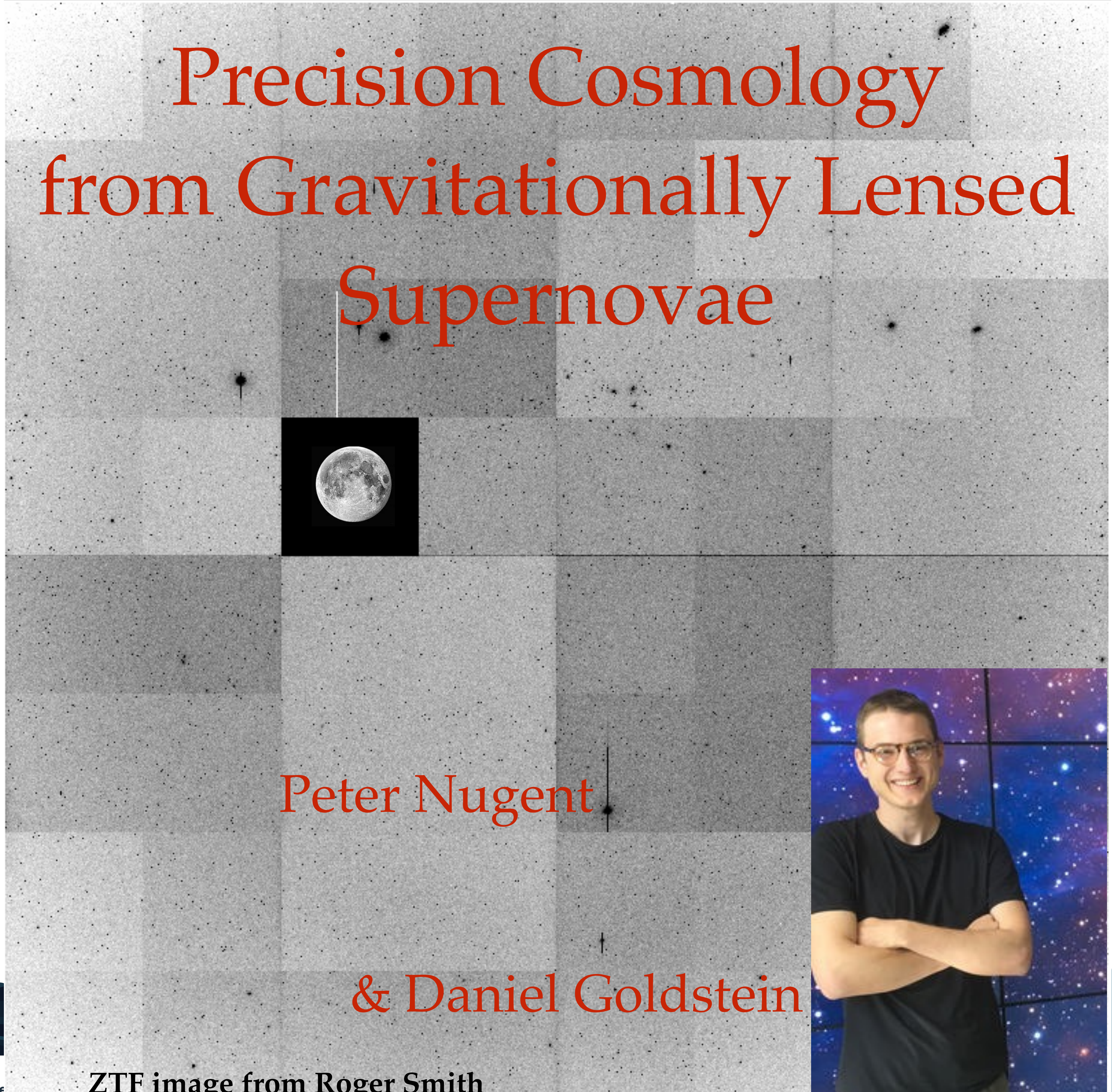
COMPUTATIONAL COSMOLOGY CENTER

Precision Cosmology from Gravitationally Lensed Supernovae



Peter Nugent

& Daniel Goldstein

ZTF image from Roger Smith

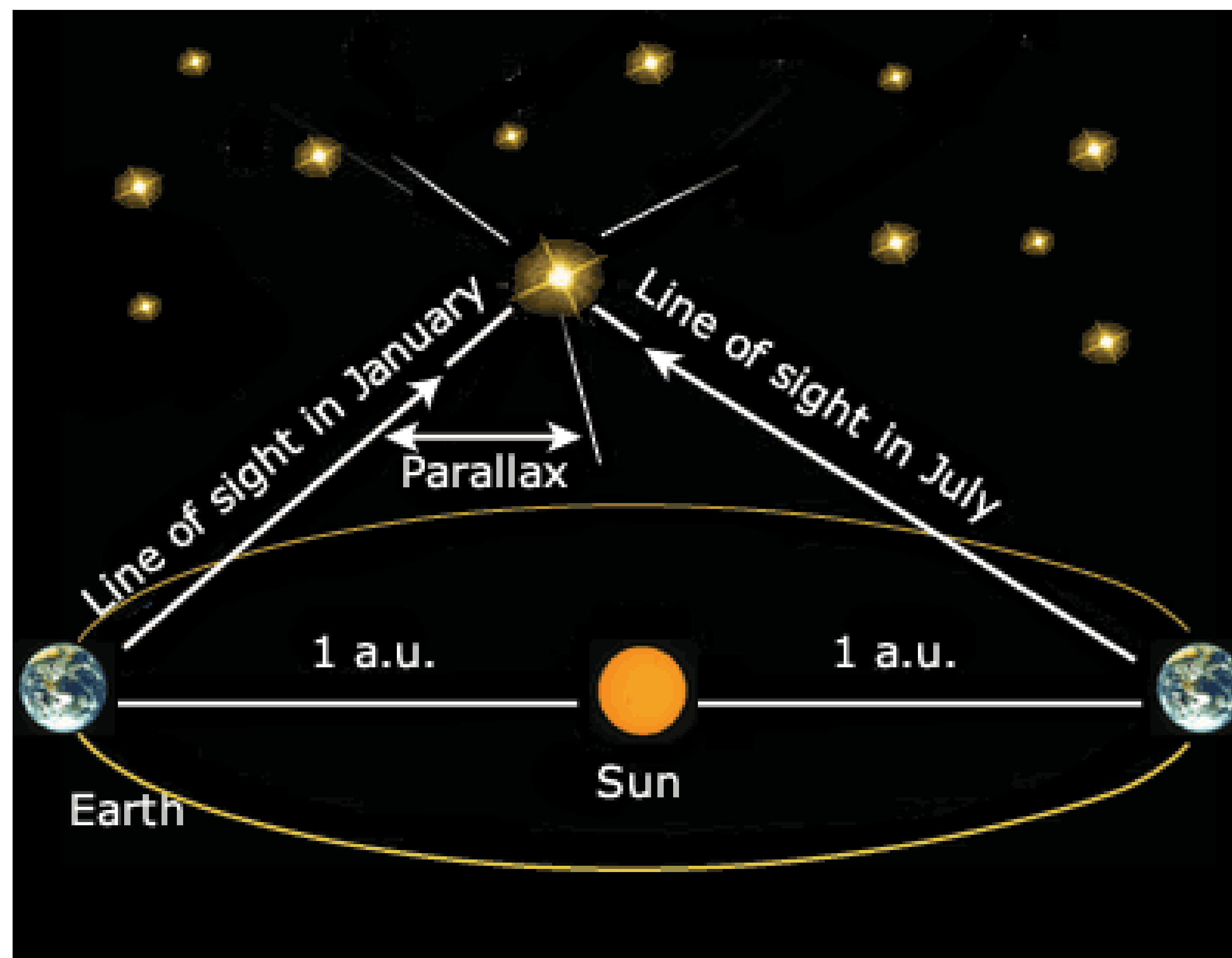
National Energy Research Scientific Computing Cente

BERKELEY LAB

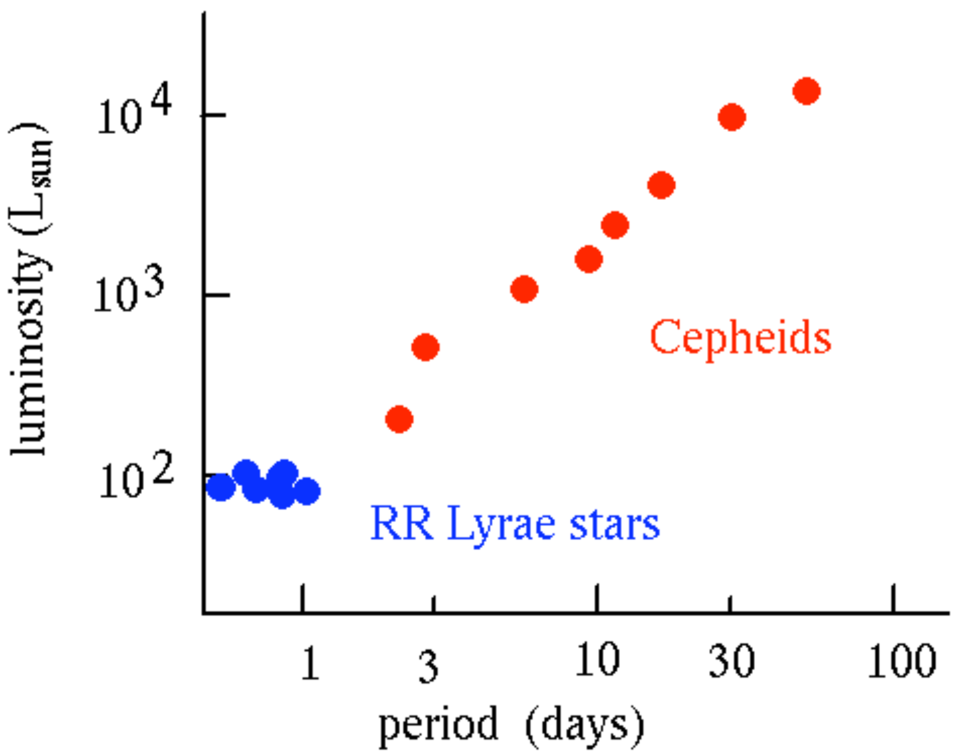
Measuring Distances in Astronomy - Parallax

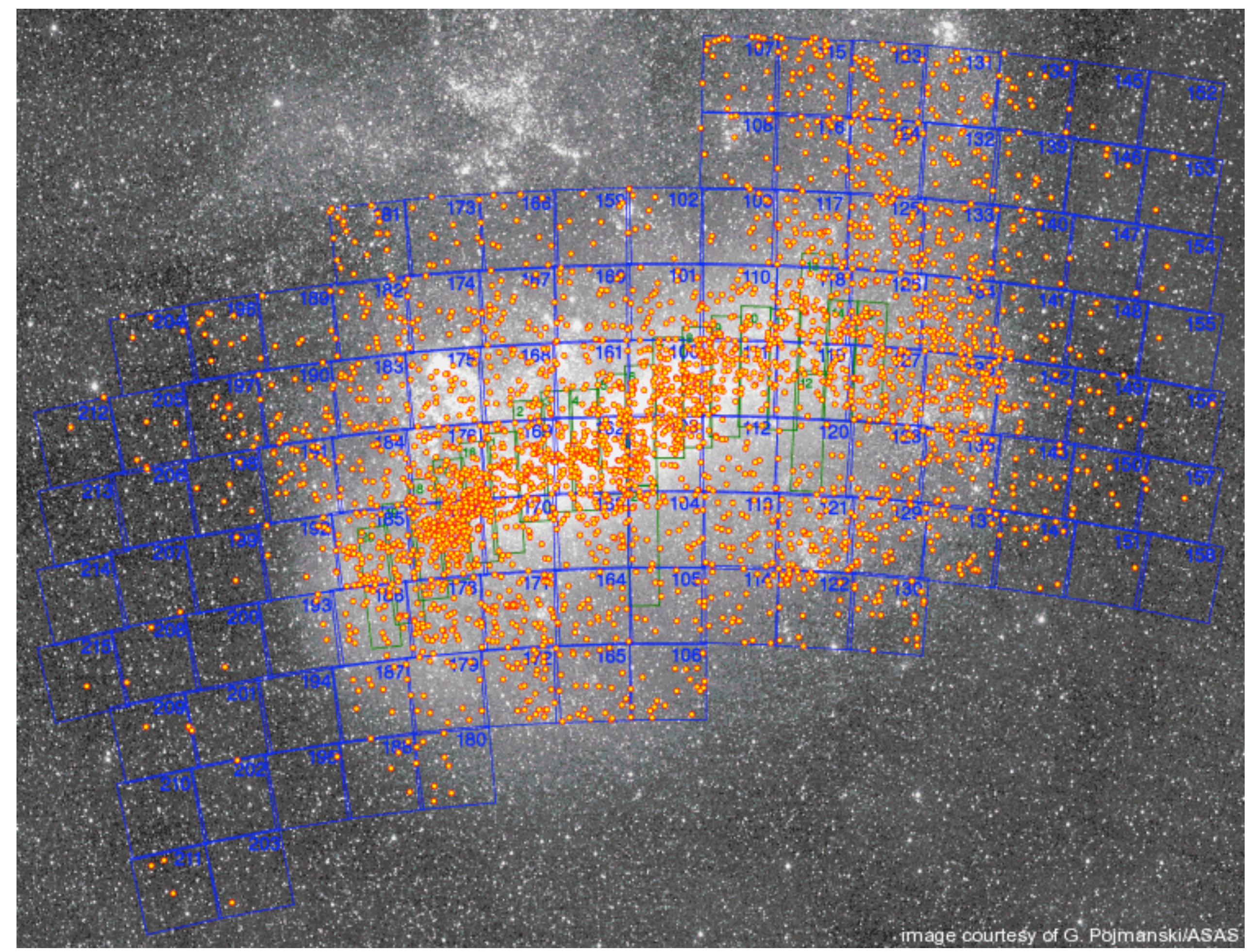
The first successful measurements of stellar parallax were made by Friedrich Bessel in 1838 for the star 61 Cygni using a heliometer. It has a parallax of 0.285″

Note that a 1/2 ₪ coin at 5 km subtends 1″: 1/3600 of a degree



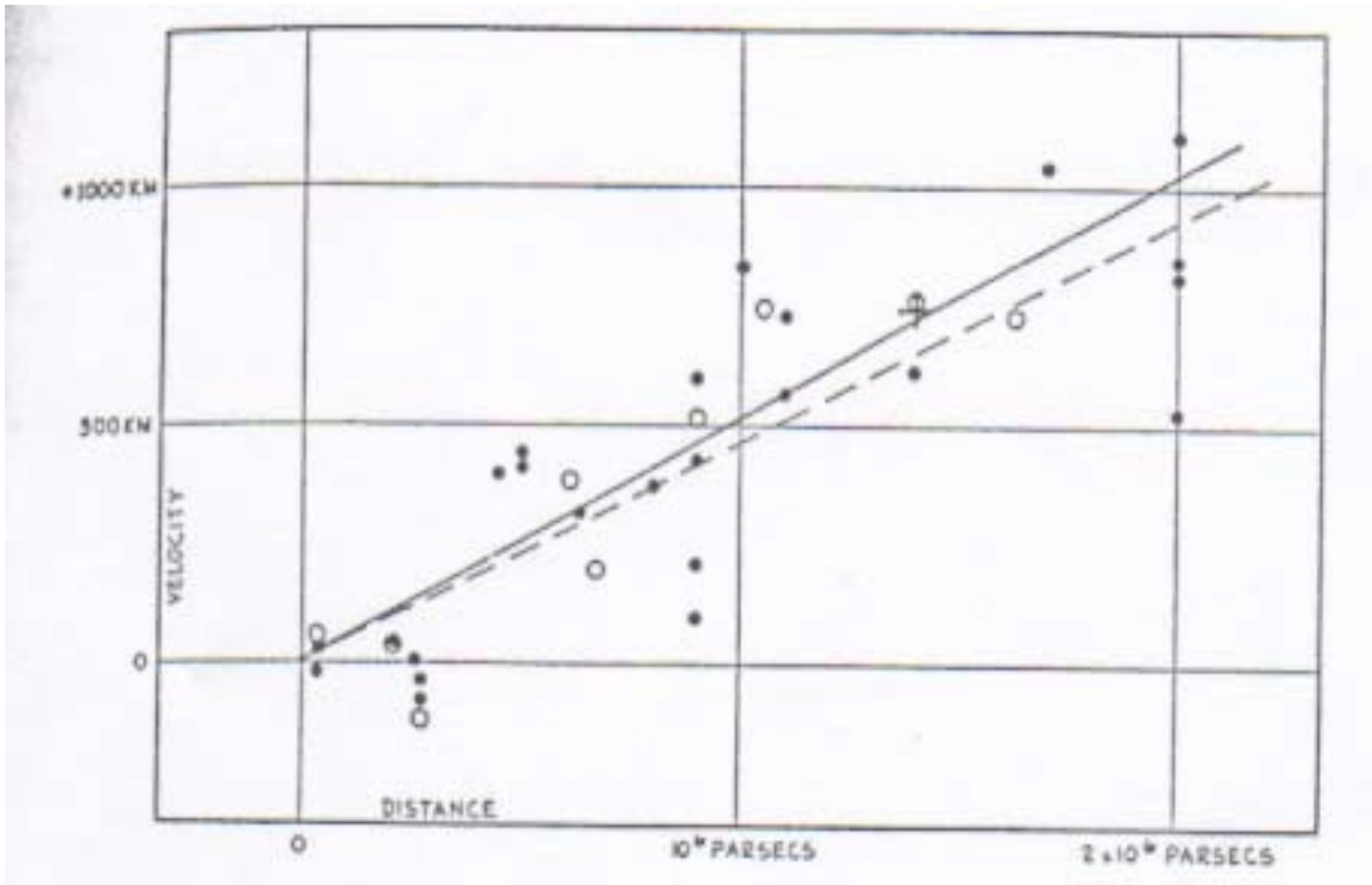
Next Rung on the Distance Ladder: Cepheids in LMC





The period-luminosity relation of Cepheids was discovered in 1908 by Henrietta Swan Leavitt in an investigation of thousands of variable stars in the LMC - now called the Leavitt Law. A year after this, Ejnar Hertzsprung measured the first parallax distance to Cepheids in the Milky Way. Sadly, due to a clerical error, it was off by 10X (too close).

The Hubble Constant - H_0



Hubble's 1929 evidence of the expansion of the universe. He looked at several nearby galaxies using velocities from Vesto Slipher's work and distances based on Cepheids. (Georges Lemaître had proposed this in 1927.)

$$v = H_0 D$$

H_0 = 500 km/s/Mpc - there were many problems with this first measurement…

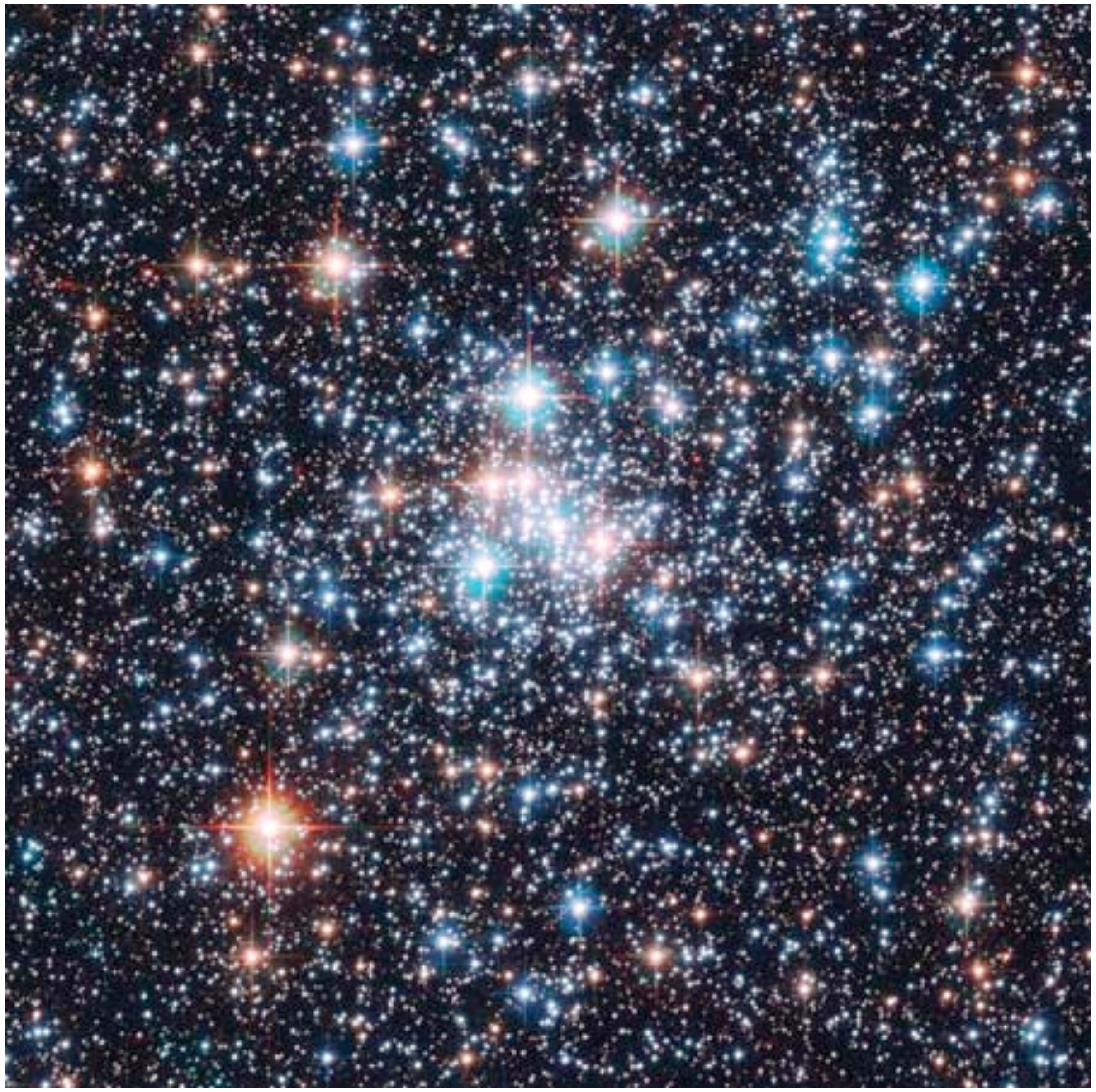
Problem 1: Age of Universe

H_0 = 500 km/s/Mpc implies

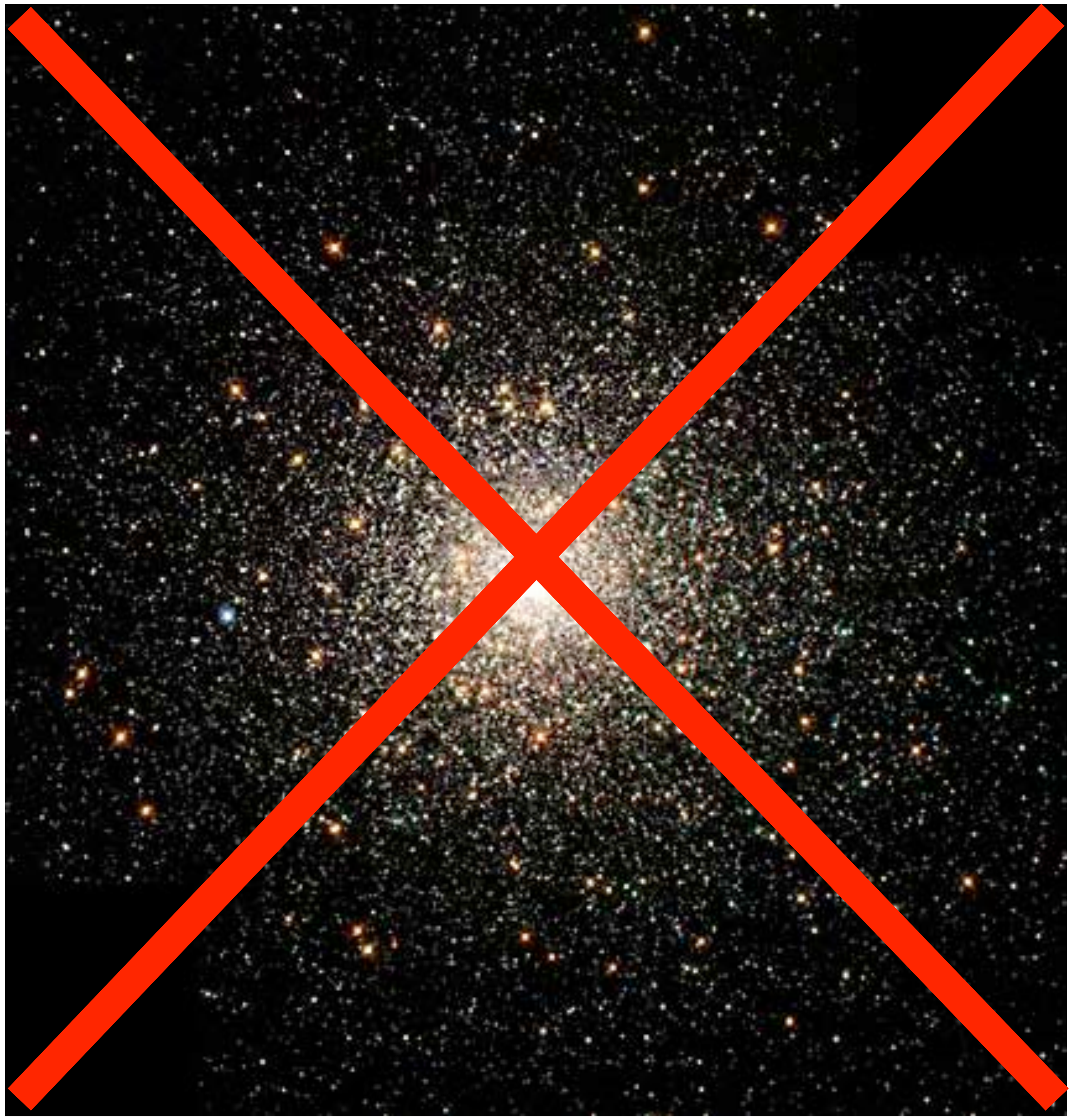
t_0 = 1/50*3.08*10^{19} seconds = 1.9 Gyr

By the early 1930's geologists knew that the earth was at least 3Gyr old.

Problem 2: More than One Type of Cepheid

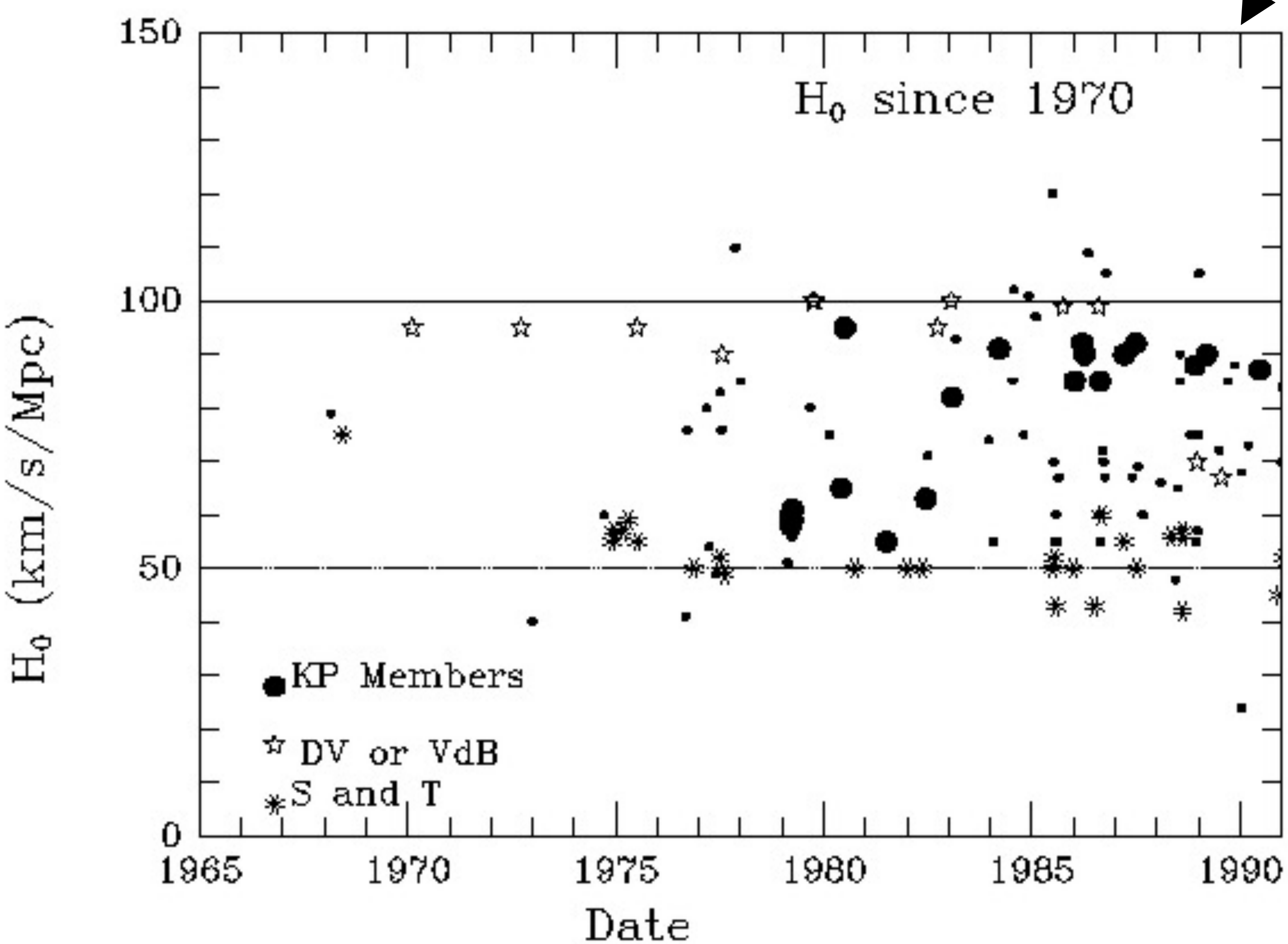


Population I



Population II

The numbers started to drop

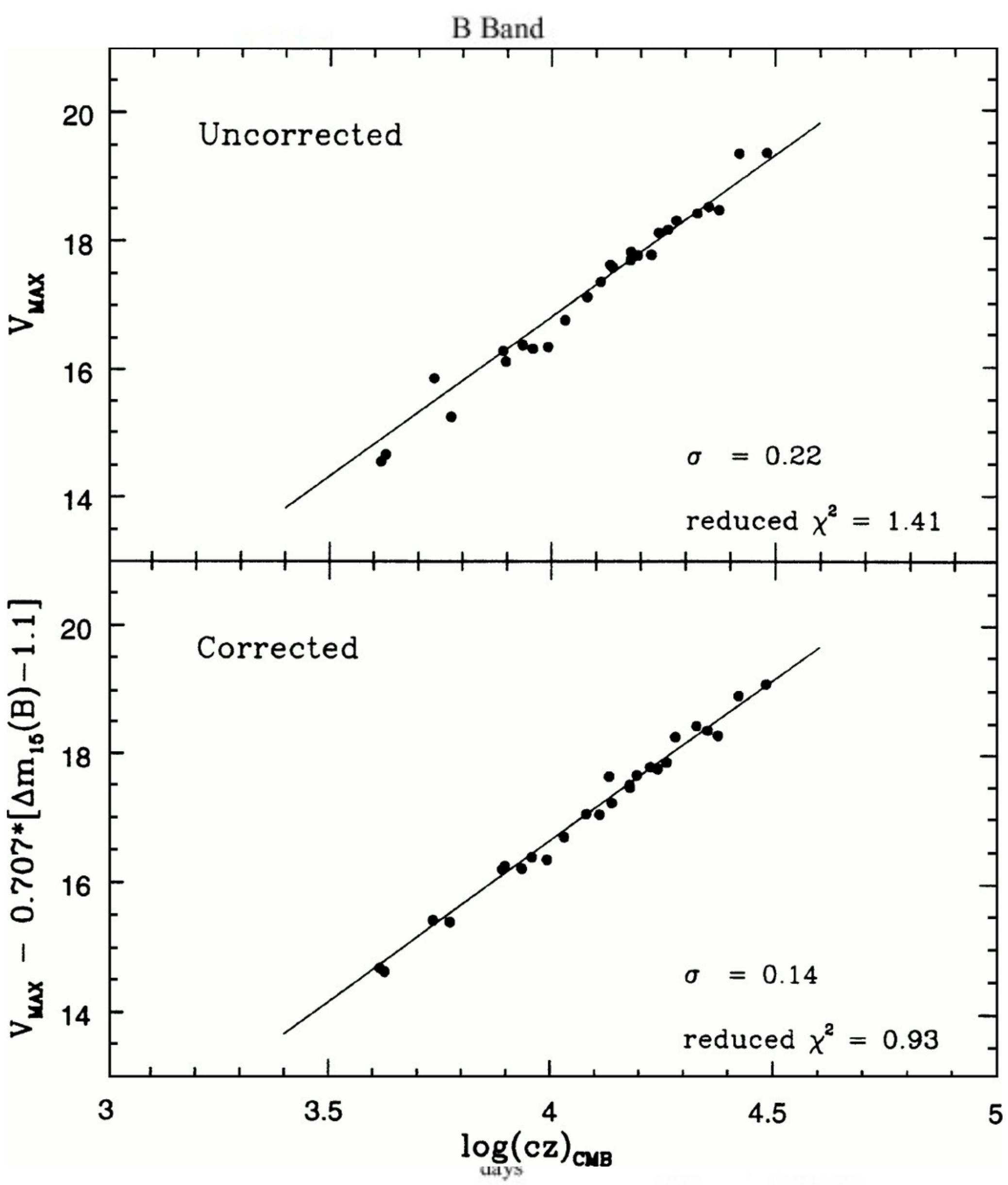


Copyright J. Huchra 2008

And this is when I entered graduate school…

Crowding, extinction, metallicity, etc. - the problems were beginning to get solved, though some differences remained.

