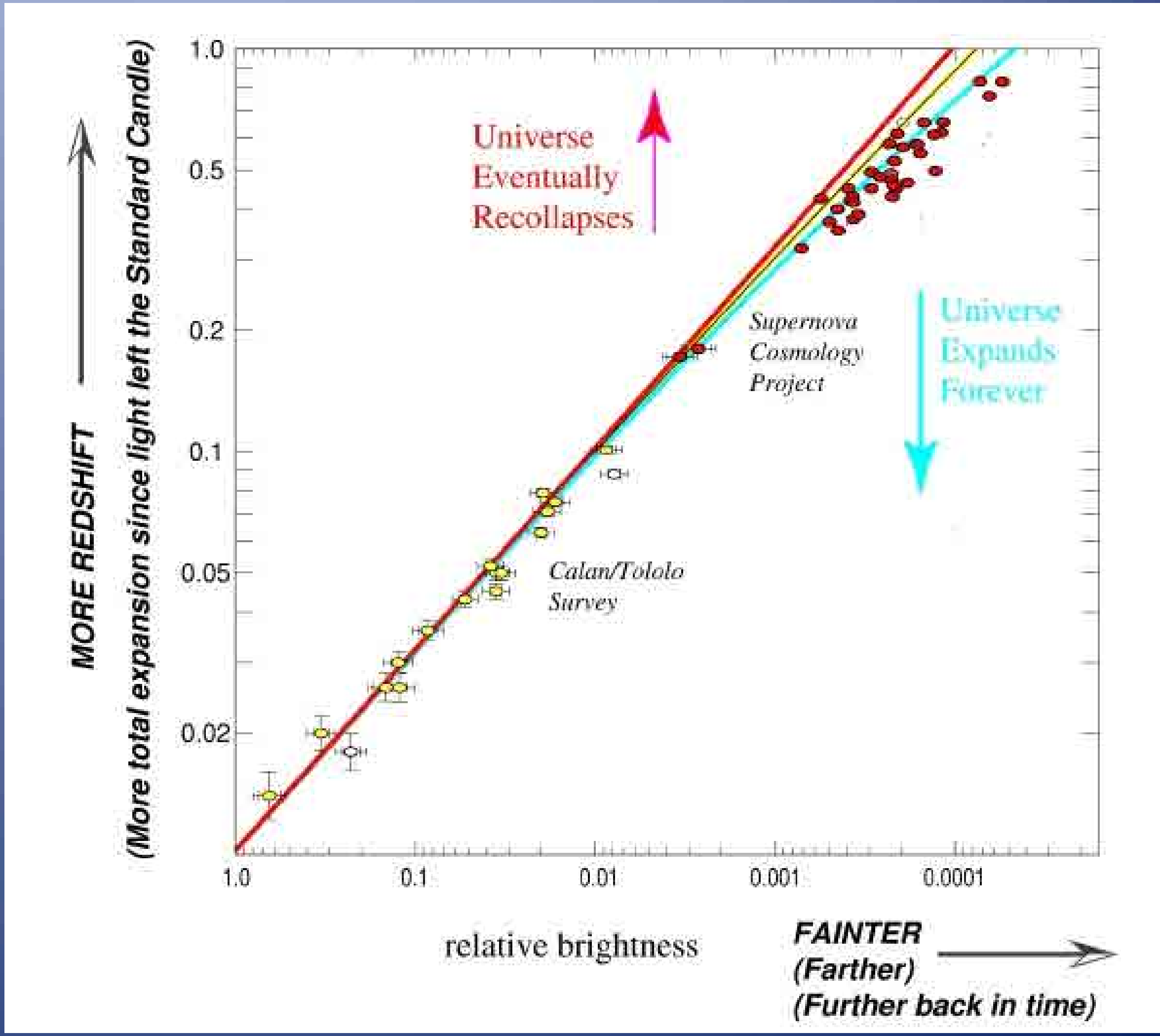


Cuts were made based on shape, motion, etc., and a scanner would have to look at ~5 candidates per image.

Supernovae circa 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.

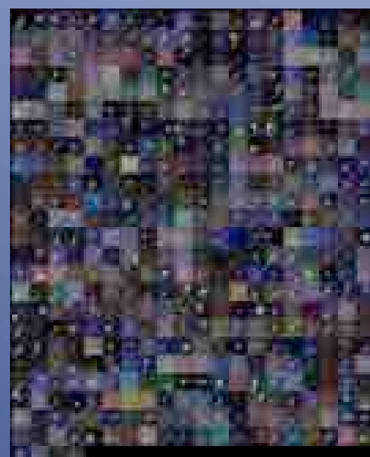


SN Searches 2000+

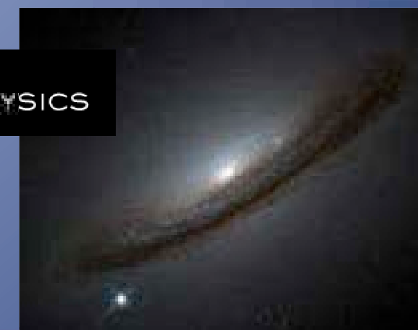
SNLS SuperNova Legacy Survey

adidas

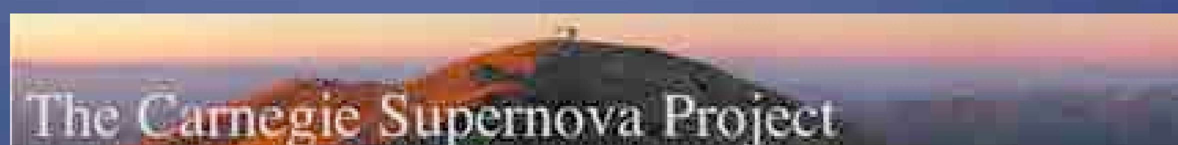
SHOES – Supernova for H0 and the Equation of State



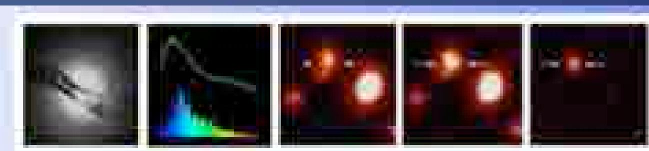
Harvard-Smithsonian Center for Astrophysics



Sloan Digital Sky Survey
Mapping the Universe

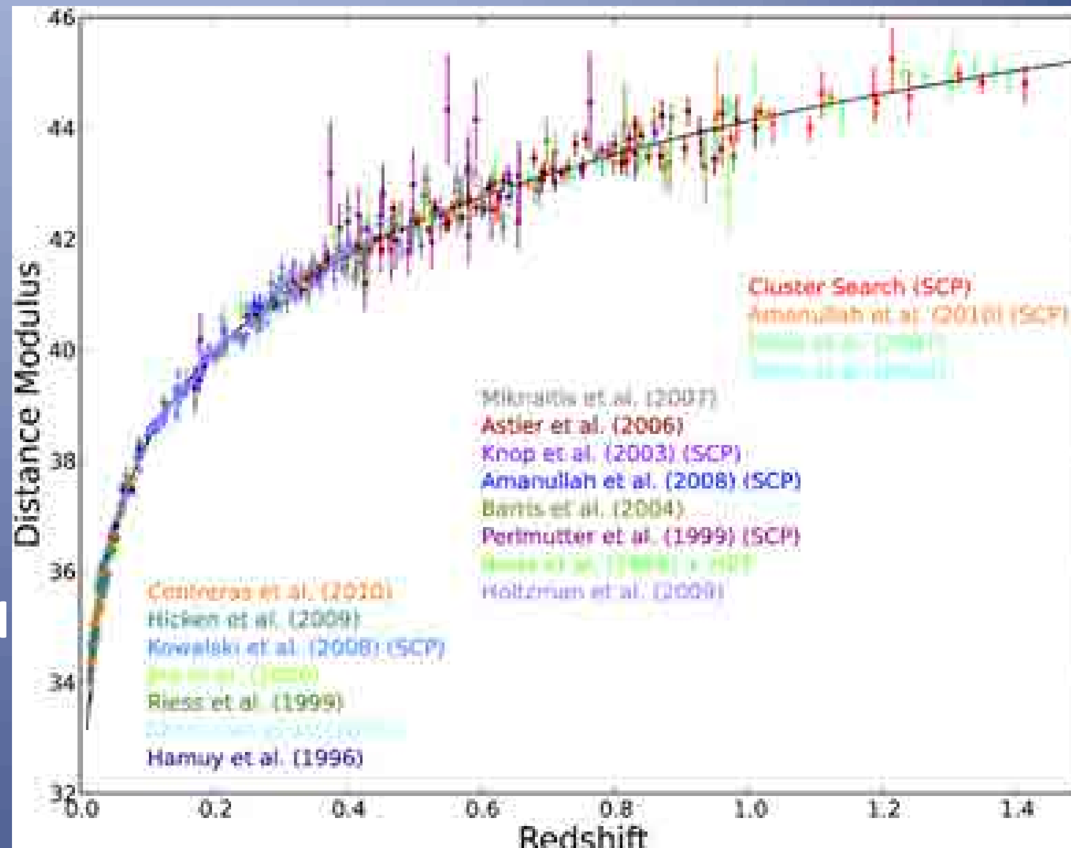


SCP Supernova Cosmology Project



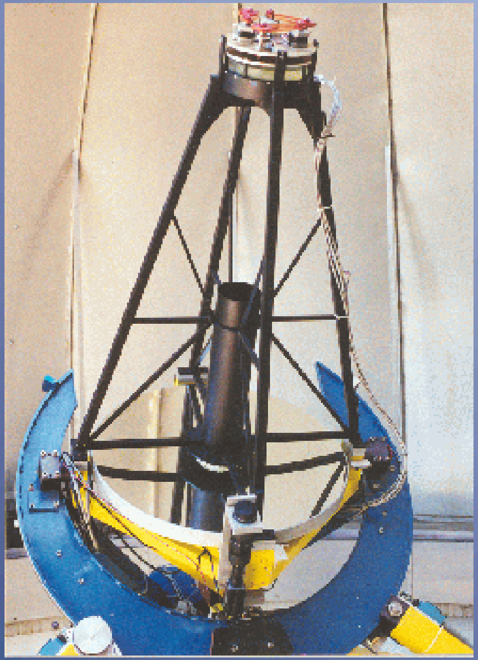
Today’s Hubble Diagram

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.



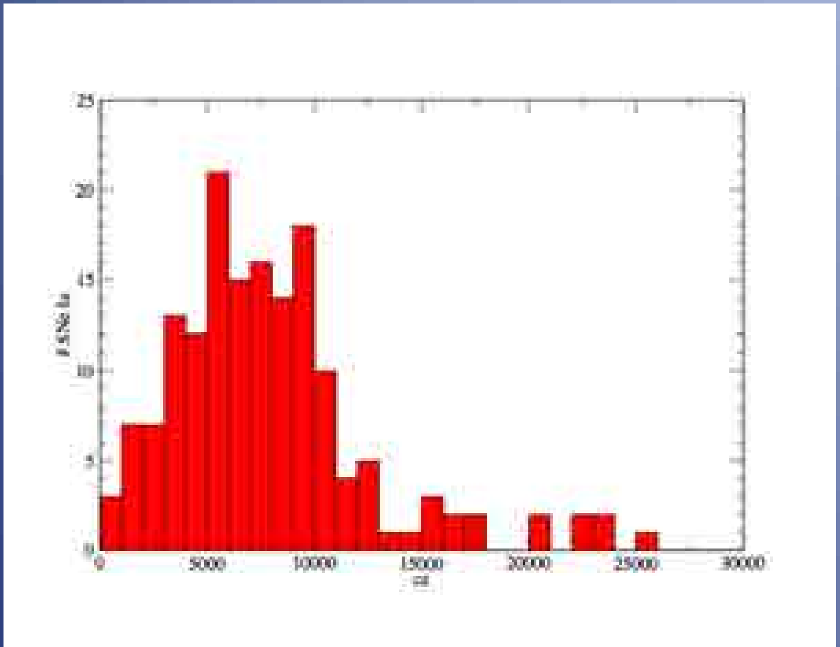
There is a strong desire to improve the low-redshift sample, as well as the high-redshift one, in order to reduce systematics which dominate these Hubble diagrams. Also, some folks are interested in *other* types of supernovae....

KAIT



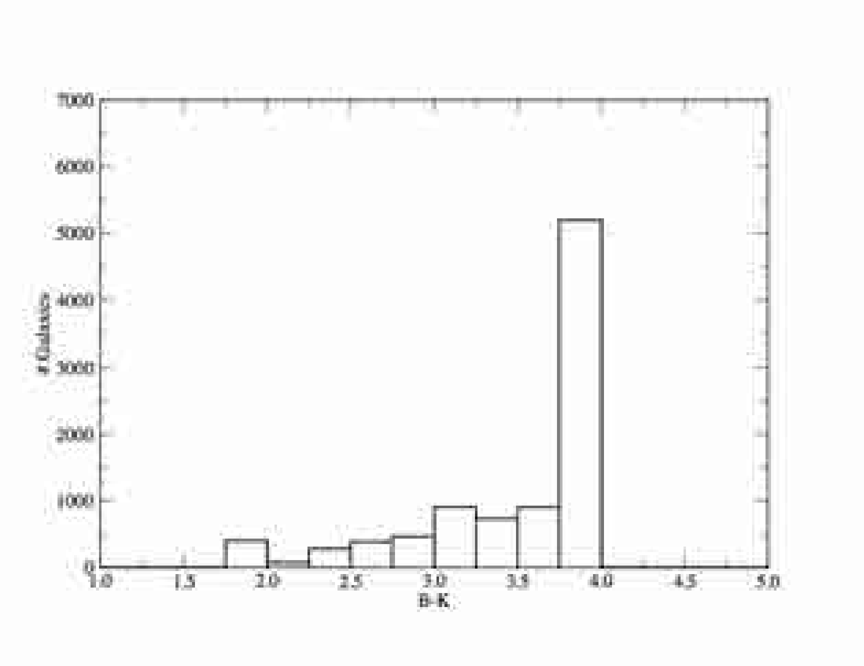
KAIT sits atop Mt. Hamilton, just above the city of San Jose. It is a fully roboticized telescope, with a limiting magnitude of 19 and keeps a cadence of 1 to 5 days on a list of 500 galaxies/night. Many of the SNe Ia from Hicken et al (2009) and Contreras et al. (2010) came from this survey.

KAIT/IAUC Biases

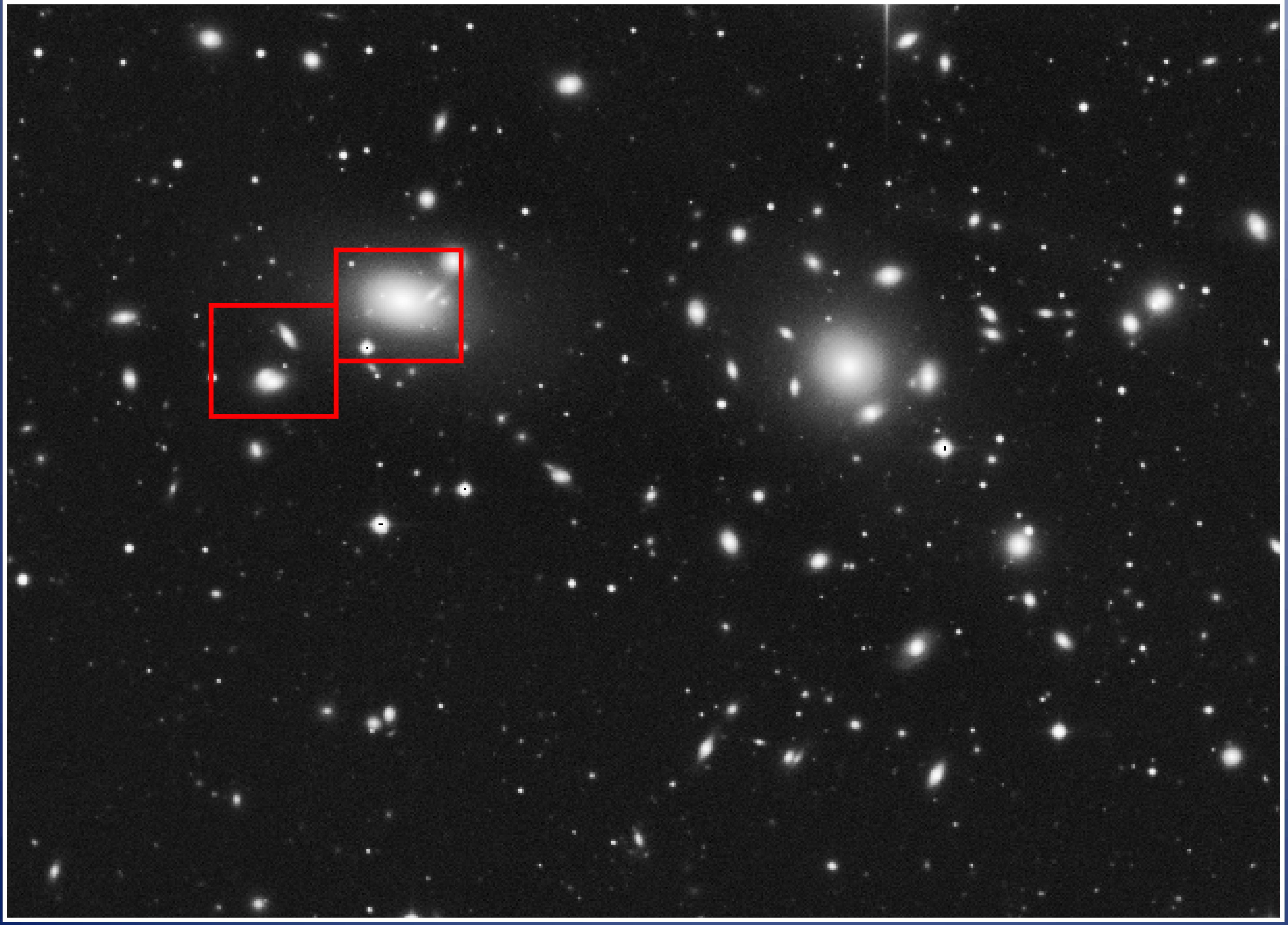


More than half the SNe Ia will suffer from uncertainties due to peculiar velocity errors which are at or above current systematic limits.

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.



KAIT/IAUC Biases



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

Supernovae circa 2000

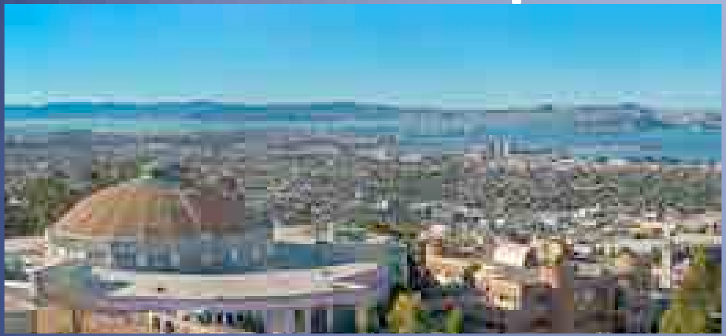
Pain begins.....

NEAT Search Facilities

Site:	Haleakala	Palomar I	[illegible]
Aperture:	1.2m	1.2[illegible]	[illegible]m
Nights/Month:	18 dark/gray	1[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 (2009-2012)
(& now iPTF from 2013 to2016)

- 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.

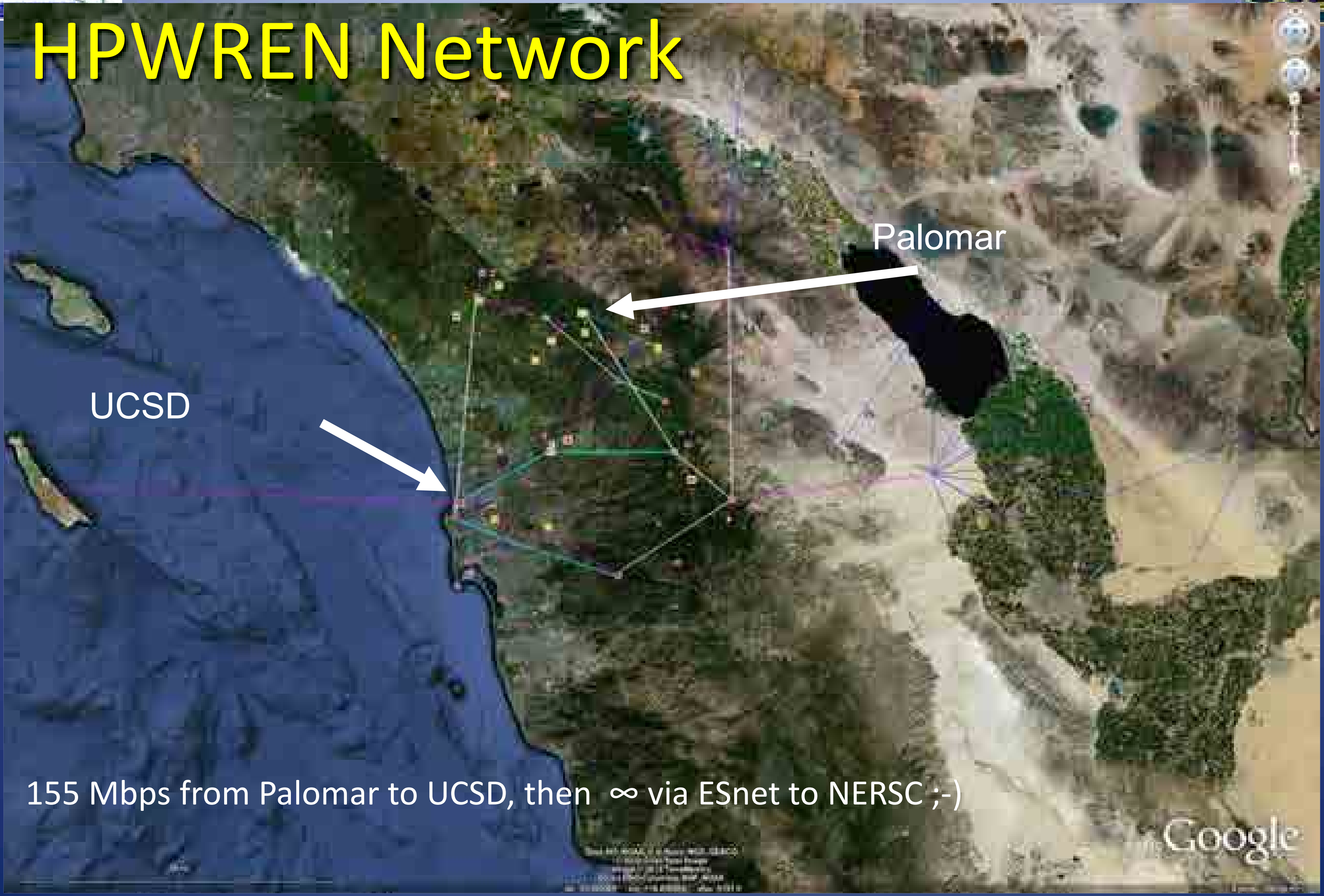
- 2 Cadences (Mar. - Nov.) 2009-2011
  - Nightly (35% of time) on nearby galaxies and clusters (g/r)
  - Every 3 nights (65% of time) on SDSS fields with minimum coverage of 2500 sq deg. (r) to 20th mag 10-sigma
  - H-alpha during bright time (full +/-2 days)

Nov-Feb, minute cadences on select fields.

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

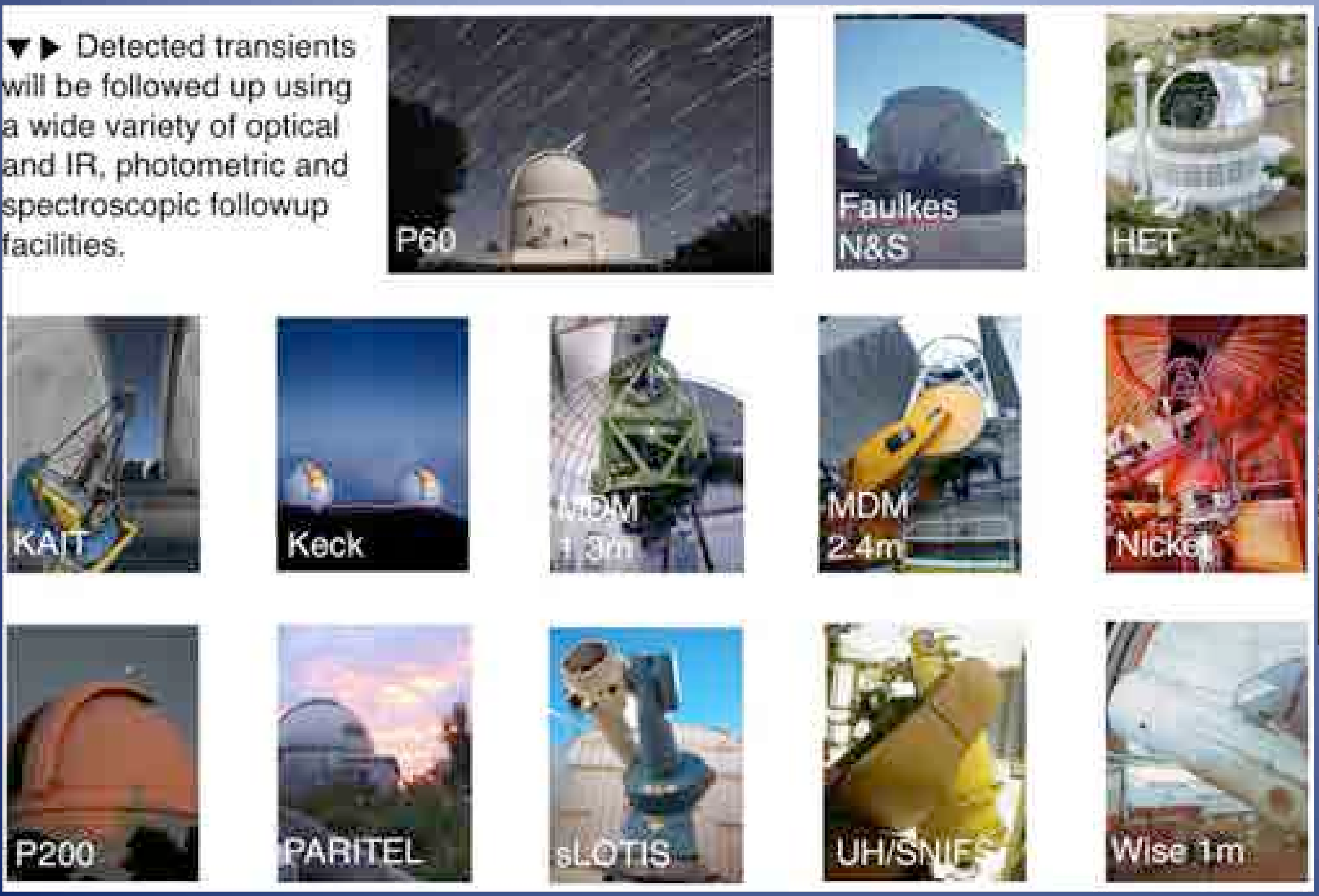
92 Mpixels, 1” resolution, R=21 in 60s

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.

