Exploring the free-floating planet population with the OGLE data

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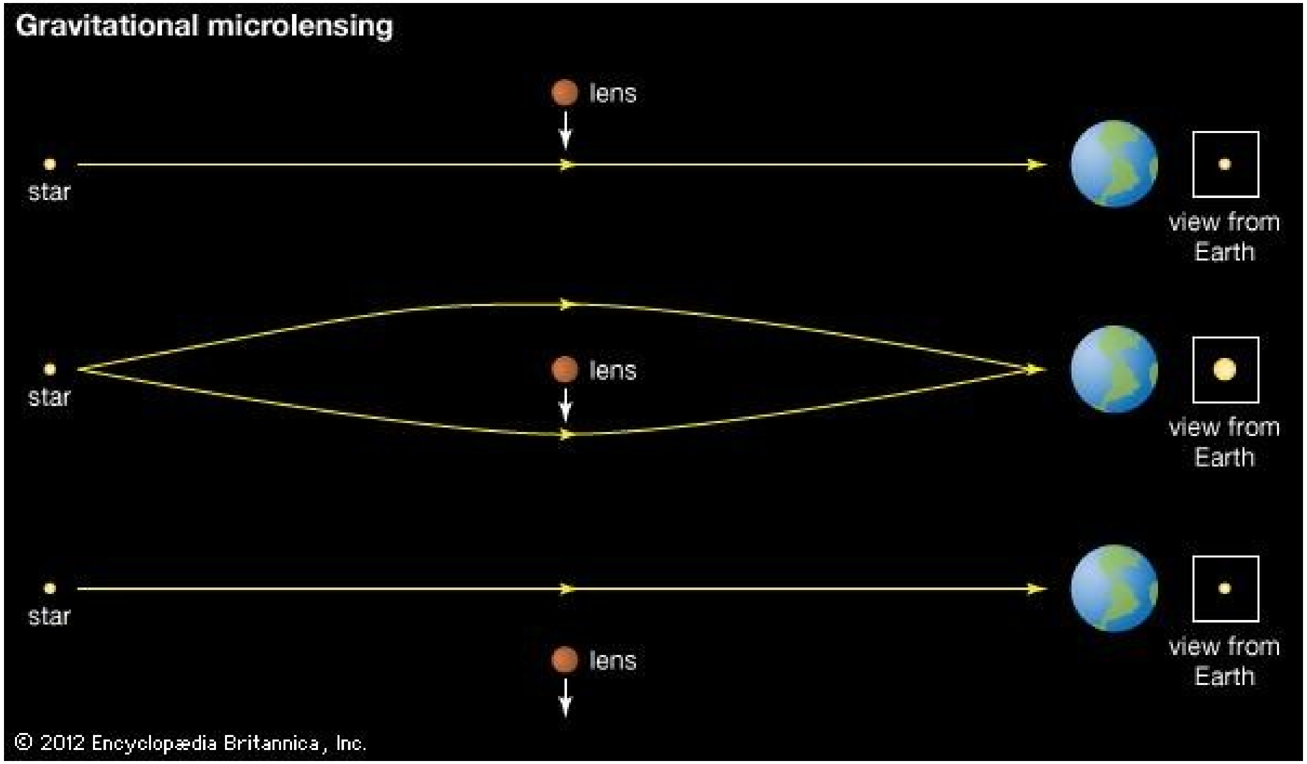
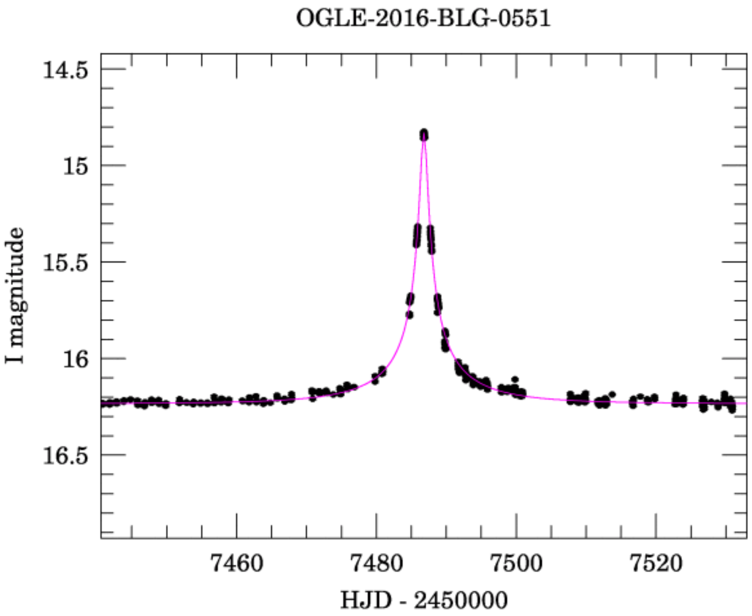
Gravitational microlensing



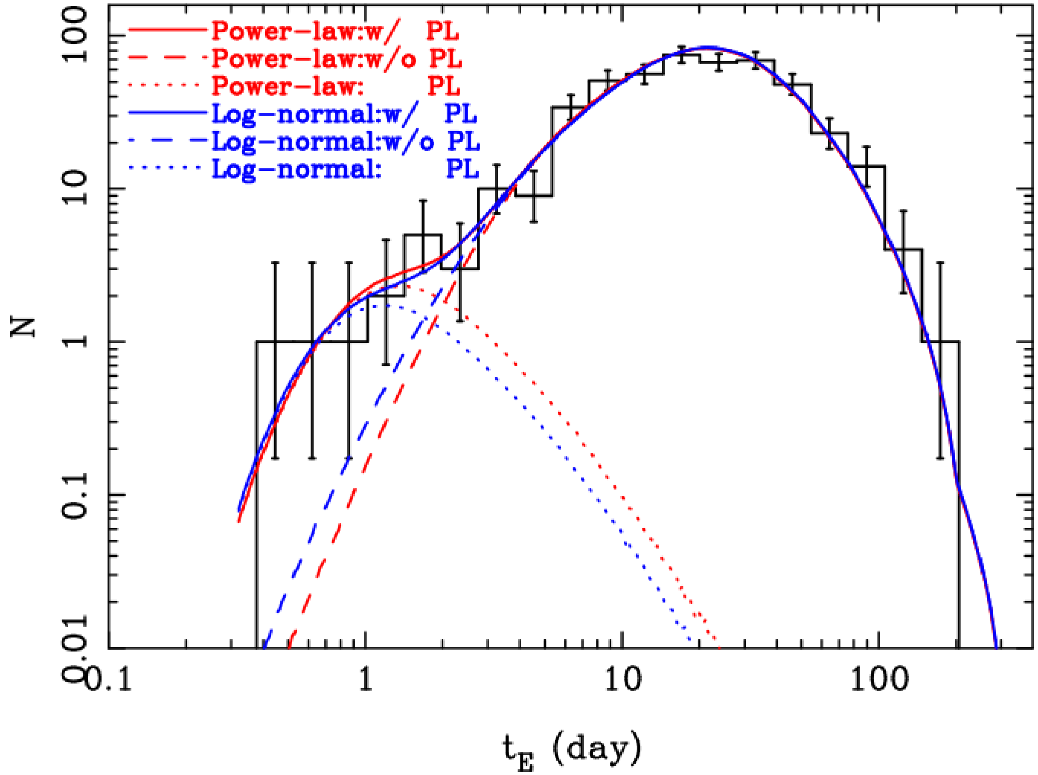


$$t_E = \frac{\theta_E}{\mu_{rel}} = \frac{\sqrt{\kappa M \pi_{rel}}}{\mu_{rel}} = 1.6\ \mathrm{d} \left(\frac{M}{M_{Jup}}\right)^{1/2} \left(\frac{\pi_{rel}}{0.12\ \mathrm{mas}}\right)^{1/2} \left(\frac{\mu_{rel}}{7\ \mathrm{mas/yr}}\right)^{-1}$$

The event timescale distribution carries information about the mass fuction of lenses.

Free-floating planets (FFPs)

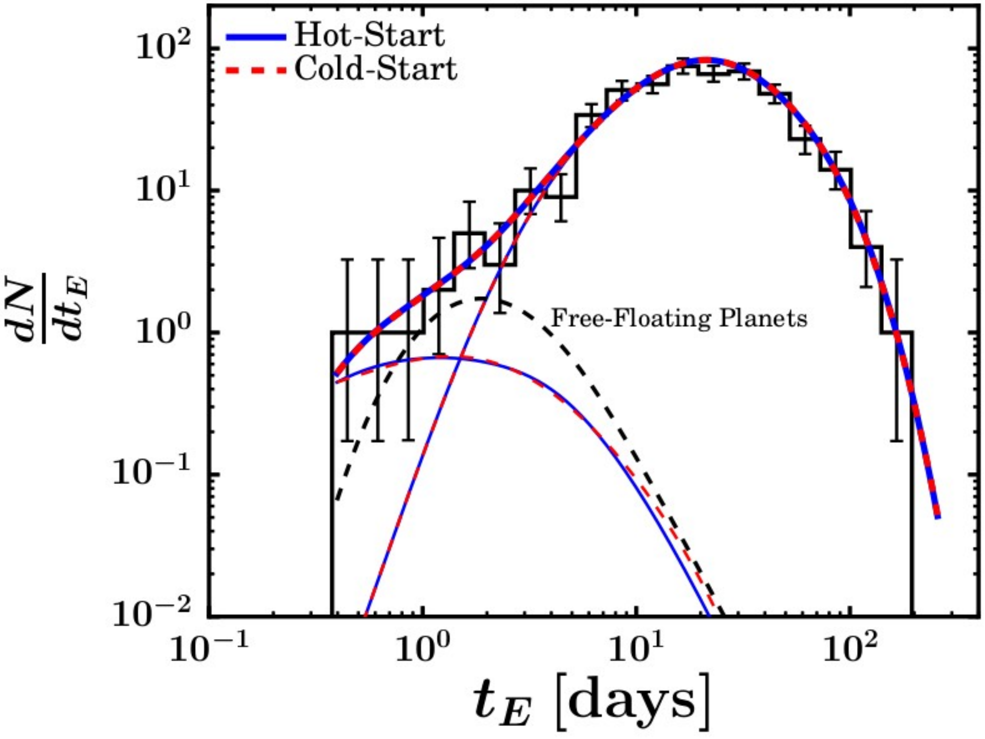
- 474 well-characterized events from 2006-2007
- excess of short events (t_E < 2 d)
- Jupiter-mass free-floating planets: almost twice as common as main-sequence stars



(Sumi et al. 2011, Nature 473, 349)

Free-floating planets

- only <42% of short timescale events can be explained by wide-orbit (but bound) planets



(Clanton & Gaudi 2017)

