Scattered light imaging and the structure of disks

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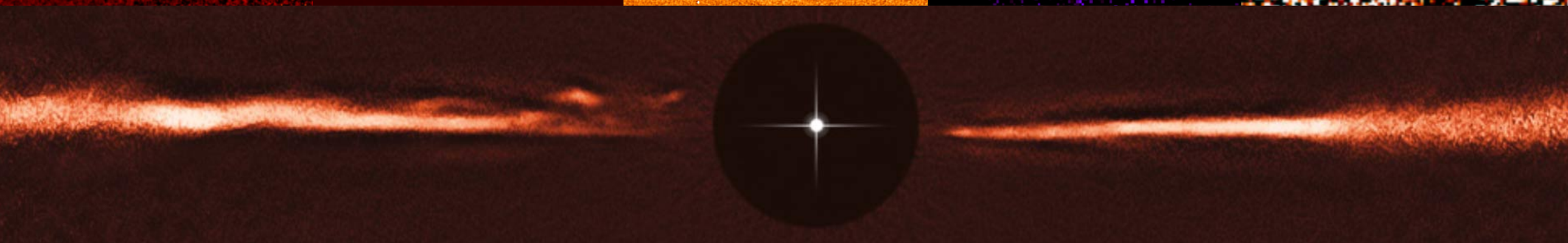
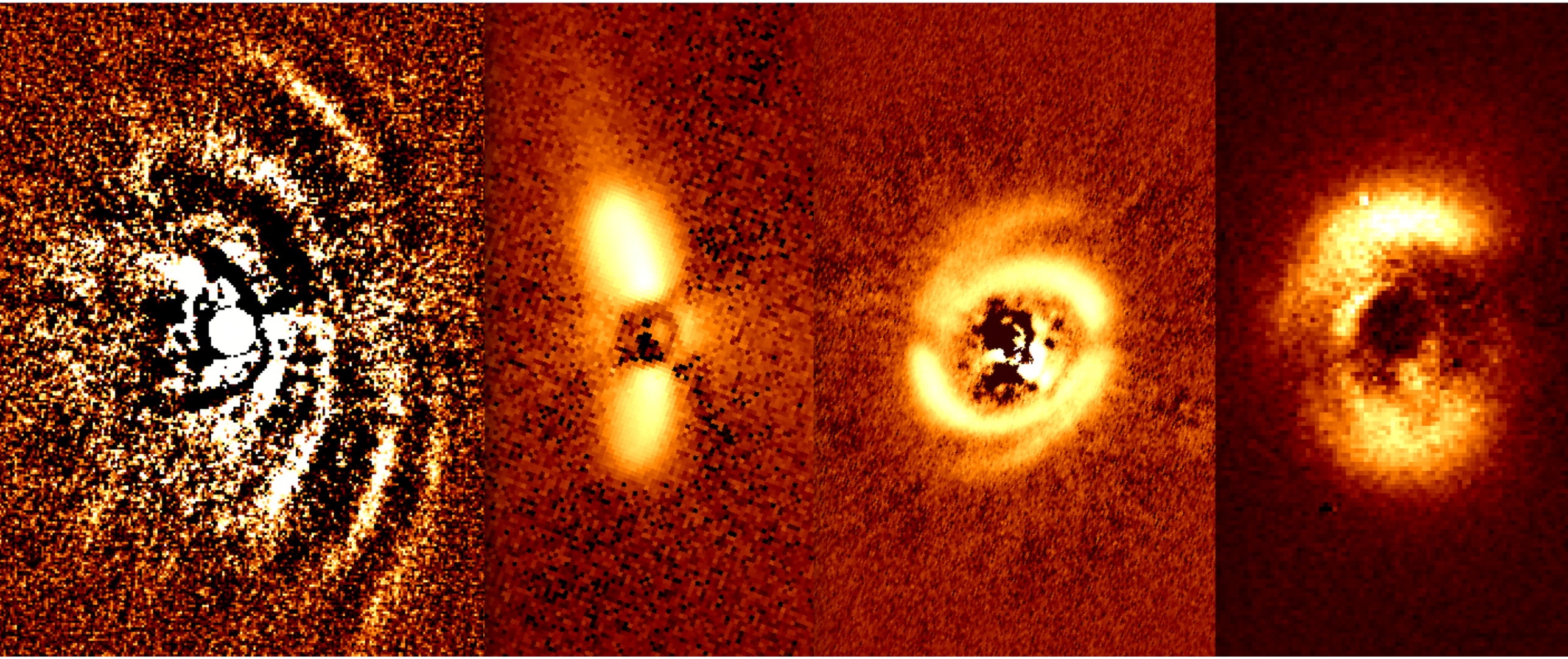
University of Amsterdam

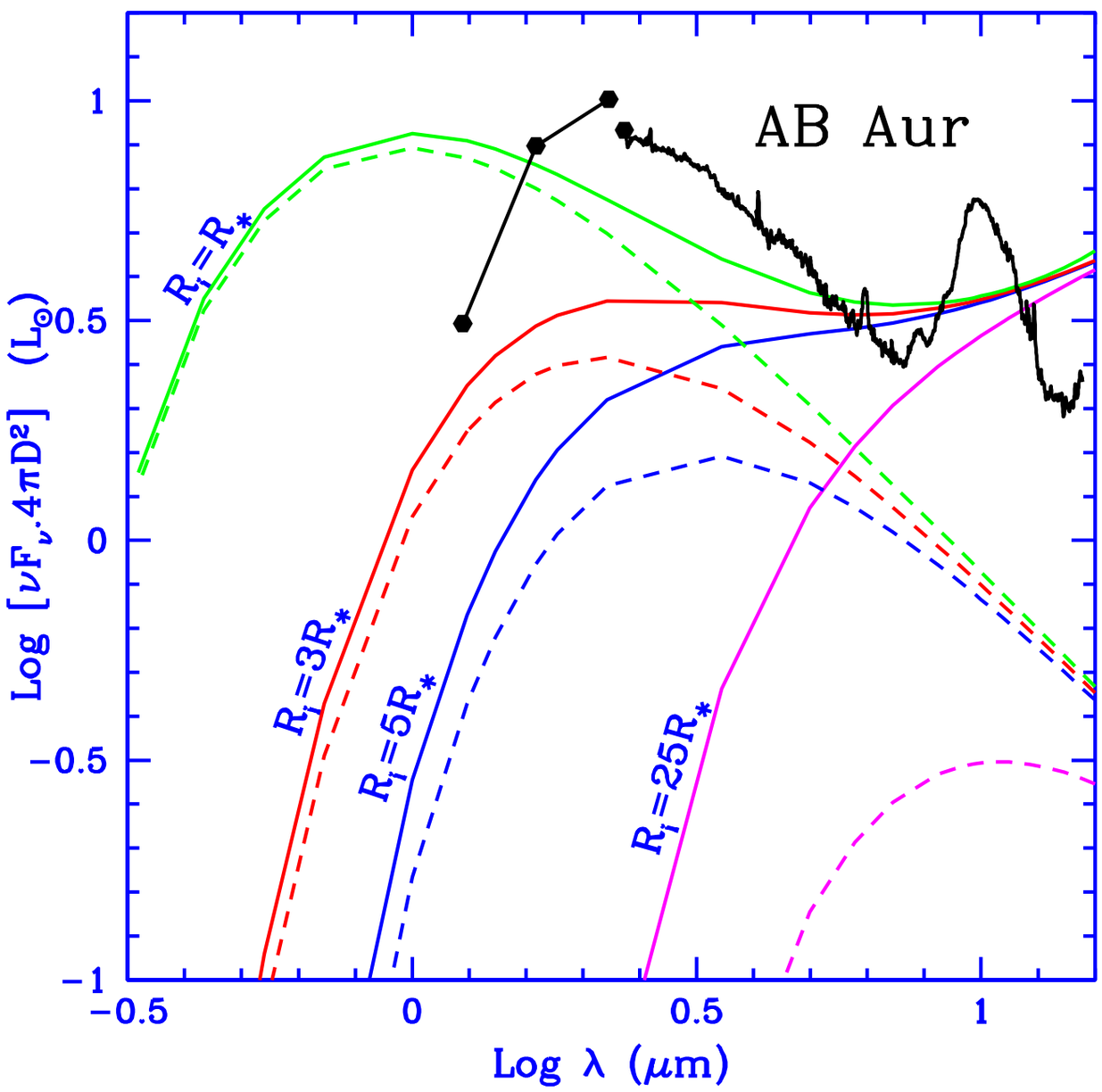
Tomas Stolker, Christian Ginski, Jos de Boer, Gabriela Muro Arena, Antonio Garufi, Myriam Benisty, Hans-Martin Schmid, Michiel Min, Rens Waters, Paola Pinilla, Francois Menard and the SPHERE disk team

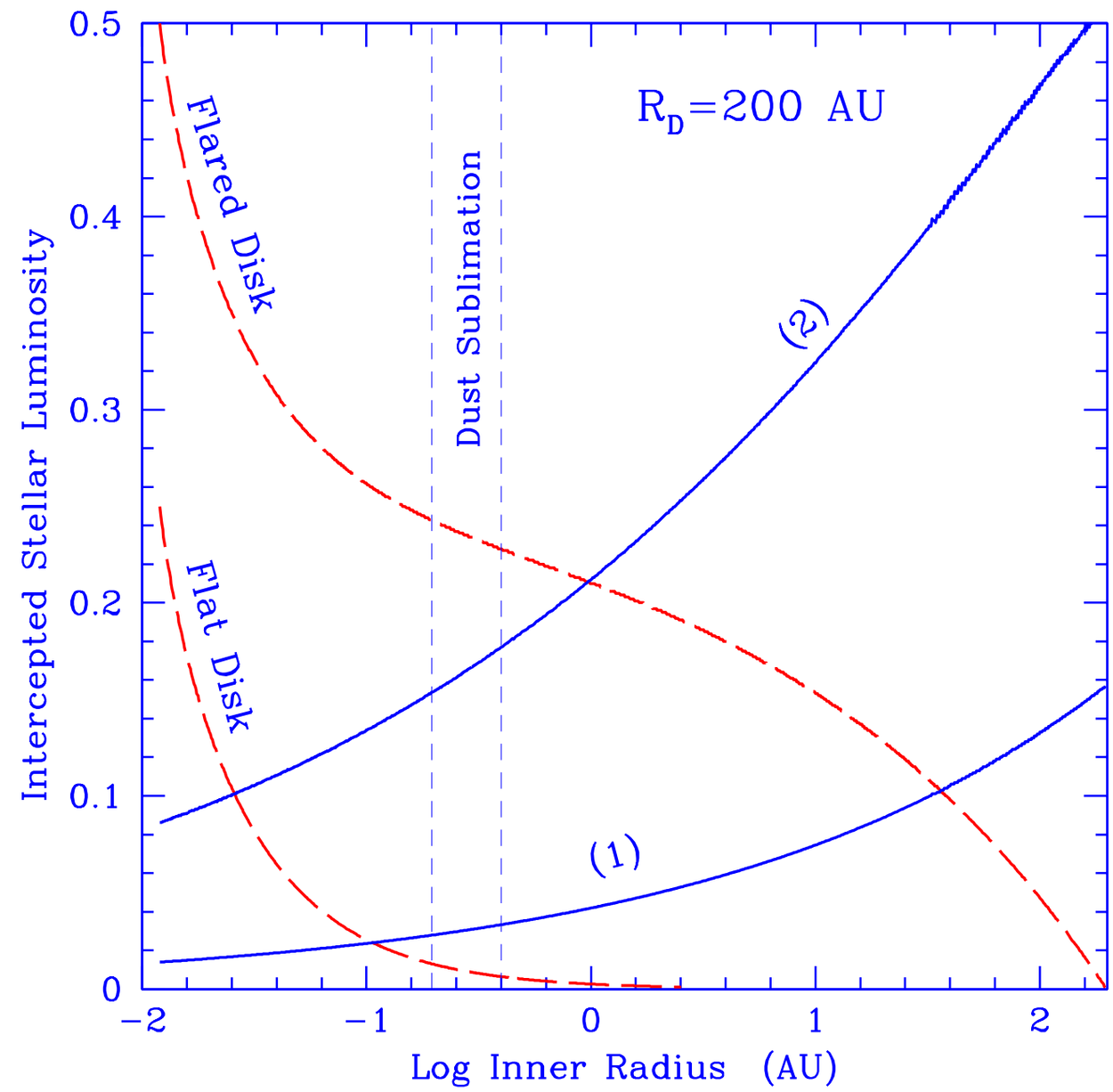




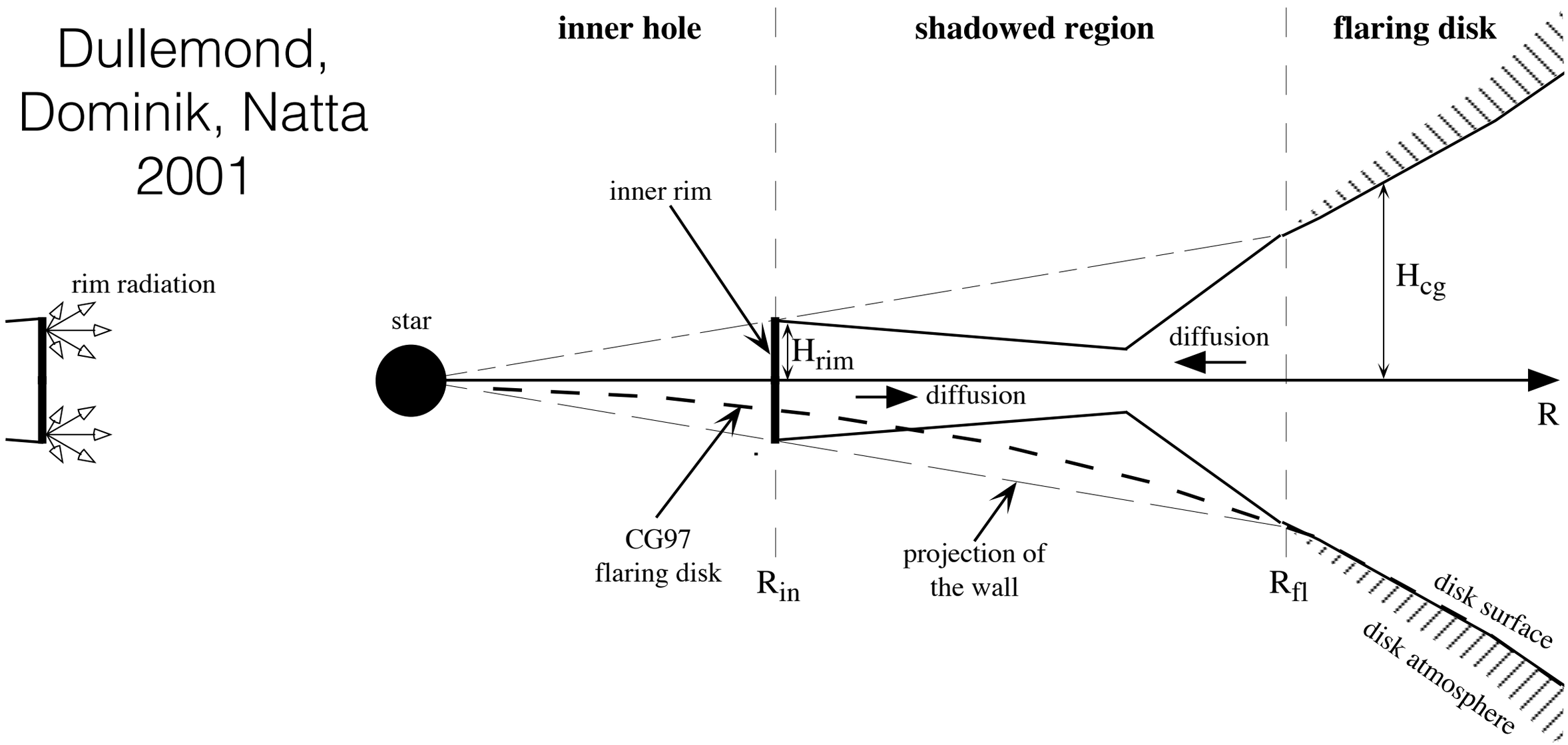
credit: Christian Ginski

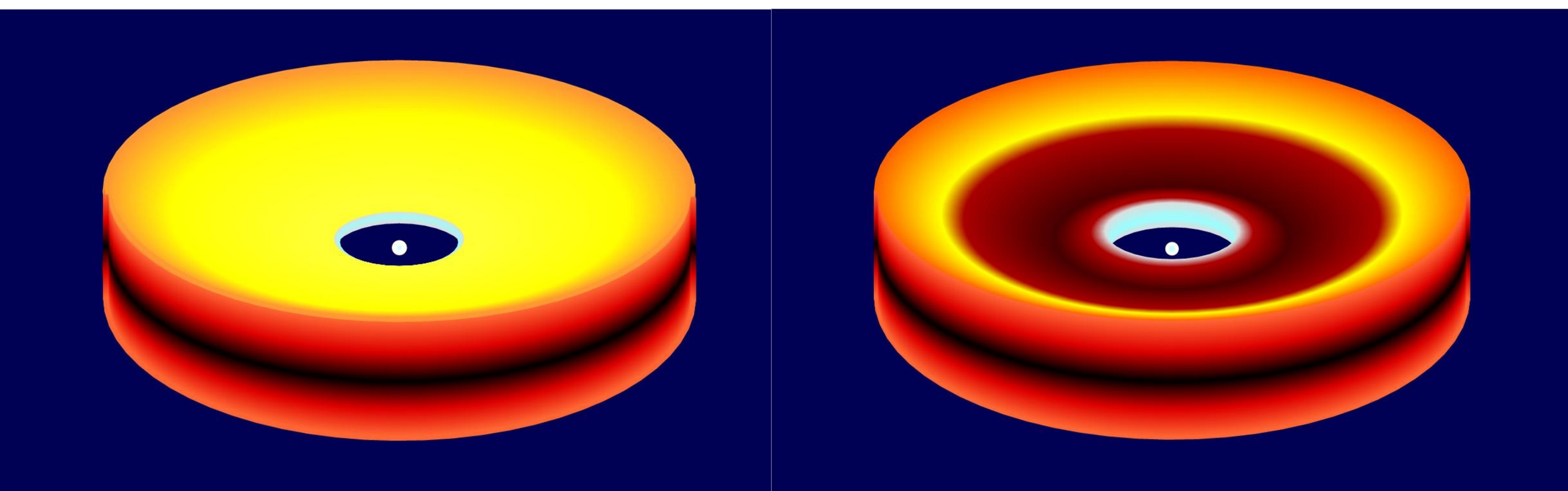
Natta et al 2001
Reconsideration of HAe disk properties