…and supernovae got caught up in the middle of it all.



Brightness —>

Hamuy *et al.* (1996)

Time —>

In 1993 Mark Phillips discovered the correlation between peak brightness and lightcurve shape.

This allowed one to calibrate SNe Ia to about 8% in distance.

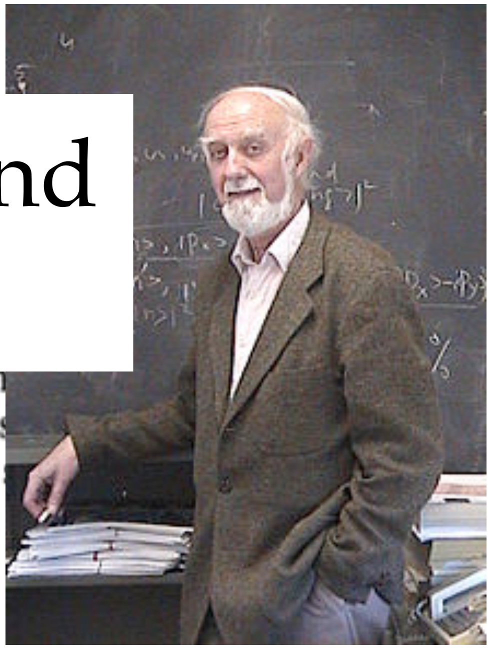
The race was on…..

…and supernovae got caught up in the middle of it all.

THE DISTANCE TO THE TYPE Ia SUPERNOVA 1972E AND ITS PARENT GALAXY NGC 5253: A PREDICTION

DAVID BRANCH, ADAM FISHER, TIBOR J. HERCZEG, DOUGLAS L. MILLER, AND PETER NUGENT
Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019
Received 1993 May 24; accepted 1993 November 9

"I should not have given your paper to Sandage and de Vaucouleurs to referee…."



A naive application of a relation between absolute magnitude and postpeak decline rate implies th
1972E was intrinsically brighter than SN 1937C and at a distance of 5.2 ± 0.6 Mpc. However, becaus
1937C and 1972E were spectroscopically normal we expect their absolute magnitudes to have been
and the NGC 5253 distance to be 4.4 ± 0.4 Mpc.

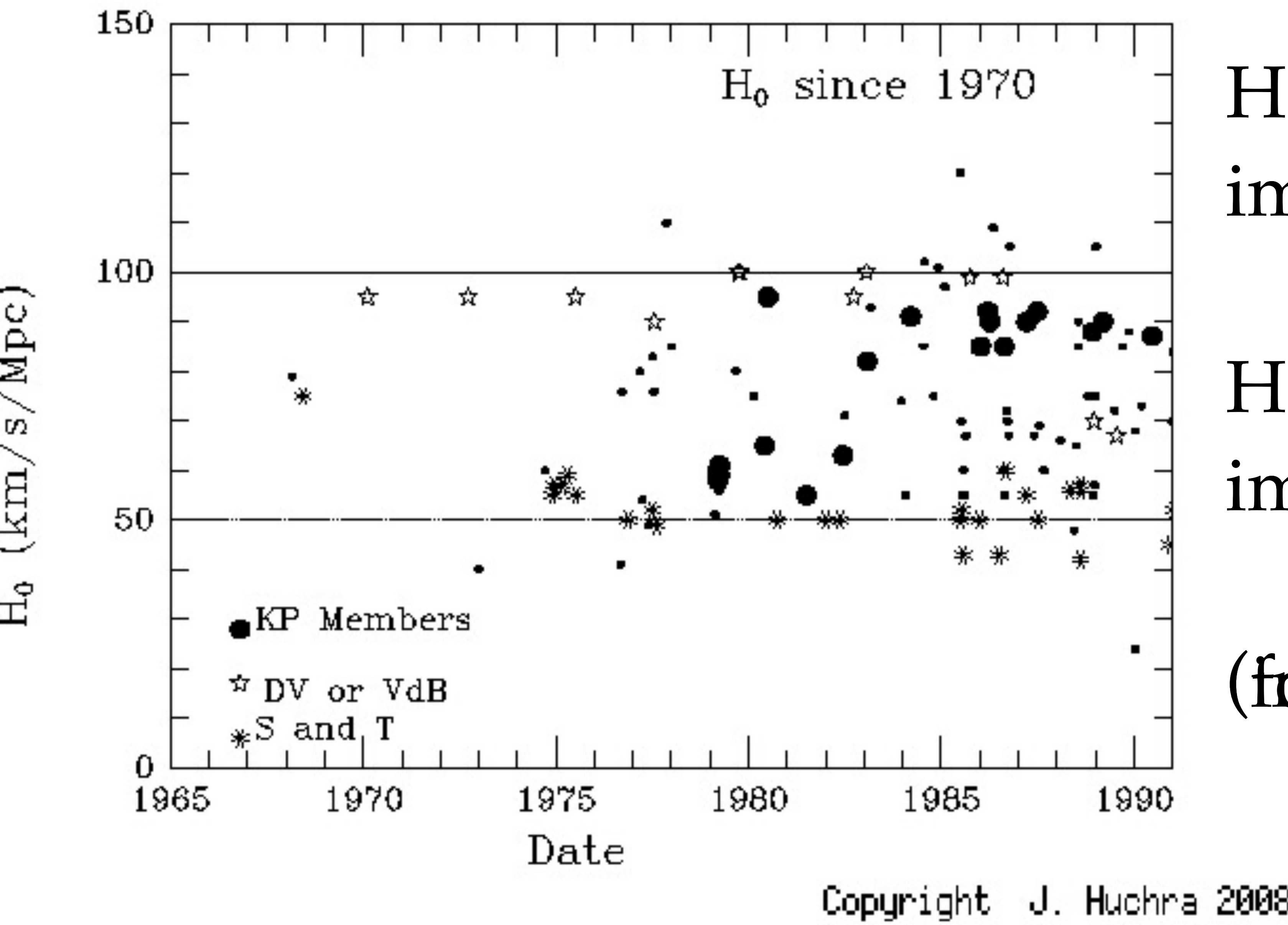
Subject headings: distance scale — galaxies: individual (IC 4182, NGC 5253) — supernovae: general — supernovae: individual (SN 1937C, SN 1972E, SN 1895B)

All we said in this letter is that the two SNe Ia were similar in sub-type, thus their distances should be captured by the difference in peak brightness… unfortunately this made us inadvertently predict H_0 of ~70 km/s/Mpc.

Referee 1: "Everyone knows H_0=100, thus this letter must be wrong."

Referee 2: "Everyone knows H_0=50, thus this letter must be wrong."

Why the fuss over H_0?



$H_0 = 50$ km/s/Mpc
implies $t_0 \sim 19$ Gyr / $t_0 \sim 13$ Gyr

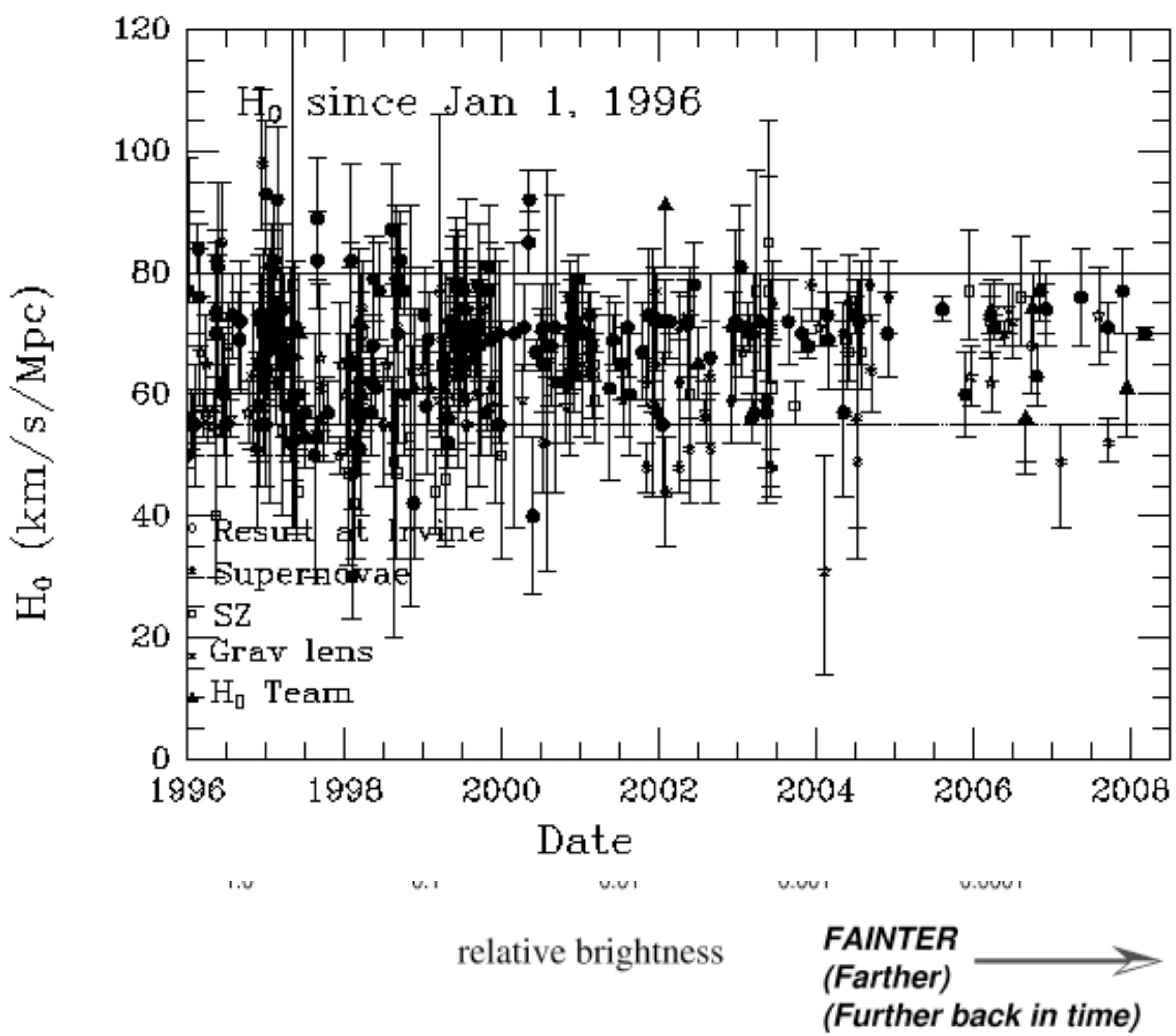
$H_0 = 100$ km/s/Mpc
implies $t_0 \sim 10$ Gyr / $t_0 \sim 7$ Gyr

(for an empty universe)
(for $\Omega_M = 1.0$ it is 2/3)

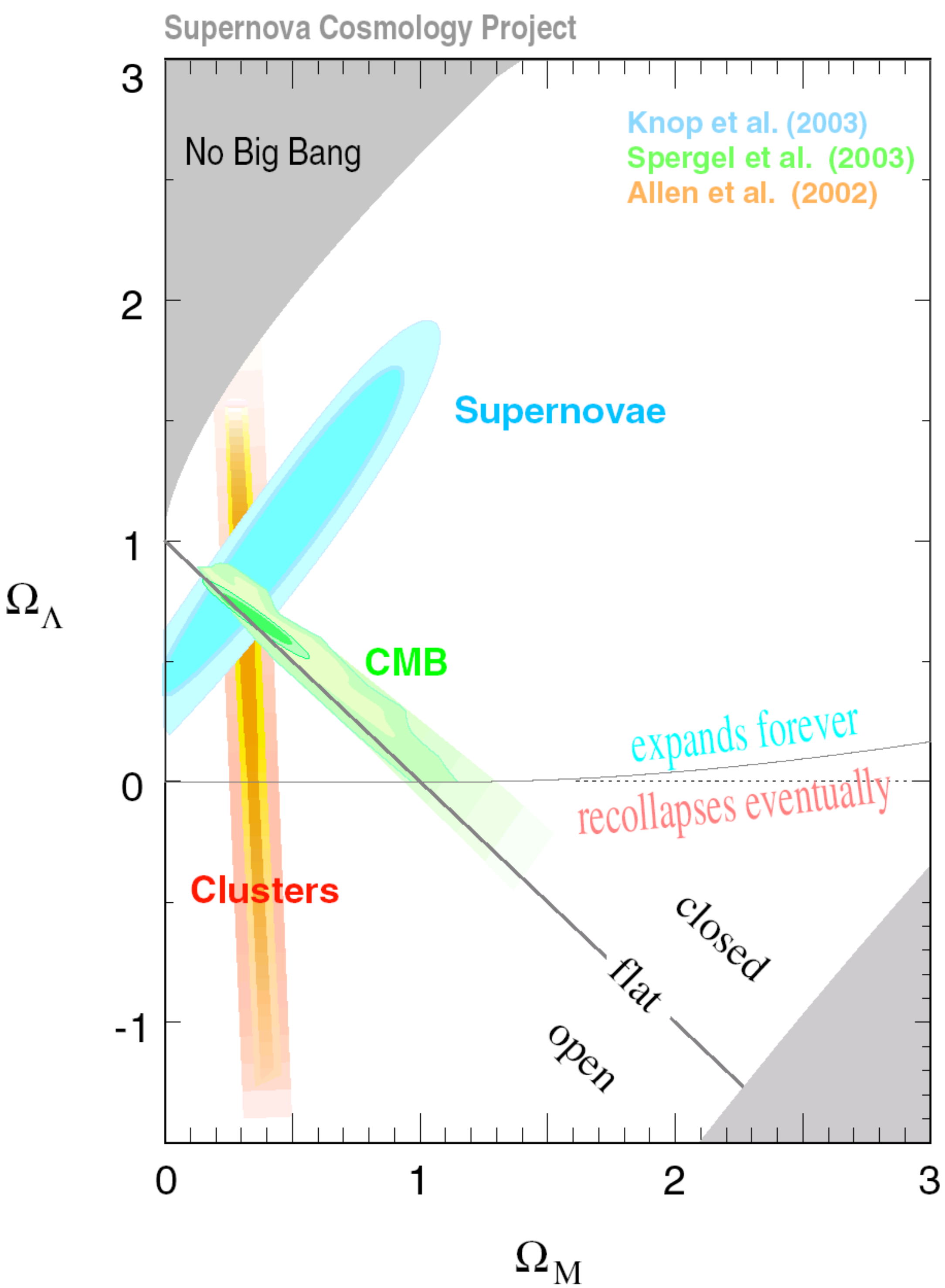
Supernovae…the solution!

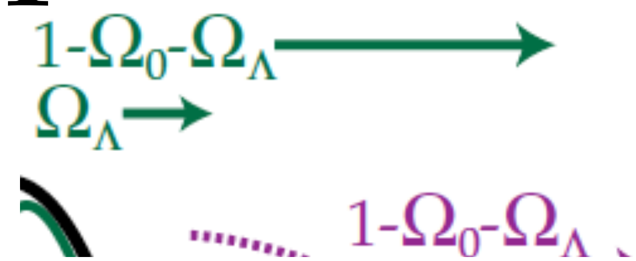
The Calan/Tololo Survey by Hamuy *et al.* pinned the low-z part of the Hubble diagram, while the work o Riess *et al.* and Perlmutter *et al.* got the high-z end.

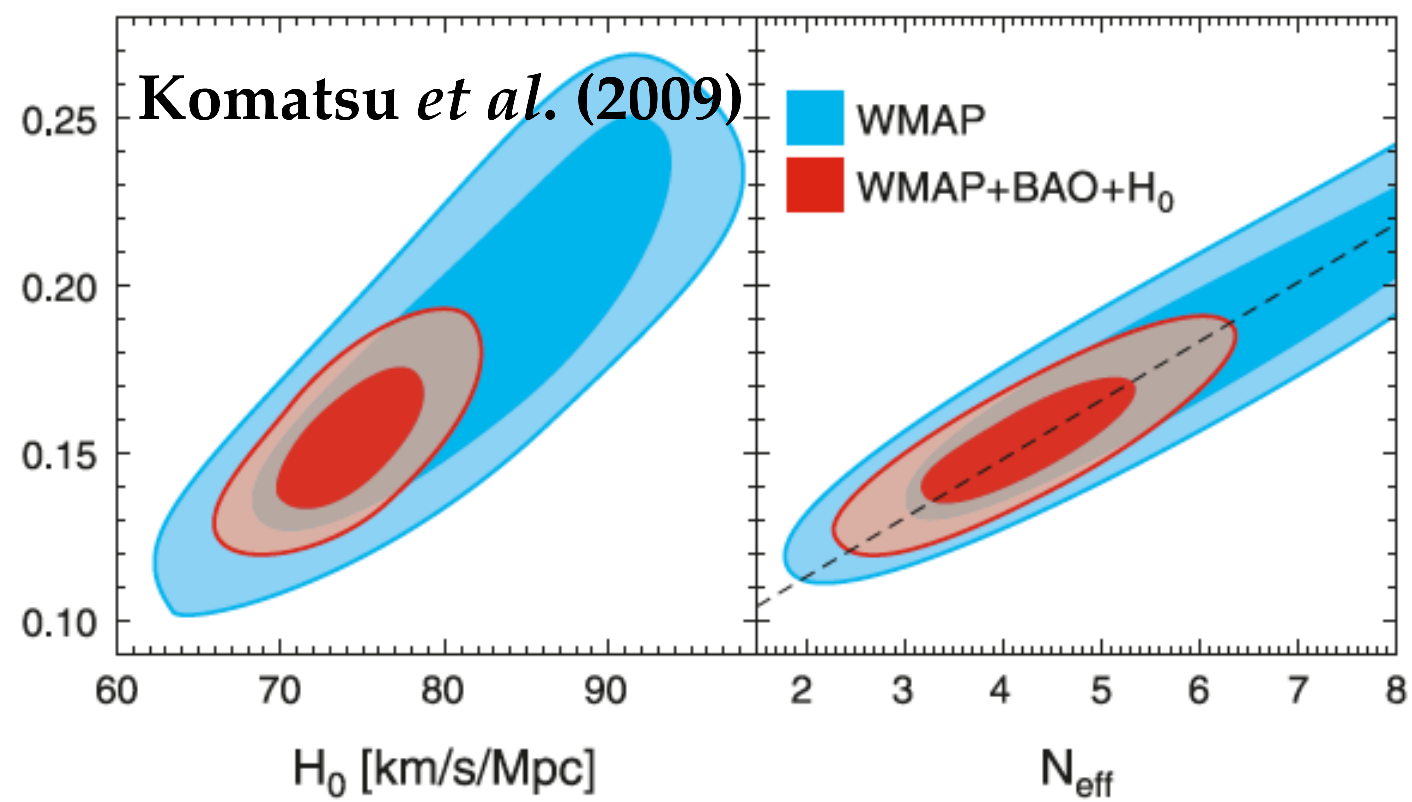
The universe was accelerating! And now there is no longer an age problem w/ H_0…

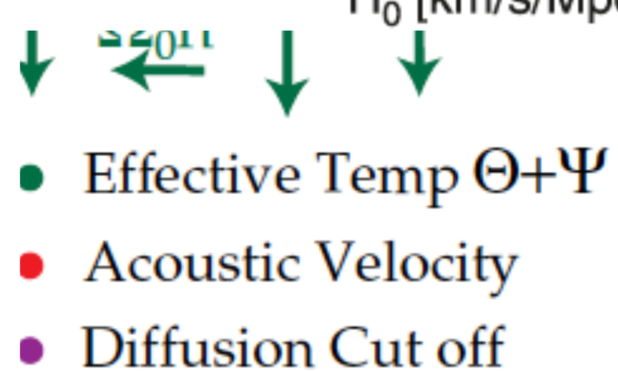


CMB & BAO start to come in to the picture…



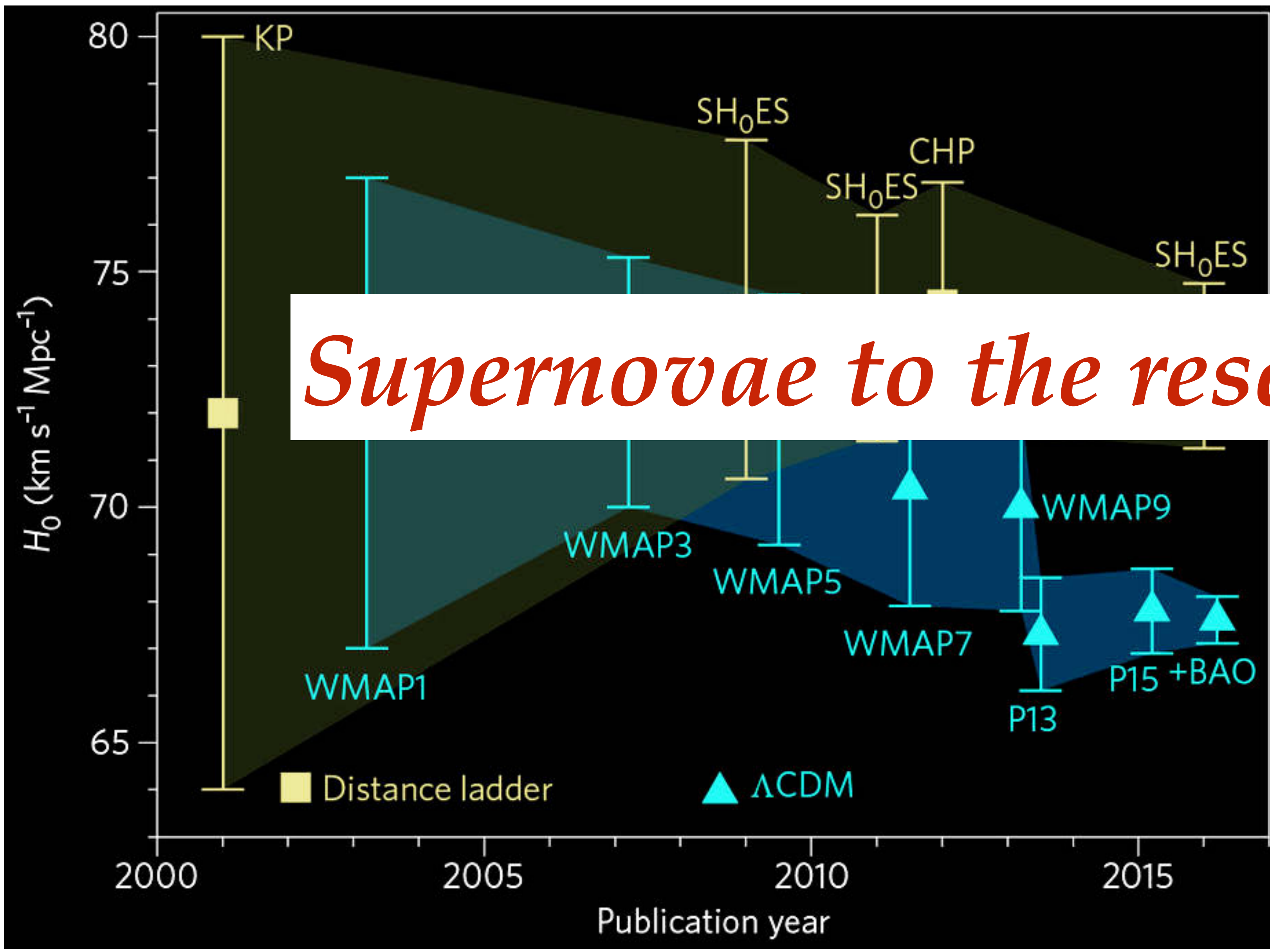






Hu, Sugiyama & Silk (1997)

Hubble Wars Revisited!



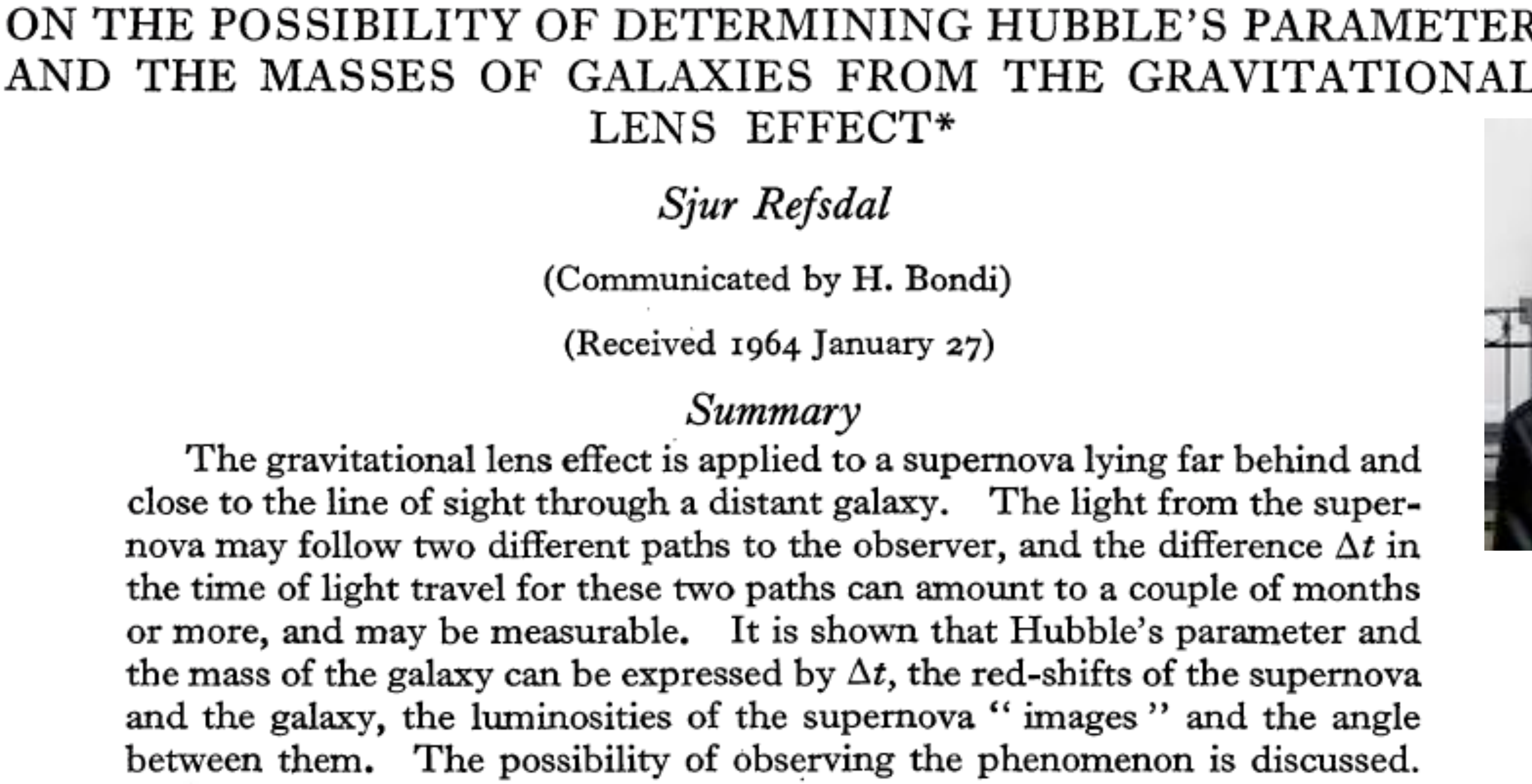
One makes a measurement at very high redshift (BAO & CMB) while the other is

heids &

Supernovae to the rescue, again….

