The complex structure of HD 141569 A inside 50 AU

Garima Singh
Marie Skłodowska-Curie Postdoctoral Fellow
LESIA, Observatoire de Paris, France
garima.singh@obspm.fr

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Contributors: A. Boccaletti, R. Boukrouche, T. Bhowmik, C. Perrot, Q. Kral, J. Milli, J. Olofsson, J. Mazoyer

l'Observatoire de Paris — LESIA

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

European Commission

SPHERE
Spectro-Polarimetric High-contrast Exoplanet REsearch

PSL
UNIVERSITÉ PARIS

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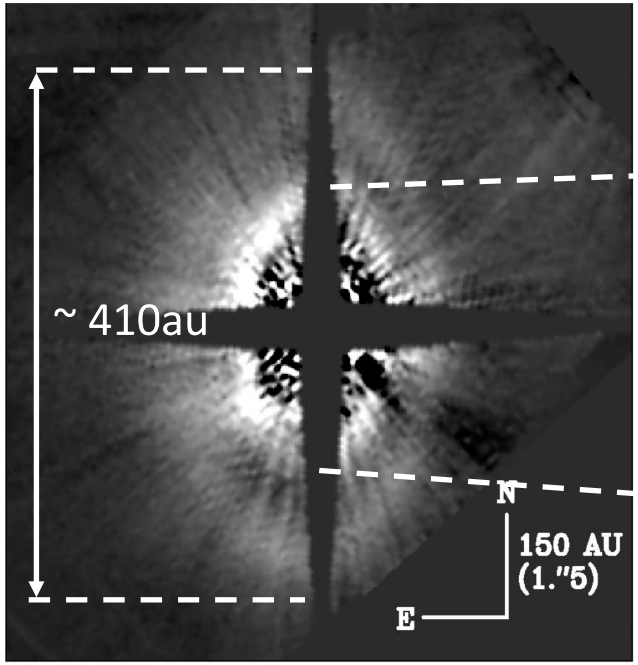
Circumstellar disk around HD 141569 A

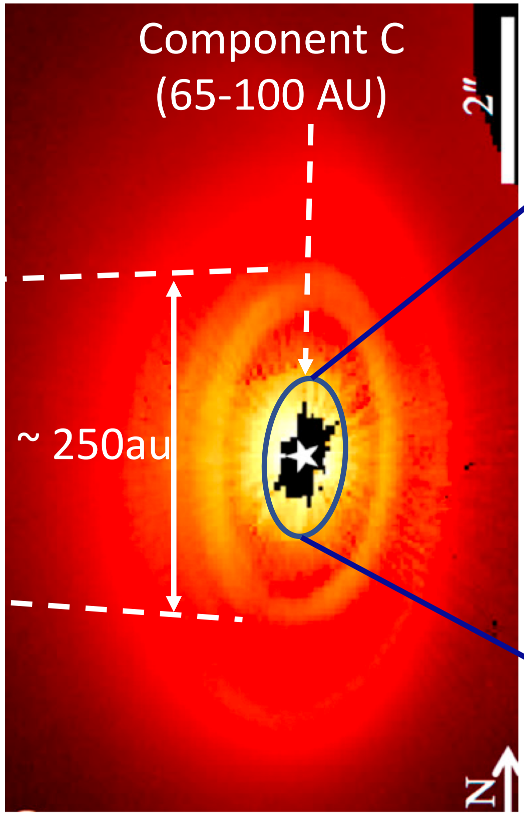
- 5±3 Myr old Gas-rich debris disk, Herbig Ae/Be star A0Ve (V = 7.12, H = 6.86) at 116^{+9}_{-8} pc.
- Most likely in a stage between transitional and debris disk.

1.1 μm NICMOS HST



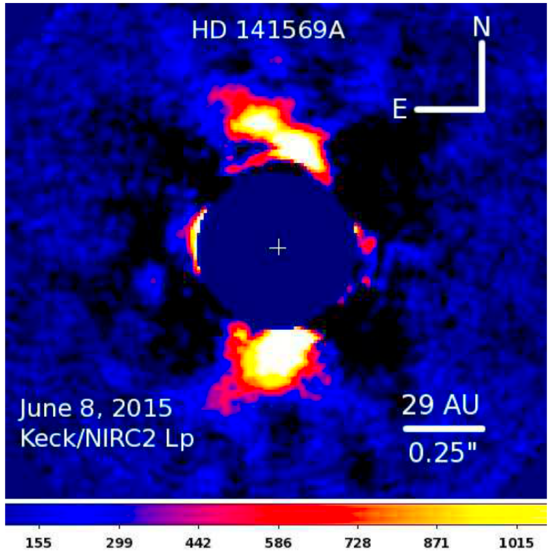
Weinberger et al. 1999
(Also Augereau et al. 1999a)

Broadband optical, HST/STIS



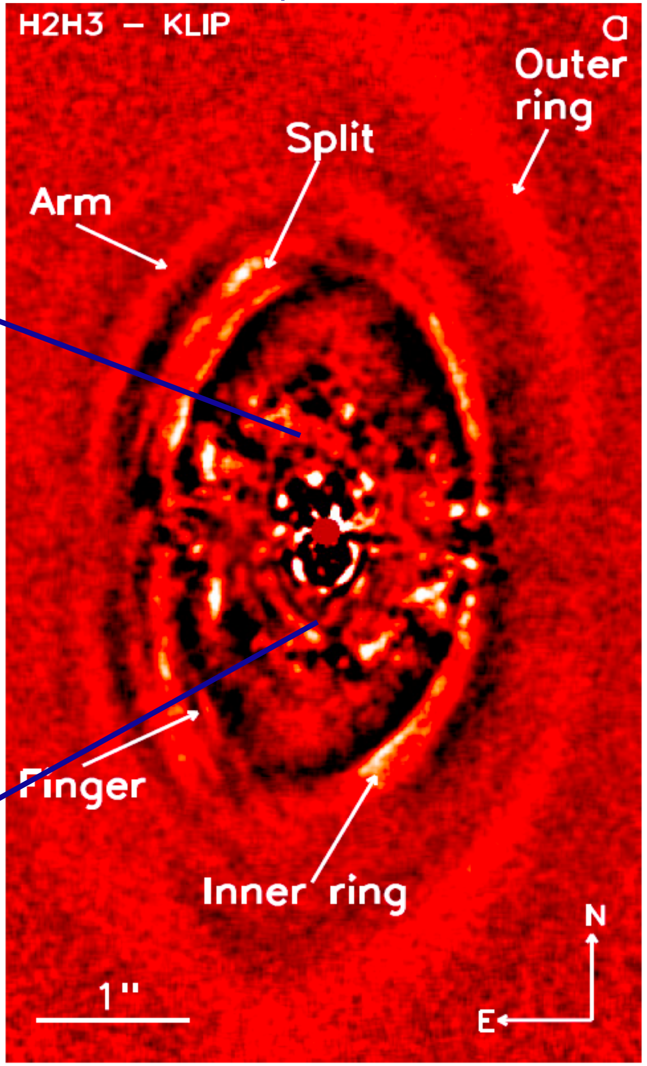
Konishi et al. 2016
(Also Fisher et al. 2000,
Goto et al. 2006)

Keck L' band, 3.778 μm
Disk feature between 30-40 au



Currie et al. 2016
(Also Mawet et al. 2017)

