Time Delay Cosmography Toward The Hubble Constant Estimation: Past, Present, and Future

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INTRODUCTION

Video Credit: Science, American Association for the Advancement of Science

The Hubble constant H_0 represents the current expansion rate of the Universe, as well as the age $(= H_0^{-1})$, size, and density of the Universe.

Introduction (cont.)

But the Hubble constant estimates have been inconsistent!
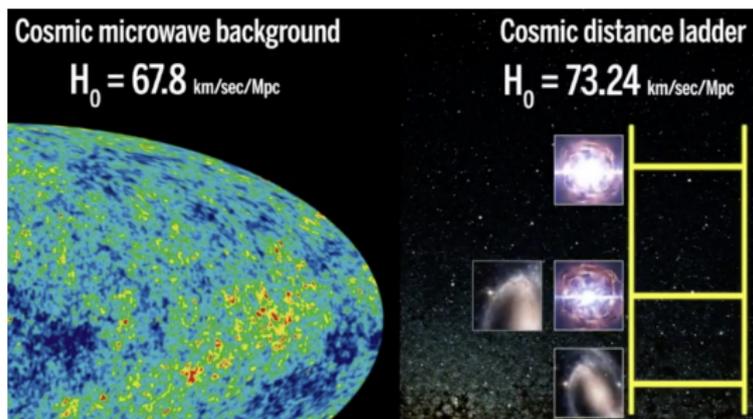
Image Credit: Science, American Association for the Advancement of Science

The most recent estimates from these two methods are

- 67.4 ± 0.5 km s^{-1}Mpc^{-1} via CMB (Plank collaboration, 2018).
- 74.0 ± 1.4 km s^{-1}Mpc^{-1} via CDL (Reiss et al., 2019).

Is this 4.4σ difference true (new physics)? Independent methods are necessary to confirm this difference.

Time delay cosmography

Quasar is a highly luminous galaxy hosting a supermassive black hole at the center. Since it is extremely bright, it can be seen at a great distance.
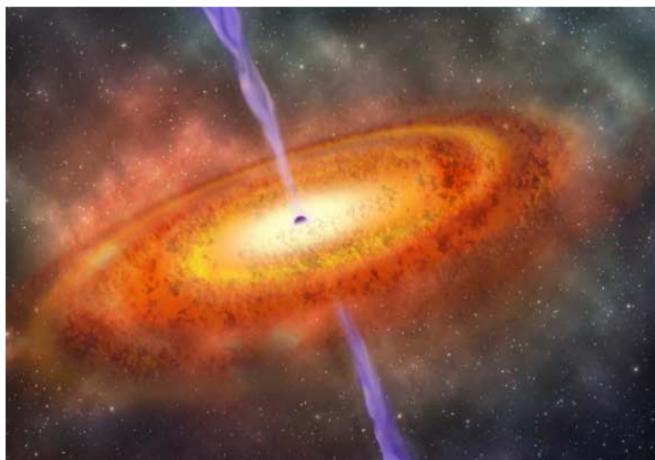
Image Credit: Carnegie Institution for Science

Time delay cosmography (cont.)

Video source: https://www.youtube.com/watch?v=iE8x9kDHCFo

Strong gravitational lensing: The strong gravitational field of the intervening galaxy bends the light rays towards the Earth (like a lens), and thus we see multiple images of the same quasar in the sky.

Credit: NASA's Goddard Space Flight Center

Time delay: Light rays take different routes and travel through different gravitational potential, and thus their arrival times can differ $\rightarrow$ time delay!

TIME DELAY COSMOGRAPHY (CONT.)

Inference on H_o via an equation for additional travel distance (Refsdal, 1964).
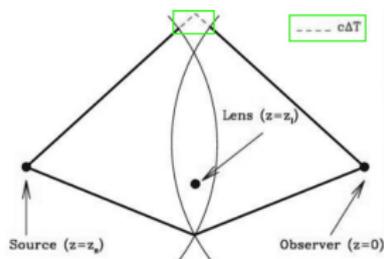
Image Credit: Tommaso Treu (UCLA) in "Dark Matter and Strong Lensing (2014)"

