Putting the Strongly Lensed SNe Discovered by LSST to Work

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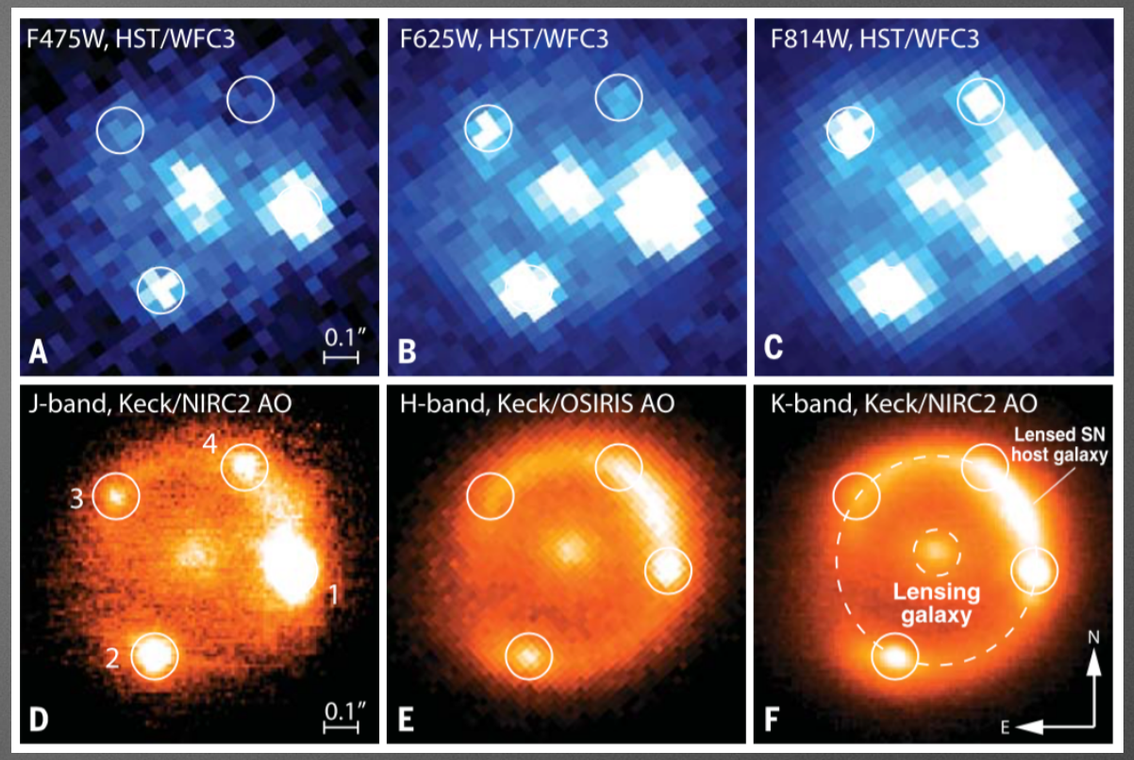
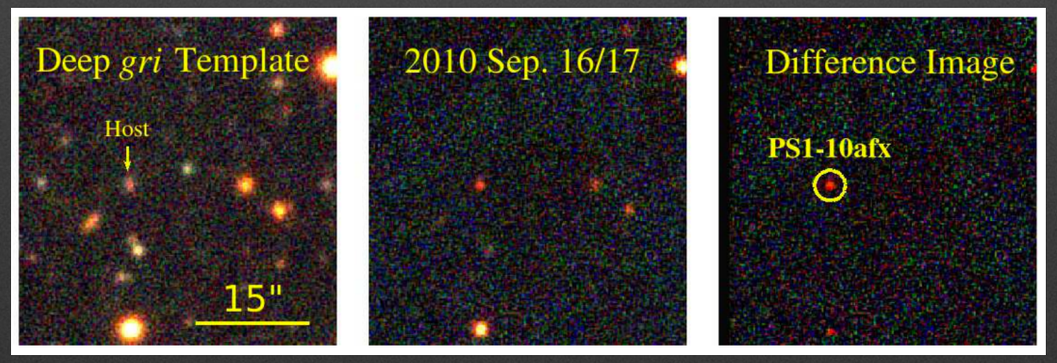
SN Refsdal (Kelly+15) z = 1.49
SN 1987A-like
μ~10
Discovered w/ *HST* (*J*~24.2 AB at peak)



iPTF16geu (Goobar+17) z = 0.41
SN Ia
μ~30
Discovered w/ P48 (*i*~19 AB at peak)



