Direct Imaging 101: Rejecting Background Sources, Artifacts and Disk Emission

Kate Follette

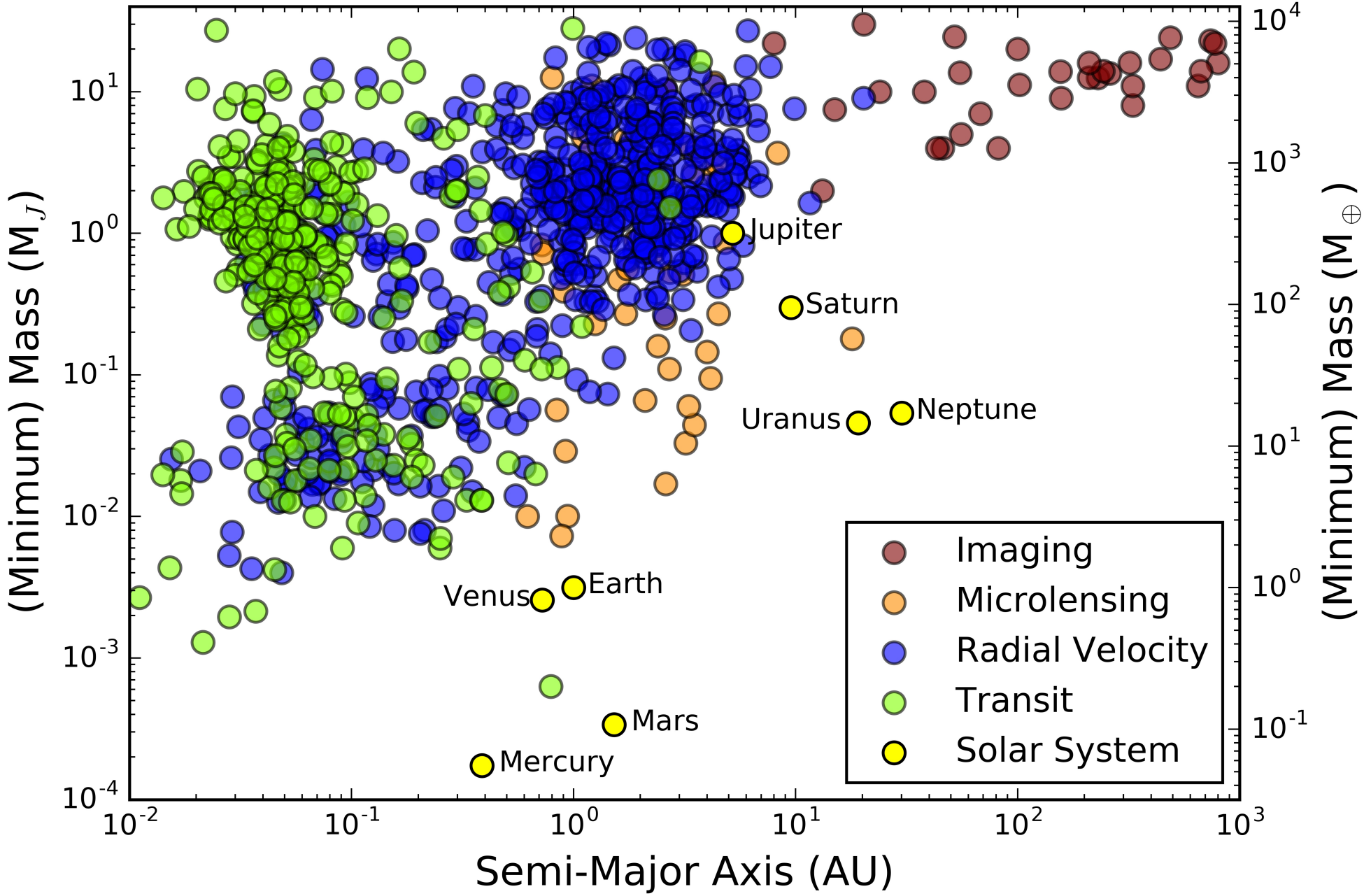
Assistant Professor, Amherst College

2018 Sagan Exoplanet Summer Workshop

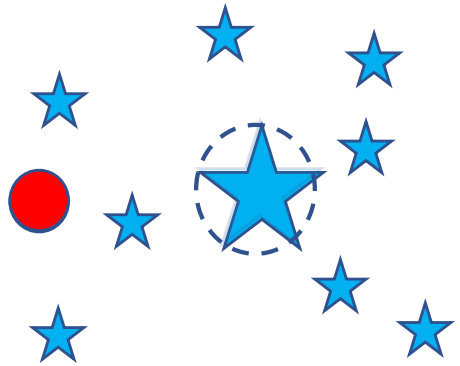
Outline

- Hardware Techniques (Jared's talk)
- Observing Strategies and Post-Processing Techniques
  - Spectral Differential Imaging (SDI)
  - Angular Differential Imaging (ADI)
  - *Polarized Differential Imaging (PDI)*
  - *Reference Differential Imaging (RDI)*
- Potential False Positives
  - Astrophysical
  - Instrumental

The Exoplanet Landscape



Terminology



Contrast = **planet** to **star** brightness ratio. Modern "high-contrast" imaging is capable of detecting planet/star brightness ratios of up to ~10^{-6}

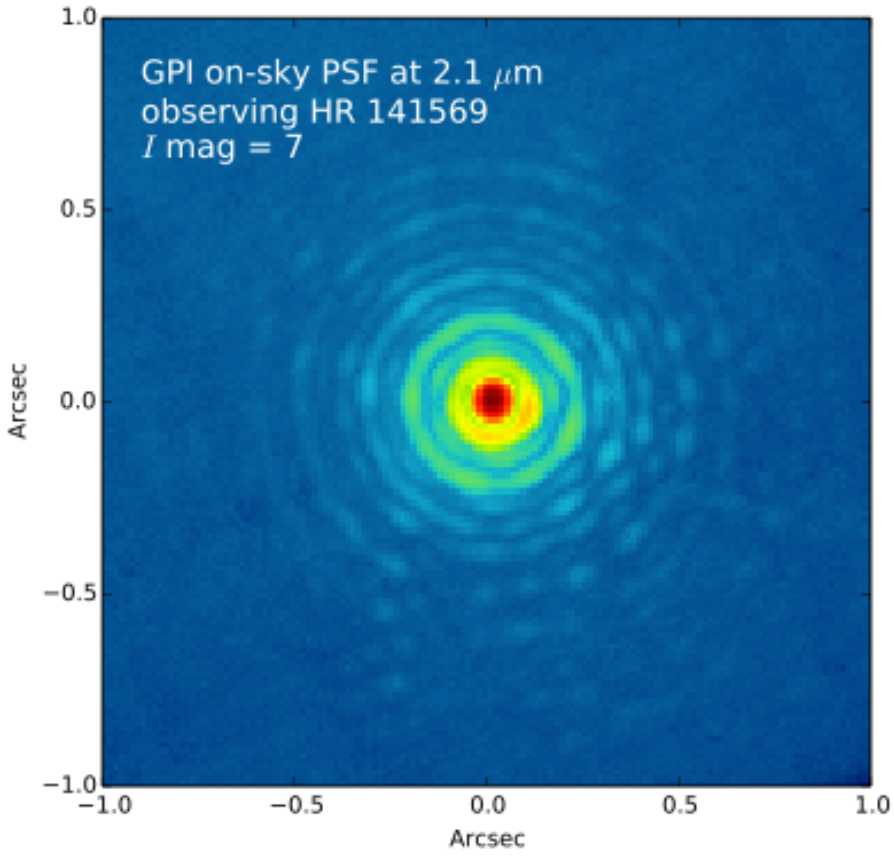
Point Spread Function = The pattern that a single point source will make on the detector. In principle, this is a simple Airy Pattern. In practice, instrumental and atmospheric phenomena conspire to make this **complex and time dependent**.

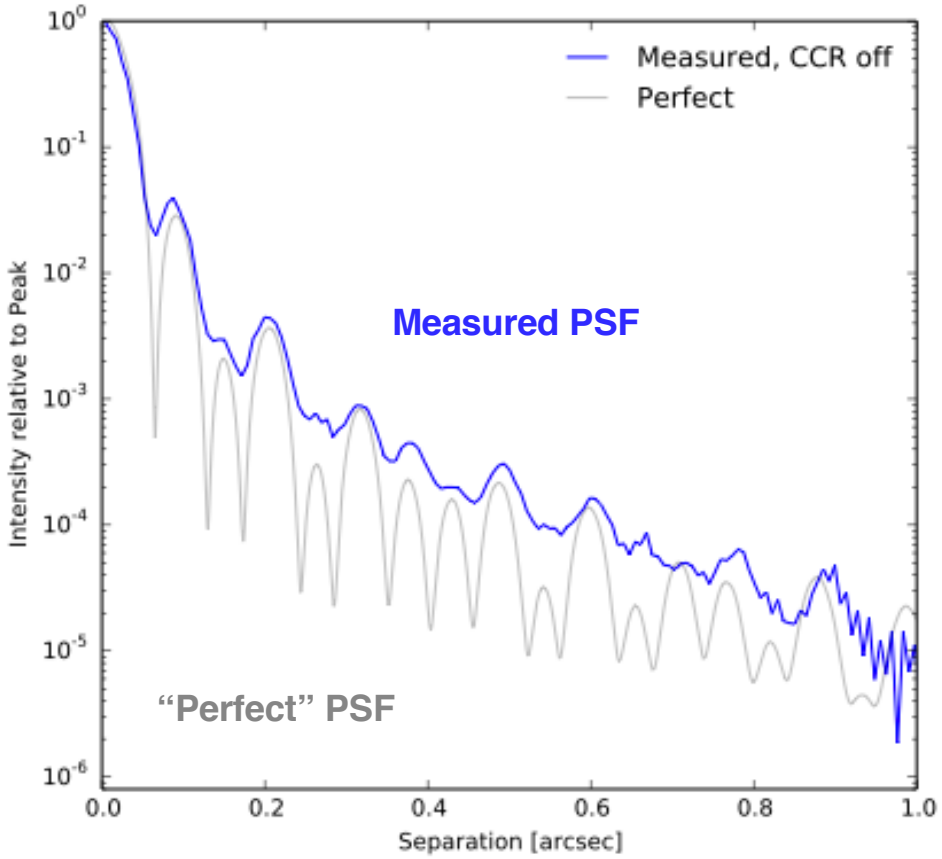
Speckle = An additional **image of the star** introduced at some location other than its actual location by instrumental or atmospheric effects. Can mimic a planet.

Post-Processing = Anything that you do to the images after acquiring them in order to remove/suppress residual starlight. Generally fall into the category of "differential imaging" techniques.

Inner Working Angle = The closest that you can get to the star. Generally set by the coronagraph.

