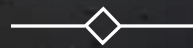


USING OBSERVATIONS OF DEBRIS DISKS TO UNDERSTAND THE LATE STAGES OF PLANETARY SYSTEM FORMATION



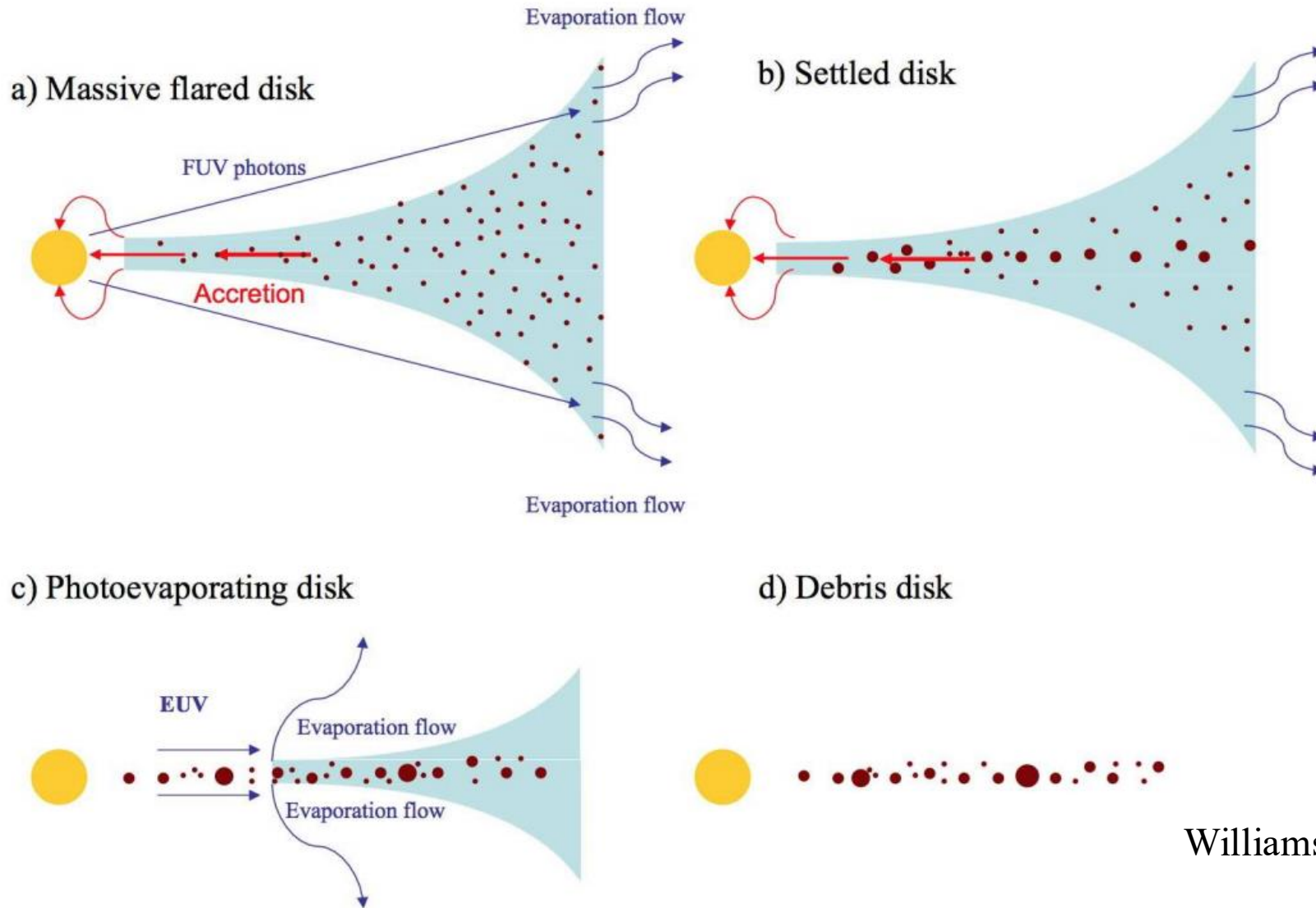
Kadin Worthen (Johns Hopkins University,
graduating May 2026)

Collaborators: Christine H. Chen, Sean Brittain,
Cicero Lu, Isabel Rebolledo, Chen Xie, Sarah
Betti, Joan Najita, Meredith Hughes, Yanqin
Wu, Carey Lisse



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What are debris disks?

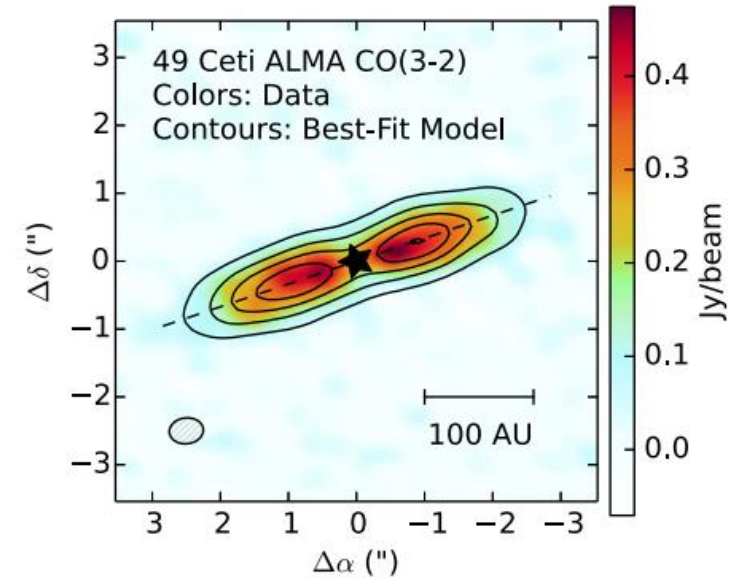


Williams and Cieza 2011

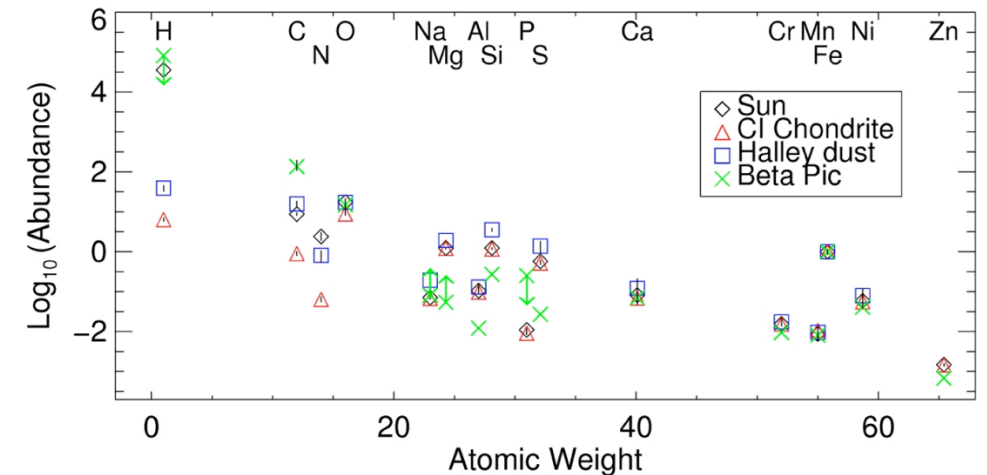
Gas in Debris Disks

- Debris disks were classically thought to be gas free, but ALMA has detected gas in ~20 debris disks
- Is the gas of primordial (H₂-rich) or secondary (H₂ depleted) origin?
- Primordial gas could increase giant planet formation timescale, secondary volatile gas could be delivered to rocky planets
- Secondary gas informs composition of minor bodies

Hughes et al. 2017

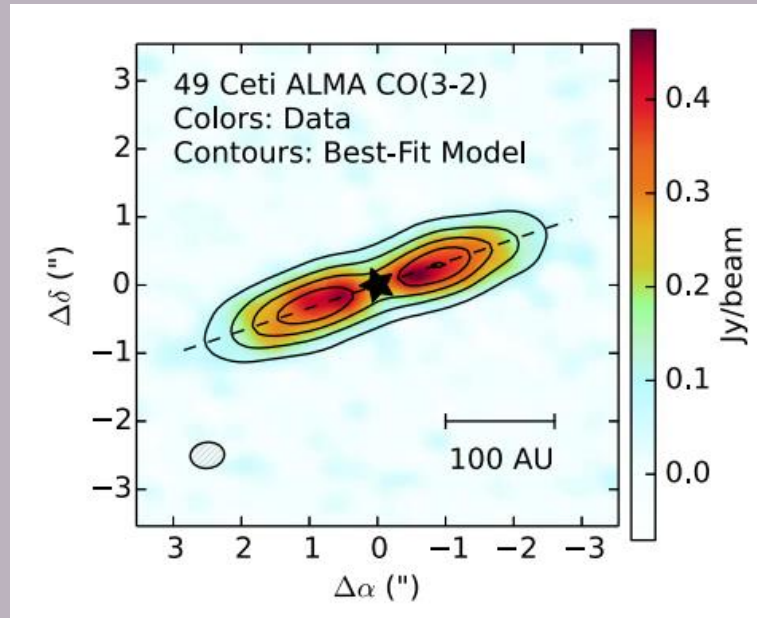


Roberge et al. 2006



JWST Case Studies with 49 Ceti and Beta Pictoris

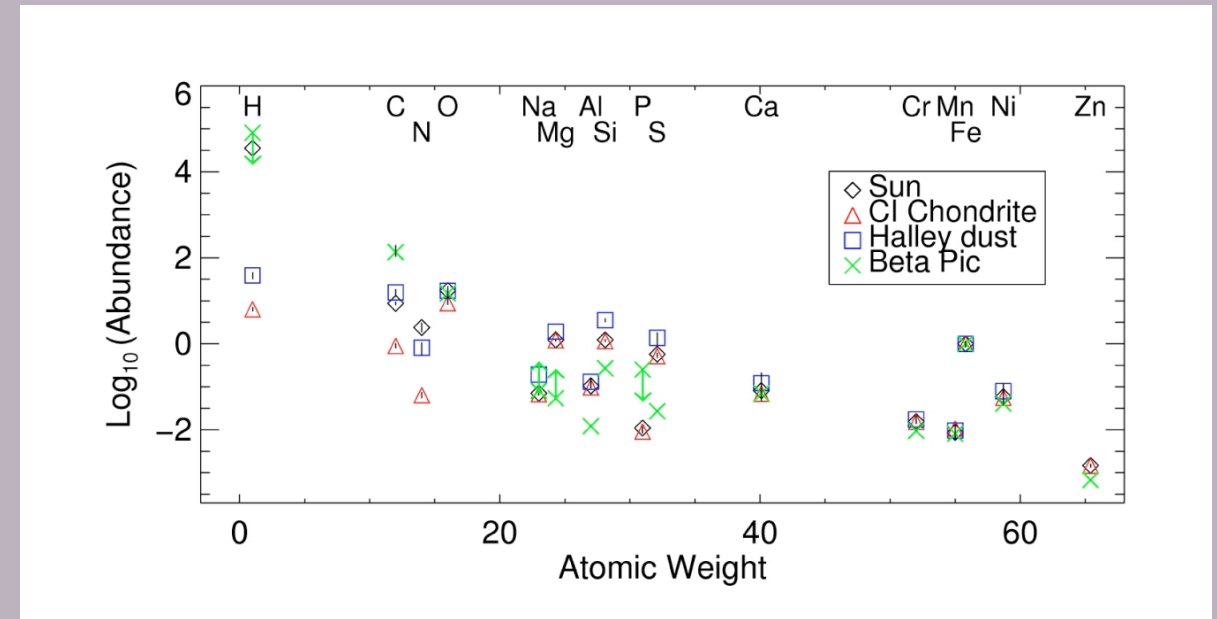
49 Ceti



Hughes et al. 2017

- 40 Myr A-type star with ~ 0.1 Earth Masses of CO
- Is the gas primordial or secondary?
- NIRSpec IFU observations

