New gravitational lenses in time domain

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2017/3/23 Seminar @ YITP, Kyoto U.

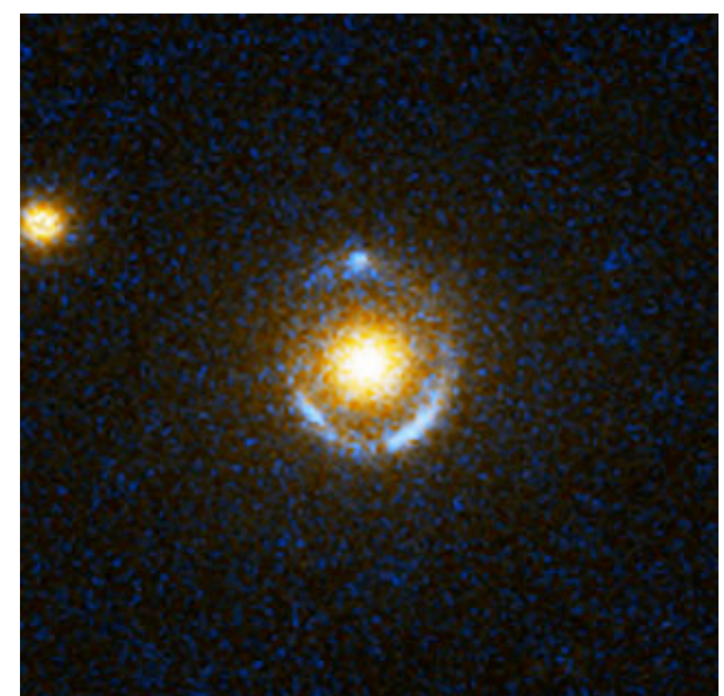
Contents

- gravitationally lensed supernovae
  - PS1-10afx
  - SN Refsdal
  - iPTF16geu
- new fast transients (caustic crossing?)
  - Icarus
  - Spock

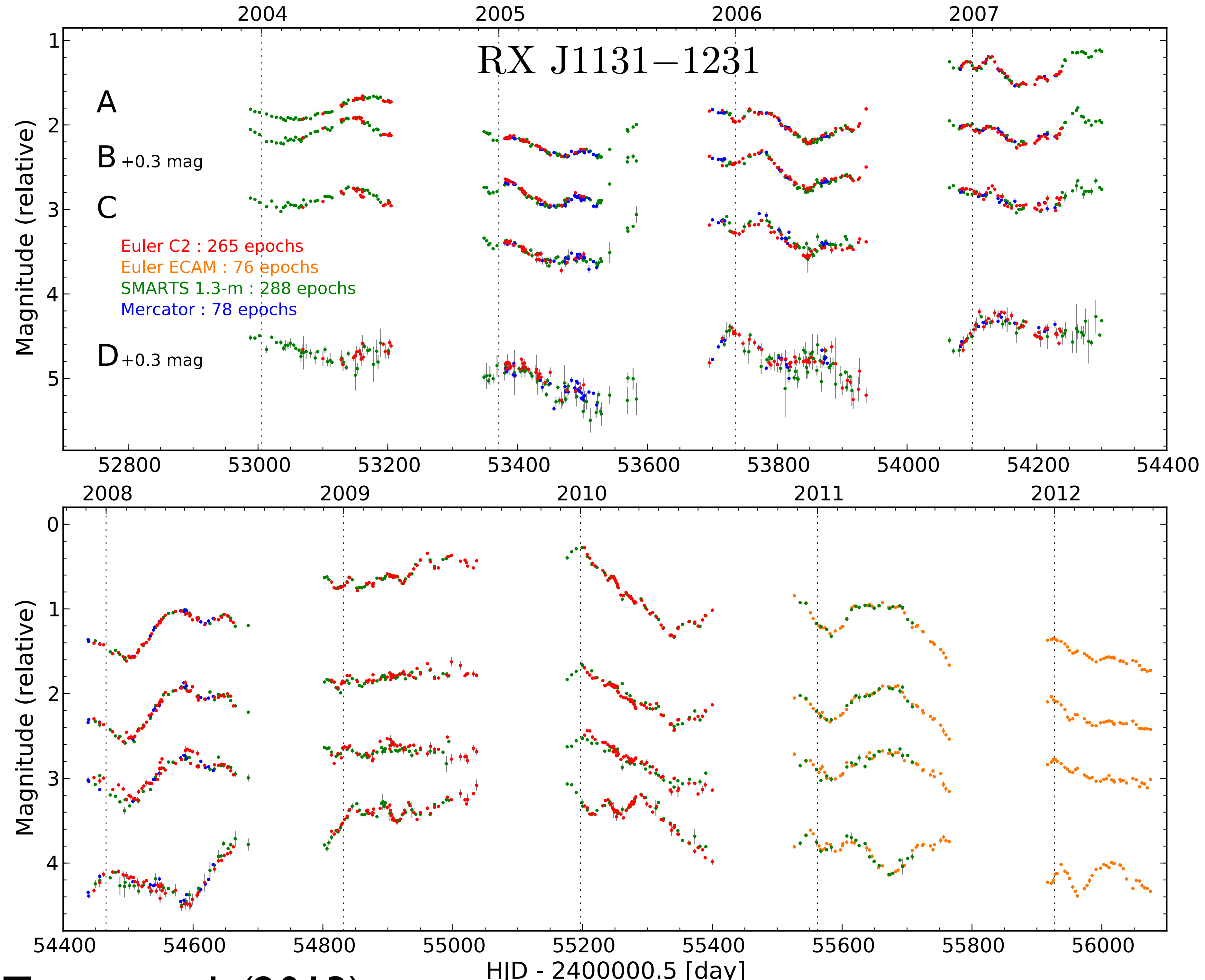
Strong gravitational lenses

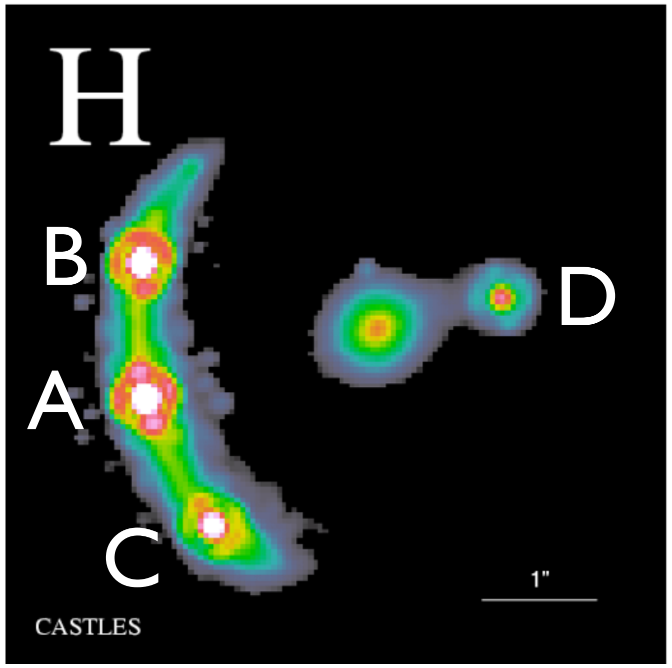
- multiply imaged, highly magnified
- many applications
  - cosmology
  - structure/evolution of galaxies
  - distant/faint sources
  - resolving fine structure

lensed quasar (SQLS)


lensed galaxy (SLACS)

Time delay





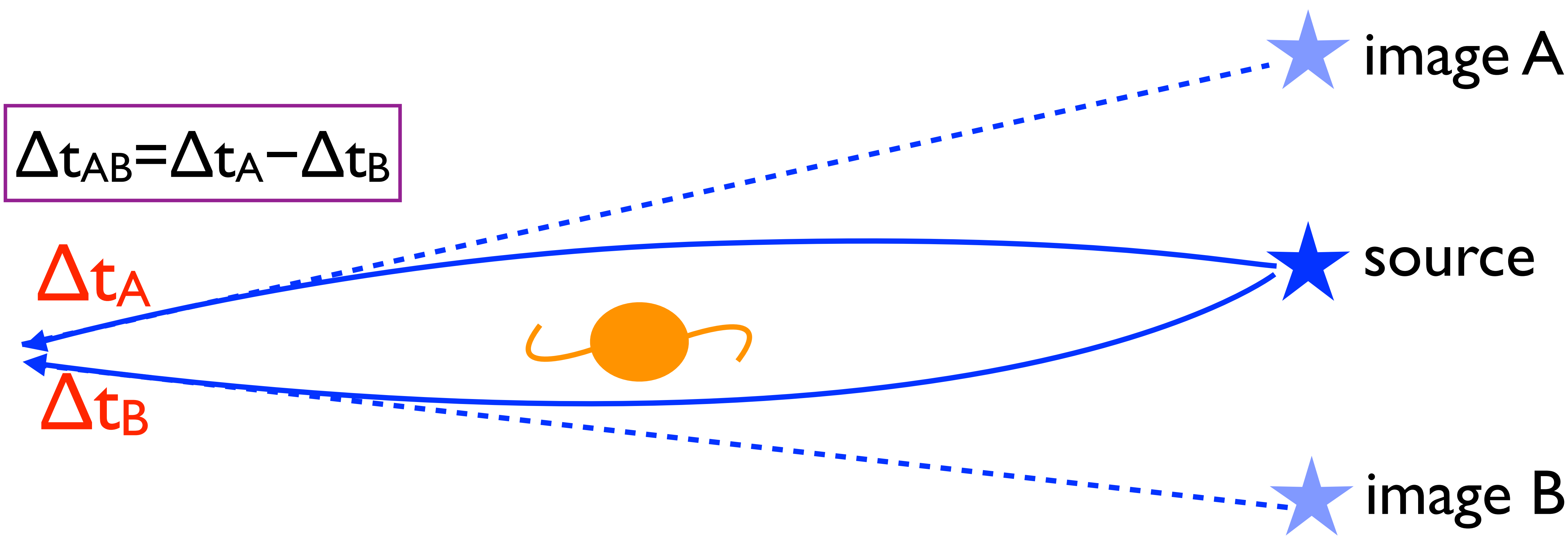
Tewes et al. (2013)

quasars are time-variable

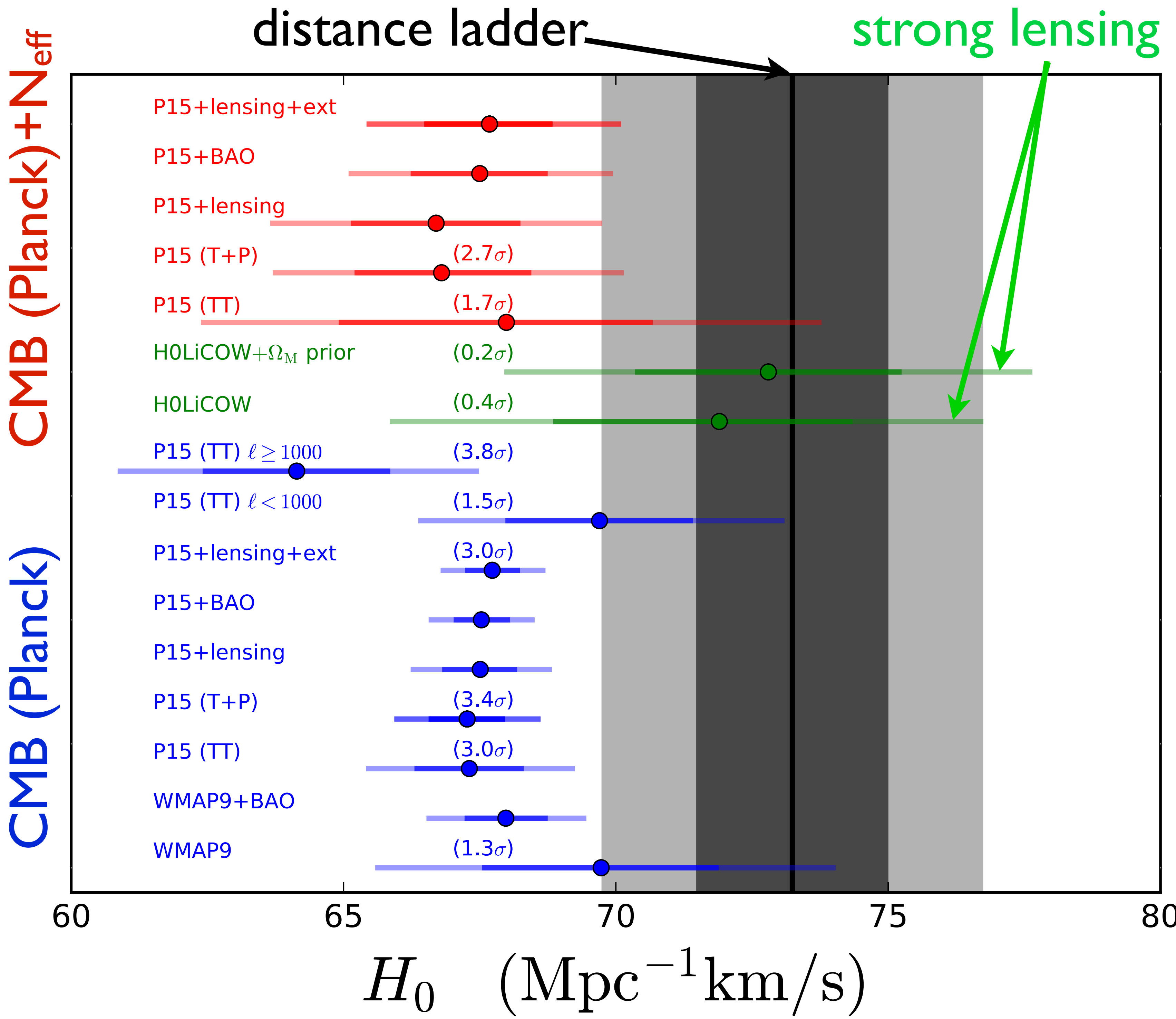
→ measure time delays btw multiple images

Time delay cosmology

- time delays measure the absolute distance scale of the Universe (Refsdal 1964)
- providing important constraints on H_0
  e.g. $H_0 = 68 \pm 6 \pm 8$ km/s/Mpc (16 lenses, Oguri 2007)
  $H_0 = 70.6 \pm 3.1$ km/s/Mpc (1 lens, Suyu et al. 2010)



Hubble trouble?



Bernal, Verde & Riess (2016)

- H_0 from distance ladder (direct) and CMB (model dependent)
- tension at ~3σ
- systematics, or new physics?

S. Refdal, MNRAS128(1964)307

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

first paper to propose H_0 from time delays

lensing of supernova has been considered!

Challenge: lens potential

$$\Delta t_{ij} = (1 + z_l)\frac{D_A(0, z_l)D_A(0, z_s)}{D_A(z_l, z_s)}(\phi_i - \phi_j)$$

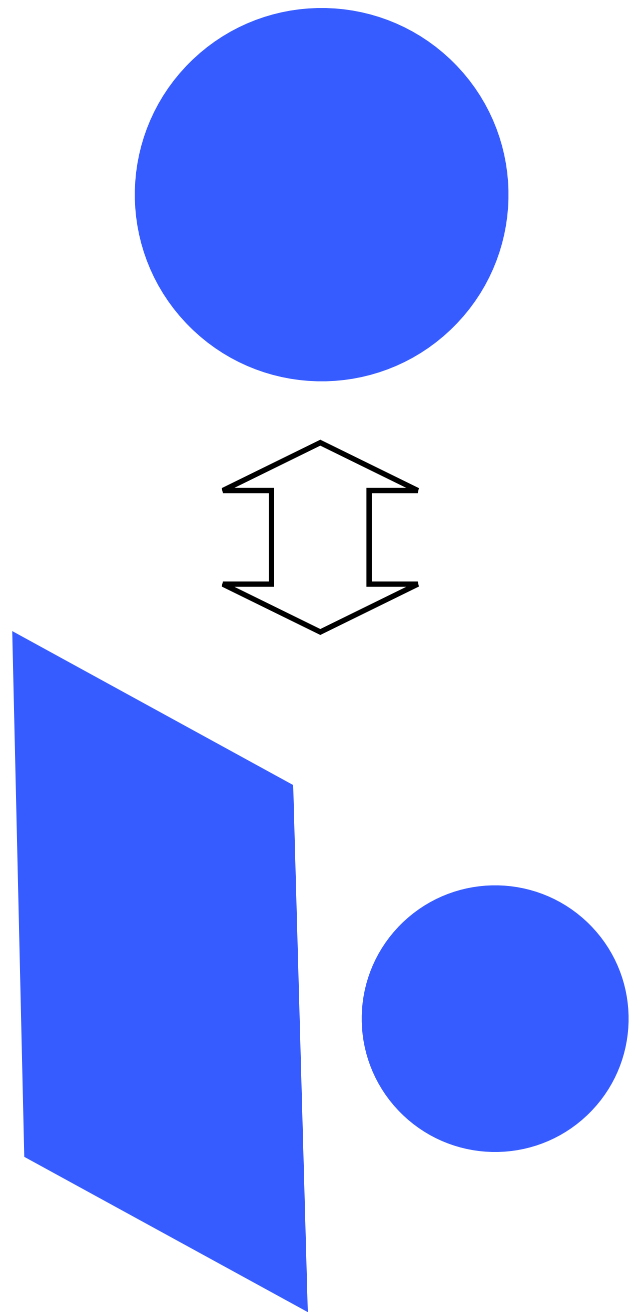
observe this

$\propto H_0^{-1}$

Fermat potential
→ depend on
lens mass dist.

- in order to measure H_0 from time delays we need to constrain lens mass distribution (lens potential) very well
- current main limiting factor for H_0

Mass-sheet degeneracy



- inserting a mass-sheet κ_0 and re-scaling the mass distribution do not change image positions and flux ratios

$$\psi(\vec{\theta}) \rightarrow (1-\kappa_0)\psi(\vec{\theta}) + (\theta^2/2)\kappa_0$$

- but it changes H_0 inferred from time delays

$$H_0 \rightarrow (1-\kappa_0)H_0$$

- this degeneracy implies other approximate degeneracies (e.g., slope-H_0 degeneracy)

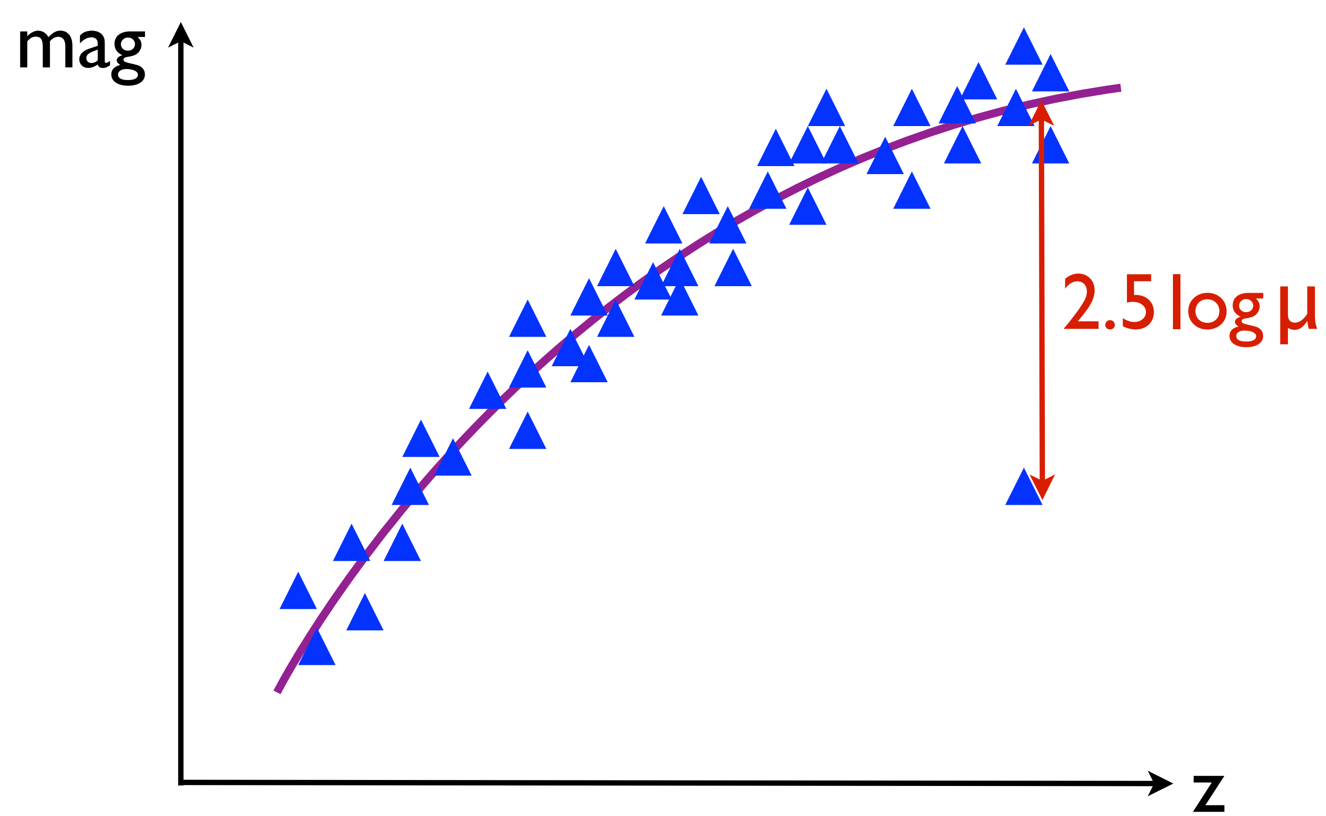
Time delay cosmology (as of 2014)

- ~150 lensed quasars know
  ~20 of them have measured time delays
- no strongly lensed supernova known
- why lensed supernova (SN)?

