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Improving Direct Imaging of Exoplanets in Ground-based Mid-IR Observations

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ExoExplorers Talk

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SCHOOL OF PHYSICAL SCIENCES

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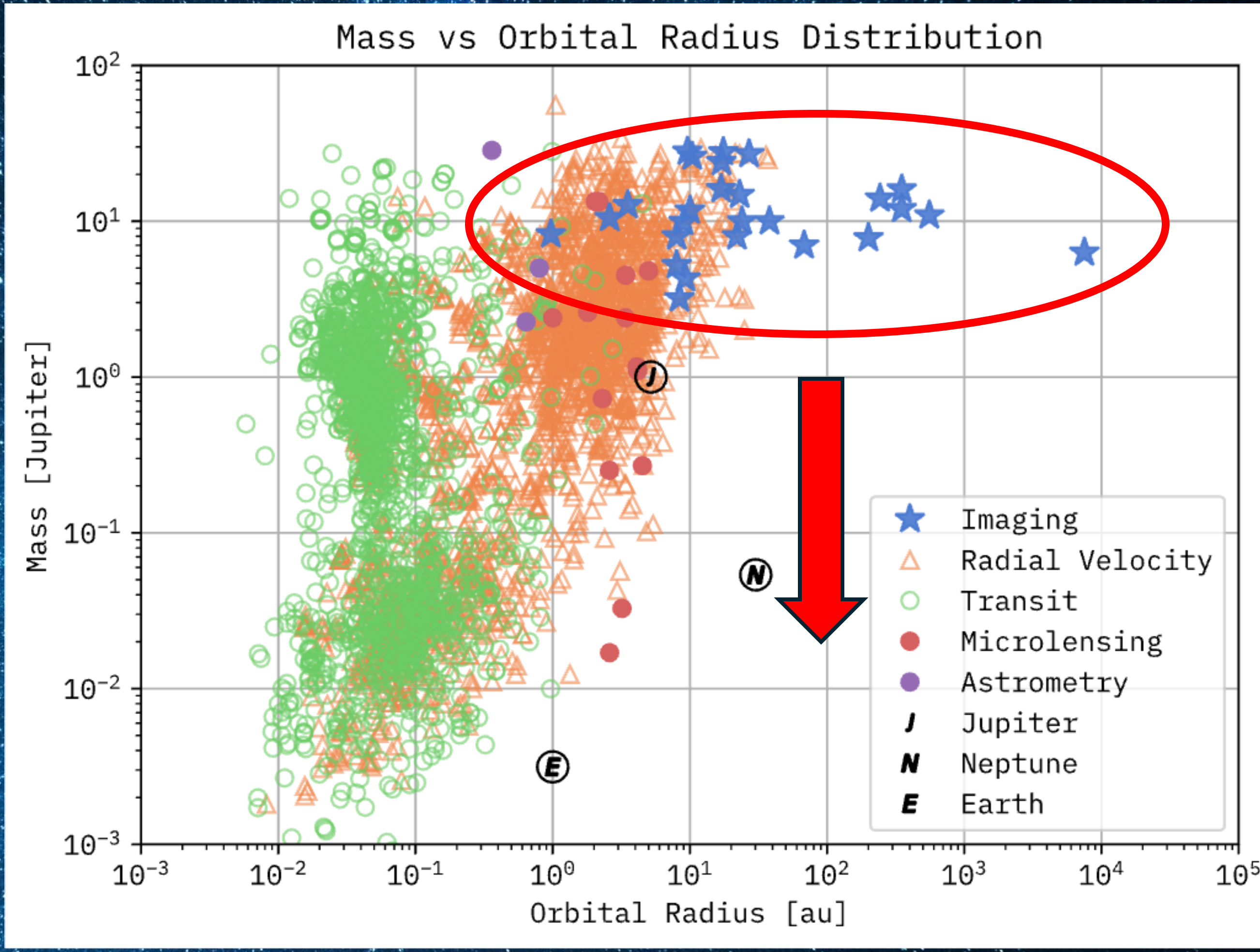
Direct Imaging

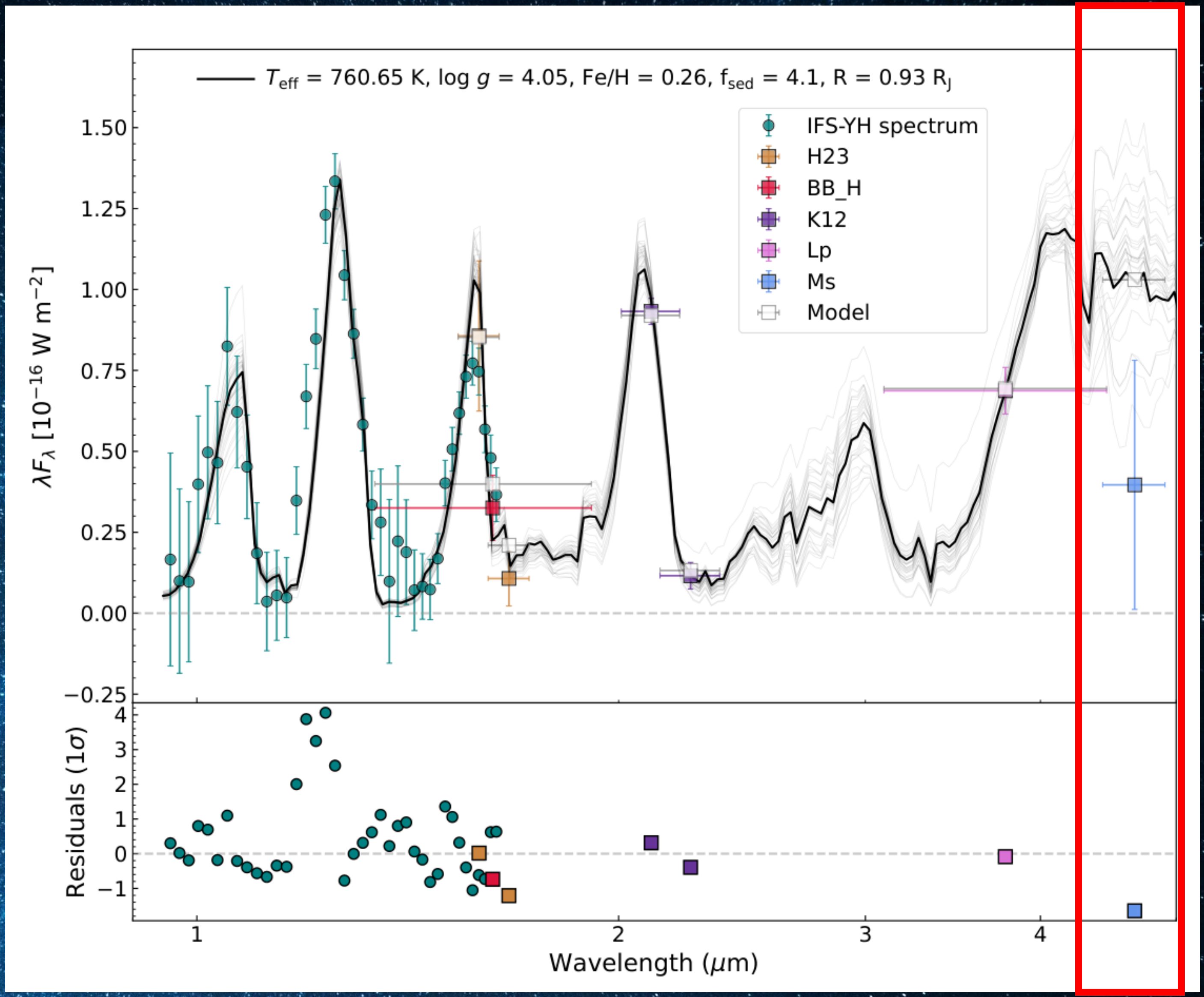
- Measuring the photons directly emitted from hot and massive planets
- Directly access planet atmospheres
- Typically observe planets in NIR wavelengths (1-3 μm)
- Want to measure **older and colder planets**



Science Goal

- Primary science goal is to directly image planets and disks in the mid-IR using M-band imaging on Keck with NIRC2
- Can model/derive atmospheric properties like:
    - C/O ratio
    - Disequilibrium chemistry
    - Cloud Coverage

