

The Restless Universe

(the rise of time domain astronomy)
(& the periodic table)

S. R. Kulkarni

Director, Caltech Optical Observatories

Principal Investigator, Zwicky Transient Facility

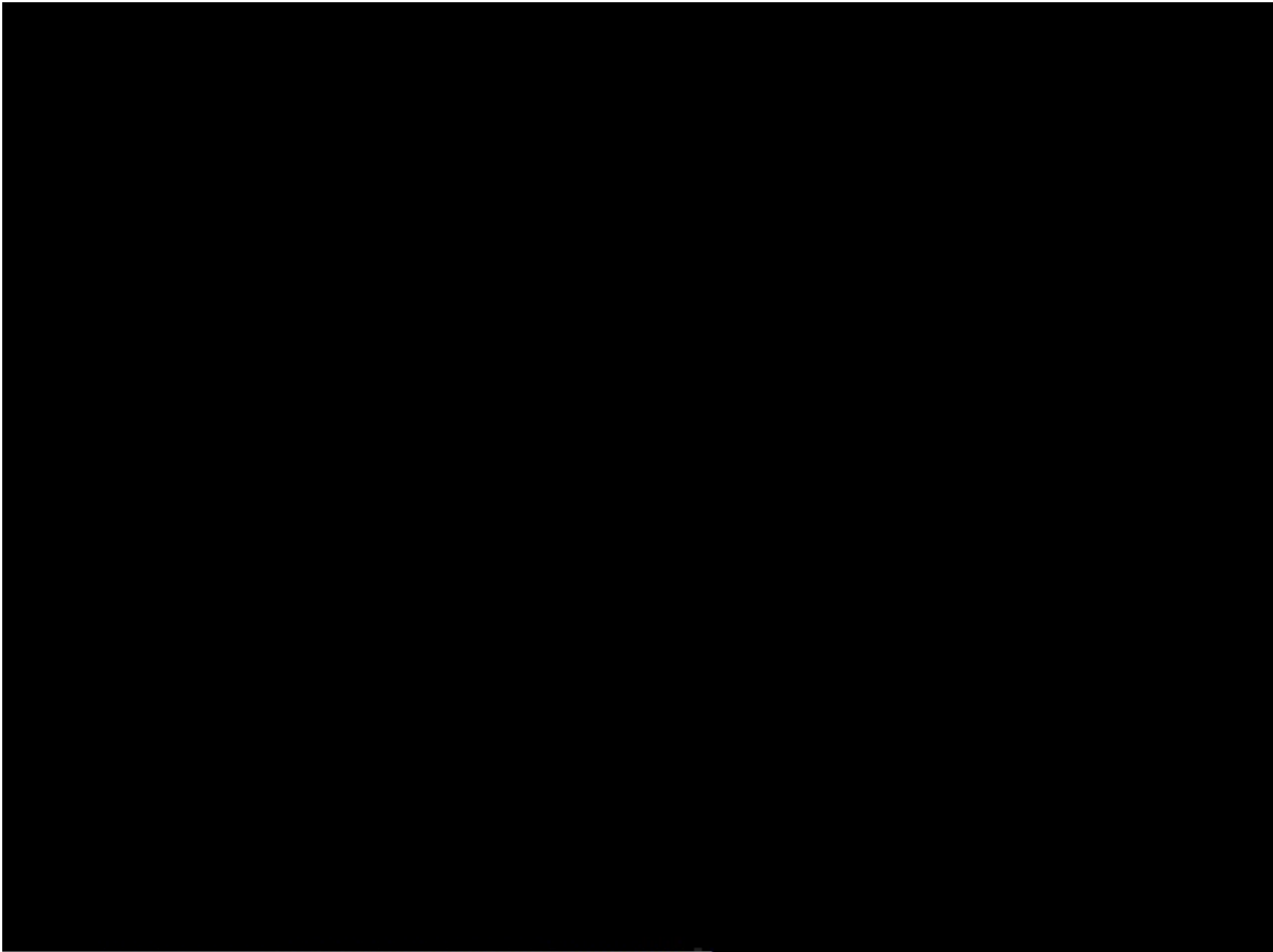
An observation

- Astronomy, like biology, geology and exo-planetology is a phenomenological subject
 - In contrast, physics is all about distilling phenomena to the ultimate essence
- Phenomenological subjects have three distinct steps
 - Discovery
 - Systematic study of phenomena: Search for patterns
 - Inference: Physical models to explain observations (and occasionally make predictions)
- Discovery is largely a function of technology

THE RISE OF TIME DOMAIN ASTRONOMY (FOCUS ON BUILD UP OF ELEMENTS)

