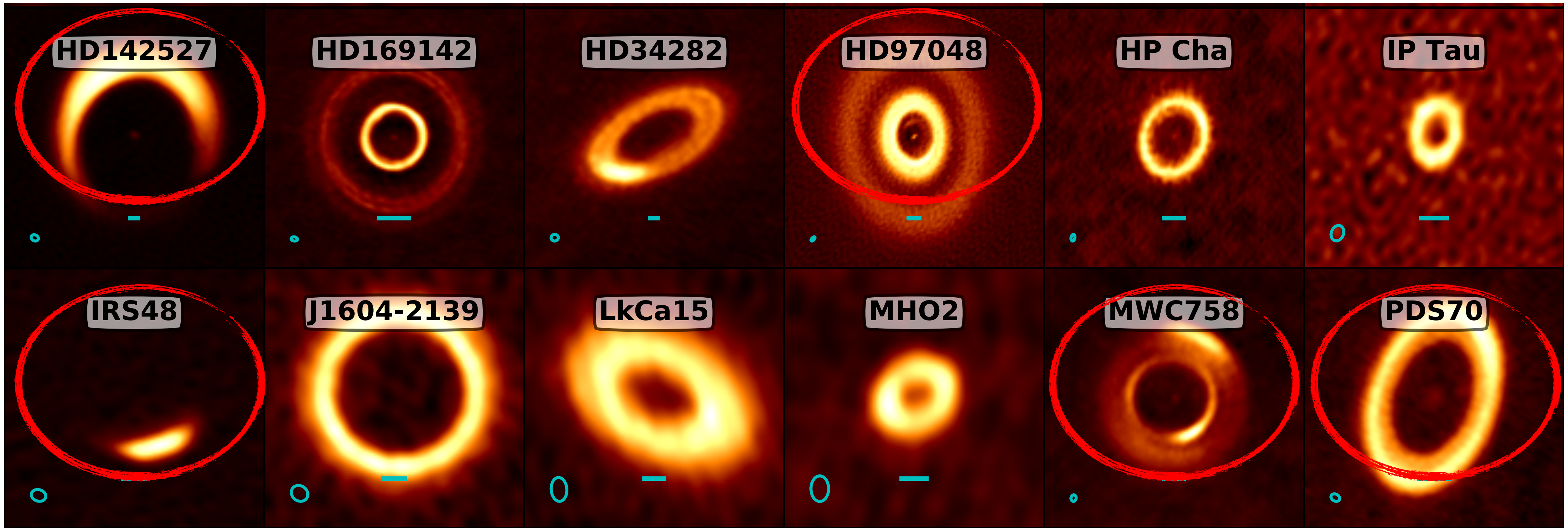


Francis & van der Marel (2020)

BINARY-DISC INTERACTION

Daniel Price (and collaborators)
Monash University
Melbourne, Victoria, Australia

Monash University

Australian Government
Australian Research Council

DUST BUSTERS

THE PROBLEM: "TRANSITIONAL" DISCS

Strom et al. (1989), Calvet et al. (2005), Espaillat et al. (2014), Casassus (2016), Owen (2016)

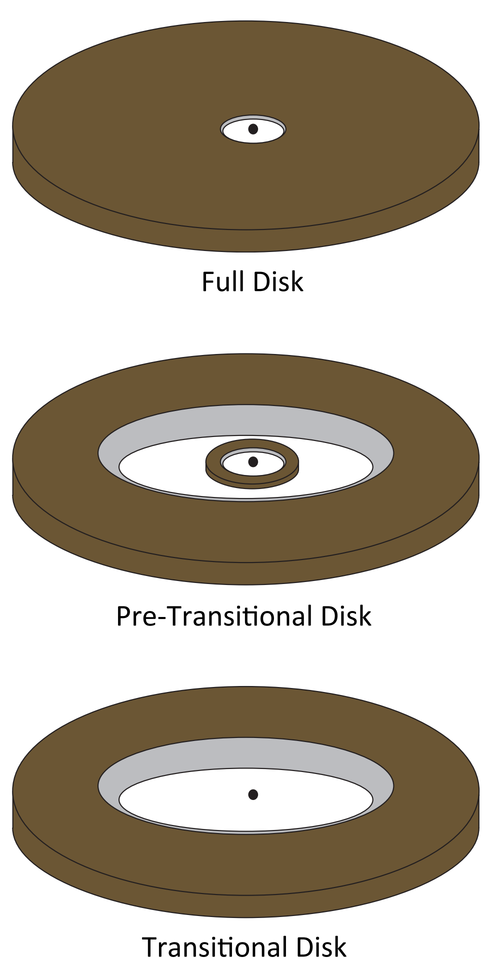
The Astrophysical Journal, 630:L185–L188, 2005 September 10

DISKS IN TRANSITION IN THE TAURUS POPULATION: *SPITZER* IRS SPECTRA OF GM AURIGAE AND DM TAURI

N. Calvet,[1] P. D'Alessio,[2] D. M. Watson,[3] R. Franco-Hernández,[1] E. Furlan,[4] J. Green,[3] P. M. Sutter,[3]
W. J. Forrest,[3] L. Hartmann,[1] K. I. Uchida,[4] L. D. Keller,[5] B. Sargent,[3] J. Najita,[6]
T. L. Herter,[4] D. J. Barry,[4] and P. Hall[4]
Received 2005 May 31; accepted 2005 July 27; published 2005 August 30

ABSTRACT

We present *Spitzer* Infrared Spectrograph (IRS) observations of two objects of the Taurus p
unambiguous signs of clearing in their inner disks. In one of the objects, DM Tau, the outer
3 AU; this object is akin to another recently reported in Taurus, CoKu Tau/4, in that the i
free of small dust. Unlike CoKu Tau/4, however, this star is still accreting, so optically tl
remain in the inner disk region. The other object, GM Aur, also accreting, has ~0.02 lunar n
in the inner disk region within ~5 AU, consistent with previous reports. However, the IR
shows that the optically thick outer disk has an inner truncation at a much larger radius than pr
~24 AU. These observations provide strong evidence for the presence of gaps in protoplane



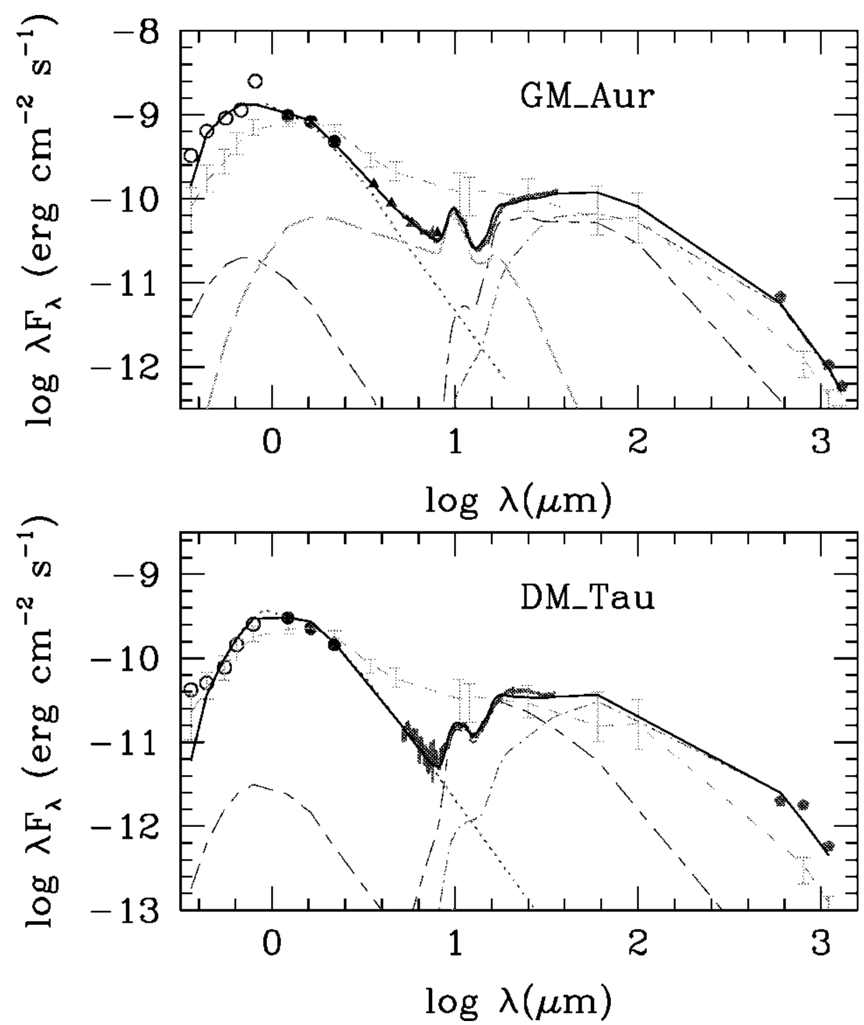
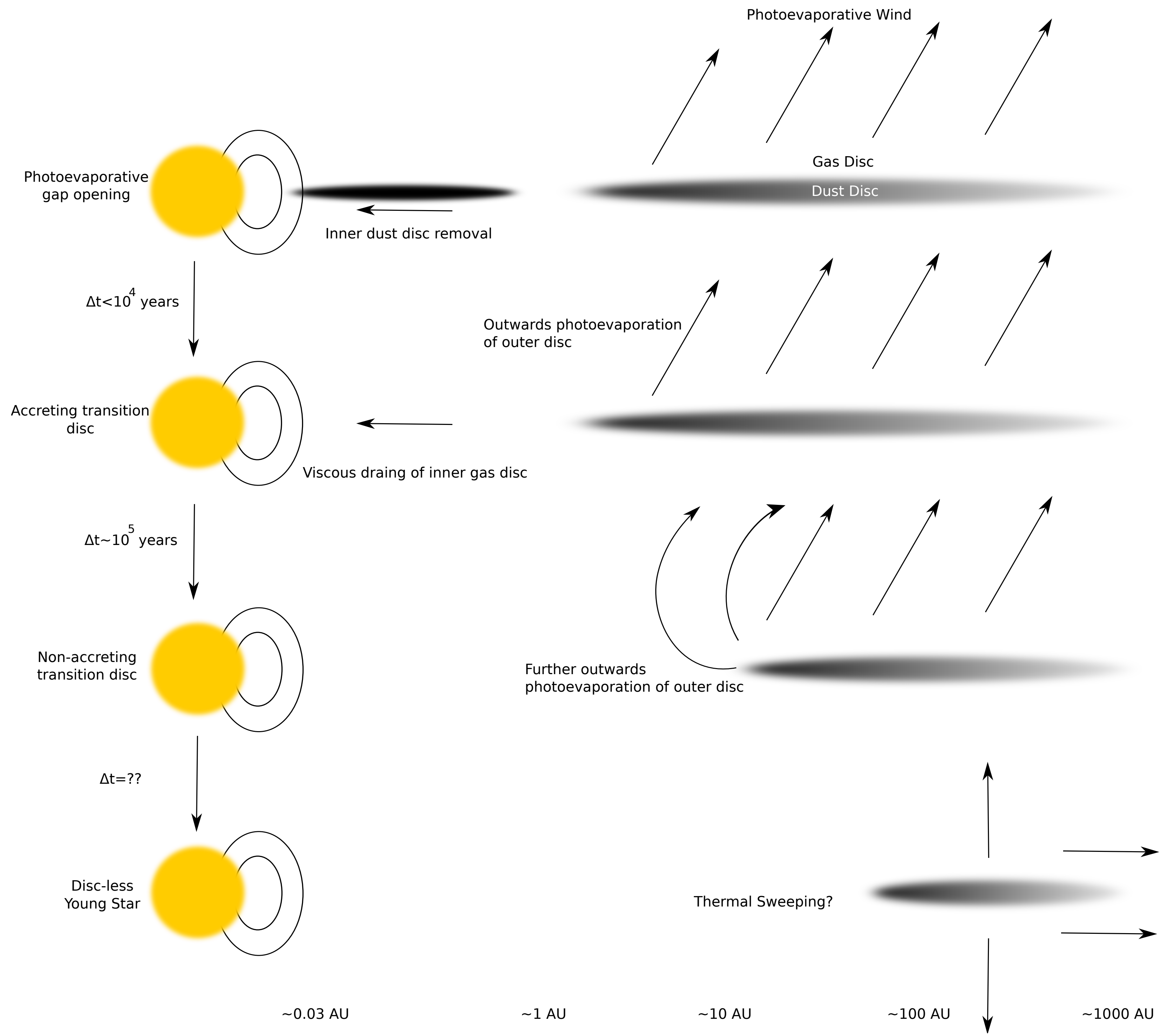


Fig. 2.—SEDs of GM Aur and DM Tau. IRS from Fig. 1. Optical (*open circles*) data from Kenyon & Hartmann (1995, hereafter KH95) and 2MASS (*solid circles*) corrected for reddening with extinctions A_V in Table 2 and the Mathis (1990) reddening law. Millimeter fluxes (*pentagons*) are from Dutrey et al. (1996). The short-dashed line is the median SED of Taurus with quartiles (error bars; D'Alessio et al. 1999). Photospheric fluxes (*dotted lines*) have being constructed from colors for standard stars in KH95, scaled at *J*. The model components are as in Fig. 1. [*See the electronic edition of the Journal for a color version of this figure.*]

PHOTOEVAPORATION?



Owen (2016)

ARE TRANSITION DISCS TRANSITIONAL?

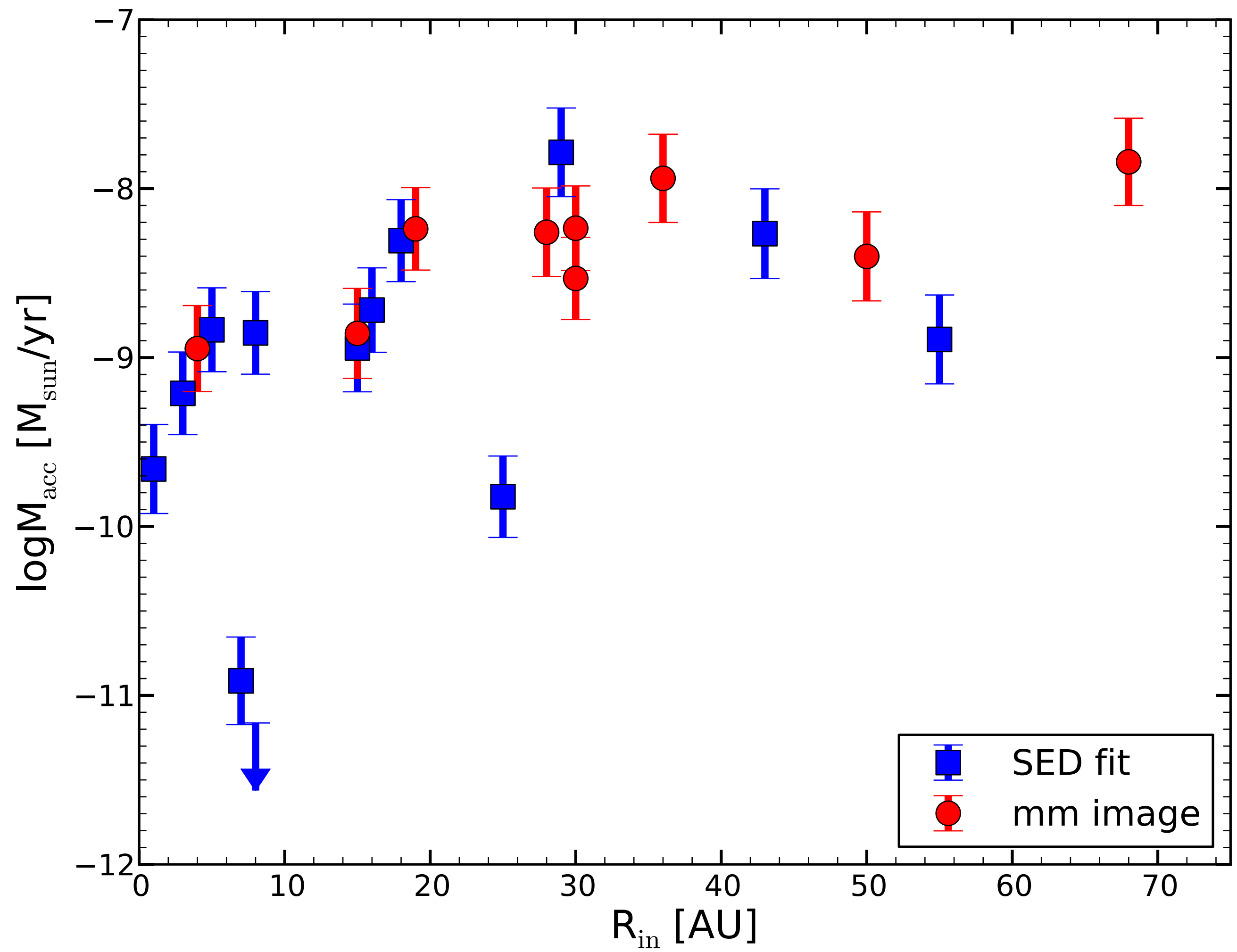
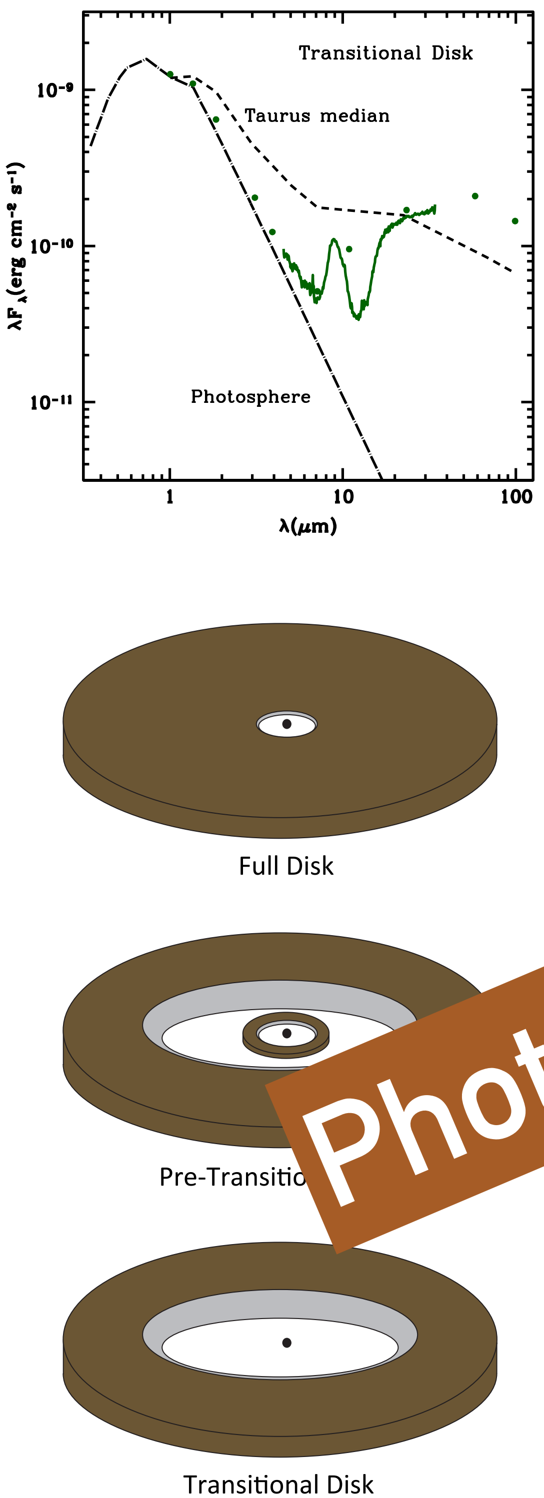


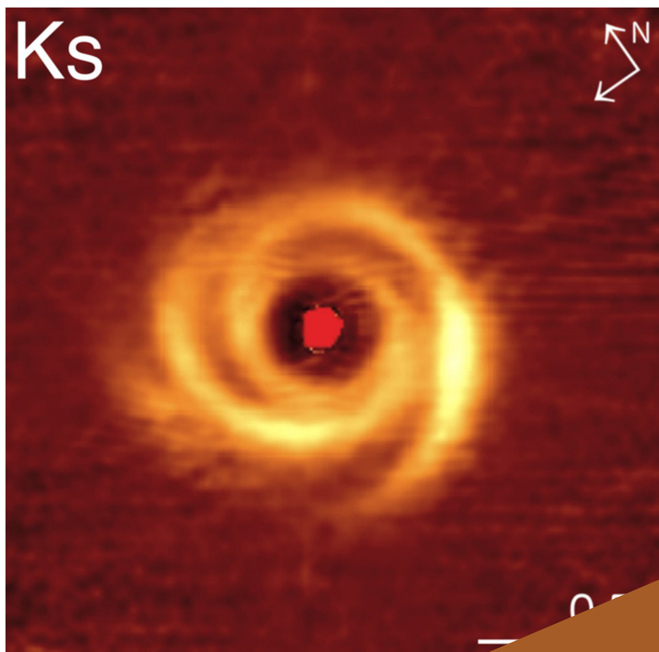
Fig. 8. Logarithm of the mass accretion rate vs inner hole size for our sample. Different symbols are used to distinguish the methods used in the literature to derive the size of the inner hole. *Blue squares* are adopted when this has been derived using

Manara et al. (2014)

TRANSITION DISCS: IMAGING WITH ALMA & VLT/SPHERE

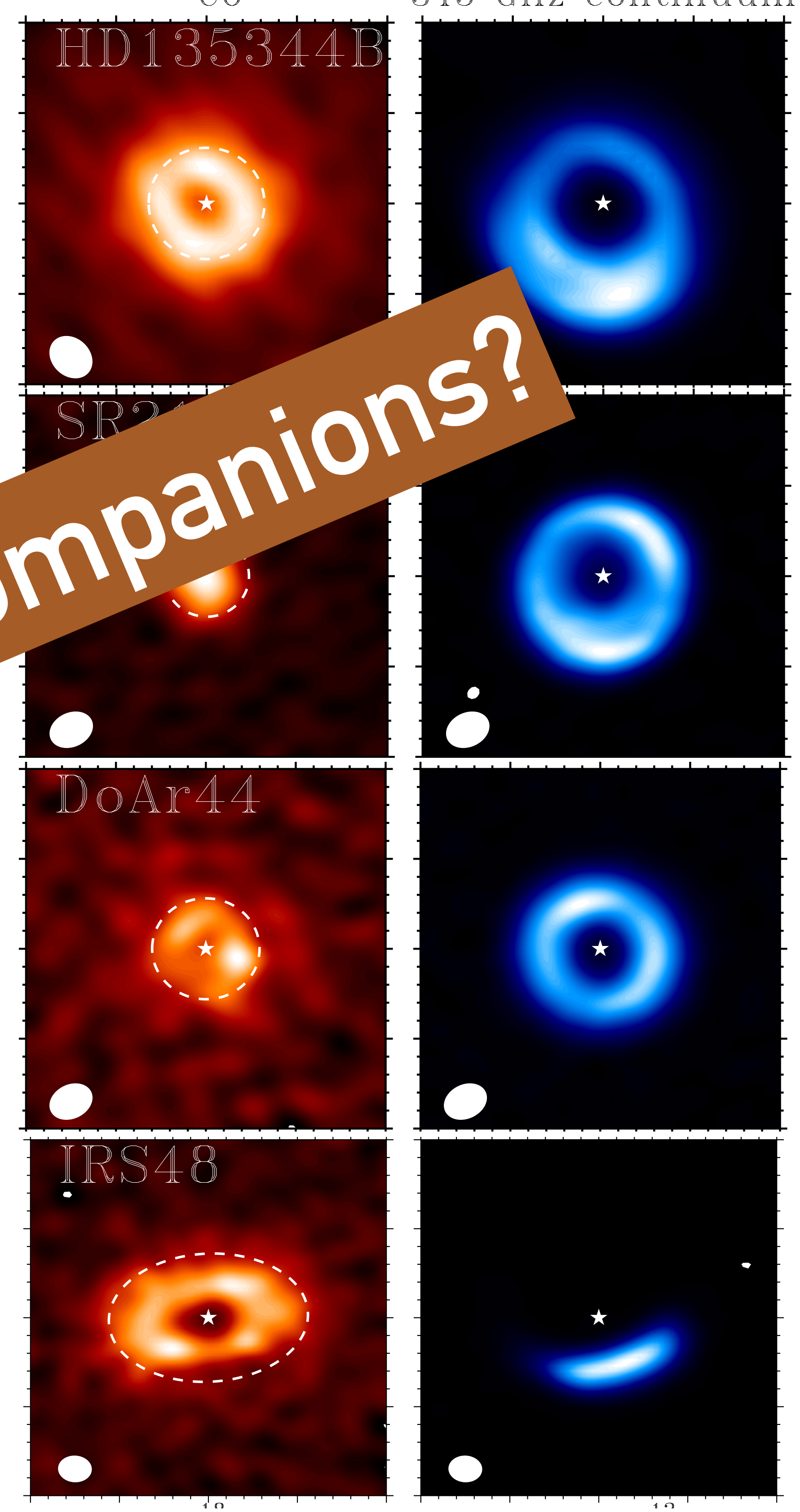


Espaillat et al. (2014)



Garufi et al.

