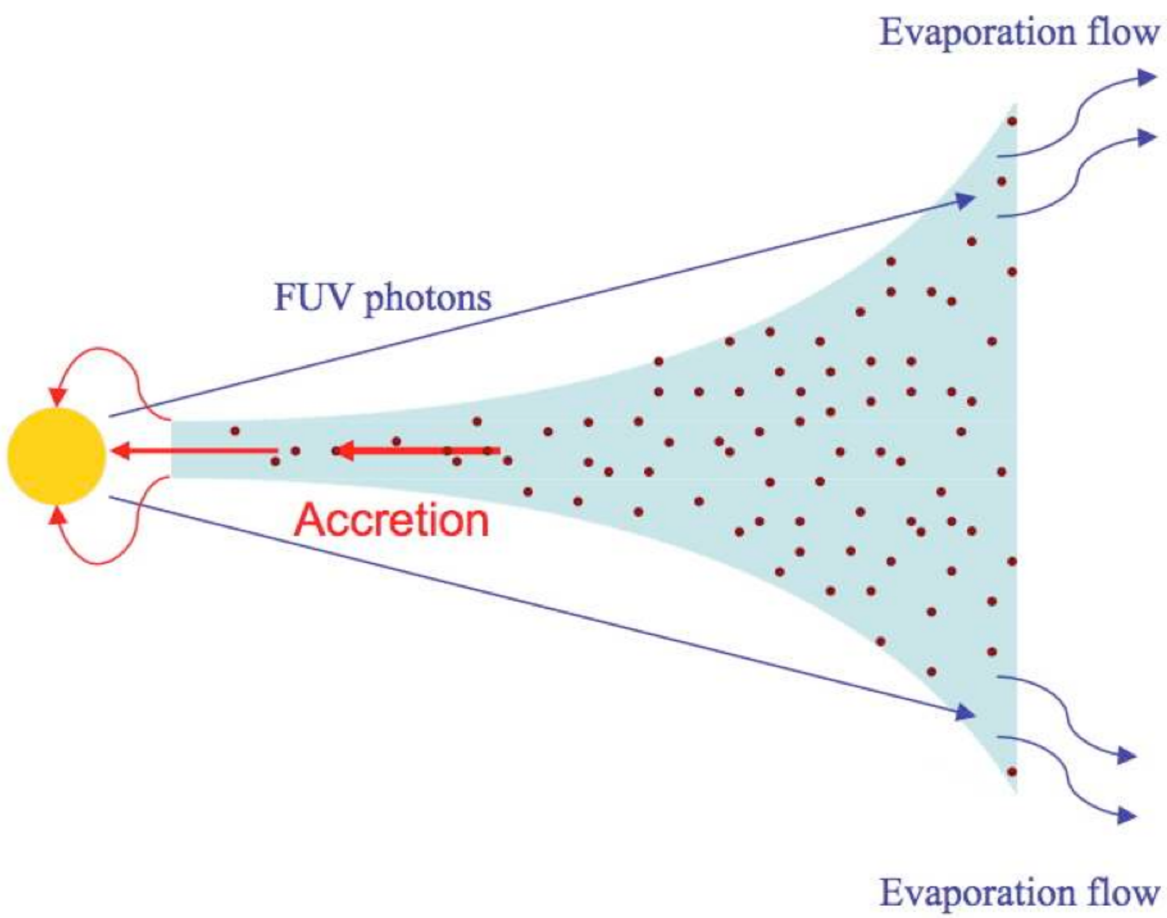
Scattered light imaging of protoplanetary disks

Myriam Benisty
UMI, U. de Chile & IPAG, Grenoble

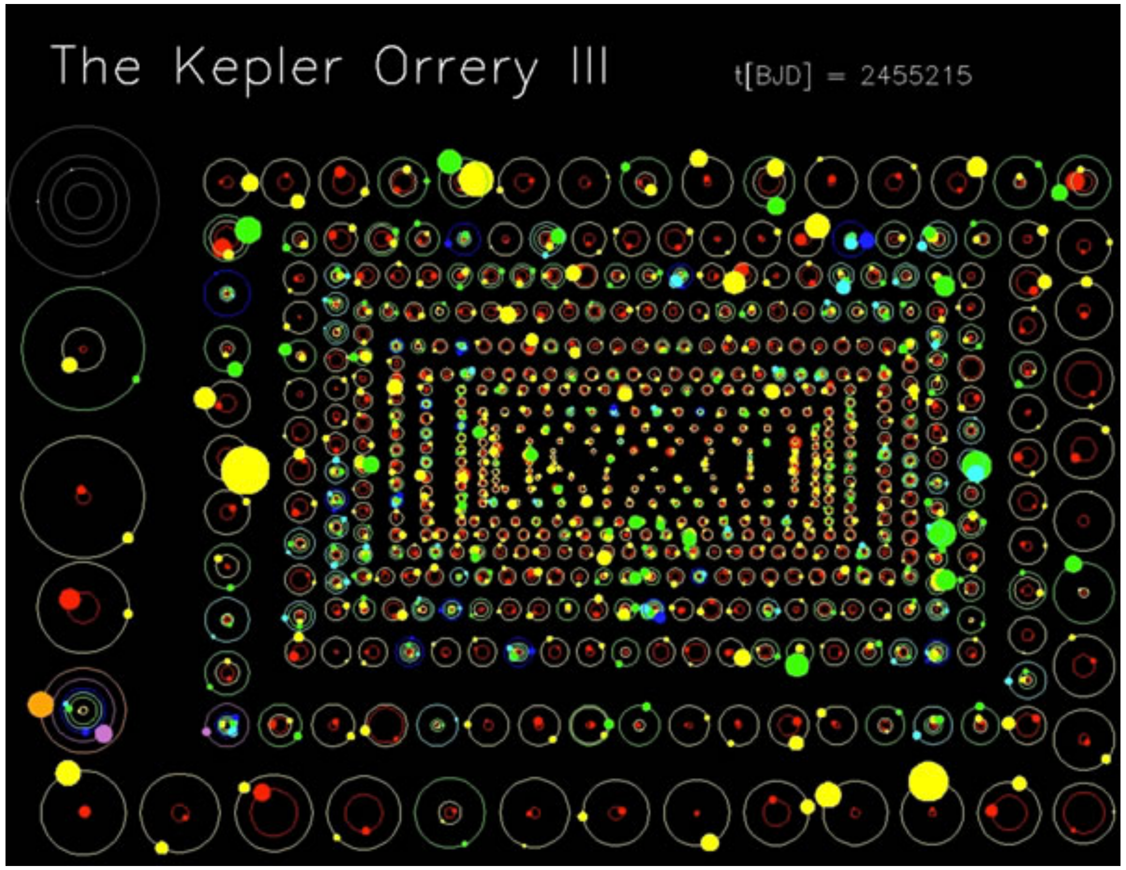
Outline

- Scattered and polarized light
- Rings, cavities, spirals, shadows
- Millimeter counterparts
- The case of PDS 70

Motivations



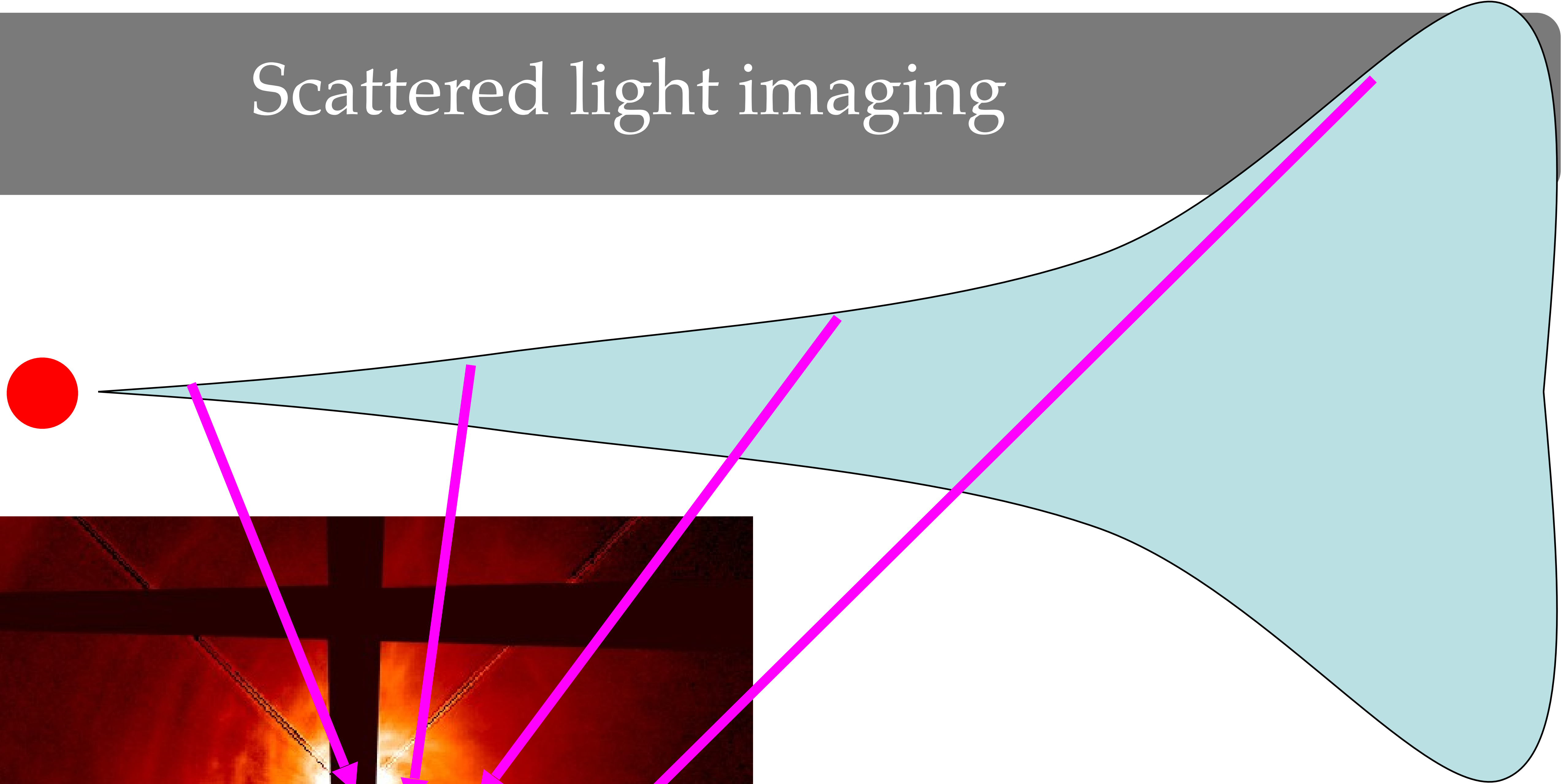
?

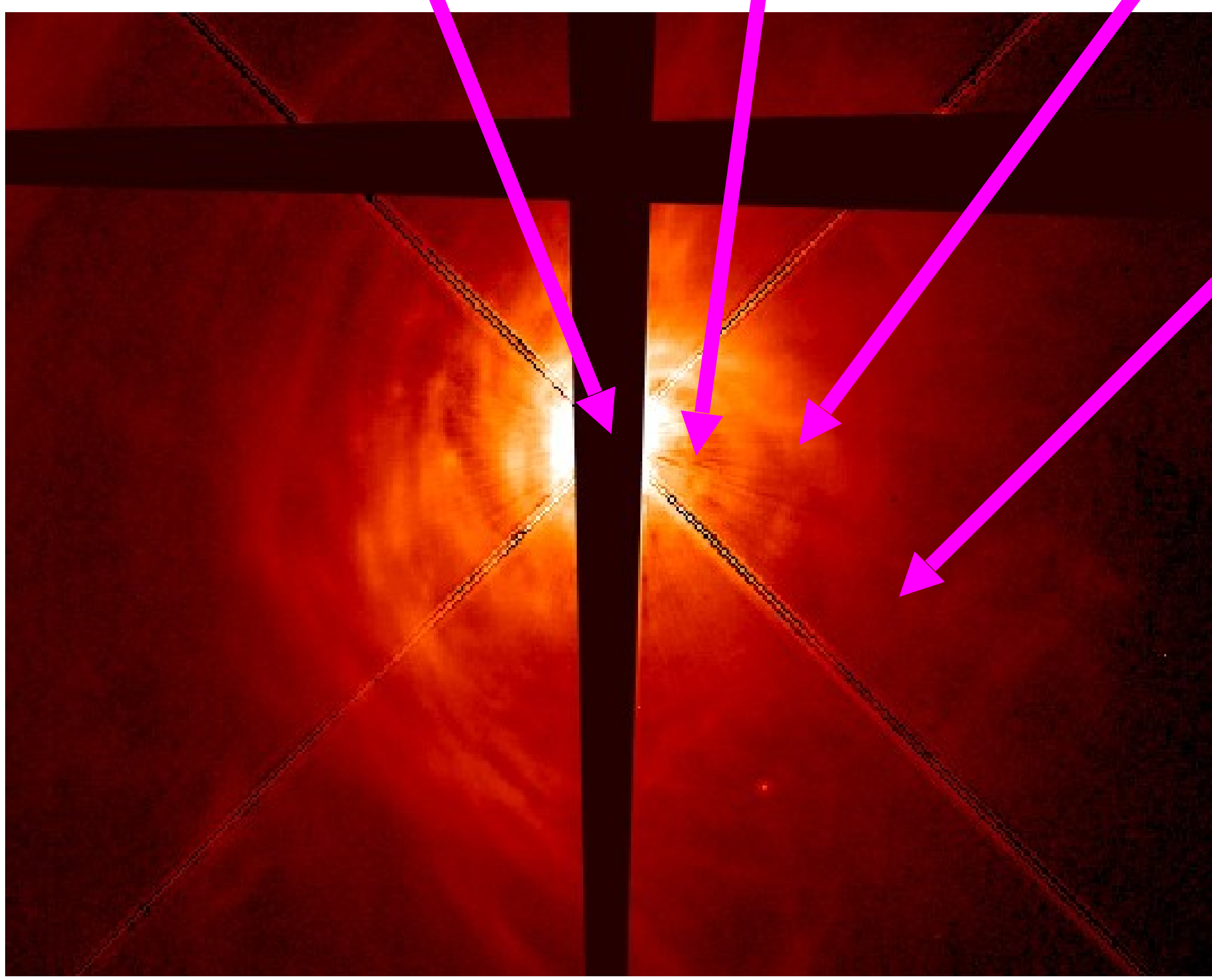


Look for disk features that trace structural changes probing disk evolution and for signposts of planets.

Williams & Cieza 2011

Scattered light imaging



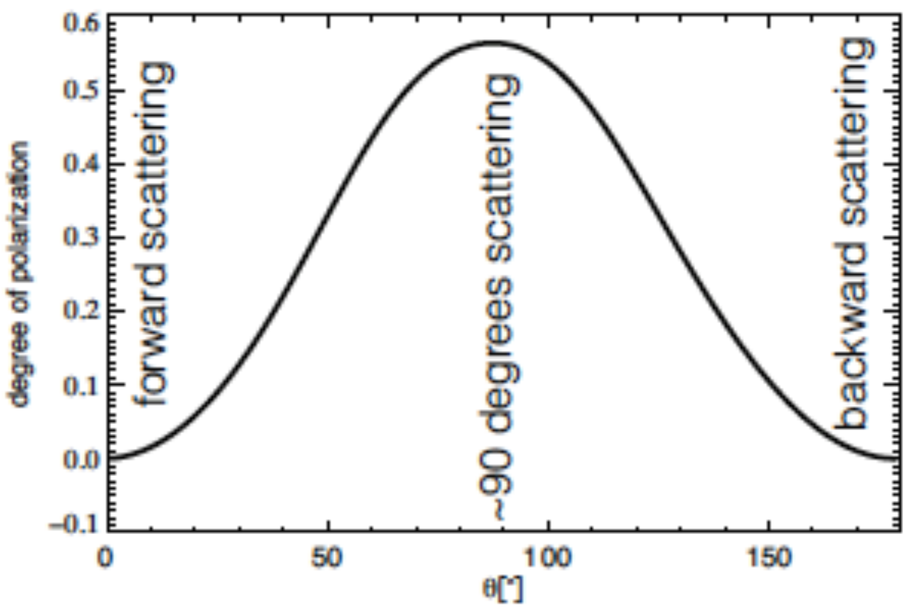


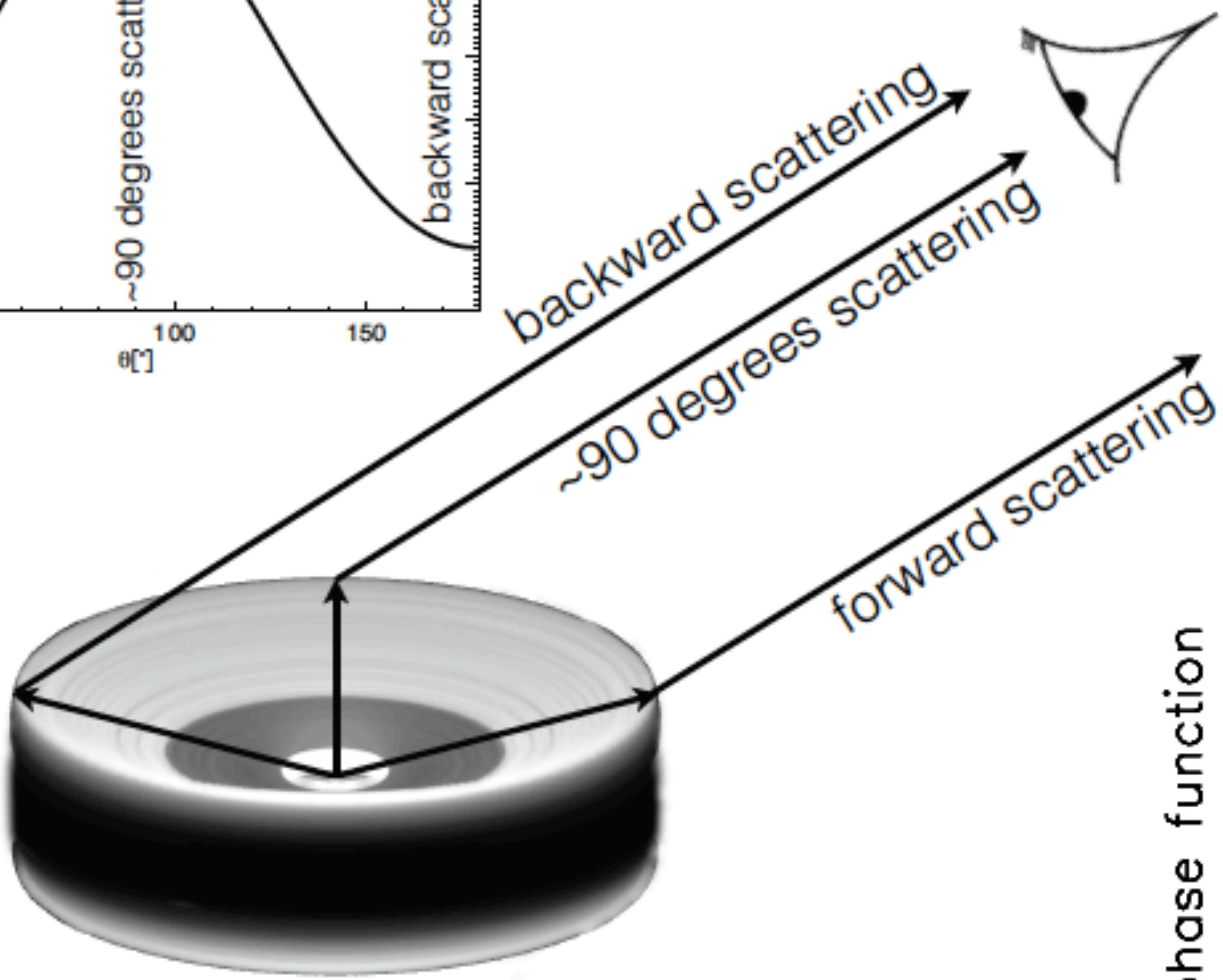
Grady et al. 1999

- Traces surface layers only.
- Stellar irradiation goes as r^{-2}
- Depends on the disk structure (e.g flaring, scale height).
- Scattered light is partly polarized.

Scattering & polarization efficiency

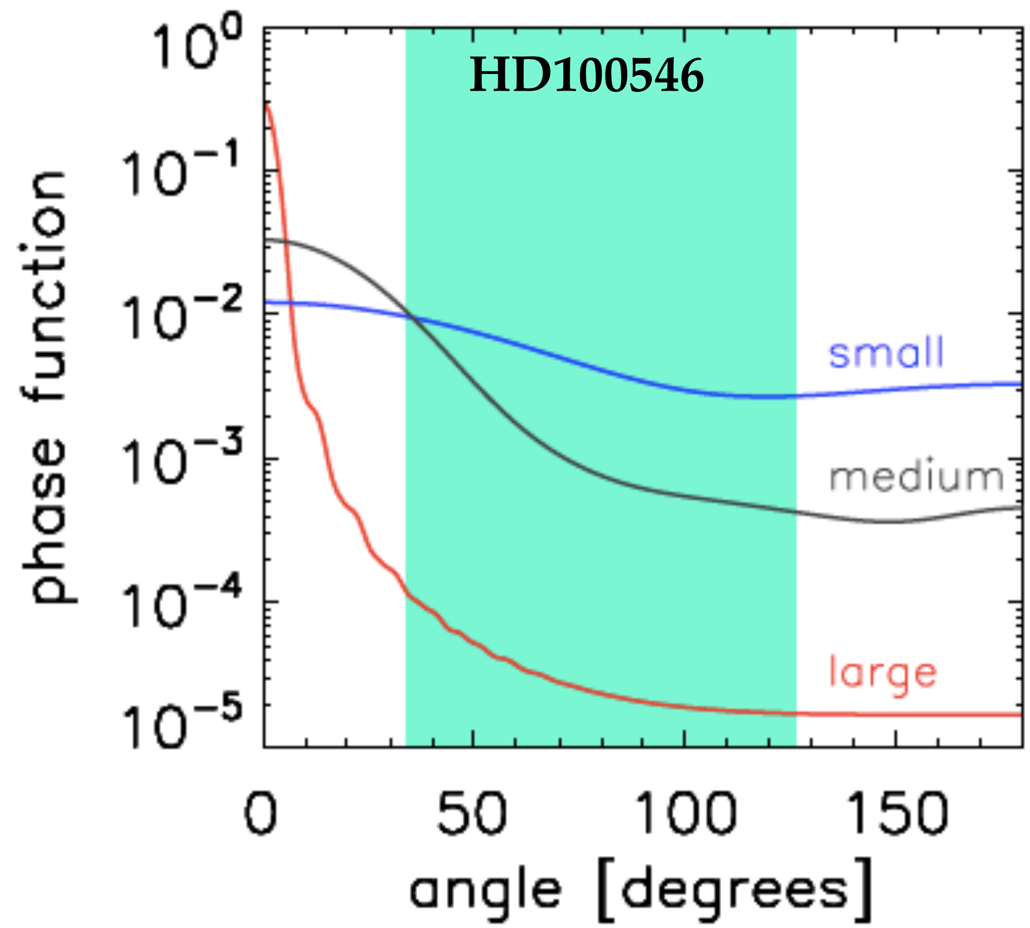
Min et al. 2015





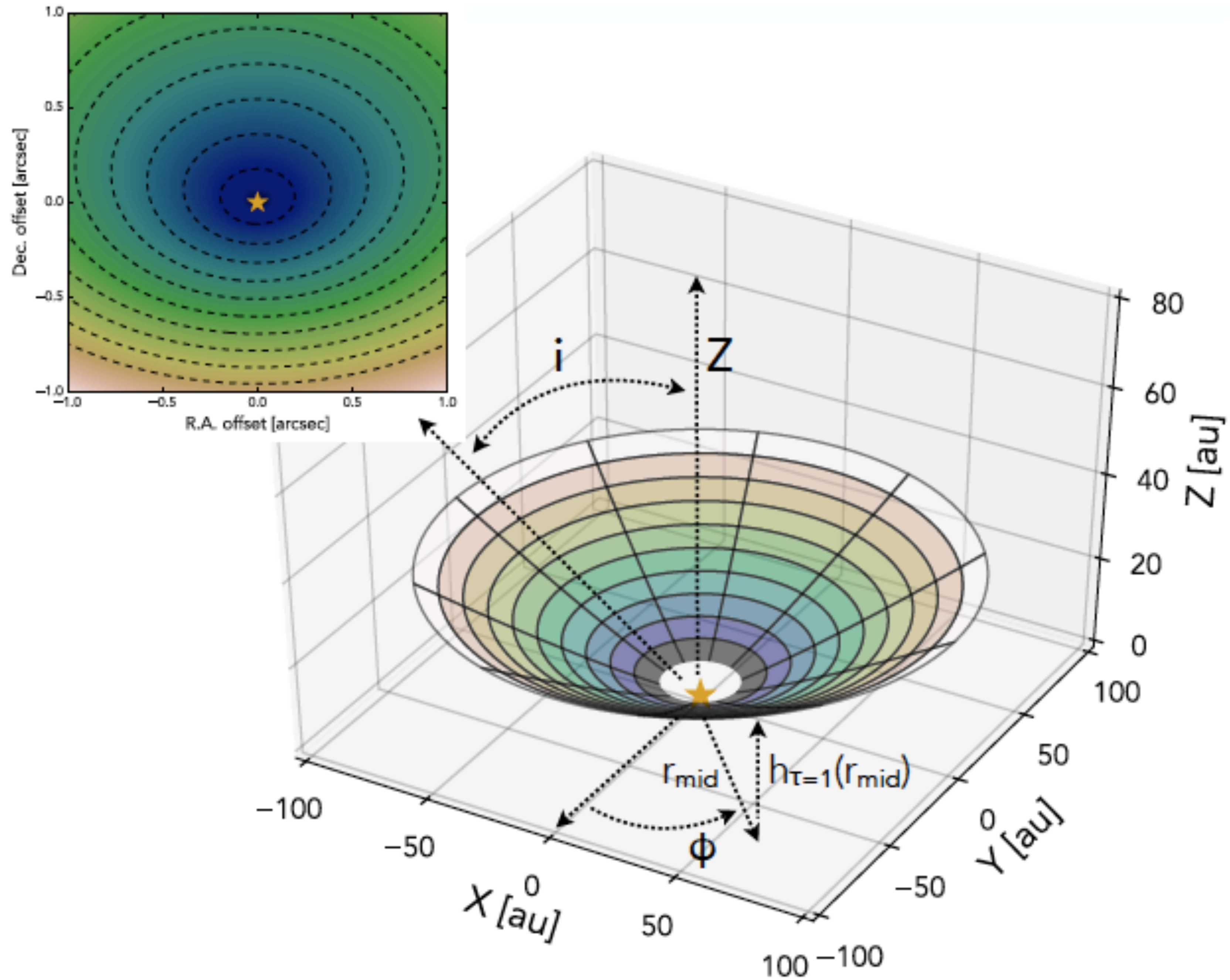
The angular distribution of scattered light by a dust grain …