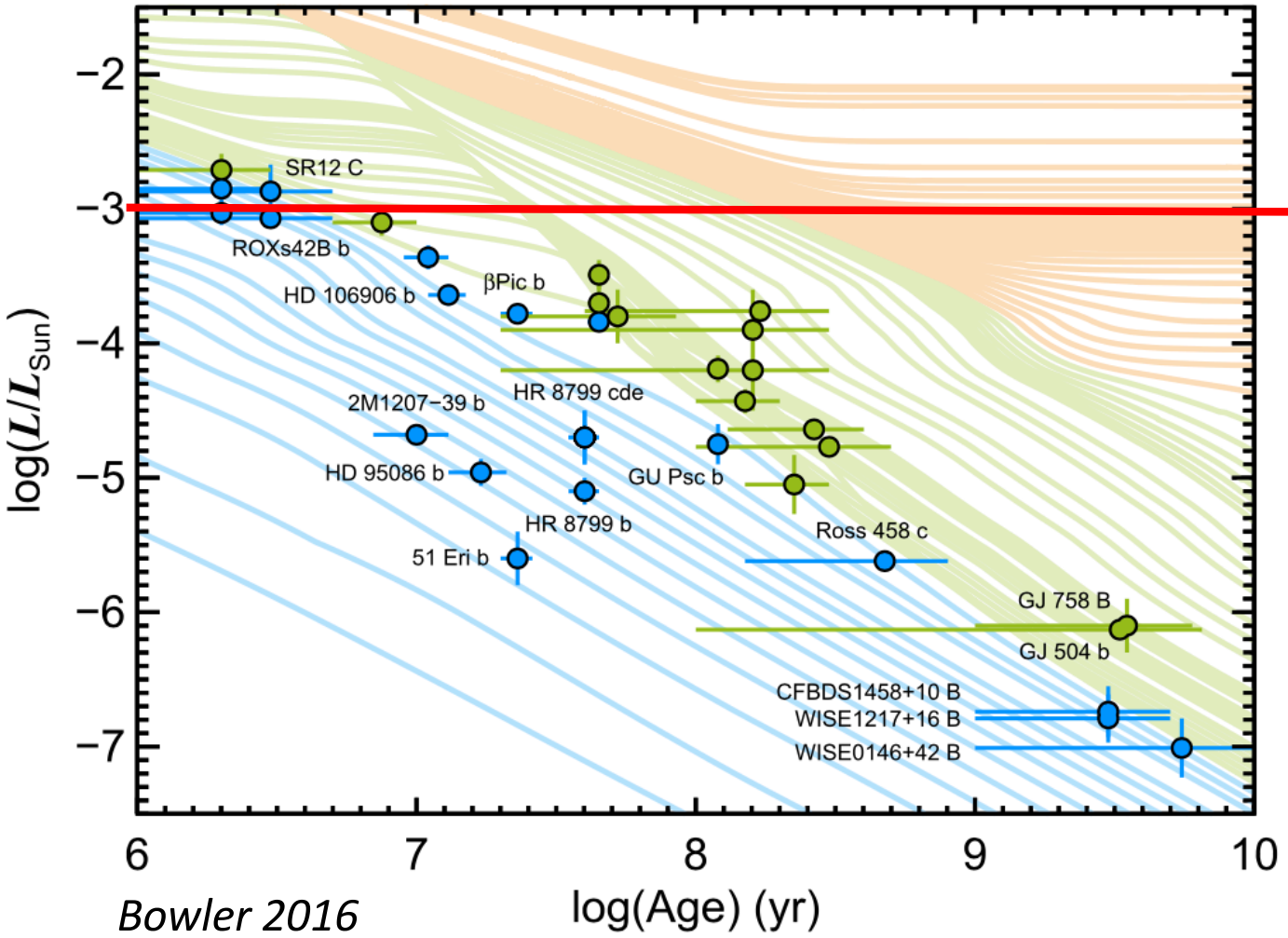
Hardware – AO + coronagraphy





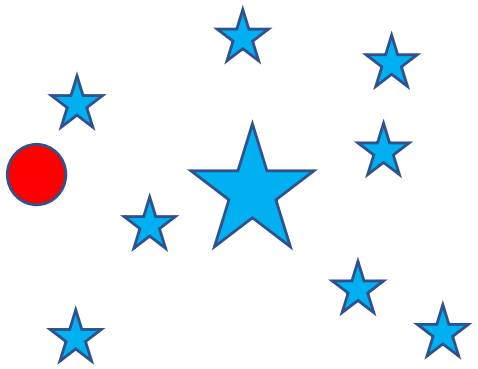
Poyneer+ 2016

The Problem

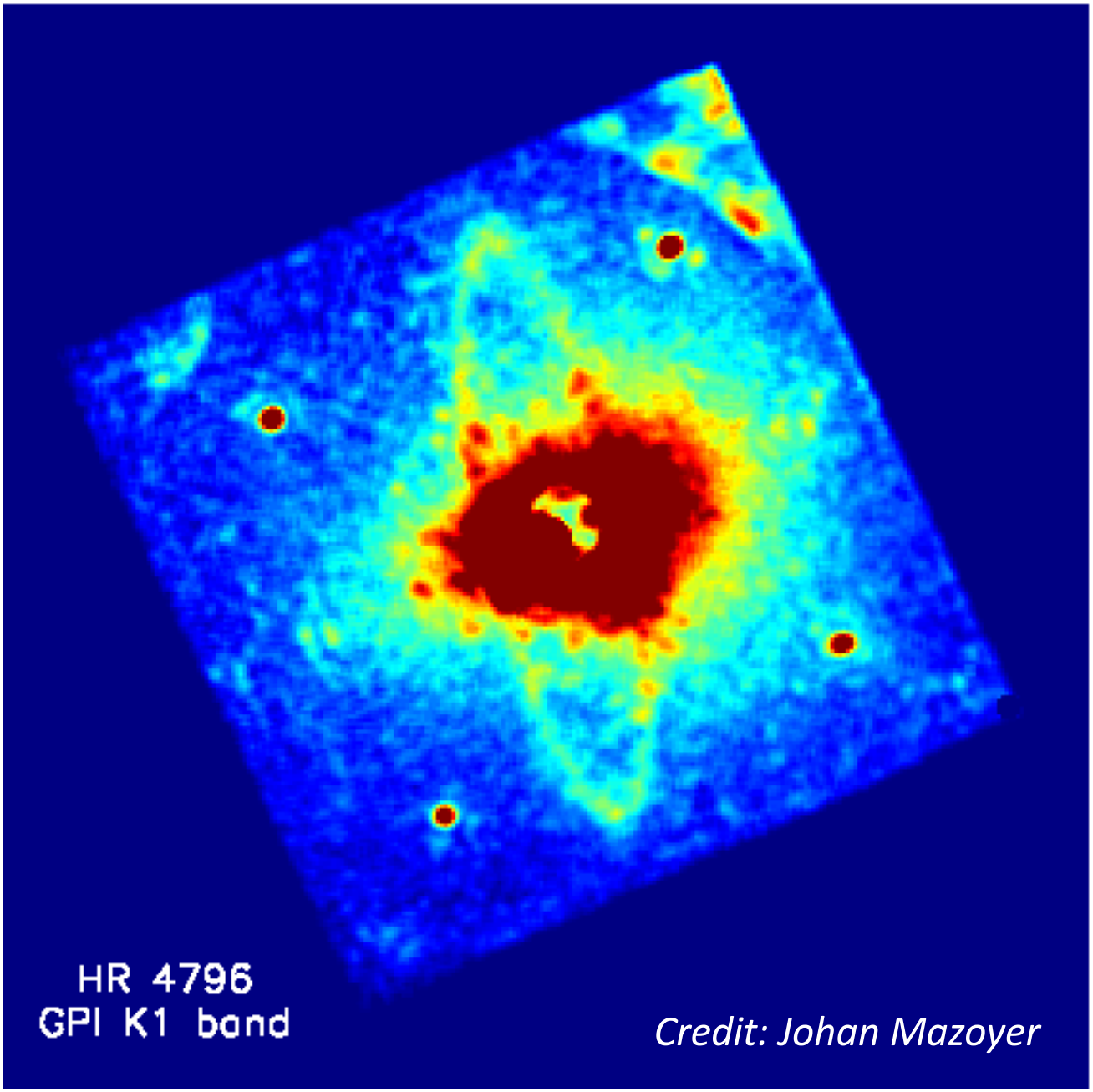


Bowler 2016

AO + Coronagraphy



Trick #1: Leverage Angular Diversity



Classical Angular Differential Imaging (cADI)

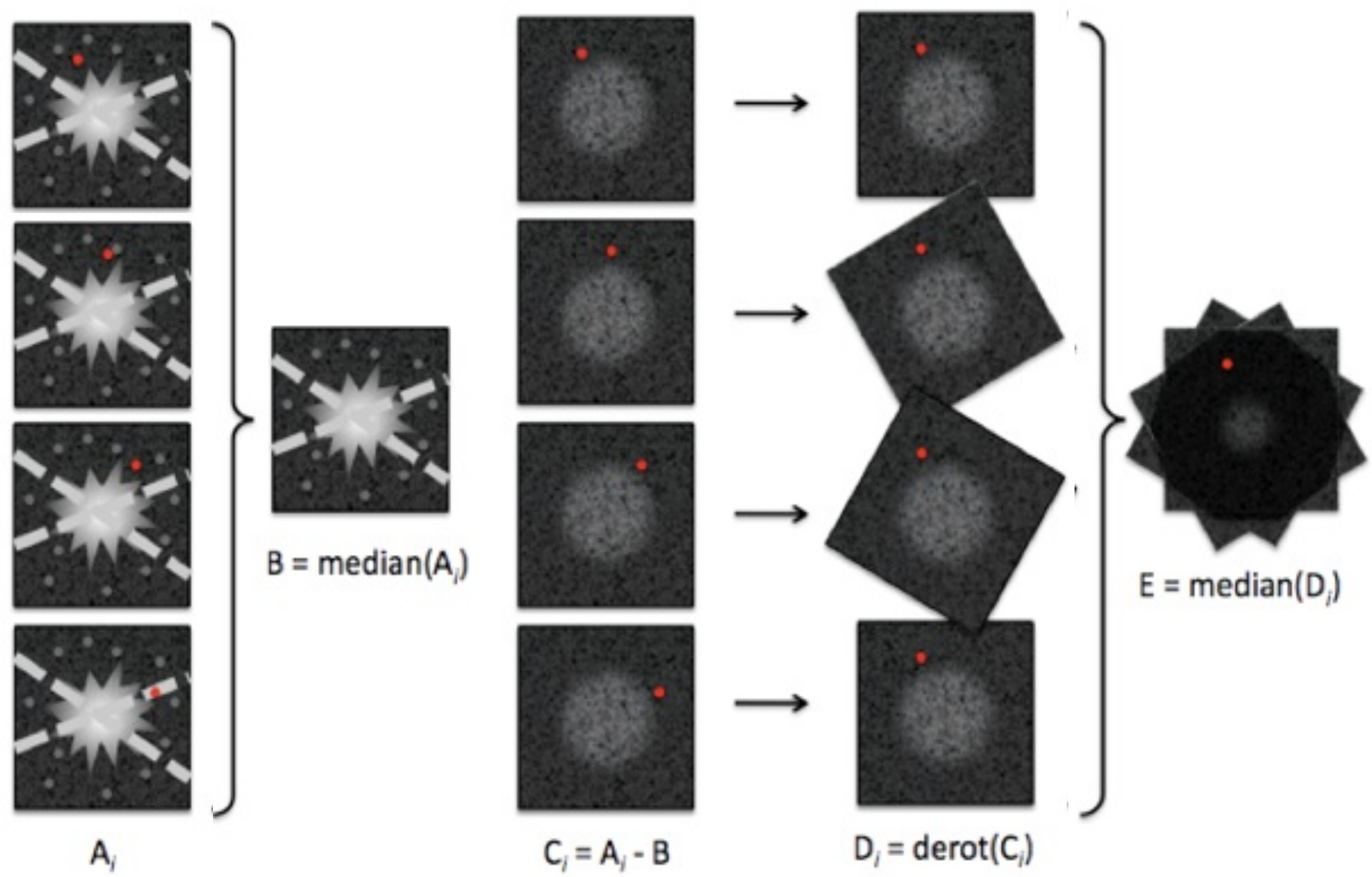
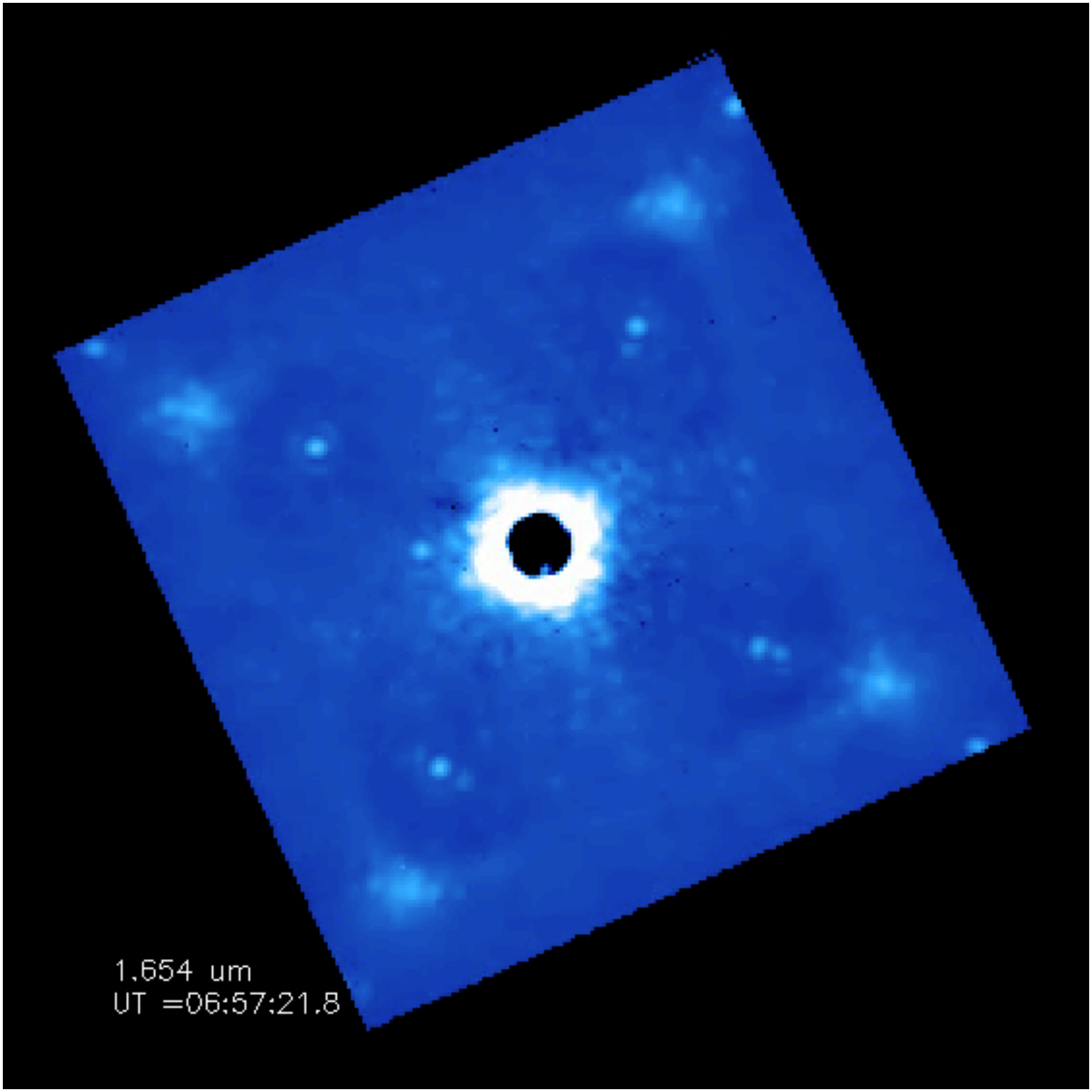


Image Credit: Jessica Donaldson

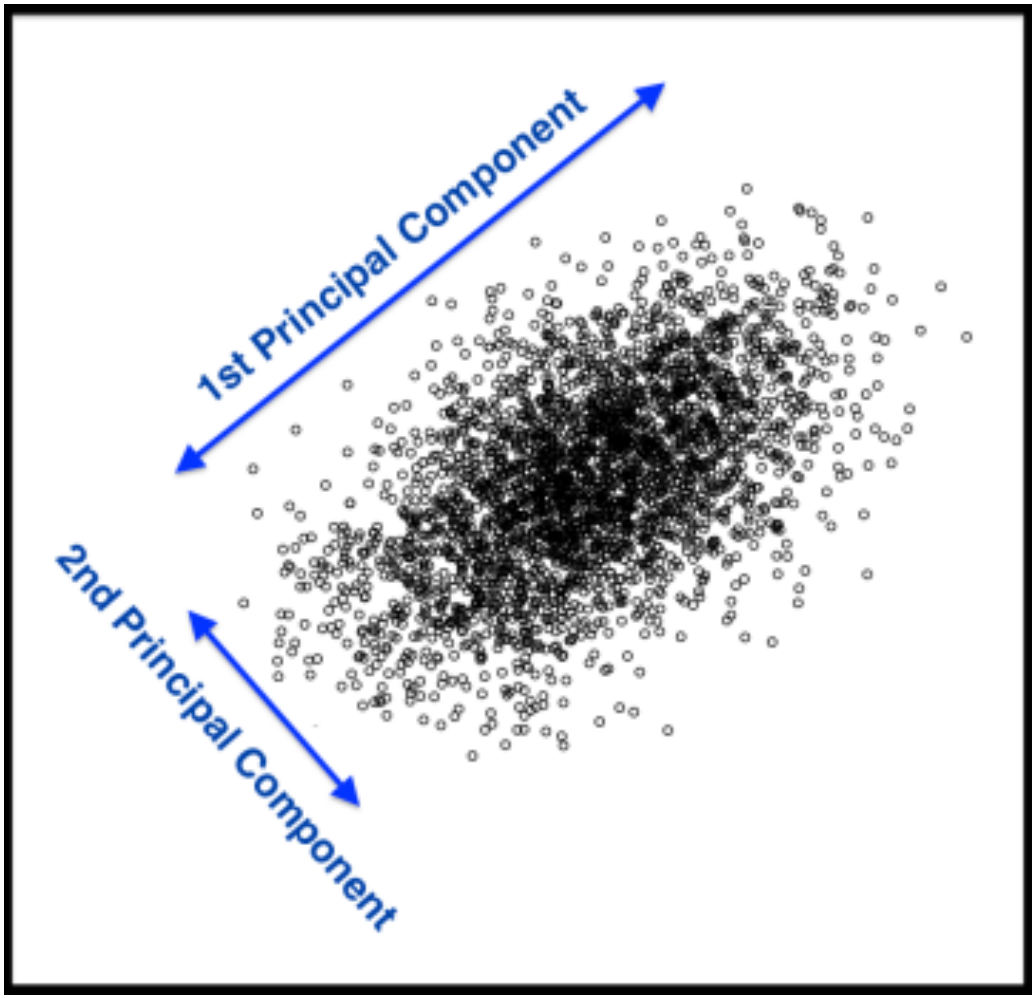

1.654 um
UT =06:57:21.8

More Sophisticated PSF Estimation

KLIP – Karhounen-Loeve Image Processing
based on Principal Component Analysis
Soummer, Pueyo and Larkin 2012