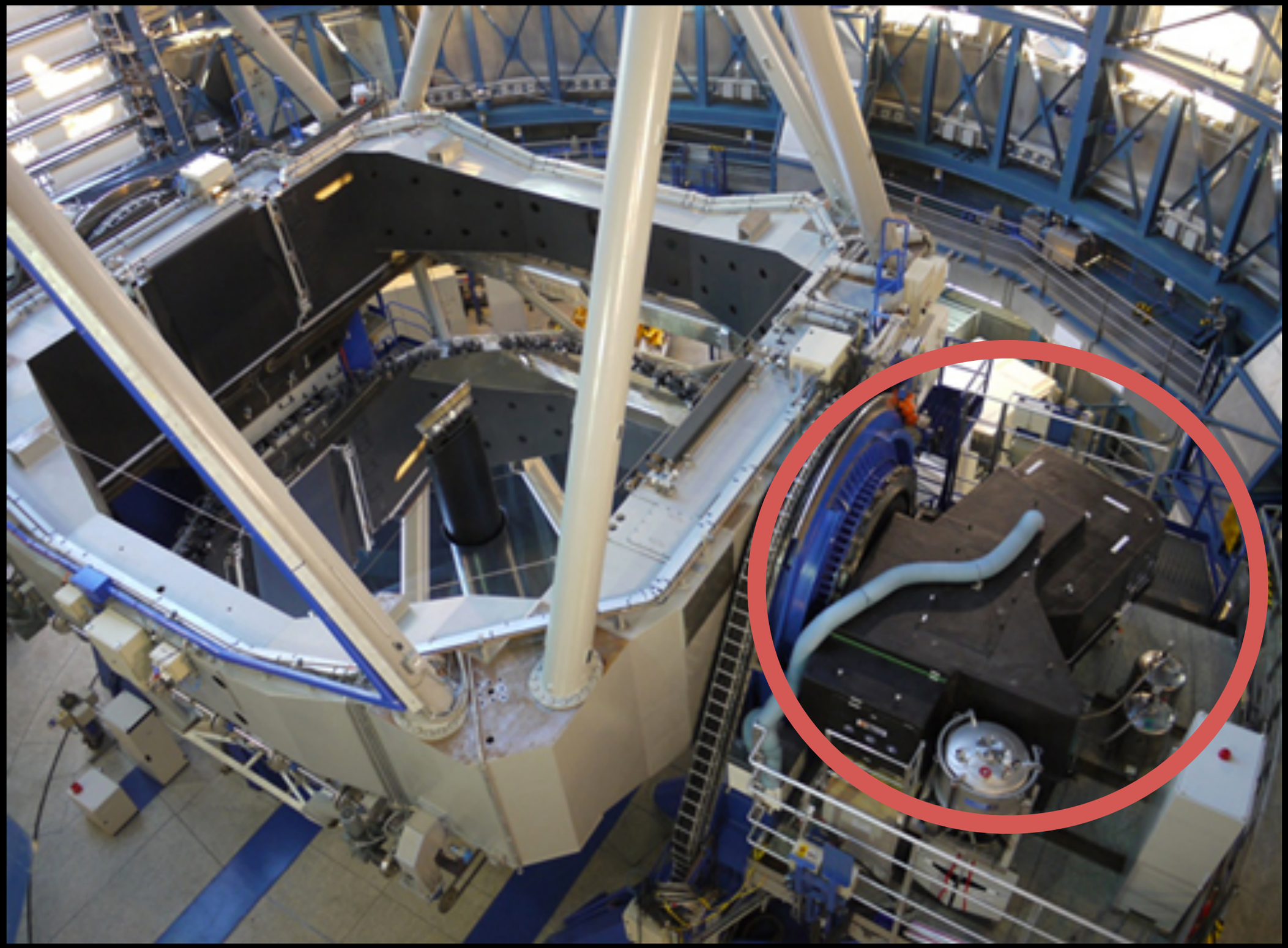


Dullemond, Dominik, Natta 2001



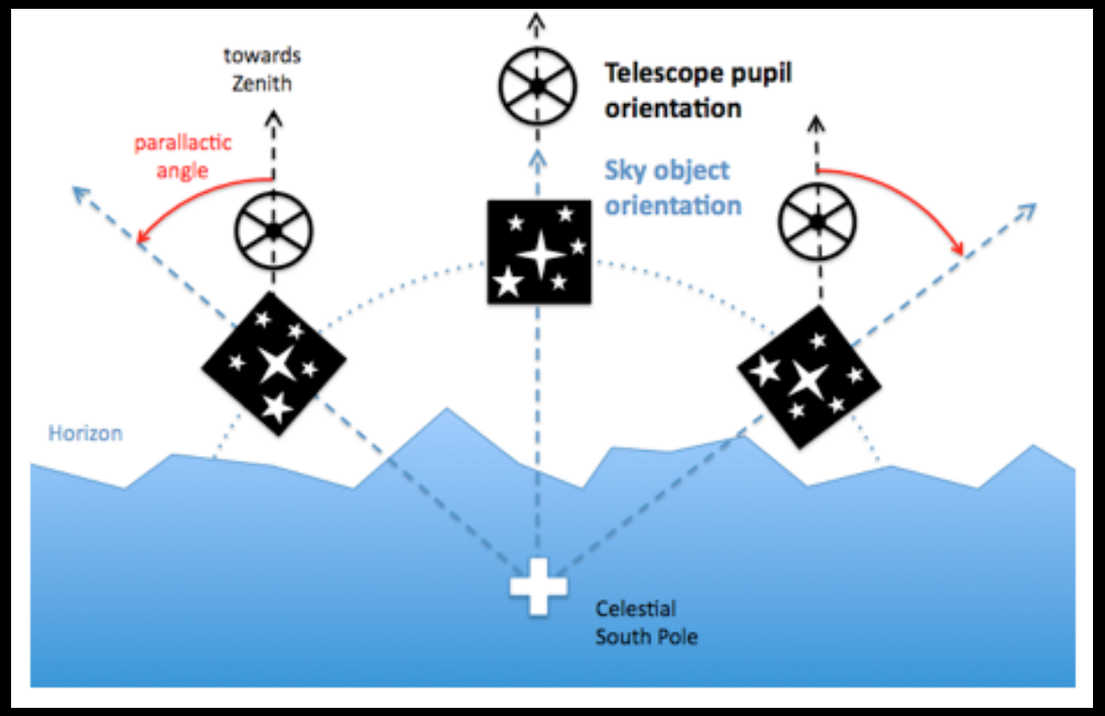


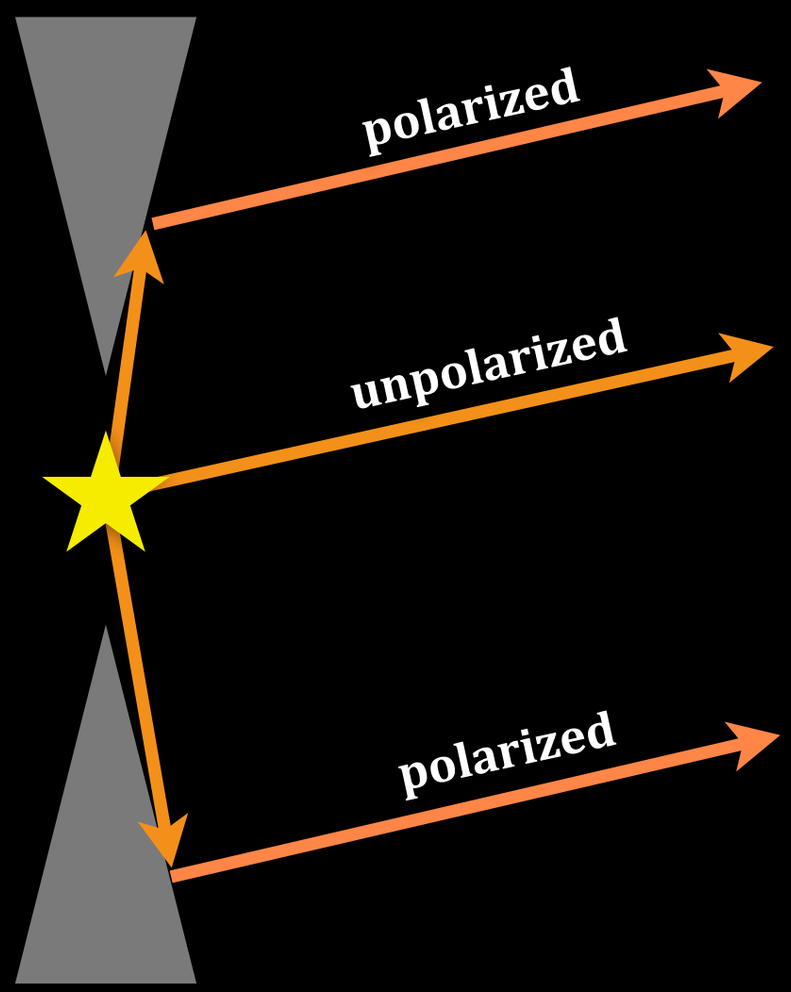
Sphere at VLT



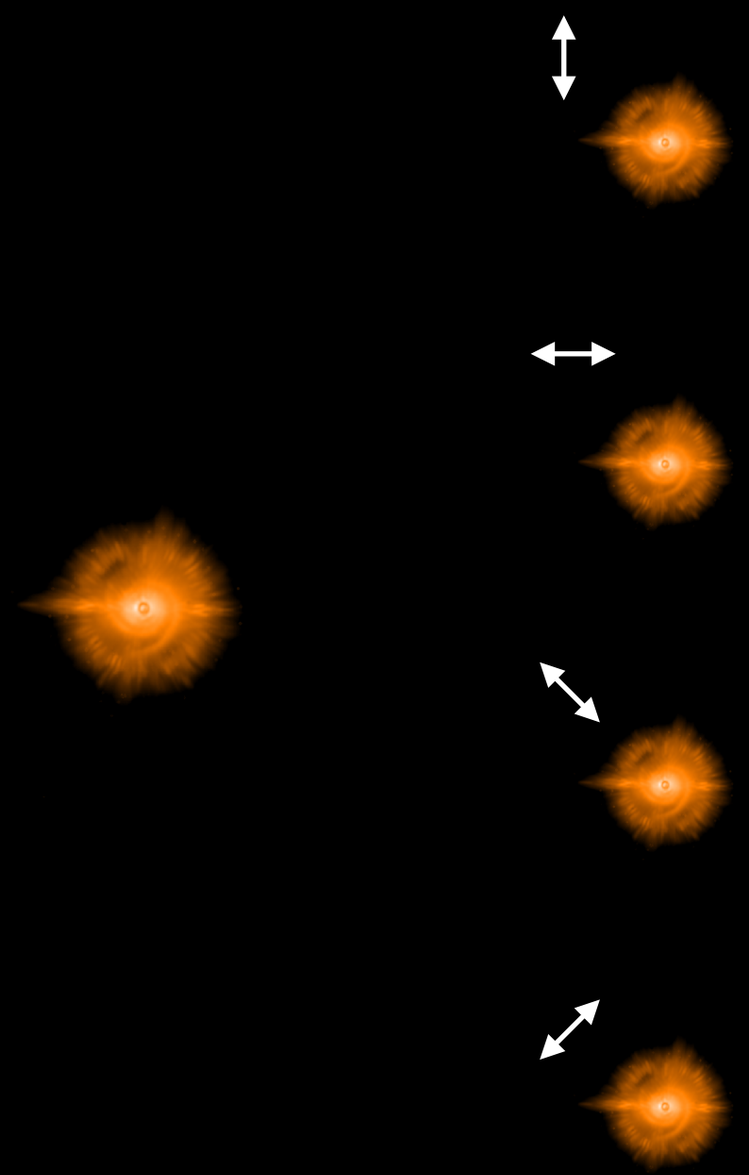
Most important techniques

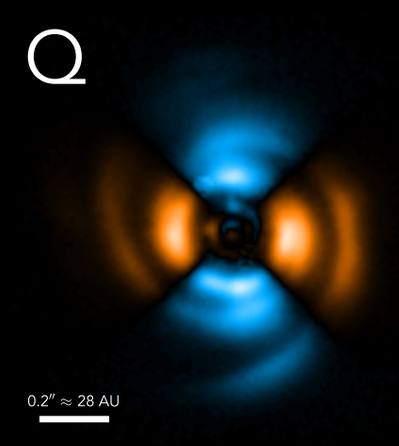
- Angular differential imaging
  - Make use of the rotation of sky versus telescope to subtract the telescope errors
  - Most sensitive method at larger separations
- Polarimetric differential imaging
  - Isolate the polarised light scattered by dust
  - Most sensitive close to the star

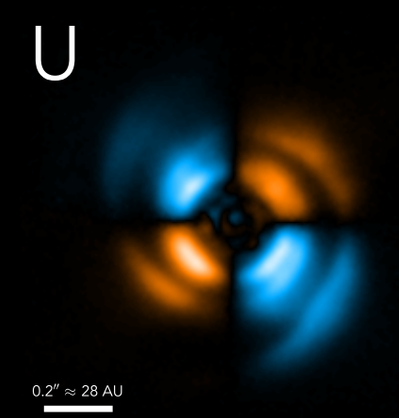


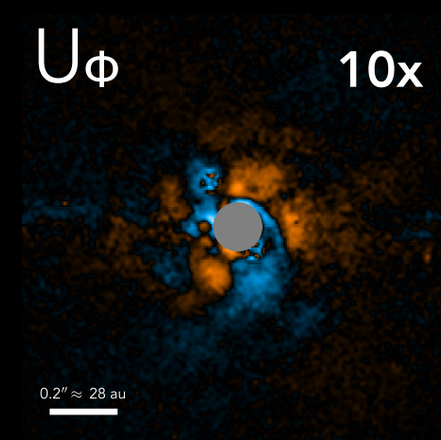


Polarimetric differential imaging (PDI)







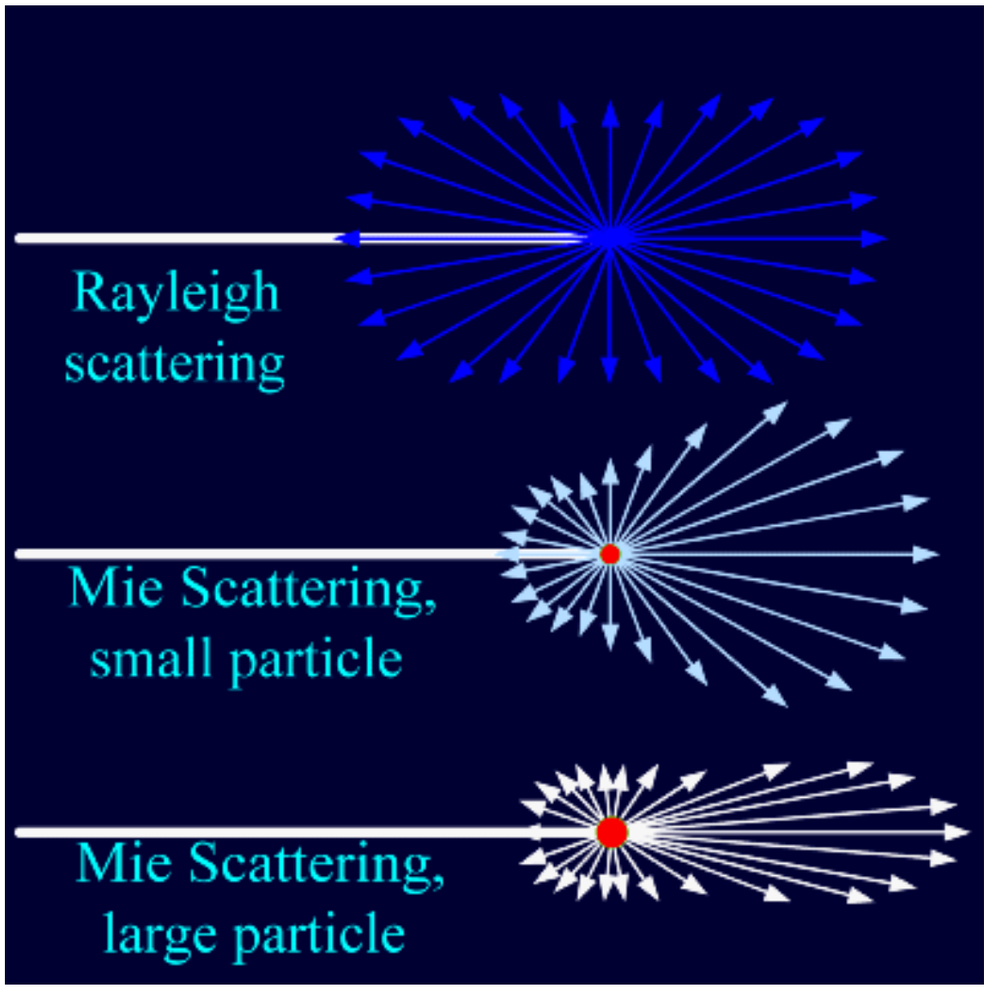


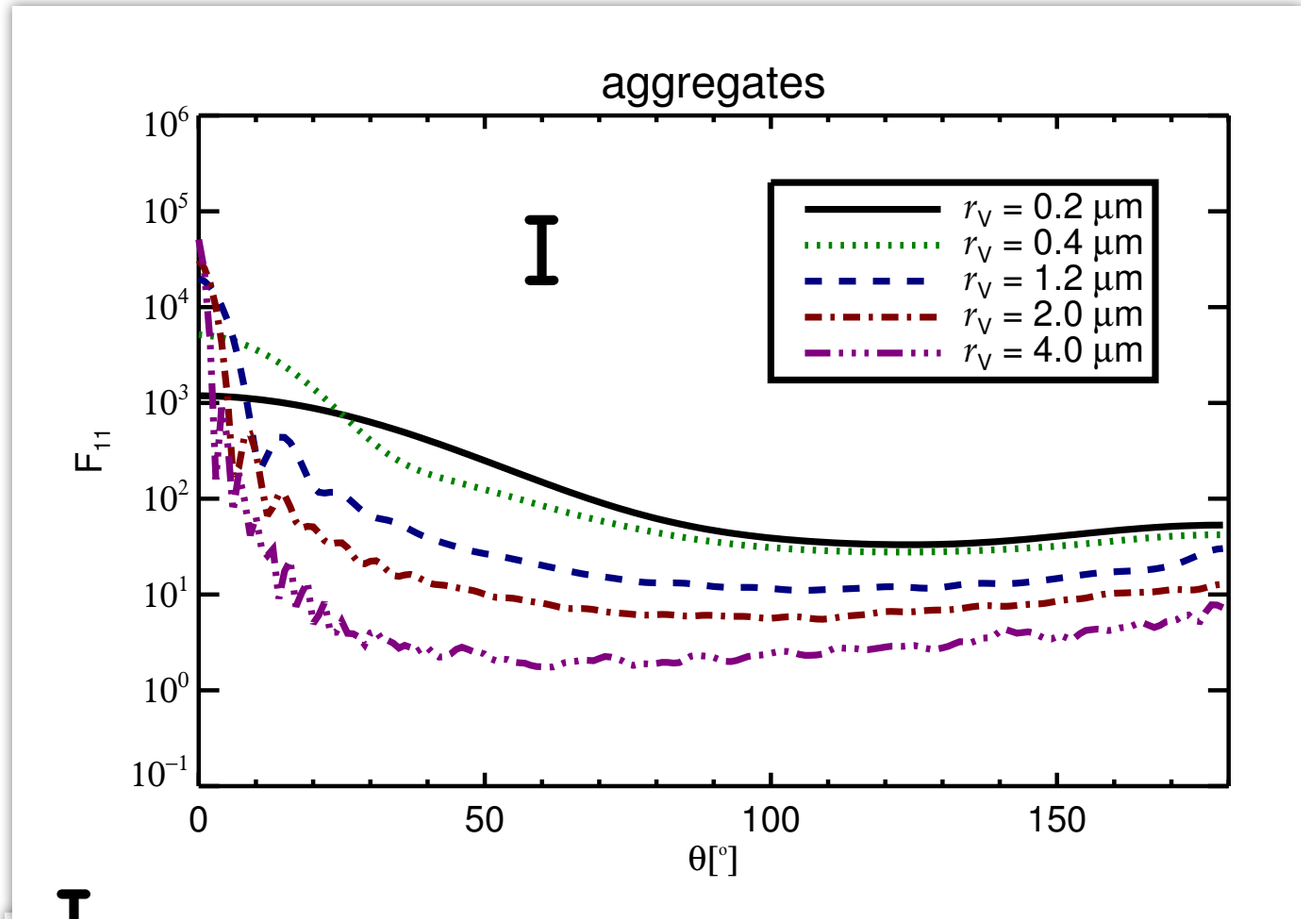
U_Φ/Q_Φ ~2-3%

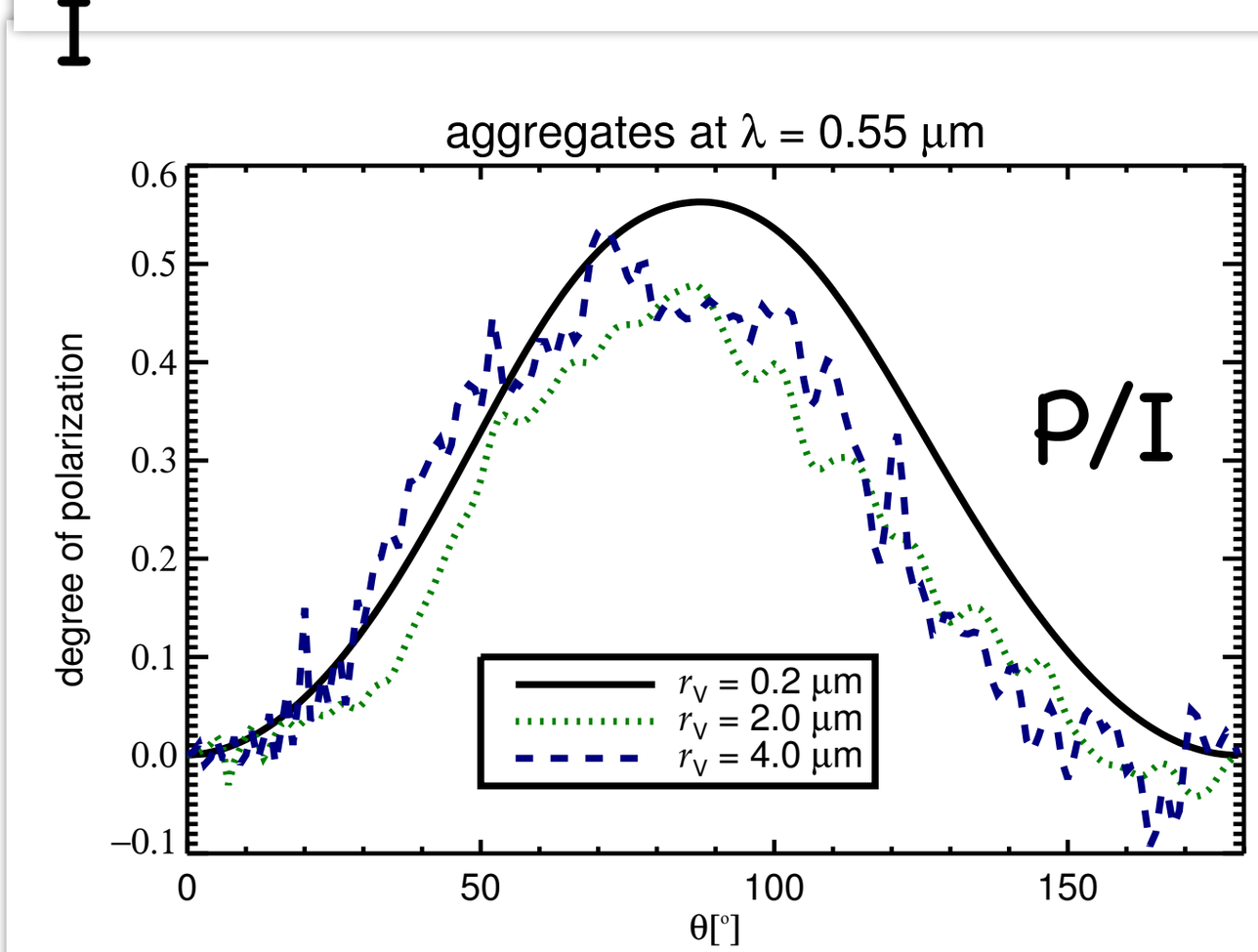
(see Canovas et al. 2015)

