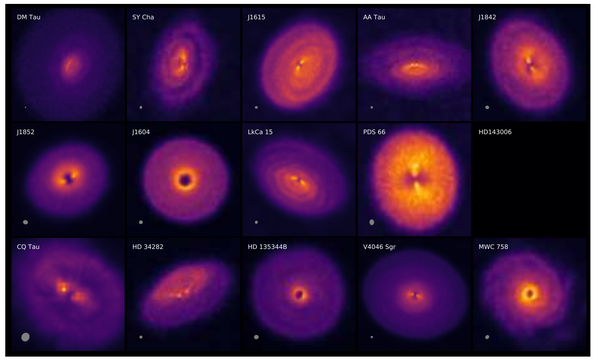


THE BABY BOOM

LE CANARD
DE EEND

WITH CHRISTOPHE PINTE, IAIN HAMMOND, VALENTIN CHRISTIAENS, LIONEL SIESS, 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

DANIEL PRICE

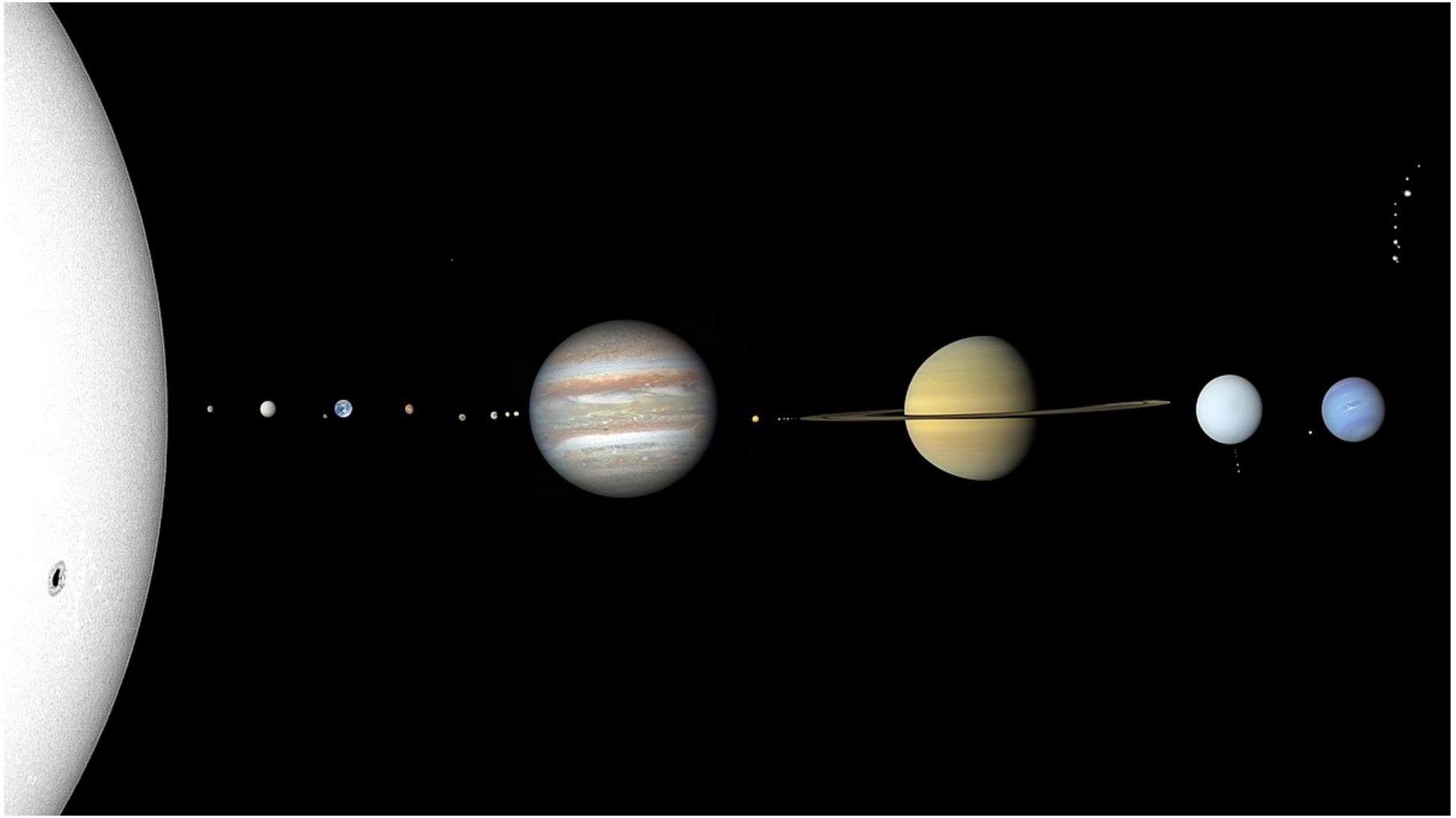
ASTRONOMY DAY OF THE ROYAL OBSERVATORY
OF BELGIUM, 14TH OCT 2025

DUST BUSTERS

Australian Government
Australian Research Council

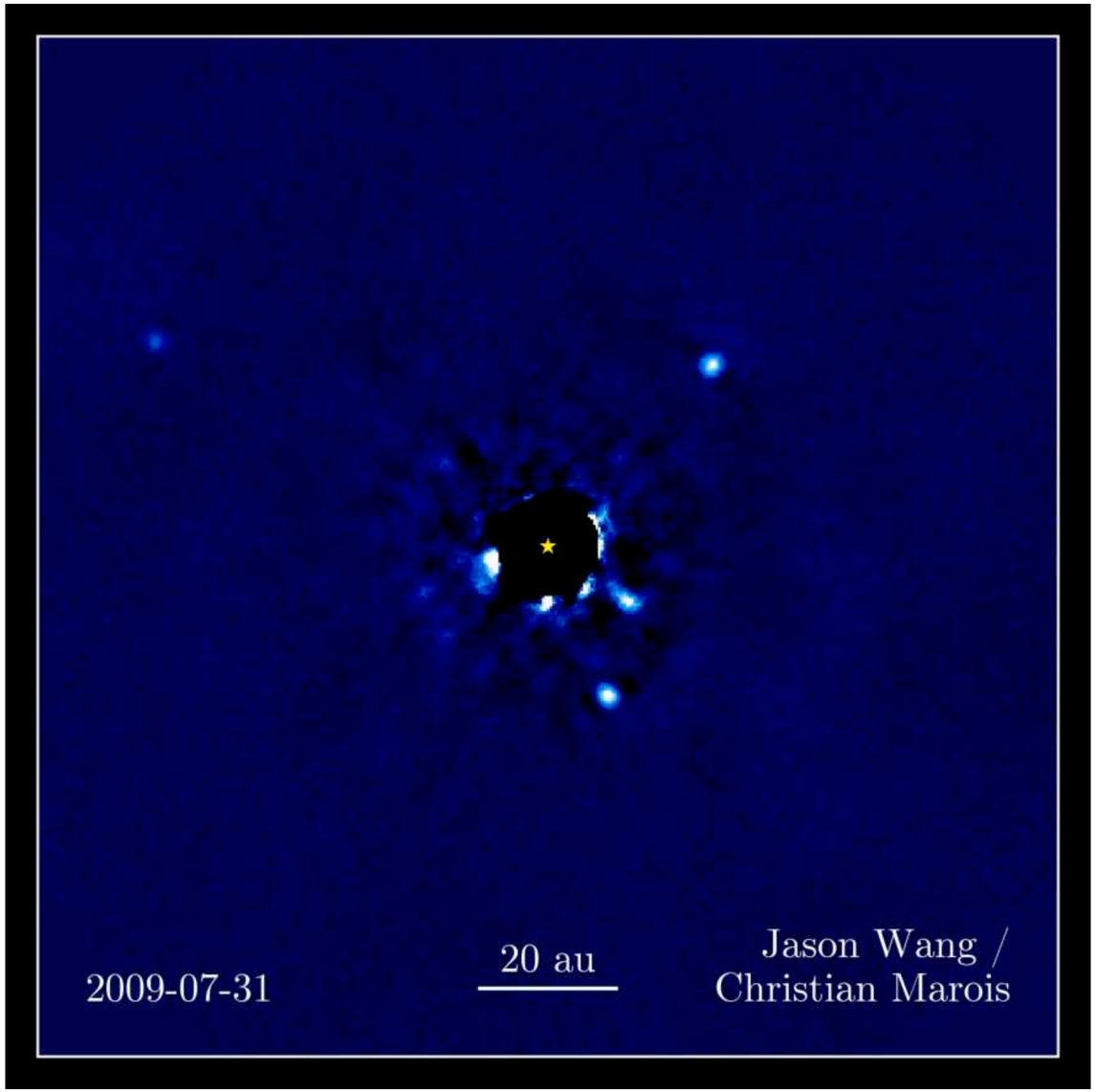
MONASH University

HOW DID THE SOLAR SYSTEM FORM?

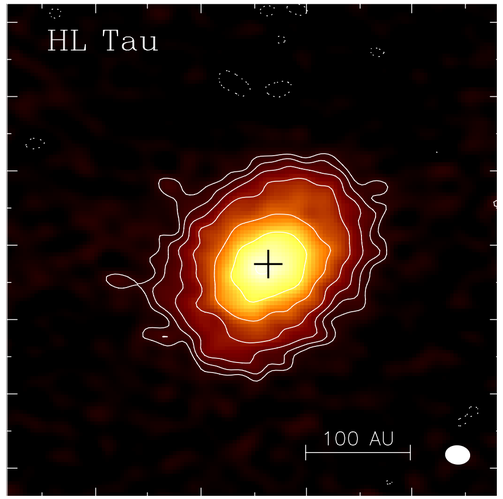


Credit: wikipedia/CactiStaccingCrane

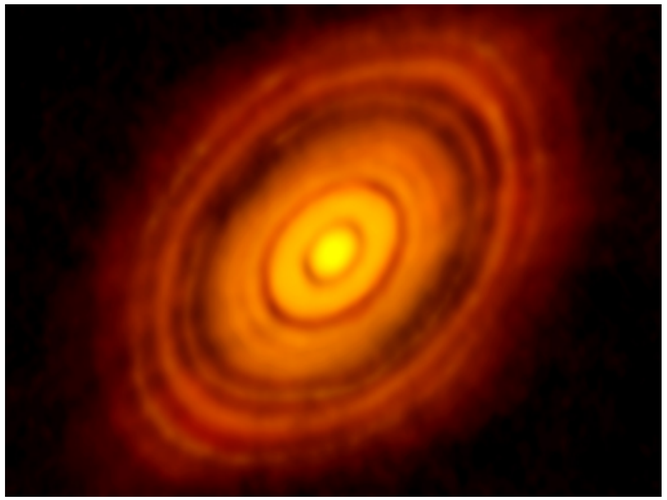
HOW DID OTHER SOLAR SYSTEMS FORM?



OBSERVATIONAL PLANET FORMATION (2015)



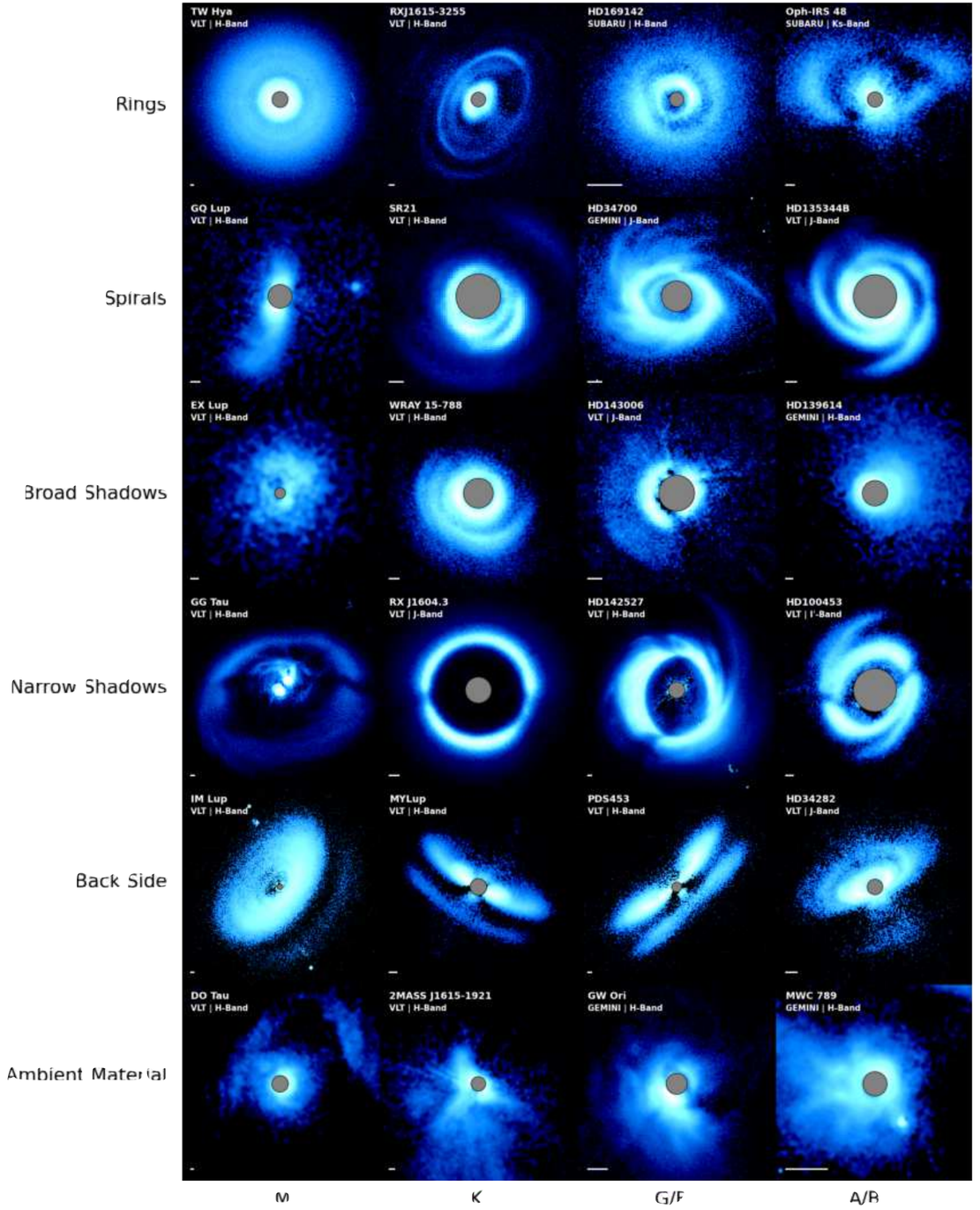
Kwon et al. (2011)



ALMA partnership et al. (2015)

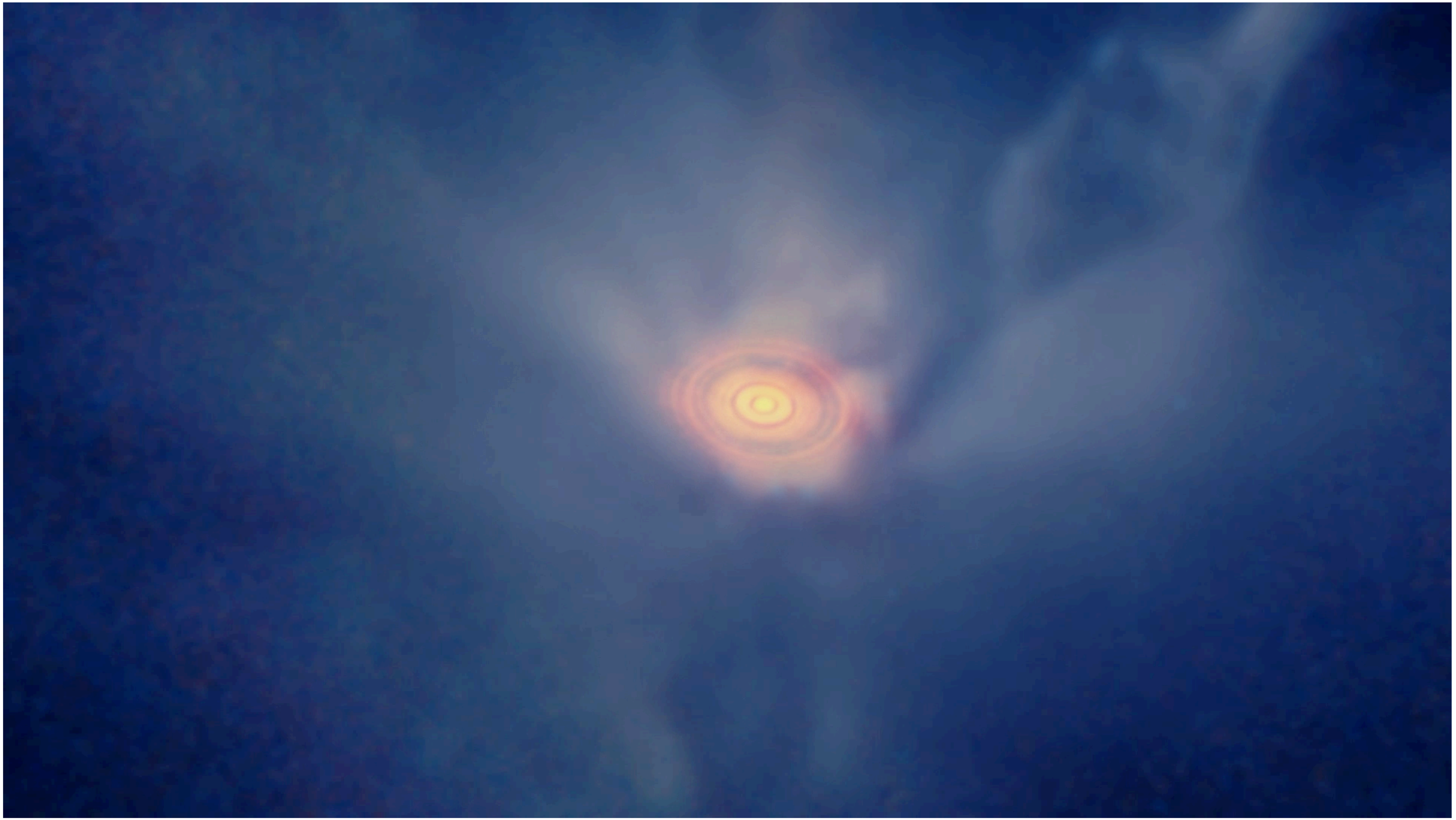
Atacama Large Millimetre/submillimetre Array (ALMA)

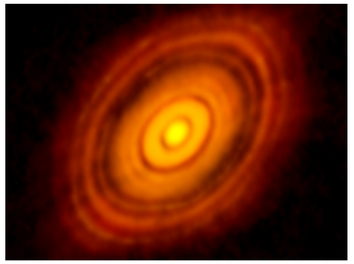
OBSERVATIONAL PLANET FORMATION (OPTICAL/NIR)



Benisty et al. (2023)

HL TAU

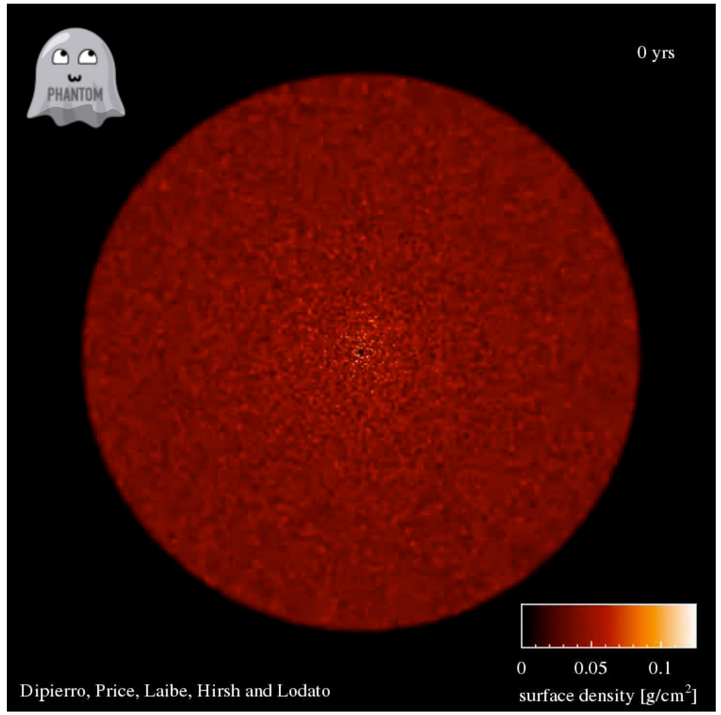


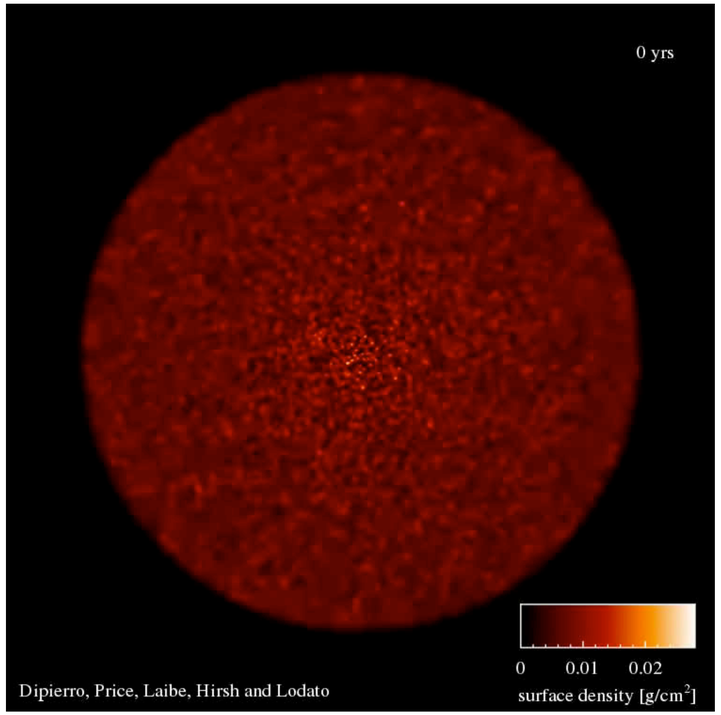


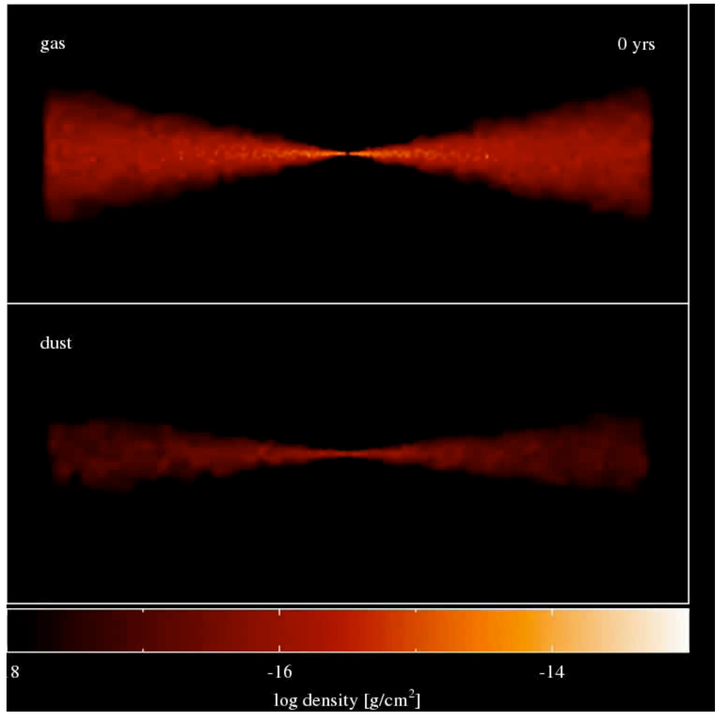
WHAT IS CARVING THE GAPS?