LOCI – Locally Optimized Combinations of Images
Lafreniere+ 2007

Principal Component Analysis



Sequential Karhunen–Loeve Basis Extraction and its Application to Images

Avraham Levy and Michael Lindenbaum

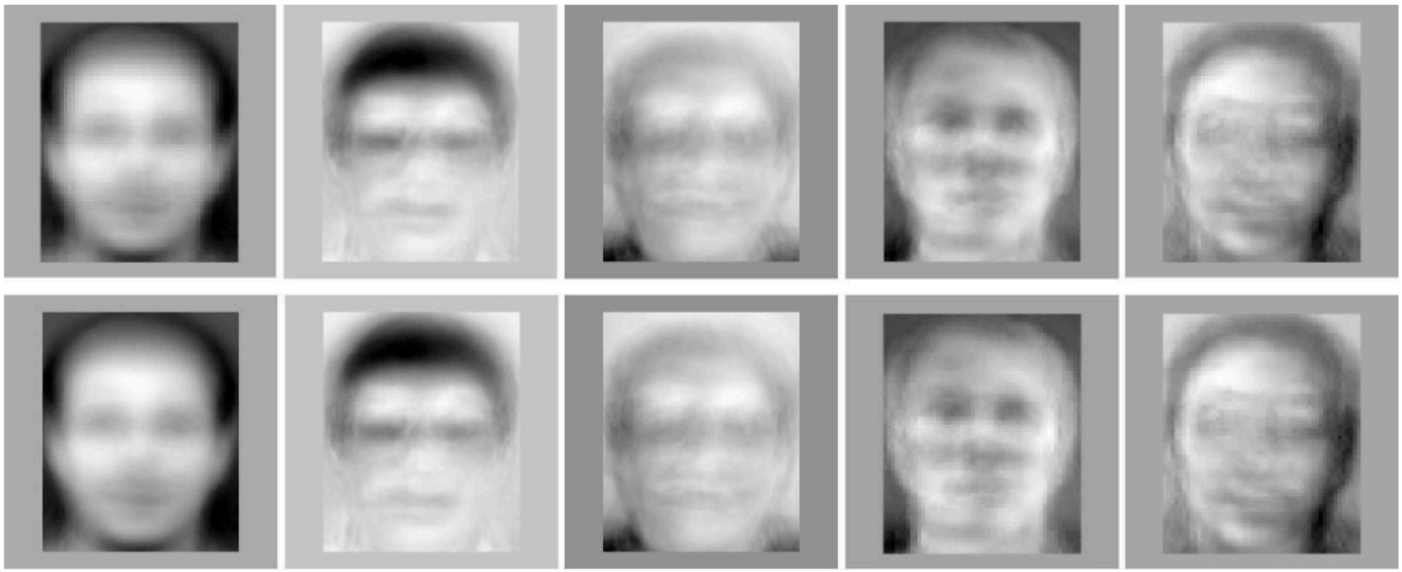
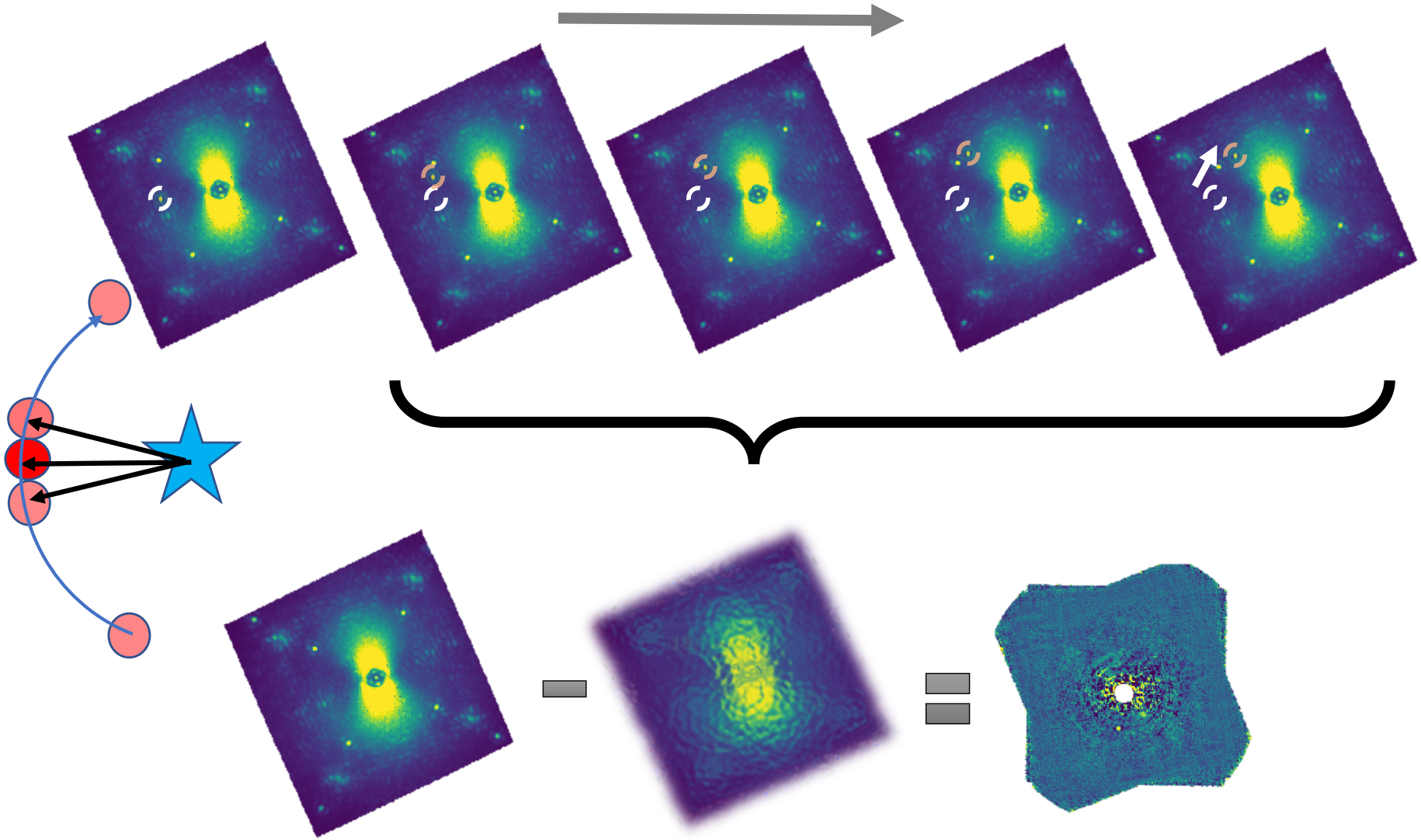


Fig. 1. The first five vectors of the KL basis (eigen-faces) produced by the standard KL algorithm (top) and the corresponding vectors produced by the proposed SKL. Scale inversion was done for some gray images to make the similarity clearer.

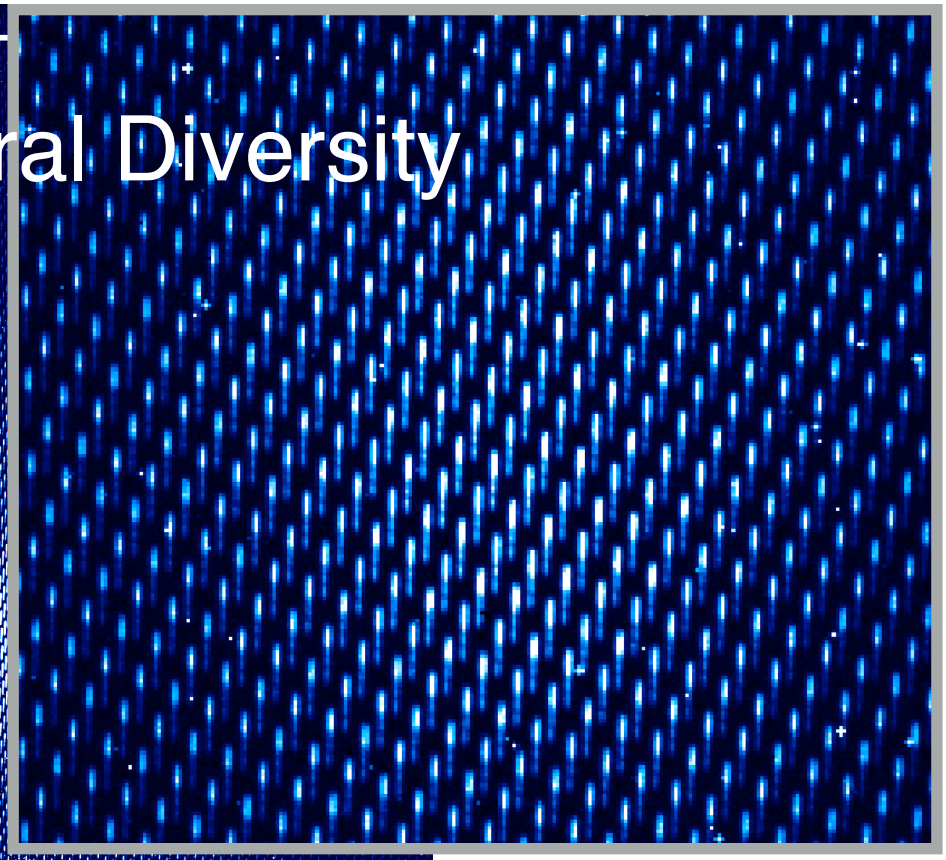
Post-Processing = LOCI/KLIP

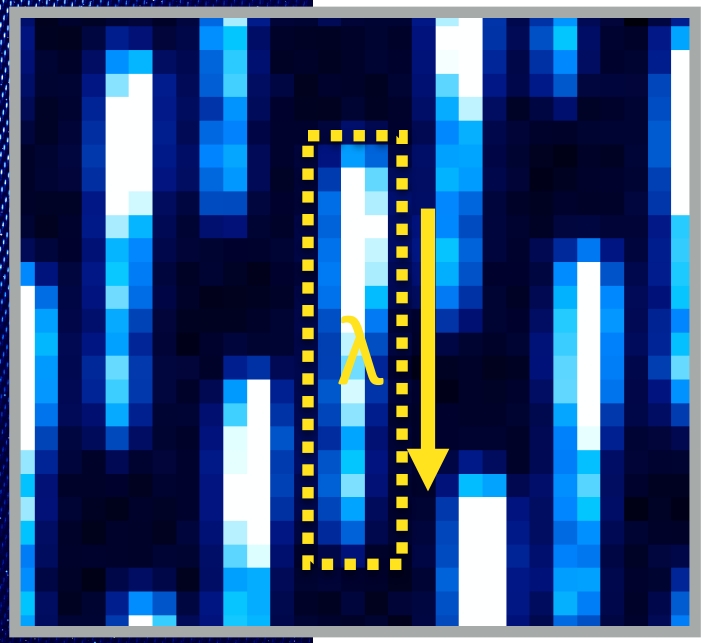


Credit: JB Ruffio

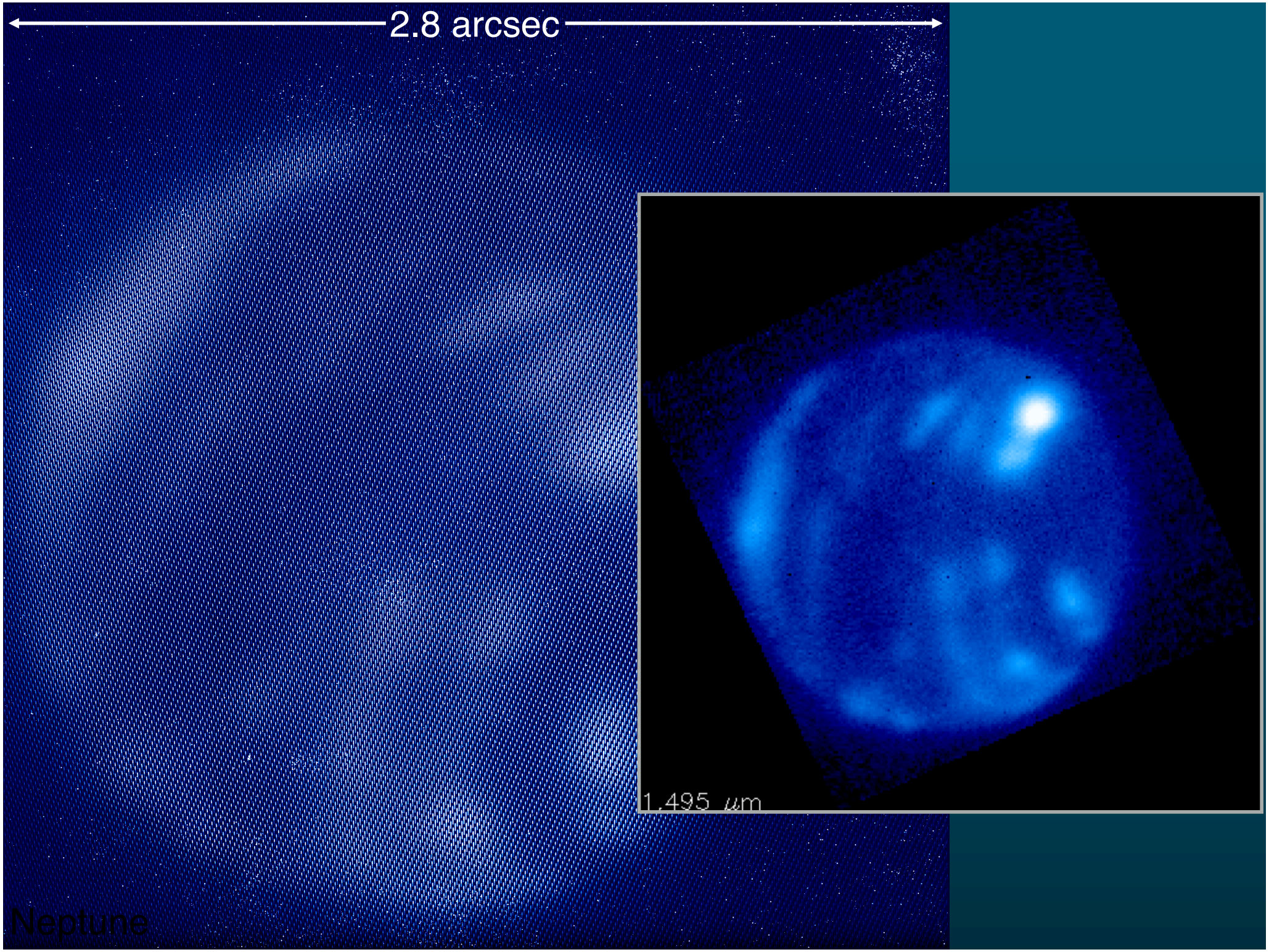
2.8 arcsec

Trick #2 – Leverage Spectral Diversity





Neptune


2.8 arcsec
1.495 μm
Neptune

Spectral Diversity

51 Eri b

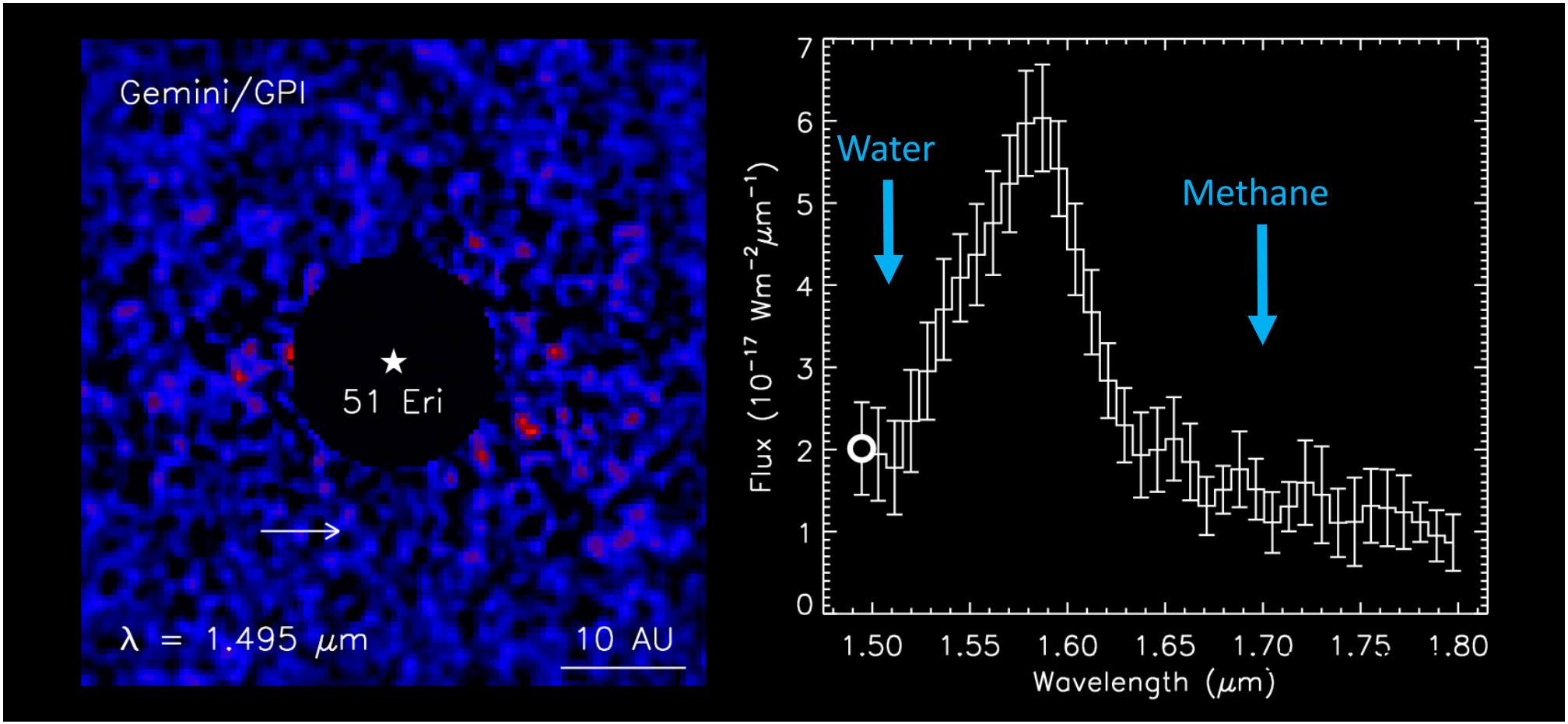
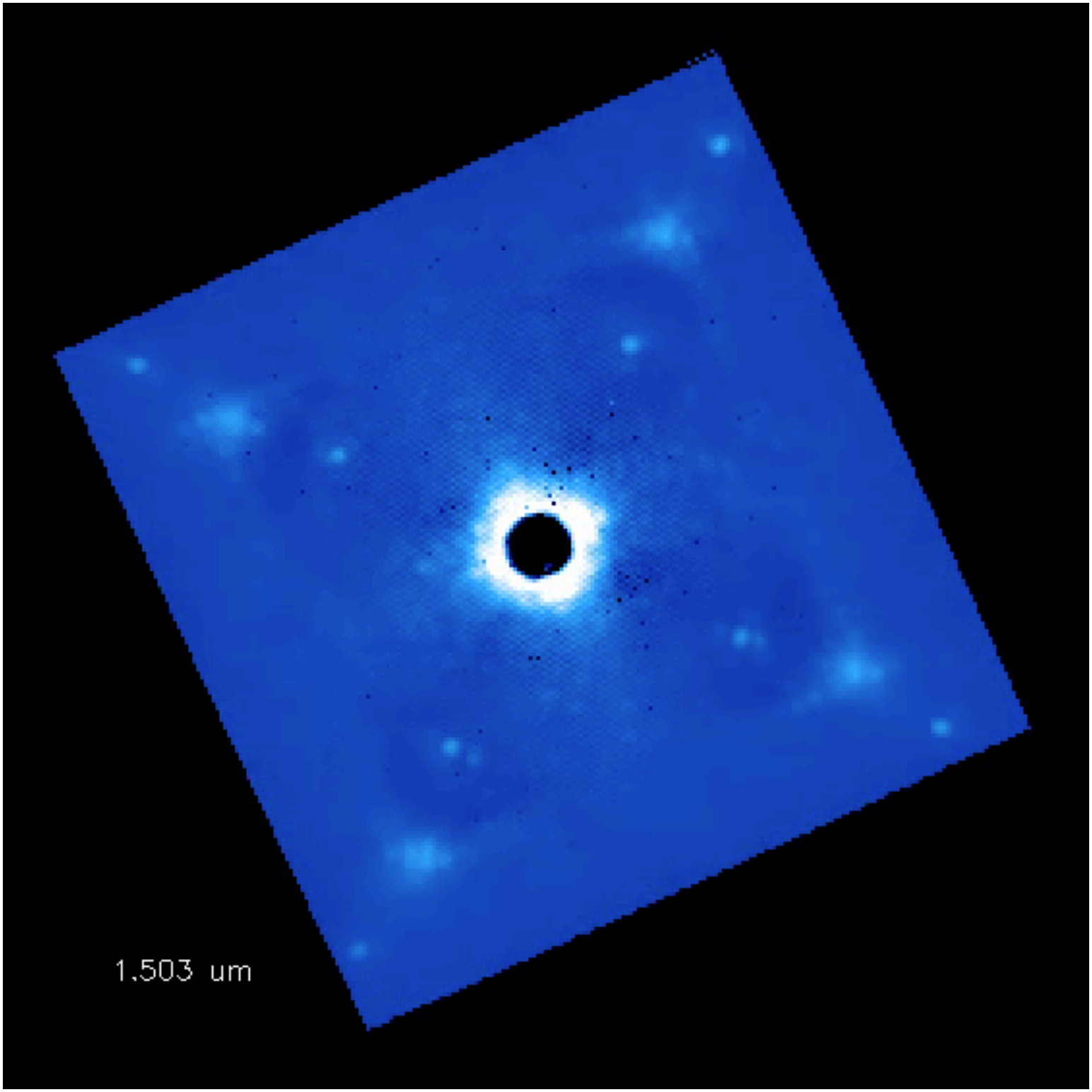
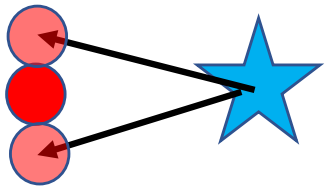