Why is lensed SN interesting? (I)

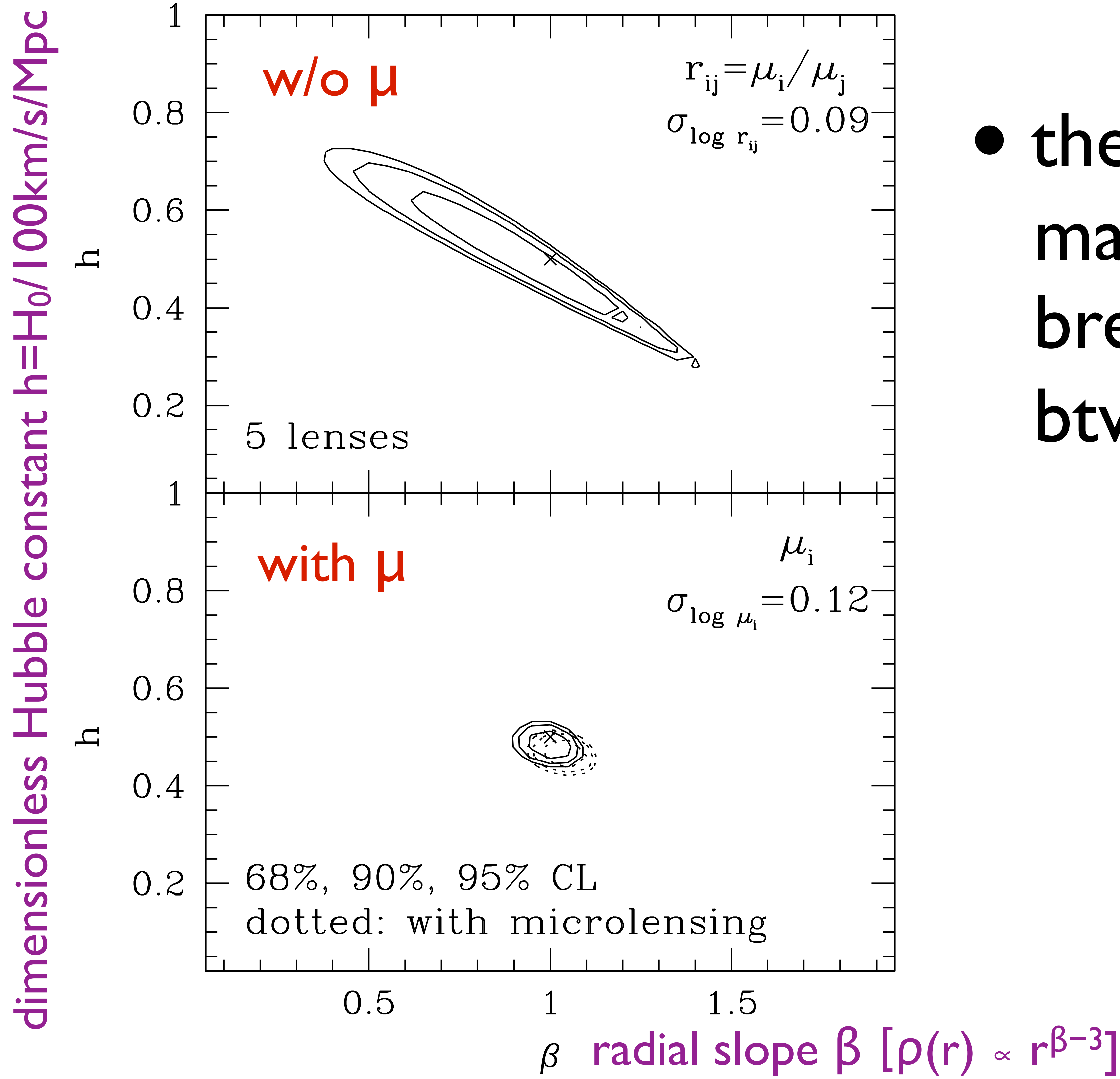
- standard candle
  direct measurement of the magnification factor for lensed type Ia supernovae

→ breaking various (e.g., mass-sheet) degeneracy



Oguri & Kawano MNRAS **338**(2003)L25

Breaking the H_0-slope degeneracy



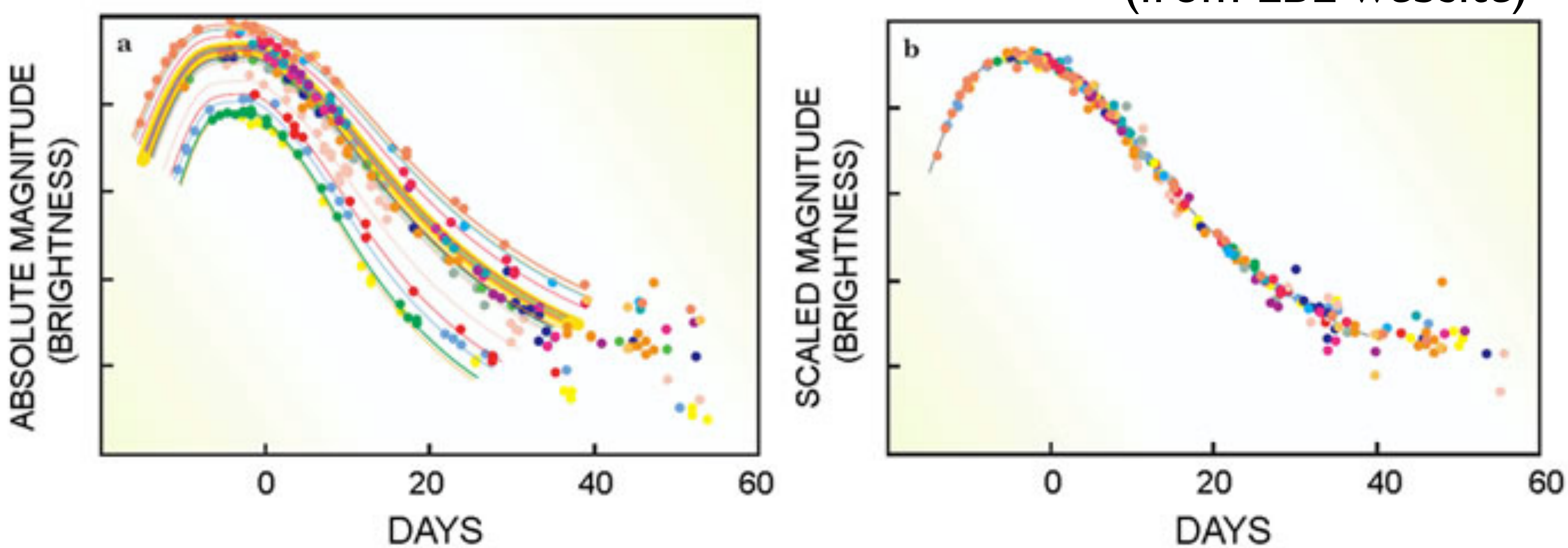
- the use of total magnifications μ breaks degeneracy btw H_0 and β

Why is lensed SN interesting? (II)

- known light curves
  we have template light-curves of SNe

→ accurate and robust time delay measurements

(from LBL website)

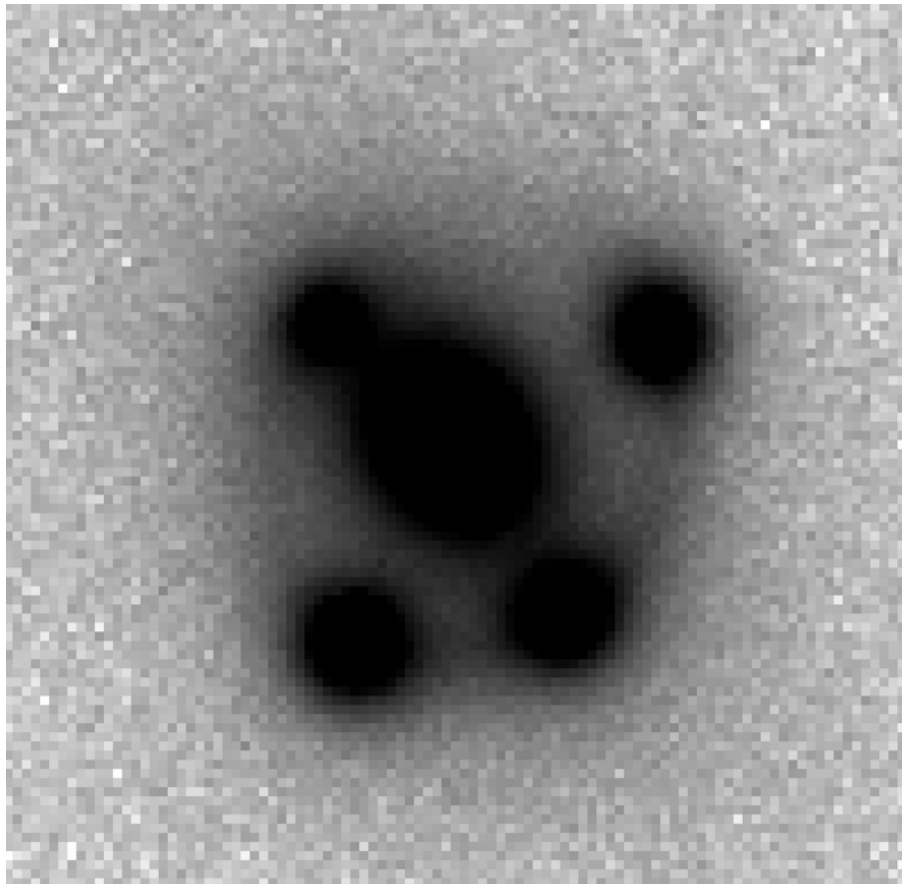


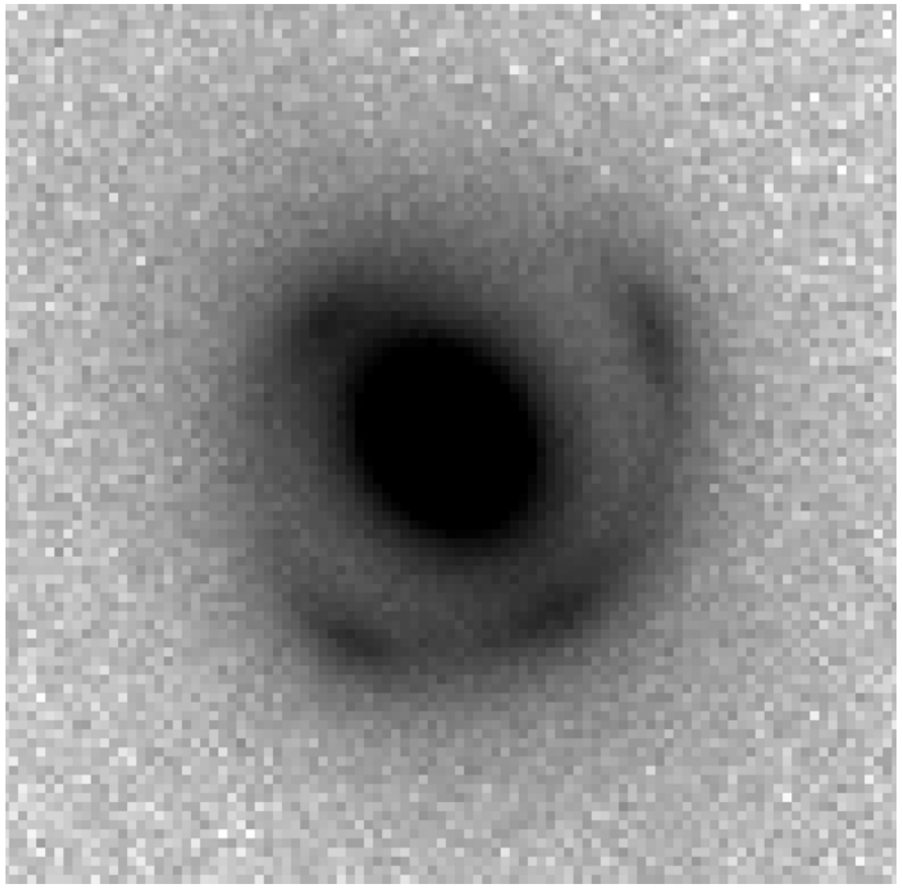
Why is lensed SN interesting? (III)

- better use of host galaxy
  better measurement of detailed morphology of lensed host galaxy after SN fades away

→ better constraints on the lens potential

w/ SN images



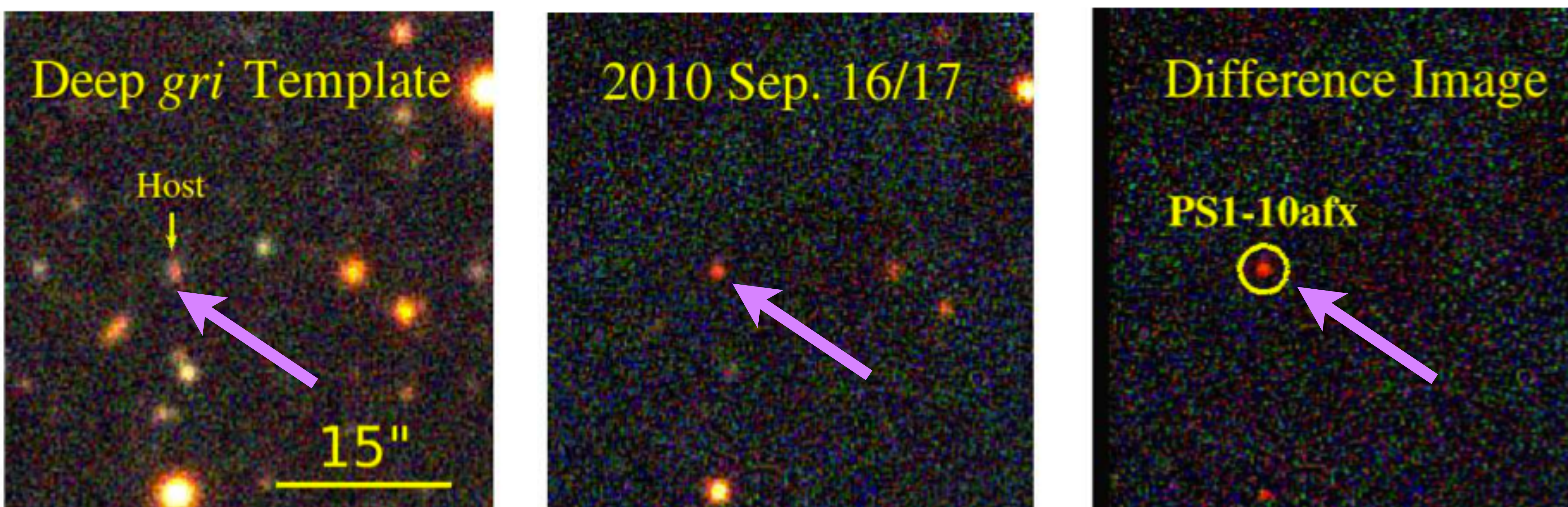


w/o SN images

simulated by *glafic*

Discovery of PS1-10afx

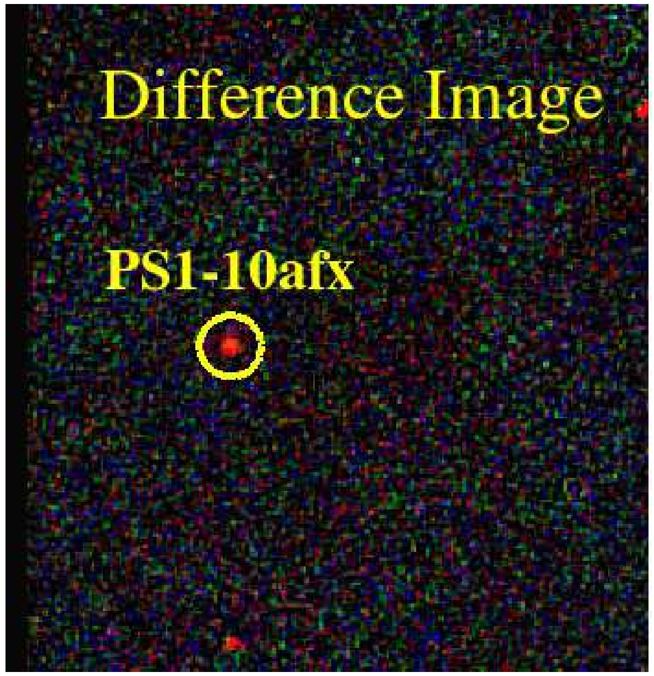
- unusually red transient at z=1.388 found on Aug 31, 2010 in the PS1 Medium Deep Survey (MDS)
- PS1 team concluded that it is a new class of super-luminous supernova (SLSN), but no physical model of SLSN can explain this event

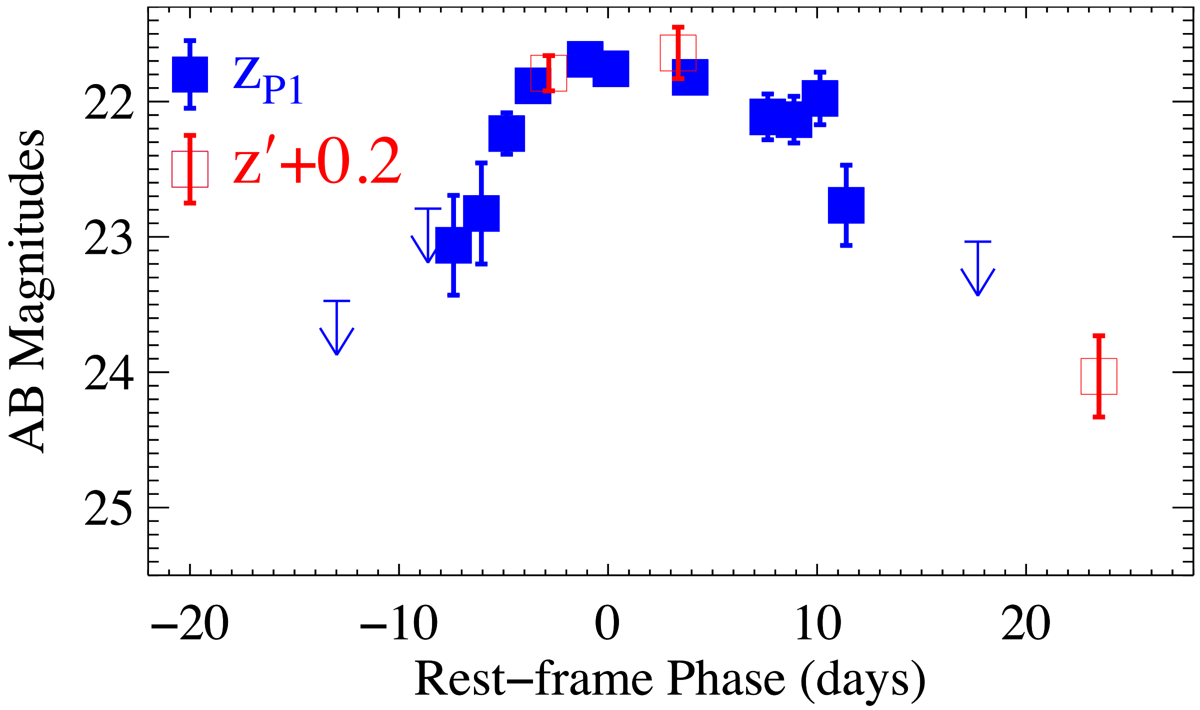


Chornock et al. (2013)

Properties of PS1-10afx

- very luminous
  one of the most luminous known supernovae
- very red
  unlike other SLSNe, it is very red (T~6800K)
- very fast
  light curve rise and fall unusually fast (~10 days)





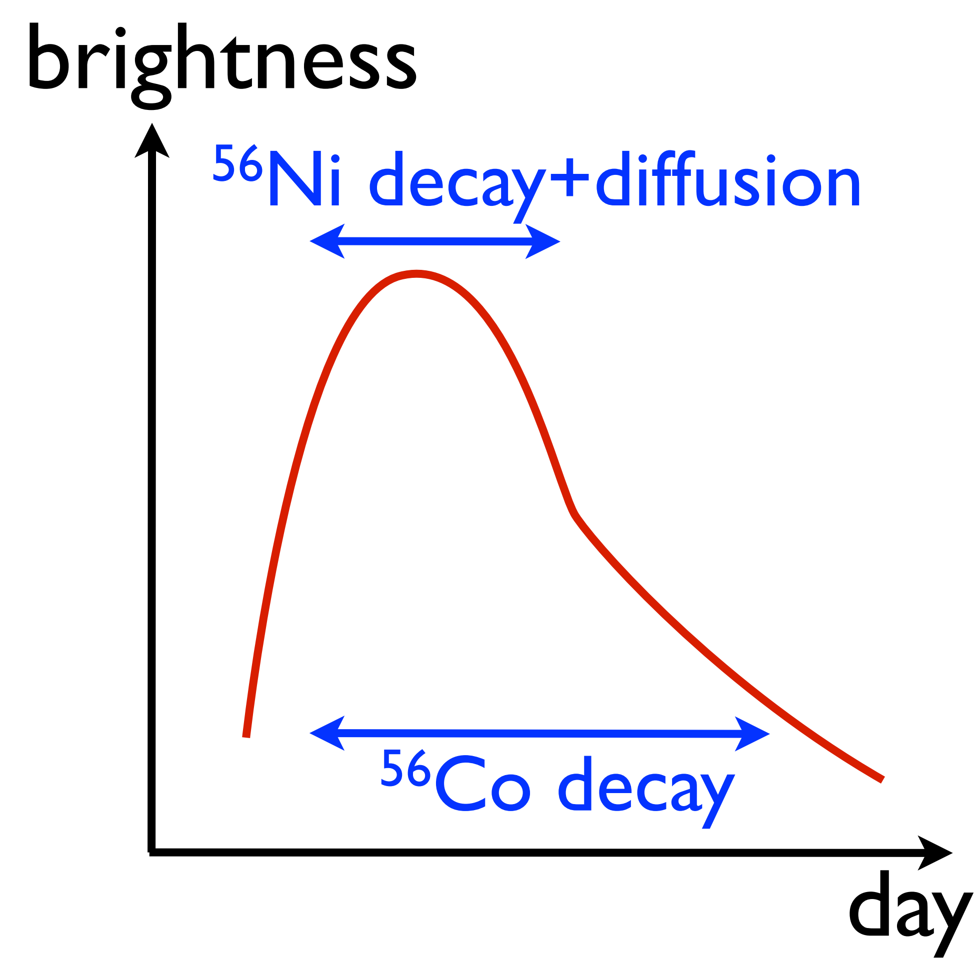
Chornock et al. (2013)

Physical models?

