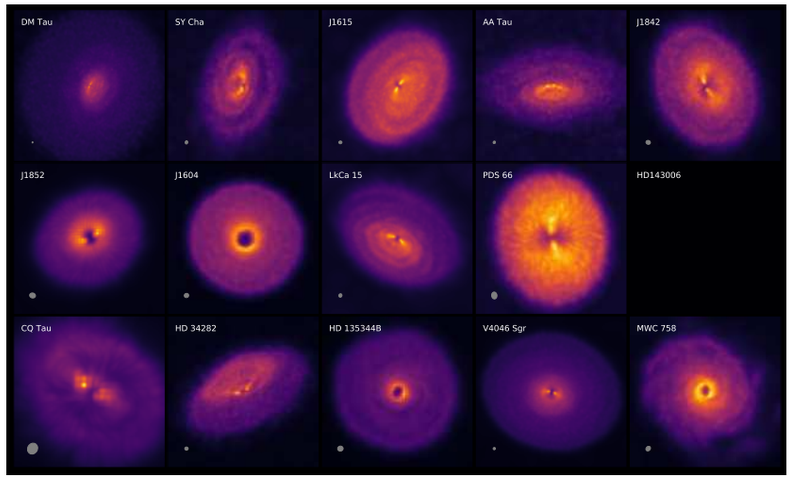


THE BABY

DANIEL PRICE

LE CANARD

BOOM

WITH CHRISTOPHE PINTE, IAIN HAMMOND, VALENTIN CHRISTIAENS, TOM HILDER, ELLI BORCHERT, HIMANSHI GARG HARRISON VERRIOS, NICOLÁS CUELLO, CLAUDIA TOCI, JOSH CALCINO, FRANCESCO BOLLATI, GIUSEPPE LODATO, REBECCA NEALON, J-F GONZALEZ, F. MÉNARD

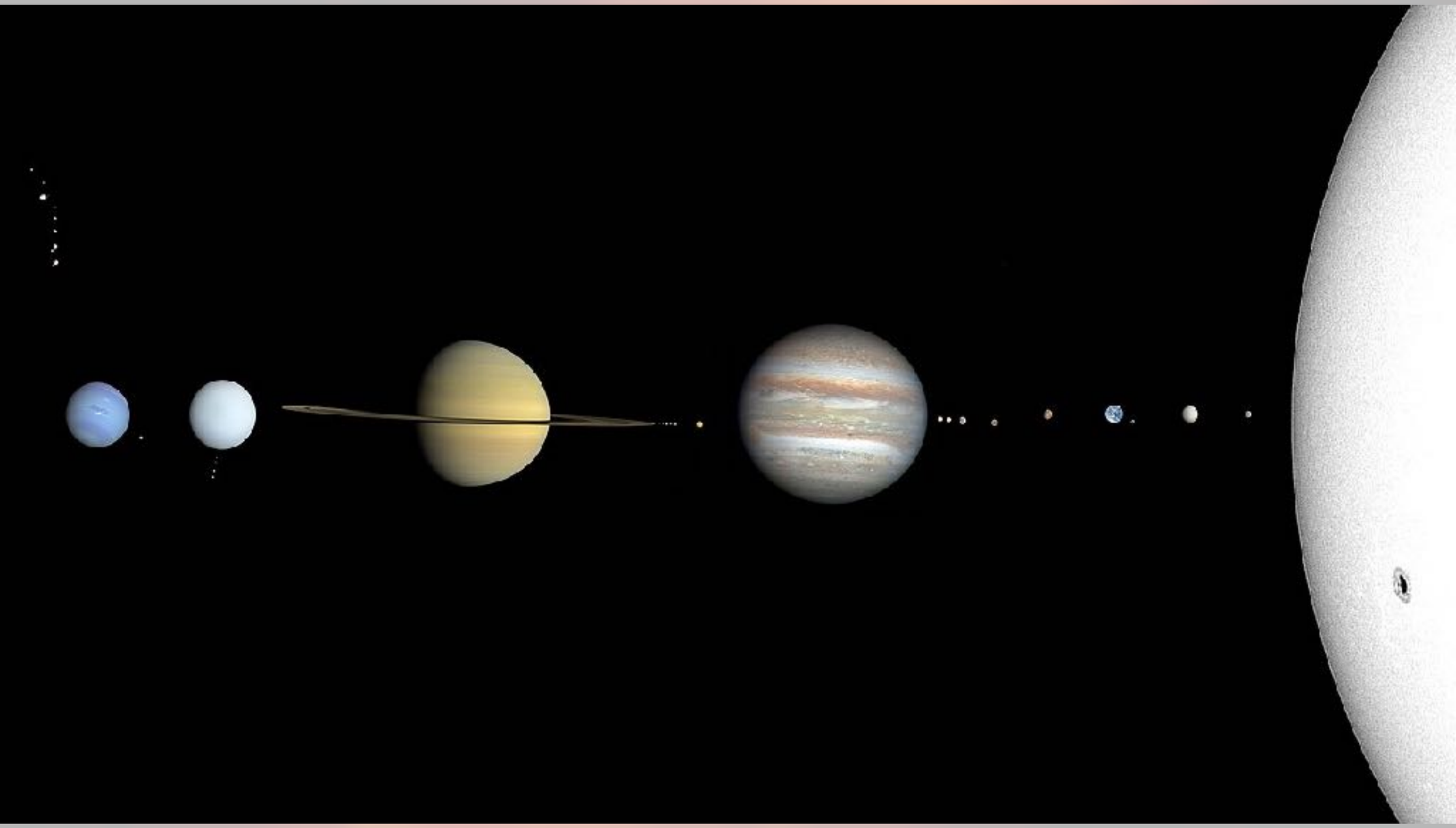
Australian Government
Australian Research Council

DUST BUSTERS

SEMINAR @ IPAG, GRENOBLE, 15TH JUNE 2023

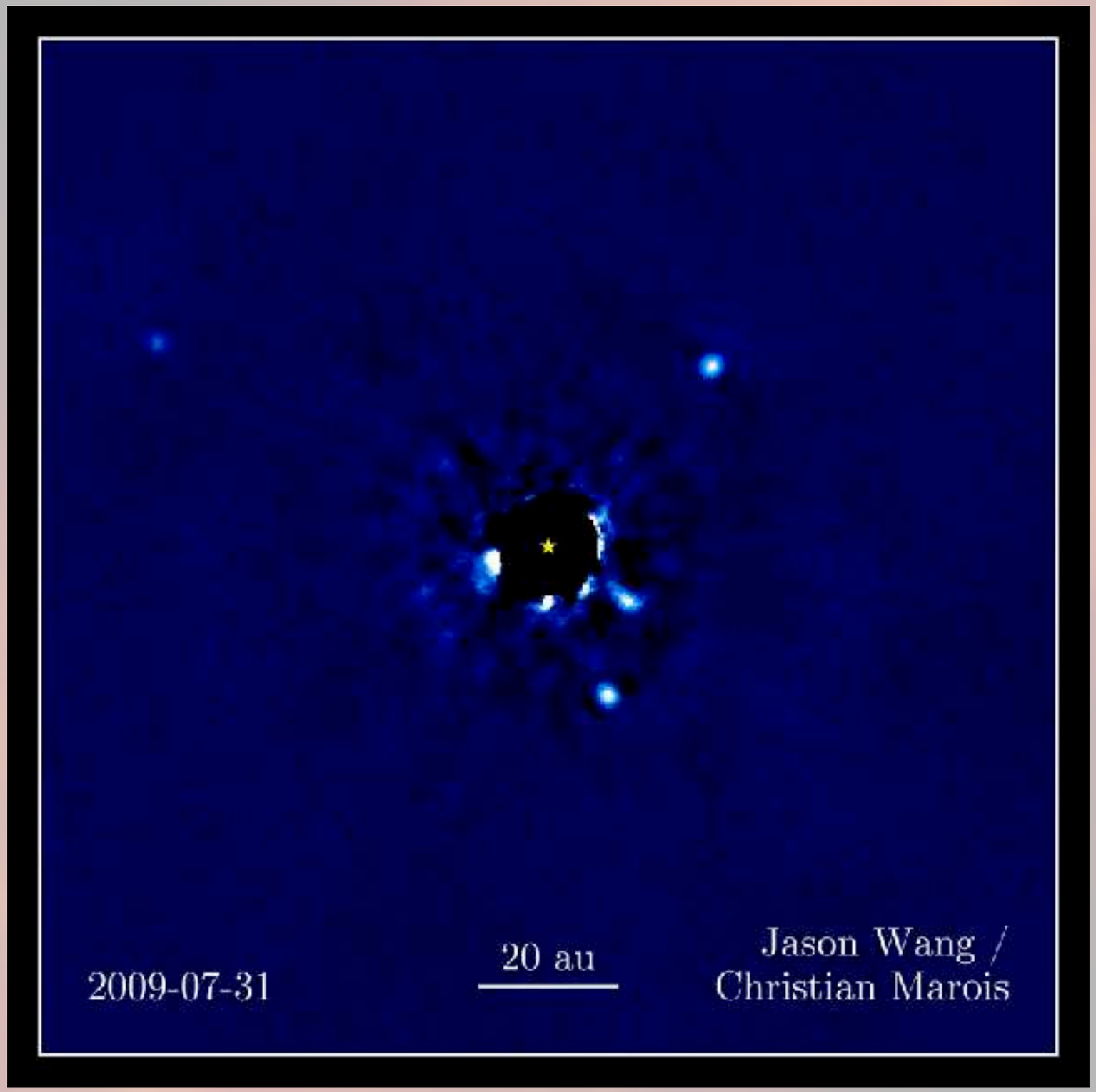
MONASH University

HOW DID THE SOLAR SYSTEM FORM?

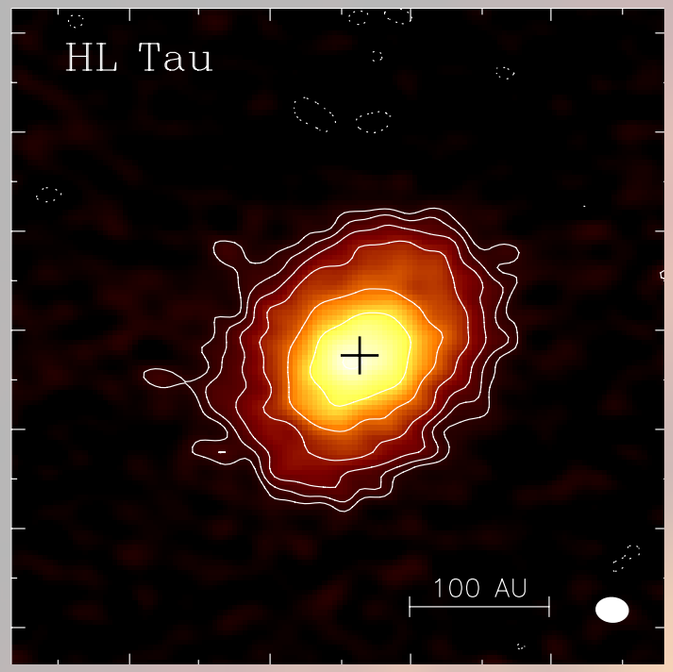


Credit: wikipedia/CactiStaccingCrane

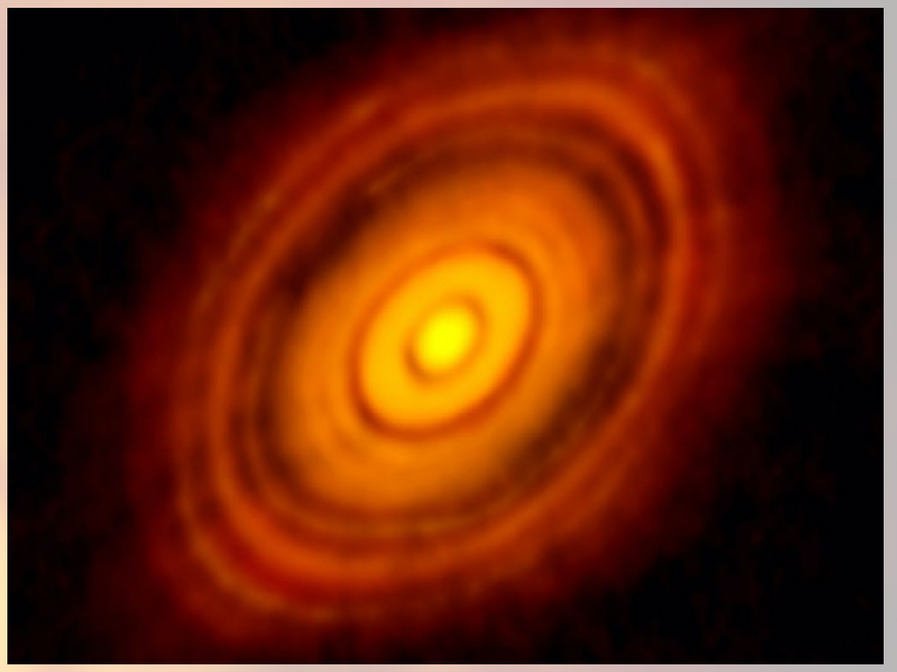
HOW DID OTHER SOLAR SYSTEMS FORM?



OBSERVATIONAL PLANET FORMATION (2015)



Kwon et al. (2011)



ALMA partnership et al. (2015)

Atacama Large Millimetre/submillimetre Array (ALMA)

OBSERVATIONAL PLANET FORMATION (OPTICAL/NIR)

Rings

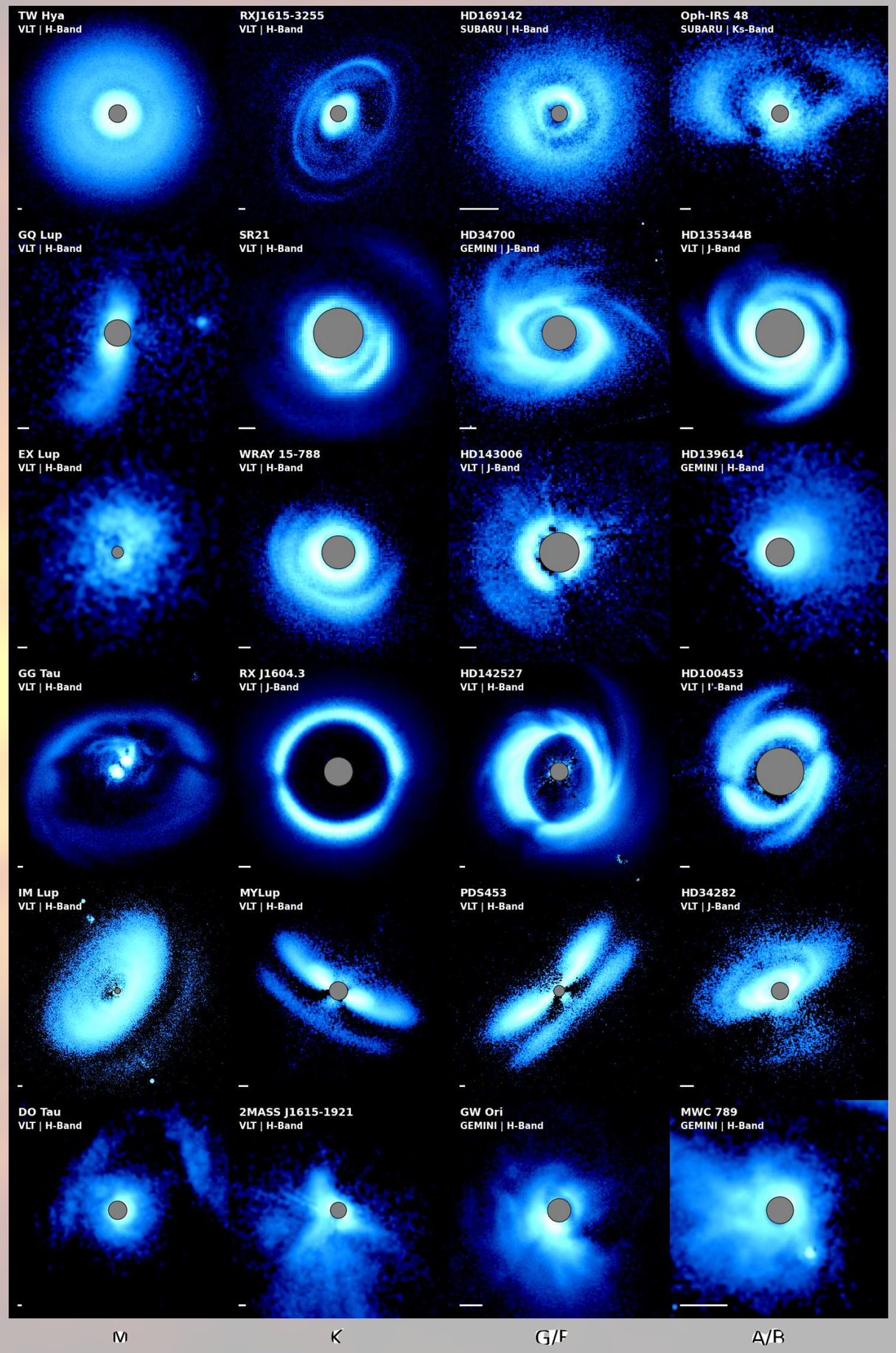
Spirals

Broad Shadows

Narrow Shadows

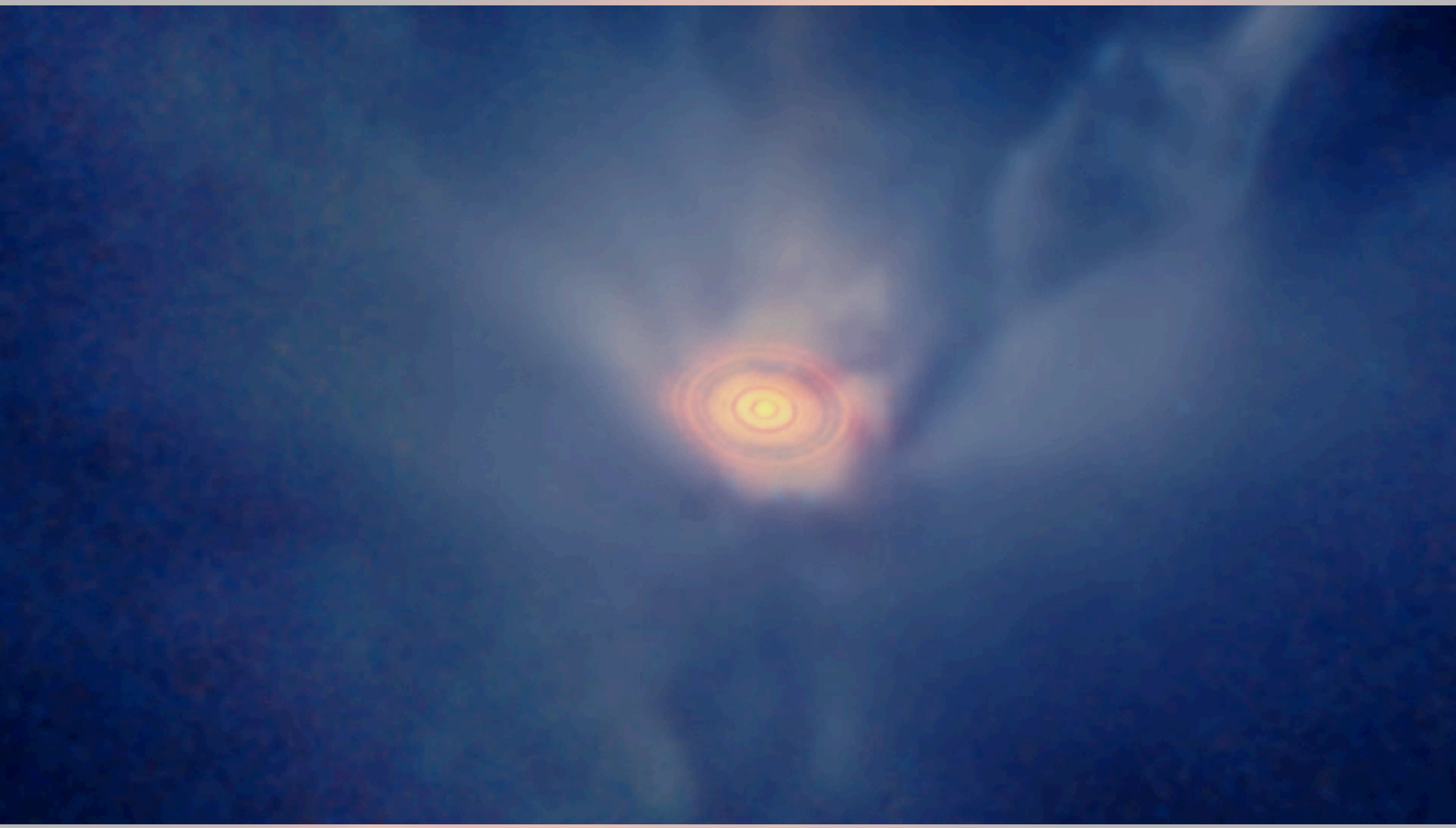
Back Side

Ambient Material



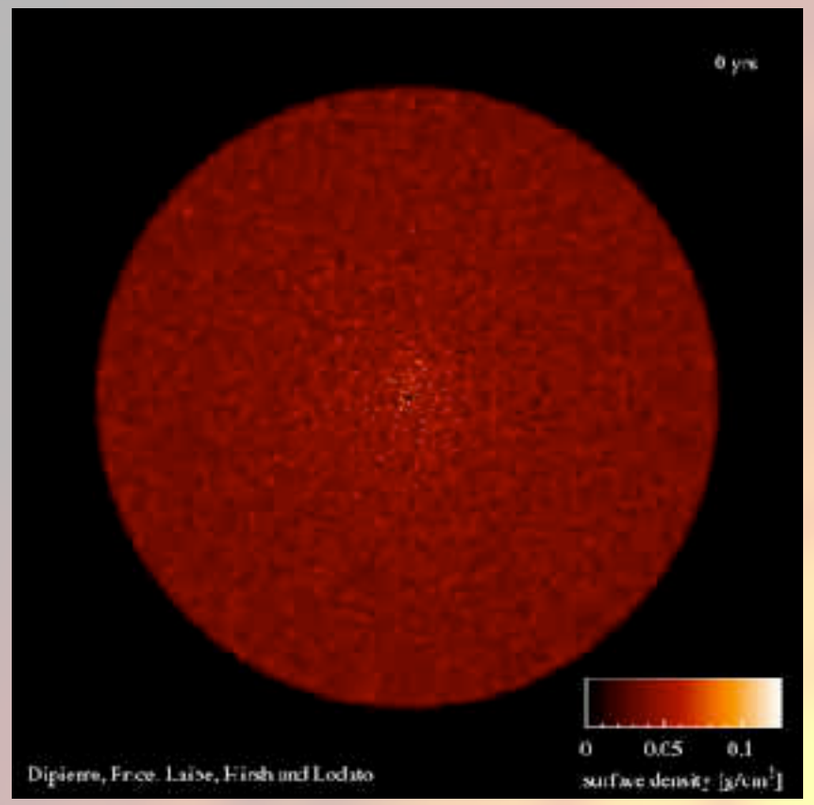
Benisty et al. (2023)

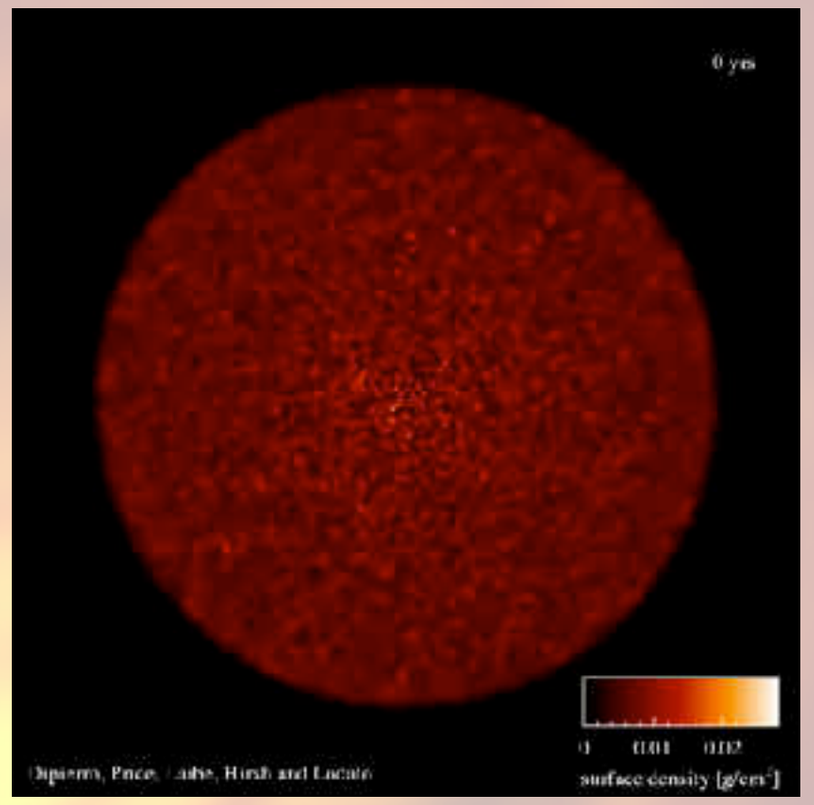
HL TAU

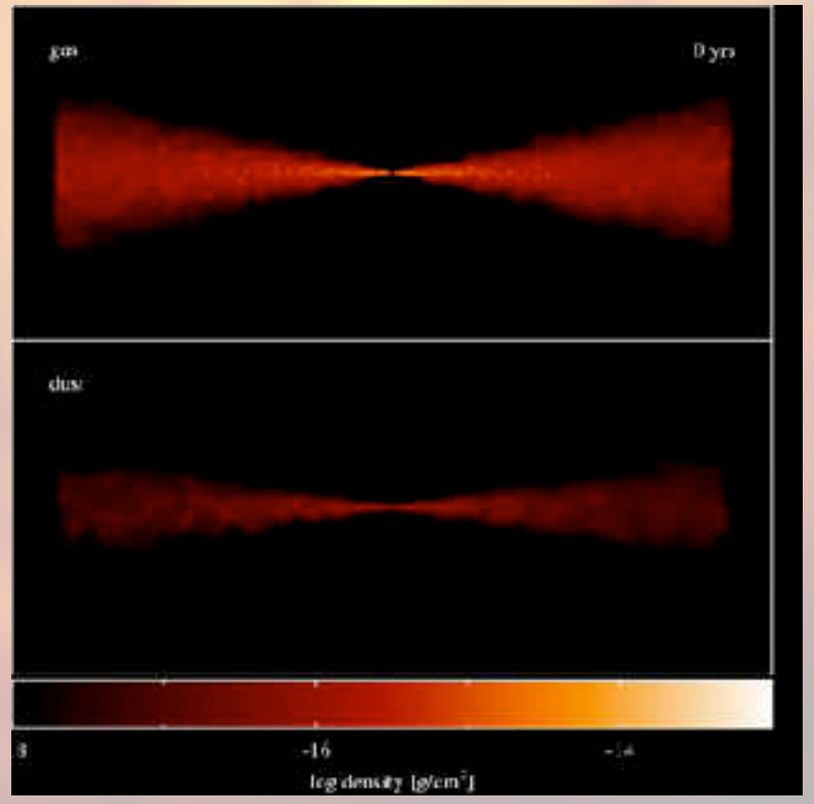


WHAT IS CARVING THE GAPS?

But why are no spirals seen?



