Why Time-Delays?

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- All sources are variable - short (<100 yrs) and long timescales (>1000 yrs)
- Variability - periodic, stochastic, flaring, quasi-periodic, dimming, brightening, other types?

- Echos of the primary variations:
    - reverberation - primary radiation reflected from the medium
    - enhanced emission as the ‘wave’ propagates through the medium
- Light bending -> gravitational lensing -> delayed variations between images

(1) Reverberation - primary radiation reflected/reprocessed by the medium

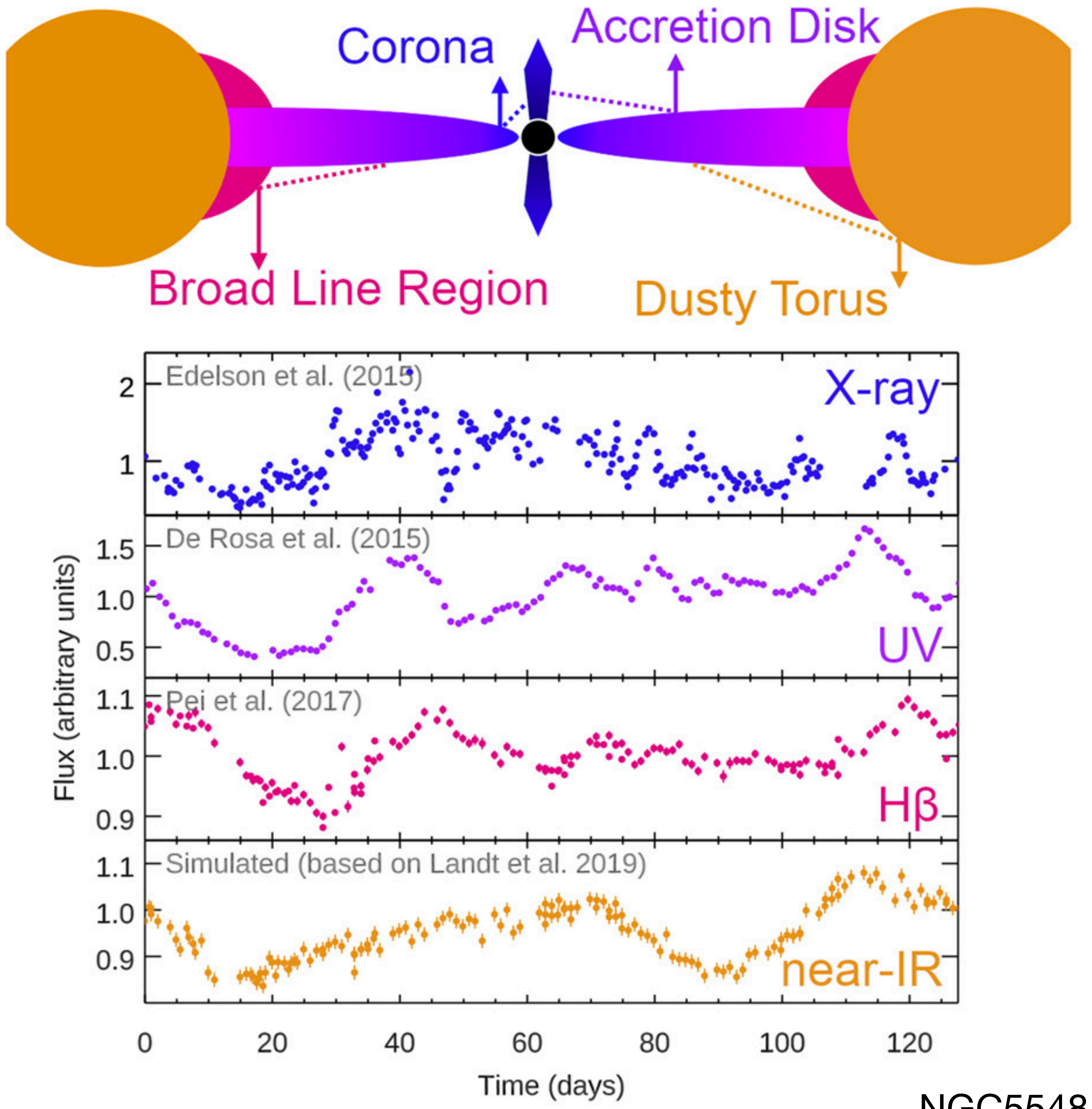
https://archive.stsci.edu/hlsp/storm

(2) **Reverberation - primary radiation reflected/reprocessed from the medium**

Structure - look into unresolved center of active galaxies (< 1pc)