51 Eri b Spectrum



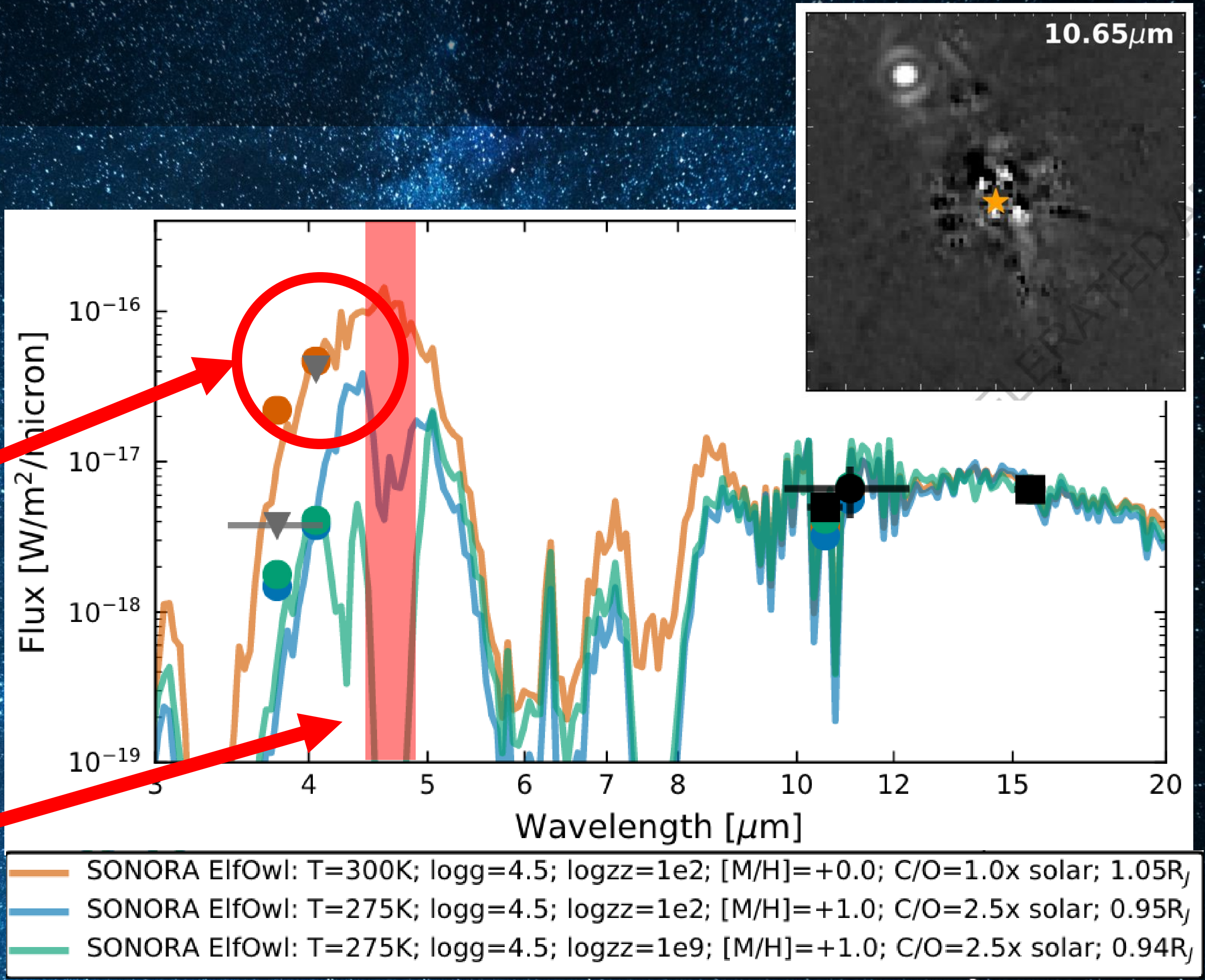
Brown-Sevilla et al. 2023

Eps Indi B

Widely separated cool target detected by JWST at >10 μm

Ground based measurement at 4 microns, set an upper limit in 2008

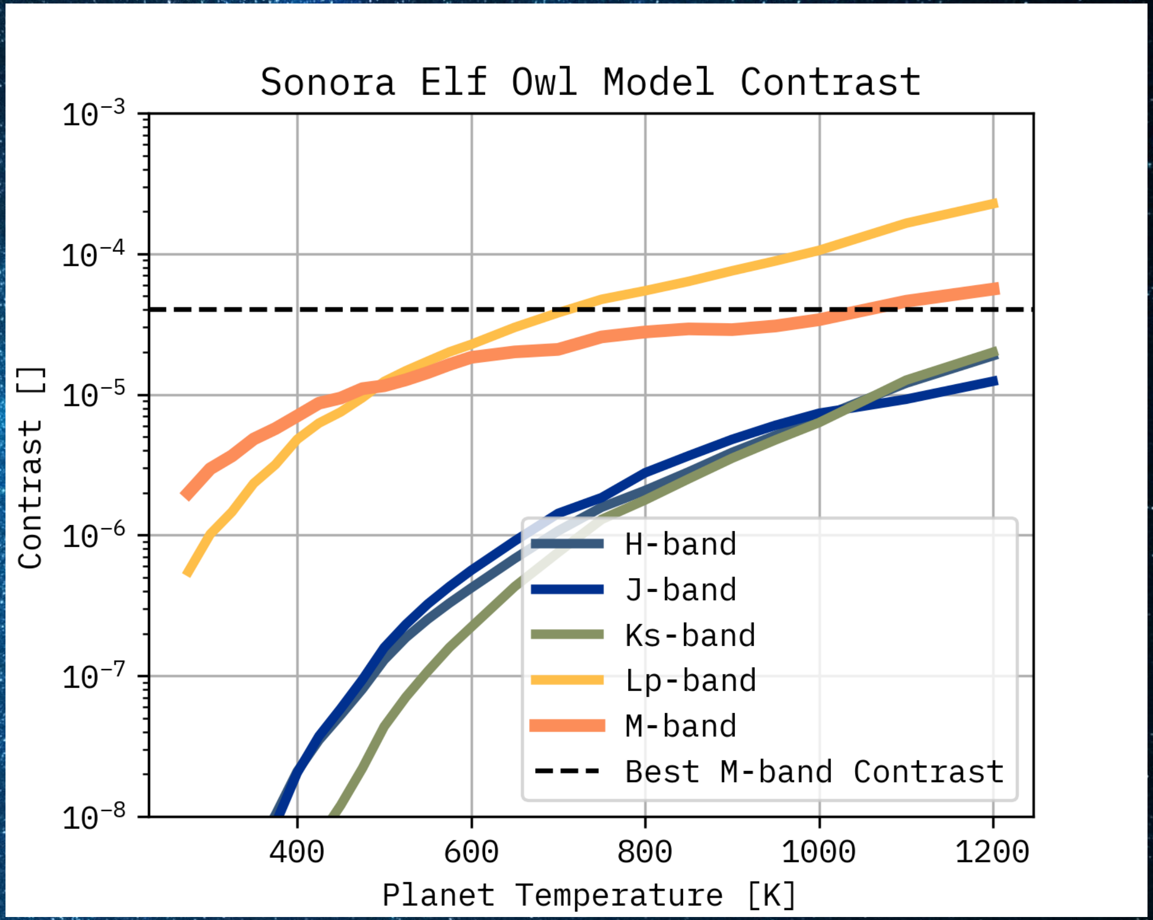
M-band data at (~4.7 μm) would have better constraining power than 4 μm



Matthews et al. 2024

Contrast Limits

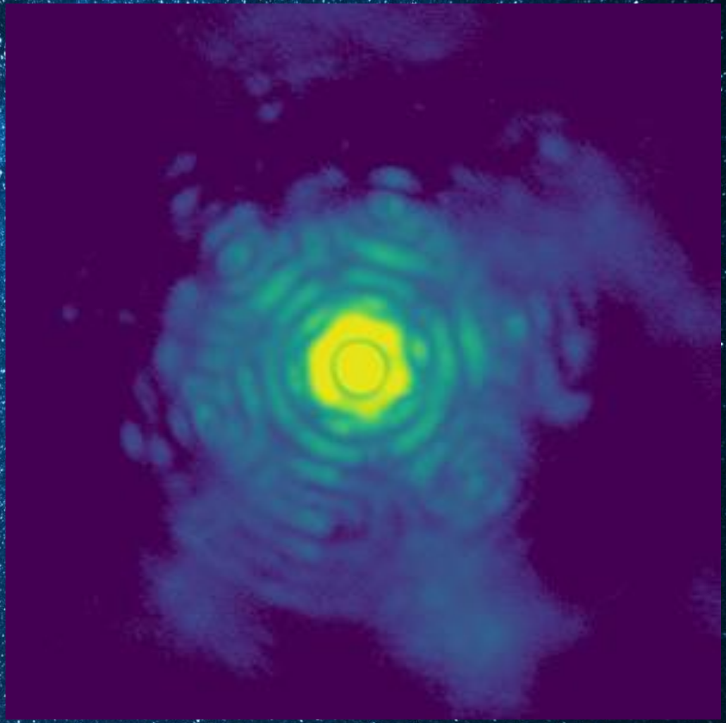
- **Host star/planet flux ratio (contrast) is typically better in M-band for very low temperatures**
- Only a little bit of improvement can vastly increase your sensitivity



Contrast estimated using Sonora Elf Owl planet models and PHOENIX stellar models

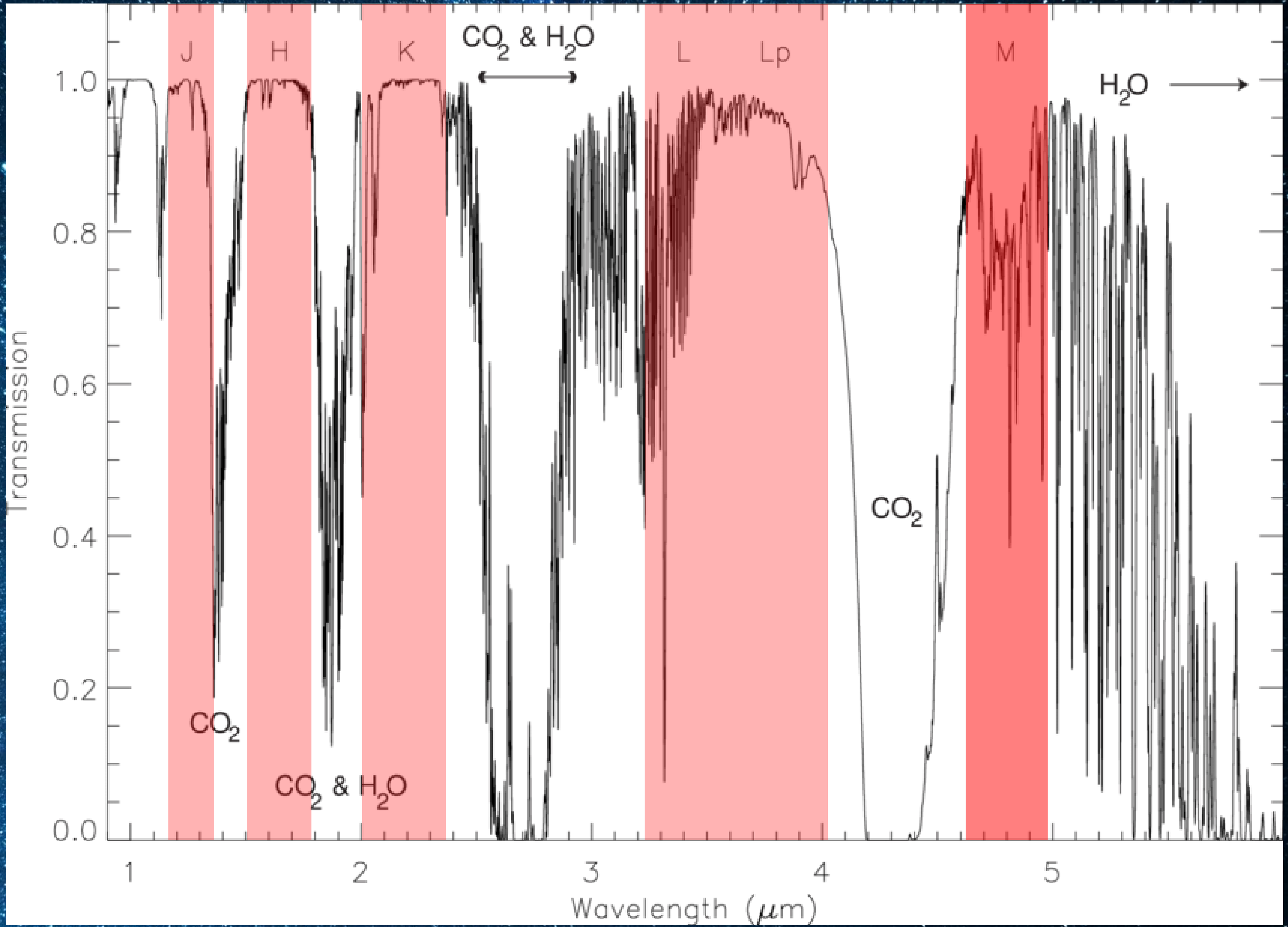
Observing Benefits of Mid-IR

- Exoplanets are generally brighter in M-band than other wavelengths
- AO system performs better
- Atmospheric coherence time scale is longer
- PSF is more stable throughout the night

