On Reverberation Mapping Lag Uncertainties

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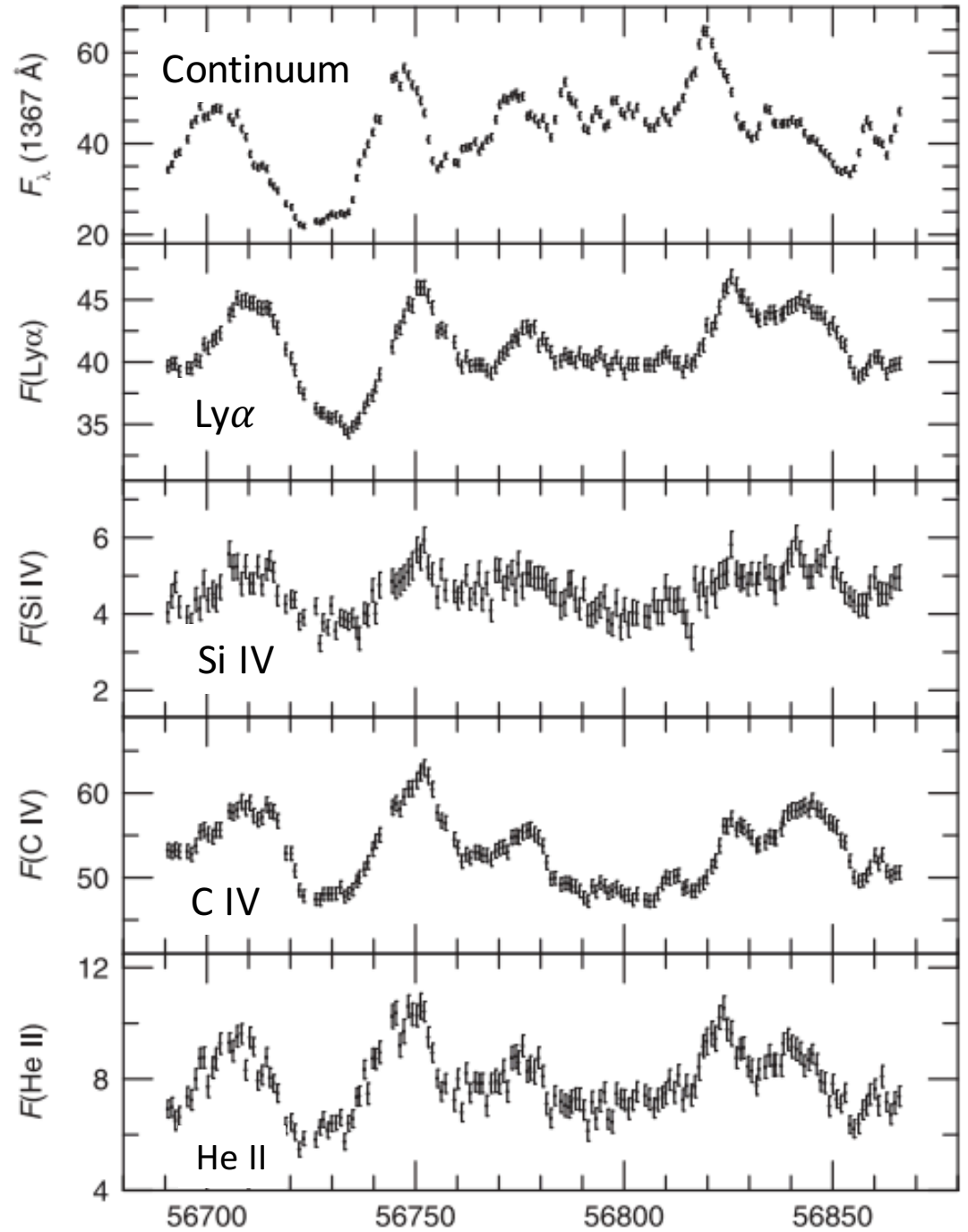
Time lag

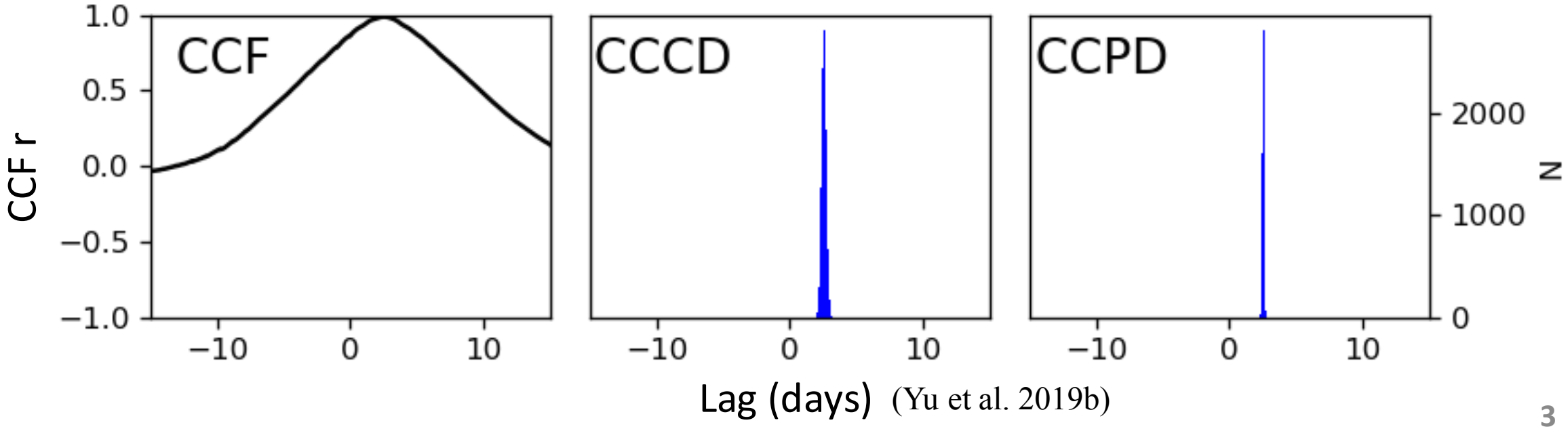
- Between continuum and lines or different continuum wavelengths
- Critical for:
  - BH mass estimates
  - R – L relation
  - Accretion physics (continuum RM)
  - ……



(De Rosa et al. 2015)

Lag measurement: ICCF

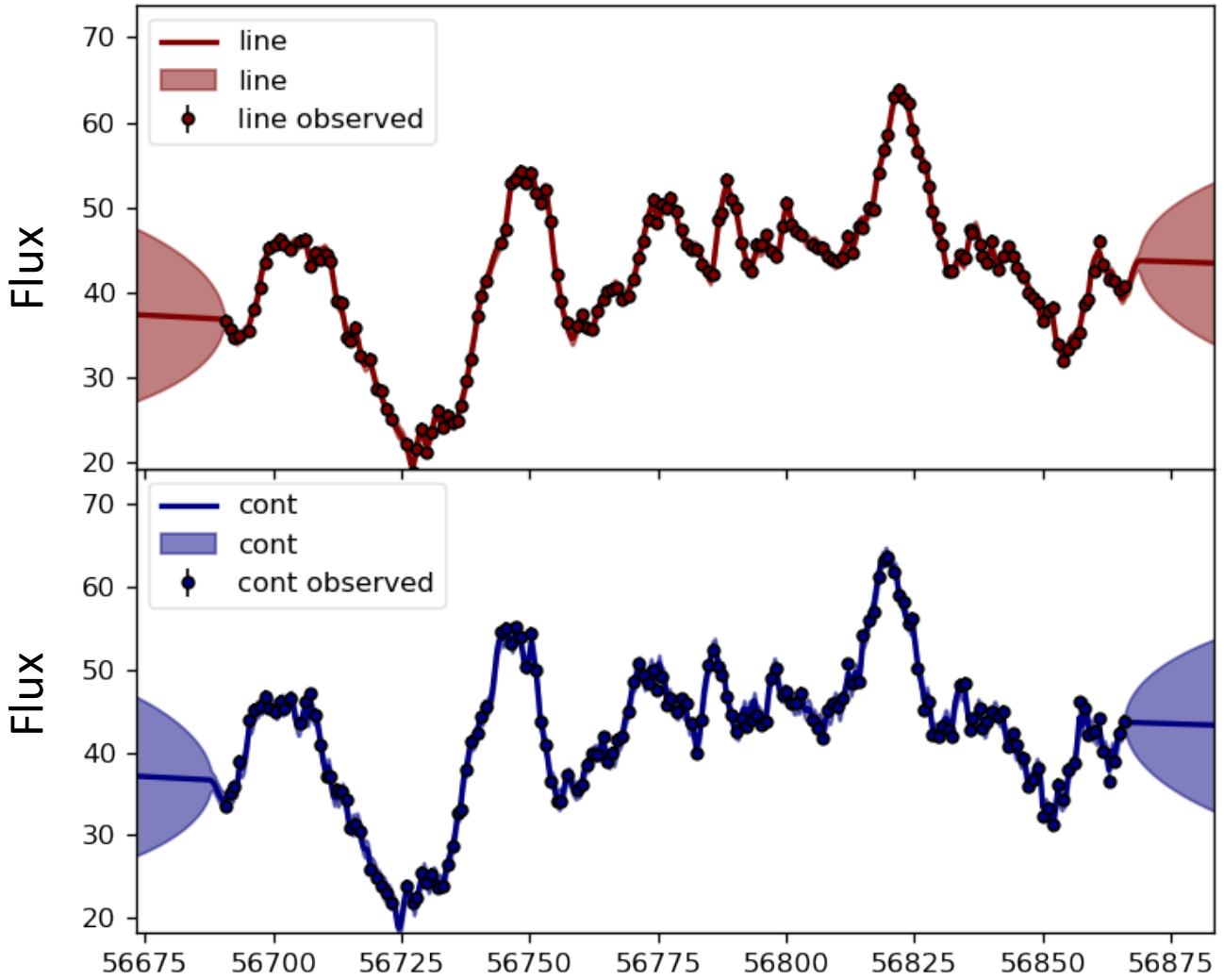
- Linearly interpolate lightcurves
- Lag: centroid / peak of the cross-correlation function
- Uncertainty: flux randomization + random subsampling



