Gravitationally lensed supernovae

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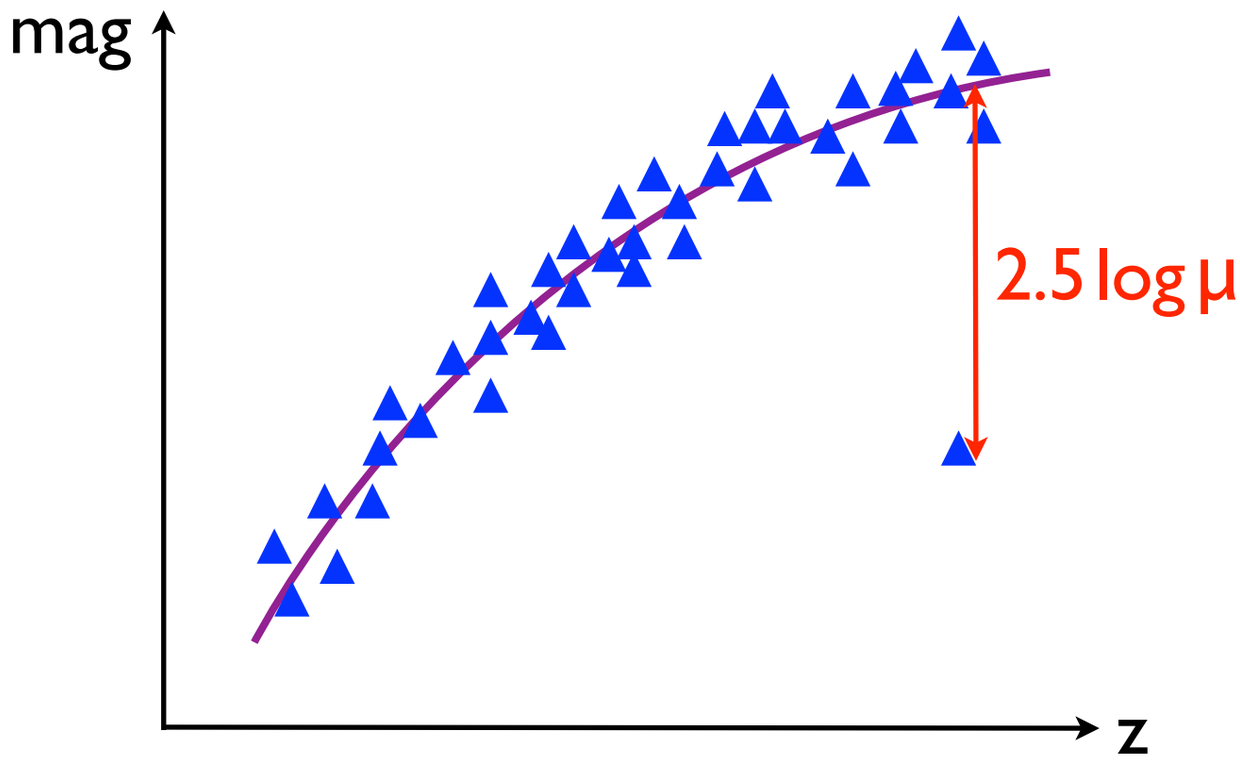
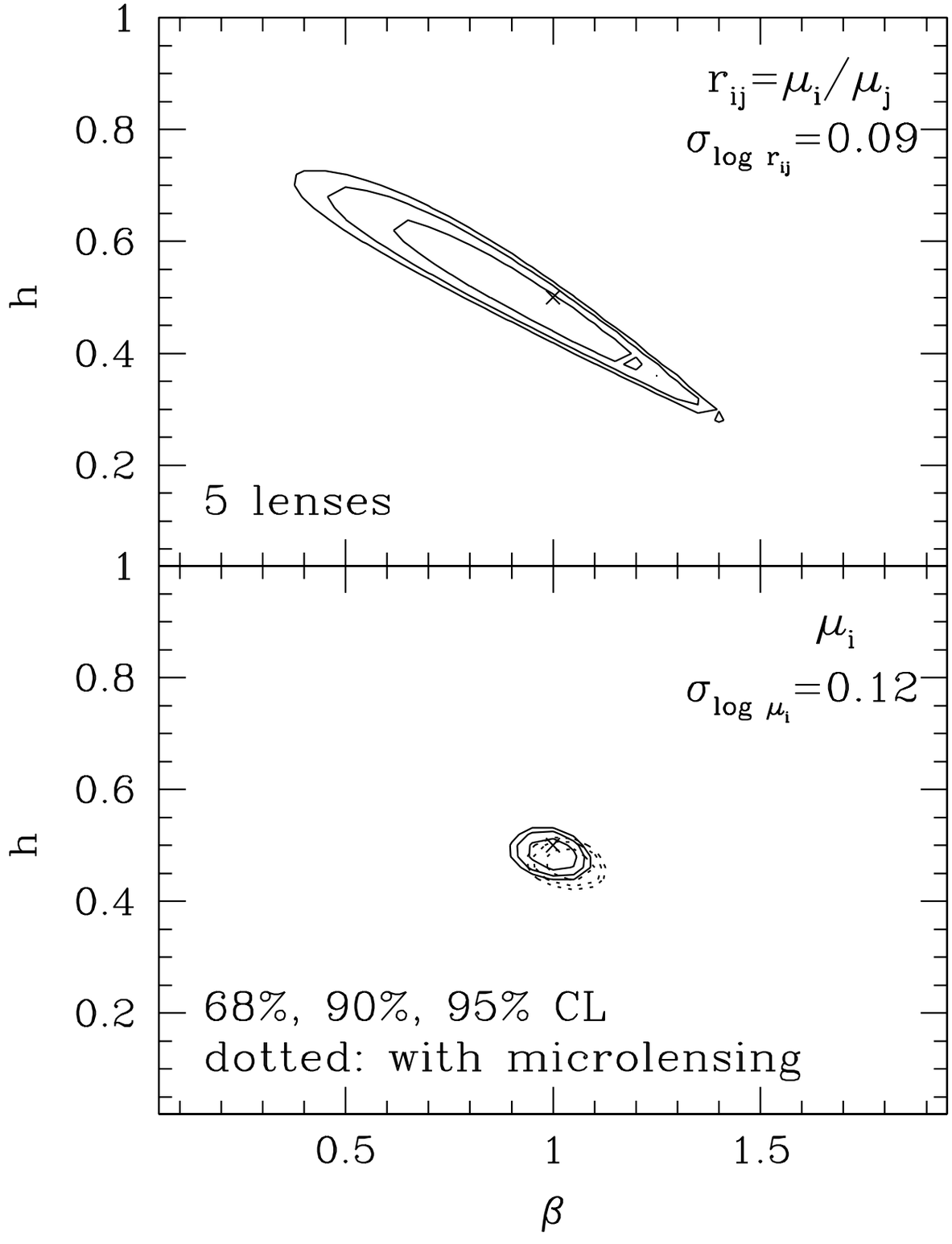
Why is lensed SN interesting? (I)

