PHAS0048/0097: Astrophysics/Physics Project 24/25 Presentation

Observability of Circum-Planetary Disks

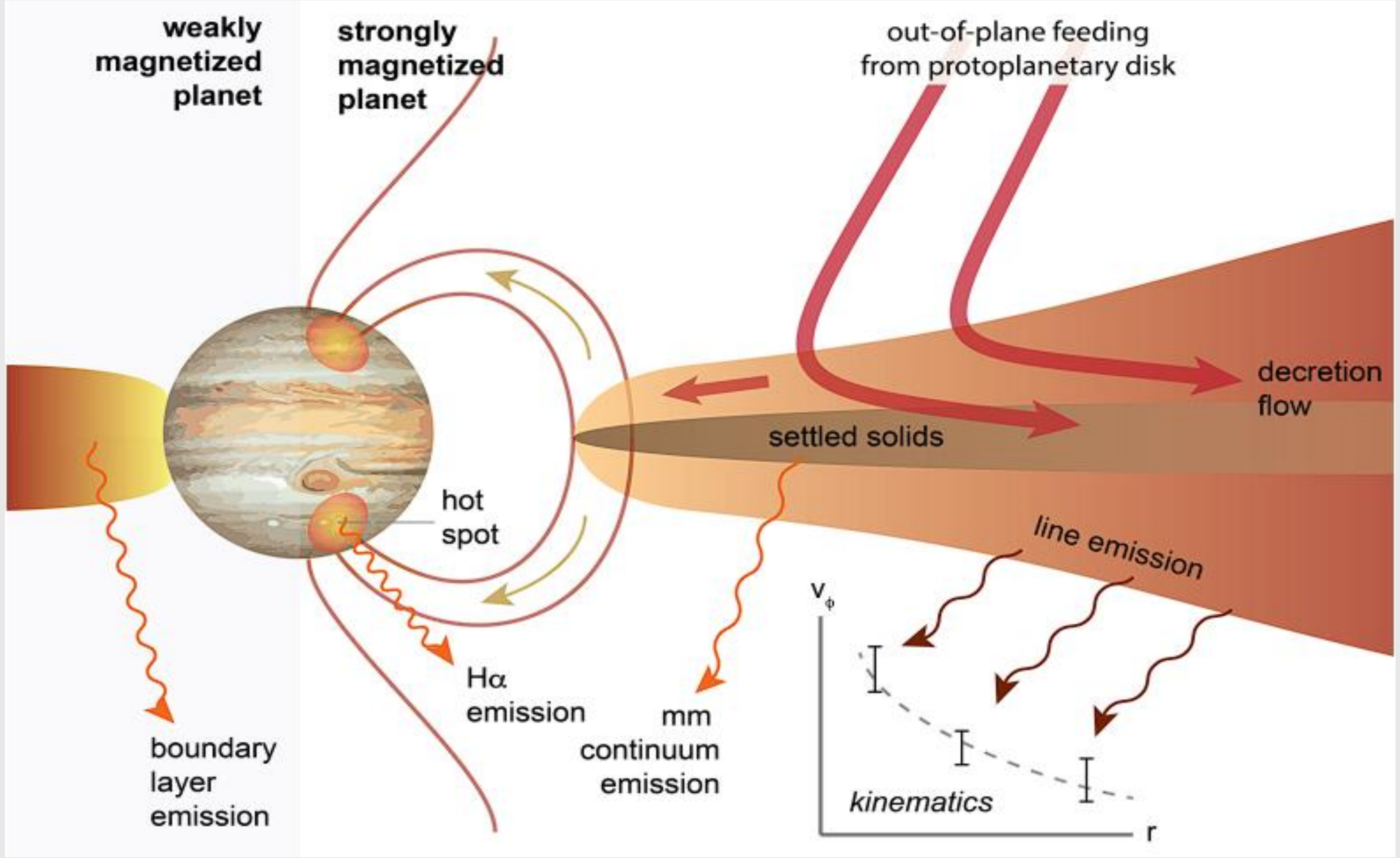
Vanessa Welke
Supervisor: Dr. Mihkel Kama

Introduction

Note:
CPDs (Circumplanetary Disks): around planets
PPDs (Protoplanetary Disks): around stars
CPDs form within PPDs

- Circumplanetary disks (CPDs) are accretion disks around protoplanets.
- Hypothesised birthplaces of exomoons, similar to Jupiter's moons (Heller et al. 2015)
- Key to understanding planet and satellite formation.

ALMA angular resolution goes as fine as 0.0048″, about the CPD size (< 1 au) in nearby distances (<100 pc).



Cross section of hypothetical CPD structure

Credit: Armitage (2024)

CPD regulates how material accretes onto the planet.

1. Feeding from PPD

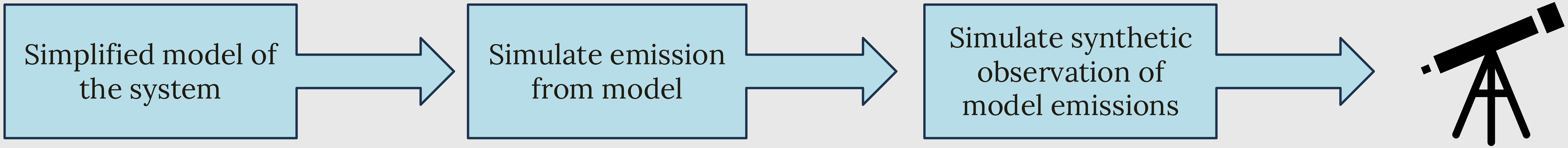
2. Settled solid = potential satellite formation zone

Project Aim:

Note:
CPDs (Circumplanetary Disks): around planets
PPDs (Protoplanetary Disks): around stars
CPDs form within PPDs

Develop an efficient, lightweight pipeline for generating mock CPD observations without relying on computationally expensive hydrodynamical simulations.

The pipeline runs from case-customized emission models to synthetic observations, supporting proposal design and interpretation of CPD detections.