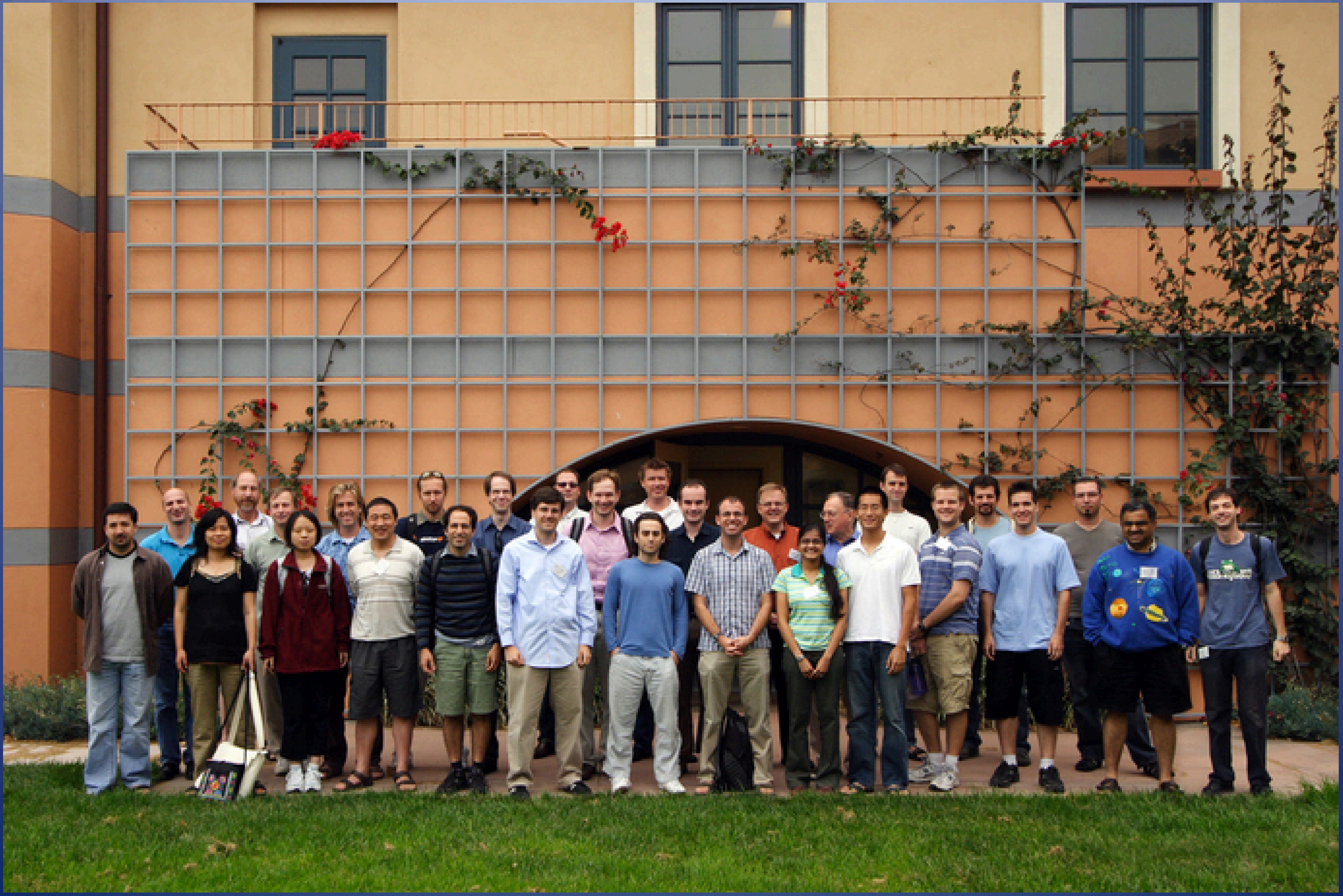
PTF Science



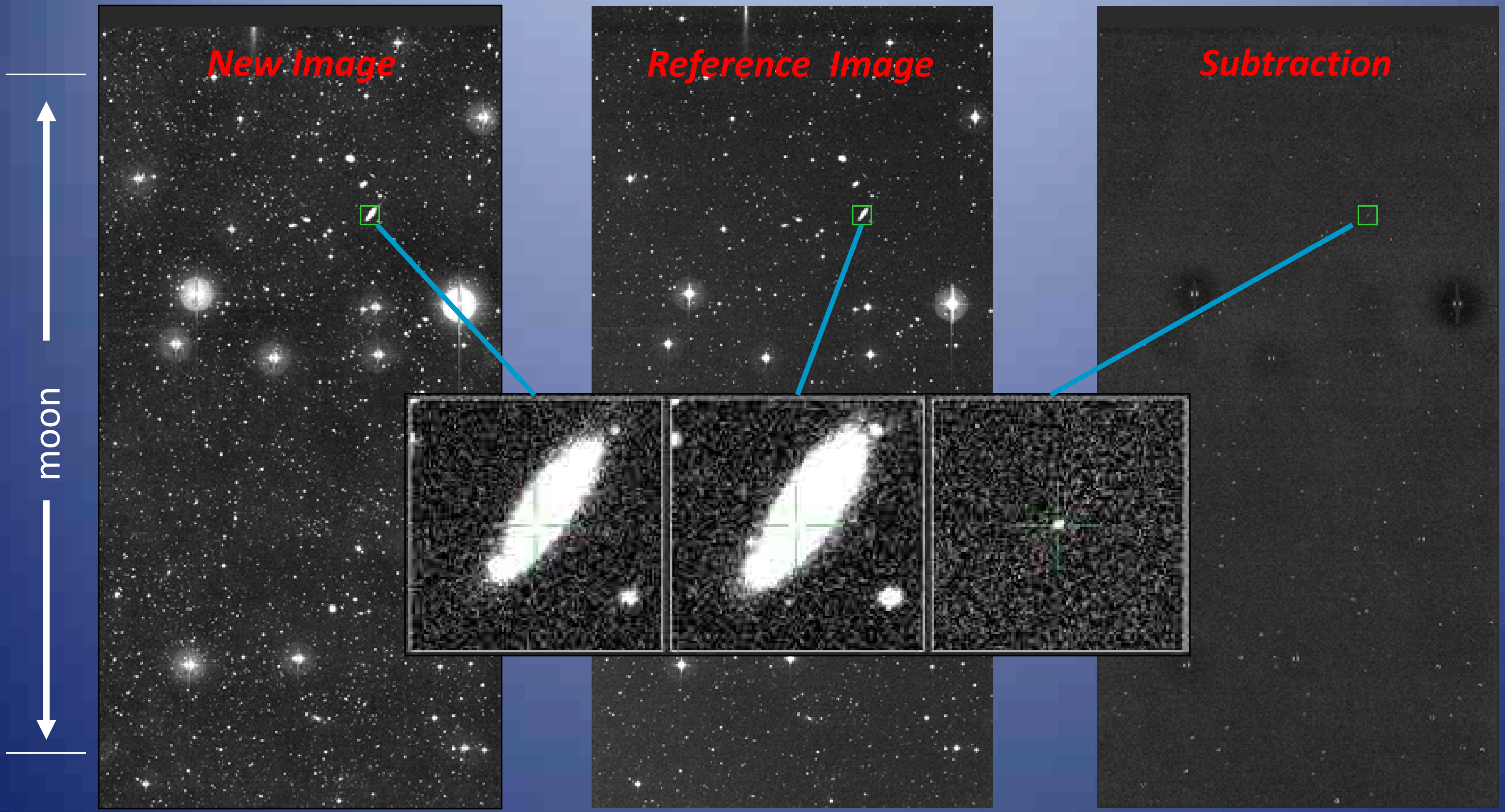
Liverpool Telescope

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

PTF Team ~ 2010



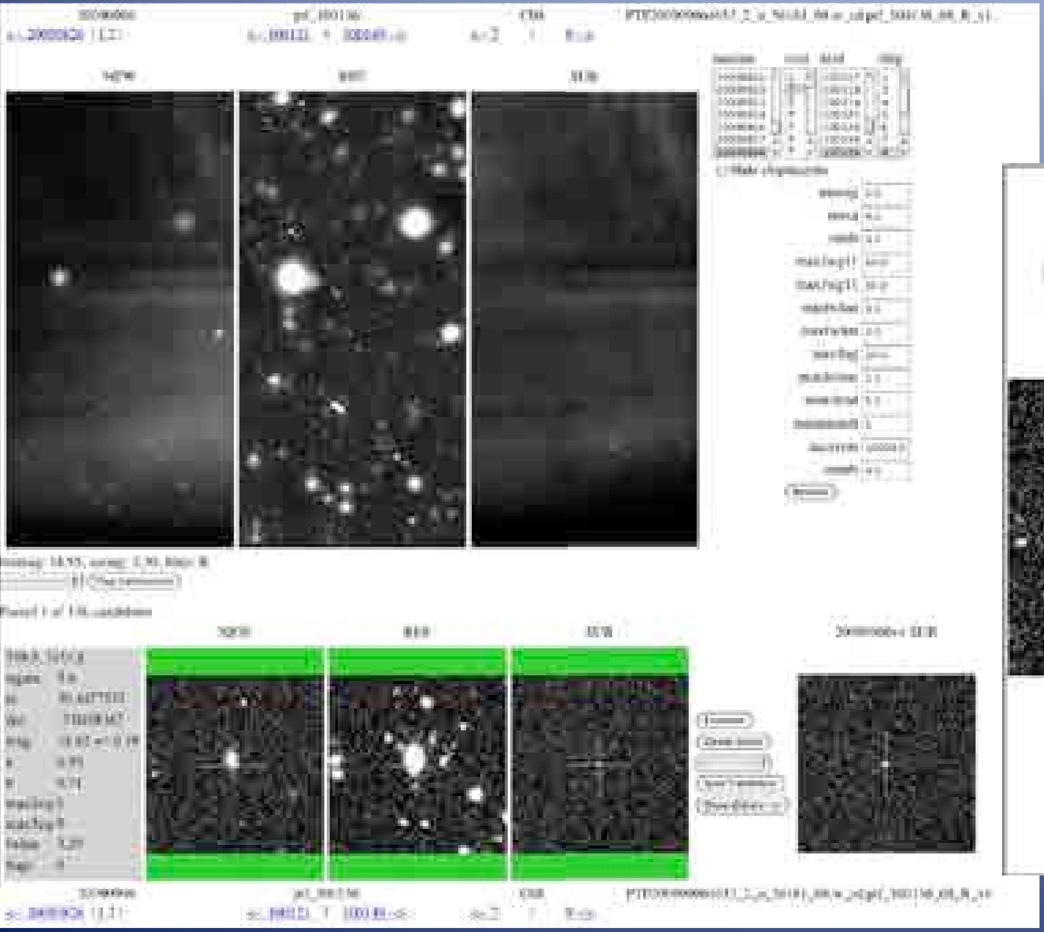
Real or Bogus – Machine Learning Analysis

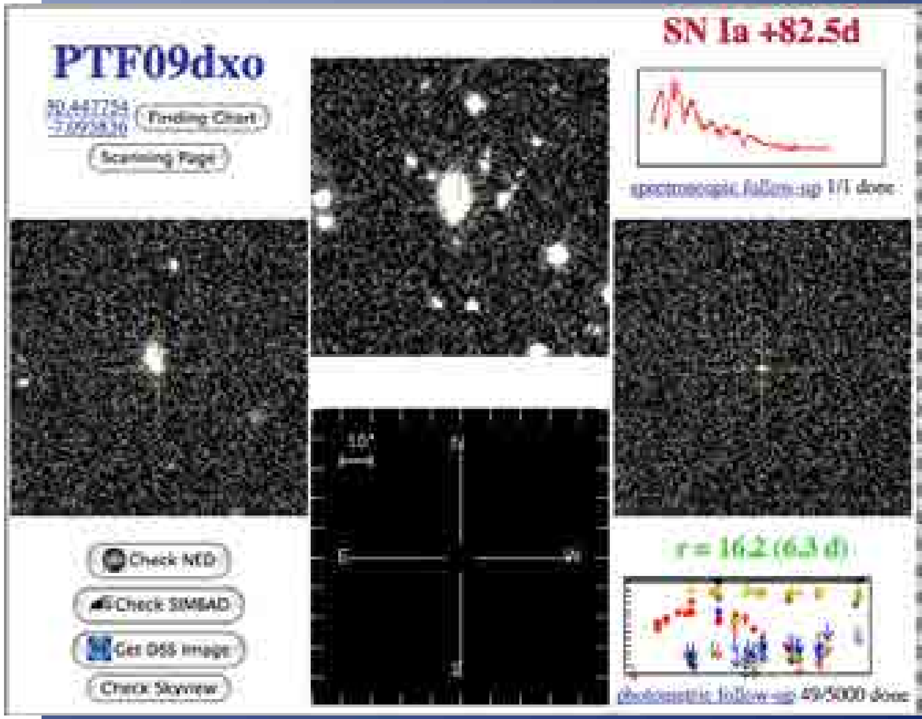


4096 X 2048 CCD images - over 3000 per night – producing 1.5M bogus detections, 50k known astrophysical objects and only 1-2 new astrophysical transients of interest every night. Machine learning is used to wade through this sea of garbage.

User Interface

January – March, 2009.



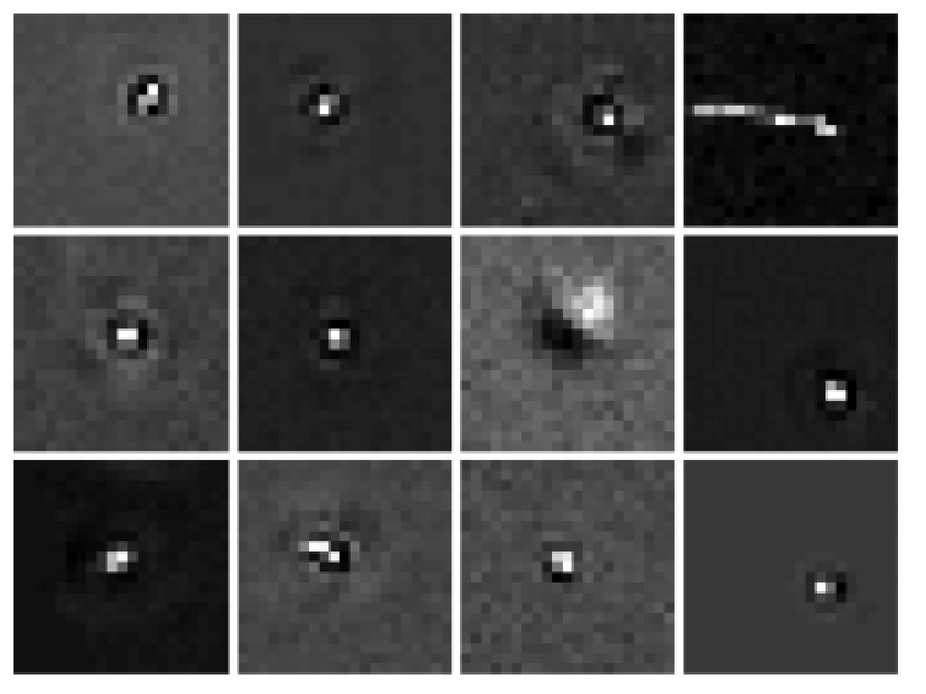


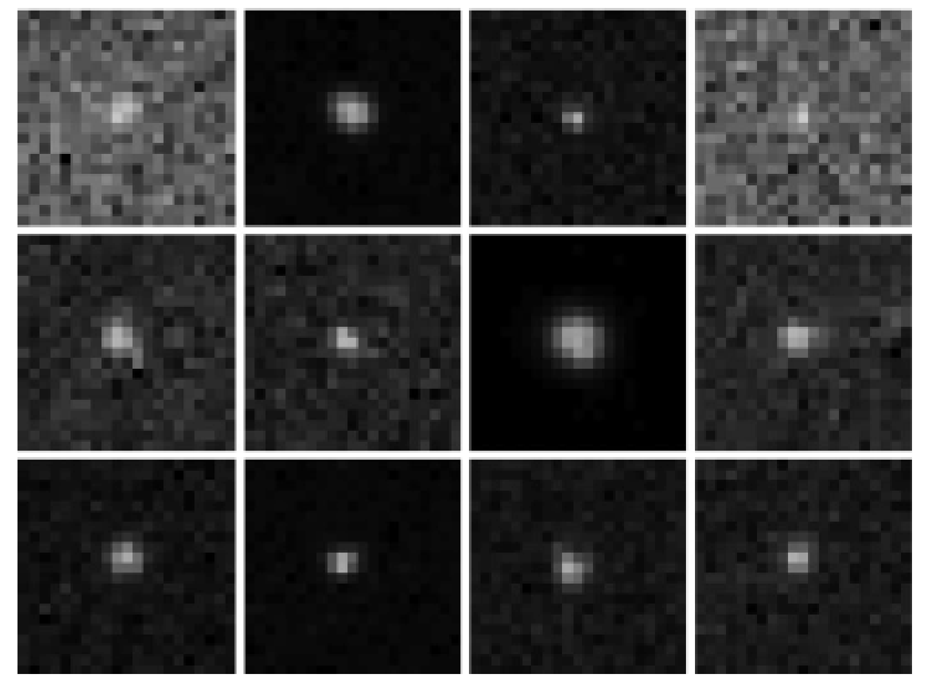
ML for determining if Real or Artifact

Using machine learning for discovery in synoptic survey imaging data

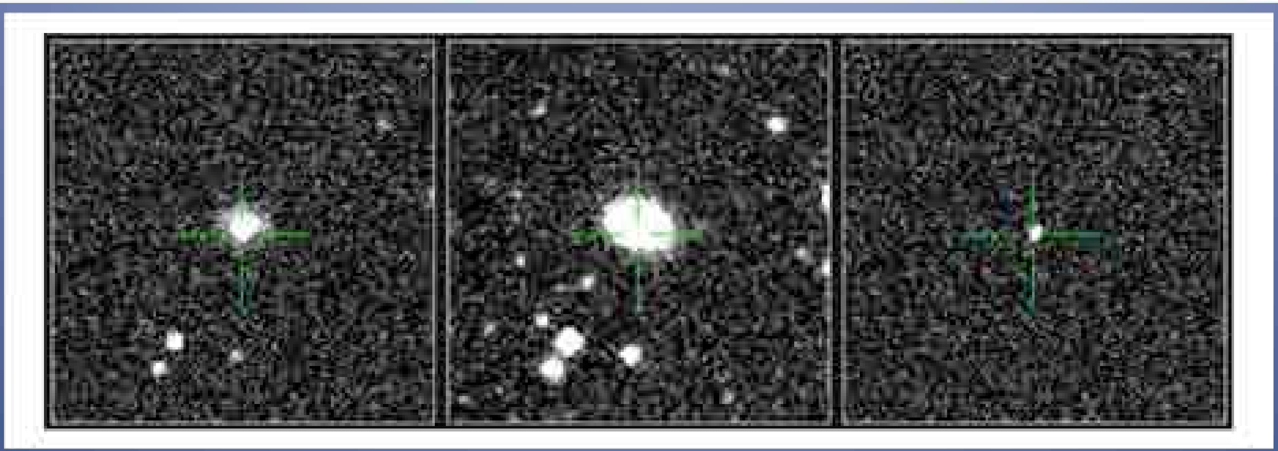
Henrik Brink,[1★] Joseph W. Richards,[1,2] Dovi Poznanski,[3] Joshua S. Bloom,[1]
John Rice,[2] Sahand Negahban[4] and Martin Wainwright[2,4]

MNRAS 435, 1047–1060 (2013)



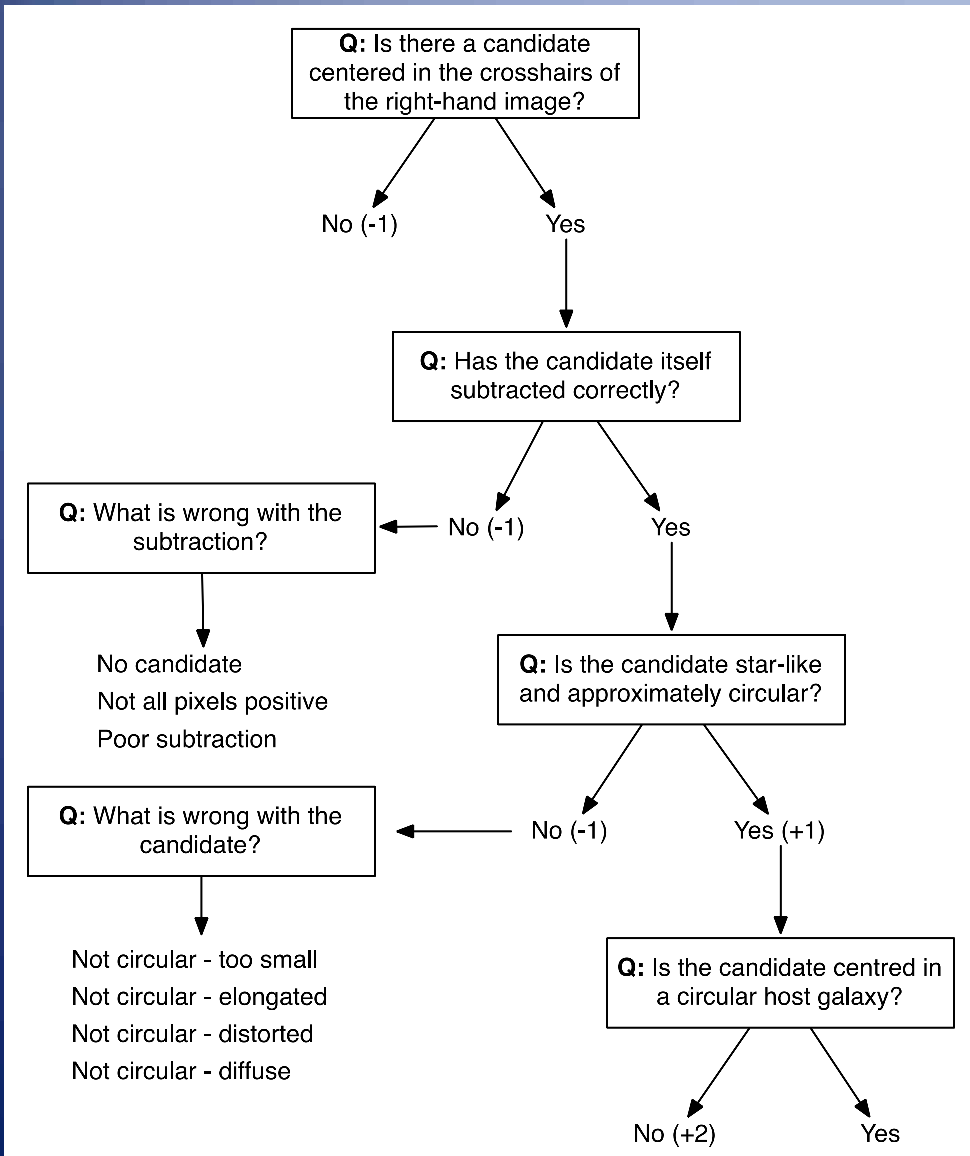


Citizen Scientists



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

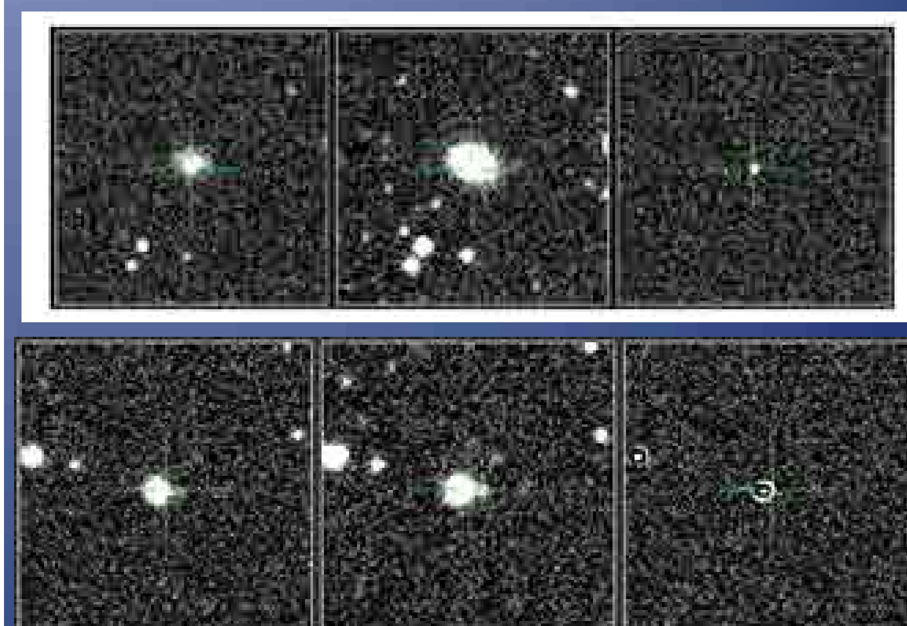
Citizen Scientists



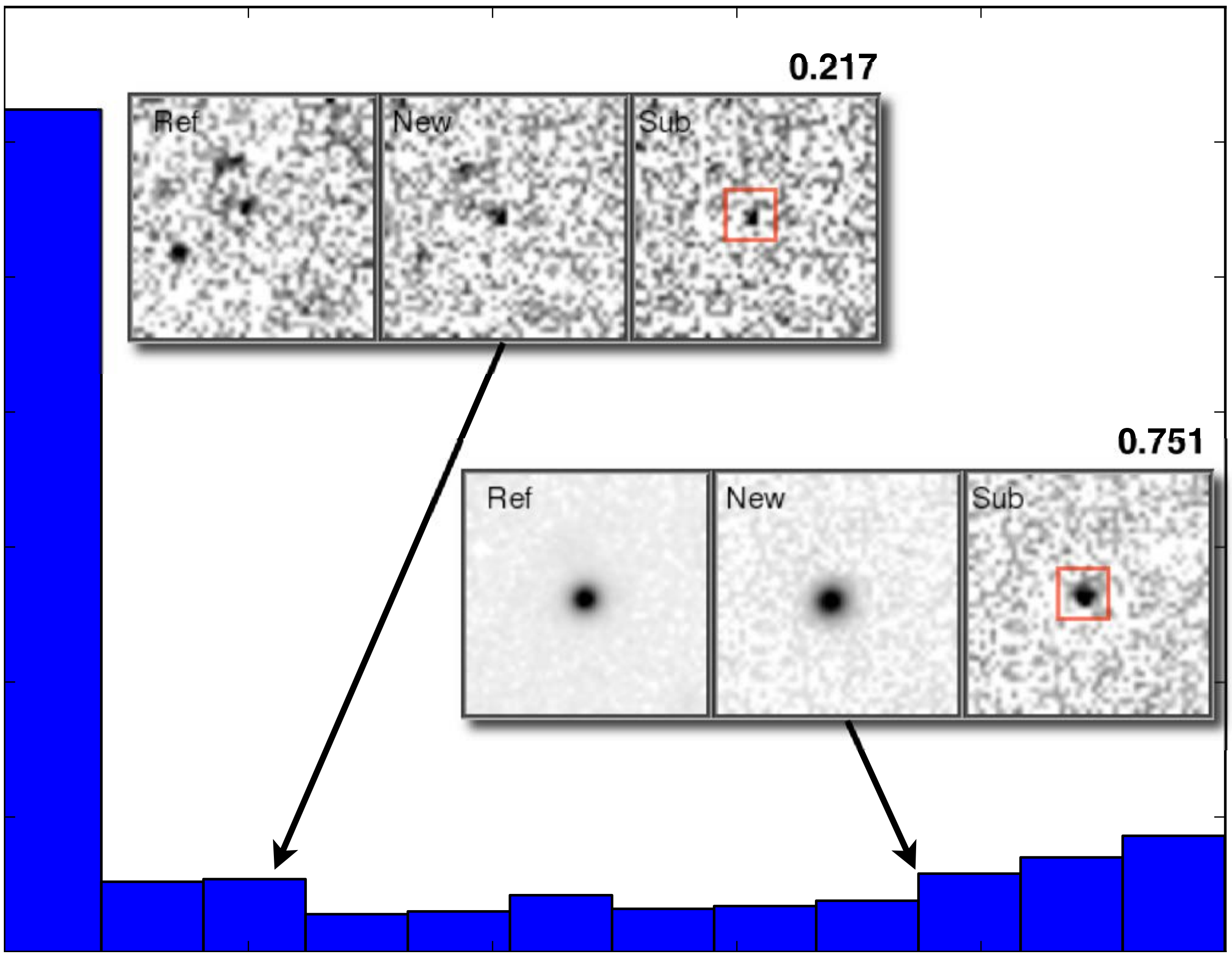
Galaxy Zoo Supernovae*

A. M. Smith,[1]† S. Lynn,[1] M. Sullivan,[1]† C. J. Lintott,[1] P. E. Nugent,[2] J. Botyanszki,[2]

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

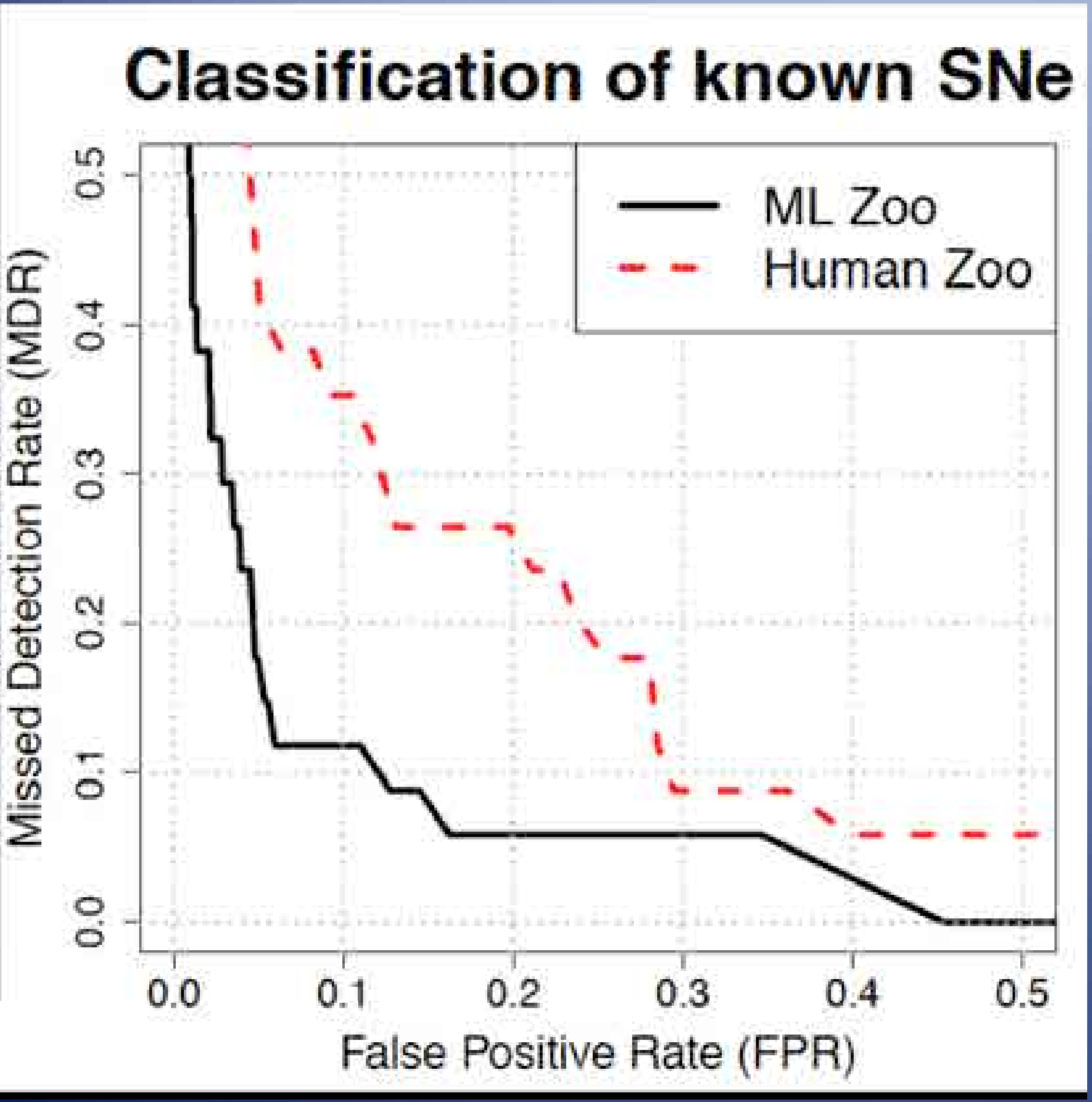


RB2



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.