Telescope → 4 HWP positions → Data reduction → Stokes transformation

Phase functions and polarisation

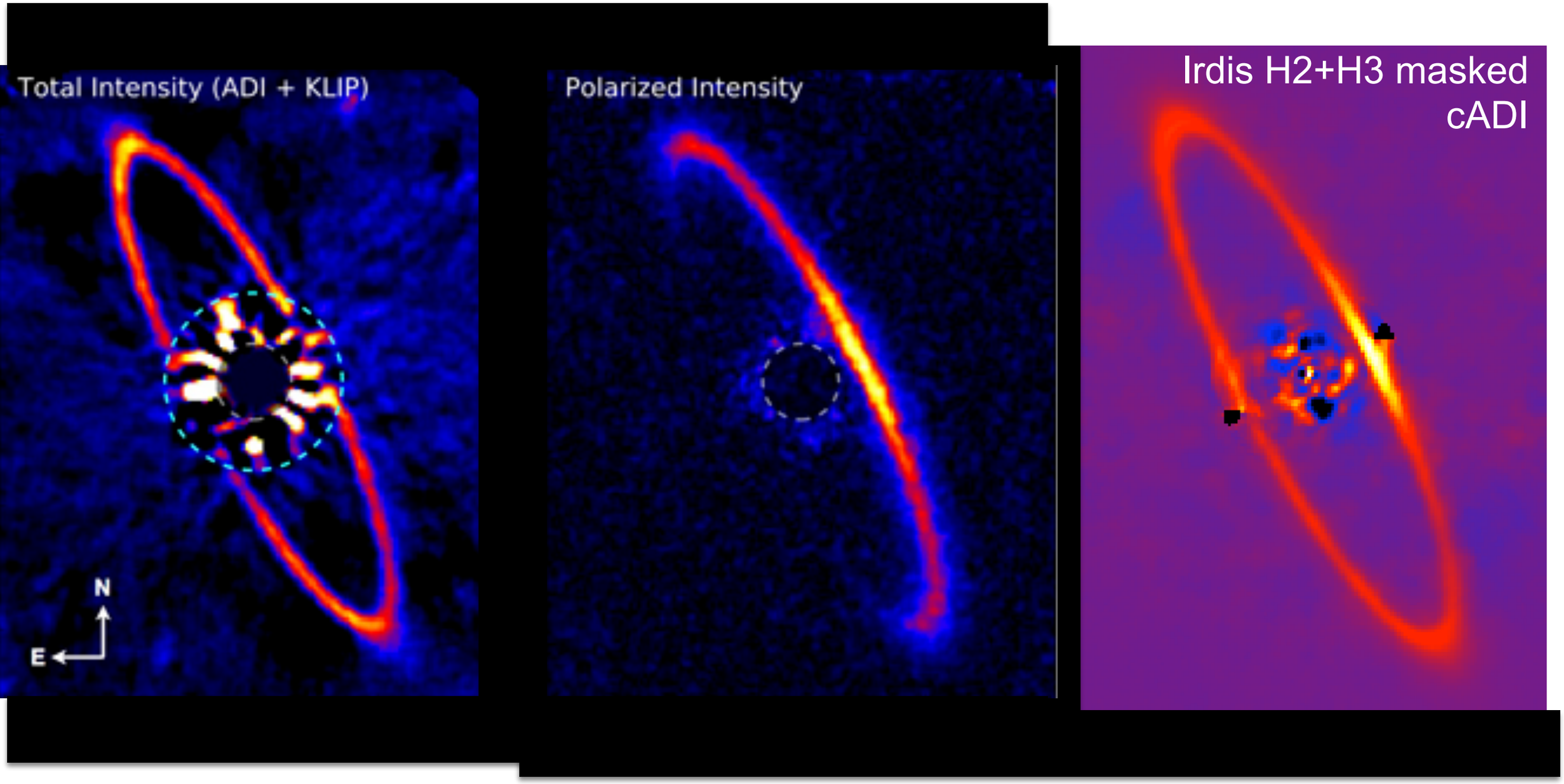






Min+ 2016

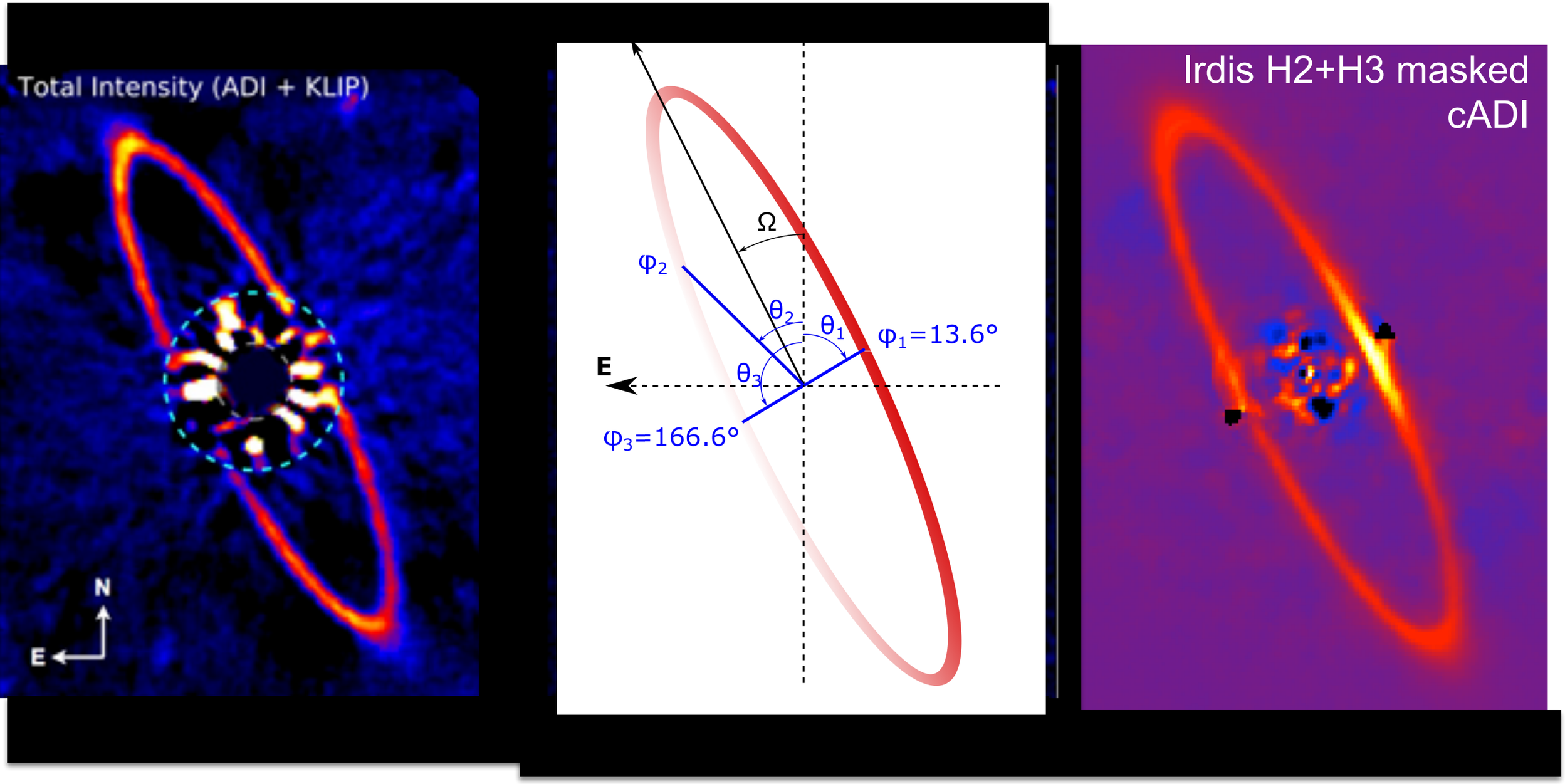
Phase functions: HR4796A



Perrin+ 2015

Milli+ 2015

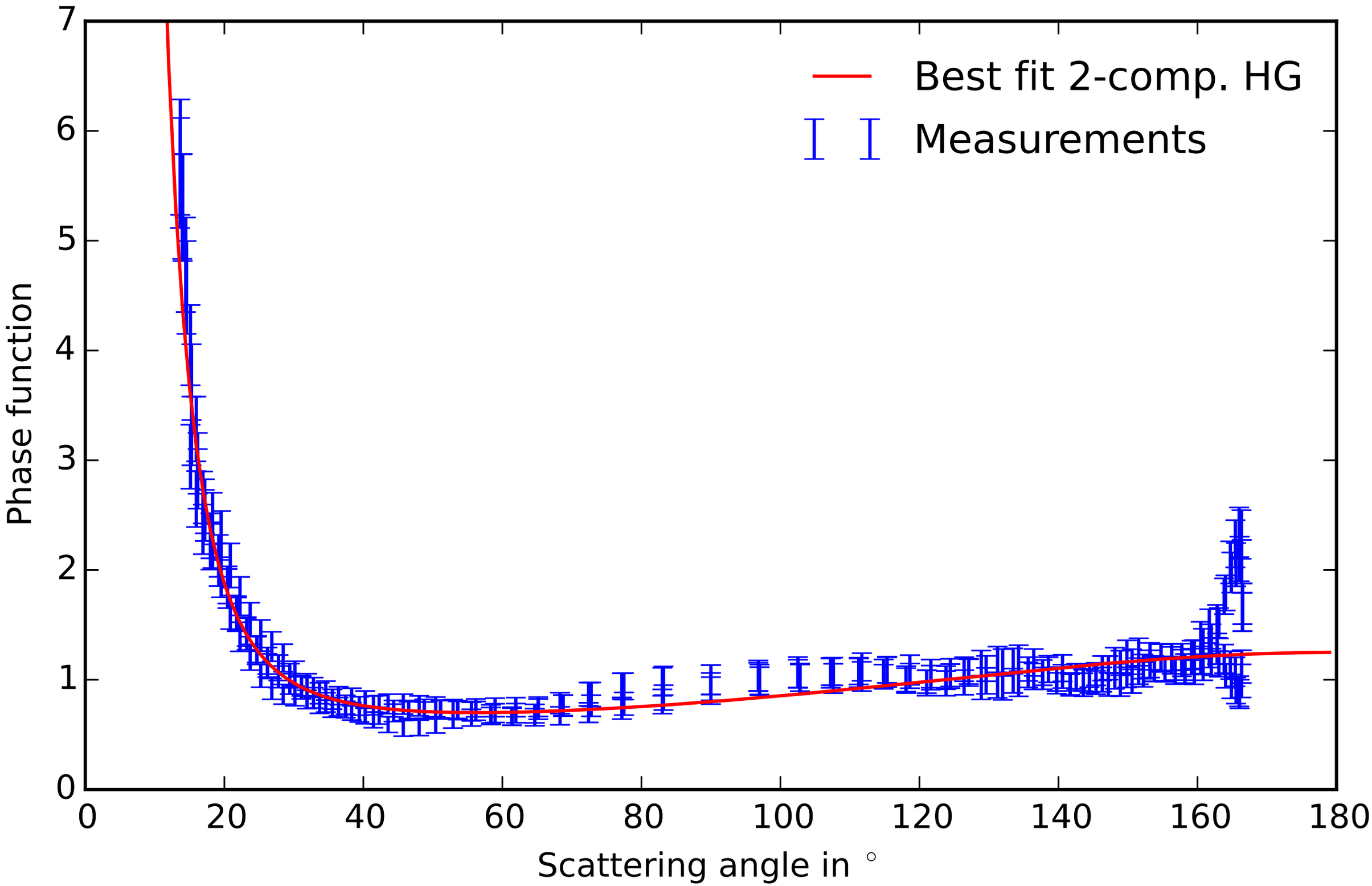
Phase functions: HR4796A



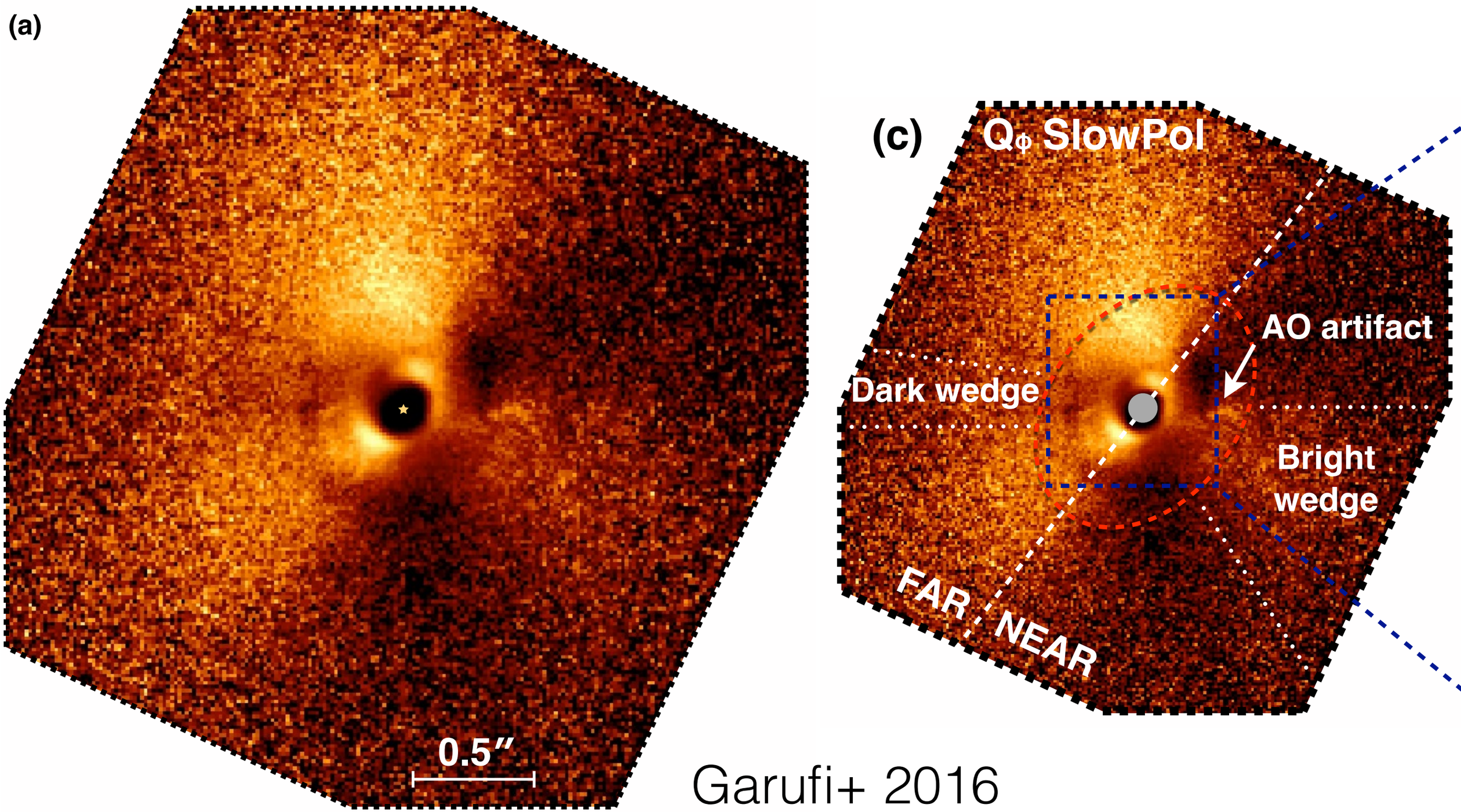
Perrin+ 2015

Milli+ 2015

A measured phase function

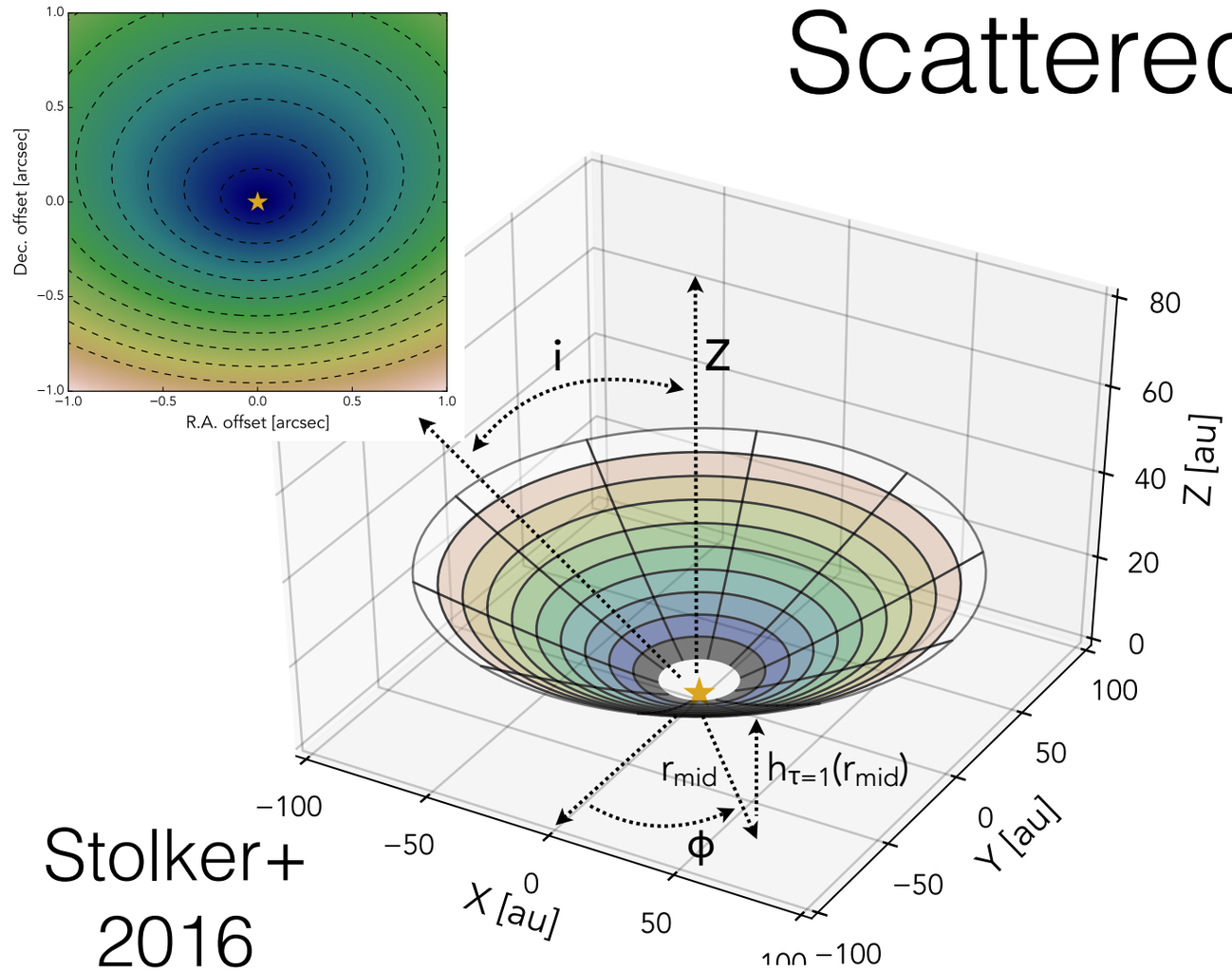


Structures cause by phase functions

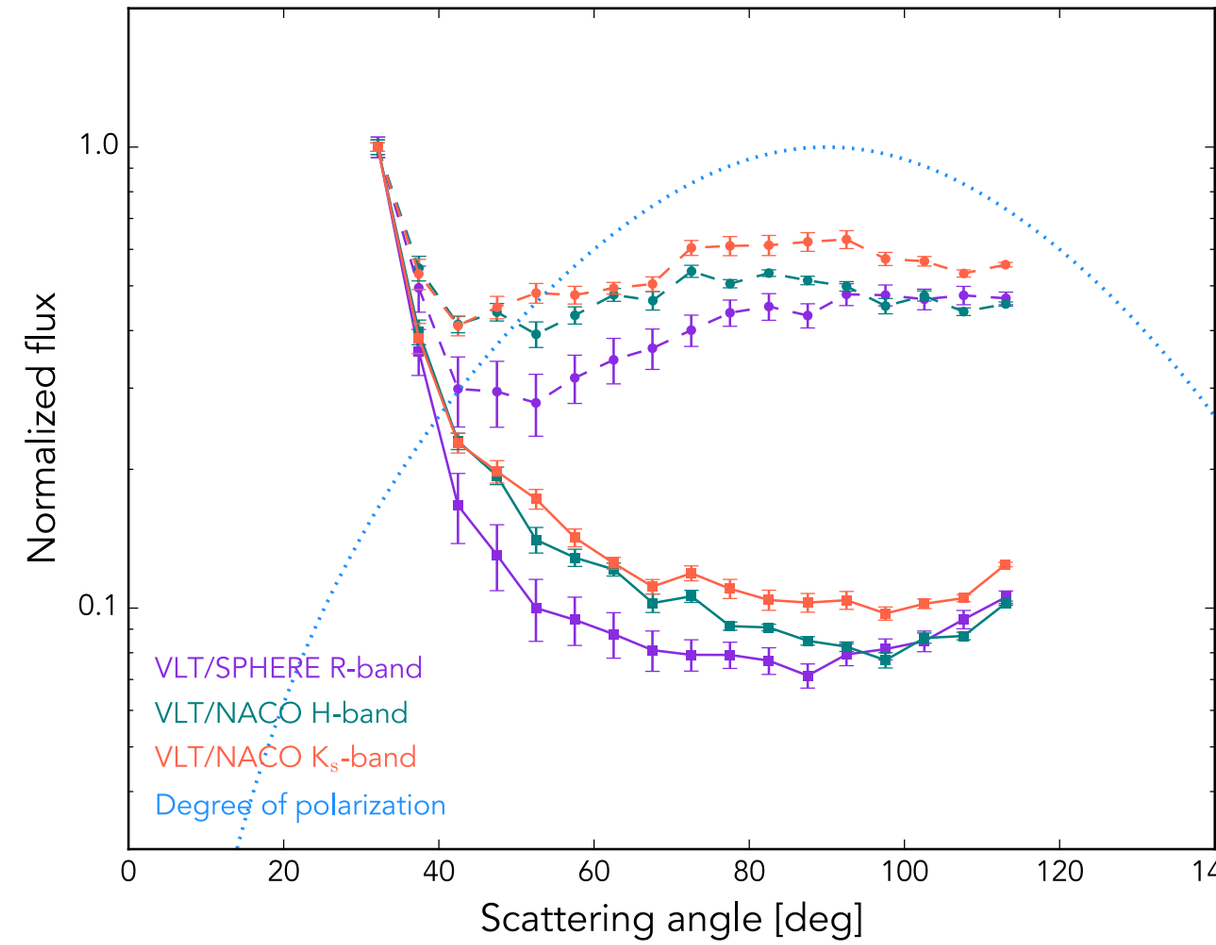


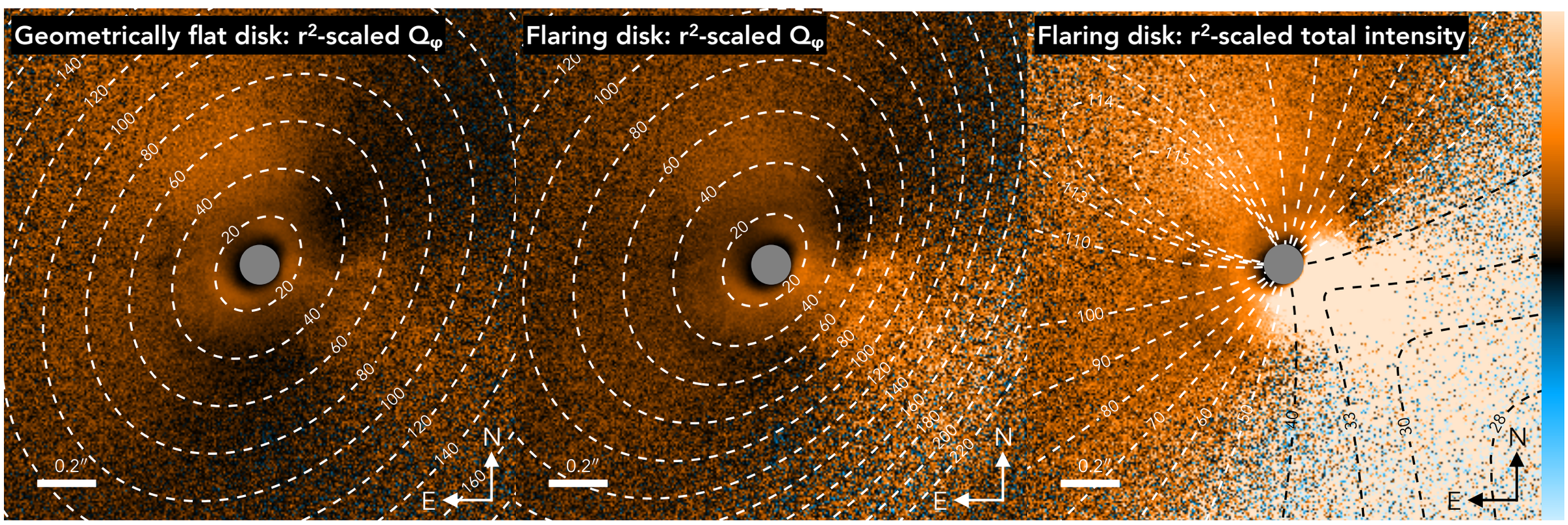
Garufi+ 2016

Scattered light mapping

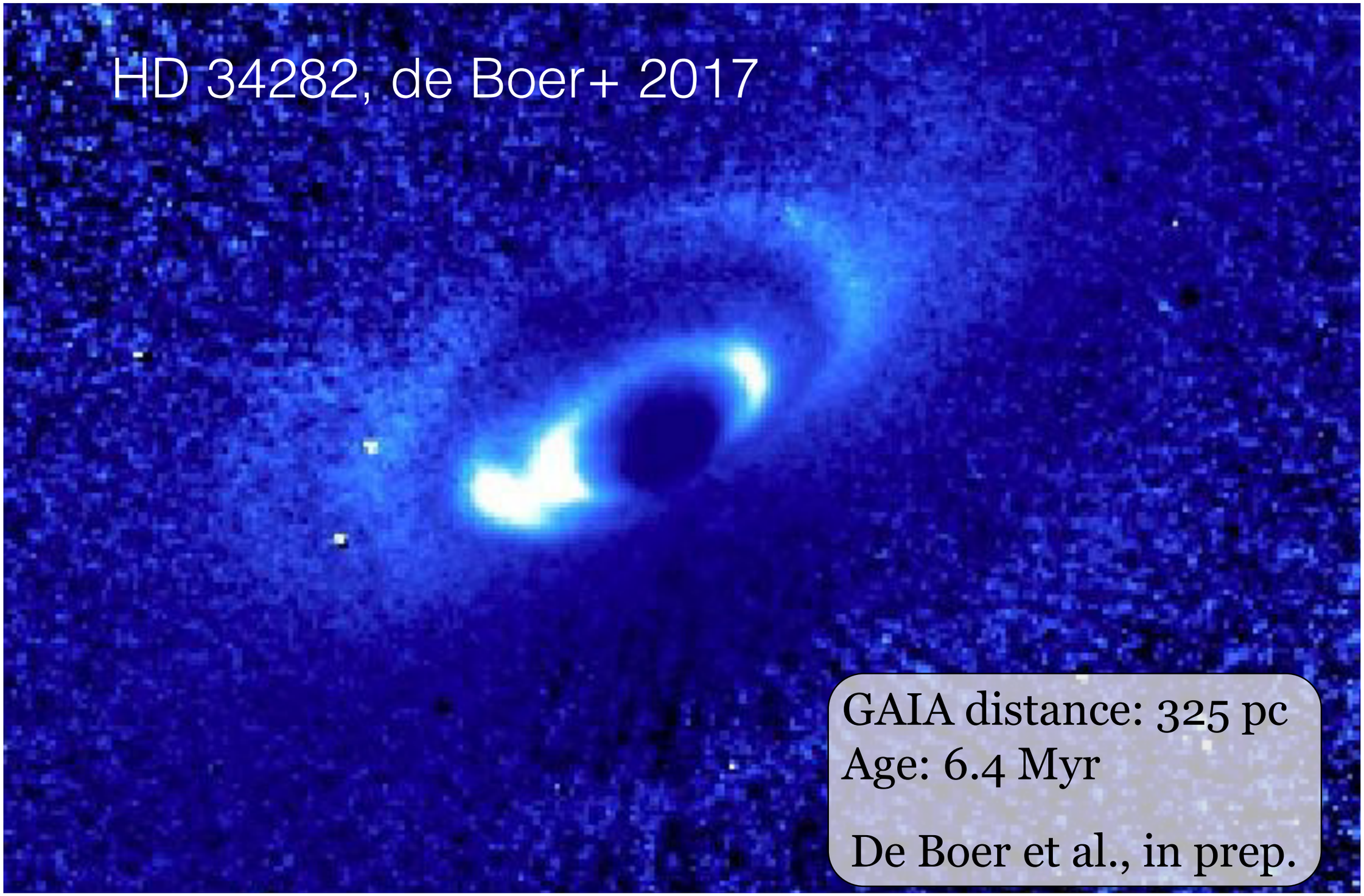


Stolker+ 2016

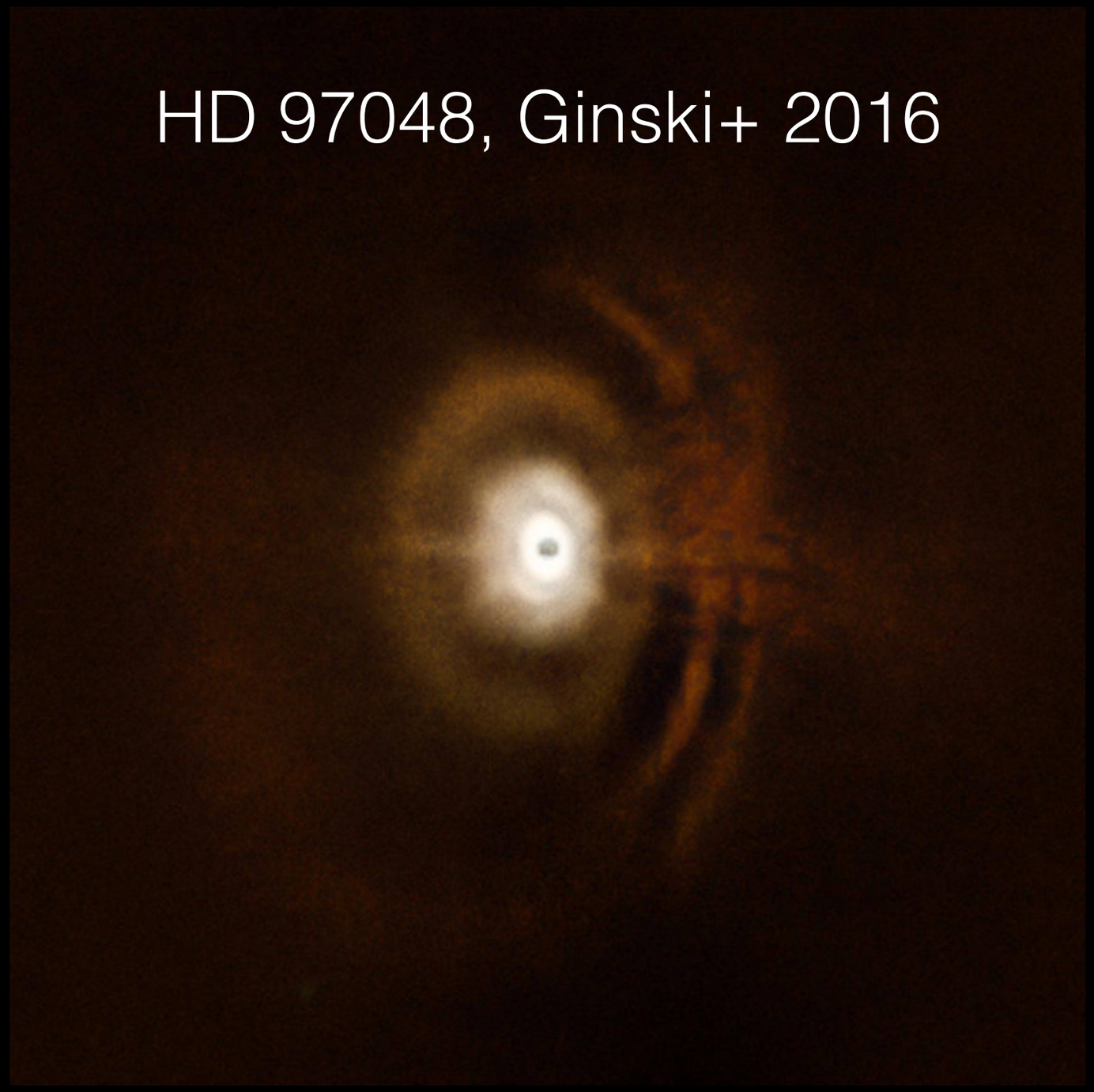




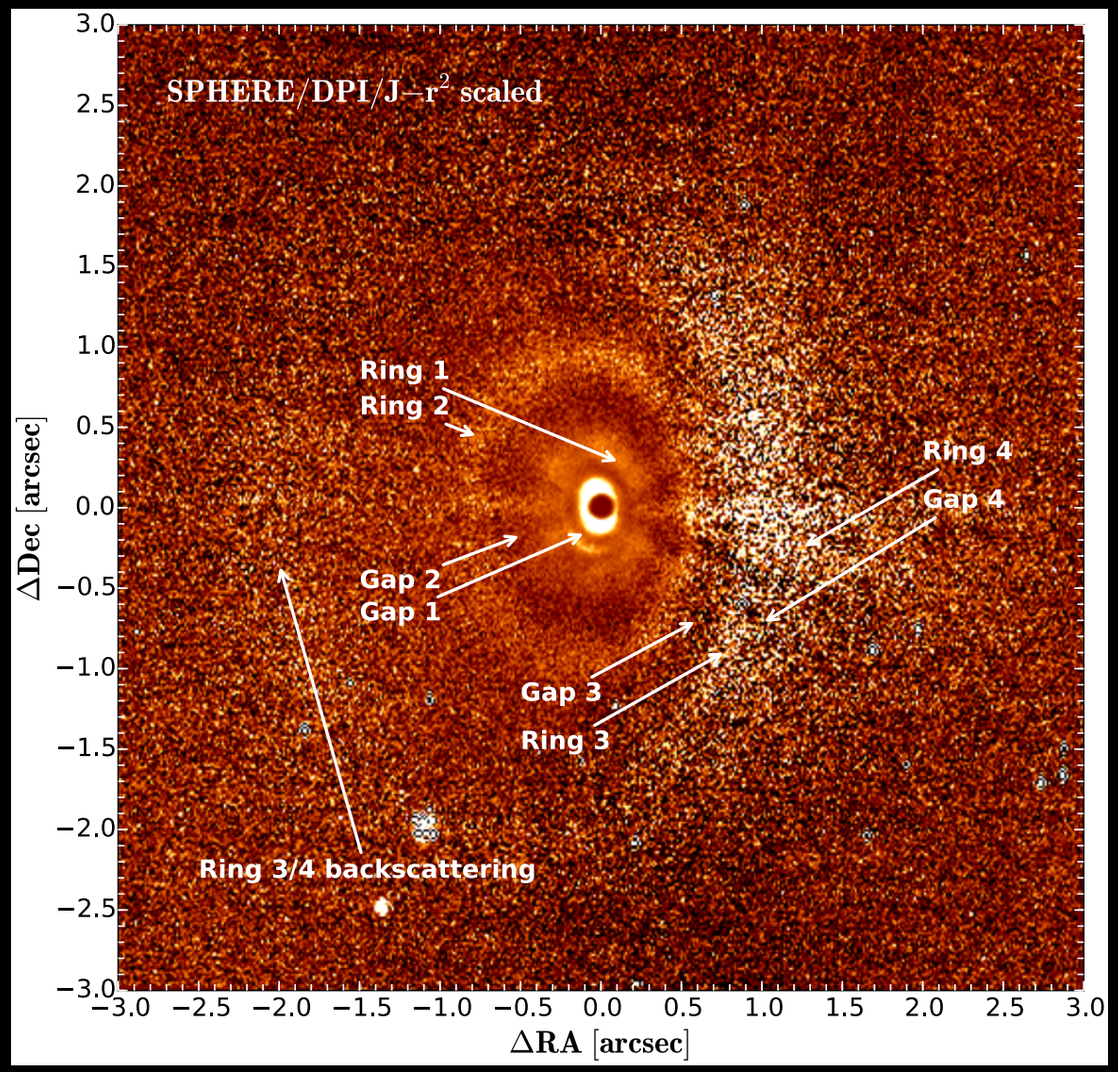
Disk flaring

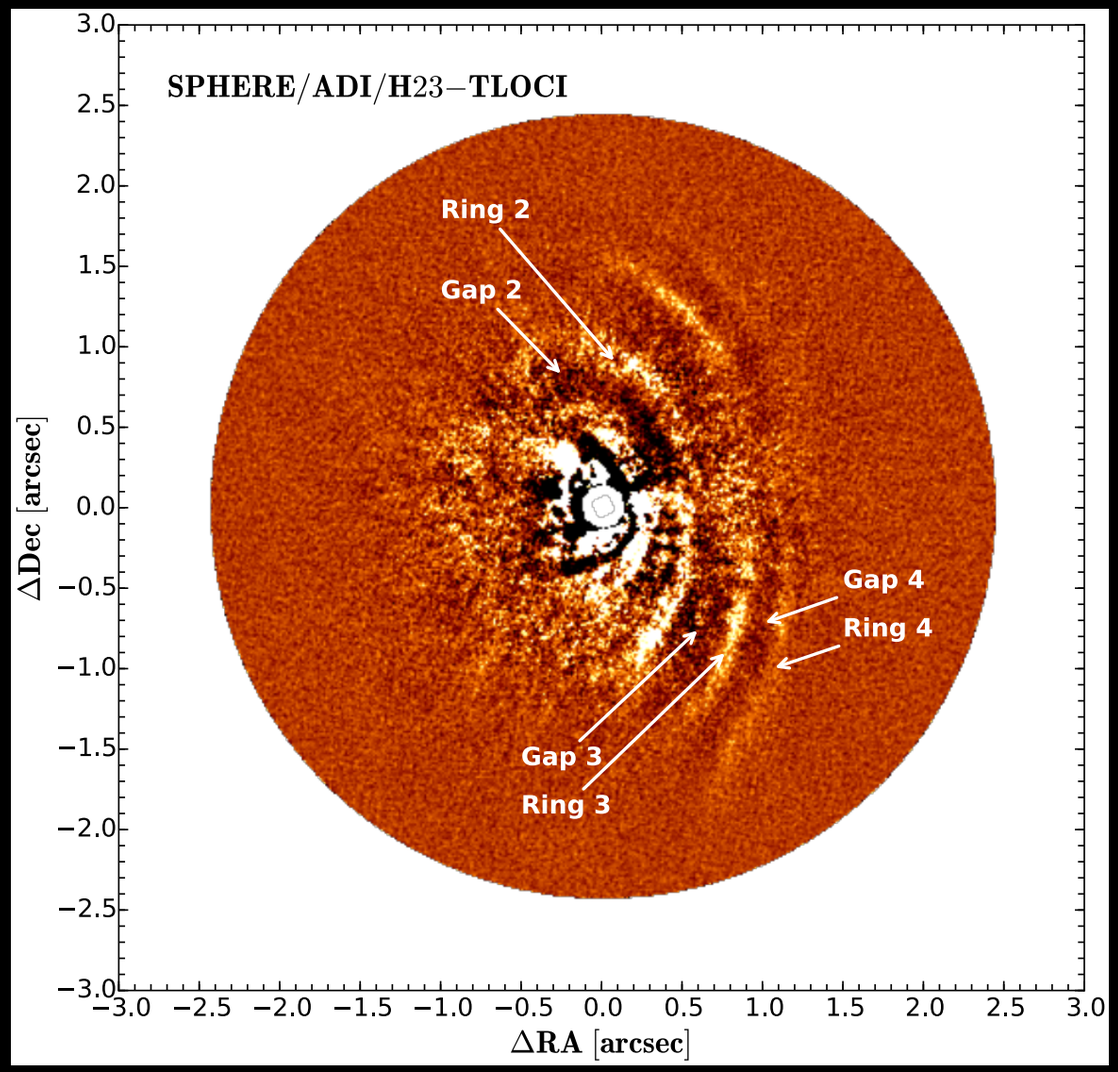


Multi-ringed disks in scattered light: bowl-shaped



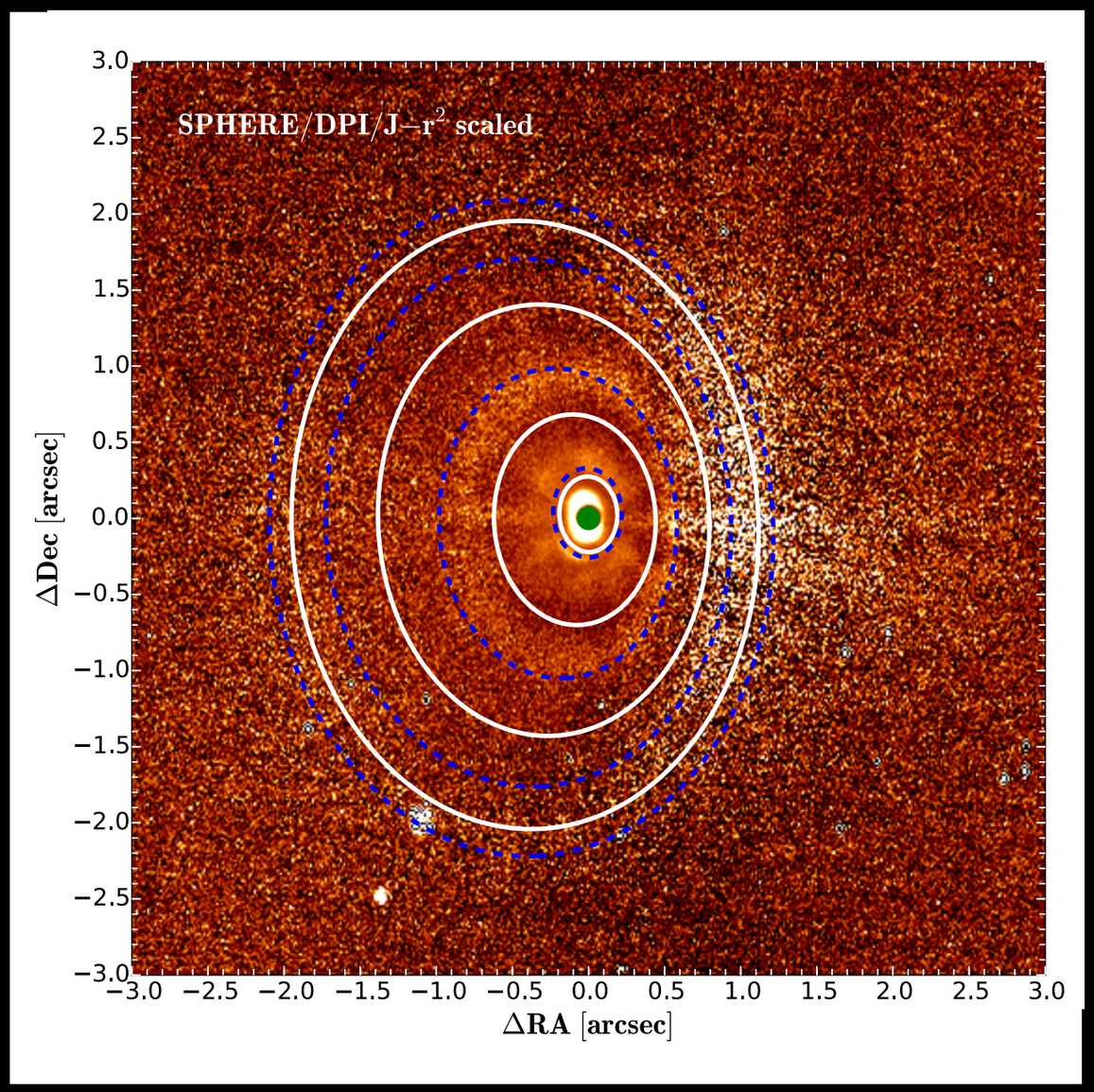
HD 97048