Near-IR (1.6 μm), SPHERE/VLT



Perrot et al. 2016

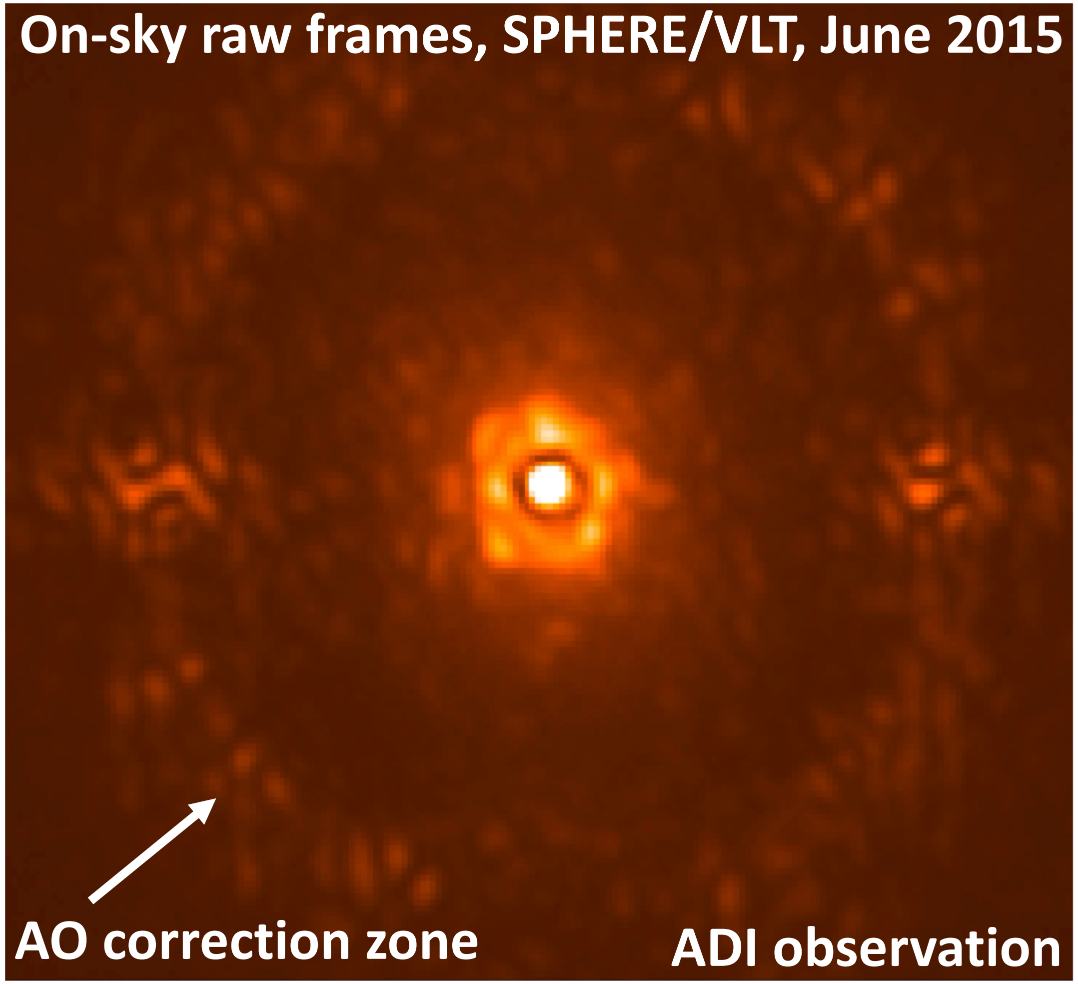
High-contrast imaging observation of HD 141569 A