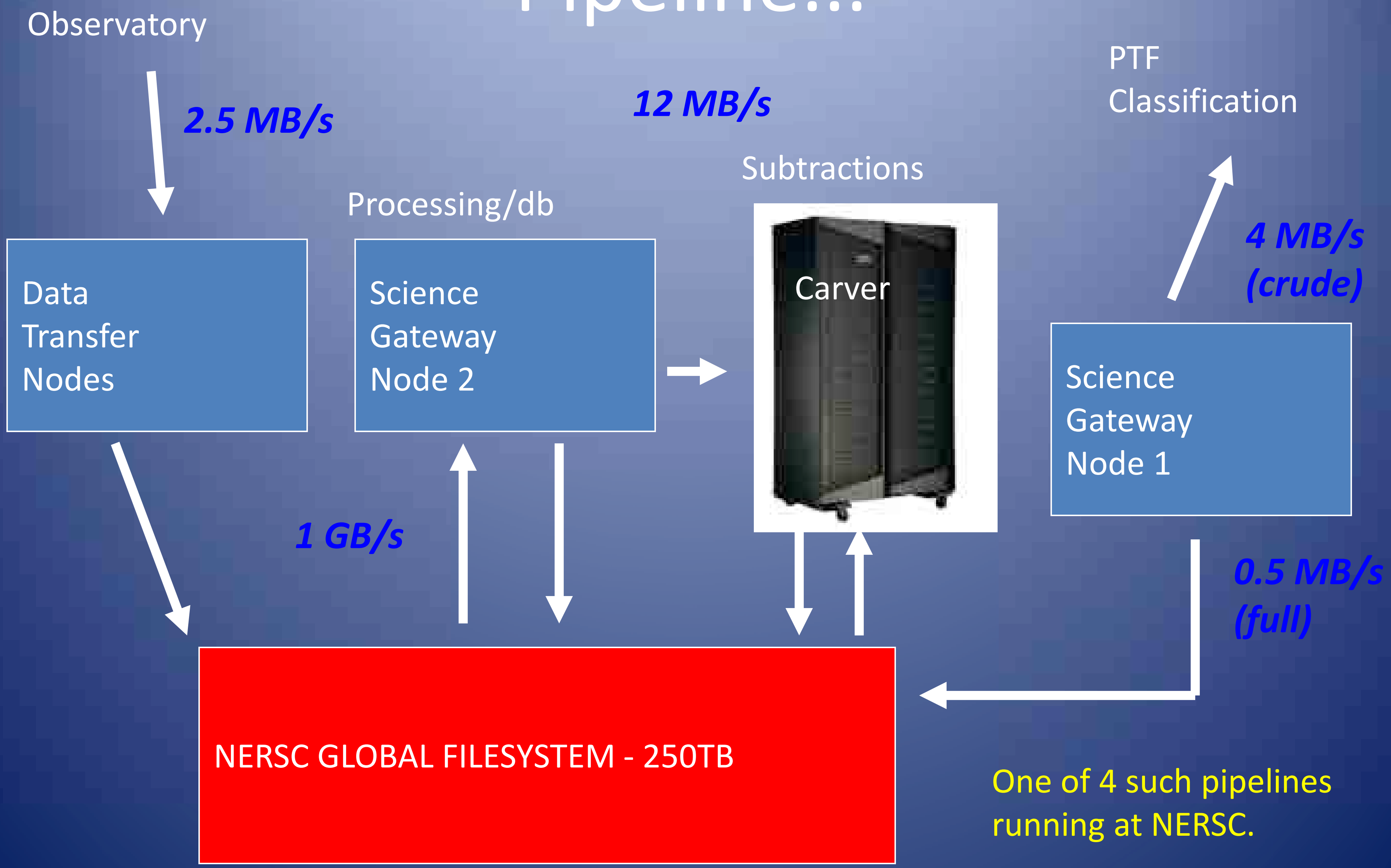
While a great way to start our project, and an excellent form of public outreach, it was no longer necessary.

PTF Database

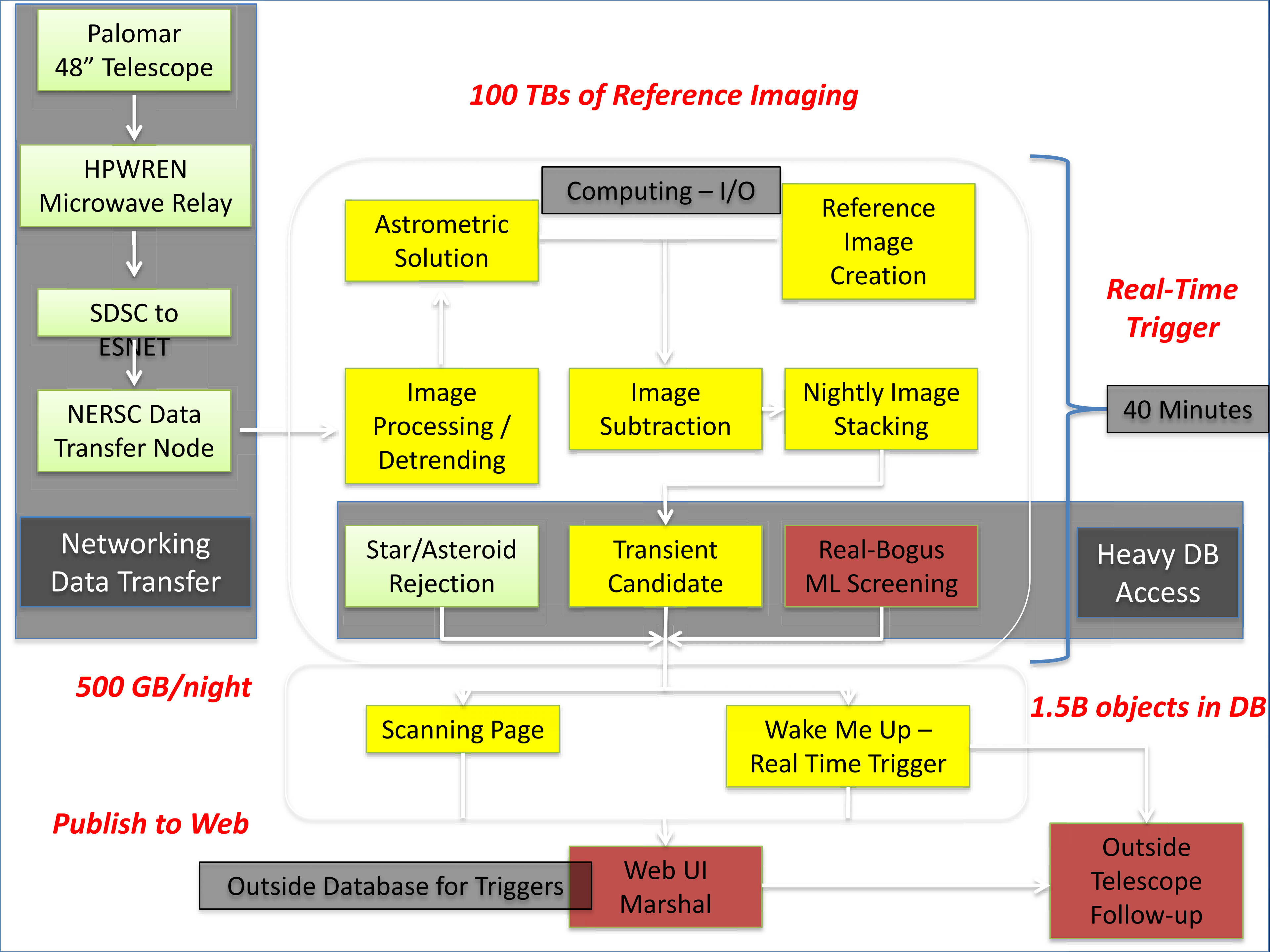
	R-band	g-band
images	1.82M	305k
subtractions	1.52M	146k
references	29.2k	6.3k
Candidates	890M	197M
Transients	42945	3120

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

Pipeline…

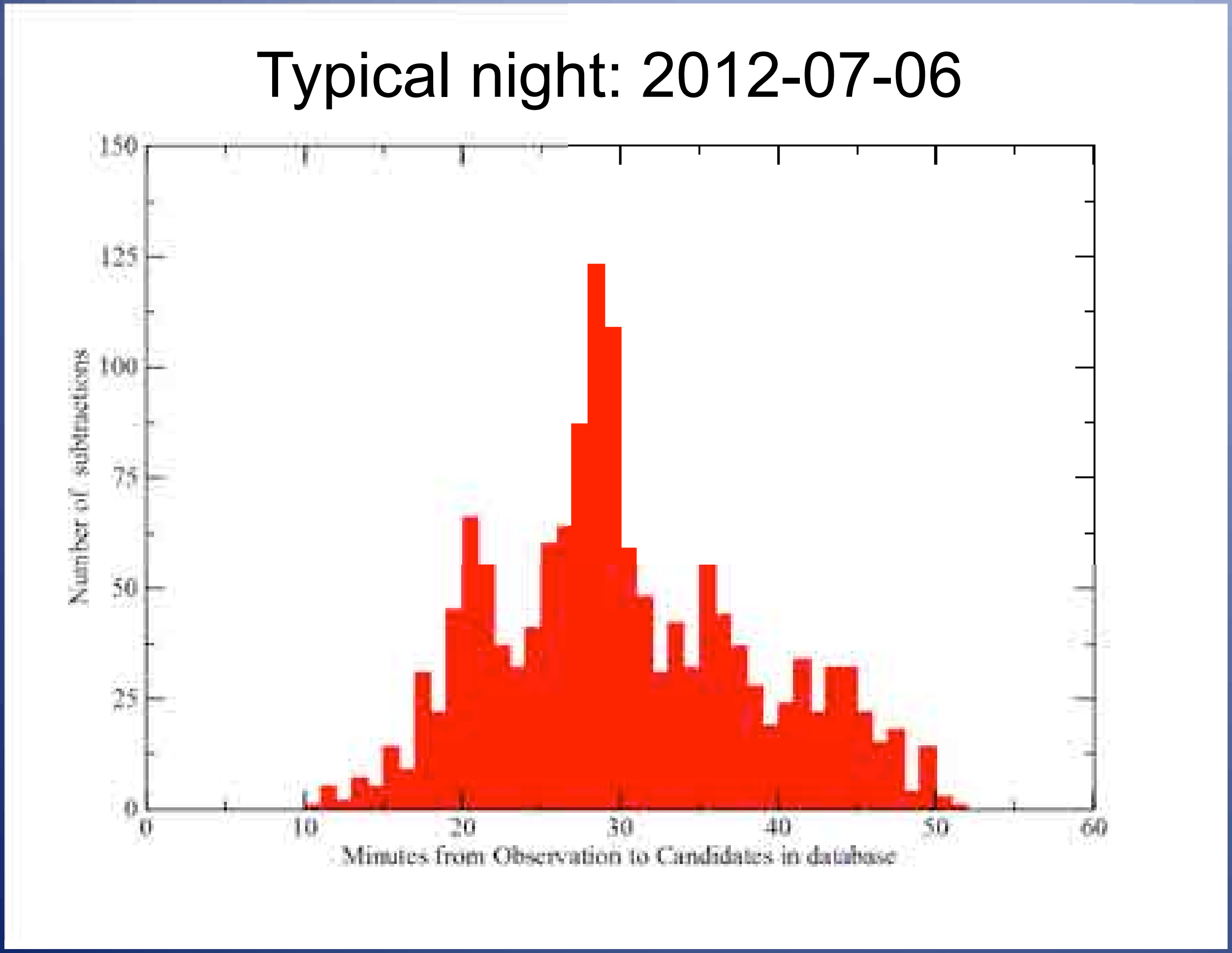


One of 4 such pipelines running at NERSC.



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
Scanning Page
Wake Me Up – Real Time Trigger
1.5B objects in DB
Publish to Web
Outside Database for Triggers
Web UI Marshal
Outside Telescope Follow-up

Turn-around



What does "real-time" subtractions really mean?

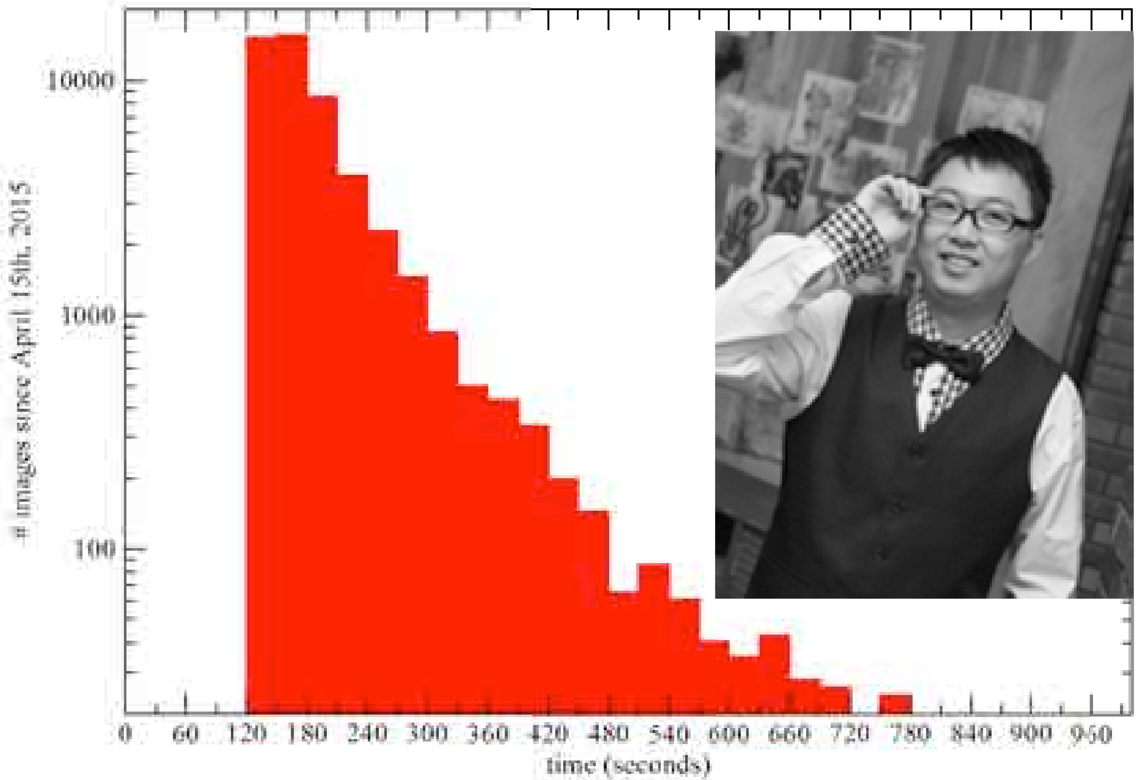
For 95% of the nights all images are processed, subtractions are run, candidates are put into the database and the local universe script is run in
< 1hr after observation.

Median turn-around was 30m.

Science demands this be quicker...

New Turn-around

First 100 nights of iPTF & new pipeline



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

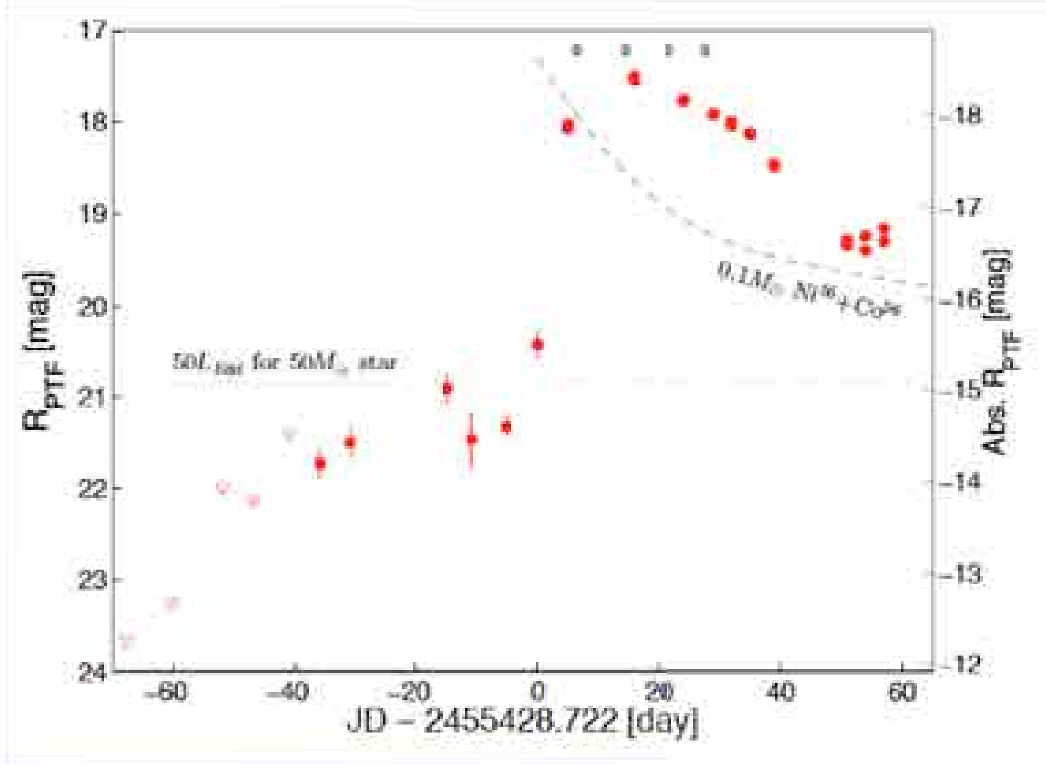
PTF Sky Coverage

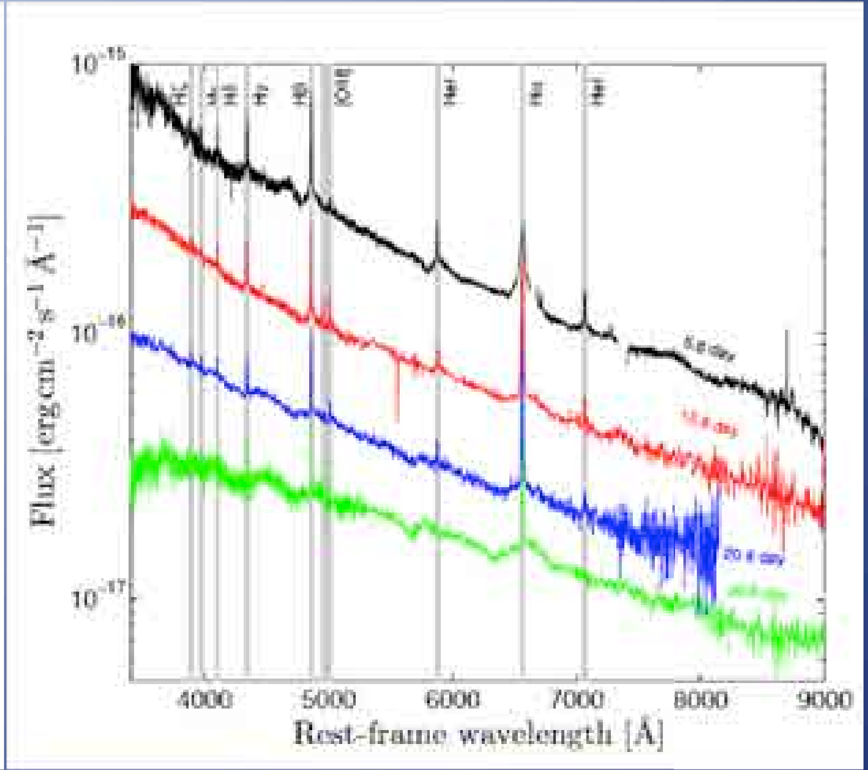
To date:

- 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

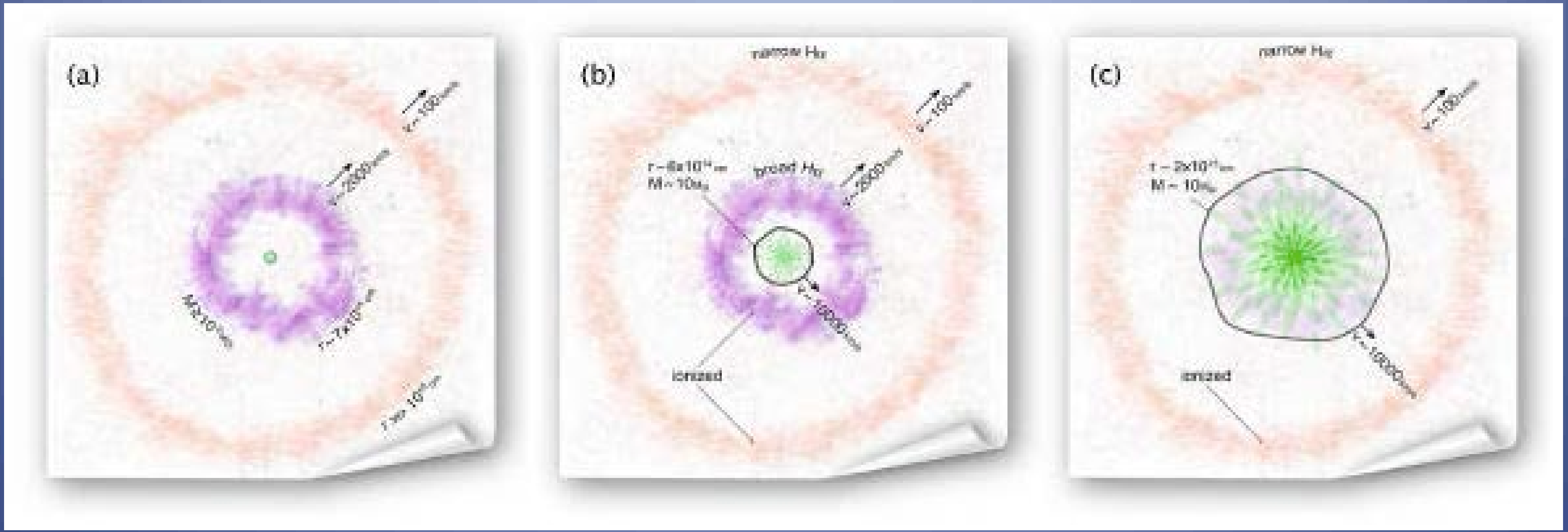




SN 2010mc - Ofek et al. (2013) *Nature &* SN 2011ht – Fraser et al. (2013) *ApJ*

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.

Pre-Outbursts

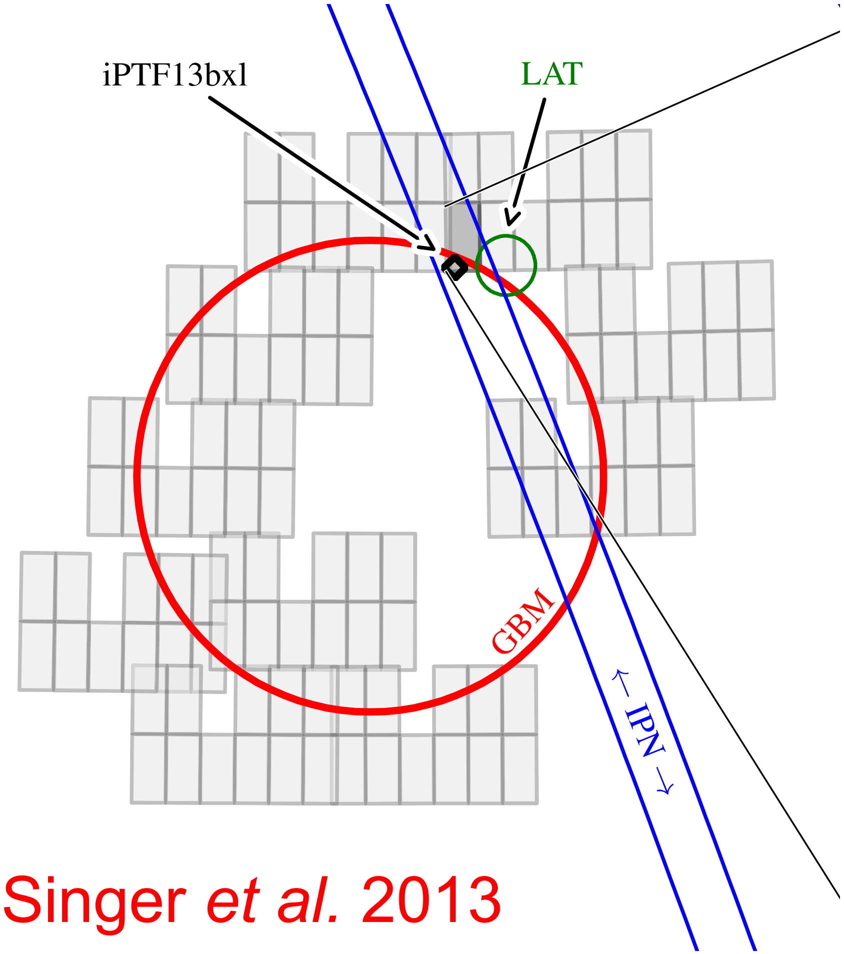


(a) 10^{-2} $M_{\odot}$ ejected one month earlier during pre-outburst ~2000 km/s

(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.