Is it new ***physics*** or a new ***systematic*** in these measurements of H_0?

Lensed Supernovae & H_0


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

Sjur Refsdal

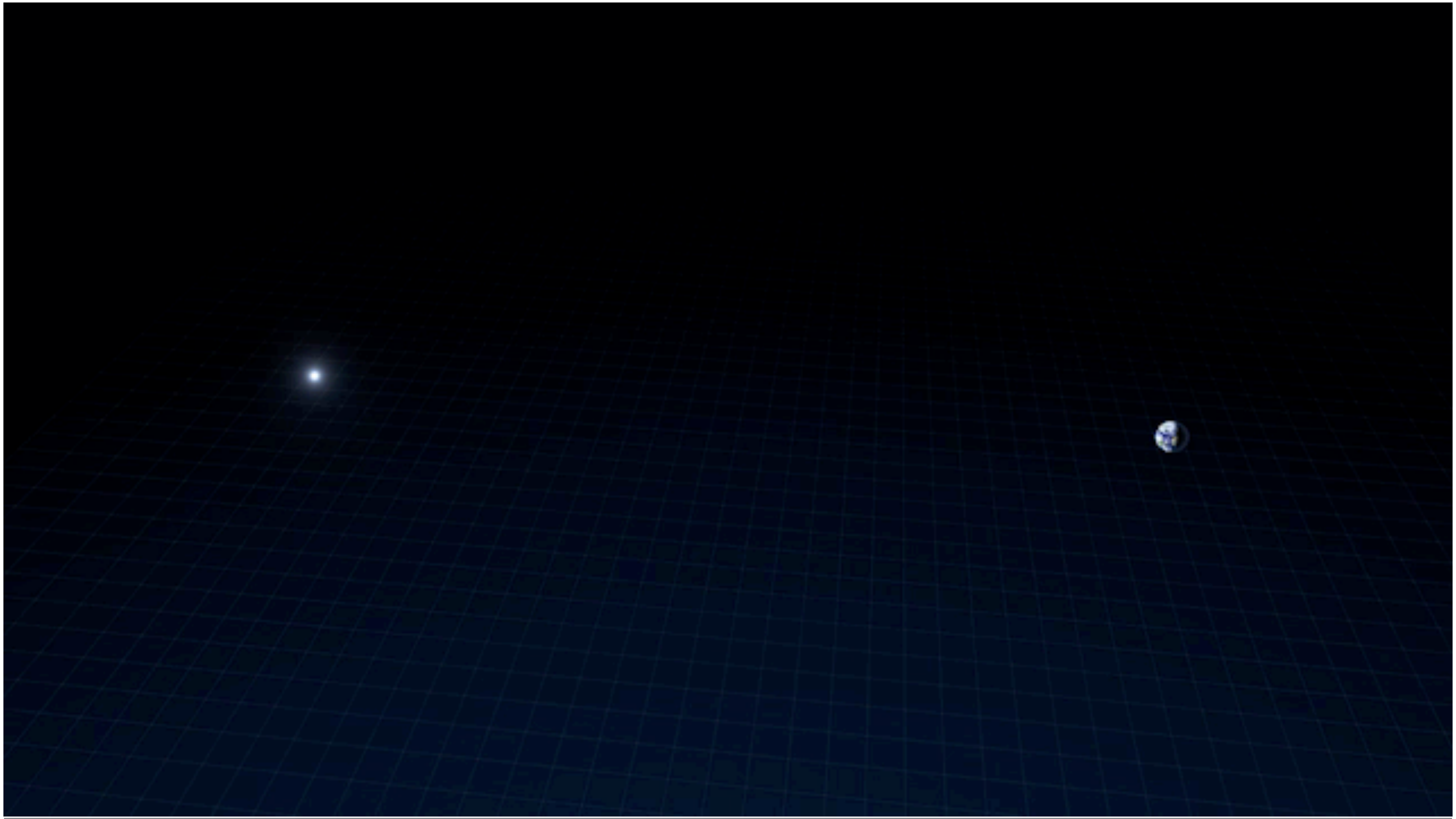
(Communicated by H. Bondi)

(Received 1964 January 27)

Summary

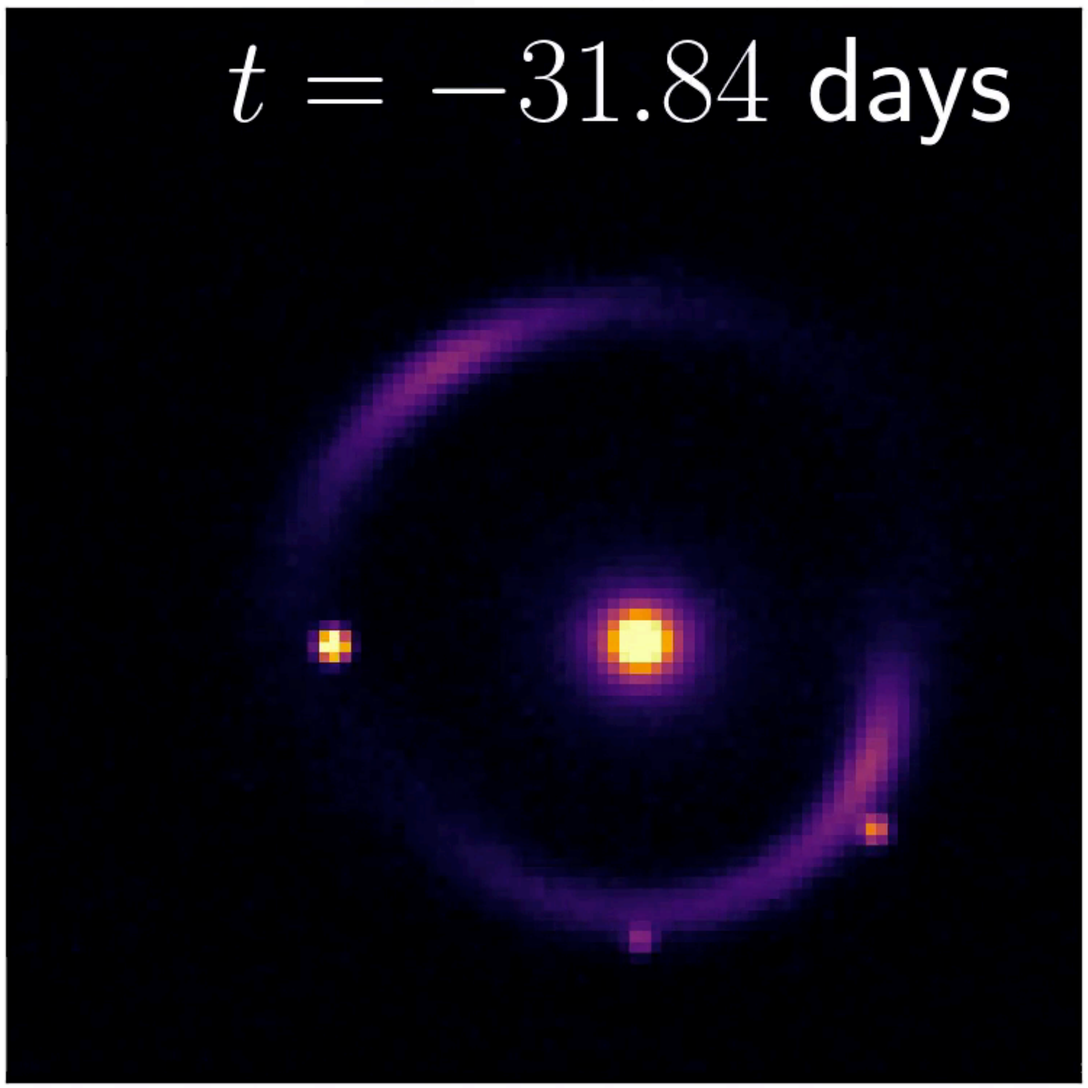
The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of 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.

Lensed Supernova



Refsdal shows that there is a time delay

simulated strongly lensed type ia supernova



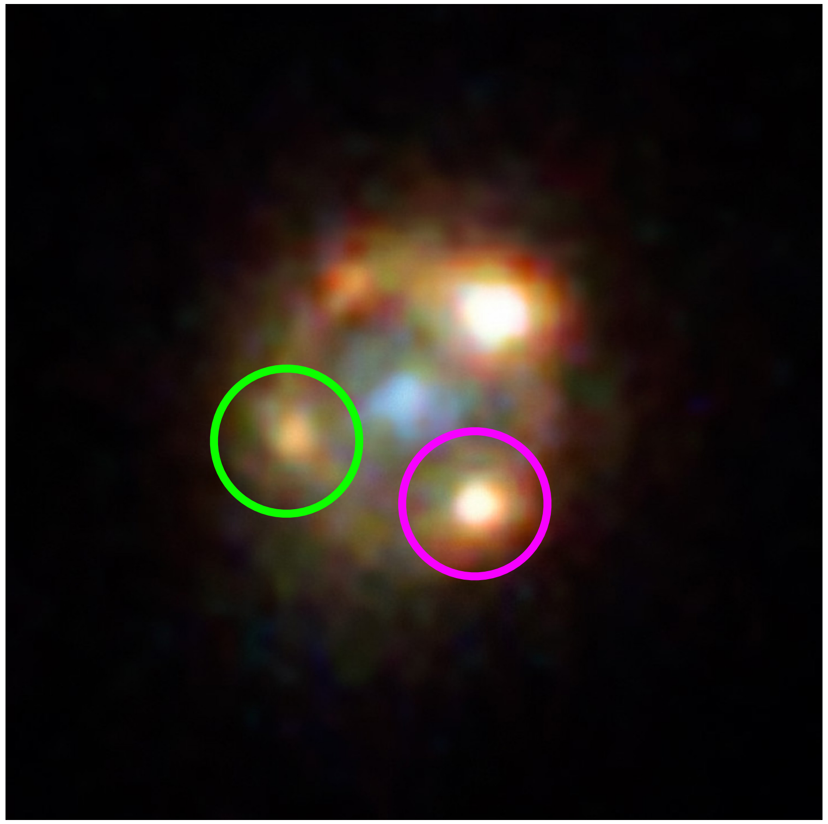
2 components:

"Shapiro Delay" - due to images traversing different gravitational potentials

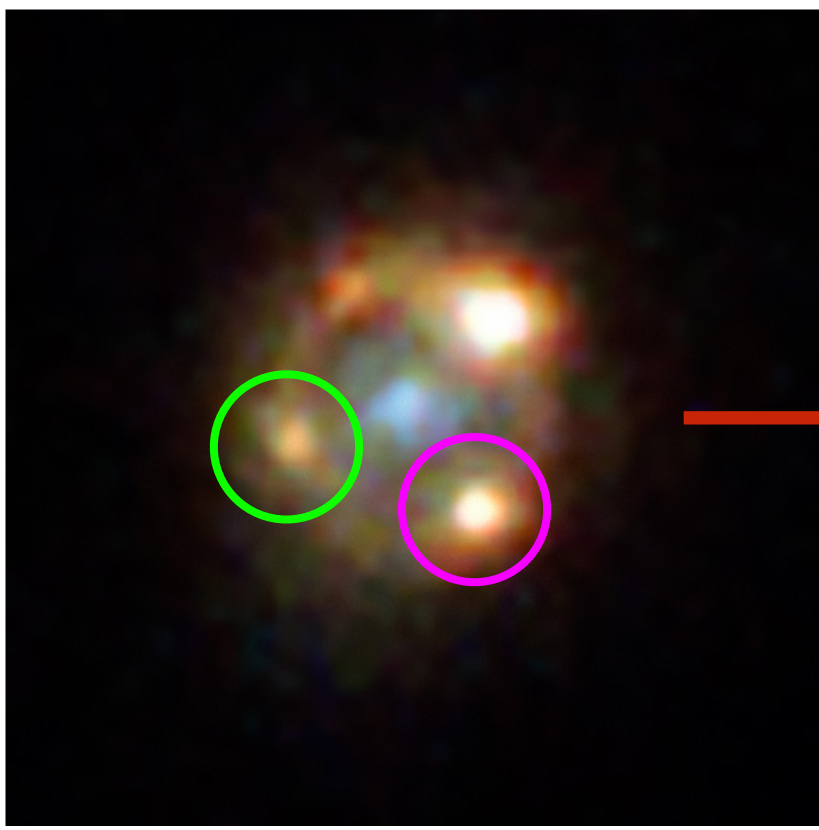
"Geometric delay" - due to images taking different paths (of different lengths) to reach us

He showed that measuring the time delays constrains H_0 geometrically

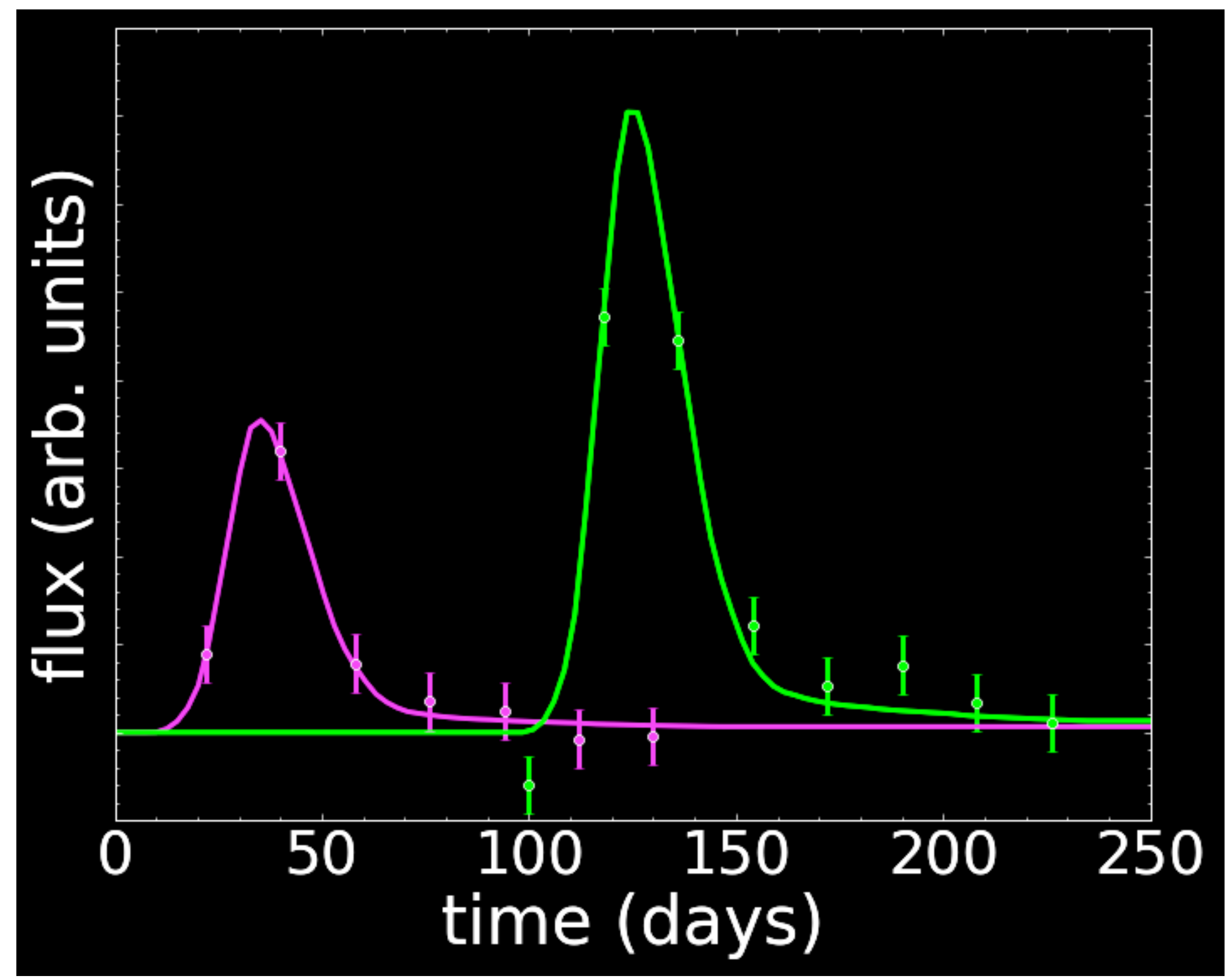
He showed that measuring the time delays constrains H_0 geometrically



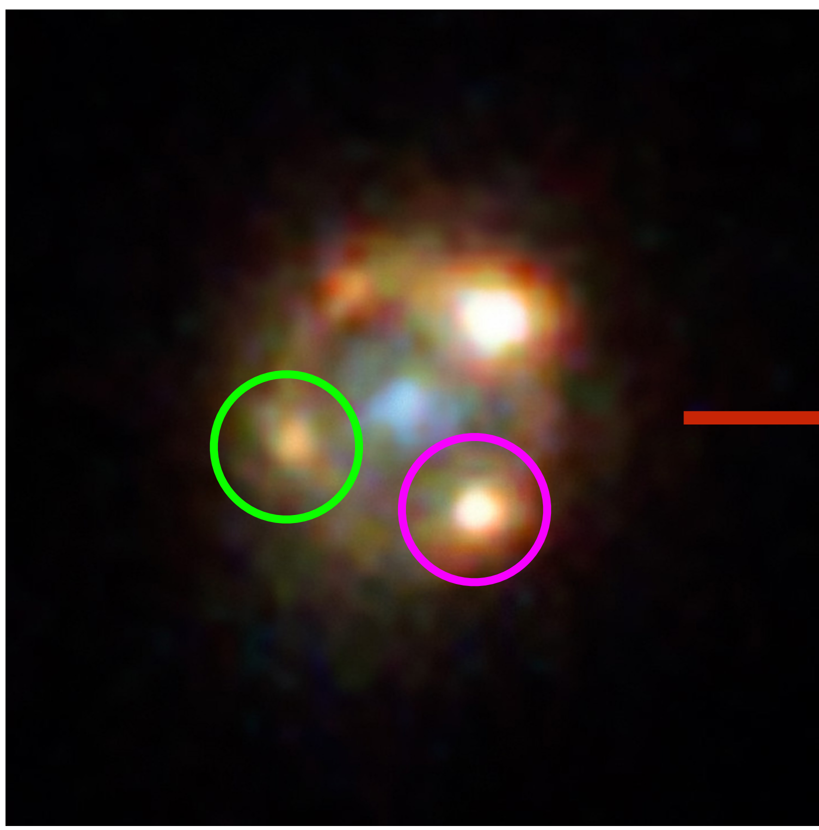
He showed that measuring the time delays constrains H_0 geometrically



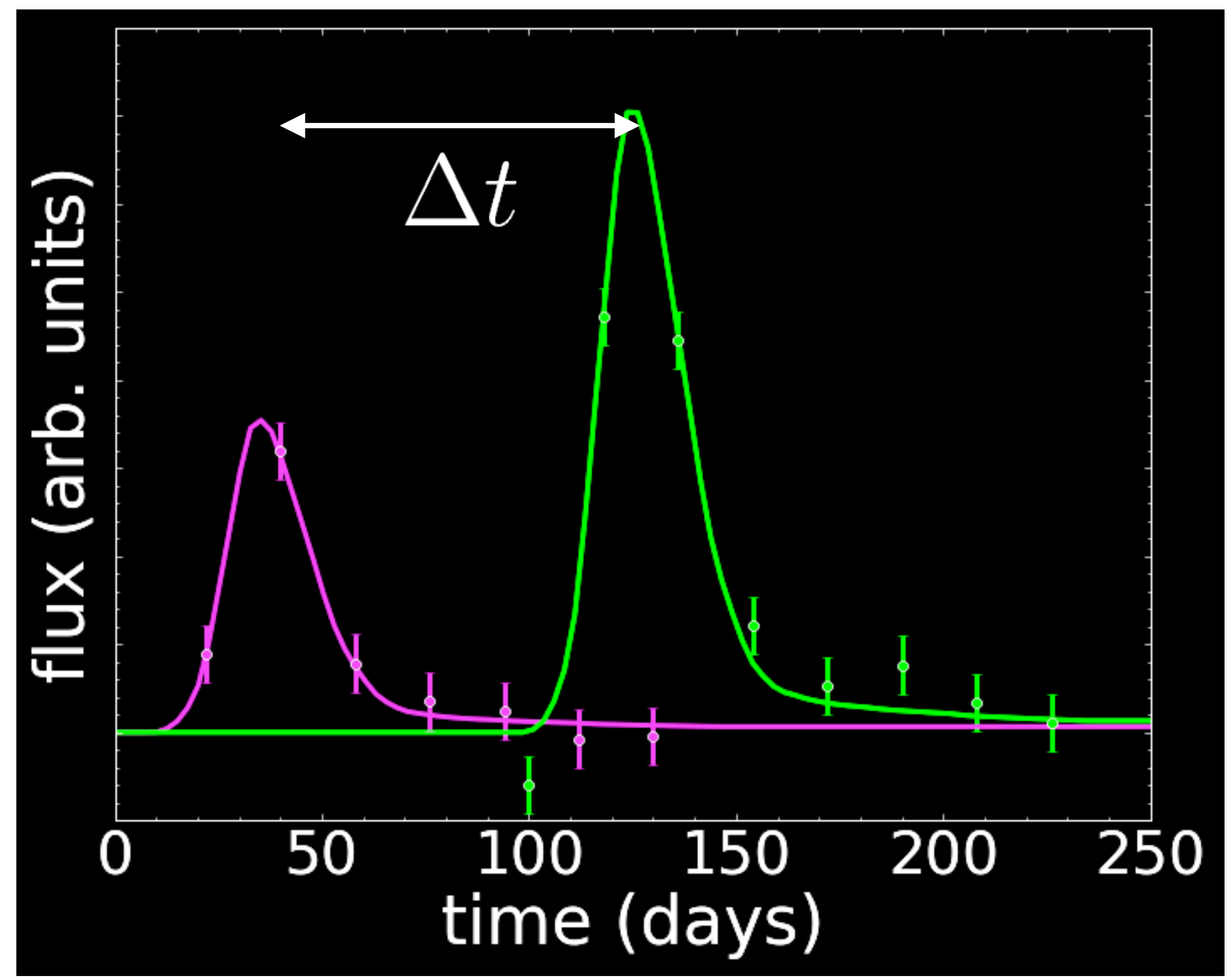
monitoring the resolved images produces light curves



He showed that measuring the time delays constrains H_0 geometrically



monitoring the resolved images produces light curves



He showed that measuring the time delays constrains H_0 geometrically

A unique cosmology distance probe

$$\Delta t \propto \frac{D_s D_l}{D_{ls}} \phi$$

Lens Potential

He showed that measuring the time delays constrains H_0 geometrically

A unique cosmology distance probe

$$\Delta t \propto \frac{D_s D_l}{D_{ls}} \phi$$

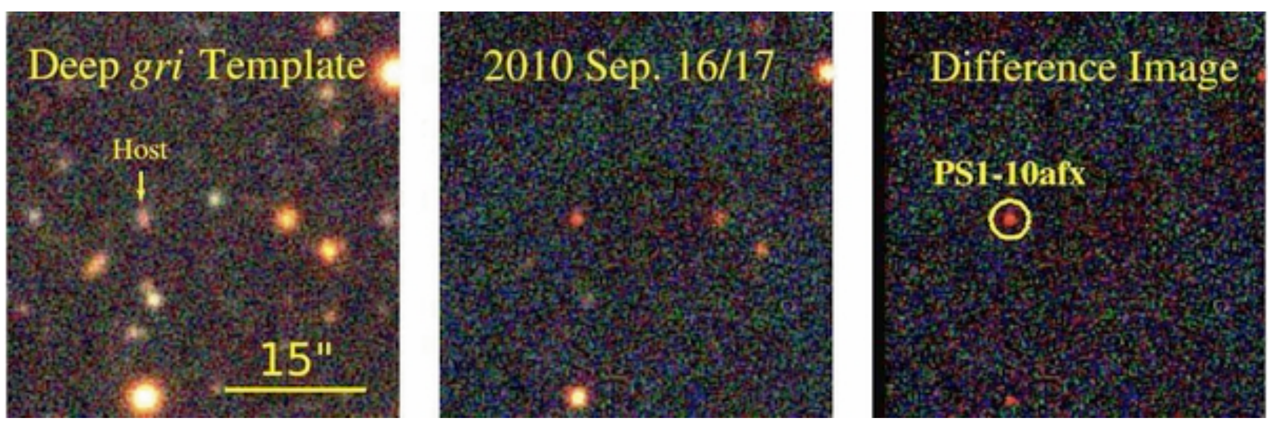
Lens Potential

$$\Rightarrow \Delta t \propto H_0^{-1} \phi$$

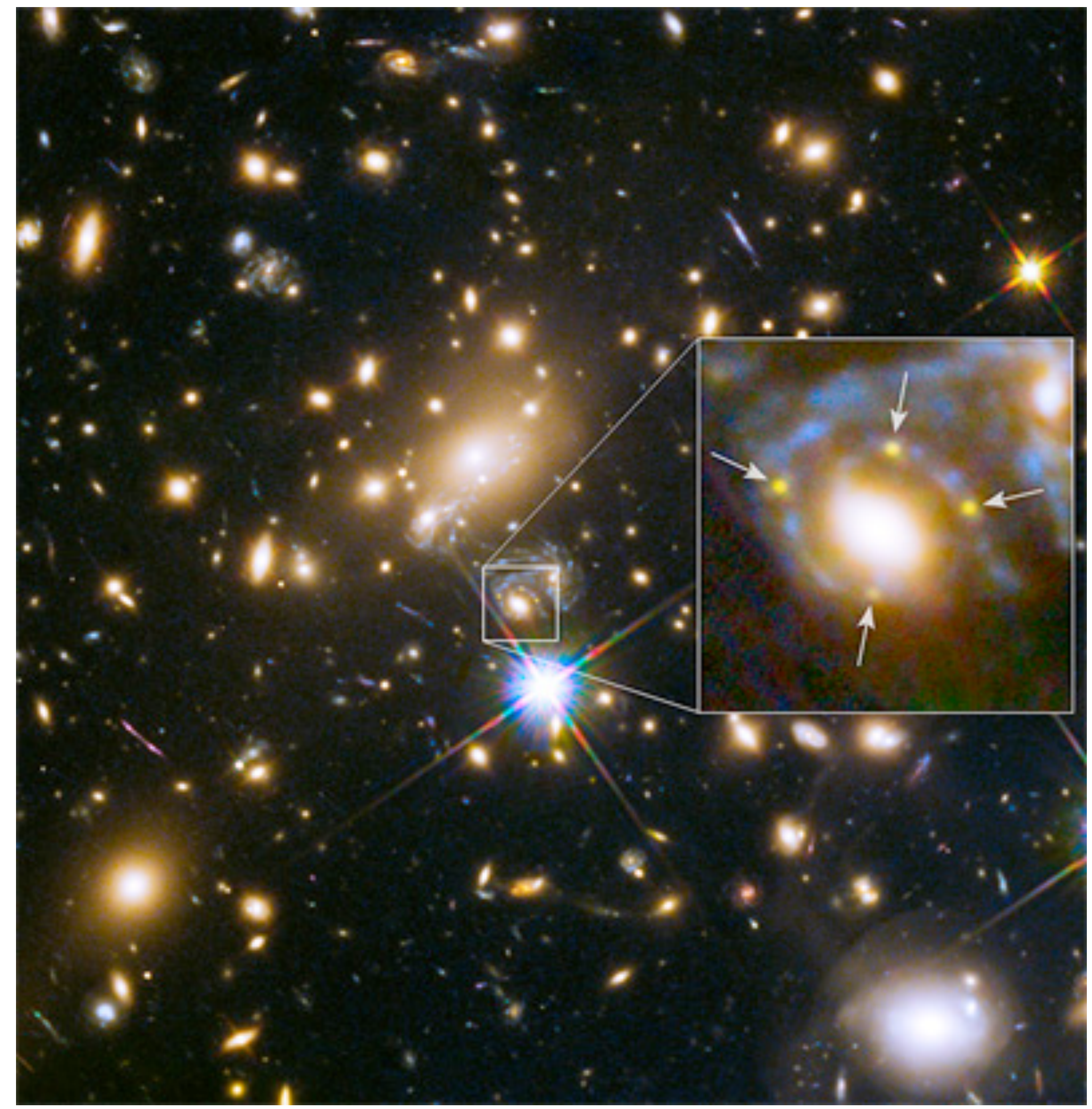
The time delays give H_0...

...up to a factor of the lens potential (Mass-sheet degeneracy).

Unfortunately we haven't found many of these (where were you in the 1990's?)