- main source of brightness is radioactive decay of ^{56}Ni
- photon diffusion time scale determines the width of light curve
- luminous SN requires high Ni mass, leading to larger diffusion time
- impossible to explain high luminosity and fast light curve simultaneously

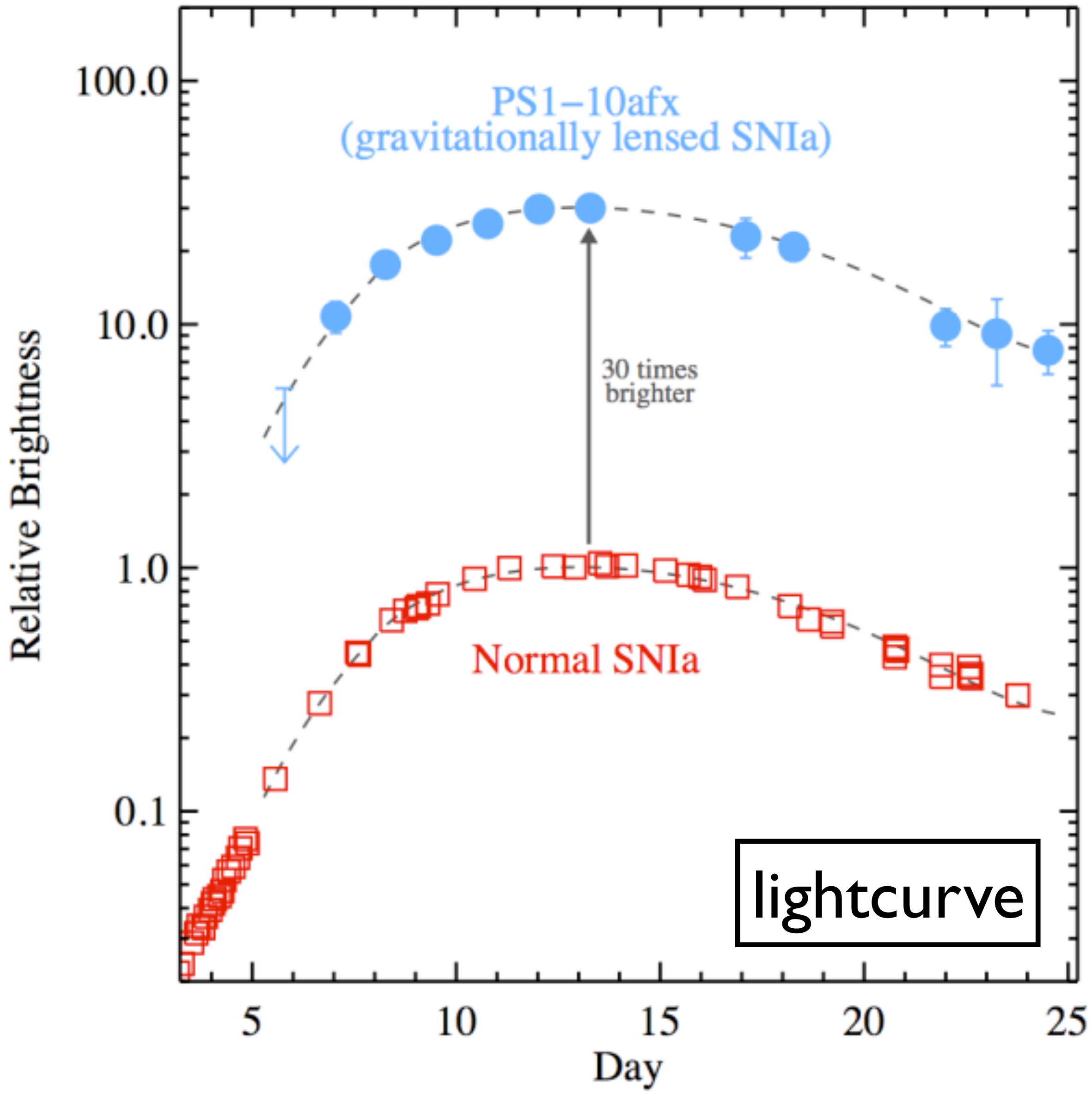
$$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$$

~6day ~77day

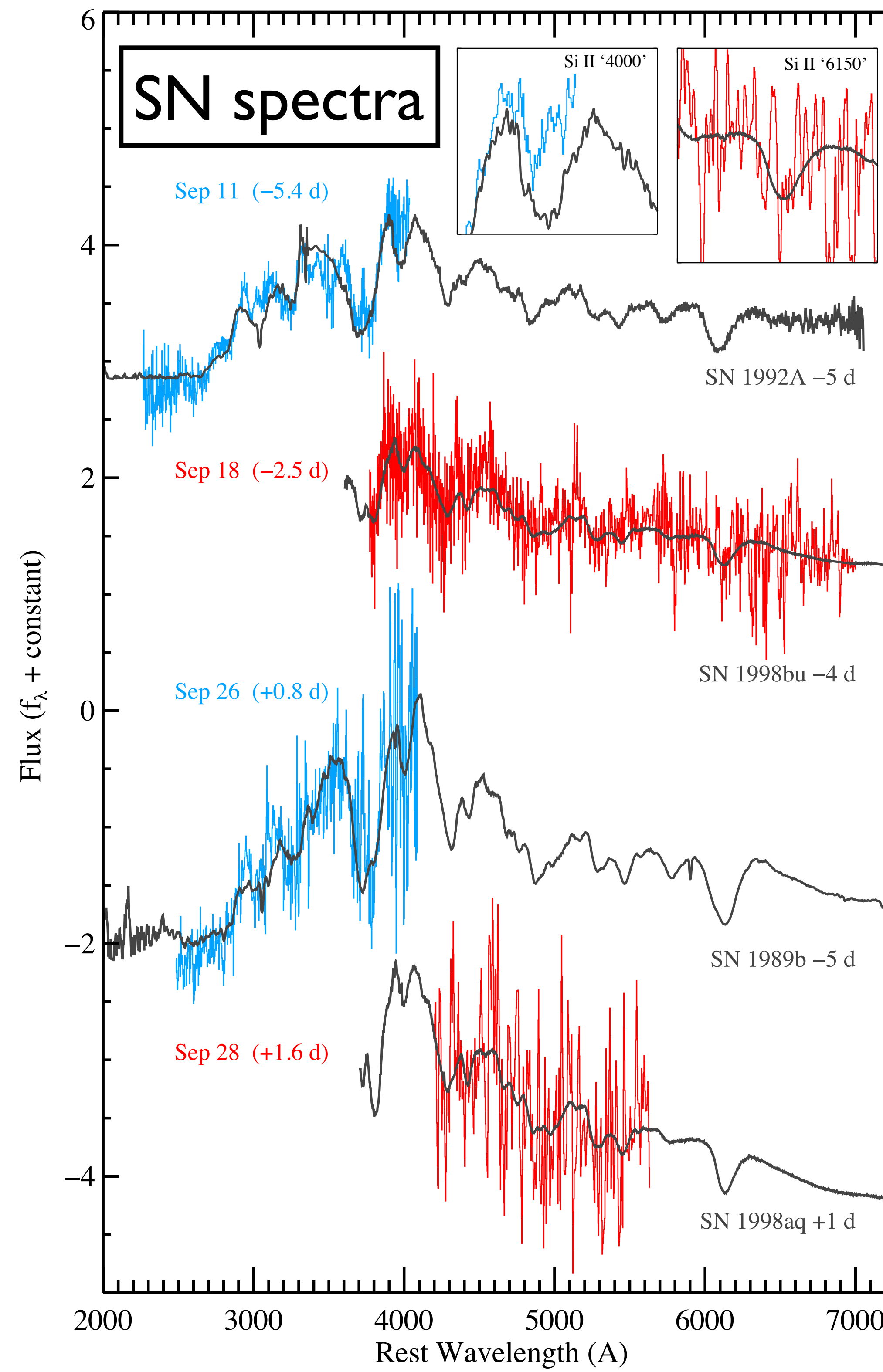


Quimby, Werner, Oguri, et al. ApJ **768**(2013)L20

Type Ia interpretation

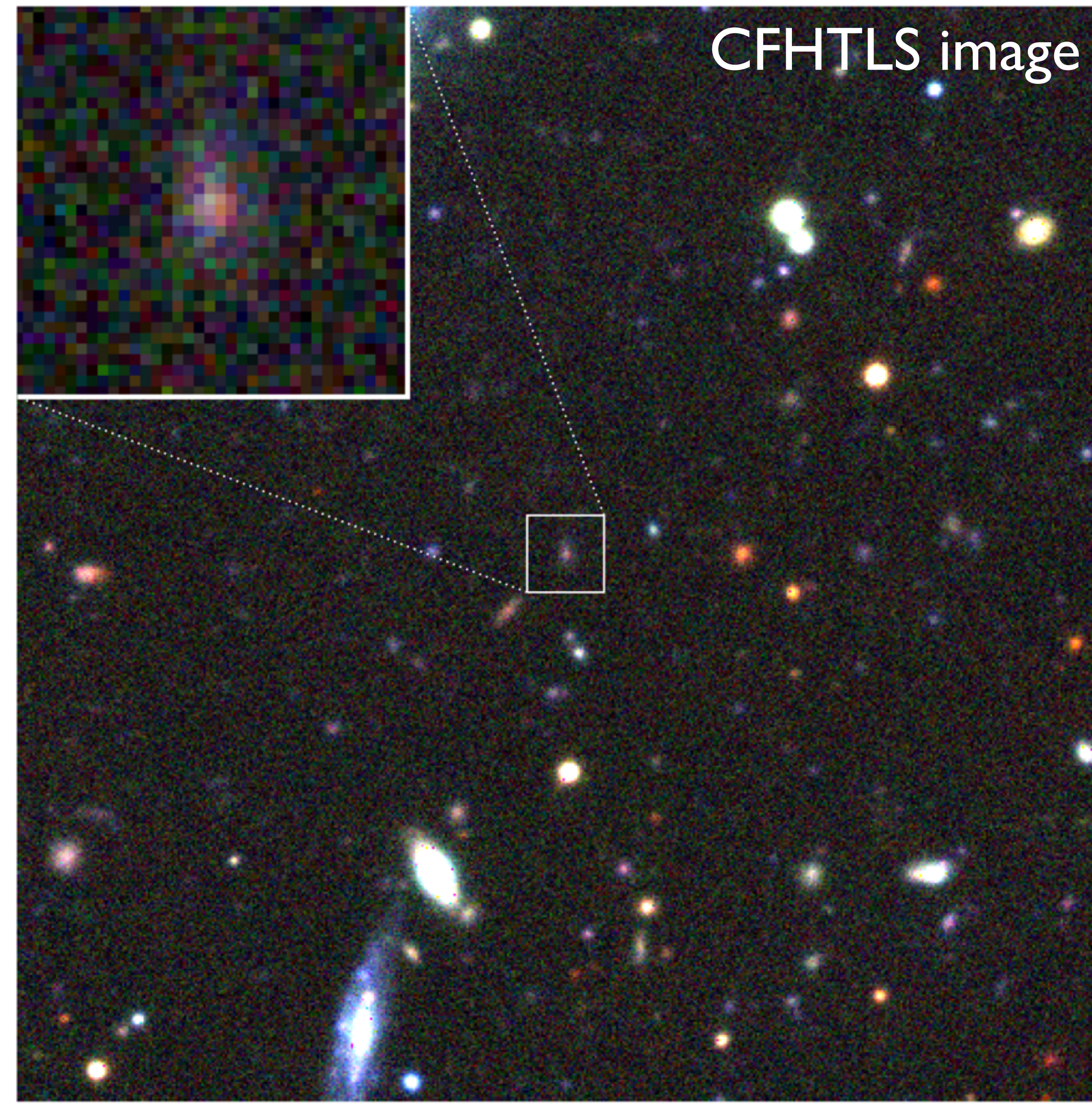


lightcurve and spectra consistent with 30x magnified type Ia SN



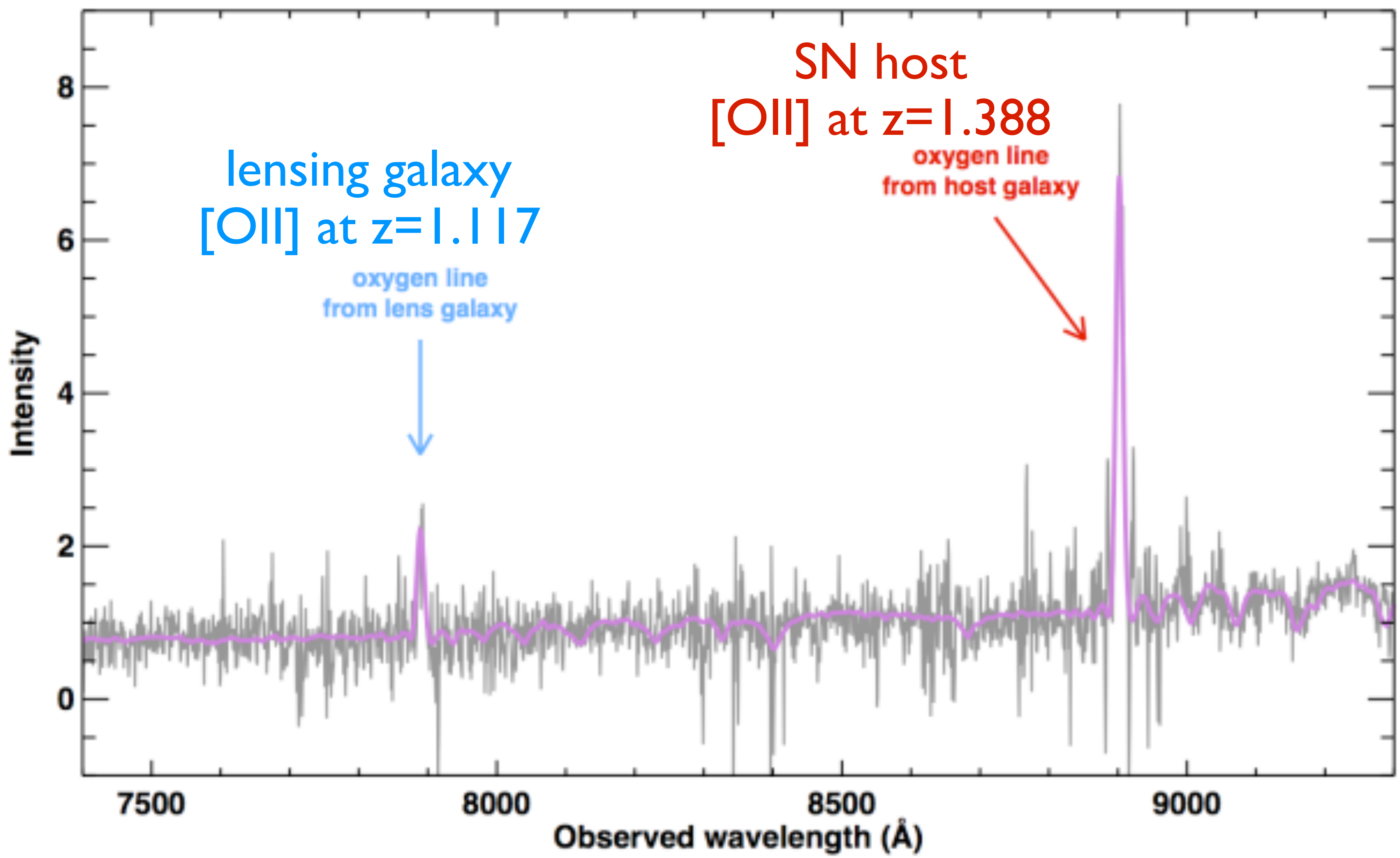
Criticism: where is the lens?

- image before SN exploded shows only one galaxy
- we speculated that this is in fact a superposition of two galaxies, SN host and foreground lens
- 6.5 hr Keck spectroscopy on Sep 7, 2013 to find out true nature of this object



Quimby, Oguri, et al. Science **344**(2014)396

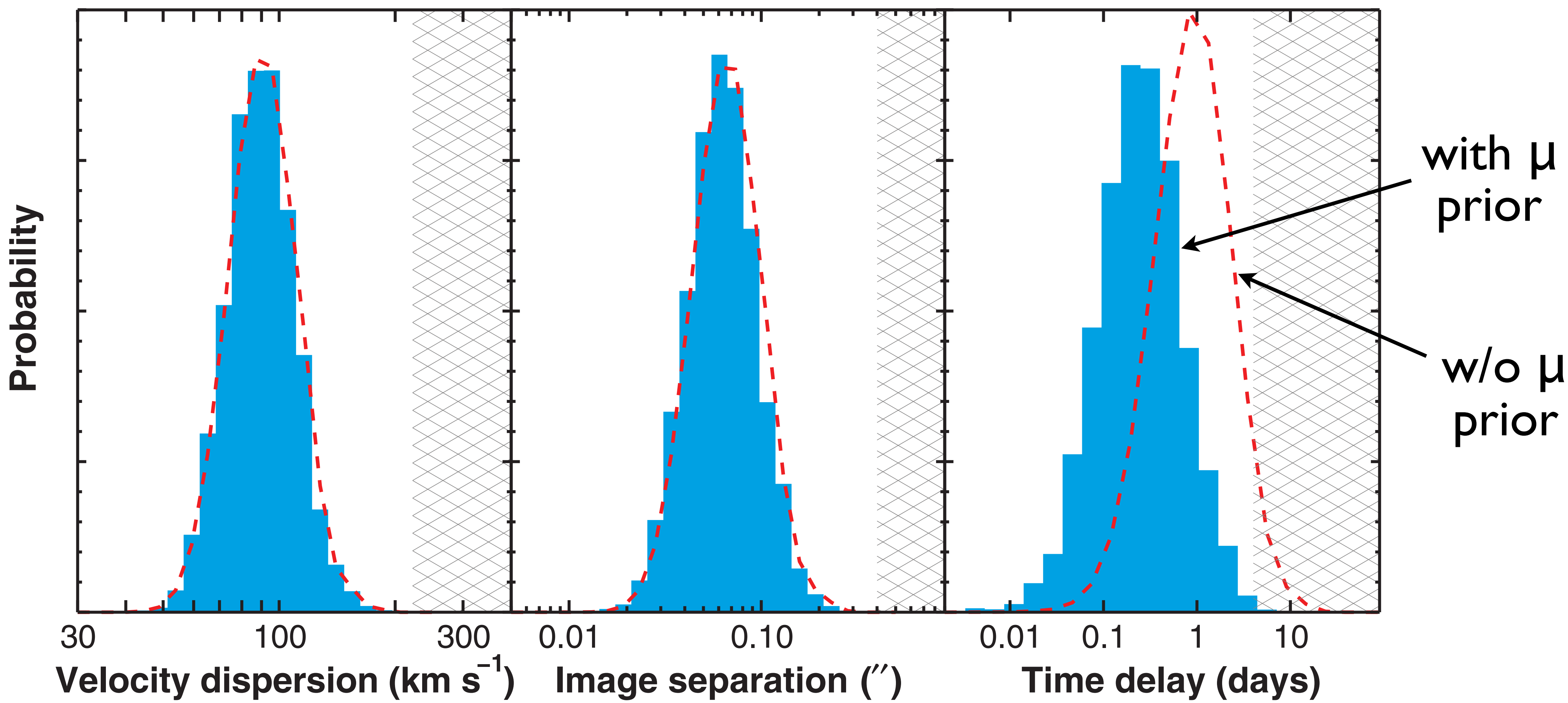
Detection of the lensing galaxy



- foreground lensing galaxy at z=1.117 discovered !

Quimby, Oguri, et al. Science **344**(2014)396

Property of the lensing galaxy



- stellar mass $M_* \sim 9\times10^9 M_\odot$ → lens parameters
- small image separation and time delay consistent with the observation

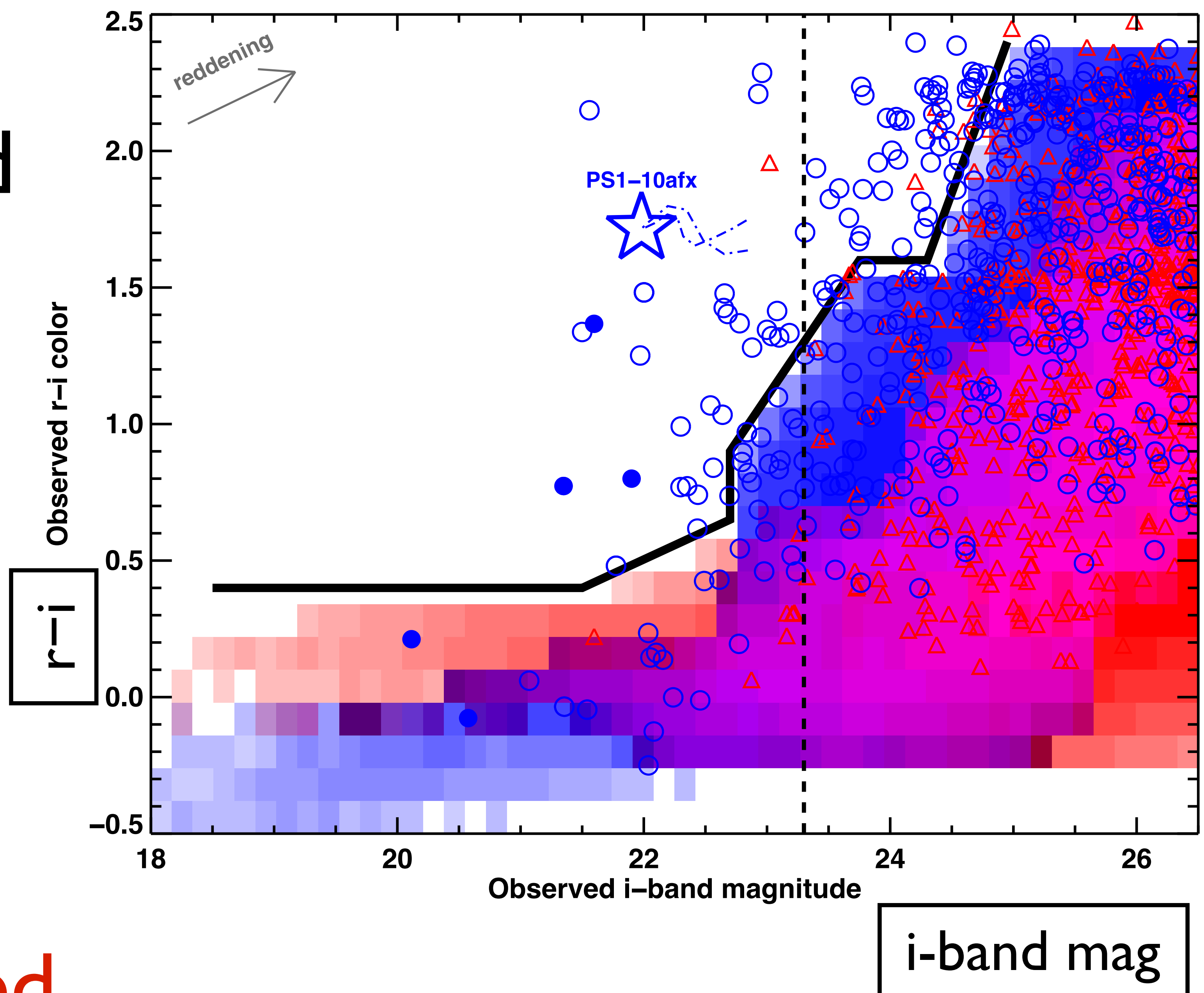
Consistent with expectation?