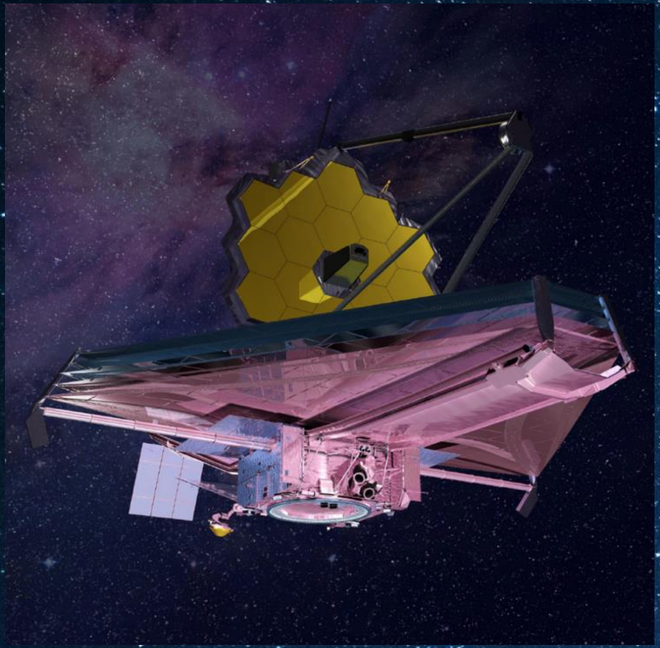


Problems in Mid-IR Imaging

- M-band is at 4.55 µm to 4.8 µm
- Atmospheric window is messy due to water vapor and absorption features
- **Seeing through blackbody emission from the atmosphere itself**



Ground Based Mid-IR



6.5m

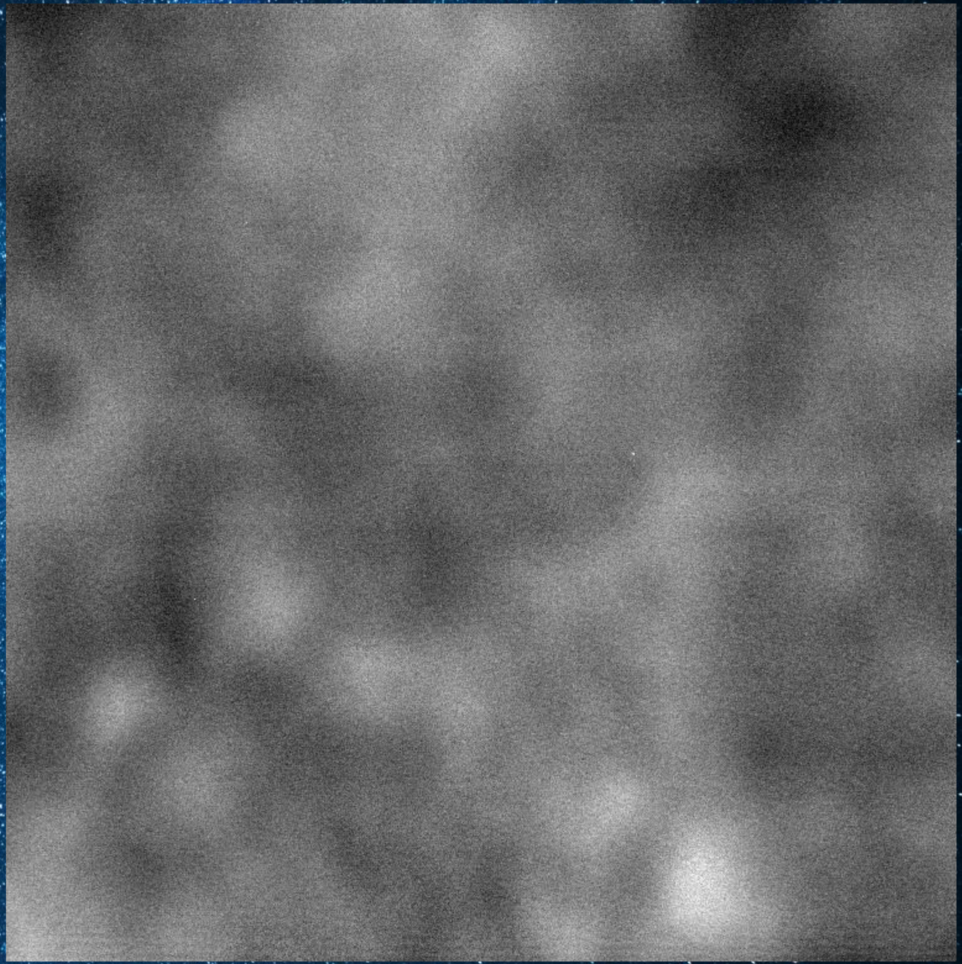
Larger apertures on the ground means higher angular resolution as you get to longer wavelengths

$$R \sim \frac{\lambda}{D}$$

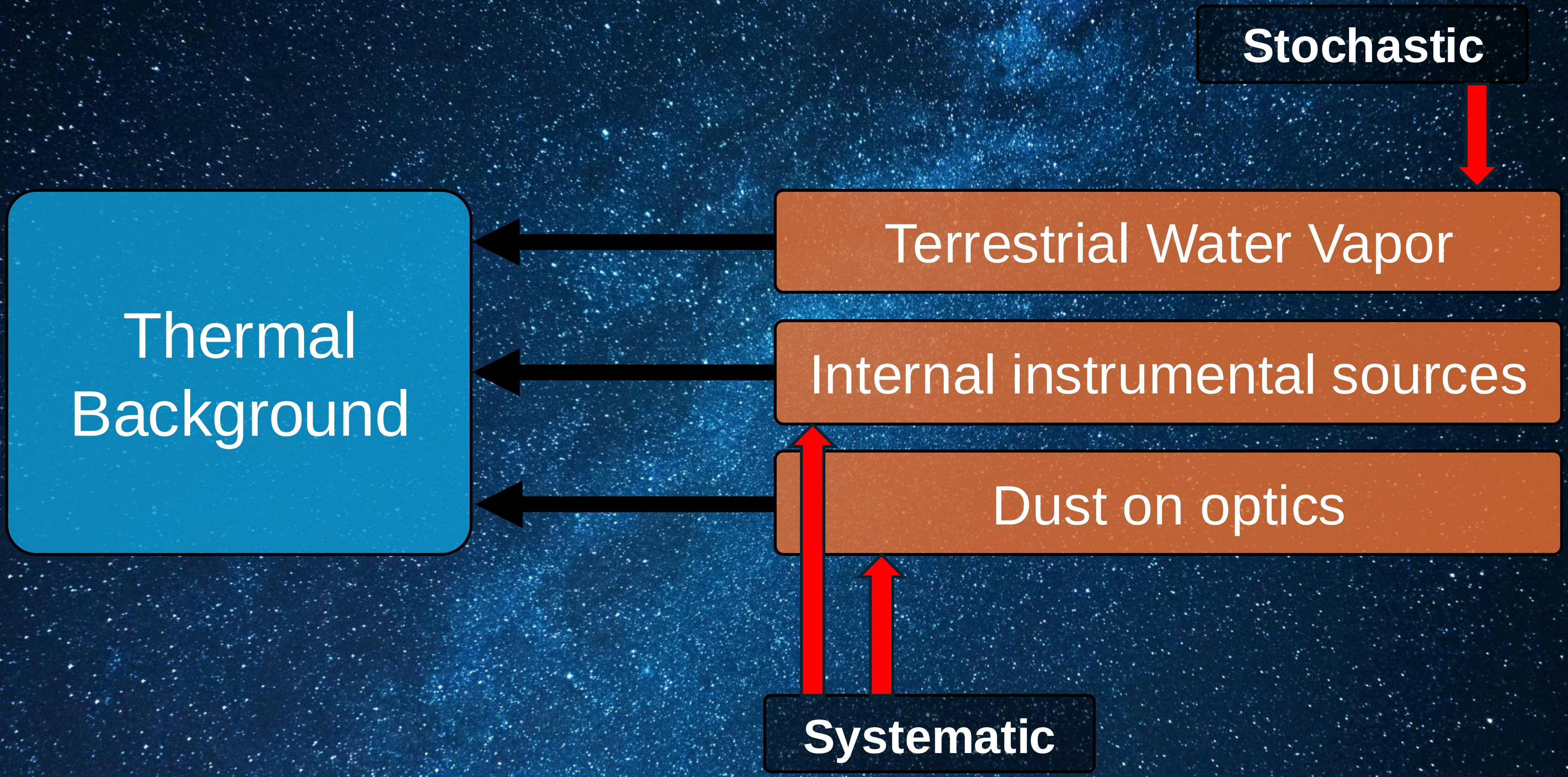
10m

Thermal Background in Sky Images

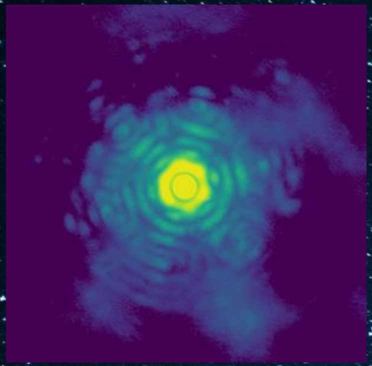
- No target in FOV, blank on-sky frames
- Quasi-static
- Large-scale features
- Not random
- Change slowly over time
- Dependent on atmospheric conditions
- **No clear origin**