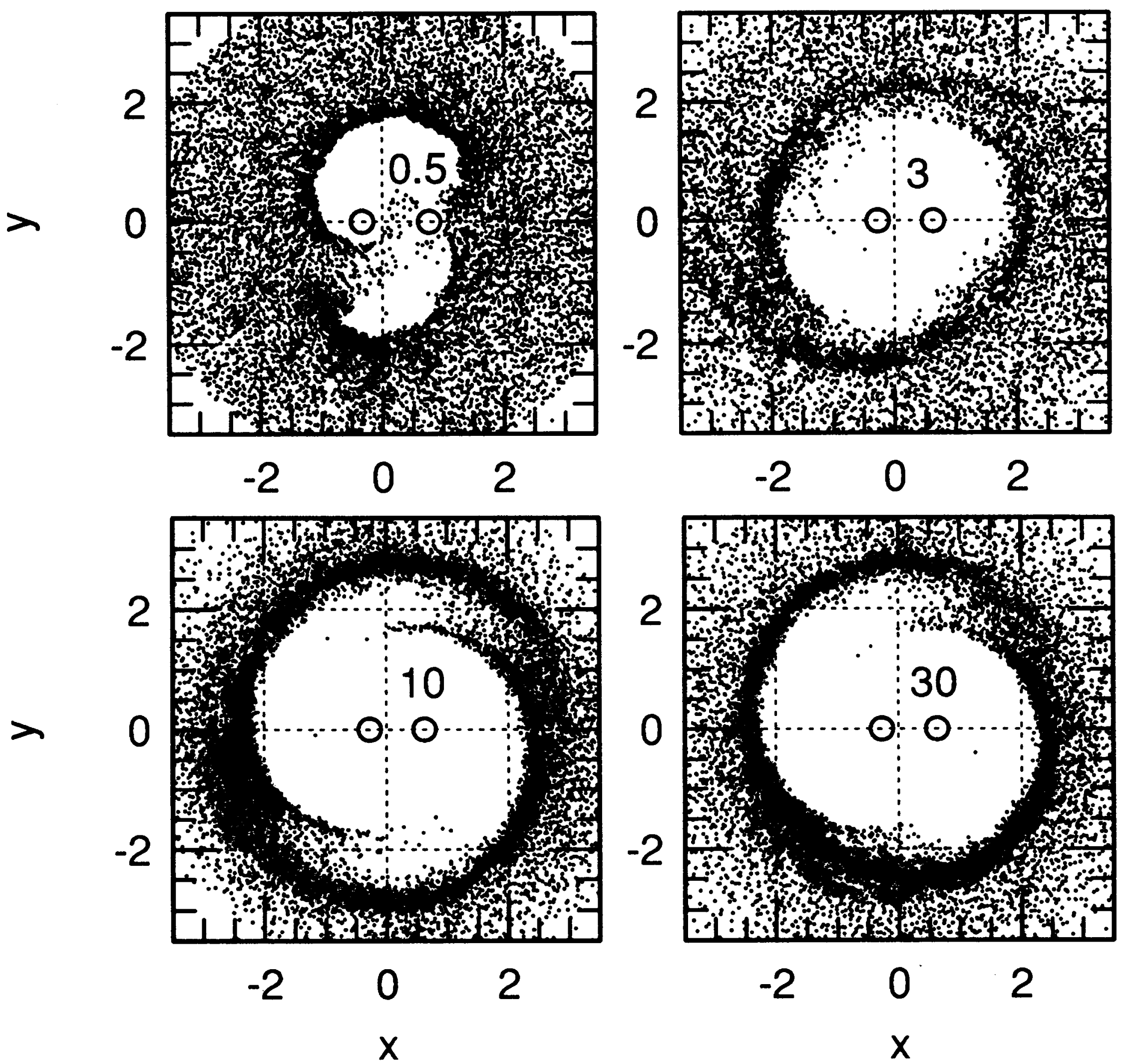
Benisty et al. (2016)

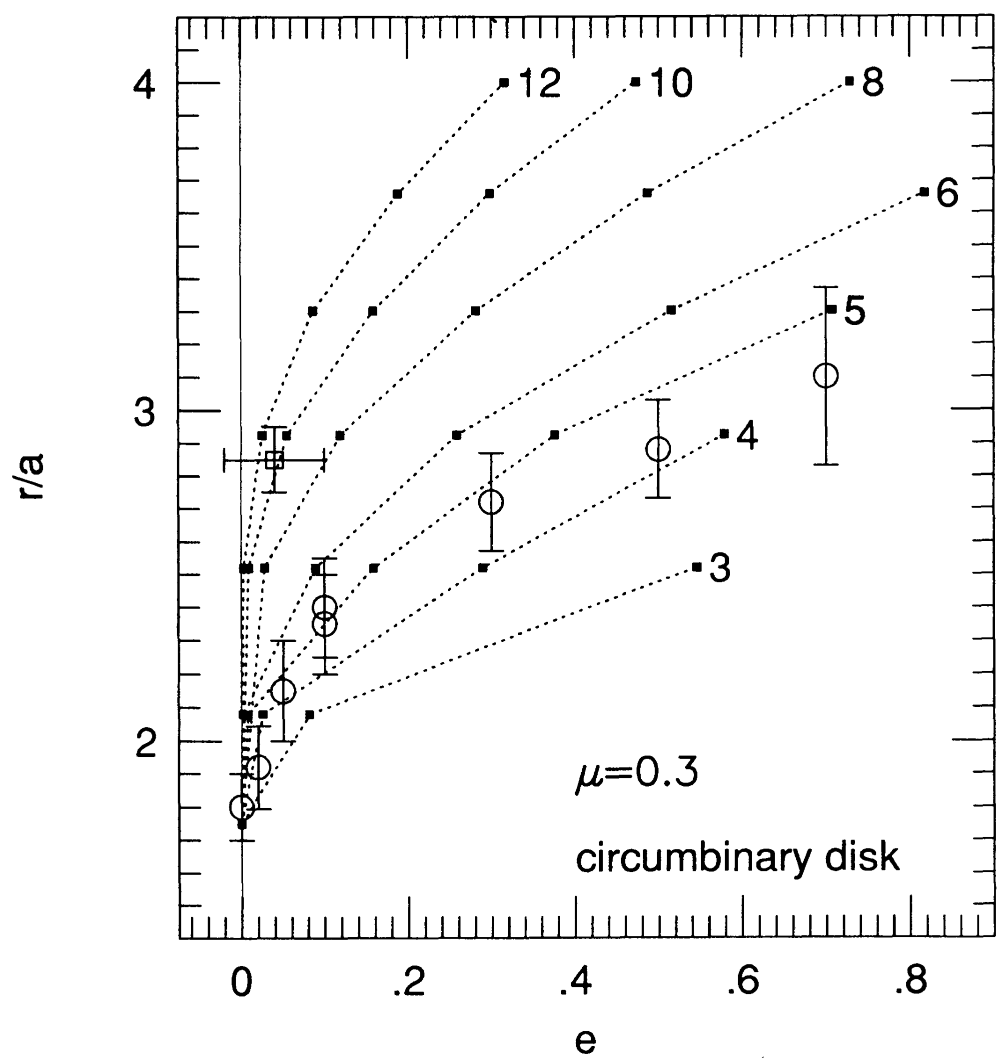


Van-der-Marel et al. (2016)

Photoevaporation or companions?

IN THE BEGINNING





DYNAMICS OF BINARY-DISK INTERACTION. I. RESONANCES AND DISK GAP SIZES

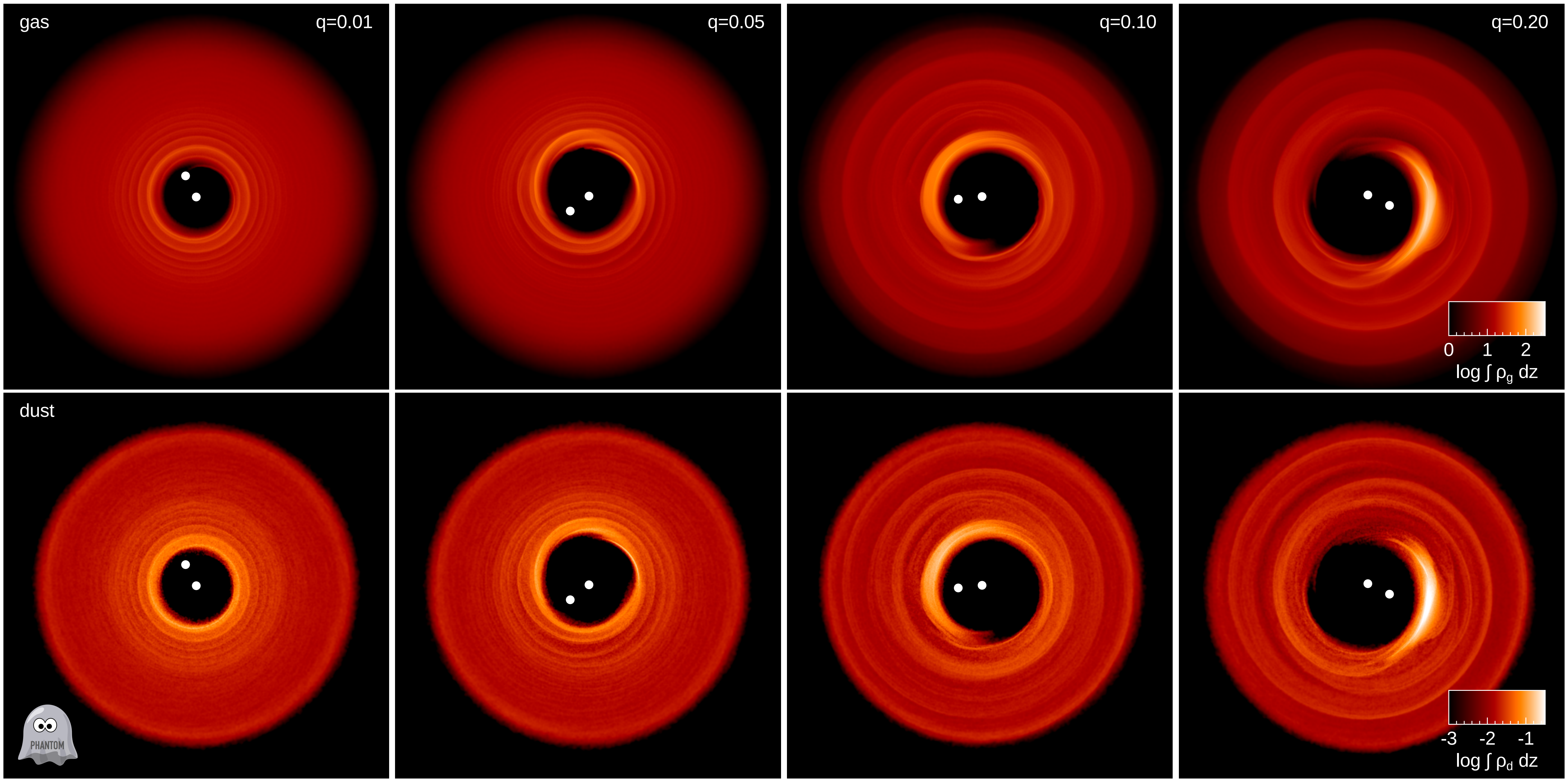
PAWEŁ ARTYMOWICZ[1,2,3] AND STEPHEN H. LUBOW[3,4]

Received 1993 June 7; accepted 1993 August 11

ABSTRACT

We investigate the gravitational interaction of a generally eccentric binary star system with circumbinary and circumstellar gaseous disks. The disks are assumed to be coplanar with the binary, geometrically thin, and primarily governed by gas pressure and (turbulent) viscosity but not self-gravity. Both ordinary and eccentric Lindblad resonances are primarily responsible for truncating the disks in binaries with arbitrary eccentricity

HORSESHOES IN CIRCUMBINARY DISCS: THE “OVERDENSE LUMP”

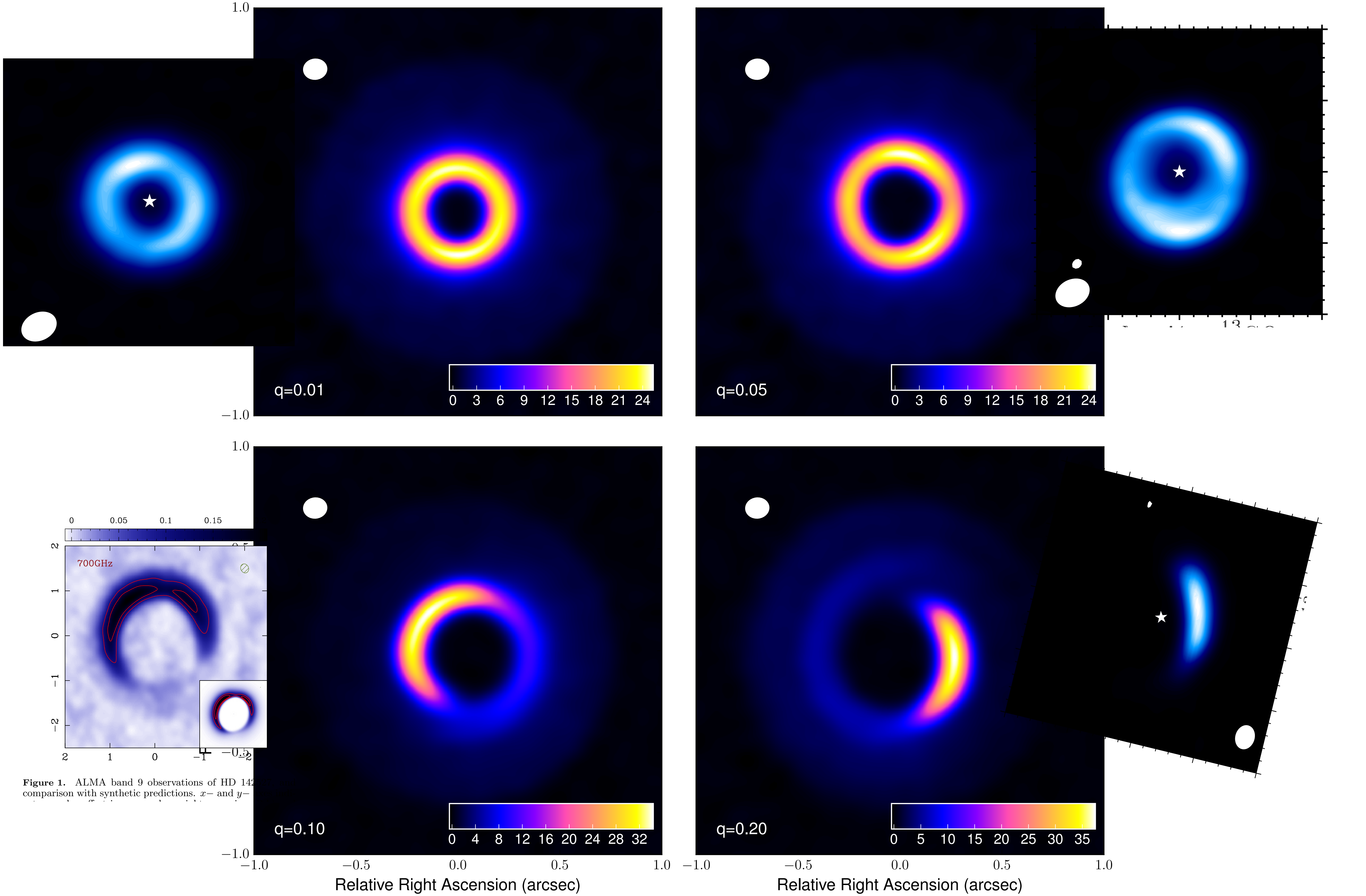


Ragusa+ (2017)

First seen in black hole binary sims by MacFadyen & Milosavljević (2008), Farris+(2014), D'Orazio+(2016), Ragusa+(2016) and others

SYNTHETIC OBSERVATIONS OF CIRCUMBINARY DISCS

Ragusa+ (2017)



HD142527

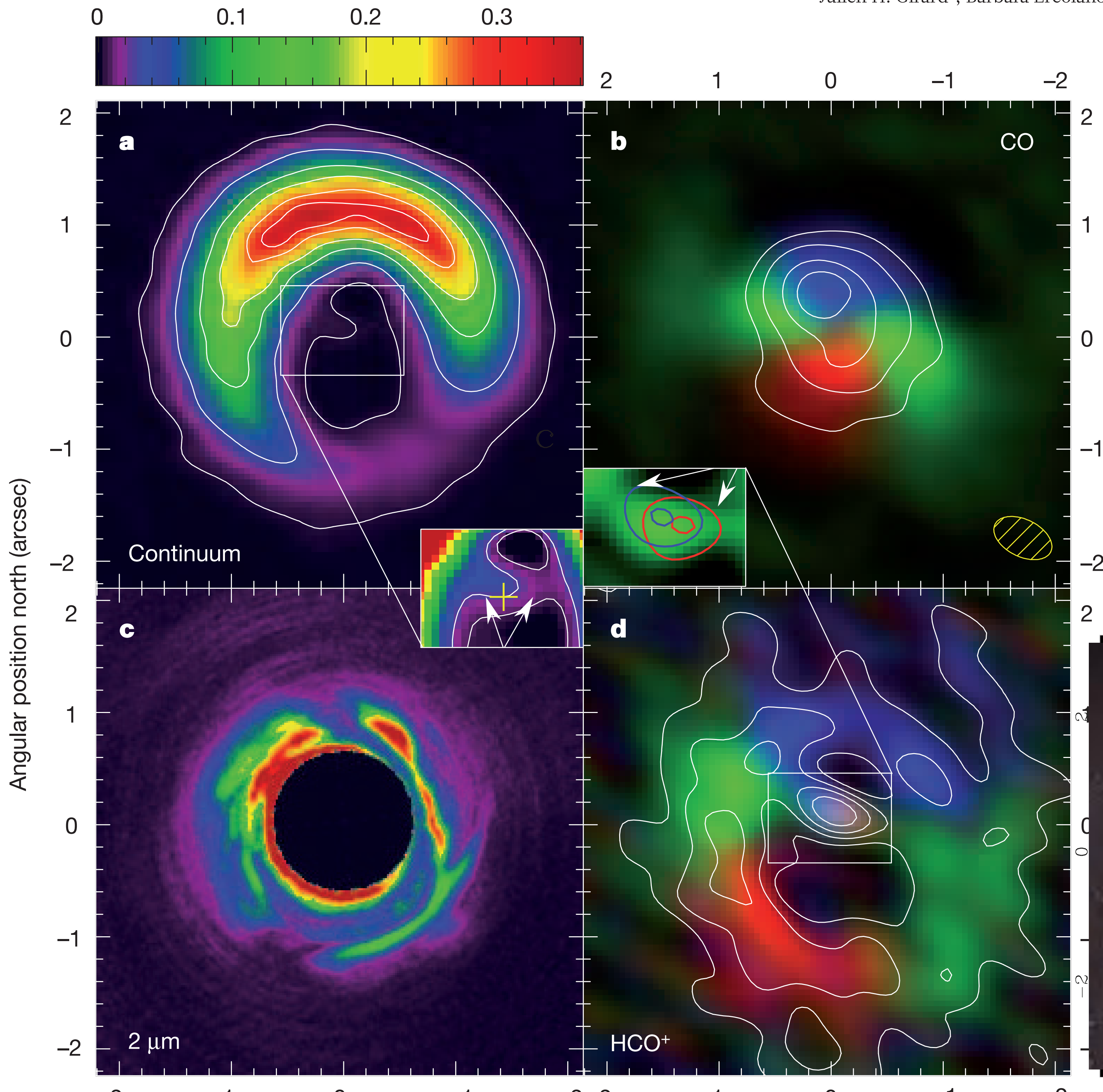
Casassus+2013

LETTER

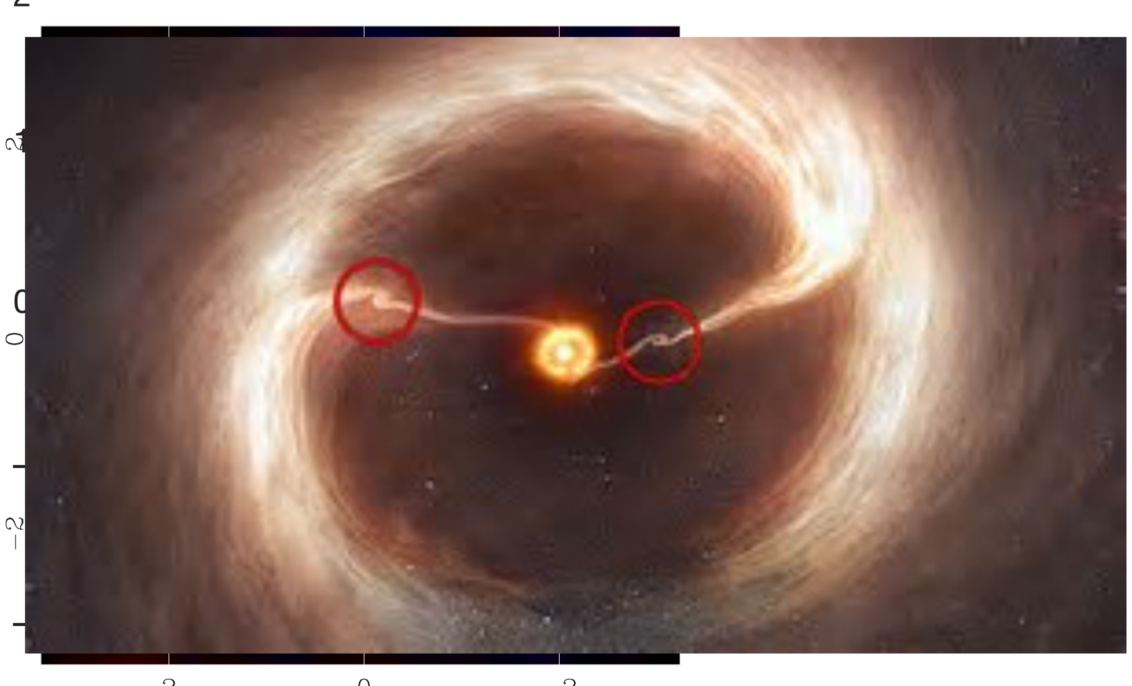
doi:10.1038/nature11769

Flows of gas through a protoplanetary gap

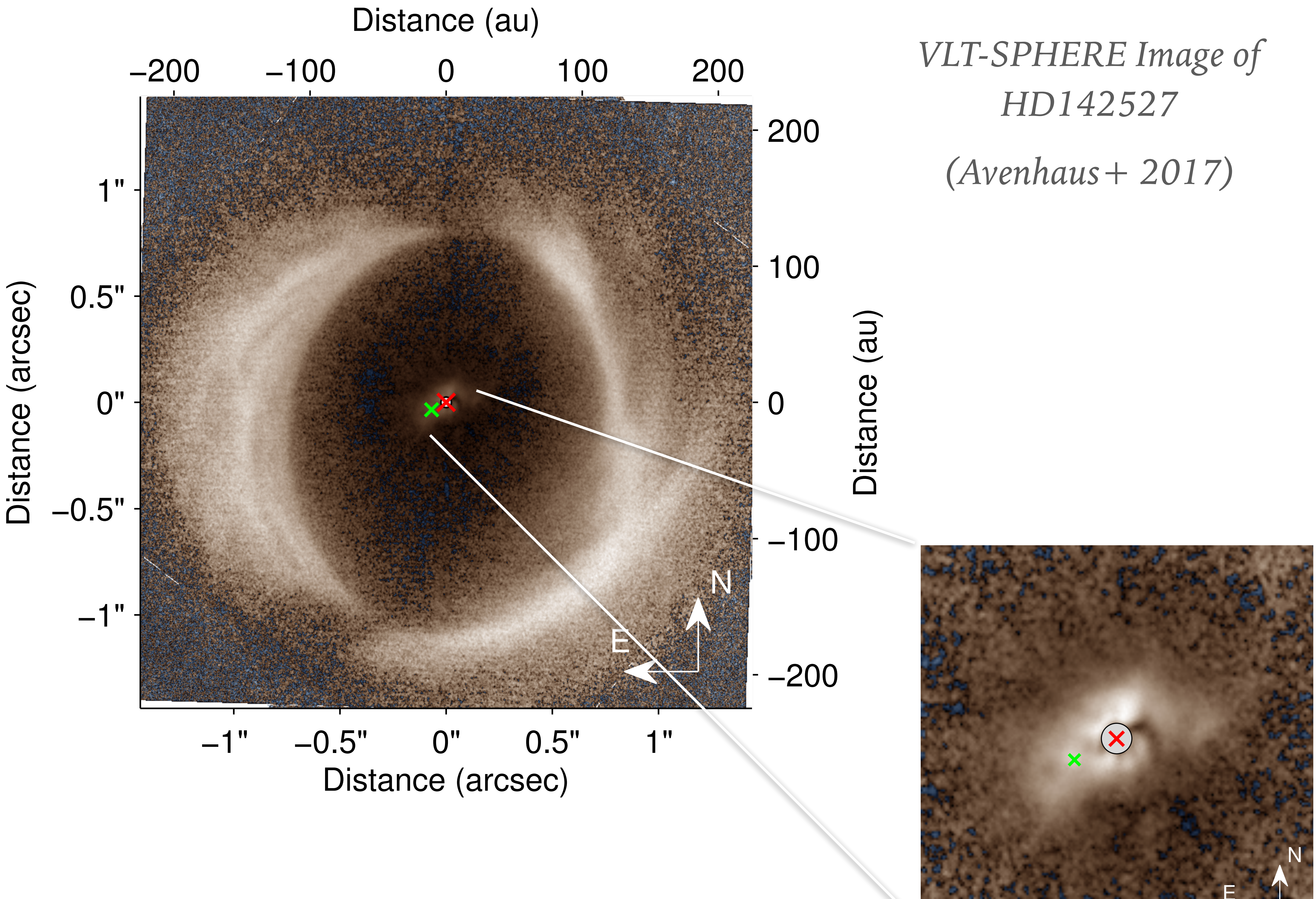
Simon Casassus[1], Gerrit van der Plas[1], Sebastian Perez M[1], William R. F. Dent[2,3], Ed Fomalont[4], Janis Hagelberg[5], Antonio Hales[2,4], Andrés Jordán[6], Dimitri Mawet[3], Francois Ménard[7,8], Al Wootten[4], David Wilner[9], A. Meredith Hughes[10], Matthias R. Schreiber[11], Julien H. Girard[3], Barbara Ercolano[12], Hector Canovas[11], Pablo E. Román[13] & Vachail Salinas[1]



- ➤ Large ~100 au cavity
- ➤ Horseshoe in mm emission
- ➤ Gap-crossing filaments?