Surveys of young clusters

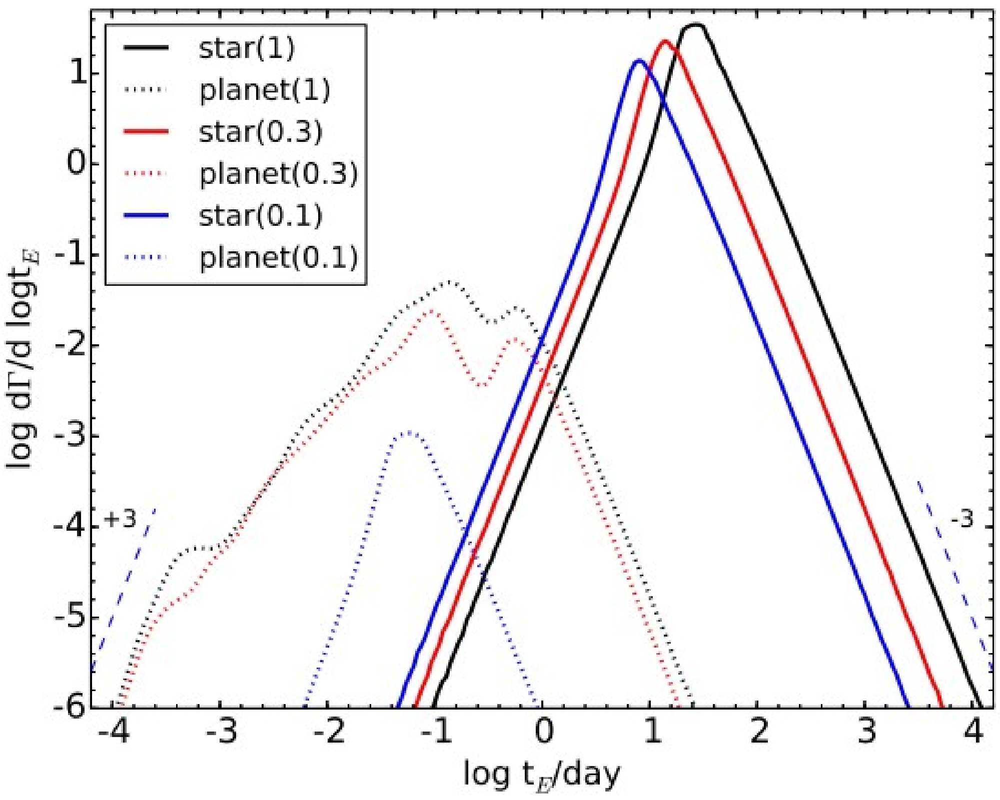
- stars are 20-50 times more frequent than FFPs in young stellar clusters and star-forming regions

  (e.g. Scholz et al. 2012, Pena Ramirez et al. 2012)

- inclomplete below < 5-6 M_{Jup}

FFPs from the core accretion theory

- It is much easier to eject an Earth-mass planet than a Jupiter-mass planet
- Event rate due to FFPs ~13x smaller than in Sumi+ (2011)
- Median timescale ~16x smaller (~0.1 day) than in Sumi+ (2011)



Ma et al. 2016, MNRAS 461, 107

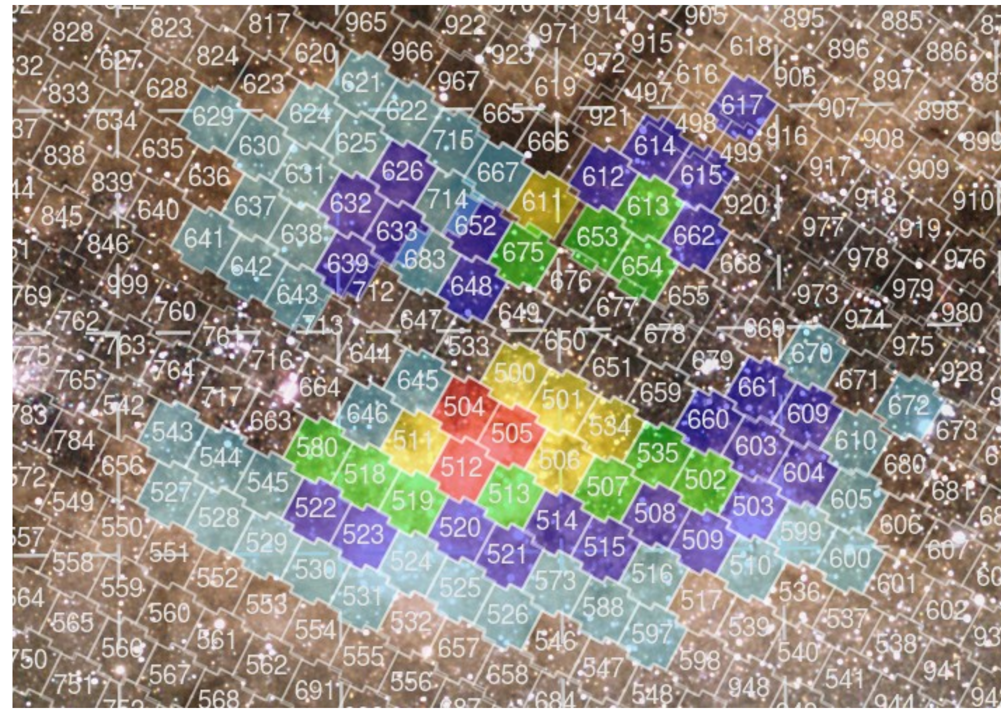
How to eject a planet?

- dynamical interactions between planets
- ejections from multiple-star systems
- stellar flybys
- dynamical interactions in clusters
- post-main-sequence evolution of the host star(s)
- ...

Veras et al. 2009, 2011, 2016, Kaib et al. 2013, Sutherland & Fabrycky 2016, Boley et al. 2012, Veras & Moeckel 2012, Liu et al. 2013, and many more...

OGLE dataset

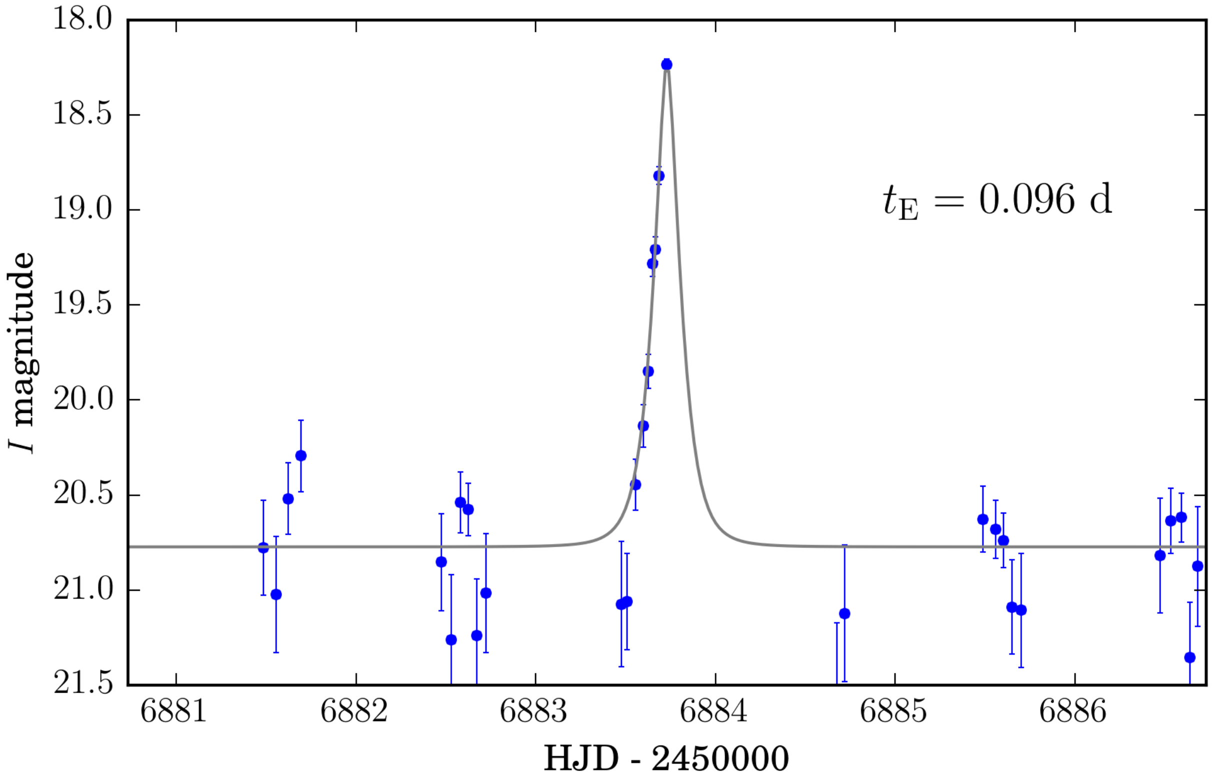
- 9 field with a cadence of either **20 min** or **60 min**
- 5.5-year-long light curves
- 50 million stars
- 4500-12,000 data points per light curve
- accuracy of the photometry: 3% @ 18 mag, 10% @ 19.5 mag
- ~4800 microlensing events
- 2617 high-quality microlensing events



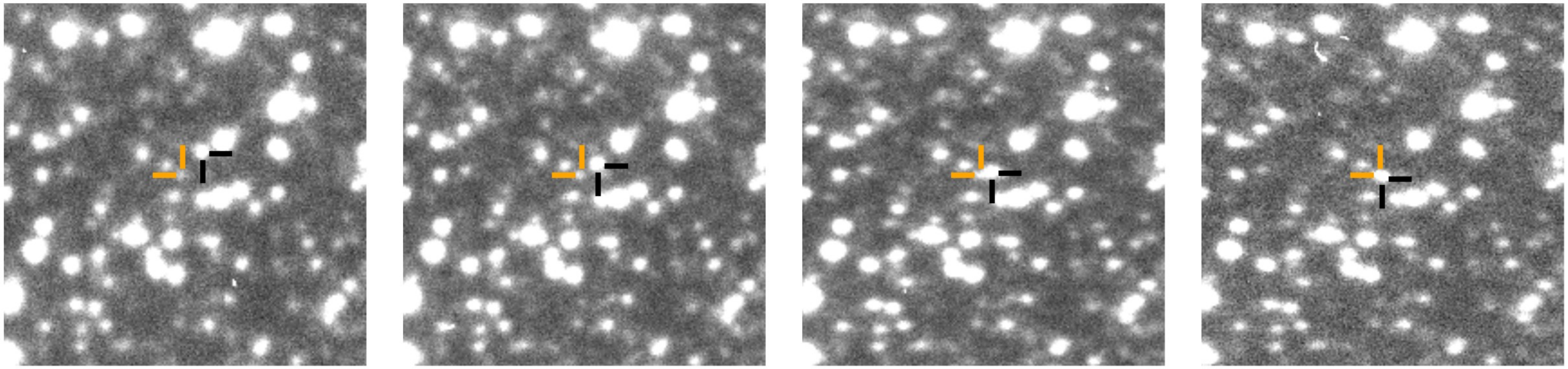
Selection cuts

- at least 3 consecutive points 3σ above the baseline
- no variability outside a 360-day window
- at least 3 detections on subtracted images
- amplitude > 0.1 mag
- χ^2 / dof < 2 for $|t-t_0|<t_E$, $|t-t_0|<2t_E$, $|t-t_0|<5$ d
- $u_0<1$, I_s < 22 mag, F_b > -0.25 (some negative blending)

