Reliable time delay estimation of strong lens systems

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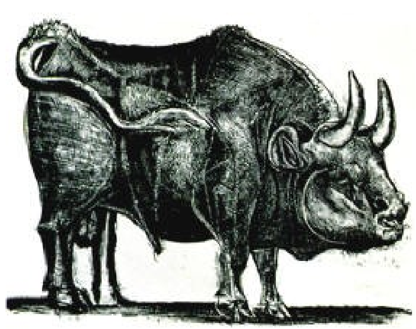
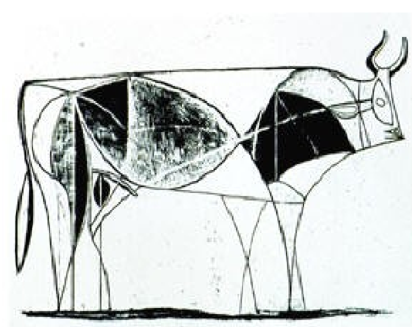
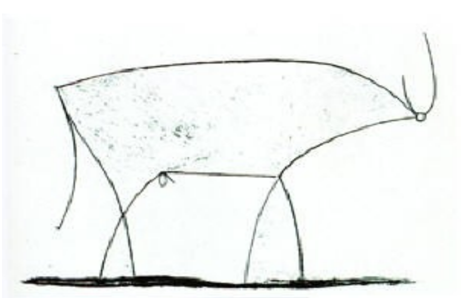
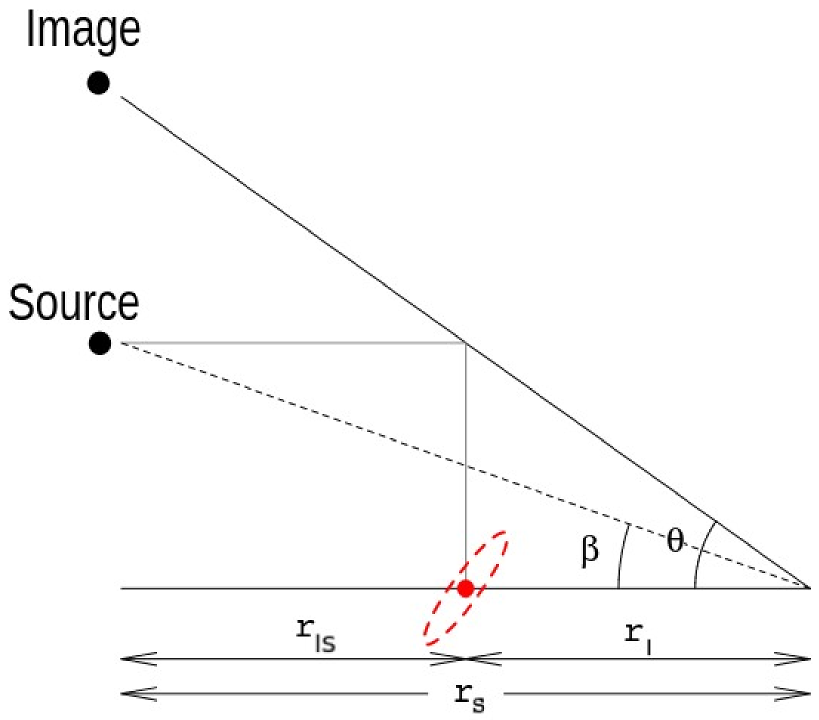


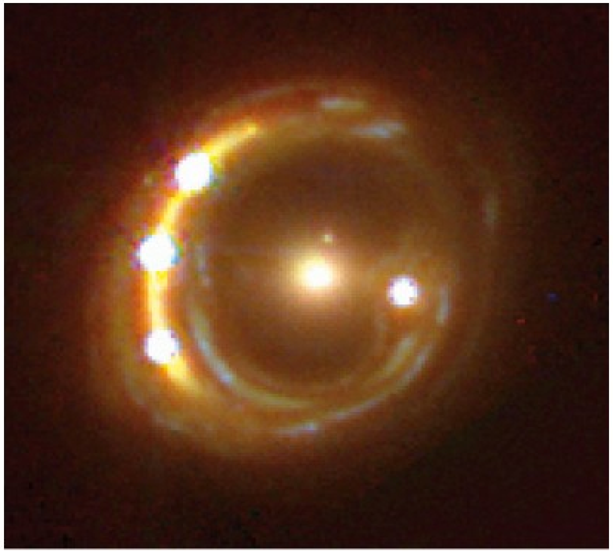




All models are false, some are useful. (George E. P. Box)

Strong gravitational lensing





HST ACS image of RXJ1131-1231

Time delay: $$\Delta t(\vec{\theta}, \vec{\beta}) = \frac{r_l r_s}{r_{ls}}(1+z_l)\phi(\vec{\theta}, \vec{\beta})$$

Fermat potential: $$\phi(\vec{\theta}, \vec{\beta}) = \frac{(\vec{\theta} - \vec{\beta})^2}{2} - \psi(\vec{\theta})$$

geometric delay

lensing potential delay

(Linder 2011, Tewes 2012)

Strong lensing surveys

- Recent survey:
  COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses
  (http://www.cosmograil.org)

- Future survey:
  LSST: the Large Synoptic Survey Telescope (LSST) with 10 years observation will be expected to monitor several thousand time delay lens systems.

