HD143006: Interferometric Confirmation of Misaligned Protoplanetary Disc with CHARA/MIRCX and VLTI/PIONIER

Submitted to MNRAS

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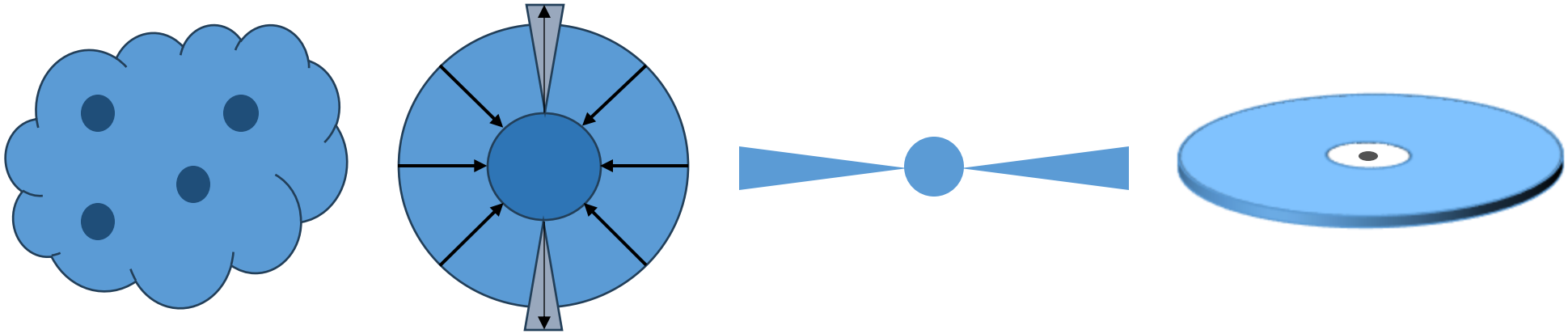
Why do we care about protoplanetary discs?

- Understanding planet formation
- Formation occurs during late stage of star formation -> protoplanetary disc
- Smaller scales host important processes
- Terrestrial planets thought to form in inner regions
- Highly dynamical processes in first au; e.g. accretion, disc winds, sublimation rim

Credit: ALMA (ESO/NAOJ/NRAO)

Protoplanetary Disc Formation



Molecular cloud with dense cores

Individual protostellar core

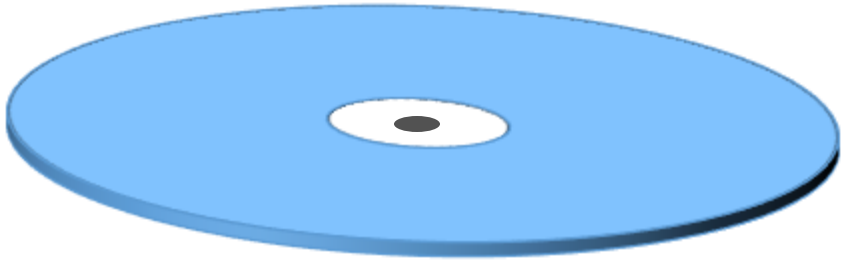
- Surrounding material collapses. Jets along rotational poles

Accretion and centripetal forces draw material to midplane

(Pre) Transitional PPDs

Identify by SEDs!

1



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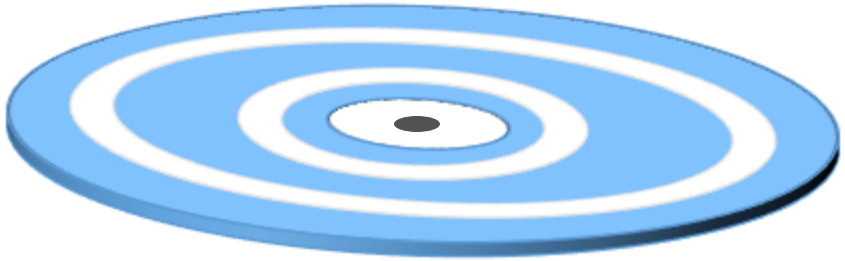
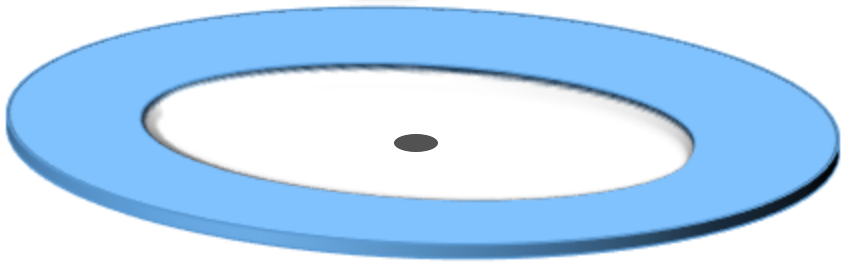
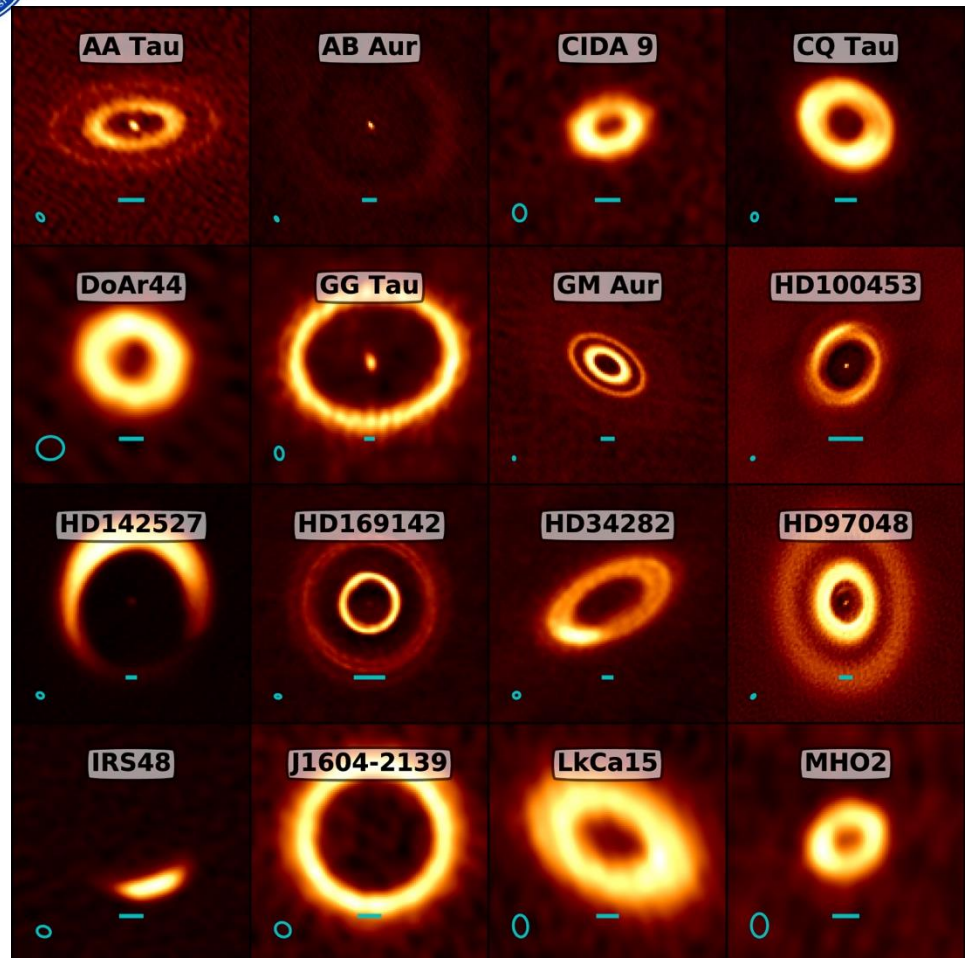


3

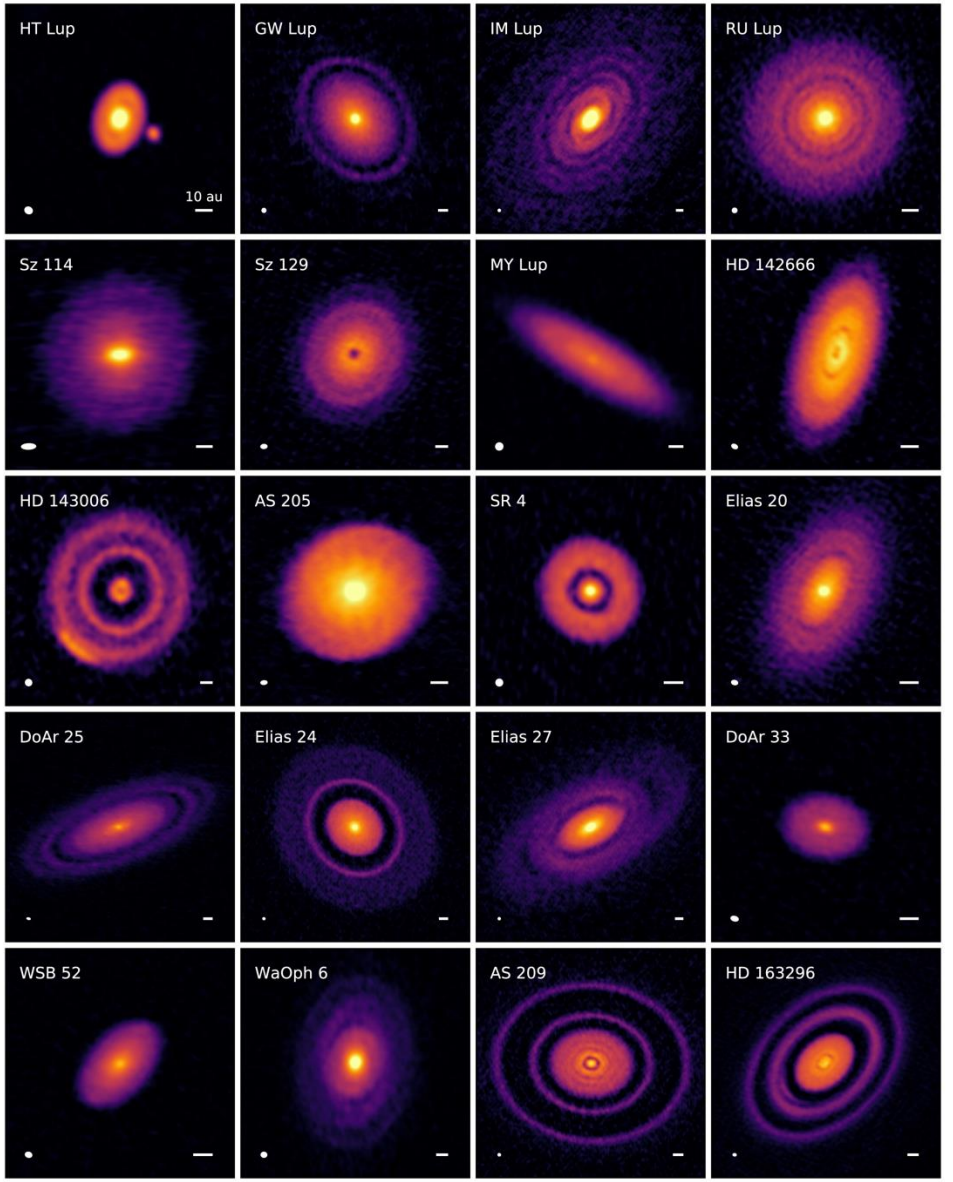


- Disc clearing mechanisms:
  - Grain growth
  - Photoevaporation
  - Planets
  - Misaligned inner/outer discs

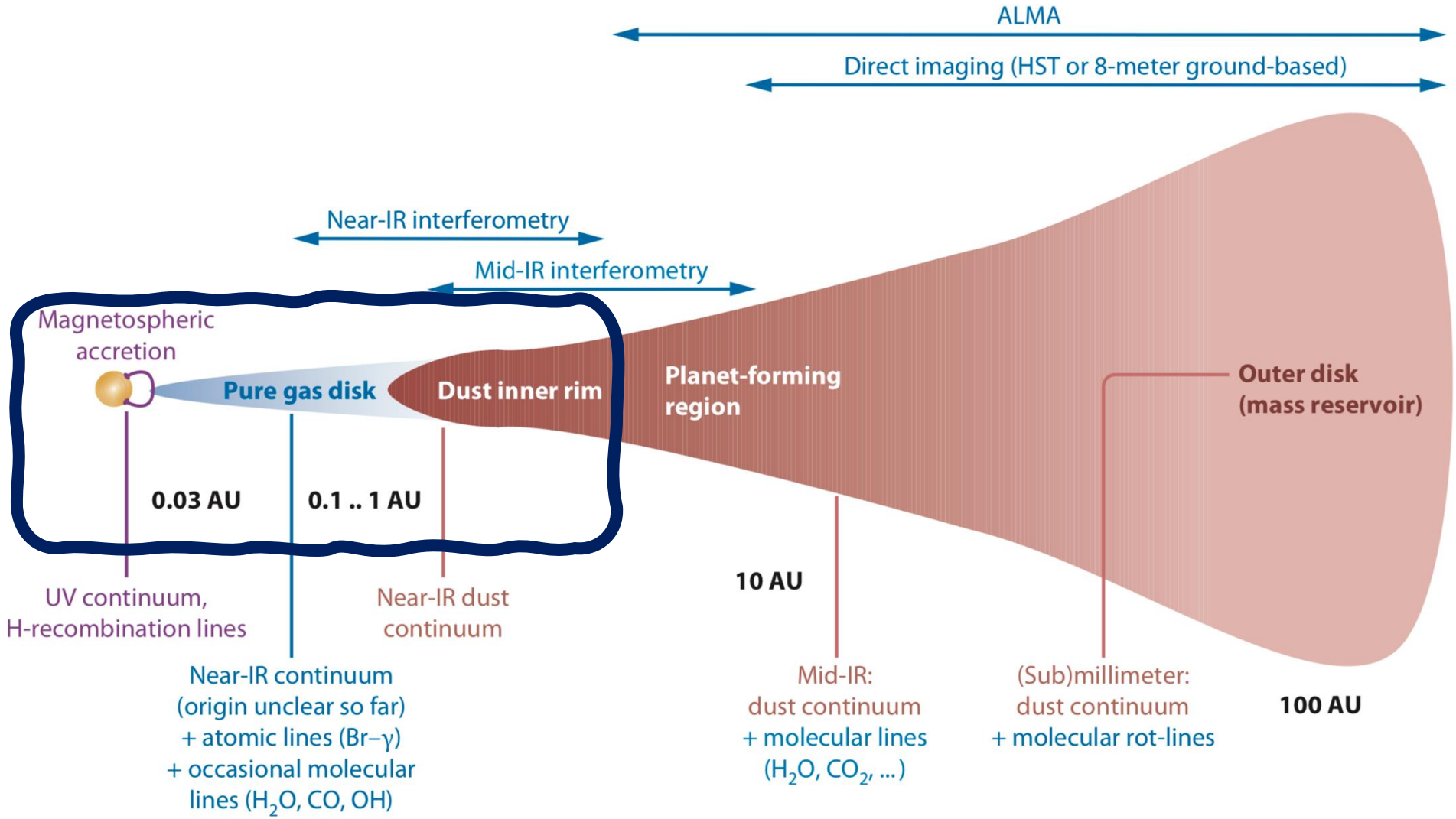
Protoplanetary Discs



Sample of ALMA continuum images of transitional discs (Francis L., & van der Marel N. 2020)