- standard candle
  direct measurement of the magnification factor for lensed type Ia supernovae, breaking various (e.g., mass-sheet) degeneracies



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

Breaking the H_0-slope degeneracy

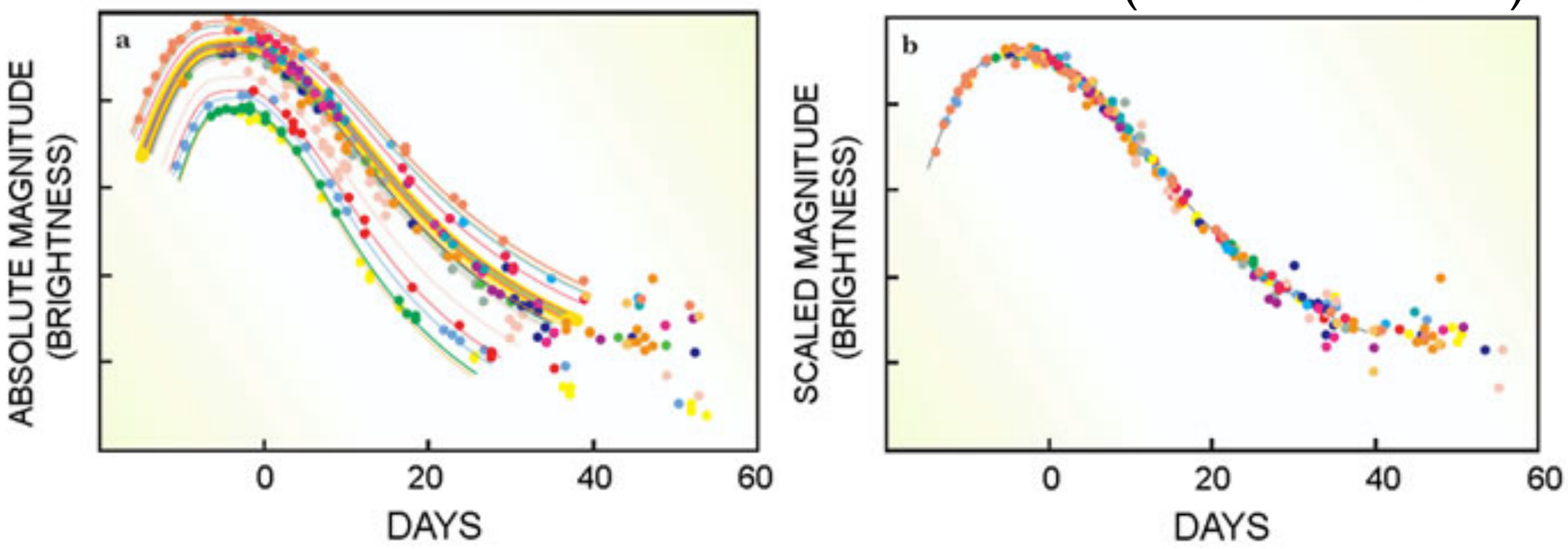


- the use of total magnifications μ breaks degeneracy btw H_0 and β [$\rho(r) \propto r^{\beta-3}$]

Why is lensed SN interesting? (II)

- known light curves
  we have template light-curves of SNe
  → accurate and robust time delay measurements
  (but microlensing can be important; Dobler & Keeton 2006)

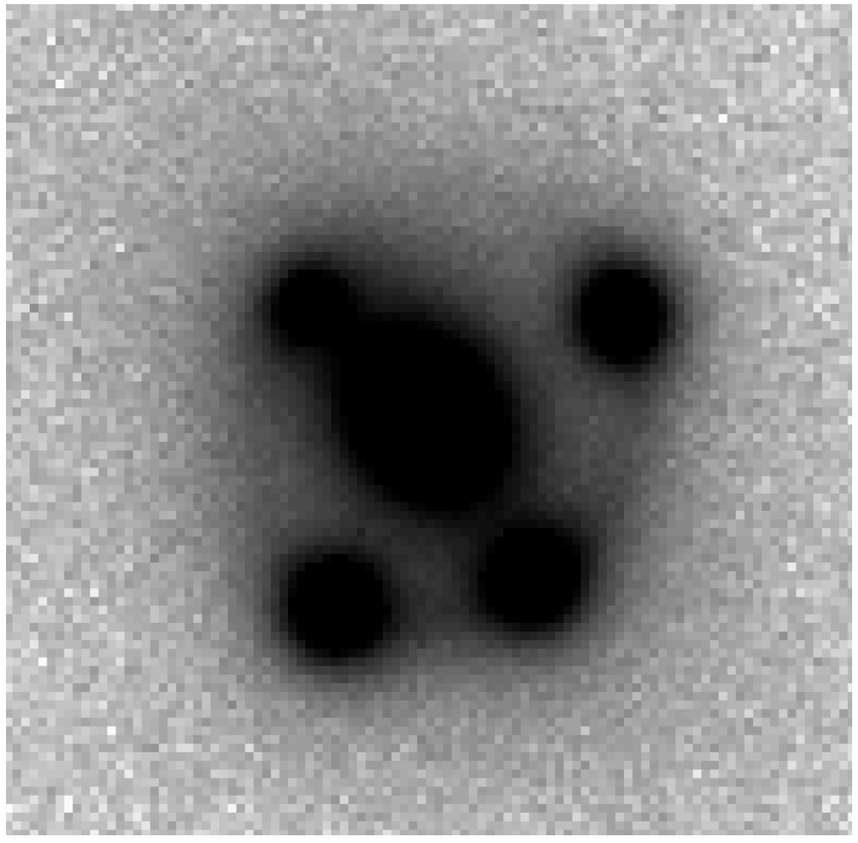
(from LBL website)

