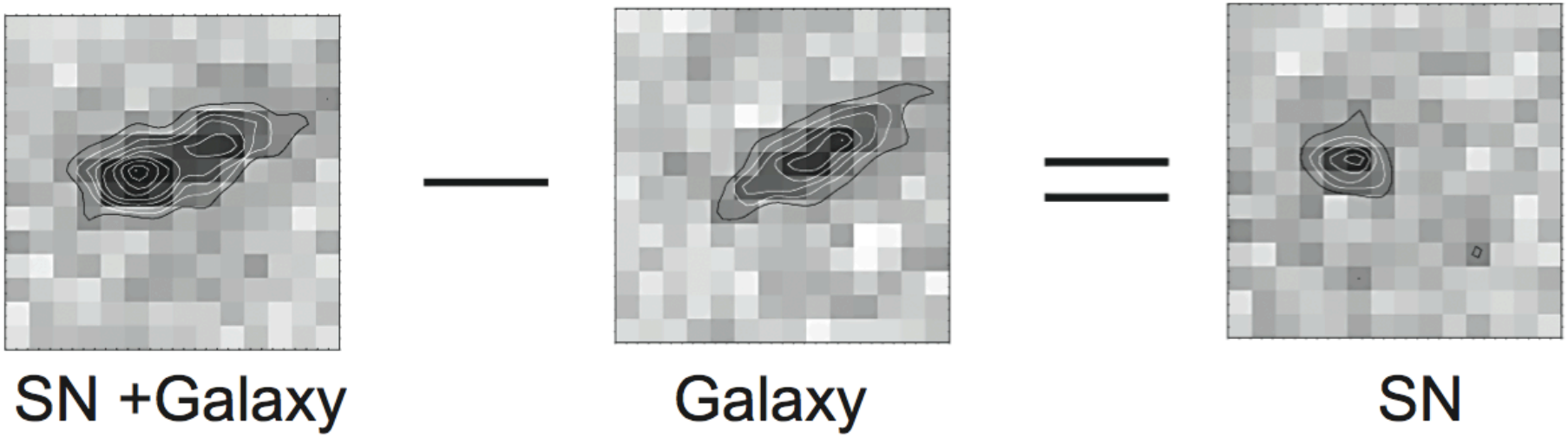
Physics breakthroughs and observations of the transient sky

F. Zwicky (1898-1974): pioneer of transient astrophysics

Introduced (with Baade in 1934) the term *supernova* (*)
– and went on to discover 120 of them!

(*) K.Lundmark, was the first one to point out that there was a class of bright novae
– called them "*upper novae*".

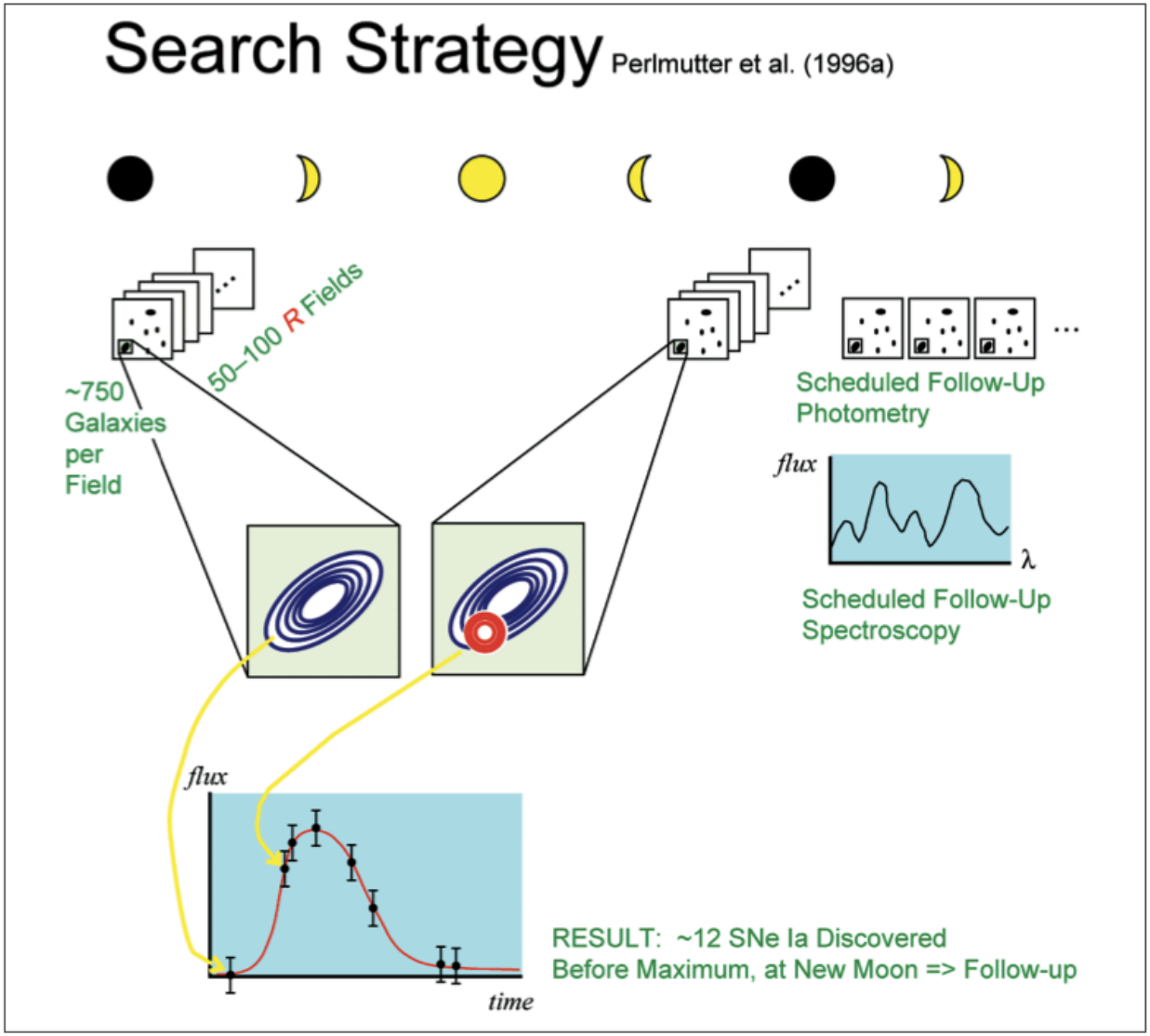
Transient astronomy in the CCD era



1980's: Type Ia supernovae are *"standard candles"*

→ Precise distances also for very remote galaxies

Time-domain astronomy in the 90's



Oskar Klein centre

Discovery of SNIa at z=0.458 (~4.5 Gyrs old) showed it was possible to get a cosmological sample of SN!

1992

currents

Berkeley, California 94720

November 13, 1992 Vol. 19 No. 42

LAWRENCE BERKELEY LABORATORY

LBL/UK team discovers most distant supernova ever seen

Could help determine if universe is finite or infinite

By Judith Goldhaber

The discovery of exploding stars almost half-way to the edge of the universe may help scientists settle the question of whether the universe is infinite and will continue to expand forever, or whether it is finite and will eventually slow down, reverse direction, and contract.

A team of LBL scientists working with scientists from the United Kingdom have reported the discovery of what they believe to be a "Type Ia" supernova in a galaxy estimated to be about five billion light years from Earth. This is the most distant supernova ever seen by observers on Earth. The recent spectacular Supernova 1987A, seen by the naked eye on Earth, was in a galaxy comparatively close to our own — less than two hundred thousand light years away.

The team of scientists making the discovery were led by astrophysicists Saul

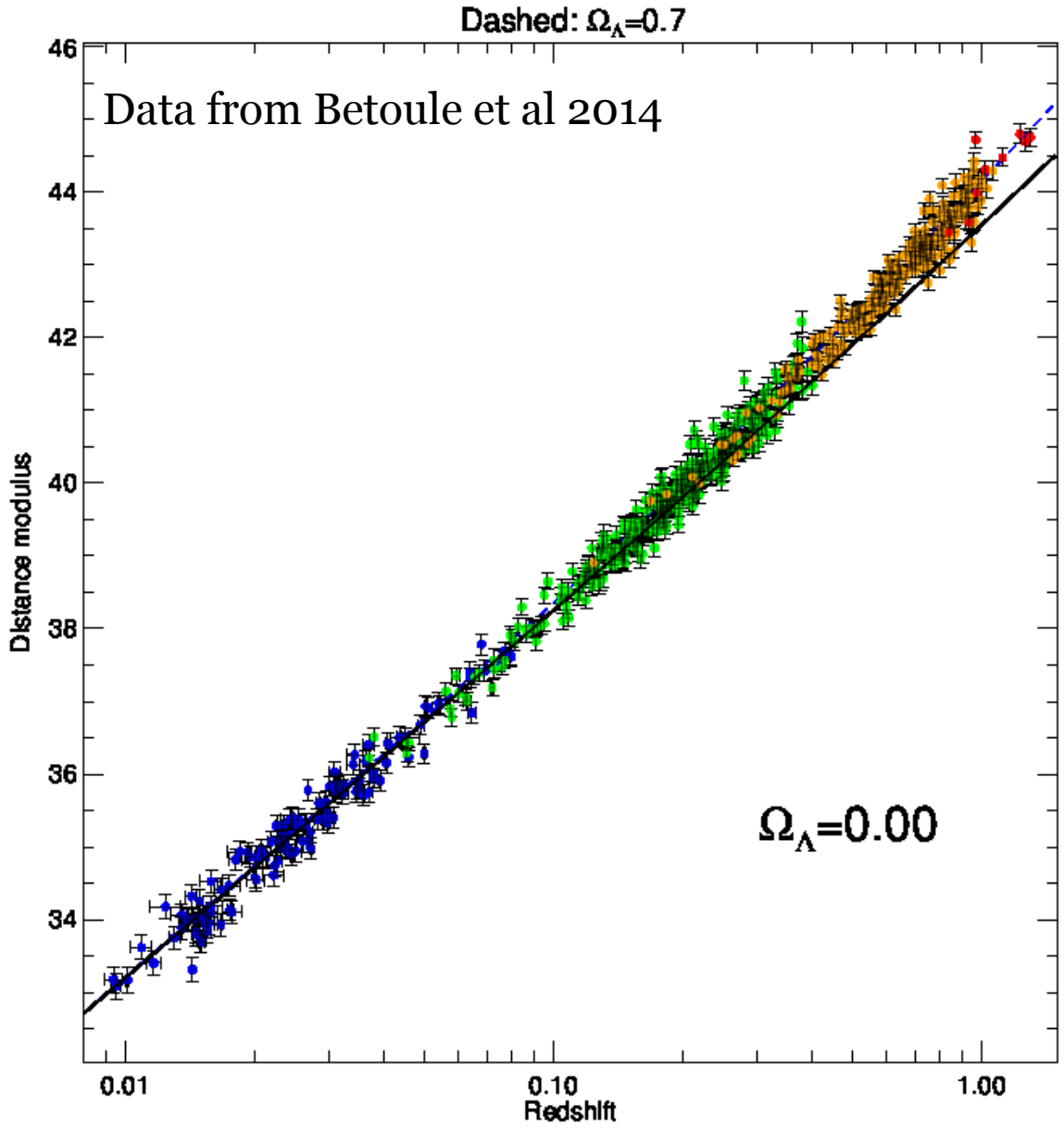
We're glad we were around to see it."

The scientists are planning to use the light from this supernova — and from others like it — to make a precise measurement of its distance from Earth and the velocity at which it is receding from us in the expanding universe. Type Ia supernovas, no matter where they occur in the universe, are believed to give off about the same amount of light. Since their brightness is a constant, such supernovas can serve as reliable indicators of distance in deep space. From information obtained from a number of such supernovas, the scientists say it may be possible to determine if the universe will expand forever, in which case the universe is infinite, or if it will eventually slow down and reverse direction, in which case the universe is finite.

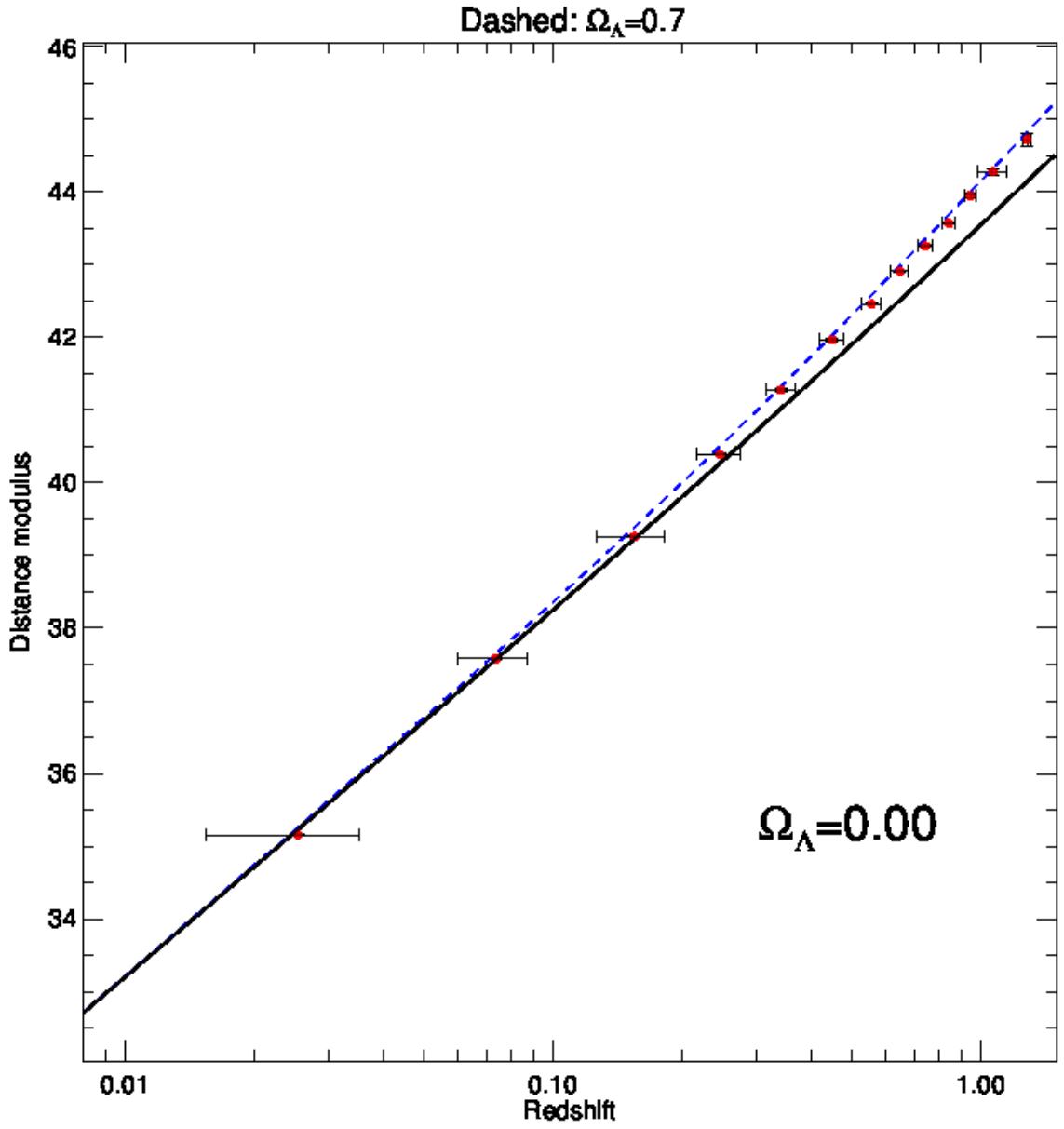
The supernova discovery was made as part of an international collaboration at

Ariel Goobar (seated), Carl Pennypacker, and Saul Perlmutter analyze images picked up by an ultrasensitive electronic camera in a 2.5-meter telescope in the Canary Islands and transmitted to powerful computers at LBL. *Photo by Paul Hames*