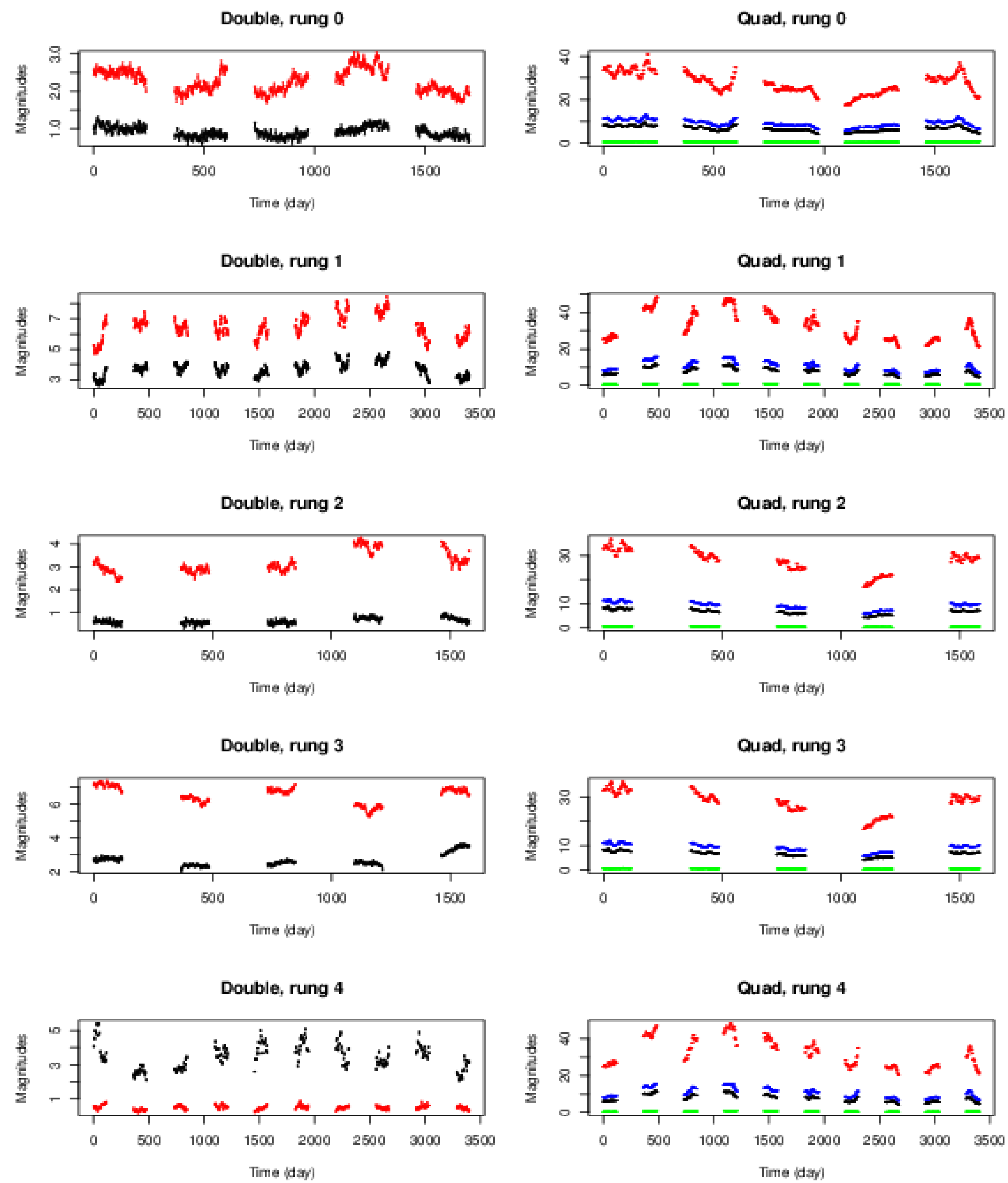
- Need to design the fast and reliable algorithms for the time delay estimation.