Image Credit: R. De Rosa/J. Wang


1.503 um

Over/Self-Subtraction



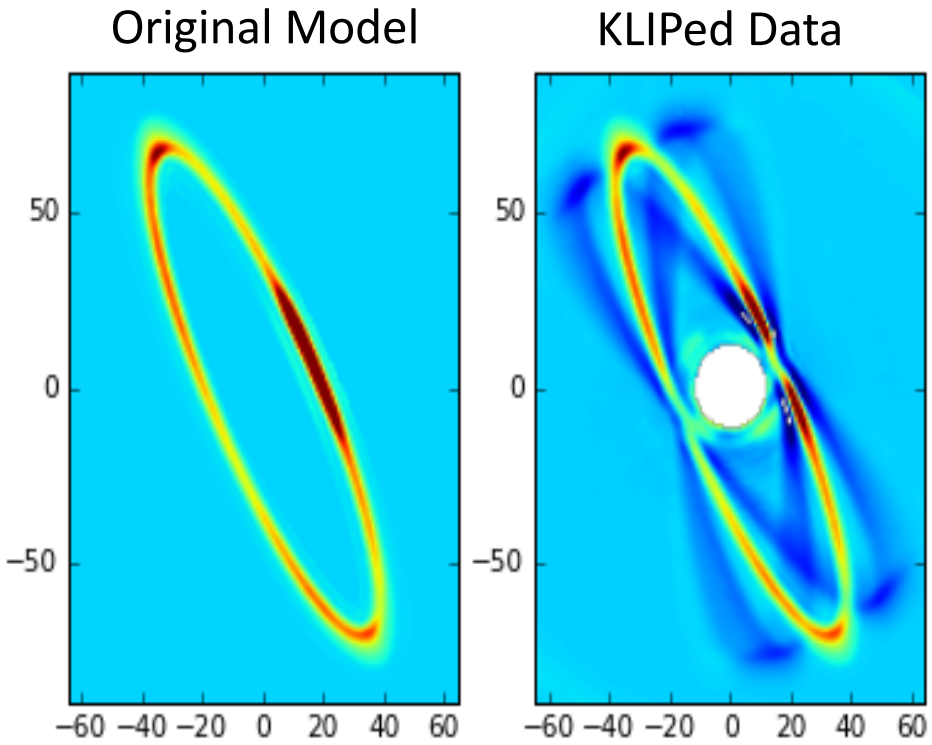
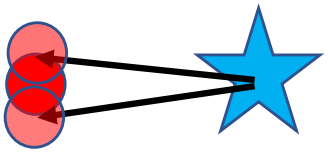


Image Credit: Pauline Arriaga

Over/Self-Subtraction



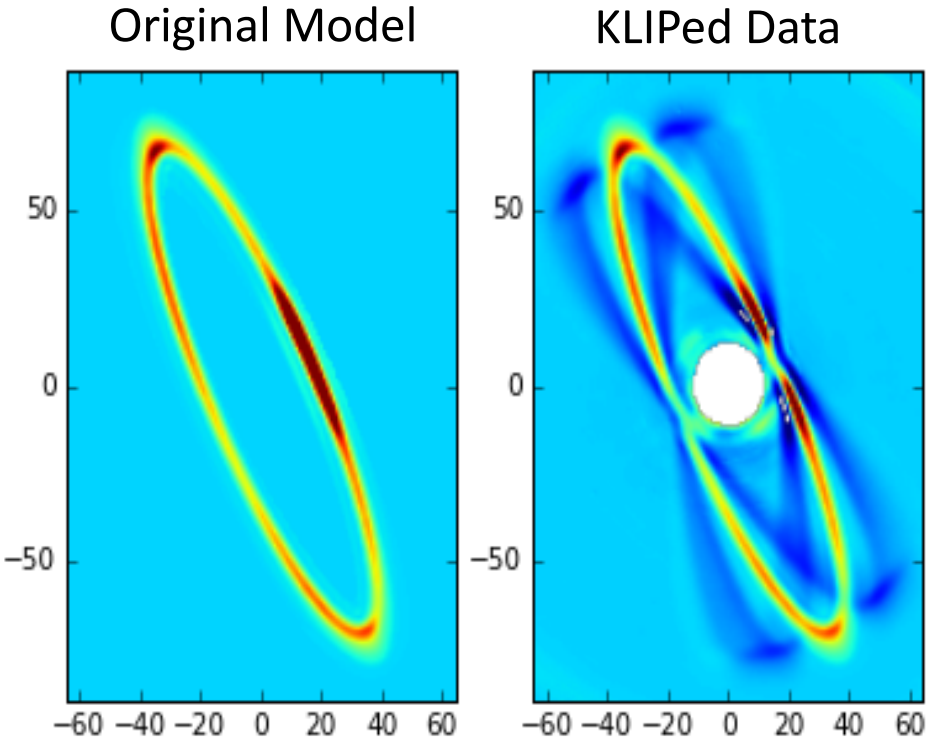


Image Credit: Pauline Arriaga

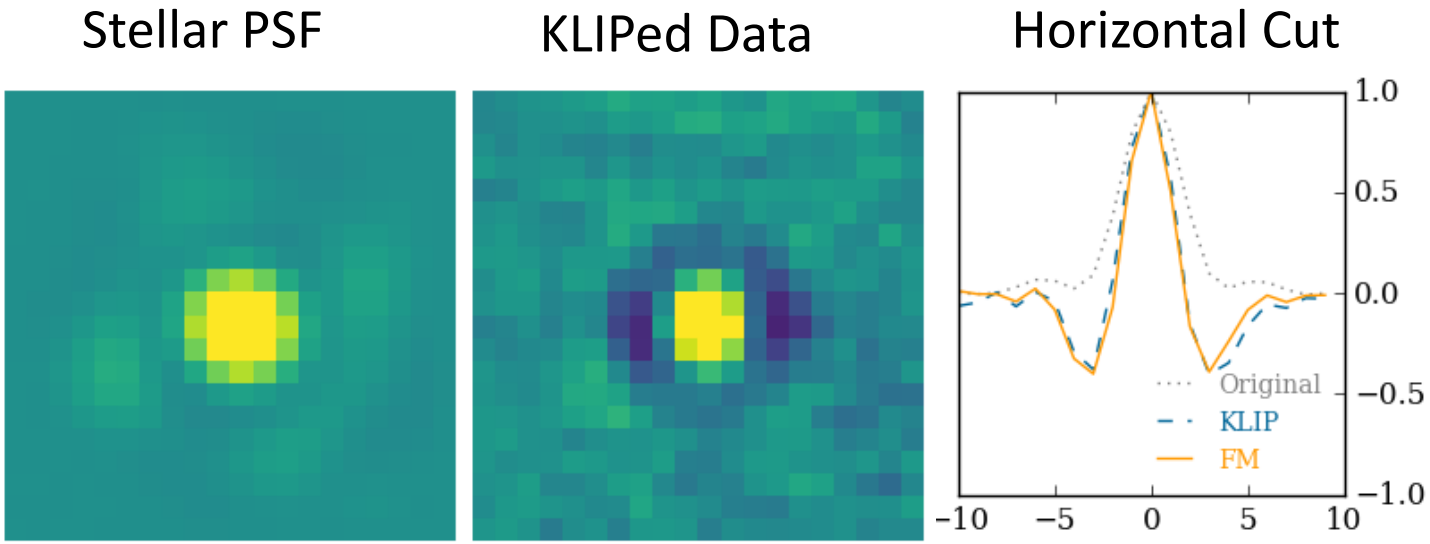
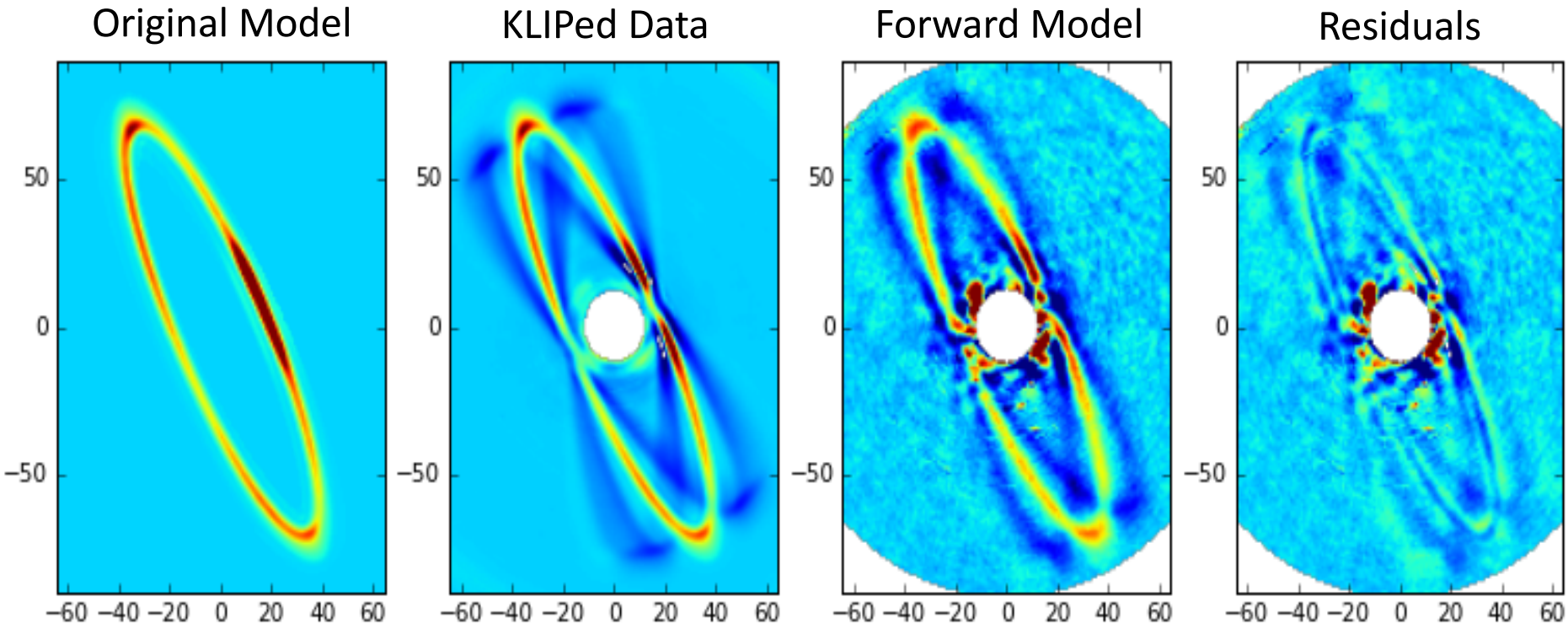


Image Credit: JB Ruffio

Forward Modeling



Credit: Pauline Arriaga (UCLA)