Dipierro, Price+ (2015)

Why rings but not spirals?



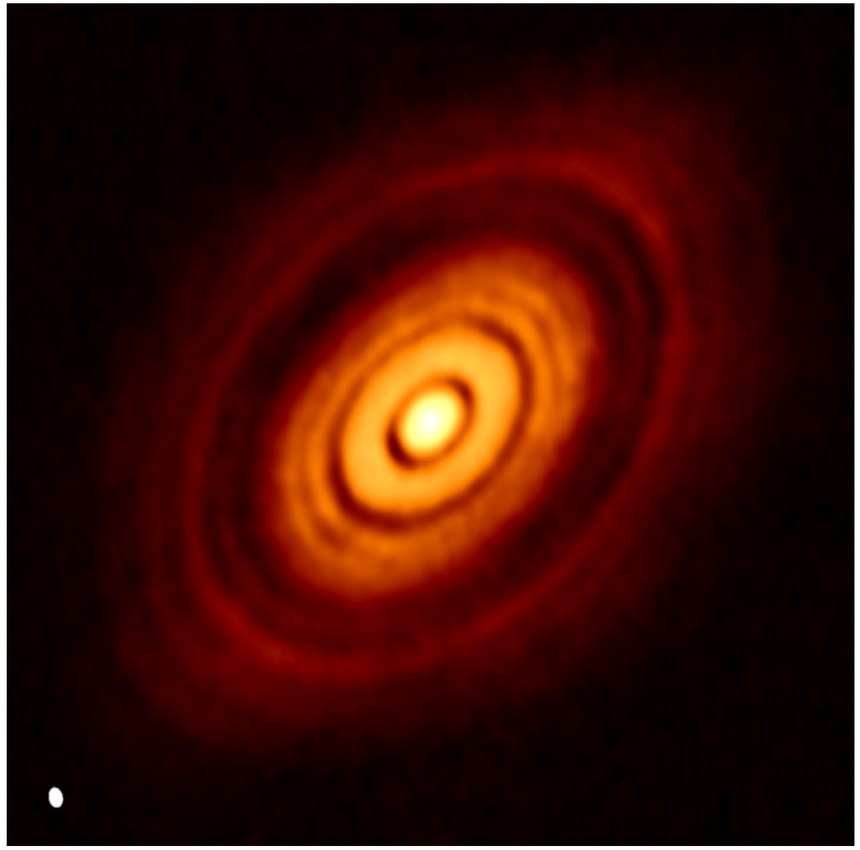




gas dust

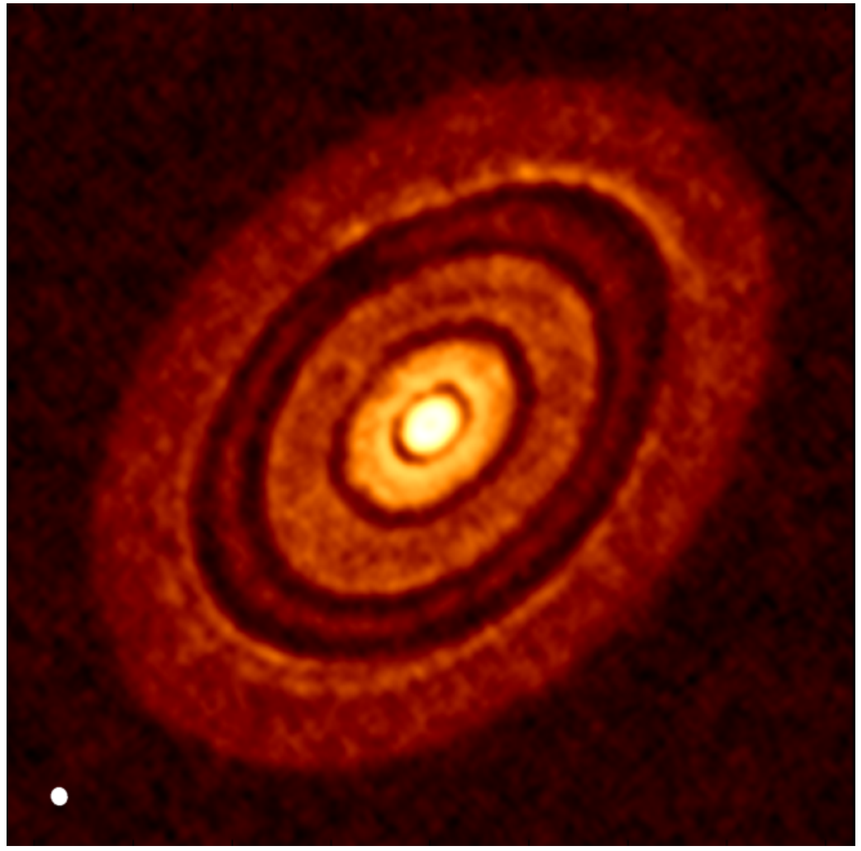
But plenty of other explanations exist (snowlines, non-ideal MHD, …)

HL TAU: OBSERVATIONS, MEET MODELS



Observed image

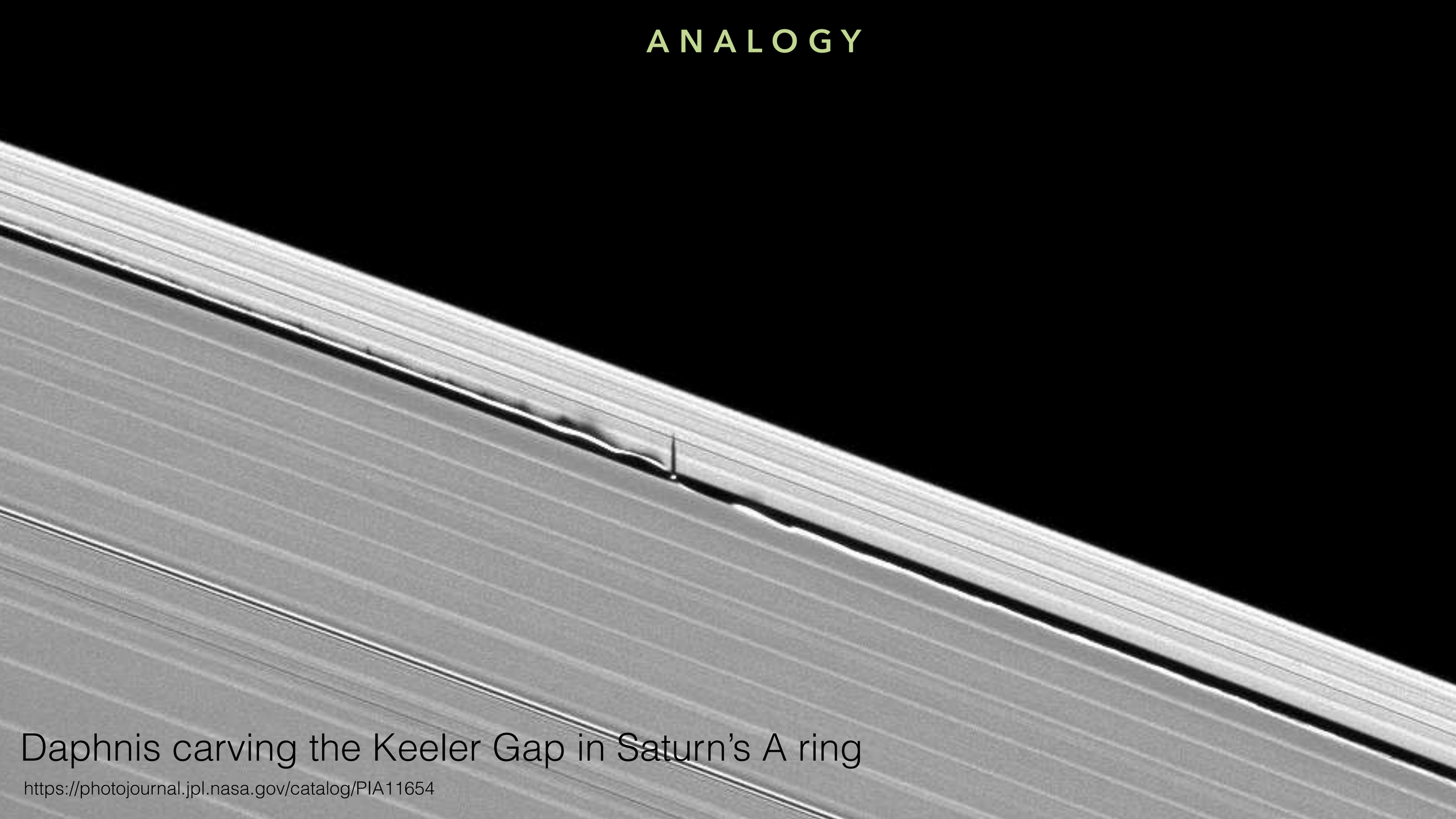
Credit: ALMA partnership et al. (2015)



Our simulation

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

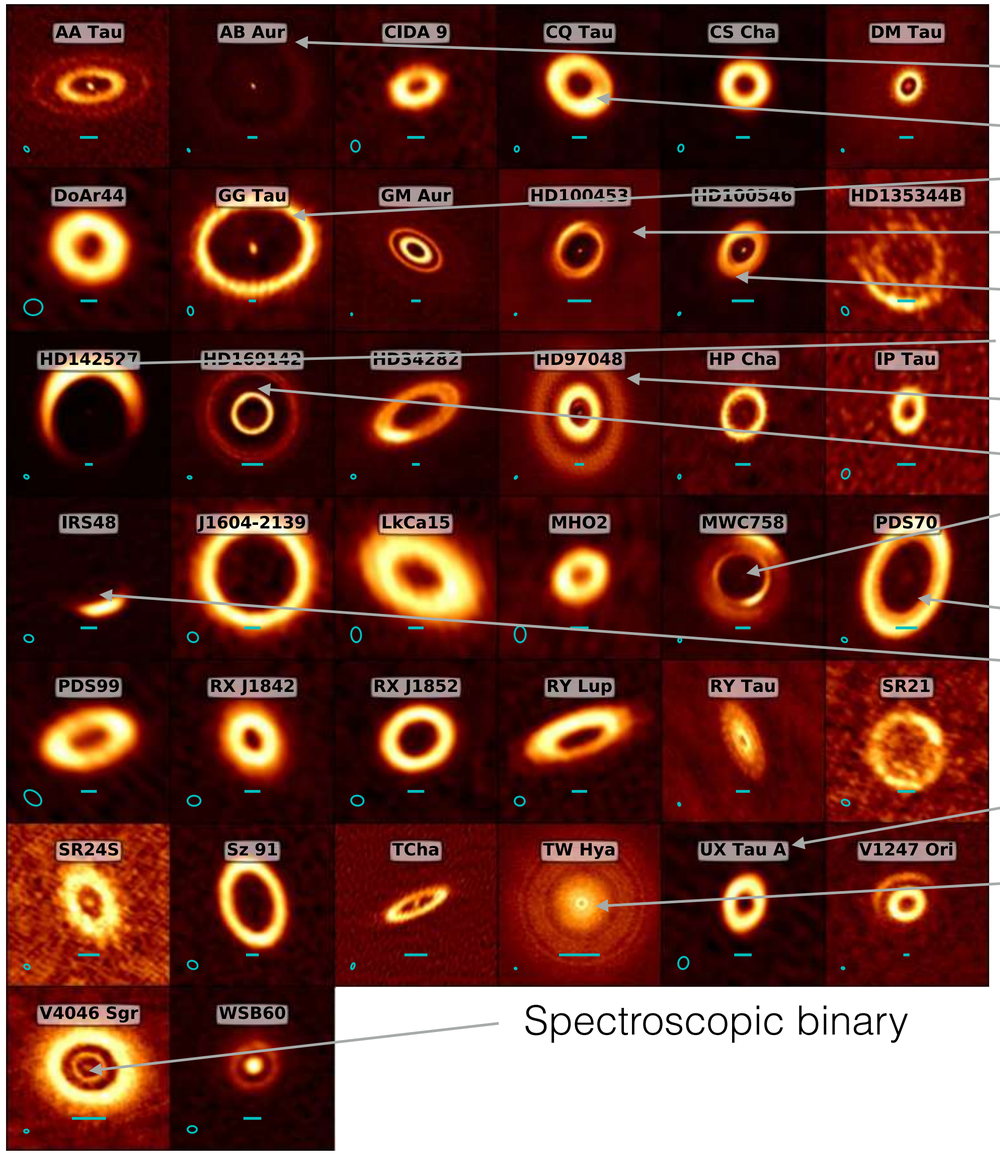
ANALOGY



Daphnis carving the Keeler Gap in Saturn’s A ring

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

WHAT CAUSES DUST TRAPS IN "TRANSITIONAL" DISCS?



Probable binary (Poblete+2020)

Probable binary (Hammond+2022)

Hierarchical quintuple (Di Folco+2014; Toci+2024)

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)

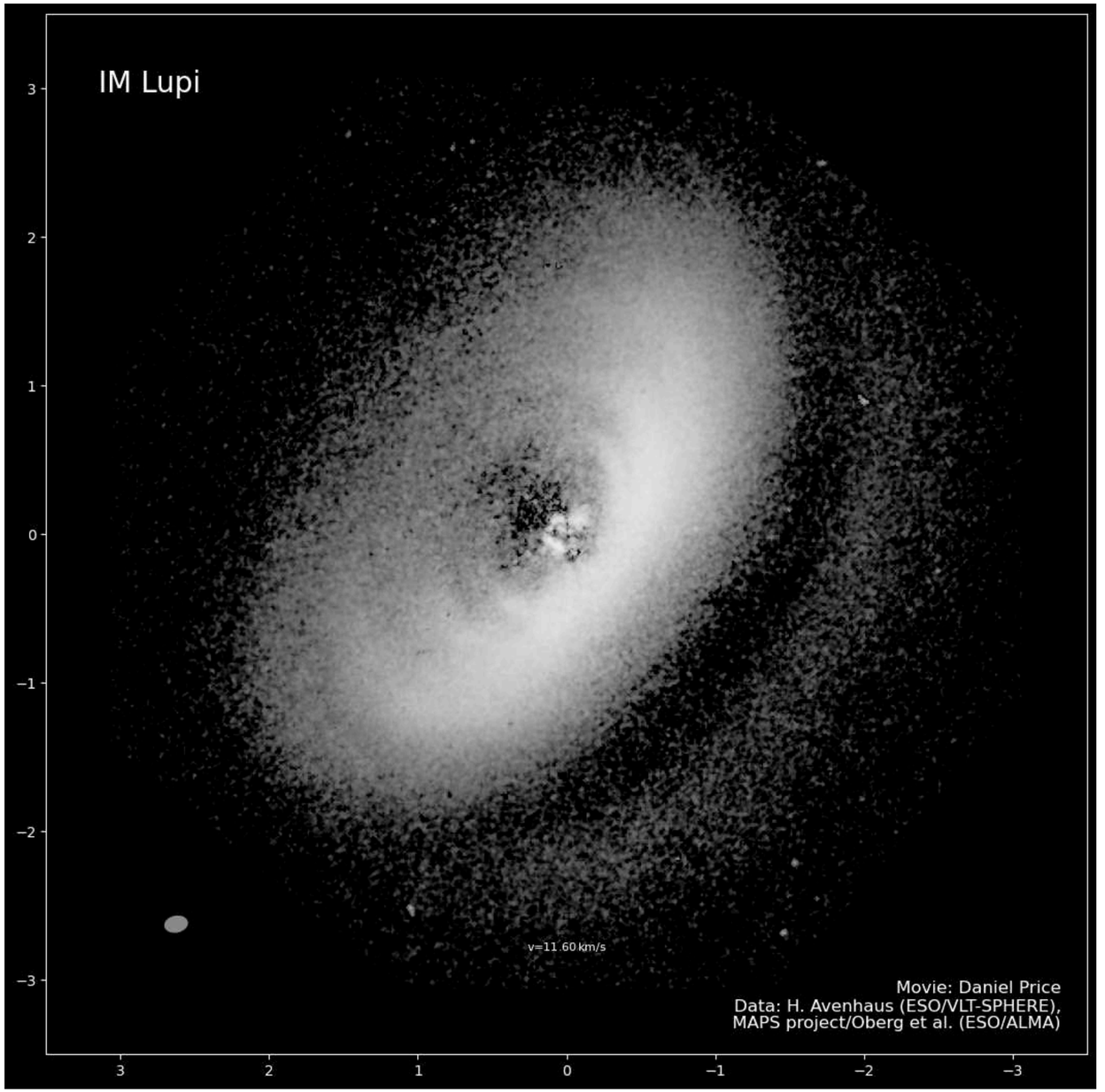
Ongoing stellar flyby (Ménard+2020)

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

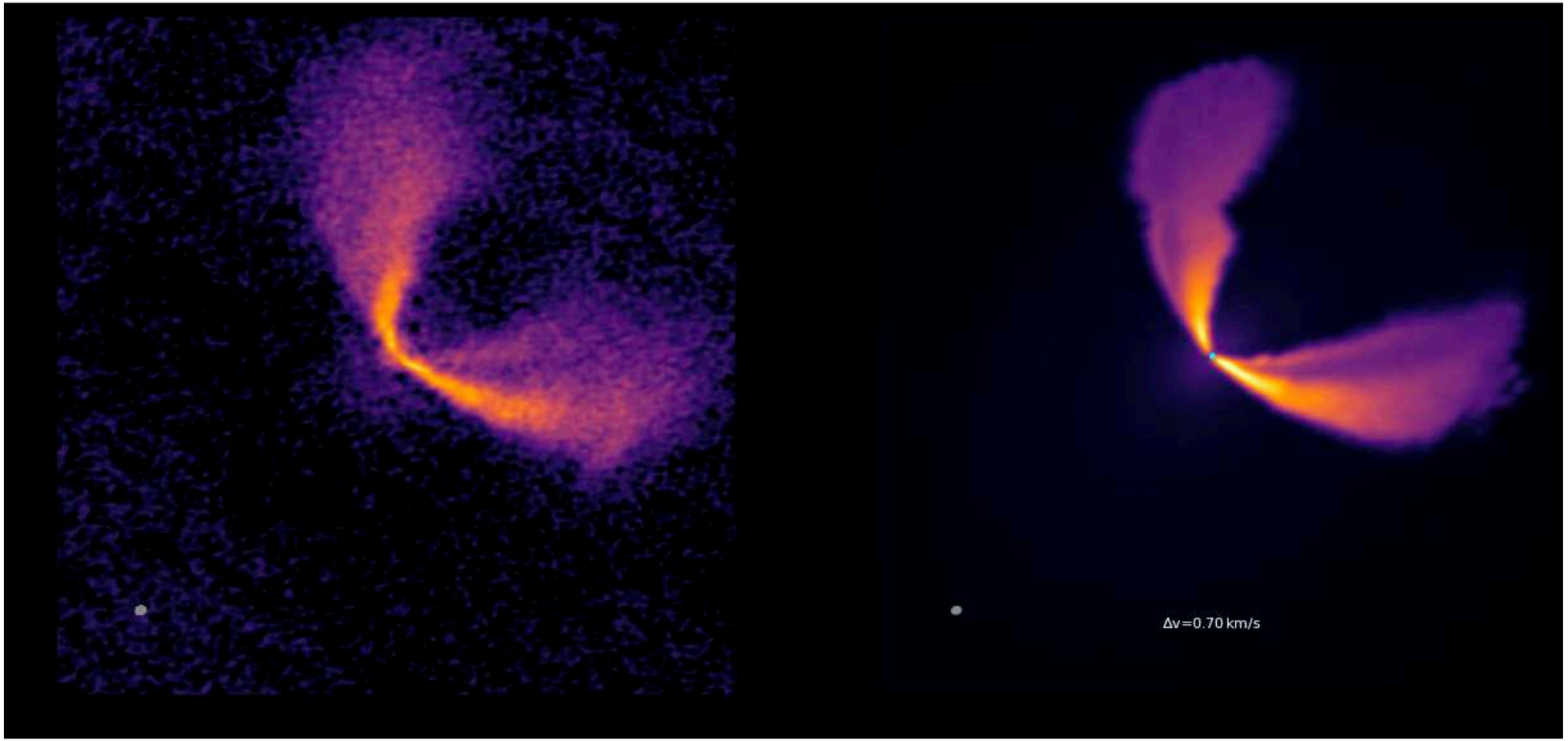
Spectroscopic binary

Francis & van der Marel (2020)