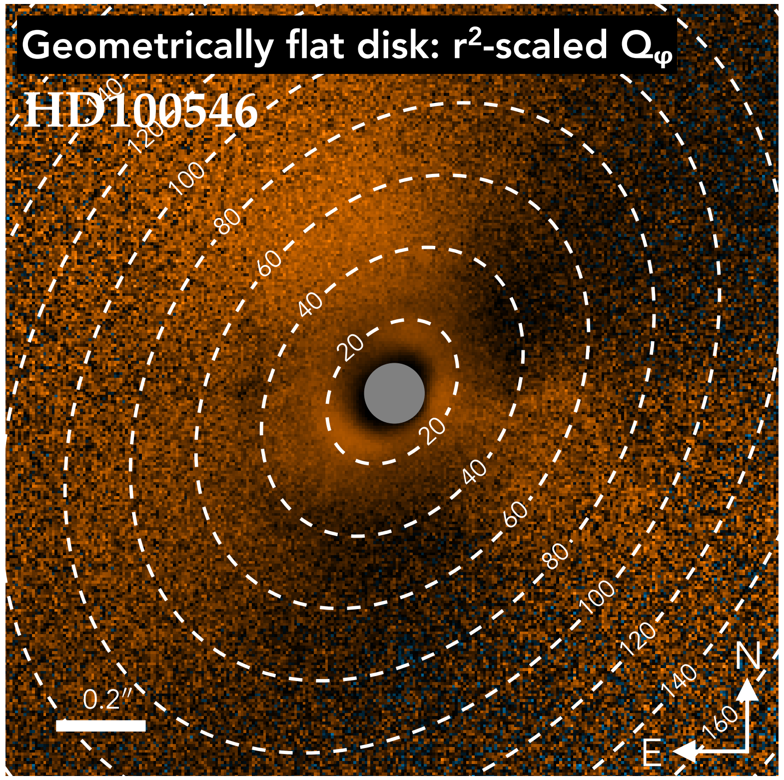
Mulders et al. 2013

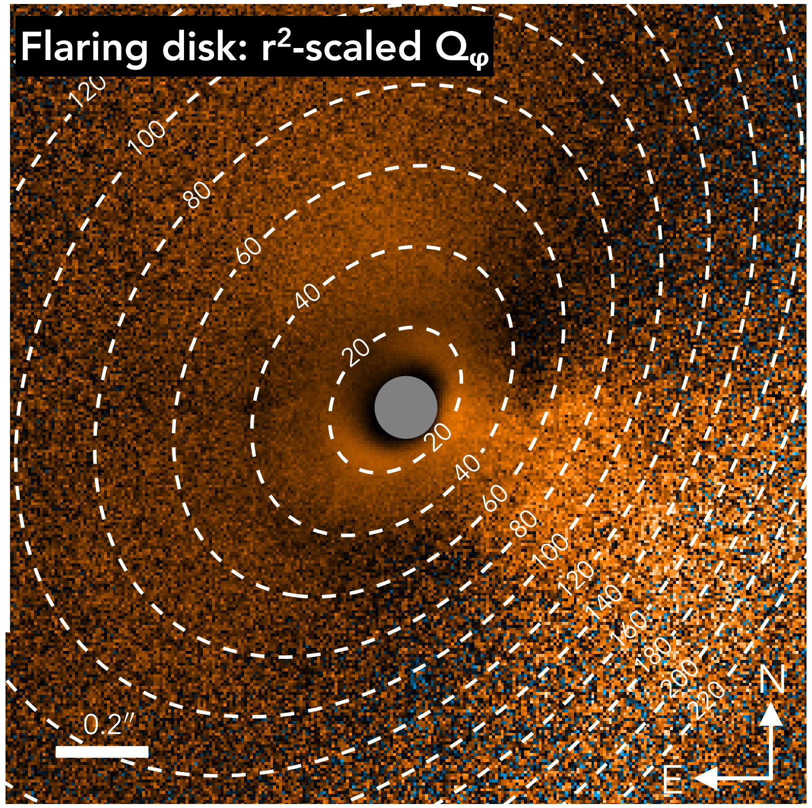


… depends on grain size, composition, porosity…

Projection effects

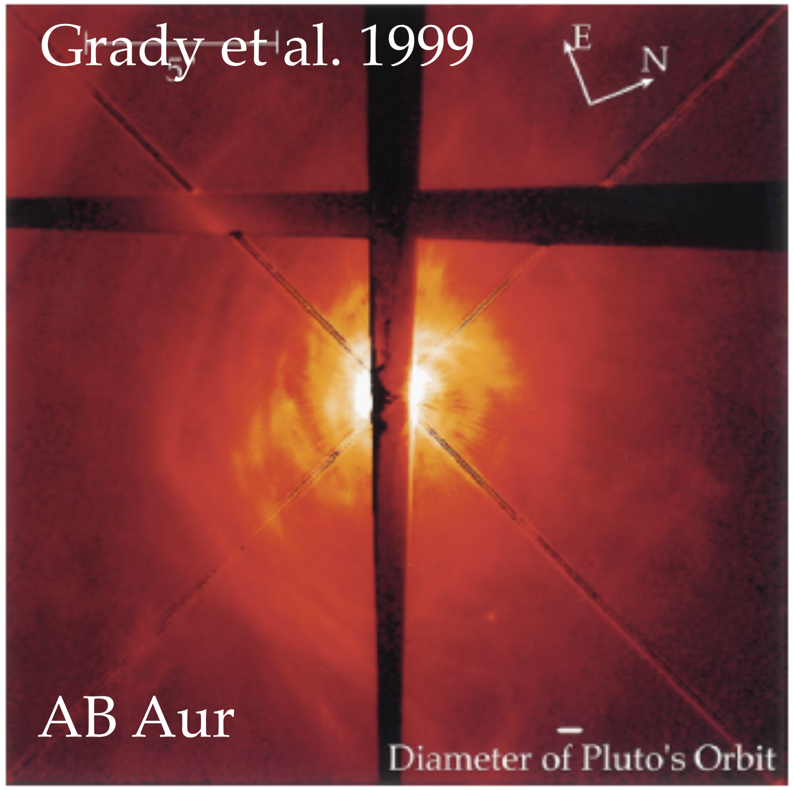


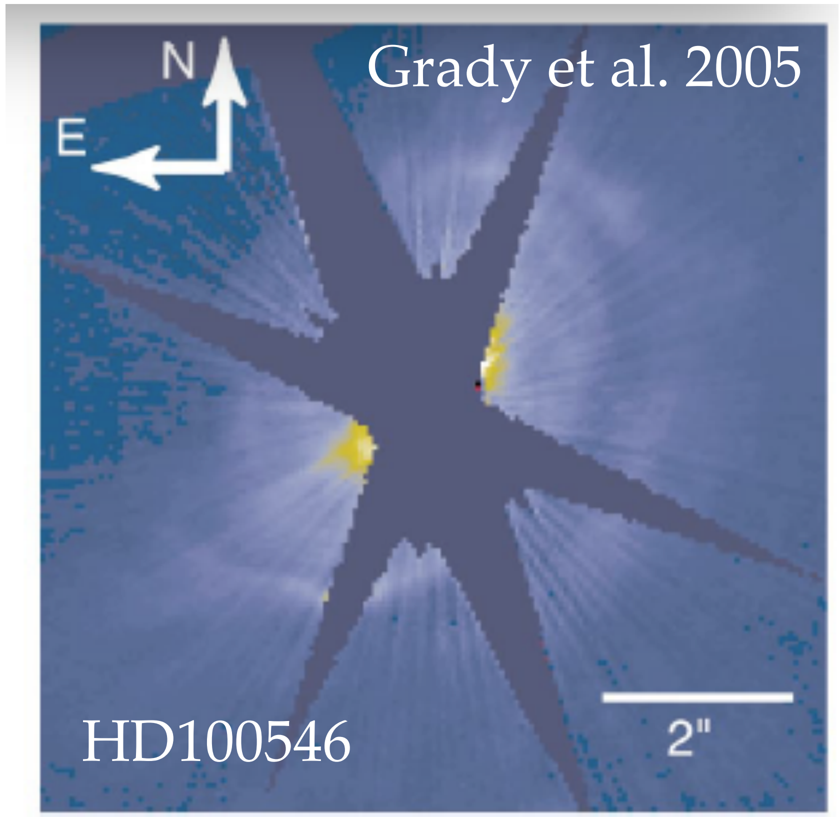


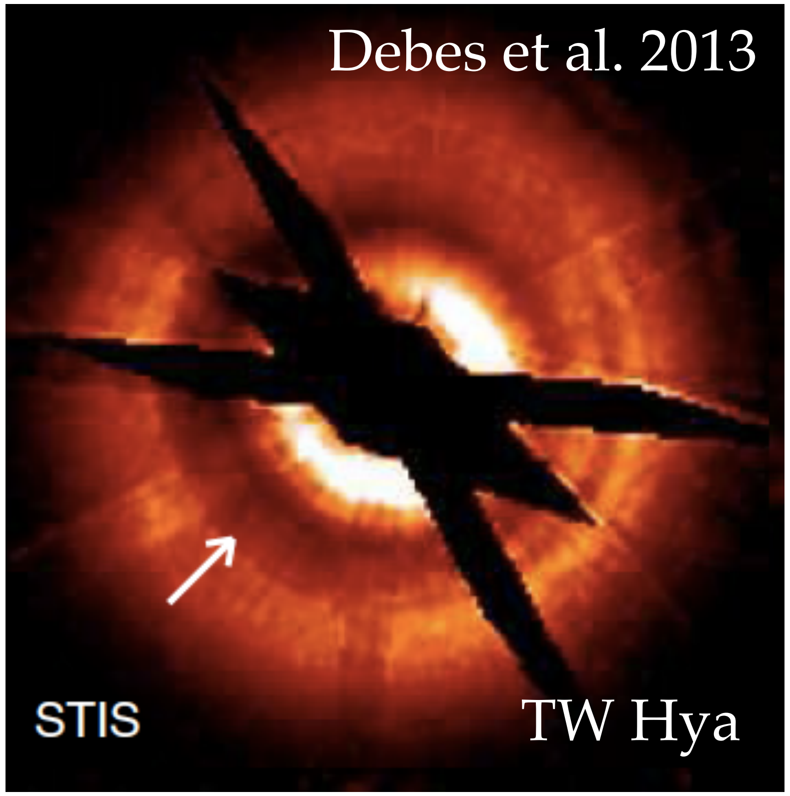


Stolker et al. 2016b. Also Mulders et al. 2013, Garufi et al. 2016

Large scale asymmetries







HST

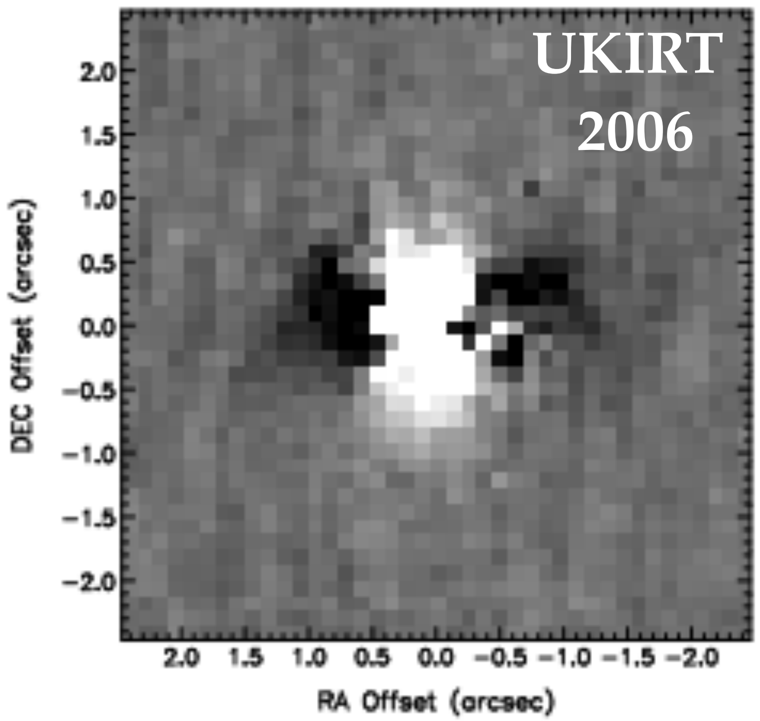
- Complex outer disk regions, large scale nebulosity in bright Herbig AeBe stars.
- Decreasing radial surface brightness.
- First asymmetries and evidence for gaps and cavities.

Weinberger et al. 1999, 2002; Grady et al. 2001, 2004; Roberge et al. 2005; Cox et al. 2013; Debes et al. 2016, 2017