This is how it all began





Chemistry in the young Universe was simple

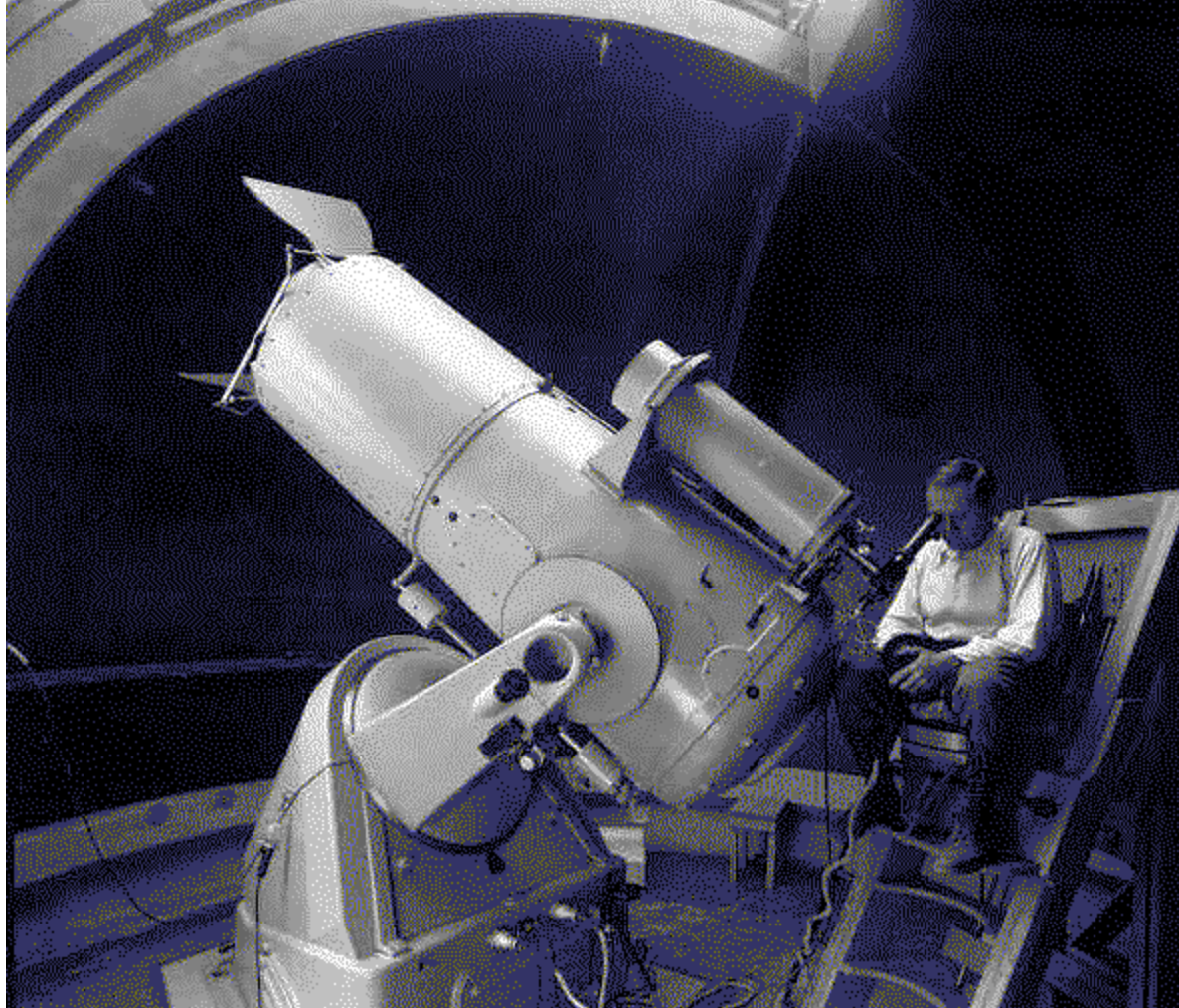
IUPAC Group → 1
Main Group → I
Period → 1

Atomic Number
Symbol

1 I	2 II																18 VIII		
1 H																		2 He	
2 3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	10 Ne
3 11 Na	12 Mg													13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4 19 K	20 Ca	3 21 Sc	4 22 Ti	5 23 V	6 24 Cr	7 25 Mn	8 26 Fe	9 27 Co	10 28 Ni	11 29 Cu	12 30 Zn		31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5 37 Rb	38 Sr												49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6 55 Cs	56 Ba	57 to 70	71 Lu	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	
7 87 Fr	88 Ra	89 to 102	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo	
			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			
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No			

Lanthanoids
Rare Earth Metals
Actinoids

Time Domain Astronomy (Supernovae): Fritz Zwicky



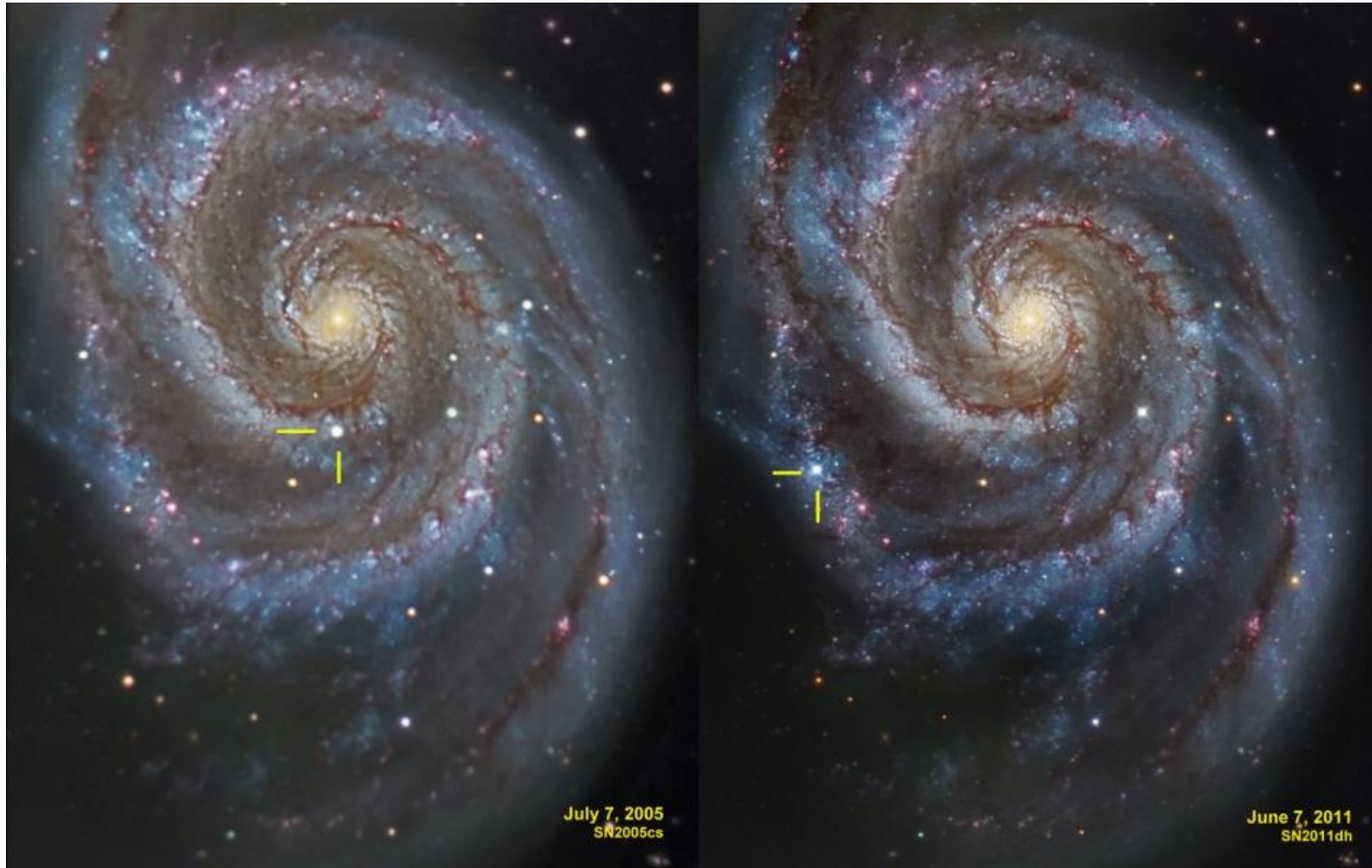
Nucleosynthesis: Burbidge, Burbidge, Fowler & Hoyle (B²FH)