Adaptive Optics (AO)/Extreme-AO → **Coronagraph** → **Speckle suppression**

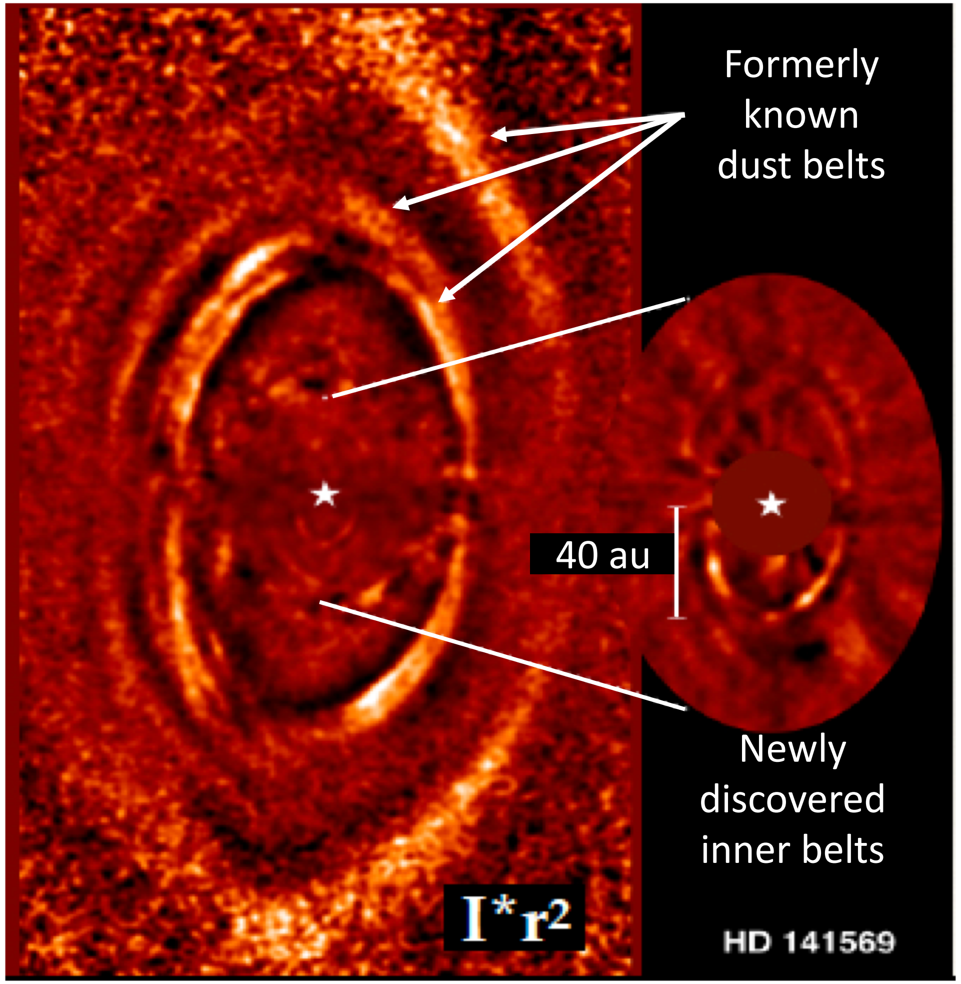
Correct and calibrate wavefront errors

Suppress starlight

Both actively and in post-processing

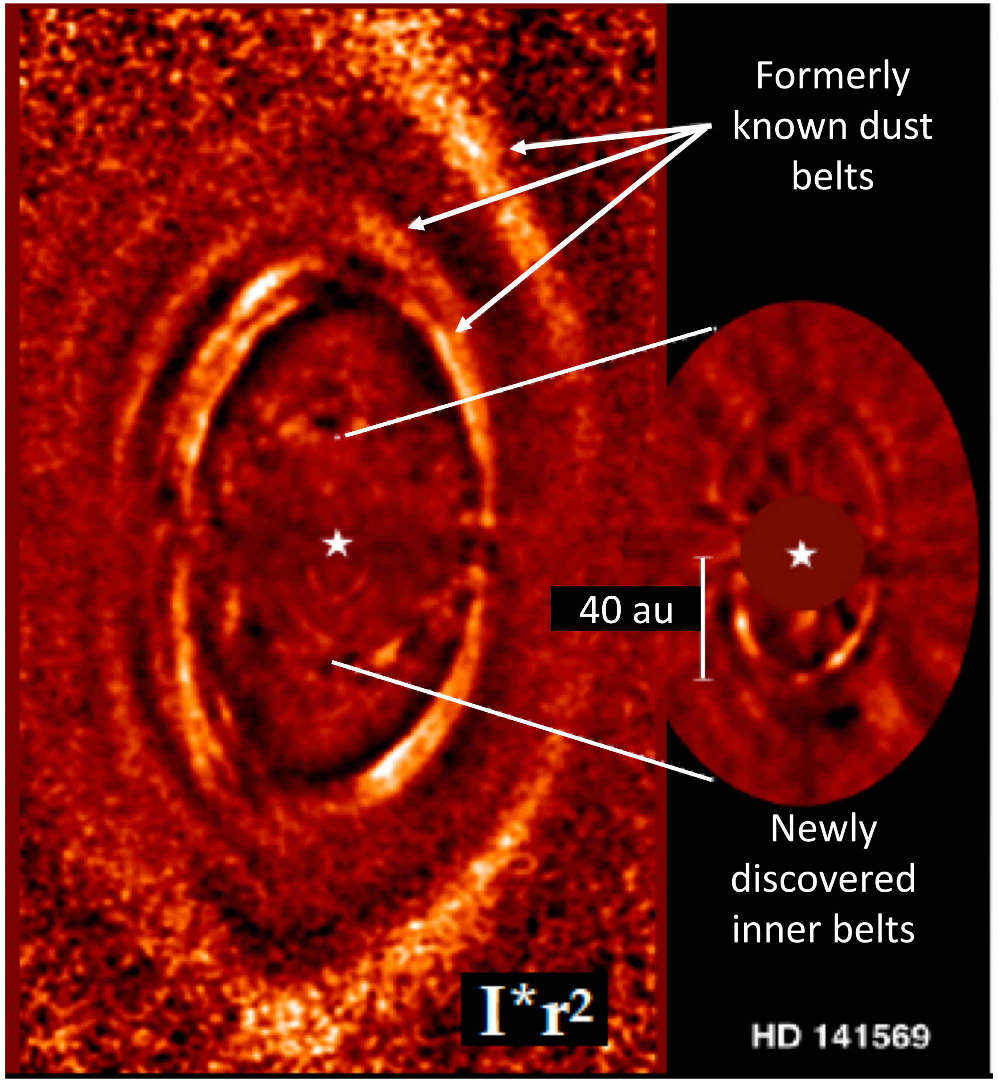


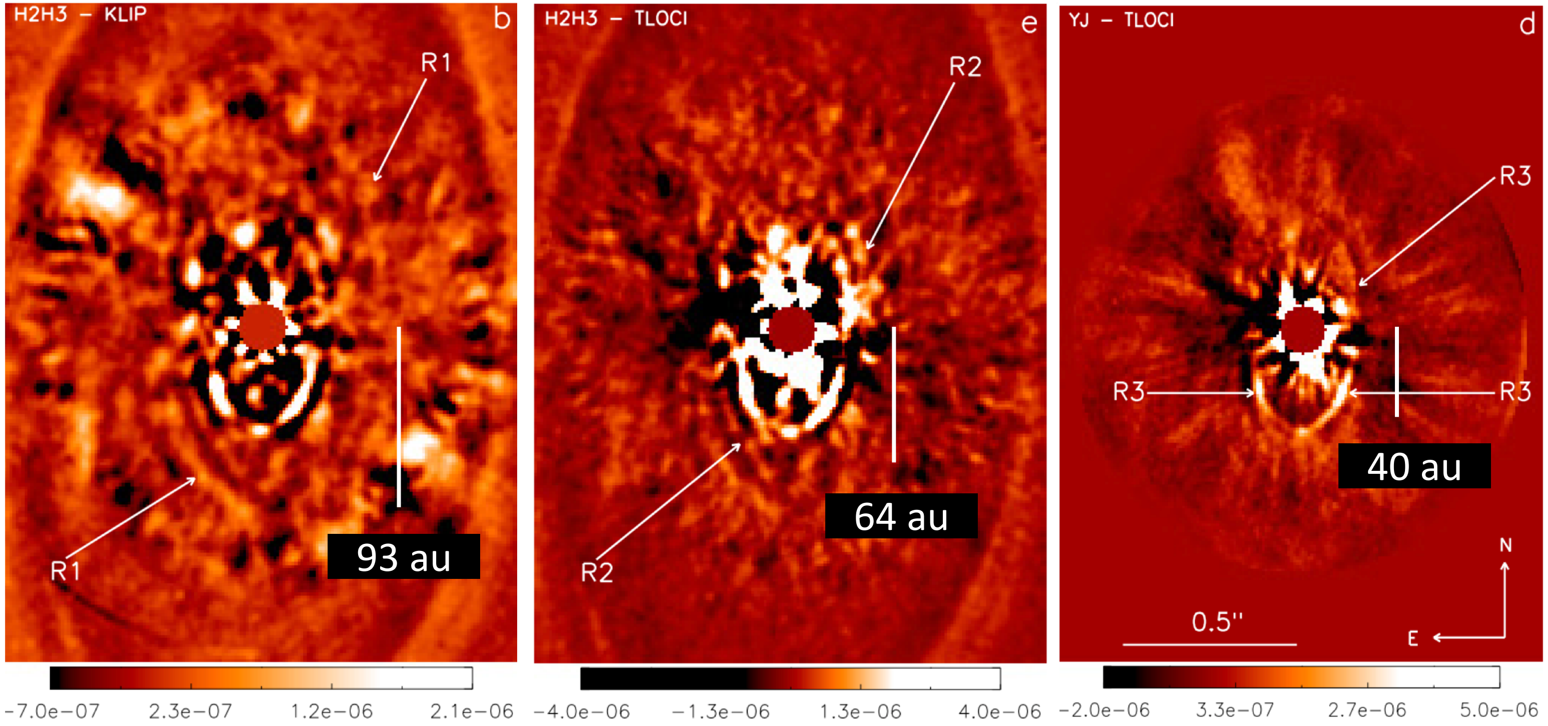
Post-processed final image →



Circumstellar disk around HD 141569 A

SPHERE/VLT resolved the scattered light emission inside 200 au revealing concentric broken rings.
Instrument: Infra-Red Dual Beam Imager and Spectrograph (IRDIS), FoV 11" x 11", 0.95 - 2.32 μm YJHK.

