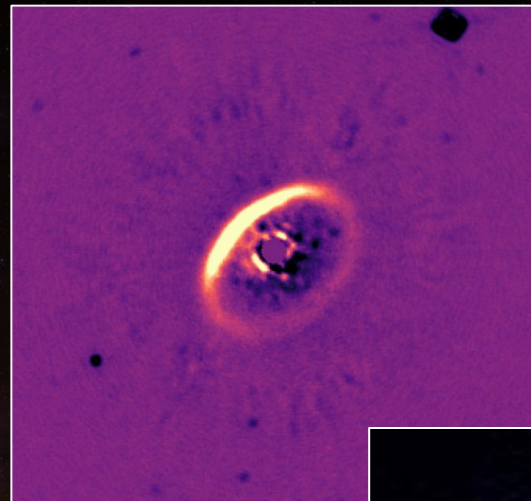




Star-hopping RDI meets ALMA : Insights into the HD 163296 Planet-Forming Disk

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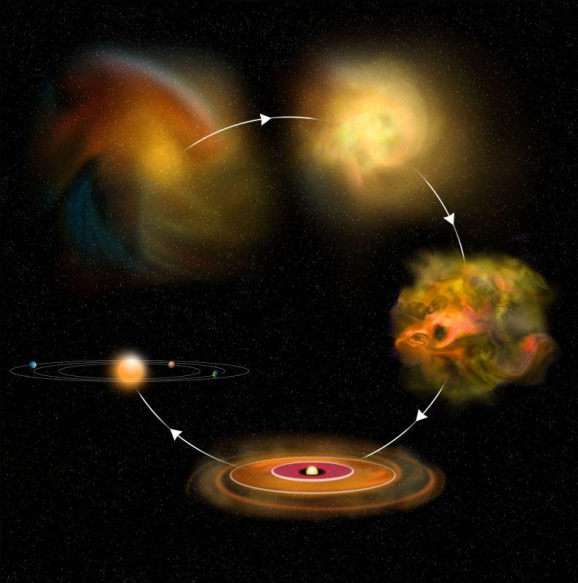
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³European Southern Observatory, Alonso de Córdova 3107, Vitacura Casilla 19001, Santiago, Chile

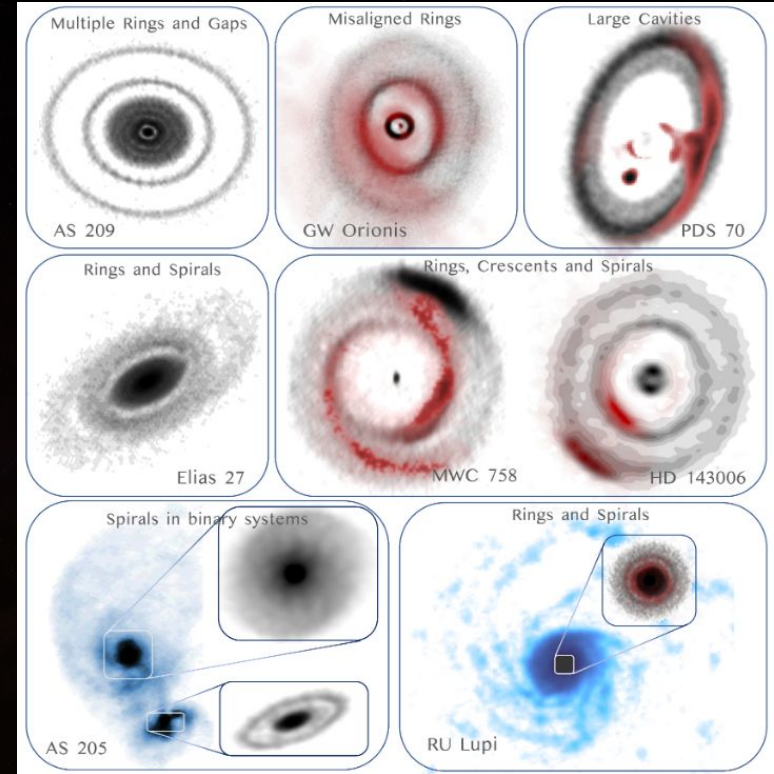
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Protoplanetary Disks?

Rotating disk of gas and dust around young stars.
Sites of planet formation...



Disks are highly structured.
Substructures are frequent, exhibit variety of morphologies, locations, and properties.



Some of the morphological features observed in protoplanetary disks. Black and white contours show mm continuum observations, blue contours show mm line observations, and red contours show NIR observations, respectively.

Tracing the disks...