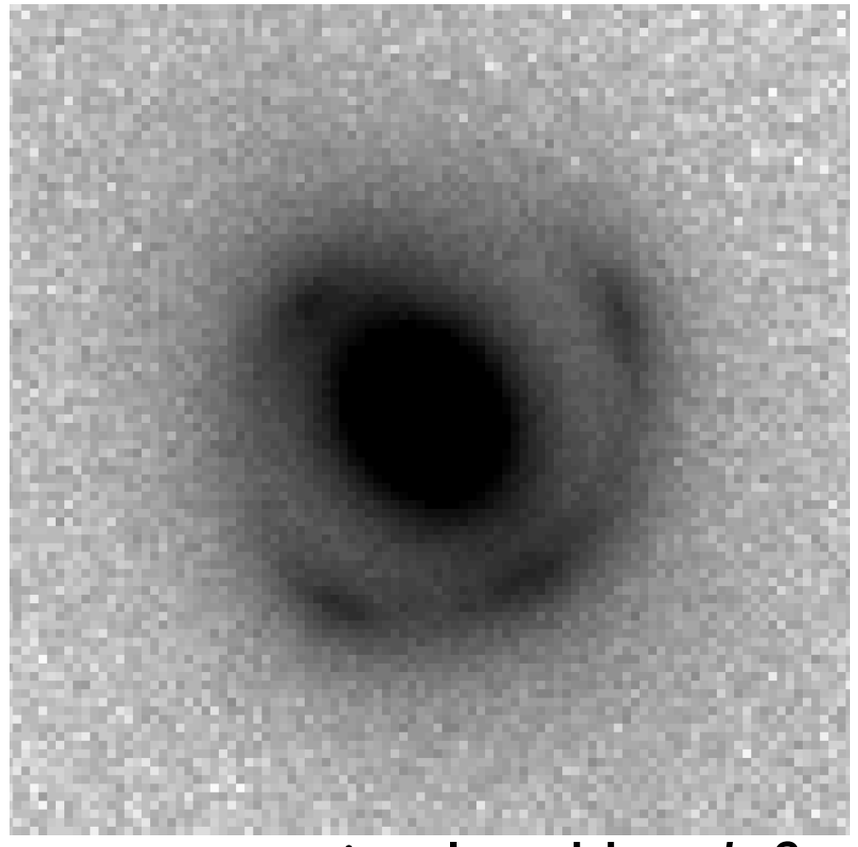


Why is lensed SN interesting? (III)

- better use of host galaxy
  better measurement of detailed morphology of lensed host galaxy after SN fades away
  → better constraints of the lens potential

w/ SN images





w/o SN images

simulated by *glafic*

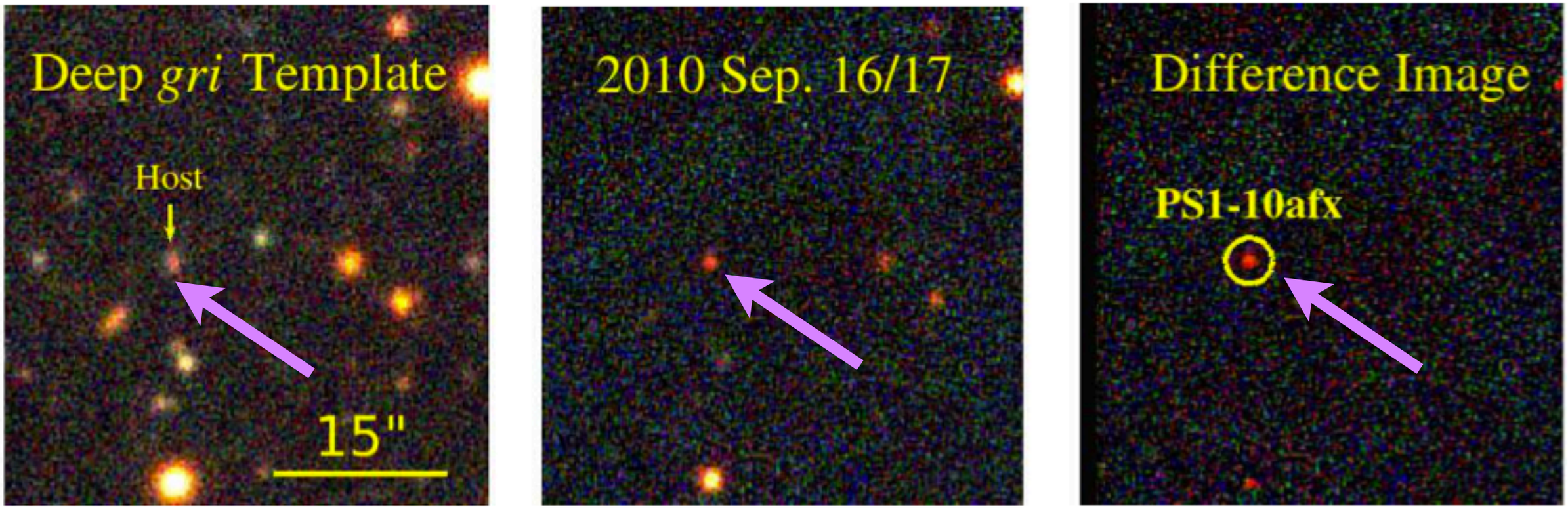
Oguri & Marshall MNRAS **405**(2010)2579

Expected number of lensed SNe

- rare, wide-field time-domain surveys are needed to find them
- O(0.1) lensed SNe expected in Pan-STARRS1 (PS1), can be the first survey to find lensed SNe
- O(100) lensed SNe expected in Large Synoptic Survey Telescope (LSST)

