

Background

TORMAC (TORus Reverberation MAPPING Code) [1, 2] is a radiative transfer simulation that models the infrared (IR) reverberation response of an active galactic nuclei (AGN) dust distribution from its physical geometric parameters (see Table in results and Knutson's poster). This IR response encodes the AGN dust structure's geometry. However, extracting geometrical information from IR reverberation responses requires model-fitting to the observed data.

In theory, each AGN dust distribution geometry has a defined transfer function, which is its response to a δ -function pulse. We approximate this transfer function with TORMAC by using a short square-wave impulse of finite height, yielding the response function $\Psi(\tau)$ [2]. The IR response to any optical light curve can then be obtained with a simple convolution with $\Psi(\tau)$, without the need to re-run a full simulation for each new input light curve.

This motivates the creation of a pre-computed library of response functions spanning the AGN torus parameter space, which would enable the ability to model IR response curves without the computational cost of a full simulation.

Method

- The response function $\Psi(\tau)$ is modeled by running TORMAC with a δ -like optical input, consisting of a single square wave pulse.
- The IR response to an optical light curve (F_{opt}) is defined by the following convolution [2]

$$F_{\text{IR}}(t) = \int_{-\infty}^{\infty} F_{\text{opt}}(t - \tau) \Psi(\tau) d\tau$$

- Equivalently, the response can be found using a multiplication of the response function and driving light curve in frequency space:

$$F_{\text{IR}} = \mathcal{F}^{-1}[\mathcal{F}(F_{\text{opt}}) \cdot \mathcal{F}(\Psi)]$$