Measurements of black hole mass

Mass ~ Emission line width * time-delay



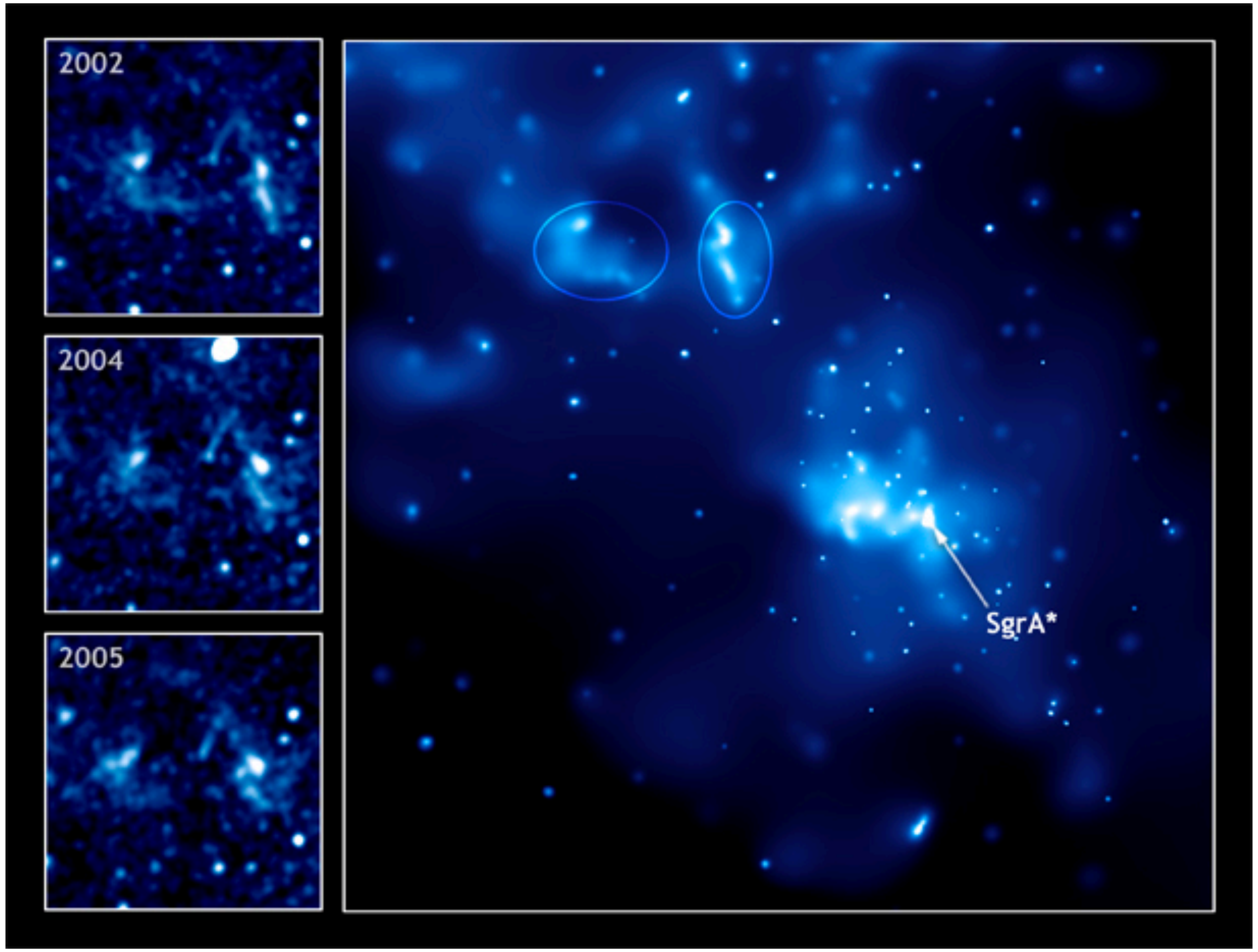
Cackett, Bentz & Kara 2021

NGC5548 STORM

Light echos - ‘enhanced’ emission as the ‘wave’ propagates through the medium

V404 Cyg

Light Echo in the Galactic Center

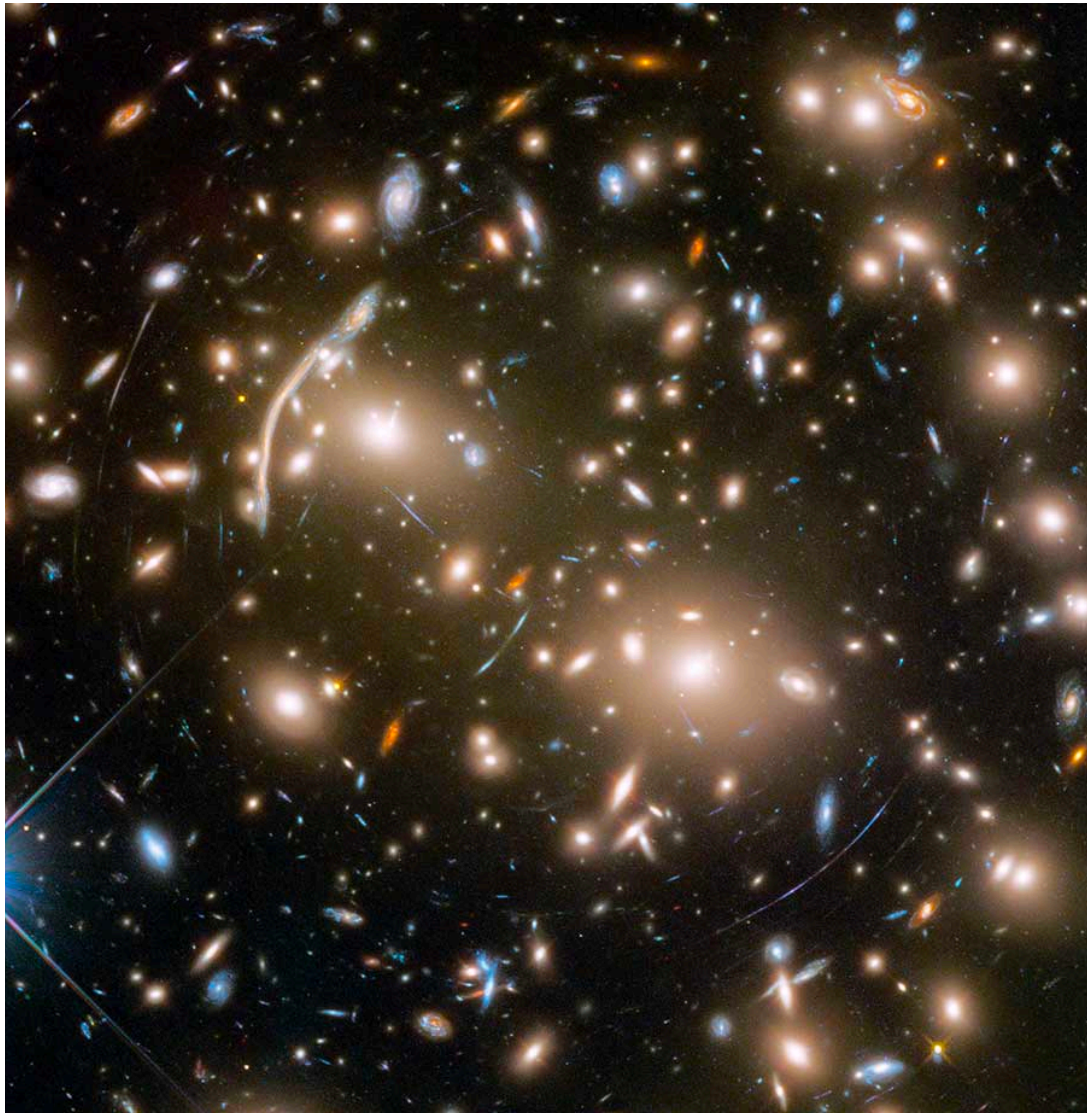


Credit: NASA/CXC/ Chandra Press Images

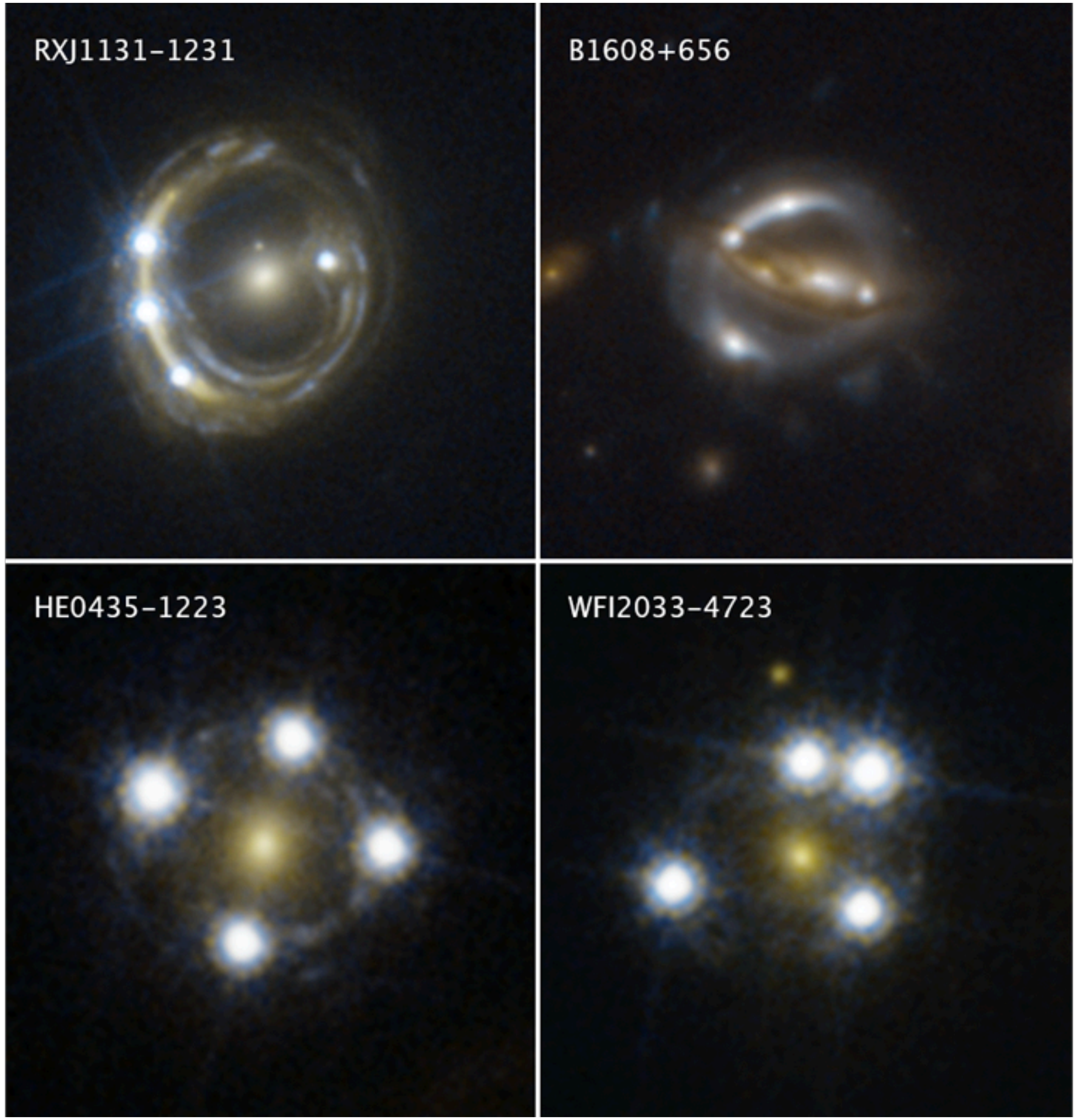