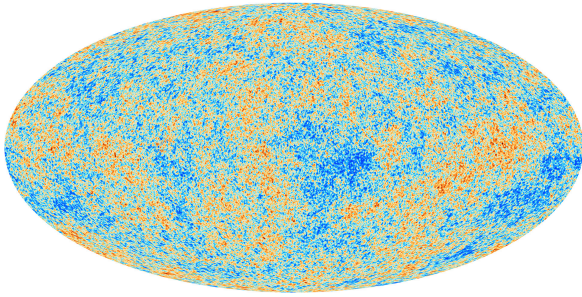
Type Ia supernovae & Dark Energy

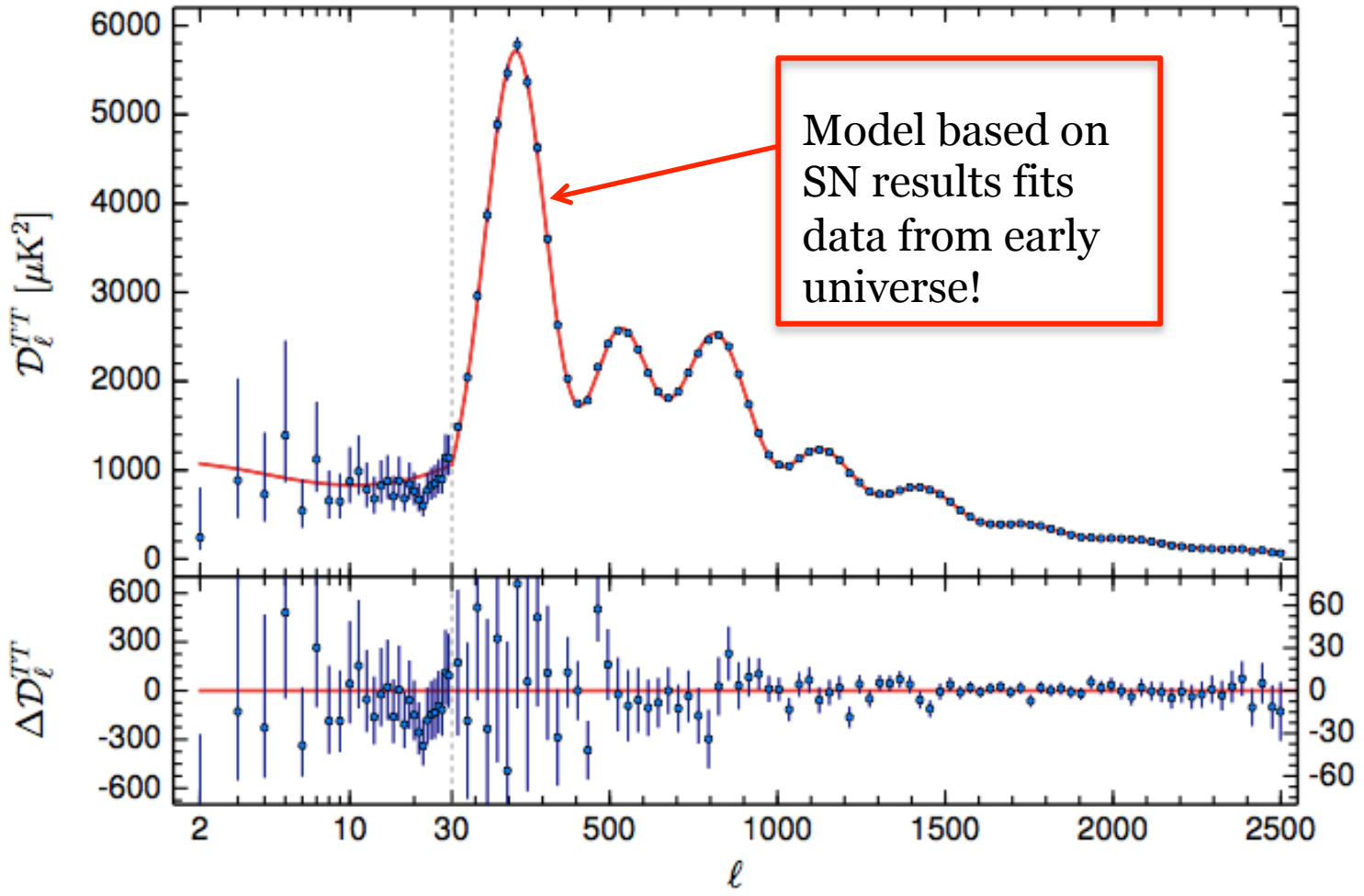


Type Ia supernovae & Dark Energy

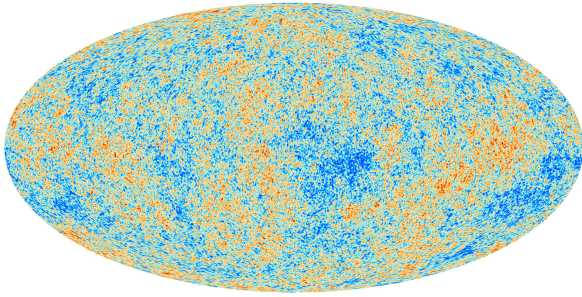


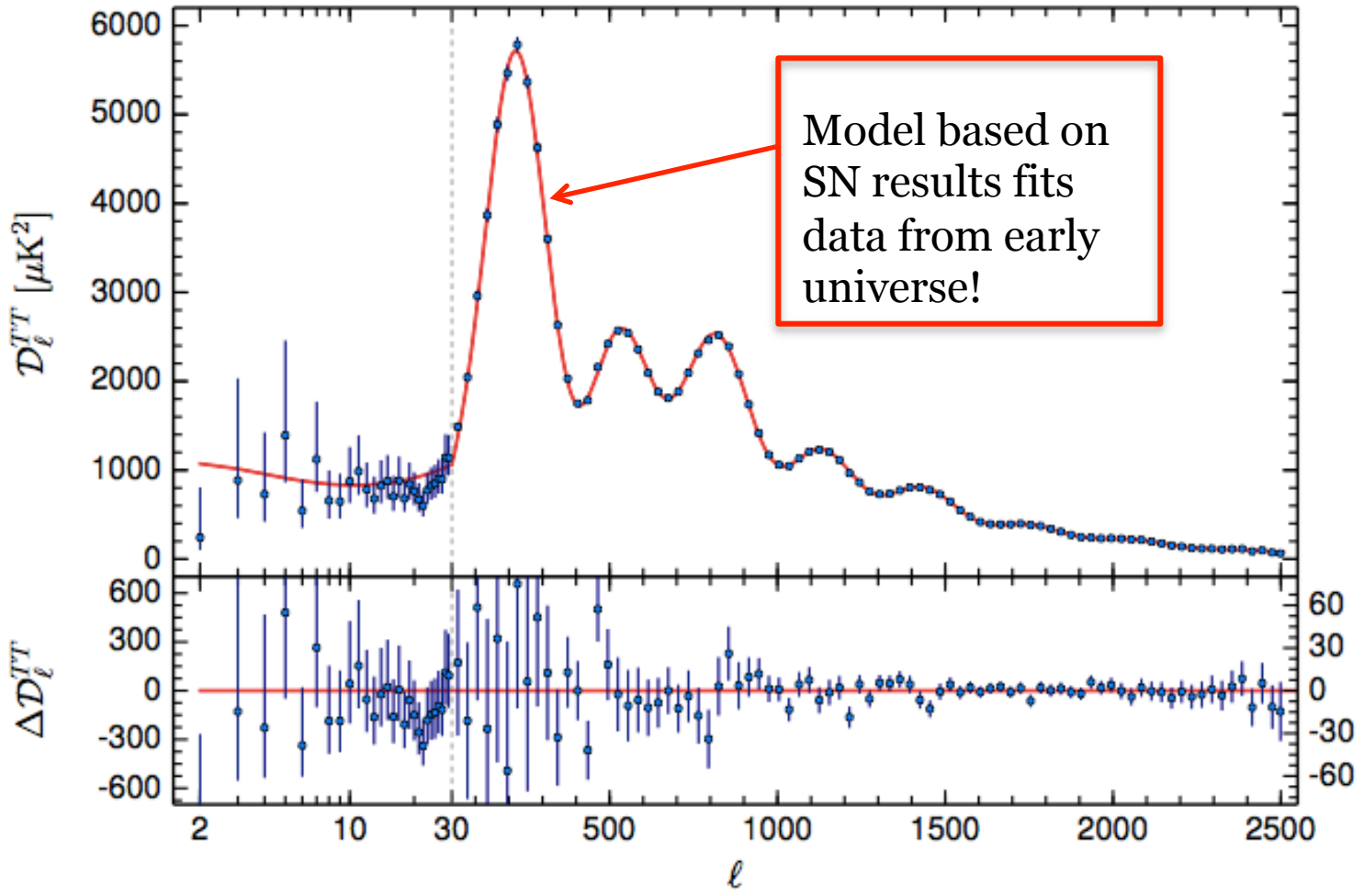
Planck 2015:
ΛCDM as healthy as ever!



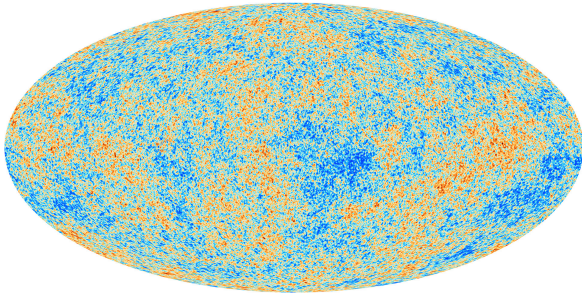


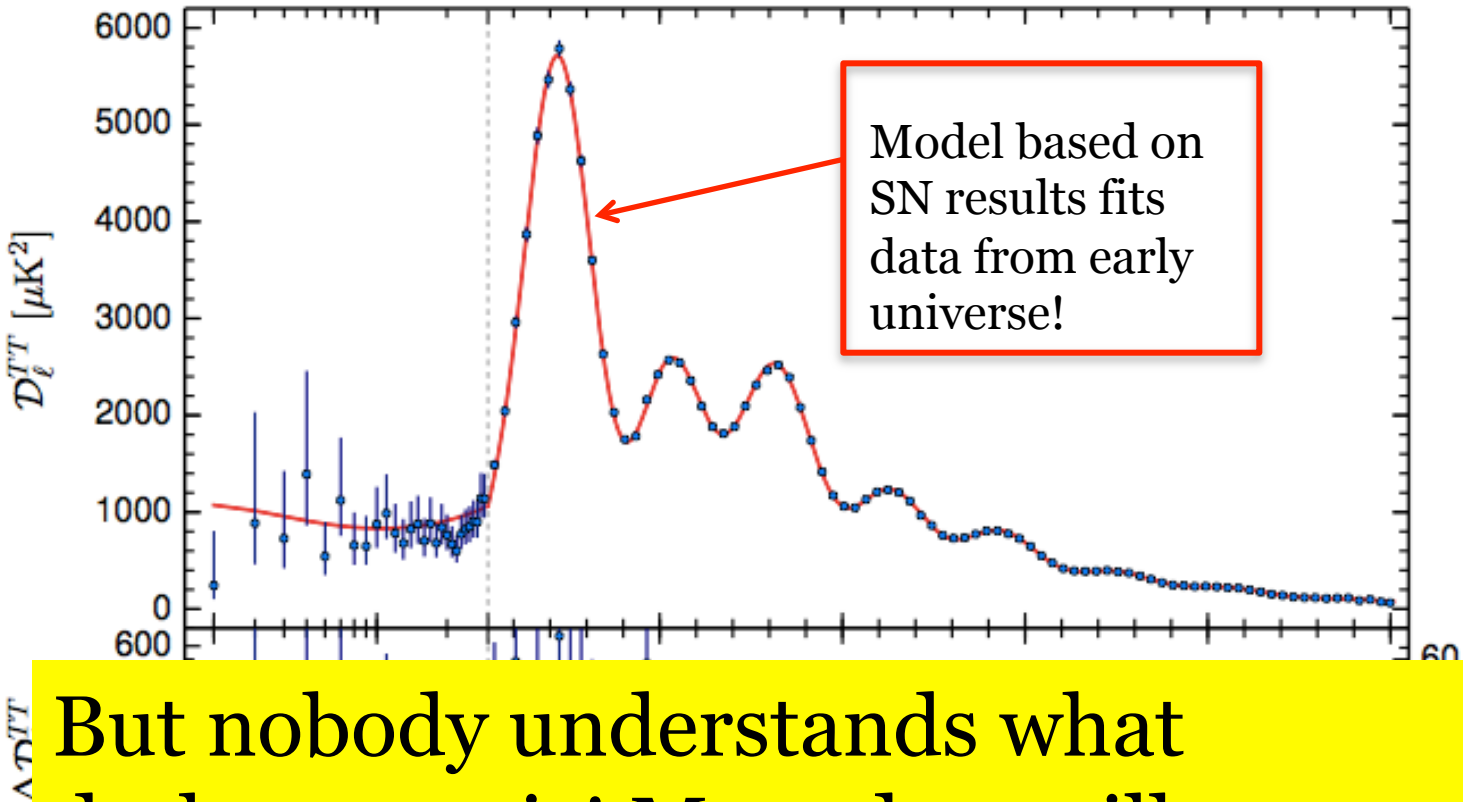
Planck 2015:
ΛCDM as healthy as ever!





Planck 2015:
ΛCDM as healthy as ever!





But nobody understands what dark energy is! More data will hopefully help solve the problem…

Optical Time domain astronomy *today:*

Great technological improvement

Larger CCD arrays: Field-of-view of cameras has changed from just a few sq.*arcminutes* to many sq.*degrees*

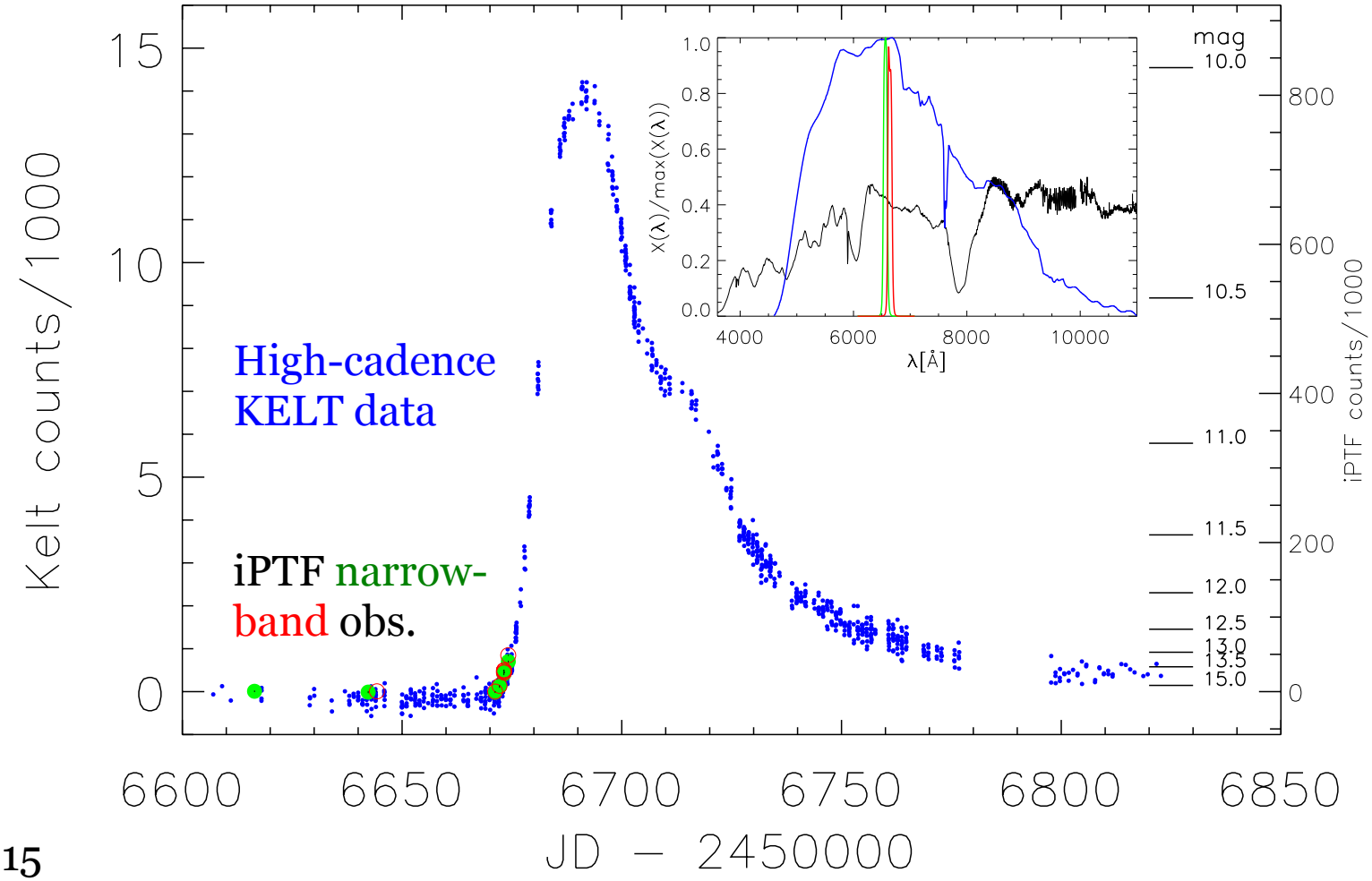
-> large statistics and improved chances to catch very rare transient phenomena.

