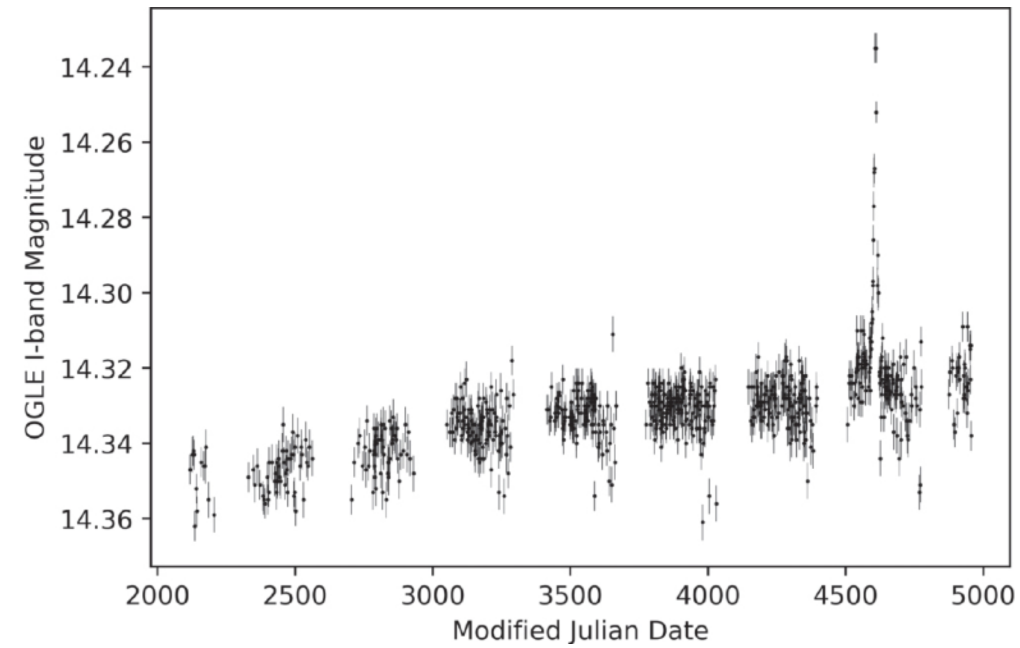


A Reanalysis of Public Galactic Bulge Gravitational Microlensing Events from OGLE-III and -IV

Golovich, Dawson, Bartolic et al. (2022, ApJS, 260, 2)

Raphael Oliveira, 12.dec.2023, Statistics Journal Club, OAUW

Problematics in studies of t_E distribution
(Abstract + Introduction)

- Systematics in individual light curves
  - Microlensing + baseline variability (Gaussian processes)

- Oversimplistic modeling: point-source point-lens (PSPL)
  - Including microlensing parallax due to Earth's motion

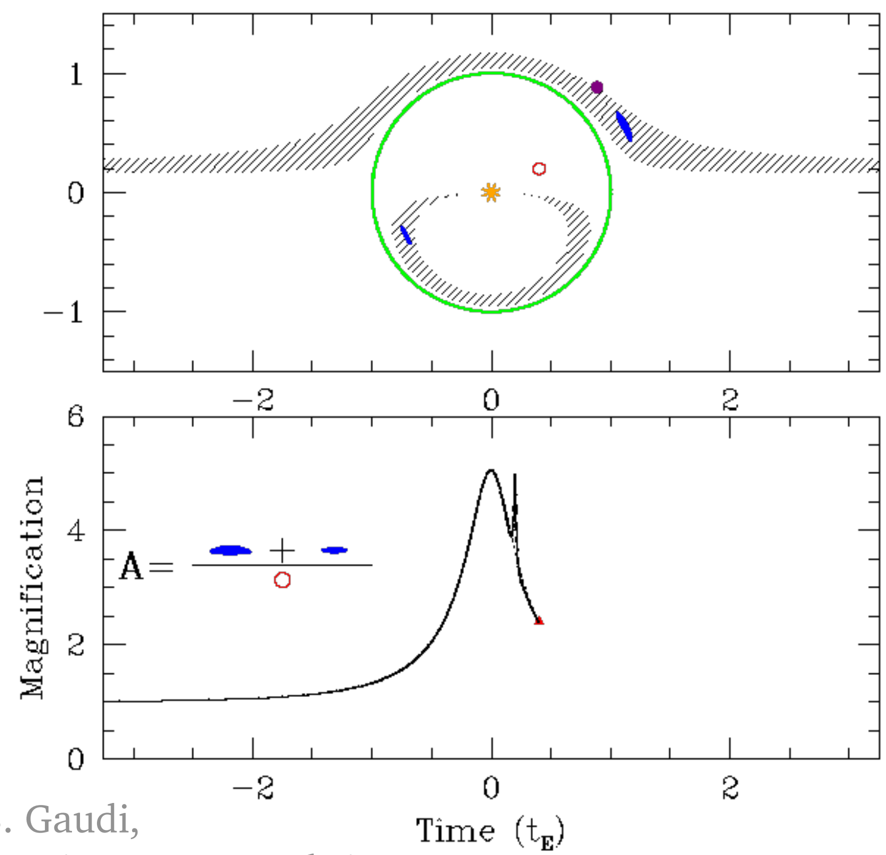
- Using point estimates from individual events: t_E histograms
  - Forward modeling the simulated chains to infer t_E distribution

- **10,000 OGLE-III and IV events:** previous analyses overestimated the number of $t_E > 100\,\mathrm{d}$ due to ignoring parallax, black holes candidates…

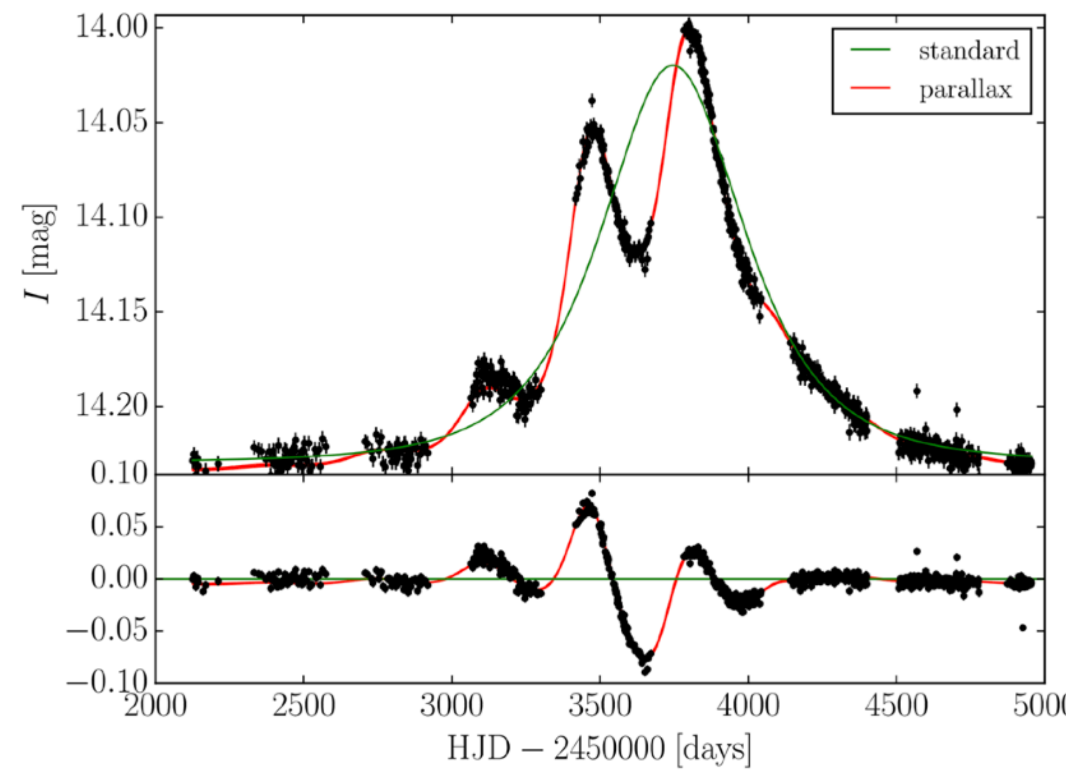
1 Introduction

- **Timeline:** Paczynski (1986) → population of dark objects (e.g. MACHOs) → time-domain photometric surveys → dense field photometry, difference imaging photometry, alerts → LSST, Roman

