How the periodic table got built up
(The Restless Universe)
(the rise of time domain astronomy)

S. R. Kulkarni

Principal Investigator, Zwicky Transient Facility

The structure of science: Phenomenology & Understanding

- Phenomenology has three distinct steps
  - Discovery
  - Systematic study of phenomena: Search for patterns
  - Inference: Physical models to explain observations (and occasionally make predictions)
- Understanding
  - Physics distills phenomena into essential rules & laws

Mathematics & Technology

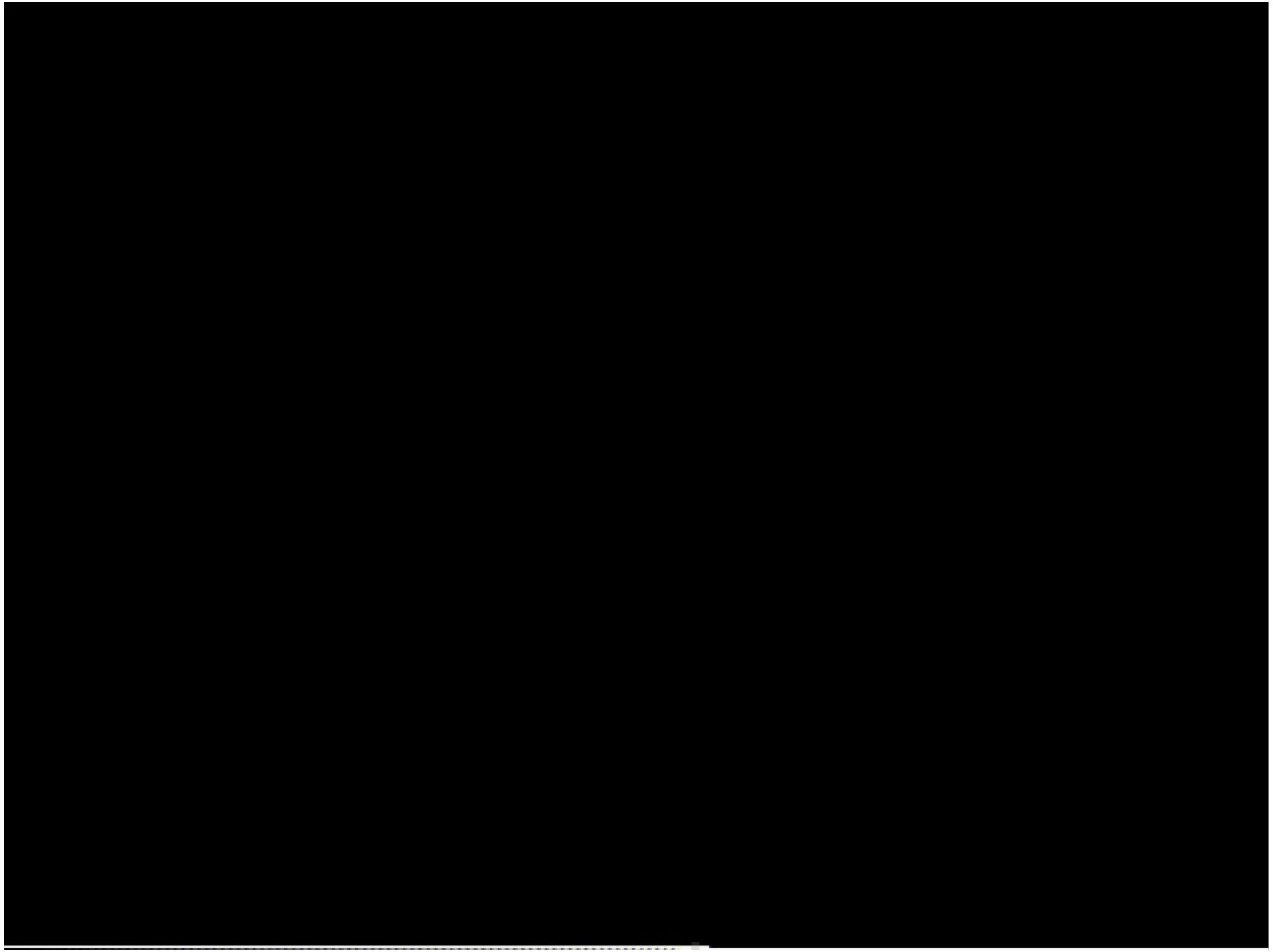
- Mathematics is an integral part of science because it allows signal levels to be calculated
- Discovery is the blood of science. It is largely a function of technology

Mathematics & Technology: Example

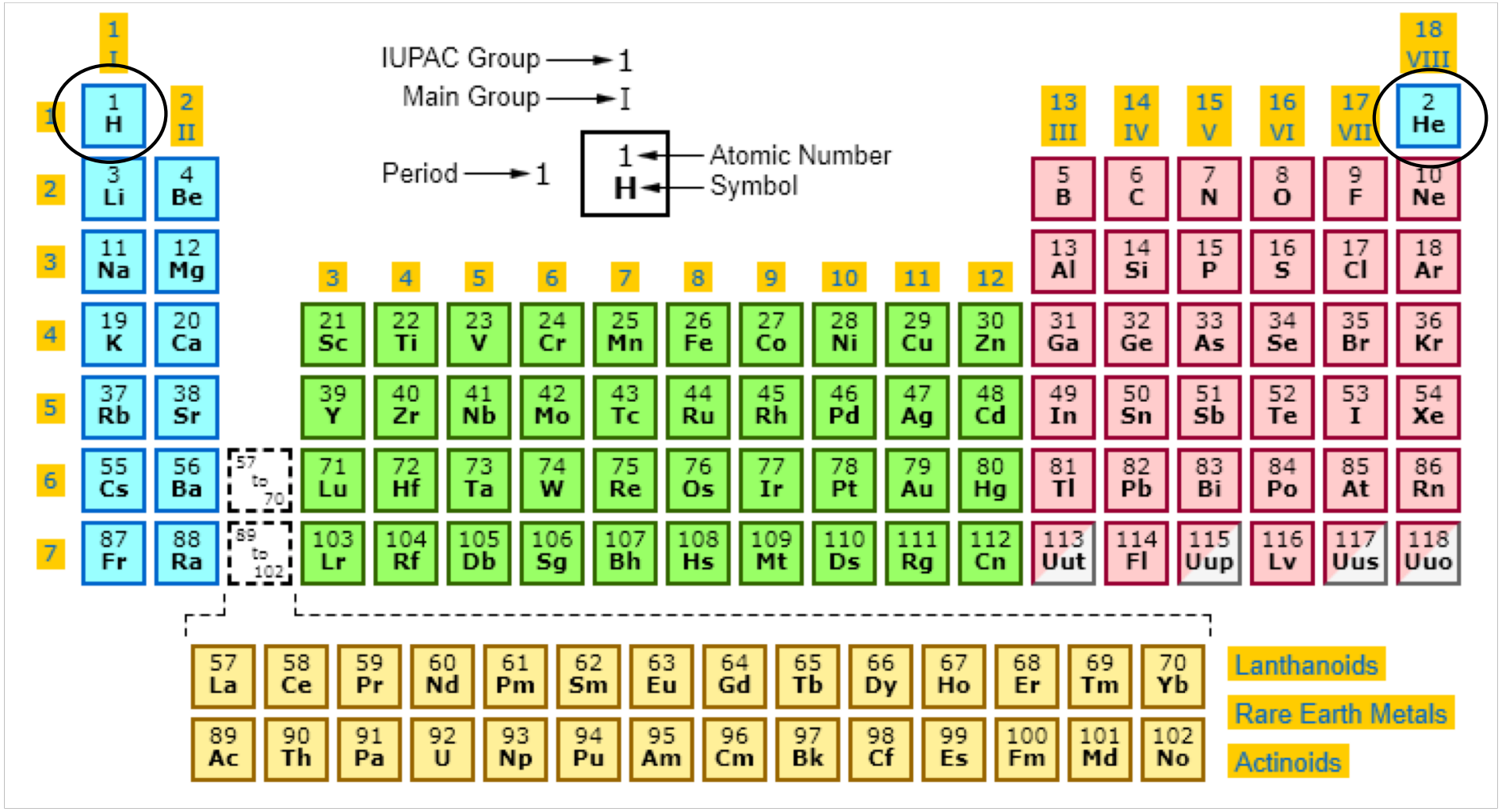
- Example: Planetary motions
  - Planetary Motion noticed by ancient scientists
  - With the first telescope Galileo discovered moons of Jupiter
  - Newton noted the falling of an apple
  - Brahe made careful observations of planetary positions
  - Kepler distilled the data into three laws of Kepler
  - Newton develop the theory of Gravity (inverse square law force)
  - Newton & Leibniz developed calculus
  - Birth of modern Mechanics
  - Gauss computed trajectories and made predictions.

THE BUILDUP OF ELEMENTS (NUCLEOSYNTHESIS)

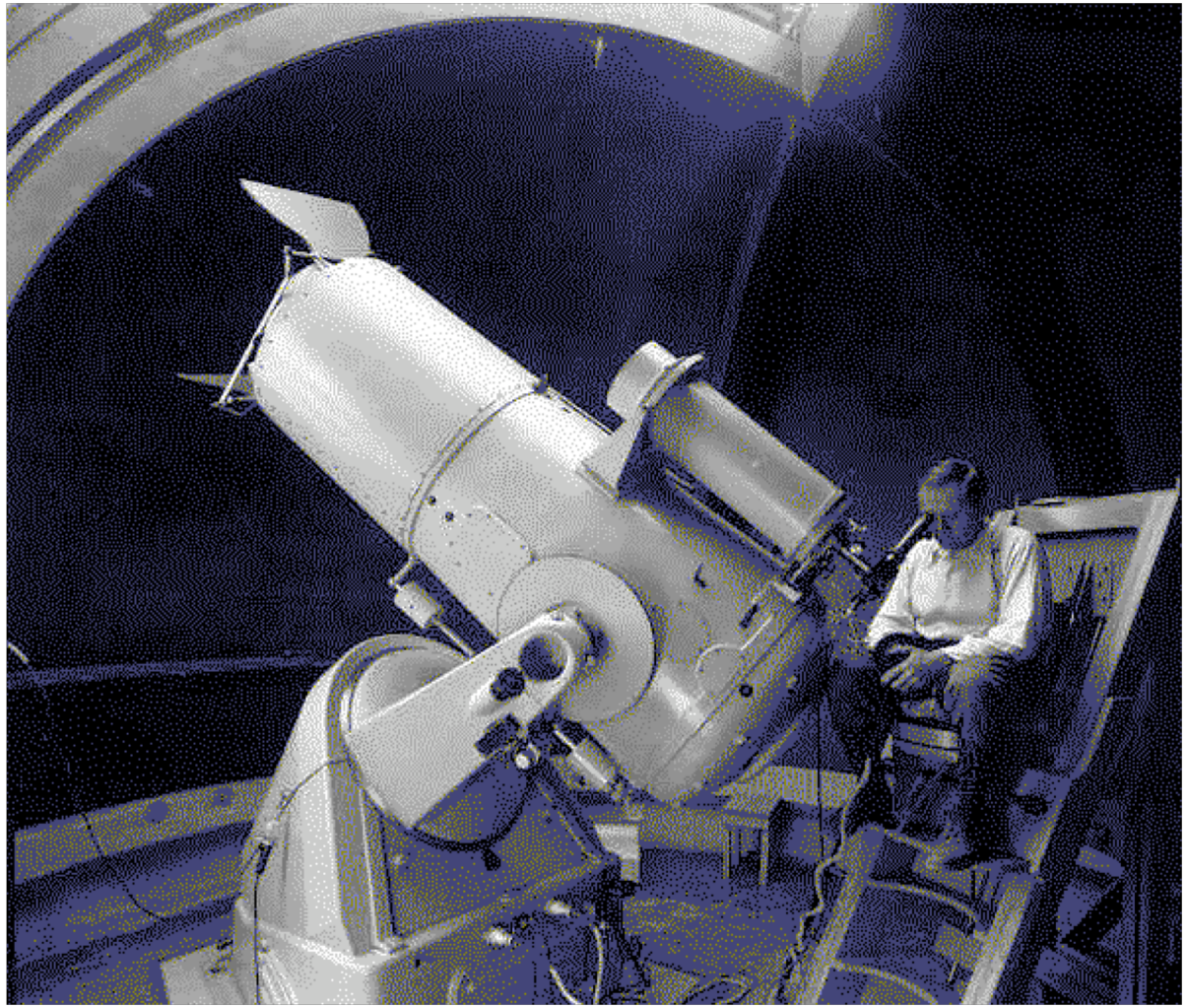
This is how it all began



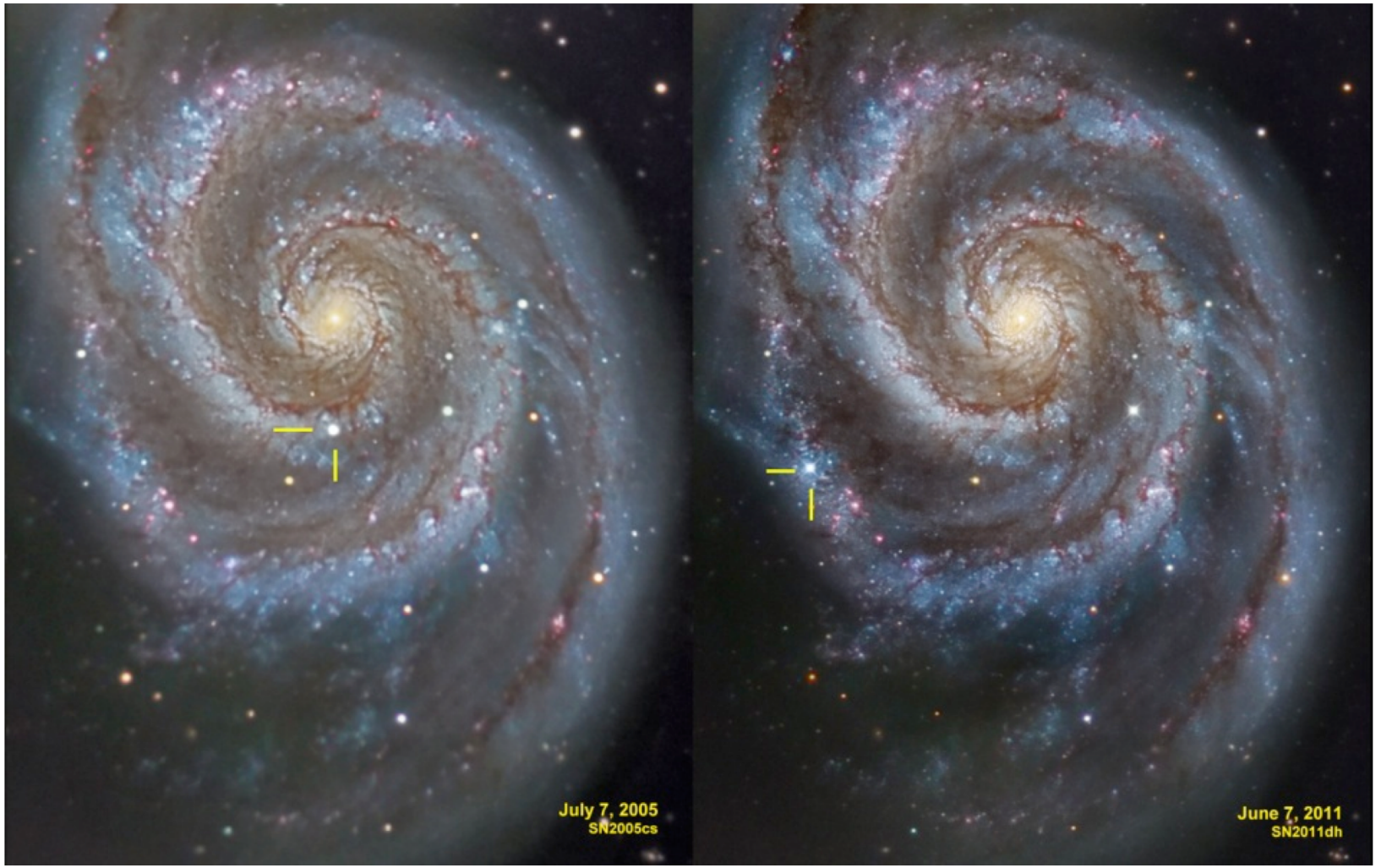
Chemistry in the young Universe was simple



Time Domain Astronomy (Supernovae): Fritz Zwicky



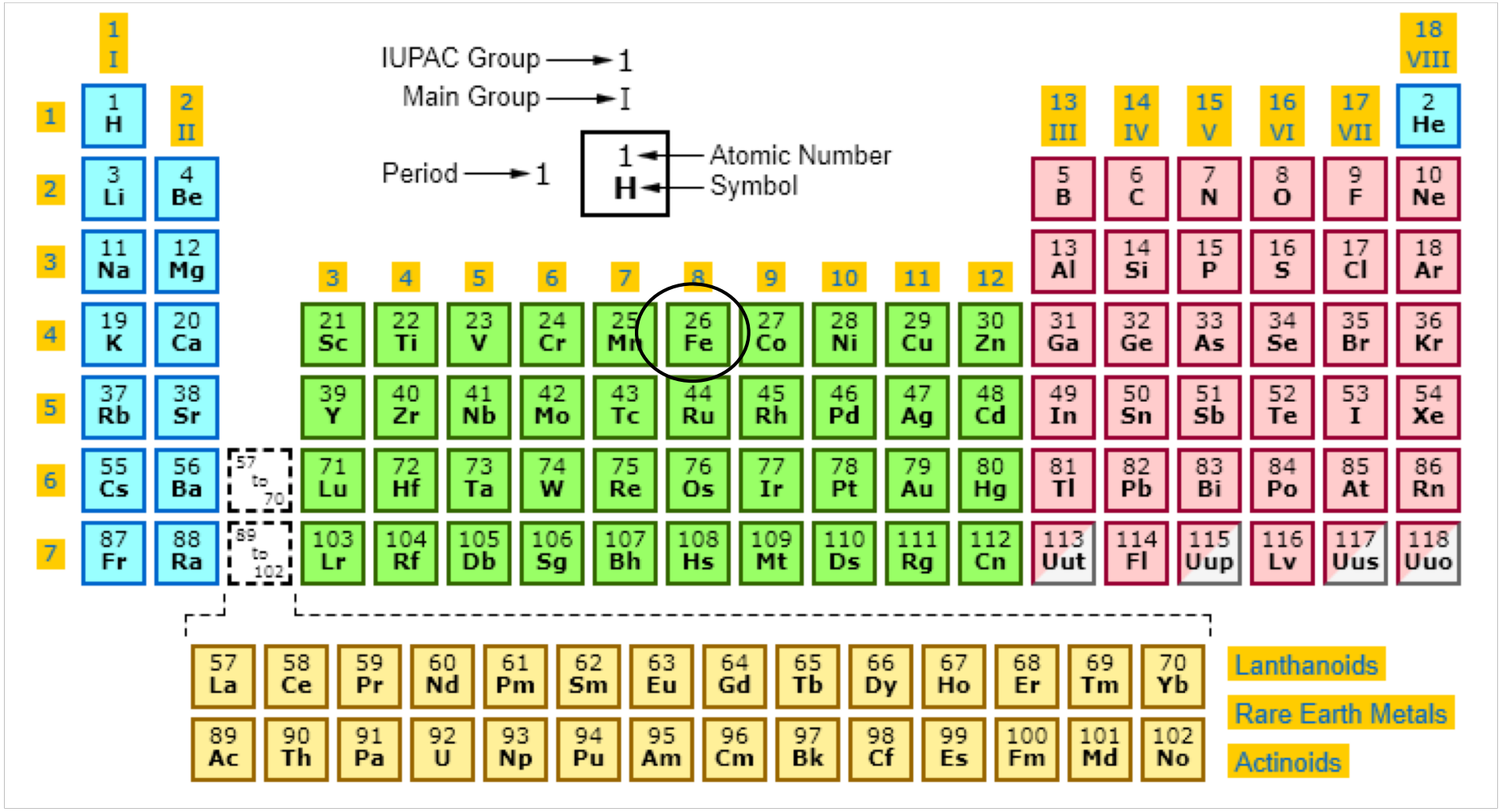
A star dies: A supernova is born & heavy elements are made