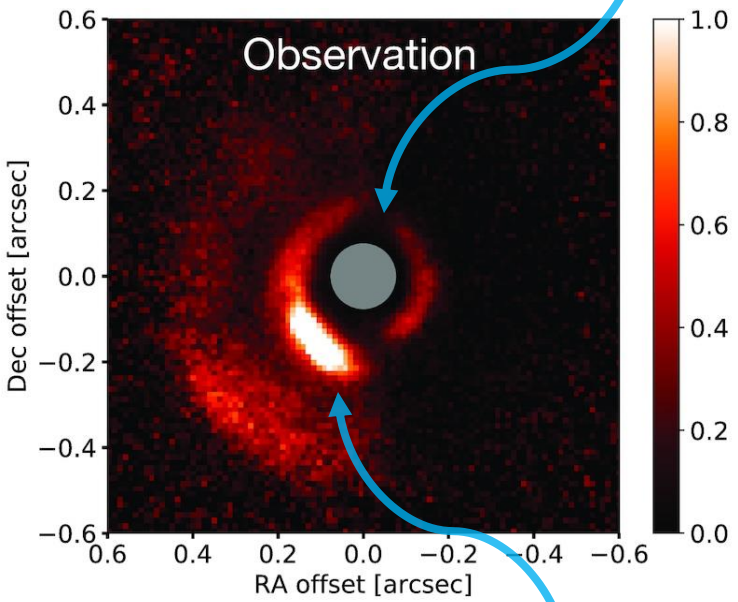
DSHARP Survey (Andrews S.+ 2018)



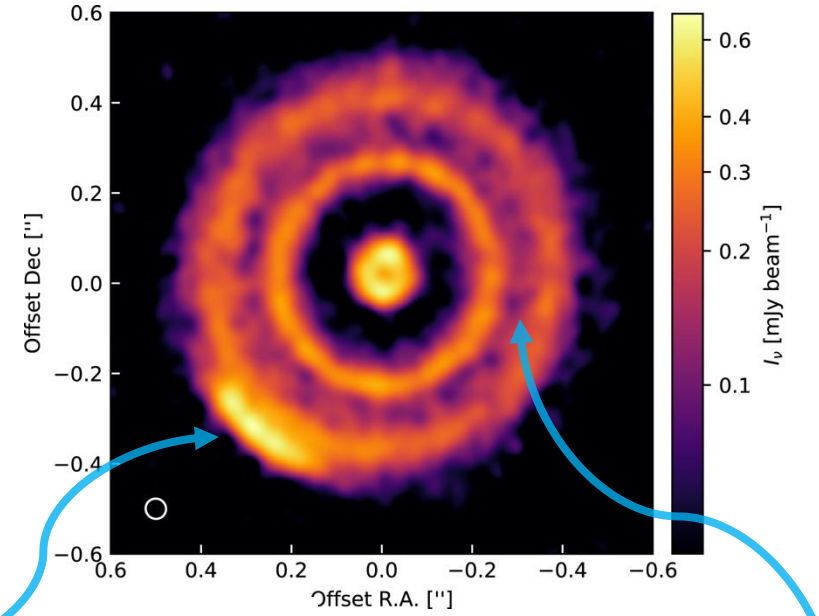
Dullemond & Monnier 2010

HD143006

Shadows



Benisty+ 2018



Perez+ 2018

T Tauri star (G7)

$4.58L_\odot$

$1.8M_\odot$

165pc Upper Sco

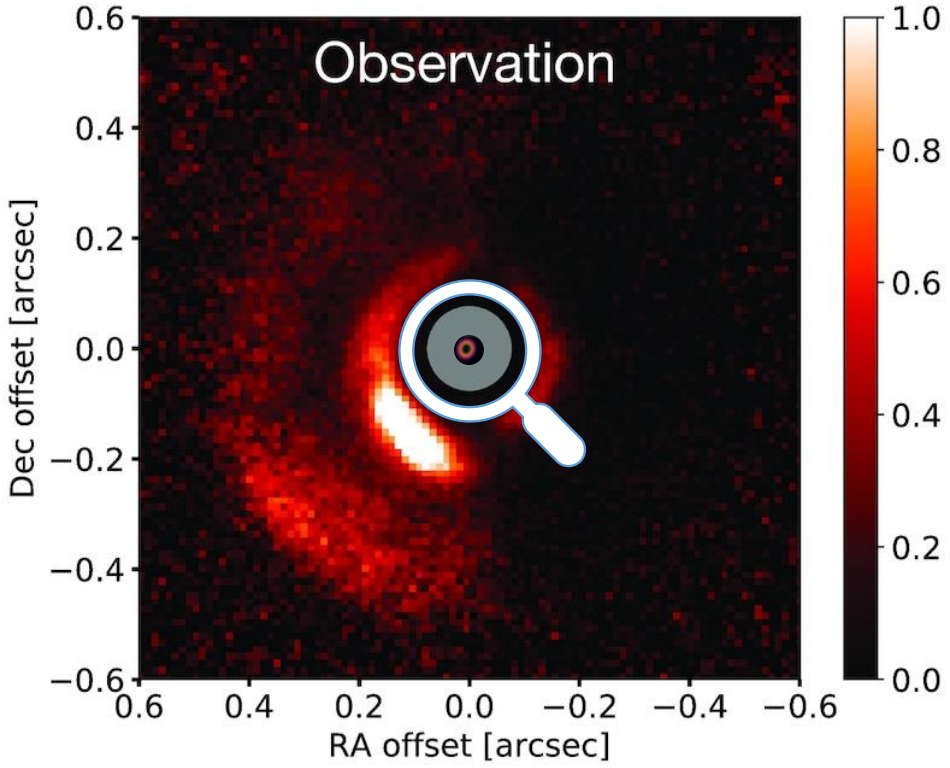
5-11Myr

(Benisty et al. 2018; Andrews et al. 2018; Gaia collaboration et al. 2018)

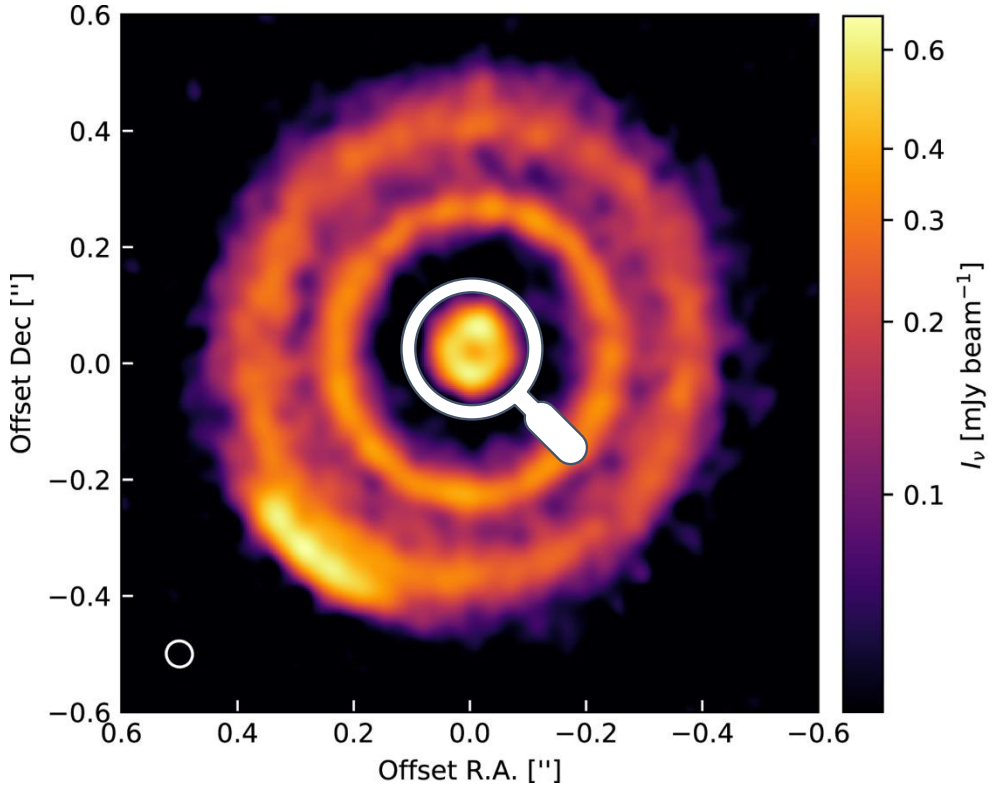
Bright spots

Gaps and rings

HD14006

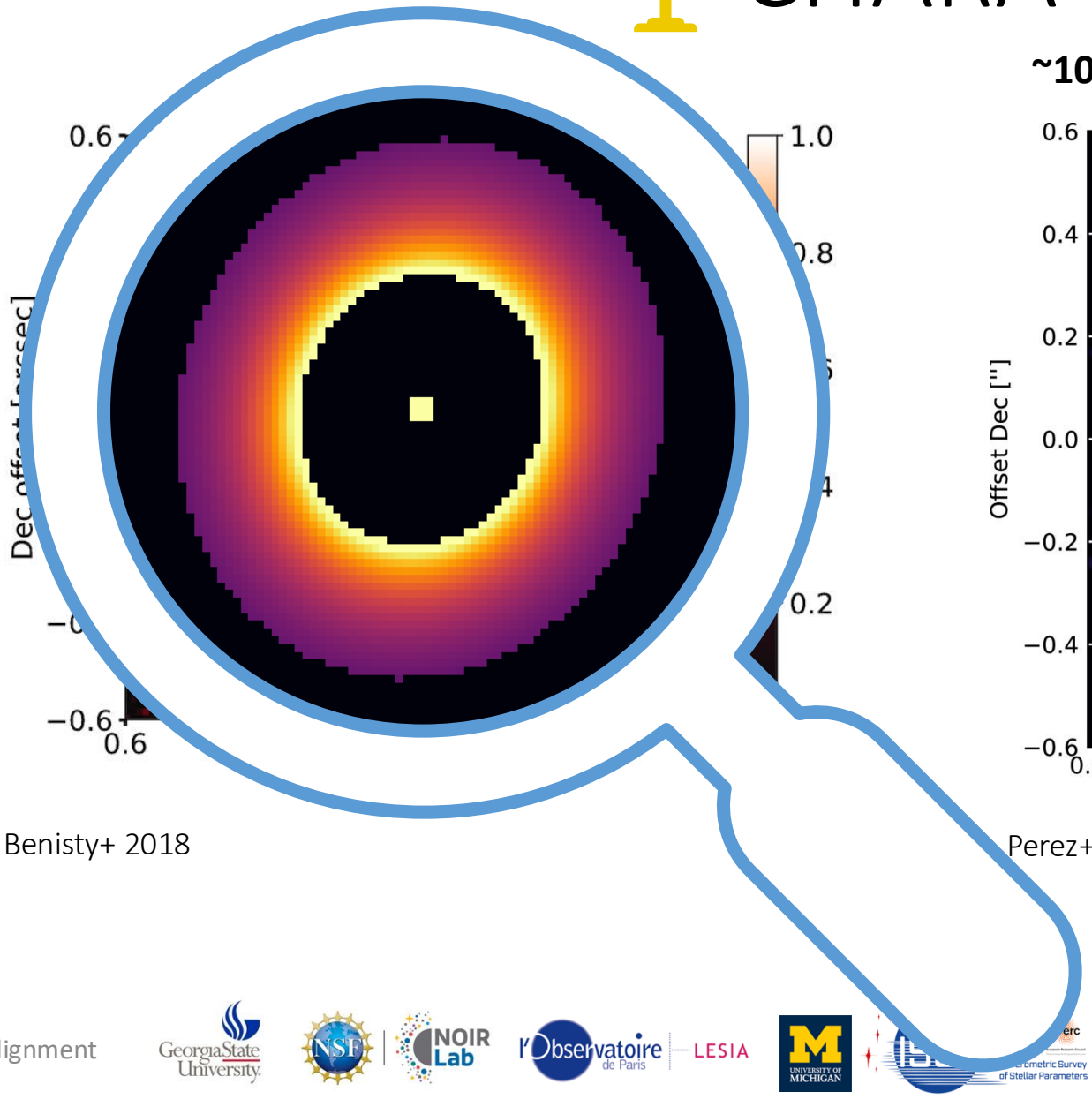


Benisty+ 2018



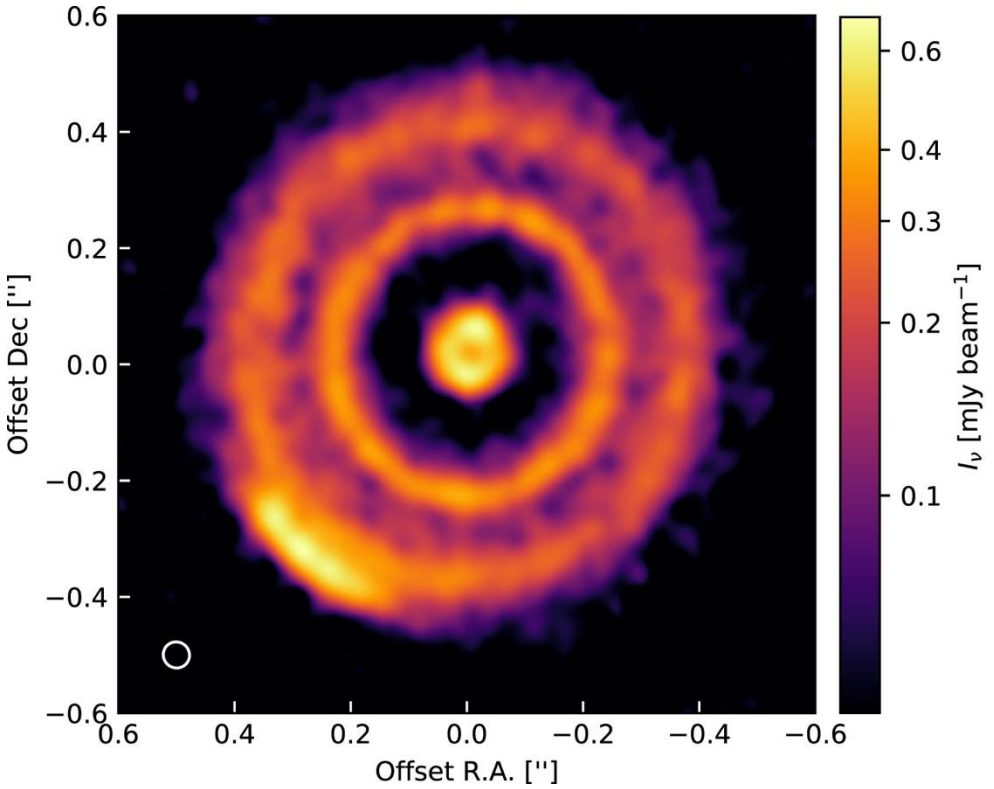
Perez+ 2018

CHARA



Benisty+ 2018

~1000x magnification



Perez+ 2018

Disc Modelling

Aim:
- Inclination and position angle
- Circumstellar vs Stellar flux
- Asymmetry?

