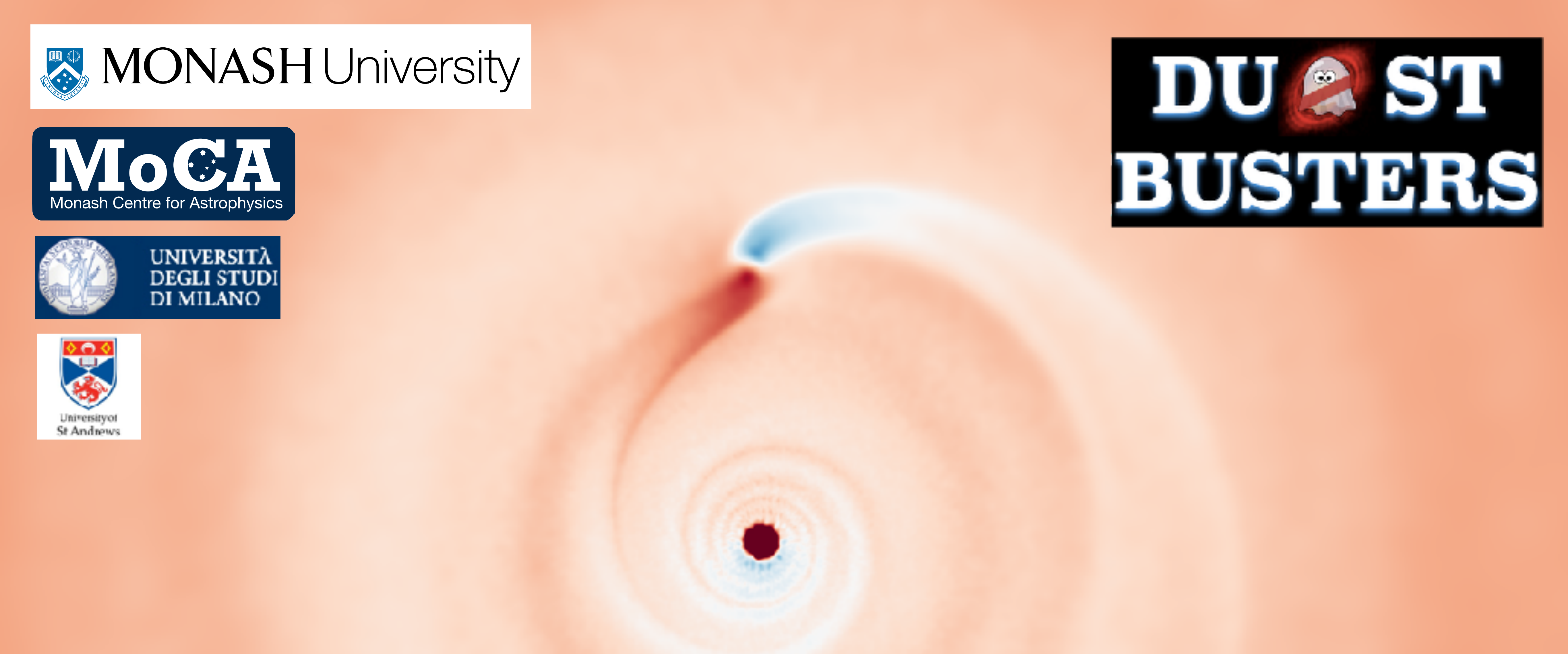


MONASH University

MoCA
Monash Centre for Astrophysics

UNIVERSITÀ
DEGLI STUDI
DI MILANO

University of
St Andrews

DUST
BUSTERS

CHAOTIC STAR FORMATION AND THE IMPLICATIONS FOR PROTOPLANETARY DISCS

Daniel Price (Monash)
Christophe Pinte (Monash/Grenoble)
Daniel Mentiplay (Monash)
Giovanni Dipierro (Milan)
Enrico Ragusa (Milan)
Guillaume Laibe (ENS Lyon)
Giuseppe Lodato (Milan)
Nicolás Cuello (PUC, Chile)
Simon Casassus (U Chile)
Valentin Christiaens (U Chile)
François Menard (Grenoble)

Daniel Price @ Core2disk workshop, Paris, May 2018

TRADITIONAL VIEW

Star formation (10 Myr)

Planet formation (5-10 Myr)

Transitional phase

Planets

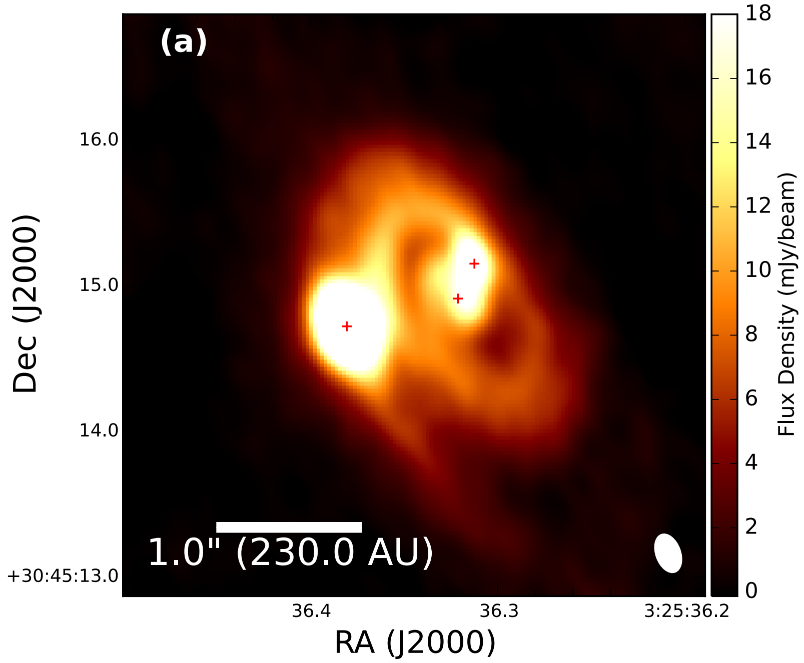
Time

CHAOTIC STAR FORMATION

CHARACTERISTICS OF CHAOTIC STAR FORMATION

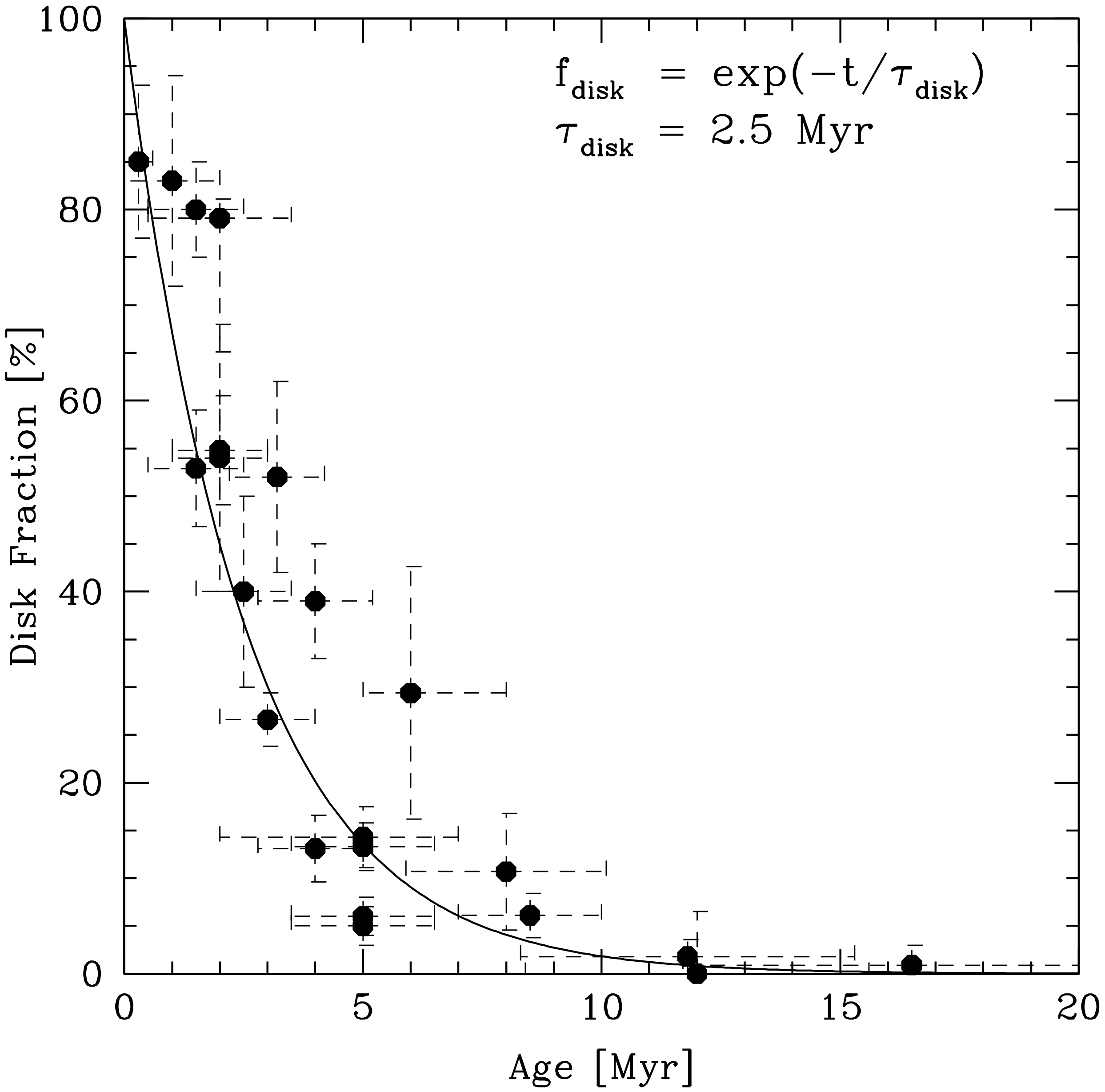
- Fast, occurs on dynamical time(~1-2Myr)
- Chaotic; dynamical interactions common
- Initial mass function arises from competition for mass
- Binary and multiple stars usual outcome
- Massive, gravitationally unstable discs in early phase
- Filaments! (A

e.g. Larson (1978, 1981), Pringle (1989), Bate & Bonnell (1994a,b), Mac Low et al. (1999), Stone et al. (1998), Bate et al. (2003), Elmegreen (2000), Mac Low & Klessen (2004), Bate & Bonnell (2005), Bonnell & Bate (2006), Offner et al. (2008), Bate (2009, 2012), Bate, Lodato & Pringle (2010), Chabrier & Hennebelle (2010, 2011), Hennebelle & Chabrier (2008, 2009, 2011)



Tobin et al. (2016)

PLANET FORMATION – FAST OR SLOW?



Mamajek (2009)

Lifetime of protoplanetary disc ~ 10 Myr

OUR 2015 VIEW OF STAR AND PLANET FORMATION

Star formation (1-2 Myr) .ation (10 Myr)

Planet formation (5-10 Myr)

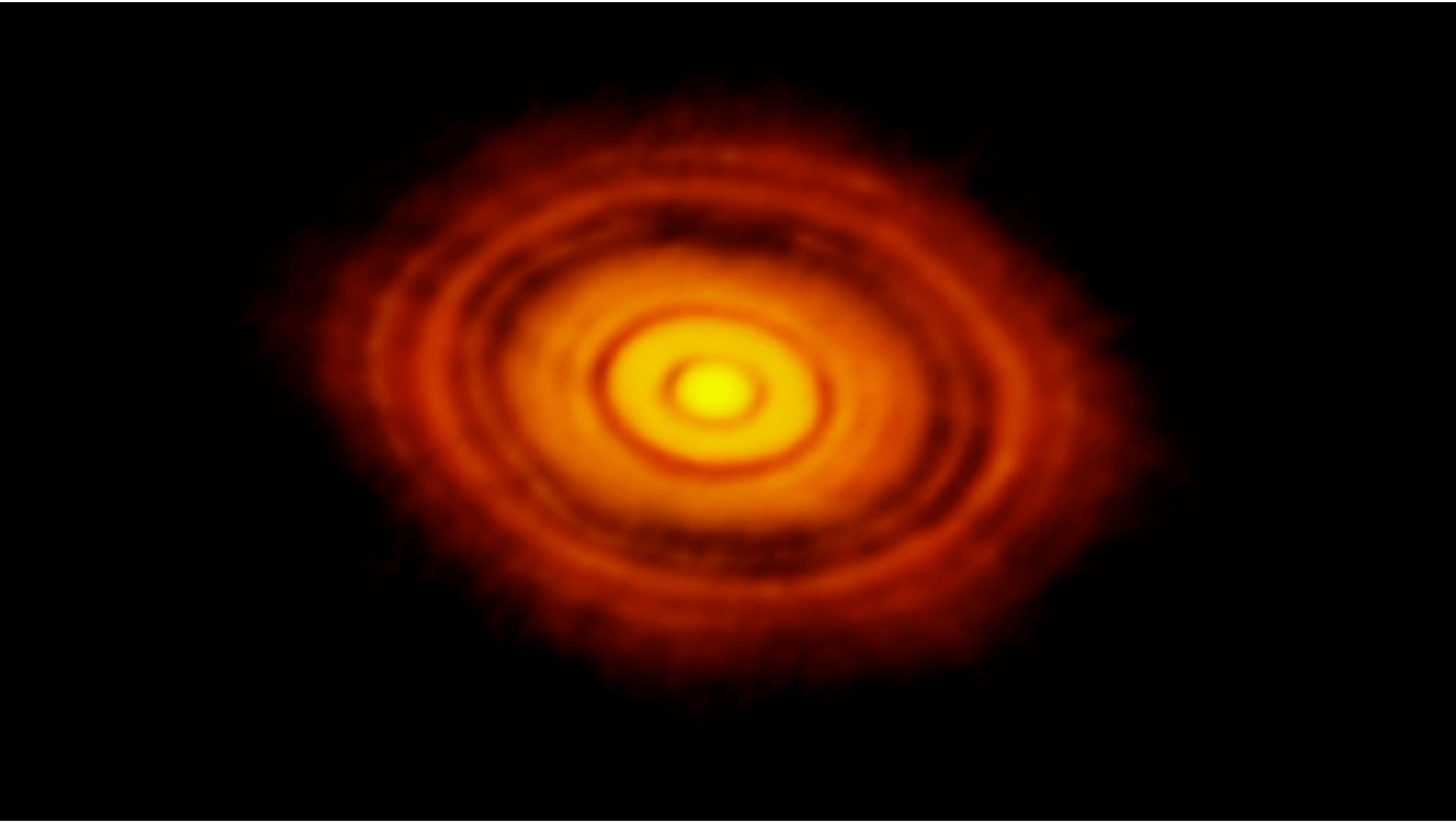
Transitional phase

Planets

Time

So what's new?