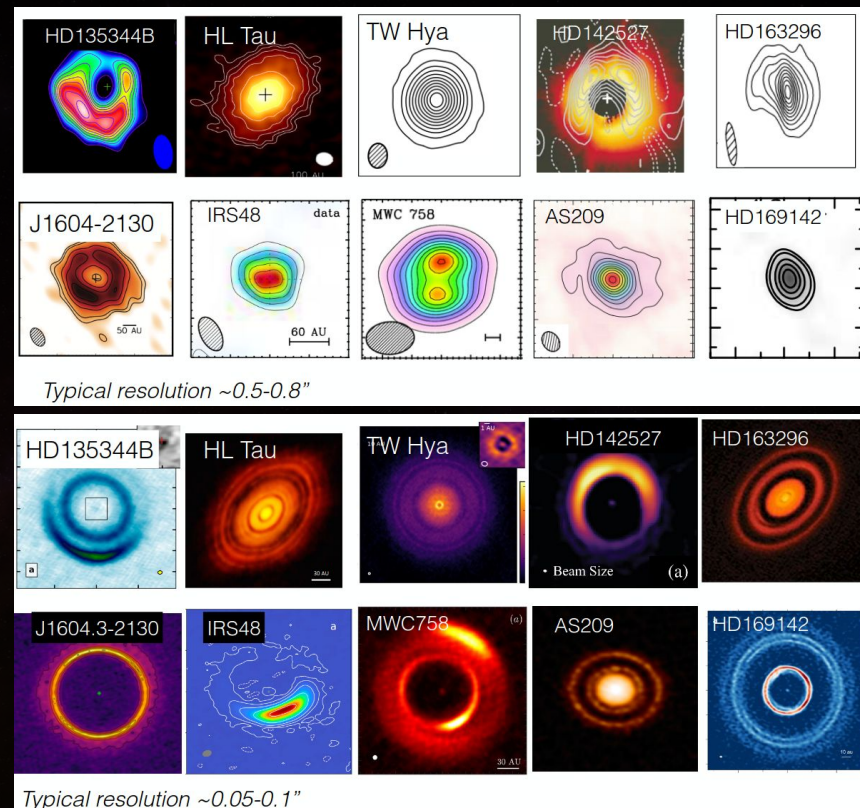
**Most powerful technique :
Long baseline Interferometry**

Nearby disks (~ 150 pc) $\rightarrow \lesssim 1''$ angular size

Most disks are cold (< 100 K)

$\rightarrow$ emit strongly at (sub-)mm wavelengths

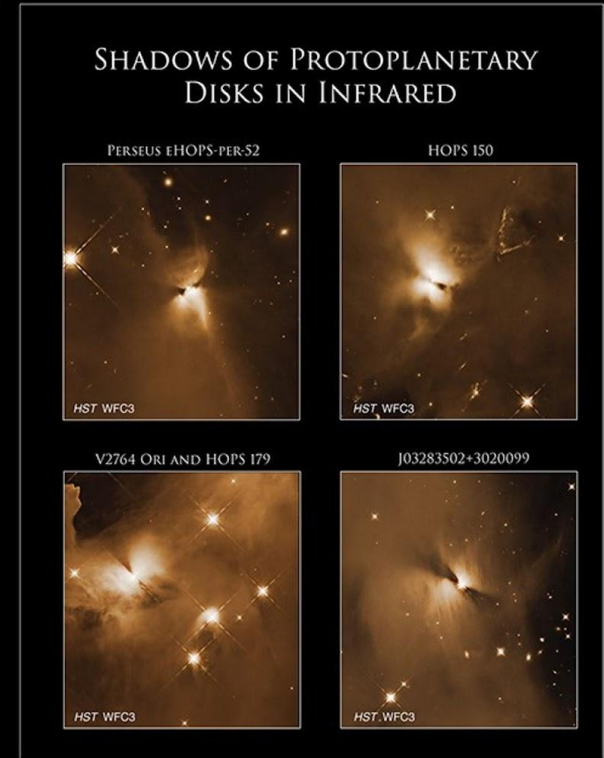
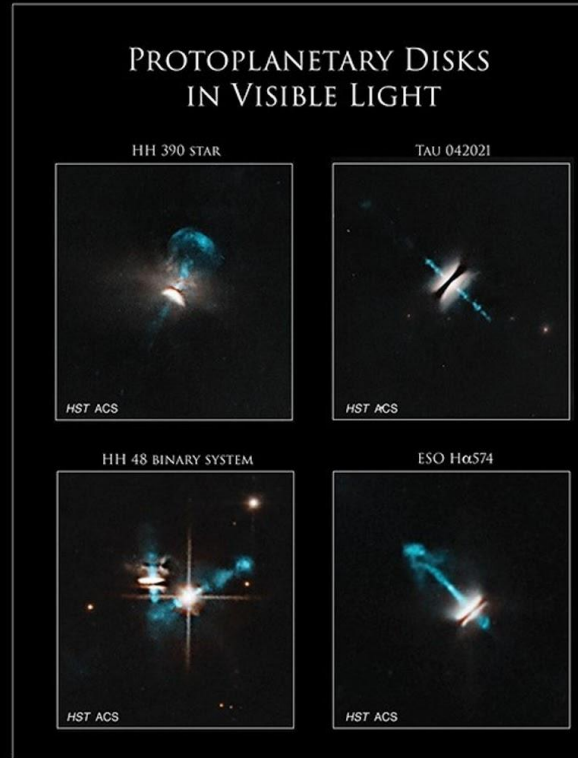
Traces large grains in disk midplane.