(Yu et al. 2019b)

Lag measurement: JAVELIN

- Assumptions:
  - Correct, Gaussian errors
  - DRW stochastic process for interpolation
  - Line lightcurve is a shifted, scaled, and top-hat smoothed version of the continuum
- Uncertainty: MCMC based

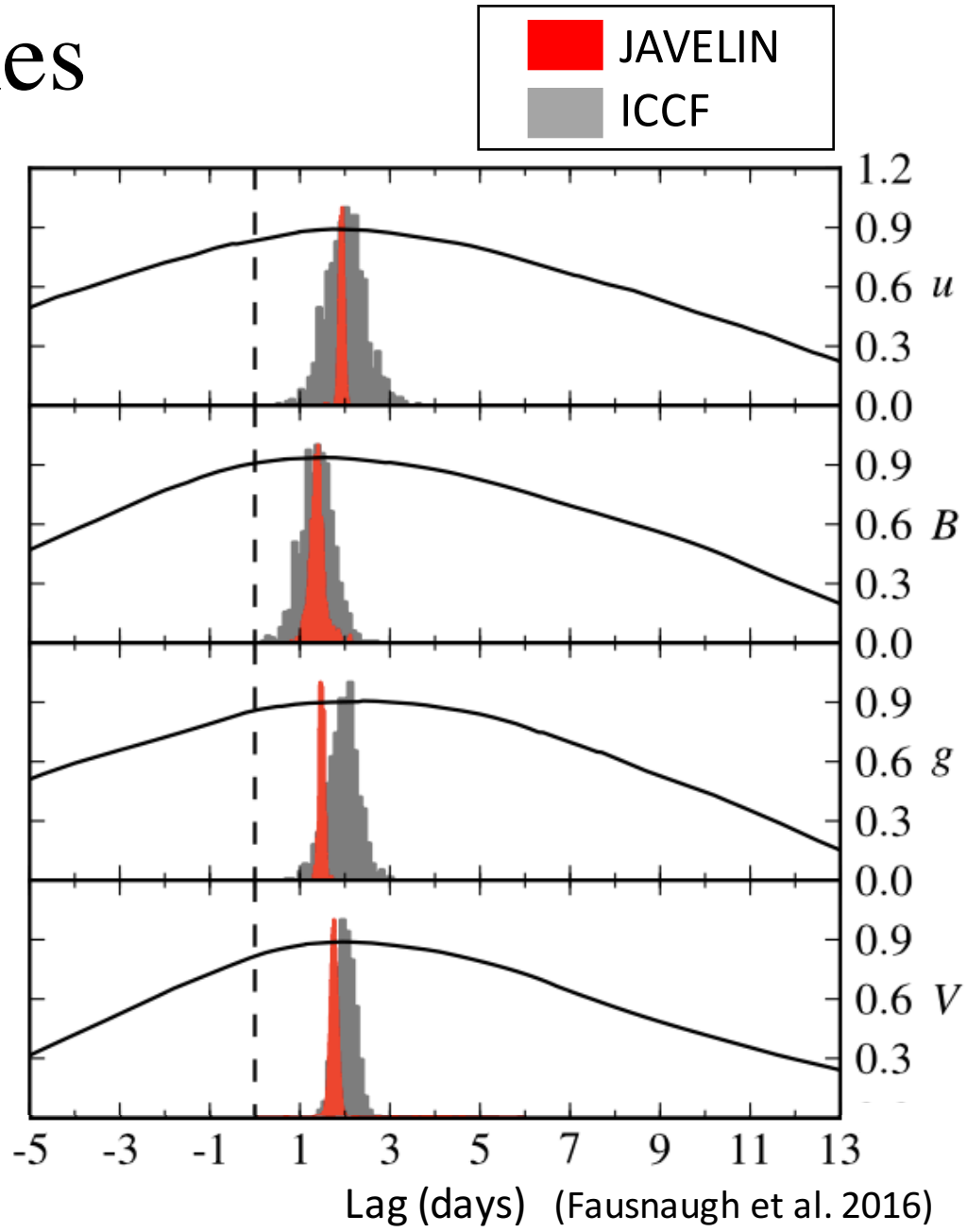


(Yu et al. 2019b)

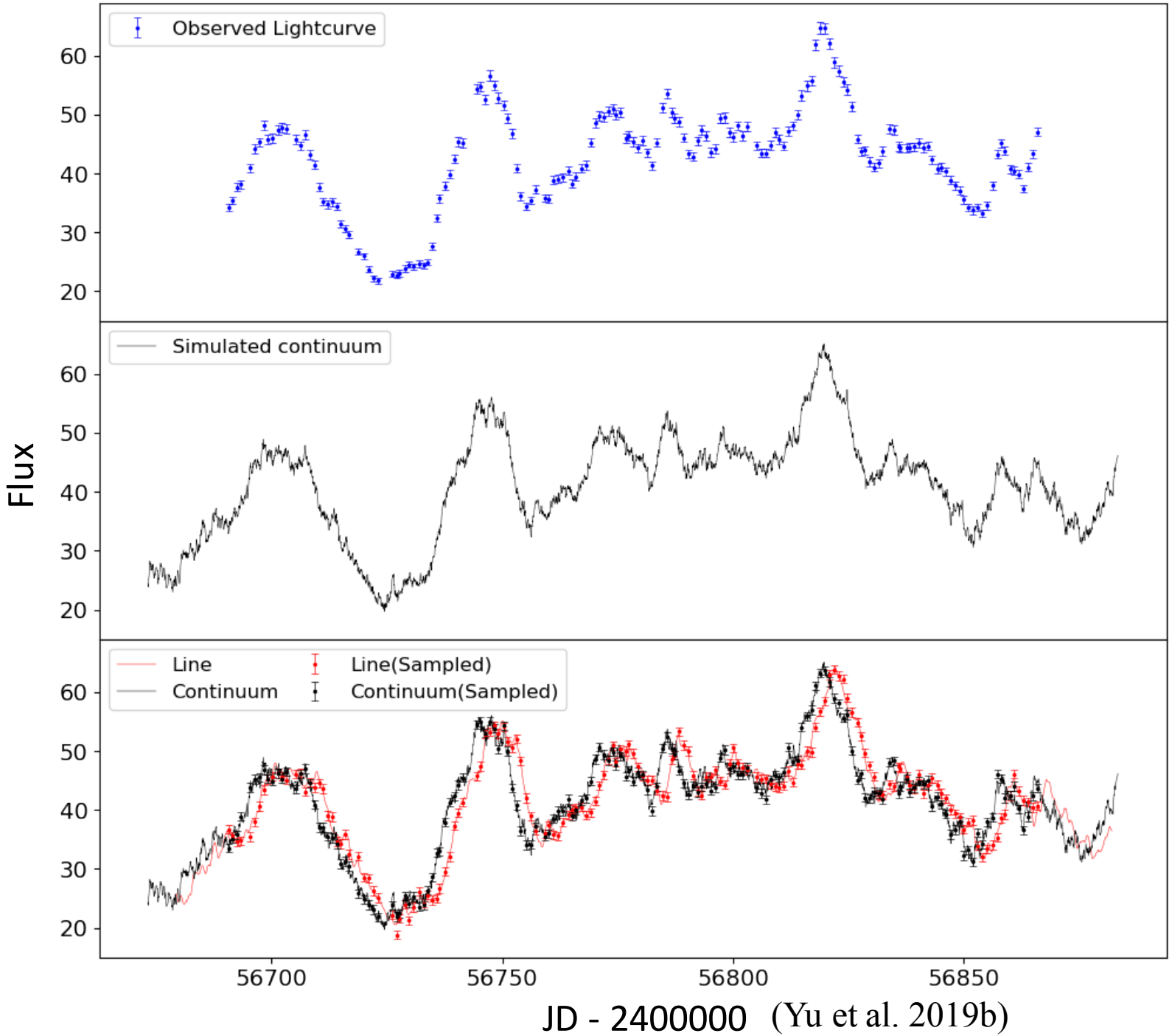
Discrepancy of lag uncertainties

- JAVELIN generally gives much smaller lag uncertainties than ICCF
- Widely noticed, but few systematic studies

- We use simulations to study:
  - Which uncertainty is more reliable?
  - How do the two algorithms behave with various systematic errors?
  - What happens to JAVELIN if its assumptions break down?