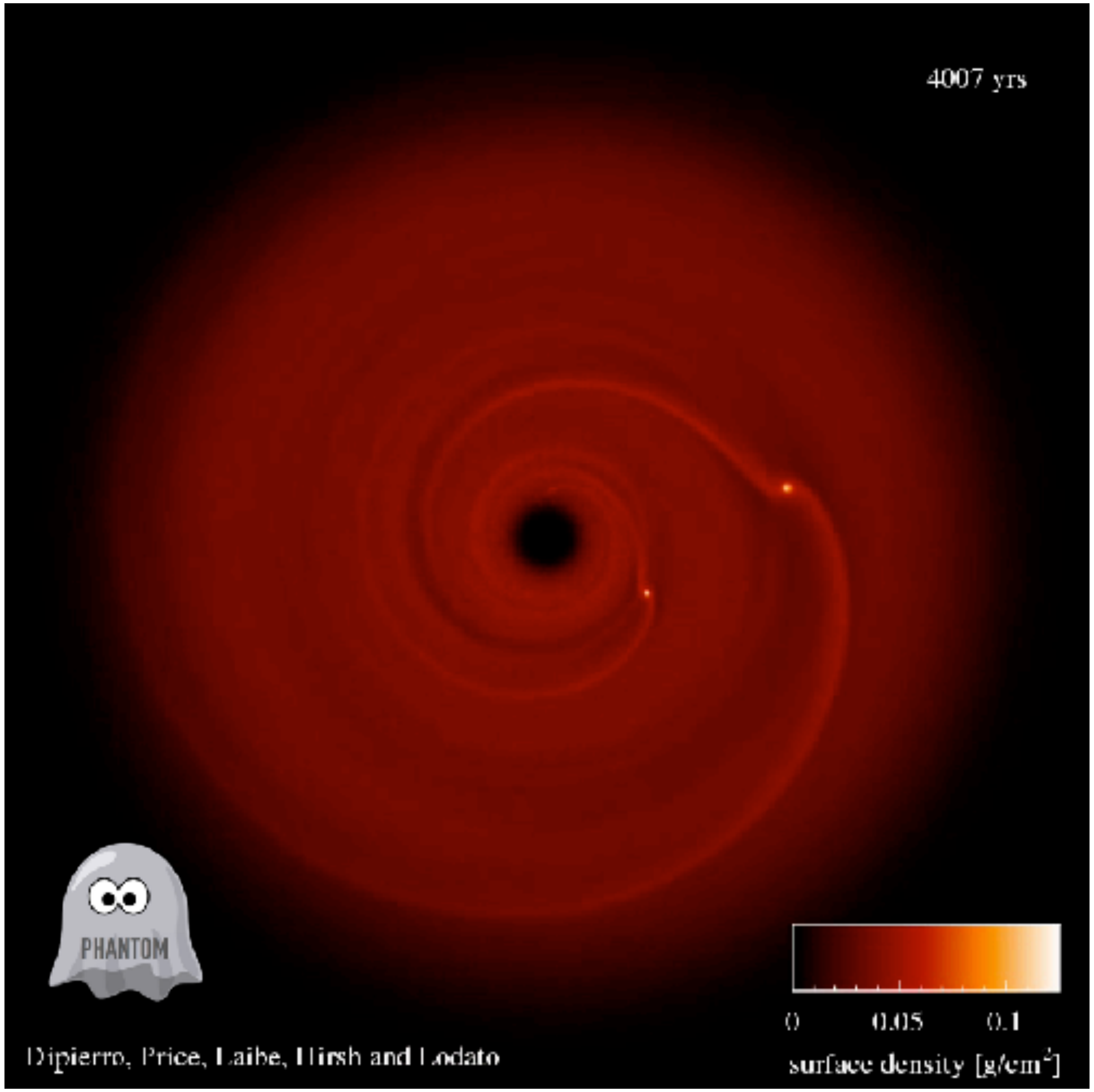
PLANET FORMATION IS INTIMATELY LINKED TO STAR FORMATION



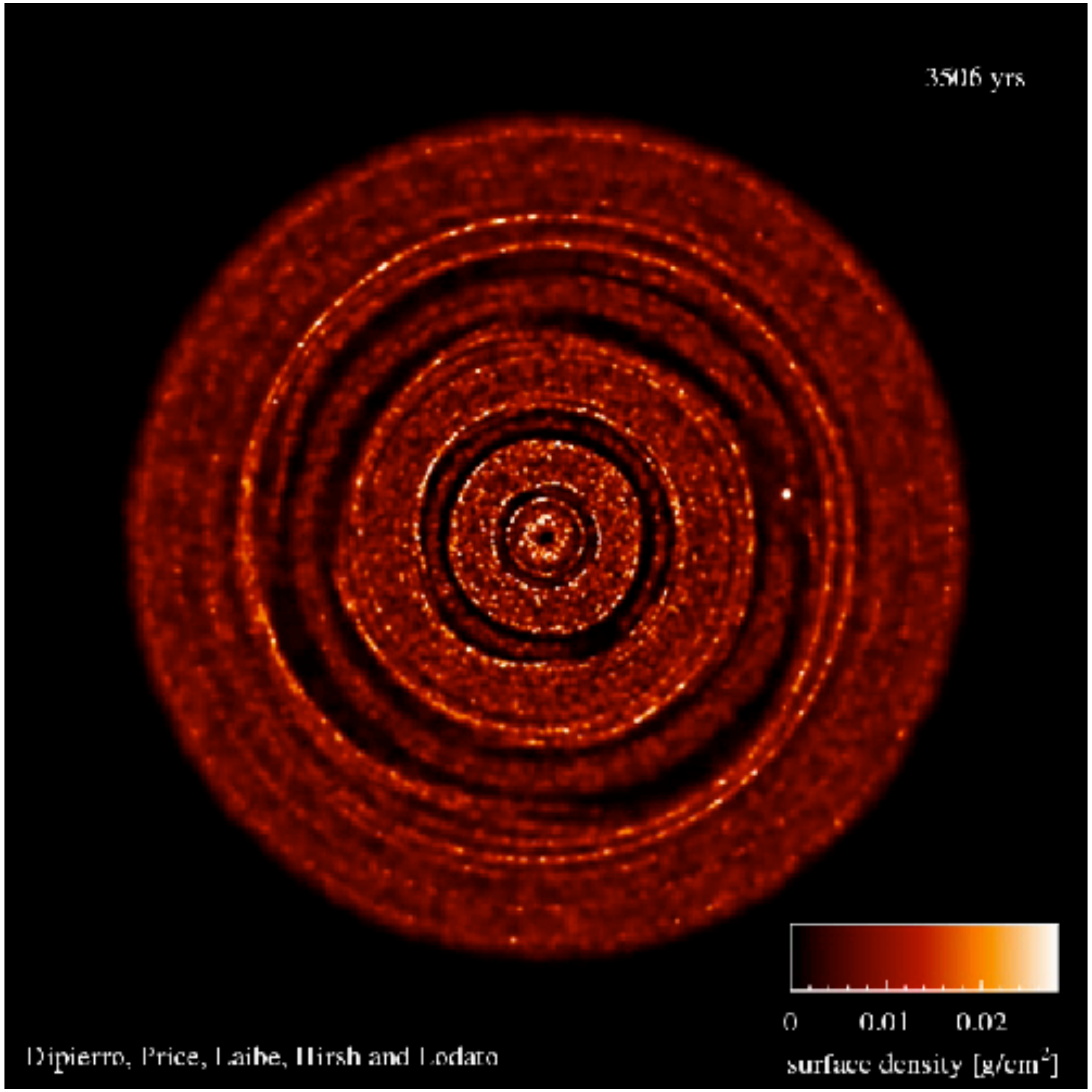
ALMA collaboration et al. (2015)

DUST, GAS AND PLANETS IN HL TAU

Dipierro et al. (2015)



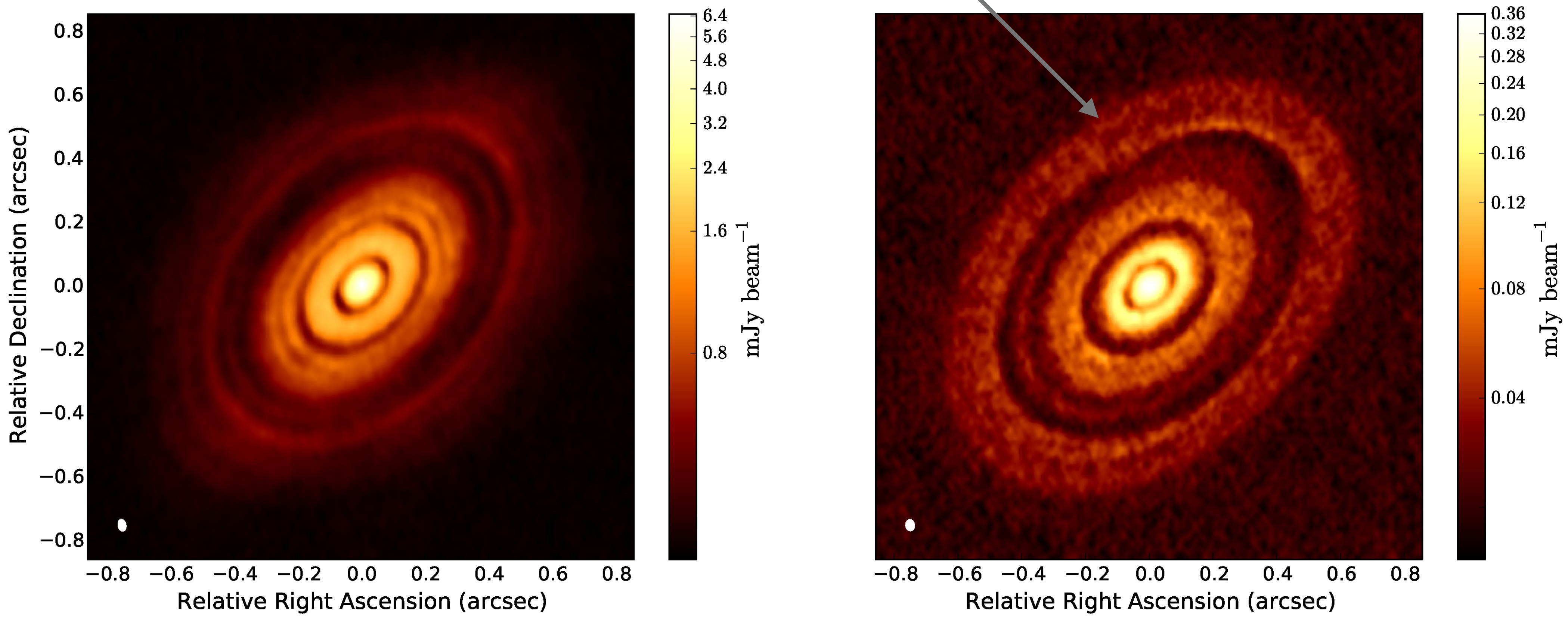
Gas



mm grains

COMPARISON

Dipierro, Price, et al. (2015), MNRAS 453, L73-L77



Observed

Computed using RADMC3D radiative transfer code (Dullemond 2012) plus ALMA simulator

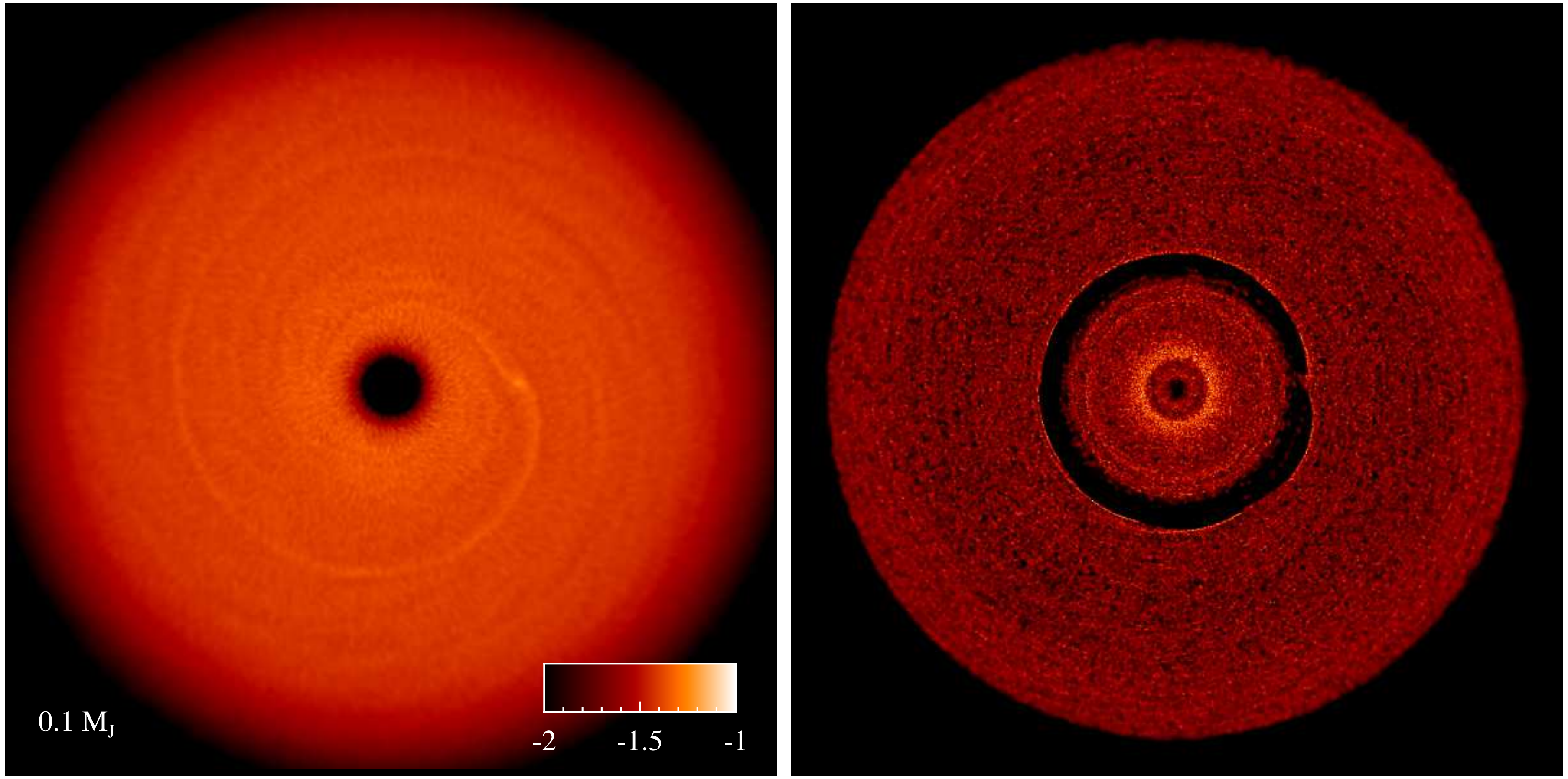
Figure 4. Comparison between the ALMA image of HL Tau (left) with simulated observations of our disc model (right) at band 6 (continuum emission at 233 GHz). The white colour in the filled ellipse in the lower left corner indicates the size of the half-power contour of the synthesized beam: (left) 0.035 arcsec × 0.022 arcsec, P.A. 11°; (right) 0.032 arcsec × 0.024 arcsec, P.A. 6°.

But need 3 x Saturn-mass planets in less than 1 million years!

Similar conclusions reached by Jin+(2016), Picogna+(2016)

DUST GAPS WITH NO GAS GAPS?

Dipierro, Laibe, Price & Lodato (2016)

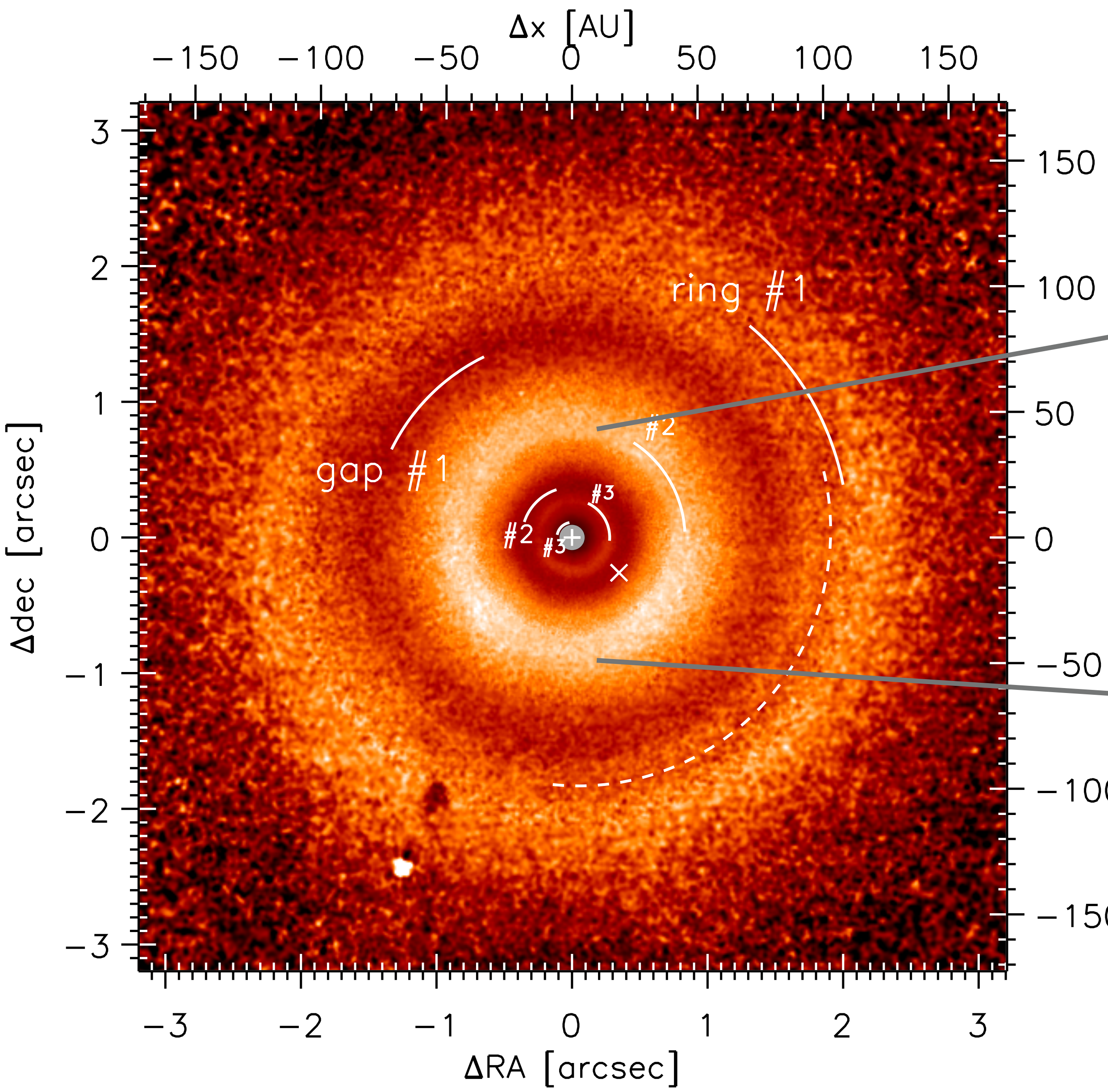


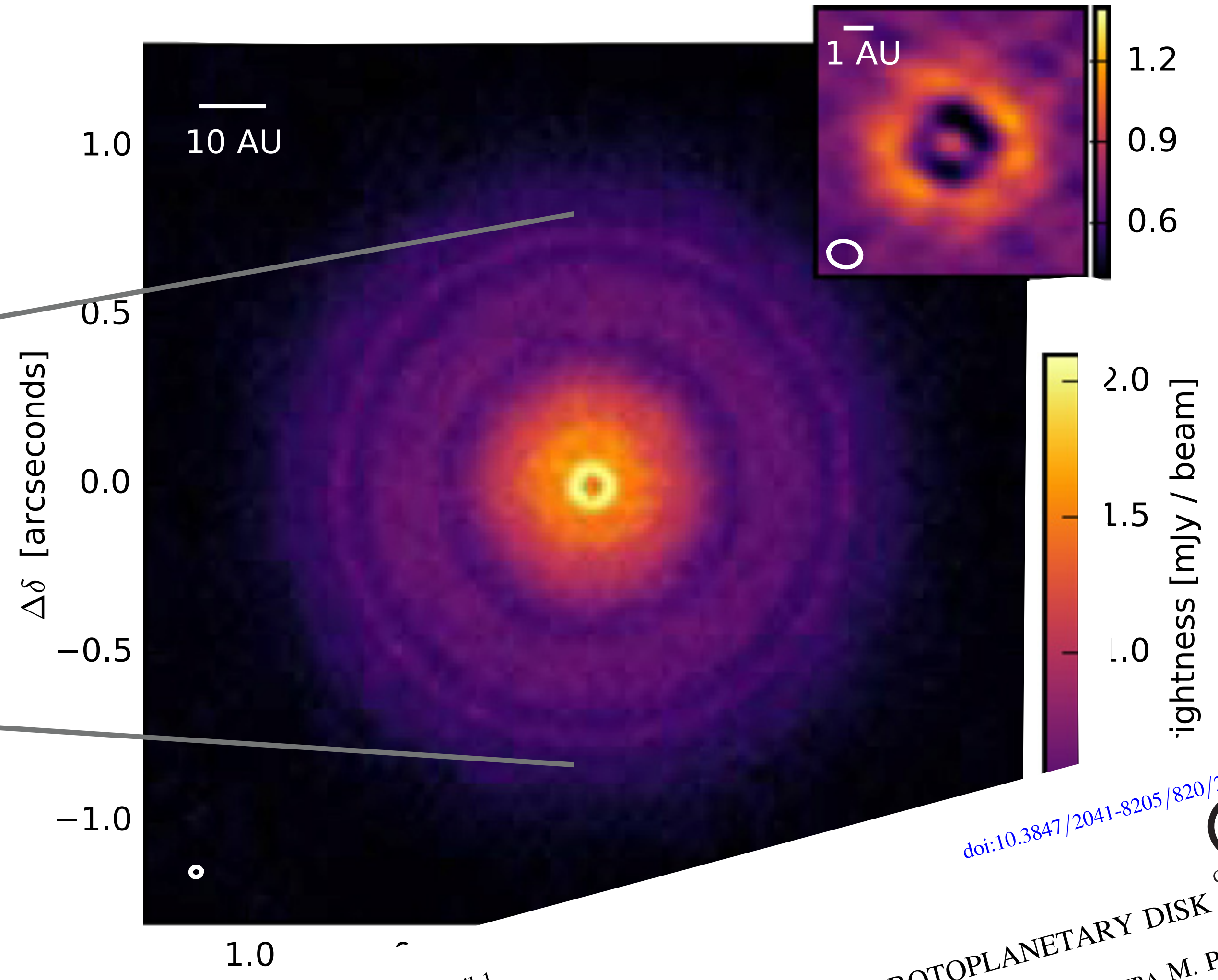
- Small planets only carve a gap in the dust

