

# *The Restless Universe*

Optical (& Radio) Transients:

The Next Big Thing

[Palomar Transient Factory]

S. R. Kulkarni

Director, Caltech Optical Observatories

# Astronomy: Golden Age

- Extra-solar planets
  - Planet formation as a physical process
- Origin of the Universe
  - Very Early Universe
  - Origin of Dark Matter, Dark Energy
- Dense Matter
  - Nature's laboratory
- Relativistic Astrophysics

# Decade of Mega Projects

- ALMA (Millimeter Wave)
- James Webb Space Telescope (IR)
- Extremely Large Telescopes (Optical)
- Laser interferometer Gravitational wave observatory
- Large Synoptic Survey Telescope
- Laser interferometer space Array
- Square Kilometer Array (Radio)

# **A SIDEWAYS REVOLUTION**









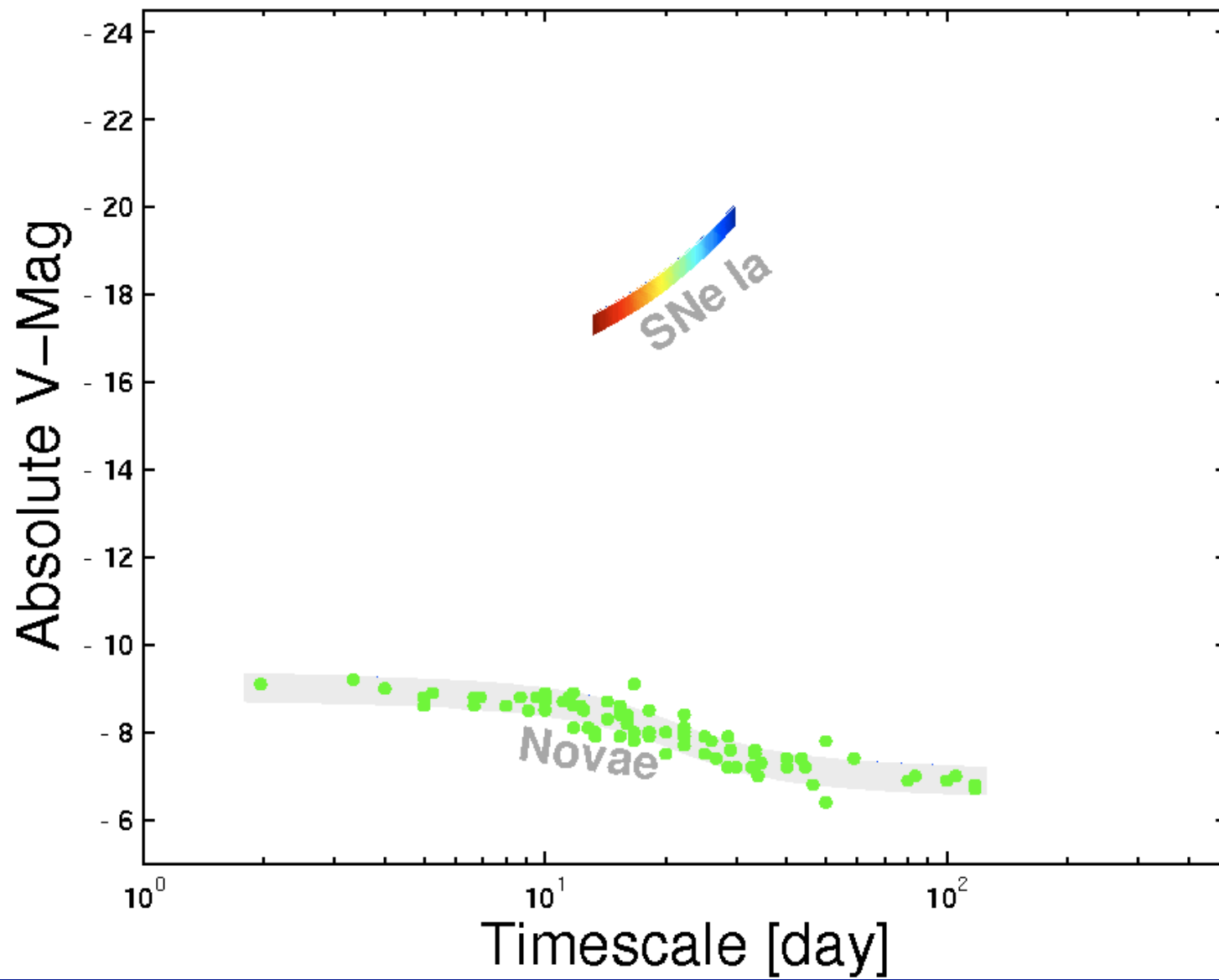
# Organization of the talk

- I. Transients in the nearby universe
- II. The Palomar Transient Factory
- III. Results from the Factory
- IV. The future

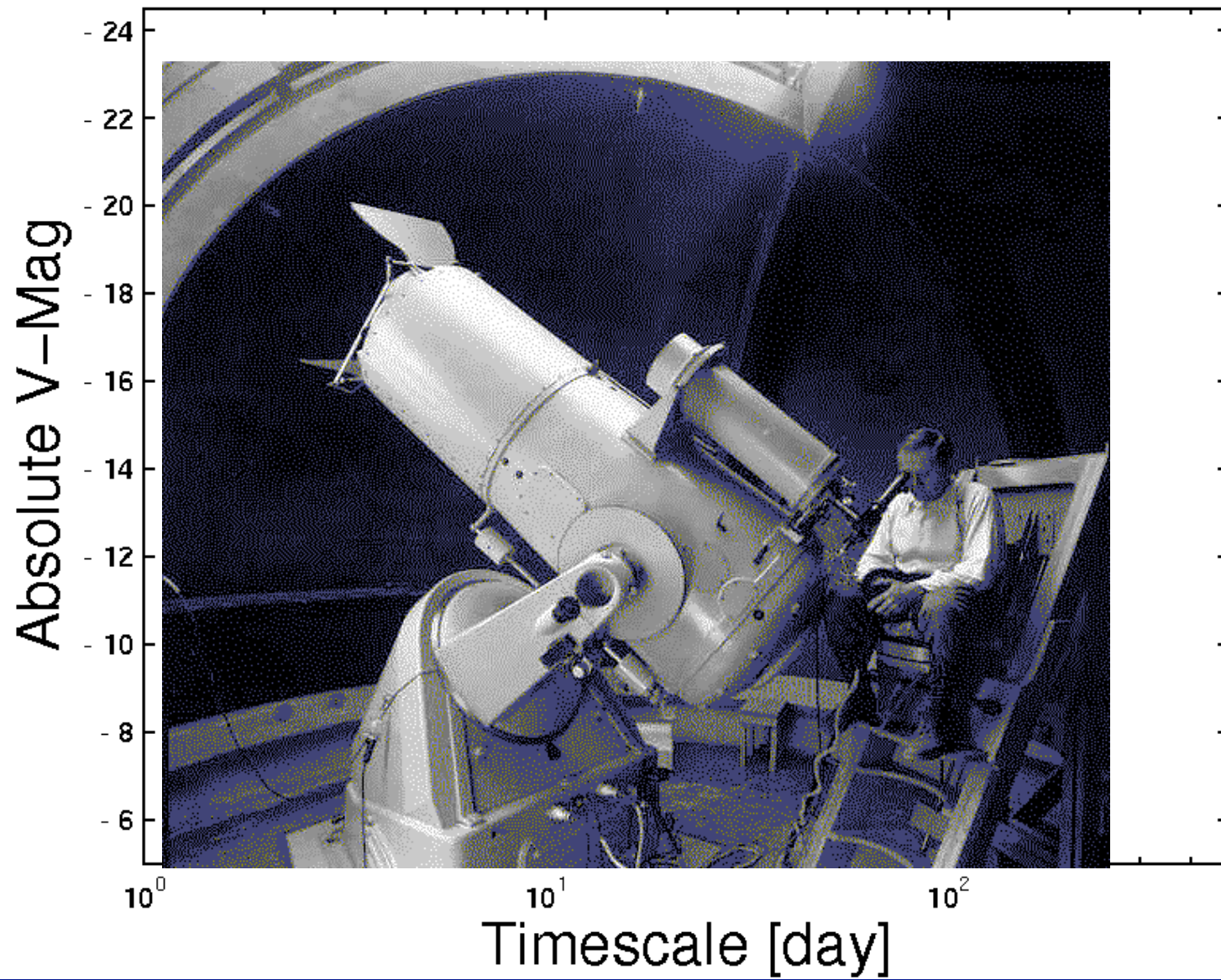
# I. Transients in the Local Universe

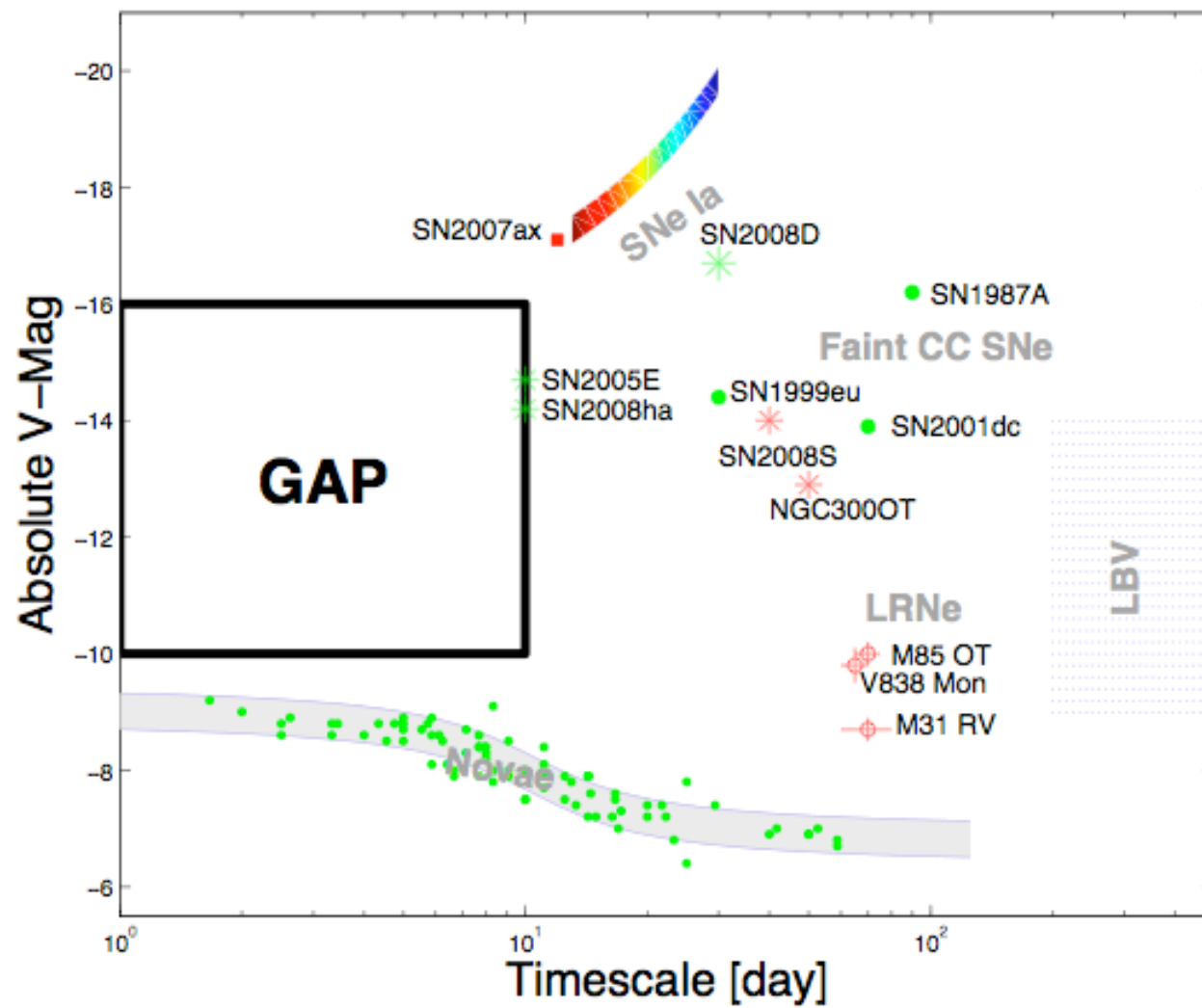
# Frontier Fields

- Ultra-high energy cosmic rays
  - GZK cutoff (proton-photon pion production)
- High Energy Neutrino Astronomy
- TeV Sources
  - Pair production on CMB photons
- GW Sources (100 Hz band)
  - eLIGO (2009), aLIGO (2013)
- Transients in the Nova-Supernova Gap



