Optical and Near-infrared View of Planet-forming Disks and Protoplanets

An overview

Adamo Sabbadin, 12.12.2023

Introduction and motivation

- Over 4500 confirmed exoplanets (*Benisty et al.* (2022))
- Extreme diversity in planetary systems
- Protoplanetary disks set initial conditions for planet formation,
  → origin for this diversity?
- Studying evolution crucial for understanding formation processes

Structure of the presentation:

- Methodology, imaging techniques
- Structures and substructures in protoplanetary disks
- Honourable observations

Methodology, differential imaging techniques

Challenge 1: Angular resolution

$$\theta = 1.22\frac{\lambda}{D}$$

Angular resolution seeing limited

→ Adaptive Optics

Challenge 2: Star overshines surrounding disk/planets

→ ***Differential Imaging***: Imaging techniques applied to subtract starlight signal from its immediate surroundings

Methodology, differential imaging techniques

Reference Differential Imaging (RDI)

Light profile from reference star used for PSF of the target star.

Subtraction removes star's signal from immediate surroundings.

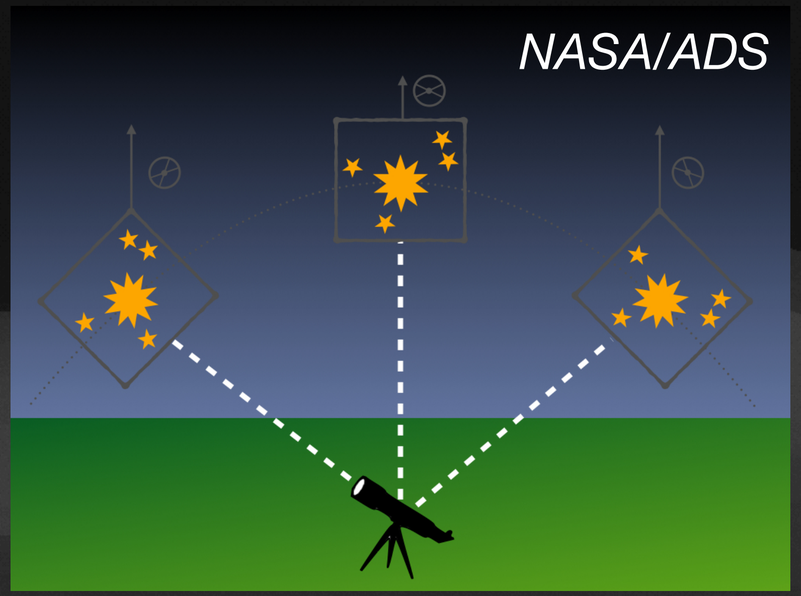
Mainly used in space-based observations as early as the late 90s (*Grady et al.* (1999), *Weinberger et al.* (1999)).

Issues:

- Not well-suited for ground-based observations
- Bright circumstellar disks cause overfitting
- Finding suitable reference star can be difficult

Methodology, differential imaging techniques

Angular Differential Imaging (ADI)



Telescopes with azimuthal-mounting used to observe apparent rotation throughout the night.

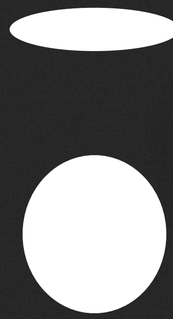
Constant center of rotation (star) is then subtracted.

Originally used for the detection of wide-separation exoplanets (*Marois et al.* (2006)).

Main issue: signal suppression (self-subtraction):