DISC KINEMATICS WITH ALMA



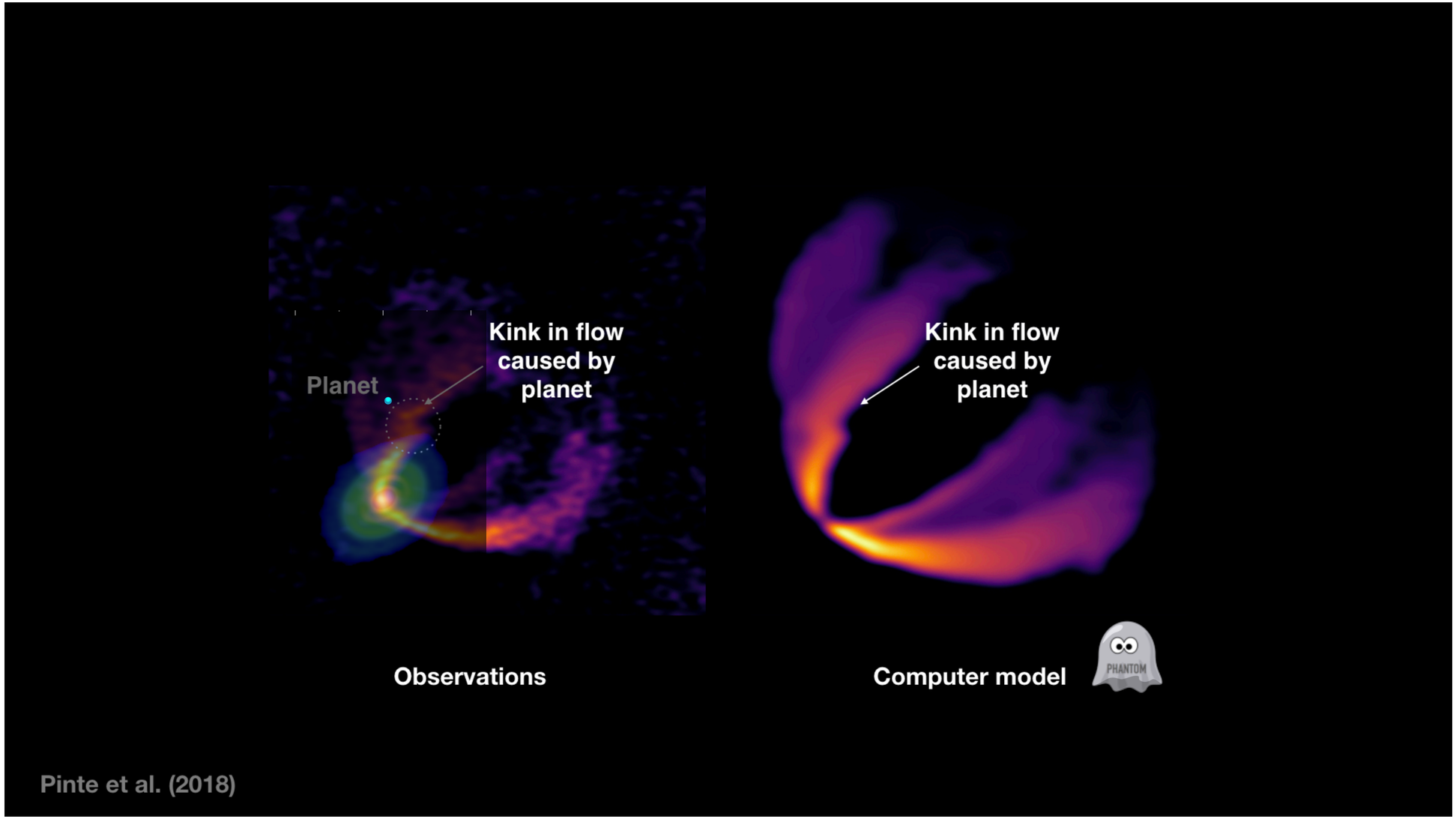
DISC KINEMATICS WITH ALMA



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

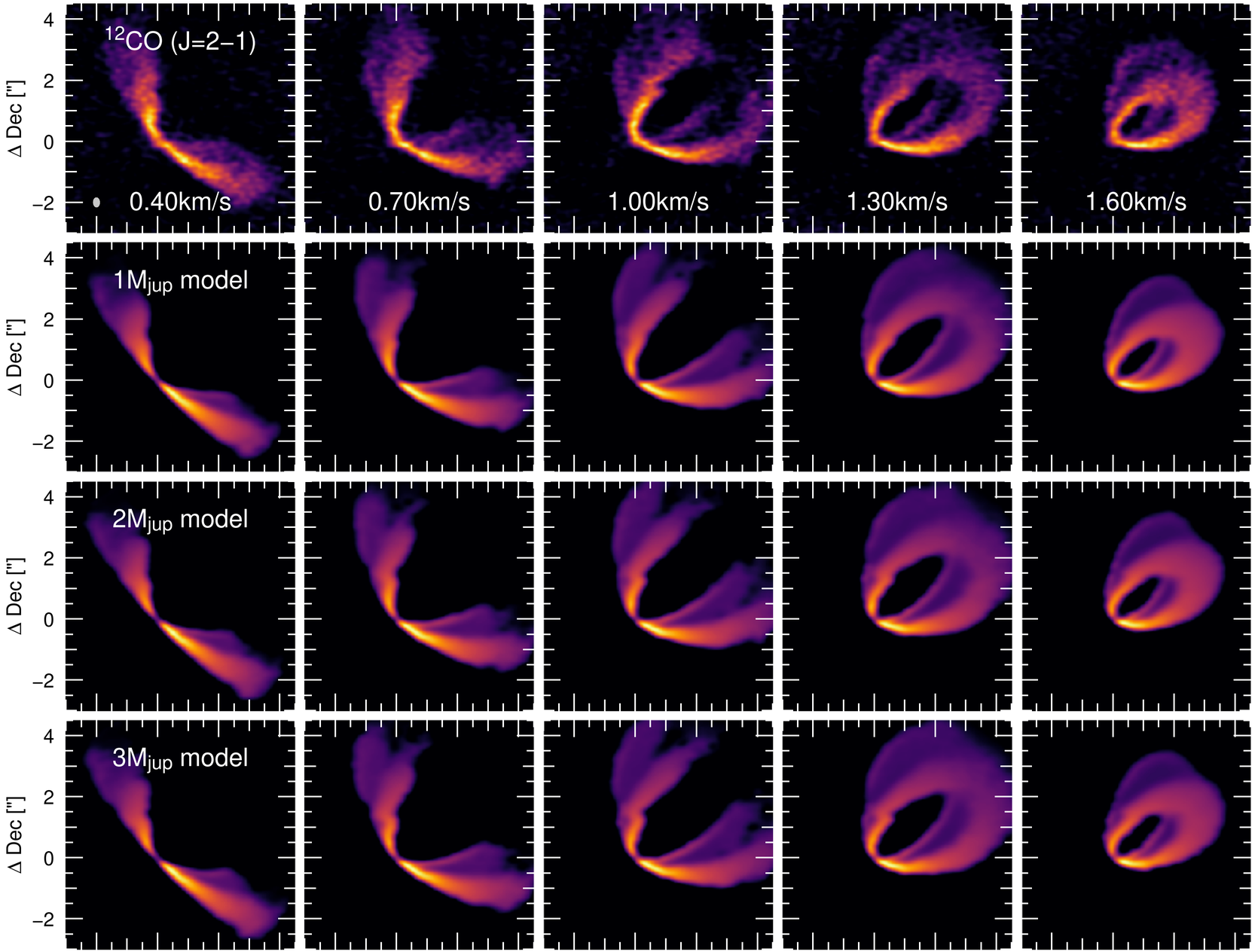
Phantom simulation by Calcino et al. (2022)

PLANET HUNTING WITH DISC KINEMATICS



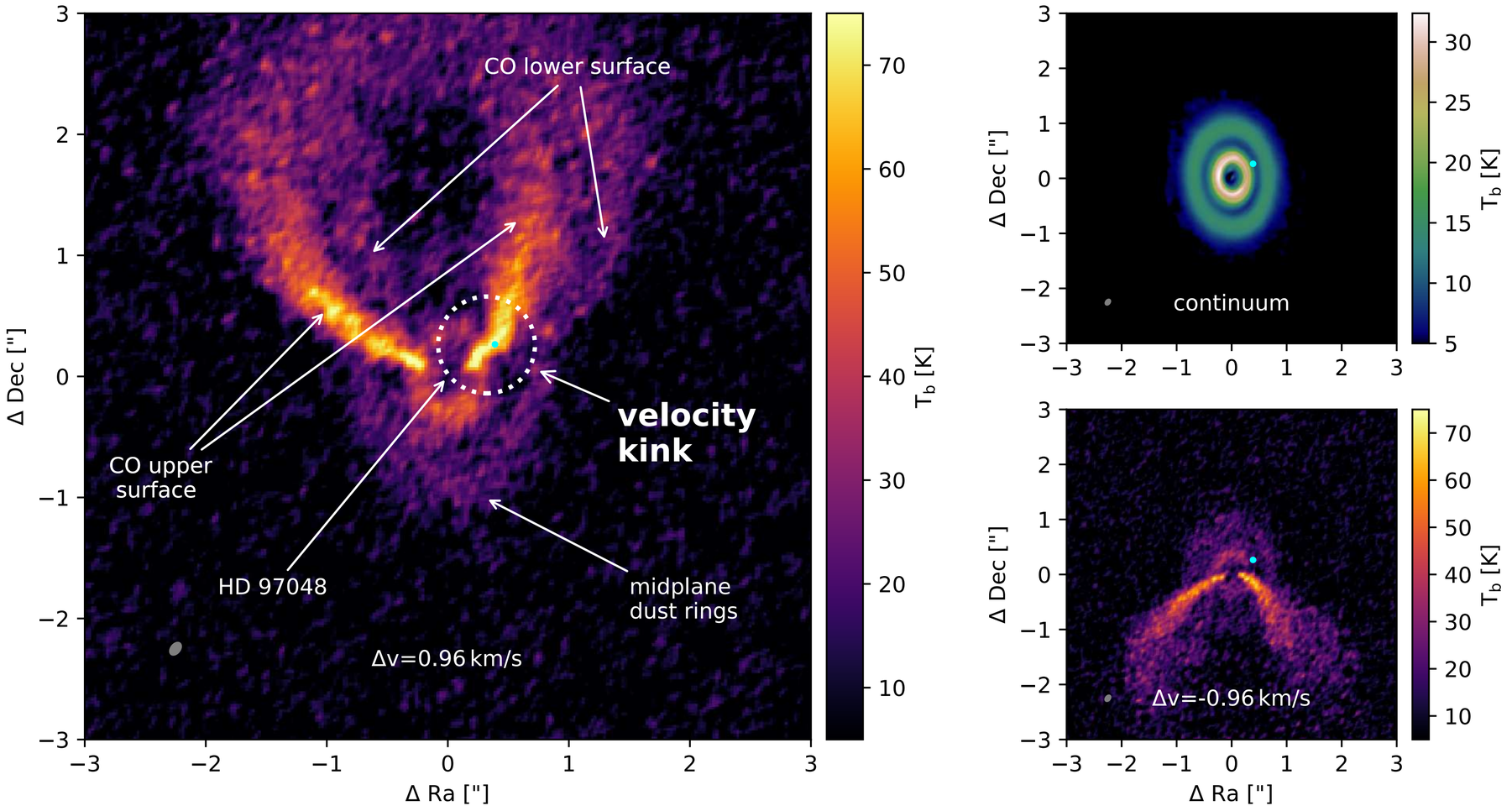
MEASURING THE PLANET MASS IN HD163296

Pinte et al. (2018)



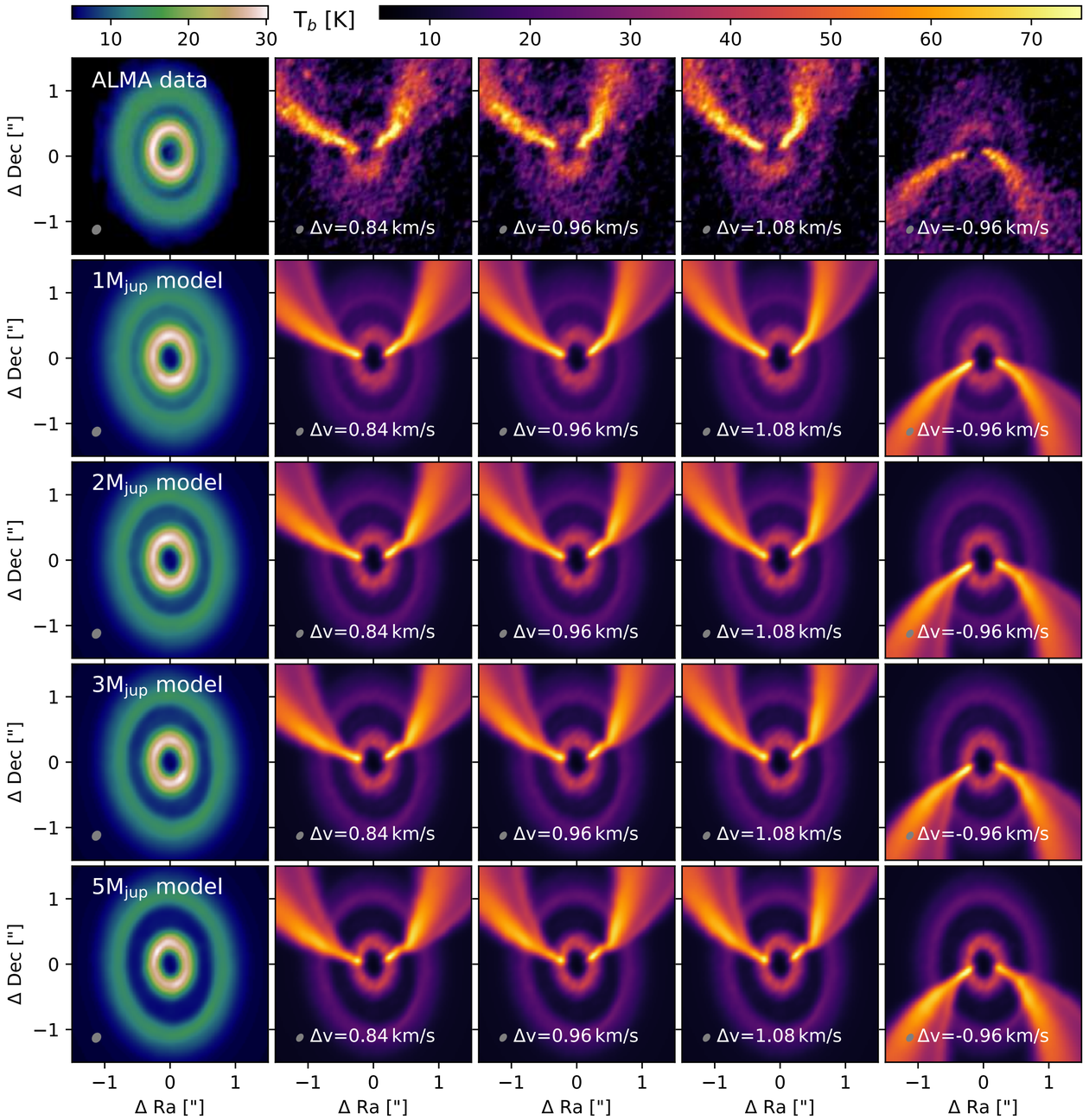
HD97048: KINEMATIC DETECTION OF A GIANT PLANET CARVING A GAP

Pinte et al. (2019)



SO PLANETS CARVE (AT LEAST SOME) GAPS

MEASURING THE PLANET MASS



+

MCFOST

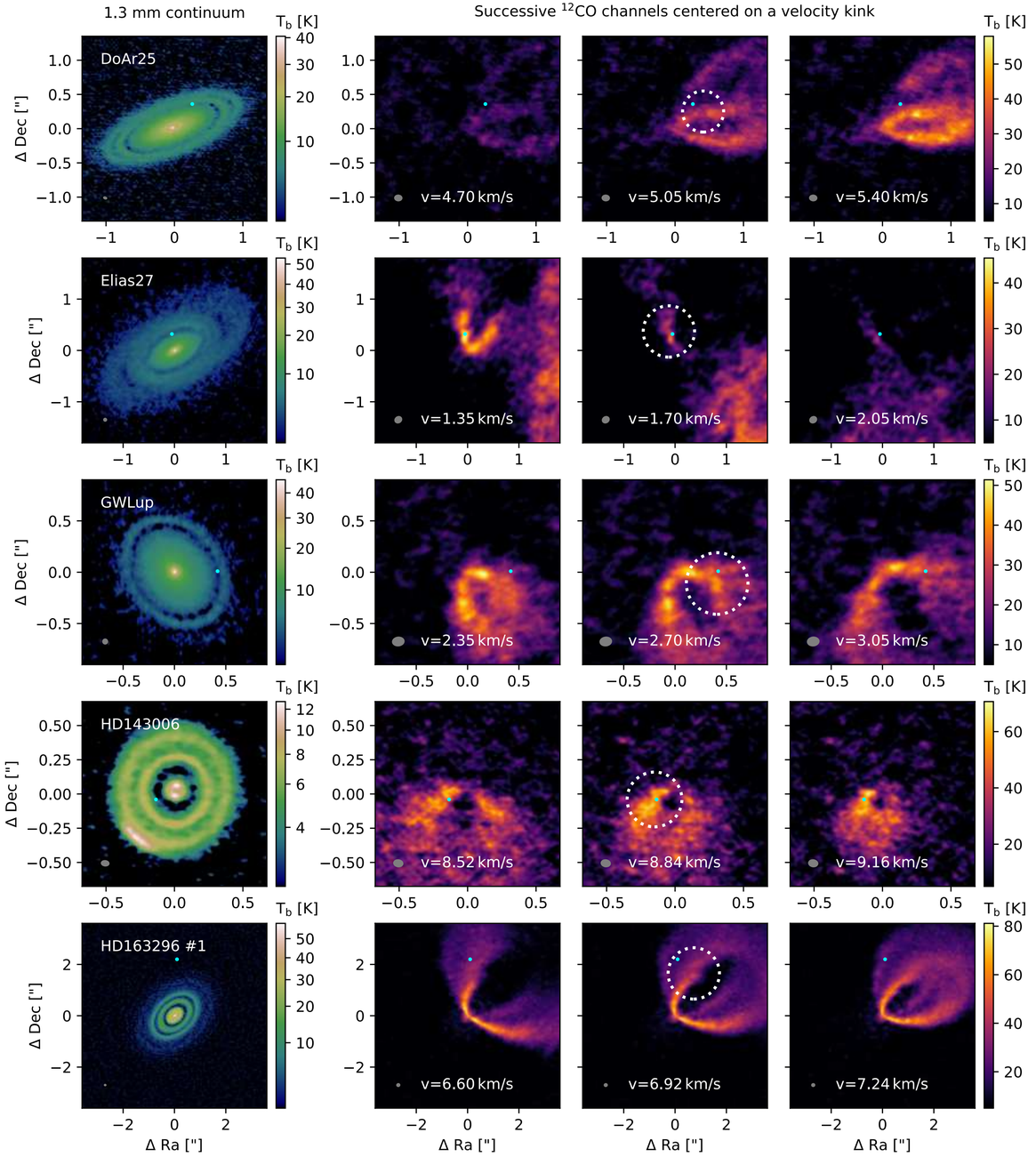
Pinte et al. (2019)

OTHER KINEMATIC PLANET DETECTIONS?

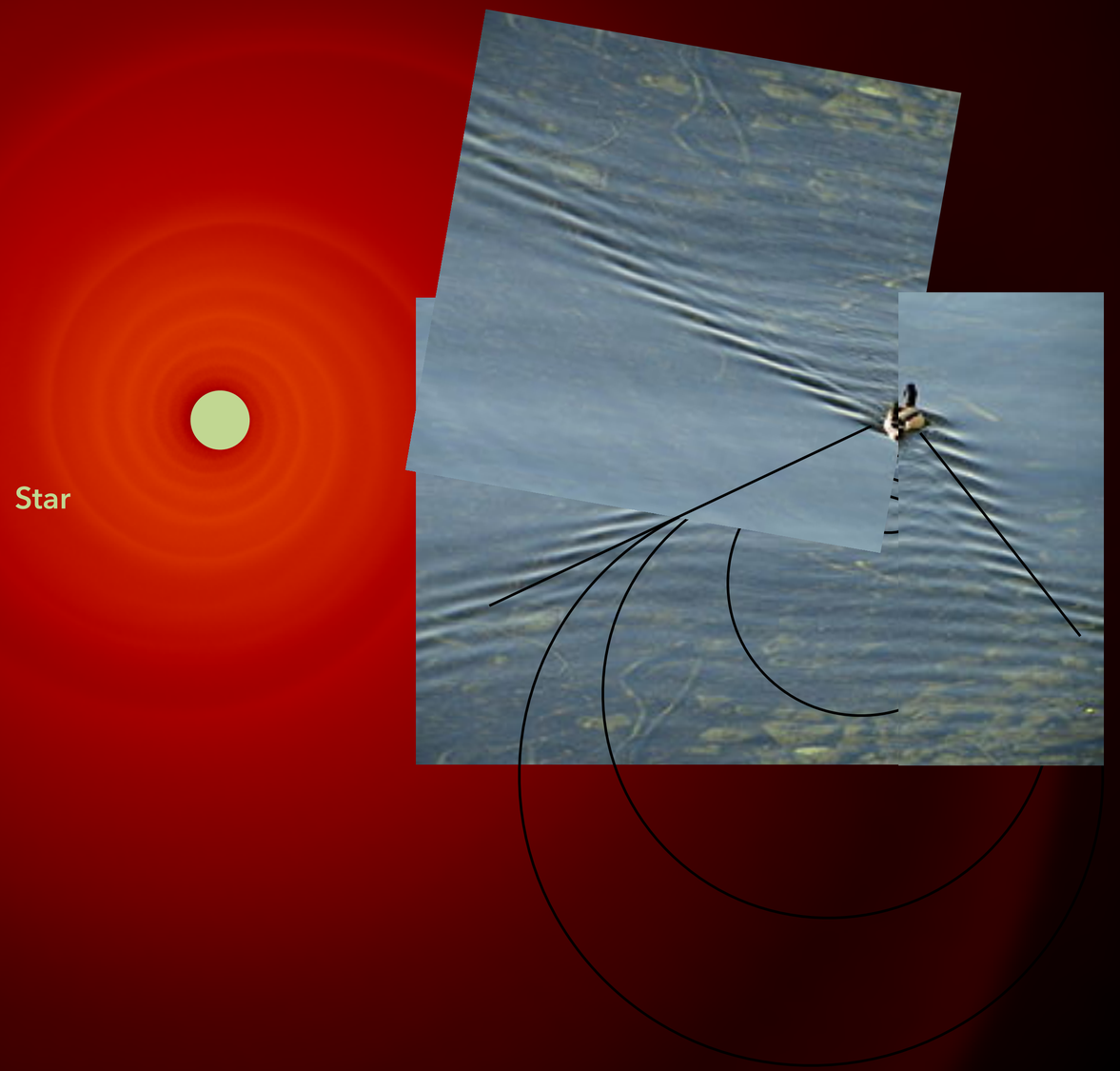
Pinte, Price et al. (2020)

8 new tentative detections + 1 redetection

All located in gap or tip of spiral when deprojected

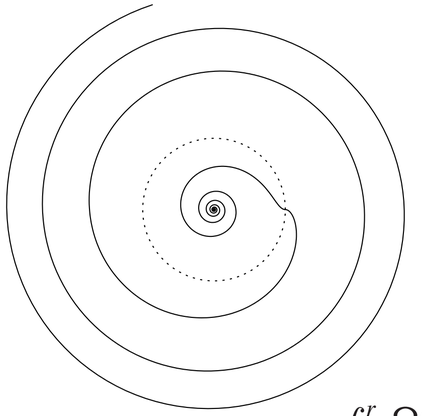


PLANET - DISC INTERACTION 101



THE THEORY OF KINKS

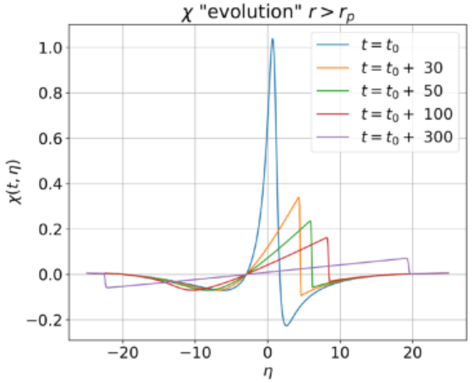
Bollati, Lodato, Price & Pinte (2021)



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

Wake shape = constructive interference of waves

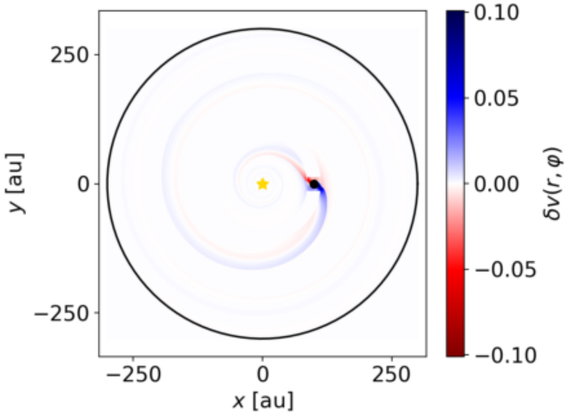
Ogilvie & Lubow (2002), Rafikov (2002)



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

Propagate wake along the line of constructive interference

Rafikov (2002)
Bollati et al. (2021)

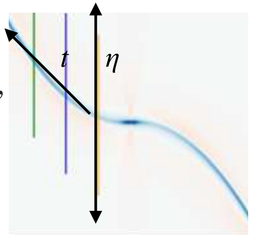


Predict velocity perturbations and compare to observations

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

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

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

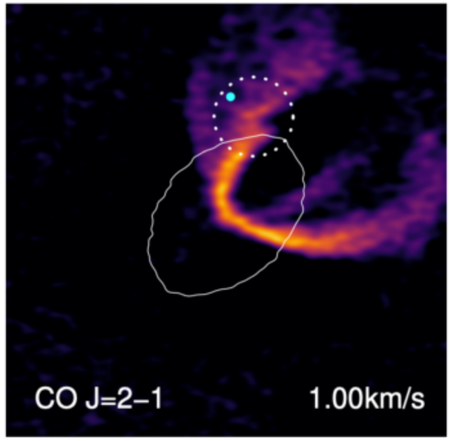


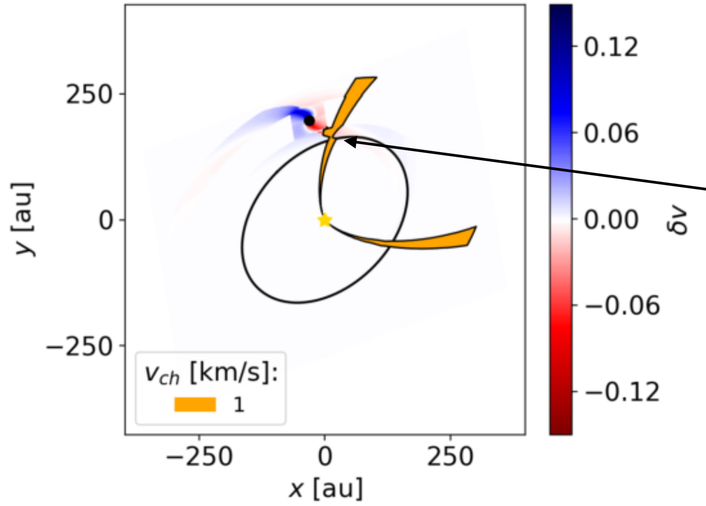
Reduce wake propagation to a 1D problem

Goodman & Rafikov (2001)
Rafikov (2002)