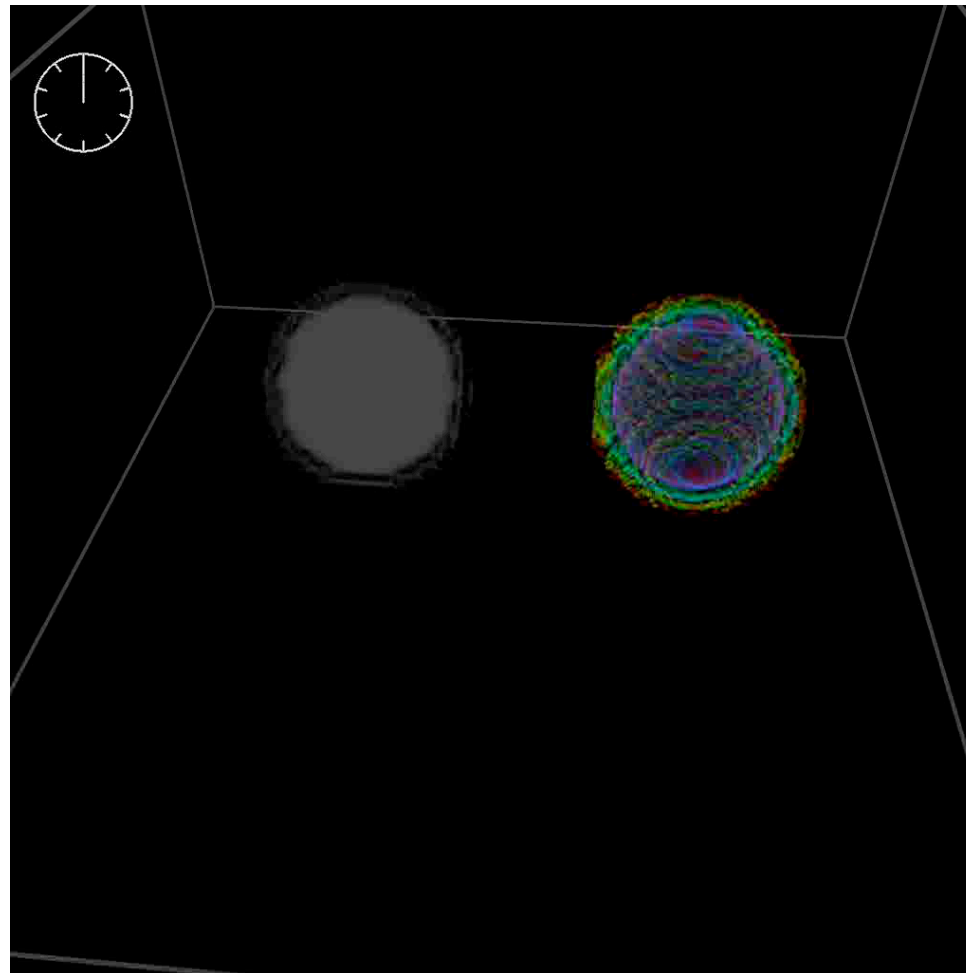


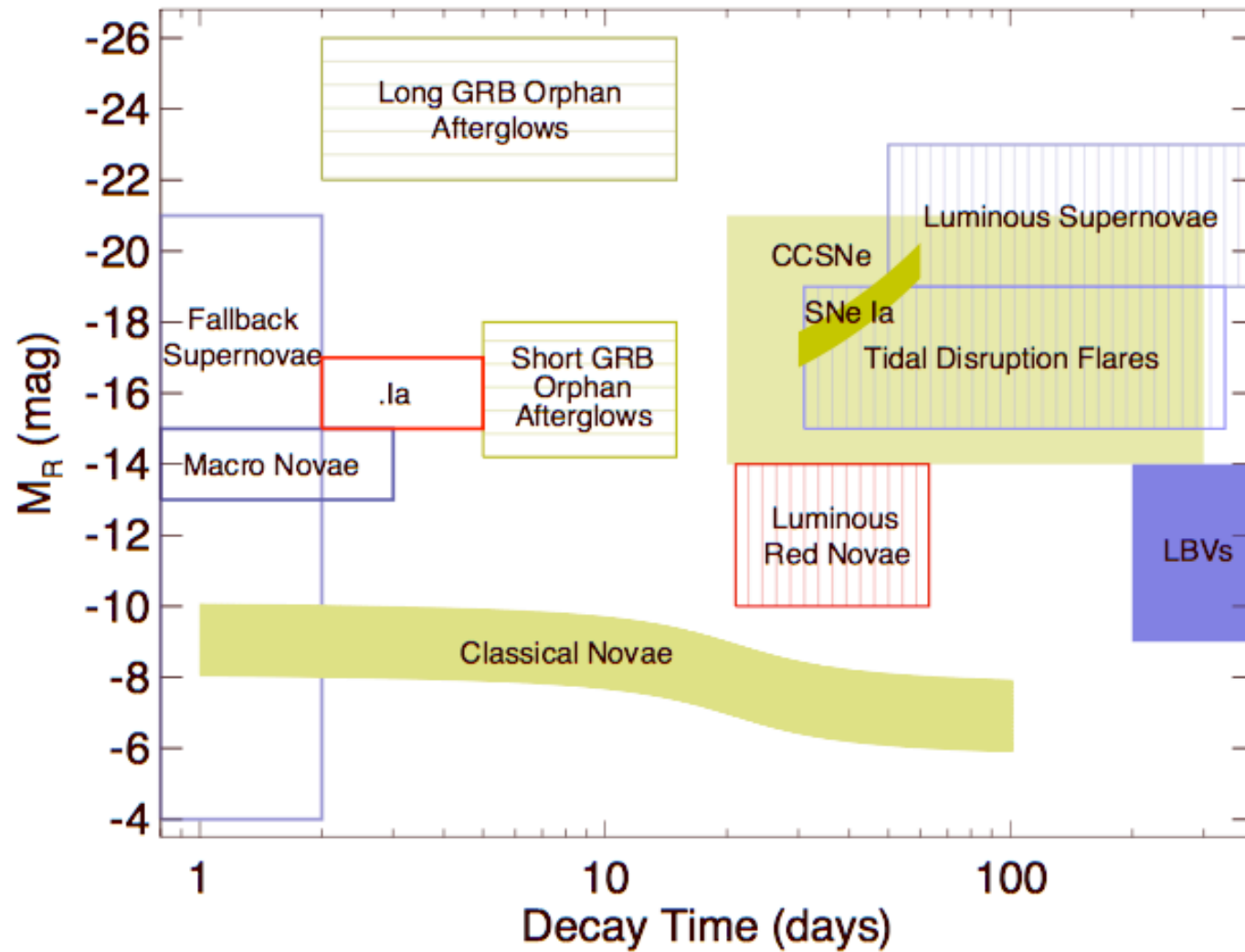






# The Holy Grail

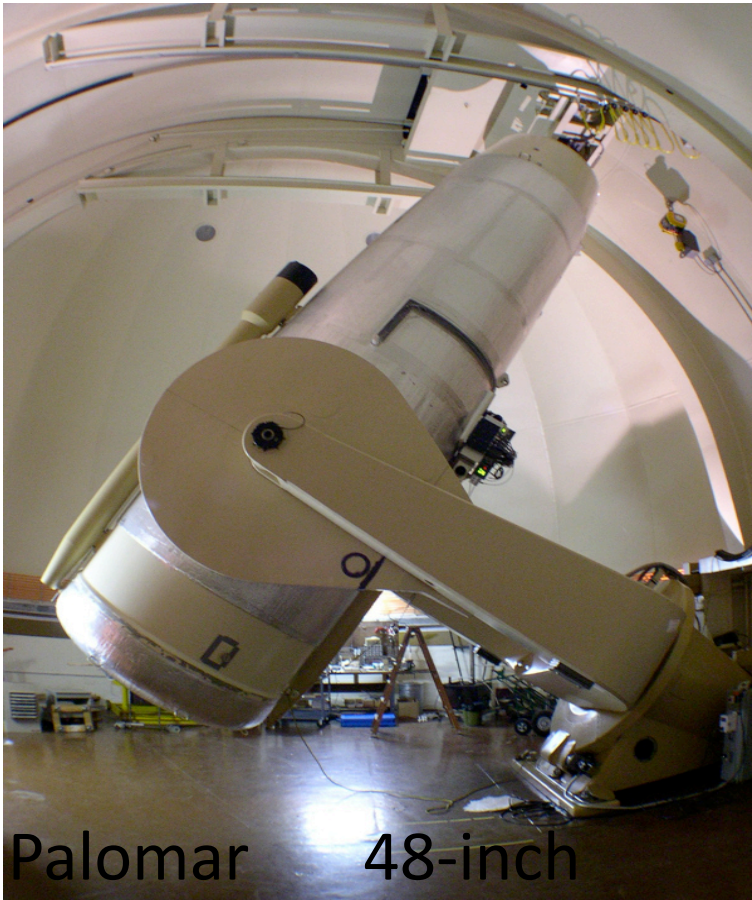




# II. Palomar Transient Factory Overview

S. R. Kulkarni  
Principal Investigator  
and the PTF collaboration

# A Novel Two-telescope Approach





# PTF collaboration



Caltech, LCOGT, Berkeley, LBL, IPAC, Columbia, Oxford, Weizmann

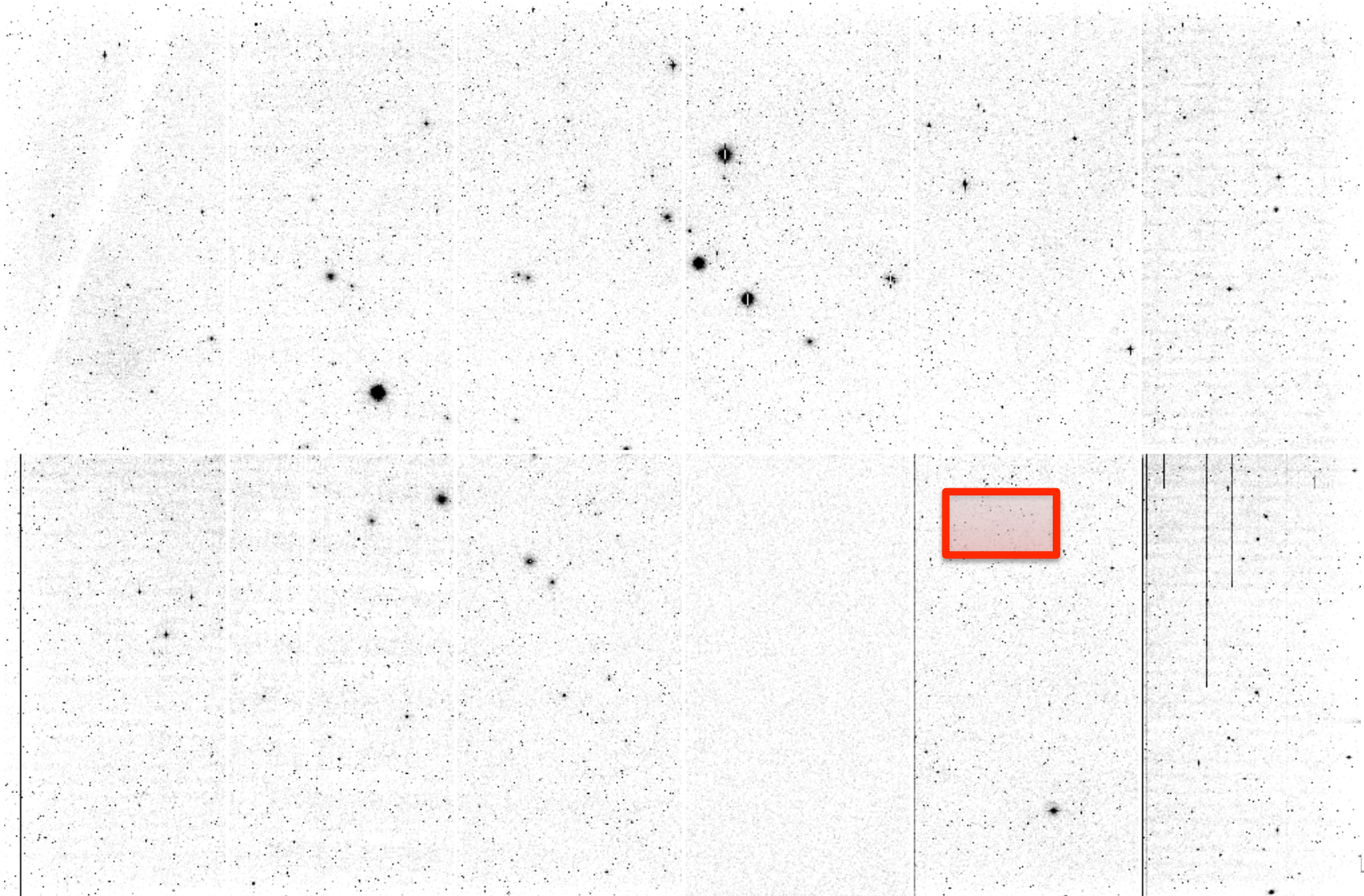


# PTF overview

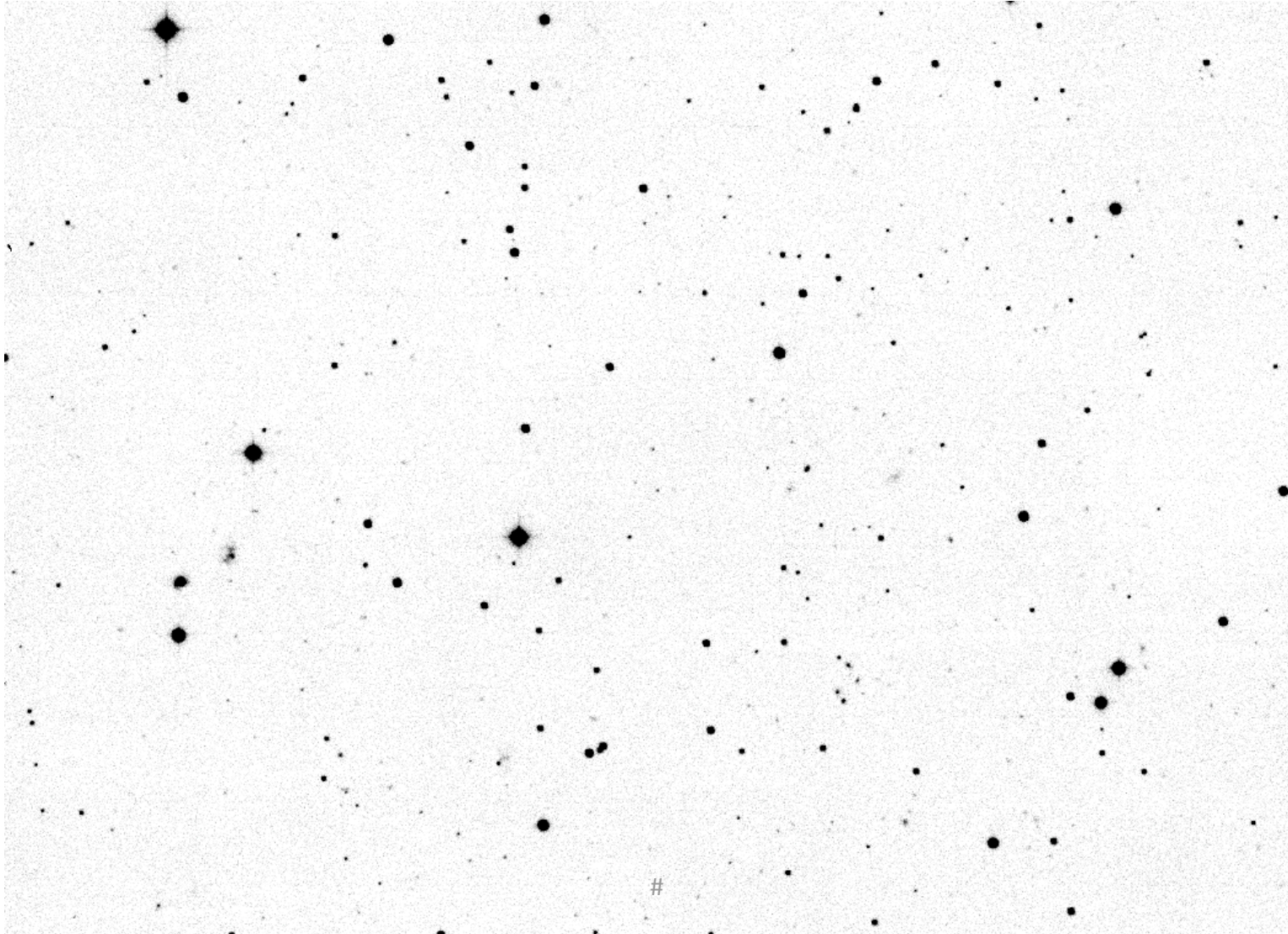
- ★ First light: December 2008
- ★ First science run: March 2009  
Finish Commissioning: late June
- ★ Typical seeing  $\sim 1.8''$  (best  $1.4''$ )
- ★ Lim. Mag ( $5\sigma$ )  $\sim 21$  in g,R



# PTF overview



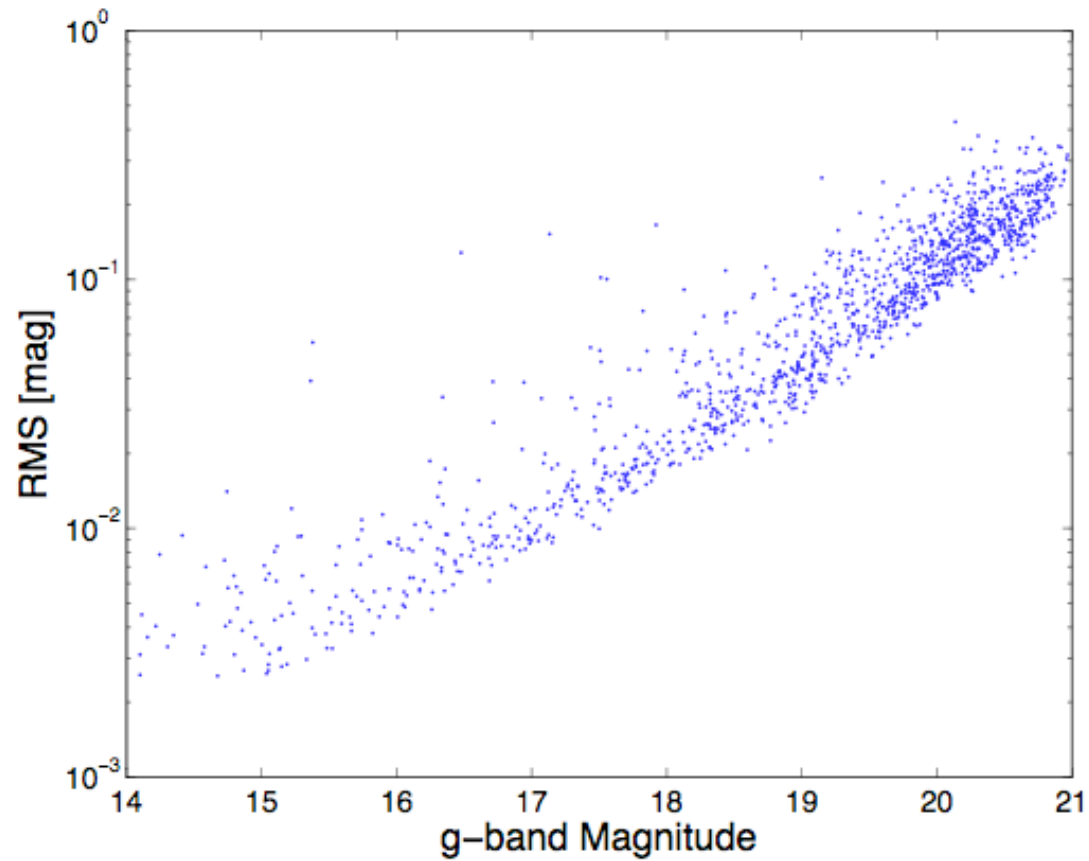
# PTF overview



#



# Relative Photometry (precision!)



Ofek

# PTF software

- ★ Robotic operations
- ★ Robust and Long lived Sequencer
- ★ Two separate pipelines

LBL image subtraction pipeline

IPAC images and catalogue pipeline

# Image subtraction

## LBL image subtraction pipeline (Nugent)

- ★ Challenge: 0.5-1 M sources detected in Subtracted images each night!
- ★ after cleaning - large number of candidates (~10%)

# Berkeley classification

Lead by J. Bloom