Evolution of AO/data quality

HD169142

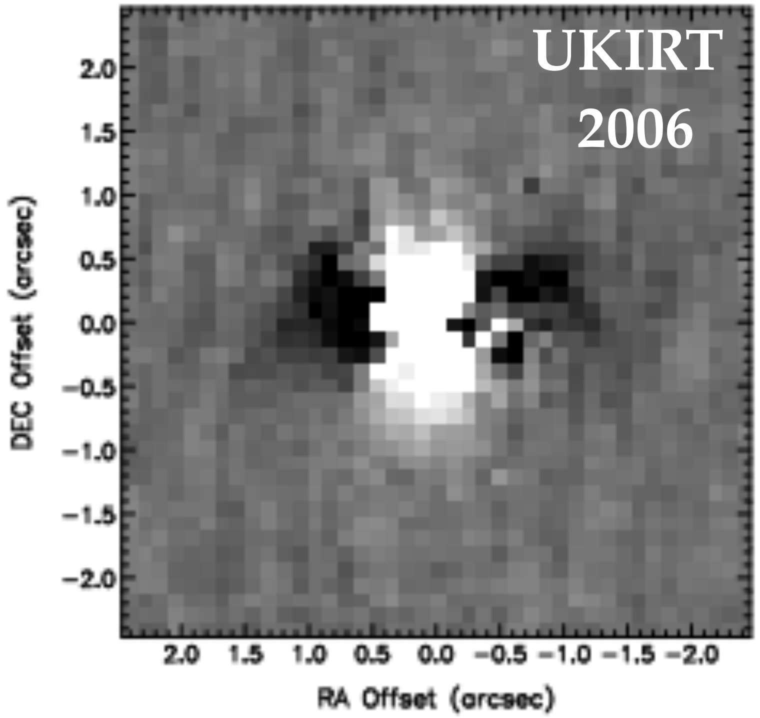
Hales et al. 2006



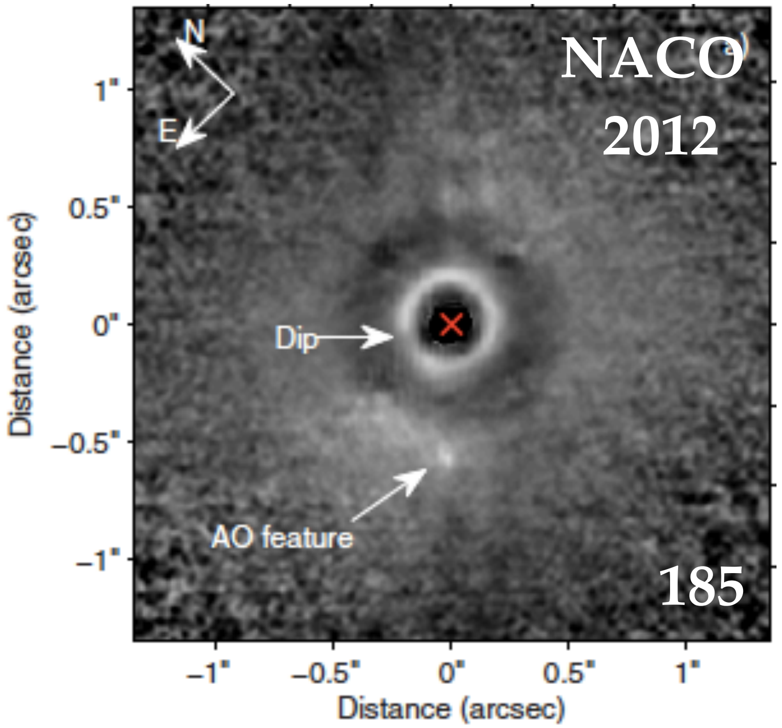
Evolution of AO/data quality

HD169142

Hales et al. 2006



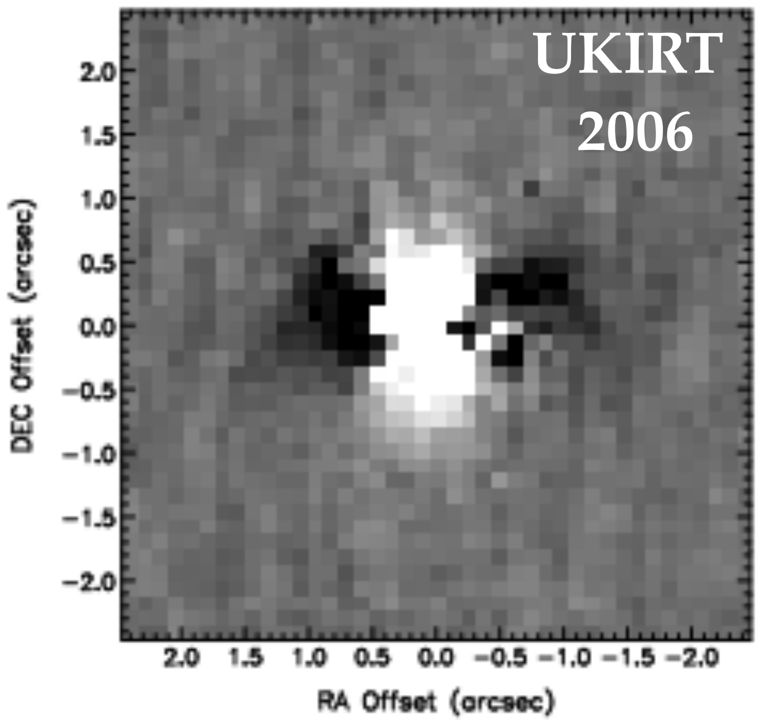
Quanz et al. 2013



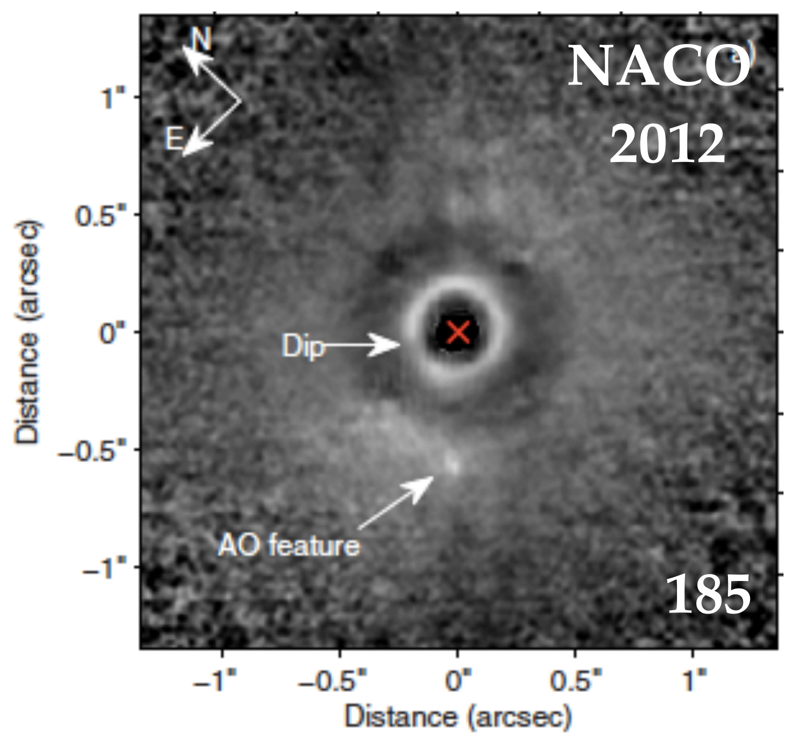
Evolution of AO/data quality

HD169142

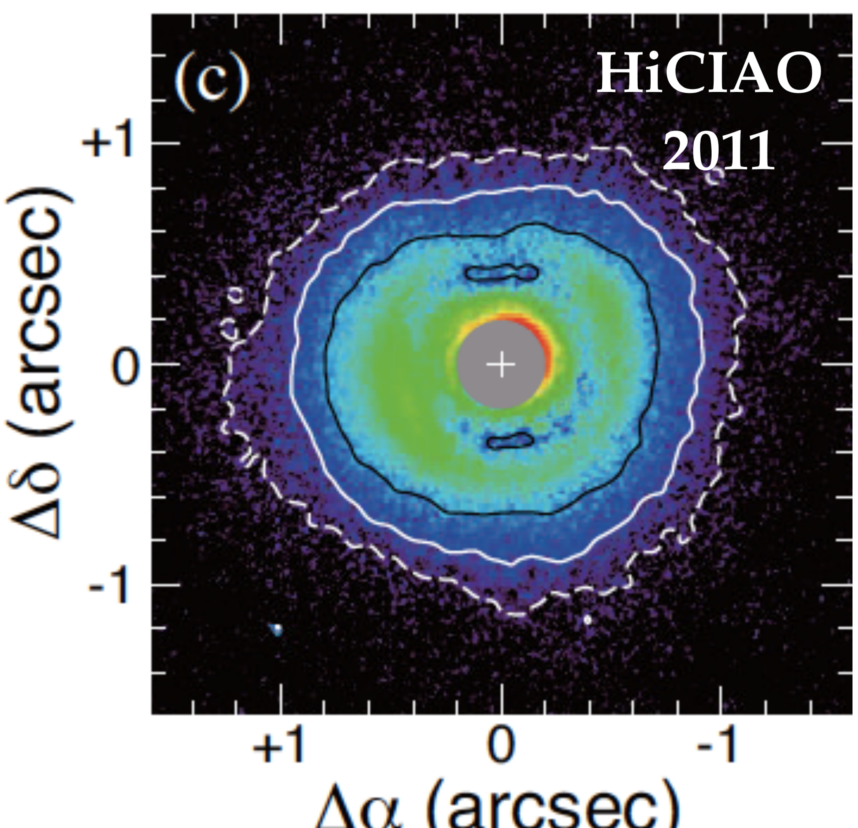
Hales et al. 2006



Quanz et al. 2013



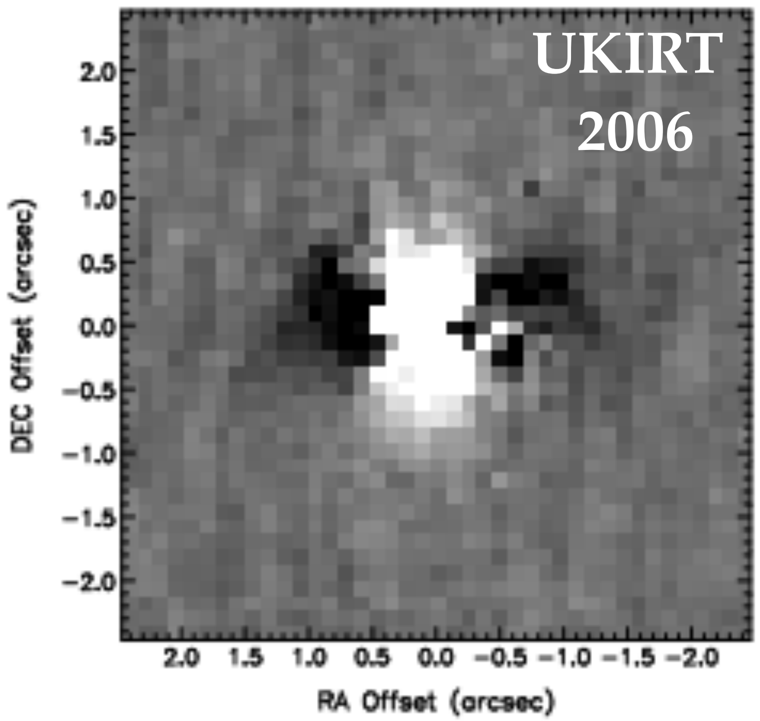
Momose et al. 2015



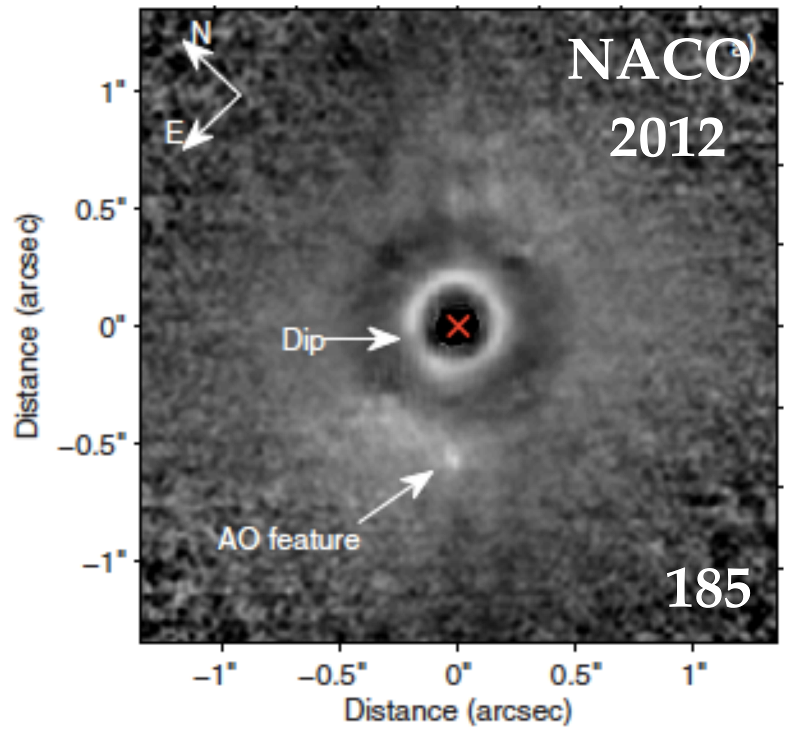
Evolution of AO/data quality

HD169142

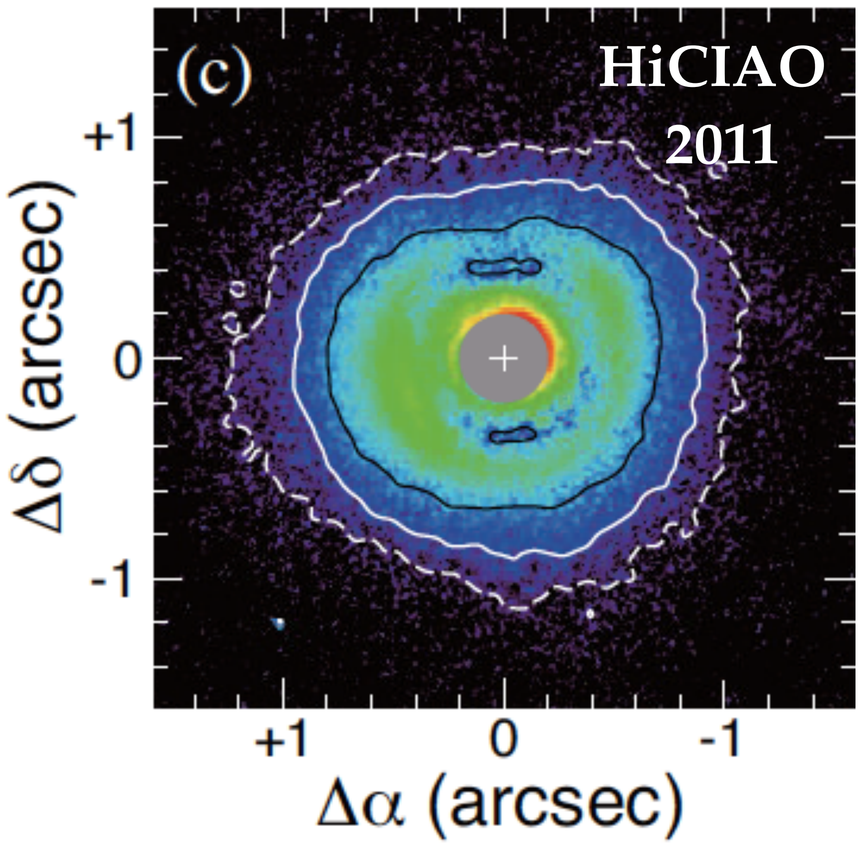
Hales et al. 2006



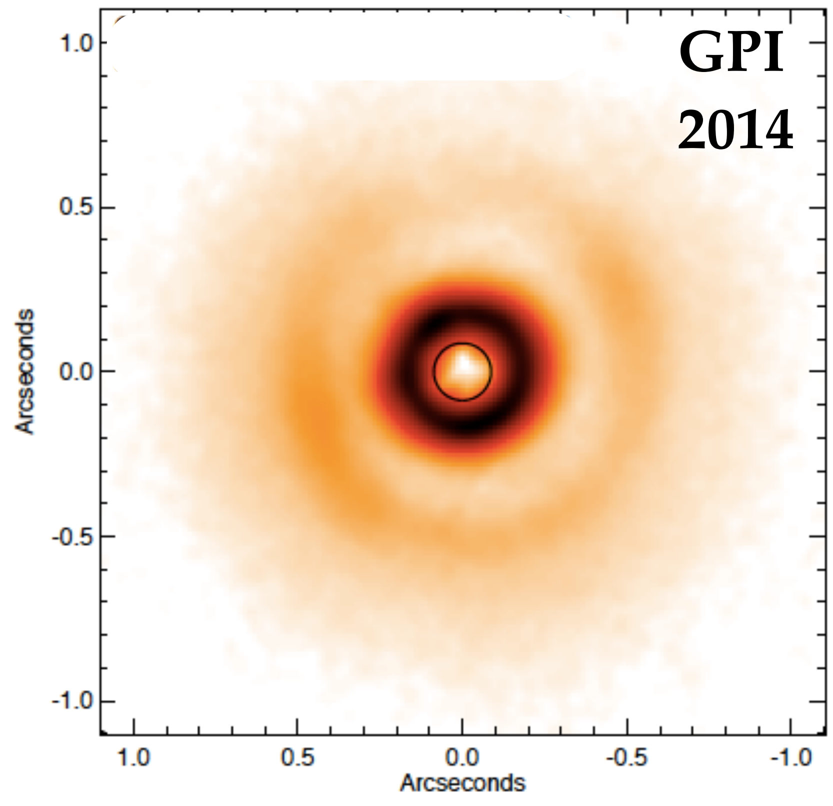
Quanz et al. 2013



Momose et al. 2015



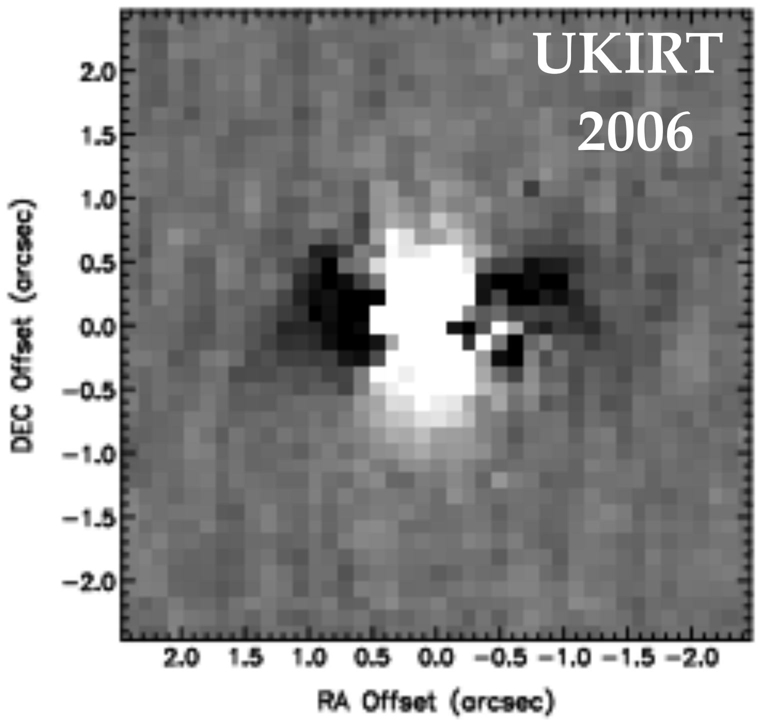
Monnier et al. 2017



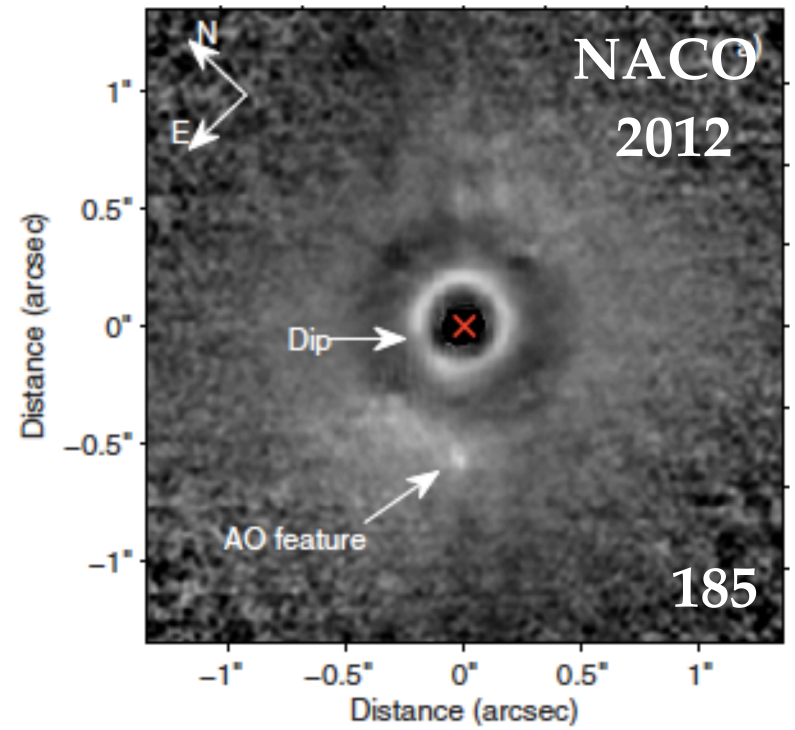
Evolution of AO/data quality

HD169142

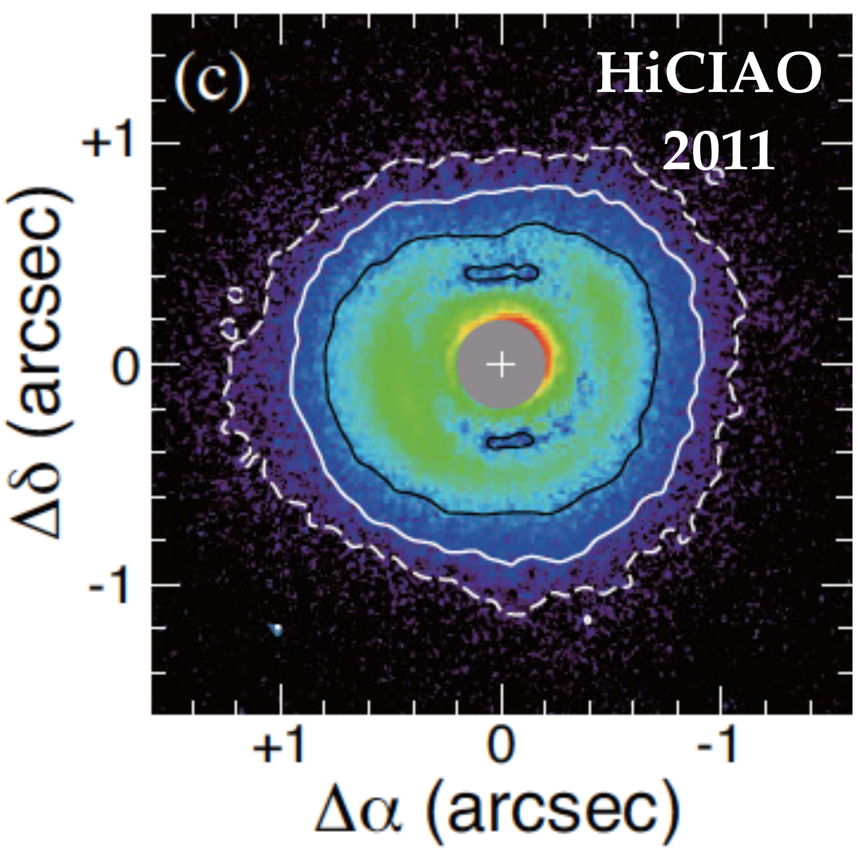
Hales et al. 2006



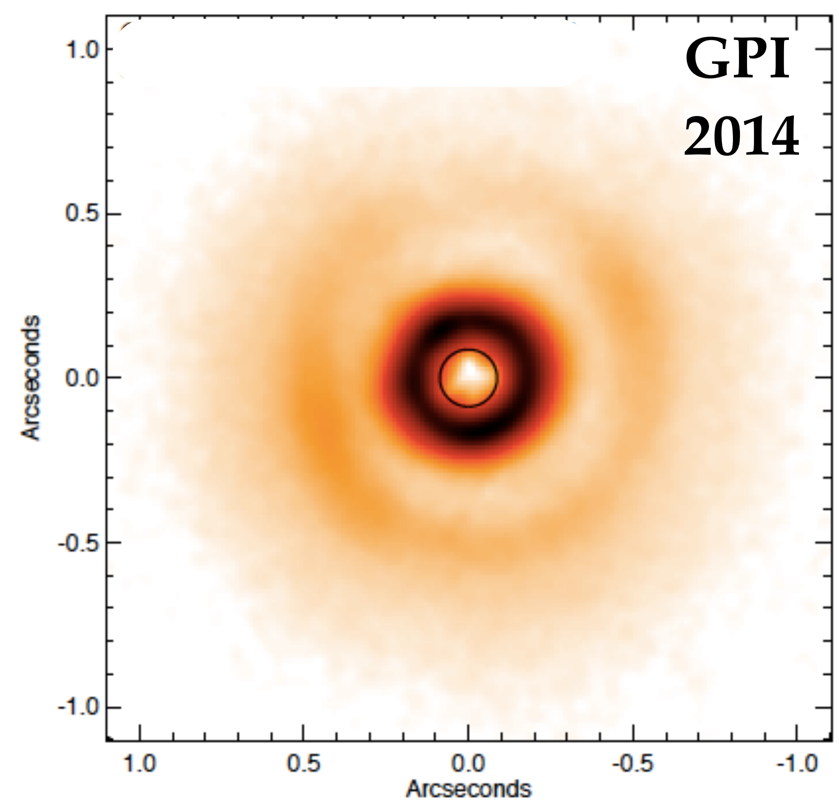
Quanz et al. 2013



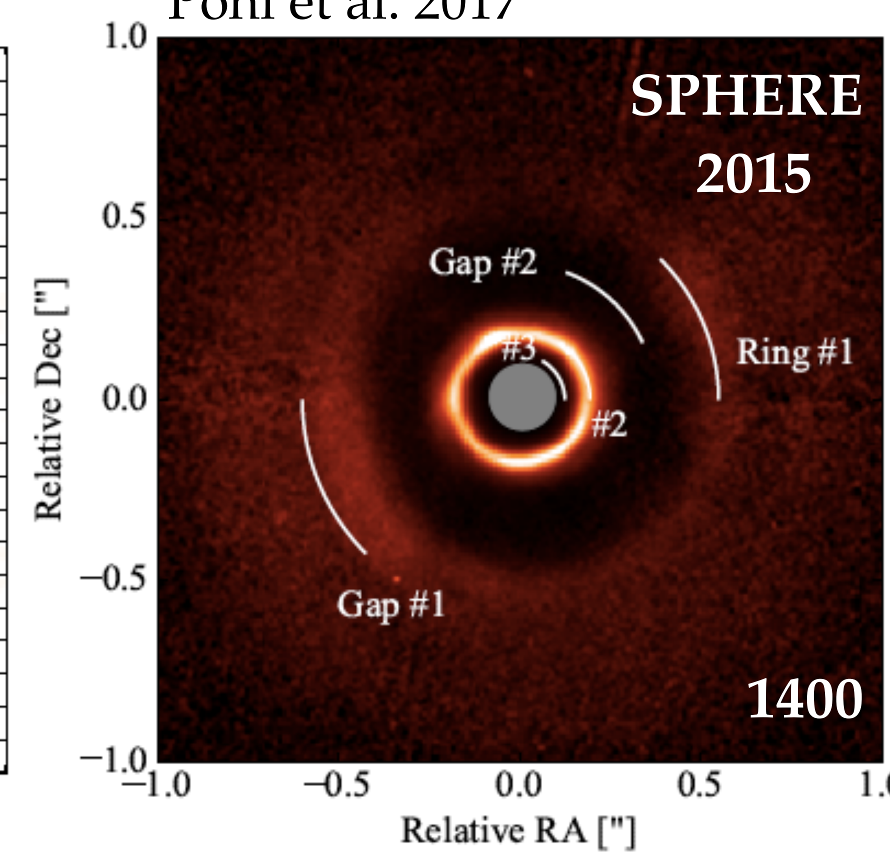
Momose et al. 2015



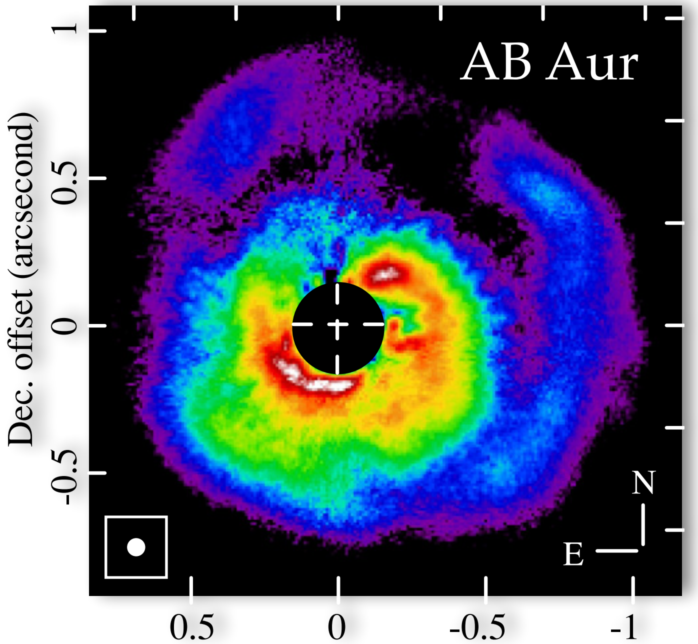
Monnier et al. 2017



Pohl et al. 2017

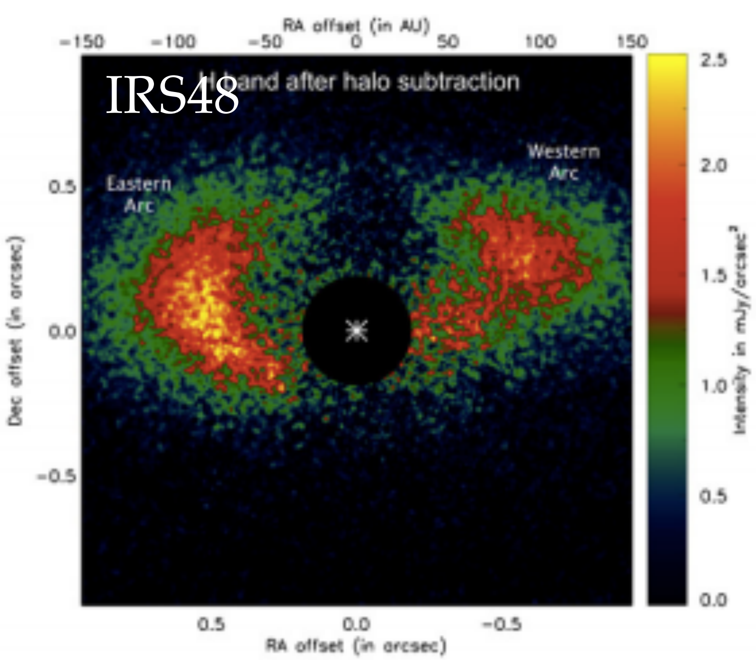


First PDI surveys

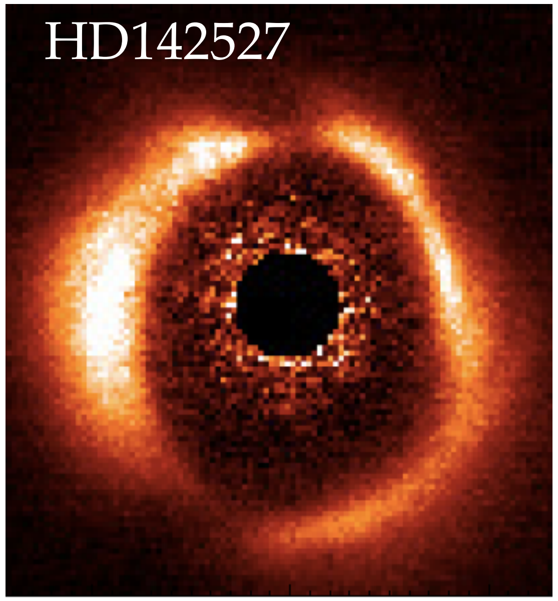


Hashimoto et al. 2011

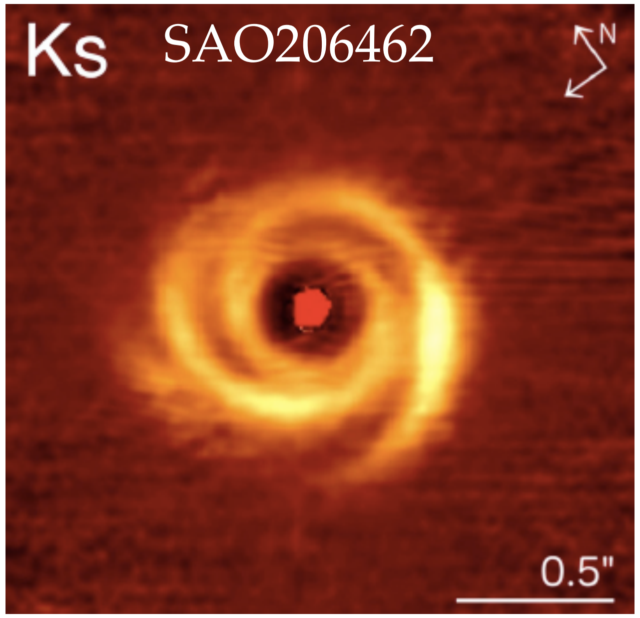
Observations of Herbig AeBe stars with Naco/VLT and HiCIAO/Subaru at high resolution show more complex features on the brightest disks.



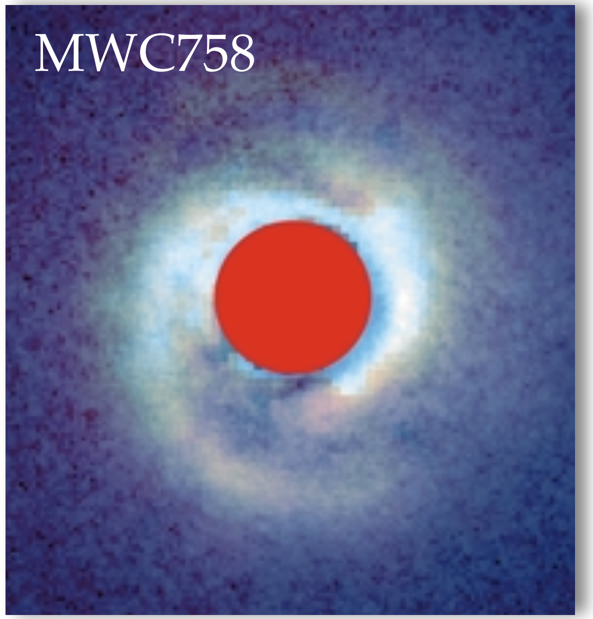
Folette et al. 2015



Canovas et al 2013



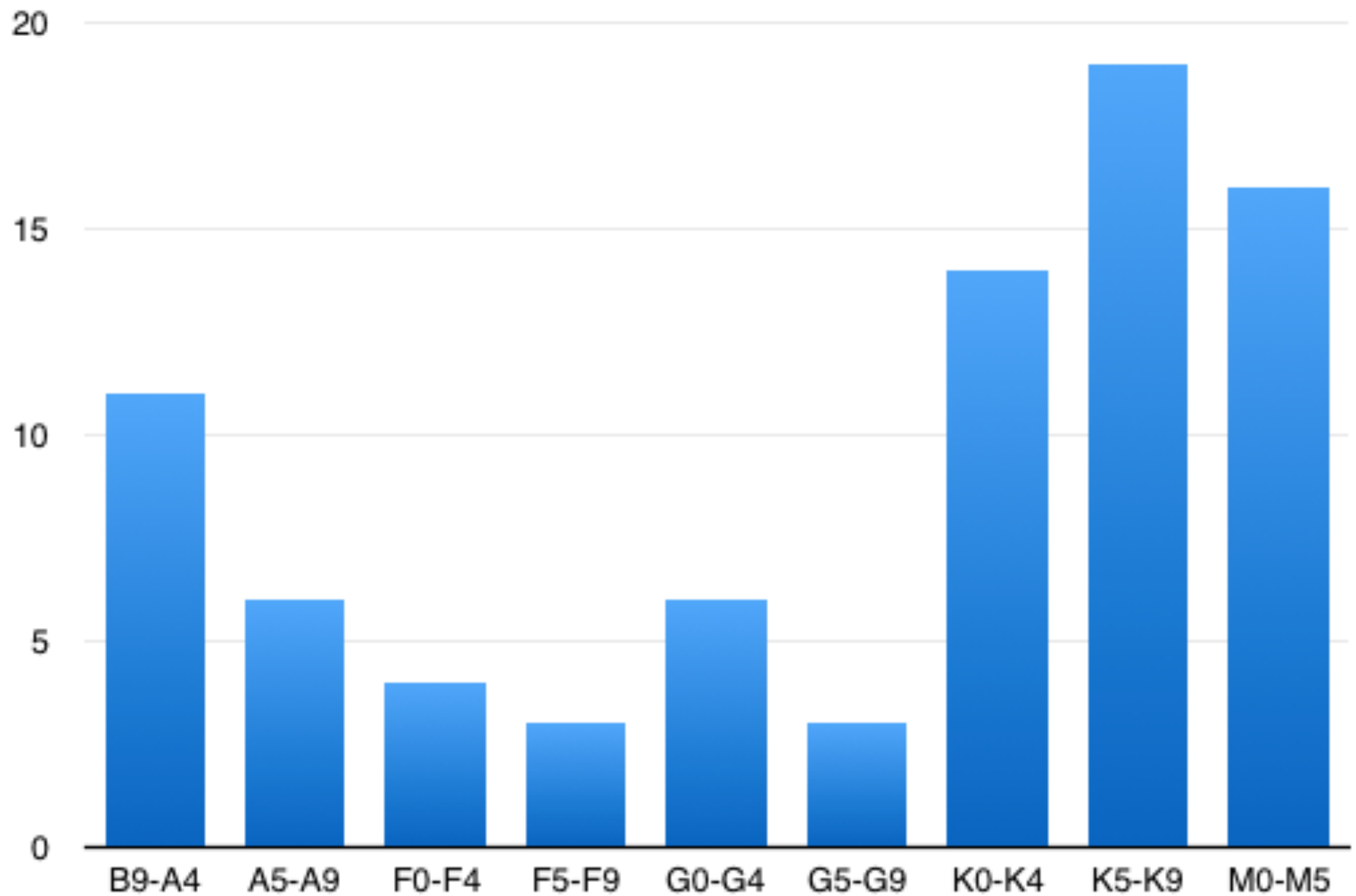
Garufi et al 2013



Grady et al 2013

Also Fukagawa et al. 2006; Hashimoto et al. 2011; Quanz et al. 2011,2012; Muto et al. 2012; Kusakabe et al 2012; Folette et al. 2013; Avenhaus et al. 2014; Garufi et al. 2014, and many more.

Disks observed with XAO



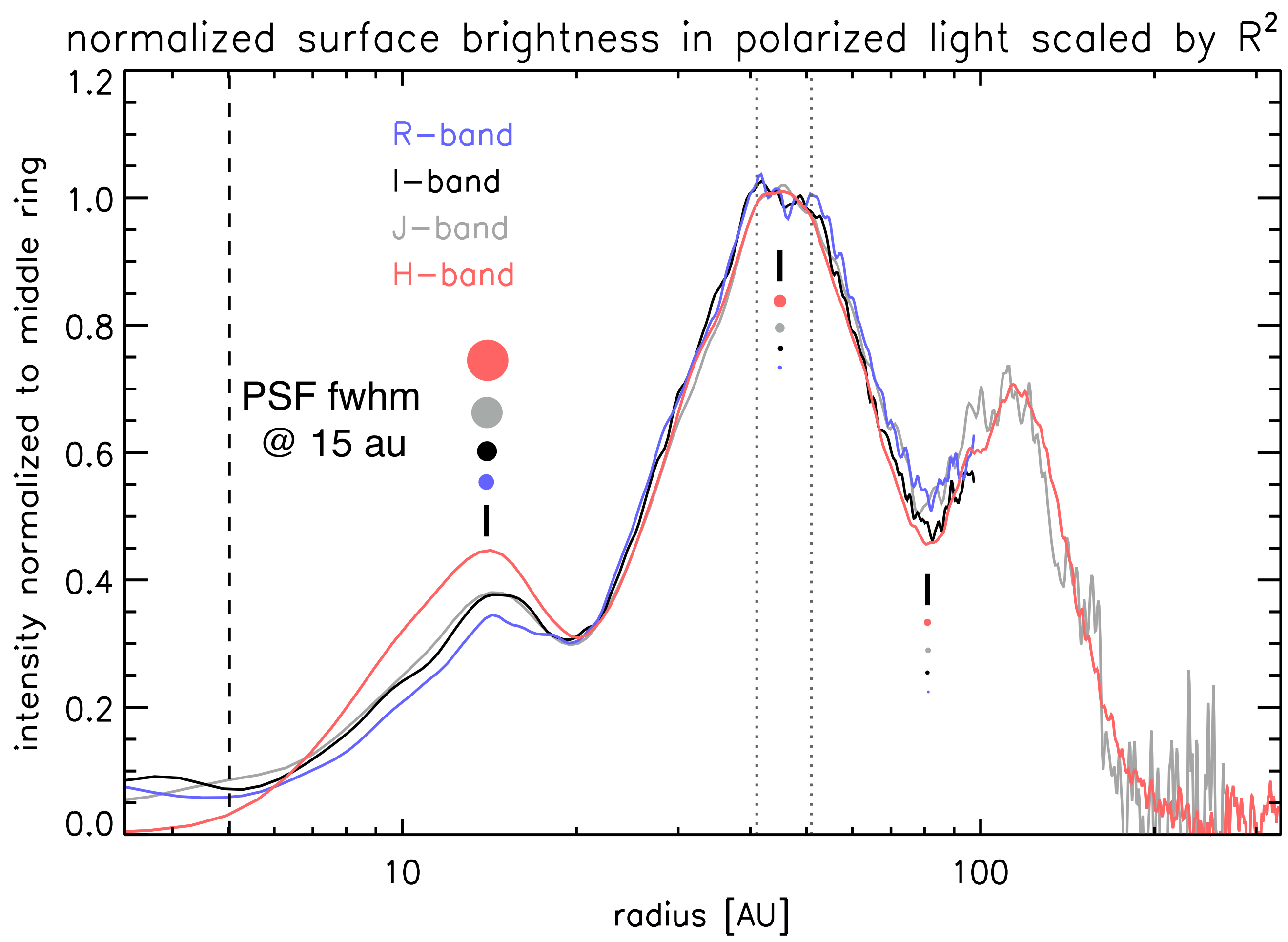
~100 objects covering a large spectral range.

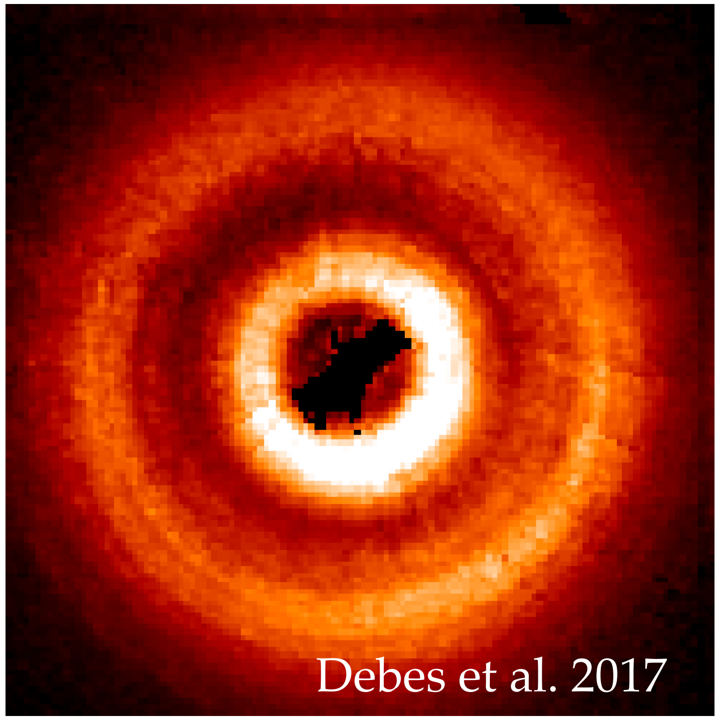
An incomplete histogram!

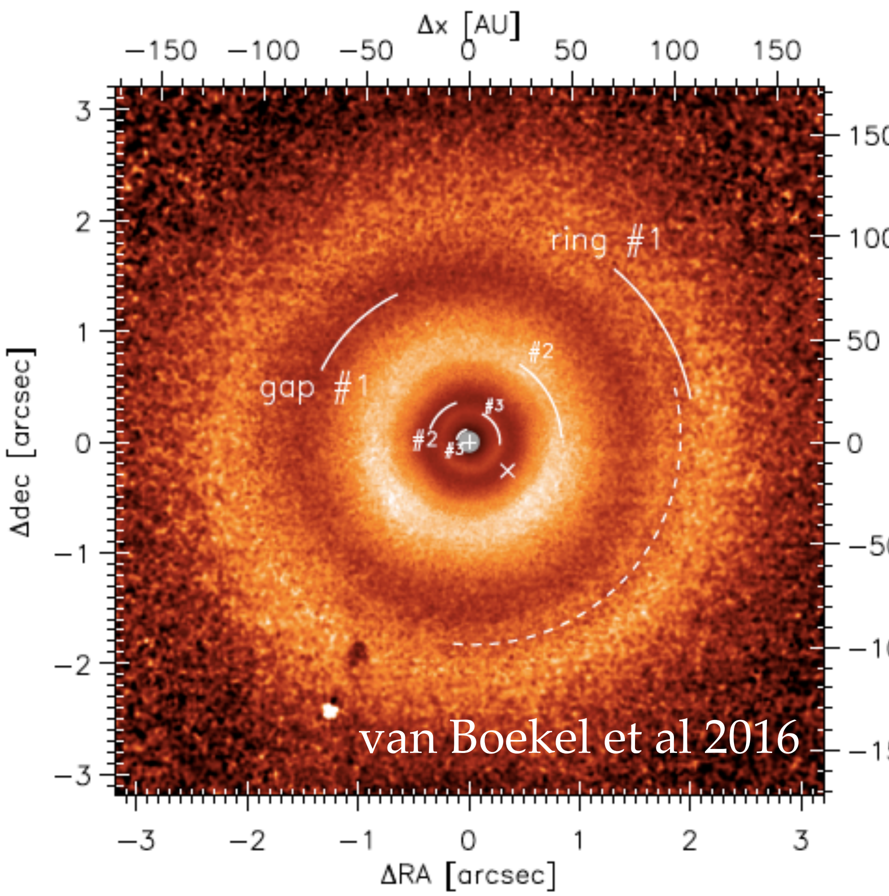
Multiple rings

TW Hya

Gap @ 6 au, 20 au, 80 au

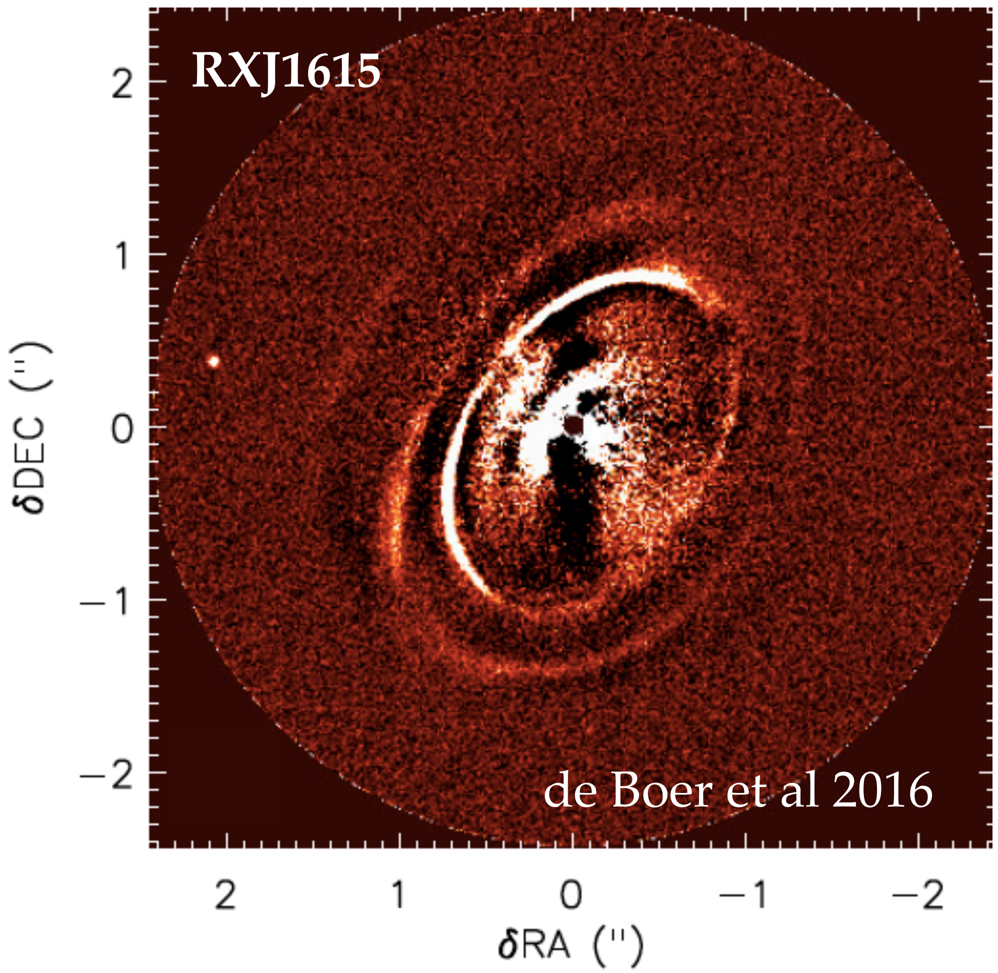


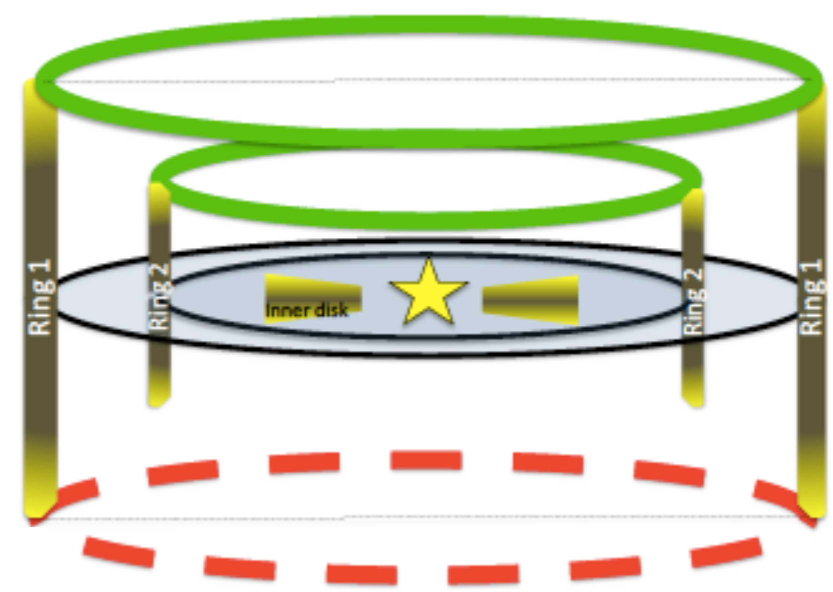




Debes et al. 2013, Akiyama et al. 2015, Rapson et al. 2015a,b.

Multiple inclined rings



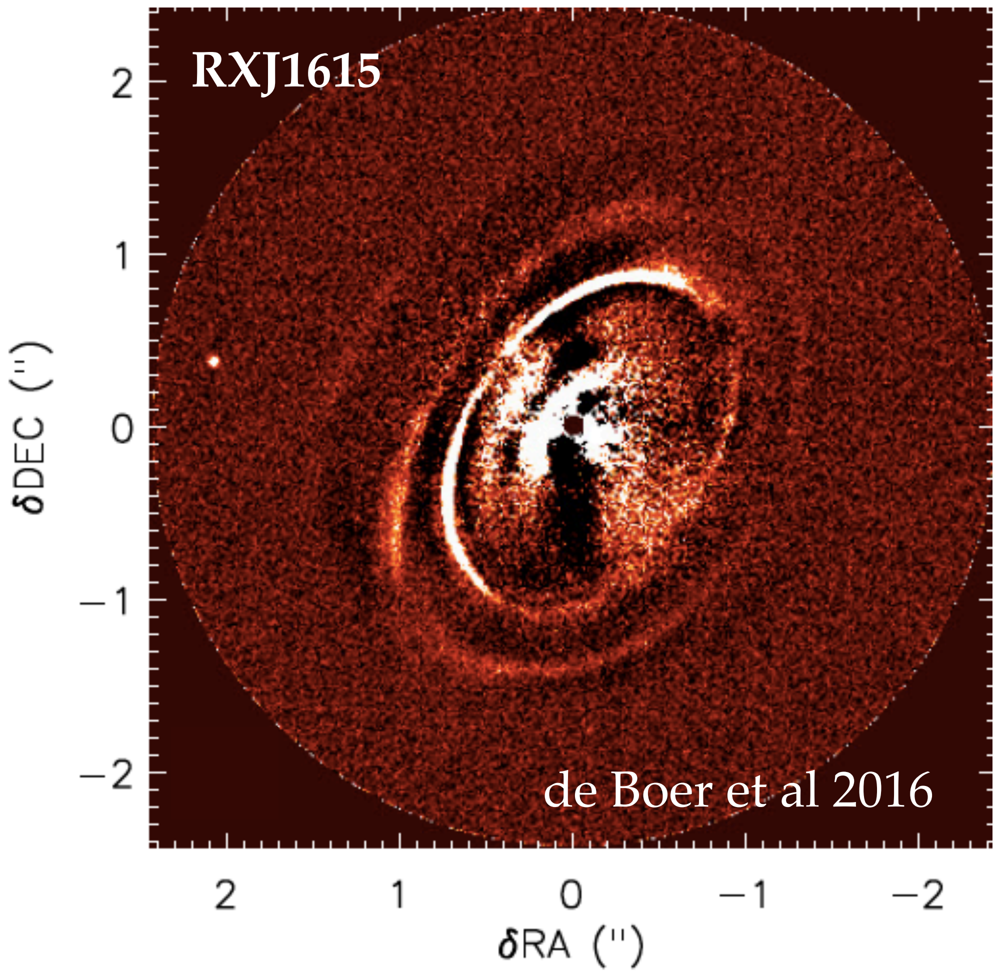


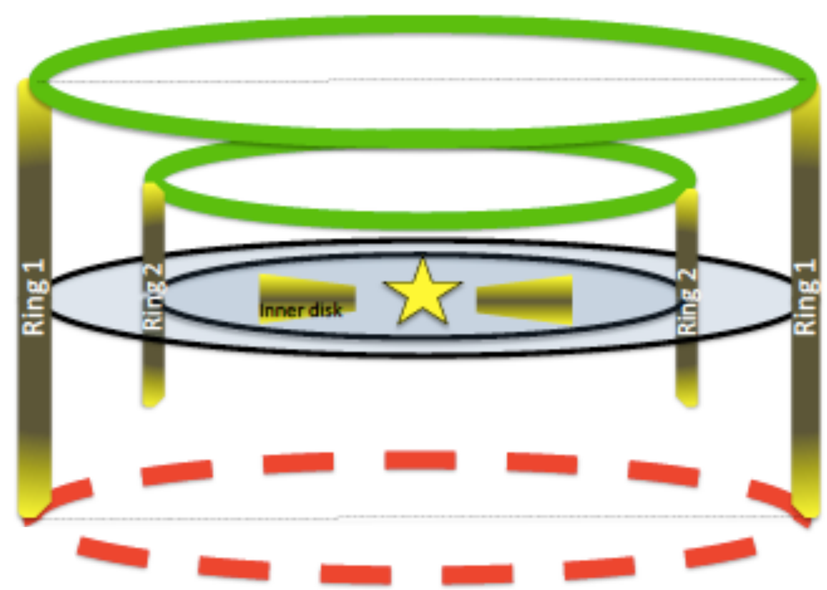
- An inner disk (up to ~56 au) and two rings (196 au; 278 au).