Gravitational Lensing

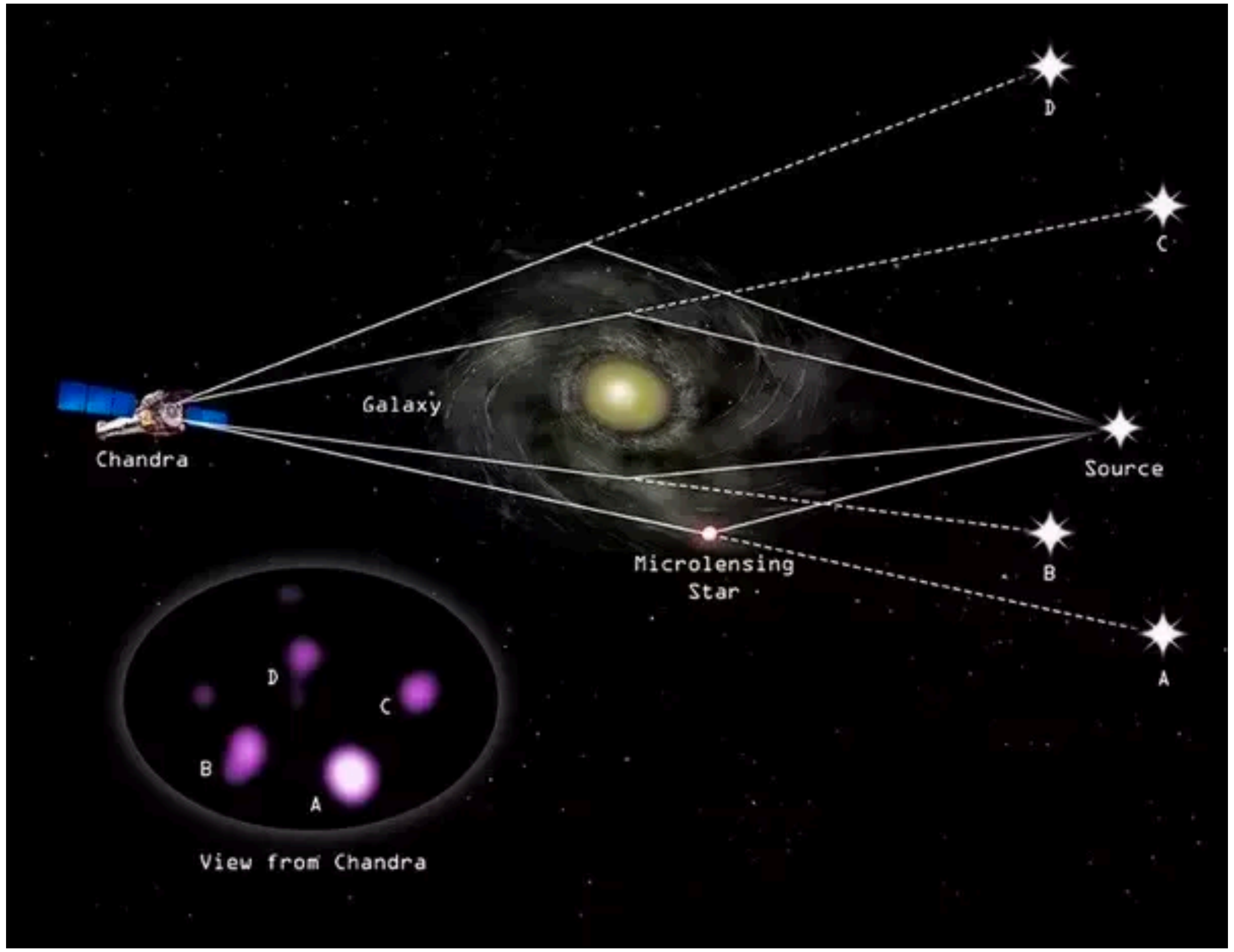
Strong gravity bends lights

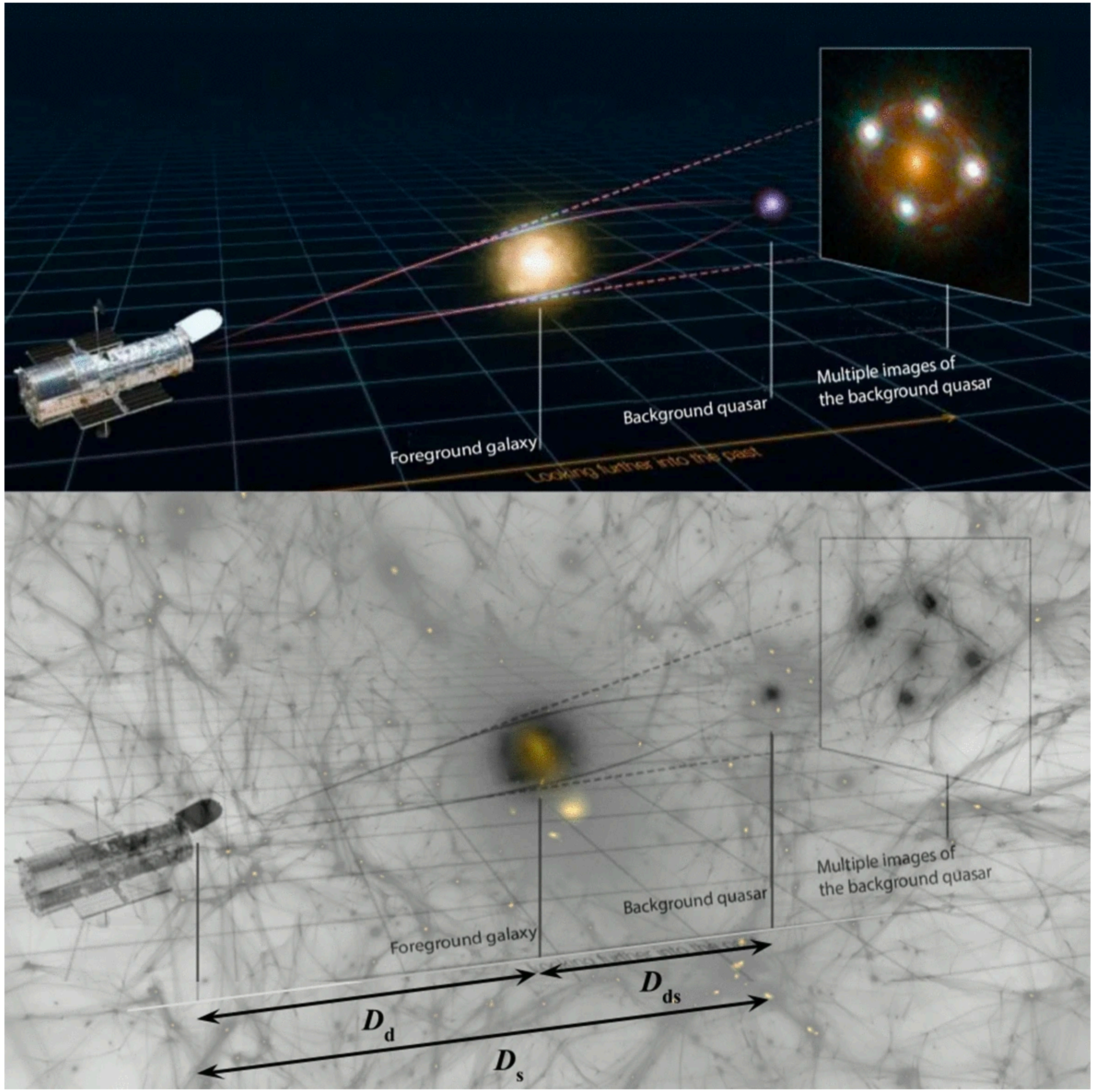
- Lens - a galaxy cluster
- Arcs - images of lensed galaxies at larger distance



Images of Lensed Quasars

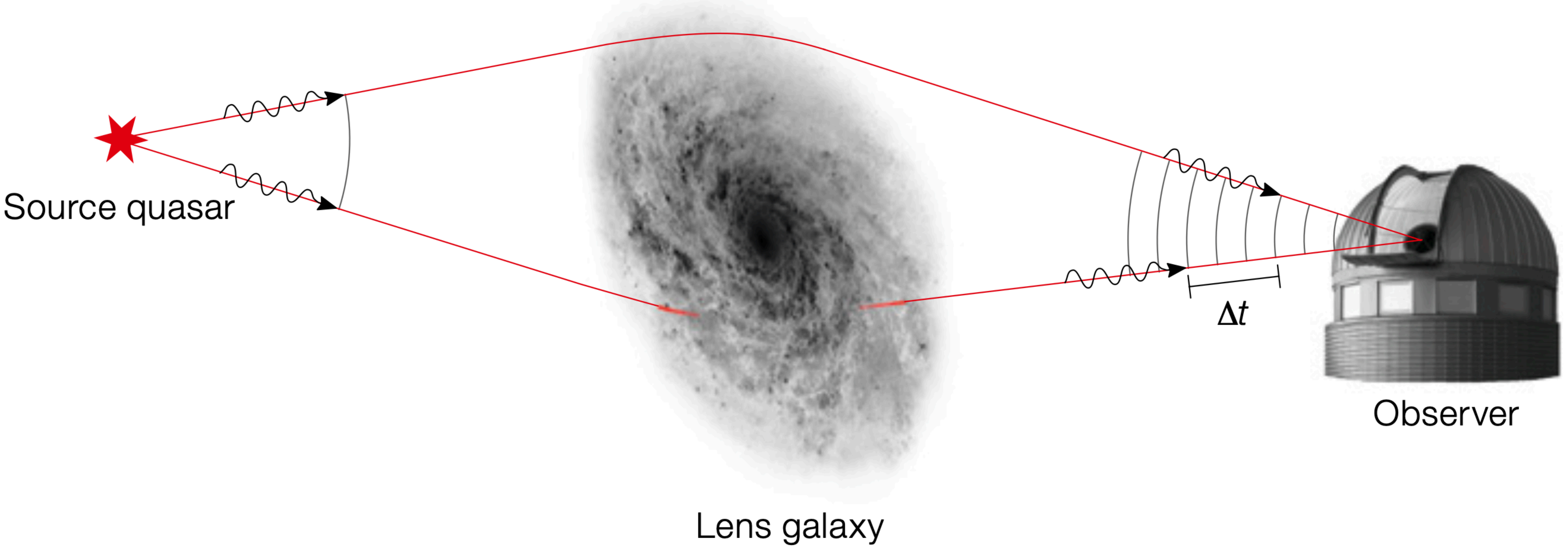






Strong Lensing time-delay cosmography in the 2020s
Astronomy & Astrophysics Review
Treu, Suyu & Marshall 2020