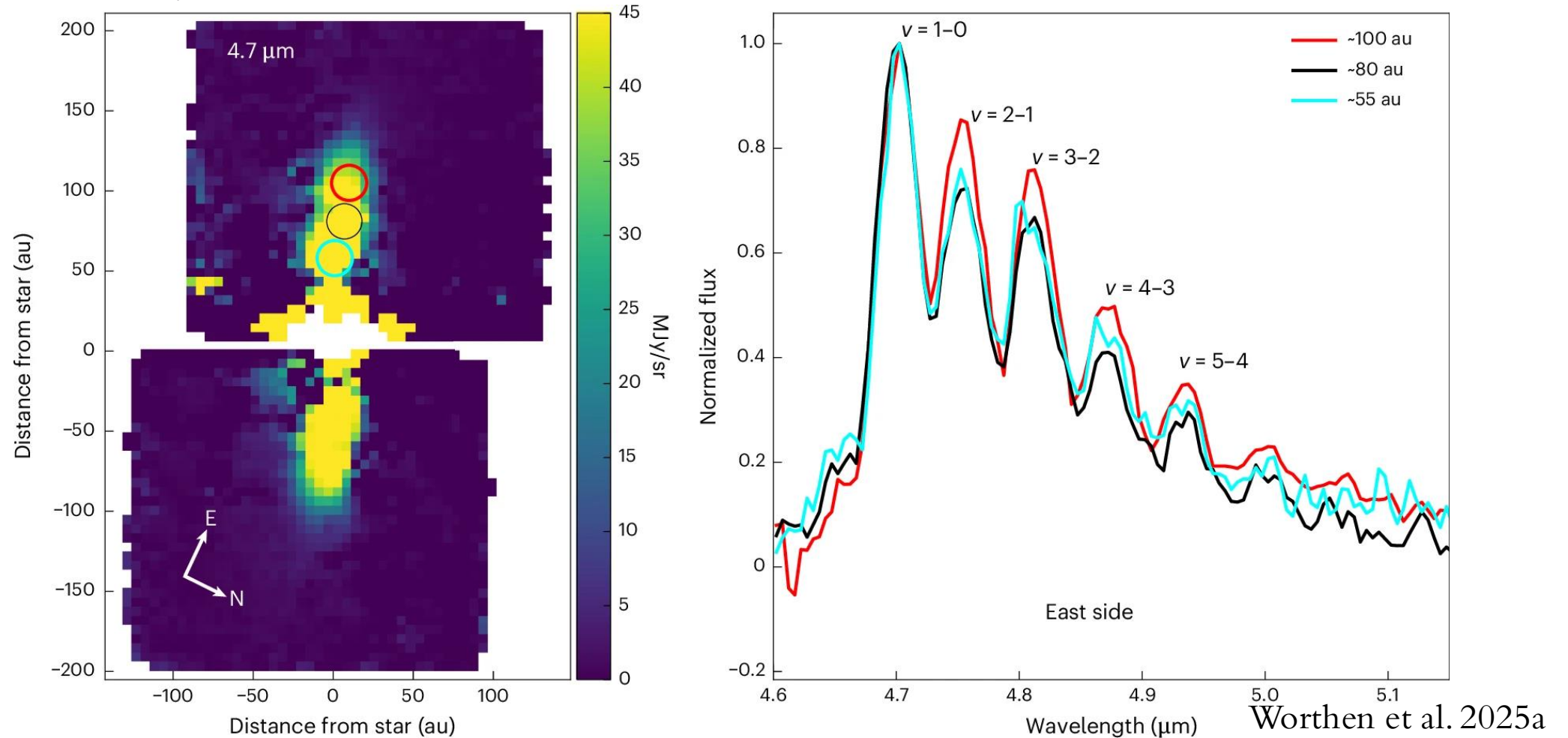
Beta Pictoris



Roberge et al. 2006

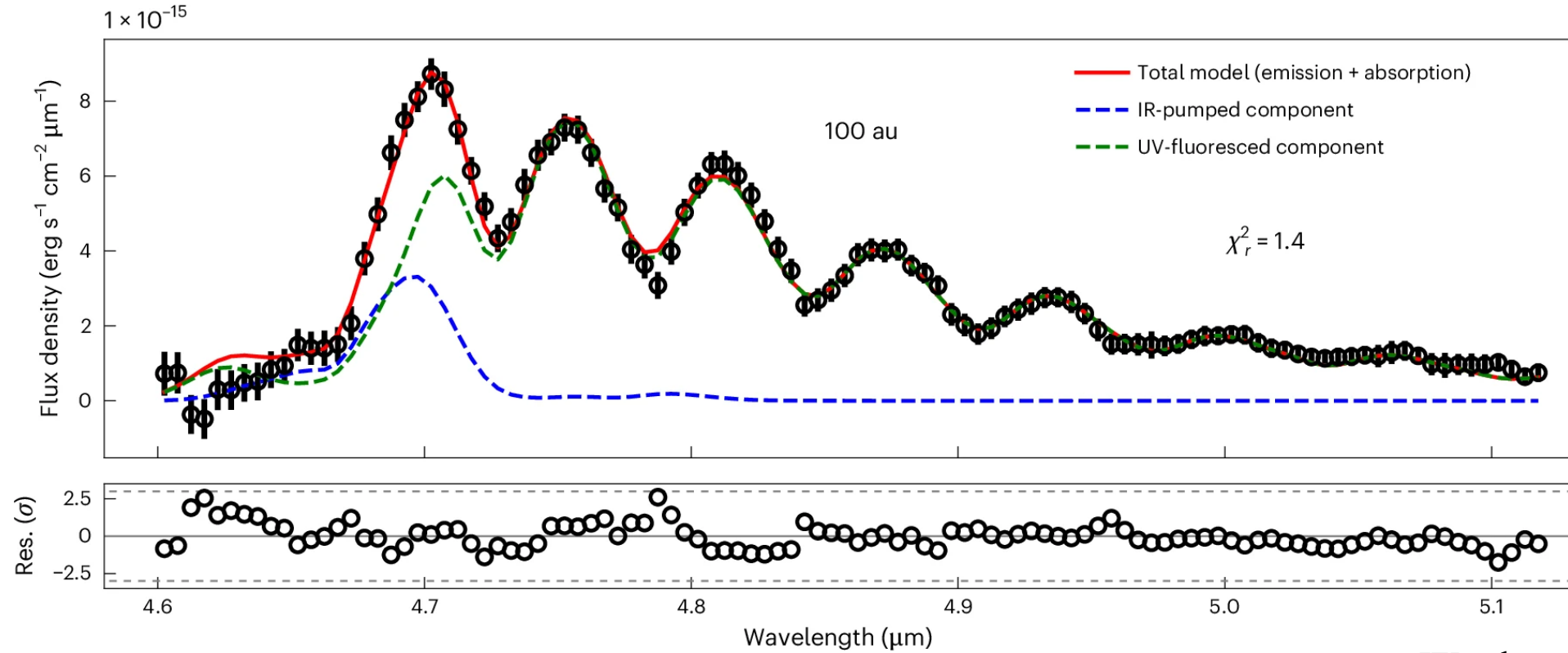
- 23 Myr A-type star with $\sim 10^{-5}$ Earth Masses of CO
- Gas is likely secondary, what is volatile composition of minor bodies?
- MIRI MRS Observations

Discovery of ro-vibrational CO emission in 49 Ceti



- We serendipitously detect ro-vibrational CO emission in the 49 Ceti debris disk with JWST NIRSpec
- Lines are blended at low spectral resolution ($R \sim 100$)
- CO is excited by fluorescence from UV and IR stellar photons