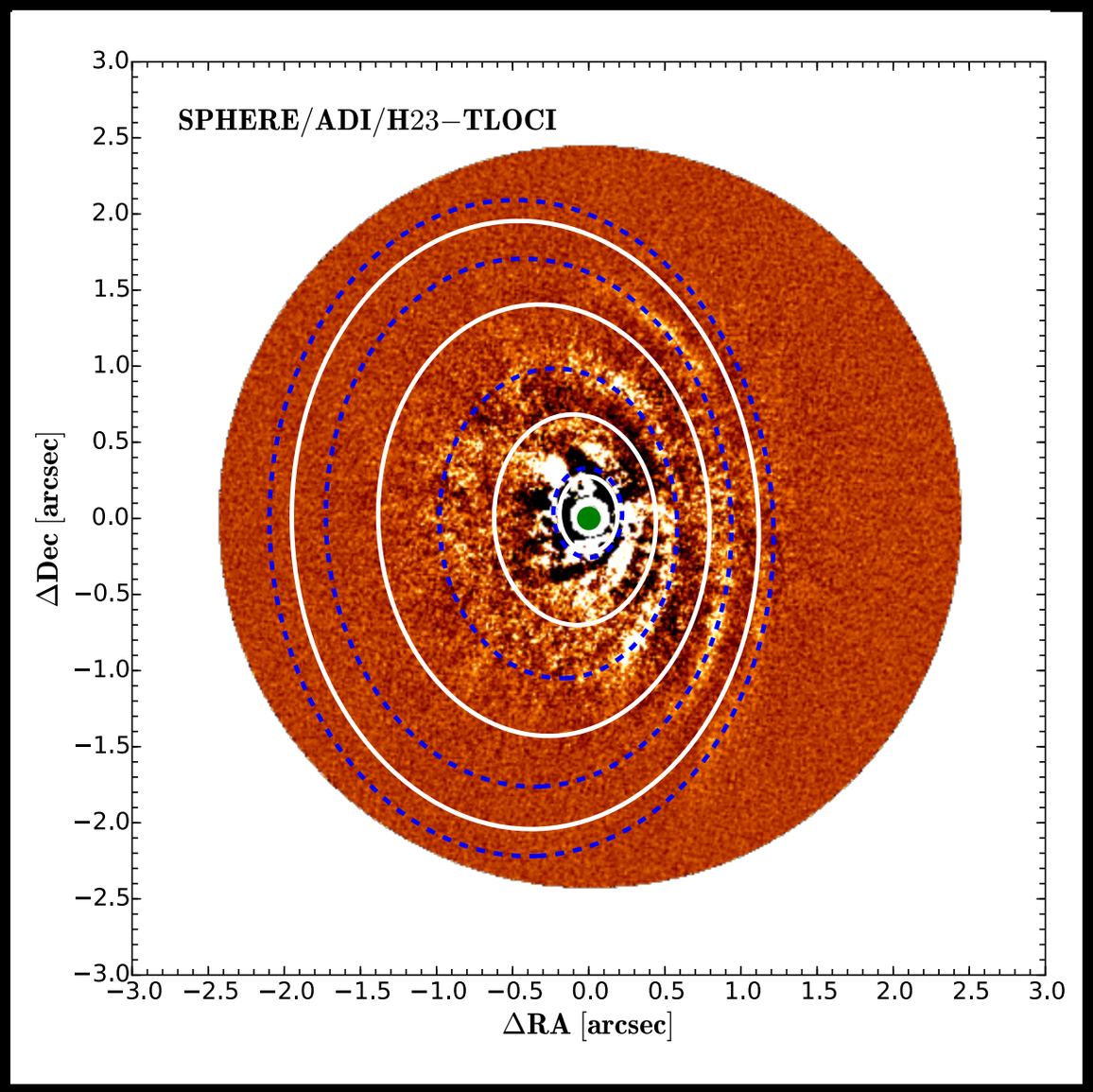




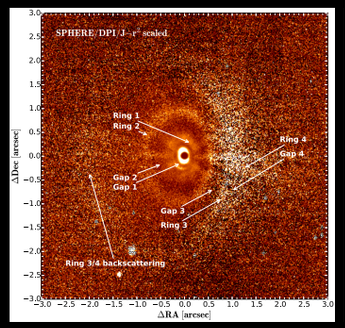
Ginski+ 2016

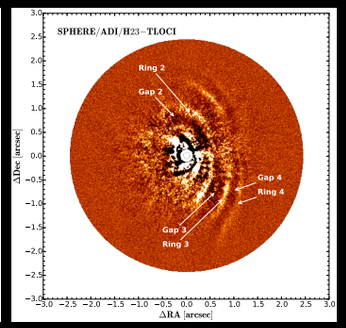
HD 97048



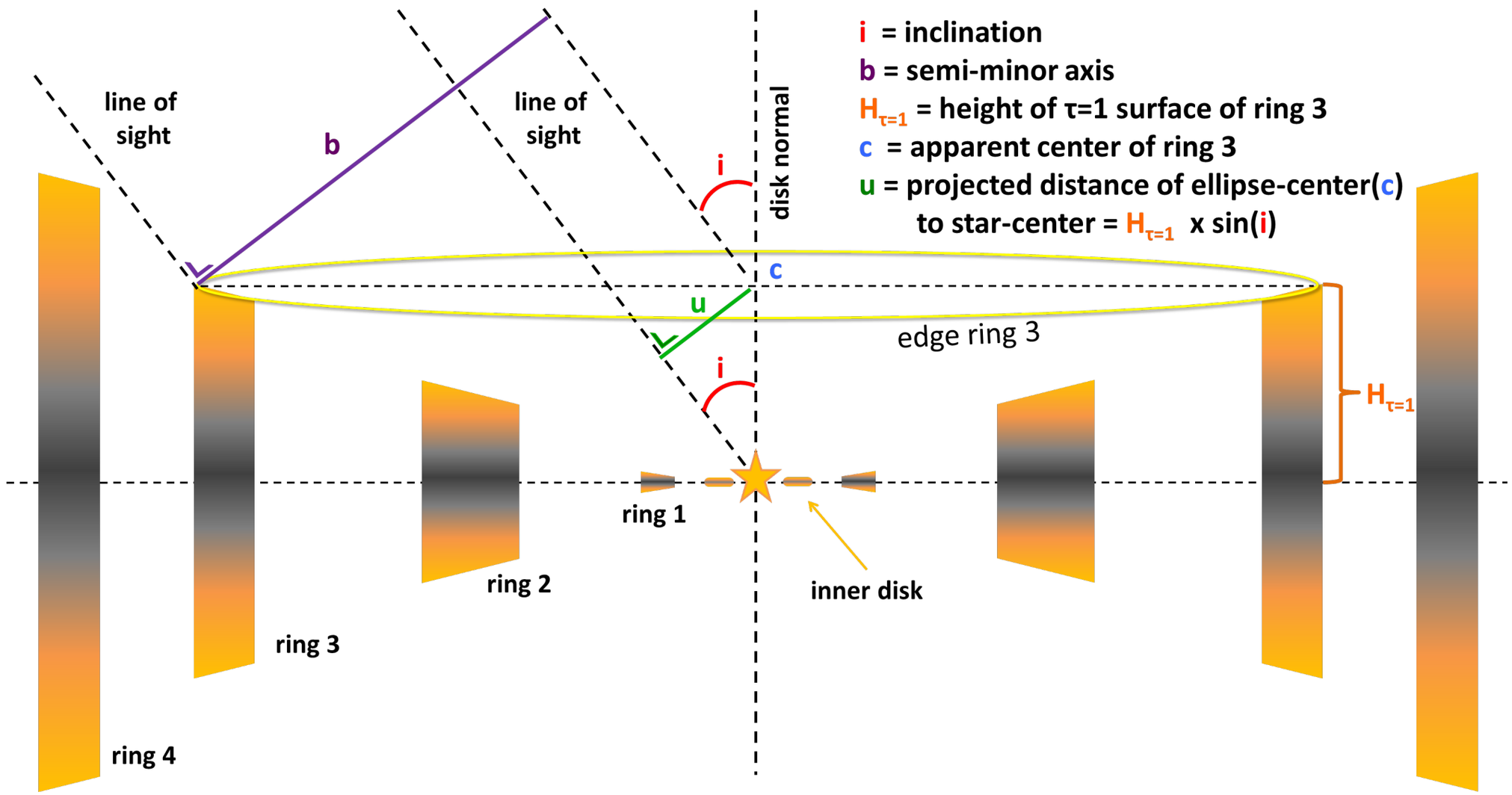


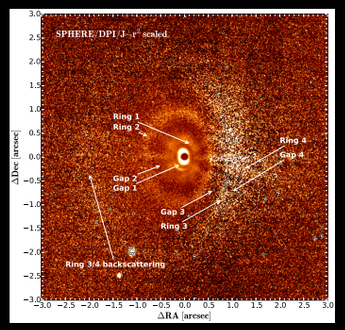
Ginski+ 2016

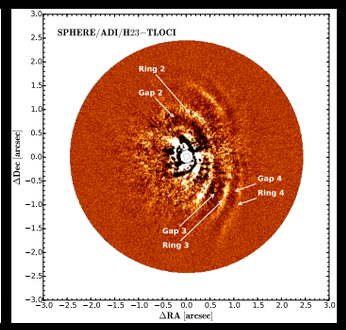

SPHERE/DPI/J-τ scaled
Ring 1
Ring 2
Gap 2
Gap 1
Ring 4
Gap 4
Gap 3
Ring 3
Ring 3/4 backscattering
ΔDec [arcsec]
ΔRA [arcsec]


SPHERE/ADI/H23–TLOCI
Ring 2
Gap 2
Gap 4
Ring 4
Gap 3
Ring 3
ΔDec [arcsec]
ΔRA [arcsec]

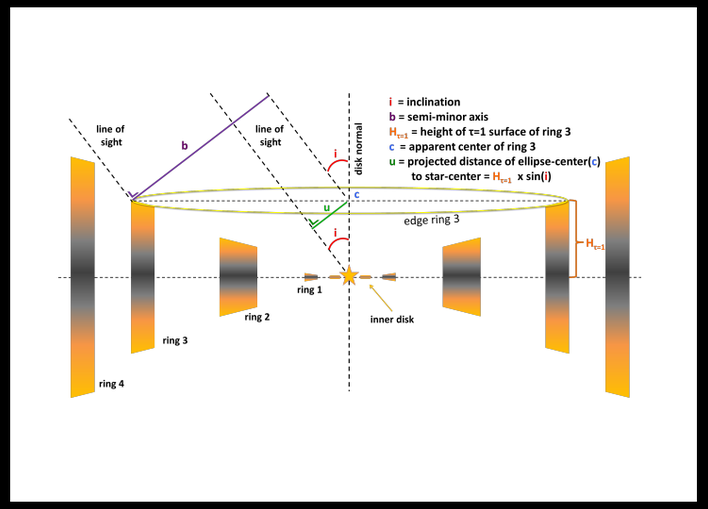
HD97048


i = inclination
b = semi-minor axis
$H_{\tau=1}$ = height of τ=1 surface of ring 3
c = apparent center of ring 3
u = projected distance of ellipse-center(c) to star-center = $H_{\tau=1}$ x sin(i)
line of sight
line of sight
b
i
disk normal
c
u
edge ring 3
i
$H_{\tau=1}$
ring 1
ring 2
inner disk
ring 3
ring 4


SPHERE/DPI/J-r' scaled
Ring 1
Ring 2
Ring 4
Gap 4
Gap 2