Large Universe, low H_0, large time delay



Small Universe, high H_0, small time delay

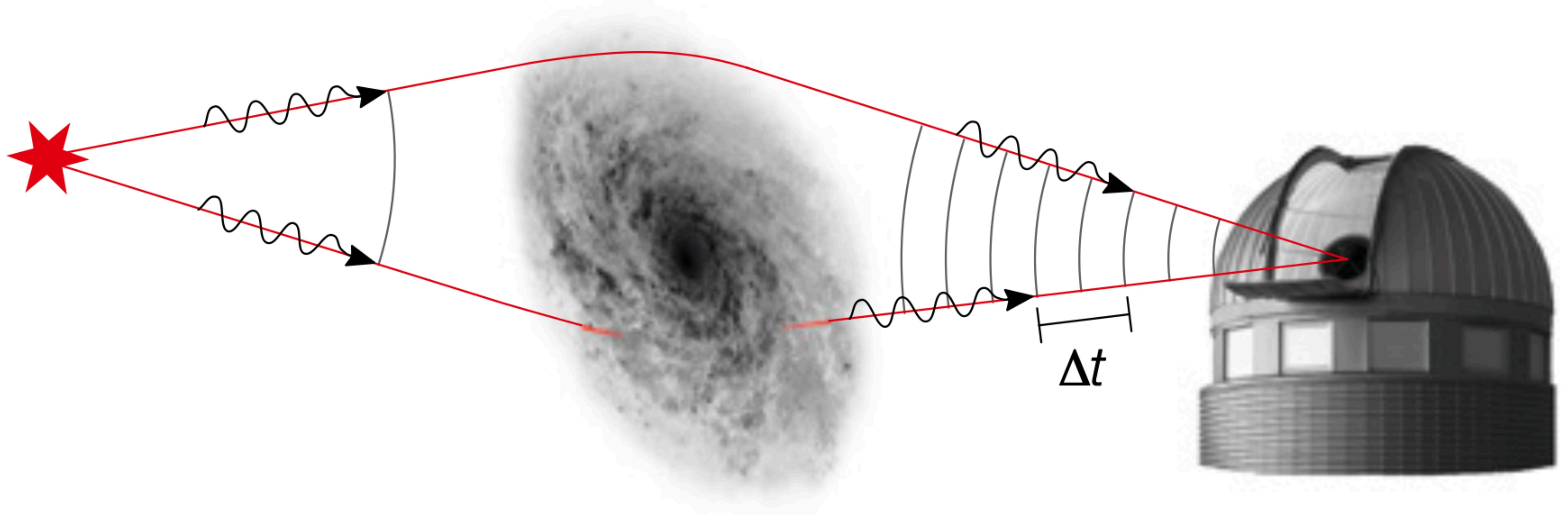


Figure 1. Schematic showing how the time delay Δt between two images of a gravitationally lensed source depends on the scale of the gravitational lens system, and hence on H_0. Illustration inspired by Narayan & Bartelmann (1996).

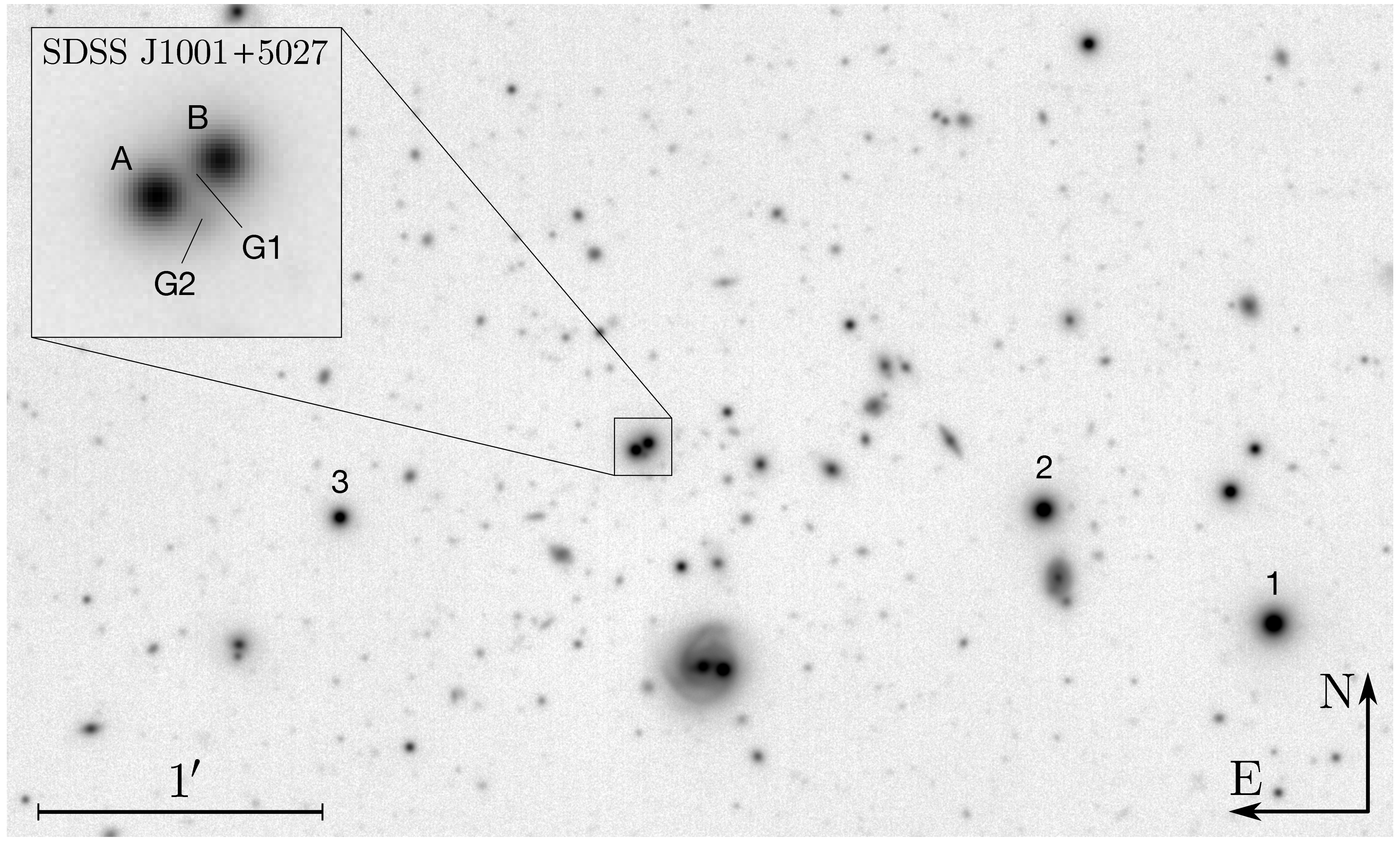
From Tewes et al 2012

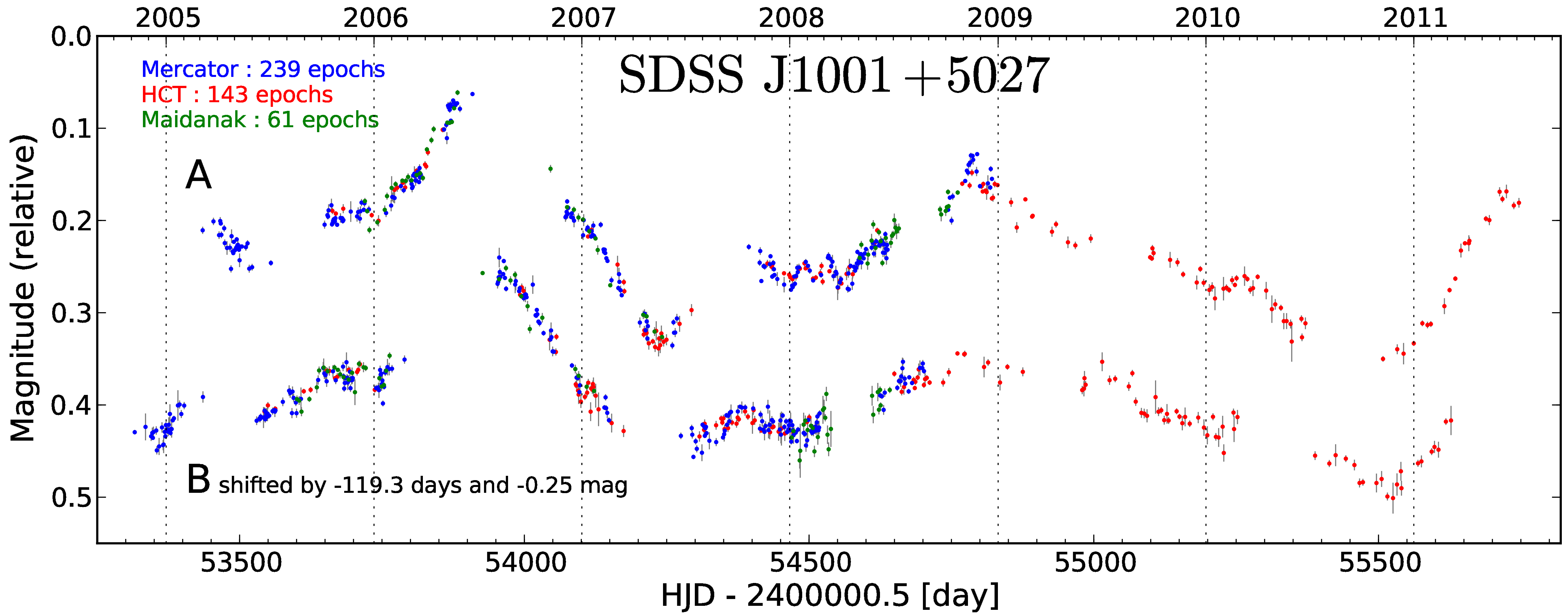
Light curves obtained from monitoring individual images of lensed quasars

