PyStarshade: A Python starshade simulation tool for modeling contrast with exoplanetary scenes

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Forward optical model

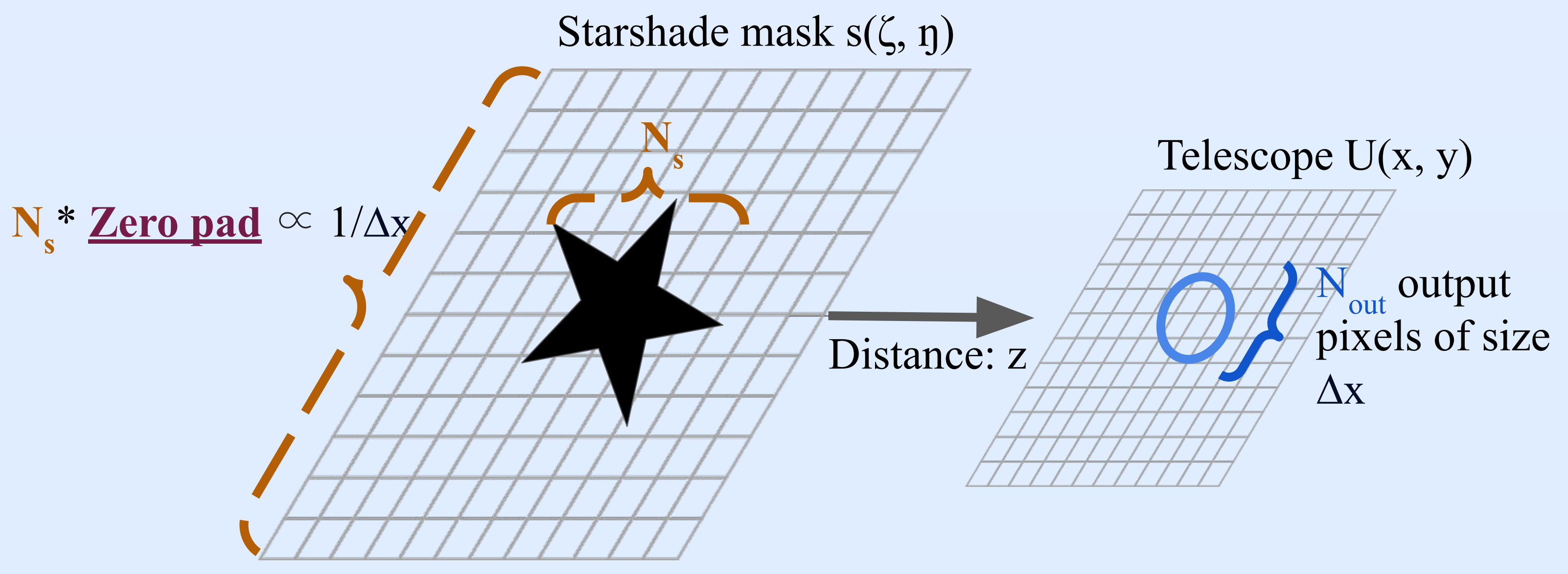
At the telescope, the propagated field past a starshade mask:

$$U(x,y) \sim \mathcal{F}\left(f_{\lambda,d}(\zeta,\eta)s(\zeta,\eta)e^{\frac{j\pi}{\lambda z}(\zeta^2+\eta^2)}\right)\left[\frac{x}{\lambda z},\frac{y}{\lambda z}\right]$$

Starshade optical propagation requires fine sampling of the mask to sample the oscillatory chirp term, and accurately simulate contrast below 10^{-10}.

NGRST starshade rendezvous example:

N_s * $\Delta\zeta$ is the starshade diameter ~ 26m
N_{out} * Δx is the telescope diameter ~ 2 m
$z \sim 7 * 10^7$ m   fresnel number ~ 15



Δζ set to ensure aliasing error < 10^{-10} contrast

Efficient simulation with a Bluestein FFT

PyStarshade uses a Bluestein FFT to calculate arbitrary spectral samples of a DFT:

$$X[k] = \sum_{n=0}^{ZP\cdot N_S-1} s[n]e^{\frac{-j2\pi kn}{ZP\cdot N_S}}$$

$$X[k] = e^{\frac{-j\pi k^2}{ZP\cdot N_S}} \sum_{n=0}^{ZP\cdot N_S-1} s[n]e^{\frac{-j\pi n^2}{ZP\cdot N_S}} e^{\frac{-j\pi (n-k)^2}{ZP\cdot N_S}}$$