PS1-10afx (Chornock+13; Quimby+13,14) *z* = 1.39
SN Ia (?)
μ~30
Discovered w/ PS1 (z~21.7 AB at peak)

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

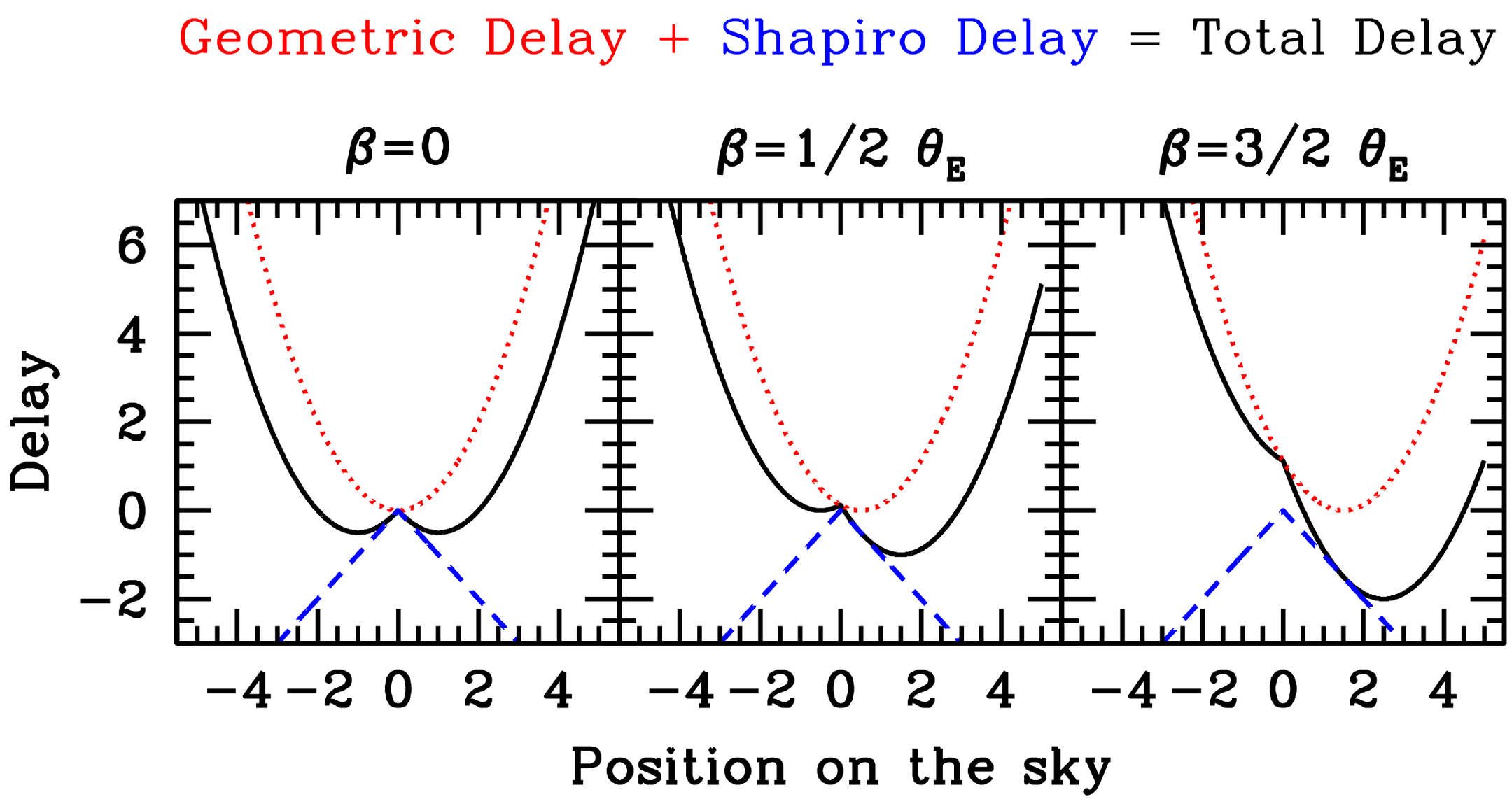
Sjur Refsdal

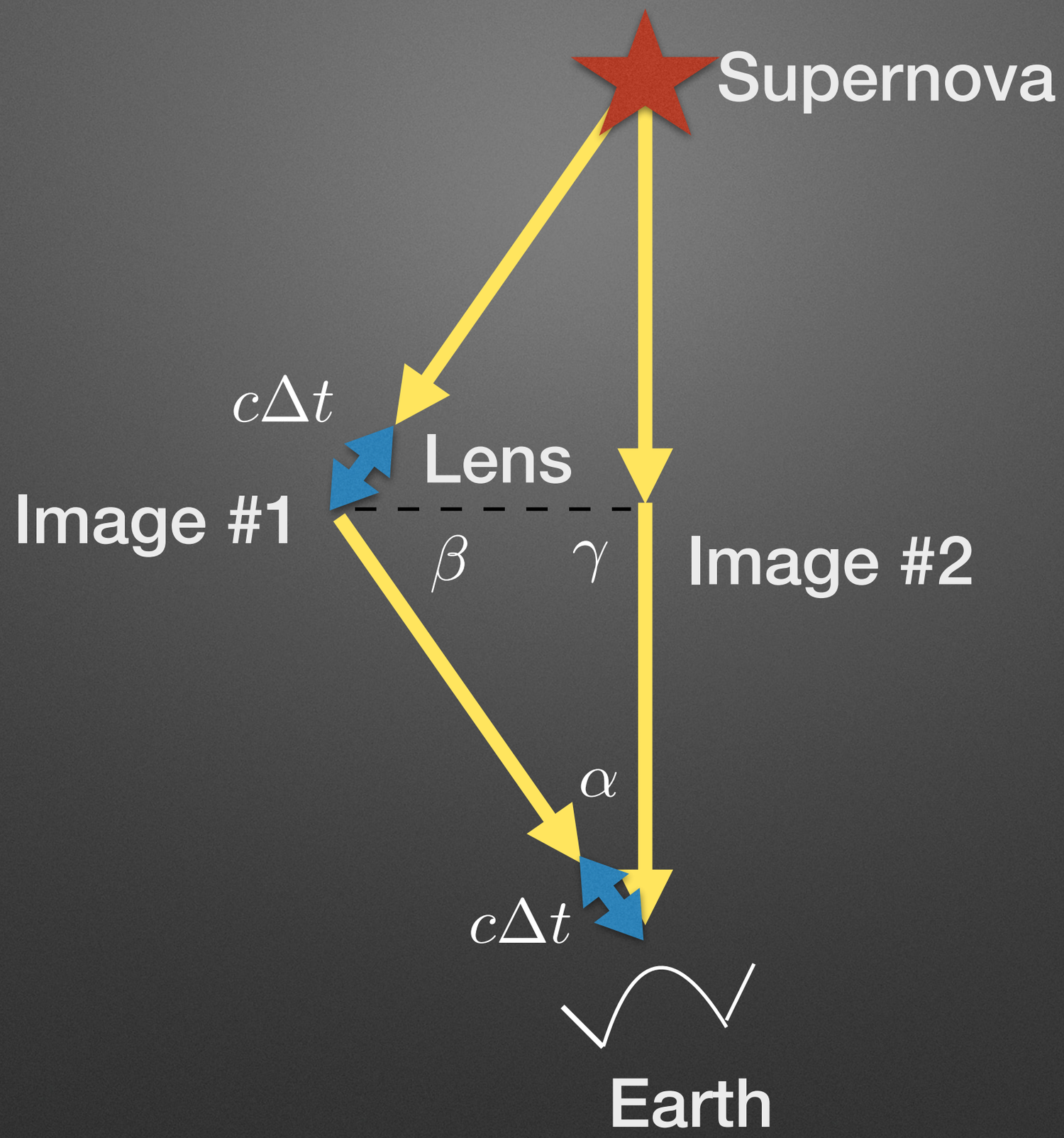
(Communicated by H. Bondi)

(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.