- **PSPL challenges:** blended flux (1–1.5” typical seeing), baseline variability* (stellar, systematics), seasonal gaps, parallax*



By B.S. Gaudi,
Microlensing Source website



Wyrzykowski et al. (2016)

1 Introduction

- **Timeline:** Paczynski (1986) → population of dark objects (e.g. MACHOs) → time-domain photometric surveys → dense field photometry, difference imaging photometry, alerts → LSST, Rubin

- **PSPL challenges:** blended flux (1–1.5" typical seeing), baseline variability* (stellar, systematics), seasonal gaps, parallax*

- **Degeneracies:** mass-distance deg. is broken with parallax inclusion; others e.g. finite source, binary lens caustics, mass-μ_{rel}/velocity…

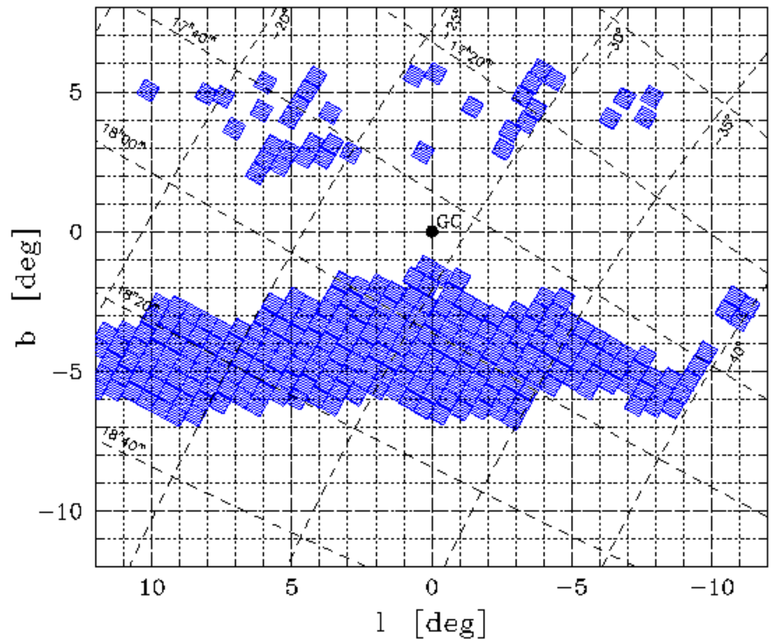
- **Large statistics:** distribution of Einstein crossing time (t_E), optical depth and event rate. Distribution of t_E is dependent on the line-of-sight distribution of parallax and relative proper motion:
  - Wyrzykowski et al. (2015): t_E histogram peaks at ~27 d
  - Mróz et al. (2019): optical depth ~ 10^{-6}, event rate = 10^{-5}–10^{-6} yr^{-1}

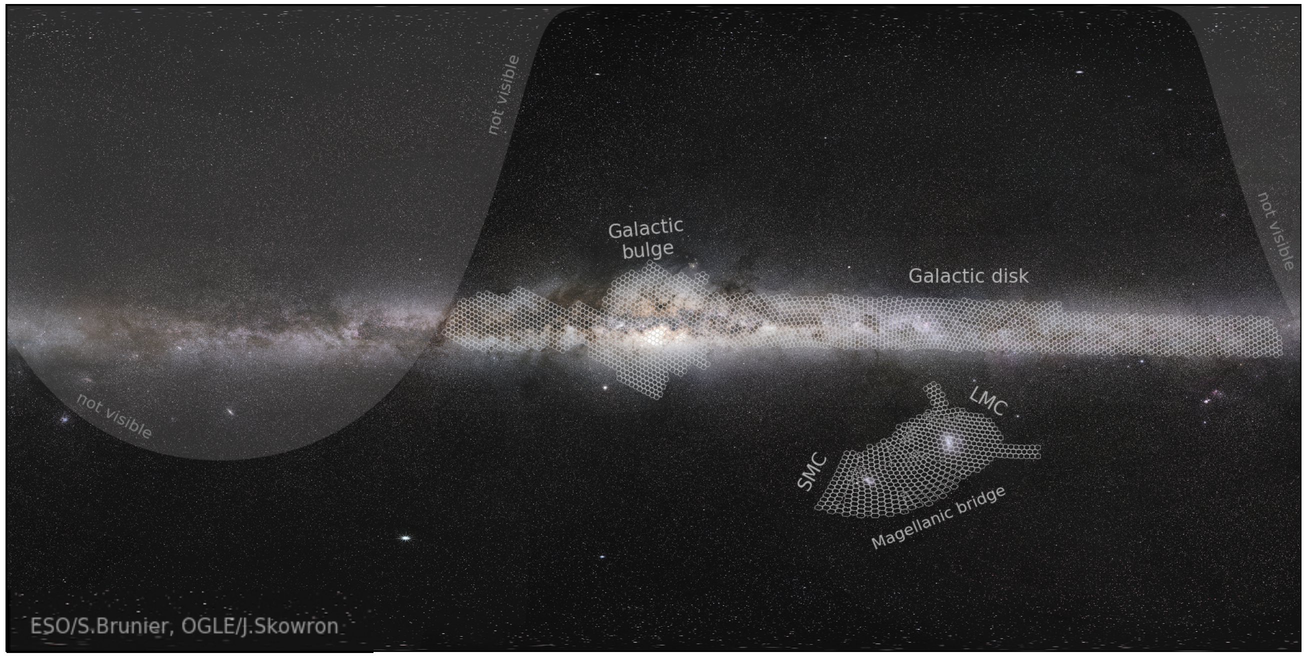
2 Data

- **OGLE-III (2002-2009):** 8 CCDs, 35’ x 35’ field of view. Wyrzykowski et al. (2015) detected 3560 microlensing events with PSPL fits

- **OGLE-IV (2010-):** 32 CCDs, 1.4 deg^2. Mróz et al. (2019) report 5790 events

OGLE-III website





- PopSyCLE (Lam et al. 2020): resolved microlensing (photometric/astrometric) simulations, including evolution and compact objects → t_E distribution

3 Event modeling: PSPL

- Observables in the light curve: t_0, u_0 and t_E (plus I_0 and f_s)
- Paczynski (1996) model for magnification:

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \text{ , where } u = \sqrt{u_0^2 + \frac{(t - t_0)^2}{t_E^2}}$$

- The mass and distance of the lens comes from the lens equation:

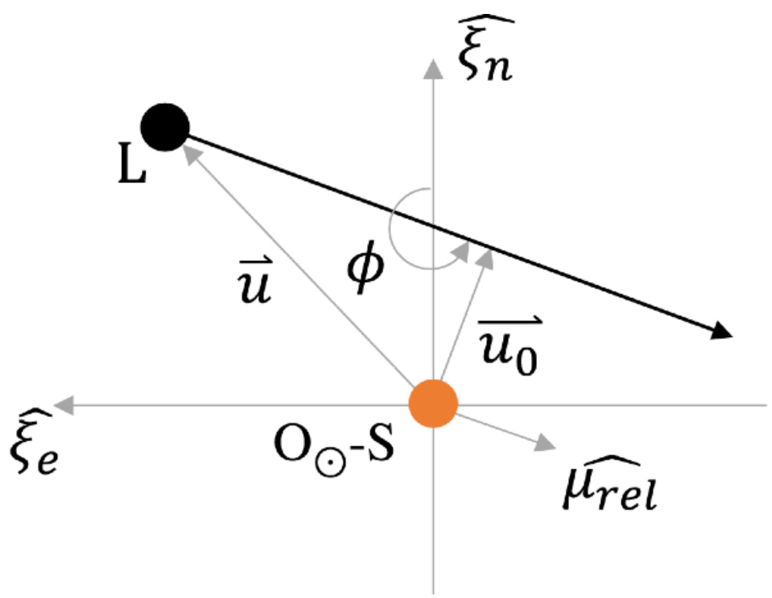
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_S - D_L}{D_L D_S}}$$