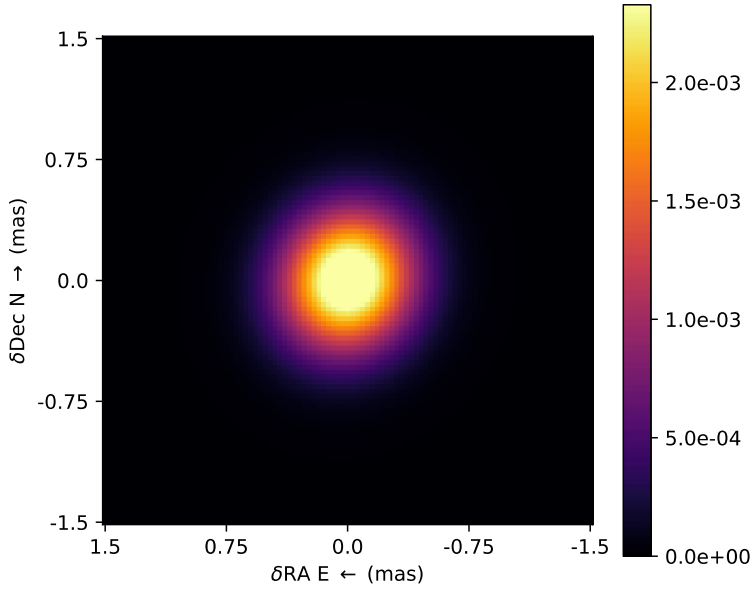
PMOIRED

Parametric Modeling of Optical InteRferomEtric Data

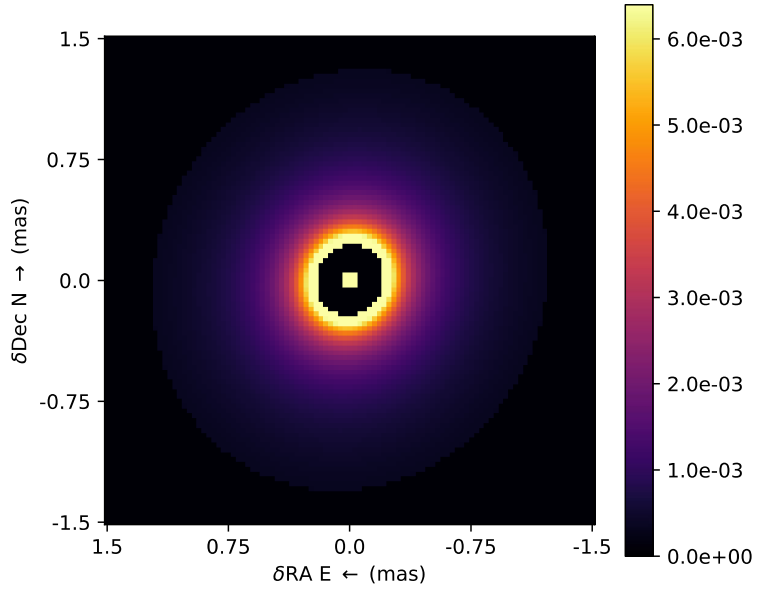
Merand et al. 2022

Geometric Modelling

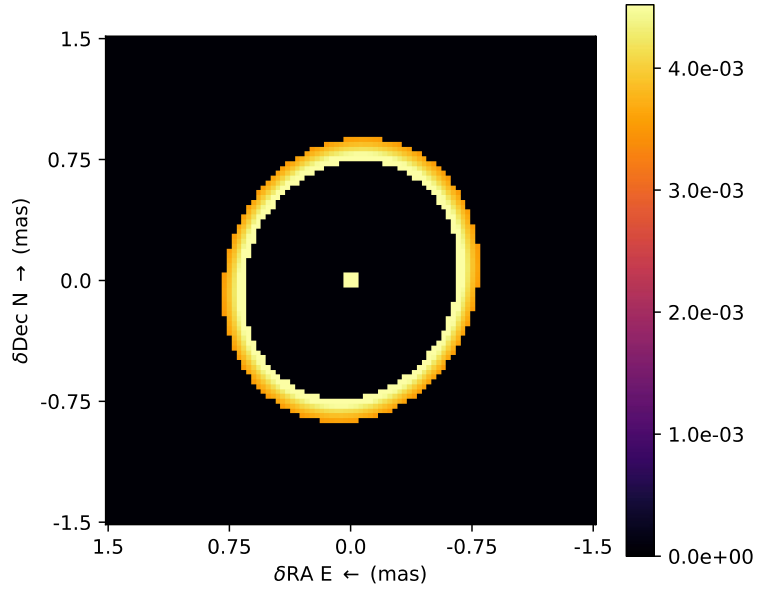
Gaussian Model



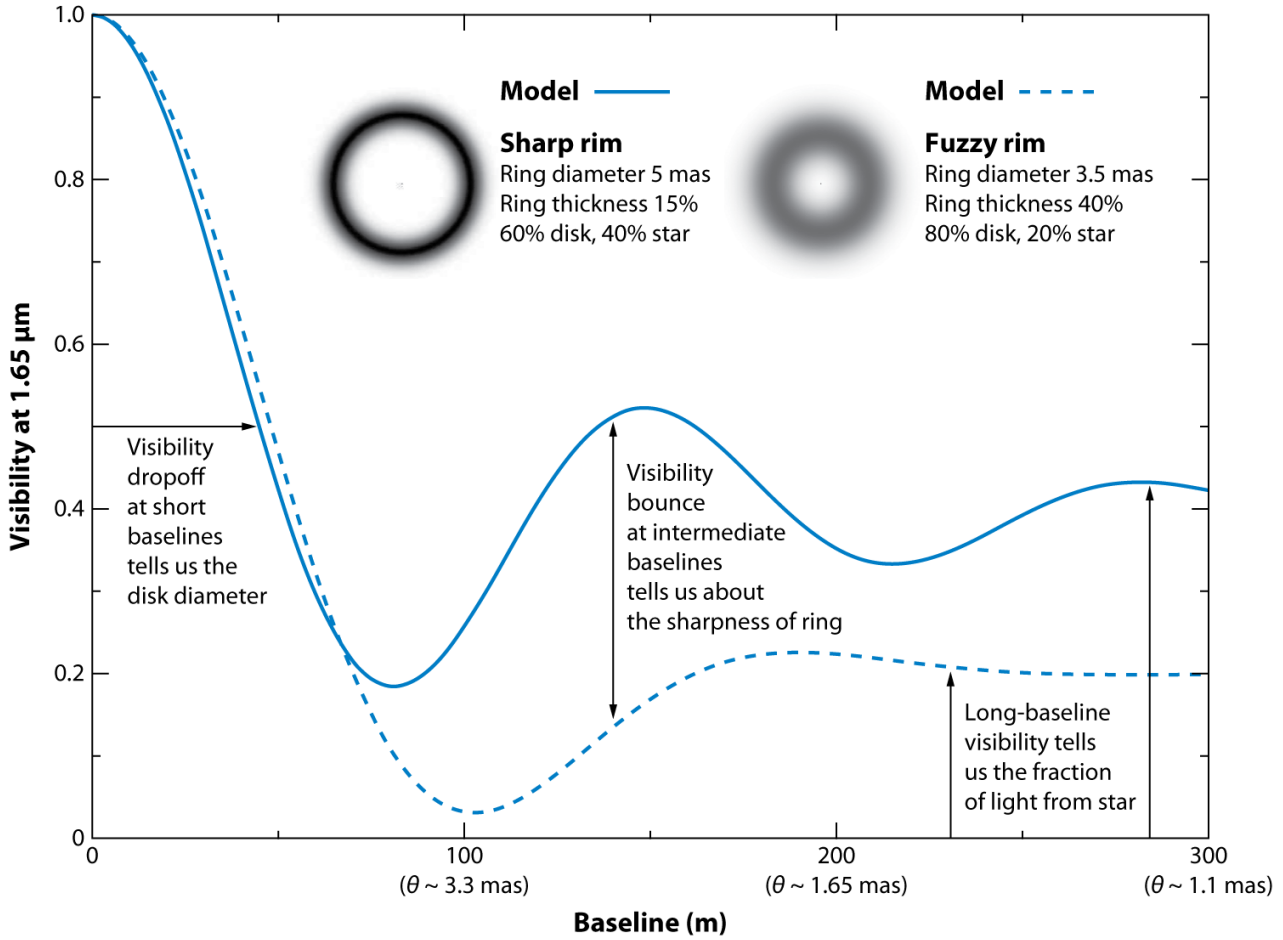
Ring Model



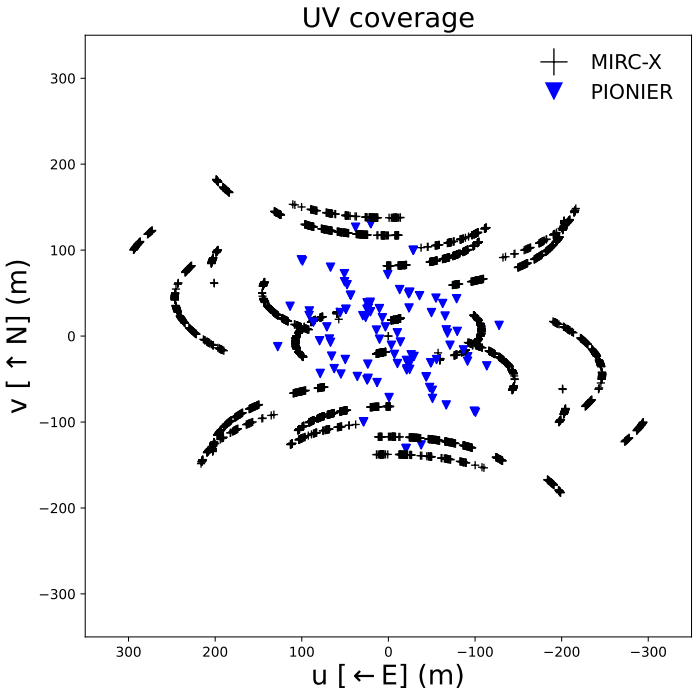
Fixed Ring Model

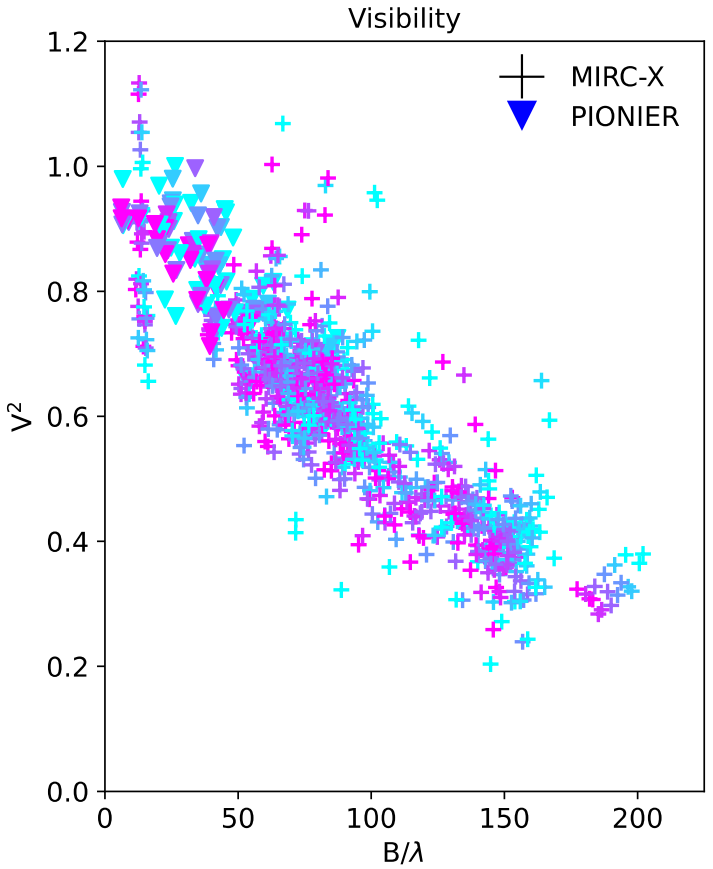


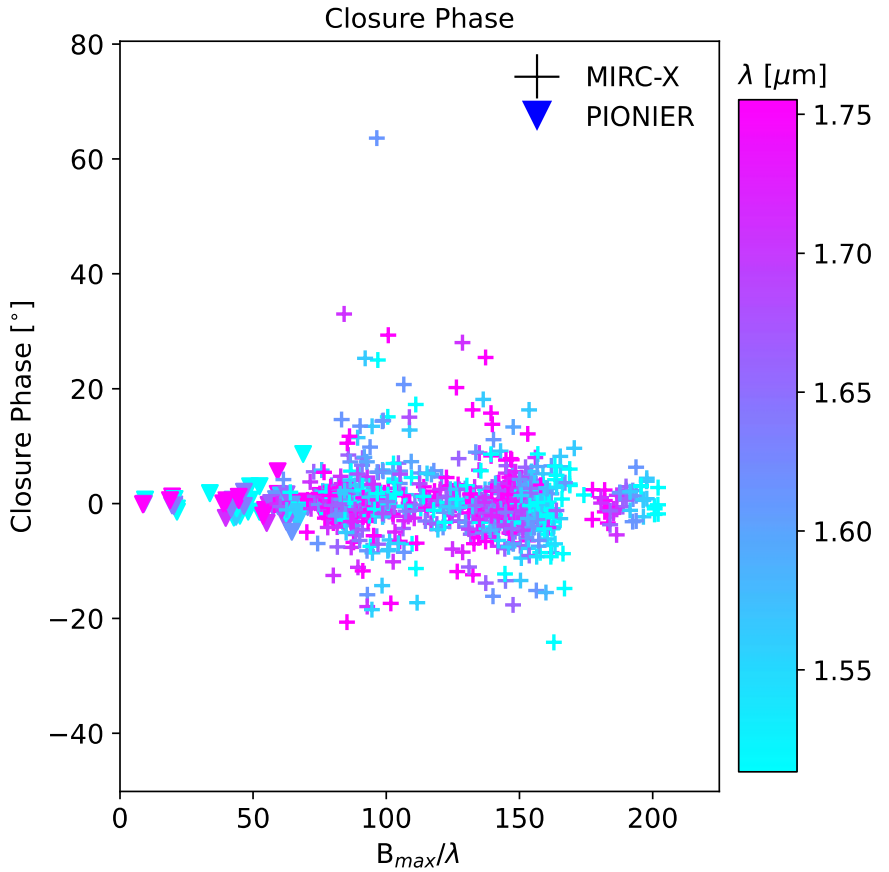
Decoding interferometry data



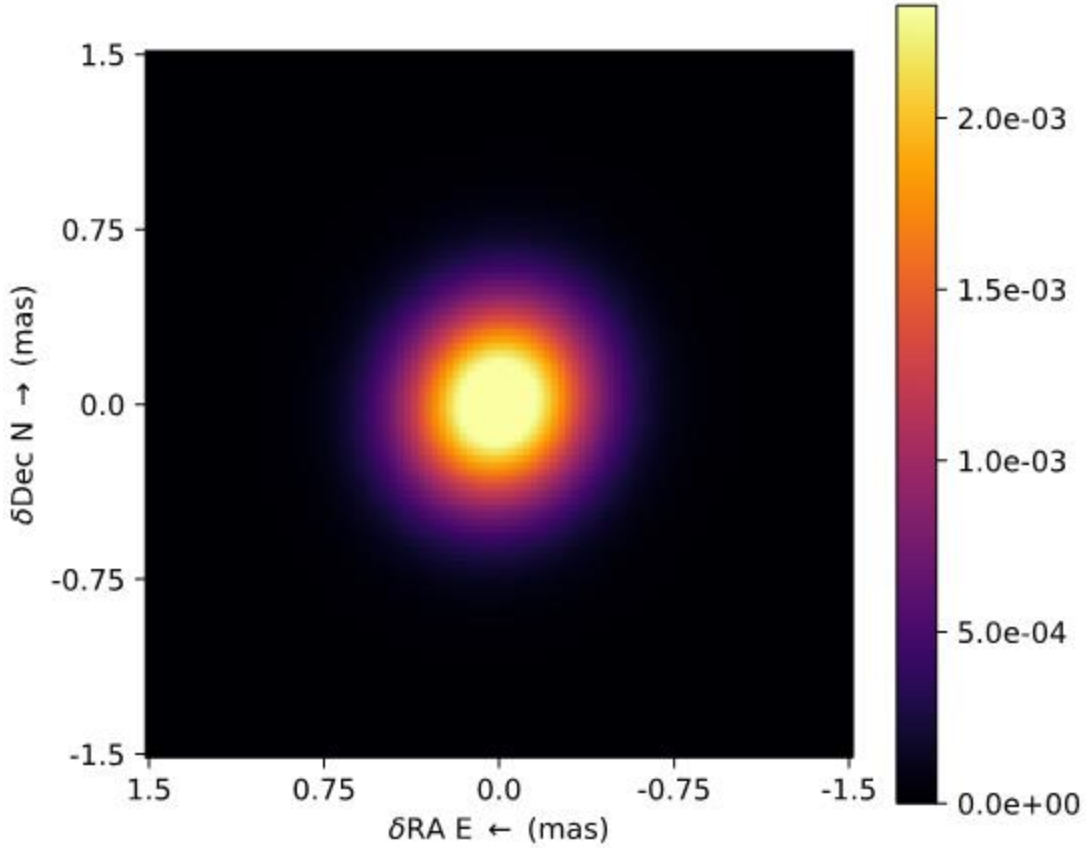
Dullemond CP, Monnier JD. 2010.
Annu. Rev. Astron. Astrophys. 48:205–39