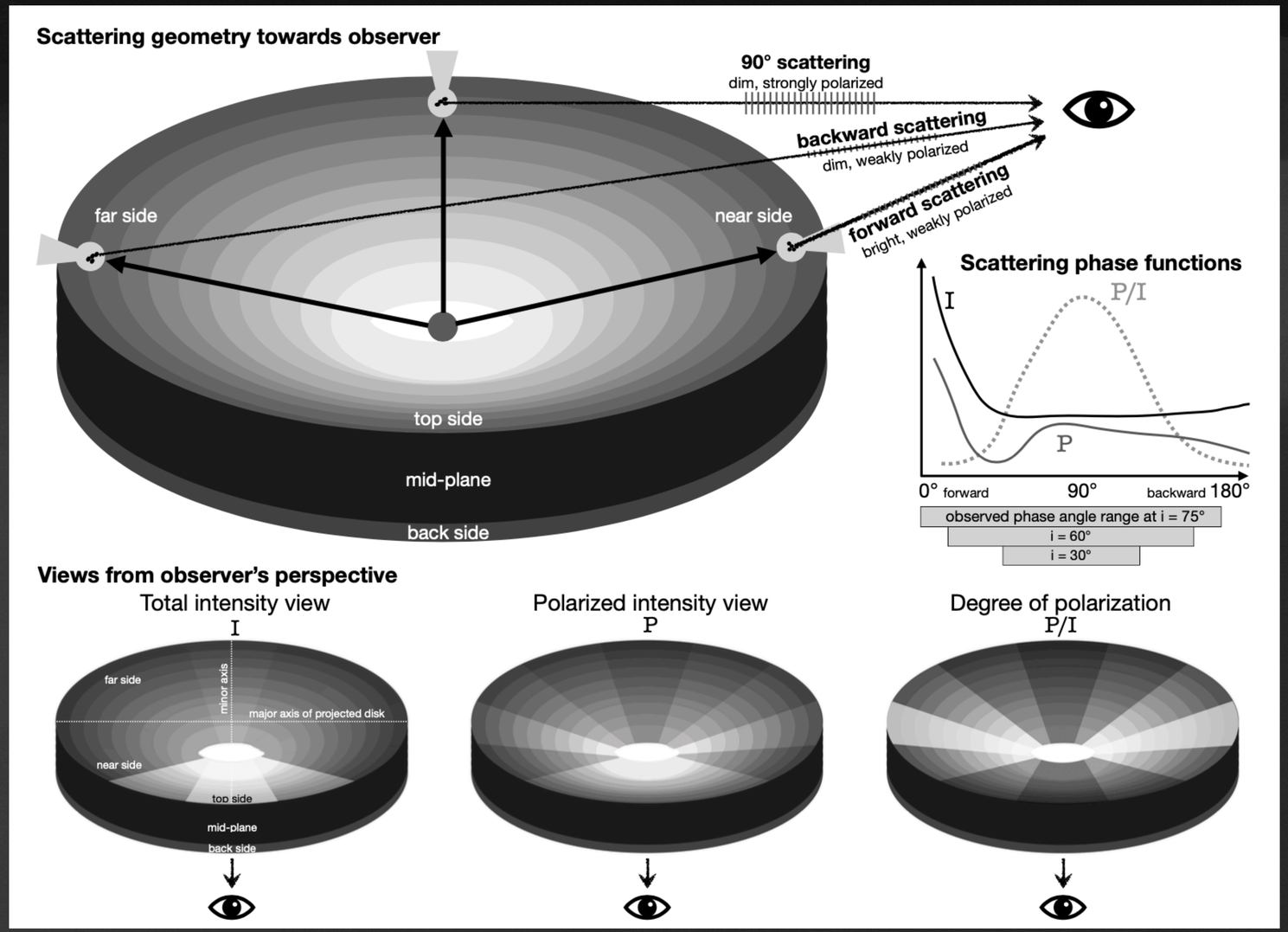
Caused by overlap of disk/planet signal with itself

→ not suited for small disks or face-on geometry



Methodology, differential imaging techniques

Polarisation differential imaging (PDI)



Benisty, Dominik, Follette et al. (2022)

Methodology, differential imaging techniques

Polarisation differential imaging (PDI)

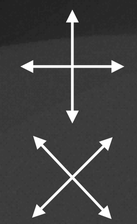
Stokes vector : $S = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$

I: total intensity

Q: linearly polarised light

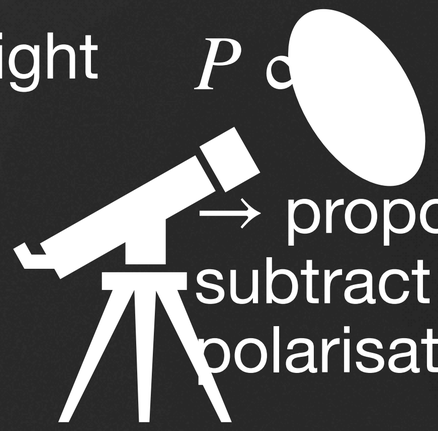
U: linearly polarised light

V: circularly polarised light



Further polarisation within instrument
Some polarisation also exhibited by stellar light
→ "double difference" method:
→ technique introduced by *Canovas et al.* (2011) and *Hashimoto et al.* (2012):

measure Q^+, Q^-, U^+, U^-



P o

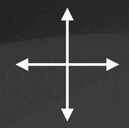
→ proportionality factor derived to subtract corresponding polarisation from double difference

Methodology, differential imaging techniques

Polarisation differential imaging (PDI)