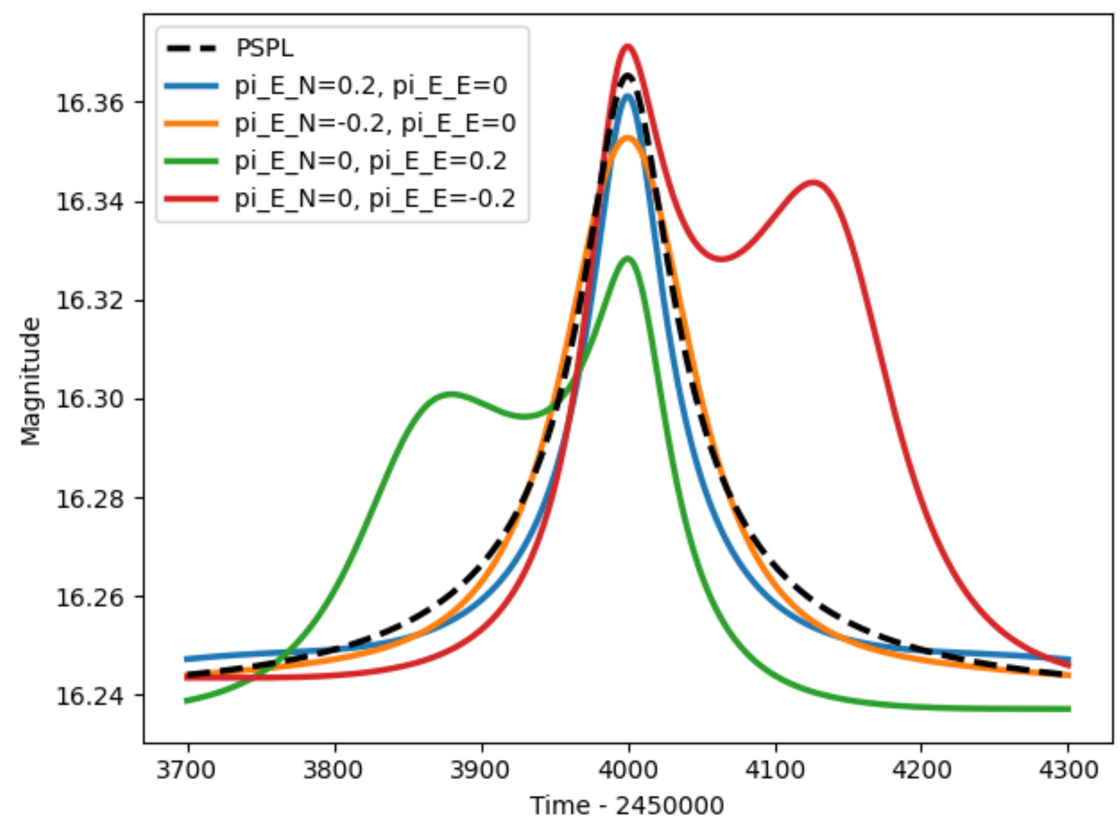
- Relatively simple to model, but parallax signal starts to be detectable around > 30-40 days depending on the magnification (u_0, t_E)

3 Event modeling: microlensing parallax

- The observer's perspective of the lens-source separation changes more quickly or slower than expected: variations in the amplifications of PSPL
- Two extra parameters: ($\pi_{E,N}$, $\pi_{E,E}$ components) or (π_E, ϕ angle)
- $\pi_{E,N}$ introduces symmetric distortion (harder to distinguish), $\pi_{E,E}$ introduces asymmetries around the peak

$$M = \frac{\theta_E}{\kappa \pi_E} \quad , \ \kappa = 8.144\,\mathrm{mas}/\mathrm{M}_\odot$$





3 Event modeling: gaussian processes

- In this case, it is used to handle the variable baseline and correlated noise, to get more accurate model estimates without losing the parallax signal
- Probability distribution over possible functions. In practice, a stationary kernel function k is added to the covariance matrix:

$$F(t) = \mathrm{physics}(t) + \mathrm{GP}(t) + \mathrm{white\ noise}$$

$$\Sigma_{ij} = \kappa(|t_i - t_j|) + K^2\sigma_i^2\delta_{ij}$$

(similarity measure between two points)

$$p(\mathbf{F}|\boldsymbol{\theta}) = \frac{1}{(2\pi)^{N/2}|\boldsymbol{\Sigma}|^{1/2}} \exp\left[-\frac{1}{2}(\mathbf{F}-\boldsymbol{\mu})^{\intercal}\boldsymbol{\Sigma}^{-1}(\mathbf{F}-\boldsymbol{\mu})\right]$$

$$\boldsymbol{\Sigma} = \begin{pmatrix} k(t_1,t_1) & \dots & k(t_1,t_N) \\ k(t_2,t_1) & \dots & k(t_2,t_N) \\ \vdots & \ddots & \vdots \\ k(t_N,t_1) & \dots & k(t_N,t_N) \end{pmatrix} + \begin{pmatrix} \sigma_1^2 & 0 & \dots & 0 \\ 0 & \sigma_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_N^2 \end{pmatrix}$$

(Summary: Rasmussen & Williams 2005)
(Other: Wyrzykowski et al. 2006, Lee et al. 2019)

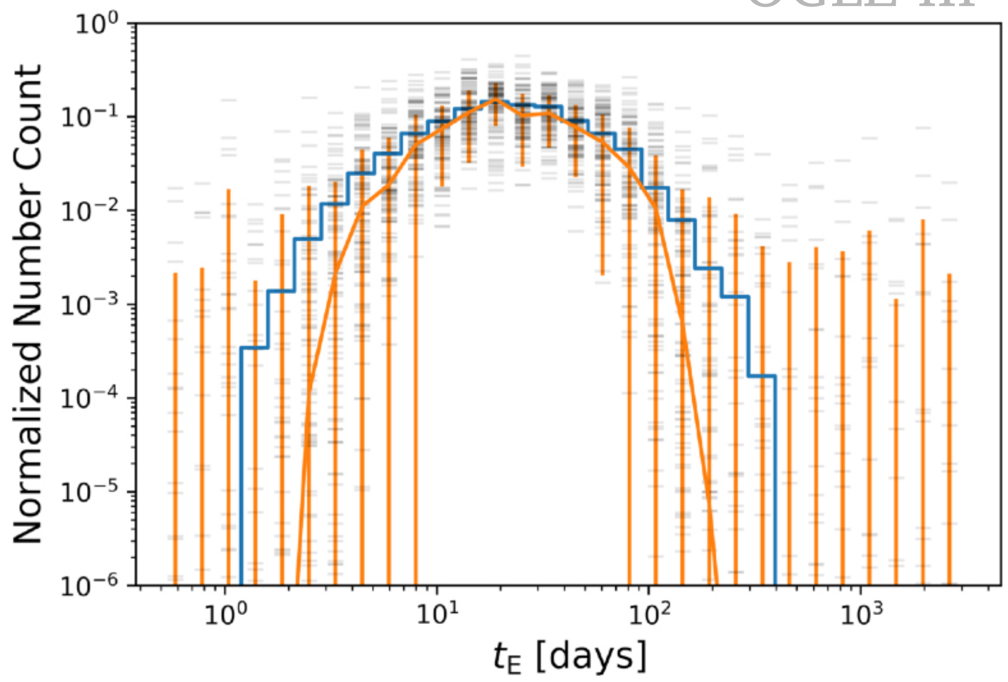
- Kernels: damped simple harmonic oscillator (S_0, ω_0), Matérn-3/2 (σ, ρ)