SPIRAL ARMS



VLT-SPHERE Image of HD142527

(Avenhaus+ 2017)

SHADOWS

The Astrophysical Journal Letters, 798:L44 (4pp), 2015 January 10 Marino, Perez, & Casassus

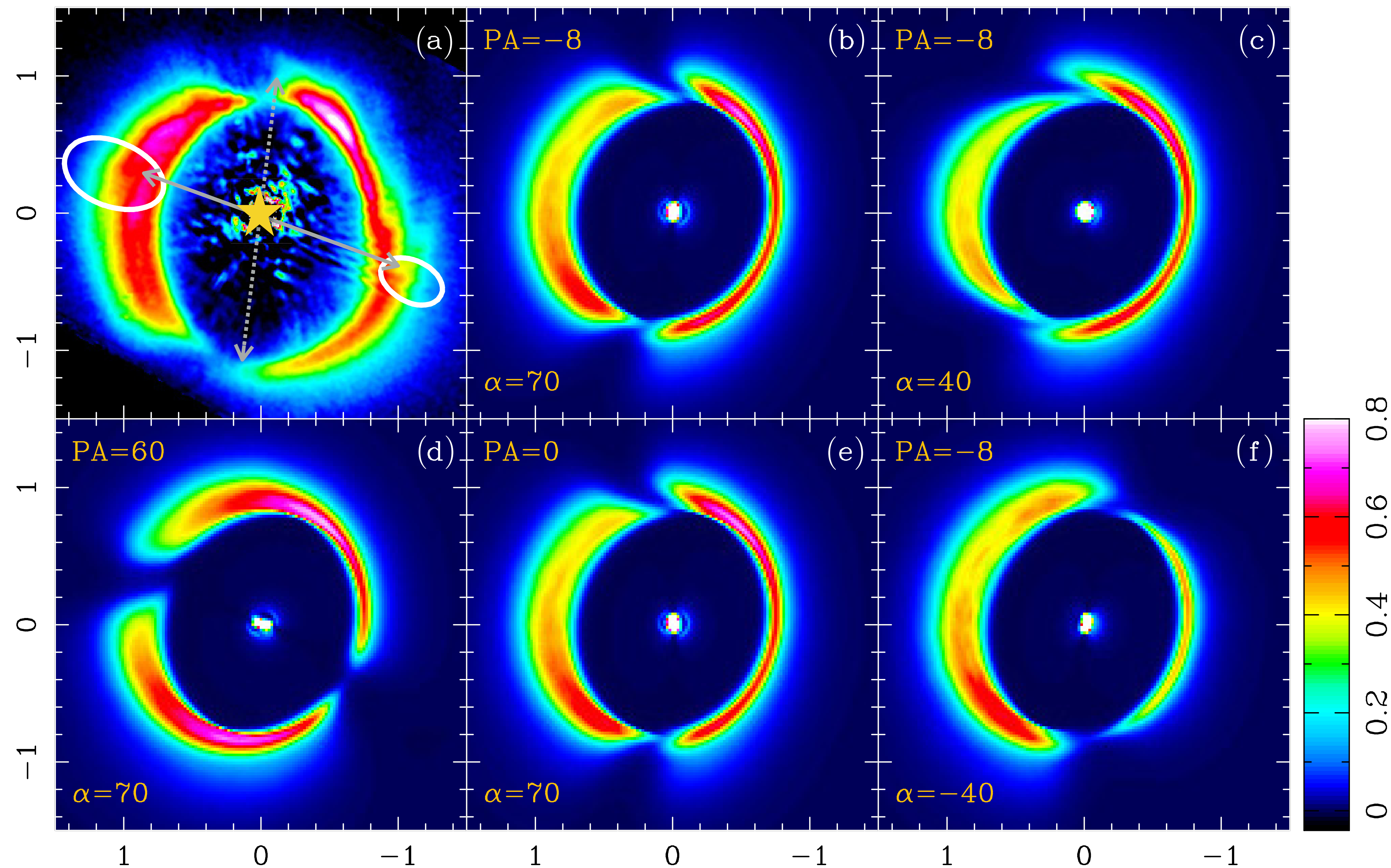
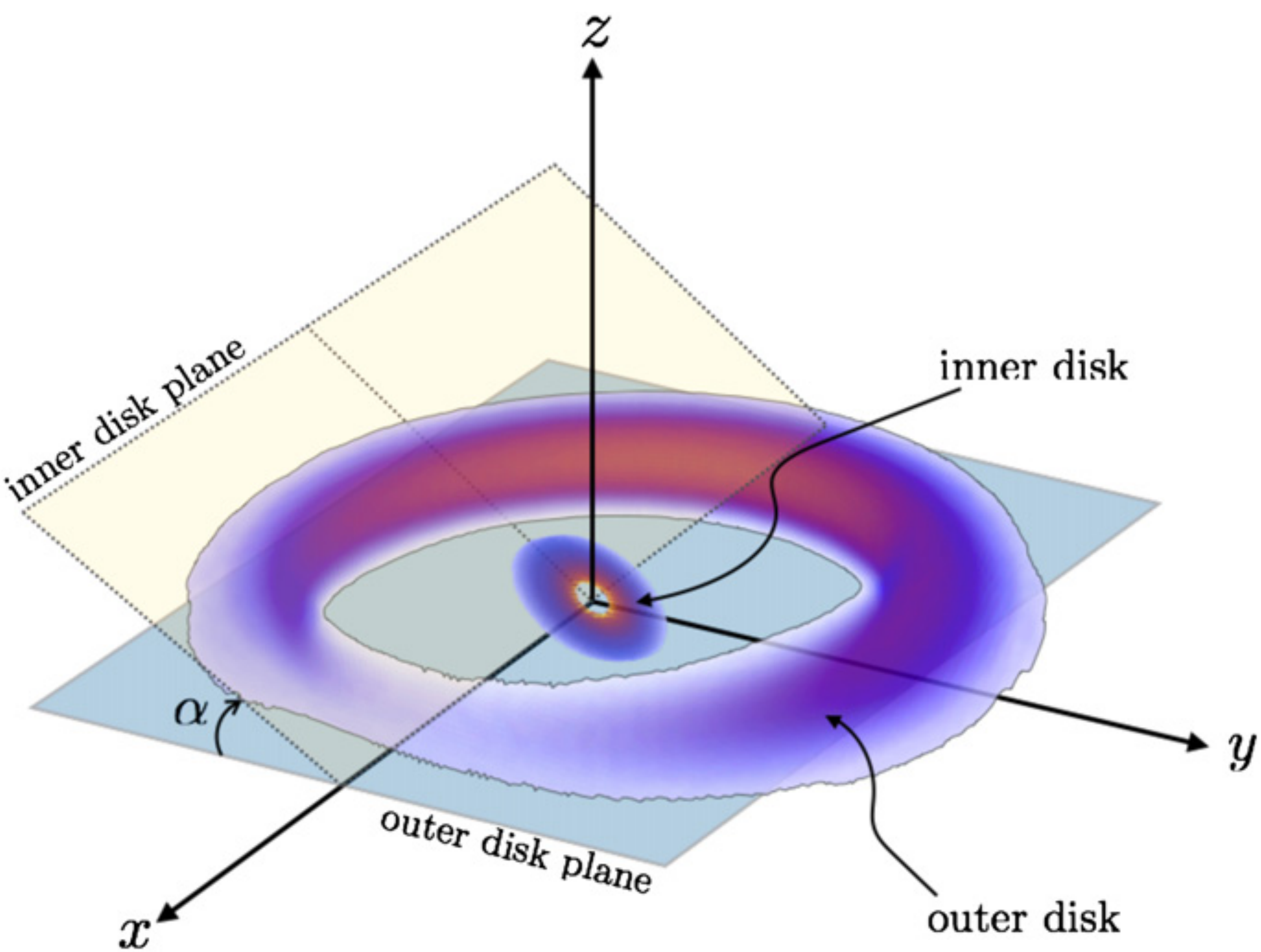


Figure 2. Impact of the inner disk orientation on the *H*-band light scattered off the outer disk. (a) NACO-PDI *H*-band image from Avenhaus et al. (2014) compared with the $C^{18}O$(2–1) emission at systemic velocity from Perez et al. (2014). The $C^{18}O$(2–1) emission, represented here as one white contour at 0.75 maximum, shows that the position angle (P.A.) of the outer disk is at −20° east of north, and perpendicular to the solid gray double arrow, while the position angle of the intensity nulls is indicated by the dashed double arrow (−8°). (b)–(f) Radiative transfer prediction for polarized intensity in the *H* band for different inner disk P.A.s (indicated in degrees on the plots) and for different relative inclinations α between the inner and the outer disks. The $x-$ and $y-$axes indicate offset along R.A. and decl., in arcsec.

SHADOWS = INCLINED INNER DISC?

The Astrophysical Journal Letters, 798:L44 (4pp), 2015 January 10



Marino, Perez & Casassus (2015)

"FAST RADIAL FLOWS" = DISC TEARING?

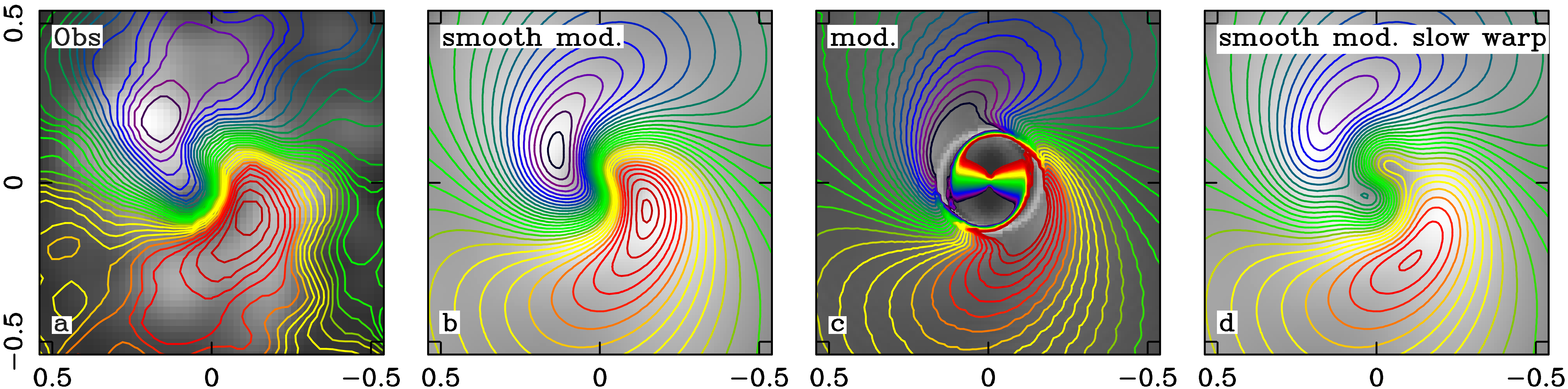
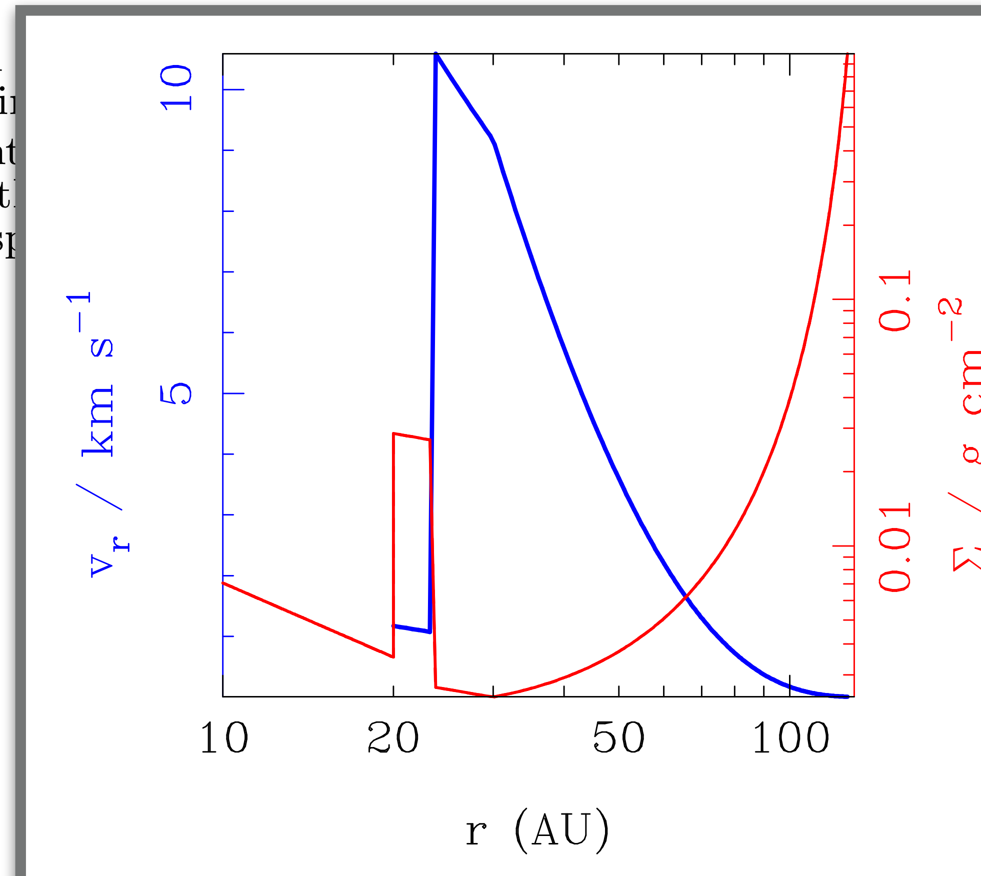


Figure 7. Comparison of observed and model CO(6-5) kinematics in … rdinates is set to
the stellar position. Velocity-integrated intensity in CO(6-5) is shown i… tant interval and
are spread over [0.21, 7.87] km s^{-1} (as in Fig. 1). **a)**: Observed moment… nts extracted on
the radiative transfer prediction, after smoothing to the resolution of t… odel resolutions,
without smoothing. Regions without contours near the origin corresp… a slow velocity
component perpendicular to the disk plane ($v_{\rm warp}$ in the text).

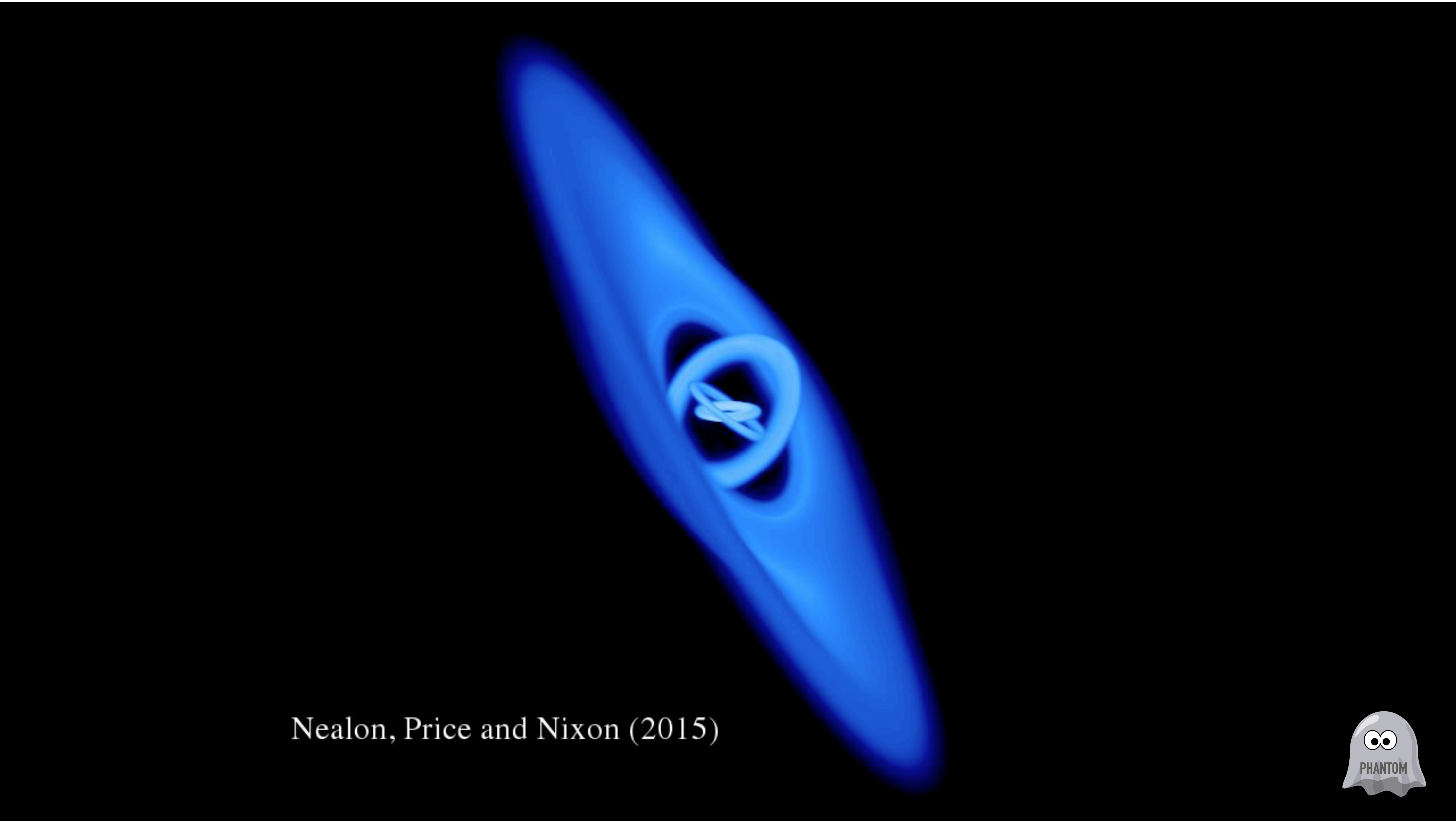
dubbed disk tearing (Nixon et al. 2013; Nealon et al. 2015; Doğan et al. 2015), where nodal precession torques induced by the binary produce a warp at the inner edge … companion on … 100 AU scale … cavity. It is



Require infall motions from cavity edge at the free-fall velocity!

DISC TEARING

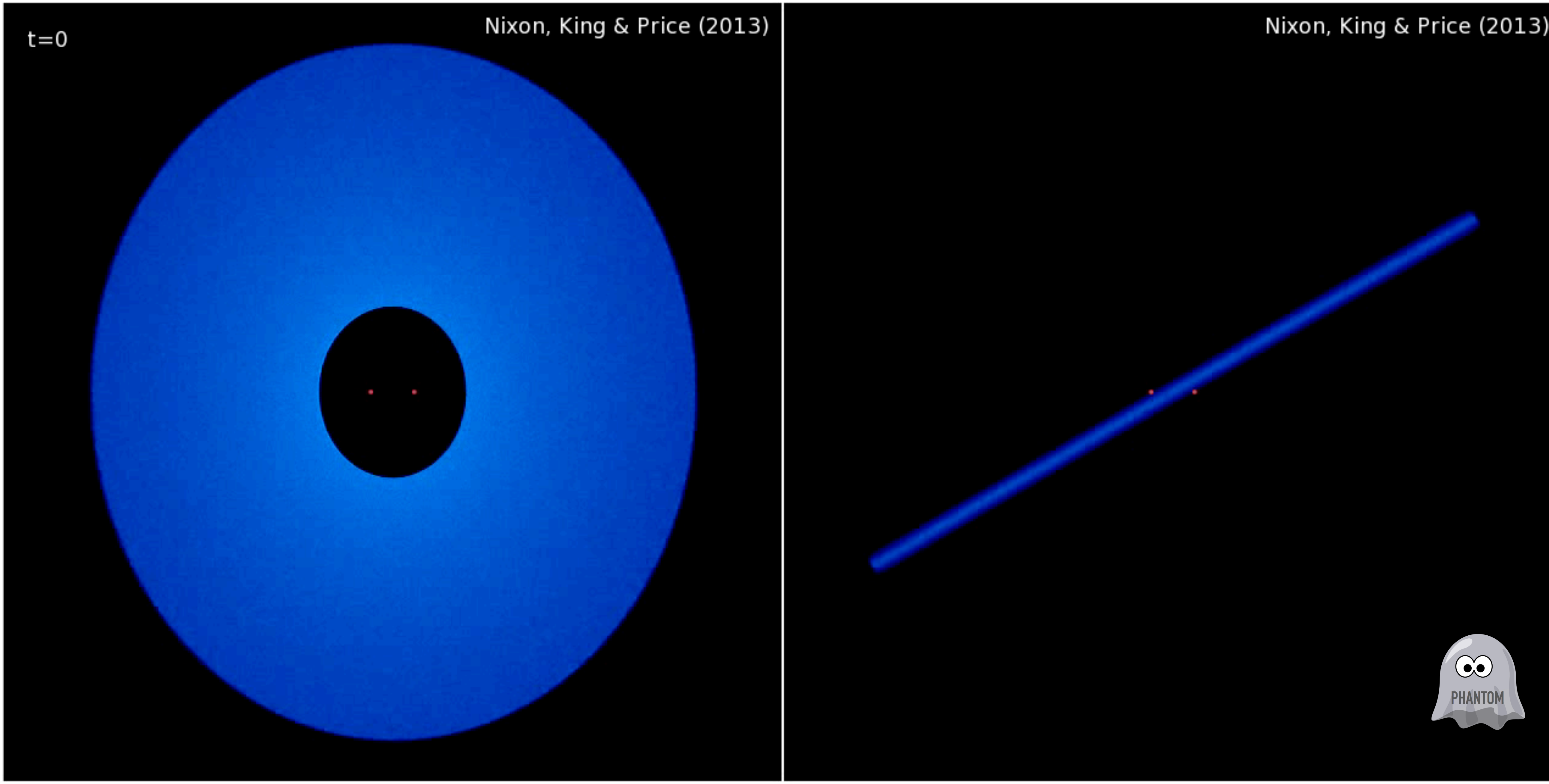
Nixon et al. (2012, 2013), Nealon et al. (2015), Dogan et al. (2015)



Viscous torque = Lense-Thirring precession torque: $R_{\rm break} \lesssim \left(\frac{4a}{3\alpha} |\sin\theta| \left(\frac{H}{R} \right)^{-1} \right)^{2/3} R_{\rm g}$

BUT WHAT ABOUT IN CIRCUMBINARY DISCS?

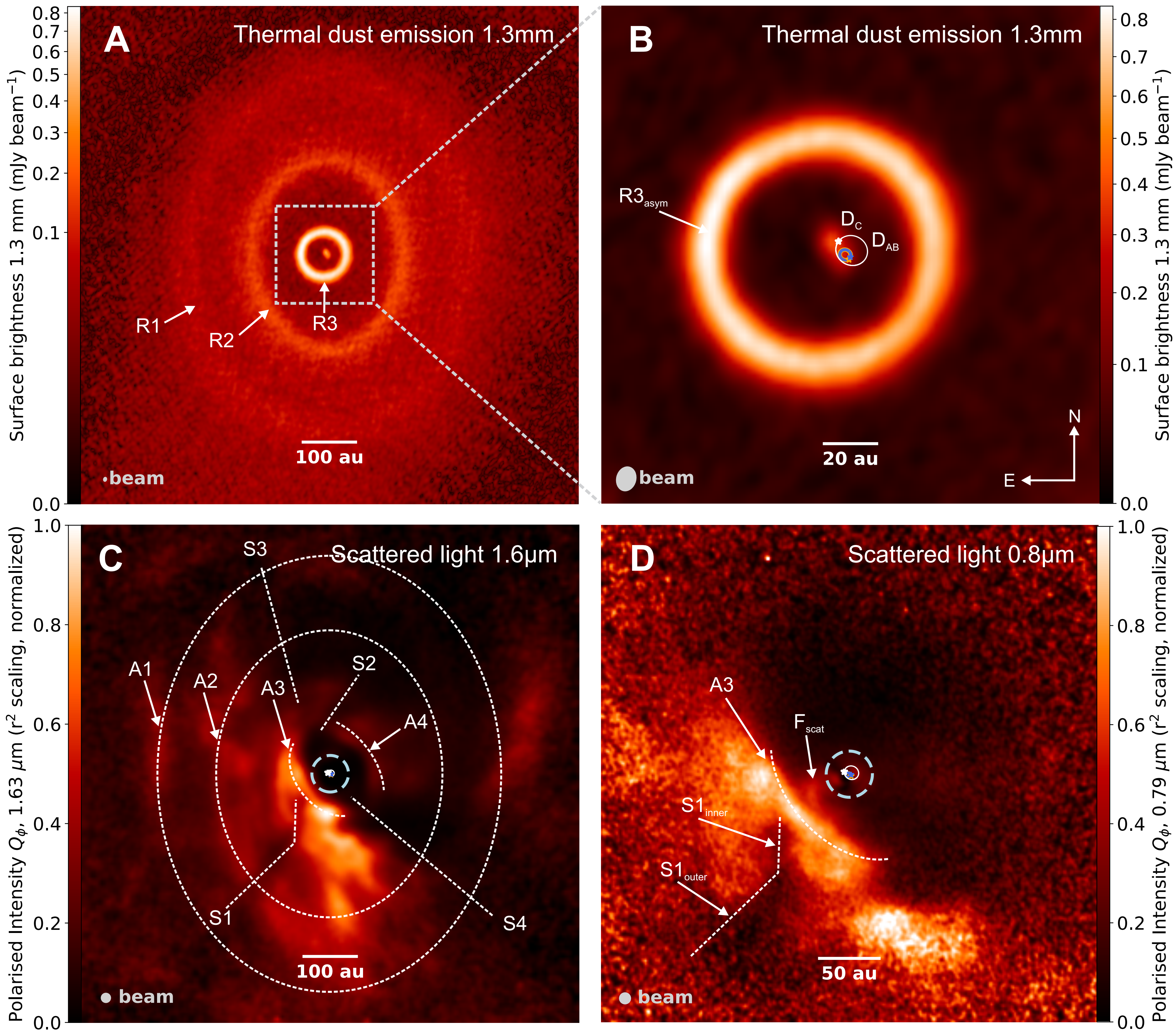
Nixon, King & Price (2013), Facchini, Lodato & Price (2013)



Viscous torque = precession torque from binary: $R_{\rm break} \lesssim 50\mu^{1/2}\,|\sin 2\theta|^{1/2}\left(\frac{H/R}{10^{-3}}\right)^{-1/2}\left(\frac{\alpha}{0.1}\right)^{-1/2} a$

2020: DISC TEARING OBSERVED IN GW ORI!