Geometric Delay + Shapiro Delay = Total Delay
β=0
β=1/2 θE
β=3/2 θE
Delay
6
4
2
0
−2
−4 −2 0 2 4
−4 −2 0 2 4
−4 −2 0 2 4
Position on the sky


Supernova
$c\Delta t$
Lens
Image #1
β
γ
Image #2
α
$c\Delta t$
Earth

What Can You Learn from Multiply Imaged SNe?

1. Constrain the Hubble constant — possible current tension b/w CMB, SN, quasar measurements

2. Assess + improve galaxy-cluster mass models

3. Probe ejecta structure of supernovae

4. Predict the reappearance of SNe in advance + take early-time data

5. Study faint SNe

How many strongly lensed SNe will LSST detect?

- Oguri & Marshall (2010): LSST will detect ~45 with image separation >0.5″ and “flux ratio”>0.1
  - LSST sees multiple adjacent transients (SN Refsdal)
- Goldstein & Nugent (2017): ~500 multiply imaged SNe with relaxed criteria
  - An unresolved transient too bright (iPTF16geu; PS1-10afx?)
- Microlensing needs to be incorporated (Goobar+2016)

Detection + follow up

- In addition, monitor known galaxy and galaxy-cluster strong lenses
- From the ground: spectroscopy + imaging w/ adaptive optics
- From space: *HST* + *JWST* + *WFIRST*
- Schedule observations of SN at early phase (e.g., SN Refsdal)