- Strong Lens Time Delay Challenge:
  TDC0
  TDC1

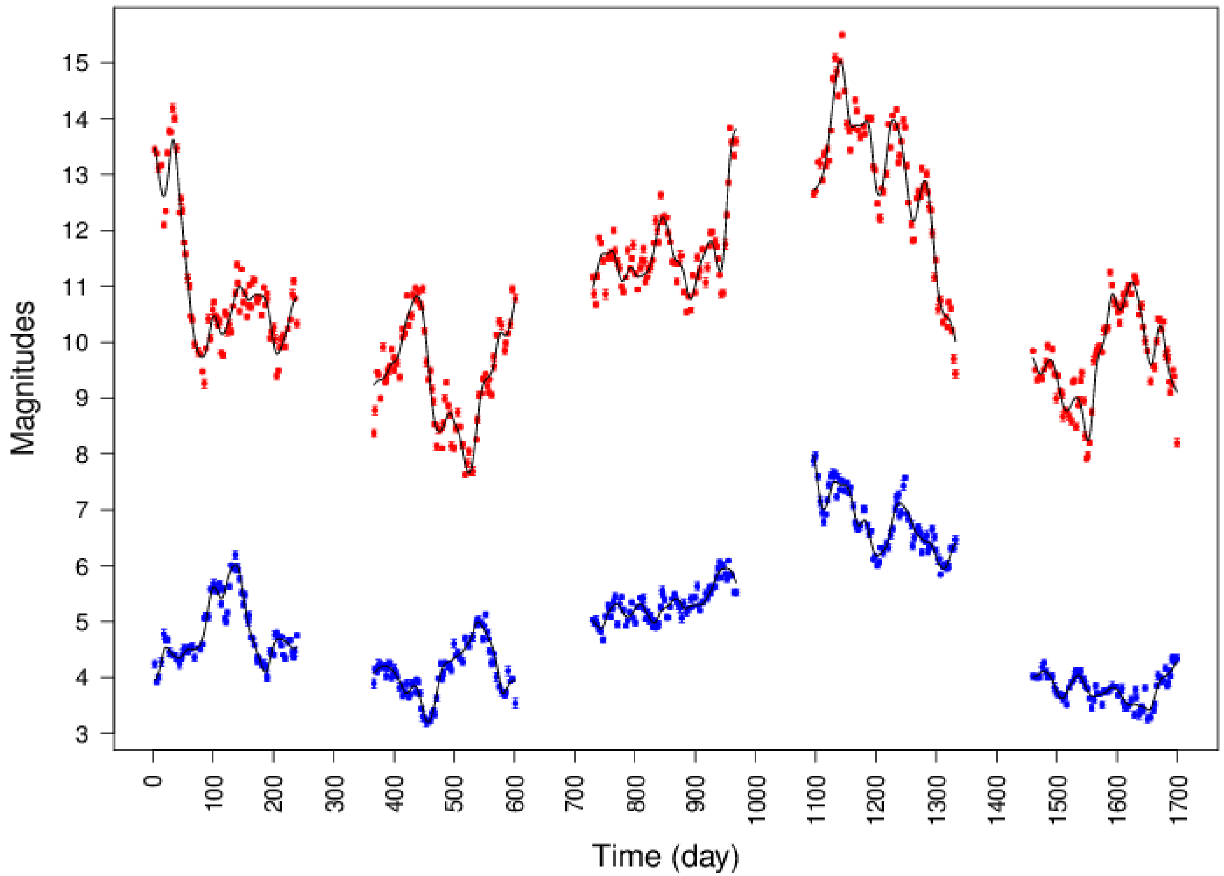
Strong Lens Time Delay Challenge: simulated data

The TDC1 simulated data is provided in five different categories (rungs)

Each rung contains the light curves of 720 Double and 152 Quad image systems.



Methodology: smoothing

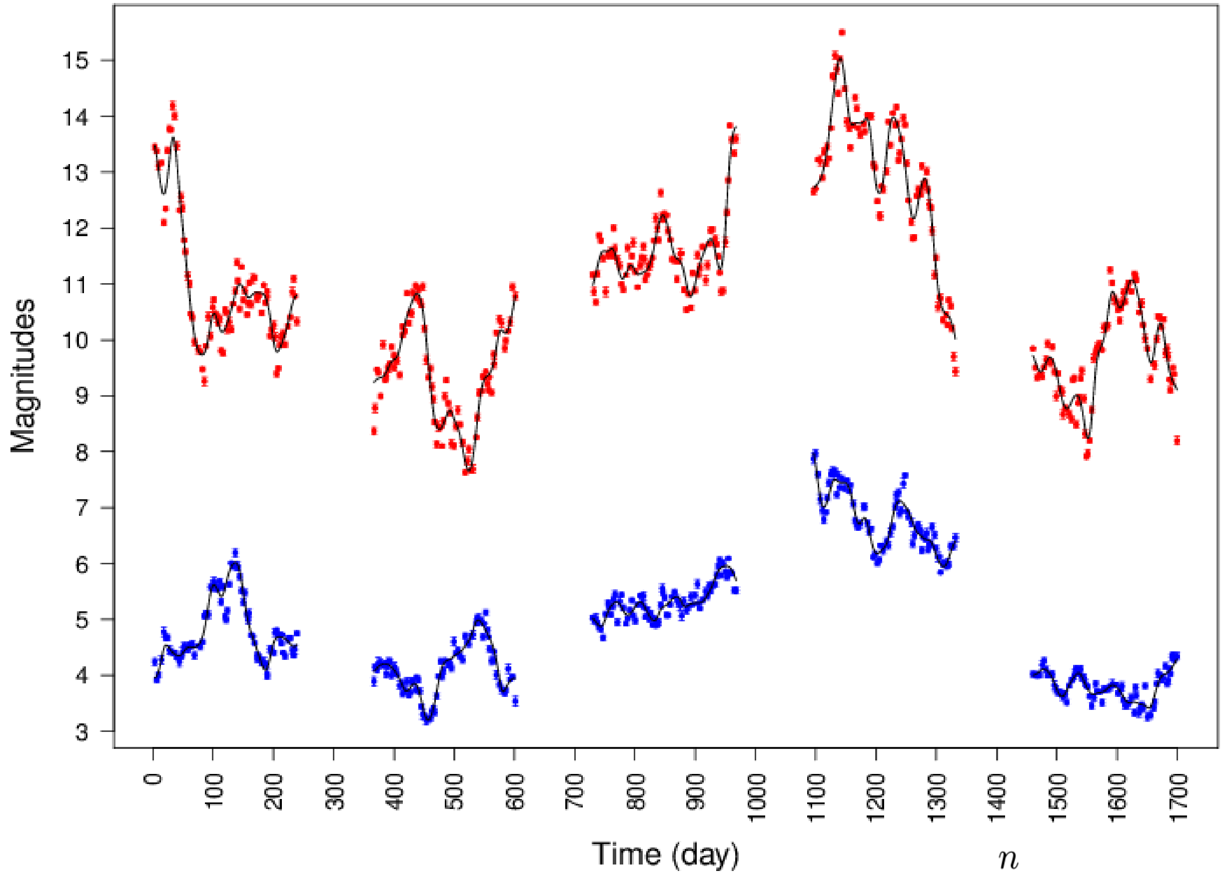


$$A^s(t) = A^g(t) + N(t) \sum_i \frac{A^d(t_i) - A^g(t_i)}{\sigma_d^2(t_i)} \times exp\left[-\frac{(t_i - t)^2}{2\Delta^2}\right]$$