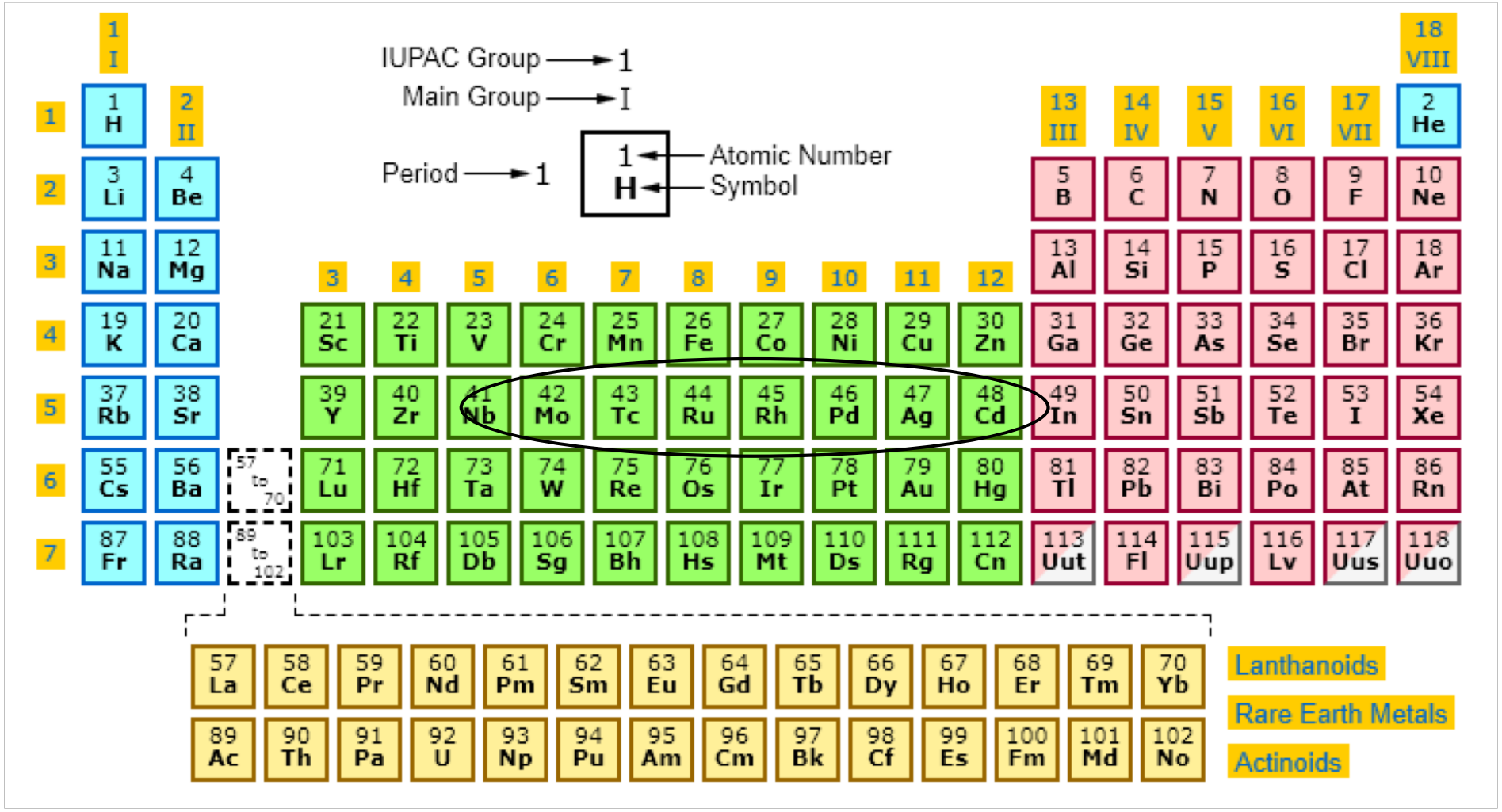
Astronomy Picture of the Day (NASA)

Nucleosynthesis:
Burbidge, Burbidge, Fowler & Hoyle (B^2FH)

Iron is special

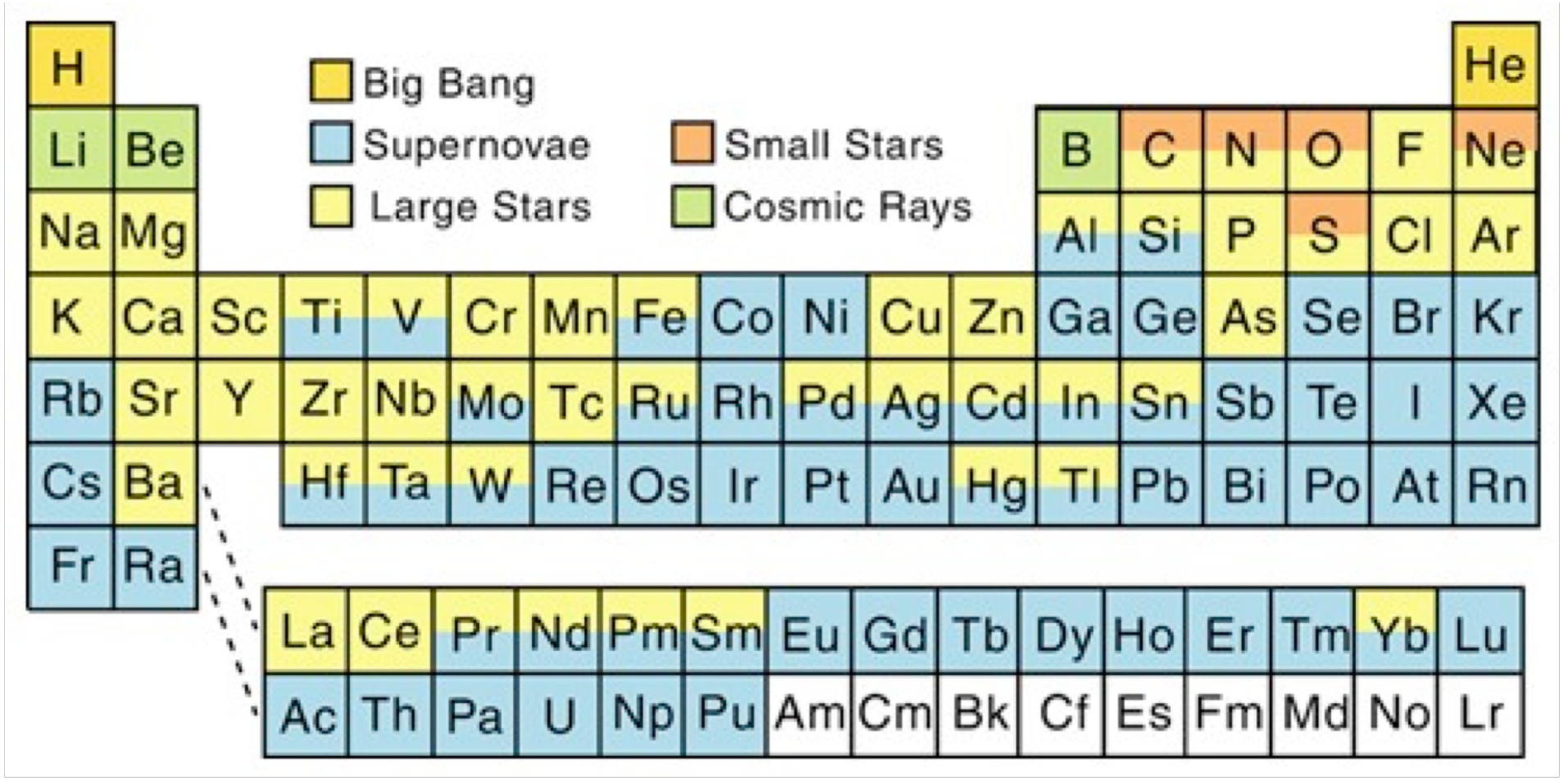


Special explosions make “precious” metals



Frontier Area: Gravitational Waves

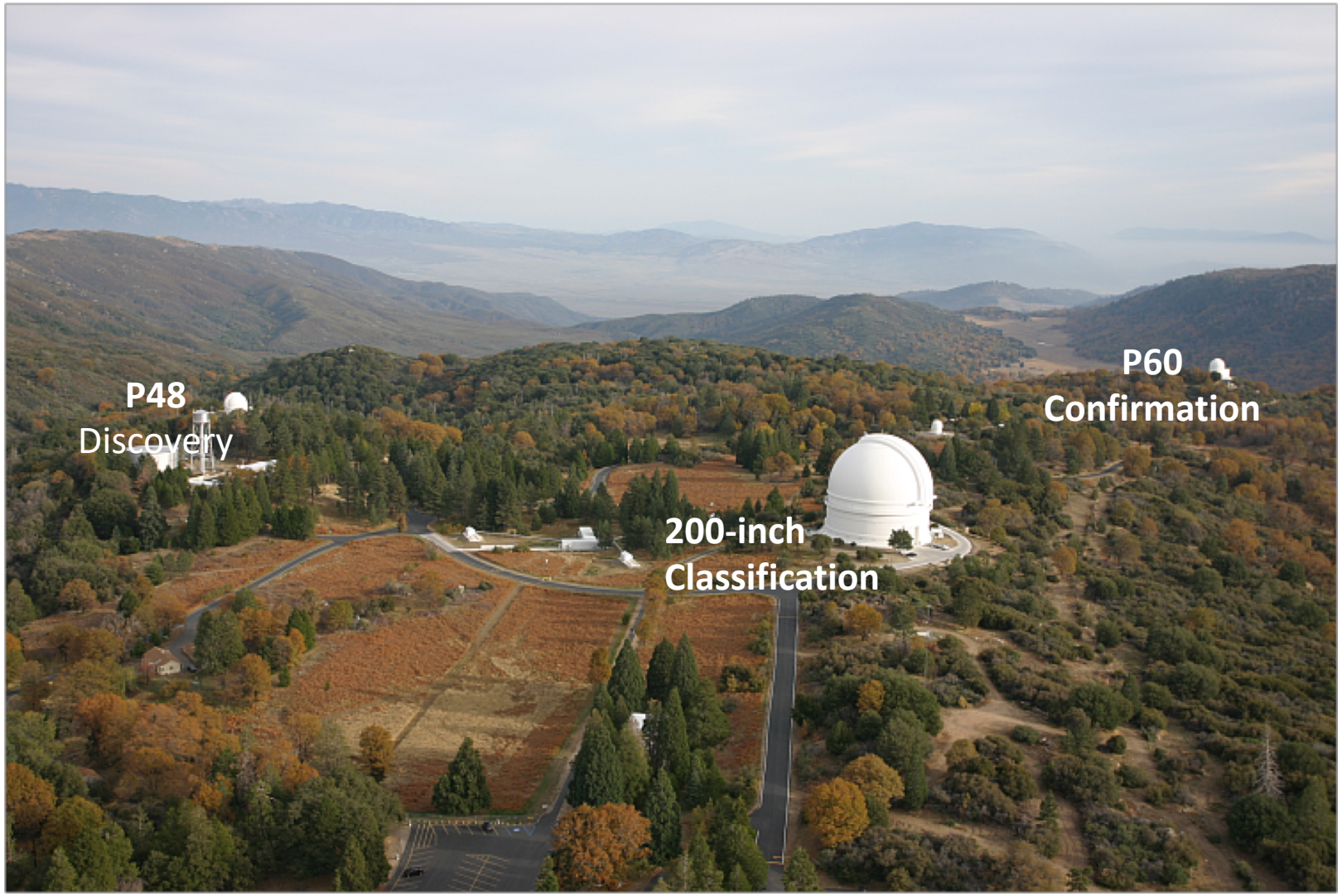
We are star dust!



From Universetoday.com

A FACTORY TO SYSTEMATICALLY DISCOVER EXPLOSIVE TRANSIENTS

Palomar Transient *Factory*



Paul Wellman

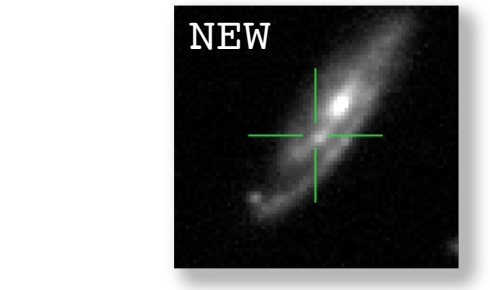
Wayne Rosing at Las Cumbres Observatory Global Telescope Network.

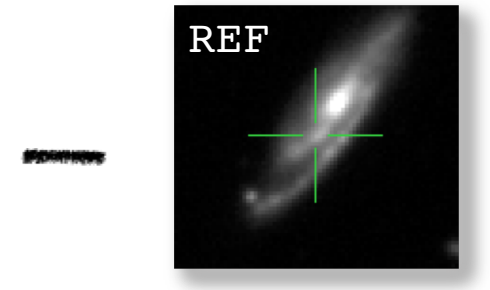
Google Mastermind Turns to the Stars

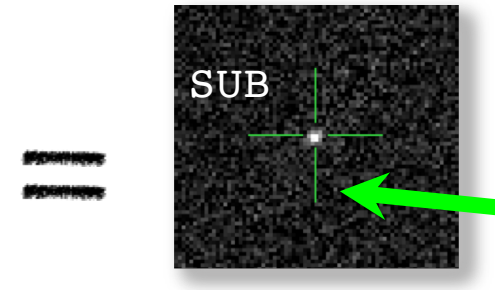
Wayne Rosing on Revolutionizing Astronomy from Goleta

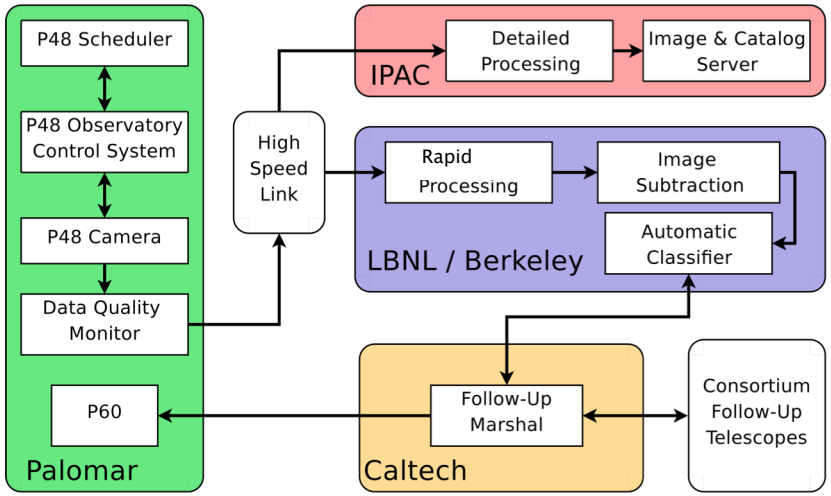
Palomar Transient Factory: Hardware, Software & *Grayware!*