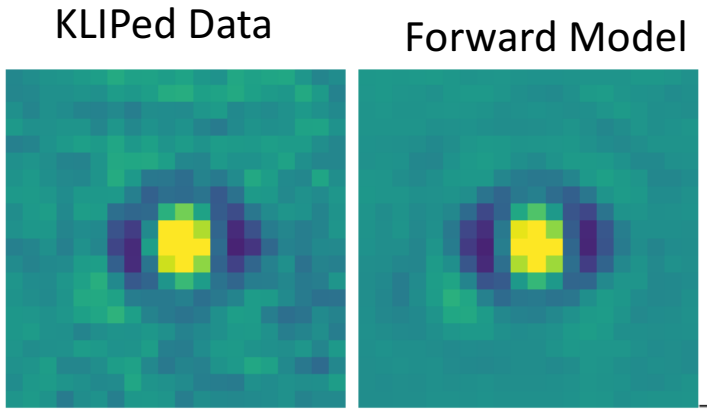
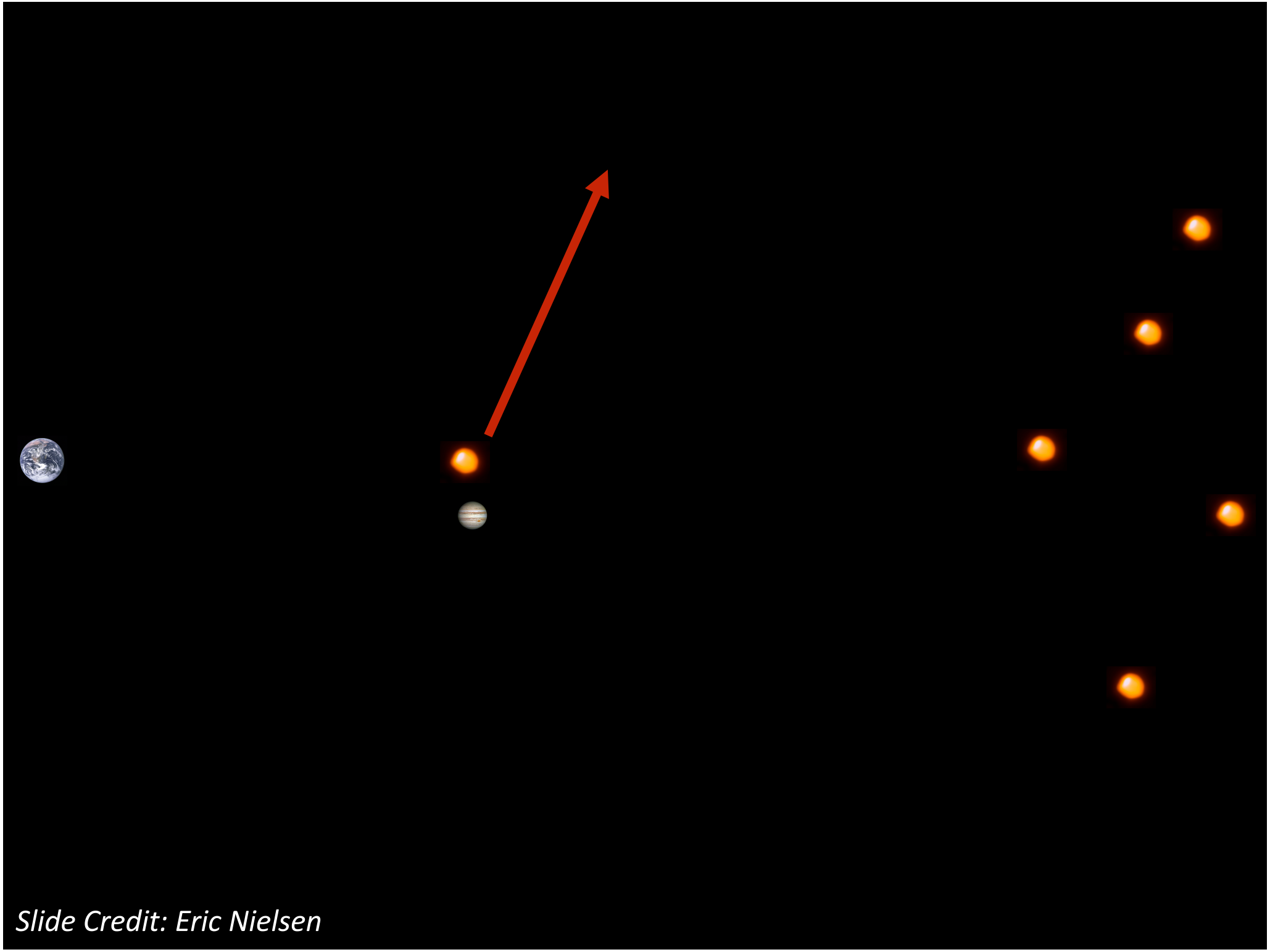
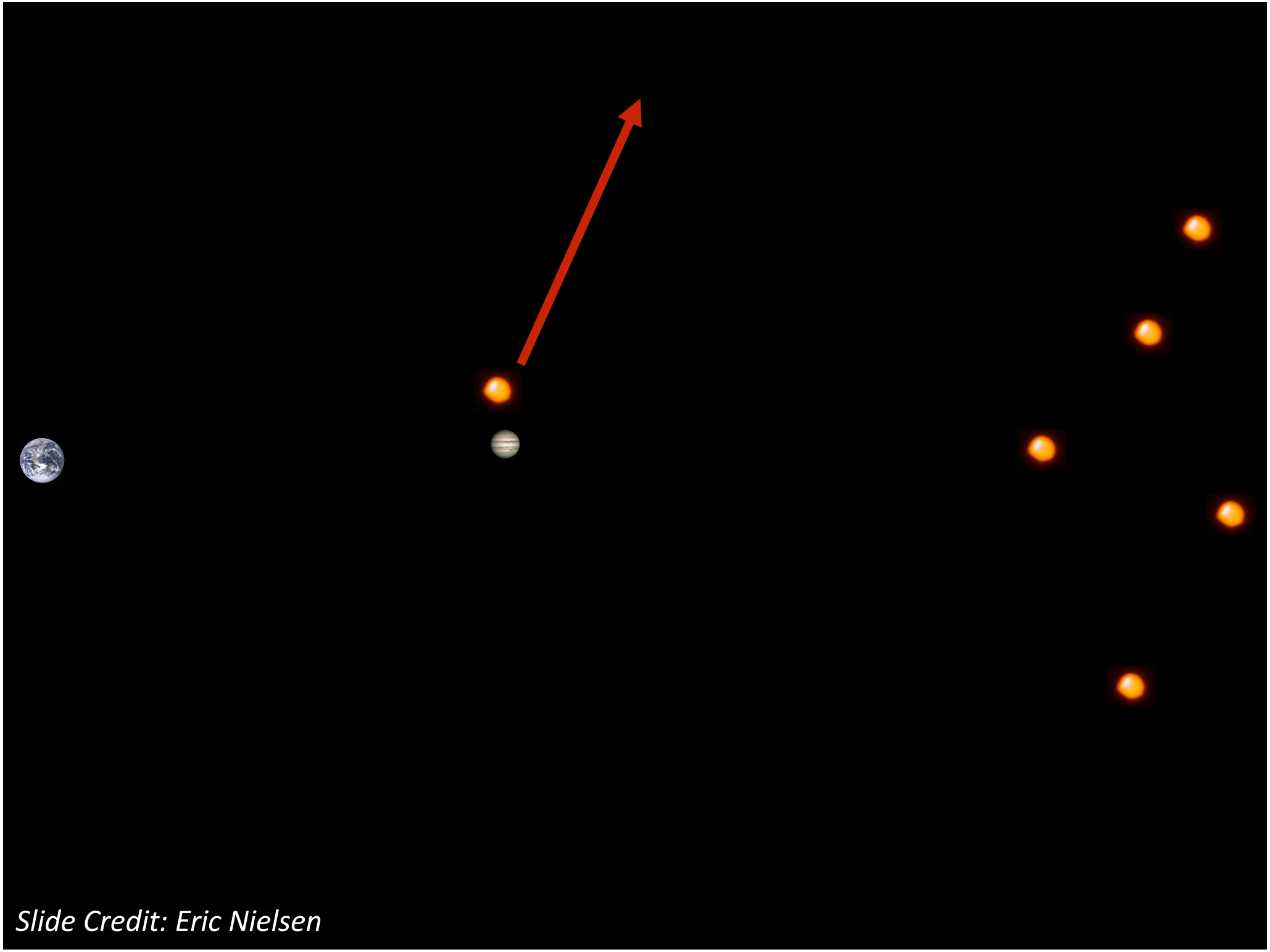