THE THEORY OF KINKS

Bollati, Lodato, Price & Pinte (2021)

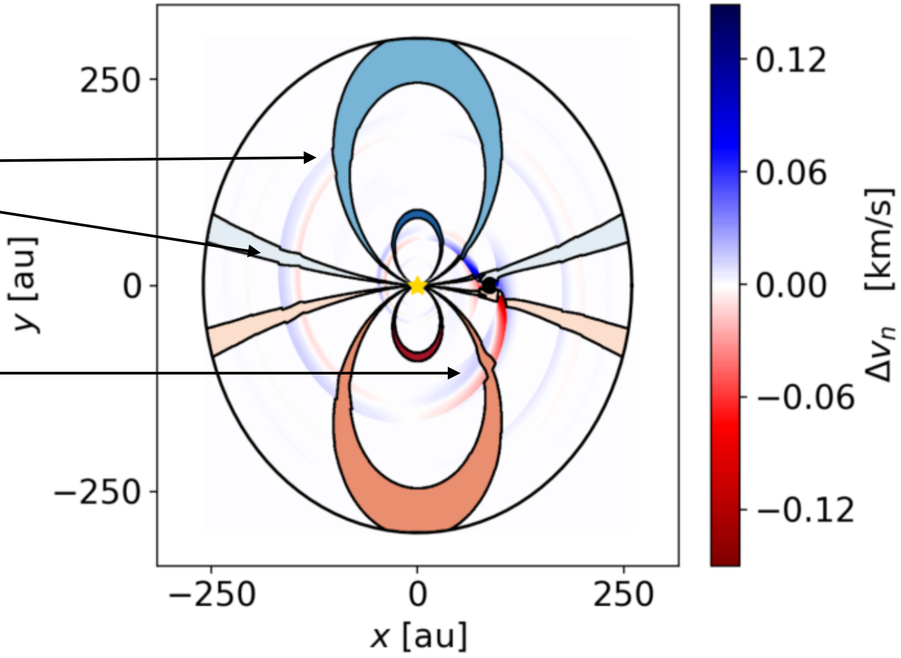




Predict a kink where the wake crosses a velocity channel

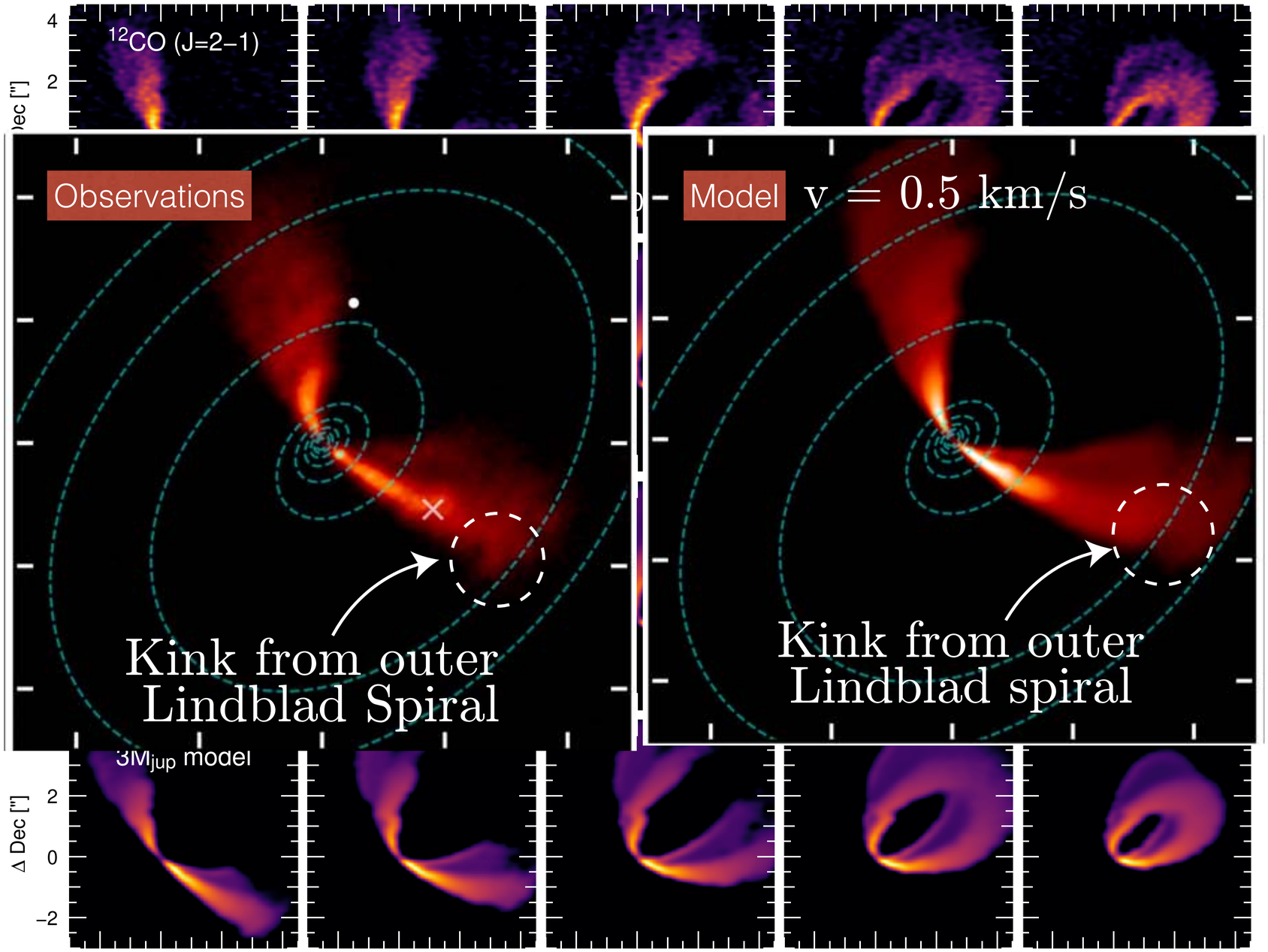
Secondary kinks?

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



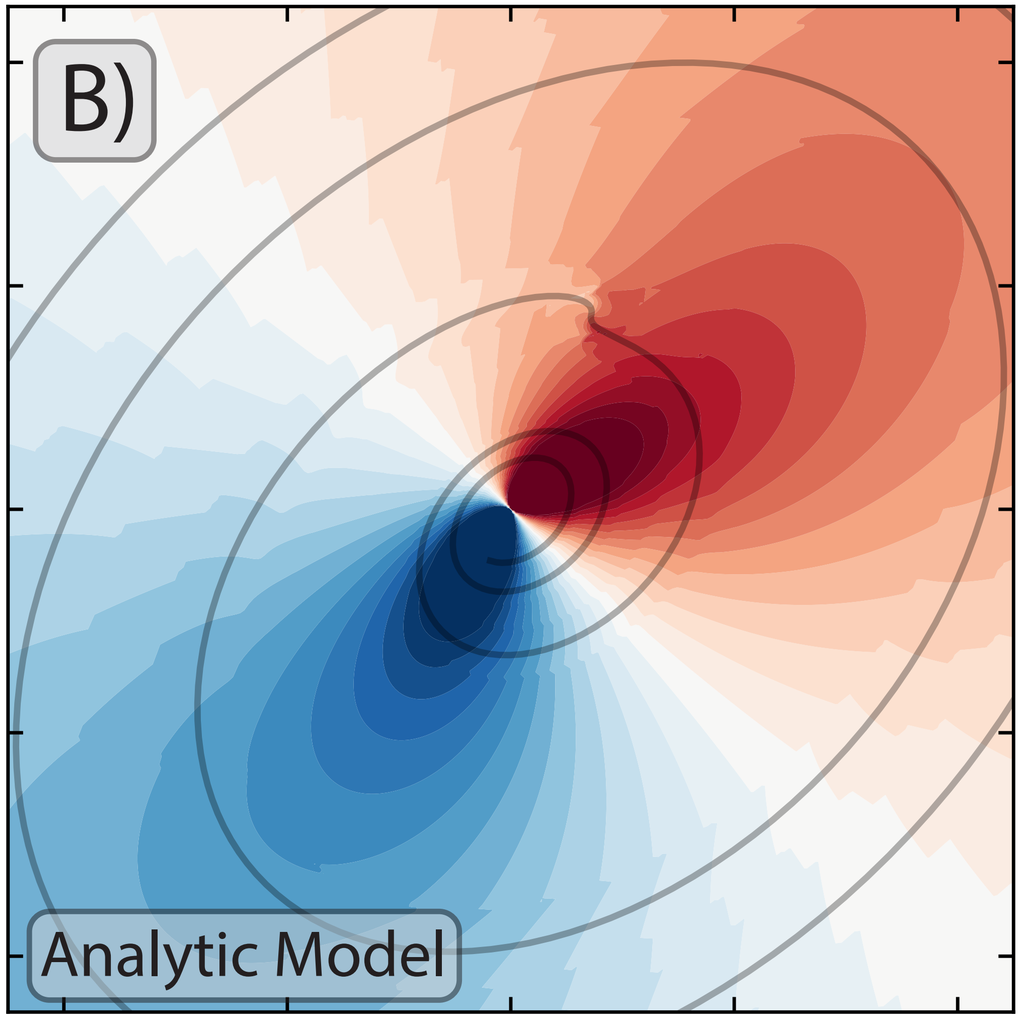
HD163296 REVISITED

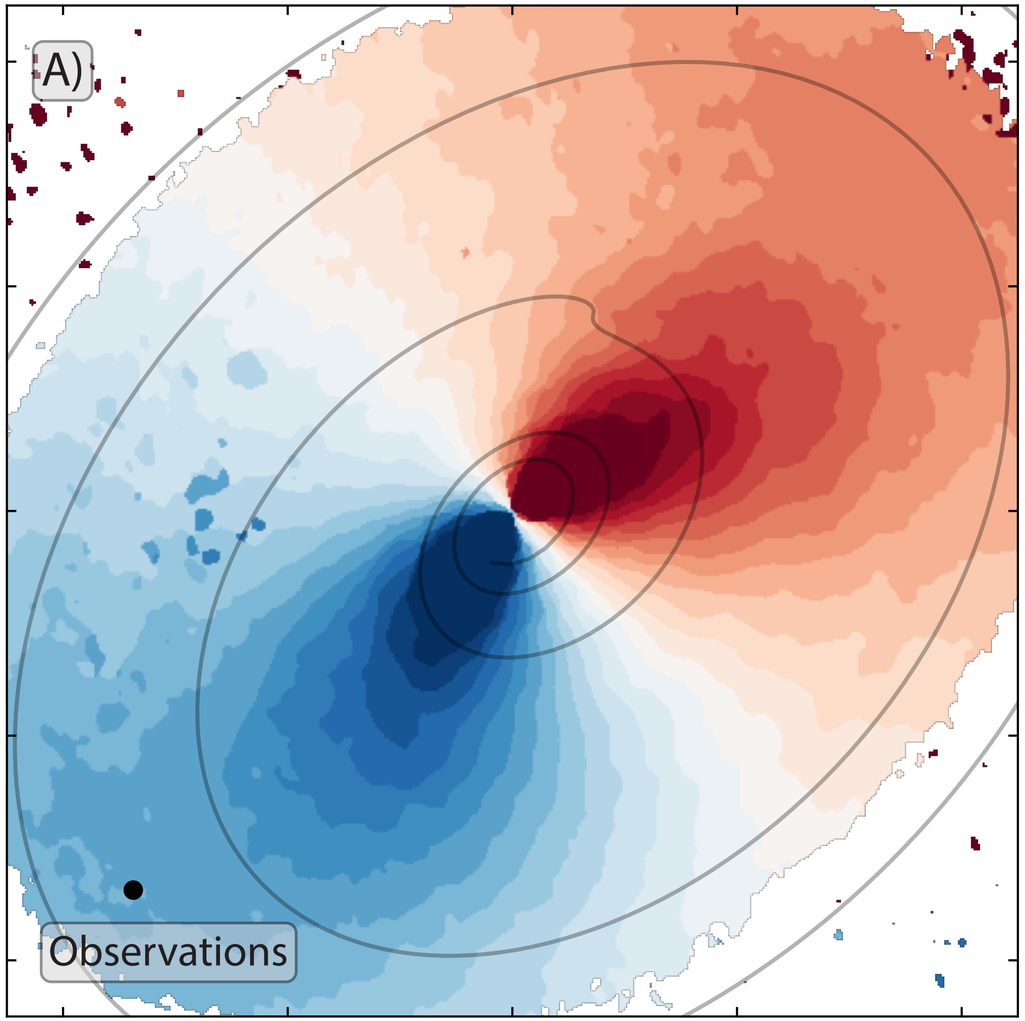
Calcino et al. (2022)



MODEL, MEET DATA

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

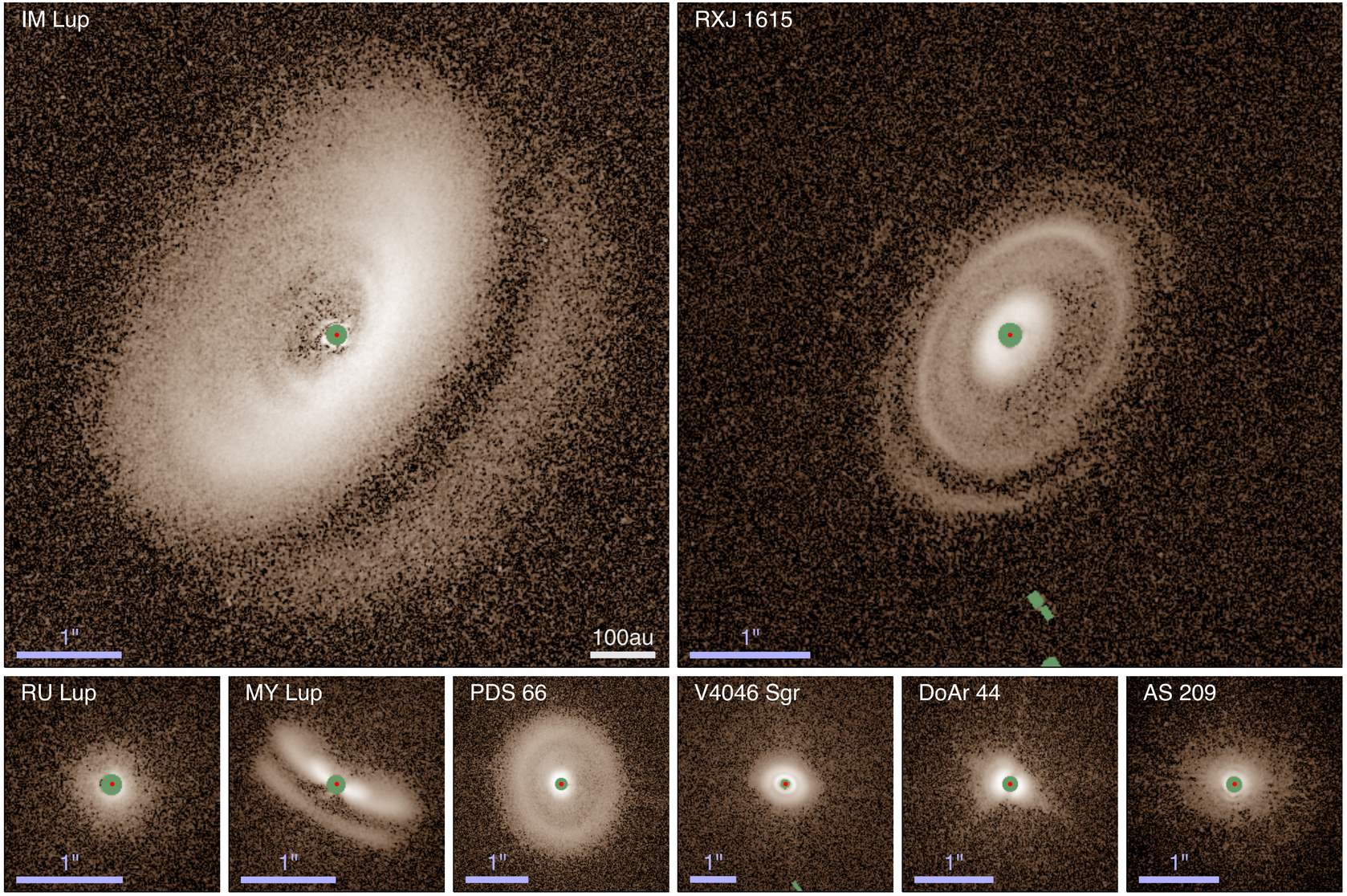




Using Bollati+(2021) analytic model

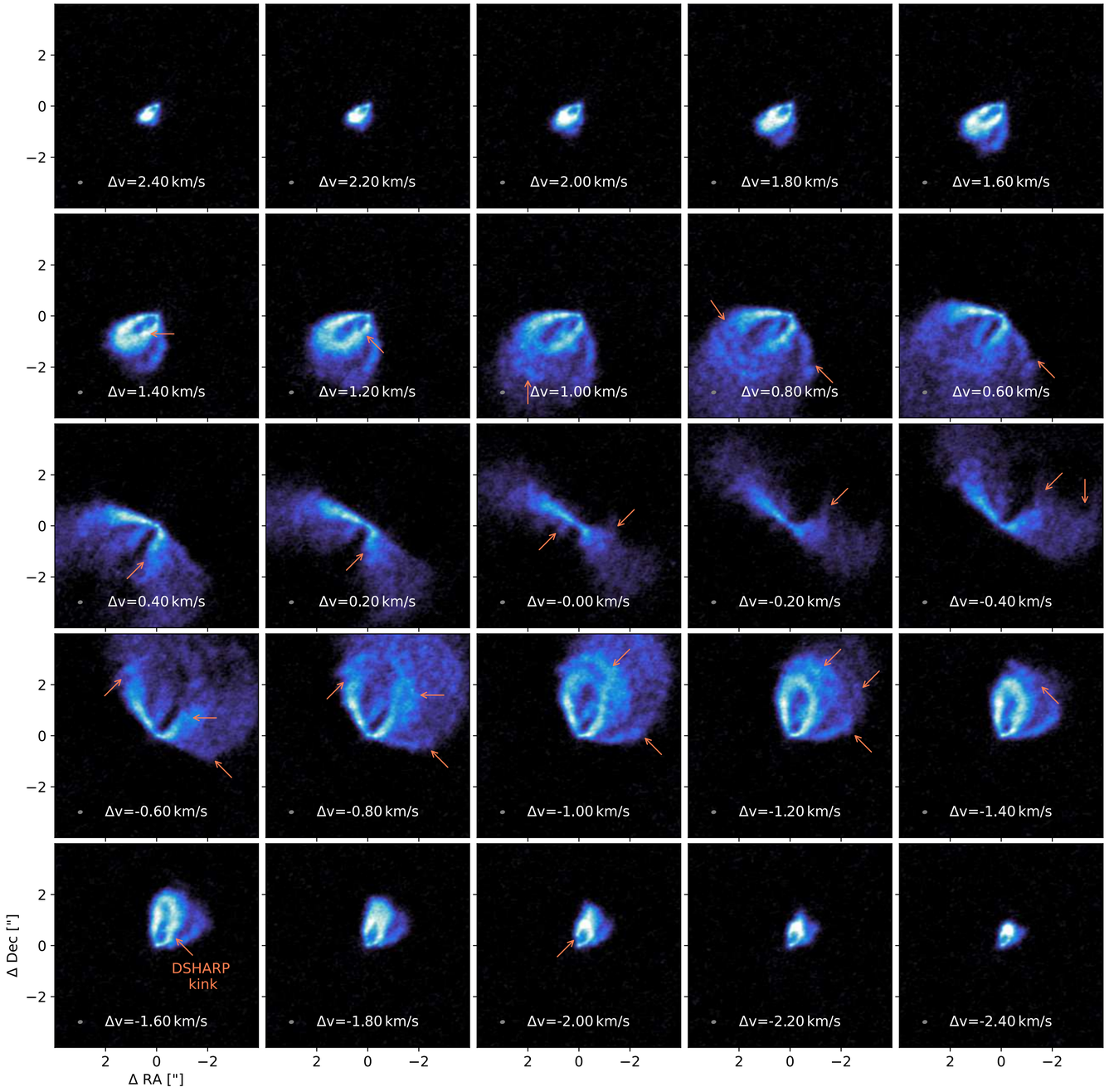
HD163296 from MAPS project (Oberg+2021)

CAN'T WE JUST SEE THE SPIRAL WAKE?