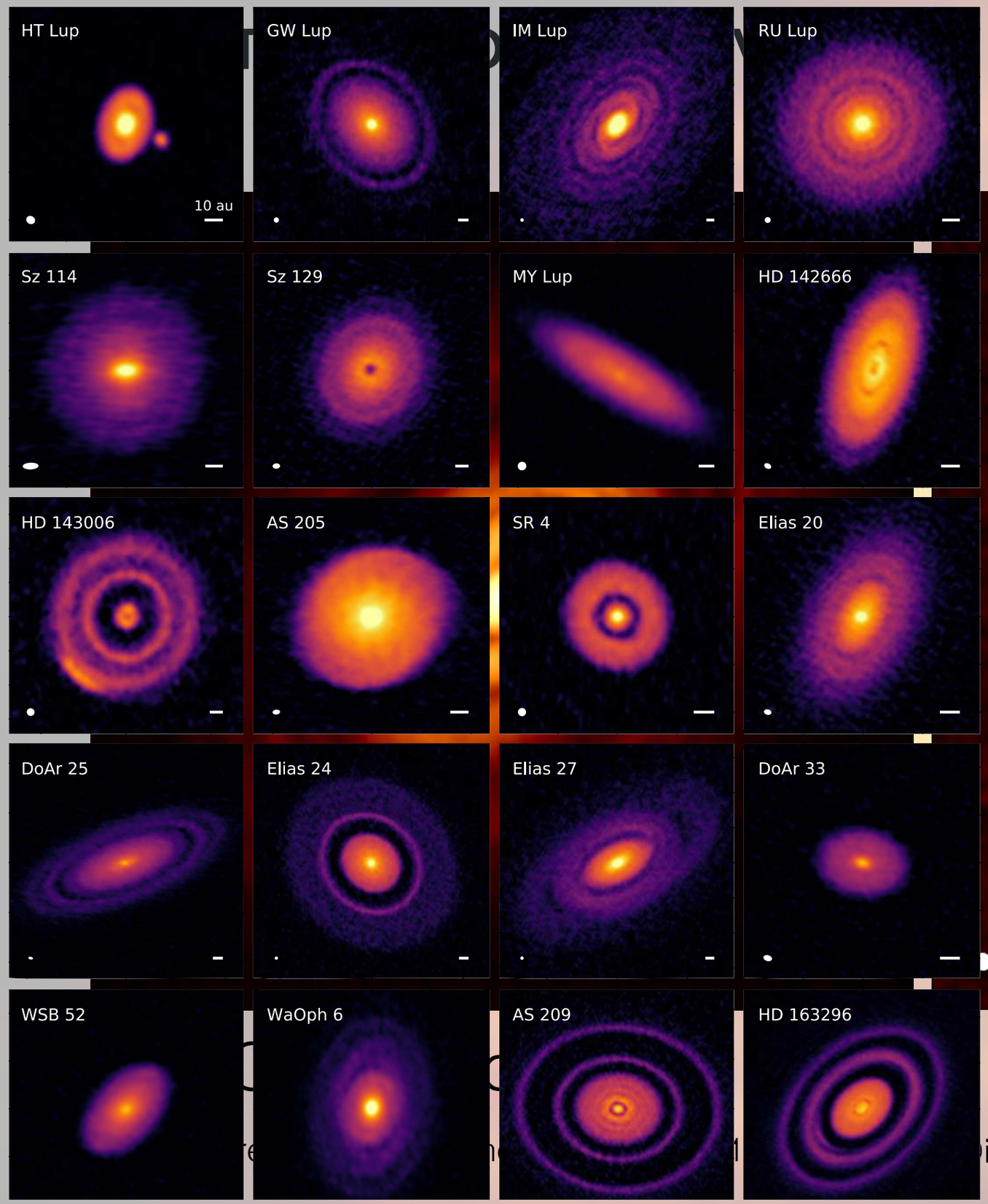


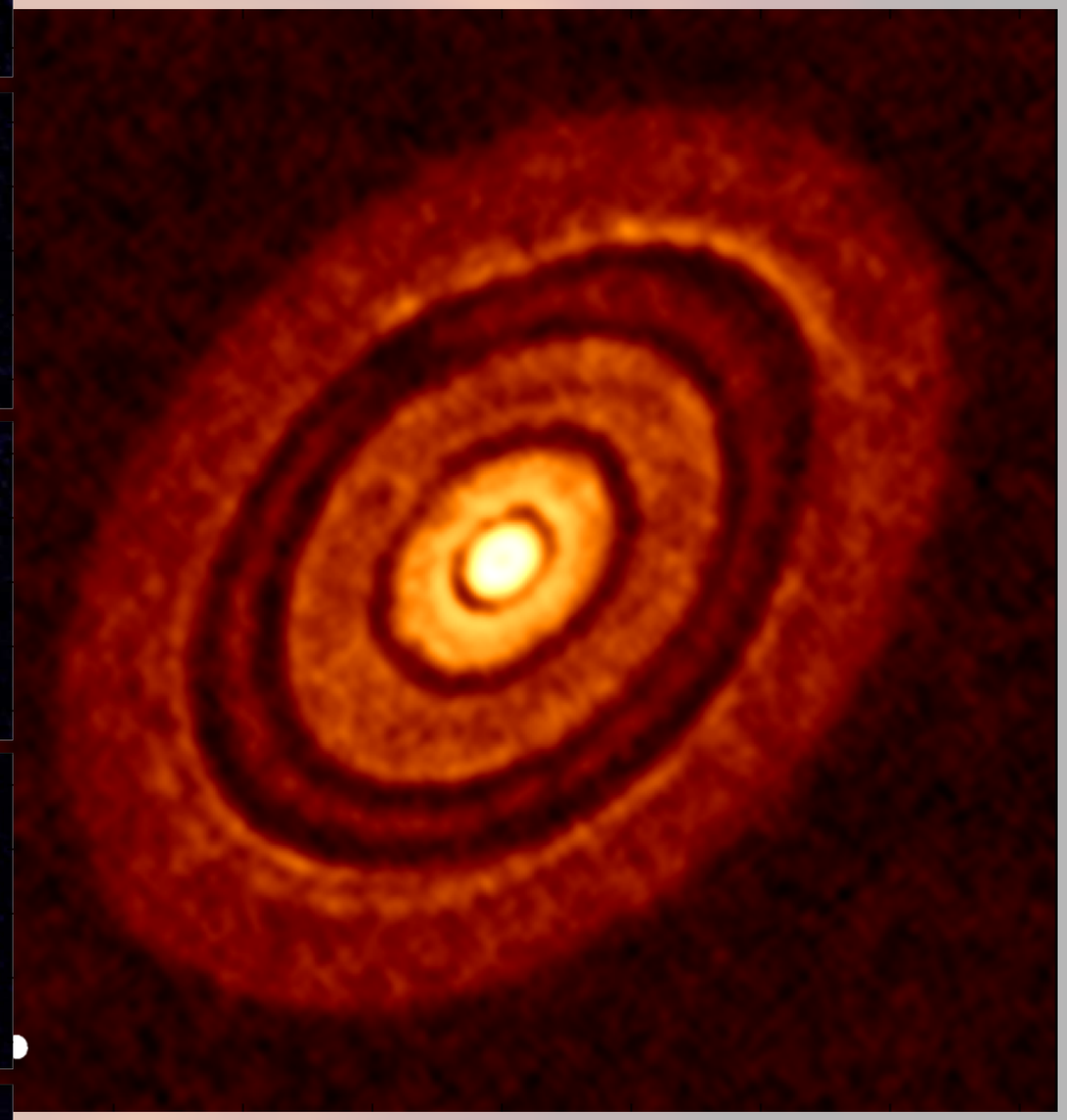


Dipierro, Price, Laibe, Hirsh, Cerioli & Lodato (2015)

But plenty of other explanations exist…

NS, MEET MODELS



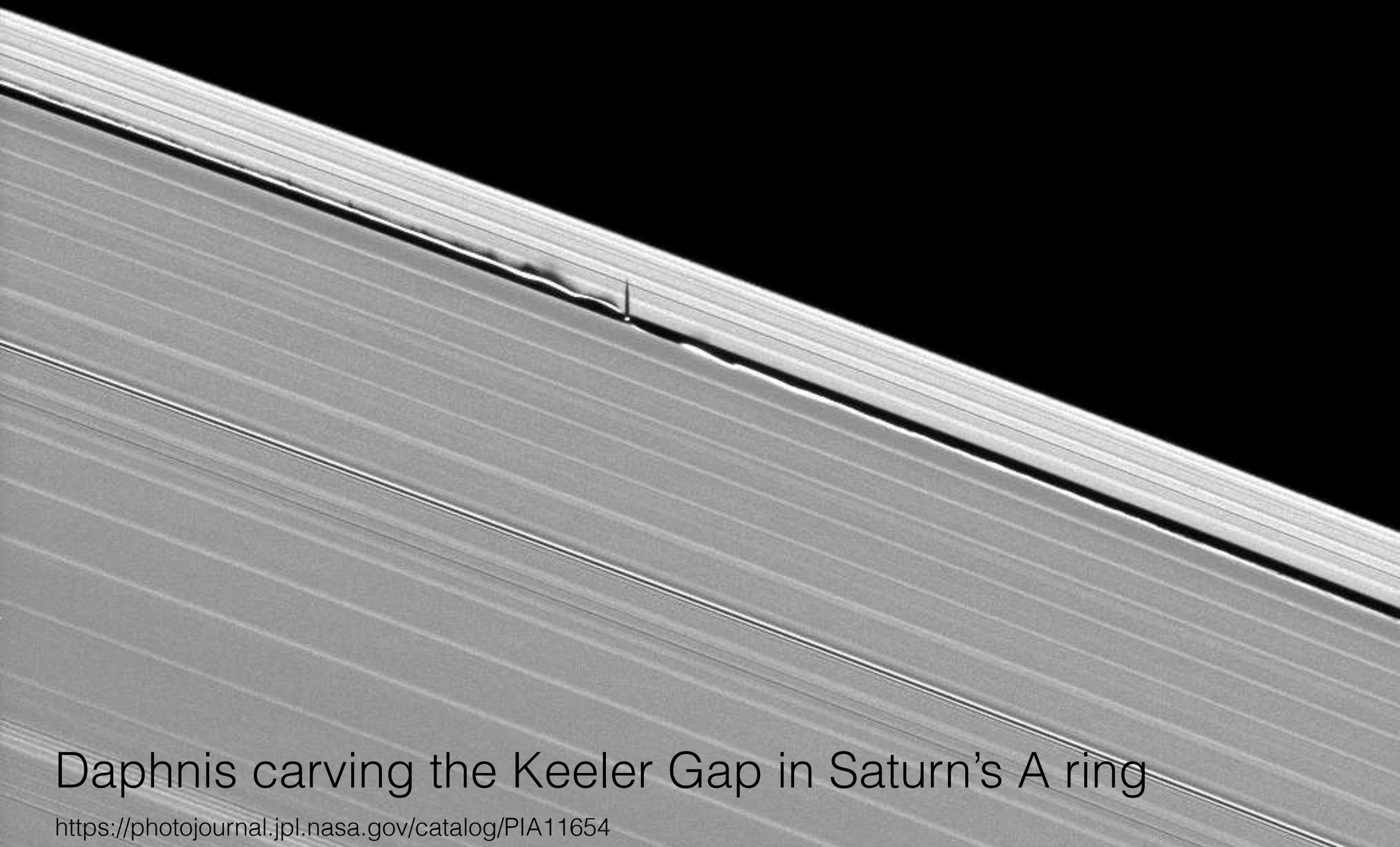


Our simulation

ipierro, Price, Laibe, Hirsh, Cerioli & Lodato (2015)

Andrews et al. (2018) DSHARP project

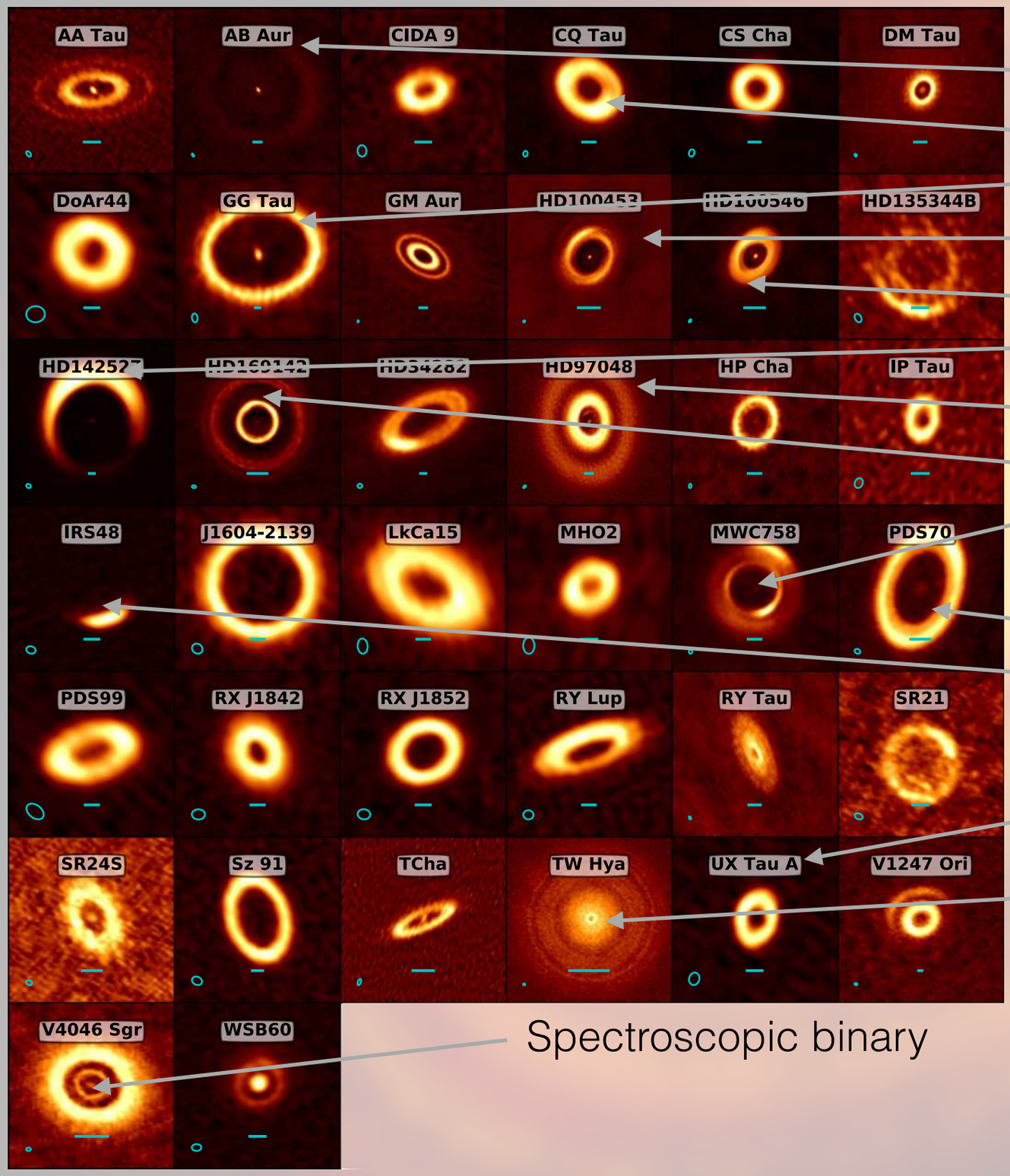
ANALOGY



Daphnis carving the Keeler Gap in Saturn’s A ring

https://photojournal.jpl.nasa.gov/catalog/PIA11654

"TRANSITIONAL" DISCS



Probable binary (Poblete+2020)

Probable binary (Hammond+2022)

Hierarchical quintuple (Di Folco+2014; GGClaui)

Misaligned binary/triple (Gonzalez+2020; Nealon+2020)

Probable binary (Norfolk+2022)

Circumbinary / misaligned (Lacour+16,Price+18)

Kinematic detection of planet in gap (Pinte+2019)

Planet imaged in gap (Hammond+2023)

Probable binary (Calcino et al. 2022) or massive planets (Ren+)

Two giant planets (Mueller et al. 2022)

Probable binary (Calcino et al. 2019)

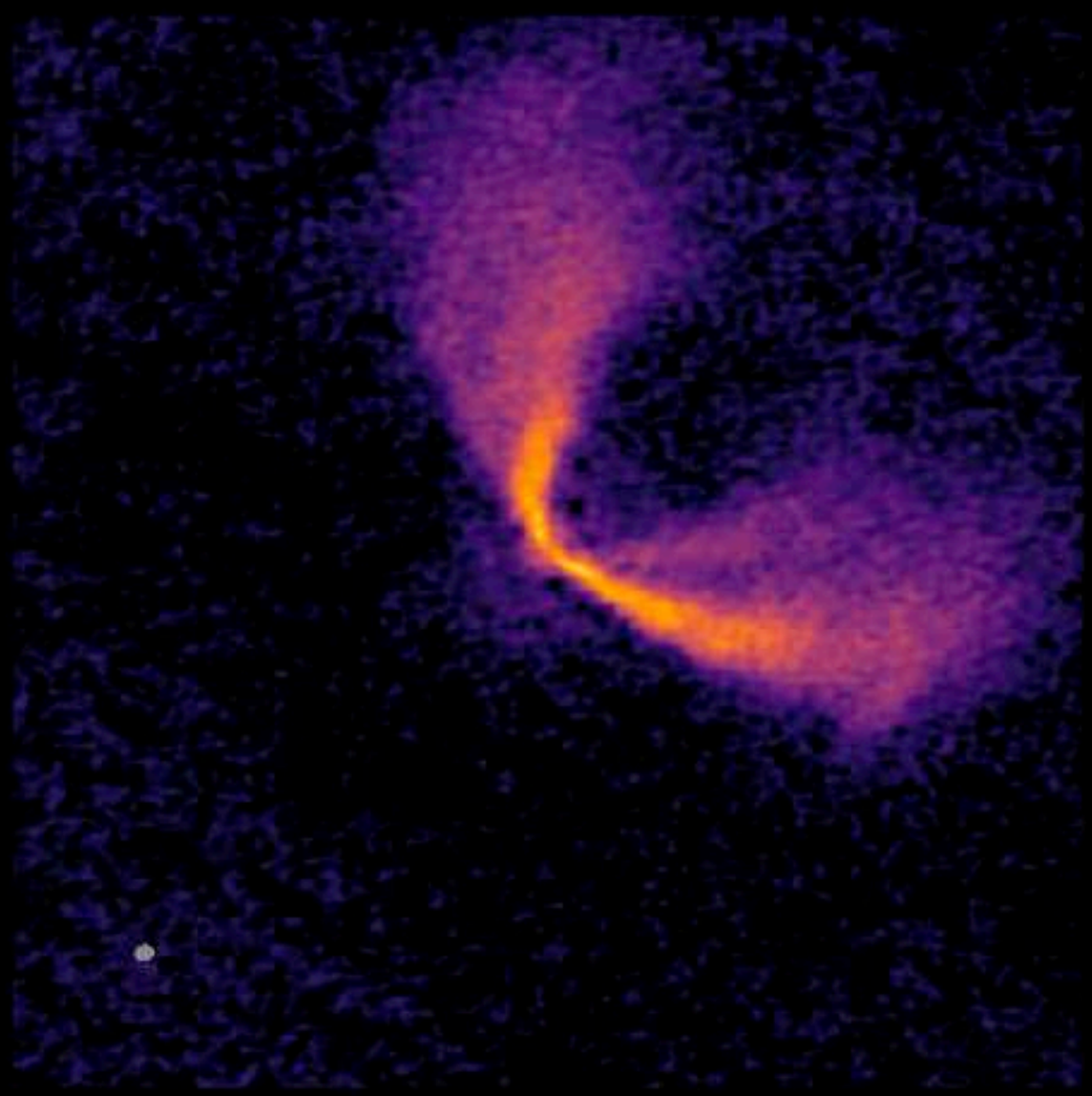
Ongoing stellar flyby (Ménard+2020)

Warped disc/moving shadows (Debes+2017) suggesting massive inner companion (Nealon+2018)+ super-Earths (Mentiplay+2019)

Spectroscopic binary

Francis & van der Marel (2020)

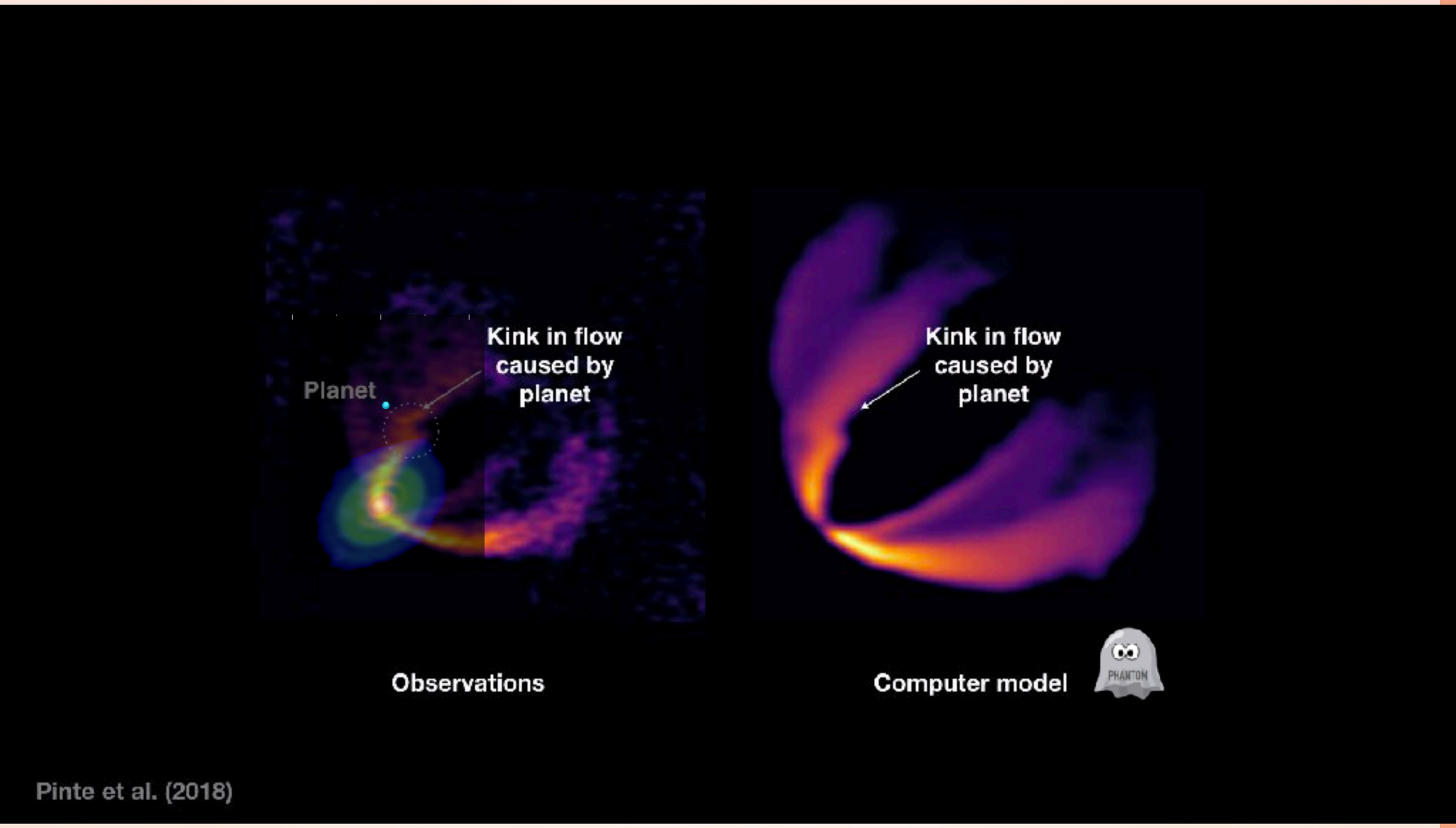
DISC KINEMATICS WITH ALMA



Data from the MAPS project (Oberg et al. 2021)

Phantom simulation by Calcino et al. (2022)

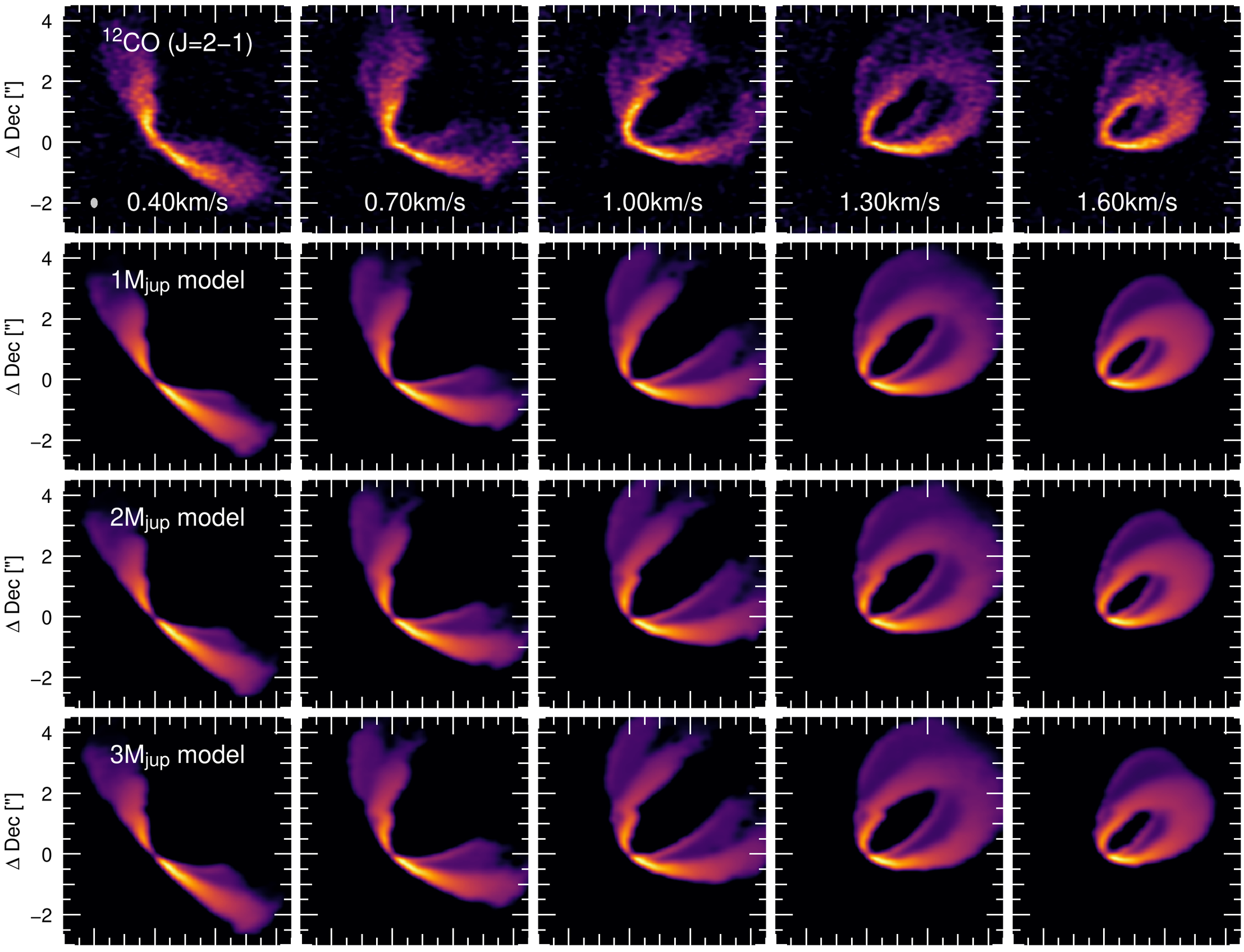
PLANET HUNTING WITH DISC KINEMATICS



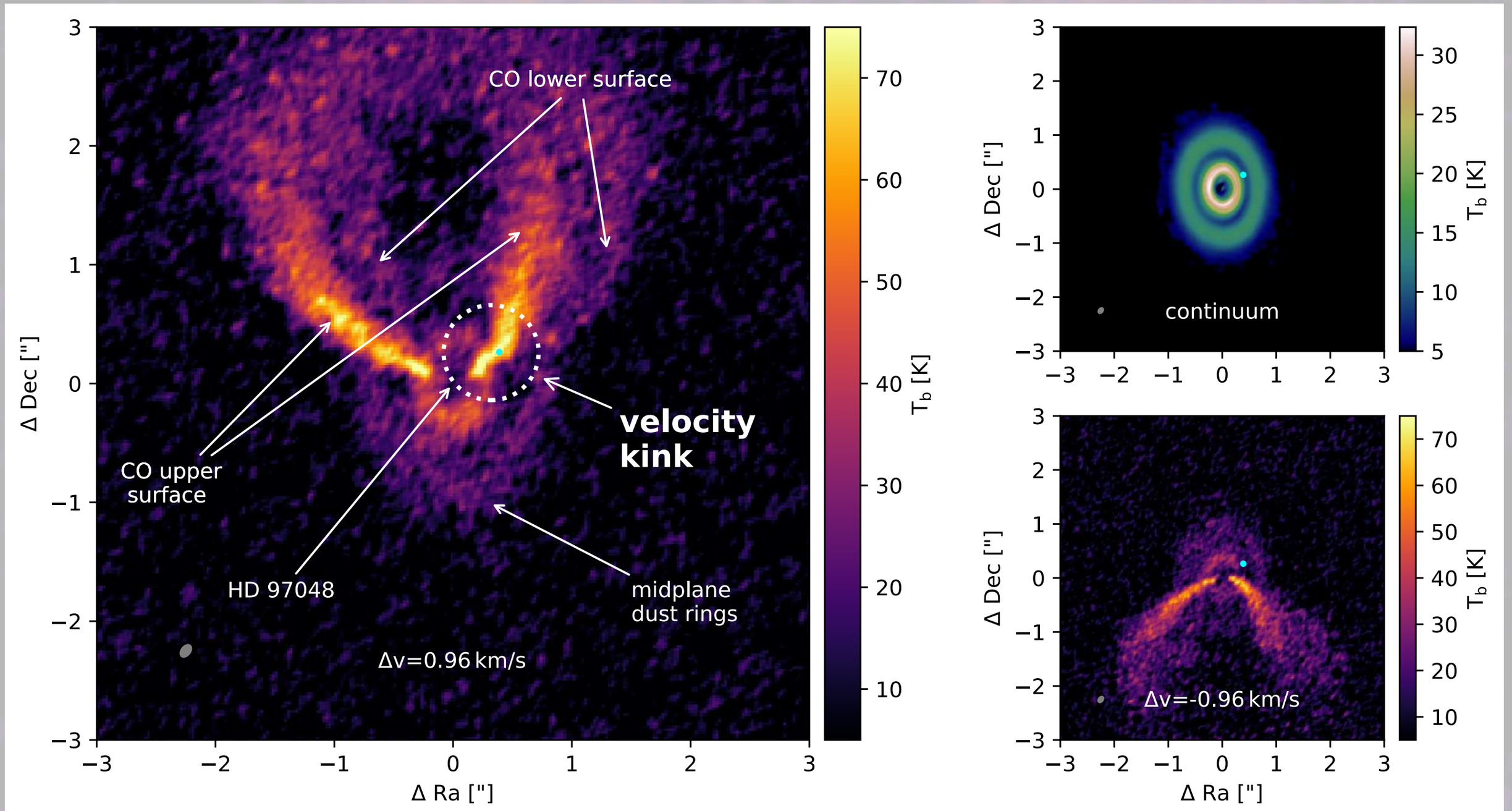
Pinte et al. (2018)

MEASURING THE PLANET MASS IN HD163296

Pinte et al. (2018)



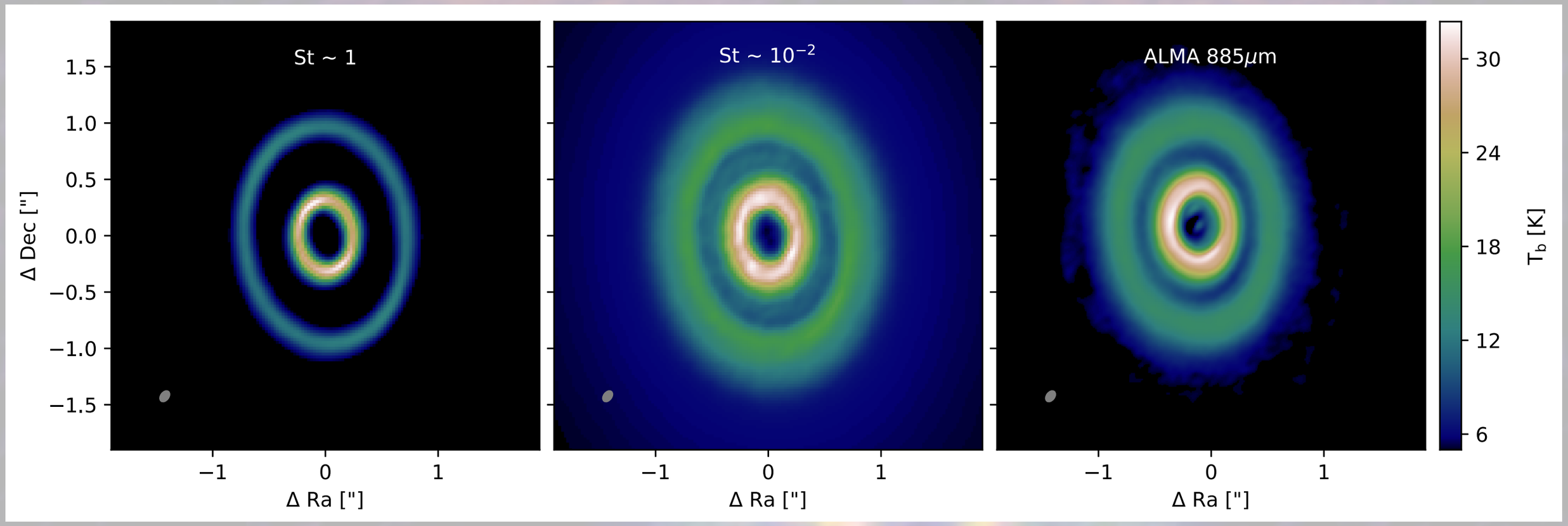
HD97048: KINEMATIC DETECTION OF A GIANT PLANET CARVING A GAP



SO PLANETS CARVE (AT LEAST SOME) GAPS

Pinte et al. (2019)

HD97048: EVIDENCE FOR FLUFFY GRAINS?