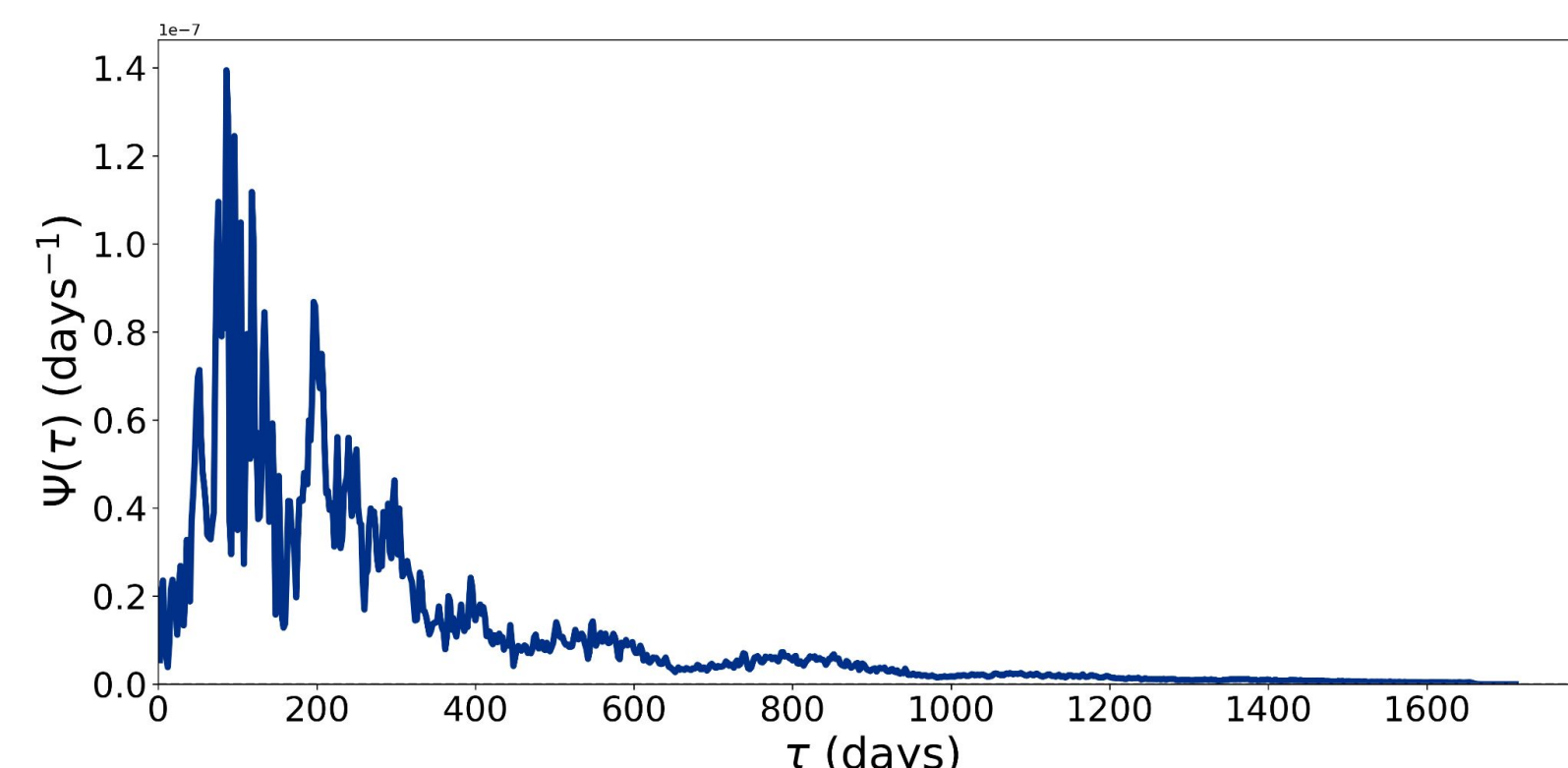


Fig. 1. (right) Example response function $\Psi(\tau)$ extracted from TORMAC using δ -like optical input, normalized to units of days^{-1} and quiescent-subtracted

Normalizing $\Psi(\tau)$:

1. Subtracting & storing quiescent state $\Psi_{\text{min}}(\tau)$ from $\Psi(\tau)$
2. Divide $\Psi(\tau)$ by the area of the input pulse [$L \cdot \text{days}$] so that its units become days^{-1}

Normalizing F_{opt} :

3. Scale F_{opt} max to the bolometric luminosity L_{AGN}
4. Subtract mean to remove constant offset from convolution

Then:

5. Multiply in frequency space (FFT), compute inverse (IFFT)
6. Multiply result by response function Δt , shift up by $\Psi_{\text{min}}(\tau)$