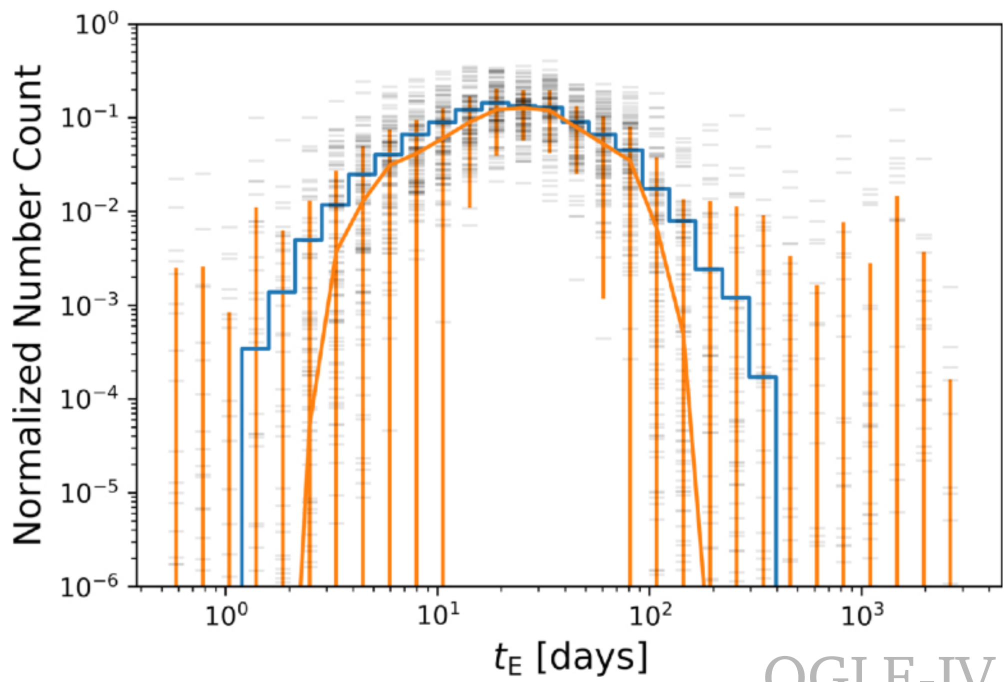
3 Event modeling: assumed priors

Table 1
Summary of Prior Probability Density Functions for Modeled Parameters

Parameter (1)	Distribution (2)	Inputs (3)
$F_{\rm base}$	$\mathcal{N}$	$\mu = {\rm med}(\boldsymbol{F})$, $\sigma = \sigma_{\boldsymbol{F}}$
$b_{\rm sff}$	$\mathcal{U}$	lower $= 0$, upper $= 1 + \epsilon_{\rm NB}$
t_0	$\mathcal{N}$	$\mu = t_{0,{\rm OGLE}}$, $\sigma = 100$ days
$\log_{10} t_{\rm E}$	$\mathcal{N}$	$\mu = 1.13435$, $\sigma = 0.67502$[a], truncated between $0.5 < t_{\rm E} < 3000$ days
$\log_{10} u_0$	$\mathcal{N}$	$\mu = -1$, $\sigma = 2$, truncated between $10^{-5} < u_0 < 3$
$\log_{10} \pi_{\rm E}$	$\mathcal{N}$	$\mu = -0.884205$, $\sigma = 0.072755$,[a] truncated between $10^{-5} < \pi_{\rm E} < 3$
ϕ	$\mathcal{U}$	lower $= 0$, upper $= 2\pi$
$\log(S_0\ \omega_0^4)$	$\mathcal{N}$	$\mu = \sigma_{\boldsymbol{F}}^2$, $\sigma = 5$
$\log \omega_0$	$\mathcal{N}$	$\mu = 0$, $\sigma = 5$
$\log \sigma$	$\mathcal{N}$	$\mu = 0$, $\sigma = 5$
ρ	Γ^{-1}	see Section 3.3.8 for details
$\log(K^2)$	$\mathcal{N}$	$\mu = 0.0953$, $\sigma = 1$