Gap 1
Gap 3
Ring 3
Ring 3/4 backscattering
ΔDec [arcsec]
ΔRA [arcsec]


SPHERE/ADI/H23-TLOCI
Ring 2
Gap 2
Gap 4
Ring 4
Gap 3
Ring 3
ΔDec [arcsec]
ΔRA [arcsec]

HD97048


i = inclination
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H_τ=1 = height of τ=1 surface of ring 3
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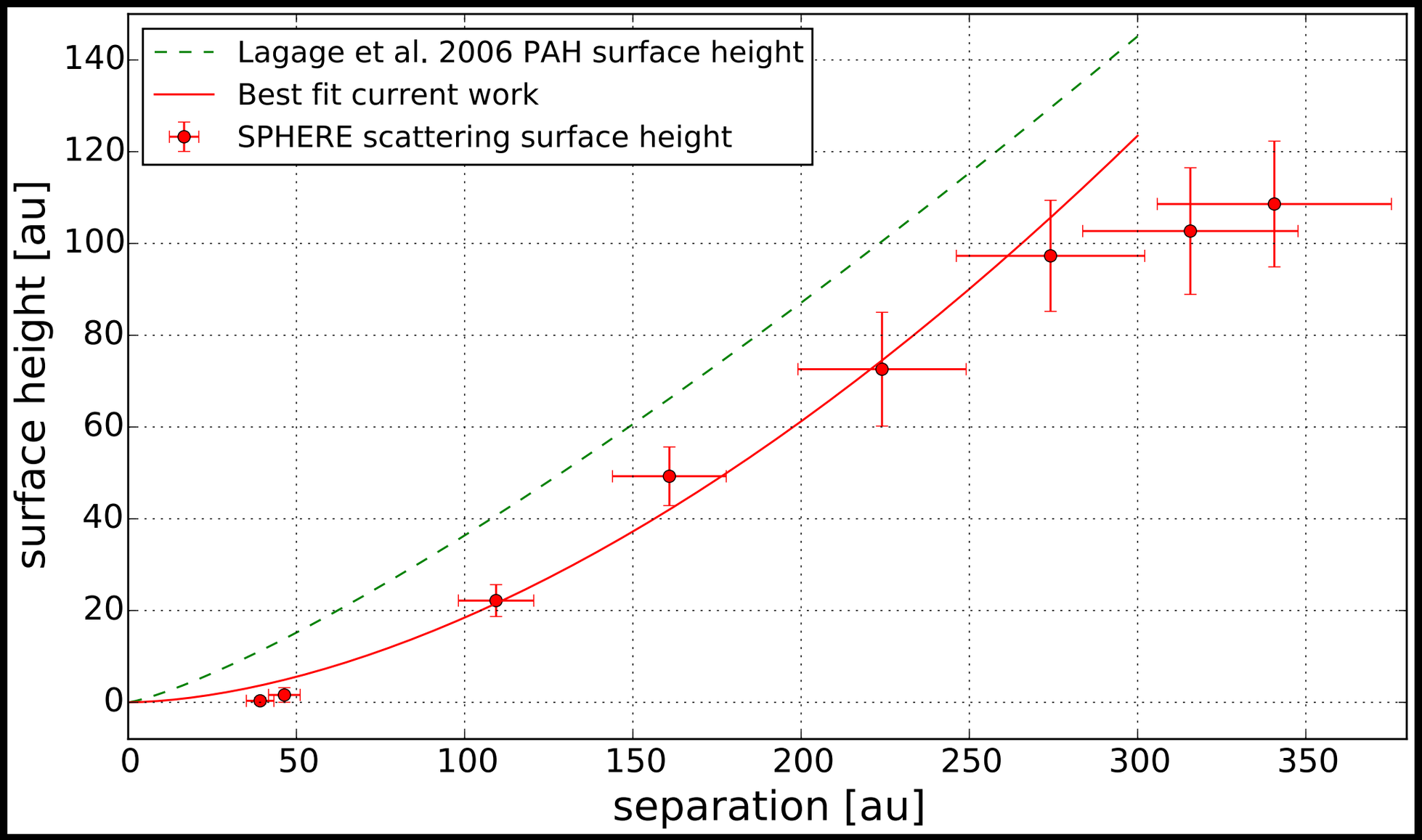
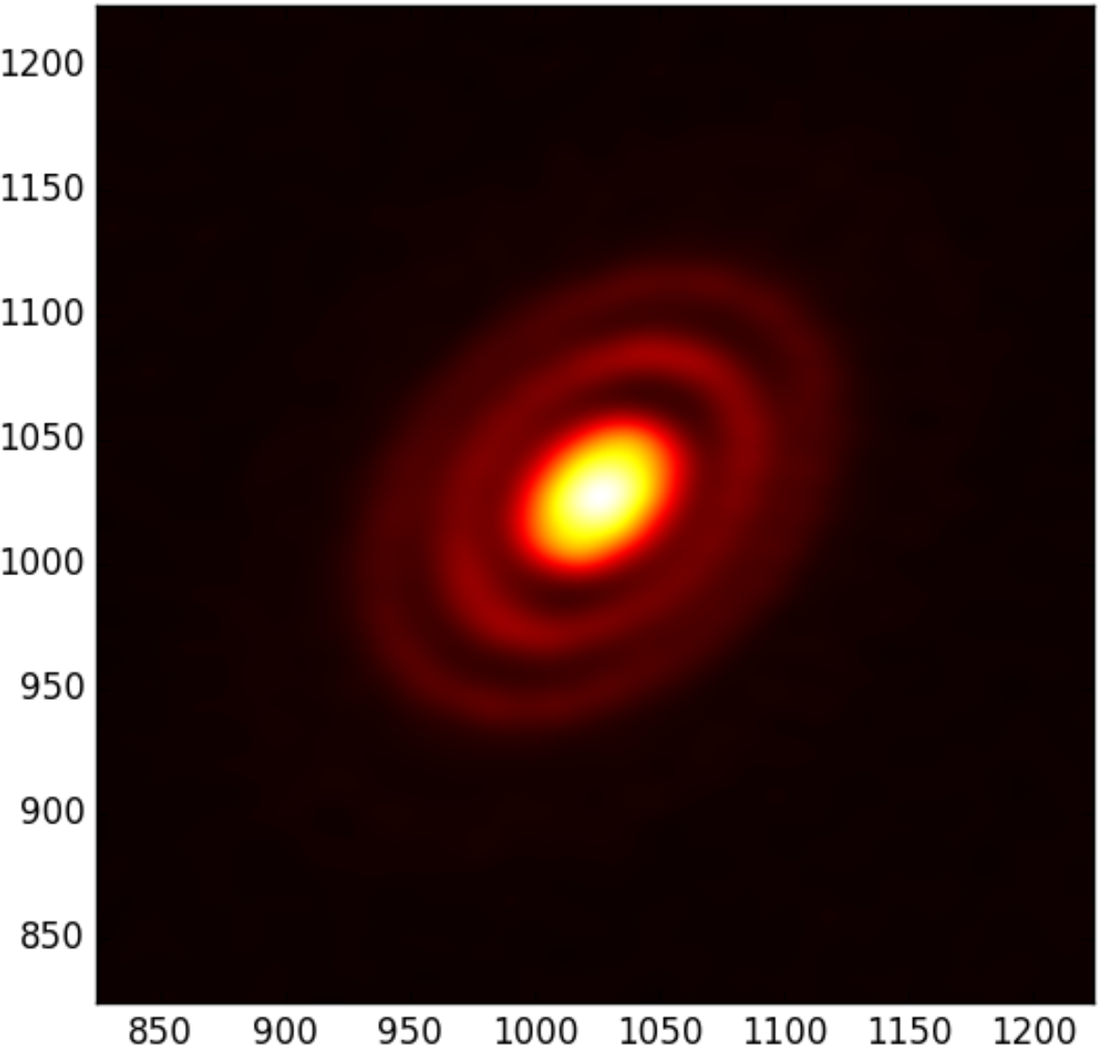
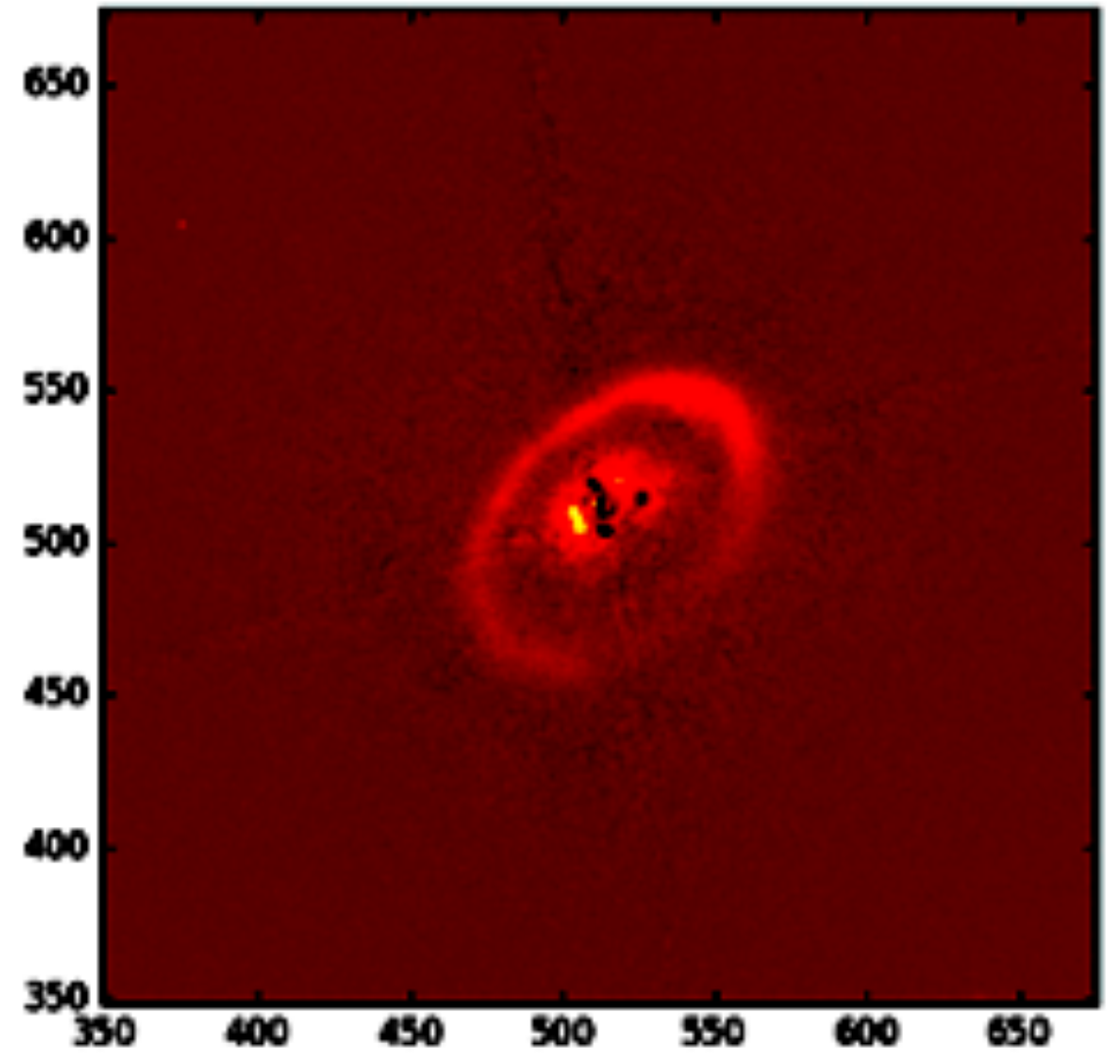
u = projected distance of ellipse-center(c) to star-center = H_τ=1 x sin(i)
line of sight
line of sight
b
i
disk normal
c
u
i
edge ring 3
H_τ=1
ring 1
ring 2
ring 3
ring 4
inner disk


Lagage et al. 2006 PAH surface height
Best fit current work
SPHERE scattering surface height
surface height [au]
separation [au]
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
350

HD 163296 with ALMA and SPHERE





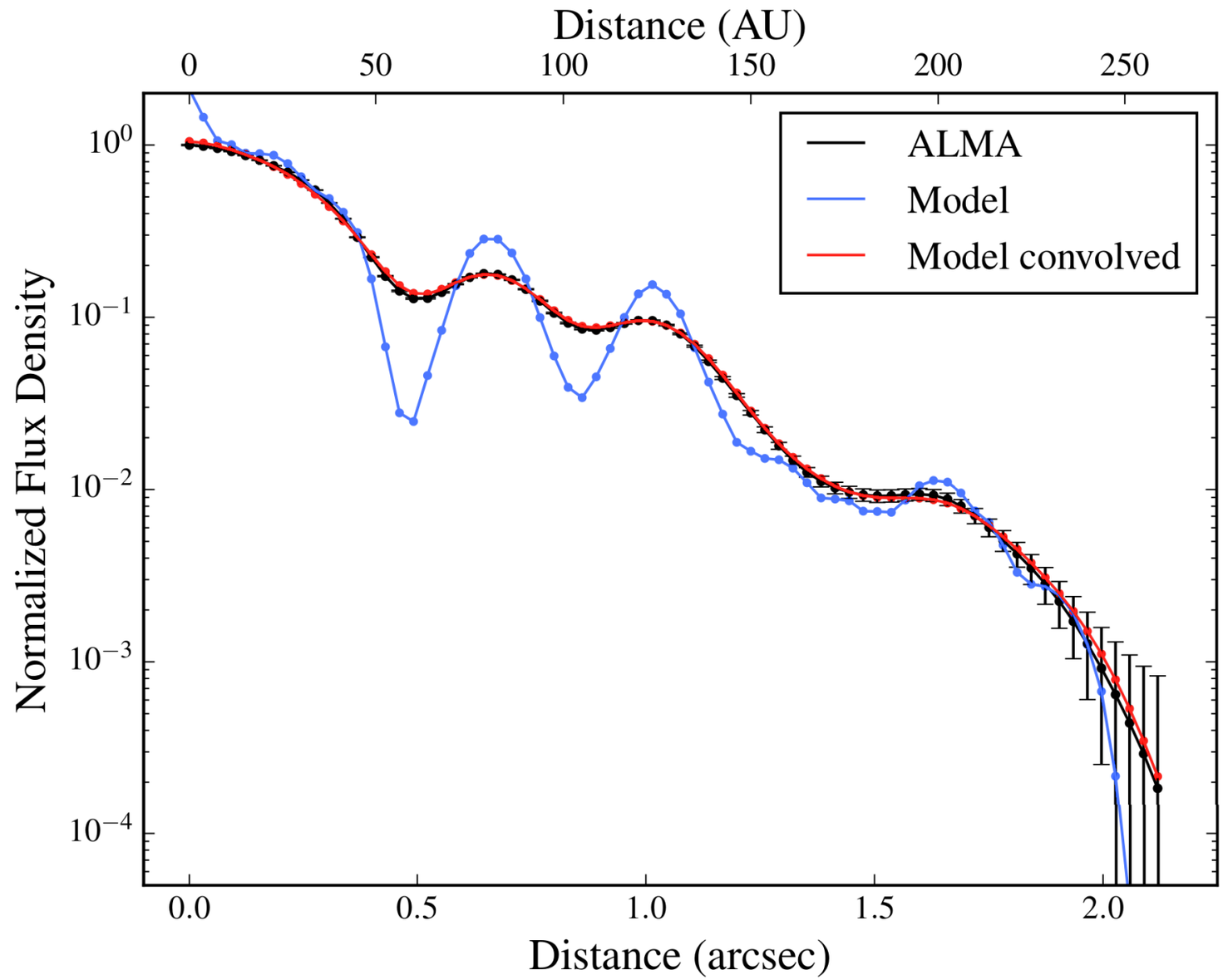
ALMA (Isella+ 2016)