- Oguri & Marshall (2010) predicted ~0.1 lensed SNIa in PS1-MDS
- however, it assumed multiple images be resolved and detected, unlike PS1-10afx
- updated calculation indicates ~1 lensed SNIa in PS1-MDS, quite consistent with the discovery!

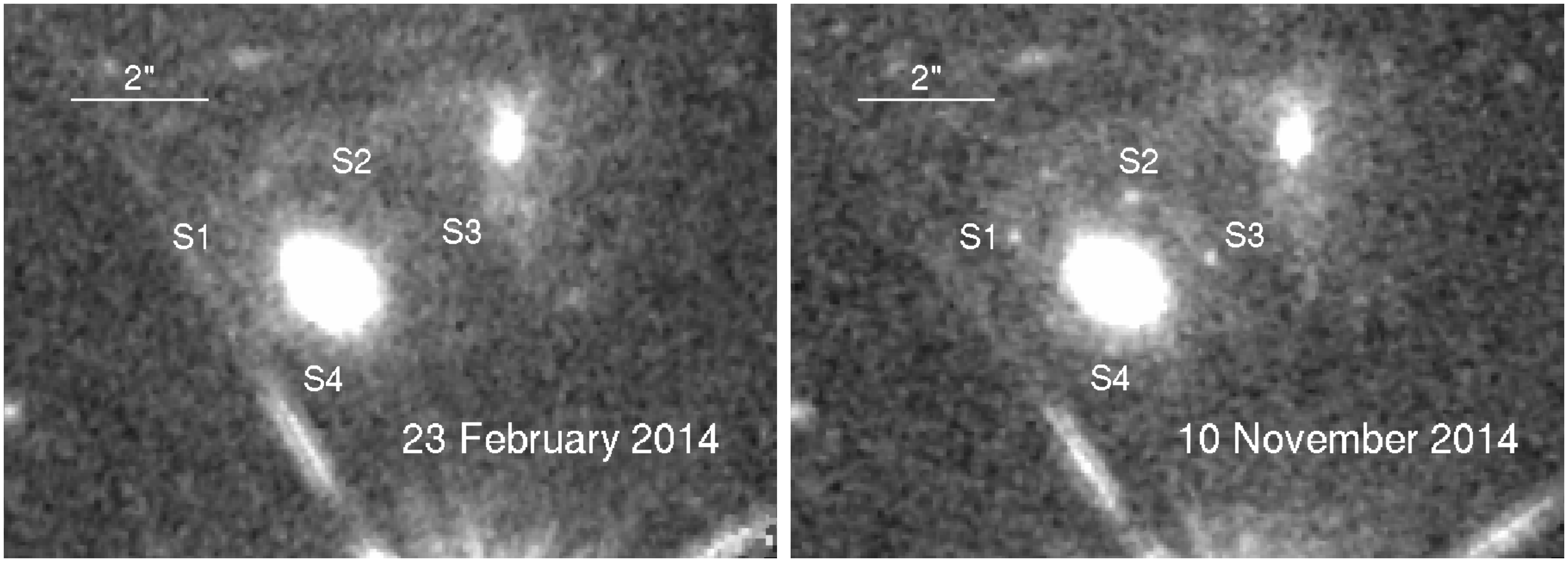
Quimby, Oguri, et al. Science **344**(2014)396

New approach to find lensed SNe

- red, bright SNe are almost always lensed SNe
- find unresolved lens events in surveys, quick follow-up to get multiple images and time delays
- can find ~1000 lensed SNe in LSST!



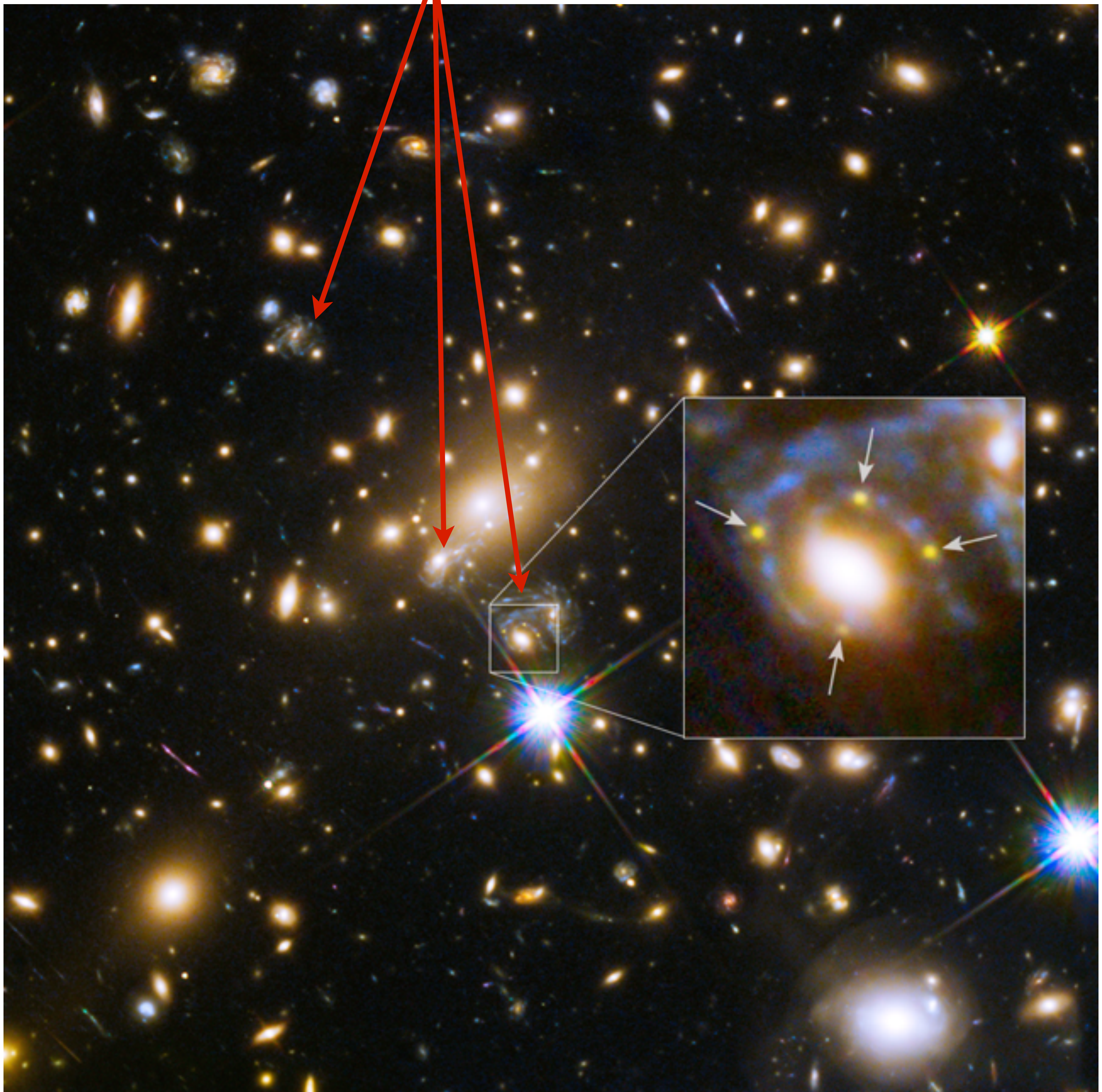
SN Refsdal



- 4 supernova images around an elliptical galaxy
  (z_{SN}=1.49, z_{lens}=0.54)
  → first lensed SN with *resolved* multiple images
  (Kelly et al. 2015 Science, **347**, 1123)

- supernova is not Type Ia, but core-collapse

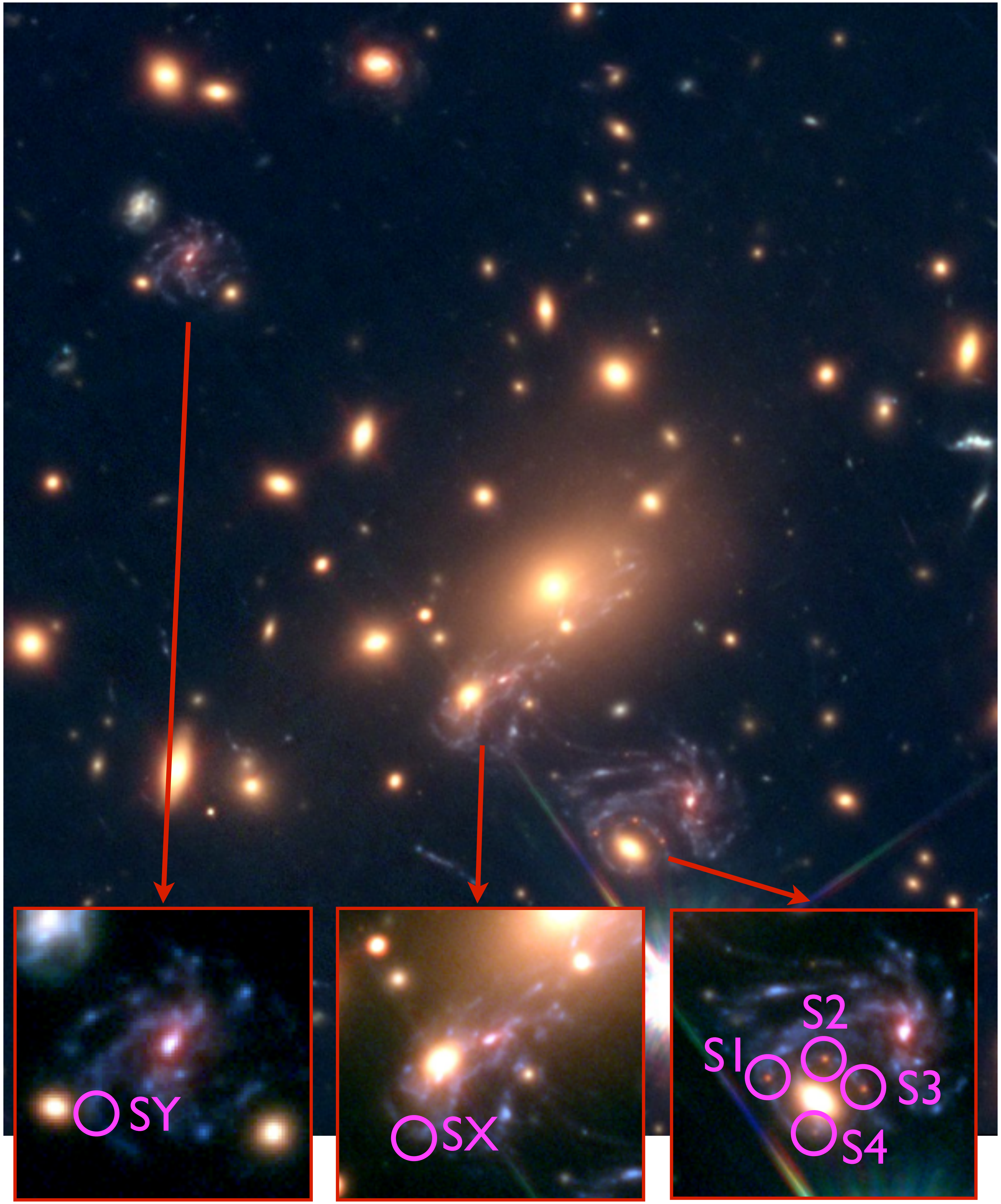
SN host galaxy



hubblesite.org

- discovered in Hubble Frontier Fields project
- massive cluster at z=0.54
- SN host lensed into 3(4) images
- additional SN images?

Oguri MNRAS **449**(2015)L86



SY (~17 years ago)　SX (~1 year later)　S1−S4 (ongoing)

- quick analysis
→ 2 more images in addition to observed 4 images
- SX will appear in one year, SY have appeared 17 years ago
- appearance of SX is a testable prediction!

"Time delay prediction" race

2014/11/23 Kelly et al. arXiv:1411.6009 (discovery paper)

2014/11/24 Oguri arXiv:1411.6443

[$\Delta t_{S4\text{-}S1}$=23days, $\Delta t_{SX\text{-}S1}$=360days, $\Delta t_{SY\text{-}S1}$=−6200days]

2014/11/25 Sharon & Johnson arXiv:1411.6933v1

[$\Delta t_{S4\text{-}S1}$=45days, $\Delta t_{SX\text{-}S1}$=1330days, $\Delta t_{SY\text{-}S1}$=−4900days]

2015/02/03 Sharon & Johnson arXiv:1411.6933v2

[$\Delta t_{S4\text{-}S1}$=7days, $\Delta t_{SX\text{-}S1}$=240days, $\Delta t_{SY\text{-}S1}$=−4300days]

2015/04/22 Diego et al. arXiv: 1504.05953

[$\Delta t_{S4\text{-}S1}$=−−−, $\Delta t_{SX\text{-}S1}$=380days, $\Delta t_{SY\text{-}S1}$=−3300days]

2015/09/30 Jauzac et al. arXiv:1509.08914v1

[$\Delta t_{S4\text{-}S1}$=−16days, $\Delta t_{SX\text{-}S1}$=530days, $\Delta t_{SY\text{-}S1}$=−4200days]

2015/10/14 Jauzac et al. arXiv:1509.08914v3

[$\Delta t_{S4\text{-}S1}$=−60days, $\Delta t_{SX\text{-}S1}$=450days, $\Delta t_{SY\text{-}S1}$=−4700days]

Why are Δt predictions different?

- cluster mass distributions are so complicated that it is difficult to perfectly reproduce image positions (typical position rms ~ 0.4″-2″)

- time delays probe the global lens potential
($\Delta t \sim \psi$, defection $\alpha \sim \partial\psi$, magnification $\mu \sim \partial^2\psi$)

- time delays in cluster-scale lenses should be useful to check the accuracy/validity of cluster mass reconstruction, rather than H_0

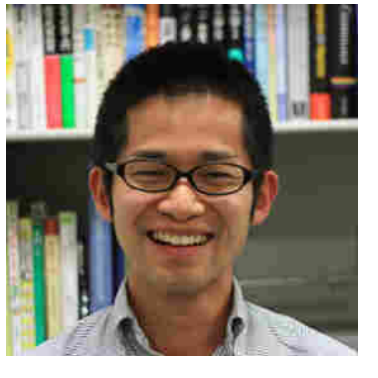
Treu et al. ApJ **817**(2016)60

Comparison project

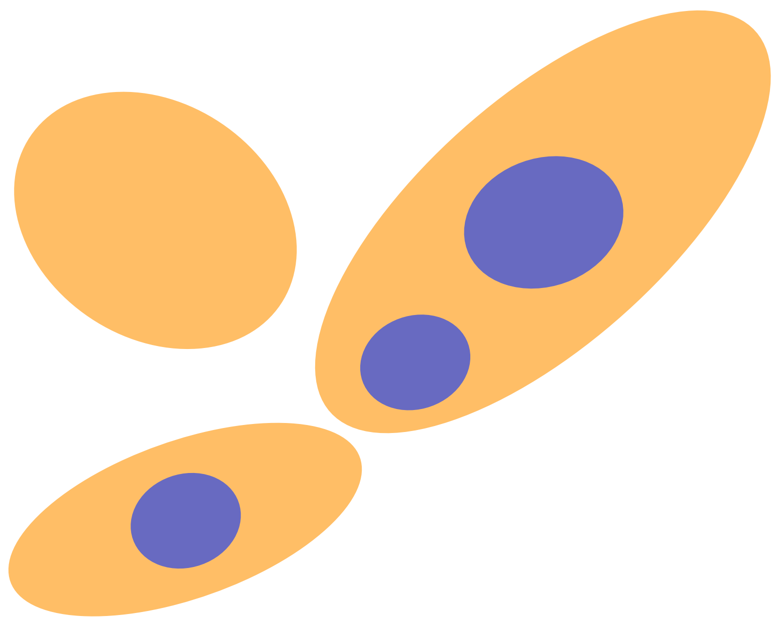
- add more follow-up data, compare modeling results from the same constraints
- participants
  - WSLAP+ (Diego, Broadhurst)
  - GLEE (Grillo, Suyu, Halkola, et al.)
  - glafic (Oguri, Kawamata, Ishigaki)
  - Lenstool (Sharon, Johnson)
  - LTM (Zitrin)





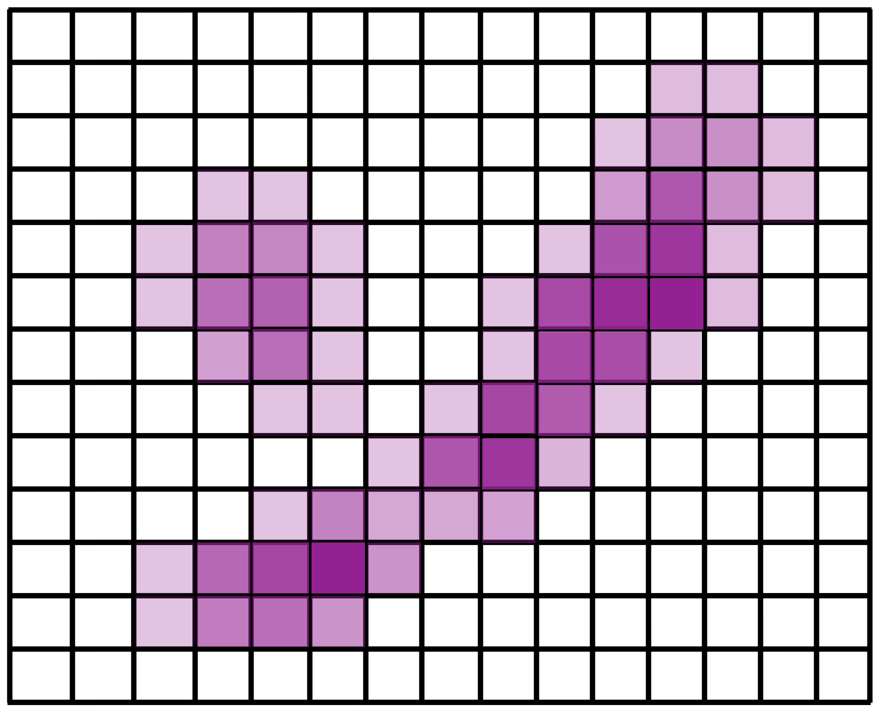



"parametric"



- use several components (galaxy, halo, ...), each component contain several free parameters
- optimize parameters to match data

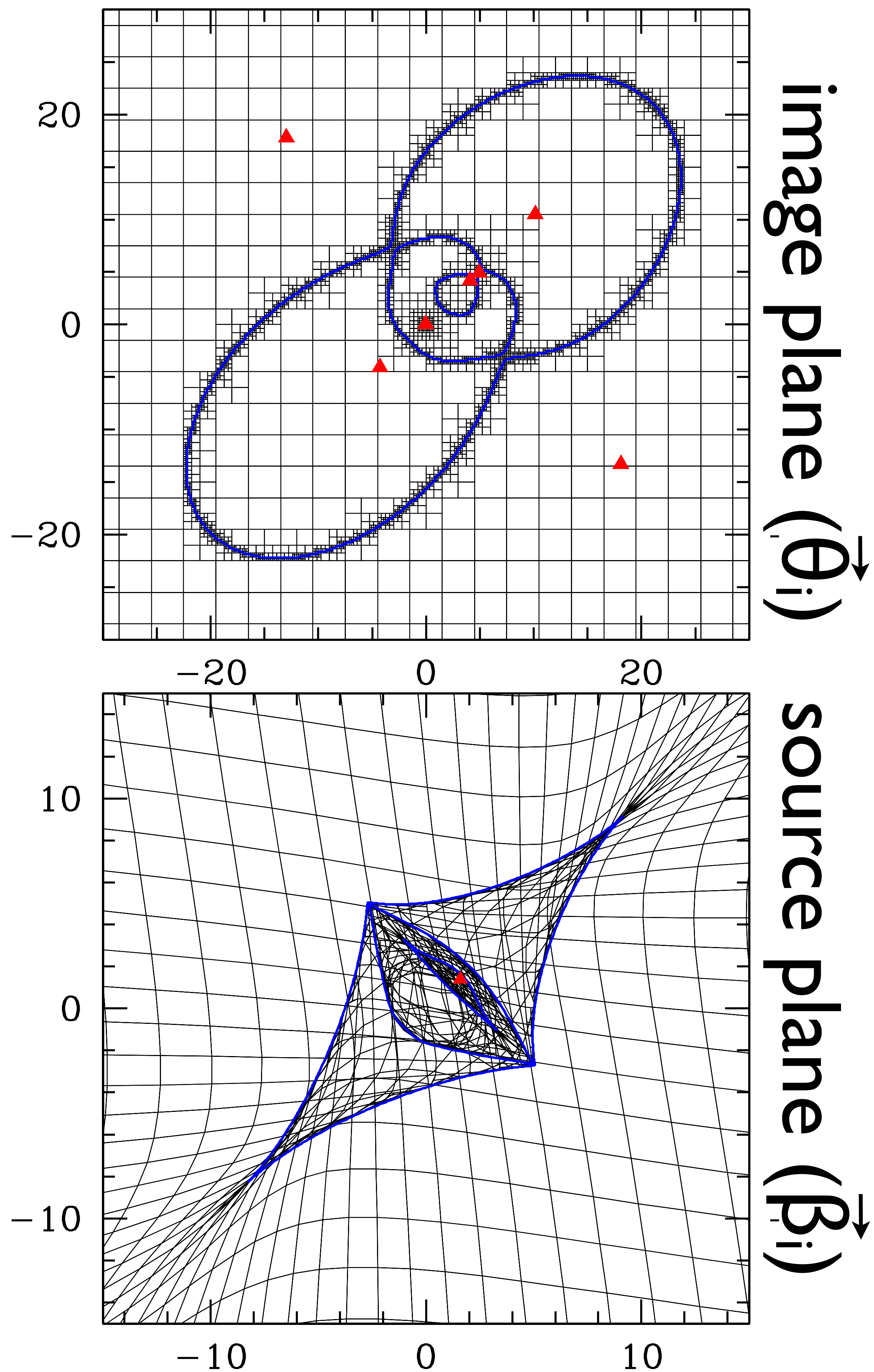
"non-parametric"



