H0LiCOW: Cosmology with Gravitational Lens Time Delays

Sherry Suyu
Max Planck Institute for Astrophysics
Academia Sinica Institute of Astronomy and Astrophysics

July 12, 2016

A century of Gravitational Lensing: from Theory to Application, Leiden
$H_0$, a key parameter

Hubble constant $H_0$ sets
- age, size of the Universe
- expansion rate: $v = H_0 \, d$

$H_0$ provides critical independent constraints on
- nature of dark energy
- neutrino physics
- spatial curvature of the Universe
[e.g., Freedman et al. 2012, Suyu et al. 2012, Weinberg et al. 2013, Sekiguchi et al. 2010]

Need Independent methods to overcome systematics, especially the unknown unknowns

Tension? New physics?
Need more precise & accurate $H_0$

[Riess et al. 2016]
Strong Gravitational Lens with Active Galactic Nucleus

Active galactic nucleus (AGN) in the source from accretion of material onto supermassive black hole:

Light emitted from AGN changes in time ("flickers")
Gravitational Lens Time Delays

[Fassnacht et al. 1999, 2002]
Movie Credits: S. H. Suyu, C. D. Fassnacht, NRAO/AUI/NSF
Gravitational Lens Time Delays

Time delay:
\[ t = \frac{1}{c} D_{\Delta t} \phi_{\text{lens}} \]

Time-delay distance:
\[ D_{\Delta t} \propto \frac{1}{H_0} \]

Obtain from lens mass model

For cosmography, need:
1. time delays
2. lens mass model
3. mass along line of sight

Advantages:
- simple geometry & well-tested physics
- one-step physical measurement of a cosmological distance
Gravitational Lens Time Delays

Time delay:

\[ t = \frac{1}{c} \frac{D_{\Delta t}}{\phi_{\text{lens}}} \]

Time-delay distance:

\[ D_{\Delta t} \propto \frac{1}{H_0} \]

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

New Distance Probe:
measure \( D_d \) with time delays and lens velocity dispersion

Inh Jee’s poster
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

B1608+656

RXJ1131-1231

H$_0$ to <3.5% precision

HE0435-1223

WFI2033-4723

HE1104-1805

[Suyu et al. 2016]
H0LiCOWers

H0LiCOW: $H_0$ Lenses in COSMOGRAIL’s Wellspring

→ Establish time-delay gravitational lenses as one of the best cosmological probes
H0LiCOW: \( H_0 \) Lenses in COSMOPHAGAIL’s Wellspring

- **B1608+656**
- **RXJ1131-1231**
- **HE0435-1223**
- **WFI2033-4723**
- **HE1104-1805**

**Completed**

**Ongoing**
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

H0LiCOW I. Program Overview [Suyu et al., arxiv:1607.00017]

H0LiCOW II. Spectroscopic survey and galaxy-group identification of the strong gravitational lens system HE0435-1223 [Sluse et al., arxiv:1607.00382]

H0LiCOW III. Quantifying the effect of mass along the line of sight to the gravitational lens HE 0435-1223 through weighted galaxy counts [Rusu et al., arxiv:1607.01047]

H0LiCOW IV. Lens mass model of HE 0435-1223 and blind measurement of its time-delay distance for cosmology [Wong et al., arxiv:1607.01403]

H0LiCOW V. New COSMOGRAIL time delays of HE 0435–1223: $H_0$ to 3.8% precision from strong lensing in a flat $\Lambda$CDM model [Bonvin et al., arxiv:1607.01790]
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

- B1608+656
- RXJ1131-1231
- HE0435-1223
- WFI2033-4723
- HE1104-1805

completed

ongoing

focus
Time Delays

COSMOGRAIL, Kochanek et al. and Fassnacht et al. have been monitoring H0LiCOW lenses

13-year light curve of HE0435-1223
Time delay with 6.5% uncertainty
[Bonvin, Courbin, Suyu et al.; arxiv:1607.01790]

Frederic Courbin’s talk
Vivien Bonvin’s poster
**Lens environment**

Spectroscopic campaign of HE0435-1223 field

- 100 spec-z within 3' from strong lens
- Identified 9 group candidates
- Spec-z of galaxies within 12" measured, important for lens mass model
- Negligible flexion shift [McCully et al. 2016]: most galaxies and groups can be treated as external shear field [Sluse, Sonnenfeld, Rumbaugh et al. arxiv:1607.00382]
Spectroscopic campaign of HE0435-1223 field

- 100 spec-z within 3’ from strong lens
- identified 9 group candidates
- spec-z of galaxies within 12” measured, important for lens mass model
- negligible flexion shift

[McCully et al. 2016]: most galaxies and groups can be treated as external shear field