Pre-ALMA and Post-ALMA observations
(lecture notes from Nienke van der Marel)

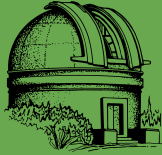
Scattered Light Imaging

Probing the surface layers
by capturing the light
scattered by small dust
grains



Hubble images of protoplanetary disks in visible and infrared light (science.nasa.gov).

From ground...



RESOLUTION

Large Telescope



ATMOSPHERE

Adaptive Optics



CONTRAST

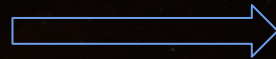
Coronagraphy



SPECKLES

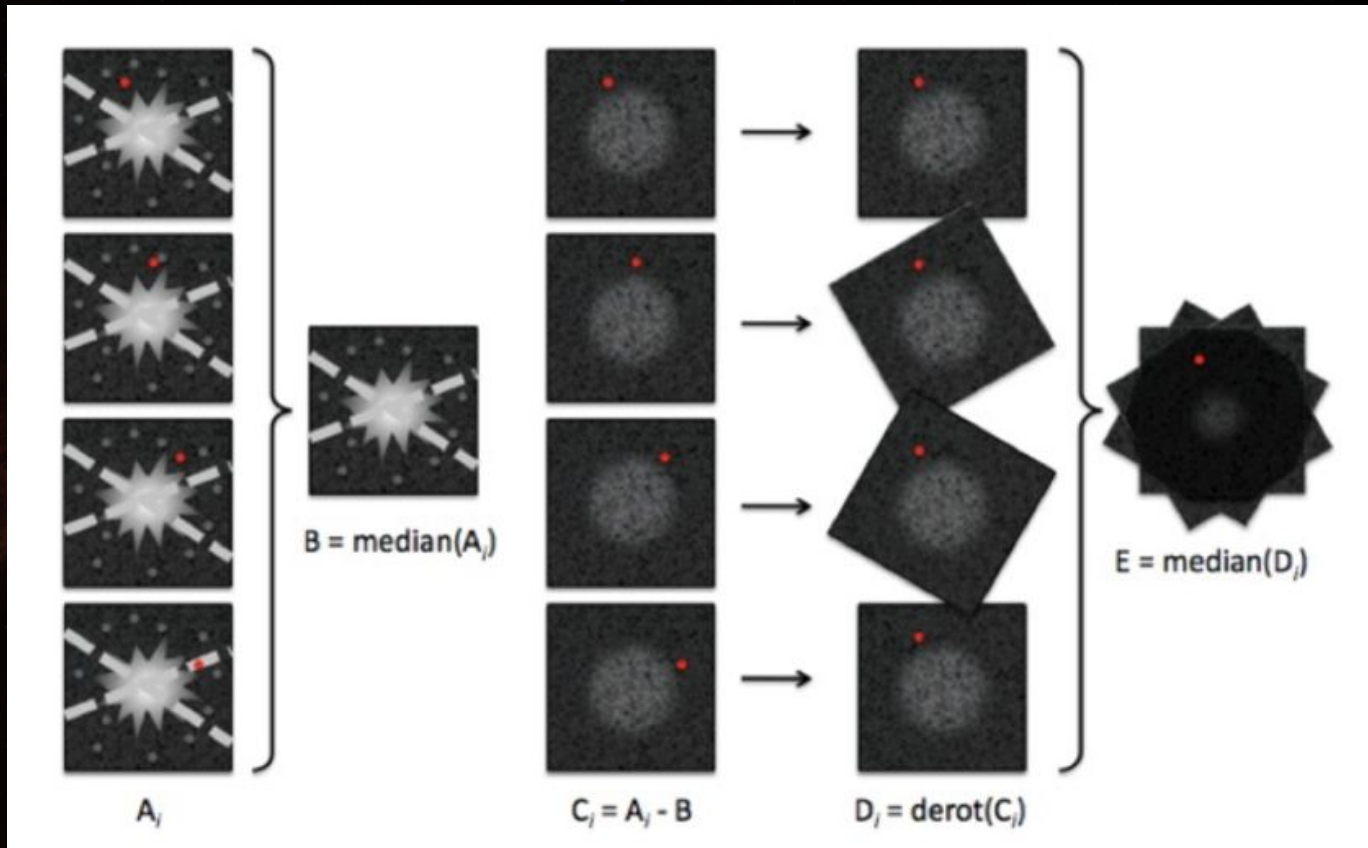
Post-processing

Speckles v/s Planets?