Stokes vector : $S = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$

I: total intensity

Q: linearly polarised light 

U: linearly polarised light 

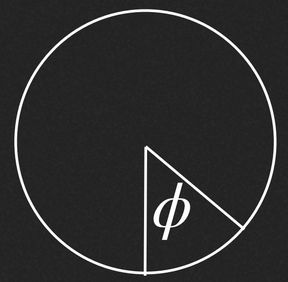
V: circularly polarised light

Polarised intensity: $PI = \sqrt{Q^2 + U^2}$

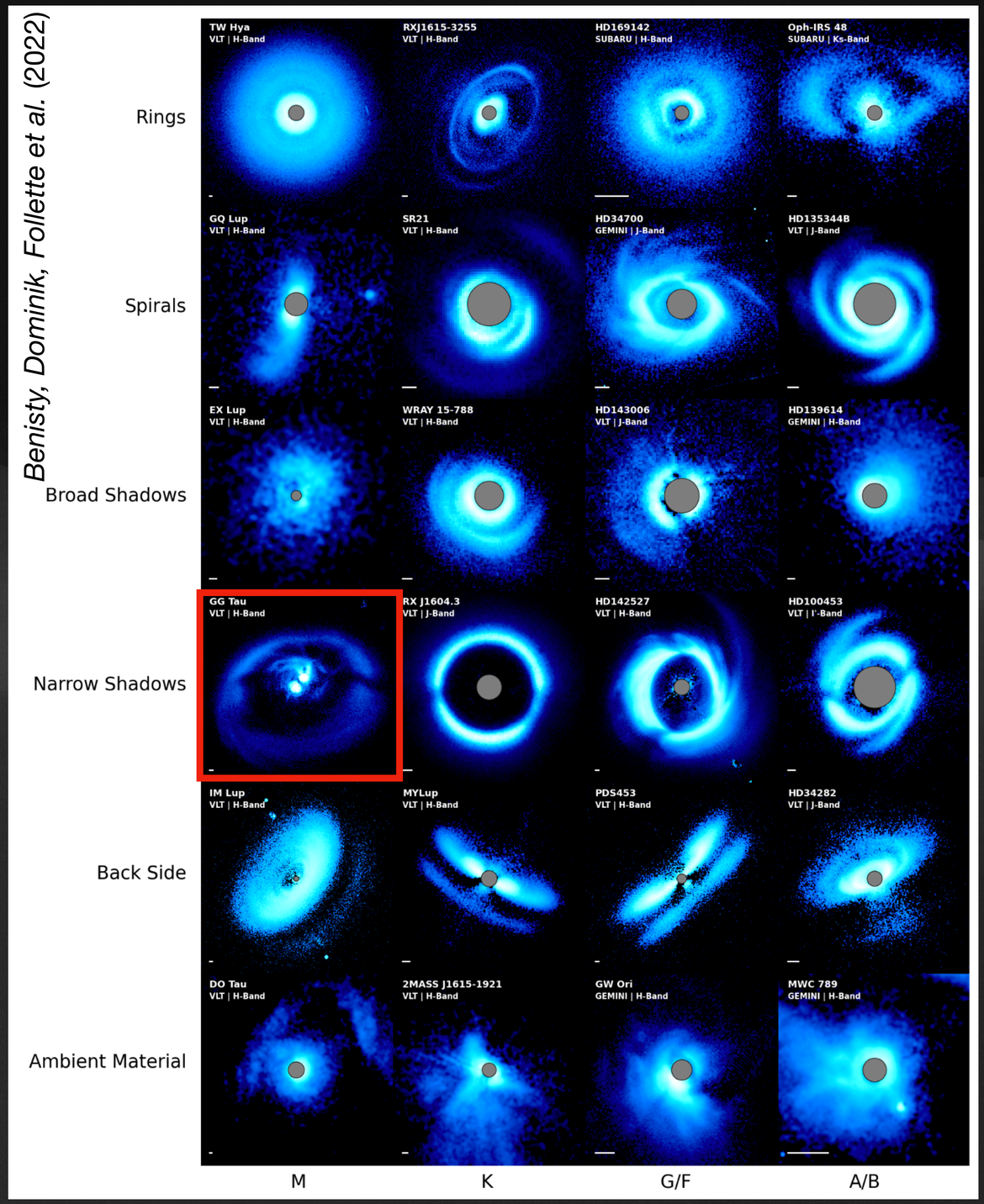
Azimuthal Stokes parameters (*Monnier et al.* (2019), *de Boer et al.* (2020)):

$$Q_\phi = -Q\cos(2\phi) - U\sin(2\phi)$$

$$U_\phi = +Q\sin(2\phi) - U\cos(2\phi)$$



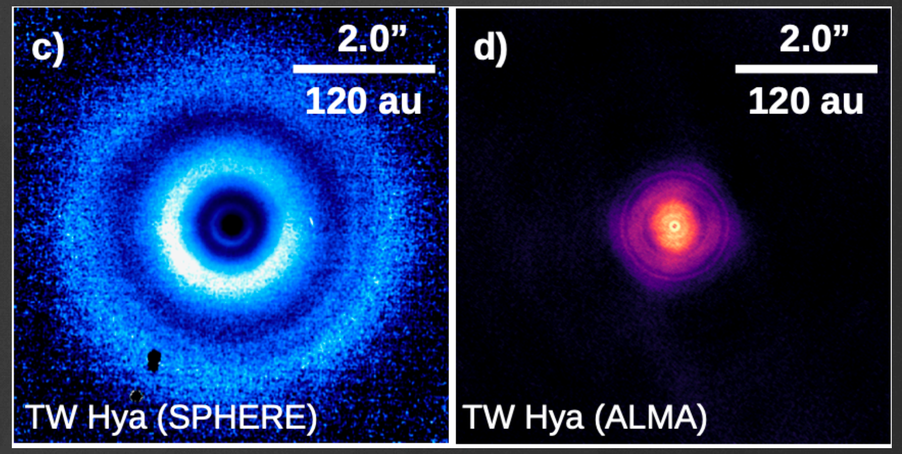
Structures and substructures in planetary disks