Additional travel distance = Speed of light (c) × Time delay (Δ_{ij})
= Time delay distance ($D_{\Delta t}(H_o, z, \Omega)$) × Fermat potential difference (ϕ_{ij})
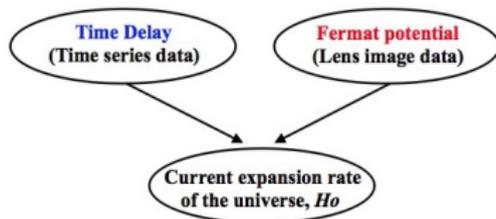
TIME DELAY ESTIMATION: DATA

Data for a doubly-lensed quasar are two time series (light curves) with known measurement errors (Tak et al., 2017)
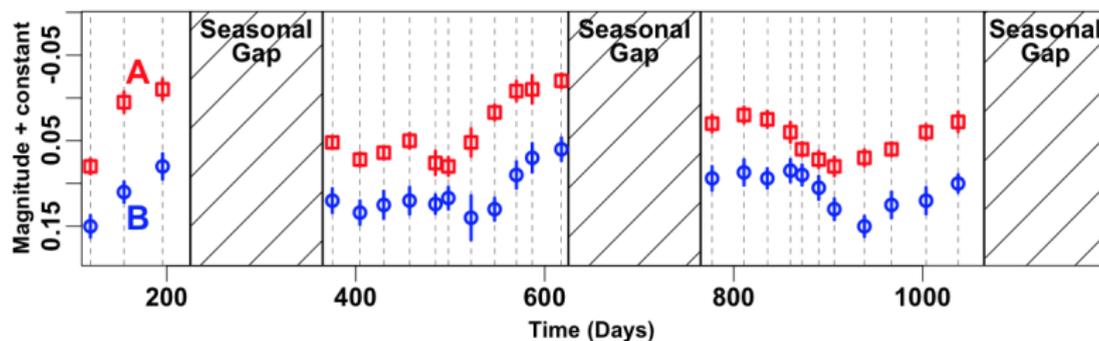
We can estimate Δ by the horizontal shift between two time series.

TIME DELAY CHALLENGE

Time Delay Challenge (Dobler et al., 2015; Liao et al., 2015)

- ▶ A blind competition held by 8 astrophysicists from 2013 to 2014.
- ▶ Goal was to improve existing estimation methods.
- ▶ 5,000+ simulated data sets with some time delays.
- ▶ 13 teams blindly analyzed the simulated data sets.

Image Credit: HBO website
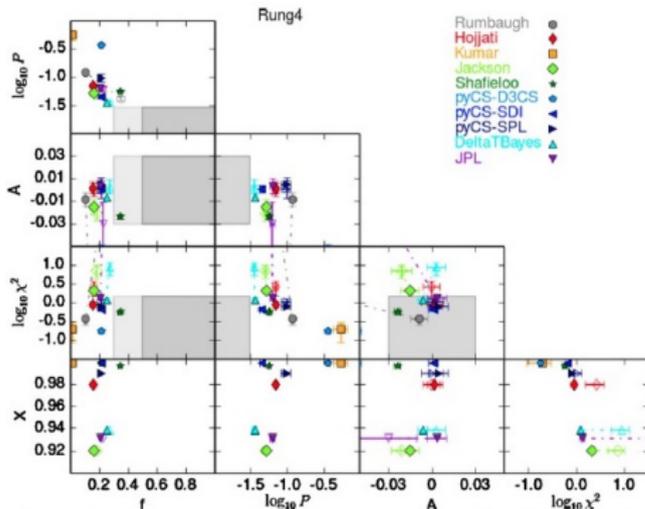
Our work after the TDC

1. Tak, H., Mandel, K., van Dyk, D. A., Kashyap, V. L., Meng, X-.L., and Siemiginowska, A. (2017) "Bayesian Estimates of Astronomical Time Delays Between Gravitationally Lensed Stochastic Light Curves", *AoAS*.
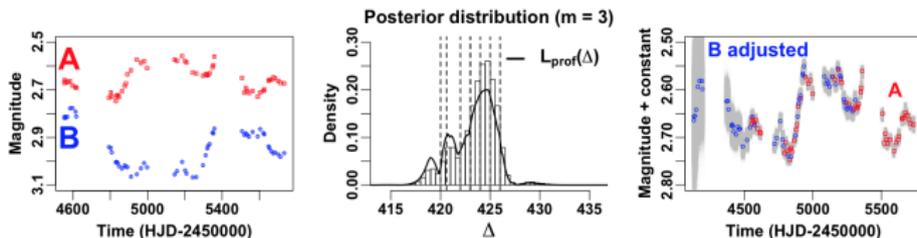
- ▸ A fully Bayesian approach / Bayesian hierarchical modeling
- ▸ A damped random walk process (Kelly et al., 2019).
- ▸ A polynomial regression for microlensing.
- ▸ Scientifically-motivated and weakly-informative priors.
- ▸ Metropolis-Hastings within Gibbs sampler.
- ▸ Adaptive Markov chain Monte Carlo (MCMC).
- ▸ Profile likelihood approach to multimodality.