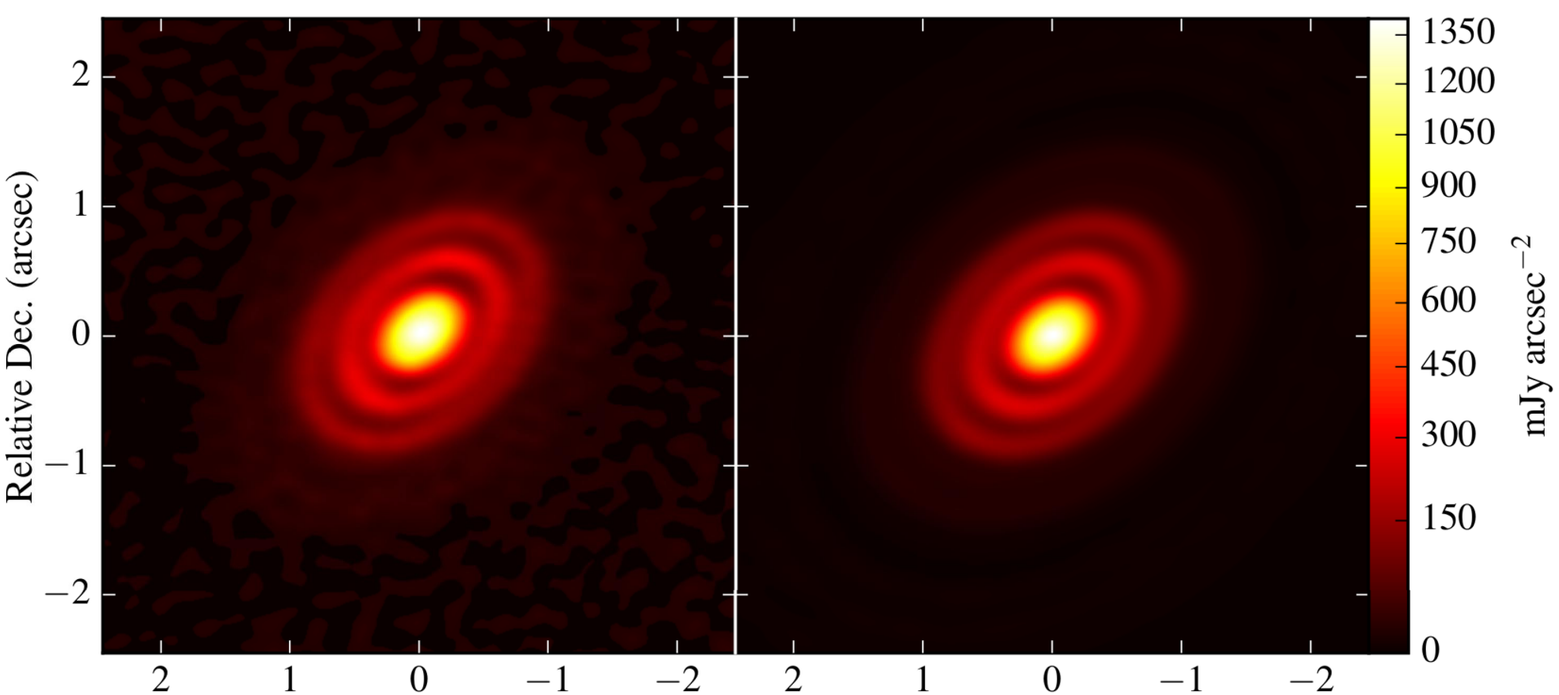
SPHERE

Height:
12.7 AU at 77 AU
aspect=0.16

Muro Arena et al 2018

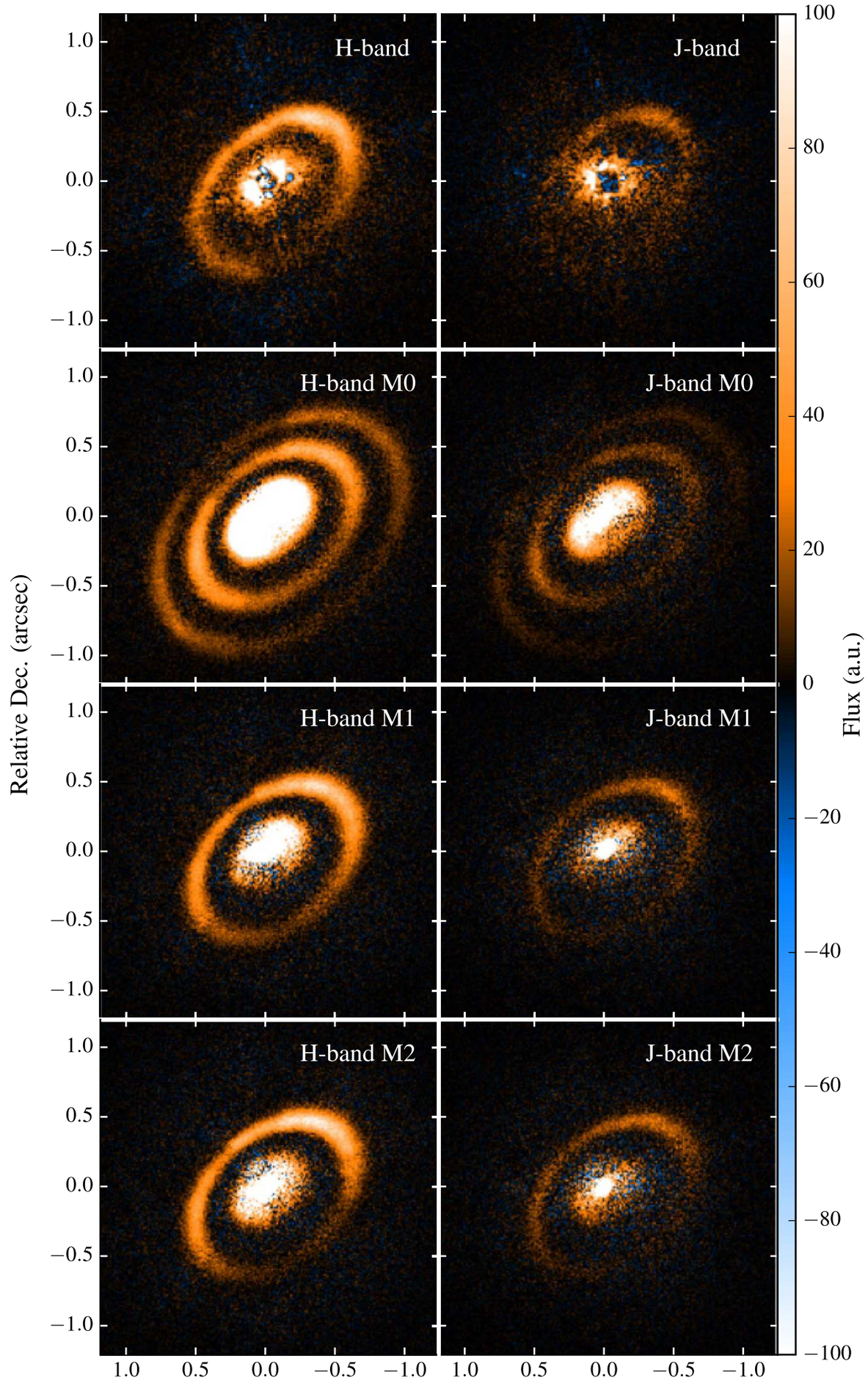
Model vs ALMA image





Height:
12.7 AU at 77 AU

Making the outer ring disappear

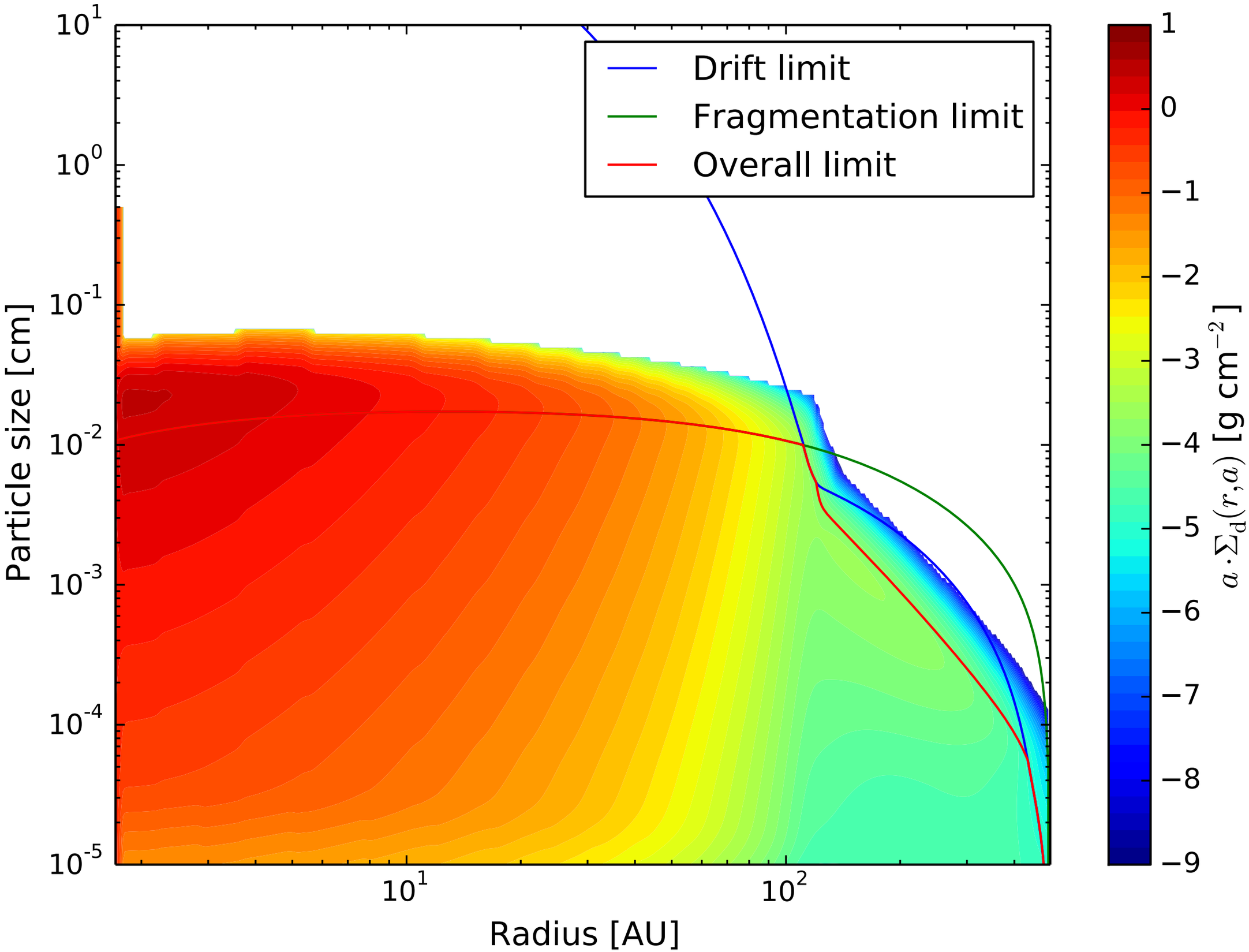


default model

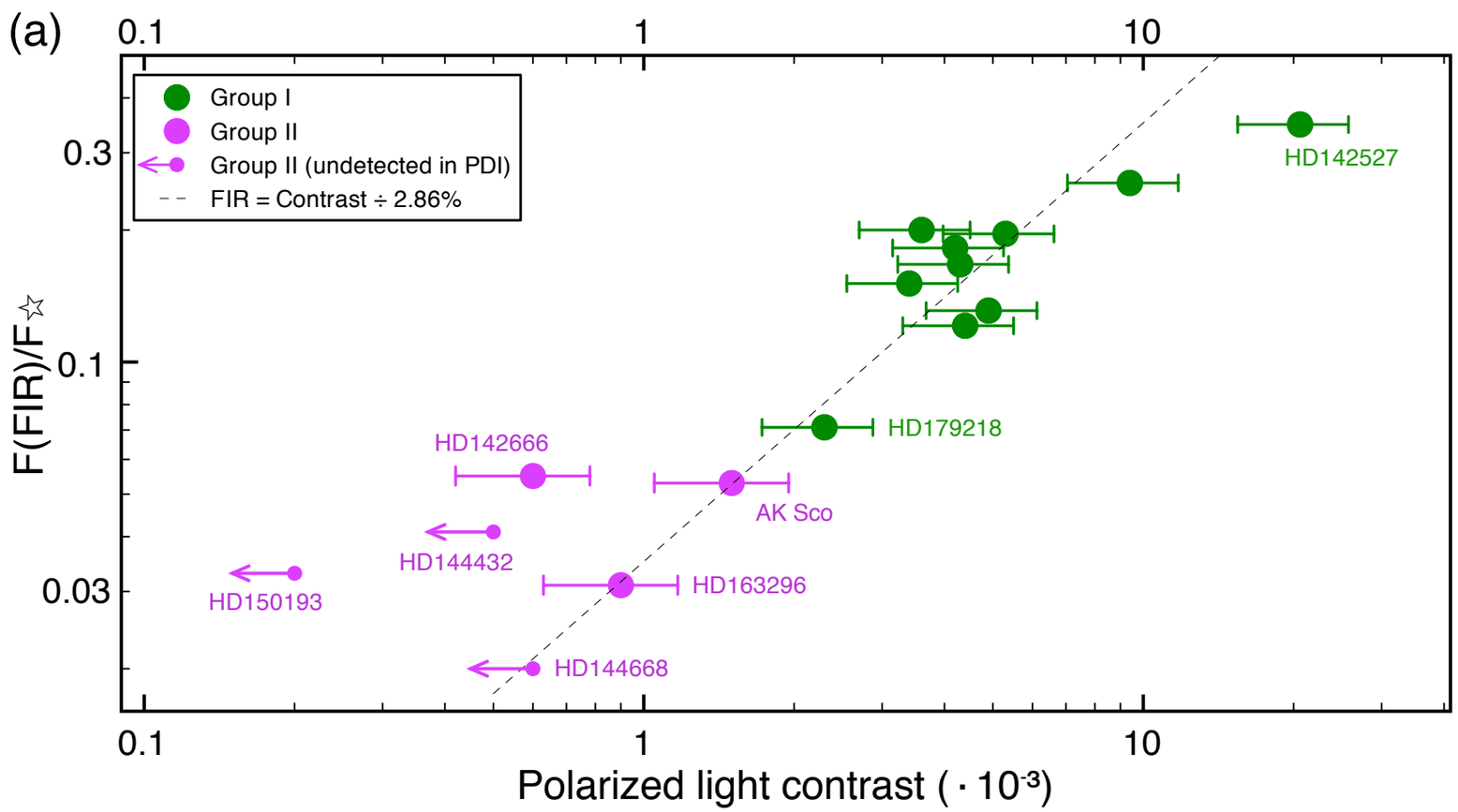
a_{min}=5μm

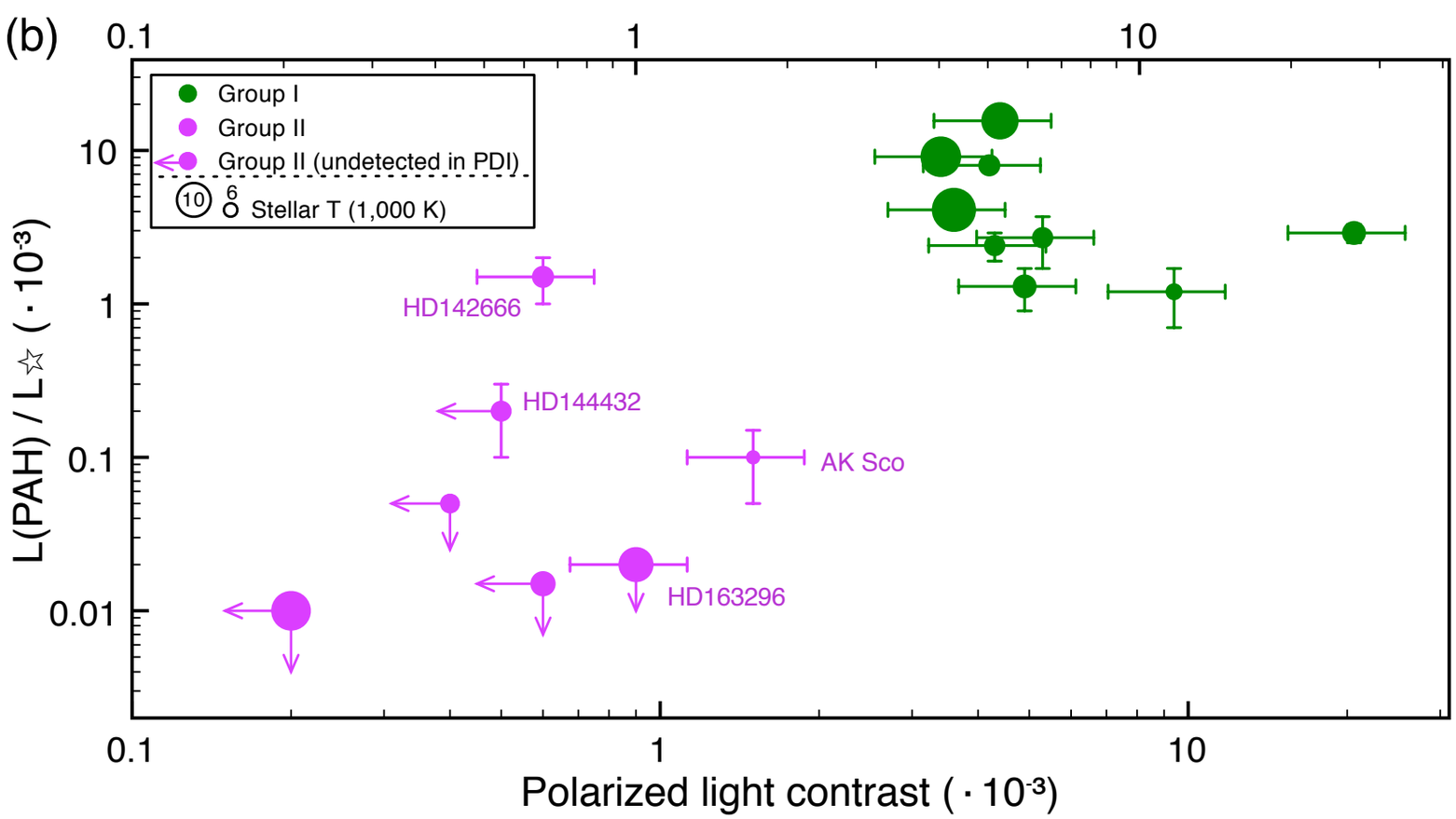
$\alpha=10^{-5}$

Depletion of outer disk by drift



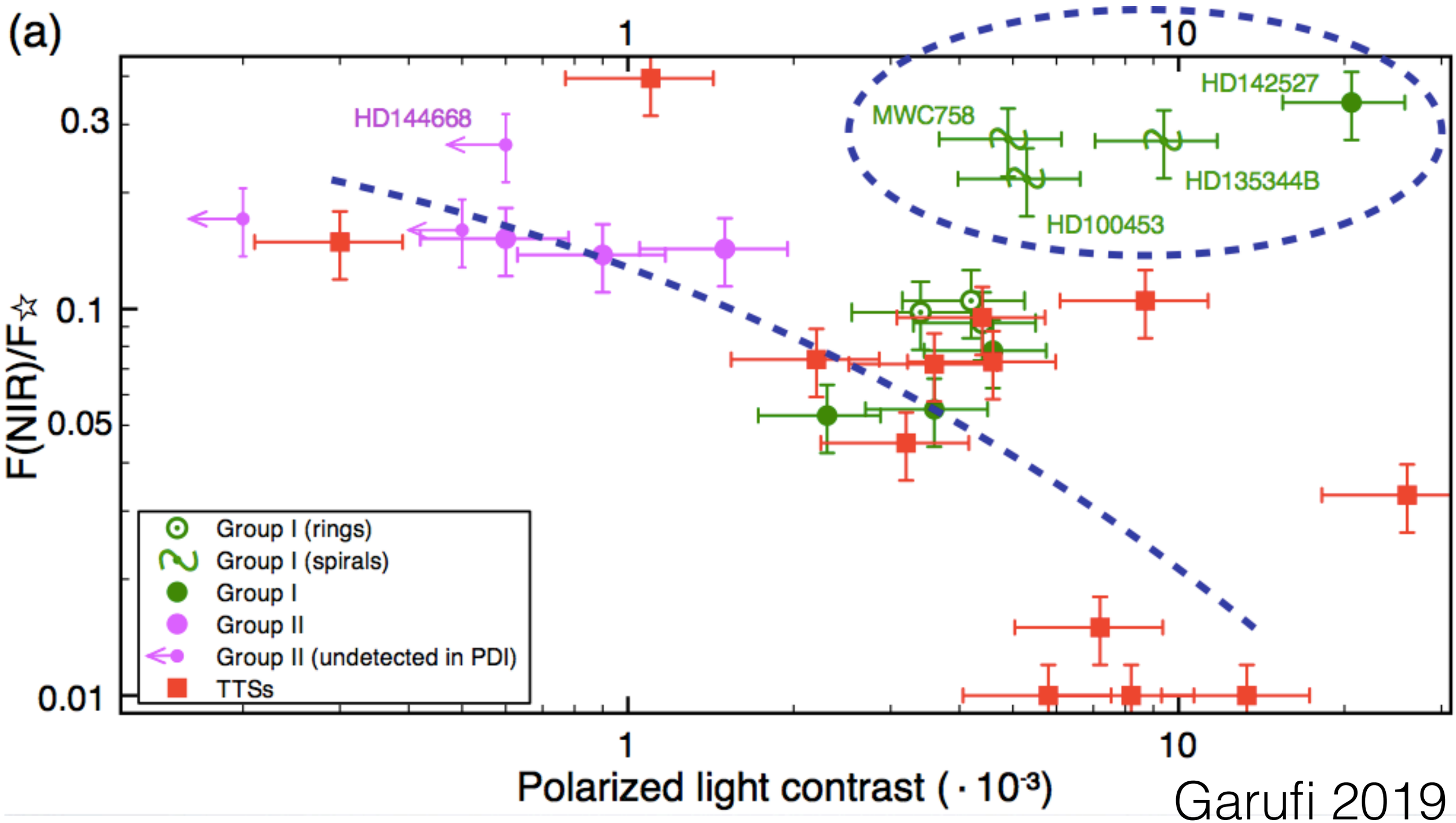
Inner/outer disk shadowing





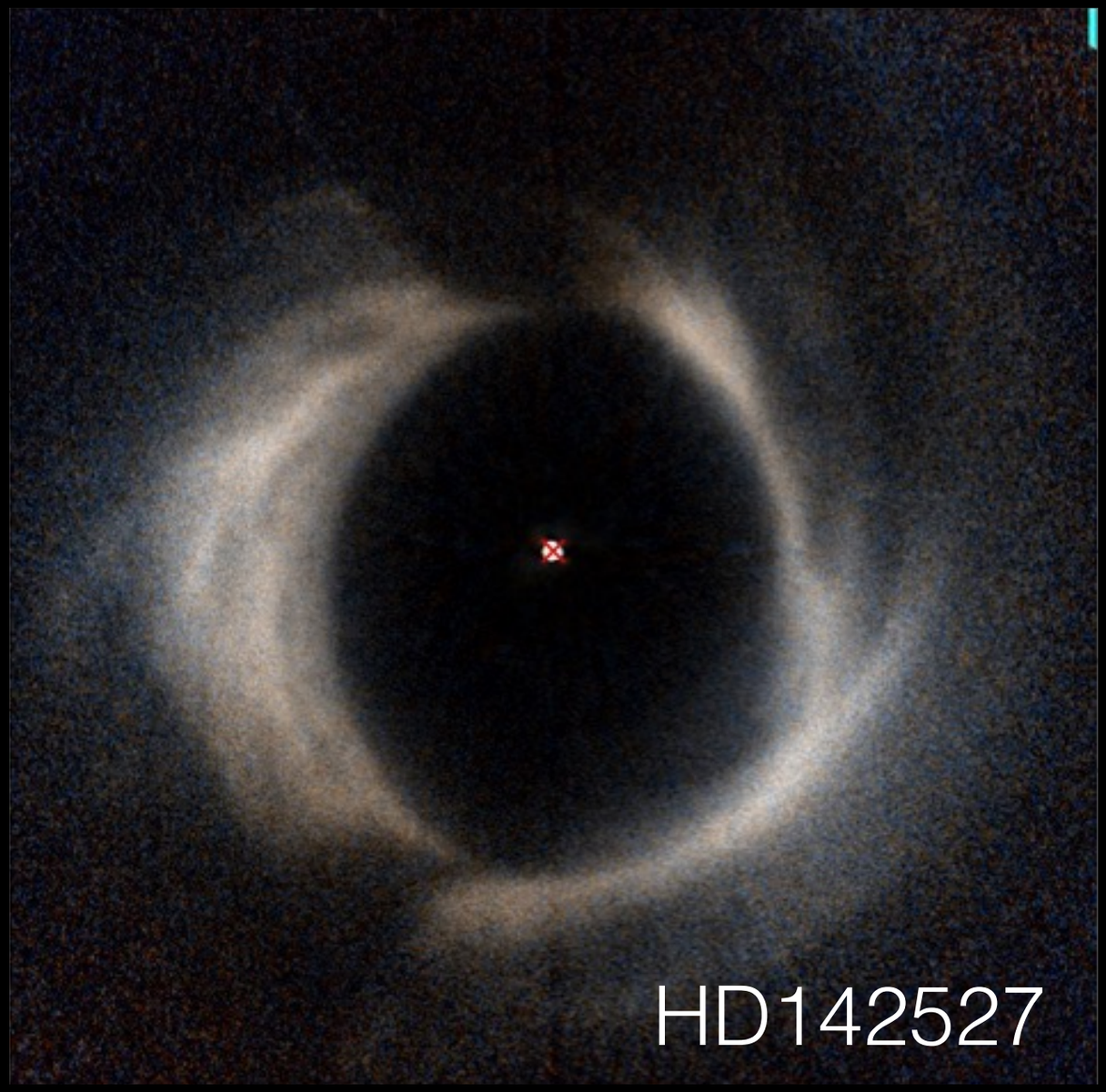
