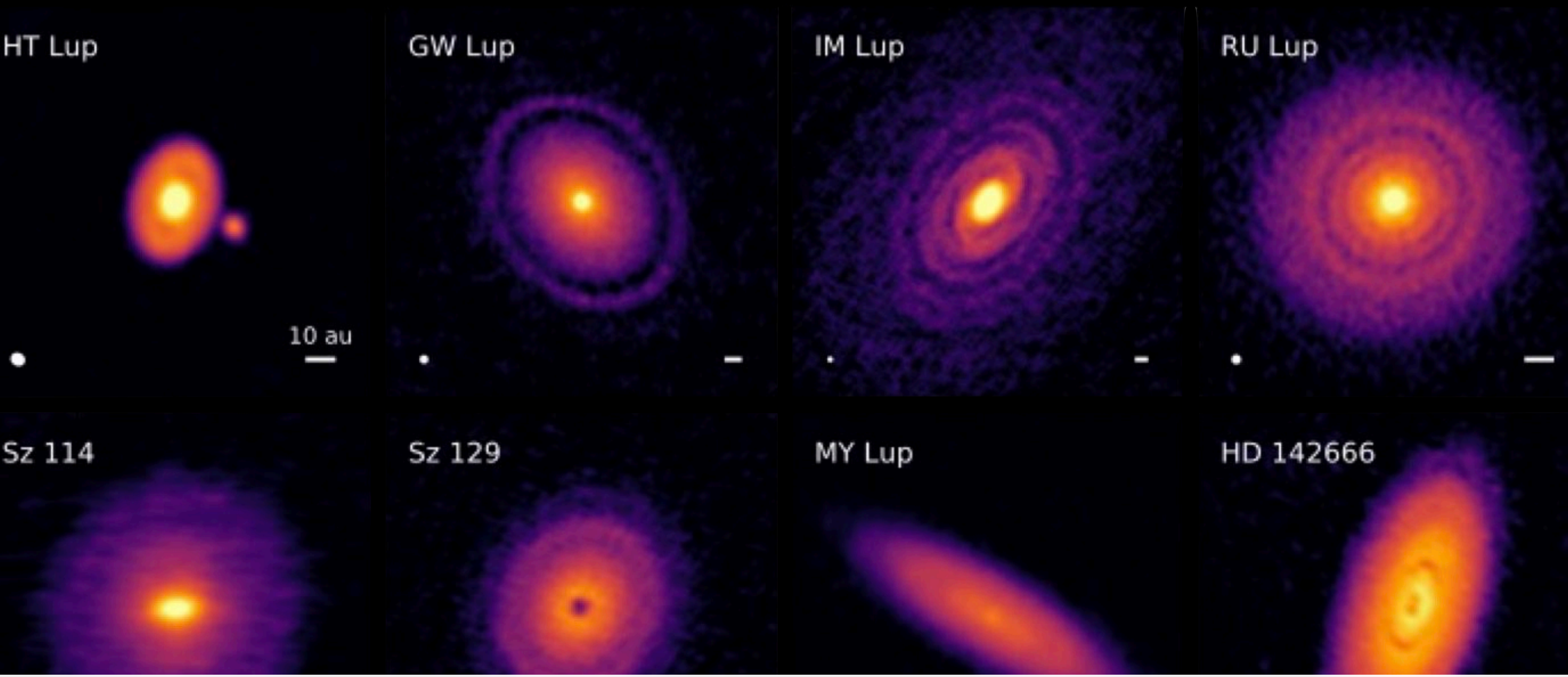


DUST BUSTERS

DUST DYNAMICS: UNLOCKING THE MYSTERIES OF PROTOPLANETARY DISCS

Daniel Price (Monash University, Melbourne, Australia)

Image credit: DSHARP

Cosmic dust (r)evolution, EWASS 2019, 24-25th June, Lyon, France

THE PROBLEM

Carina Nebula with HST (NASA/ESA/Hubble Heritage)

ISM: dust/gas = 1/100

Pinnacles desert, Western Australia (Price family)

Rocky planets: dust/gas $\approx \infty$

How?

Daniel Price

THE PHYSICS

DRAG

Daniel Price

DUST AND GAS AS MULTIPHASE MIXTURE

e.g. Harlow & Amsden (1975), Monaghan & Kocharyan (1995), Laibe & Price (2012a,b)

$$\frac{\partial \rho_{\rm g}}{\partial t} + \nabla . (\rho_{\rm g} \mathbf{v}_{\rm g}) = 0,$$

$$\frac{\partial \rho_{\rm d}}{\partial t} + \nabla . (\rho_{\rm d} \mathbf{v}_{\rm d}) = 0,$$

$$\frac{\partial \mathbf{v}_{\rm g}}{\partial t} + (\mathbf{v}_{\rm g} . \nabla) \mathbf{v}_{\rm g} = -\frac{\nabla P_{\rm g}}{\rho_{\rm g}} + \frac{K}{\rho_{\rm g}} (\mathbf{v}_{\rm d} - \mathbf{v}_{\rm g}) + \mathbf{f},$$

$$\frac{\partial \mathbf{v}_{\rm d}}{\partial t} + (\mathbf{v}_{\rm d} . \nabla) \mathbf{v}_{\rm d} = -\frac{K}{\rho_{\rm d}} (\mathbf{v}_{\rm d} - \mathbf{v}_{\rm g}) + \mathbf{f},$$

(assuming a single grain species)

No pressure term for dust

Drag terms: exchange of momentum due to gas-dust collisions

THE "STOPPING TIME"

$$\frac{\partial \Delta \mathbf{v}}{\partial t} = -\frac{\Delta \mathbf{v}}{t_{\rm stop}}$$

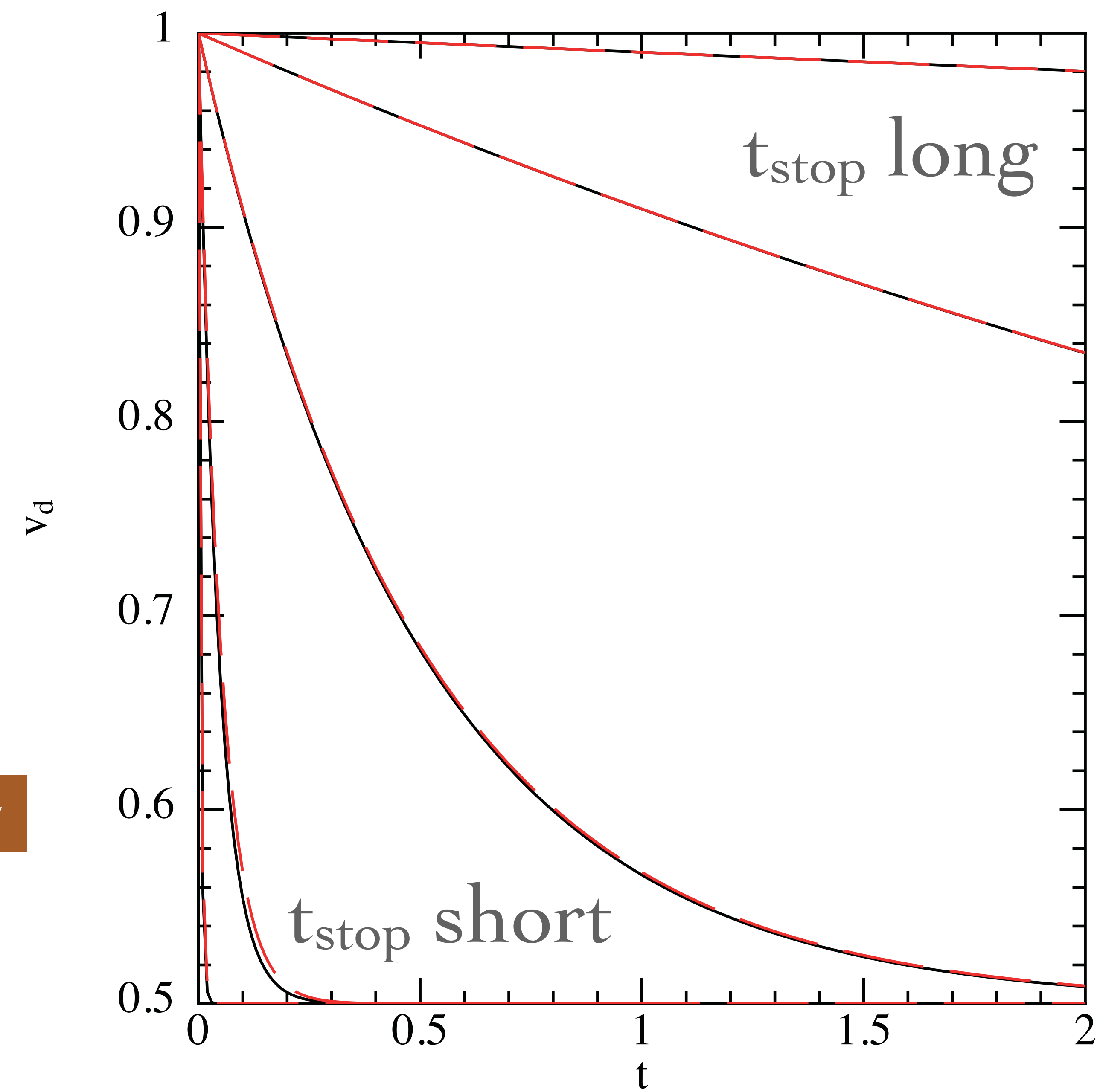
Differential velocity between gas and dust

$$t_{\rm stop} \equiv \frac{\rho_{\rm d}\rho_{\rm g}}{K(\rho_{\rm d} + \rho_{\rm g})}$$

Characteristic timescale for exponential decay

$$t_{\rm stop} = \frac{\rho_{\rm gr} s}{\rho c_{\rm s}}$$

Proportional to grain size /
Inversely proportional to gas density



"Dustybox" problem from Laibe & Price (2011)

T_{STOP} CAN GO FROM ZERO TO INFINITY

Daniel Price

ONE FLUID DUST/GAS

Laibe & Price (2014a,b,c), Price & Laibe (2015), Hutchison et al. (2018), Ballabio et al. (2018)

- Rewrite equations with dust fraction, total density, drift velocity
- Assume short stopping time / low St / large drag, get:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho(\nabla\cdot\mathbf{v})$$

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} + \mathbf{f}$$

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = -\frac{1}{\rho}\nabla\cdot\left(\epsilon t_{\mathrm{s}}\nabla P\right) \qquad \epsilon \equiv \frac{\rho_{\mathrm{d}}}{\rho}$$

- Can use explicit timesteps even when stopping time is short
- Easily extended to multi-grain populations (Laibe & Price 2014c, Hutchison et al. 2018), implemented in PHANTOM SPH code (Price et al. 2018; http://bitbucket.org/danielprice/phantom)

STOKES NUMBER

Weidenschilling (1977)

$$t_{\rm stop} = \frac{\rho_{\rm gr} s}{\rho c_{\rm s}}$$

$$S_{\rm t} = t_{\rm stop}\Omega$$

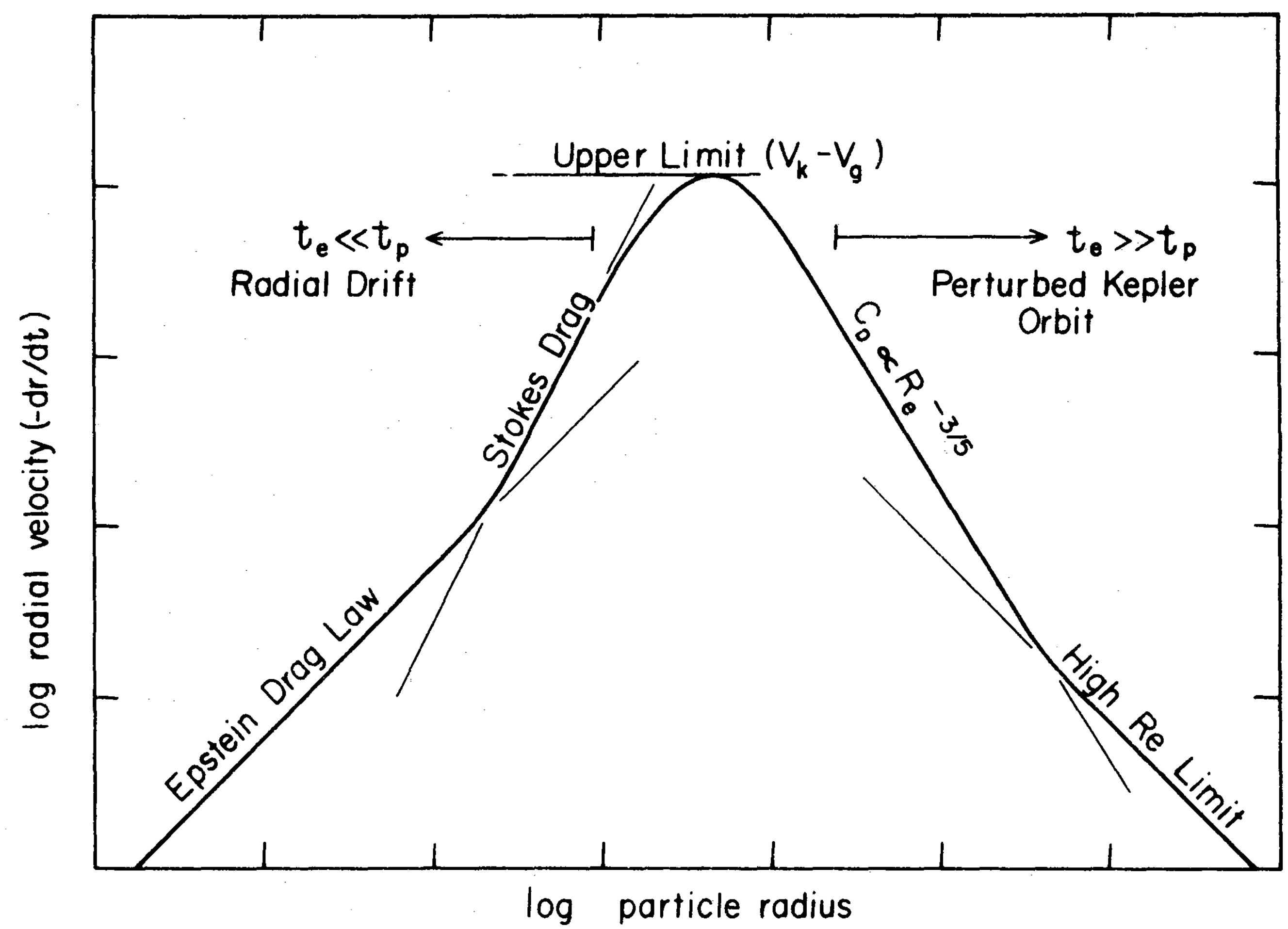


Figure 1. Radial velocity versus particle size (schematic). The shape of the curve is determined by the drag laws, but the peak value depends only on the nebular structure.