Fluorescent excitation model



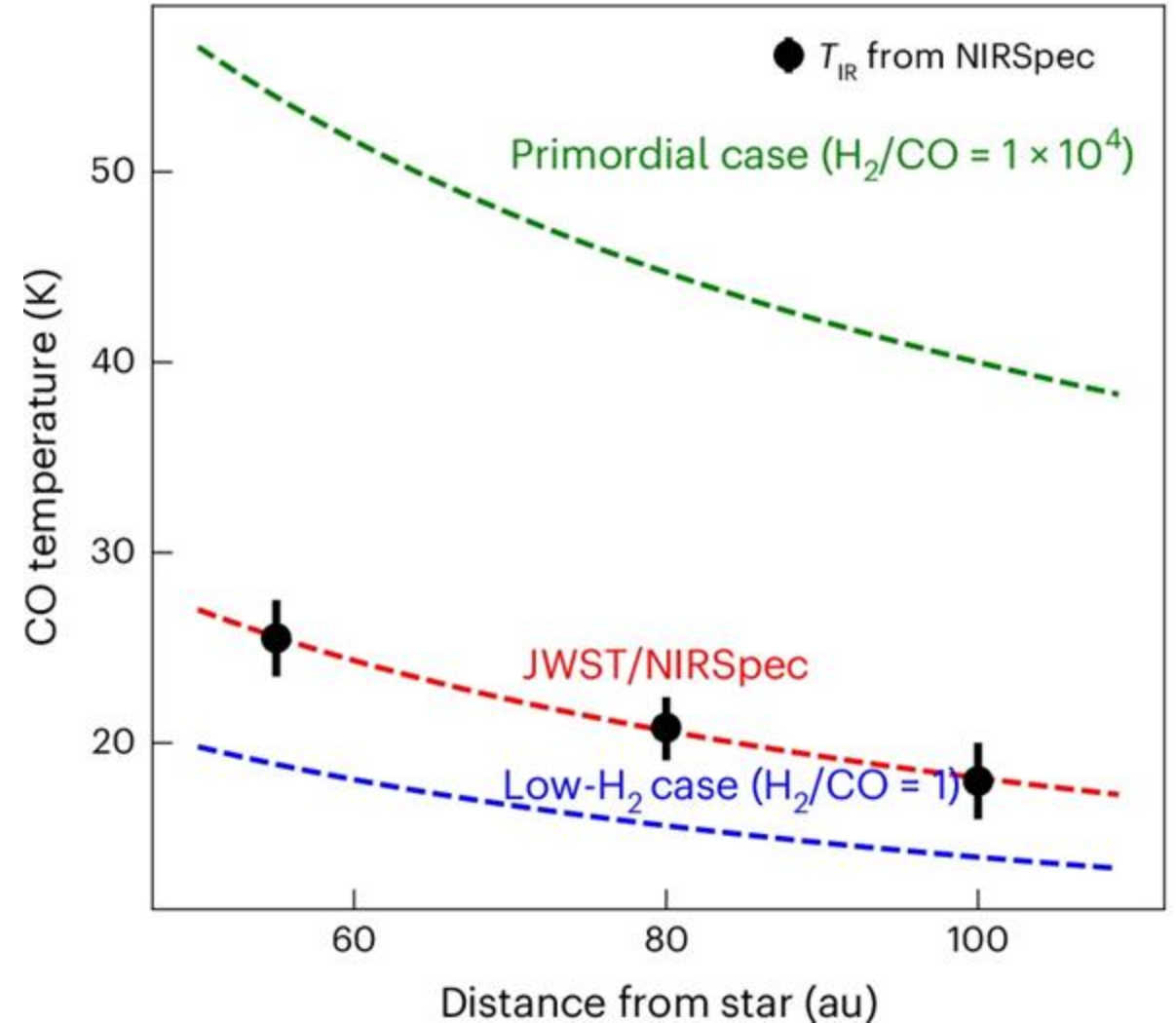
Worthen et al. 2025a

- Balance fluorescent excitation and de-excitation to generate model spectra
- Include IR pumping and UV fluorescence components
- Fit for column densities, isotopologue ratios, excitation temperatures.

A low CO excitation temperature

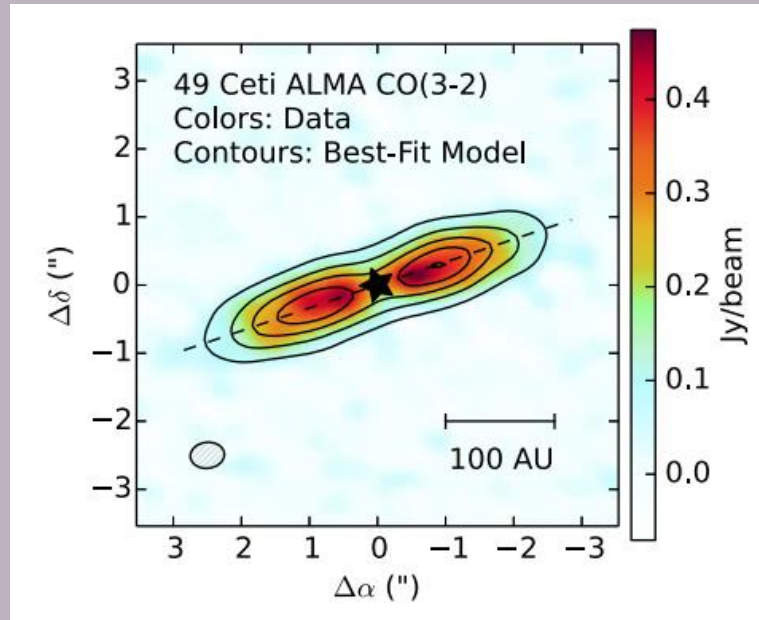
Worthen et al. 2025a

- Measured excitation temperature is low compared to predictions of primordial gas from ALMA observations
- Potentially not enough H₂ in the disk to thermalize the lines and reach LTE
- This low excitation temperature may favor secondary gas



JWST Case Studies with 49 Ceti and Beta Pictoris

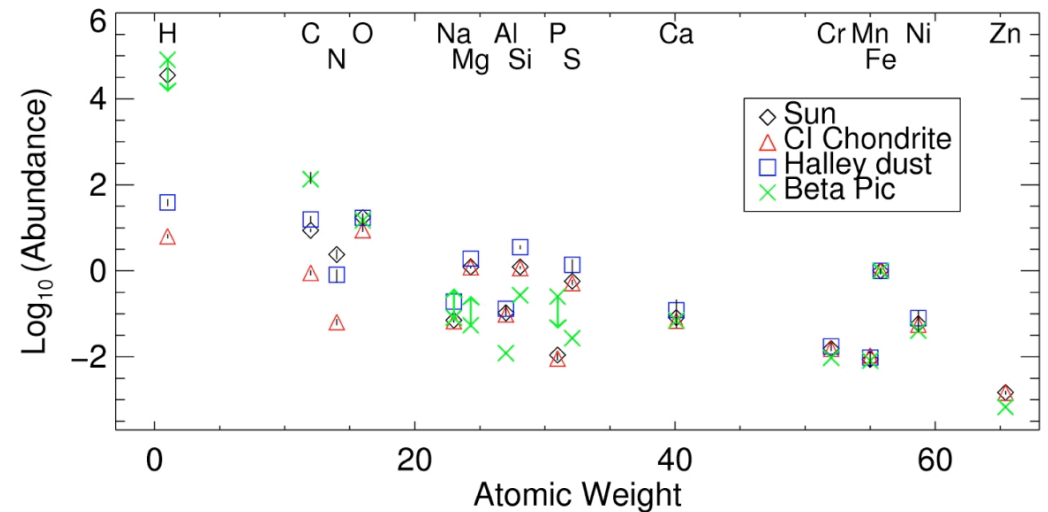
49 Ceti



Source: Hughes et al. 2017

- 40 Myr A-type star with ~ 0.1 Earth Masses of CO
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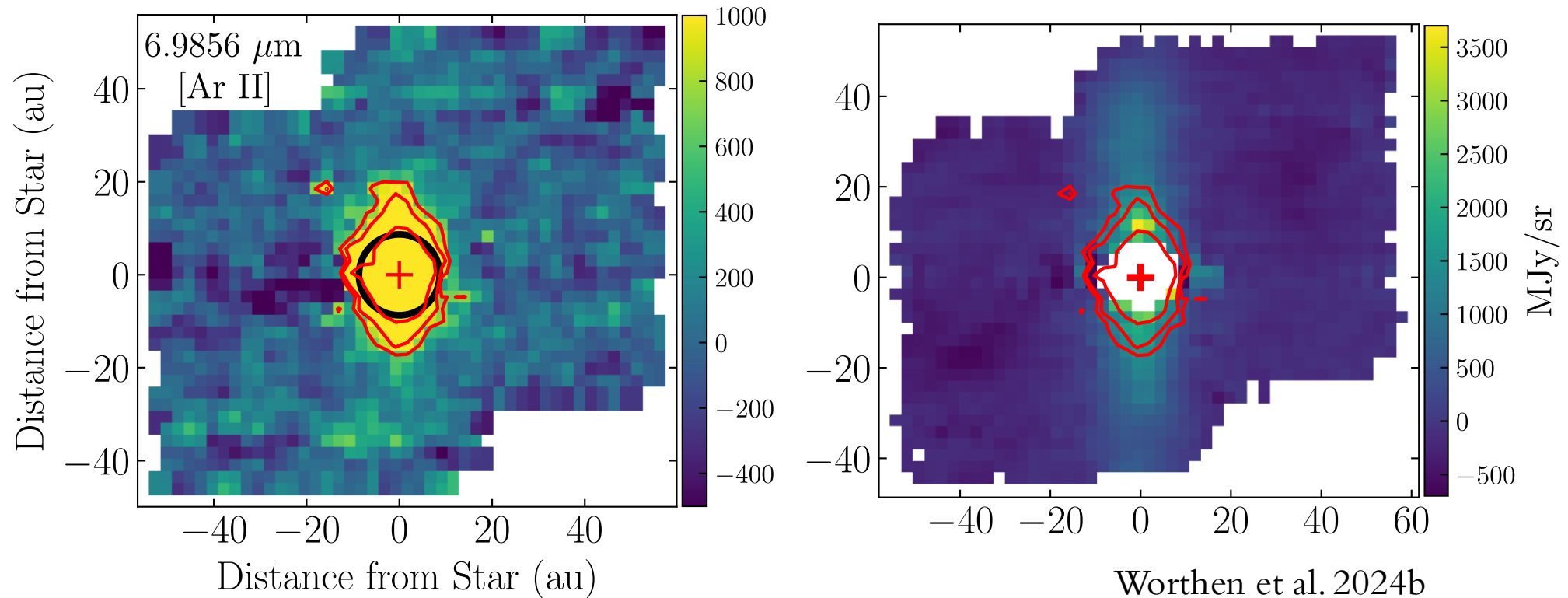
Beta Pictoris



Source: Roberge et al. 2006

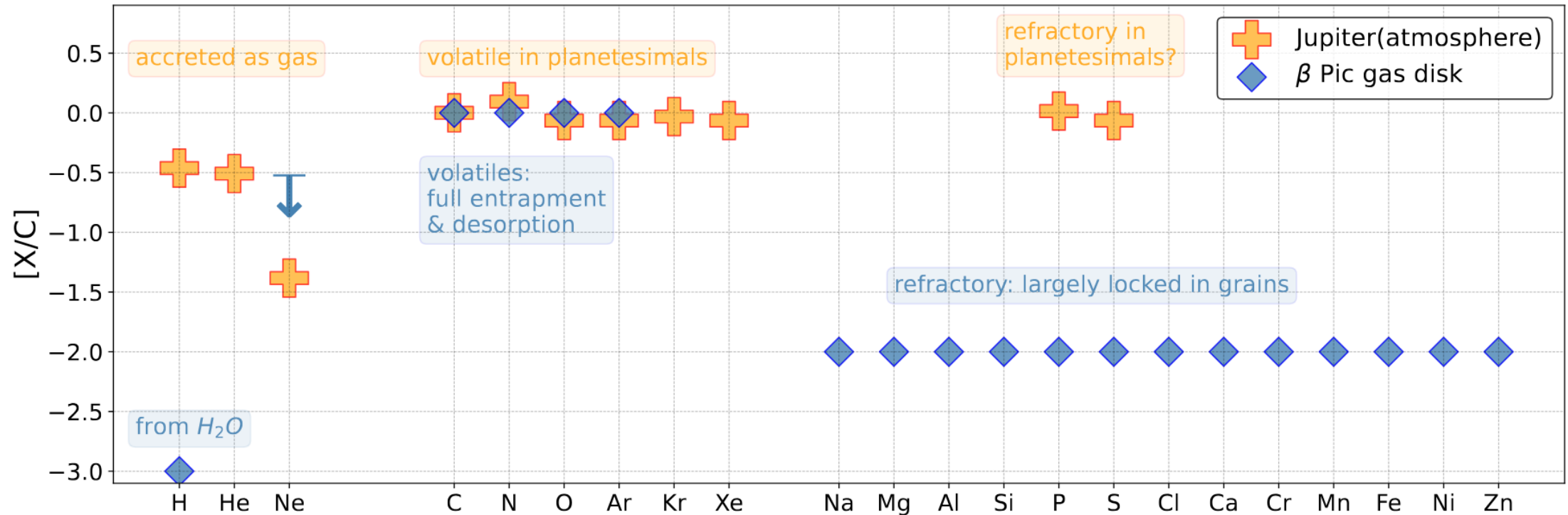
- 23 Myr A-type star with $\sim 10^{-5}$ Earth Masses of CO
- Gas is likely secondary, what is volatile composition of minor bodies?
- MIRI MRS Observations