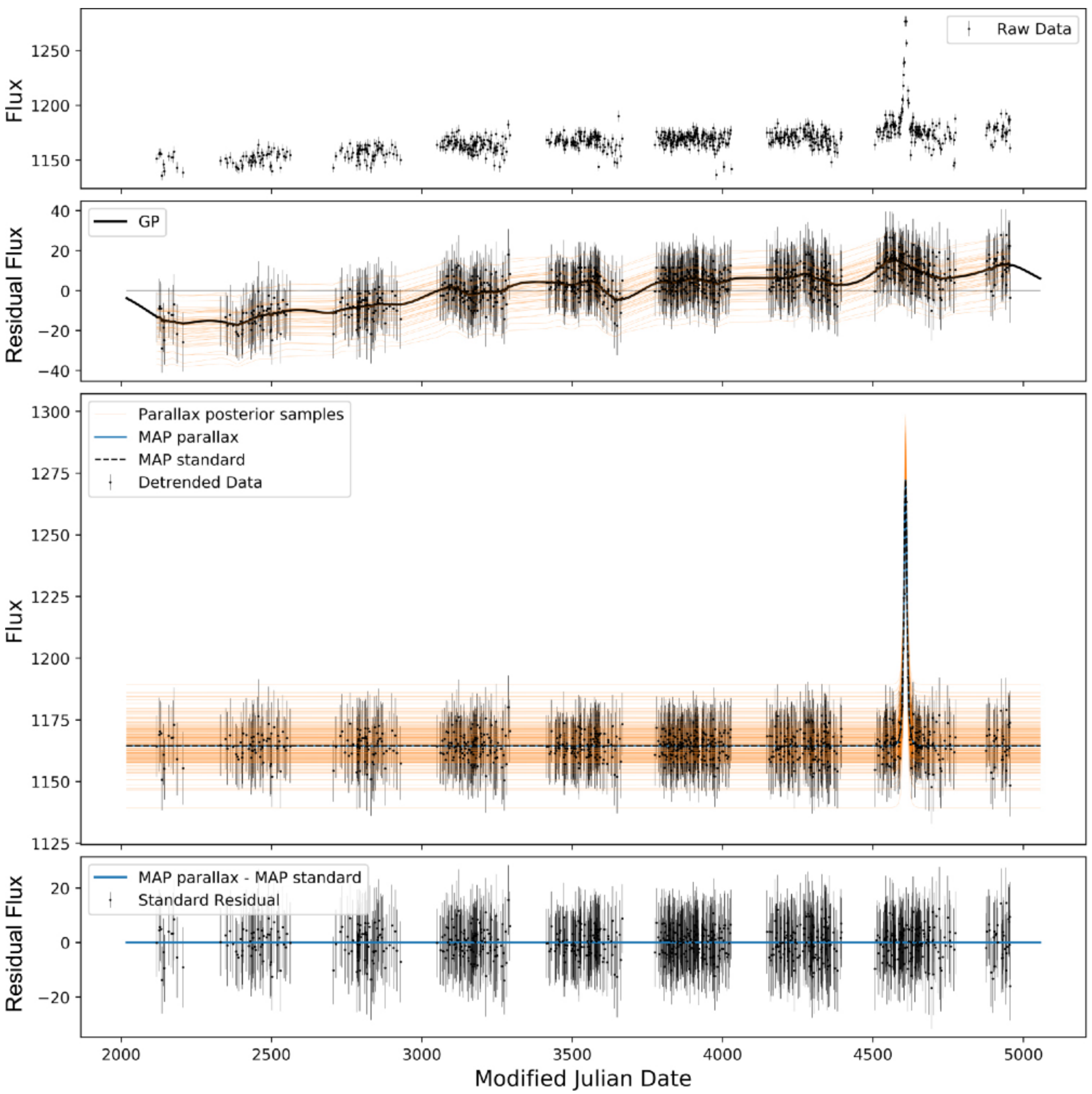
OGLE-III



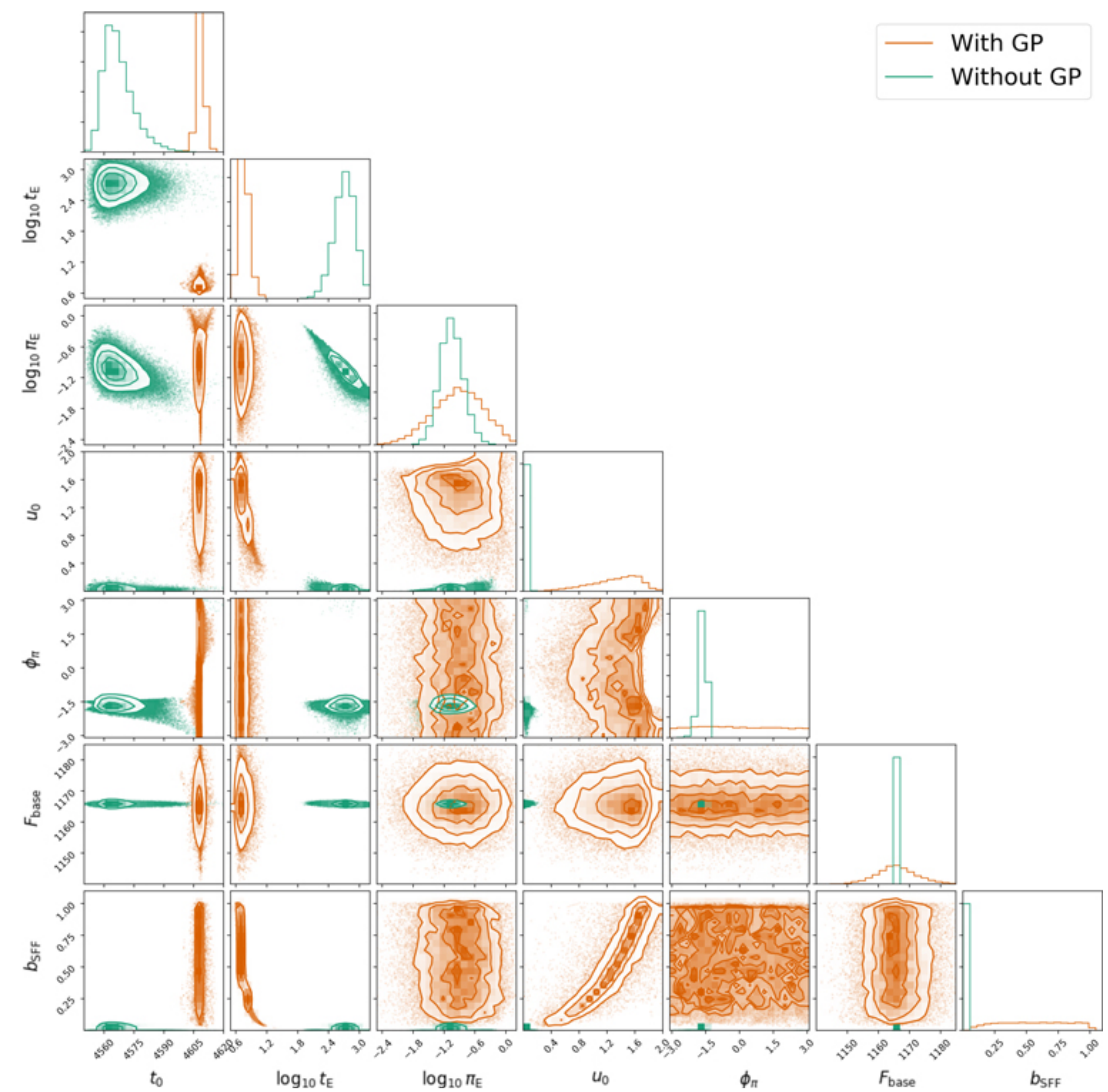


OGLE-IV

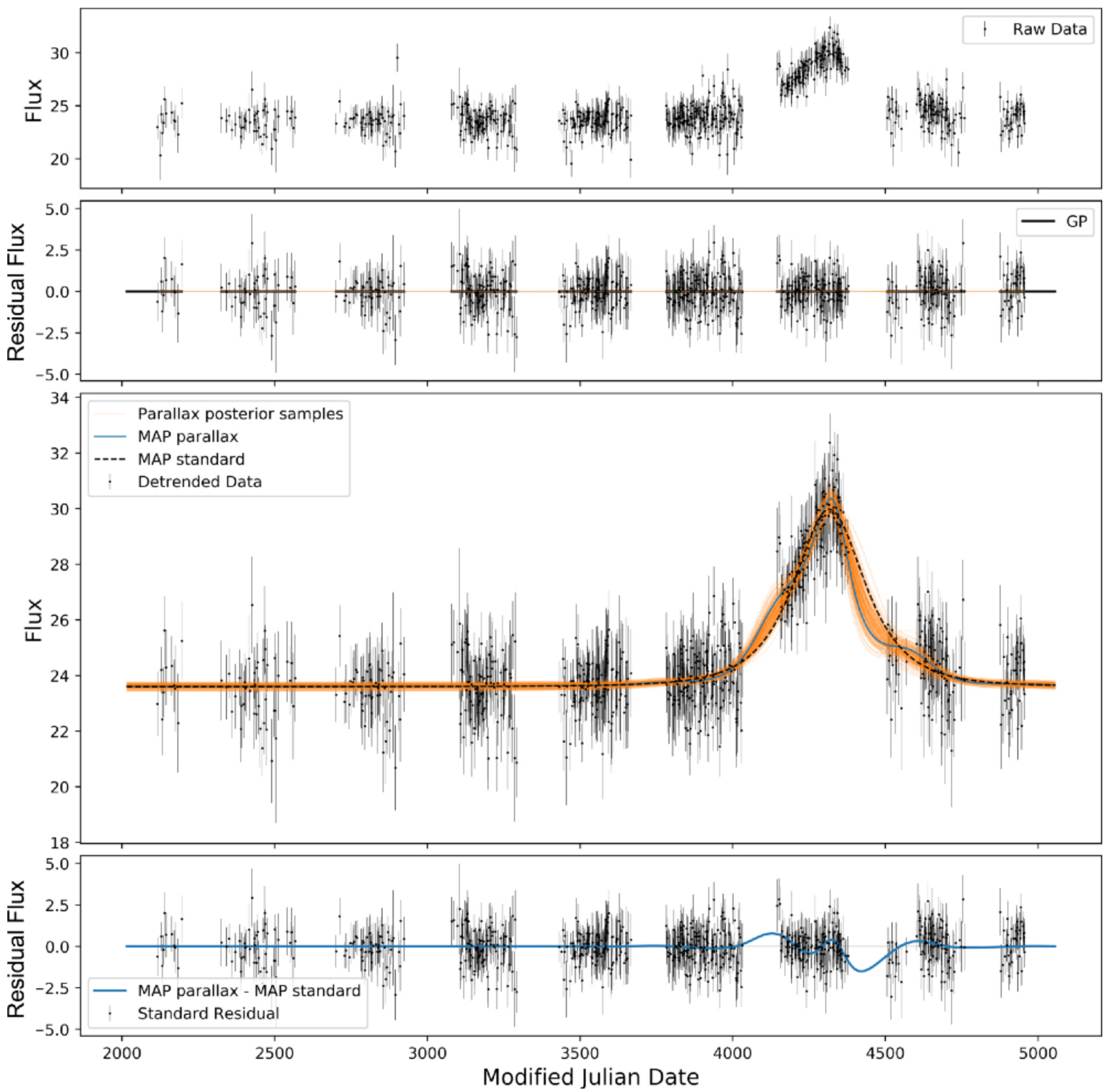
5 Results: OGLE BLG 156.7.141434

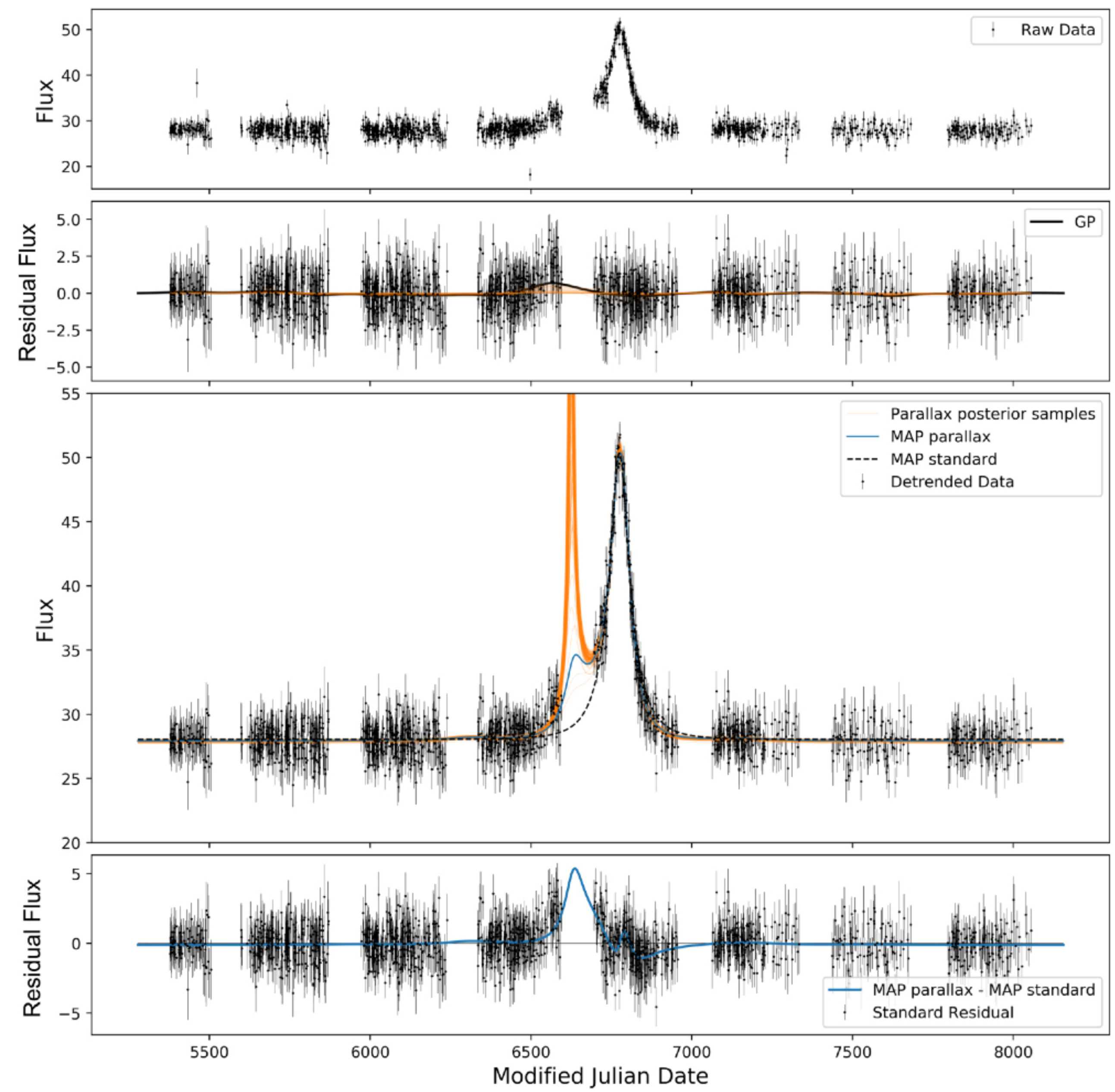


- Large baseline variation