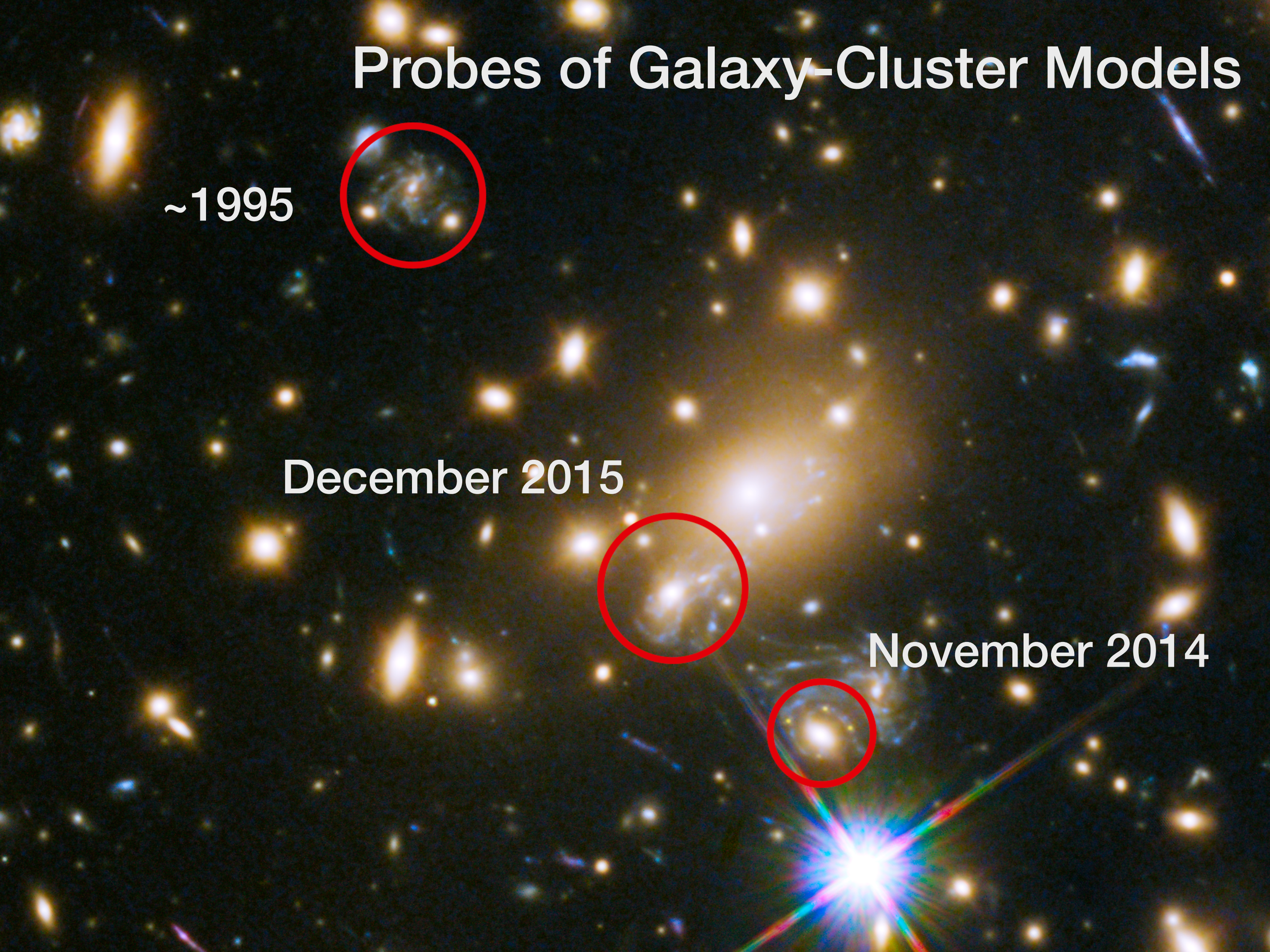
Measuring H_0 Using Time Delays

- SN light curves are simpler than quasar light curves
- Time delays typically a day to weeks
- Longer time delays better, since constraint on H_0 is proportional to fractional error in time delay
- Microlensing affects light curves (Dobler & Keeton 2006) but perhaps not *color* strongly (Goldstein & Nugent 2017)

Measuring H_0 Using Time Delays

- Calibrated luminosities of SNe Ia — can in principle break important lens model degeneracies
- Use SNe Ia to correct for extinction along multiple lines of sight through lens (may be small for early-type lenses)