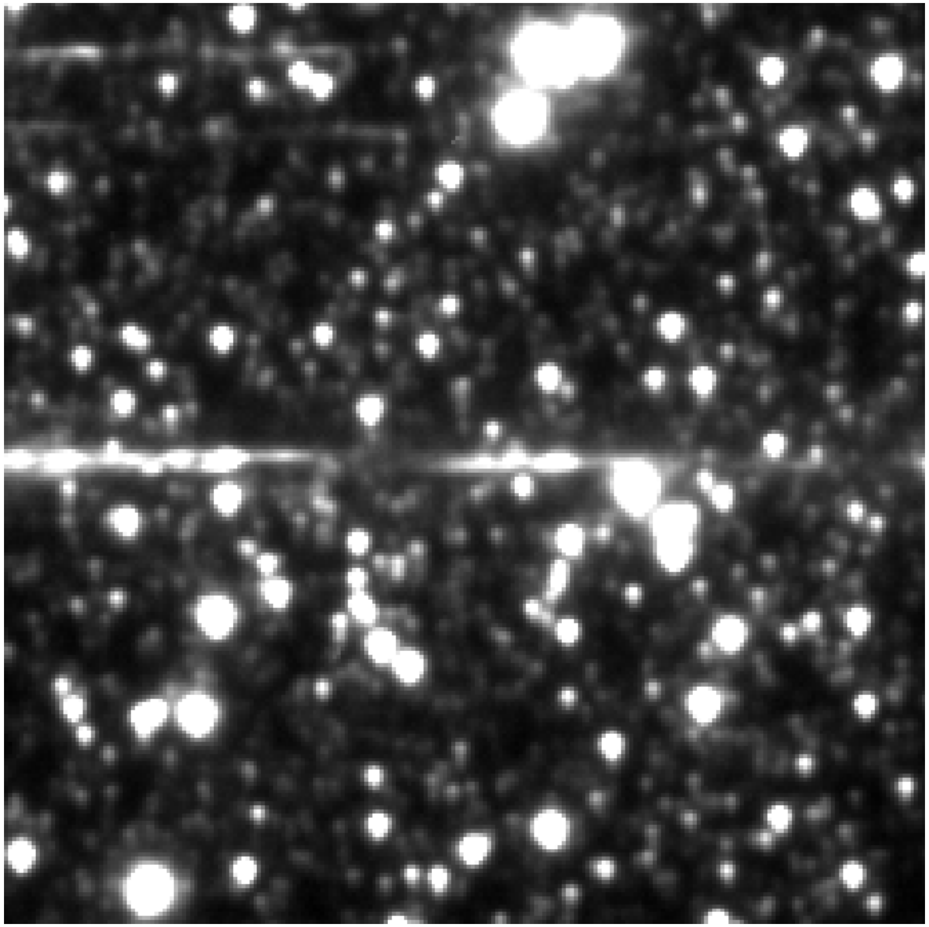
Contaminants: asteroids

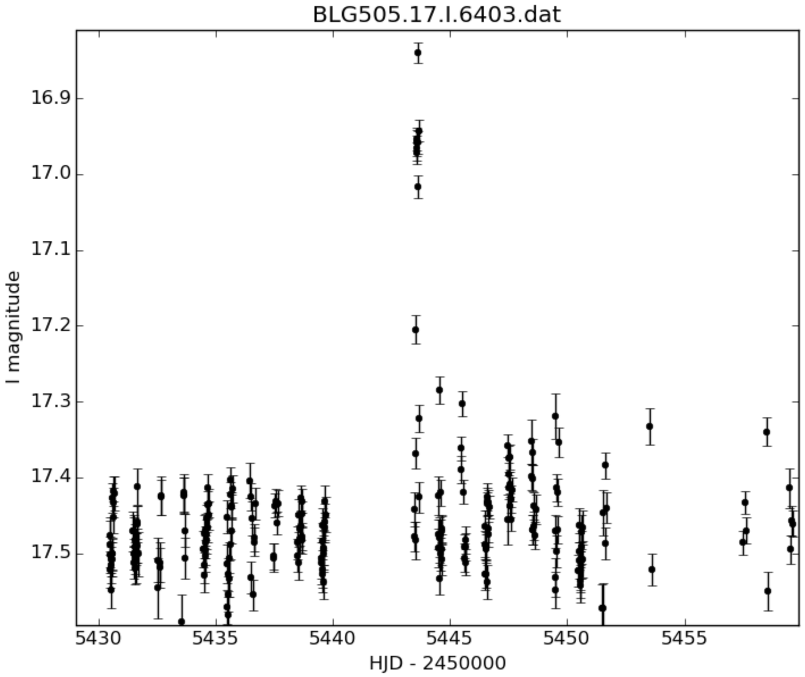


(7294) 1992LM

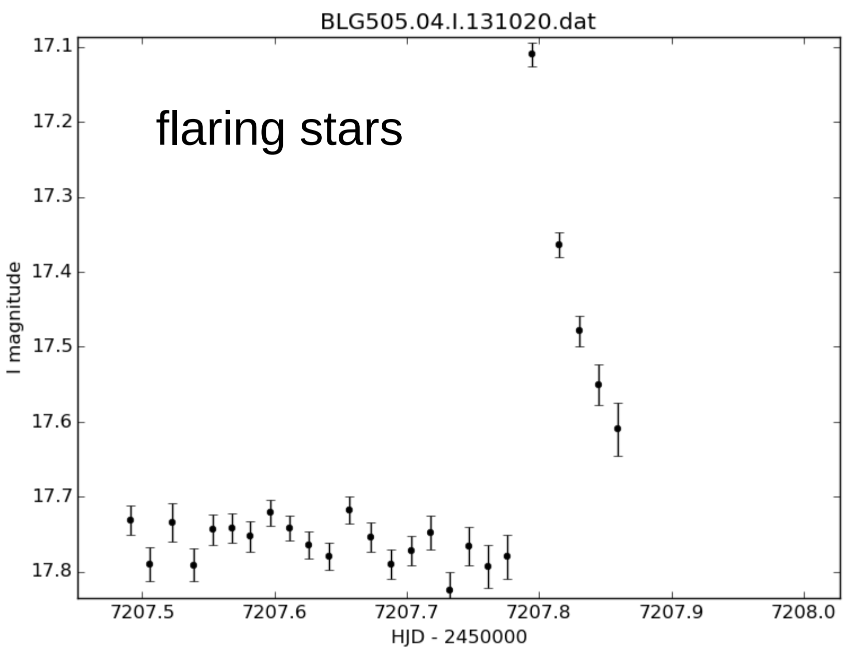


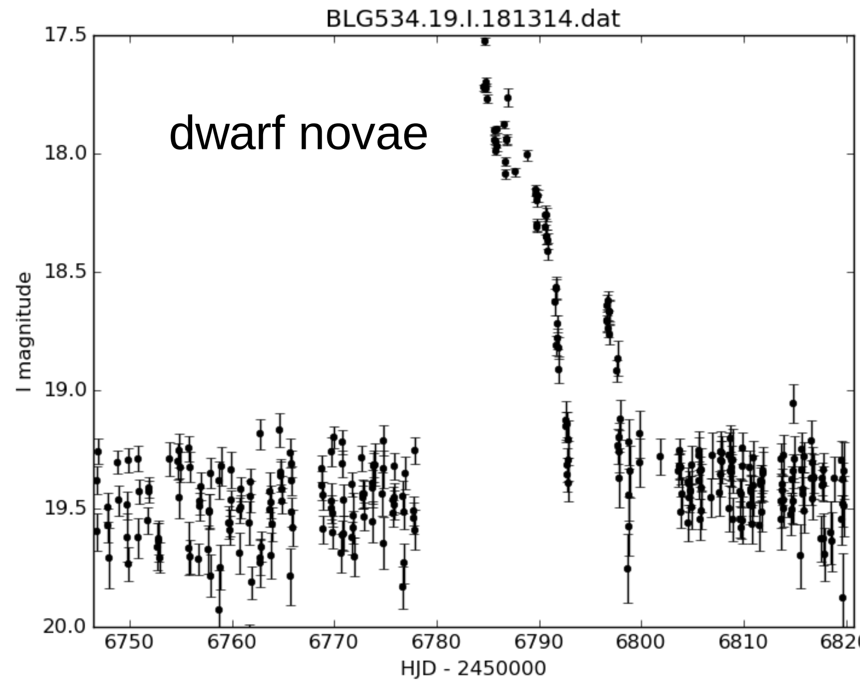
Contaminants: artifacts

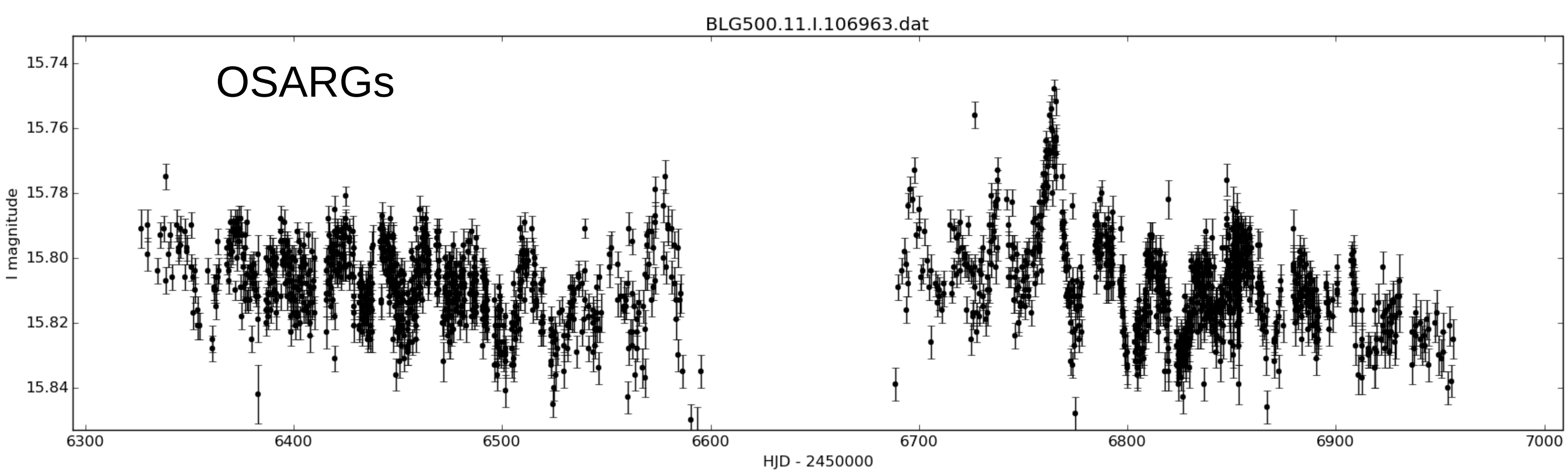




Contaminants: variable stars

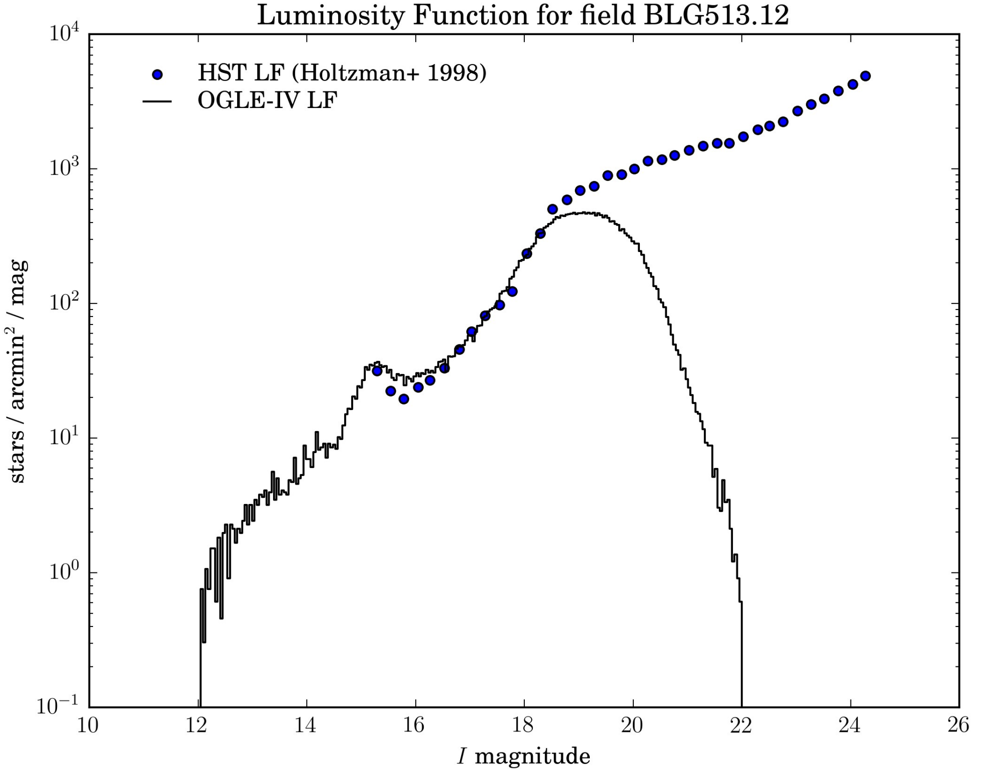




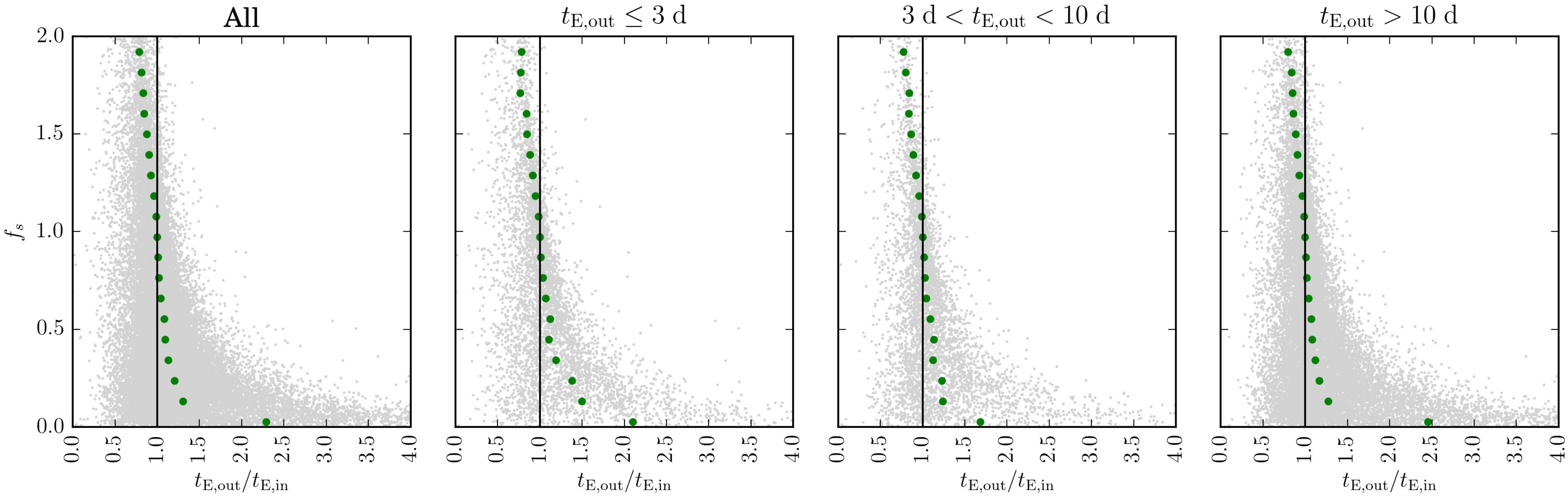


Simulations