Background Sources

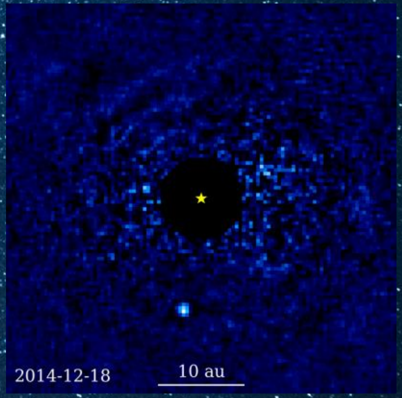


Typical Direct Imaging Workflow



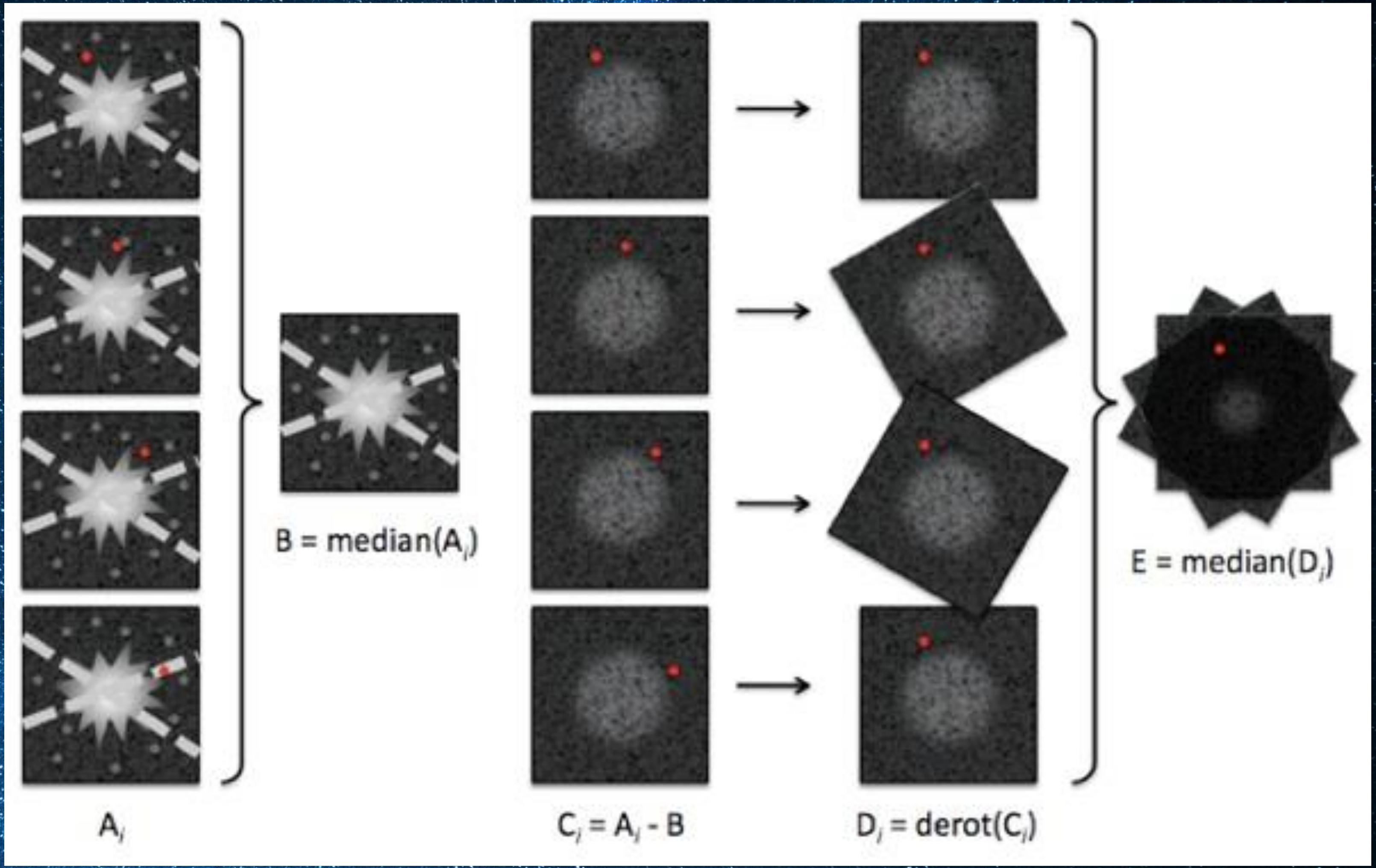
Observations (using angular differential imaging) → Align frames in stack → Subtract the PSF in each frame (Using LOCI or PCA)

→ Rotate the frames to align the planet signal → Median the stack



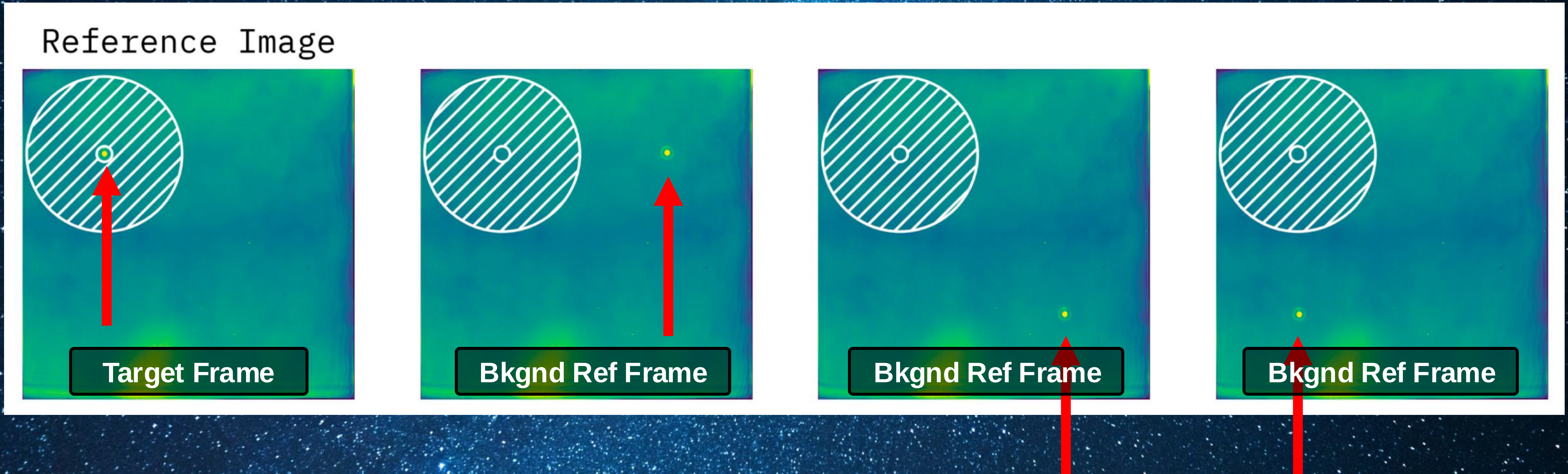
Angular Differential Imaging

Using the natural sky rotation, **separate the planet signal from the star signal**



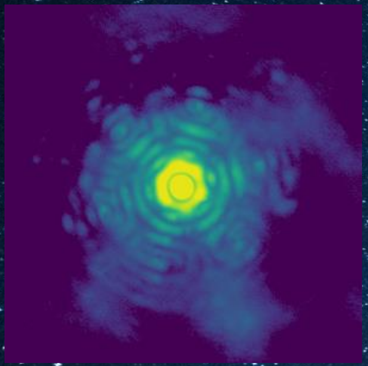
Current Background Subtraction Approaches

- LOCI Background Subtraction (Galicher 2011)
- Dither the point source and minimize the background variation
- Main assumption is that the thermal background is similar between frames



Mid-IR Direct Imaging Workflow

Observations (using angular differential imaging ***and dithering***)



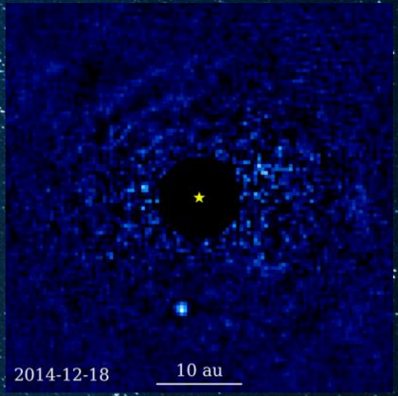
Subtract Thermal Background

Align frames in stack

Subtract the PSF in each frame

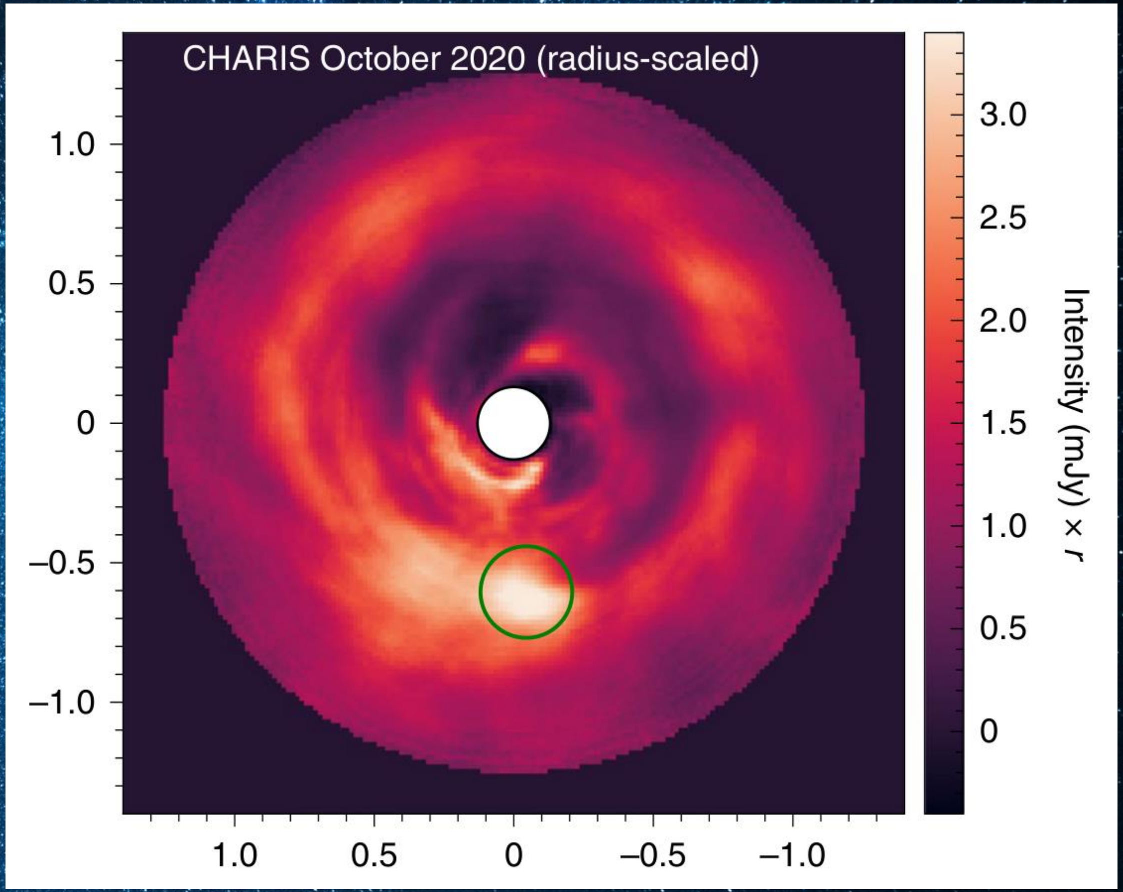
Rotate the frames to align the planet signal