Preliminary Results

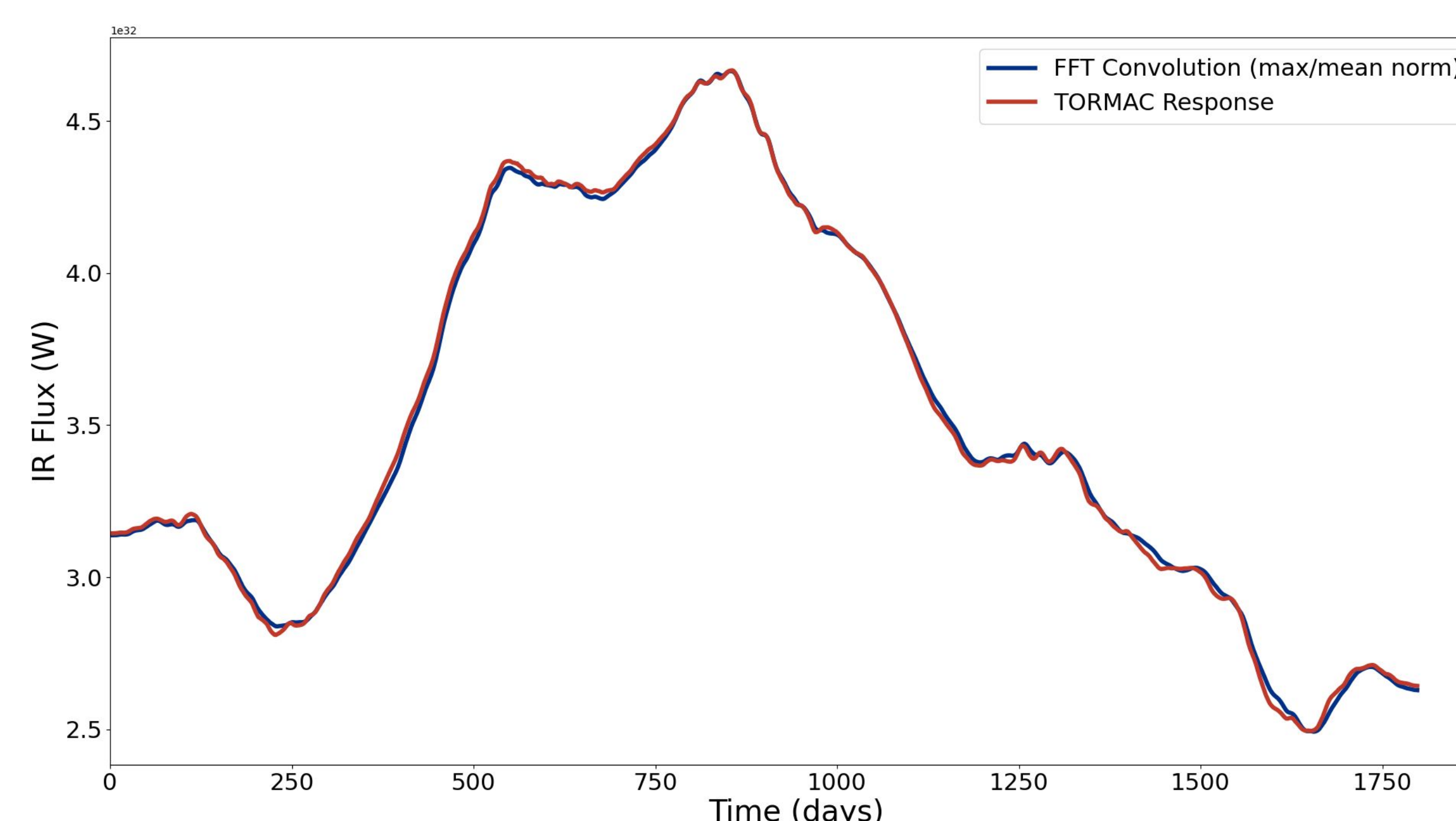


Fig. 2. (above) FFT-convolved IR response (blue) compared to direct TORMAC output (red) for NGC 3783 [3] using modest radial extent ($y_{\text{max}} = 10$) and power law index of 1 ($p = 1$) for cloud distribution. The resulting curves match strongly in variance and amplitude, with slight deviations.