-> High "cadence", i.e., frequency by which the same piece of sky is revisited:

1) ability to discover supernovae much earlier in the lightcurve and trigger follow-up observations with specialized instruments (e.g., from space)

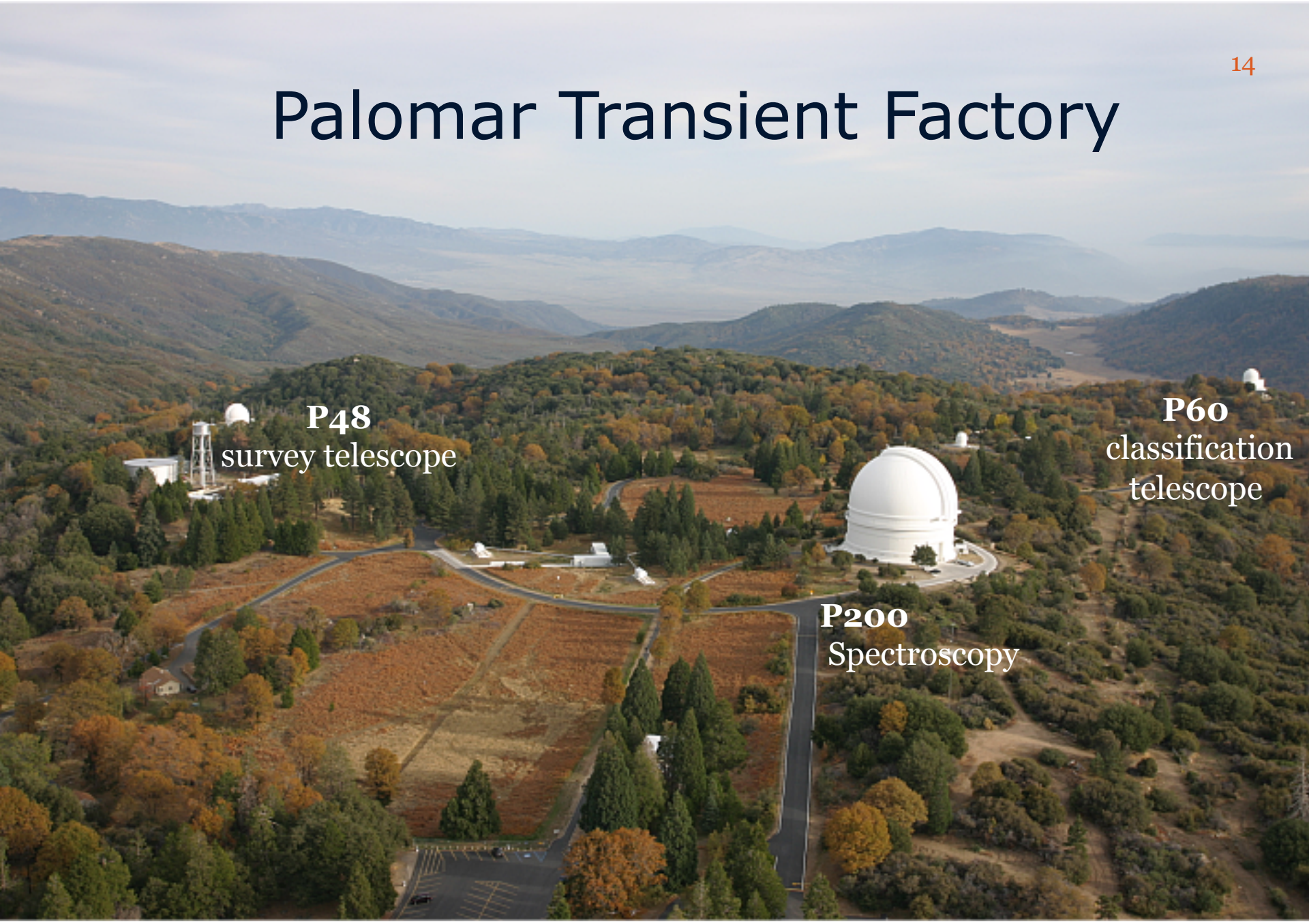
2) opened up the possibility to find new phenomena, with much shorter time scales

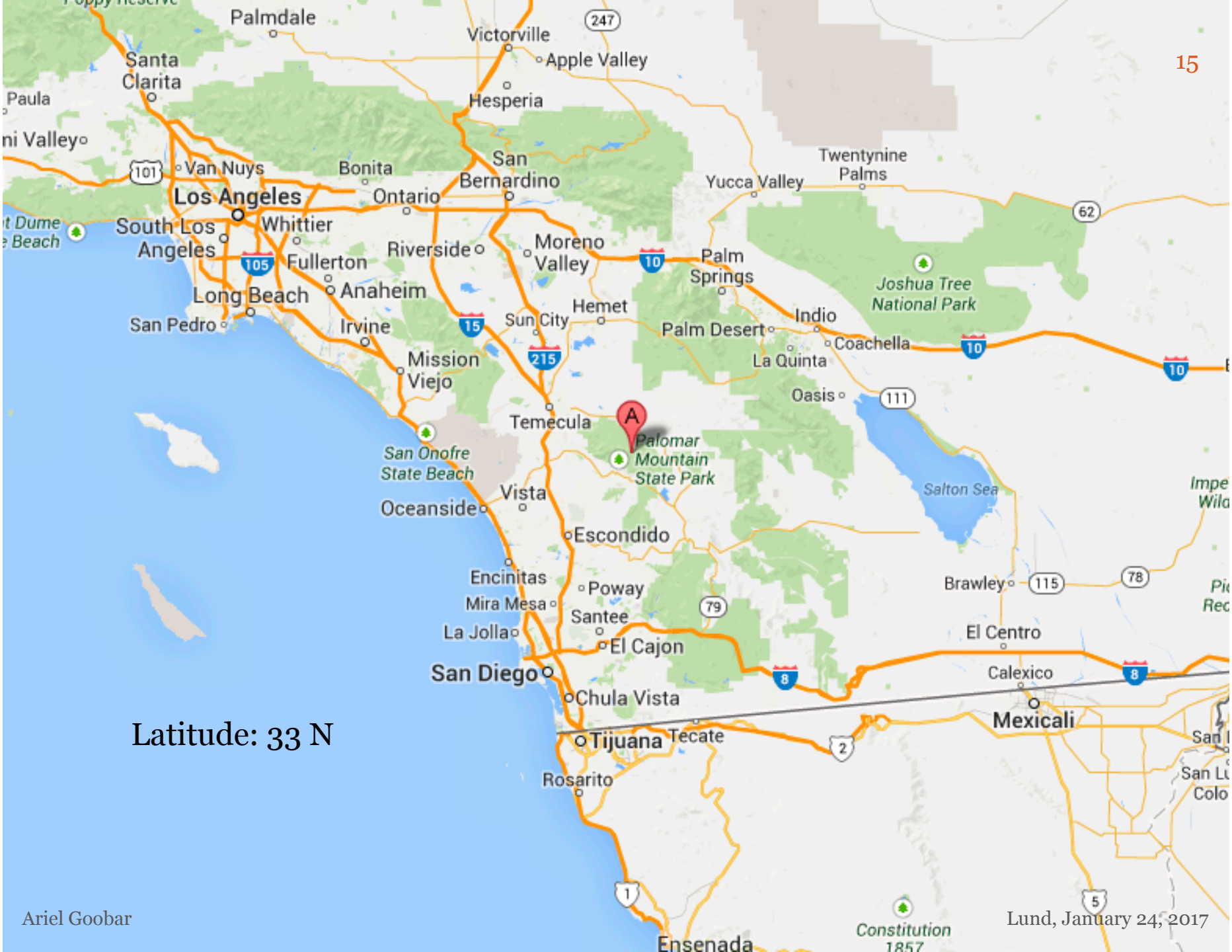
SN2014J in M82: see explosion as it happens!



AG+2015
Siverd, AG+2015

Palomar Transient Factory

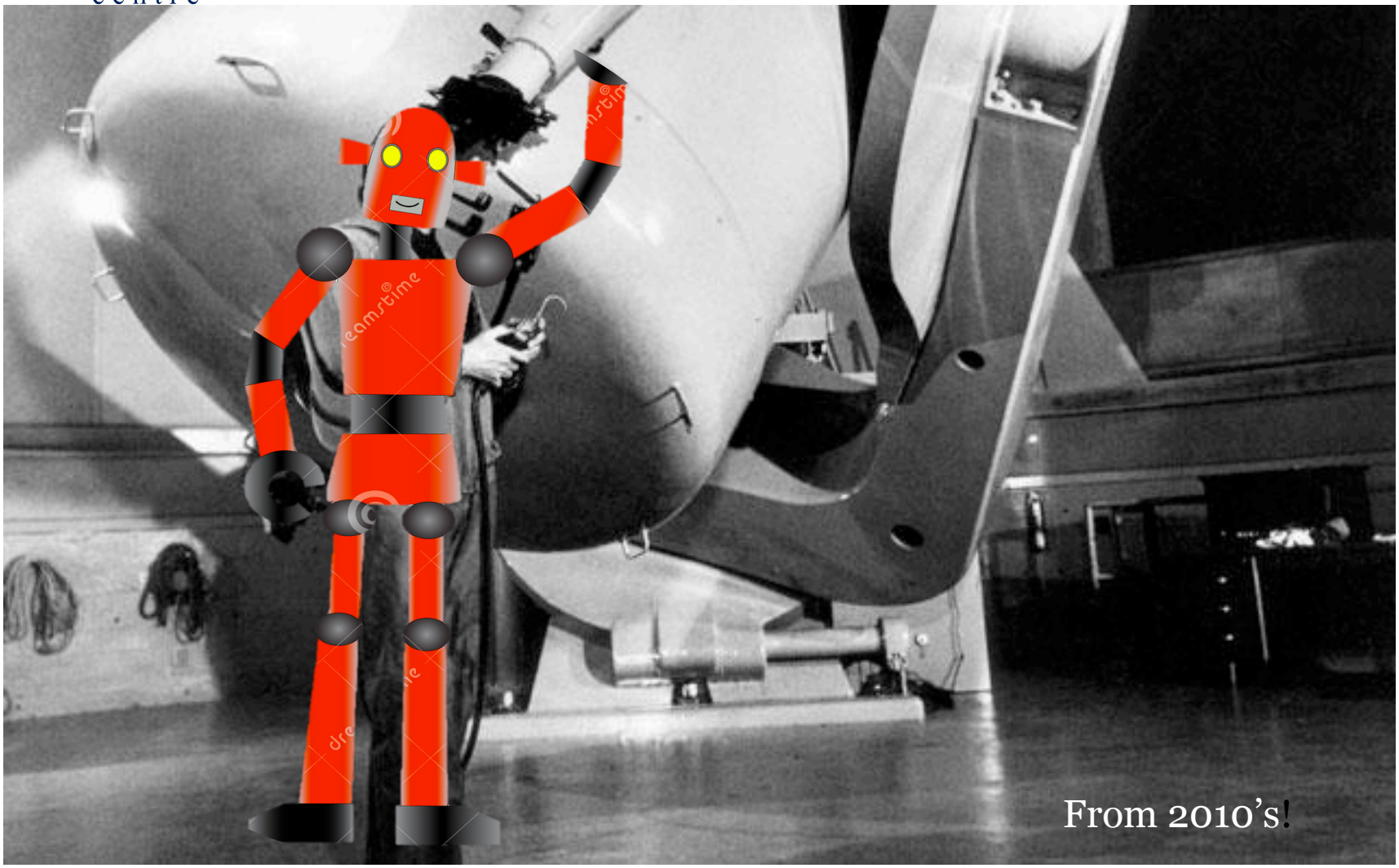


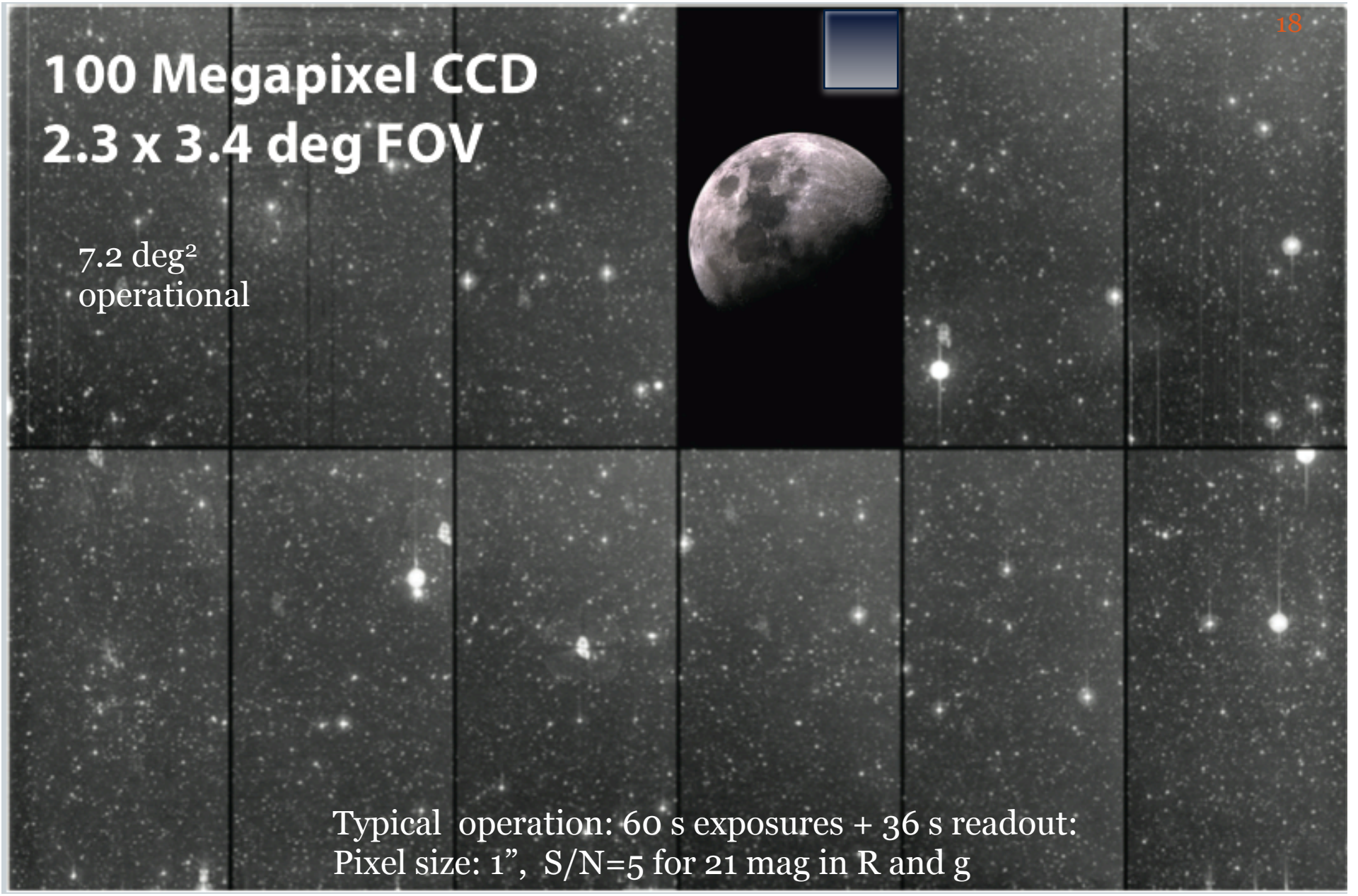


Latitude: 33 N

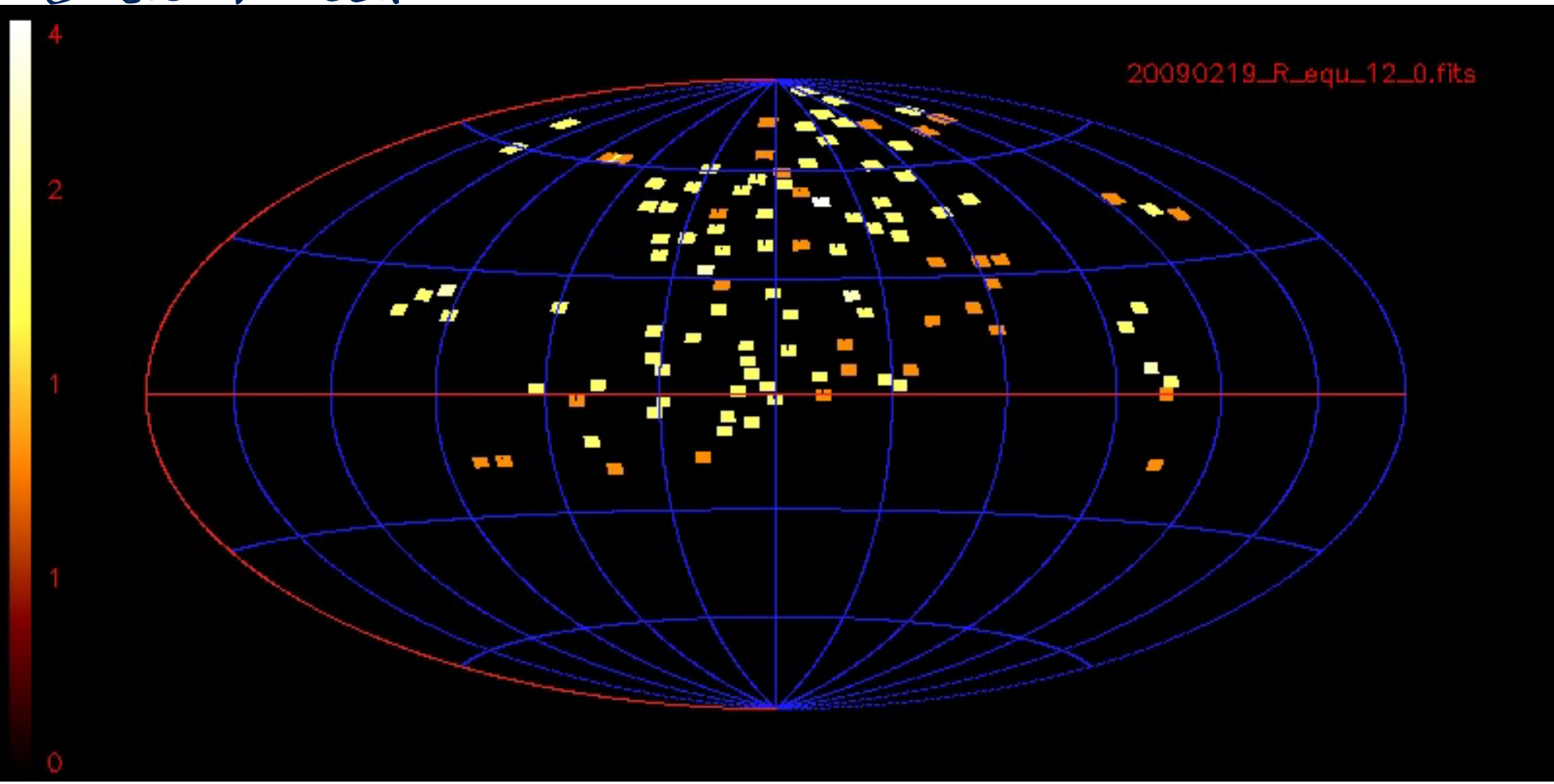
P48 (Samuel Oschin Telescope)

P48 (Samuel Oschin Telescope)