COSMOGRAIL

Millon et al 2020 - data release

https://obswww.unige.ch/~millon/d3cs/COSMOGRAIL_public/





Rathna Kumar et al 2013

Modeling gravitational time delay

Tak, Mandel, van Dyk, Kashyap, Meng, Siemiginowska, 2017, Ann. Appl. Stat. 11(3): 1309, doi: 10.1214/17-AOAS1027 arXiv:1602.01462.
Meyer, van Dyk, Tak, Siemiginowska 2023, ApJ, 950, 37. doi:10.3847/1538-4357/acbea1

Time Shift

$$Y(t) = X(t-\Delta)$$

Magnitude shift

$$Y(t) = X(t-\Delta) + \theta_0$$

Microlensing

$$Y(t) = X(t-\Delta) + \boldsymbol{w}_m(t-\Delta)\boldsymbol{\theta}$$

$$\boldsymbol{w}_m(t-\Delta) = \{1, t-\Delta, \ldots, (t-\Delta)^m\}$$

$$\boldsymbol{\theta} = \{\theta_0, \ldots, \theta_m\}$$

$$\boldsymbol{t}^{\boldsymbol{\Delta}} = \{t_i\}_{i=1}^n \cup \{t_i - \Delta\}_{i=1}^n$$

'Combined' light curve - discrete realizations of the continuous-time light curve $Z(t)$

$$z_j = \begin{cases} x_i & \text{for some } i \text{ if } t_j^\Delta \text{ is in } \boldsymbol{t}, \\ y_i - \boldsymbol{w}_m(t_j - \Delta)\boldsymbol{\theta} & \text{for some } i \text{ if } t_j^\Delta \text{ is in } \boldsymbol{t} - \Delta \end{cases}$$

Measurement errors

$$\delta_j^z = \begin{cases} \delta_i^x & \text{for some } i \text{ if } t_j^\Delta \text{ is in } \boldsymbol{t}, \\ \delta_i^y & \text{for some } i \text{ if } t_j^\Delta \text{ is in } \boldsymbol{t} - \Delta \end{cases}$$

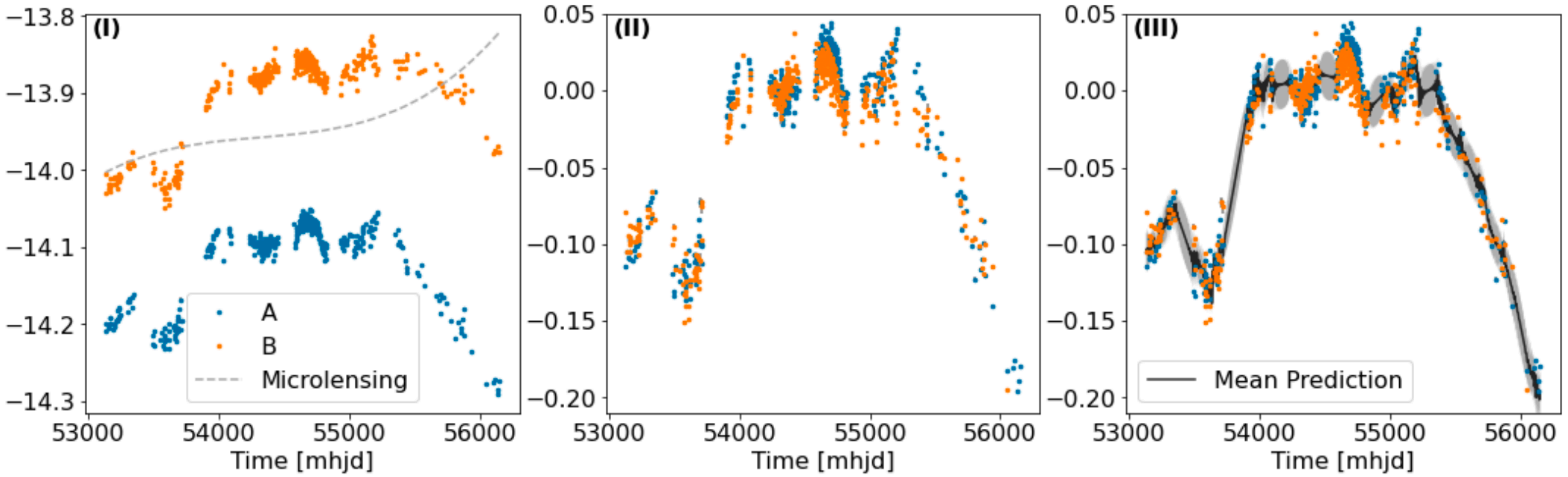
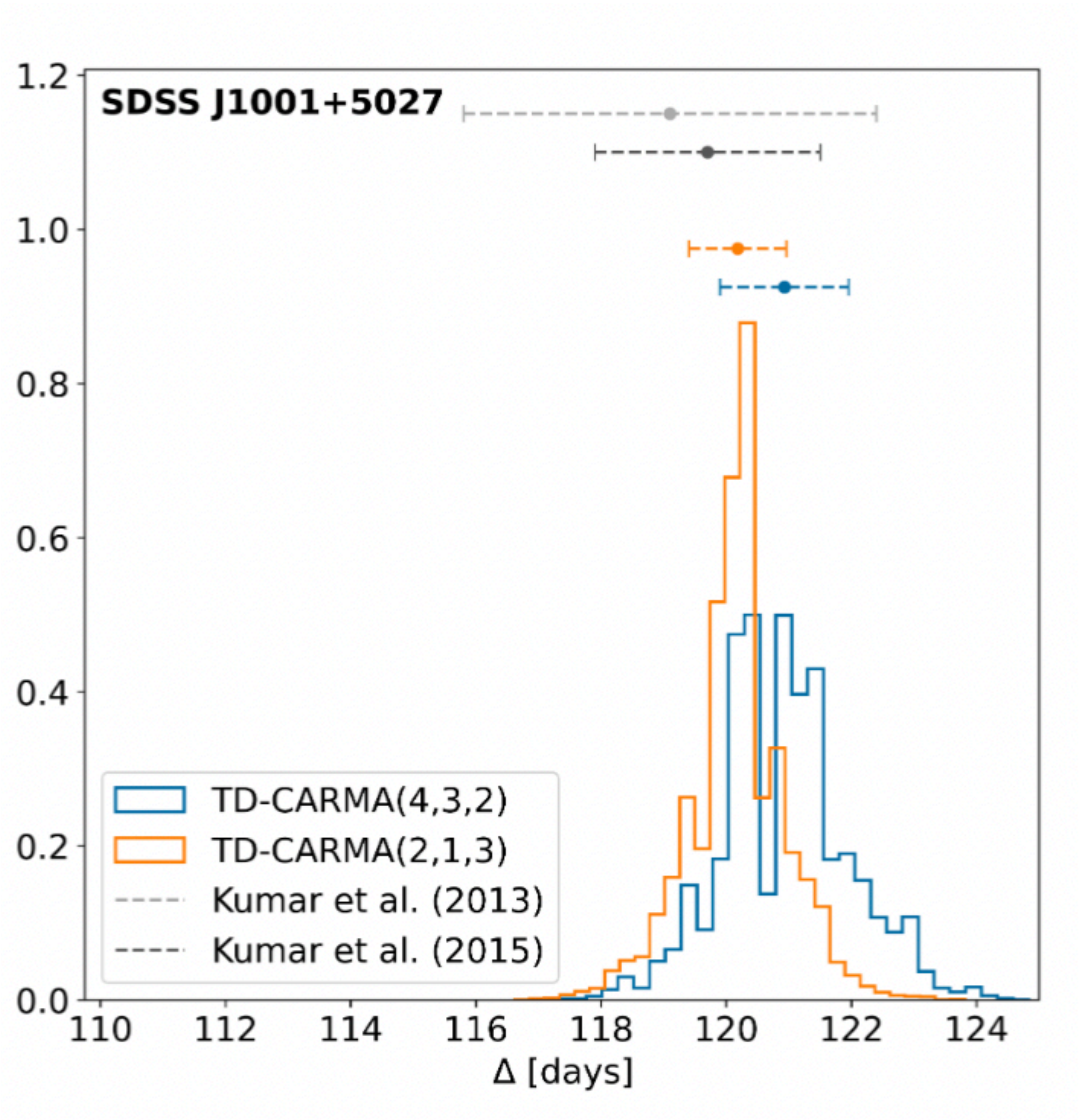
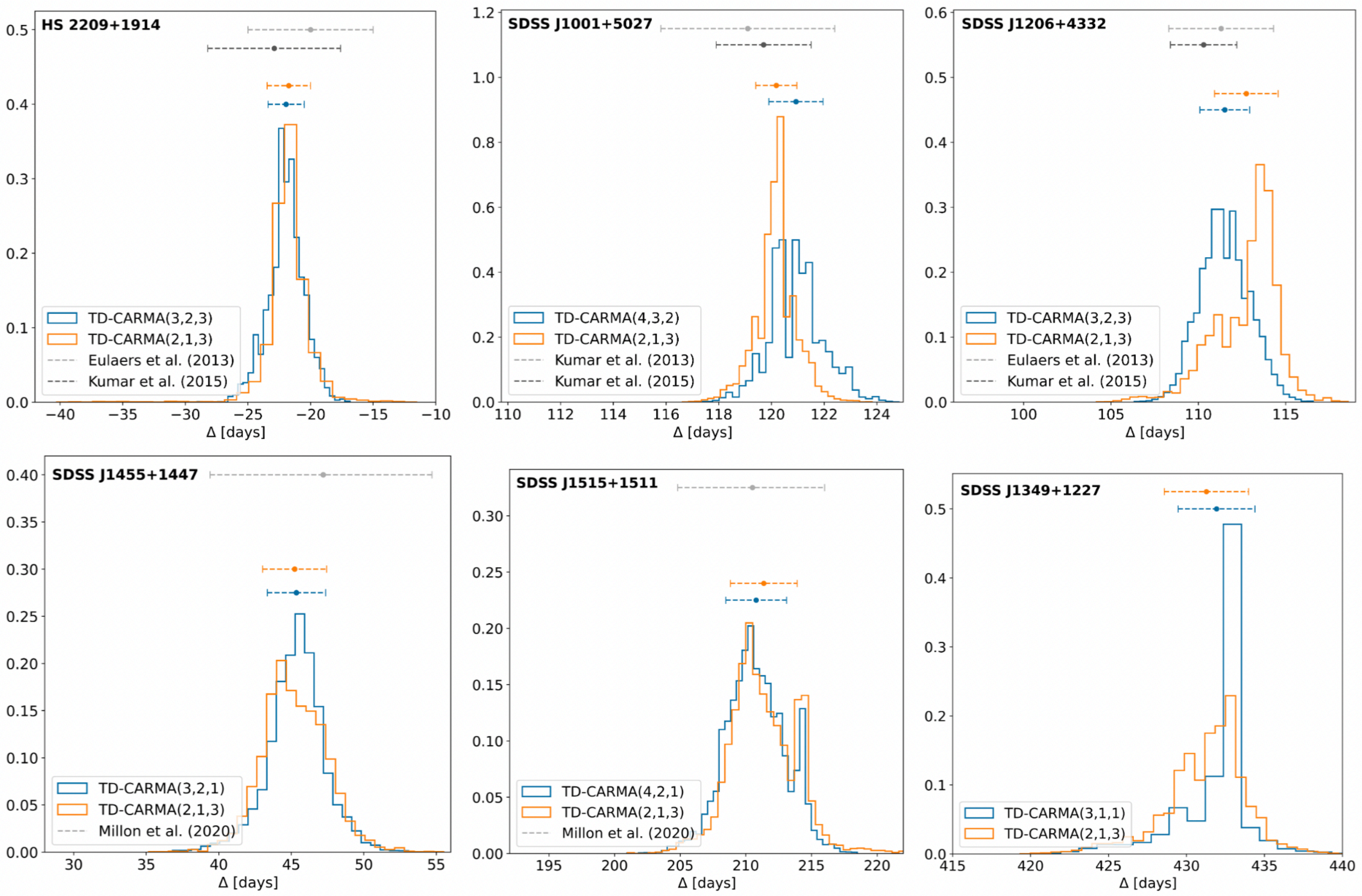


