Cosmology and Stellar Physics with Gravitational Lens Time Delays

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Hubble tension

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
Distance Ladder

ladder to reach objects in Hubble flow \((v_{\text{peculiar}} << v_{\text{Hubble}} = H_0 d)\)

1 (Kpc) 2 (Mpc) 3 (Gpc)

1: Geometry \(\rightarrow\) Cepheids
2: Cepheids \(\rightarrow\) SN Ia
3: SN Ia \(\rightarrow\) \(z, H_0\)

[slide material courtesy of Adam Riess]
Distance Ladder

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[slide material courtesy of Adam Riess]
Distance Ladder

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[slide material courtesy of Adam Riess]
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)

- **Supernovae, \( H_0 \) for the dark energy Equation of State “SH0ES” project** [Riess et al. 2021]
  - \( H_0 = 73.2 \pm 1.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (1.8% 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
  - \( H_0 = 69.6 \pm 0.8 \text{ (stat)} \pm 1.7 \text{ (sys) km s}^{-1} \text{ Mpc}^{-1} \) [Freedman et al. 2019, 2020]
Megamasers

Direct distance measurement without any calibration on distance ladder

1. Distance: \[ D = \frac{r}{\Delta \theta} \] (for \( D >> r \))

2. Gravitational acceleration in a circular orbit:
\[ a = \frac{V_0^2}{r} \]
\[ r = \frac{V_0^2}{a} \]

\[ D = \frac{V_0^2}{a} \Delta \theta \]

\[ D = \frac{V_0^2 \sin i}{a} \Delta \theta \]

[slide material courtesy of C.-Y. Kuo]
Megamasers

\[ D = V_0^2 \sin i / a \Delta \theta \]

How to measure \( V_0, \Delta \theta, a \) and \( i \)?

[slide material courtesy of C.-Y. Kuo]
Megamasar Cosmology Project

$H_0 = 73.9 \pm 3.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$

- assuming uncertainty of 250 km/s for peculiar motions
- peculiar motion is currently the dominant source of uncertainty

[Pesce et al. 2020]
Cosmic Microwave Background

CMB Temperature fluctuations

[Planck Collaboration 2016]

\( \Omega_m h^2, \Omega_b h^2 \) \[ h = H_0 / 100 \text{ km/s/Mpc} \]

\( \Omega_m h^{3.2} \)

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 \( \Lambda \text{CDM} \) \( \rightarrow \) \( \Omega_m h^{3.2} \)

- Under flat \( \Lambda \text{CDM} \) assumption, (1) and (2) yield \( h = 0.674 \pm 0.005 \) \[ \text{Planck collaboration 2020} \]
- Without flat \( \Lambda \text{CDM} \) assumption, \( h \) highly degenerate with other cosmological parameters (e.g., curvature, \( w \), \( N_{\text{eff}} \))
Standard Siren

Gravitational wave form ➔ 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 gravitational lensing
Cosmology with time delays

[COSmological MOonitoring of GRAvItational Lenses;
PI: F. Courbin, G. Meylan]
Cosmology with time delays

[Credit: V. Bonvin]
Cosmology with time delays

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

[Refsdal 1964]

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

HE0435-1223

[Suyu et al. 2017]
H0LiCOW

$H_0$ Lenses in COSMOGRAIL’s Wellspring

B1608+656

RXJ1131-1231

H0 to <3.5% precision

HE0435-1223

WFI2033-4723

HE1104-1805

[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
$H_0$ from 6 strong lenses

Blind analysis to avoid confirmation bias

$H_0 \in [0, 150]$ \hspace{1cm} $\Omega_m \in [0.05, 0.5]$

$H_0 : 71.0^{+2.9}_{-3.3}$
$H_0 : 78.2^{+3.4}_{-3.4}$
$H_0 : 71.7^{+4.8}_{-4.5}$
$H_0 : 68.9^{+5.4}_{-5.1}$
$H_0 : 71.6^{+3.8}_{-4.9}$
$H_0 : 81.1^{+8.0}_{-7.1}$

$H_0 : 73.3^{+1.7}_{-1.8}$

$H_0$ with 2.4\% precision in flat $\Lambda$CDM

[Wong, Suyu, Chen et al. 2020]
Residual systematics?