DUST BEHAVIOUR IN DISCS DEPENDS ON GAS COLUMN DENSITY

Gas column density

Grain composition

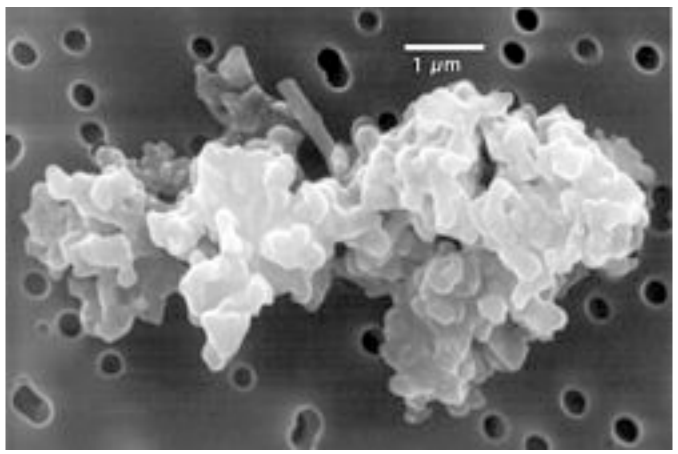
Grain size

$$S_{\mathrm{t}} = 1 \left(\frac{\Sigma}{0.2\mathrm{g/cm}^2} \right)^{-1} \left(\frac{\rho_{\mathrm{grain}}}{3\mathrm{g/cm}^3} \right) \left(\frac{s}{1\mathrm{mm}} \right) \left(\frac{f}{1} \right)^{-1}$$

Dipierro et al. (2015)

No dependence on stellar mass or mass of dust disc!

PHYSICS I WILL NOT DISCUSS: GRAIN GROWTH



en.wikipedia.org

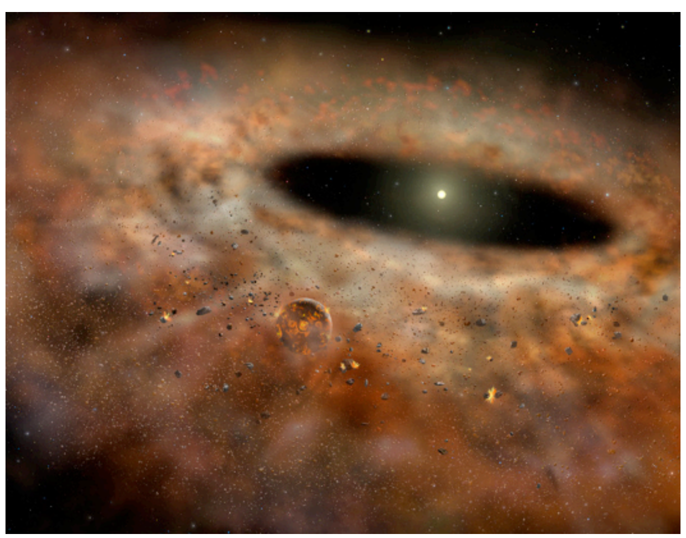
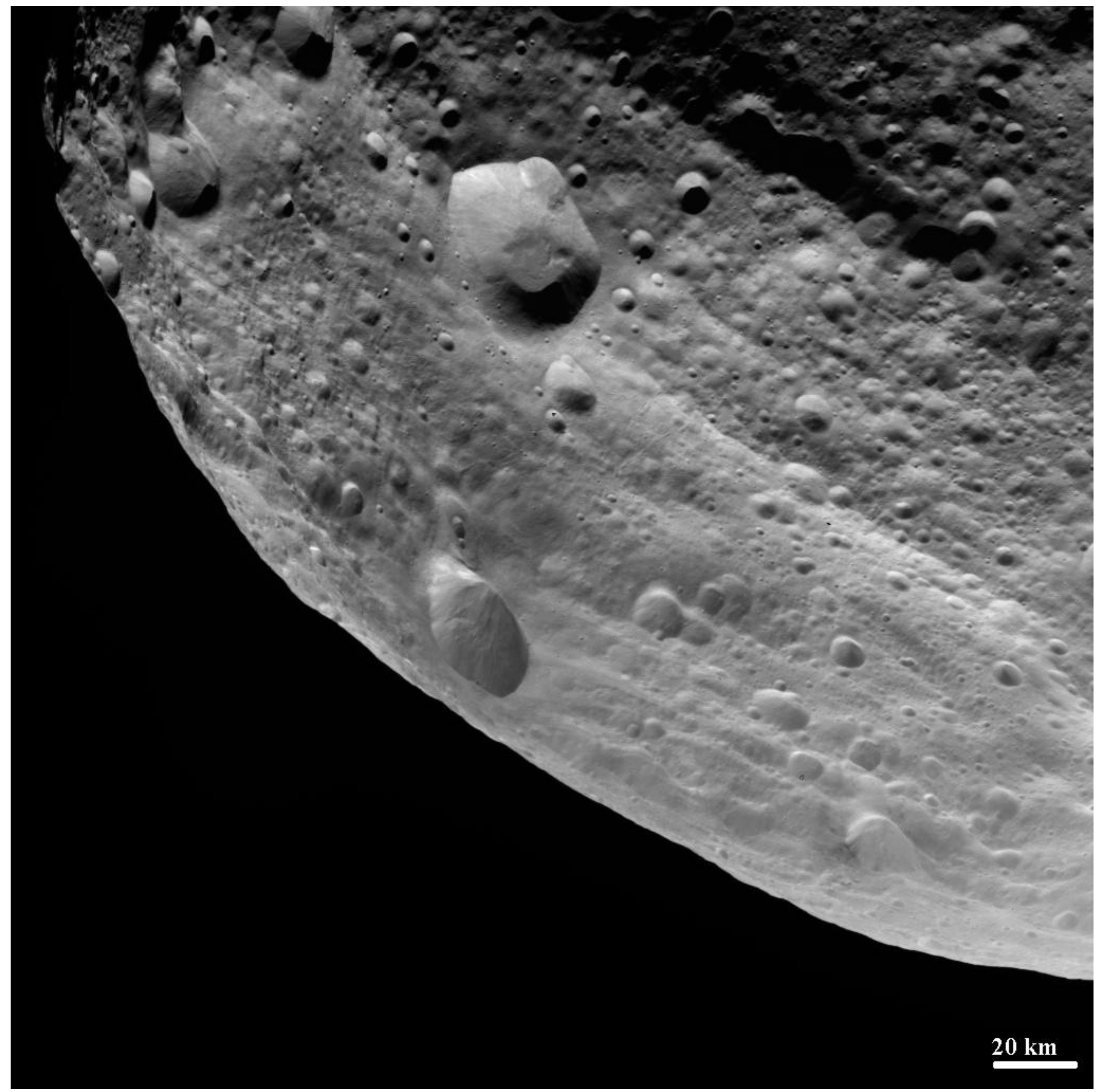
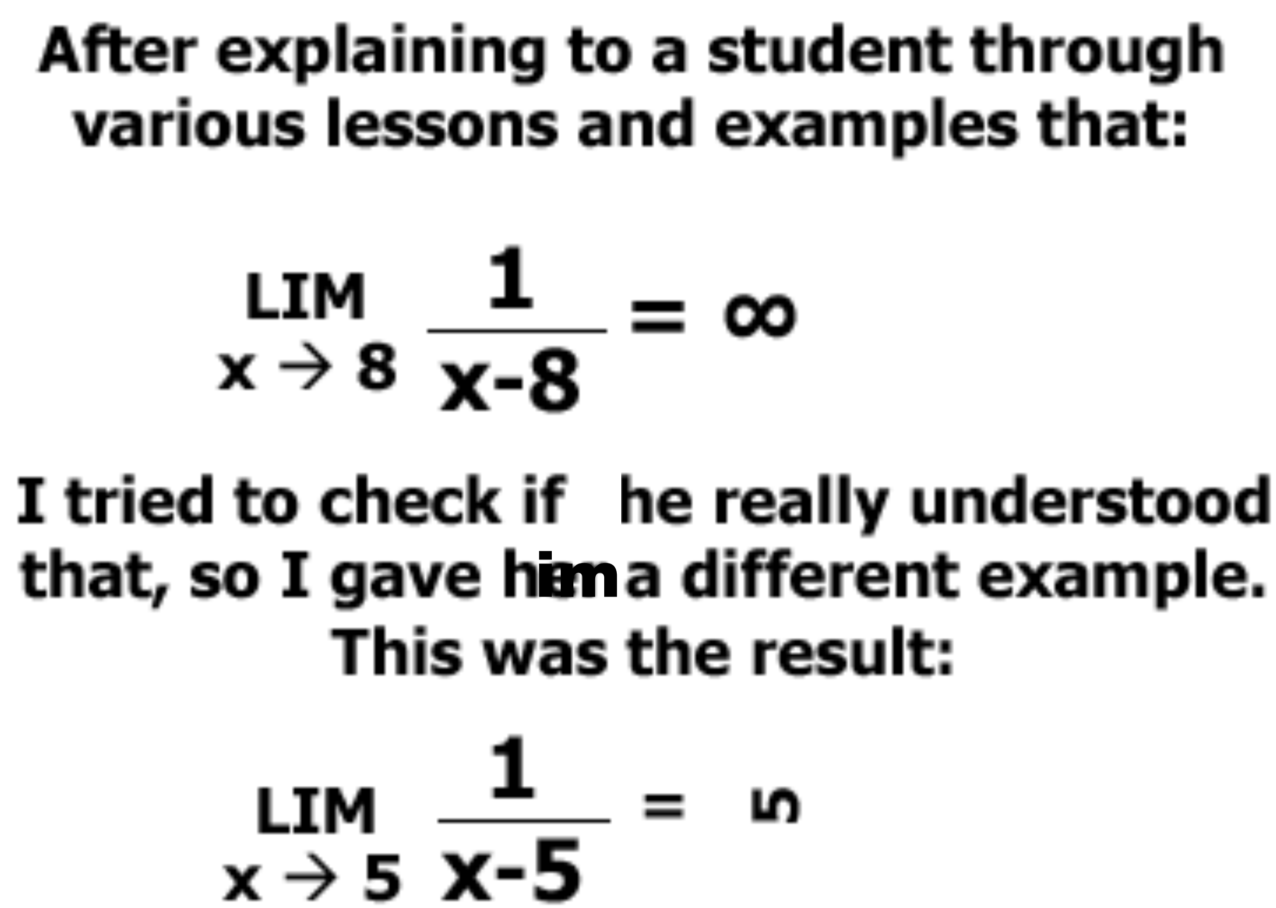