Modelling the System

- Hydrostatic, radiative equilibrium models of passive flared disks are well established for PPD (Chiang et al. 1997)
- CPD structure remains theoretical and debated; future observations are needed. (Armitage 2024)
- Same scaled-down framework applied to CPDs, prioritizing computational feasibility at small scales.
- Static model: no viscosity, photoevaporation, accretion, or time evolution included
- Grid resolution: 150 × 200 × 80 cells ($N_R \times N_\phi \times N_\theta$)

$$\Sigma(r) = \Sigma_0 \cdot \left(\frac{r}{r_0}\right)^\gamma$$

Surface density distribution

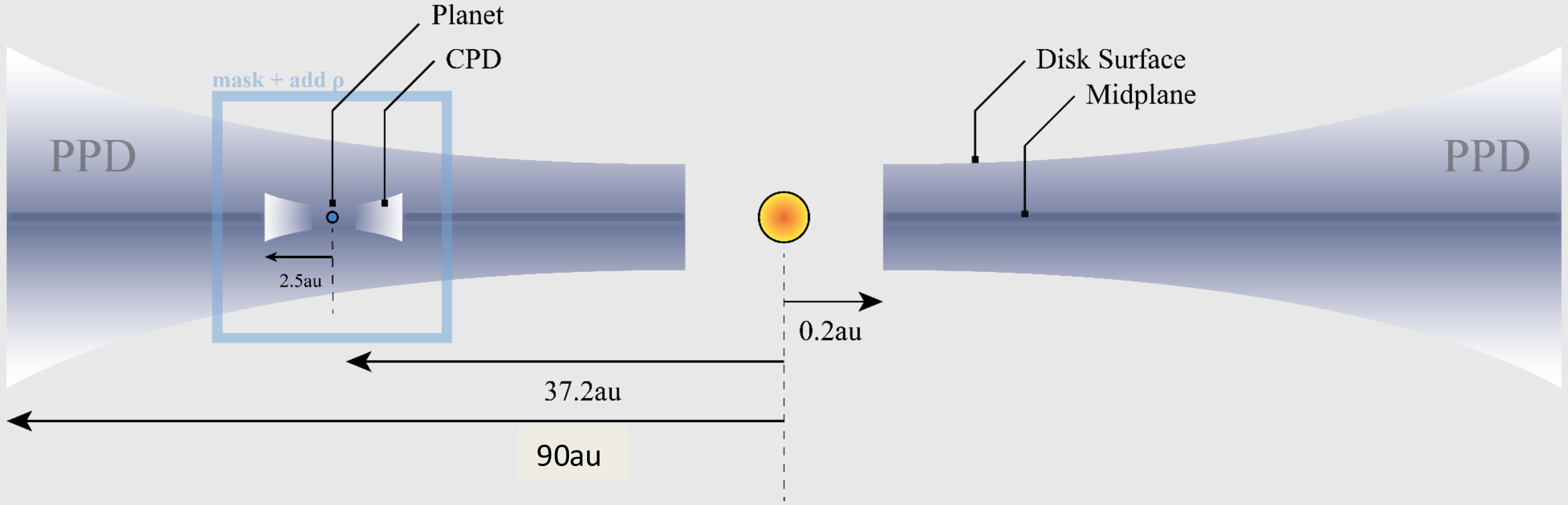
$$\rho(r,z) = \frac{\Sigma(r)}{\sqrt{2\pi}\,h} \exp\left[-\frac{1}{2}\left(\frac{z}{h}\right)^2\right]$$

Vertical density distribution

$$h(r) = \frac{c_s}{\Omega_k} = h_0 \cdot \left(\frac{r}{r_0}\right)^\beta$$

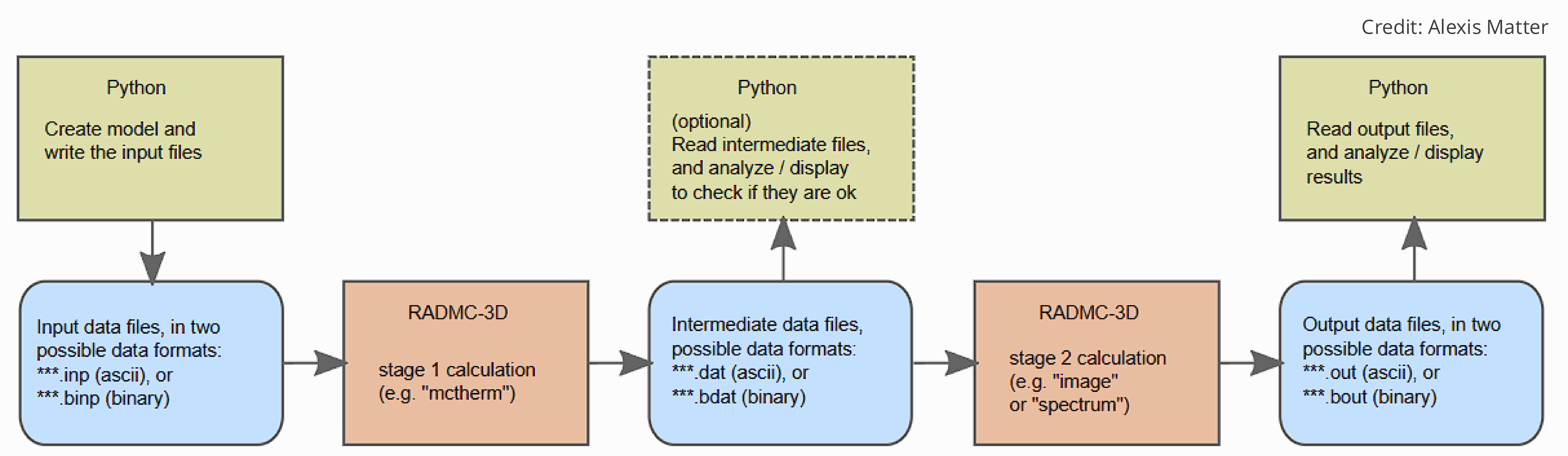
Pressure scale height

How much the disk flares



RADMC-3D

To simulate dust continuum emission from model:



Monte-Carlo run (temperature-distribution)

Ray tracing (image, spectrum)