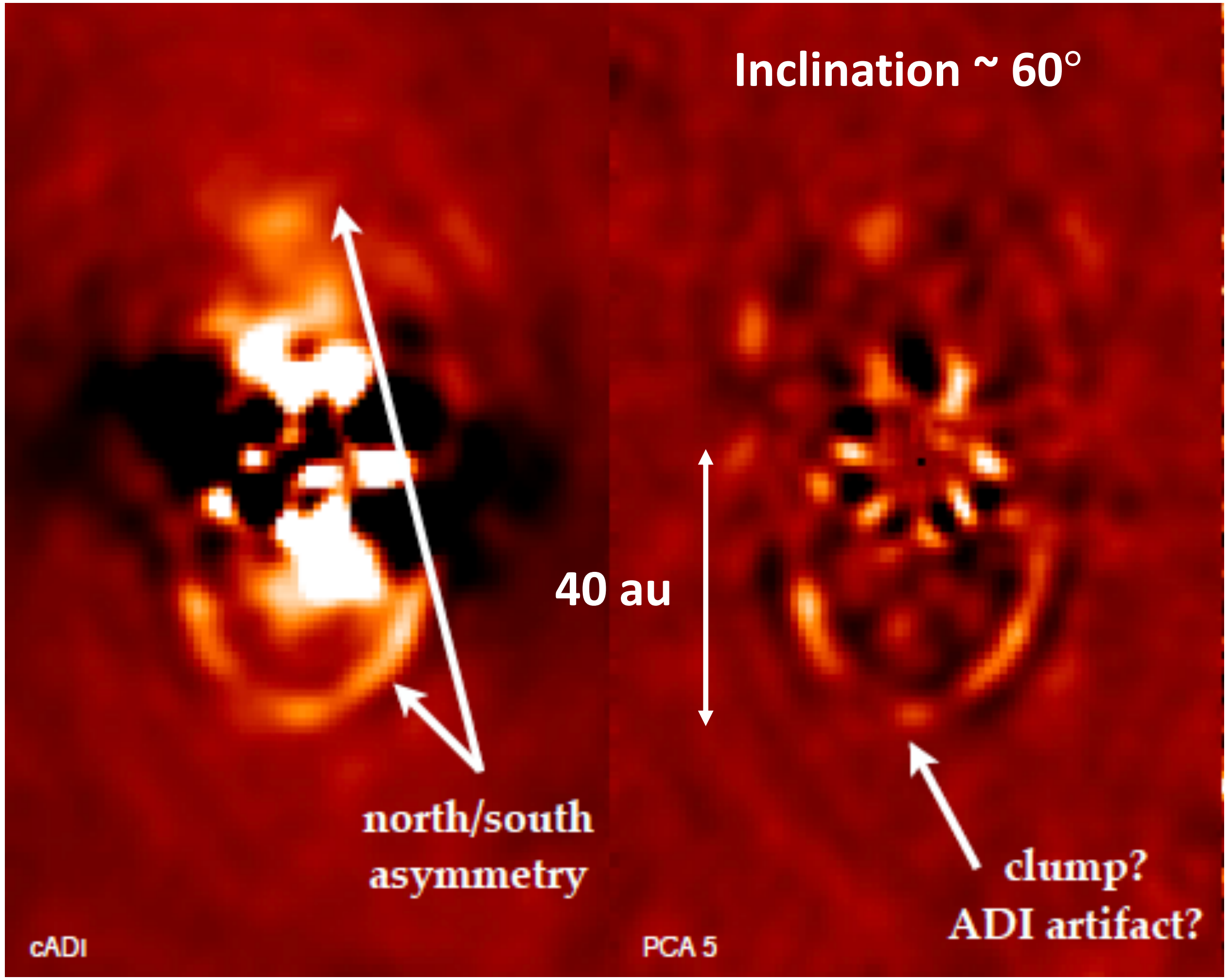




Asymmetries in intensity is observed within 40 au. (Perrot et al. 2016)

Circumstellar disk around HD 141569 A: The innermost ring at 40 au

Scattered light observation in total intensity (Angular Differential Imaging (ADI) reduced data)



Perrot et al. 2016

North-South asymmetry aligned with the disk projected major axis.

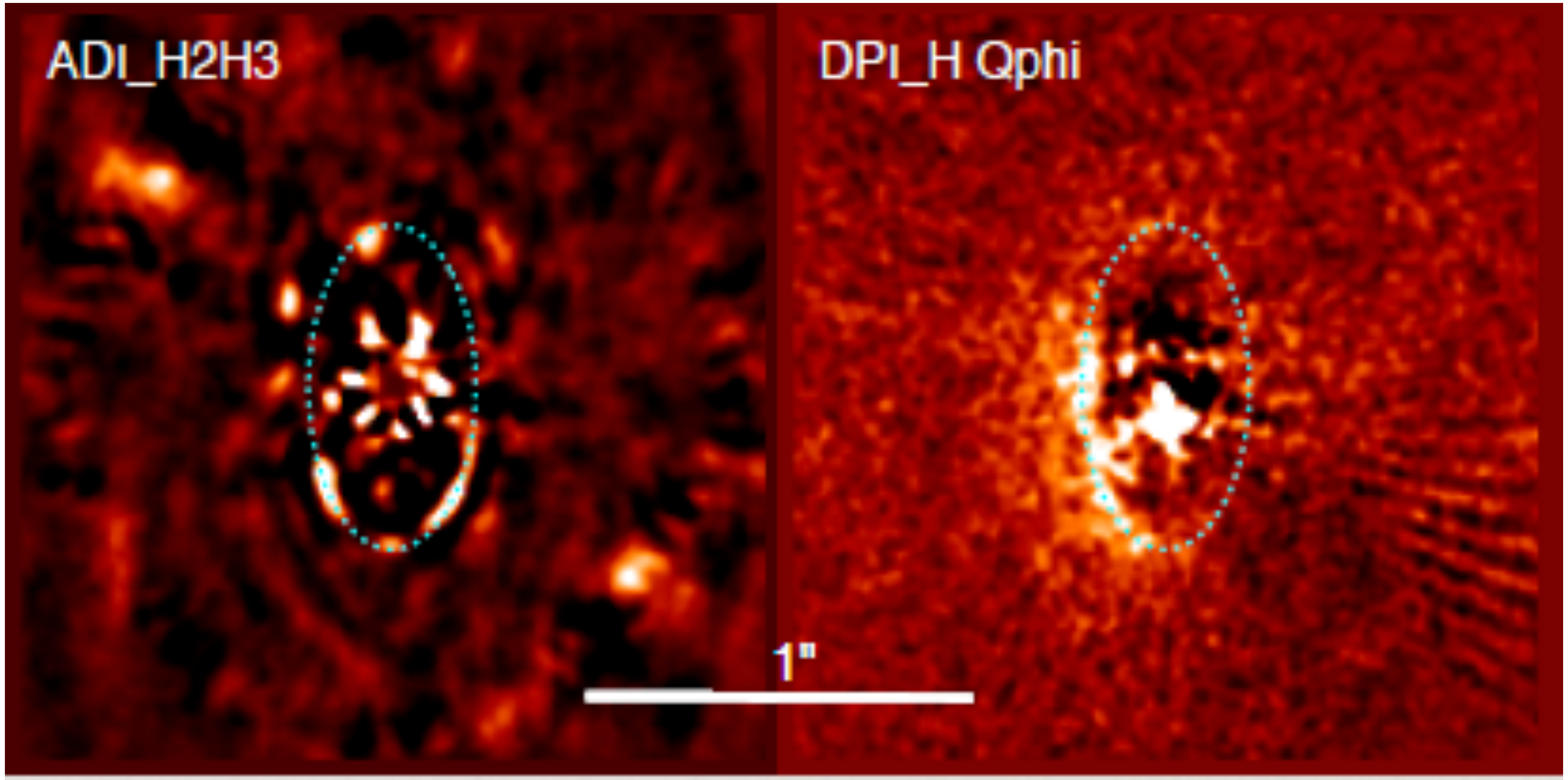
- Dust scattering phase function?
- Self subtraction due to ADI that can strongly modify the azimuthal distribution of the intensity.
- Azimuthal variation of the dust density?