★ Only a few percent of "events" are real!

★ Solutions:

Machine vetting

Humans vetting

Scientists

Public (SN Zoo)

★ Next: Transients need to be classified  
context (host galaxies)  
previous history  
other catalogs etc

# IPAC images & catalogue pipeline

Lead by J. Surace

★ Data products:

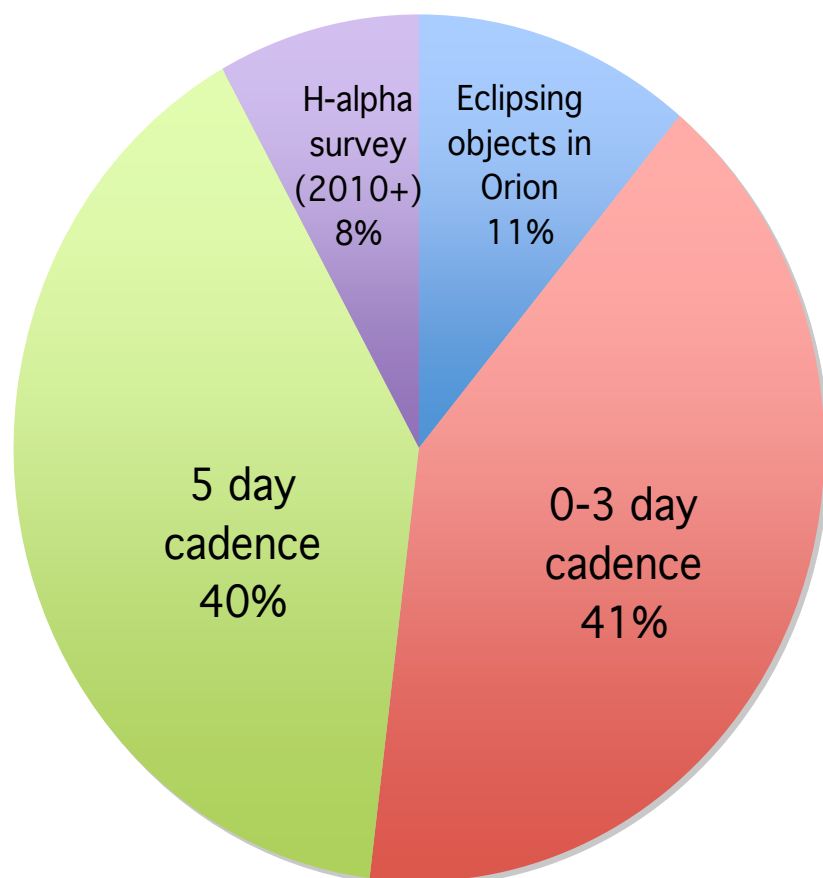
Reduced images

~100TB per year

Catalogue

~ $10^{12}$  sources per year (10 TB)

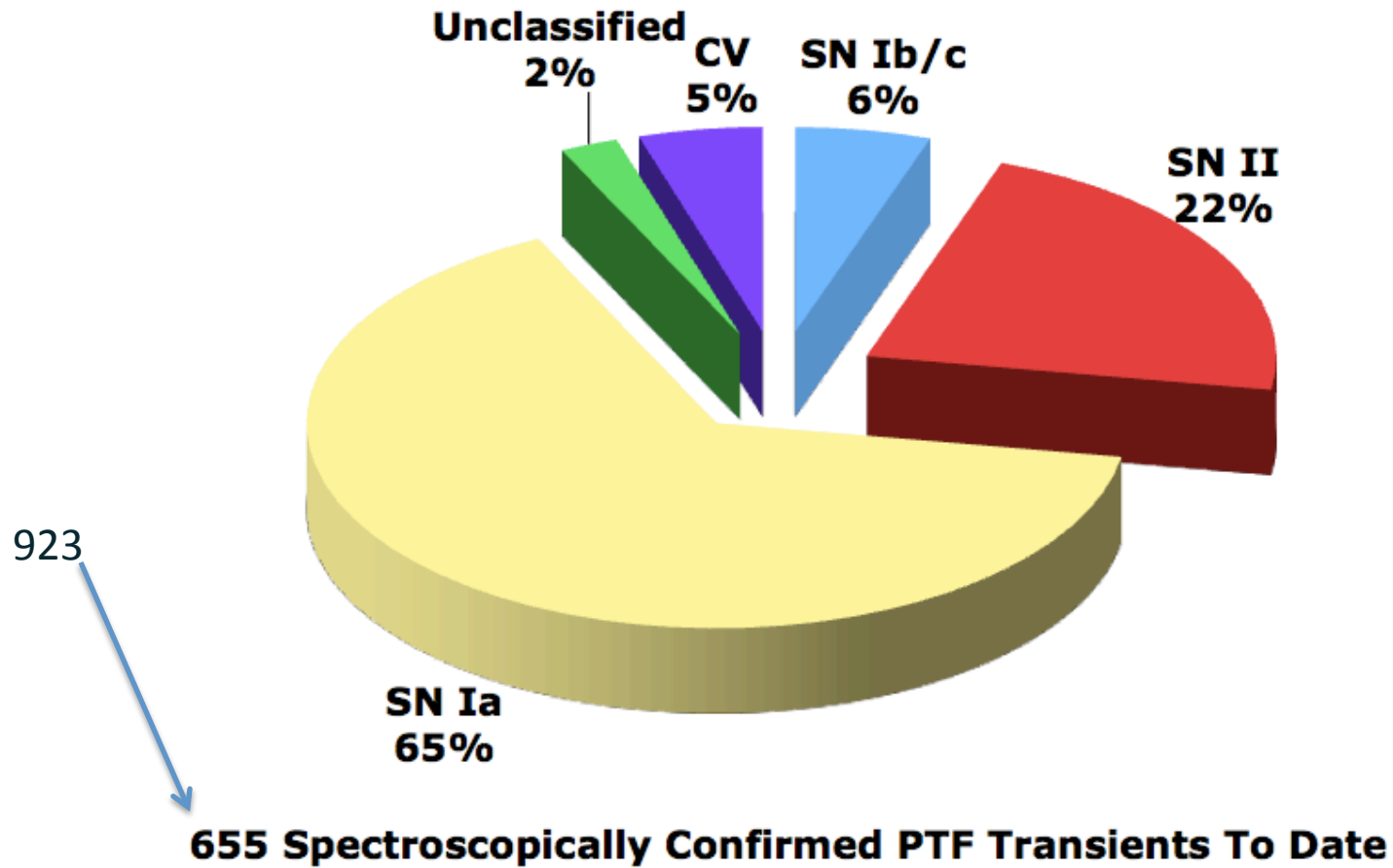
# PTF projects



## PTF Key Projects

Transients in nearby galaxies	Search for eLIGO/neutrino EM counterpart
Thermonuclear SNe	Core Collapse SNe
Blazars/AGN	Tidal Disruption Flares
H-alpha Sky Survey	Orphan GRB afterglow
AM CVn	CVs
Galactic dynamics	RR Lyrae
Flare stars	Rotation in clusters
Nearby Star Kinematics	Eclipsing stars and planets
Asteroids	KBOs

# PTF haul (to date)



### III. Some Results from PTF



# Shock break out

## Supernova: Five Stages in the Death of a Star

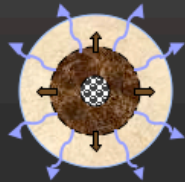
### 1. Just before explosion

A red super-giant star approaches the end of its life. There is no more fuel to burn and make it shine. Soon its massive dense core is bound to collapse under its own weight.