Image: Gemini
Observatory/AURA
Artwork by Lynette Cook



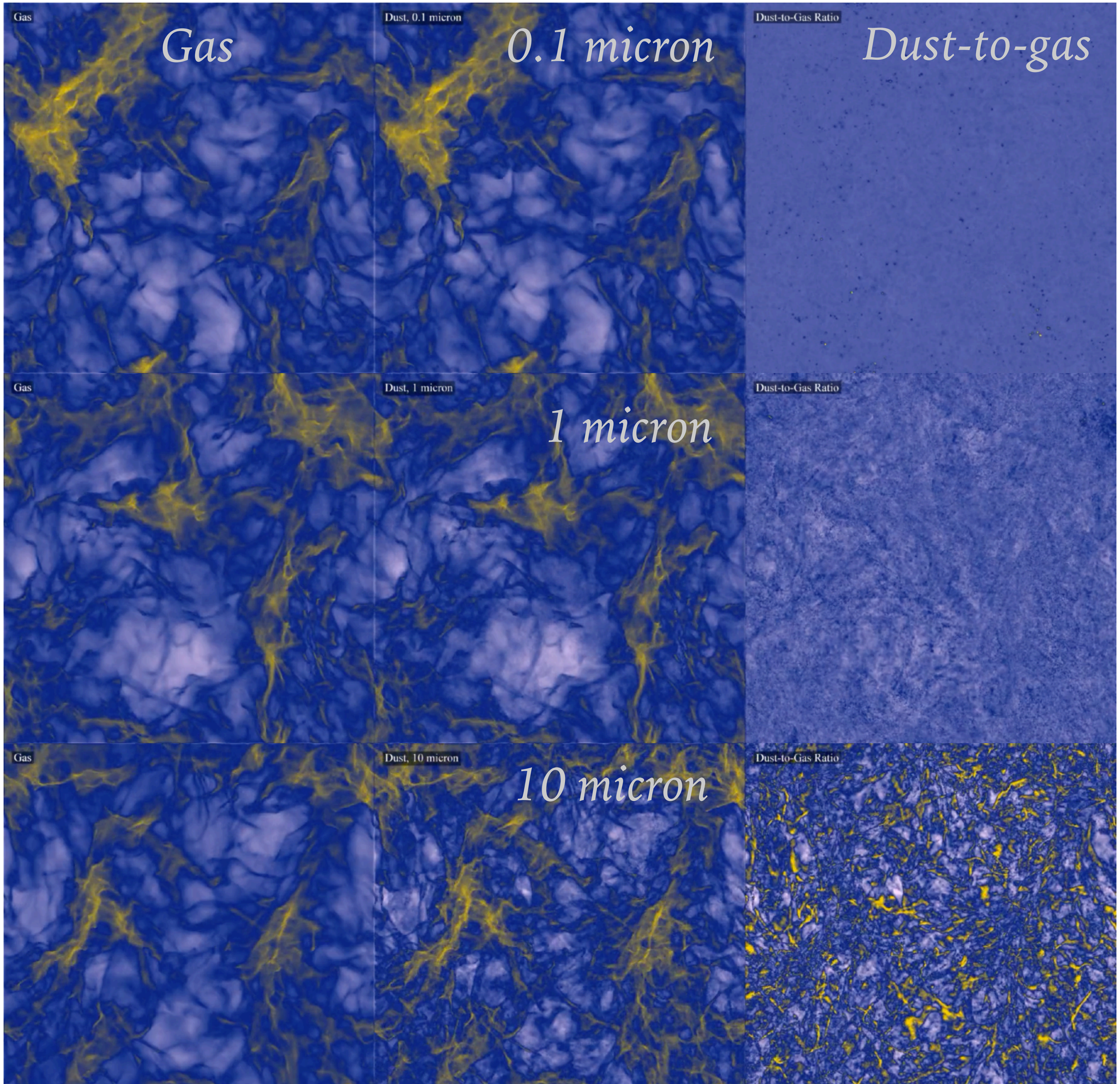
FROM 0.01 TO INFINITY

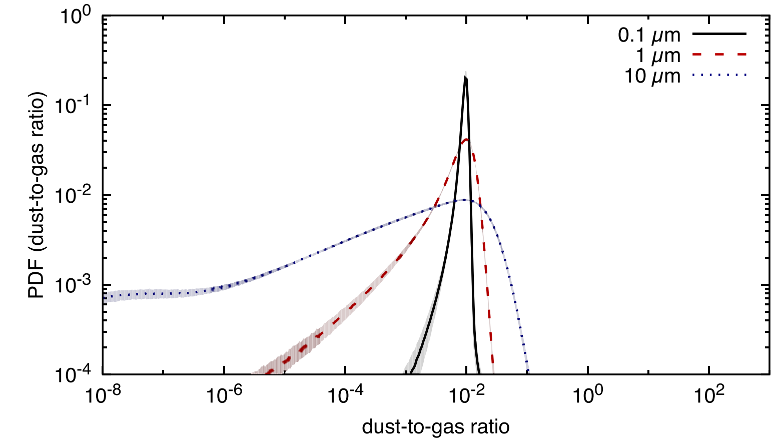


Credit: bad internet jokes

IS THE DUST TO GAS RATIO CONSTANT IN MOLECULAR CLOUDS?

Tricco, Price & Laibe (2017)



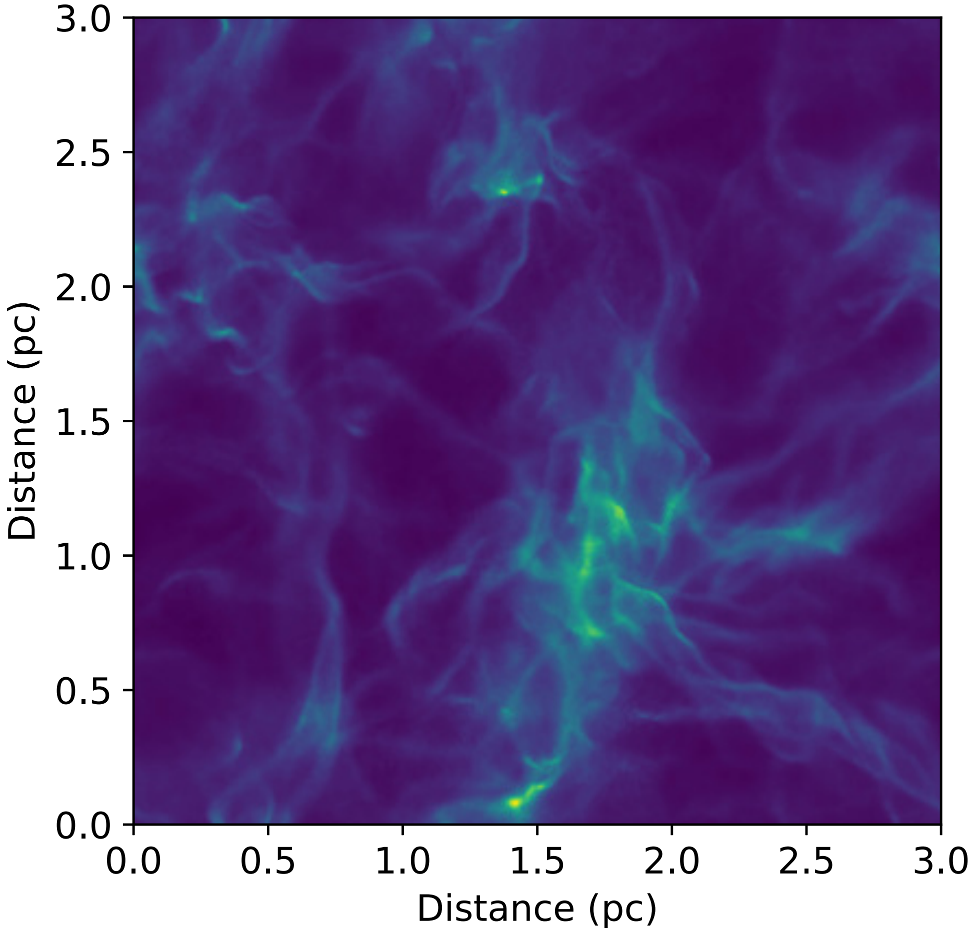


Dynamical size-sorting of grains

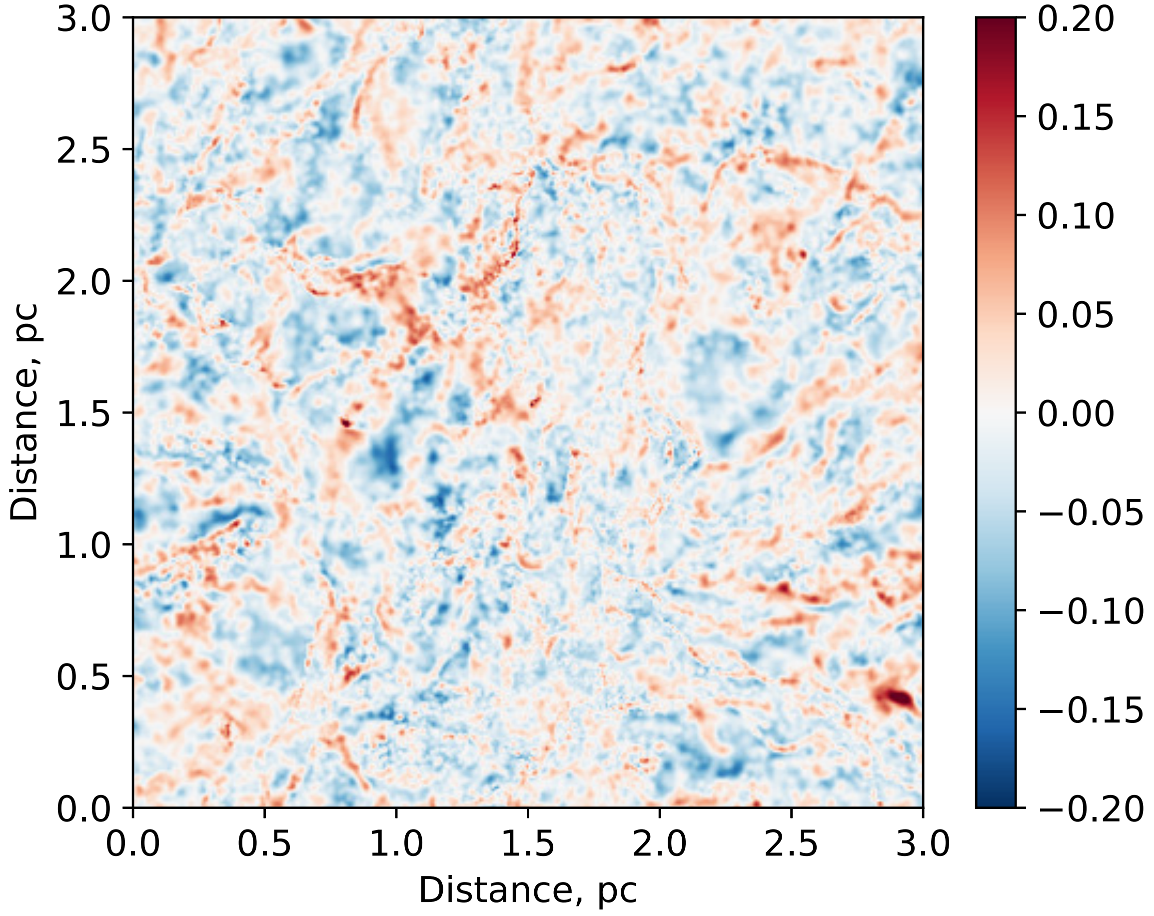
Decoupling of grains begins in the ISM!

(but no stars made of metal…)

DYNAMICAL SORTING OF GRAINS



Credit: Tom Maunder



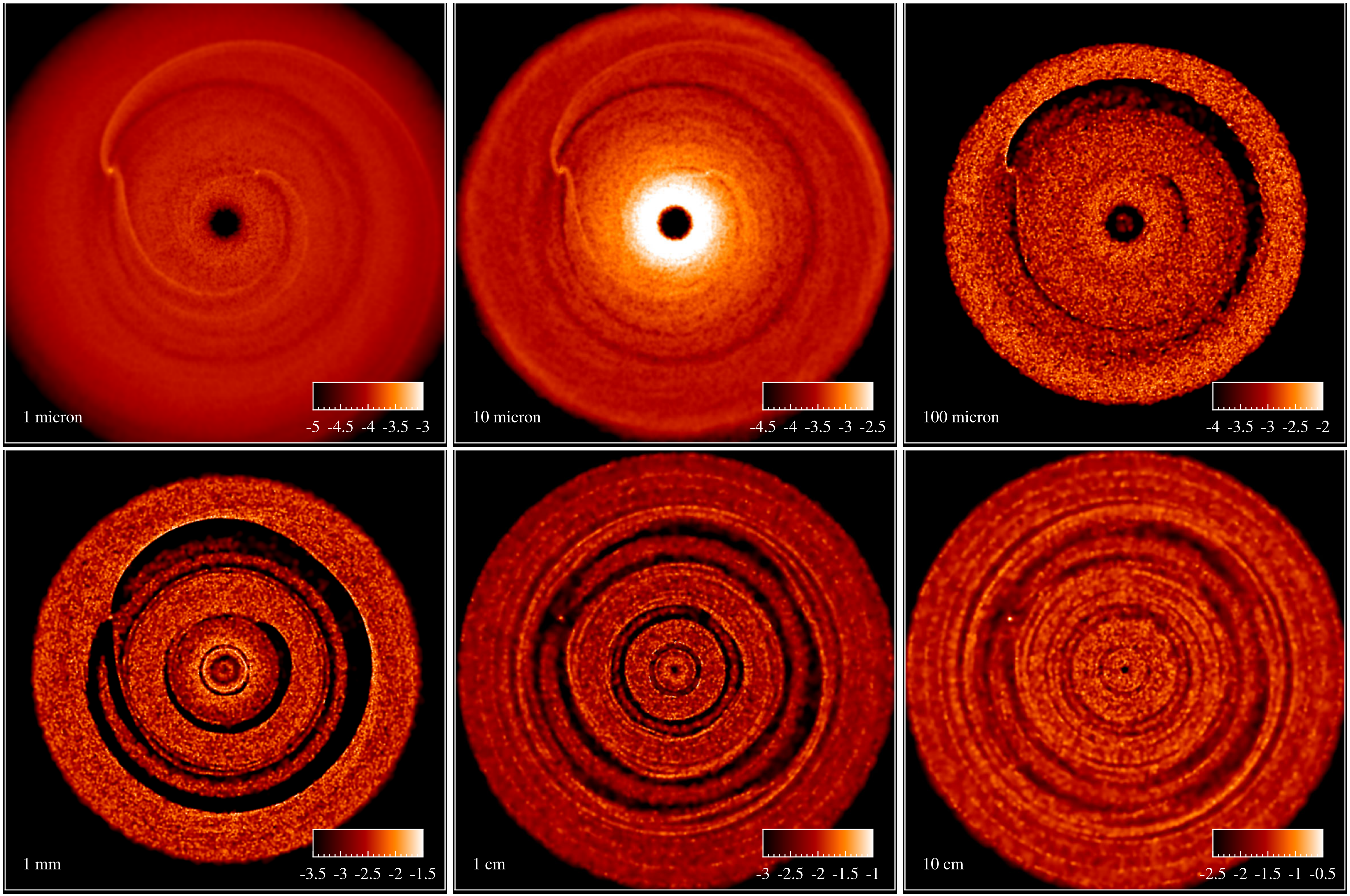
Change in power-law slope caused by dynamical sorting (from MRN)

Price, Laibe, Maunder, in prep.