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

IM LUPI KINEMATICS - OBSERVATIONS



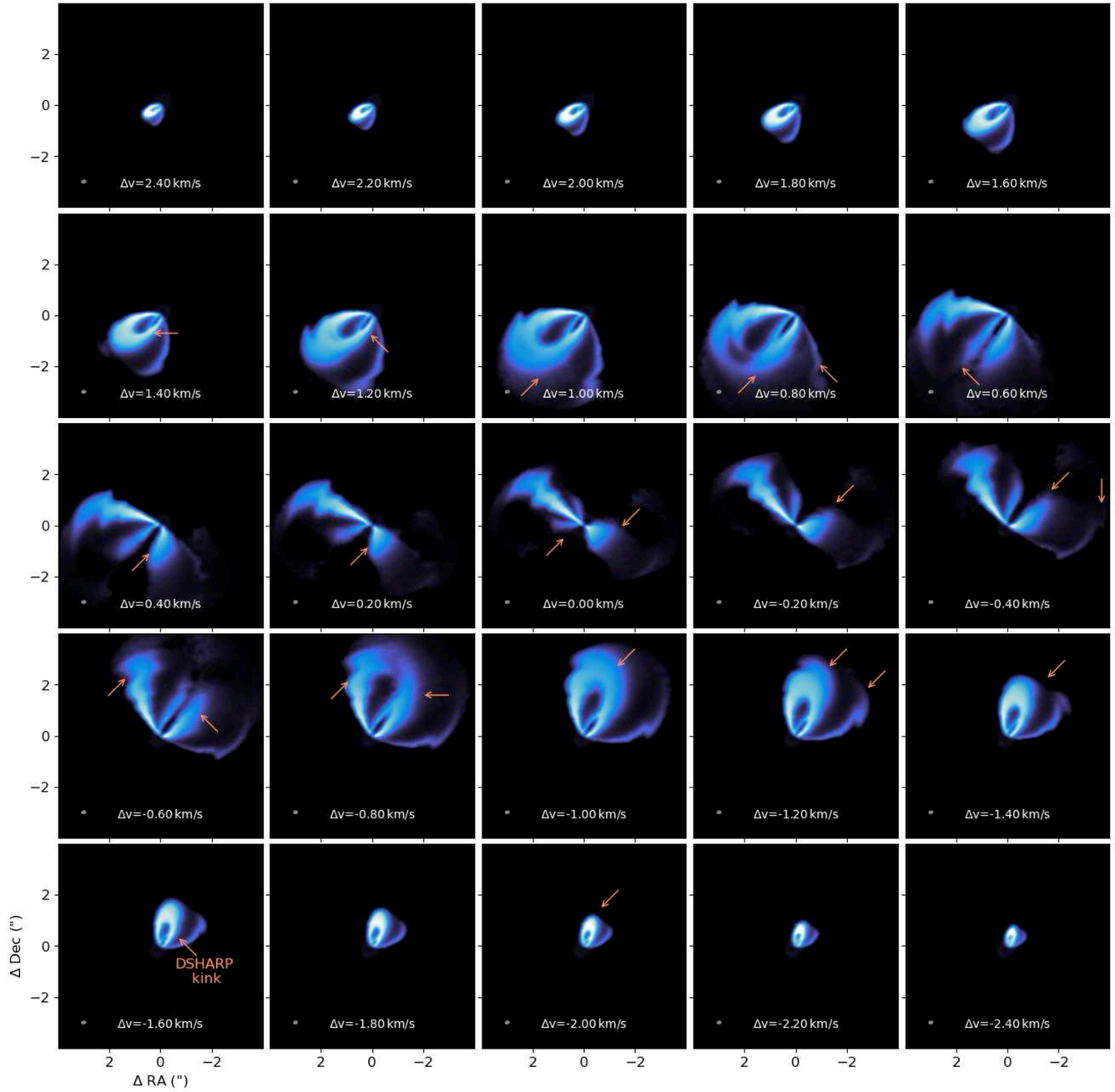
Verrios, Price et al. (2022)

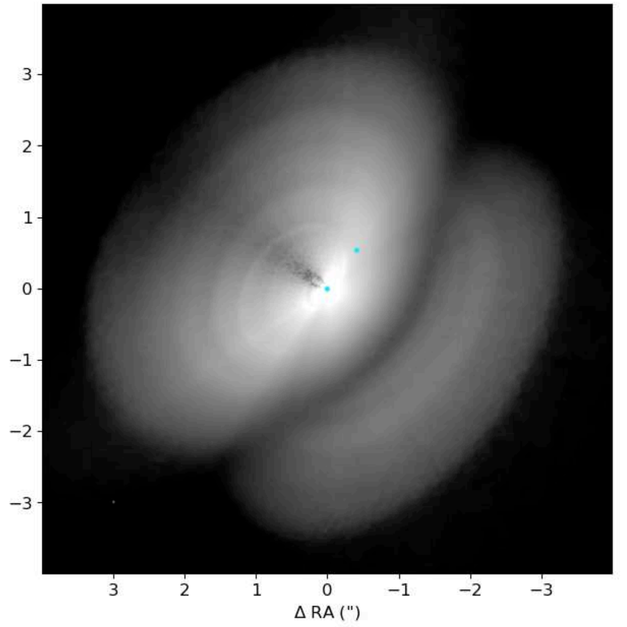
Data from MAPS project (Oberg+2021)

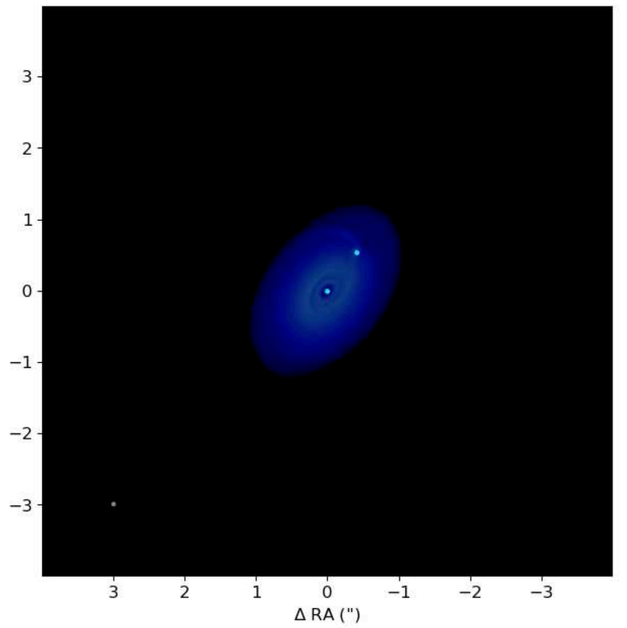
IM LUPI KINEMATICS - MODELS

Verrios, Price et al. (2022)

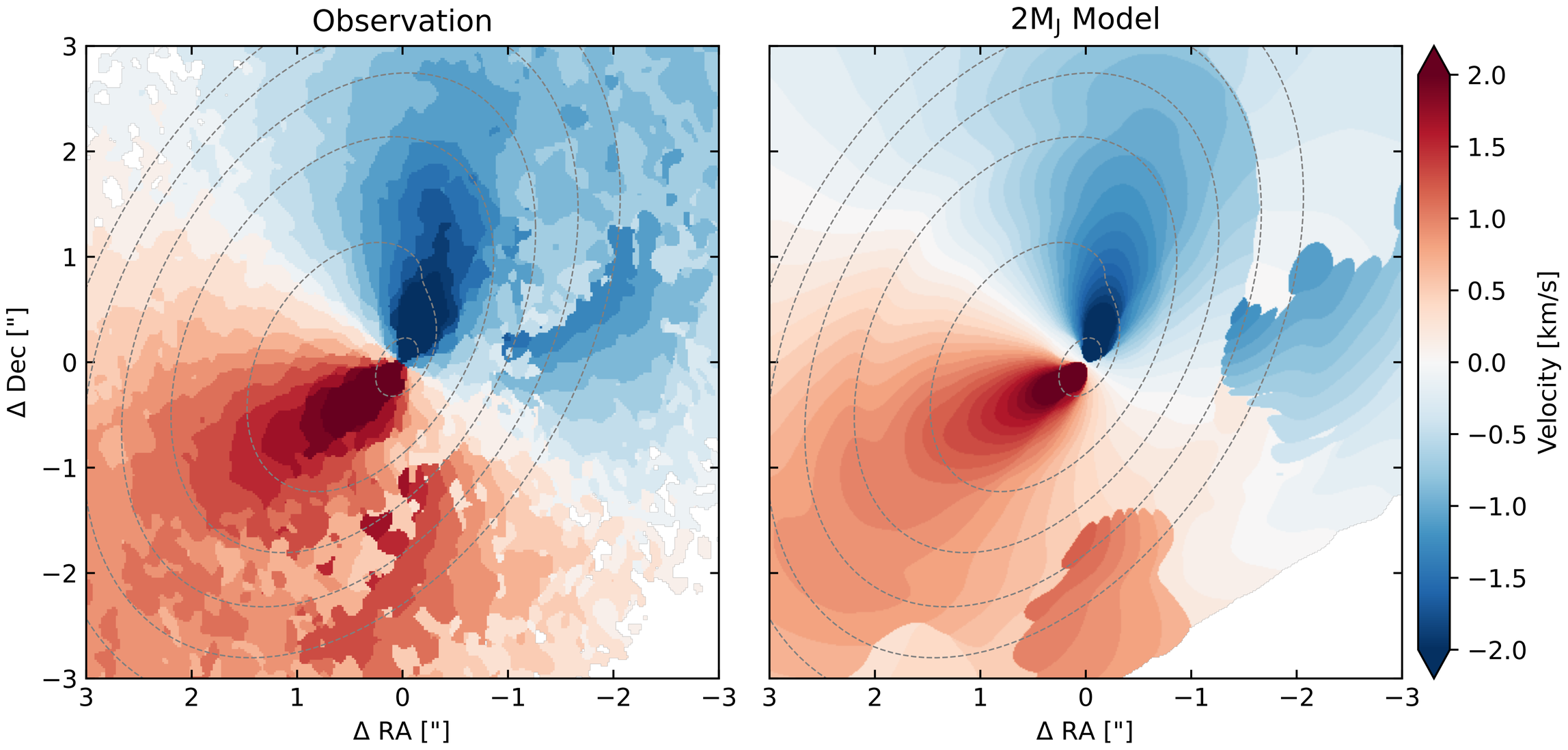
Simulations using Phantom SPH hydro + MCFOST radiative transfer





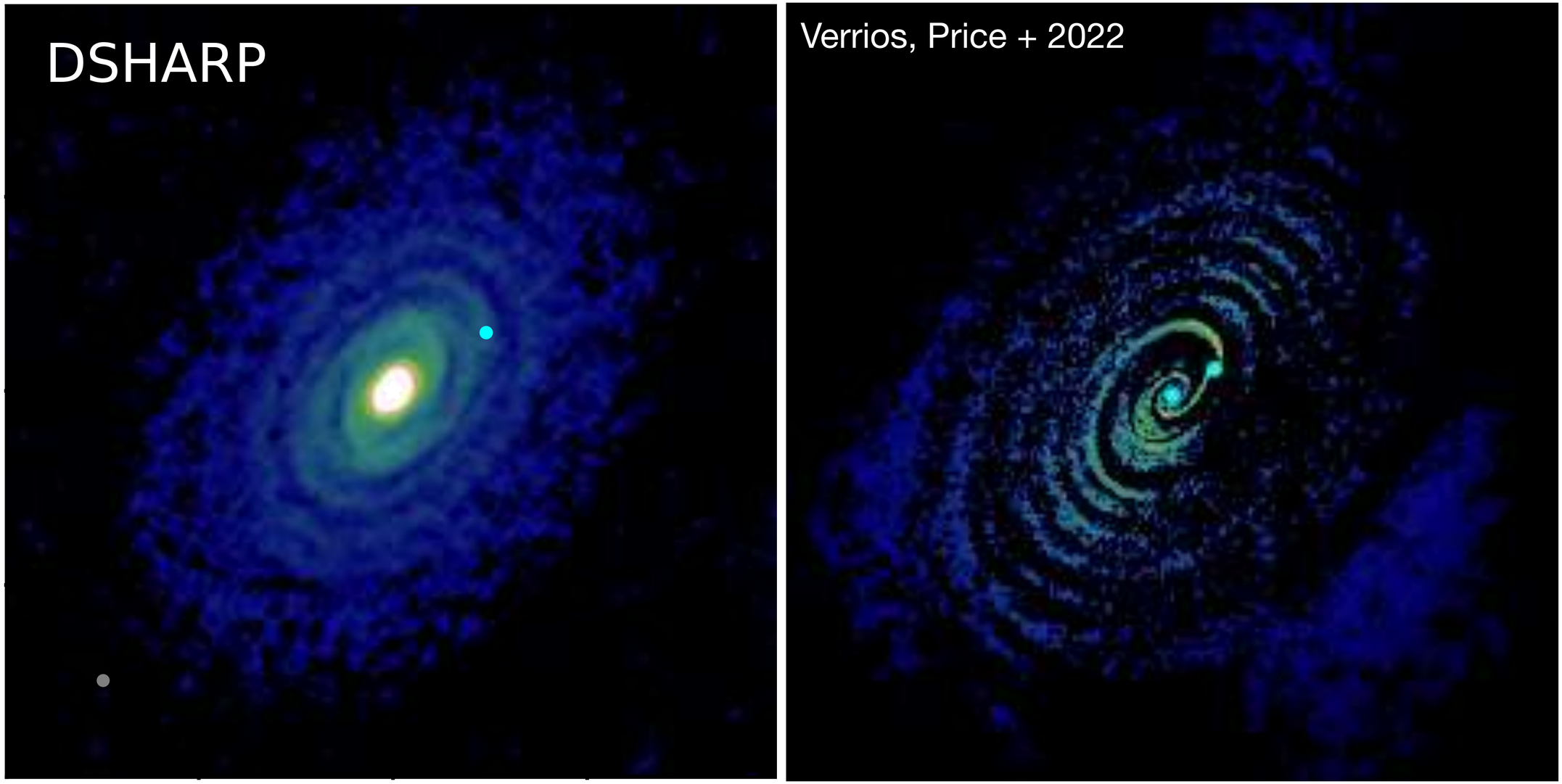


THE PLANET WAKE IN IM LUPI



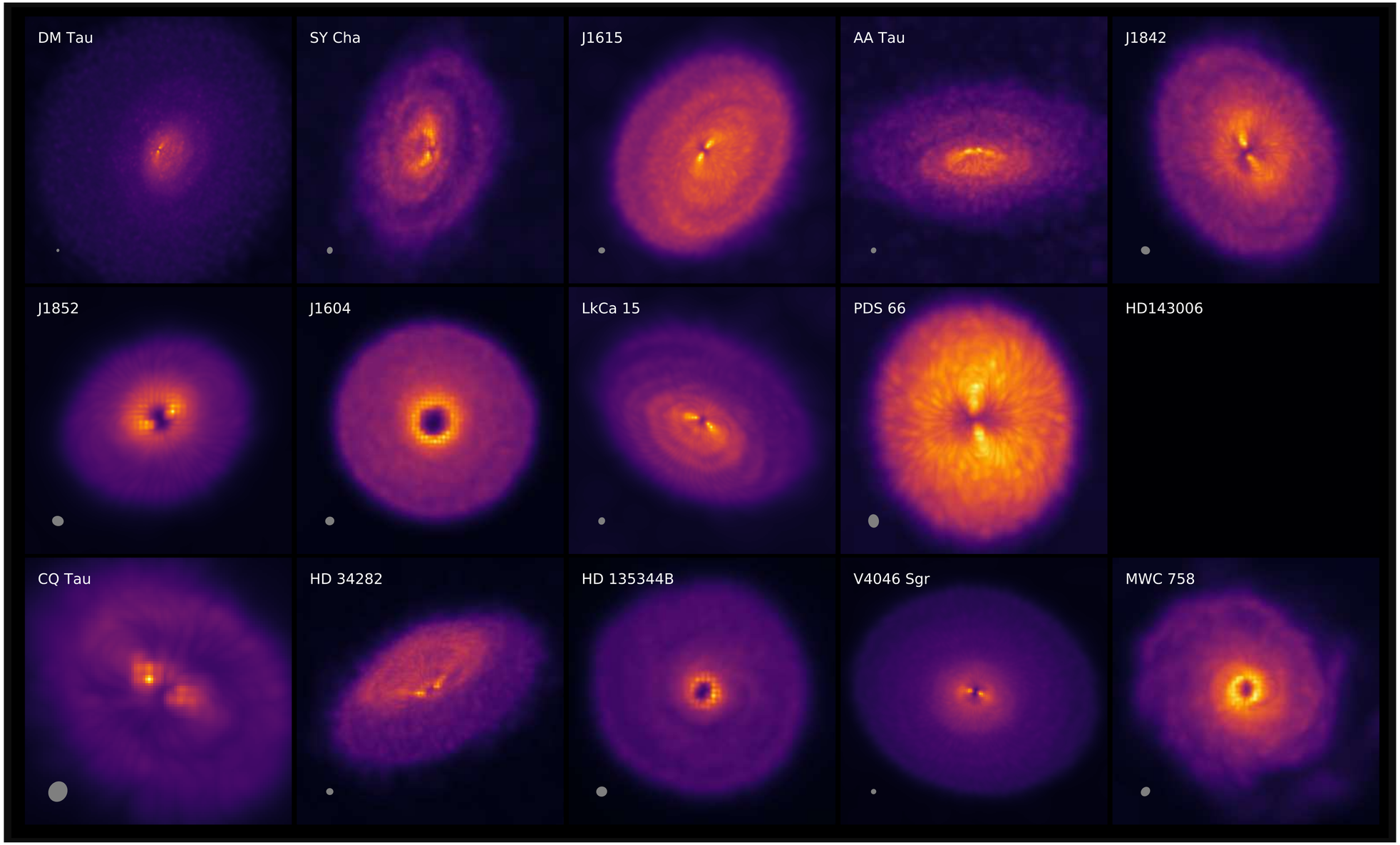
Verrios et al. 2022

THE PLANET WAKE IN IM LUPI



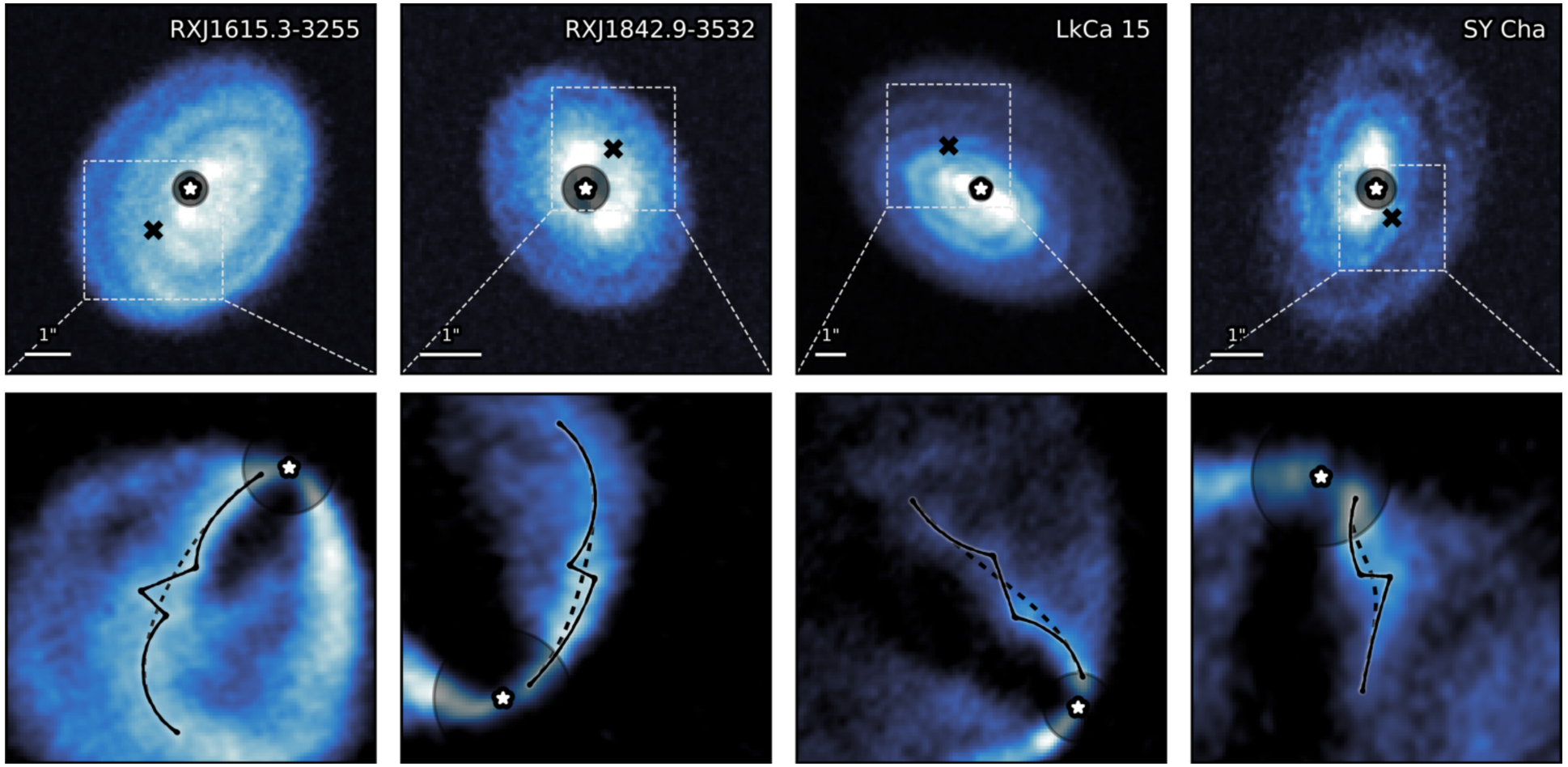
Verrios et al. 2022

EXOALMA PROJECT: SPIRALS EVERYWHERE!



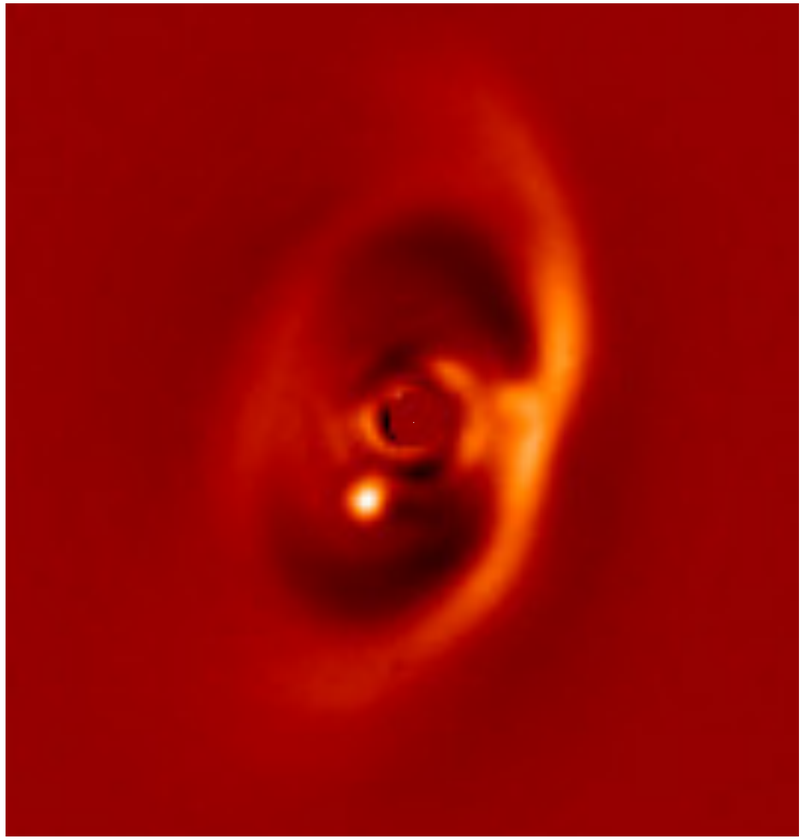
exoALMA collaboration (www.exoalma.com; Teague+2025)

EXOALMA: PLANET SIGNATURES

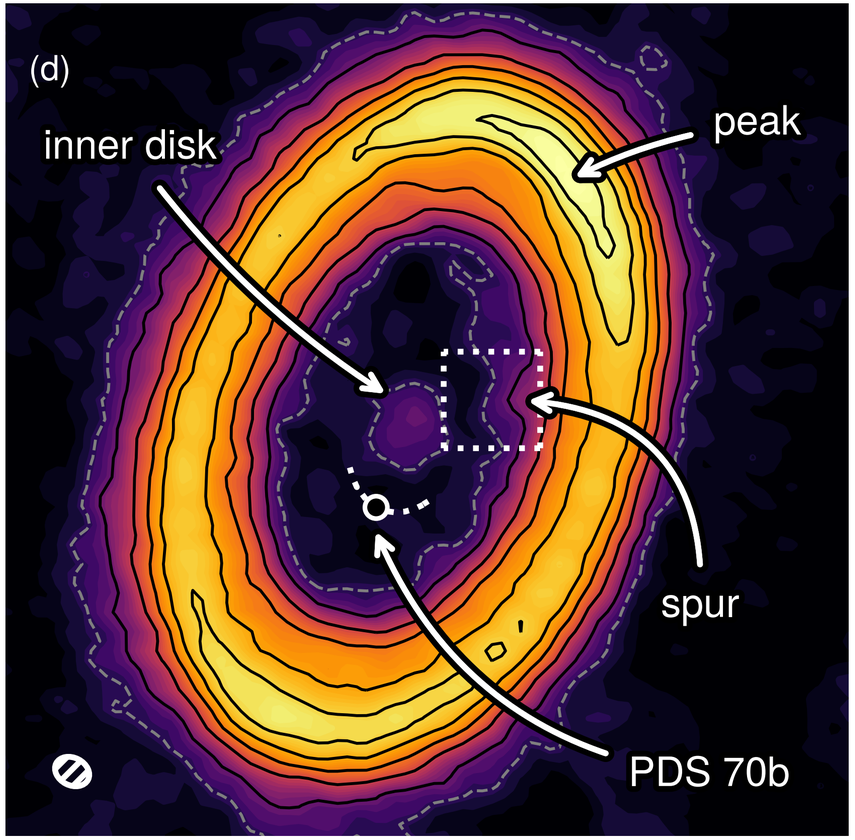


exoALMA collaboration (Pinte et al. 2025)