- Image-level simulations (all frames processed with the standard OGLE pipeline: Udalski+ 2015)
- sources from the OGLE + HST luminosity function



Can we measure real t_E?



$f_s = F_s / (F_s + F_b) = F_s / F_{baseline}$

F_s – source flux

$F_{baseline}$ – source + blend

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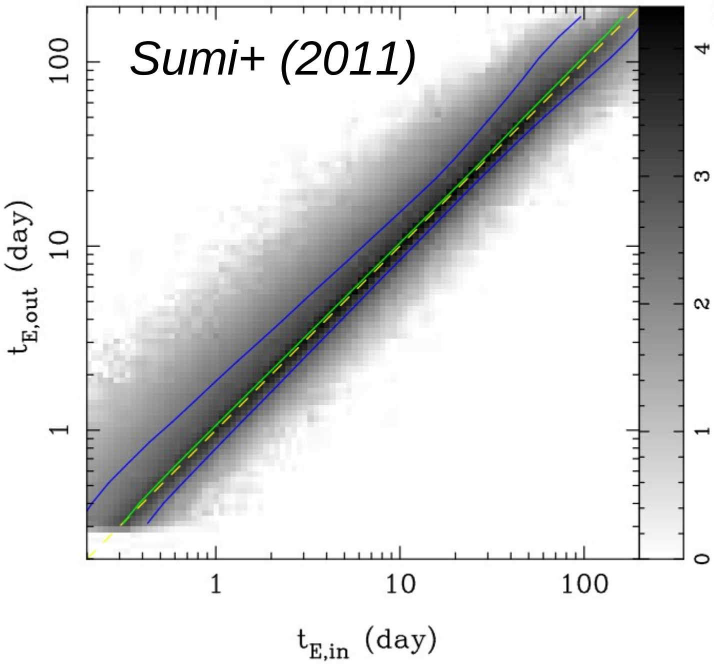
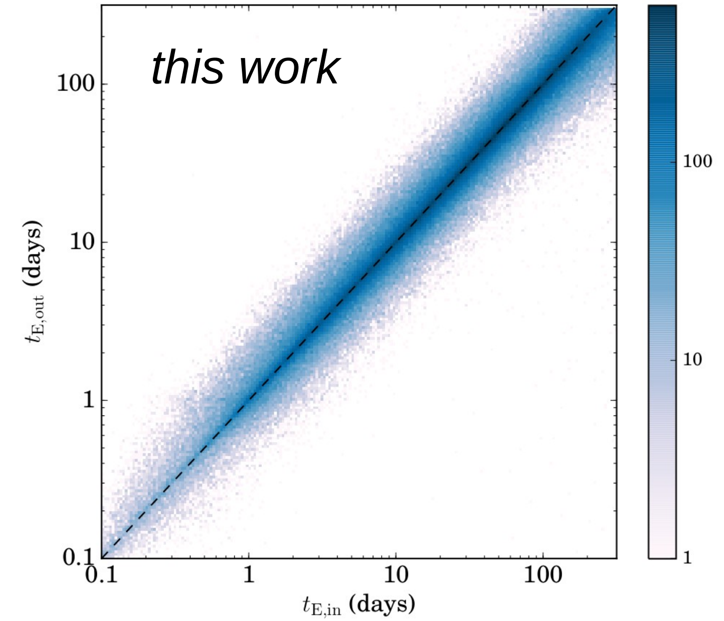
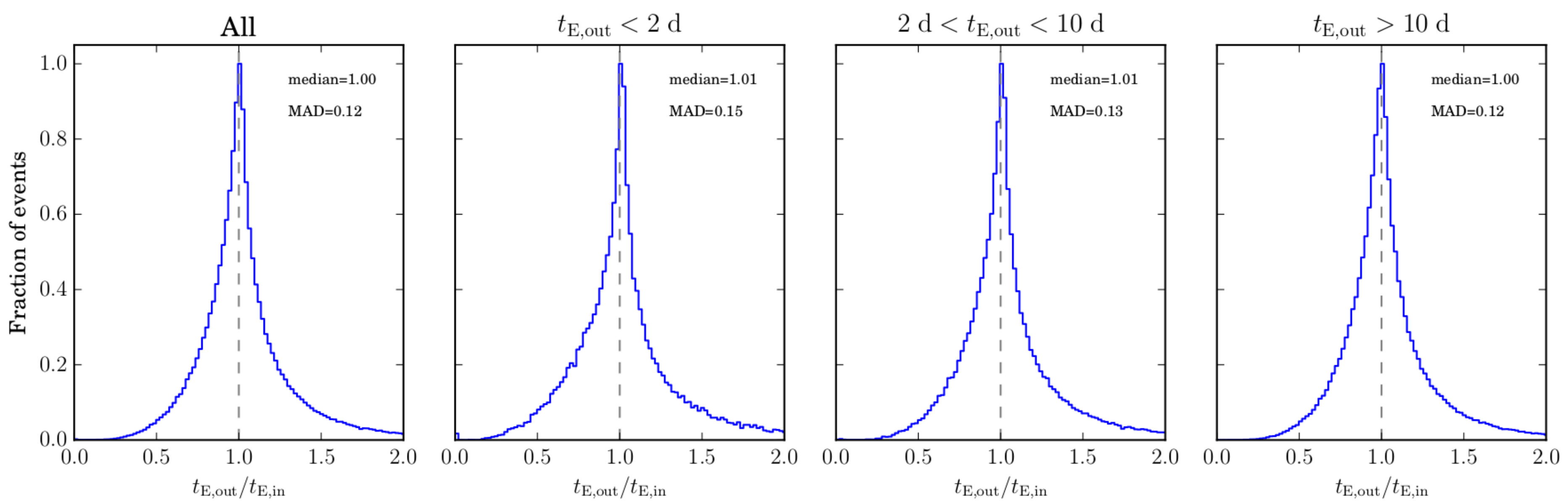
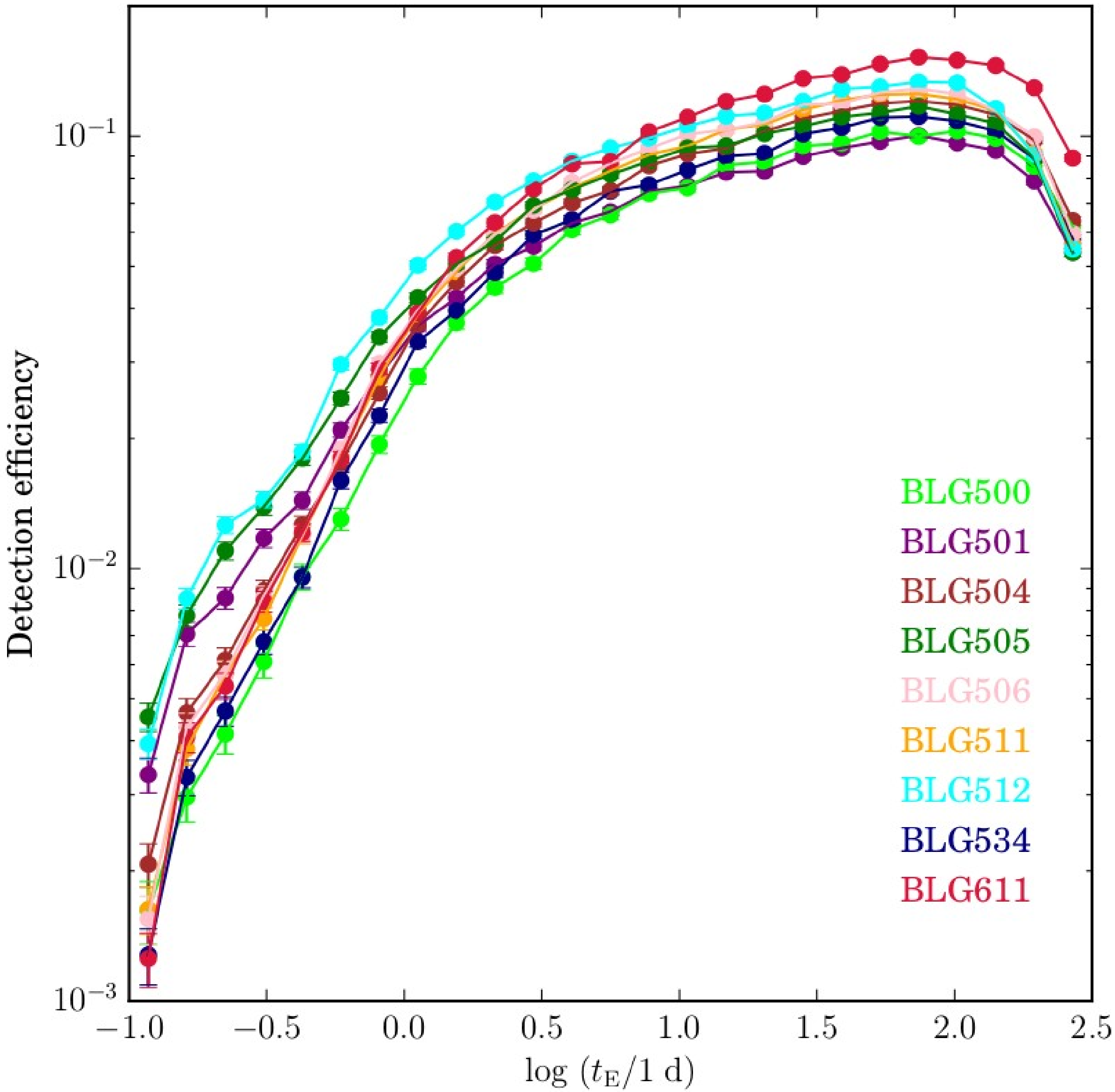