- Small parallax signal



5 Results: BLG 122.6.83113 and 514.15.53029

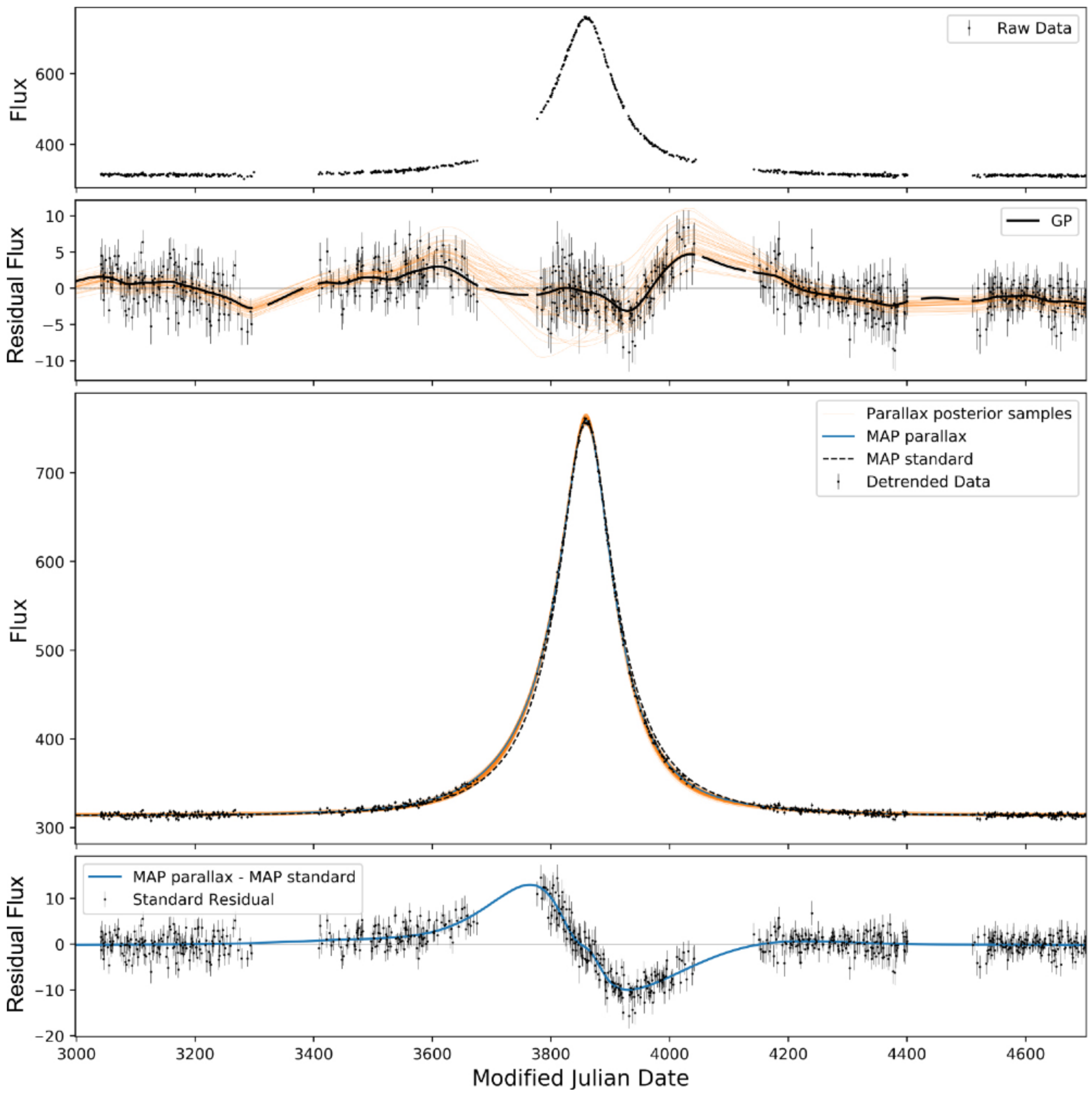


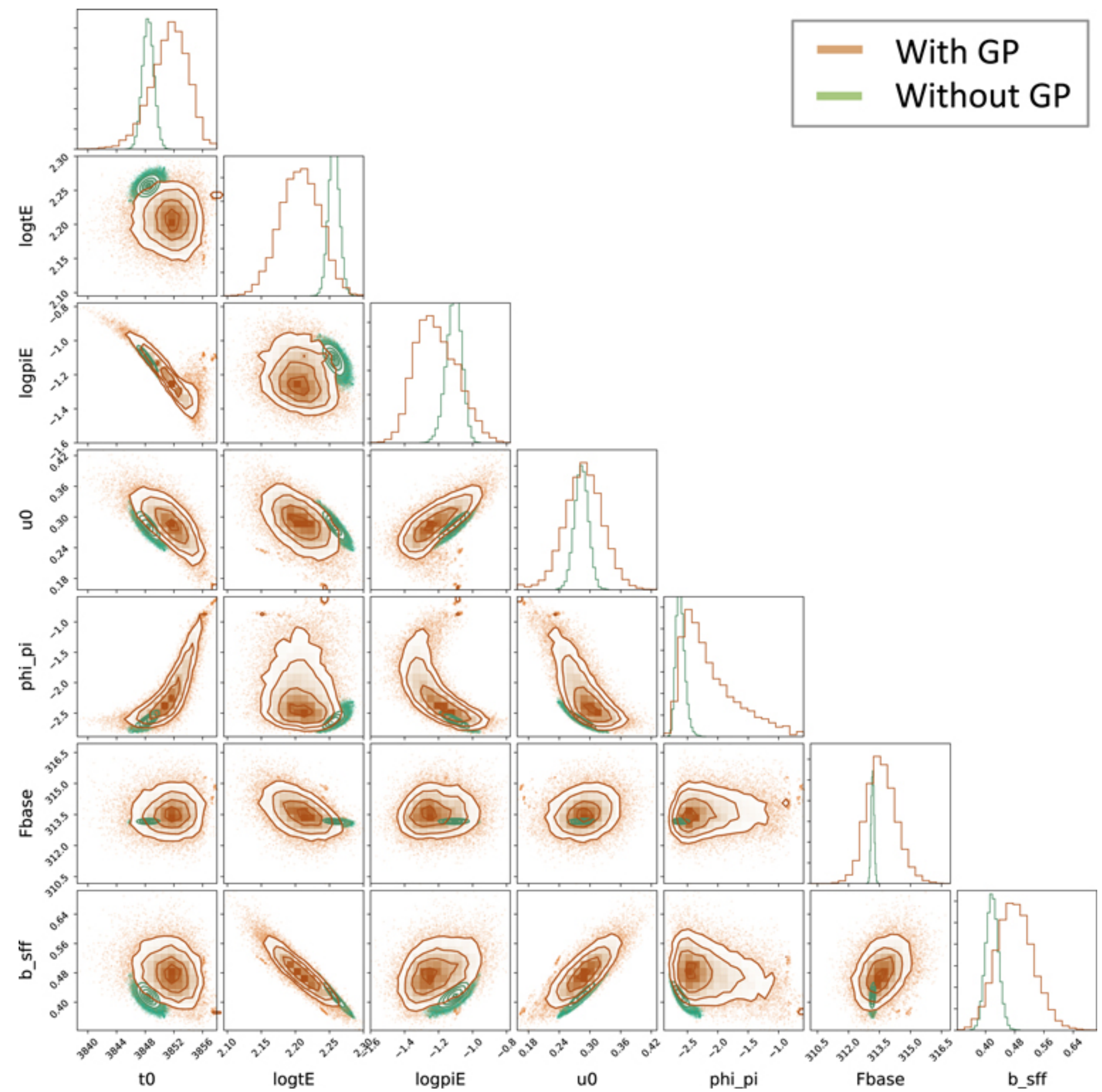


- No baseline variation
- Parallax signal in the gaps (likel. ratio=4.8)