Discovery of PS1-10afx

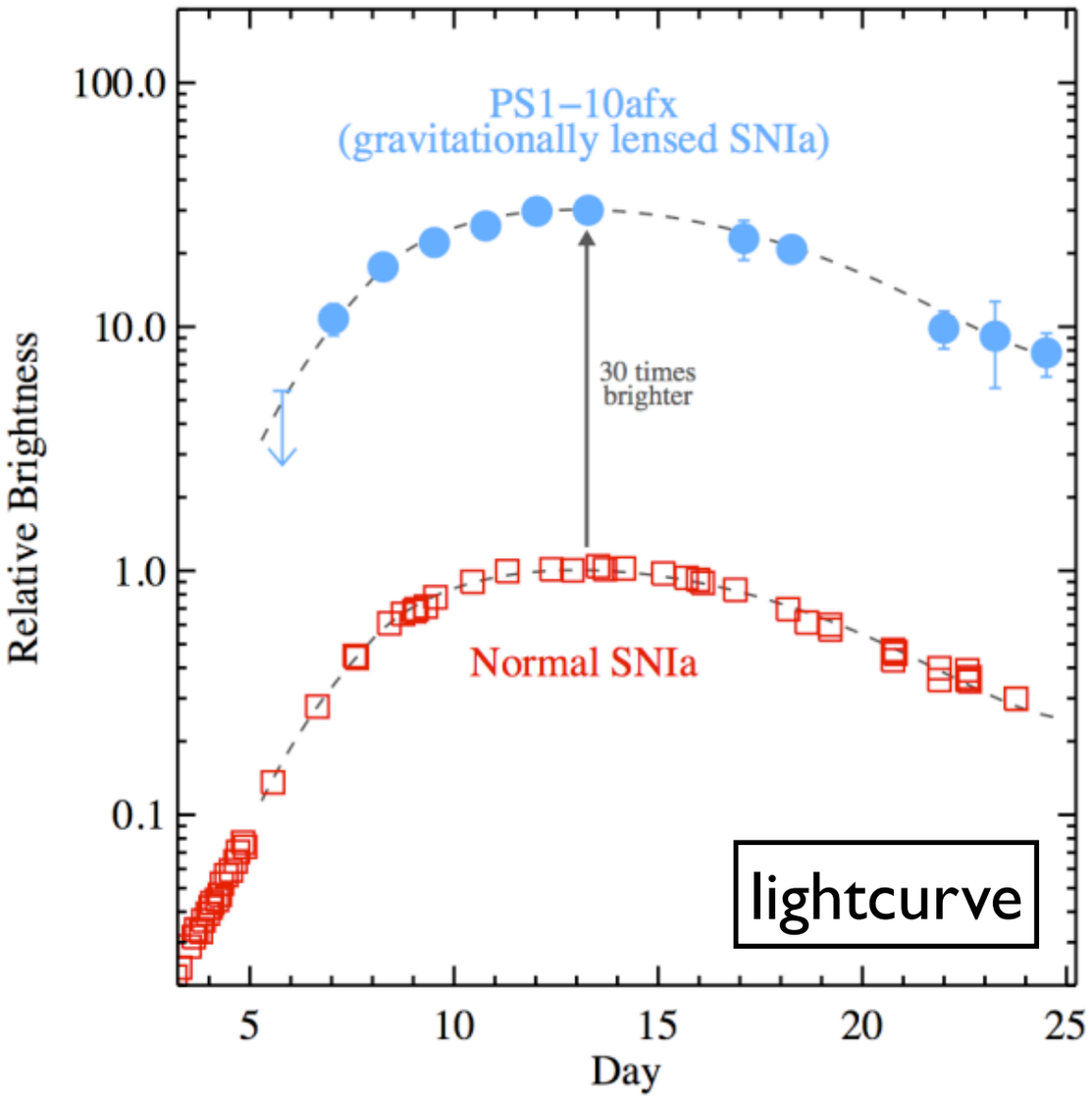
- unusually red transient at z=1.388 found on Aug 31, 2010 in the PS1 Medium Deep Survey (MDS)
- PS1 team concluded that it is a new class of super-luminous supernova (SLSN), but no physical model of SLSN can explain this event



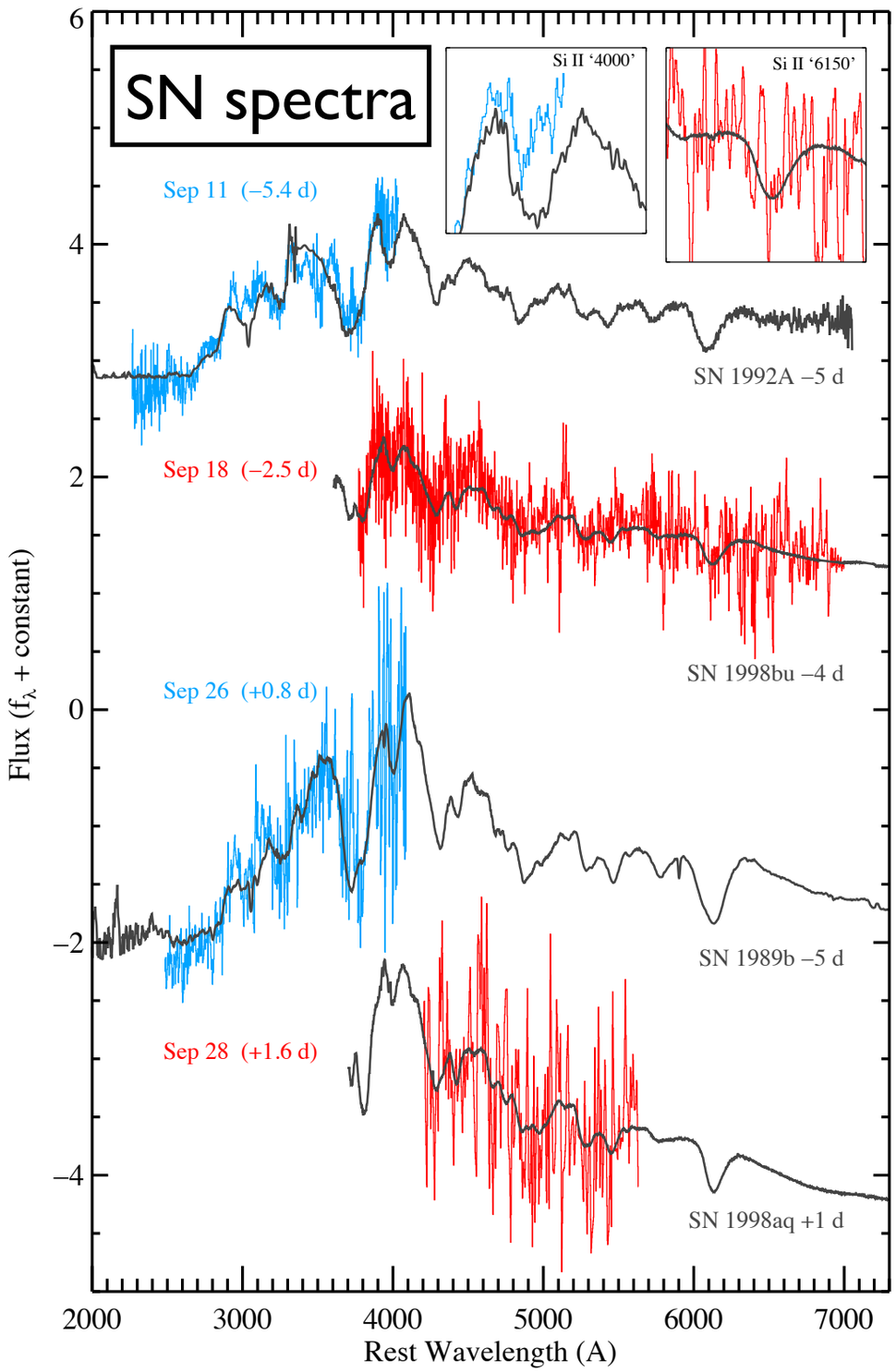
Chornock et al. (2013)