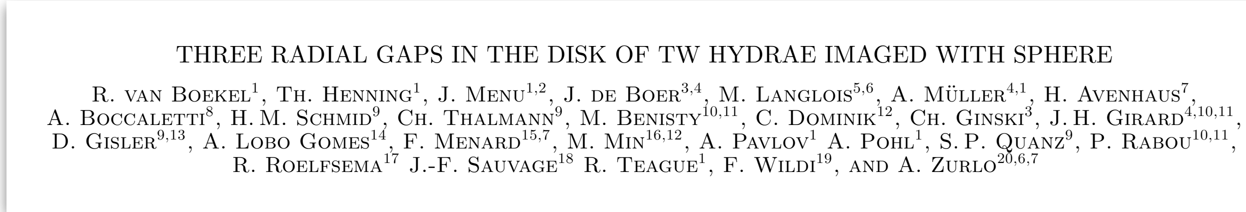
But lots of other explanations for dust gaps in discs! e.g. Lesur et al. (2014), Pinilla et al. (2012), Meheut et al. (2012b), Lyra & Kuchner (2013), Zhang, Blake & Bergin (2015), Takahashi & Inutsuka (2012), Flock et al. (2015), Loren-Aguilar & Bate (2015, 2016), Gonzalez et al. (2015, 2017)

For planets, see also Wolf et al. (2002); Fouchet et al. (2007; 2012); Gonzalez et al. (2012)

TW HYA: OUR NEAREST PROTOPLANETARY DISC



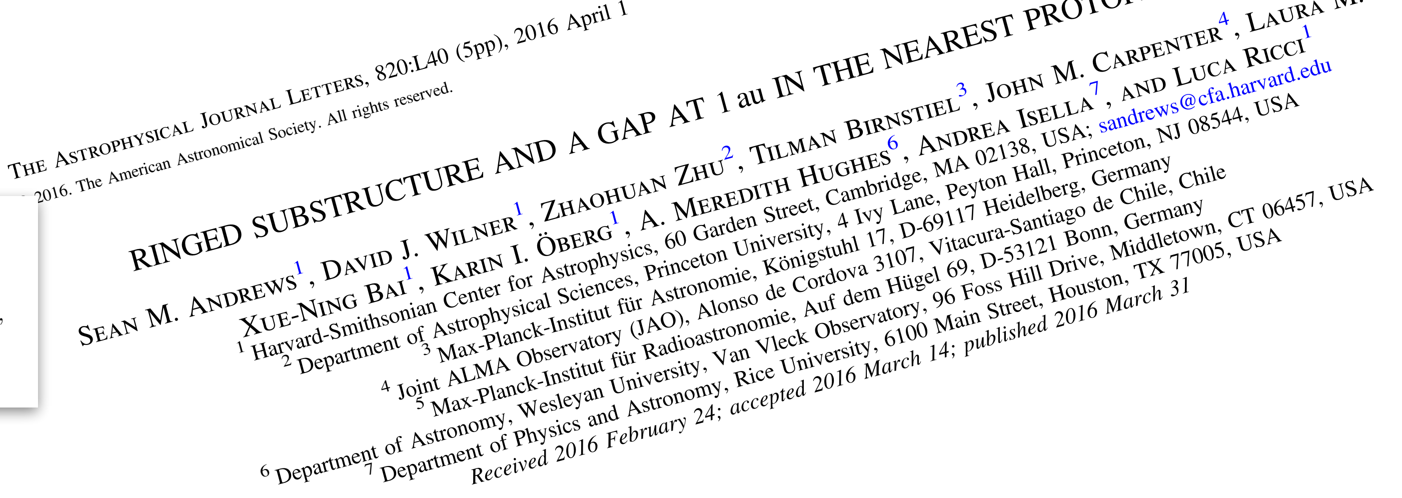



THREE RADIAL GAPS IN THE DISK OF TW HYDRAE IMAGED WITH SPHERE

R. van Boekel[1], Th. Henning[1], J. Menu[1,2], J. de Boer[3,4], M. Langlois[5,6], A. Müller[4,1], H. Avenhaus[7], A. Boccaletti[8], H. M. Schmid[9], Ch. Thalmann[9], M. Benisty[10,11], C. Dominik[12], Ch. Ginski[3], J. H. Girard[4,10,11], D. Gisler[9,13], A. Lobo Gomes[14], F. Menard[15,7], M. Min[16,12], A. Pavlov[1] A. Pohl[1], S. P. Quanz[9], P. Rabou[10,11], R. Roelfsema[17] J.-F. Sauvage[18] R. Teague[1], F. Wildi[19], and A. Zurlo[20,6,7]

doi:10.3847/2041-8205/820/2/L40

CrossMark


The Astrophysical Journal Letters, 820:L40 (5pp), 2016 April 1

RINGED SUBSTRUCTURE AND A GAP AT 1 au IN THE NEAREST PROTOPLANETARY DISK

Sean M. Andrews[1], David J. Wilner[1], Zhaohuan Zhu[2], Tilman Birnstiel[3], John M. Carpenter[4], Laura M. Pérez[5], Xue-Ning Bai[1], Karin I. Öberg[1], A. Meredith Hughes[6], Andrea Isella[7], and Luca Ricci[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; sandrews@cfa.harvard.edu
[2] Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Peyton Hall, Princeton, NJ 08544, USA
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[4] Joint ALMA Observatory (JAO), Alonso de Cordova 3107, Vitacura-Santiago de Chile, Chile
[5] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[6] Department of Astronomy, Wesleyan University, Van Vleck Observatory, 96 Foss Hill Drive, Middletown, CT 06457, USA
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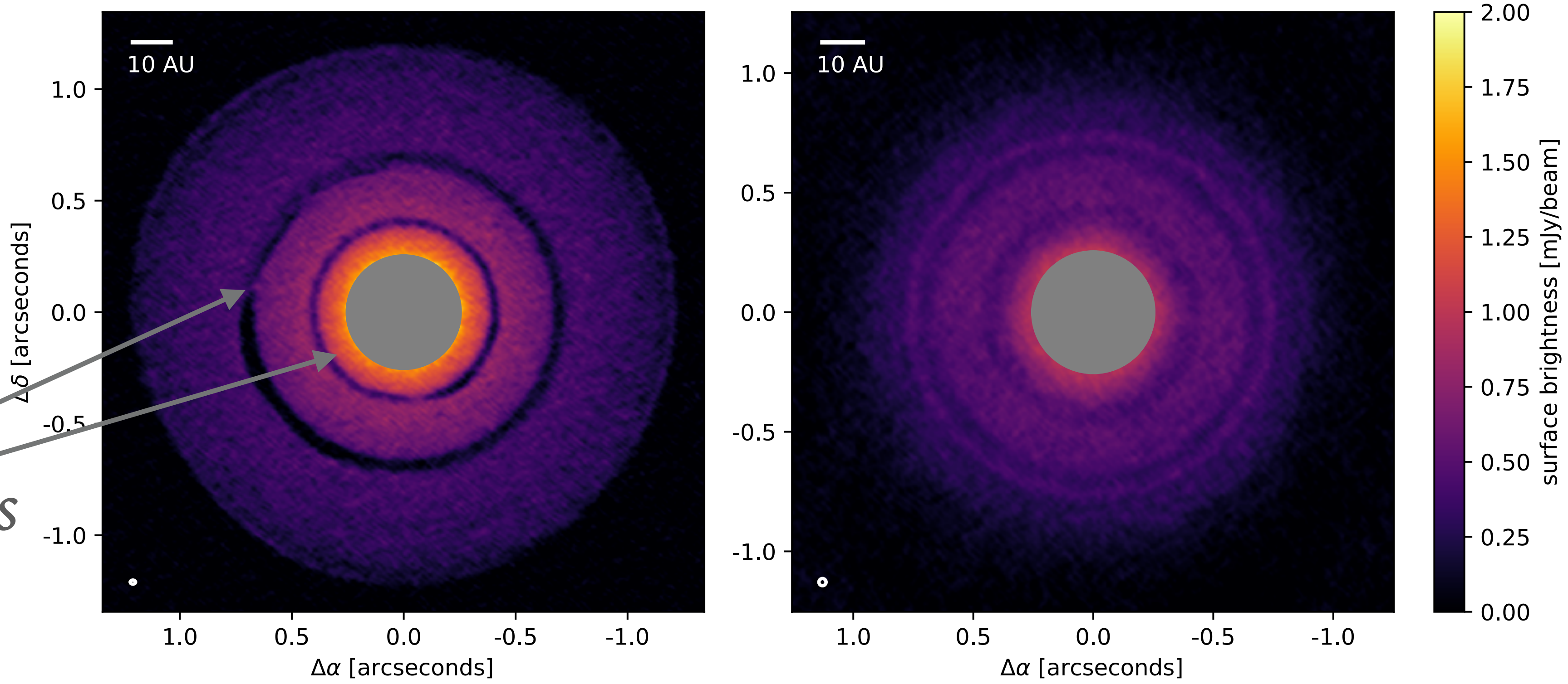
Received 2016 February 24; accepted 2016 March 14; published 2016 March 31

See also Huang et al. (2018) for CO data

TW HYA MODELLING

Mentiplay, Price & Pinte (submitted)

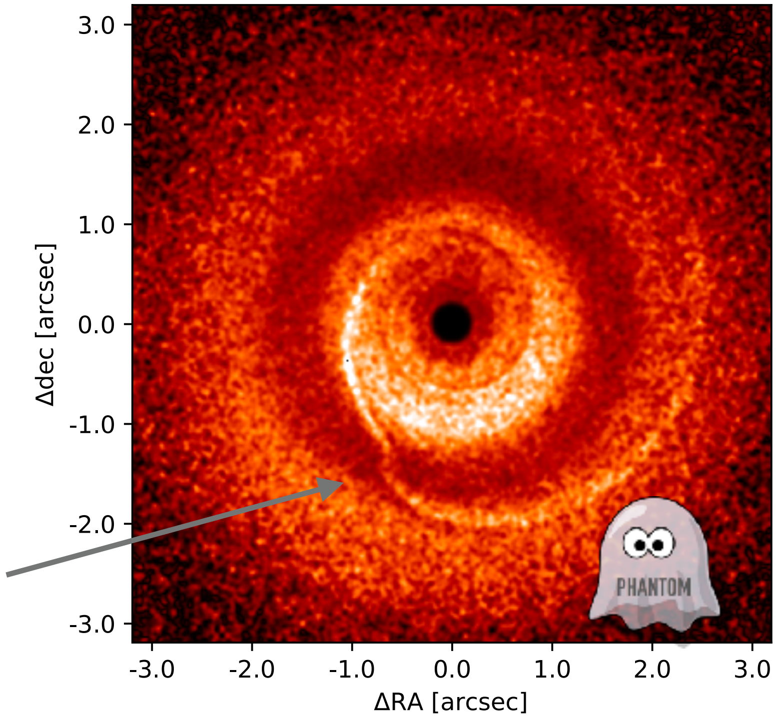
Super-earths in TW Hya



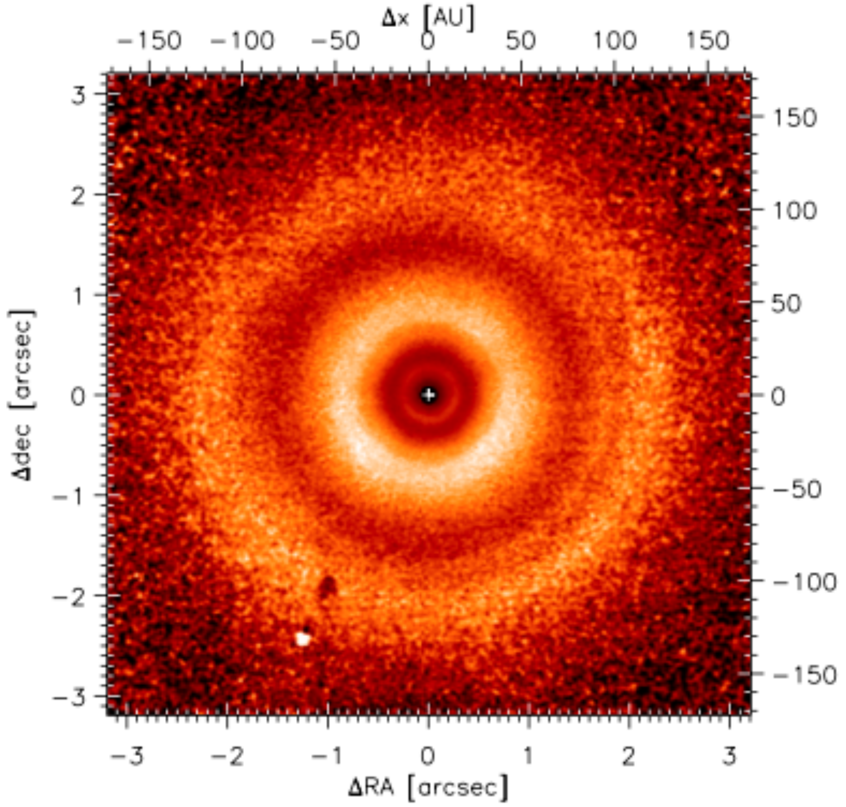
Super Earths

Left: Our simulation

Right: Andrews et al. (2016)



Saturn

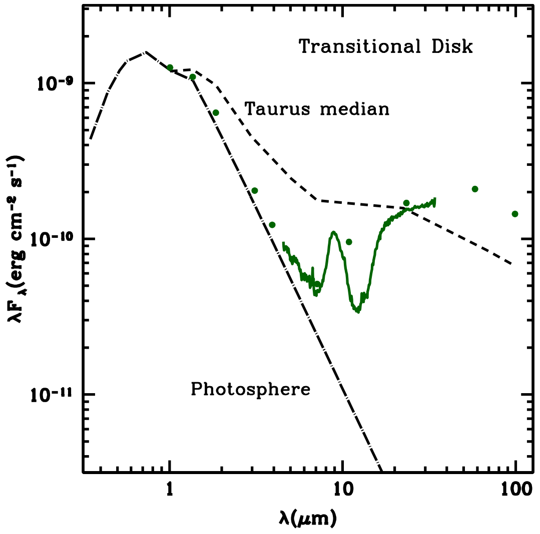


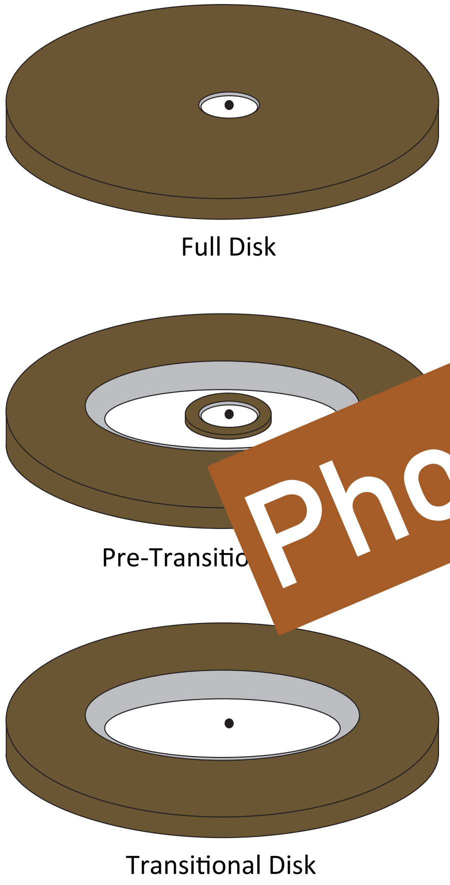
Left: Our simulation

Right: Van Boekel et al. (2017)