(Fausnaugh et al. 2016)



Observed Lightcurve of NGC 5548

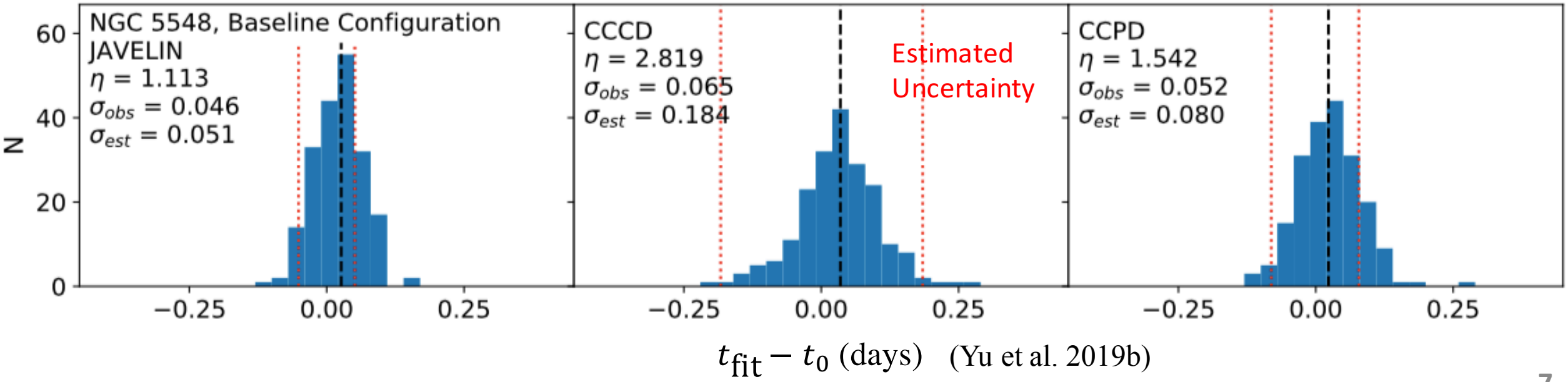
Simulated Lightcurve

Simulated Lightcurve (Observed Cadence)

Input lag: 2 – 4 days

Parameterization & Baseline results

- $\sigma_{\rm obs}$: width of the $(t_{\rm fit}-t_0)$ distribution ("true" uncertainty)
- $\sigma_{\rm est}$: uncertainty from the algorithms
- $\eta = \sigma_{\rm est}/\sigma_{\rm obs}$ ($\eta > 1$: Overestimate | $\eta < 1$: Underestimate)
- Result: JAVELIN gets closest to correct uncertainty; ICCF overestimates the uncertainty



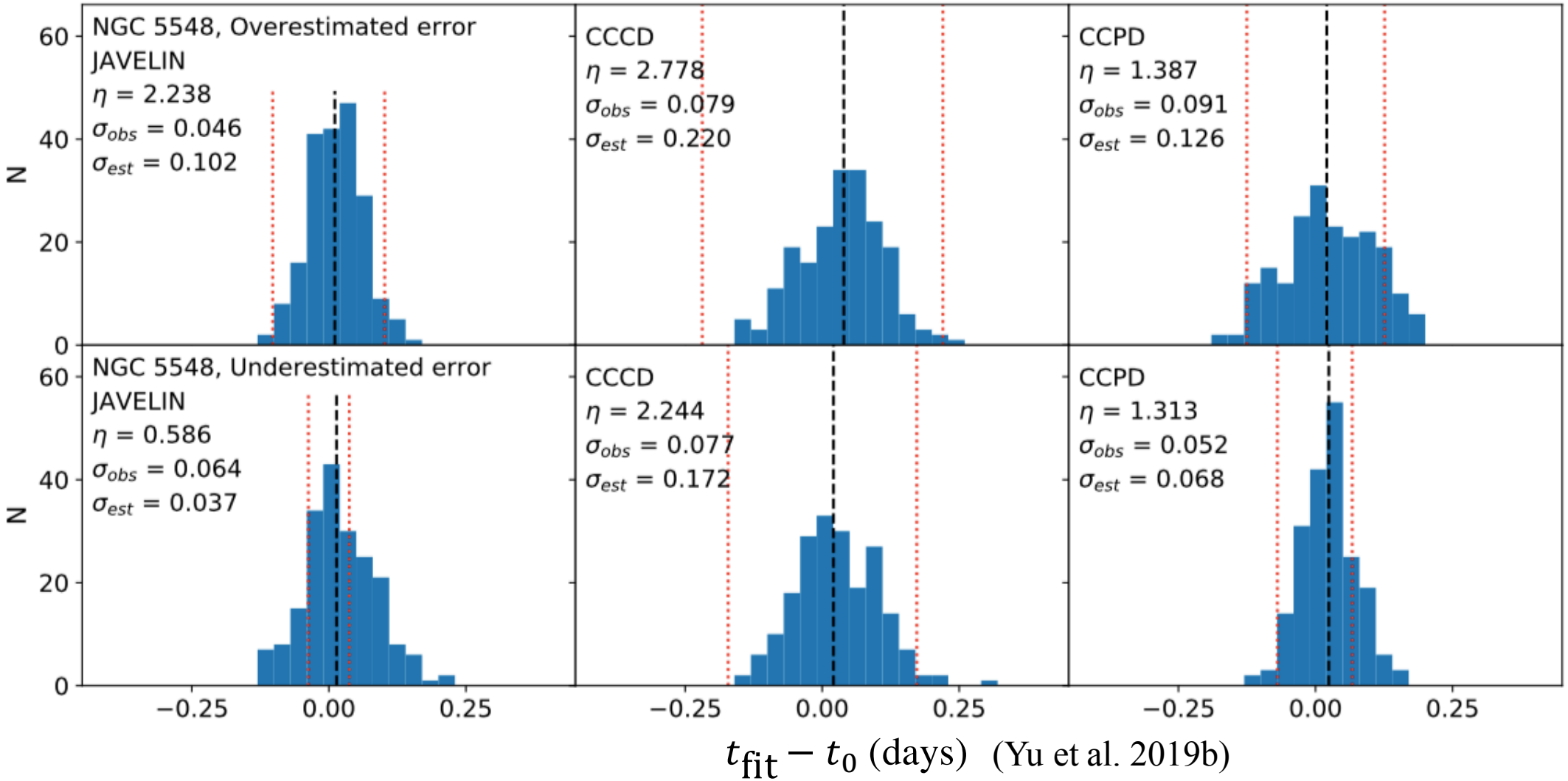
(Yu et al. 2019b)

Violating JAVELIN assumptions

- ~~Correct, Gaussian errors~~
- DRW stochastic process
- Line lightcurve is a shifted, scaled and top-hat smoothed version of the continuum

Results: incorrect lightcurve errors

- JAVELIN is more sensitive than ICCF



(Yu et al. 2019b)