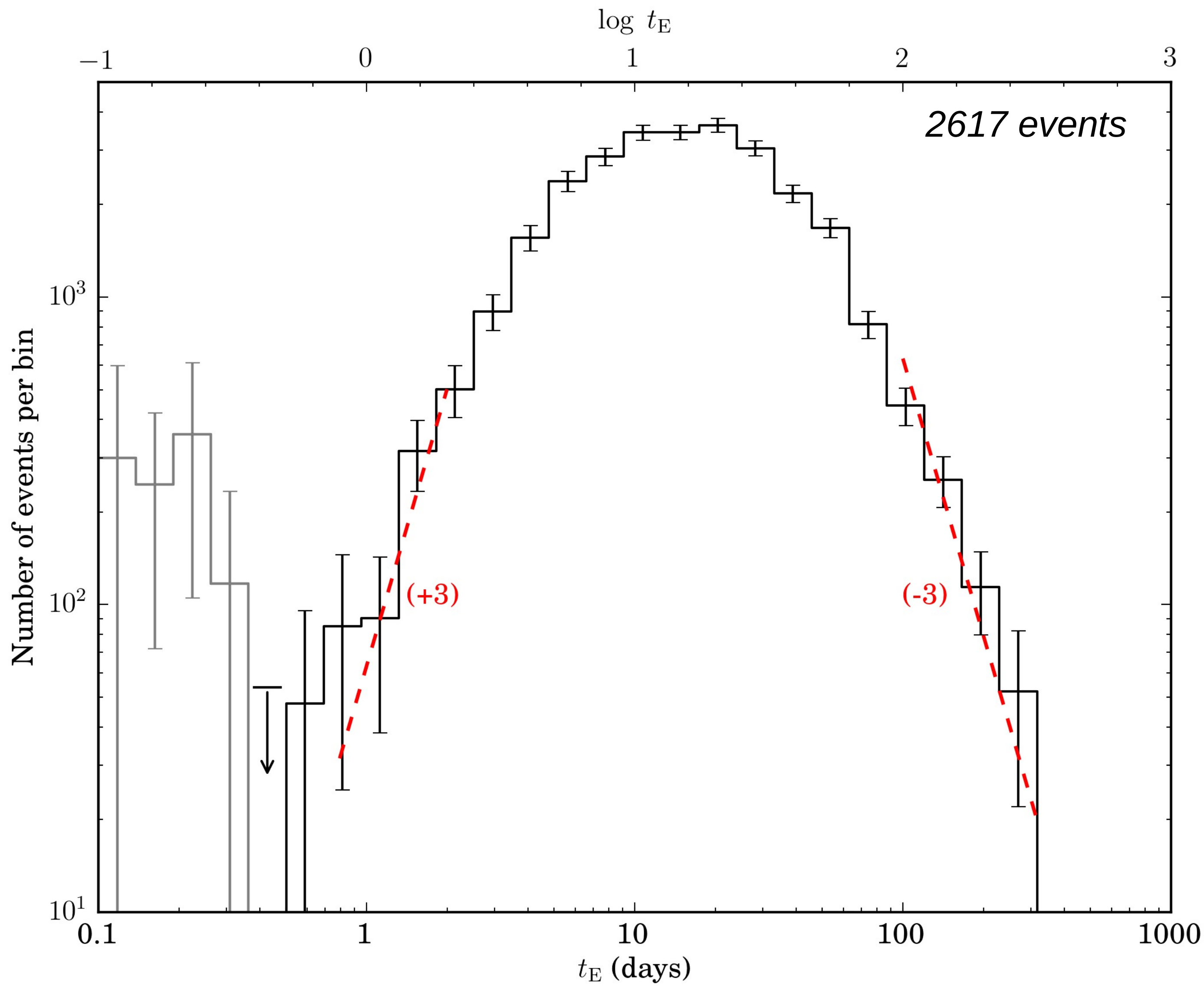
Detection efficiency



simulations took ~10 weeks

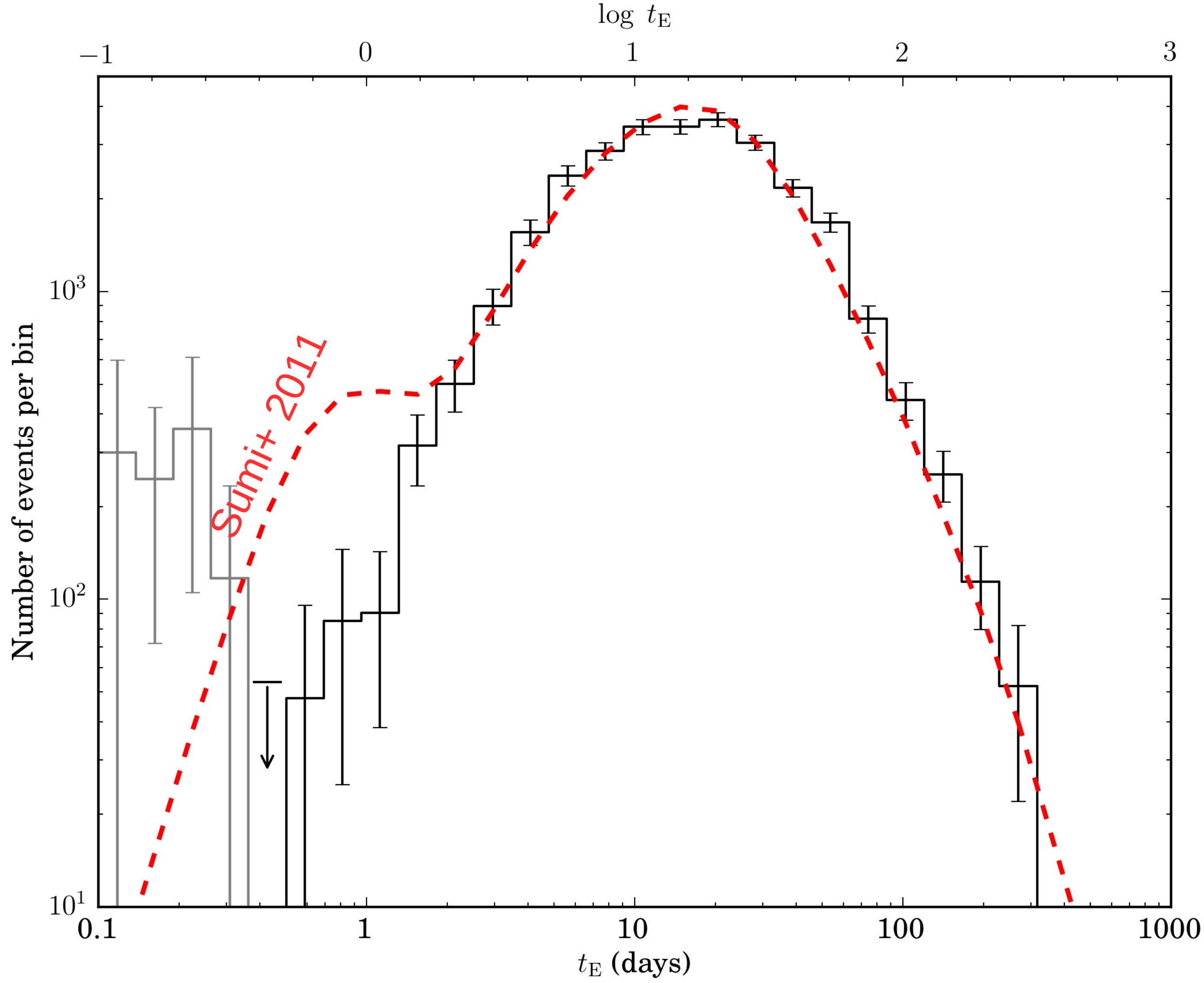
eff (t_E = 2 d) = 53% eff (t_E = 100 d)