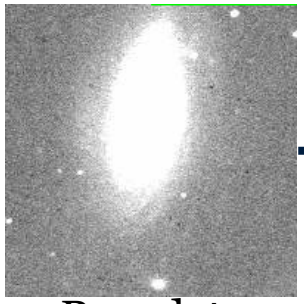

100 Megapixel CCD
2.3 x 3.4 deg FOV
7.2 deg²
operational
Typical operation: 60 s exposures + 36 s readout:
Pixel size: 1”, S/N=5 for 21 mag in R and g

PTF/iPTF in action: R-band



- ”Cadence” for PTF/iPTF has been changing over time/seasons
- 350 identified SNe/yr, ~70% SNIa

Pipeline flow-chart

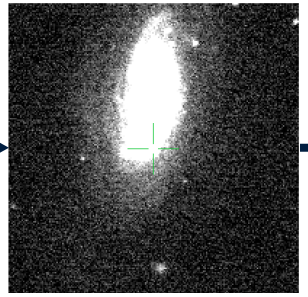


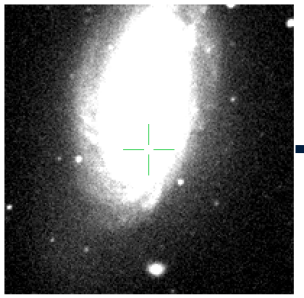
Raw data

(Palomar -> Caltech -> LBL)

processing

3 min

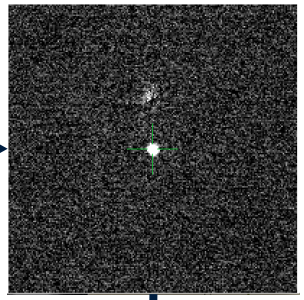




Reference Image

Image Subtraction

1.5 min/ image



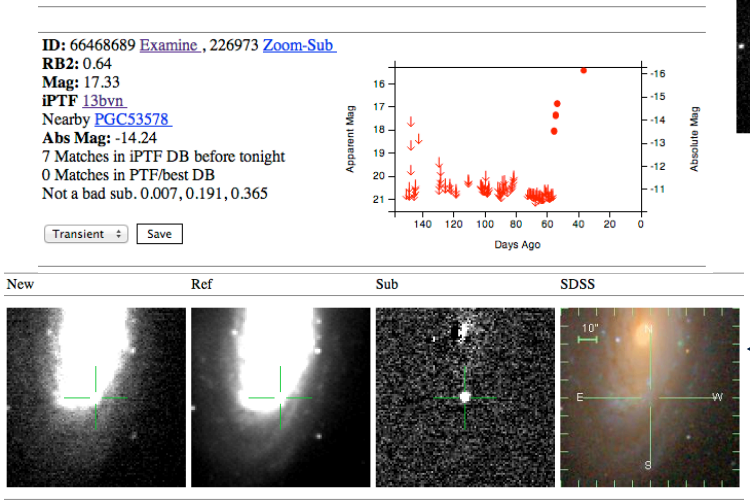
Real-Bogus (reject false alarms) 0.5 min/ image

Load candidates Into database

Database

Star/asteroid Identification
Local galaxy match

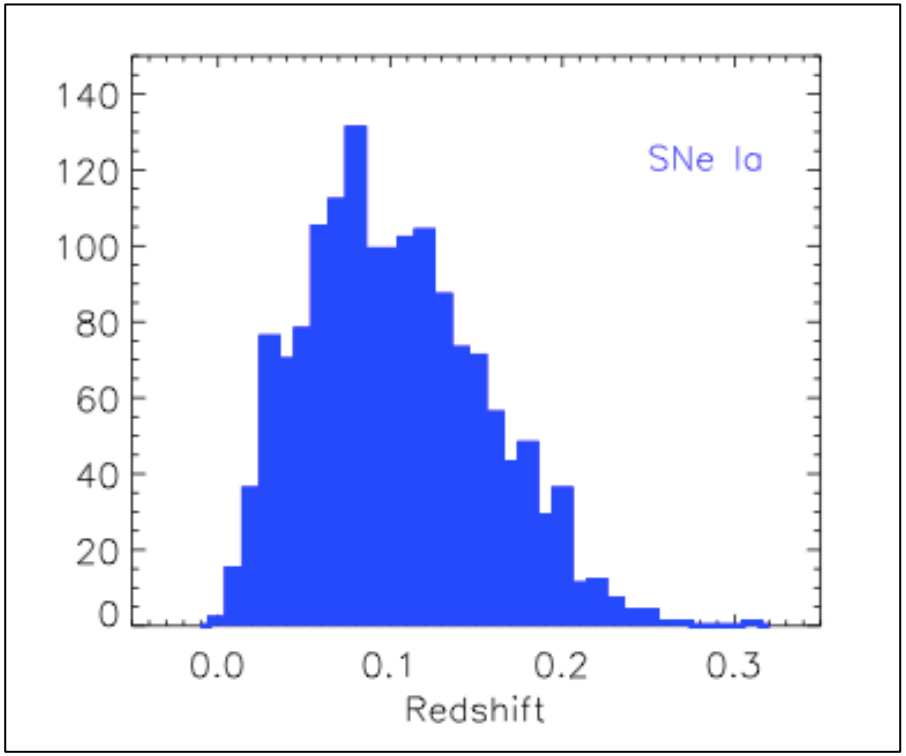
0.5 min/image

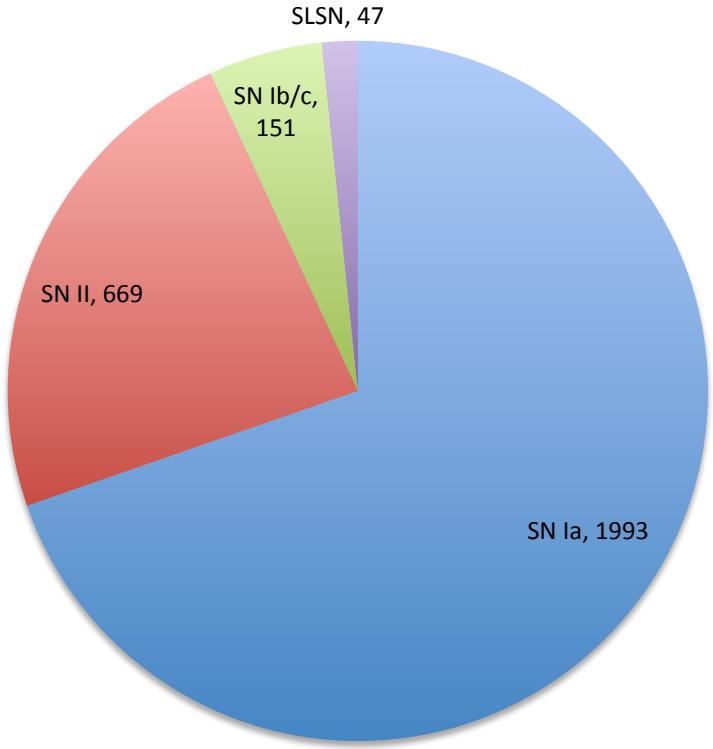


Scanning Page: human screening mainly in Israel and Stockholm

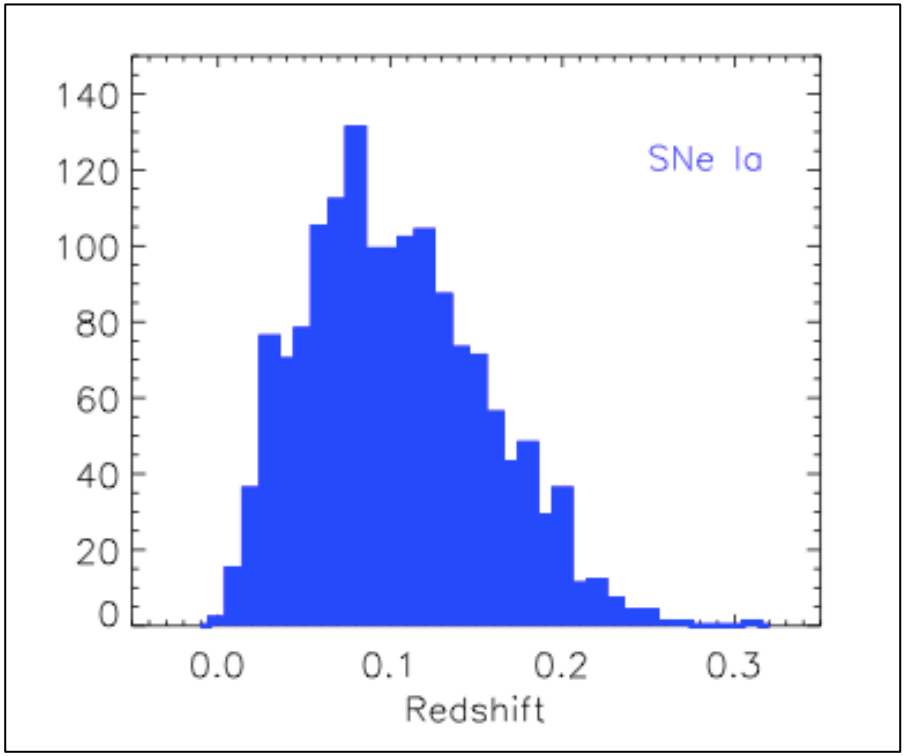
COURTESY OF YI CAO & MANSI KASLIWAL

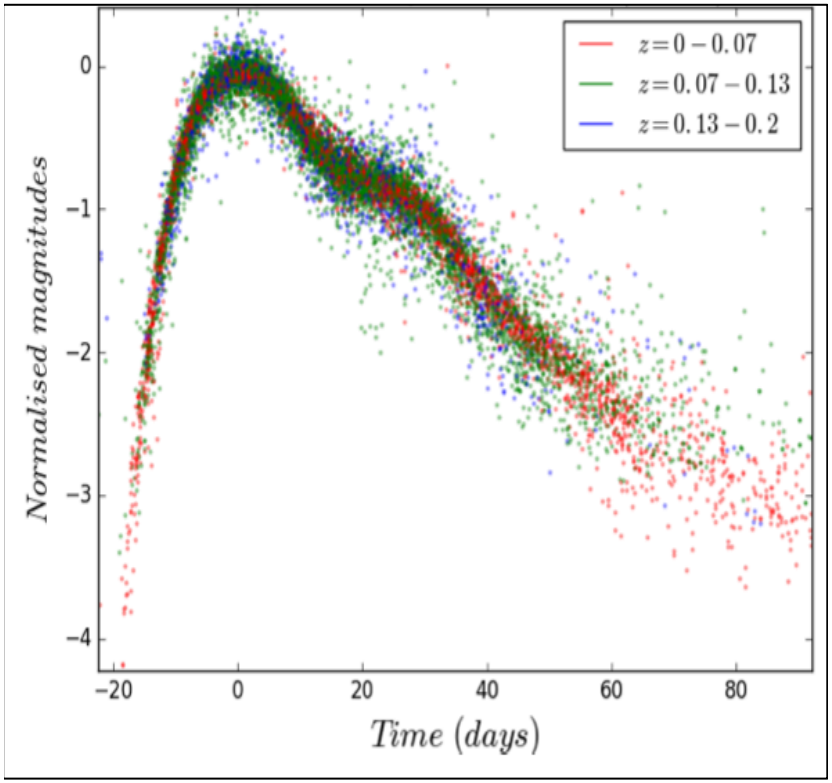
(i)PTF: a low-redshift Type Ia SN factory





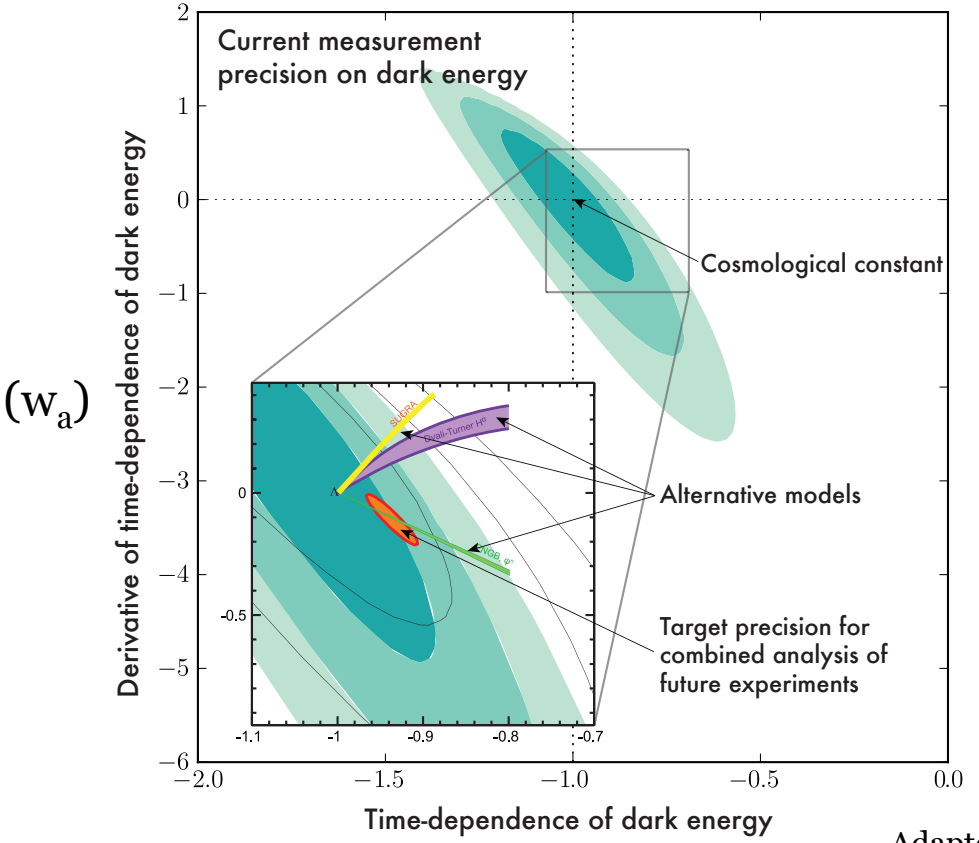
(i)PTF: a low-redshift Type Ia SN factory





What is the origin of the accelerated cosmic expansion?

- Cosmological constant (Λ), consistent with *existing* data but is 10^{60}-10^{120} times lower than the expected vacuum energy density
- **Completely new physics?**
- *Combined studies of low- and high-redshift SNe provides the key for testing models for the cosmic acceleration: time-evolution*



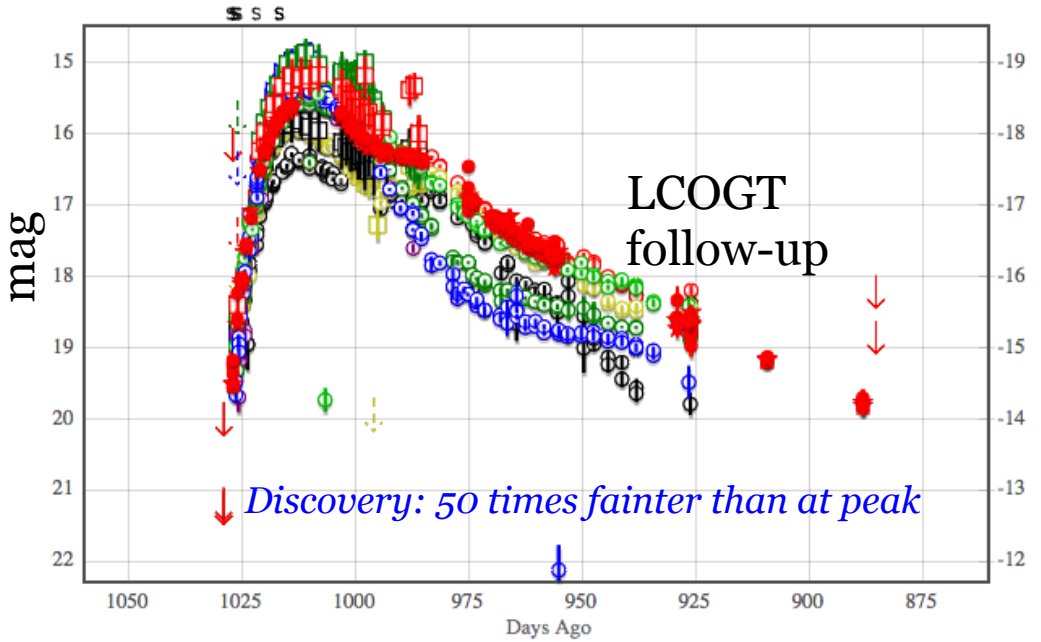
Adapted from AG & Leibundgut 2011

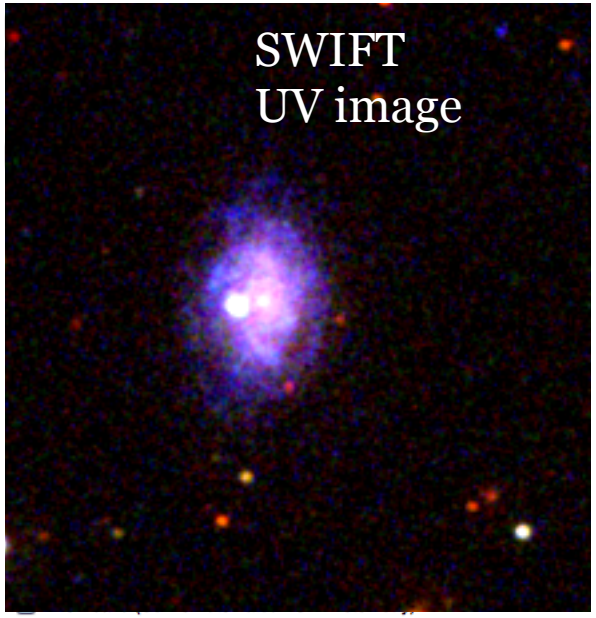
$$\rho_{DE} = \rho_{DE}^{0} a^{-3(1+w)}; w = w_0 + w_a(1-a)$$

$$\rightarrow w = -1 \text{ makes } \rho_{DE} \text{ constant}$$

Examples of iPTF early detections

D~100 Mpc (z=0.0159)