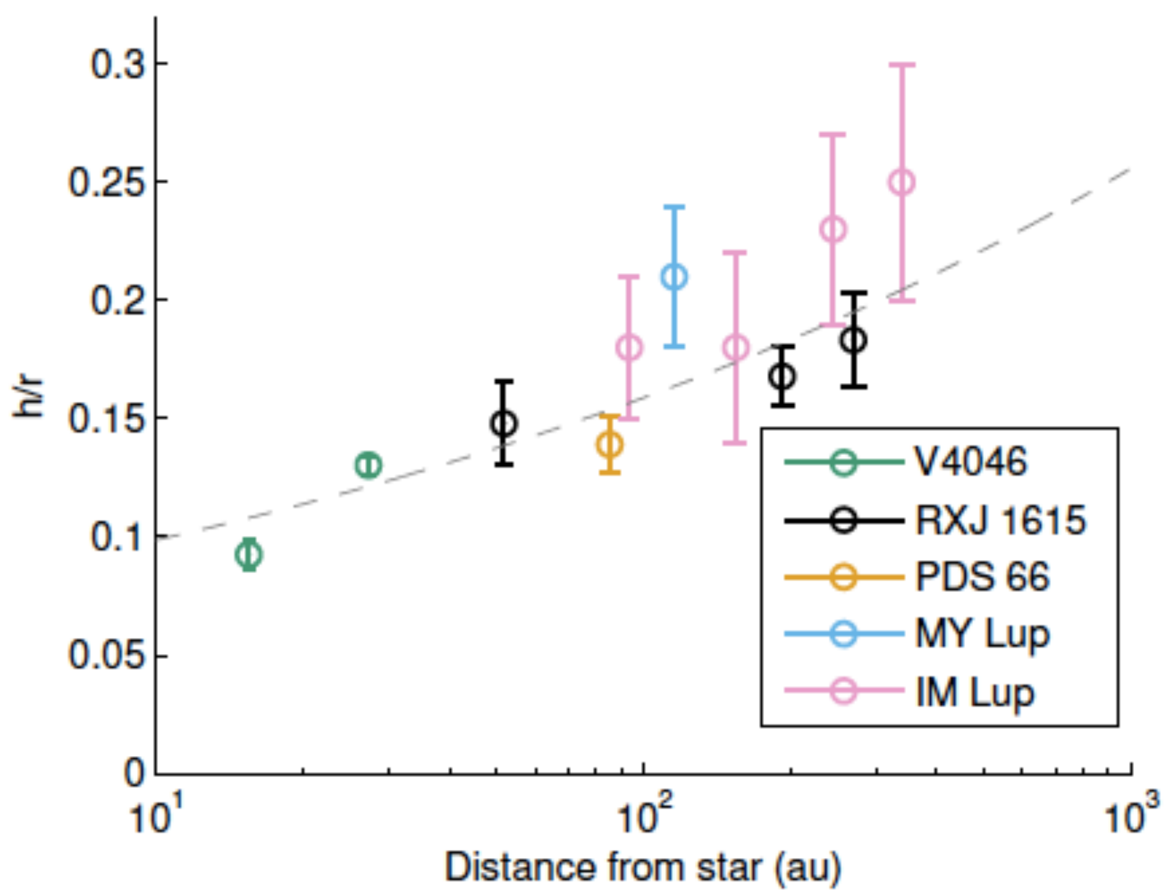
- Apparent offset provides the shape of the scattering surface

Avenhaus et al. 2018

Multiple inclined rings



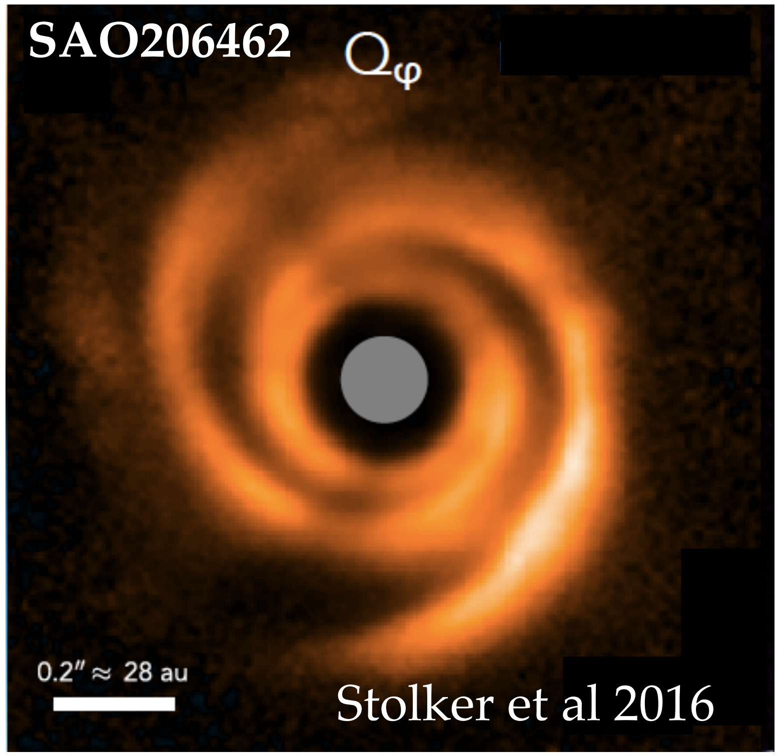




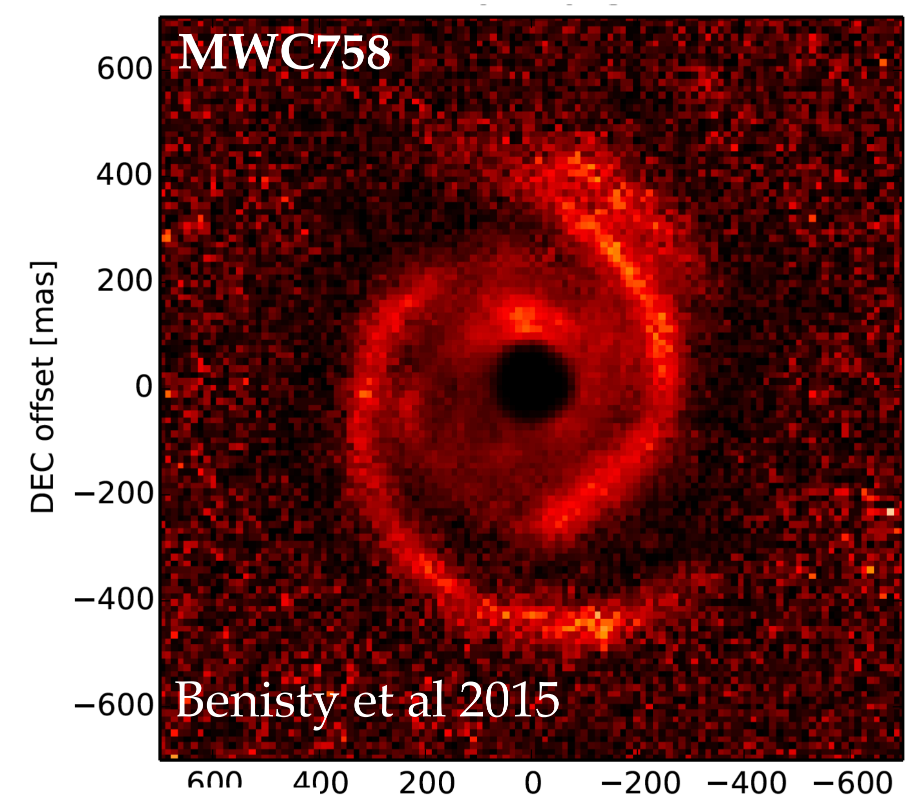
Avenhaus et al. 2018

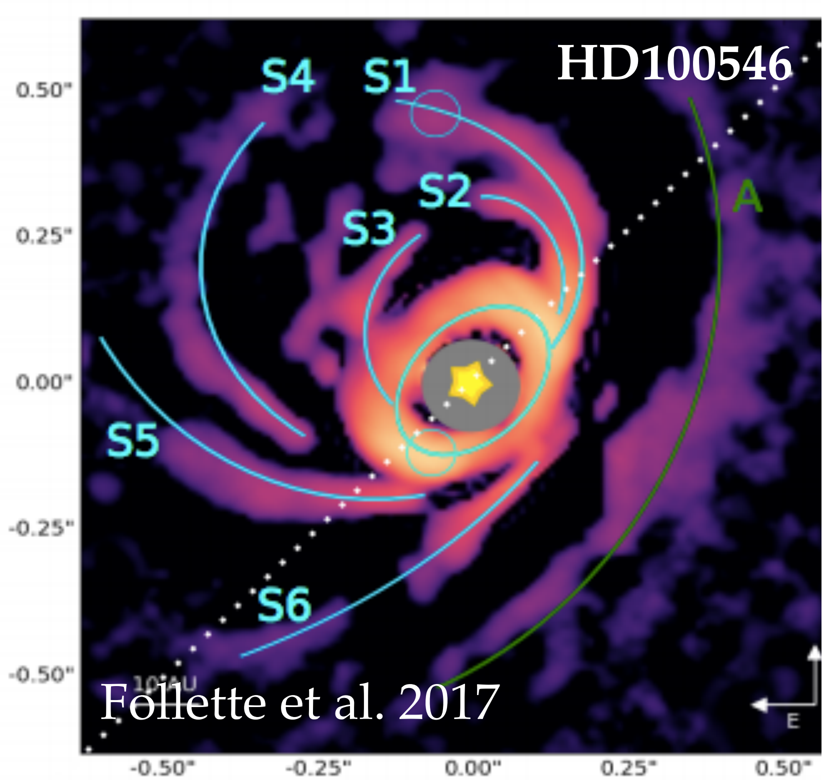
- An inner disk (up to ~56 au) and two rings (196 au; 278 au).
- Apparent offset provides the shape of the scattering surface

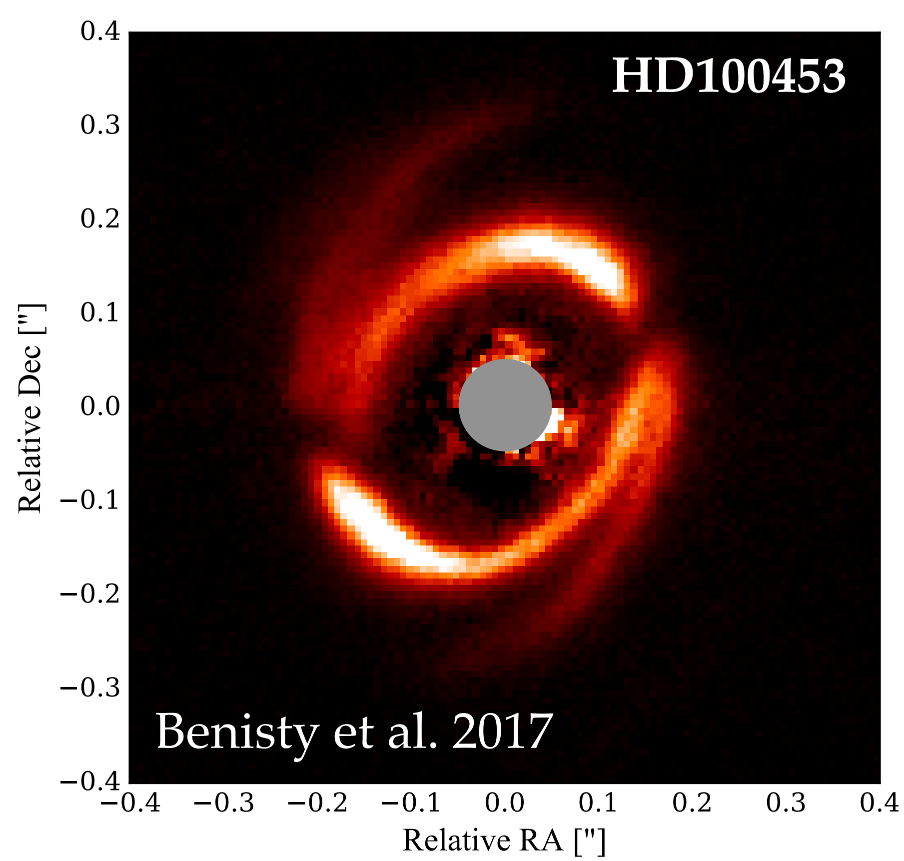
Spiral arms

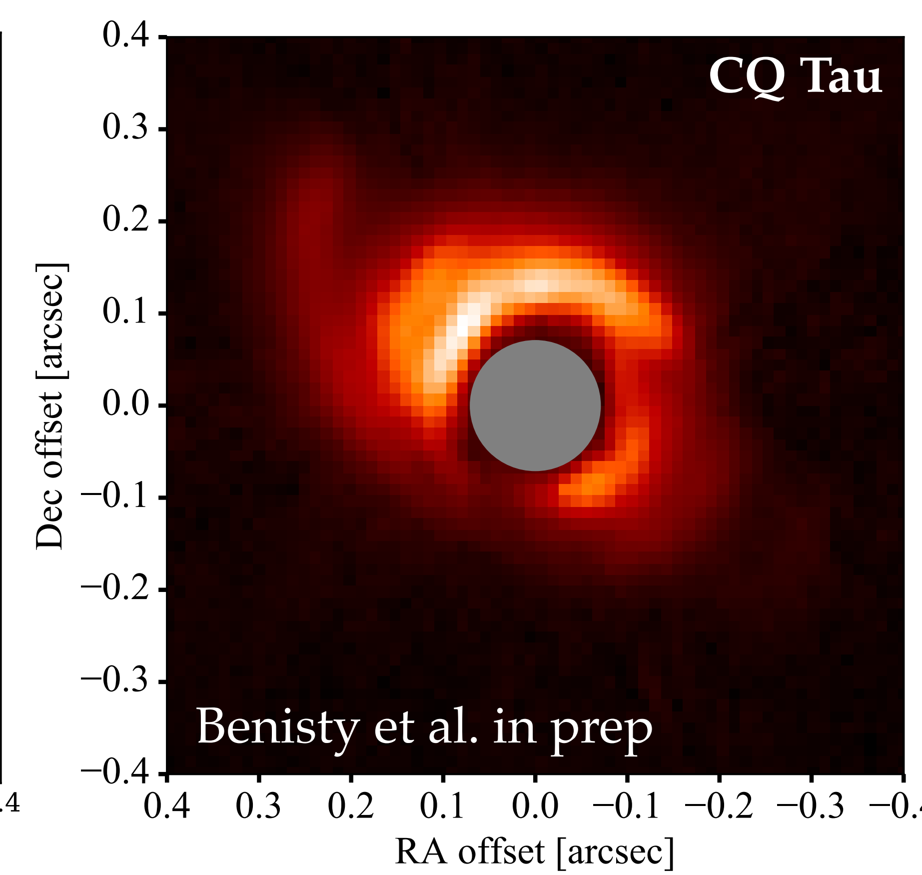


- All are Herbig stars transition disks
- Show 2 or more arms
- Some also have shadows

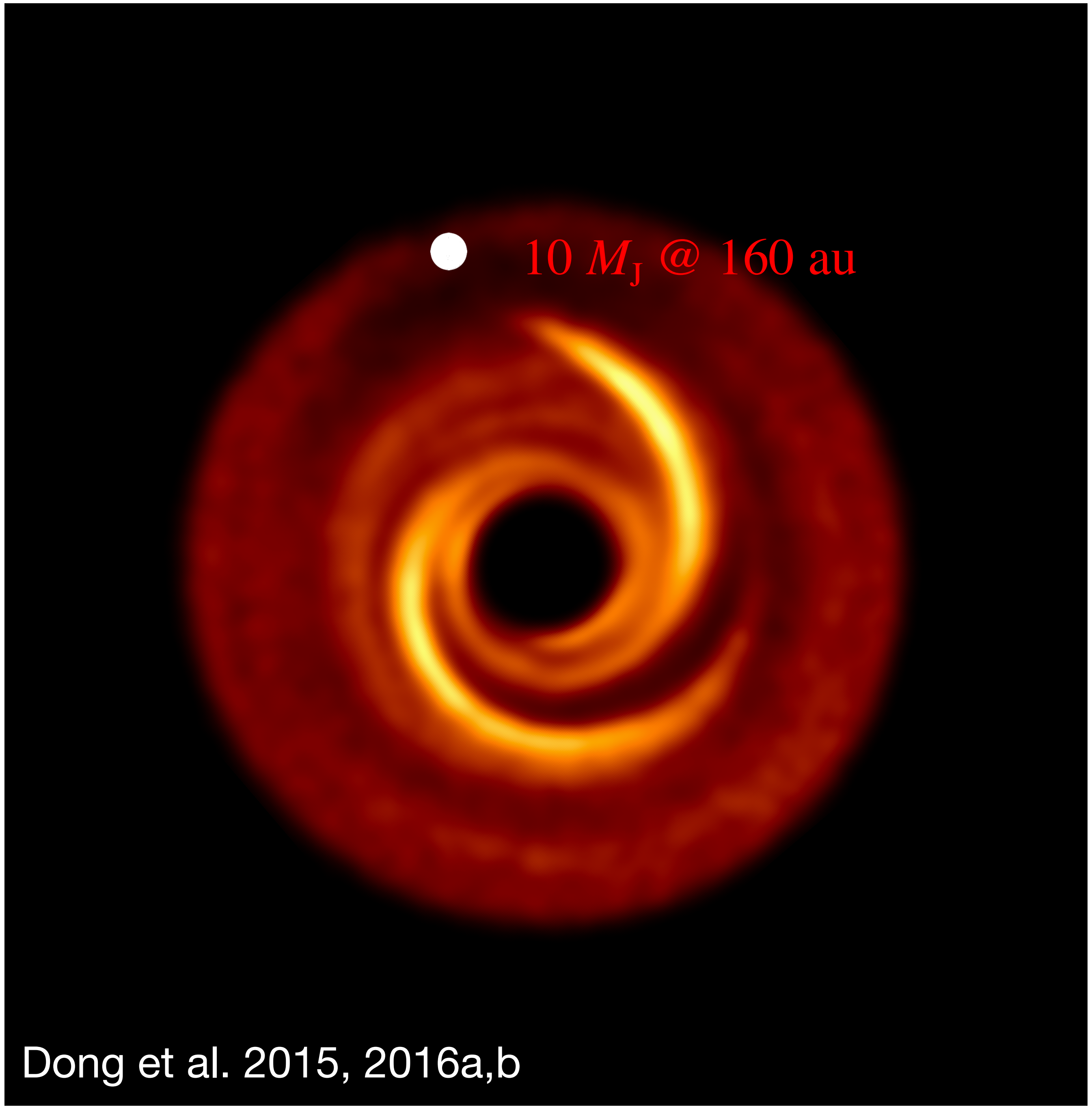








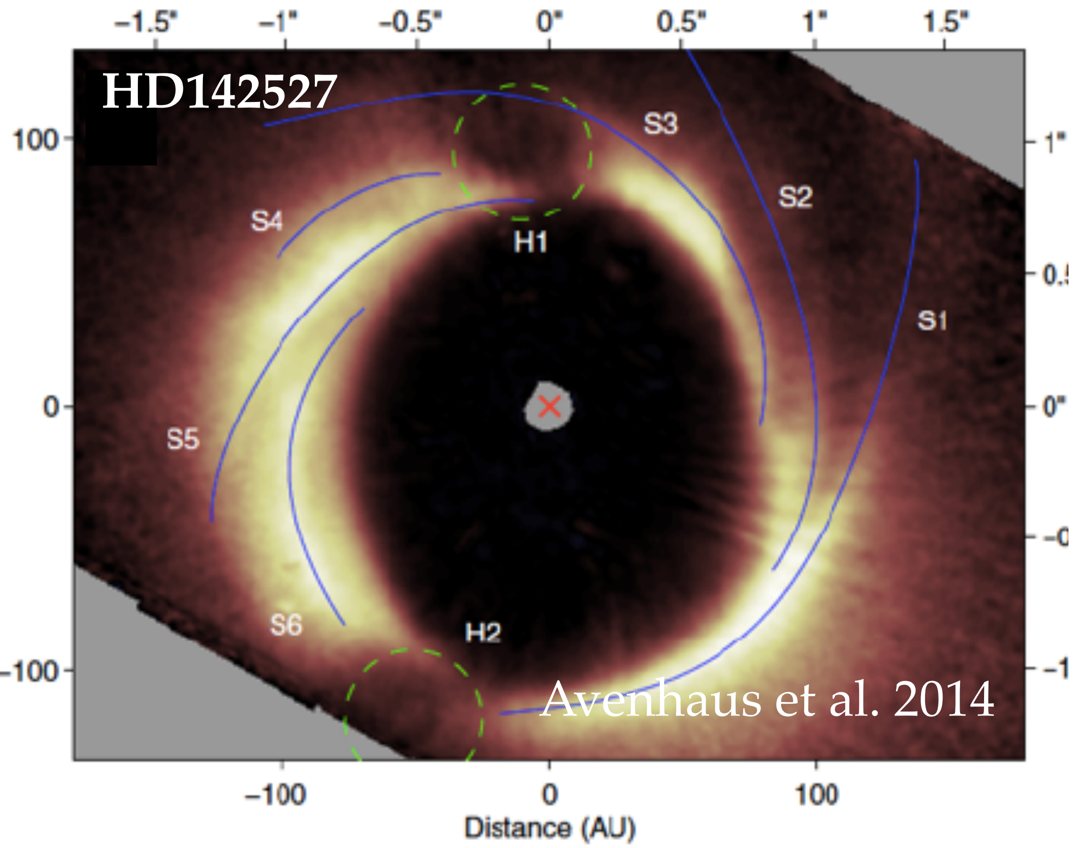
Origin of spiral arms

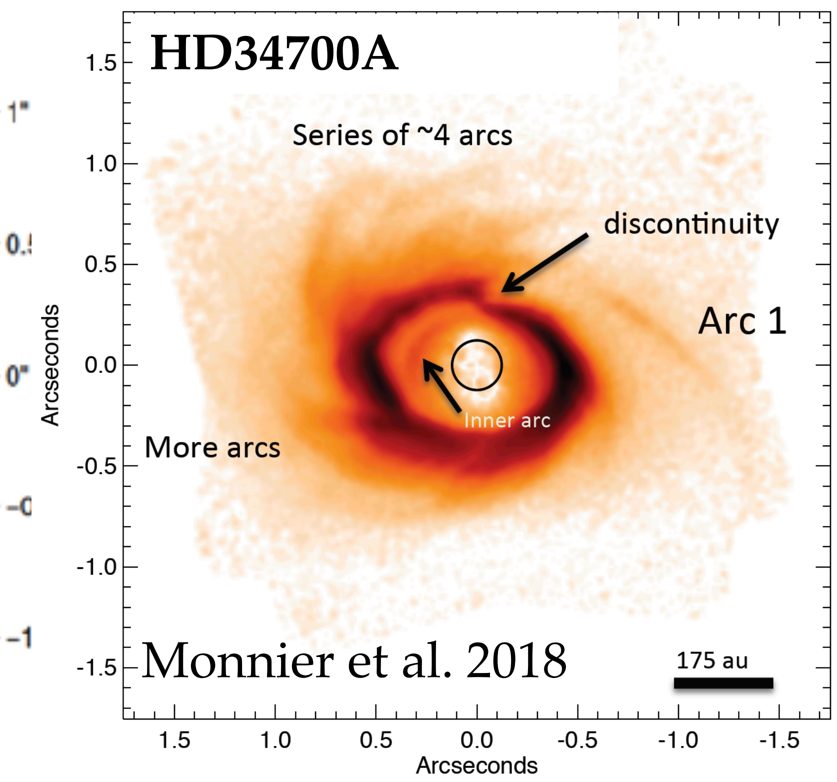


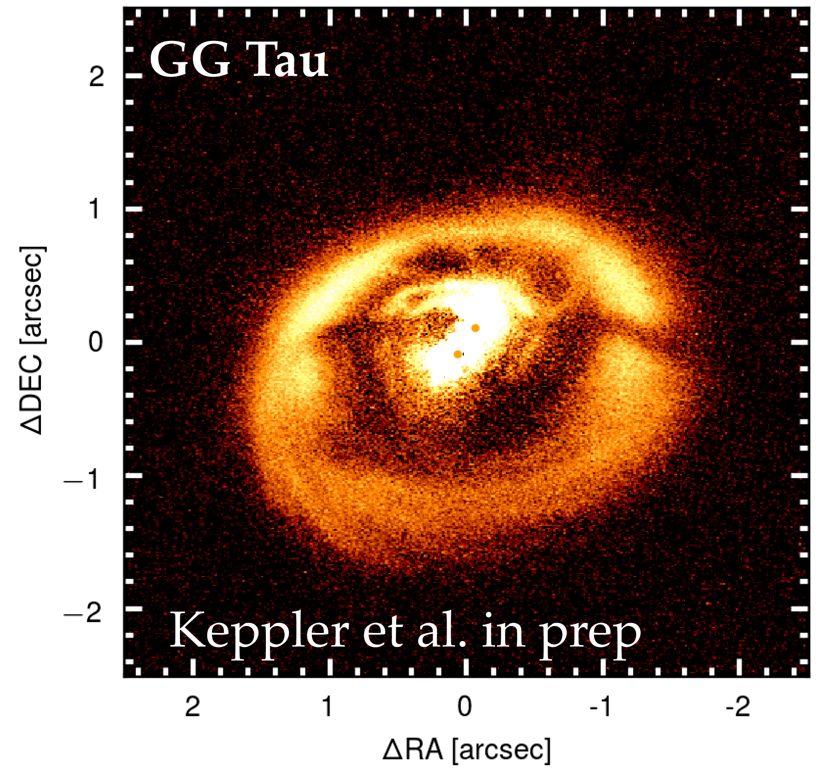
- GI : maybe??
- Planets inwards of the spirals imply non realistic disk temperatures
- A massive planet outwards of the spiral provide a larger pitch angle for the spirals and a reasonable H/r
- Could/should be detectable by direct imaging surveys ?
- A 5 MJup planet outside & a 1.5 MJup planet inside the spirals (Baruteau et al. 2019)

Also Fukugawa et al. 2011, Muto et al. 2012, Grady et al. 2009, Grady et al. 2013, Garufi et al. 2013, Rodigas et al. 2014, Wagner et al. 2015, Akiyama et al. 2016, Long et al. 2017, Wagner et al. 2018