Violating JAVELIN assumptions

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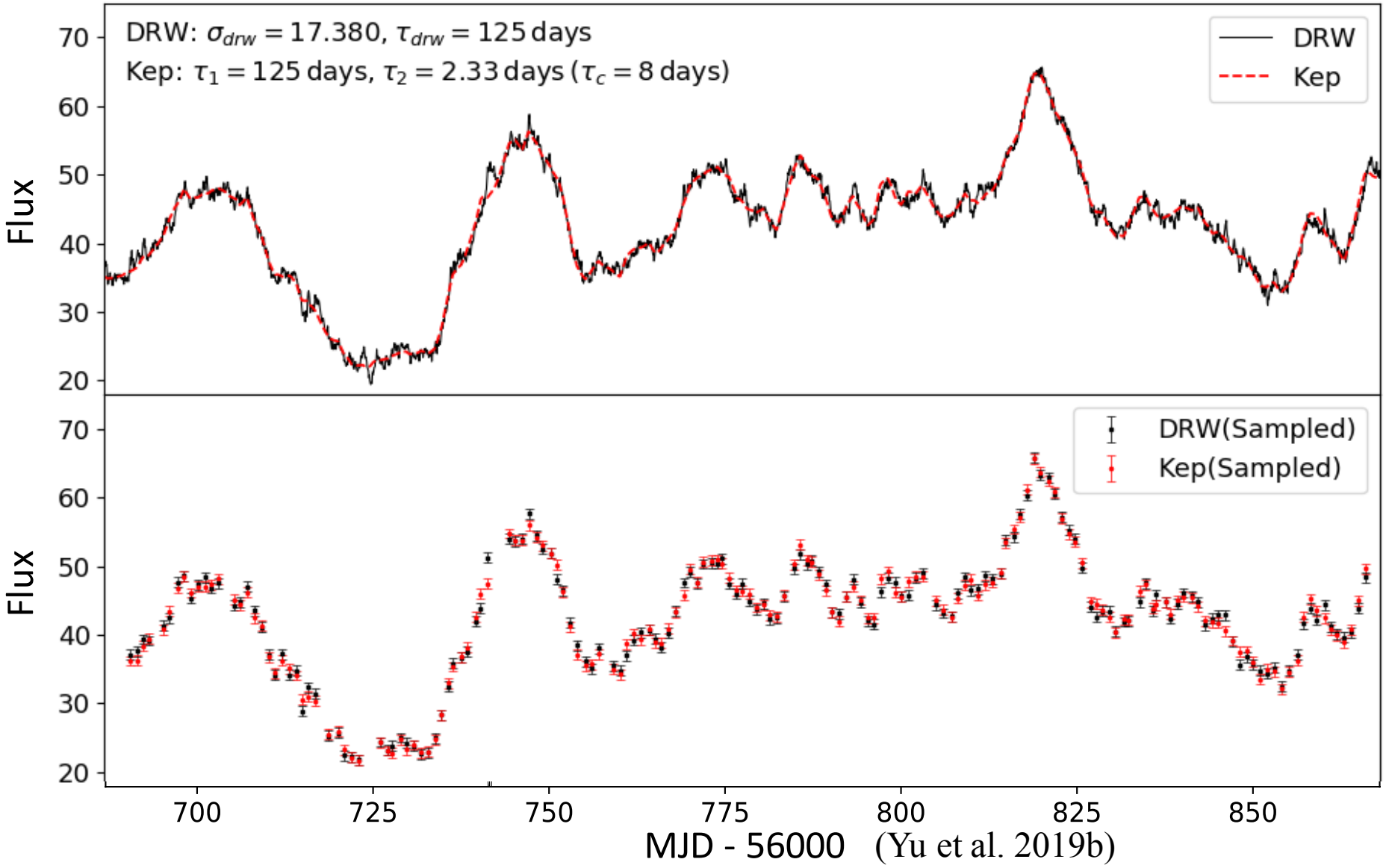
Stochastic process: “Kepler” process

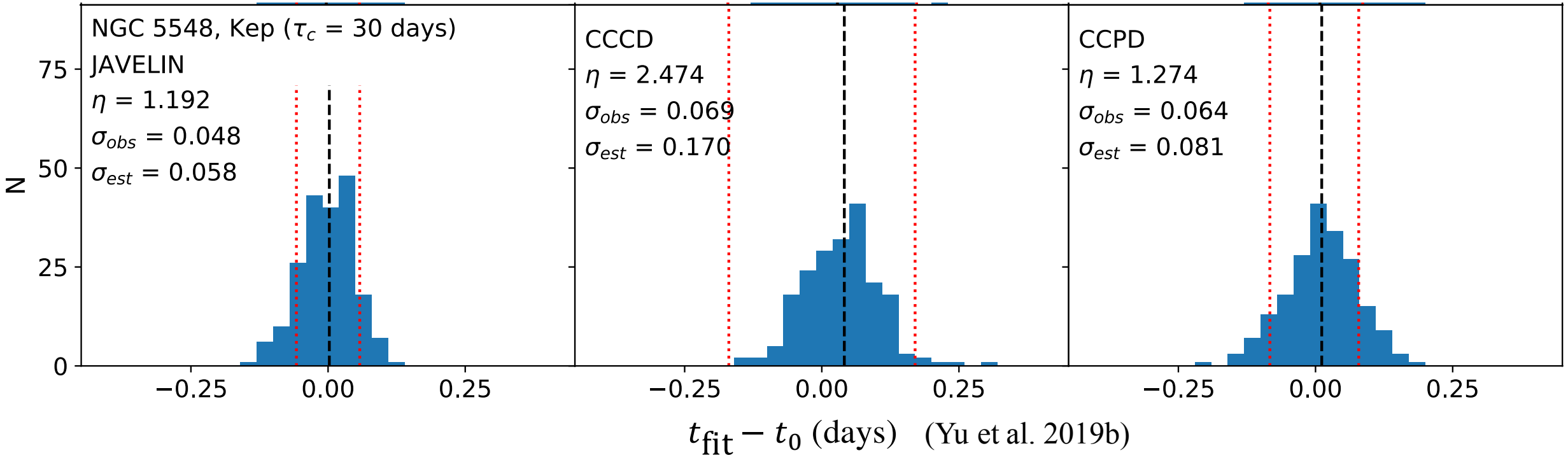
- Less variability at short time scales



(Yu et al. 2019b)

Results: “Kepler” process

- No significant effect



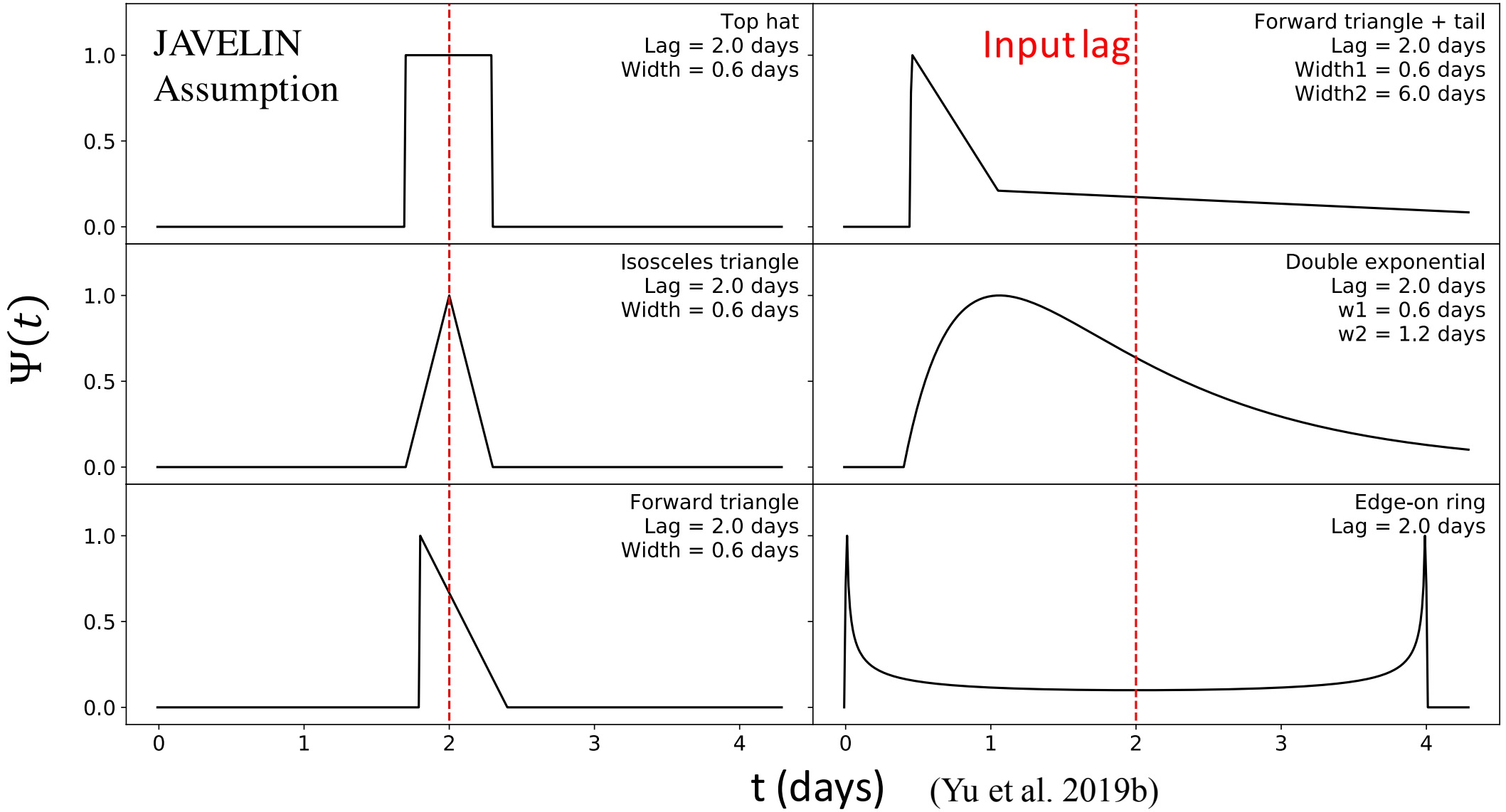
(Yu et al. 2019b)