Image Credit: JB Ruffio

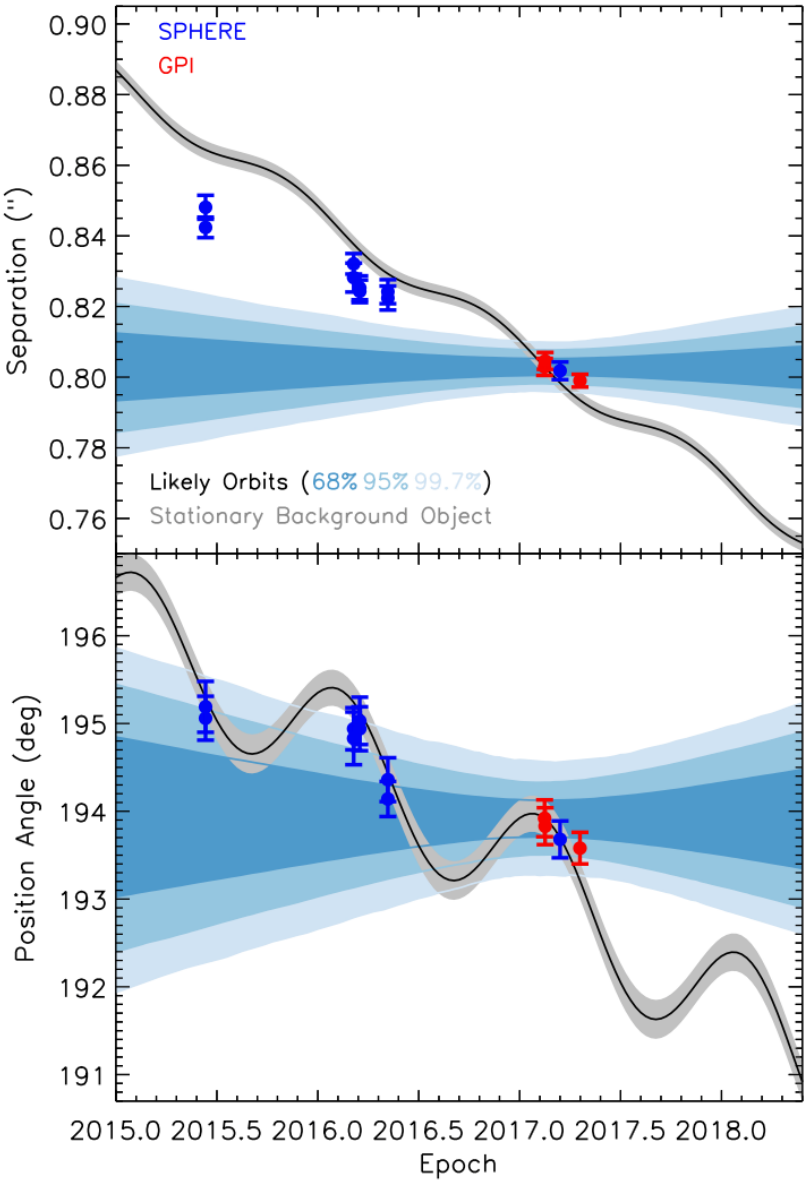
For more info, see *Pueyo 2016*



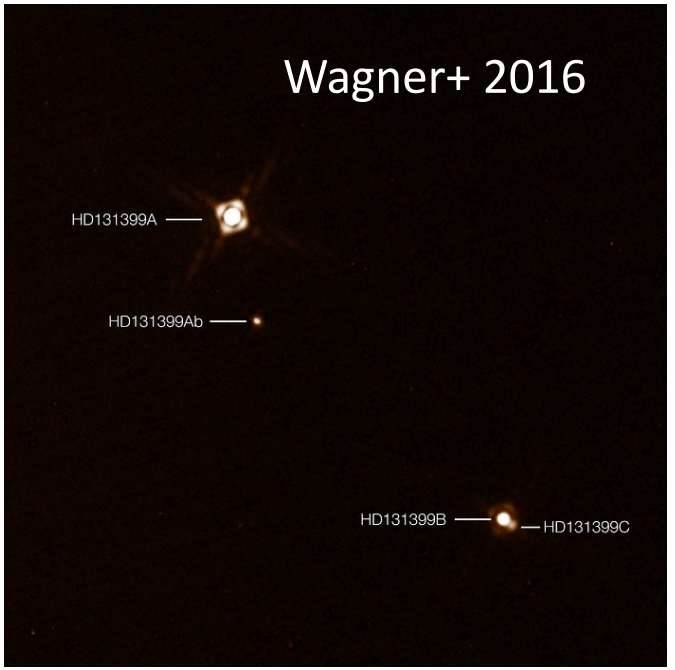
Slide Credit: Eric Nielsen

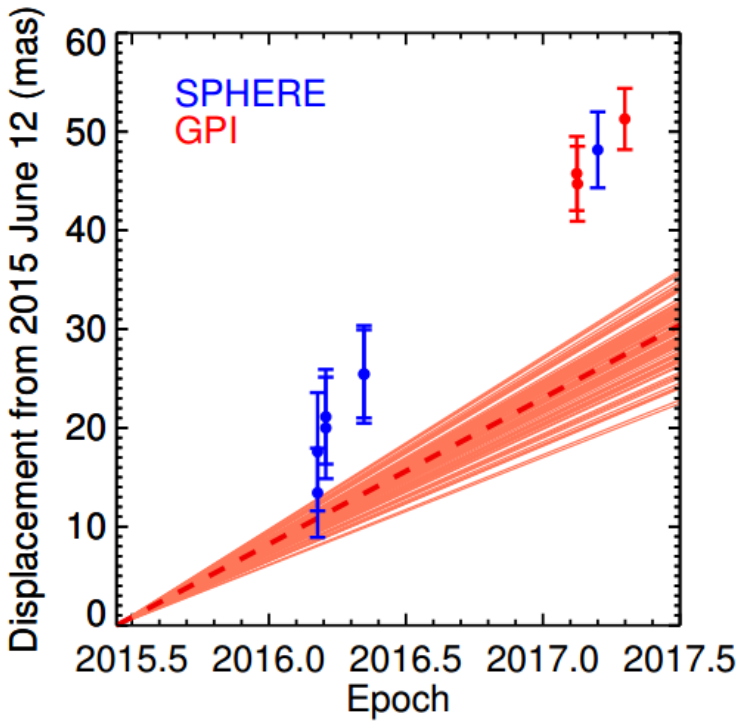

Slide Credit: Eric Nielsen

Case 1 – HD 131399

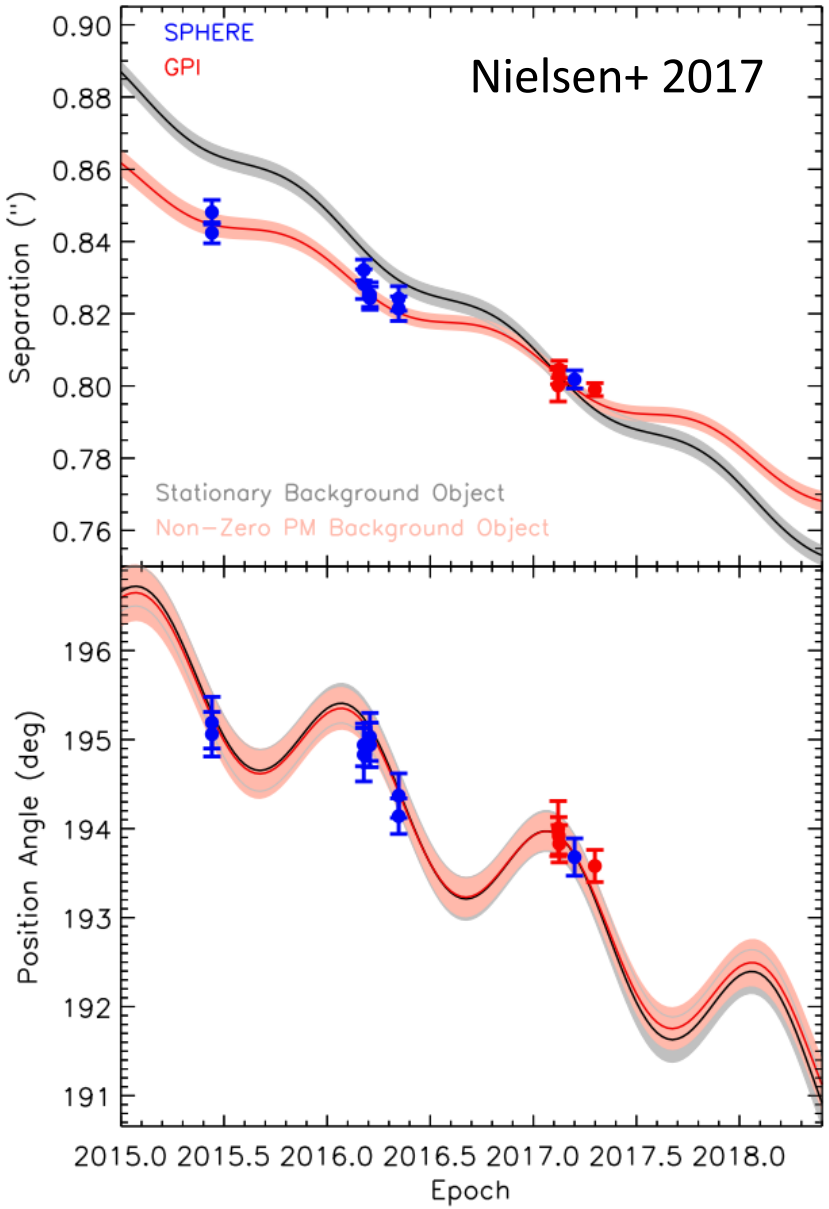


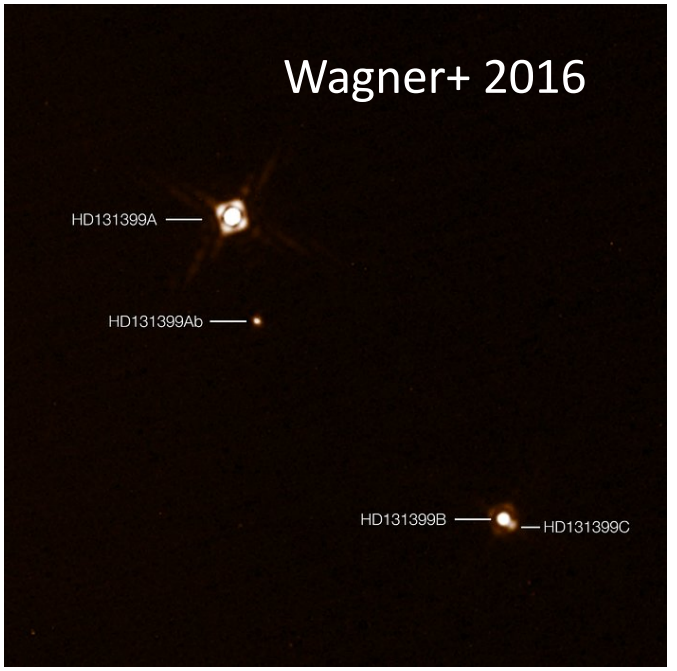
Nielsen+ 2017

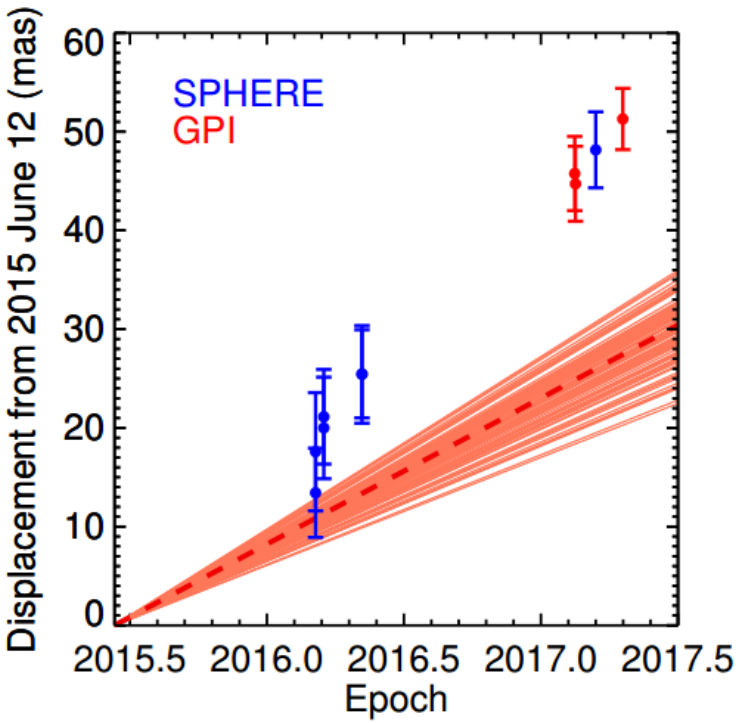




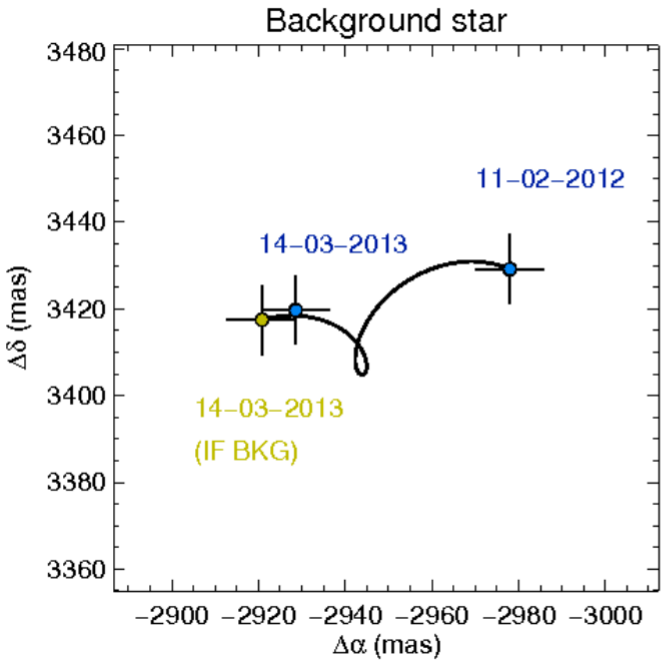
X Case 1 – HD 131399

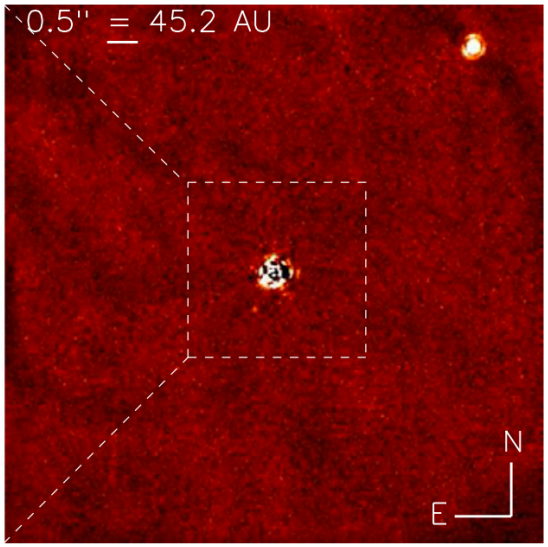






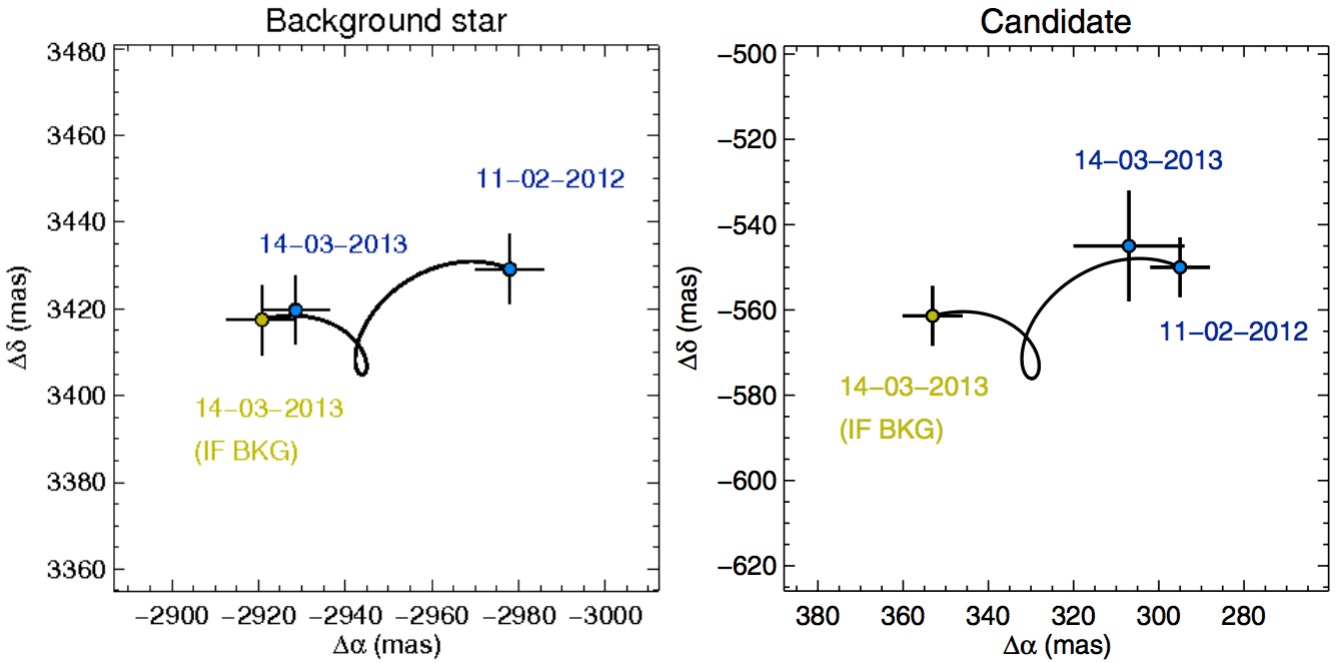
Case 2 – HD 95086

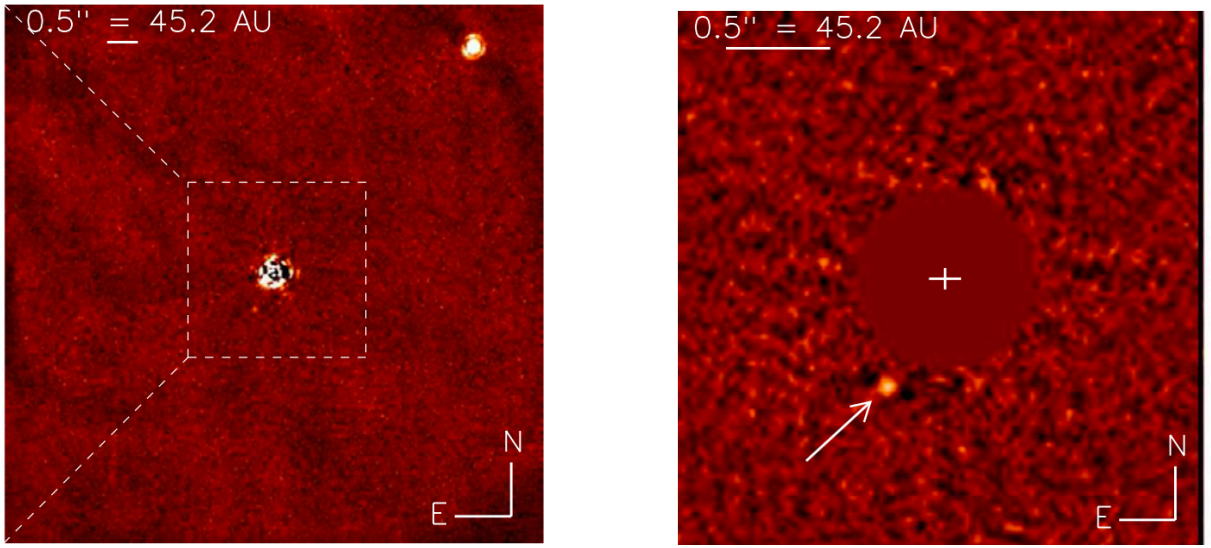




Rameau+ 2013