### 2. The first light flash

The core collapses and sends a shock wave out. For a few hours the shock compresses and heats the envelope, thus producing a very bright flash of light from the inside of the star.



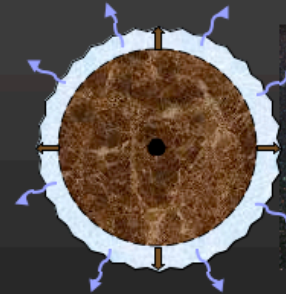
### 3. The flash has gone

After hitting the surface at 50 million km/h the shock blows the star apart. The core turns into a neutron star, a compact atomic nucleus with the mass of the Sun but 10 km in size.



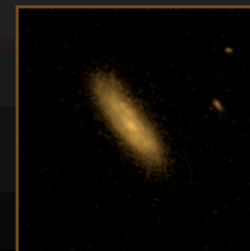
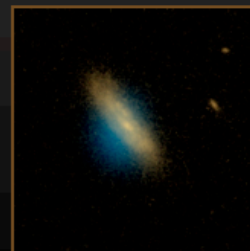
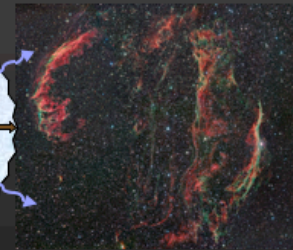
### 4. The proper Supernova

The hot glowing surface expands quickly making the fireball brighter again. In a few days it will be 10x the size of the original star and will be discovered by supernova hunters.

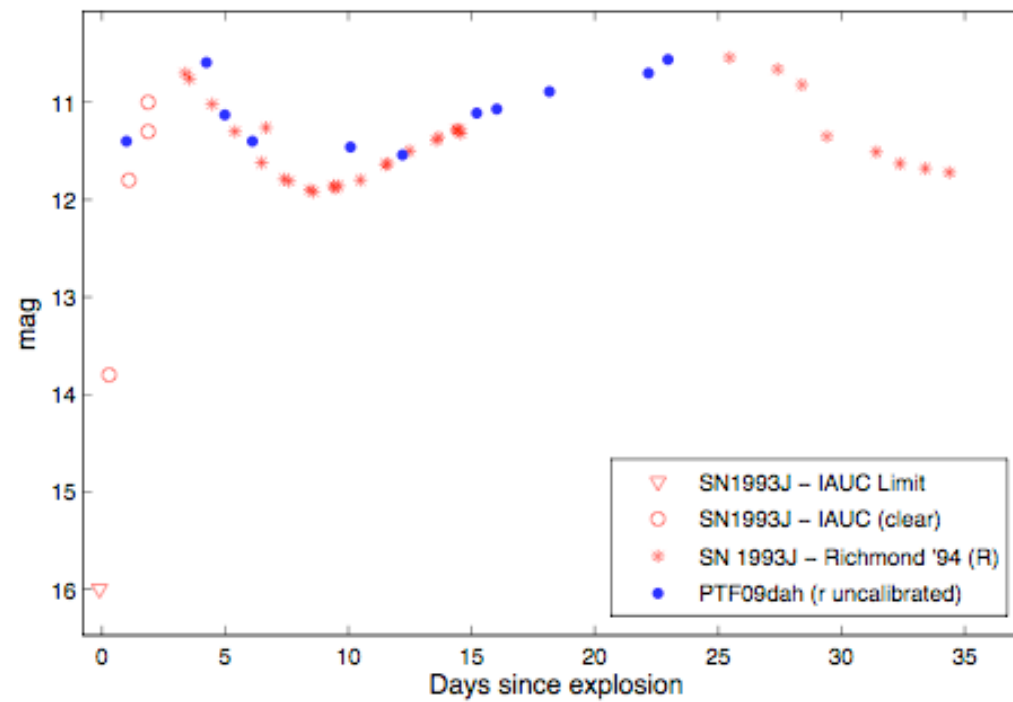


### 5. A long time after

The remains of the former star are spread over light years of space. They keep floating quickly, sweeping up interstellar gas here and there, leaving a faint beautiful glow behind...

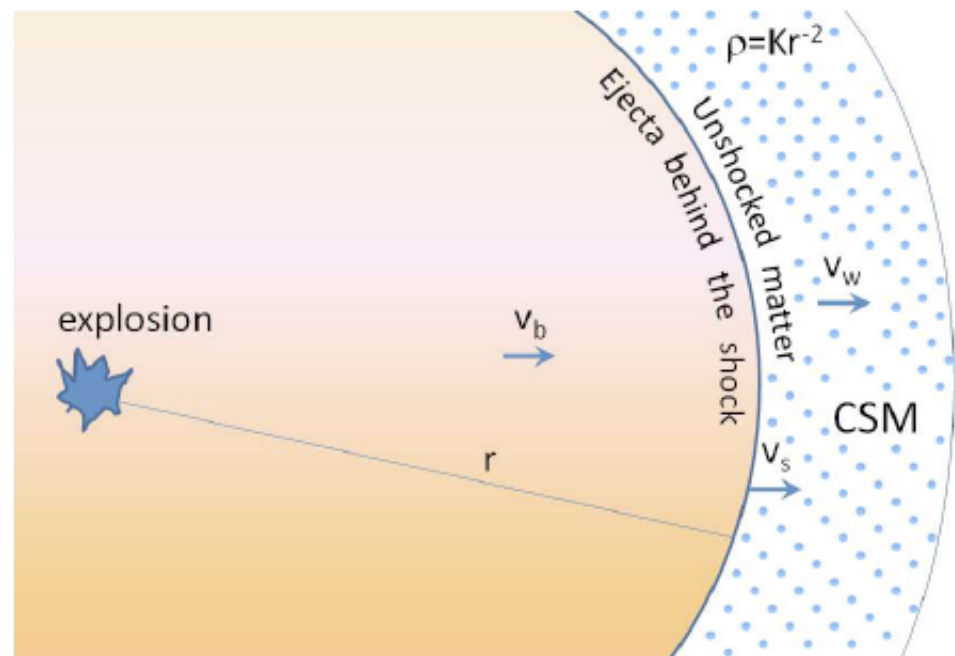
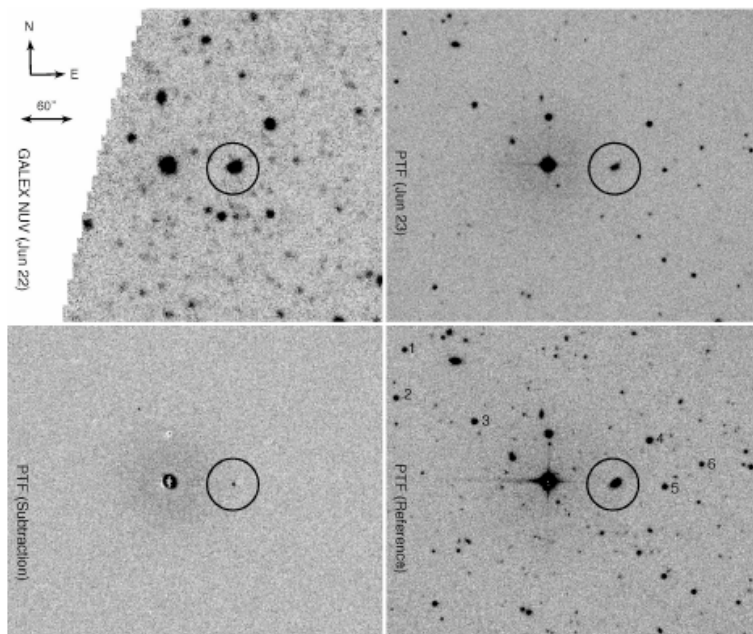