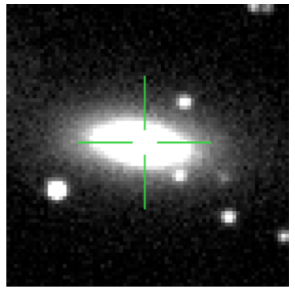
Software, software & more software

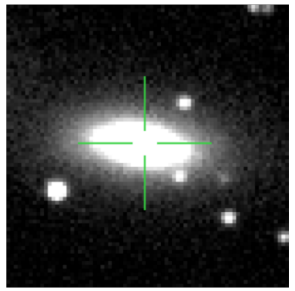


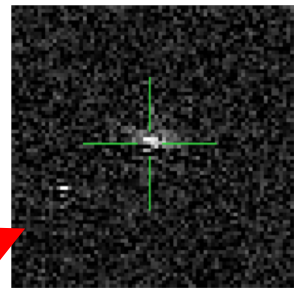








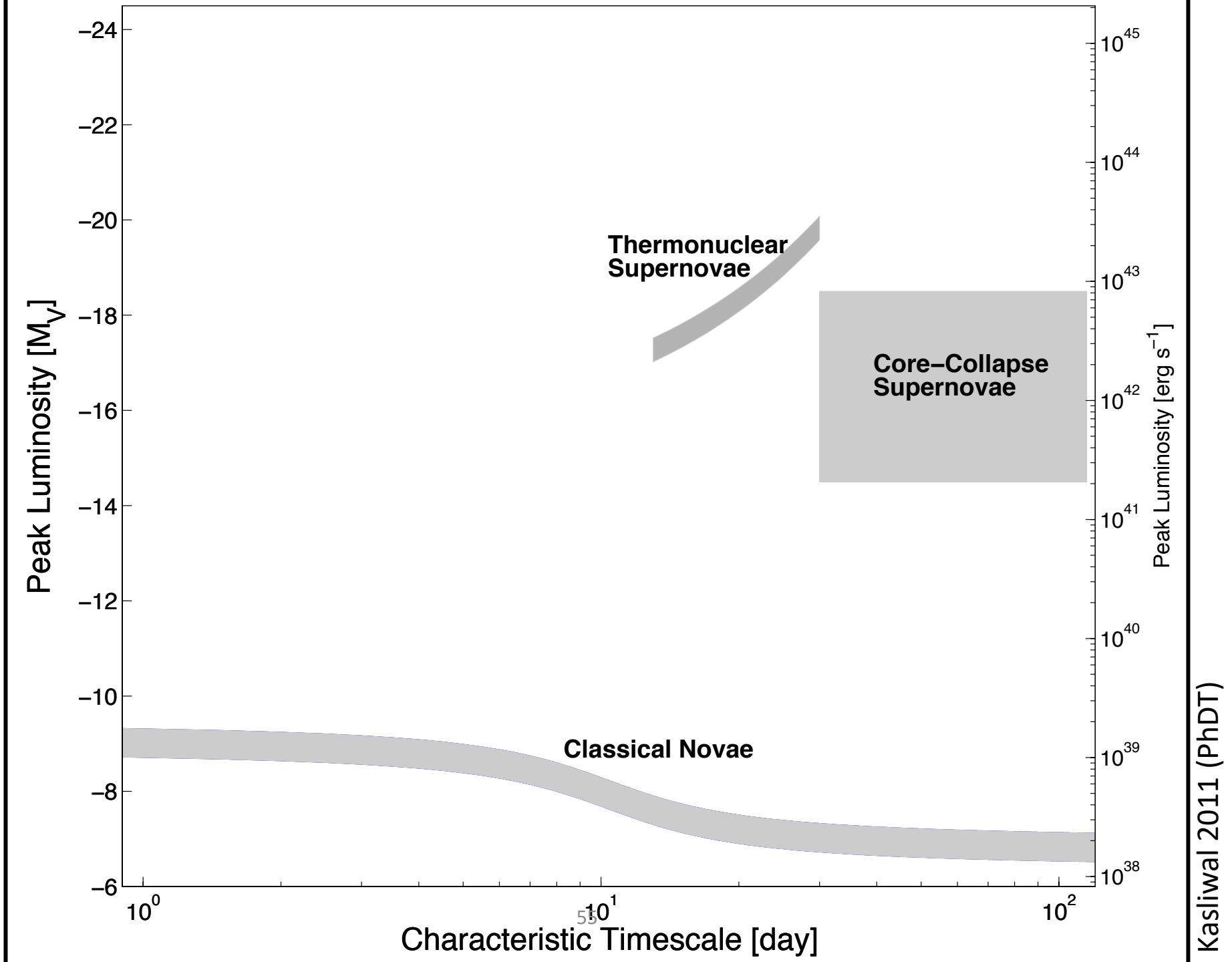




Time from exposure to candidates in the subtraction database: **<10 minutes**

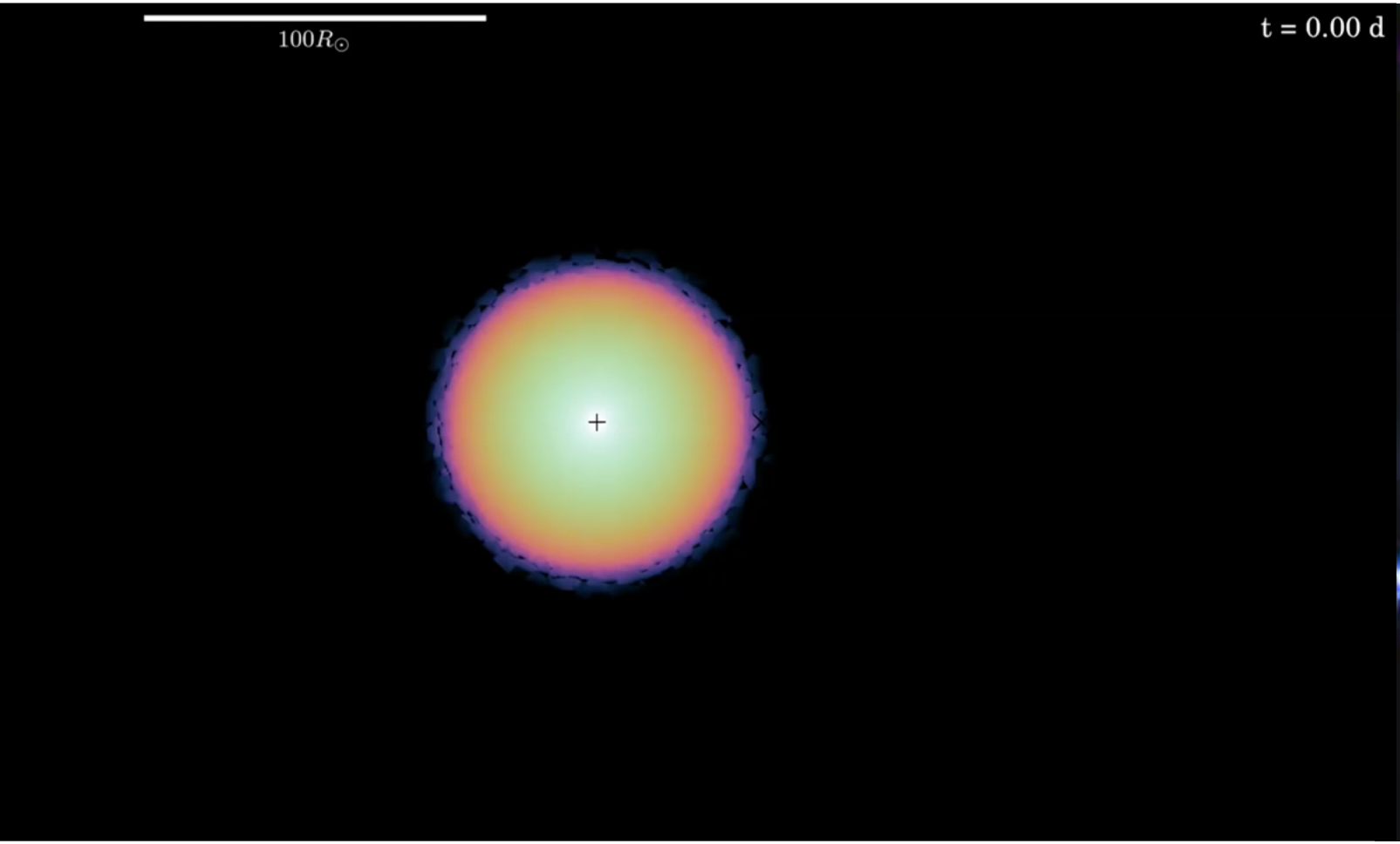
Supernova, good!

Subtraction artifacts, bad!



Kasliwal 2011 (PhDT)

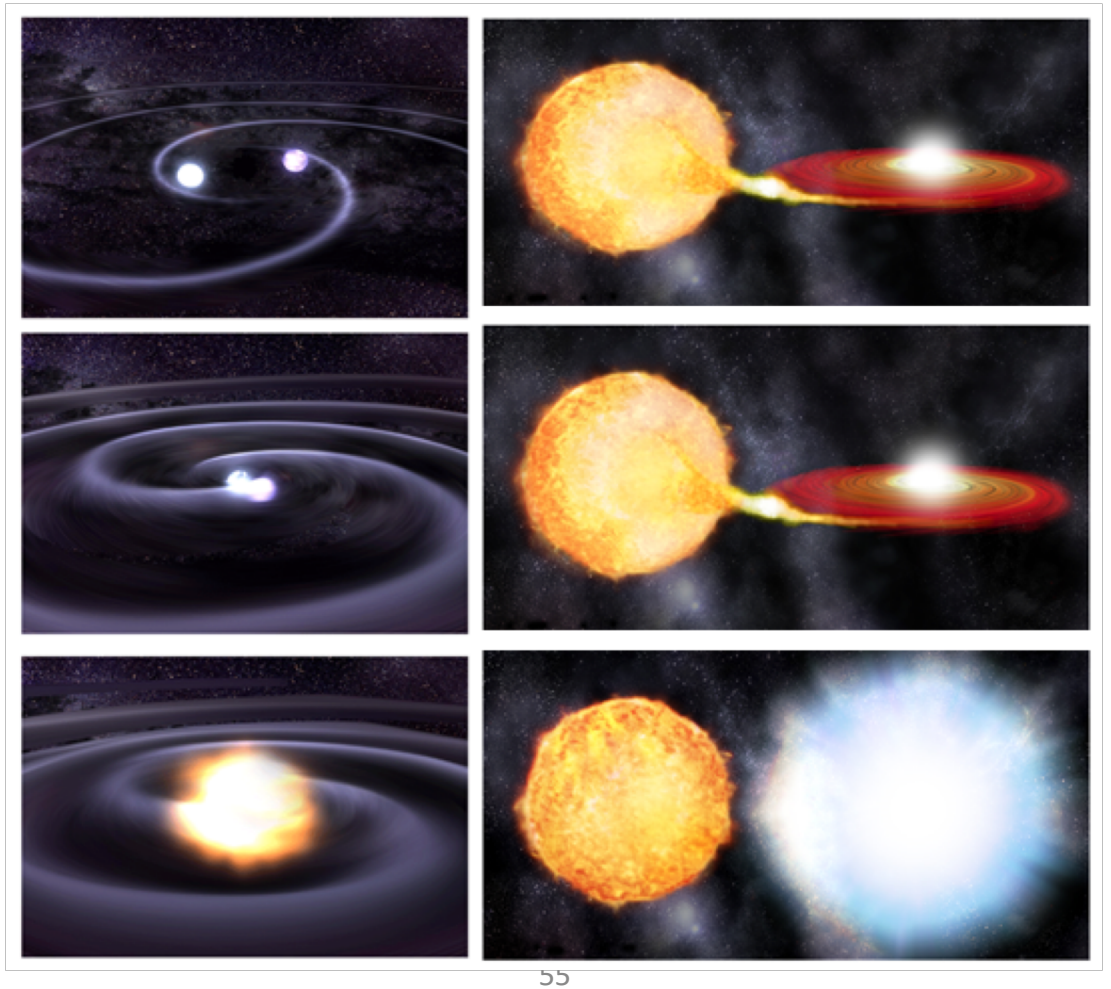
Luminous Red Novae (Binary Stars Merge)



PTF11ky: A Type Ia SN only 10 hours old!

Source: PTF Collaboration

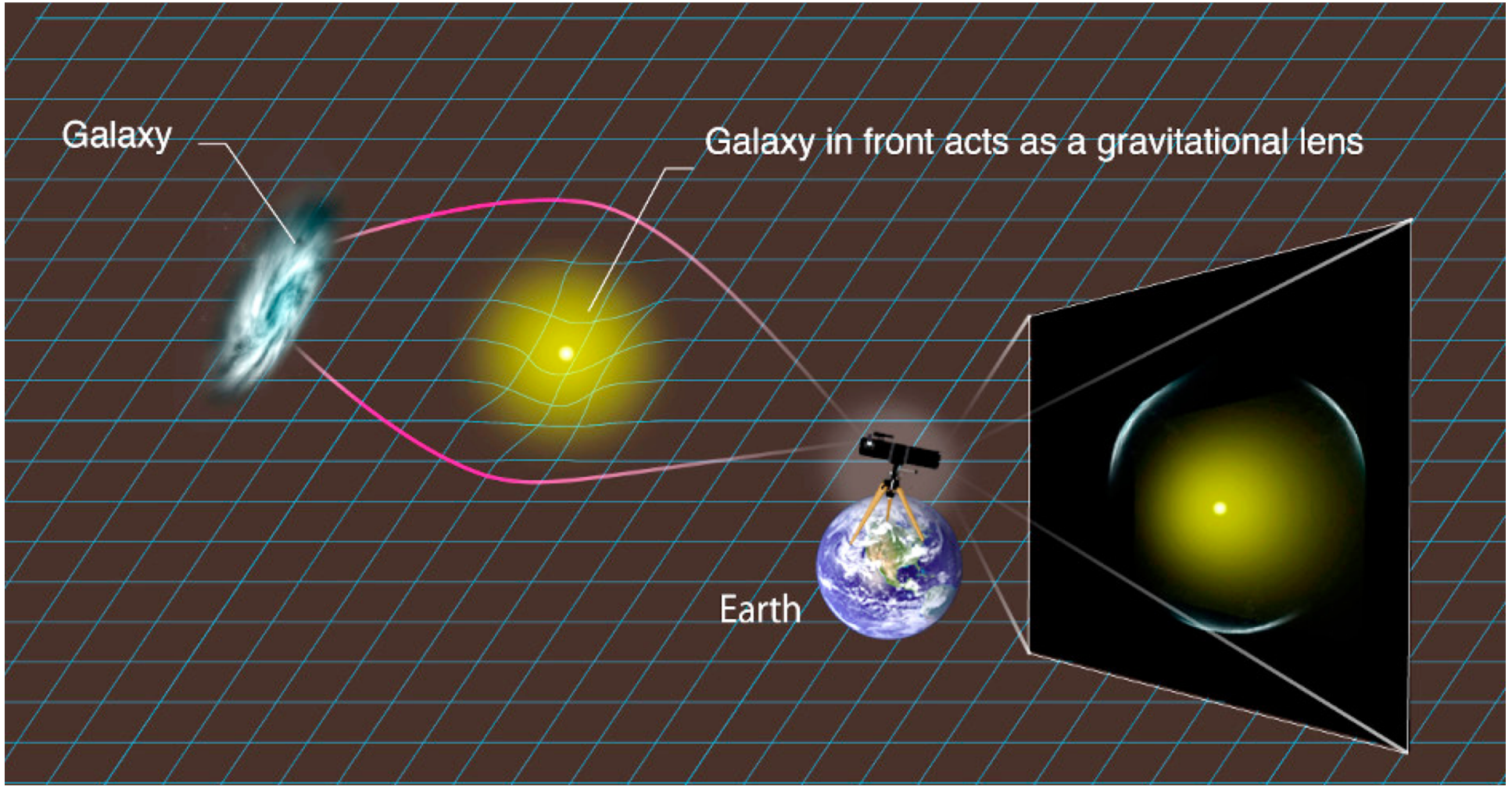
Nature makes Type Ia SN in two ways!



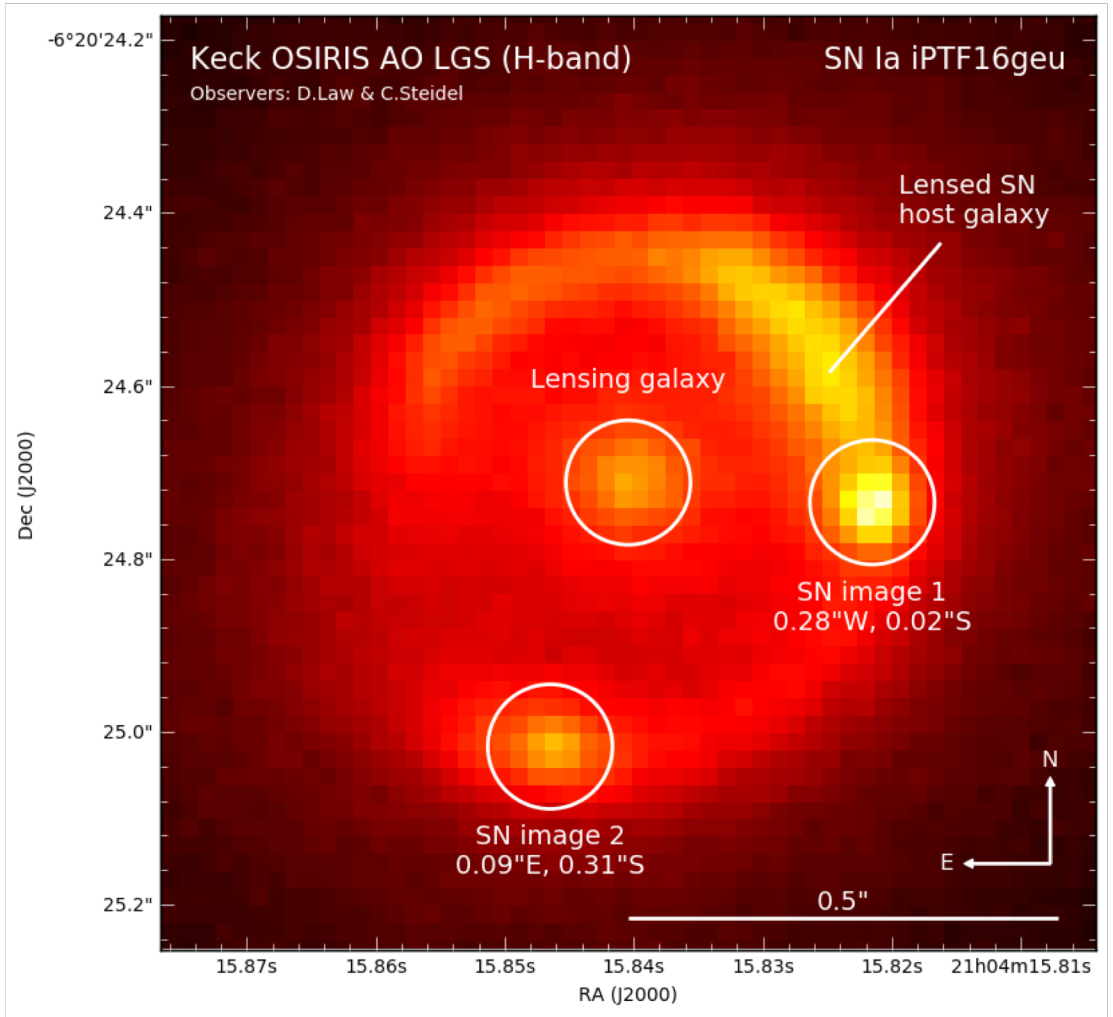
Li et al.
Nugent et al.