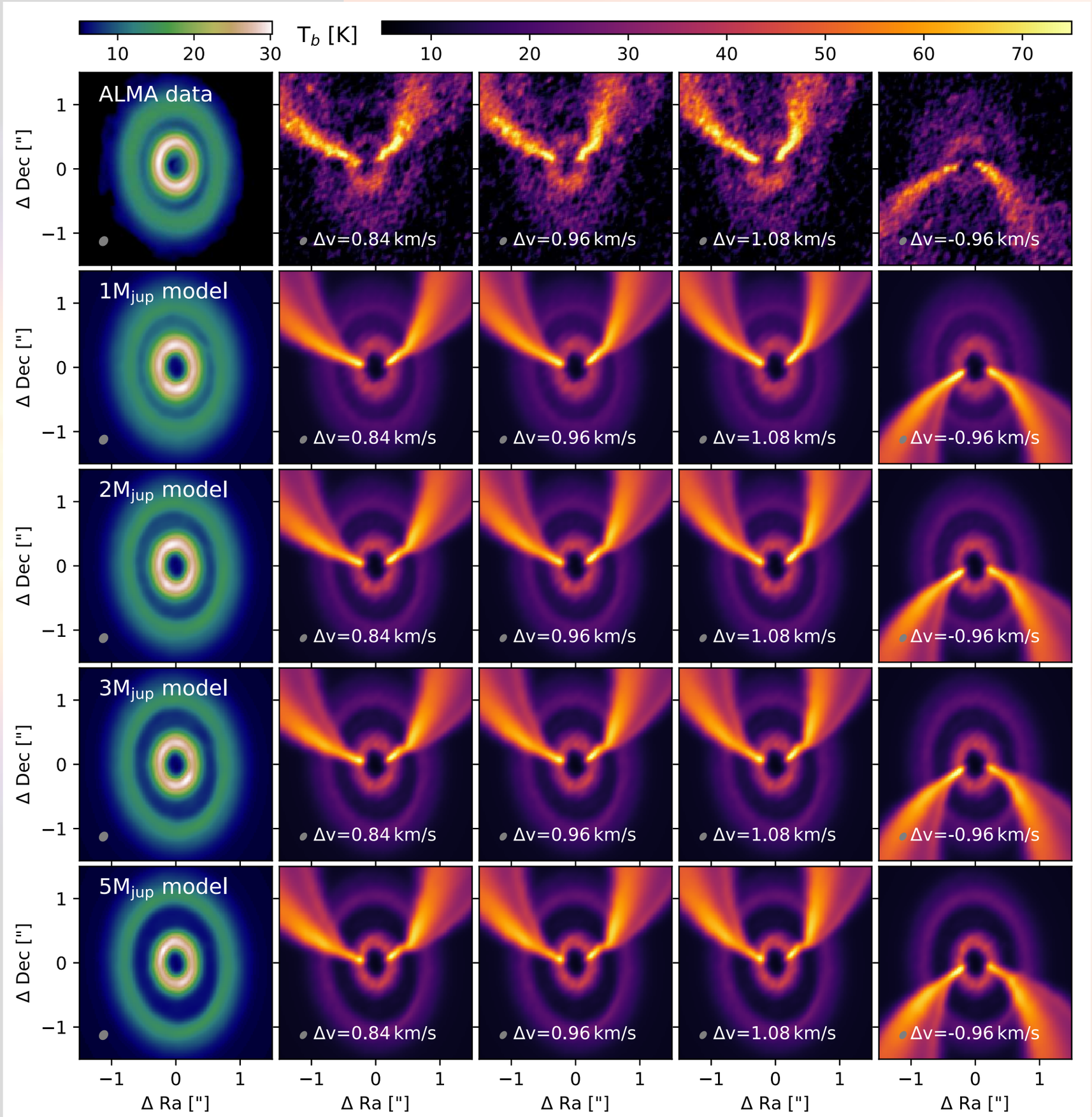
Synthetic images from 11 grain species dust-gas simulation using Laibe & Price (2014); Price & Laibe (2015); Hutchison et al. (2018) MULTIGRAIN algorithm

ALMA observation

To reproduce ALMA dust + kinematics need fluffy/porous mm-emitting grains

Pinte et al. (2019) supplementary material

MEASURING THE PLANET MASS



+
MCFOST

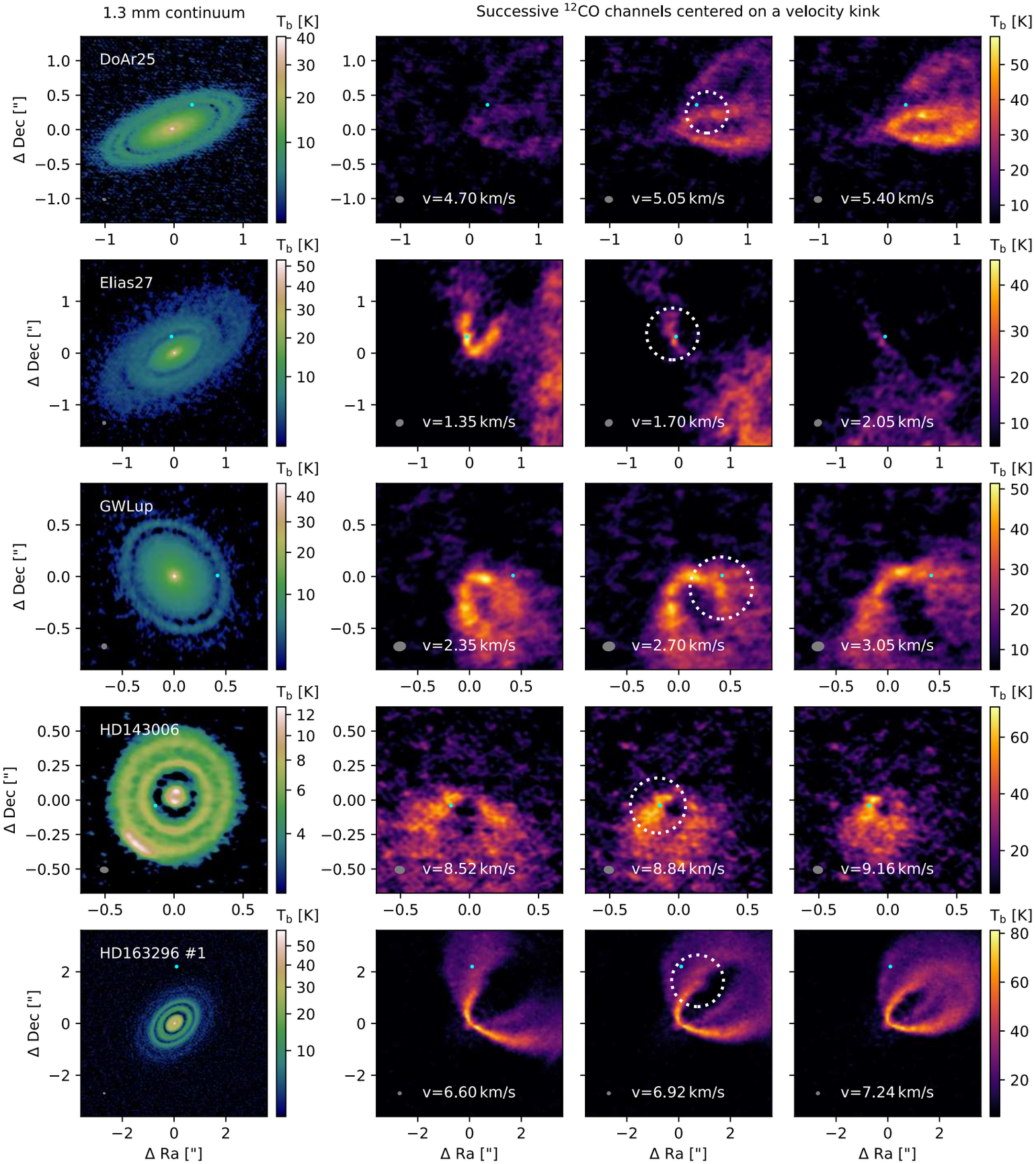
Pinte et al. (2019)

PROSPECTS FOR KINEMATIC PLANET DETECTION?

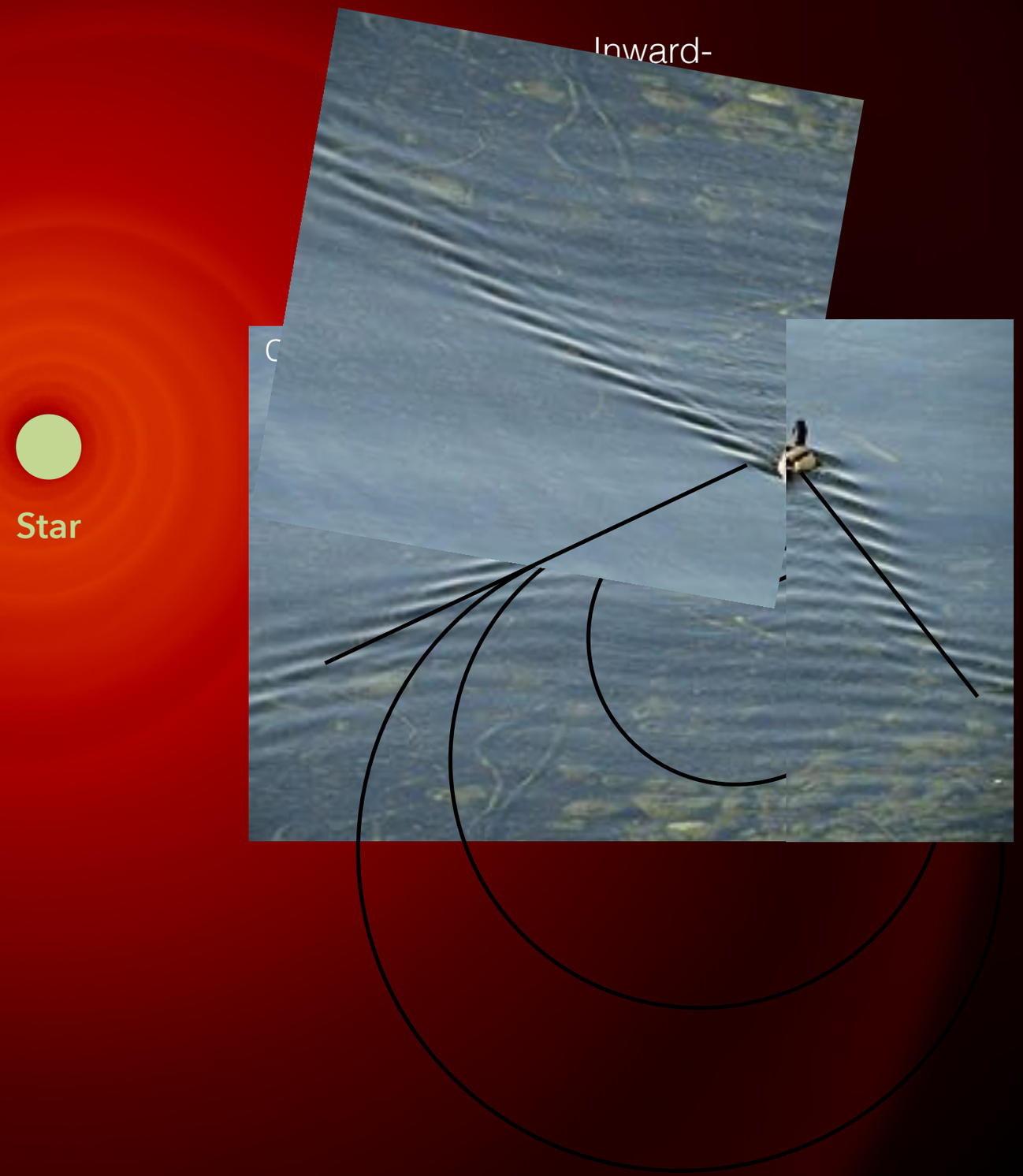
Pinte, Price et al. (2020)

8 new tentative detections + 1 redetection

All located in gap or tip of spiral when deprojected

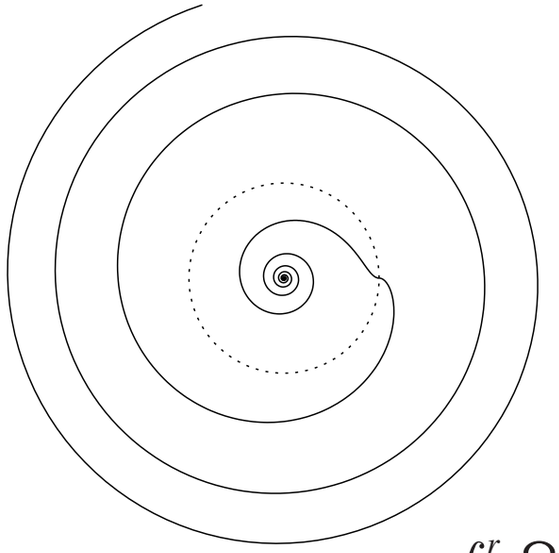


PLANET - DISC INTERACTION 101



THE THEORY OF KINKS

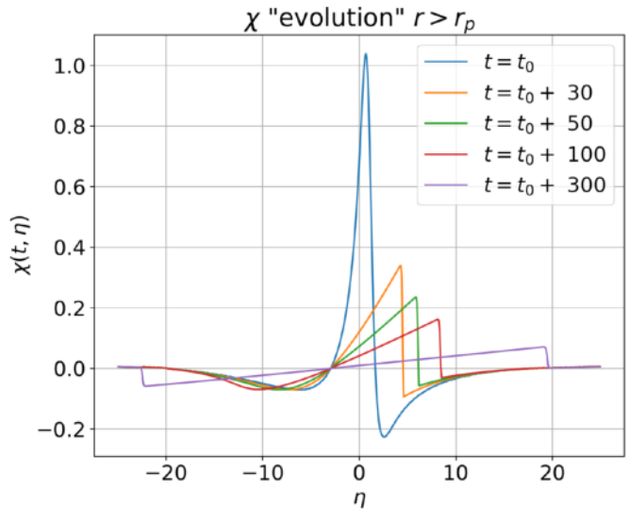
Bollati, Lodato, Price & Pinte (2021)



$$\varphi_{\rm wake}(r) = \varphi_{\rm p} + {\rm sgn}(r - r_{\rm p}) \int_{r_{\rm p}}^{r} \frac{\Omega(r') - \Omega_{\rm p}}{c_0(r')} {\rm d}r',$$

Wake shape = constructive interference of waves

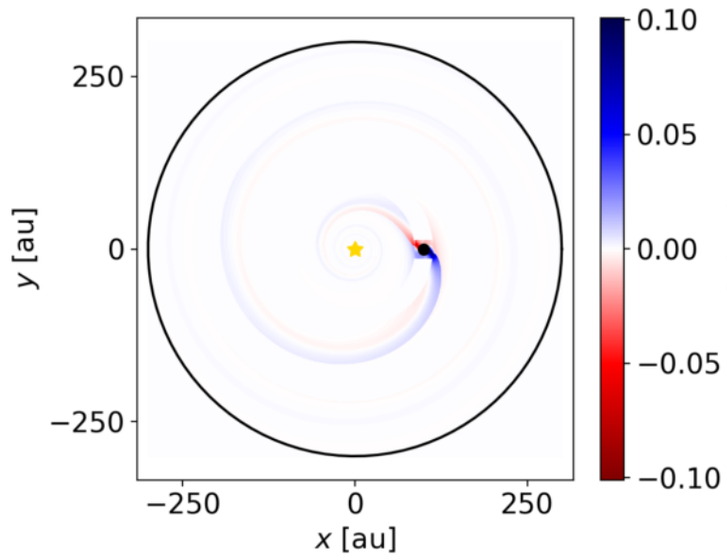
Ogilvie & Lubow (2002),
Rafikov (2002)



$$\frac{\partial \chi}{\partial t} + \chi \frac{\partial \chi}{\partial \eta} = 0$$

Propagate wake along the line of constructive interference

Rafikov (2002)
Bollati et al. (2021)

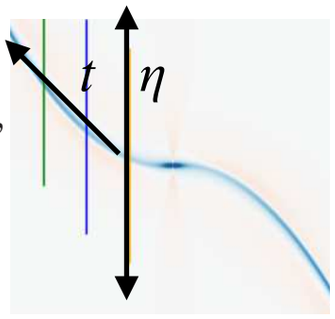


Predict velocity perturbations and compare to observations

Bollati et al. (2021)
Calcino et al. (2022), Hilder et al. (2022)

$$t(r) \equiv -\frac{r_{\rm p}}{2h_{\rm p}/3} \int_{r_{\rm p}}^{r} \frac{\Omega(r') - \Omega_{\rm p}}{c_0(r')g(r')} {\rm d}r',$$

$$\eta(r, \varphi) \equiv \frac{r_{\rm p}}{2h_{\rm p}/3} [\varphi - \varphi_{\rm wake}(r)],$$

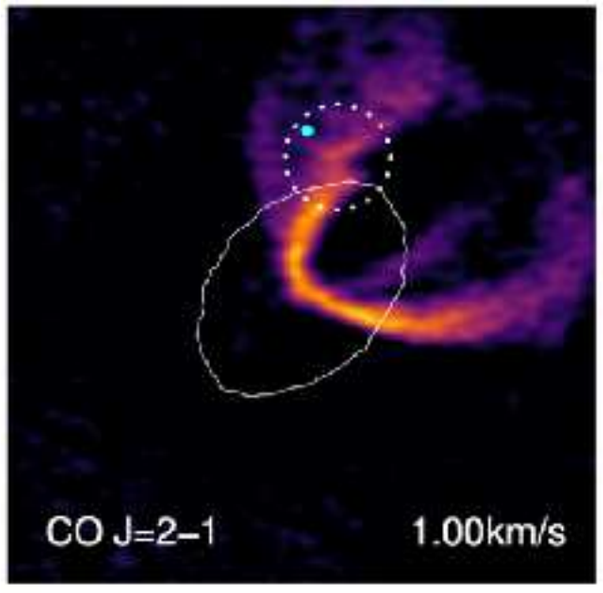


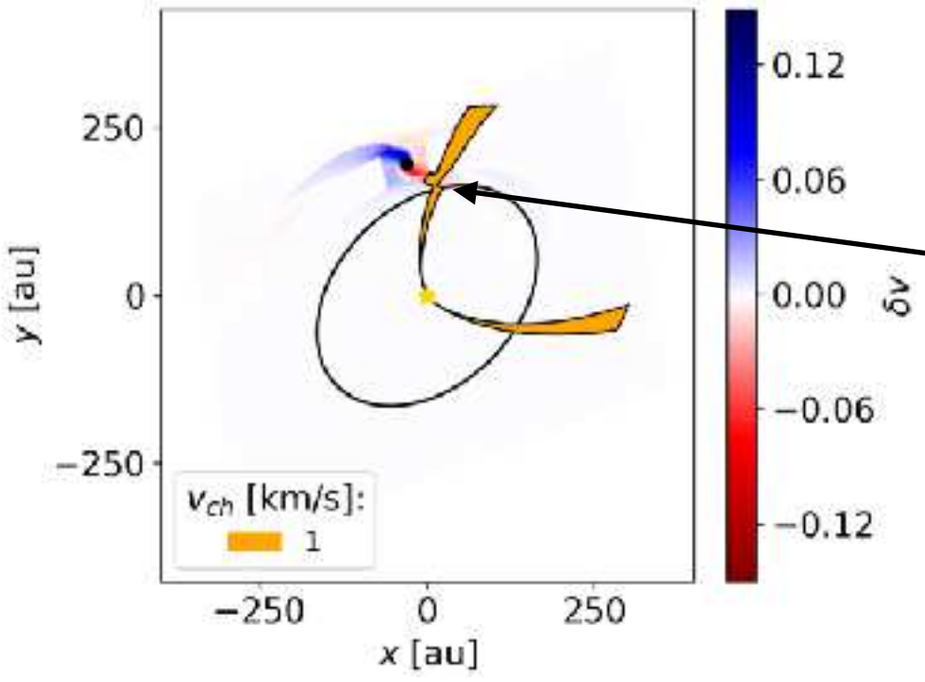
Reduce wake propagation to a 1D problem

Goodman & Rafikov (2001)
Rafikov (2002)

THE THEORY OF KINKS

Bollati, Lodato, Price & Pinte (2021)

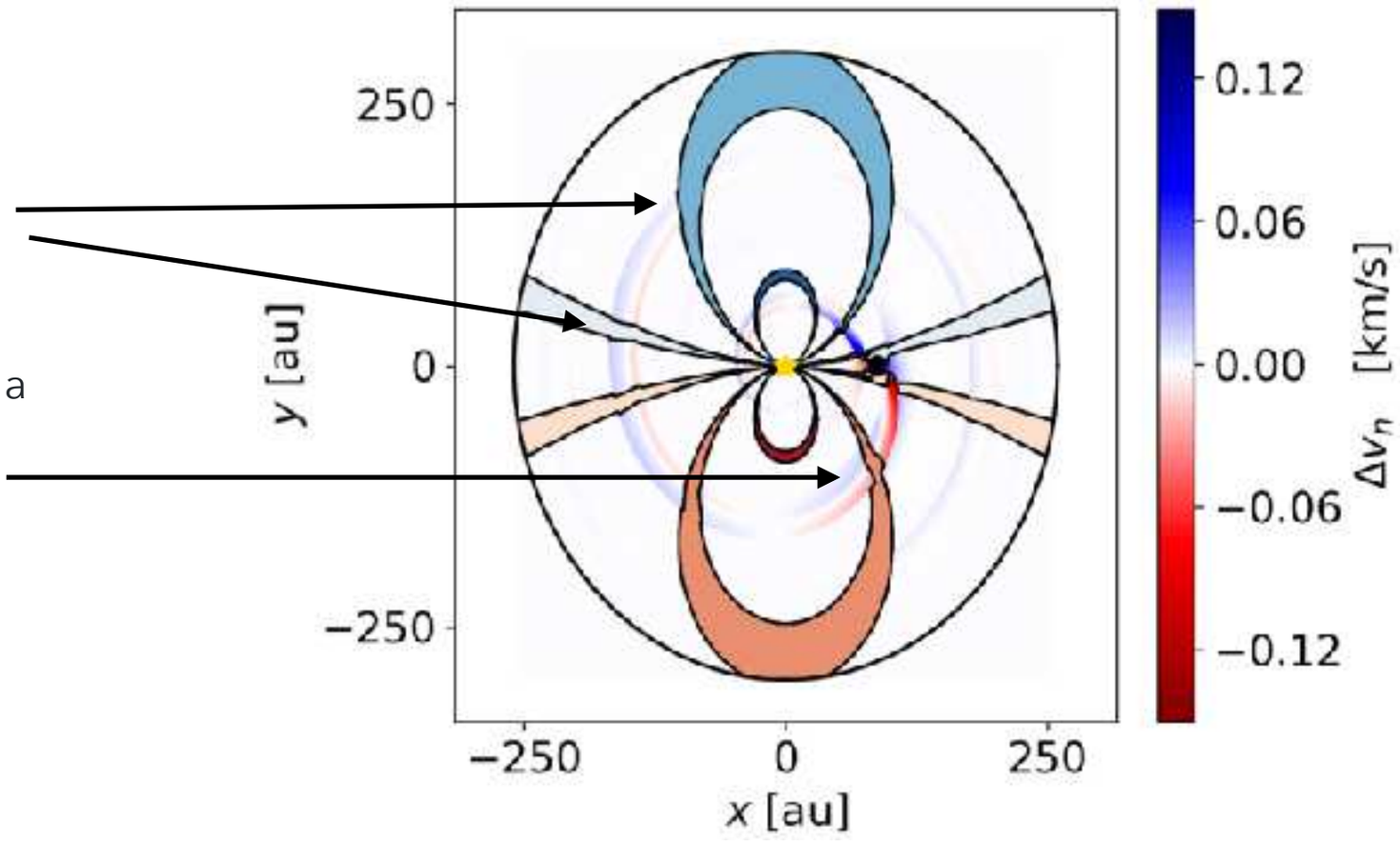




Predict a kink where the wake crosses a velocity channel

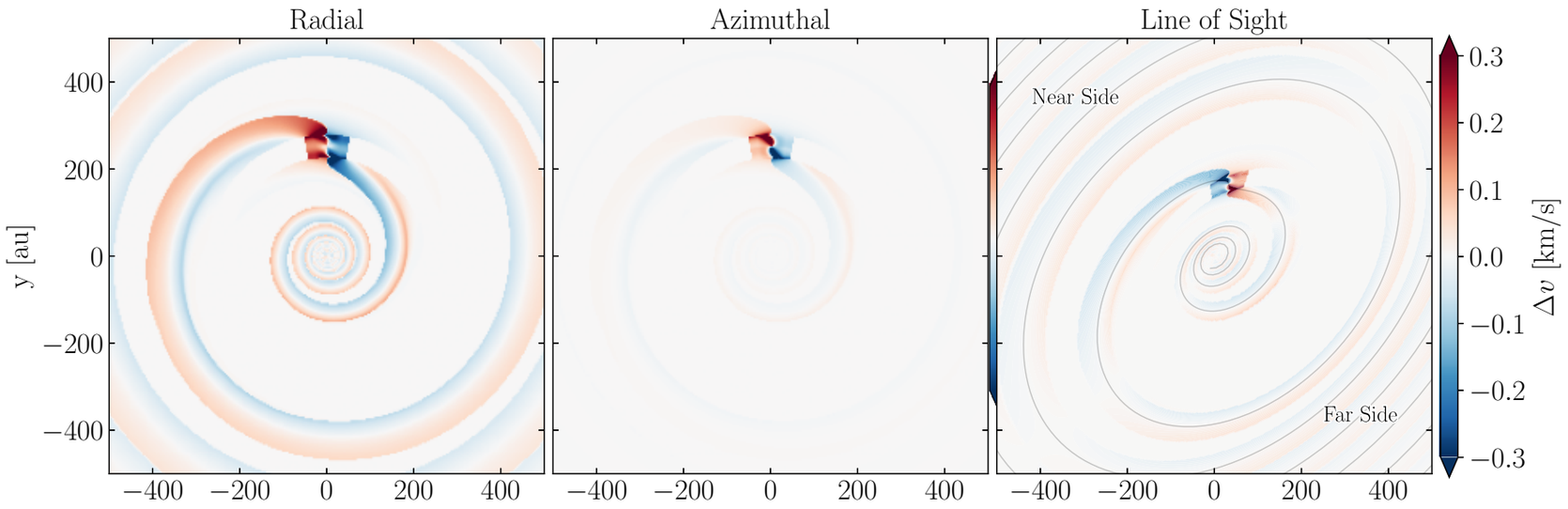
Secondary kinks?

