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

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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.
But the Hubble constant estimates have been inconsistent!

The most recent estimates from these two methods are

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

Is this $4.4\sigma$ difference true (new physics)? Independent methods are necessary to confirm this difference.
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
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.
Time delay cosmography (cont.)

Time delay: Light rays take different routes and travel through different gravitational potential, and thus their arrival times can differ → time delay!
Inference on $H_o$ via an equation for additional travel distance (Refsdal, 1964).

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\text{Additional travel distance} = \text{Speed of light} \times \text{Time delay} = \text{Time delay distance} \times \text{Fermat potential difference}
\]

Image Credit: Tommaso Treu (UCLA) in “Dark Matter and Strong Lensing (2014)”
**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 $\Delta$ 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.

![Game of Thrones poster](Image Credit: HBO website)
Our work after the TDC


- 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.
Our work after the TDC (cont.)

2. An R package “timedelay” is publicly available.

- First launched in 2015 with the last update in 2018.
- Its median daily-download-count was 9 last year.
Our work after the TDC (cont.)


- A collaboration with Japanese astronomers thanks to the timedelay package.

- 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.

- A multivariate generalization of a univariate damped random walk 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 walk process is in preparation. The existing R package, `timedelay`, will be updated to incorporate this multivariate feature.

- 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.)


- 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+)**

- **Univariate CARMA(1, 0)** (Kelly et al., 2009)
- **Single-band Time Delay Estimation** (Tak et al., 2017)
- **Univariate CARMA(p, q)** (Kelly et al., 2014)
- **Multivariate CARMA(p, q) & Multi-band Time Delay Estimation**
- **Multivariate CARMA(1, 0) & Multi-band Time Delay Estimation** (Hu and Tak, 2020+)
- **Hubble Constant Estimation**
- **A Closed-Form Marginal Posterior Distribution of the Hubble Constant** (Tak, Ding, Birrer, 2020+)

- **Published or done**
- **Future work**