Circumstellar disk around HD 141569 A: The innermost ring at 40 au

Scattered light observation:

In total intensity (H2H3* filter)

In Polarimetric intensity (boradband H, 1.6255 ± 0.146 μm)

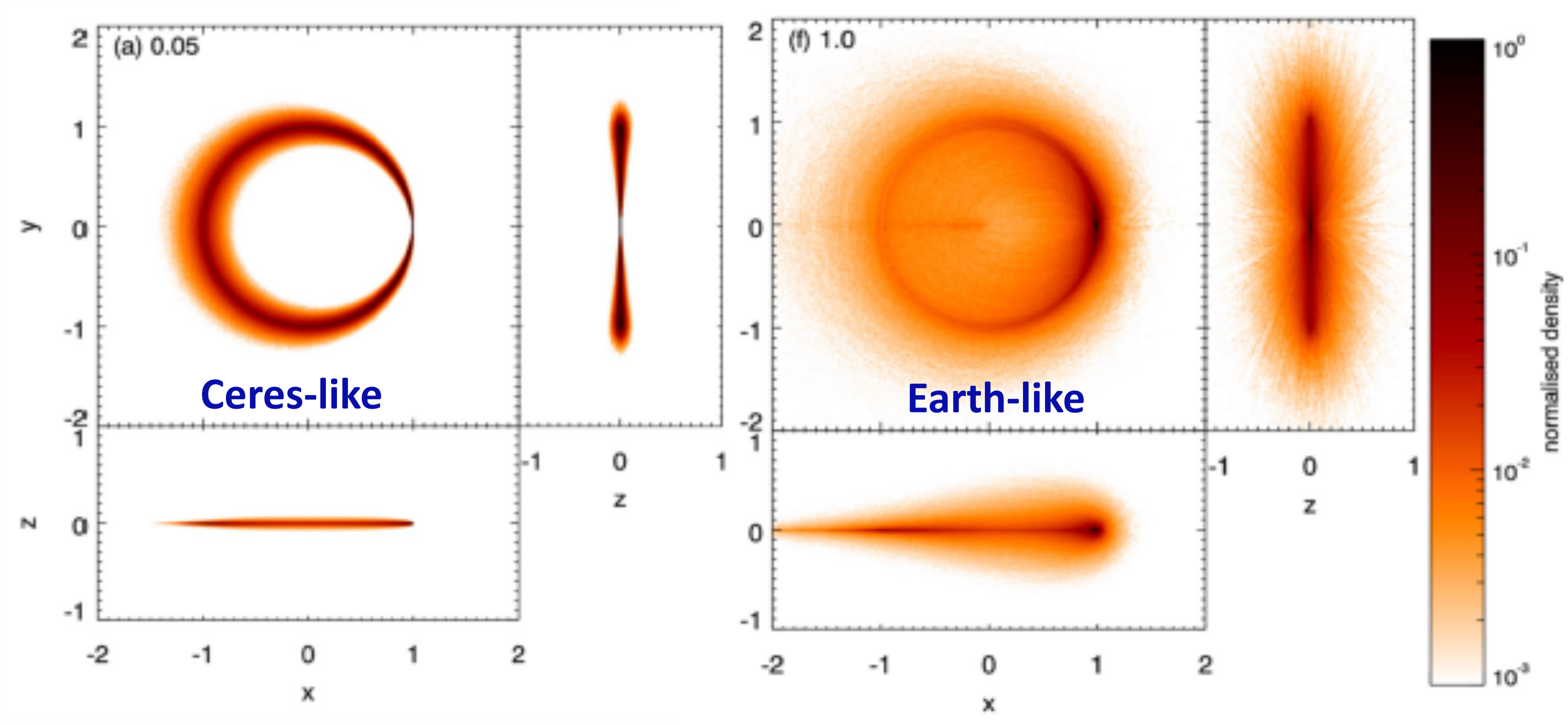


- N/S asymmetry in total intensity,
- E/W asymmetry in polarimetric intensity, North ansae indicates probable depletion of dust.
- S/E side is the front side

*H2H3 filter: 1.588 ± 0.023 μm, 1.67 ± 0.145 μm

Asymmetries in the innermost ring at 40 au

Hypothesis: Azimuthal variation of the dust density, possibly connected to massive collisions between planet embroys (Jackson et al. 2014).

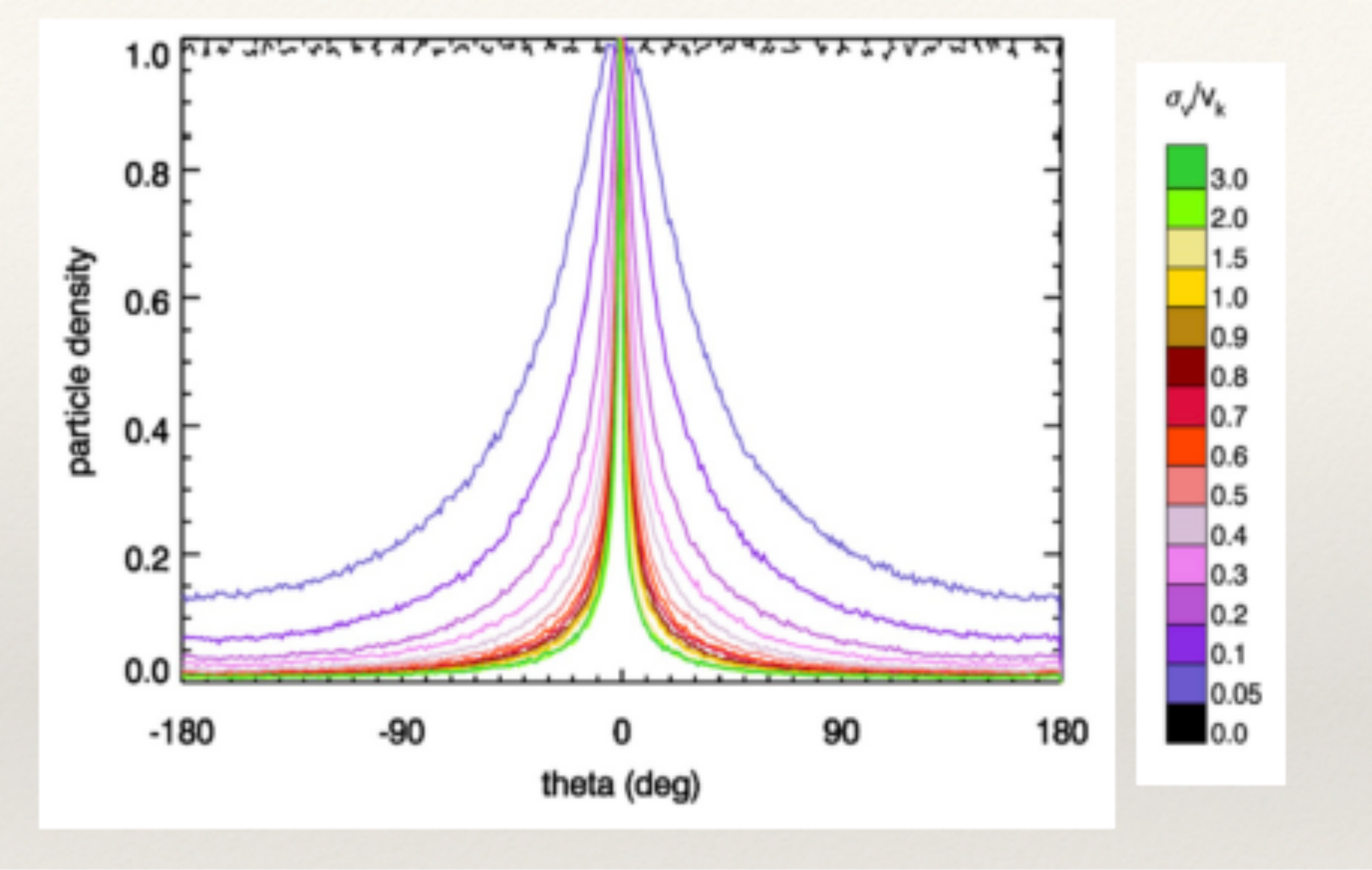


Expected density maps of the dust grains launched from their progenitor (semi major axis 50 au around a 1 $M_\odot$ star)

Density structure depends on:

- Magnitude of the velocity kick.
- Mass of the progenitor
- Observing wavelength