Figure 5. Panel (I) shows the data for the HS2209+1914 doubly lensed quasar, and the microlensing polynomial regression curve (with $m = 3$) fit to lightcurve B (corresponding to measurements $\boldsymbol{y}$ in our mathematical notation reported in Table 1). The effect of microlensing can be seen, for example in the time period between 55500 and 56000 mhjd, where lightcurve B features a slower decay in magnitude than lightcurve A. This is successfully captured and adjusted for by the increasing behaviour in the fitted microlensing curve. Panel (II) shows the data in Panel (I), adjusted for time delay Δ and the microlensing effect modeled by the polynomial regression, which corresponds to the composite light curve $\boldsymbol{z}$ defined in Equation 4. Panel (III) shows the mean fitted values (and uncertainties) of the CARMA(3,2) process to composite light curve $\boldsymbol{z}$.

Meyer et al 2023



Meyer A.~D., van Dyk D.~A., Tak H., Siemiginowska A., 2023, ApJ, 950, 37. doi:10.3847/1538-4357/acbea1



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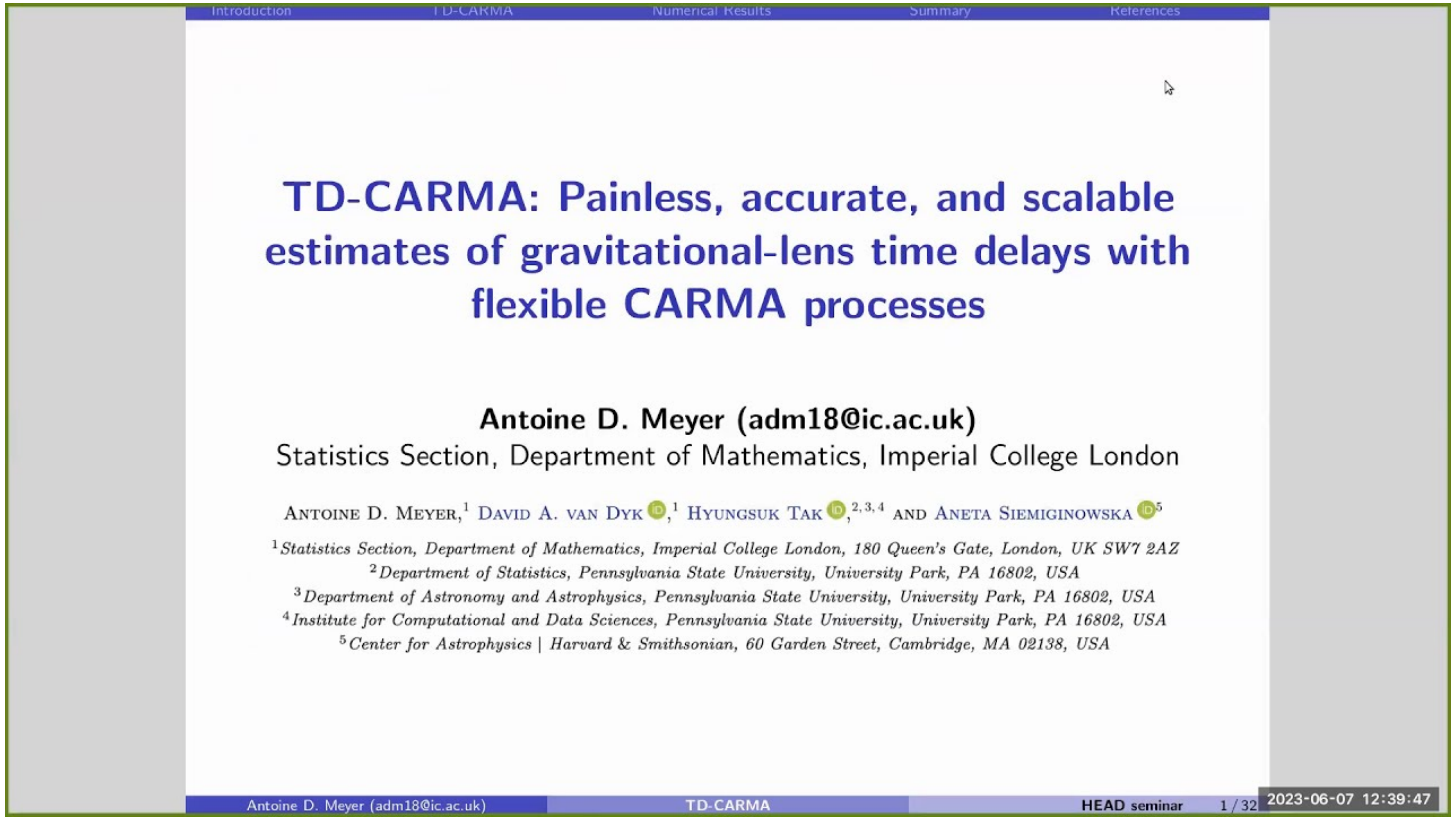

- https://www.youtube.com/watch?v=fLEX5AGzK40&ab_channel=CfAHEADivision

Some Future Projects

- Time-delays for a complete set of available lensed images
- Unresolved light curves in gravitationally lensed systems
- Modeling light curves in multiple bands
- Meta-analysis - use all available data

The Astronomical Journal, 160:265 (12pp), 2020 December https://doi.org/10.3847/1538-