- mass dist. by grid data (very flexible)
- optimize grid values to match data

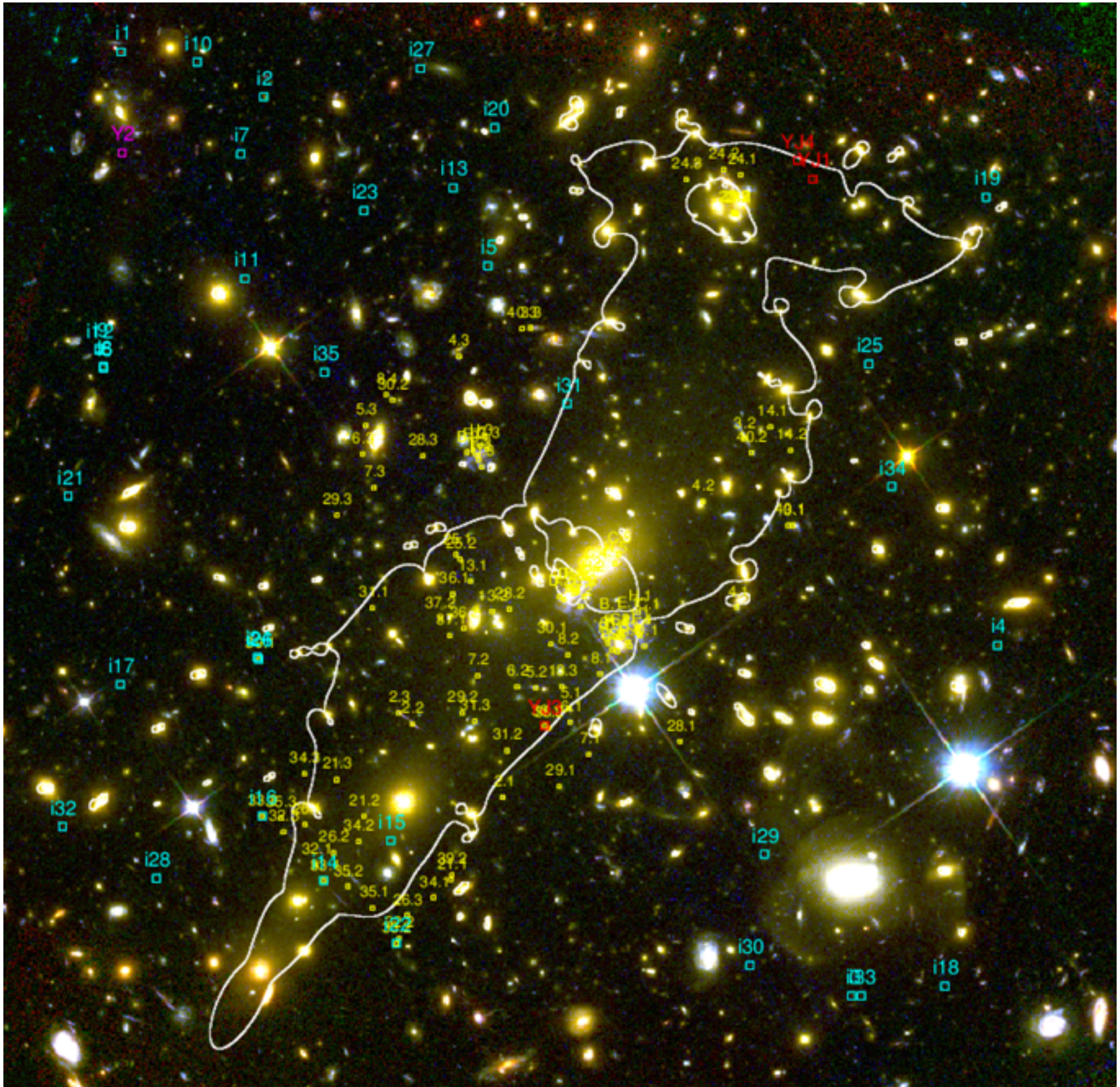
http://www.slac.stanford.edu/~oguri/glafic/

glafic



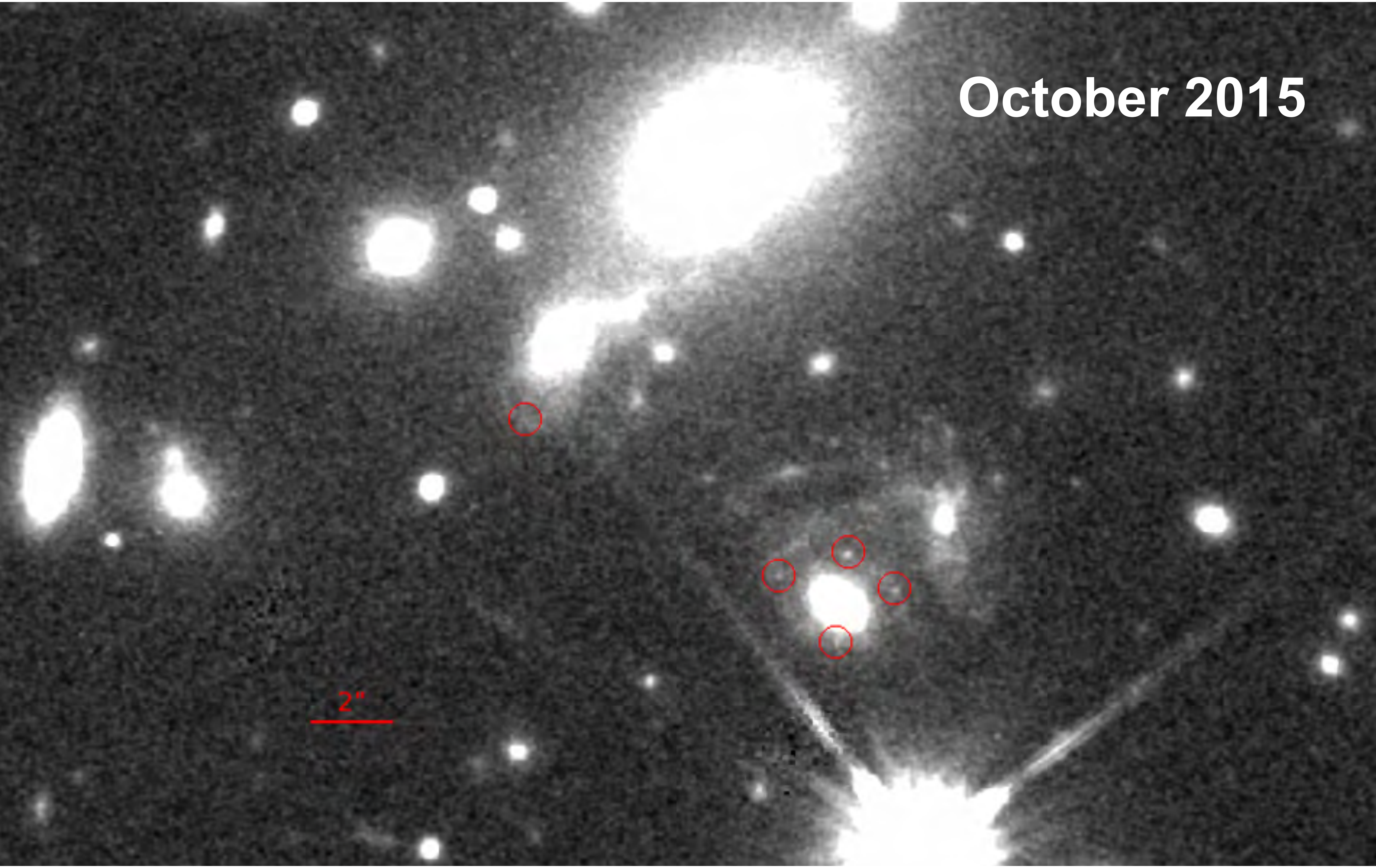
- public software for strong lensing analysis ("parametric" mass modeling)
- adaptive grid to solve lens equation efficiently
- support many lens potentials
- please use!

Kawamata, Oguri, et al. ApJ **819**(2016)114

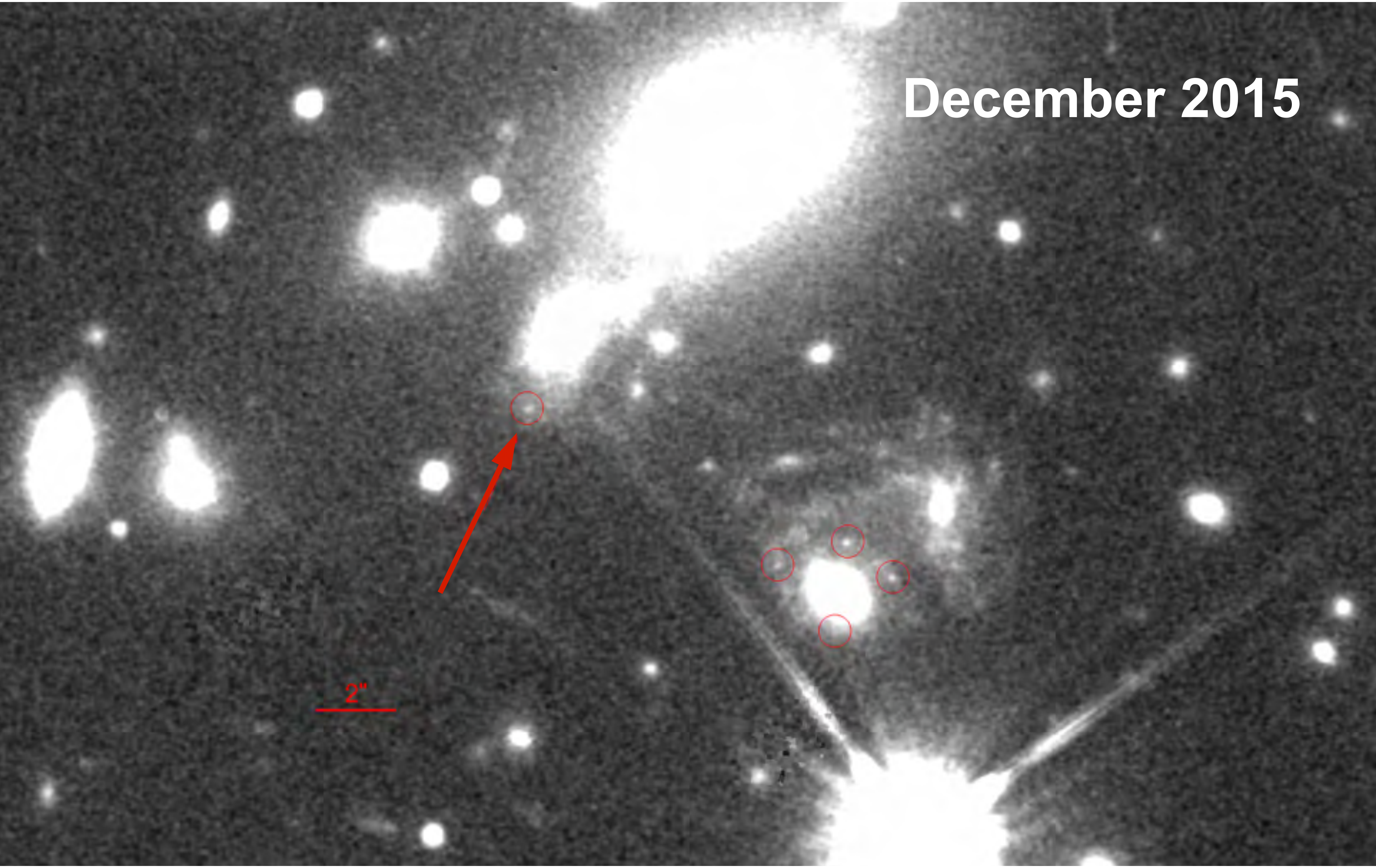


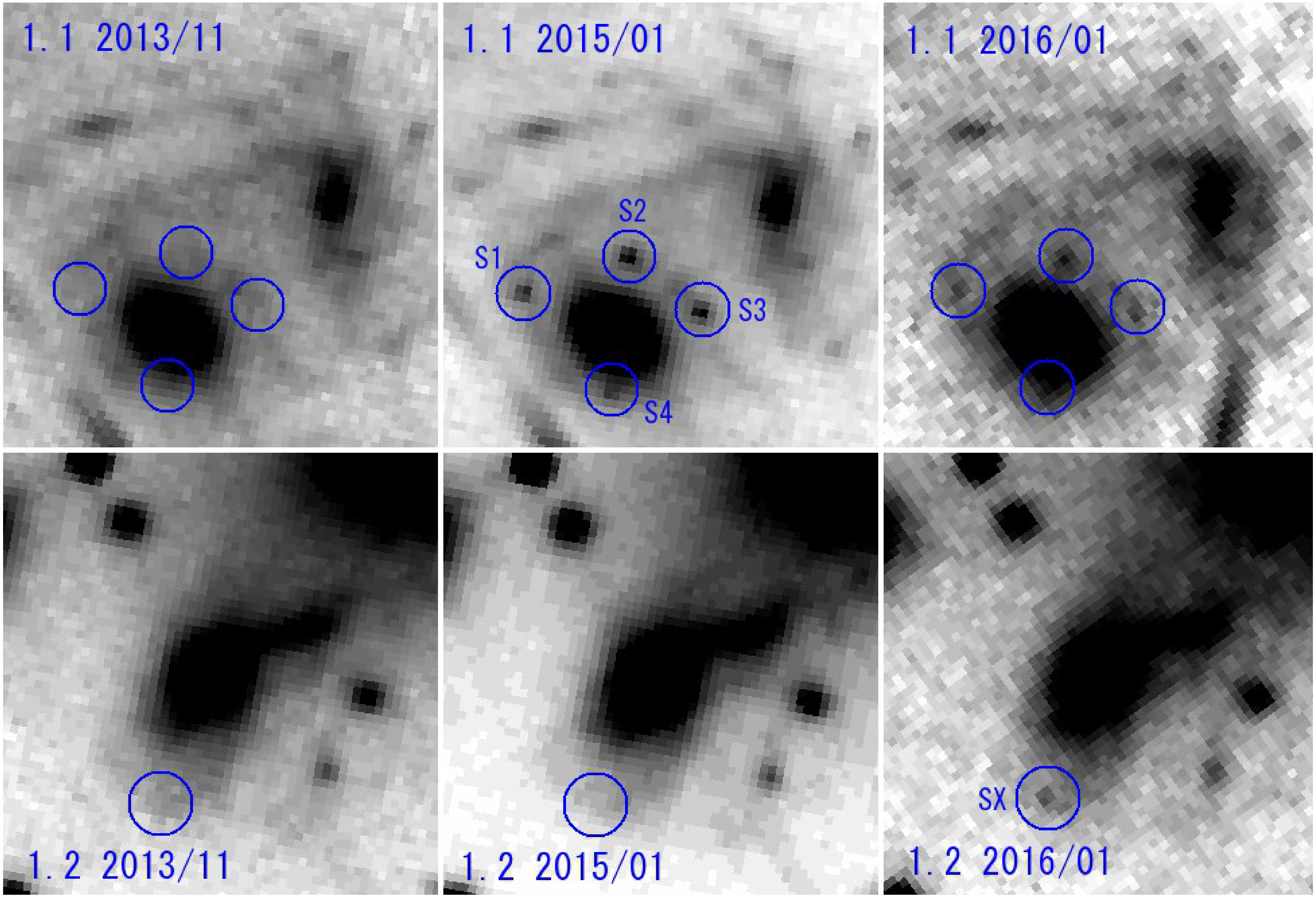
- modeling w/ glafic
- model determined to reproduce positions of >100 multiple images (~200 constraints, ~100 parameters)
- best-fit model reproduce image positions with rms~0.4″ (very good)

HST cycle 23 monitoring (PI: P. Kelly)



HST cycle 23 monitoring (PI: P. Kelly)



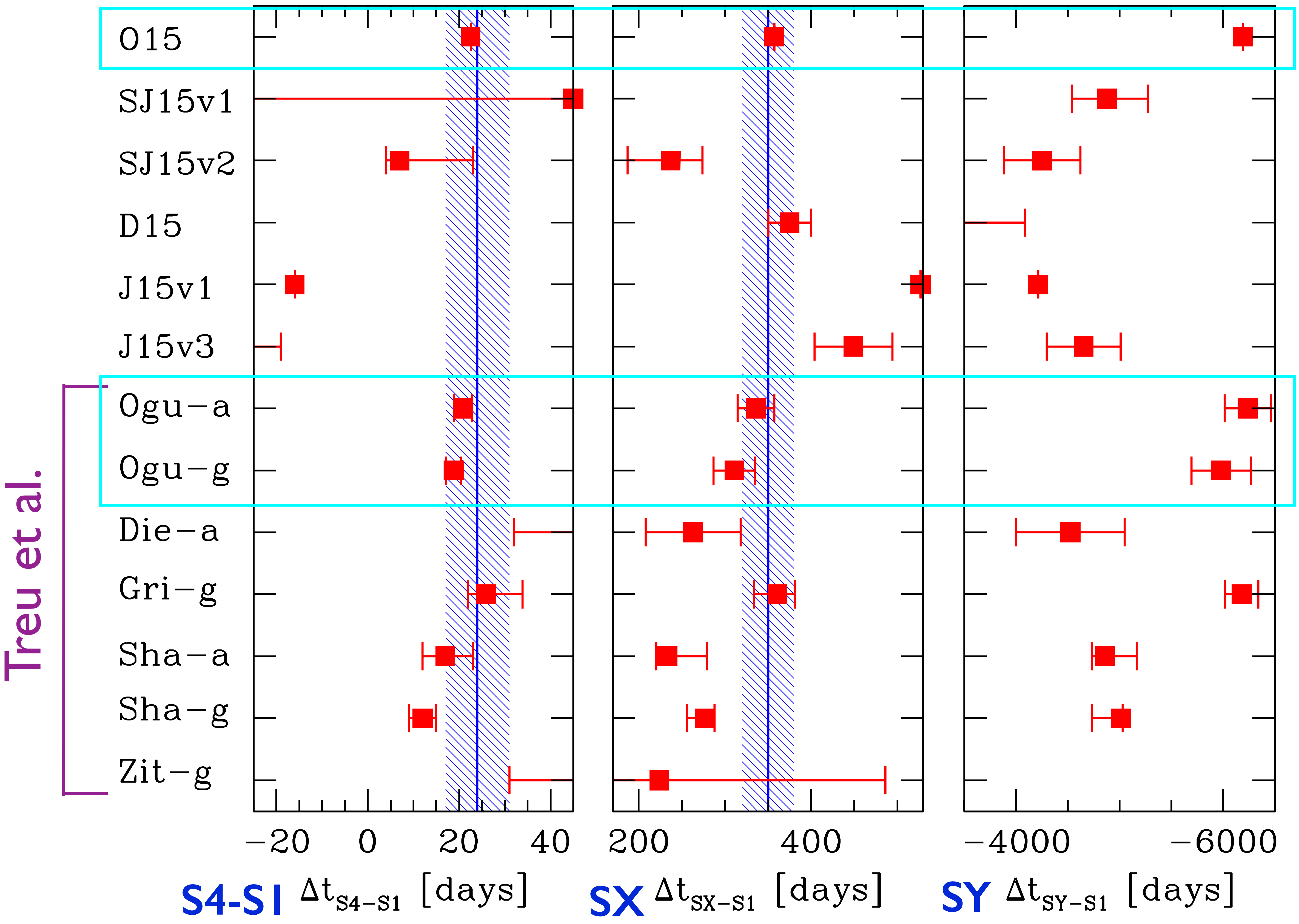


before SN

image S1-S4 appears

image SX appears

Checking answers



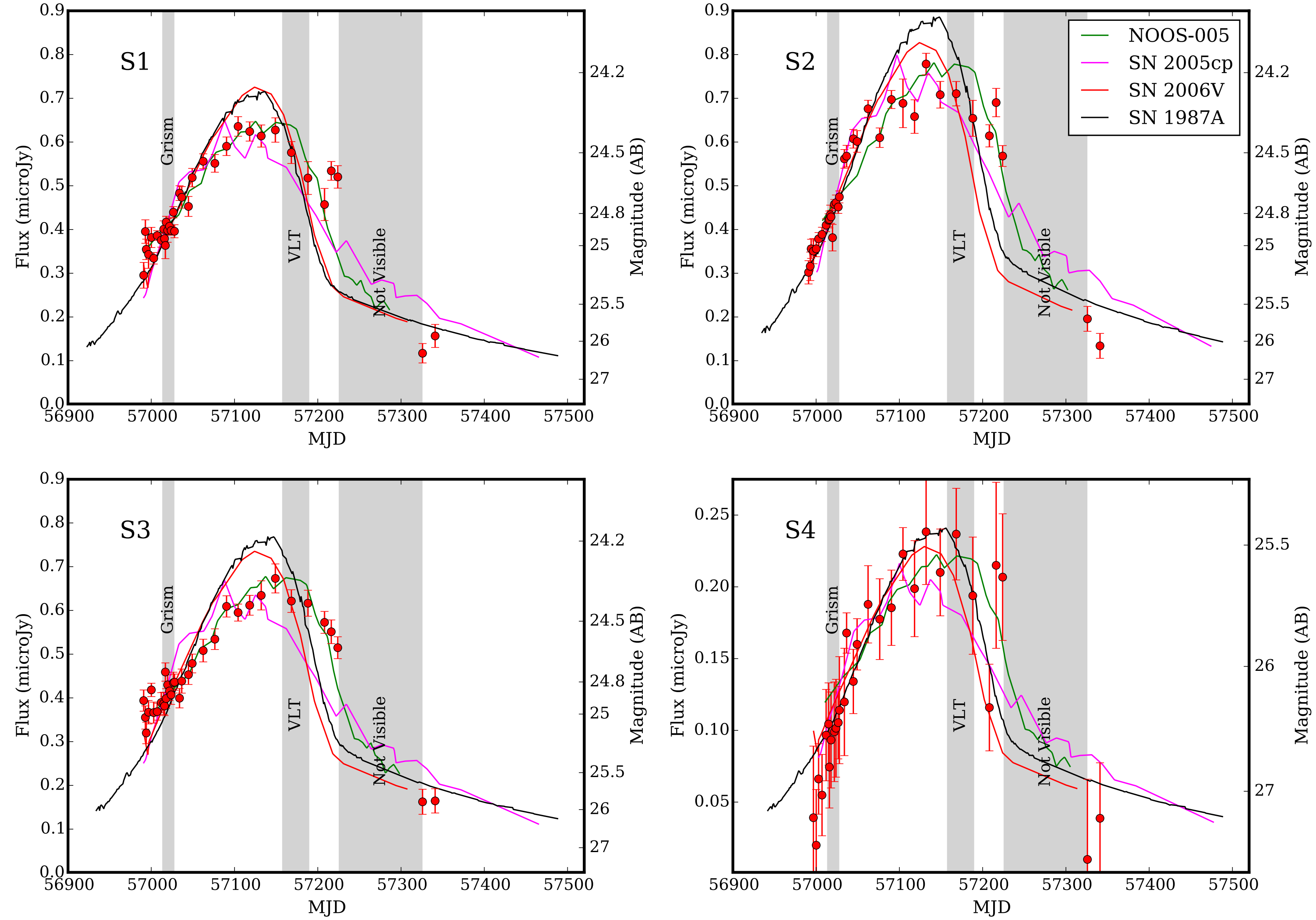
What have we learned?