Kraus et al. (2020)



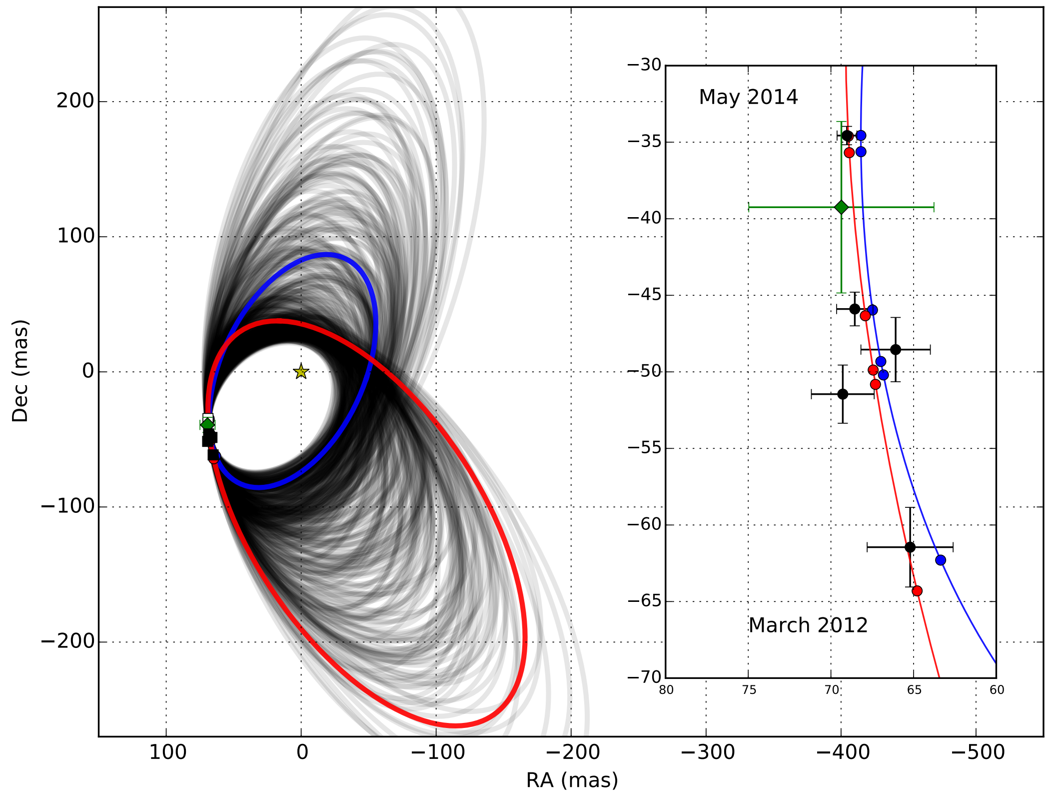
THINGS THAT NEED EXPLAINING IN HD142527

- Shadows
- Fast radial flows
- Spiral arms
- Central cavity
- Dust horseshoe
- Gap-crossing filaments
- Accretion of gas at “normal rates” through cavity
- Warp/inclined inner disc?
- Highly variable accretion rate

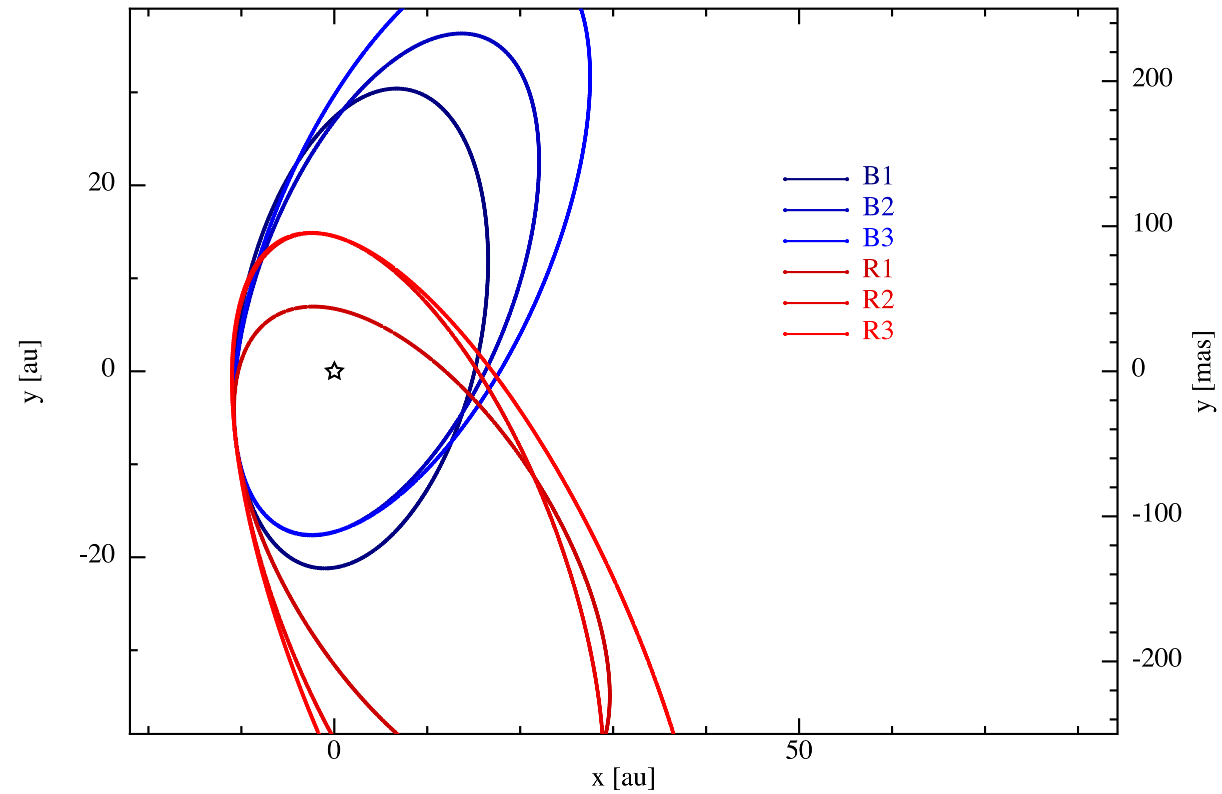
Understanding HD142527 could help to understand all the various features seen in transition discs!

MODELLING HD142527

Price et al. (2018)



Lacour et al. (2016)

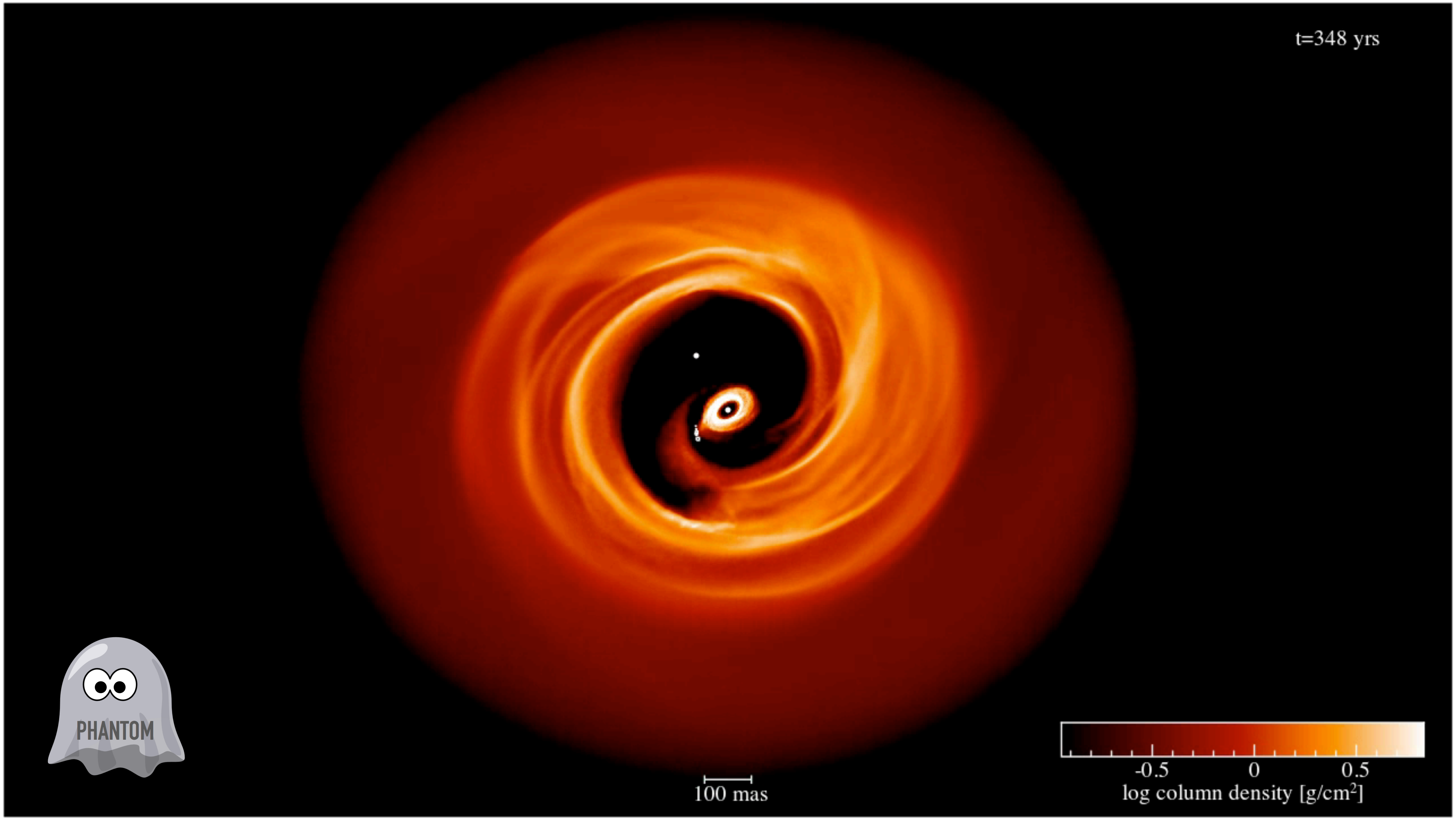


Orbital arc fits using IMORBEL (Pearce, Kennedy & Wyatt 2015)

	a	e	i	Ω	ω	f
Orbit B1	26.5	0.24	119.9	349.7	218.0	25.93
Orbit B2	28.8	0.40	120.4	340.3	201.5	33.78
Orbit B3	34.3	0.50	119.3	159.2	19.98	35.04
Orbit R1	31.4	0.74	131.3	44.95	27.88	249.3
Orbit R2	38.9	0.61	120.3	19.25	354.0	268.3
Orbit R3	51.3	0.70	119.3	201.4	173.3	270.4

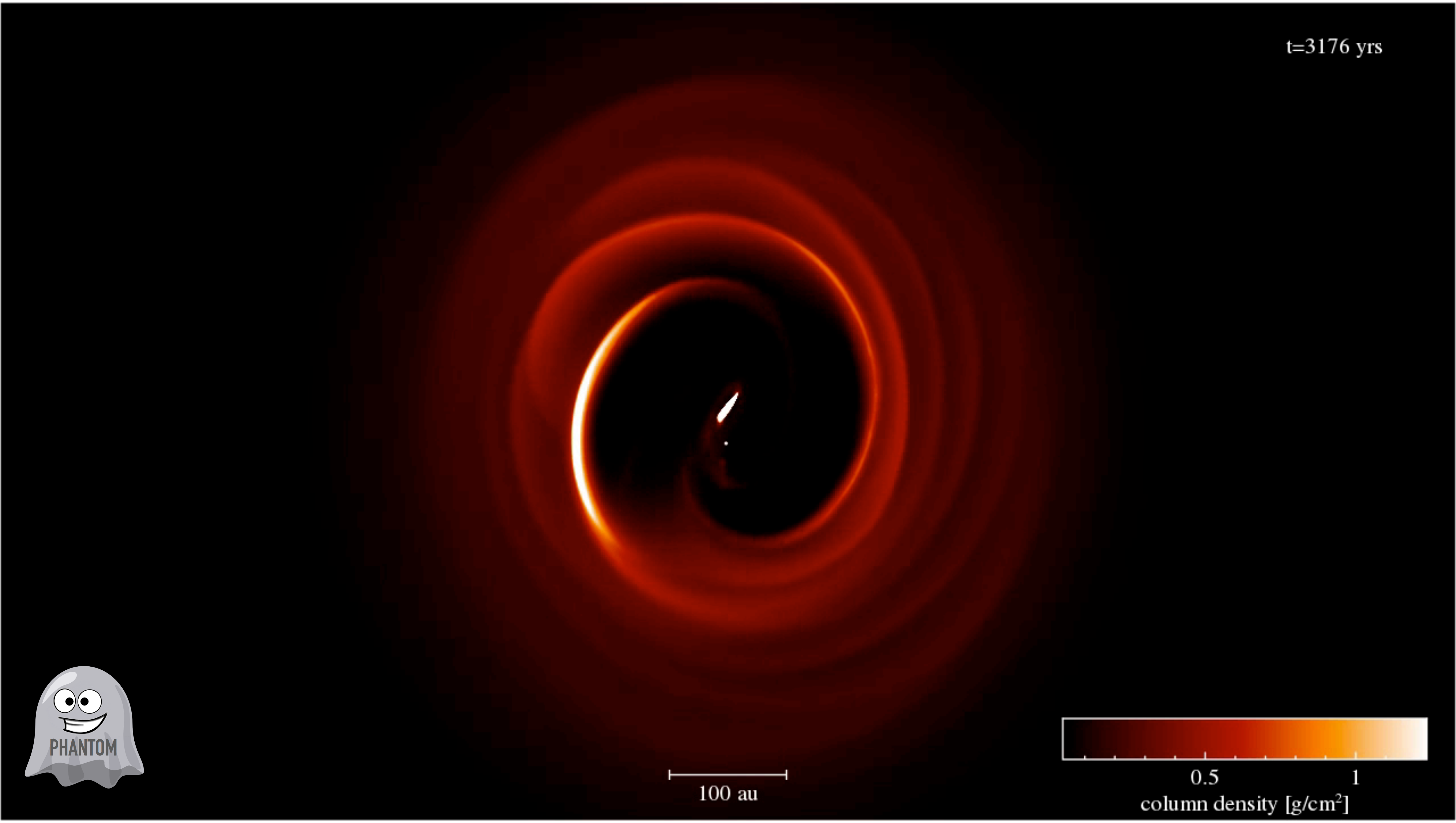
BLUE ORBIT

Price et al. (2018)



RED ORBIT

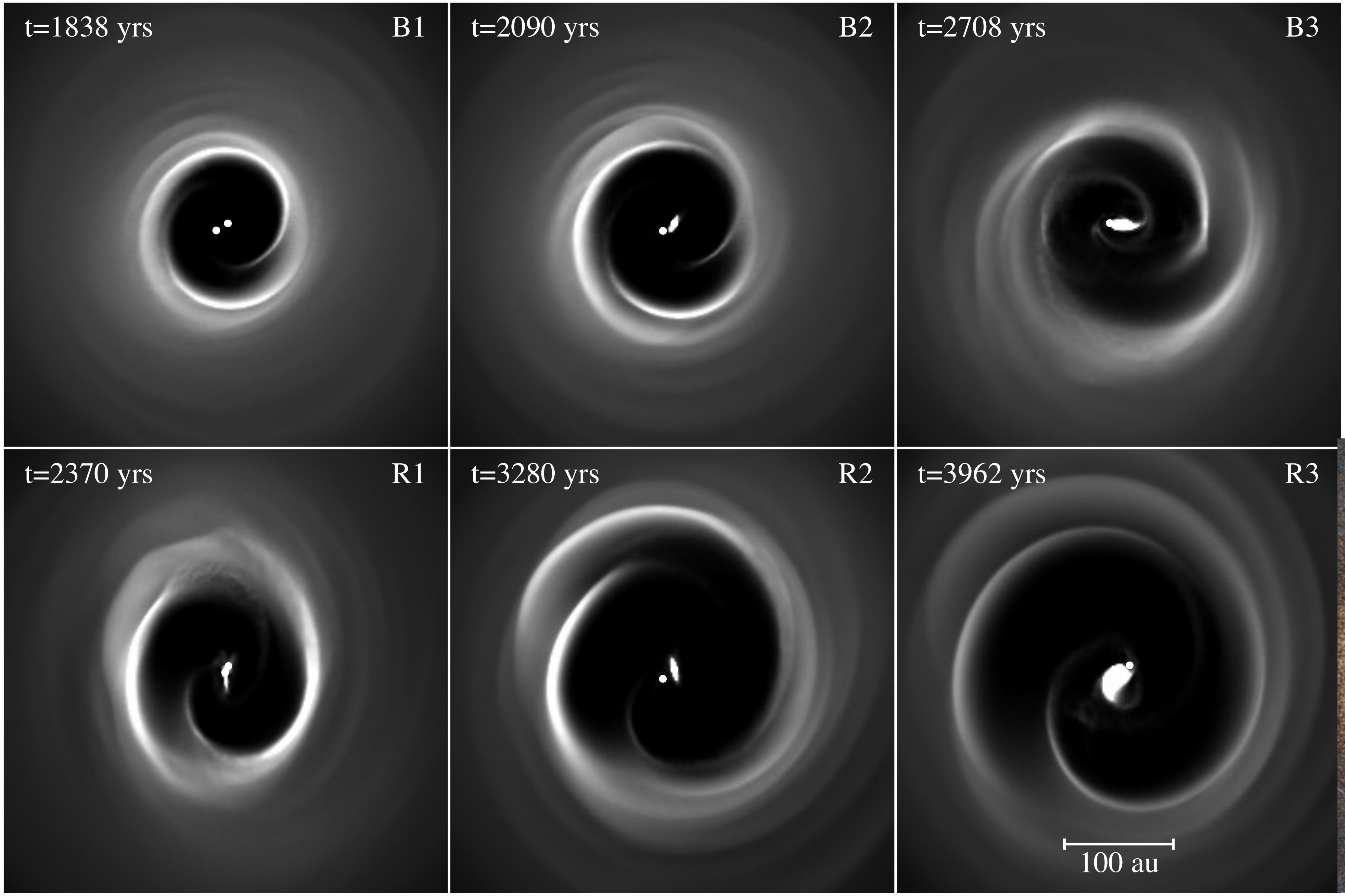
Price et al. (2018)

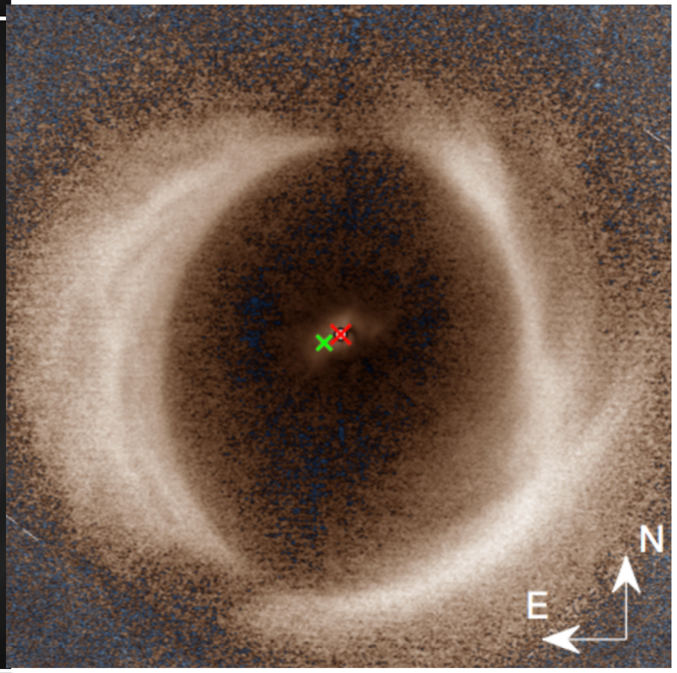


See almost polar alignment of binary to disc, c.f. Aly et al. (2015), Martin & Lubow (2017)

SPIRALS

See also Ogilvie & Lubow (2002), Rafikov (2002), Fung & Dong (2015)



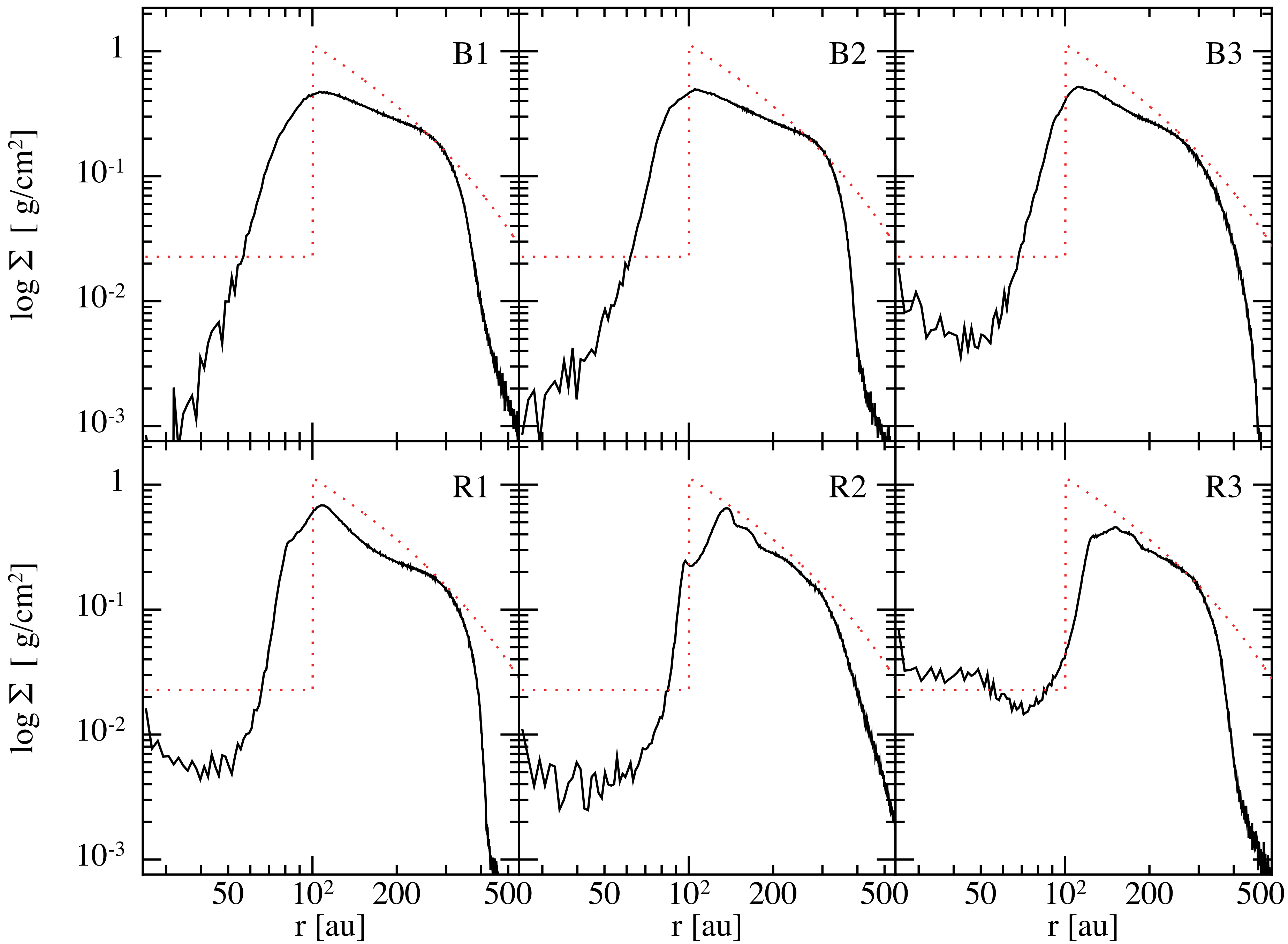


Price et al. (2018)

Binary must be on RED orbit!

CAVITY SIZE *Perez+(2015)*

an axisymmetric disk. The total mass of gas surviving inside the cavity is high $(1.7 \pm 0.6) \times 10^{-3}\ M_{\odot}$.

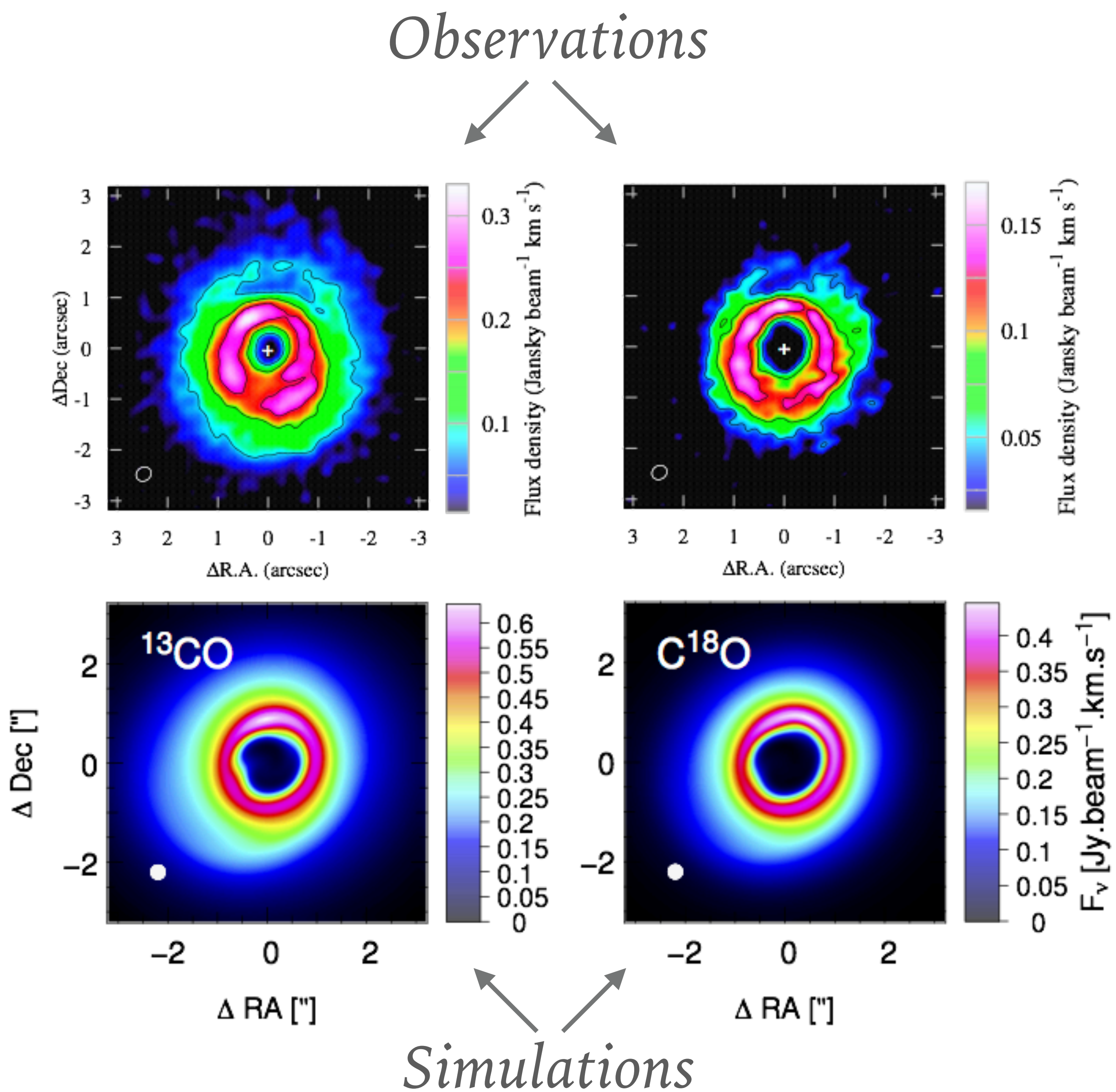


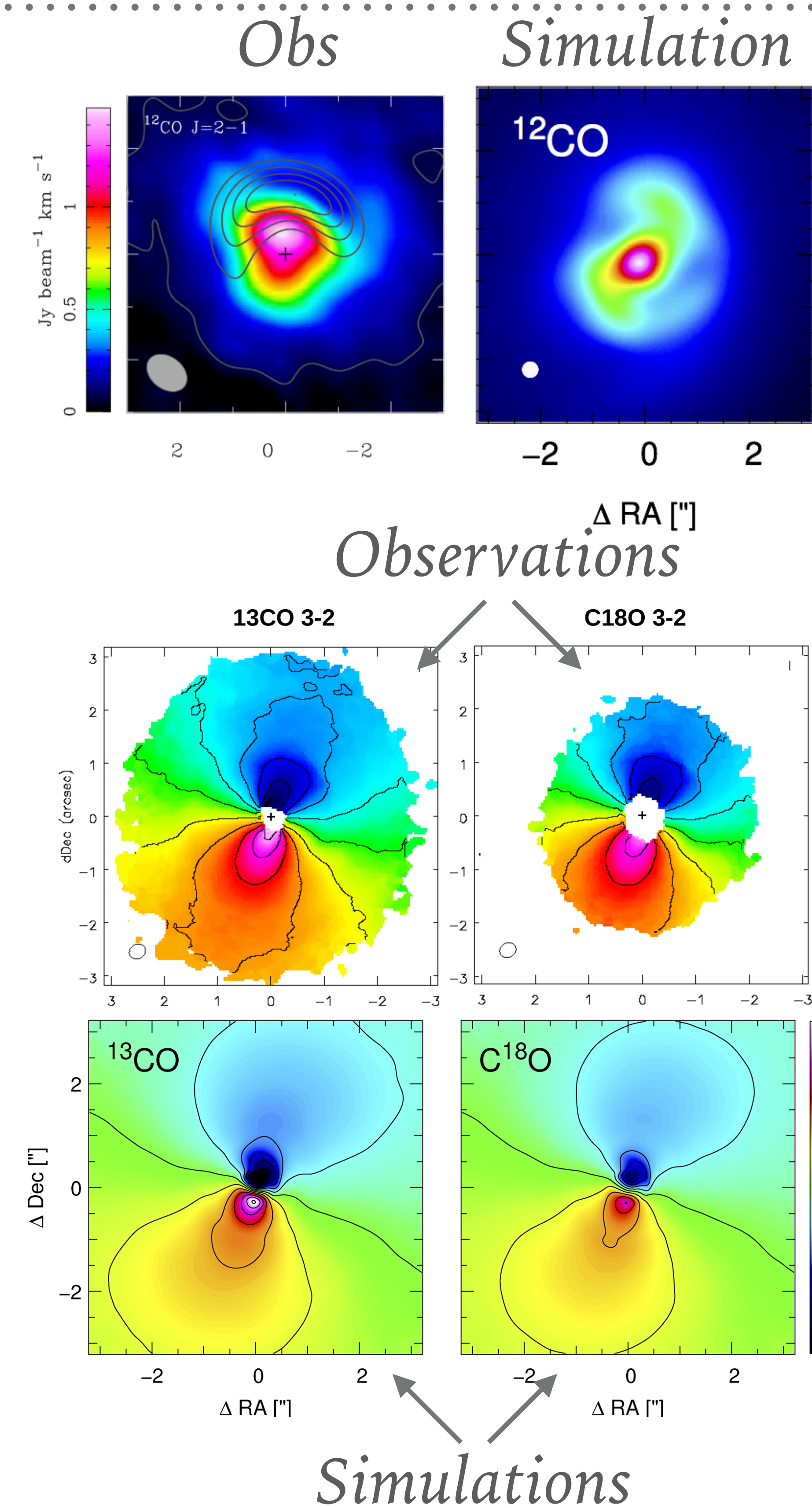
Mass inside the cavity:

Disc	M<90 au
B1	2×10^{-3}
B2	1.9×10^{-3}
B3	1.6×10^{-3}
R1	2.1×10^{-3}
R2	1.5×10^{-3}
R3	1.4×10^{-3}

Red = Best fit model used in Perez + (2015) to fit the observed data!