where $$N(t)^{-1} = \sum_i exp\left[-\frac{(t_i - t)^2}{2\Delta^2}\right] \frac{1}{\sigma_d^2(t_i)}$$

(Shafieloo et al. 2006, Shafieloo 2007, Shafieloo & Clarkson 2010)

Methodology: cross-correlation

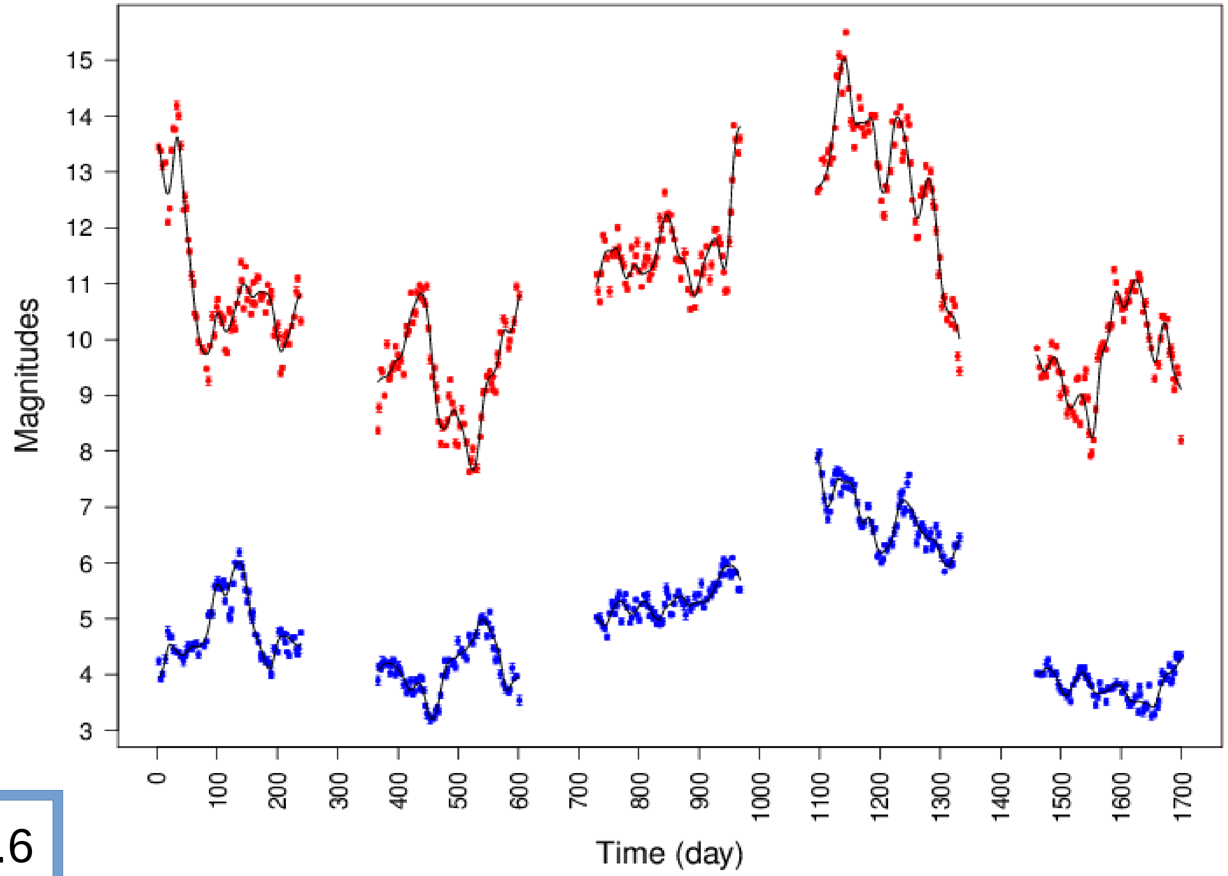


$$\rho_{XY} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y} \quad \Rightarrow \quad r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}},$$

$$\left.\begin{aligned} X' &= a_x X + b_x \\ Y' &= a_y Y + b_y \end{aligned}\right\} \Rightarrow \rho_{XY} = \rho_{X'Y'}$$

(Peterson 2001, Wasserman 2004)

Methodology: time delay estimation



Correlation > 0.6

$$|\tilde{\Delta t}_{A_1 A_2}| = \frac{|\tilde{\Delta t}_{A_1;A_2^s}| + |\tilde{\Delta t}_{A_2;A_1^s}|}{2} \qquad \sigma^{ini}_{A_1 A_2} = \sqrt{2} \times \frac{\left| |\tilde{\Delta t}_{A_1;A_2^s}| - |\tilde{\Delta t}_{A_2;A_1^s}| \right|}{2}$$