Predict a kink *every time* the wake crosses a velocity channel

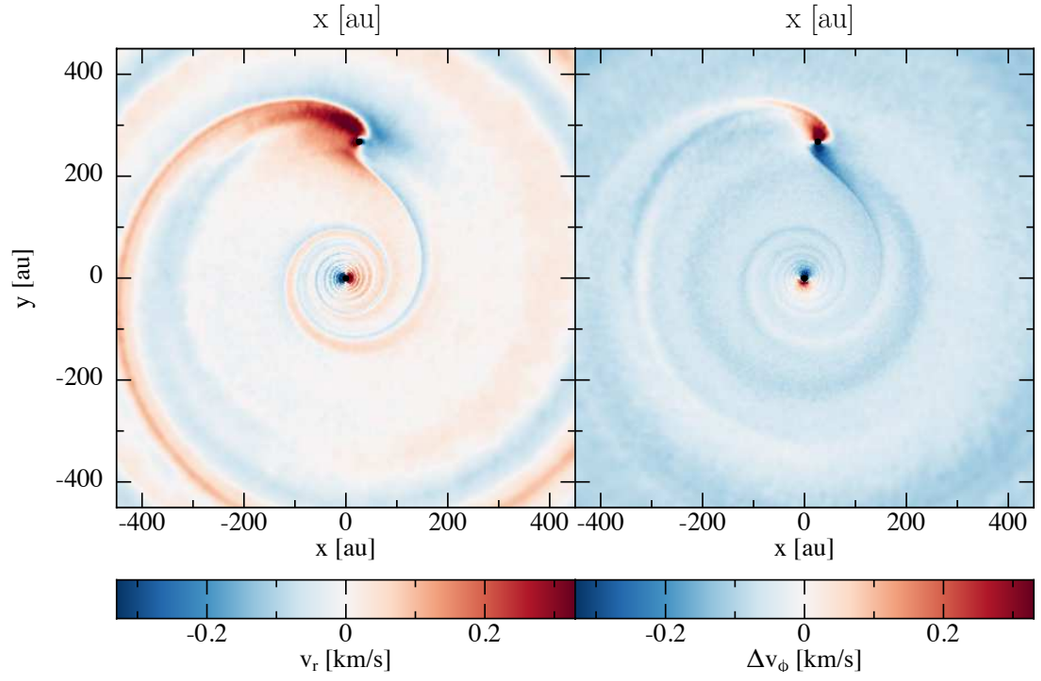


THE THEORY OF KINKS

analytics

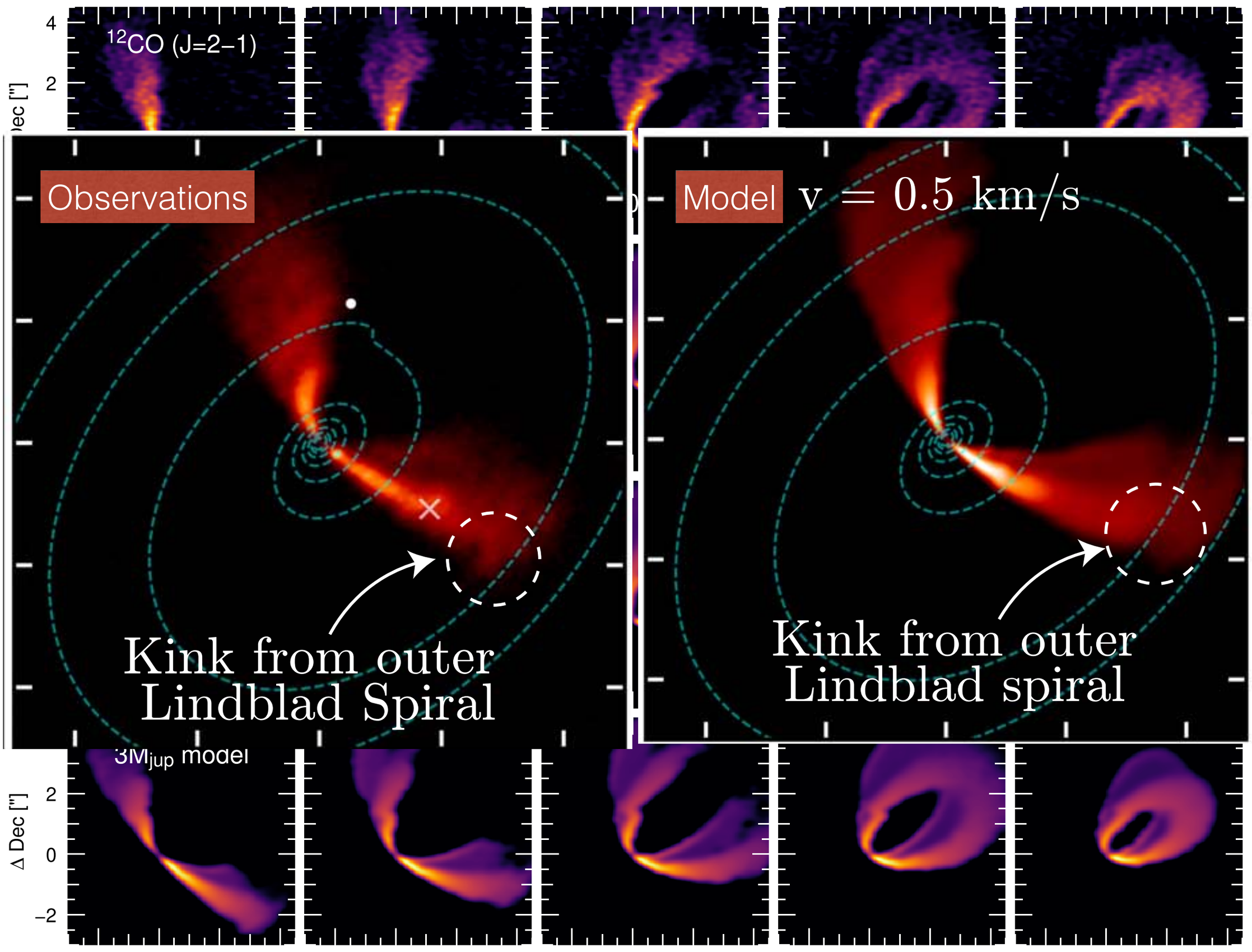


simulation



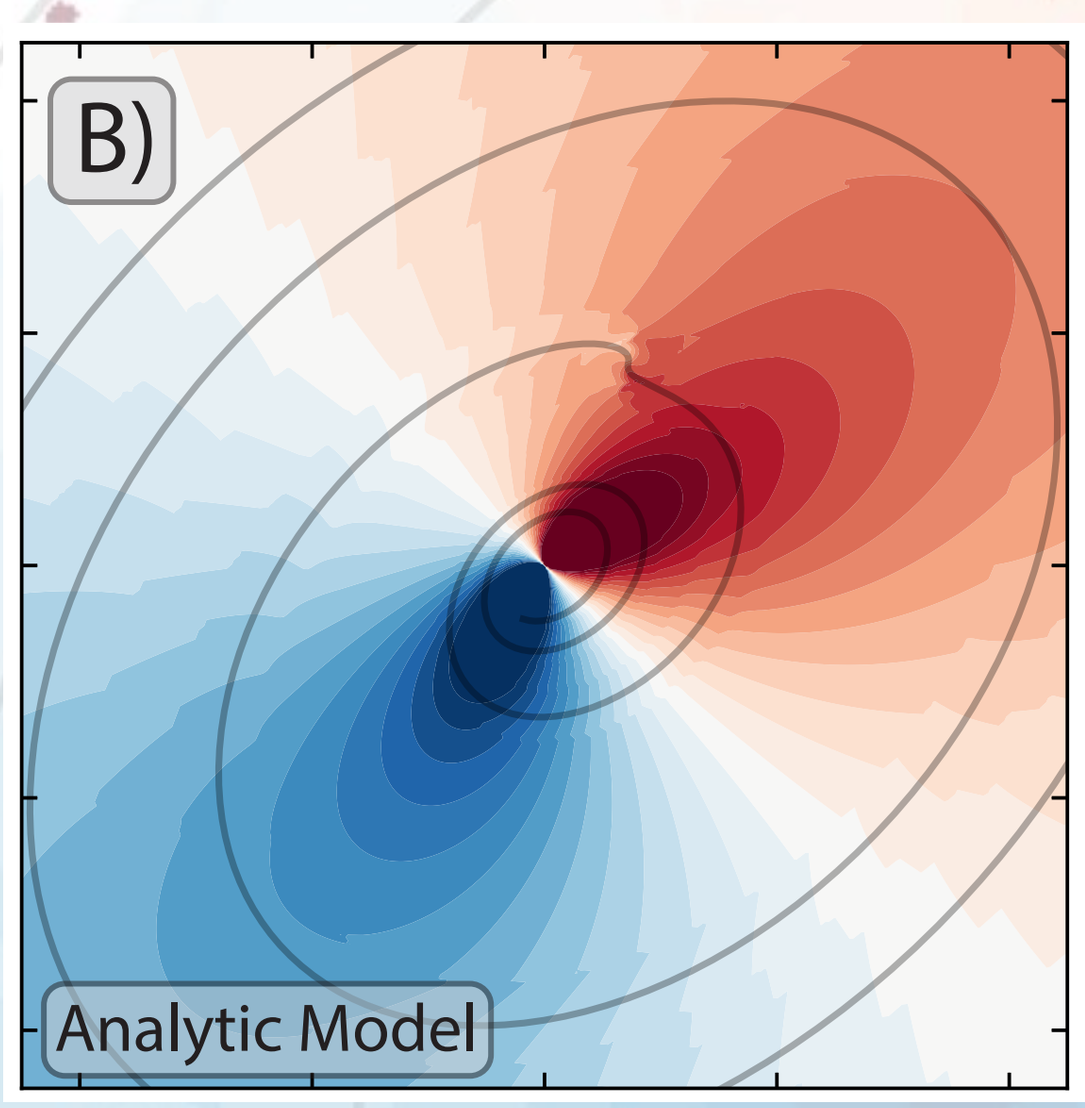
HD163296 REVISITED

Calcino et al. (2022)

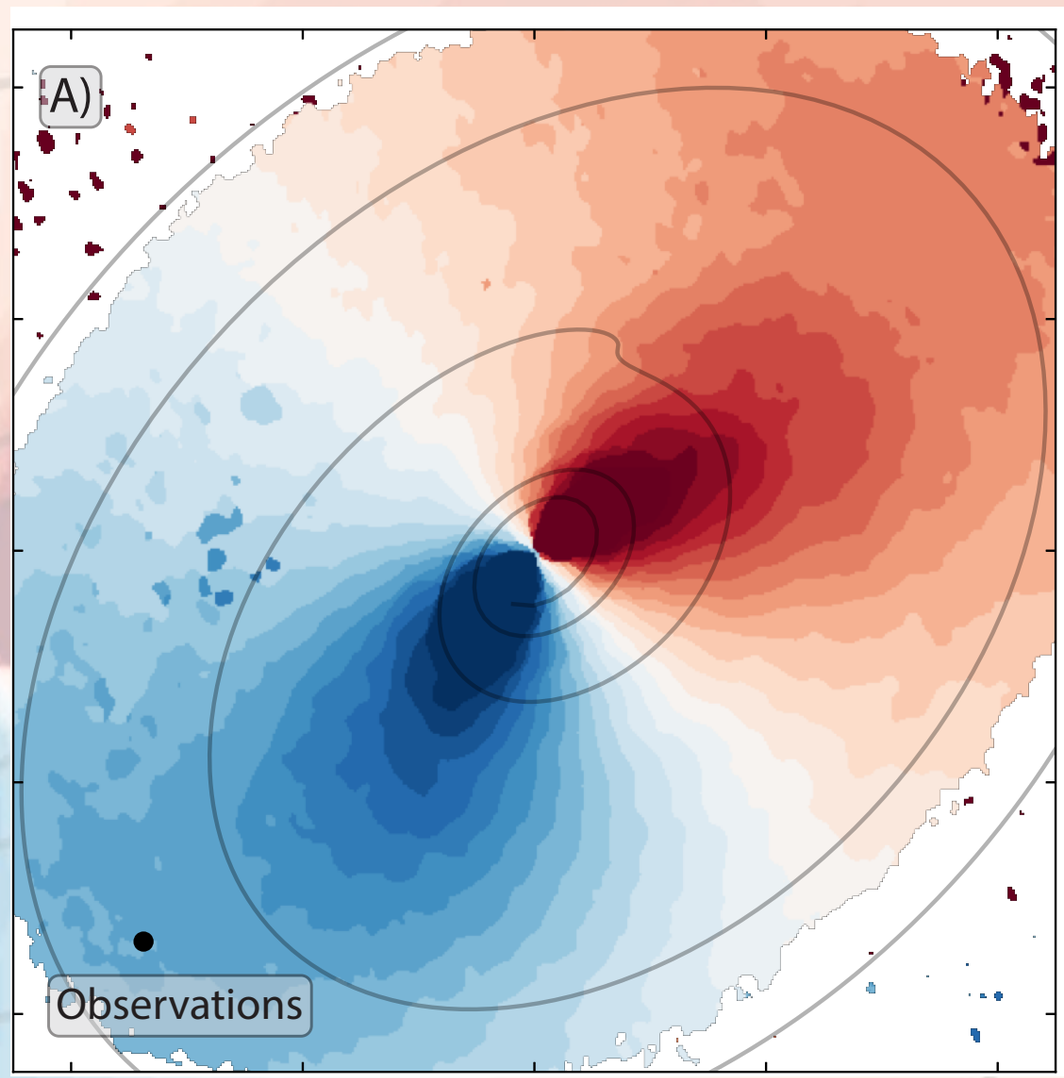


MODEL, MEET DATA

Calcino, Hilder, Price, Pinte, Bollati & Lodato (2022)

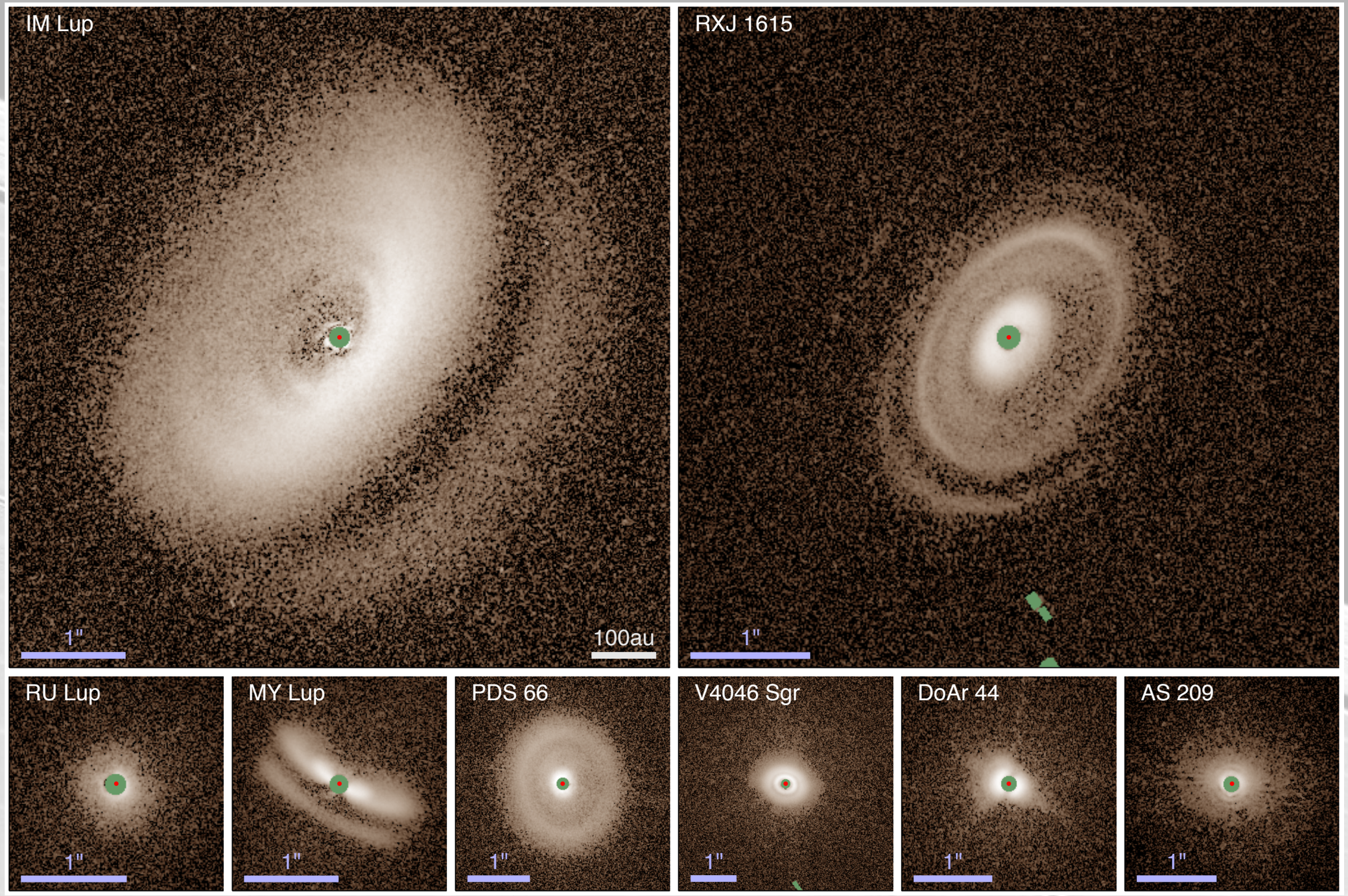


Using Bollati+(2021) analytic model



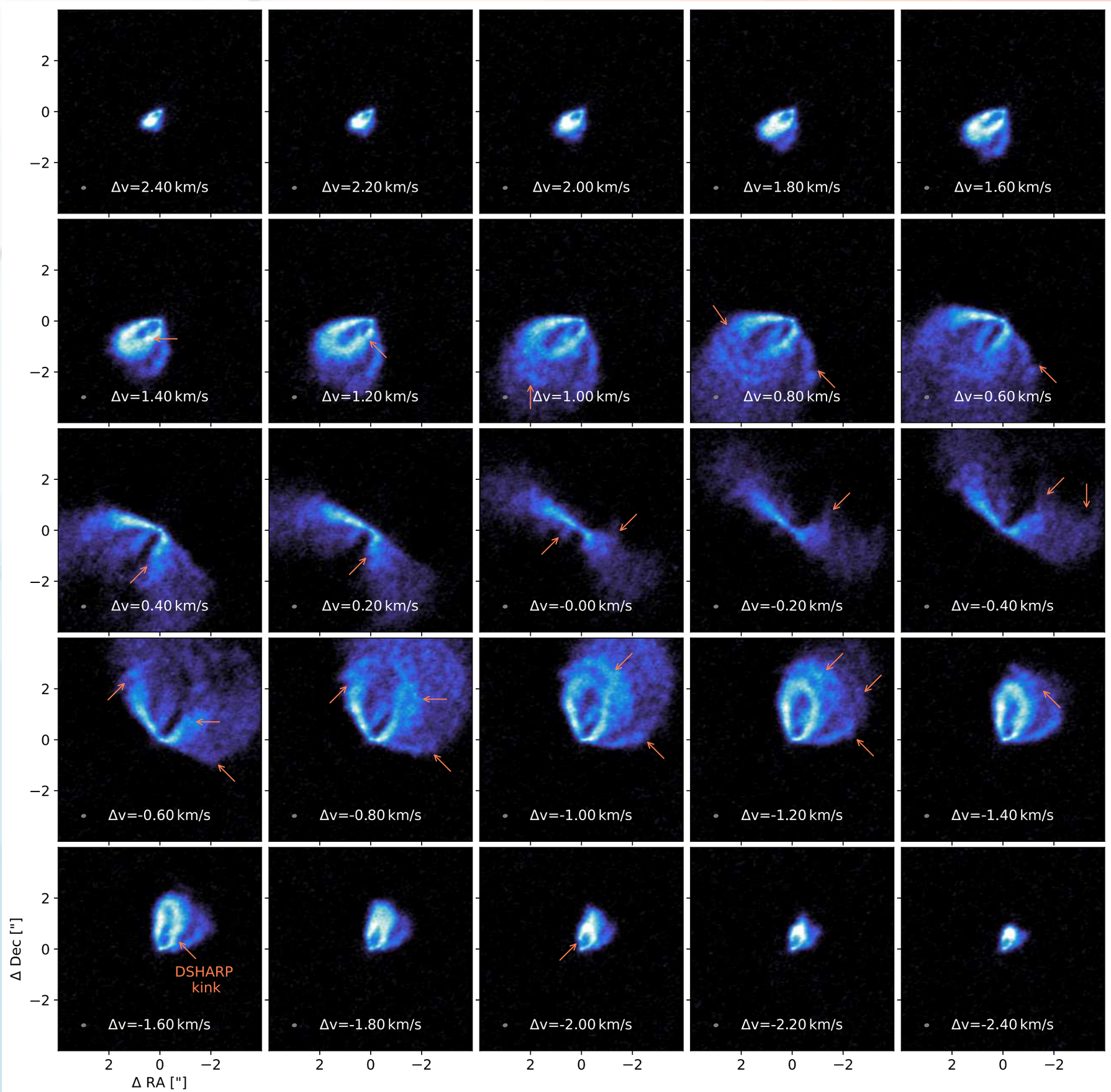
HD163296 from MAPS project (Oberg+2021)

CAN'T WE JUST SEE THE SPIRAL WAKE?



Avenhaus+(2018), aka "The Miracle Run"

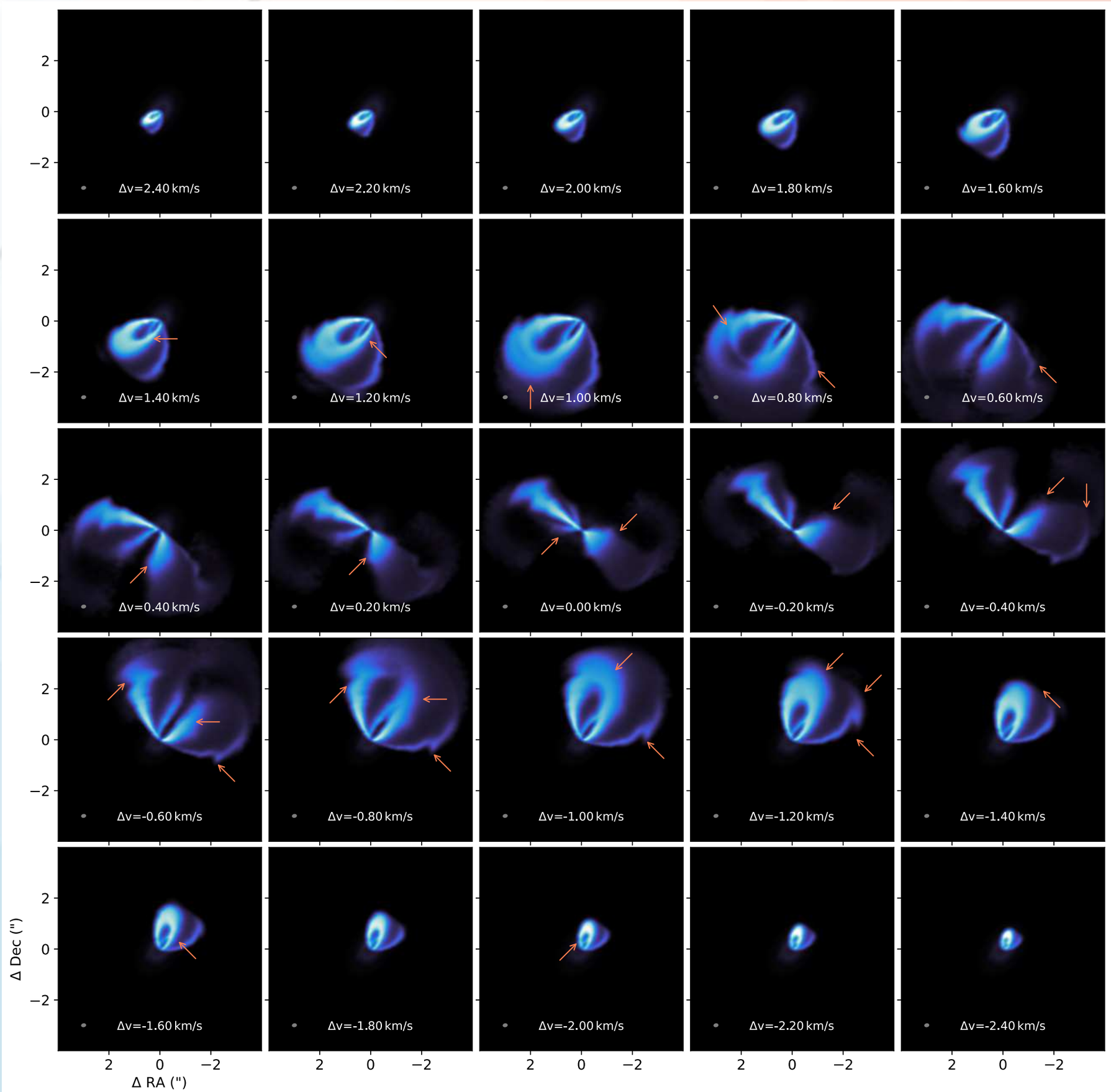
IM LUPI KINEMATICS - OBSERVATIONS



Verrios, Price et al. (2022)

Data from MAPS project (Oberg+2021)

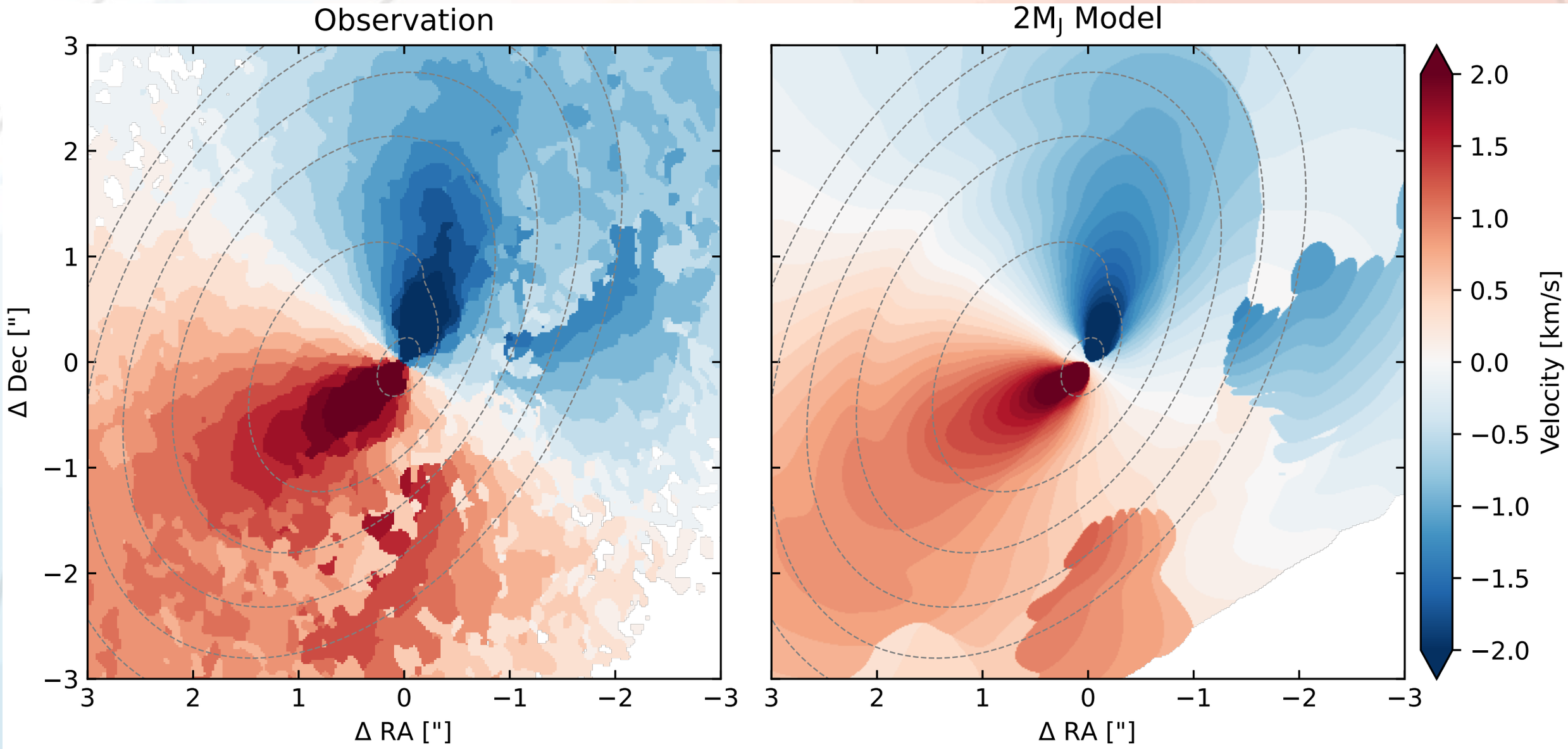
IM LUPI KINEMATICS - MODELS



Verrios, Price et al. (2022)