Timescale distribution: all events



Mao & Paczyński (1996): power-law tails with slopes (+3) and (–3)

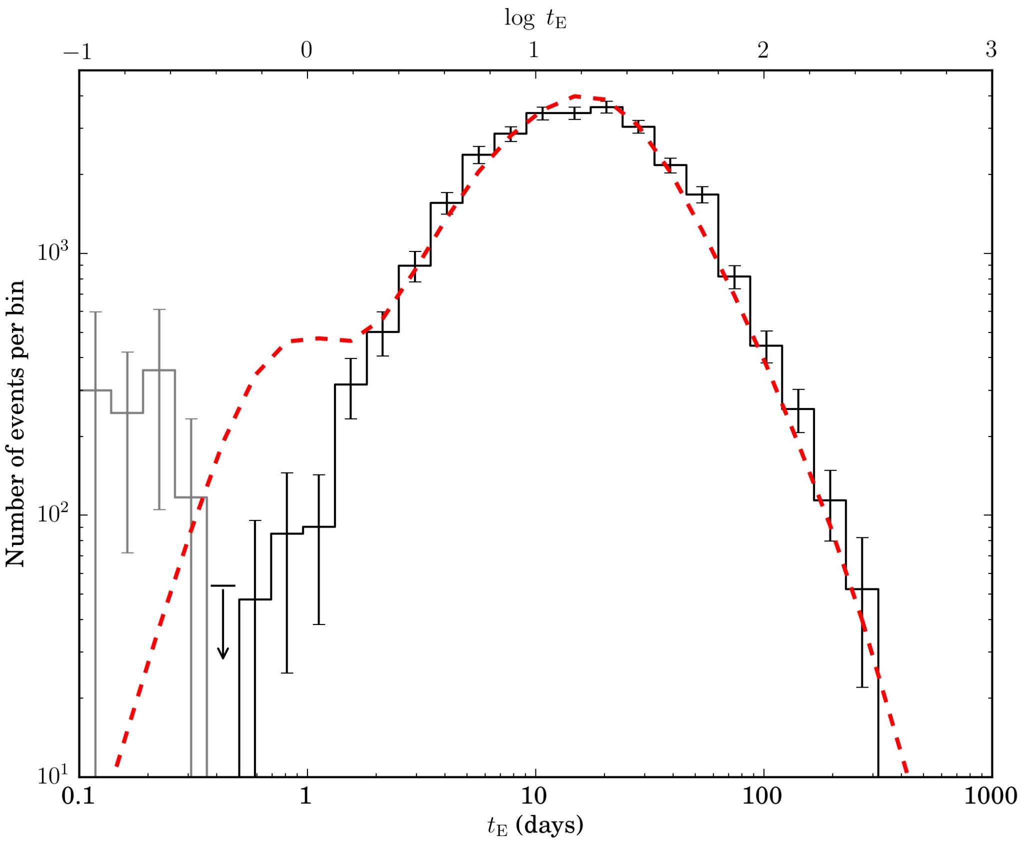
Comparison with Sumi+ (2011)



0,3 < t_E < 1,8 d: 21 events (64 expected)
0,3 < t_E < 1,3 d: 6 events (42 expected)

Comparison with Sumi+ (2011)

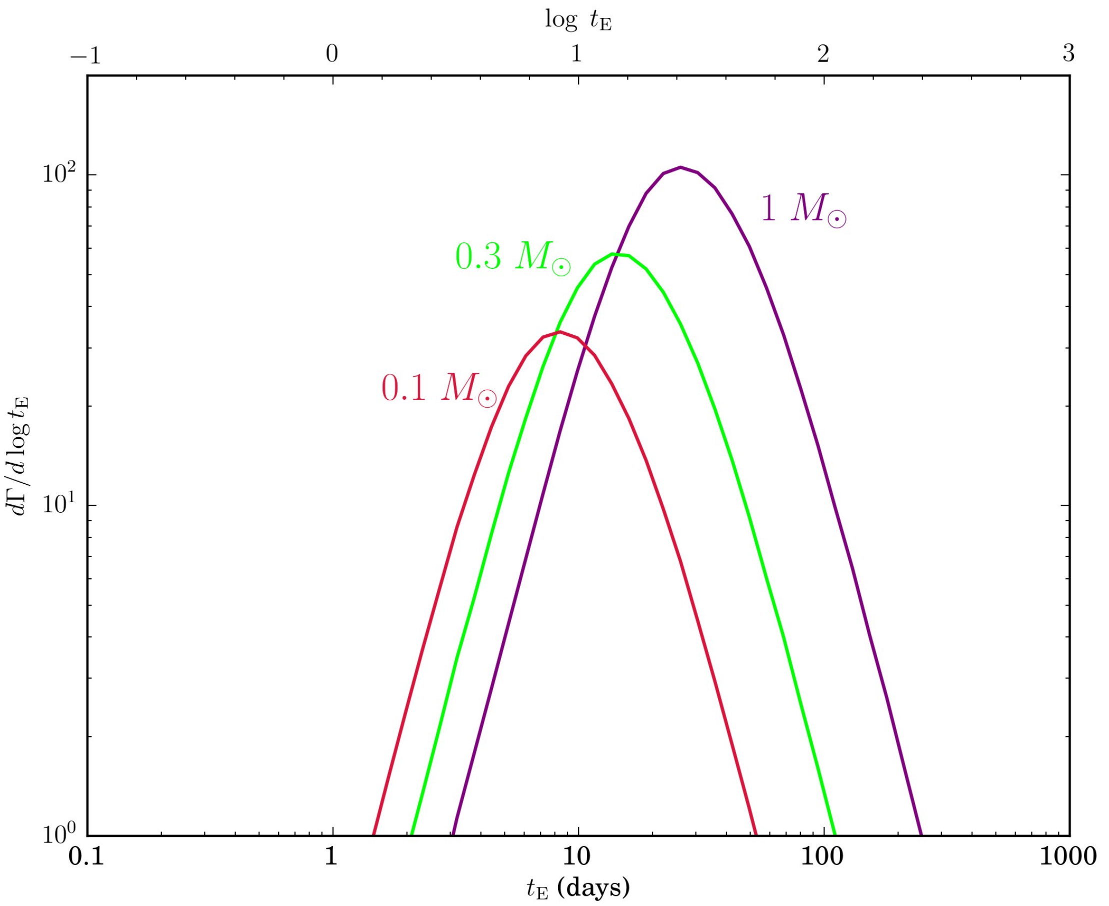
- 2.5σ-3σ difference (small sample?)
- >20 short-duration binary events (could they have been mistaken with single events?)
- systematics in the data? (differential refraction, unphysical treatment of negative blending)



Timescale distribution models

- Milky Way model of Han & Gould (1995, 2003)
- mass function:

$$\Phi(M) = \begin{cases} a_1 M^{-\alpha_{\rm bd}} & 0.01M_\odot \leq M < 0.08M_\odot \\ a_2 M^{-\alpha_{\rm ms}} & 0.08M_\odot \leq M < M_{\rm break} \\ a_3 M^{-2.0} & M \geq M_{\rm break} \end{cases}$$