We are star dust!

H																			He
Li	Be											B	C	N	O	F		Ne	
Na	Mg											Al	Si	P	S	Cl		Ar	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br		Kr	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I		Xe	
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At		Rn	
Fr	Ra																		
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		Lu	
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		Lr	

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



Iron is special

IUPAC Group → 1
Main Group → I
Period → 1

Atomic Number
Symbol

	1 I																	18 VIII	
1	1 H	2 II										13 III	14 IV	15 V	16 VI	17 VII	18 VIII	2 He	
2	3 Li	4 Be										5 B	6 C	7 N	8 O	9 F	10 Ne		
3	11 Na	12 Mg										13 Al	14 Si	15 P	16 S	17 Cl	18 Ar		
4	19 K	20 Ca	3 Sc	4 Ti	5 V	6 Cr	7 Mn	8 Fe	9 Co	10 Ni	11 Cu	12 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr											49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	57 to 70	71 Lu	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
7	87 Fr	88 Ra	89 to 102	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

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
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No

Lanthanoids
Rare Earth Metals
Actinoids

Frontier Area: Gravitational Waves



Las Campanas Observatory,



Discovery Image
August 17, 2017



Special explosions make “precious” metals

IUPAC Group → 1
Main Group → I
Period → 1

1 ← Atomic Number
H ← Symbol

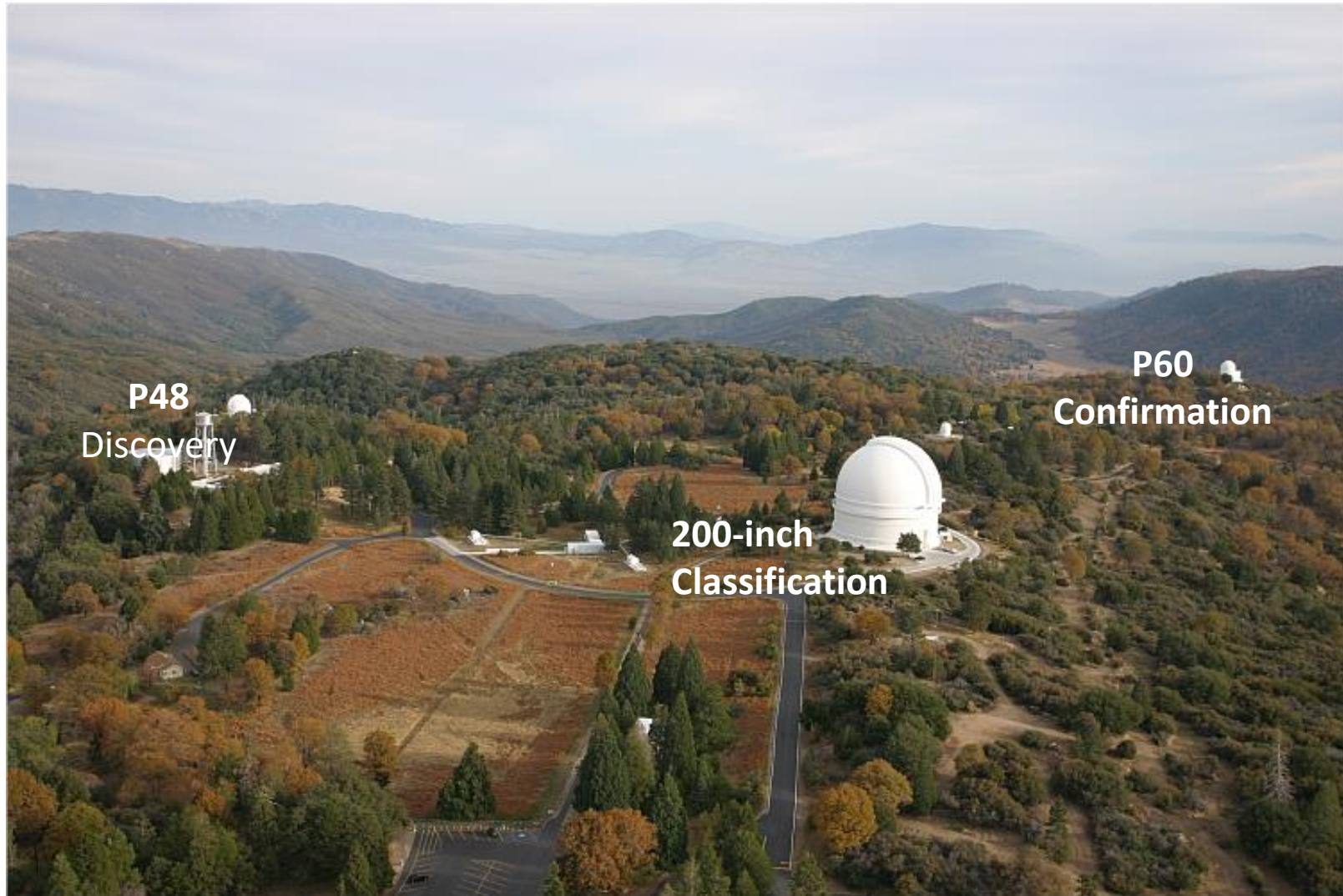
1	18																		
I	VIII																		
1	2	13	14	15	16	17	18												
H	He	III	IV	V	VI	VII	VIII												
2		5	6	7	8	9	10												
Li	Be	B	C	N	O	F	Ne												
3		13	14	15	16	17	18												
Na	Mg	Al	Si	P	S	Cl	Ar												
4		3	4	5	6	7	8	9	10	11	12								
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn								
5		39	40	41	42	43	44	45	46	47	48								
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd								
6		57 to 70	71	72	73	74	75	76	77	78	79	80							
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg								
7		89 to 102	103	104	105	106	107	108	109	110	111	112							
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn								