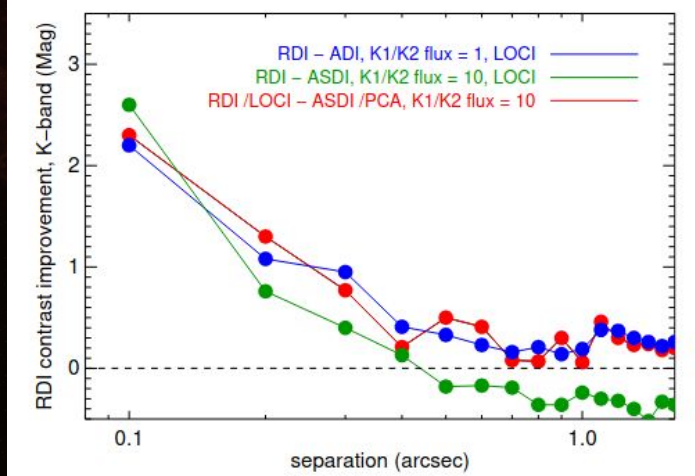
Differential Imaging Techniques

Angular Differential Imaging and the issue of self-subtraction

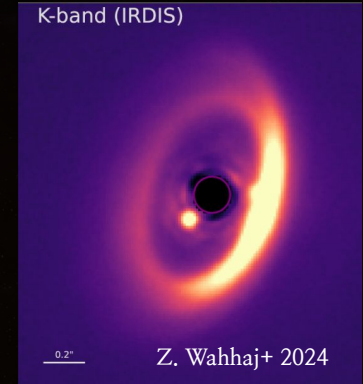
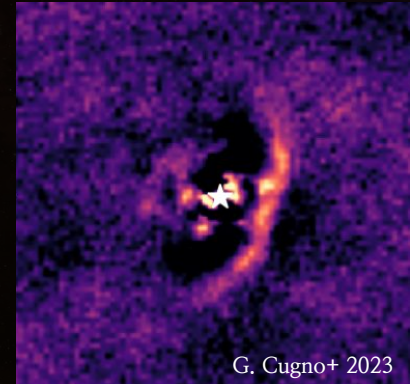
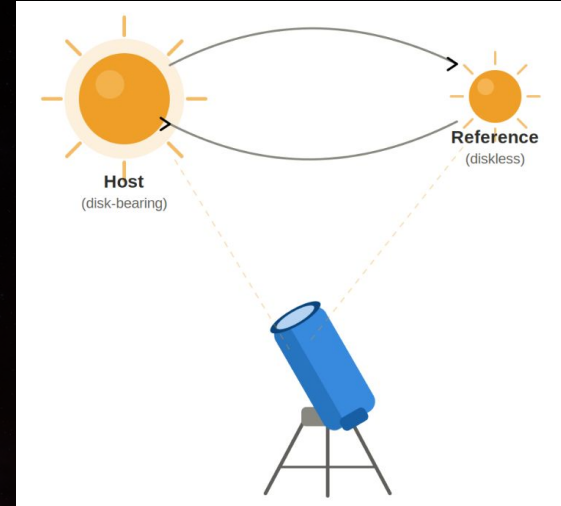


Star-hopping RDI

- Alternate targets every ~10 minutes, with 1 minute gap.
- Better sampling of the stellar PSF and speckle pattern.
- Reduces quasi-static speckle effects and mitigates self-subtraction artifacts.
- At least 2 mag contrast improvement over ADI at close separations



Z. Wahhaj+ 2021



The planet forming disk of HD 163296

TARGET

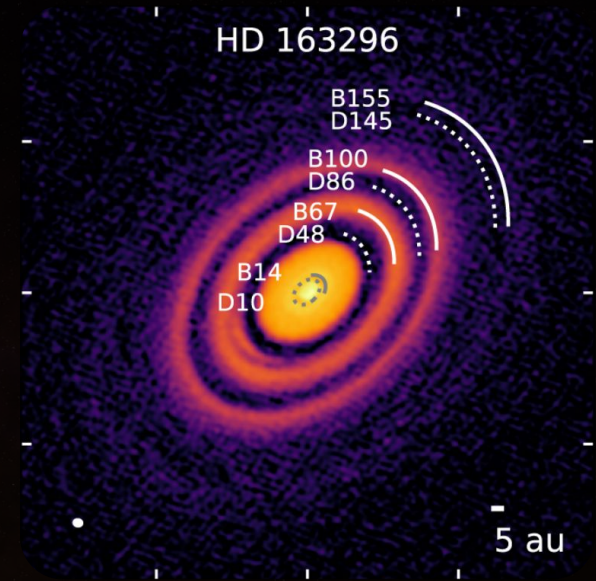
- Herbig Ae star ($\sim 2 M_{\odot}$, 7–10 Myr, ~ 101 pc)
- One of the best-studied protoplanetary disk systems.

