PSF Subtraction for Space Telescopes

(but mostly JWST)

EUREKA Seminar

2025-12-06

Why model the PSF?

- Photometry, especially in crowded fields of point sources

- Subtract it away:
    - Quasar and AGN host galaxies
    - Exoplanet/debris disk studies
    - More precision required

- Get smaller angular separations than a coronagraph allows

Science image:
(PSF + extended
component + noise)

PSF reference
(with or without noise)

Extended emission
+ statistical noise
+ systematic noise

Key components:

- Design of observations
- Construction of reference PSF to *minimize PSF mismatch*

What causes PSF variation?

- **Flux** variation: “Brighter-fatter effect”
    - broader PSFs at large flux (charge deflection)
- **Time** variation (from changes to telescope wavefront)
    - JWST wavefront is corrected ~2-3 times/month
    - Observations happen continuously
- **Spatial** variation across detector
    - Different optical paths = different distortion at different pixel locations
- Variation with **spectral shape**
    - PSF in photometric filter is a superposition of multiple wavelengths
    - Convolution of source spectrum w/filter affects PSF shape
    - Redder spectral shape = broader PSF

(intermission: Jupyter Notebook)

Strategies for modeling the PSF

I. Simulating a reference PSF

How: Create a simulated PSF, incorporating most instrumental effects using the STPSF package, and subtract from the science image

Pros:

- No extra statistical noise added (simulated PSF is noiseless)
- No extra observation time

Cons:

- STPSF does not include all instrumental effects (e.g. brighter-fatter) and artifacts; wavefront variation not perfectly sampled
- Can be difficult to align/normalize

Best practices:

- Simulate the PSF at the target's detector position
- Use JWST wavefront measured on orbit near observation time

II. Single-star empirical PSF

How: Observe a PSF star immediately before/after the science target and subtract its image from the science image

Pros:

- Wraps in all telescope effects
- Minimizes residuals - single PSF most analogous to science target's

Cons:

- Adds additional statistical noise from the star image
- Requires extra exposure time and (especially) overhead

Best practices:

- Science target, reference star observations performed identically (except for exposure time)
- High SNR for reference star without approaching nonlinearity

III. Multi-star empirical PSF

How: Use stars in the image to construct an empirical PSF w/e.g. **`galight`** or **`photutils`** and subtract from science image

Pros:

- Creates high-SNR reference PSF without extra exposure time*
- Takes all wavefront effects into account*

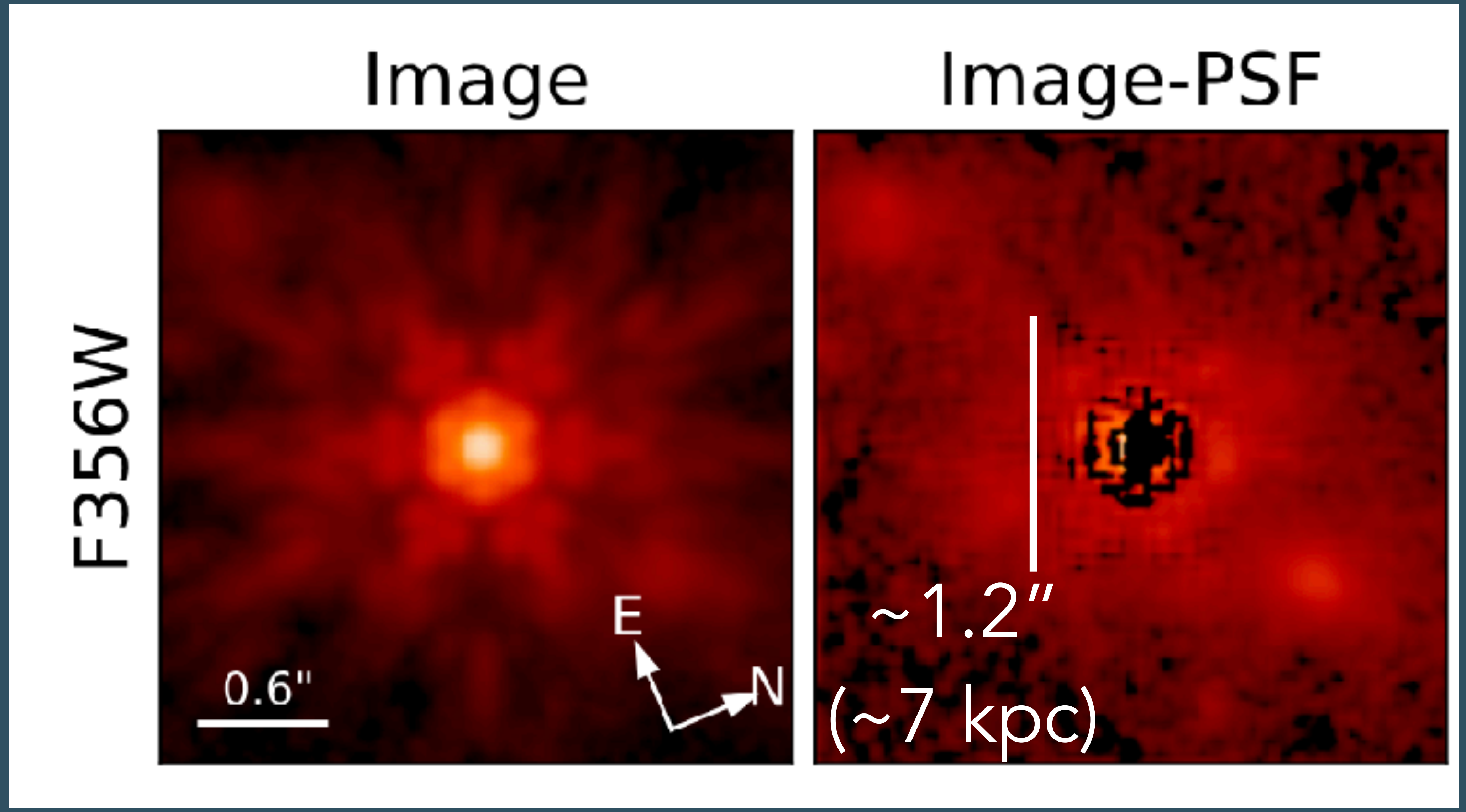
Cons:

- Adds additional statistical noise from the star images
- Requires enough stars in the field to construct PSF: typically survey/mosaic observations
- Produces broader PSF w/worse residuals due to PSF variation across the field

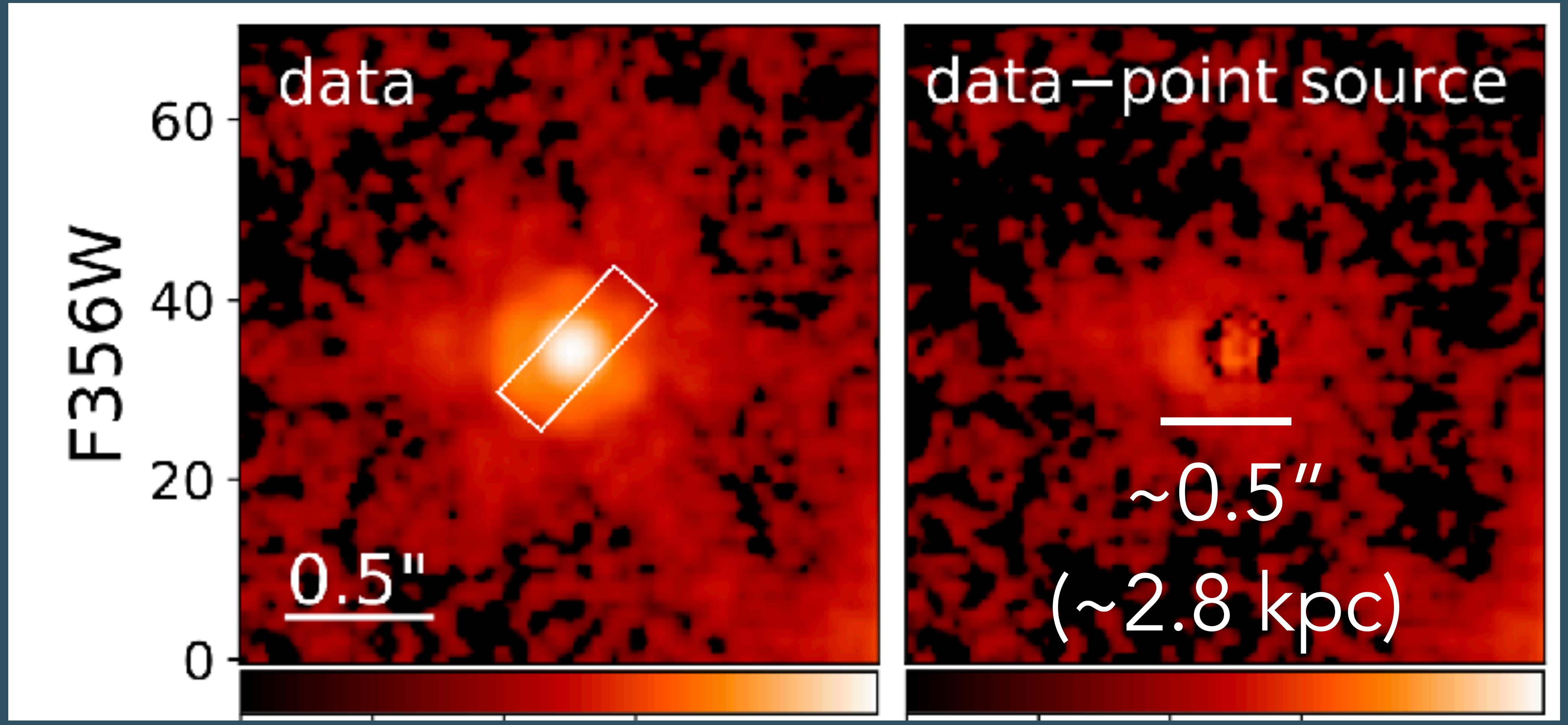
Best practices:

- Enough stars to reject the very bright/close to the edge of the detector
- Ensure no other quasars/debris disk stars are included in PSF building

Which method works best?

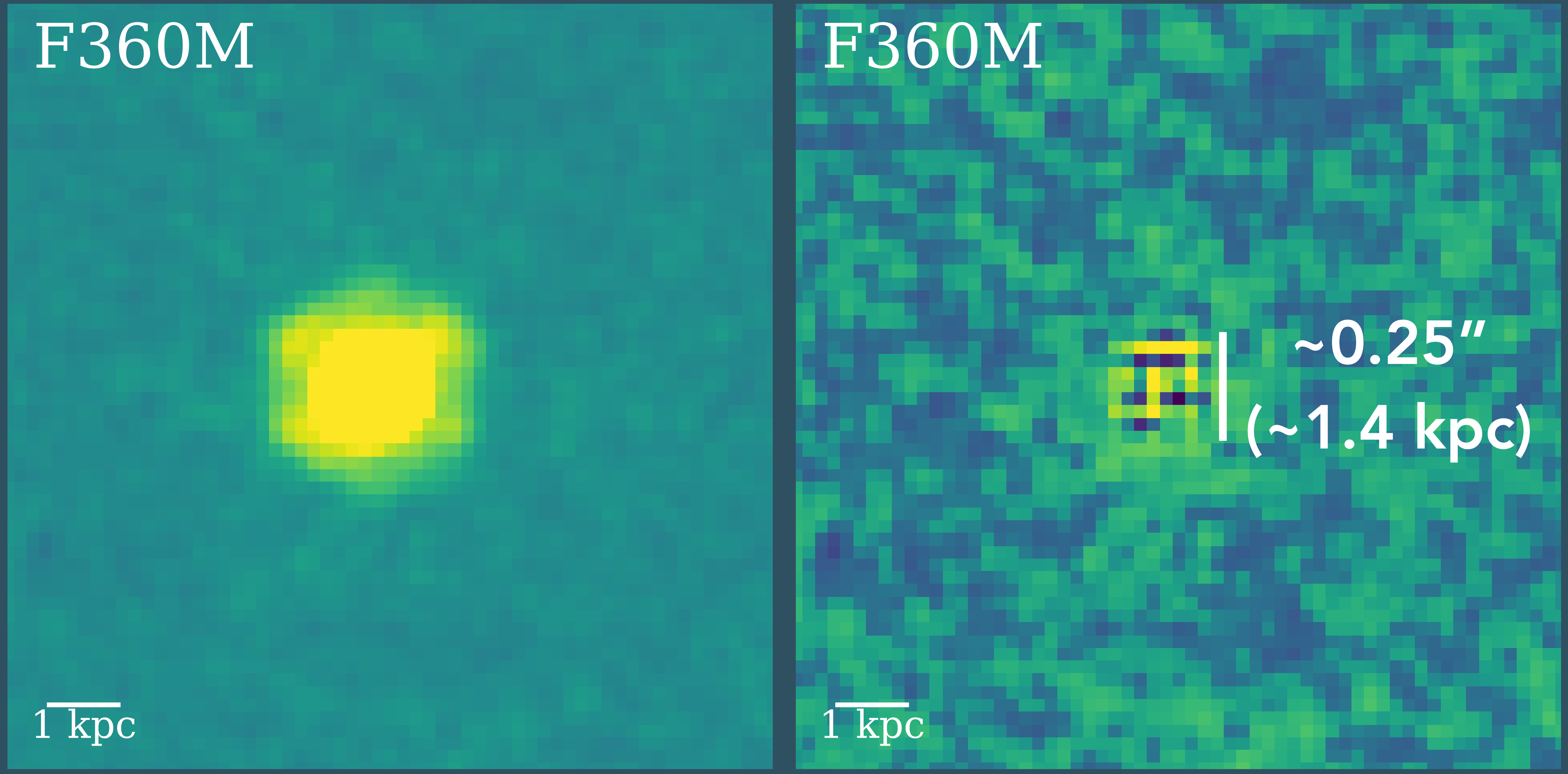


M. Yue et al. (2024), J0148+0600 (z = 5.98)



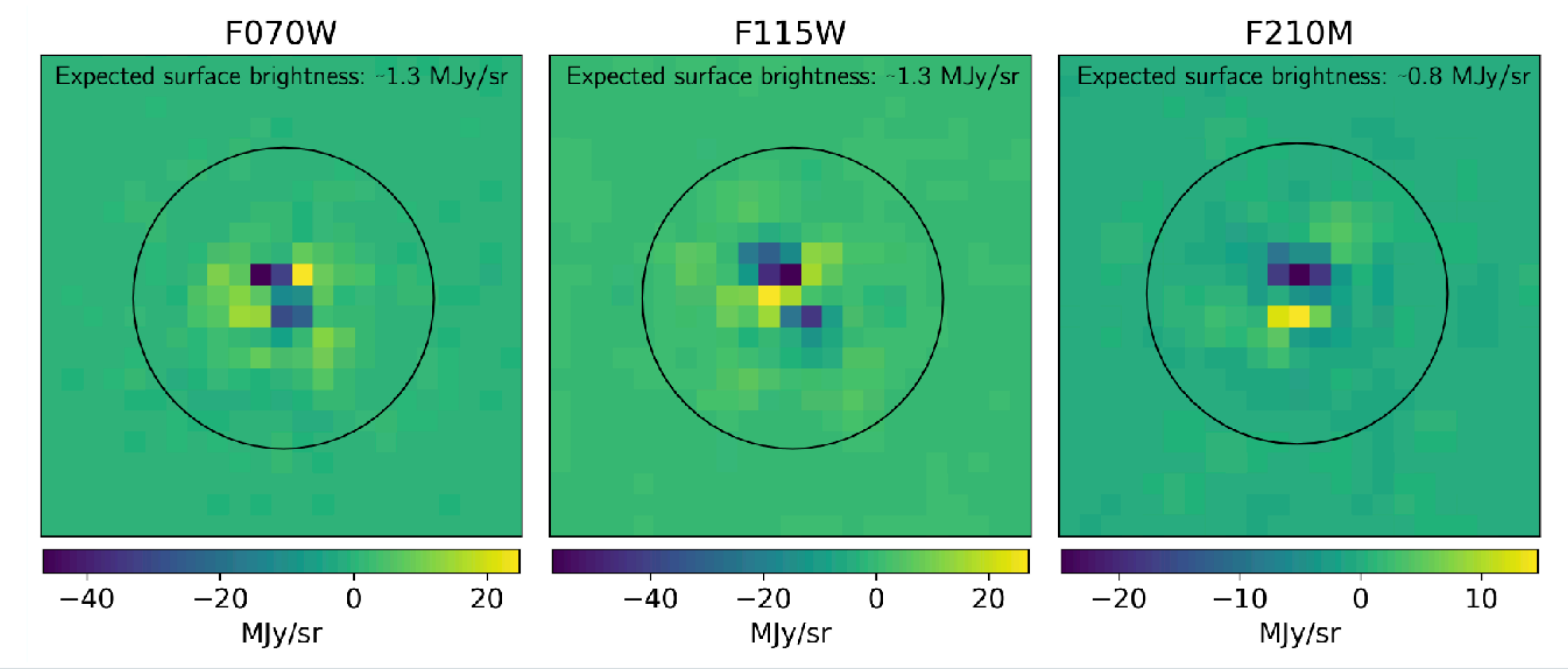
X. Ding et al. (2023), J2255+0251 (z = 6.34)

Medium bands + dedicated PSF star = best residuals, but harder to achieve SNR



Stone et al. (2023), J2239+0207 (z=6.25)

Which method works best?



Proudfoot et al. (2025); searching for companions to KBO Quaoar

STPSF results have improved significantly since 2022/23: still not useful within ~0.2″ of center

Planning observations

- **If subtracting a stellar PSF**, narrower bands = less variation due to spectral shape. = better residuals
    - Medium bands yield good residuals, but tougher to reach desired SNR

- Ensure PSF is well-sampled
    - Dithering helps ensure empirical PSF matches science image
    - Subpixel dithering if operating in LW channels to get Nyquist sampling

- Special requirements
    - Timing - the closer together, the better
- More sophisticated use of reference PSFs - see Schuyler Wolff et al. (2023)
    - Karhunen–Loéve Image Projection, Non-Negative Matrix Factorization - best for high S/N extended components