Shedding Light on the Dark Cosmos through Gravitational Lensing

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Puzzles in cosmology

What is the nature of dark energy and dark matter?

Is our Universe spatially flat?

How many relativistic species are present in the early Universe?

Measuring the Hubble constant \((H_0)\) provides a way to address these questions
Hubble Constant: key parameter

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

Tension? New physics?

Need more precise & accurate $H_0$

Need independent methods to overcome systematics, especially the unknown unknowns

[Riess et al. 2016]
Distance Ladder

ladder to reach objects in Hubble flow \((v_{\text{peculiar}} \ll v_{\text{Hubble}} = H_0 d)\)
Distance Ladder Measurements

- *Hubble Space Telescope* Key Project [Freedman et al. 2001]
  - $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (10% uncertainty)
  - resolving multi-decade “factor-of-two” controversy

- Carnegie Hubble Program [Freedman et al. 2012]
  - $H_0 = 74.3 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (2.8% uncertainty)

- Carnegie-Chicago Hubble Program [Beaton et al. 2016]
  - aim 3% precision in $H_0$ via independent route with RR Lyrae, the tip of red giant branch, SN Ia

- Supernovae, $H_0$ for the dark energy Equation of State “SH0ES” project [Riess et al. 2016]
$H_0$ from SH0ES

[slide material courtesy of Adam Riess]

[Riess et al. 2016]
Cosmic Microwave Background

CMB Temperature fluctuations

[Planck Collaboration 2016]

(1) Ratio of peak heights $\rightarrow \Omega_m h^2, \Omega_b h^2 \ [h = H_0 / 100 \text{ km/s/Mpc}]

(2) Location of the first peak in flat $\Lambda$CDM $\rightarrow \Omega_m h^{3.2}$

- Under flat $\Lambda$CDM assumption, (1) and (2) yield $h = 0.678 \pm 0.009$ [Planck collaboration 2016]
- Without flat $\Lambda$CDM assumption, $h$ highly degenerate with other cosmological parameters (e.g., curvature, $w$, $N_{\text{eff}}$)
Standard Siren

Gravitational wave form $\rightarrow$ luminosity distance $D$
Measure recessional velocity of EM counterpart $v$

$$H_0 = \frac{v}{D}$$

GW170817: First measurement of $H_0$

[Image credit: M. Garlick]
Strong Optical Lensing

Image Credit: P. J. Marshall
Gravitational Lensing

Mass “bends” light and acts like a lens

Image Credit: P. J. Marshall
Gravitational Lens

HST image: SLACSJ0737+3216

Strong Gravitational Lensing

B1608+656

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
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

B1608+656
RXJ1131-1231

1" [Suyu et al. 2017]

HE0435-1223
WFI2033-4723
HE1104-1805

$H_0$ to <3.5% precision
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 COSMOGRAIL’s Wellspring

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

**completed**

**ongoing**
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

completed


focus

ongoing
Time Delays

**[Cosmological Monitoring of Gravitational Lenses]**

- monitoring lensed quasars since 2004 in the optical
- expect to have delays with a few percent error for ~10 lenses

**EPFL**: G. Meylan, F. Courbin, V. Bonvin, M. Tewes, Y. Revaz, N. Cantale, C. Faure, A. Eigenbrod, C. Vuissoz

**IIA Bangalore**: T. Prabhu, C.S. Stalin, R. Kumar, D. Sahu

**Univ. Liège**: D. Sluse, P. Magain, E. Eulaers, V. Chantry

**UzAS Tashkent**: I. Asfandiyarov

**Univ. Zürich**: P. Saha, J. Coles

**Univ. Nottingham**: S. Dye

Now also in close collaboration (monitoring, microlensing) with:
C. Kochanek, A. Mosquera (Ohio), C. Morgan, C. MacLeod, L. Hainline (USNA)
Time Delays

13-year light curve of HE0435-1223
Time delay with 6.5% uncertainty
[Bonvin, Courbin, Suyu et al. 2017]
Lens environment

HE0435 has nearby mass structures at different redshifts [e.g., Morgan et al. 2005, Momcheva et al. 2015]

Wide-field spectroscopy for group identification [Sluse, Sonnenfeld, Rumbaugh et al. 2017]

Wide-field imaging to get external mass distribution [Rusu, Fassnacht, Sluse et al. 2017]
Lens environment

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Lens mass modeling

Modeling with GLEE :)  

Gravitational Lens Efficient Explorer  

[Suyu & Halkola 2010]
Lens mass modeling

- Light distribution of extended source
- Mass distribution of lens
- Light of lensed AGN + time delays
- Light of lens (Sersic)
- PSF reconstruction
- Multi-lens plane modeling including nearby perturbers [Suyu et al., in prep]
Lens reconstruction

[Wong, Suyu, Auger et al. 2017]
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. 2017]
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. 2017]
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. 2017]
$H_0$ from 3 strong lenses

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

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

$w = -1$

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

[Bonvin, Courbin, Suyu et al. 2017]
$H_0$ with 3 Lenses

[Riess et al. 2016]
Lensing REALLY helps

[Bonvin, Courbin, Suyu et al. 2017]
Looking forward

- 2 more H0LiCOW lenses
- 4 more doubles with HST imaging in c23 (PI: Treu)
- follow-up data partly in-hand and partly pending
- HST 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. 2017]
How to get more lenses?