[Sluse, Sonnenfeld, Rumbaugh et al. arxiv:1607.00382]
Lens environment

- wide-field multi-band imaging to quantify $\kappa_{\text{ext}}$
- weighted number counts + Millennium Simulation
- thorough investigation of weighting schemes with CFHTLenS
  as control field, get $\kappa_{\text{ext}}$ distribution with uncertainty $\sigma_{\kappa}=0.025$
  [Rusu, Fassnacht, Sluse et al. arxiv:1607.01047]
Lens environment

- wide-field multi-band imaging to quantify $\kappa_{\text{ext}}$
- thorough investigation of weighting schemes with CFHTLenS as control field, get $\kappa_{\text{ext}}$ distribution with uncertainty $\sigma_{\kappa}=0.025$ [Rusu, Fassnacht, Sluse et al. arxiv:1607.01047]
Lens mass modeling

HST imaging in 3 bands

• modeled with power-law and composite profiles
• New lens modeling capabilities developed in GLEE [Suyu & Halkola 2010]:
  • PSF reconstruction
  • multi-lens plane modeling
  [Suyu et al. in prep.]
• Modeled strong lens including up to 5 nearest neighboring galaxies

[Wong, Suyu, Auger et al., arxiv:1607.01403]
Lens velocity dispersion

- Keck LRIS spectra (PI: Fassnacht)
- velocity dispersion $\sigma = 222 \pm 15$ km/s
- complement lens mass modeling, particularly to mitigate effects of mass-sheet degeneracy [e.g. Schneider & Sluse 2013, 2014, Unruh et al. 2016]

[Wong, Suyu, Auger et al., arxiv:1607.01403]
Blind analysis in action

- Blind analysis to avoid confirmation bias
- Throughout analysis, cosmological distances and parameters are offset from median, i.e., blinded

[Wong, Suyu, Auger et al. arxiv:1607.01403]
Blind analysis in action

- Blind analysis to avoid confirmation bias
- Throughout analysis, cosmological distances and parameters are offset from median, i.e., blinded
- Collaboration agreed: when unblind, publish $D_{\Delta t}$ without modification
- Scheduled unblinding telecon on June 2
- Scheduled again for June 16

[Wong, Suyu, Auger et al. arxiv:1607.01403]
Time-delay distance of HE0435

\[ D_{\Delta t} = 2612^{+208}_{-191} \text{ Mpc} \]

Analytic fit for \( D_{\Delta t} \)

\[
P(D_{\Delta t}) = \frac{1}{\sqrt{2\pi}(x - \lambda_D)\sigma_D} \exp \left[ -\frac{(\ln(x - \lambda_D) - \mu_D)^2}{2\sigma_D^2} \right]
\]

where

\[
x = D_{\Delta t} / (1 \text{ Mpc}) \\
\lambda_D = 653.9 \\
\mu_D = 7.5793 \\
\sigma_D = 0.10312
\]

Can be combined with any other probe

[Wong, Suyu, Auger et al. arxiv:1607.01403]
$H_0$ from 3 strong lenses

$H_0 \in [0,150]$ km/s/Mpc

$\Omega_m = 1 - \Omega_\Lambda \in [0,1]$ w = -1

$H_0$ with 3.8% precision for flat $\Lambda$CDM

Frederic Courbin’s talk: inference on cosmological models

[Bonvin, Courbin, Suyu et al.; arxiv:1607.01790]
Looking forward

- 2 more H0LiCOW lenses
- follow-up data partly in-hand and partly pending
- HST WFC3 image show Einstein ring

Expectation from H0LiCOW: <3.5% uncertainty on $H_0$ for most cosmologies with $w=-1$ (HST proposal aim of 3.8% achieved with 3/5 lenses thanks to the improved time delays from COSMOGRAIL)

[Suyu, Bonvin, Courbin et al., arxiv:1607.00017]
Strongly lensed supernova

MACS 1149.6+2223

[Kelly et al. 2015]
Magnification and delay

[Kelly et al. 2016]
Magnification and delay

Predicted with GLEE (code for cosmography) [Grillo, Karman, Suyu et al. 2016]

[Kelly et al. 2016]
Spot on!

[Kelly et al. 2016]
Future Prospects

Current/future surveys including HSC, DES, KiDS, Euclid, LSST and WFIRST will provide \(~10,000\) lensed quasars and \(~100\) lensed supernovae [Oguri & Marshall 2010]

[Jee, Komatsu, Suyu, Huterer 2016]
Summary

• Time-delay distances $D_{\Delta t}$ of each lens can be measured with uncertainties of ~5-8% including systematics
• Recent blind analysis of HE0435-1223 using time delays from COSMOGRAIL, wide-field imaging/spectroscopy, HST imaging, and lens velocity dispersion from Keck
• With 3 time-delay lenses: $H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc in flat $\Lambda$CDM
• SN Refsdal blind test demonstrated the robustness of our mass modeling approach and software GLEE
• H0LiCOW: $H_0$ to <3.5% precision from 5 lenses
• Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology
Thank you!