UV coverage
MIRC-X
PIONIER
v [↑ N] (m)
u [← E] (m)
300
200
100
0
−100
−200
−300


Visibility
MIRC-X
PIONIER
V²
B/λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
50
100
150
200


Closure Phase
MIRC-X
PIONIER
λ [μm]
Closure Phase [°]
B_max/λ
80
60
40
20
0
−20
−40
1.75
1.70
1.65
1.60
1.55

2D Elliptical Gaussian Model



$i = 22° \pm 3°$

$PA = 155° \pm 7°$

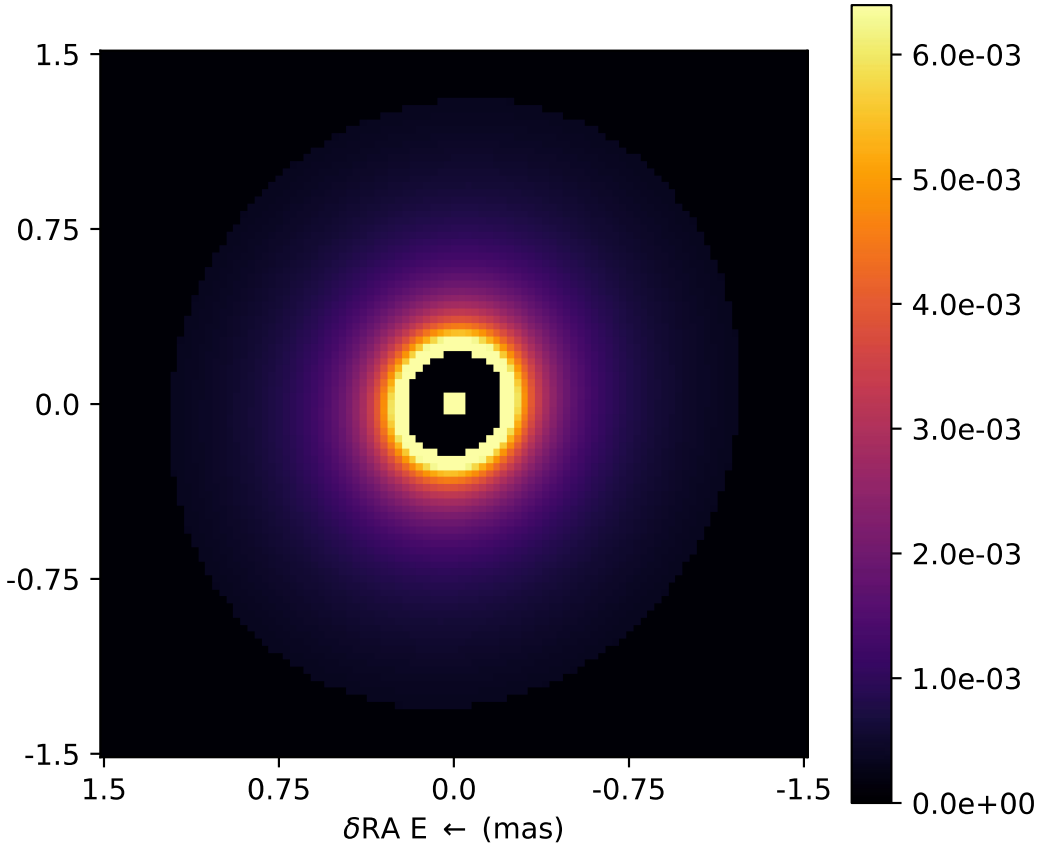
$\chi_r^2 = 1.68$

Ring Model

$i = 22° \pm 3°$

$PA = 157° \pm 9°$

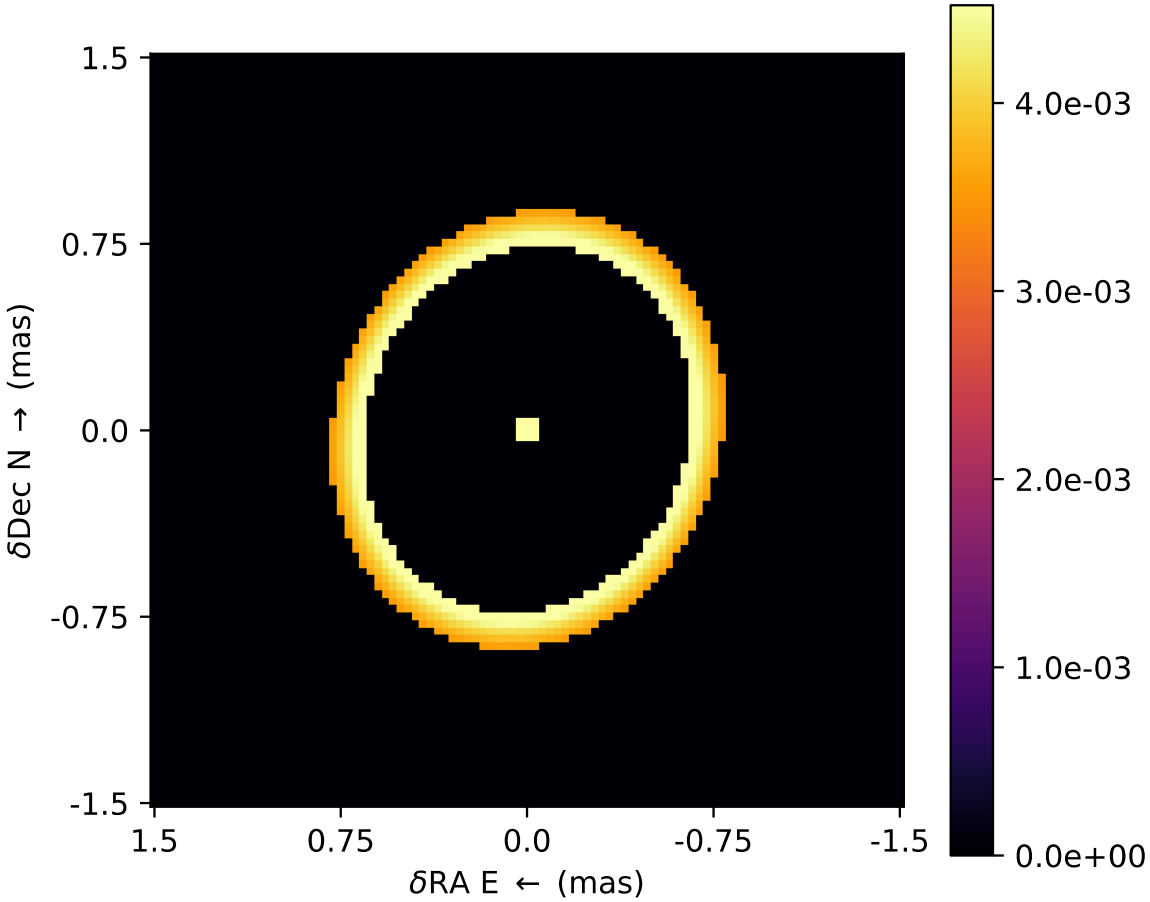
$\chi_r^2 = 1.62$



Fixed Ring Model

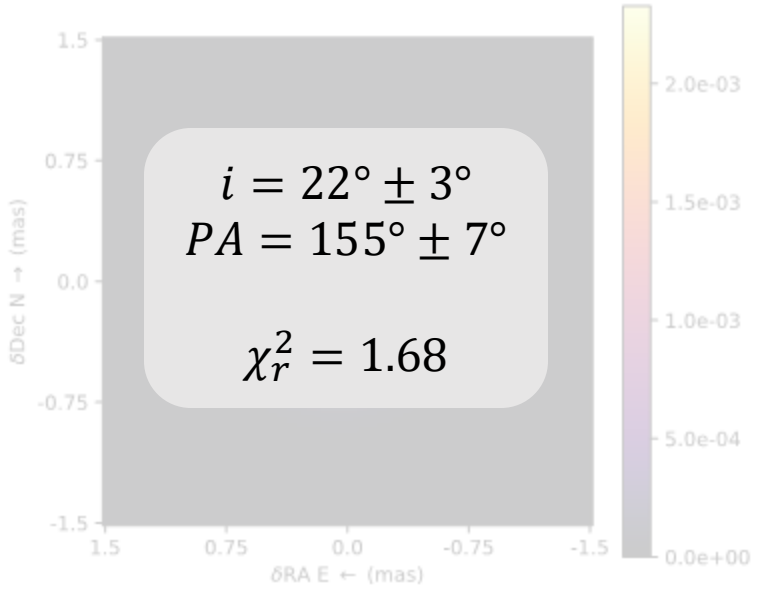
$$i = 26° \pm 3°$$
$$PA = 161° \pm 6°$$

$$\chi_r^2 = 1.75$$

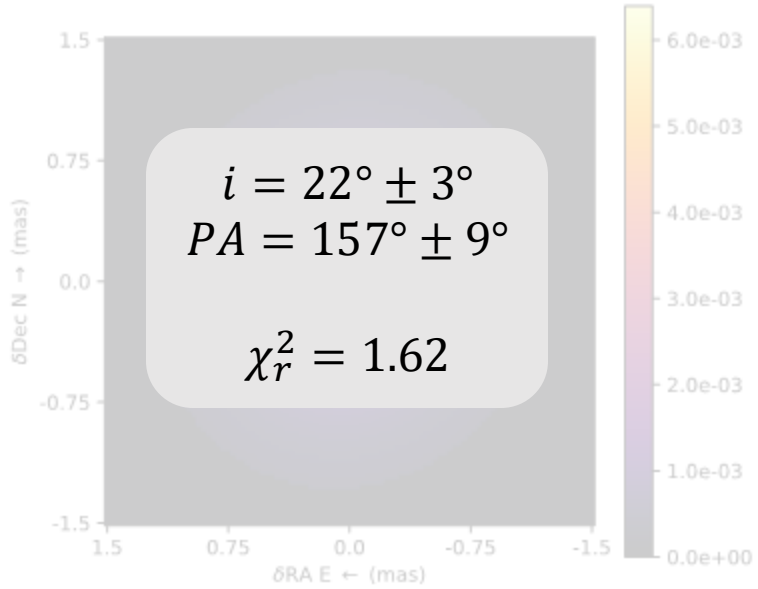


Geometric Modelling

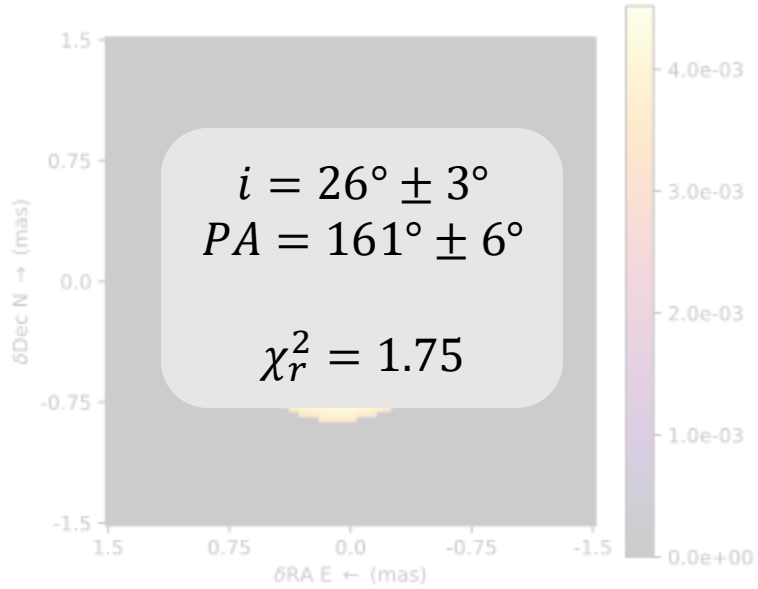
Gaussian Model



Ring Model

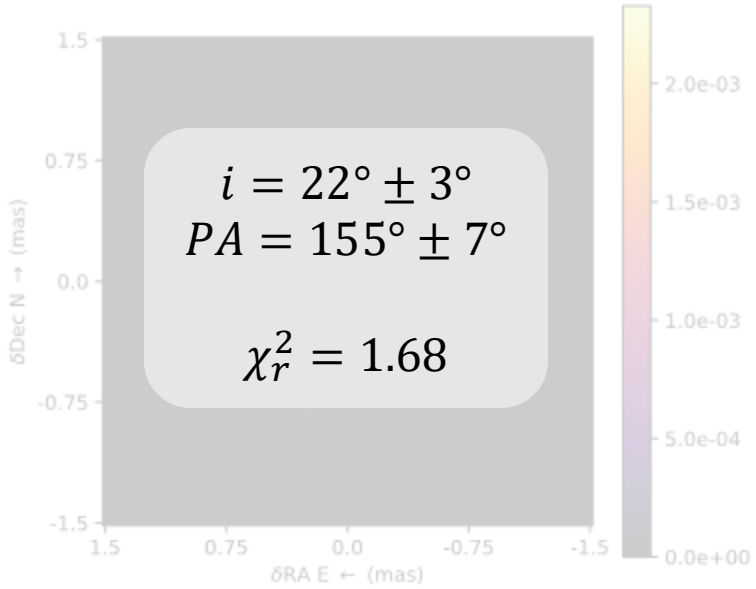


Fixed Ring Model

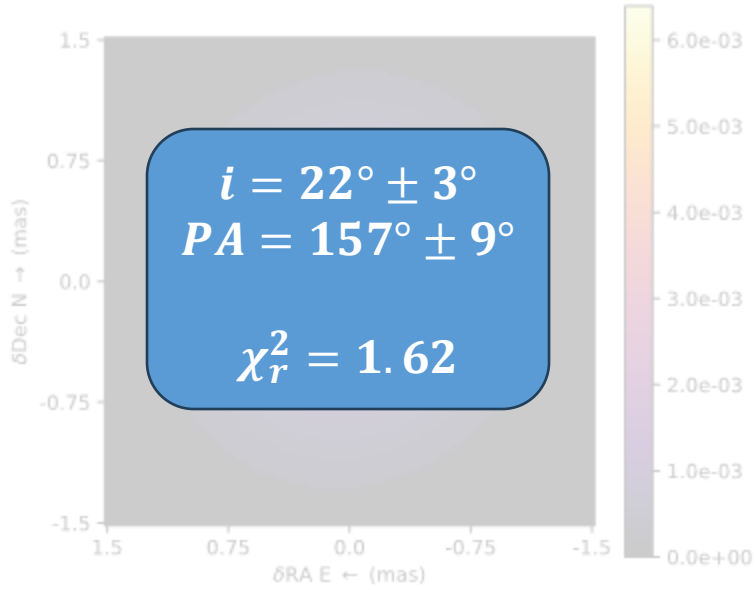


Geometric Modelling

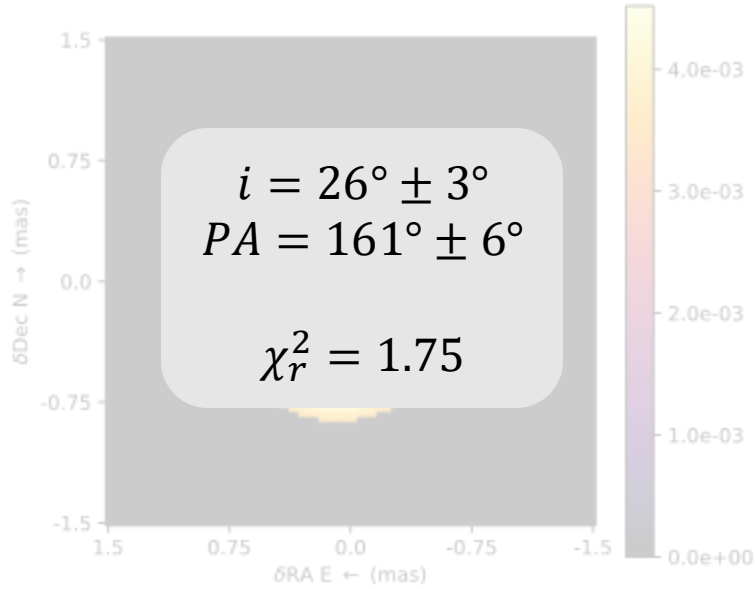
Gaussian Model



Ring Model