Median the stack



AB Aur B

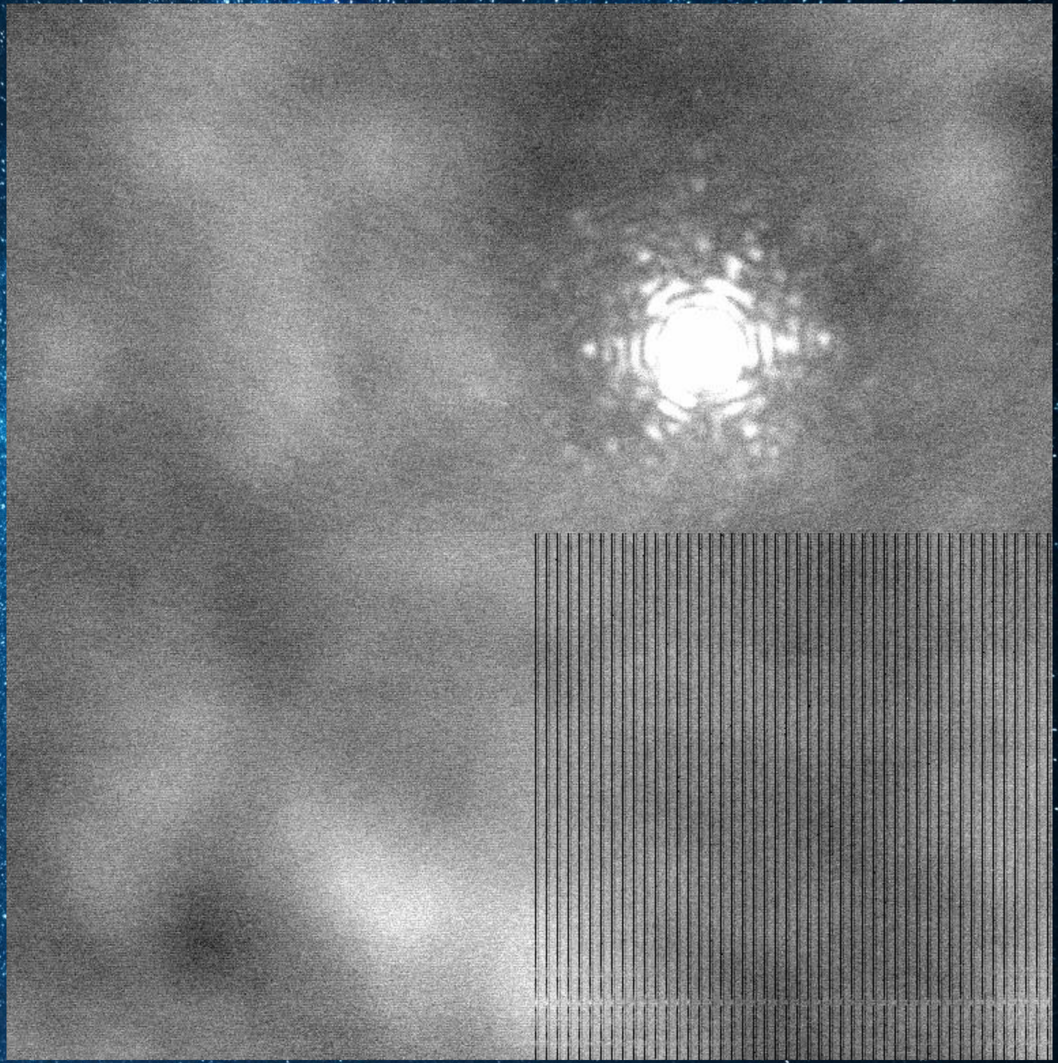
- AB Aur is a nearby Herbig Ae star, hosting a forming embedded protoplanet and an extended disk
- Data obtained at JHKL-bands
- Relatively hot planet, but does not have an M-band data point



Currie et al. 2022

AB Aur Observations

- Non-coronagraphic imaging observations over 4 half-nights of AB Aur taken using NIRC2 imager on Keck II
- 4 hours of on-target integration time
- 24 sky frames taken in between dither positions

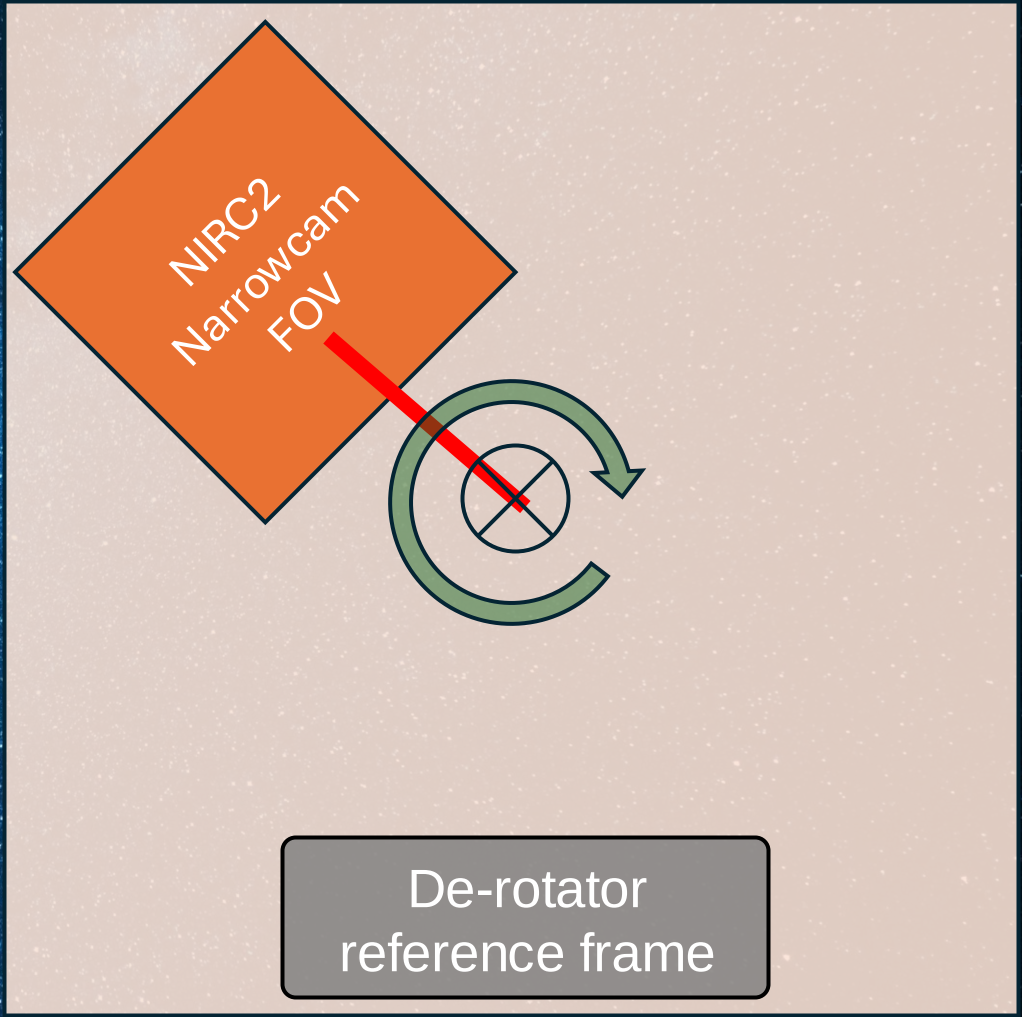


De-Rotator Geometry

Seeing the underlying signal of the de-rotator mirror in the optical path

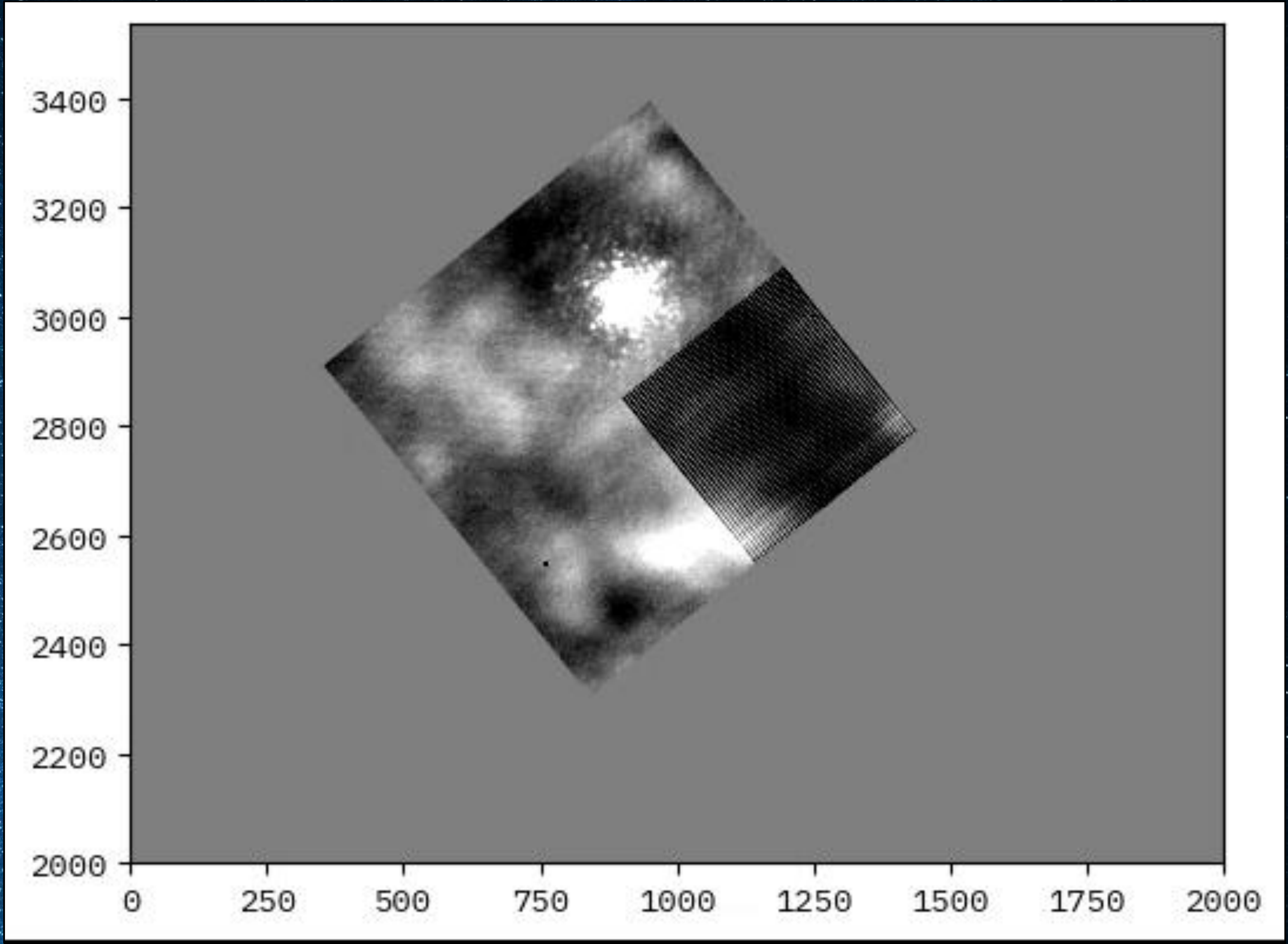
The de-rotator keeps the image in a particular orientation for your observation

De-rotator rotates the image within the focal plane, offset from the central axis