PS1-10afx – SN Ia (Quimby+ 2013) , but originally thought to be a funky core-collapse SN (Chornock+ 2013). No lens observations…

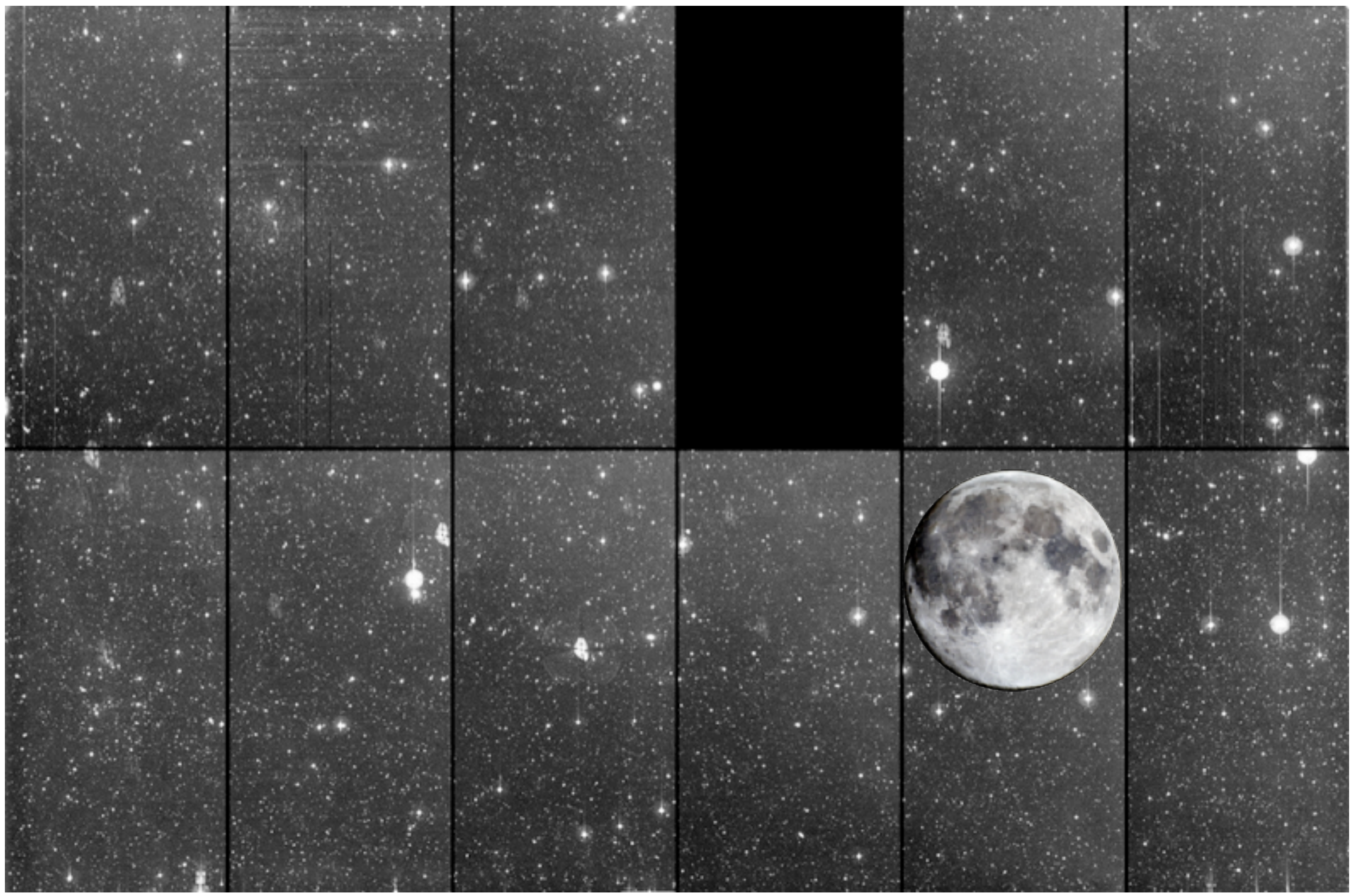


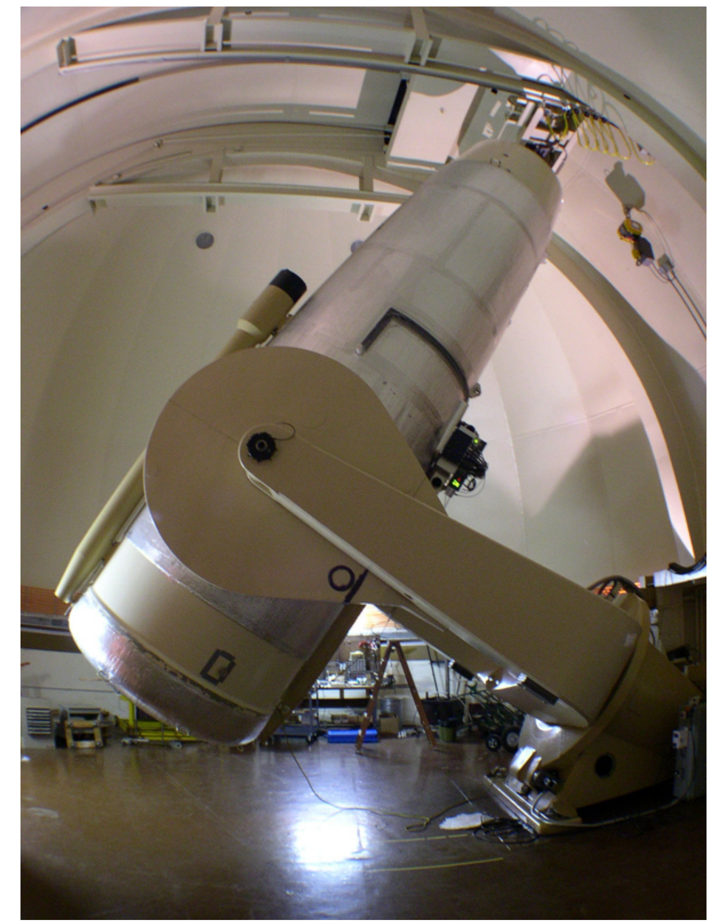
SN Refsdal – core collapse SN (Kelly+ 2015)
Can only be seen w/ HST at R~24 mag.

PTF & iPTF

Instrumentation, system design, first results	Law, et al. 2009, PASP 121 1395L
Science plans	Rau, et al. 2009, PASP 121 1334R
Detection Pipeline	Cao, Nugent & Kasliwal 2016, PASP 128 4502C

PTF Camera



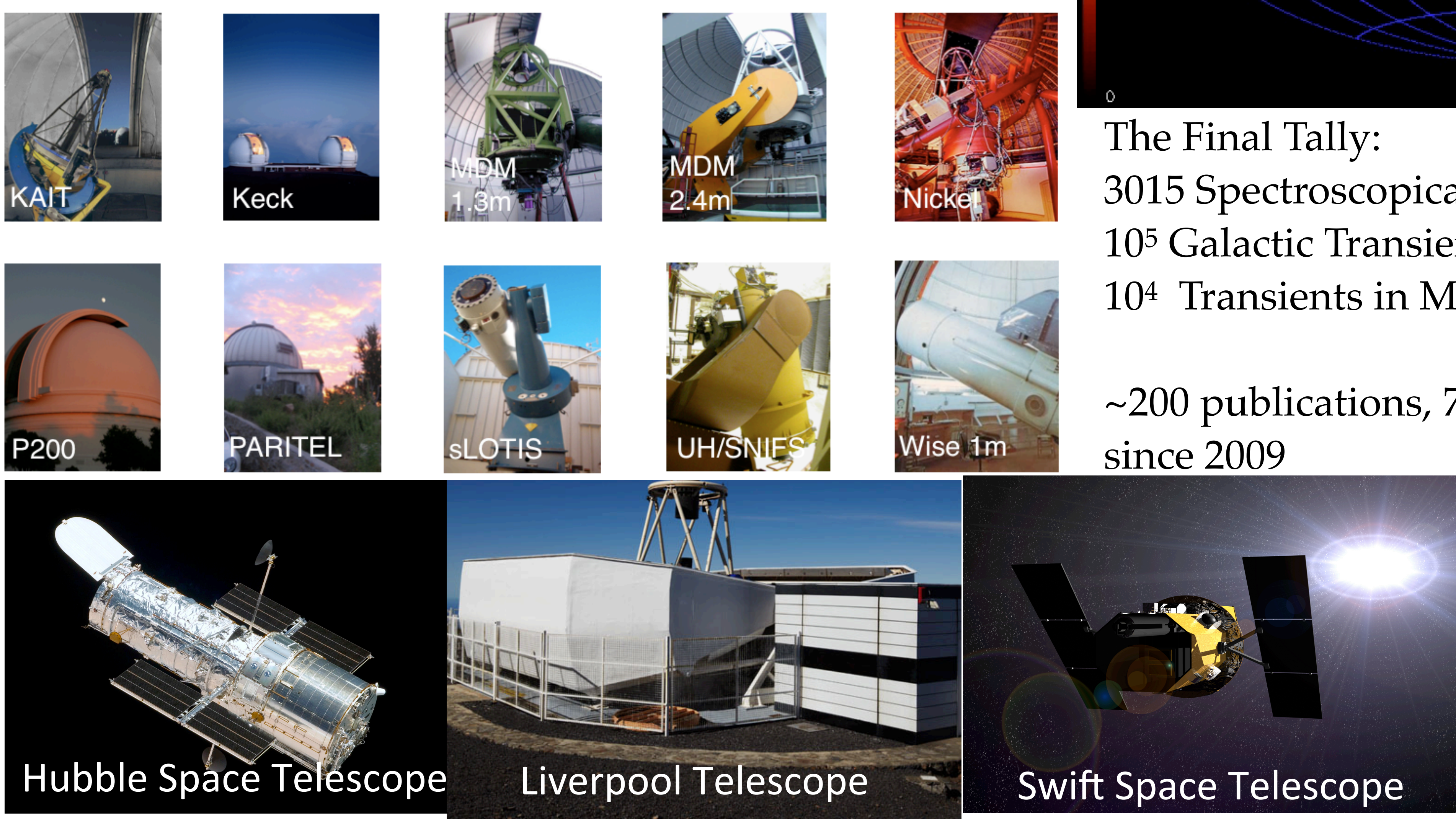


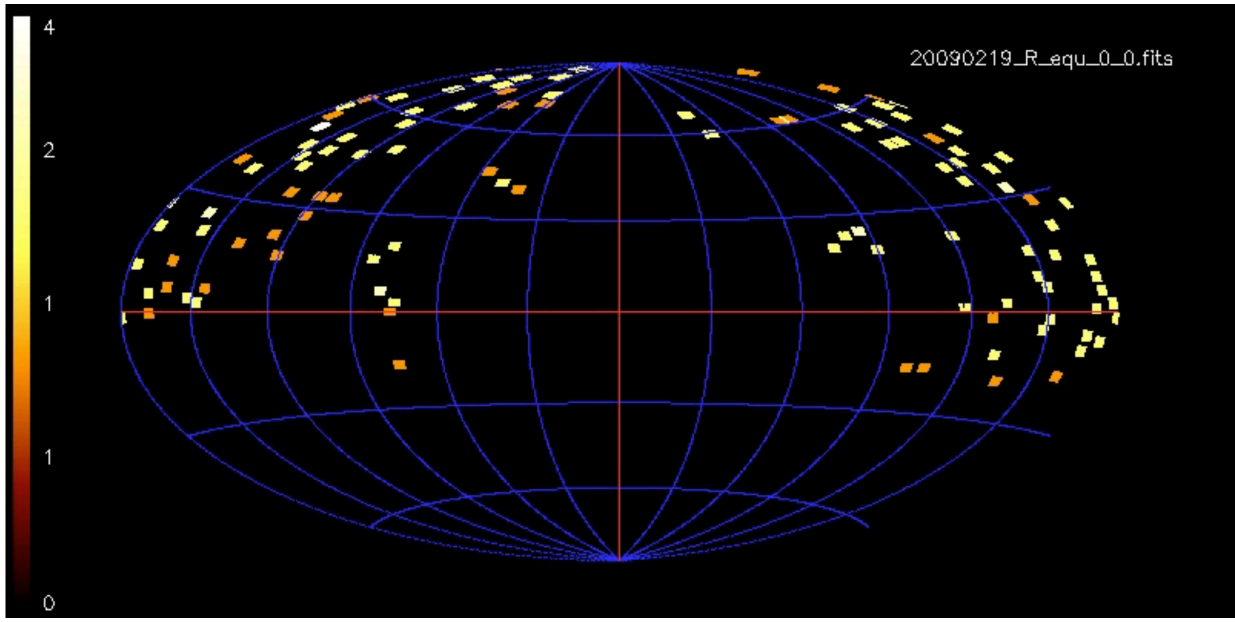
92 Mpixels, 1″ resolution, R=21 in 60s with a fov = 7.26 sq.deg.

Open every night, rolling on ~800 sq. deg. each night save for 5 nights around full moon when we conduct an H-alpha survey.

PTF & iPTF Science

▼▶ Detected transients will be followed up using a wide variety of optical and IR, photometric and spectroscopic followup facilities.





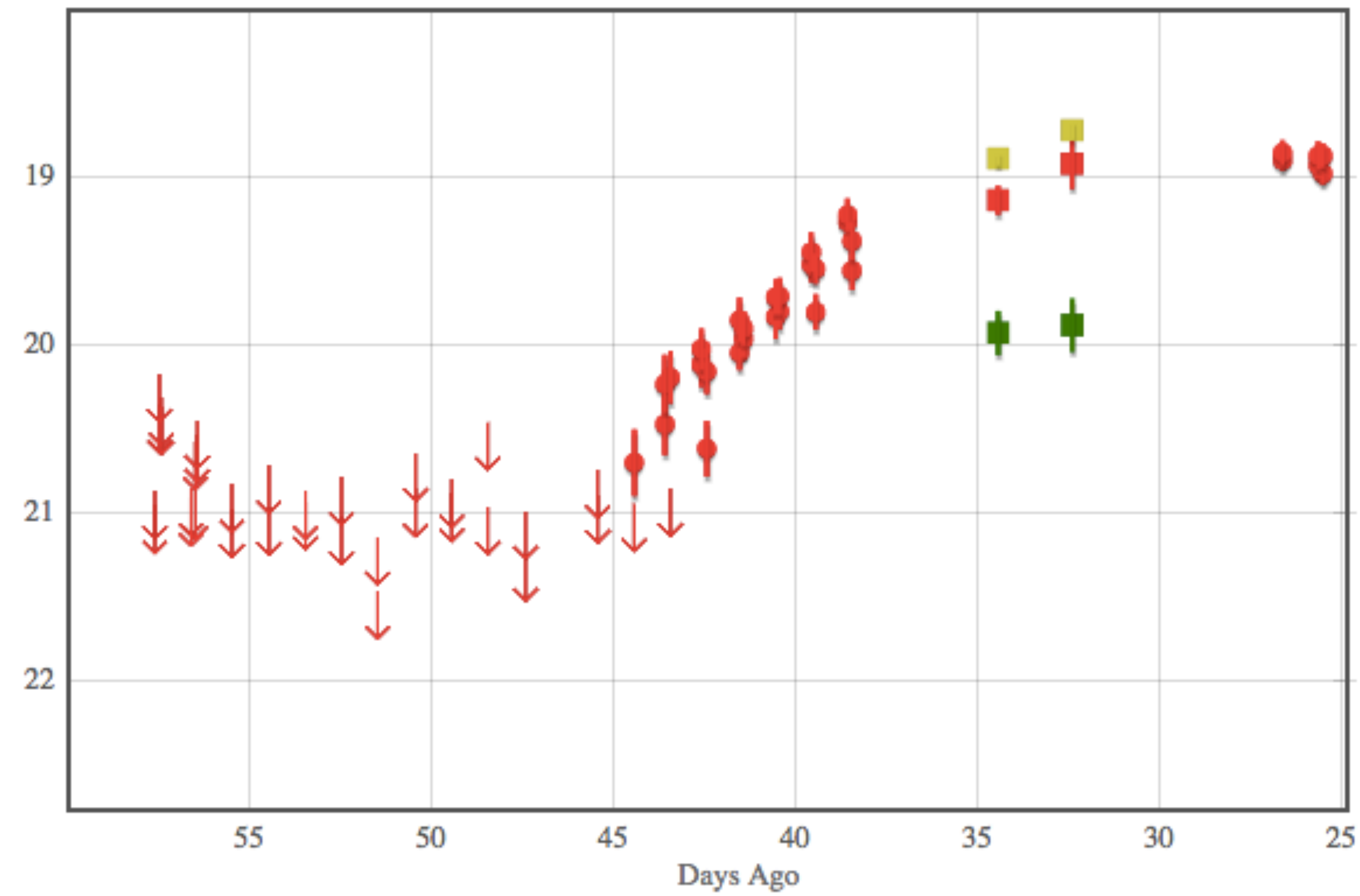
The Final Tally:
3015 Spectroscopically typed supernovae
10^5 Galactic Transients
10^4 Transients in M31

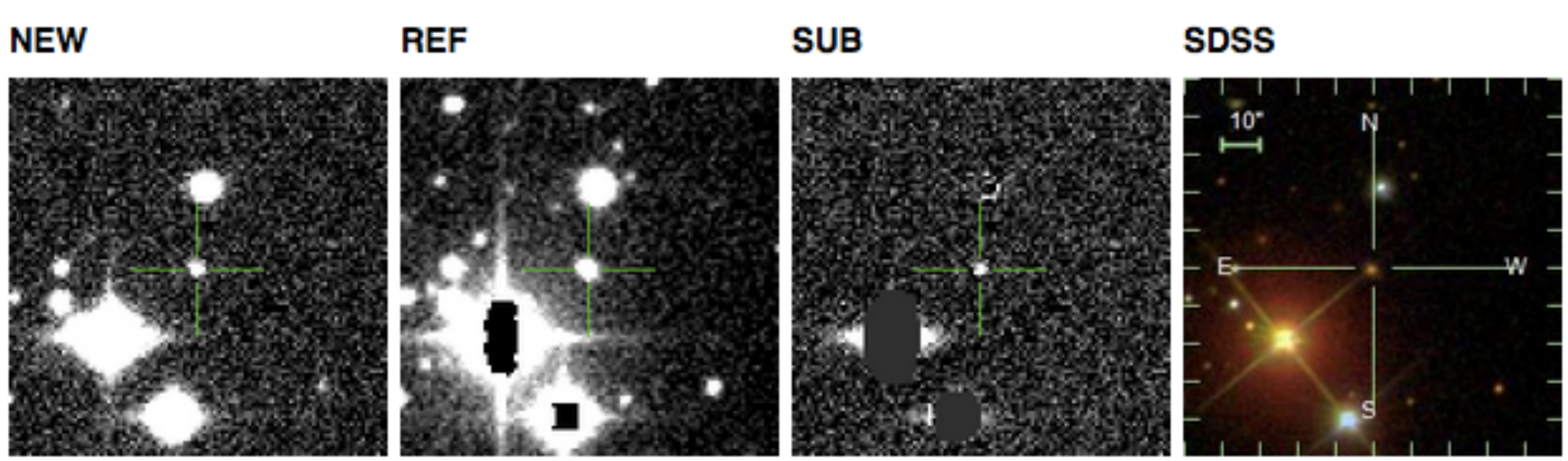
~200 publications, 7 in *Nature* and 3 in *Science* since 2009

iPTF16geu

The original onset of the transient was ***not*** awe inspiring.

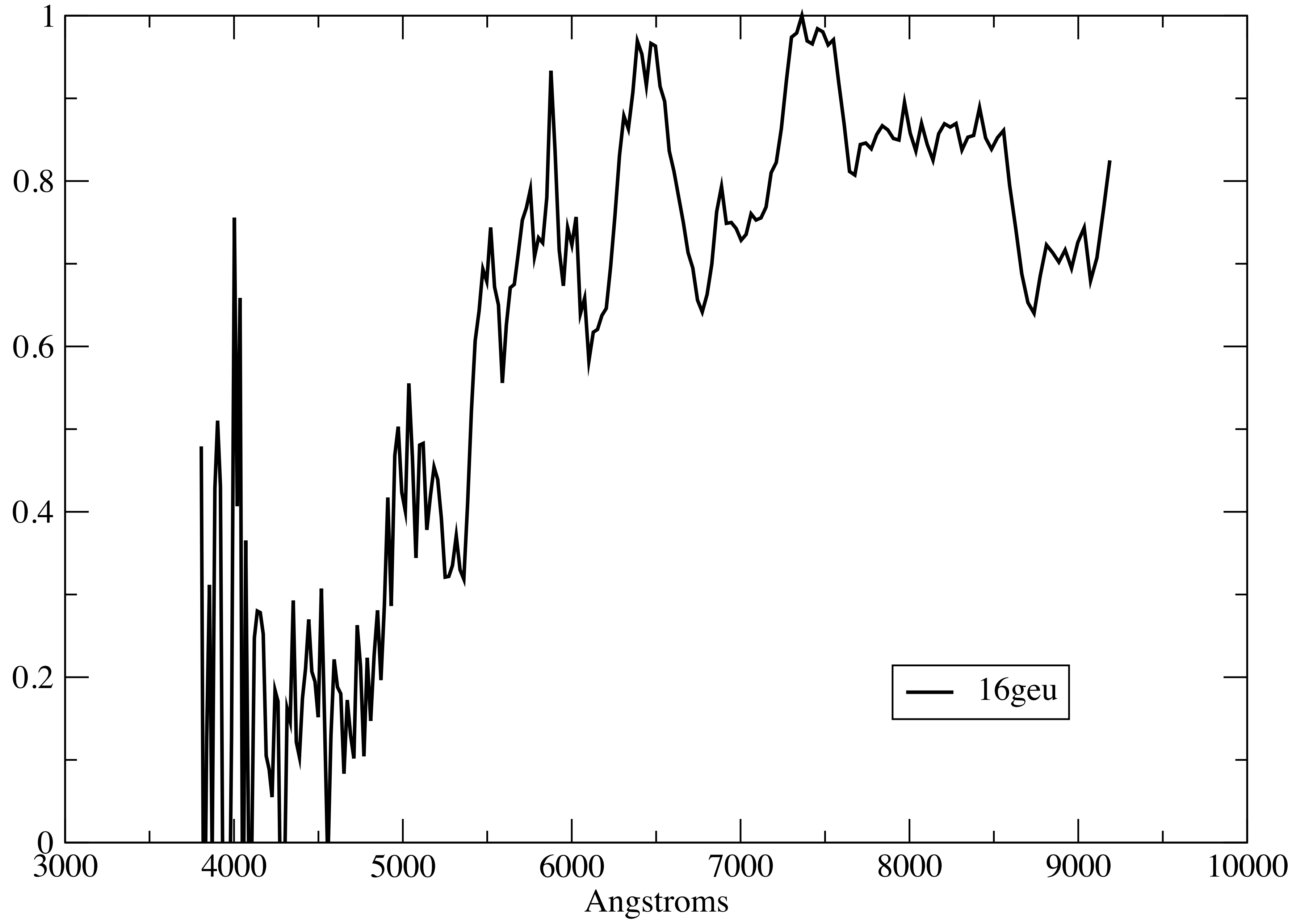
Typical rise and brightness for a z~0.1 SN Ia – about the maximum redshift we find SNe Ia.





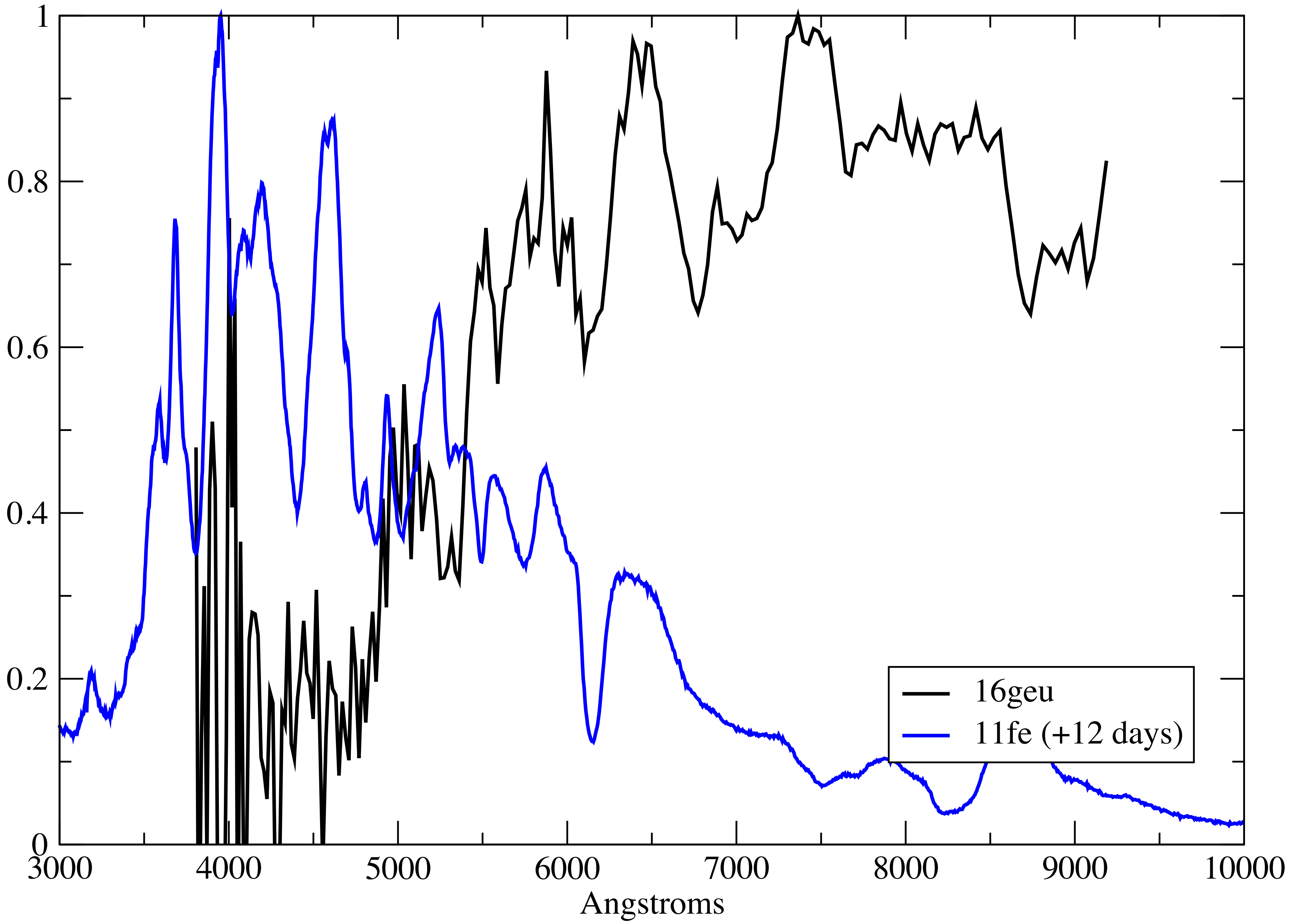
iPTF16geu

However, after it hit 19th magnitude it was bright enough to get a spectrum from the SED-Machine. And this threw us for a loop…



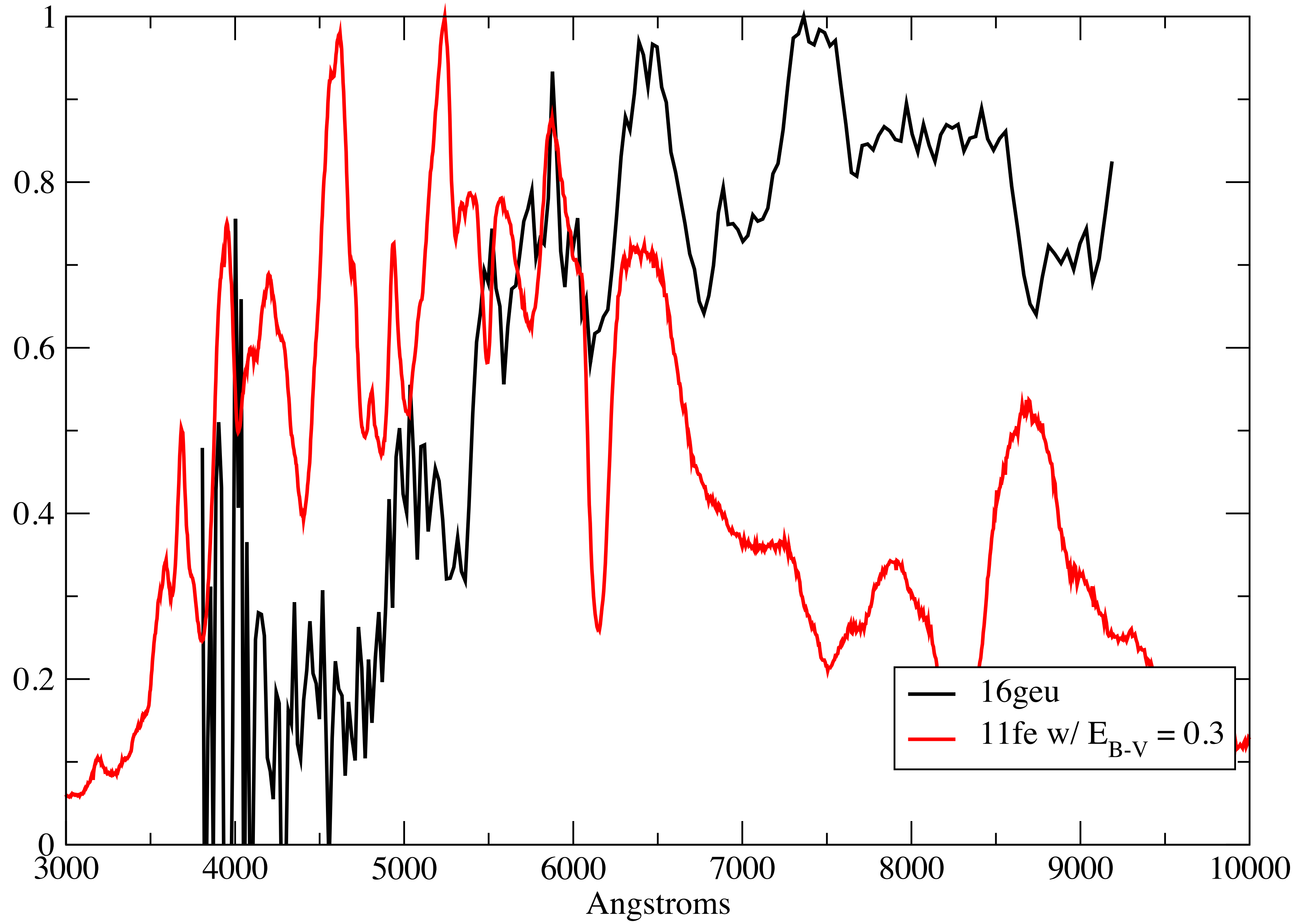
iPTF16geu

However, after it hit 19th magnitude it was bright enough to get a spectrum from the SED-Machine. And this threw us for a loop…



iPTF16geu

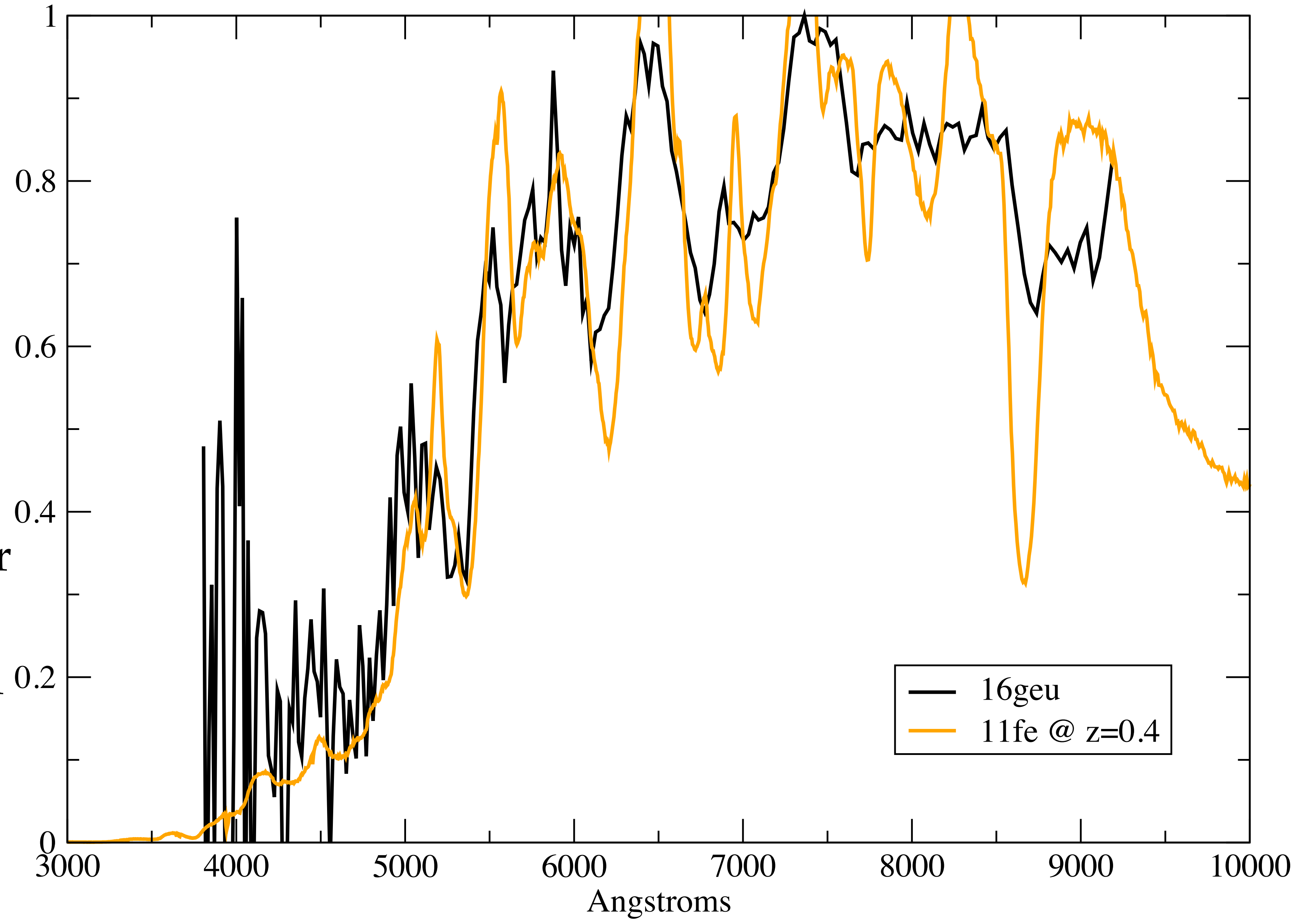
However, after it hit 19th magnitude it was bright enough to get a spectrum from the SED-Machine. And this threw us for a loop…