- first predicted appearance of a supernova at a particular time and location
- this true blind test of model predictions indicates that our basic understanding of cluster mass distributions is not bad
- (my mass models are among the best!)

  [see also Meneghetti et al. arXiv:1606.04548]

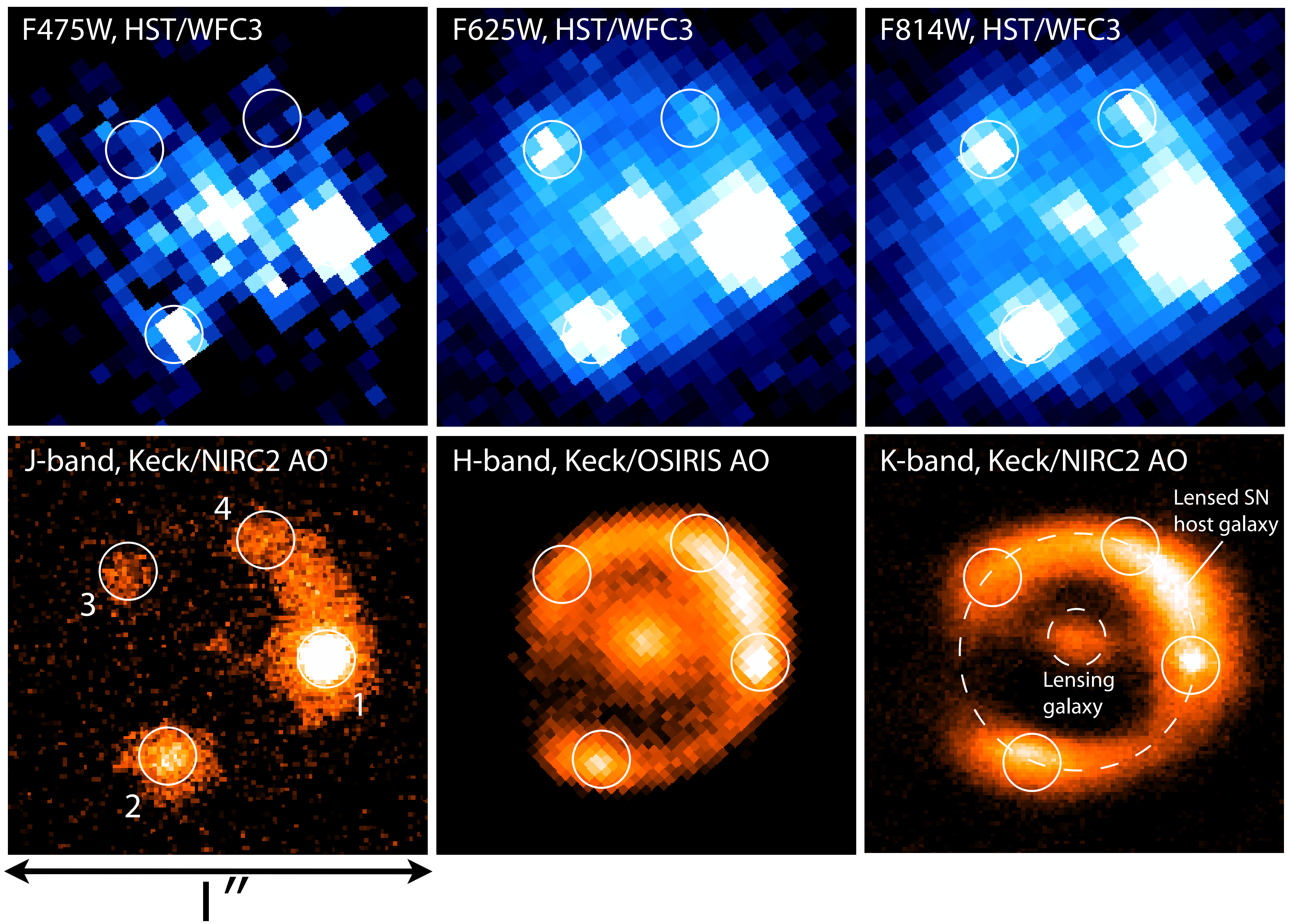
Note: classification of SN Refsdal

- best match to SN1987A-like SNe, which are rare at low-z
- progenitor is a blue supergiant with M~20Msun



(Kelly et al. 2016)

iPTF16geu



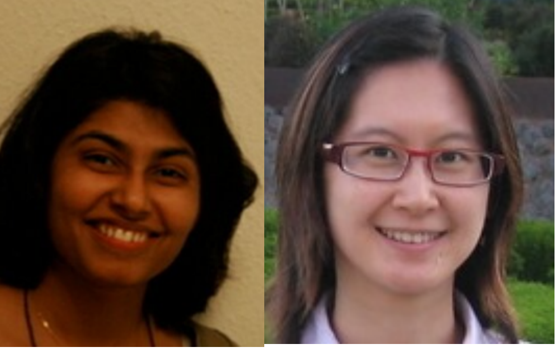
lensed Type Ia supernova (z_{SN}=0.409, z_{lens}=0.216)

four multiple images with total μ~56

discovered in iPFT survey

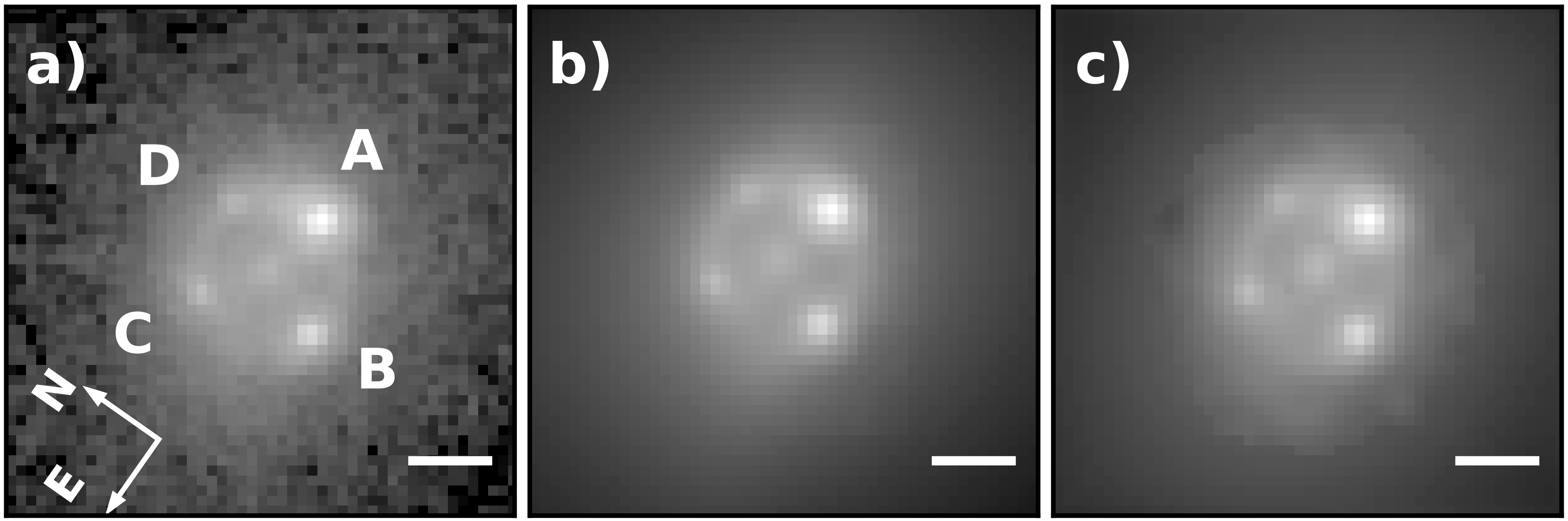
first lensed Type Ia SN with resolved multiple images

(Goobar et al. arXiv:1611.00014)



More, Suyu, Oguri, et al. ApJ **835**(2017)L25

Interpreting iPFT16geu



observation model (glafic) model (GLEE)

- best-fit models predict $\Delta t < 1$ day
  → too short to constrain H_0 accurately
- flux ratios mismatch (microlensing?)

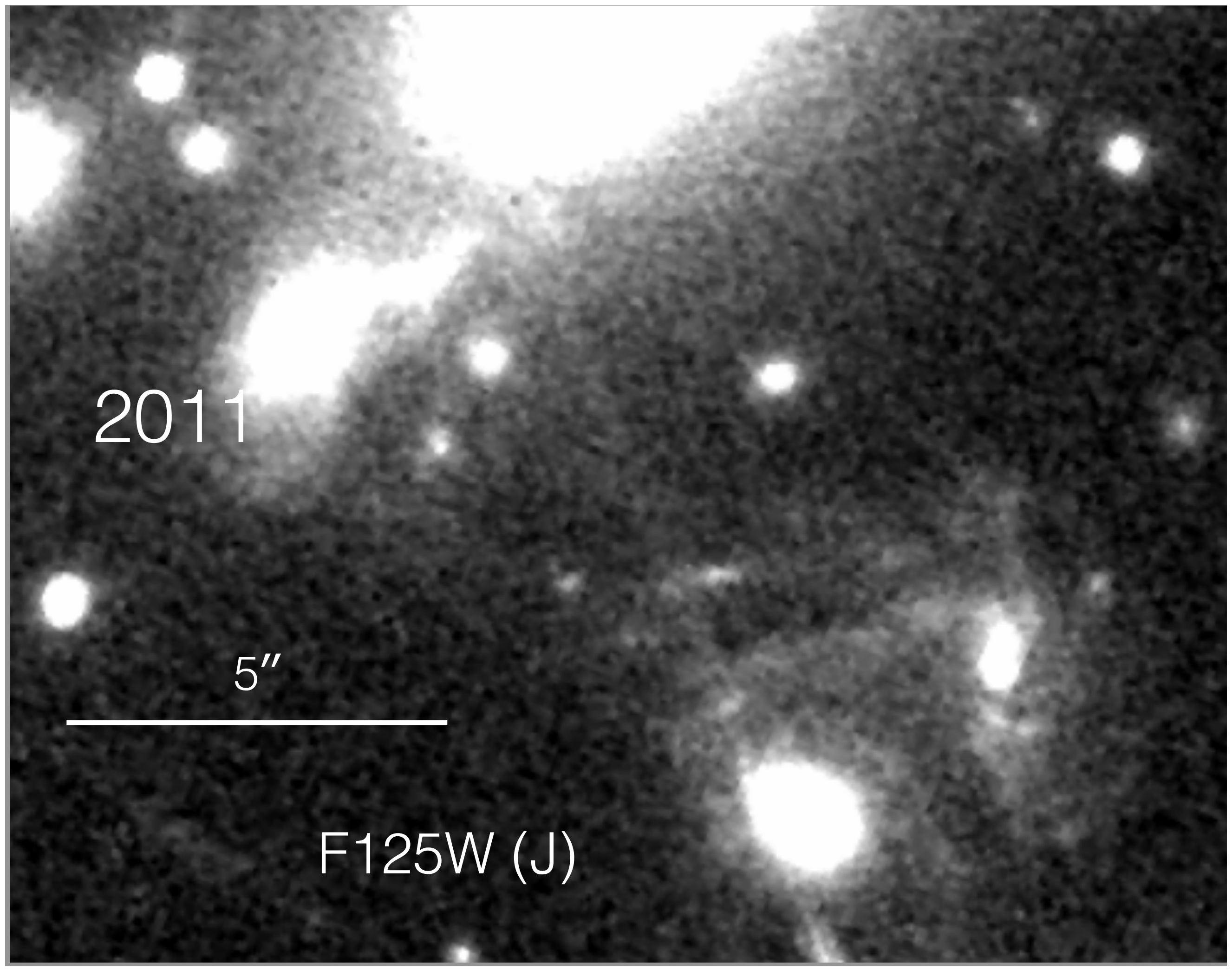
Lensed supernovae: Summary

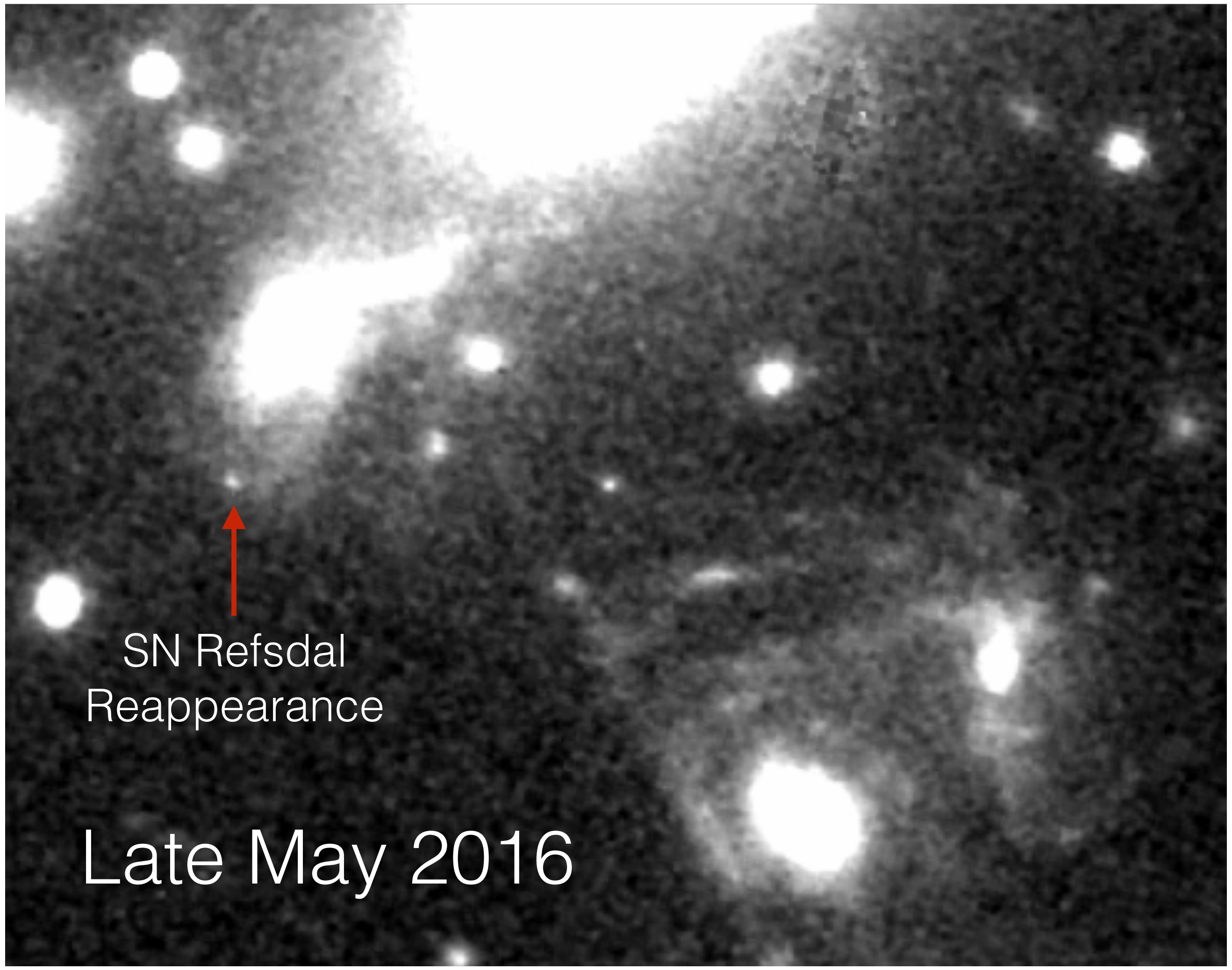
- PS1-10afx – first strongly lensed SN, Type Ia with μ~30, multiple images not resolved
- SN Refsdal – first strongly lensed SN with *resolved* multiple images, lensing by a cluster, appearance of a new image
- iPTF16geu – multiply imaged Type Ia SN with μ~56, time delays too short
- new era of gravitationally lensed SN has begun!

New types of transients from HFF

- Hubble Frontier Fields: deep HST imaging of 6 clusters for studying high-z galaxies with help of lensing magnifications (Lotz et al. 2017)
- deep repeated observations of cluster cores revealed new types of transients, in addition to SN Refsdal