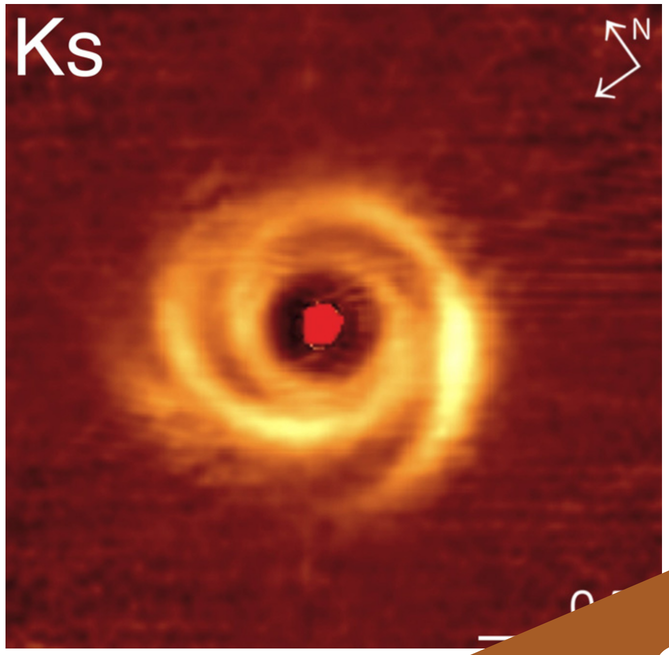
“TRANSITION” DISCS

Strom et al. (1989), Dullemond et al. (2001), Calvet et al. (2005), Espaillat et al. (2014), Casassus (2016), Owen (2016)



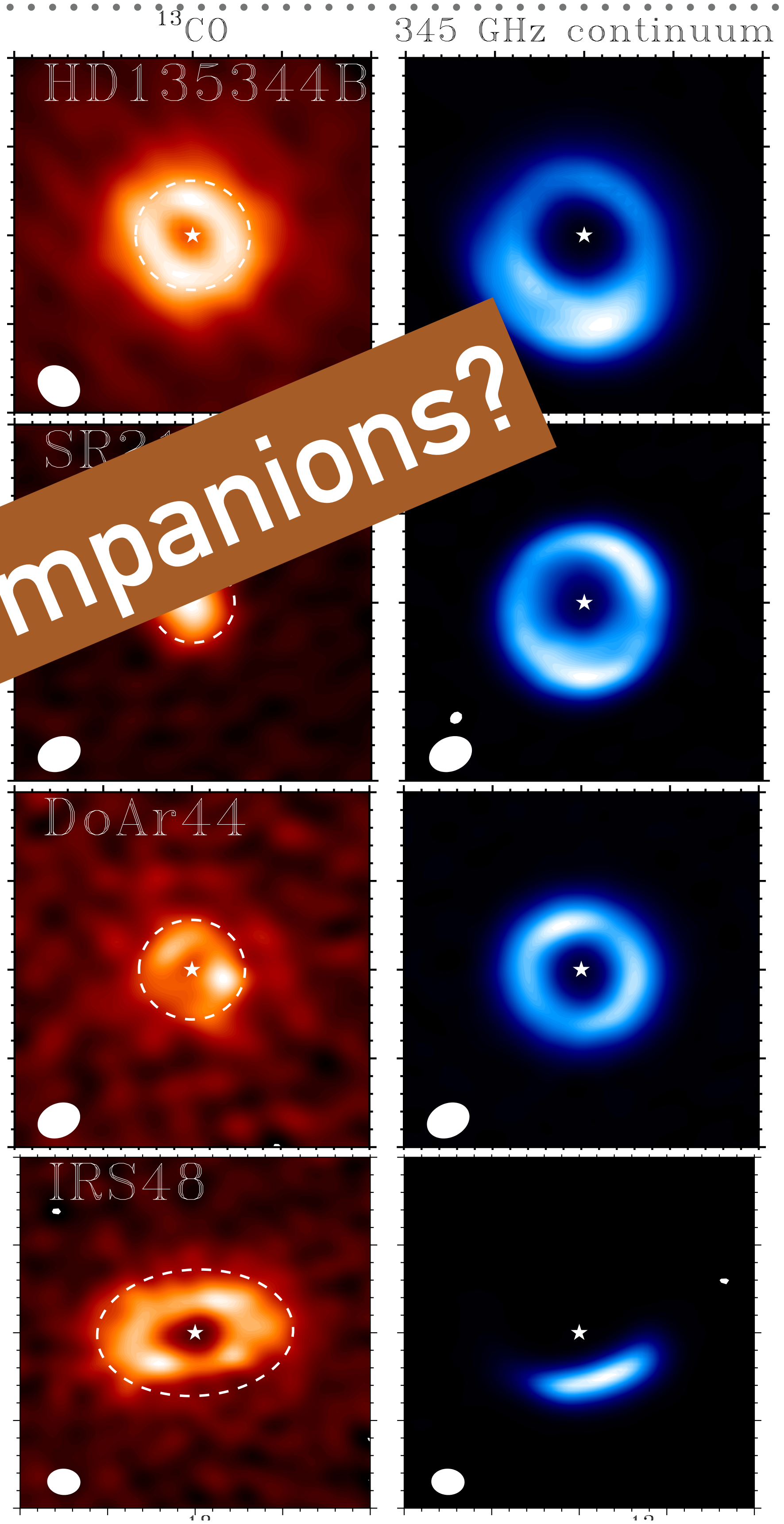


Espaillat et al. (2014)



Garufi et al

Benisty et al. (2016)



Van-der-Marel et al. (2016)

Photoevaporation or companions?

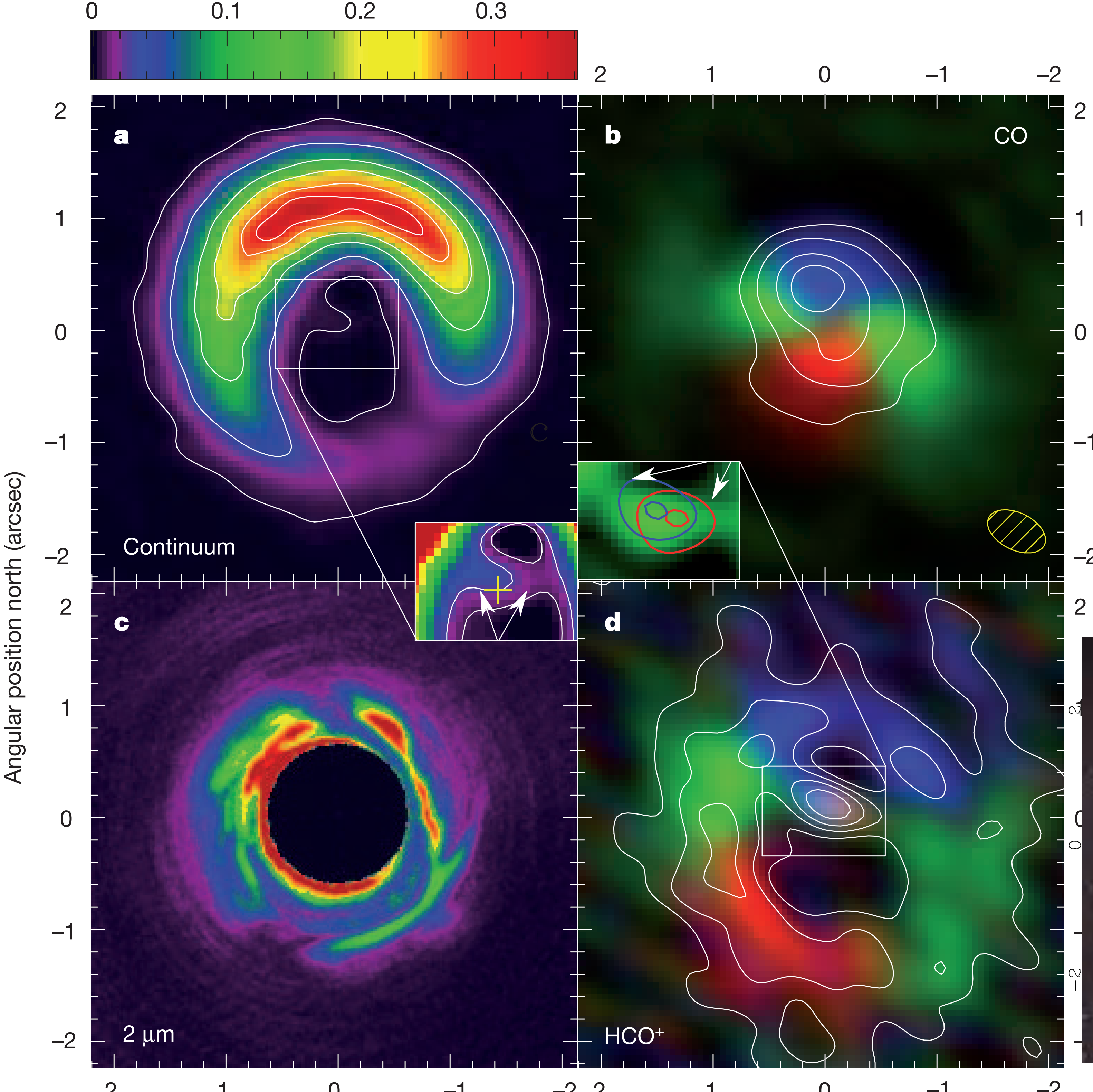
HD142527

LETTER

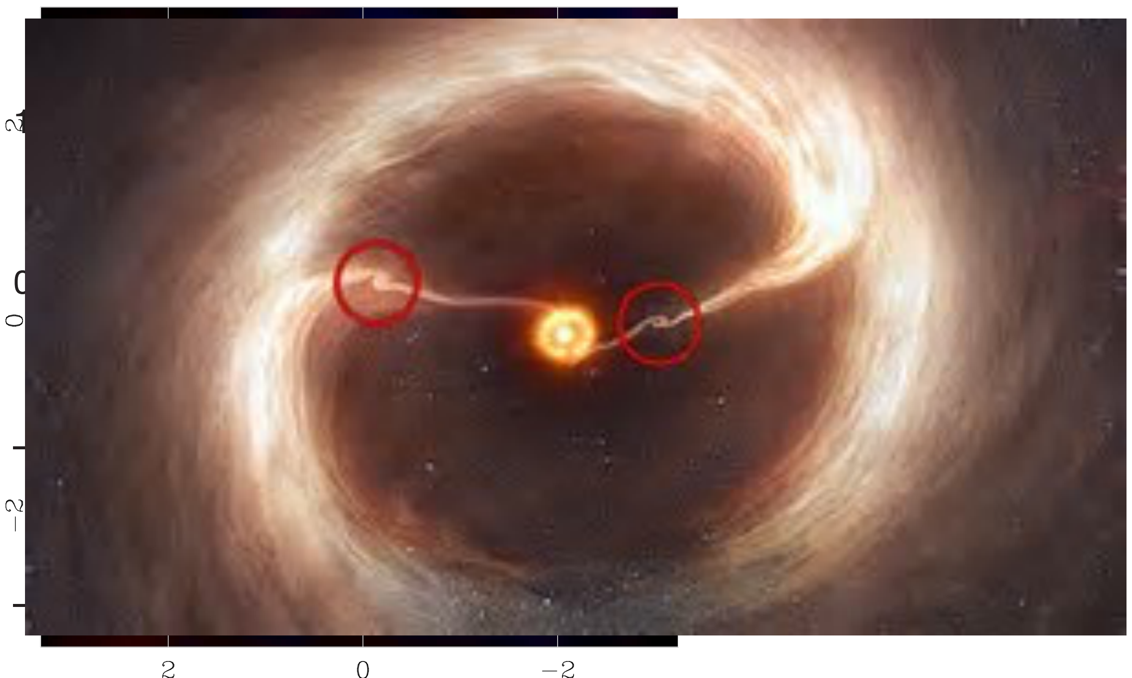
doi:10.1038/nature11769

Flows of gas through a protoplanetary gap

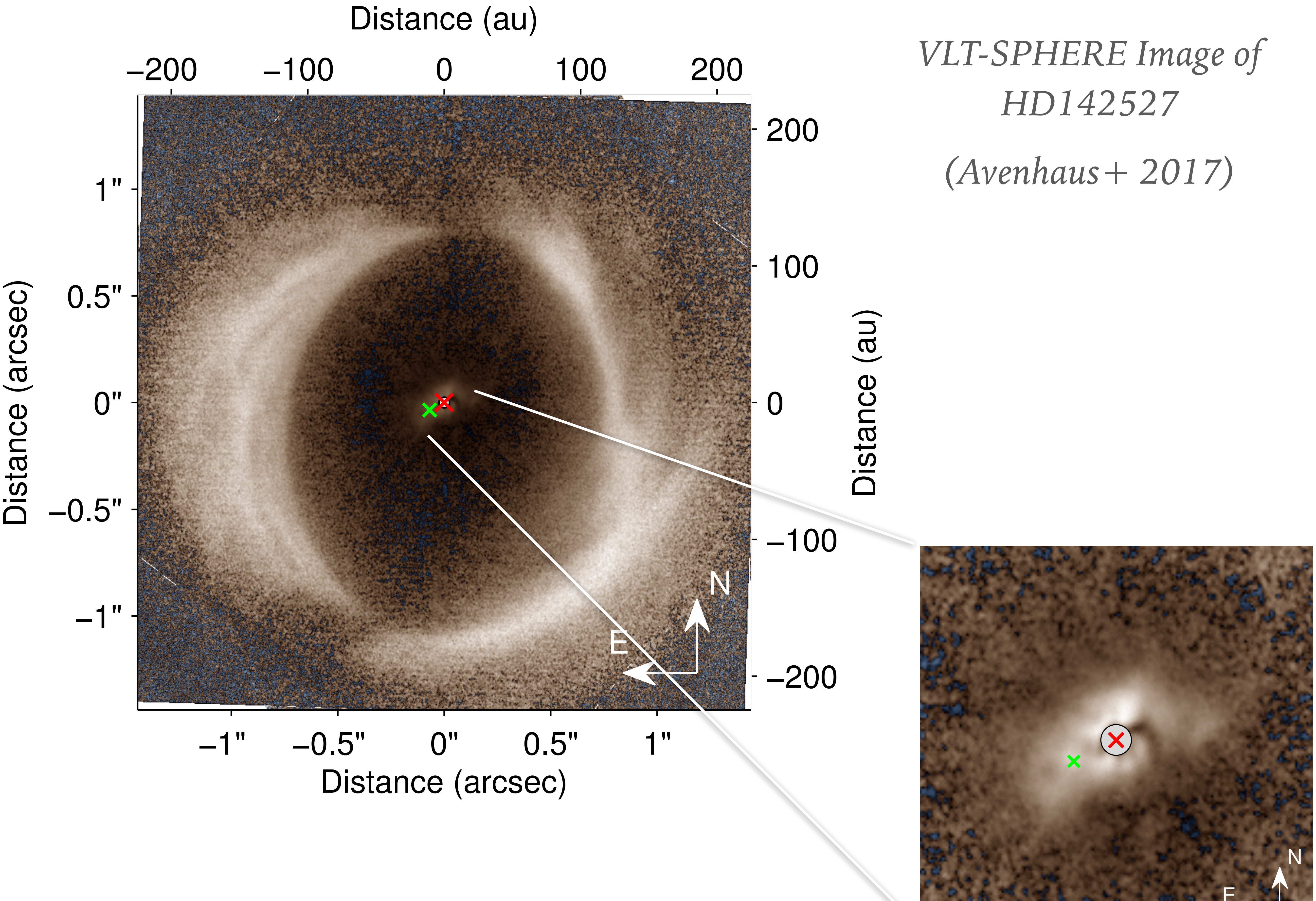
Simon Casassus[1], Gerrit van der Plas[1], Sebastian Perez M[1], William R. F. Dent[2,3], Ed Fomalont[4], Janis Hagelberg[5], Antonio Hales[2,4], Andrés Jordán[6], Dimitri Mawet[3], Francois Ménard[7,8], Al Wootten[4], David Wilner[9], A. Meredith Hughes[10], Matthias R. Schreiber[11], Julien H. Girard[3],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



- Large ~100 au cavity
- Horseshoe in mm emission (Ohashi 2008)
- Gap-crossing filaments?



SPIRAL ARMS

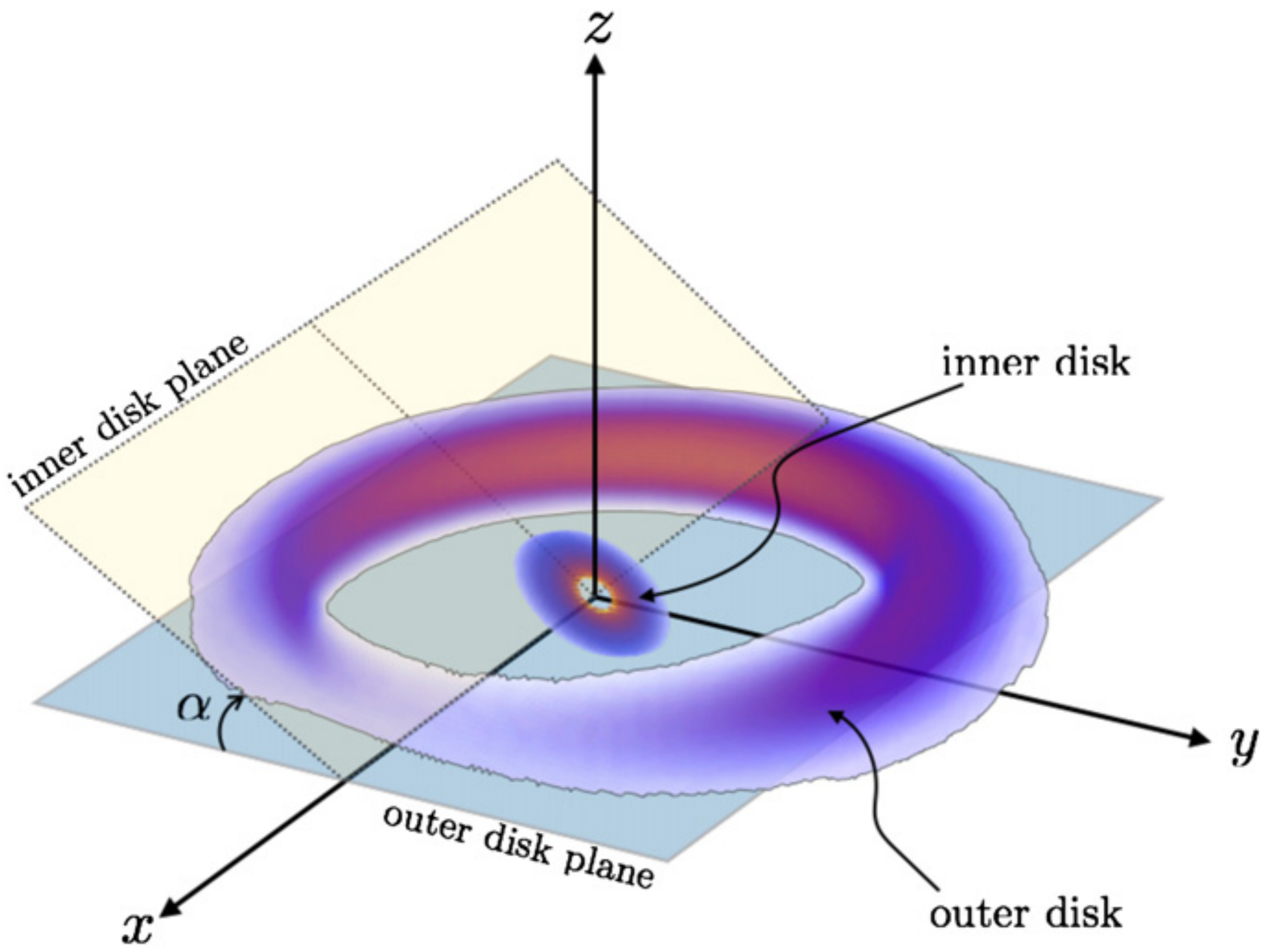


VLT-SPHERE Image of HD142527

(Avenhaus+ 2017)

SHADOWS = INCLINED INNER DISC?