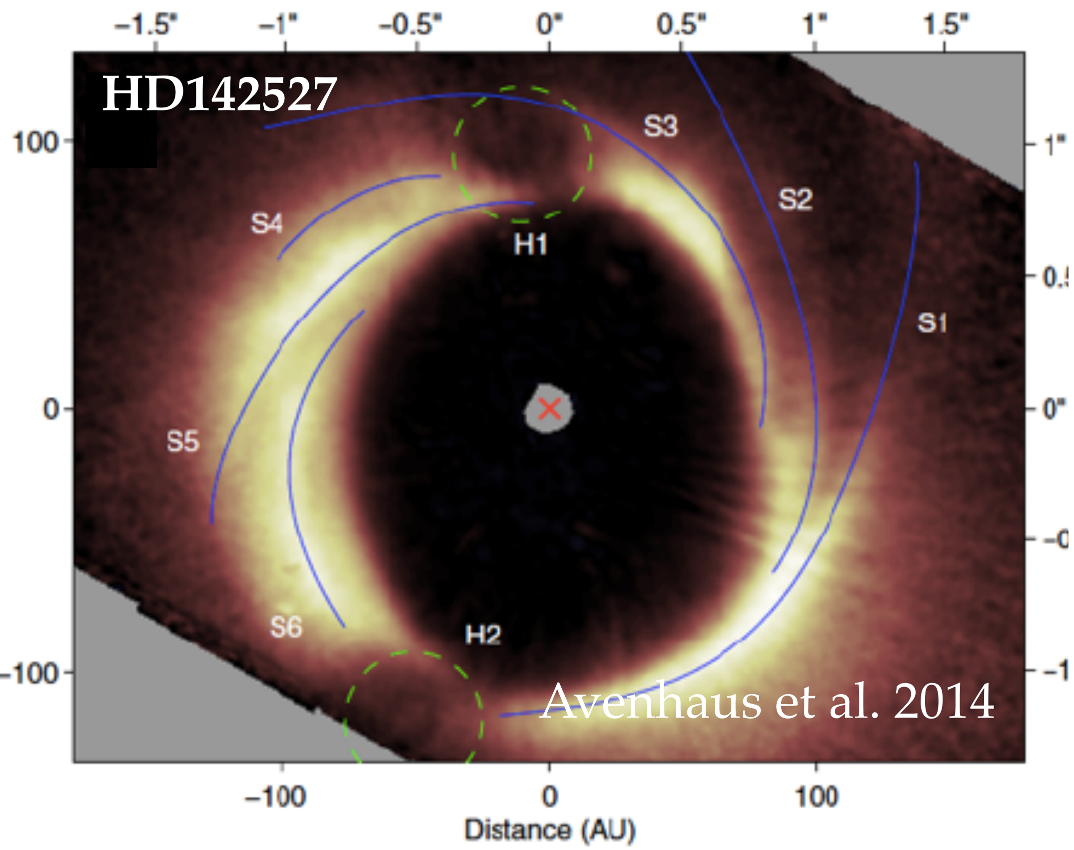
Spirals in circumbinary disks

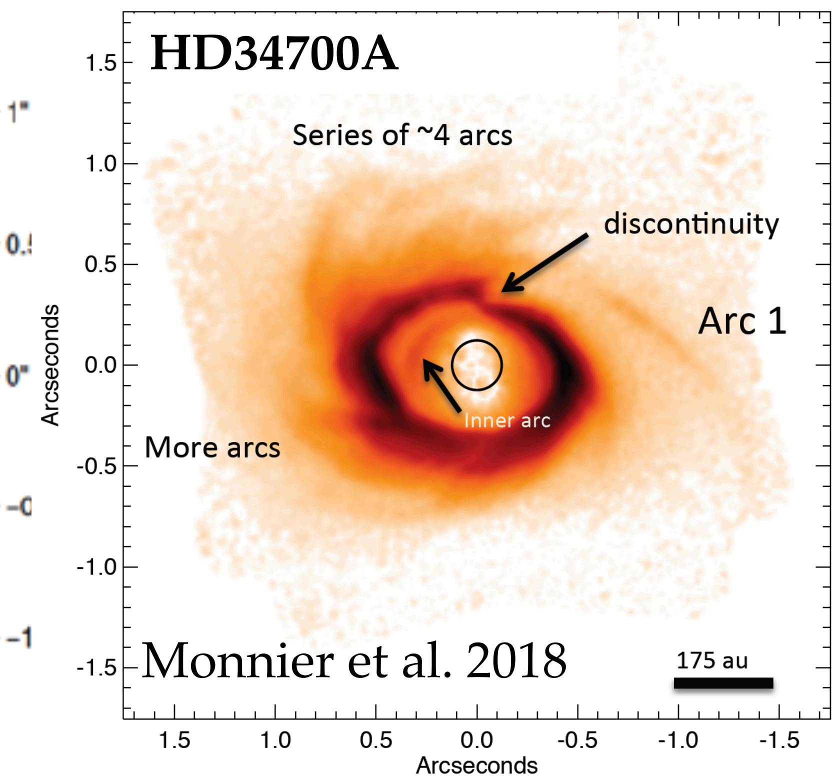


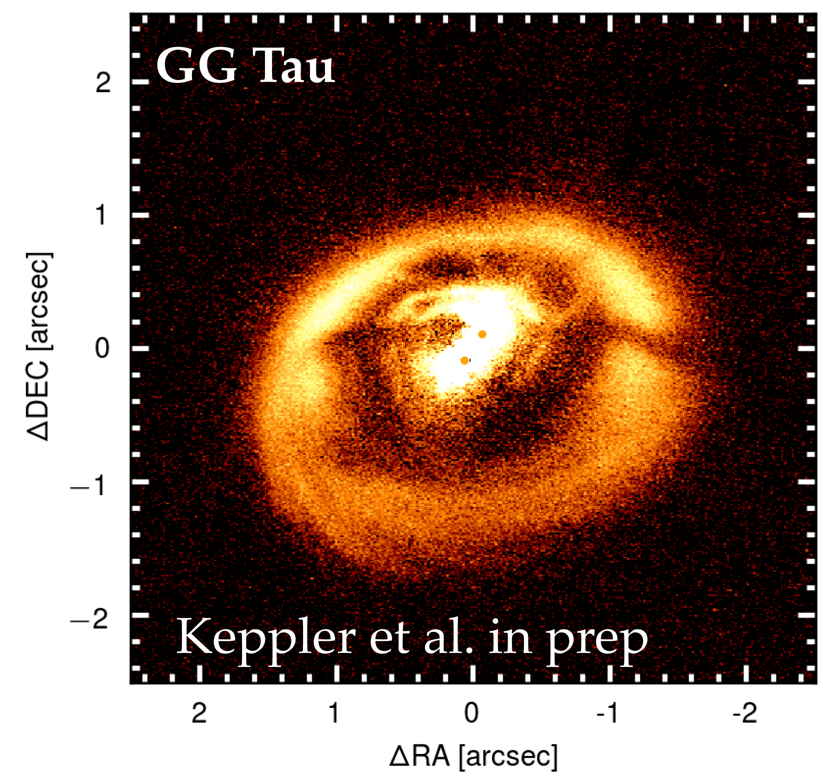


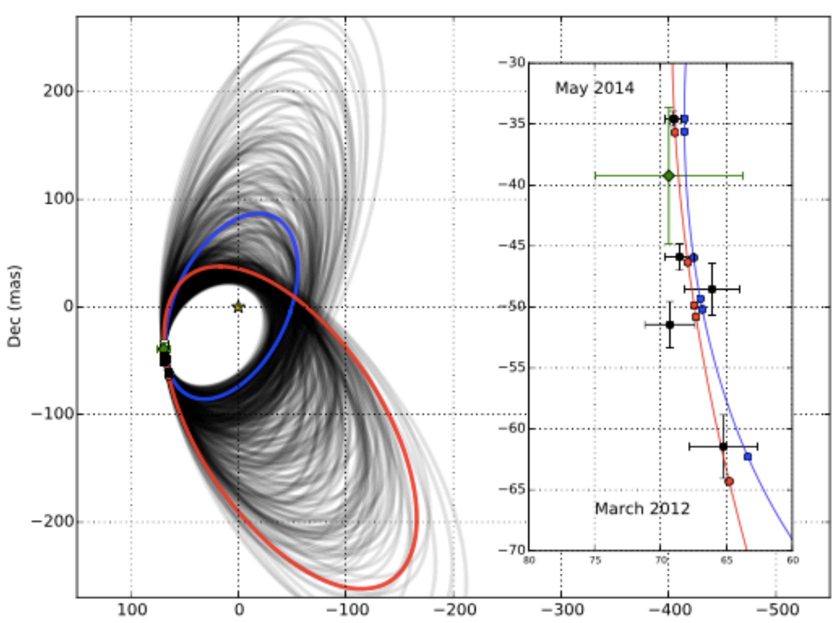


Spirals in circumbinary disks



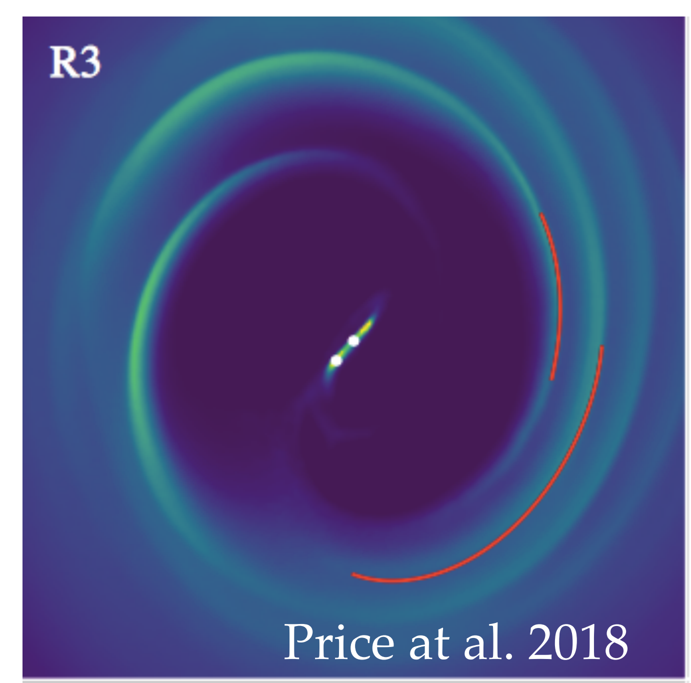




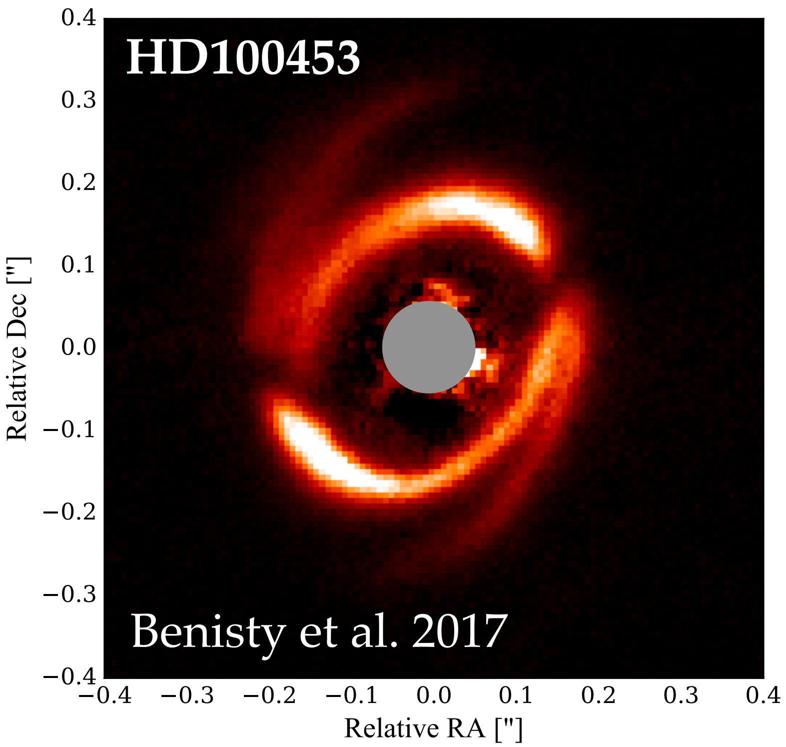


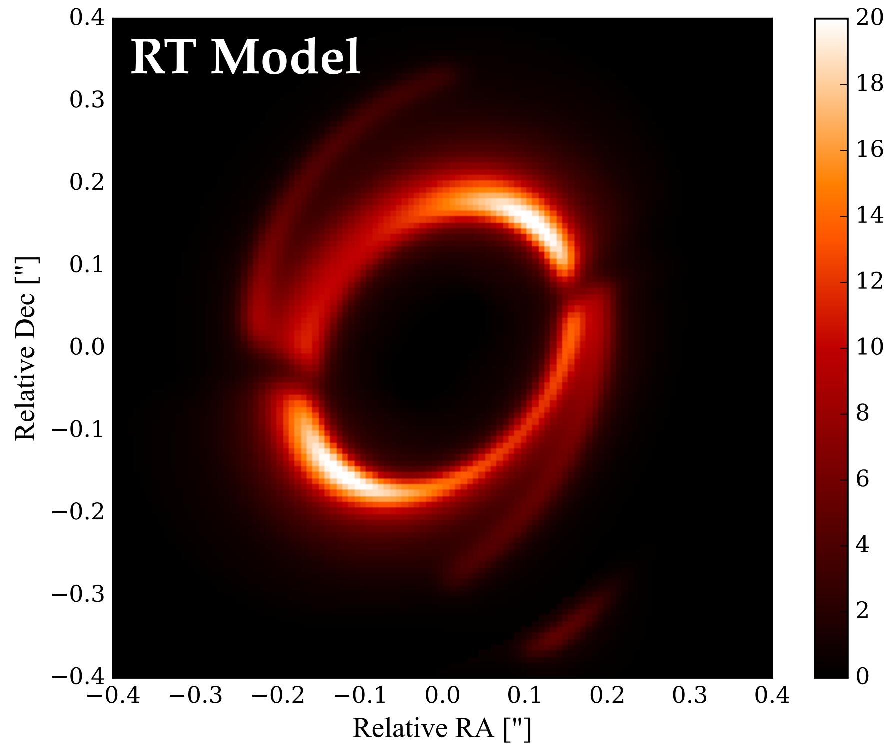
Lacour et al. 2016

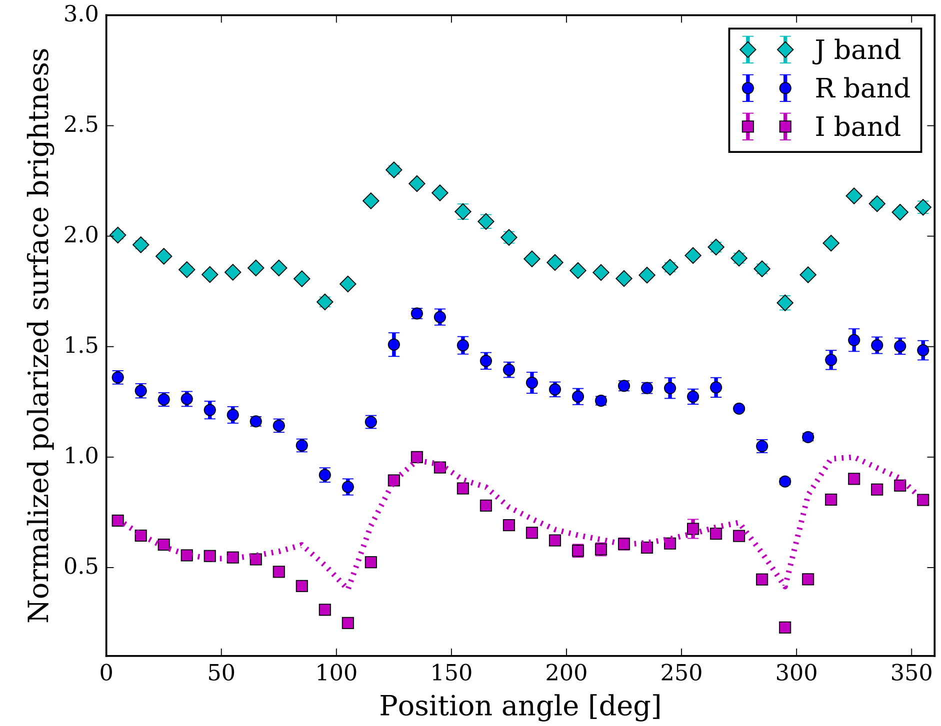
- 0.2-0.4 $M_\odot$ companion at ~ 12 au [Biller et al. 2012, Christiaens et al. 2018]
- ~40-50 au semi major axis, e~0.6-0.7, almost polar inclination [Price et al. 2018]



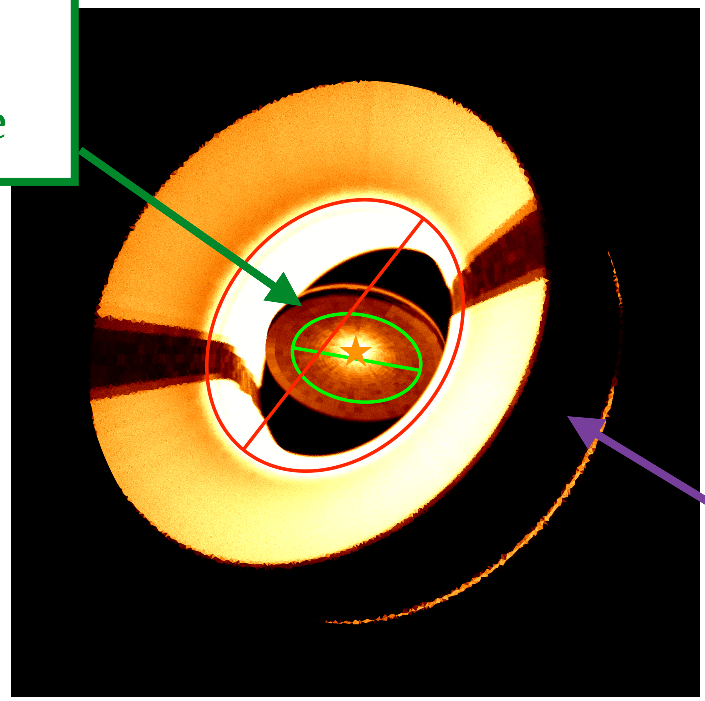
Shadows: inner / outer disk misalignment







i~48°, PA~80°
NE = near side

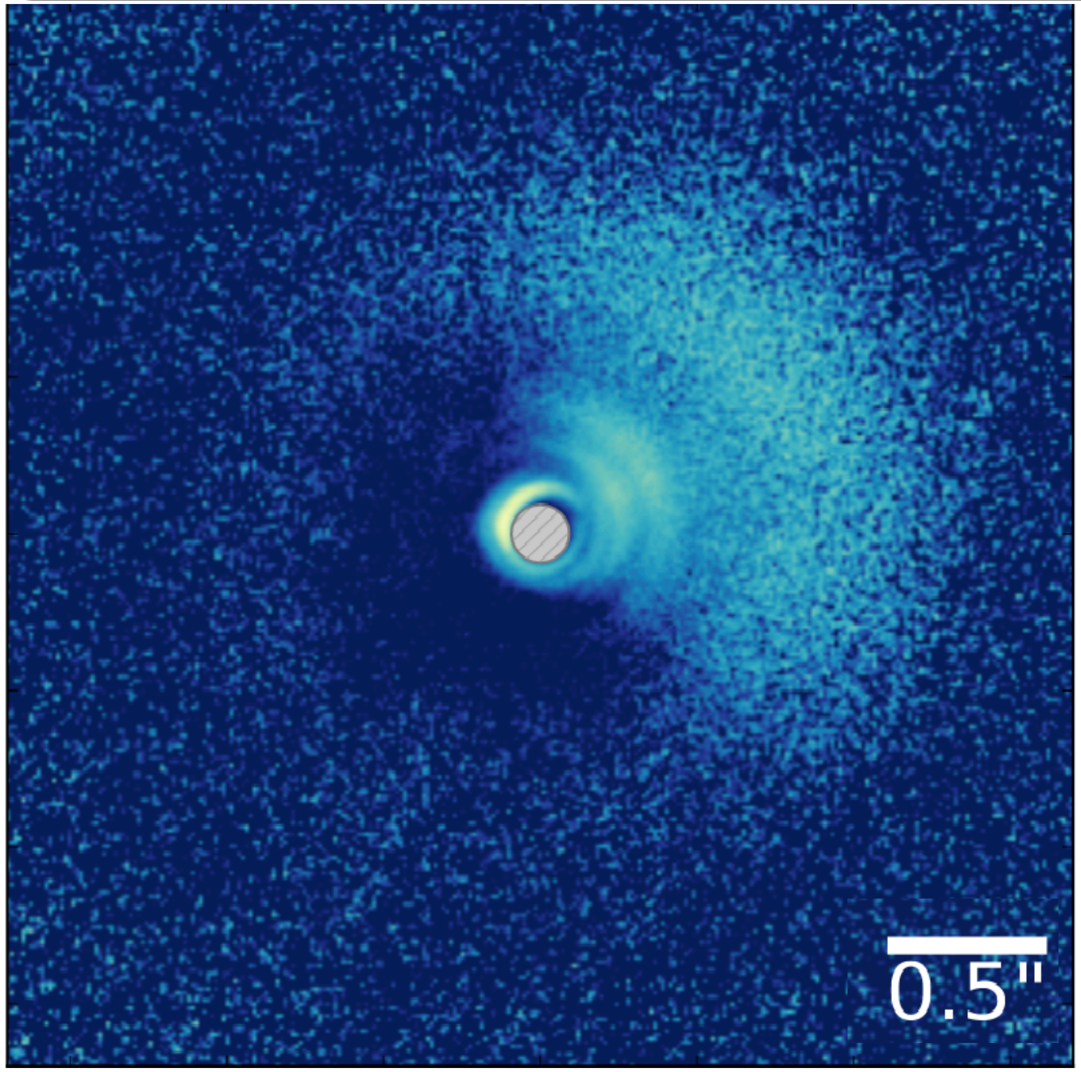


i~38°, PA~142°
SW = near side

- Use a misalignment of 72°
- Shape of the shadows depends on both inner / outer disk morphology

Marino et al. 2015, Long et al. 2017, Wagner et al. 2018

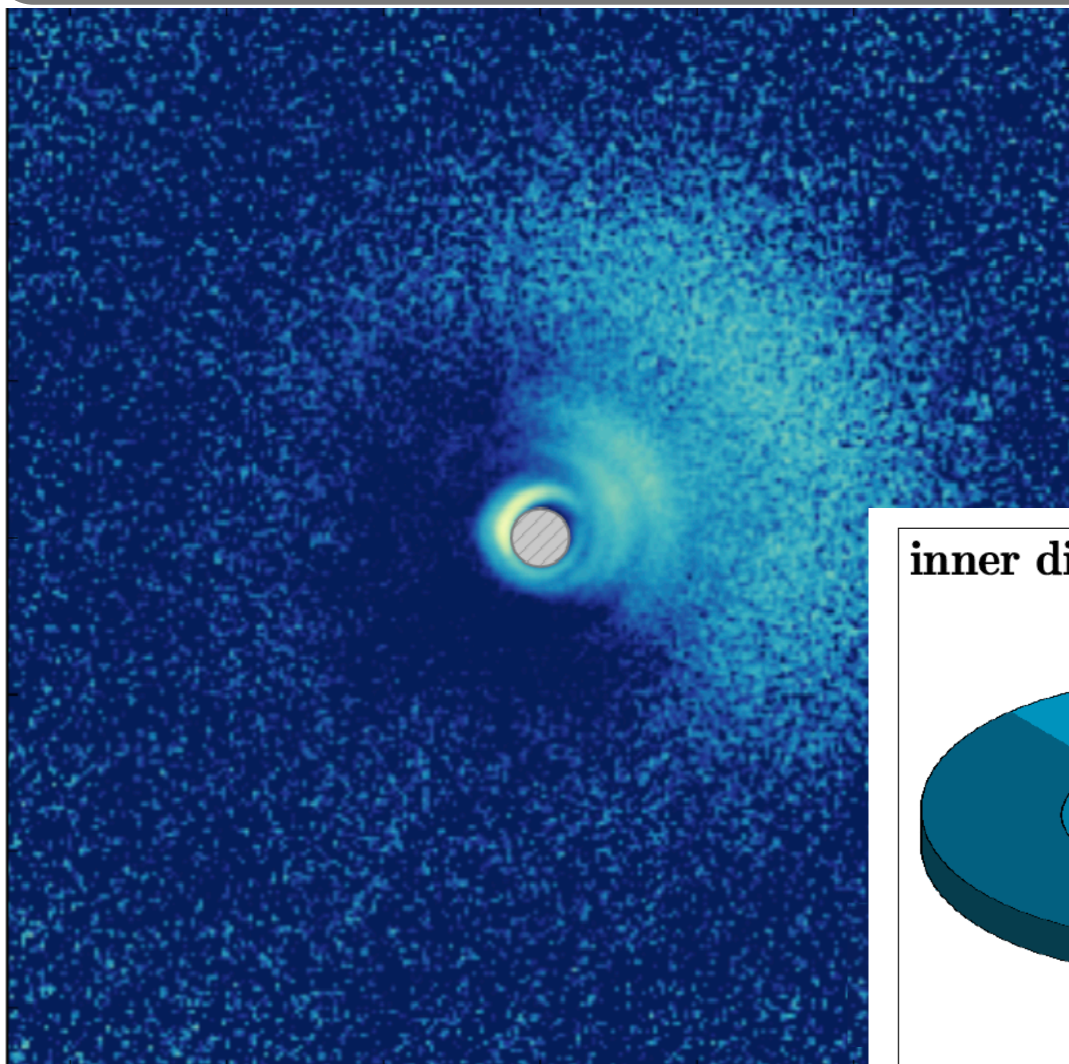
Broad shadows



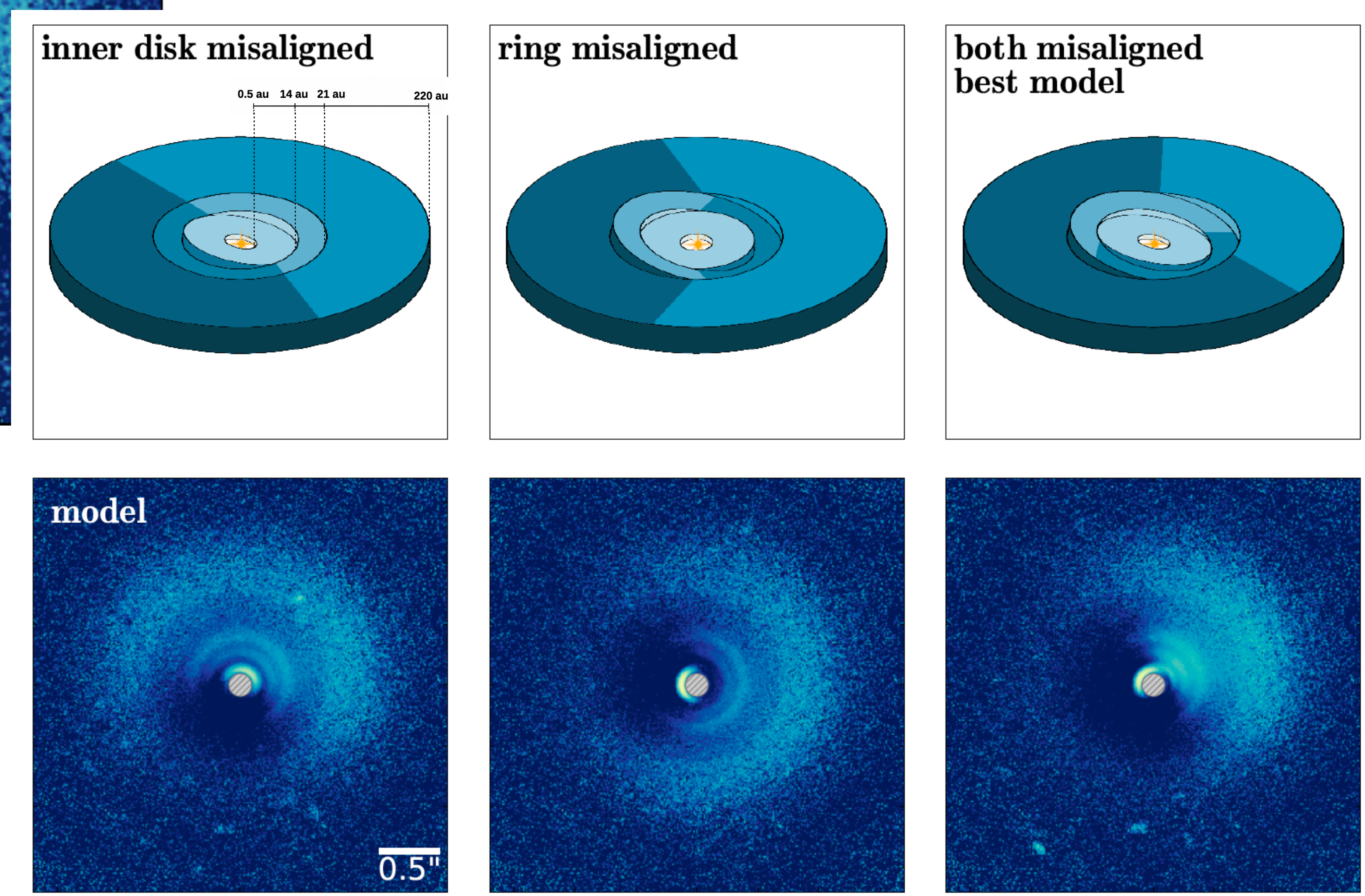
- Broad shadows can result from small misalignments (Nealon et al. 2019)
- Shadow observed over > 180 deg, requires a combination of two misaligned regions

Muro-Arena et al. in prep

Broad shadows

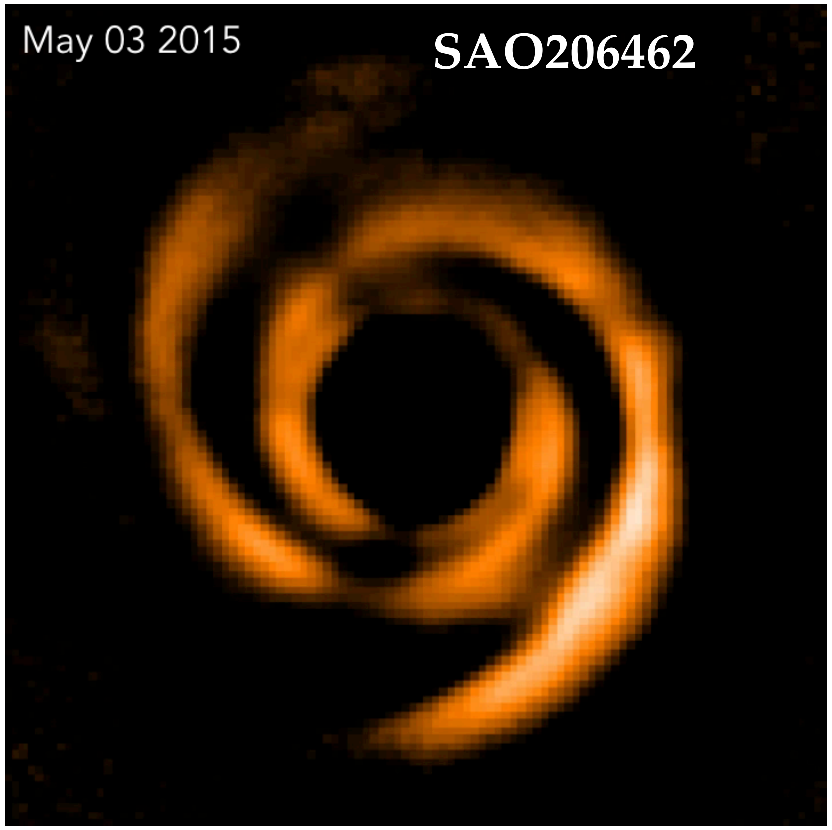


- Broad shadows can result from small misalignments (Nealon et al. 2019)
- Shadow observed over > 180 deg, requires a combination of two misaligned regions

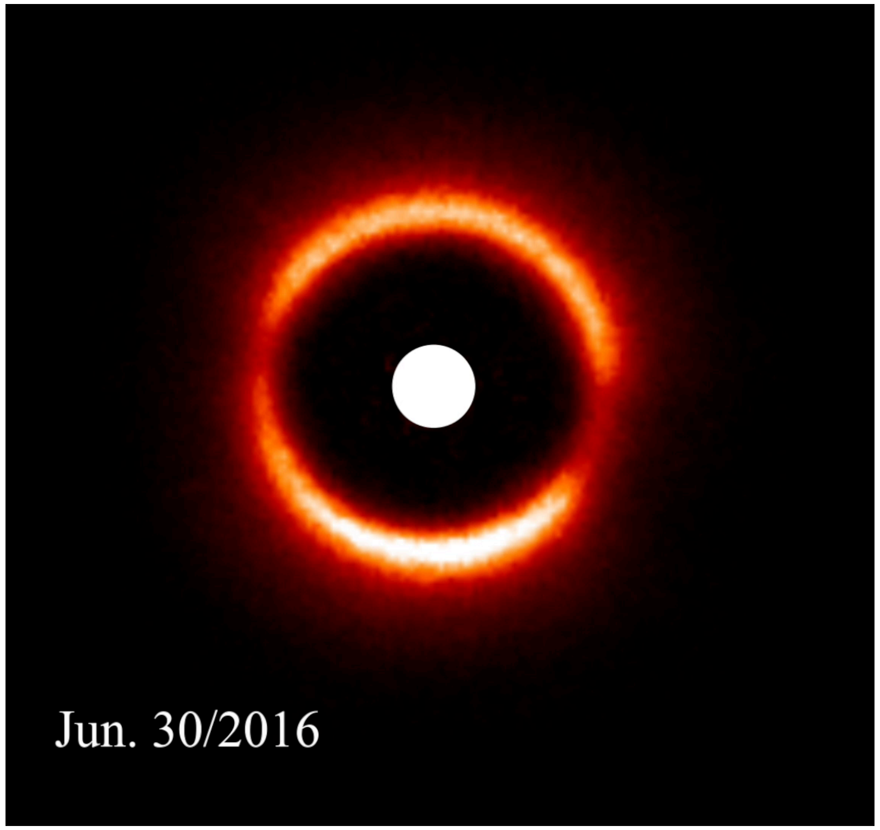


Muro-Arena et al. in prep

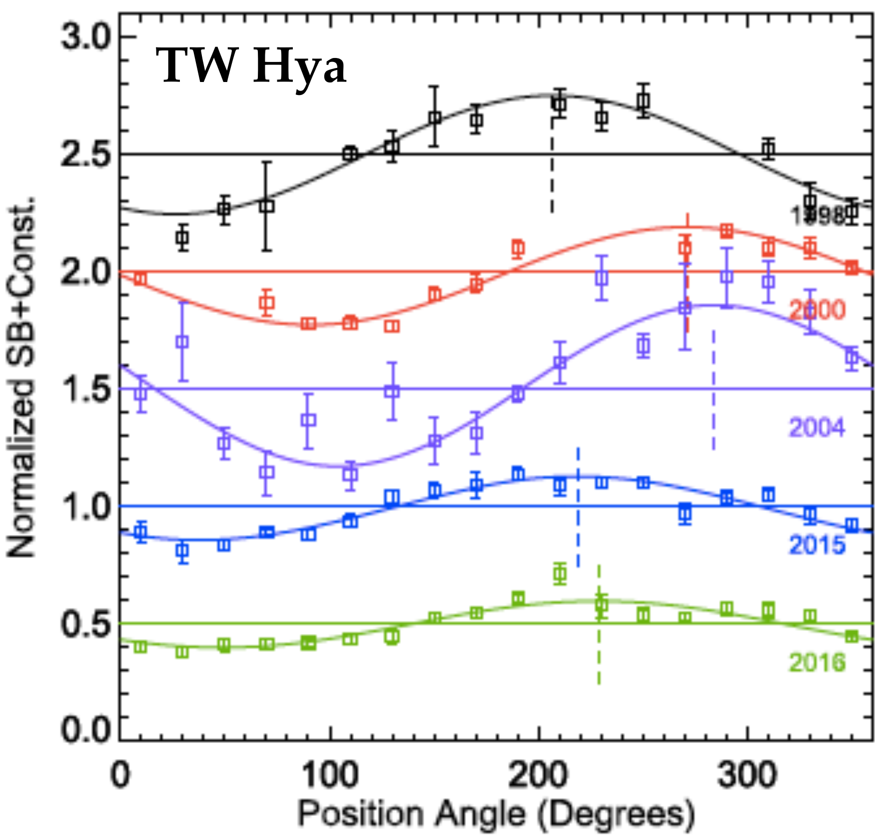
Variable shadows



Stolker et al. 2017b



Pinilla et al. 2018



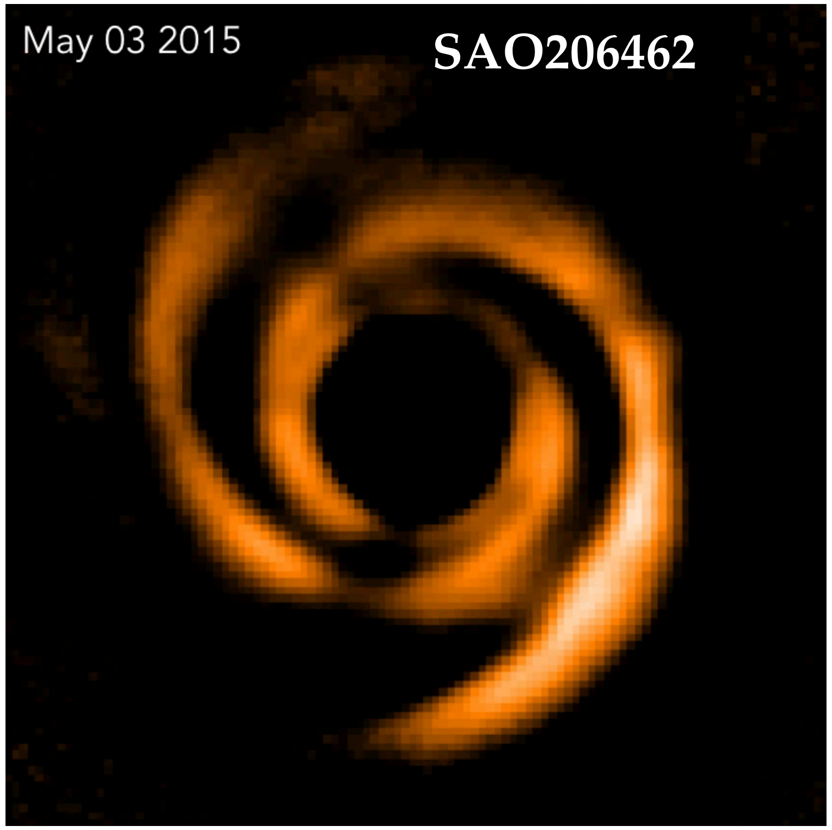
Debes et al. 2017, Nealon et al. 2019

- Strongly dynamic inner regions
- Significantly misaligned and optically thick dust in the innermost regions

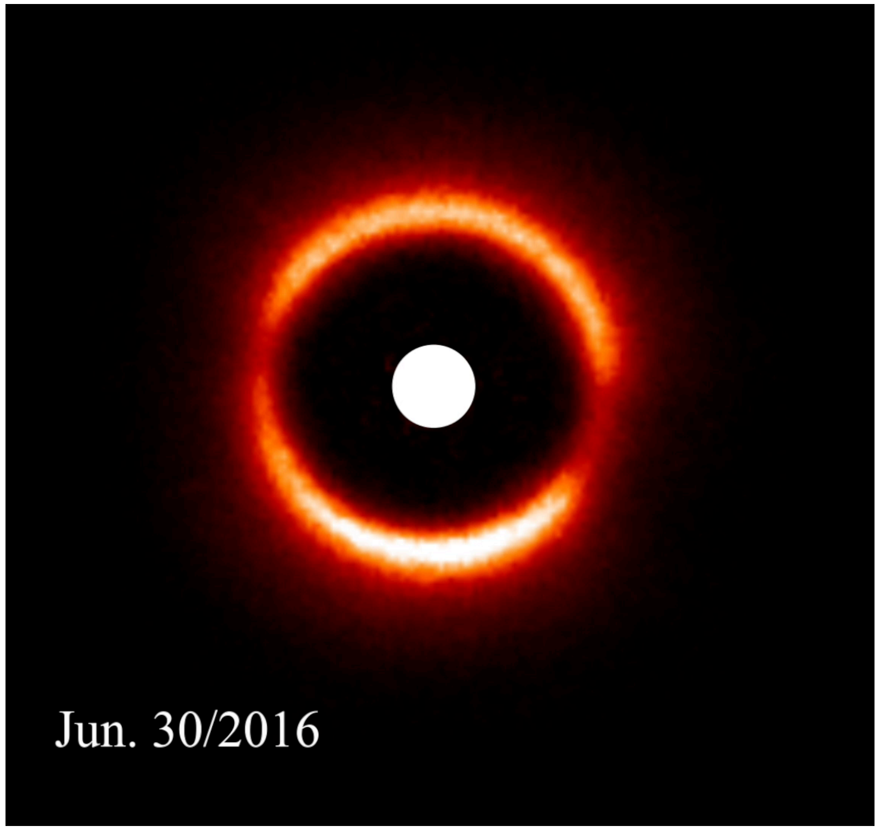
An inclined inner disk < 1 au precessing with a period of ~16 yrs