Yi Cao 2016 thesis

(Dark) Matter bends light



A strongly magnified supernova



Keck Adaptive Optics

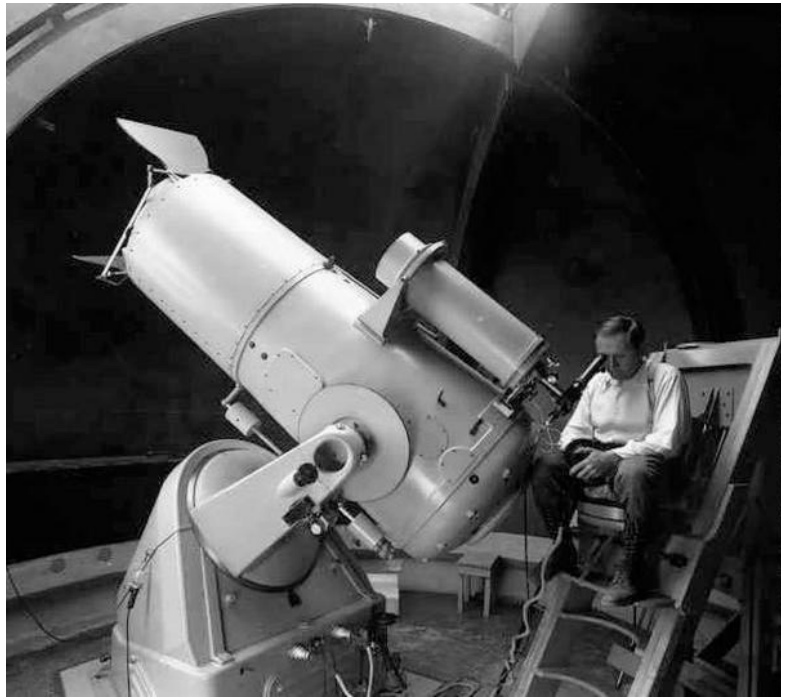
Methodology & Technological Developments

- Phase I (Palomar Transient Factory): 2009-2012
  - Machine Learning for classification
  - Same night classification & follow up
- Phase II (intermediate Transient Factory): 2013-2016
  - Mixed cadence observing
  - Multi-band observing
  - Robotic IFU spectroscopy (SEDM on P60)
  - Demonstration of Needle in a haystack Search
- Phase III (Zwicky Transient Factory): 2018-2020
  - Pre-cursor to LSST for Time Domain Astronomy
  - Industrialization of alert distribution

AUTOMATING THE DISCOVERY OF THE UNIVERSE

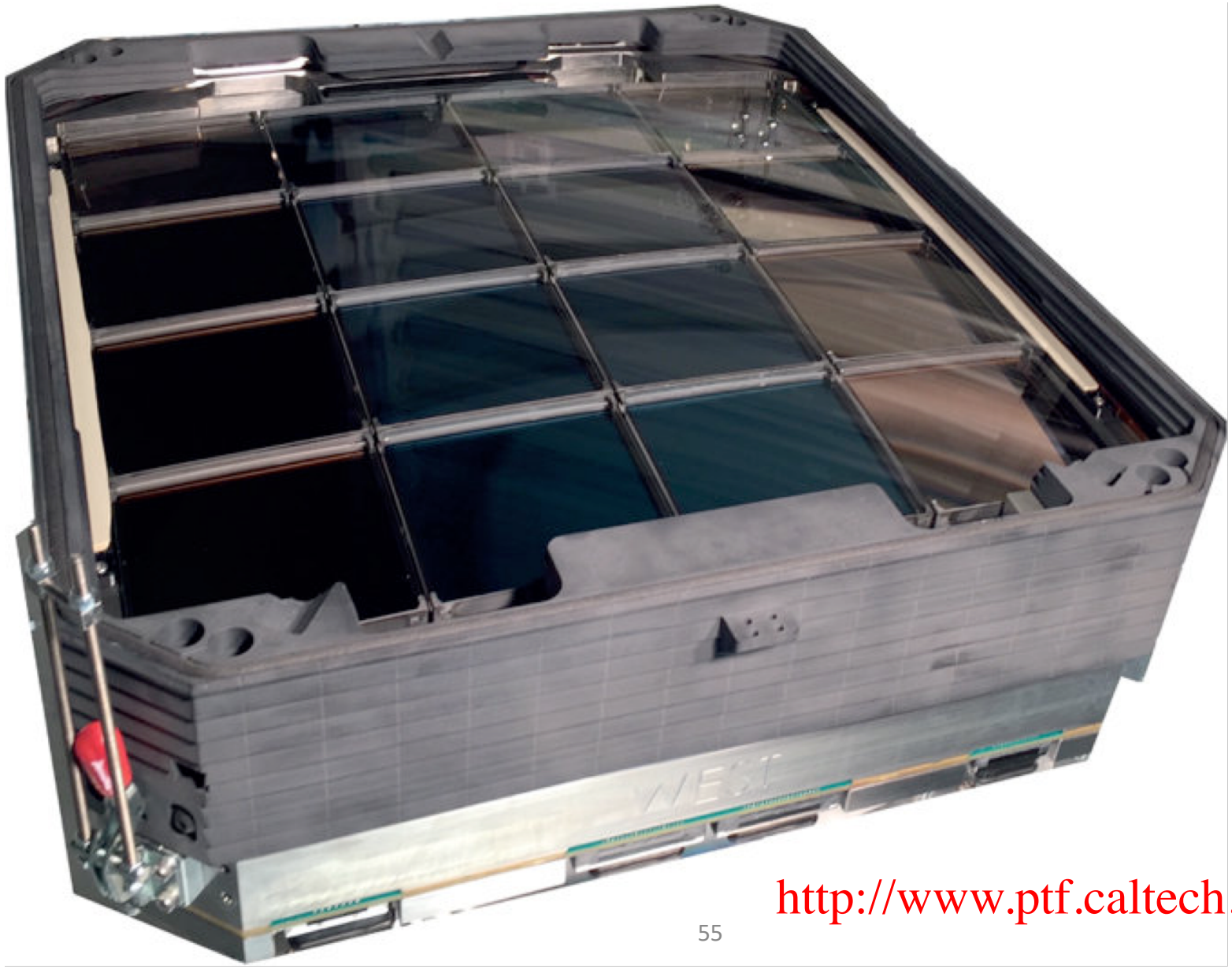
Zwicky Transient Facility

SRK, Principal Investigator
Eric Bellm, Survey Scientist
Matthew Graham, Project Scientist
Richard Dekany, Project Manager
Roger Smith, Focal Plane Engineer



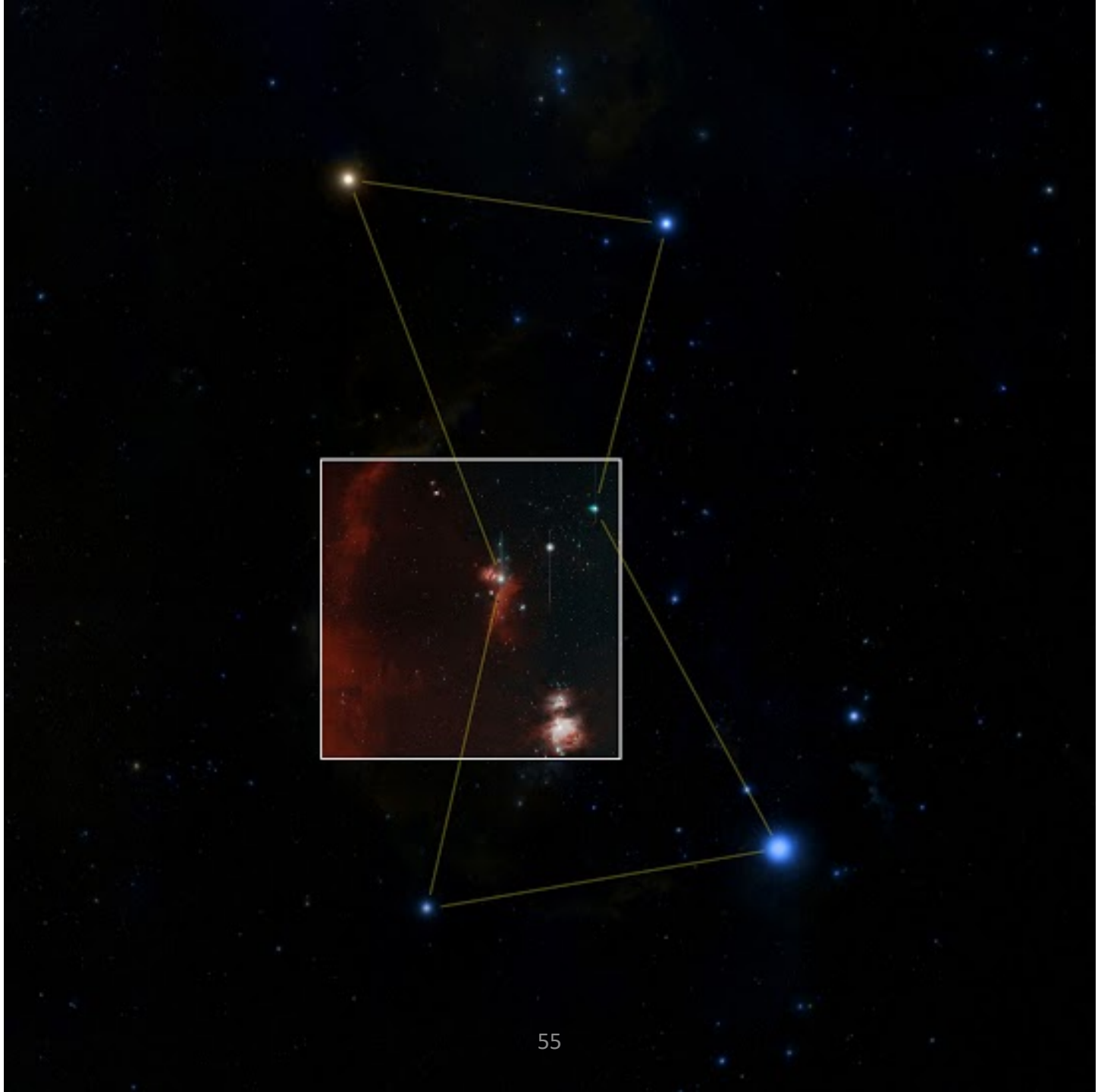
Field of view & aperture comparison (desisgned for wide & shallow TDA)

The 600 Mega-Pixel Camera!

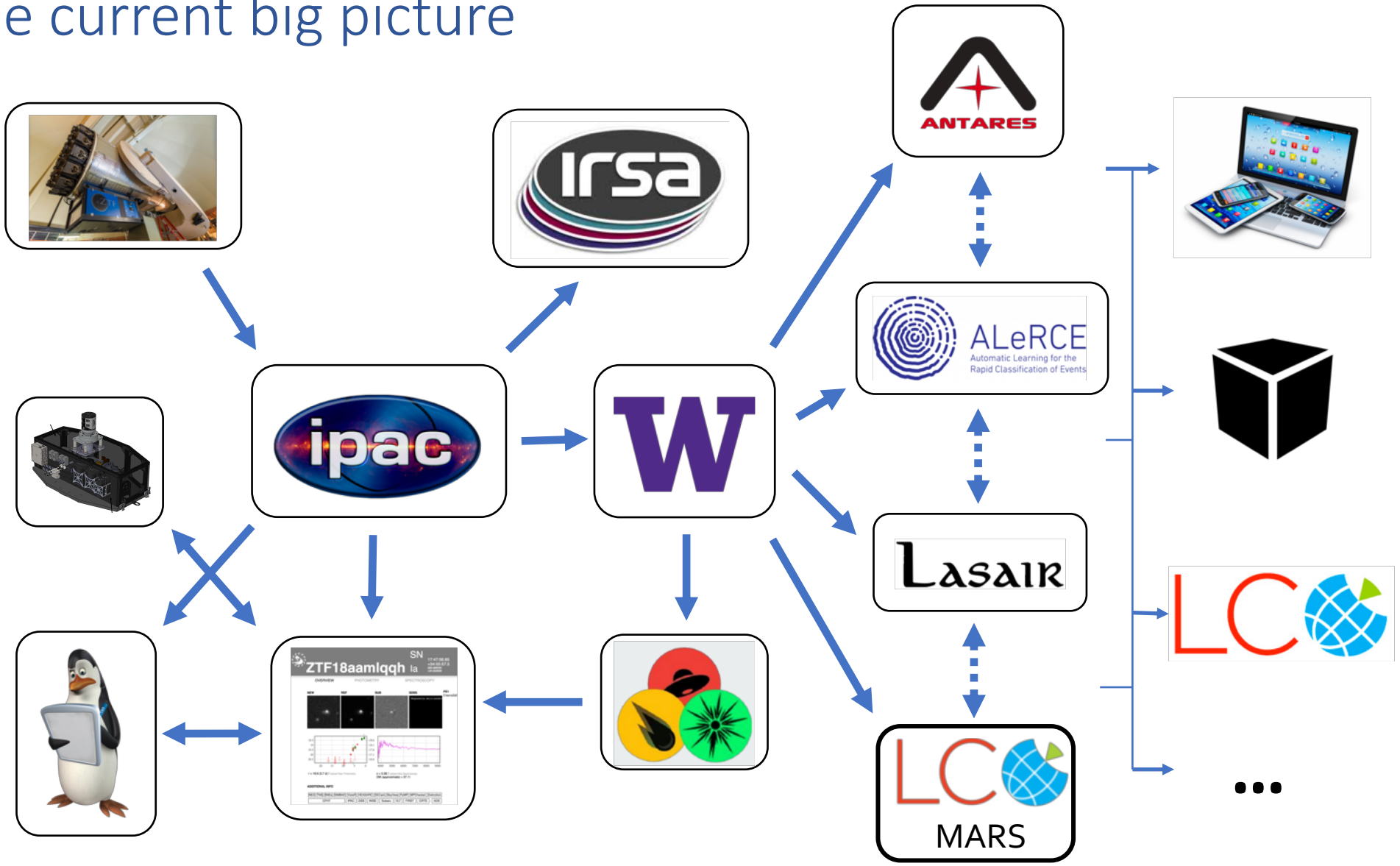


http://www.ptf.caltech.edu/ztf

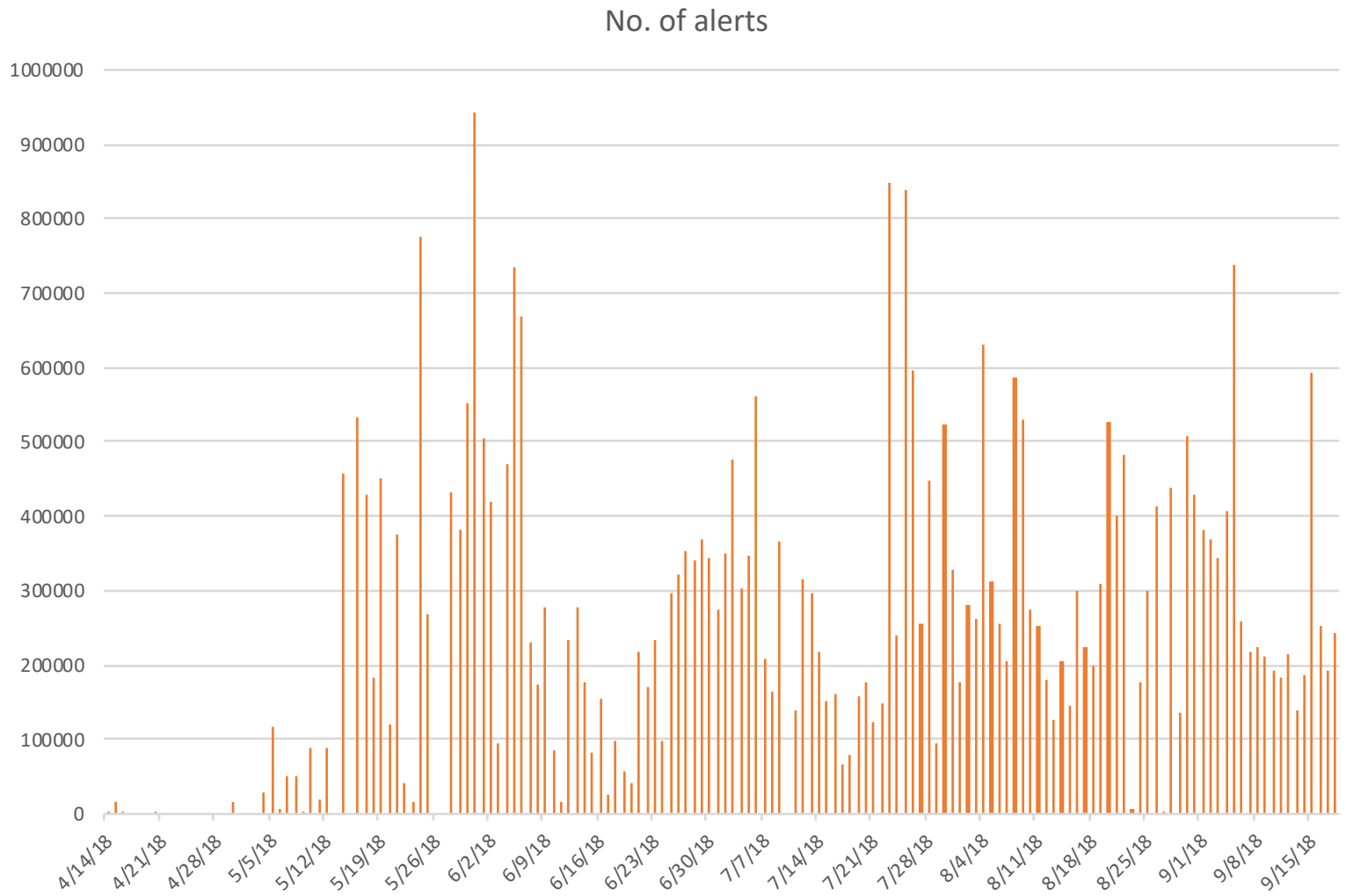
FIRST LIGHT!