Asymmetries in the innermost ring at 40 au



Particle density variation along a line cut across the ring

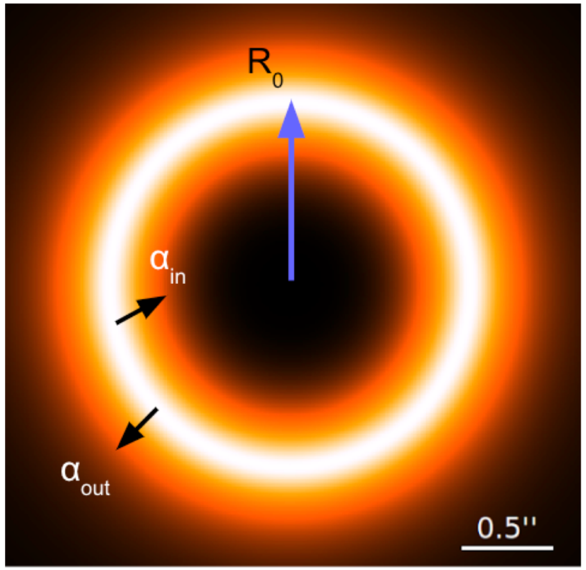
- Dispersion of velocities in the ring related to embryos masses indicates standard deviation $\sigma_{\upsilon}/\upsilon_{k}$ = 0.05 (for Ceres), 0.1 (for Pluto), 0.3 (for Moon).
- Dispersion of velocities in the ring = **width of the Lorentzian function**

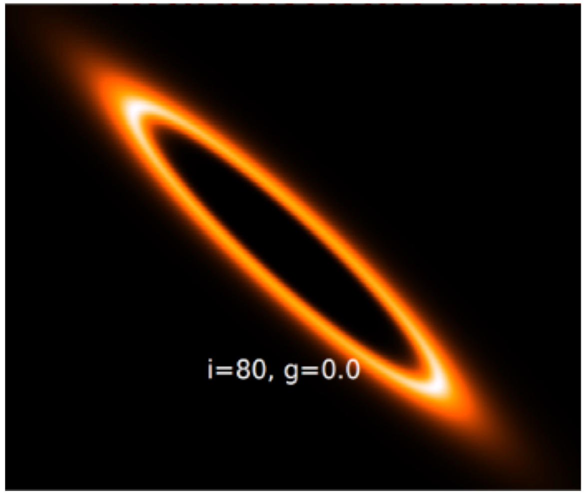
Jackson et al. 2014

Modelling intensity asymmetry: GRaTER radiative transfer code

Synthetic scattered-light images of optically thin debris disk models assuming simple anisotropic scattering (density distribution function + scattering phase function).

- Geometrical model with parameters
  - Parent dust belt radius (R_0)
  - Surface density distribution using two power law index α_{in} , α_{out}
  - Inclination (i)
  - Position angle (PA)
  - Anisotropic parameters (g)
    - Degree of forward scattering grains: 0<g≤1,
    - Backward scattering grains: -1≤g<0
  - Vertical scale height aspect ratio ($h=H/R_0$)



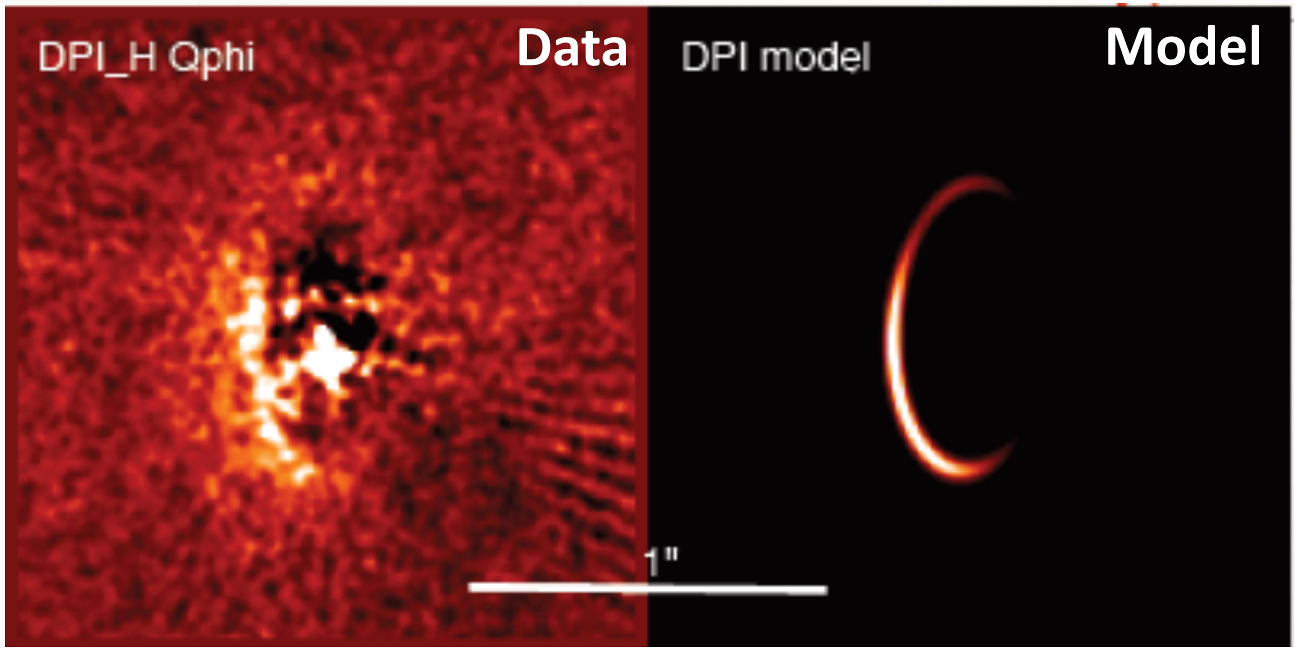


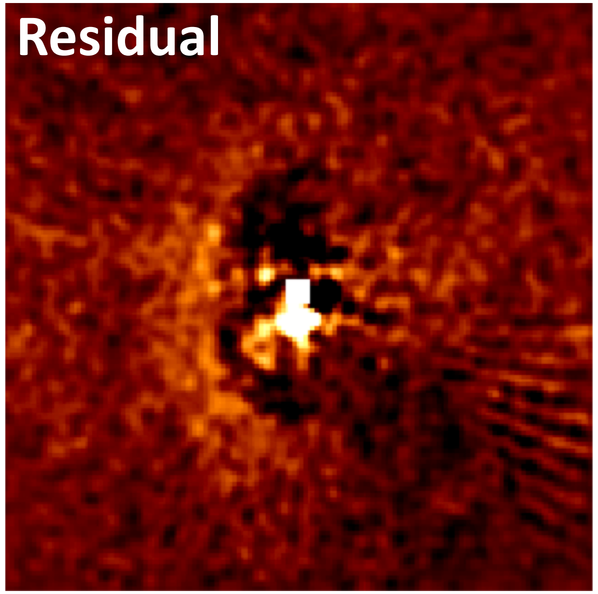
Augereau et al. 1999

Modelling intensity asymmetry: GRaTER ray-tracing code

- Theoretical models Jackson et al 2014 indicates that the dust density distribution takes a Lorentzian profile.
- Azimuthal variation in the dust density is implemented in GRaTER.
- Three degrees of freedom are accounted in GRaTer models
    - Anisotropic scattering factor, g
    - Azimuth of the peak in density, θ_{max} (peak in dust emission spectrum)
    - Width in the azimuth of the Lorentzian function, *HWHM*
    - Rest of the parameters such as PA, inclination etc are fixed from Perrot et al. 2016