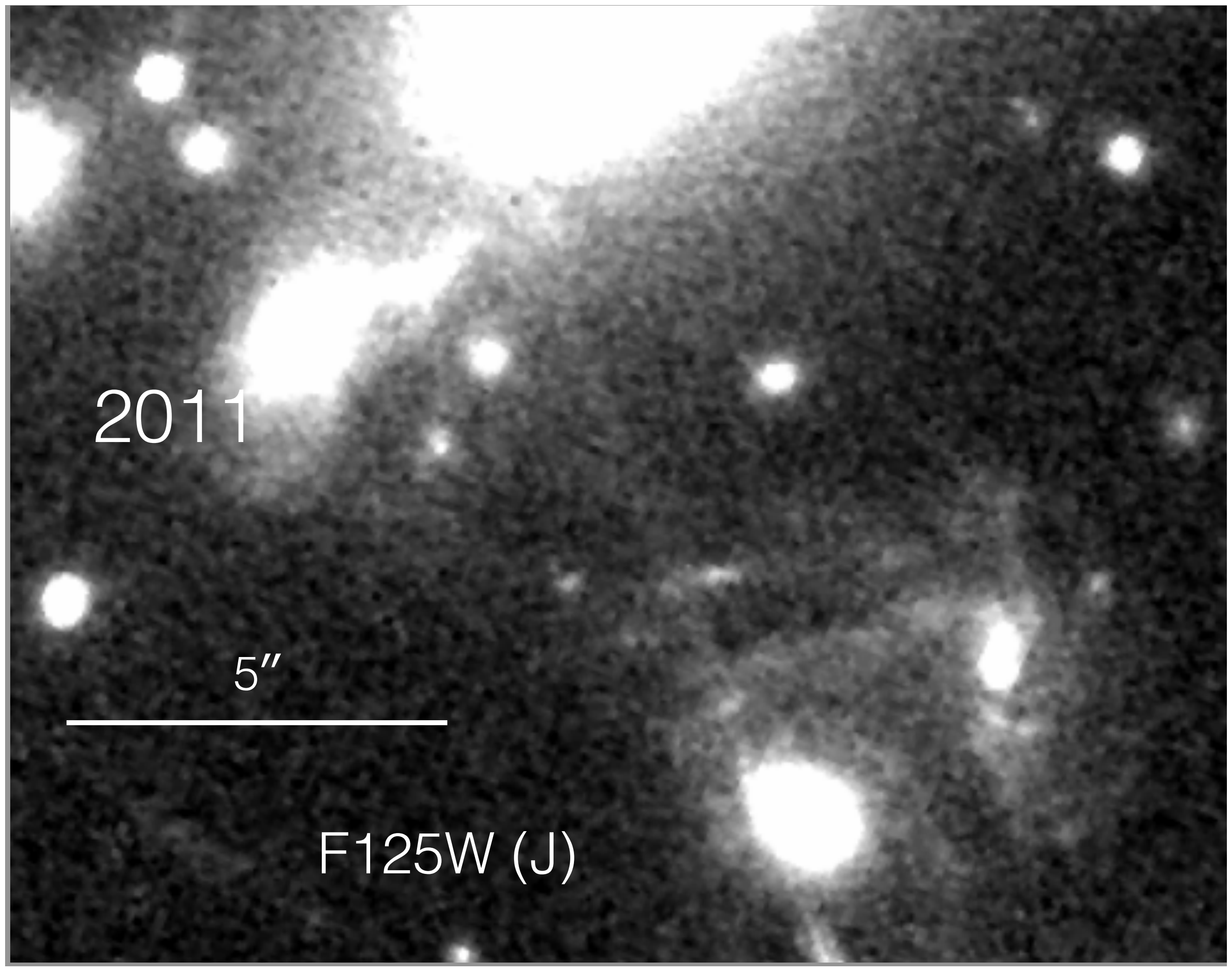
Icarus

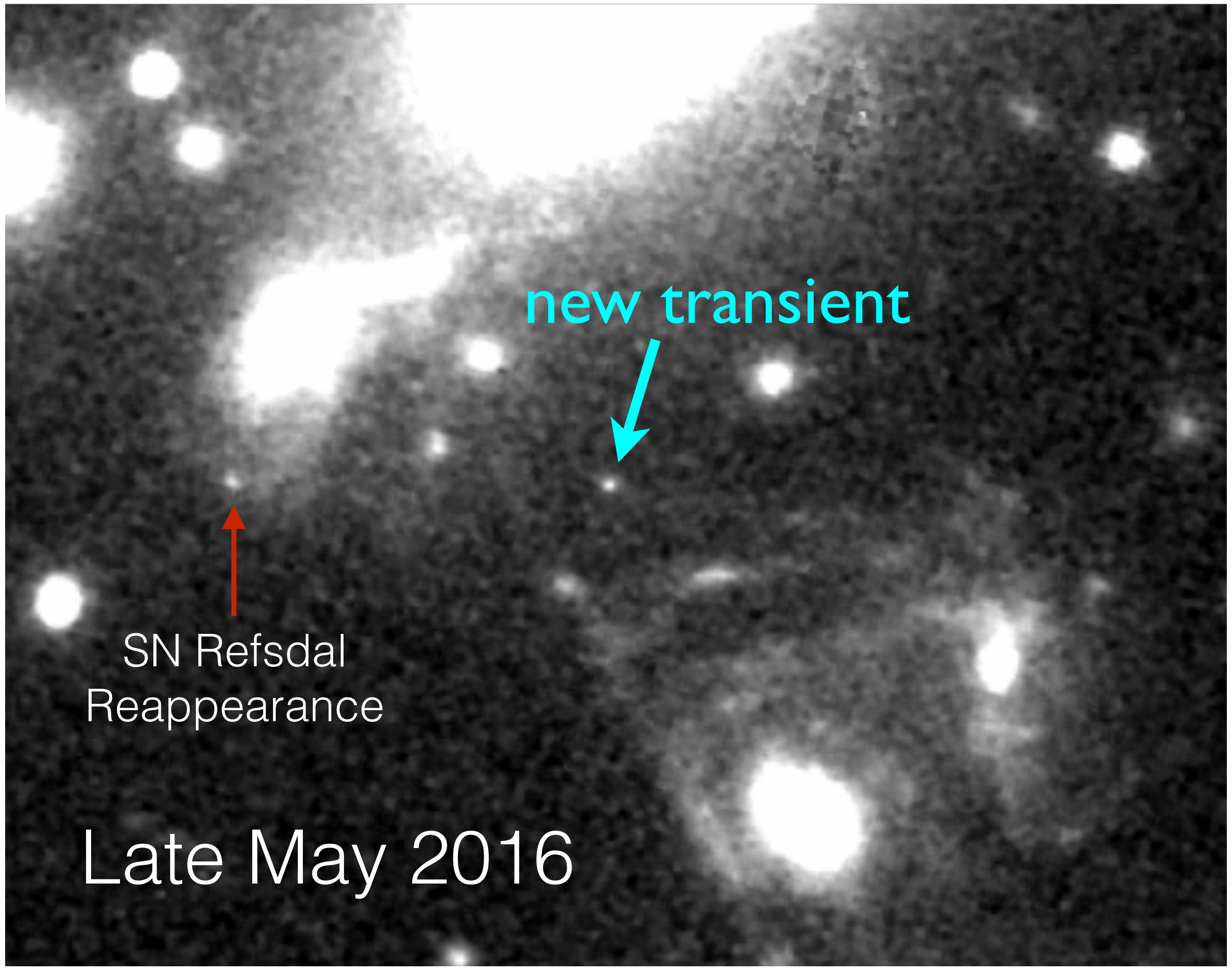




(P. Kelly)

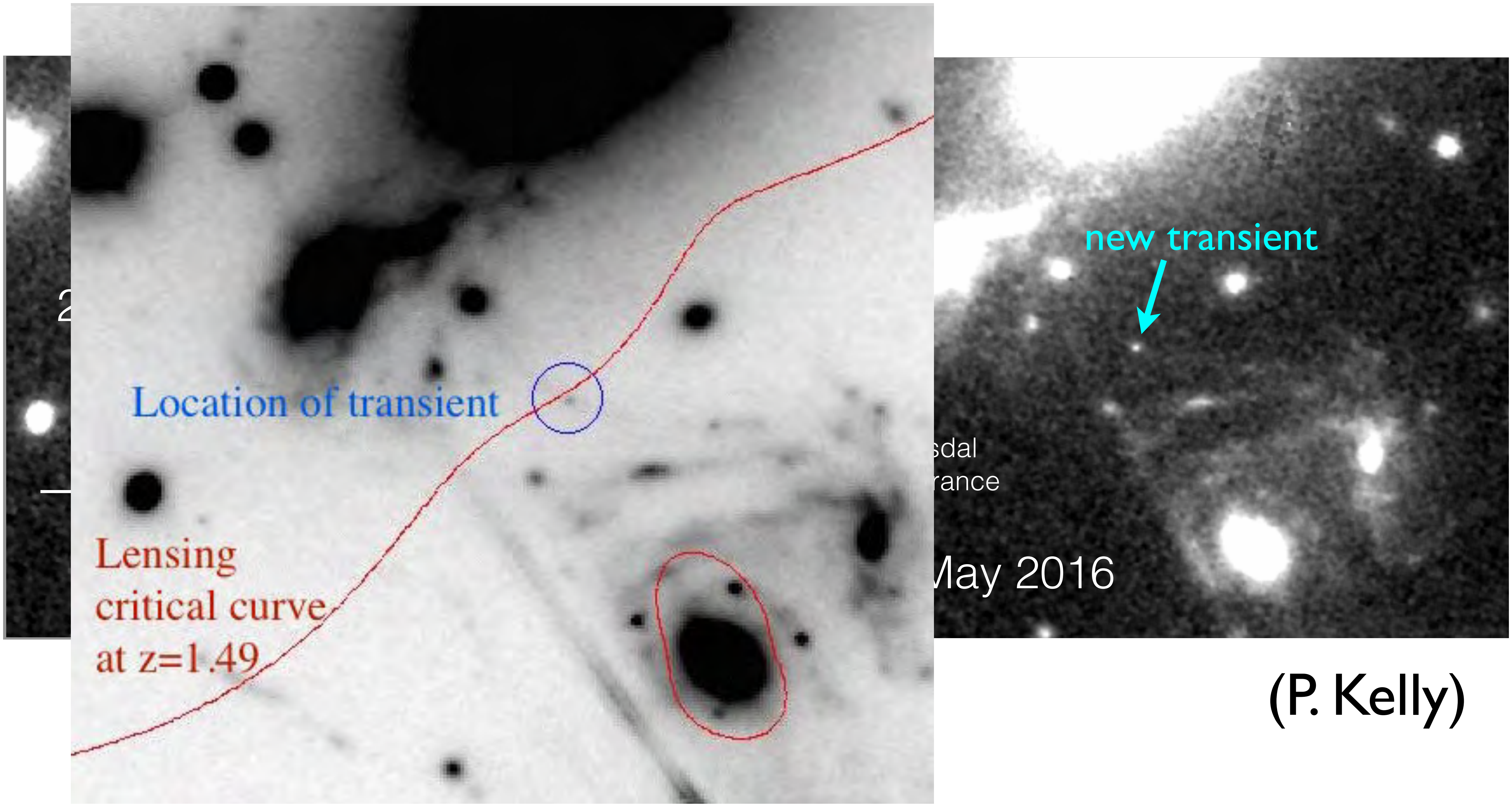
Icarus





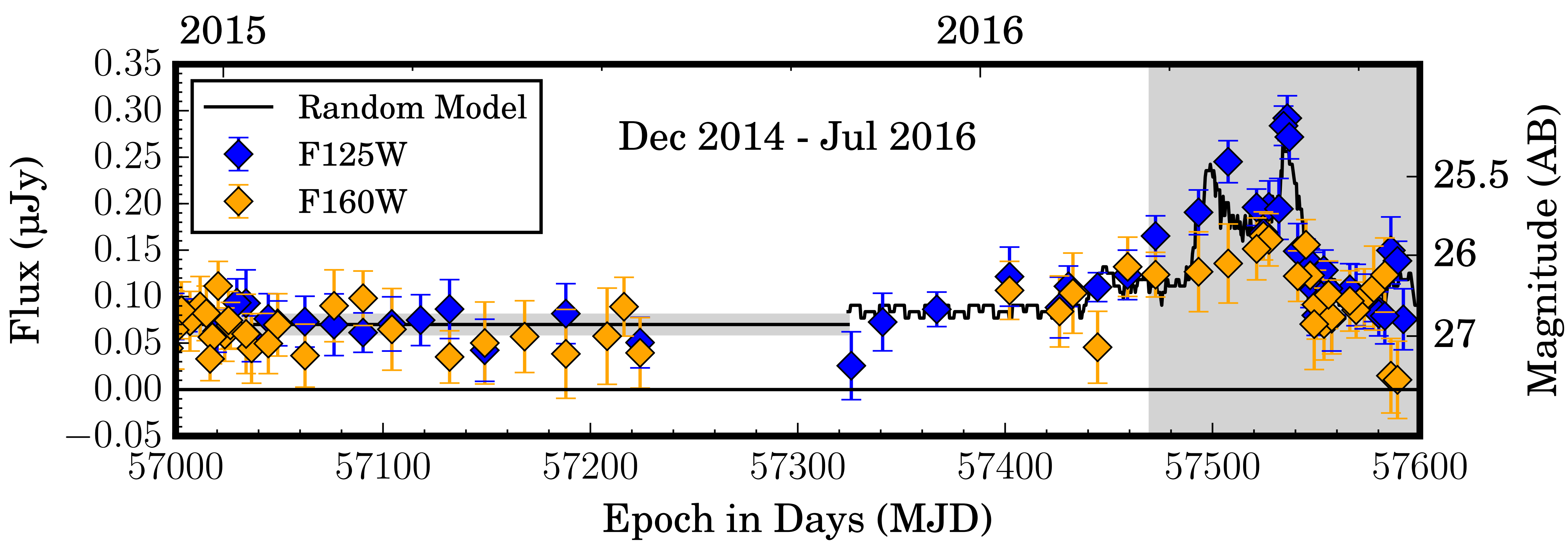
(P. Kelly)

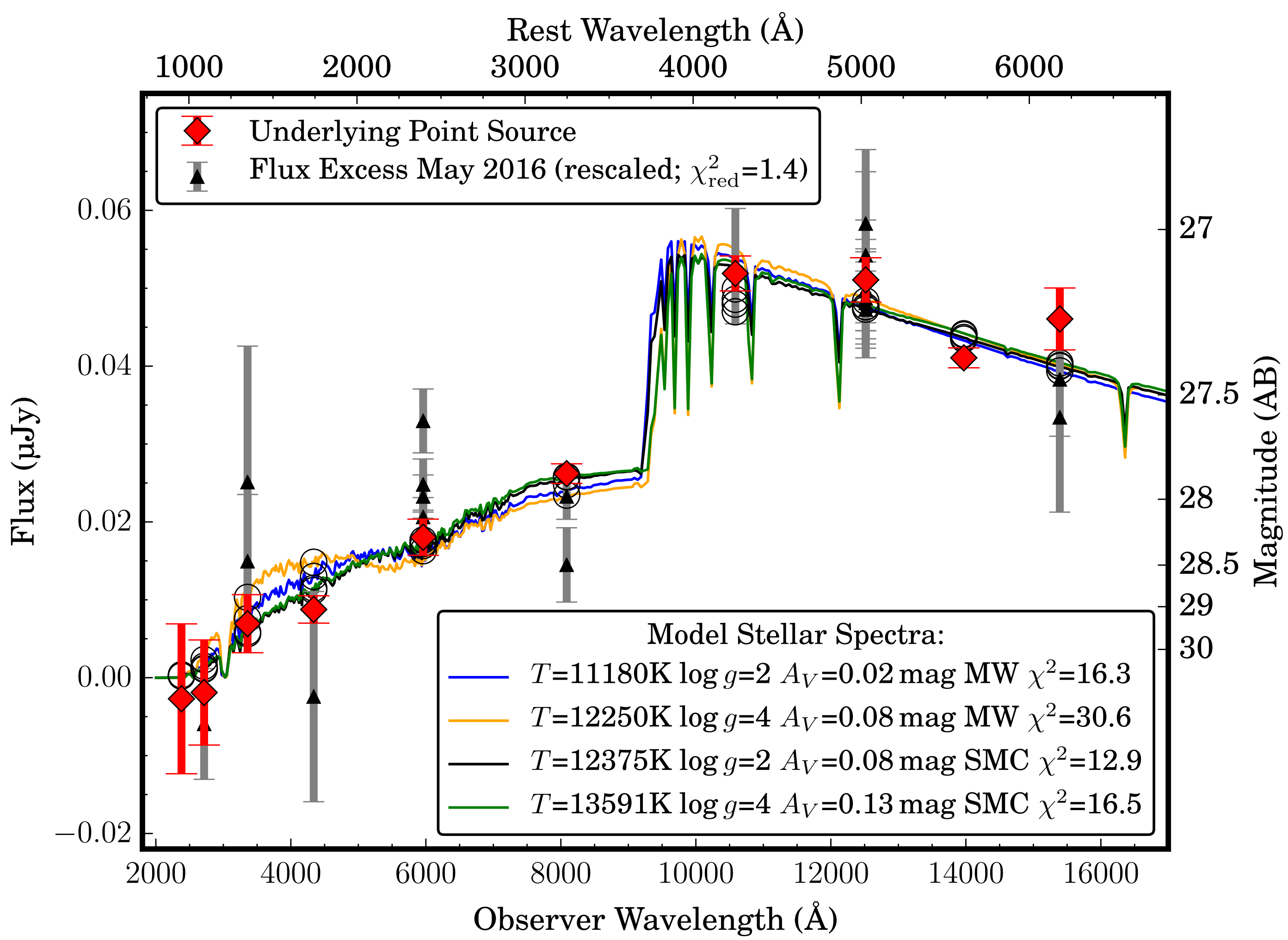
Icarus



(P. Kelly)

Kelly et al., in prep.

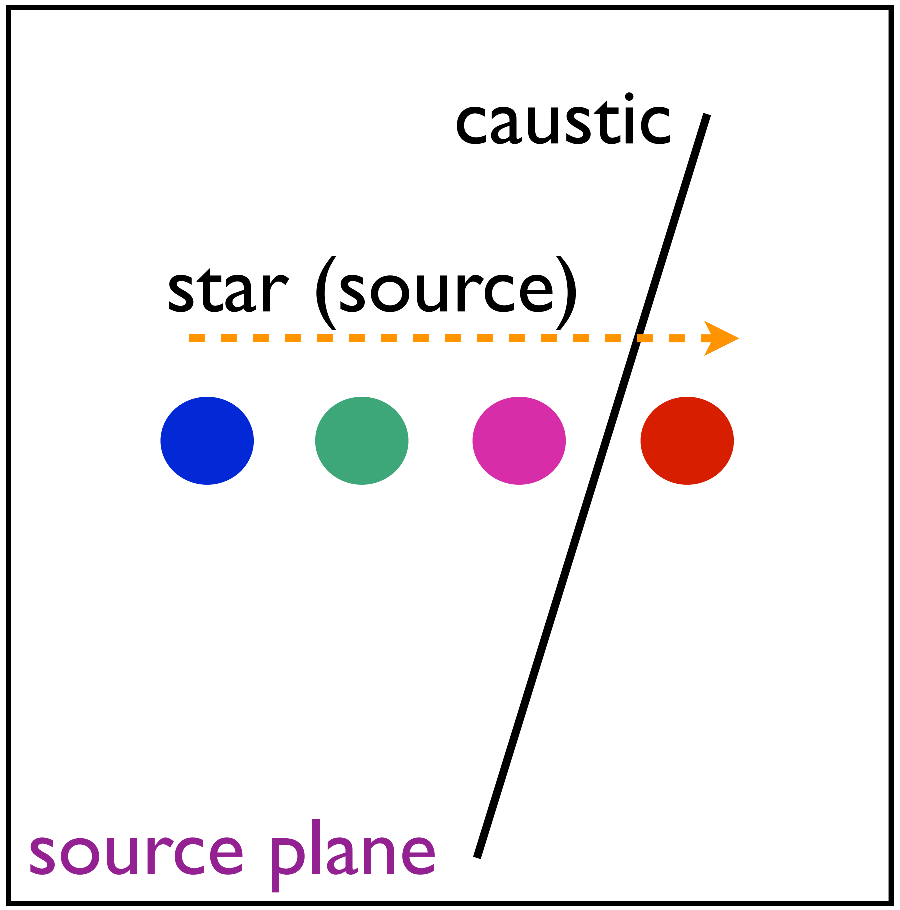


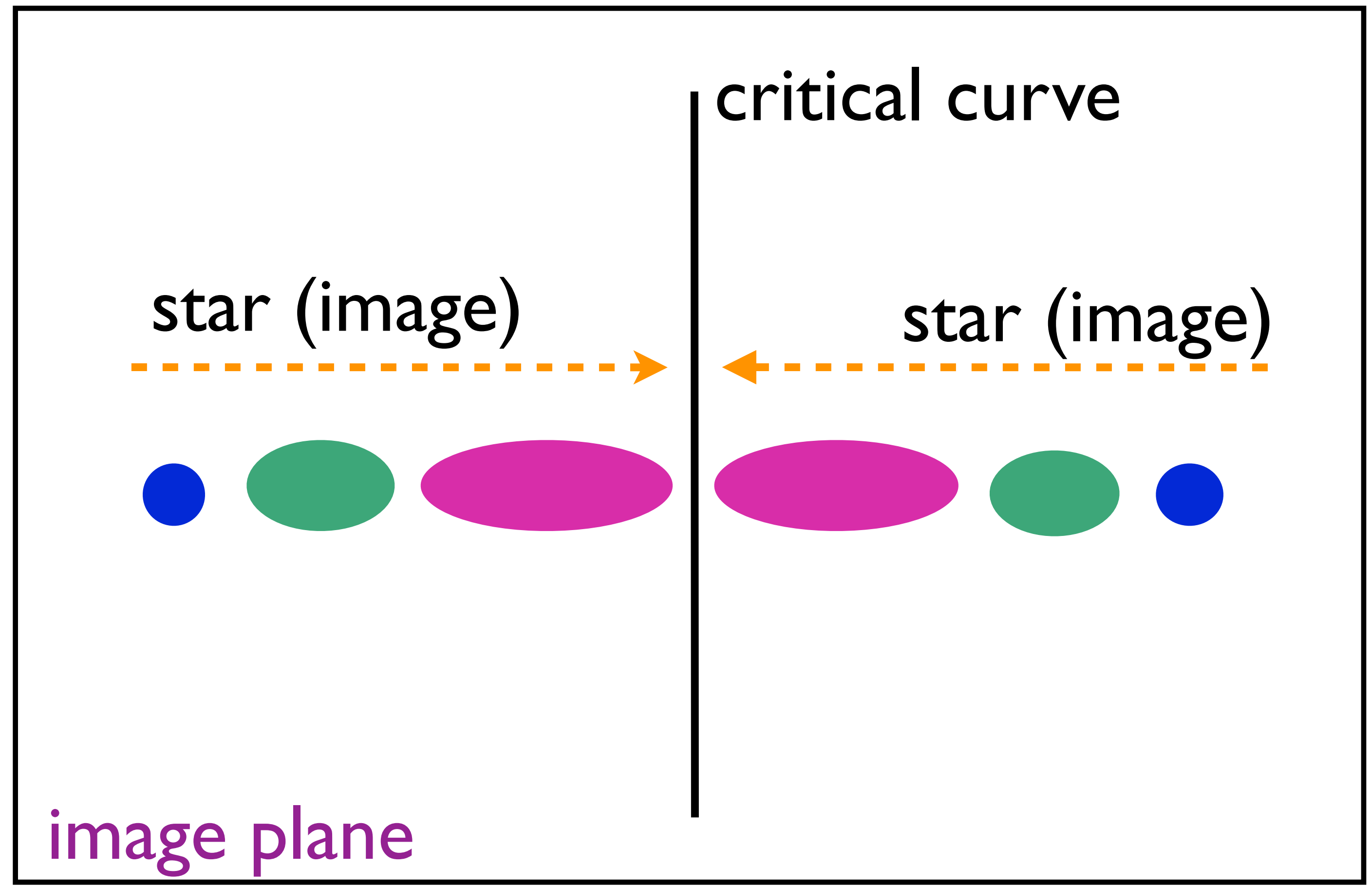


- increased over several months, faded rapidly within a week
- SED consistent with a B-type star (T ~ 10^4K)

e.g., Miralda-Escude (1991)

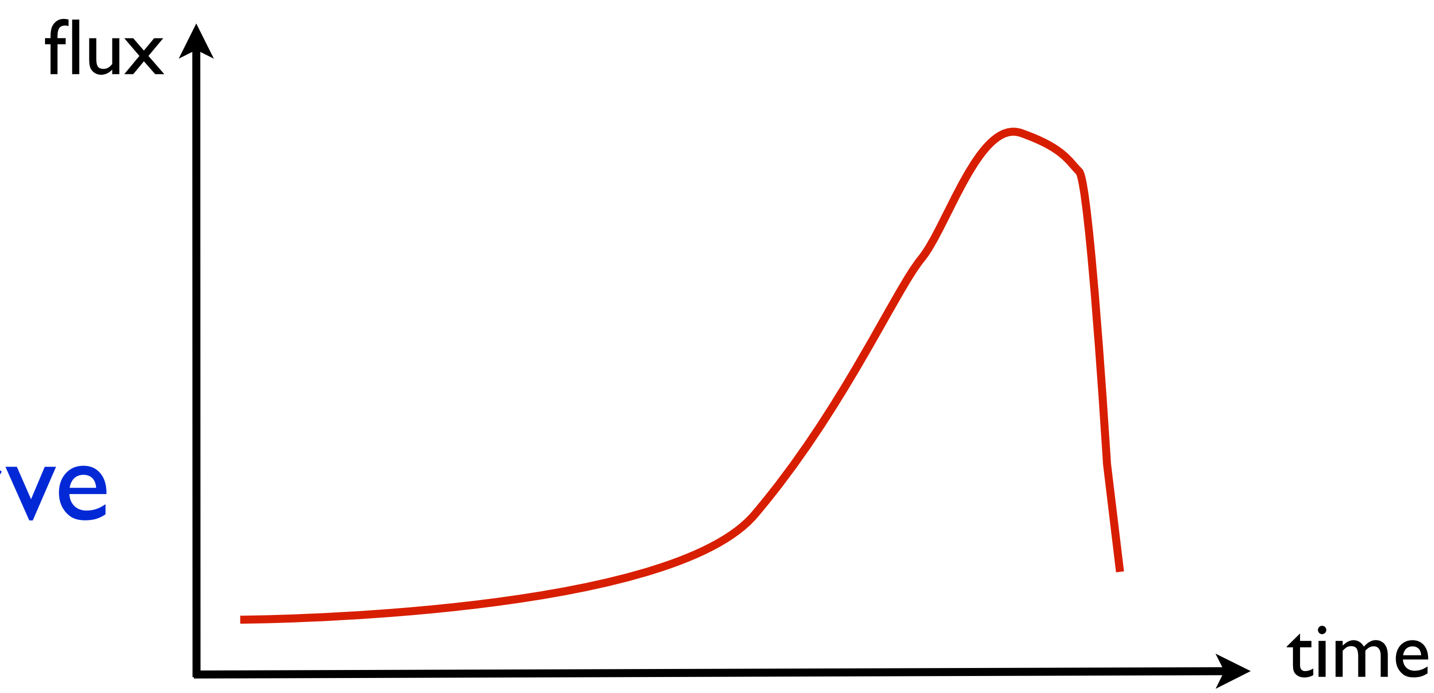
Caustic crossing?