Modeling Stochastic Variability in Multiband Time-series Data

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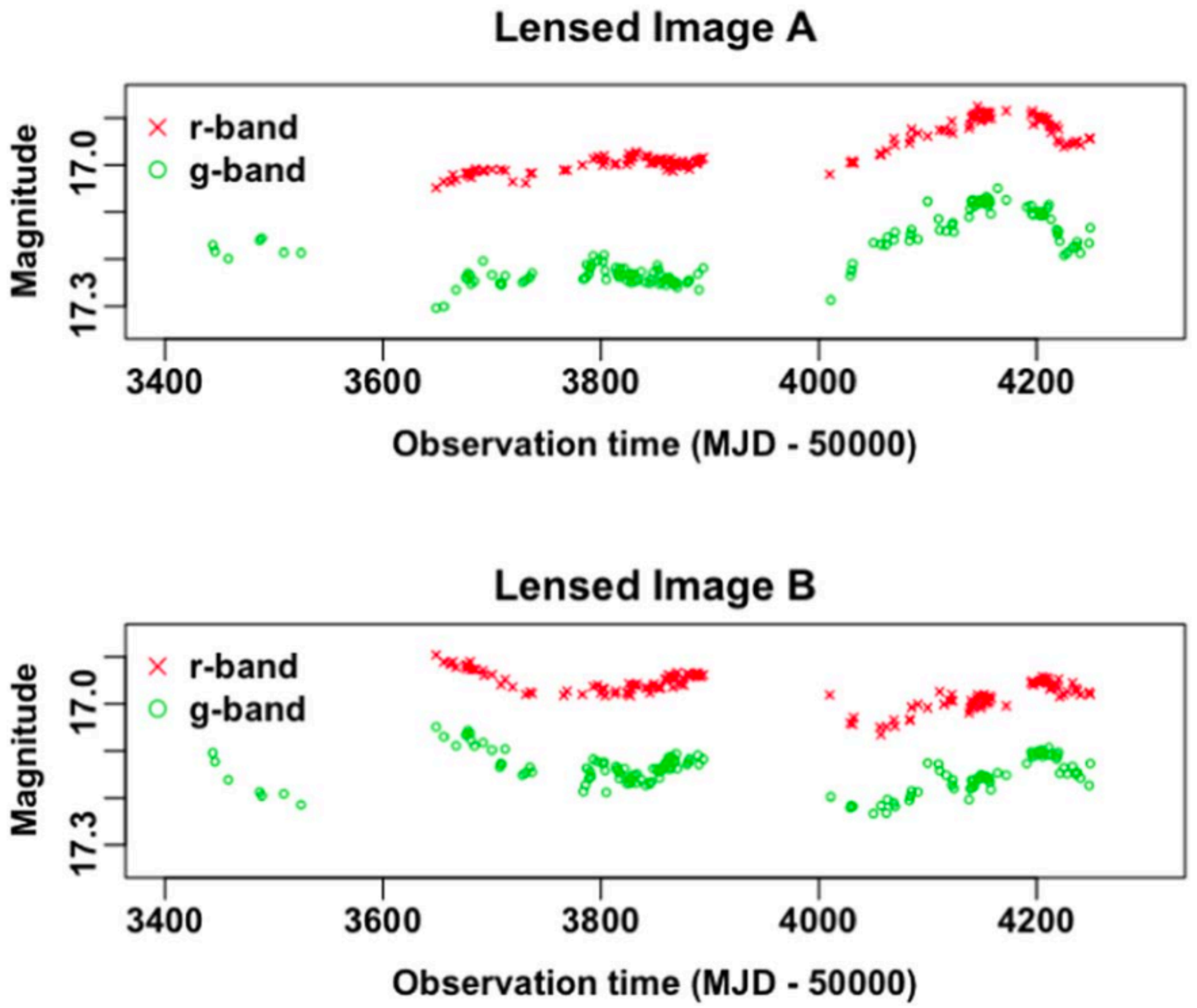


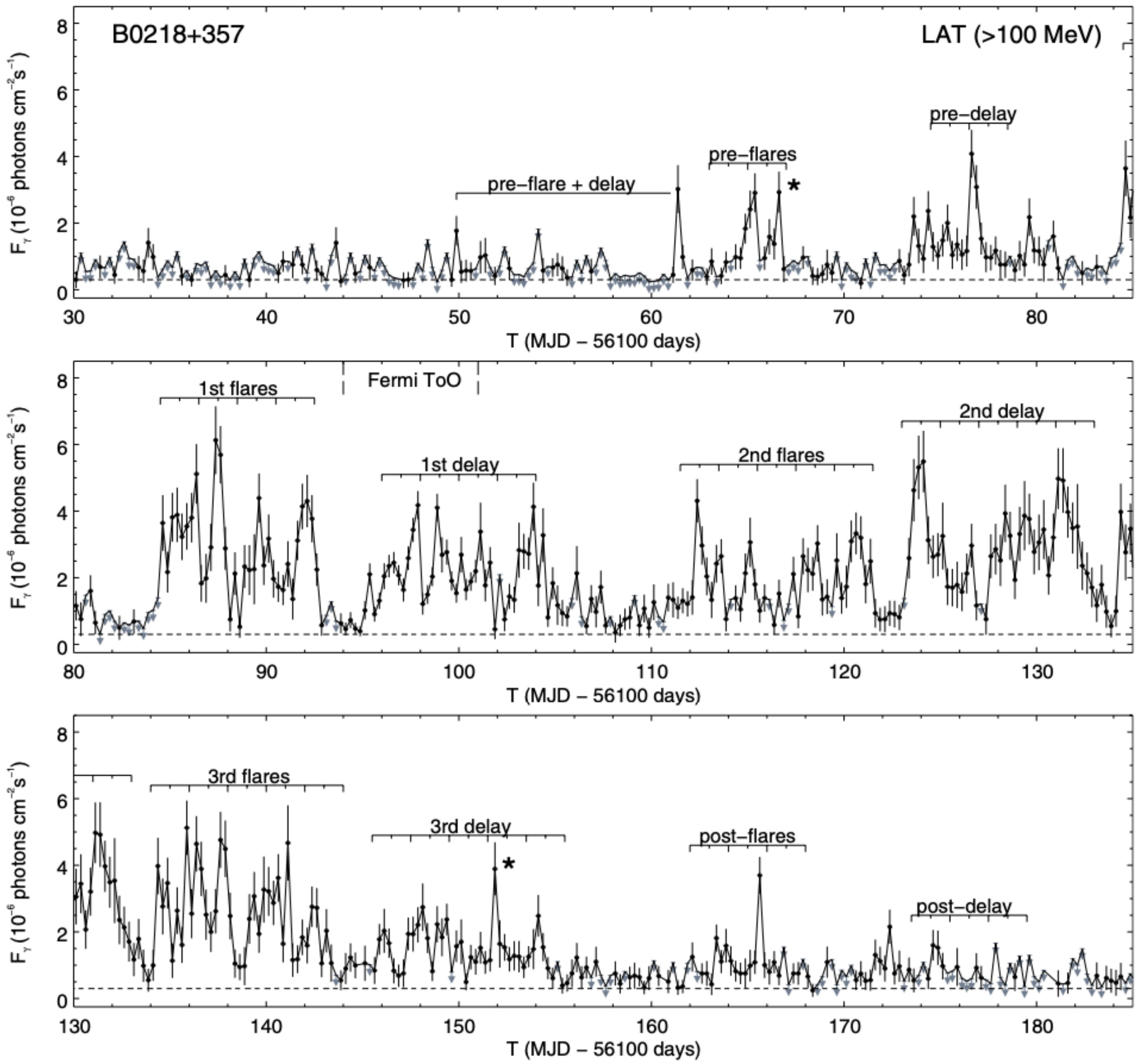
Figure 7. Light curves of doubly lensed quasar Q0957+561 (Shalyapin et al. 2012). The *g*- and *r*-band light curves of lensed image *A* appear in the top panel and those of lensed image *B* appear in the bottom panel. Due to strong gravitational lensing, multiband light curves of one image lag behind by the time delay. The *g*-band light curve has more fluctuations, which is crucial in estimating the time delay.

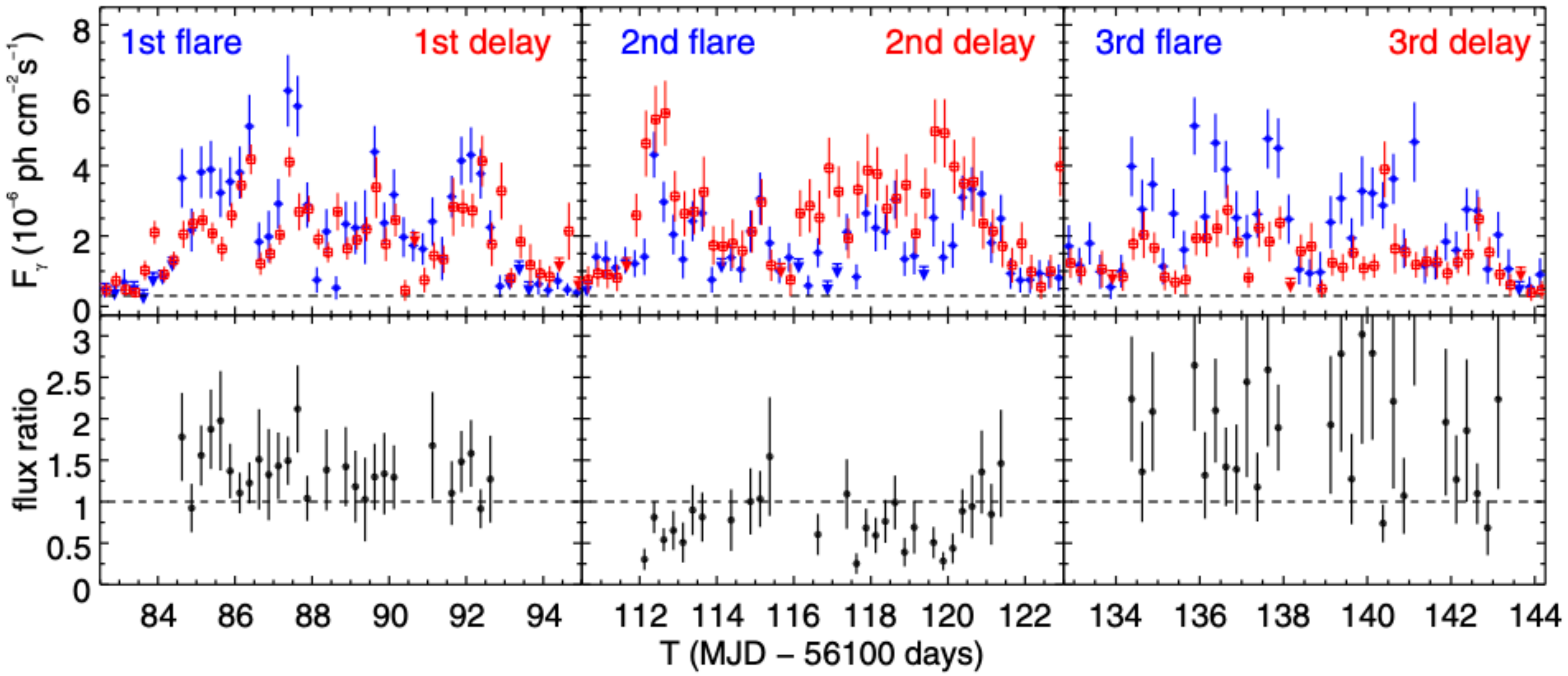
(The data used to create this figure are available.)