(Aghamousa & Shafieloo arXiv:1410.8122)

Methodology: error estimation, using Quad systems

The light curves of a Quad image are labeled A1 , A2 , B1 and B2. For every Quad system we should have:

$$\underbrace{\tilde{\Delta} t_{A_1A_2} - (\tilde{\Delta} t_{A_1B_1} + \tilde{\Delta} t_{B_1A_2})}_{T_{dif}} \pm \underbrace{\sqrt{(\sigma^{ini}_{\tilde{\Delta} t_{A_1A_2}})^2 + (\sigma^{ini}_{\tilde{\Delta} t_{A_1B_1}})^2 + (\sigma^{ini}_{\tilde{\Delta} t_{B_1A_2}})^2}}_{\sigma_{T_{dif}}} \equiv 0$$

$$T_{dif} \pm \sigma_{T_{dif}} \equiv 0$$

$$|T_{dif}| \leqslant \sigma_{T_{dif}}$$

Yes → We can assume that all time delays and their corresponding errors are estimated consistently.

No → $$\sigma^2_{ec} = |T_{dif}|^2 - \sigma^2_{T_{dif}} \;\longrightarrow\; \sigma^{new}_{\tilde{\Delta} t_{A_1A_2}} = \sqrt{(\sigma^{ini}_{\tilde{\Delta} t_{A_1A_2}})^2 + \frac{\alpha}{3}\sigma^2_{ec}}$$

(Aghamousa & Shafieloo arXiv:1410.8122)

Methodology: error estimation, using Quad systems

Error profile for Double systems

For **Rung 0**,

if $|\tilde{\Delta t}| \leqslant 20 \Rightarrow \sigma_R = 0.06 \times |\tilde{\Delta t}|$,   if $|\tilde{\Delta t}| > 20 \Rightarrow \sigma_R = 1.2$

For **Rung 1**,

if $|\tilde{\Delta t}| \leqslant 20 \Rightarrow \sigma_R = 0.06 \times |\tilde{\Delta t}|$,   if $|\tilde{\Delta t}| > 20 \Rightarrow \sigma_R = 1.3$

For **Rung 2**,

if $|\tilde{\Delta t}| \leqslant 30 \Rightarrow \sigma_R = 0.07 \times |\tilde{\Delta t}|$,   if $|\tilde{\Delta t}| > 30 \Rightarrow \sigma_R = 1.3$

For **Rung 3**,

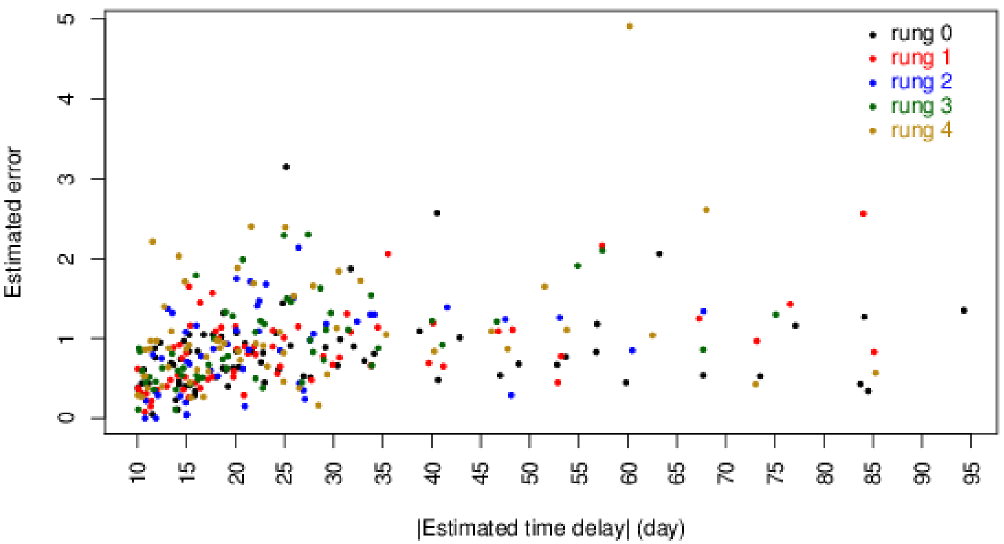
if $|\tilde{\Delta t}| \leqslant 30 \Rightarrow \sigma_R = 0.08 \times |\tilde{\Delta t}|$,   if $|\tilde{\Delta t}| > 30 \Rightarrow \sigma_R = 1.5$