- Small baseline variation
- Samples different than best parallax

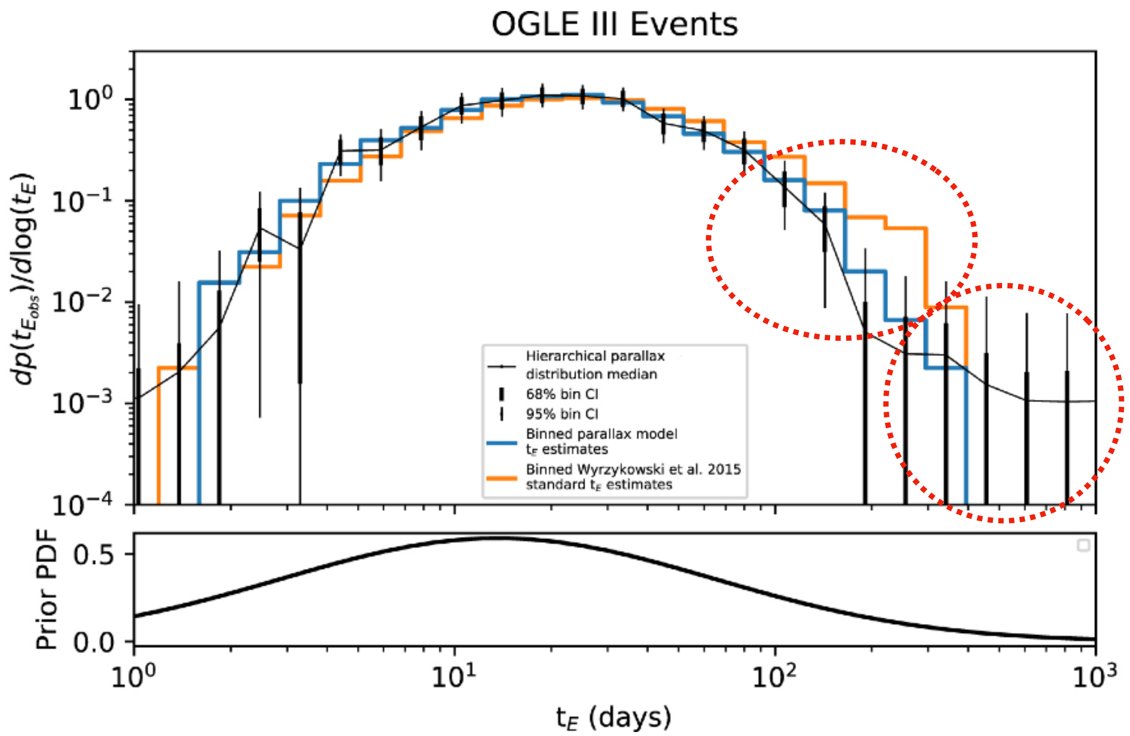
5 Results: OGLE BLG 102.7.44461

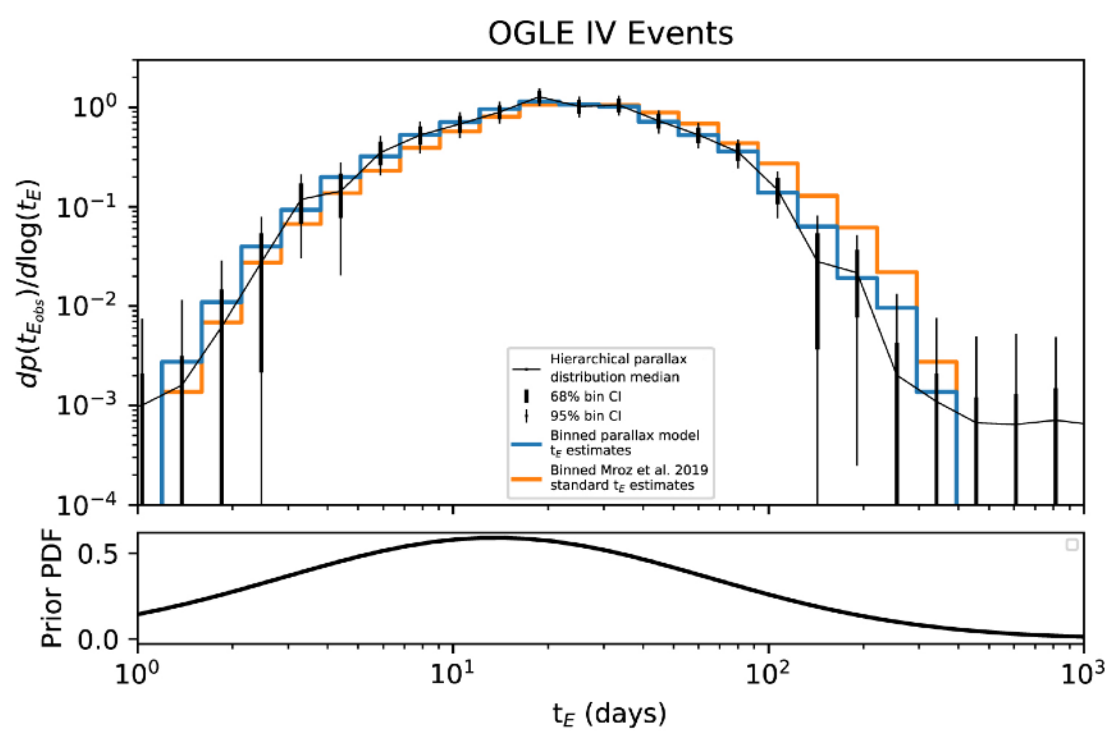




- Large baseline variation, strong parallax signal (likel. ratio=30), extended posteriors

5 Results: population modeling





- Instead of getting the maximum likelihood or the median values for the t_E distribution, the authors use all the t_E chains to forward model the distribution
- N events, M_n flux measurements ($1 \leq j \leq M_n$). The likelihood for a set of parameters alpha that describe the t_E distribution:

$$\mathcal{L}_{\boldsymbol{\alpha}} \equiv p(\{F_n\}_{n=1}^{N}|\boldsymbol{\alpha}) = \prod_{n=1}^{N} \int d\boldsymbol{\theta}_n \, p(F_n|\boldsymbol{\theta}_n) p(\boldsymbol{\theta}_n|\boldsymbol{\alpha})$$