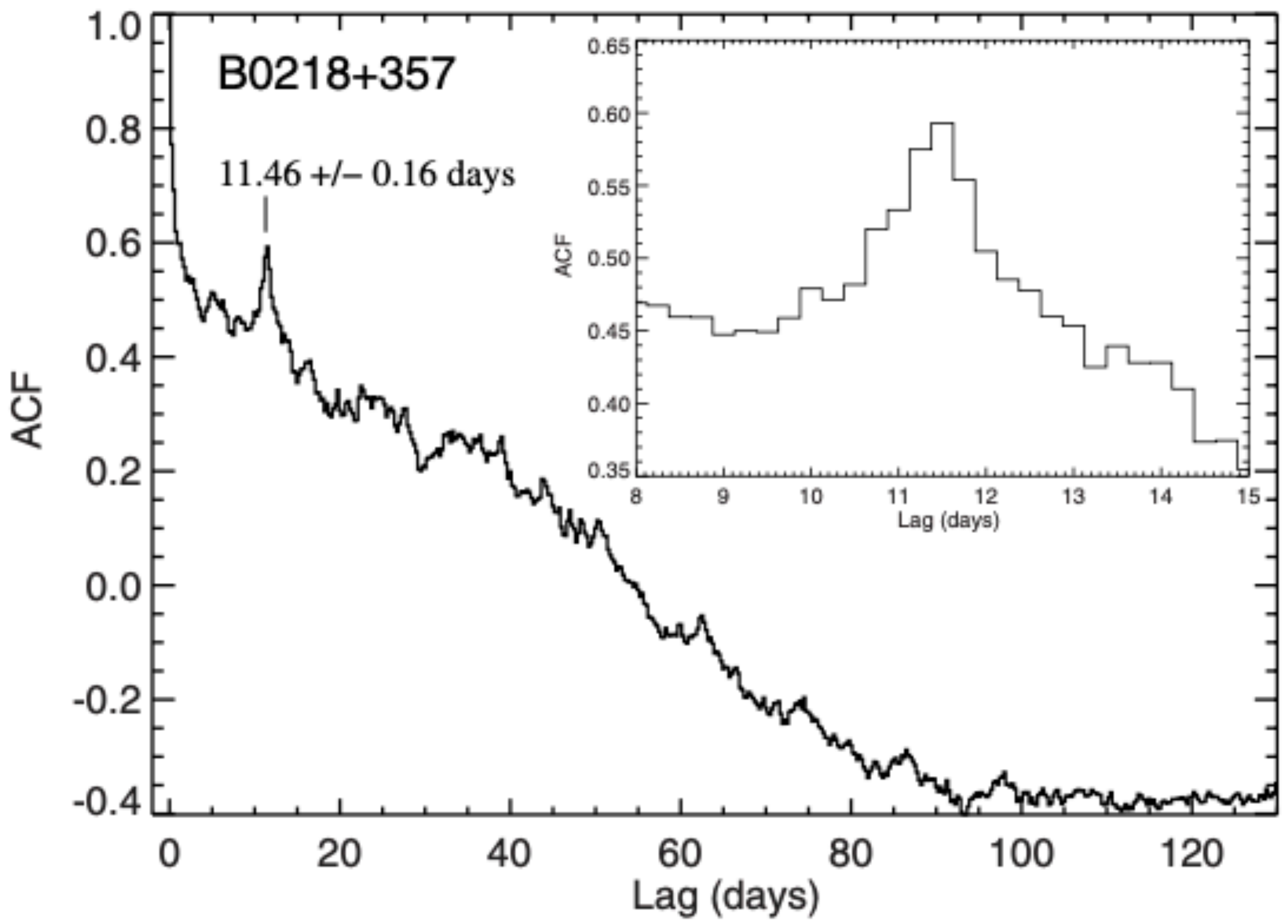
Unresolved Light curves

Barnacka et al 2011

Cheung et al 2014

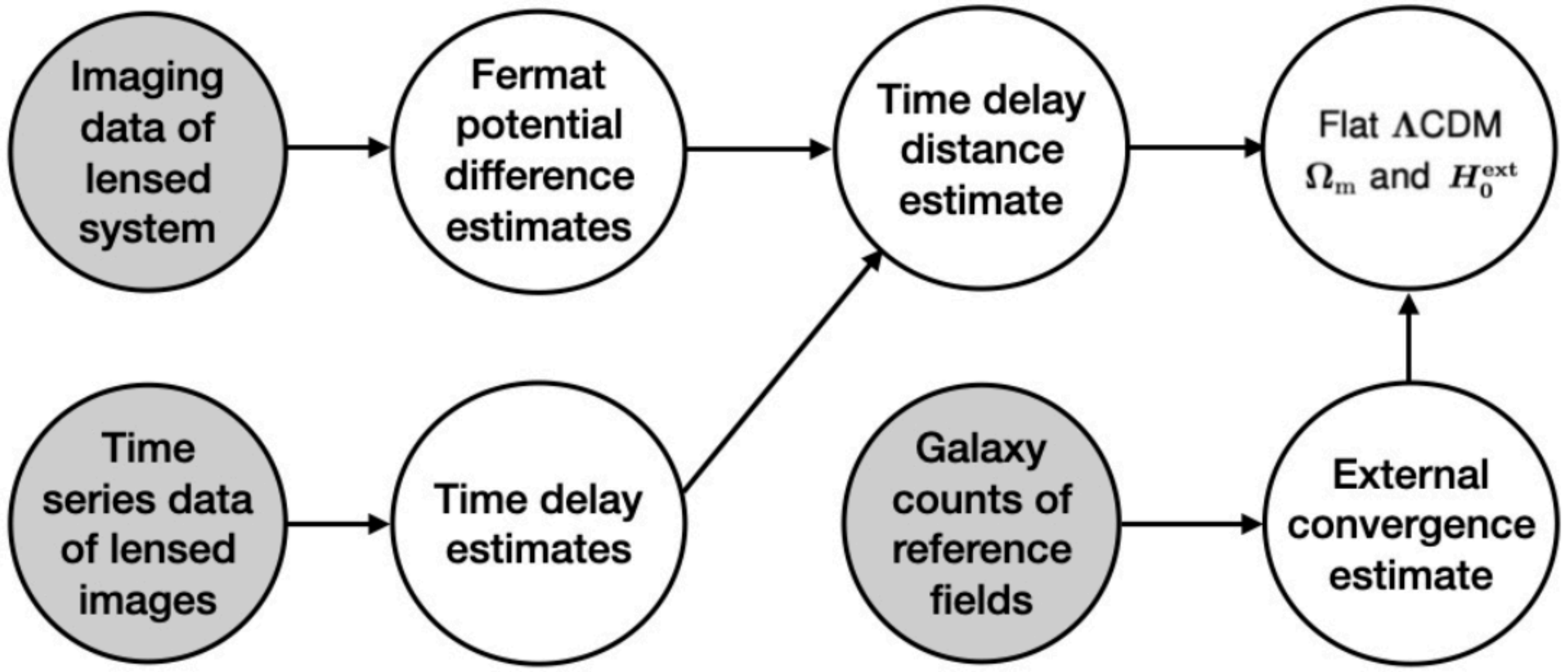






A ROBUST BAYESIAN META-ANALYSIS FOR ESTIMATING THE HUBBLE CONSTANT VIA TIME DELAY COSMOGRAPHY

BY HYUNGSUK TAK[1,a] AND XUHENG DING[2,b]



arXiv:2308.13018. doi:10.48550/arXiv.2308.13018