DUST+GAS IN DISCS

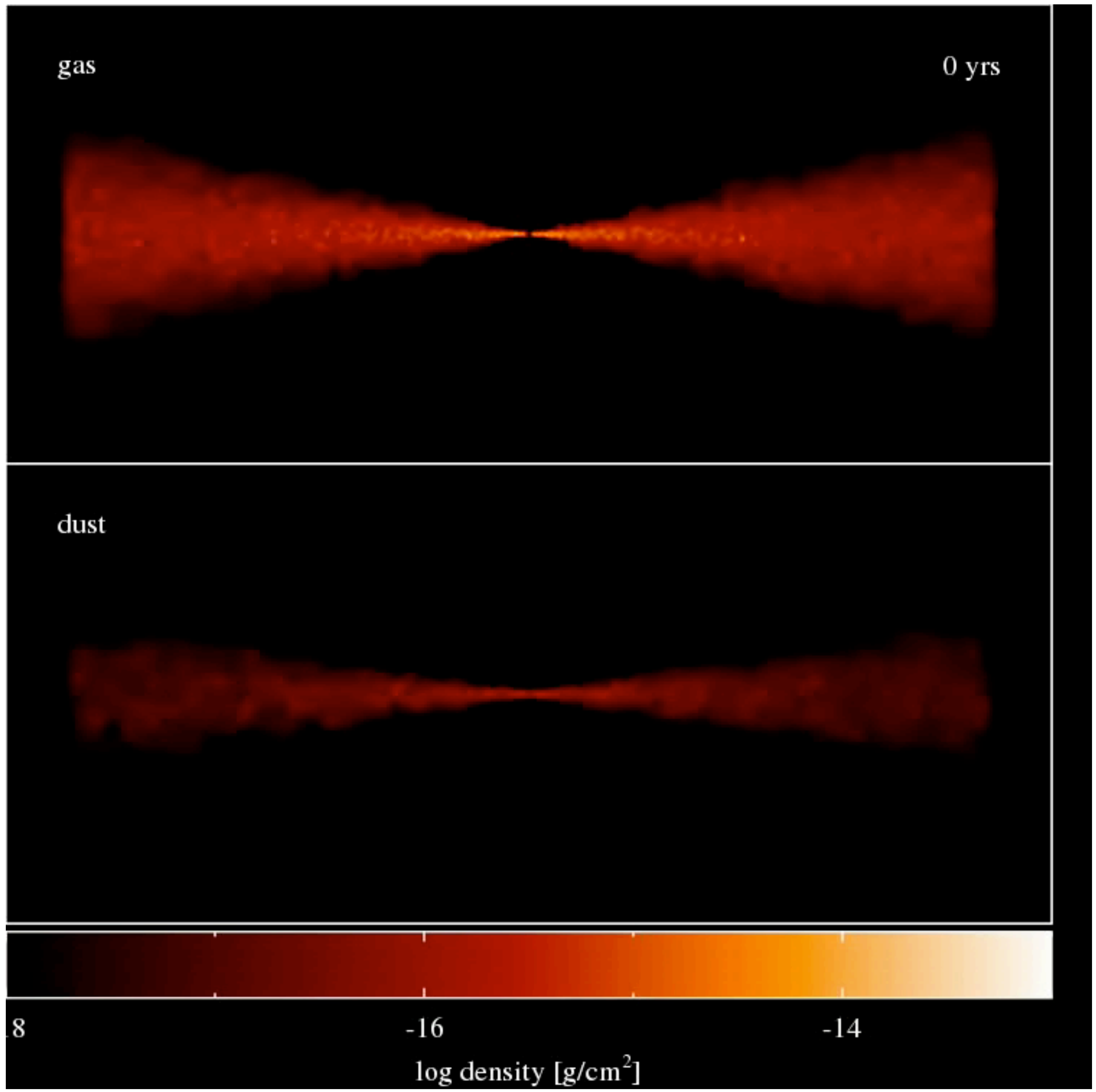
GAS VS DUST IN PROTOPLANETARY DISCS

GAS VS DUST IN PROTOPLANETARY DISCS



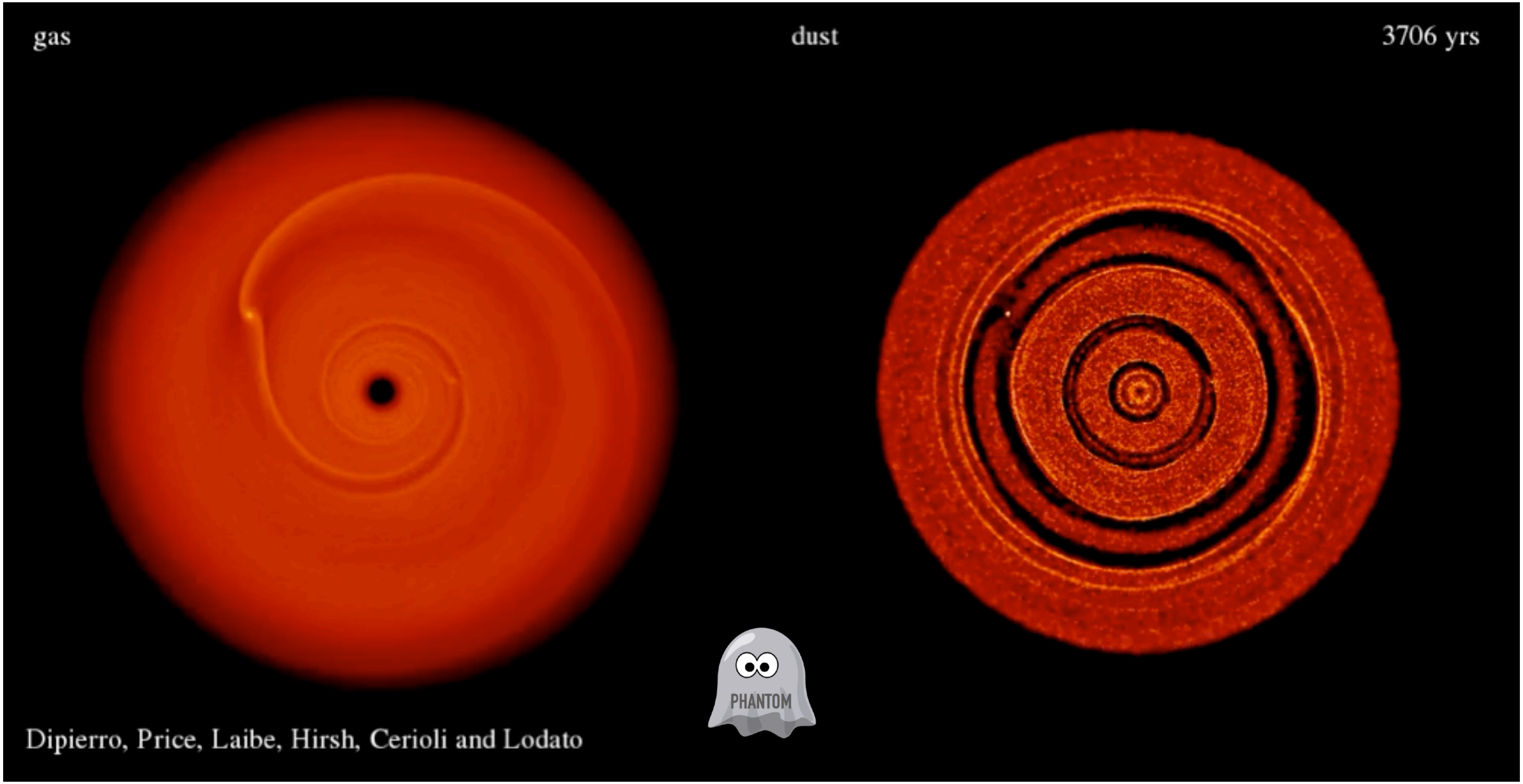
Dipierro et al. (2015)

GAS VS DUST IN PROTOPLANETARY DISCS



GAP CARVING: GAS VS DUST

Require 3 approximately Saturn mass planets

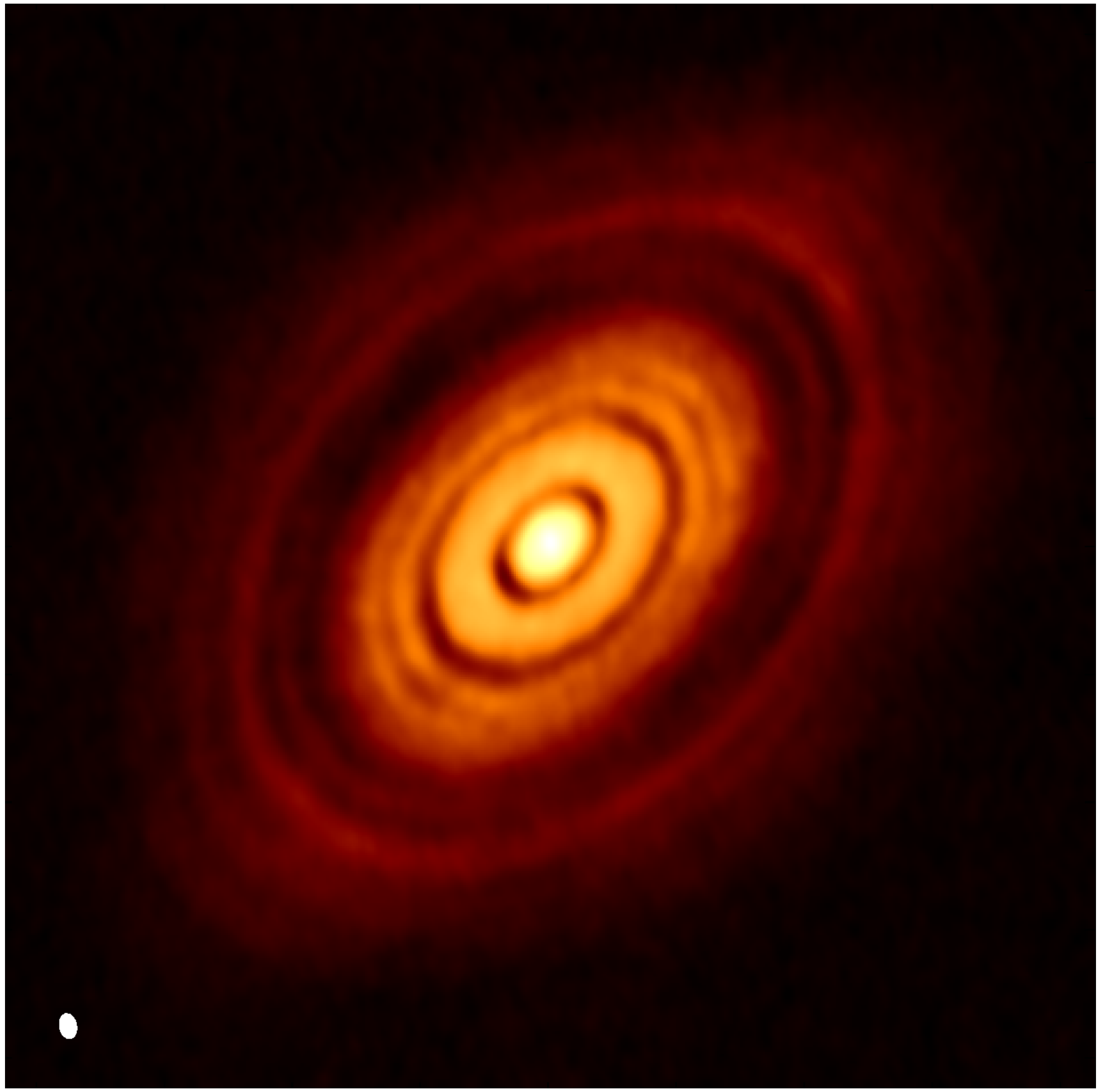


No gas gap, but sharp rings in dust!

Dipierro et al. (2015)