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

Type Ia interpretation of PS1-10afx

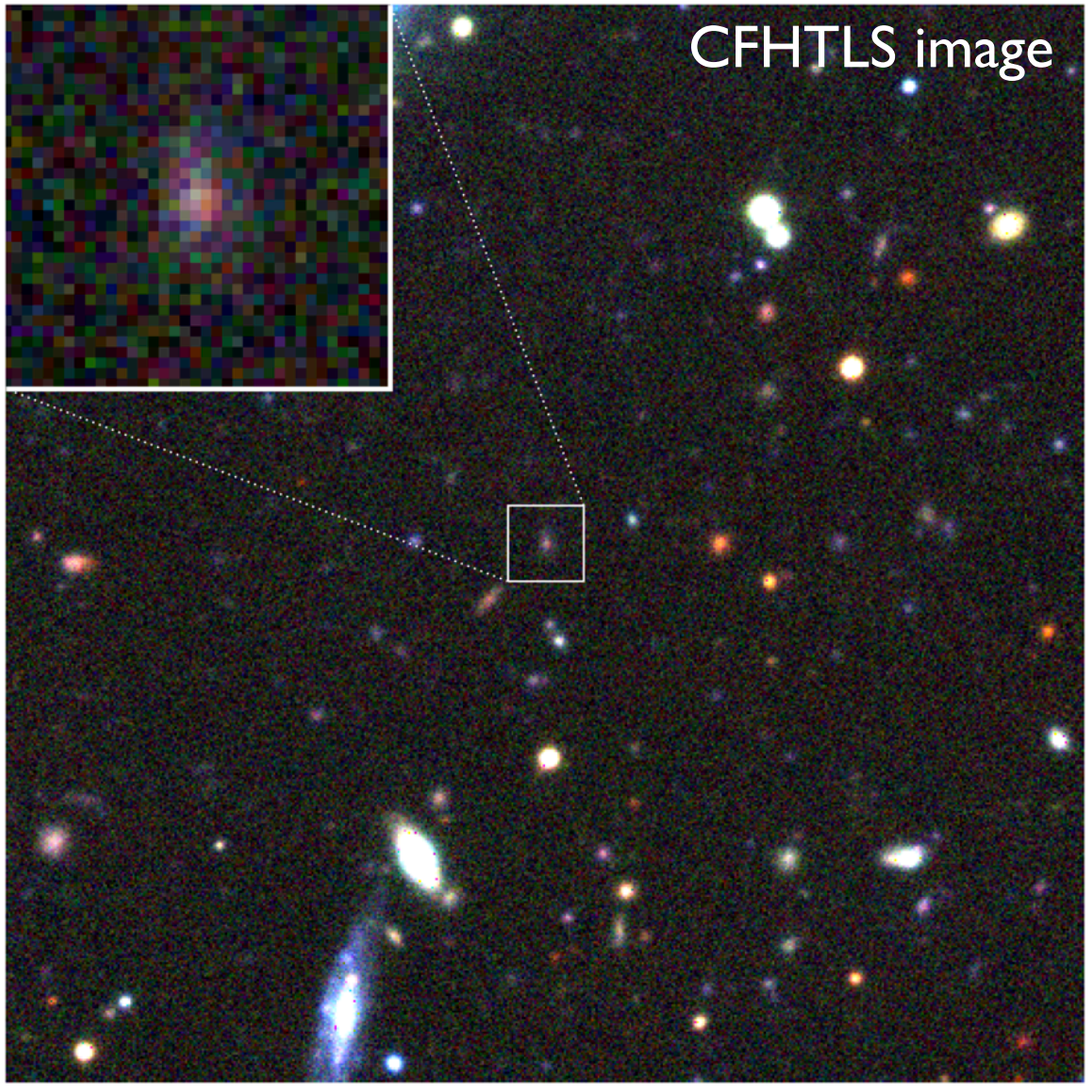


lightcurve and spectra consistent with 30x magnified type Ia SN



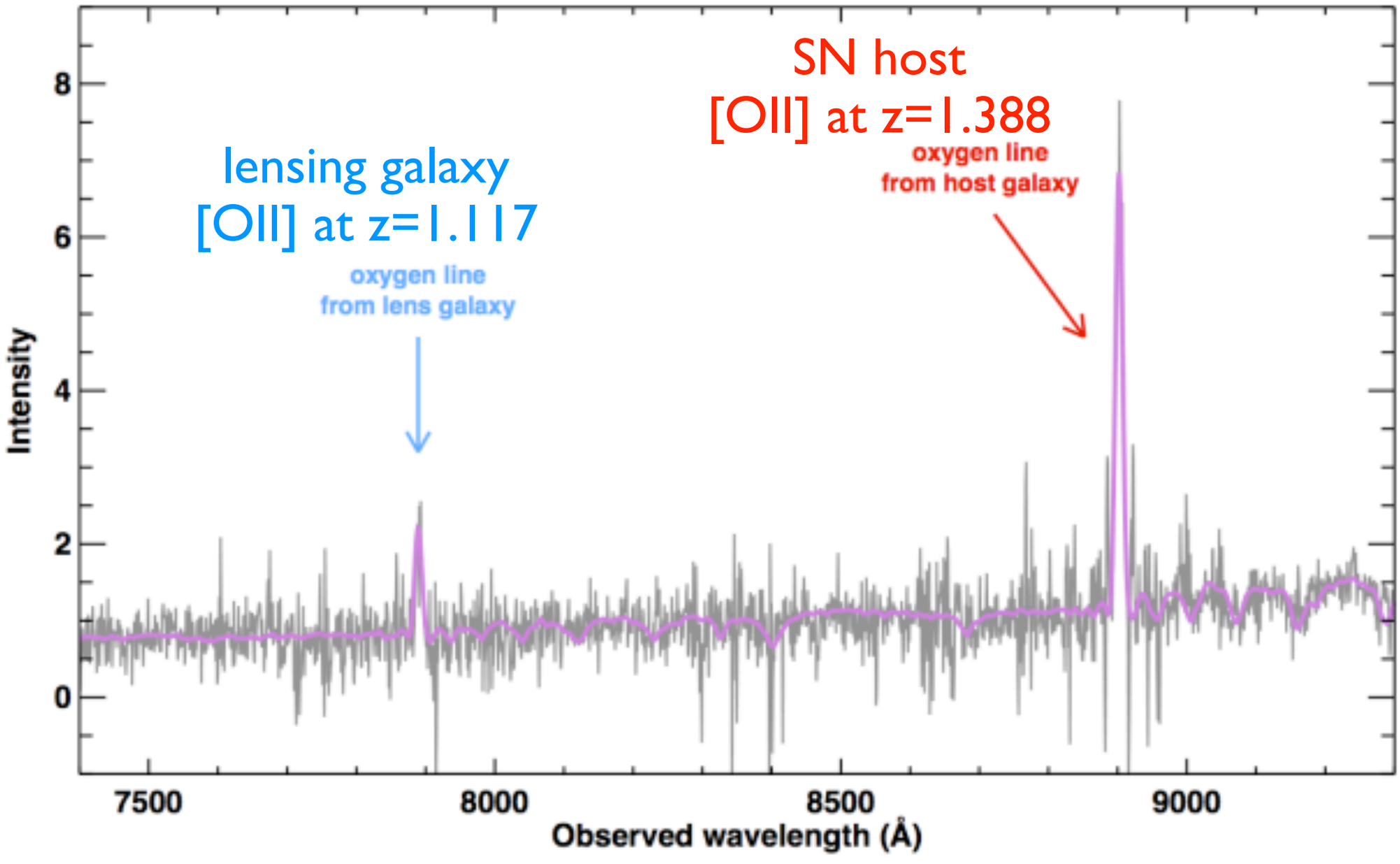
Where is the lens?

- 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 !