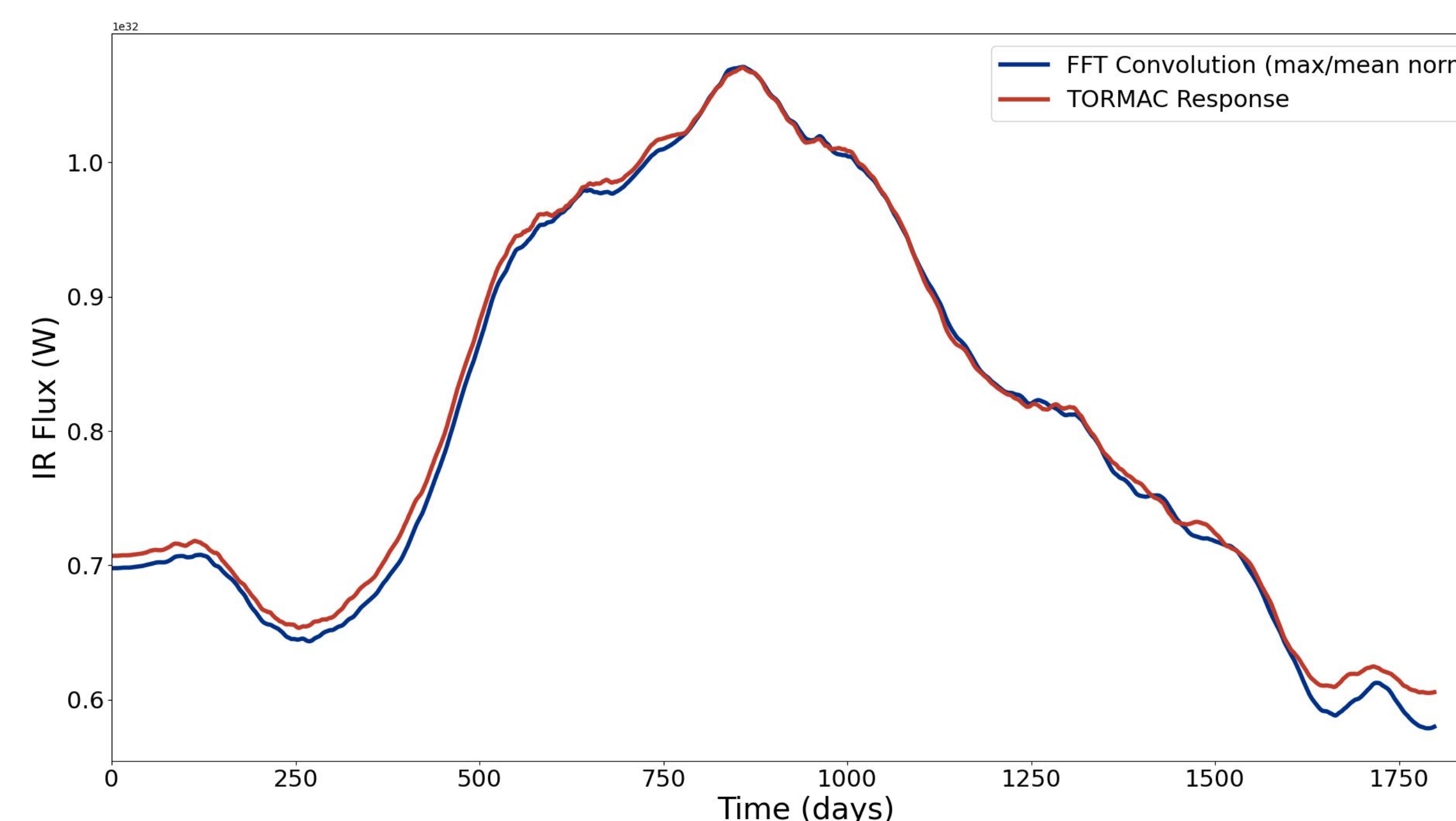


Fig. 3. (below) FFT-convolved IR response (blue) compared to direct TORMAC output (red) for NGC 3783 [3], using the same parameters as Fig. 2, except for using a power law index of 2 ($p = 2$) for cloud distribution. This change in parameters leads to greater deviations, especially at lower flux values.

Parameter	Fig. 2.	Fig. 3.
$\sigma, \sigma_{\text{pol}}$ (angular width)	$2^\circ, 2^\circ$	$2^\circ, 2^\circ$
Y, Y_{pol} (ratio of outer to inner radii)	10, 10	10, 10
i (inclination)	0	0
p, p_{pol} (radial dust distribution)	1, 1	2, 2
Φ, Φ_{pol} (volume filling factor)	0.0001	0.0001
ϕ_{mid} (opening angle)	10	10
f_{cl} (cloud fraction distribution)	0.333	0.333