Constraining disk morphology in polarimetric intensity

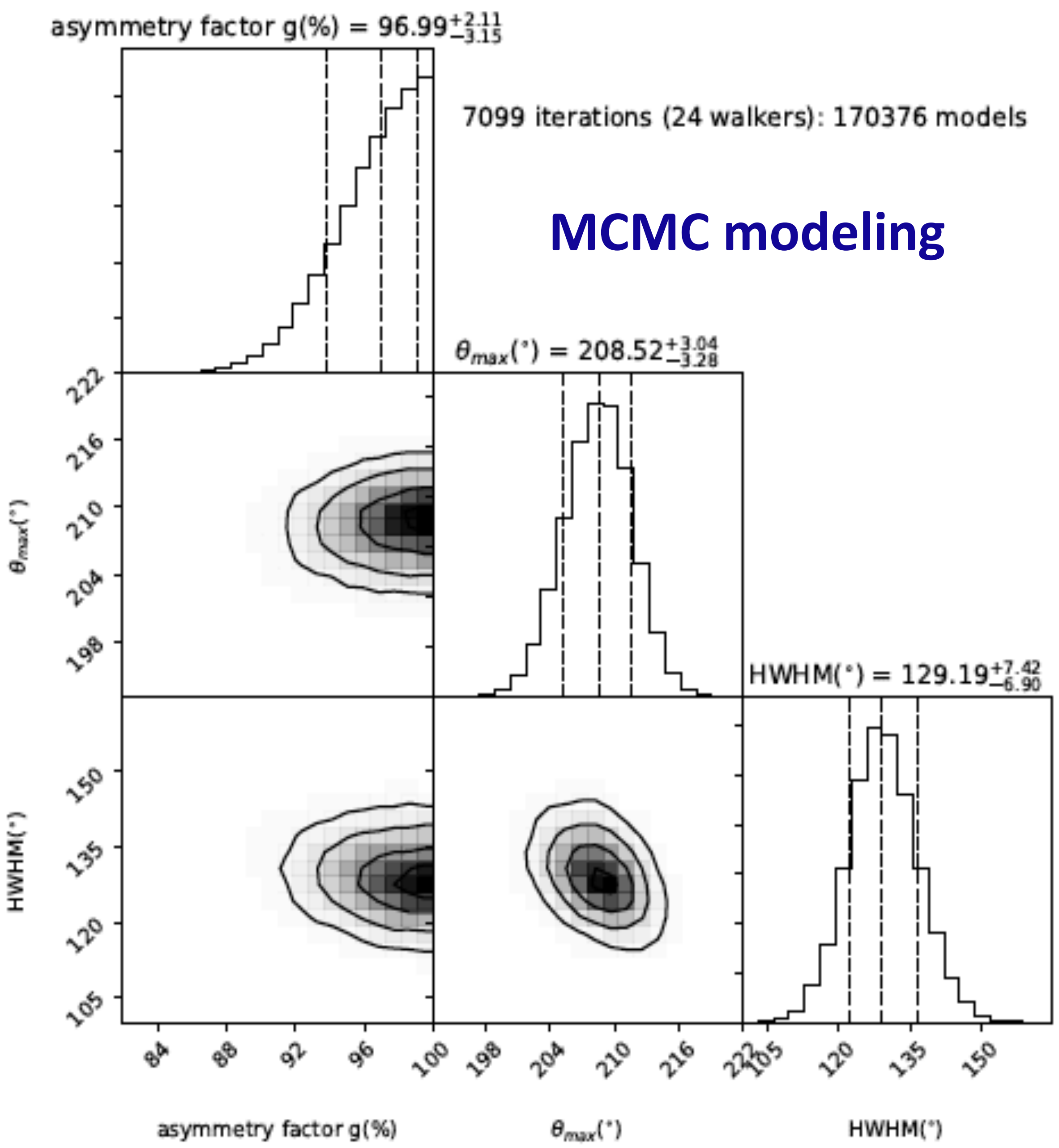




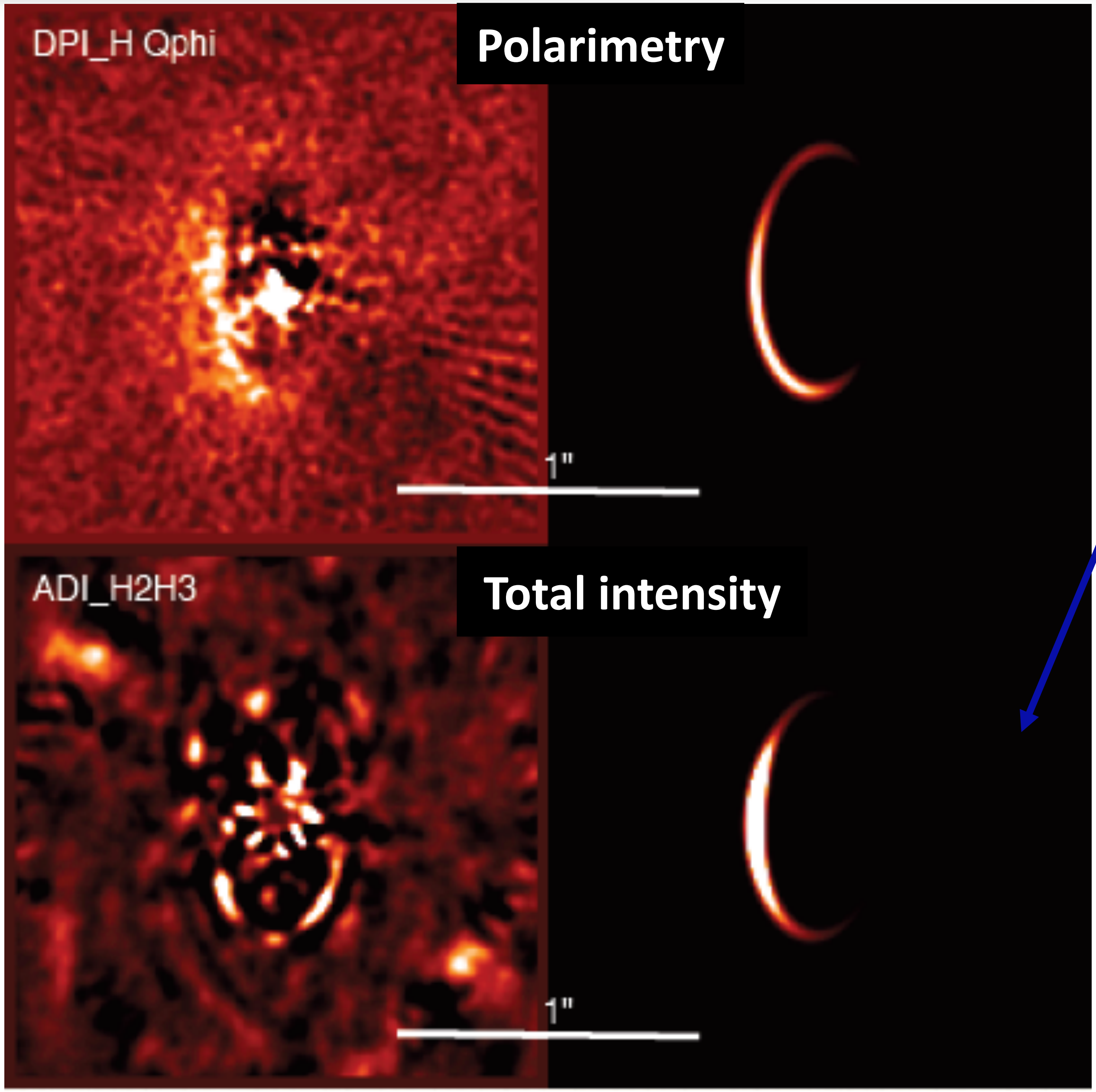
Best model

g	= 0.96	± 0.03
θ_{max}	= 208.5°	± 3.3
HWHM	= 129°	± 7.0

Singh et al. in preparation



Constraining disk morphology in total intensity



Best model for Polarimetry

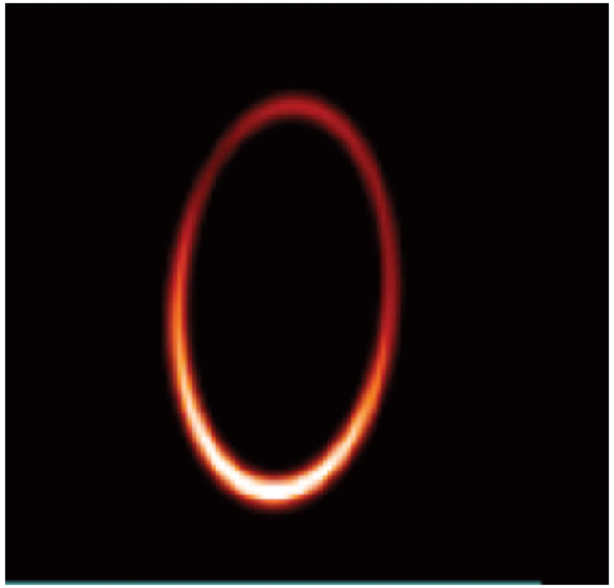
$g = 0.96 \pm 0.03$

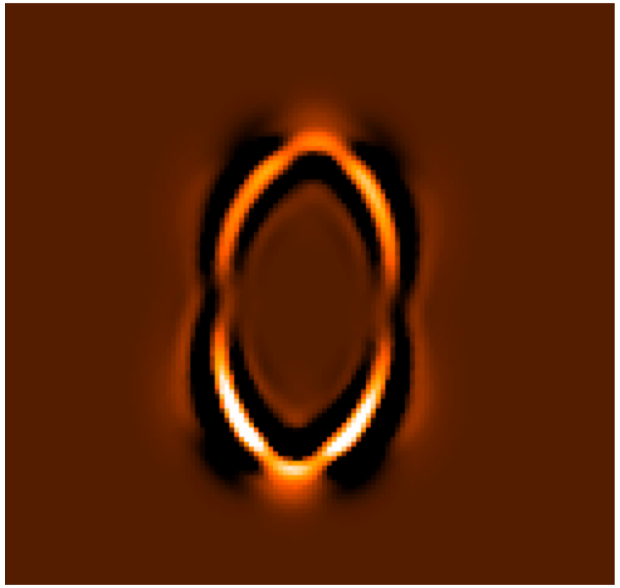
$\theta_{max} = 208.5° \pm 3.3$

$HWHM = 129° \pm 7.0$

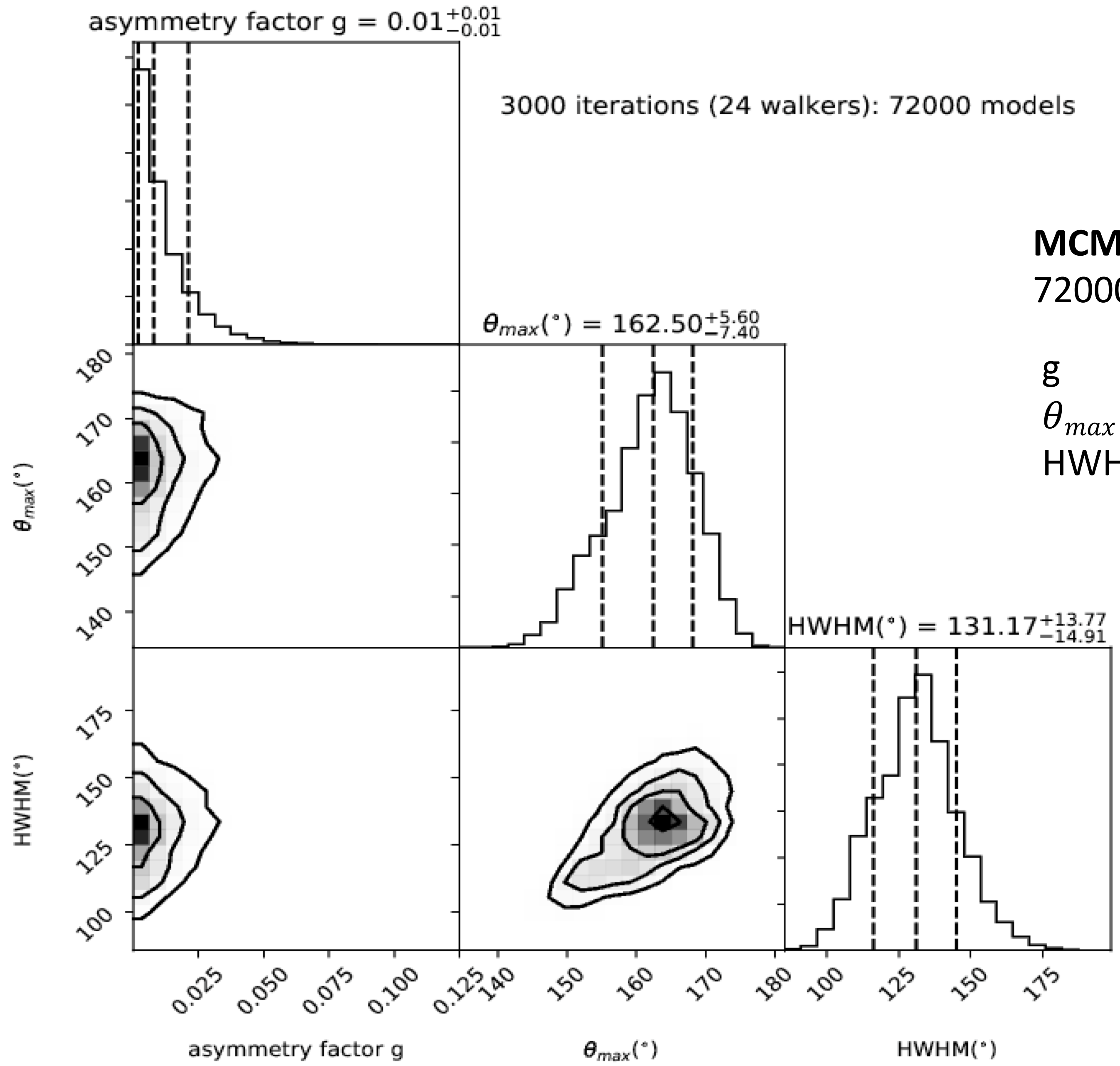
GRaTER model | **ADI reduced forward model**

$g = 0.1$, $\theta_{max} = 208.5°$, $HWHM = 129°$





Constraining disk morphology in total intensity



MCMC modeling, KLIP reduction, PCA 5
72000 models (24 walkers, 3000 iterations, **~ 50 hours**)

g	(0.0 – 0.99)	= 6e-05 ± 0.01	**(0.96 ± 0.03 for Pola.)**
θ_{max}	(90° - 300°)	= 162.5° ± 7.0	**(208.5° ± 3.3 for Pola.)**
HWHM	(10° - 200°)	= 131° ± 15.0	**(129° ± 7.0 for Pola.)**

Discussion

- Polarimetric data is well explained by a combination of a phase function and azimuthal dust density variation and provide constrains on the density distribution of the dust grains.

- Width of the Lorentzian function = dispersion of velocities in the ring.

  Inferred velocity dispersion with standard deviation $\sigma_{\upsilon}/\upsilon_{\kappa}$ < 0.05 could indicate collision between asteroid-size objects (Singh et al in preparation).

Ongoing investigation

North-South asymmetry aligned with the disk projected major axis could be due to:

- Dust scattering phase function? **(possibly not)**
- Self subtraction due to ADI that can strongly modify the azimuthal distribution of the intensity.
  (yes in case of total intensity)
- Azimuthal variation of the dust density? **(strong candidate)**
- Shadowing effect (Bohn et al. 2019)?
- Coupling of gas and dust triggering instabilities in the form of narrow eccentric rings (Lyra & Kuchner 2013)?

SPHERE images of Wray 15-788
(Bohn et al. 2019)