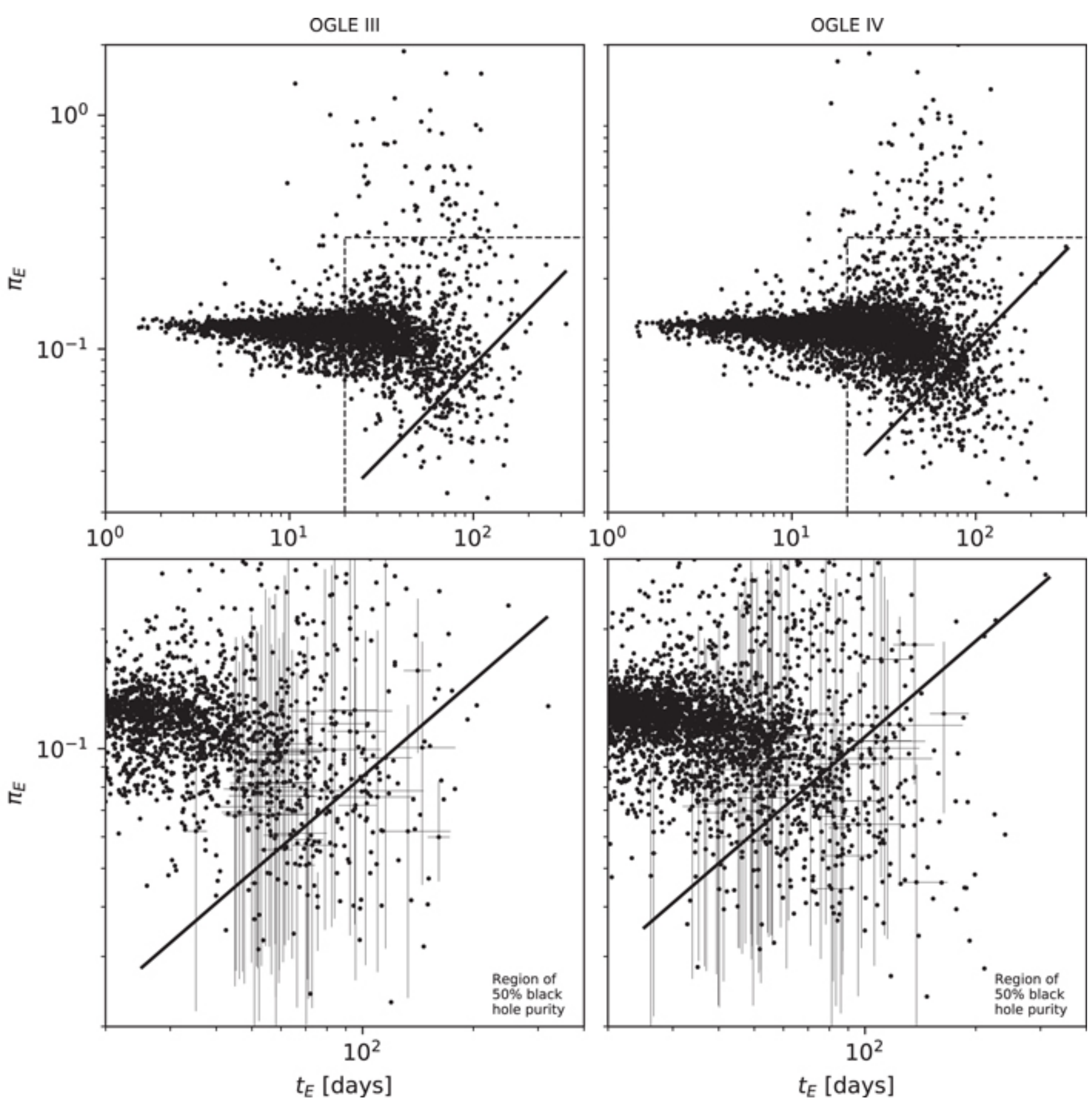
$$p(\boldsymbol{\theta}_n|\boldsymbol{\alpha}) = \frac{f_{\boldsymbol{\alpha}}(t_{\mathrm{E}}) p(\boldsymbol{\theta}_n)}{p(t_{\mathrm{E}})}.$$

$$f_{\boldsymbol{\alpha}}(\log_{10}(t_{\mathrm{E}})) \equiv \sum_{m=1}^{M} \alpha_m \, s\left(t_{\mathrm{E}};\, \frac{m-1}{M},\, \frac{m}{M}\right),$$

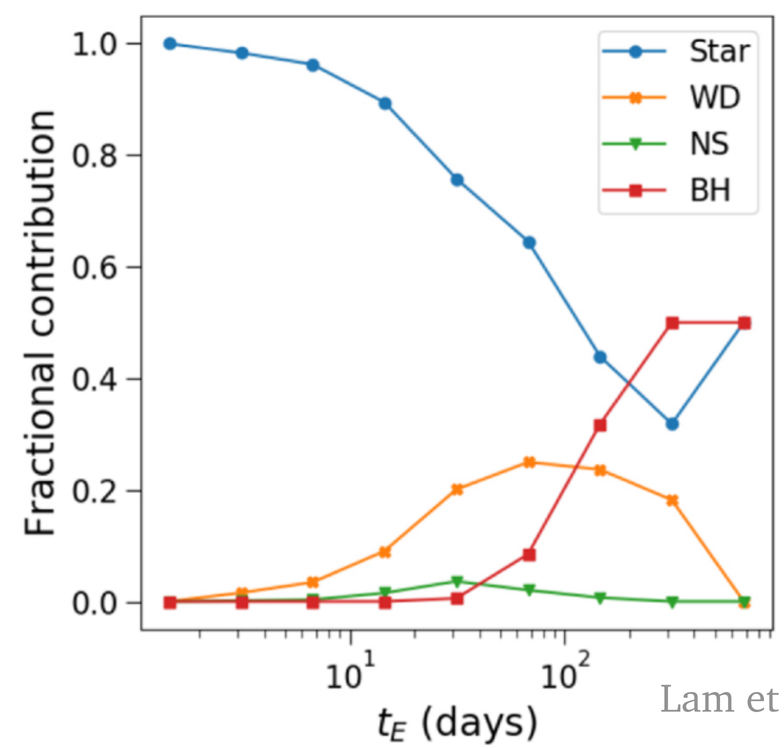
$$s(x;\, L, H) \equiv \begin{cases} 0, & \text{for } x < L \\ (H-L)^{-1}, & \text{for } L \leqslant x \leqslant H, \\ 0, & \text{for } H < x \end{cases}$$

(Normalized histogram with M equal width bins in $\log10(t_E)$)

5 Results: black hole candidates

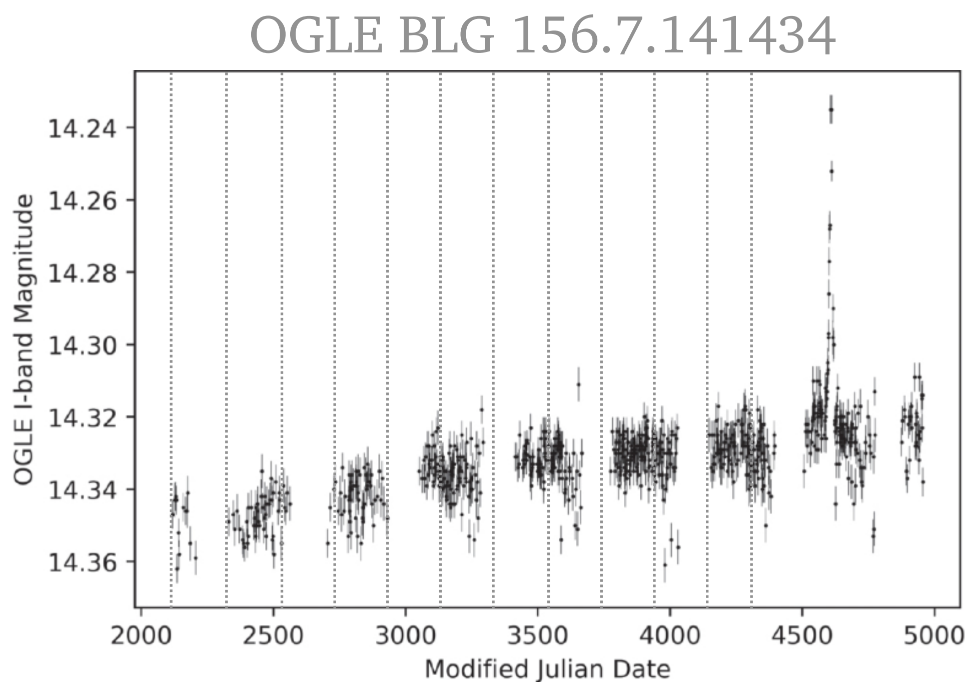


- Large error bars, but 107 candidates in OGLE-III and 283 in OGLE-IV
- Lam et al. (2020, PopSyCLE): region of largest occurrence of black holes and other stellar remnants… Above $t_E > 100$ d, the fractional contribution of stars and black holes are almost 50-50.



Lam et al. (2020)

- Bonus: tests to deal with the variable baseline



- *Test 1:* use increasingly smaller time intervals (also common in 2L1S methods). While the original data returns $t_E \sim 2000$ days, the ones with smallest time intervals result in t_E = 70-200 days
- *Test 2:* correct the variable baseline with a linear regression, resulted $t_E = 6\,$d