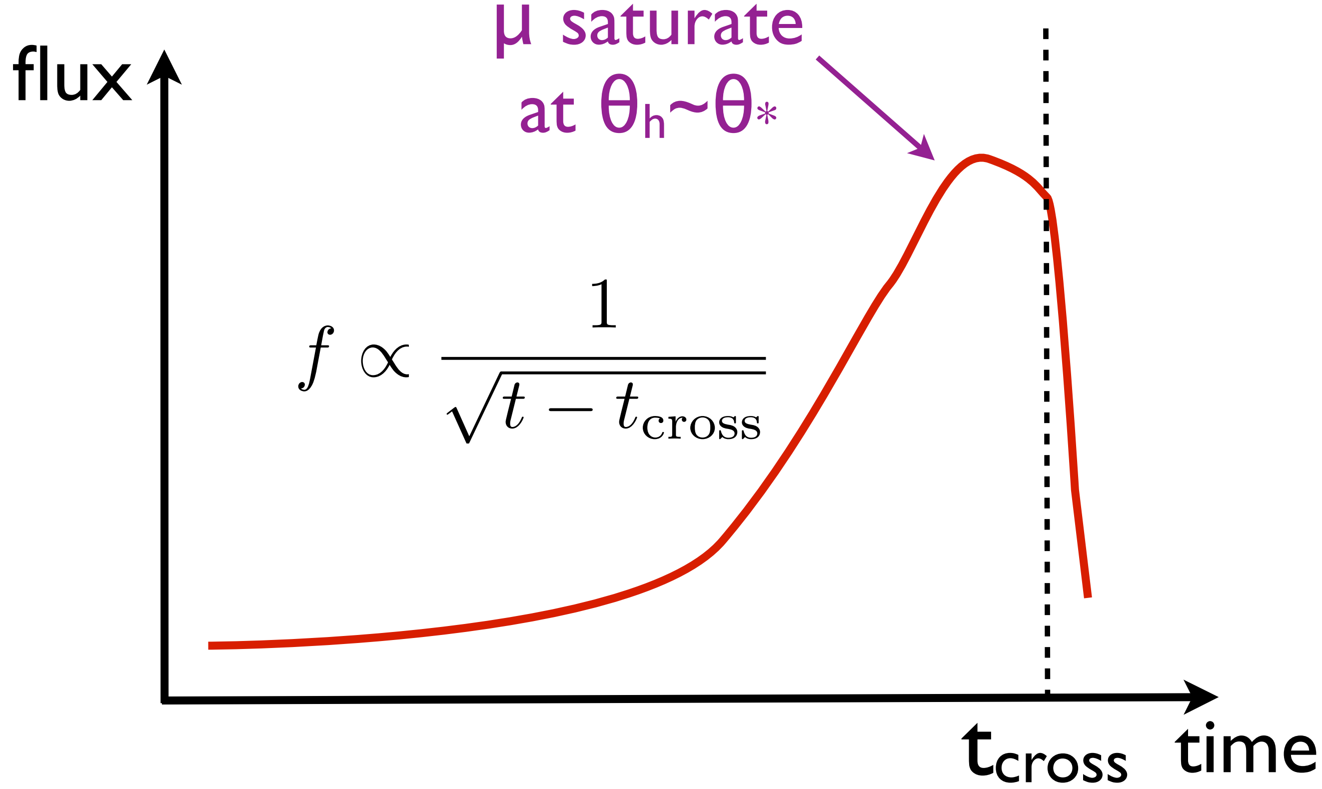


- single star crossing a caustic

→ asymmetric light curve



Caustic crossing scenario



from cluster mass model:

$$\mu_{\rm tot} \sim \frac{16}{\sqrt{(\theta_{\rm h}/'')}} \sim \frac{10^7}{\sqrt{(\theta_{\rm h}/\theta_\odot)}}$$

(θ_h: distance to caustic)

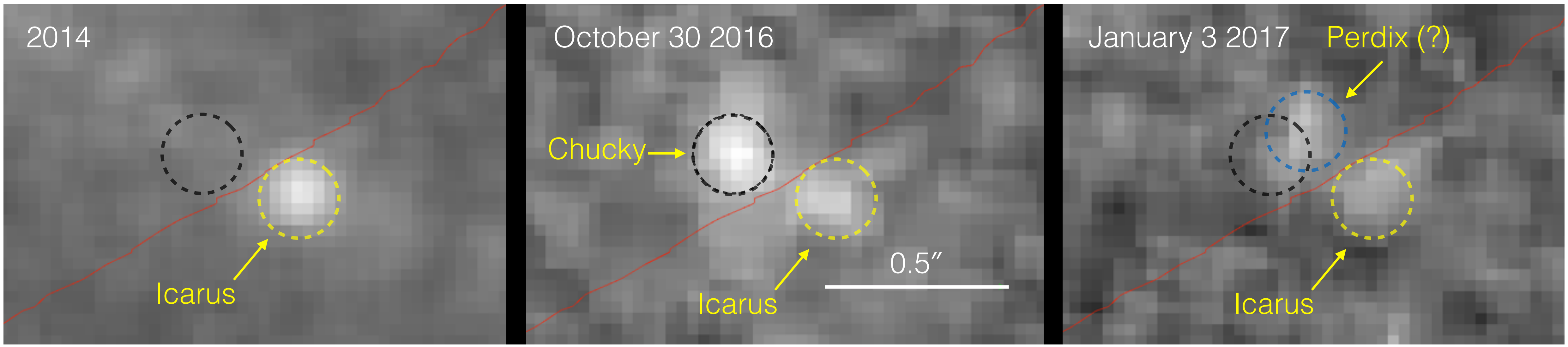
$$\mu_{\rm peak} \sim \frac{10^7}{\sqrt{(\theta_*/\theta_\odot)}}$$

~25 mag at peak

$$\rightarrow M_* \sim -20 + 2.5\mu_{\rm peak}$$

- inferred quantities
  $M_* \sim -5$, $\mu \sim 10^6$ blue supergiant??

Additional events: Chucky/Perdix



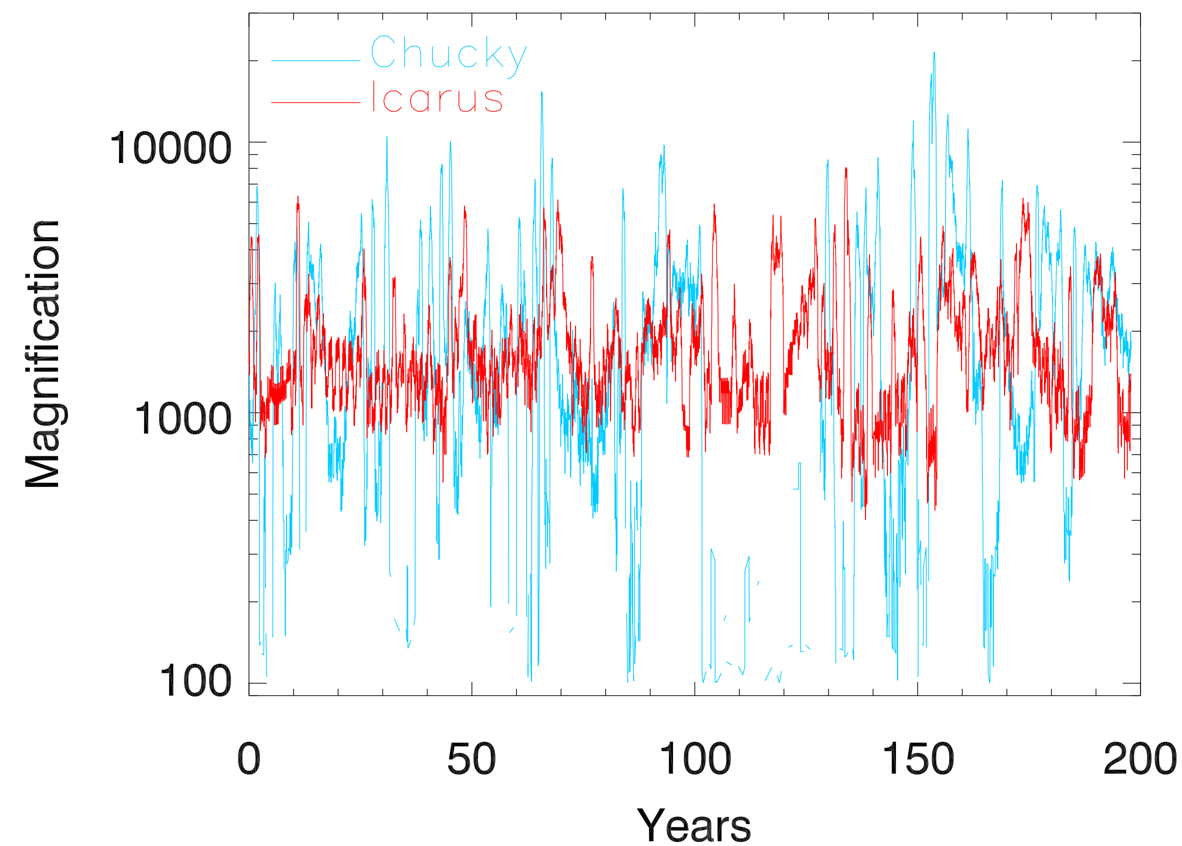
(P. Kelly)

- additional events discovered near Icarus!
- across critical curve
  → merging pair of images?

New scenario (?)

- merging pair of images separated by ~0.26″
  → magnifications of ~300-1000 for each image
- additional magnification/demagnification by microlensing up to μ ~10⁴
- lens candidates?
  - ICL (low prob.)
  - $30M_{sun}$ BH?
  - ultra-light scalar field DM??

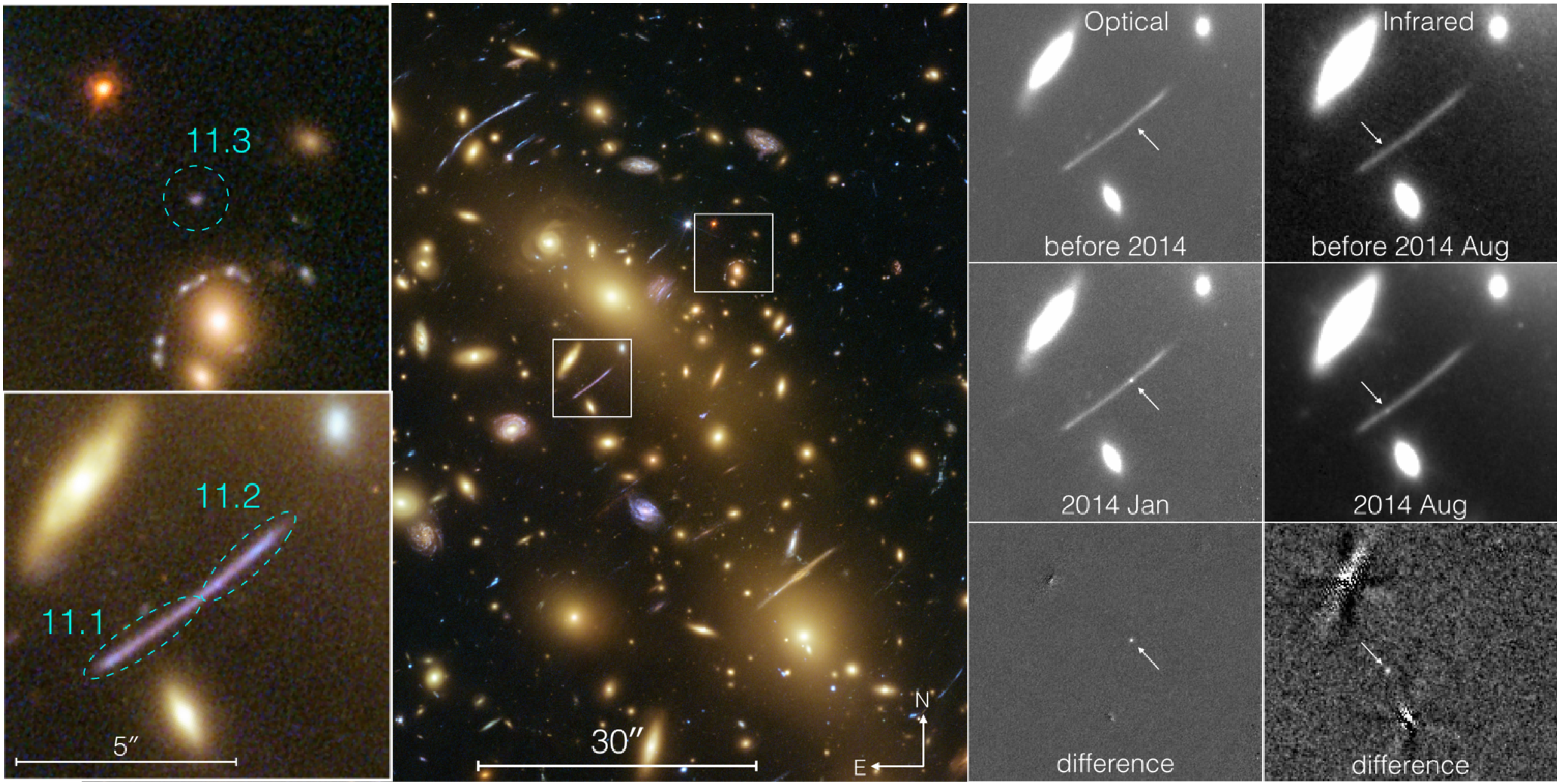
work in progress....



(J. M. Diego)

Rodney et al., in prep.

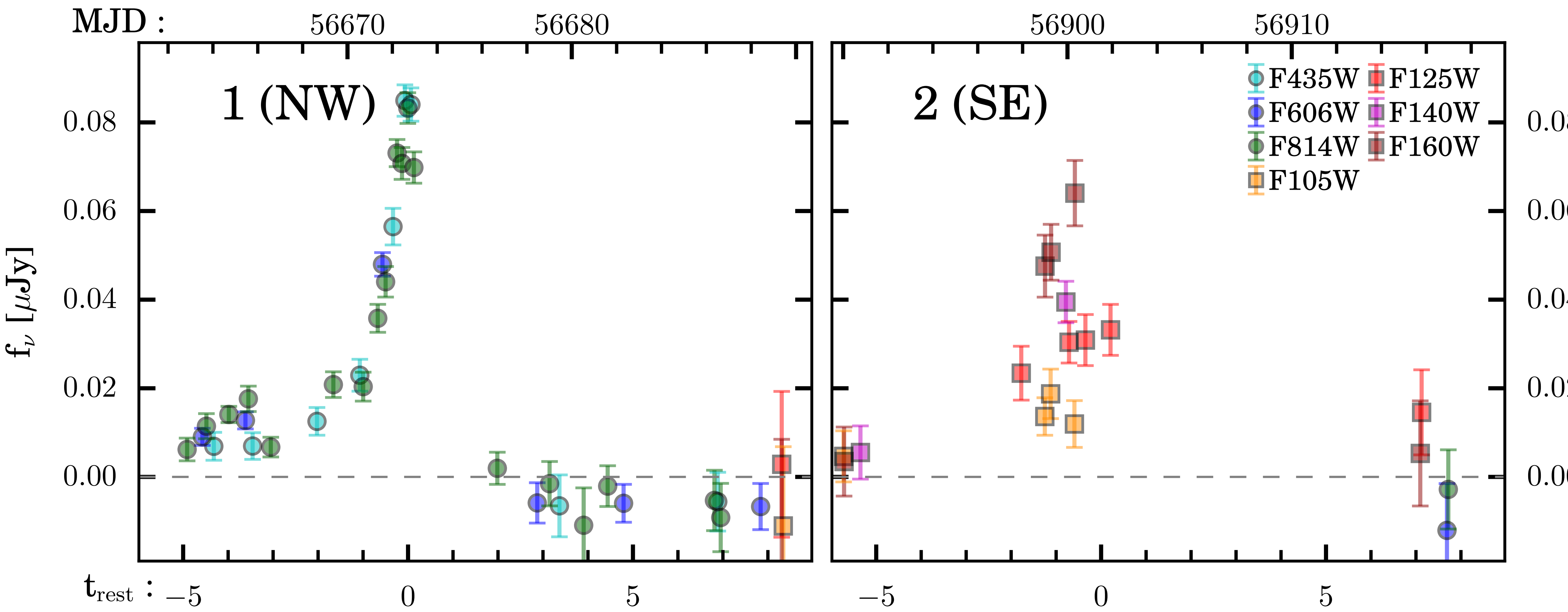
Spock



- discovered in HFF cluster MACSJ0416
- peak L~10^{41}erg/s, time scale < 5 days

Rodney et al., in prep.

Spock light curves

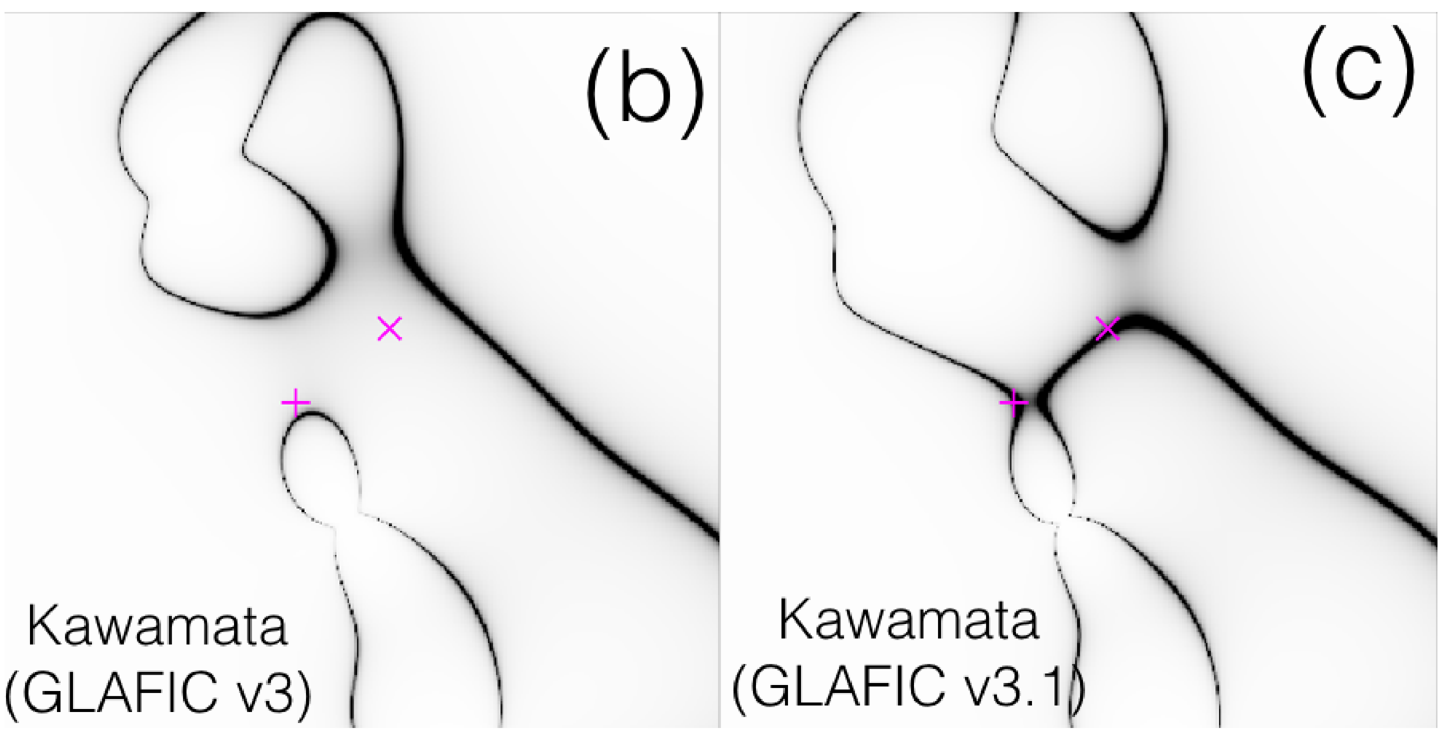


- two events separated by >200 days, expected time delays < 50 days
  → distinct events

Possible scenarios

- luminous blue variable
- recurrent nova outburst
- caustic crossing?

need extreme events, but still possible



critical curve right across the arc

New types of transients from HFF

- deep repeated observations of cluster cores revealed new (mysterious) types of transients
- possibly highly magnified single stars? (up to $\mu \sim 10^{4-6}$)
- might provide a new clue to nature of DM?? follow-up observations/analysis are ongoing, stay tuned!