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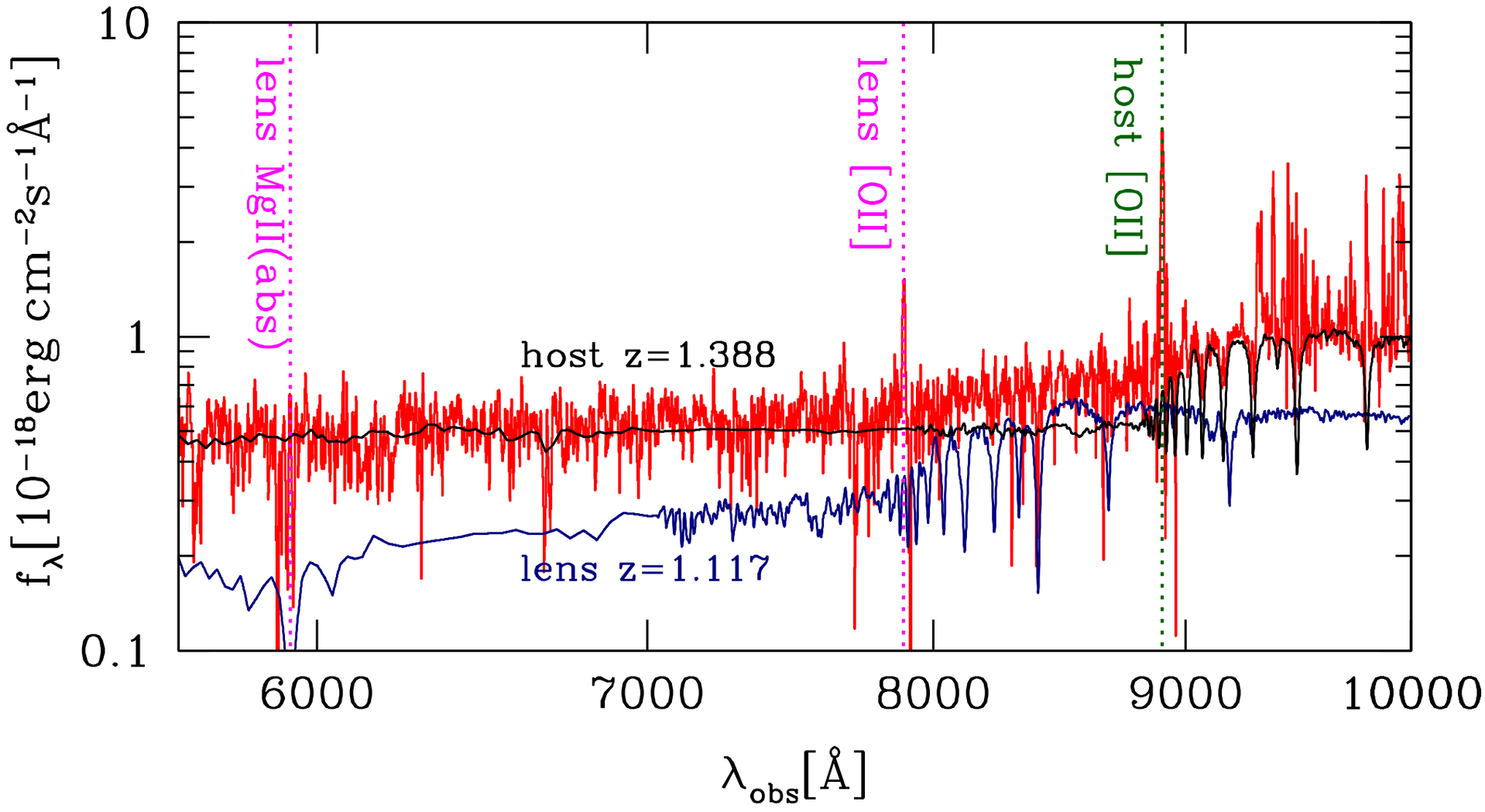
Property of the lensing galaxy



- best-fit stellar mass $M_* \sim 9\times10^9 M_\odot$, age ~ 1Gyr
- low lens mass suggests small image separation and time delay, which are consistent with obs

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!