DISK STRUCTURE

- Extent: ~ 500 au(gas), ~ 200 au(dust)
- ALMA reveals:
 - Gaps : 10, 48, 86, and 145 au; Crescent : 55 au.

OBSERVATIONS

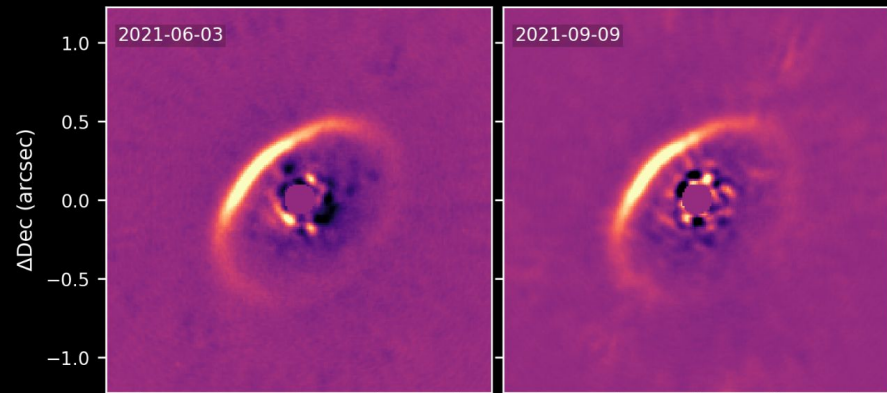
- Gas Kinematic + HD simulations $\rightarrow$ 1–2 M_J planets at multiple radii.
- Crescent formation $\rightarrow$ Jupiter mass planet or Sub-Saturn pairs.
- Scattered-light imaging with HST, SUBARU, GPI, VLT/NACO/SPHERE, KECK/NIRC2, JWST:
 - Rings, asymmetries, vertical structure
 - No confirmed planet detections.



ALMA 1.3 mm continuum map of HD 163296 showing rings and gaps.

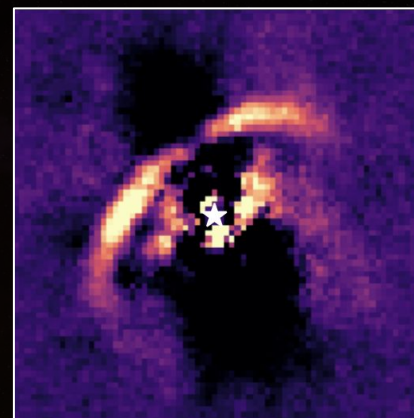
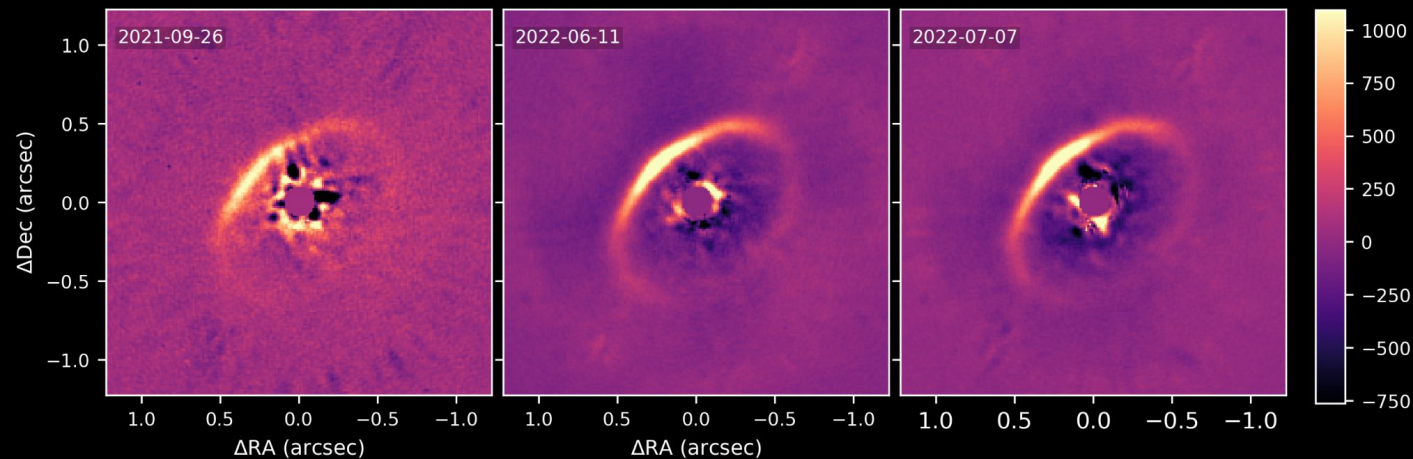
J. Huang+ 2018

Strong indirect evidence, but no direct detections!