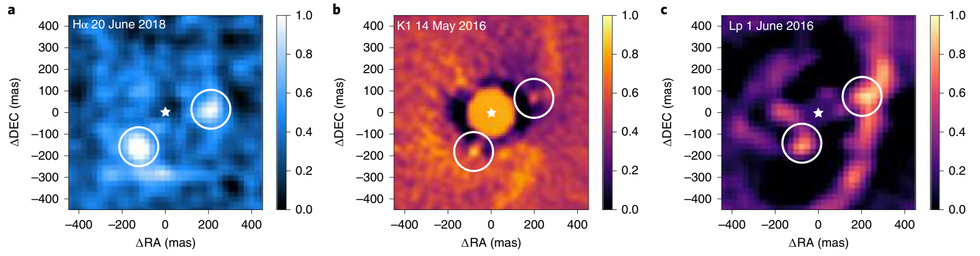
DIRECT IMAGING OF YOUNG PLANETS: PDS 70



Müller+(2018)

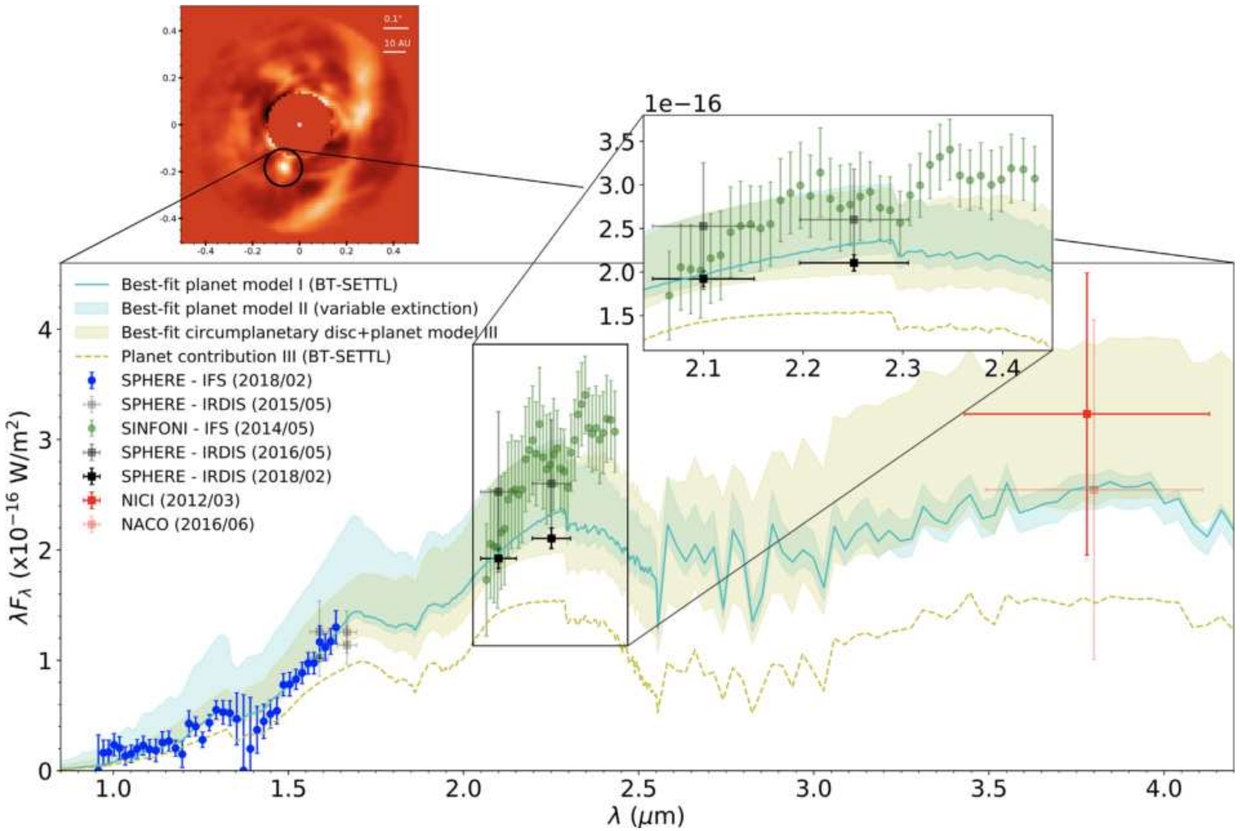


Keppler+(2019)

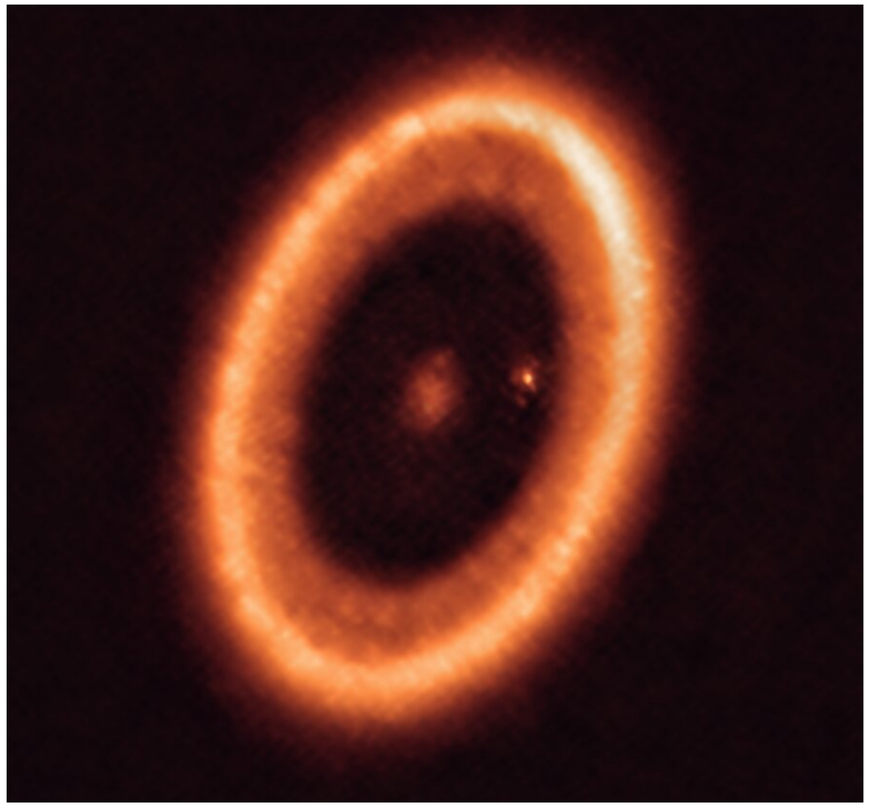


Haffert+(2019)

EVIDENCE FOR CIRCUMPLANETARY DISCS: PDS70B & C



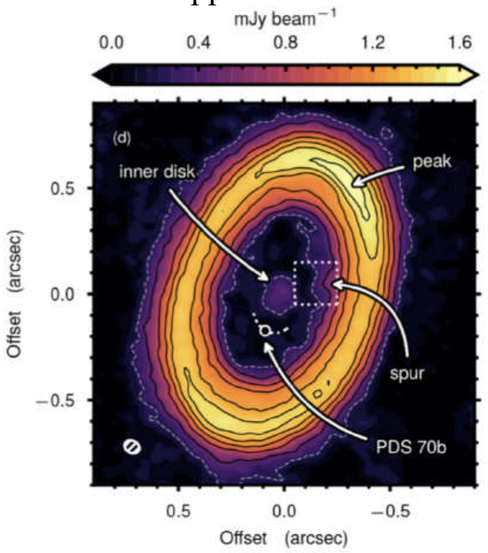
Christiaens et al. (2019) incl. DP:
evidence for CPD around PDS70b based on excess emission at $\lambda > 2.3\mu\mathrm{m}$



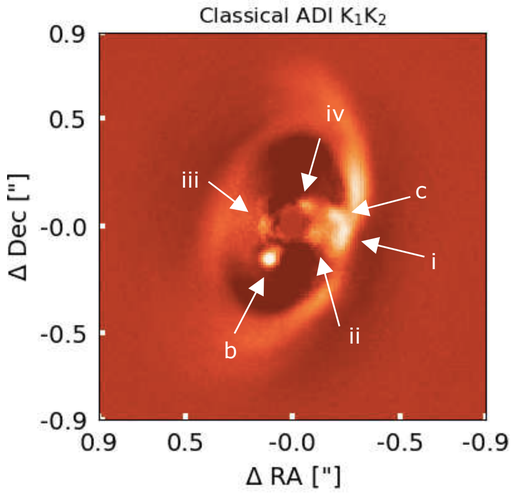
Benisty et al. (2021): CPD around PDS70c at mm-wavelengths with ALMA

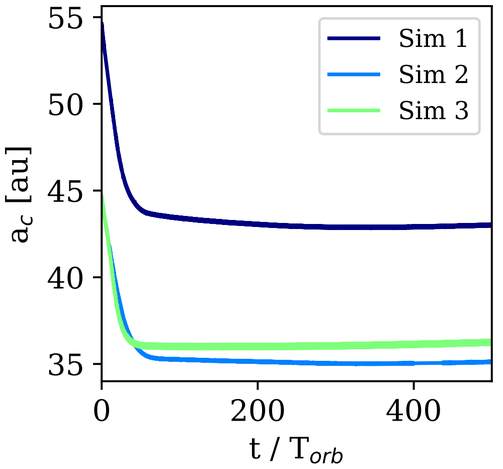
RESONANT LOCKING IN PDS70

Keppler et al. 2019

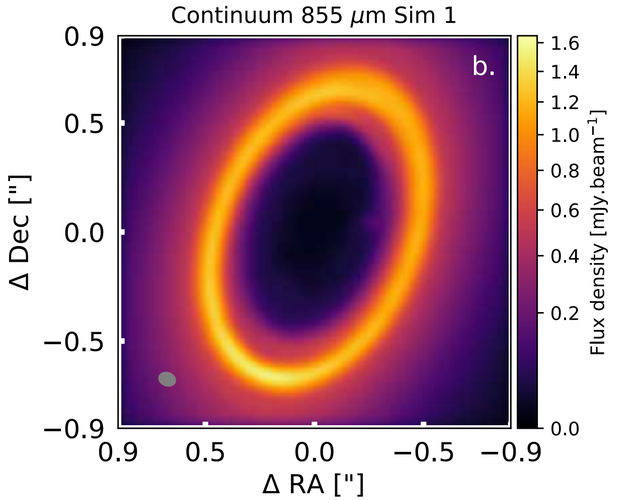


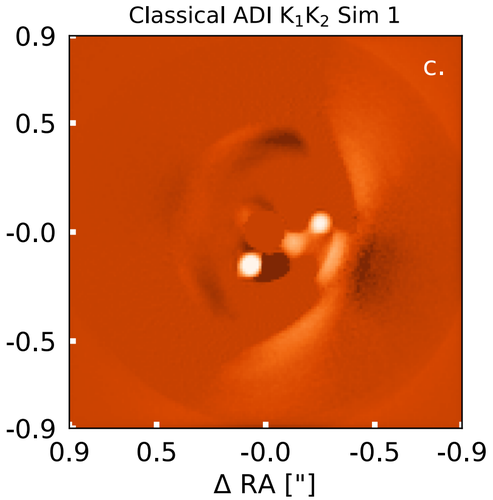
Muller et al. 2018

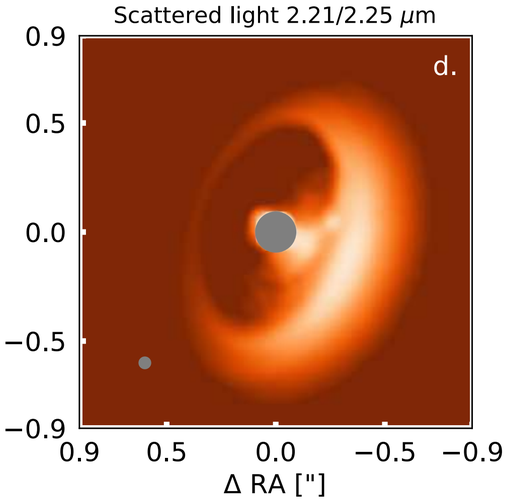




Sim1

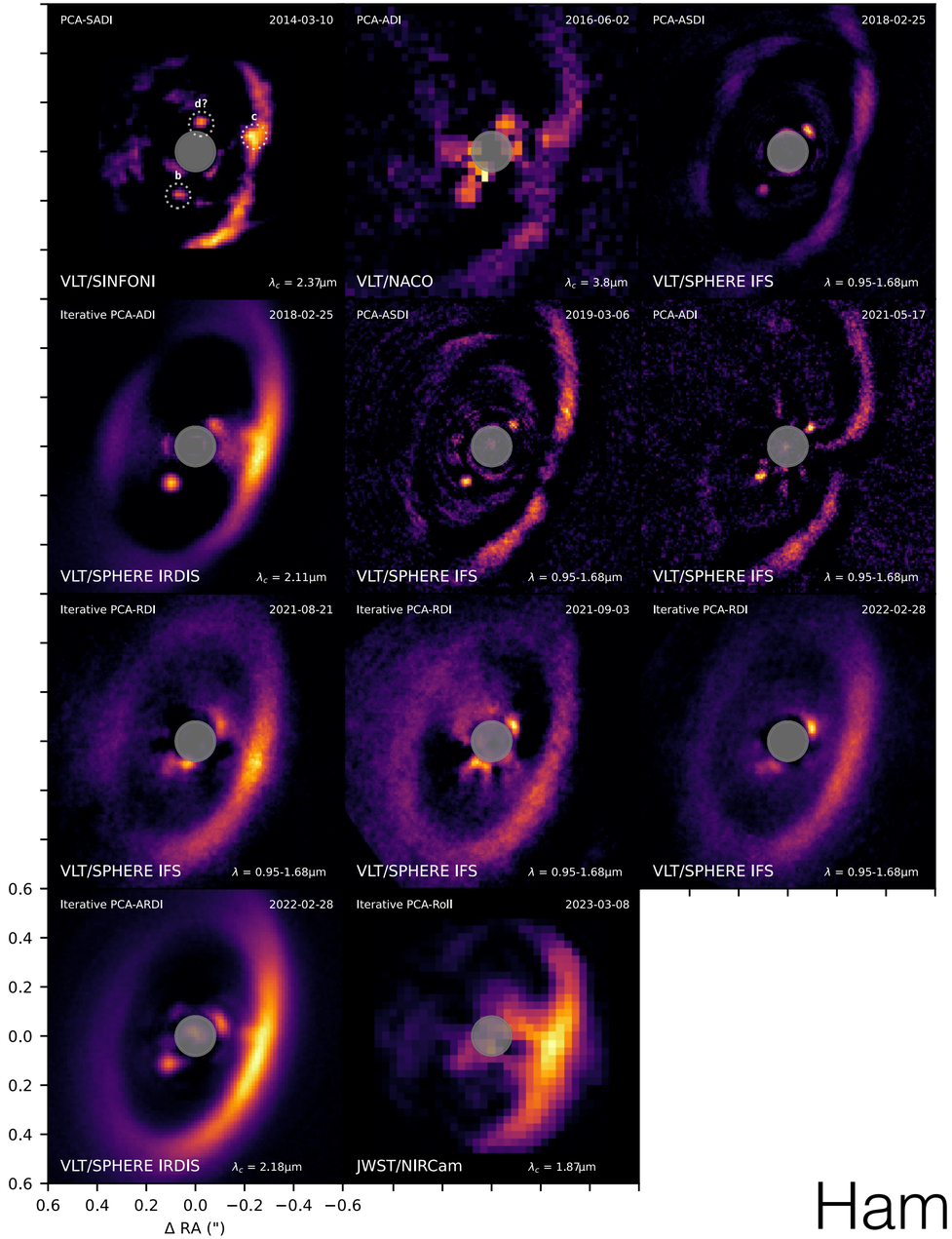


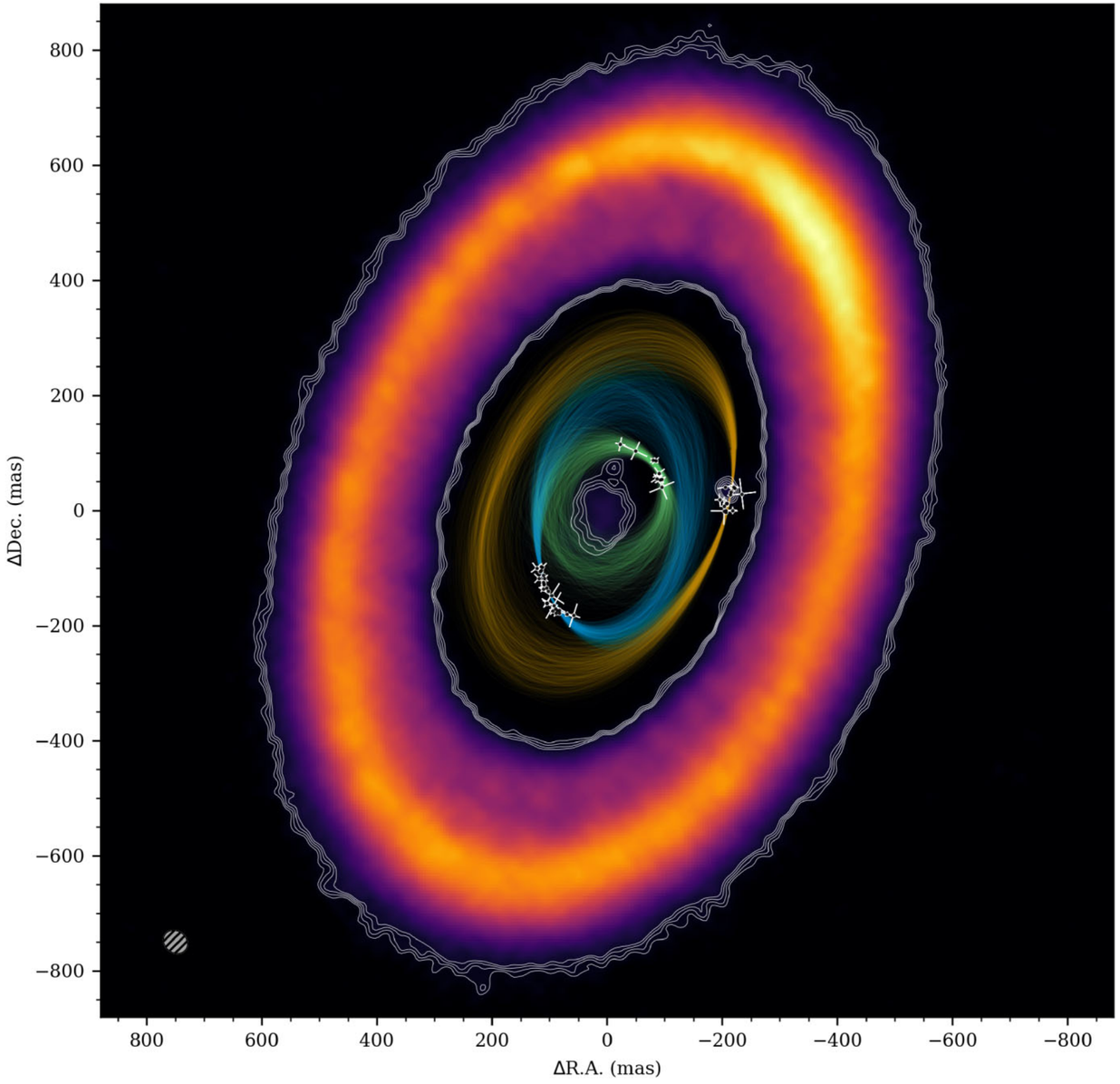




Toci+2020

A THIRD PLANET IN PDS 70??