Garufi 2019
see also Acke+ 2009

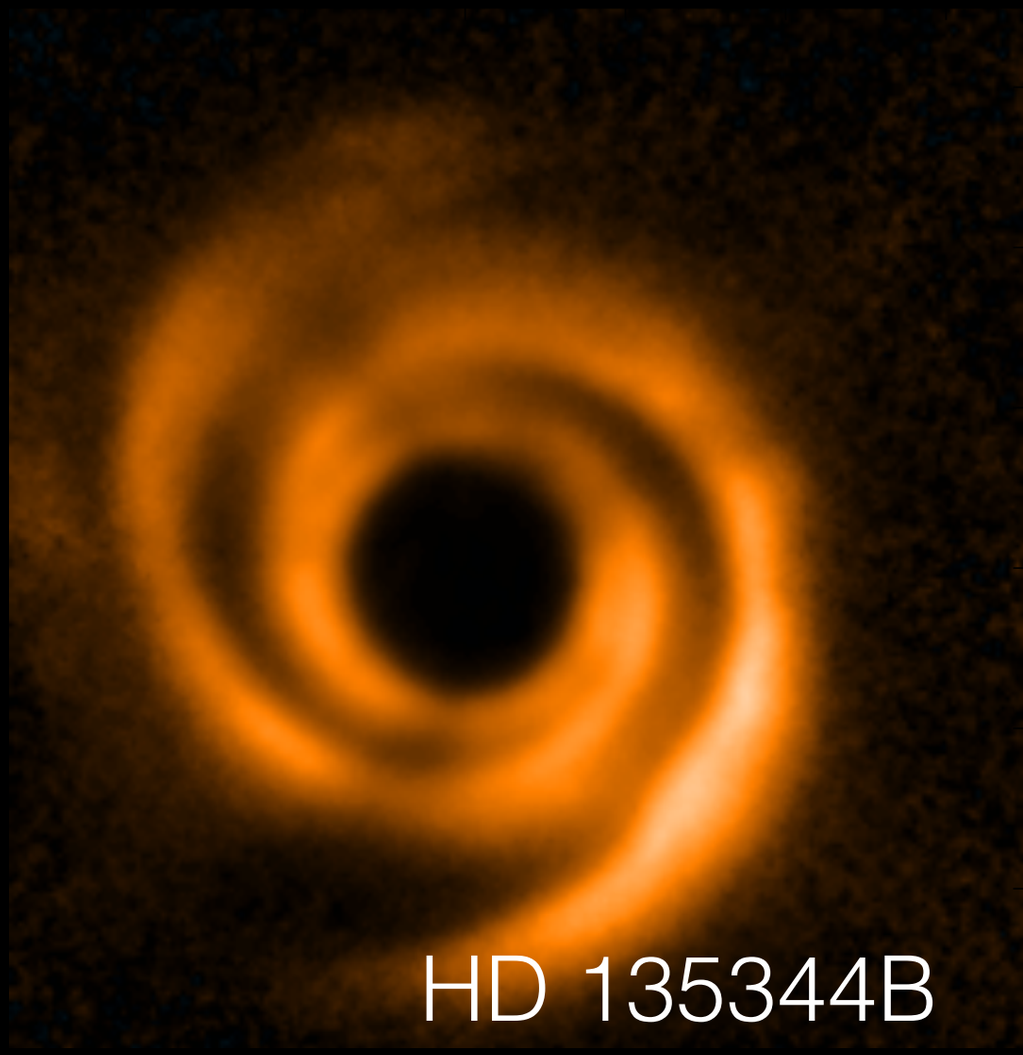
Inner/outer disk shadowing



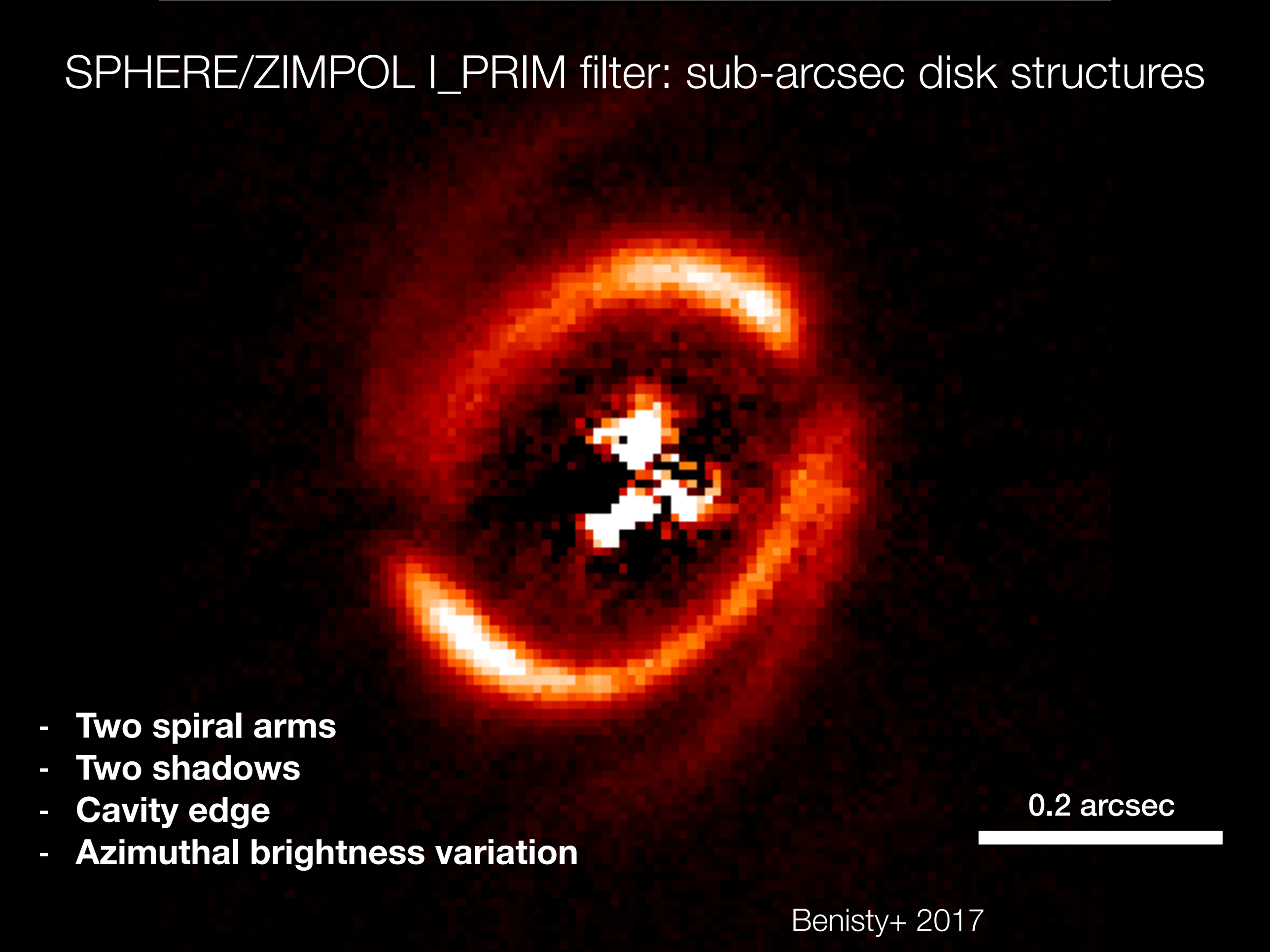
Garufi 2019

Shadows





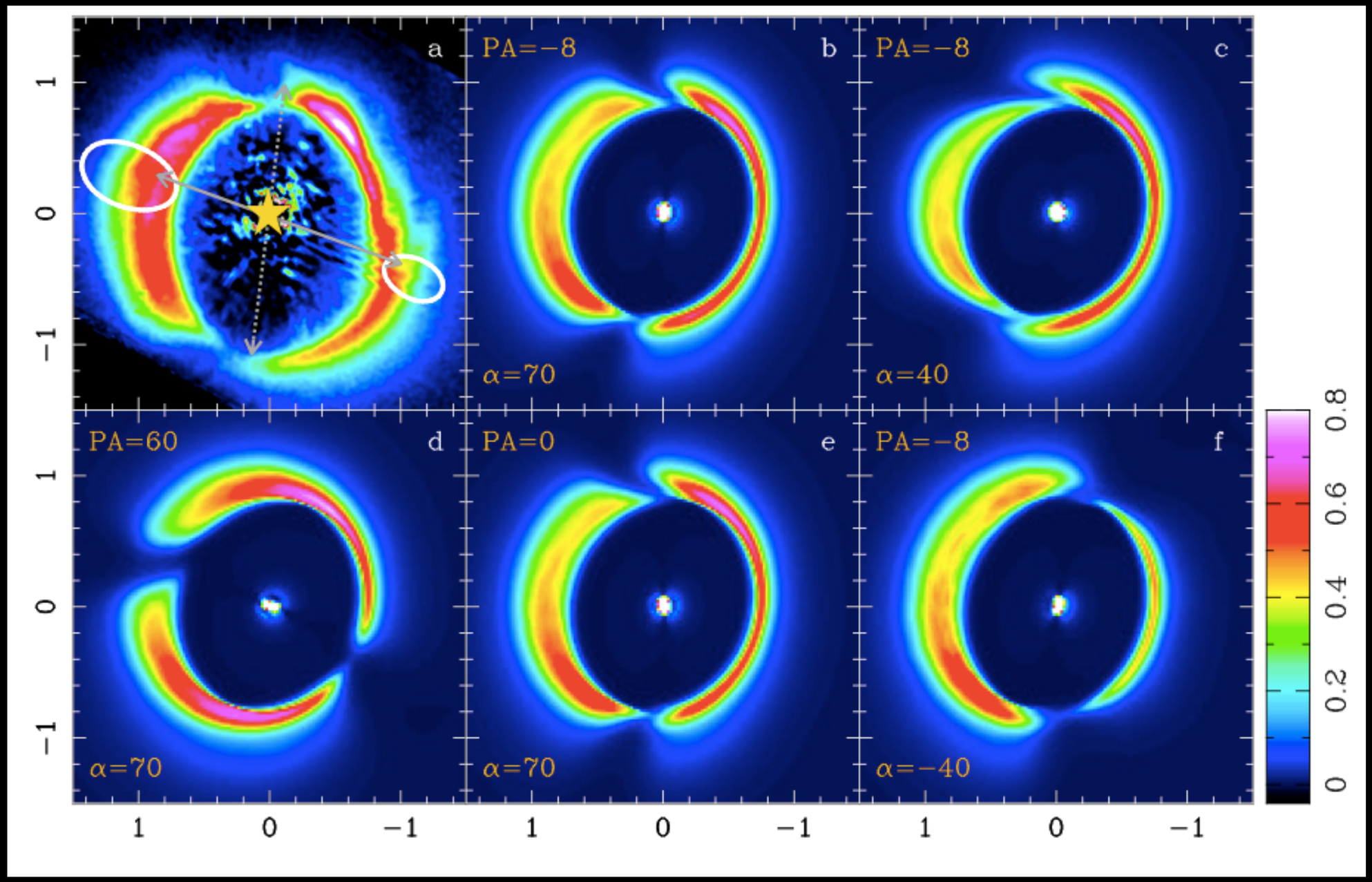
SPHERE/ZIMPOL I_PRIM filter: sub-arcsec disk structures



- **Two spiral arms**
- **Two shadows**
- **Cavity edge**
- **Azimuthal brightness variation**

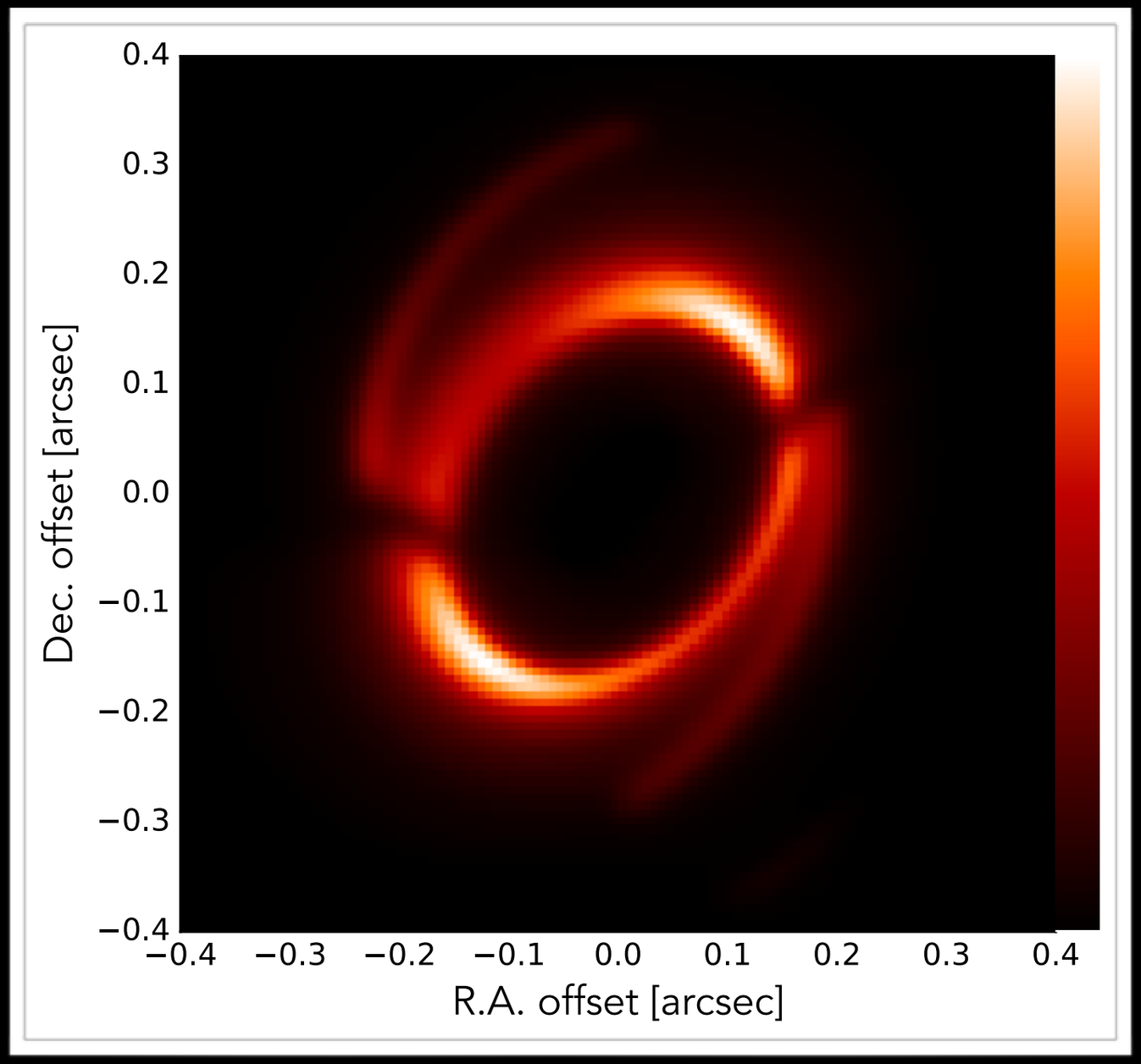
Benisty+ 2017

SHADOWS

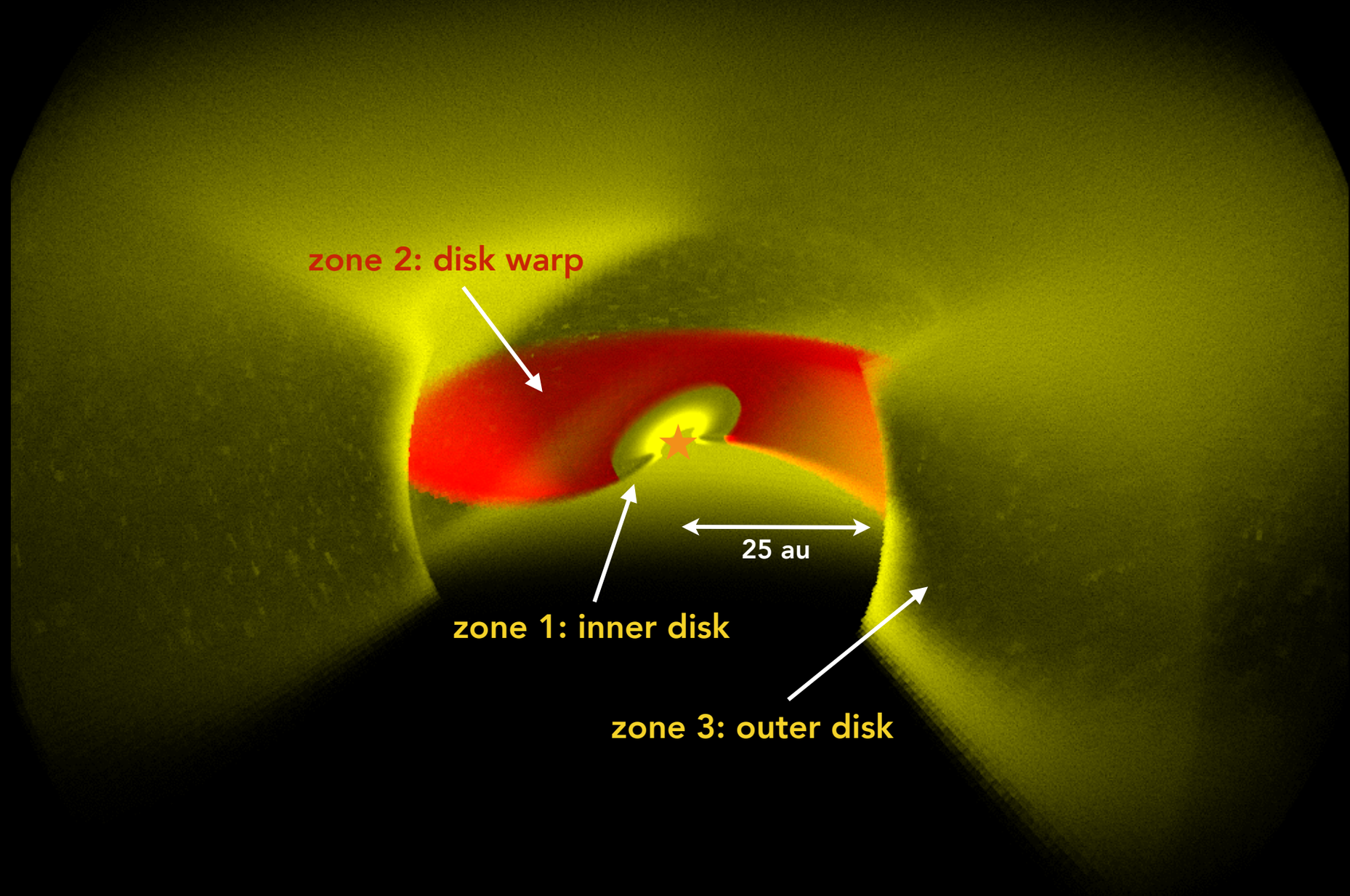


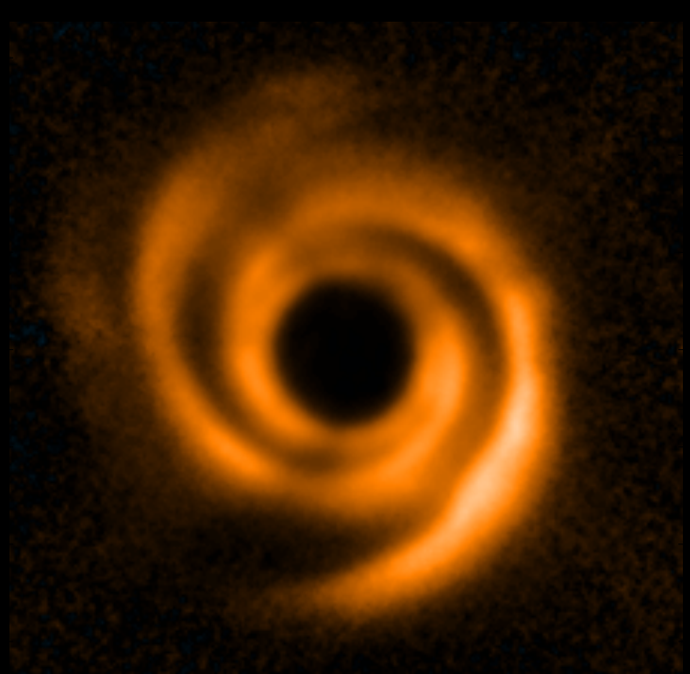
Marino, Perez, Casassus 2014, ApJ Letters