# Shock break out



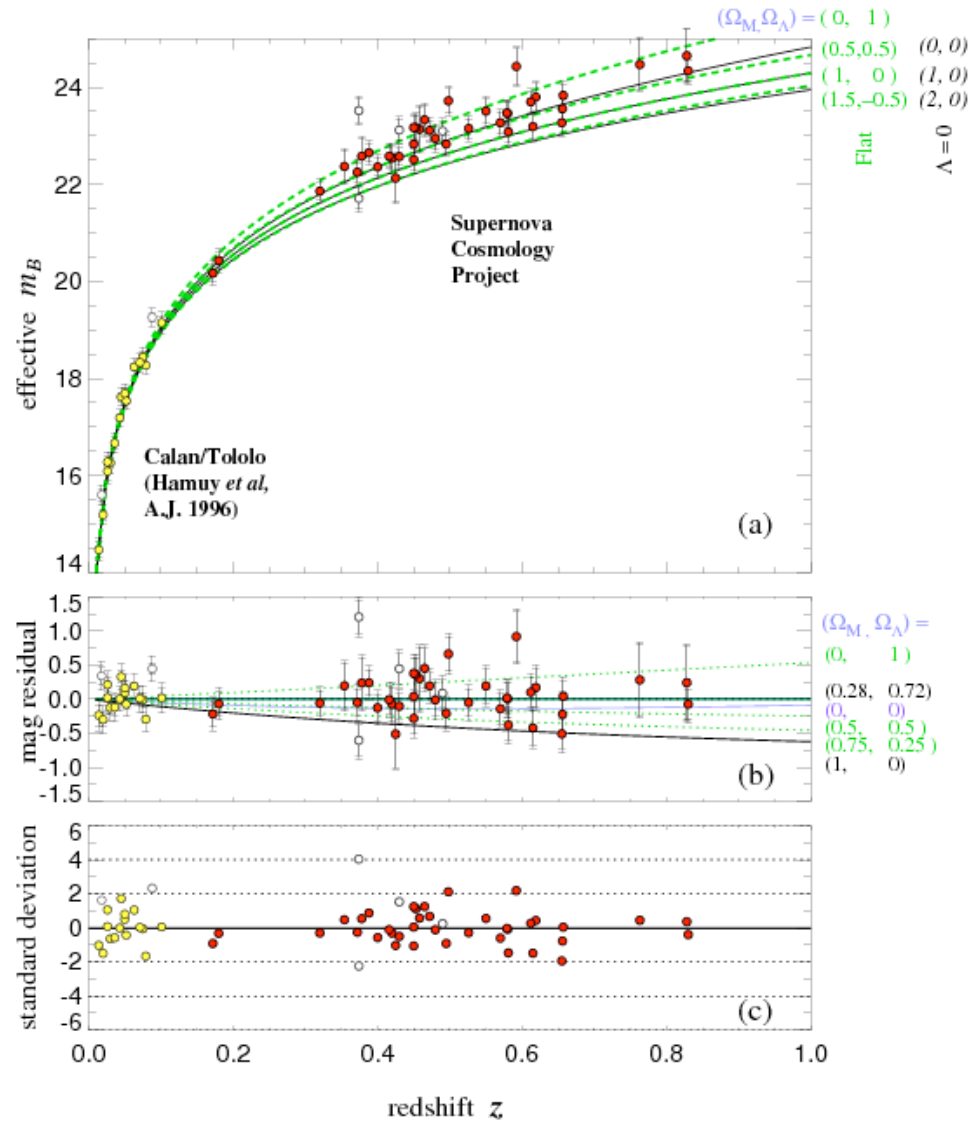
Arcavi

# Shock break out

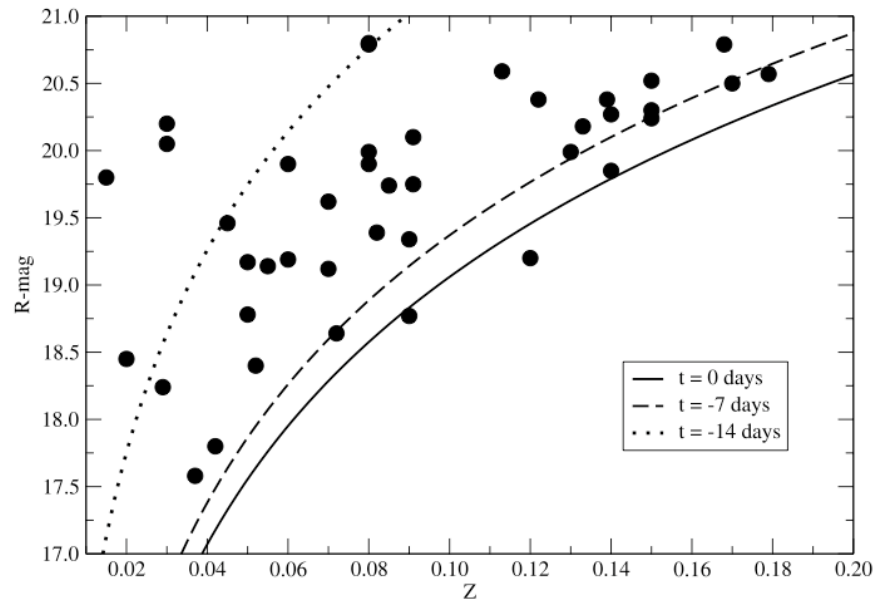


Ofek, Neill

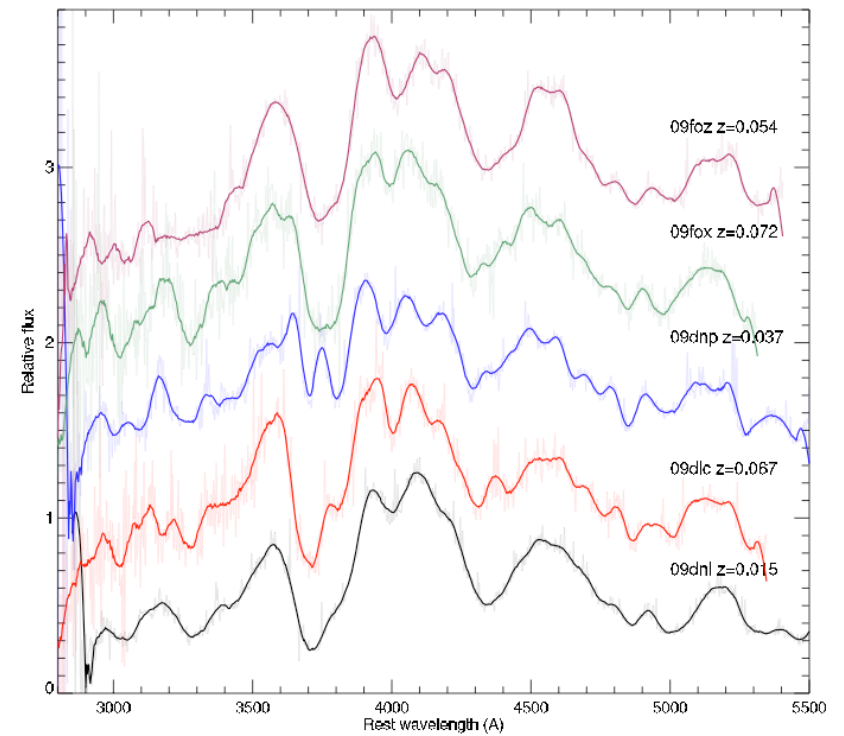
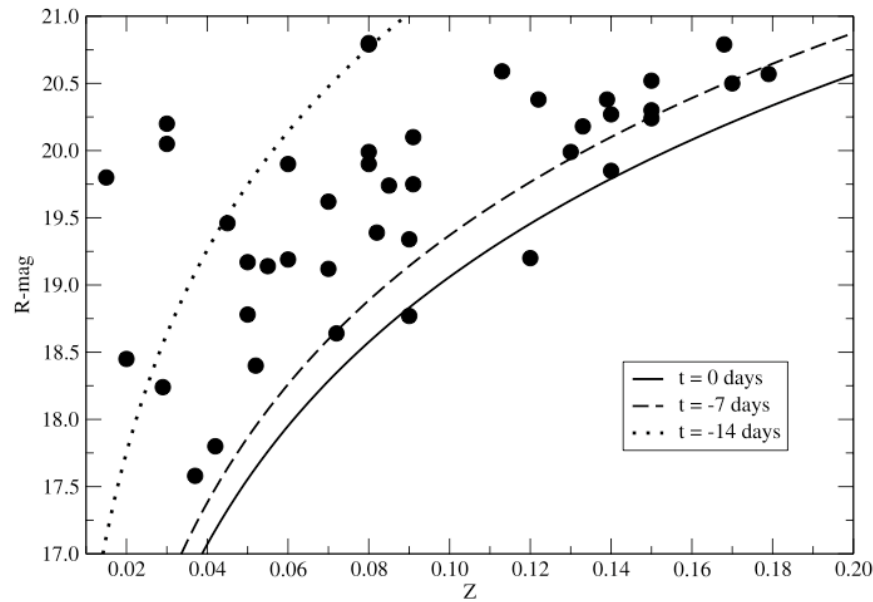
# Supernovae for Cosmography



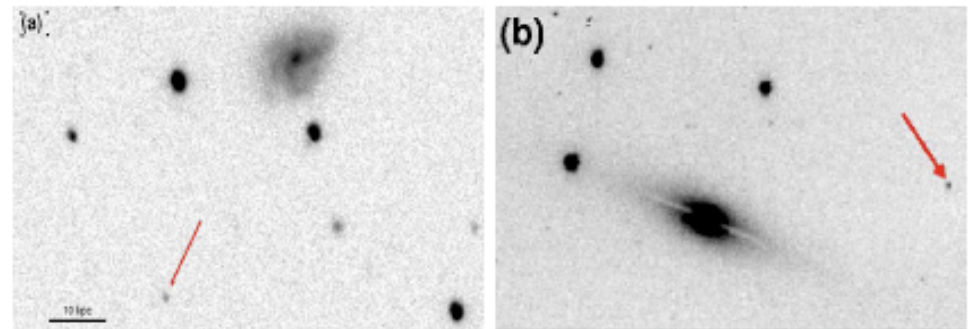
# UV spectroscopy of local Ia



# UV spectroscopy of local Ia

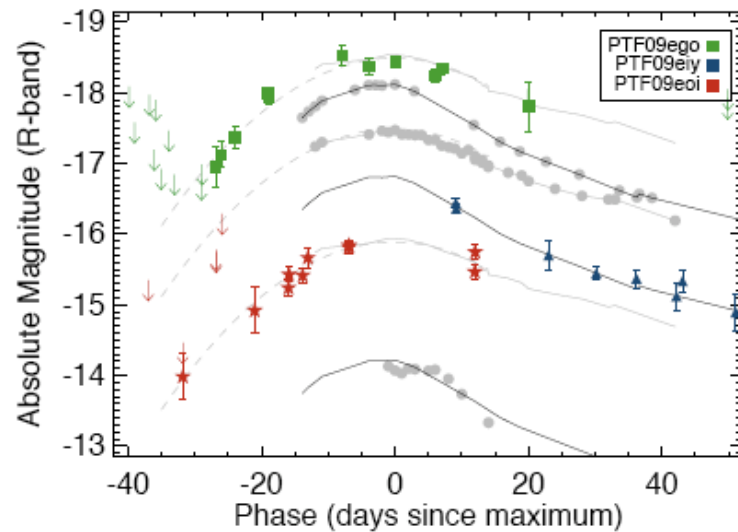


# Sorting out mysteries (via large samples)



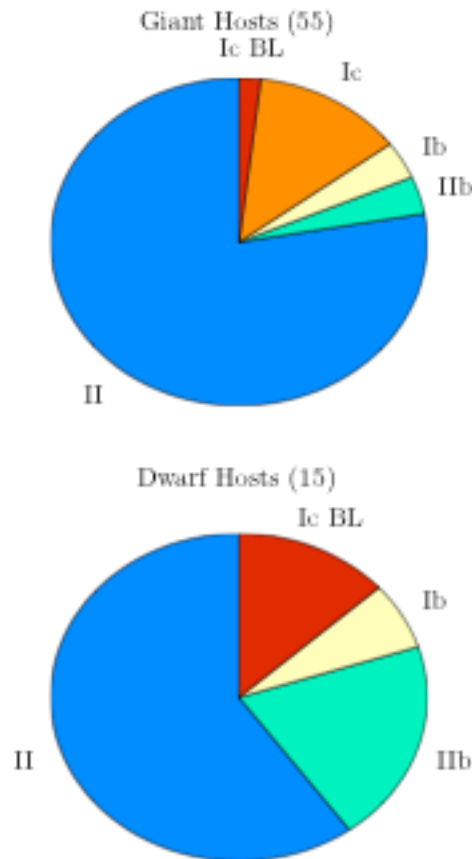
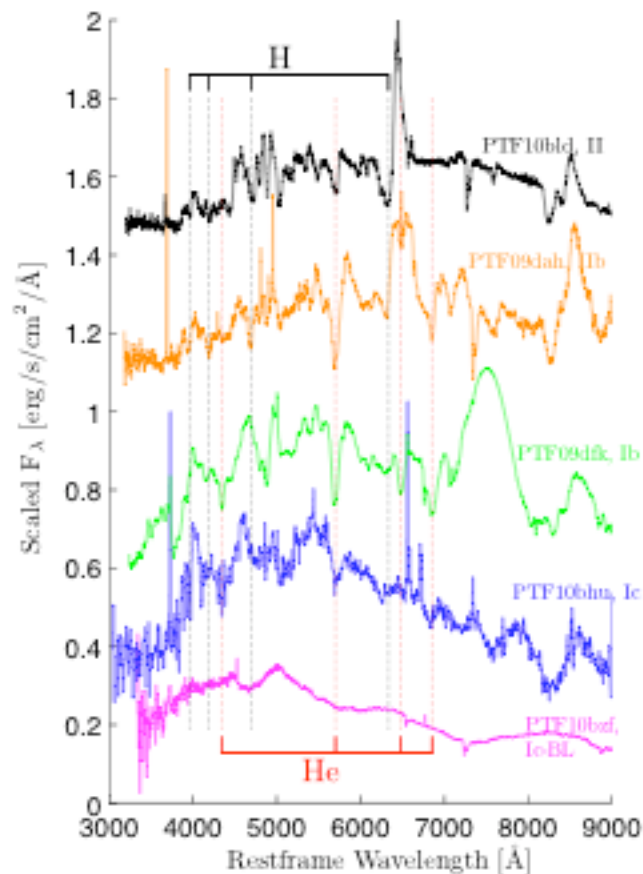
2002cx-family

2005E-family



Kasliwal

# Statistics of Core Collapse

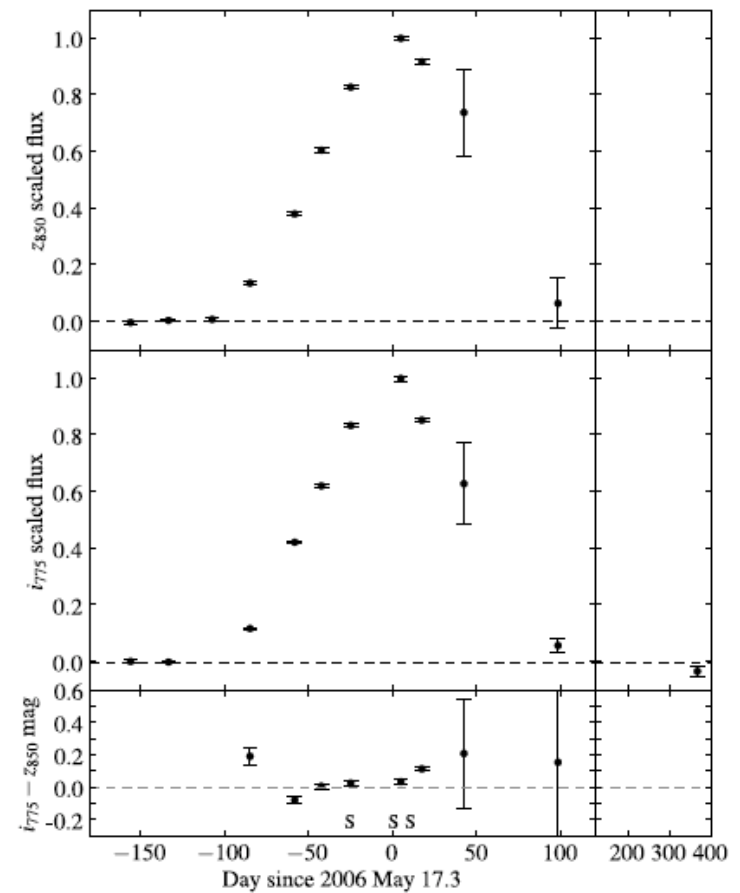
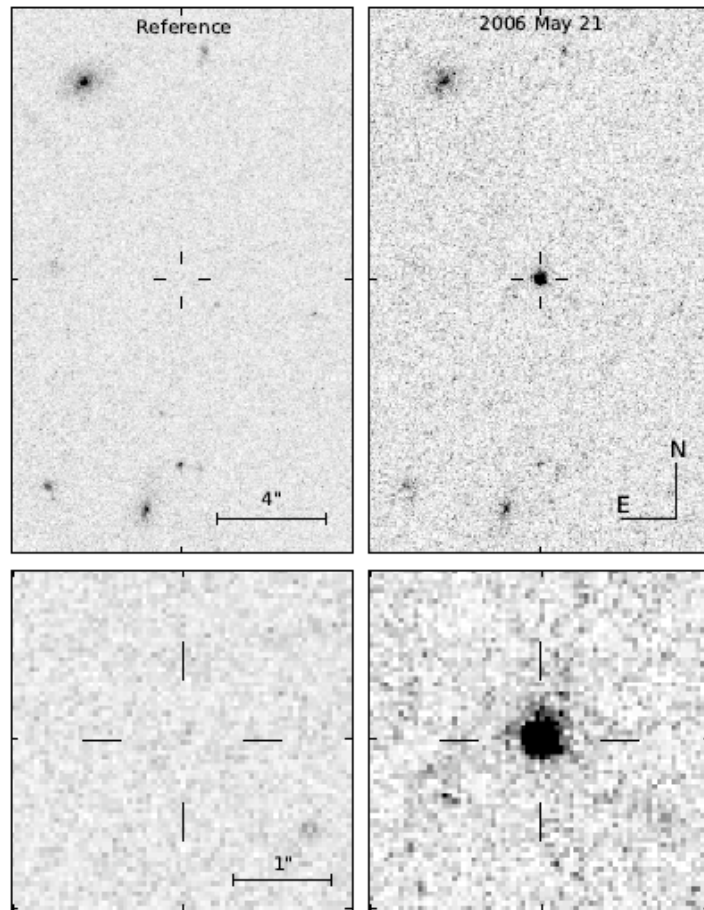