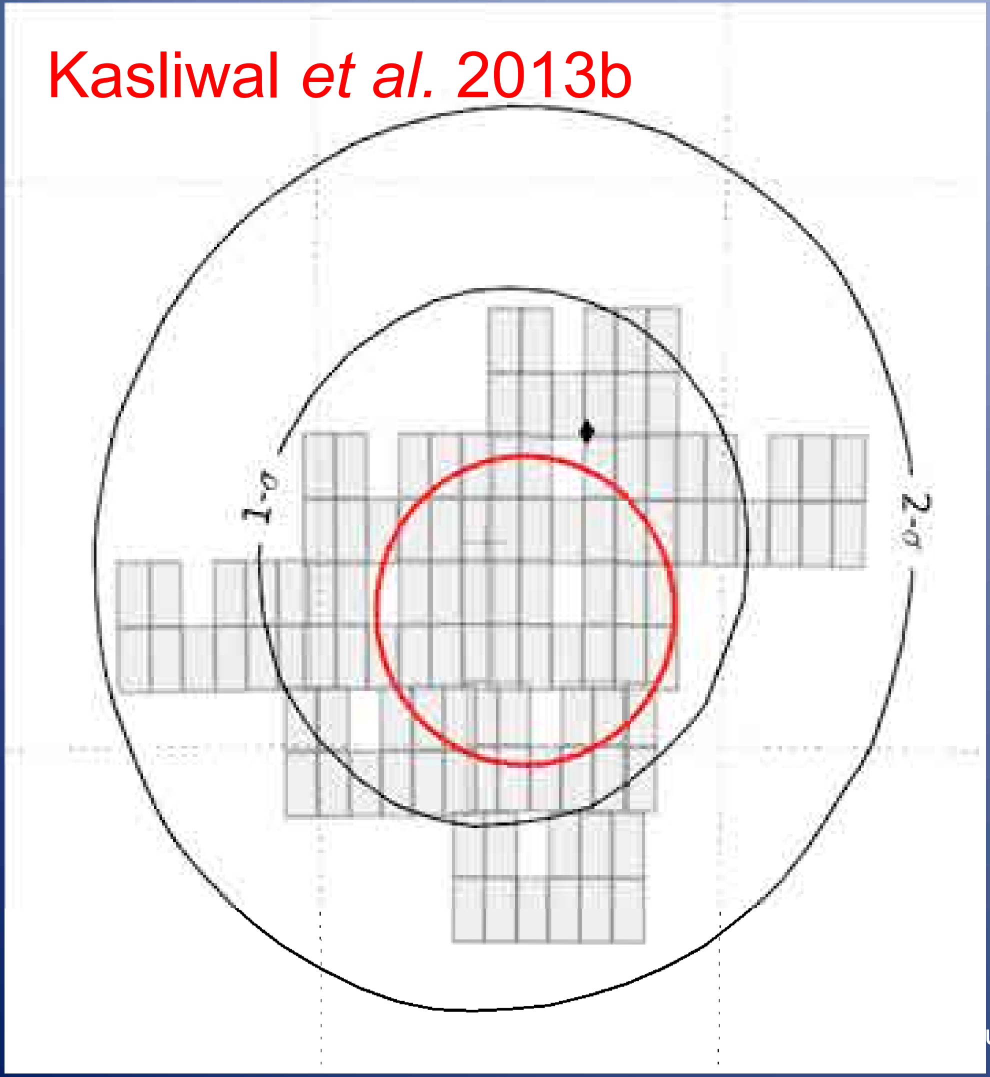
(c) At day ~ 20, the SN shock engulfs the inner shell, and the intermediate-width H α vanishes and narrower features appear: pre-pre-outbursts.

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



Singer *et al.* 2013

The second Fermi afterglow: iPTF13dsw at z=1.87!

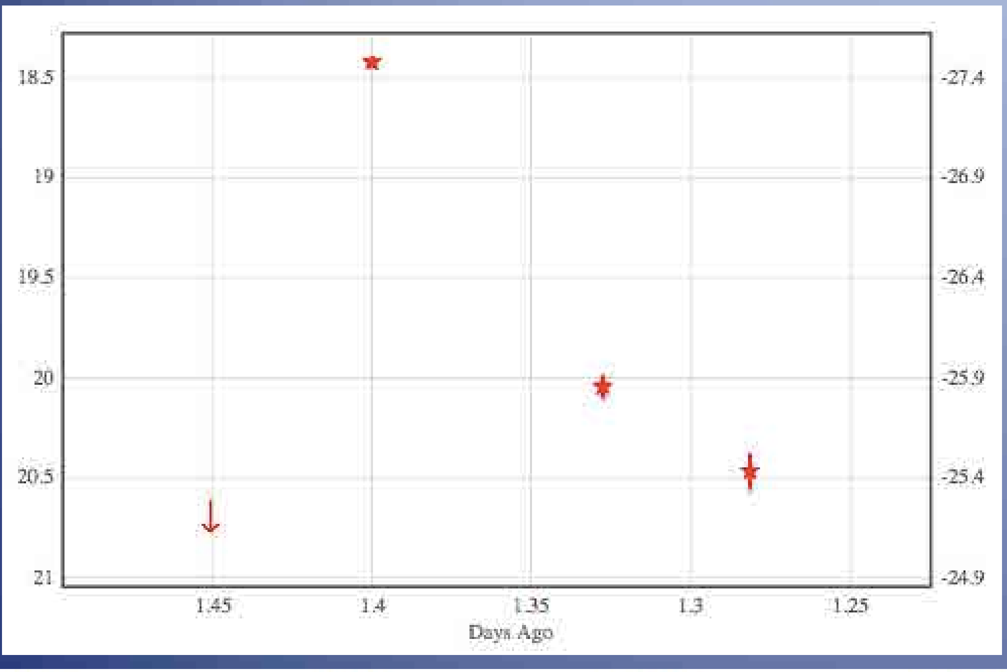


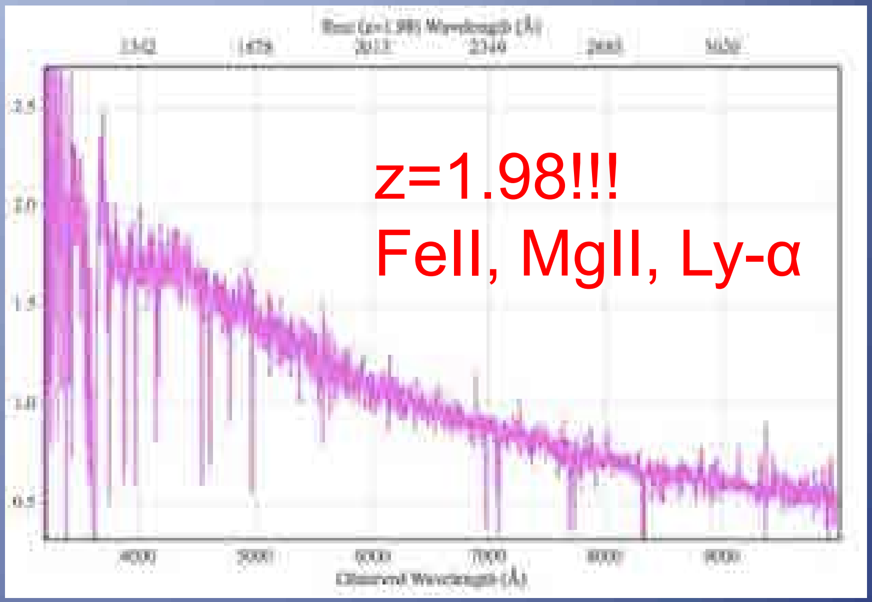
Overcoming
Wide, Fast & Faint

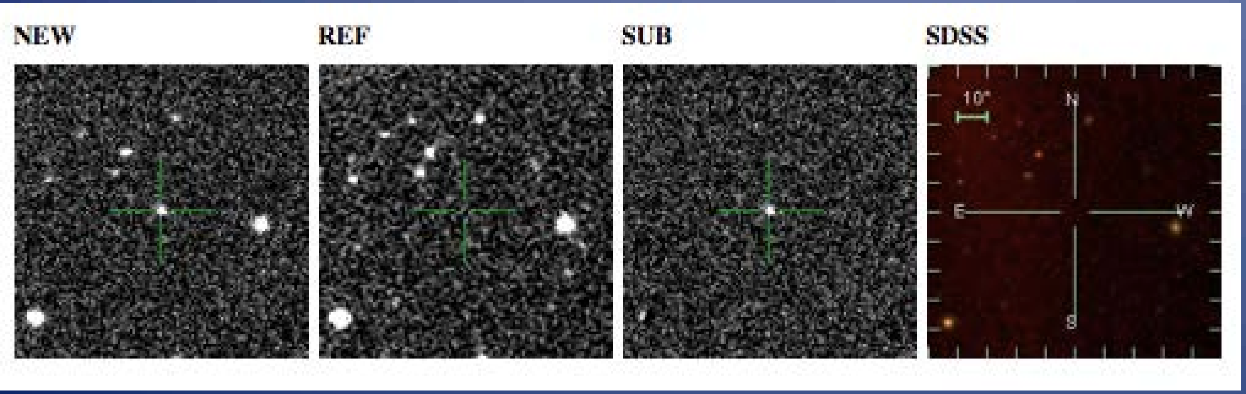
Pinpointing the afterglow
amidst 30,000 candidates