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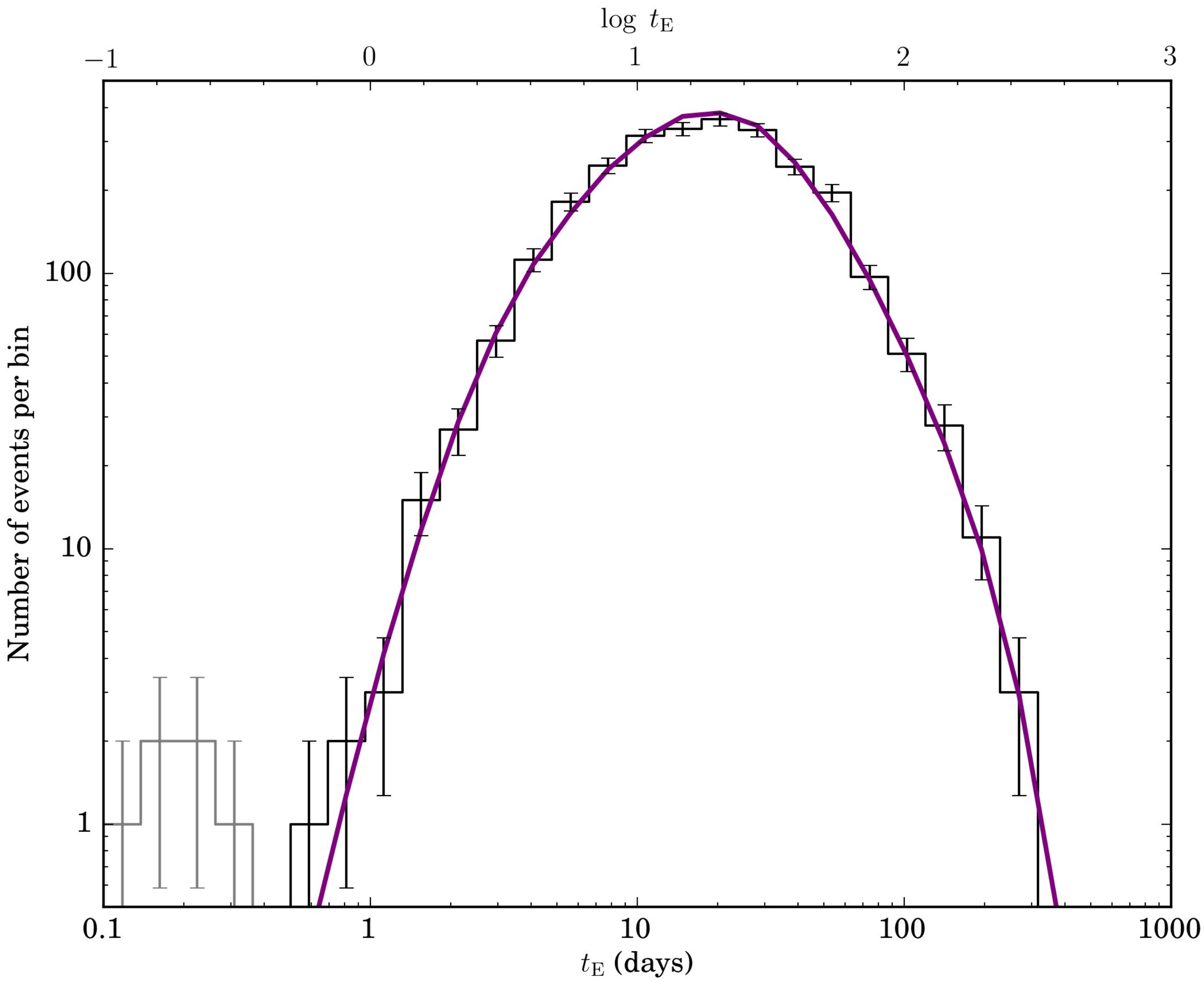
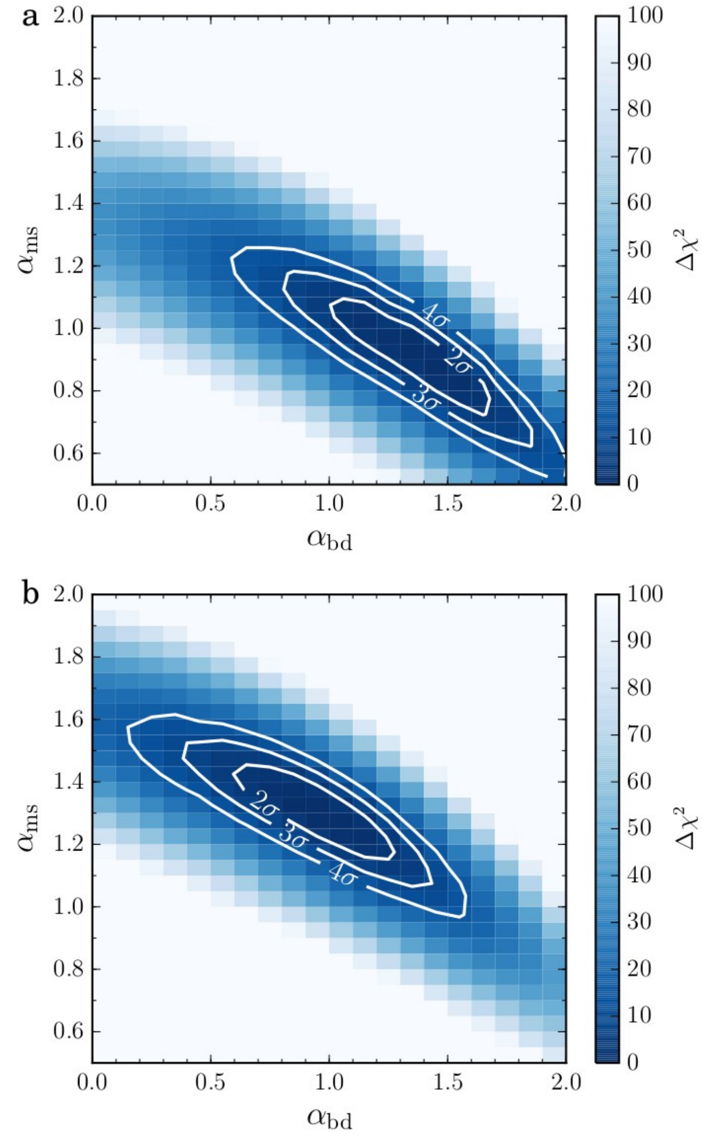
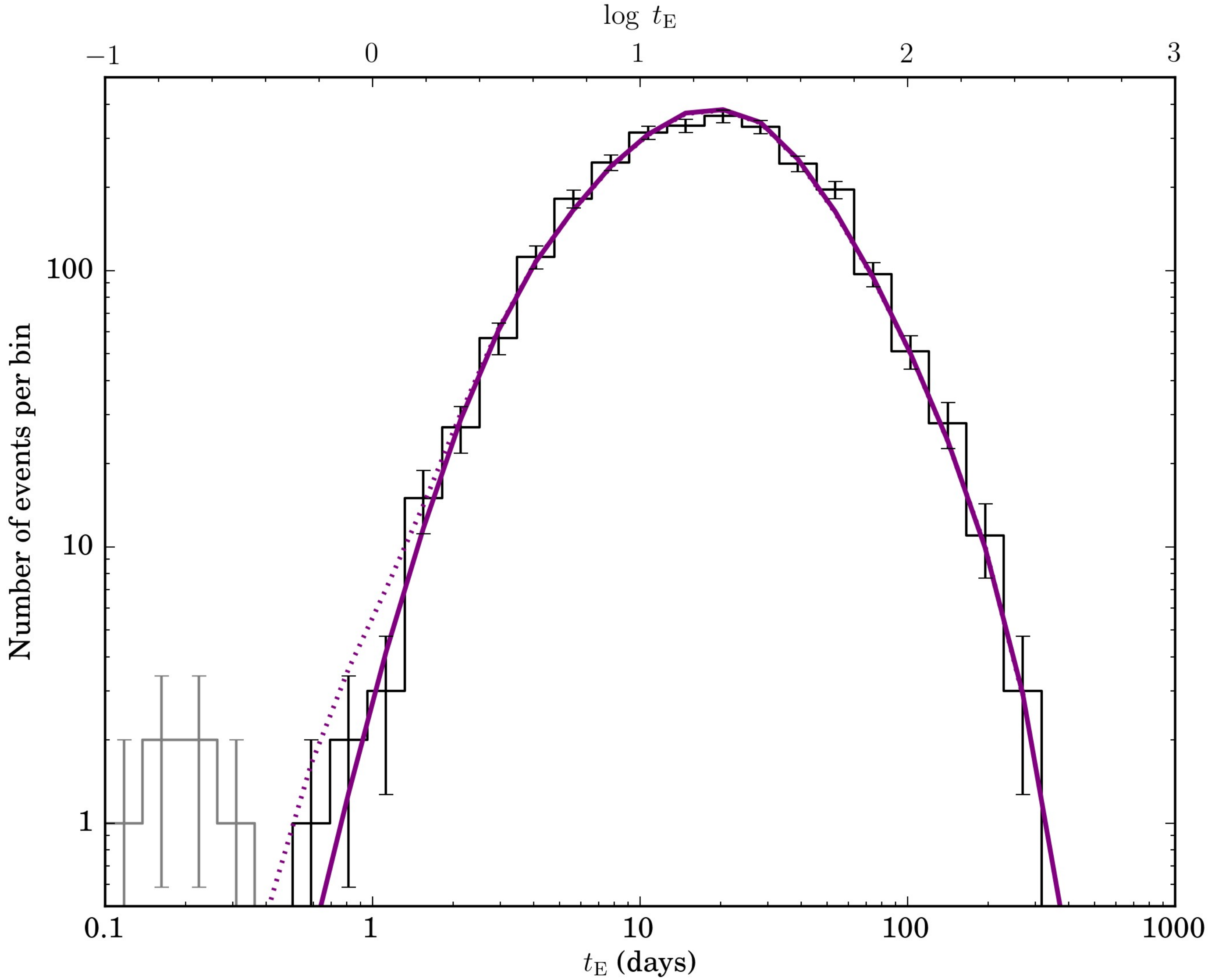




Jupiter-mass planets

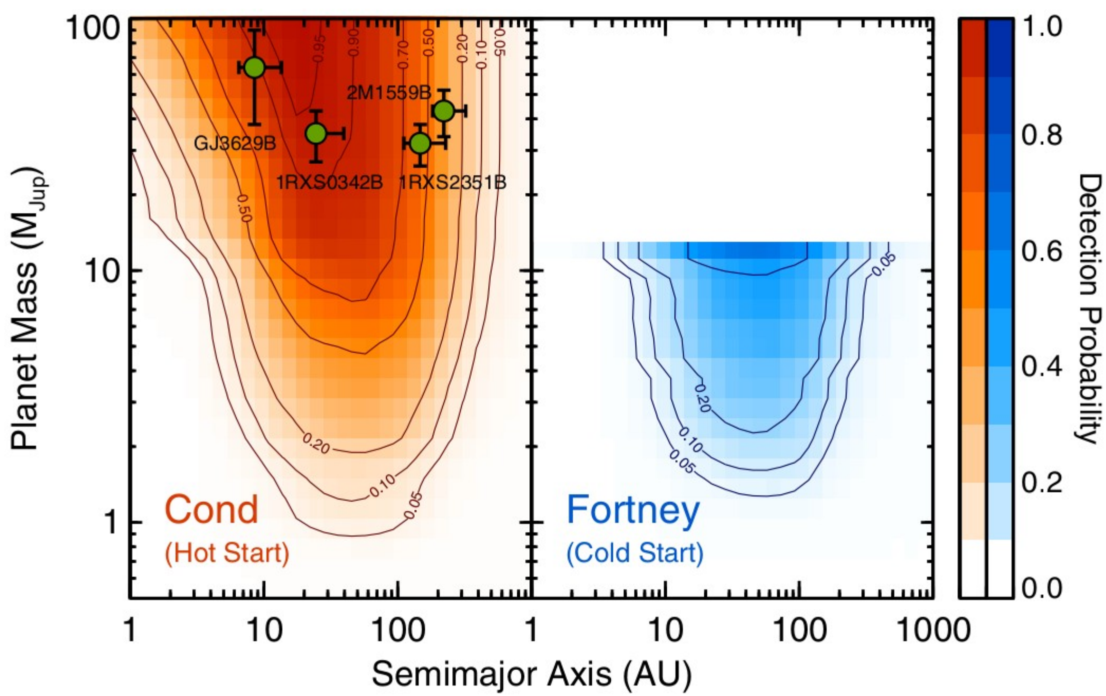


1 sigma: [0,0.12] Jupiter-mass planets per star
95%: < 0.25 Jupiter-mass planets per star

