Living the Phantom Dream

Simulating Protoplanetary Disks, Protoplanets, and Beyond

Claudia Toci

ESO Fellow

7th Phantom workshop, 2nd European Phantom code family user workshop Grenoble, 2-5 Jun 2025

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The importance of working in a community

Daniel Price, 02.06.2025

Legacy

What is a legacy?

It's planting seeds in a garden you never get to see.

Lin Manuel Miranda, Hamilton

The importance of working in a community

Daniel Price, 02.06.2025

40 minutes with Claudia

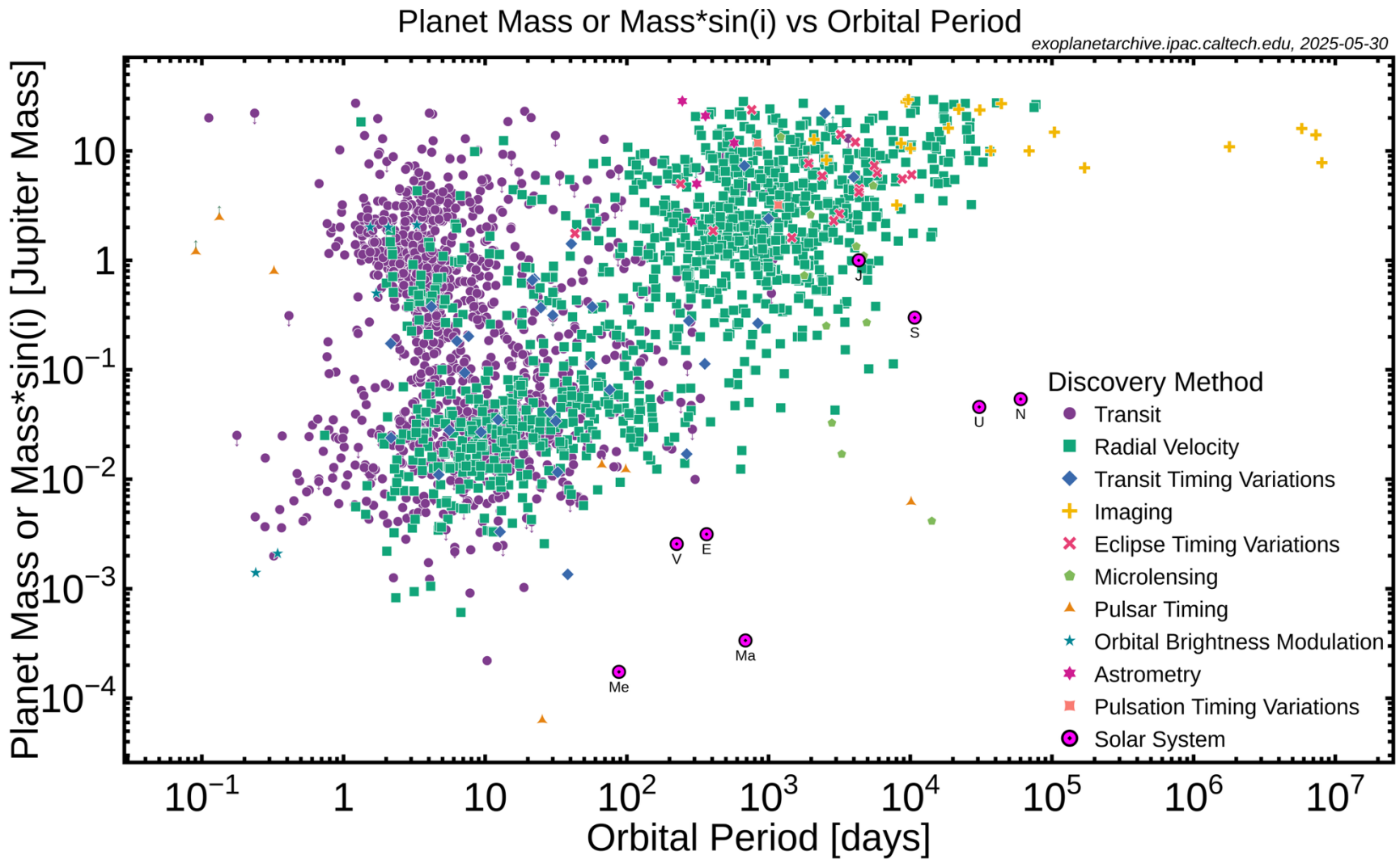
A bit of context

- Exoplanets: the final products
- Substructures in discs
- Protoplanets/binaries in discs