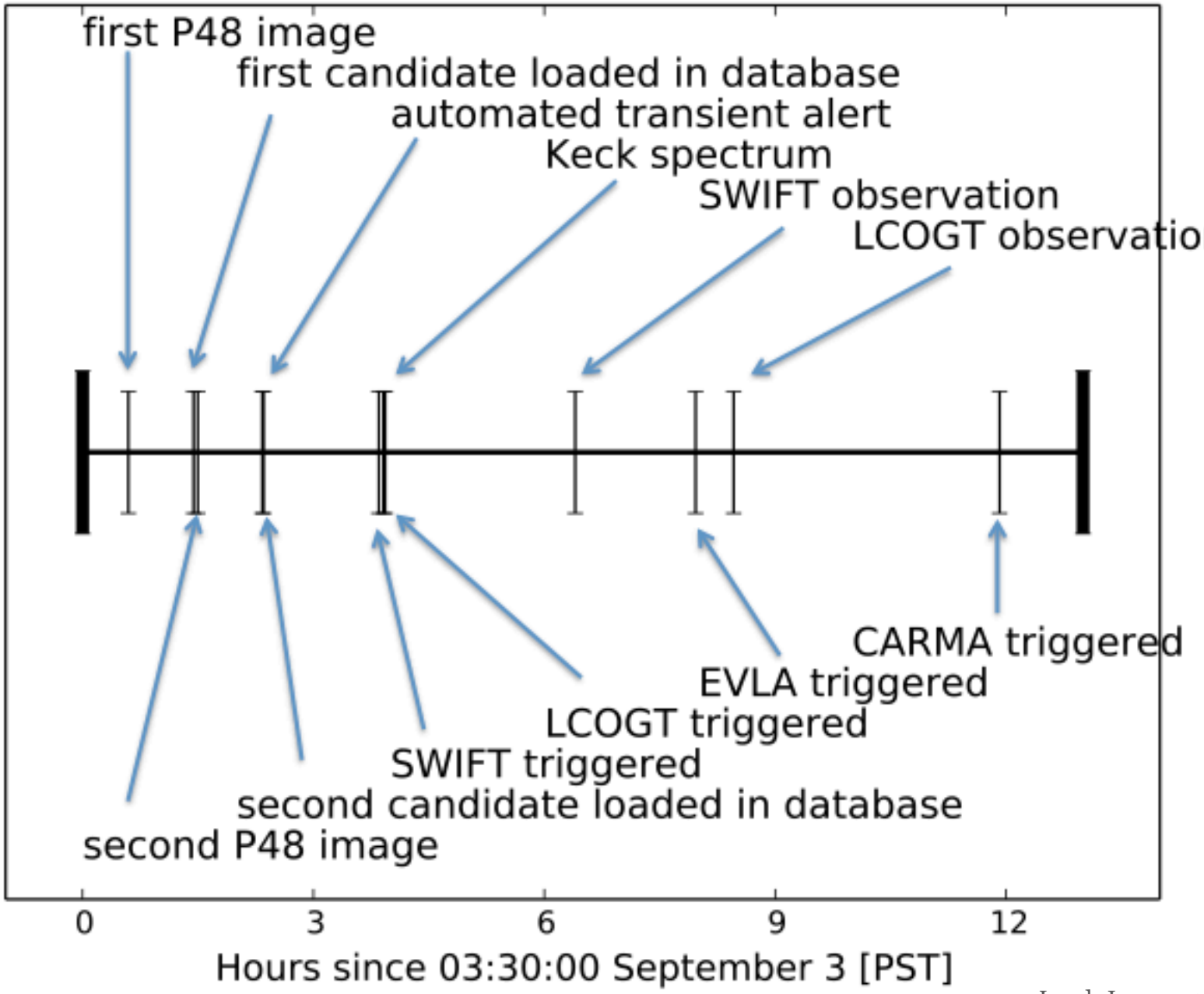


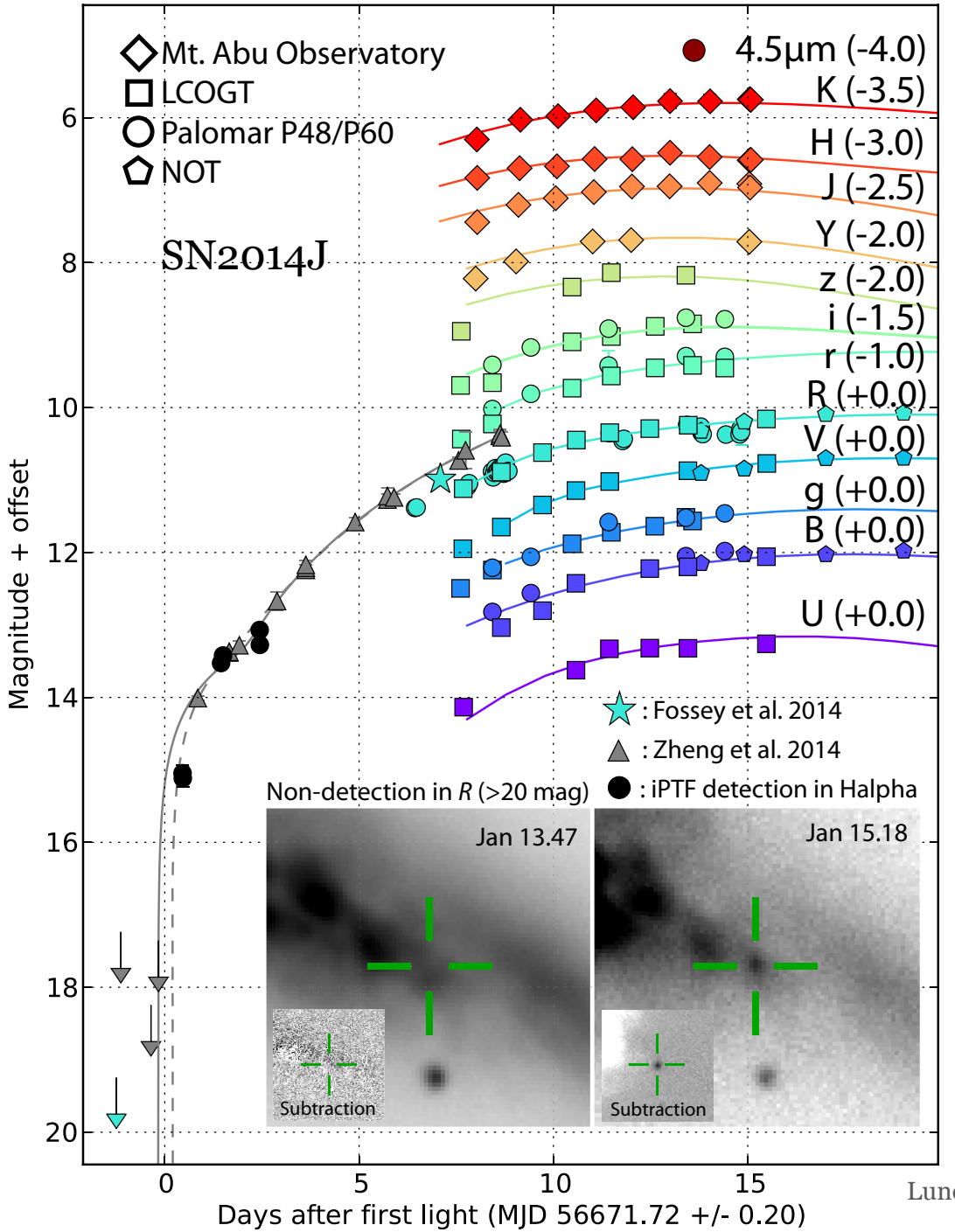


Early observations of SNe – astrophysical unknowns:

- Search for evidence of shock heating of outer layers of exploding star, interaction with companion star, circumstellar medium, surface radioactivity, etc
- Multi-wavelength follow-up observations to study extinction along line of sight.

Time-line of follow-up of iPTF13dge

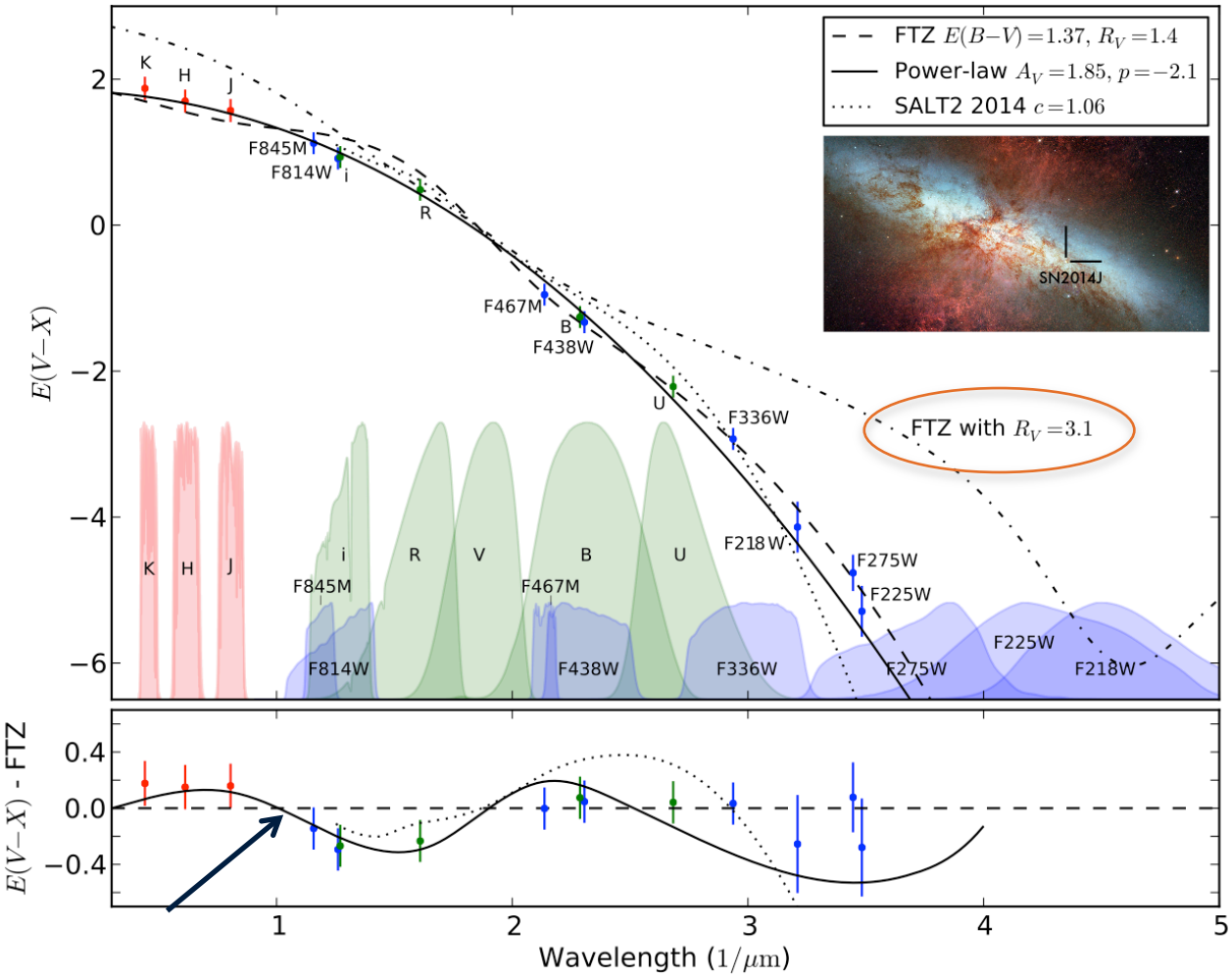



Mt. Abu Observatory
LCOGT
Palomar P48/P60
NOT
SN2014J
4.5μm (-4.0)
K (-3.5)
H (-3.0)
J (-2.5)
Y (-2.0)
z (-2.0)
i (-1.5)
r (-1.0)
R (+0.0)
V (+0.0)
g (+0.0)
B (+0.0)
U (+0.0)
: Fossey et al. 2014
: Zheng et al. 2014
: iPTF detection in Halpha
Non-detection in R (>20 mag)
Jan 13.47
Jan 15.18
Subtraction
Subtraction
Magnitude + offset
Days after first light (MJD 56671.72 +/- 0.20)

AG+14

HST+Ground: The reddening law: Milky Way type dust **ruled-out**!

Amanullah et al 2014,15



Goobar 08, circumstellar dust model fits data well.

Discovery of *rare* transient phenomena

On Oct 2, 2016, something quite unexpected happened…

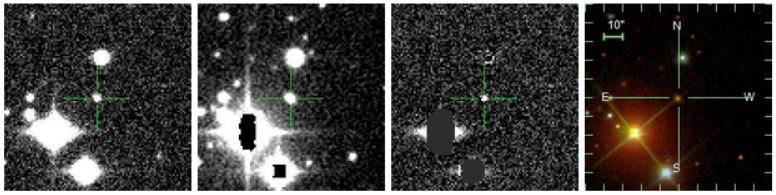
Oskar Klein centre

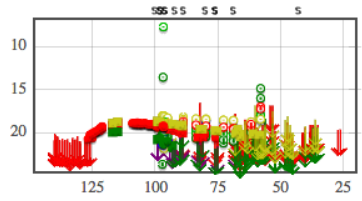
16geu SN Ia +112.3d 21:04:15.86 -06:20:24.5 316.066097 -6.340139

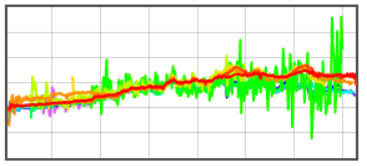
View another

OVERVIEW PHOTOMETRY SPECTROSCOPY OBSERVABILITY FINDING CHART NERSC EXAMINE IPAC EXAMINE

NEW REF SUB SDSS







r >19.7 (26.2 d) | Upload New Photometry

z = 0.409 | Upload New Spectroscopy
DM (approximate) = 41.76

ADDITIONAL INFO

NED | TNS | SNEx | SIMBAD | VizieR | HEASARC | DECam | SkyView | PyMP | MPChecker | Extinction
CFHT | IPAC | DSS | WISE | Subaru | VLT | FIRST | CRTS | Variable Marshal (Search) | ADS

CURRENT FOLLOWUP REQUEST

Requester	Start Date	End Date	Program	Priority	Filters	Cadence
tiara	2016-09-12	2016-09-20	P60 Transient Vetting	4	g,r,i	2.0
nadia	2016-09-26	2016-09-27	P60 Transient Vetting	3	IFU	1.0
ariel	2016-10-02	2016-10-03	Type Ia Supernovae	4	g,r,i,u	1.0
ariel	2016-10-03	2016-10-09	Type Ia Supernovae	5	g,r,i,u	2.0
ariel	2016-10-08	2016-10-15	Type Ia Supernovae	5	g,r,i,u	1.0
ariel	2016-10-14	2016-10-21	Type Ia Supernovae	5	g,r,i,u	1.0
joeljo	2016-10-23	2016-10-30	Type Ia Supernovae	5	r,g,i	1.0

ADD P60 FOLLOWUP

Select an observing sequence below.