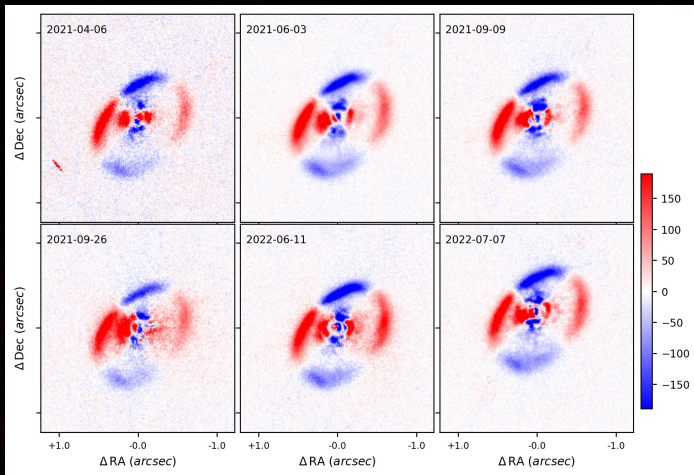


VLT/SPHERE Star Hopping Ks band total intensity observations of HD 163296 taken across 5 nights.

Data reduction is done by Star hopping reduction pipeline by Z. Wahhaj+(2021) and C. Swastik+(2025)



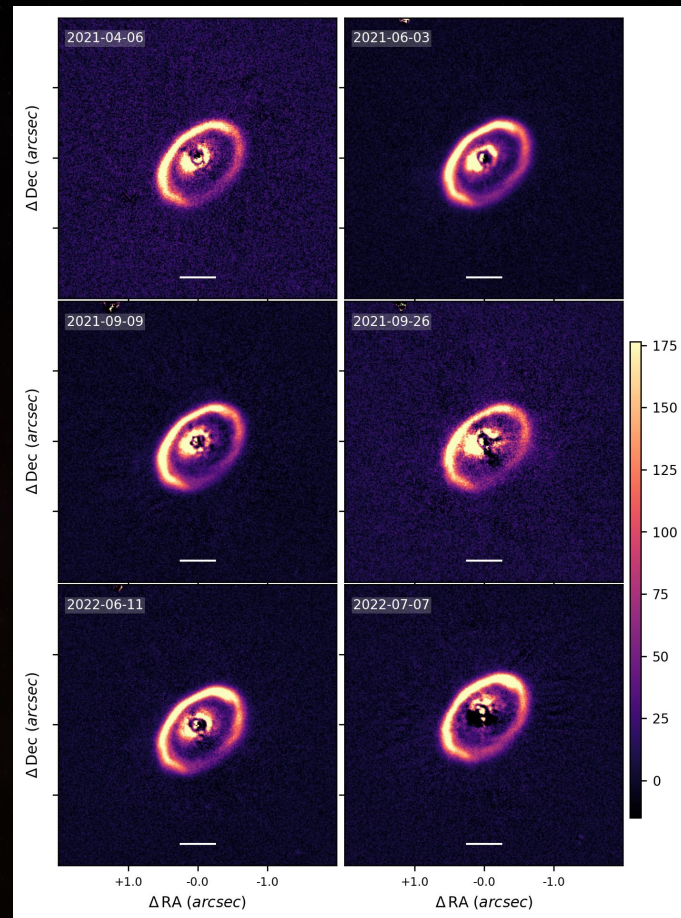
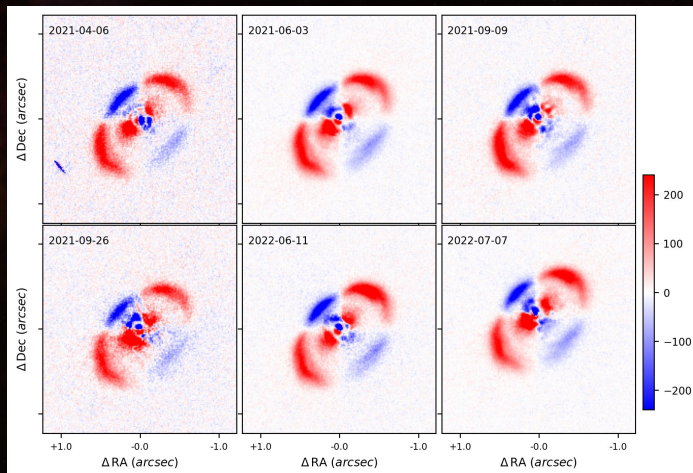
HD163296 imaged with VLT/NaCO, using angular differential imaging(ADI) (G. Cugno+ 2023)