Violating JAVELIN assumptions

- Correct, Gaussian errors
- DRW stochastic process
- Line lightcurve is a shifted, scaled and ~~top-hat~~ smoothed version of the continuum

Transfer functions

- No significant effect



(Yu et al. 2019b)

Violating JAVELIN assumptions

- Correct, Gaussian errors
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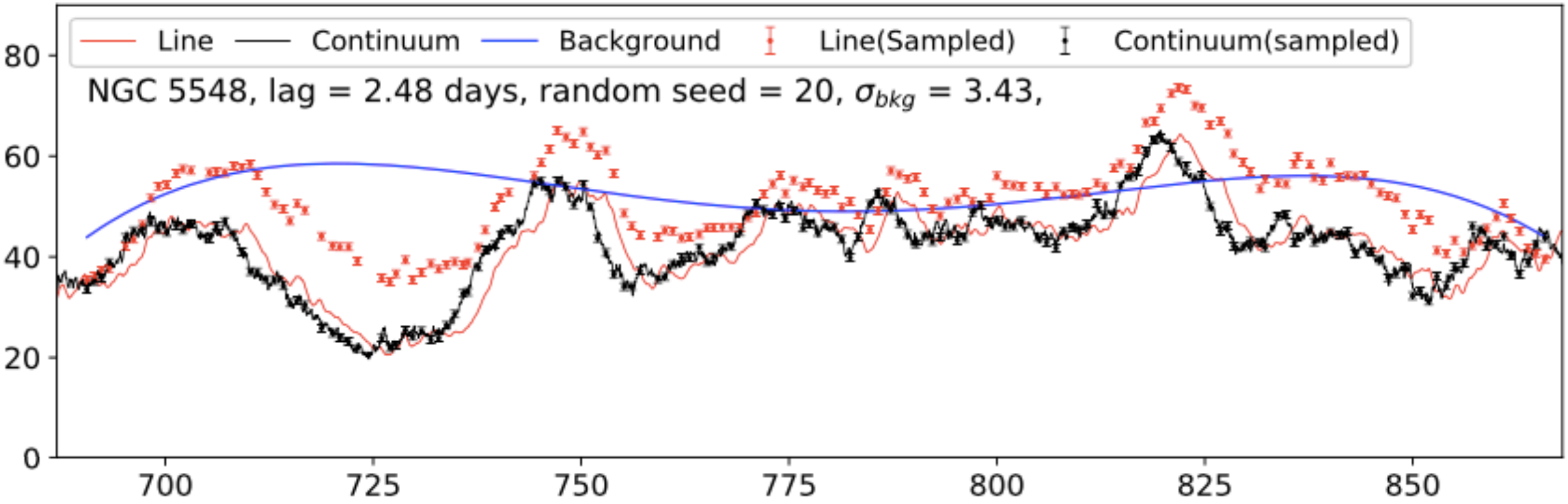
Varying background

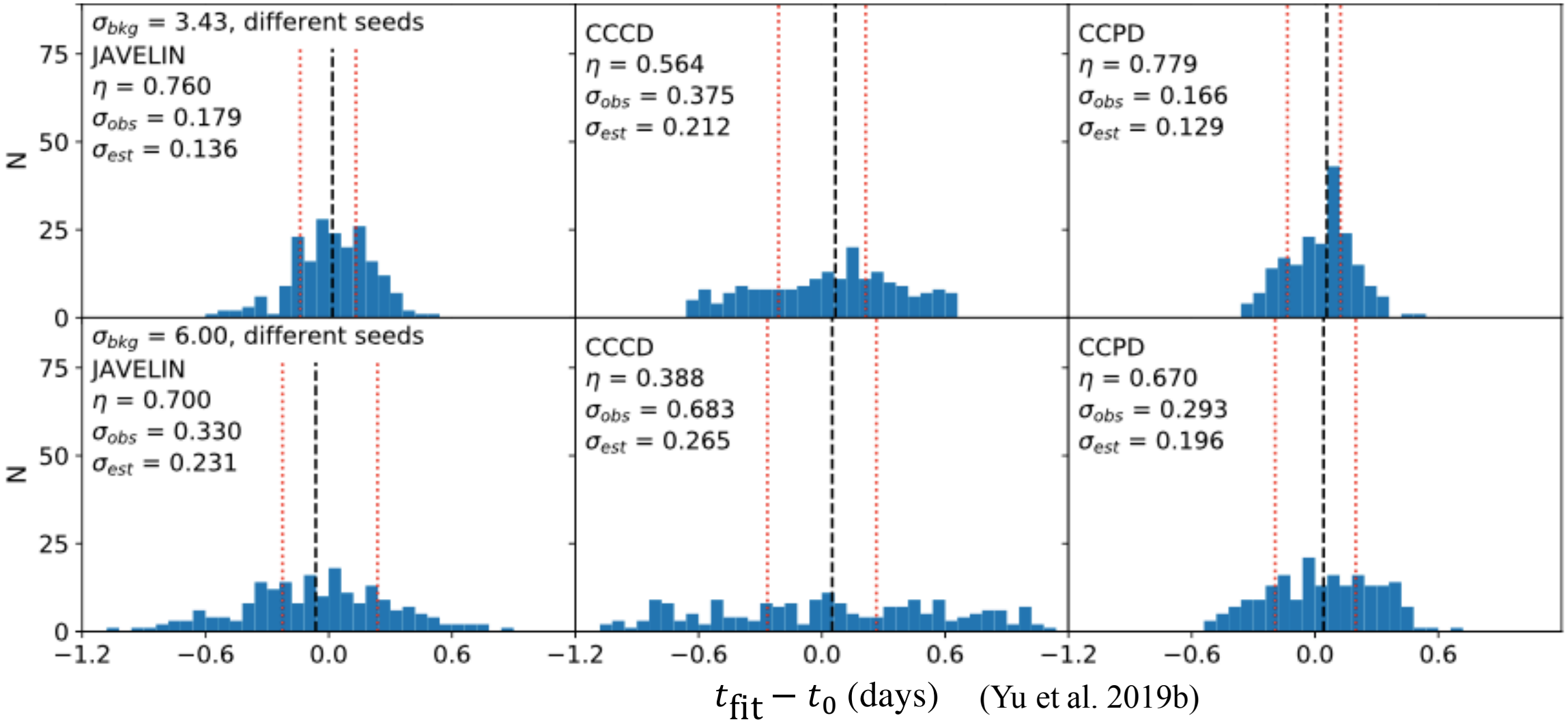
- Additional long time scale variability



(Yu et al. 2019b)