57 to 70
89 to 102

57	58	59	60	61	62	63	64	65	66	67	68	69	70
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Lanthanoids													
89	90	91	92	93	94	95	96	97	98	99	100	101	102
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
Rare Earth Metals													
Actinoids													

A FACTORY TO SYSTEMATICALLY DISCOVER EXPLOSIVE TRANSIENTS

Palomar Transient *Factory*



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

PI:
Shri Kulkarni

Project Scientist:
Nicholas Law

Software Lead
Robert Quimby

COO Hardware
Richard Dekany

Robot Wrangler
Eran Ofek

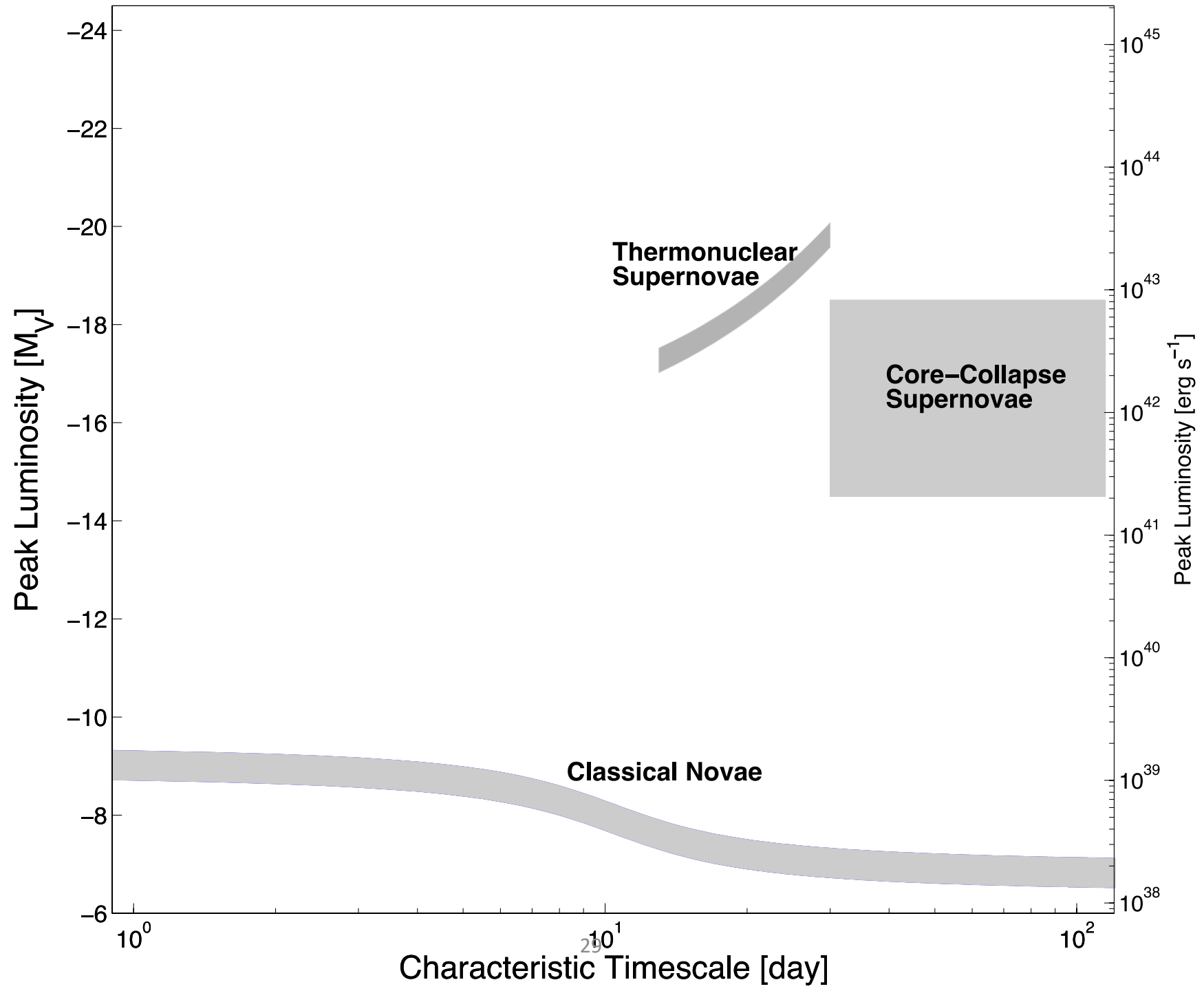
LBNL Pipeline
Peter Nugent

IPAC Pipeline