Probes of Galaxy-Cluster Models



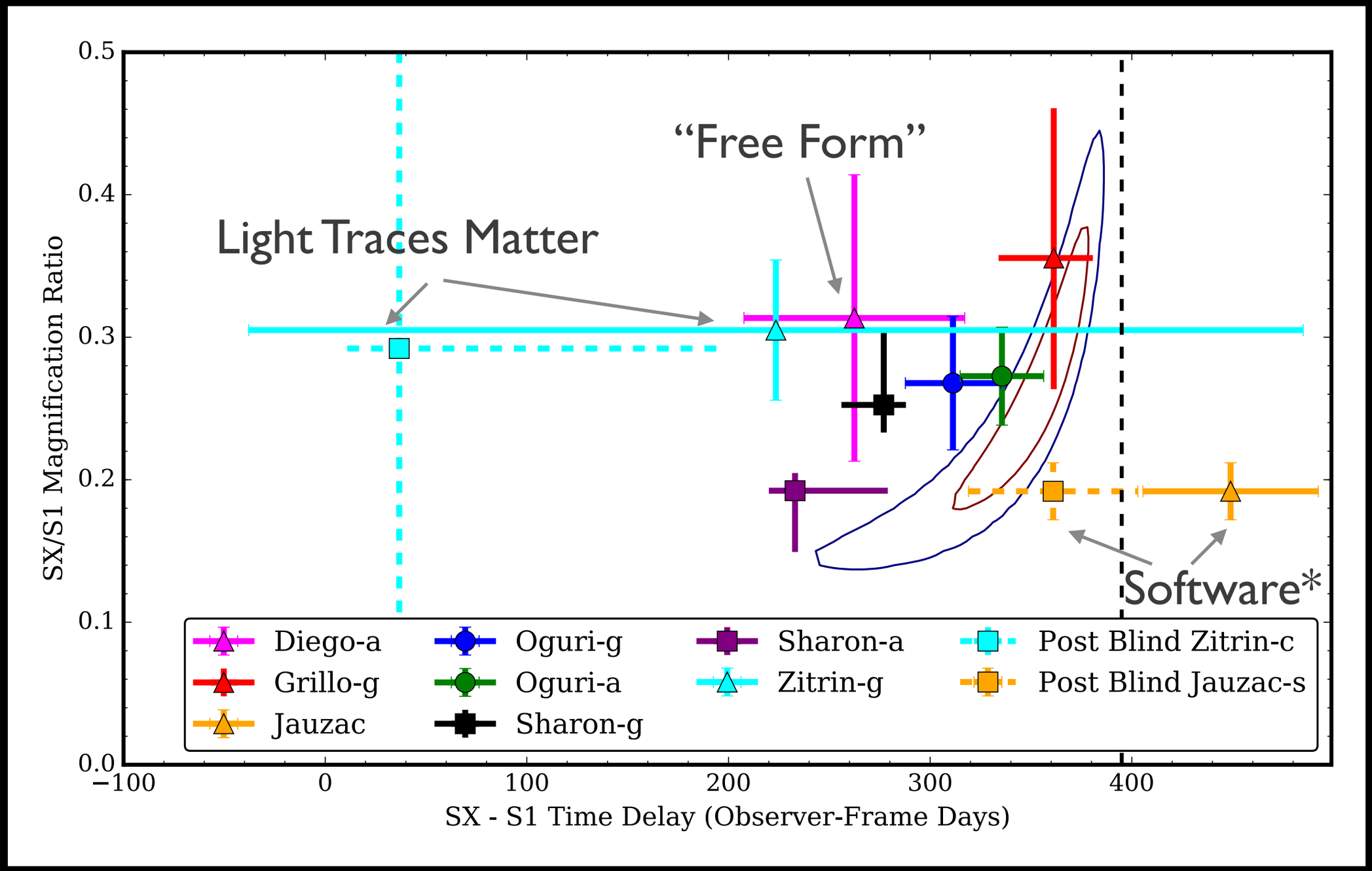
Improve Cluster Mass Models

- *James Webb Space Telescope* should be able to detect sources with ~35 AB near critical curves
- Probe low-luminosity galaxies (M_{UV} ~ -8 — -10 mag at z~6), which may drive reionization
- For *Hubble* Frontier Field clusters, disagreement about magnification is of order the magnification itself (e.g., Livermore+ 2016; Bouwens+ 2016; Jett+17)