No significant residual systematics detected wrt mass model assumptions

\[ H_0 : 74.2^{+1.6}_{-1.6} \]

[Shajib et al. 2020]

\[ H_0 : 74.0^{+1.7}_{-1.8} \]

[Millon, Galan, Courbin et al. 2020; TDCOSMO I]

TDCOSMO = COSMOGRAIL + H0LiCOW + STRIDES + SHARP

Two different families of model yield same \( H_0 \) within 1%
TDCOSMO $H_0$ measurements

- No assumption on the radial mass density profile of the lens galaxy
- Galaxies are described by power law/stars+NFW mass profile

- Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property
  - $73.3^{+5.8}_{-5.8}$ km s$^{-1}$ Mpc$^{-1}$ (TDCOSMO+SLACS$_{\text{ifu}}$ (anisotropy constraints from 9 SLACS lenses))

- Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy and radial mass density property
  - $67.4^{+4.1}_{-3.2}$ km s$^{-1}$ Mpc$^{-1}$ (TDCOSMO+SLACS$_{\text{SDSS+ifu}}$ (anisotropy and profile constraints from SLACS))

- $73.3^{+1.7}_{-1.8}$ km s$^{-1}$ Mpc$^{-1}$ (HOLICOW)
- $74.0^{+1.7}_{-1.8}$ km s$^{-1}$ Mpc$^{-1}$ (TDCOSMO (NFW + stars/constant M/L))
- $74.2^{+1.6}_{-1.6}$ km s$^{-1}$ Mpc$^{-1}$ (TDCOSMO (power-law))

[Figure credit: Geoff C.-F. Chen]
Stellar kinematics really helps

simulated James Webb Space Telescope NIRSpec observations of stellar kinematic map of lens

[Yıldırım, Suyu, Halkola 2020]
Stellar kinematics really helps

- Inferred $D_{\Delta t}$ depends on assumptions of mass model
- Including kinematic data:
  - reduces dependence of $D_{\Delta t}$ on mass model assumption
  - tightens constraints on $D_{\Delta t}$

[Yıldırım, Suyu, Halkola 2020]
Including spatially-resolved (2D) kinematic data:
• drastically reduces the uncertainty of $D_A$ from $\sim 15\%$ to $\sim 3\%$
• sensitive to systematic errors in kinematic measurements

[Yıldırım, Suyu, Halkola 2020; see also Paraficz & Hjorth 2009; Jee, Komatsu & Suyu 2015; Jee, Suyu, Komatsu et al. 2019]
Calibrating SNe distances with $D_{\Delta t}$

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

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

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

- **SDSS1206+4332**
  - part of extended sample
  - [Birrer, Treu Rusu et al. 2018]
Reduced cosmological dependence

[Taubenberger, Suyu, Komatsu et al. 2019]
Reduced cosmological dependence

[Figure showing comparison of cosmological models with Planck + BAO + SNe Ia and lenses + SNe Ia results.]

[Taubenberger, Suyu, Komatsu et al. 2019; see also Arendse, Agnello & Wojtak 2019]
New quads imaged with HST

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

[Shajib et al. 2018]
Supernova Refsdal: lensed supernova

MACS 1149.6+2223

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

[Kelly et al. 2016]
$H_0$ 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, 2020]
HOLISMOKES
Highly Optimised Lensing Investigations of Supernovae, Microlensing Objects, and Kinematics of Ellipticals and Spirals
PI: S. H. Suyu

Lensed supernovae provide great opportunities for
1) Constraining the progenitor of Type Ia supernova
   single degenerate  double degenerate
   White dwarf (WD) accreting from non-degenerate companion  WDs merging

2) Measuring the expansion rate of our Universe

[Suyu, Huber, Cañameras et al. 2020]
Future Prospects

Experiments and surveys in the 2020s including Euclid, Rubin, and Roman observatories will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]
Summary

- From 6 lensed quasars in H0LiCOW, $H_0 = 73.3^{+1.7}_{-1.8}$ km/s/Mpc in flat $\Lambda$CDM with physically motivated mass models, completely independent of other probes
- New lensed quasar systems being discovered, observed and analysed as part of TDCOSMO
- SN Refsdal blind test demonstrated the robustness of our cluster mass modeling approach and software GLEE
- HOLISMOkes! Lensed supernovae to constrain supernova progenitors and cosmology
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology and supernova physics