Turning Gravitationally Lensed Supernovae into Cosmological Tools

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“Understanding Type Ia Supernova Distance Biases by Simulating Spectral Variations”

Pierel et al. in prep.
Why?
flat – $\Lambda$CDM

- Planck (Planck Collaboration 2018)
- DES+BAO+BBN (Abbott et al. 2018)
- SH0ES (Riess et al. 2019)
- CCHP (Freedman et al. 2019)
- Miras (Huang et al., in prep)
- H0LiCOW (Wong et al. 2019)
- MCP (Reid’s talk)
- SBF + Cepheids / TRGB (Blakeslee’s talk)

Image Credit: Anowar Shajib
\( H_0 \) measured to 2.4%, combining 6 lensed QSOs from H0LiCOW, each with \( \sim 6-10\% \) precision.

Plausible \( H_0 \) precision from a single well-observed GLSN : \( \sim 7\% \)

Wong+ 2019
Based on Linder 2011
Figure 2: Anticipated constraints on the dark energy equation of state parameters $w_0$ and $w_a$ after a decade of LSST operations. (a) Contours show the 1- and 2-$\sigma$ confidence regions that could be achieved after 10 years of LSST operation, for each of the primary cosmological tools: strongly-lensed quasar time delays (blue), cluster number counts (red, a probe of the growth of structure), large scale structure (yellow, executed through 3- and 2-point correlation function analysis), Type Ia SN luminosity distances (purple), and the composite constraint from all four probes (orange). The figure of merit (FOM) listed for each probe is the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the $w_0$-$w_a$ plane. Larger FOM indicates greater accuracy.

(b) Projected constraints from glSN time delay measurements. The top panel shows a plausible glSN sample, comprising 100 time delay distance measurements, each with 4% precision. This relatively modest sample would achieve a FOM comparable to the FOM delivered by 400 quasar time delays at 7% precision. To demonstrate the value of improving precision and controlling systematic errors, the lower panel shows a very optimistic scenario, where those 100 glSN time delays reach 1% precision. In this case the FOM would match the contribution from several hundred thousand Type Ia SN luminosity distance measurements. The Fisher matrix analysis for these projections follows the assumptions of the LSST Science Requirements Document (LSST Dark Energy Science Collaboration et al., 2018) which also contains details of the other cosmological probes.

The equation of state that allows this time variation is $w(a) = w_0 + w_a(1-a)$ (Linder, 2003). In this dynamical dark energy model, $w_0$ measures the equation of state in the present day (where $a=1$) and $w_a$ reflects the degree of time variation. Any cosmological distance probe can be used to constrain $w_0$ and $w_a$, such as the "standard ruler" of baryon acoustic oscillations or the "standard candle" of Type Ia SN luminosity distances (see Figure 2a for projected LSST constraints from many probes). Gravitational lensing time delay distance measurements have not yet been developed to the same degree as those more established tools, but there are strong theoretical reasons to believe that such an investment will pay off. Time delay cosmography holds great promise as a new probe of dynamical dark energy because the time delay distance ratio, $D_t/D_D$, has an unusual characteristic that helps to break degeneracies between the dark energy parameters $w_0$ and $w_a$ (Linder, 2004, 2011). This makes the time delay distance ratio highly complementary to existing probes, which in turn means that an investment in time delay cosmography can yield a more powerful improvement in cosmological precision, even with a dramatically smaller sample size. Figure 2b uses an extreme example to illustrate this: a sample of just 100 glSN time delay distances with 1% precision could improve the ($w_0$, $w_a$) figure of merit by the same factor as some 100,000 SNIa distances from LSST.

Although 1% precision from individual lenses is unlikely to be achievable, it is plausible to aim for 3–4%.
Why Supernovae?
Quasar light curves are stochastic and unpredictable...
(most) SN Light curves are fast, simple, and predictable

Scaled Flux (Arbitrary Units)

Observer-frame days

Pierel & Rodney 2019
Achromatic Microlensing?

Goldstein et al. 2017
SN Refsdal: SNTD (parameterized)
J. Pierel
S. Rodney
Accuracy in fitting simulated light curves: SX-S1
Composite Time Delays: SX-S1

$\Delta t$ precision $< 2\%$

$350 \pm 6.5$ days

~final

blinded
ZTF should find a handful, LSST will find hundreds.
Only a small fraction will be suitable for time delay cosmography.

2. Why use GLSN? *They have natural strengths for time delay cosmography.*

3. Measuring time delays: SNTD is designed to leverage those strengths.

4. SN Refsdal is delivering a time delay measurement <2%, will deliver H0~7%

5. Expect a handful more by 2025, hundreds by 2030