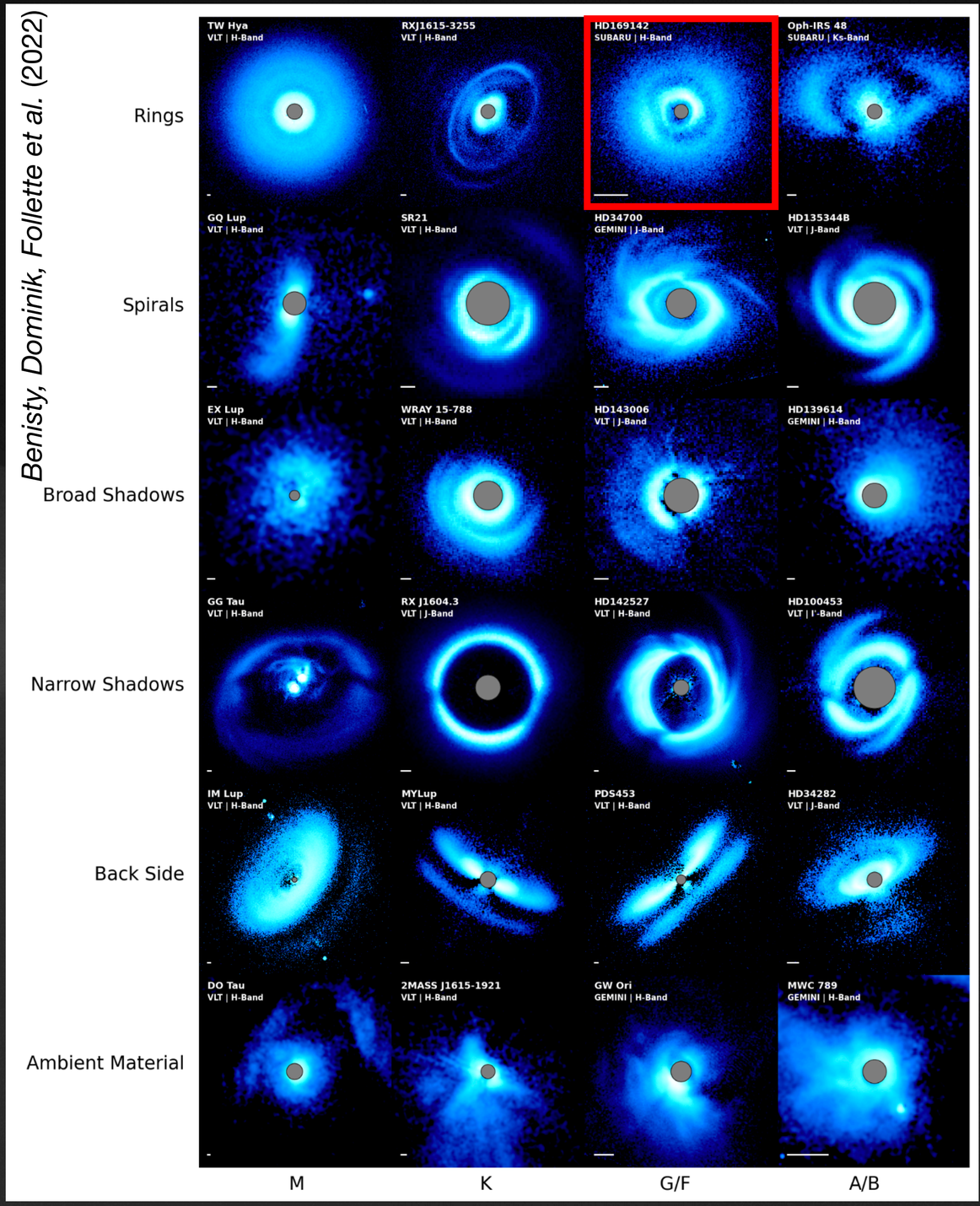
Structures and substructures in planetary disks

Rings

- First detected in PDI in HD169142
- Found at all radii accessible to direct imaging
- Mainly result of massive planets creating gaps
- Disks with rings in sub mm also exhibit rings in IR, but with no correspondence.