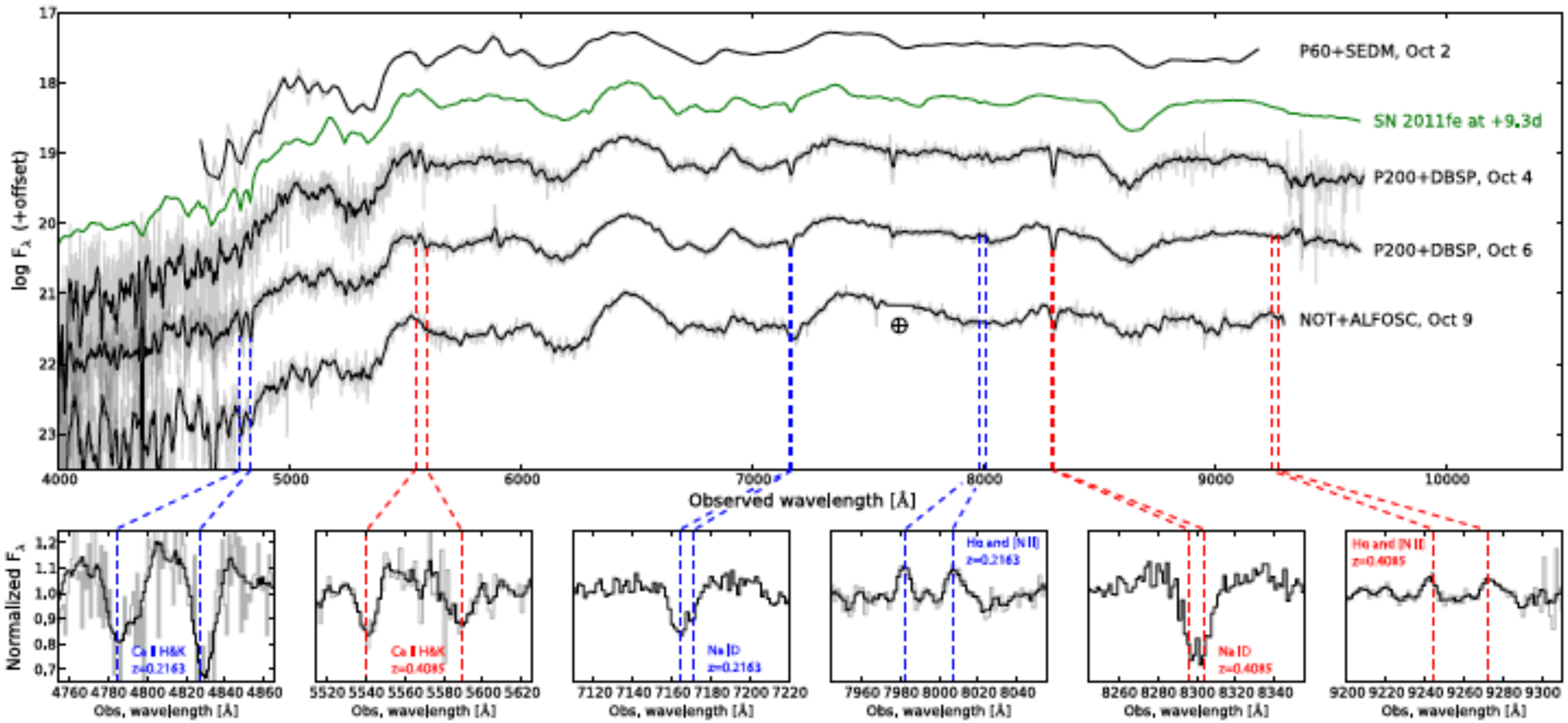
iPTF16geu

However, after it hit 19th magnitude it was bright enough to get a spectrum from the SED-Machine. And this threw us for a loop…

At z=0.4 this was a SN Ia that was 30 times brighter than it should be...something we should ***never*** find w/ PTF.

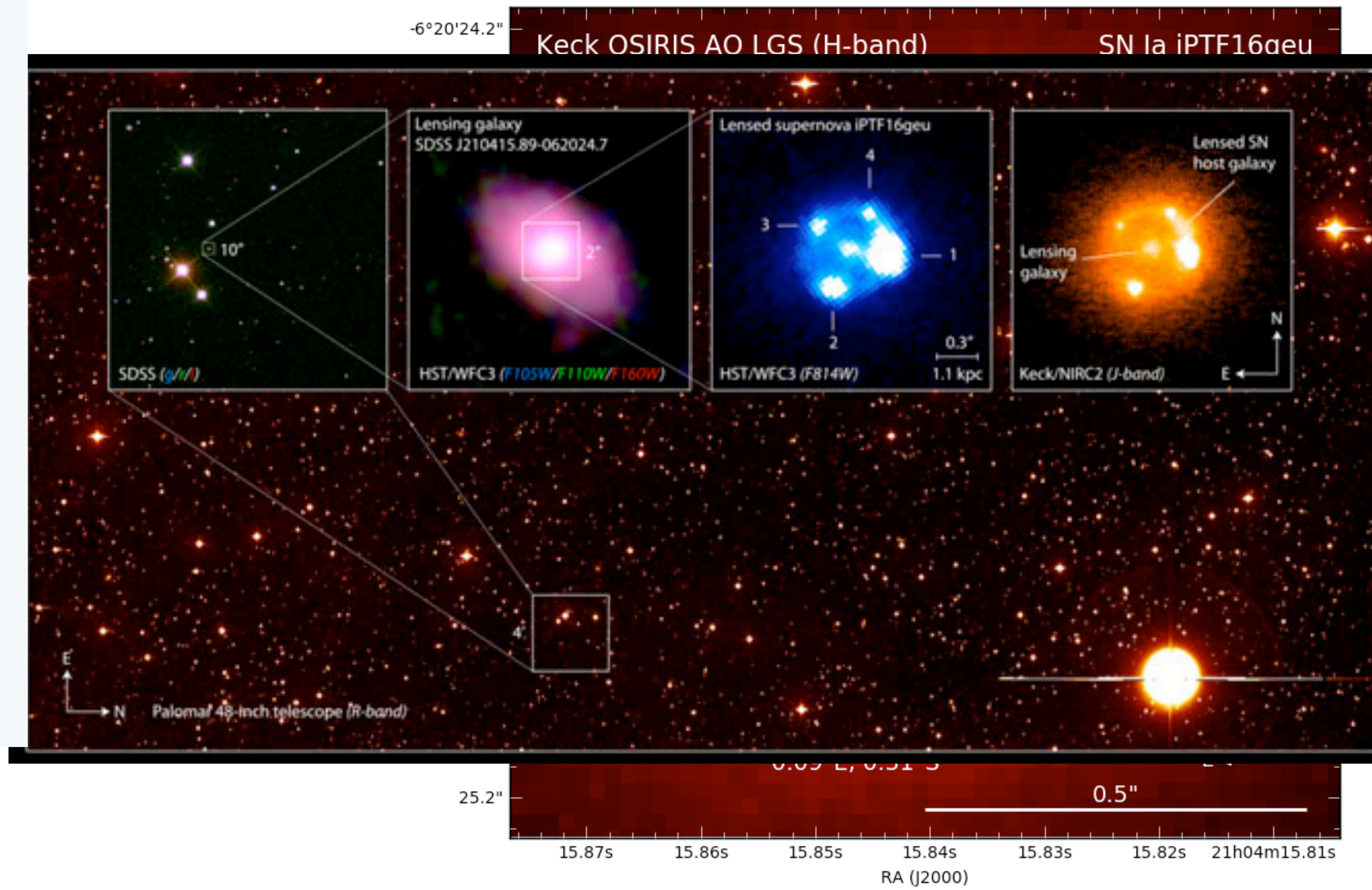


iPTF16geu



Better spectra confirmed the nature of the supernovae and showed emission and absorption lines from the SN host galaxy as well as absorption lines from the lens.

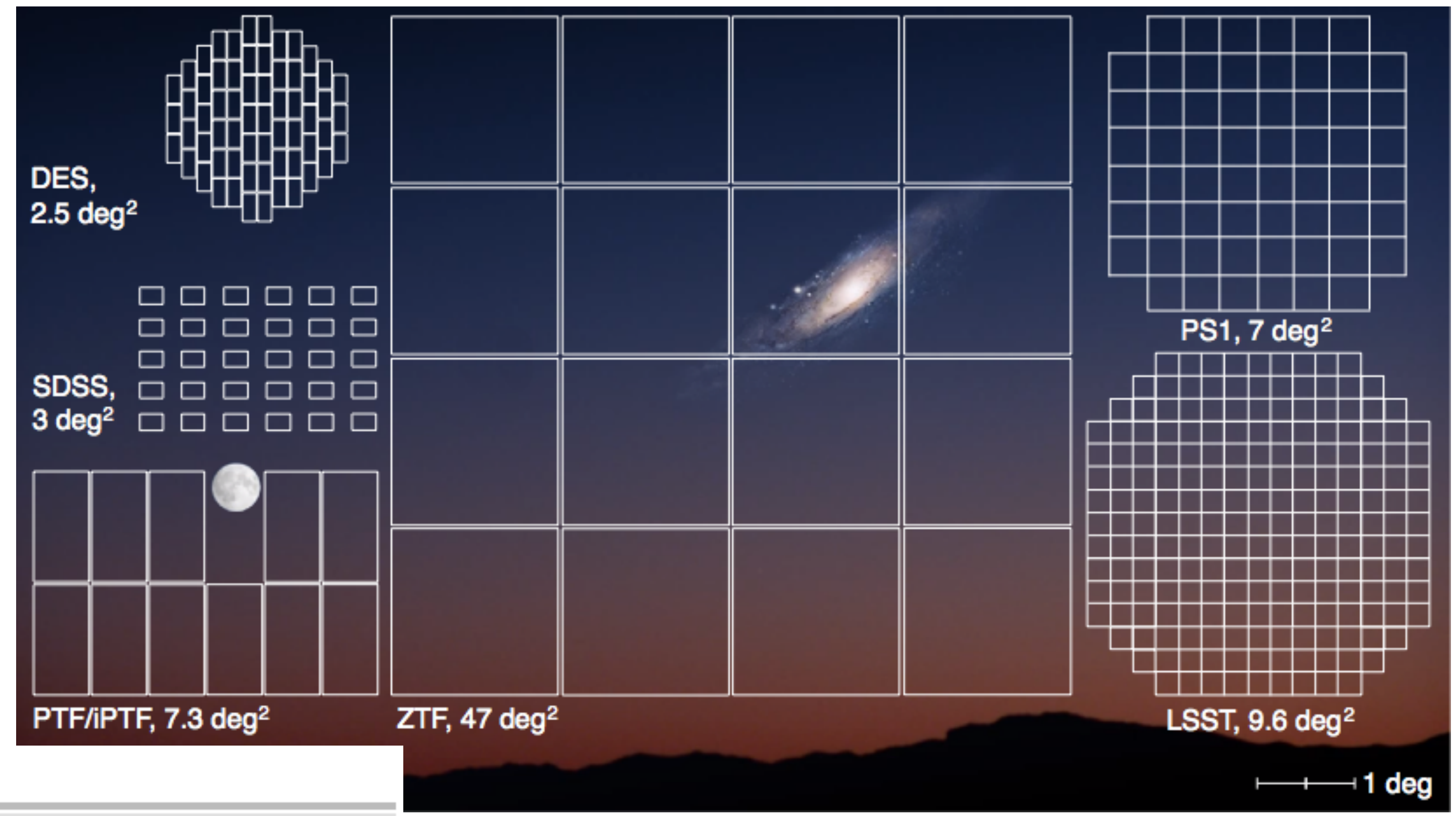
iPTF16geu

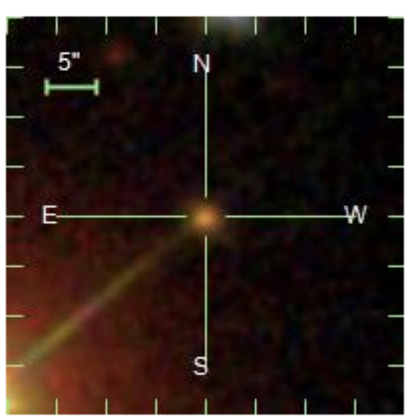


HST follow-up commenced shortly afterwards… Goobar *et al.* (2017), ***Science***

Future…

Given ZTF and then LSST we should be able to find a lot more of these…





Magnitudes				
u	g	r	i	z
22.78	20.51	19.16	18.46	18.00

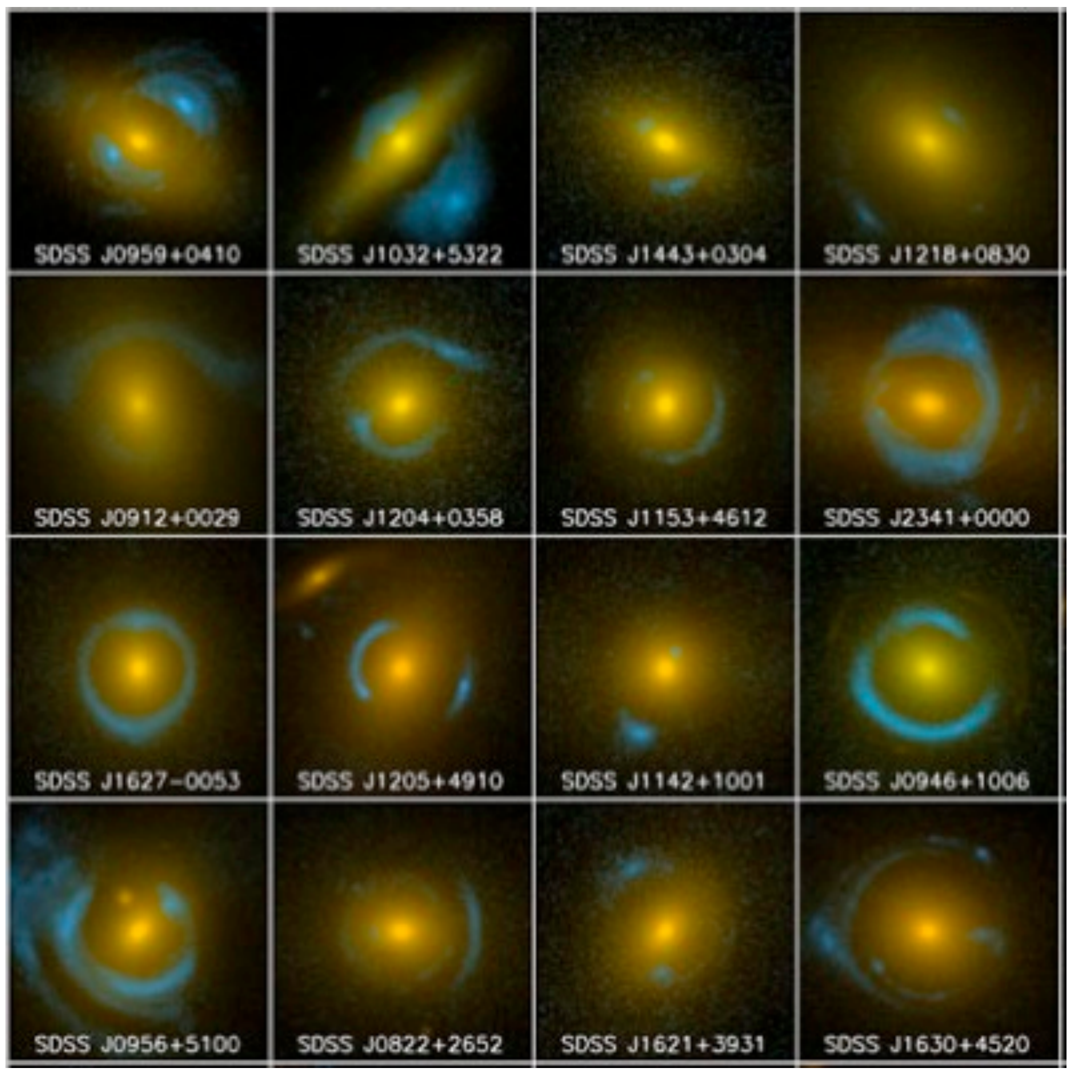
Magnitude uncertainties				
err_u	err_g	err_r	err_i	err_z
0.52	0.03	0.02	0.01	0.03

Image MJD	mode	Other observations	parentID	nChild	extinction_r	PetroRad_r (arcsec)
51790	PRIMARY	0	1237652600099766369	0	0.19	2.00 ± 0.074

Mjd-Date	photoZ (KD-tree method)	Galaxy Zoo 1 morphology
09/03/2000	0.227 ± 0.0451	-

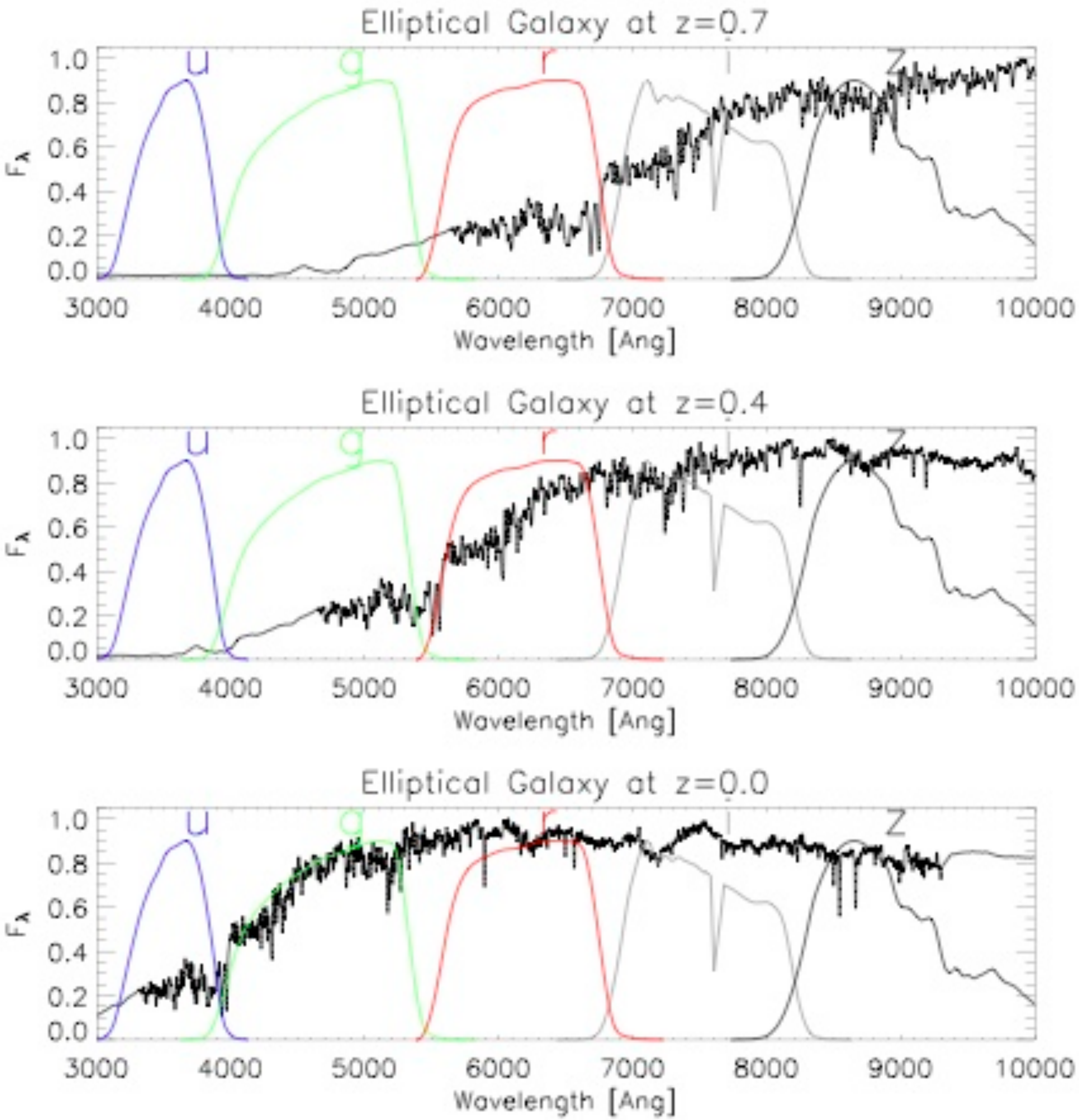
But it'll only be good if we can react well, as we can not take spectra of all the SNe we find in ZTF, let alone the numbers we will find in LSST….

A method for finding LSNe



Elliptical galaxies represent 80% of all the SL galaxies.

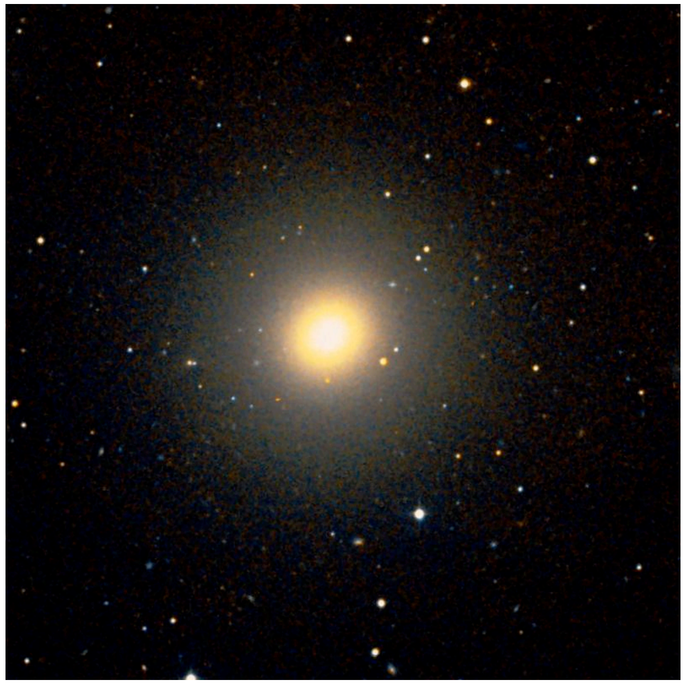
A method for finding LSNe

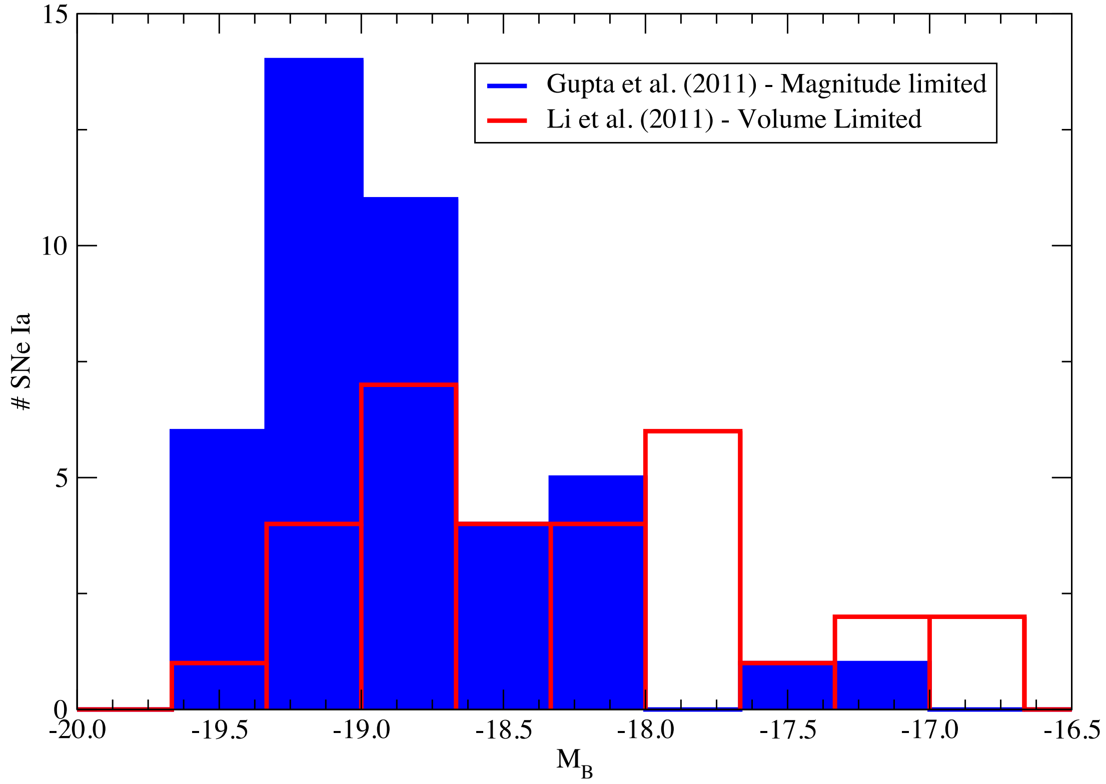


Elliptical galaxies have great photometric redshifts since they are comprised of low-mass, old stars.

Padmadabhan (2007)

A method for finding LSNe





The brightest supernovae in elliptical galaxies are Type Ia.

Putting this all together:

If you find a supernova in an elliptical with $M_B < -20$, based on the photo-z, it is likely a lensed supernova.

Powerful Tool

HOW TO FIND GRAVITATIONALLY LENSED TYPE Ia SUPERNOVAE

Daniel A. Goldstein[1,2] and Peter E. Nugent[1,2]

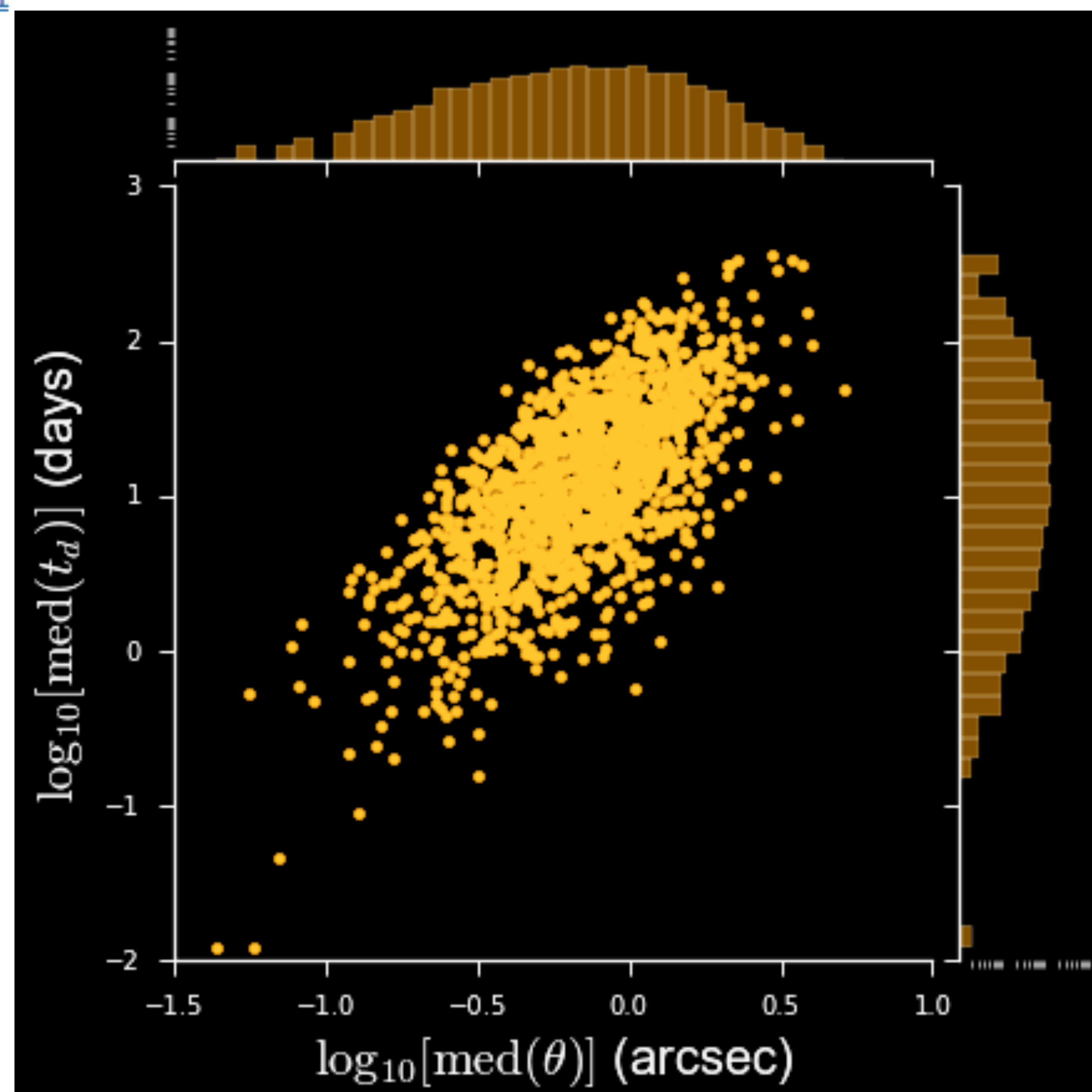
Published 2016 December 30 • © 2016. The American Astronomical Society. All rights reserved.