Radiative transfer model for HD 100453



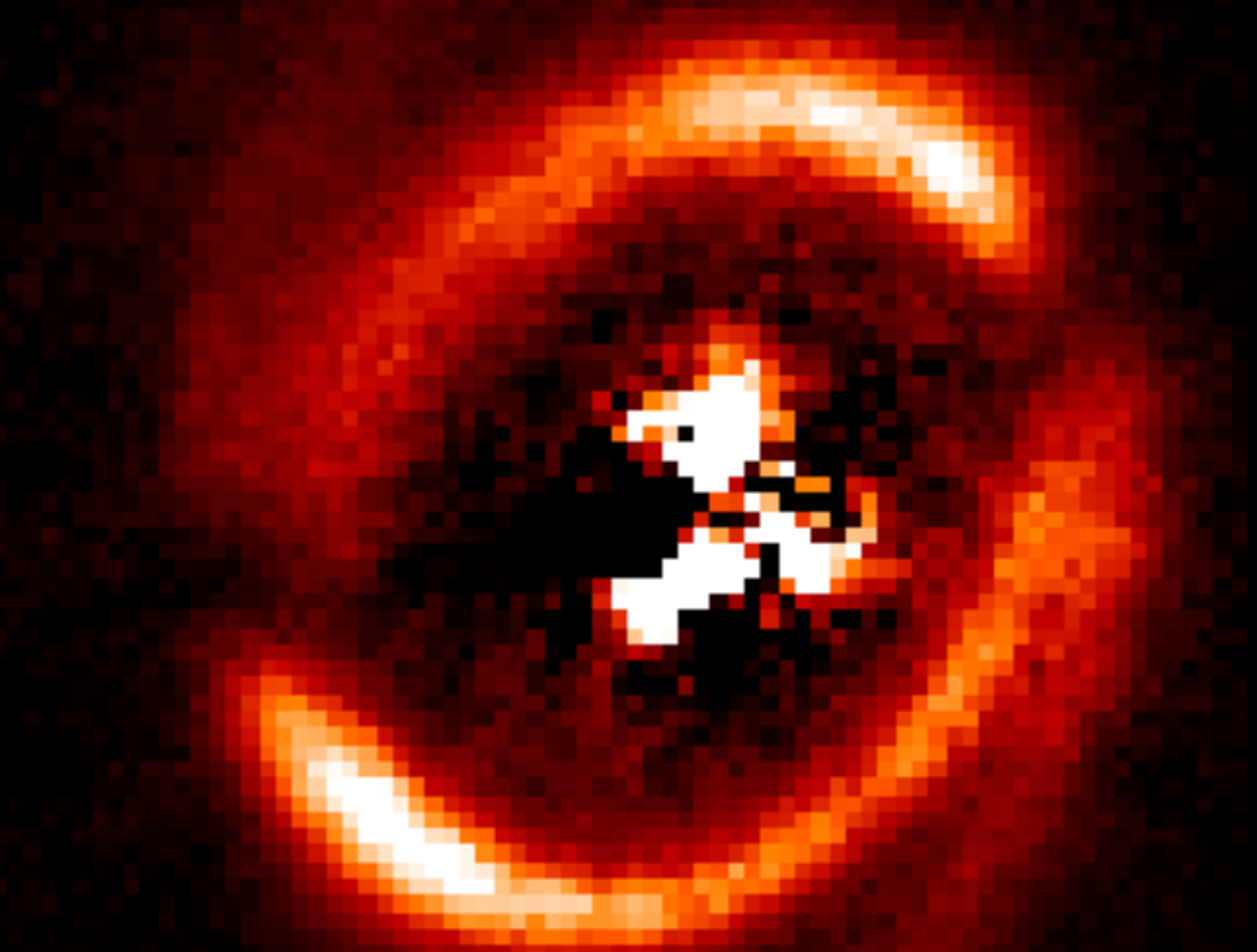
Benisty+ 2017

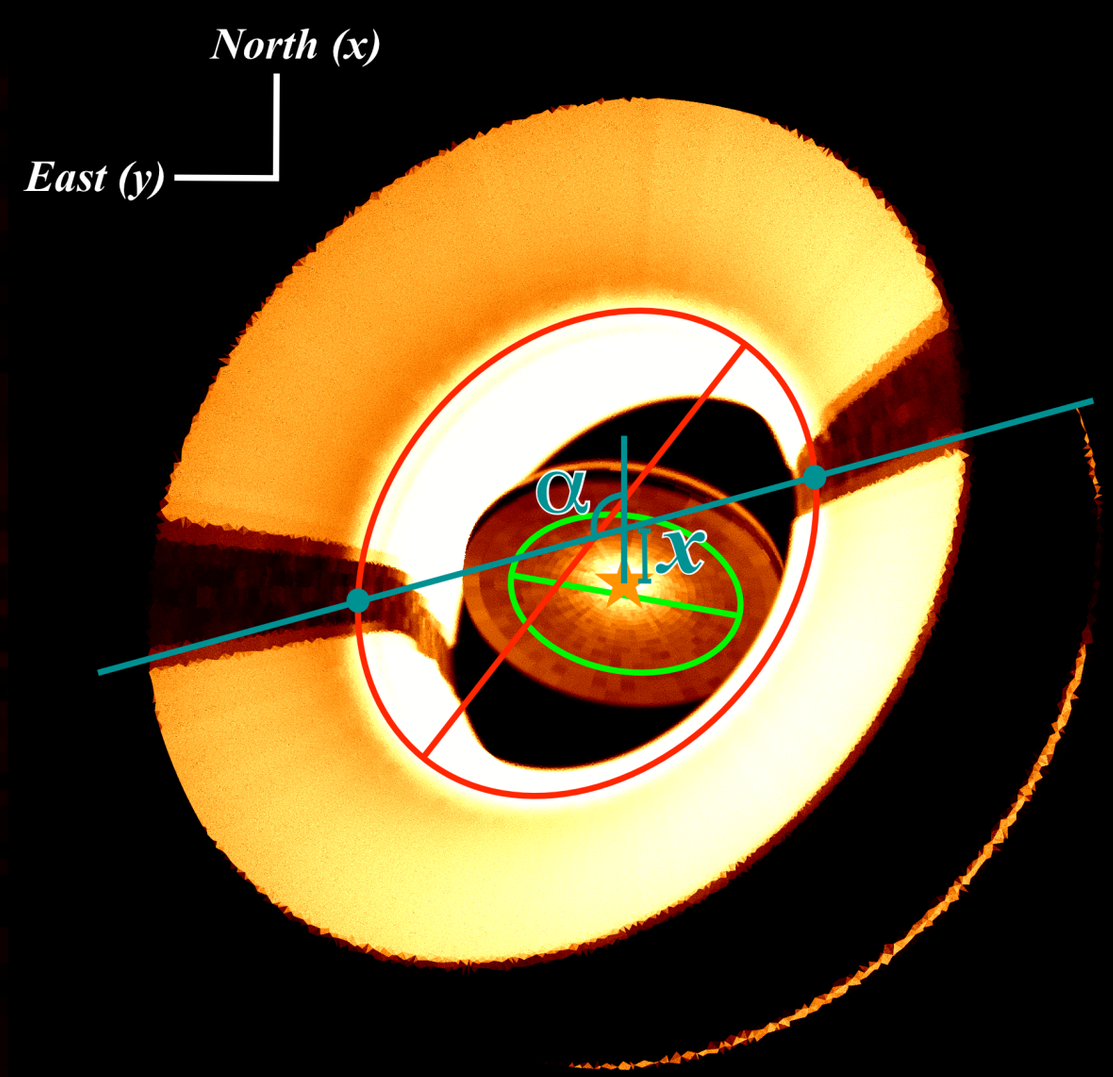




Stolker+ 2016

SPHERE/ZIMPOL I_PRIM filter: sub-arcsec disk structures

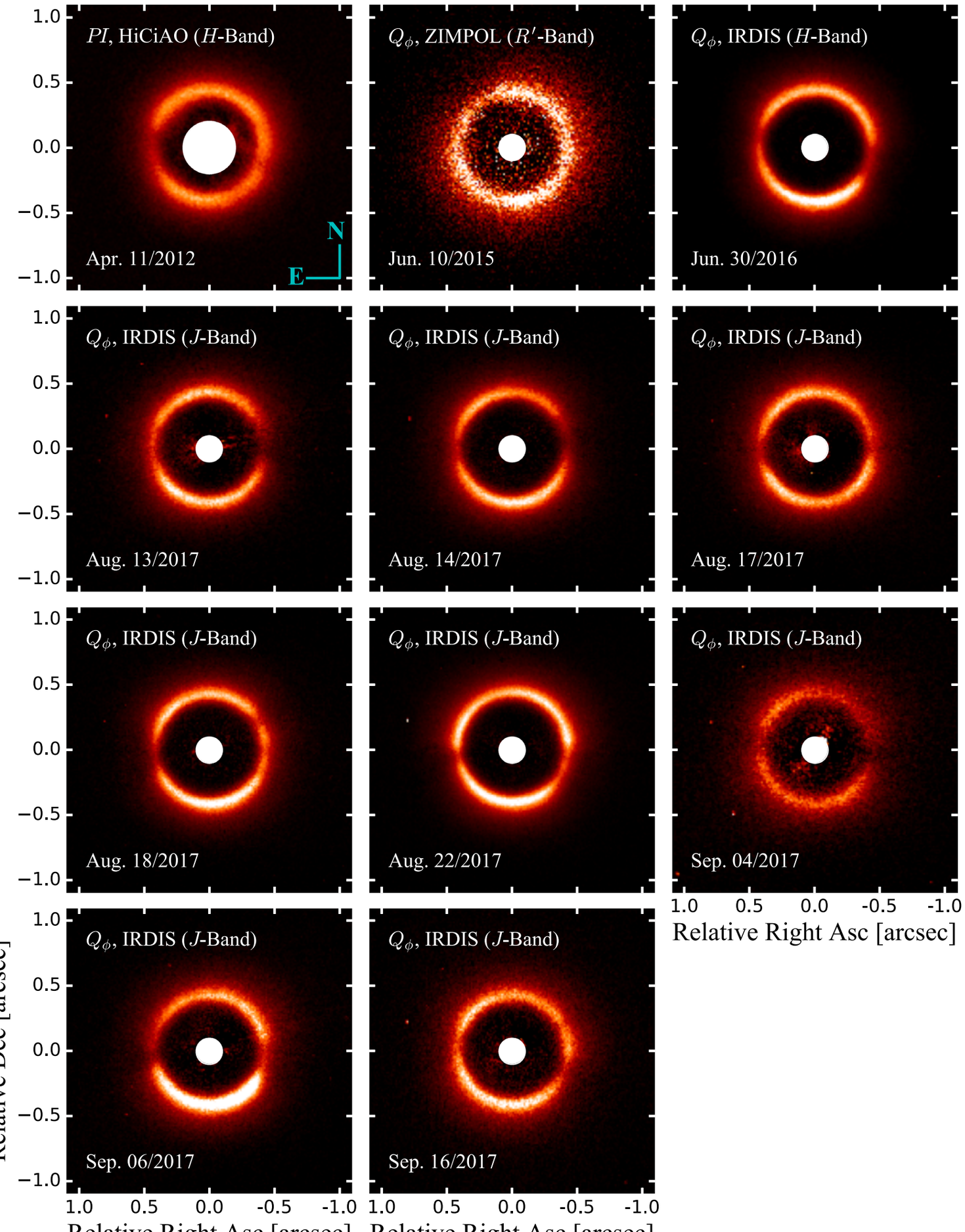




- **Two spiral arms**
- **Two shadows**
- **Cavity edge**
- **Azimuthal brightness variation**

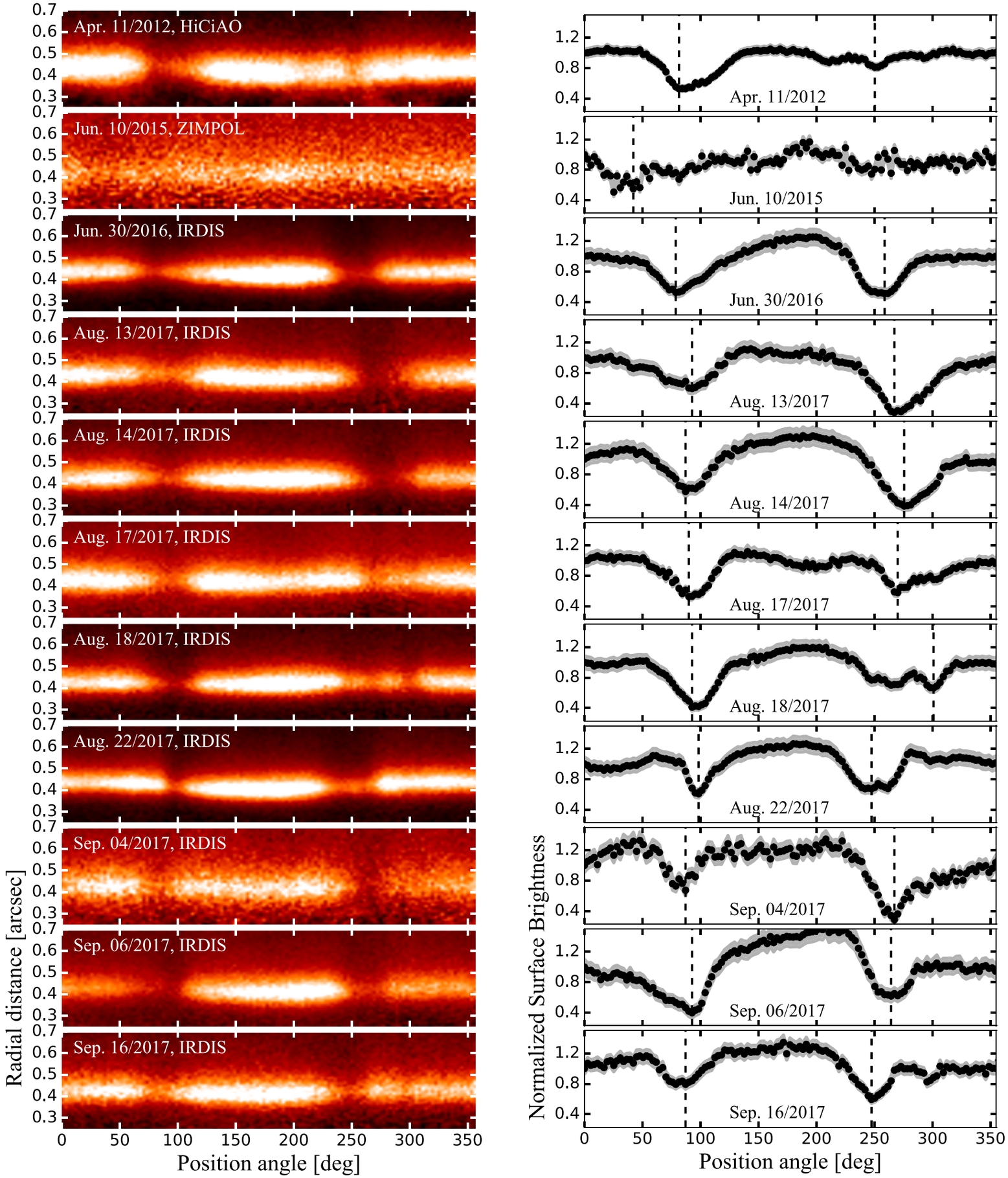
0.2 arcsec

Benisty+ 2017 Min+ 2017



Time-variable shadowing of RXJ1604

Pinilla+ 2018



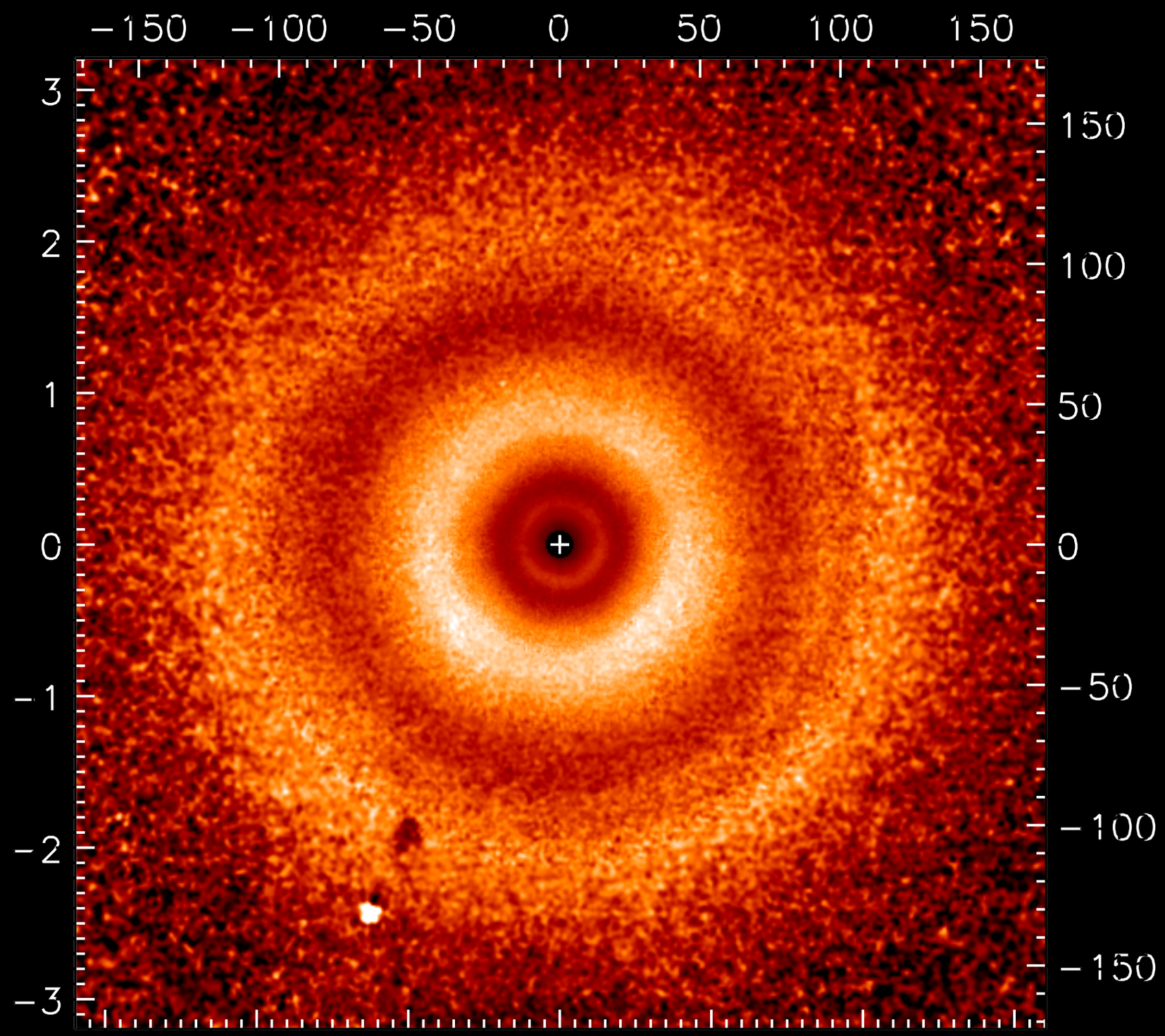
Time-variable shadowing of RXJ1604

Pinilla+ 2018

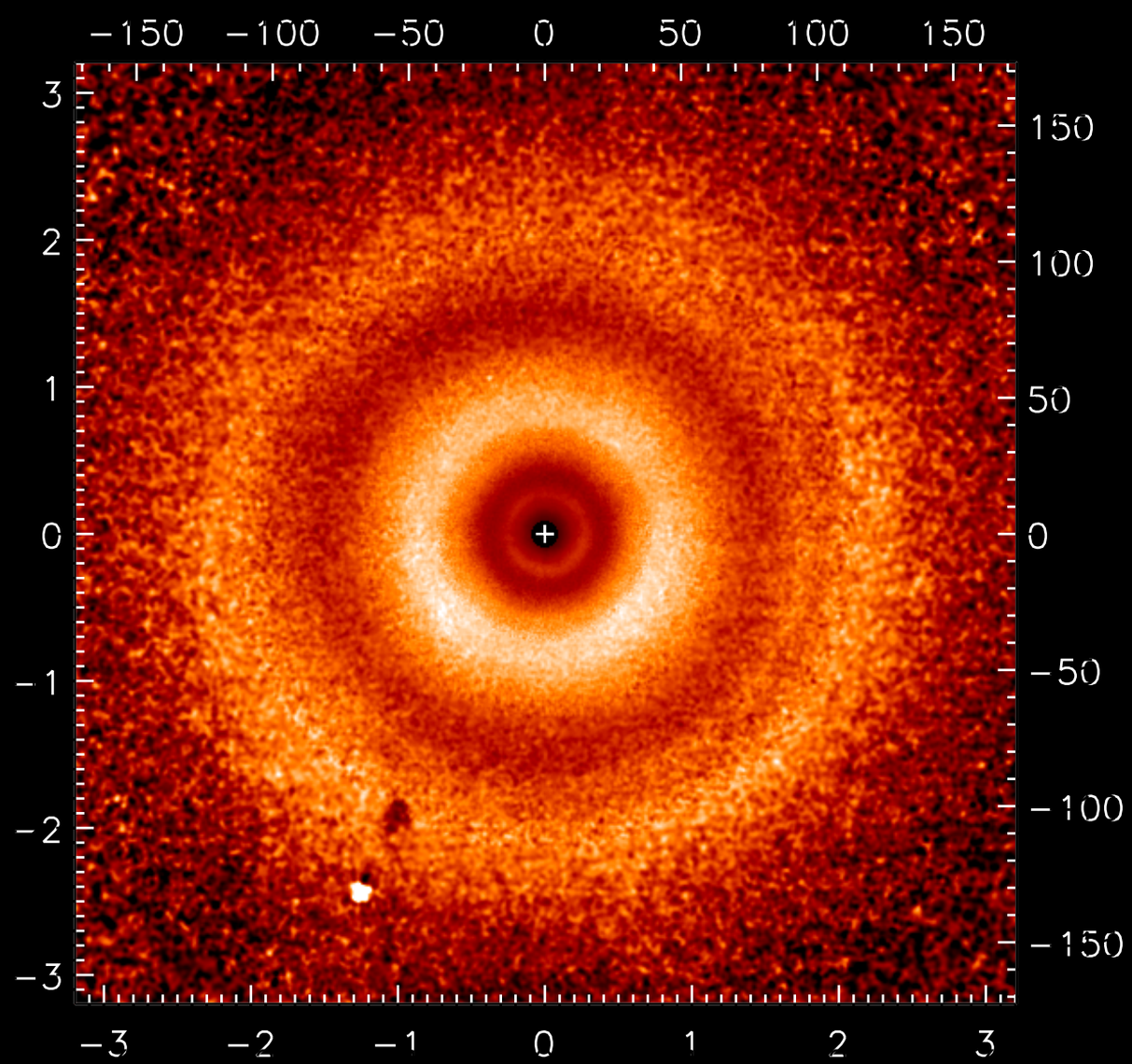
Take-home messages

- Care needs to be taken when interpreting scattered light images of disks because of illumination. WYSI**N**WYG
  - The (polarized) **phase function** creates structures that have no relation to the structure of the disk
  - **Ring structures are real** in that the surface get steeper or sicks out of a shadows region. The same is true for **spirals**.
  - **Gaps** can be gaps or surface height dips.
  - **Radial structures** spanning large parts of the disk are generally caused by shadows.
- What is real?
  - **Rings** can be used to measure the shape of the surface, with significant implications for mixing and settling.
  - **Locally bright features,** once phase function effects have been removed represent structure in the disk (increased scale height)
  - **Shadows** allow to peak into the inner disk and are sometimes time-variable.
  - Scattered light is **very** complementary to ALMA thermal emission.

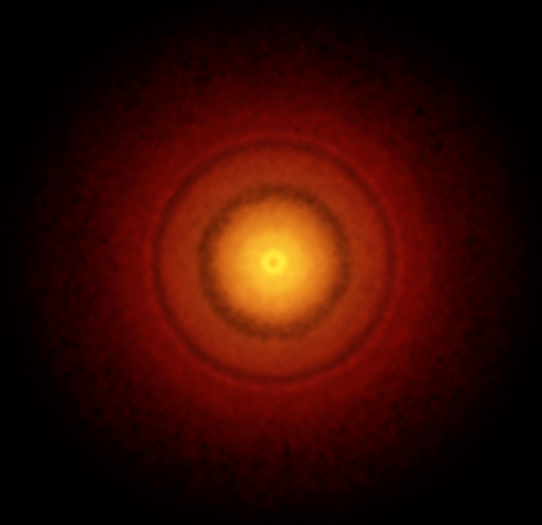
Rings: TW Hydra



SPHERE vs ALMA



van Boekel+ 2016



Andrews+ 2016