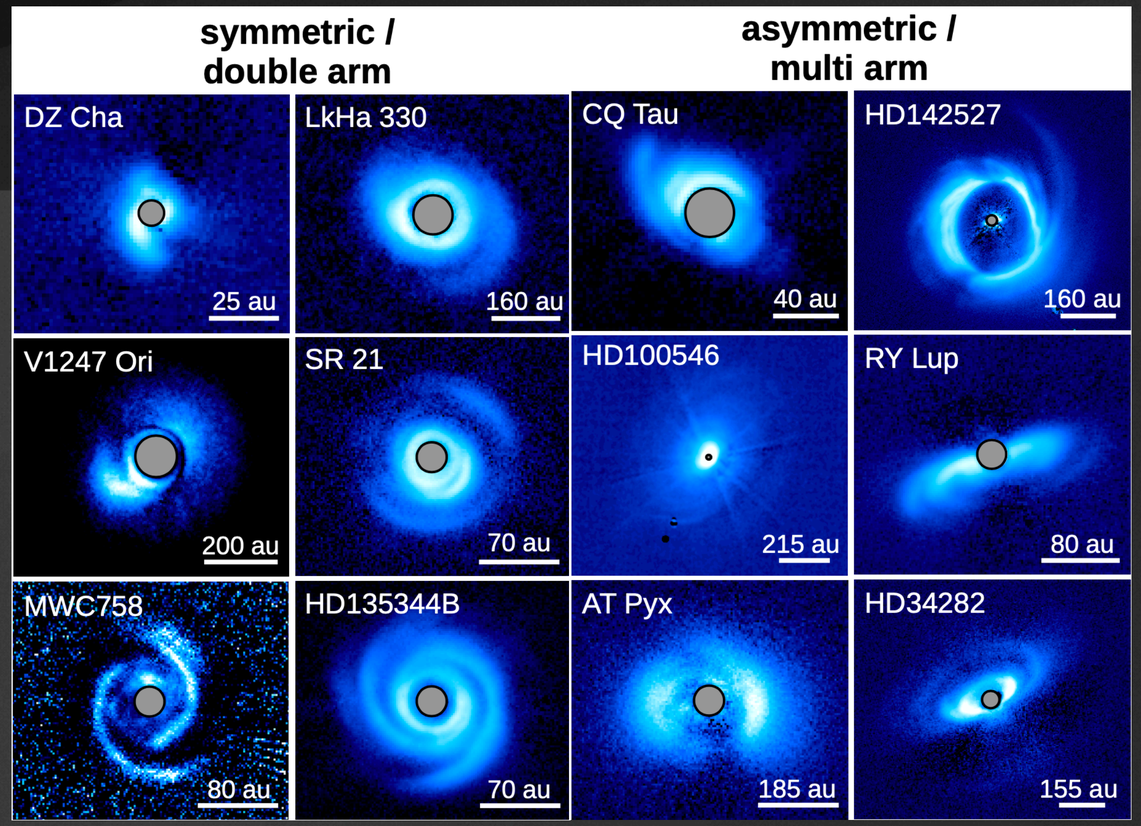
Benisty, Dominik, Follette et al. (2022)



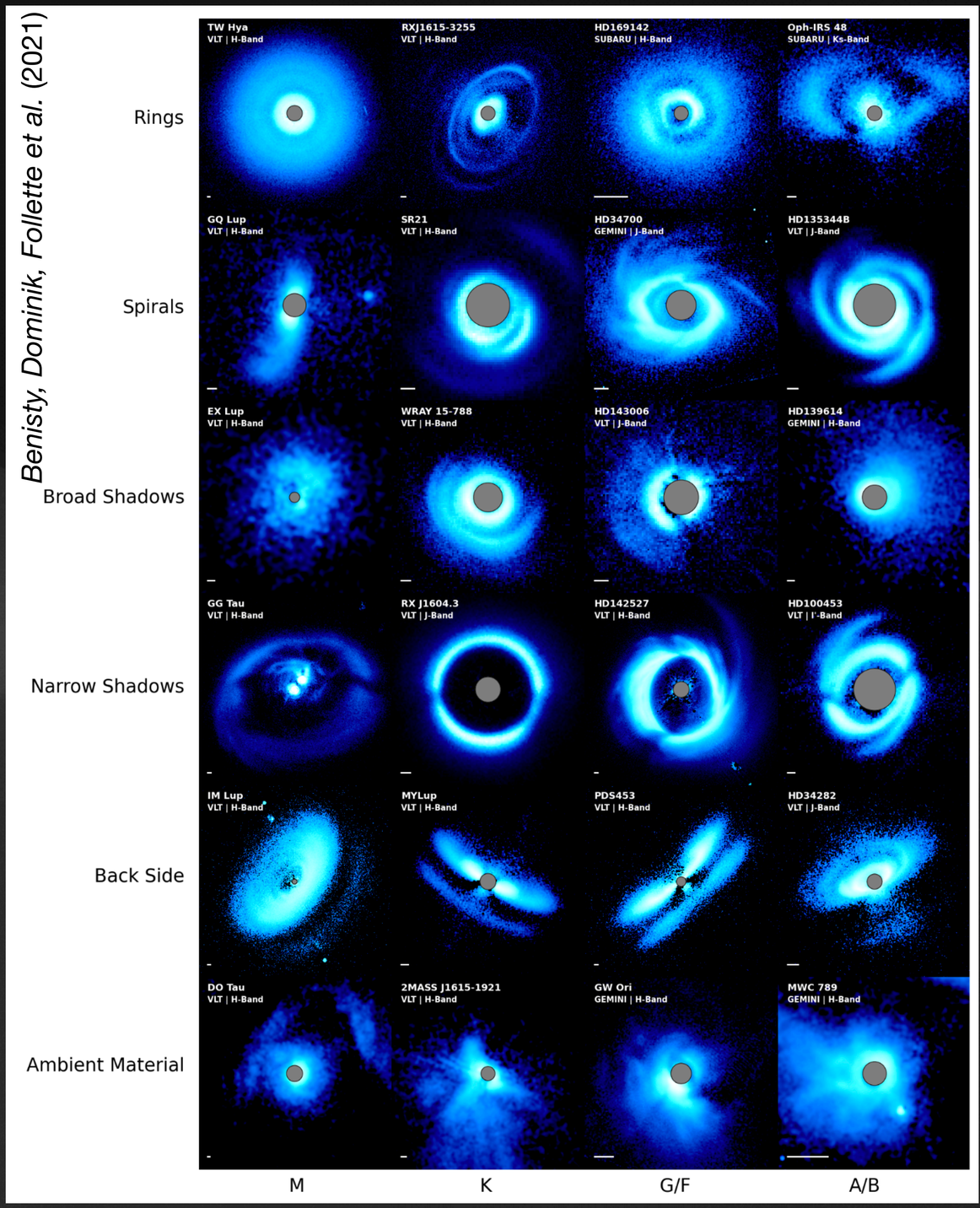
Structures and substructures in planetary disks