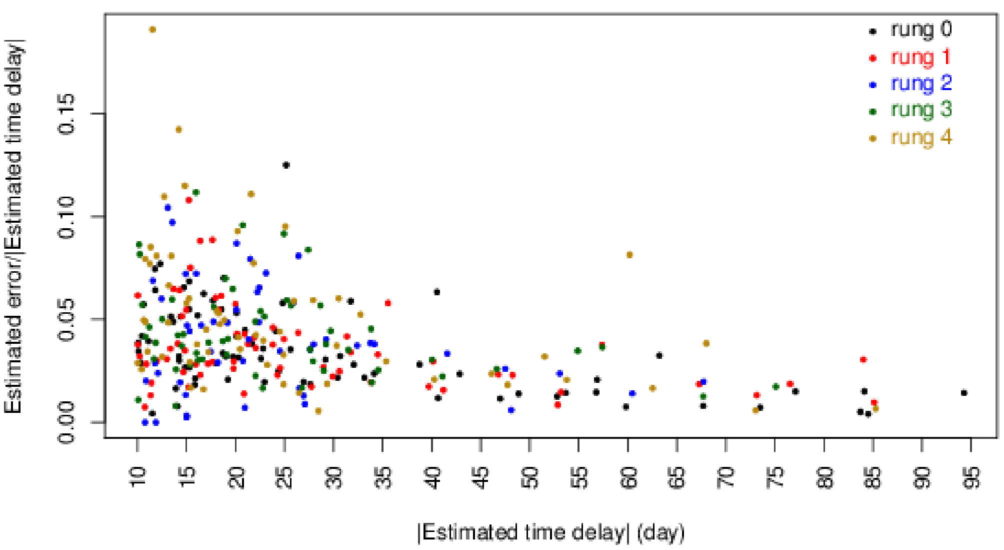
For **Rung 4**,

if $|\tilde{\Delta t}| \leqslant 25 \Rightarrow \sigma_R = 0.08 \times |\tilde{\Delta t}|$,   if $|\tilde{\Delta t}| > 25 \Rightarrow \sigma_R = 1.5$

$$\sigma_{\tilde{\Delta t}_{A_1 A_2}} = \sqrt{(\sigma^{ini}_{\tilde{\Delta t}_{A_1 A_2}})^2 + \sigma_R^2}$$

(Aghamousa & Shafieloo arXiv:1410.8122)





Results: TDC1 paper

STRONG LENS TIME DELAY CHALLENGE: II. RESULTS OF TDC1

Kai Liao[1,2*], Tommaso Treu[2*], Phil Marshall[3], Christopher D. Fassnacht[4], Nick Rumbaugh[4], Gregory Dobler[5,20], Amir Aghamousa[9], Vivien Bonvin[13], Frederic Courbin[13], Alireza Hojjati[6,7], Neal Jackson[12], Vinay Kashyap[17], S. Rathna Kumar[14], Eric Linder[8,18], Kaisey Mandel[17], Xiao-Li Meng[15], Georges Meylan[13], Leonidas A.Moustakas[11], Tushar P. Prabhu[14], Andrew Romero-Wolf[11], Arman Shafieloo[9,10], Aneta Siemiginowska[17], Chelliah S. Stalin[14], Hyungsuk Tak[15], Malte Tewes[19], and David van Dyk[16]

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ABSTRACT

We present the results of the first strong lens time delay challenge. The motivation, experimental design, and entry level challenge are described in a companion paper. This paper presents the main challenge, TDC1, which consisted in analyzing thousands of simulated light curves blindly. The observational properties of the light curves cover the range in quality obtained for current targeted efforts (e.g. COSMOGRAIL) and expected from future synoptic surveys (e.g. LSST), and include "evilness" in the form of simulated systematic errors. 7 teams participated in TDC1, submitting results from 78 different method variants. After a describing each method, we compute and analyze basic statistics measuring accuracy (or bias) A, goodness of fit χ^2, precision P, and success rate f. For some methods we identify outliers as an important issue. Other methods show that outliers can be controlled via visual inspection or conservative quality control. Several methods are competitive, i.e. give $|A| < 0.03$, $P < 0.03$, and $\chi^2 < 1.5$, with some of the methods already reaching sub-percent accuracy. The fraction of light curves yielding a time delay measurement is typically in the range f =20–40%. It depends strongly on the quality of the data: COSMOGRAIL-quality cadence and light curve lengths yield significantly higher f than does sparser sampling. We estimate that LSST should provide around 400 robust time-delay measurements, each with $P < 0.03$ and $|A| < 0.01$, comparable to current lens modeling uncertainties. In terms of observing strategies, we find that A and f depend mostly on season length, while P depends mostly on cadence and campaign duration.

Subject headings: gravitational lensing — methods: data analysis

$$f \equiv \frac{N_{submitted}}{N}$$

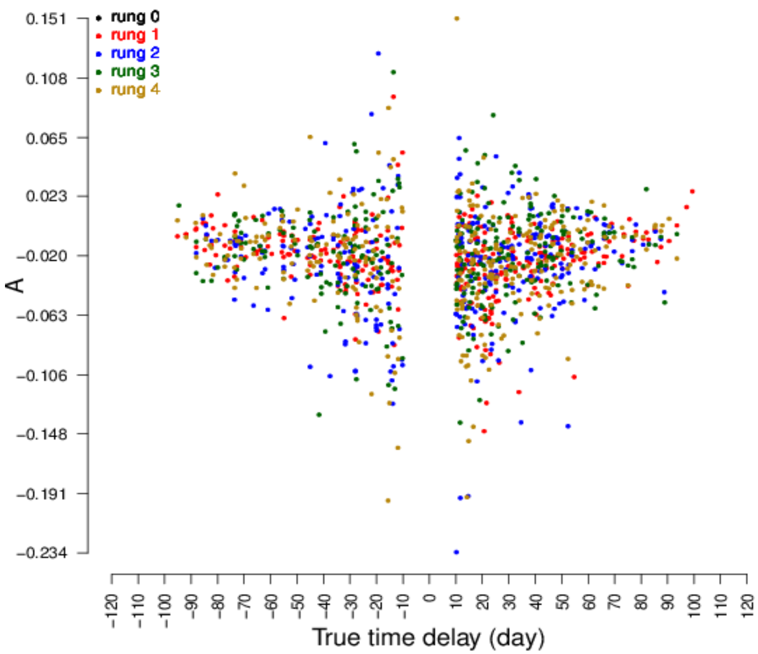
$$P = \frac{1}{fN} \sum_i \left(\frac{\sigma_i}{|\Delta t_i|} \right)$$