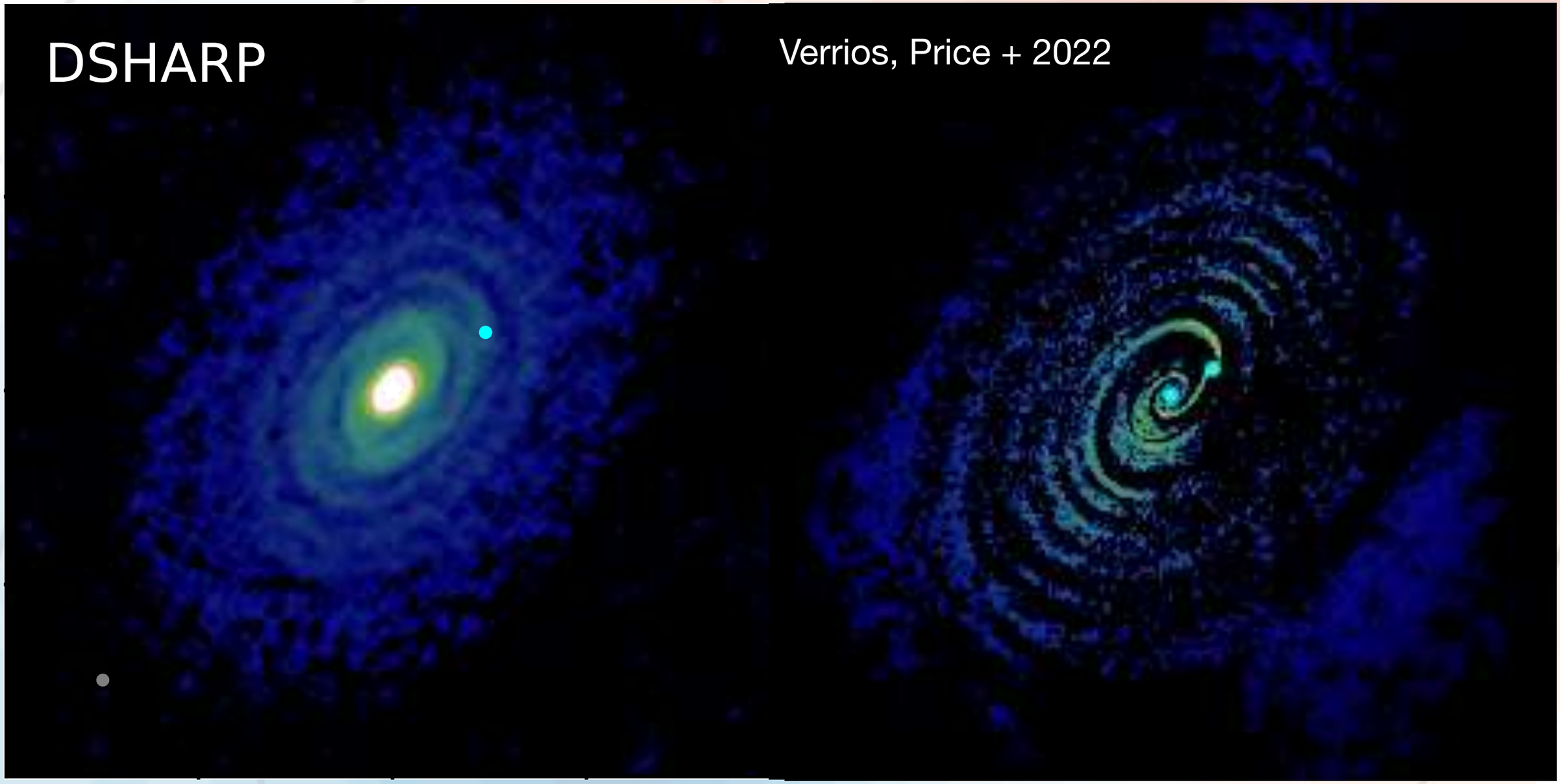
Simulations using Phantom SPH hydro + MCFOST radiative transfer

THE PLANET WAKE IN IM LUPI



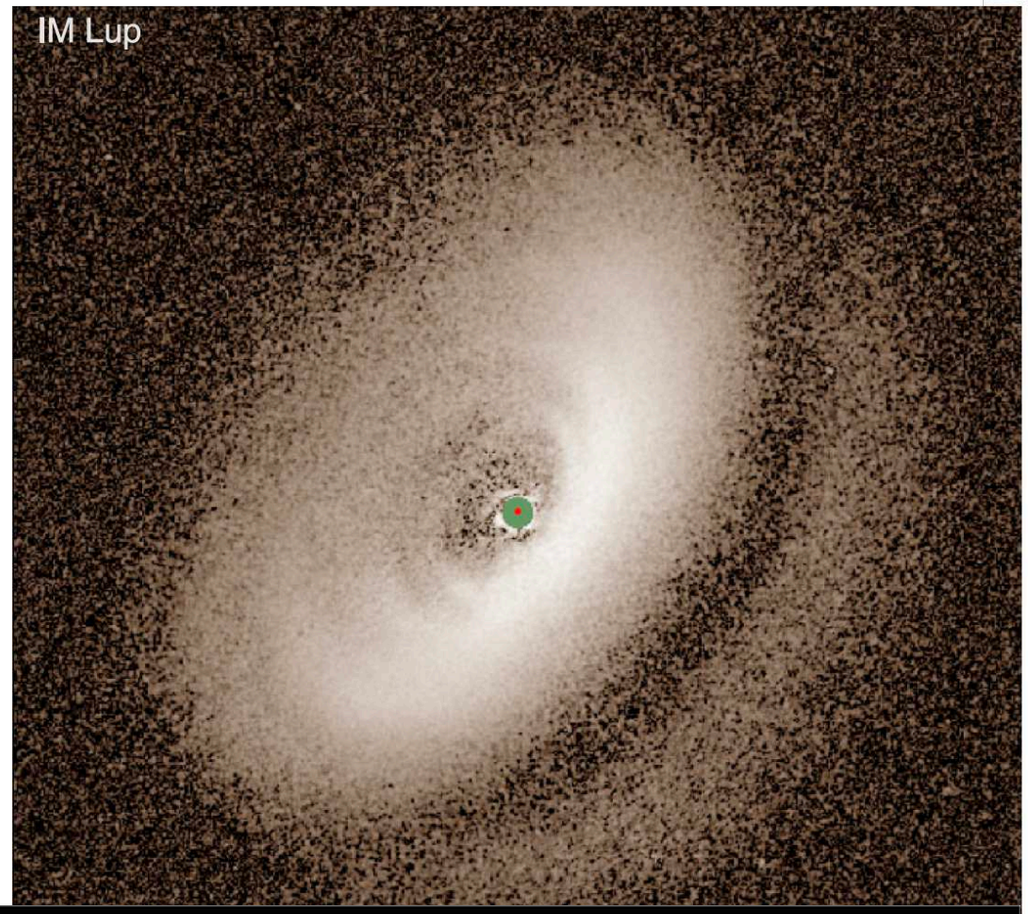
Verrios et al. 2022

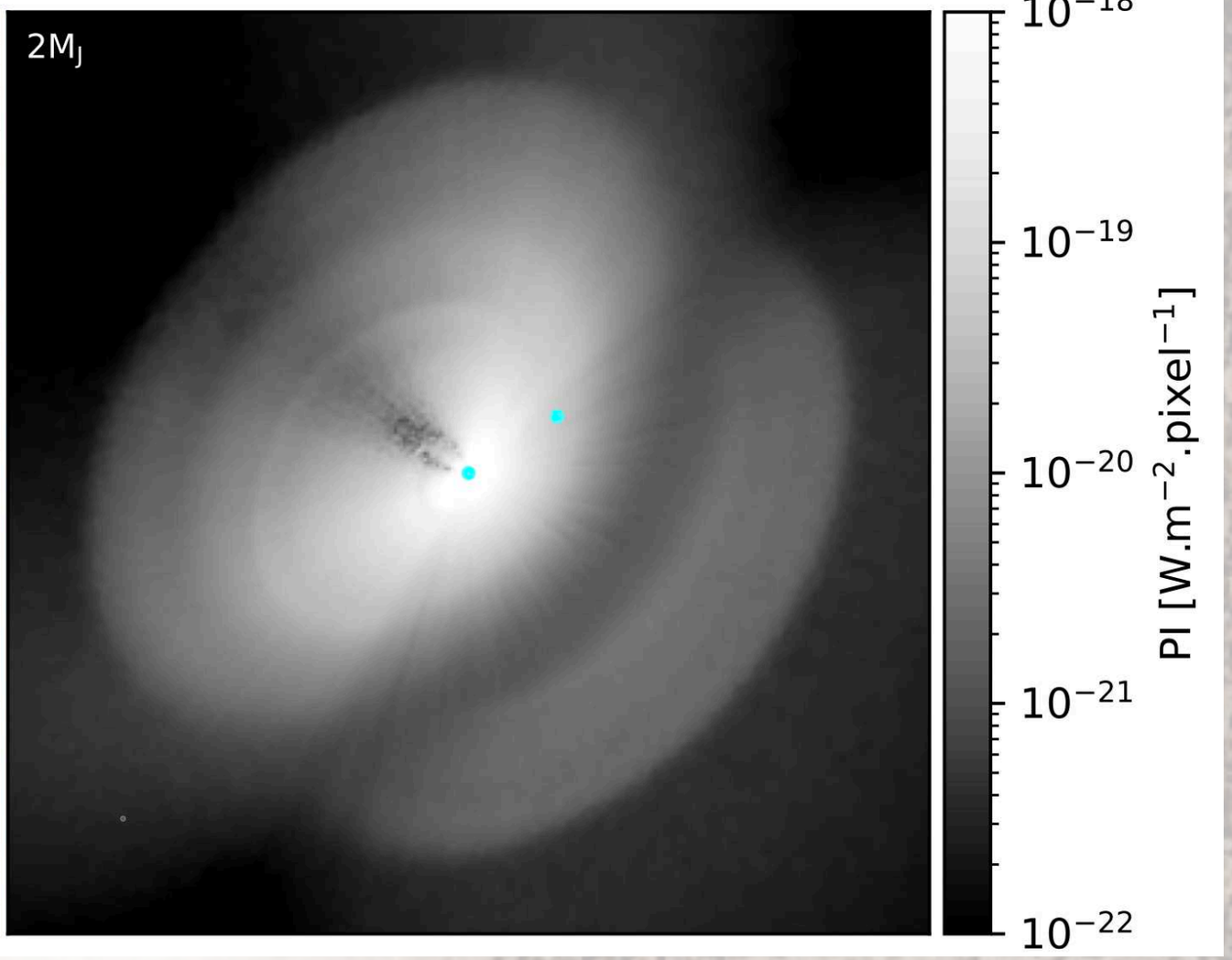
THE PLANET WAKE IN IM LUPI



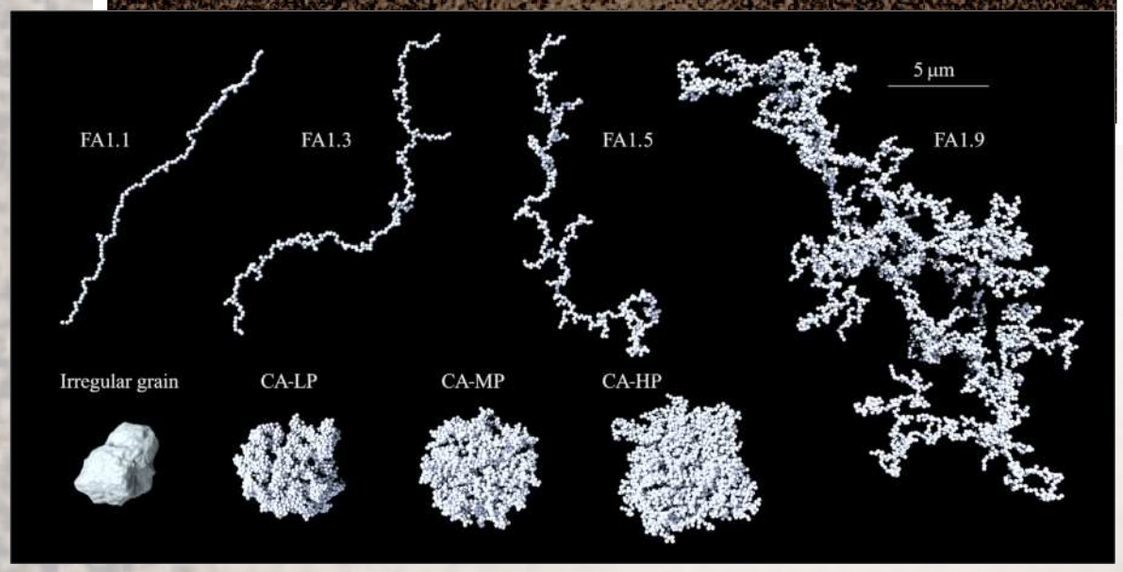
Verrios et al. 2022

IM LUPI, OR AM I?





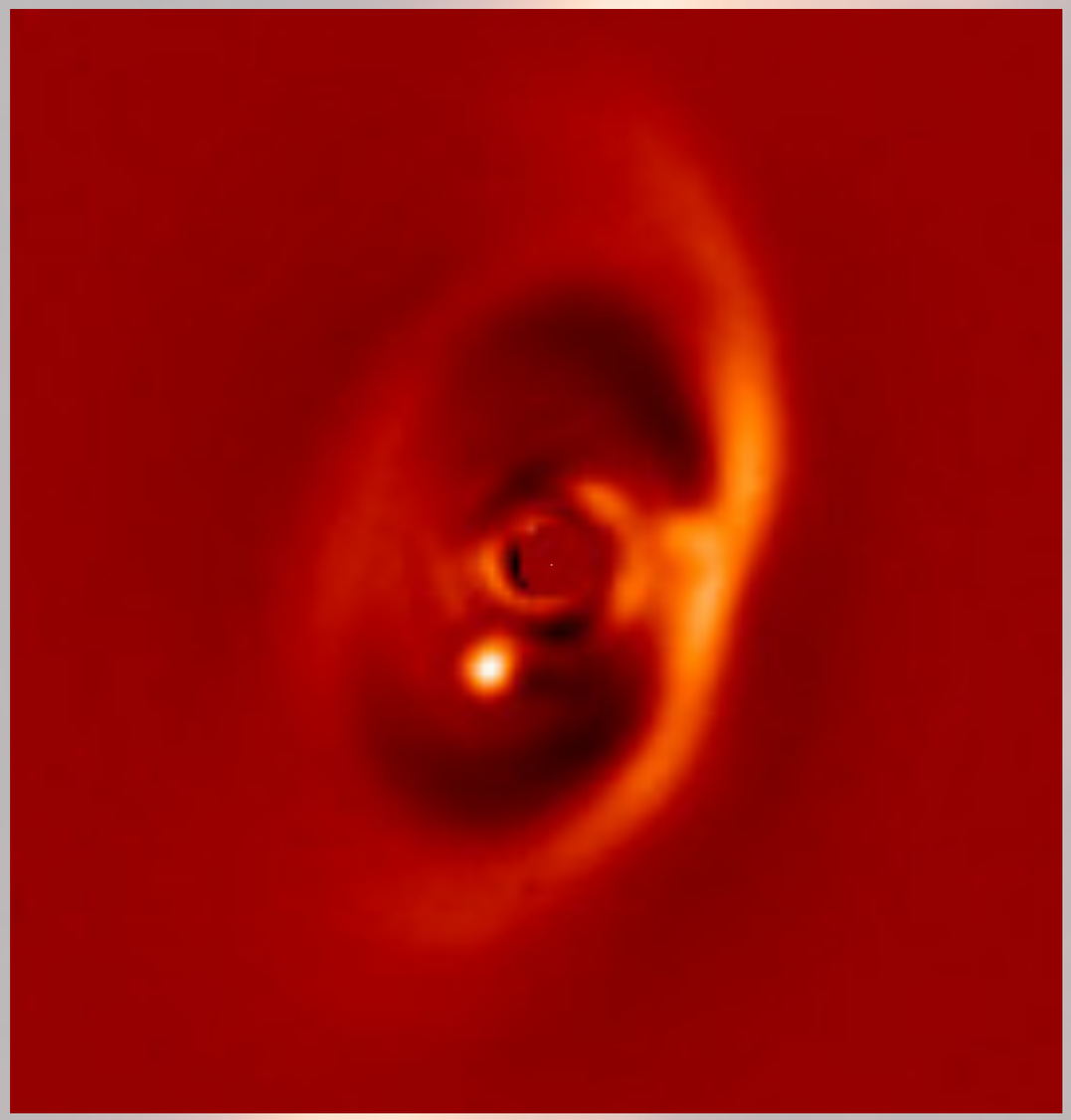
Verrios, Price+ (2022)



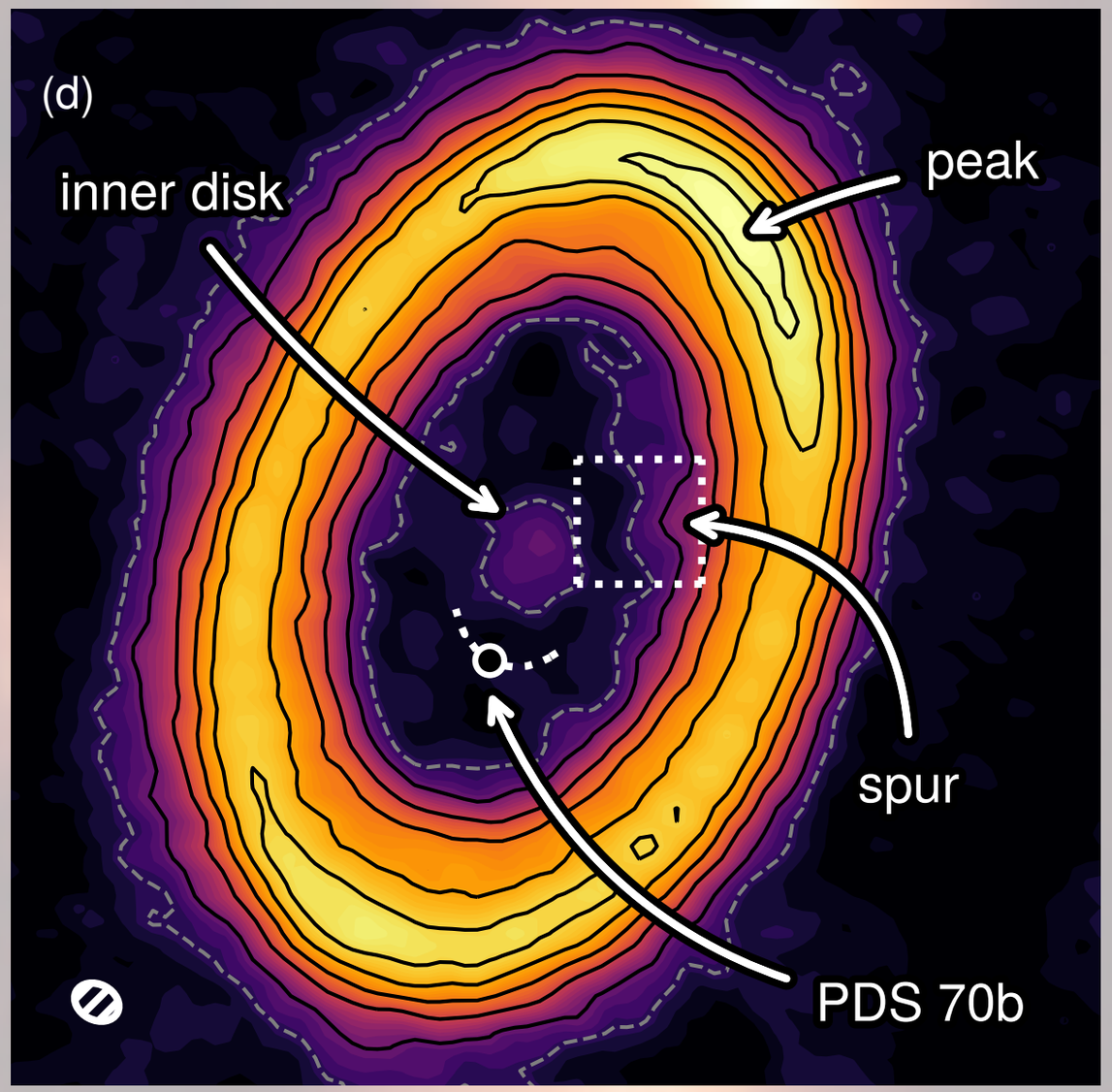
Reproduction of the polarised intensity image requires high disc mass (0.1 Msun) and fluffy grains so that small grains stick in upper atmosphere of disc

Consistent with Tazaki et al. (2023) “fractal aggregates in IM Lupi”

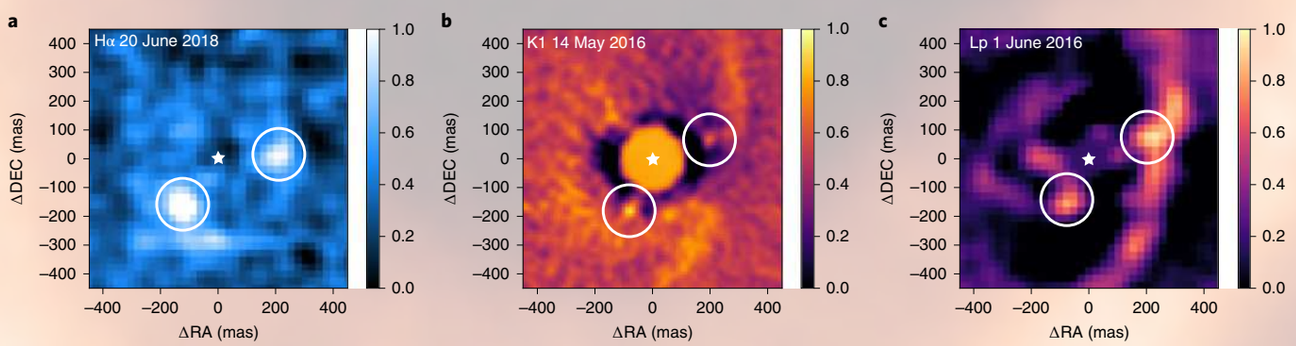
DIRECT IMAGING OF YOUNG PLANETS: PDS 70



Müller+(2018)

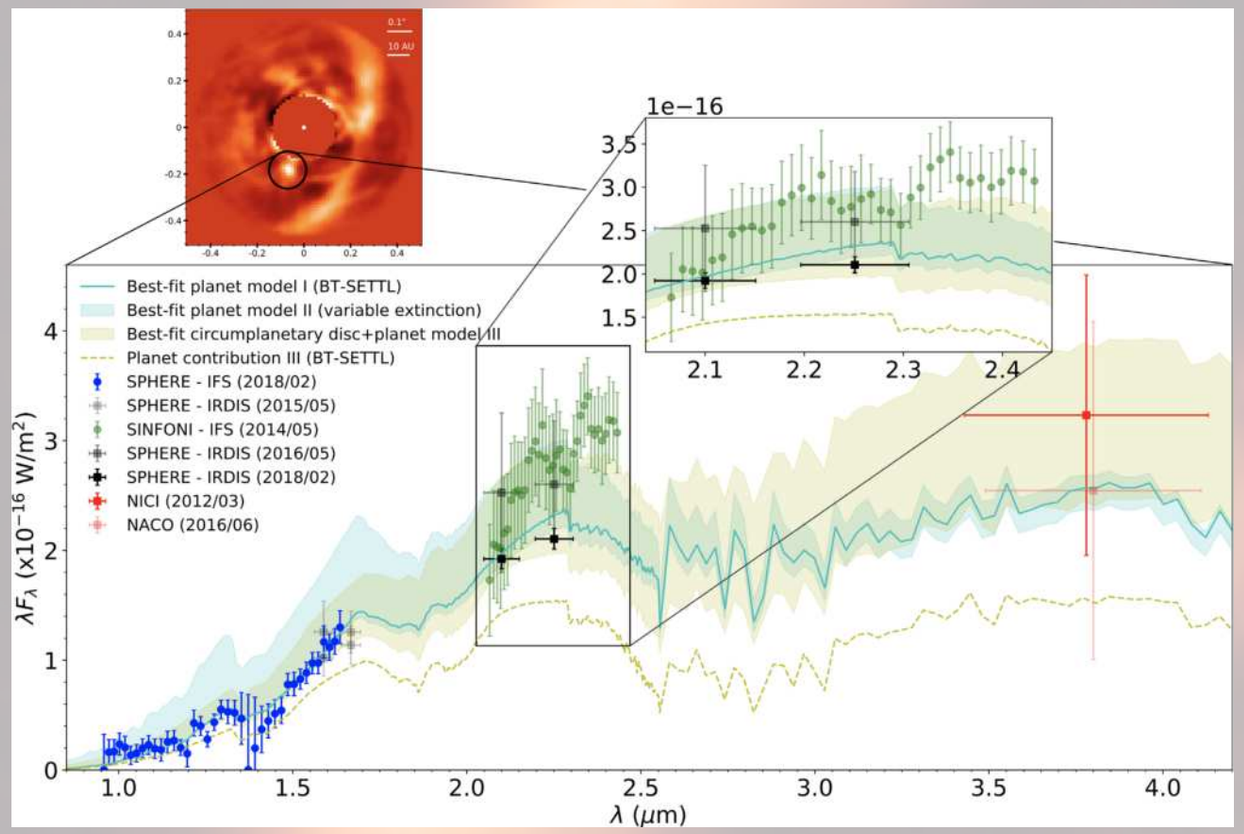


Keppler+(2019)



Haffert+(2019)

EVIDENCE FOR CIRCUMPLANETARY DISCS: PDS70B & C

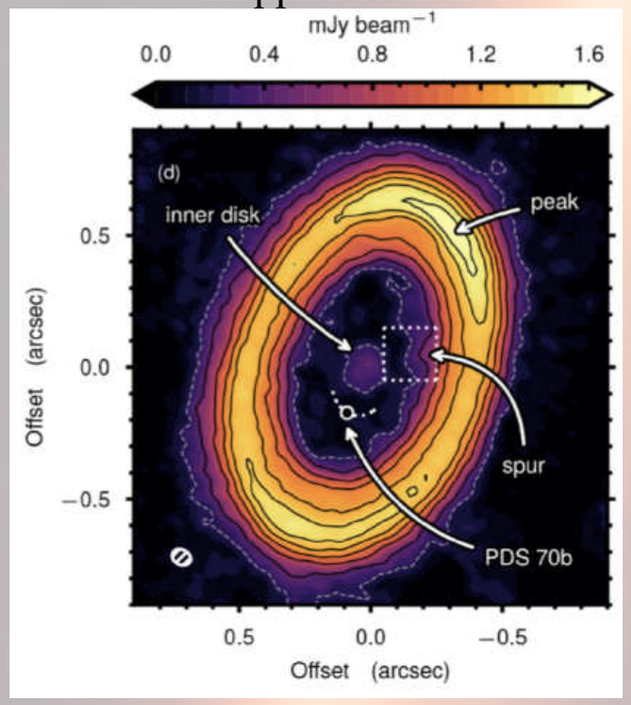


Christiaens et al. (2019) incl. DP:
evidence for CPD around PDS70b based on excess emission at $\lambda > 2.3\mu\mathrm{m}$

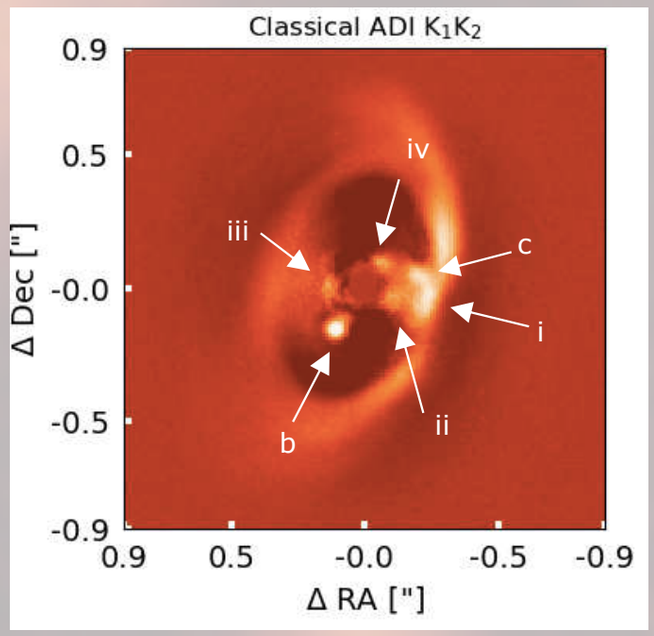
Benisty et al. (2021): CPD around PDS70c at mm-wavelengths with ALMA