Results: varying background

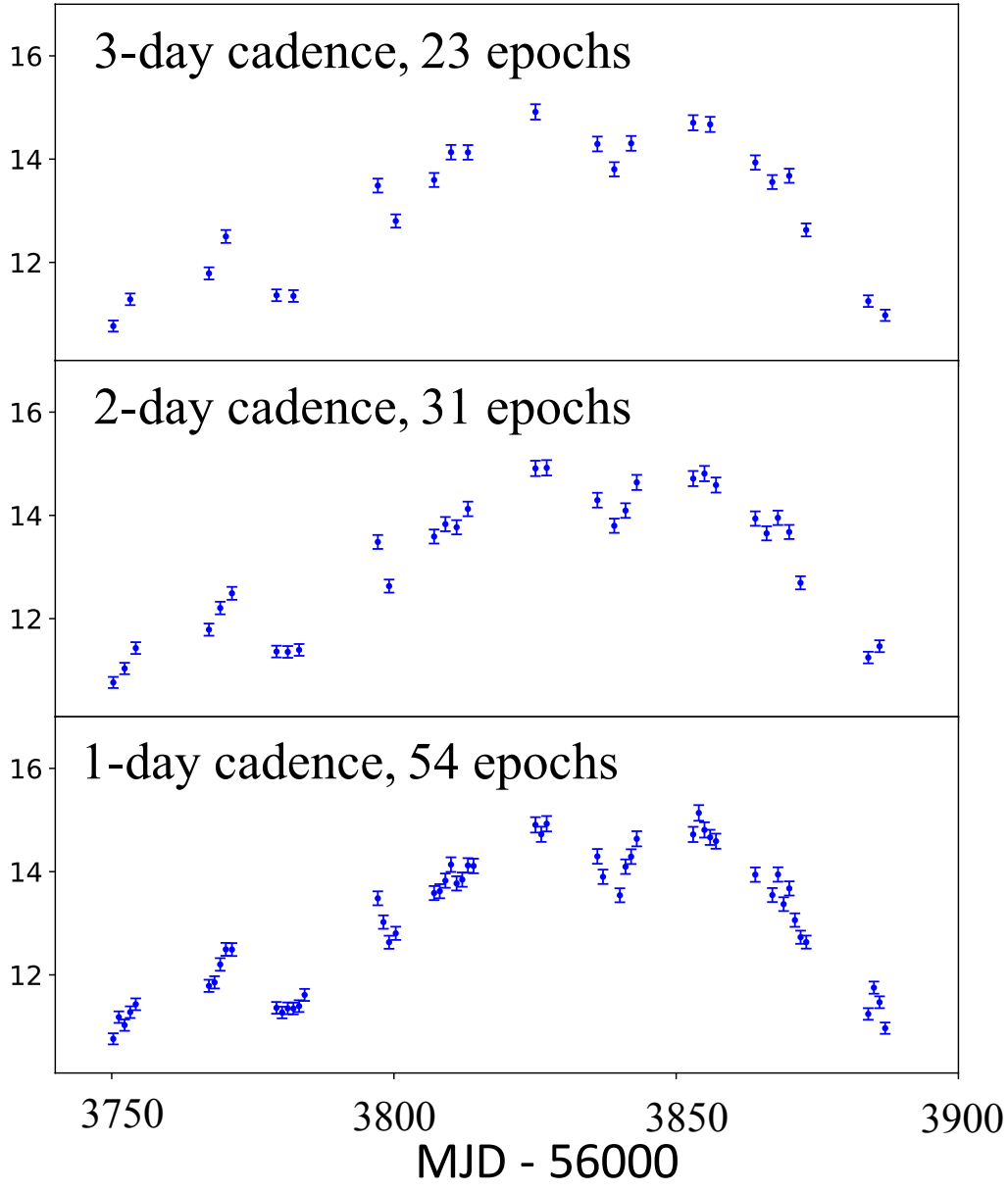
- Strong deviation from input

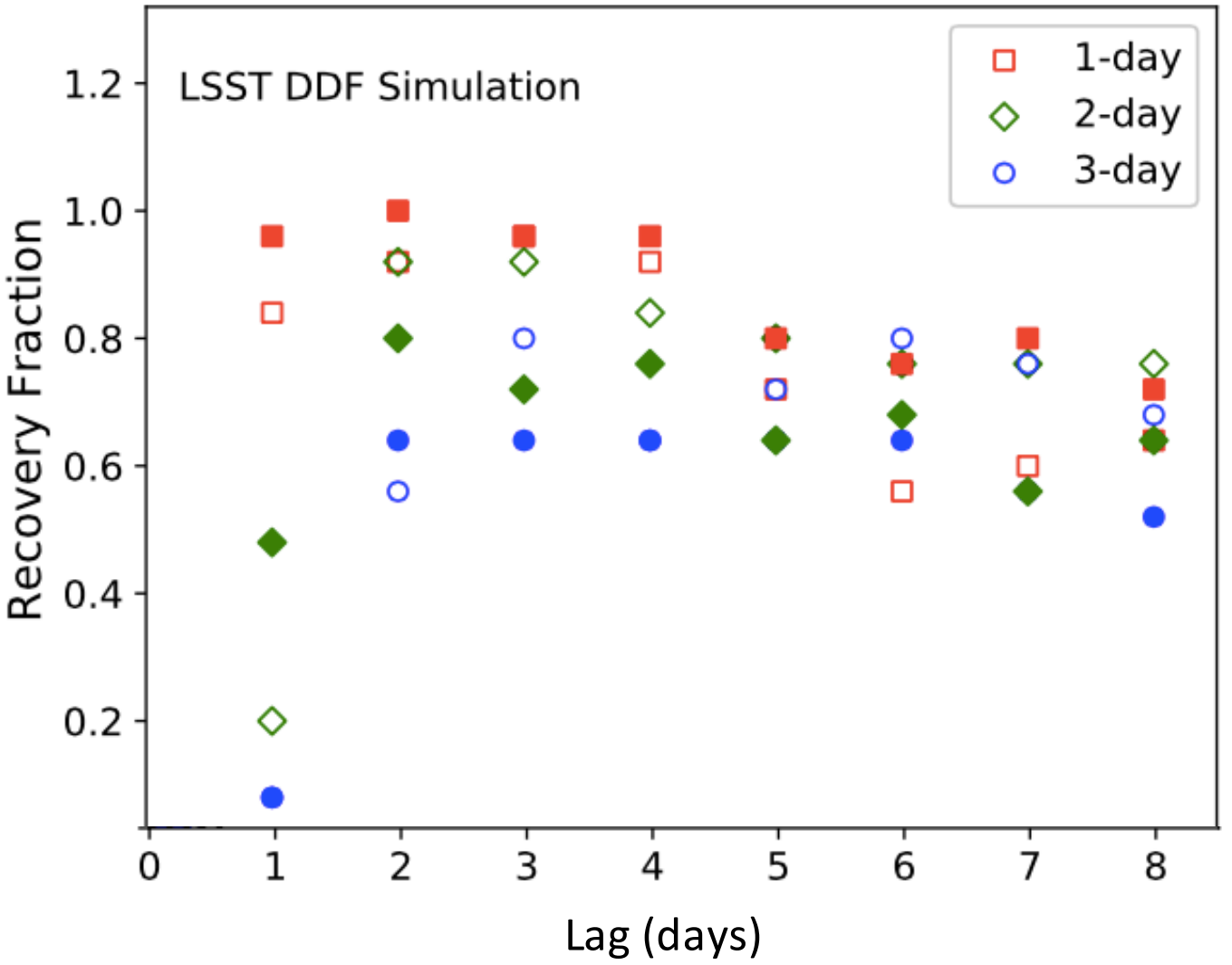


(Yu et al. 2019b)

Cadence and SNR (previous work)