galaxy positions ∝ 1st derivative of potential

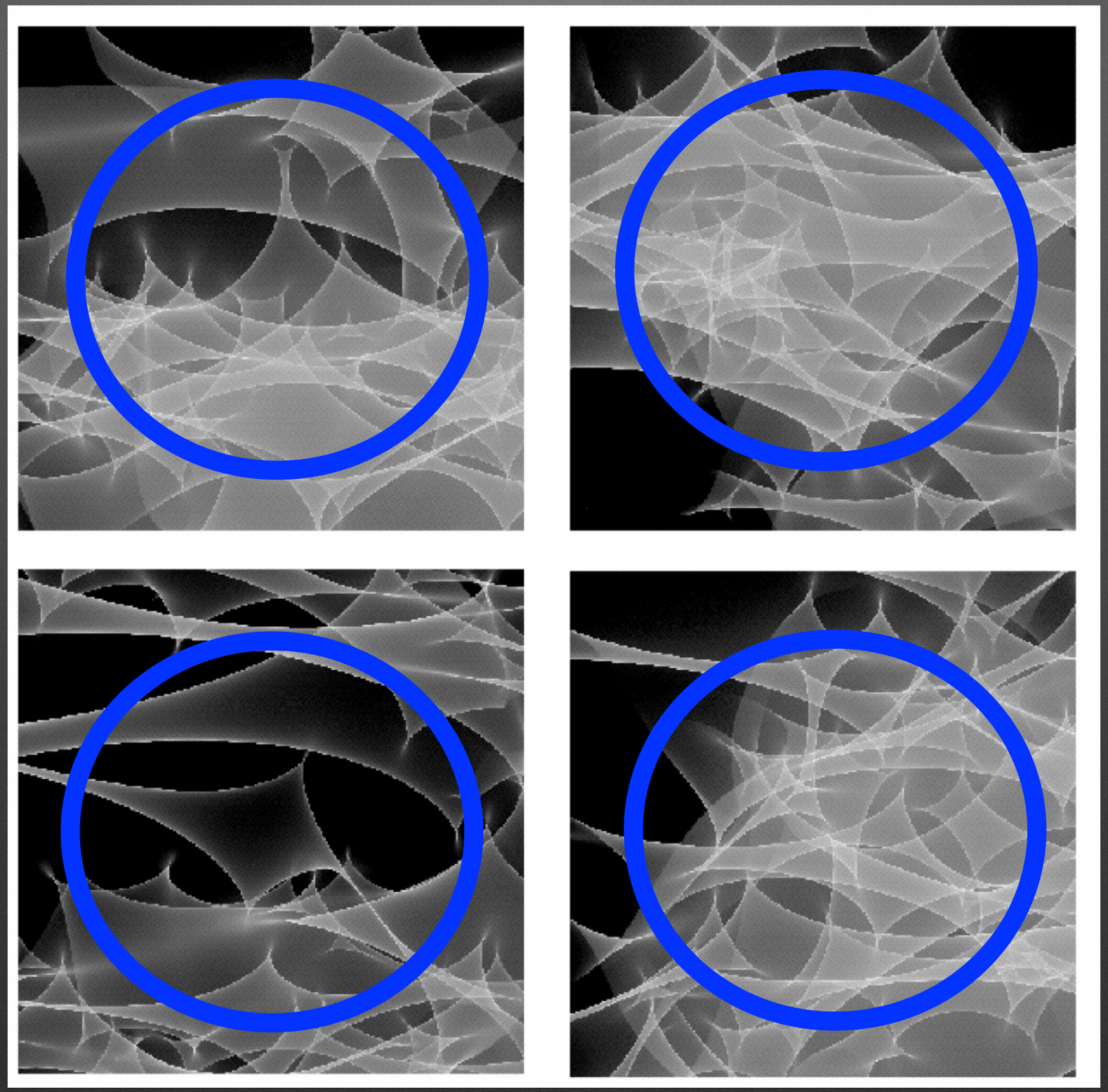
time delay ∝ potential

Predictions for Relative Delay and Magnification of Reappearance of SN Refsdal, Based on Different Cluster Models



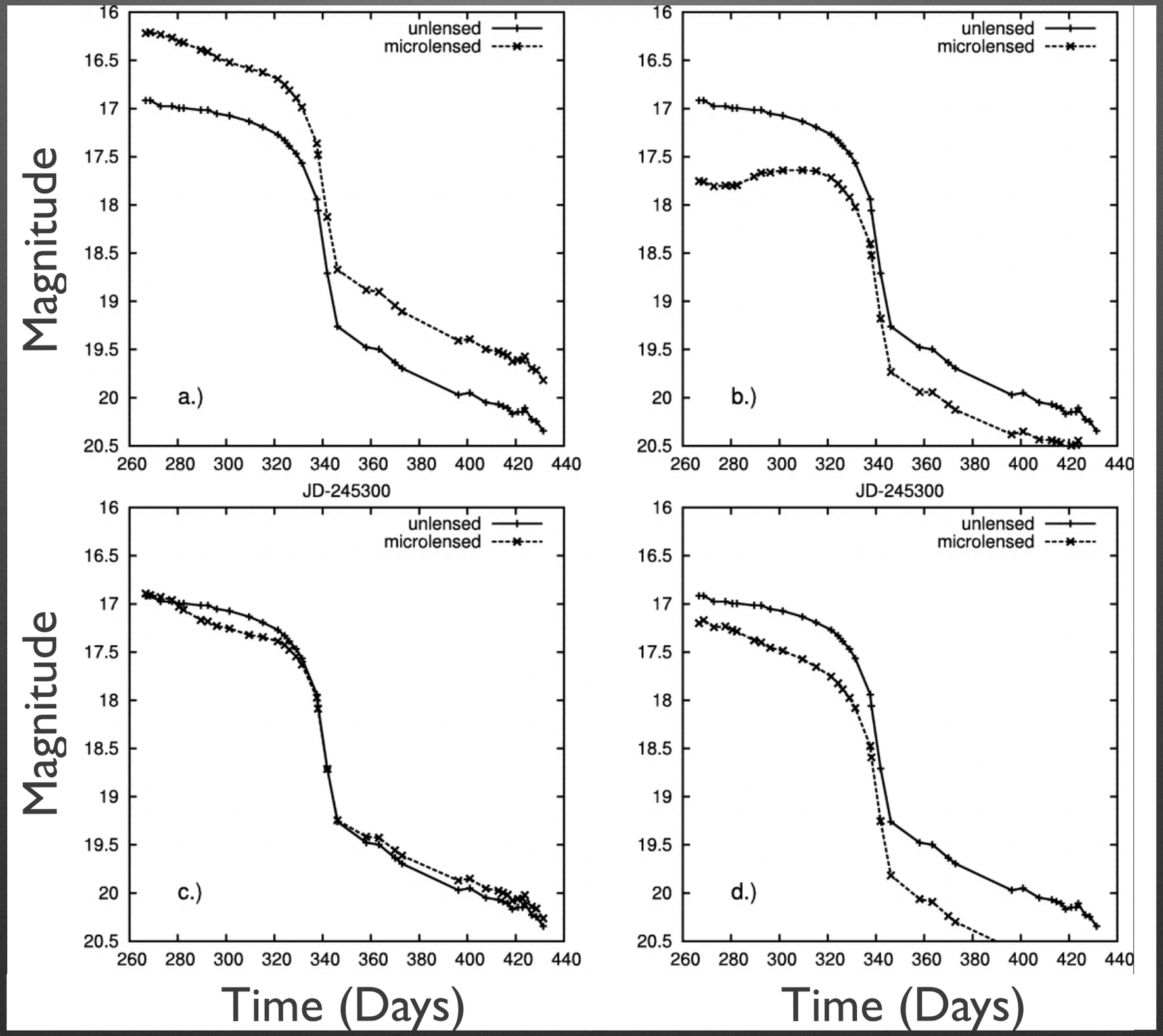
(Kelly, Rodney, Treu et al. 2016)