2. An R package "`timedelay`" is publicly available.

Daily download count of 'timedelay' from 1/1/2019 to 12/31/2019 (CRAN log)
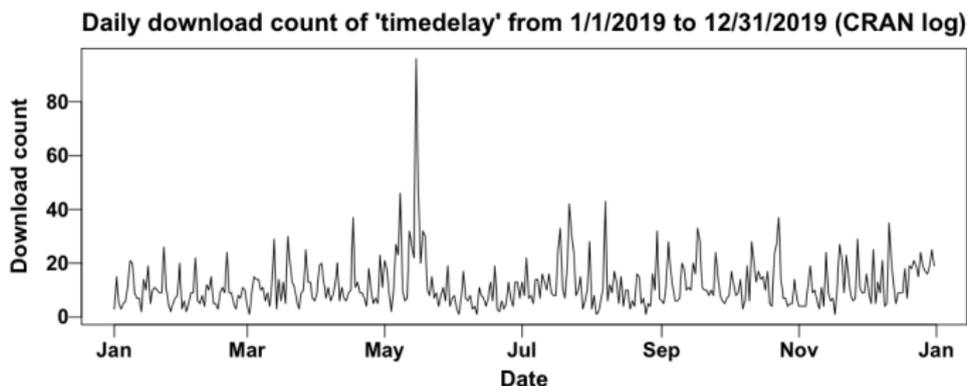
▶ First launched in 2015 with the last update in 2018.

▶ Its median daily-download-count was 9 last year.

3. Kimura, M., Kato, T., Isogai, K., Tak., H., and 23 people (2017)
"Rapid optical variations correlated with X-rays in the 2015 second
outburst of V404 Cygni (GS 2023+338)", *MNRAS*.
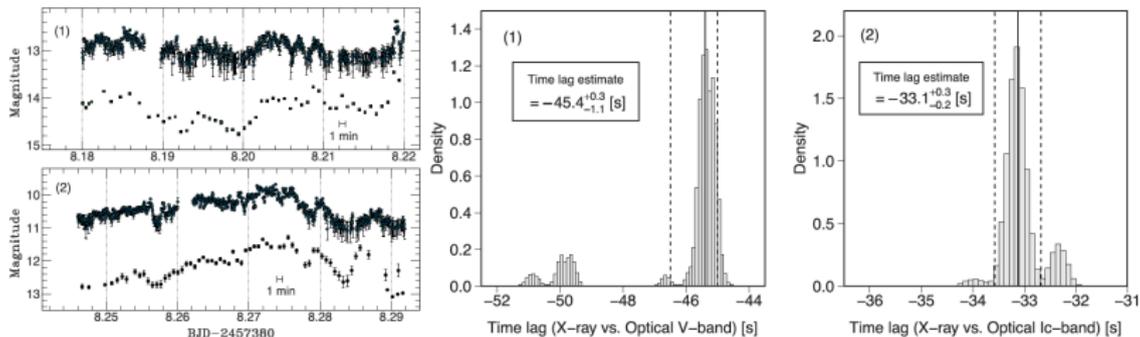
▶ A collaboration with Japanese astronomers thanks to the
  timedelay package.

OUR WORK AFTER THE TDC (CONT.)