Fixed Ring Model

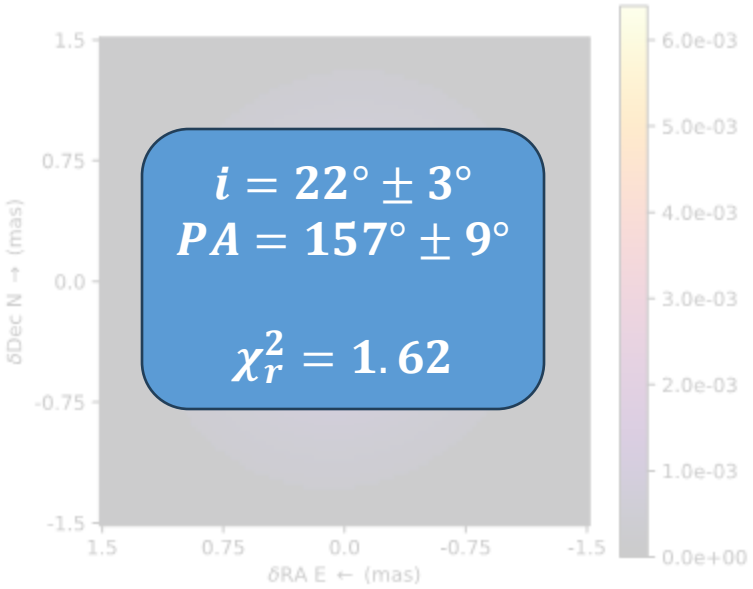


Geometric Modelling

Ring Model

$f_{star} = 60\%$

Compared to SED from Woitke+19: $f_{star} = 55\%$



$i = 22° \pm 3°$
$PA = 157° \pm 9°$

$\chi^2_r = 1.62$

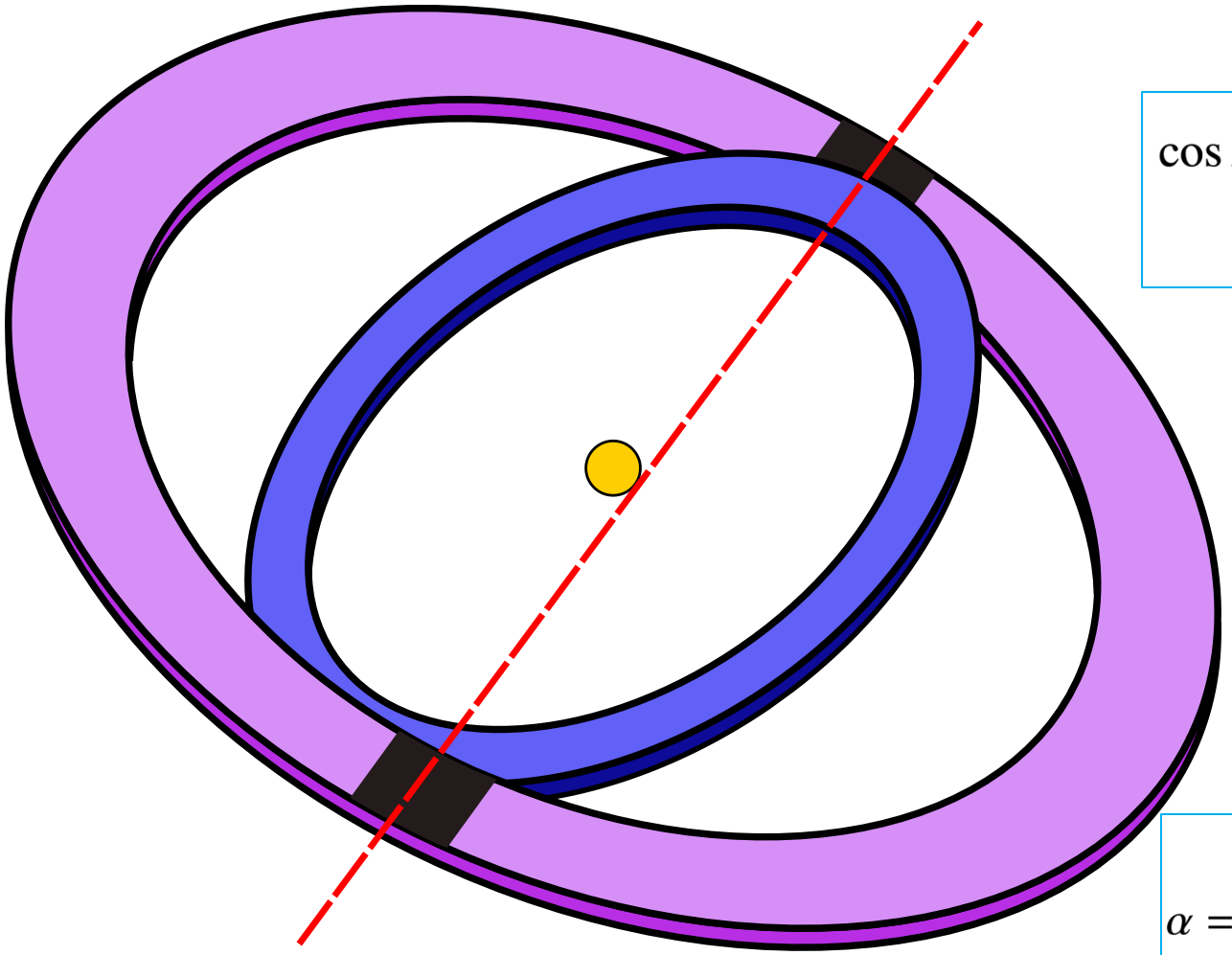
Inner disc radius = 0.23 ± 0.04mas
= 0.038 ± 0.007au

Optically thick gas in cavity?

Misalignments and Shadows

Misalignments and Shadows

Min+2017

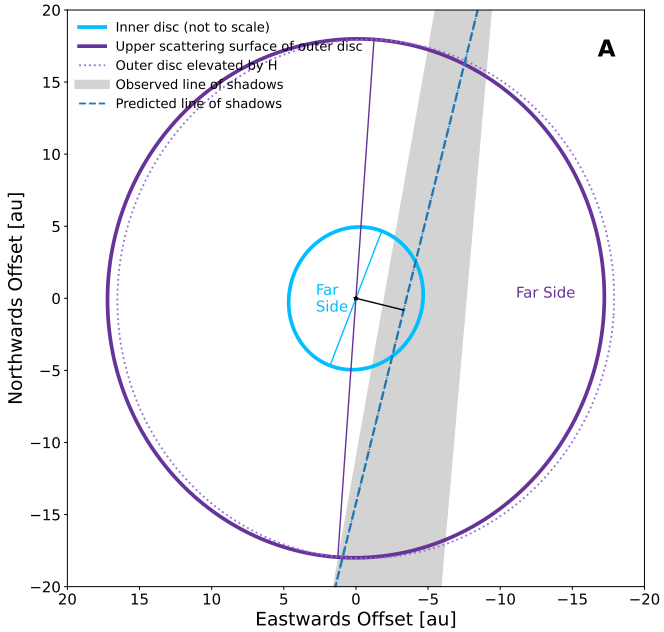


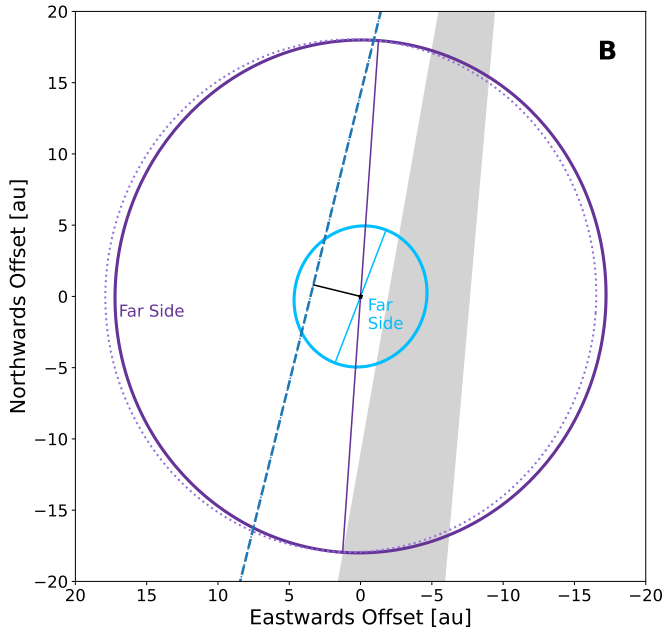
$$\cos\Delta\theta(i_1, \mathrm{PA}_1, i_2, \mathrm{PA}_2) = \sin(i_1)\sin(i_2)\cos(\mathrm{PA}_1 - \mathrm{PA}_2) + \cos(i_1)\cos(i_2)$$

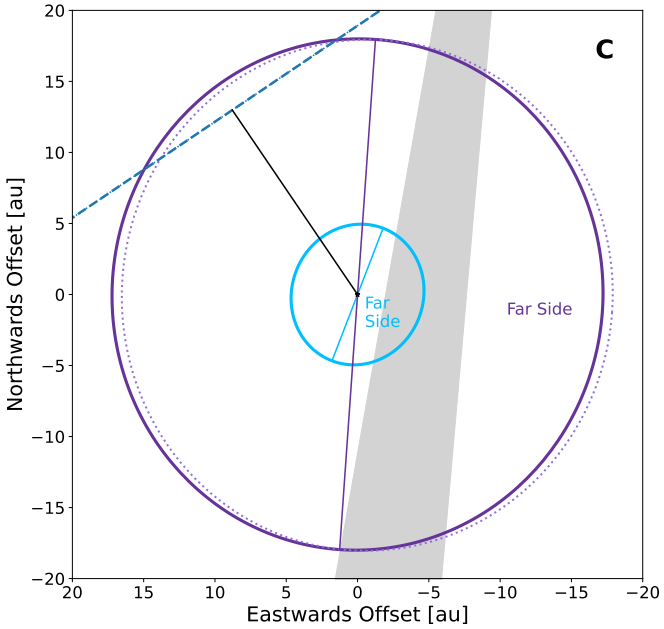
θ =Mutual misalignment

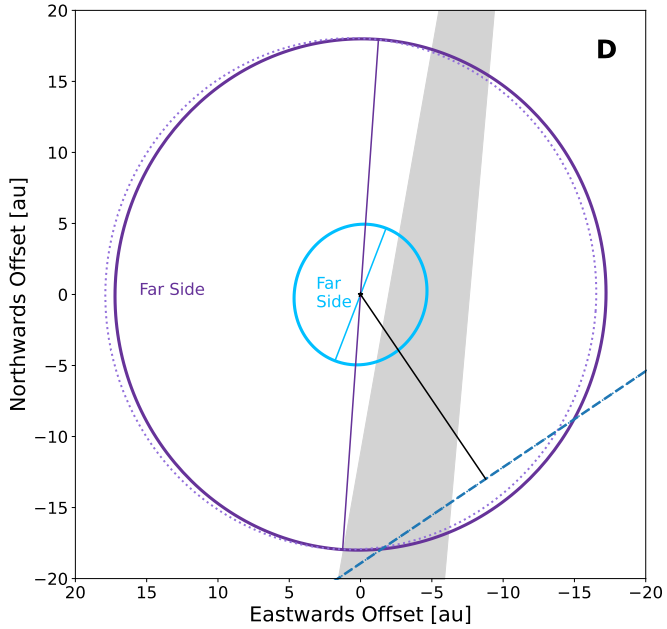
α = Position angle of line of line of shadow

$$\alpha = \tan^{-1}\left(\frac{\sin(i_1)\cos(i_2)\sin(\mathrm{PA}_1) - \cos(i_1)\sin(i_2)\sin(\mathrm{PA}_2)}{\sin(i_1)\cos(i_2)\sin(\mathrm{PA}_1) - \cos(i_1)\sin(i_2)\cos(\mathrm{PA}_2)}\right)$$