The Astrophysical Journal Letters, Volume 834, Number 1

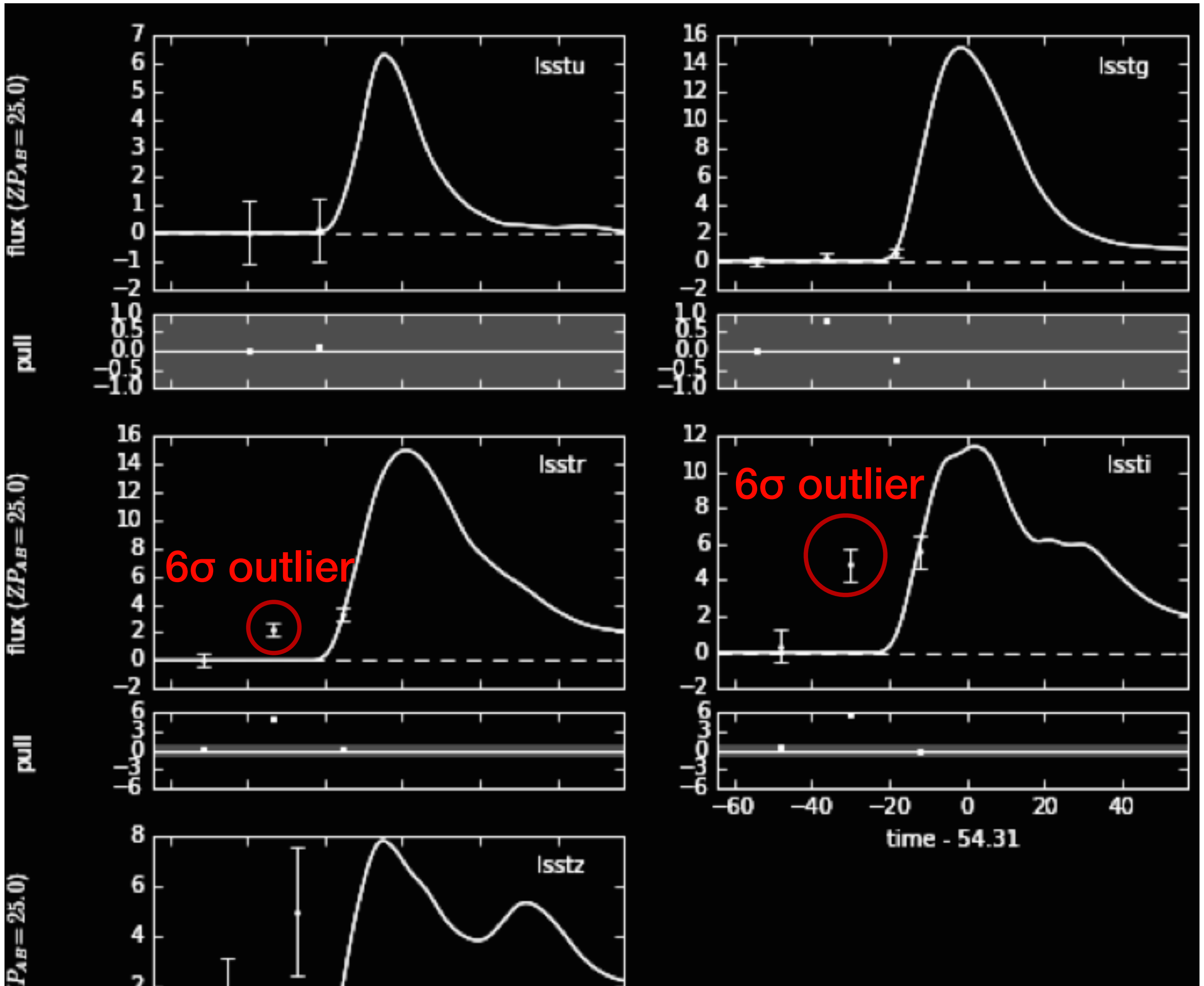
iPTF16geu had $M_B < -21$

Critical is that there is no need to resolve the system.

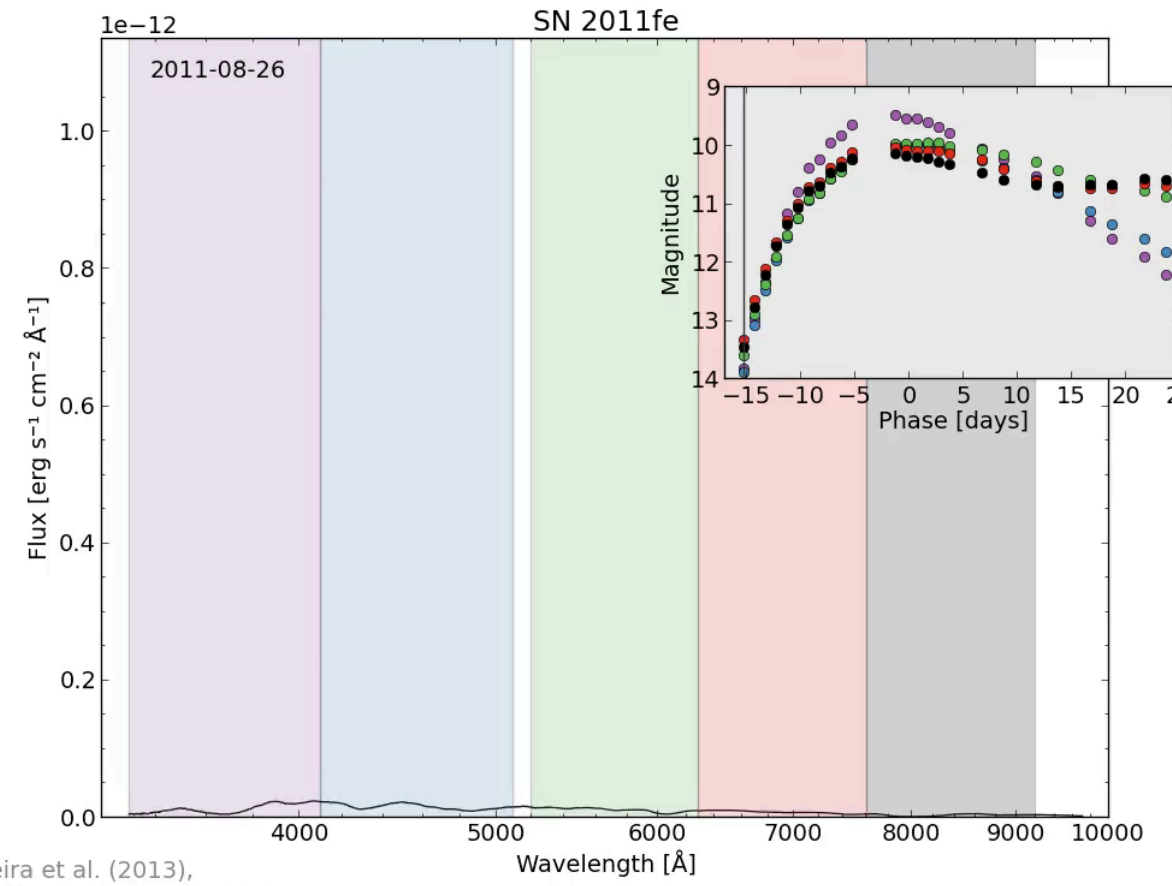
10X improvement in numbers over methods which require one to resolve the system. (Oguri & Marshall 2010)



But wait, there's more…



Template fitting works a lot better!

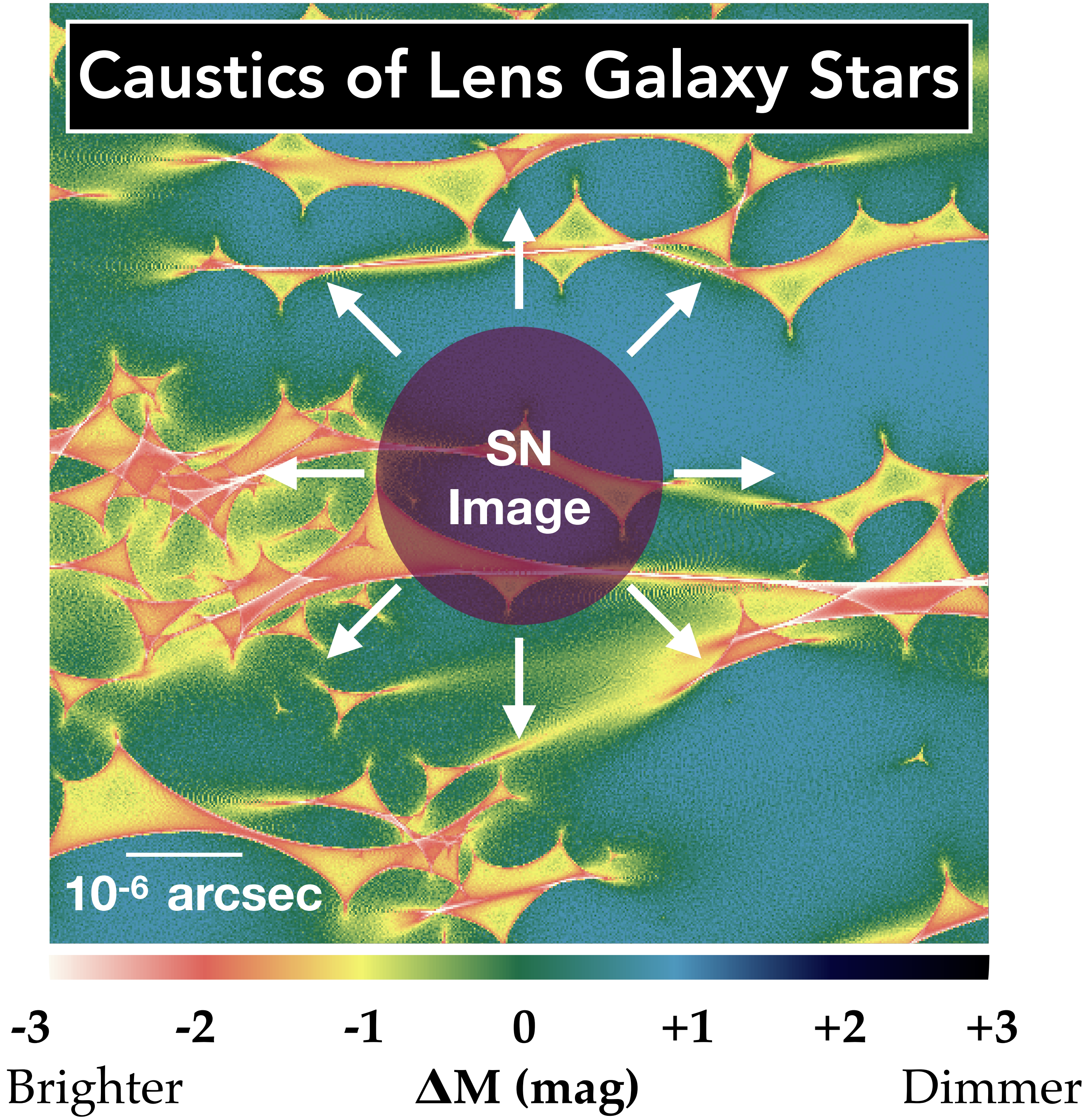


Pereira et al. (2013),
The Nearby Supernova Factory

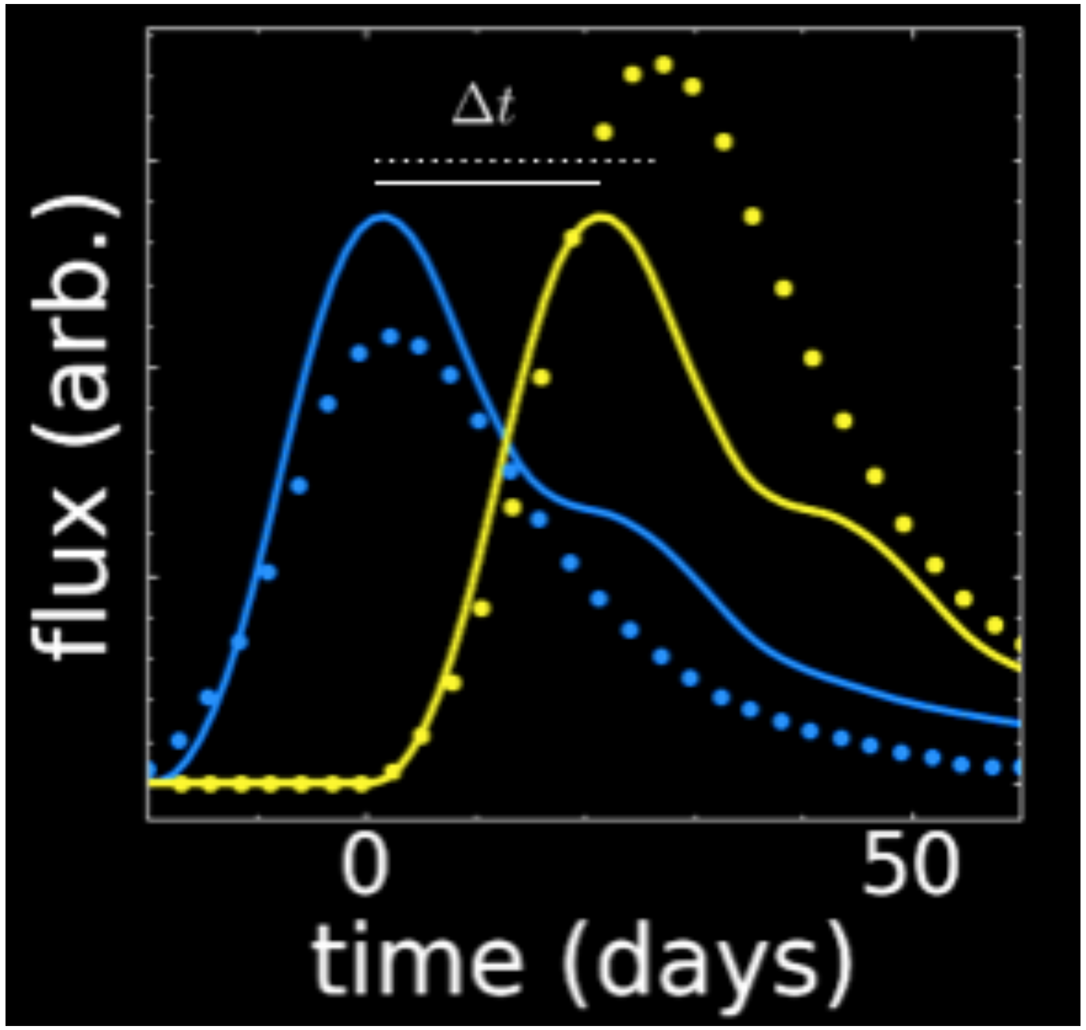
Because SNe Ia are so similar, we can use their spectrophotometric evolution to predict exactly what colors they should have as a function of time in an elliptical galaxy - given the galaxy's photo-z. 2X more!!!

Also lets us find core-collapse SNe!

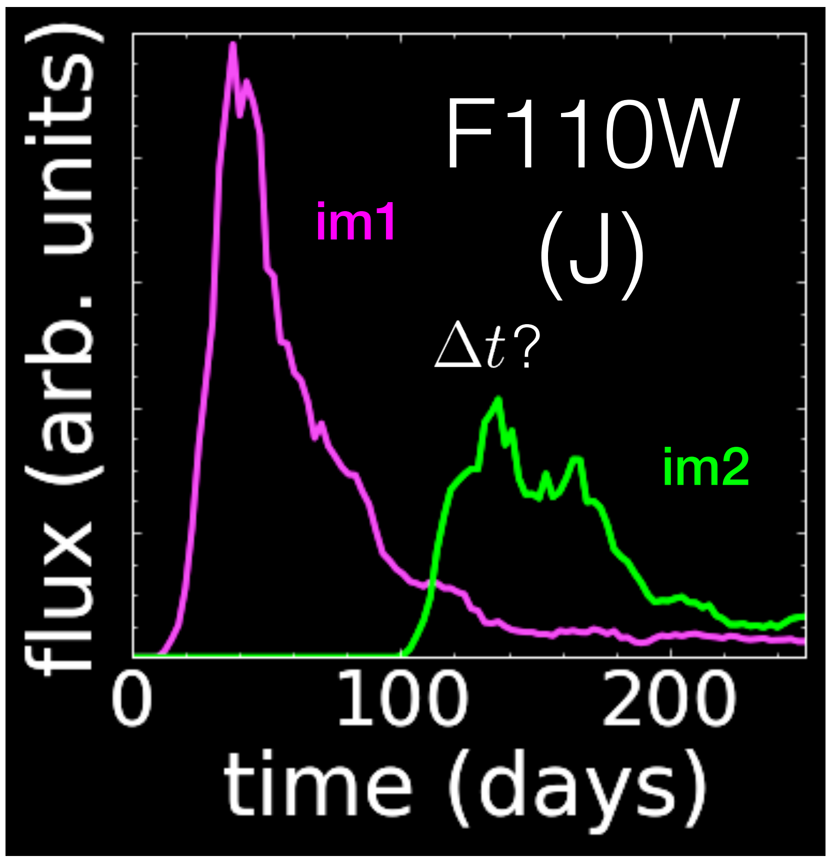
A killer systematic?



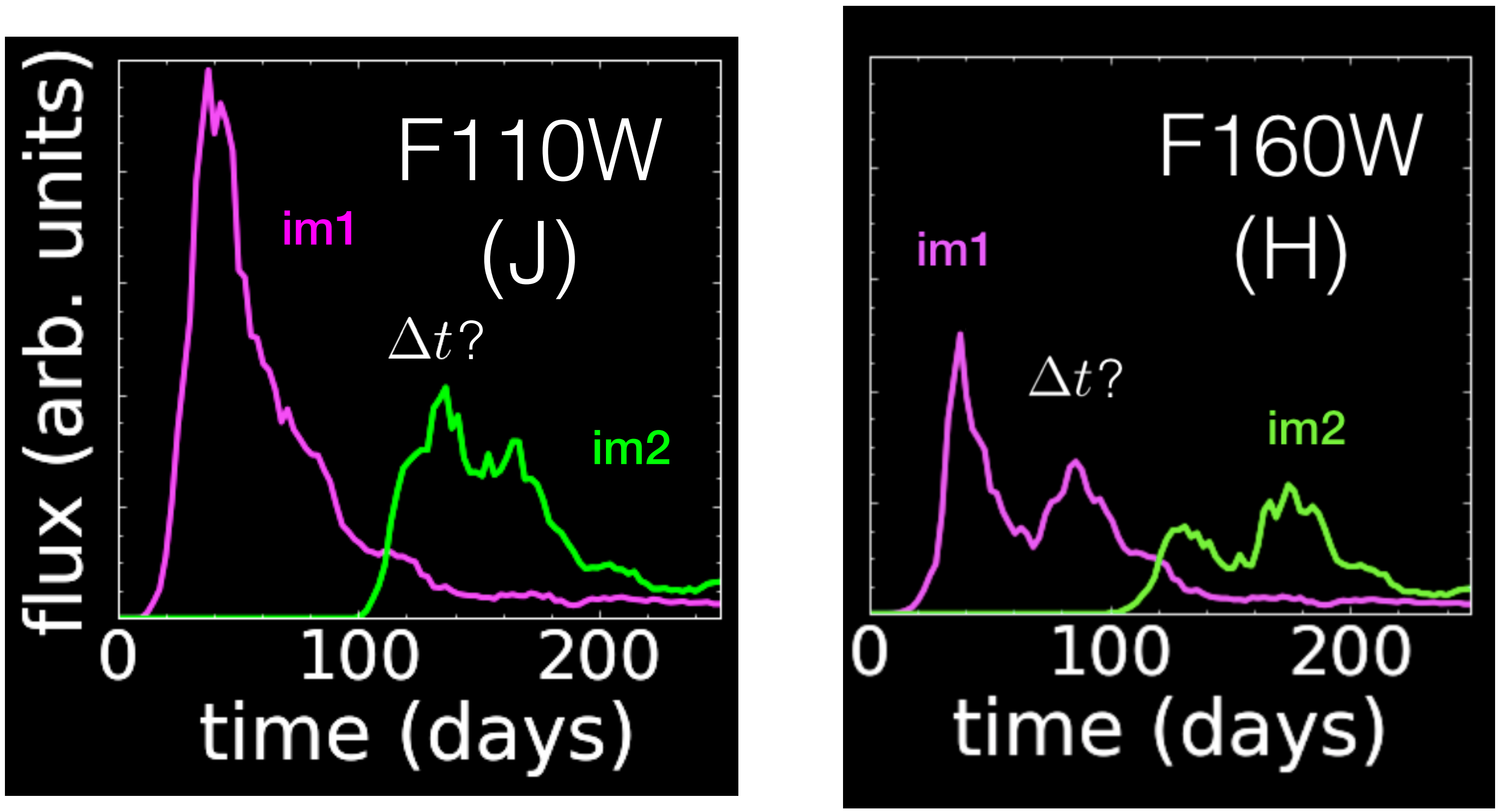
Micorlensing (dots) can cause the wrong time delay to be inferred.



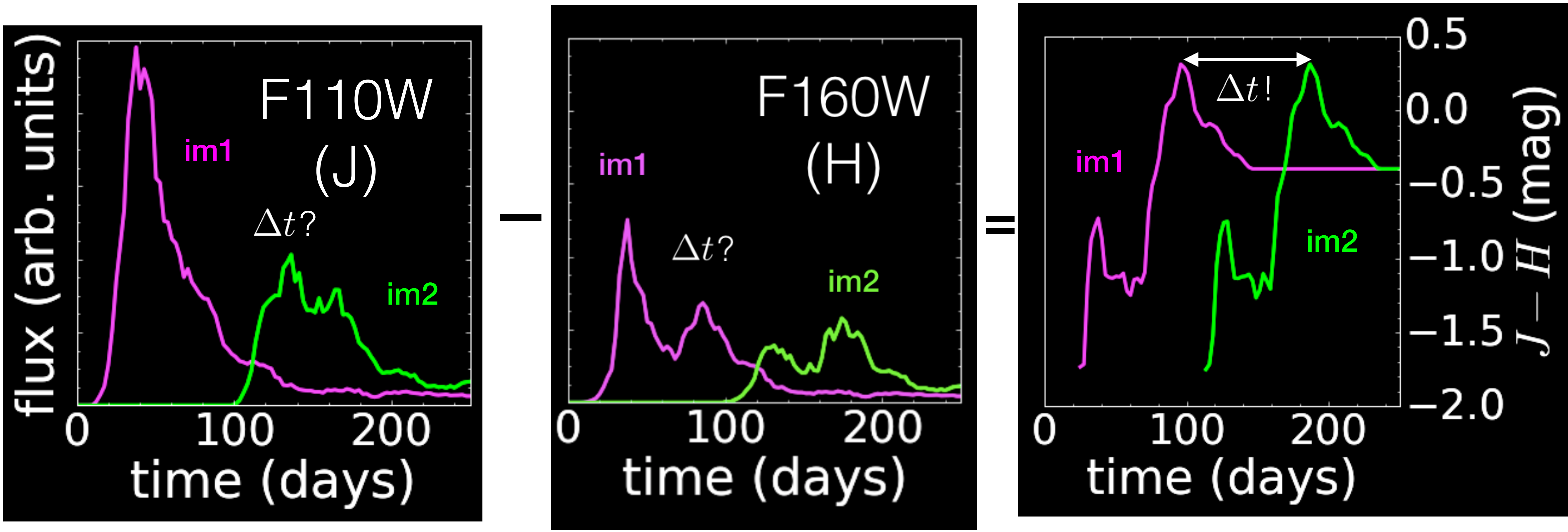
Not if SNe Ia are achromatic…



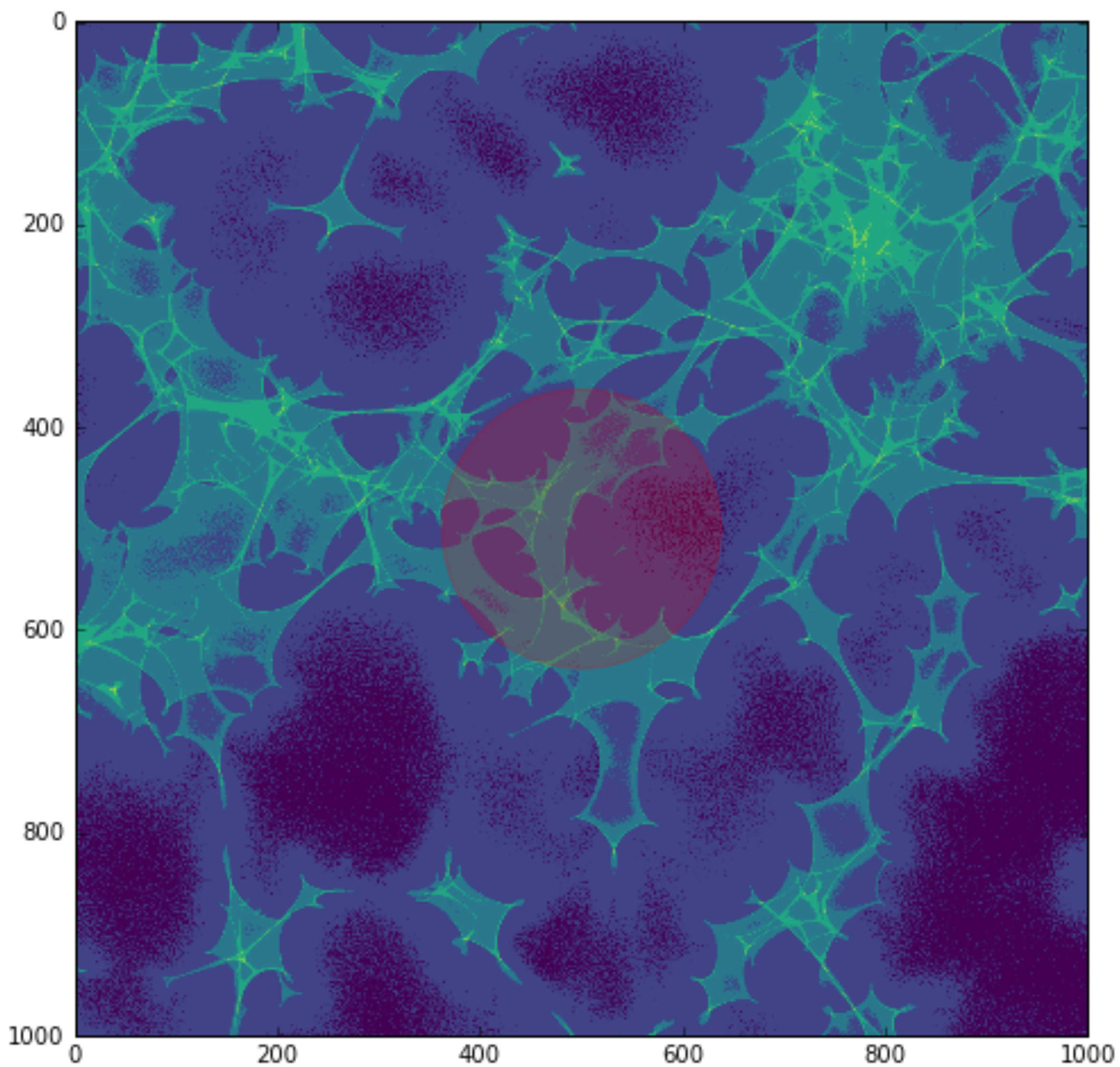
Not if SNe Ia are achromatic…



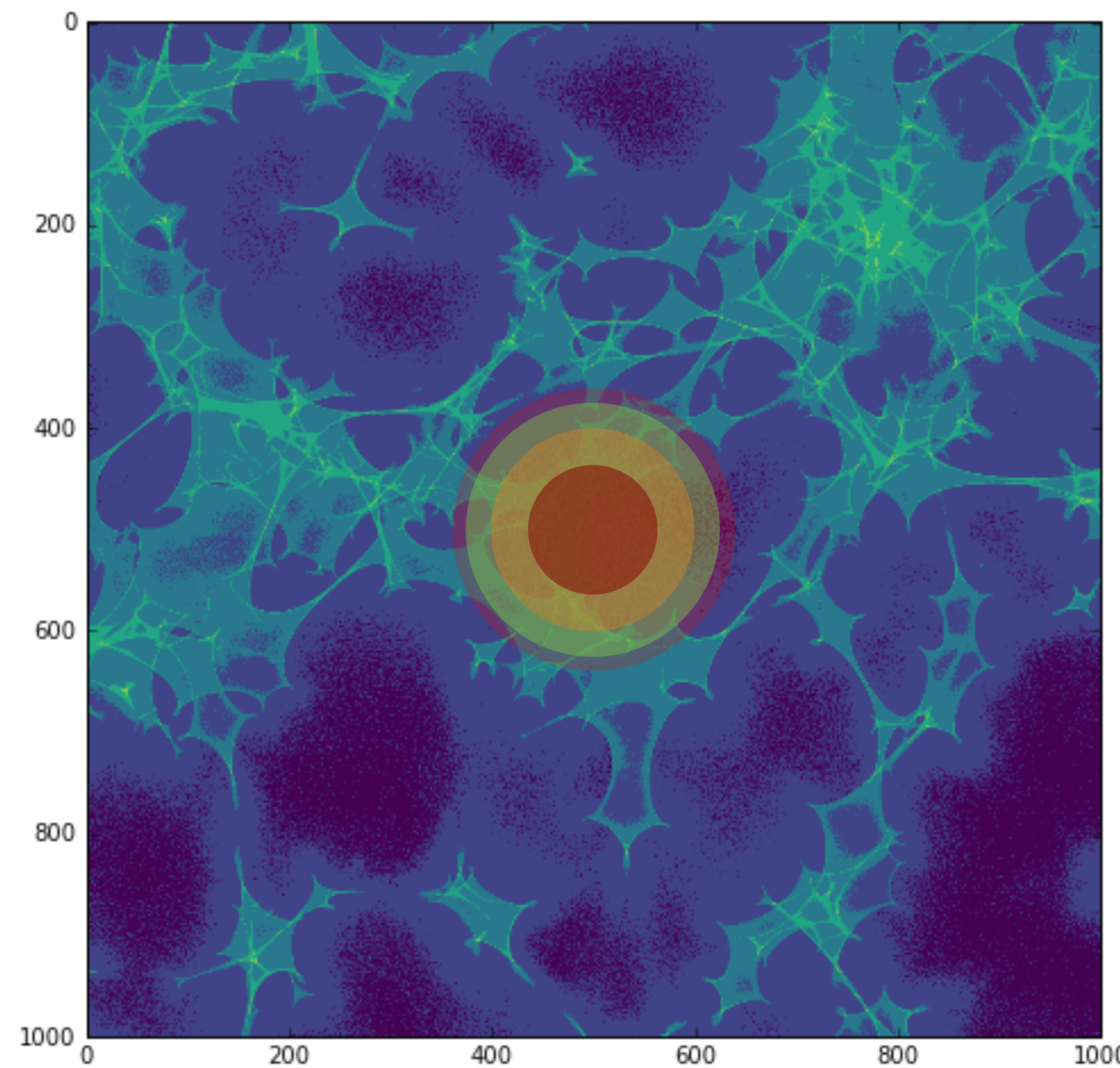
Not if SNe Ia are achromatic…



A priori, no reason to think that they are achromatic.