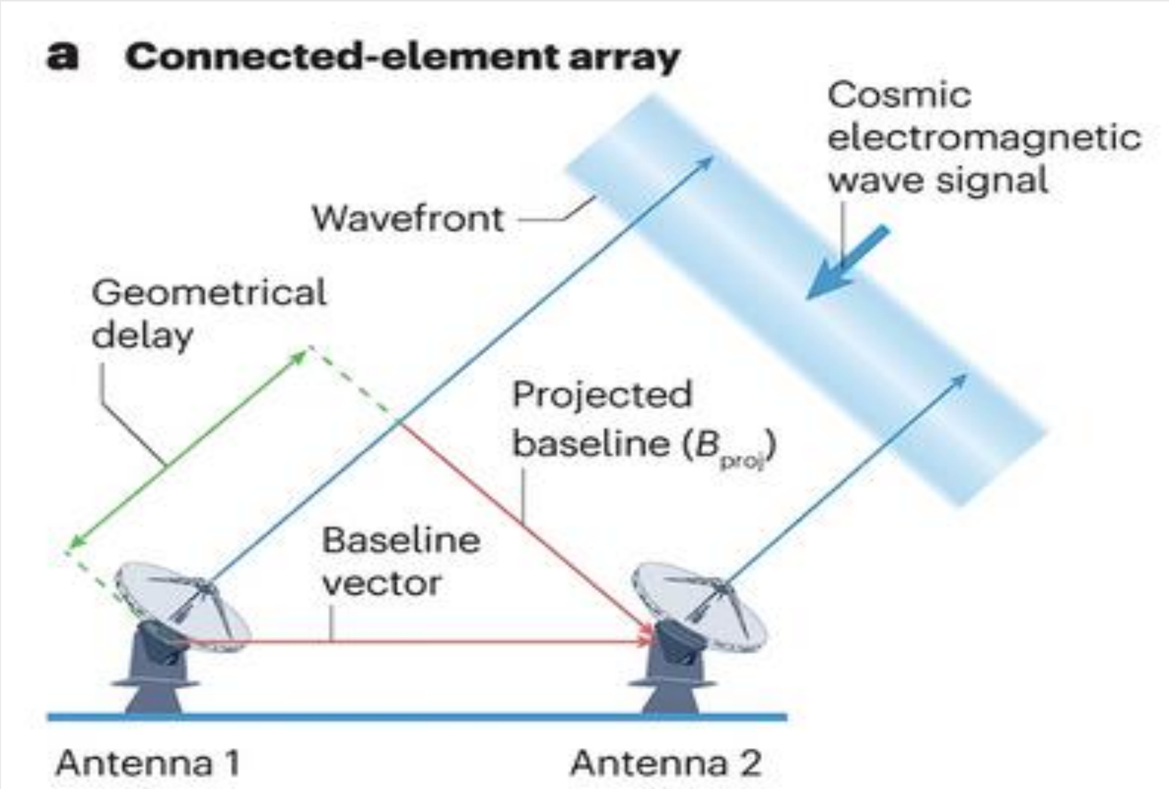
The ALMA Telescope and CASA

Atacama Large Millimeter/submillimeter Array (ALMA):

- Ground-based telescope array in Chile
- Designed to study the cold Universe at mm/sub-mm λ
- Excels at resolving fine structures in protoplanetary disks
- In 2021, first confirmed CPD detection made around PDS 70c (Benisty et al. 2018)

CASA (Common Astronomy Software Applications) Tools Used:

- simobserve: Simulates ALMA observations from model images
- simanalyze: Processes and images the simulated data



Interferometric signals are sampled in the (u, v) plane and Fourier transformed to reconstruct the sky brightness distribution.

Observational Planning

- Convert CPD intensity from Jy/pixel to Jy/beam (ALMA resolution)
- Use ALMA longest baseline (16.2 km) for maximum angular resolution
- Estimate total integration time for 5σ detection of CPD signal

$$\sigma = \frac{kT_{\text{sys}}}{AN^2\sqrt{N_p \Delta\nu \Delta t}}$$

σ = Noise level (mJy)