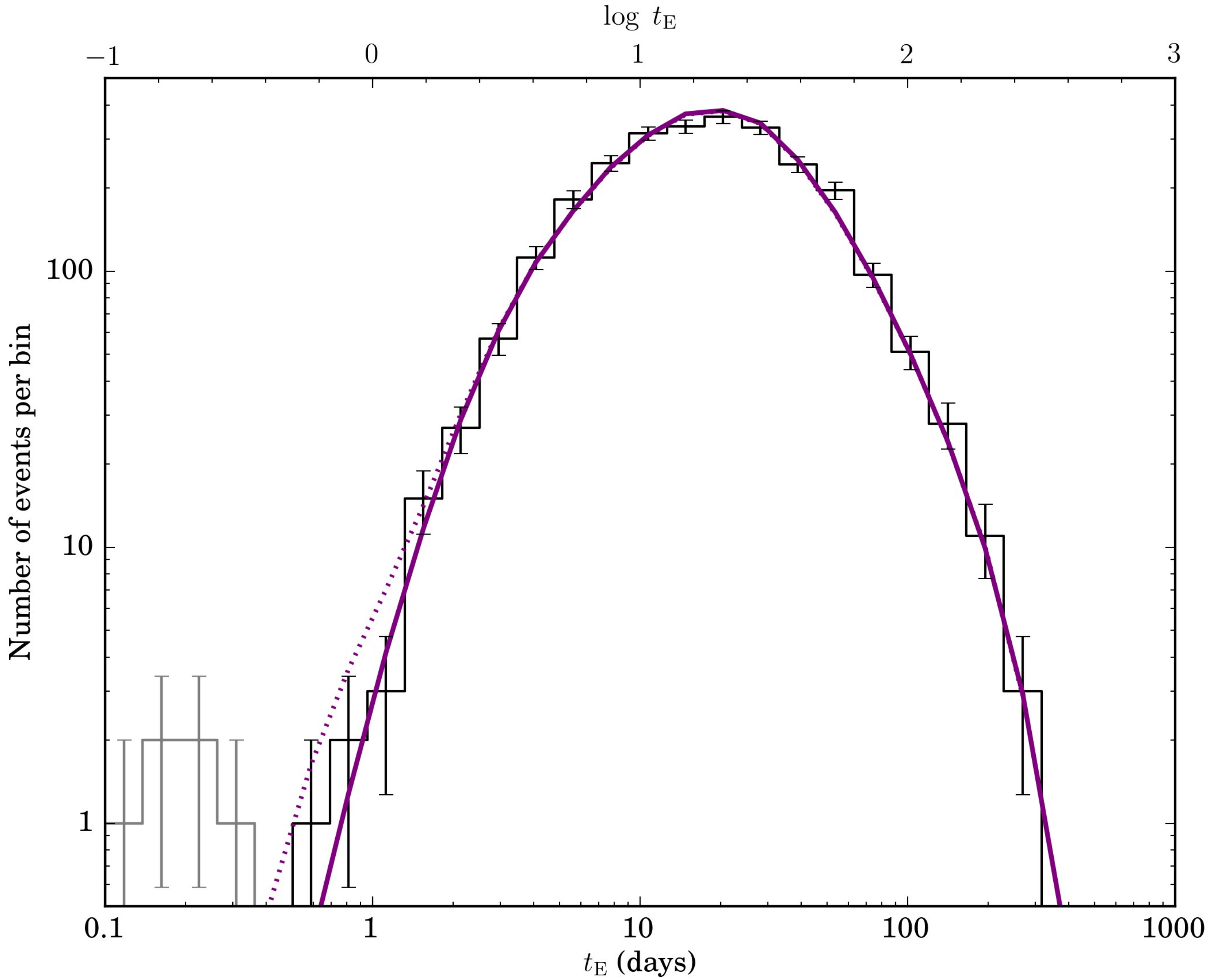
Jupiter-mass planets

- Constraints from direct imaging surveys:

  <10-16% M-type stars host a Jupiter-mass planet 1-13 M_{Jup} at 10-100 AU (Bowler+ 2015)



Free-floating Earths?



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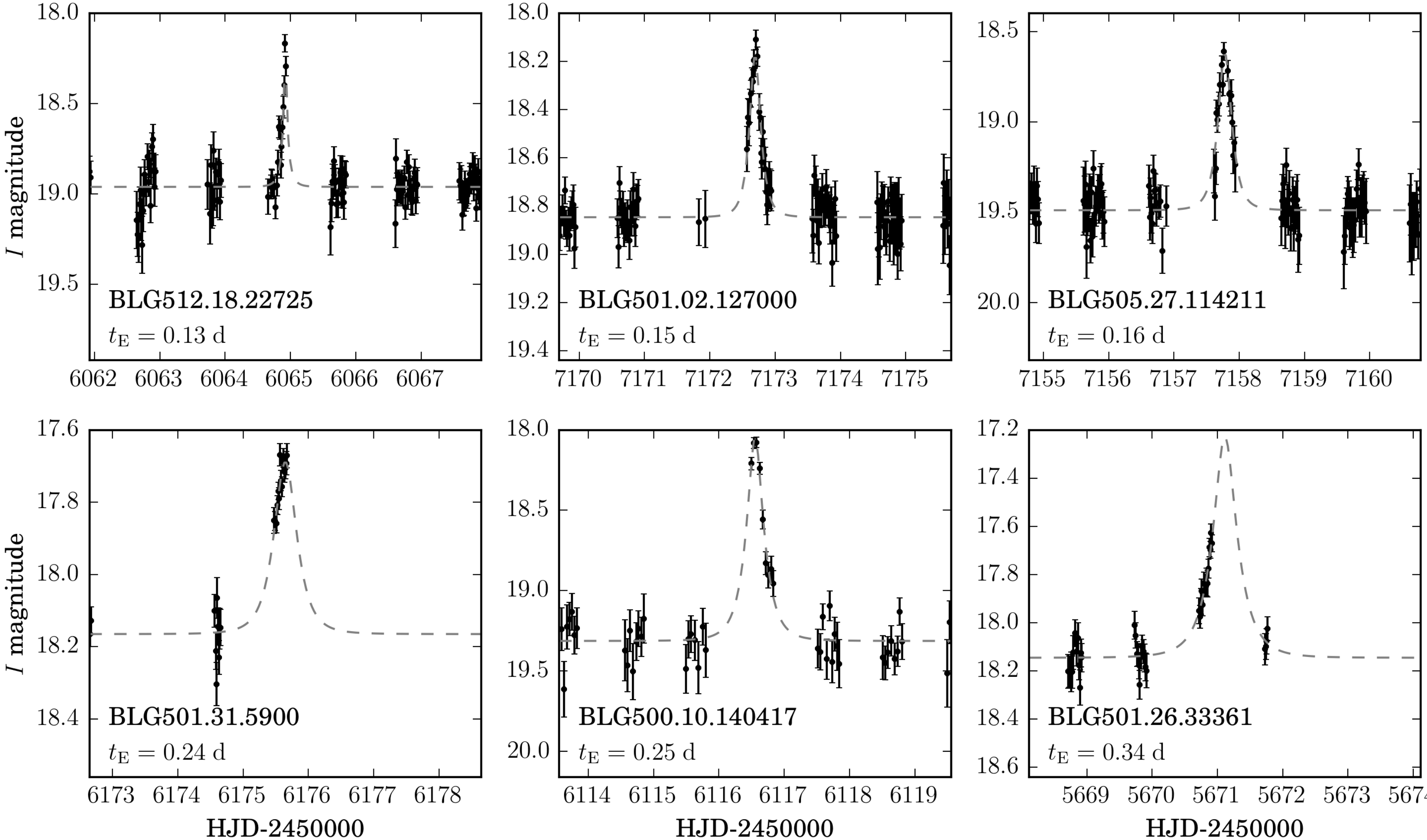
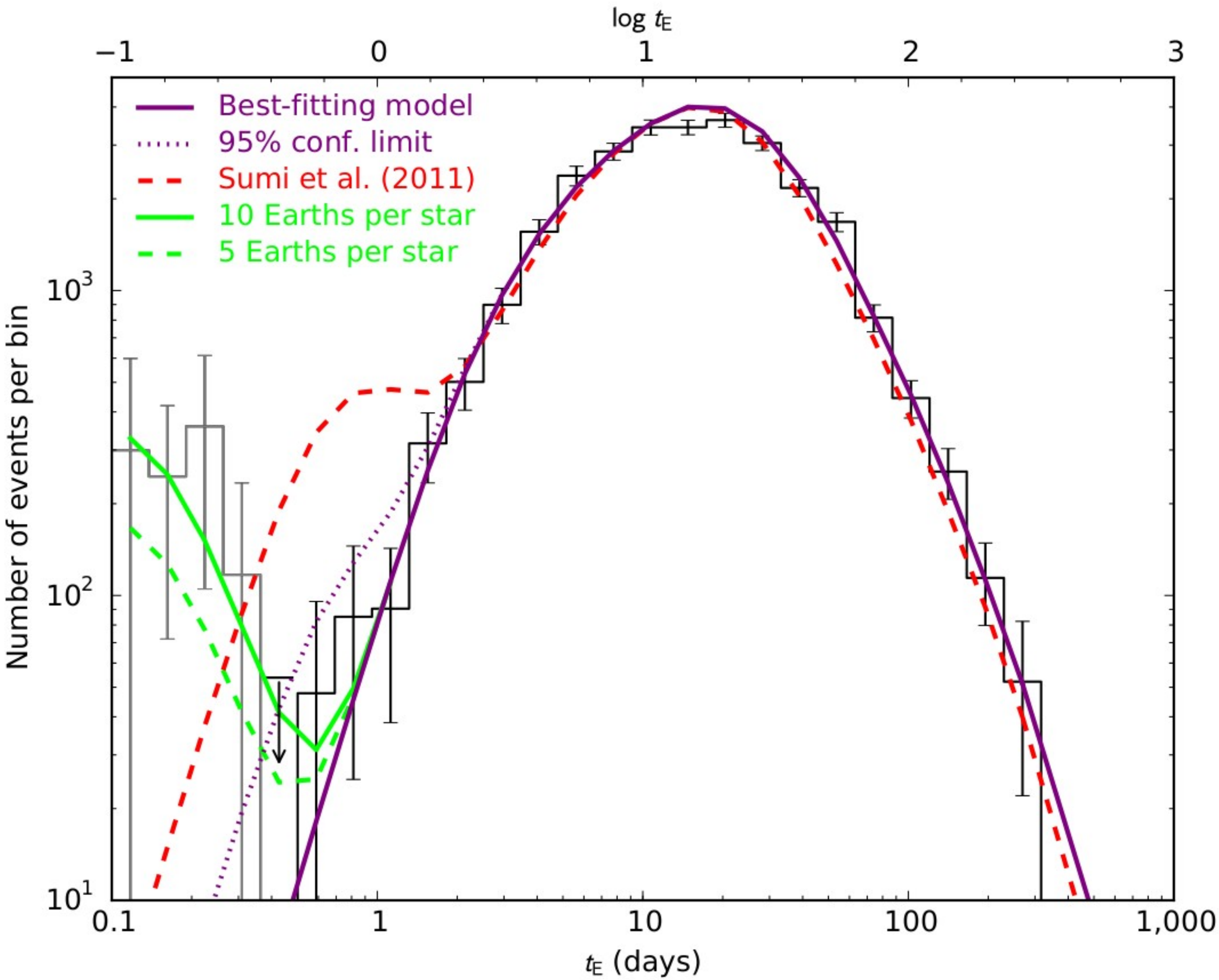


Timescales t_E ~ 0.1 – 0.4 d → mass 1-10 $M_\oplus$

Free-floating Earth?



Are they more common than stars?

Summary

- over 2600 high-quality events from 5.5 years of OGLE-IV
- less than 0.25 free-floating Jupiter-mass planets per star
- hints of Earth-mass free-floating planets!

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NATURE | LETTER

No large population of unbound or wide-orbit Jupiter-mass planets

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