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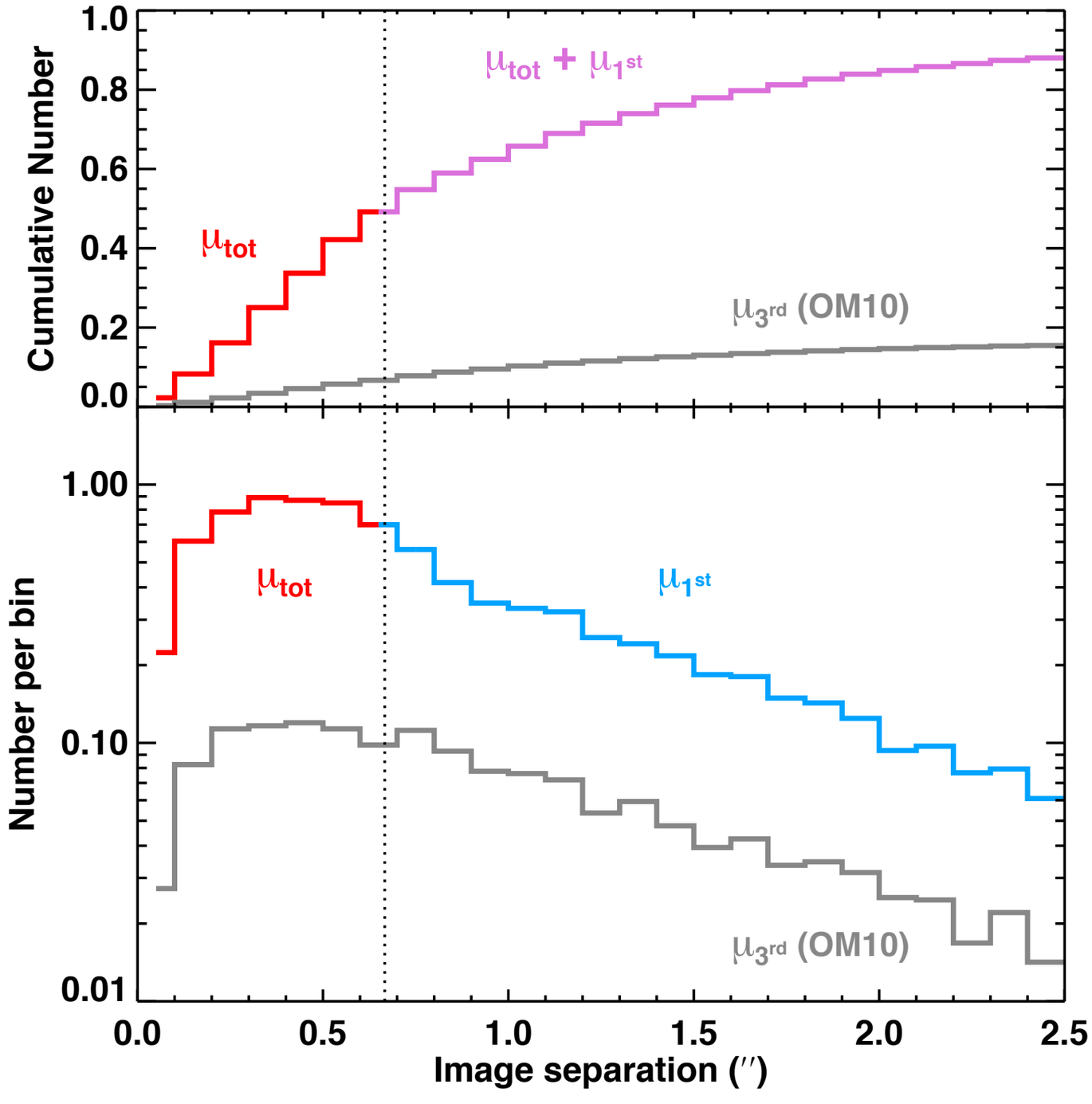
Expected number distribution



allow unresolved and/or single image detection

enhance the expected number by an order of magnitude

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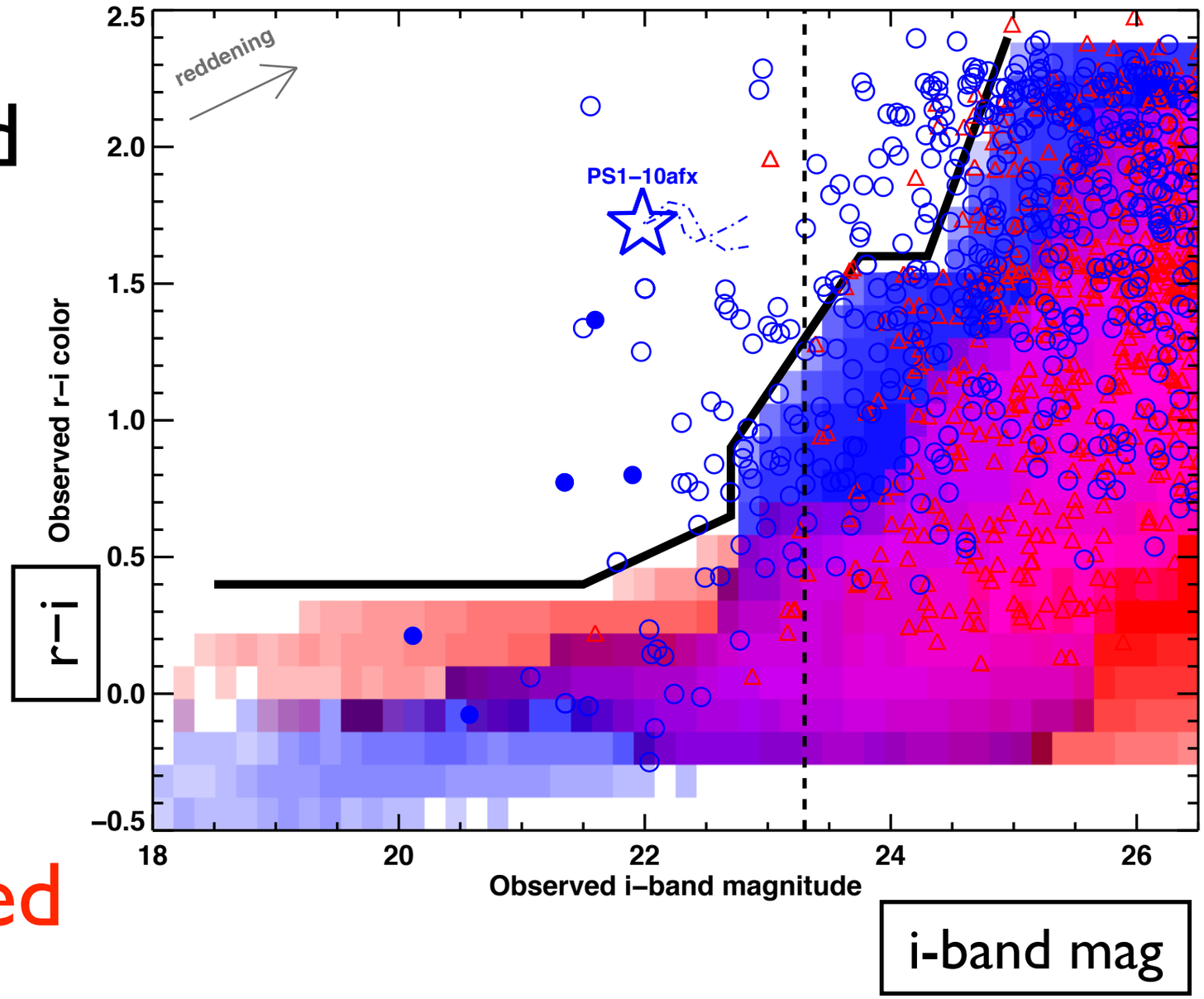
New approach to find lensed SNe