k = Boltzmann's constant

T_{sys} = System temperature

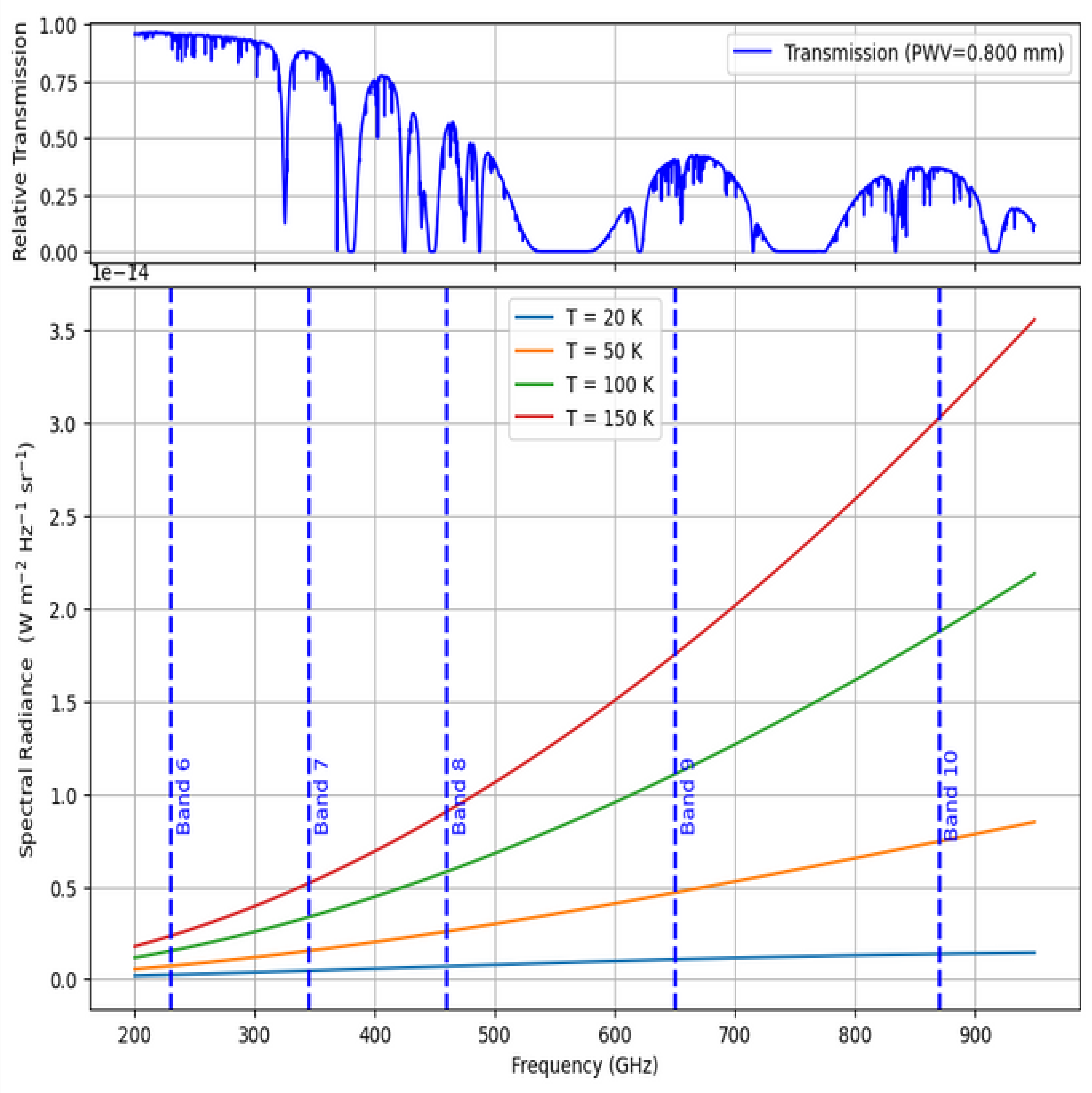
A = Area of each antenna

N = Number of antennas

N_p = Number of polarizations

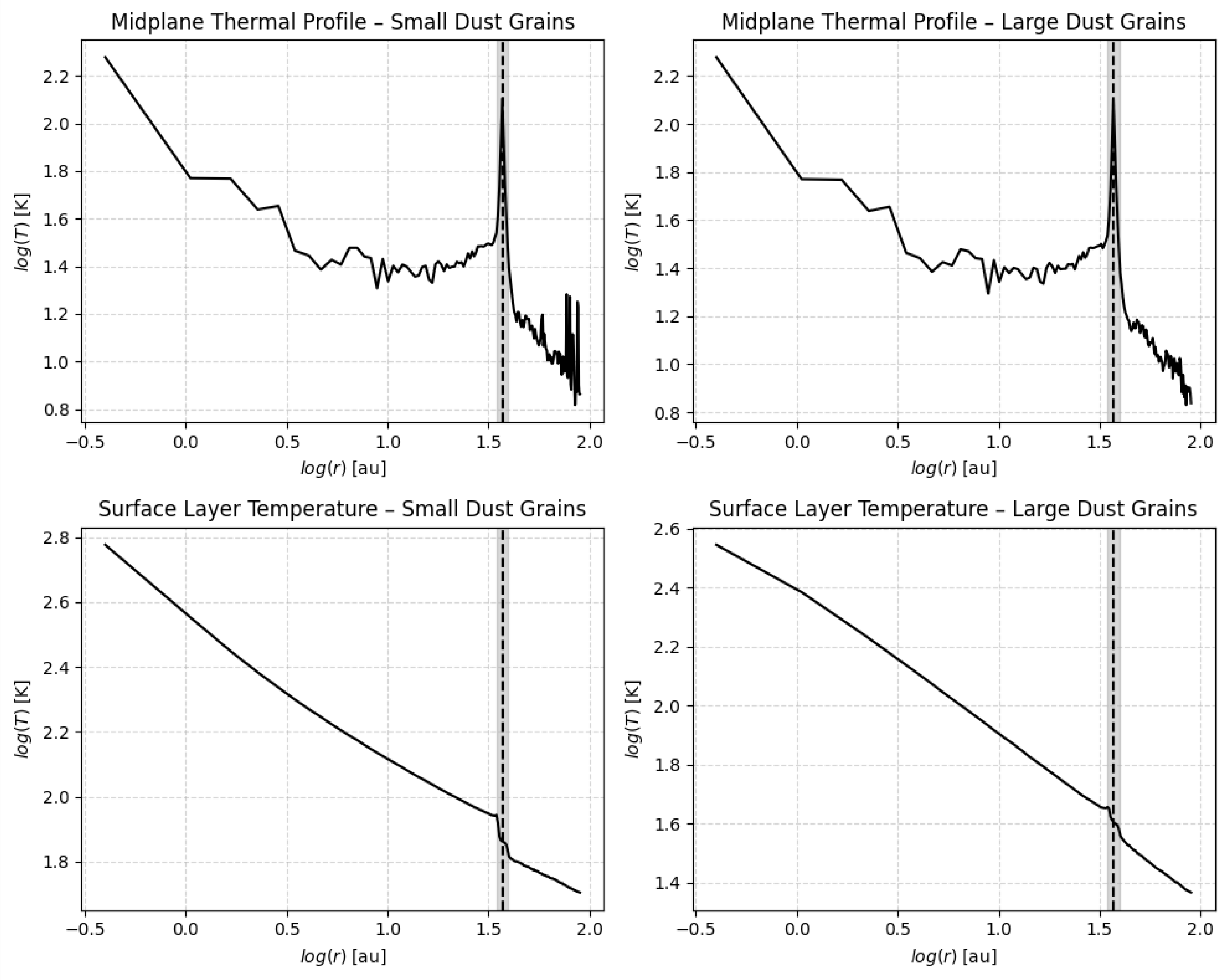
$\Delta\nu$ = Available bandwidth

t = integration time

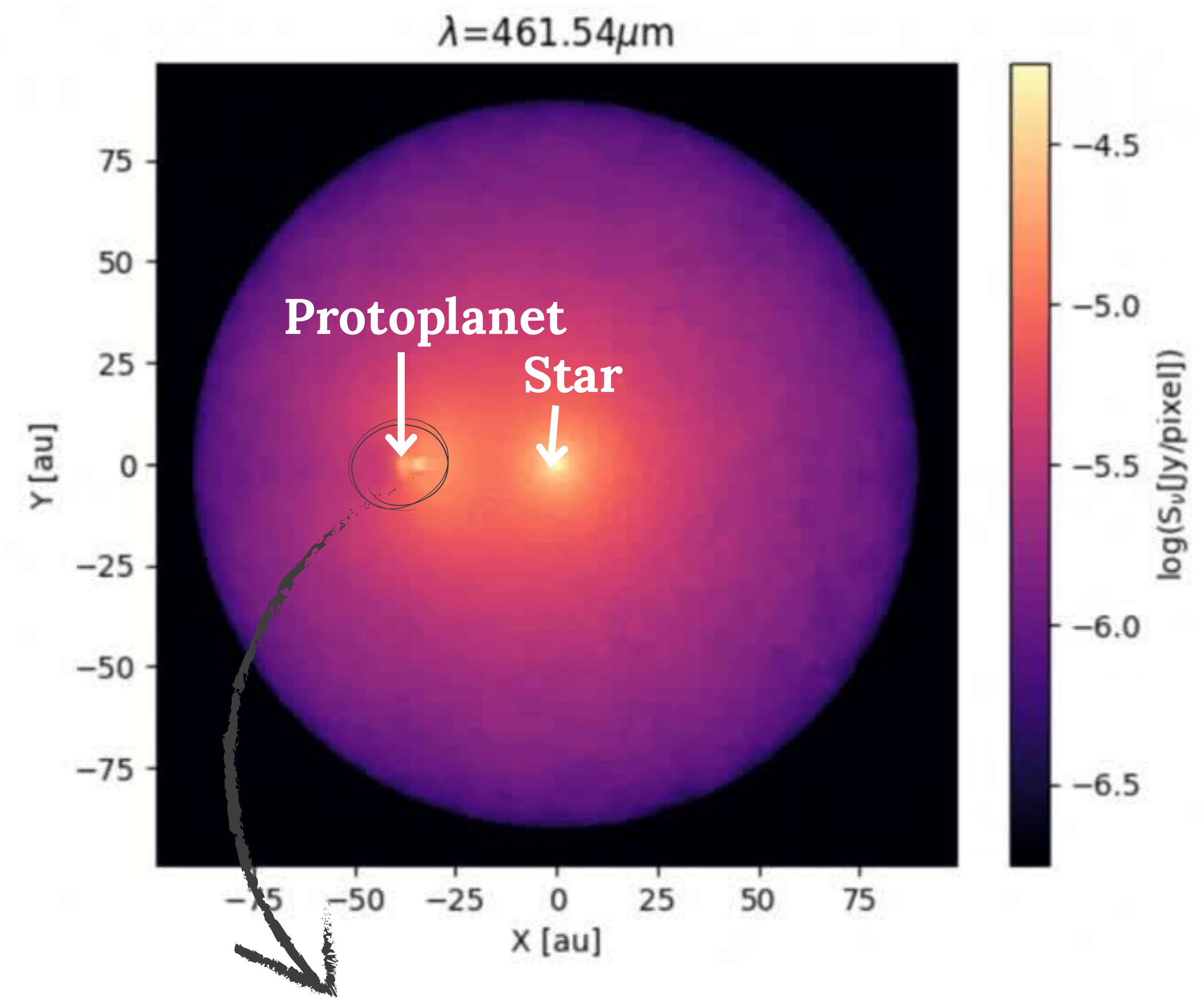


