H0LiCOW: Measurement of $H_0$ from lensing

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Strong gravitationally lensed quasar
Time delays

[Credit: ESA/Hubble, NASA]
Time delays
Variability of quasar emission

HE0435-1223

quasar powered by accretion of material onto supermassive black hole:

light emitted from quasar changes in time ("flickers")

[Suyu et al. 2017]
Time delays
Time delays
Cosmology with time delays

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

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

HE0435-1223

[Suyu et al. 2017]
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

B1608+656

RXJ1131-1231

HE0435-1223

WFI2033-4723

HE1104-1805

$H_0$ to <3.5% precision

[Suyu et al. 2017]
H0LiCOWers

H0LiCOW: $H_0$ Lenses in COSMOGRAIL’s Wellspring

Establish time-delay gravitational lenses as one of the best cosmological probes
H0LiCOW: latest results

- **B1608+656**
  - [Suyu et al. 2010]

- **RXJ1131-1231**
  - [Suyu et al. 2013, 2014; Tewes et al. 2013]

- **HE0435-1223**
  - [Wong, Suyu et al. 2017; Rusu et al. 2017; Sluse et al. 2017; Bonvin et al. 2017]

- **SDSS1206+4332**
  - part of extended sample
  - [Birrer et al. 2018]
$H_0$ from 4 strong lenses

Blind analysis to avoid confirmation bias

$H_0$ with 3% precision in flat $\Lambda$CDM
Looking forward

WFI2033-4723:
blind analysis ongoing
[Rusu et al., Sluse et al., Wong et al., in prep.]

HE1104-1805

PG1115+080:
blind analysis of adaptive-optics and HST images ongoing
[Chen et al., in prep.]
Towards hundreds of lenses

**Hyper Suprime-Cam Survey**
- 8m Subaru Telescope
- Mauna Kea, Hawaii
- 1400 deg$^2$ with $i_{\text{limit}} \sim 26$
- 2014-2019
- Expect ~600 lenses
  [Oguri & Marshall 2010]

**Dark Energy Survey**
- STRong-lensing Insights into Dark Energy Survey
- (PI: Treu)
- 4m Blanco Telescope, CTIO, Chile
- 5000 deg$^2$ with $i_{\text{limit}} \sim 24$
- 2012-2017
- Expect ~1100 lenses
  [Oguri & Marshall 2010]

**Kilo Degree Survey**
- 2.6m VLT Survey Telescope
- Paranal, Chile
- 1500 deg$^2$ with $r_{\text{limit}} \sim 25$
- 2011-~2018
New quads imaged with HST

New lens systems discovered in DES, Pan-STARRS, SDSS, ATLAS:

[Shajib et al. 2018]
Strongly lensed supernova

MACS 1149.6+2223

[Kelly et al. 2015]
Supernova “Refsdal”

discovered serendipitously in November 2014

[Kelly et al. 2015]
When will the other SN images appear?

MACS 1149.6+2223

[Kelly et al. 2015]
Predicted magnification and delay

[Kelly et al. 2016]
Predicted magnification and delay

in October 2015: predict detection of SX before end of 2015 [Treu et al. 2016]
Predicted magnification and delay

*In October 2015: predict detection of SX before end of 2015* [Treu et al. 2016]

HST observations in Oct 2015: no sign of SX
in Nov 2015: no sign of SX…
Appearance of image SX

December 2015

[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]
• Grillo et al. predicted successfully and precisely all three observables of image SX: time, magnification and location

• GLEE [Suyu & Halkola 2010] accurately and precisely predicted the appearance of SX as a result of its ability to reconstruct the entire SN host galaxy
$H_0$ à la Supernova Refsdal

feasibility study of using SN Refsdal for $H_0$ measurement

- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)

[Grillo, Rosati, Suyu et al. 2018]
Future Prospects

Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]
Summary

• Time-delay distances $D_{\Delta t}$ of each lens can be measured with uncertainties of ~5-8% including systematics.
• From 4 lenses in H0LiCOW, $H_0 = 72.5^{+2.1}_{-2.3}$ km/s/Mpc in flat $\Lambda$CDM, a 3% precision measurement independent of other probes.
• Search is underway to find new lenses in DES, HSC, PanSTARRS, and Gaia surveys.
• SN Refsdal blind test demonstrated the robustness of our lens mass modeling approach.
• Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology.
Thank you!