Jason Surace

Machine Learning
Josh Bloom

Logos: CALIFORNIA INSTITUTE OF TECHNOLOGY, ipac, BERKELEY LAB, LCOGT.net, WEIZMANN INSTITUTE OF SCIENCE

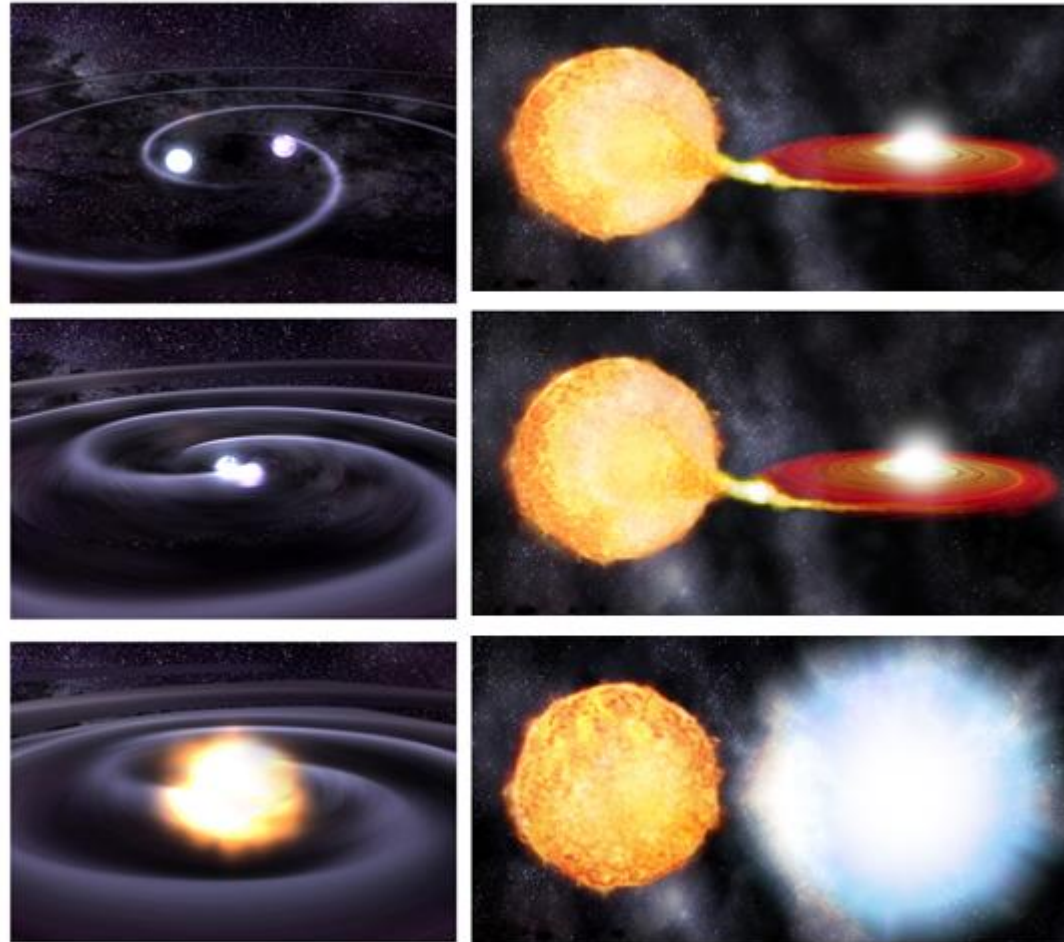
Group Photo: A large group of approximately 40 people, including students and staff, posing for a group photo outdoors in front of a building.



PTF11ky: only 10 hours old!



Nature makes Type Ia SN in two ways!



Li et al.
Nugent et al.

Yi Cao 2016 thesis

**NEEDLE IN A HAYSTACK SEARCH (GETTING
READY FOR LIGO)**

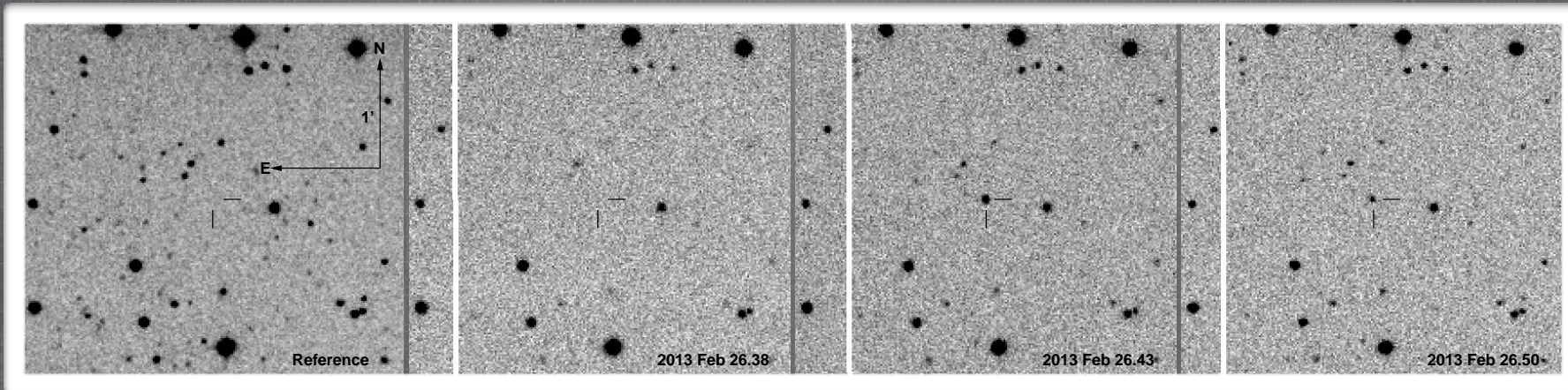
iPTF14yb: "UNTRIGGERED" GRB

Reference

2013 Feb 26.38

2013 Feb 26.43

2013 Feb 26.50



SBC+, in prep.