Also Schneider et al. 2014, Wolff et al. 2016

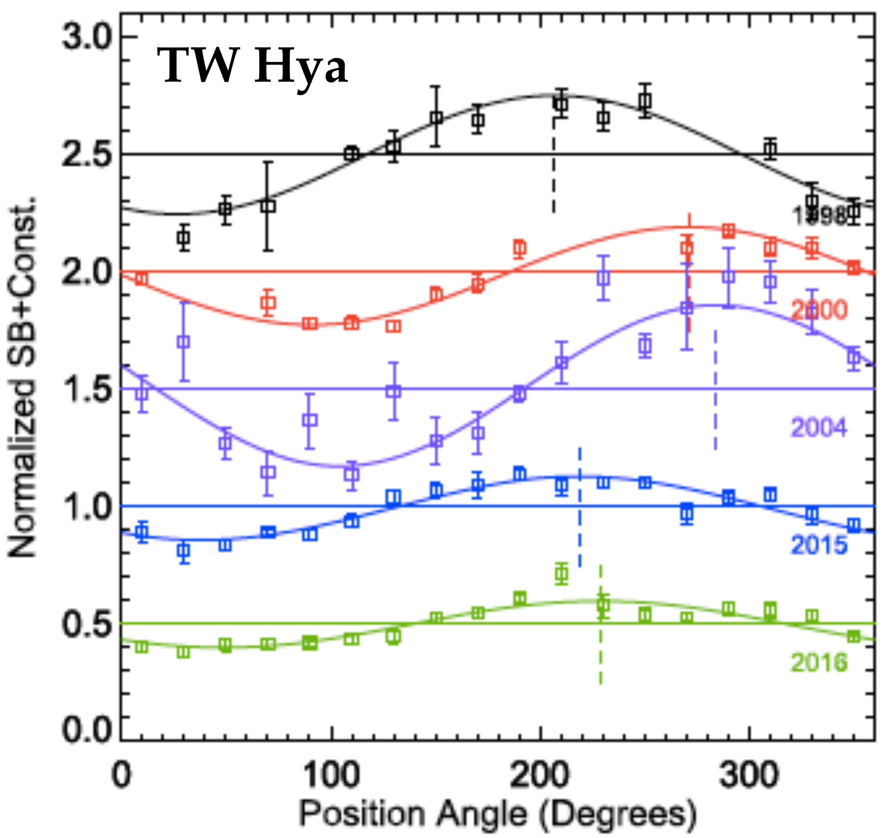
Variable shadows



Stolker et al. 2017b



Pinilla et al. 2018



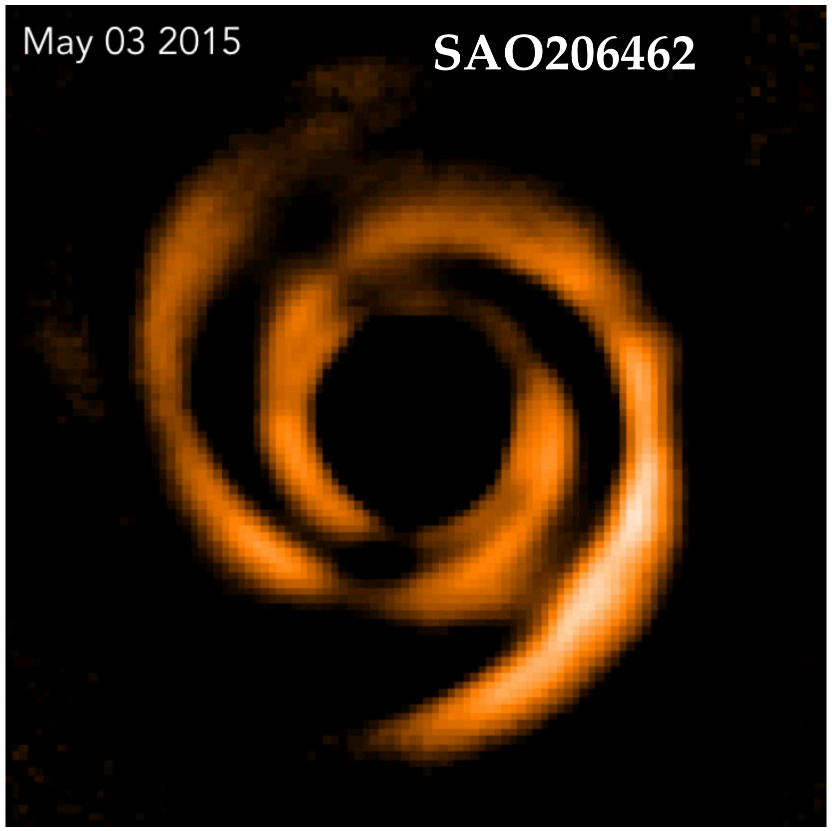
Debes et al. 2017, Nealon et al. 2019

- Strongly dynamic inner regions
- Significantly misaligned and optically thick dust in the innermost regions

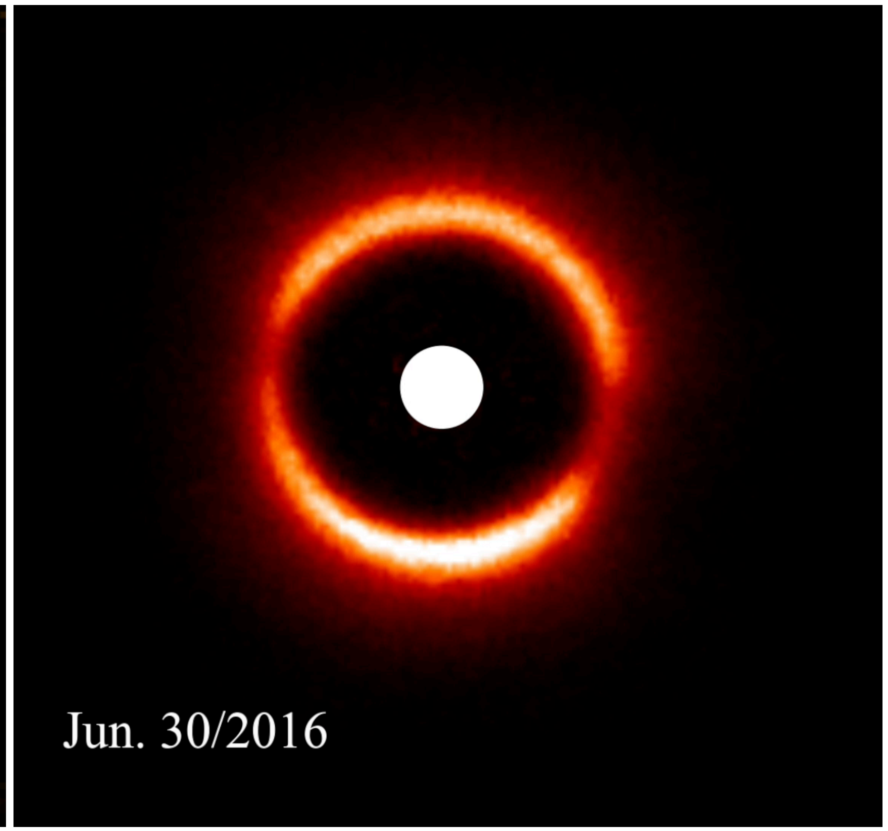
An inclined inner disk < 1 au precessing with a period of ~16 yrs

Also Schneider et al. 2014, Wolff et al. 2016

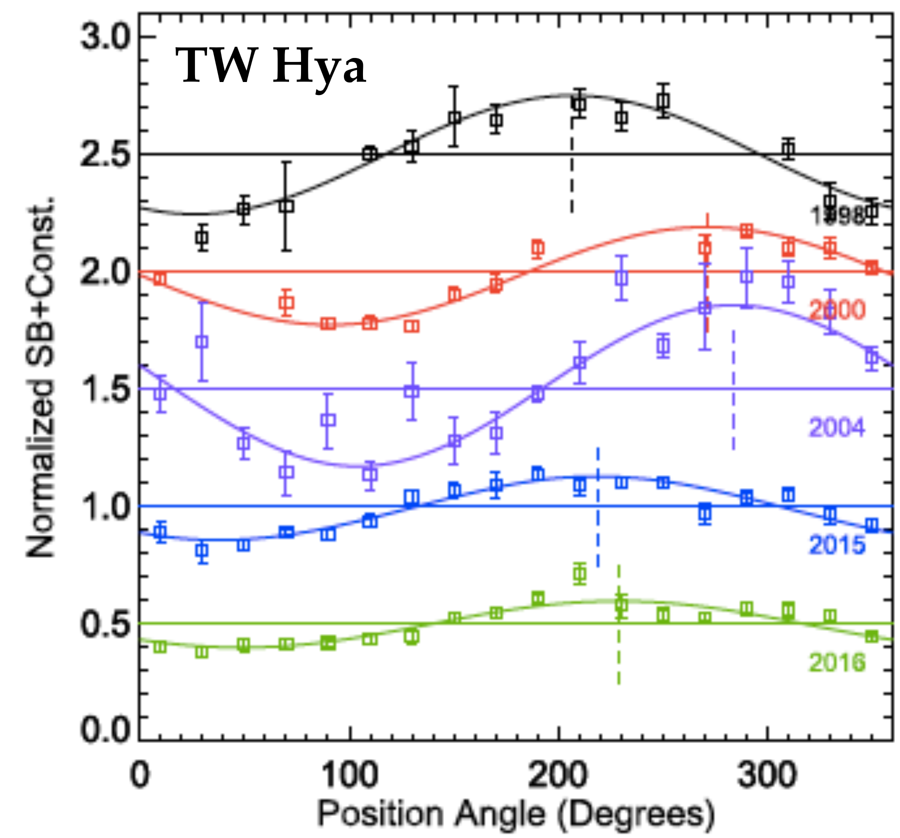
Variable shadows



Stolker et al. 2017b



Pinilla et al. 2018



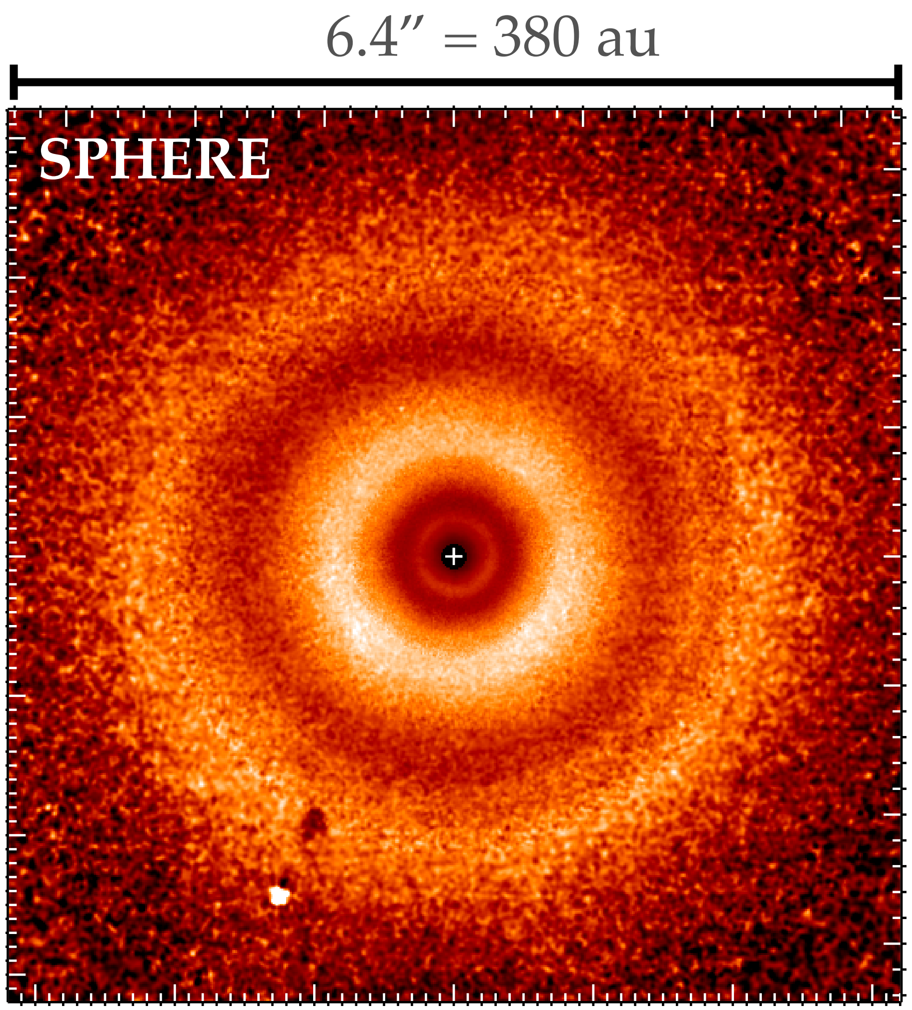
Debes et al. 2017, Nealon et al. 2019

- Strongly dynamic inner regions
- Significantly misaligned and optically thick dust in the innermost regions

An inclined inner disk < 1 au precessing with a period of ~16 yrs

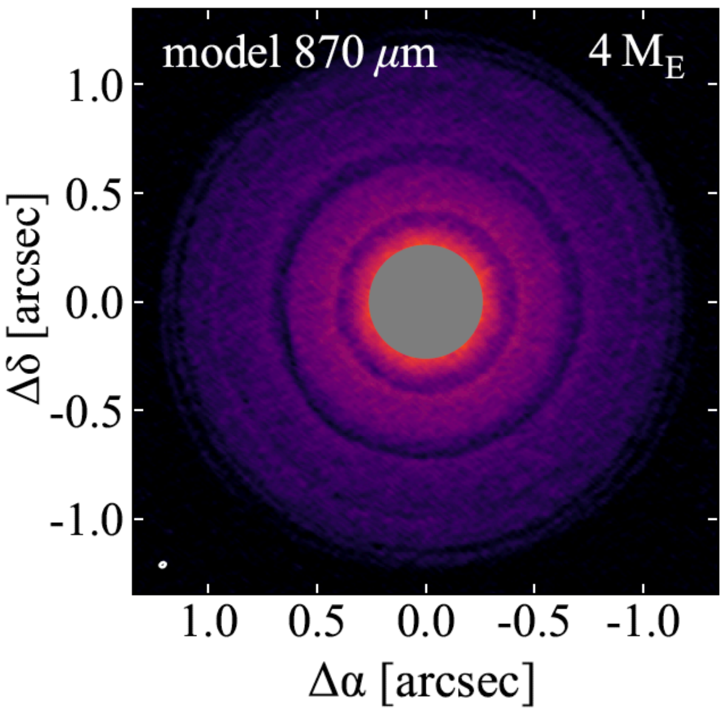
Also Schneider et al. 2014, Wolff et al. 2016

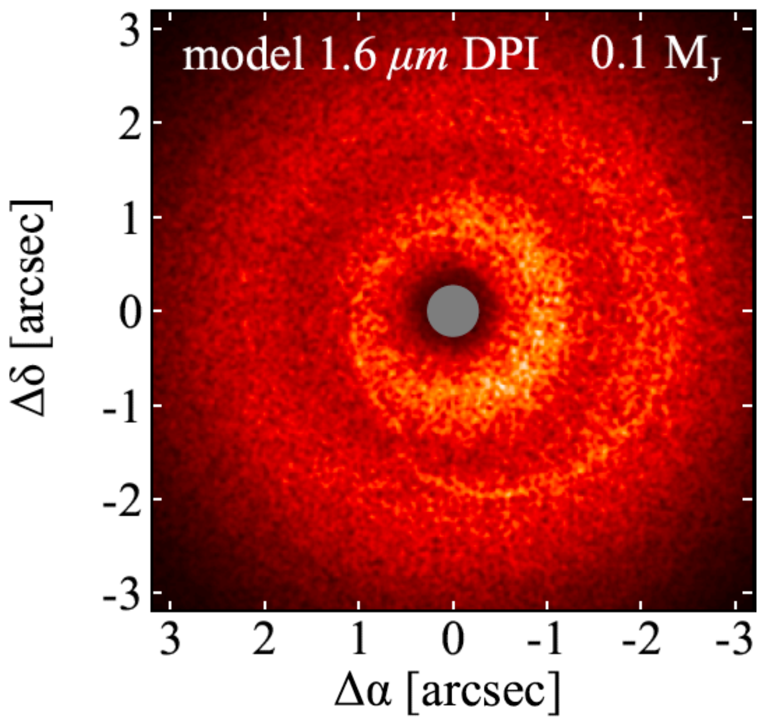
Rings/Gaps counterparts in the mm



van Boekel et al. 2016,
Andrews et al. 2016

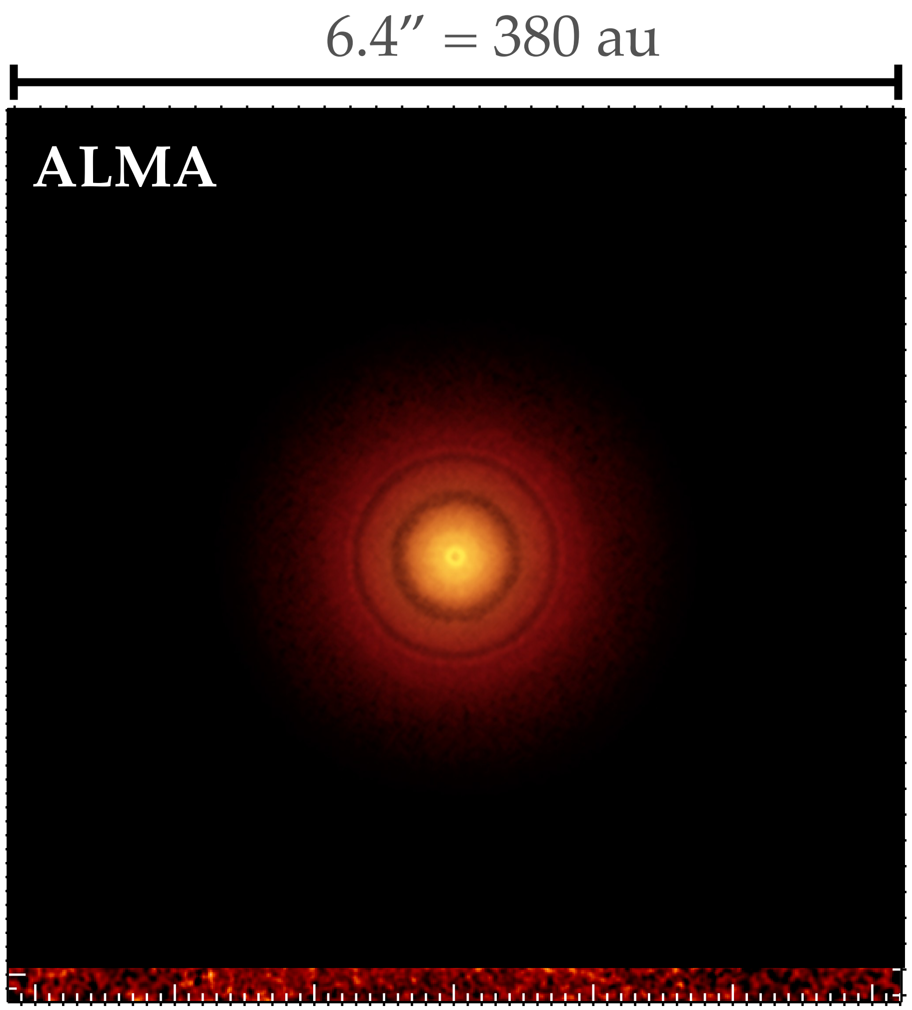
- Comparison of scattered light & mm data can constrain dust dynamics (small / large grains)
- Spatial extent, gap locations, widths and depths differ.
- TW Hya: mm gaps carved by super-Earths, the scattered gap by a Saturn mass planet.





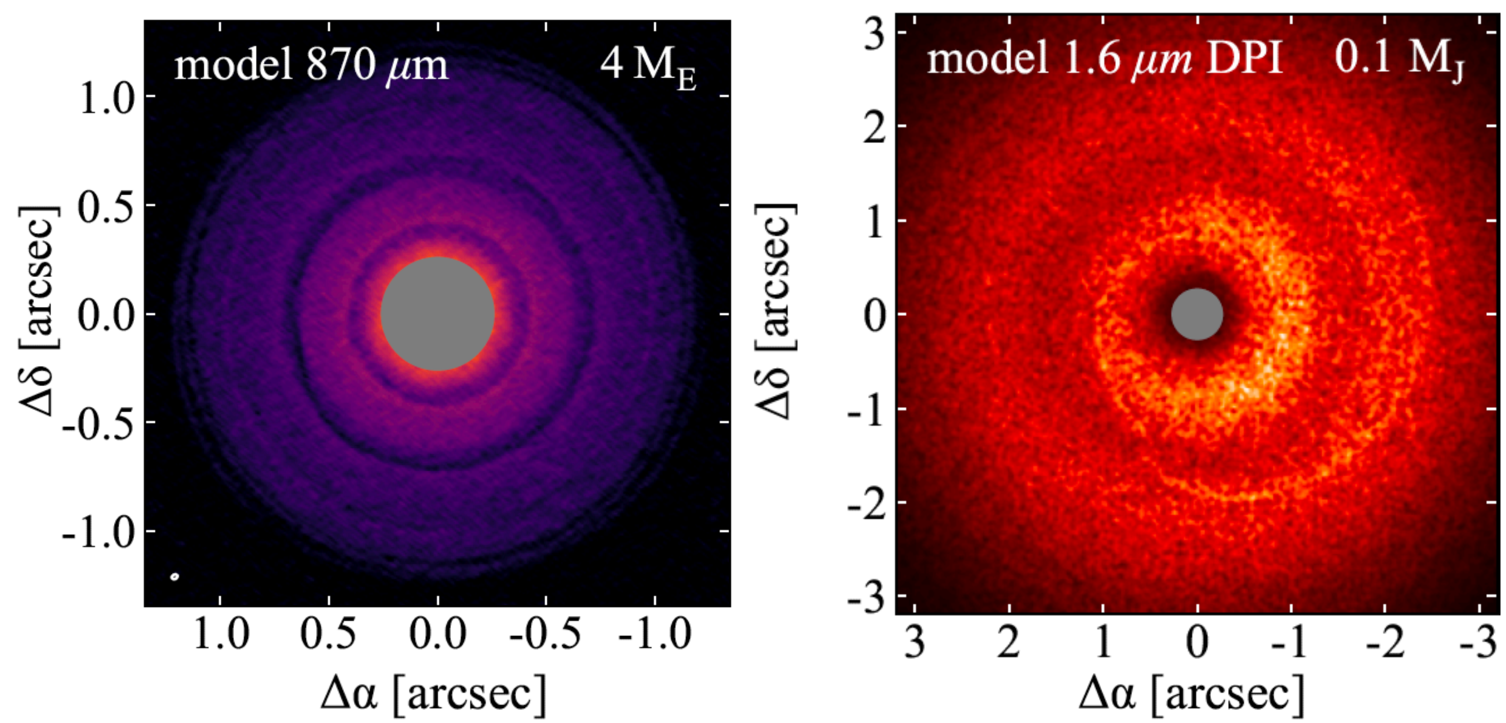
Mentiplay et al. 2019

Rings/Gaps counterparts in the mm



van Boekel et al. 2016,
Andrews et al. 2016

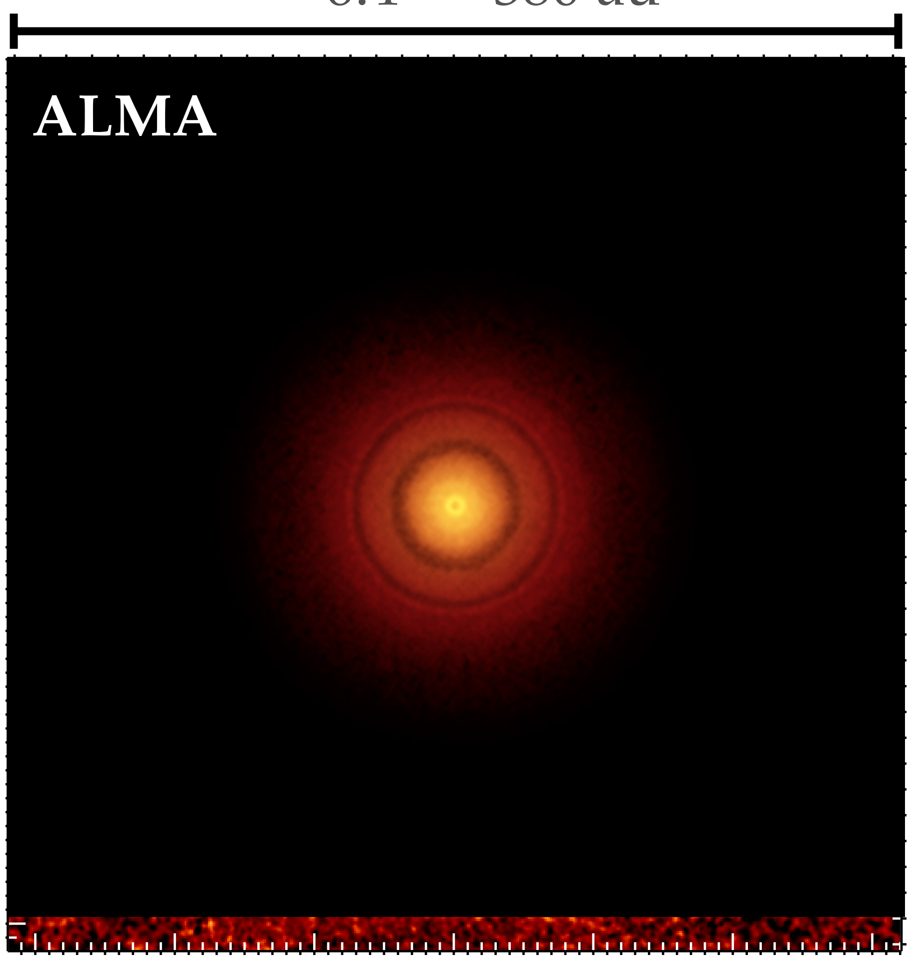
- Comparison of scattered light & mm data can constrain dust dynamics (small / large grains)
- Spatial extent, gap locations, widths and depths differ.
- TW Hya: mm gaps carved by super-Earths, the scattered gap by a Saturn mass planet.



Mentiplay et al. 2019

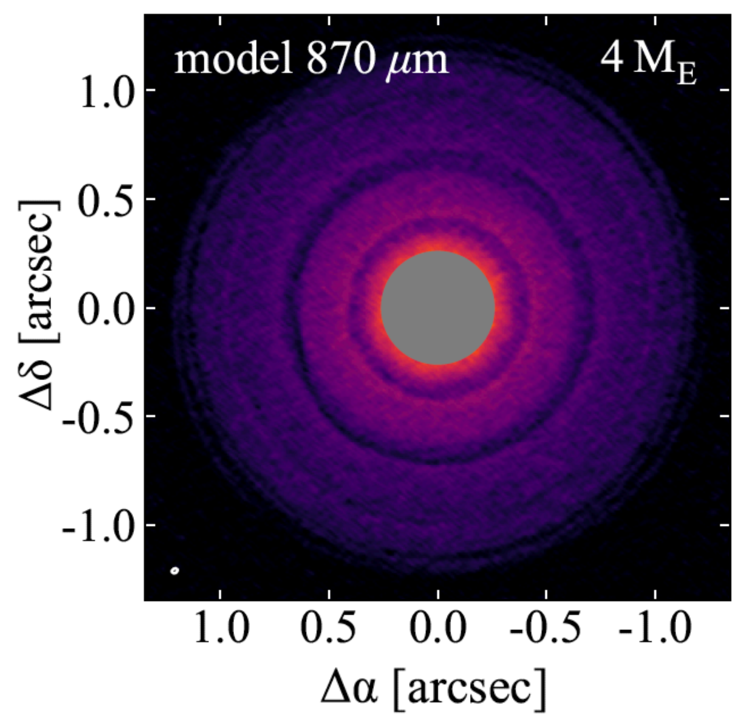
Rings/Gaps counterparts in the mm

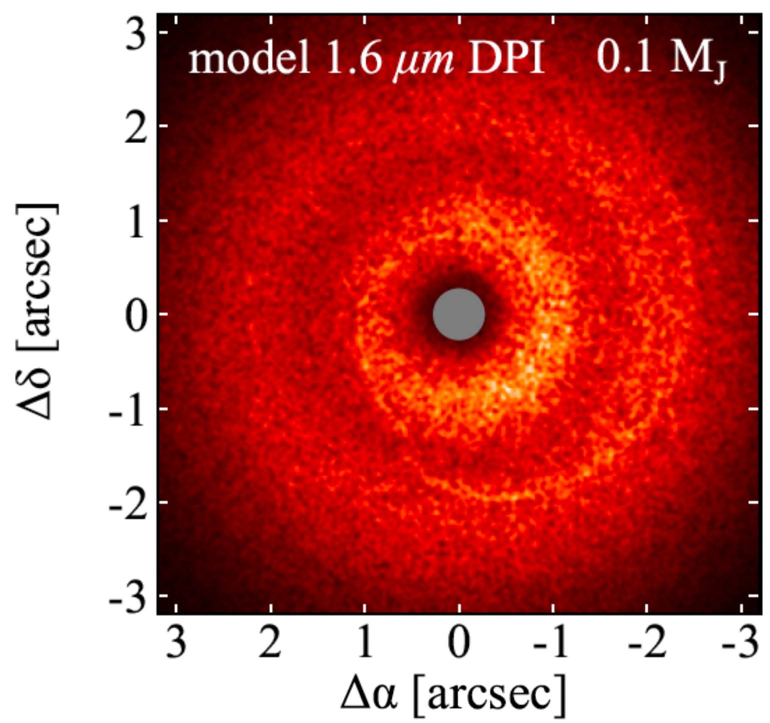
6.4″ = 380 au



van Boekel et al. 2016,
Andrews et al. 2016

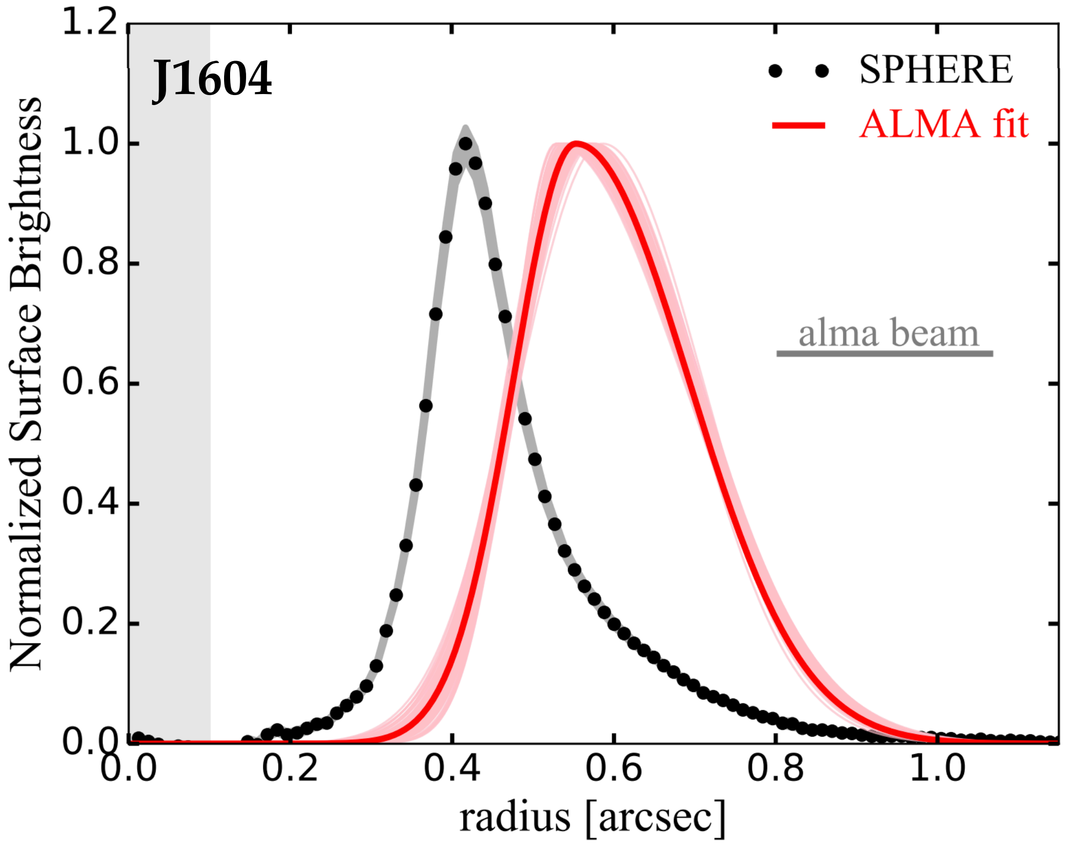
- Comparison of scattered light & mm data can constrain dust dynamics (small / large grains)
- Spatial extent, gap locations, widths and depths differ.
- TW Hya: mm gaps carved by super-Earths, the scattered gap by a Saturn mass planet.