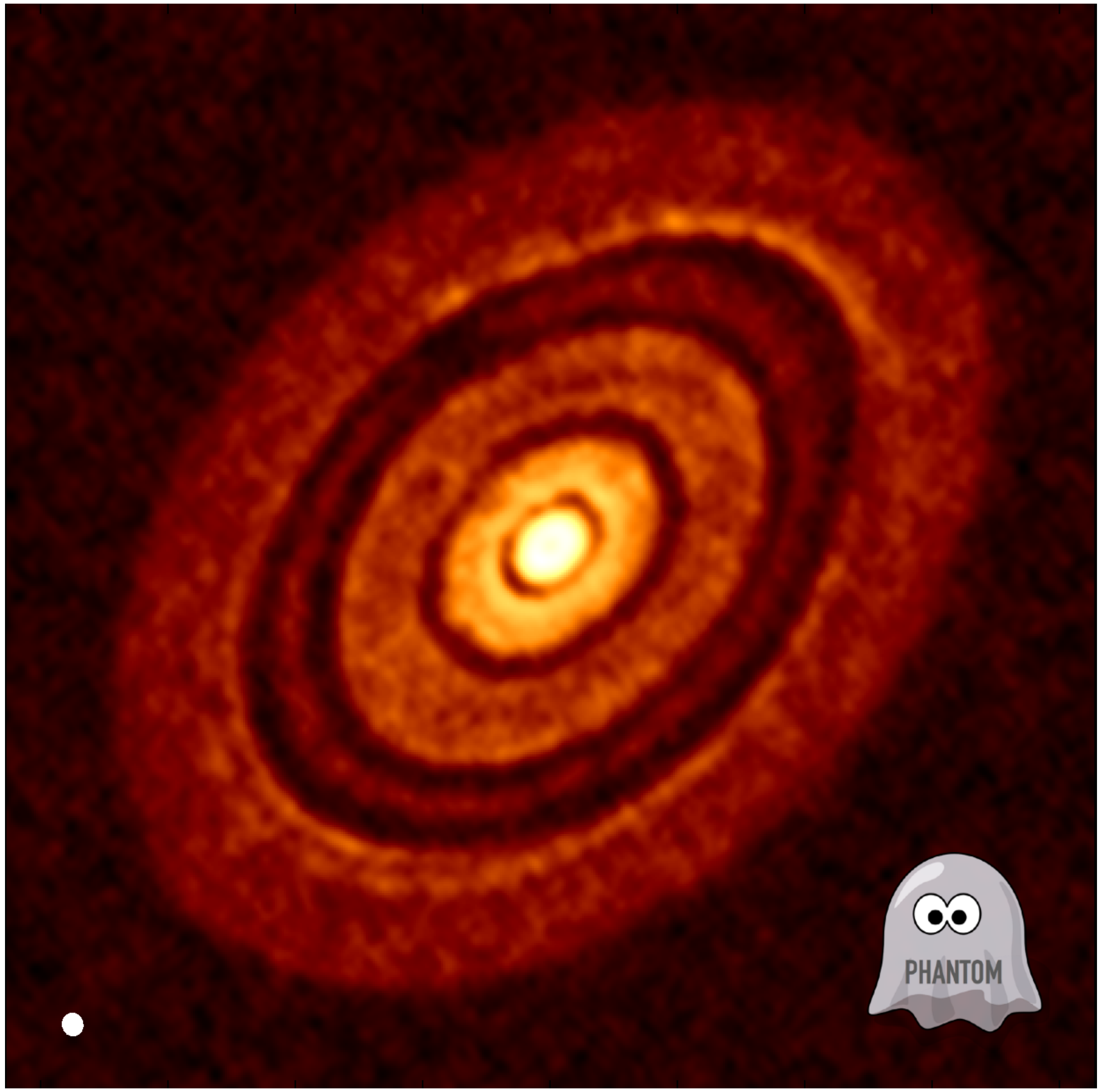
HL TAU: OBSERVATIONS MEET THEORY

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



Observed image

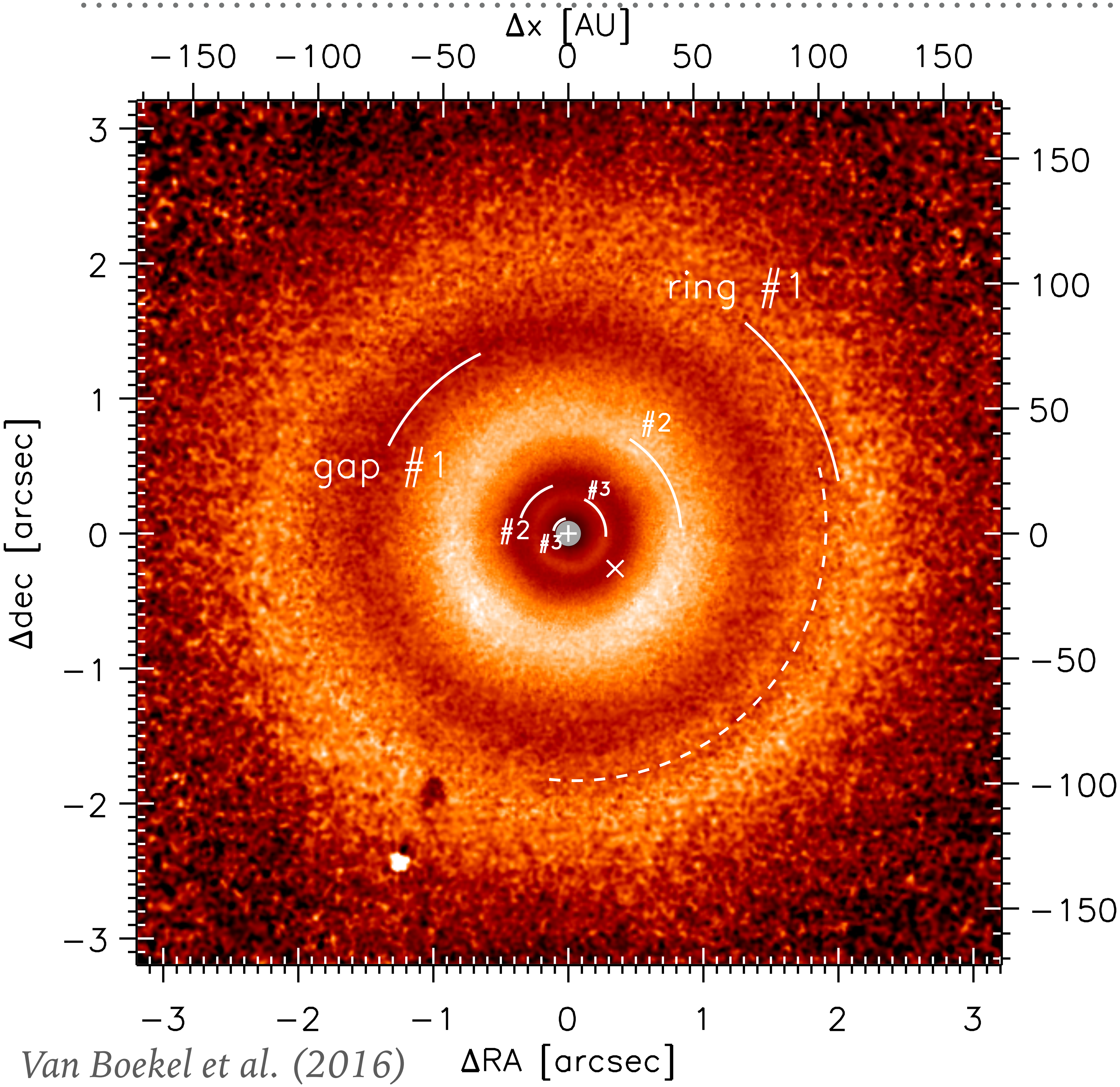
Credit: ALMA partnership et al. (2015)



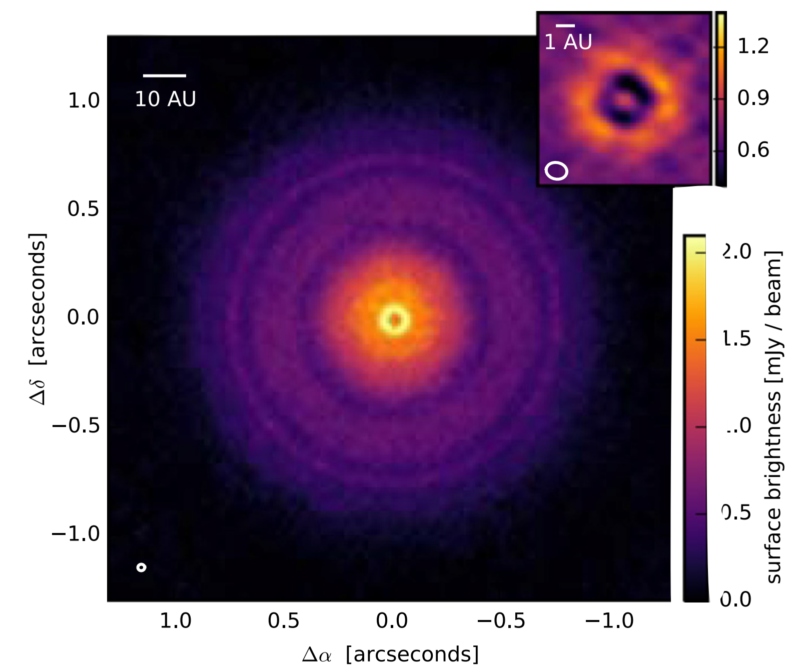
Our simulation

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

TW HYA: GAS VS DUST



Van Boekel et al. (2016)

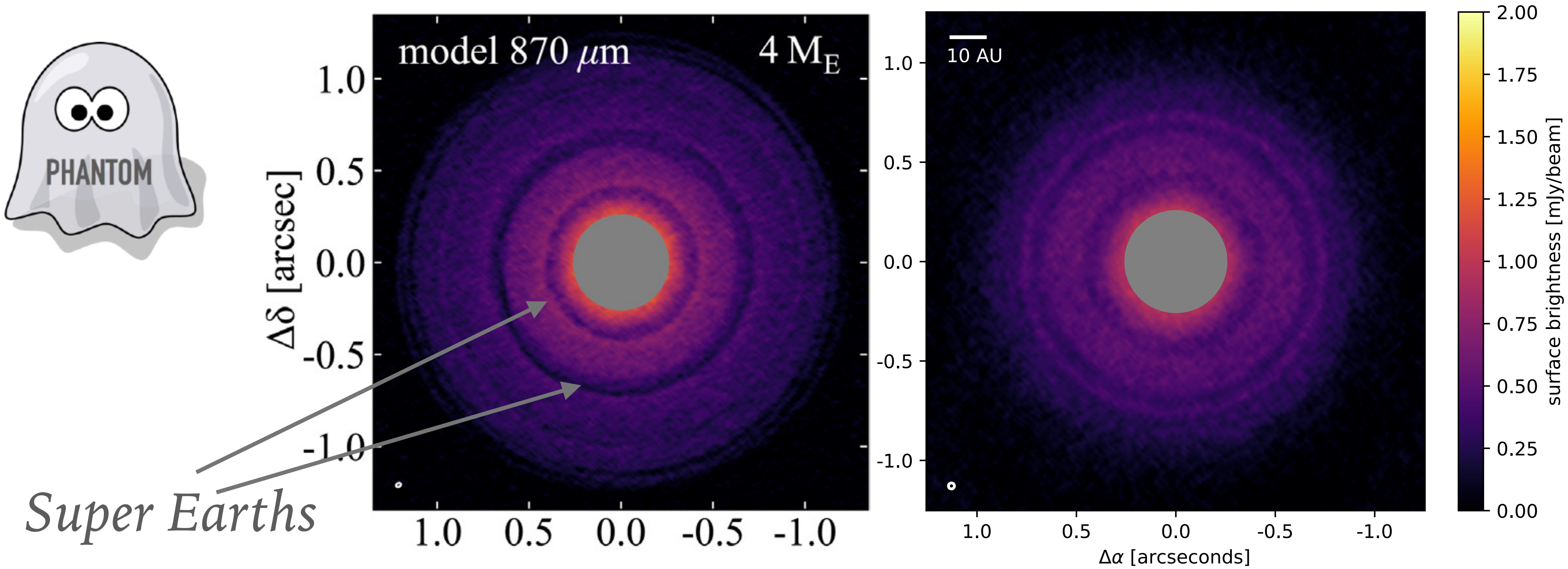


Andrews et al. (2016)

TW HYA: MODELS VS OBSERVATIONS

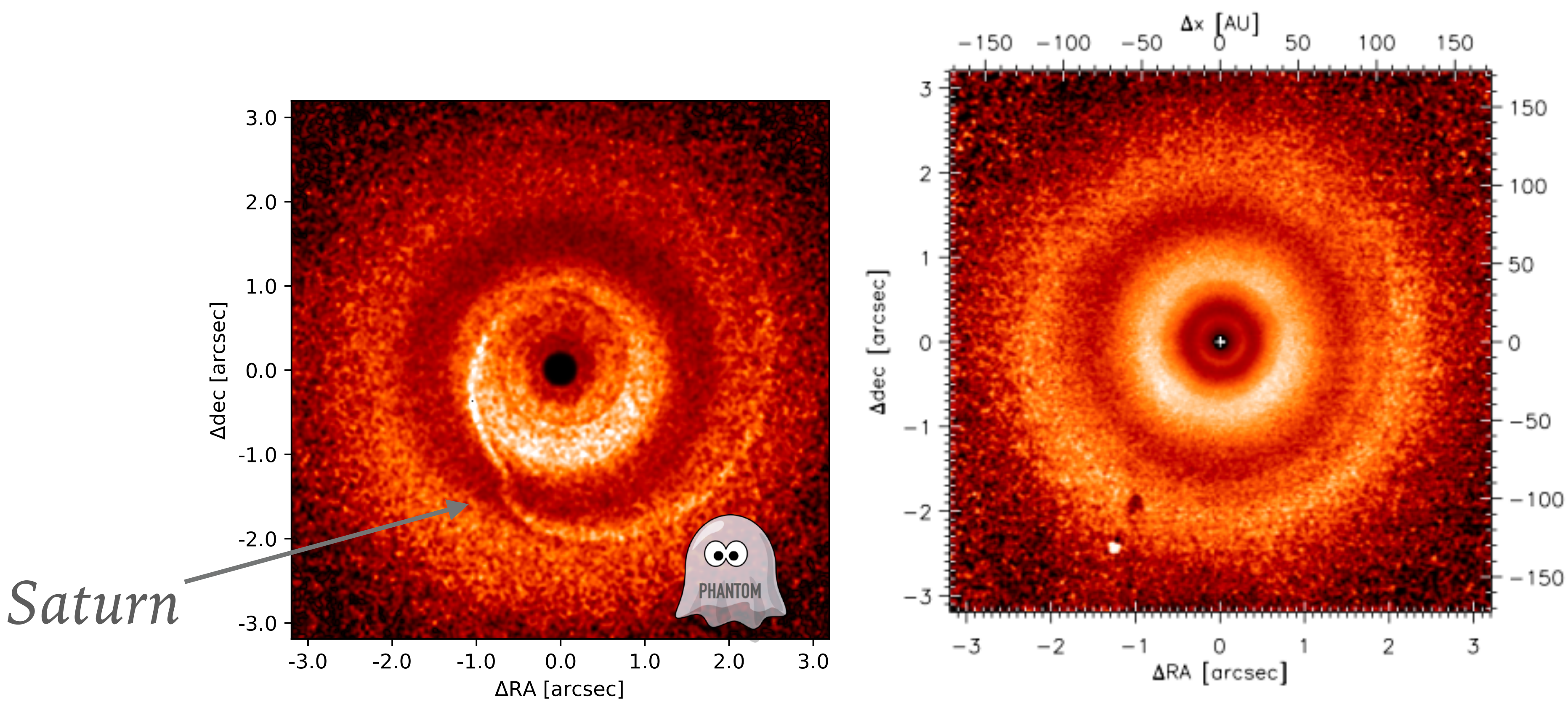
Mentiplay, Price & Pinte (2019)

Super-earths in TW Hya



Left: Our simulation

Right: Andrews et al. (2016)