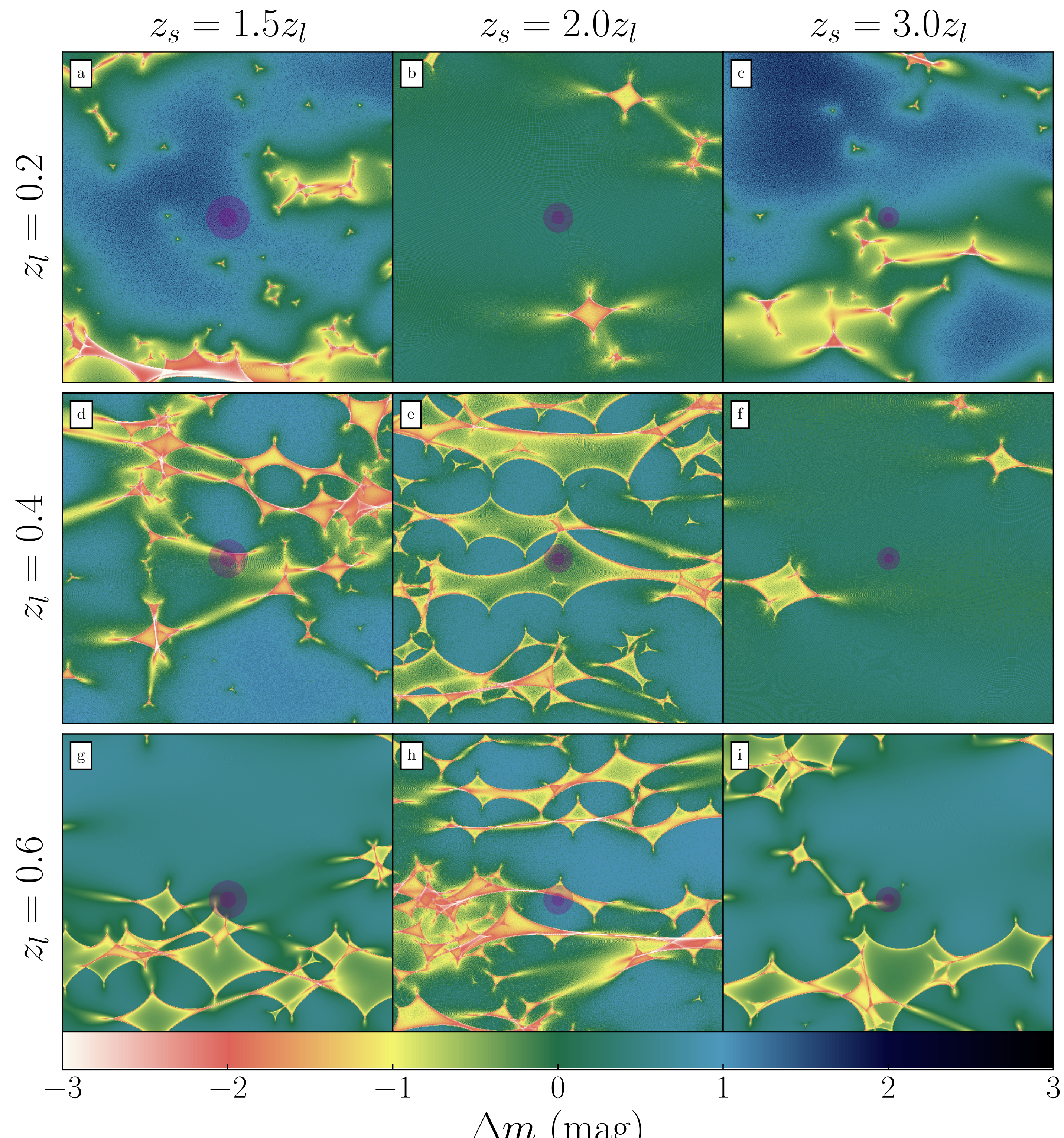


Simplified Picture

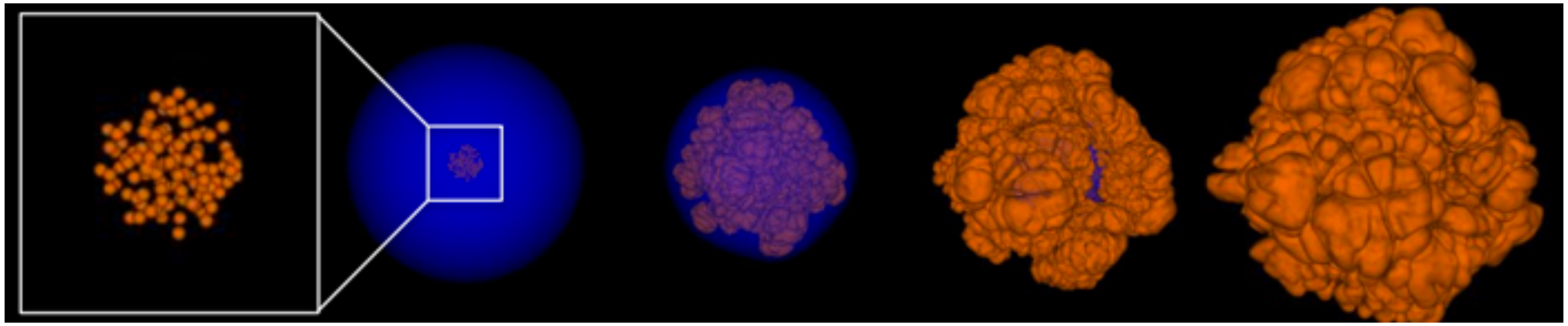


More realistic Picture

Simulate a lot of microlens systems (80k)



Danny's thinking about selling these t-shirts if things don't work out in astro…

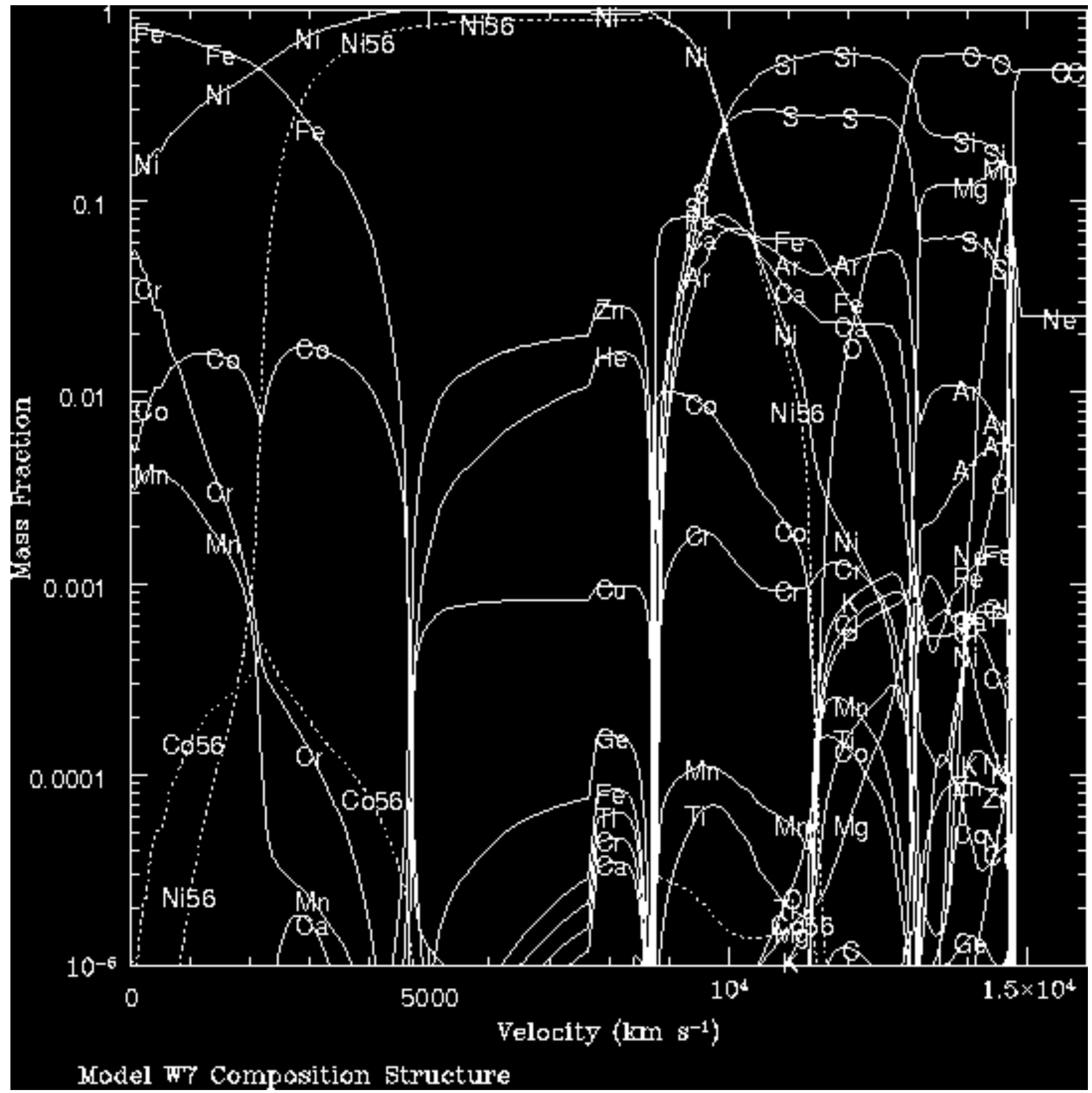


Model W7

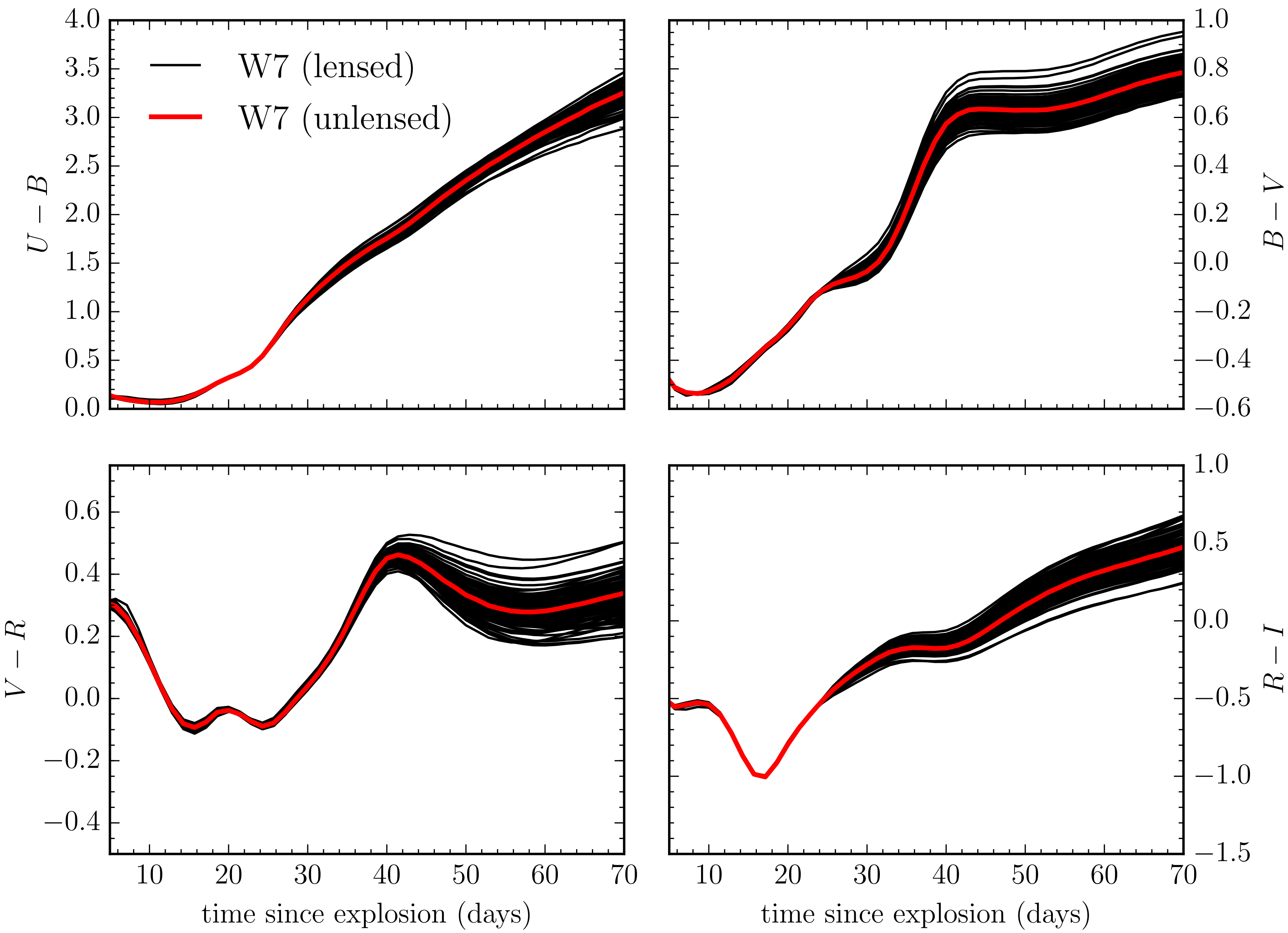
Nomoto+84

Took a representative SN Ia Model

Pure deflagration of Chandrasekhar-mass white dwarf which captures the observational properties of observed SNe Ia.



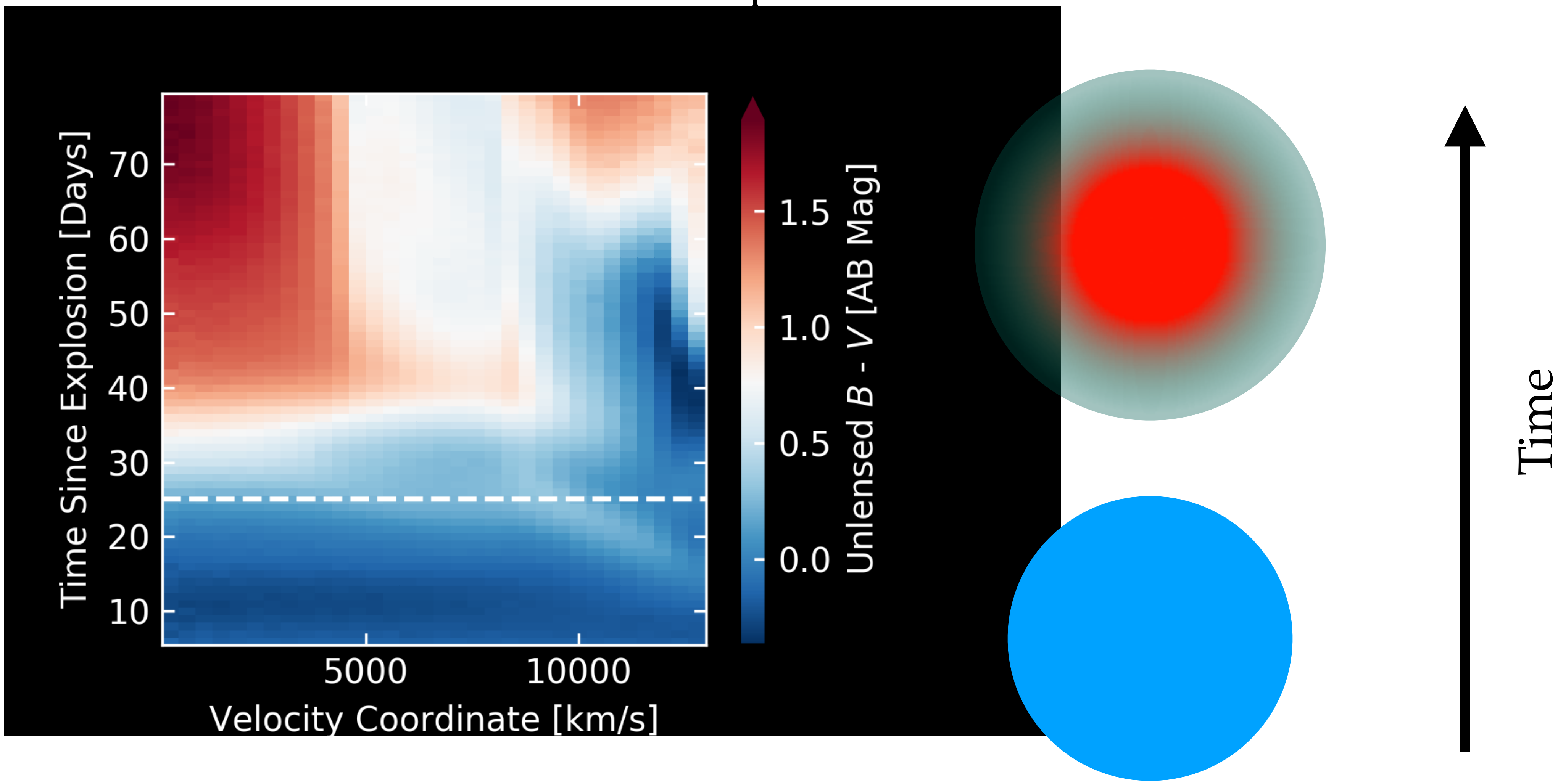
And ran it through the radiation hydrodynamics code SEDONA



Until just before 40 days after explosion, SNe Ia appear to be achromatic.

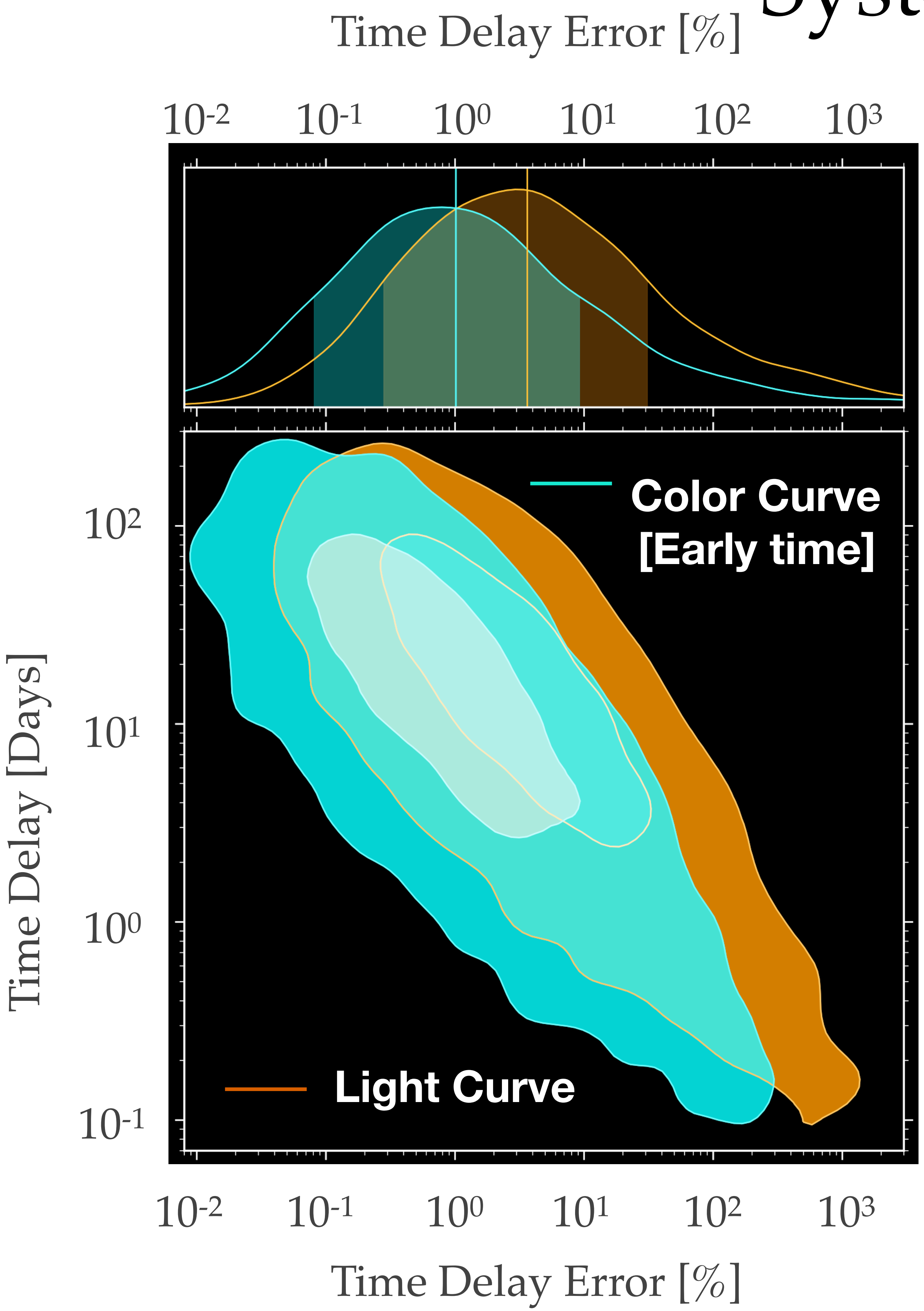
Chromaticity can be Understood as an Opacity Effect in SNe Ia

Iron line blanketing allows one to see redder emission from deeper in SN at late times



Color does not vary much across atmosphere at early times

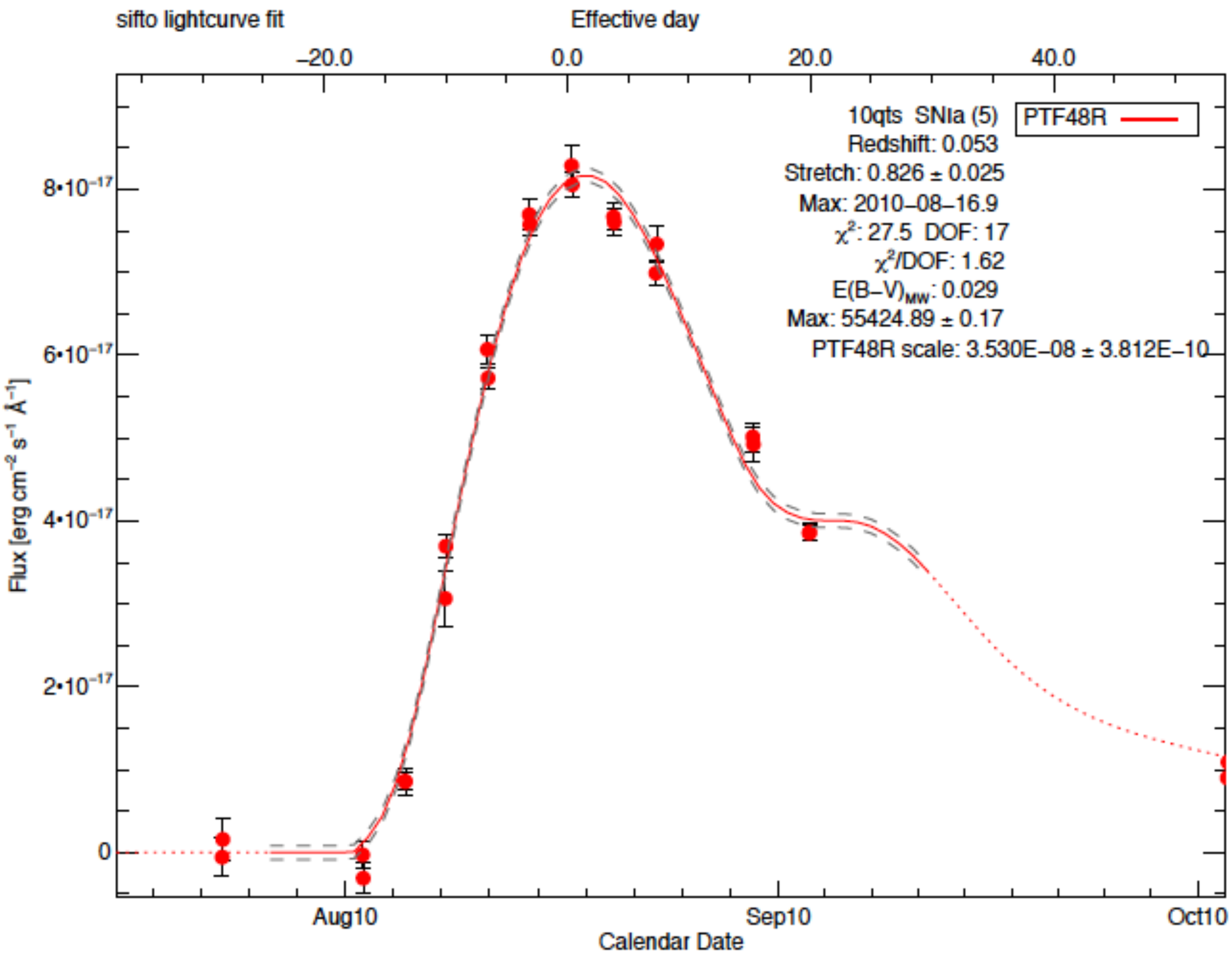
Systematics under control!



Measuring time delays from the colors at early times, as opposed to the lightcurves, reduces the effect of microlensing to 1%.

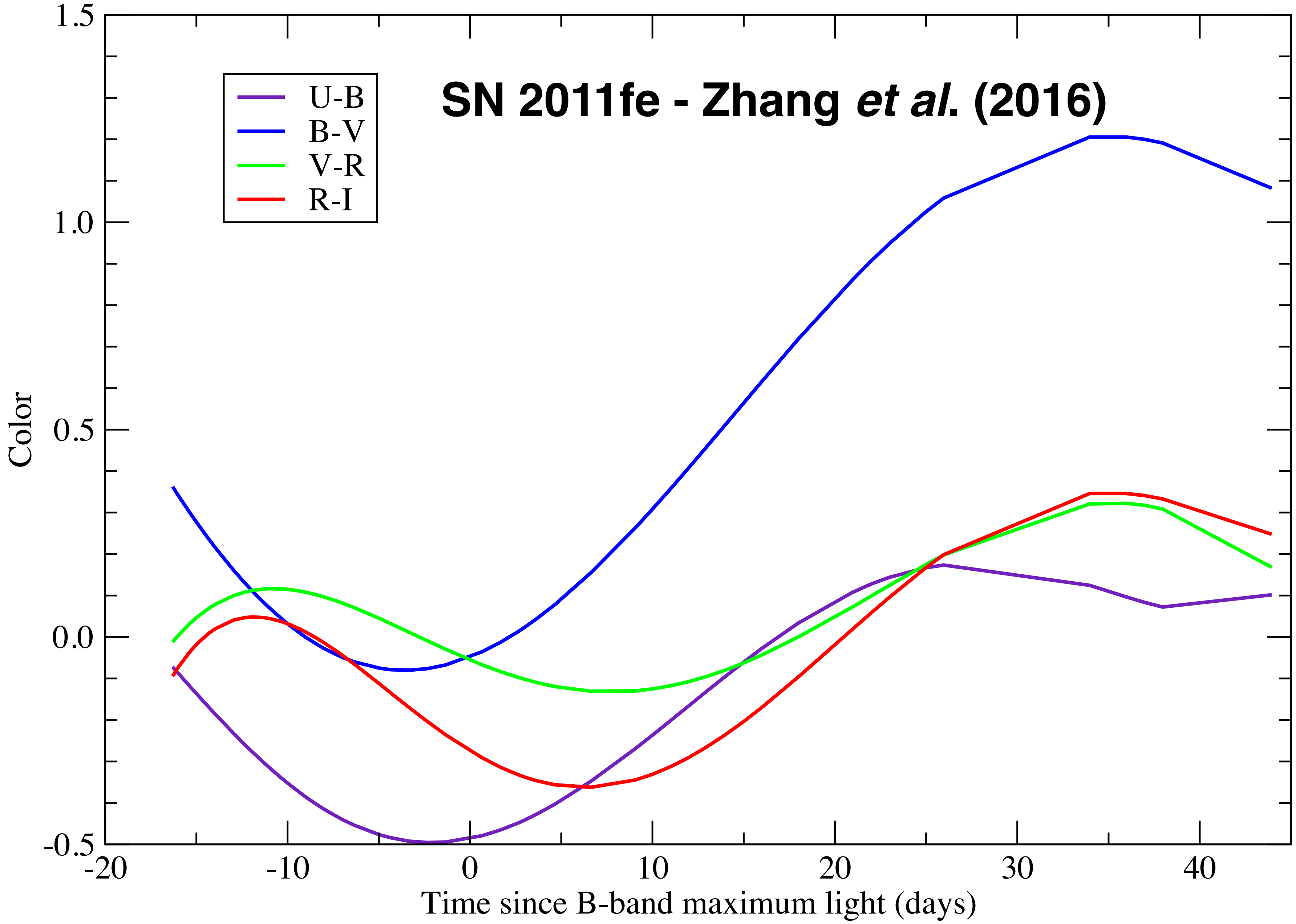
Goldstein *et al.* (2018)

How good can SNe Ia time delays be statistically?



Using a single filter with ~10 points having S/N of 10-20 results in an uncertainty in peak brightness of 4hrs.