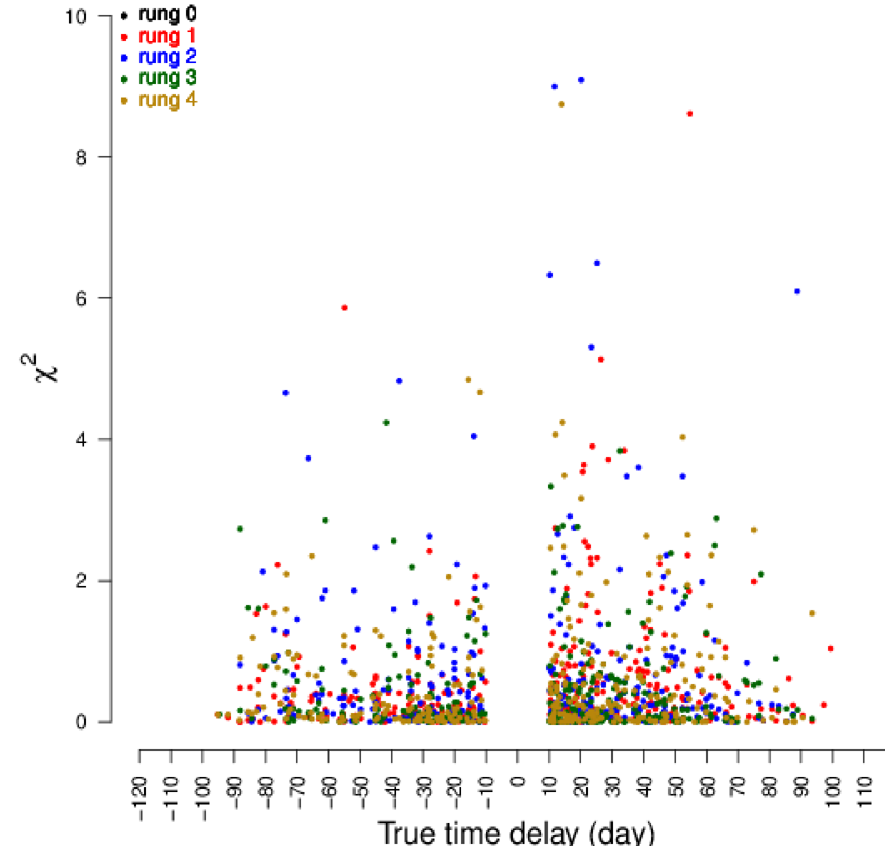
$$A = \frac{1}{fN} \sum_i \left(\frac{|\tilde{\Delta t}_i| - |\Delta t_i|}{|\Delta t_i|} \right)$$

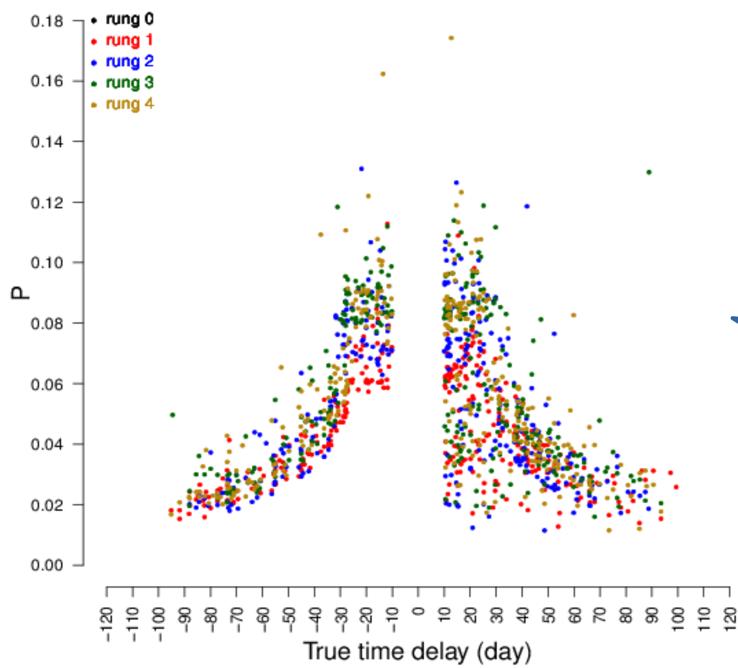
$$\chi^2 = \frac{1}{fN} \sum_i \left(\frac{\tilde{\Delta t}_i - \Delta t_i}{\sigma_i} \right)^2$$

Rung	f	χ^2	P	A
0	0.529	0.579	0.038	-0.018
1	0.366	0.543	0.044	-0.022
2	0.350	0.885	0.053	-0.025
3	0.337	0.524	0.059	-0.021
4	0.346	0.608	0.056	-0.024