- Dwarf galaxies:
  - Over-abundance of IIb
  - No normal Ic
  - BL Ic
  - Ib
- Large Galaxies:
  - Over-abundance of II

Arcavi



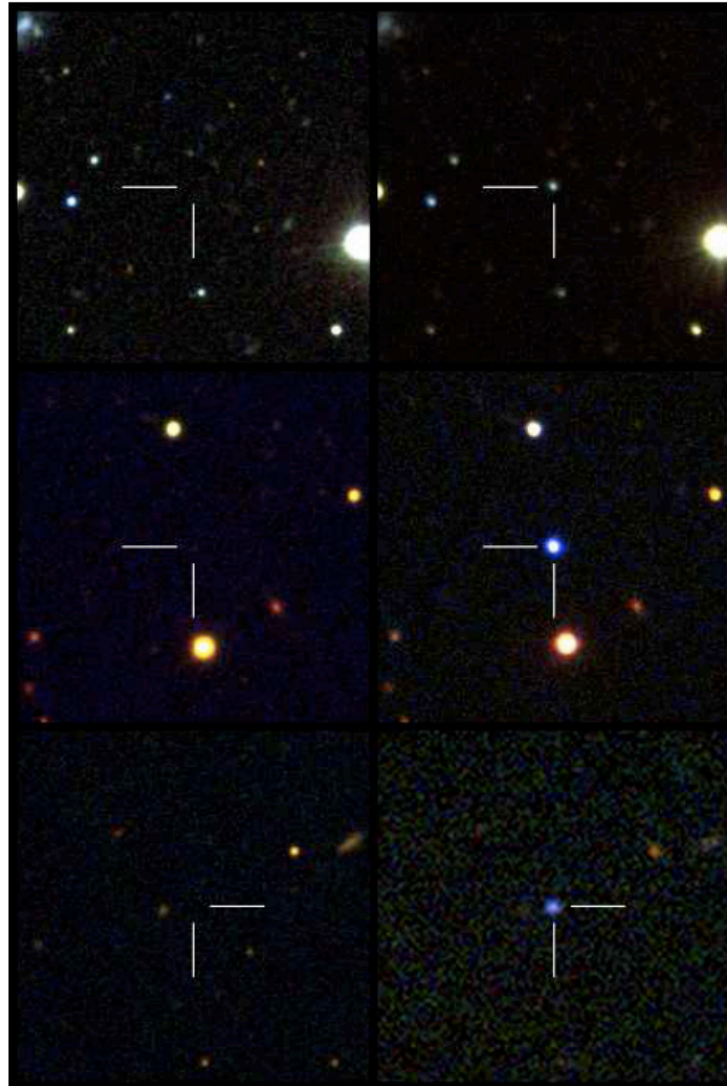
# The Mysterious SCP06F6



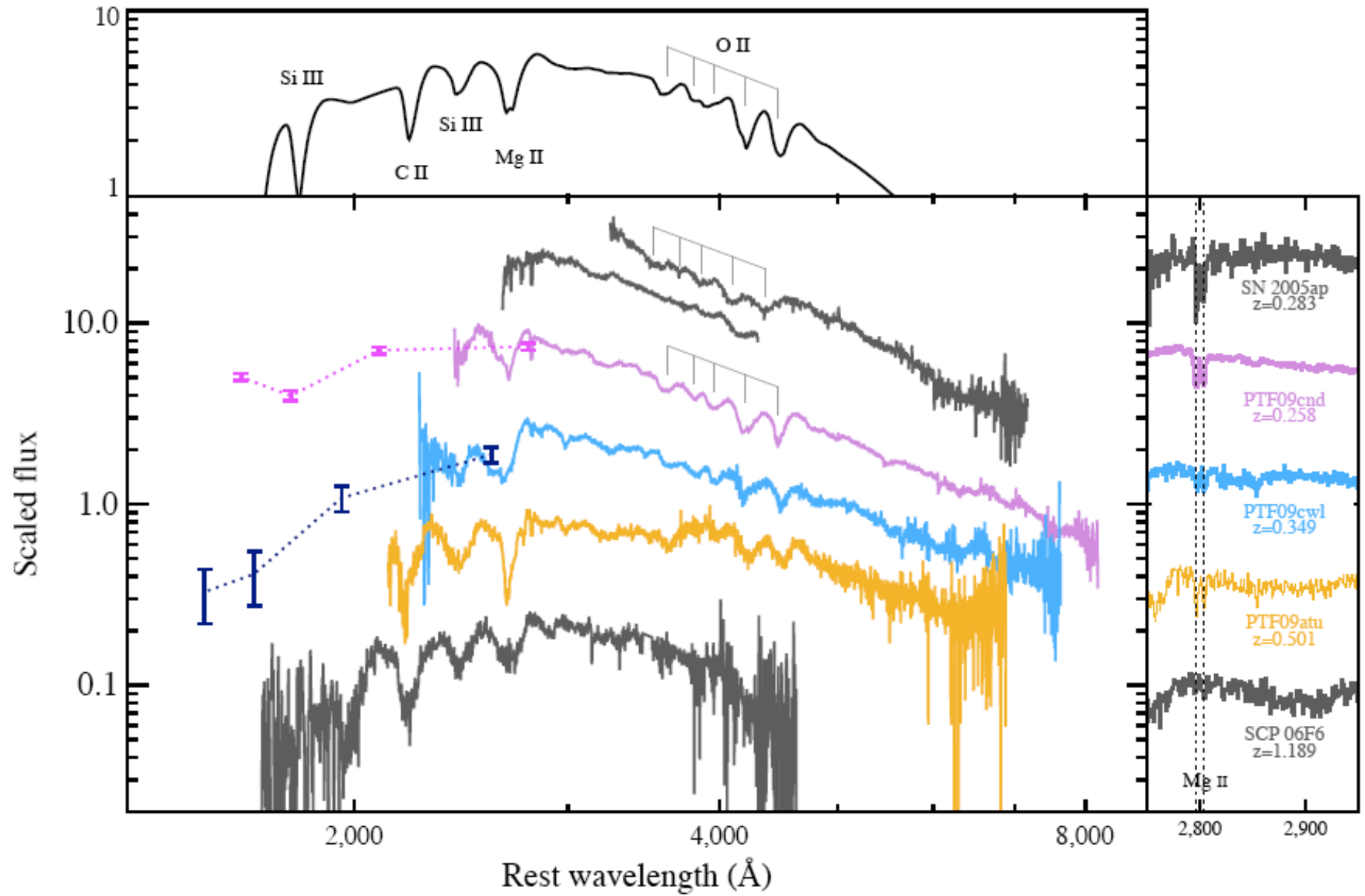
Barbary et al.

# PTF Discovery

*Quimby et al.*



**Quimby**



# Luminous Supernovae: New Avenues

- Deaths or death throes of very massive stars (but not like those found locally)
- Arise in tiny galaxies (likely metal poor)
- Long-lived optical/UV emission allows both IGM and ISM to be probed
- Fading source offers powerful way to study DLA
- Arm-chair astronomy?

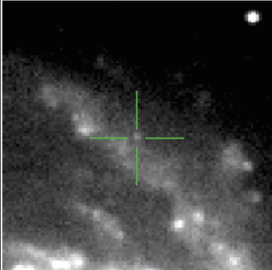
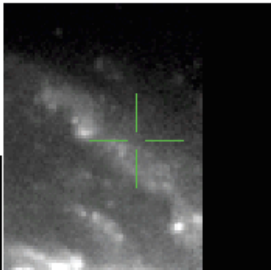




# In the six months

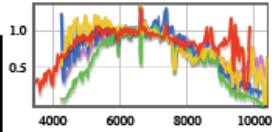
- PTF09dav, PTF10iuv may answer the mystery of 2005E subclass
- A family of 2002cx supernovae
- A trove of eclipsing M dwarfs
- Discovery of weird FU Ori events
- An eclipsing binary in Praesepe
- Discovery of two AM CVn stars
- The rotational history of stars in the Orion and Praesepe clusters (via high cadence observations)

# Six months ago

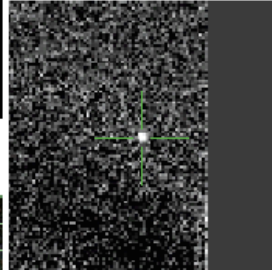
**PTF10fqs**  
**12:18:50.16**  
**+14:26:39.2**  
[184.709009](#)  
[+14.444228](#)

[Finding Chart](#)  
[Scanning Page](#)



[no spec fup scheduled](#)  
[Upload New Spectrum](#)



**r = 19.6 (6.0 d)**  
[photometric follow-up 8/3003 done](#)  
[Upload New Photometry](#)

**Comments:**

- May 15 IAIR [info]: Observed with Keck/LRIS on May 15
- May 11 AVISHAY [info]: Ca H+K is absorption (correction for previous comment)
- May 11 AVISHAY [comment]: Ca H+K in emission, [Ca II] and Ca II IR triplet in emission. No obvious broad bump.
- May 07 IAIR [info]: Observed with P200/DBSP on 100507
- Apr 30 PTFROBOT [type]: Transient
- Apr 19 DEREK [info]: Submitted to HET queue (Priority 1)
- Apr 17 PTFROBOT [rosat\_cps]: 0.021
- Apr 17 PTFROBOT [SDSS\_class]: galaxy
- Apr 17 PTFROBOT [SDSS\_photz]: 0.3079 +- 0.1680
- Apr 17 PTFROBOT [SIMBAD\_class]: SN
- Apr 17 MANSI [nearpgc]: 39578
- Apr 17 MANSI [distmod]: 31.13
- Apr 17 MANSI [type]: Transient

[Add a Comment:](#)  
  
[Attach File:](#)  
 [Browse...](#)  
[info](#) [Save Comment](#)

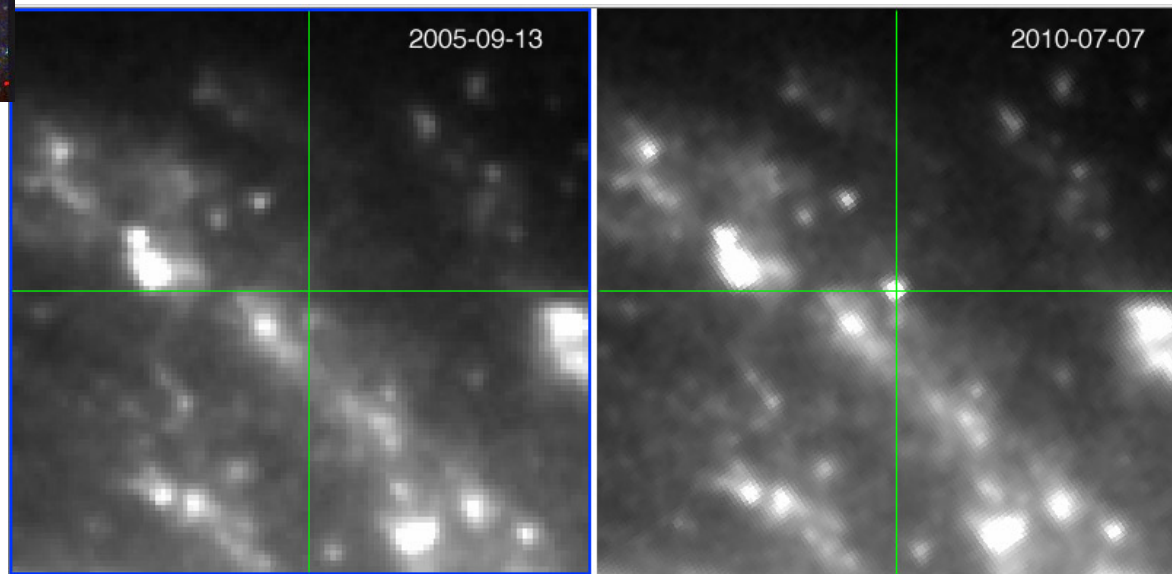
[Quick P48 LC](#)  
[PyMPChecker](#)