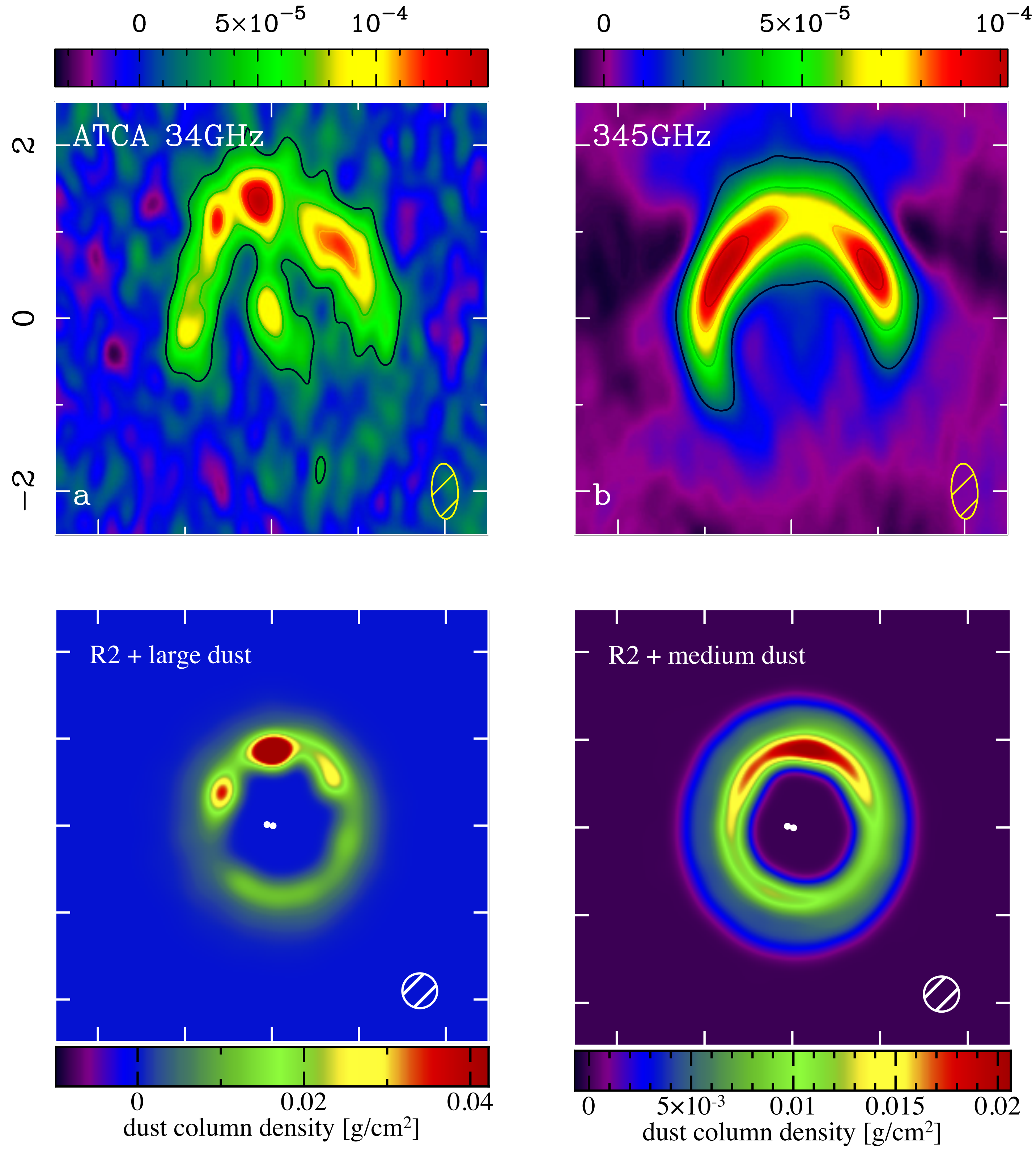
CO EMISSION + KINEMATICS (USING MCFOST, PINTE ET AL. 2006)





Explains why inner holes are dust-free!
e.g. Dominik & Dullemond (2011)

HORSESHOE

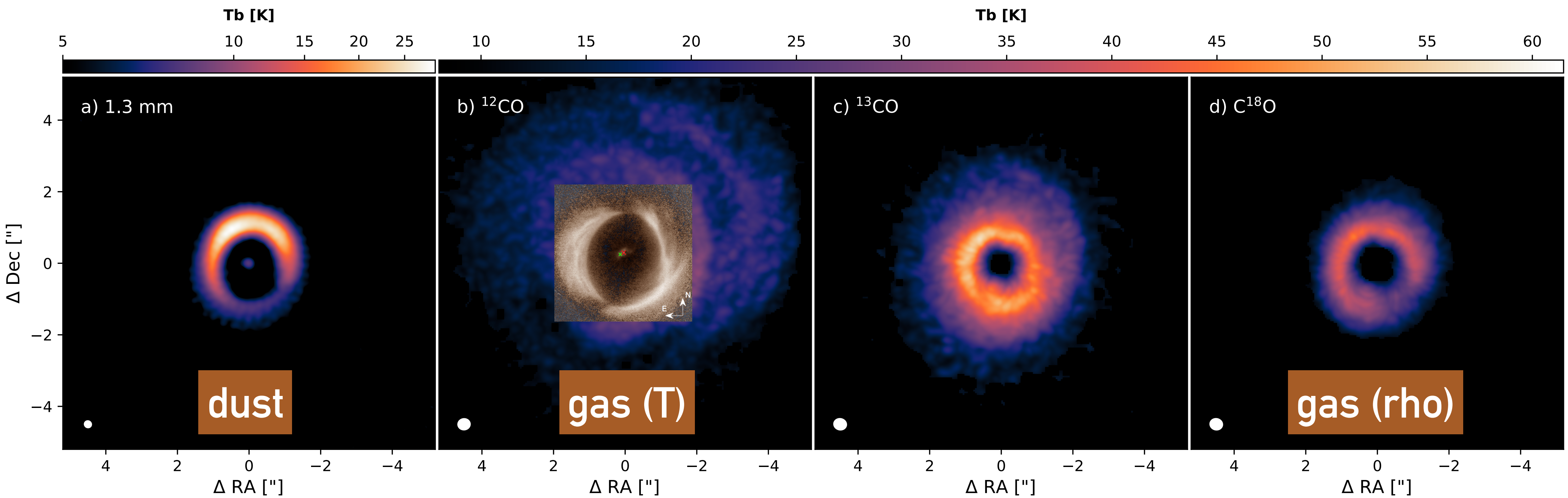


Observations

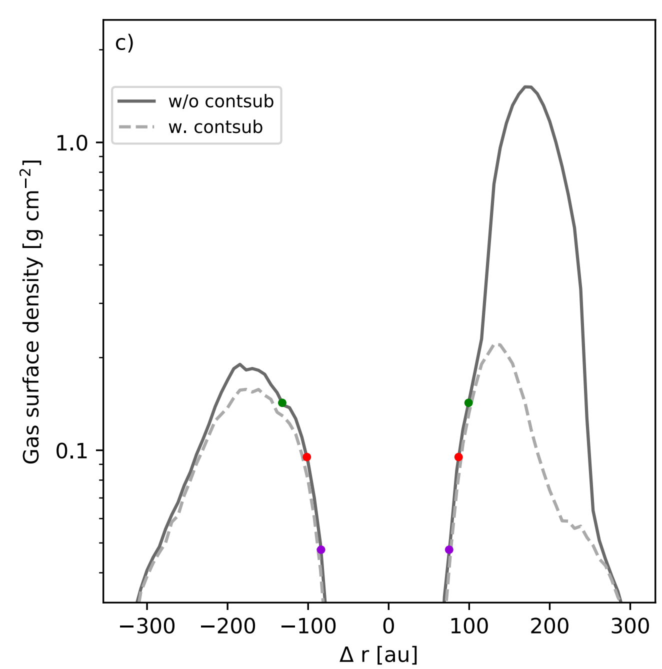
Simulations

IS THIS THE HOLE STORY?

Garg et al. (2021); fresh ALMA data



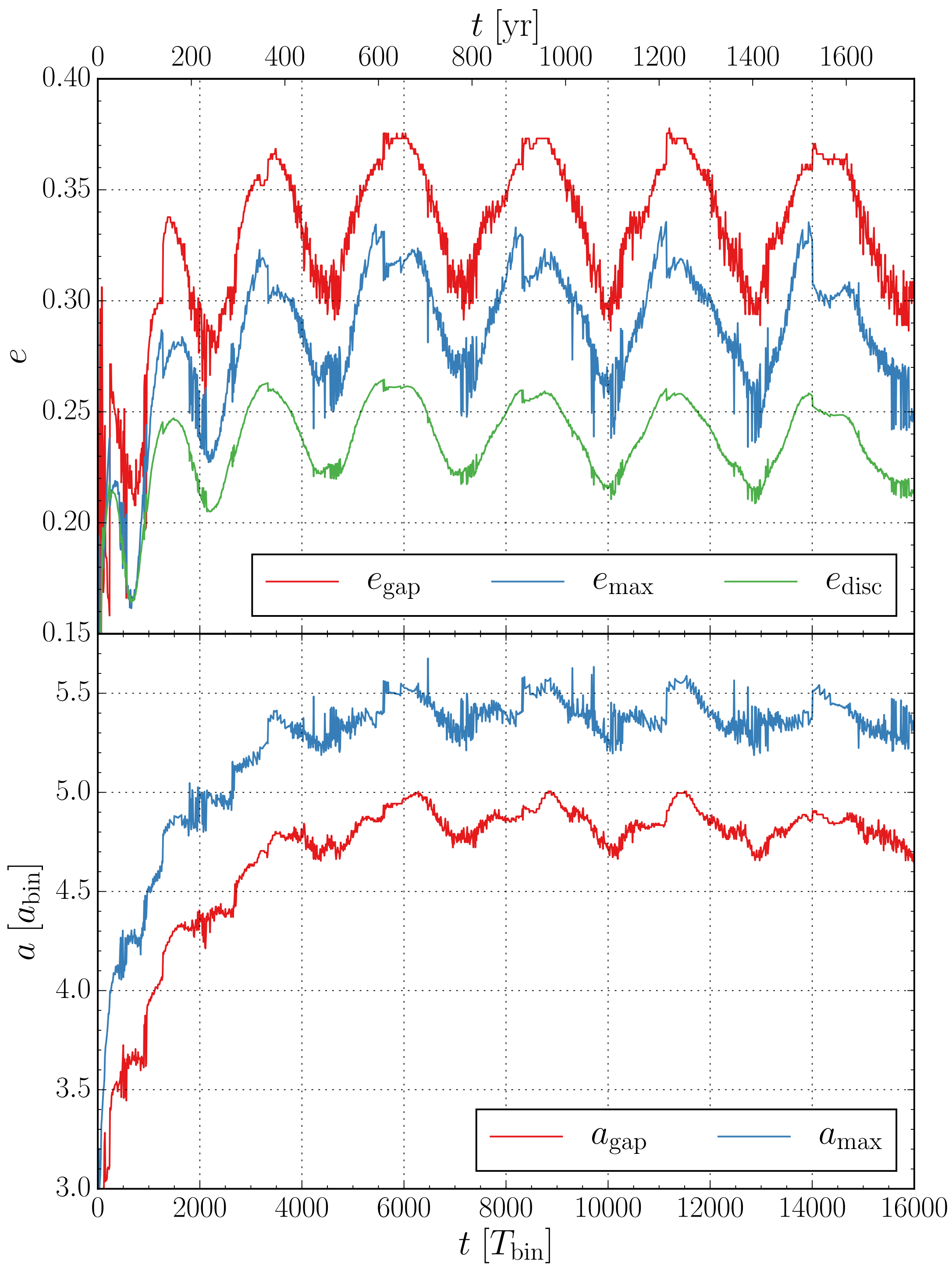
- Surface density maximum is ~100 au
- BUT precise tracking of the orbit with VLTI/GRAVITY indicates a~11 au, e~0.46 (Nowak+ priv. commun.)
- Discrepancy with binary-disc theory? (rcav=2-3 a; Artymowicz & Lubow 1994)



Can reconstruct gas surface density profile

CAVITY SIZE IN CIRCUMBINARY DISCS

Thun+2017



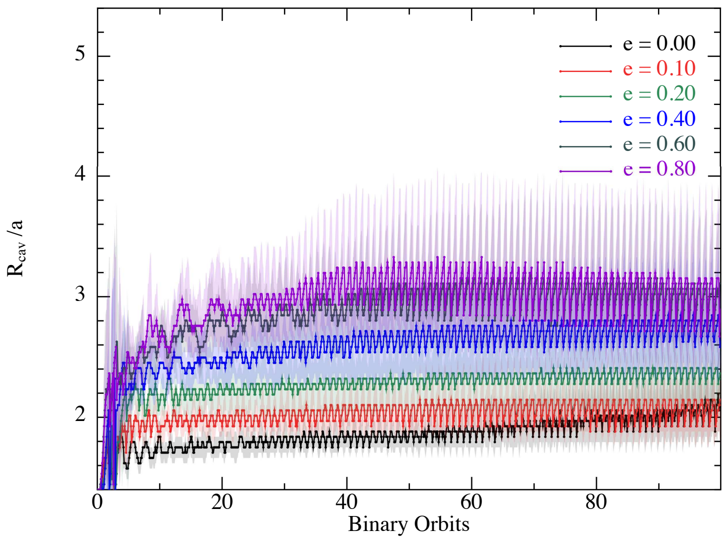
r_{cav} up to 5 times binary semi-major axis over long timescales?

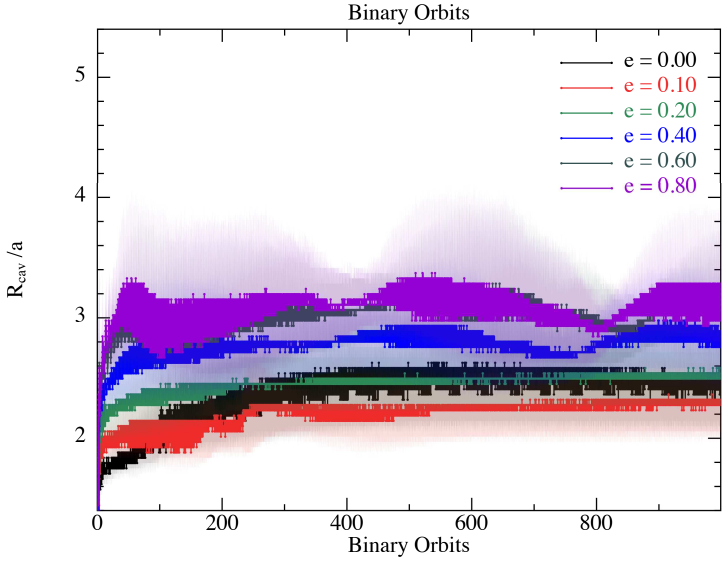
But may depend on inner boundary condition, get artificially large cavities if Rin > a? (Mutter+2017, Pierens+2020)

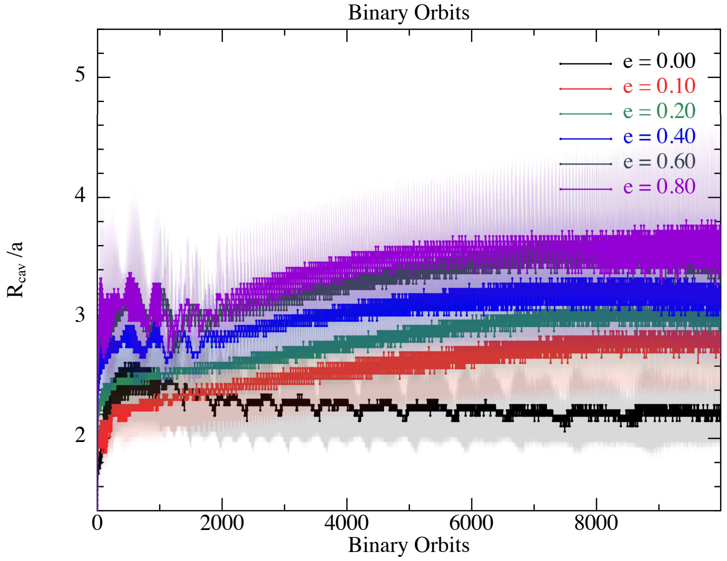
Can we solve this in KITP code comparison?

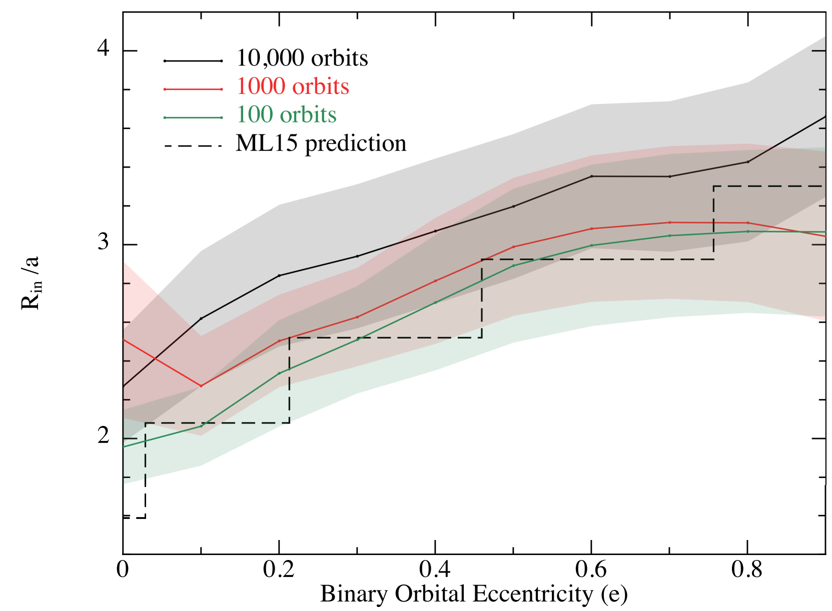
CAVITY SIZE IN CIRCUMBINARY DISCS

Hirsh+2020

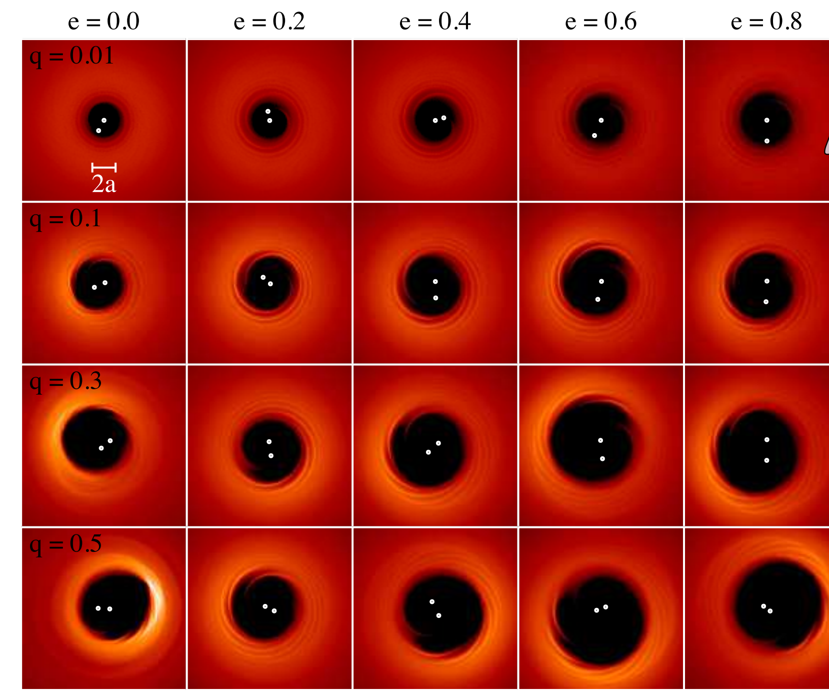




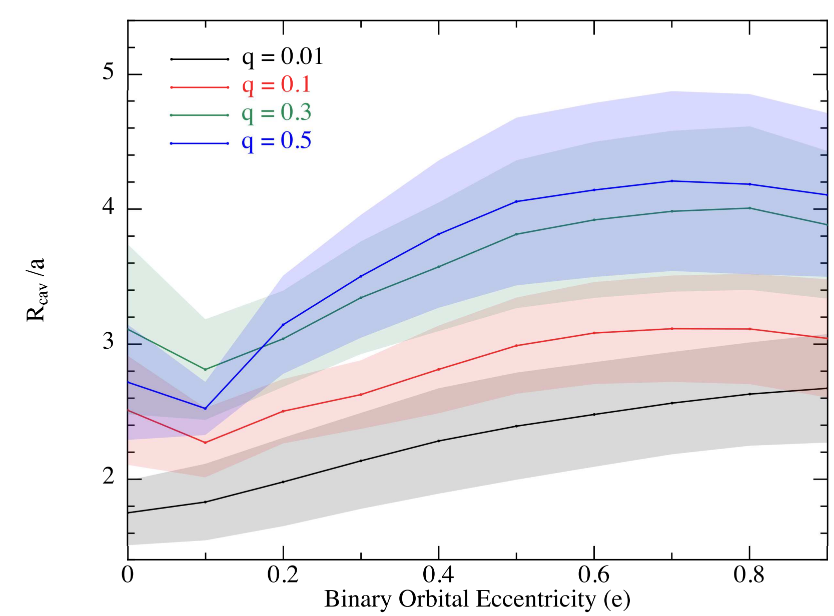




Matches analytic predictions from AL94 and Miranda & Lai (2015)



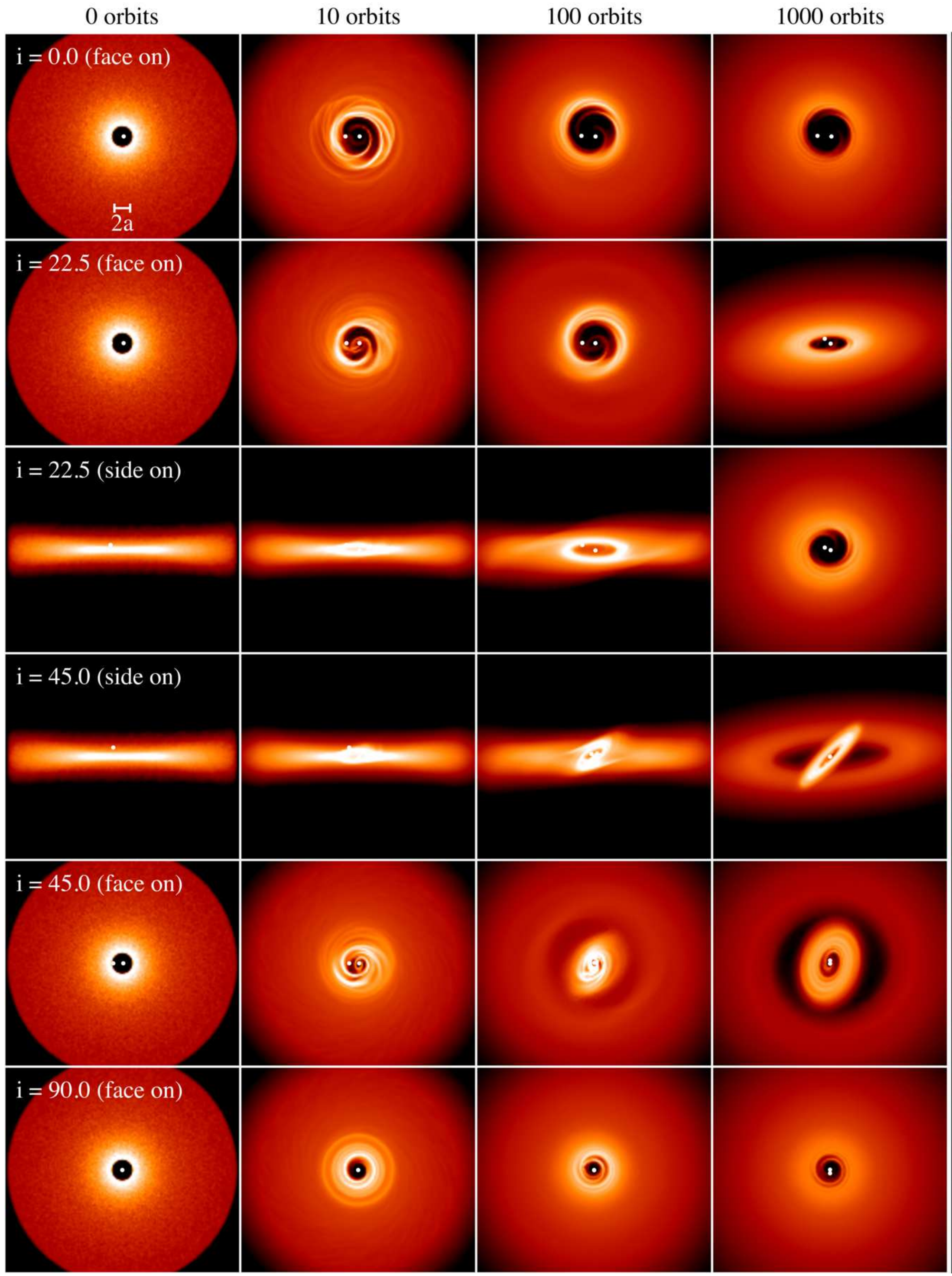
Largest cavities for equal mass, eccentric binary in low H/R disc, but r/a~4