Beta Pictoris Argon gas detection with MIRI MRS



- First ever detection of argon in a debris disk
- Gas is spatially resolved out to ~ 20 au
- Argon is hyper volatile (sublimates at ~ 30 K)

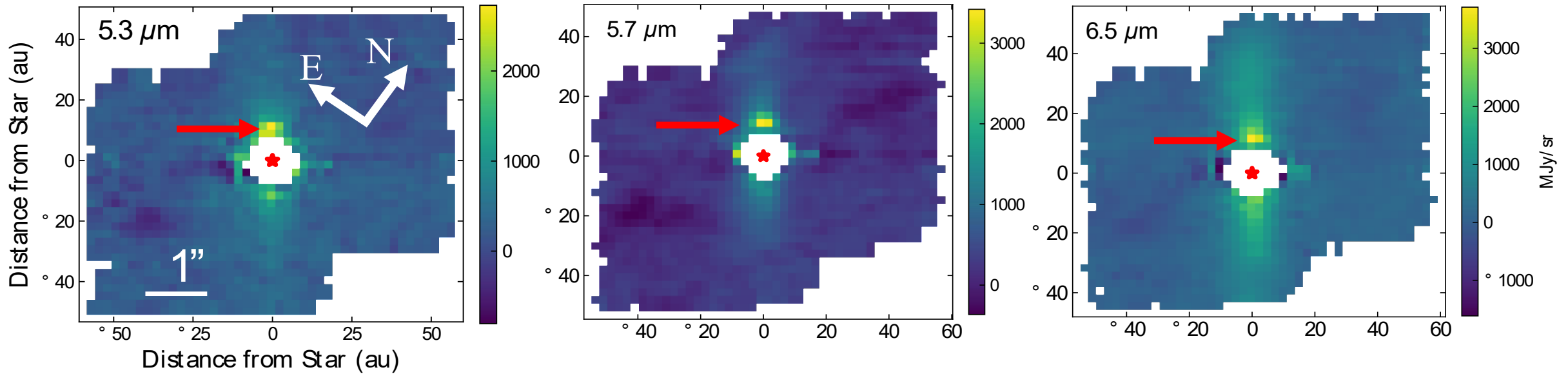
Beta Pic gas is enhanced in volatiles



- Ar, C, N, O are enriched by a factor of 100 relative to refractory elements
- Ar is most volatile, planetesimals formed in cold environment to entrap argon
- Enrichment of planetesimals in Ar is similar to Ar enrichment in Jupiter

Wu, Worthen et al. 2025

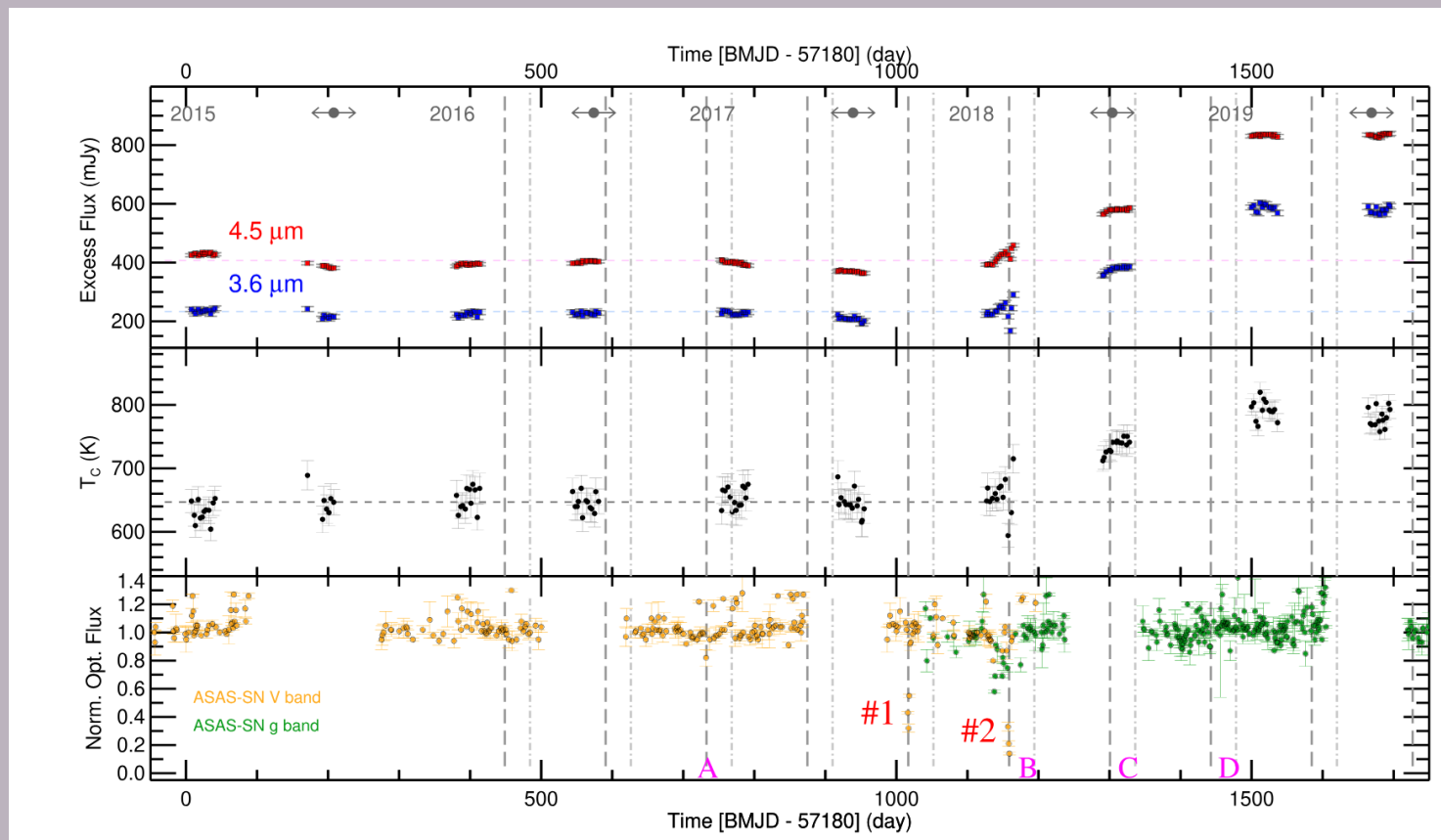
Detection of Planet Beta Pic b



Worthen et al. 2024b, ApJ, 964, 2, 168

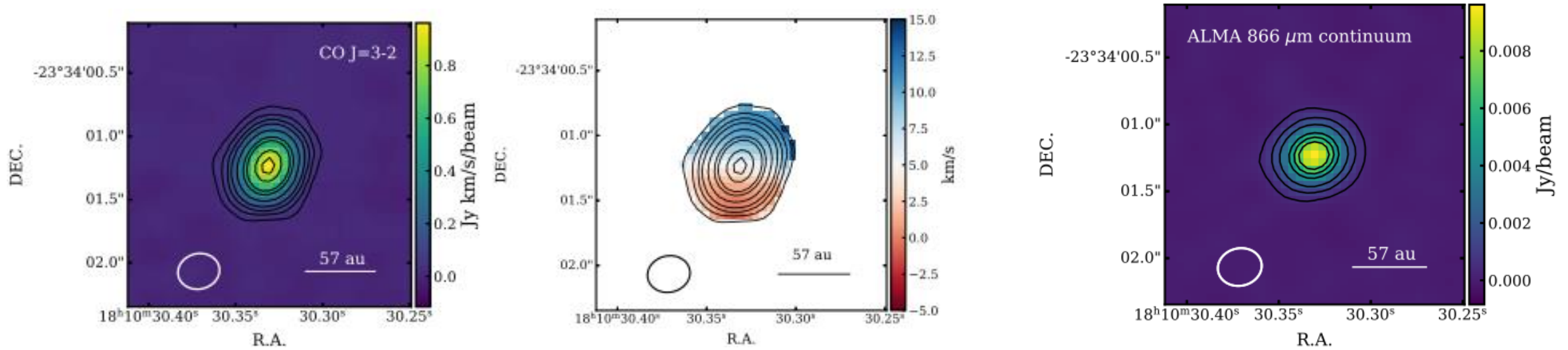
Terrestrial Planet Formation around HD 166191?

- HD 166191 is a 4–10 Myr F-type star
- Time monitoring with *Spitzer* revealed variability in its infrared excess
- Likely giant collision in terrestrial planet zone
- What is evolutionary state of the system (protoplanetary disk or debris disk?)



Su et al. 2022

ALMA Observations of HD 166191



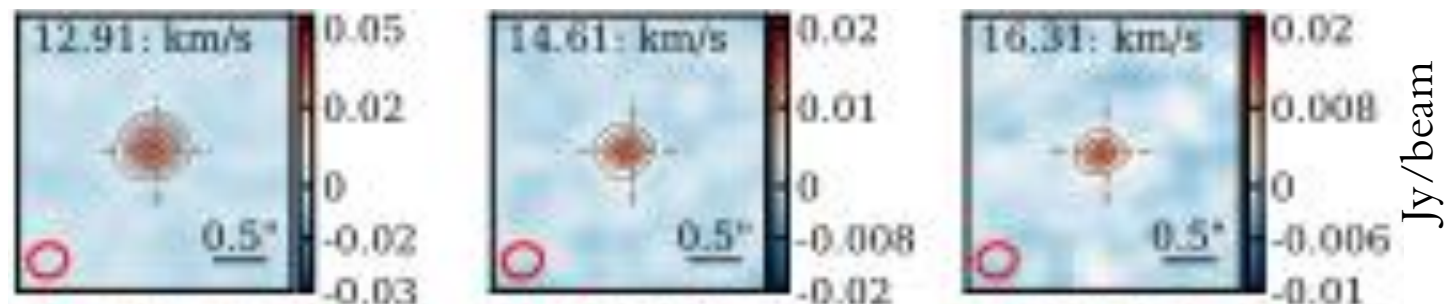
Worthen et al. 2026

- We observed ALMA in Band 7 (0.3'' resolution at 100 pc, PI: K. Worthen)
- First detection of gas in the system with spatially resolved CO
- Modeling suggests gas and dust are compact, within 20 au from the star
- Gas rich debris disk or protoplanetary disk?