ZTF: The current big picture



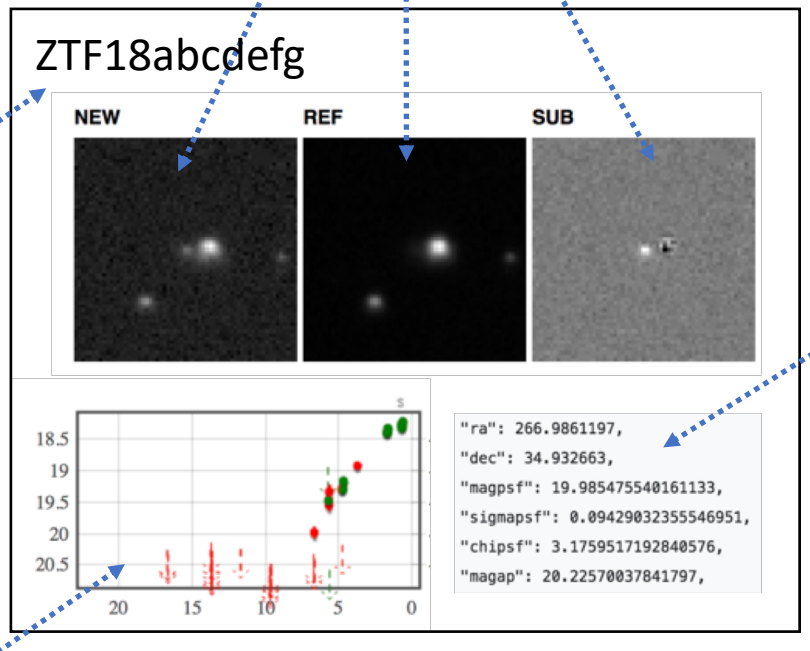
Alerts : 44876669 to Sep 20



Alert structure: AVRO format

63 x 63 pixel 32-bit images

Unique spatially matched alert name



- ZOGY parameters
- Real-bogus score
- Star/galaxy score
- 3 nearest PS1 sources
- Nearest SS object
- Alert history

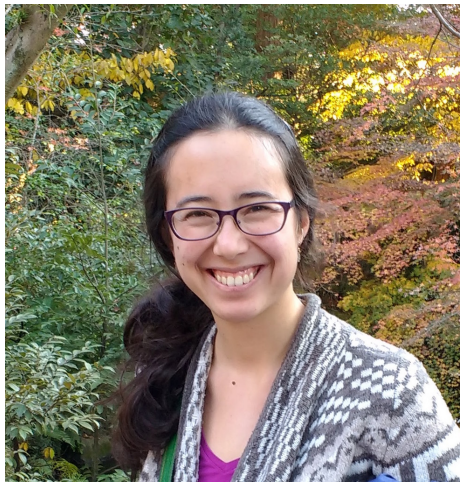
Rolling 30-day window light curve

https://github.com/ZwickyTransientFacility/ztf-avro-alert

Team: Young people!

Y. Sharma
IITB (UG)

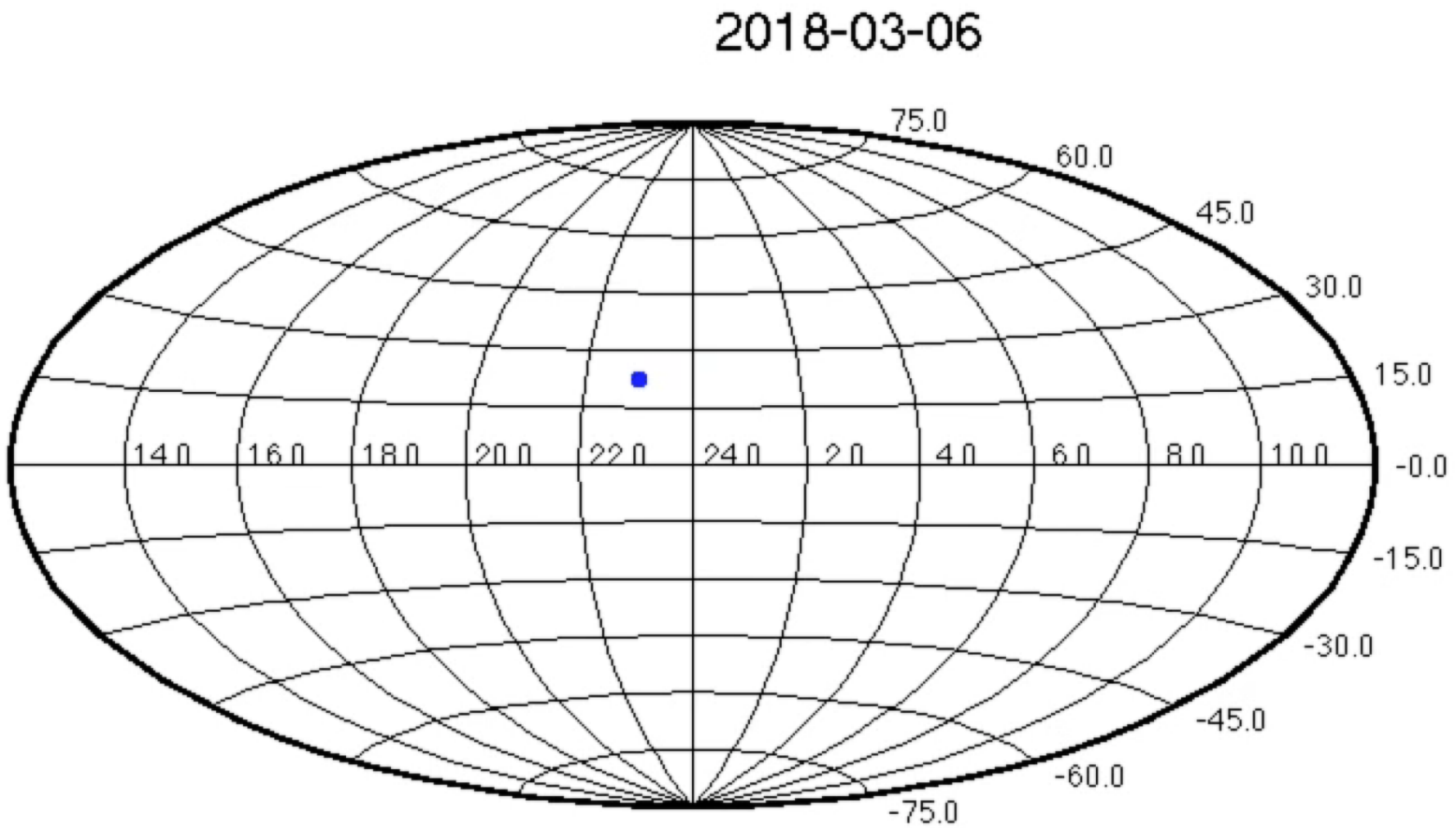
Anna Ho
Caltech (G)



K. De
Caltech (G)

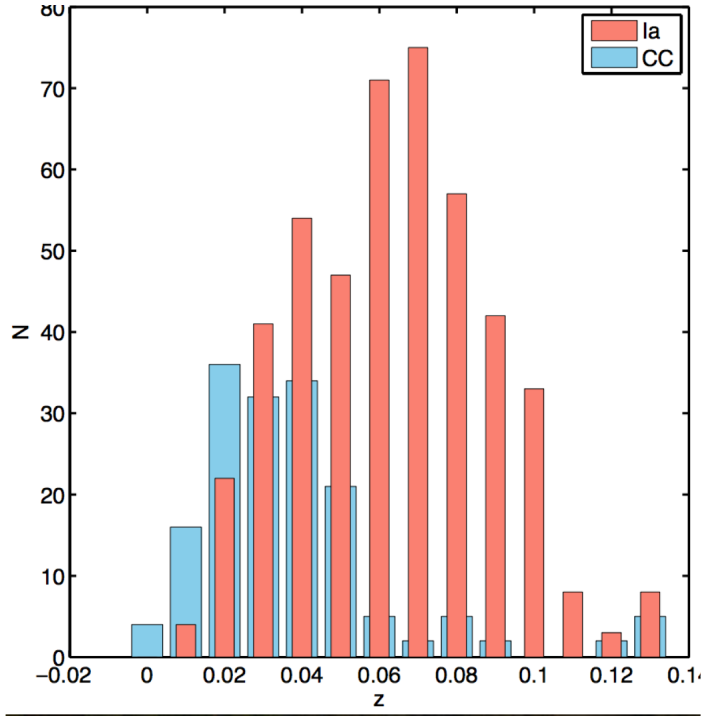
Principal Investigator for BTS: C. Fremling
Caltech,

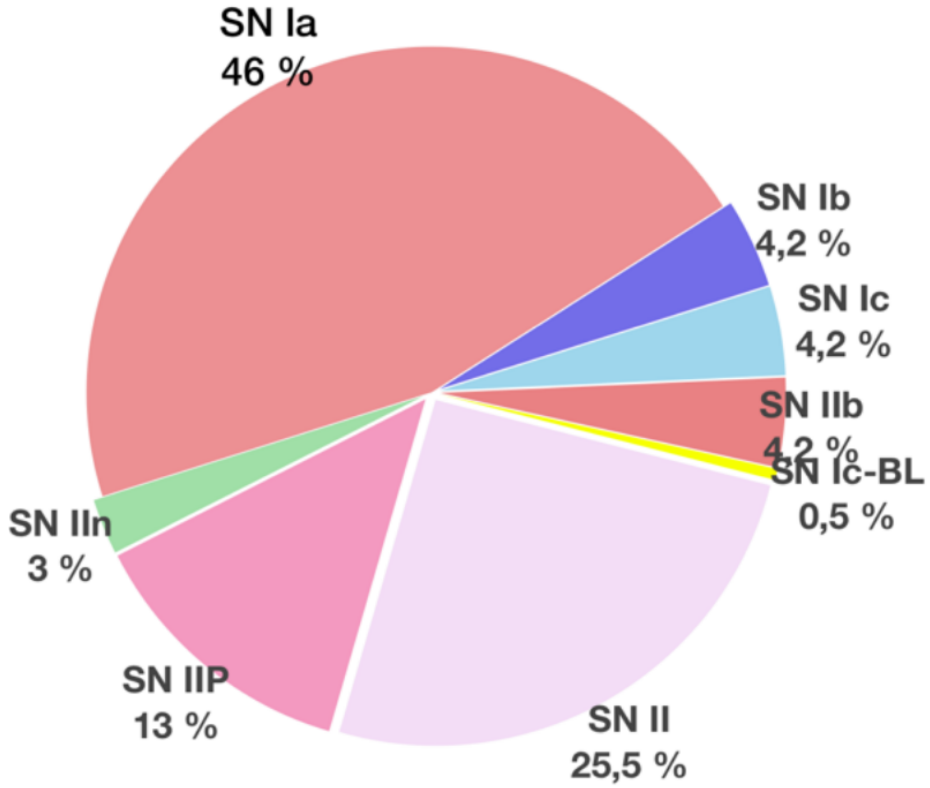
Principal Investigator for CLU:
Mansi Kasliwal (Ass Porf)


2018-03-06
75.0
60.0
45.0
30.0
15.0
-0.0
-15.0
-30.0
-45.0
-60.0
-75.0
14.0
16.0
18.0
20.0
22.0
24.0
2.0
4.0
6.0
8.0
10.0

Supernova – (1) rates and luminosity functions:

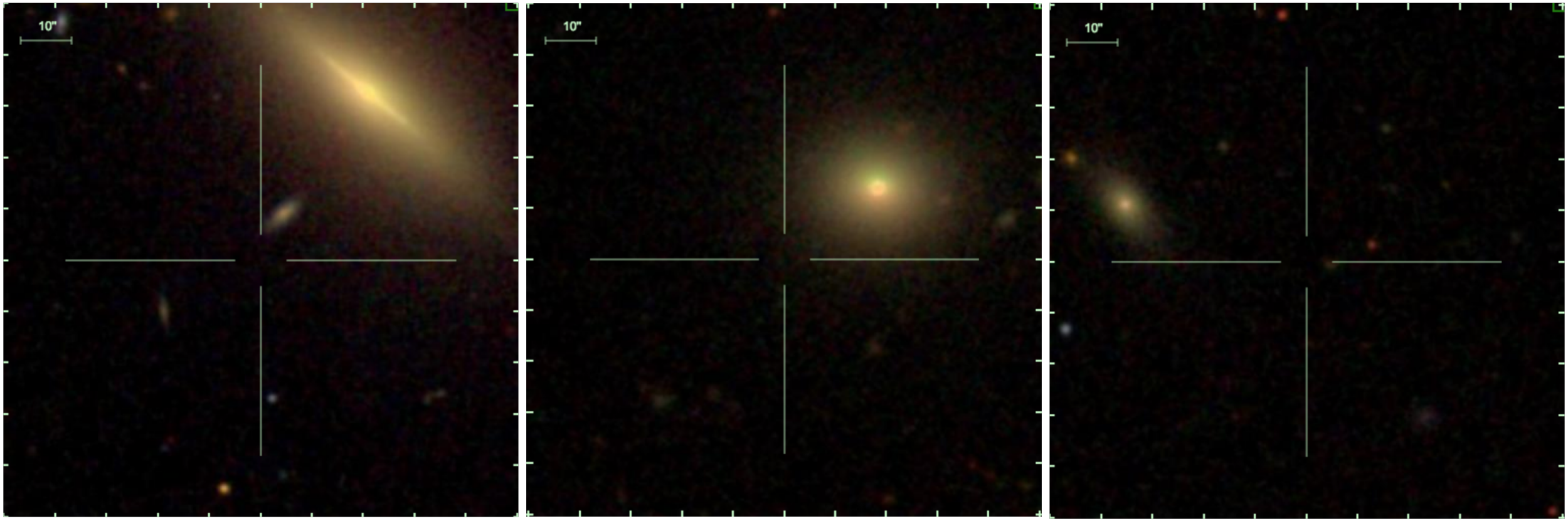
- The ZTF Bright Transient Survey (BTS)
  - All alerts brighter than 18.5mag are spectrally classified, primarily using SEDM on Palomar 60inch
  - Total classified: 622 (477 Ia, 177 ccSN)





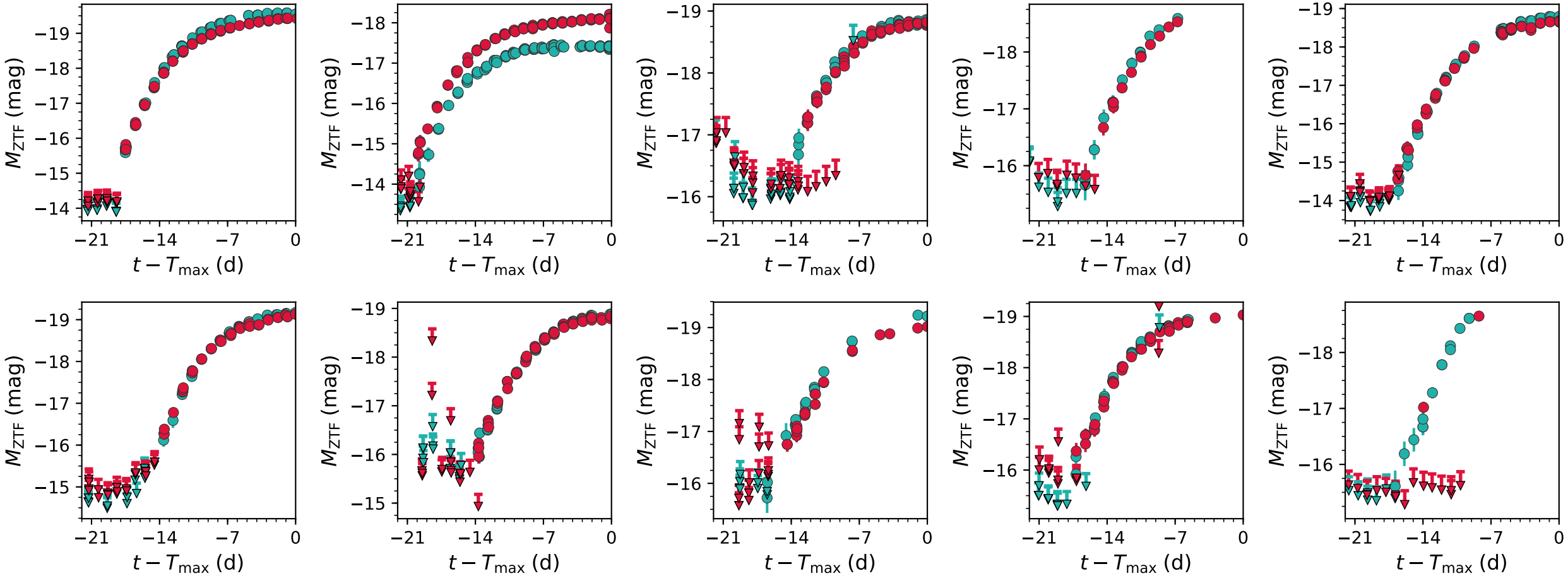
Volume Limited →Rare transients

Ca rich transients in the outskirts of galaxies



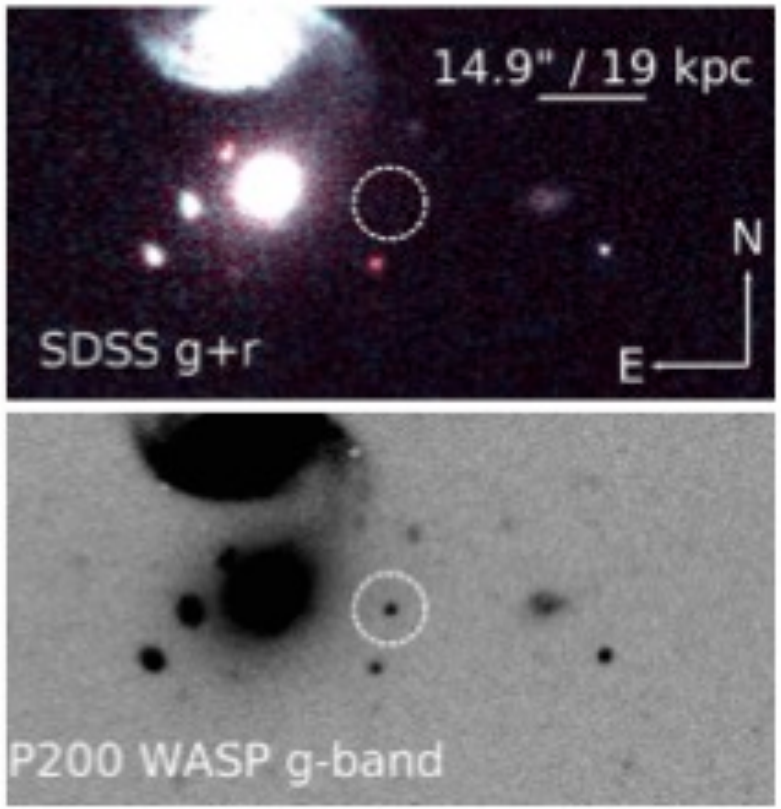
Early SNe Ia Observations with ZTF

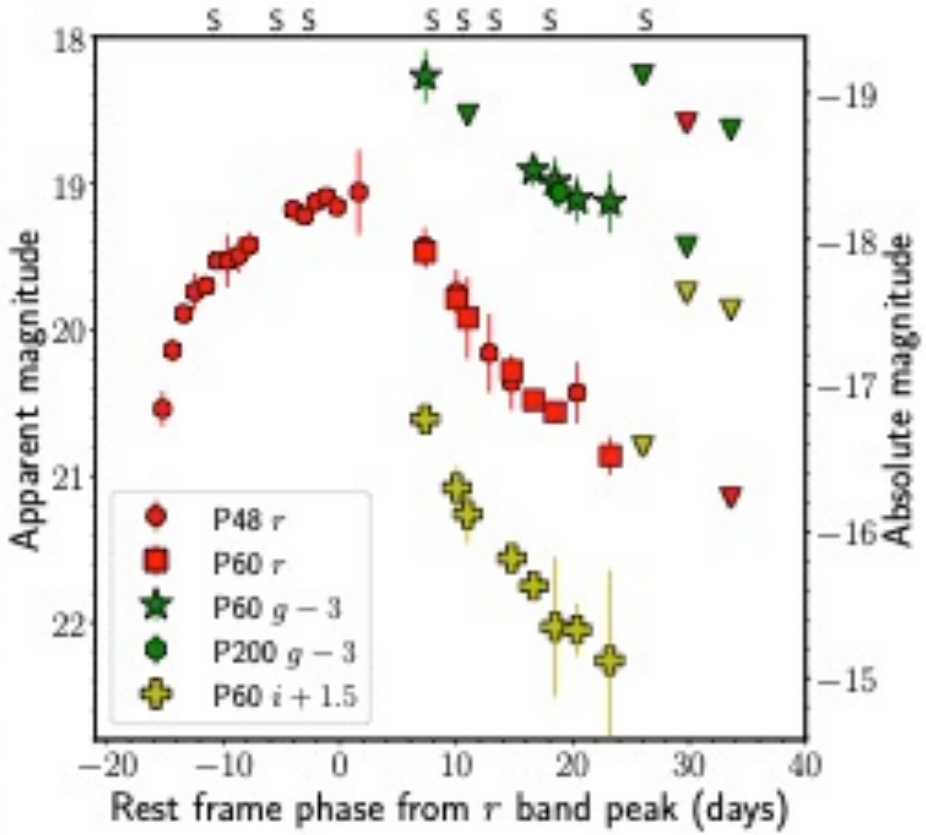
ZTF routinely finds young SNe Ia (> 12 in the period from 01 Jun – 15 Sept)