Program: <-- Select Program -->

Observing Group: No Follow Up

1 (1=low, 5=high)

ASSIGNMENTS

Assignment

CROSS REFERENCES

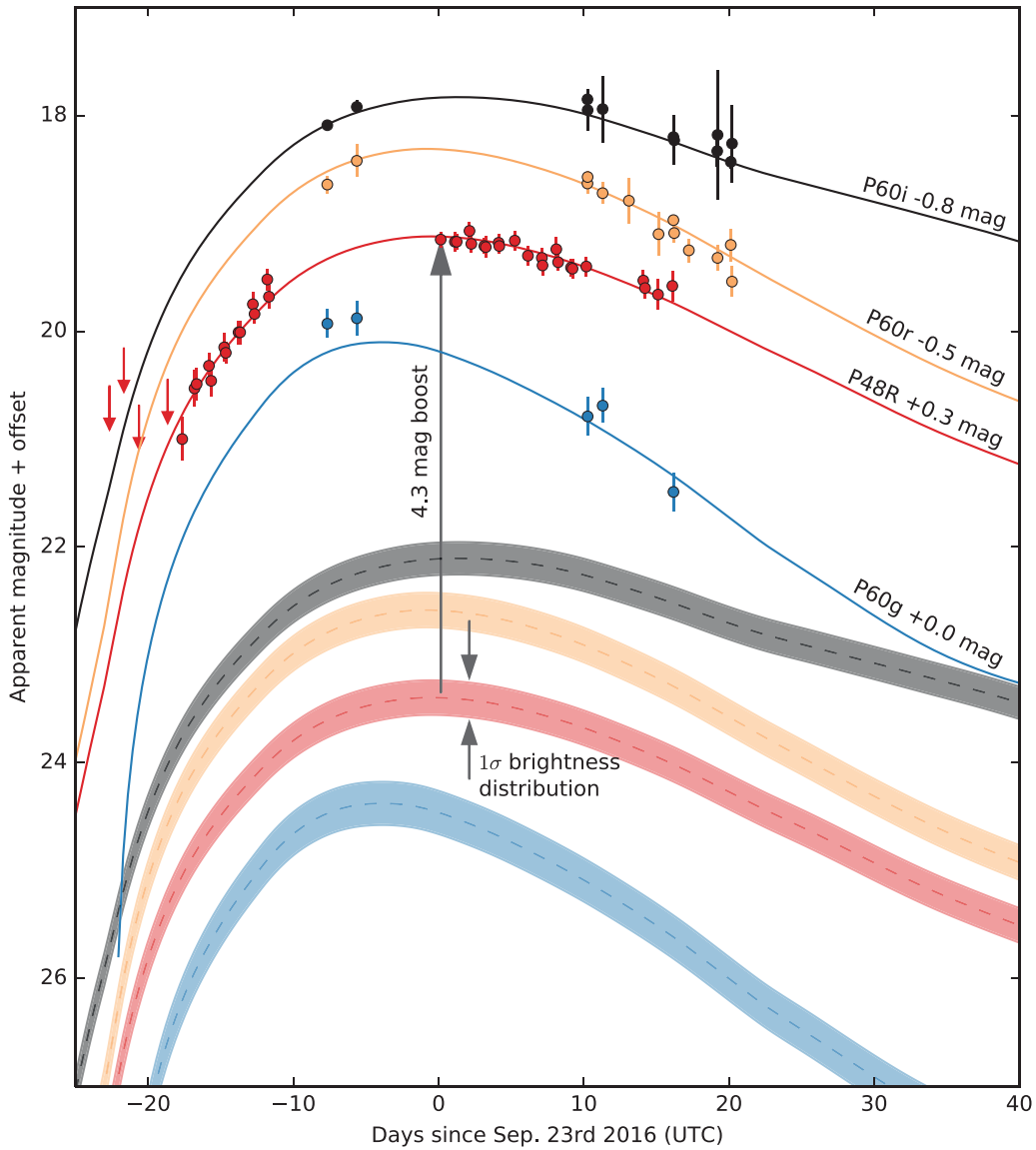
ATel 9603: Detection of a highly magnified Type Ia Supernova by the intermediate Palomar Transient Factory *Ariel Goobar et al., 2016 Oct 07*

COMMENTS

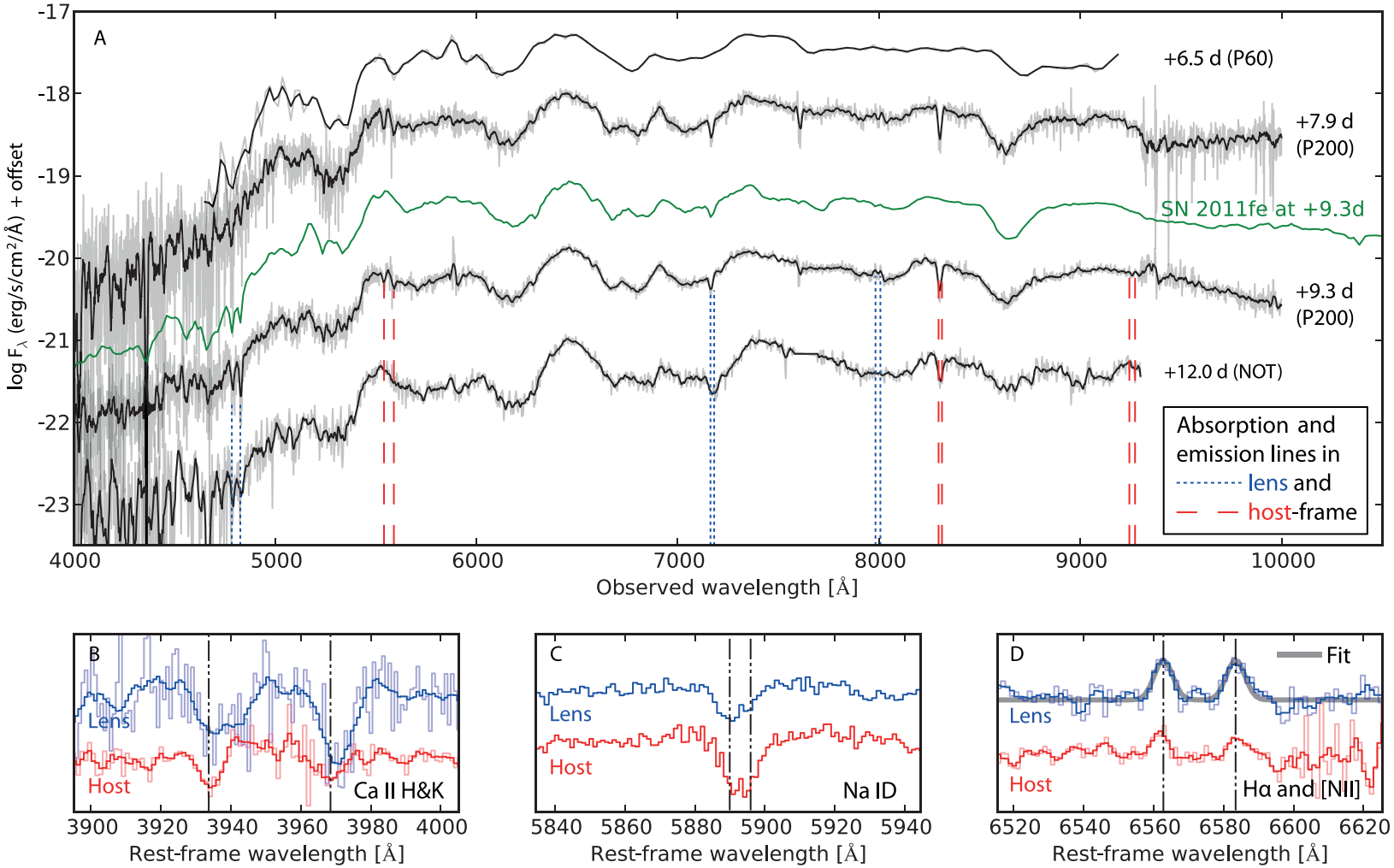
2016 Dec 24 penugent [classification]: SN Ia
2016 Oct 20 joeljo [comment]: Maybe [SII]λλ6716, 6731 at z=0.2163
2016 Oct 13 jesper [info]: There is also a spectrum from NTT/PESSTO from Oct 8 [view attachment]
2016 Oct 13 penugent [classification]: SN Ia
2016 Oct 13 penugent [phase]: +12 days
2016 Oct 12 rahman [info]: Updated light curve fit with new P60 data at max. Vanilla Ia @ z=0.41 with E(B-V)=0.2-0.3 depending on extinction law. [view attachment]
2016 Oct 12 joeljo [info]: There is P60 imaging from Sep. 12 and i,z images from SkyMapper on Sep 20.
2016 Oct 06 tkupfer [comment]: reduced with the standard DBSP pipeline
2016 Oct 06 tkupfer [comment]: re-reduced DBSP spectrum from Oct. 04
2016 Oct 06 avishay [comment]: Also, weak Halpha + NII complex in emission at z=0.2163
2016 Oct 06 avishay [comment]: And another set of Na D and Ca II H+K at z=0.2163 or so. Nice!
2016 Oct 06 avishay [comment]: Na D and Ca II secure at z=0.409
2016 Oct 06 jesper [info]: New spectrum does show Na and Ca in absorption at 0.4087 but also at 0.2164, the latter (lens) also seem to show emission lines at this redshift, Halpha NII and OII
2016 Oct 06 ofer [comment]: Maybe slightly cleaner...
2016 Oct 06 ofer [comment]: Another reduction
2016 Oct 06 ariel [classification]: SN Ia
2016 Oct 06 ariel [redshift]: 0.409
2016 Oct 05 robert [info]: plausible OII and Ca II H&K at z=0.409 (and NaI D as already noted).
2016 Oct 05 robert [info]: possibly also OII emission and Ca II H&K absorption at z=0.216
2016 Oct 05 raphael [info]: Feature at 7200Å may coincided with NaID at proposed lens redshift at z=0.22
2016 Oct 04 ariel [info]: SNID match of P200 spectrum [view attachment]
2016 Oct 04 ariel [info]: Na ID @ z = 0.4081?
2016 Oct 04 ariel [info]: P200 spectrum consistent with SEDM!
2016 Oct 03 ariel [info]: Possible scenario: the galaxy we see in the ref and SDSS with photo-z = 0.23 is a lensing galaxy: the host galaxy is behind!?
2016 Oct 03 ariel [info]: Multi-color Lightcurve for z=0.4 Normal SNIa [view attachment]
2016 Oct 03 ariel [info]: Multi-band data from P60 supports z=0.4 Ia hypothesis. Lensing? Need a better spectrum!
2016 Oct 02 rahman [info]: Light curve shape consistent with a 91T assuming z=0.4, but with low stretch. [view attachment]
2016 Oct 02 ariel [info]: Very uncertain, but a peculiar Ia SED does provide a reasonable match, but about 4 mags too bright... [view attachment]
2016 Oct 02 ariel [redshift]: 0.4
2016 Sep 11 ofer [info]: Rising over last 5 d.
2016 Sep 11 ofer [type]: Transient (=AT2016geu)

Add a Comment:

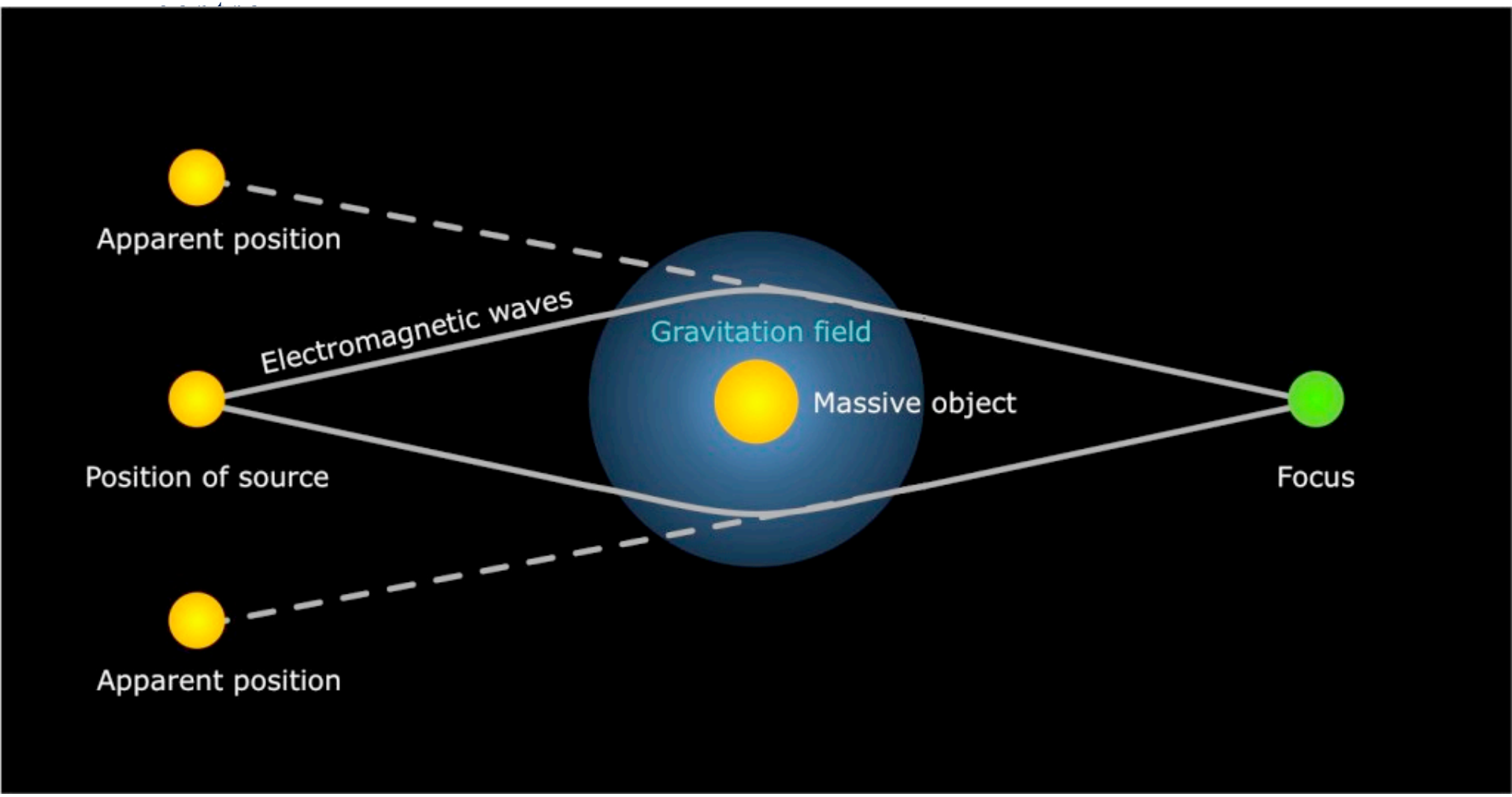
> 50 times brighter than normal SNIa: a 30σ outlier!



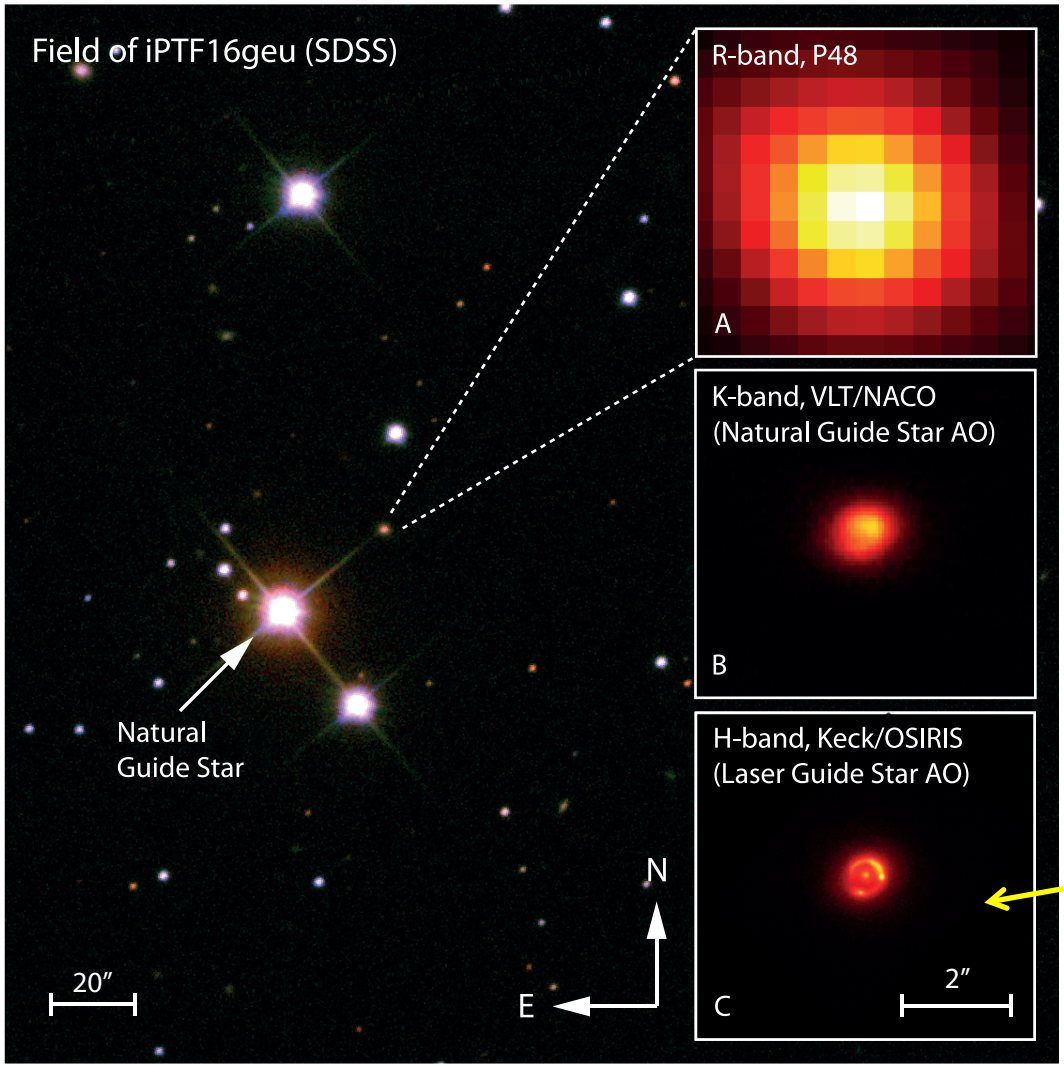
Perfect match to z=0.409 SN Ia + intervening galaxy at z=0.216

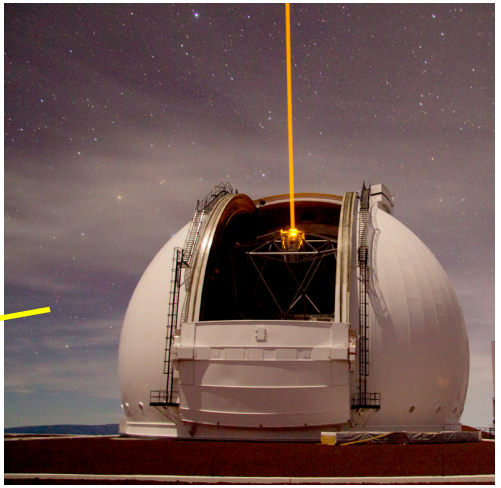


Gravitational lensing by foreground galaxy?!



Multiple images?