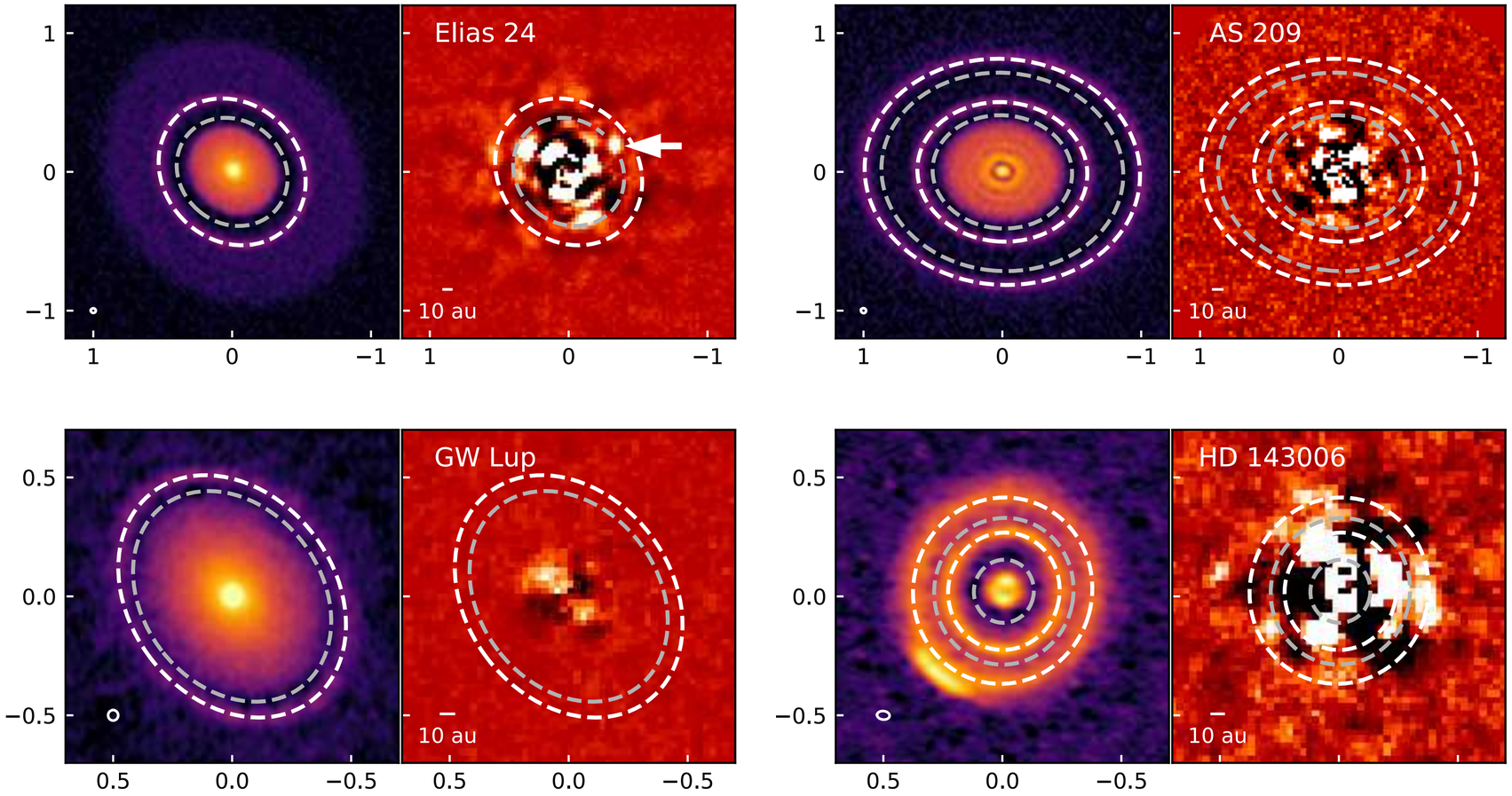




Hammond+2025

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

Direct imaging search for companions on DSHARP disks

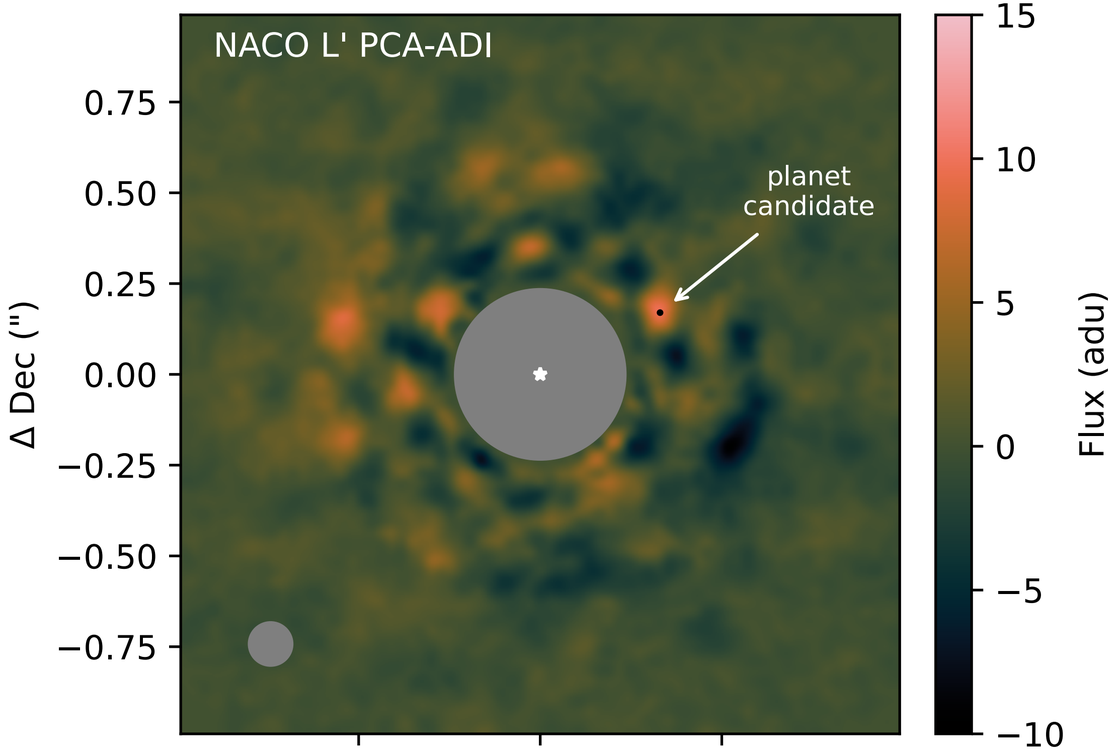


Jorquera+2021

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

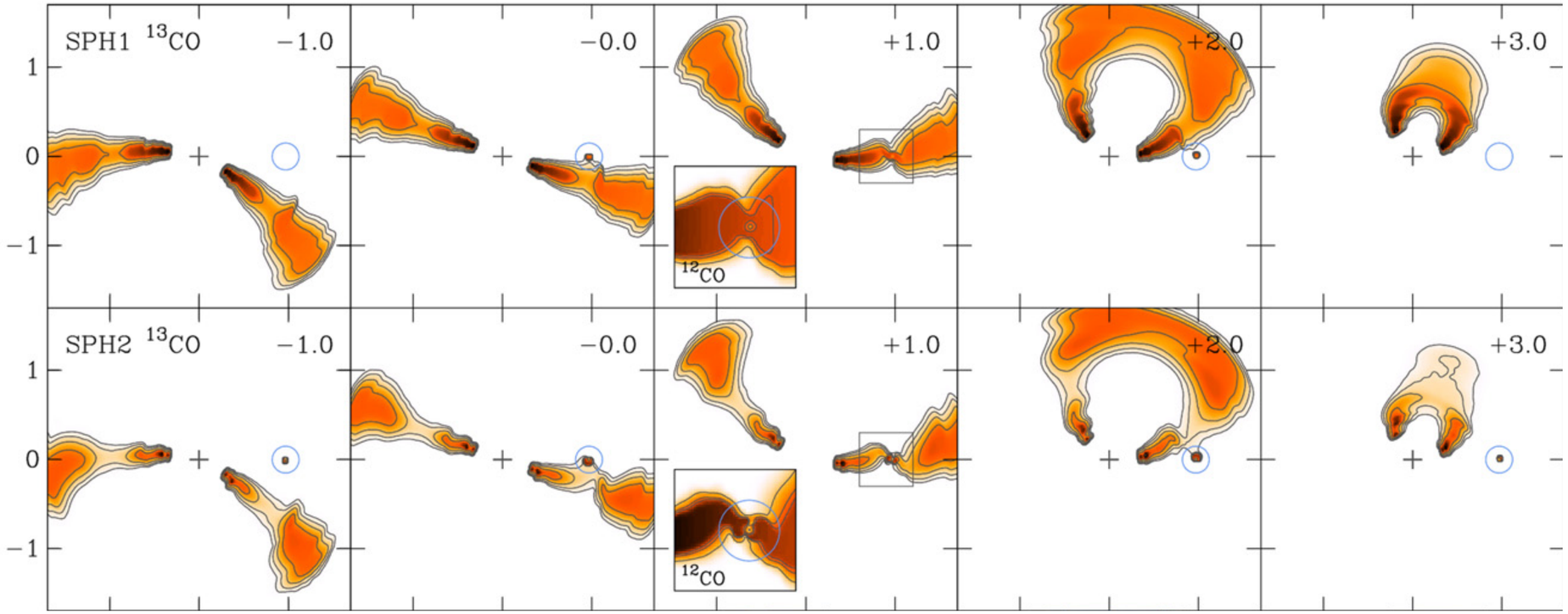
Kinematic and thermal signatures of the directly imaged protoplanet candidate around Elias 2-24

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?

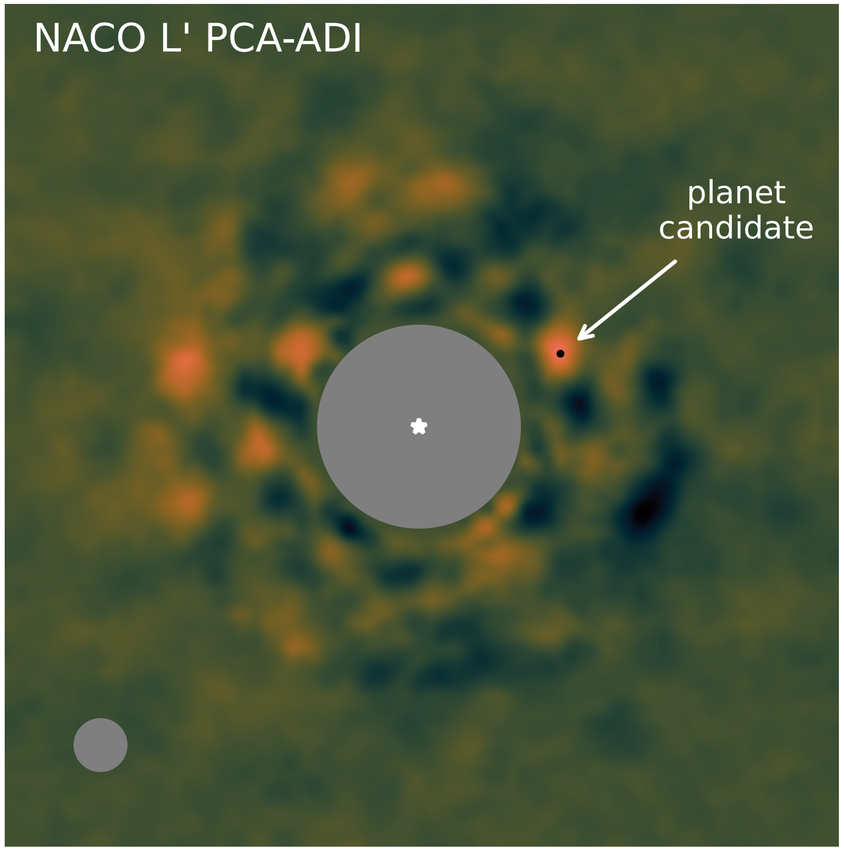


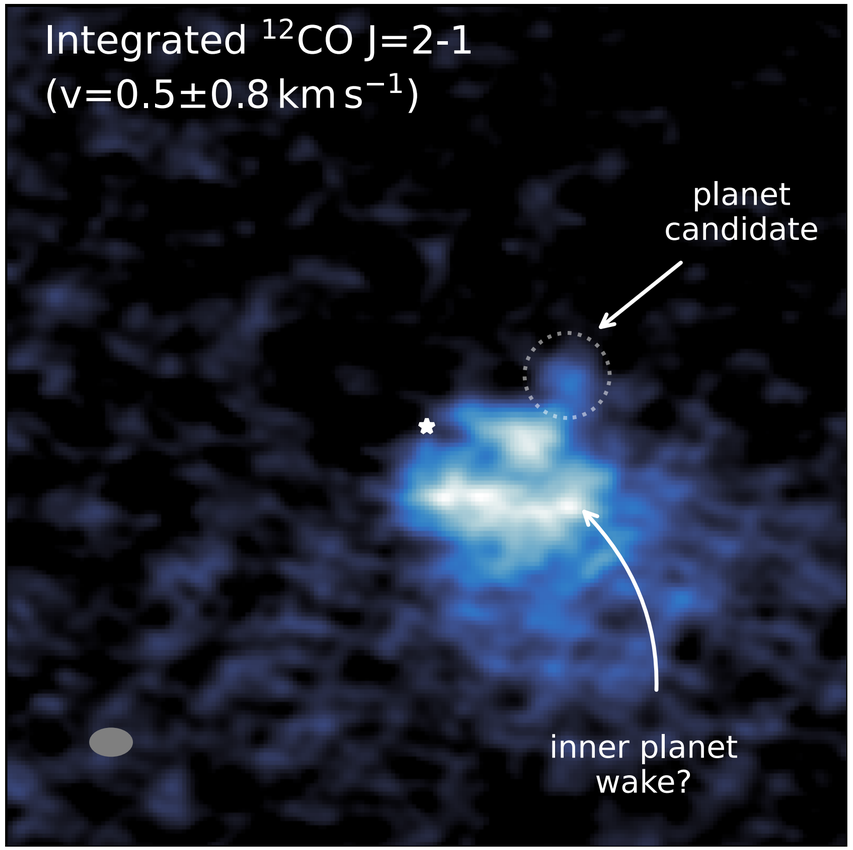
PLANET FORMATION SIGNPOSTS: OBSERVABILITY OF CIRCUMPLANETARY DISKS VIA GAS KINEMATICS

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)

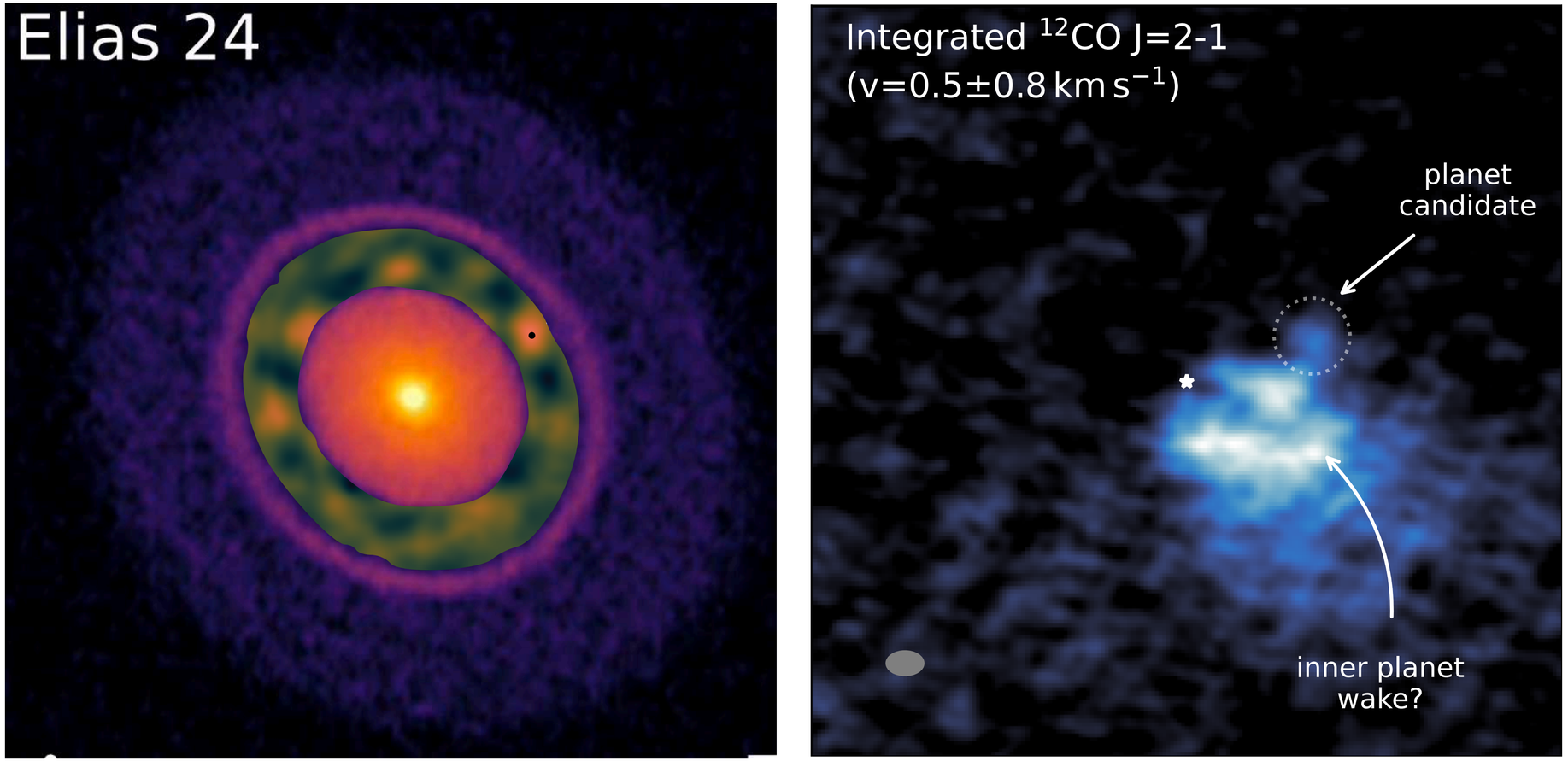
ELIAS 2-24





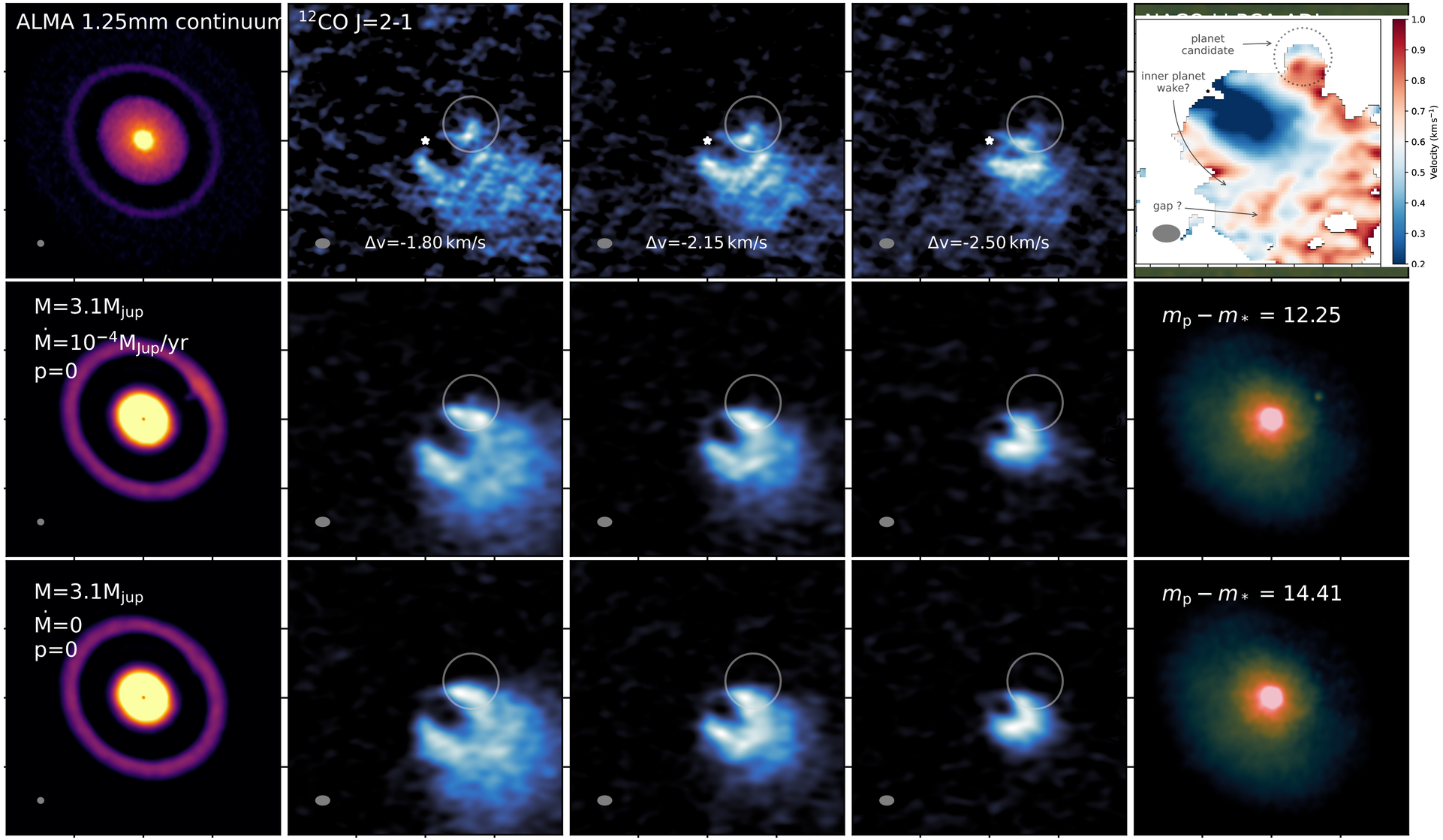
Pinte, Hammond, DP et al. (2023)

ELIAS 2-24



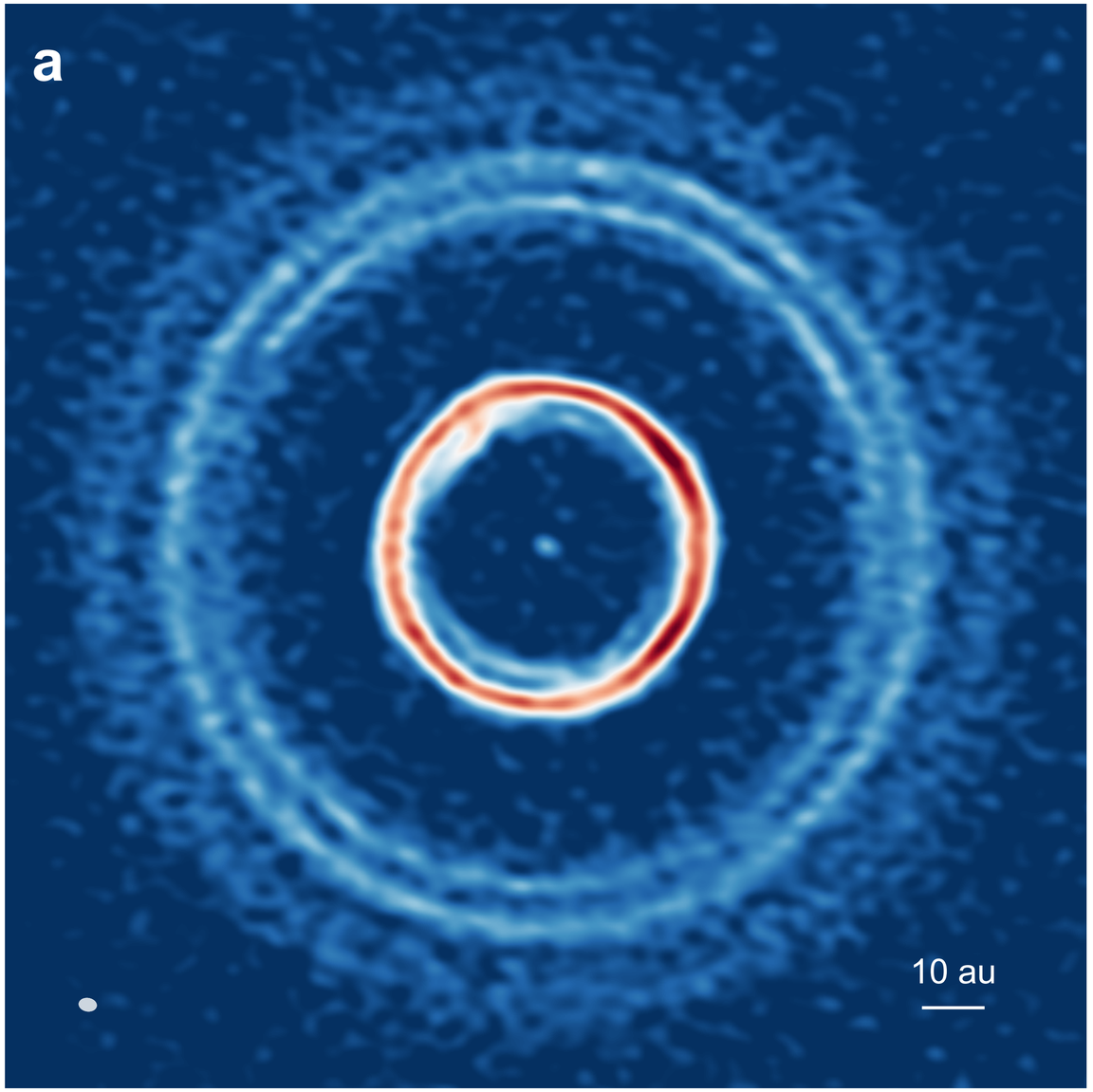
Pinte, Hammond, DP et al. (2023)

ELIAS 2-24

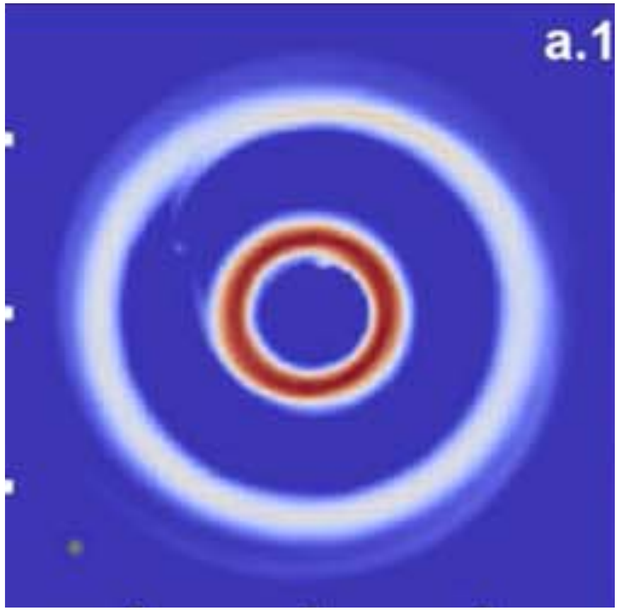


Pinte, Hammond, DP et al. (2023)