✔ Case 2 – HD 95086

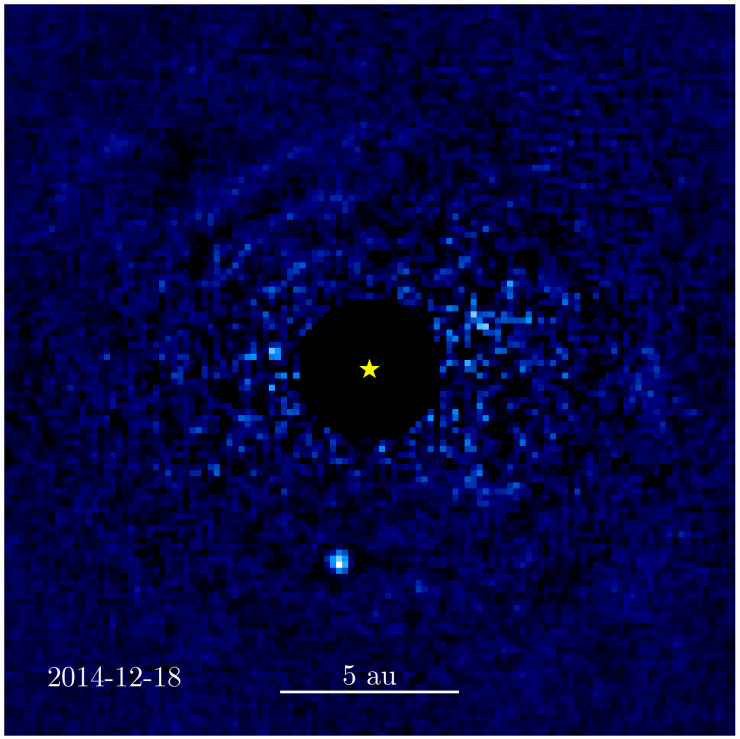


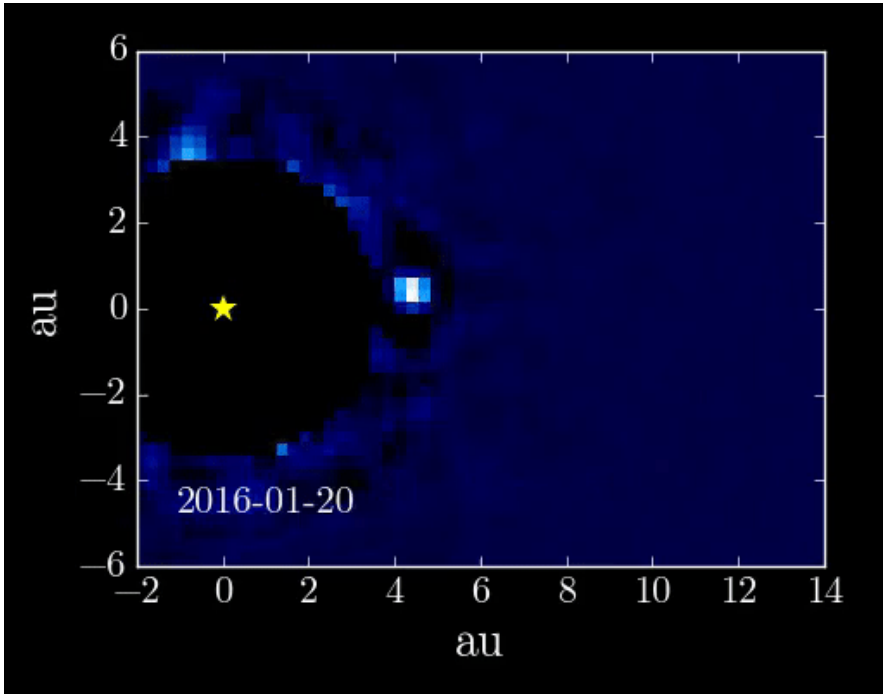


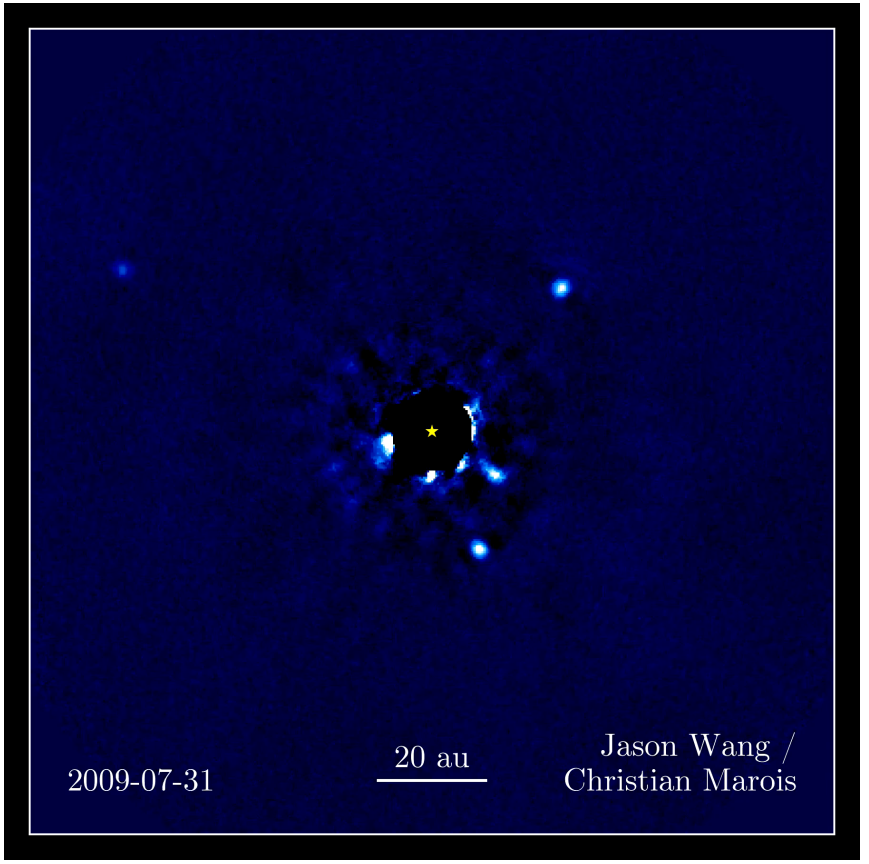
Rameau+ 2013

Real Planets Orbit Their Stars

Movies: Jason Wang and Christian Marois







Spectral Validation

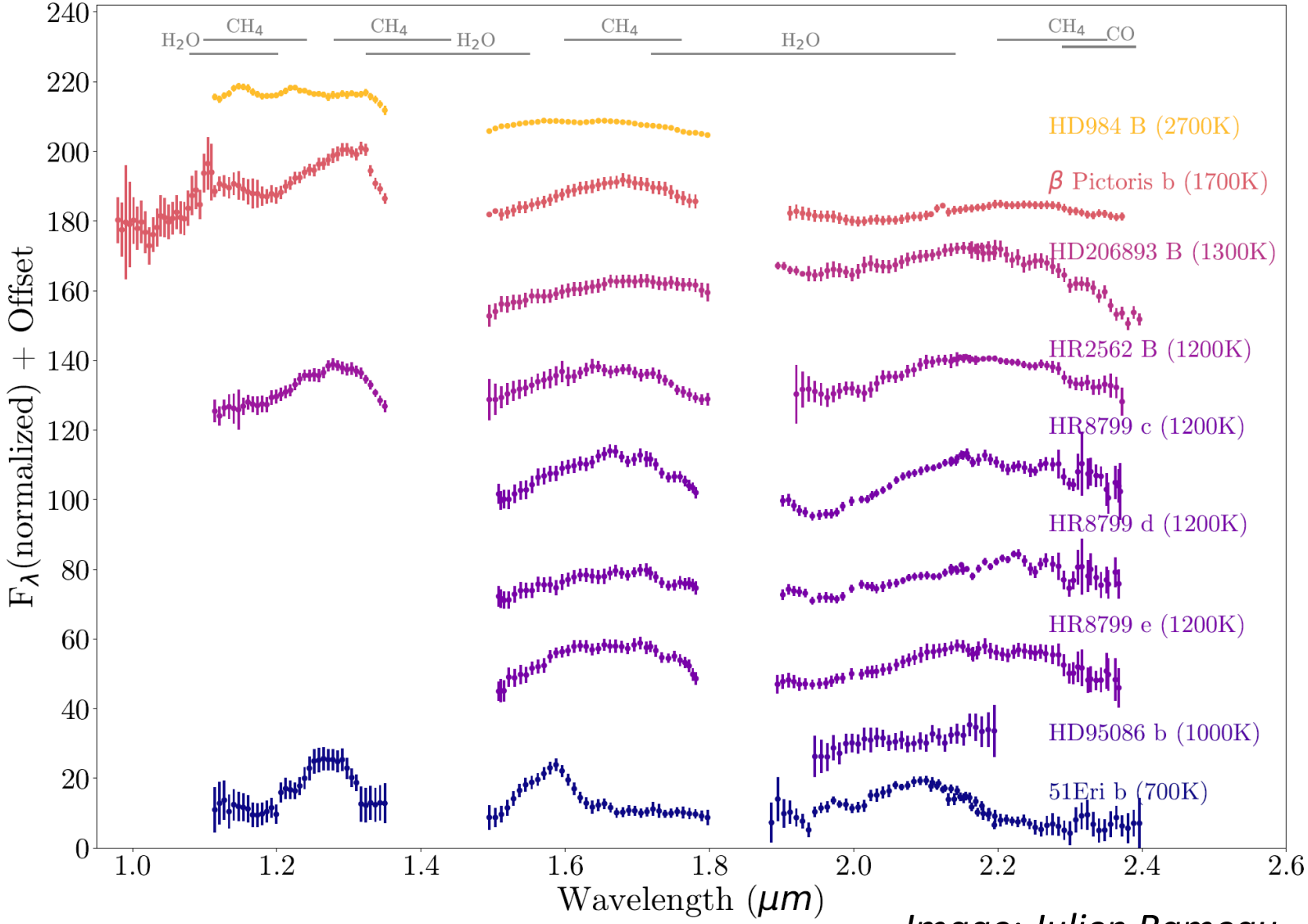
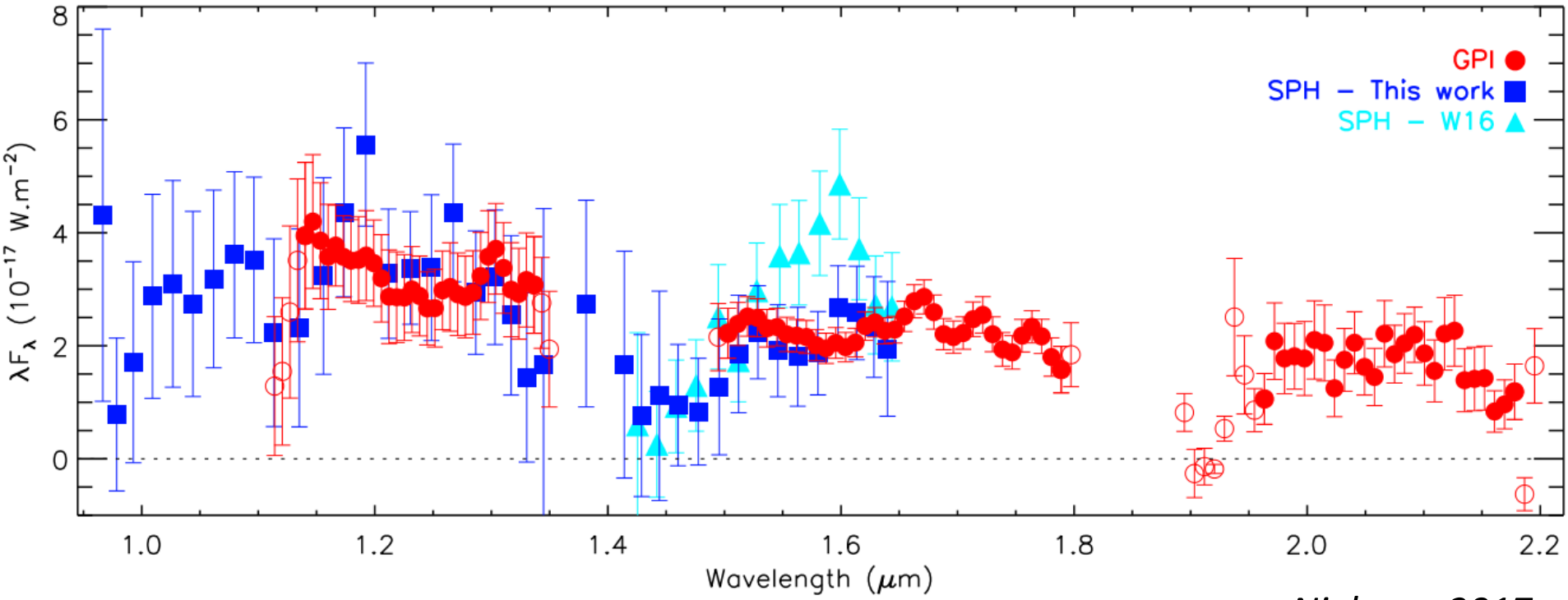


Image: Julien Rameau

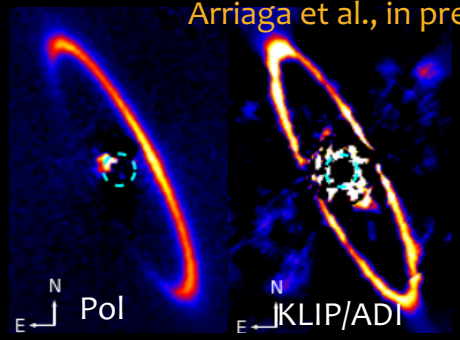
Spectral Validation



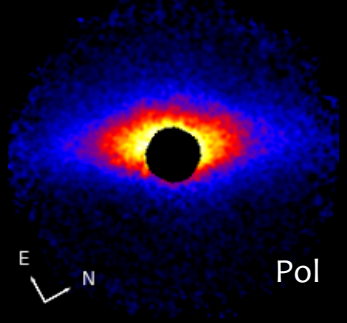
Nielsen+ 2017

Young Stars Have Disks (with Lots of Structure)

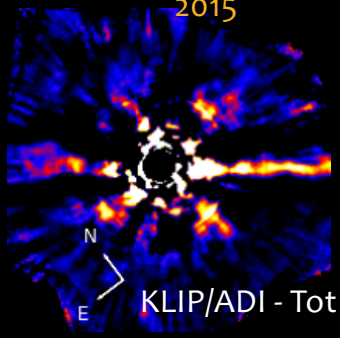
HR 4796A Perrin et al. 2015, Arriaga et al., in prep