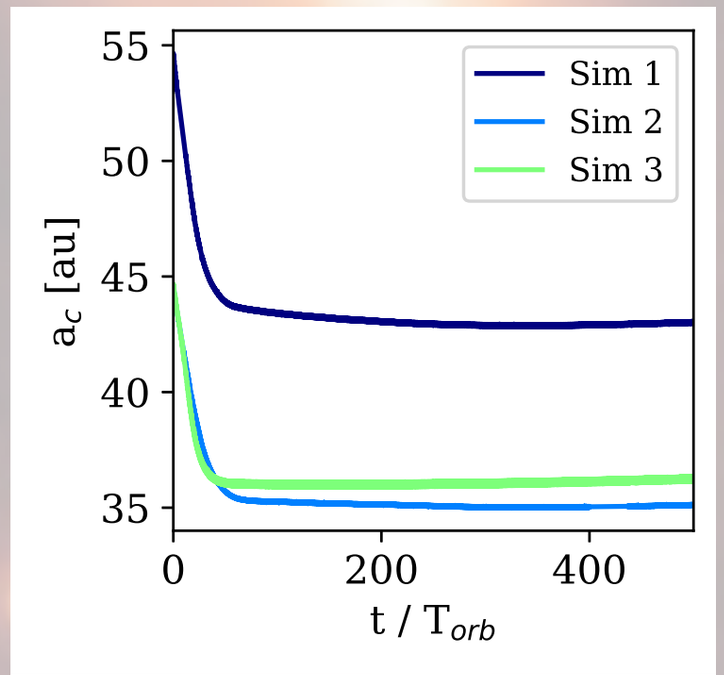
RESONANT LOCKING IN PDS70

Keppler et al. 2019

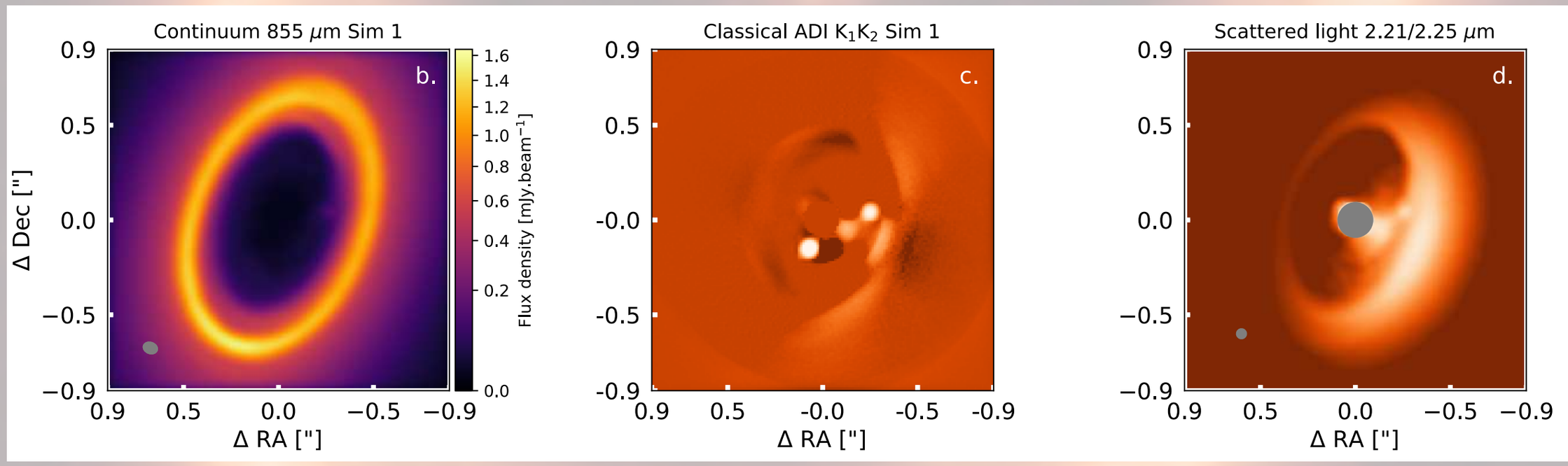


Muller et al. 2018





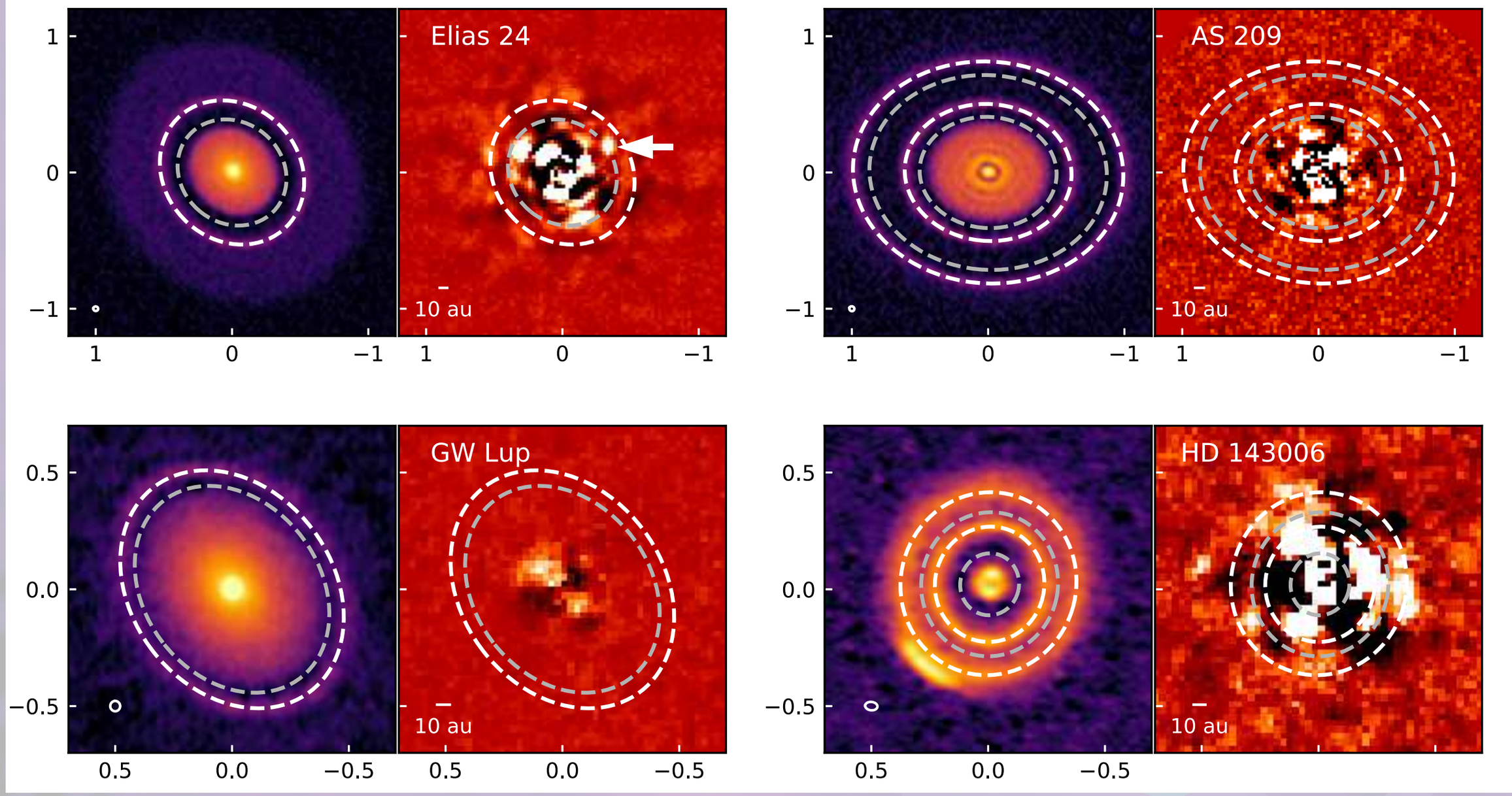
Sim1



Toci+2020

CAN WE GET A DIRECT IMAGE AND KINEMATICS AT THE SAME TIME?

Direct imaging search for companions on DSHARP disks

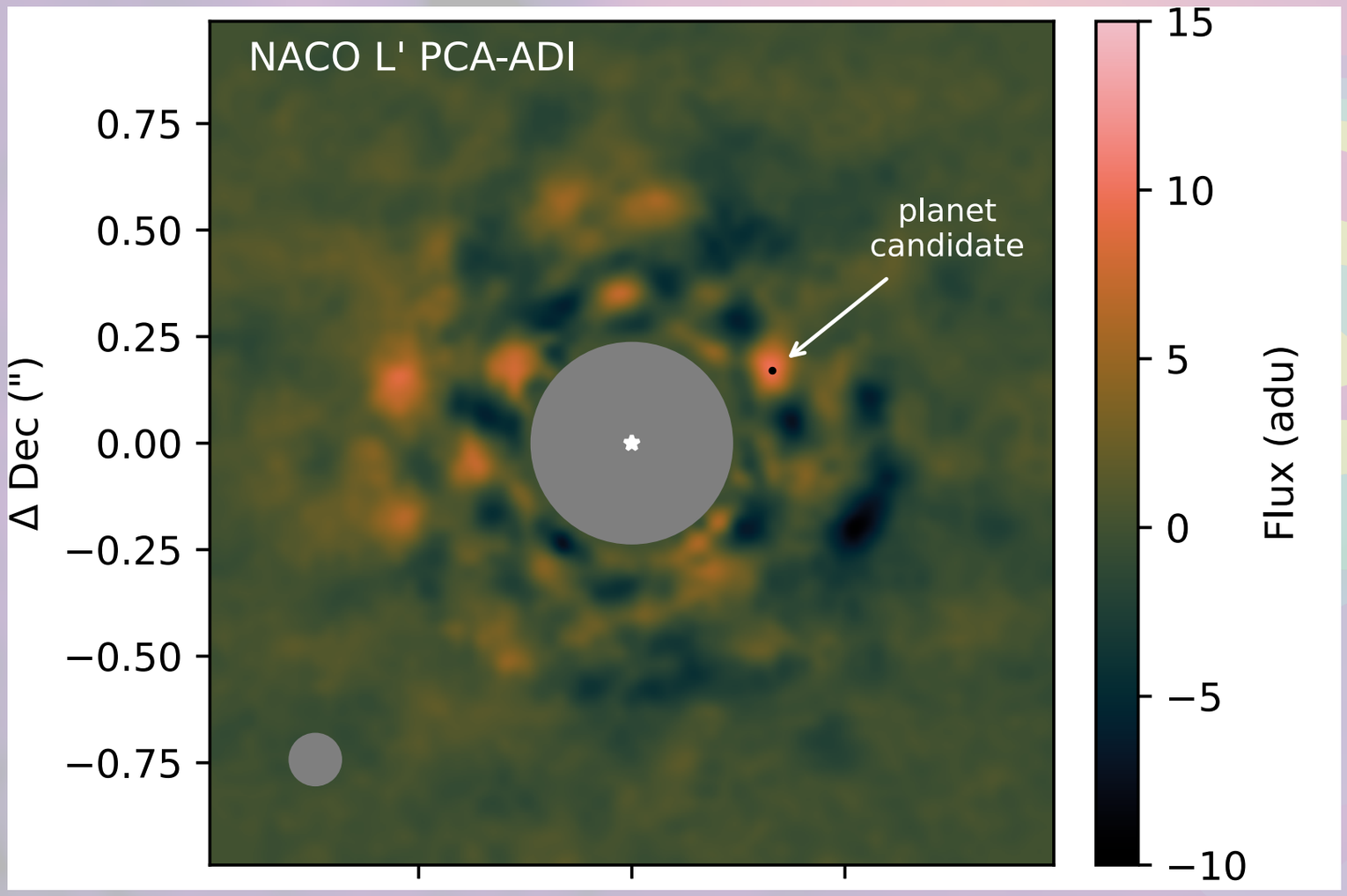


Jorquera+2021

CAN WE GET A DIRECT IMAGE AND KINEMATICS AT THE SAME TIME?

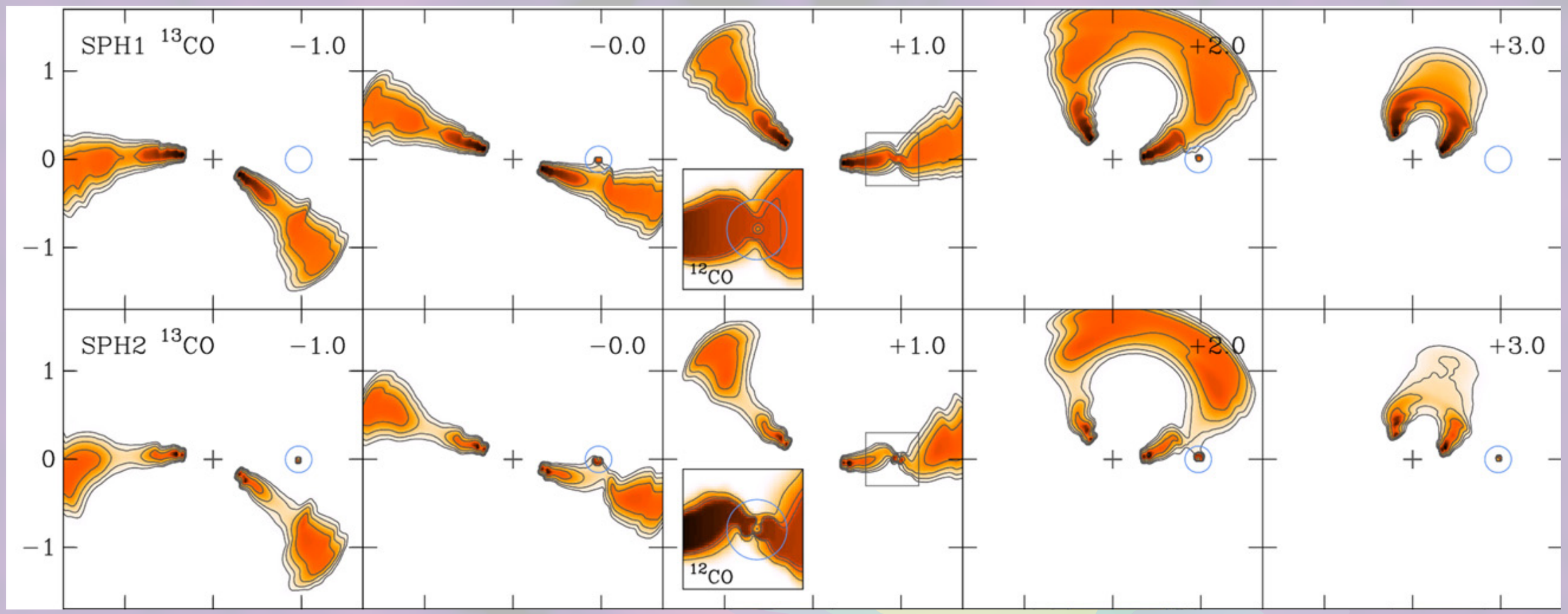
Kinematic and thermal signatures of the directly imaged protoplanet candidate around Elias 2-24

C. Pinte[1,2], I. Hammond[1], D. J. Price[1], V. Christiaens[1,3], S. M. Andrews[4], G. Chauvin[5,2], L. M. Pérez[6,7], S. Jorquera[6], H. Garg[1], B. J. Norfolk[8], J. Calcino[9], M. Bonnefoy[2]



Elias 2-24 was the best direct imaging candidate from the SHINE survey (Jorquera et al. 2021)

HOW SHOULD A CIRCUMPLANETARY DISC APPEAR IN KINEMATICS?

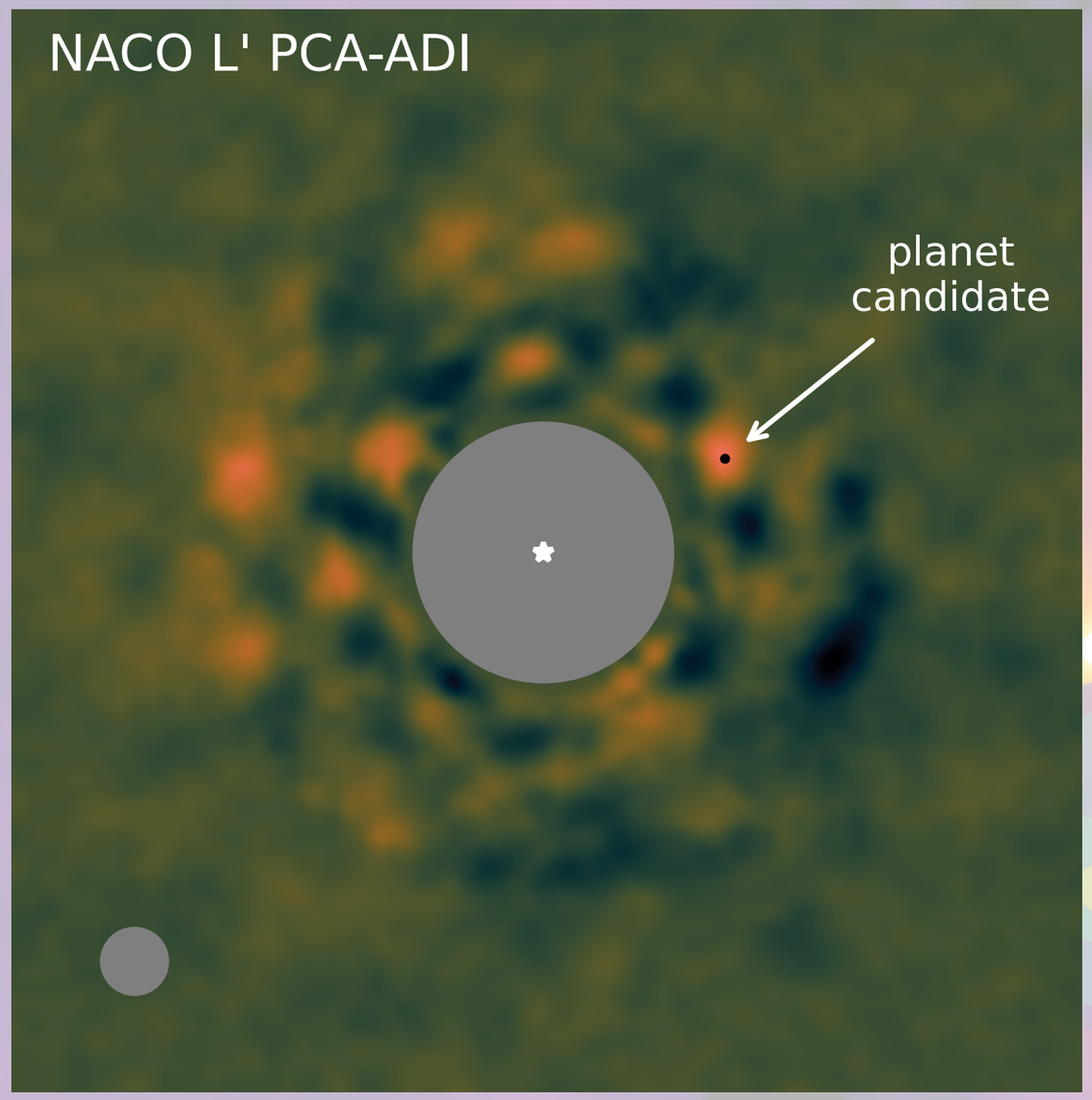


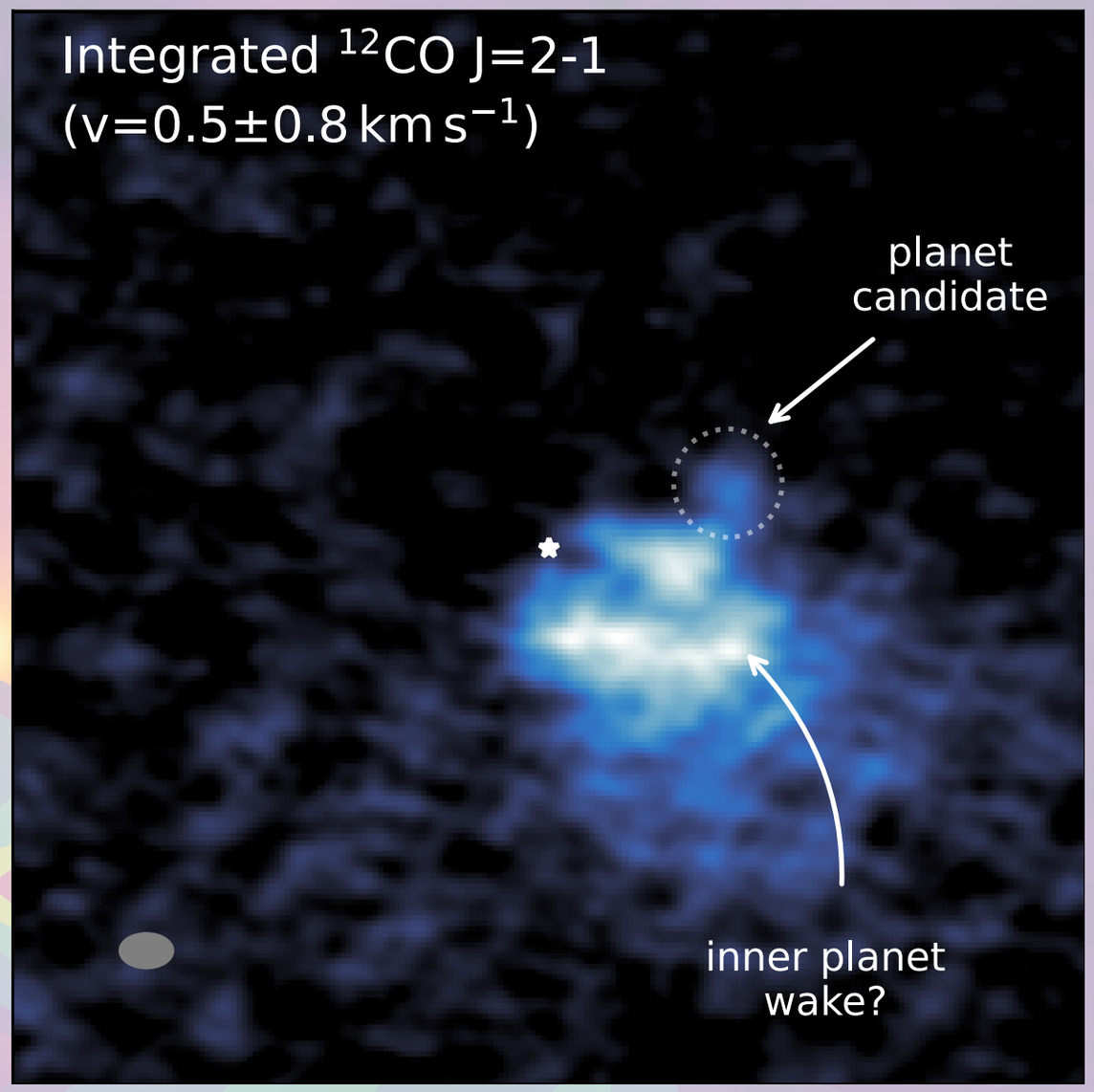
PLANET FORMATION SIGNPOSTS: OBSERVABILITY OF CIRCUMPLANETARY DISKS VIA GAS KINEMATICS

Sebastian Perez[1,2], A. Dunhill[3], S. Casassus[1,2], P. Roman[2,4], J. Szulágyi[5], C. Flores[1,2], S. Marino[1,2], and M. Montesinos[1,2]

Perez et al. (2015)

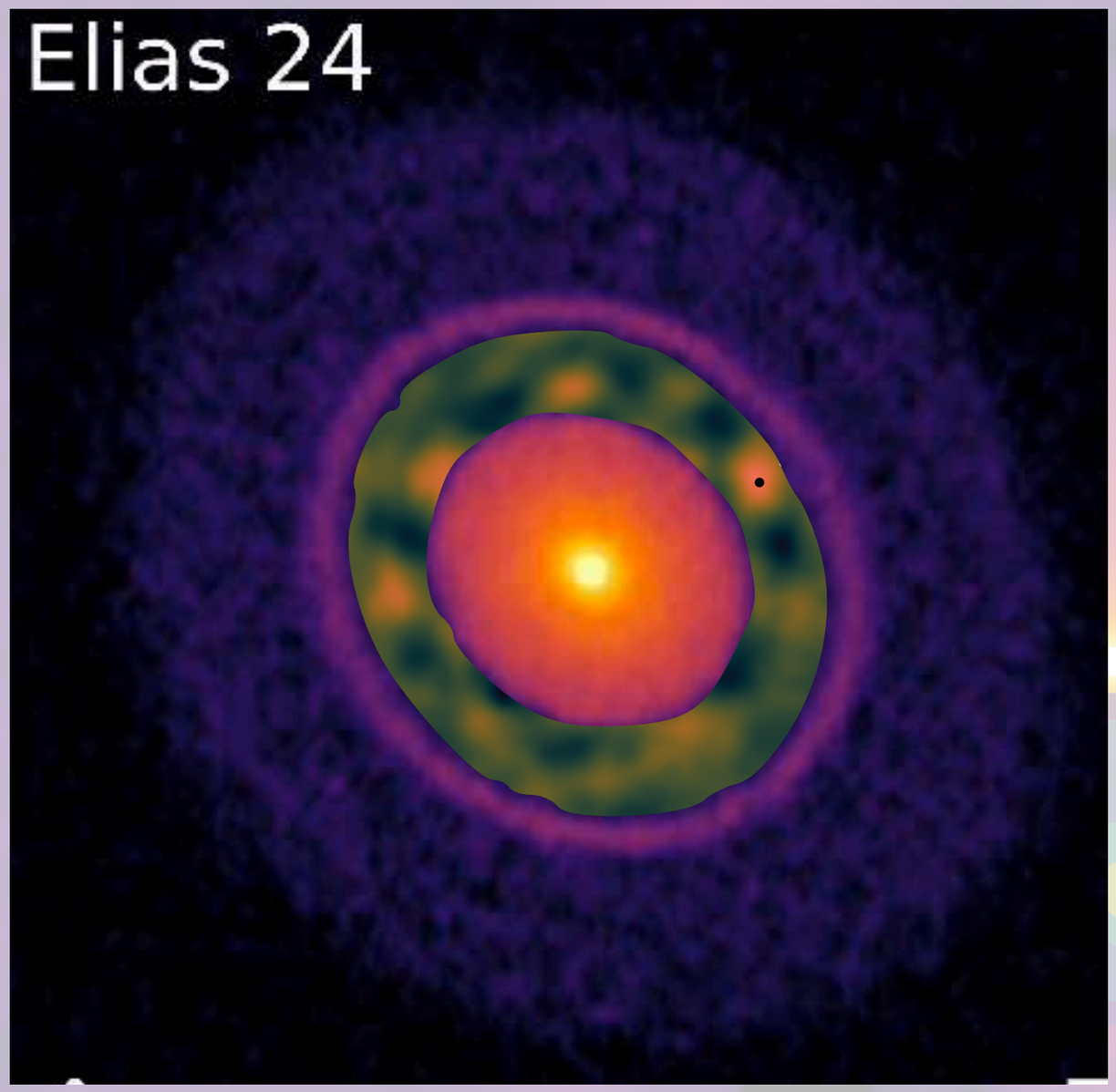
ELIAS 2-24

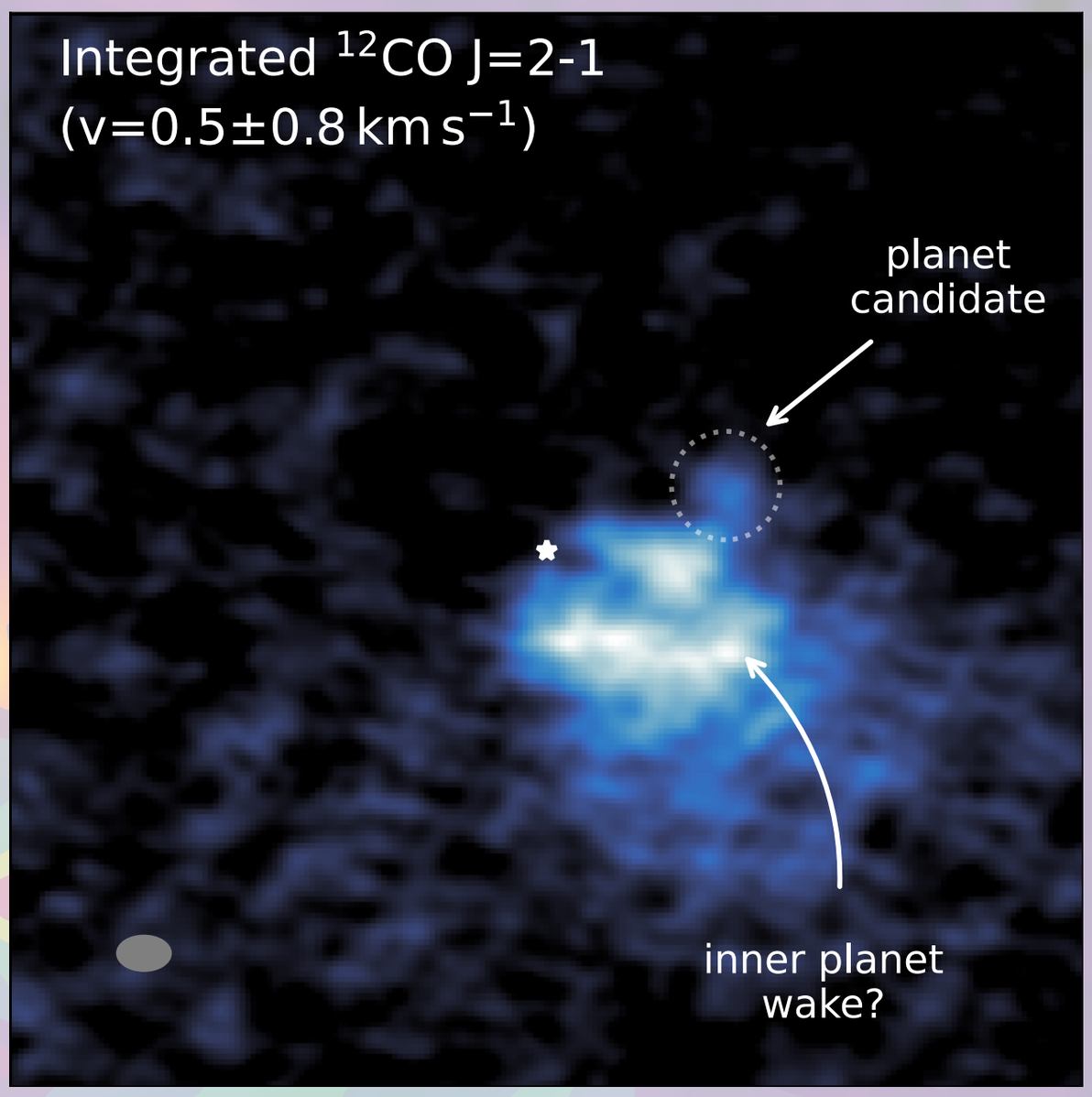




Pinte, Hammond, DP et al. (2023)