**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]

**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]

**Kilo Degree Survey**
- 2.6m VLT Survey Telescope
- Paranal, Chile
- 1500 deg$^2$ with $r_{\text{limit}} \sim 25$
- 2011-~2018
Lensed quasars from the ground

Space (HST)  
[Anguita et al. 2009]

Ground (Subaru)

How to tell if this is a lens? 
Use configuration of blended images and lens modeling
### Image configurations of lenses

<table>
<thead>
<tr>
<th>Source Plane</th>
<th>Einstein Cross</th>
<th>Cusp Caustic</th>
<th>Fold Caustic</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Einstein Cross" /></td>
<td><img src="image2.png" alt="Cusp Caustic" /></td>
<td><img src="image3.png" alt="Fold Caustic" /></td>
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<td><img src="image4.png" alt="Image Plane" /></td>
<td><img src="image5.png" alt="Image Plane" /></td>
<td><img src="image6.png" alt="Image Plane" /></td>
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[Image credit: A. Amara]
Ways to find lensed quasars

For a system to qualify as a lens candidate, it must be explained by a plausible lens model

Direct Modeling

• **LensTractor**
  [Marshall et al., in prep.]
  classification based on explicit model comparison

• **CHITAH**
  [Chan et al., 2015]
  classification based on simple lens model fitting

Machine Learning

implicit lens model (prior) enters via the training set
[e.g., Agnello et al. 2014]

Citizen Science

[Marshall et al. 2015; More et al. 2015]
citizens visually identify lenses after familiarizing with lens configurations
New hunter for lensed quasars

James Chan has developed an automated and fast algorithm to use multiband imaging for lens classification [Chan, Suyu et al. 2015]
New hunter for lensed quasars

Chung-li He In-hsiang Tan Ao Hao

CHITAH
Testing CHITAH with mock lenses

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<td>bright</td>
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<td>ultra-faint</td>
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<td></td>
<td><img src="image1" alt="Bright large-separation lenses" /></td>
<td><img src="image2" alt="&lt;90% true-positive rate" /></td>
<td><img src="image3" alt="&lt;3% false-positive rate" /></td>
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<td><img src="image5" alt="large sep. (r_{\text{ein}} &gt; 1.1'')" /></td>
<td><img src="image6" alt="large sep. (r_{\text{ein}} &lt; 1.1'')" /></td>
<td><img src="image7" alt="large sep. (r_{\text{ein}} &lt; 1.1'')" /></td>
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<td><img src="image9" alt="Bright large-separation lenses: &gt;90% true-positive rate &lt;3% false-positive rate" /></td>
<td><img src="image10" alt="CHITAH is hunting for lensed quasars in HSC and DES Surveys" /></td>
<td><img src="image11" alt="Bright large-separation lenses: &gt;90% true-positive rate &lt;3% false-positive rate" /></td>
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[Chan, Suyu et al. 2015]
New lensed quasars systems

[Agnello et al. 2015]

[More et al. 2017]

[Ostrovski et al. 2017]

[Lin et al. 2017]

[Berghea et al. 2017]
SuGOHI: new lenses from HSC
[Survey of Gravitationally-lensed Objects in HSC Imaging]

[Sonnenfeld, Chan, Shu et al., 2017]
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]

[Grillo et al. 2016]

[Xiao et al. 2016]
Spot on!

[j Kelly et al. 2016]
Successful prediction

- 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.

[Image of graph and SX image with labels: Diego-a, Oguri-g, Sharon-g, Zitrin-g, Grillo-g, Oguri-a, Sharon-a, Zitrin-c, Jauzac, SX (New Image), and labels for Diego, Grillo, Jauzac, Suyu, Halkola, Kelly et al. 2016]
First spatially-resolved lensed Type Ia discovered in iPTF [Goobar et al. 2017]
we modeled the HST image with GLEE [Suyu & Halkola 2010] and glafic [Oguri 2010] to estimate the time delays [More, Suyu, Oguri et al. 2017]
$H_0$ 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]
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.

[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.
- From 3 lenses in H0LiCOW, $H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc in flat $\Lambda$CDM, a 3.8% precision measurement independent of other probes.
- Search is underway to find new lenses in HSC and DES surveys.
- SN Refsdal blind test demonstrated the robustness of our cluster mass modeling approach and software GLEE.
- First strongly lensed Type Ia discovered by iPTF team, but with small time delays.
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology.
Thank you!