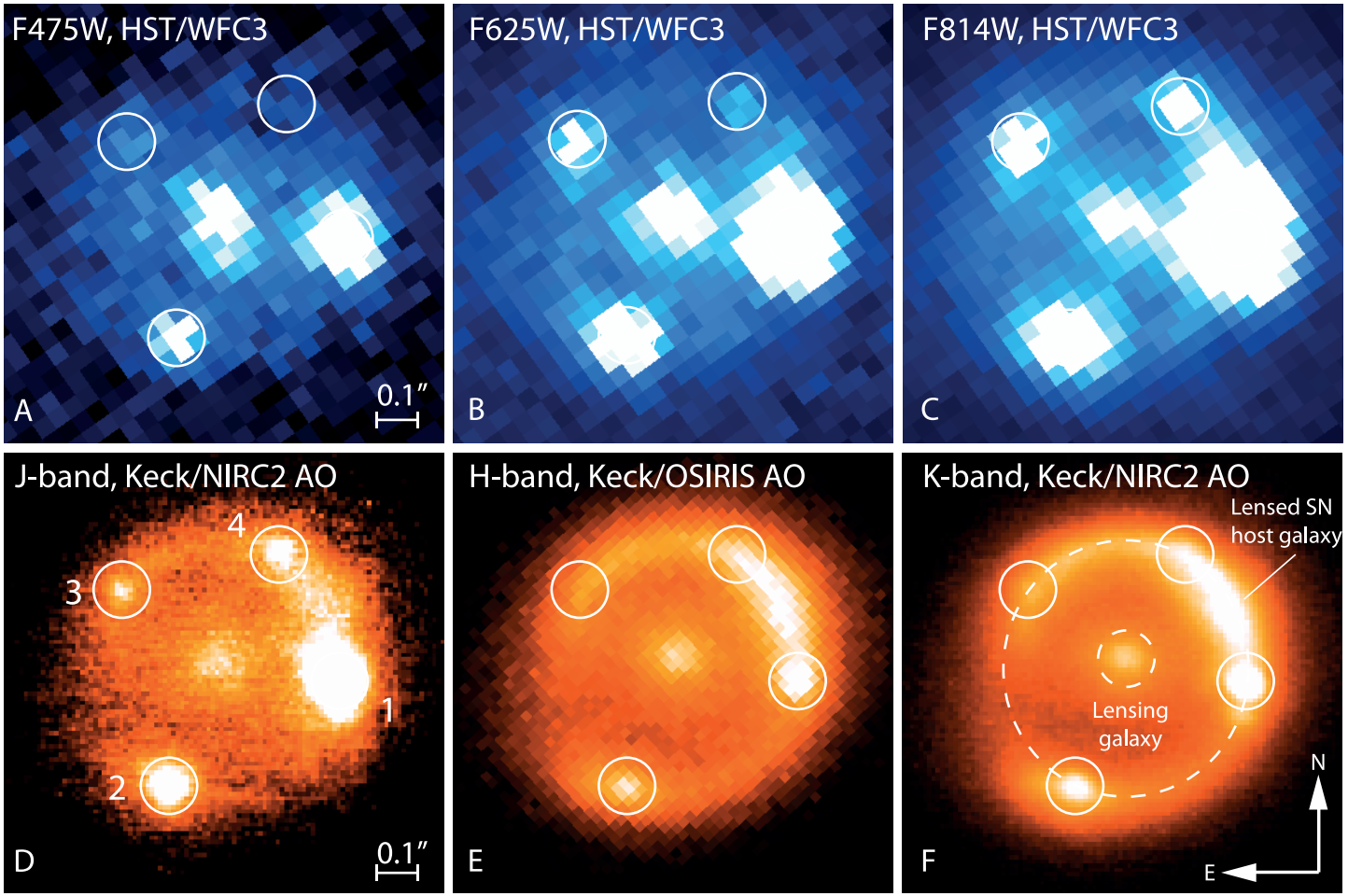




A quadruple lens configuration! Strong evidence for extra "help" by microlensing by compact lenses

Hubble Space Telescope

Keck LGAO



Goobar et al, submitted; arXiv:161100014

Sjur Refsdal

ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

Sjur Refsdal

(Communicated by H. Bondi)

(Received 1964 January 27)

Summary

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt, the red-shifts of the supernova and the galaxy, the luminosities of the supernova "images" and the angle between them. The possibility of observing the phenomenon is discussed.

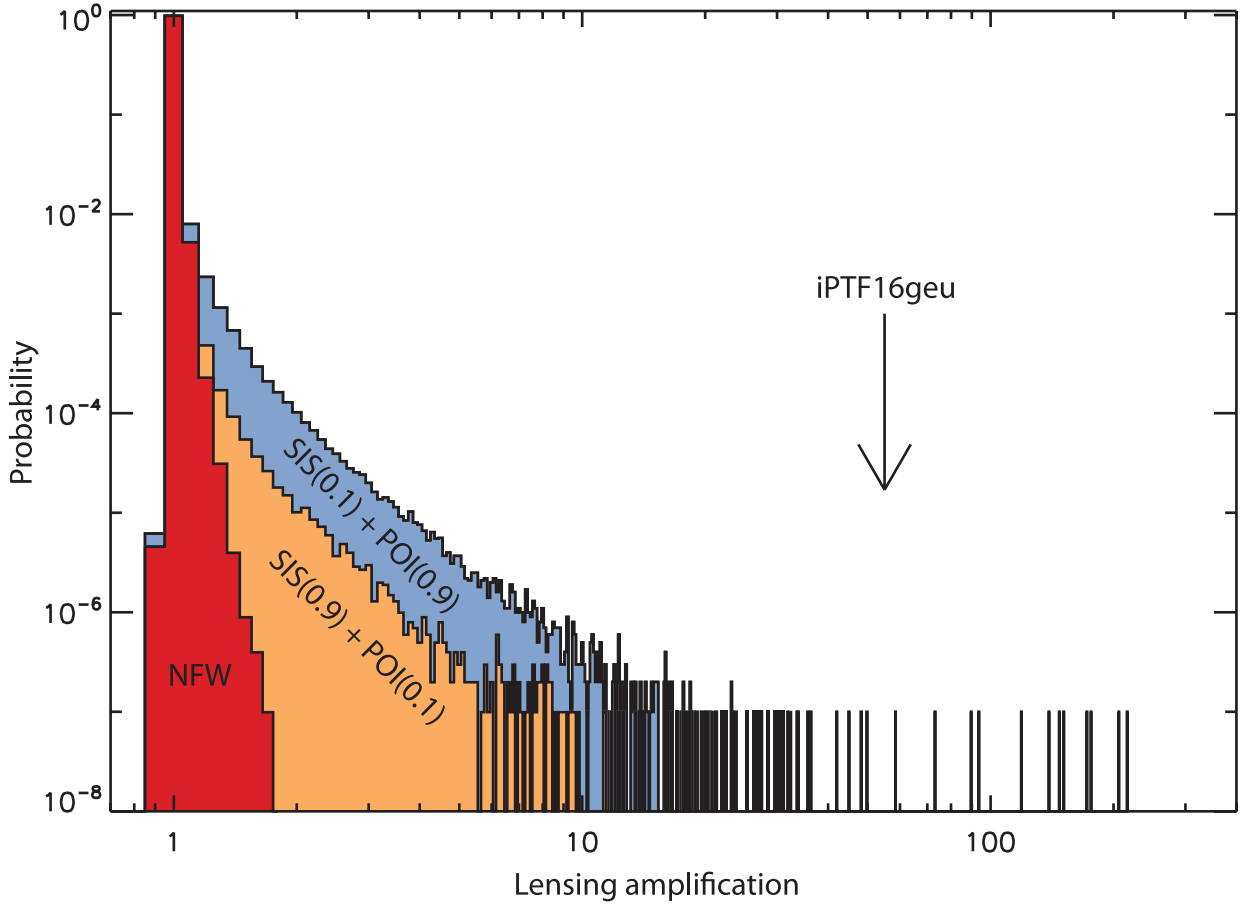
1. *Introduction.*—In 1937 Zwicky suggested that a galaxy, due to the gravitational deflection of light, may act as a gravitational lens. He considered the case of a galaxy A lying far behind and close to the line of sight through a distant galaxy B. If the line of sight through the centre of B goes through A, the "image" of A will be a ring around B, otherwise two separated "images" appear, on opposite sides of B. The phenomenon has later been discussed by Zwicky (1957) and Klimov (1963), and they both conclude that the possibility of observing the phenomenon should be good. In the present paper the case of a supernova lying behind a galaxy is considered. Two "images" of the supernova may then be seen, and we will show that from one such "double image" observation, Hubble's parameter and the mass of the deflecting galaxy can be determined. The possiblity of observing such a "double image" will be discussed.

Time delay measurements for iPTF16geu in progres...

x50 amplification! How unlikely is this?

- Unknown territory!? Lensing of SN iPTF16geu probes inner 0.3”, 1 kpc, of lensing galaxy. This is an otherwise very challenging scale for lensing studies.
- Why could we find it? System found with >2” ang. resolution, since *discovery based on time and brightness, not angular resolution*.
- Microlensing by substractures?! A substantial fraction of Dark Matter in compact objects would greatly enhance probability!
- Hard to tell with only one event... Next generation surveys will tell!

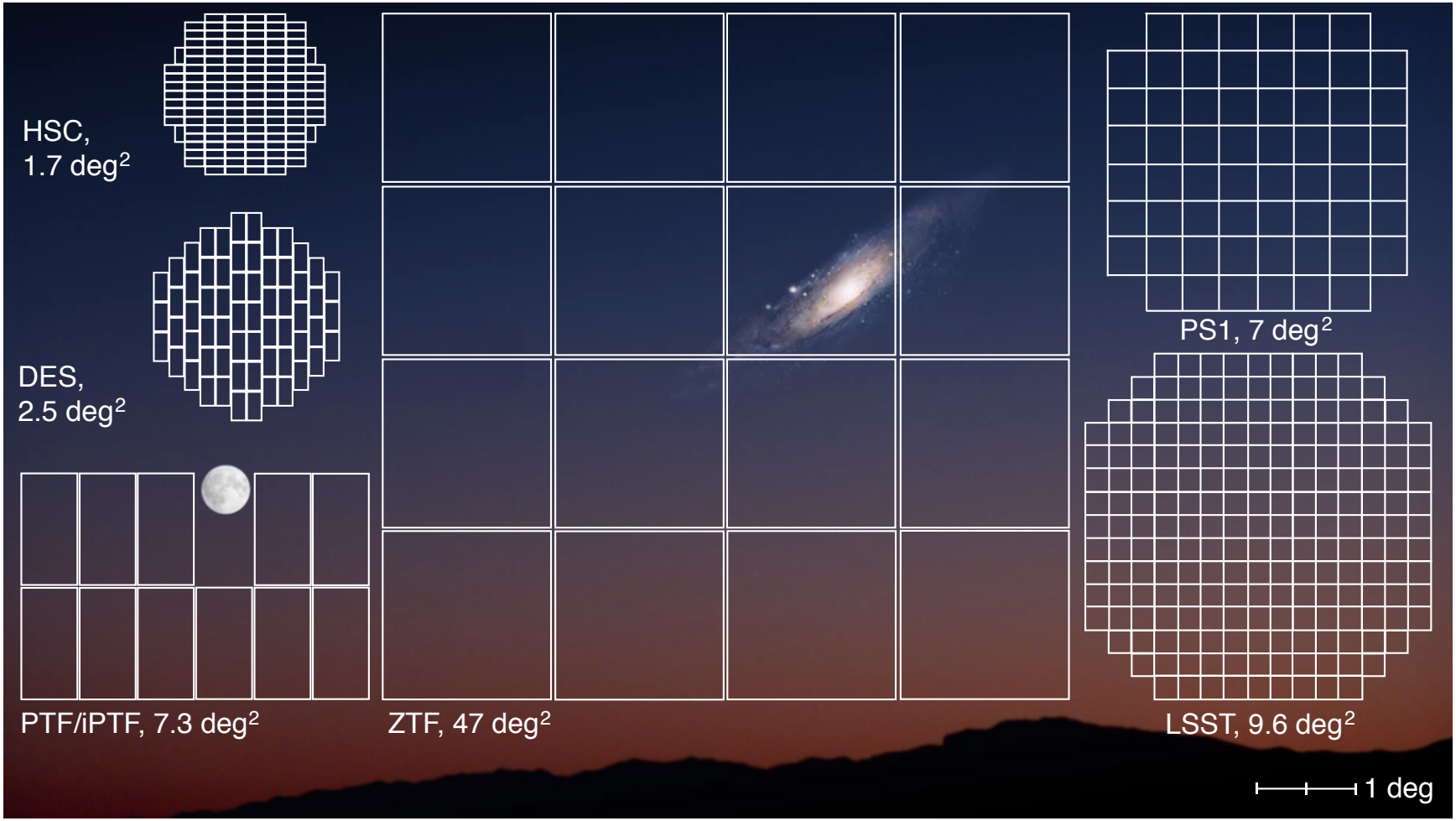
Very unlikely event?!



Measured amplification requires extraordinary alignment of source and lens – suggests lensing by substructures, e.g., black holes, in addition to a smooth matter component from the galaxy. Just lucky or something profound?

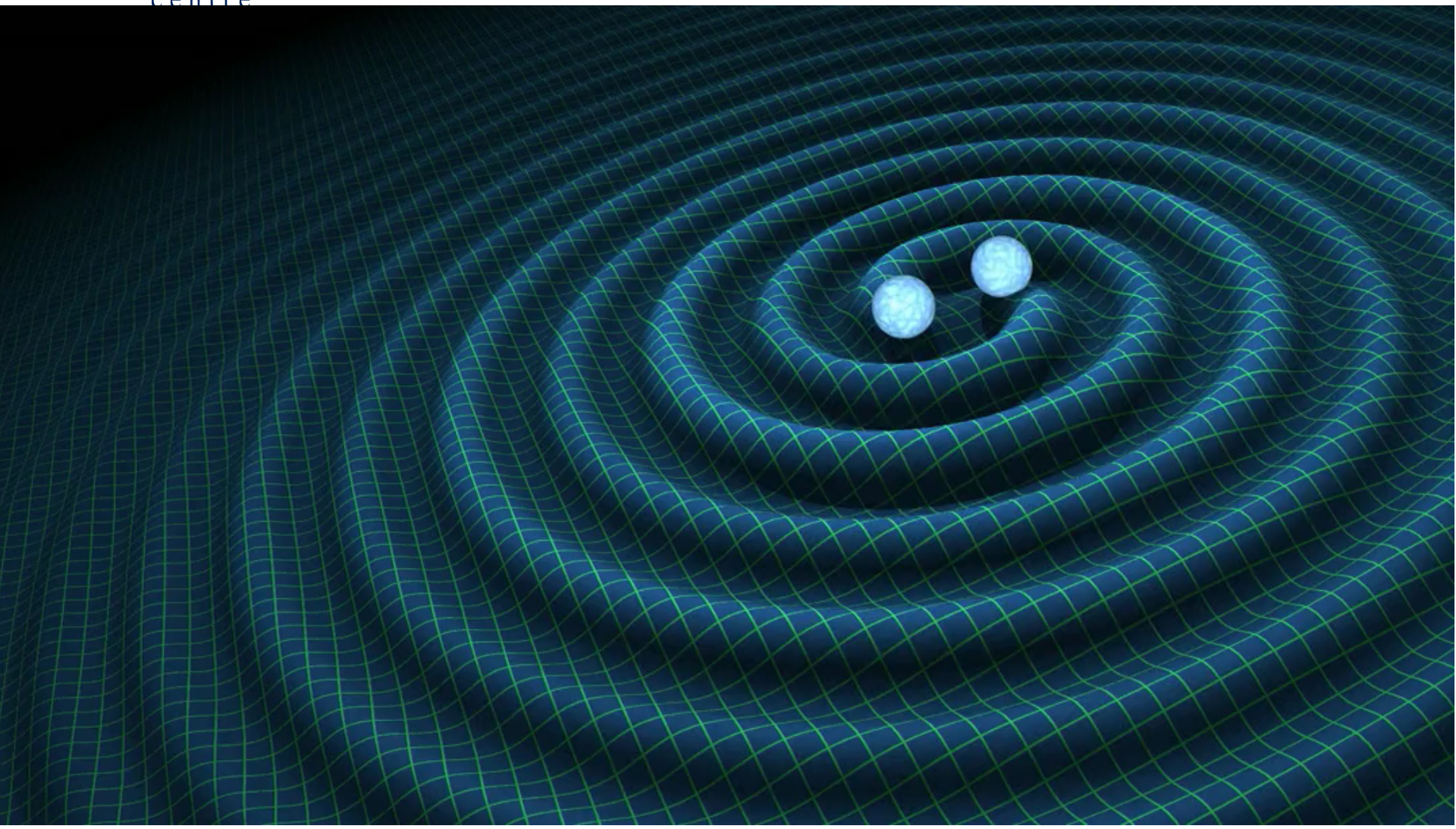
Scaling up: ZTF x15 faster!

- can do all available sky every clear night



Survey start: one year from now

Next big leap?
GW-EM counterparts?



- Hoping for an optical event coincident event with LIGO!