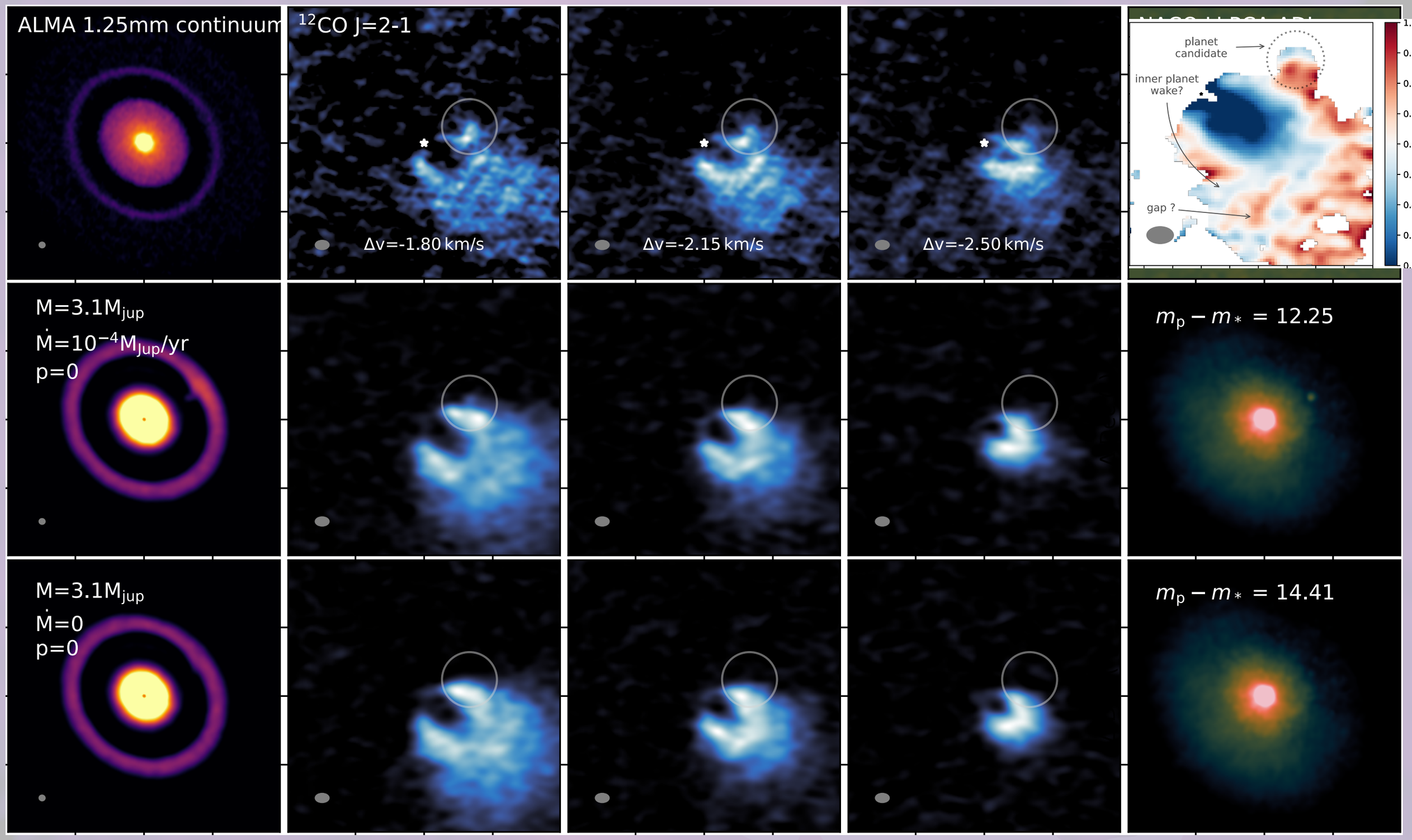
ELIAS 2-24





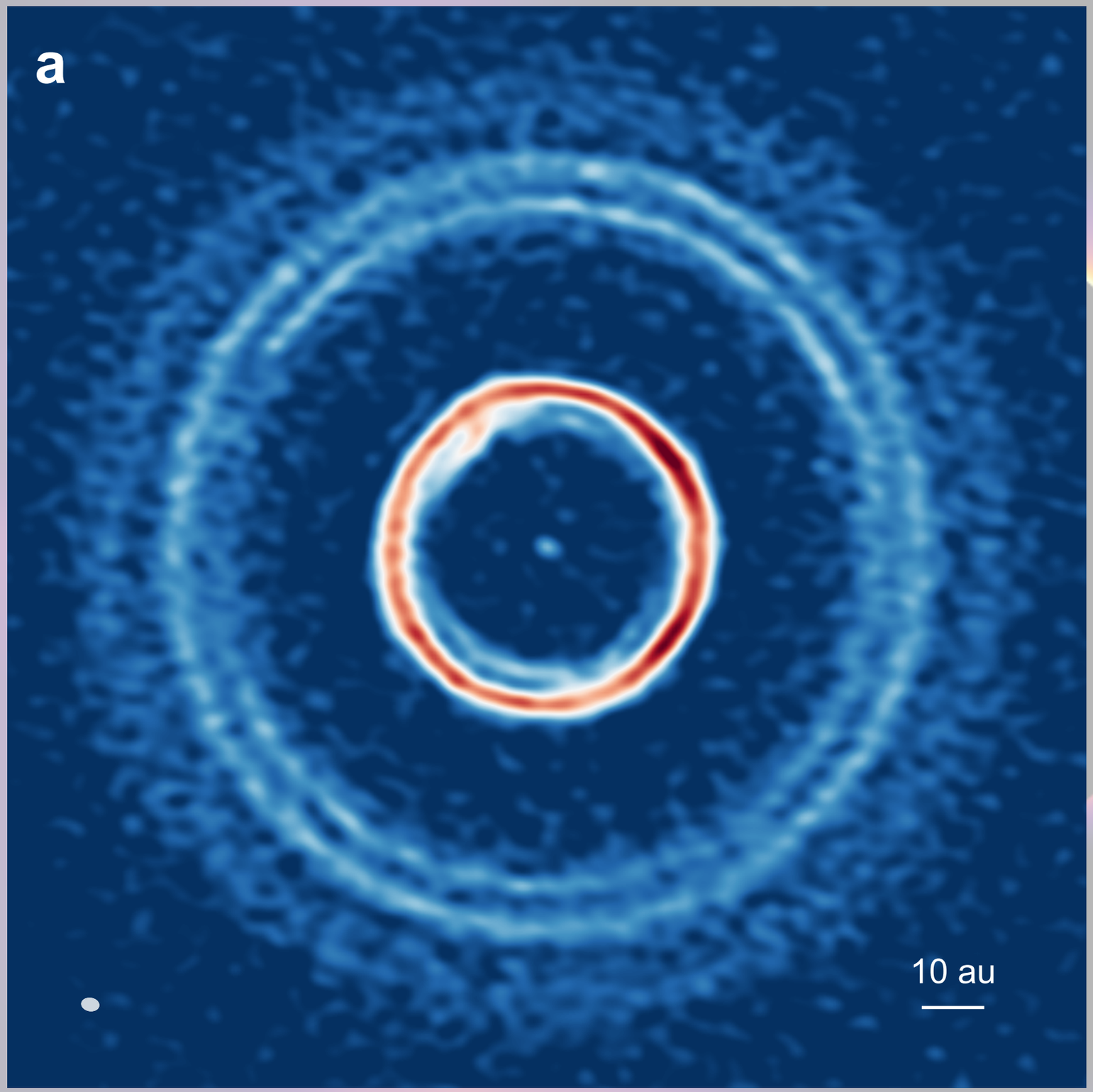
Pinte, Hammond, DP et al. (2023)

ELIAS 2-24

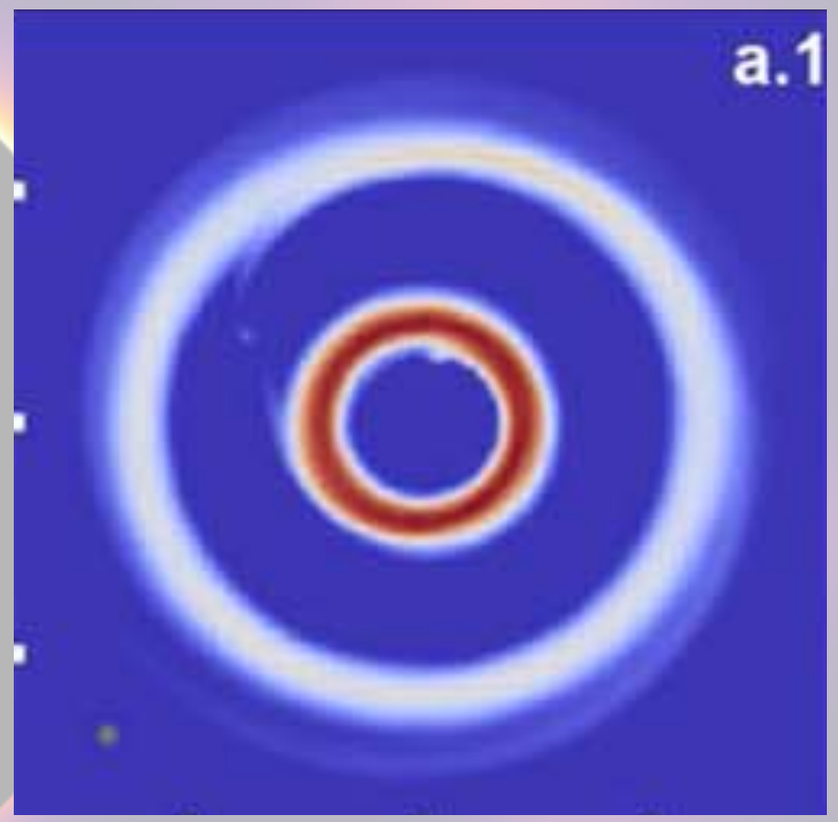


Pinte, Hammond, DP et al. (2023)

HD 169142 WITH ALMA

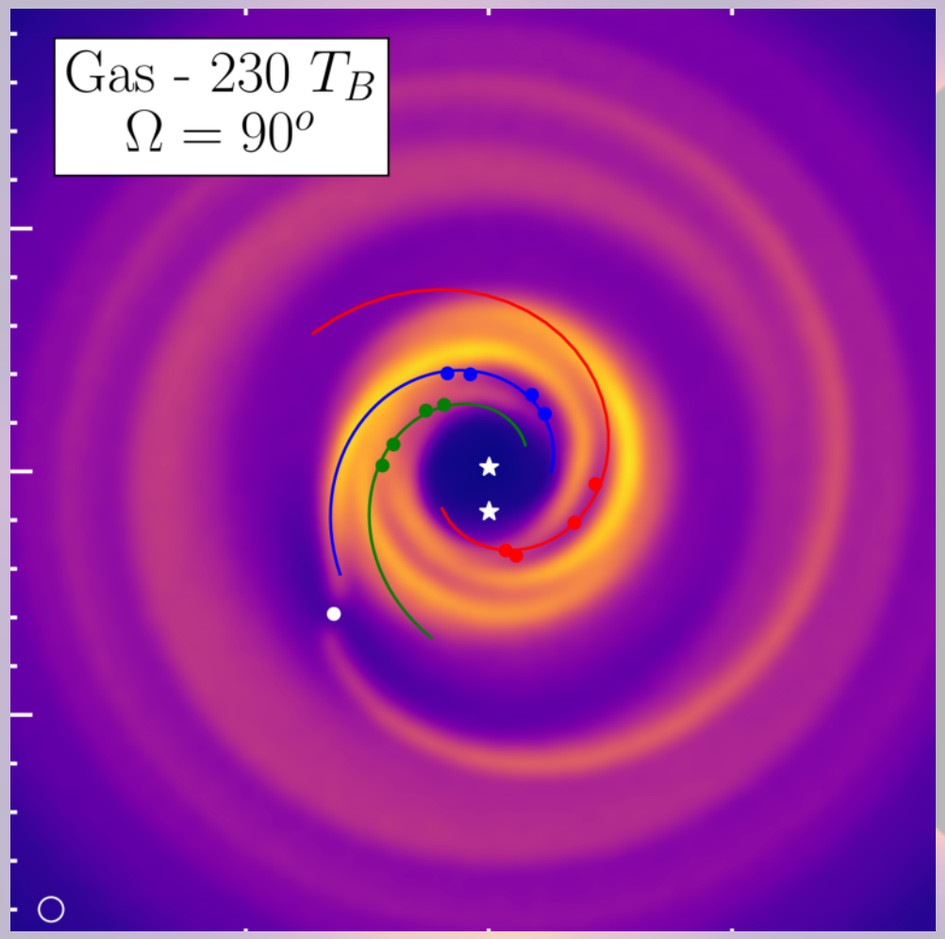


Perez et al. (2019)

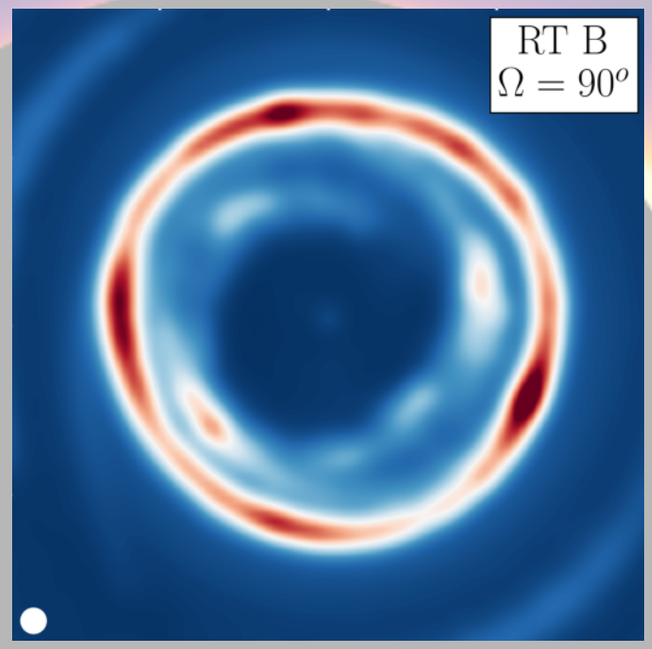


Toci et al. (2020)

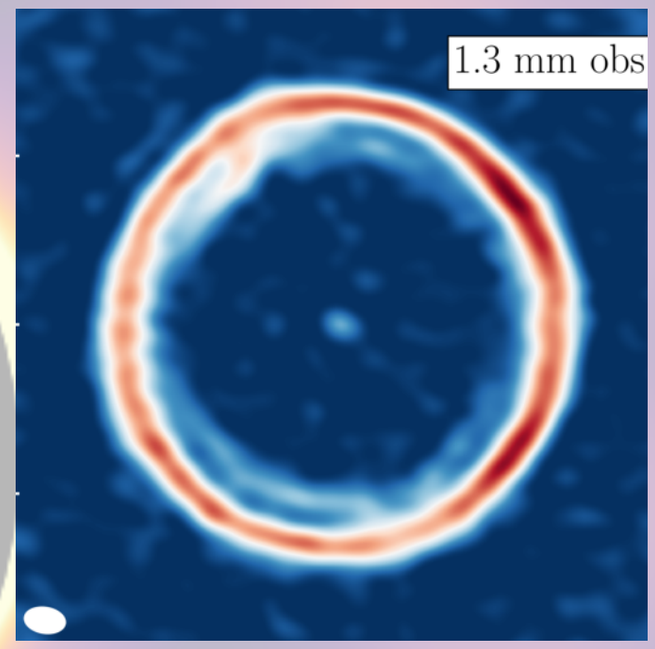
A POLAR BINARY?