THE ASTROPHYSICAL JOURNAL LETTERS, 798:L44 (4pp), 2015 January 10



Marino, Perez & Casassus (2015)

“FAST RADIAL FLOWS” = DISC TEARING?

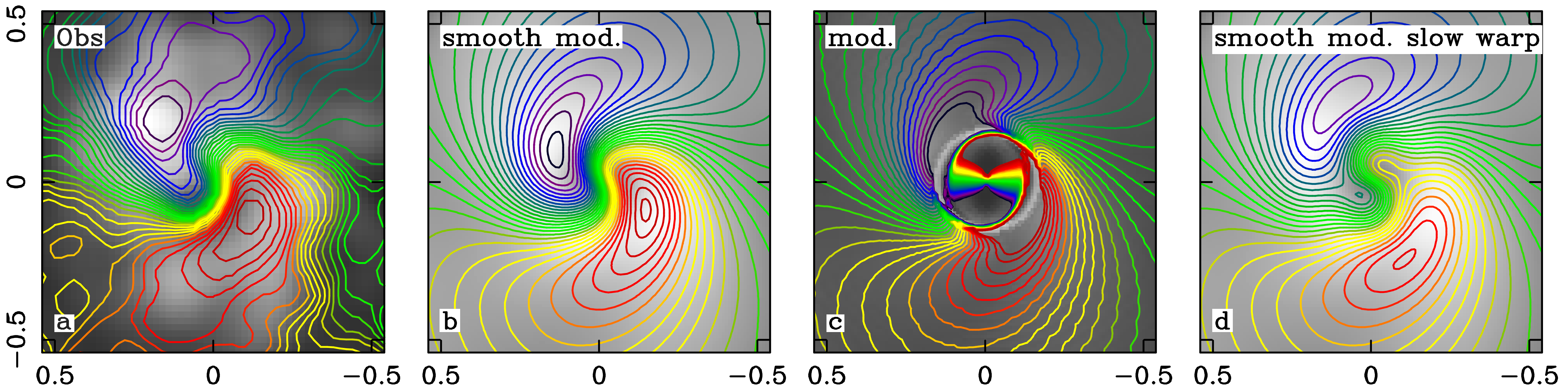
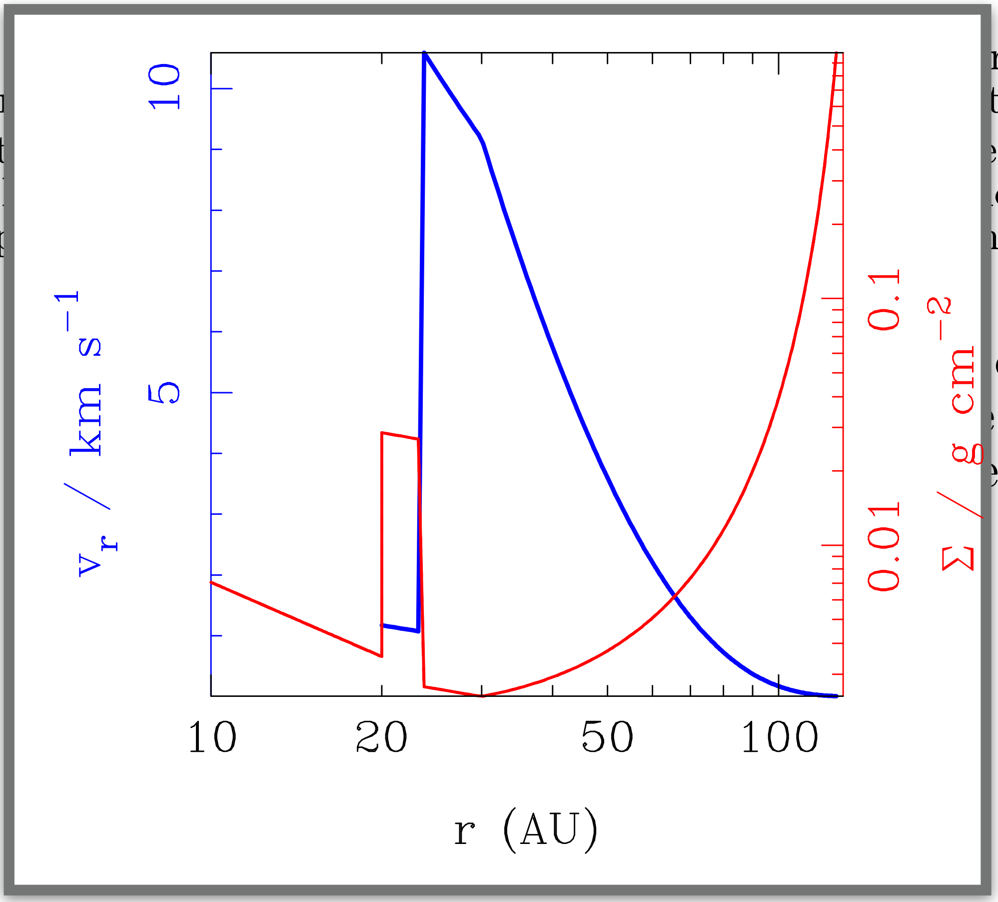


Figure 7. Comparison of observed and model CO(6-5) kinematics in … rdinates is set to
the stellar position. Velocity-integrated intensity in CO(6-5) is shown i … tant interval and
are spread over $[0.21, 7.87]$ km s^{-1} (as in Fig. 1). **a)**: Observed moment … ents extracted on
the radiative transfer 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).

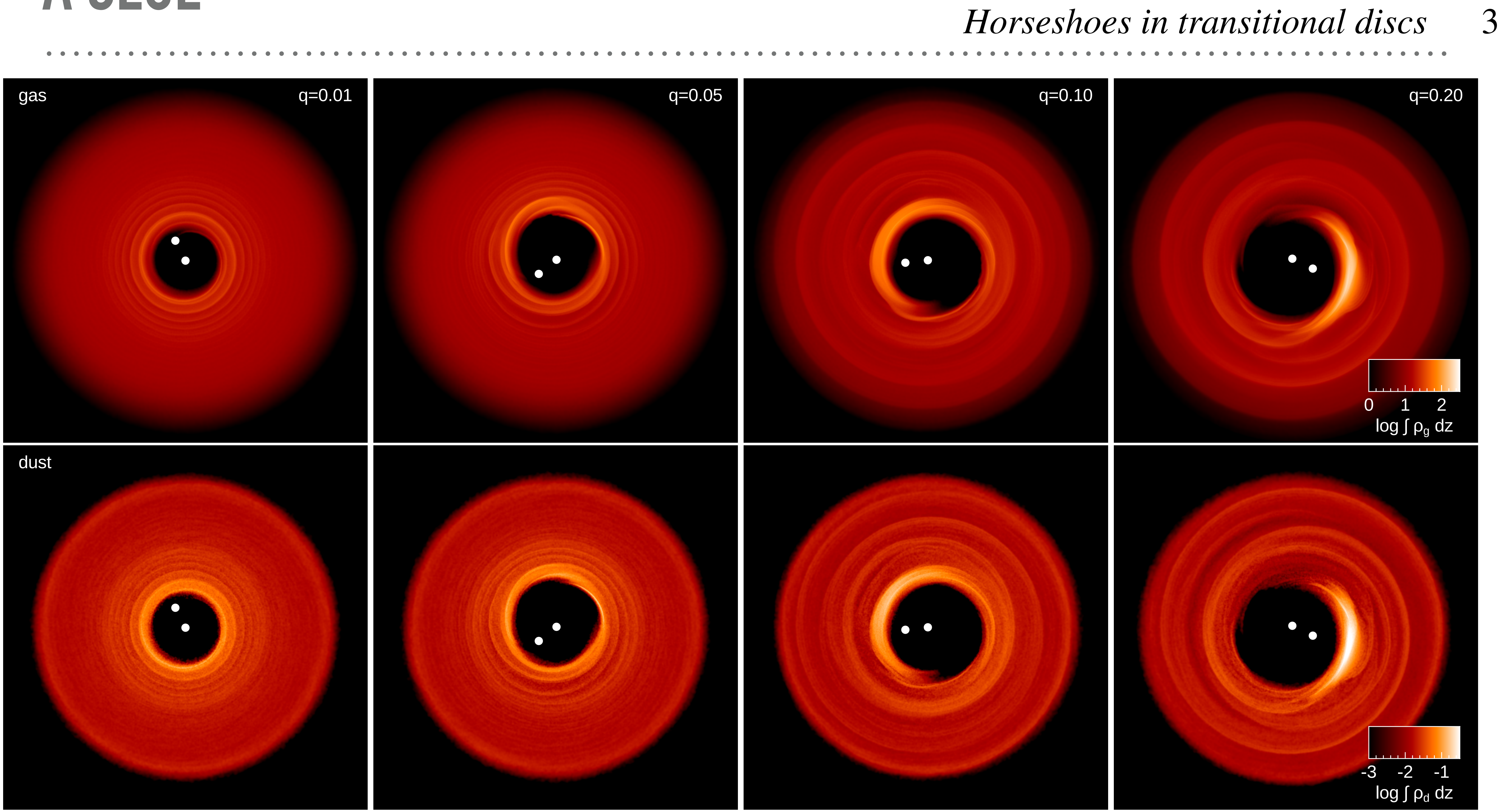
dubbed disk tearing (Nixon et al. 2013; Nealon et al. 2015; Doğan et al. 2015), where nodal precession torques induced by the binary produce a warp at the inner edge

companion on
100 AU scale
cavity. It is

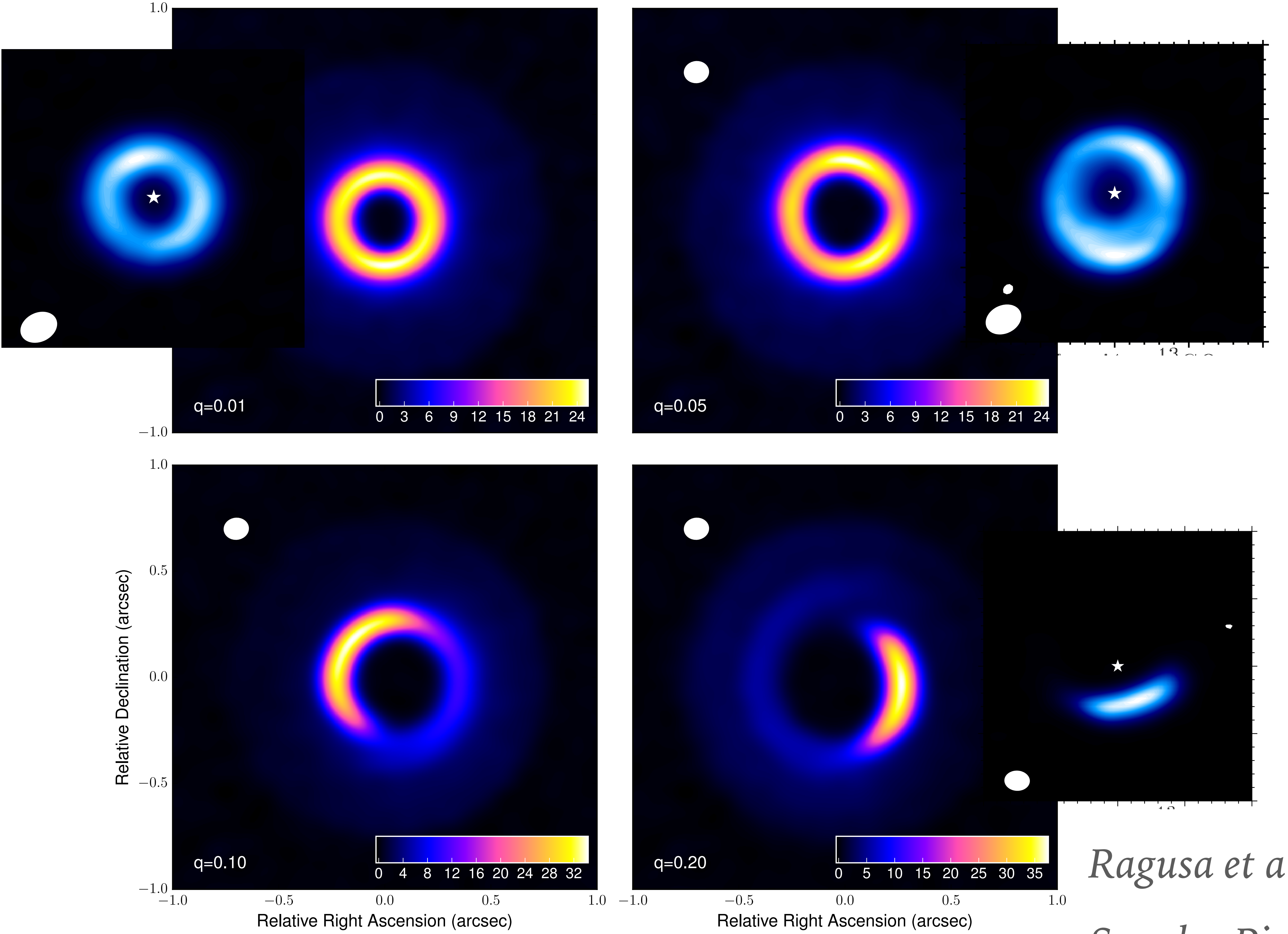
Require infall motions from cavity edge at the free-fall velocity!



A CLUE



Ragusa et al. (2017), see also Ataiee et al. (2013)



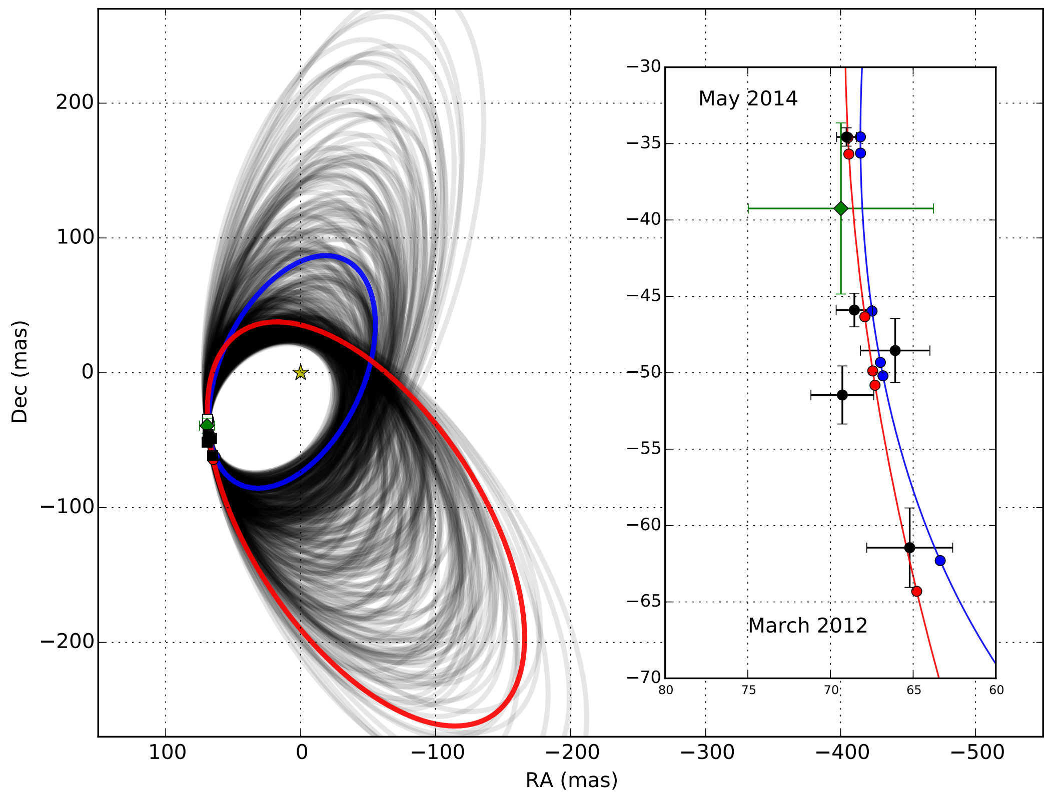
Ragusa et al. (2017)

See also Pinilla+ (2018)