Keck ToO program is particularly important for obtaining early spectra to search for unburned C & velocity of the ejecta

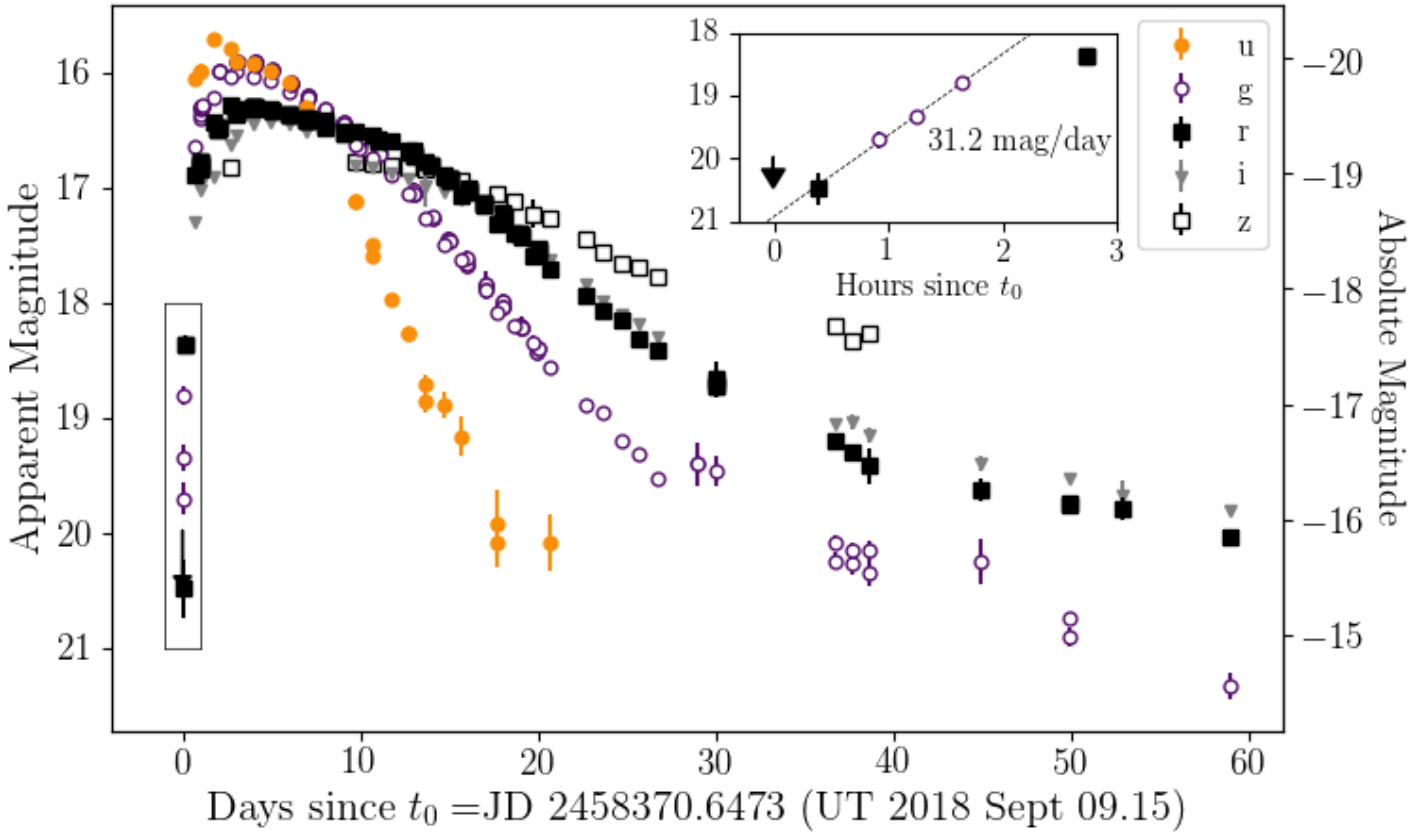
Double detonation!





De thesis

Early Observations of core-collapse SNe

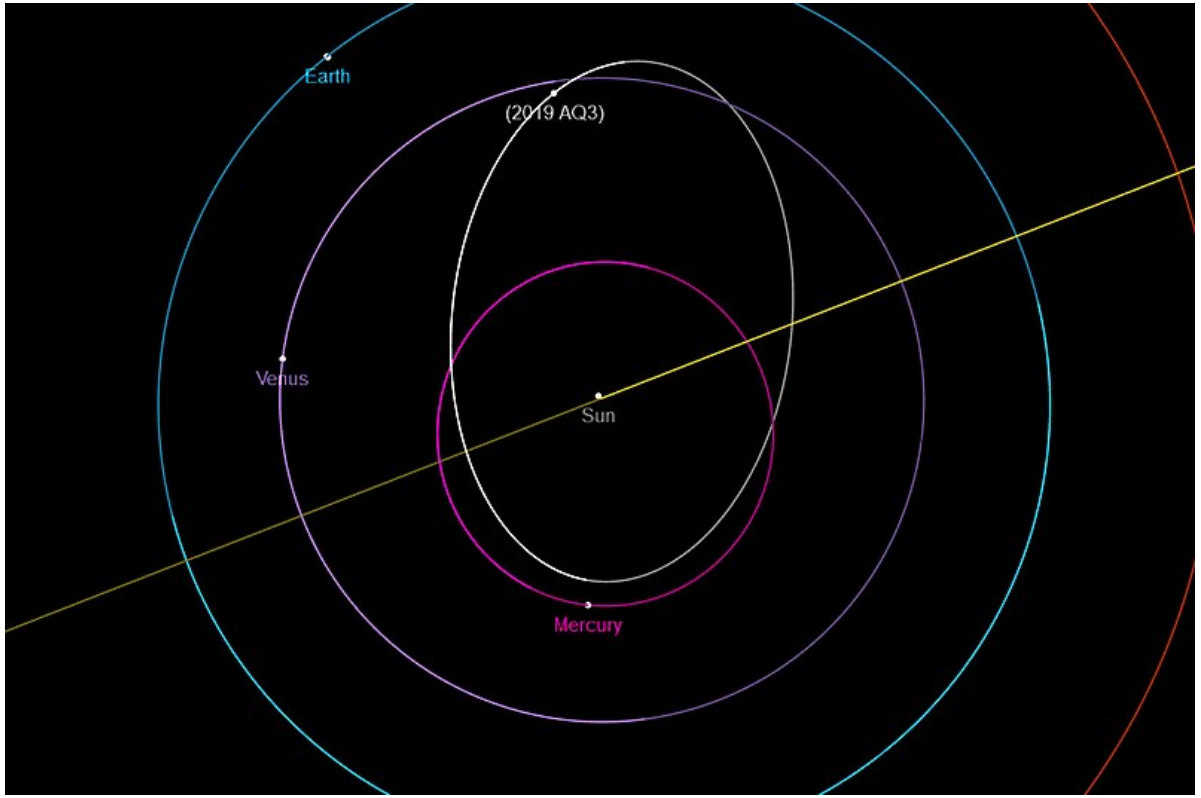


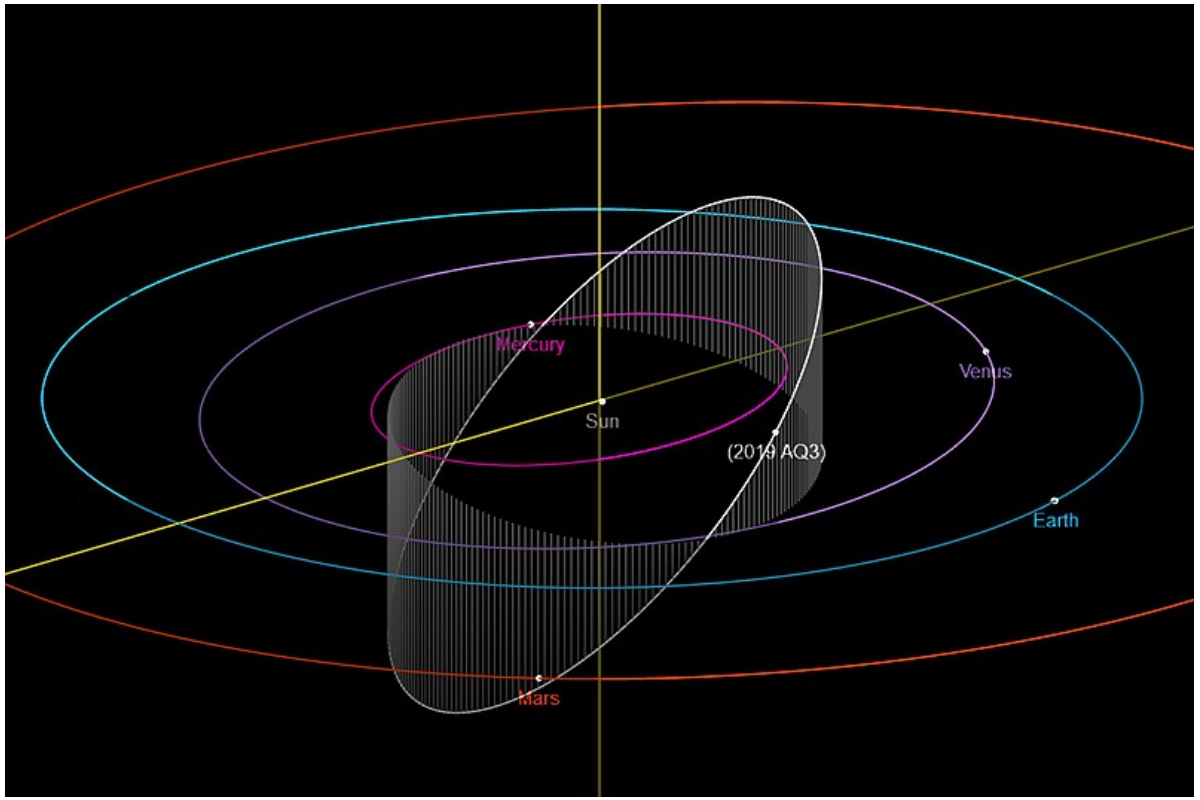
Anna Ho thesis

Figure 1. Optical light curves compiled from the P48, the P60+SEDM, and LT.

Streakers: Near Earth Asteroids

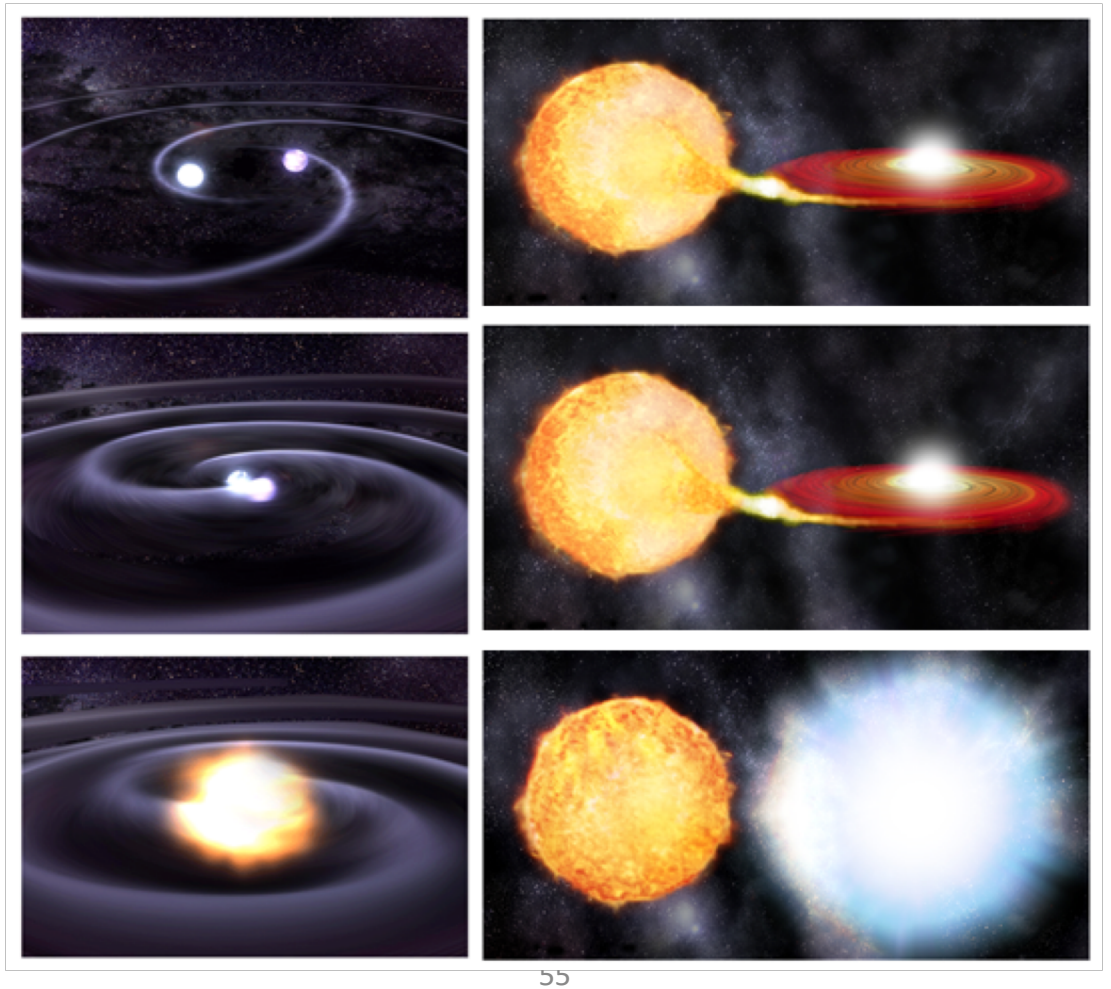
2019AQ$_3$ (rare Atira group; 1.4 km)





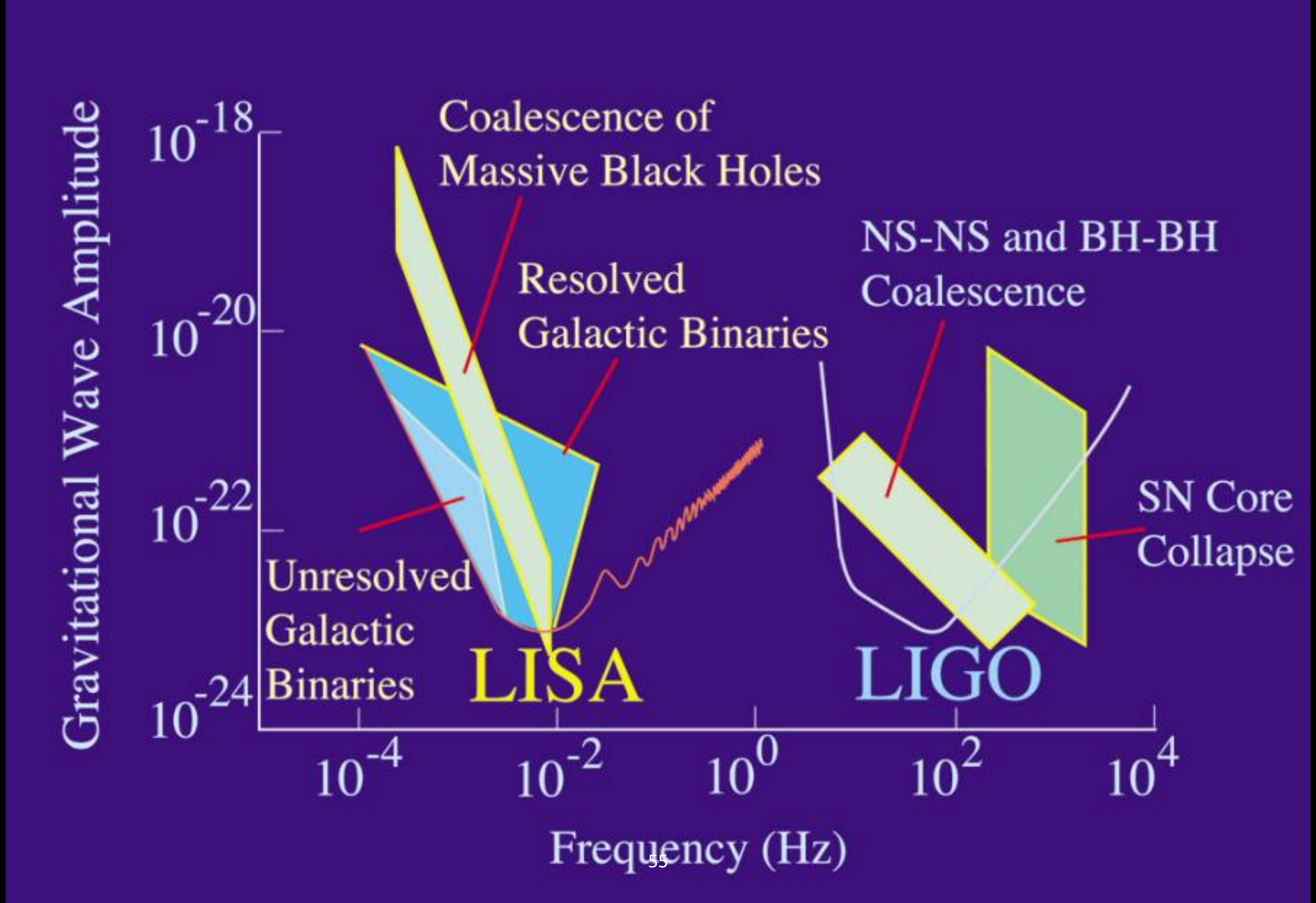
DOUBLE DEGENERATES (LEADING TO EXPLOSIONS)

Nature makes Type Ia SN in two ways!