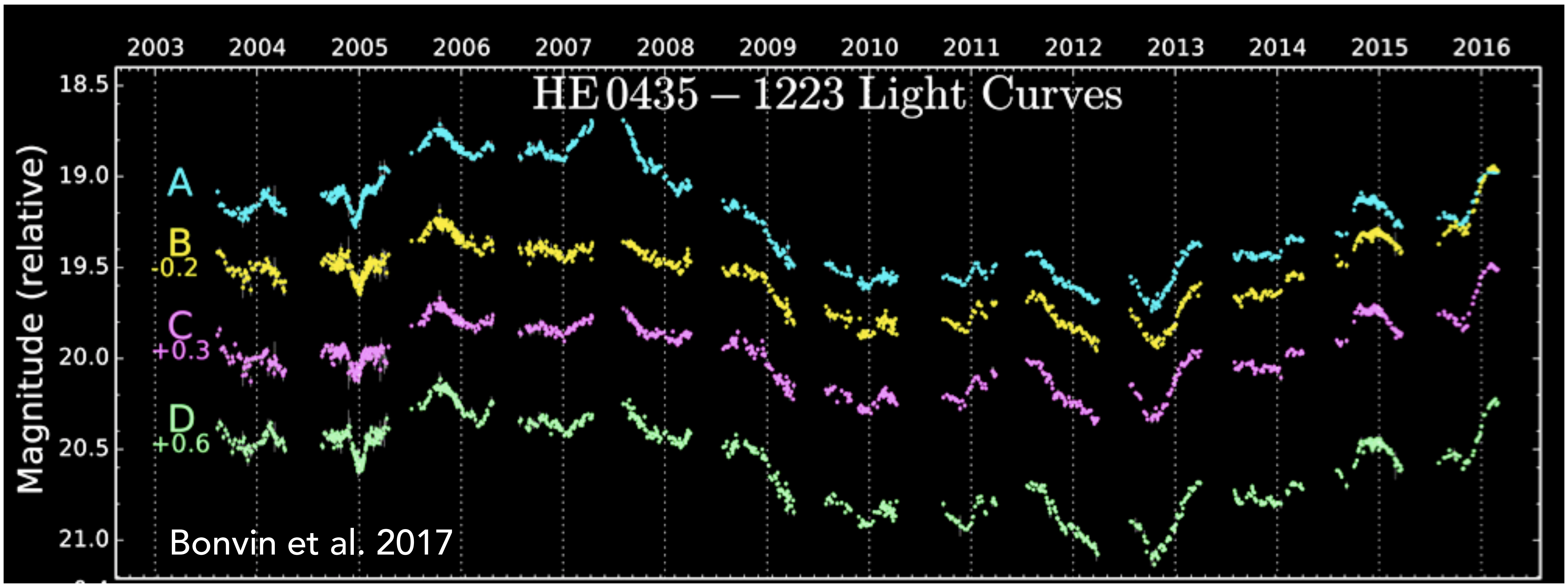
How good can SNe Ia time delays be statistically?

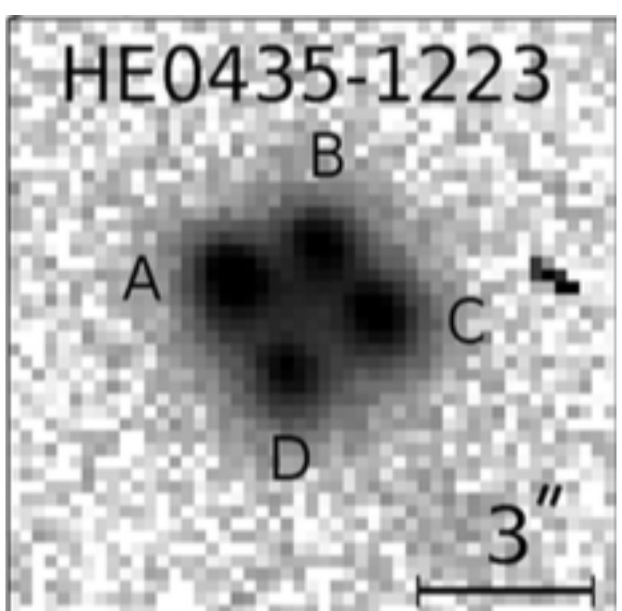


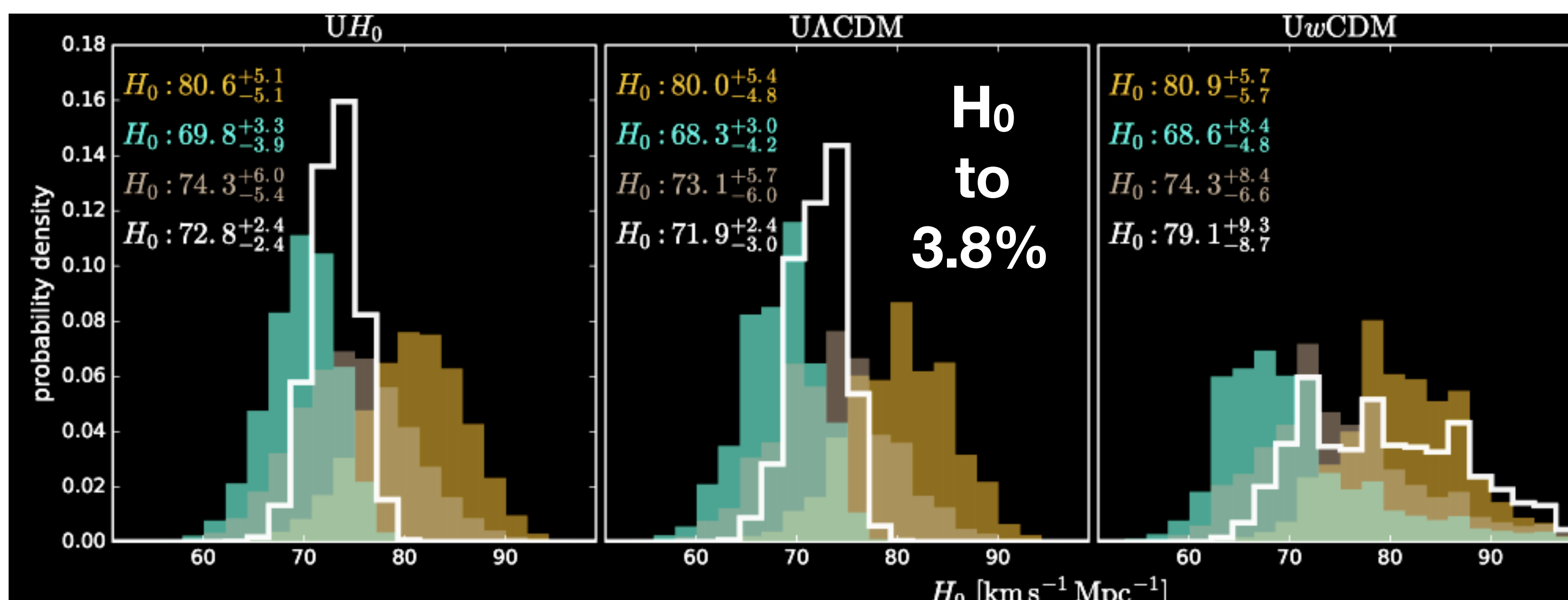
Because SN Ia colors have several inflection points, time delays are even better - 30 minutes is possible with 10 points in 2 filters and reasonable S/N around maximum light.

For a z=0.4 SN Ia, this is 1 part in 10^{14}!

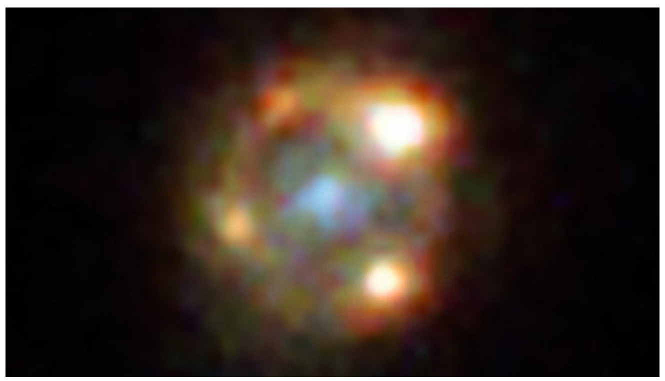
The state of the art is to instead use strongly lensed *quasars*







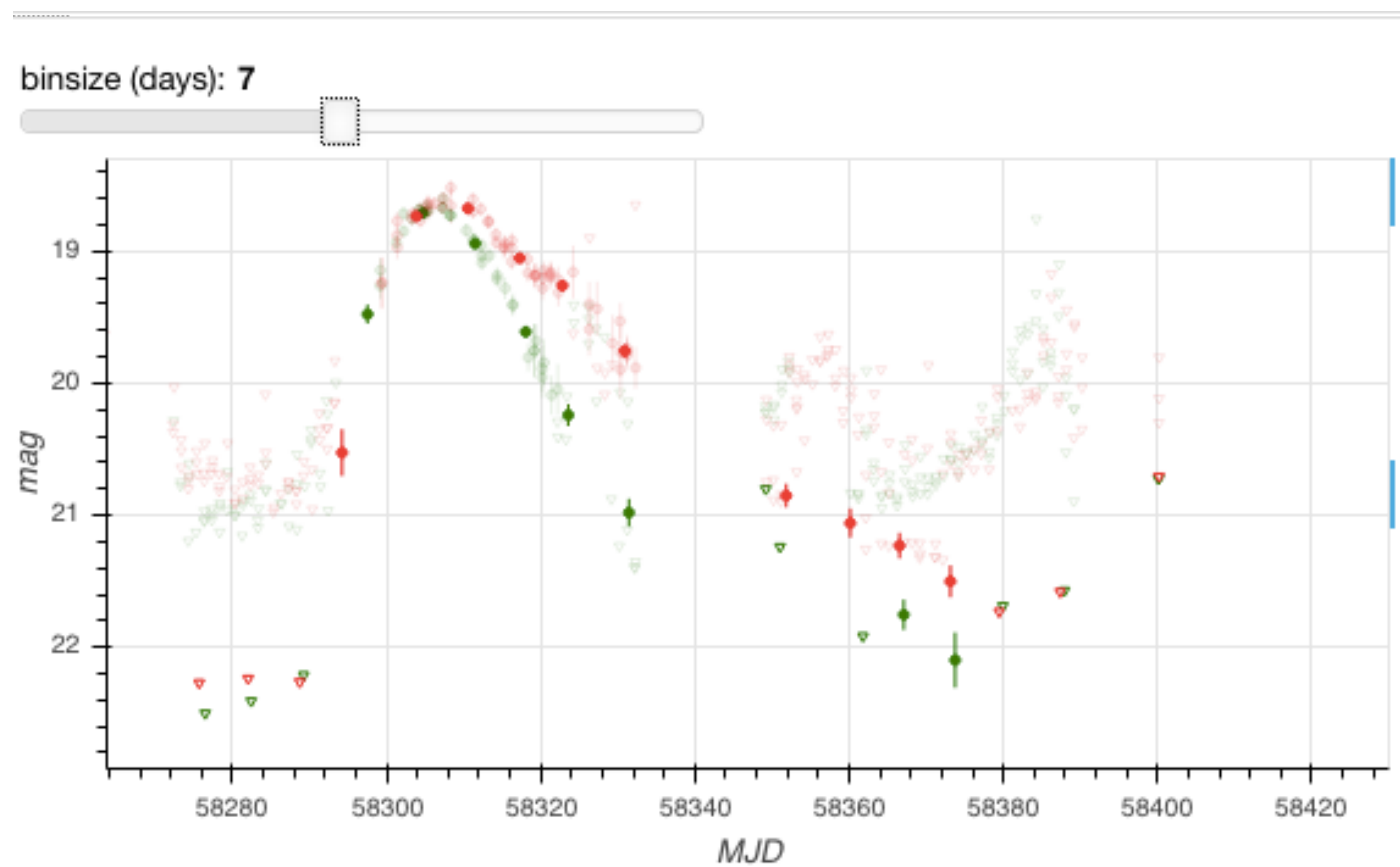
But lensed quasars face many challenges… lensed Type Ia supernovae are far better.



Lensed Type Ia Supernovae	Lensed Quasars / AGNs
Require ~weeks of monitoring	Require 10+ years of monitoring
SED modeled precisely	SED not known
Break mass-sheet degeneracy	Suffer from mass-sheet degeneracy
Time delays unaffected by microlensing at early times	Time delays affected by microlensing at all times

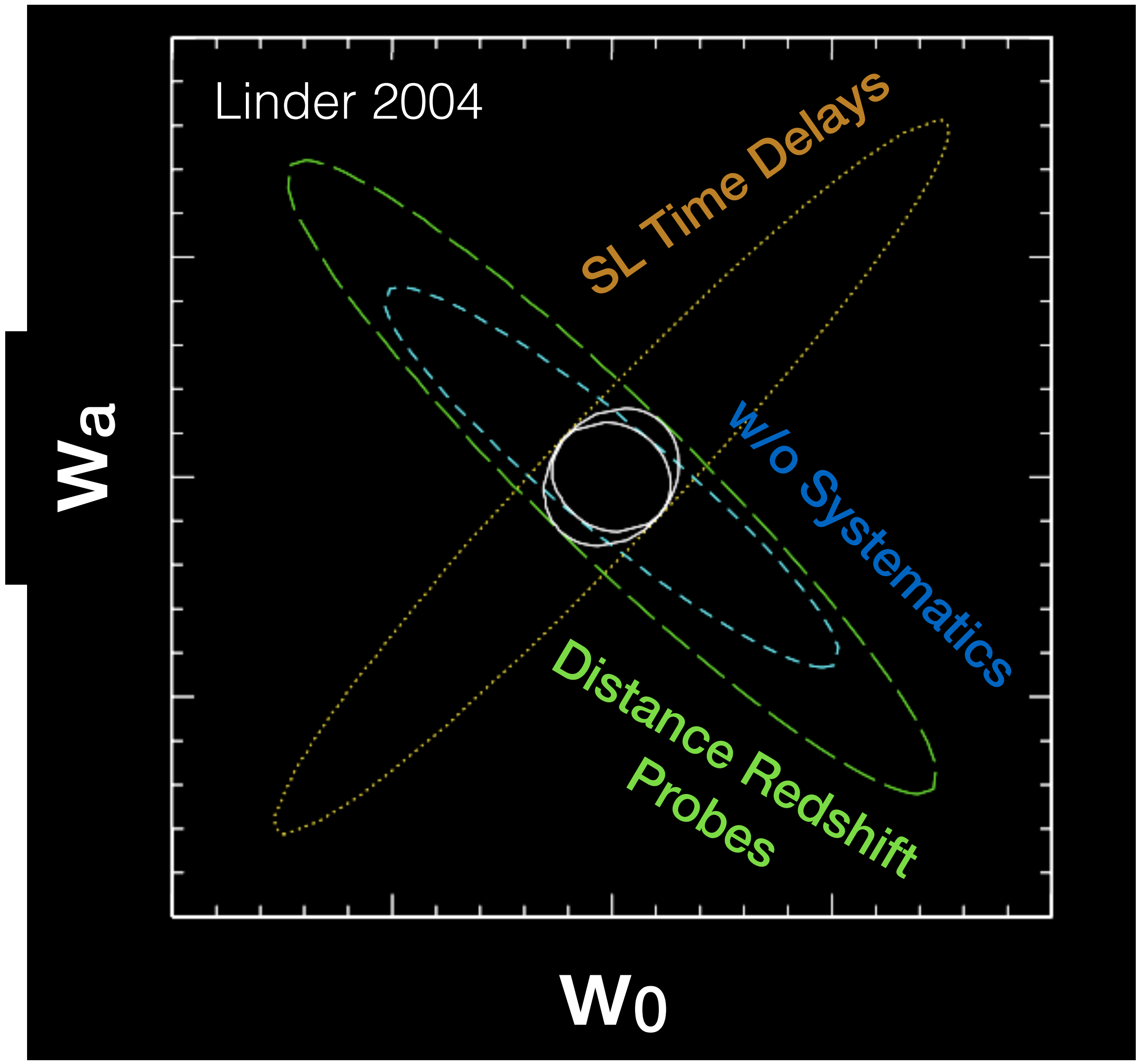
Current Status w/ ZTF

We now have a new co-addition pipeline written by Goldstein & Nugent which allows us to hit ~22.5 mag $5-\sigma$ on a weekly basis given the current partnership field cadence.

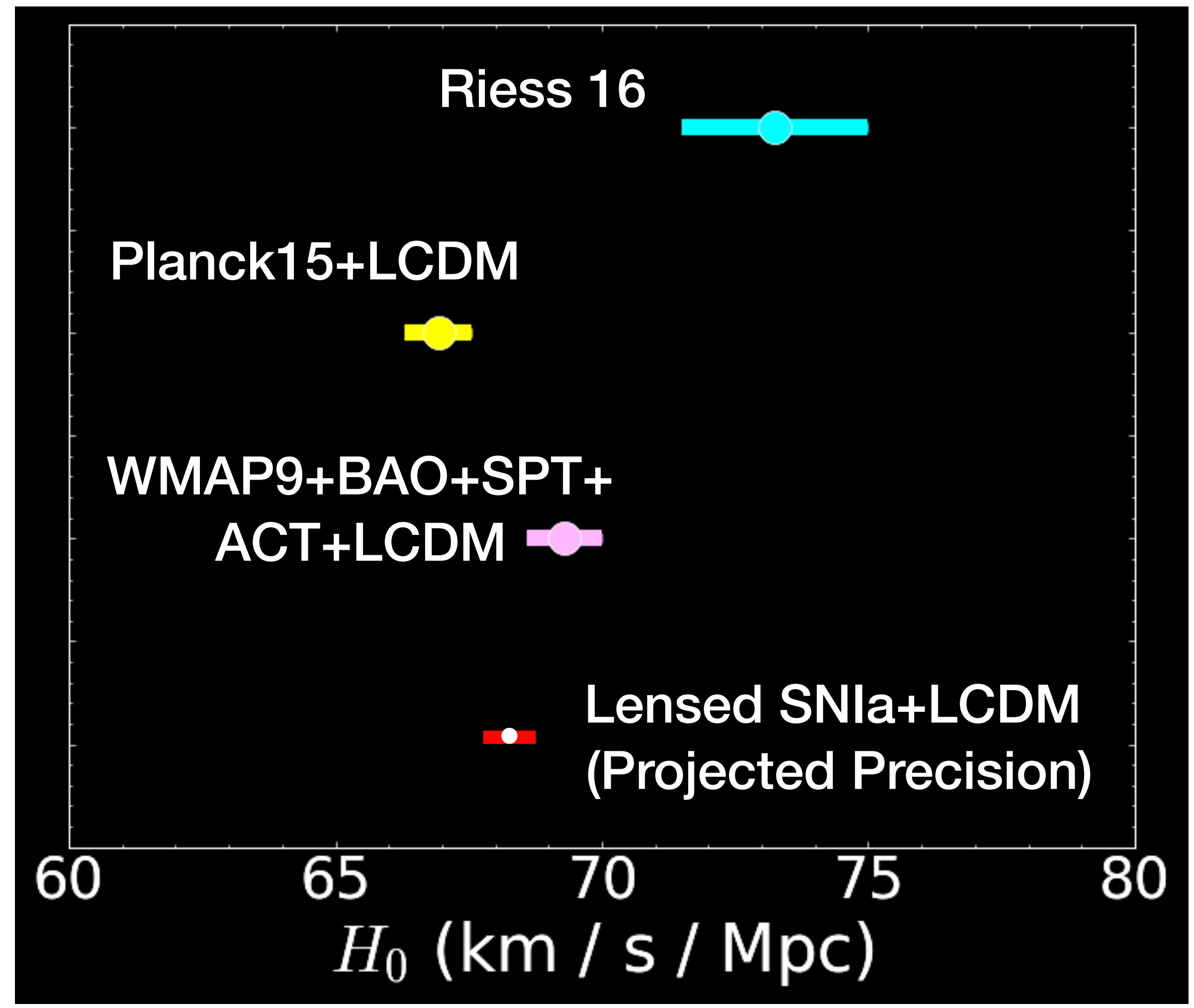


ZTF could do an experiment with 180s exposures (+ 15s readout/slew), which could go to 23rd mag in three filters in 1 hour over 50 sq. deg.

Future Cosmology Measurement Not Just Constrained to H_0

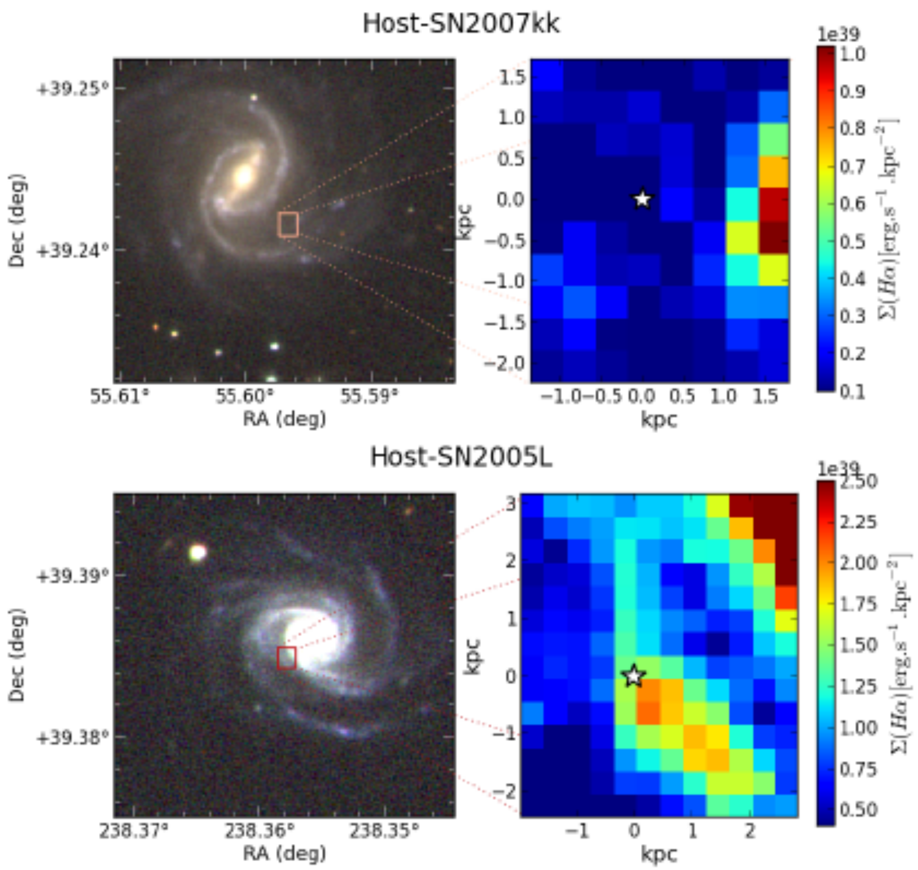


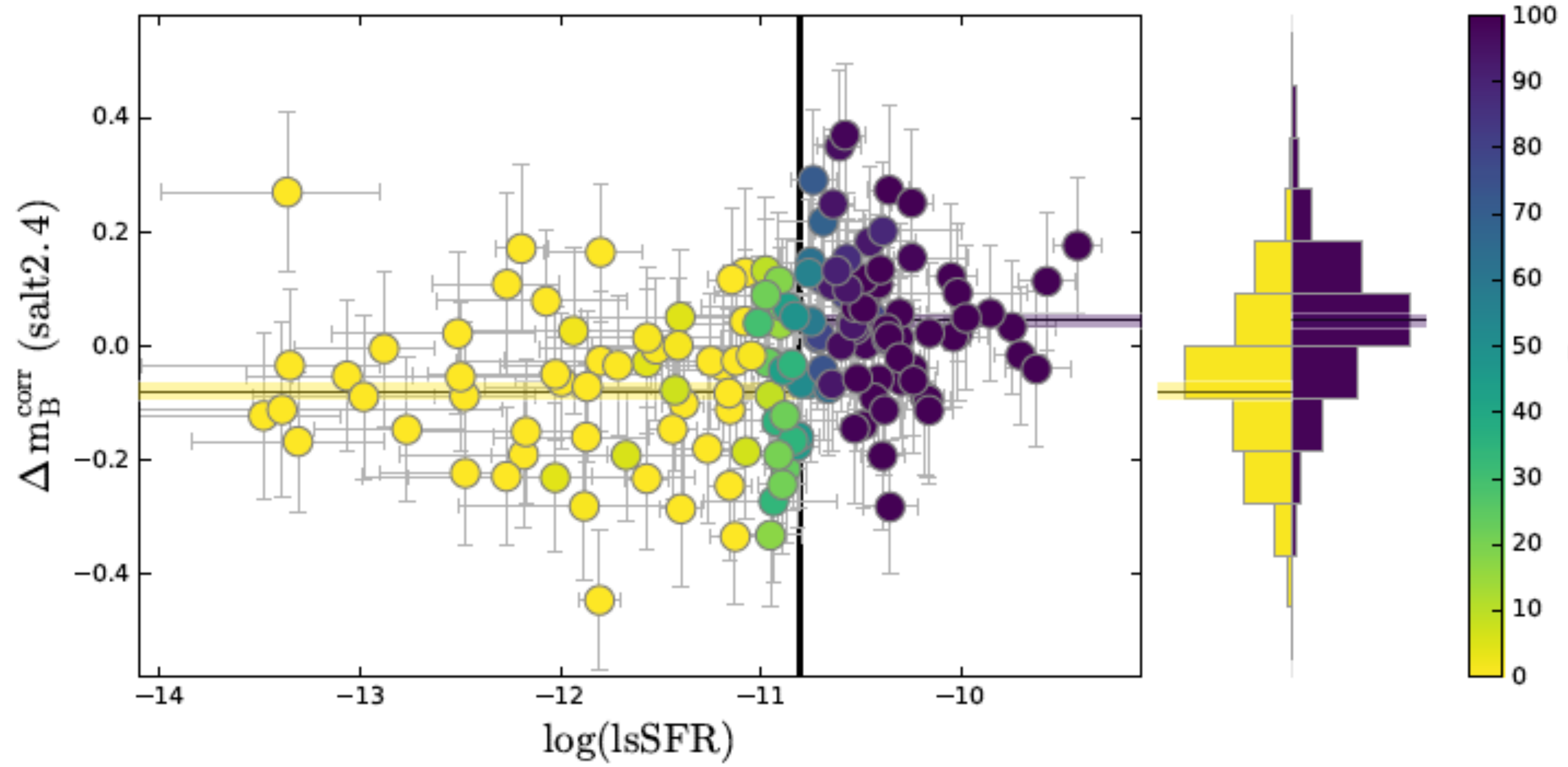
Strong complementarity with other probes on dark energy



1% measurement of H0 independent of distance ladder to resolve current tension

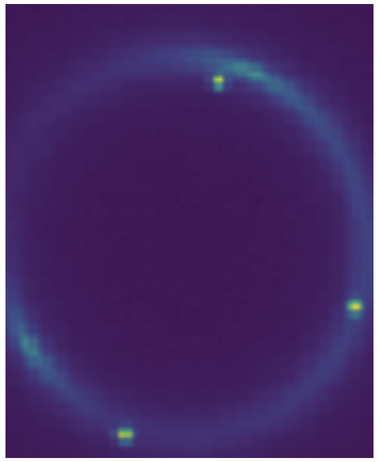
Likely a bias in the Riess *et al.* H_0



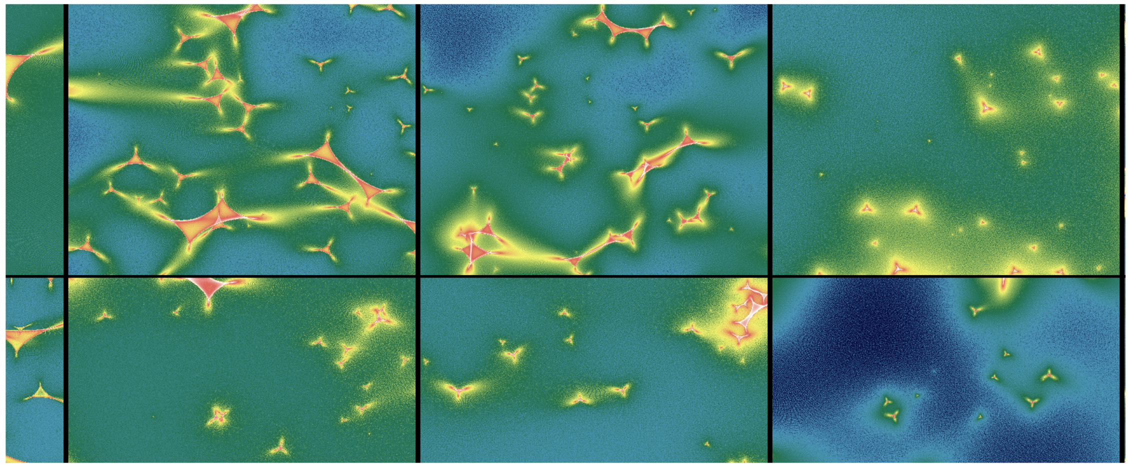


M. Rigault *et al*. (2018) show a systematic offset in the Hubble residuals between in SNe Ia in local star forming regions vs. those from quiescent parts of the galaxy. TF distances (and the Maser) are biased towards higher SFR.

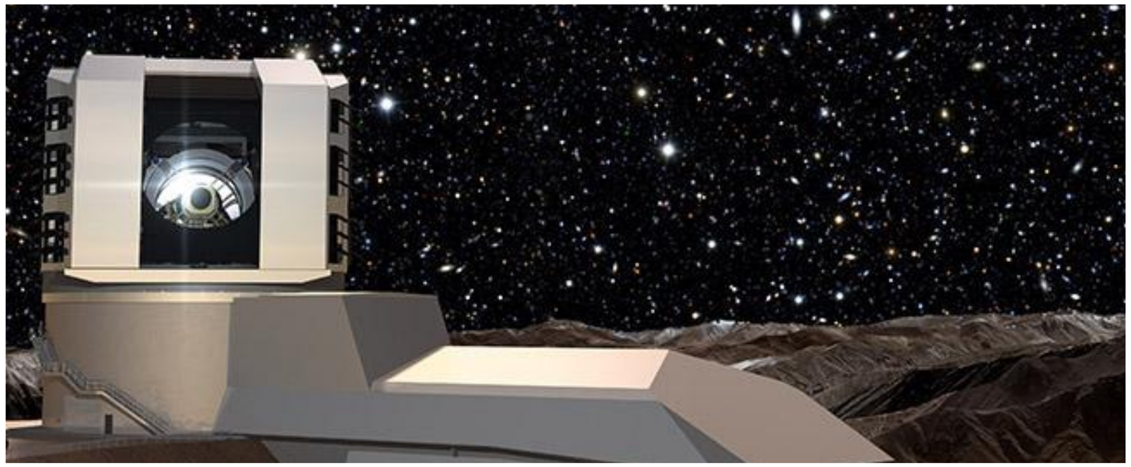
Summary



- LSST should find ~1,000 strongly lensed SNe Ia (~2 per week). ZTF (starting January) should find 10-20 (and a good amount of core-collapse SNe for both).



- Using our new method, microlensing uncertainties on each time delay from these systems can be reduced to 1%.



- A sub-percent measurement of the Hubble constant should be possible with strongly lensed SNe Ia in the near future.