Evolution of cavity size continues over long timescales (c.f. Thun+ 2017)

CAVITY SIZE IN MISALIGNED CIRCUMBINARY DISCS

Hirsh+2020

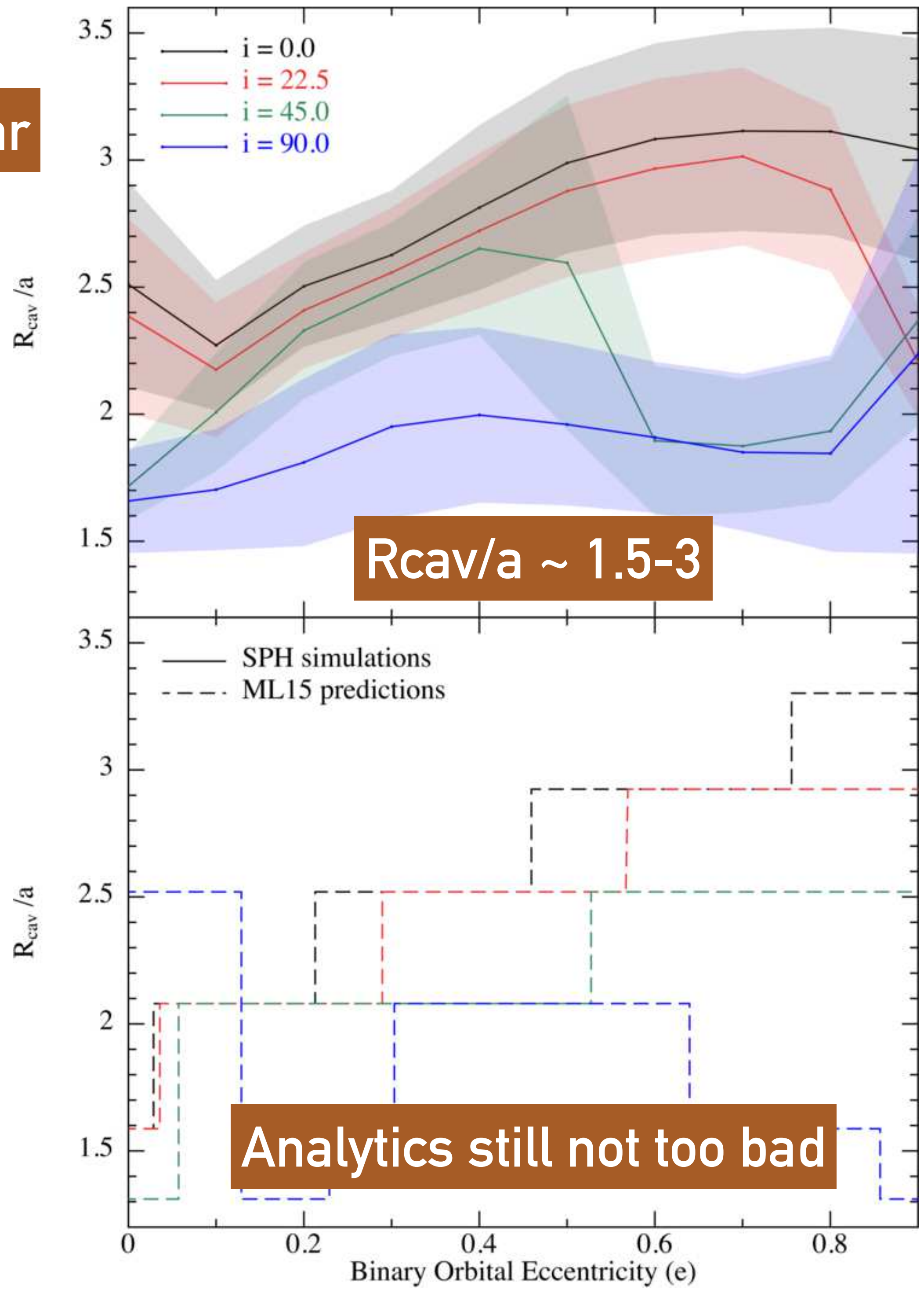


Stays coplanar

Warps and evolves to coplanar

Breaks and evolves to polar

Stays polar

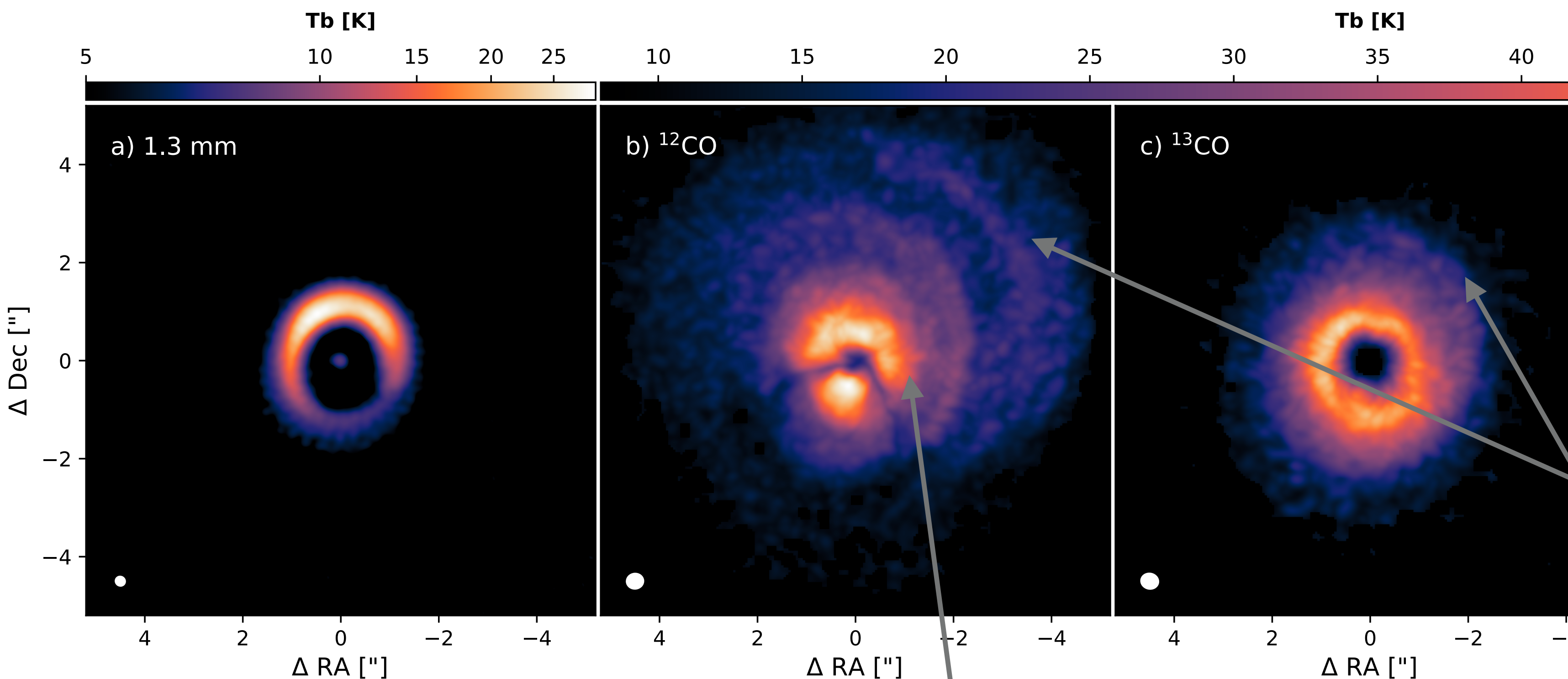


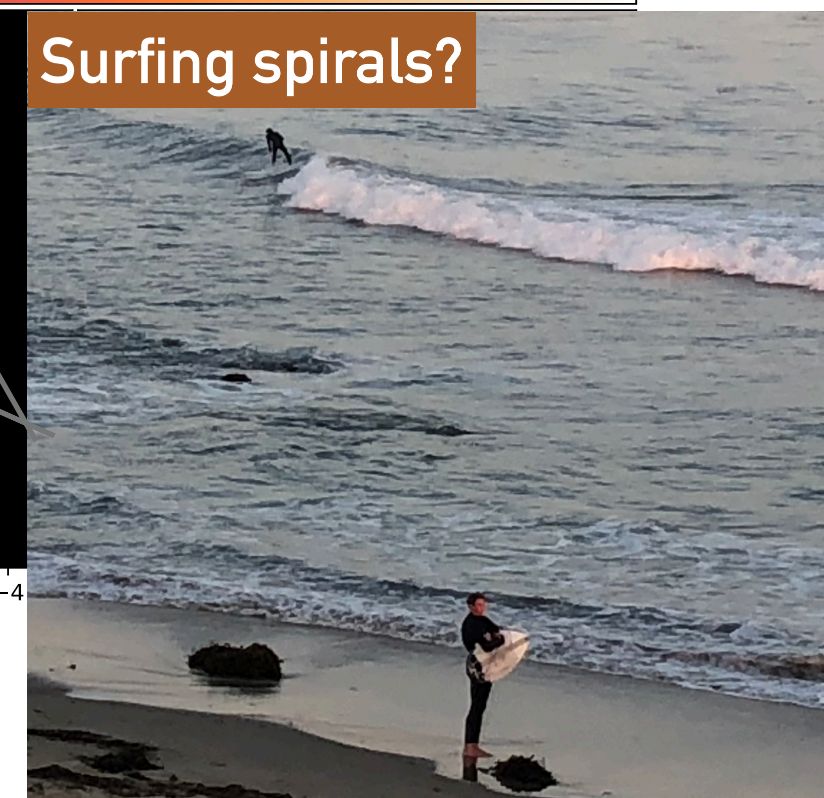
Rcav/a ~ 1.5-3

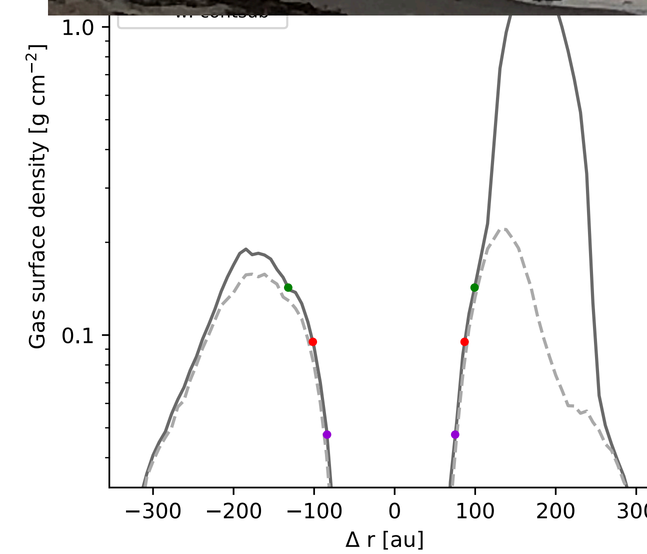
Analytics still not too bad

IS THIS THE (W)HOLE STORY?

Garg et al. (2021)



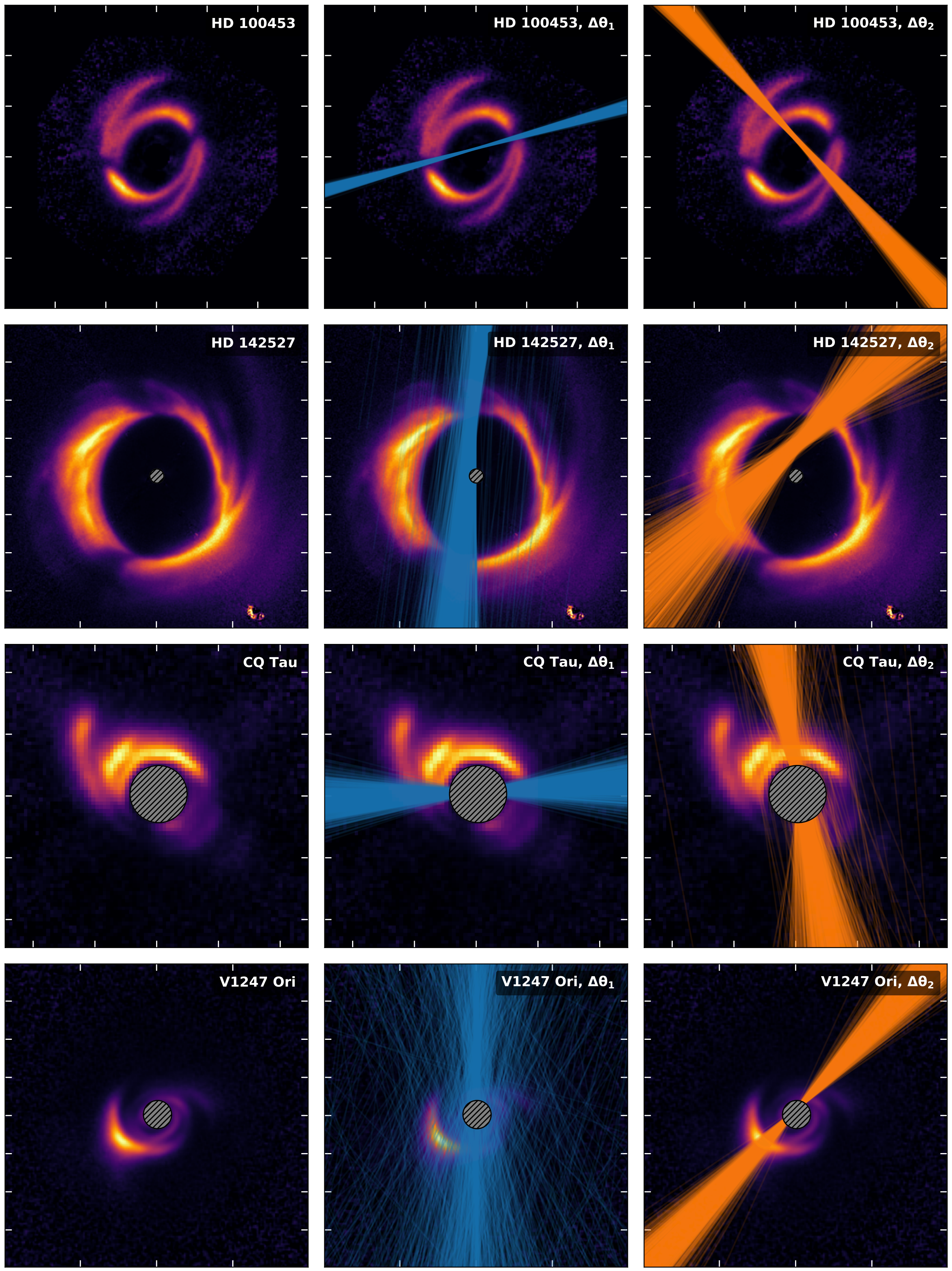




Still a possible discrepancy here if $r_{cav}/a \sim 10$!

Also difficult to explain high pitch angle spirals at such large separation from the binary - a warp (e.g. Quillen et al. 2005)? Or

ARE CIRCUMBINARY DISCS TWO DIMENSIONAL? No



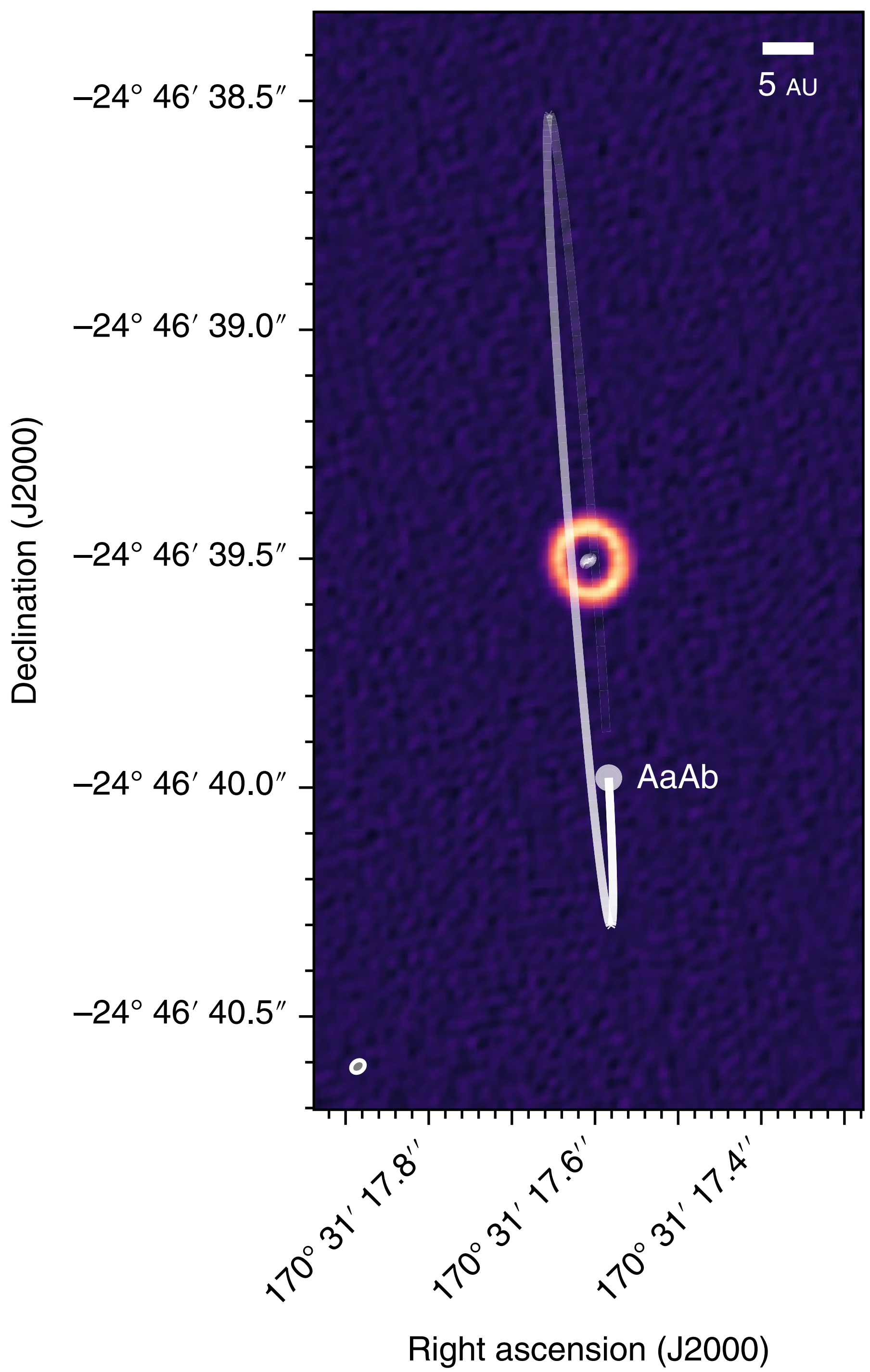
Bohn+2021 using VLTI/GRAVITY

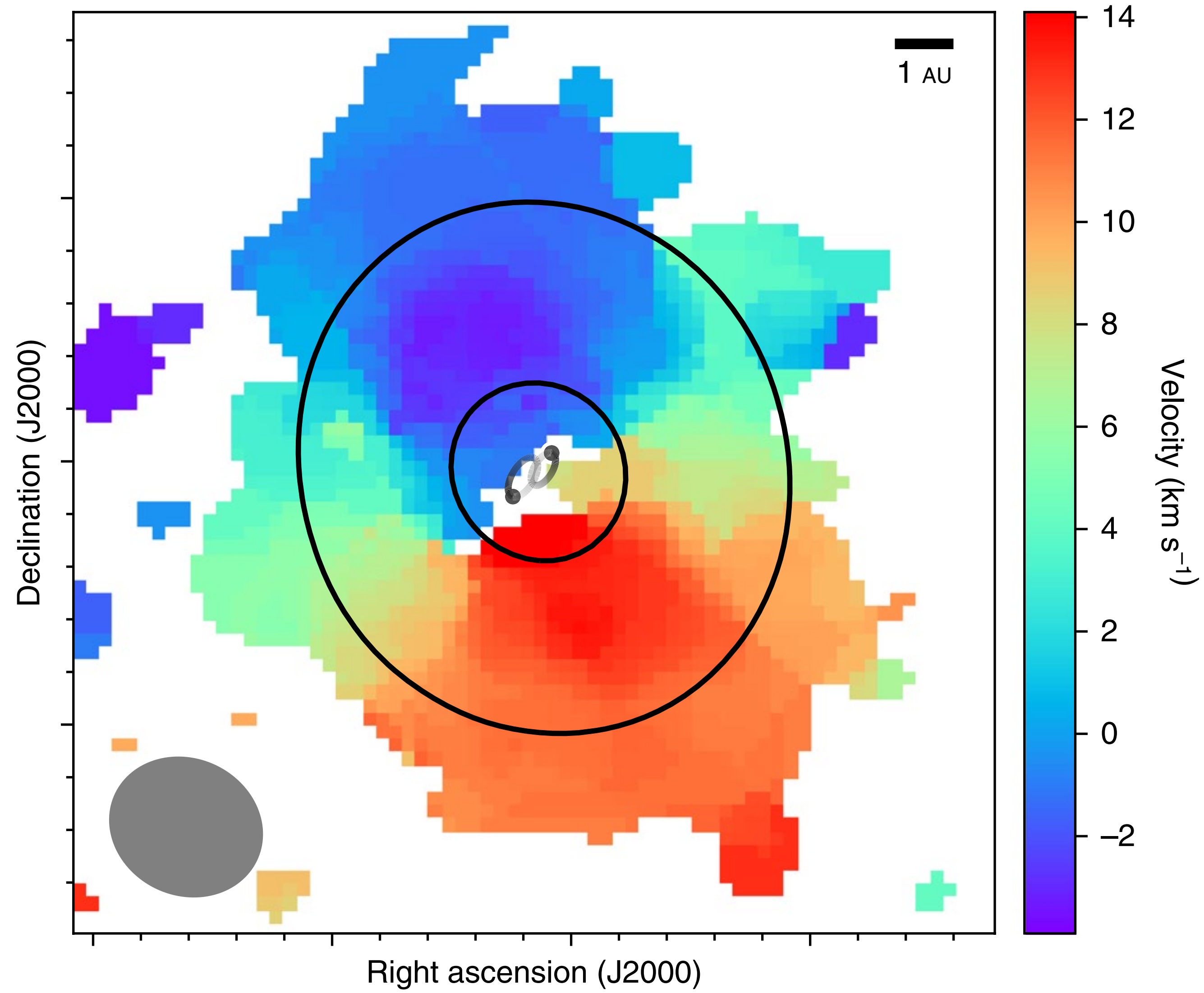
Measured inner disc misalignments match observed shadows!

Misalignment is common!

HD98800: A POLAR CIRCUMBINARY DISC

Kennedy+(2019)





Polar is alignment is expected for discs around very eccentric binaries!