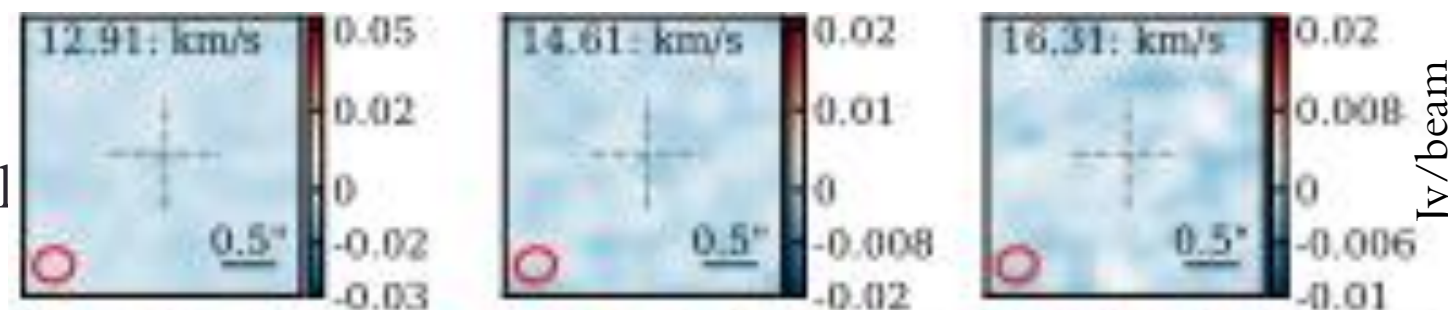
CO Modeling

- Radiative transfer models favor CO mass of few Earth masses (larger than any gas rich debris disk)
- Best fit inner radius of ~ 2 au
- HD 166191 may be in a transitional state where primordial gas is being cleared from the inner regions enabling debris producing collisions

ALMA Data (subset)



Residuals (subset)

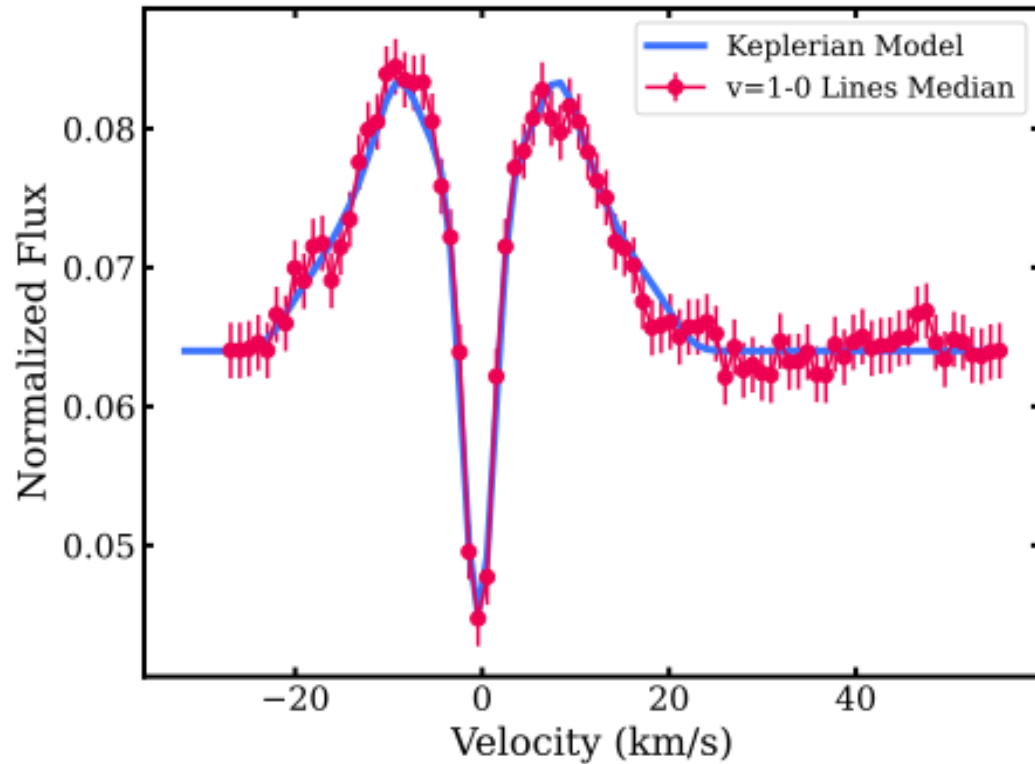


Conclusions

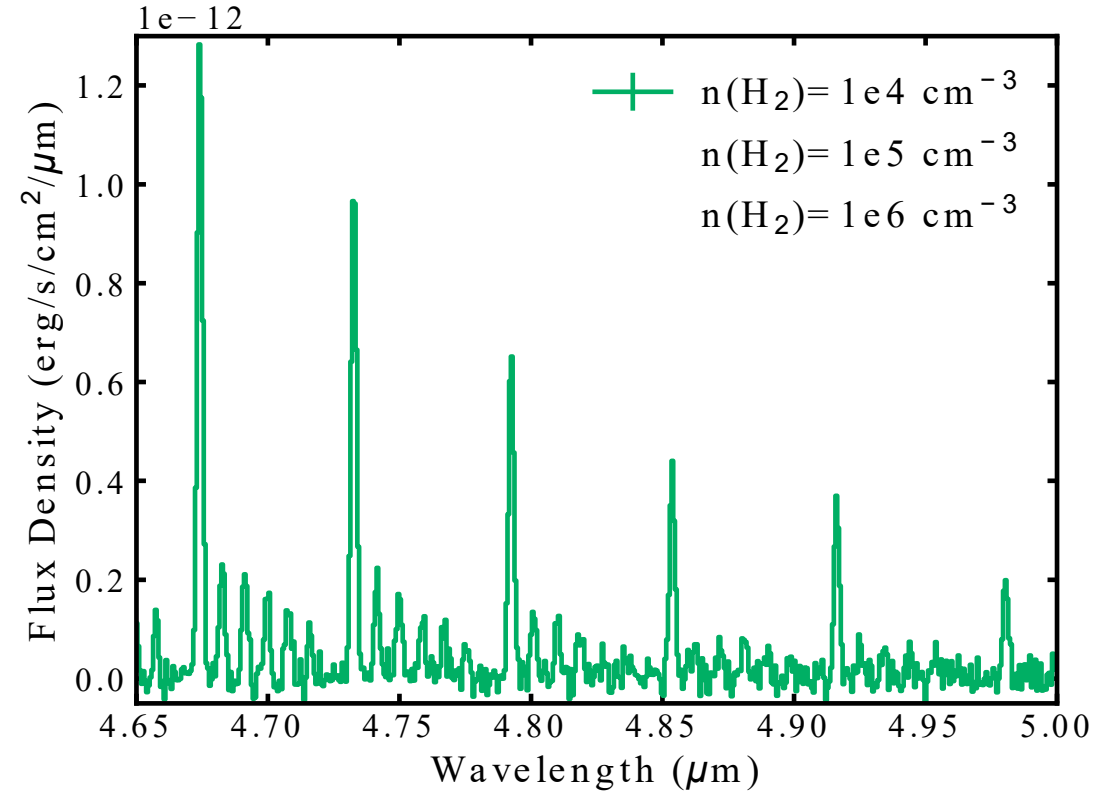
1. We spatially resolved fluorescently excited ro-vibrational CO emission for the first time in a disk. Modeling of this data appears inconsistent with primordial gas in the 49 Ceti disk. (Worthen et al. 2025a, *Nat Astron* **9**, 1680–1691)
2. The Beta Pic planetesimals are enriched in Argon, implying they formed in a cold environment in the parent protoplanetary disk. (Worthen et al. 2024b, *ApJ*, 964, 2, 168)
3. MIRI MRS observations of Beta Pic b are consistent with a substellar C/O ratio, implying pollution from icy planetesimals. (Worthen et al. 2024b, *ApJ*, 964, 2, 168)
4. ALMA observations of HD 166191 show that it is gas rich and potentially transitioning between a protoplanetary and debris disk. (Worthen et al. 2026, arXiv:2511.11535, *ApJ* in press)

Future work on gas in debris disks

CRIRES Observations of Warm Gas



JWST follow up of 49 Ceti



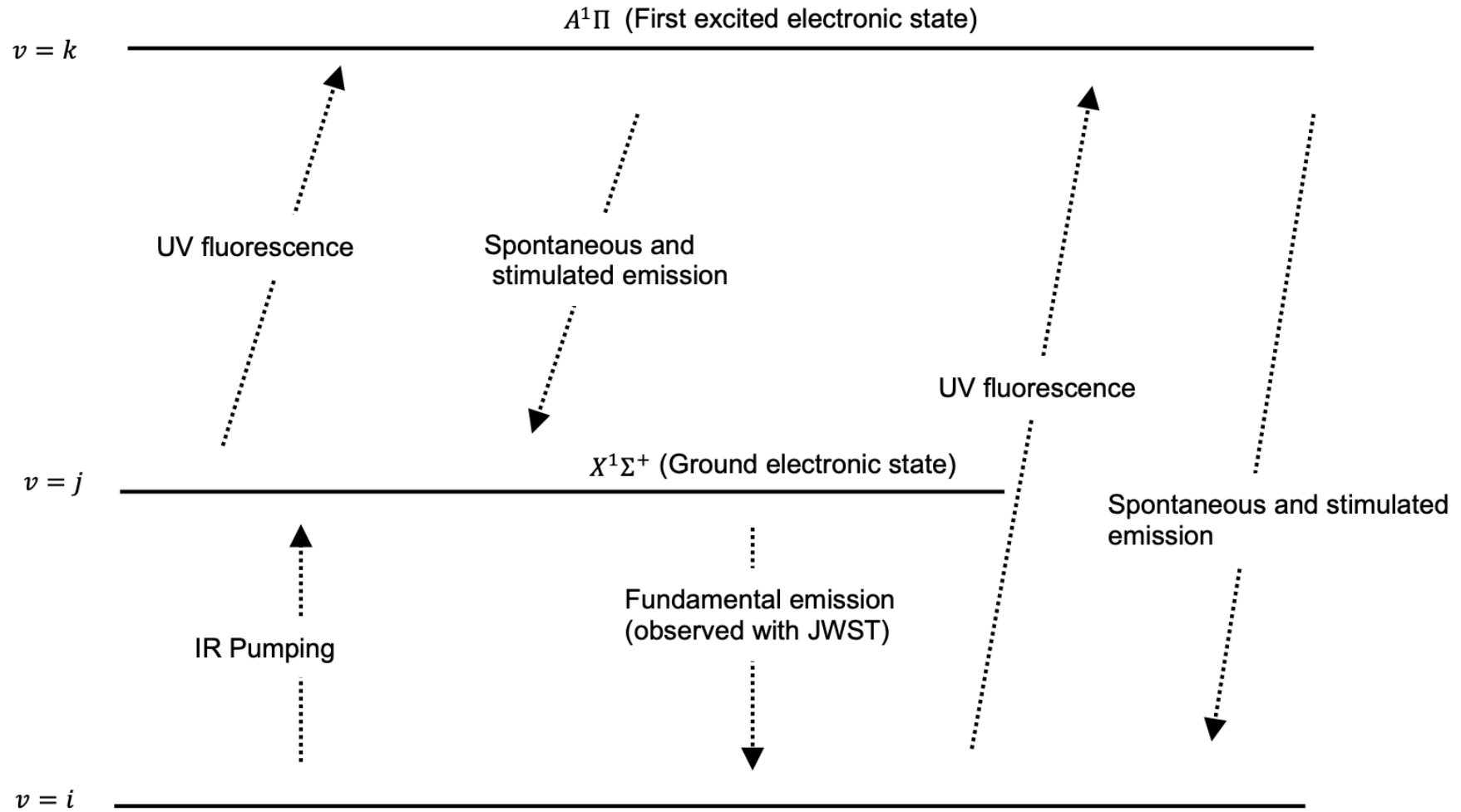
Worthen et al. in prep.