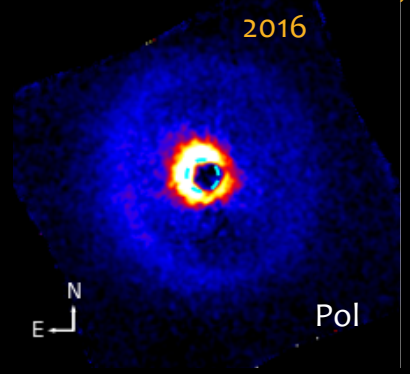
Beta Pic Millar-Blanchaer et al. 2015



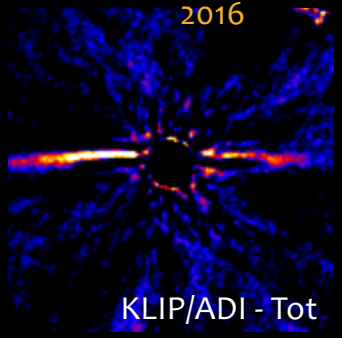
AU Mic Wang et al., 2015



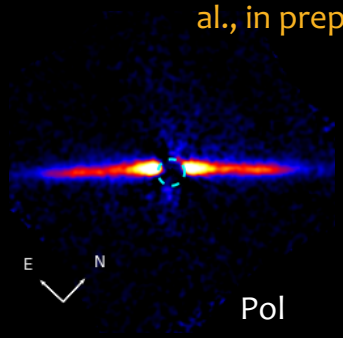
PDS 66 Wolff et al., 2016



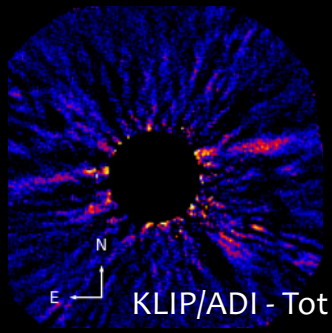
HD 106906 Kalas et al., 2016



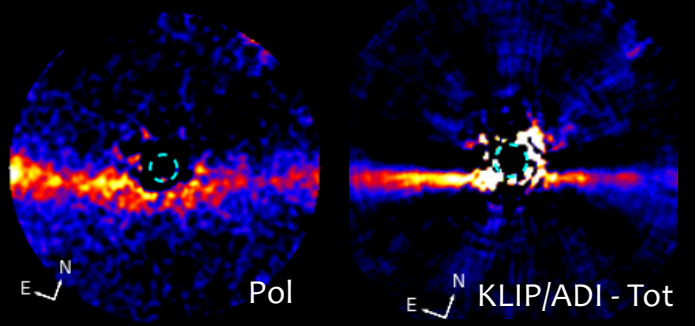
HD 32297 Duchene et al., in prep



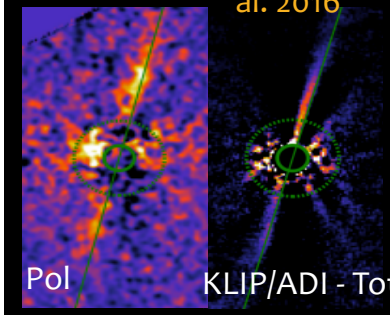
HD 15115



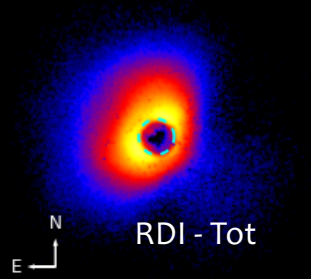
HD 61005 Esposito et al., in prep



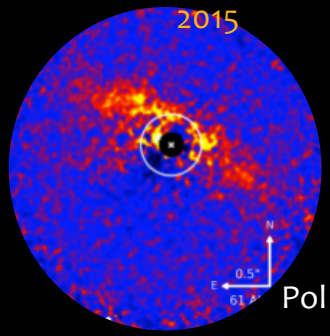
HD 111520 Draper et al. 2016



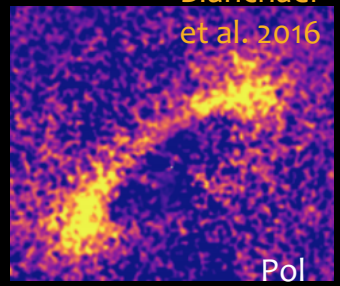
HD 100546 Follette et al., submitted



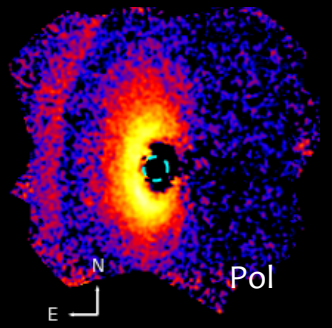
HD 32297 Hung et al. 2015



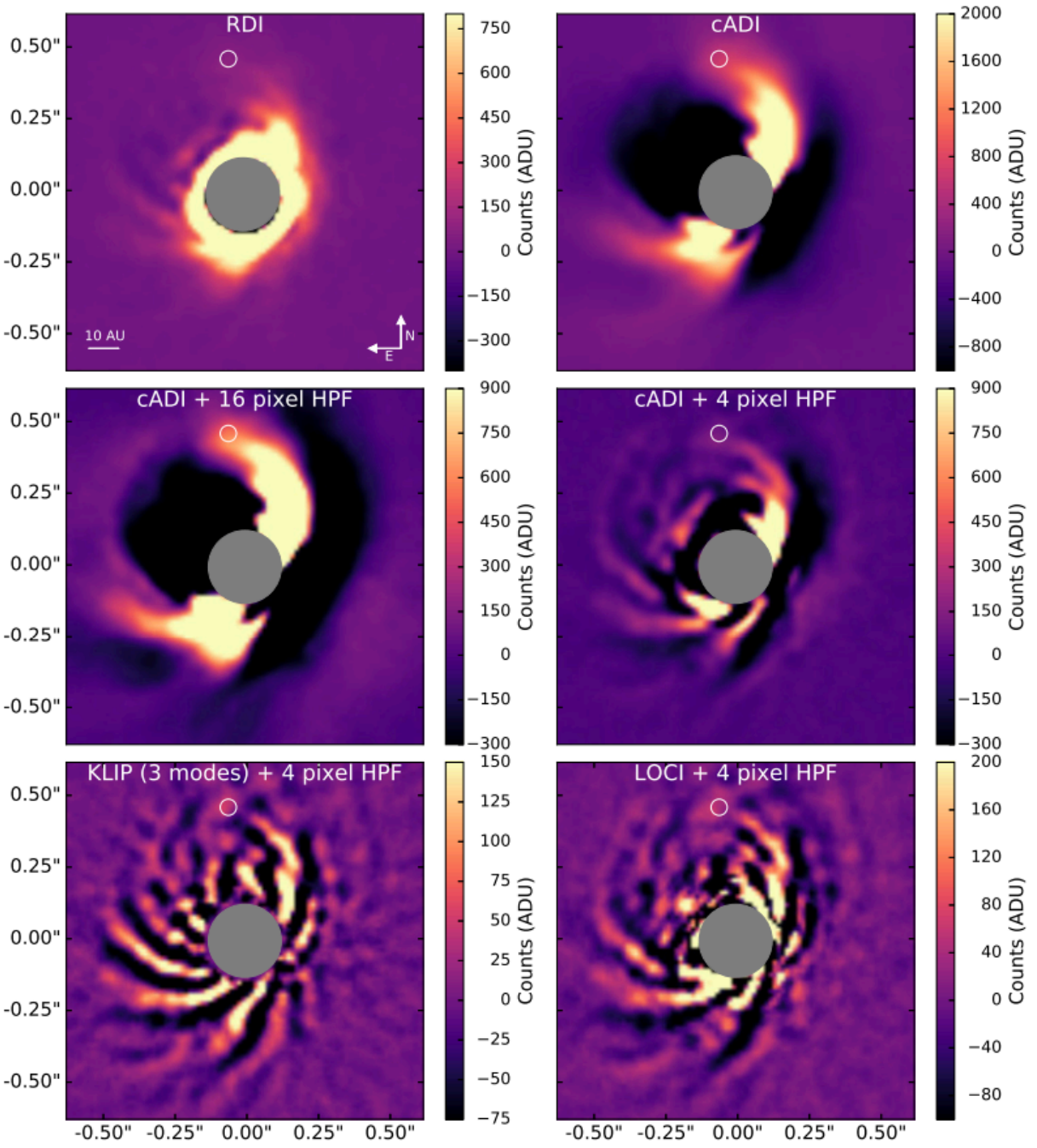
HD 157587 Millar-Blanchaer et al. 2016



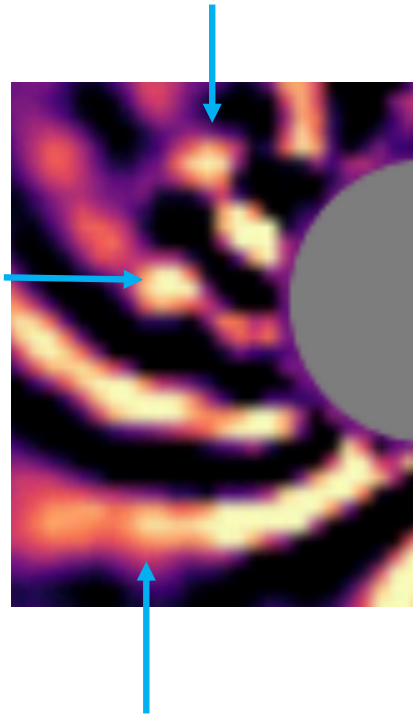
HD 141569 Bruzzone et al., in prep



Continuity of Scattered Light Structures

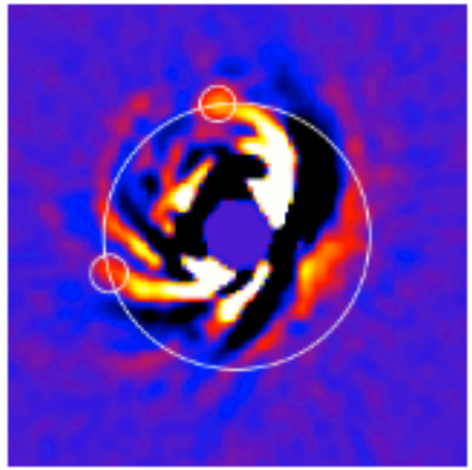


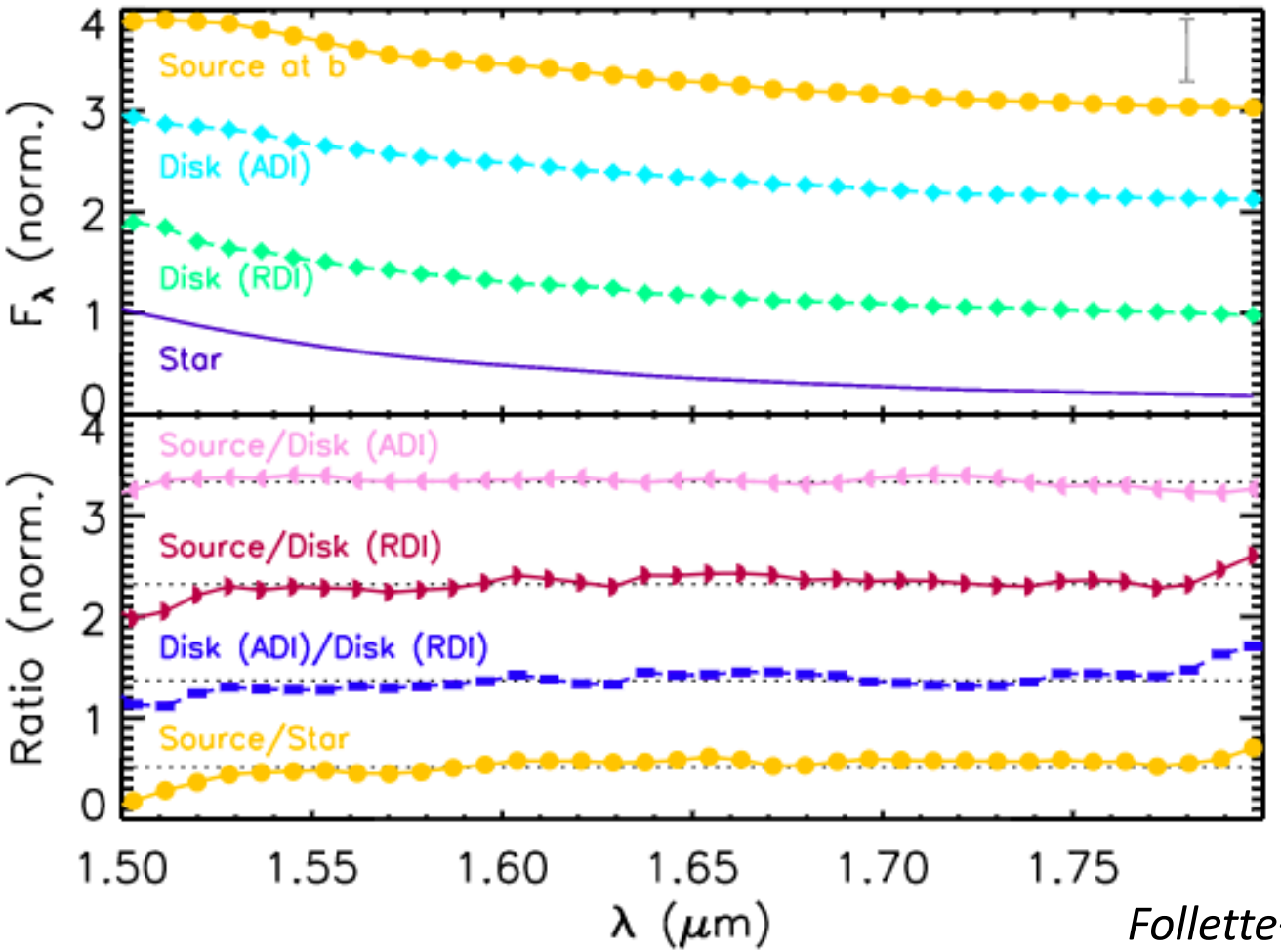
"aggressiveness"



Follette et al. 2017

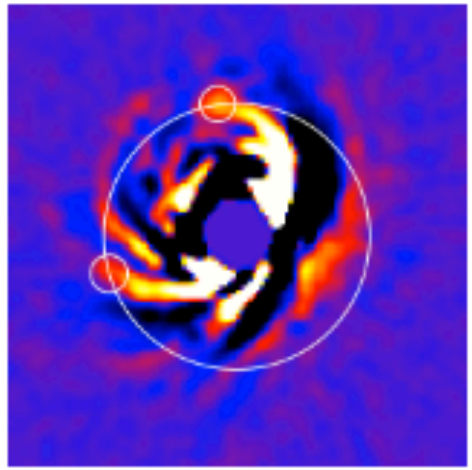
Case Study 3 - HD100546

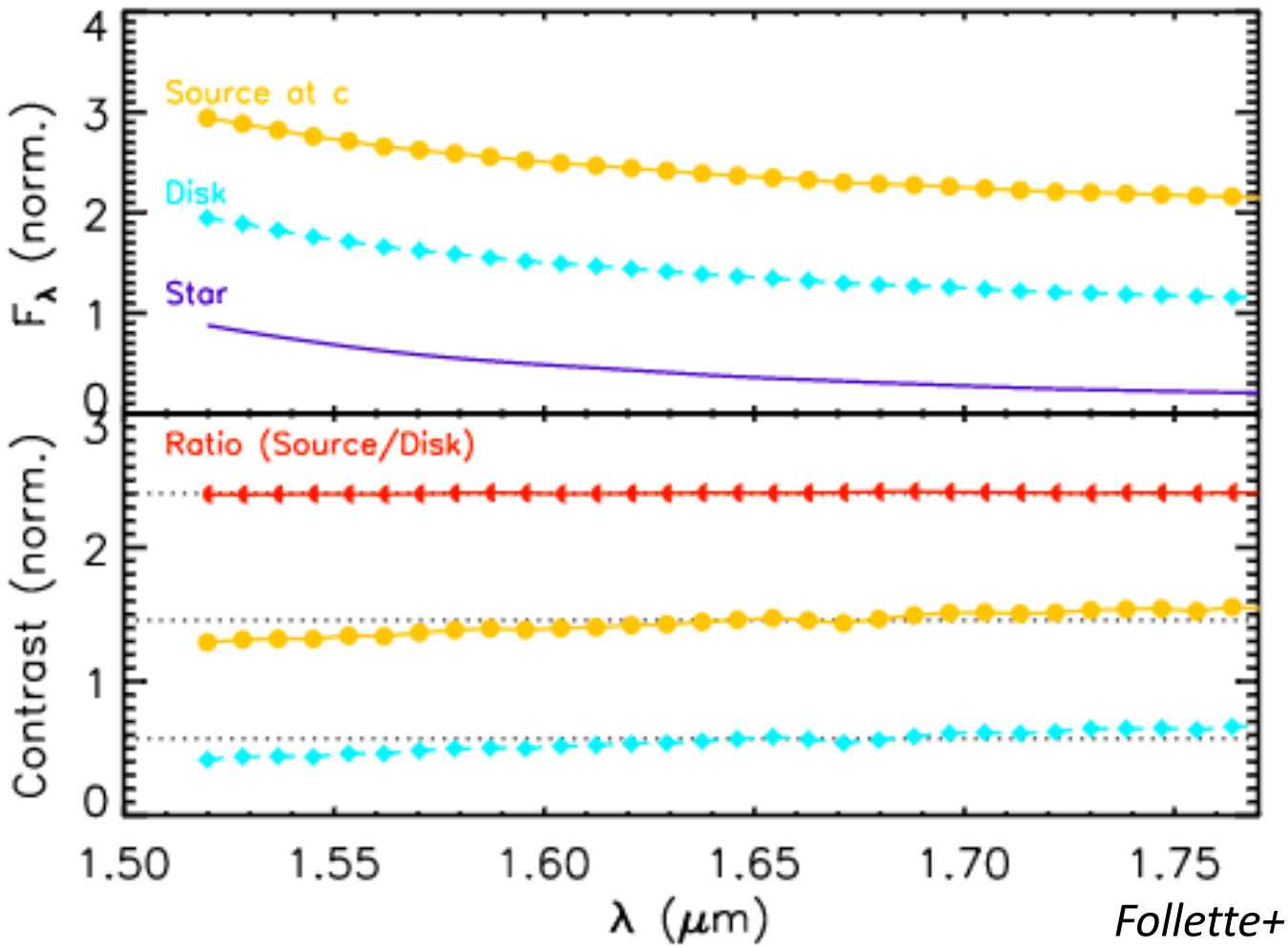




Follette+ 2017, Rameau+ 2017

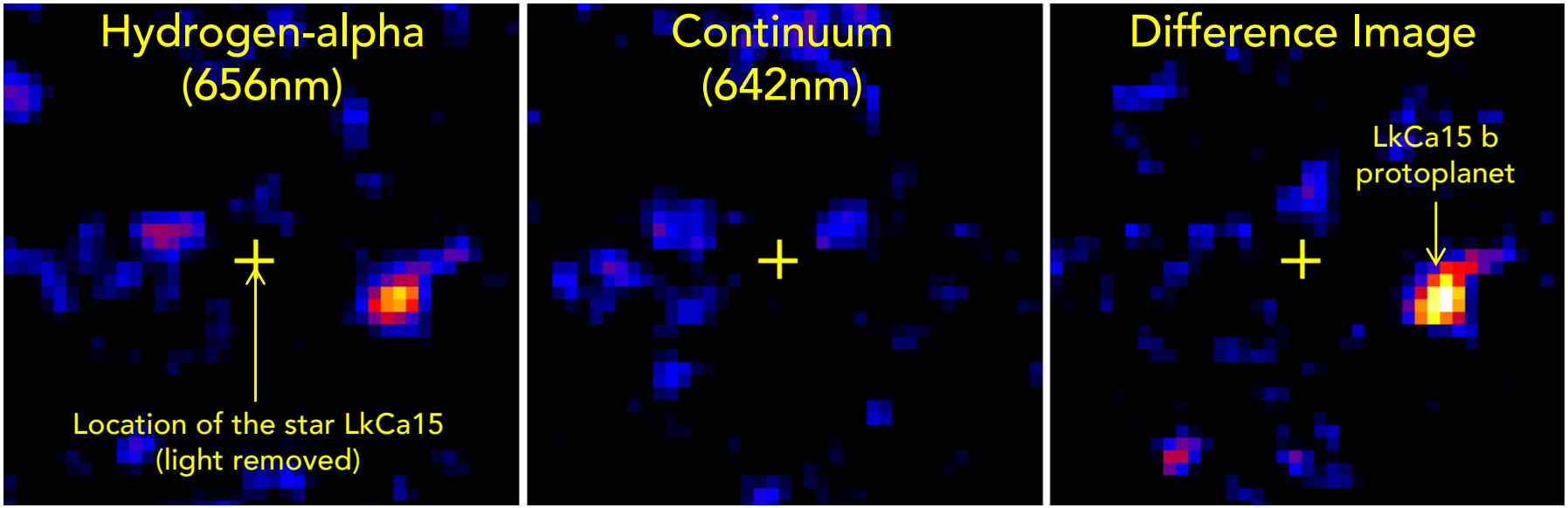
Case Study 3 - HD100546

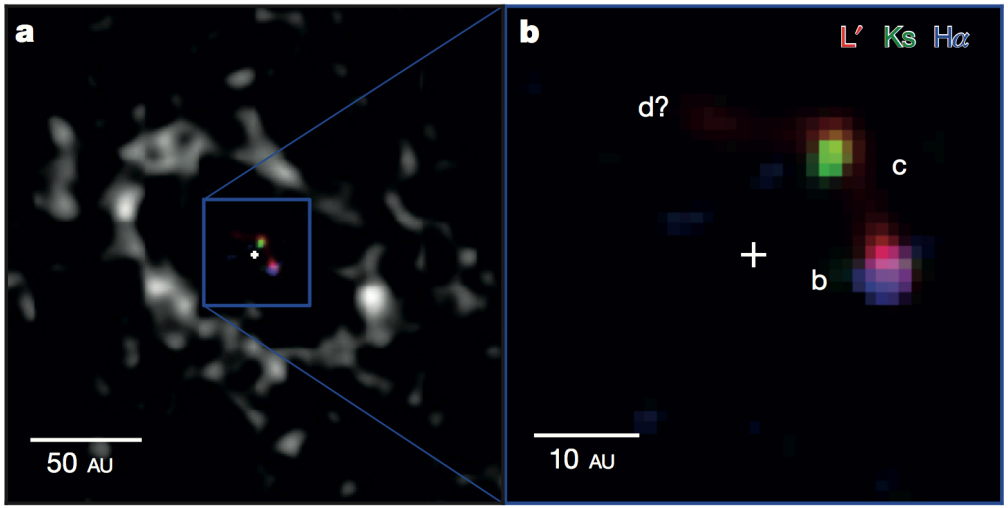




Follette+ 2017, Rameau+ 2017

Case Study 4 – LkCa 15





Sallum, Follette et al. 2015 *Nature*

✔ Spectrum distinct from star

✔ Detected at multiple wavelengths

Summary – You know it's a planet if...

- It rotates with the sky
- It's location does not change with wavelength
- It moves with its star (common proper motion)
- It's spectrum is distinct from the star's spectrum
- It is robustly detected with multiple PSF subtraction algorithms and/or multiple sets of algorithmic parameters