## Follow-up Priorities

Date	Program	Type	Priority	
2010 Apr 17	P60 Transient Vetting	phot	3	<a href="#">Edit</a>
2010 Apr 17	Transients in the Local Universe	phot	1	<a href="#">Edit</a>
2010 Apr 18	Transients in the Local Universe	all	5	<a href="#">Edit</a>
2010 Apr 19	HET Spectroscopic Follow-Up	spec	3	<a href="#">Edit</a>
2010 May 21	Transients in the Local Universe	all	5	<a href="#">Edit</a>



# Spitzer & Hubble Images



# Two months later

## PTF10fq: A LUMINOUS RED NOVA IN THE SPIRAL GALAXY MESSIER 99

MANISH M. KASLIWAL, S. R. KULKARNI, ROBERT M. QUIMBY, ERAN O. OFEK  
Cahill Center for Astrophysics, California Institute of Technology, Pasadena, CA, 91125, USA

PETER NOGENT, JANET JACOBSEN  
Computational Cosmology Center, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

AVISHAY CAL-YAM, YOAV GREEN, LAIR ARCAVI, OFER YARON  
Ben-Zion Center for Astrophysics, Faculty of Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

JACOB L. HOWELL, DEREK B. FOX  
Astronomy and Astrophysics, Eberly College of Science, The Pennsylvania State University, University Park, PA 16802, USA

S. BRADLEY CENKO, IO KLEISER, JOSHUA S. BLOOM, ADAM MILLER, DOWI POZNANSKI, WEIDONG LI, ALEXEI V.  
FILIPPENKO, DAN STARR  
Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

NICHOLAS M. LÖW  
Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto M5S 3H4, Ontario, Canada

GEORGE HELOU  
Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, USA

DALE A. FRAIL  
National Radio Astronomy Observatory, Array Operations Center, Socorro, NM 87801, USA

JAMES D. NEILL, KARL FORSTER, D. CHRISTOPHER MARTIN, SHRIMANSH P. TENDULKAR  
Cahill Center for Astrophysics, California Institute of Technology, Pasadena, CA, 91125, USA

NEIL GEMRELE  
NASA-Goddard Space Flight Center, Greenbelt, MD 20771, USA

JAMIE KENNEA  
Department of Astronomy and Astrophysics, Pennsylvania State University, State College, PA 16802, USA

MARK SULLIVAN  
Department of Physics, Oxford University, Oxford, OX1 3RH, UK

RICHARD DEKANY, GUSTAVO RAHMER, DAVID HALE, ROGER SMITH, JEFF ZOLKOWER, VIJAYA VELUR, RICHARD WALTERS,  
JOHN HENNING, KAHNH BUI, DAN MCKENNA  
Caltech Optical Observatories, California Institute of Technology, Pasadena, CA 91125, USA

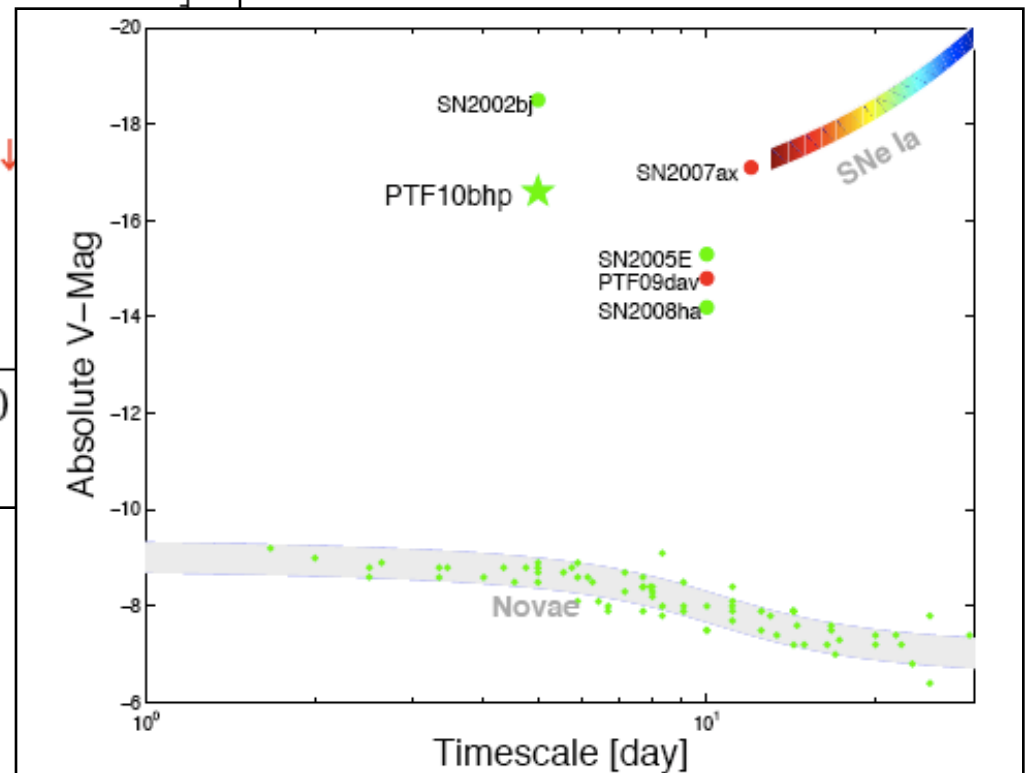
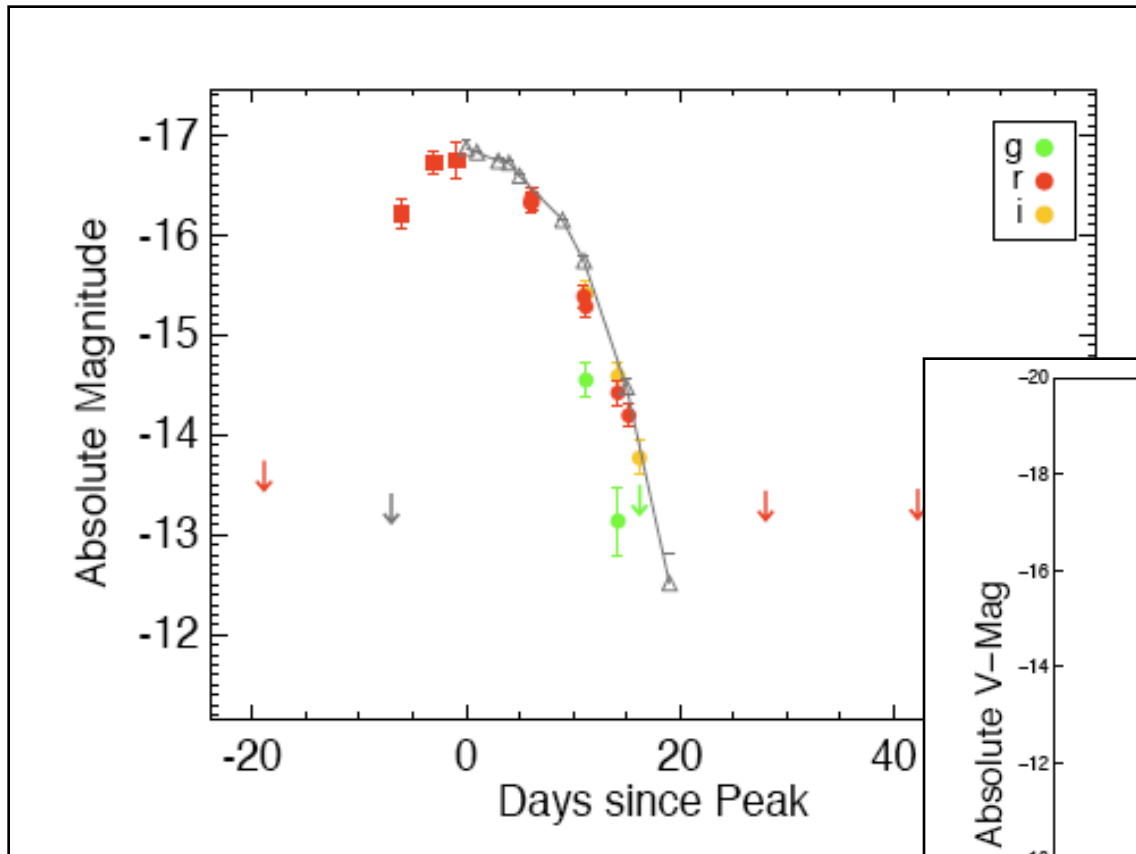
CULLEN BLAKE  
Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA  
*Draft version May 11, 2010*

## ABSTRACT

The Palomar Transient Factory (PTF) is systematically charting the optical transient and variable sky. A primary science driver of PTF is building a complete inventory of transients in the local Universe (distance less than 200 Mpc). Here, we report the discovery of PTF10fq, a transient in the luminosity “gap” between novae and supernovae. Located on a spiral arm of Messier 99, PTF10fq



# PTF10bhp:



# Puzzling Sources (Blazars?)

**PTF10hJz**

no spec fup scheduled  
[Upload New Spectrum](#)

Scanning Page

Requested (ra, dec) is outside the field

$r = 19.4$  (0.9 d)

photometric follow-up 0/3003 done  
[Upload New Photometry](#)

Check NED  
Check SIMBAD  
Get DSS Image  
Check Skyview

Quick P48 LC  
PyMPChecker

## Follow-up Priorities

Date	Program	Type	Priority	
2010 May 16	P60 Transient Vetting	phot	5	<a href="#">Edit</a>
2010 May 16	Transients in the Local Universe	all	5	<a href="#">Edit</a>

## Observing Groups

Name	Cadence	Maximum Age	
gri single snapshot	1 day	10 days	<a href="#">Edit</a>
group 1 day gri	1 day	150 days	<a href="#">Edit</a>

## Set Follow-up Priority

**PTF10iYa**

unknown

Finding Chart

Scanning Page

no spec fup scheduled  
[Upload New Spectrum](#)

Check NED  
Check SIMBAD  
Get DSS Image  
Check Skyview

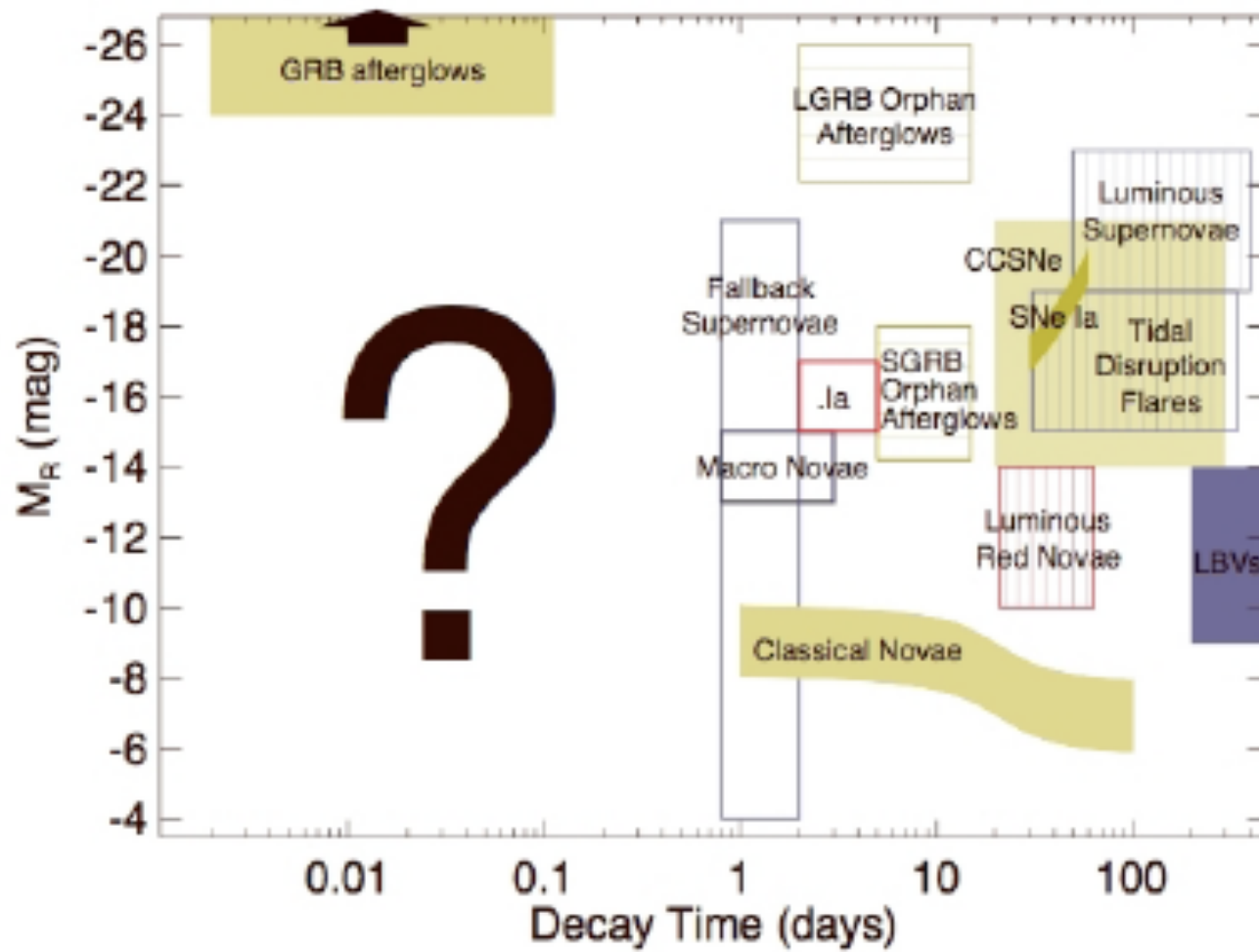
[Upload New Photometry](#)