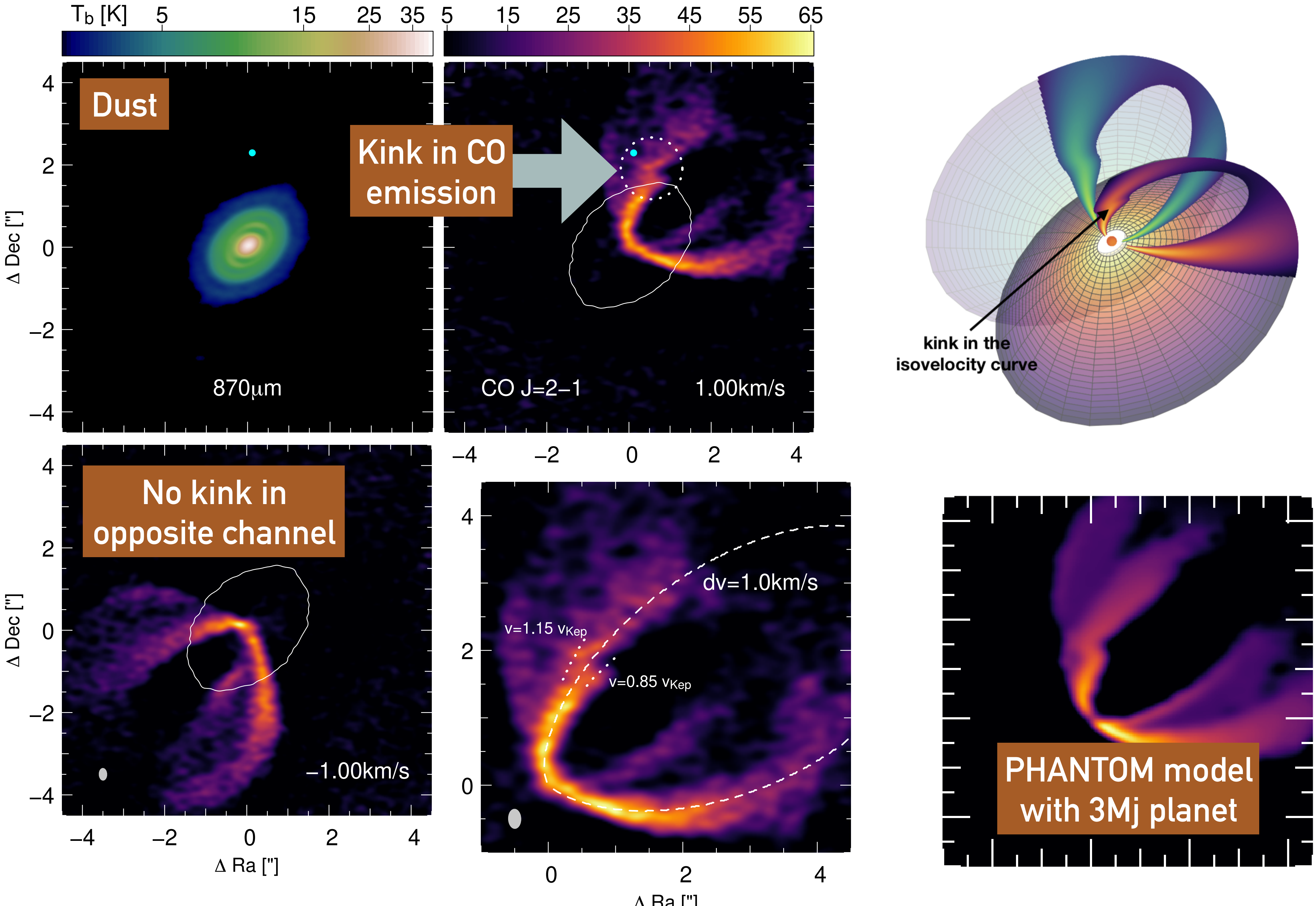


Left: Our simulation

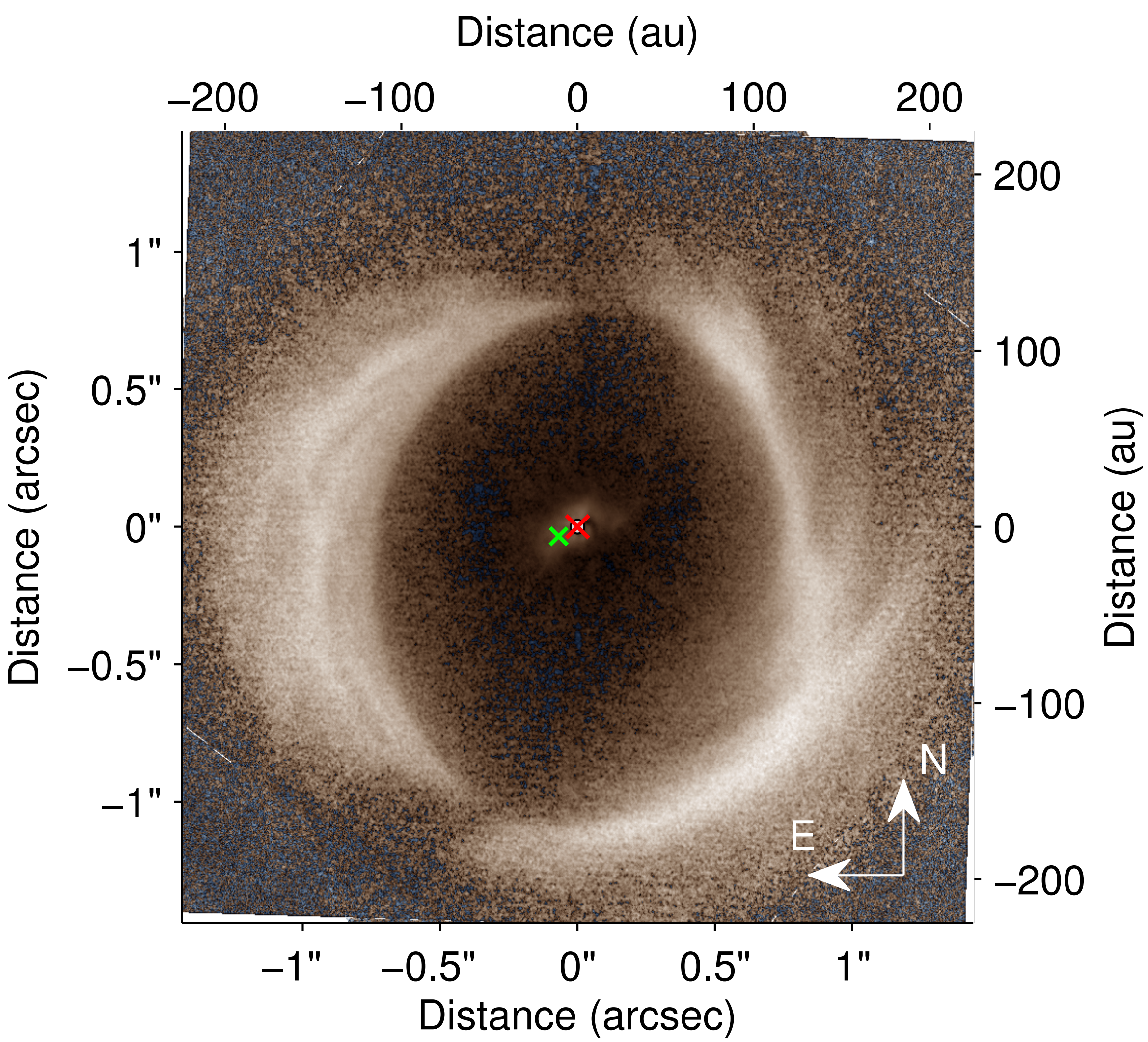
Right: Van Boekel et al. (2016)

KINEMATIC DETECTION OF A PROTOPLANET

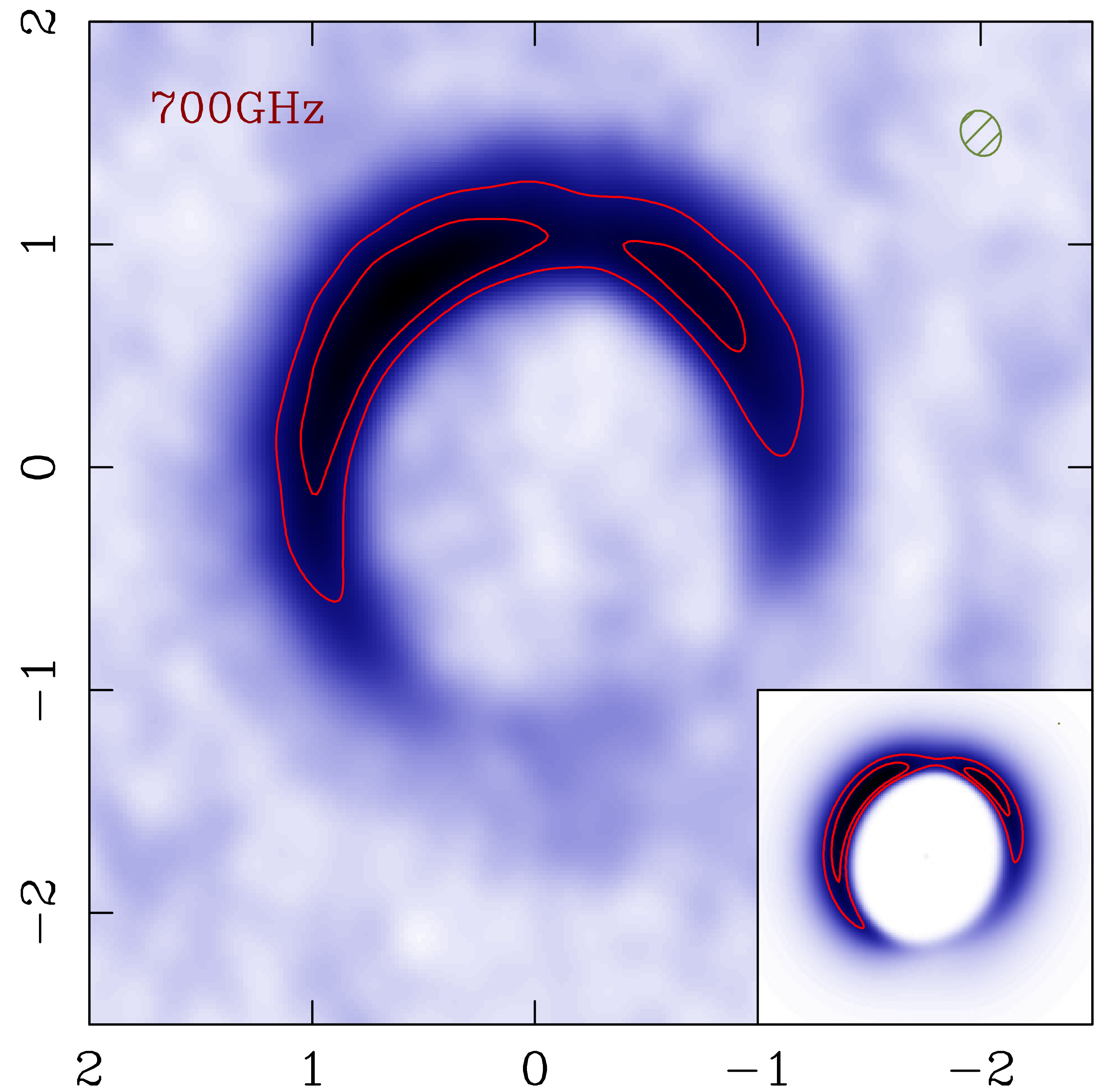
Pinte et al. (2018)



HD142527: GAS VS DUST



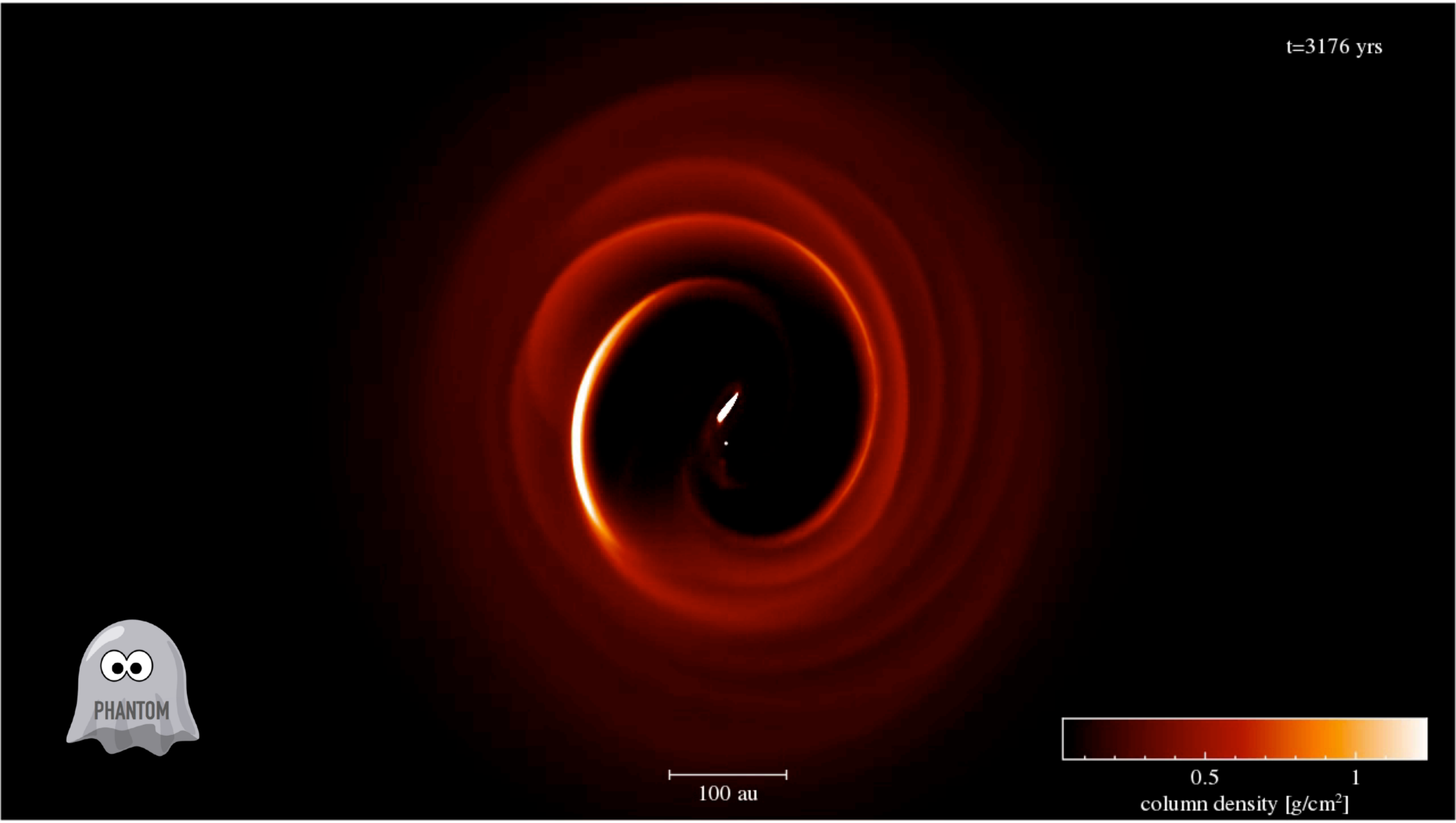
Avenhaus+(2017)