um

Orphan Afterglow



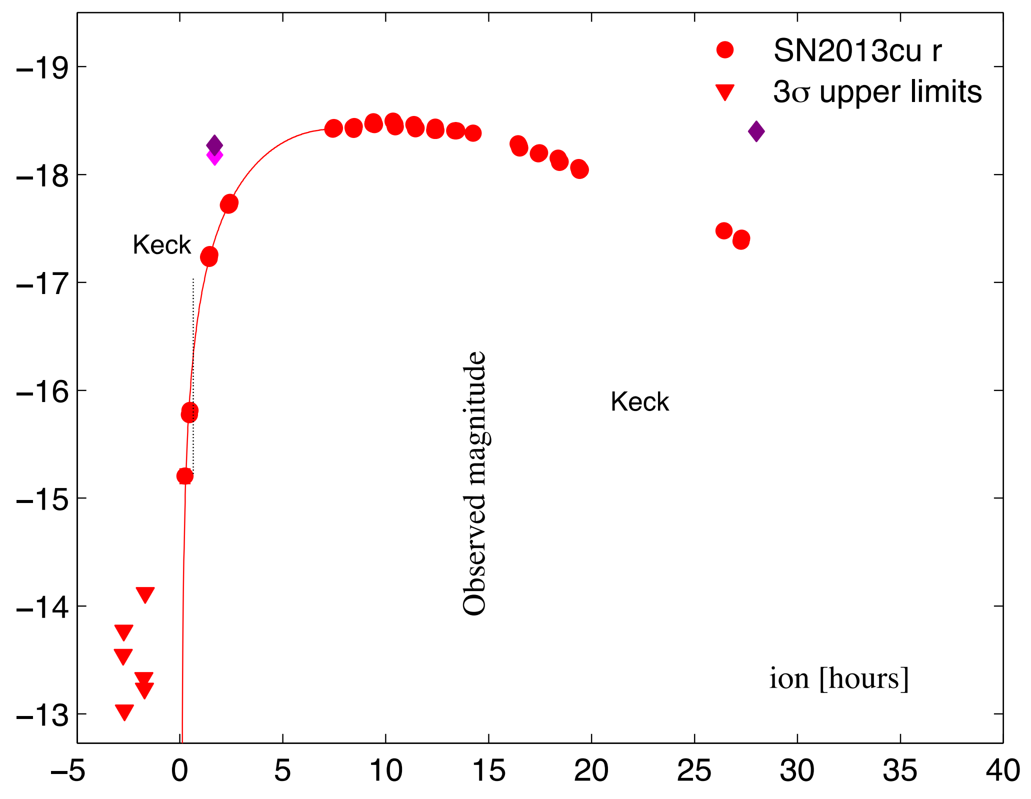




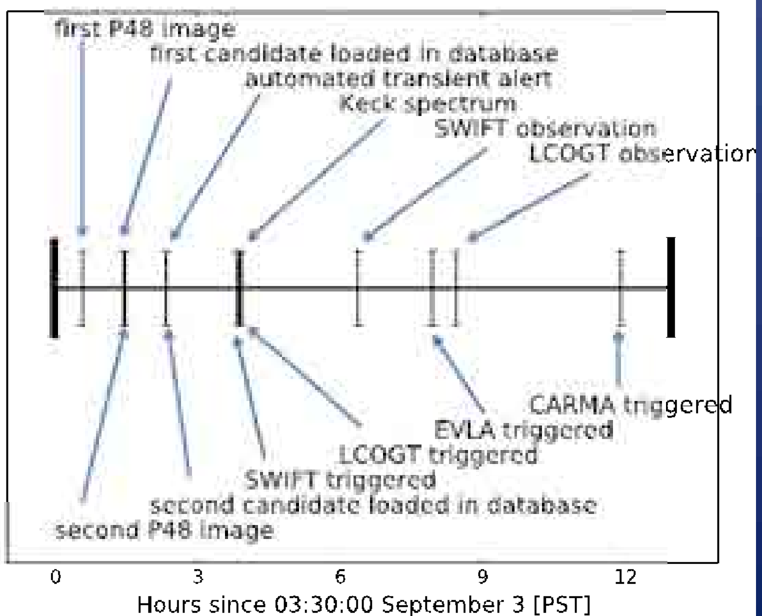
iPTF14yb
Cenko et al. 2014

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

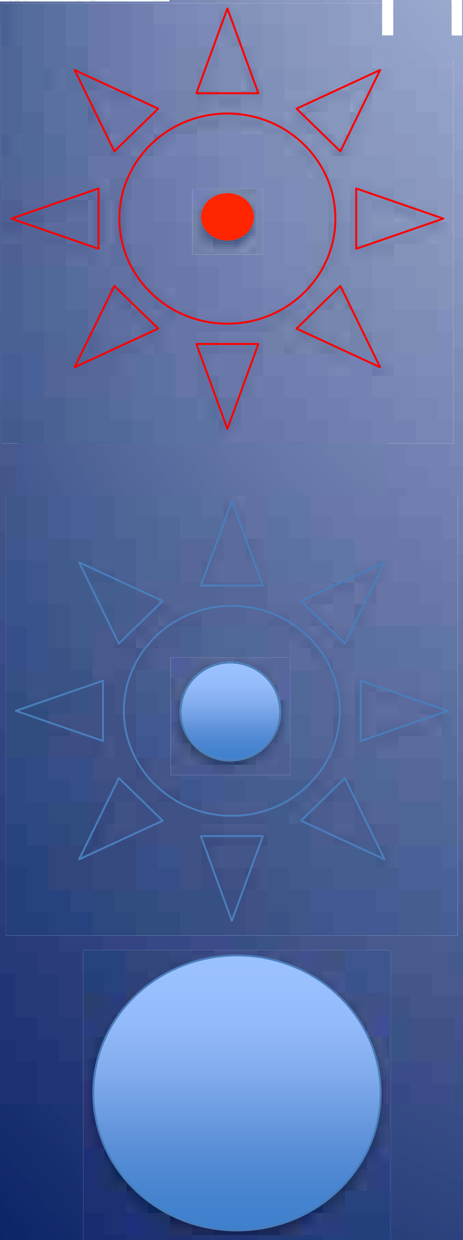
Flash Spectroscopy

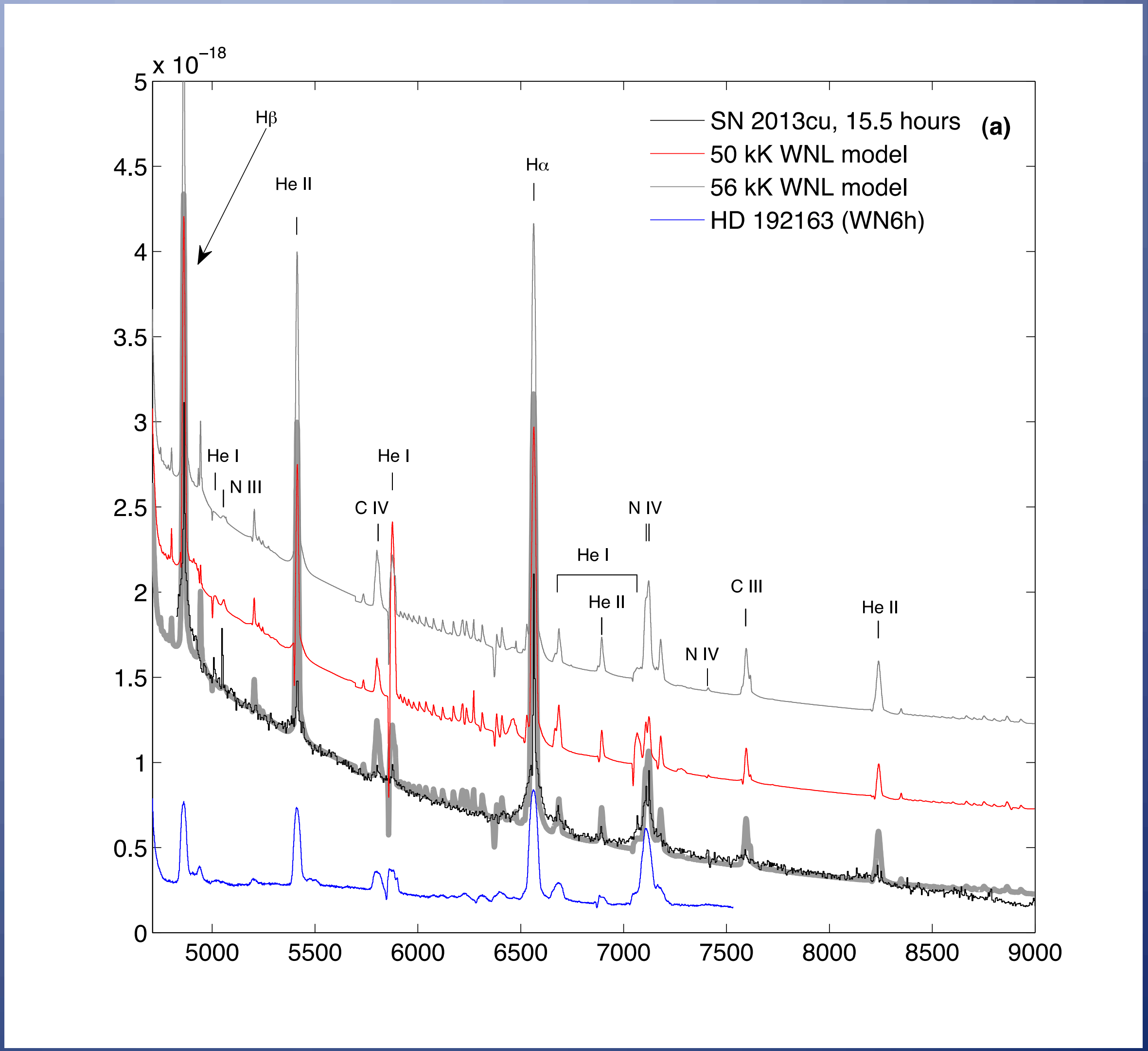


SN2013cu (iPTF13ast)
Gal-Yam et al. (2014) *Nature*

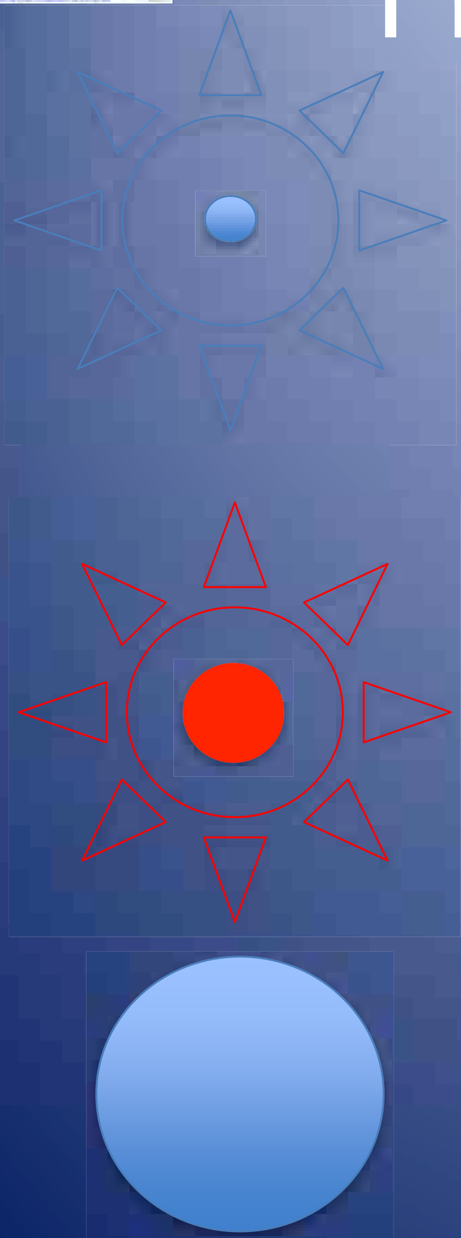


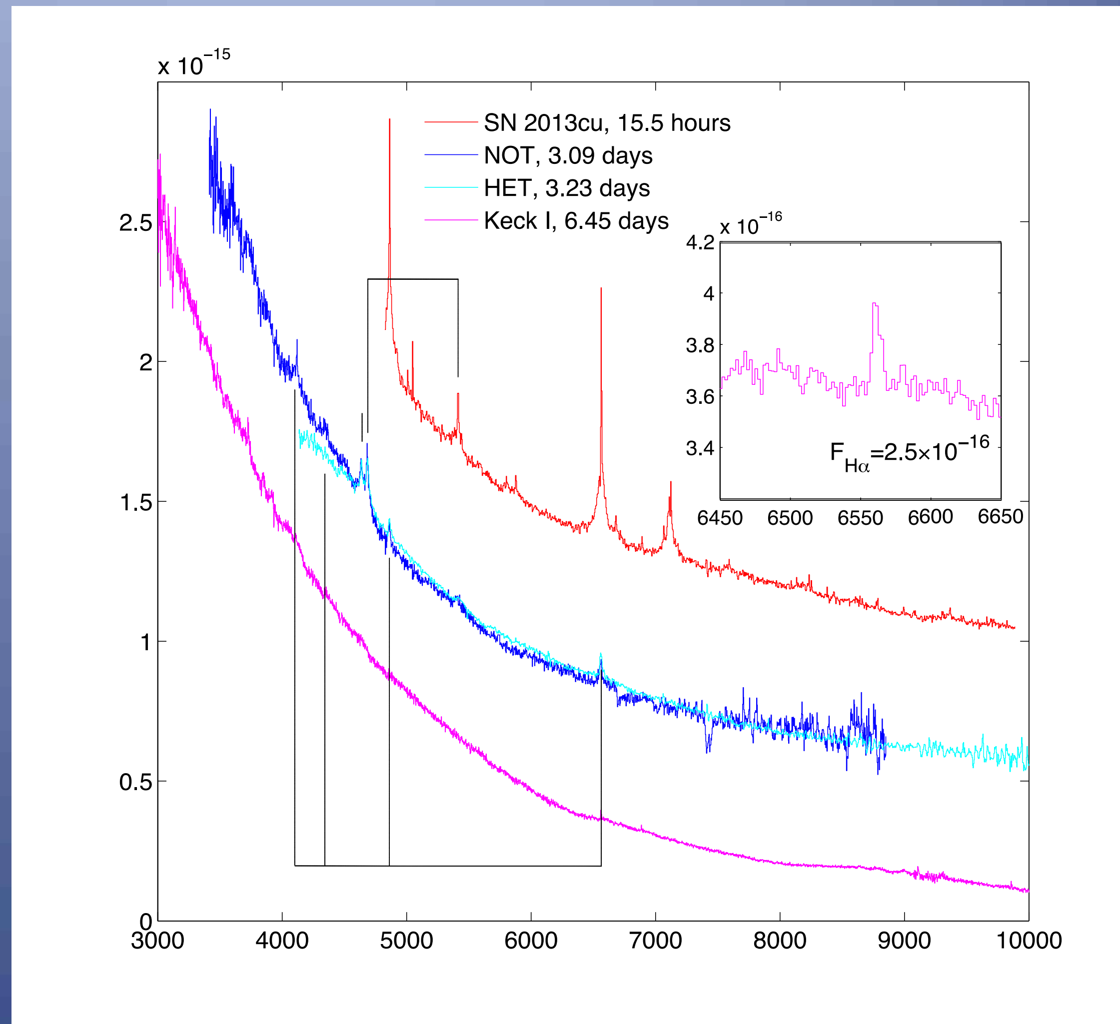
Flash Spectroscopy



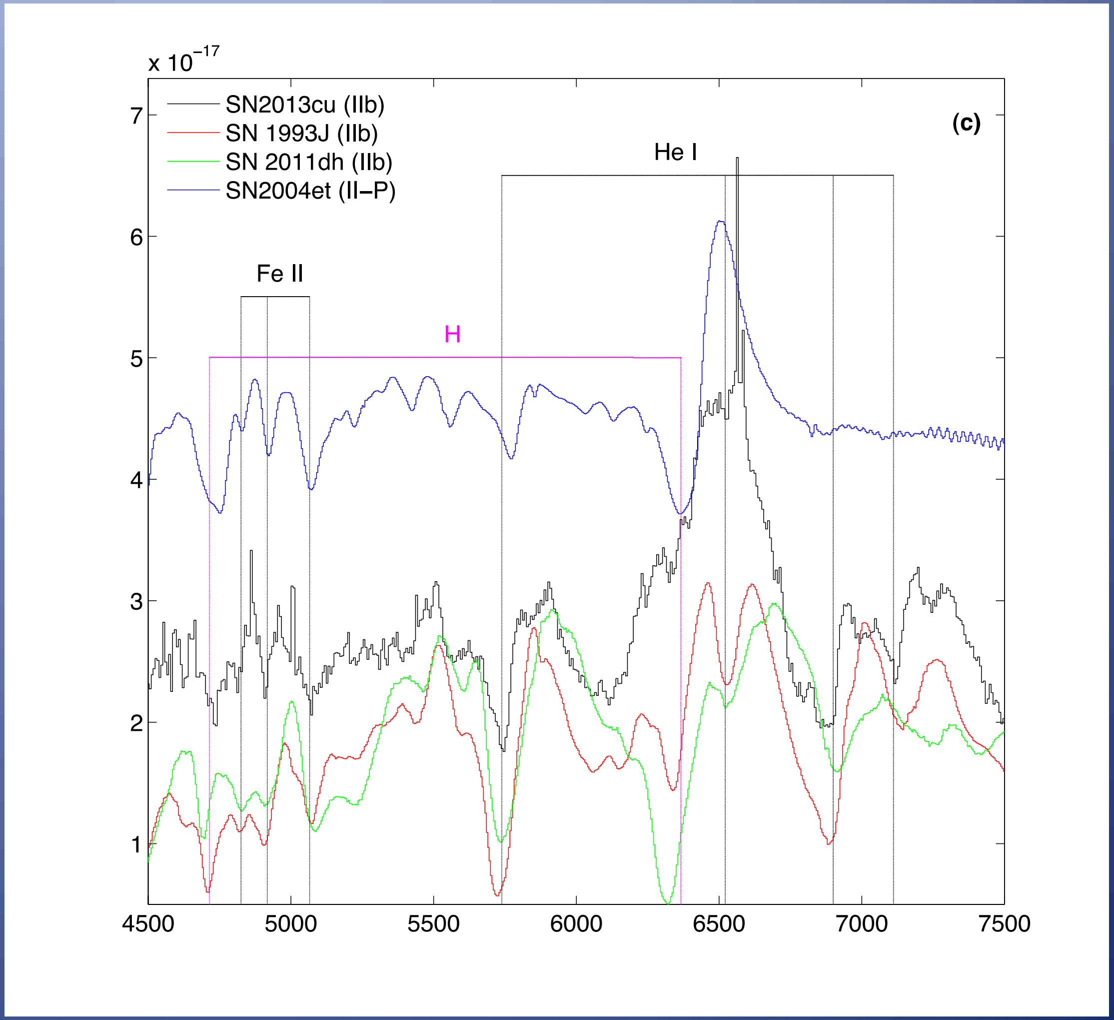


Flash Spectroscopy

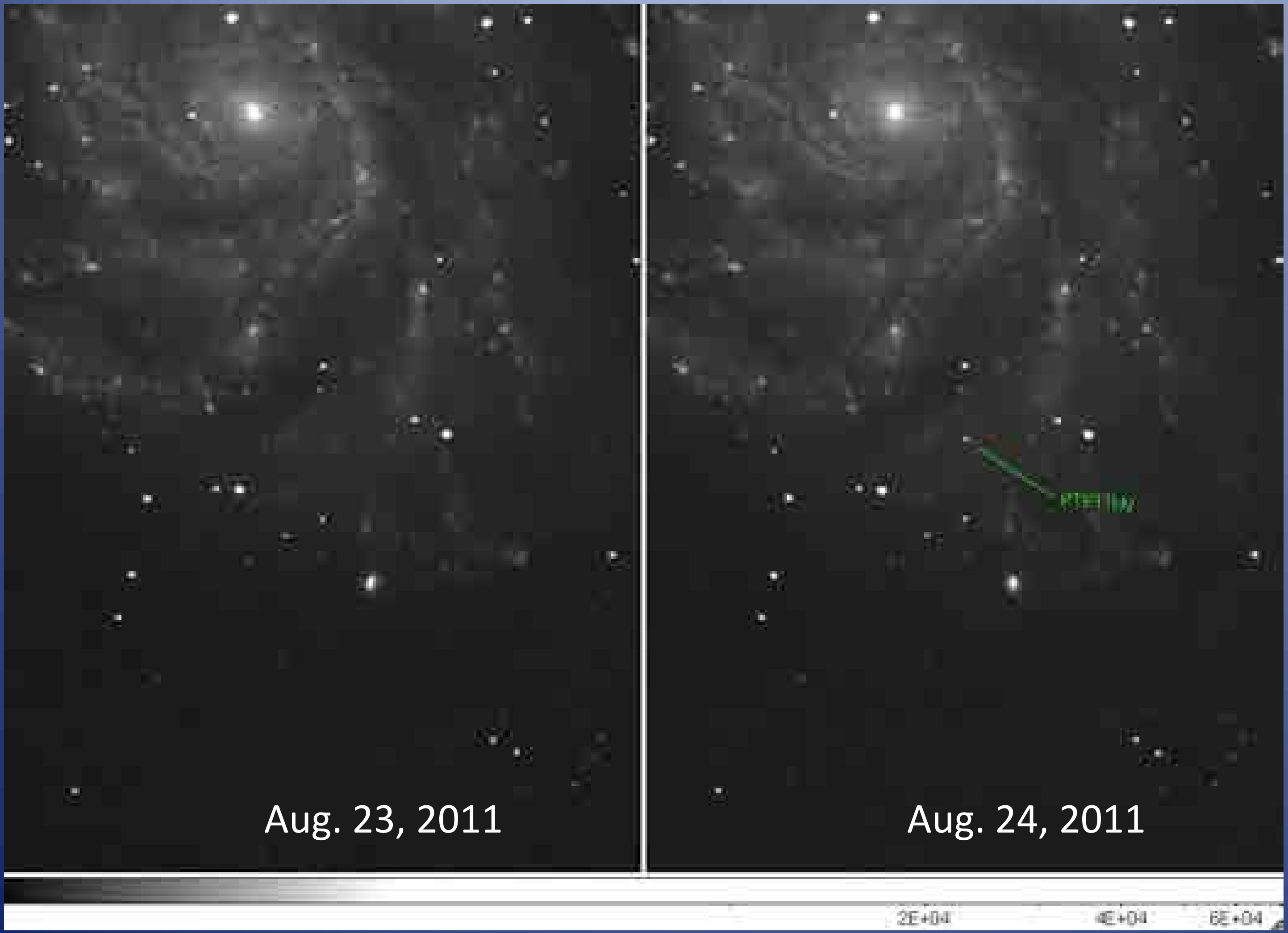




Flash Spectroscopy



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

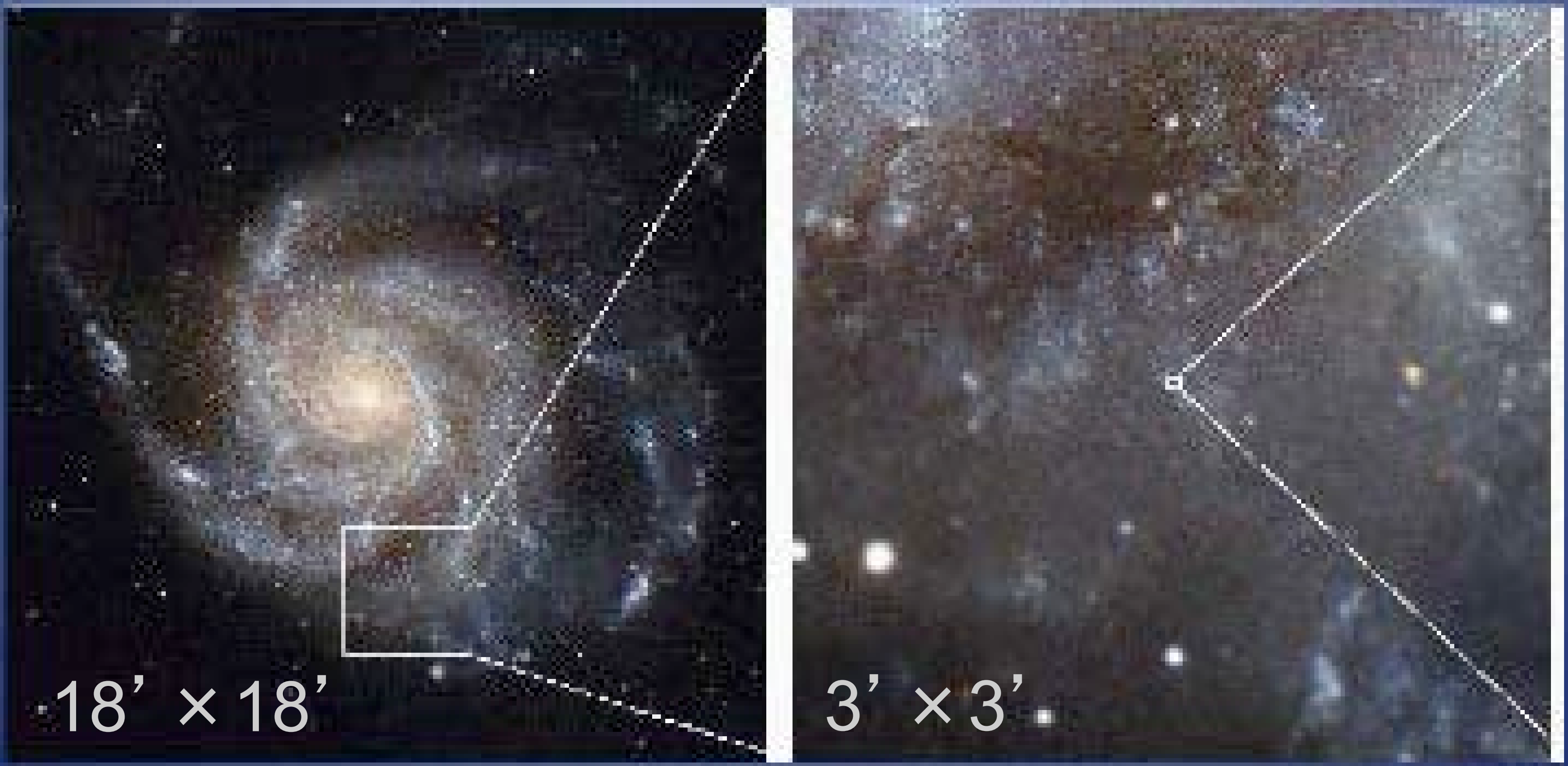
The Type Ia supernova science working group of the Palomar Transient Factory (ATEL #1964) reports the discovery of the Type Ia supernova PTF11kly at RA=14:03:05.81, Dec=+54:16:25.4 (J2000) in the host galaxy M101. The supernova was discovered on Aug. 24 UT when it was at magnitude 17.2 in g-band (calibrated 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 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.

PTF11kly/SN2011fe

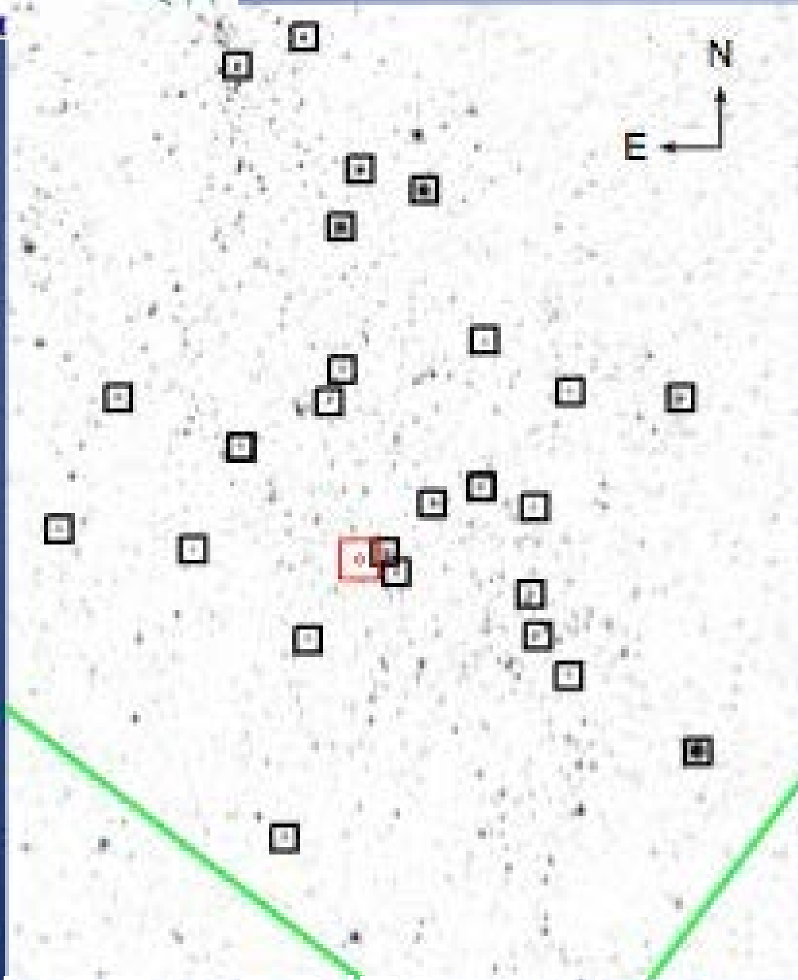


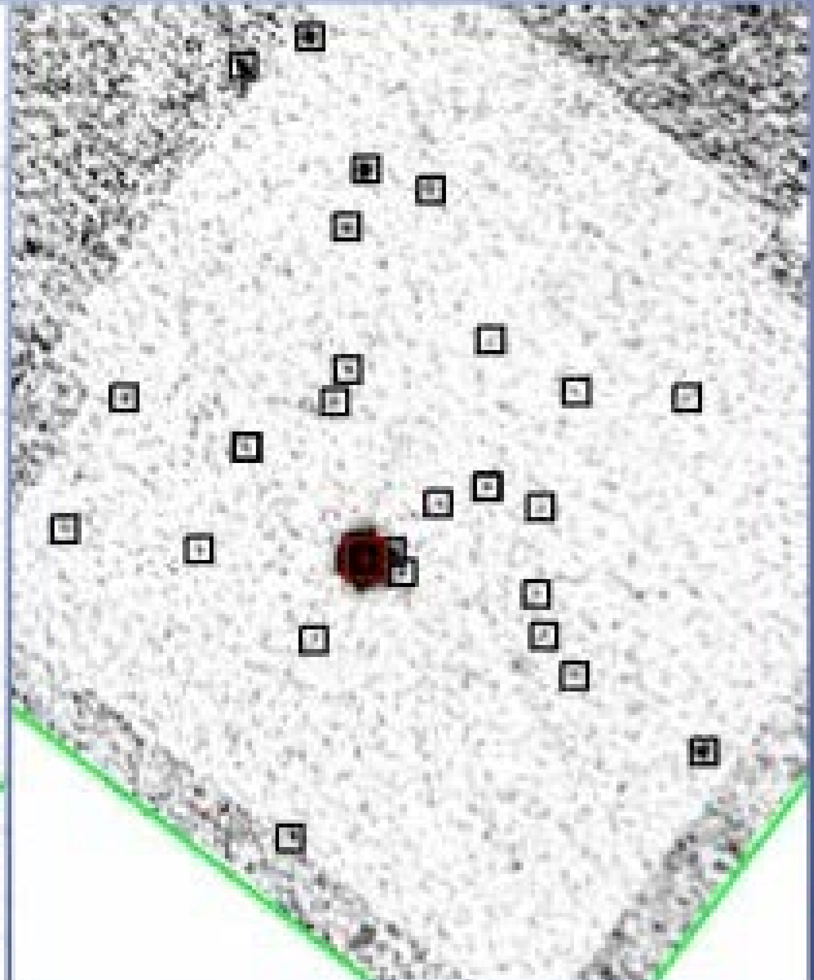
DM=29.04 ± 0.23

Shrappe,Stanek 11

Li+2011

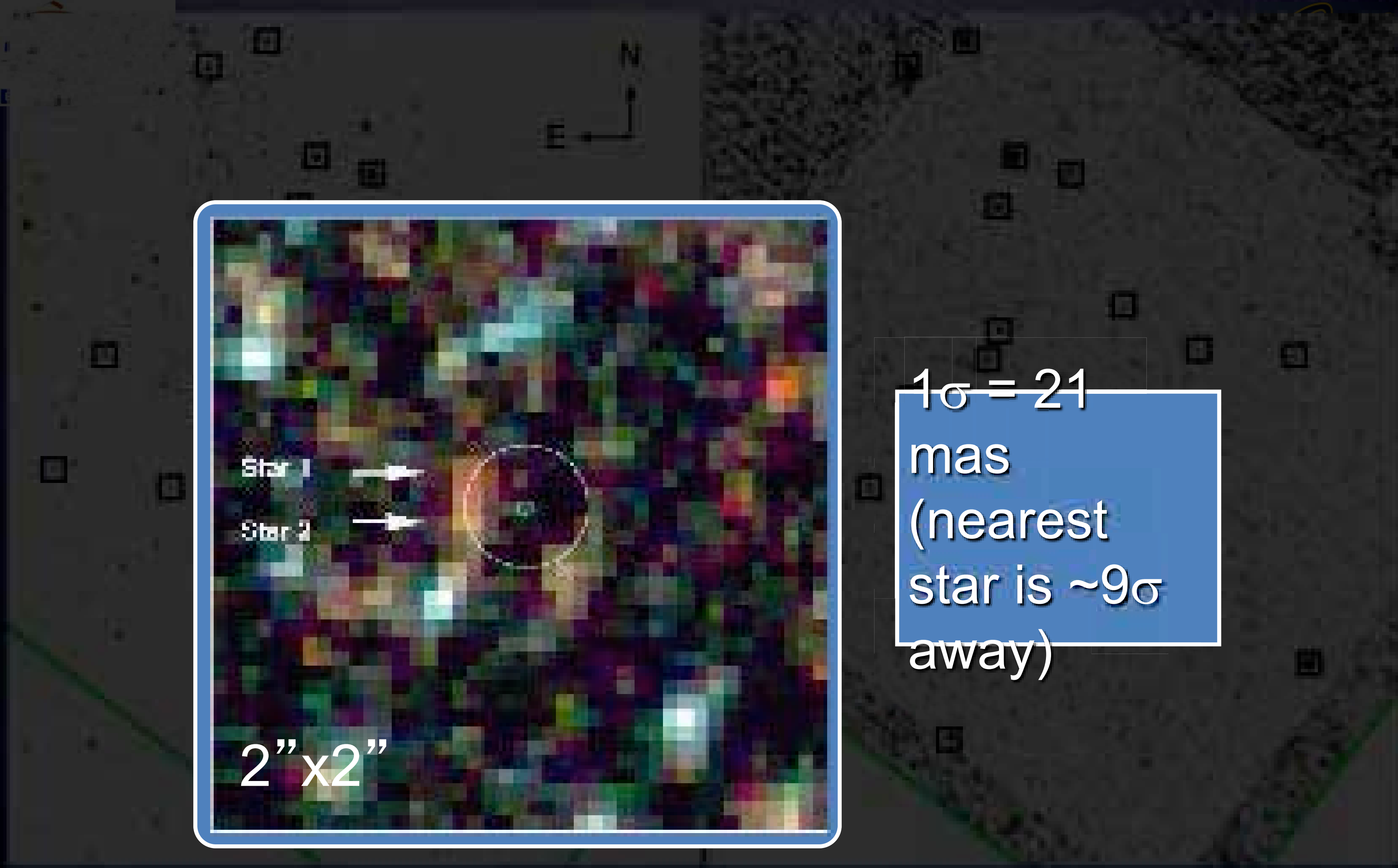
Keck/NIRC2/H-band
Aug 26, 2011 (t_0+3day)





HST/ACS/F814W (~I band)
Nov 11, 2002

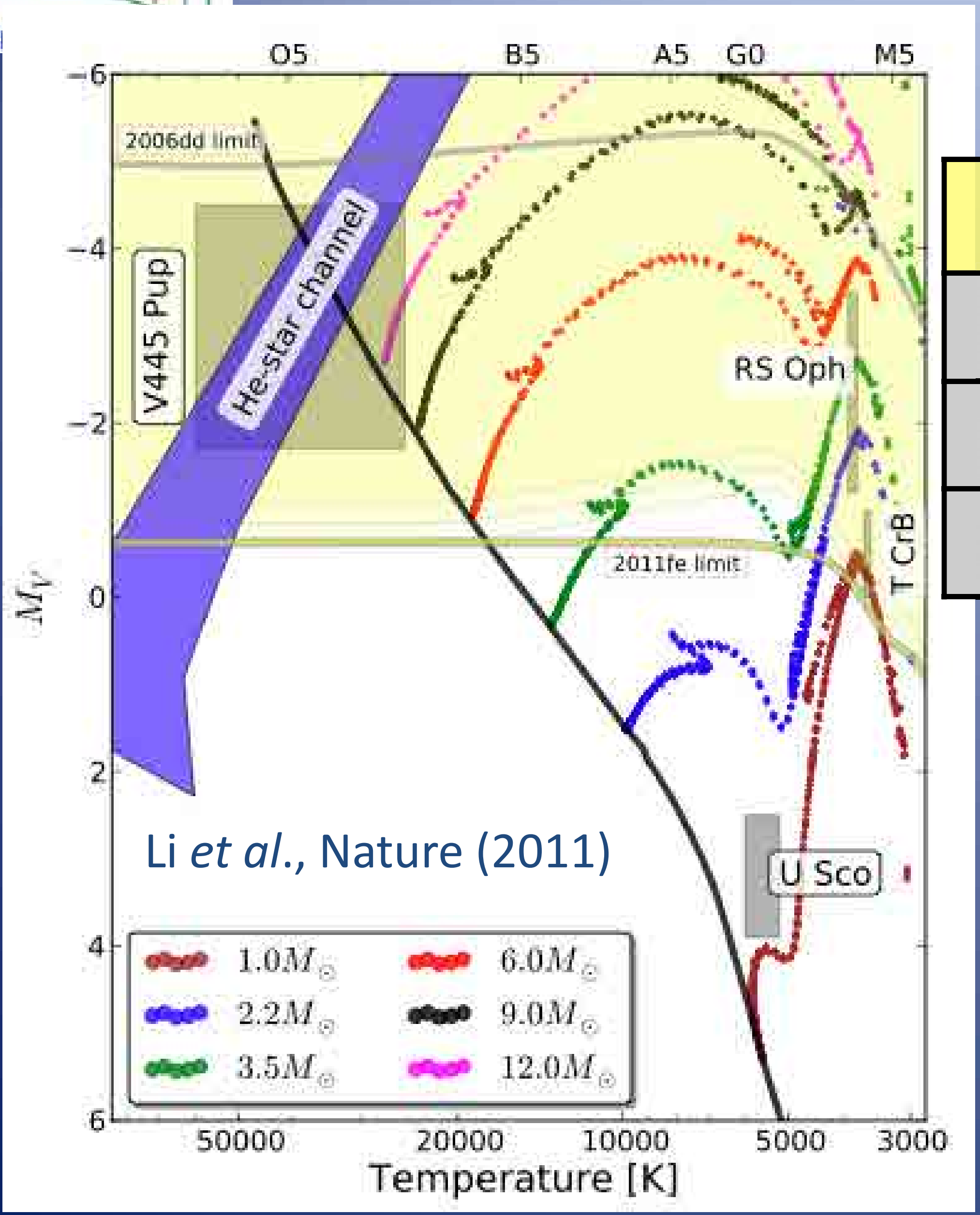
Keck/NIRC2/H-band
Aug 26, 2011 (t_0+3day)



HST/ACS/F814W (~I band)
Nov 11, 2002

Keck/NIRC2/H-band
Aug 26, 2011 (t_0+3day)

IPMU Colloquium

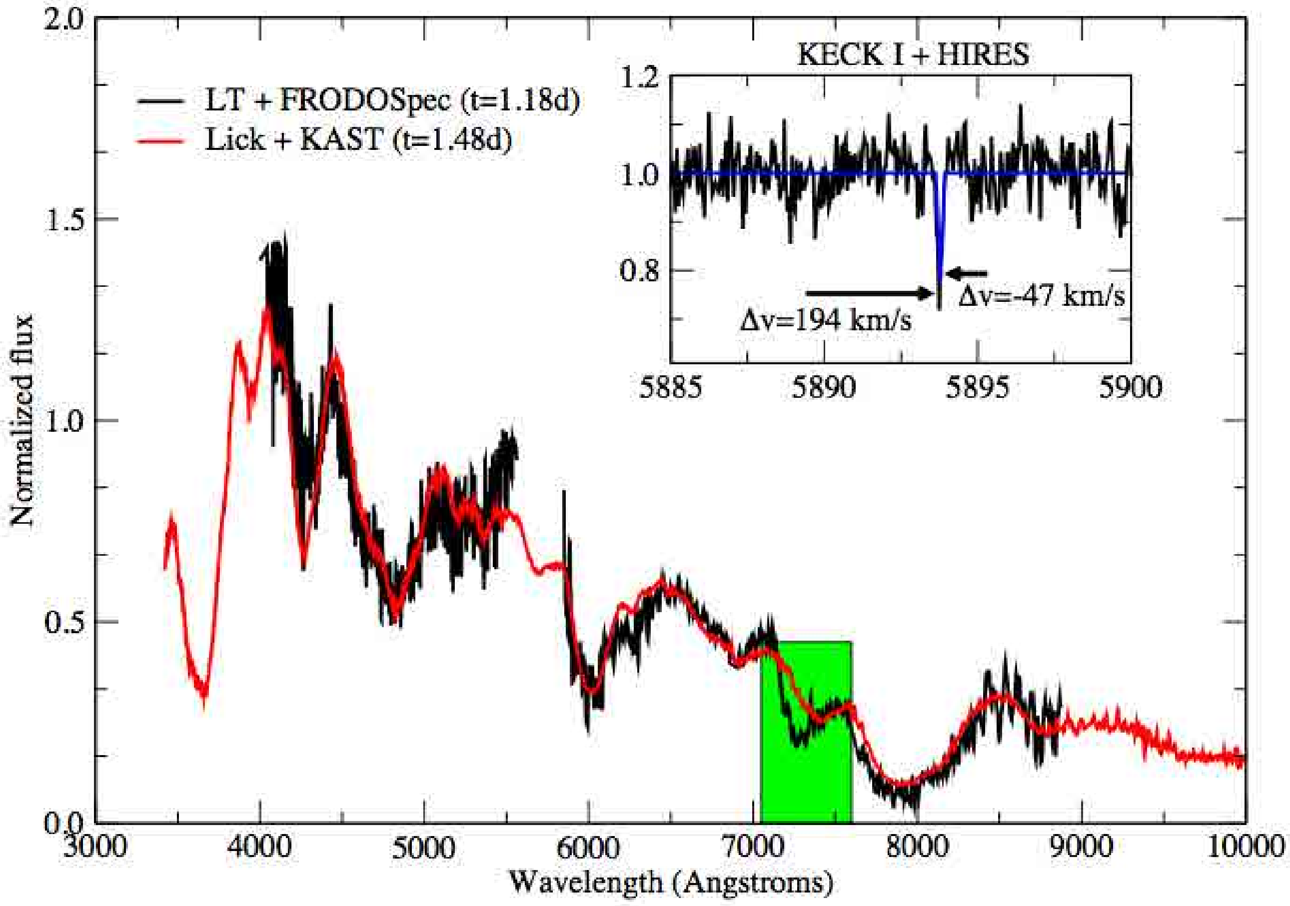


T_{eff}	M_V	Reff
3010	> 0.59 m	240 $R_\odot$
3490	> 0.24 m	63 $R_\odot$
4050	> -0.22 m	32 $R_\odot$

Constraints on the progenitor system.

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

Nugent *et al.*, Nature (2011)



LT, Lick & Keck HIRES spectra.

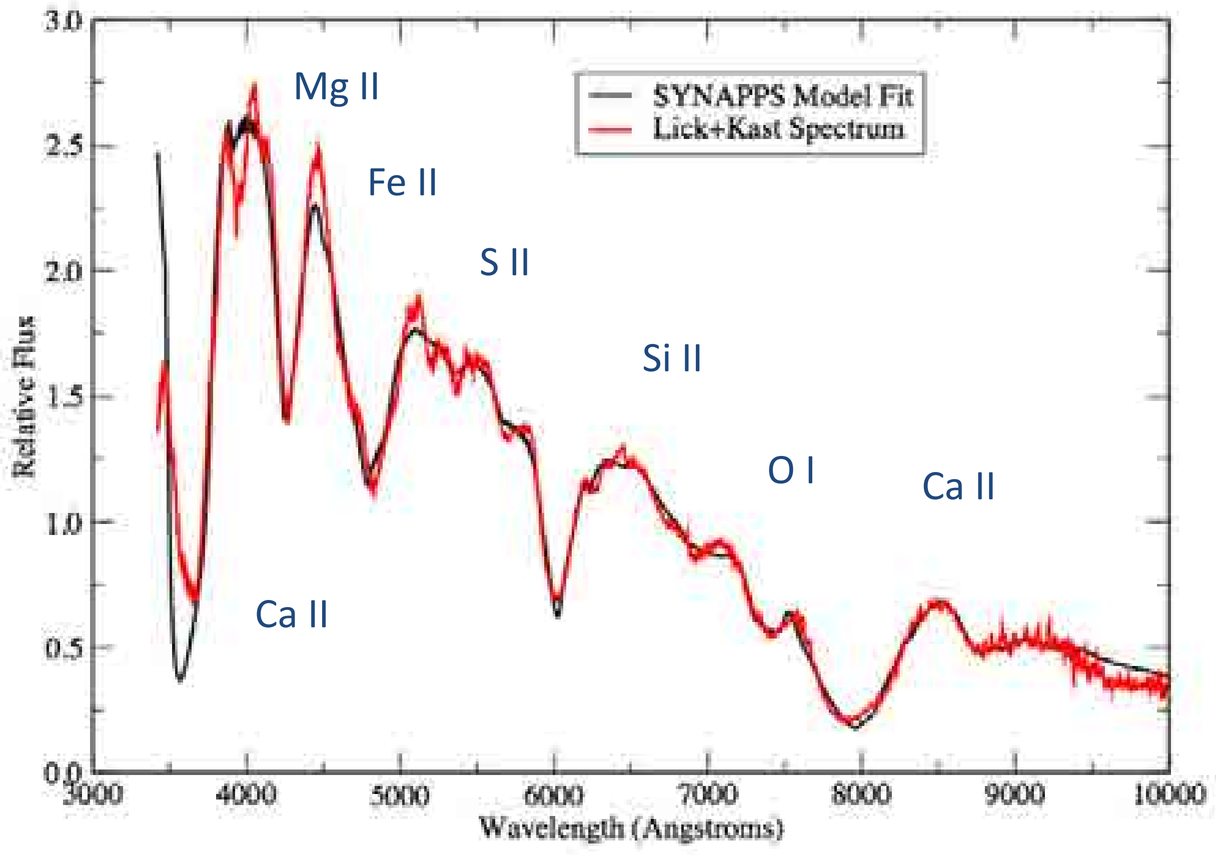
No dust along the line of sight.

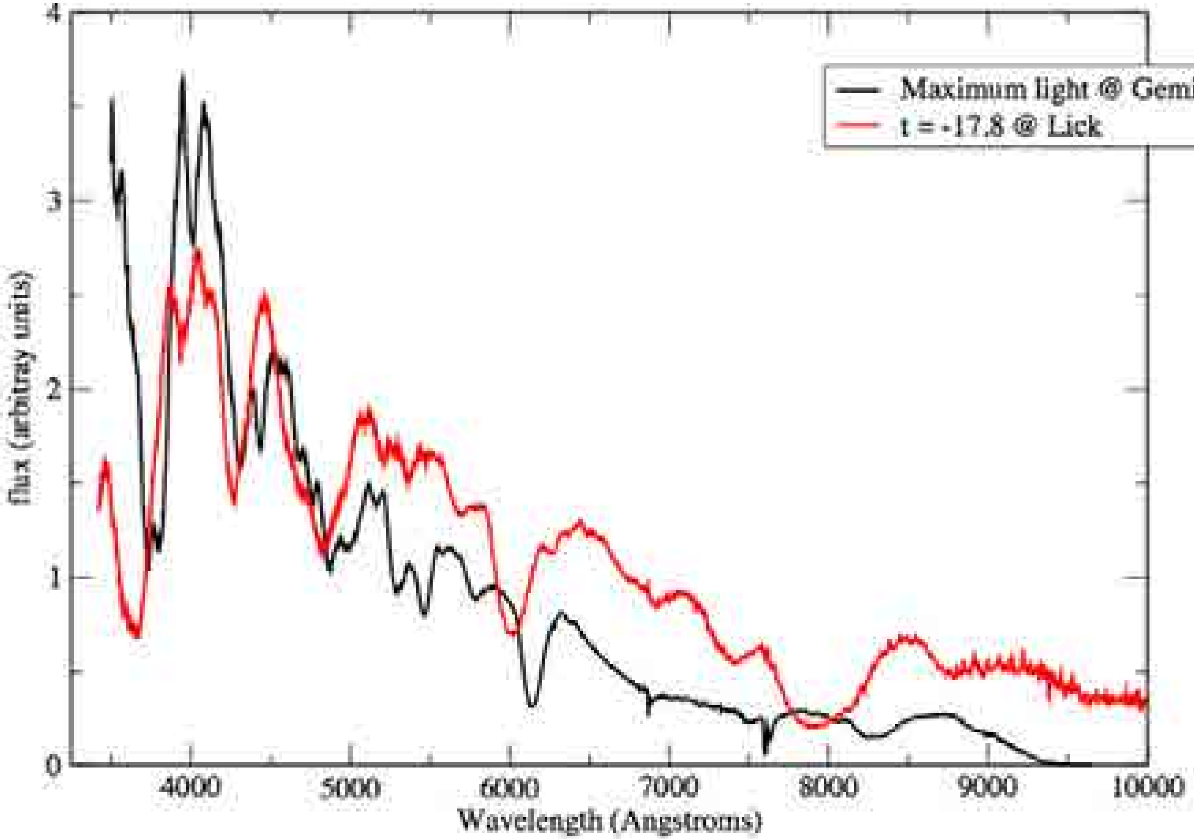
OI line suffers geometrical dilution in 8hrs...