09:04 UT:!
P48 Non-detection

12:01 UT:!
P48 $r = 19.77$

15:26 UT:!
Keck/ LRIS Spectrum

10:17 UT:!
P48 $r = 18.16$

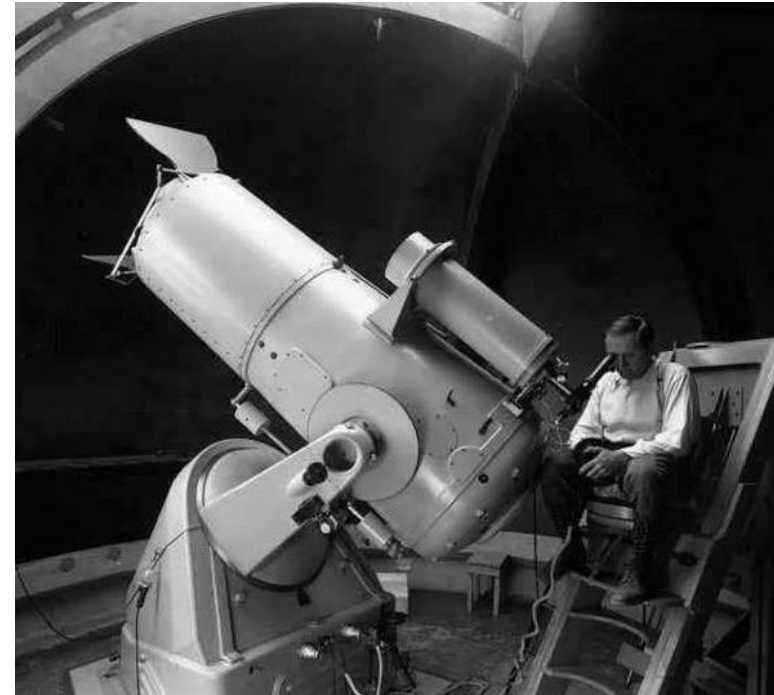
12:46 UT:!
Flagged by software

17:11 UT:!
Swift X-ray+UV

AUTOMATING THE DISCOVERY OF THE UNIVERSE

ZWICKY TRANSIENT FACILITY

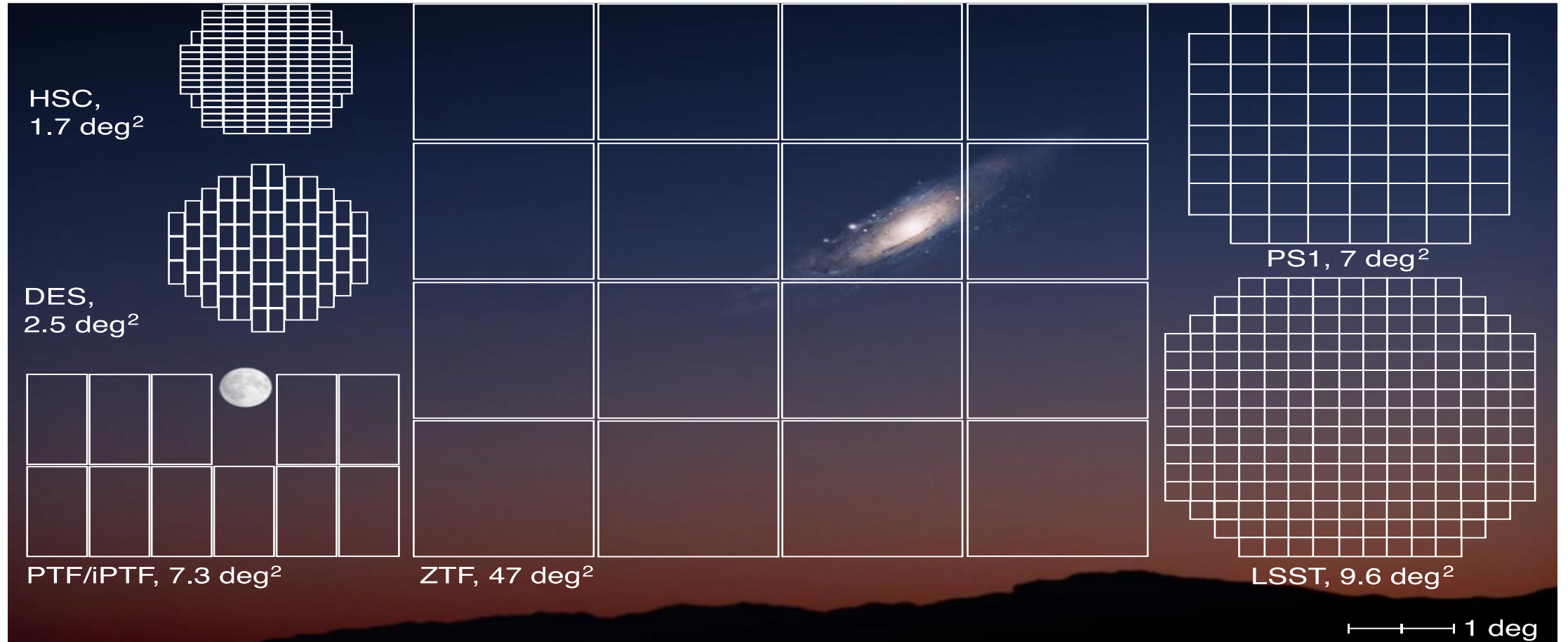
S. Kulkarni, Principal Investigator
E. Bellm. Survey Scientist
M. Graham, Project Scientist