Spirals

- Various types of morphologies and origins



Benisty, Dominik, Follette et al. (2022)

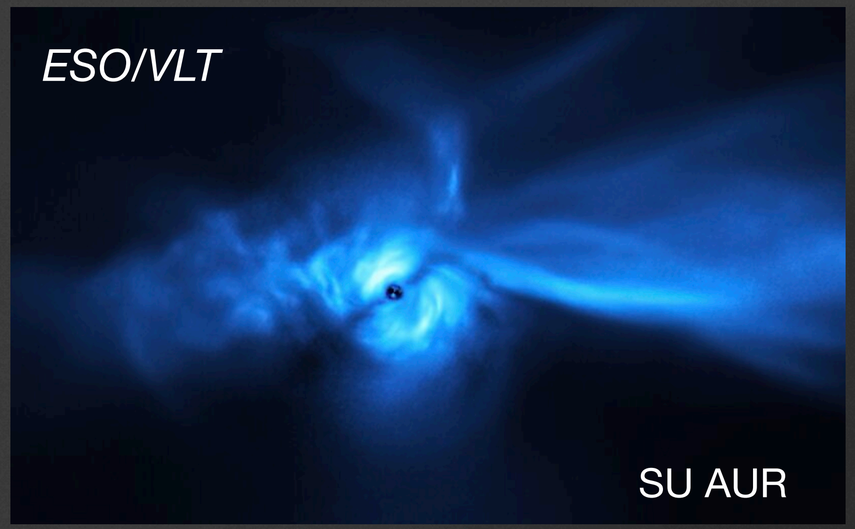


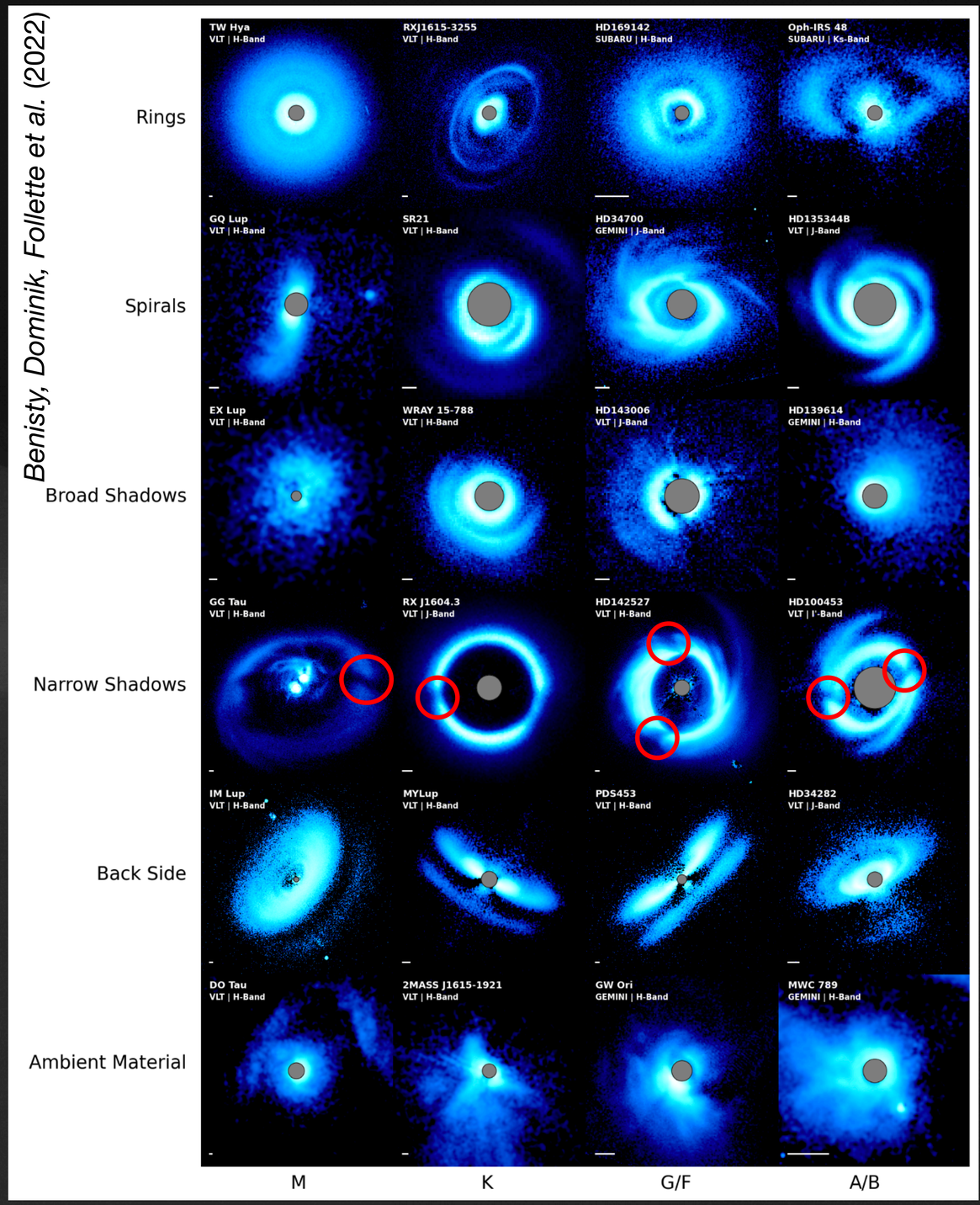
Benisty, Dominik, Follette et al. (2021)