Thermal Structure and Radiative Emission of the Model Disk

Mass-weighted average dust temperature of 45.75 K

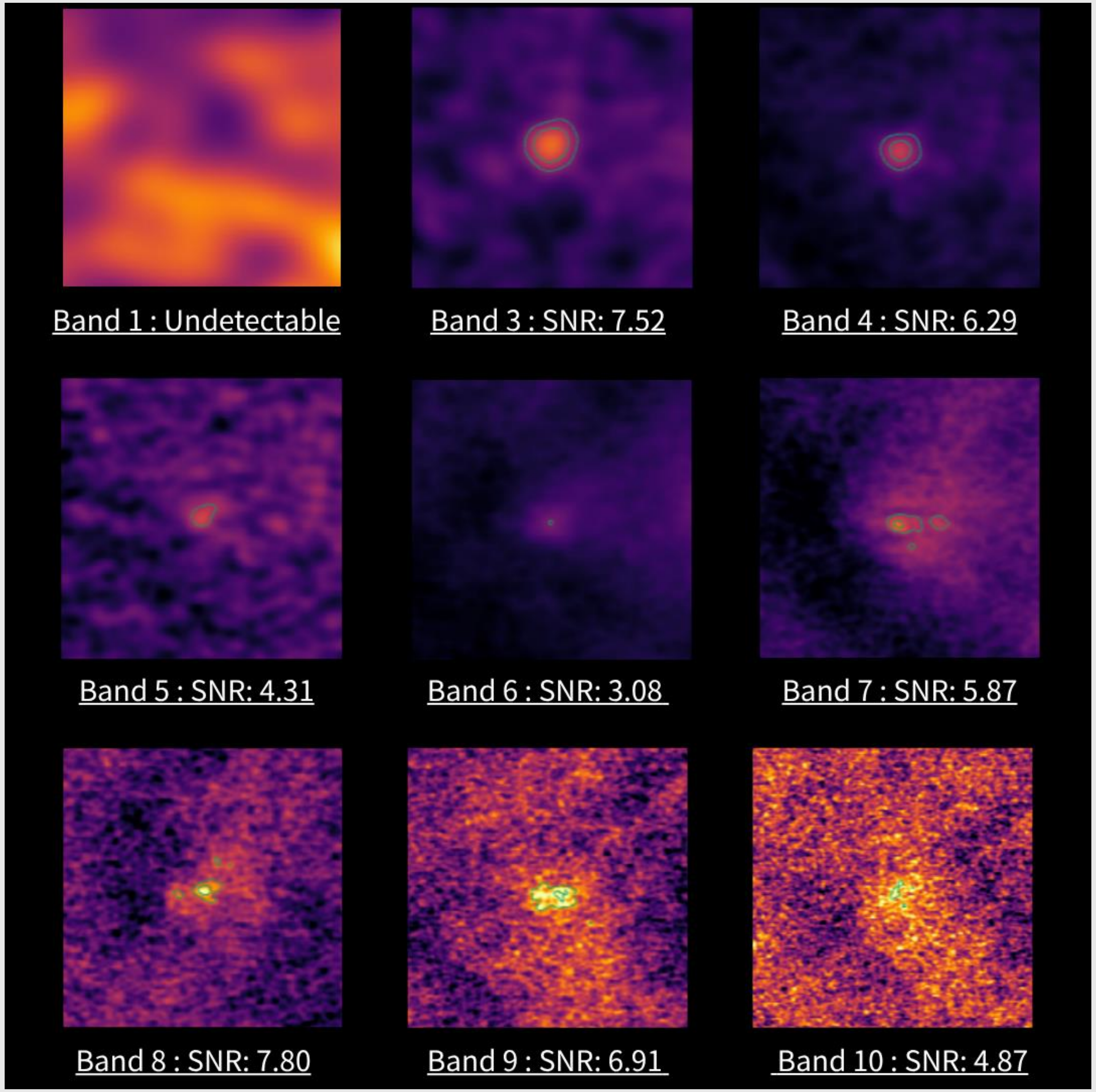


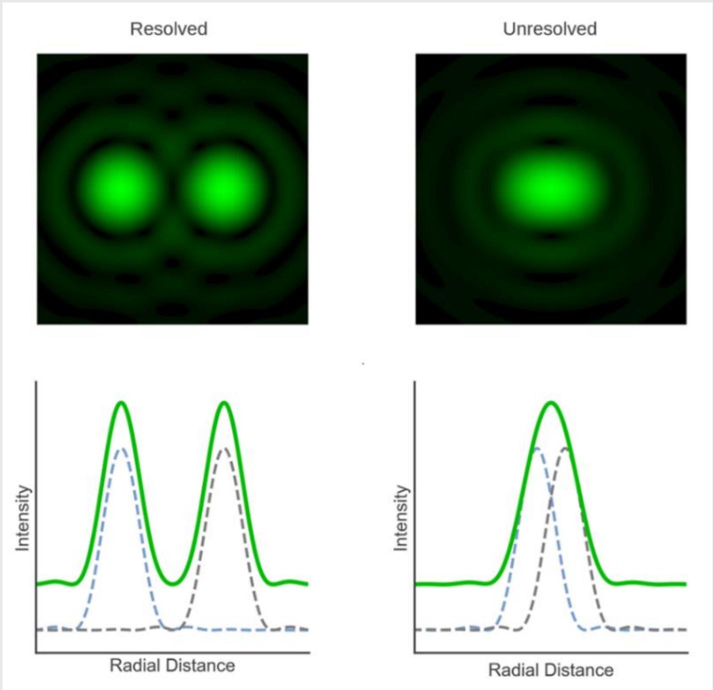
Brighter emission at higher frequency



Circum-planetary Disk

Impact of Observational Parameters on CPD Detectability





Green Contours:

- Represent 3σ / 5σ levels

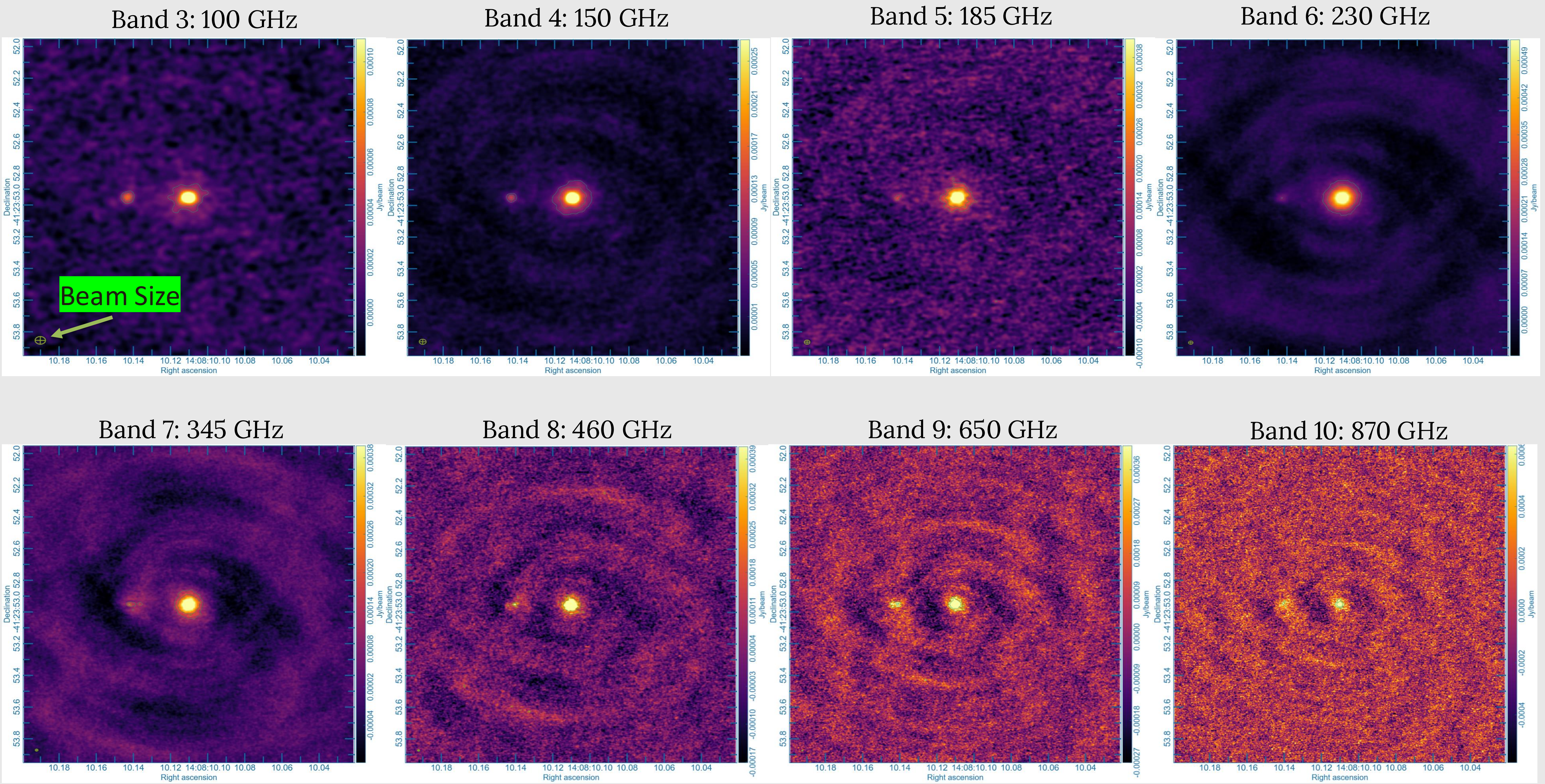
Lower Frequency Bands:

- CPD unresolved, smooth shape
- More background contamination from PPD

Higher Frequency Bands:

- Stronger CPD emission
- Higher atmospheric noise
- Irregular CPD contours, less shape confidence