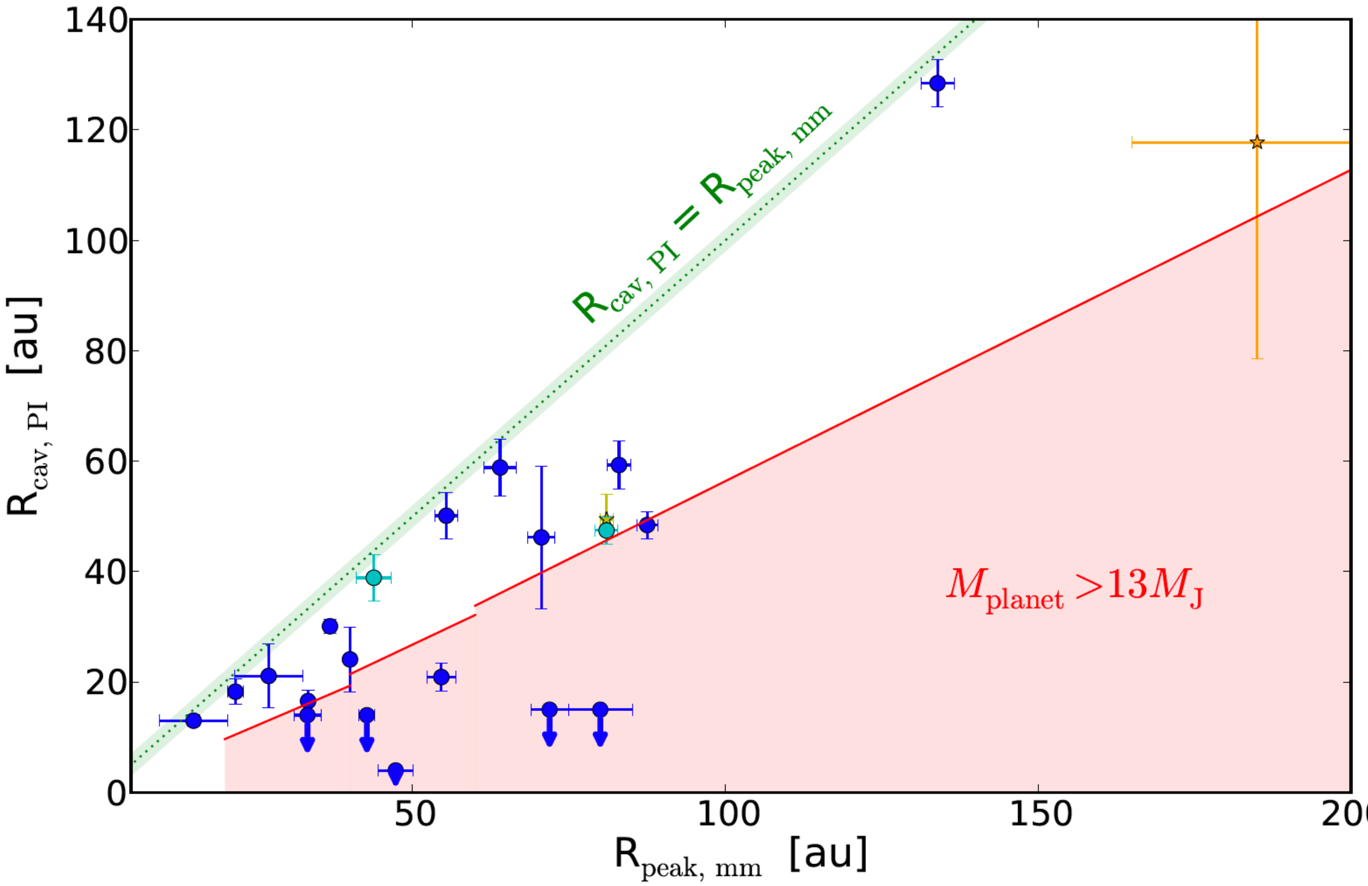


Mentiplay et al. 2019

Cavities counterparts & planet masses



Pinilla et al. 2018



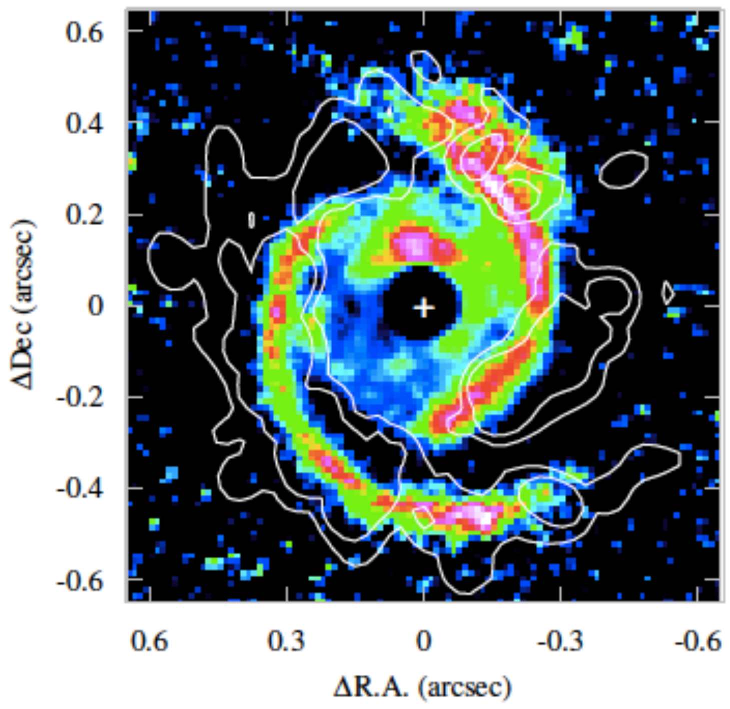
Villenave et al. 2018

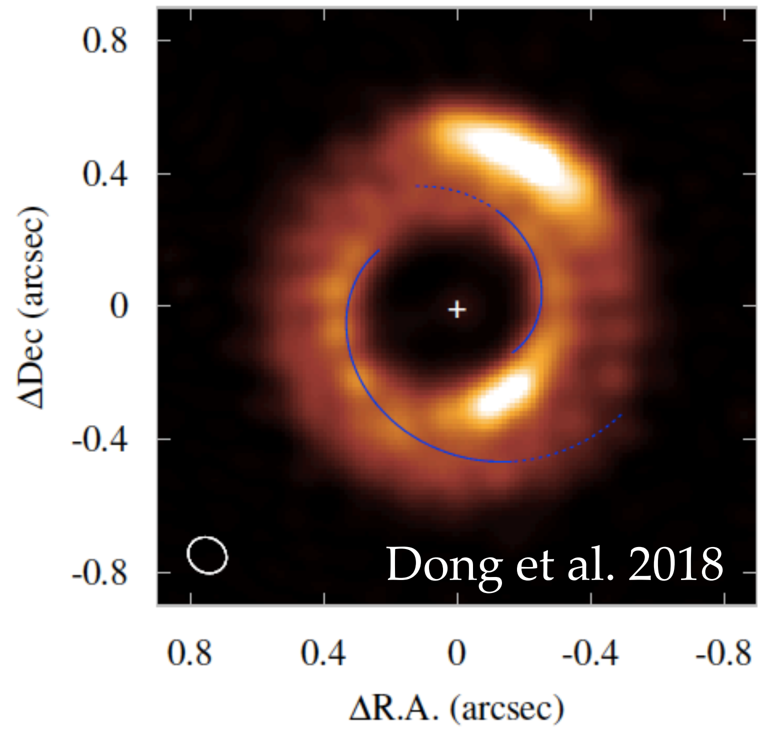
- Small grains inside the mm cavity
- Evidence for dust trapping (> 4 MJup)

- 22 TD observed with SPHERE and ALMA. For 15/22 objects, the difference in radii is consistent with a planetary mass object.

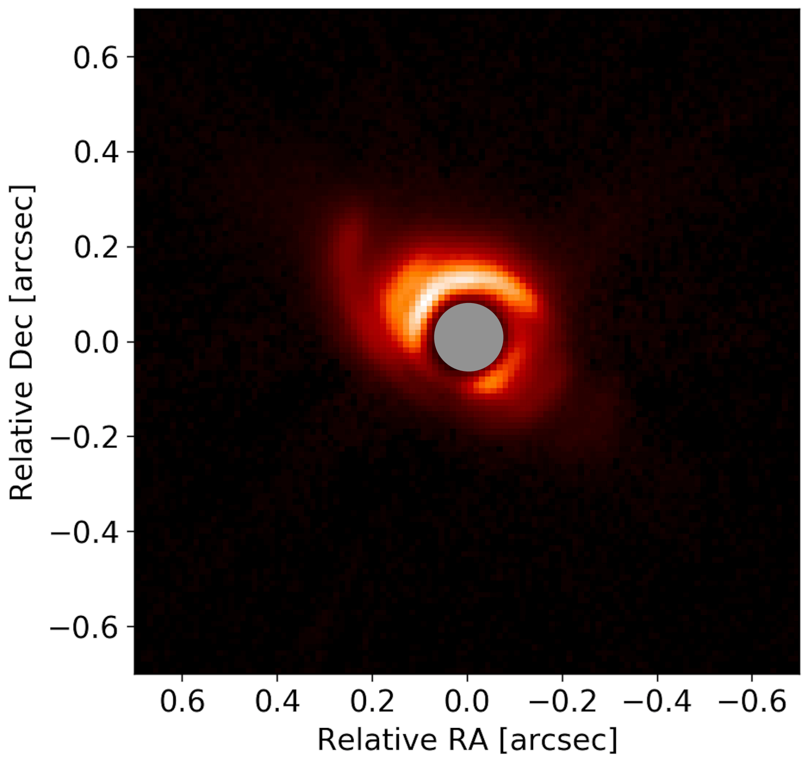
also Garufi et al. 2013, Hornbeck et al. 2018, Boehler et al. 2018

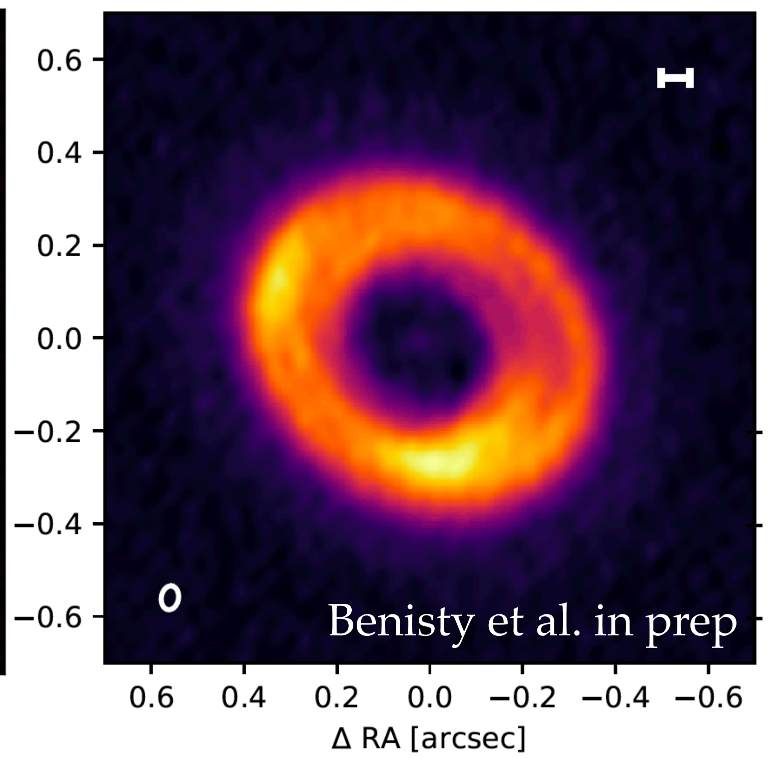
Spiral counterparts in the mm





- Weak spirals in mm
- Different radial locations result from projection effects.
- Pitch angles trace the vertical temperature profile (Juhasz & Rosotti 2018, Rosotti et al. subm)

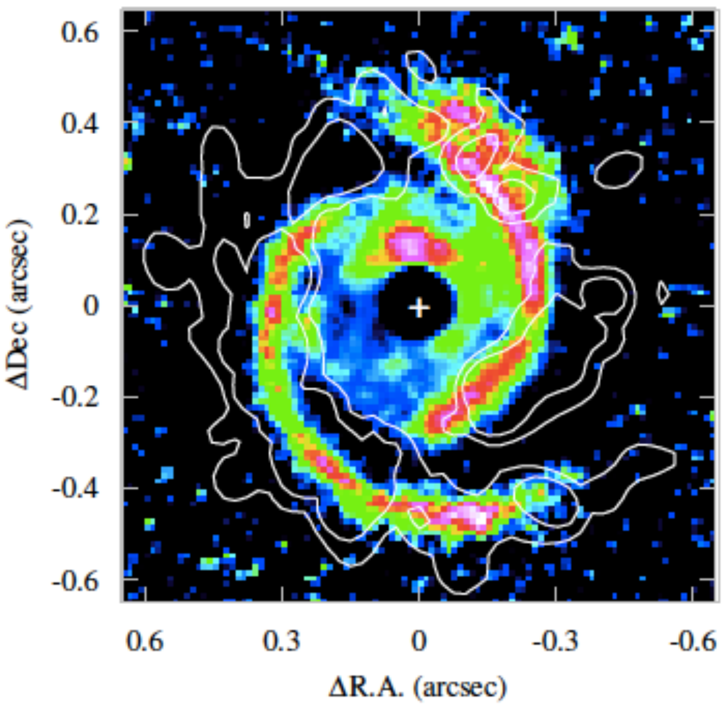


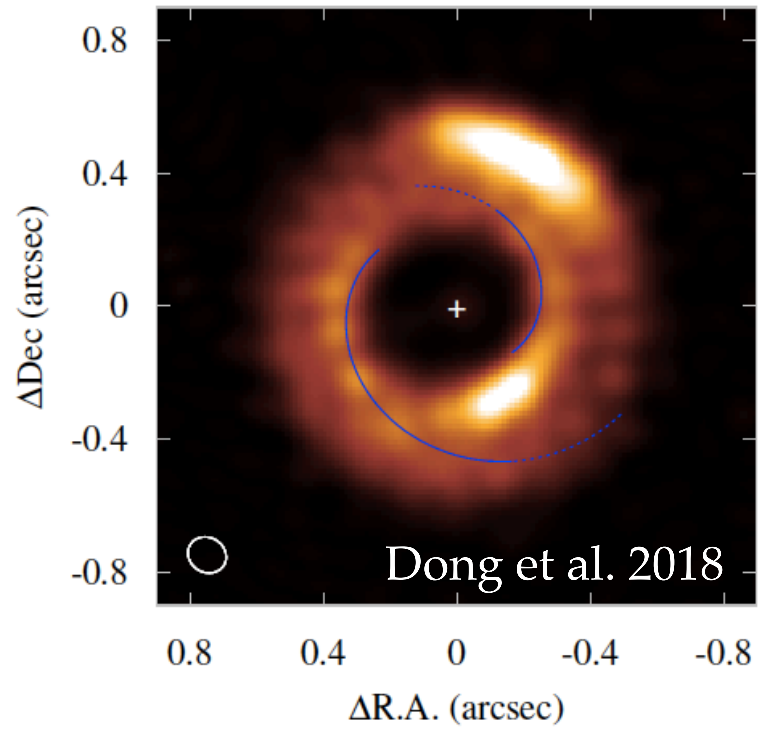


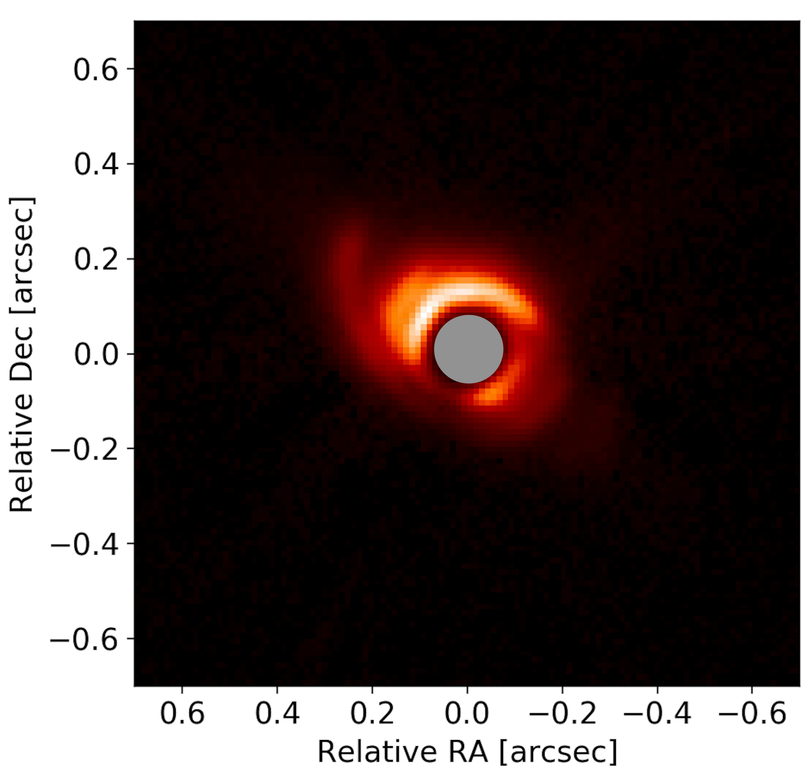
Also van der Marel et al. 2016, Kraus et al. 2017, Boehler et al. 2017, Cazzoletti et al. 2018, van der Plas et al. 2018

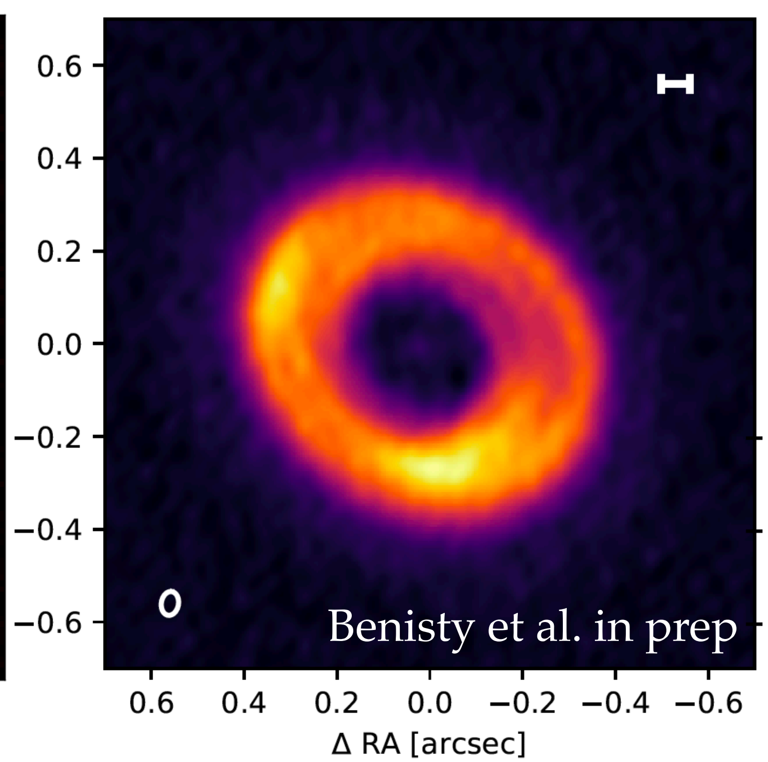
Spiral counterparts in the mm

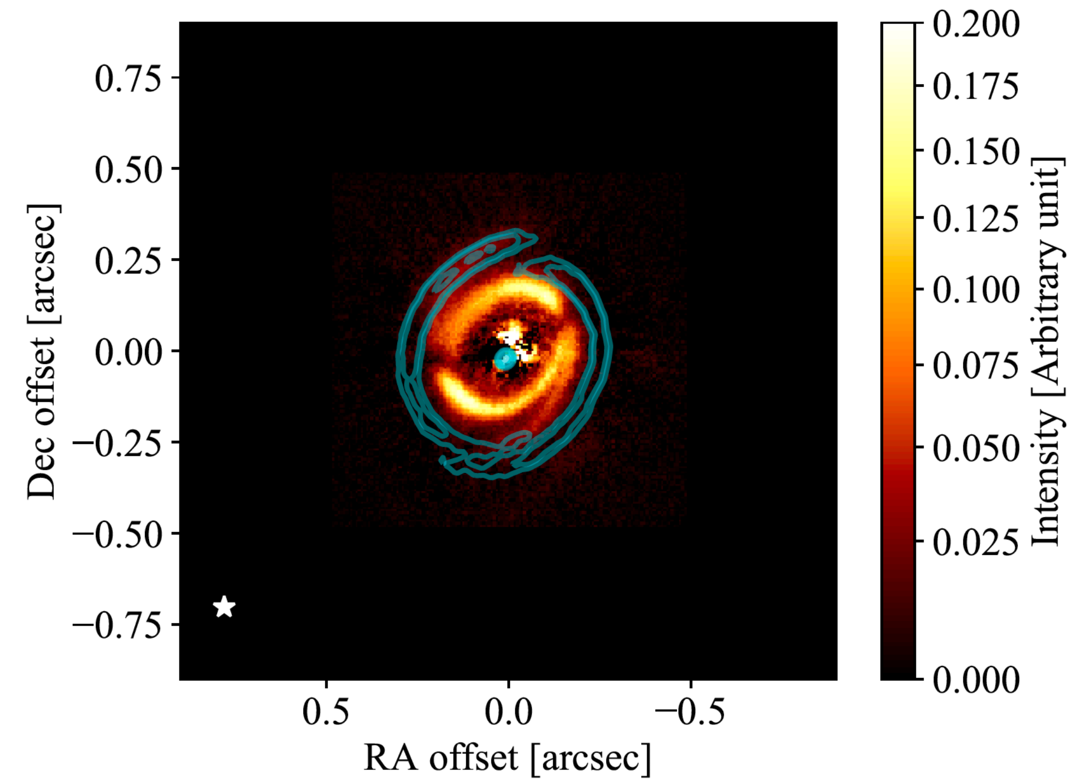
- Weak spirals in mm
- Different radial locations result from projection effects.
- Pitch angles trace the vertical temperature profile (Juhasz & Rosotti 2018, Rosotti et al. subm)





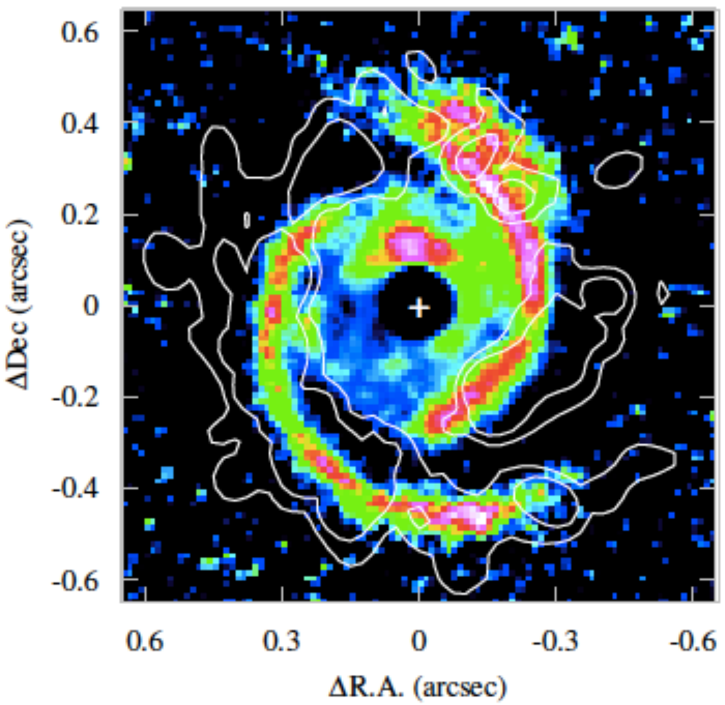


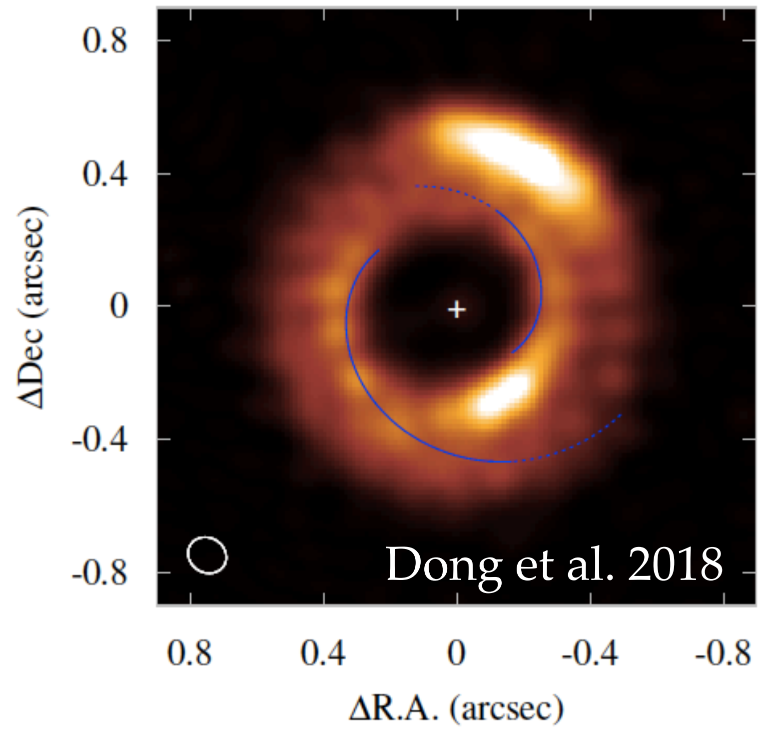




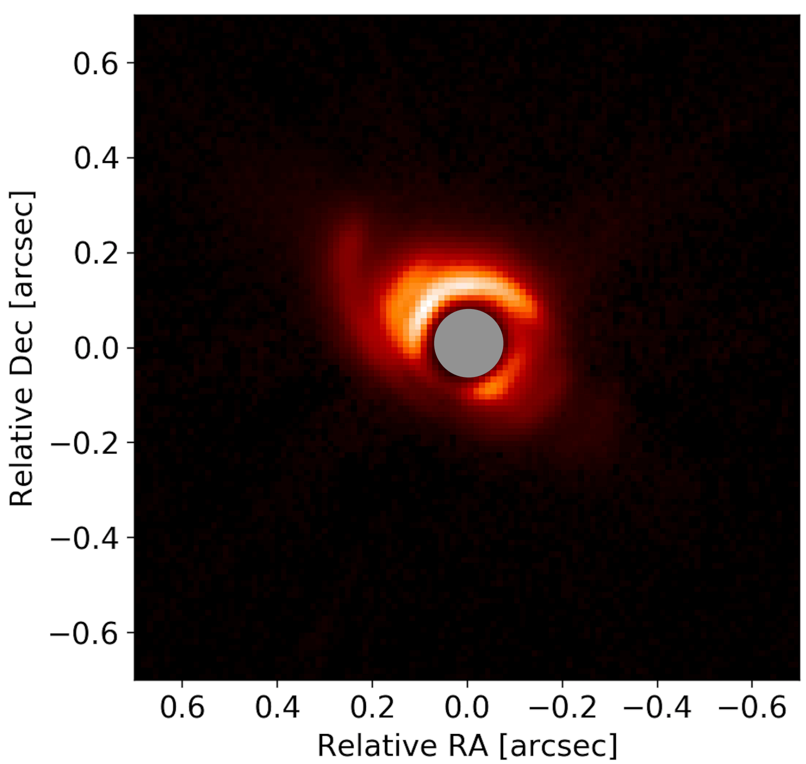
Also van der Marel et al. 2016, Kraus et al. 2017, Boehler et al. 2017, Cazzoletti et al. 2018, van der Plas et al. 2018

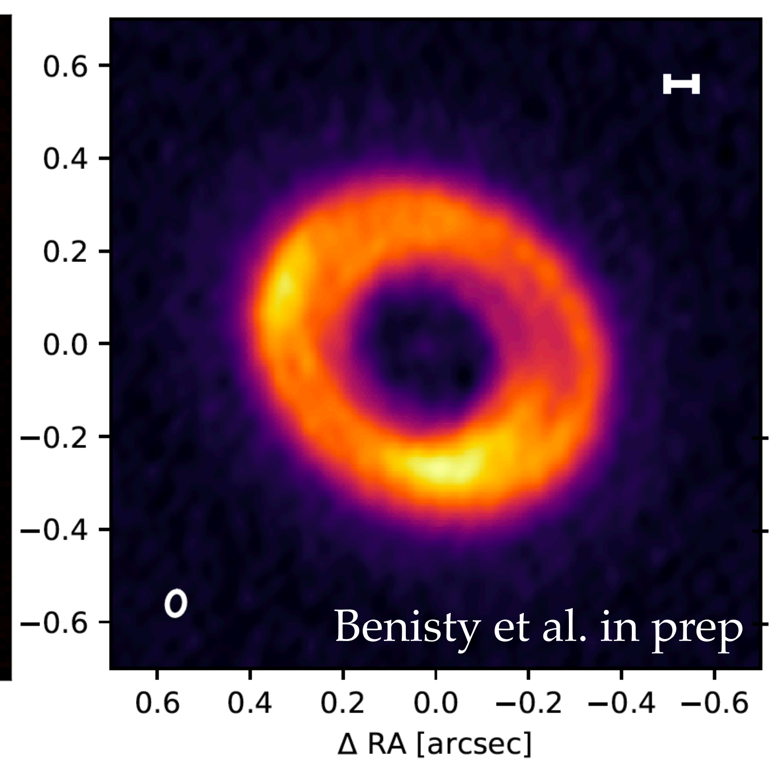
Spiral counterparts in the mm





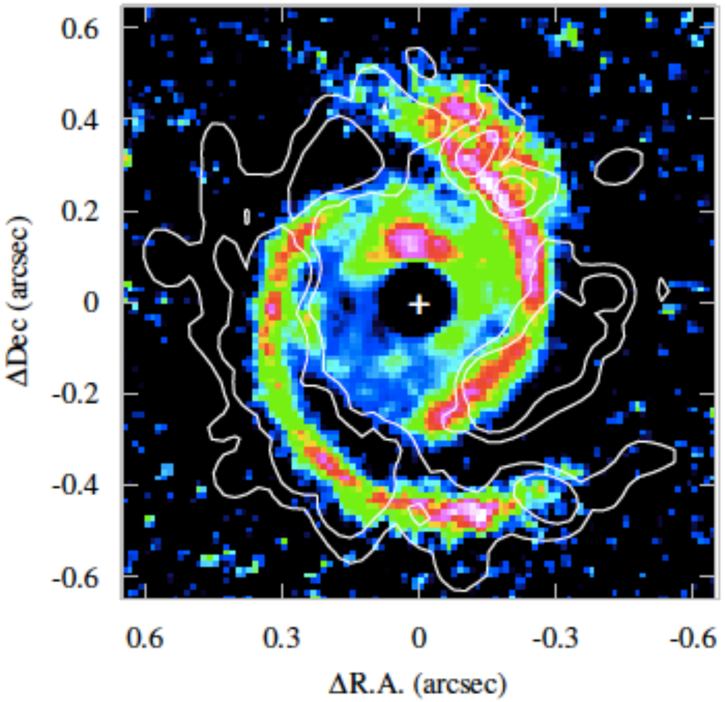
- Weak spirals in mm
- Different radial locations result from projection effects.
- Pitch angles trace the vertical temperature profile (Juhasz & Rosotti 2018, Rosotti et al. subm)

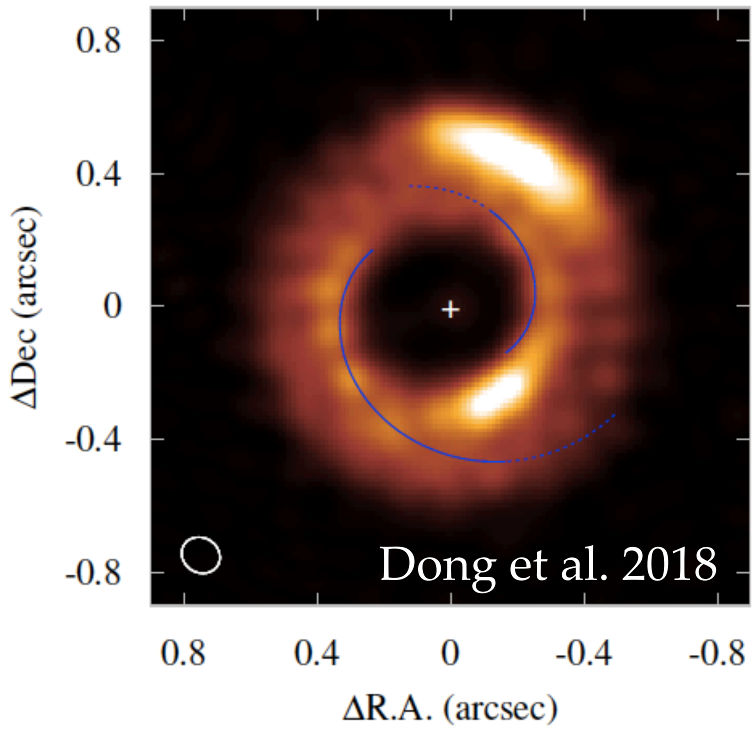




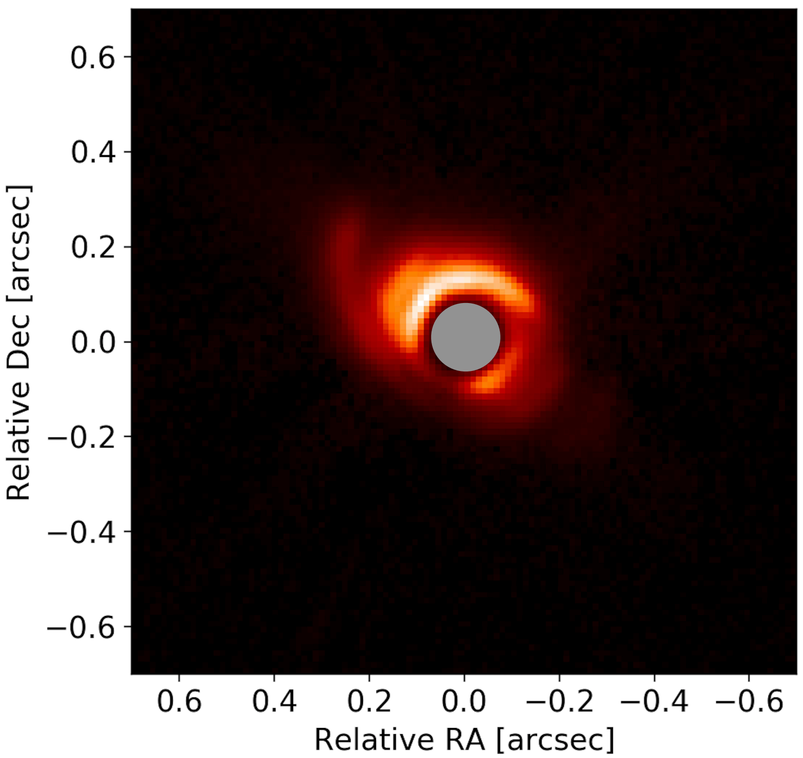
Also van der Marel et al. 2016, Kraus et al. 2017, Boehler et al. 2017, Cazzoletti et al. 2018, van der Plas et al. 2018