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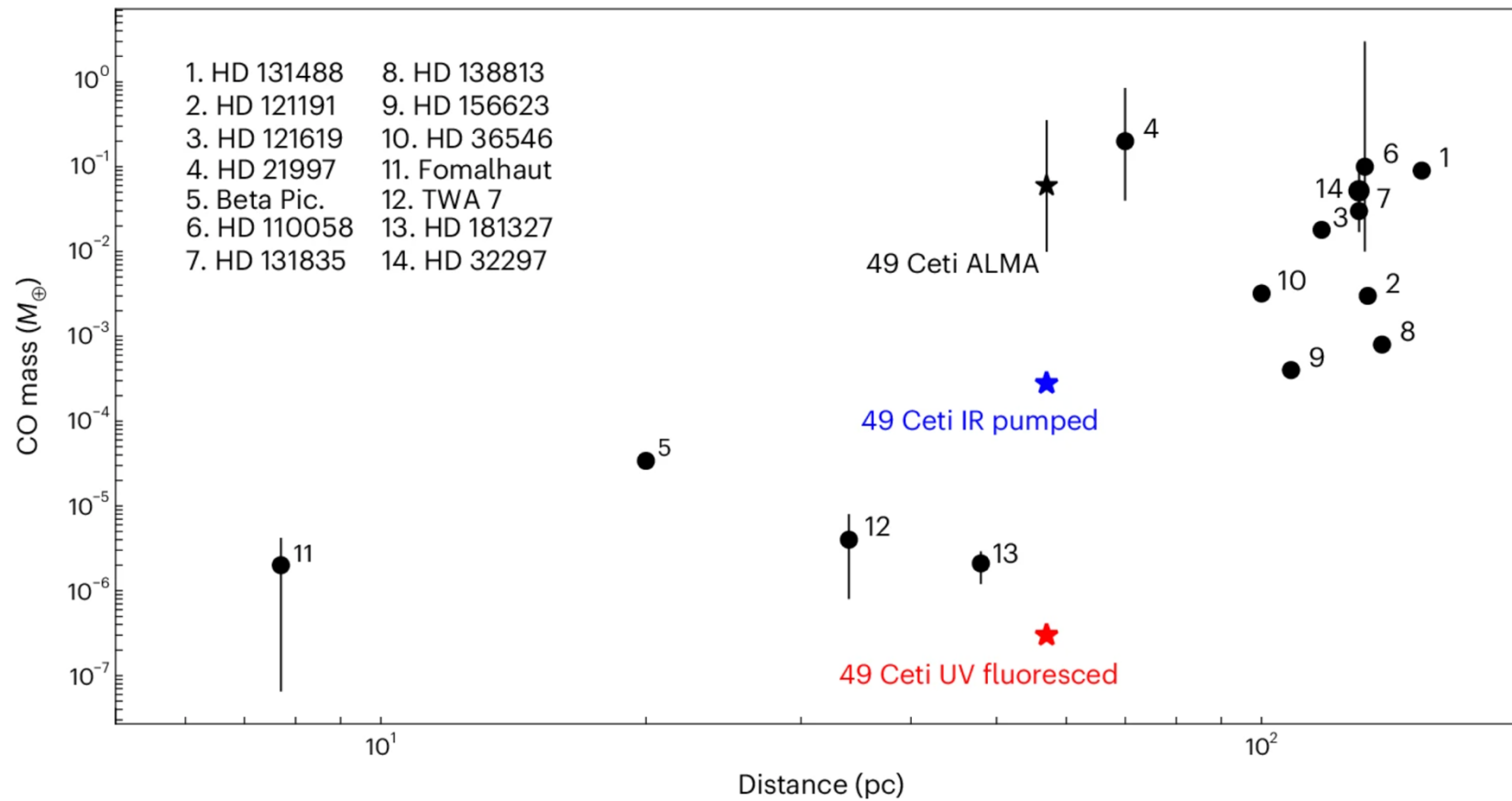
Determining the Origin of the Gas in the
49 Ceti Debris Disk