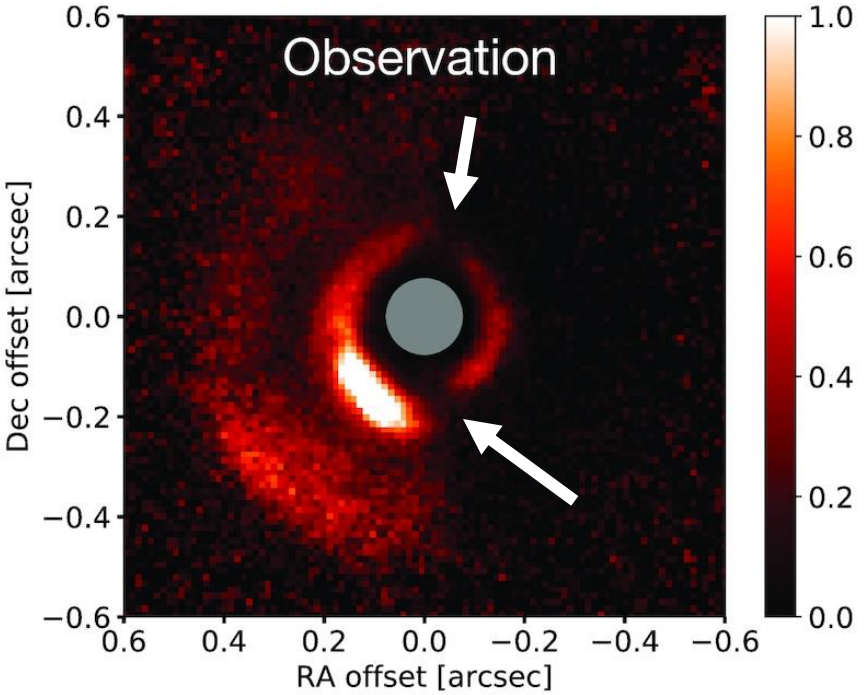








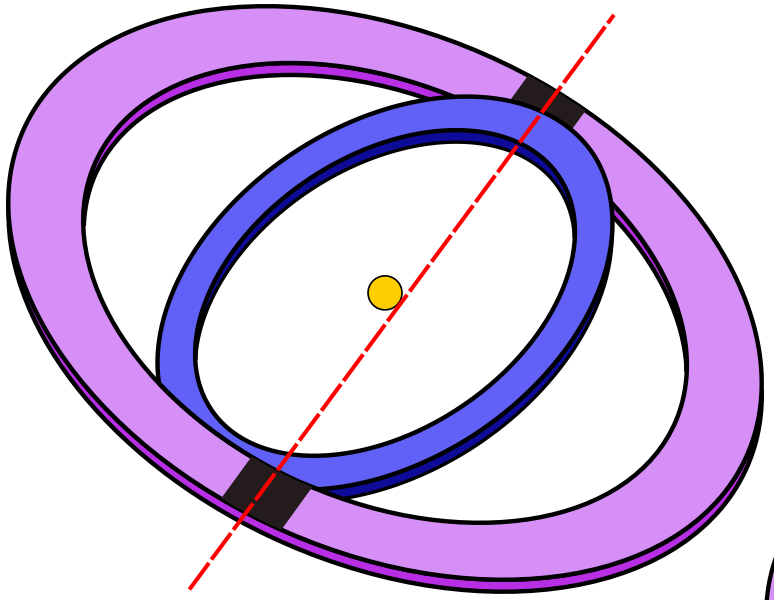
- 4 Scenarios depending on disc orientation
- Grey region = shadows from SPHERE image

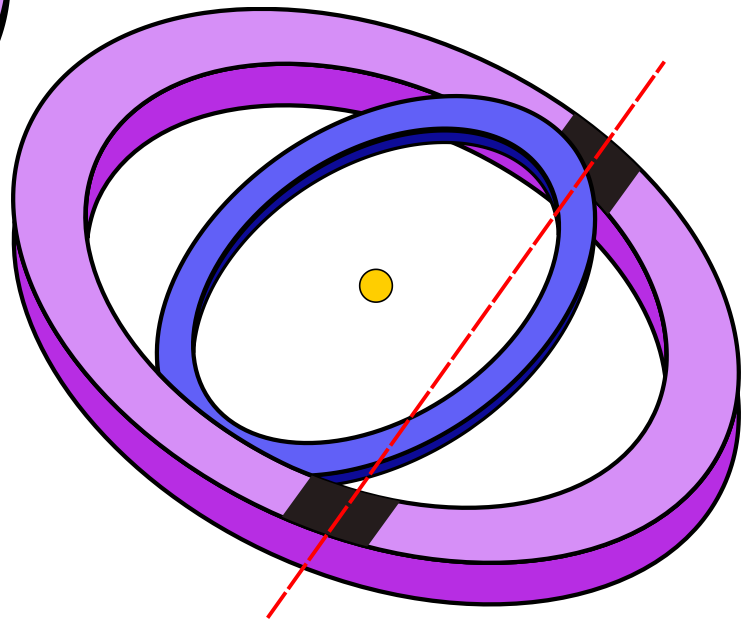


Benisty+18

Misalignments and Shadows

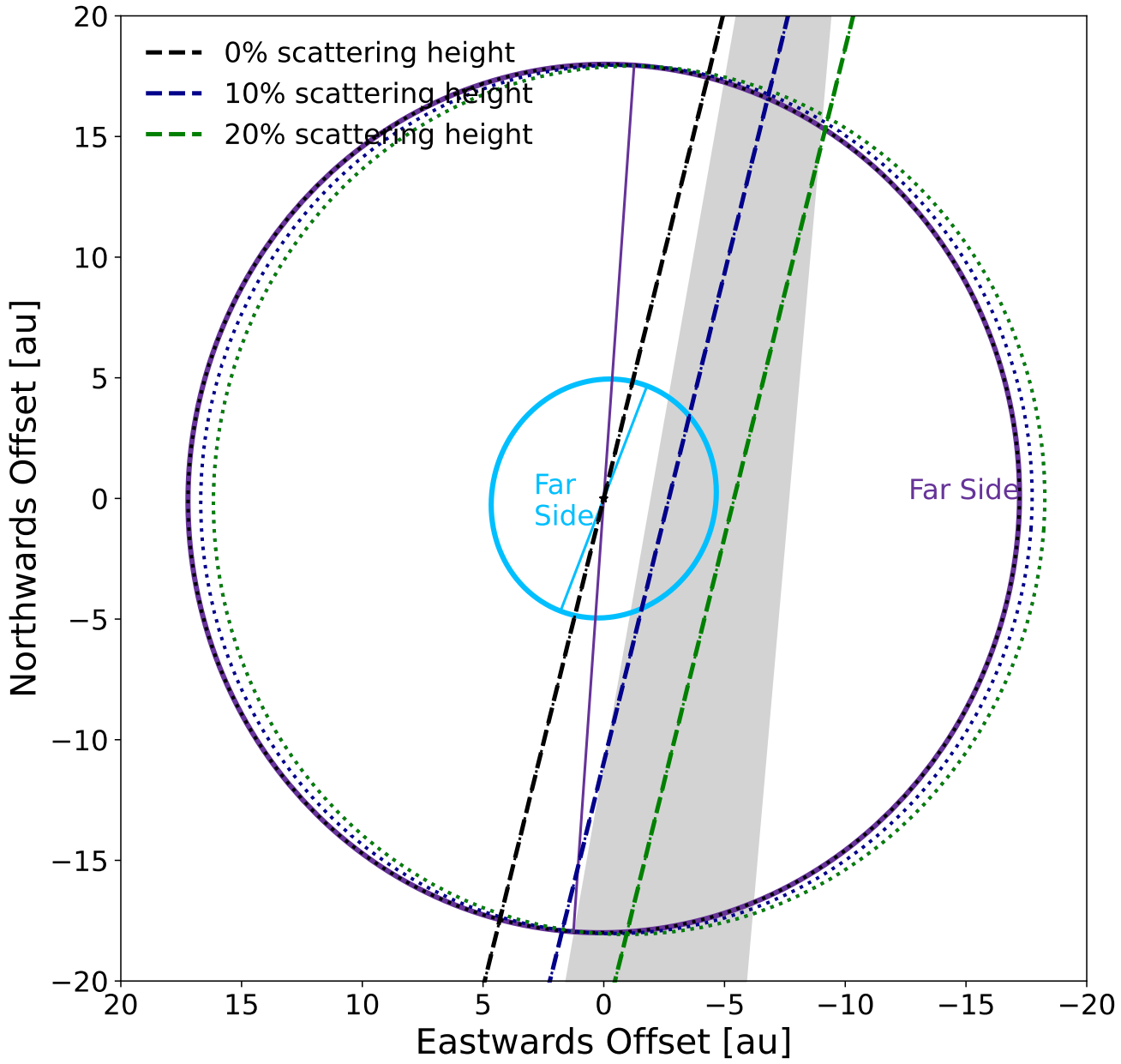
Min+2017





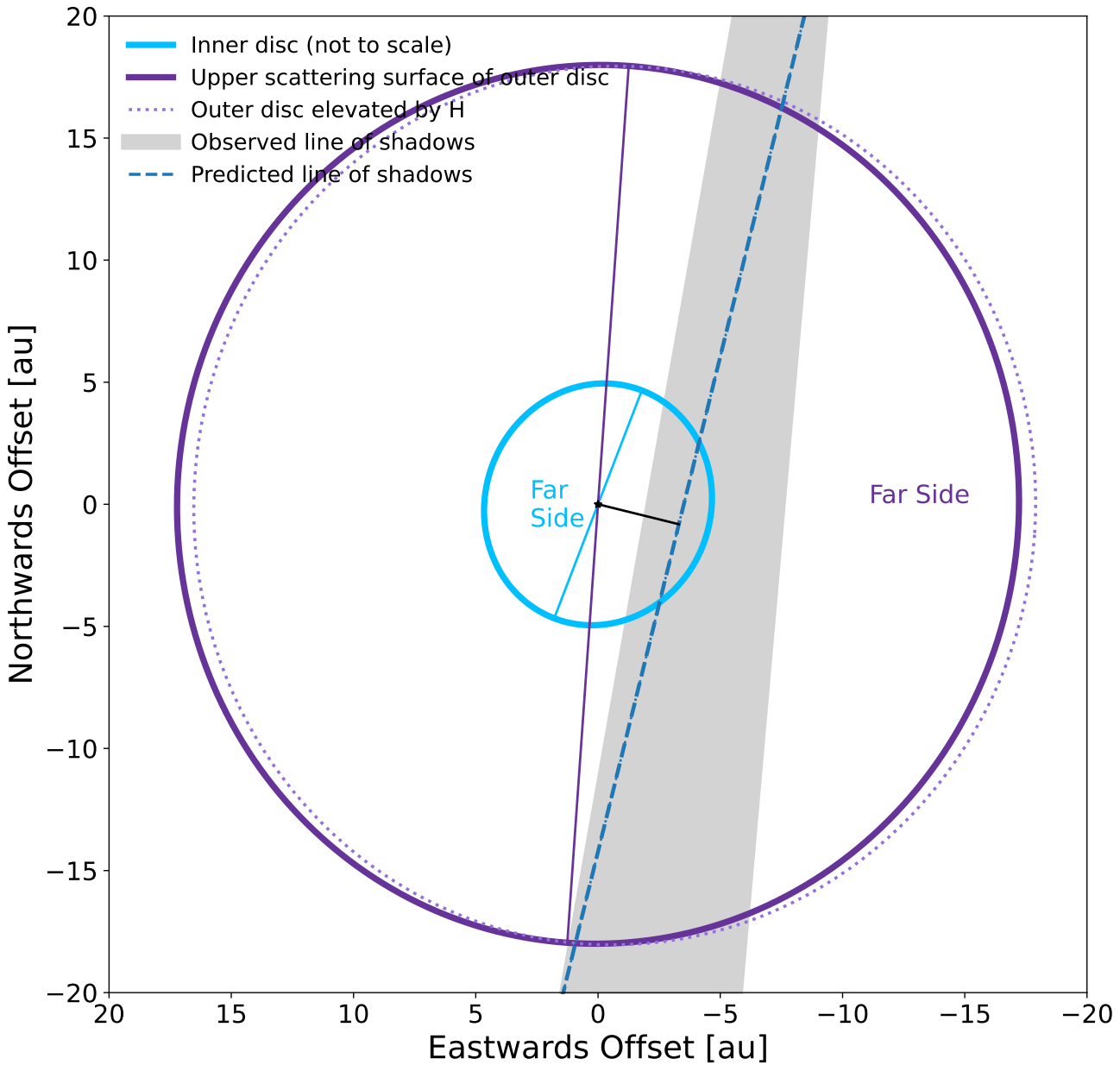
$$x = \frac{h \cdot \cos(i_1)}{\cos(i_2)\sin(i_1)\sin(\mathrm{PA}_1) - \cos(i_1)\sin(i_2)\sin(\mathrm{PA}_2)}$$