# What next?

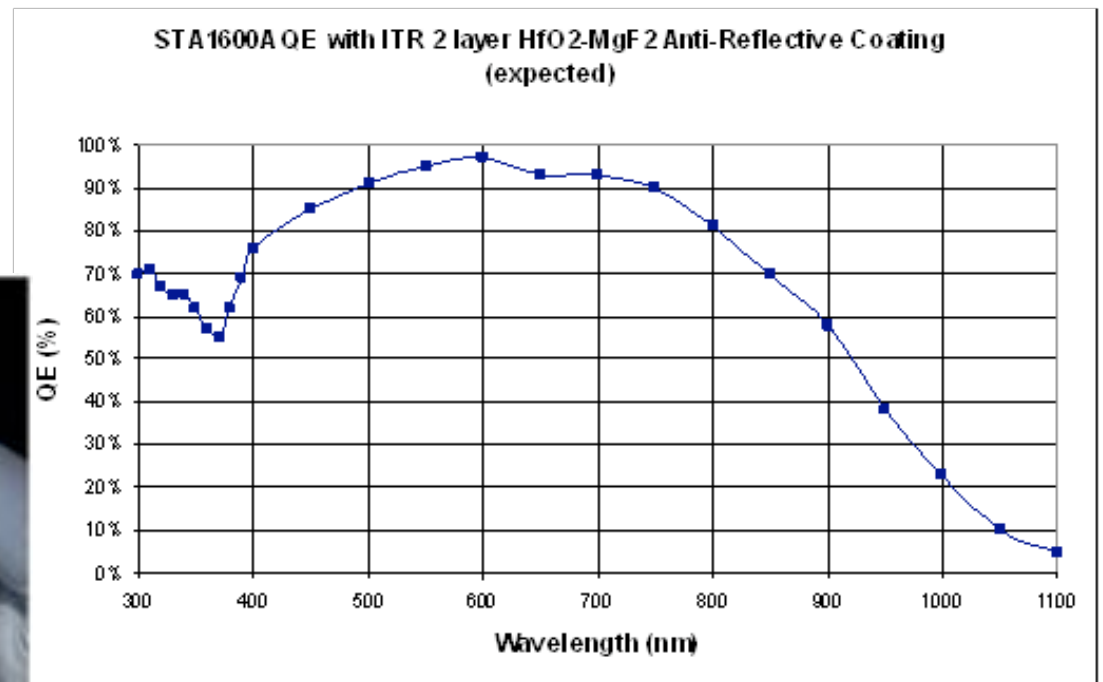
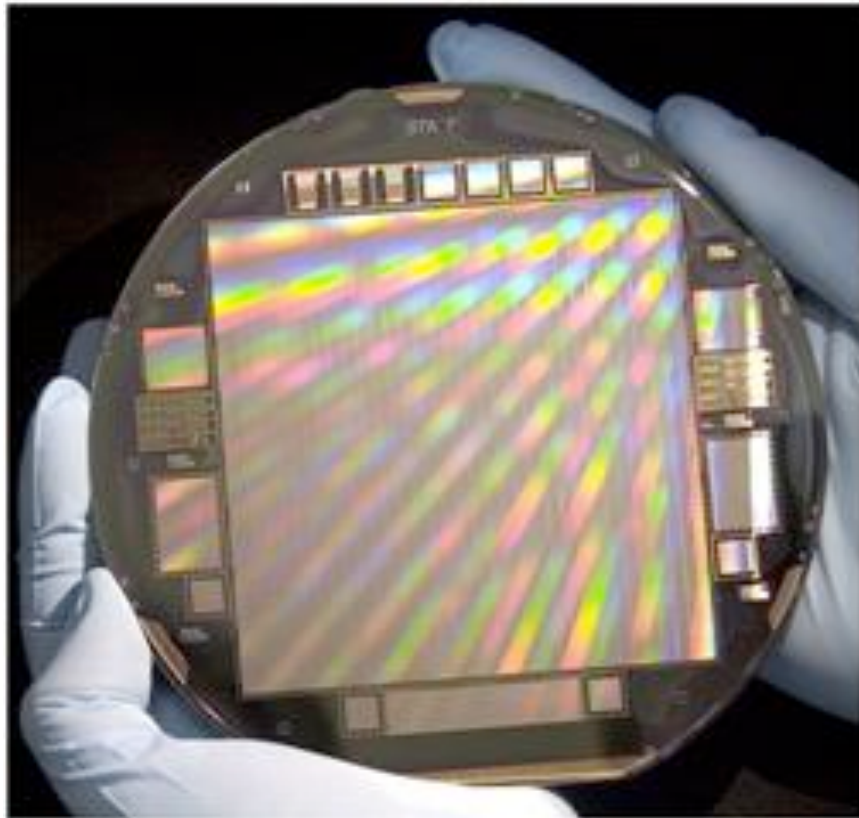
- The transient game will split into two paths:
  - High cadence
  - High Sensitivity
- Lesson learnt:
  - No classification => no (little) value

# Next Generation Transient Facility (NGTF)

# Short timescale is terra incognita



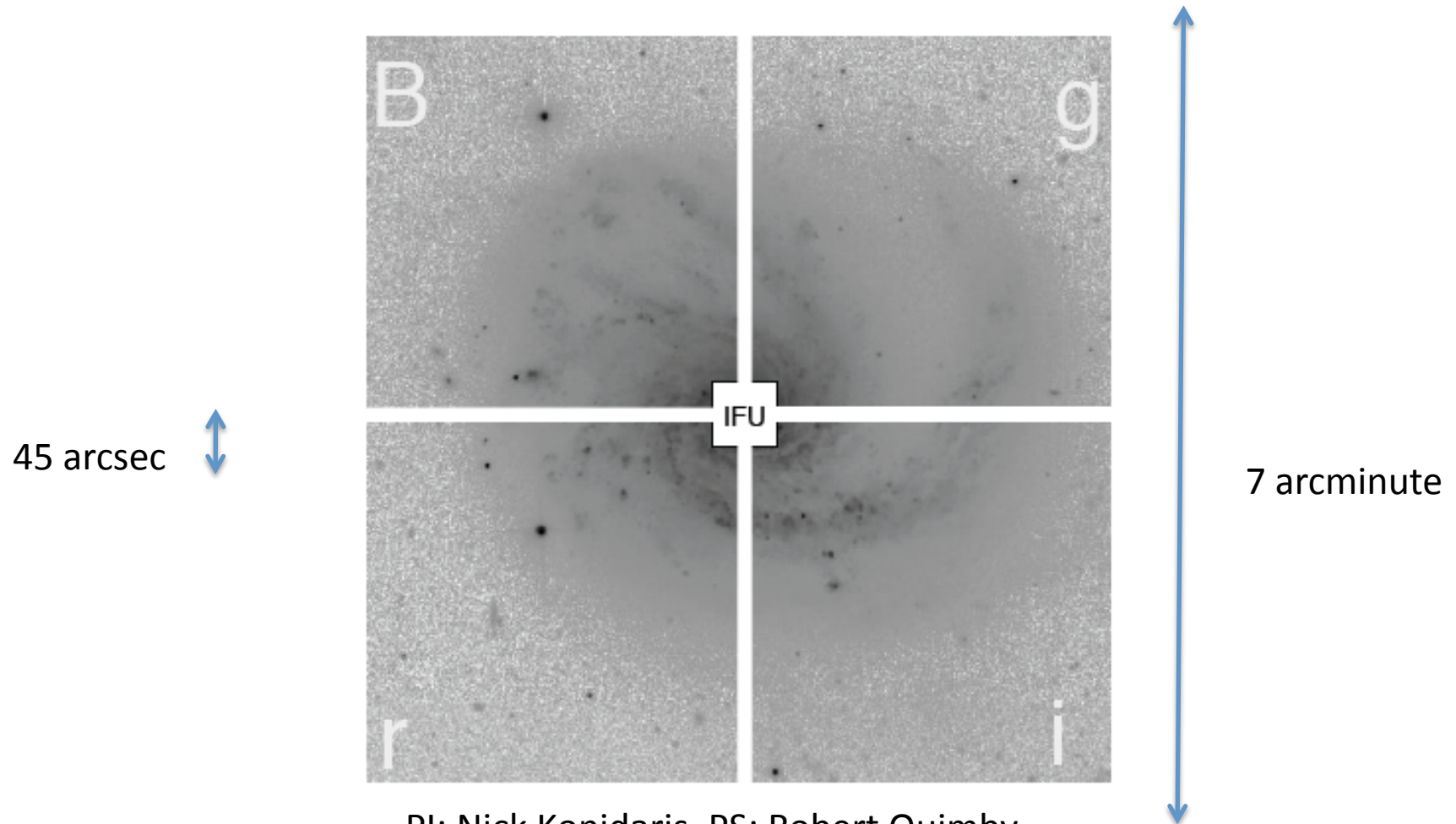
# STA CCD (An example)



9micron pitch, 92-mm on the side



# The SED Machine

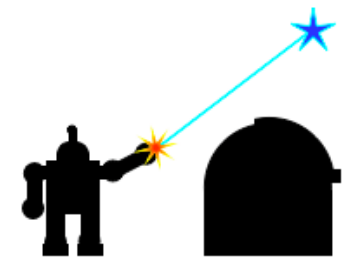
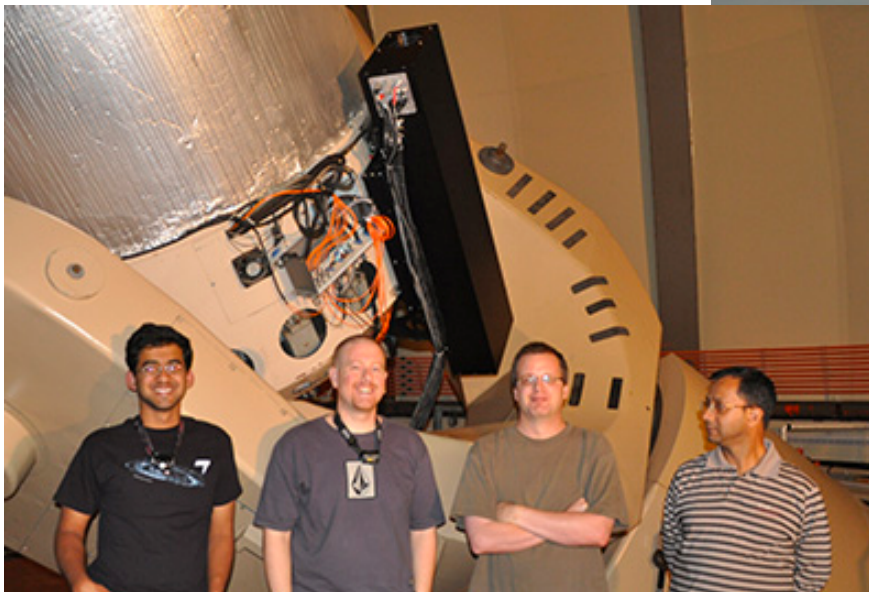


PI: Nick Konidaris, PS: Robert Quimby  
In collaboration with NCU-Taiwan

# TOO Telescope

- Dedicate one or more telescopes whose job is classification
  - e.g. KPNO 84-inch
  - Other 2-m telescopes around the world
- SED Machine is designed bearing in mind the differing f-ratio of 1.5-m to 3-m class telescopes

# (AO+)Photometric Machine



IUCAA-Caltech ROBO-AO

## III.A Dedicated UV satellite (Less is More)

# Axis of Excellence (Slaved UV satellite)