PI: Kadin Worthen
Co-PIs: Christine Chen

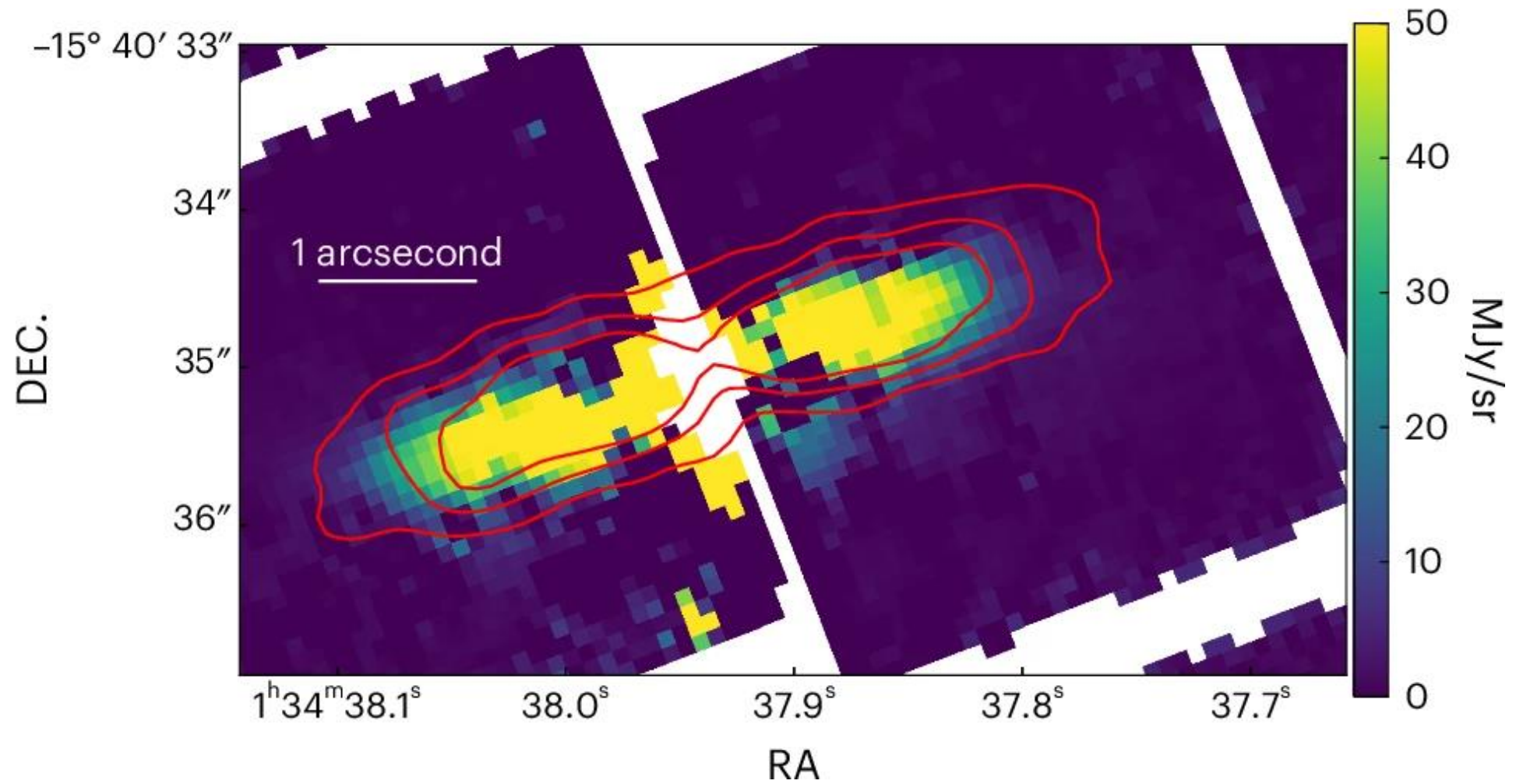
Fluorescent Pumping



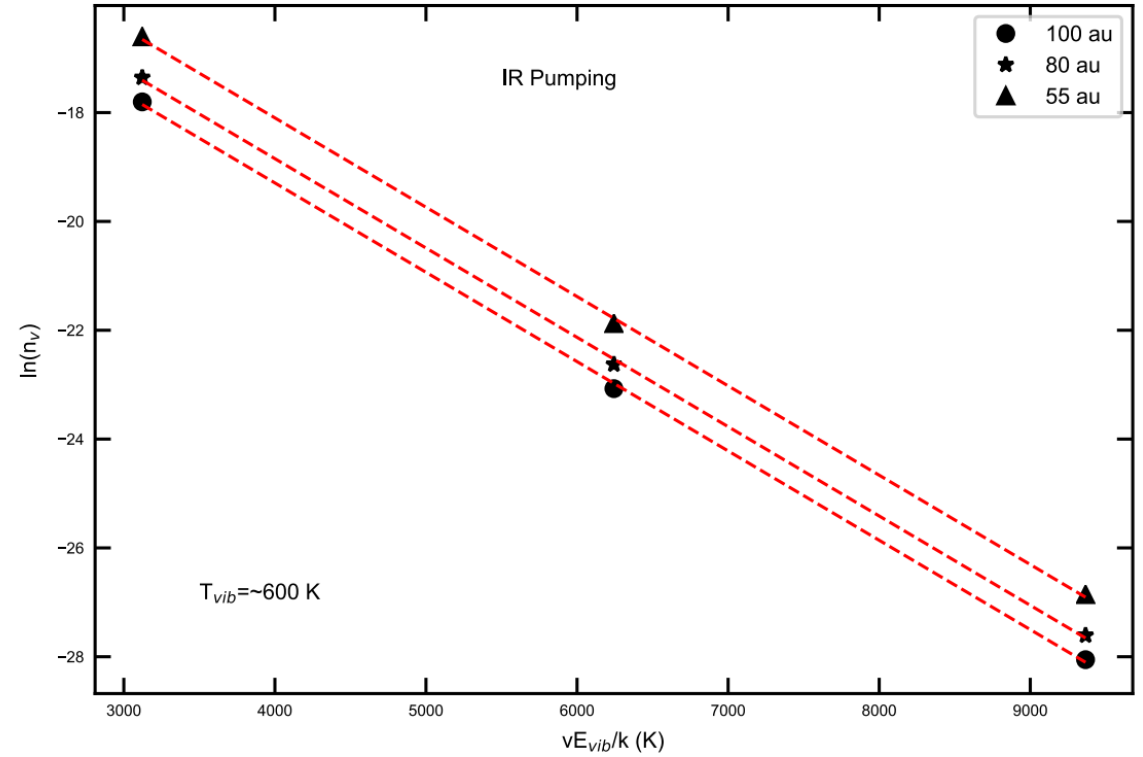
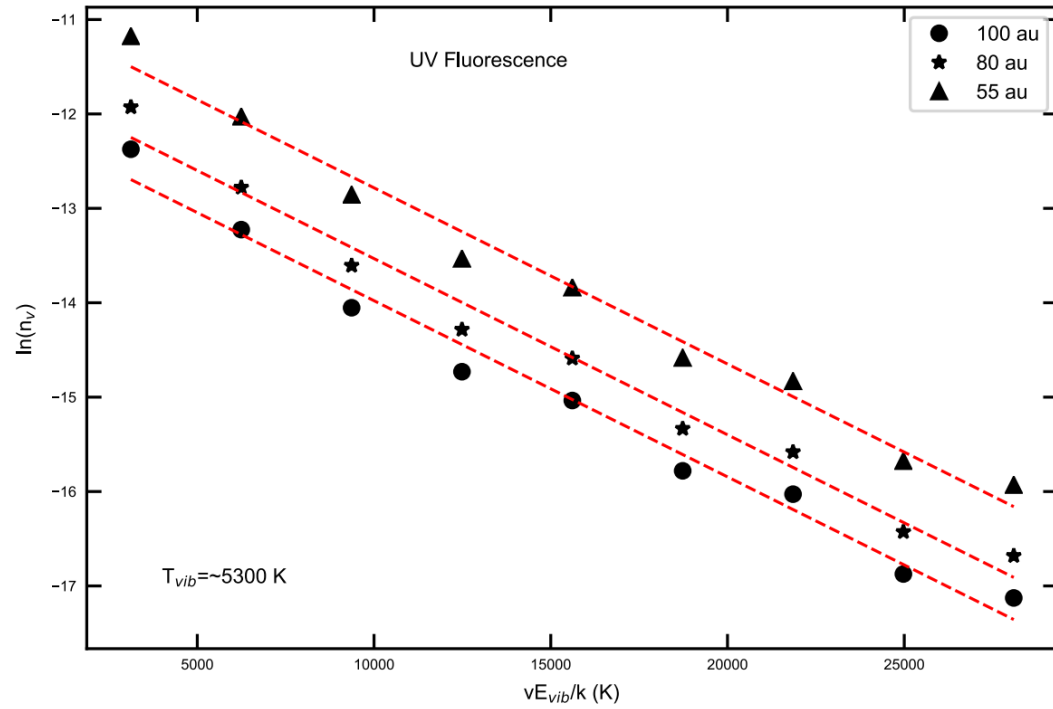
Sensitivity to low masses of CO