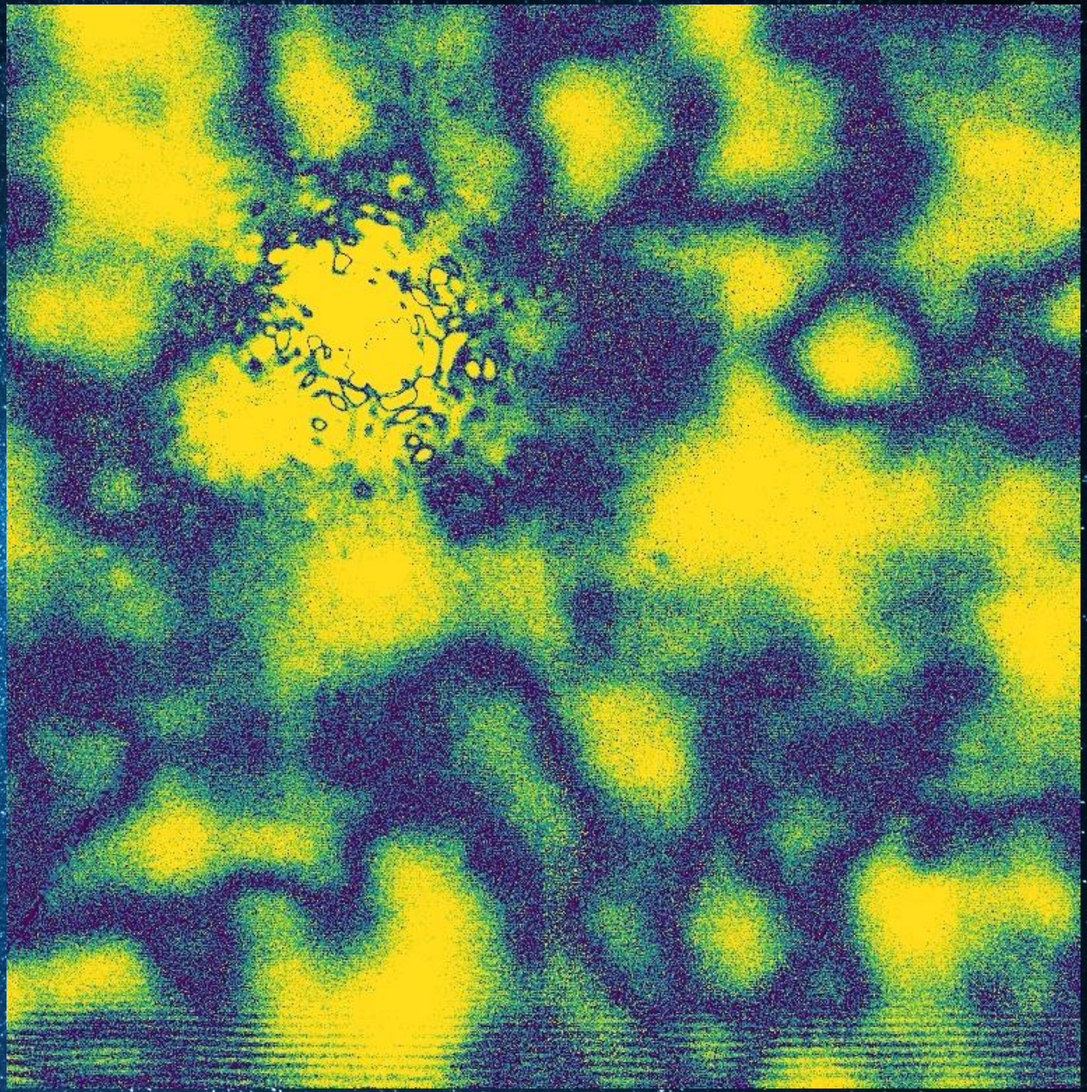
Seeing The De-rotator

- After transforming into the de-rotator reference frame, we track our mysterious thermal background signal!



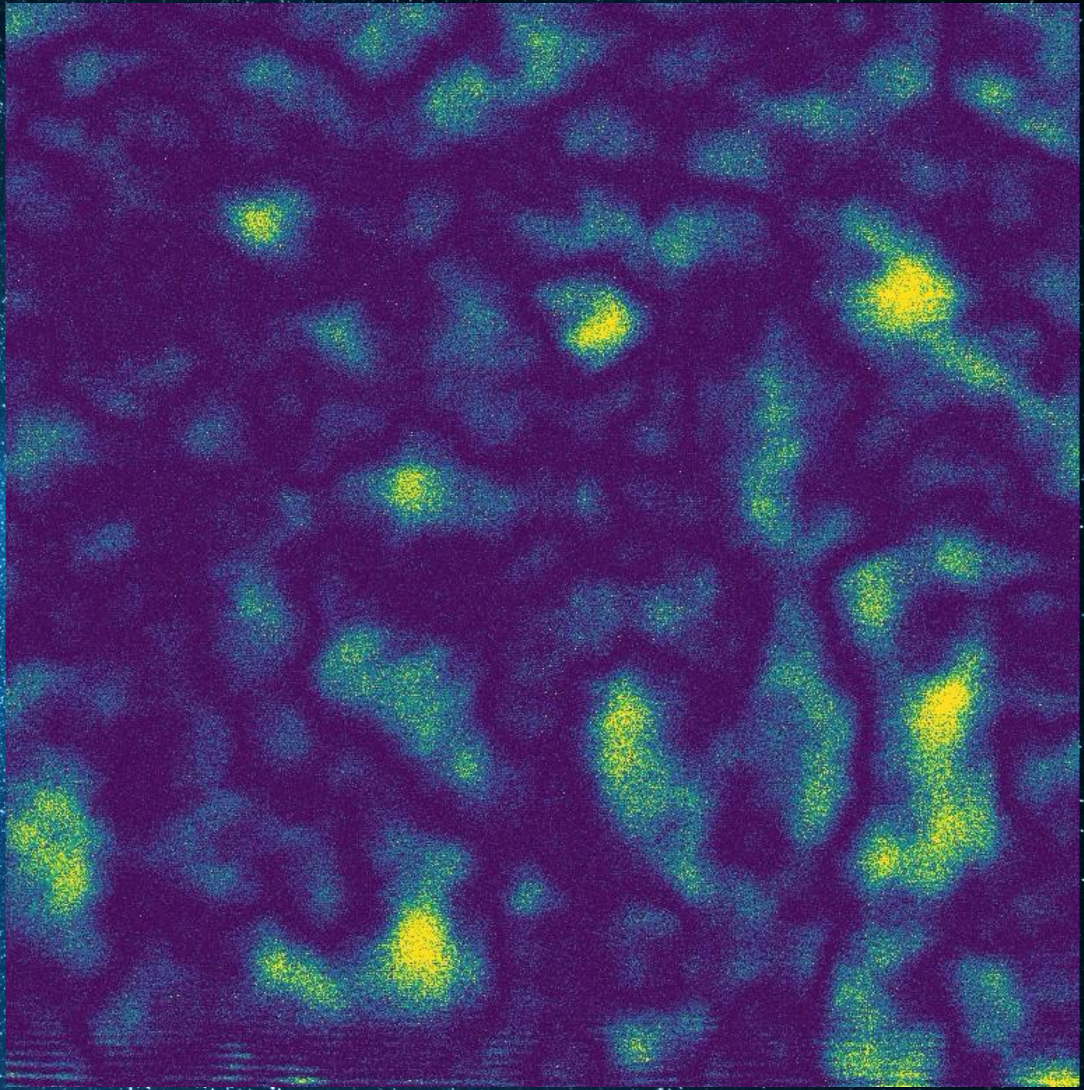
Static De-Rotator

- In one set of observations, we set the **de-rotator to a stationary position**
- Normally, the de-rotator tracks the pupil of the telescope for ADI
- Kept the AO system locked on target in closed-loop



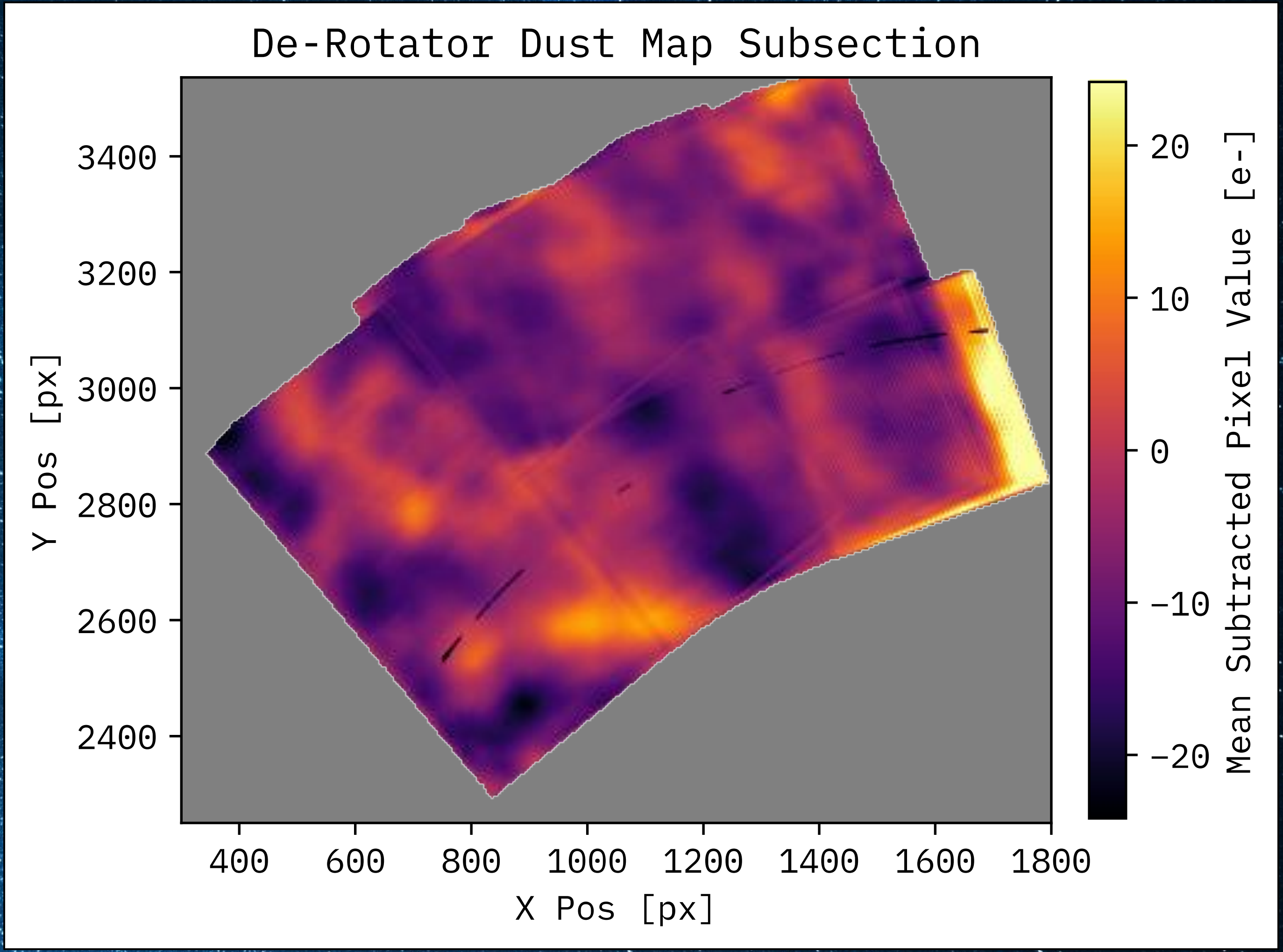
Static De-Rotator

- Also took a small amount of open-loop data
- Variation between frames is due to the AO system!