Synthetic Observations



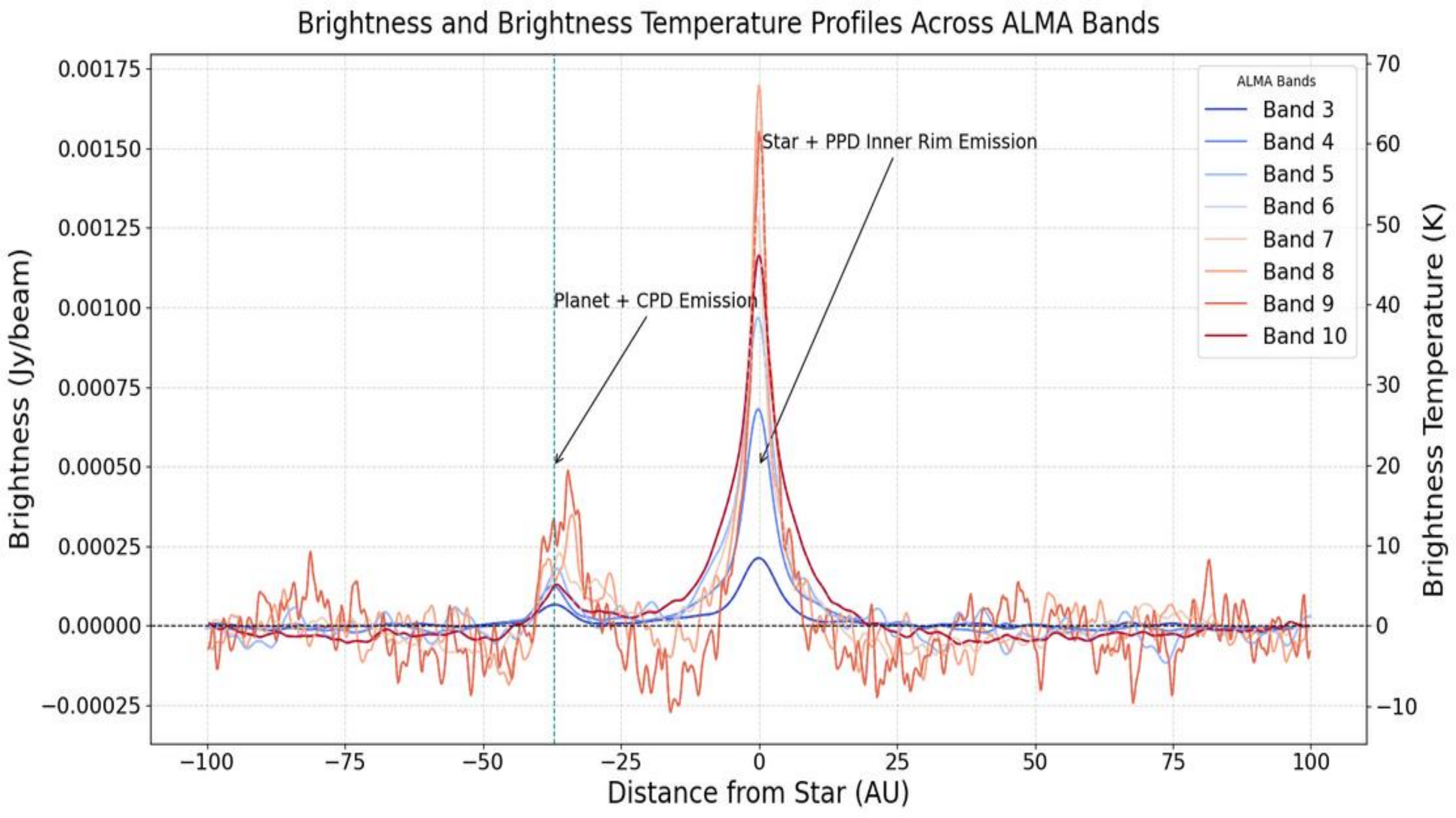
Jy/beam

Declination

Right Ascension

Noisier, but higher resolution and brighter CPD

From Synthetic Observations:



Radial Flux 2D Cut

$$T = 1.222 \times 10^3 \frac{I}{\nu^2 \theta_{\mathrm{maj}} \theta_{\mathrm{min}}}$$

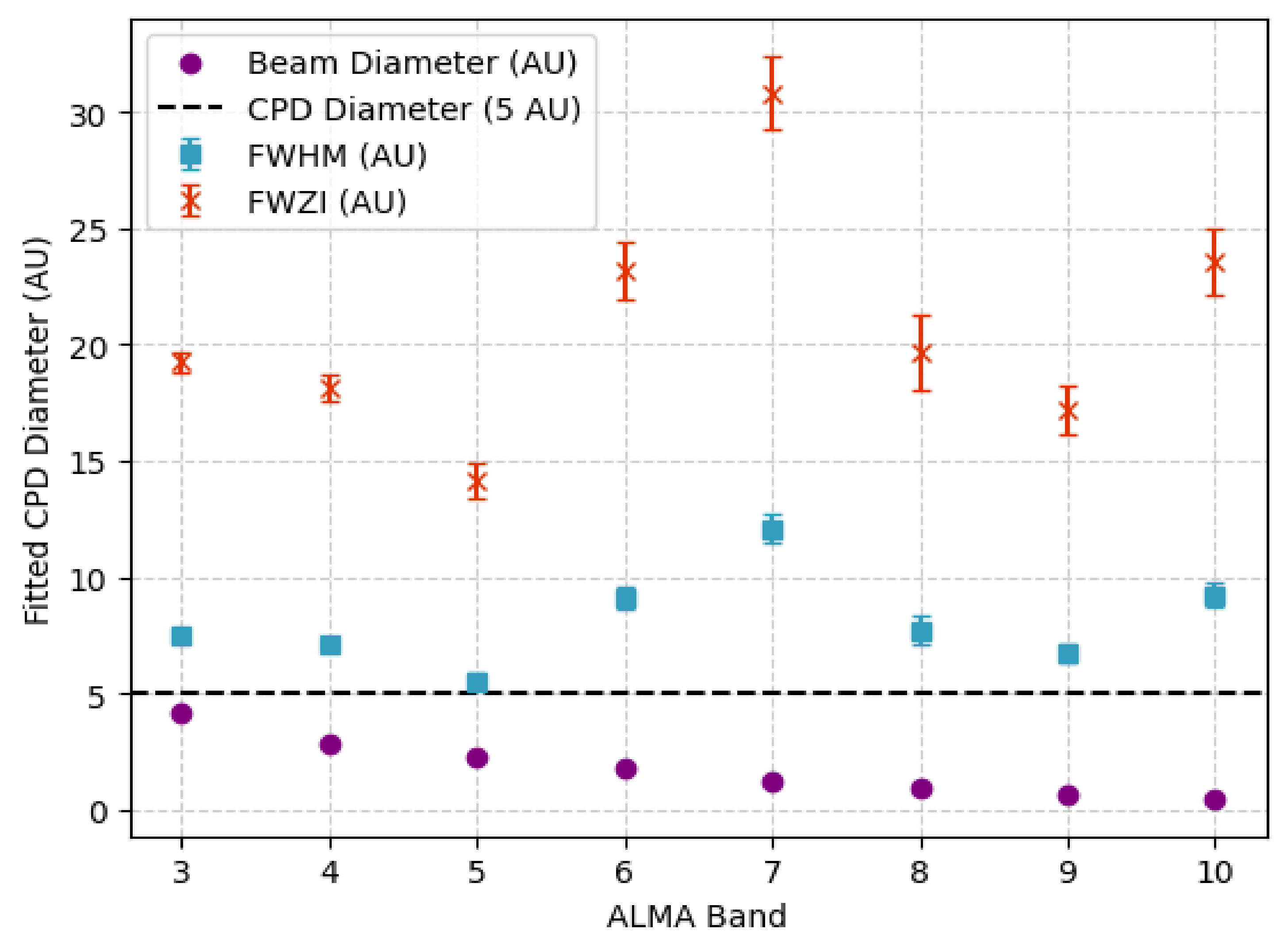
RMS noise of image

$$\mathrm{FWHM} = 2\sqrt{2\ln 2} \cdot \sigma$$

Full Width at Half Maximum

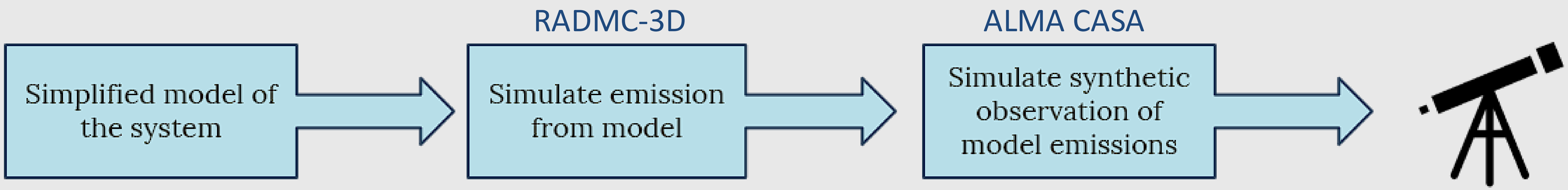
$$\mathrm{FWZI} \approx 6 \cdot \sigma$$

Full Width at Zero Intensity



Fitted CPD diameter

Conclusion



- 10-hour observation (ideal weather) enables 5σ detection in most bands
- Band 1 remains undetected; Band 10 shows fragmented detection
- CPD detection is feasible, but structural recovery is limited by atmospheric noise and beam dilution.
- Optimizing ALMA bands to match CPD size offers the best trade-off between signal strength and resolution.