Casassus+(2015)

DISC-BINARY INTERACTION IN HD142527

Price et al. (2018)

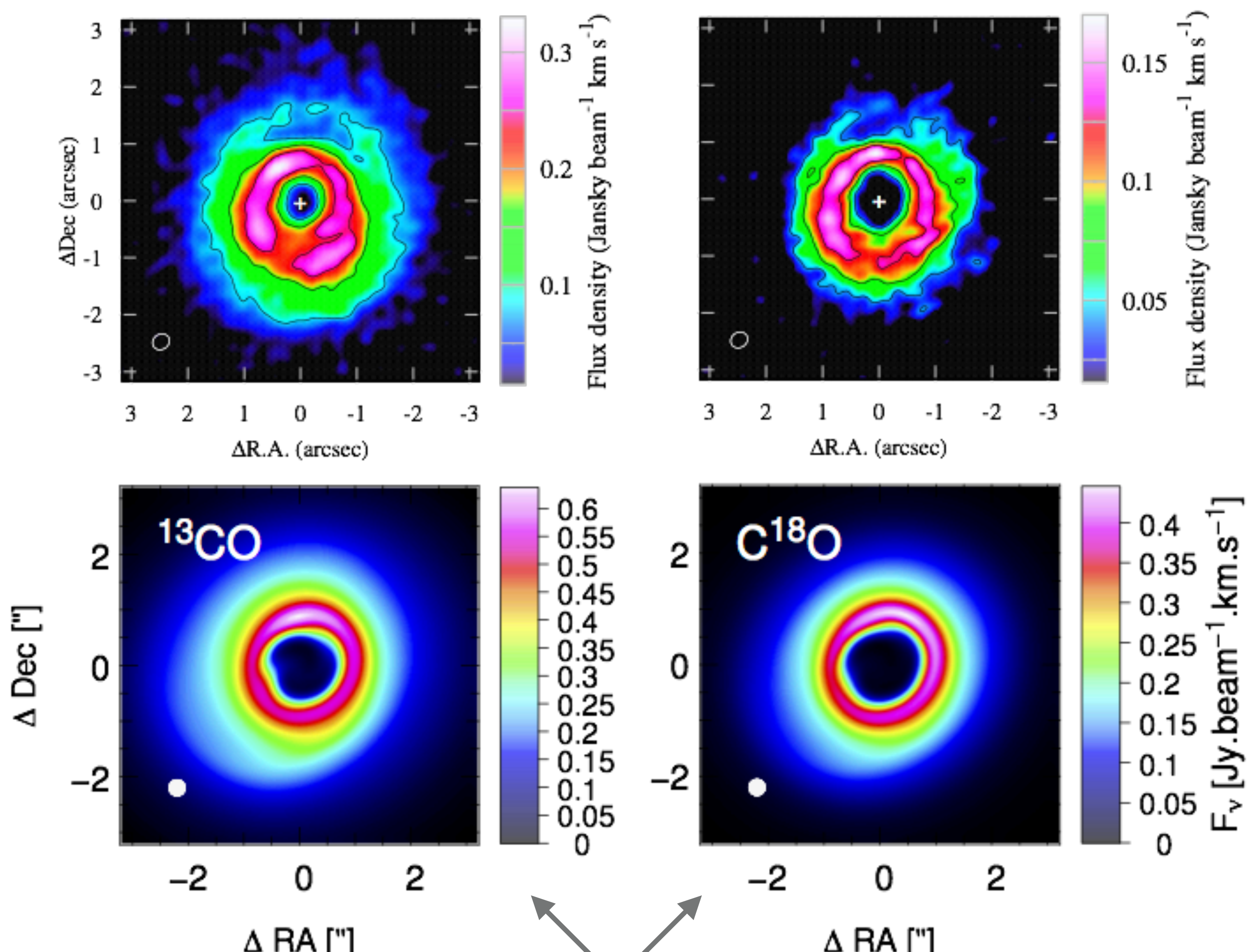


See almost polar alignment of binary to disc, c.f. Aly et al. (2015), Martin & Lubow (2017)

OBSERVATIONS VS MODELS USING MCFOST (PINTE+2006)

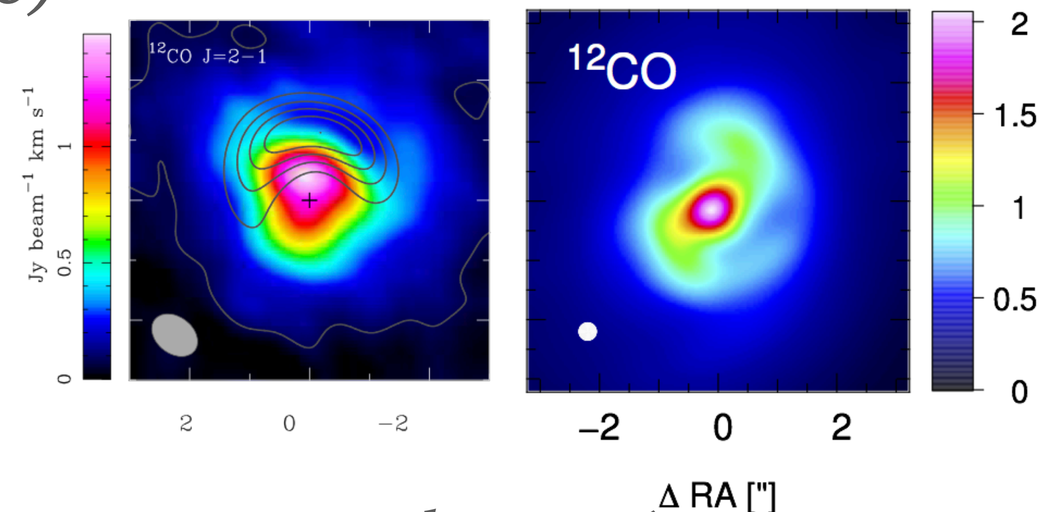
Price et al. (2018)

Observations

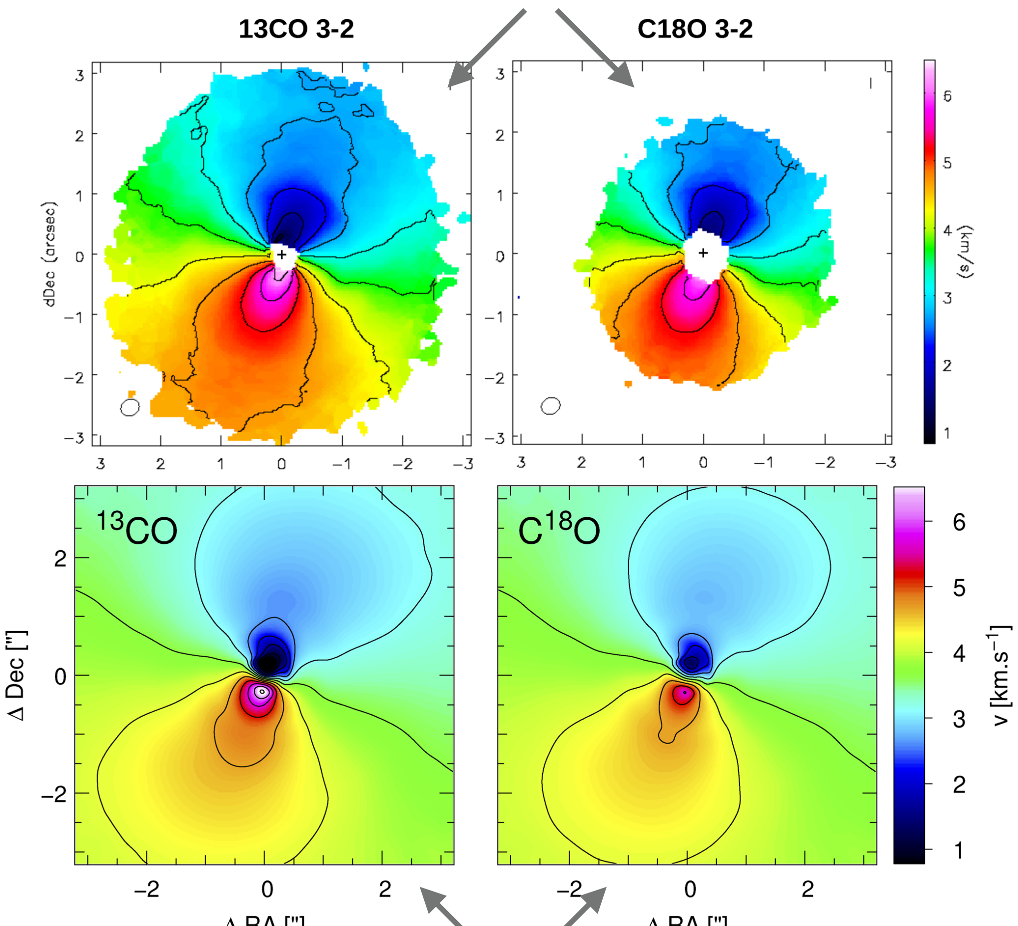


Simulations

Obs *Simulation*



Observations

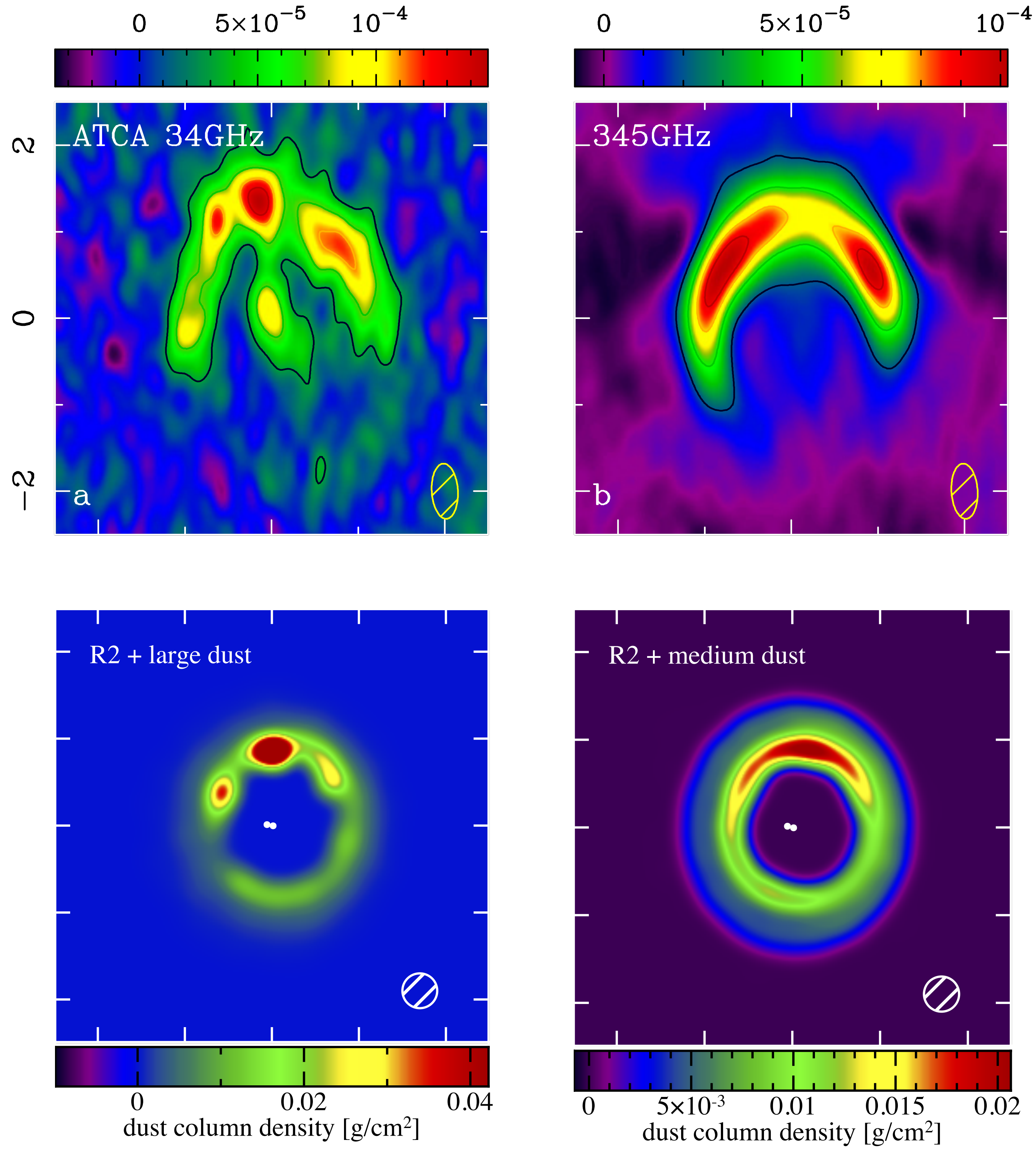


Simulations

Explains why inner holes are dust-free!