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!

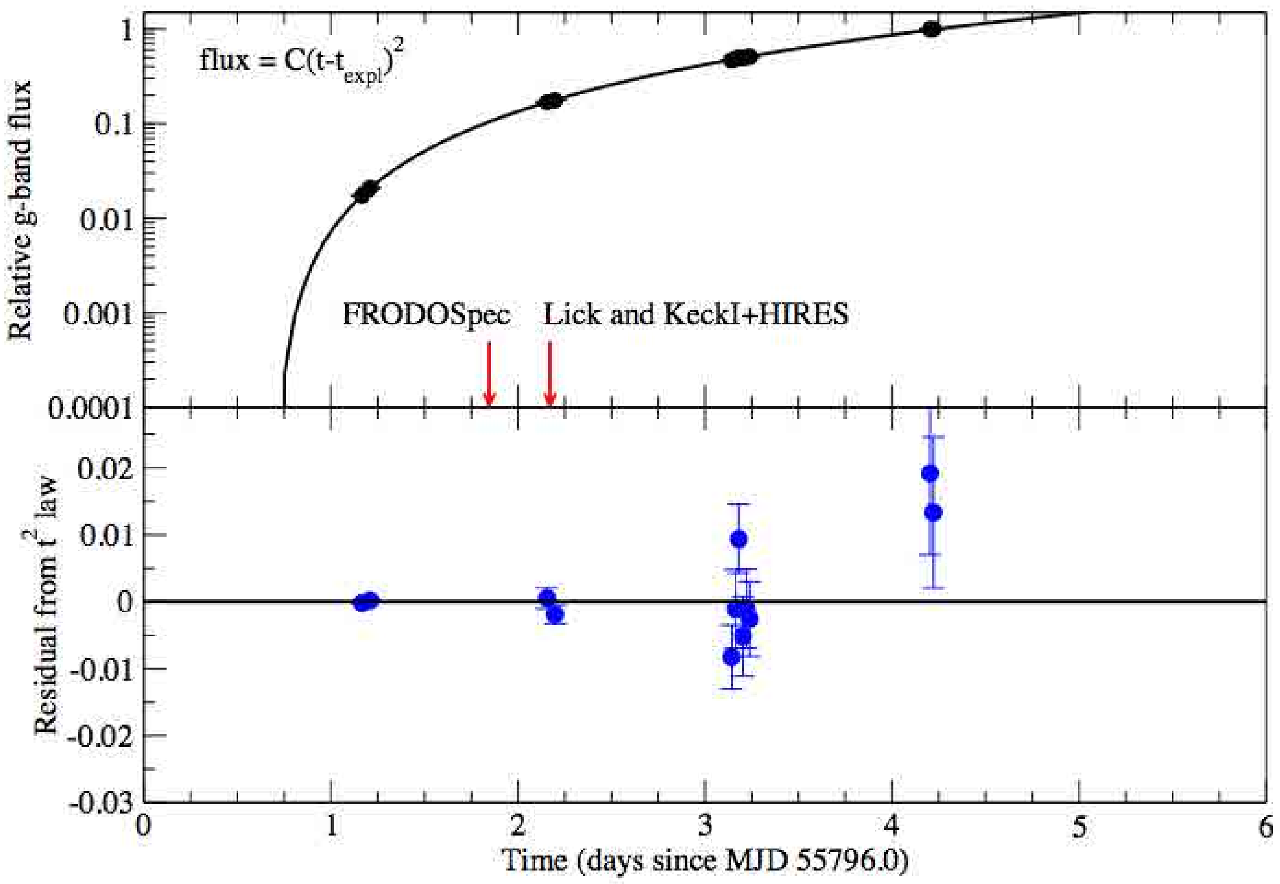
Nugent *et al.*, Nature (2011)





So similar to the maximum light spectrum abundance-wise that it is clear there is a lot of mixing in the SN explosion.

Nugent *et al.*, Nature (2011) *Swift* *HST*

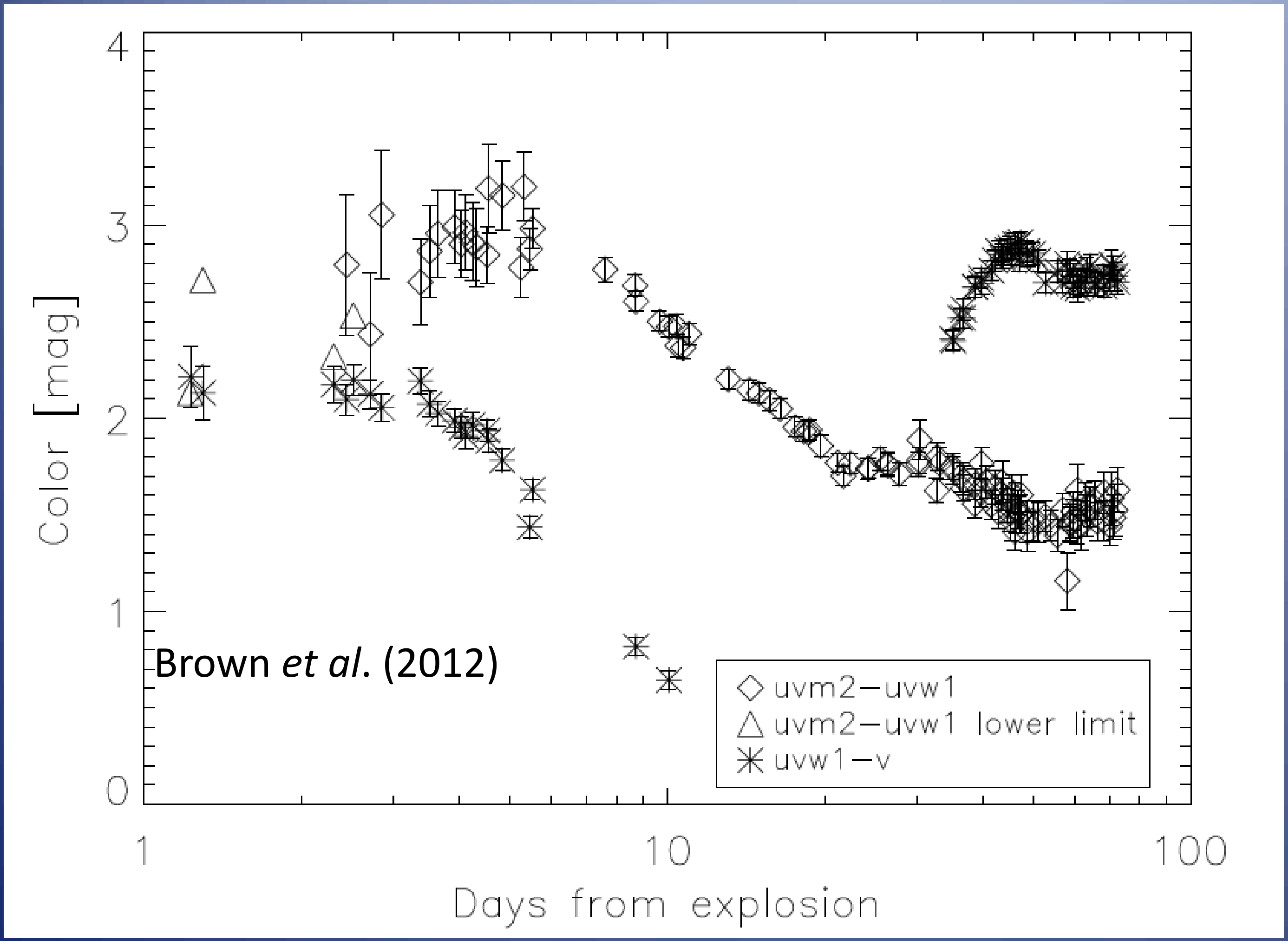


SN 2011fe was caught within 11 hrs +/- 20 min. of explosion following t^2 fireball law. From homologous expansion and:

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

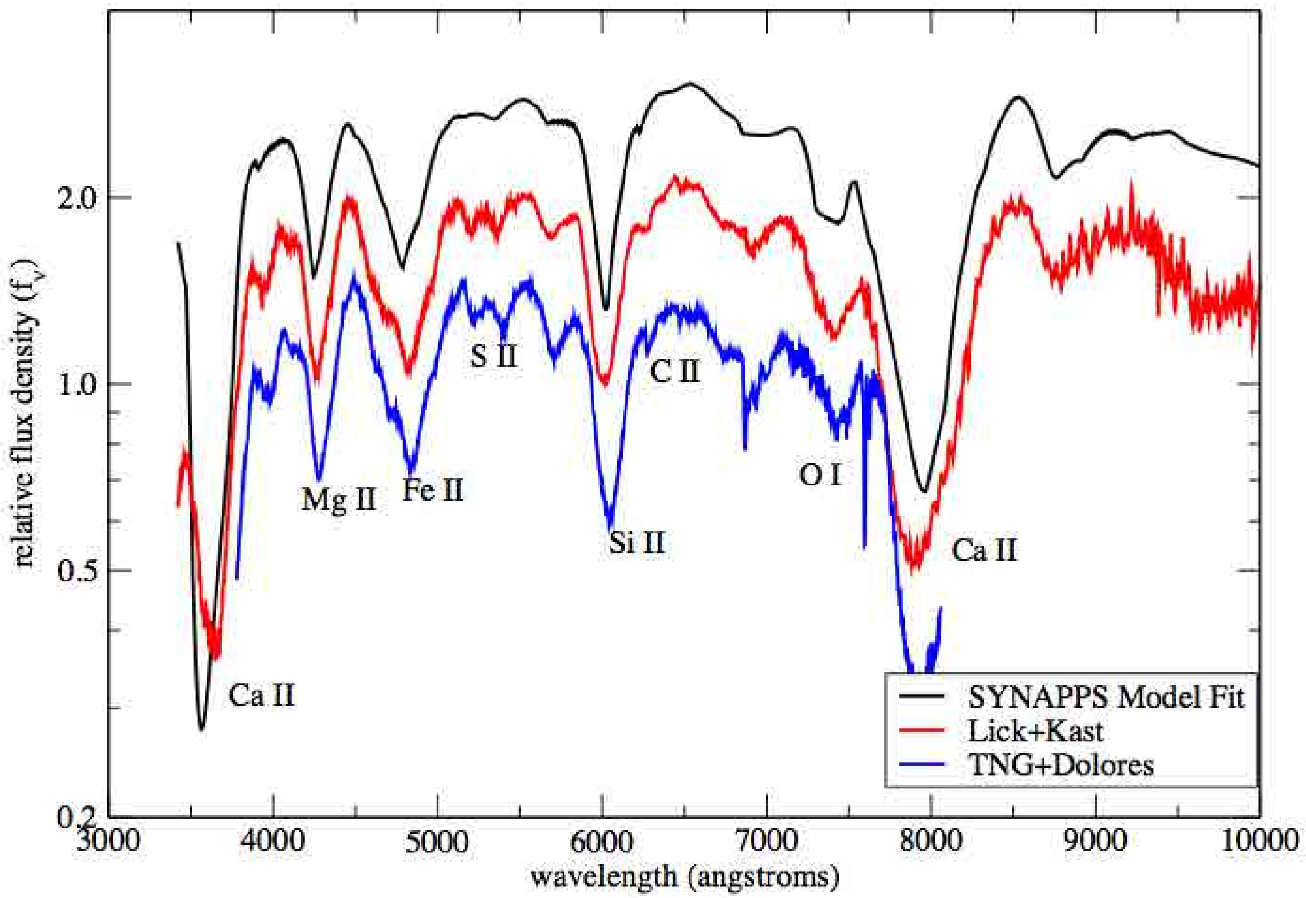
First spectra came in ~24 hr later.

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.

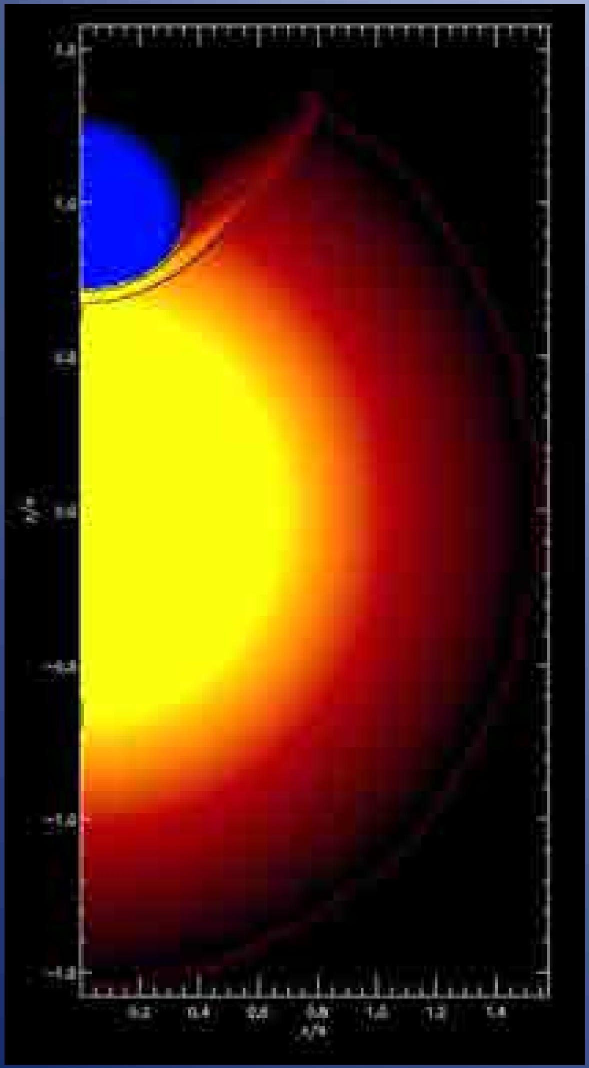
Nugent *et al.*, Nature (2011)

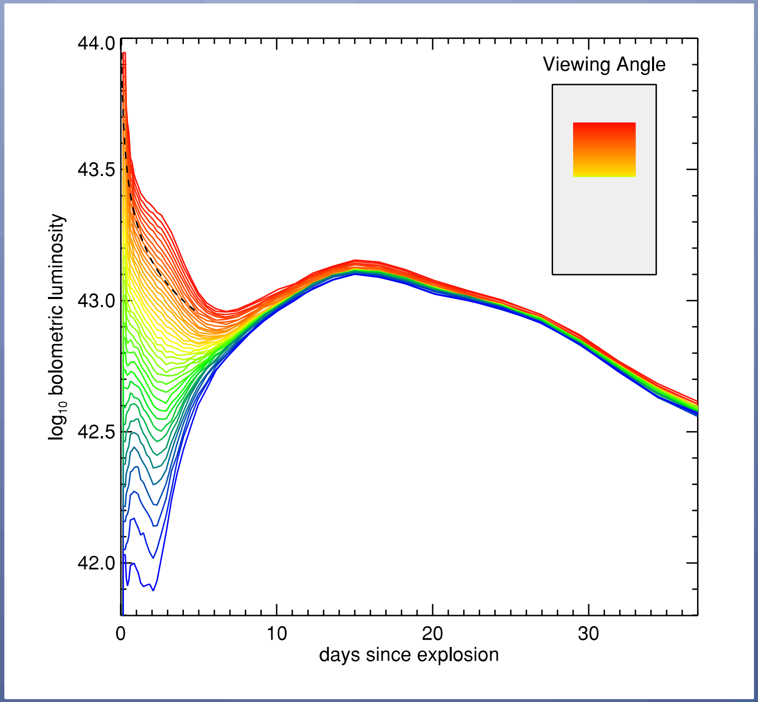


Why follow t^2 law? Pure Luck!

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

Collisions & Shocks

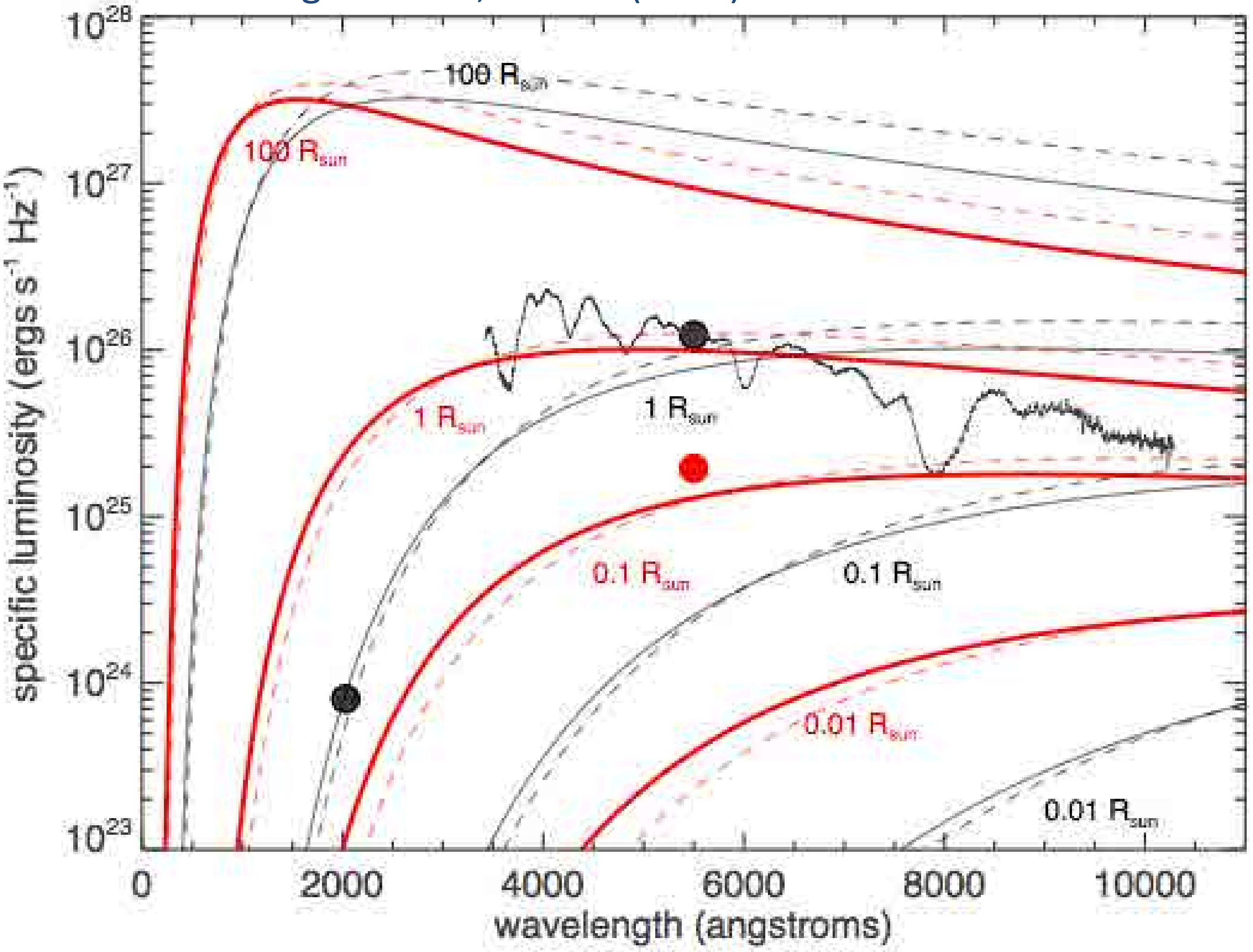




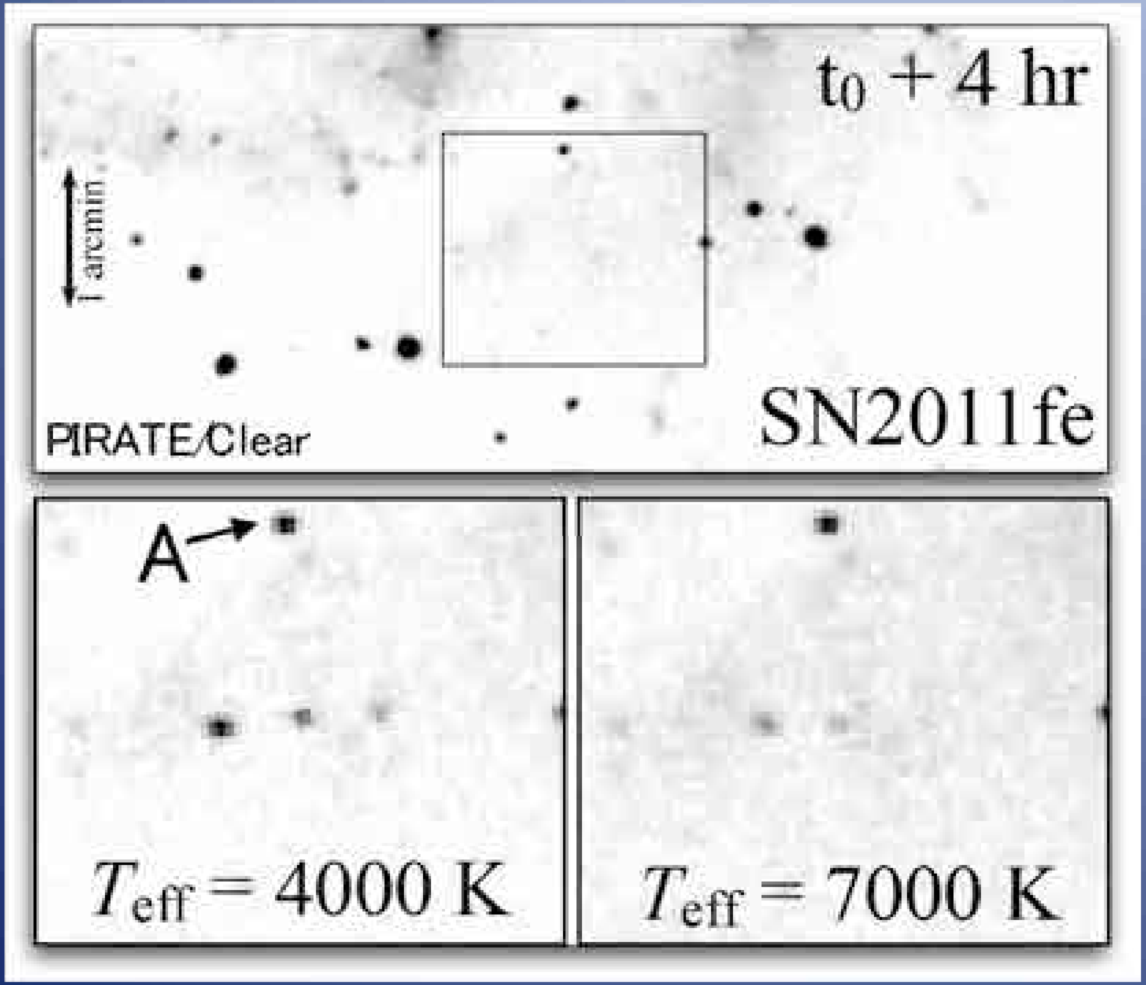
Kasen (2010)

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.

Nugent *et al.*, Nature (2011)



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.

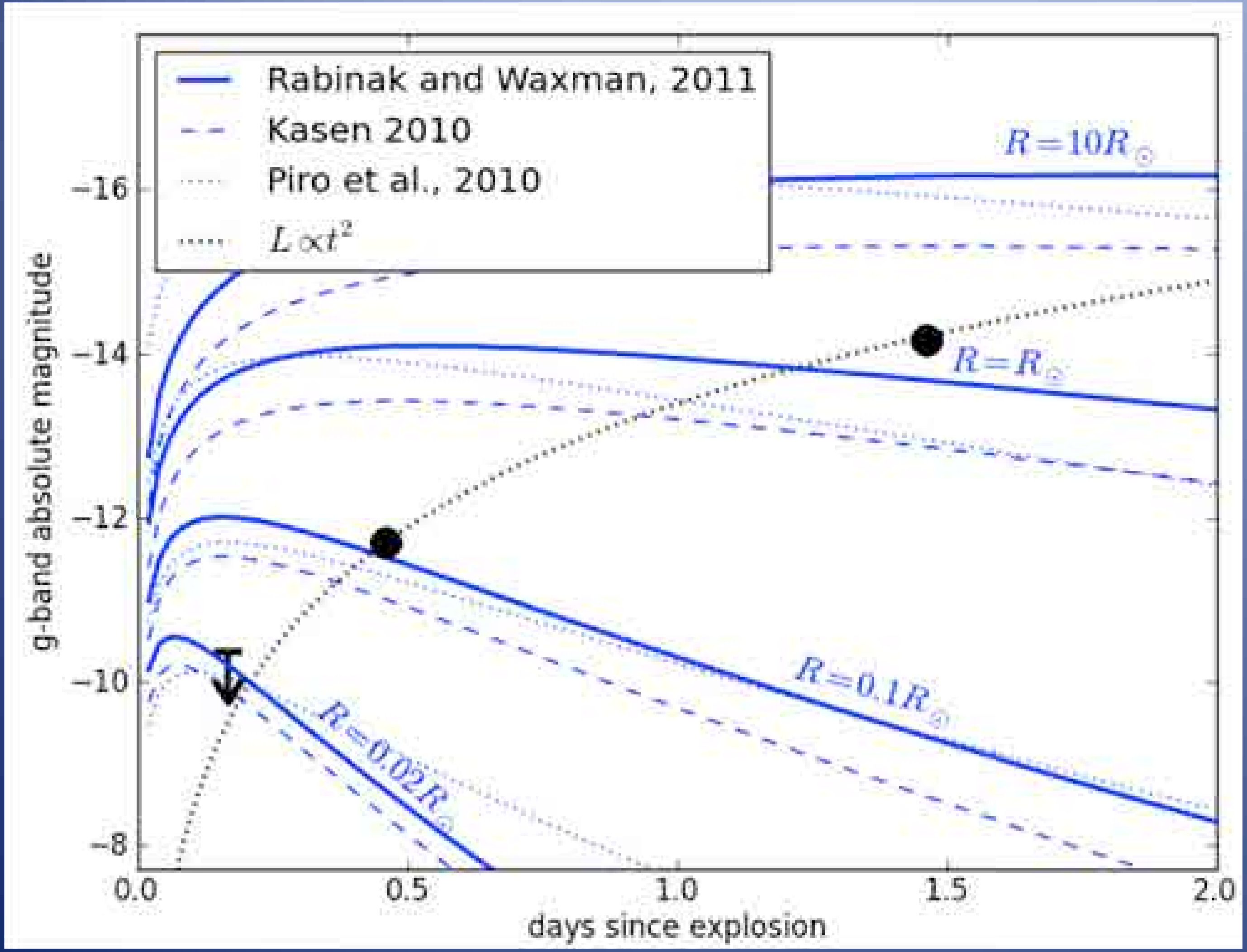


Open University observations on Mallorca only 4hrs after explosion.

Fakes put in assuming 4000K and 7000K blackbodies.