4. Tak., H., Meng, X-.L., van Dyk, D. A. (2018) "A Repelling-Attracting Metropolis Algorithm for Multimodality", *JCGS*.
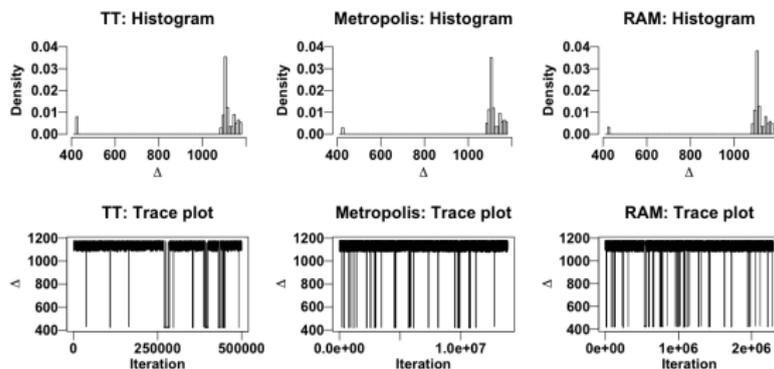
- ▶ A multi-modal MCMC sampler motivated by Time Delay Estimation.
- ▶ Easy-to-implement.
- ▶ Effective in low-dimensional parameter sampling (possibly embedded in high-dimensional problem).
- ▶ The R package, `timedelay`, is equipped with this sampler.

CURRENT WORK IN PREPARATION

1. Hu, Z. and Tak., H. (2020+) "A Multivariate Damped Random Walk Process for Modeling Irregularly-Spaced Multi-Band Light Curves with Heteroscedastic Measurement Errors."
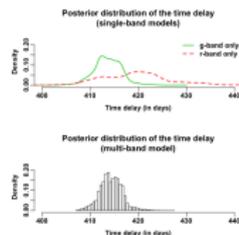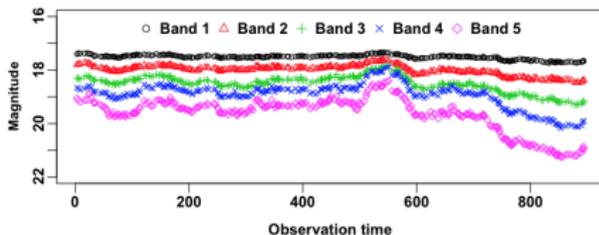
- ▶ A multivariate generalization of a univariate damped random work process (Kelly et al., 2009).
- ▶ A multivariate generalization of a univariate time delay estimation (Tak et al., 2017).
- ▶ A new R package, `drw`, to fit a multivariate damped random work process is in preparation. The existing R package, `timedelay`, will be updated to incorporate this multivariate feature.

2. Tak., H., Ding, X., Birrer, S. (2020+) "A Bayesian Estimate of the Hubble Constant via Time Delay Cosmography."
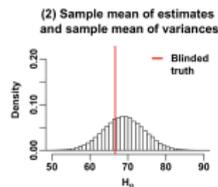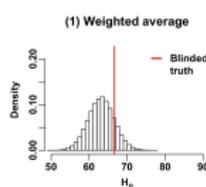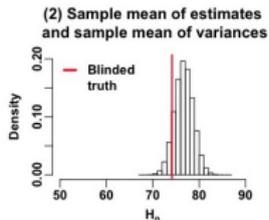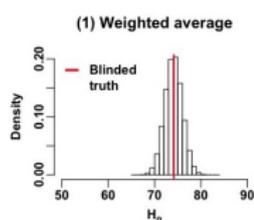
- ▶ Based on another blind competition called Time Delay Lens Modeling Challenge (TDLMC) held from 2018 to 2019 (Ding et al., 2020+).
- ▶ A closed-form marginal posterior distribution of the Hubble constant.

CURRENT WORK IN PREPARATION (CONT.)

3. Vishwanath, S. and Tak., H. (2020+) "A Repelling-Attracting Metropolis for High-Dimensional Multimodality."
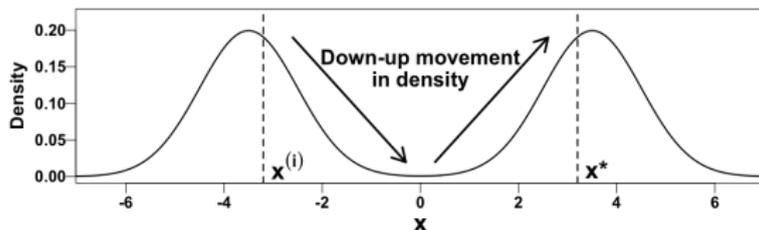
- ▶ Mixing anti-Langevin and Langevin algorithms to incorporate gradient information to RAM, as Christian Robert suggested.
- ▶ Preventing a chain from going back to the original mode.
- ▶ Detailed balance condition is already proven.
- ▶ Working on simulations.

FUTURE WORK (2021+)