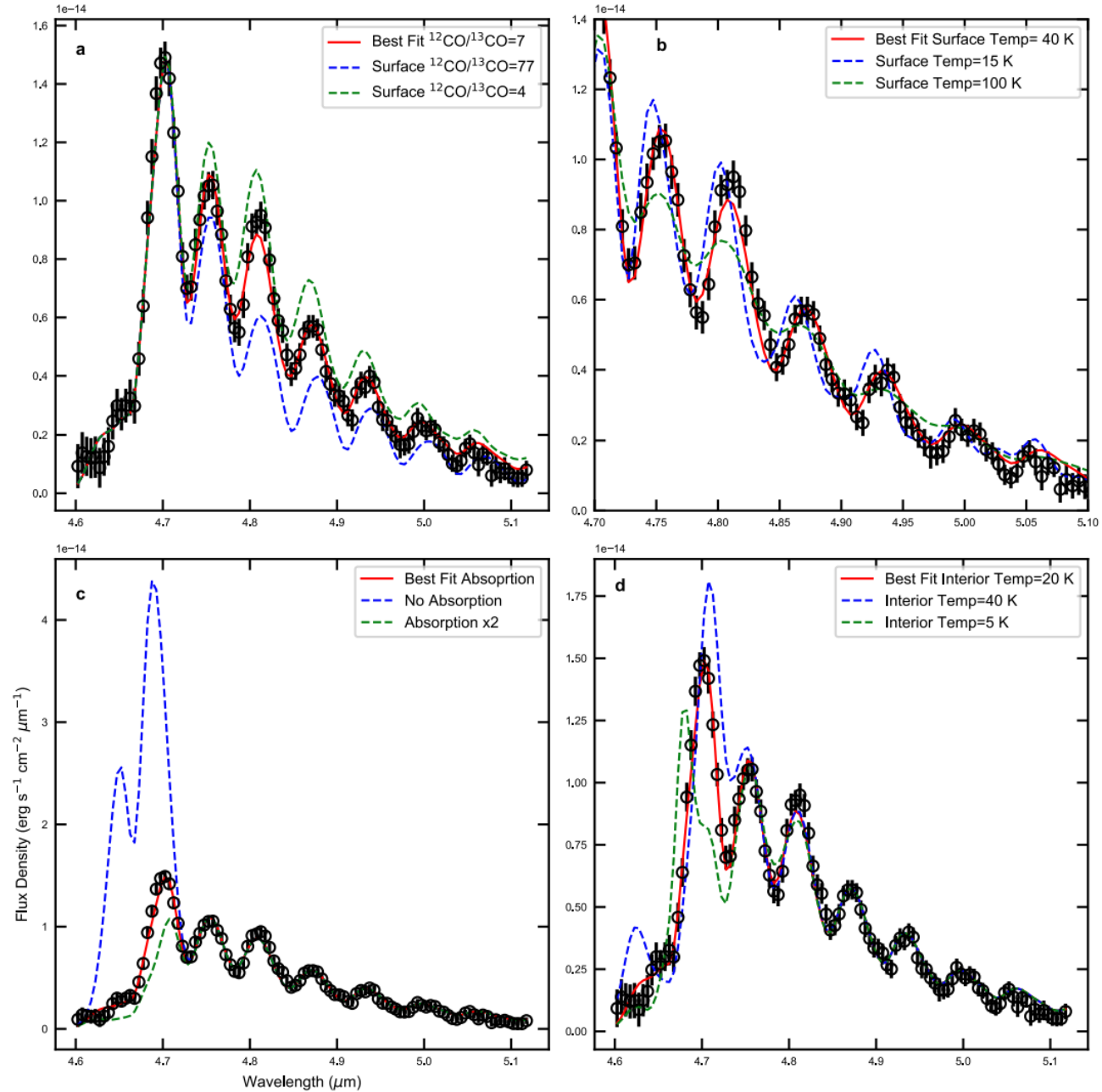
49 Ceti CO JWST vs ALMA



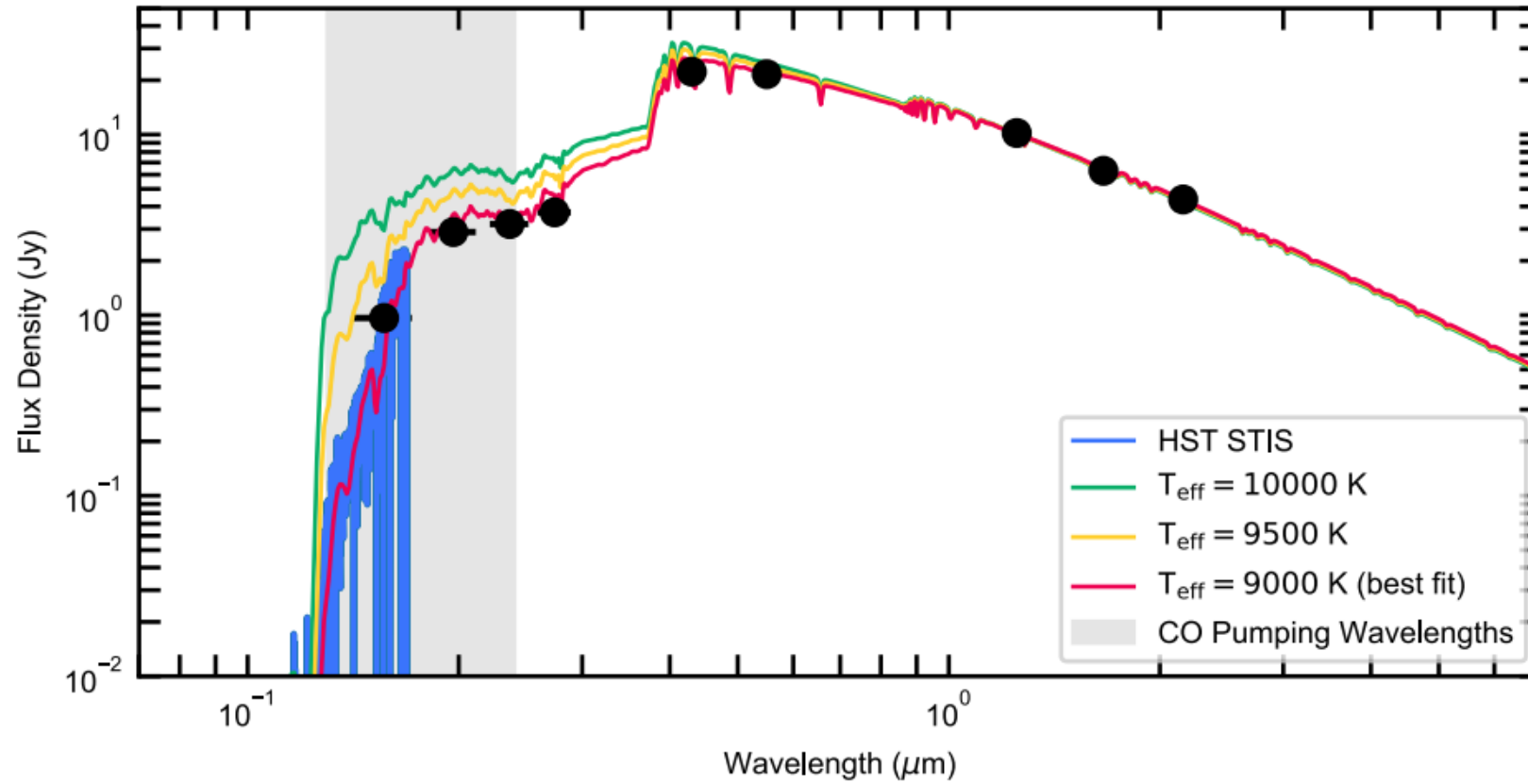
Fluorescent Model



Model Fitting

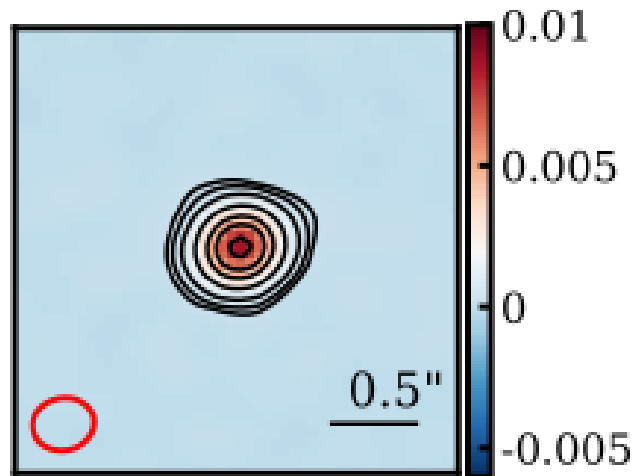


49 Ceti UV flux

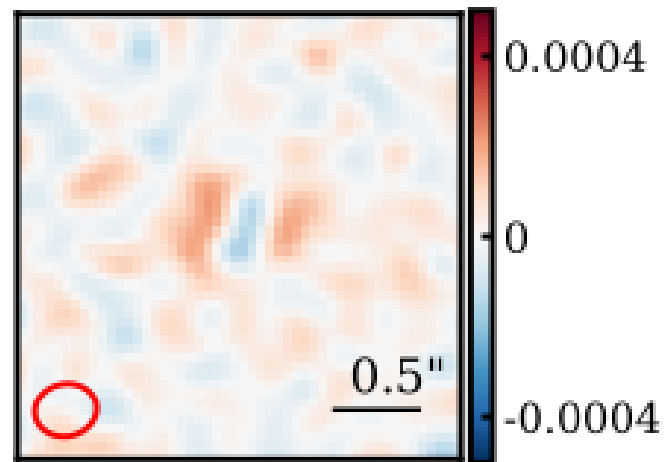


HD 166191 Continuum Modeling

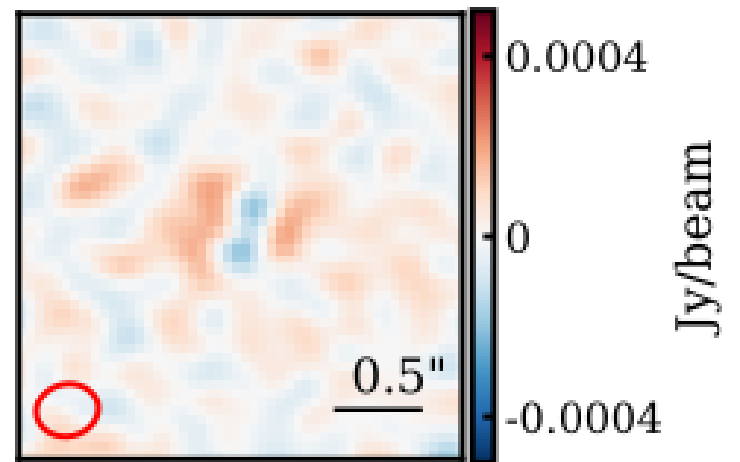
ALMA Continuum Data



Residuals (low-mass)

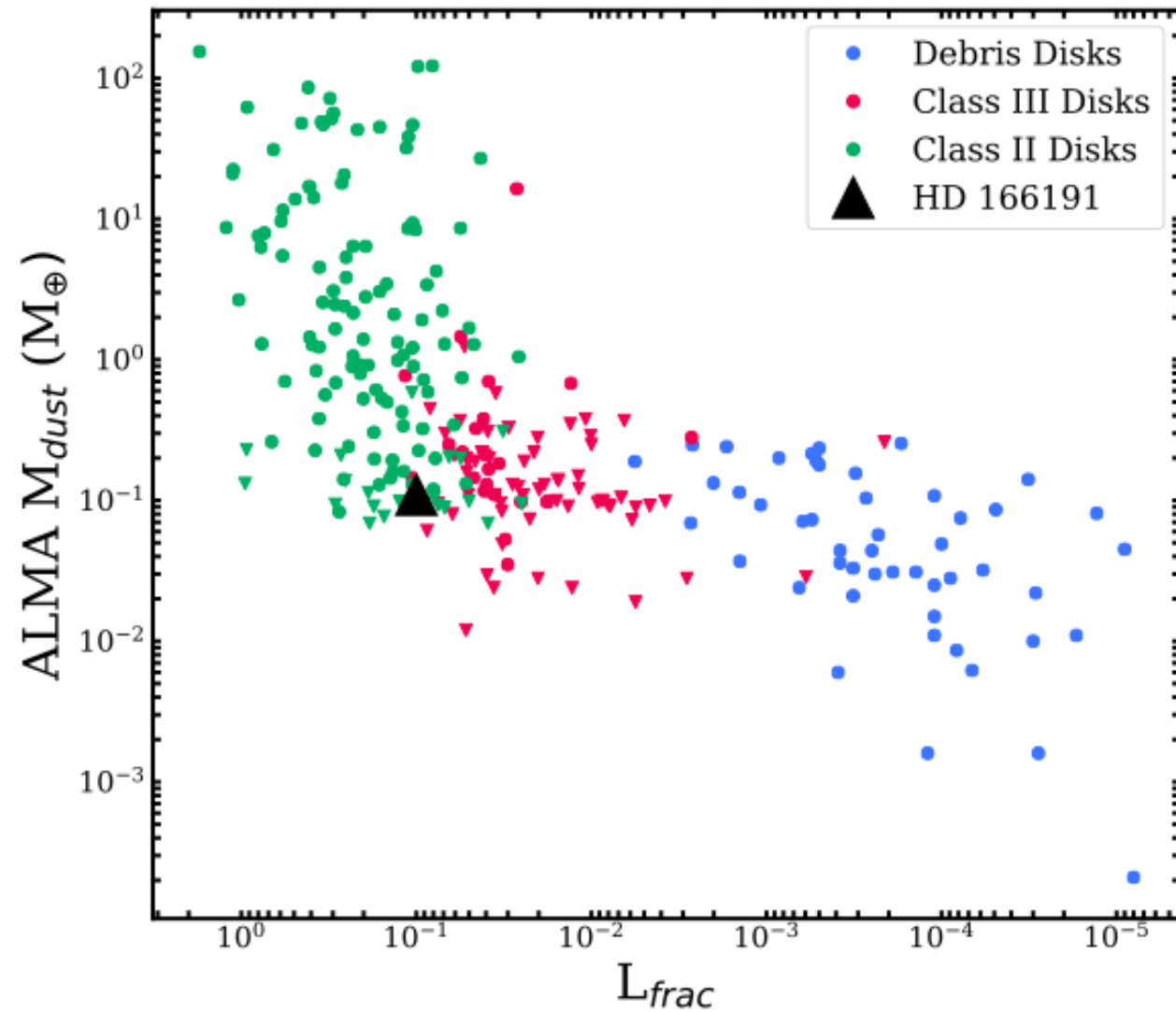


Residuals (high-mass)

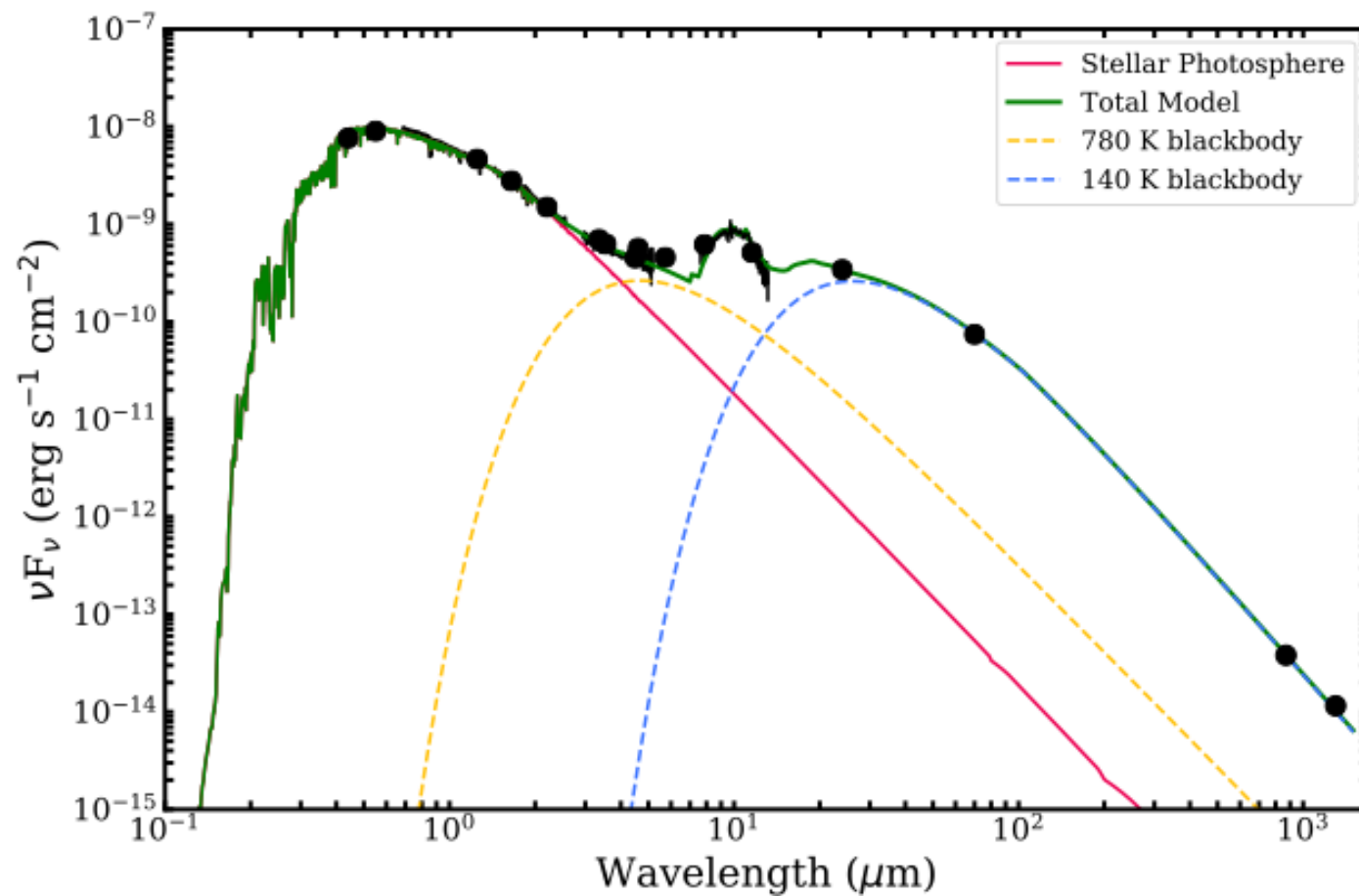


Jy/beam

HD 166191 Comparison with other disks



HD 166191 SED



HD 166191 Dust and CO Distributions