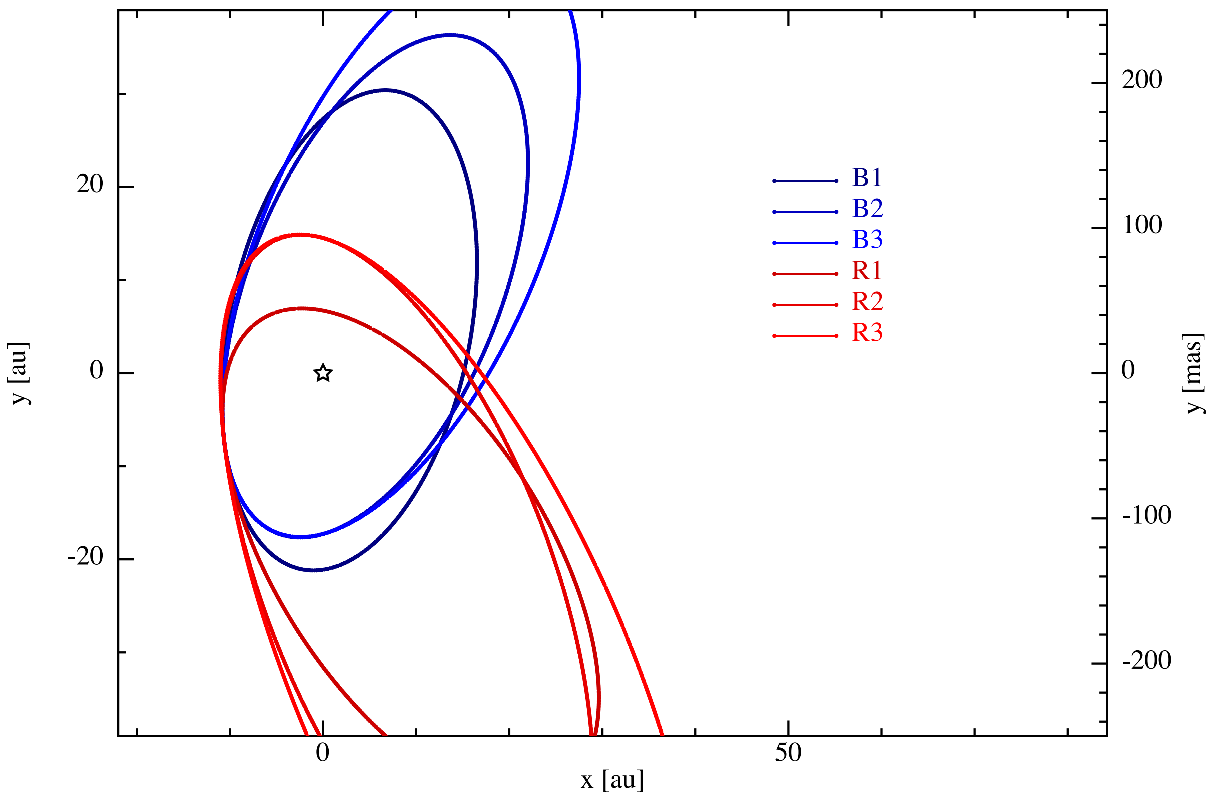
Figure 2. Comparison of ALMA simulated observations at 345 GHz of disc models with a mass ratio $q = 0.01$ (upper left), $q = 0.05$ (upper right), $q = 0.1$ (bottom left) and $q = 0.2$ (bottom right). Intensities are in mJy beam^{-1}. The white colour in the filled ellipse in the upper left corner indicates the size of the half-power contour of the synthesized beam: 0.12×0.1 arcsec ($\sim 16 \times 13$ au at 130 pc.).

MODELLING HD142527

Price et al. (2018), MNRAS 477, 1270



Lacour et al. (2016)

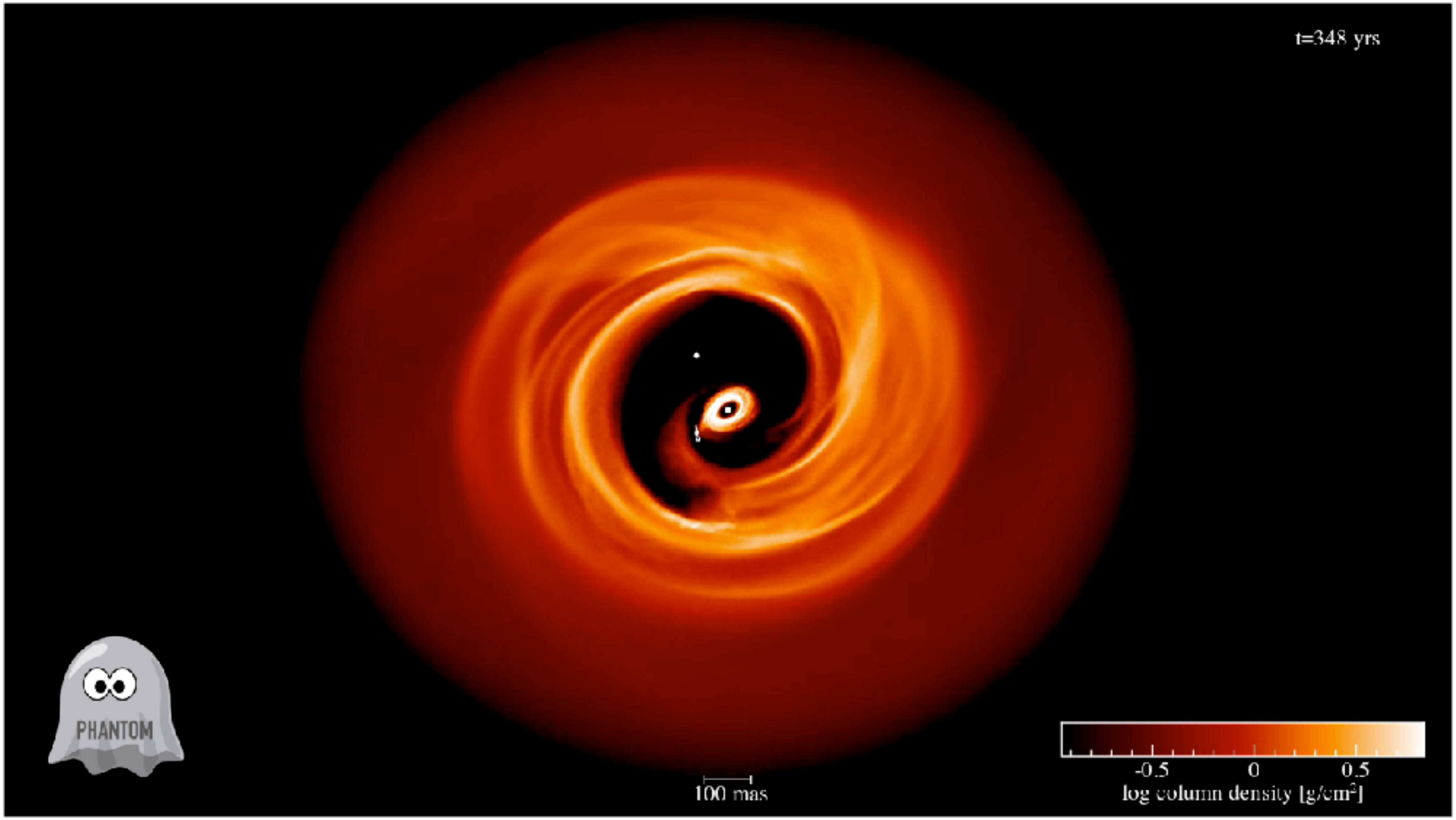


Orbital arc fits using IMORBEL (Pearce, Kennedy & Wyatt 2015)

	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

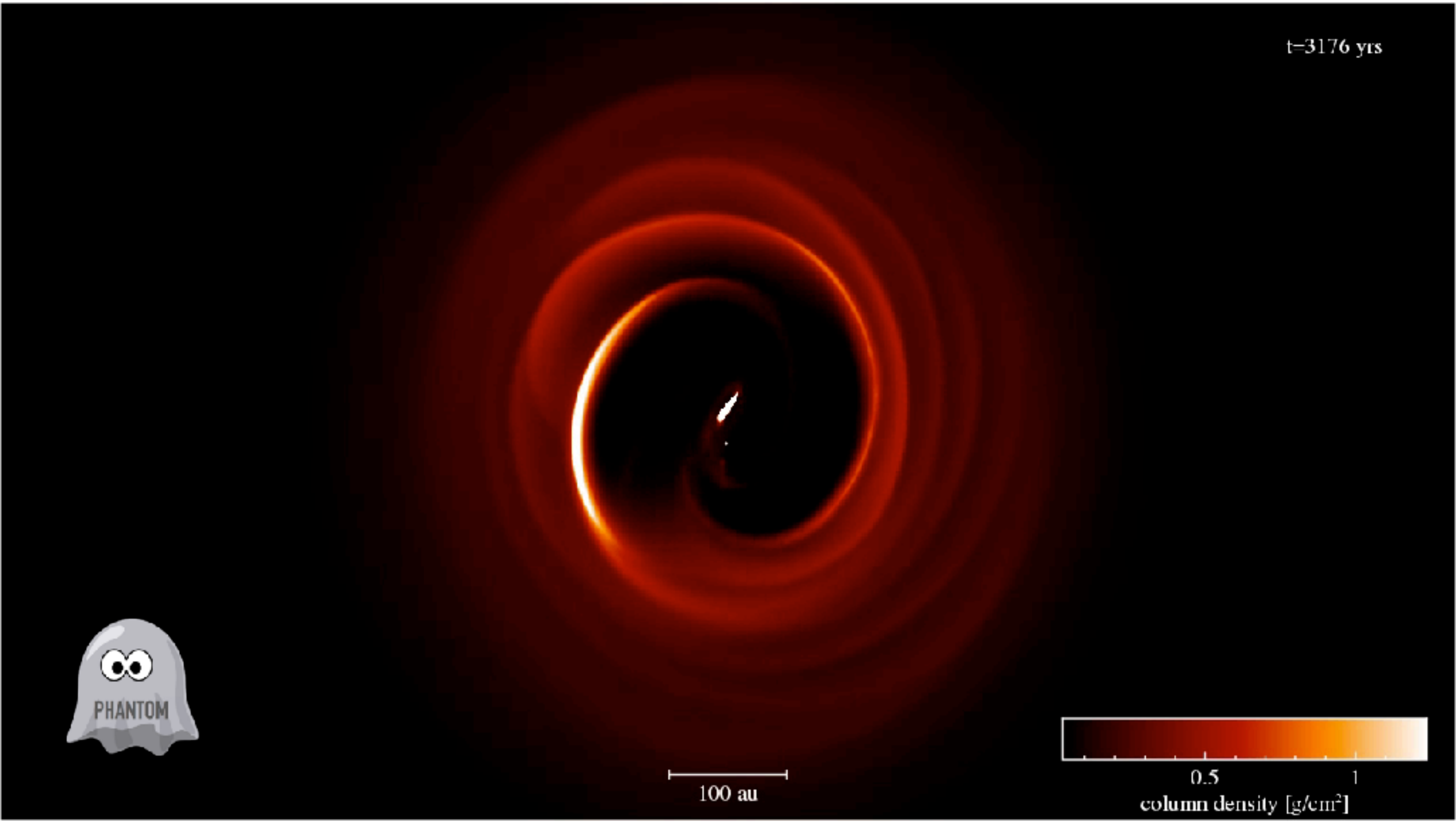
BLUE ORBIT

Price et al. (2018)



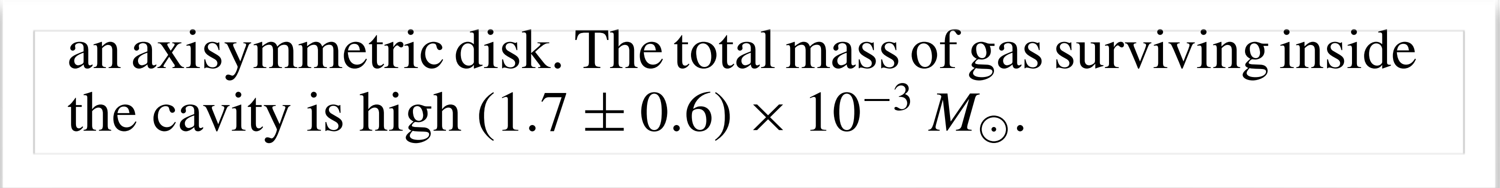
RED ORBIT

Price et al. (2018)

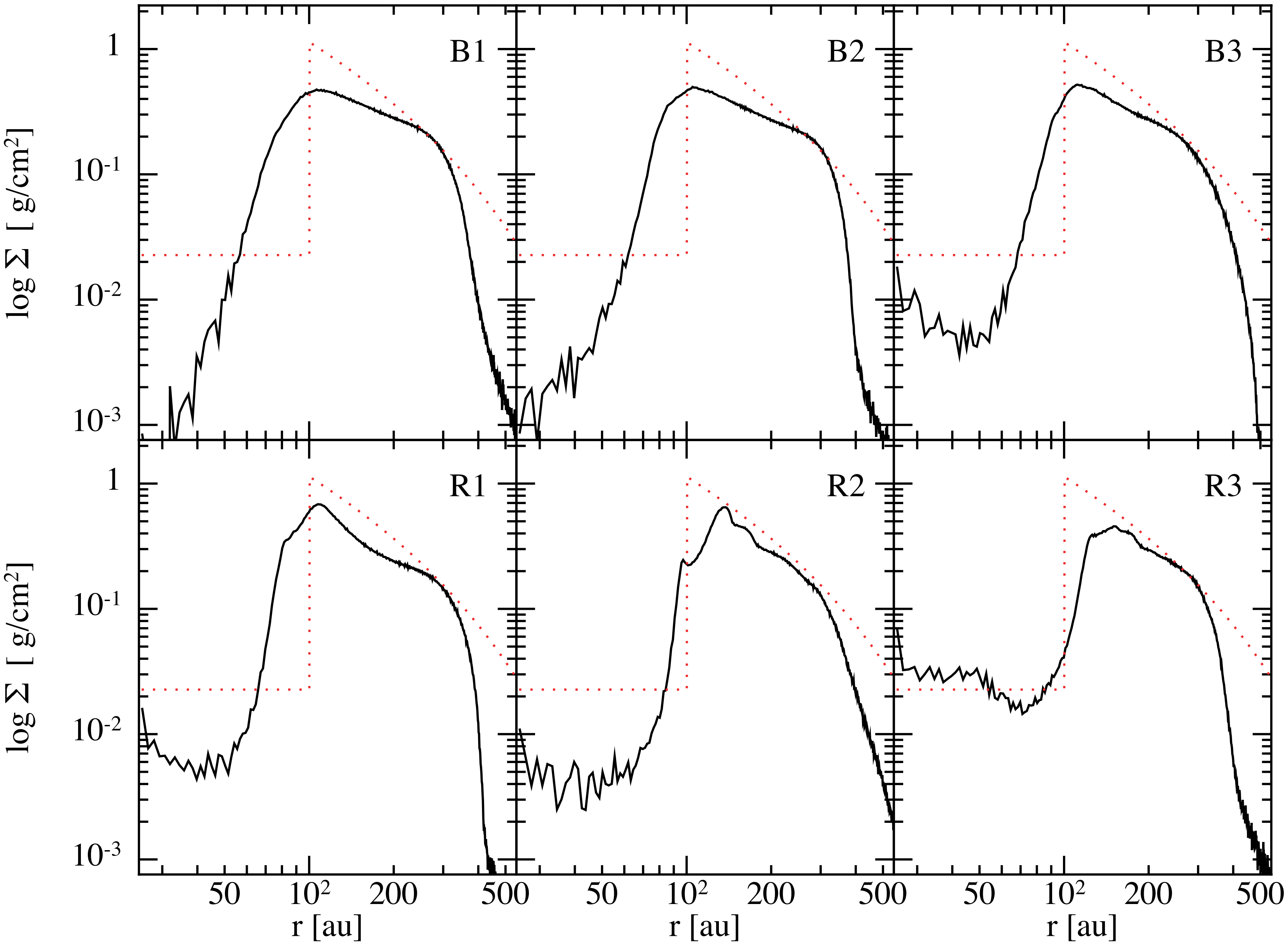


See almost polar alignment of binary to disc, c.f. Aly et al. (2015), Martin & Lubow (2017)

CAVITY SIZE *Perez+(2015)*



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



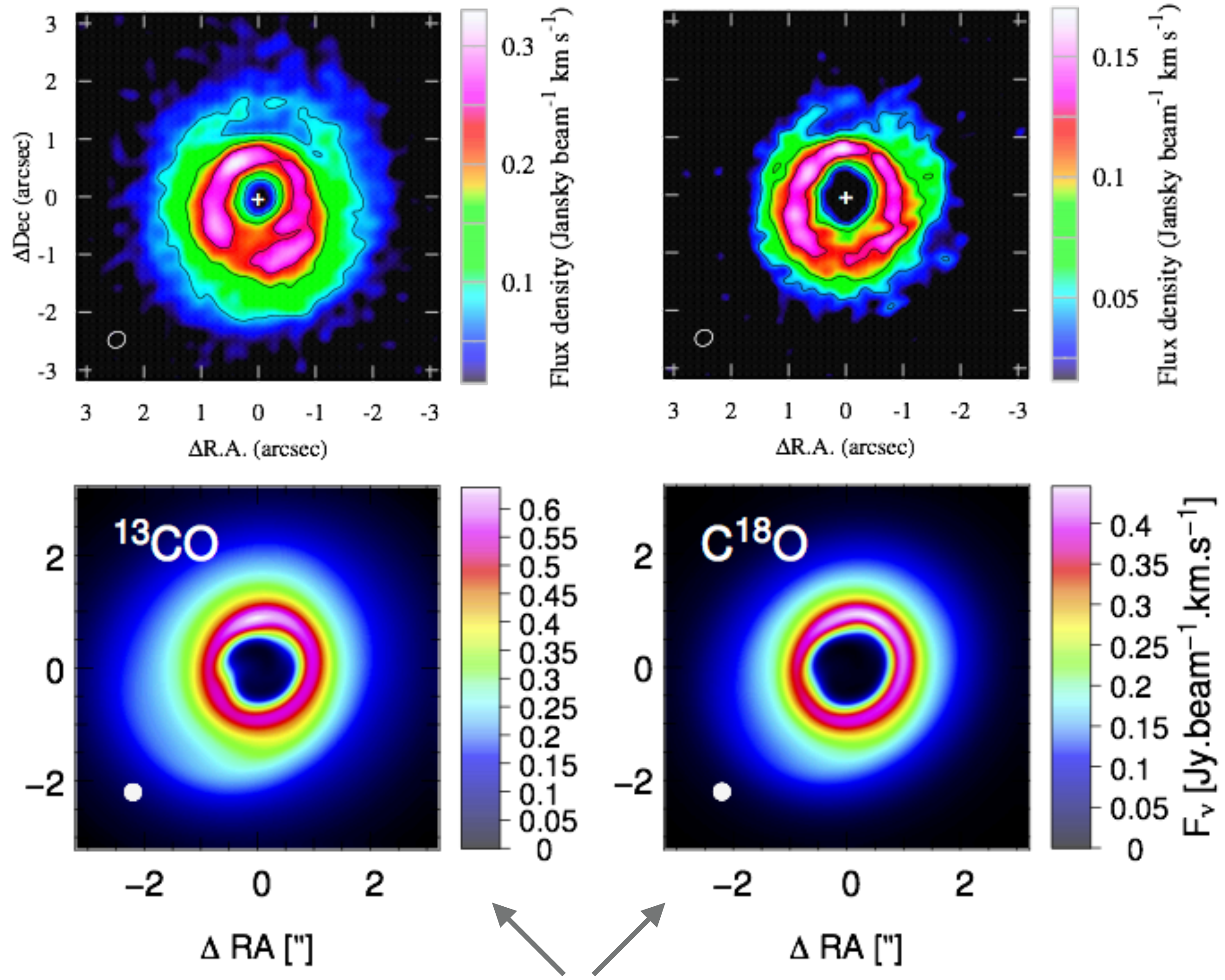
Mass inside the cavity:

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)

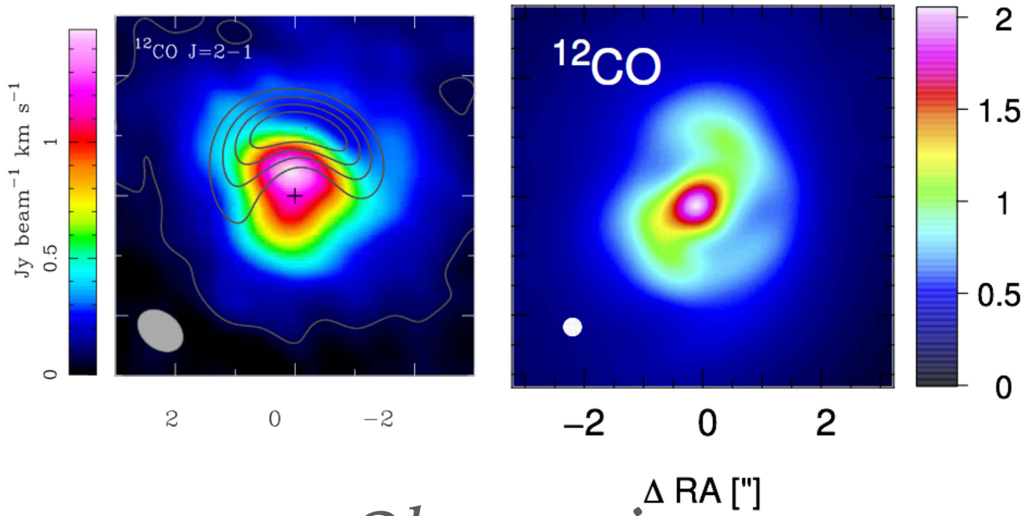
Observations



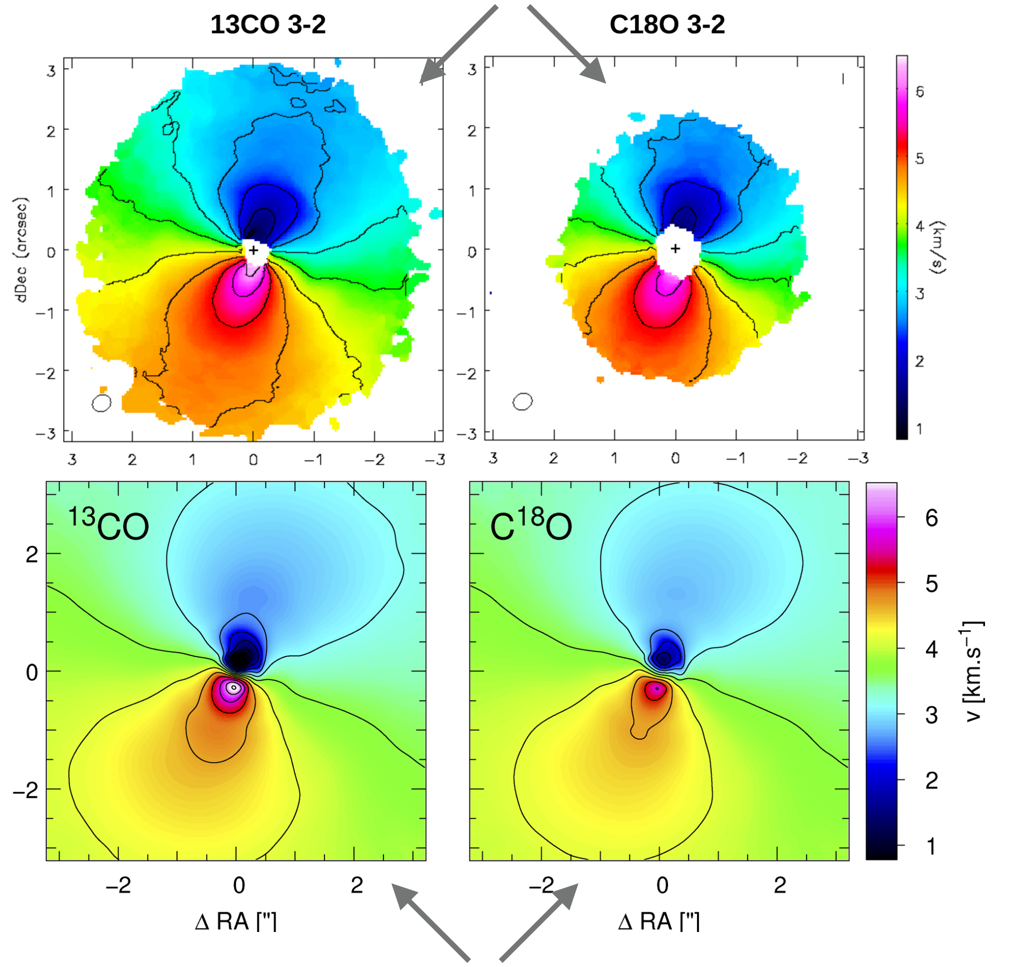
Simulations

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

Obs *Simulation*

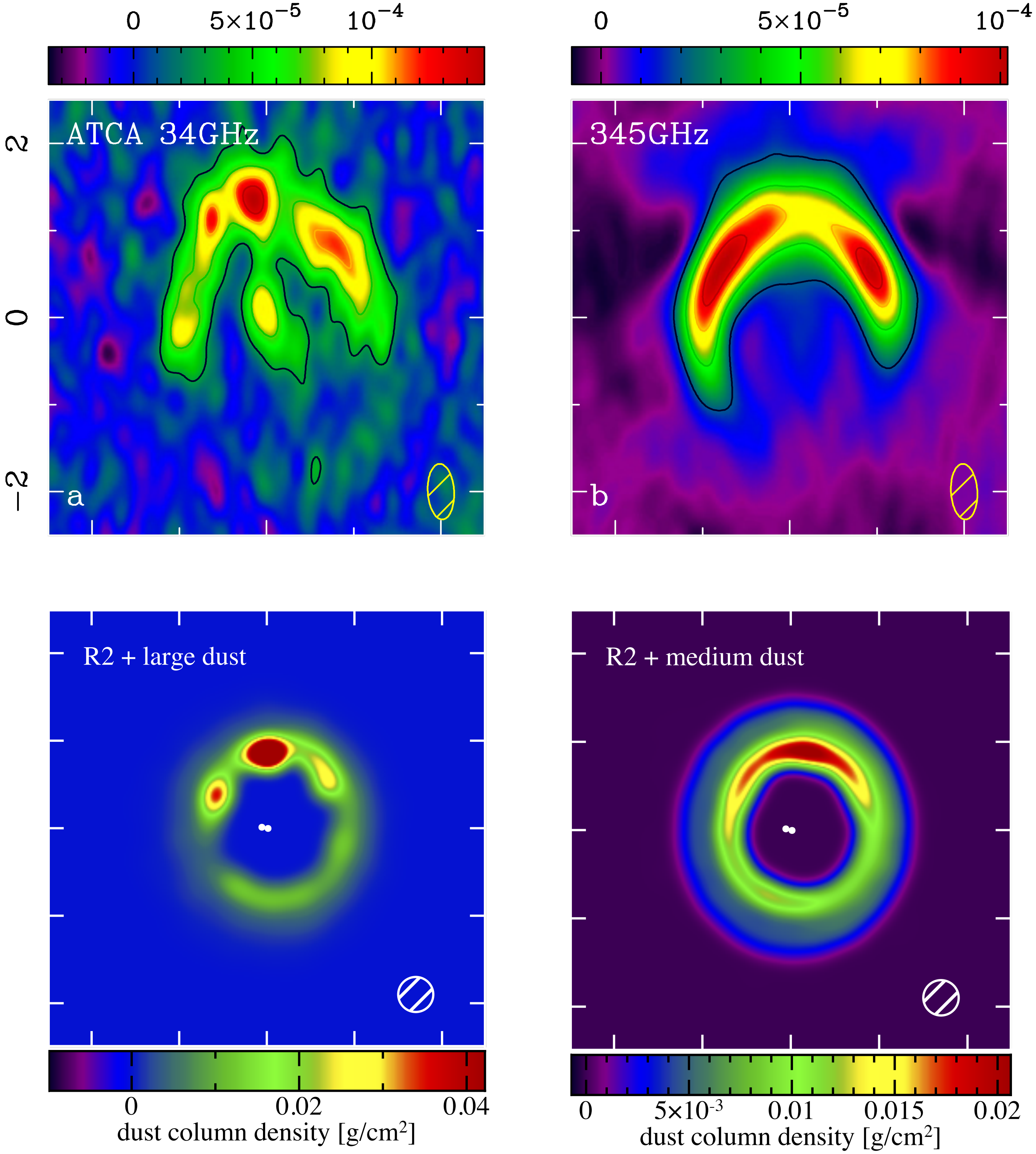


Observations



Simulations

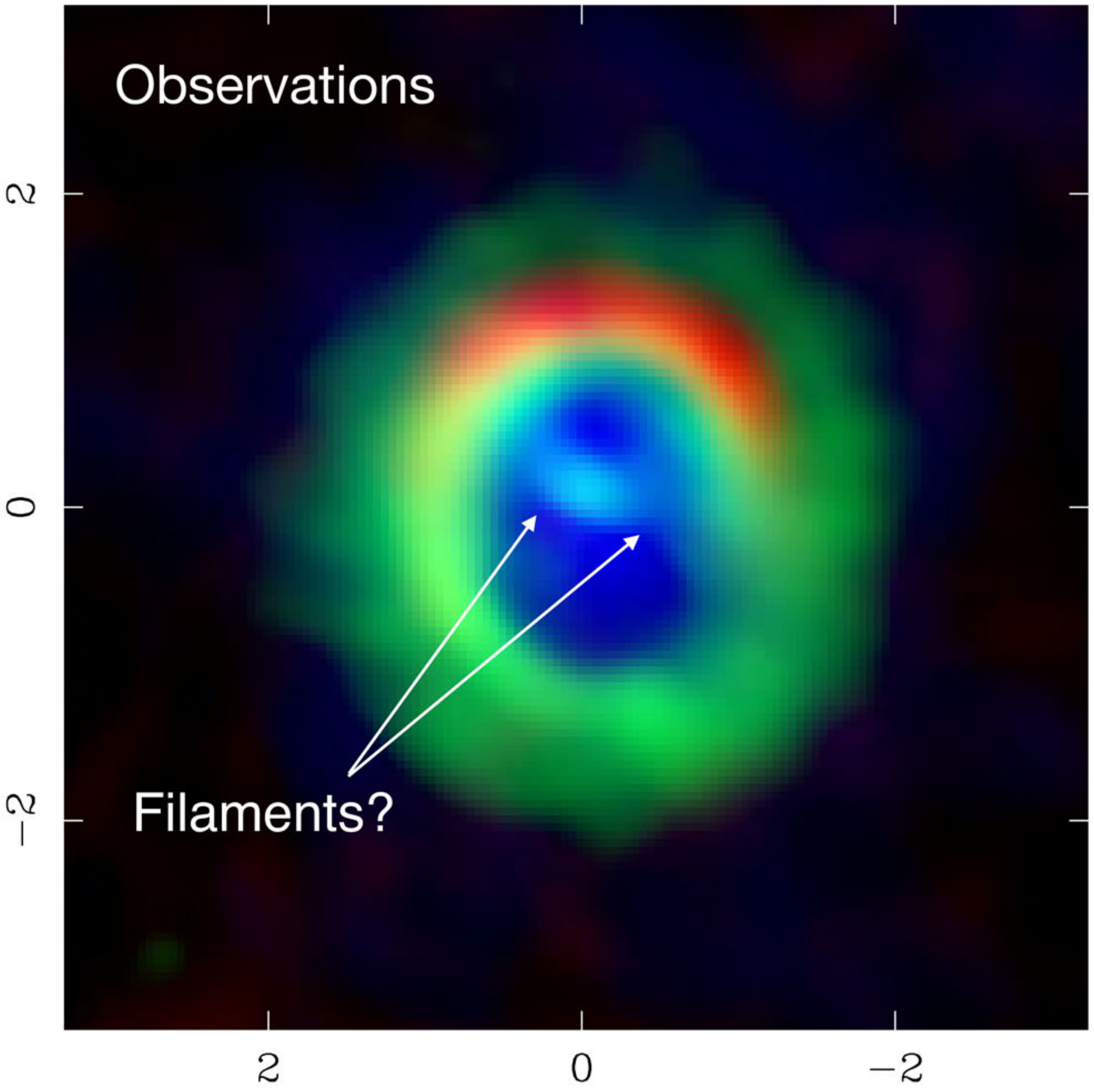
HORSESHOE



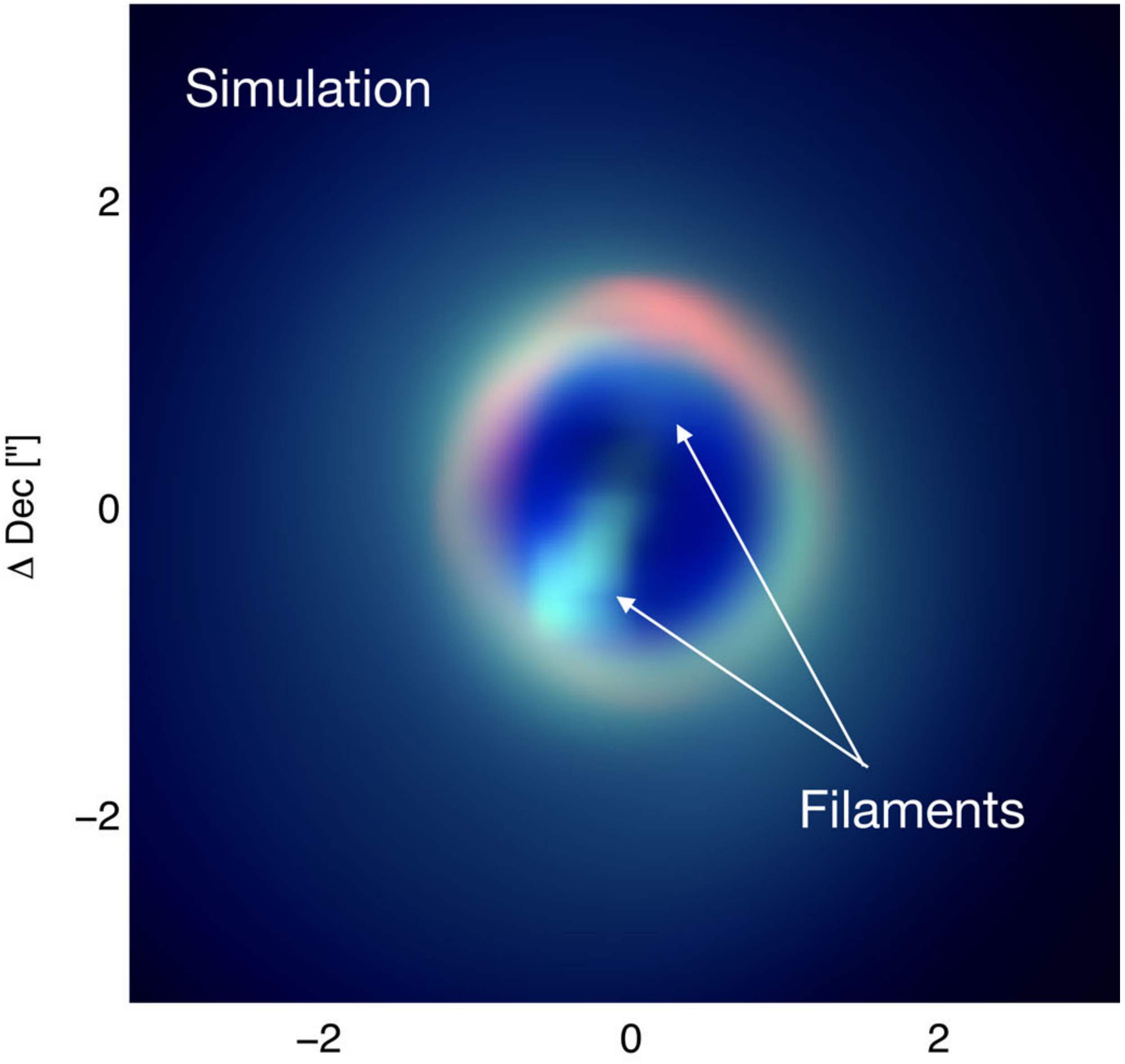
Observations

Simulations

GAP CROSSING FILAMENTS



Casassus et al. (2015)