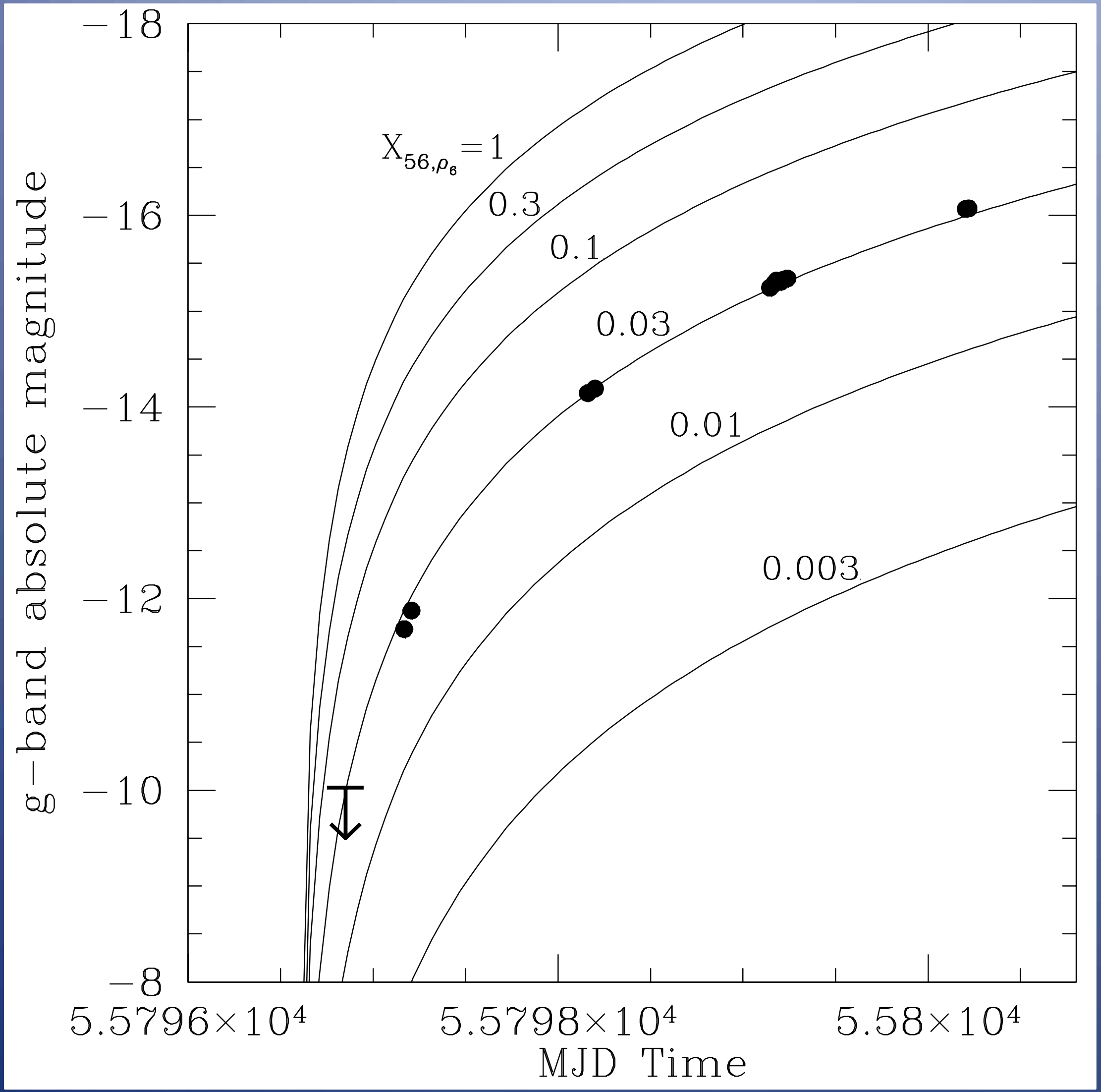
Constrains limiting magnitude to 19.0-19.5 in g-band

Bloom *et al.*, ApJL (2012)



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

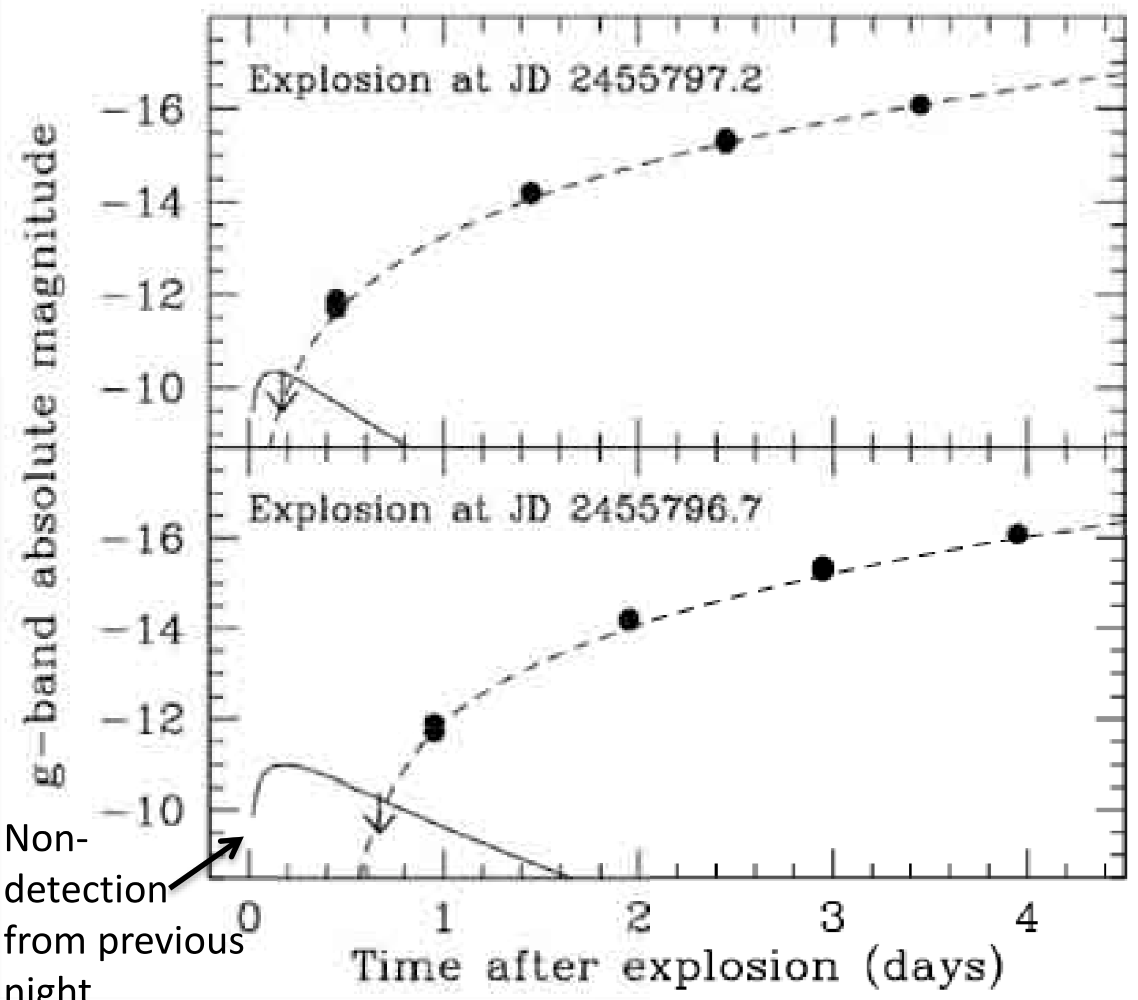
Bloom *et al.*, ApJL (2012)



Piro *et al*. (2012)

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...



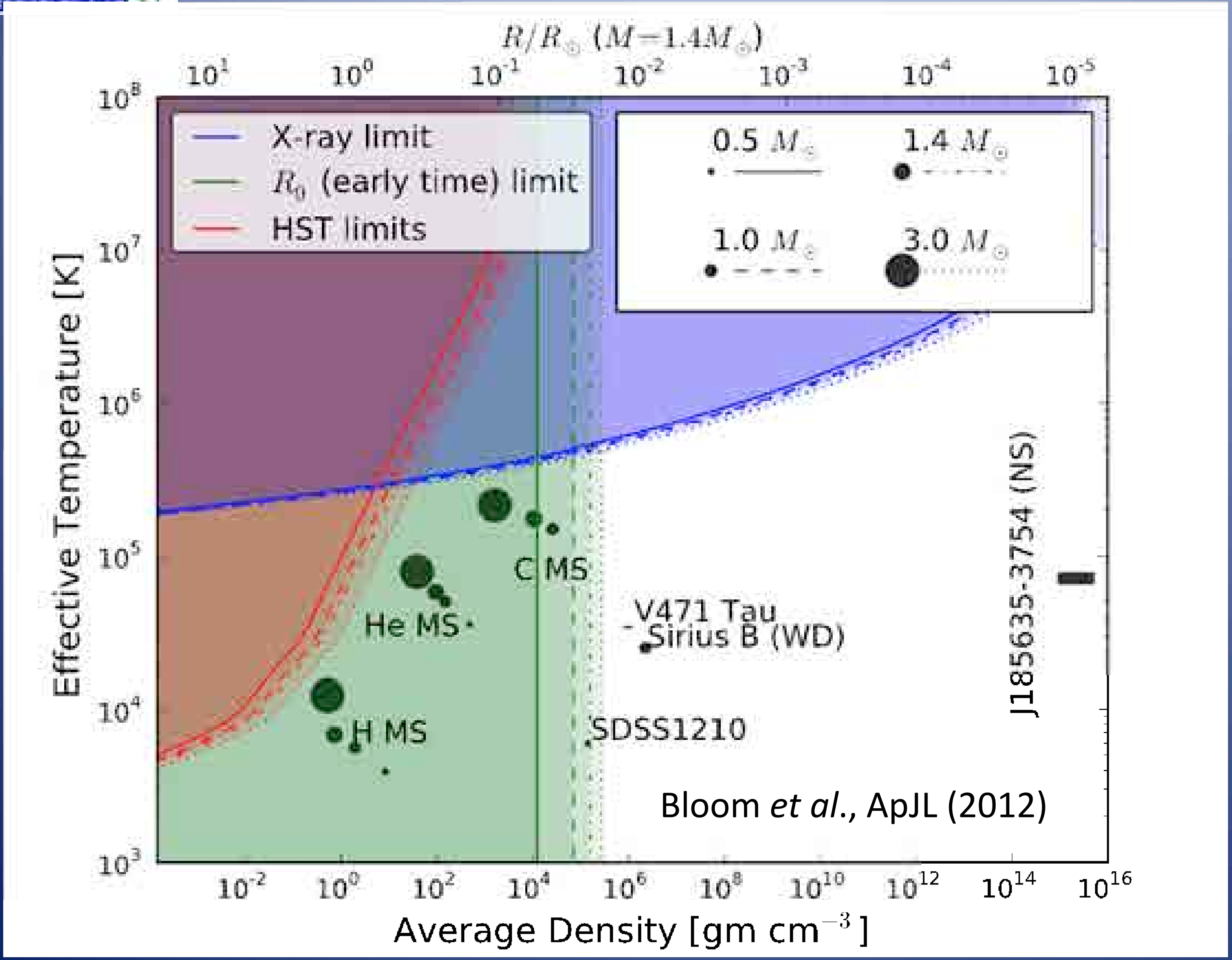
Non-detection from previous night

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

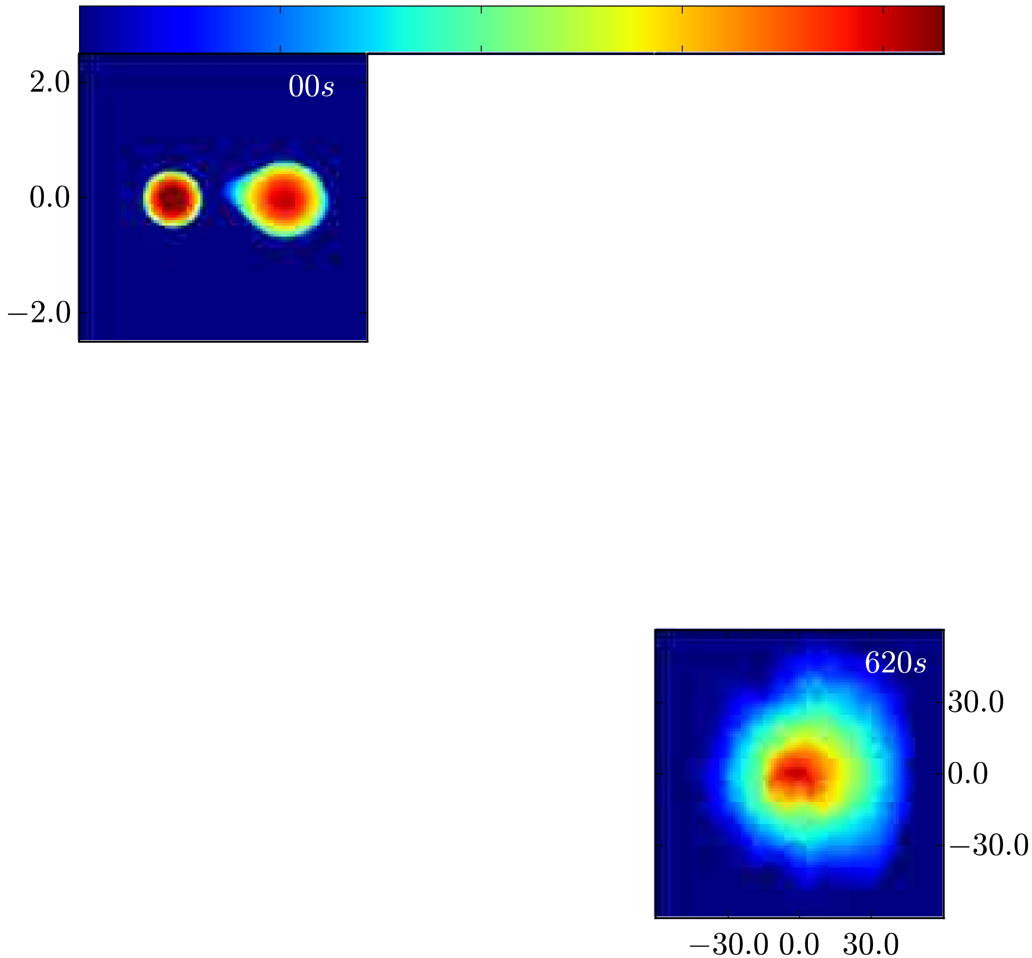
But there could be a "dark day".... adds more time and a possible cool down phase.

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

Piro & Nakar (2013)



Limits the progenitor to a WD or NS.

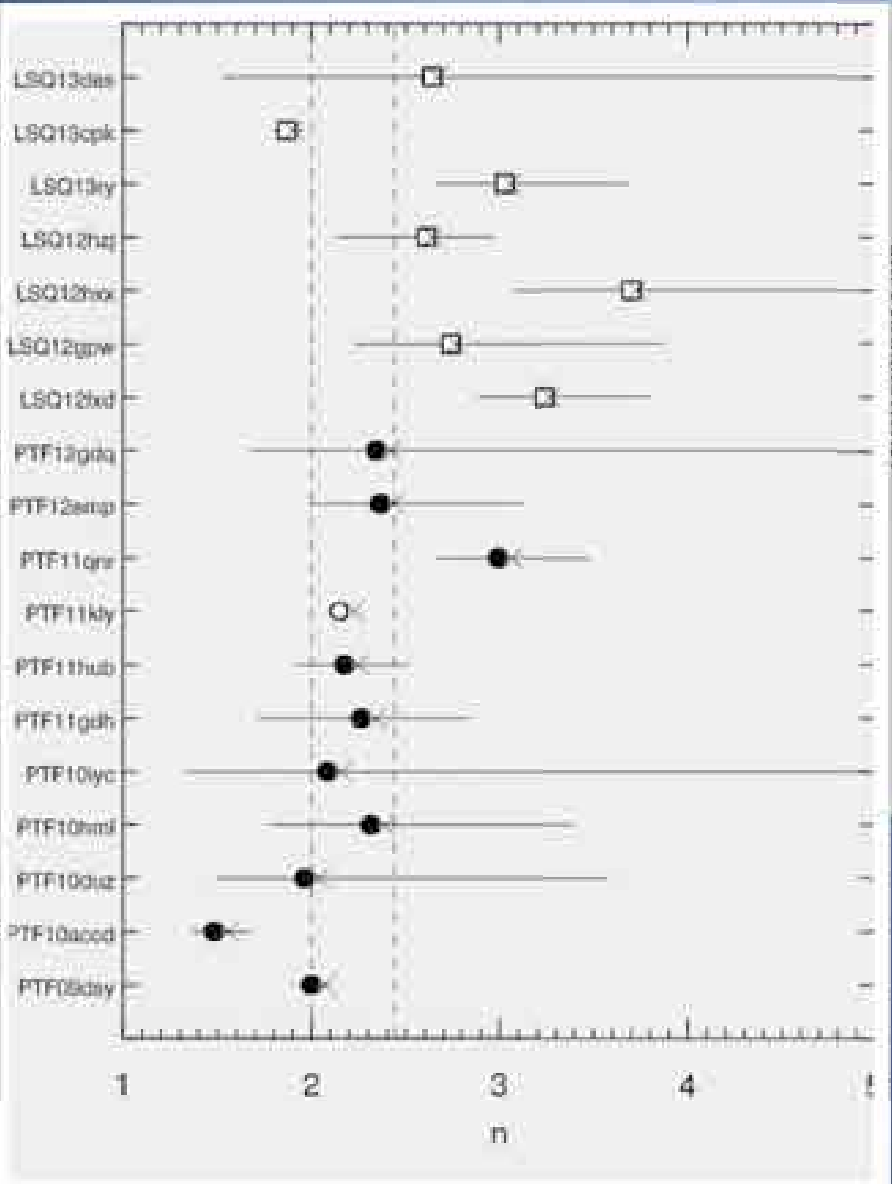


Companion from a WD+WD merger?

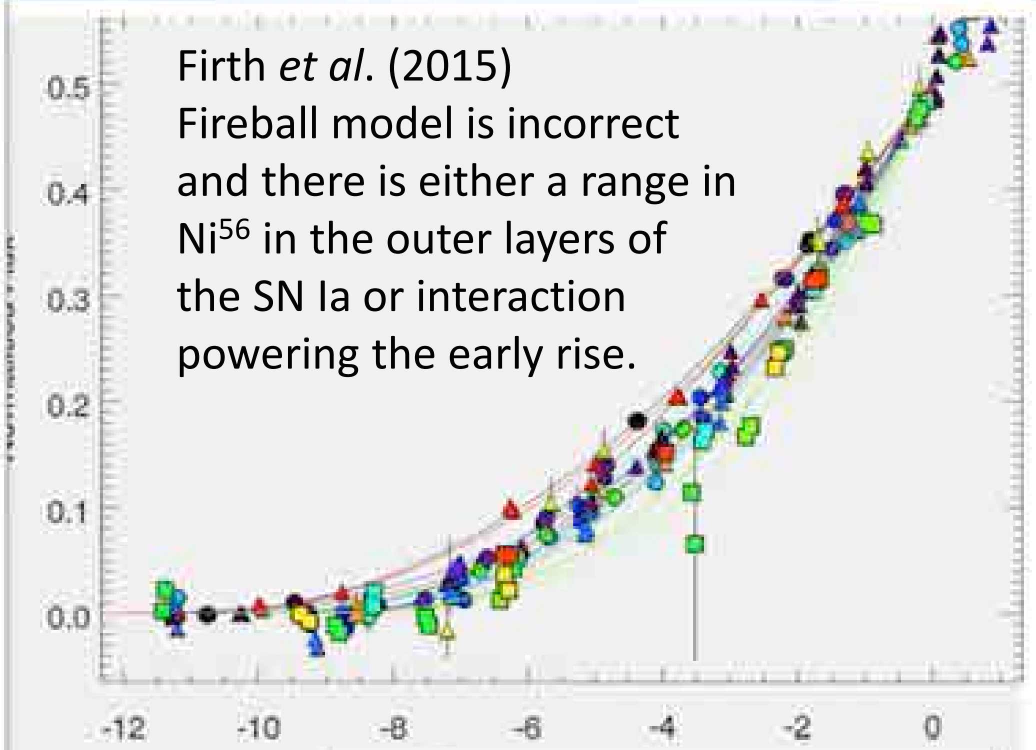
0.4 $R_\odot$ at as the detonation makes its way out…

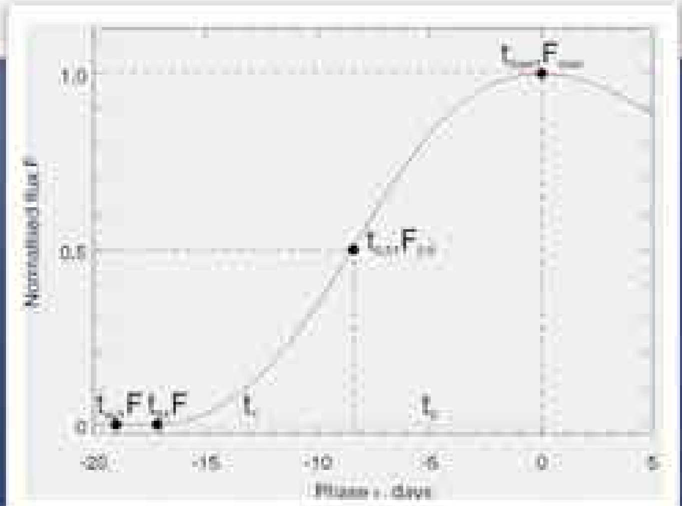
Pakmor *et al.*, (2012)

Sample of Early SNe Ia

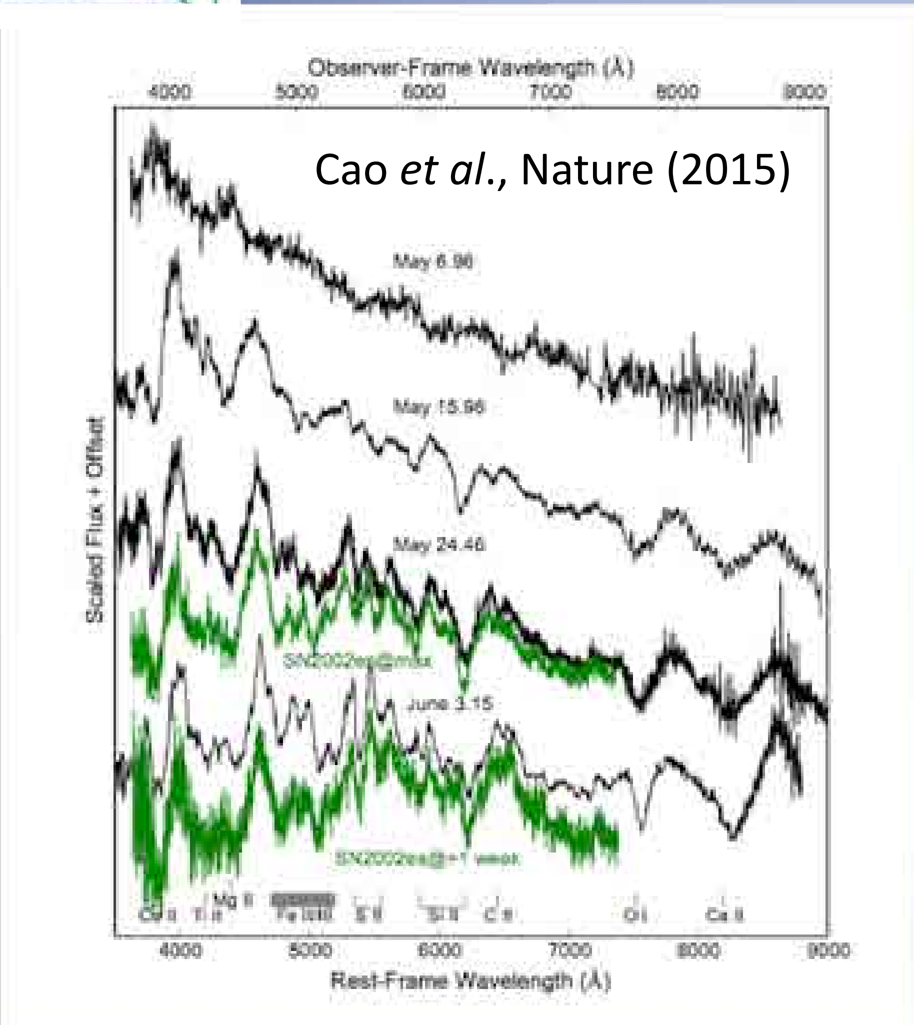


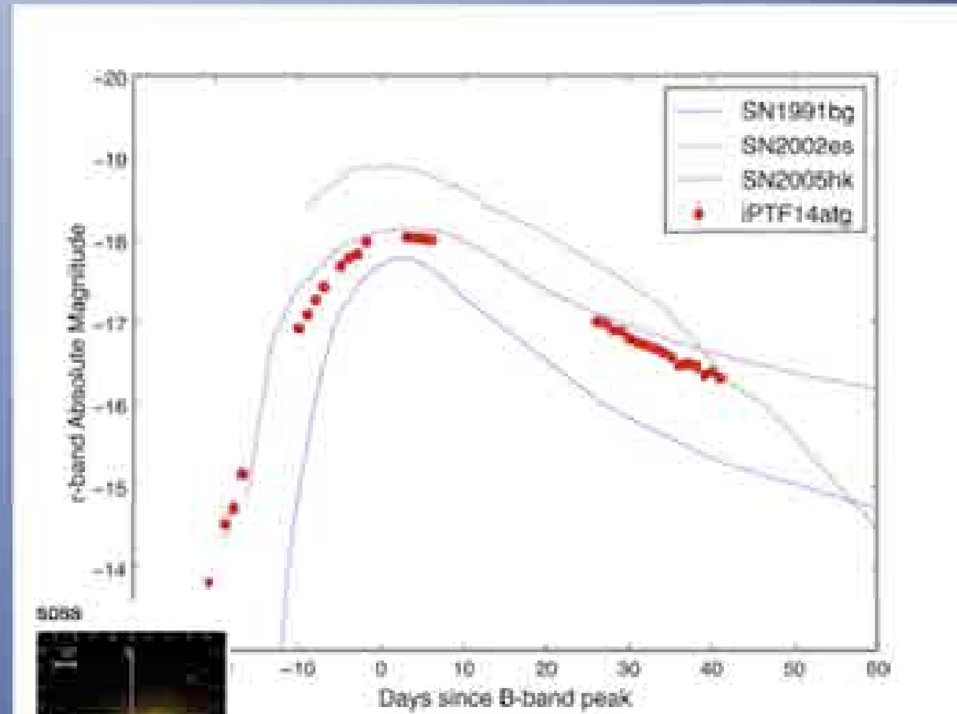
Firth *et al*. (2015)
Fireball model is incorrect and there is either a range in Ni^{56} in the outer layers of the SN Ia or interaction powering the early rise.