Aly et al. (2015)

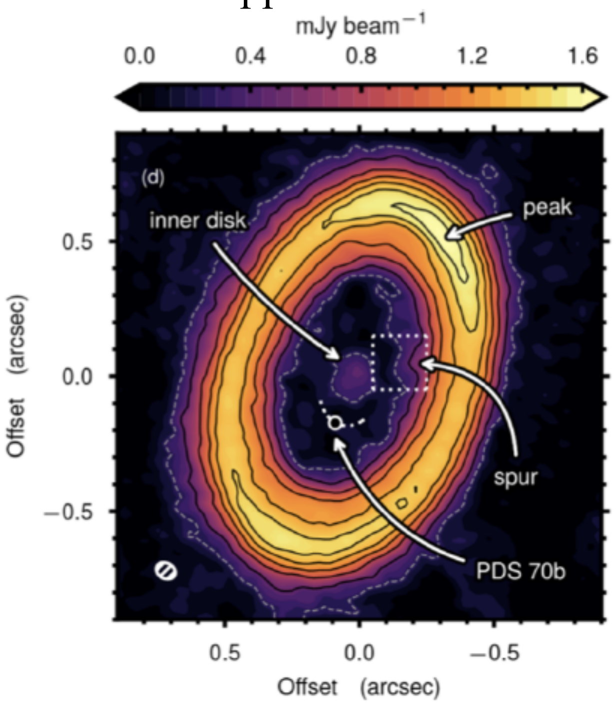
Martin & Lubow (2017,2018,2019)

FINDING THE BODIES

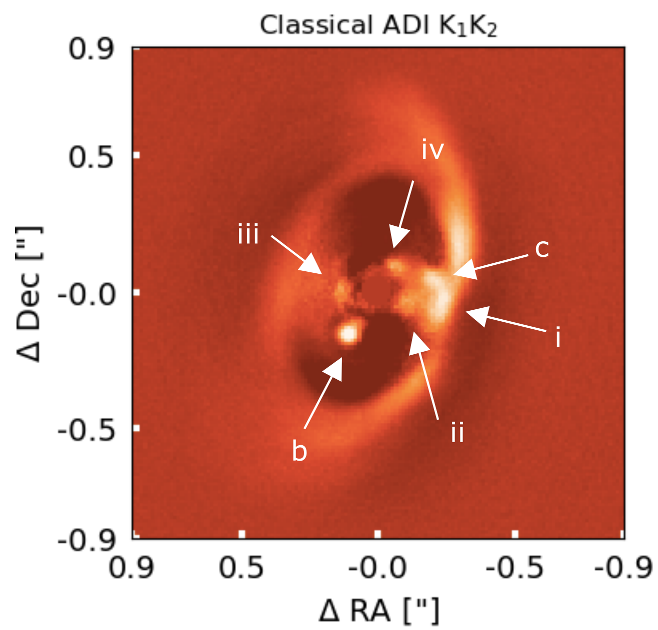
PDS70: TWO GIANT PLANETS IN CAVITY

Keppler+2018, Muller+2018, Haffert+2019, Keppler+2019

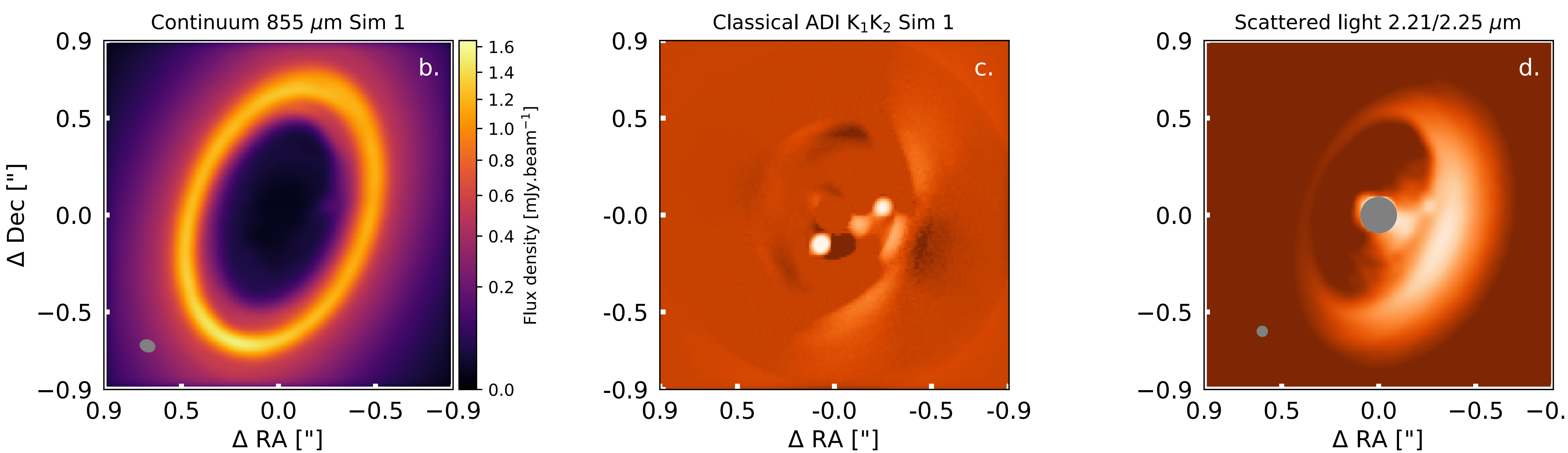
Keppler et al. 2019



Muller et al. 2018

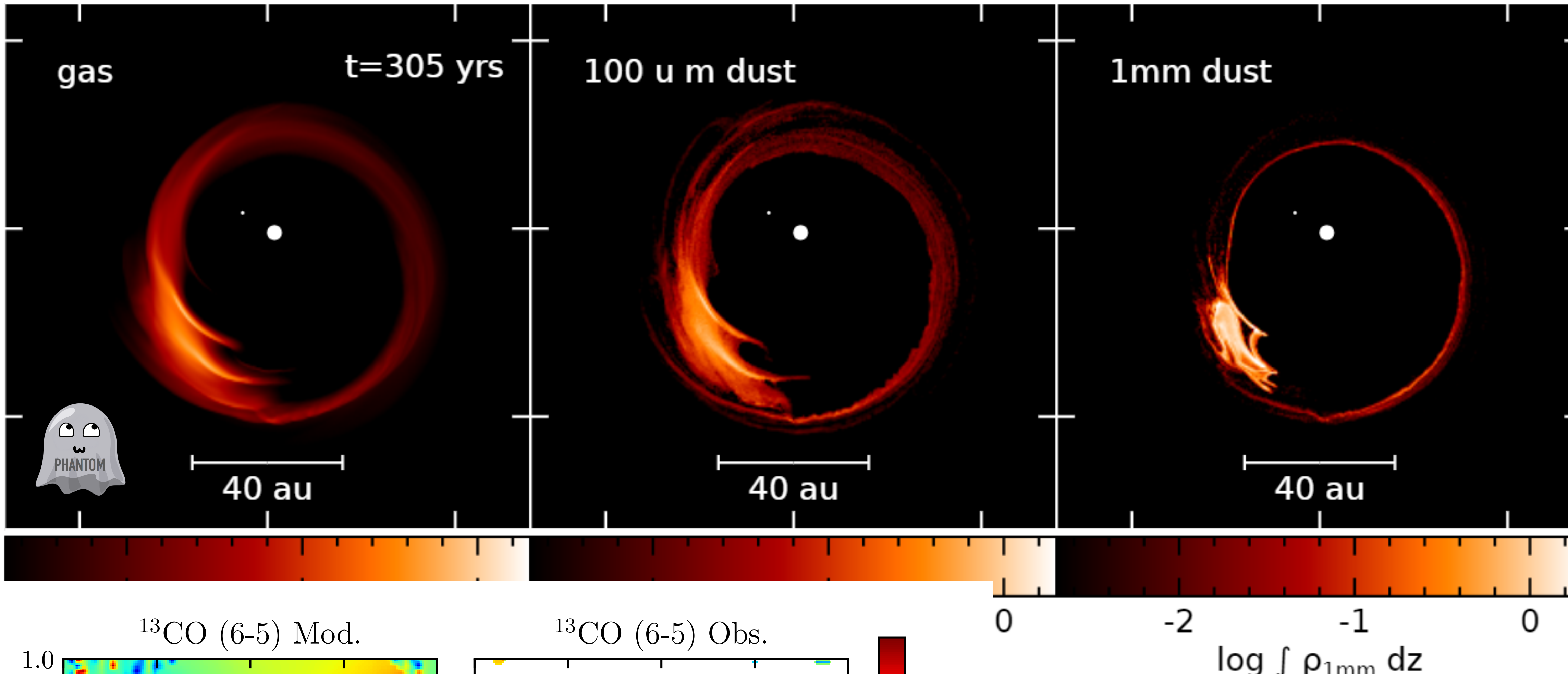


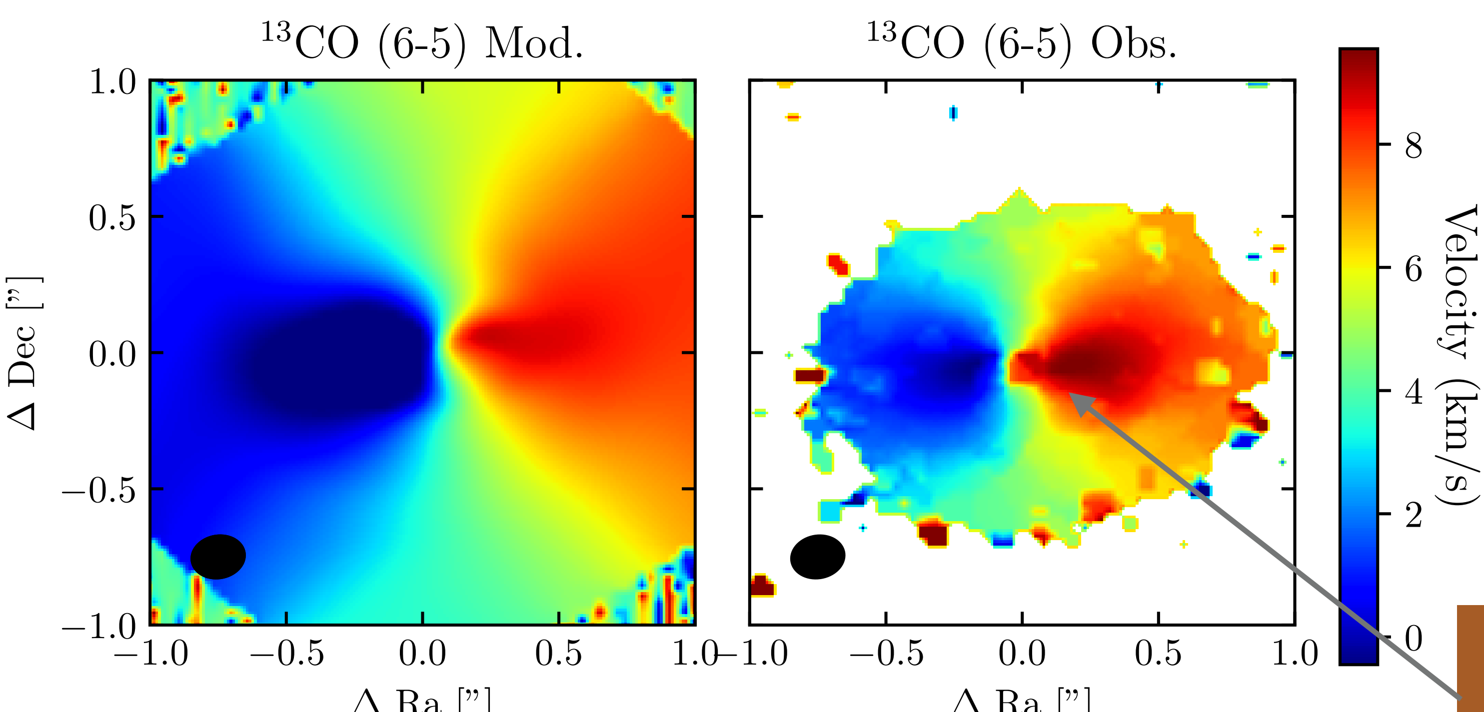
Sim1 *Toci+ (inc DP) 2020*

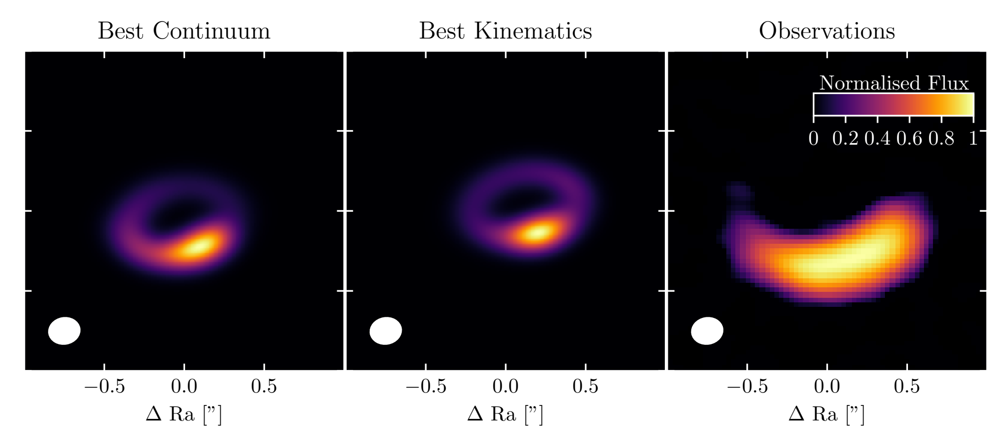


DUST AND GAS WITH A BINARY IN IRS48

Calcino+2019



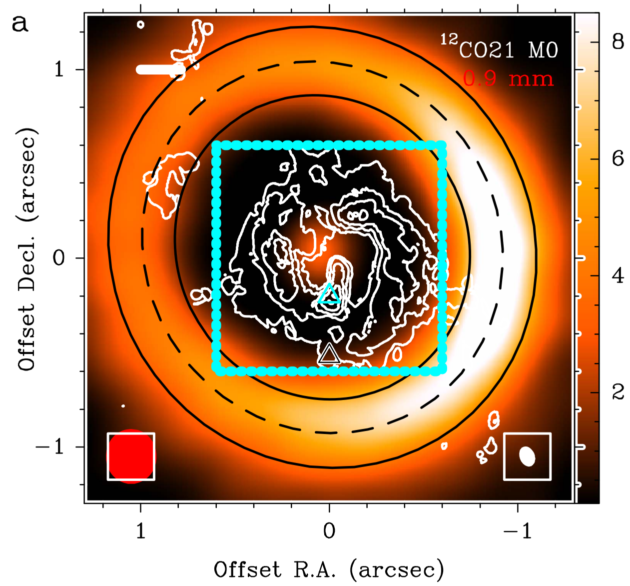


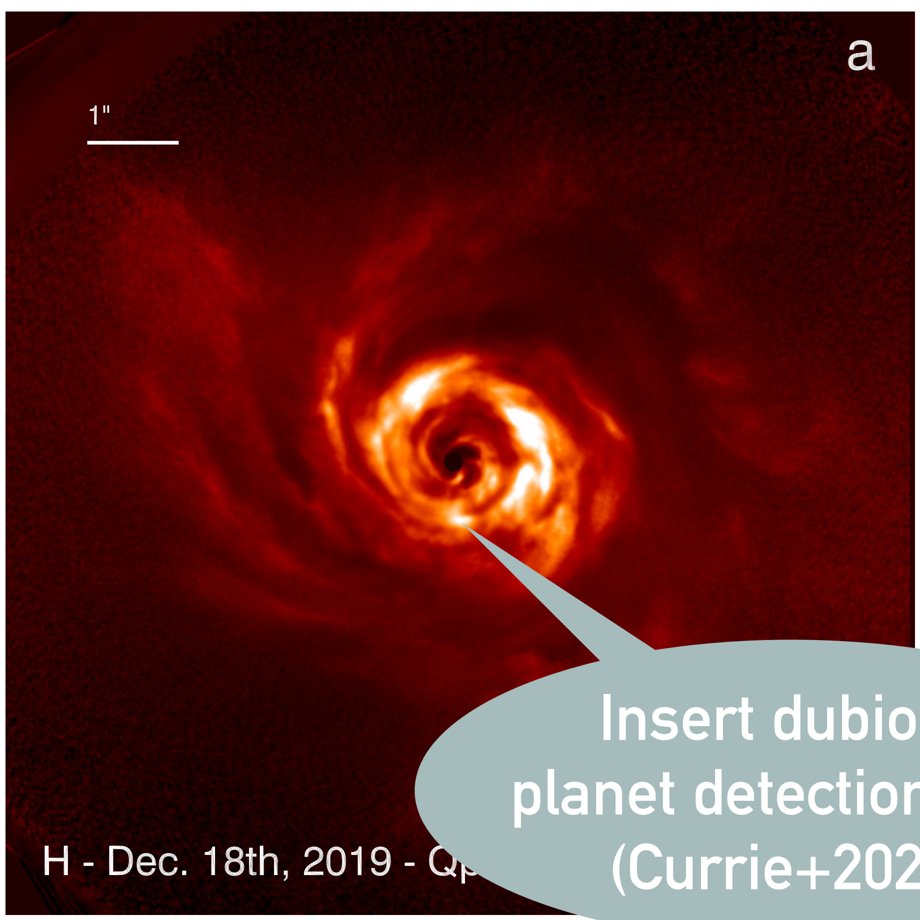


Twist in kinematics due to presence of binary companion

AB AUR: A CIRCUMBINARY DISC?

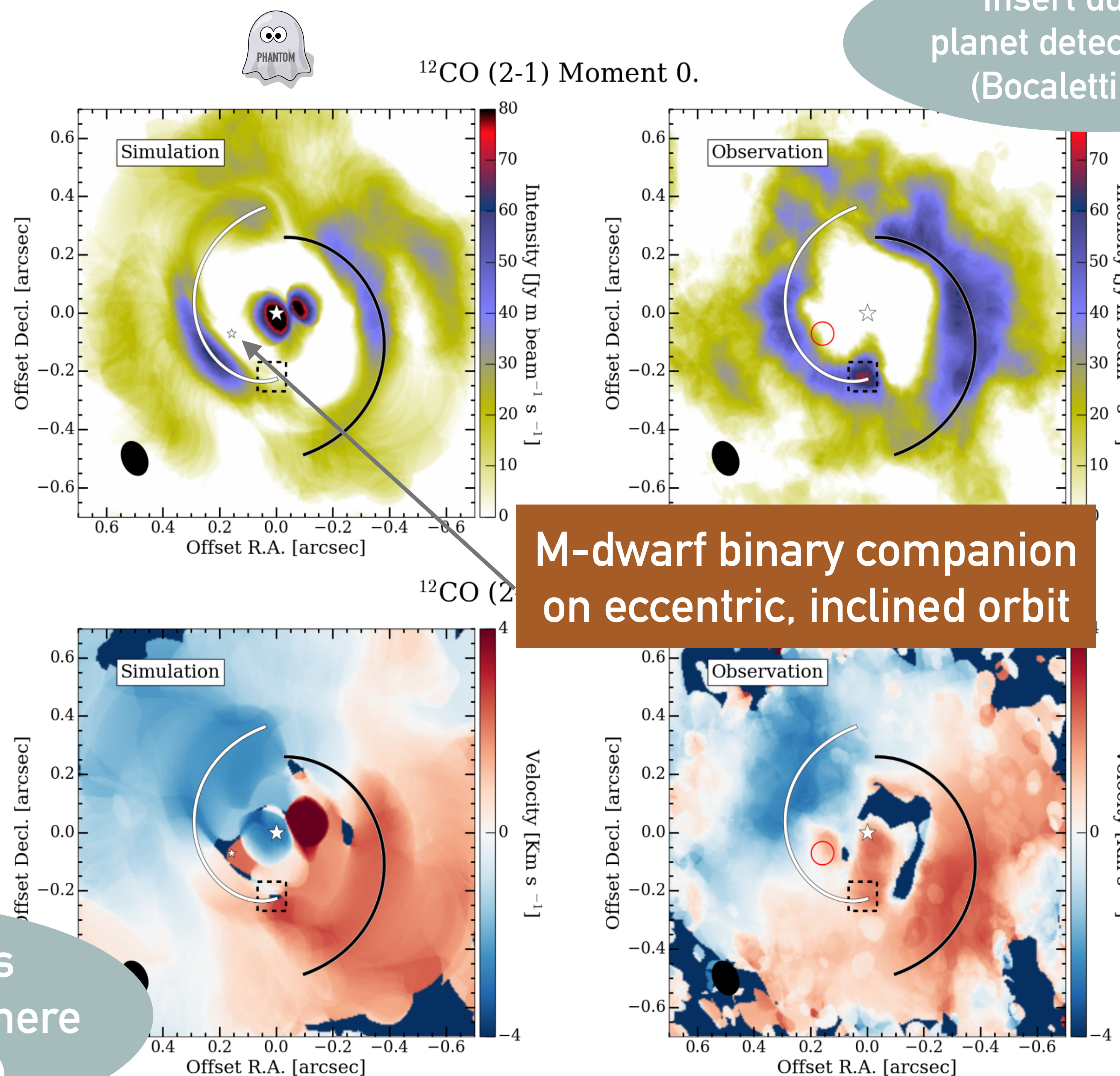
Insert dubious planet detection here (Bocaletti+2020)





Insert dubious planet detection here (Currie+2022)

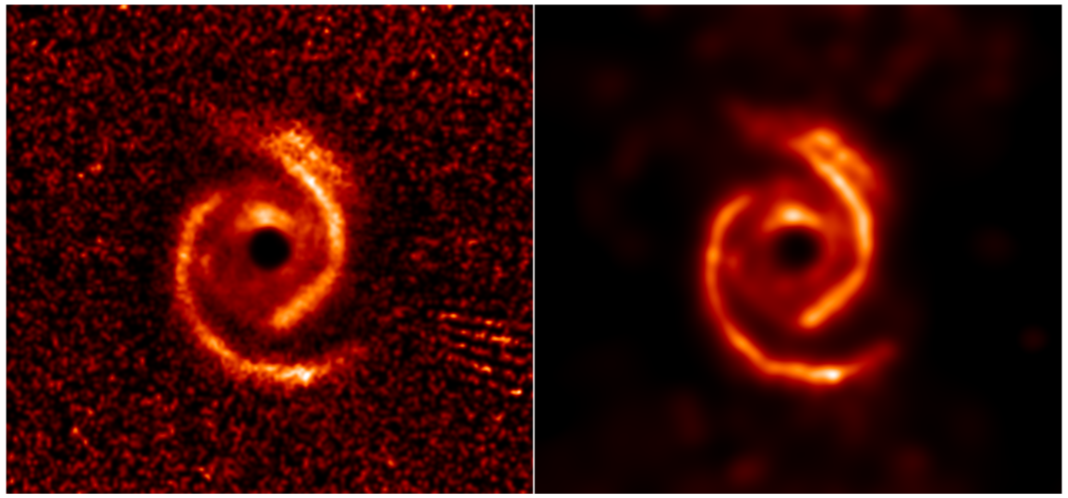
Boccaletti+2020



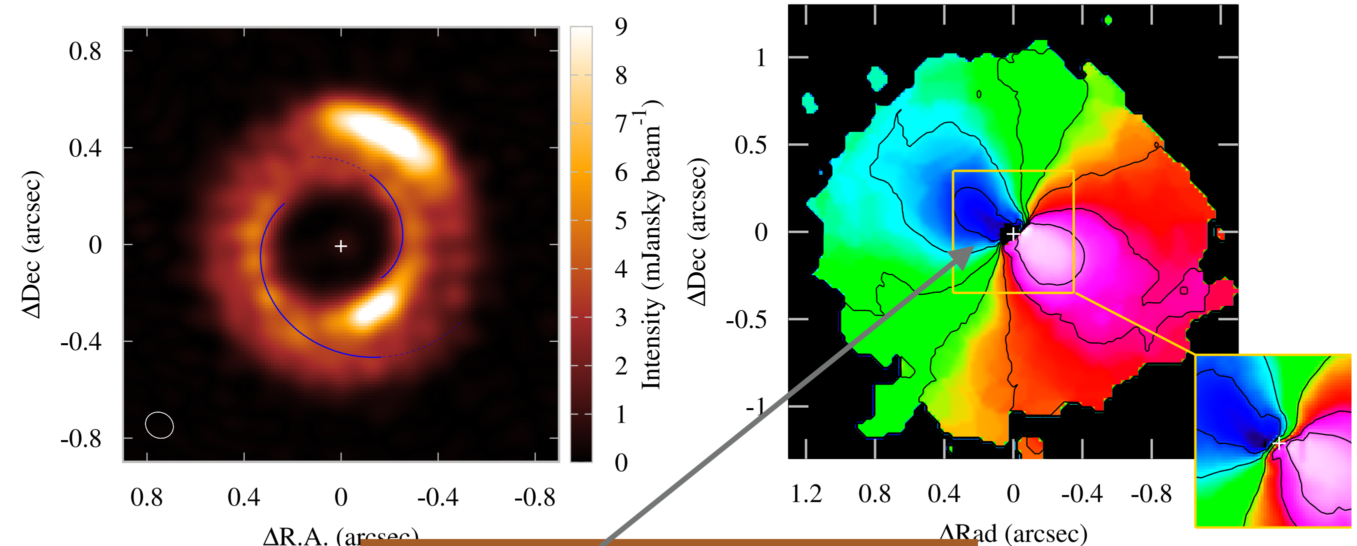
M-dwarf binary companion on eccentric, inclined orbit

Poblete+2020

MWC758: AN INNIE OR AN OUTIE?

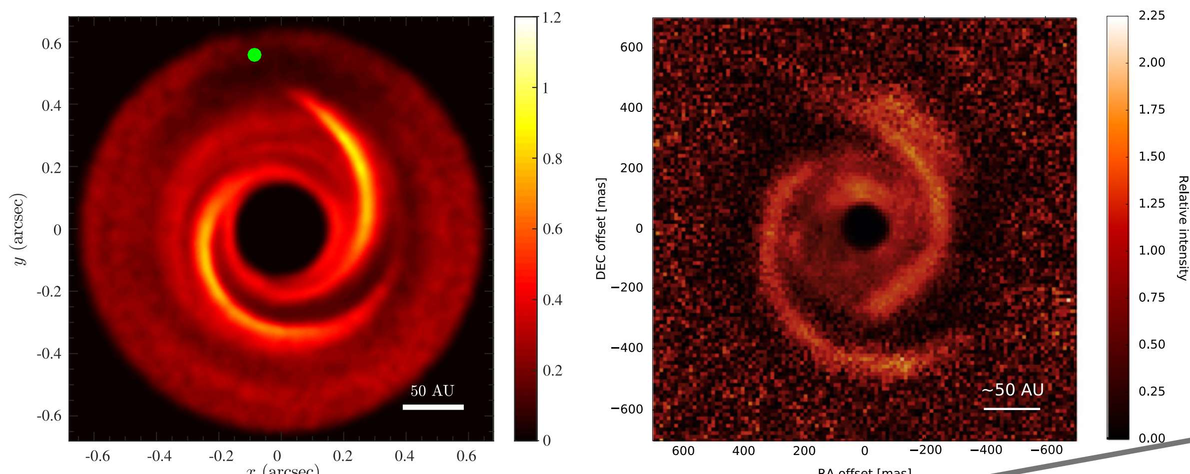


Benisty+2015



Highly non-Keplerian kinematics!

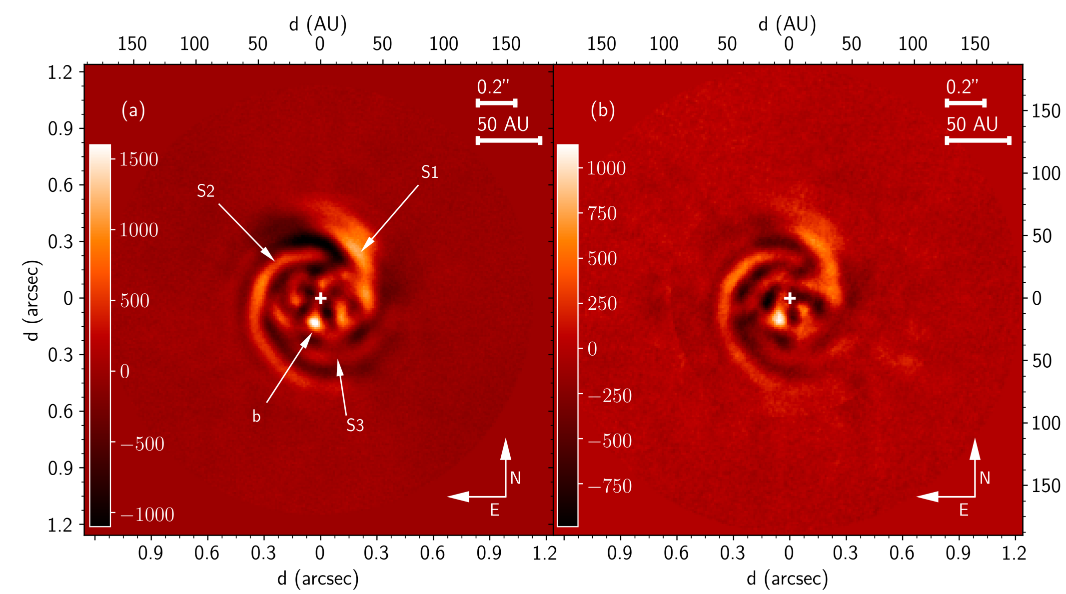
sing ALMA



Dong+2015

A Decade of MWC 758 Disk Images: Where Are the Spiral-arm-driving Planets?