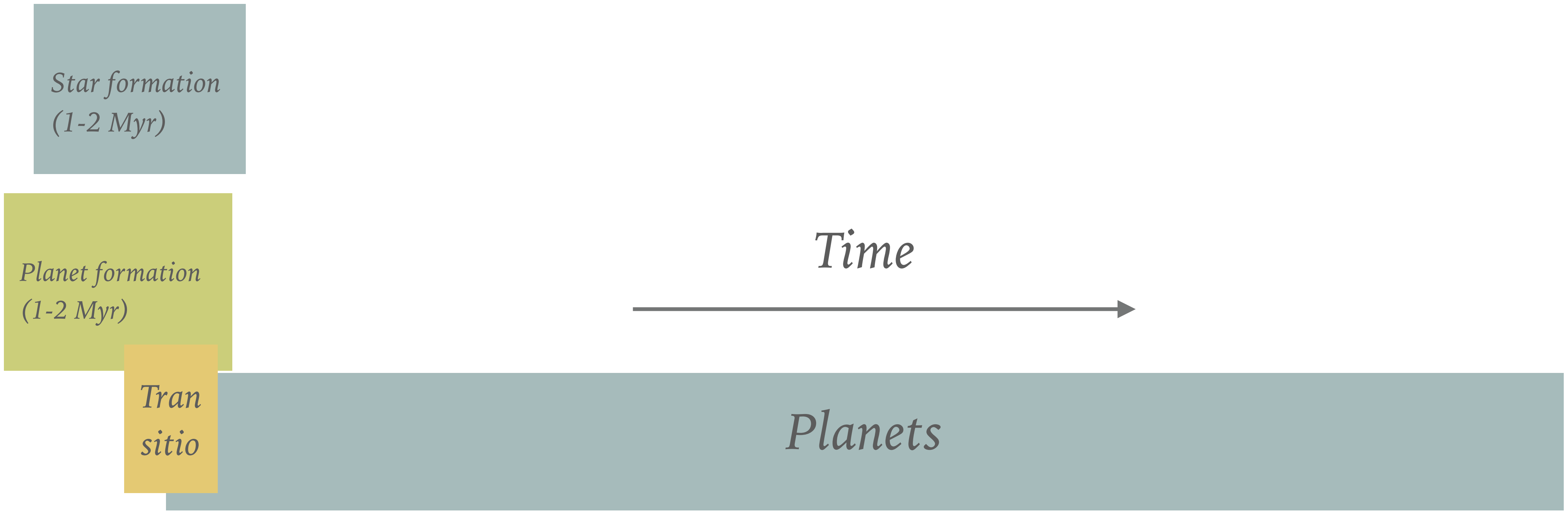


Price et al. (2018)

SUMMARY

- Every disc imaged so far shows signs of interaction with already-formed planets or low mass companions
- Lots of discs similar to HD142527 - disturbed morphologies, asymmetries, spirals. Suggests highly misaligned, eccentric companions are common?
- Discs with holes telling us about chaotic star formation - how discs are born - not how they die
- Suggests planet formation occurs on < 5 Myr timescales

NEW VIEW?

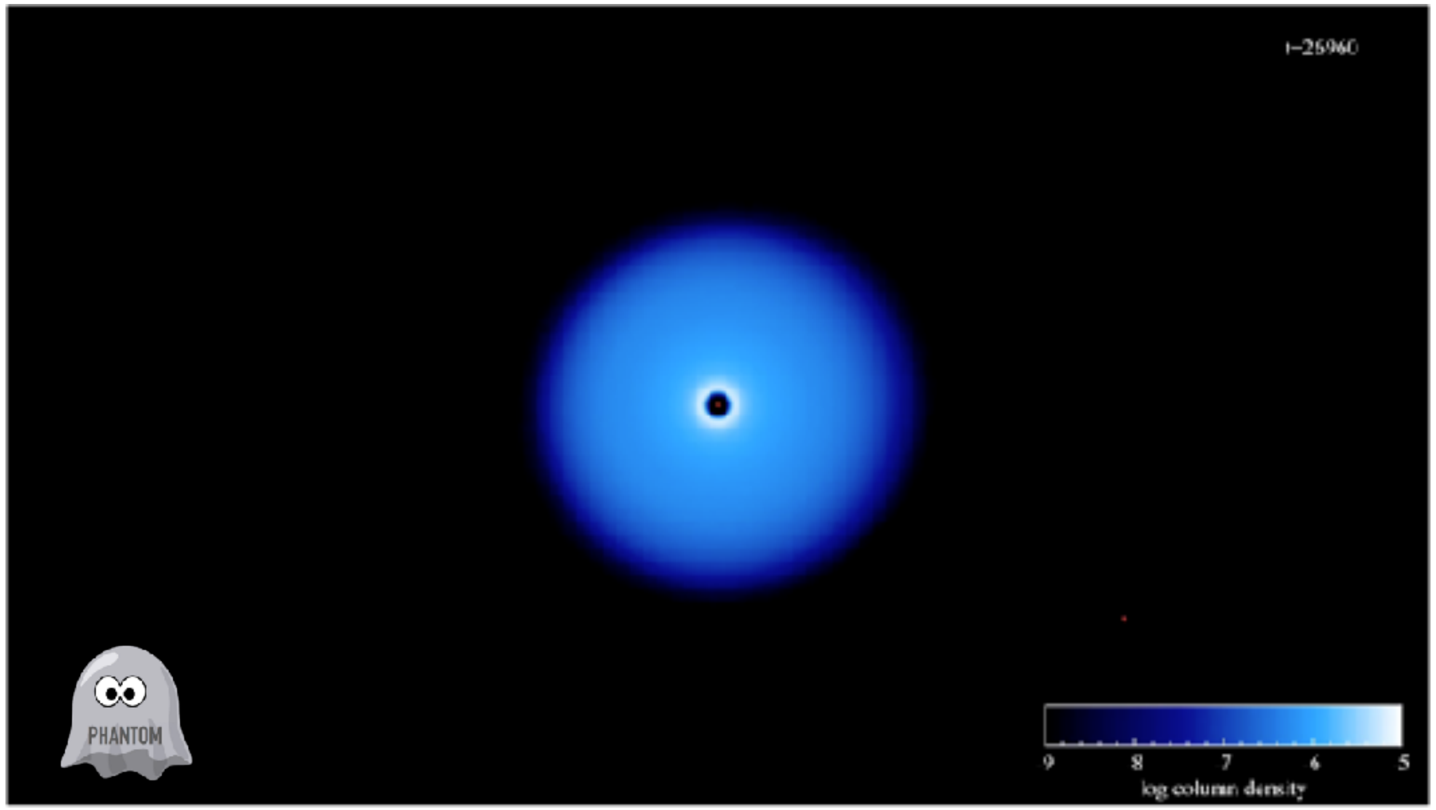


Hypothesis: Star and planet formation are both fast, dynamical processes

PREDICTIONS:

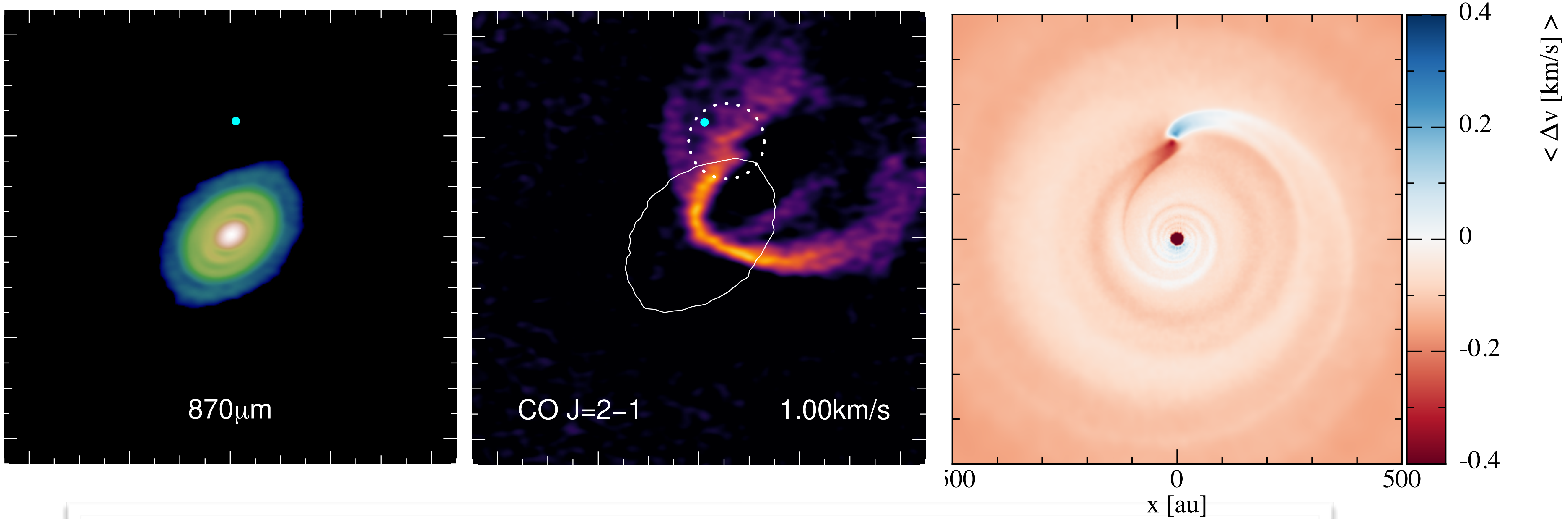
Lodato & Price (in prep)

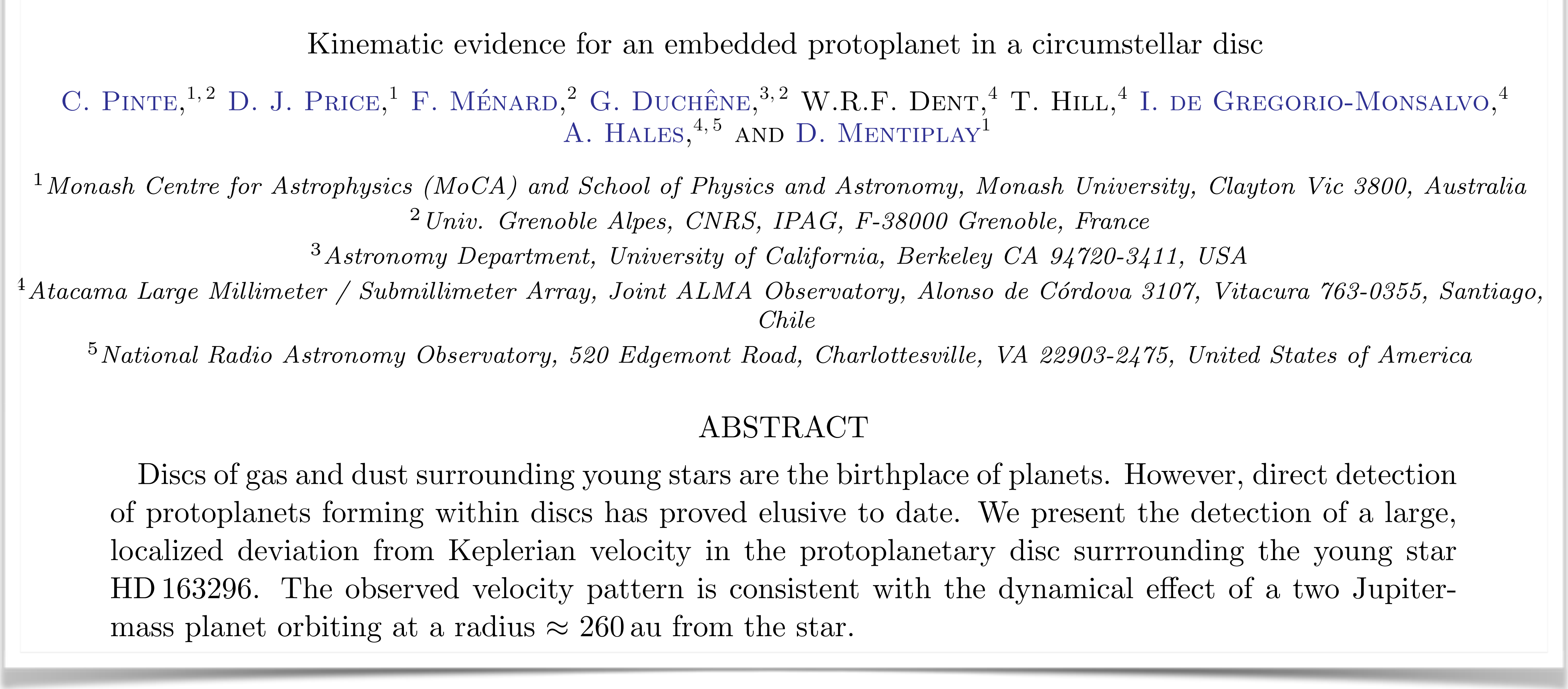
- Expect lots more discs with companions on wild orbits
- Discs around more massive stars should be more disturbed
- Rings and gaps caused by planets will be found everywhere
- Tidal encounters common!



Credit: Nicolás Cuello

BUT WHERE ARE THE PLANETS?





Kinematic evidence for an embedded protoplanet in a circumstellar disc

C. Pinte,[1,2] D. J. Price,[1] F. Ménard,[2] G. Duchêne,[3,2] W.R.F. Dent,[4] T. Hill,[4] I. de Gregorio-Monsalvo,[4]
A. Hales,[4,5] and D. Mentiplay[1]

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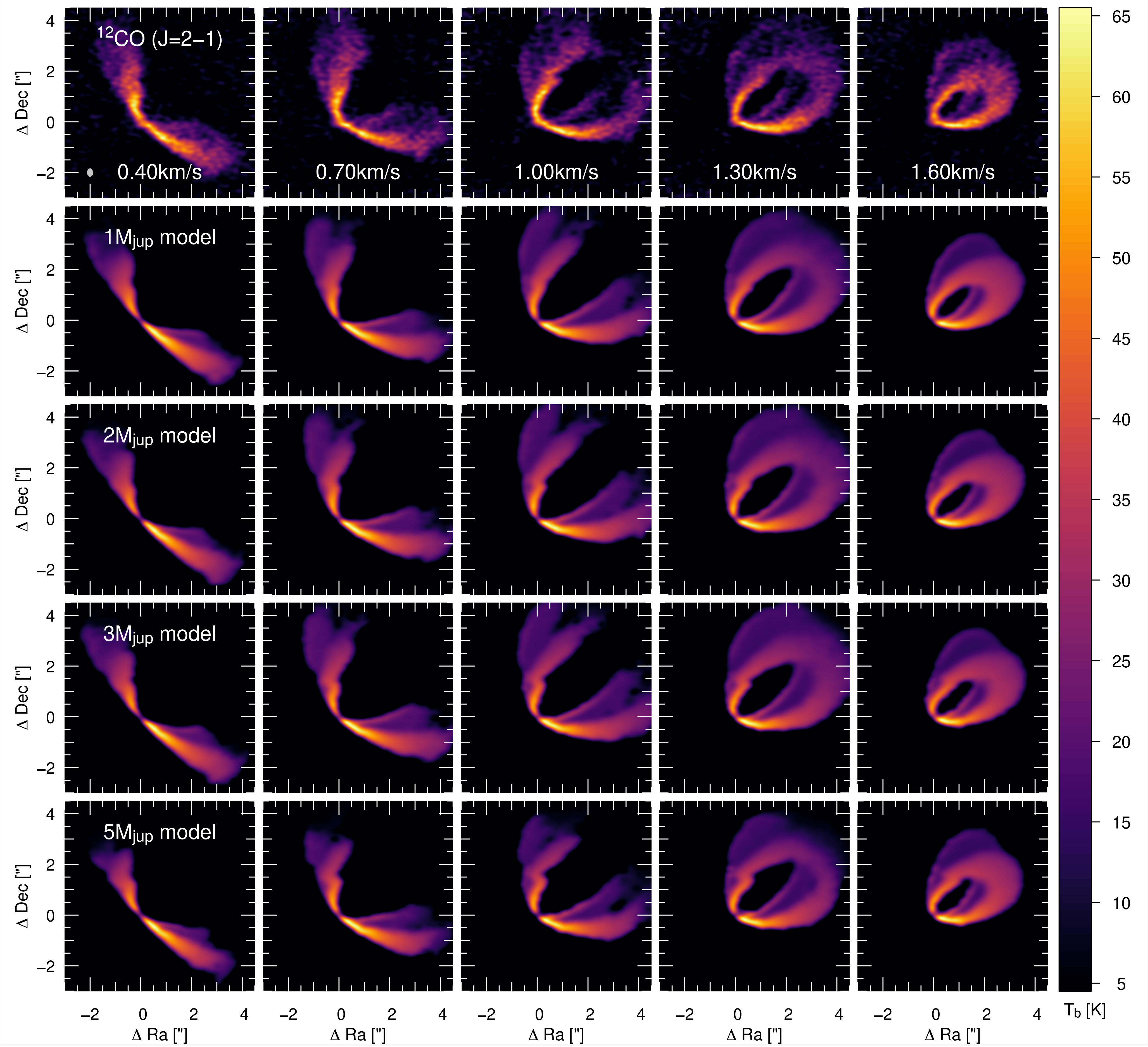
ABSTRACT

Discs of gas and dust surrounding young stars are the birthplace of planets. However, direct detection of protoplanets forming within discs has proved elusive to date. We present the detection of a large, localized deviation from Keplerian velocity in the protoplanetary disc surrrounding the young star HD 163296. The observed velocity pattern is consistent with the dynamical effect of a two Jupiter-mass planet orbiting at a radius ≈ 260 au from the star.

See also Teague et al. (2018) for claims of more planets in HD163296!


^{12}CO (J=2–1)
0.40km/s
0.70km/s
1.00km/s
1.30km/s
1.60km/s
1M$_{\rm jup}$ model
2M$_{\rm jup}$ model
3M$_{\rm jup}$ model
5M$_{\rm jup}$ model
Δ Dec ["]
Δ Ra ["]
4
2
0
−2
−2
0
2
4
T$_b$ [K]
65
60
55
50
45
40
35
30
25
20
15
10
5