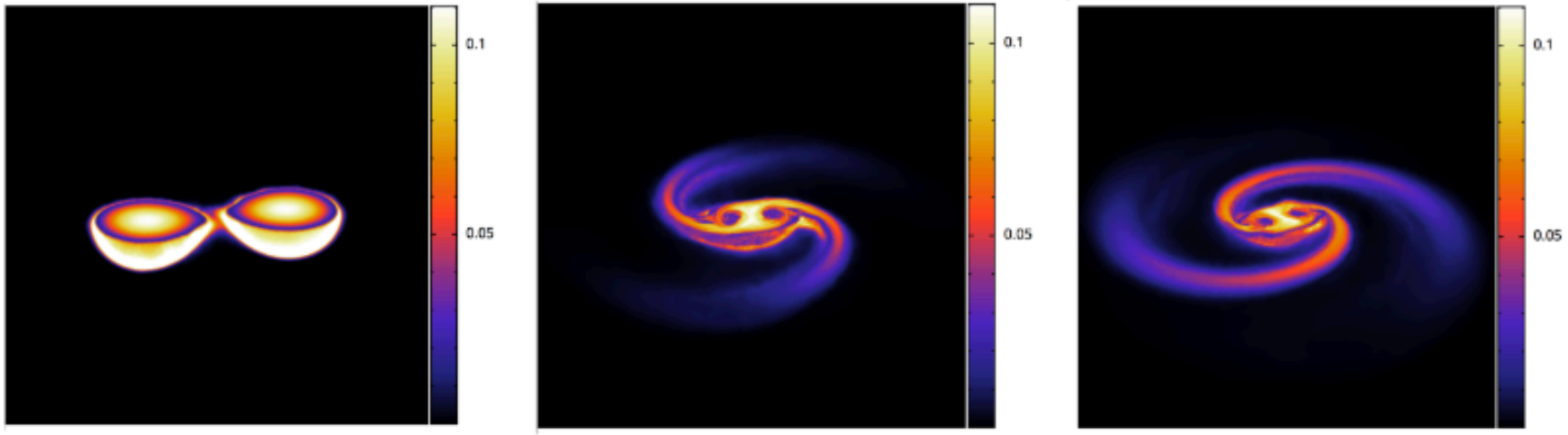
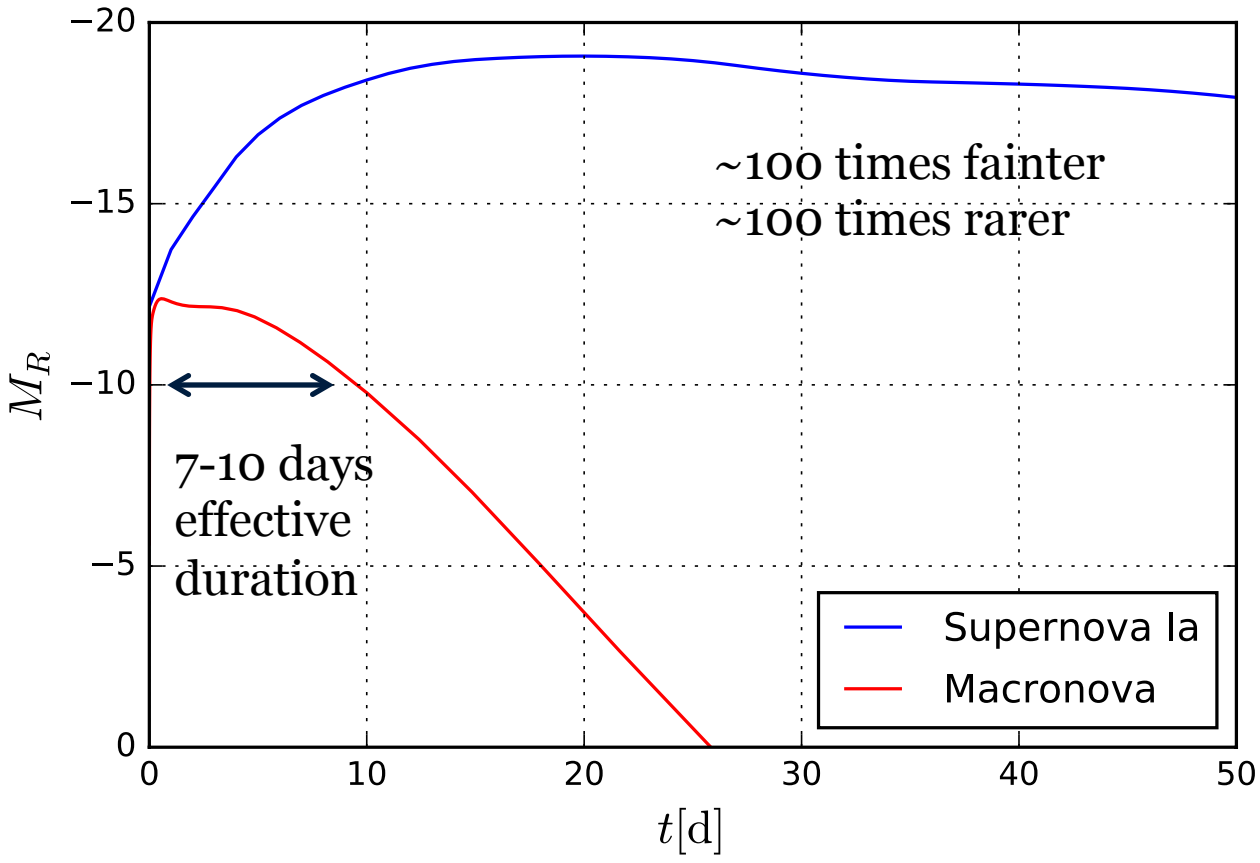


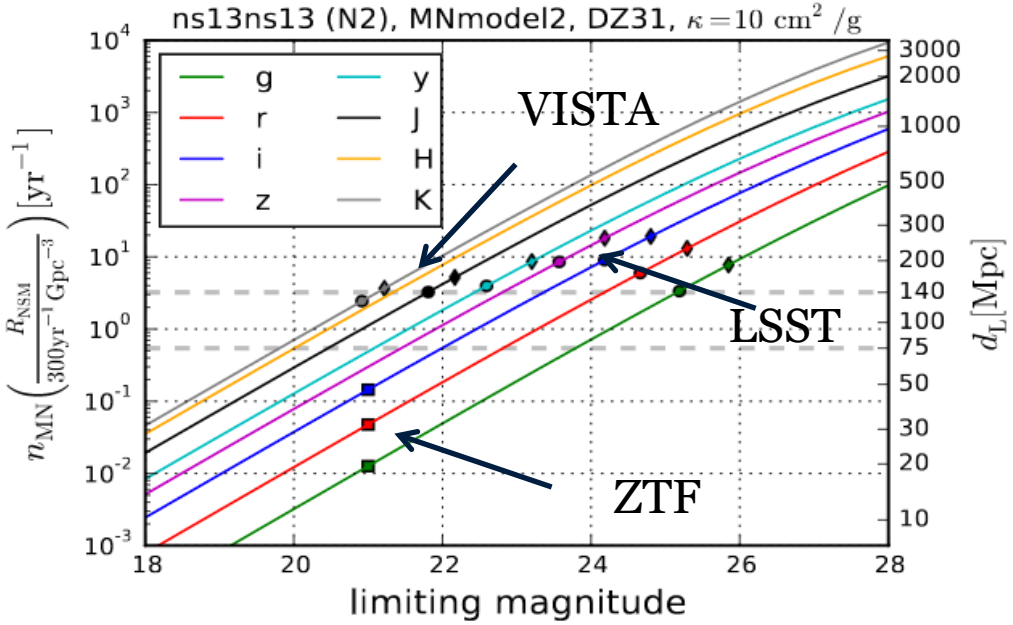
Figure 3. Electron fraction in a 1.3-1.3 $M_\odot$ merger (model N2; only matter below orbital plane shown) at t= 7.06, 11.6 and 12.4 ms.

"Macronovae"
merger of **neutron star- neutron star**
or
black hole- neutron star

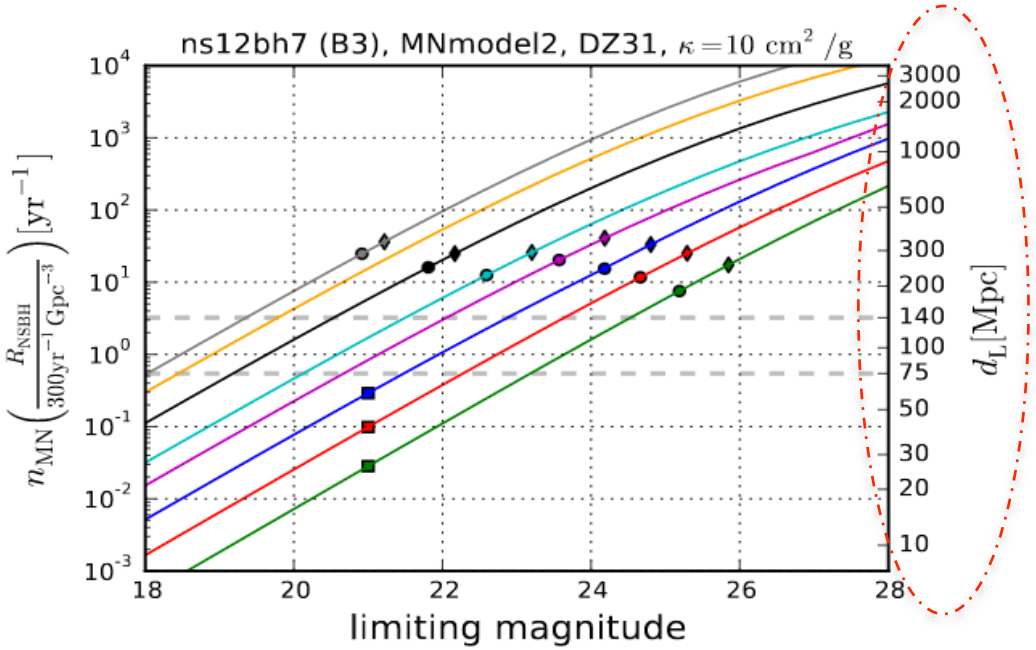
Rosswog et al
arXiv:1611.09822

Rare, Faint, Red and Fast!



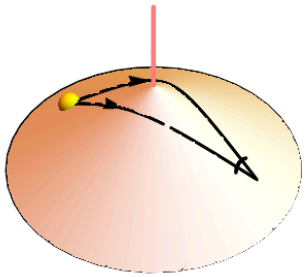


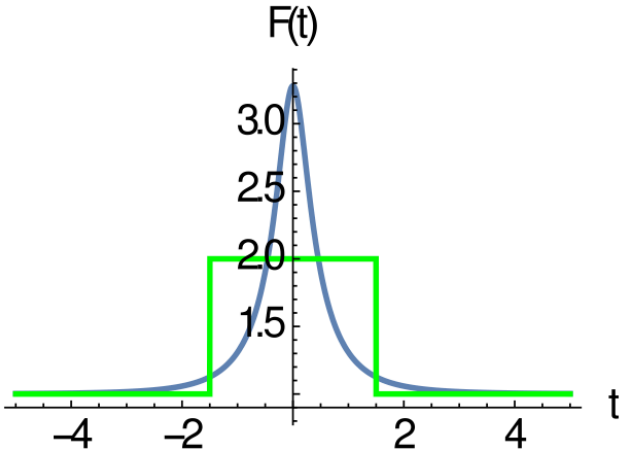
Rosswog et al arXiv:1611.09822



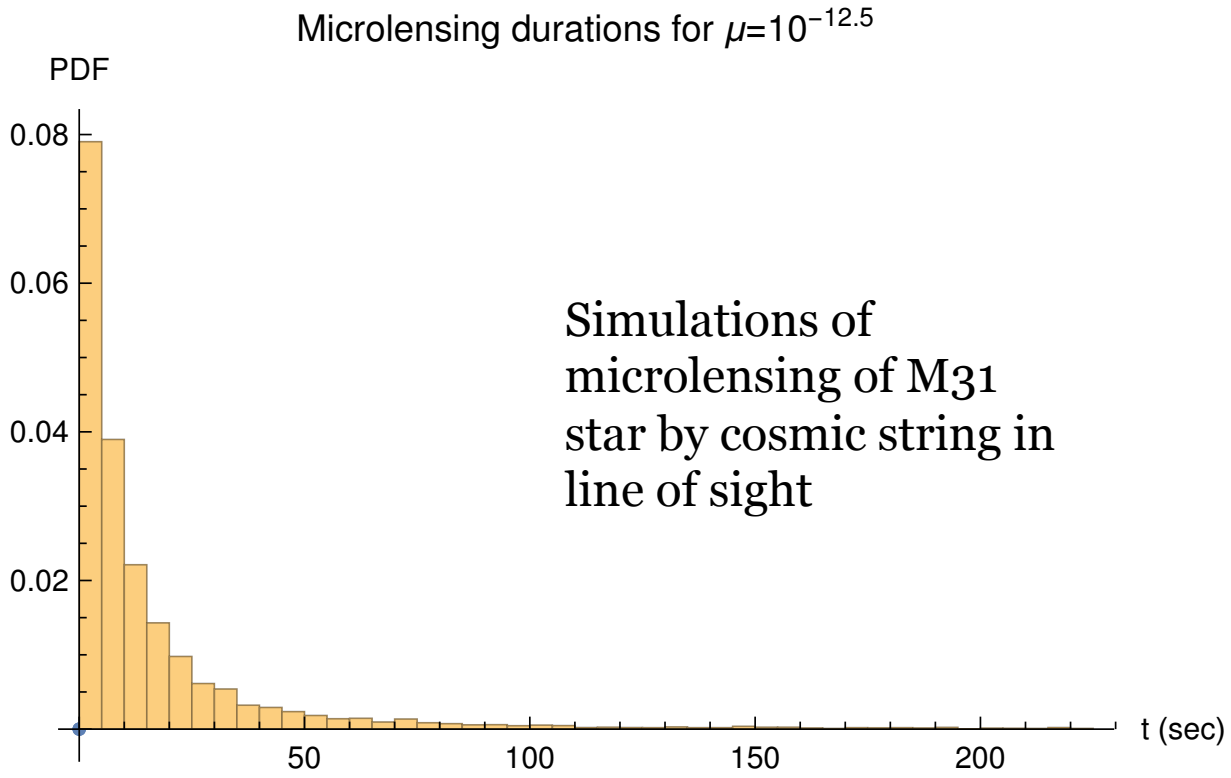
Exotic transients?

- Microlensing of stars in Andromeda by *early universe relics*. Very short time scales (**seconds or minutes!**) may be expected. Possible lenses:
  - Cosmic Strings, cosmological defects from Inflation
  - Axion "miniclusters", condensates of DM ($\sim 10^{-12}\, M_\odot$)





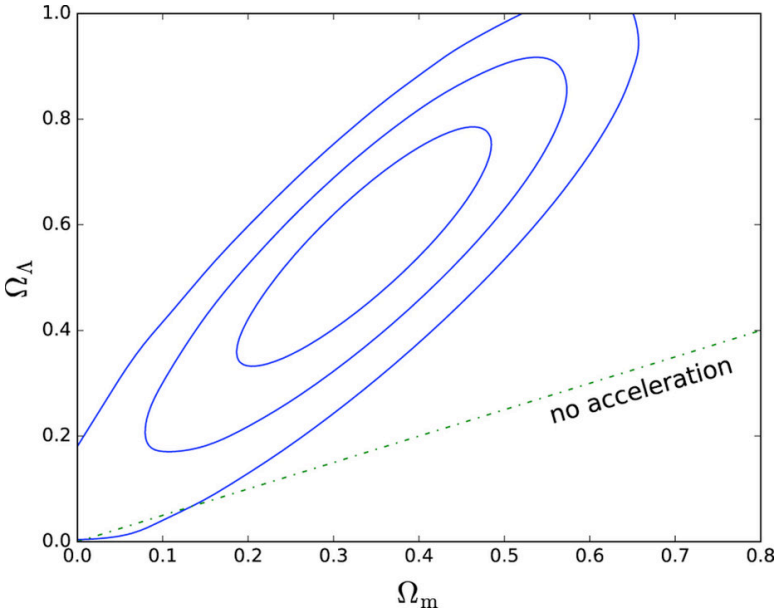
Short time scales: new frontier



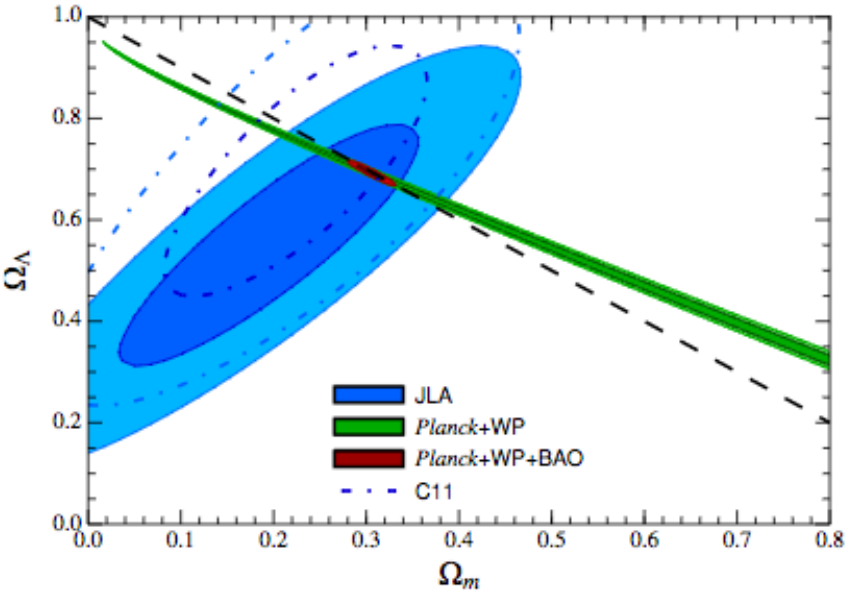
Simulations of microlensing of M31 star by cosmic string in line of sight

Thank you!

News? What News?



Nielsen et al 2016



Betoule et al 2014