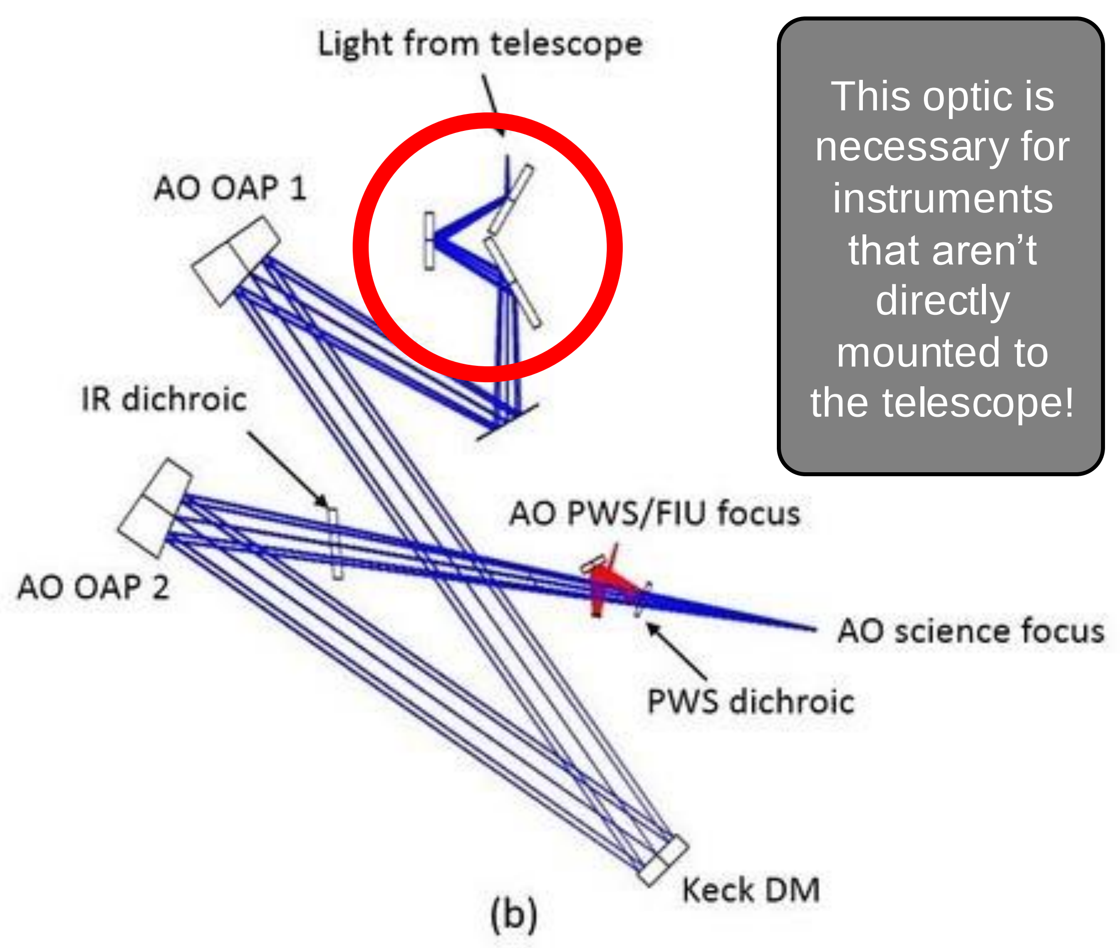
De-rotator Signal

- The de-rotator represents an extra rotating signal underneath our data!
- Just like ADI, we need to separate out this signal in our post-processing



Origin of The Thermal Emission

- Emission is likely dust on the de-rotator mirror surface on the Keck AO Bench
- Could also be imperfections in the optics
- The de-rotator is very close to the focal plane of the telescope



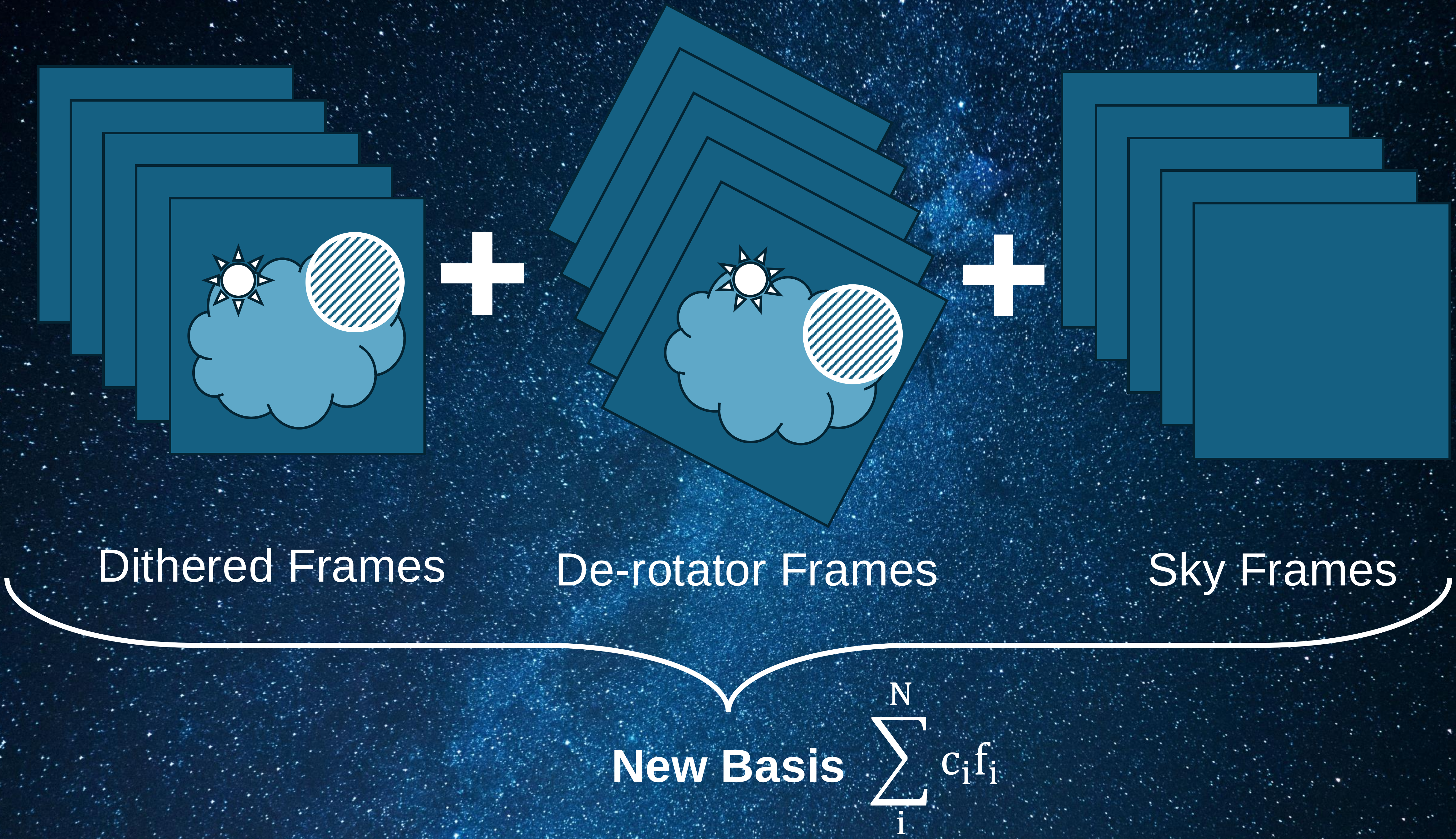
This optic is necessary for instruments that aren't directly mounted to the telescope!

Background Mitigation

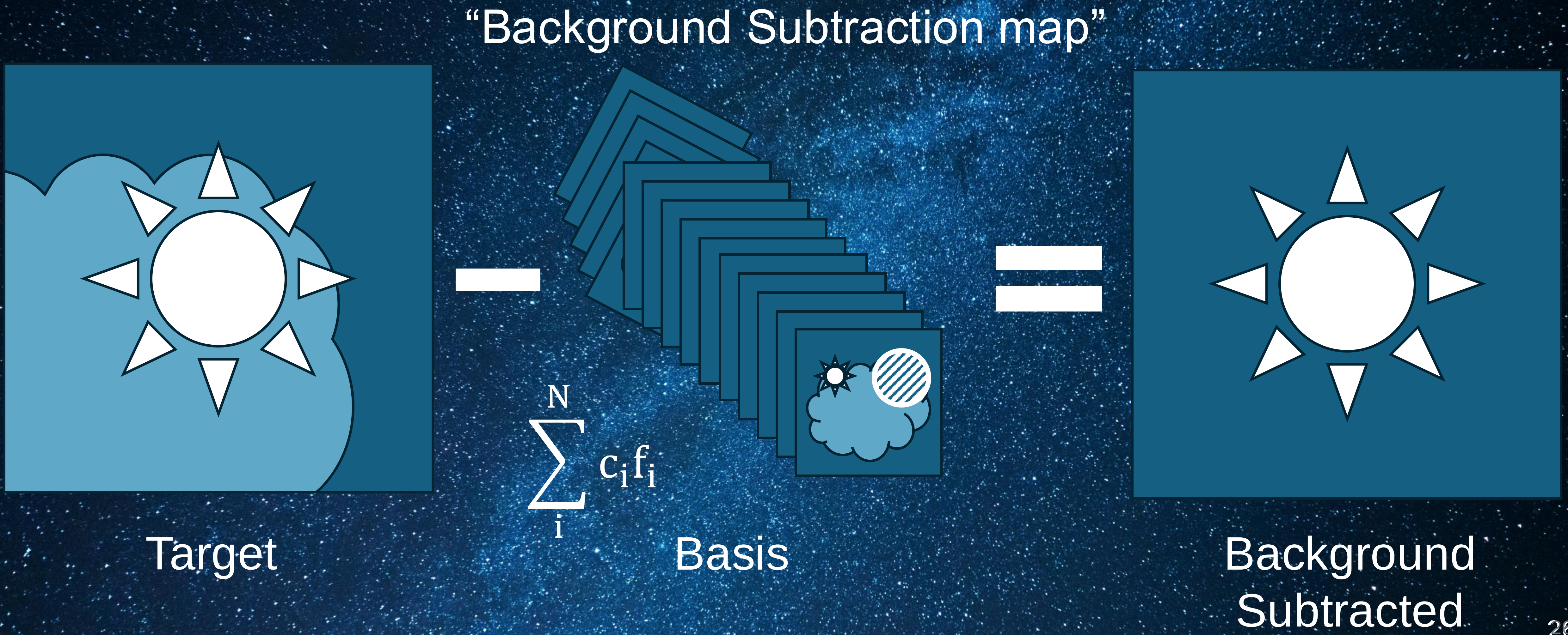
- LOCI/PCA techniques are essentially least-squares noise minimization techniques
- Solve for a linear combination of ”basis” frames that minimize the residual signal in the target frame
- **Need to construct your background basis using all the information possible**
- The de-rotator signal is not accounted for in standard background subtraction techniques