Results: histogram of metrics



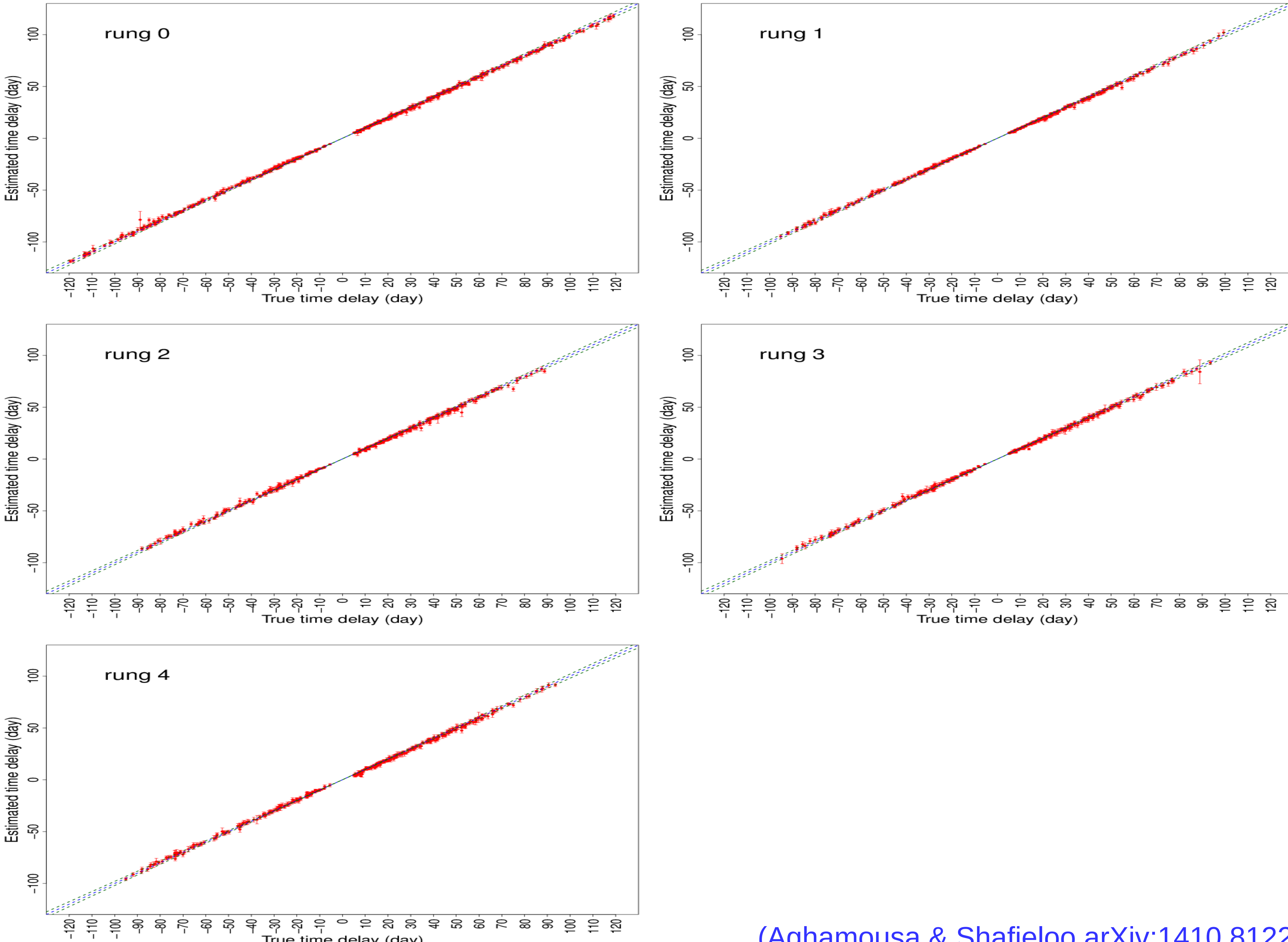




there are only 5 items with
$\chi^2 \geq 10$
out of few thousand entries

(Aghamousa & Shafieloo arXiv:1410.8122)

Results: estimated vs true time delay



(Aghamousa & Shafieloo arXiv:1410.8122)

Results: calibration

Rung	f	χ^2	P	A
0	0.529	0.579	0.038	-0.018
1	0.366	0.543	0.044	-0.022
2	0.350	0.885	0.053	-0.025
3	0.337	0.524	0.059	-0.021
4	0.346	0.608	0.056	-0.024

$$\tilde{\Delta t_i} + 0.5 \quad \text{and} \quad \sigma_i/\sqrt{2}$$

Rung	f	χ^2	P	A
0	0.529	0.792	0.027	-0.0014
1	0.366	0.660	0.031	-0.0036
2	0.350	1.439	0.038	-0.0058
3	0.337	0.766	0.041	-0.0010
4	0.346	0.868	0.040	-0.0048

(Aghamousa & Shafieloo arXiv:1410.8122)

Summary

- The strong lensing is going to be a rich data field which can reveal new information about the Universe.
- Time delay estimation has a crucial role in analysis of strong lensing systems. Hence precise and accurate algorithms are needed for time delay estimation.
- To prepare for the future there have been the strong lens Time Delay Challenge: TDC0, TDC1, ...?
- We have designed a fast and reliable algorithm based on smoothing method and cross-correlation with which we could get outstanding results in the challenges.
- Our method is fully automated and after a small calibration our algorithm can yield very accurate and precise estimation of time delay.
- Using our algorithm we can estimate the time delay in systems affected by microlensing.
- We are planning to apply our method on currently available data.