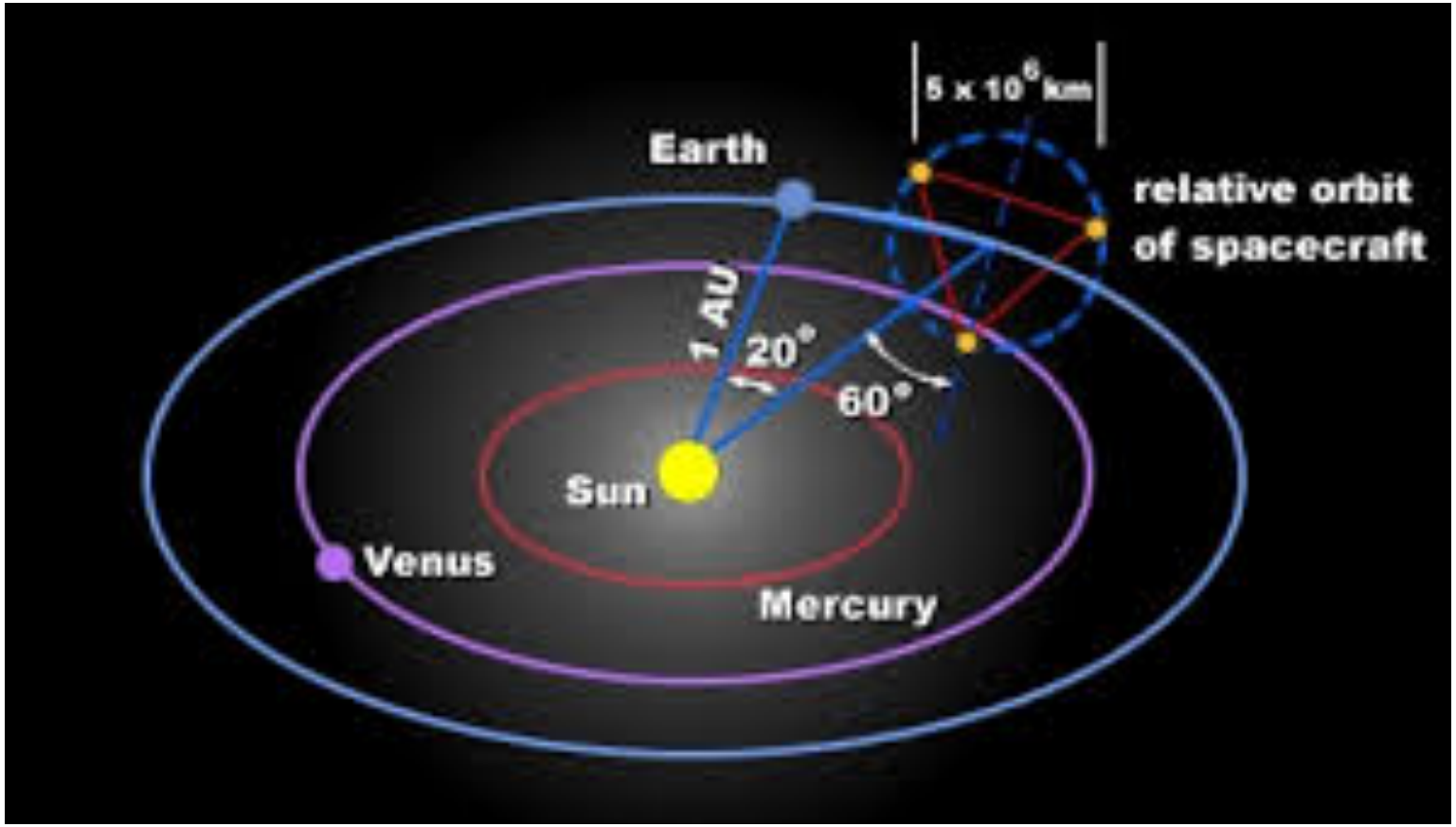


Li et al.
Nugent et al.

Yi Cao 2016 thesis

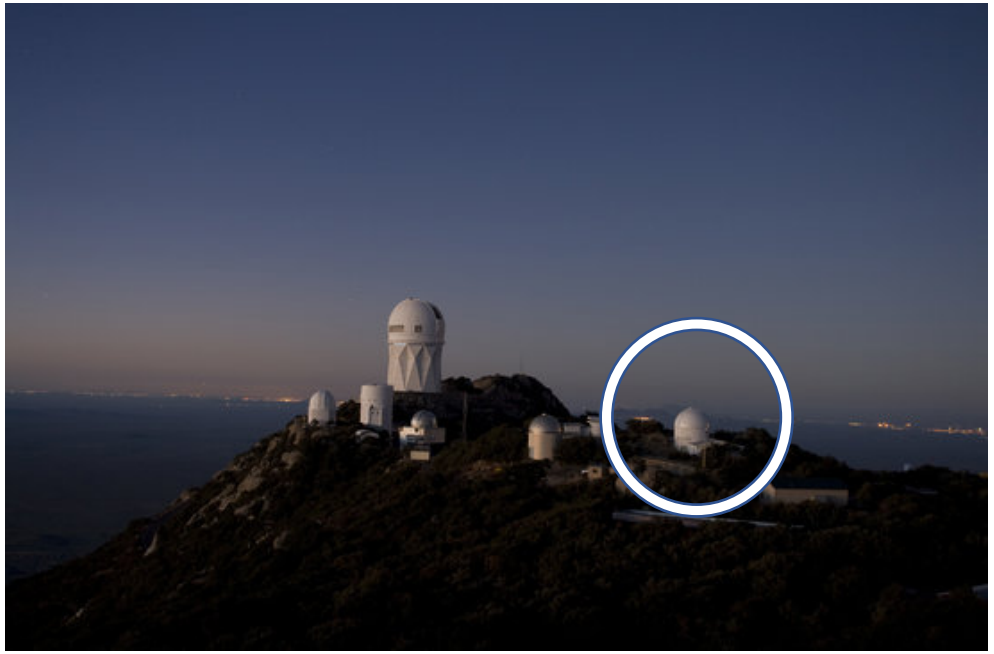

Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
LISA
NS-NS and BH-BH Coalescence
SN Core Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)

Laser Interferometer Space Antenna (LISA)



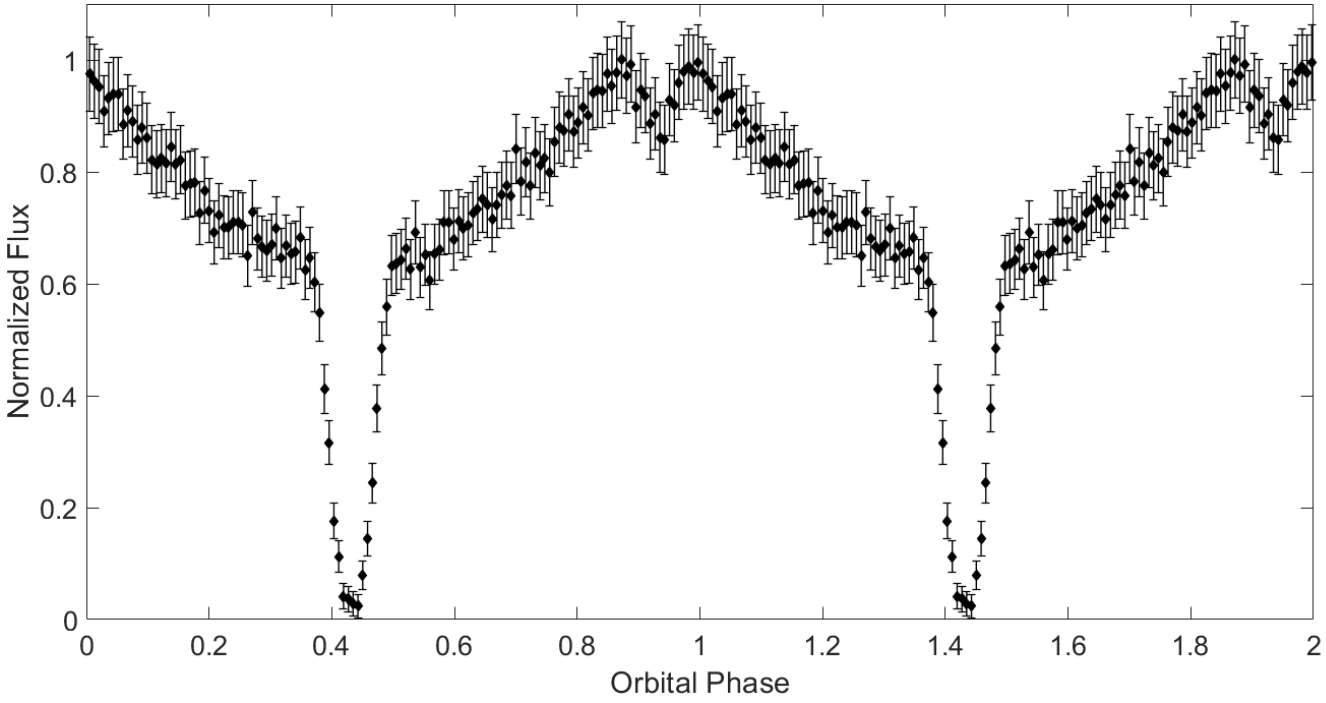
A loud double degenerate

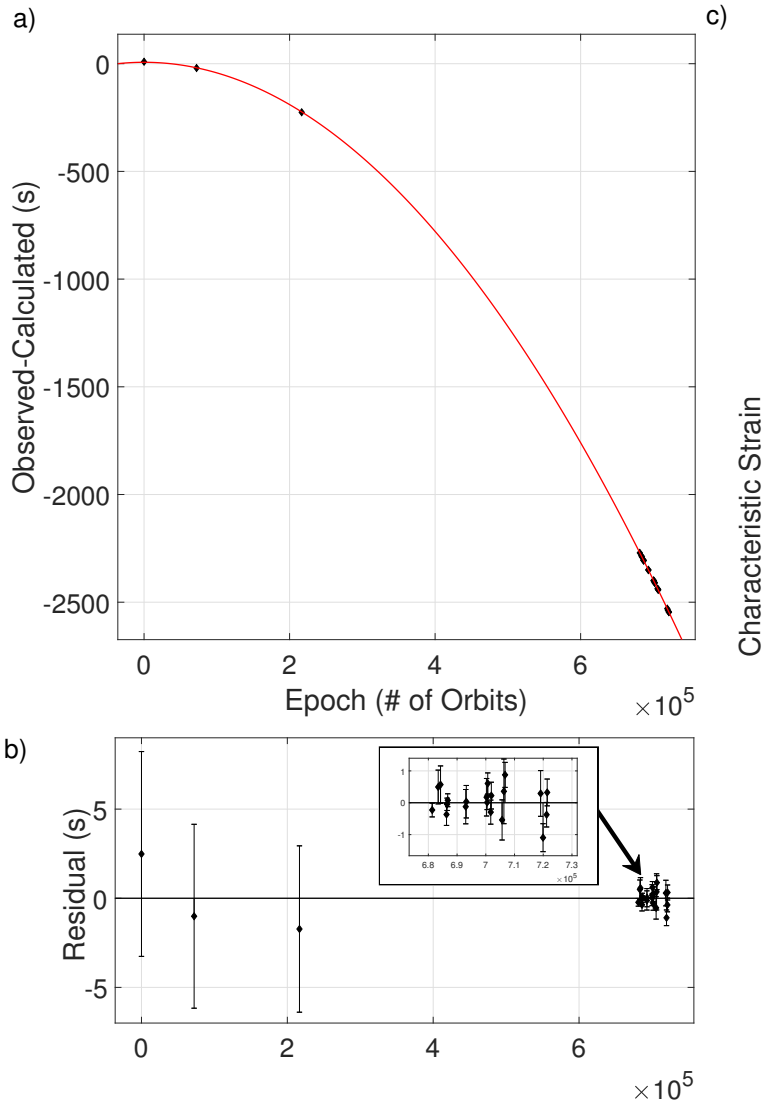
- K. Burdge performed a global period search of the first set of ZTF data
- M. Coughlin immediately followed up candidates with Kitt Peak 84-inch

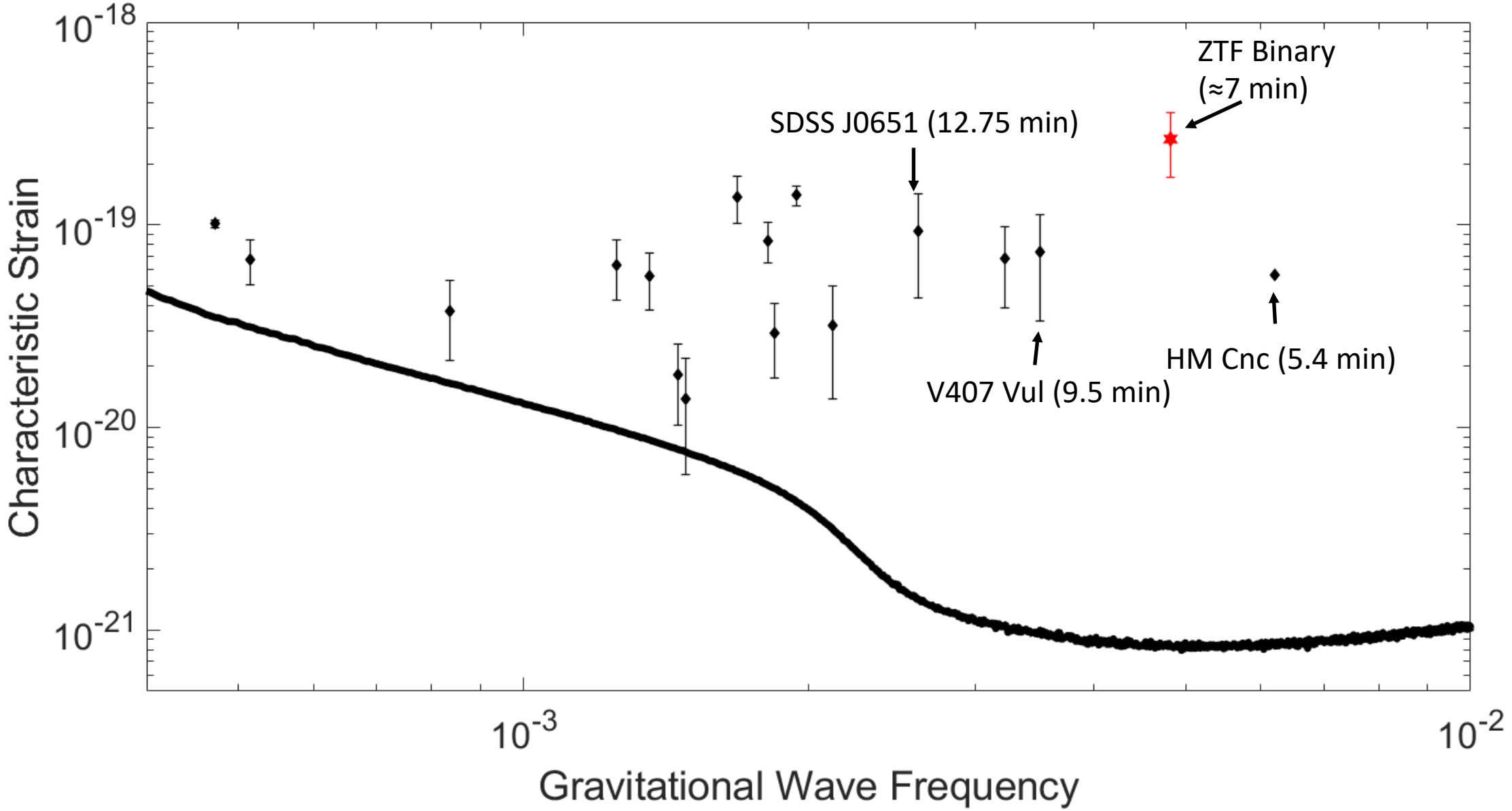


On loan from NSF/NOAO (Portfolio Divestment)
Equipped with an EMCCD imager
Candidate vetting of compact binaries
Project Scientist: Michael Coughlin

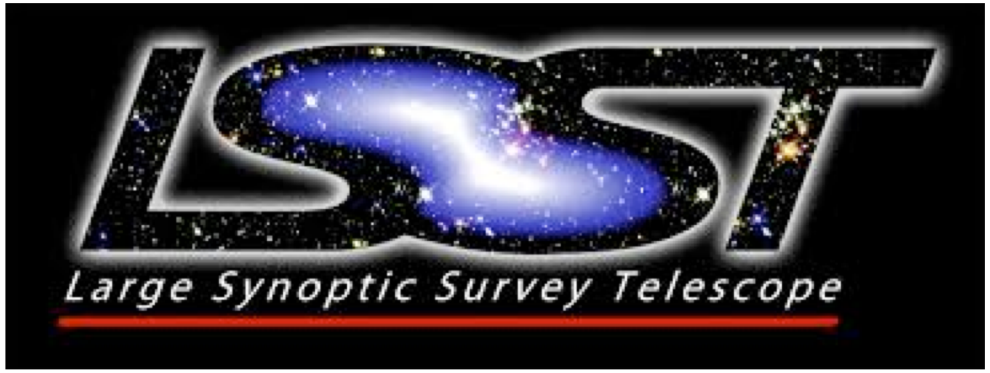
A new double lined eclipsing binary: 6.9 *minutes*






ZTF Binary
(≈7 min)
SDSS J0651 (12.75 min)
V407 Vul (9.5 min)
HM Cnc (5.4 min)
Characteristic Strain
Gravitational Wave Frequency
10^-18
10^-19
10^-20
10^-21
10^-3
10^-2

Ultimate Celestial Cinematography in 2022

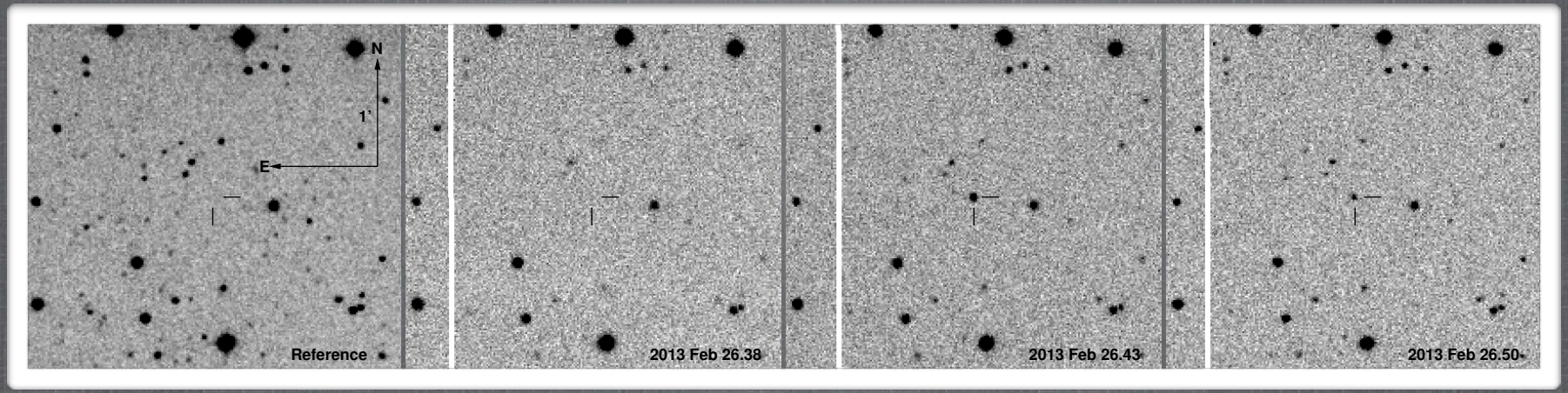


55

NEEDLE IN A HAYSTACK SEARCH (GETTING READY FOR LIGO)

iPTF14yb: "UNTRIGGERED" GRB

Reference | 2013 Feb 26.38 | 2013 Feb 26.43 | 2013 Feb 26.50



SBC+, in prep.