Bin Ren (任彬)[1], Ruobing Dong (董若冰)[2,13], Thomas M. Esposito[3], Laurent Pueyo[4], John H. Debes[4], Charles A. Poteet[4], Élodie Choquet[5,6,14], Myriam Benisty[7,8], Eugene Chiang[9,10], Carol A. Grady[11], Dean C. Hines[4], Glenn Schneider[12], and Rémi Soummer[4]

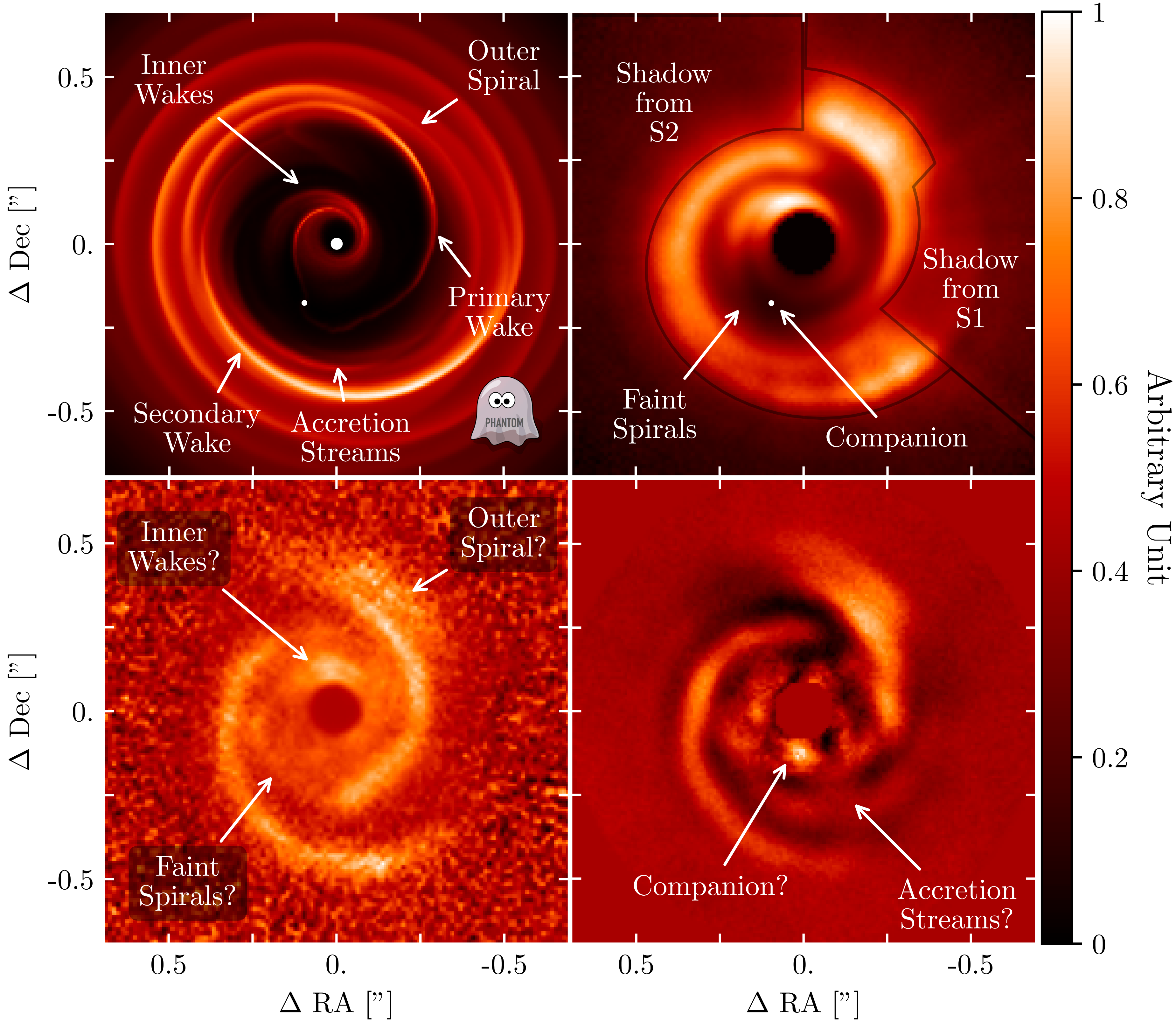


Reggiani+2018, using ADI

See also Isella+2008, 2010, Grady+2013, Marino+2015, Boehler+18, Huelamo+2018, Baruteau+2019, Wagner+2019

MWC758

Calcino+2020



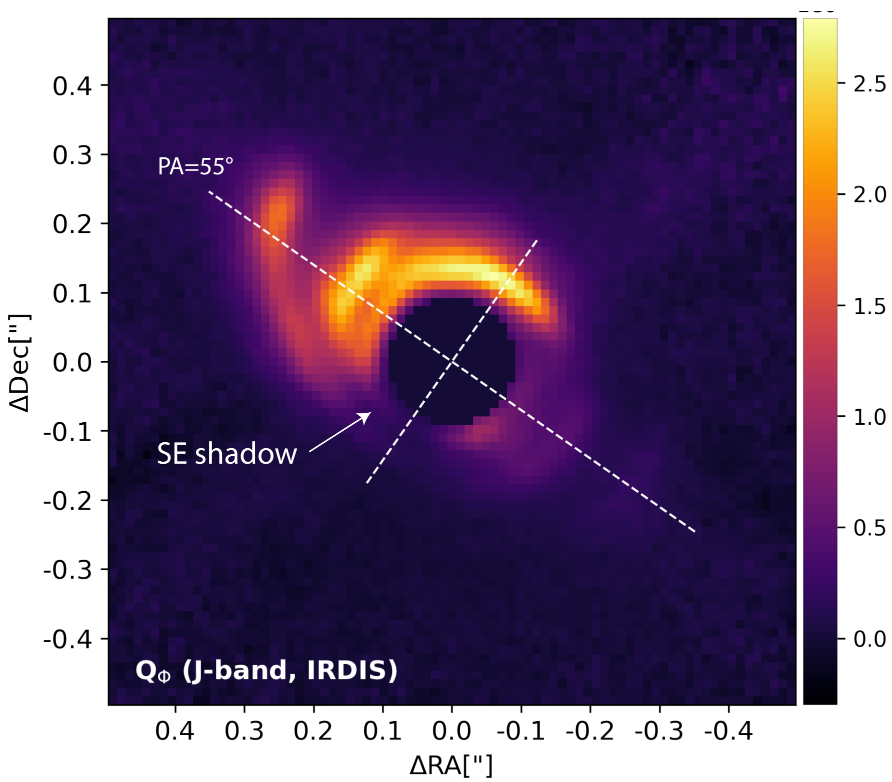
Predict 10 MJup planet/brown dwarf INTERNAL to the spiral arms with e~0.4

Similar to location of companion found by Reggiani+2018

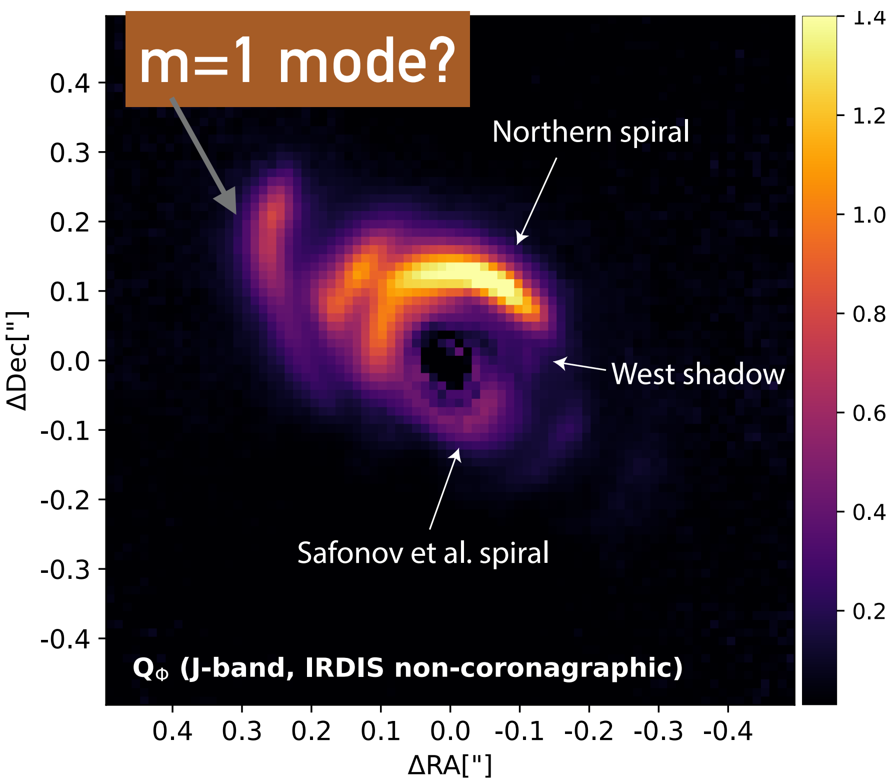
Model works, but needs confirmation

CQ TAU

Tripathi+2017, Pinilla+2018, Ubeira Gabellini+2019, Uyama+2020, Wölfer+2021; van der Marel+2021



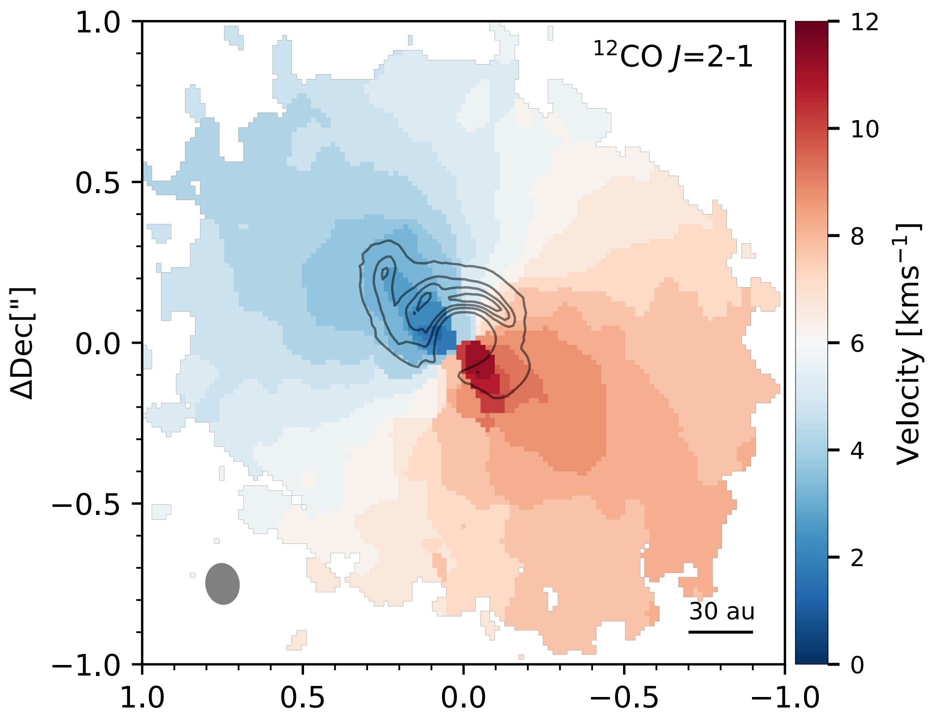
m=1 mode?



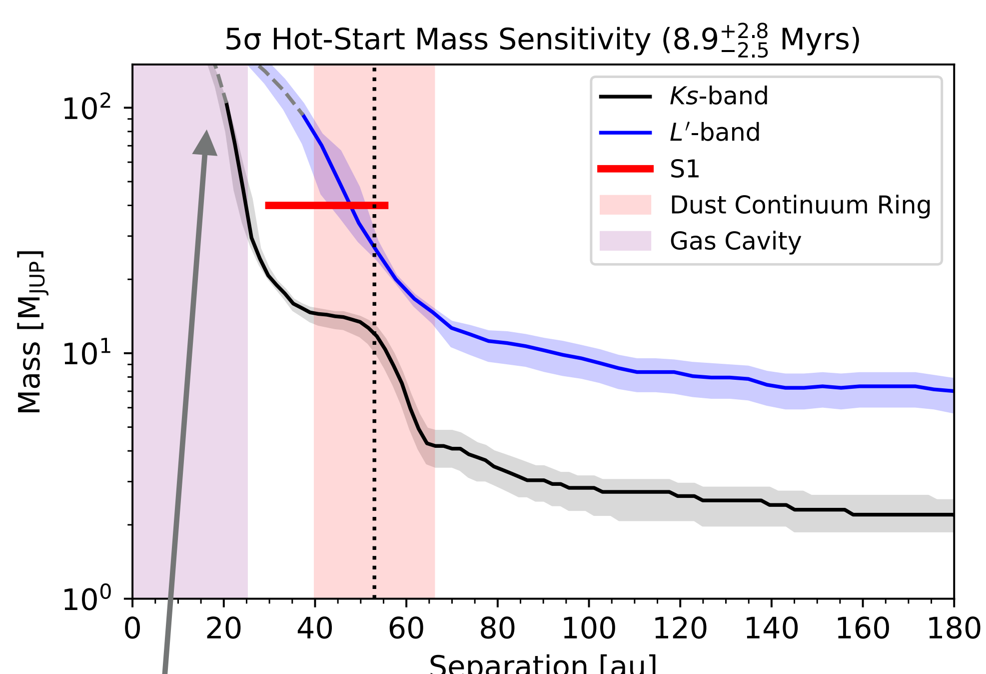
Hammond+2022, submitted to MNRAS

Shakhovskoj + 2005 report 21 year period from almost a century of observations!

+ large errors in GAIA!

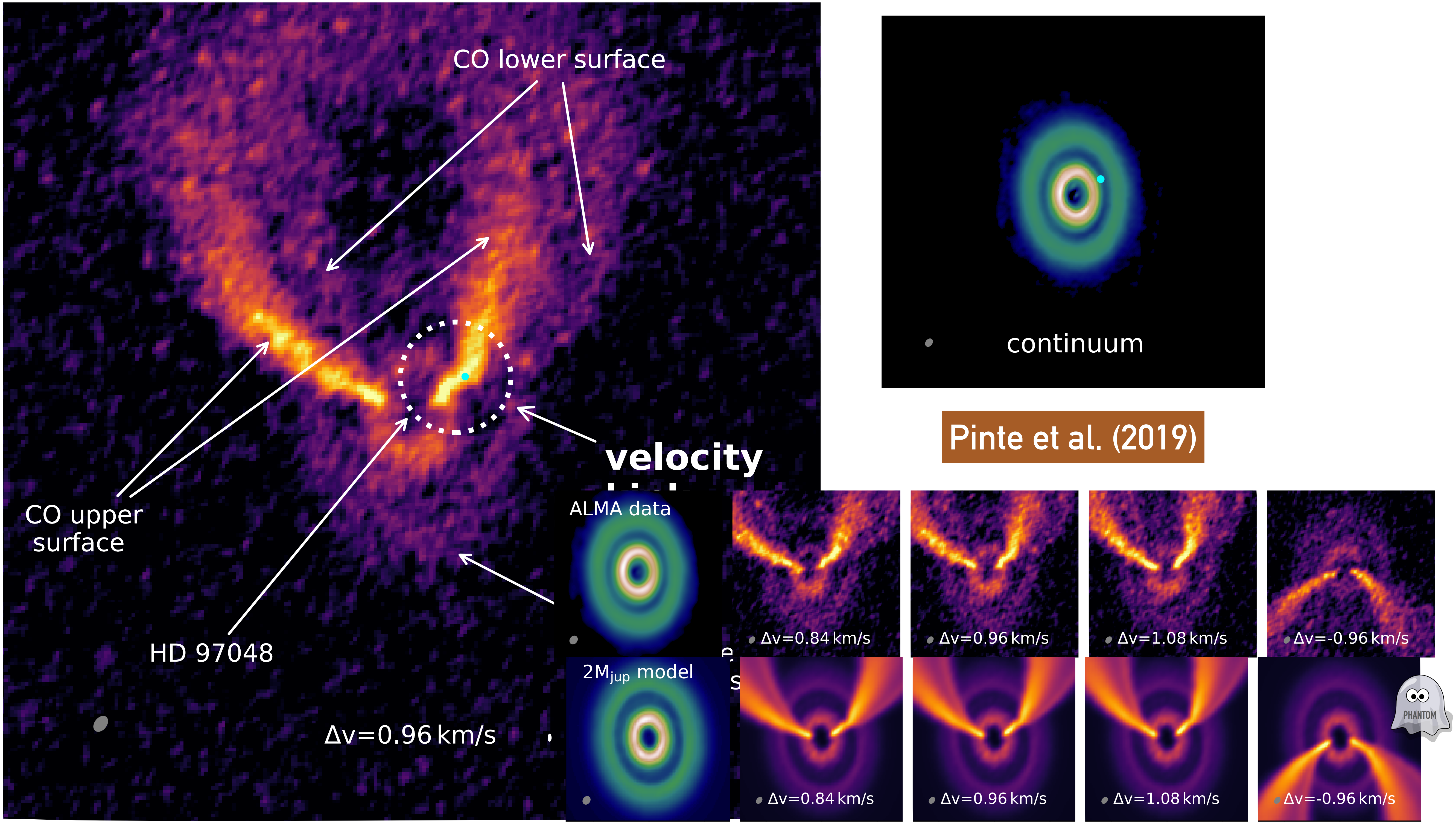


See spiral arm in kinematics!



Poor constraints on close companions from direct imaging

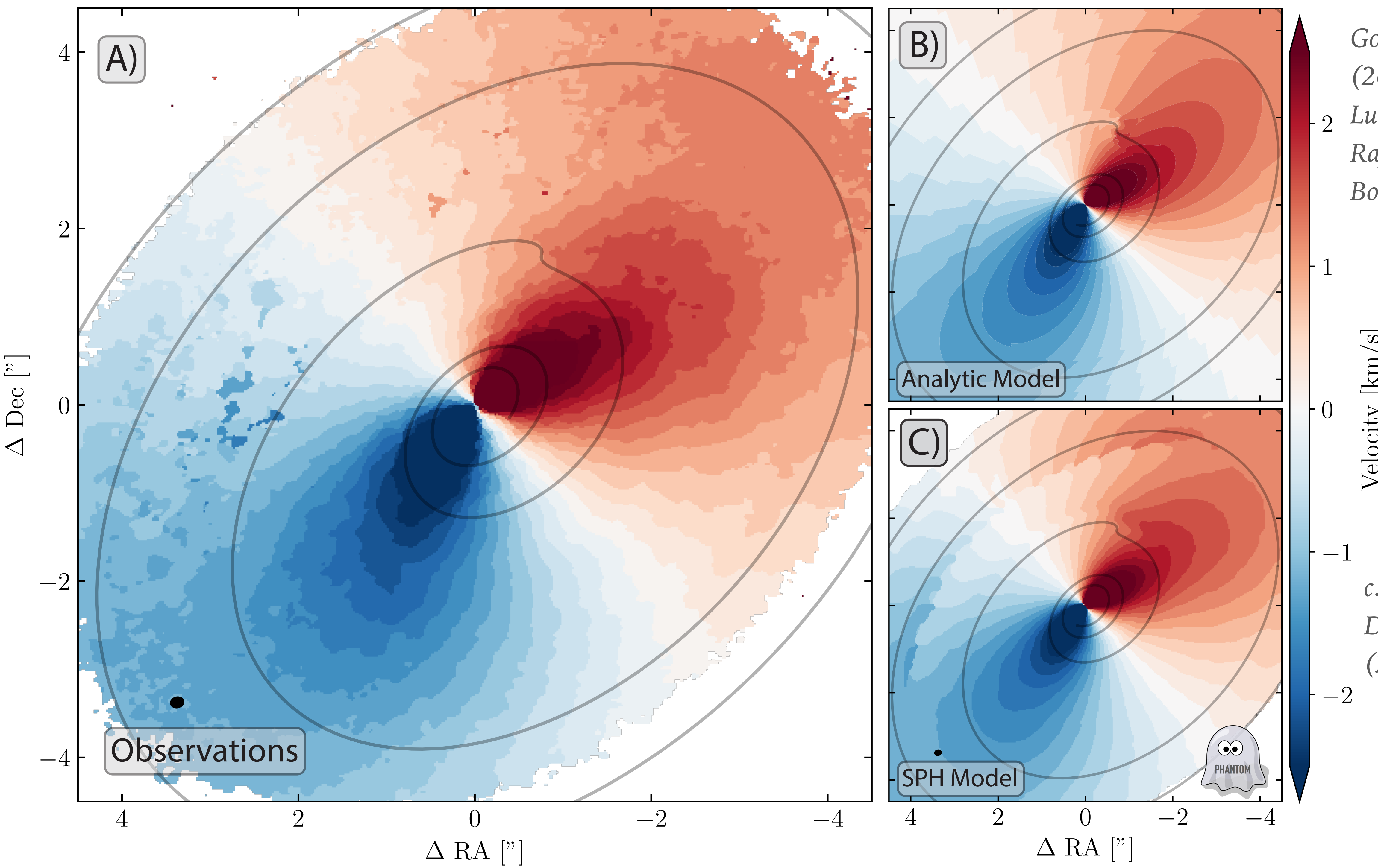
HD97048: KINEMATIC DETECTION OF PROTOPLANET WITH ALMA



Pinte et al. (2019)

WE DETECTED THE GAP-CARVING BODY - A 2-3 MJup PLANET AT 130AU!

OBSERVATIONAL PLANET-DISC INTERACTION IN HD163296

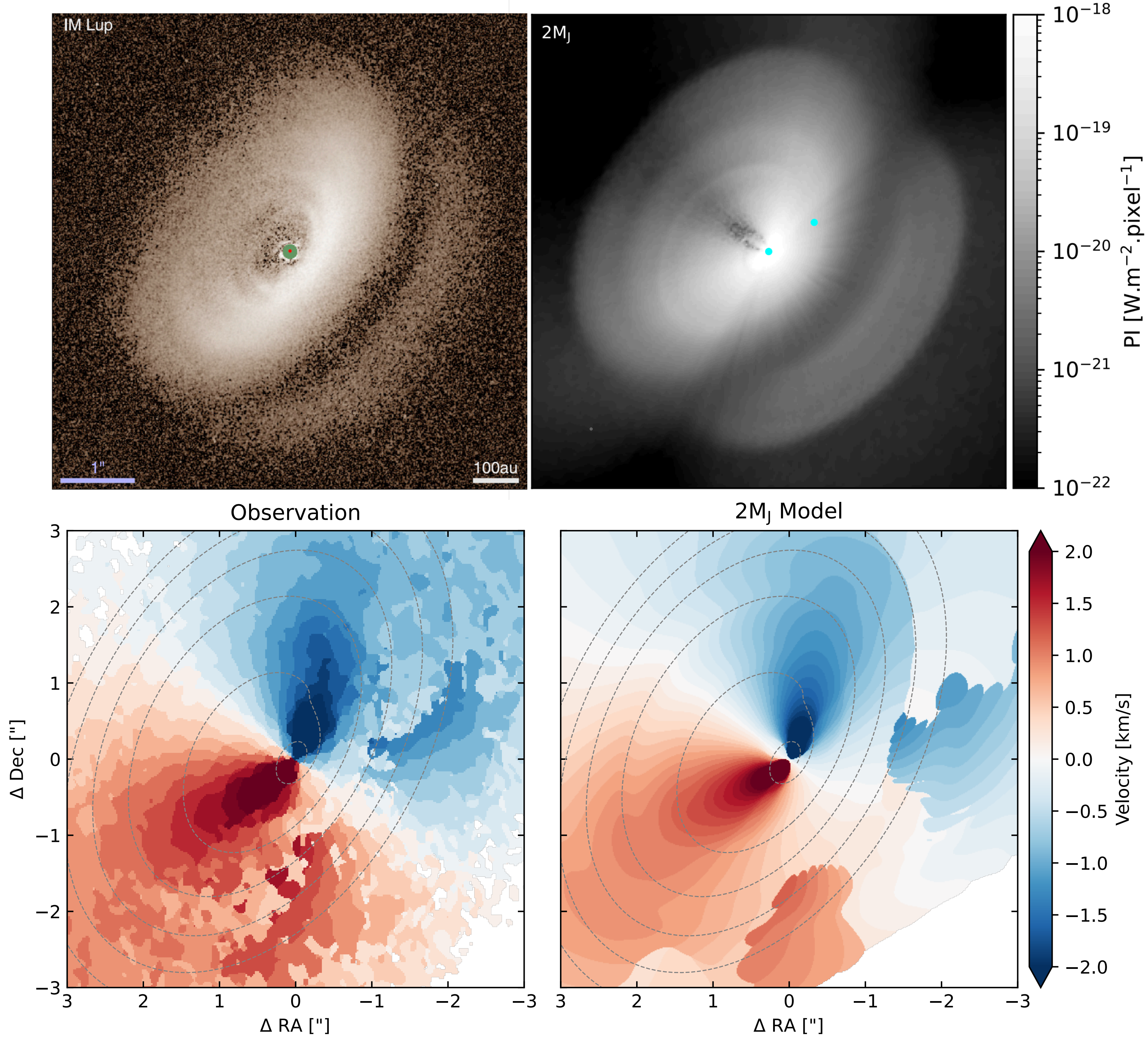


Goodman & Rafikov (2001), Ogilvie & Lubow (2002), Rafikov (2002), Bollati+(2021)

c.f. Dong+(2011a), Duffel & MacFadyen (2012), Zhu+(2015)

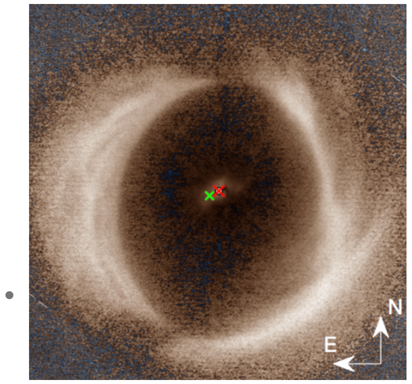
Calcino+2022, arXiv:2111.07416

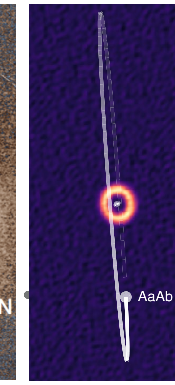
OBSERVATIONAL PLANET-DISC INTERACTION IN IM LUPI

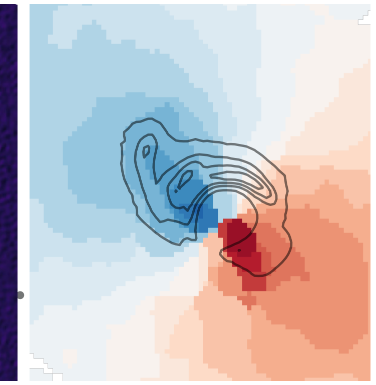


Verrios, Price+2022, submitted to ApJL

SUMMARY







- Large-cavity transition discs show all the hallmarks of binary-disc interaction: spirals, gas accretion, streamers, non-Keplerian motions, eccentric cavities and overdense lumps. But this explanation remains controversial in most cases.
- Misalignment is commonplace, polar alignment is default if binary is eccentric
- Kinematics are a powerful probe of binary-disc interaction

FOR DISCUSSION:

- How can we find the missing companions? GAIA DR3?
- Discrepancy with binary-disc interaction theory for cavity size? But only in some cases?
- Can we invert observed non-Keplerian kinematics to infer companion mass?
- Can we predict spiral arms analytically for binaries?