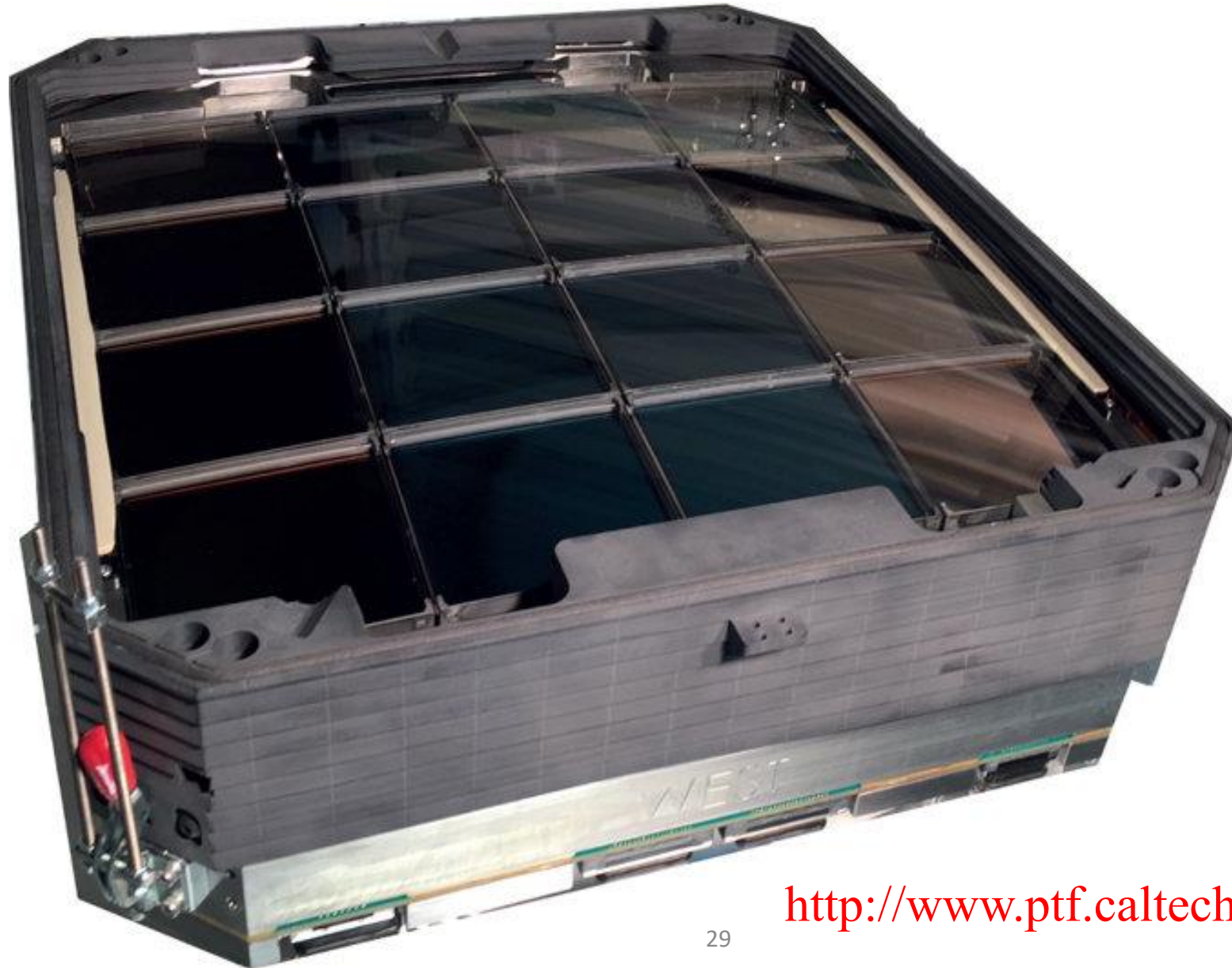
Caltech



Wide field Imagers



The 600 Mega-Pixel Camera!