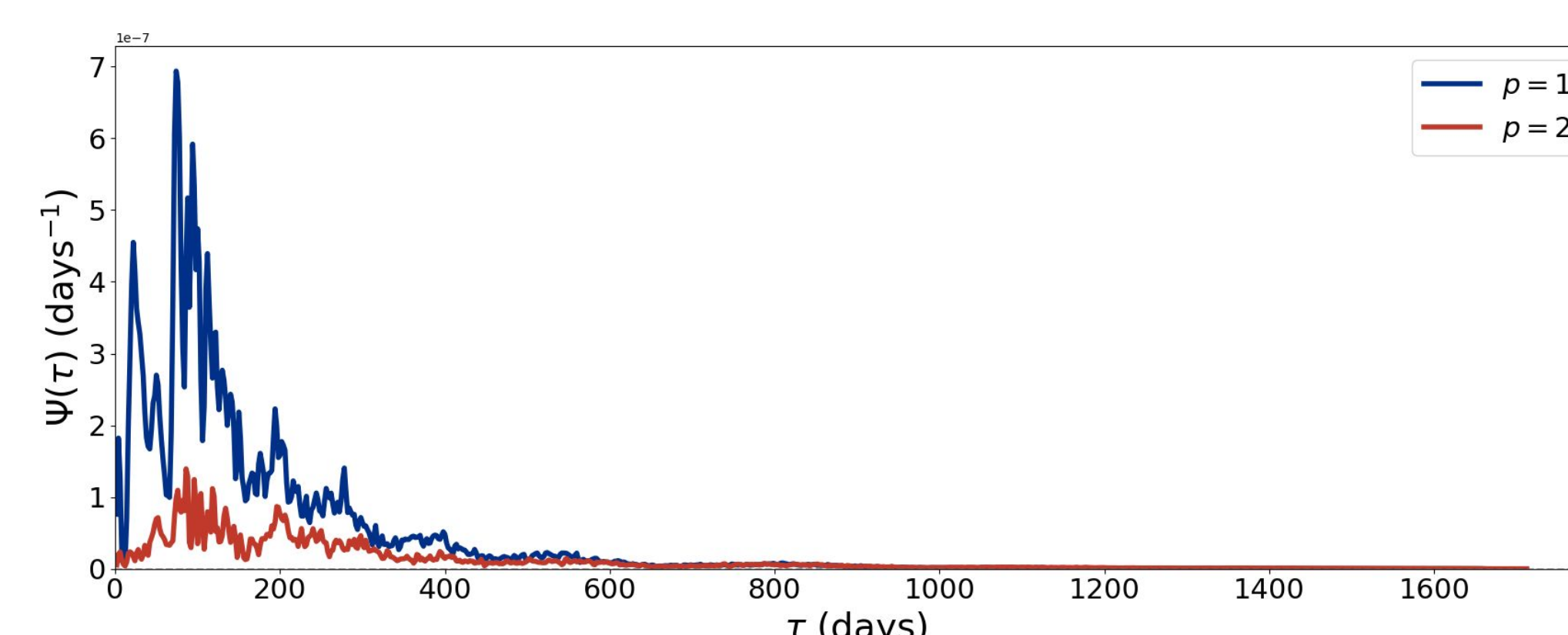


Fig. 4. (left) Comparison of response functions $\Psi(\tau)$ for convolved curves shown in Fig. 2-3

Conclusions

Using FFT convolution between an optical light curve and response function can successfully reproduce the TORMAC IR response, demonstrating that a pre-computed $\Psi(\tau)$ may be able to replace a full simulation.

However, agreement degrades for different torus parameters, as shown by the $p = 2$ case. The differences in $\Psi(\tau)$ shape between parameter sets suggest the response function may carry some parameter dependence, and that further work is needed to understand and characterize this dependence before a reliable response function library can be created.

In Progress & Future Work

Identifying sources of deviation

Convolved IR response should theoretically match TORMAC exactly

- Testing a simplified spherical torus with no polar wind, shadowing, or cloud occultation
- Systematically re-enabling components to isolate what causes the deviation between the convolved and TORMAC responses
- Testing different methods of normalization to better understand the effects of cloud saturation on the convolved response

Delta impulse height dependence

Pulse height appears to affect the normalized shape of $\Psi(\tau)$

- Best agreement when impulse-to-quiescence ratio matches the max/mean flux ratio of the driving light curve
- Underlying cause and proper methodology for setting pulse height still under investigation

Next steps

- Establish a robust, physically motivated normalization for the input pulse
- Run TORMAC across the full torus parameter space to build the response function library
- Publicly release the library to enable AGN IR reverberation modeling without high-performance compute

References

- [1] Almeyda, T., et al. 2020, ApJ, 891(1), 26
 [2] Almeyda, T., et al. 2017, ApJ, 843(1), 3
 [3] Lira, P., et al. 2011, MNRAS, 415(2), 1290–1303