h = height of scattering surface



$$\frac{h}{R} \sim scattering\ height\ \%$$

h = height of scattering surface
R = radius of scattered light

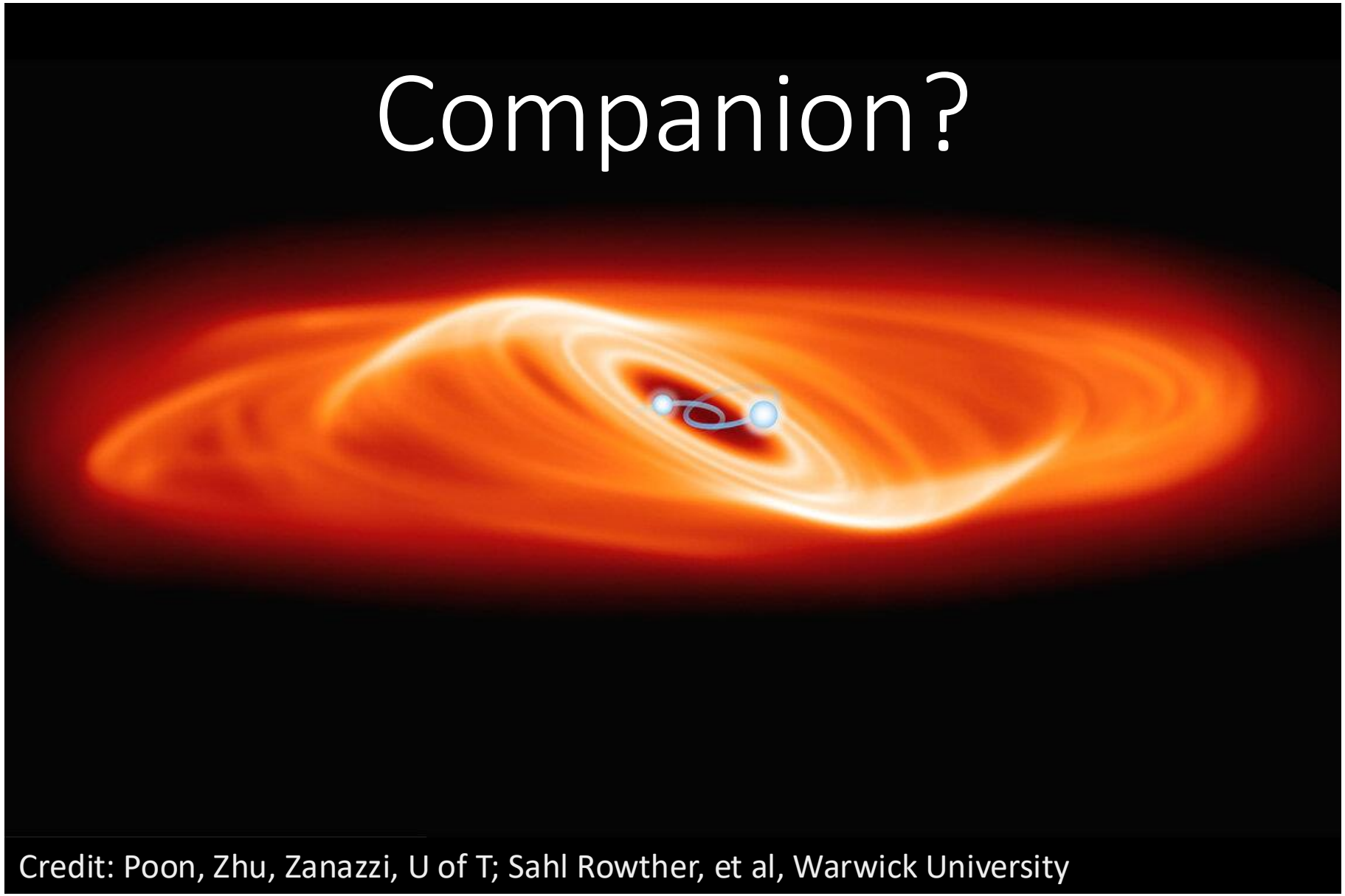


$$\boldsymbol{\theta = 40°}$$

$$\frac{\boldsymbol{h}}{\boldsymbol{R}} \sim \mathbf{13\%}$$

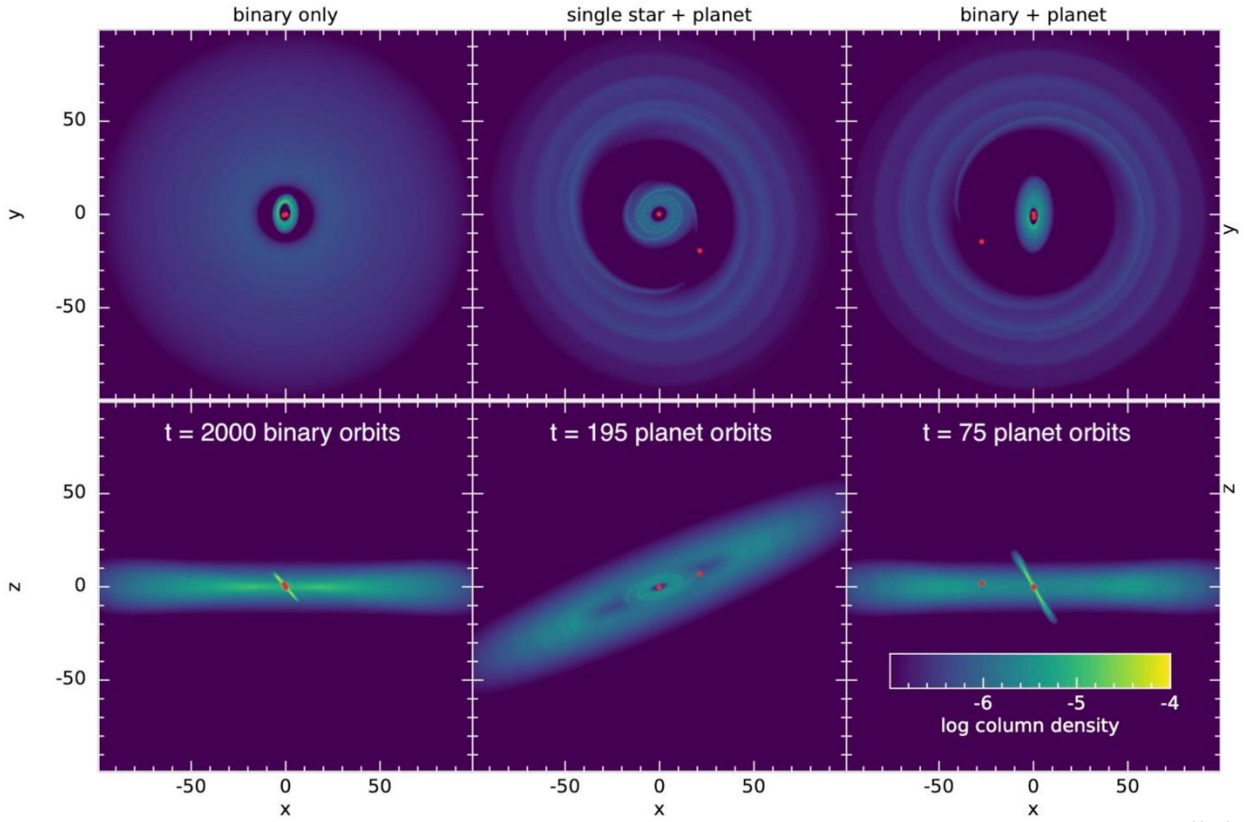
θ = misalignment angle
h = height of scattering surface
R = radius of scattered light

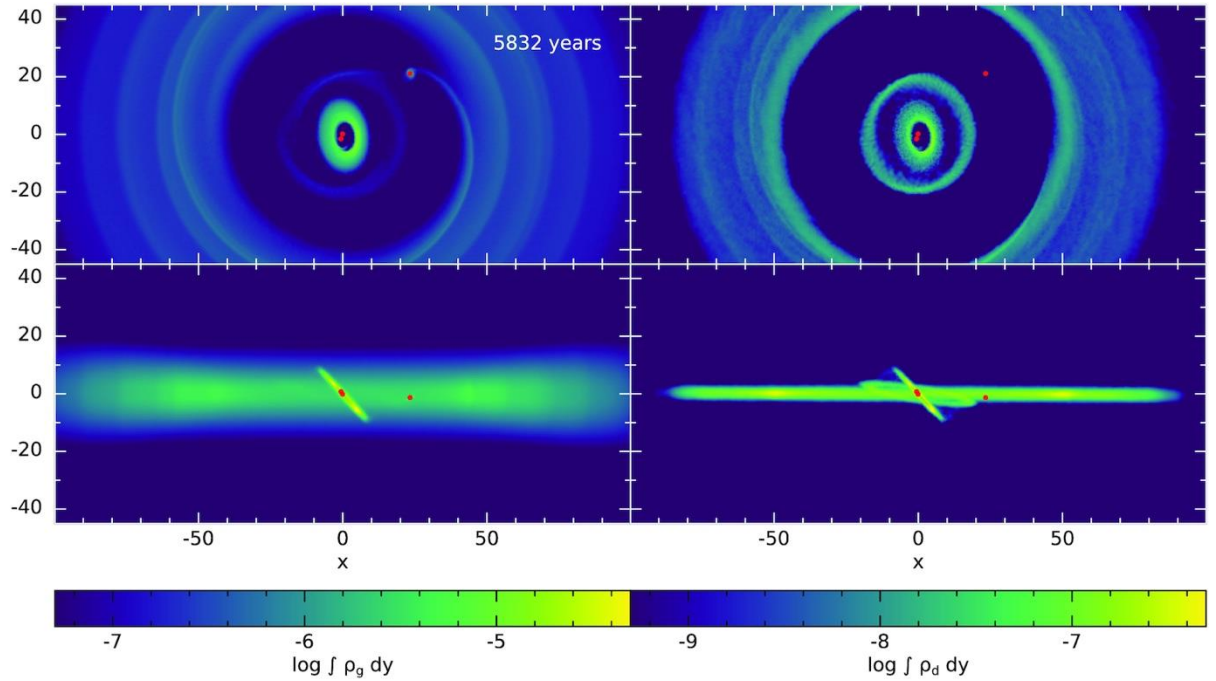
Companion?



Credit: Poon, Zhu, Zanazzi, U of T; Sahl Rowther, et al, Warwick University

Possible explanations?

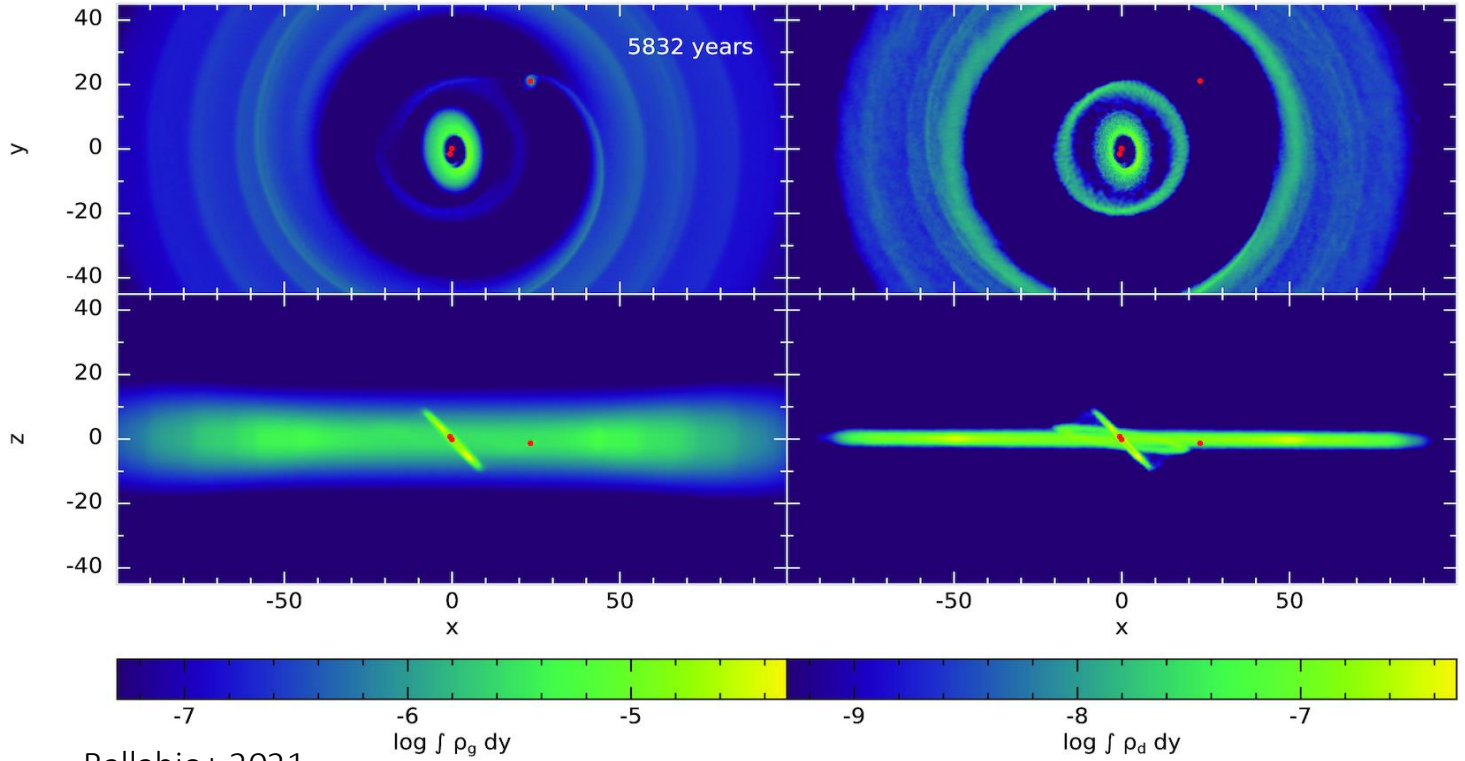




Ballabio+ 2021

Possible explanations?

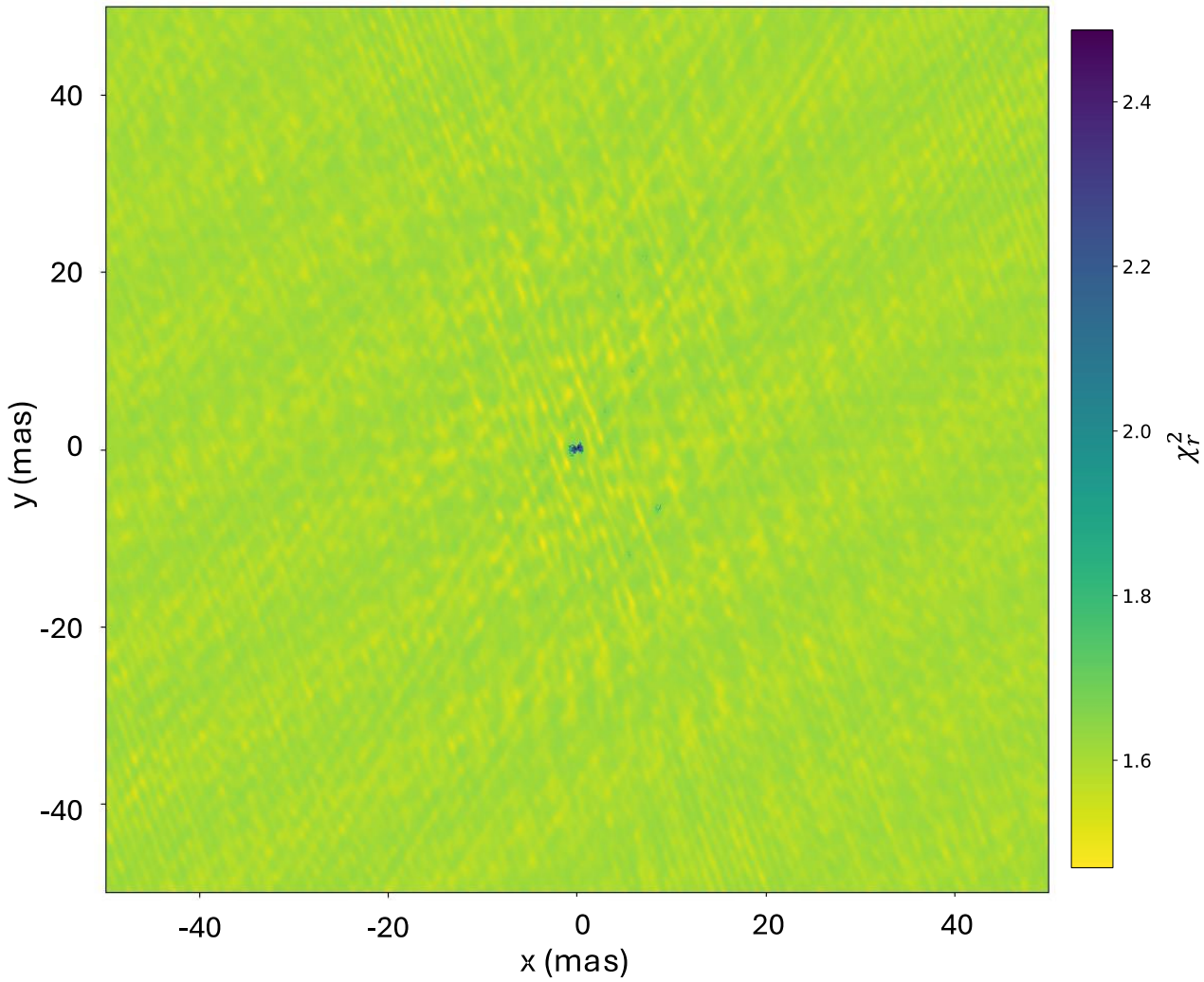
- Stellar companion at inclined orbit
- Binary separation = 2au
- Companion mass = $0.36M_{\odot}$
- Planetary companion at 32au
- Planetary mass = $10M_{J}$