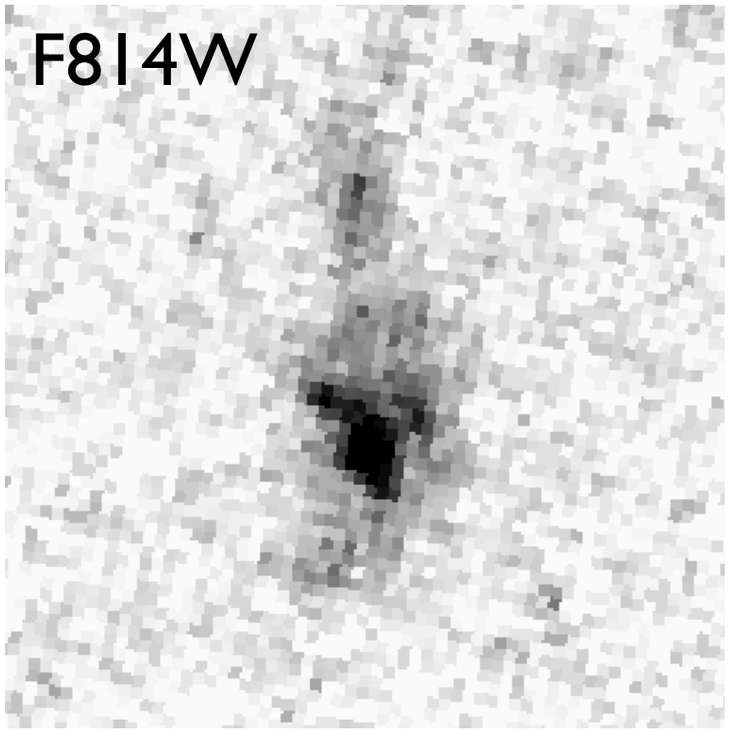
- red, bright SNe are almost always lensed SNe!
- find unresolved lens events in surveys, quick follow-up to get multiple images and time delays
- can find ~1000 lensed SNe in LSST!

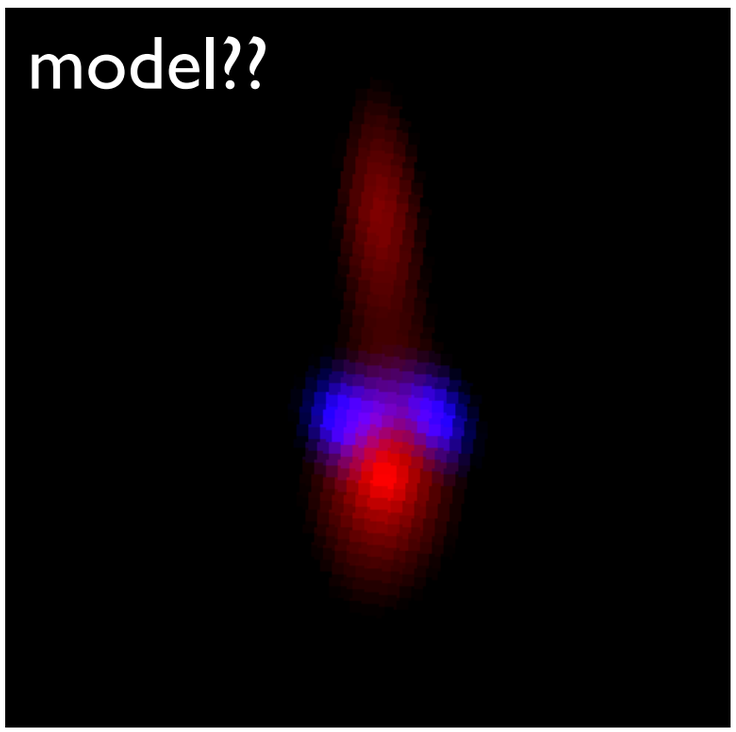


red: core-collapse

blue: type Ia

HST image of PS1-10afx





- F814W HST image taken by Pan-STARRS team (after SN faded away)
- reveal its complex structure, further supporting lensing scenario
- need more observations to robustly disentangle lens and host galaxies

Summary

- gravitationally lensed supernovae are rare but very interesting phenomena
- in particular the standard candle nature of SNIa enables direct measurement of magnification factor, which contains rich info on the lens
- we show that the very unusual SN in PS1-MDS, PS1-10afx, is in fact the normal type Ia SN magnified by a factor of 30, representing the first discovery of strongly lensed SN
- in LSST, we can discover of order 1000 lensed SNe by identifying them in the color-mag space