◀ Stokes Q

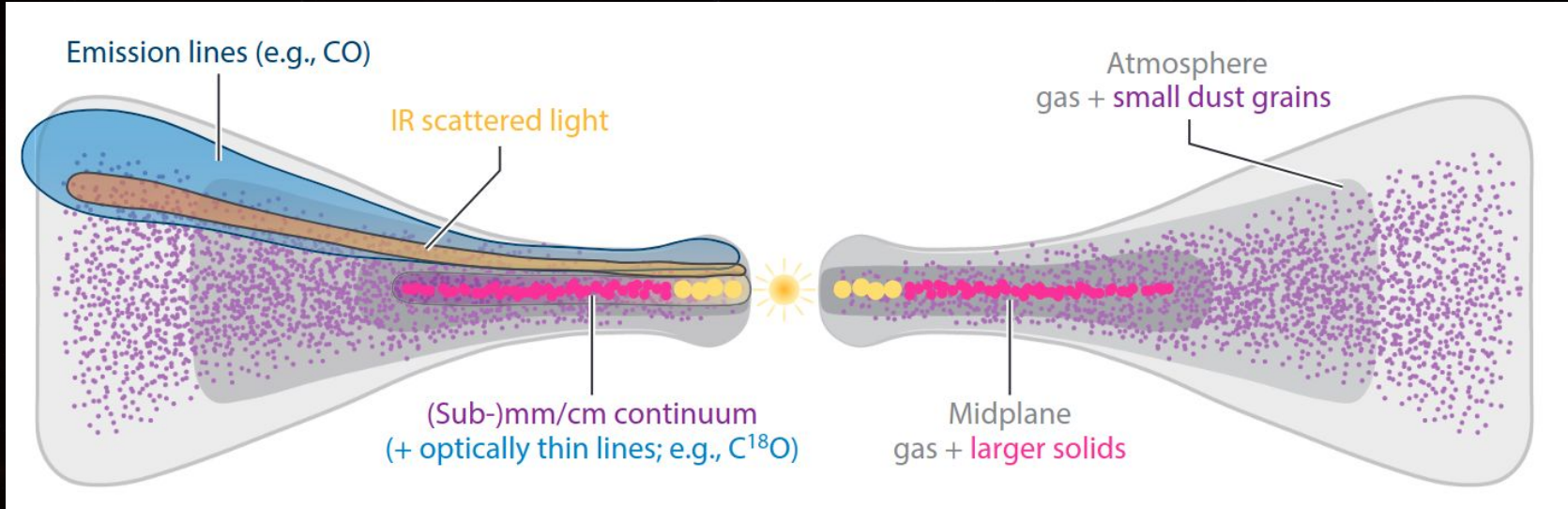
Q_phi ▶

Stokes U ▶



Multi-wavelength view of the disk

Why combined ALMA-SPHERE disk modeling is necessary?



SM Andrews 2020

A diagram of a disk structure viewed in cross-section. The gas is denoted in grayscale, and solids are marked with exaggerated sizes and colors. The left side highlights the approximate locations of emission tracers; the right side defines some structure and contents terminology.

Disk Modeling

- Generate synthetic images for direct comparison with observations.
Enables constraints on: Disk mass, Grain size distribution, Substructures (gaps, rings)
- Archival ALMA 1.3 mm continuum map of the disk is obtained. Combined ALMA-SPHERE modeling of the disk, tracing both micron, and mm sized grains.
- Radiative Transfer Models generated using RADMC-3D (Dullemond+ 2012).

Create a self-consistent disk model that fits Ks band total intensity, Stokes Q and U, and ALMA 1.3mm data simultaneously.

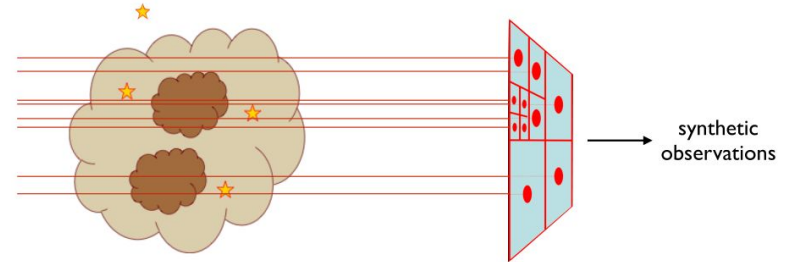
RADMC- 3D : Method

Input data

- provide a density distribution (gas or dust)
- add stars & map over a grid
- provide physical data (atomic / molecular / dust)

Computation & output

- compute dust temperature & radiative transfer
- compute line rad transfer
- images and spectra from ray tracing towards observer