$$X[k] = e^{\frac{-j\pi nk^2}{ZP\cdot N_S}}(a_n * b_n)_k$$

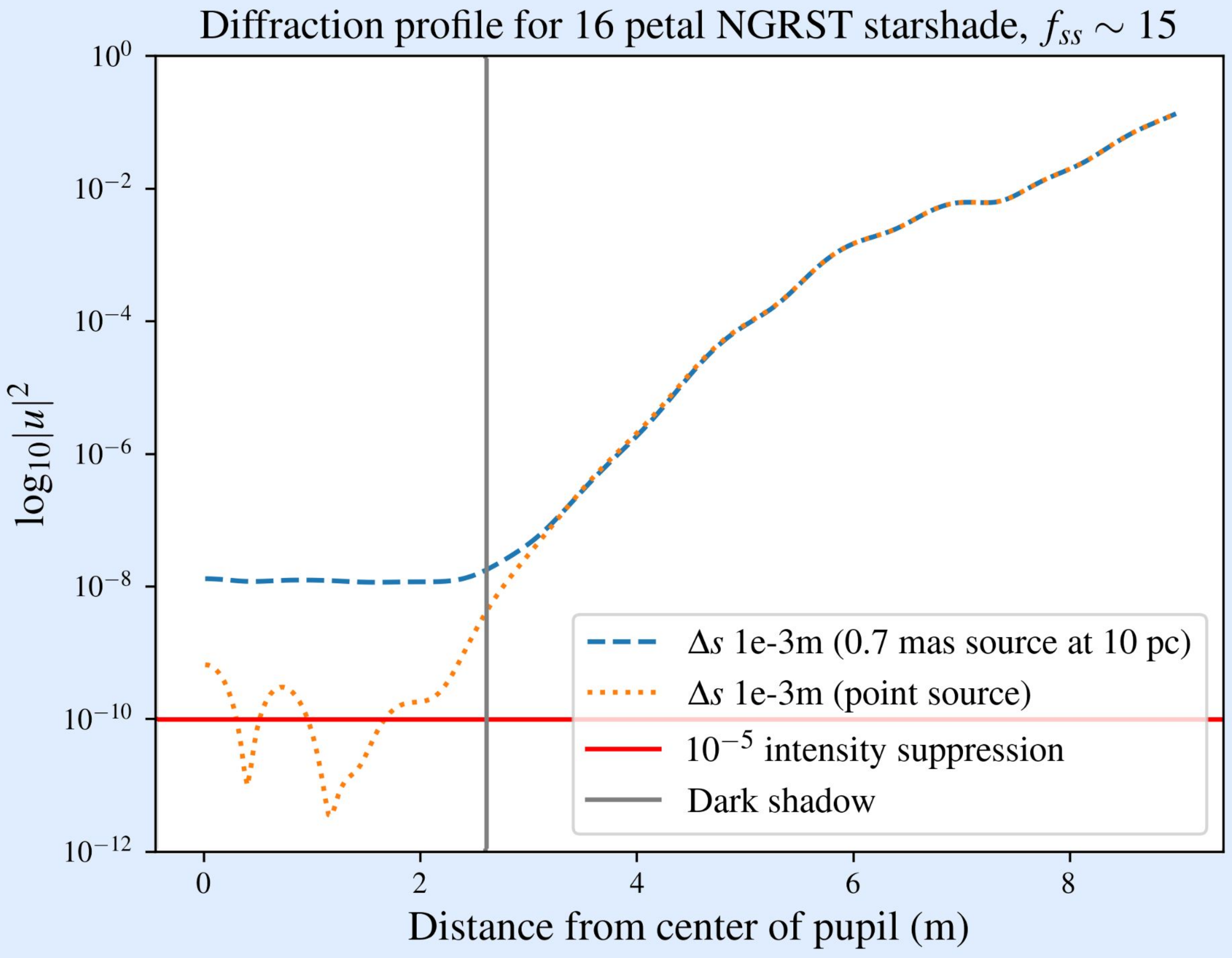
A Bluestein FFT indirectly uses FFTs to obtain complexity $O((N_s^2 + N_{out}^2)\log(N_s + N_{out}))$ with no zero-padding! Furthermore, can perform chunked FFT's (parallelizing both input and output) avoiding memory bottlenecks when performing large 2D FFT's.

Validation

Comparison with alternate simulation approaches *Diffraq* (err < 10^{-16}). Comparison with an approximation of the analytic Fresnel diffraction for a circular mask via a truncated expansion of Lommel variables (err < 10^{-6}).

Simulations

Case study 1: Modeling finite stellar diameter (our Sun 0.7mas at a distance of 10 pc) starlight suppression is reduced compared to ideal point source.



Case study 2: Assessing realistic starshade imaging performance for both the NGRST and HabEx starshades on physically plausible exoplanetary scenes simulated with exoVista which include dust, and planets within the IWA .

Future work entails using PyStarshade on ensembles of scenes to simulate PSF data and develop PSF model-approximation and calibration.

github.com/xiaziyna/PyStarshade
pip install pystarshade

Parameter	Scene 1 (1215)	Scene 2 (894)
Distance [pc]	3.2	7.2
Star type	K2V	K3V
Star/planet contrast	1: $1\cdot10^{-7}$ 2: $2\cdot10^{-9}$ 3: $5\cdot10^{-10}$ 4: $1\cdot10^{-10}$ 5: $3\cdot10^{-8}$	1: $3\cdot10^{-8}$ 2: $6\cdot10^{-8}$ 3: $3\cdot10^{-10}$ 4: $5\cdot10^{-11}$ 5: $6\cdot10^{-10}$ 6: $6\cdot10^{-11}$ 7: $1\cdot10^{-11}$ 8: $9\cdot10^{-13}$ 9: $3\cdot10^{-10}$ 10: $3\cdot10^{-10}$
Semi-major axis [AU]	1: 0.05 2: 0.07 3: 0.62 4: 0.76 5: 0.83	1: 0.31 2: 0.72 3: 0.91 4: 1.27 5: 1.70 6: 2.46 7: 4.71 8: 3.65 9: 4.74 10: 7.28
Inner zodi level	0.05	0.6
Outer zodi level	0.04	1.4
IWA (NGRST) [AU]	0.38	0.74
IWA (HabEx) [AU]	0.2	0.43
FOV shown [AU]	6.4	14.4