09:04 UT:
P48 Non-detection

10:17 UT:
P48 r = 18.16

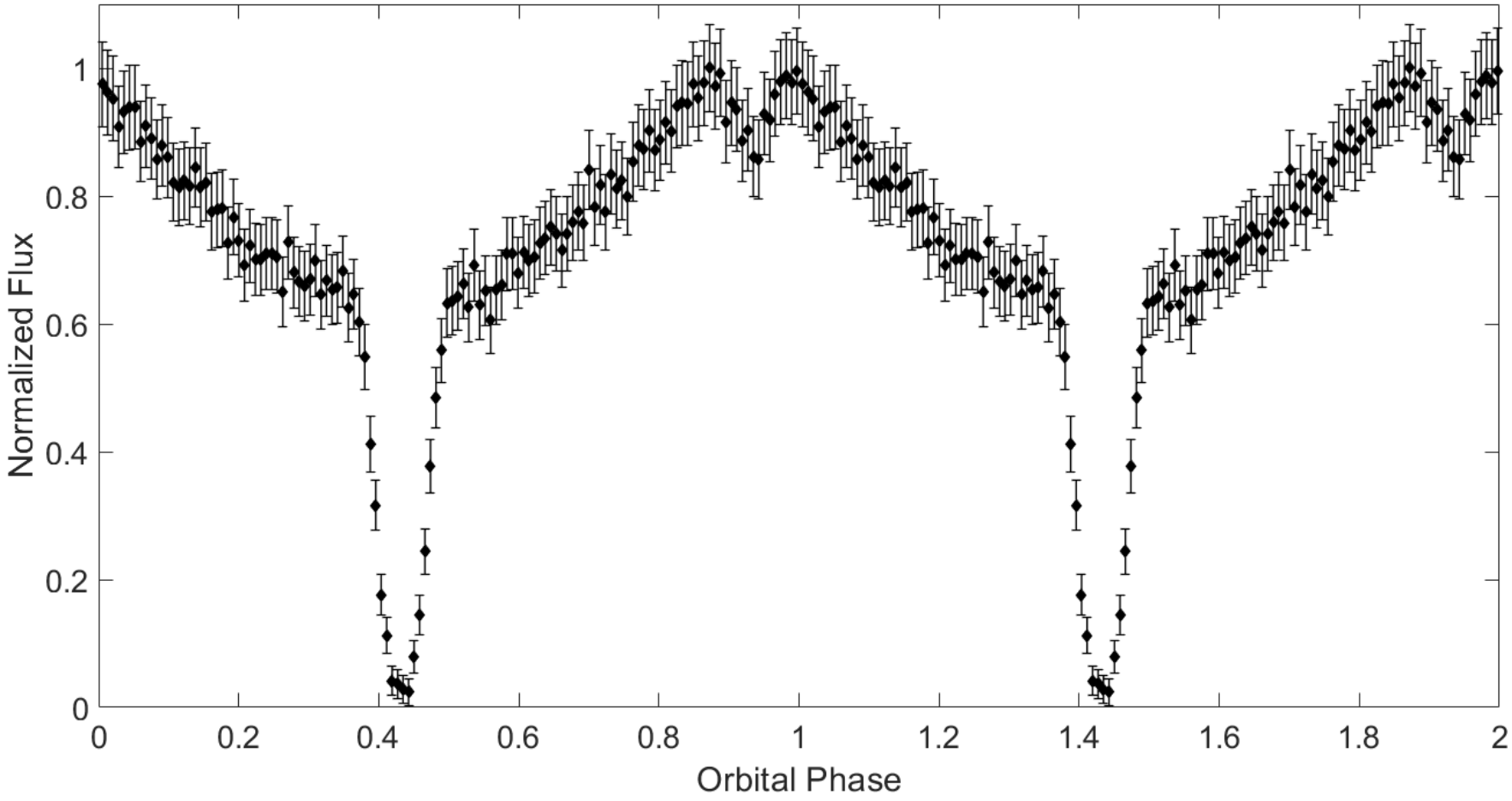
12:01 UT:
P48 r= 19.77

12:46 UT:
Flagged by software

15:26 UT:
Keck/LRIS Spectrum

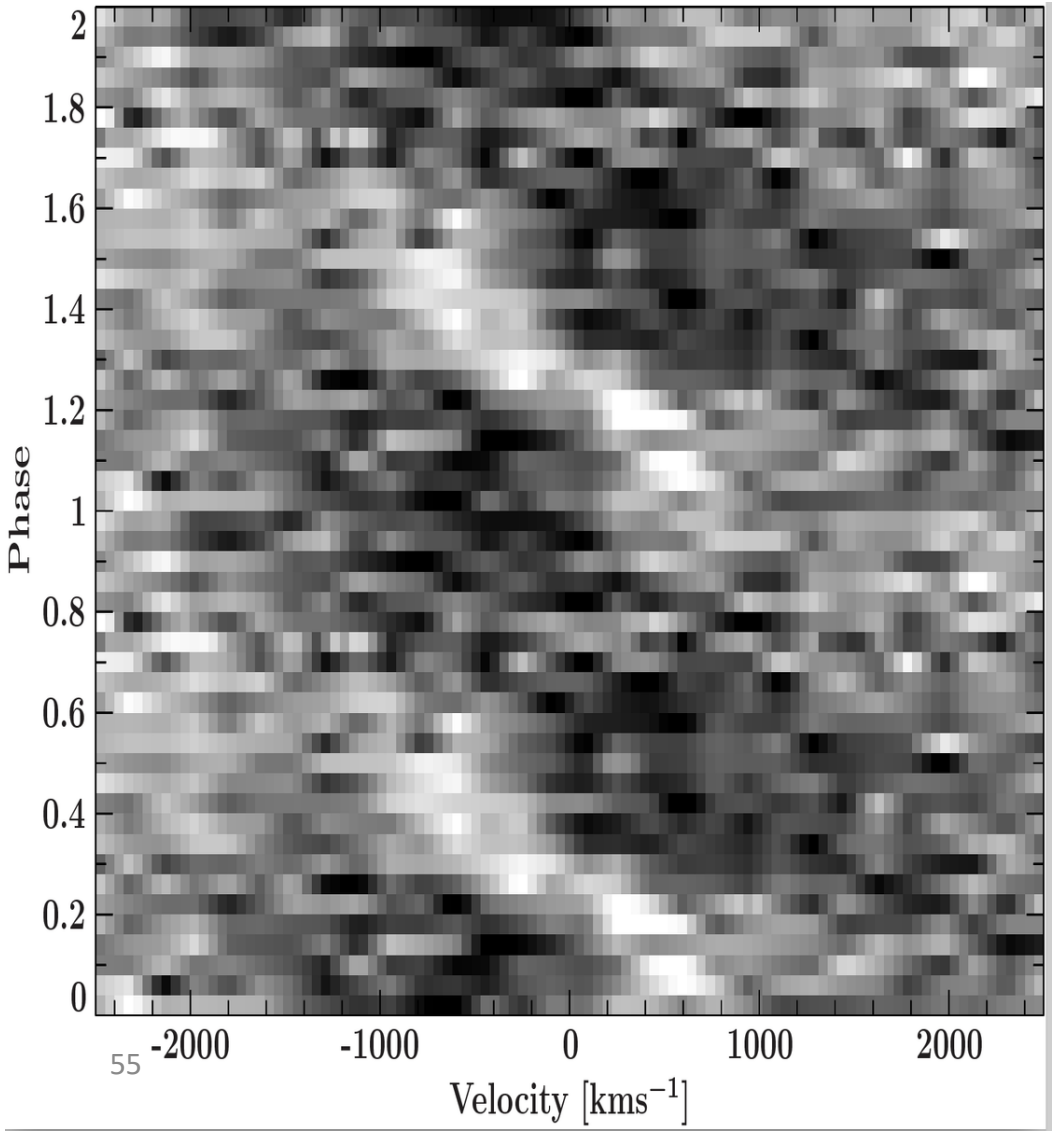
17:11 UT:
Swift X-ray+UV

A new double lined eclipsing binary:



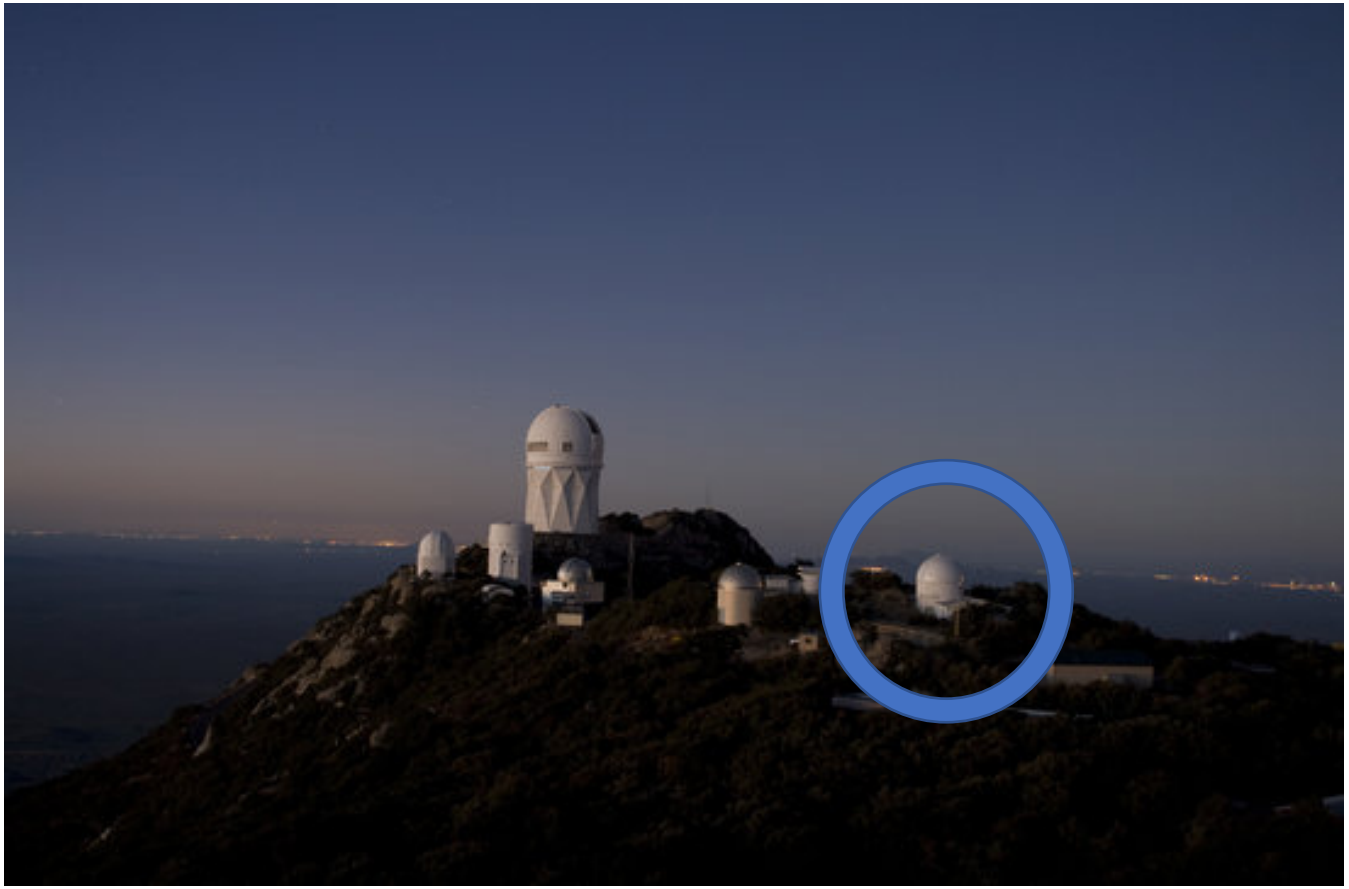
Followed up with LRIS for spectra

- In order to capture time resolved dynamics of the system, we had to use 50s exposures
- Because this is an eclipsing double lined binary, we can measure masses for both objects in the system.

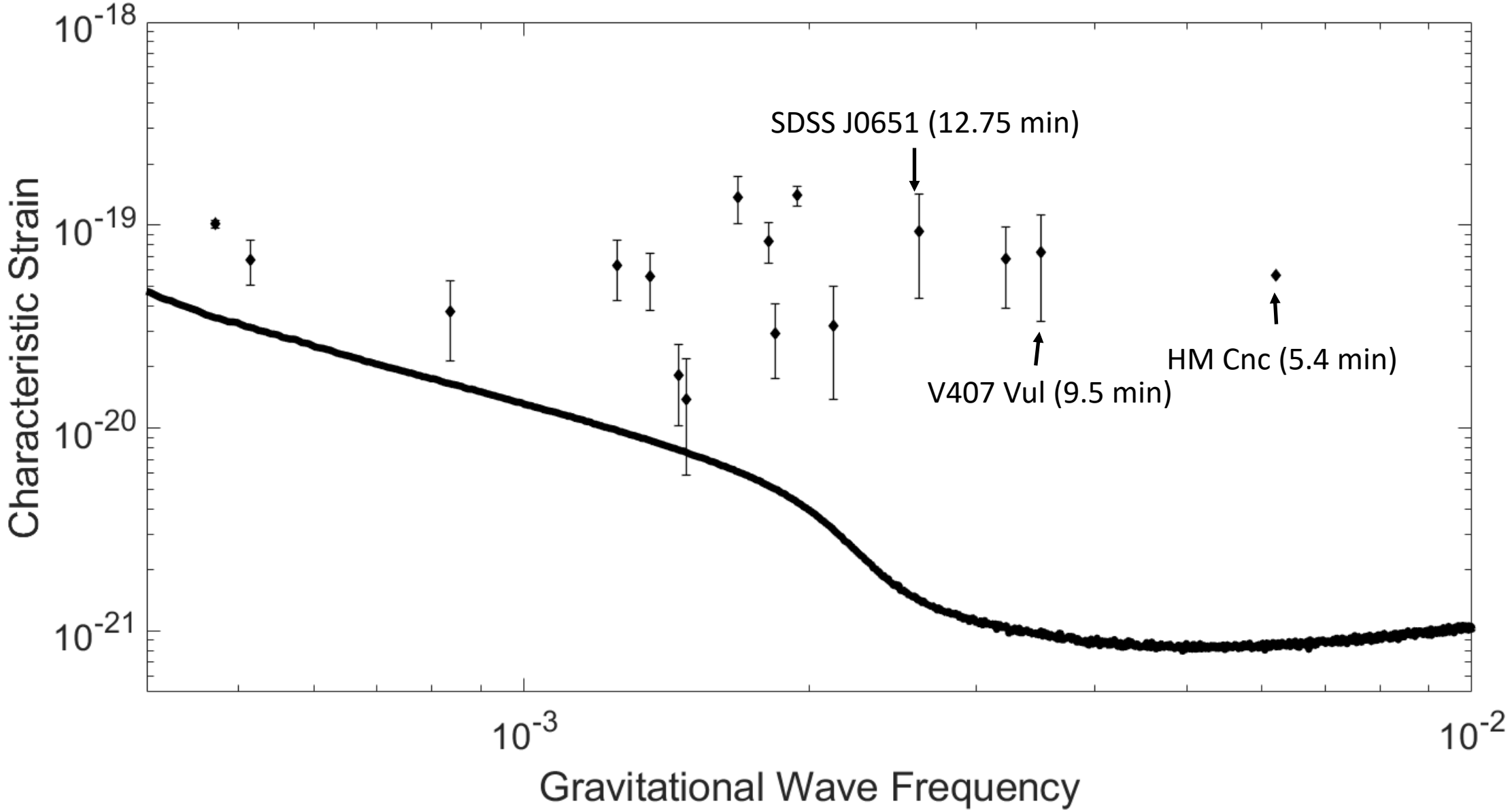


Kevin Burdge thesis

… and the Kitt Peak 84-inch (KPED)



- On loan from NSF/NOAO (Portfolio Divestment)
- RoboAO → UH88 (Baranec)
- Equipped with an EMCCD imager (Kitt Peak EMCCD Demonstrator)
- Candidate vetting of compact binaries
- Project Scientist: Michael Coughlin


SDSS J0651 (12.75 min)
V407 Vul (9.5 min)
HM Cnc (5.4 min)
Characteristic Strain
Gravitational Wave Frequency
10-18
10-19
10-20
10-21
10-3
10-2