Dithered Frames

Basis $\sum_{i}^{N} c_i f_i$

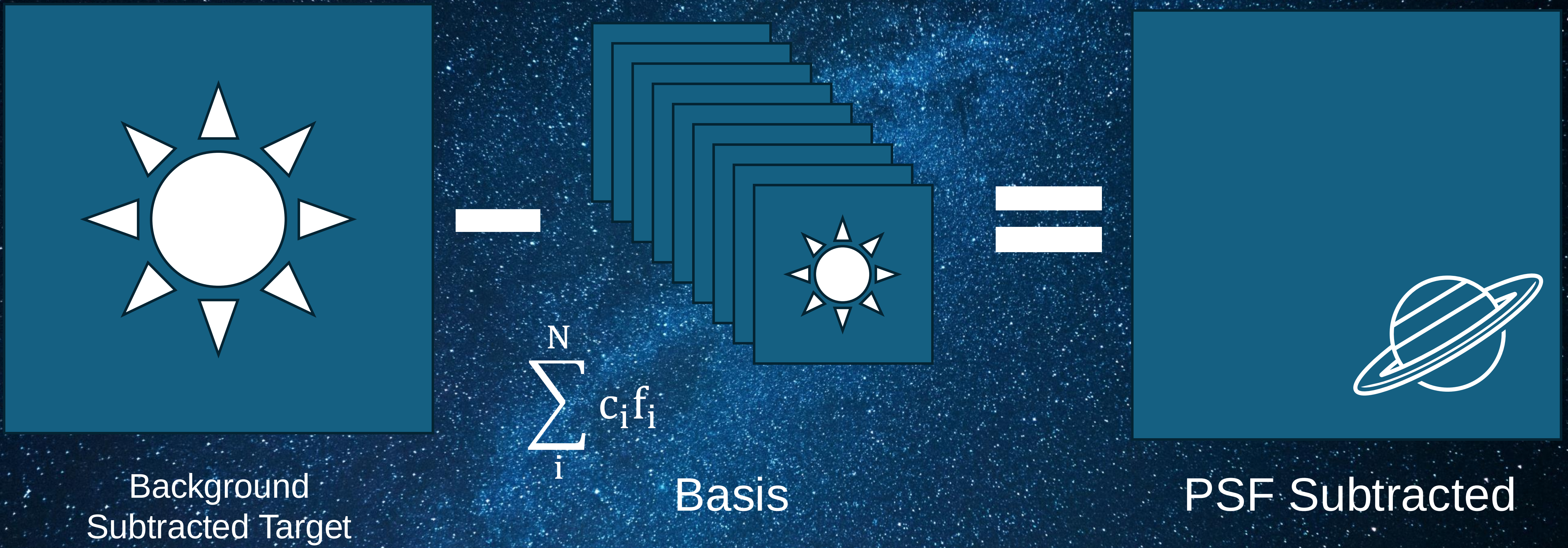

Dithered Frames
De-rotator Frames
Sky Frames
New Basis $\sum_{i}^{N} c_i f_i$

Background Subtraction

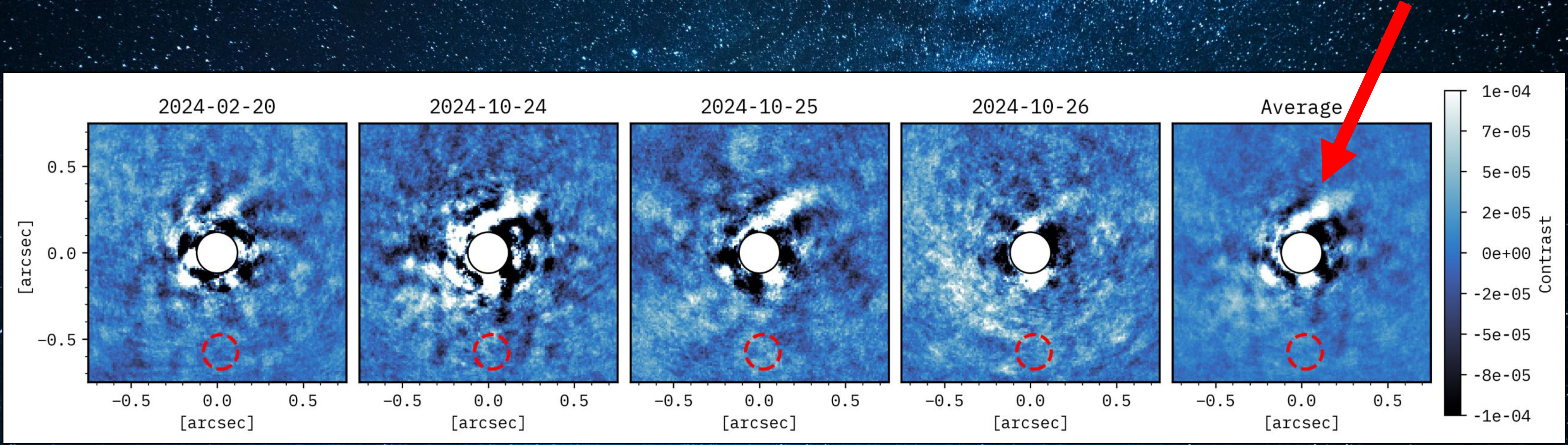


PSF Subtraction

Least Squares PSF Subtraction

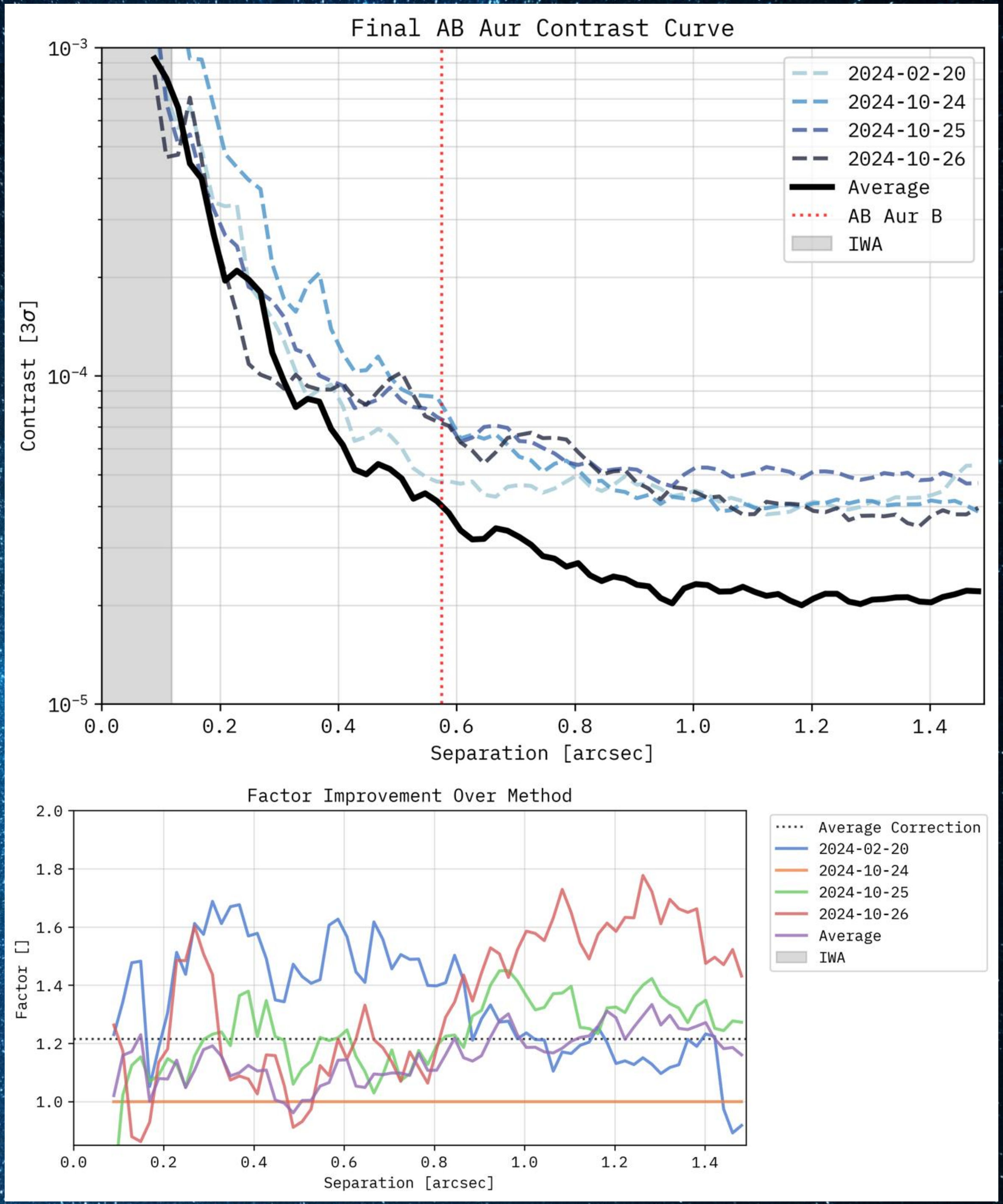


Reduced AB Aur Data



Contrast Curves

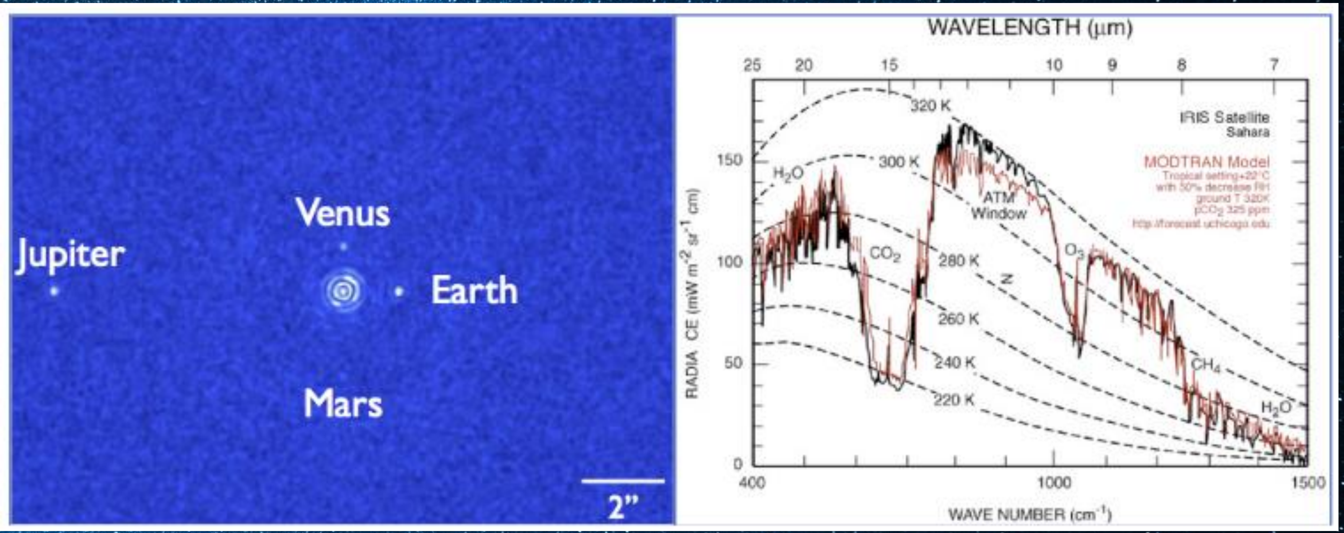
- Removing the background, at best, we average ~1.6x better than no background subtraction
- Final limiting contrast is ~2e-5
- Further out, we generally do better
- Planet is expected to be below our contrast limits



Future Ground Based Mid-IR

- ERIS (1-5 µm imager) on the VLT
- SCALES (1-5 µm IFS) going on Keck (next year!)
- 30-m Class Instruments:
  - MICHI (3-14 µm IFU) TMT
  - METIS (3-13 µm IFU) ELT

MICHI Simulation



Conclusion

- Deep-dive on the thermal background systematics present in our data
- Developed a method for removing this thermal background
- De-rotator + AO unveiled as the source of the mystery thermal background signal on Keck
- Similar thermal background features observed on other telescopes/instruments
- The de-rotator affects all instruments downstream the AO bench