HD 169142 WITH ALMA

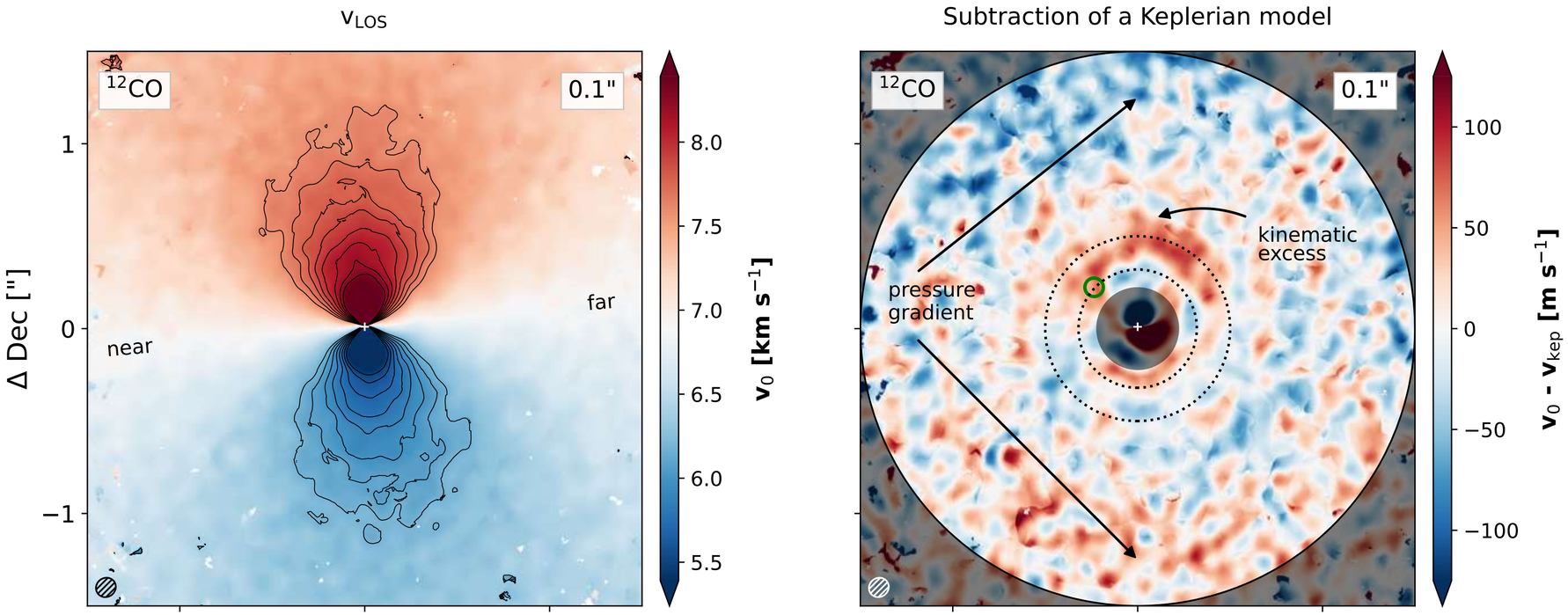


Perez et al. (2019)



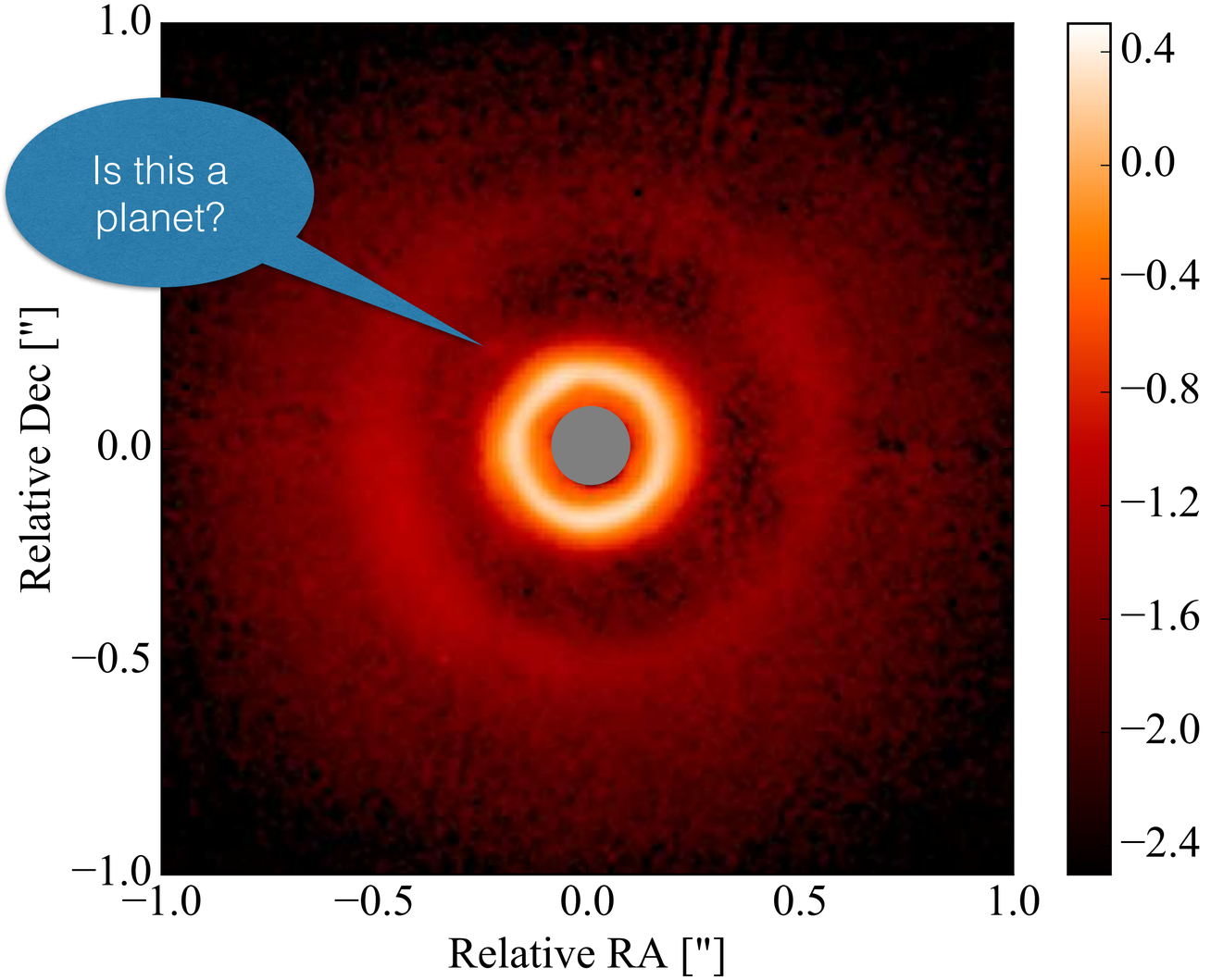
Toci et al. (2020)

HD 169142 KINEMATICS



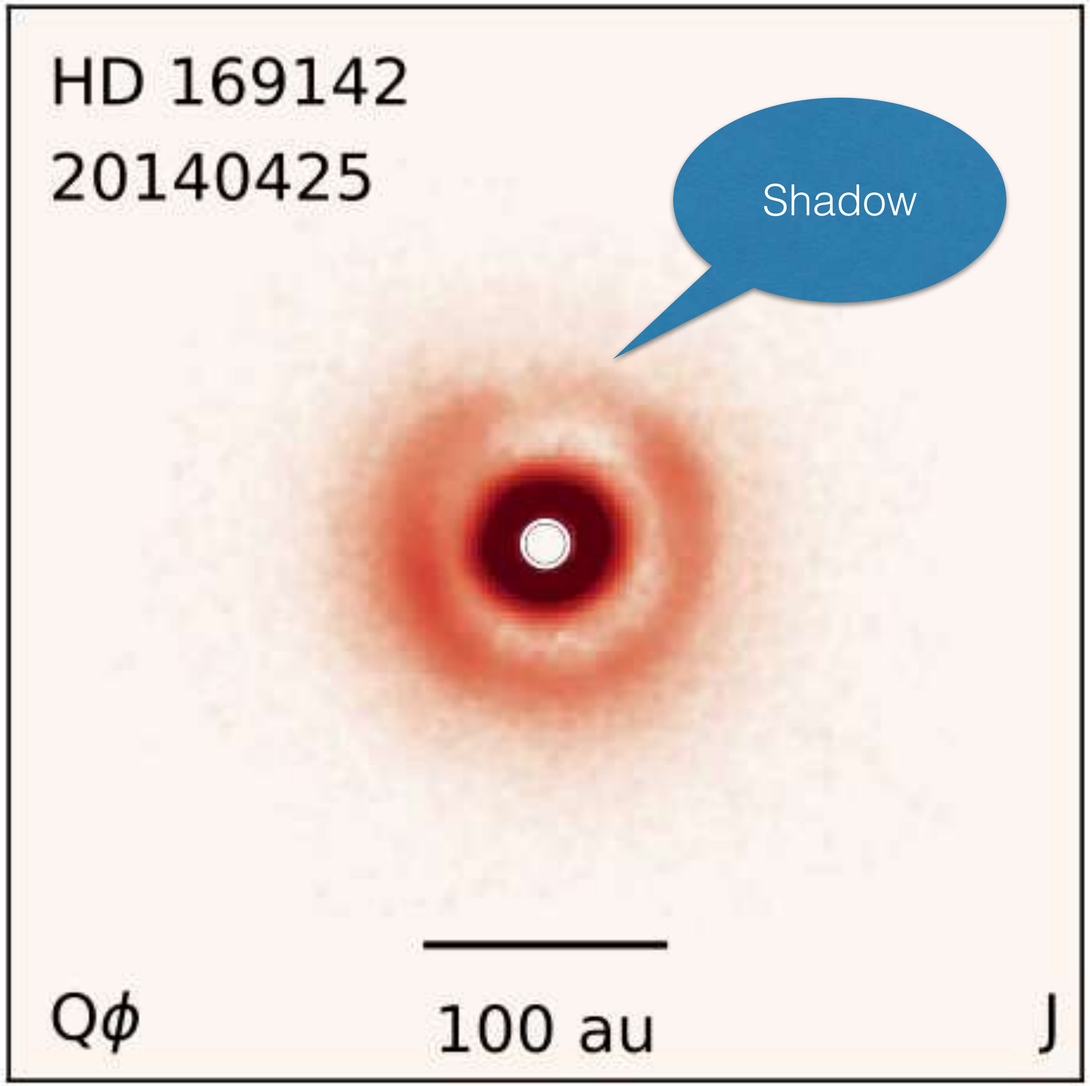
Garg et al. (2022)

HD 169142 DIRECT IMAGING



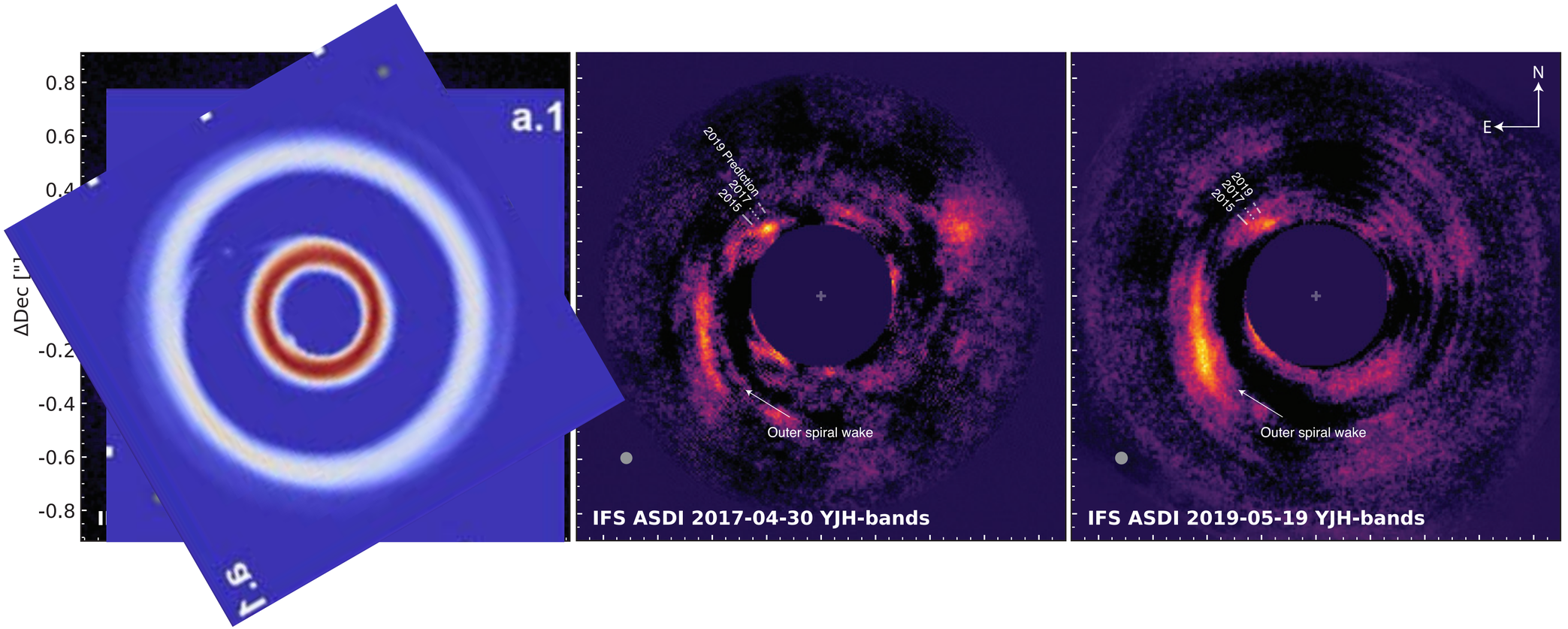
Pohl et al. (2017) using VLT/SPHERE

HD 169142 DIRECT IMAGING



Rich et al. (2022) with Gemini Planet Imager

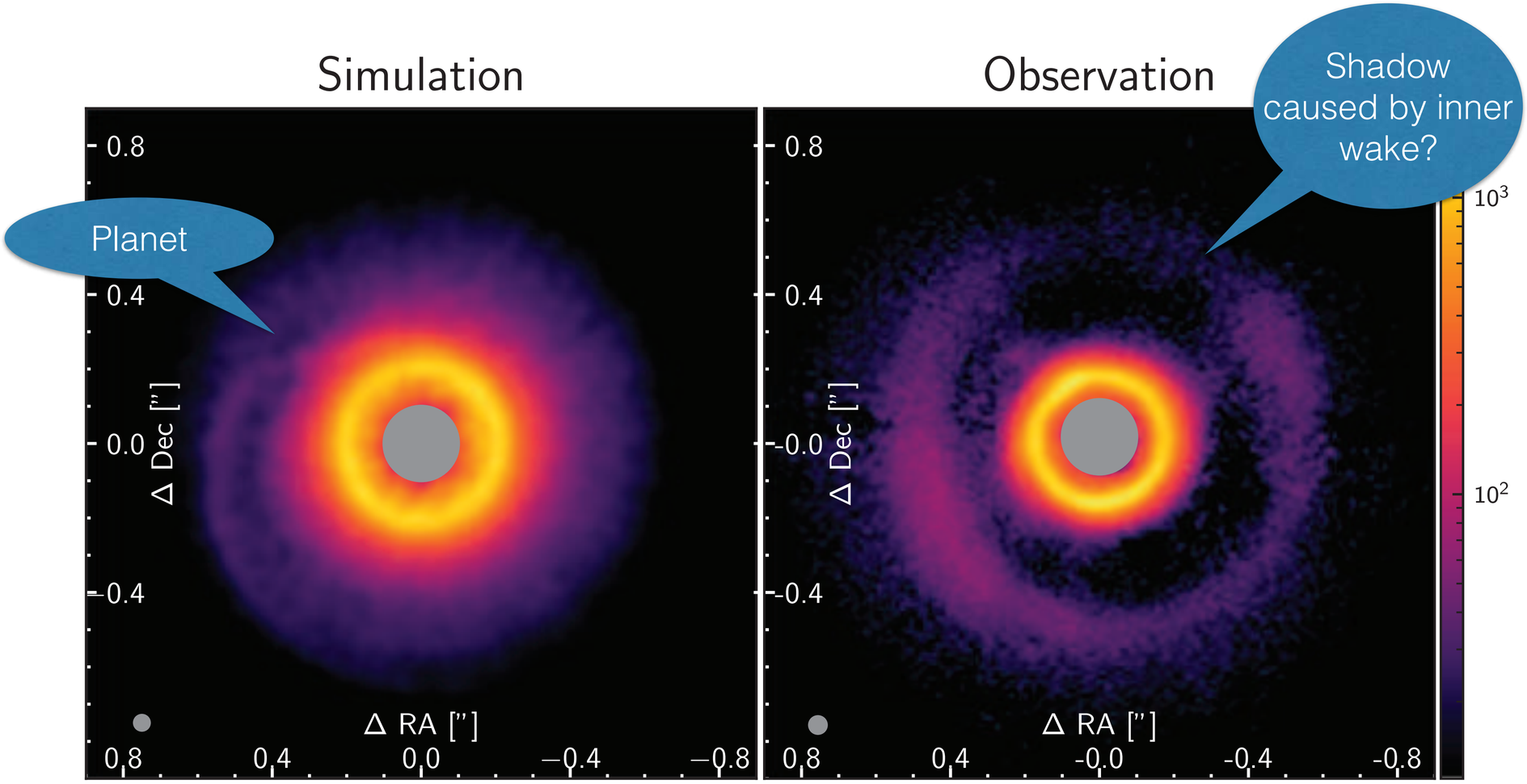
HD 169142 DIRECT IMAGING



Toci et al. (2020)

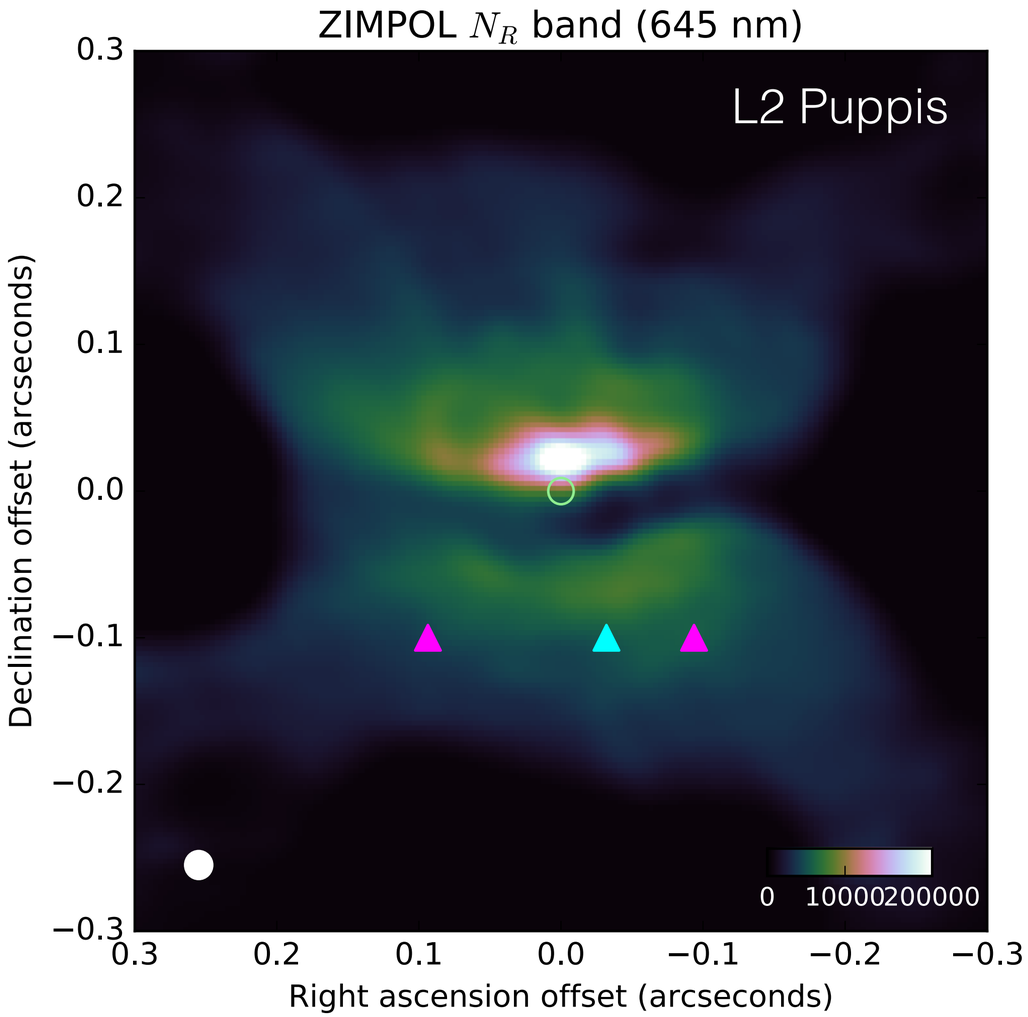
Hammond et. al. (2023) using archival VLT images

HD 169142 DIRECT IMAGING

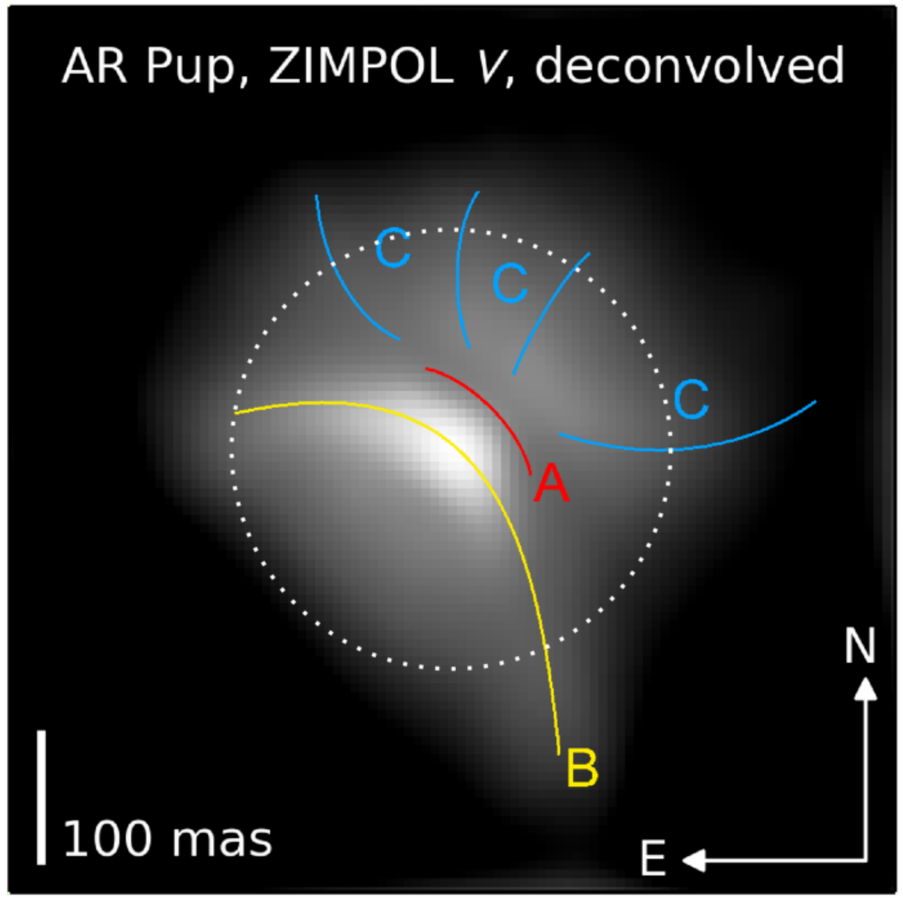


Hammond et. al. (2023)

COULD PLANETS FORM AROUND GIANT STARS?



e.g. Kervella+2015, 2016, Haworth+2018, van de Sande+2024



Ertel+2019

Circumbinary disc

Unclear how these discs form in the winds of dying stars, but they're there!

See Chen+2016 for attempt at forming L2 Puppis disc from AGB wind + binary companion

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
- SAME TECHNIQUES NOW BEING APPLIED TO DISCS AROUND AGB AND POST-AGB STARS