Limitations

Model resolution of CPD

CPDs are optically thick and compact

High optical depth packed into more refined grid cells or smaller CPD might yield computational error.

Incorporate internal heating

Accretion and shock heating are modeled by calculating energy deposited in each grid cell.(Collins et al 1998; D'Angelo et al. 2003)

Alters thermal structure and overall disk morphology (shock fronts).

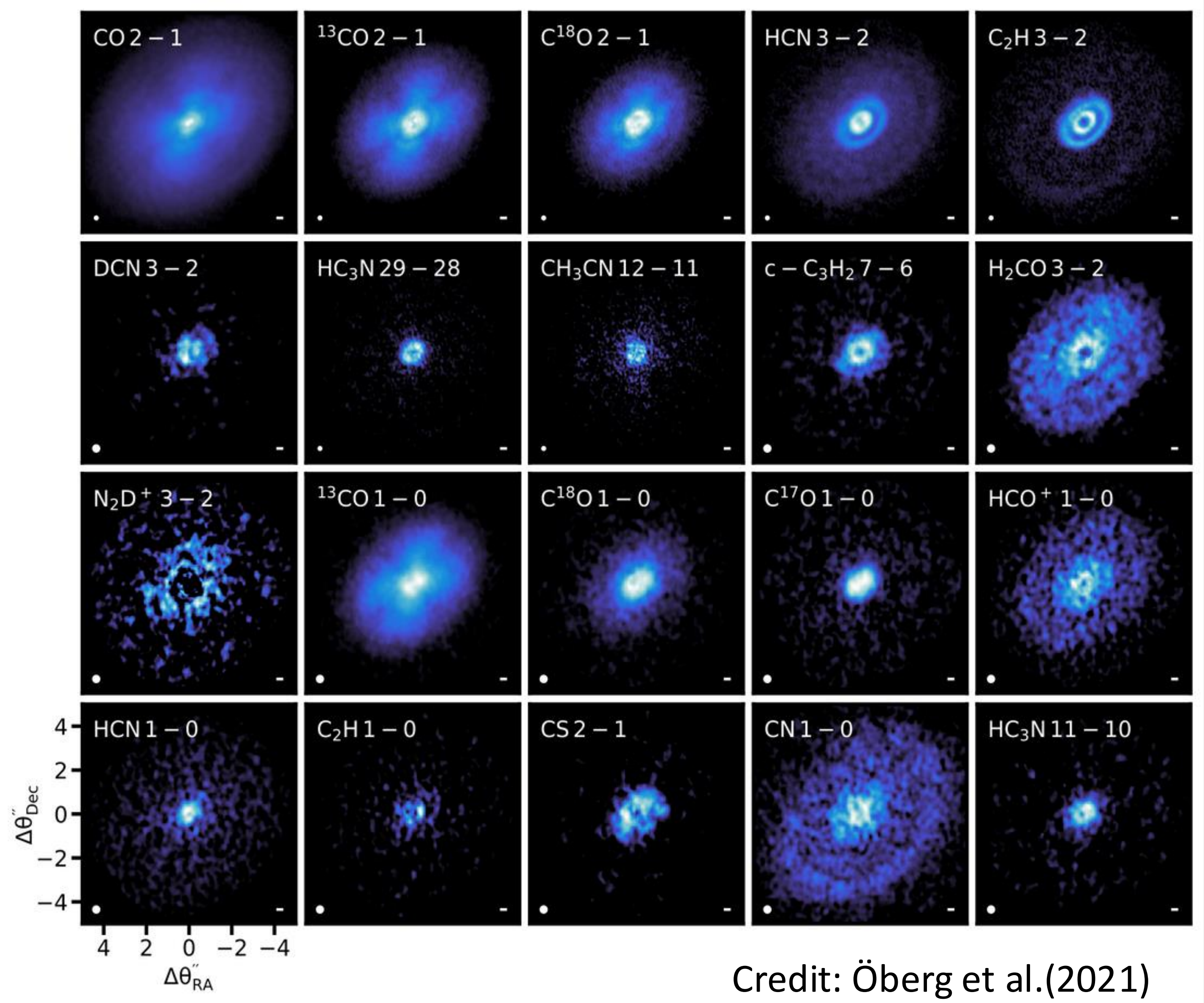
Grain Distribution & Disk Gap

Massive planets carve out gap in PPD improves brightness contrast.

Current model uses two discrete dust sizes.

A continuous grain size distribution is more realistic and affects CPD opacity.

Future Developments



Credit: Öberg et al.(2021)

PPD observed in different molecular gas emission wavelengths

➢ *Show significant morphological diversity and rich substructure*

Add Gas Component

Include gas (e.g., SiS, SO, CO) in the model.

Useful for detecting shocks and probing CPD surface dynamics.

Polarized Light Observations

Apply polarized differential imaging to isolate disk-scattered light.
May reveal dust grain alignment in CPDs

Derive CPD properties

Experiment more ways to extract physical constraints from CPD observations.

Reference

- Armitage, Philip J. (2024). Planet formation theory: an overview. arXiv: 2412 . 11064[astro-ph.EP]. url: https://arxiv.org/abs/2412.11064.
- Benisty, Myriam et al. (July 2021). “A Circumplanetary Disk around PDS70c”. en. In: The Astrophysical Journal Letters 916.1. Publisher: The American Astronomical Society, p. L2.issn: 2041-8205. doi: 10.3847/2041-8213/ac0f83. url: https://dx.doi.org/10.3847/2041-8213/ac0f83 (visited on 11/05/2024).
- Chiang, E. I. et al. (Nov. 1997). “Spectral Energy Distributions of T Tauri Stars with Passive Circumstellar Disks”. In: The Astrophysical Journal 490.1, pp. 368–376. issn: 1538-4357.650doi: 10.1086/304869. url: http://dx.doi.org/10.1086/304869.
- Collins, T. J. B. et al. (Aug. 1998). “Accretion Disk and Boundary Layer Models Incorporating OPAL Opacities”. In: 502.2, pp. 730–736. doi: 10.1086/305949.
- D’Angelo, Gennaro et al. (Dec. 2003). “Thermohydrodynamics of Circumstellar Disks with High-Mass Planets”. In: The Astrophysical Journal 599.1, pp. 548–576. issn: 1538-4357. doi:10.1086/379224. url: http://dx.doi.org/10.1086/379224.