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*

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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 $\Delta t$ 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 $\Delta t$, 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.
Contemporary Physics

Figure 3. Illustration of gravitational lensing in terms of Fermat's principle. For a given source position (\(\beta = 0\)), the time delay surface (black solid lines) is given by the sum of the geometric delay (red dotted lines) and the Shapiro delay (blue dashed lines) as a function of position in the image plane (\(\theta_s\)). Images then form at the extrema of the time delay surface. The three panels show a section of the time delay surface in three different regimes of circularly symmetric deflector. Left panel: the source is perfectly aligned with the deflector (\(\beta = 0\)); the time delay has a local maximum at the center and two minima at the same height. This configuration gives rise to a perfect Einstein Ring, with an infinitely demagnified image in the center (see centre panel of Figure 3 for example). Middle panel: the source is now set to one side by half an Einstein Radius; the image forming on the outer minimum arrives first, then the central image corresponding to the local maximum, and last the image corresponding to the inner minimum. This configuration gives rise to the classic double configuration, with two bright images and an infinitely demagnified central image. Right panel: the source is now set by more than the Einstein Radius; in this case there is only a minimum and thus only one image, i.e. no gravitational lensing.

The transformation from source to image plane is given by Fermat’s principle. As in conventional optics, photons seem to “choose” special paths from the source to the observer, i.e. images form at the extrema of the arrival time surface (usually they pick the shorter time, i.e. minima, but also maxima or saddle points are allowed). However, whereas in standard optics the light travel time depends on the speed of light in the material as well as on the path length, in gravitational optics the role of the refractive material is played by the gravitational potential of the deflector via the so-called Shapiro delay [25], i.e. the delay measured by the observer for a light ray passing through a deep gravitational potential caused by general relativistic time dilation. The competition between the Shapiro delay, which increases with the gravitational potential, and the length of the light path gives rise to the variety of observed phenomena. The description of gravitational lensing in terms of Fermat’s principle is illustrated in Figure 3.

Under rare circumstances, if the Shapiro delay is strong enough, multiple images can appear to the observer, giving rise to the phenomenon of strong lensing. In this case the time delay between the arrival of light to the various images encodes information about the absolute path lengths traversed and hence the size of the Universe as function of cosmic time. As we describe in Section 2.2, this provides an opportunity for a direct measurement of various cosmological parameters. Conversely, if the Shapiro delay is not strong enough to counterbalance the geometric delay, only a single distorted image of the source appears to the observer. This phenomenon is called weak lensing and is a powerful tool to trace the distribution of dark matter outside of the confines of massive structures like cluster of galaxies (Section 3).

2. Strong Lensing

Strong lensing is perhaps gravitational lensing's most visually impressive feature. A rich cluster of galaxies such as that in Figure 1 produces striking distorted images of background galaxies...
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

~1995

December 2015

November 2014
Improve Cluster Mass Models

- *James Webb Space Telescope* should be able to detect sources with ~35 AB near critical curves

- Probe low-luminosity galaxies ($M_{UV} \sim -8 \sim -10$ mag at $z \sim 6$), 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)

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galaxy \text{ positions} \propto 1\text{st derivative of potential} \]

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time \text{ delay} \propto \text{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