- Yu et al. 2019a: effect of cadence on LSST Deep Drilling Fields





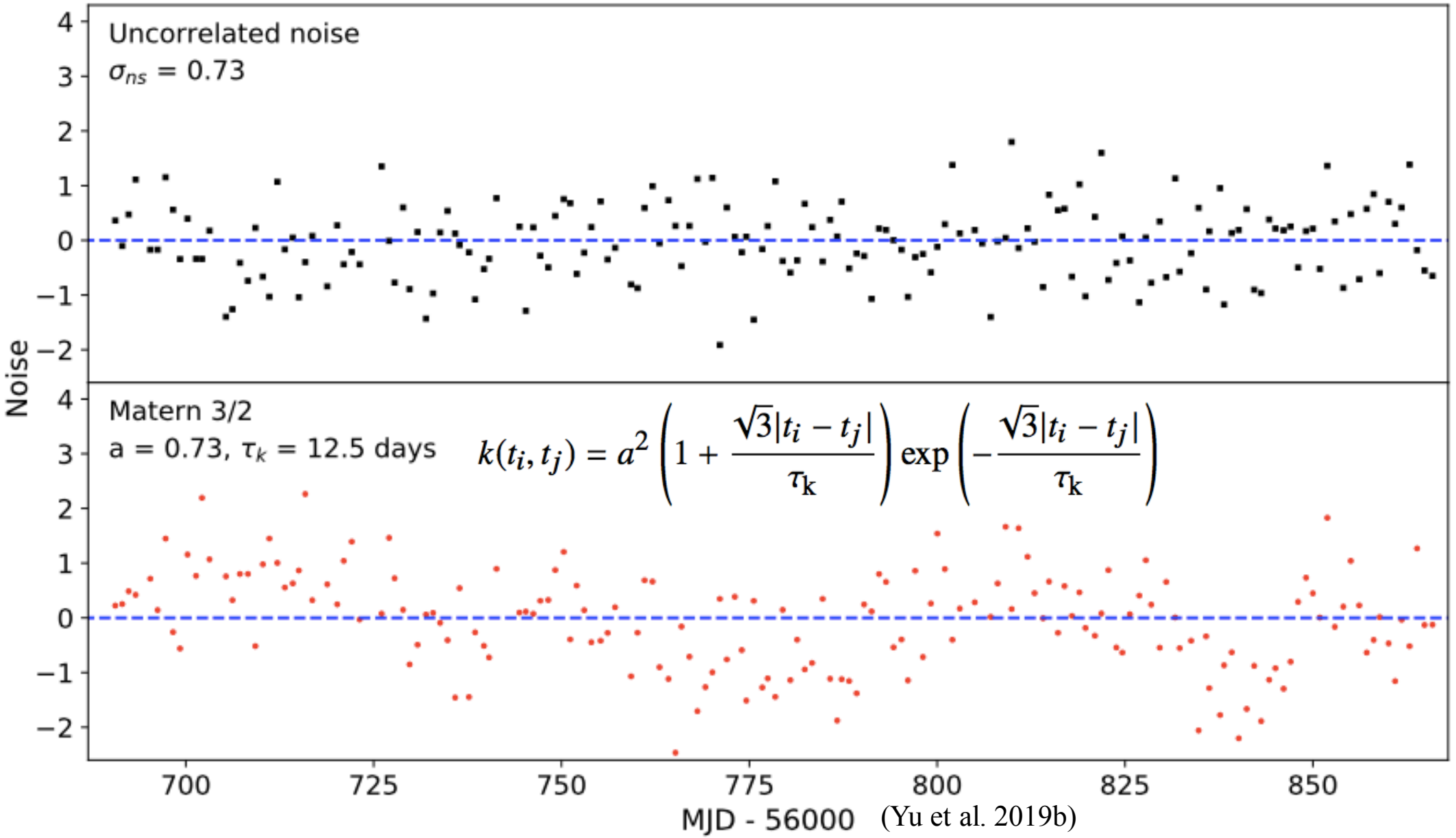
Summary

- Systematic study on lag uncertainties with simulated lightcurves
- JAVELIN gets closest to correct lag uncertainties in most circumstances, while ICCF tends to overestimate lag uncertainties. JAVELIN is more sensitive to incorrect single-epoch errors.
- Underlying stochastic processes and transfer functions do not significantly affect lag measurements.
- Both methods are significantly biased by additional sources of variability

(Related papers: Yu et al. 2019a: arxiv 1811.03638

Yu et al. 2019b: arxiv 1909.03072)

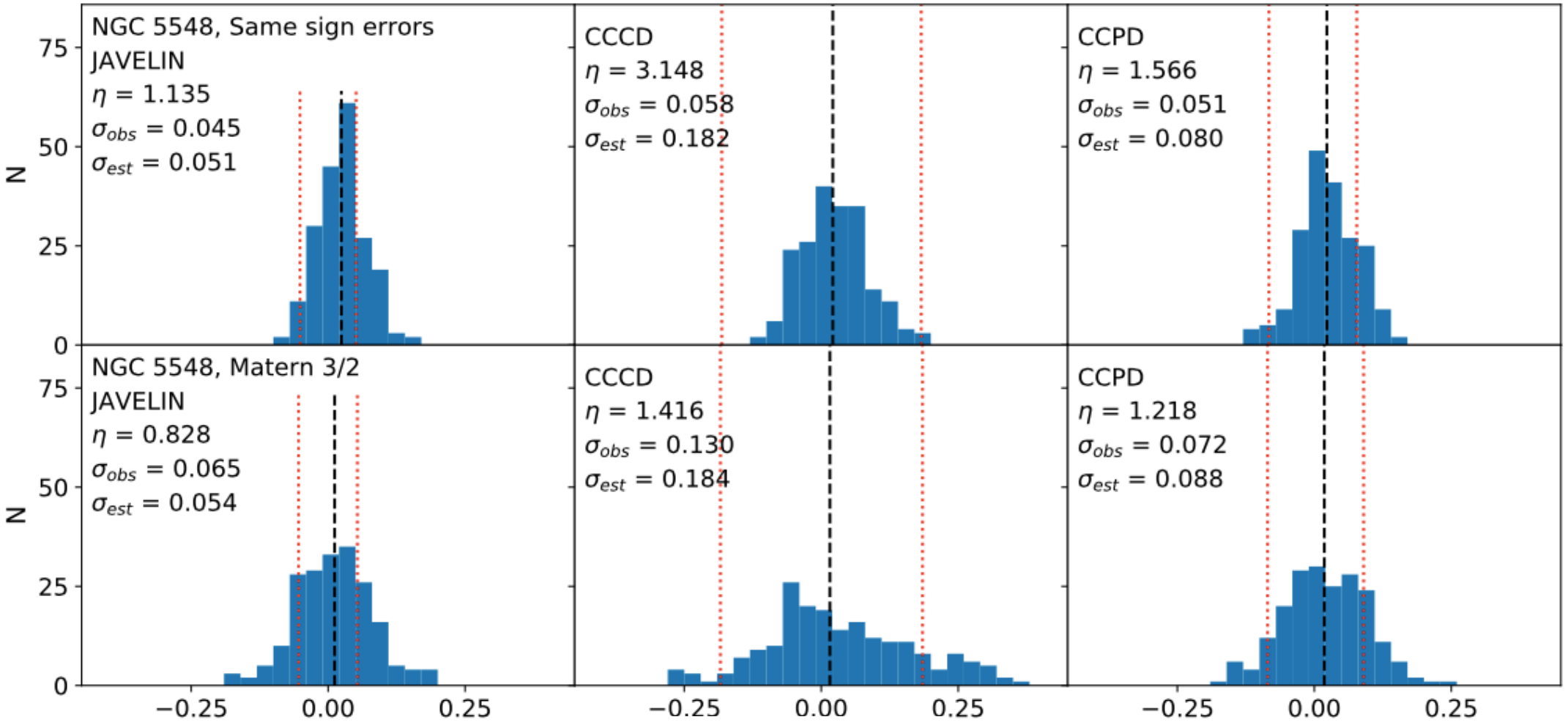
Correlated Errors



(Yu et al. 2019b)