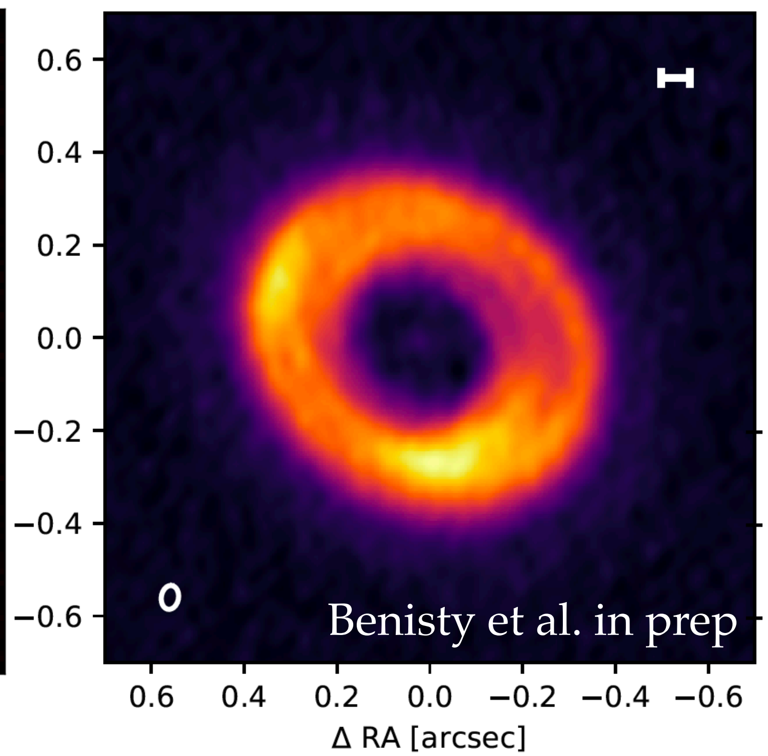
Spiral counterparts in the mm





- Weak spirals in mm
- Different radial locations result from projection effects.
- Pitch angles trace the vertical temperature profile (Juhasz & Rosotti 2018, Rosotti et al. subm)



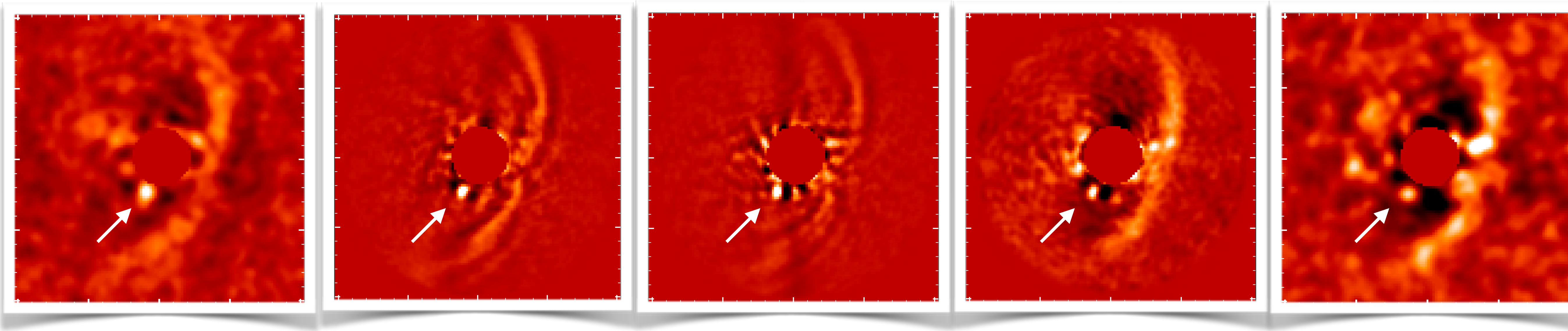


- A handful show evidence for shadow counterparts in mm (Casassus et al. 2018, 2019, Mayama et al. 2019)
- Transition disks show fascinating substructures possibly indicating the presence of multiple planets (Perez et al. 2019)

Also van der Marel et al. 2016, Kraus et al. 2017, Boehler et al. 2017, Cazzoletti et al. 2018, van der Plas et al. 2018

Discovery of PDS70b

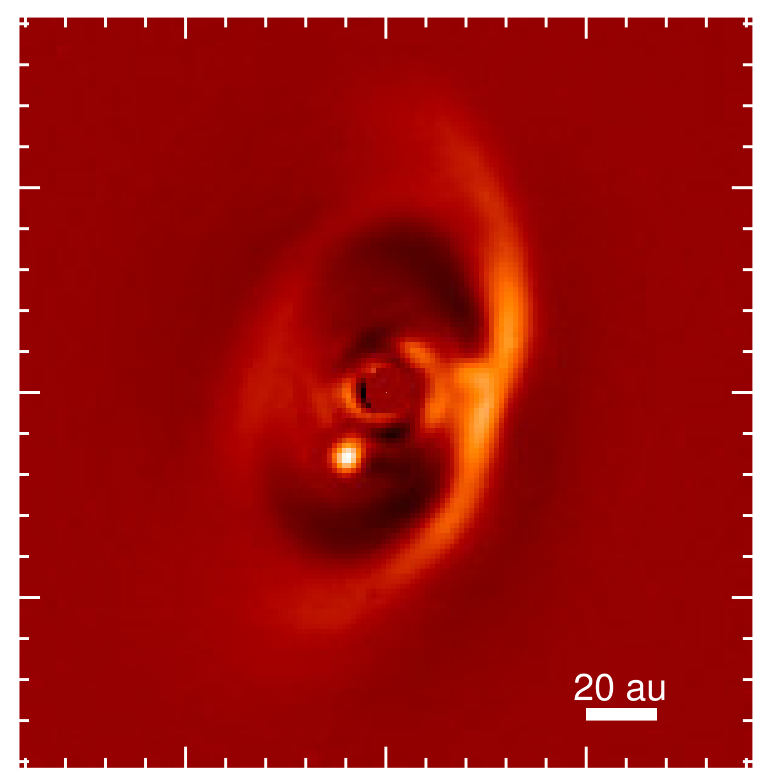
Gemini/NICI 2012-03-31 | VLT/SPHERE 2015-05-03 | VLT/SPHERE 2015-05-31 | VLT/SPHERE 2016-05-14 | VLT/NACO 2016-06-01



L' (3.8 microns) | H-band (1.6 microns) | H-band (1.6 microns) | K-band (2.1 microns) | L' (3.8 microns)

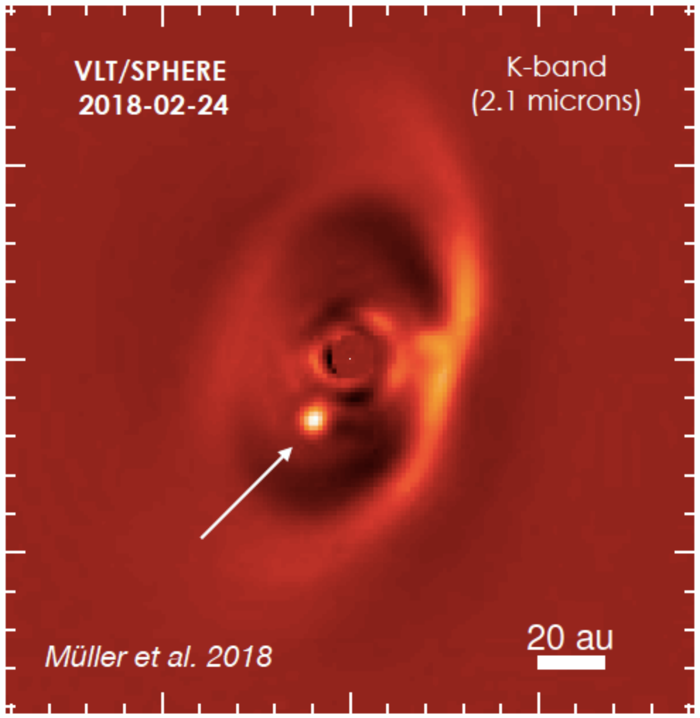
Point source ~ 22 au at PA~155 deg.
with very red colours : young planet with dusty/cloudy atmosphere or a circumplanetary disk.

T~1000-1600 K, R~1.4-3.7 RJup, Mass 2-17 MJup.

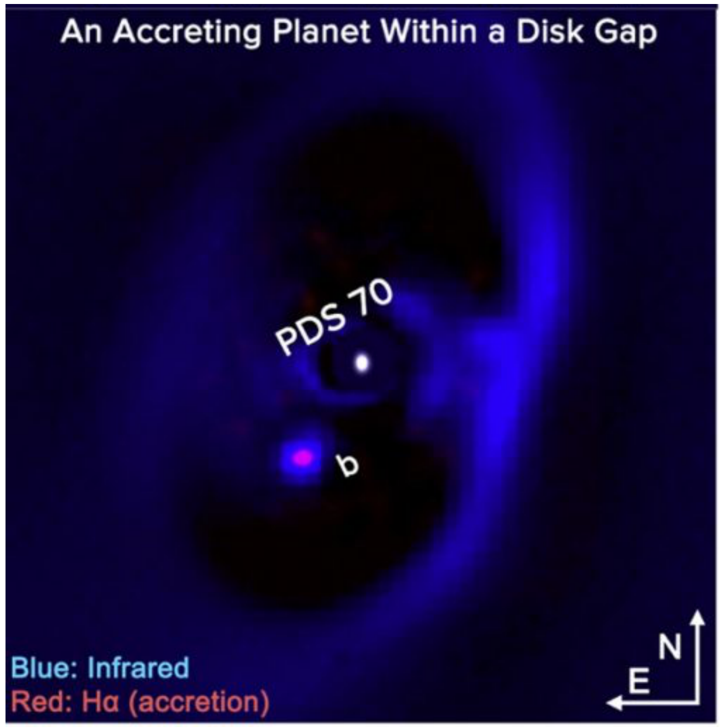


Keppler et al. 2018; Müller et al. 2018; Christiaens et al. 2019b

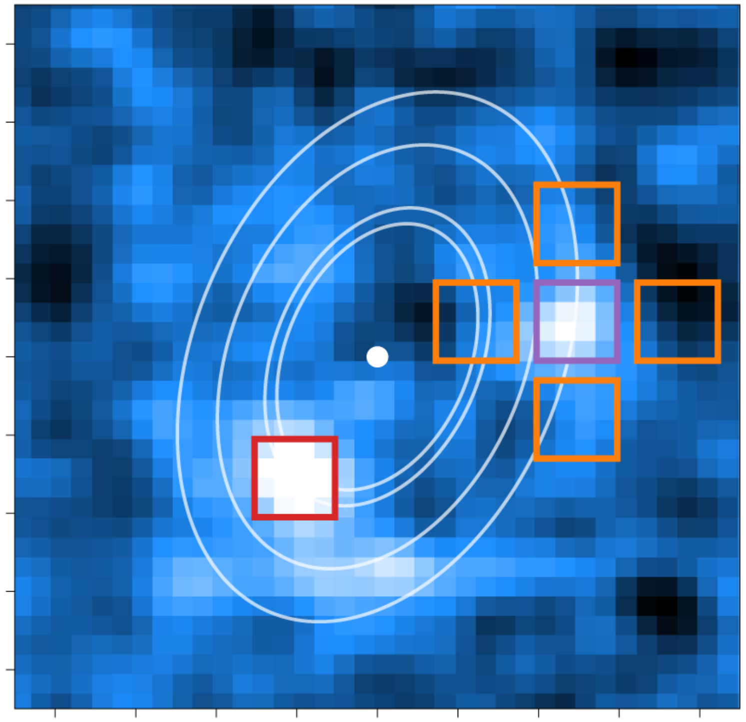
A multiple planetary system



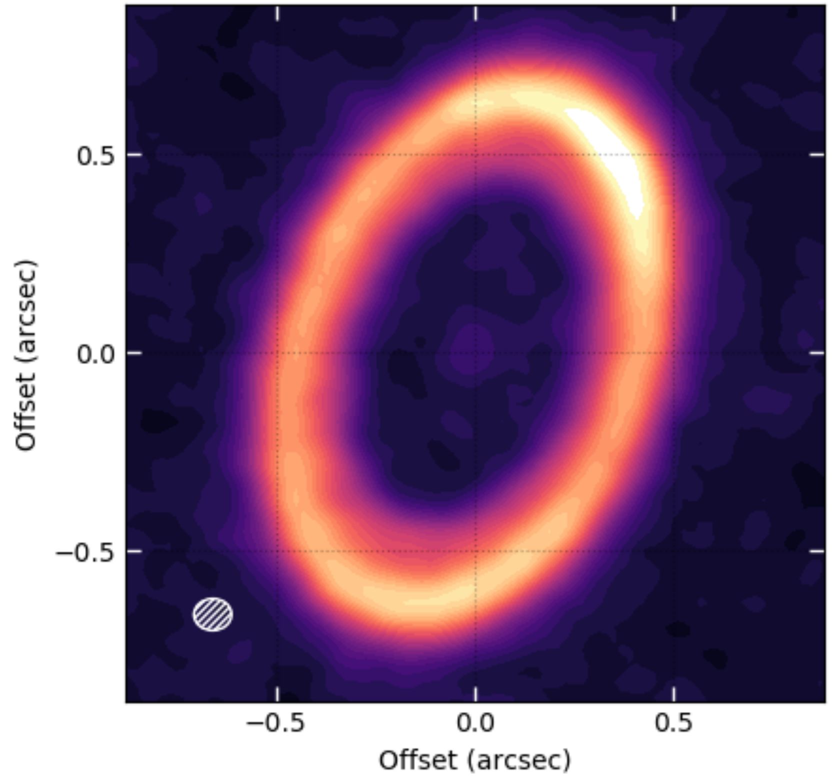
Muller et al. 2018

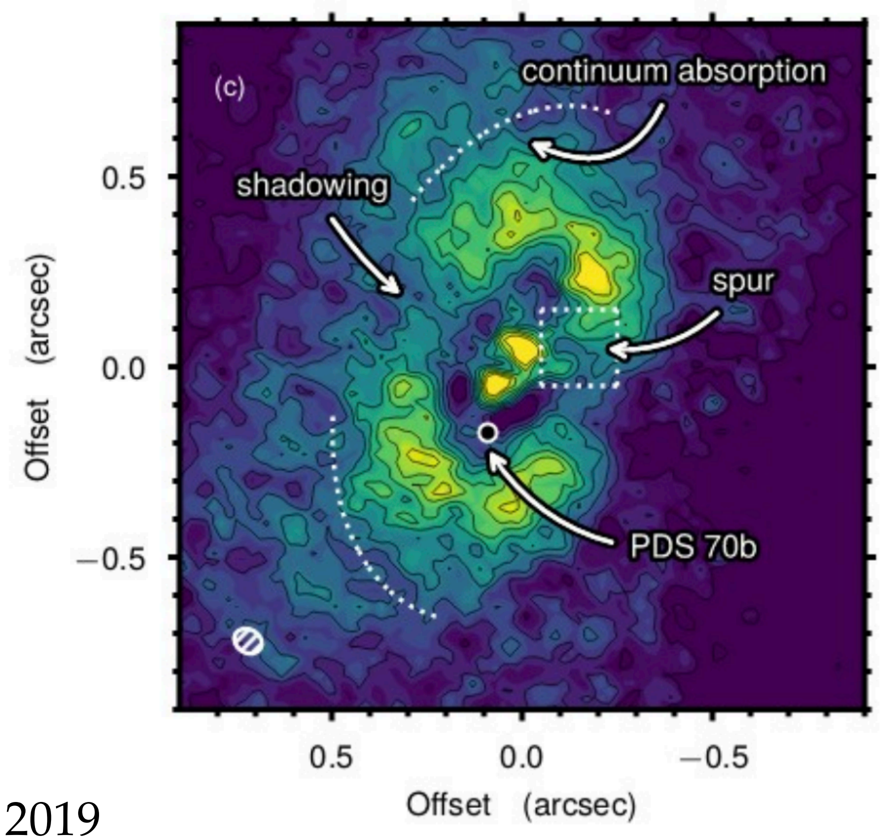


Wagner et al. 2018



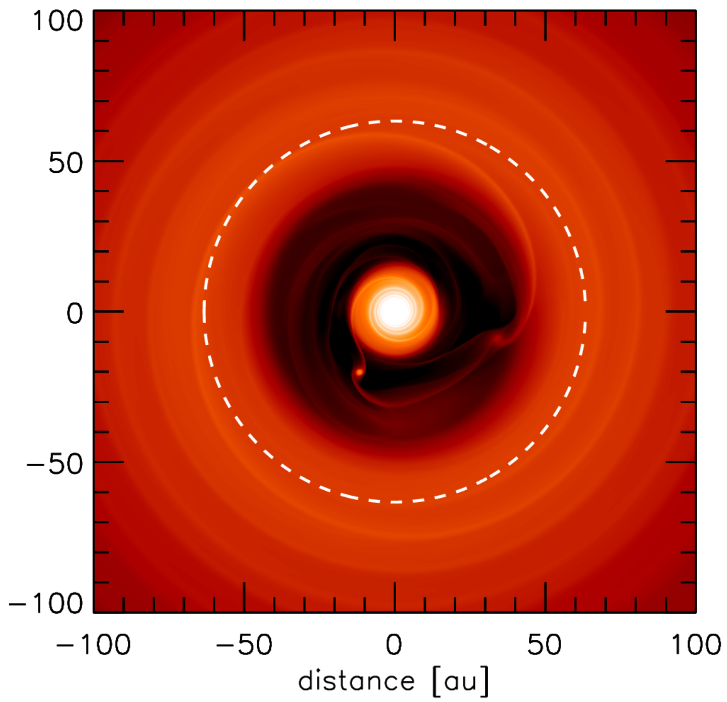
Haffert et al. 2019



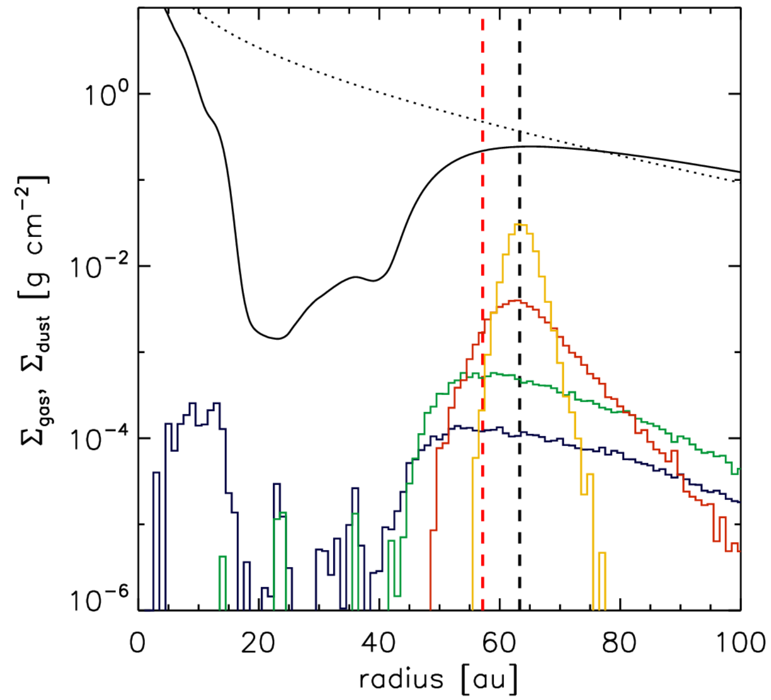


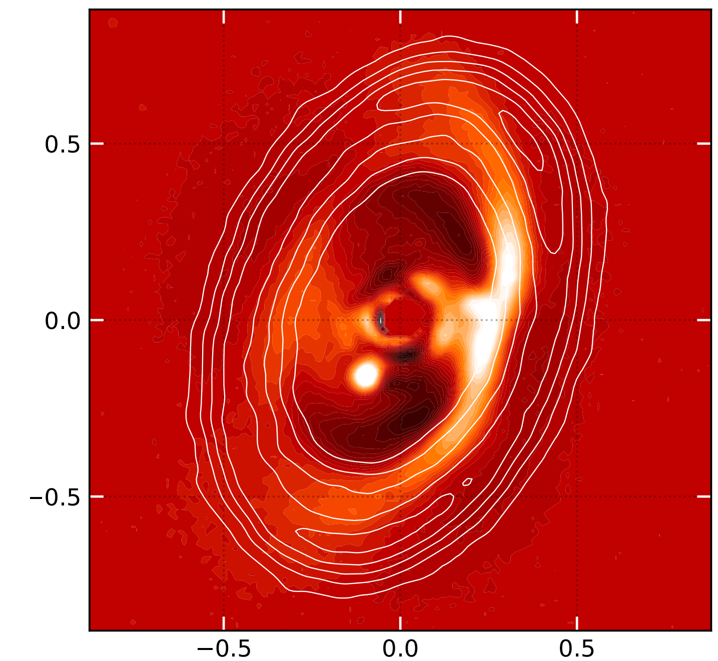
Keppler et al. 2019

A multiple planetary system

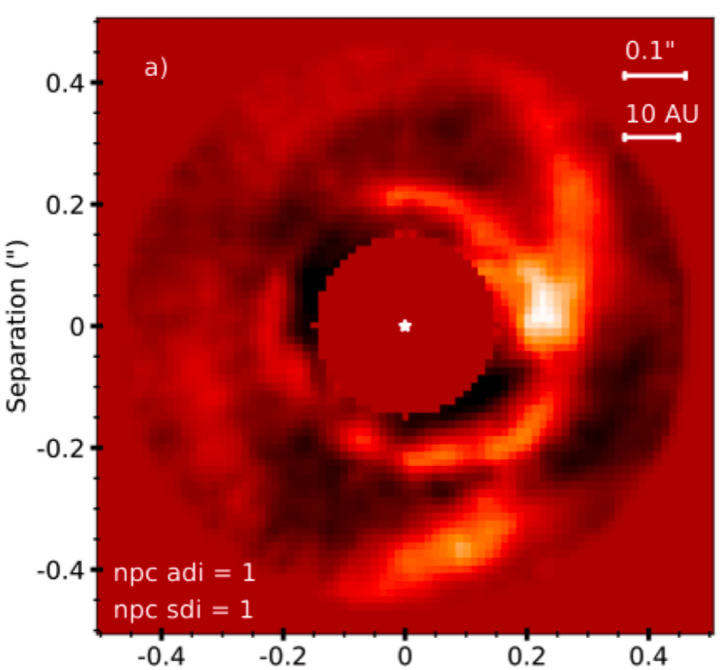


Bae et al. in prep





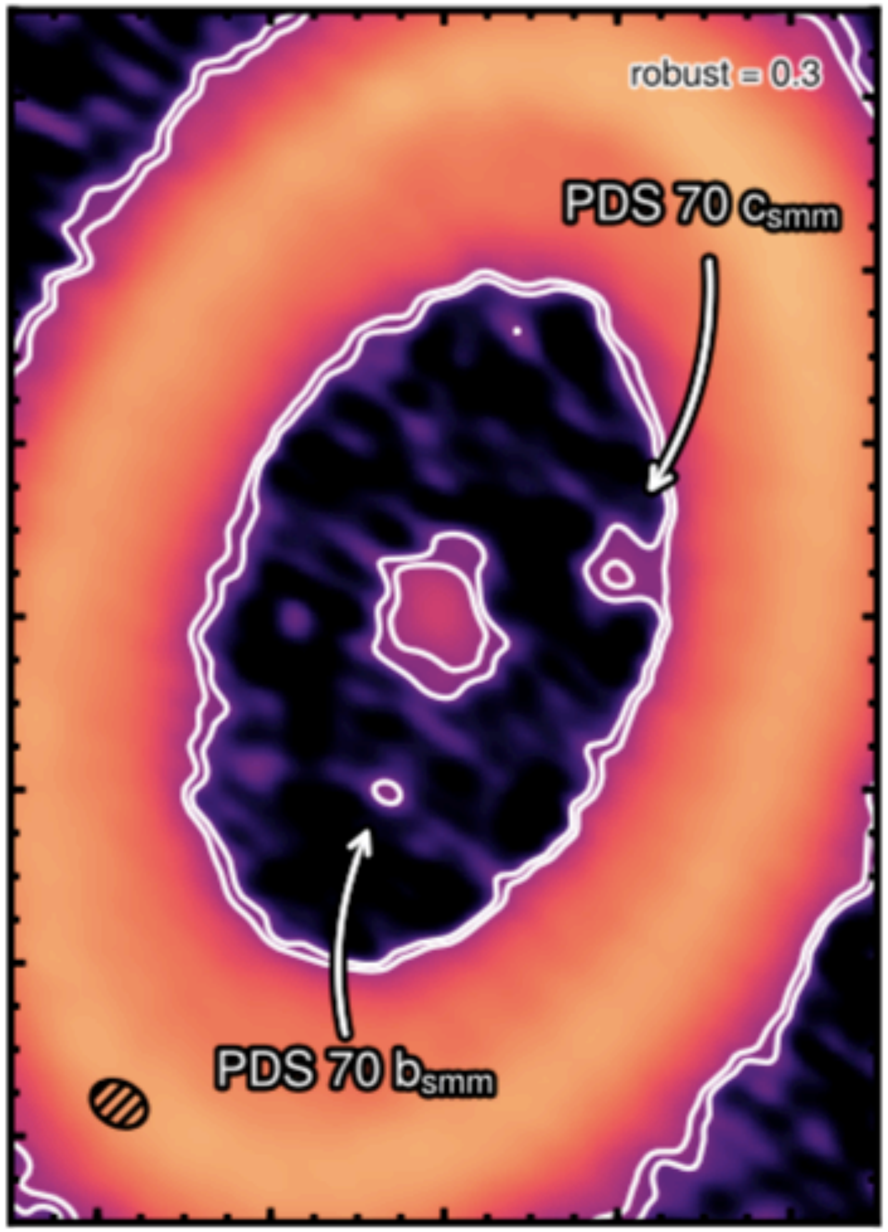
Keppler et al. 2019



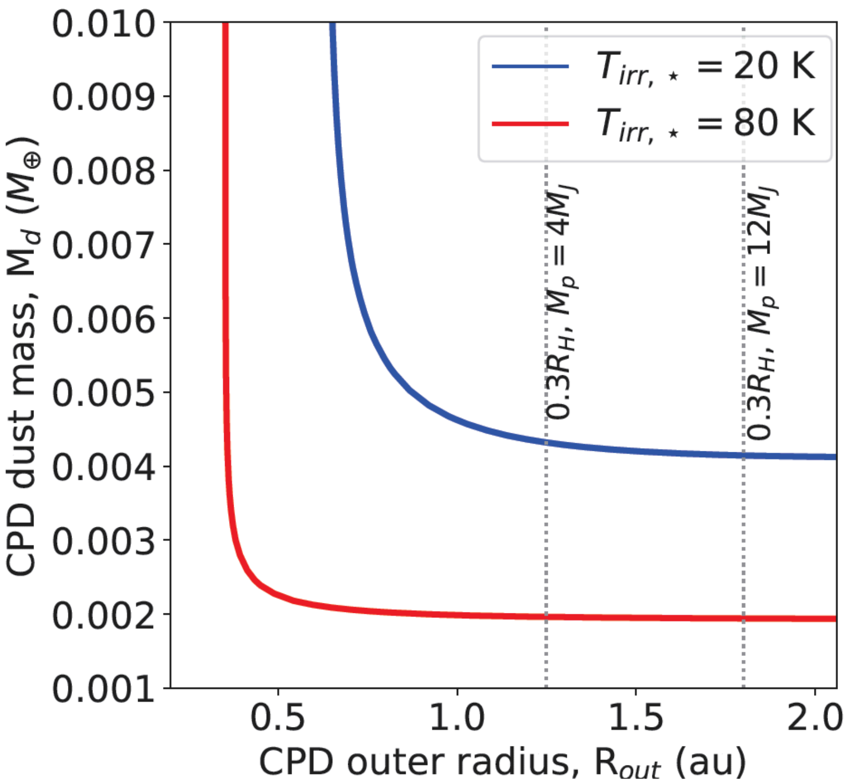
Christiaens et al. 2019a

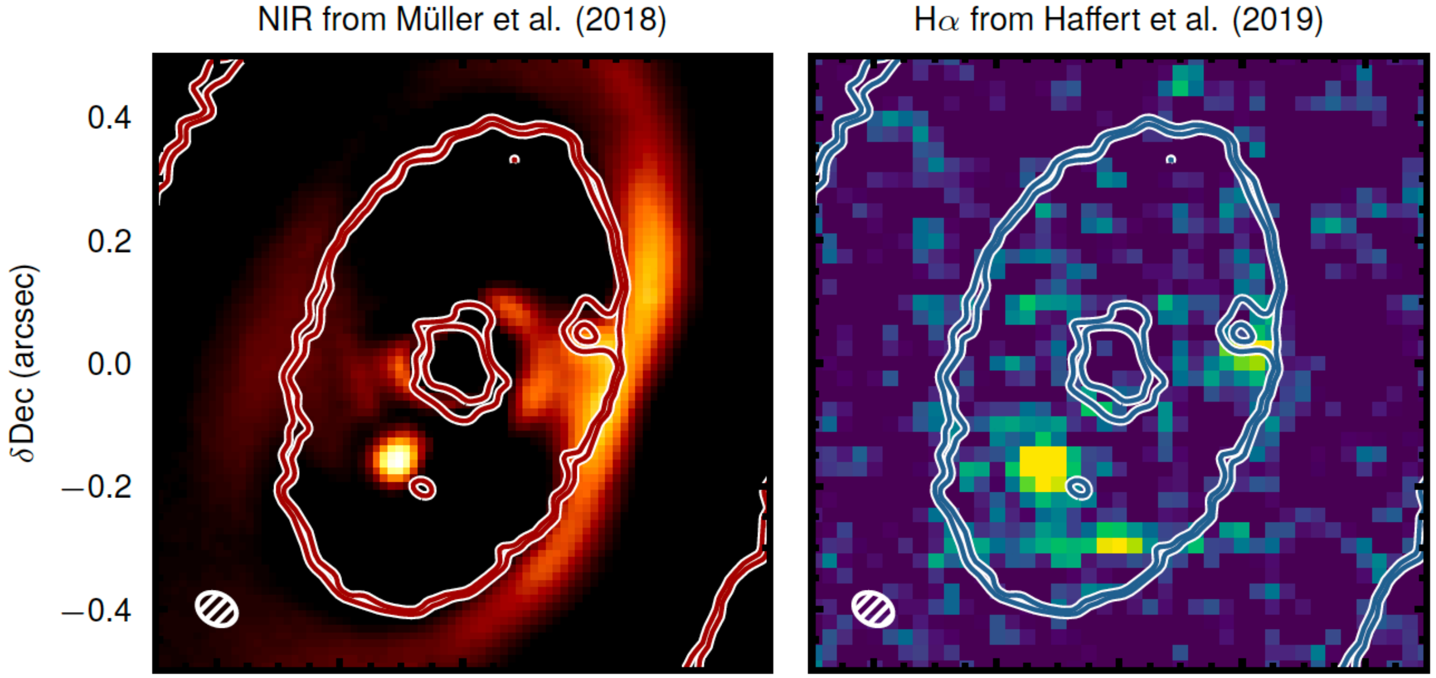
Simulations with two planets in resonance allow to reproduce most features (gap width, dust radii, …)

Sub-mm detections



Isella et al. 2019





Assuming vertically isothermal CPD, considering viscous heating & external irradiation.

Continuum emission associated with PDS70 c: 2-4e-3 M_E

Conclusions

All disks seem to show features when observed with high-enough resolution.

1. Rings are frequent and can be used to derive the shape of the surface layers.

2. Spirals are found around old (> 8 Myr), intermediate-mass stars with transition disks, or in circumbinary disks.

3. Shadows indicate small (~few deg) and large (~70 deg) misalignments between disk regions. Targets with strong misalignments also have high NIR excess.

4. The combination scattered light & mm data can help constrain the (possible) planet population in disks and vertical temperature structure.

5. PDS70 is an excellent case to study disk + multiple planet interactions.

Conclusions

All disks seem to show features when observed with high-enough resolution.

1. Rings are frequent and can be used to derive the shape of the surface layers.

2. Spirals are found around old (> 8 Myr), intermediate-mass stars with transition disks, or in circumbinary disks.

3. Shadows indicate small (~few deg) and large (~70 deg) misalignments between disk regions. Targets with strong misalignments also have high NIR excess.

4. The combination scattered light & mm data can help constrain the (possible) planet population in disks and vertical temperature structure.

5. PDS70 is an excellent case to study disk + multiple planet interactions.

Brightness (AO) limited sample!!

Our next step

SPHERE LP DESTINYS PI: C. Ginski (U. Amsterdam)

Disk Evolution Study Through Imaging of Nearby Young Stars

- **85 targets**
- **1 – 10 Myr**
- **probing low stellar masses and dust masses**