Ballabio+ 2021

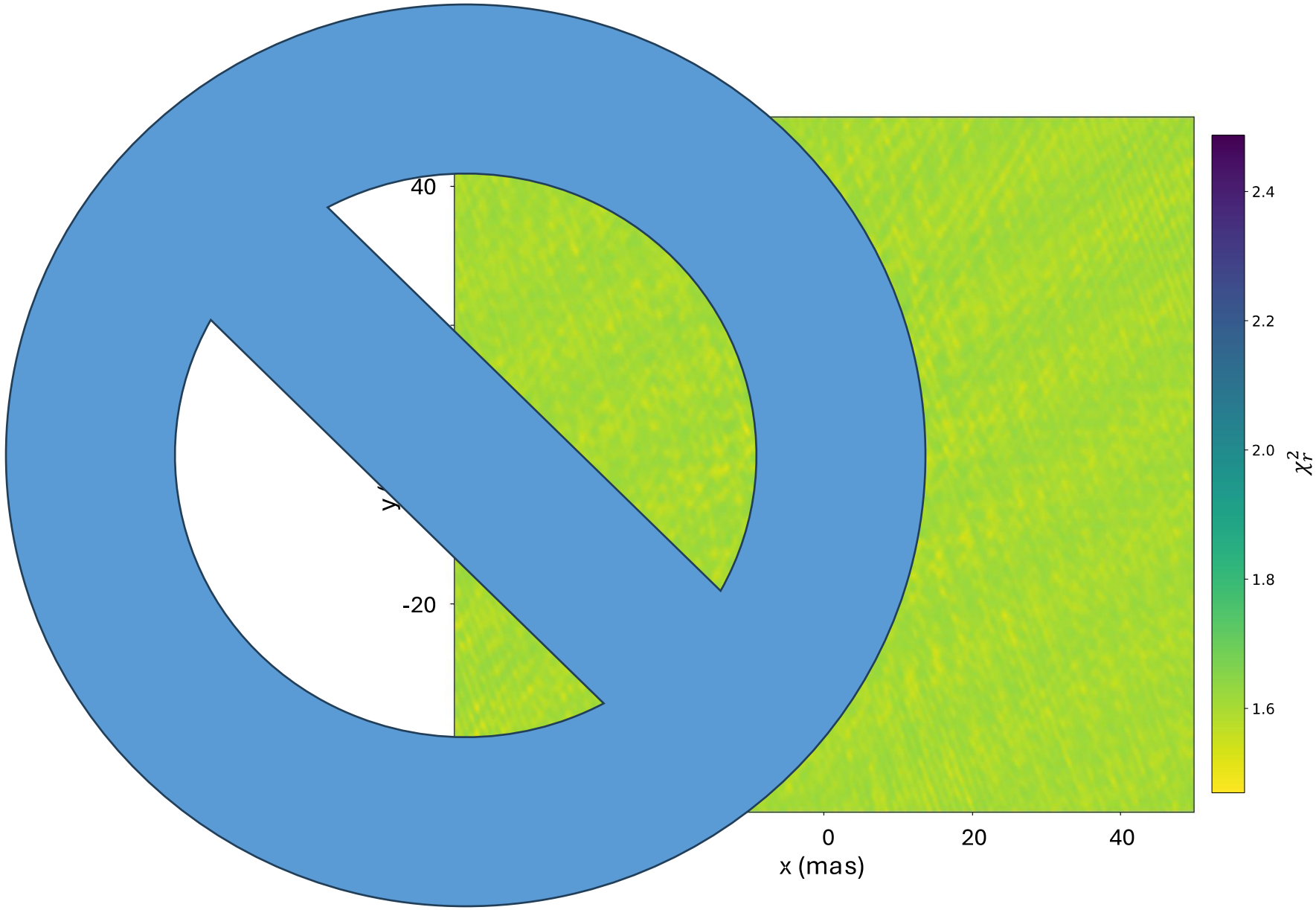
Companion Search:

- 50x50mas grid
- 0.1mas step size
- Run with fixed ring model



Companion Search:

- 50x50mas grid
- 0.1mas step size

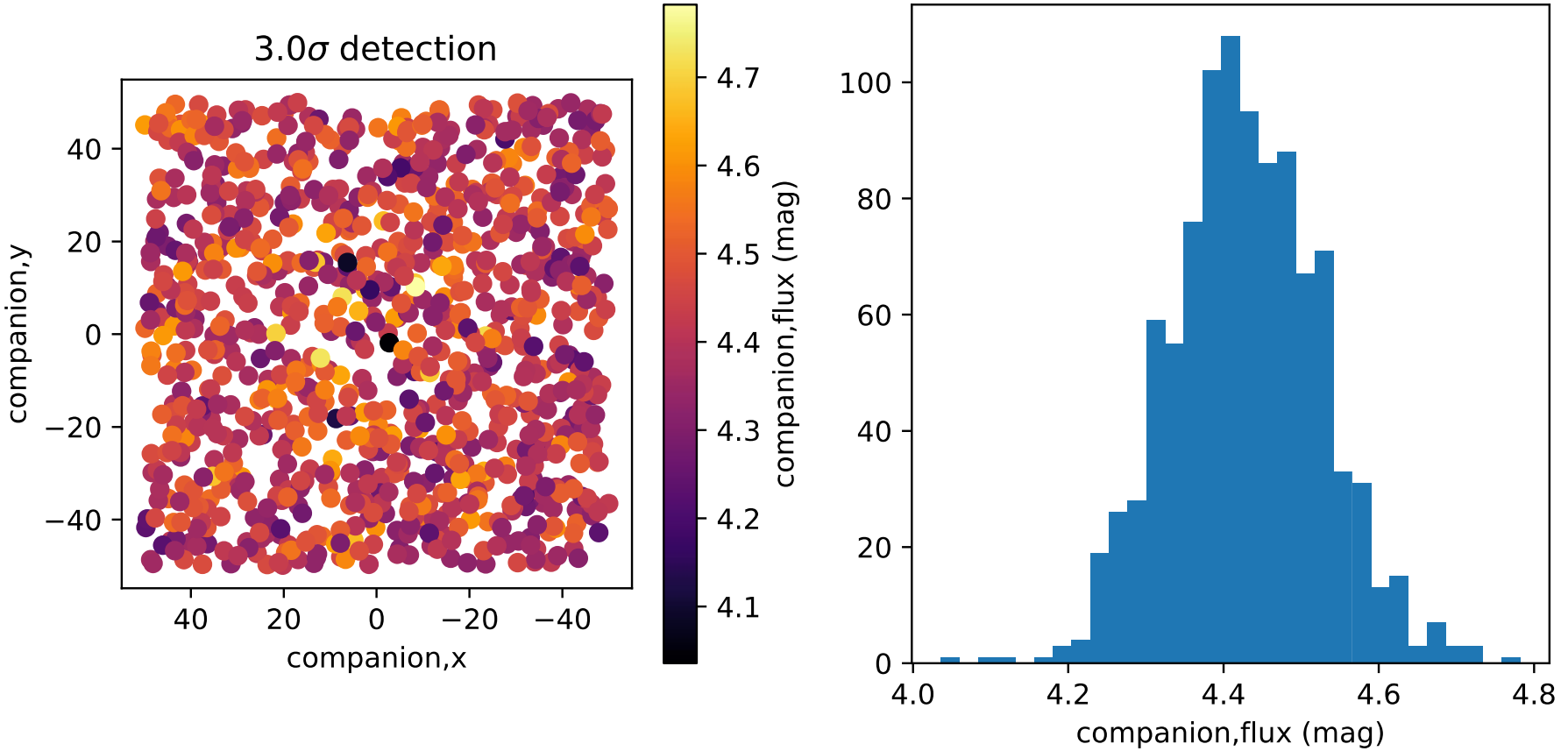


Can we find an upper limit?

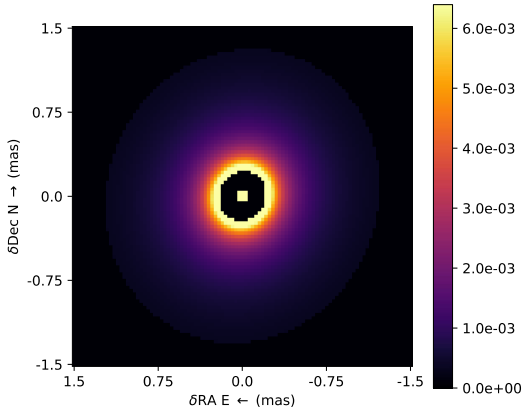
$\Delta Mag(H) = 4.5$

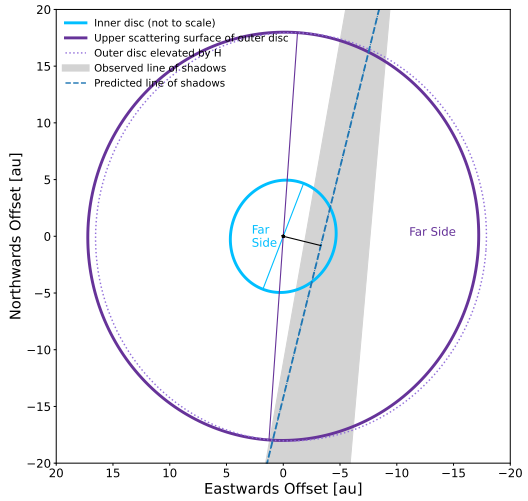
$\rightarrow 0.17 M_{\odot}$

(using Baraffe+2002 isochrones)



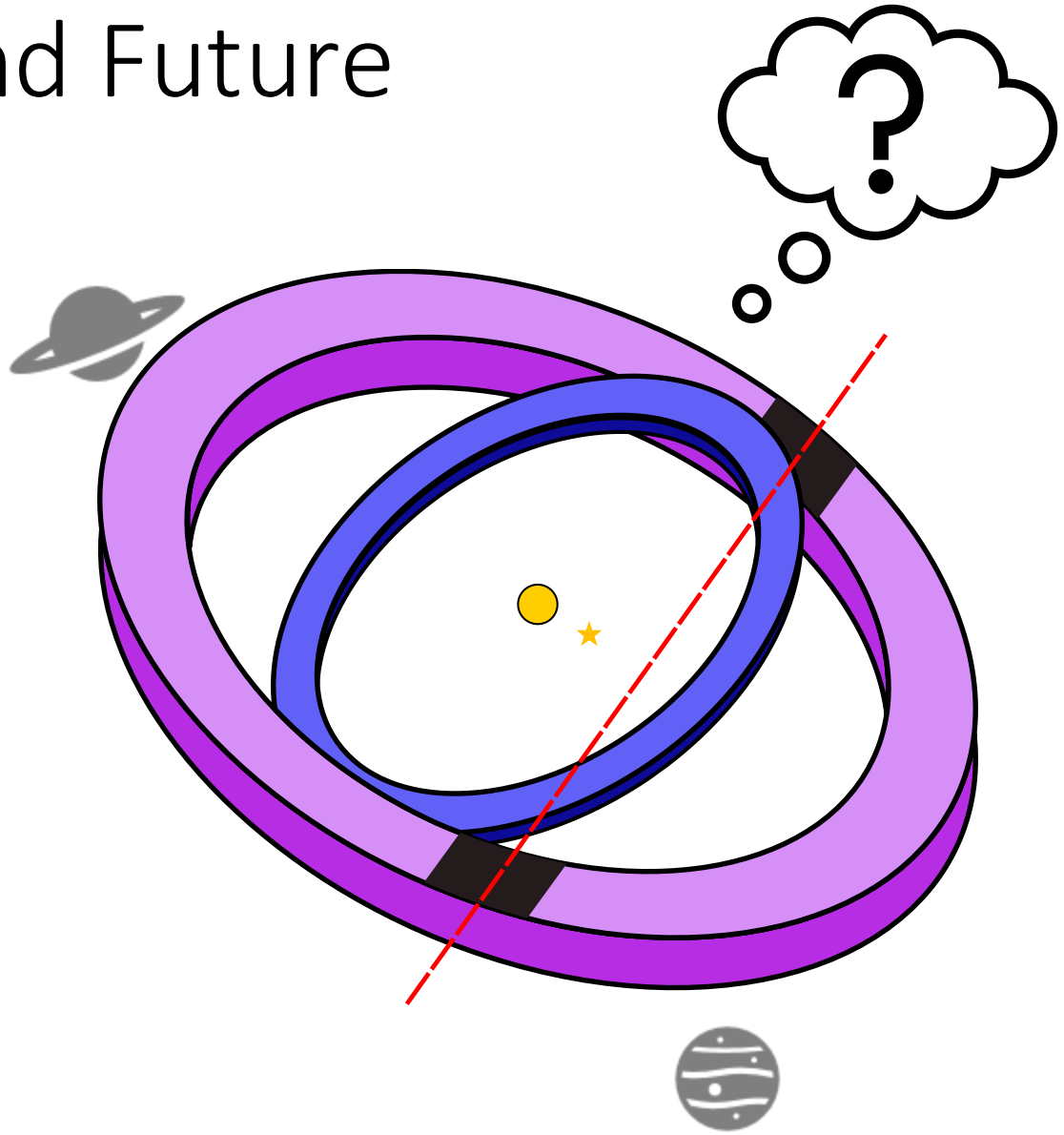
Summary and Future



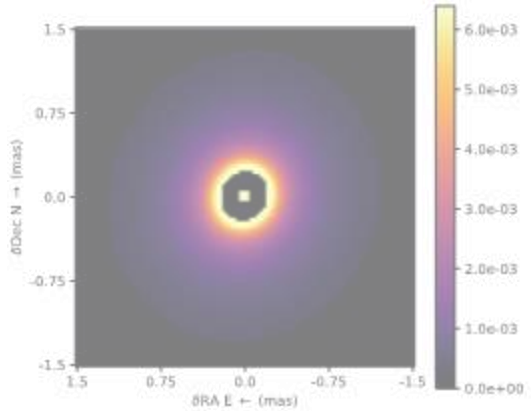


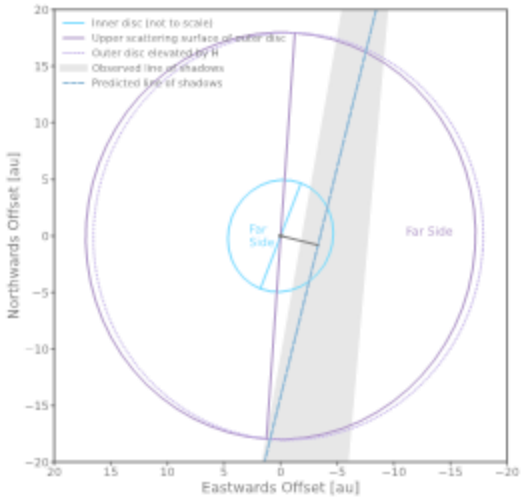
- ✓ **Obtain disc model & constrain inclination and position angle**
- ✓ **Confirm misalignment**
- ✓ **Upper mass limit found**

? **Hidden planet and/or companion?**



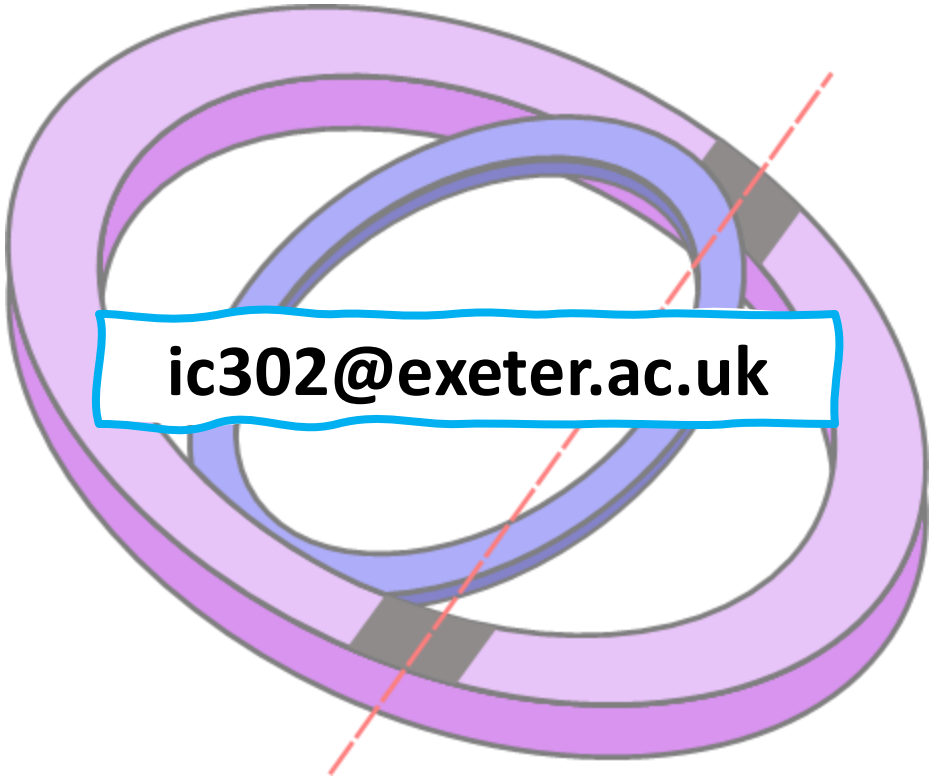
Thank you!





- ✓ **Obtain disc model & constrain inclination and position angle**
- ✓ **Confirm misalignment**
- ✓ **Upper mass limit found**

- ? **Hidden planet and/or companion?**



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