Structures and substructures in planetary disks

Azimuthal Shadows

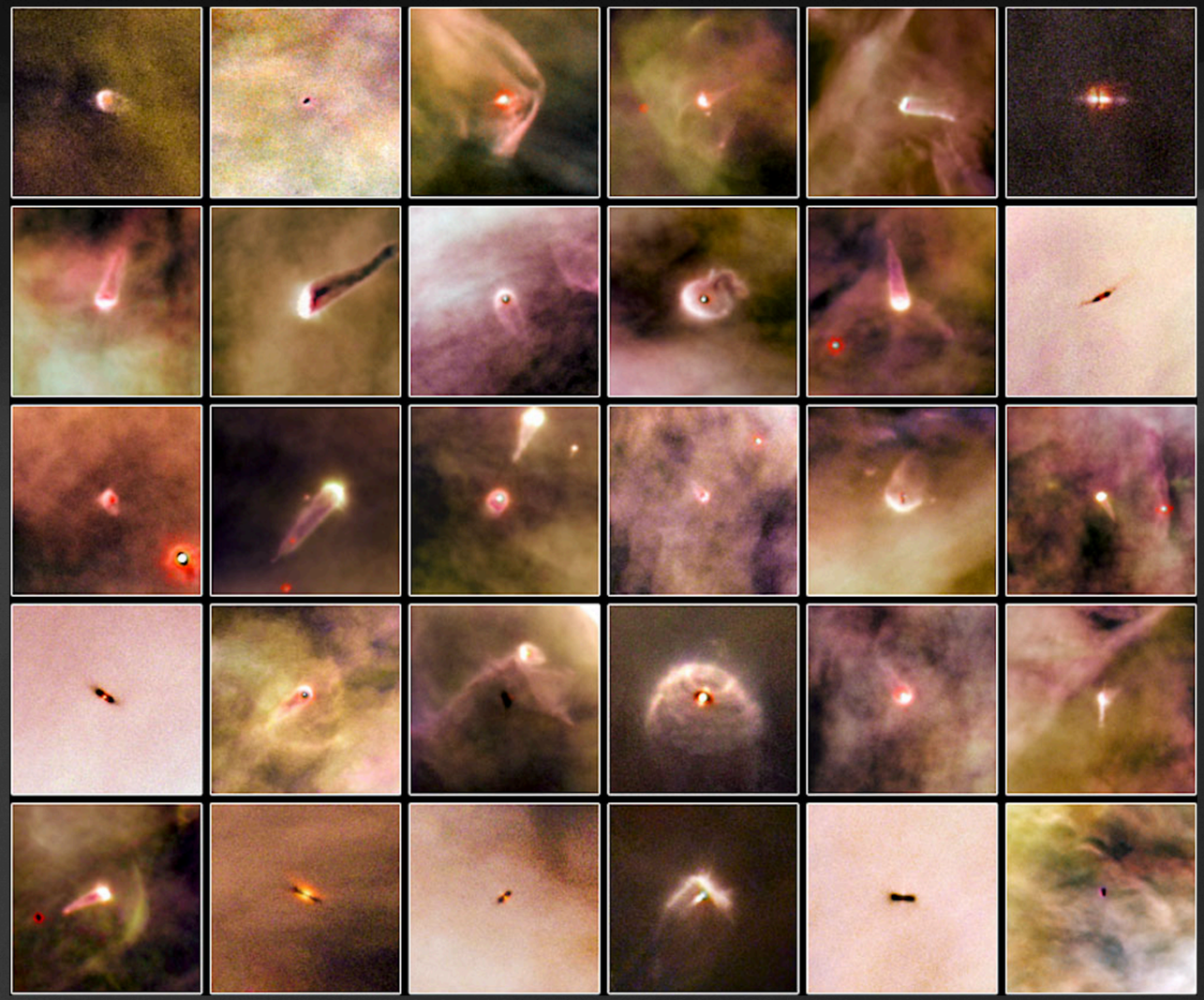
- Two main classes: Broad and Narrow
- Distinctive shadow patterns provide information on inner disk geometry.