SN Microlensing



Magnification map: Dobler & Keeton (2006)

Distortion of Light Curves



Dobler & Keeton (2006)

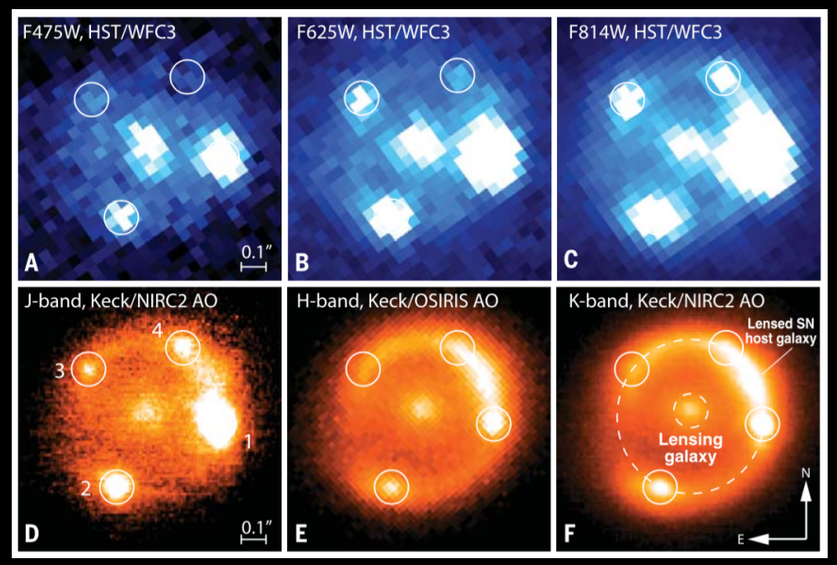
What can we do with microlensed SNe?

- Compare spectra of multiple images of SN
- Differential magnification should indicate how various atomic species are distributed (e.g., jets, high-velocity Si, Ca, etc.)
- Probe the mass function in surviving stars and remnants (e.g., Dobler & Keeton 2006)

LSST + Multiply Imaged SNe

- LSST should detect at least ~500 strongly lensed SNe
- Require prompt follow up — high angular resolution required for large majority of SNe

SN Refsdal (Kelly+15)



iPTF16geu (Goobar+17)