Inner binary + planet model



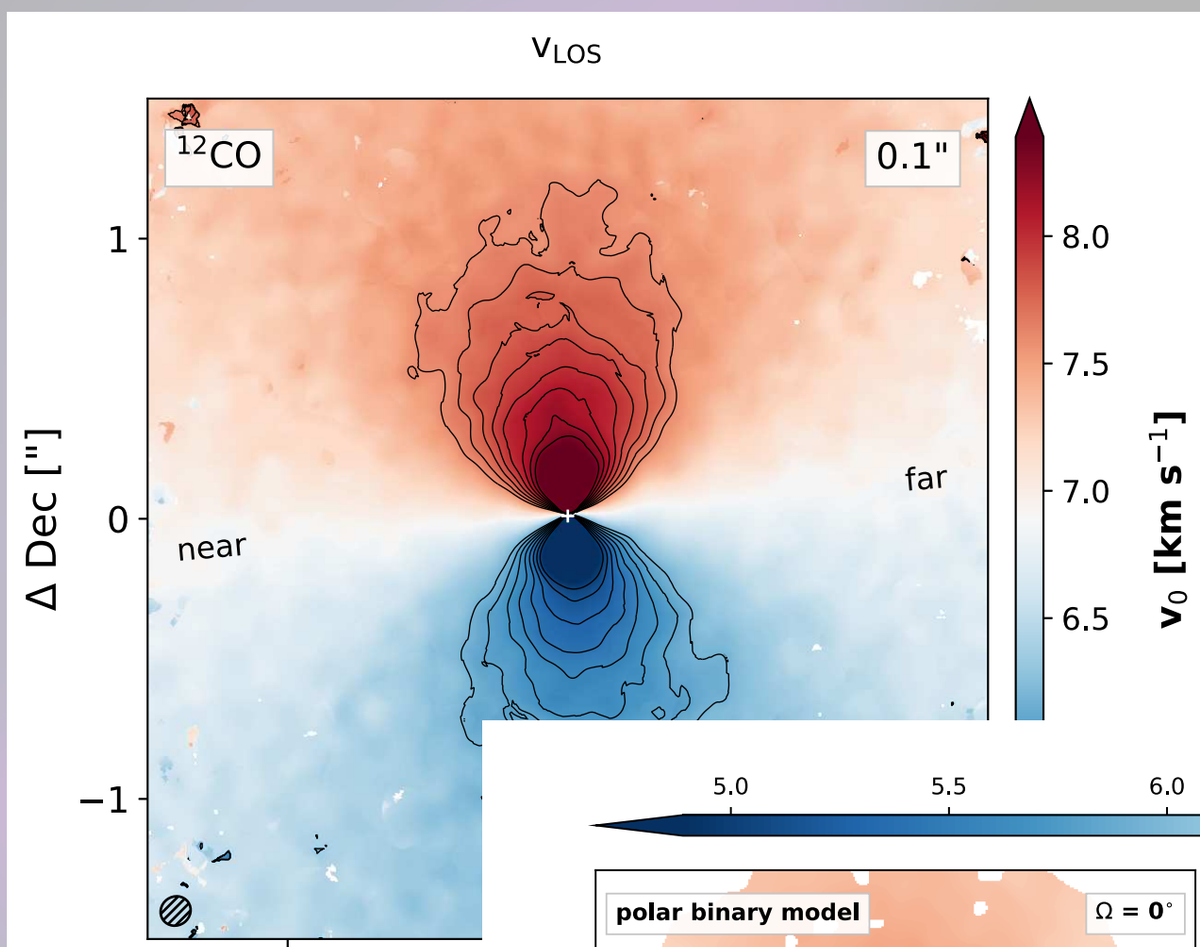
Model

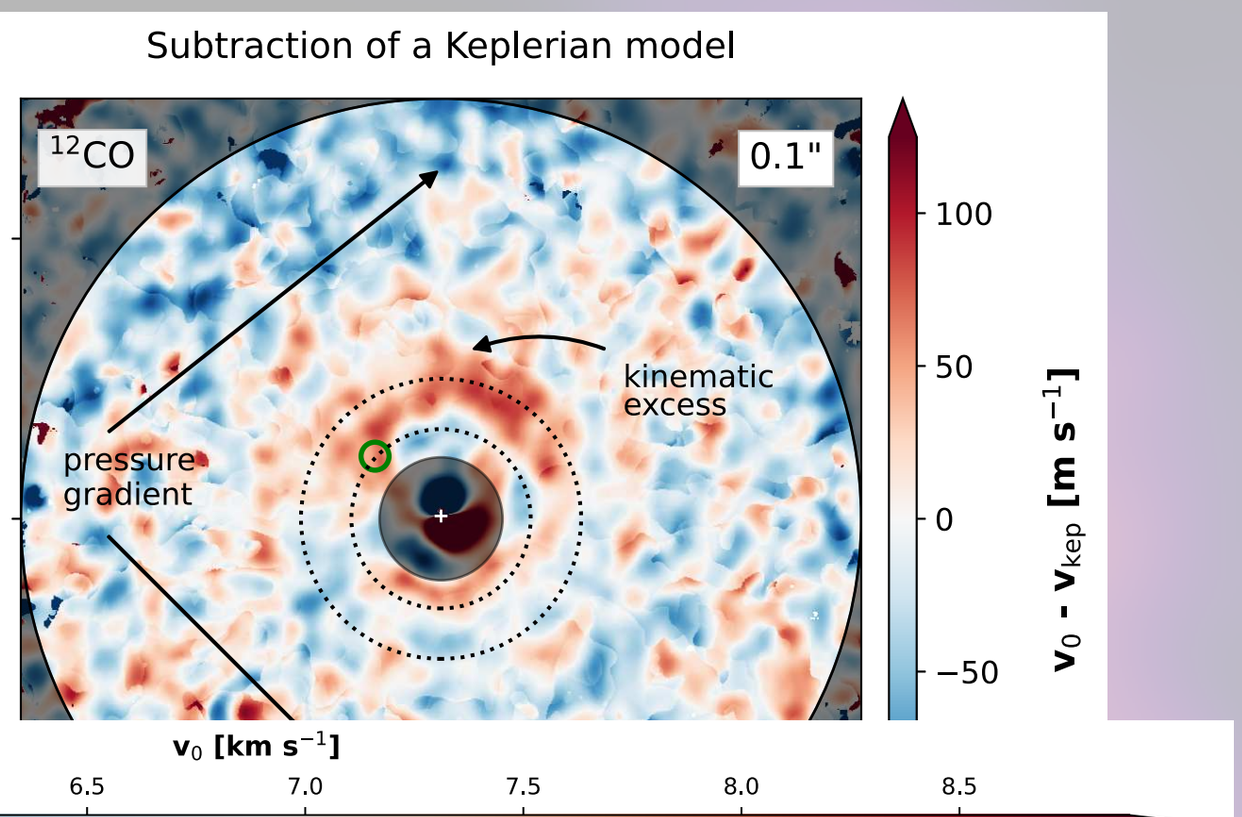


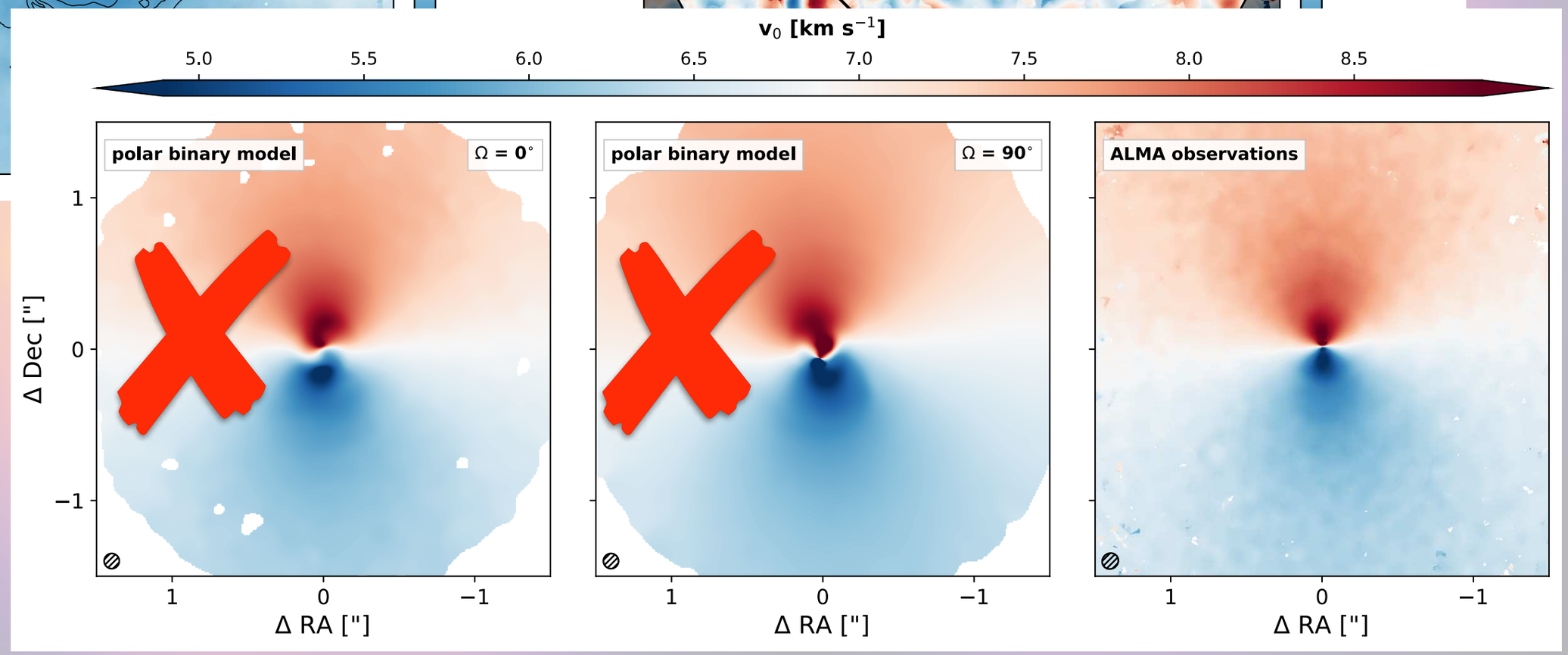
Obs

Poblete, Cuello et al. (2022) incl. DP

HD 169142 KINEMATICS

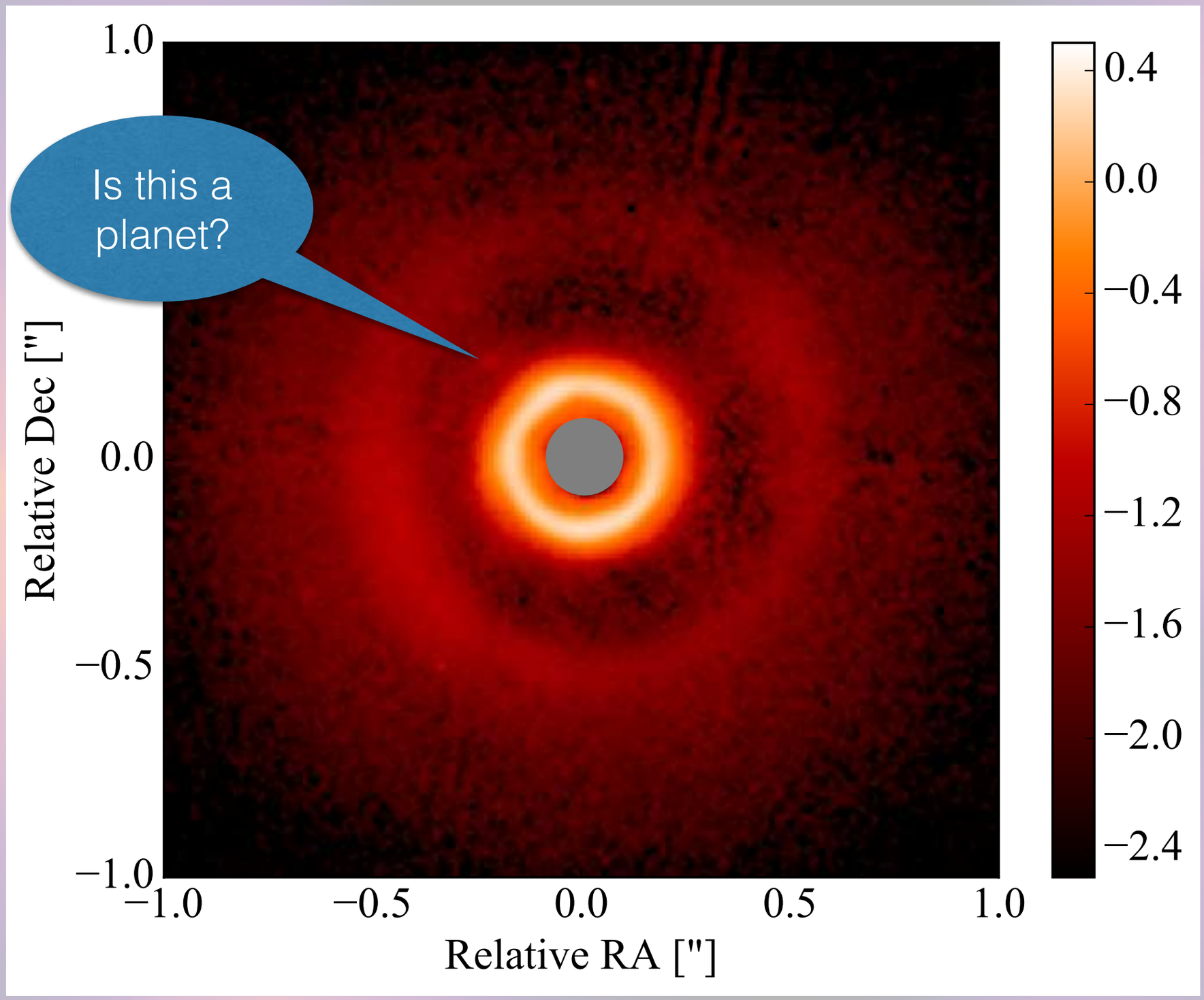






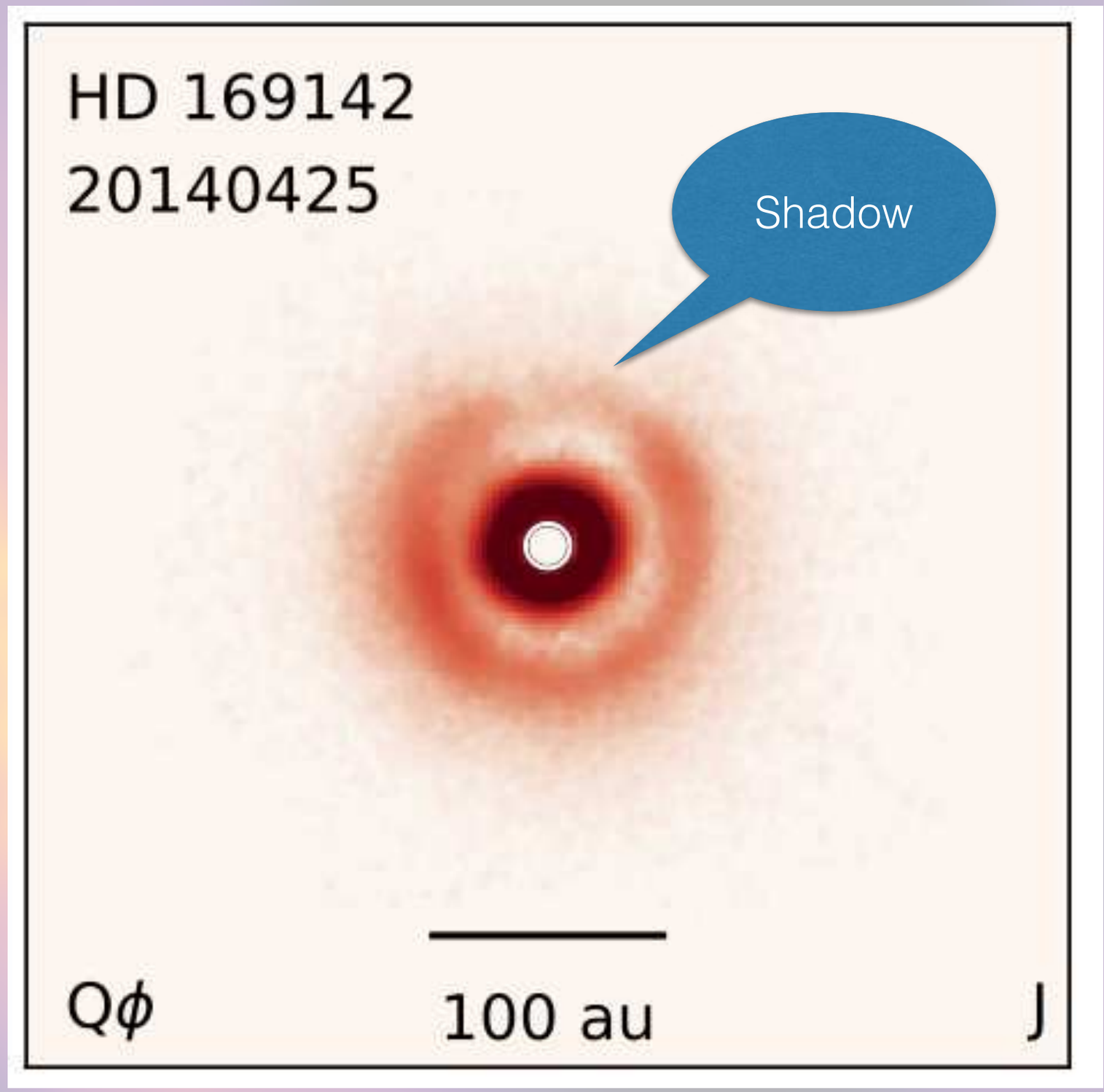
Garg et al. (2022) incl. DP

HD 169142 DIRECT IMAGING



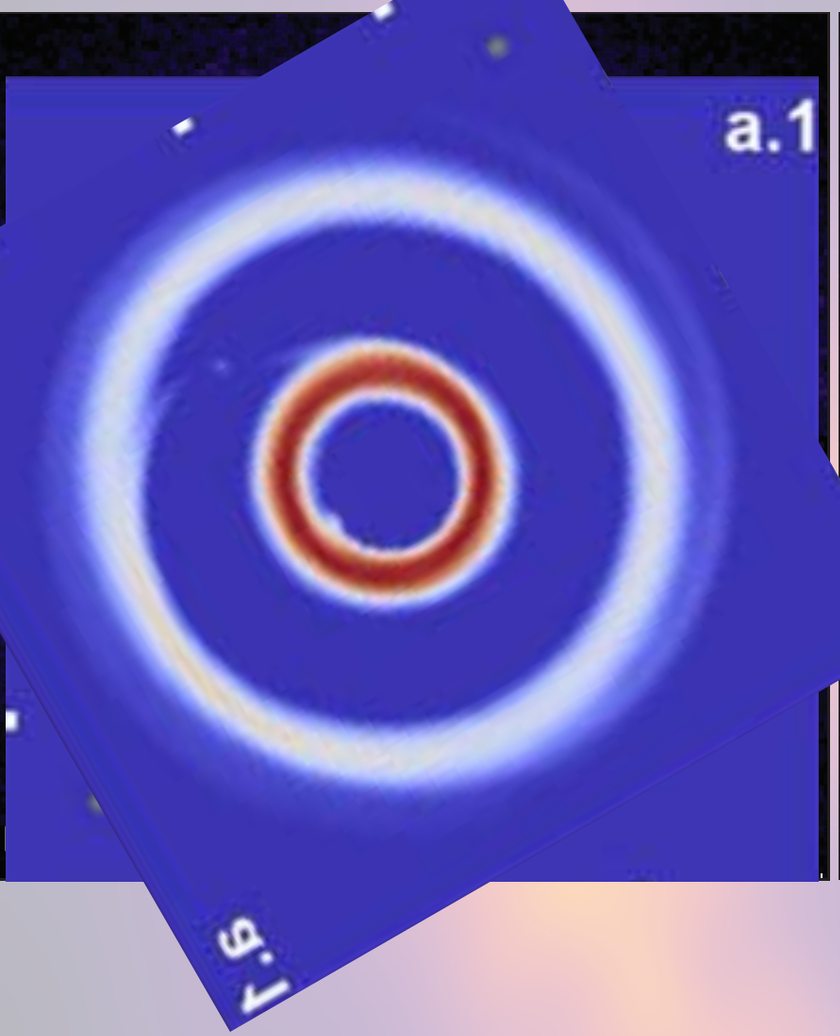
Pohl et al. (2017) using VLT/SPHERE

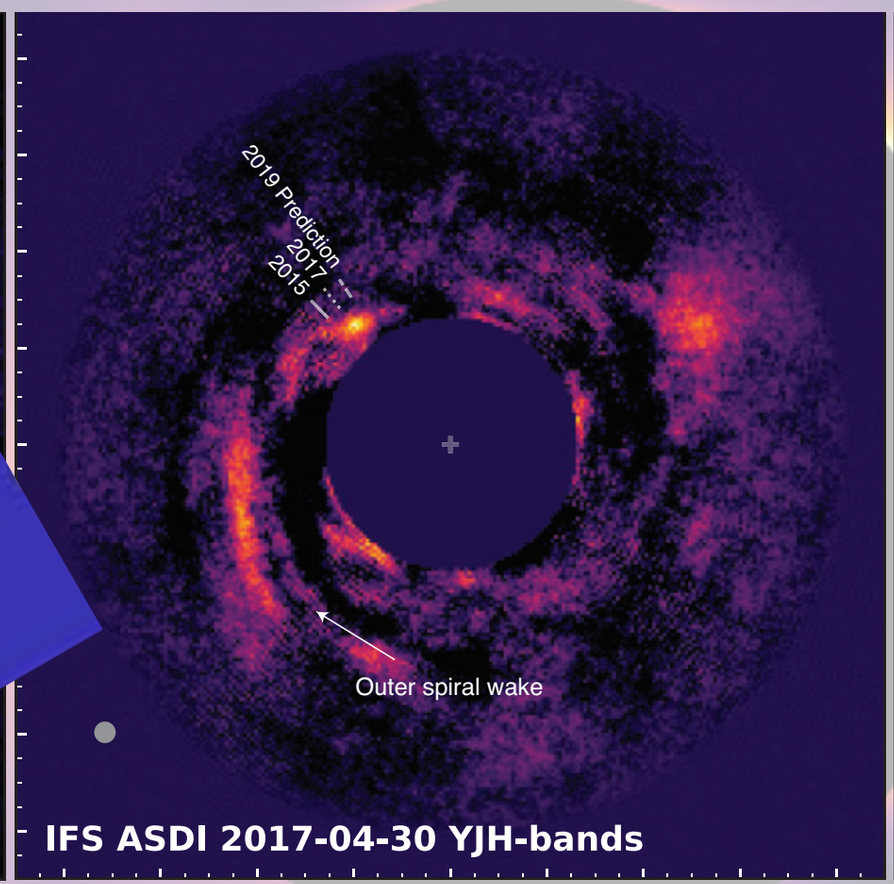
HD 169142 DIRECT IMAGING

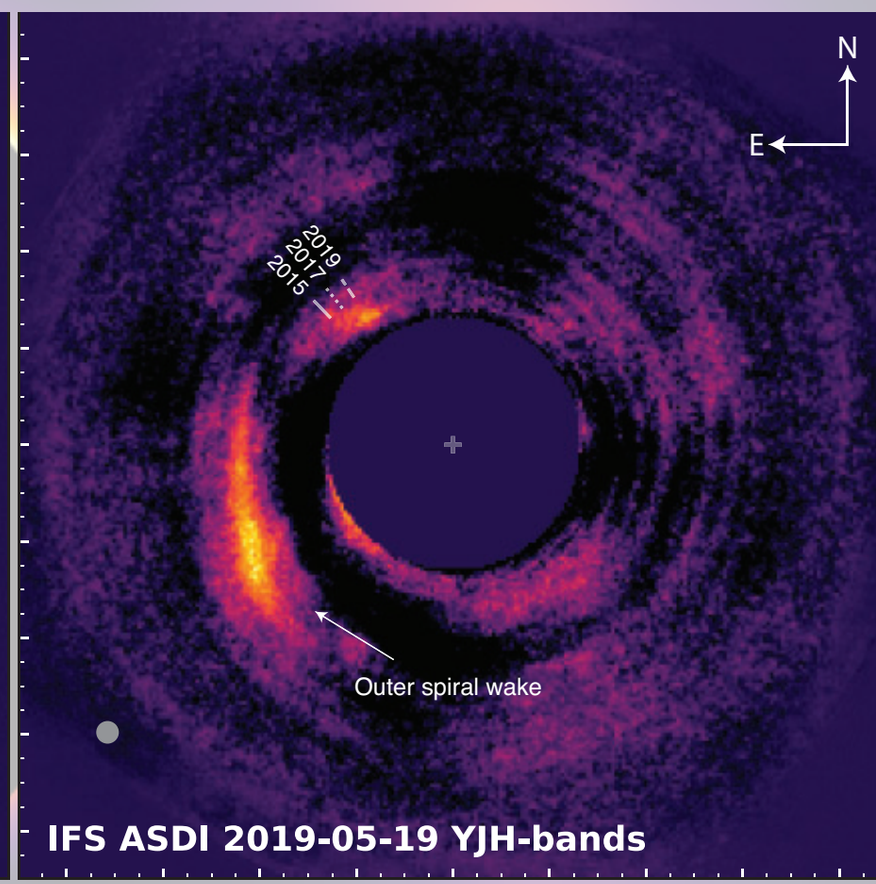


Rich et al. (2022) with Gemini Planet Imager

HD 169142 DIRECT IMAGING



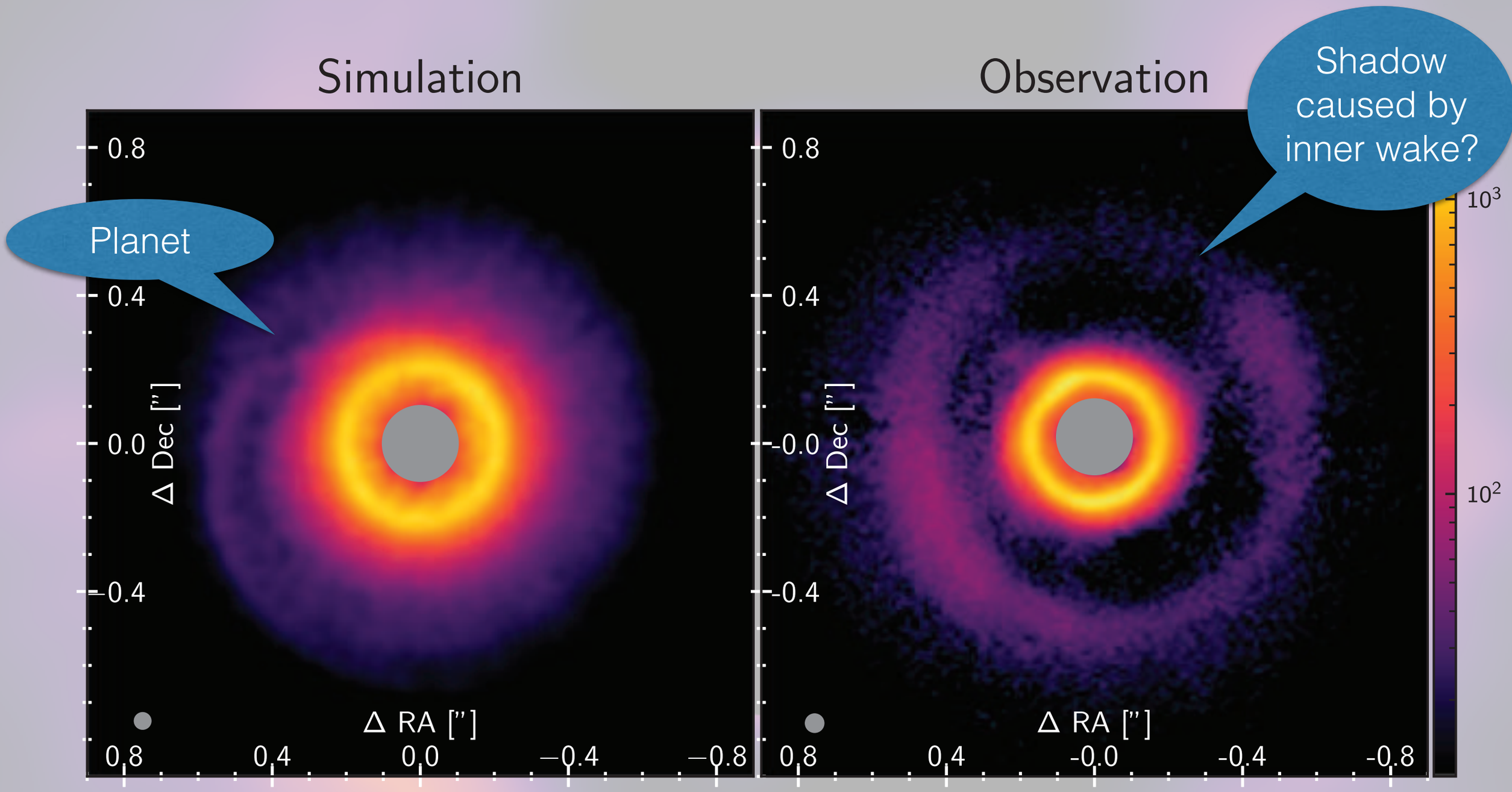




Toci et al. (2020)

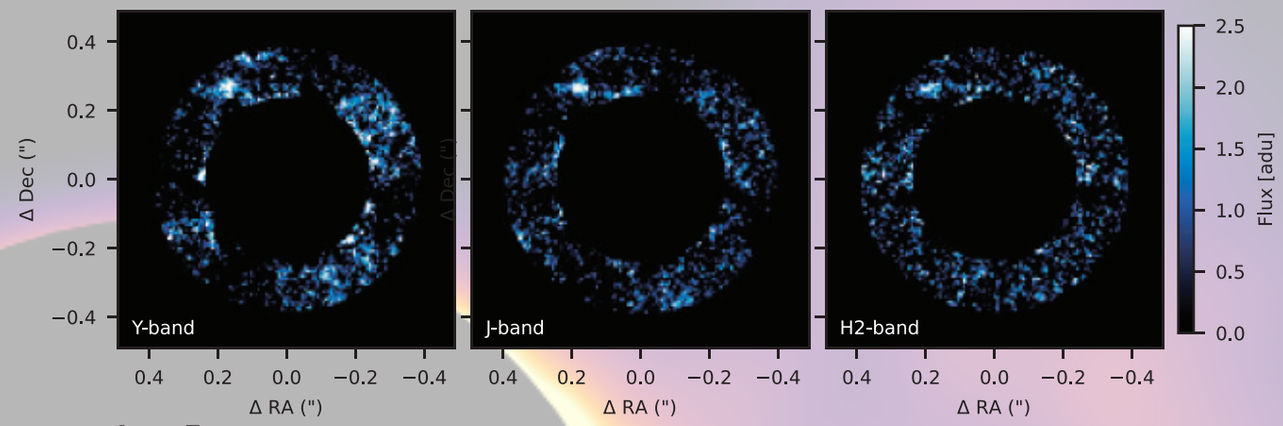
Hammond et. al. (2023) using archival VLT images

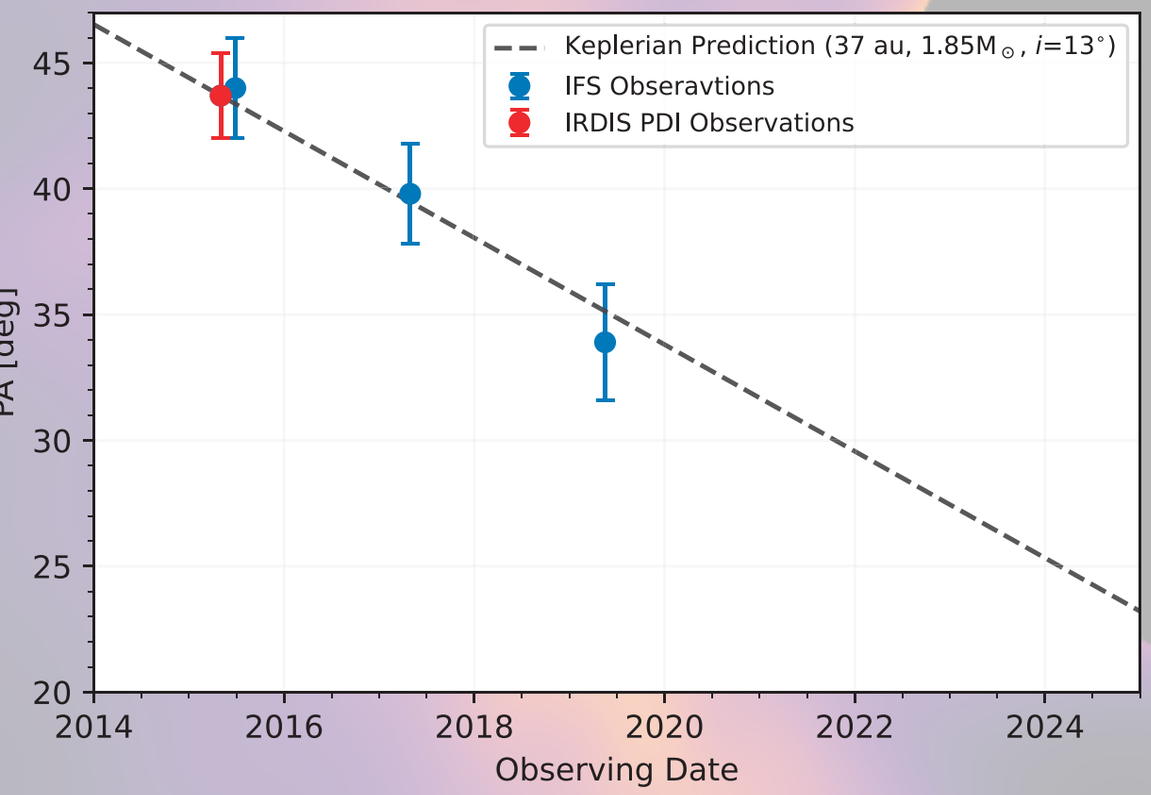
HD 169142 DIRECT IMAGING



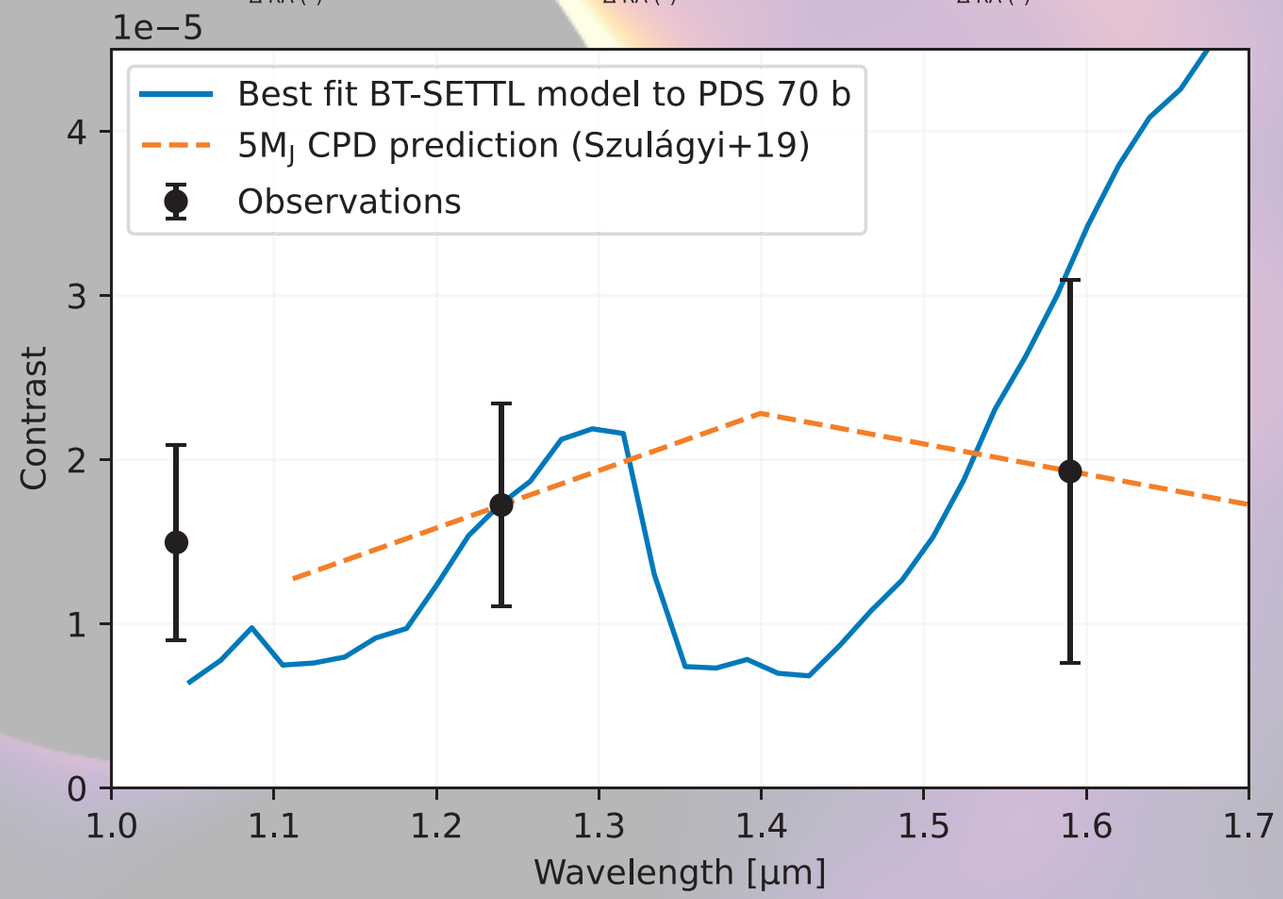
Hammond et. al. (2023)

HD 169142 DIRECT IMAGING





Consistent with Keplerian orbit at 37 au around 1.85 solar mass star

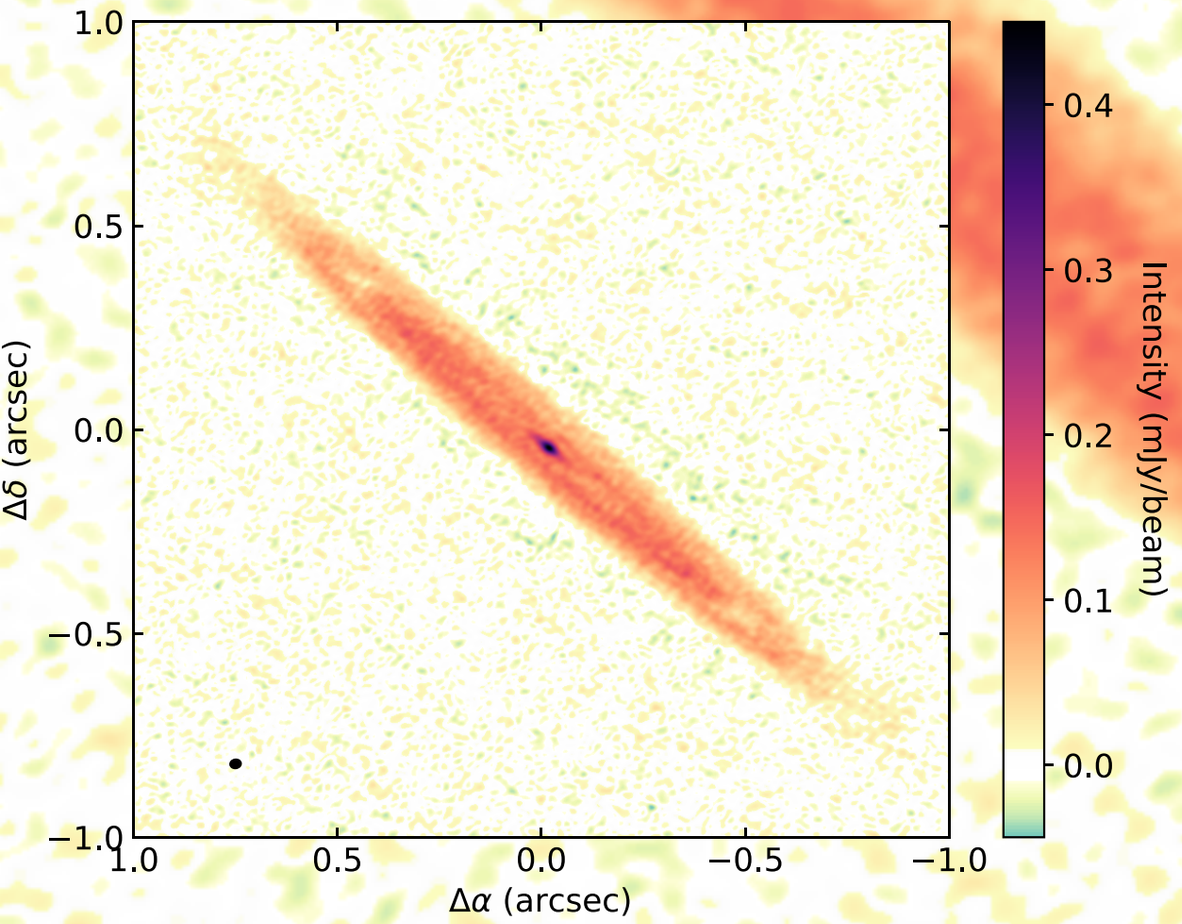


Planet is deeply embedded in material

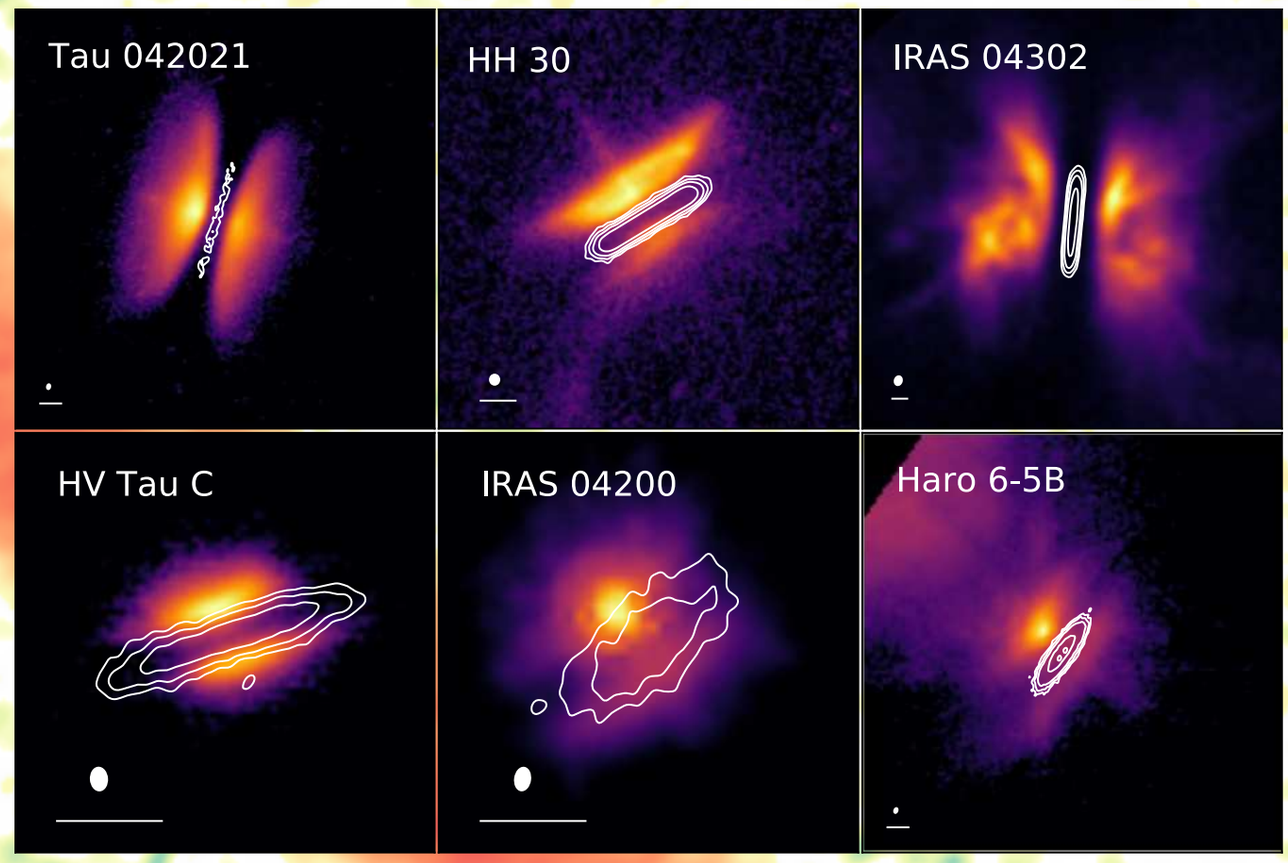
Hammond et. al. (2023)

HOW DO THESE PLANETS GET THERE?

Edge-on discs program (PI: Ménard)



Villenave et. al. (2022)



Villenave et. al. (2020)

Highly settled dust discs suggestive of direct fragmentation of dust into planets…?

SUMMARY

- WE ARE NOW ABLE TO DIRECTLY DIRECT PLANETS DURING THEIR FORMATION PROCESS

- PLANET FORMATION APPEARS TO OCCUR QUICKLY

- PLANETS FORM EVERYWHERE

- FIRST INDICATIONS OF HOT START FORMATION FROM KINEMATICS+IMAGING