e.g. Dominik & Dullemond (2011)

DUST HORSESHOE: OBSERVATION VS MODELS



Observations

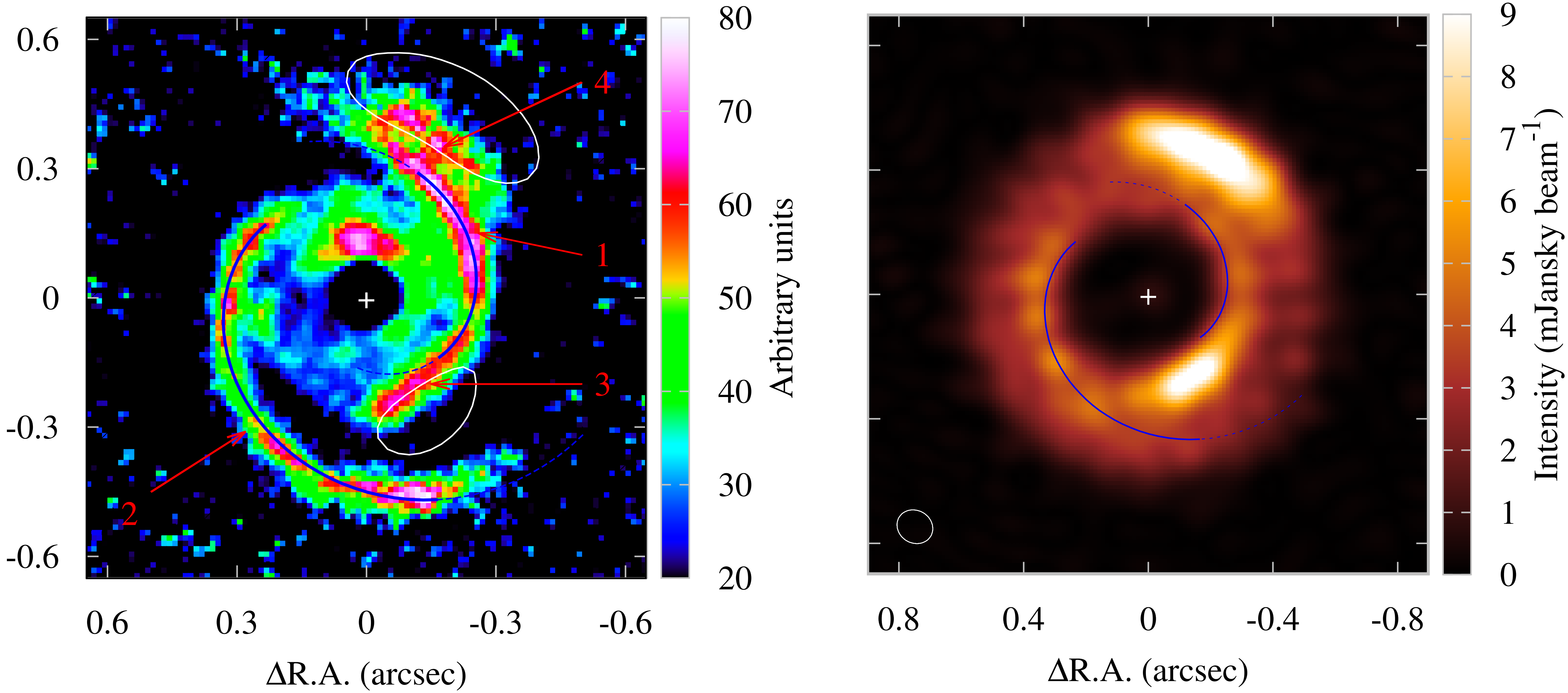
Casassus et al. (2015)

Simulations

Price et al. (2018)

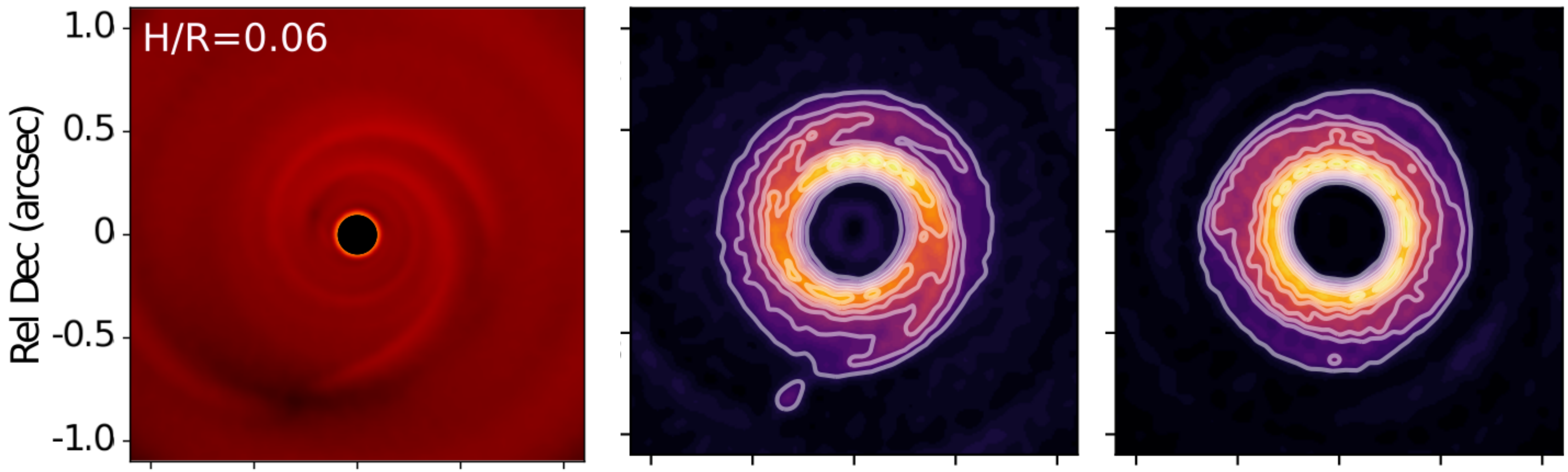
MWC758: GAS VS DUST

Boehler+(2018)



GAS VS DUST AROUND PLANET-CARVED CAVITY

Increasing Stokes number →



Spirals become rings as Stokes number approaches unity

Can use as proxy for the gas disc mass

Explains morphology difference in MWC758

Veronesi+2019, submitted

CONCLUSIONS

THE COSMIC DUST (R)EVOLUTION

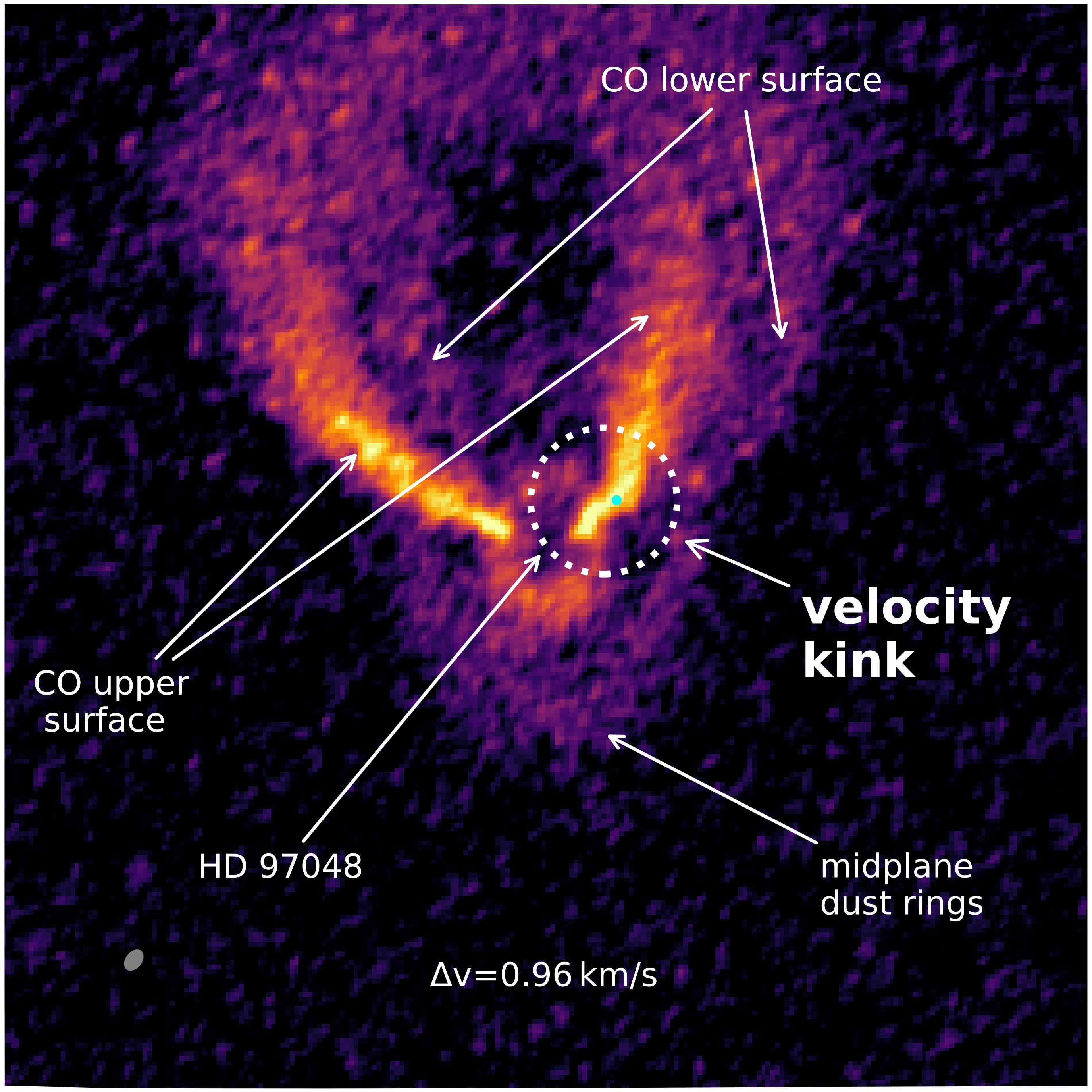
- Gas and dust already start to decouple in the ISM
- Dust and gas are DECOUPLED in protoplanetary discs - doing completely different things
- Planet formation is well underway (maybe even finished) by the time we observe protoplanetary discs

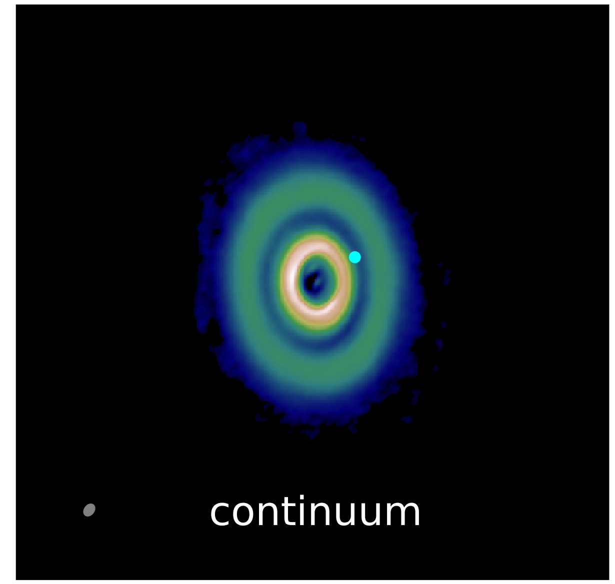
DUST BUSTERS

PS: Thanks to the EU for funding the Dustbusters RISE network!

SECOND ALMA PROTOPLANET DETECTION!!

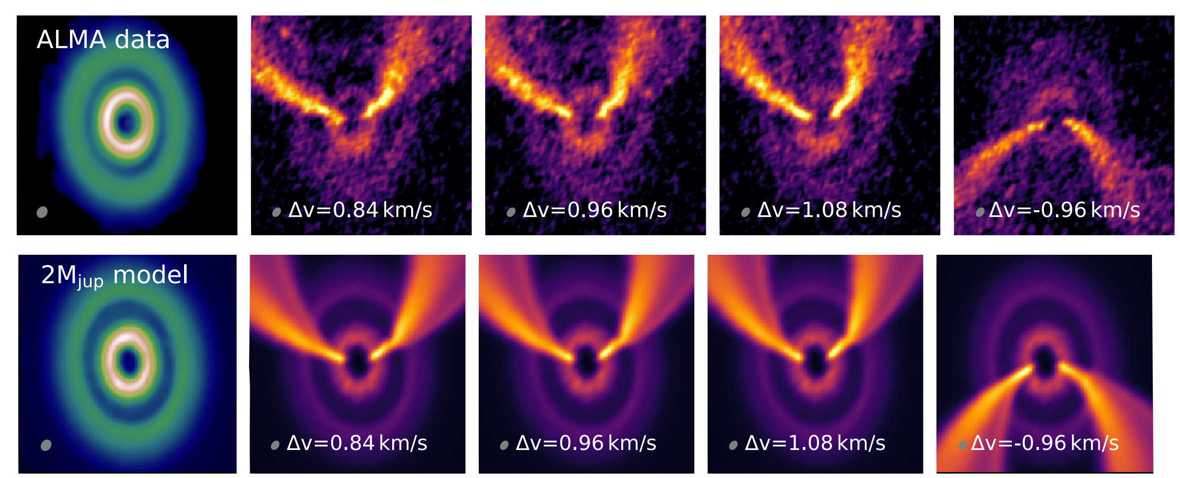
Pinte et al. (2019)





Pinte et al. (2019)

howmanyplanetshaschristophefound.com



2-3 MJup PLANET CARVING A GAP AT 130AU!