Honourable observations

Externally Illuminated Protoplanetary Disks (Proplyds) in the Orion Nebula

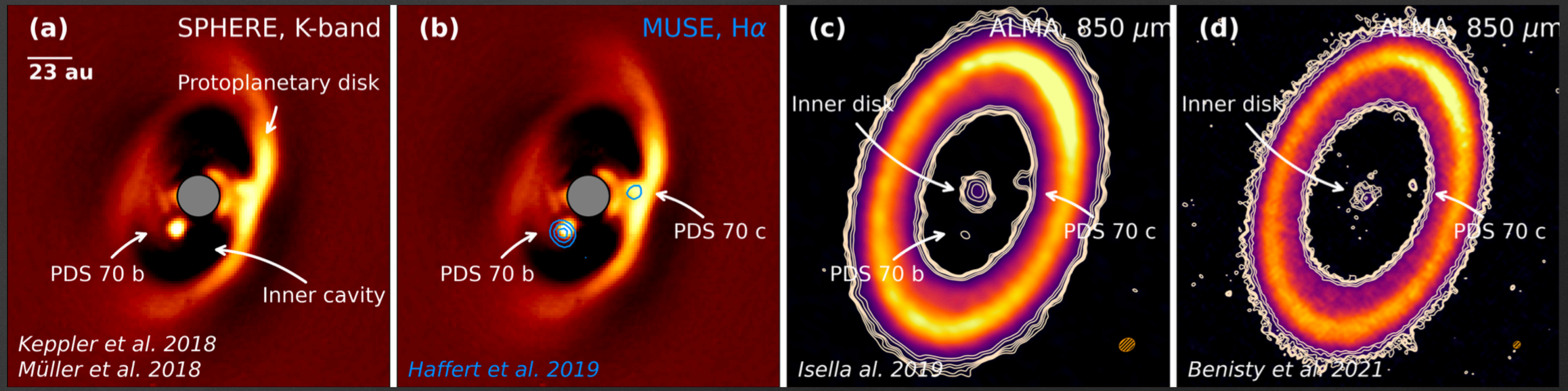


ESA/HUBBLE

Honourable observations

Direct imaging of planets, PDS70

- Young, giant planets still radiating energy from formation process
- Observed near-IR thermal emission may be contaminated by circumplanetary material → mass estimates come with high uncertainty



References

1] Benisty M. et al, 2022 arXiv.2203.09991.

2] Grady C. A. et al., 1999 *ApJL*, *523*, L151.

3] Weinberger A. J. et al., 1999 *ApJL*, *525*, L53.

4] Marois C. et al., 2006 *ApJ*, *641*, 556 .

5] Canovas H. et al., 2011 *A&A*, *531*, A102.

6] Hashimoto J. et al., 2012 *ApJL*, *758*, L19.

7] de Boer J. et al., 2020 *A&A*, *633*, A63.

8] Monnier J. D. et al., 2019 *ApJ*, *872*, 2, 122.

9] Dullemond C. P. et al., 2019 *A&A*, *628*, A20.

10] Isella A. et al., 2019 *ApJL*, *879*, 2, L25

11] Wang J. J. et al., 2021 *AJ*, *161*, 3, 148

12] Bae J. et al., 2019 *ApJL*, *884*, 2, L41

13] Keppler M. et al., 2018 *A&A*, *617*, A44

14] Müller A. et al., 2018a *A&A*, *617*, L2

15] Haffert S. Y. et al., 2019 *Nature Astronomy*, *3*, 749

16] Mesa D. et al., 2019b *A&A*, *632*, A25

17] Stolker T. et al., 2020 *A&A*, *644*, A13

18] Wang J. J. et al., 2020 *AJ*, *159*, 6, 263

19] Hashimoto J. et al., 2020 *AJ*, *159*, 5, 222

Questions?