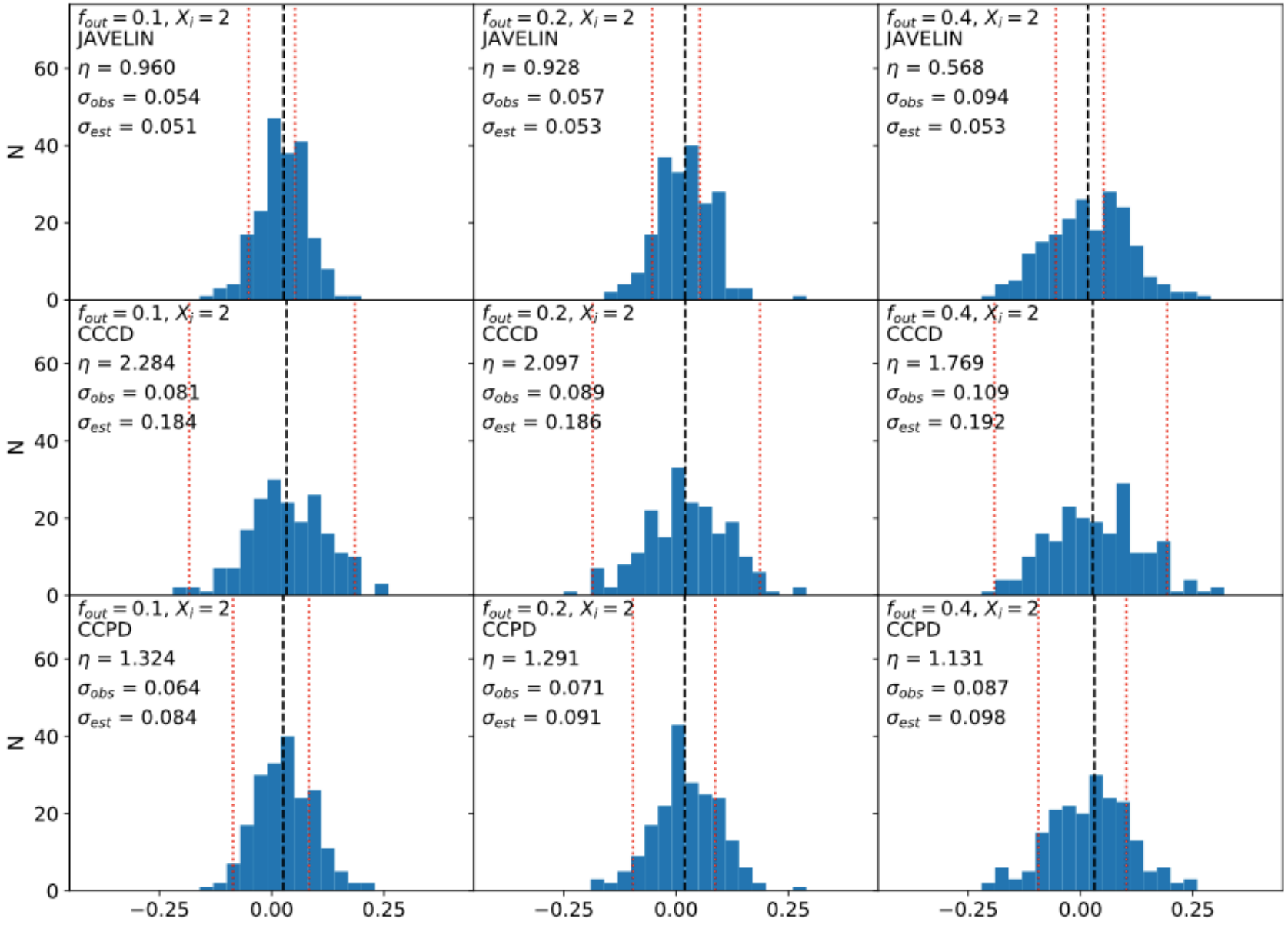
Result: Correlated Errors

- No effect for the same sign errors
- Declination of η for the Matern 3/2 model



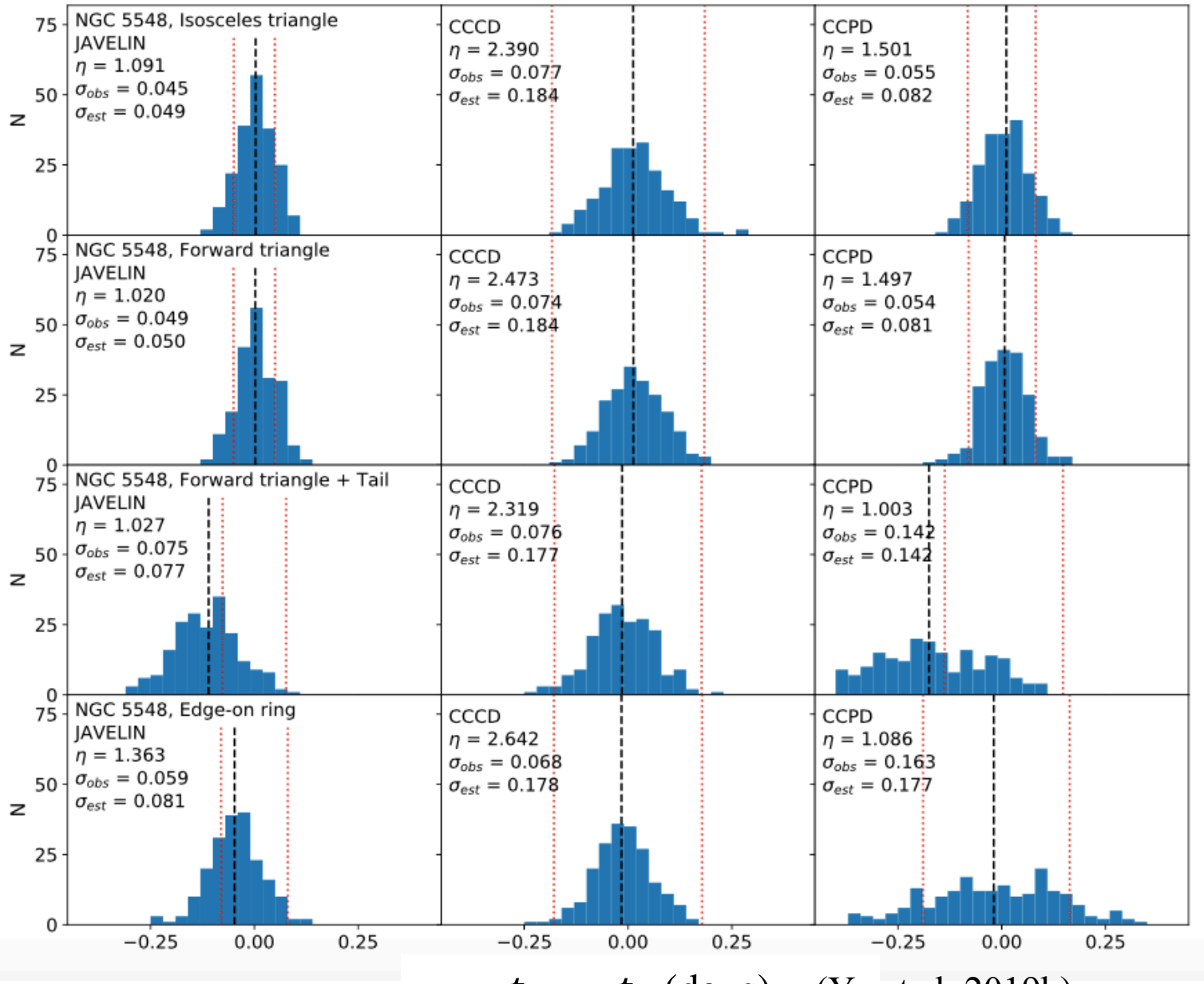
(Yu et al. 2019b)

Effect of Outliers



(Yu et al. 2019b)

Transfer functions: results



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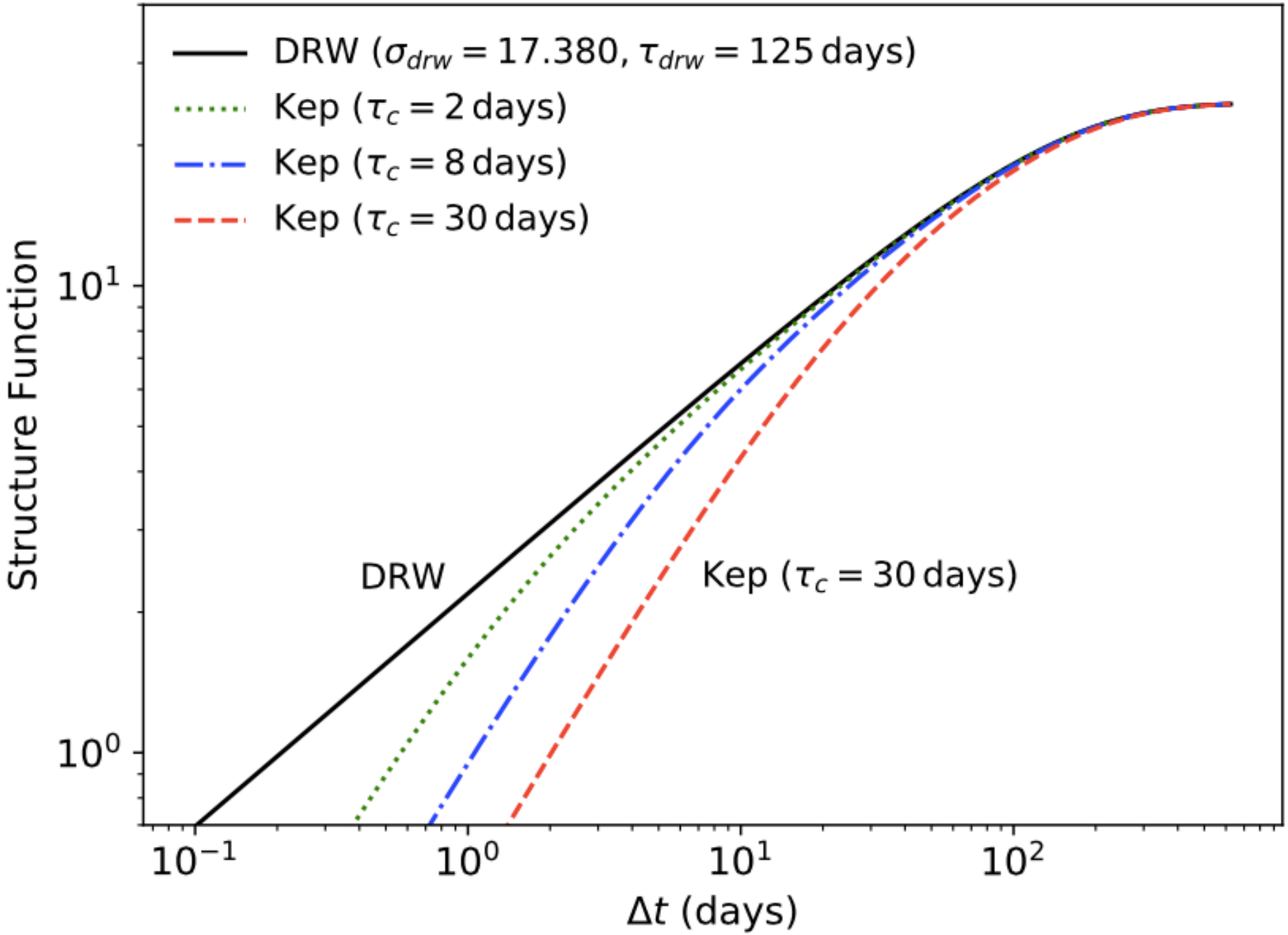
DRW ($\sigma_{drw} = 17.380$, $\tau_{drw} = 125$ days)
Kep ($\tau_c = 2$ days)
Kep ($\tau_c = 8$ days)
Kep ($\tau_c = 30$ days)
DRW
Kep ($\tau_c = 30$ days)
Structure Function
10^1
10^0
10^{-1}
10^0
10^1
10^2
Δt (days)