Taken from Lecture notes by Benjamin Godard

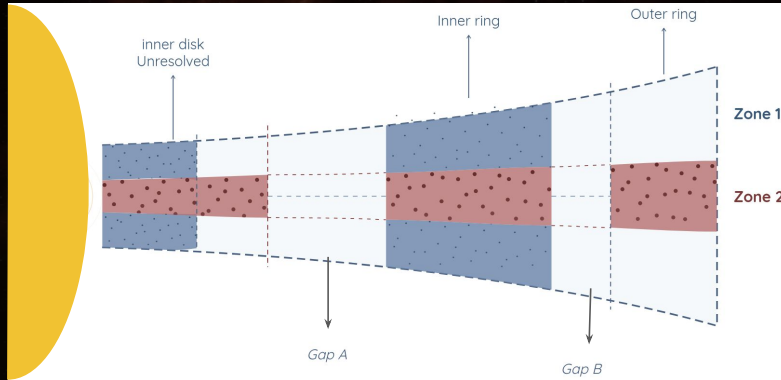
Disk Modeling

Axisymmetric, two-zone disk structure

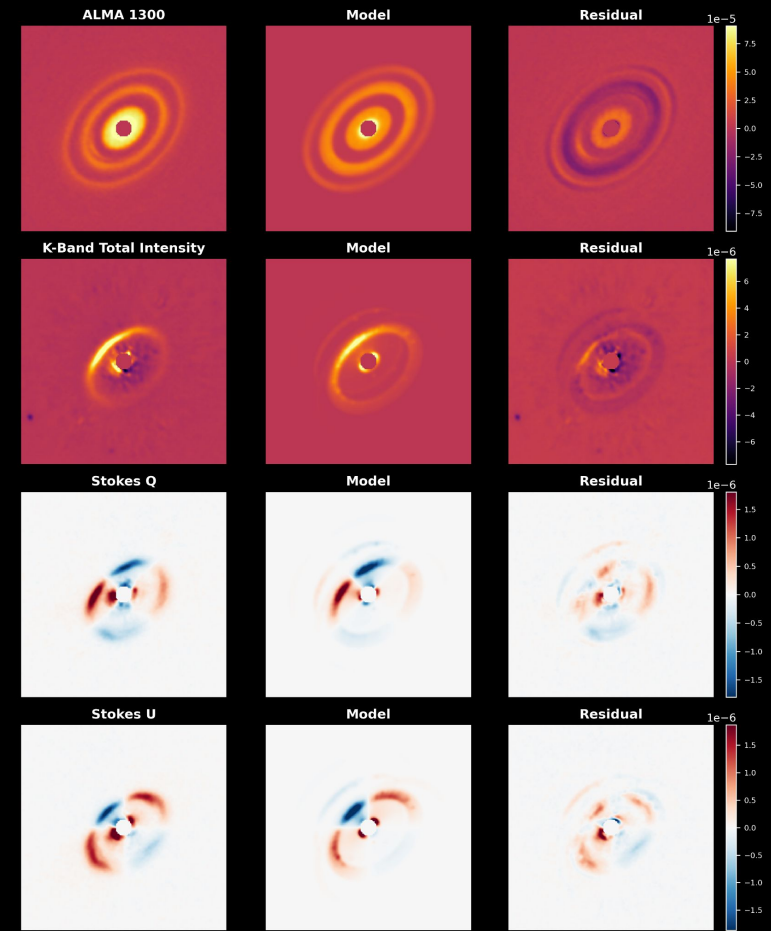
Zone 1 (surface) : micron sized grains coupled to gas, probed by SPHERE NIR imaging (scattered light), flared morphology

Zone 2 (midplane) : mm-sized grains settled to midplane, traced by ALMA 1.3 mm continuum emission.

Compact homogeneous Mie spheres of Olivine grains with opacities generated using OPTOOL.



Schematic of the disk model



Comparison of RADMC-3D model with Olivine grains and observed data. The sequence from left to right shows the data, the simulated model, and the residuals. The top row is the ALMA 1.3mm continuum, followed K band total intensity, K-band Stokes Q, and the Stokes U.

Key Takeaways

- Star-hopping total intensity reduction images successfully reveal bright ring and inner disk regions.
 - Generated a consistent two-zone disk model with different grains populating different regions. Overall disk geometry and ring-gap location are consistent with scattered-light, and thermal continuum observations.
 - Ring visible in scattered light images are roughly co-spatial with the 67AU ring seen in ALMA.
 - Our best-fit olivine model fits the observations, but scattered light models show less forward scattering, and significant backward scattering.
 - Scattering asymmetry, and polarimetric residuals indicate a different dust size/composition/model.
-
- Phase-function analysis to constrain dust size, composition, and scattering properties.
 - Incorporate porous/fractal aggregate dust models into the radiative transfer framework.
 - Total-intensity planet search, candidate validation, and characterization.

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