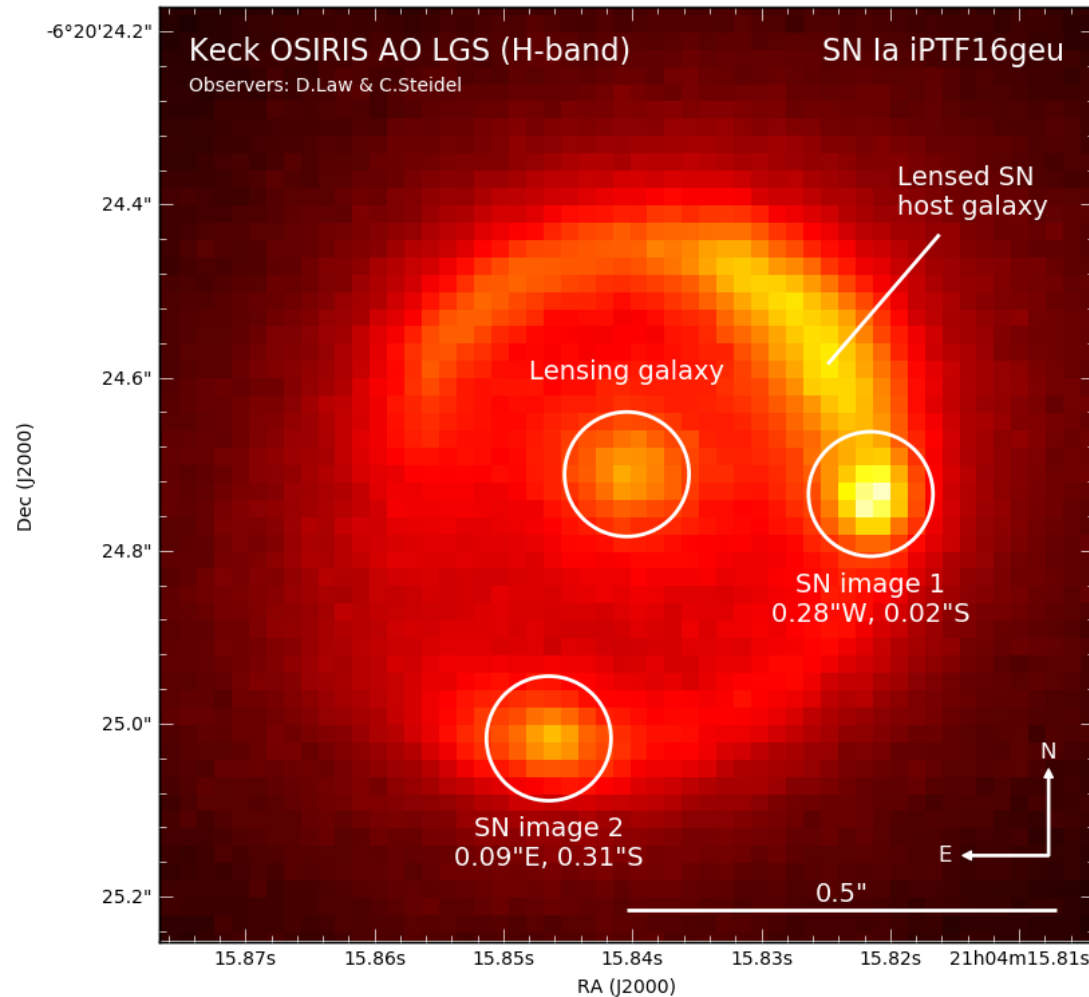
<http://www.ptf.caltech.edu/ztf>

**TO COMPLETE THE DISCOVERY FOLLOW UP &
NEW TOOLS ARE ESSENTIAL**

Followup & Tools

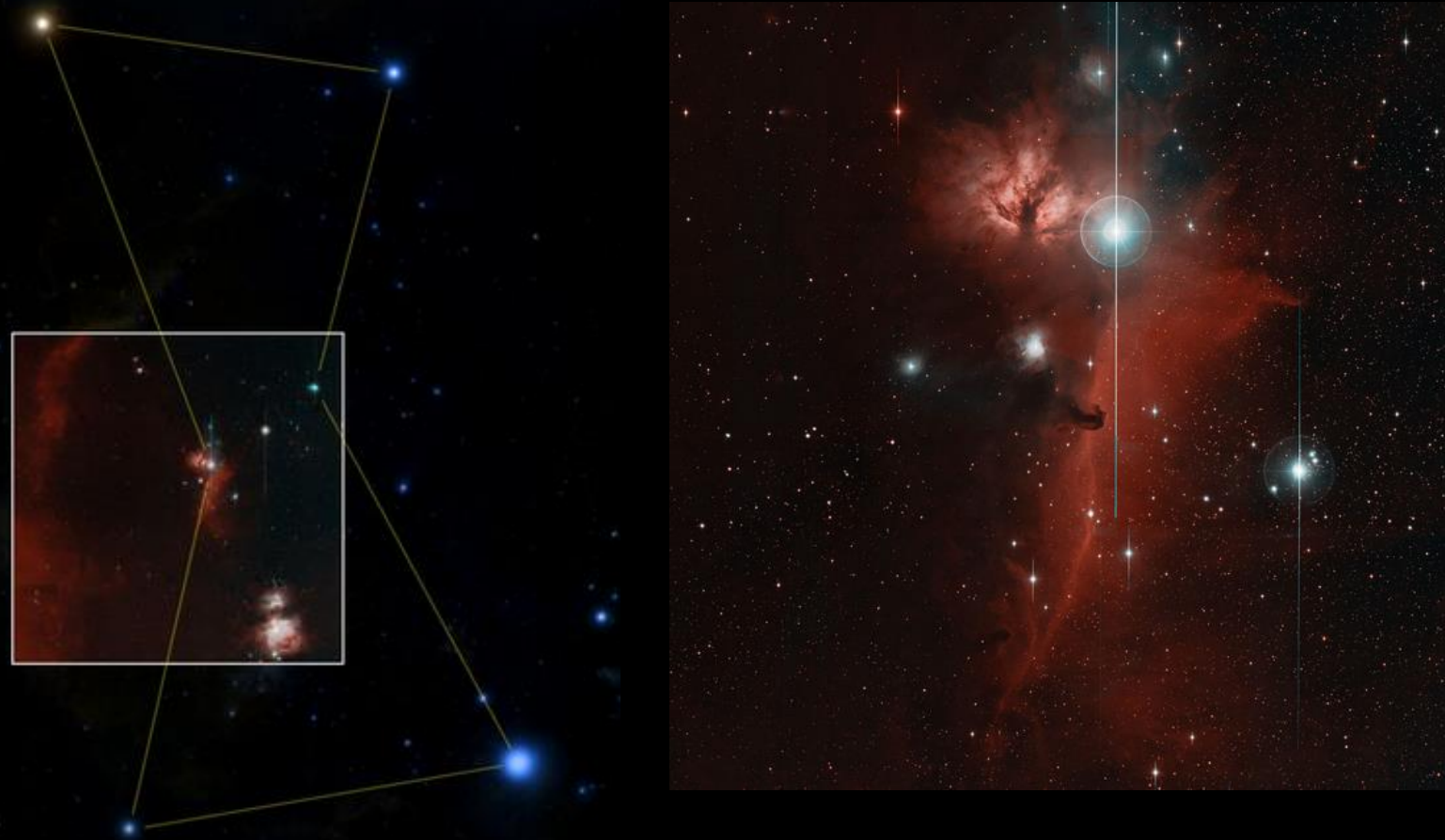
- Spectroscopy on demand
- Novel ultra-low resolution spectrograph aimed at rapid classification
- Mounted on Palomar 60-inch
- Already great success (highly magnified gravitational lensed supernova, nearest TDE)
- Robo-Adaptive Optics (Robo AO)
 - Dedicated telescope (Kitt Peak 84-inch)
 - Collaboraton with IUCCA, UH
- Tool Development
 - "Broker" services
 - "Sentinels"

A strongly magnified supernova



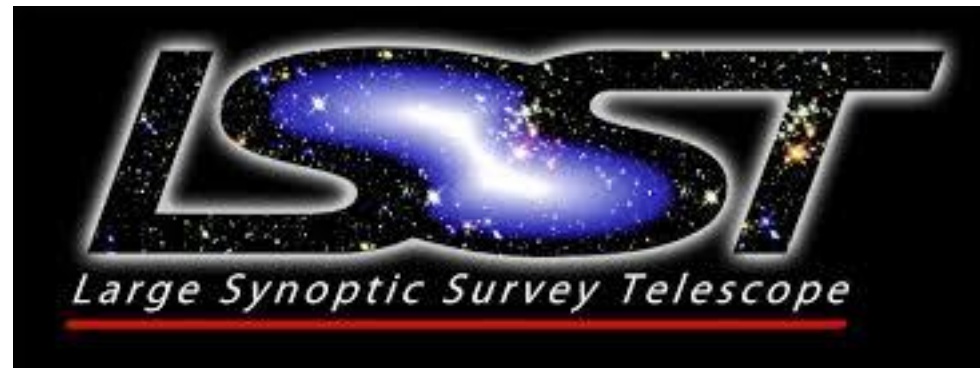
Keck Adaptive Optics

Zwicky Transient Facility: First Light



FoV 47 sq deg. Survey Speed: 3750 sq deg per hour to a depth of 20.4 mag
Real-time public alert stream in LSST format this summer!

Ultimate Celestial Cinematography in 2022



(Dark) Matter bends light