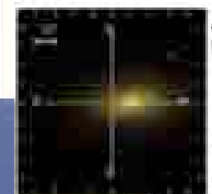


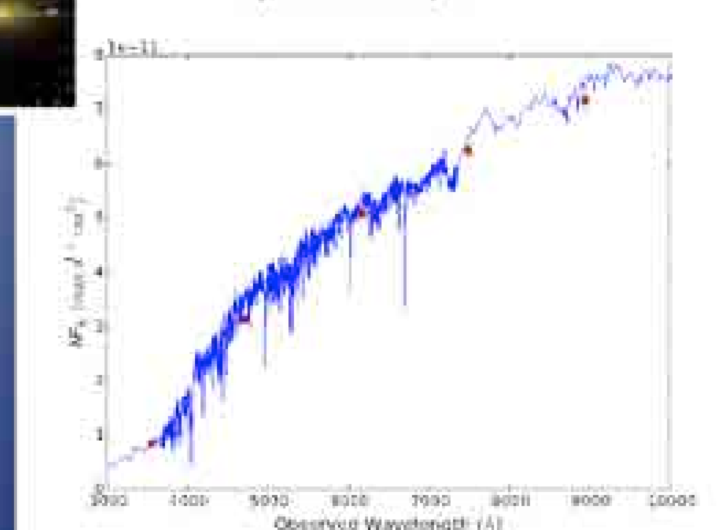


PTF14atg



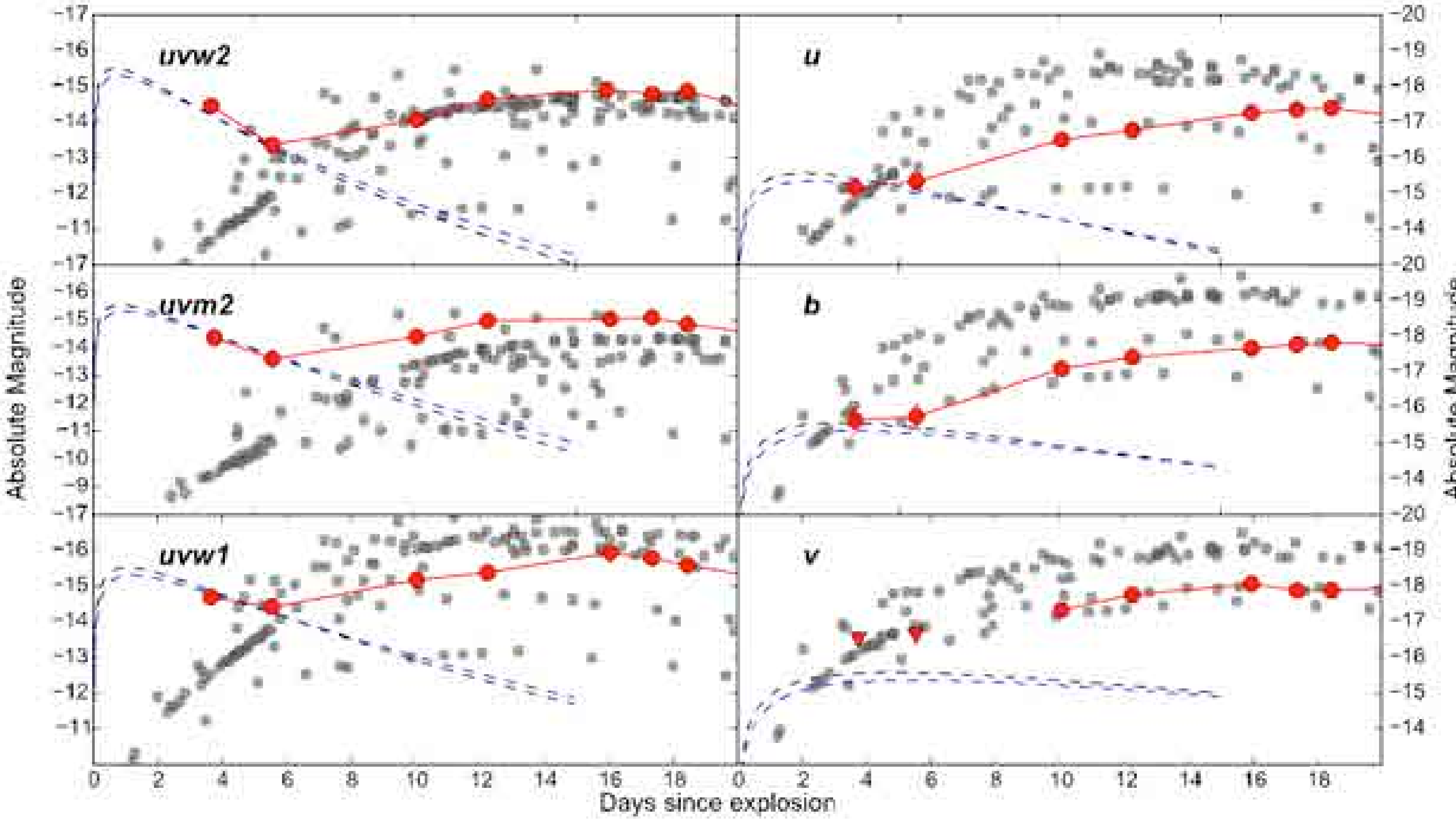






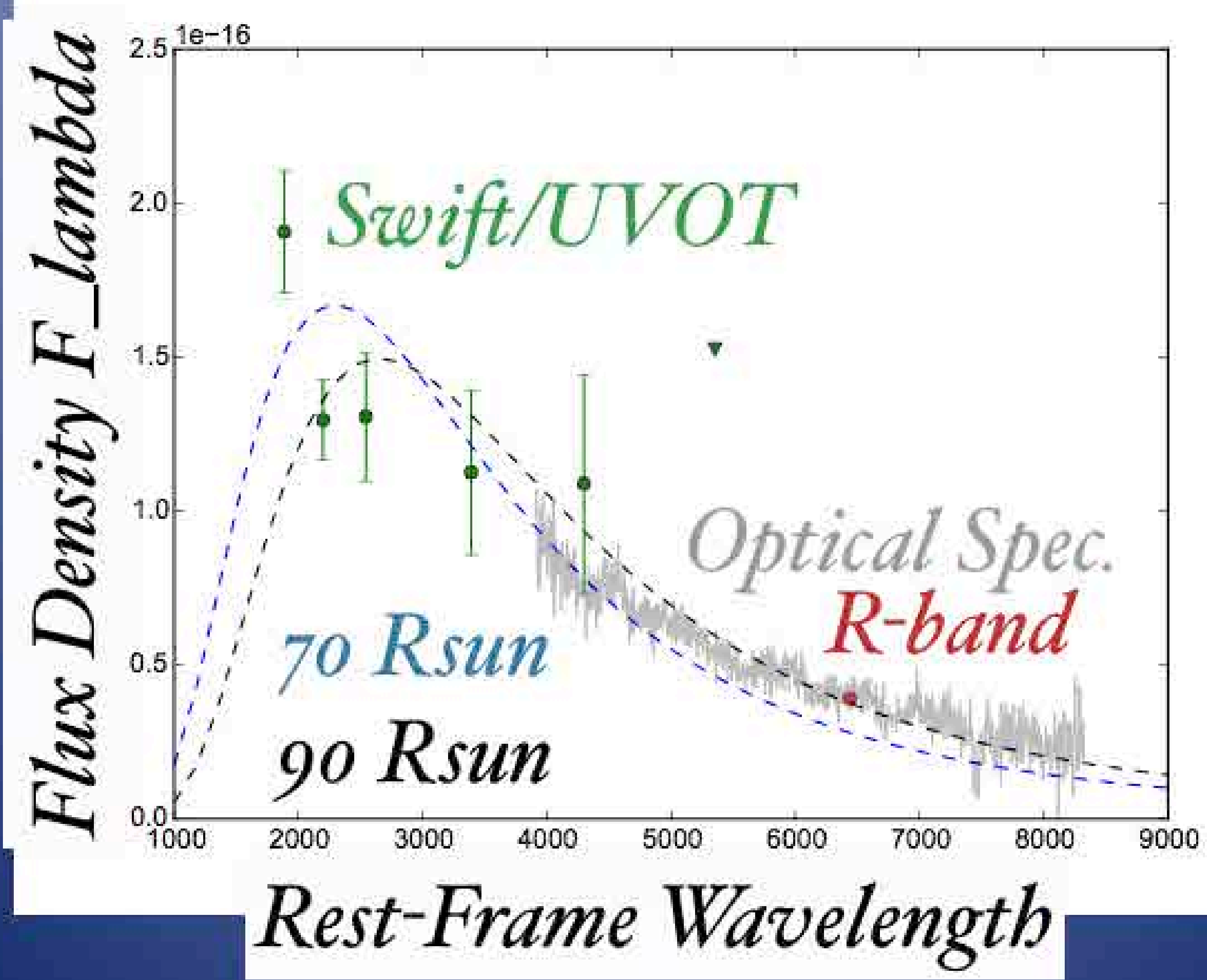
Interestingly, not a normal SN Ia, a low-velocity one like SN 2002es or SN 2005hk

PTF14atg



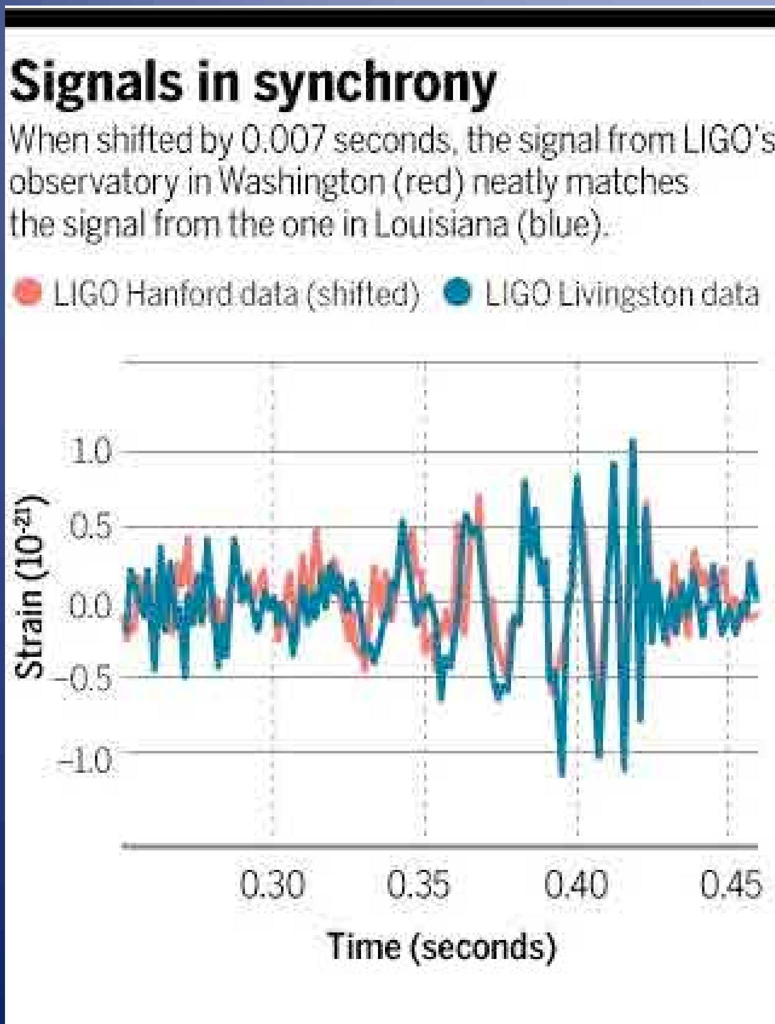
UV Luminosity ~3X10^{41} ergs/s

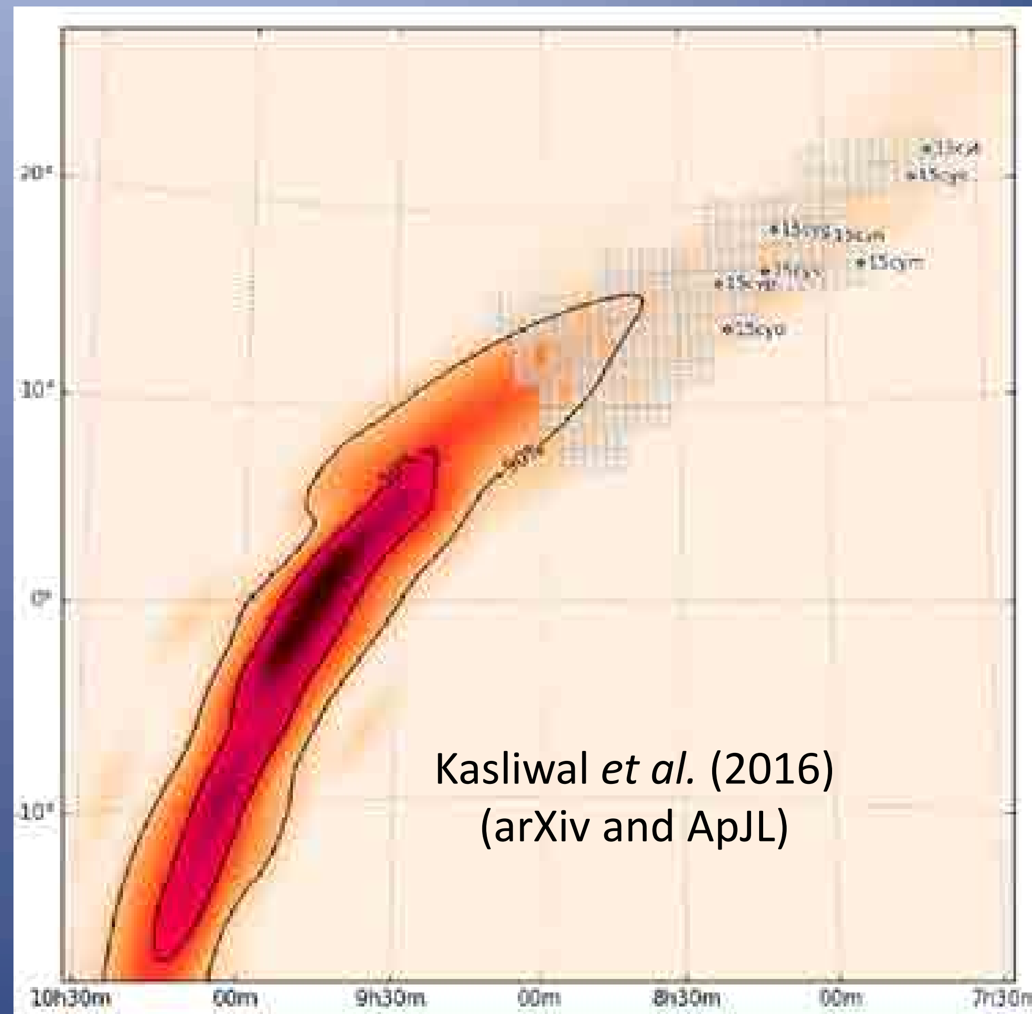
Companion at 70-90 $R_{\odot}$ away



Interaction w/ a companion

Gravitational Wave Trigger GW150914

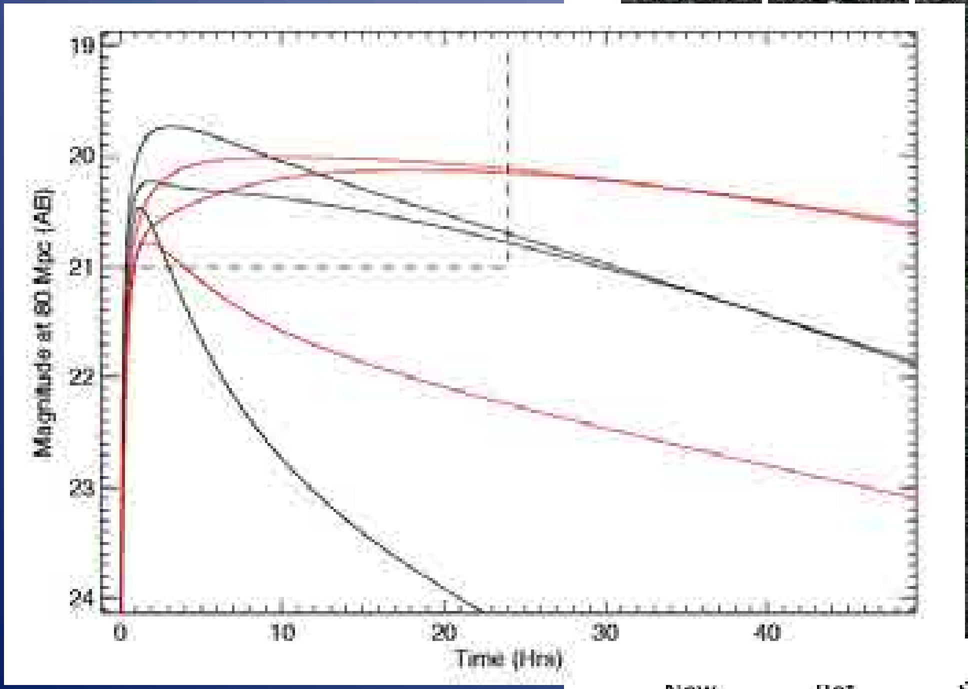


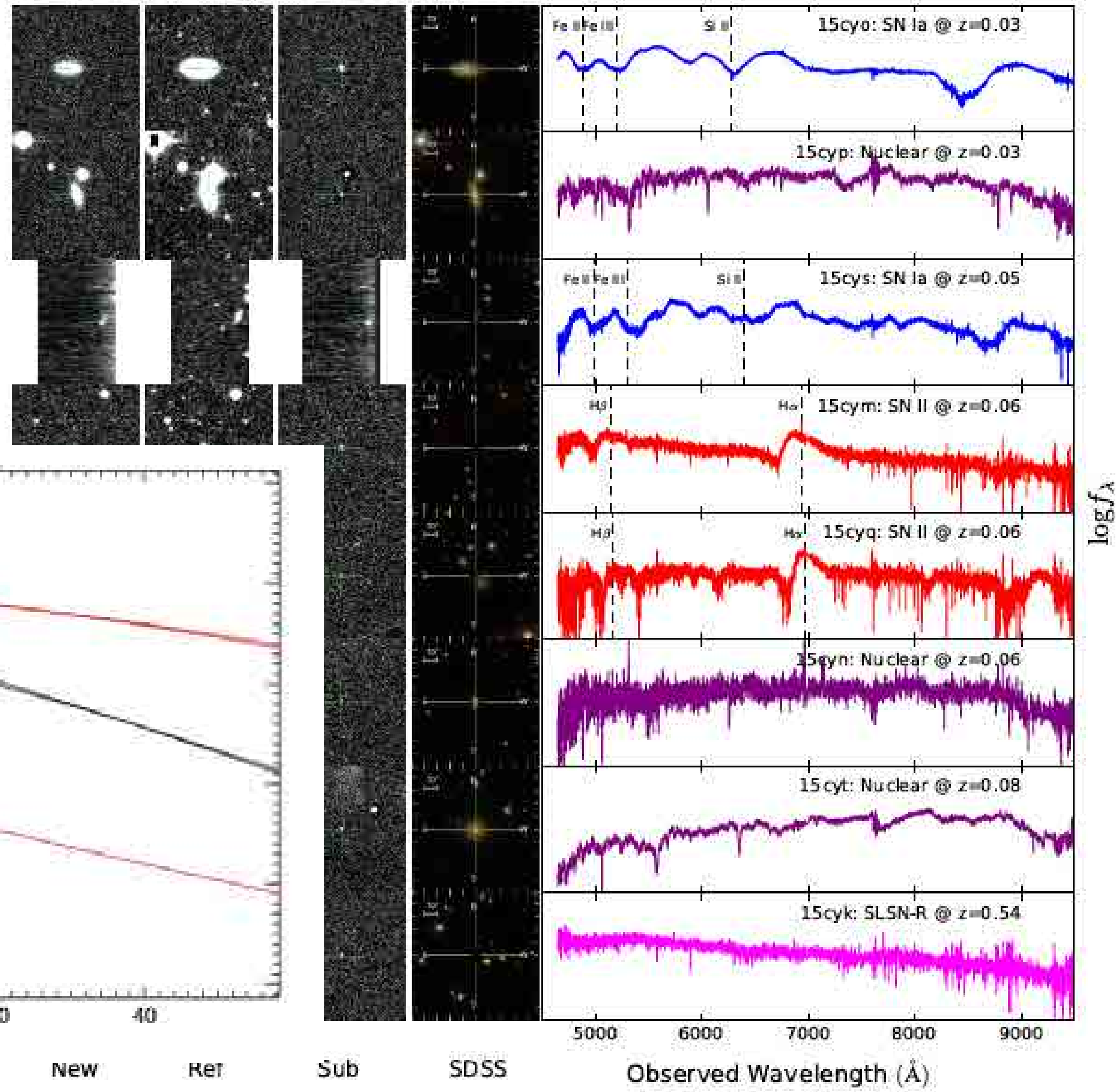


Kasliwal *et al.* (2016)
(arXiv and ApJL)

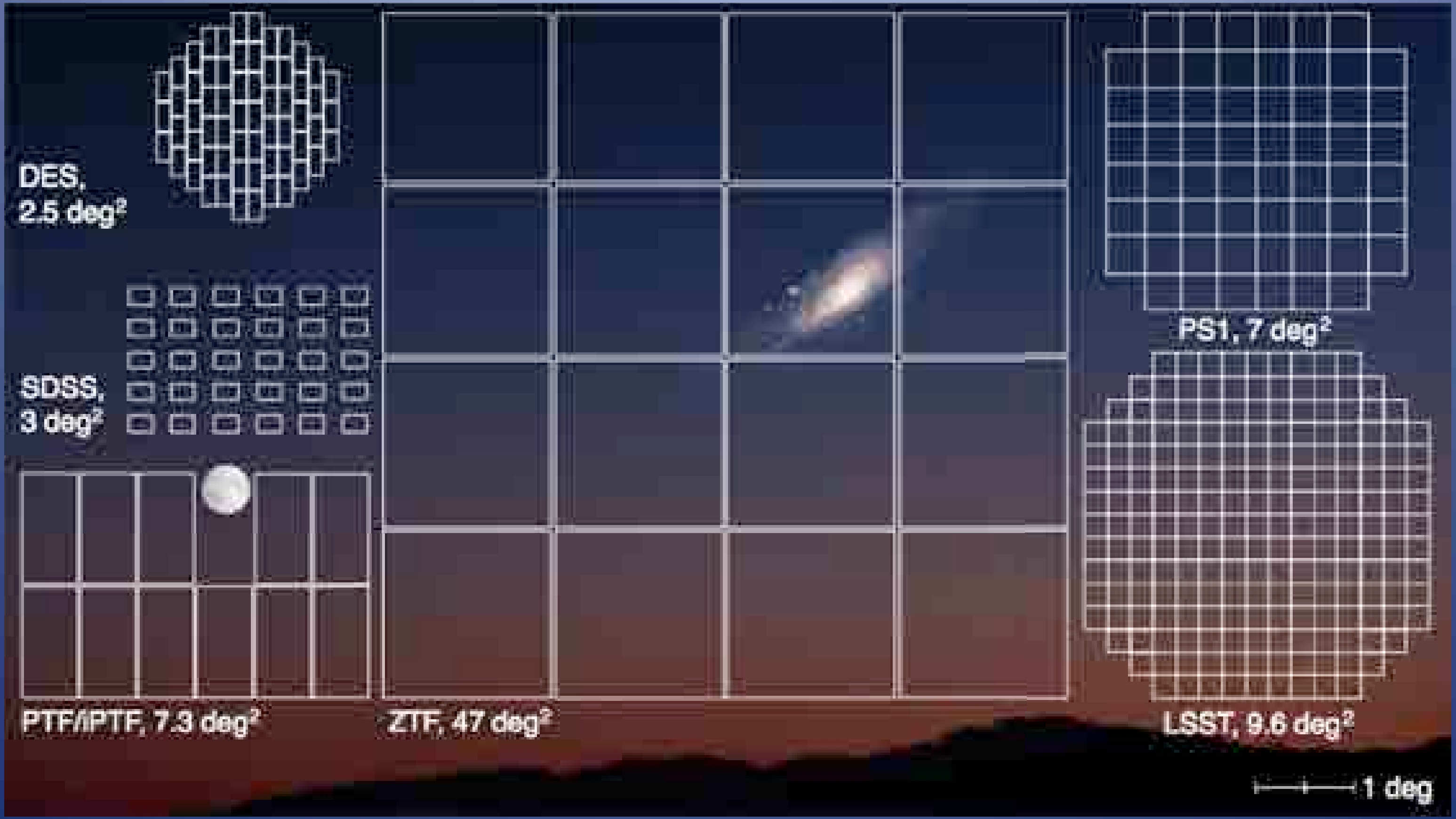
GW150914

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.





Zwicky Transient Facility



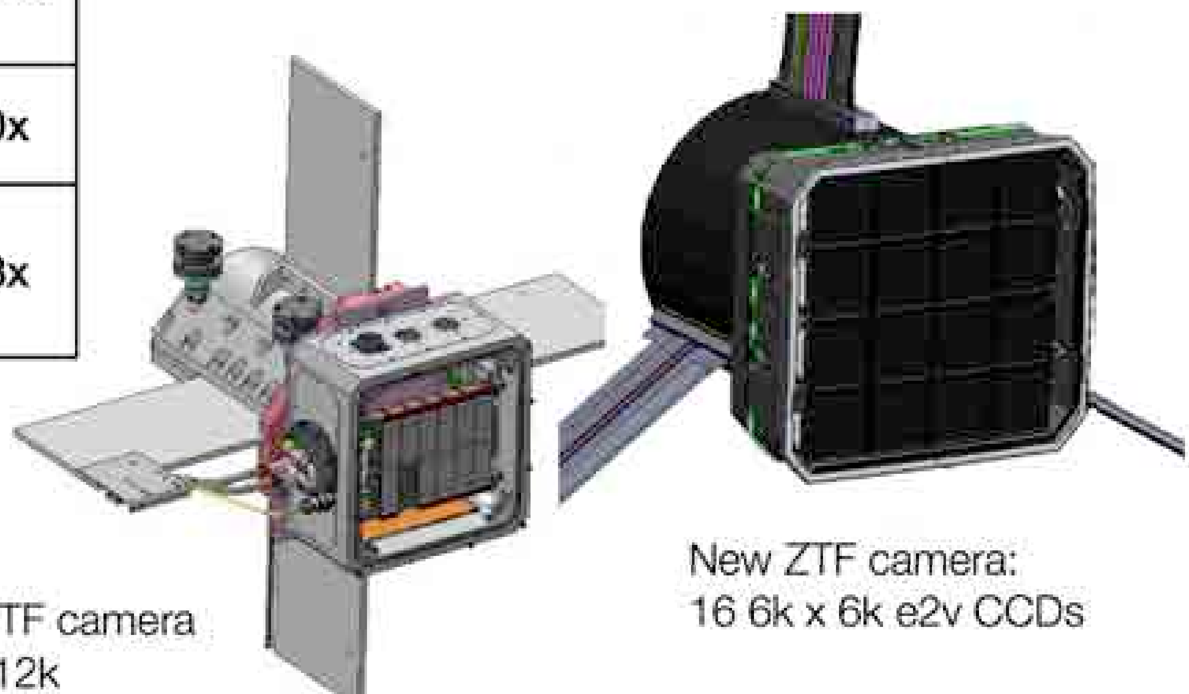
ZTF will survey an order of magnitude faster than PTF.

	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



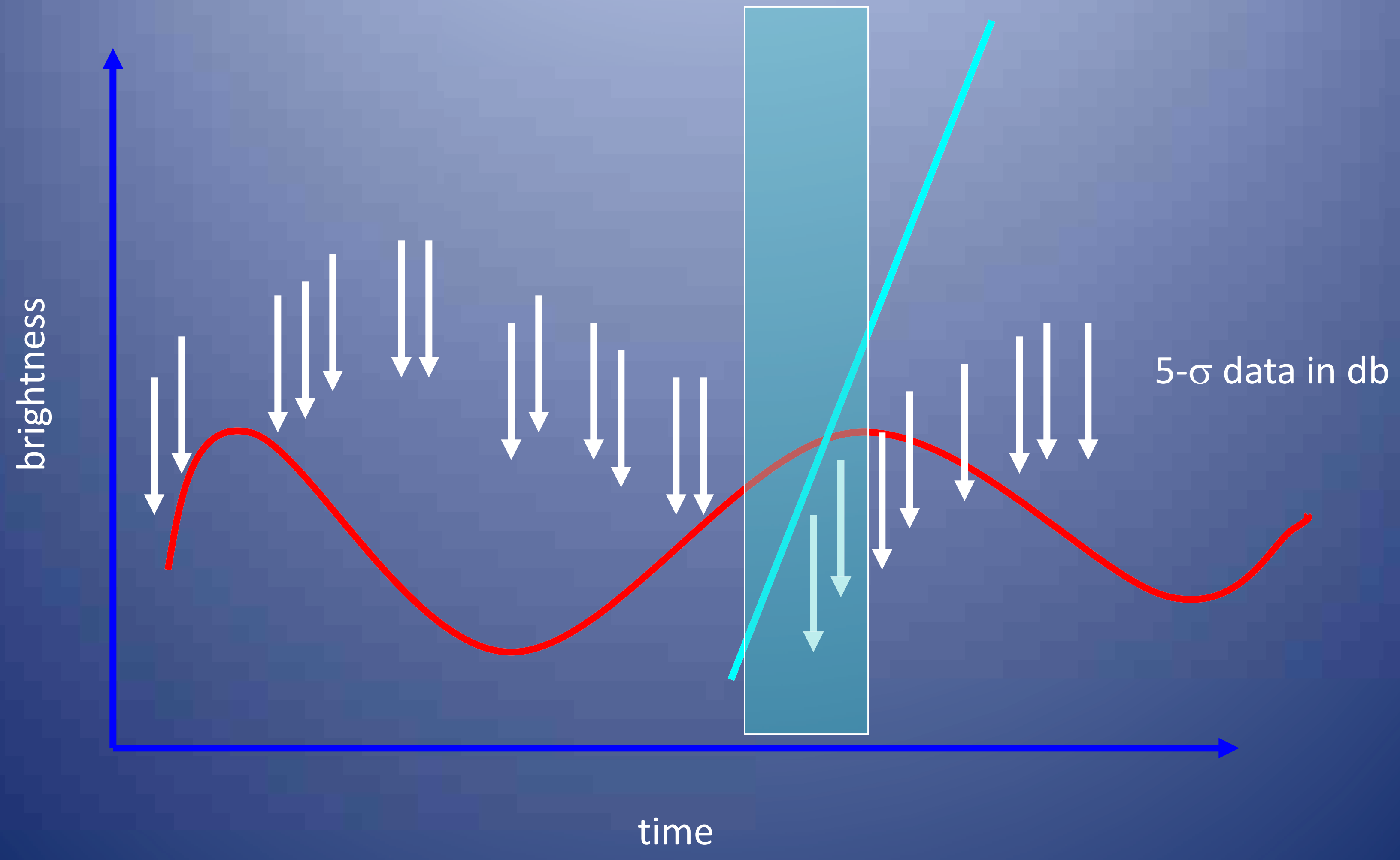
Existing PTF camera
MOSAIC 12k

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

Future

LSST - 15TB data/night
Only one 30-m telescope
How many triggers can we handle???

Bottlenecks…crude *vs*. real



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....