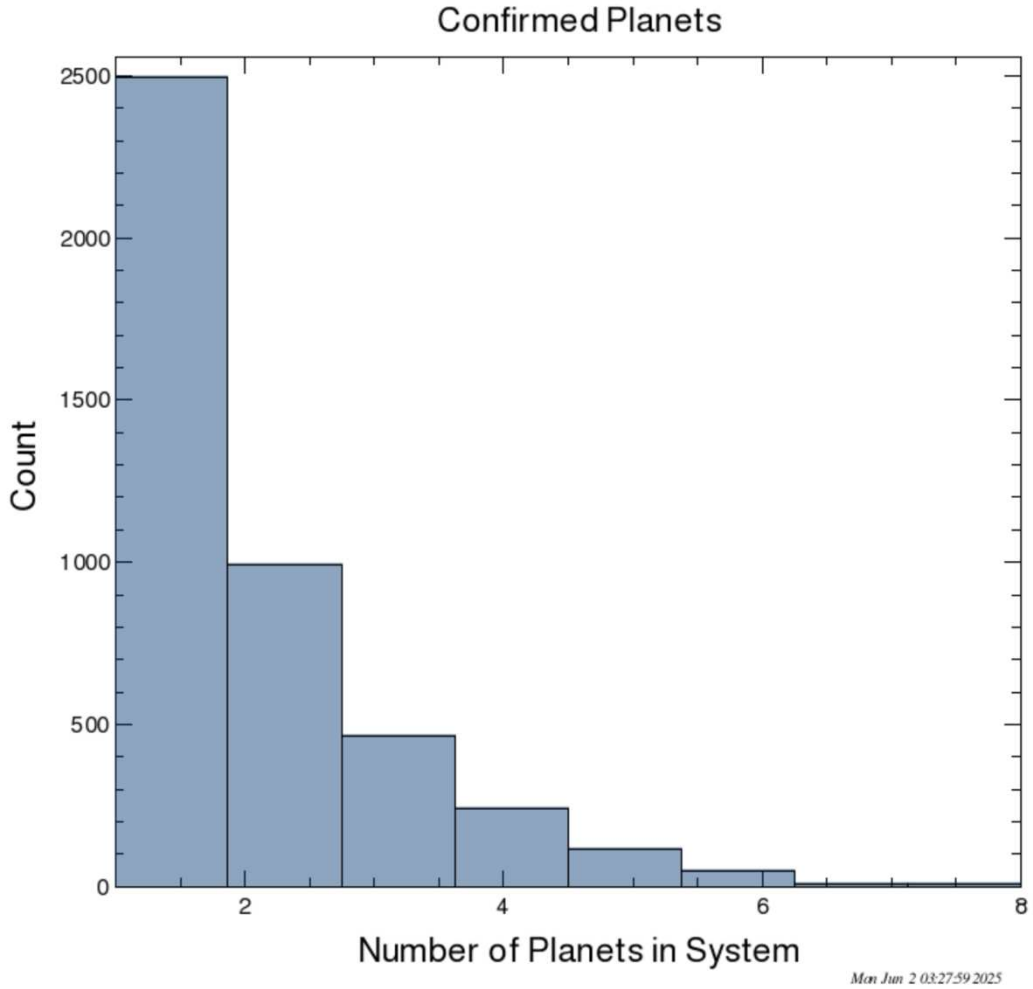
Living the Phantom dream

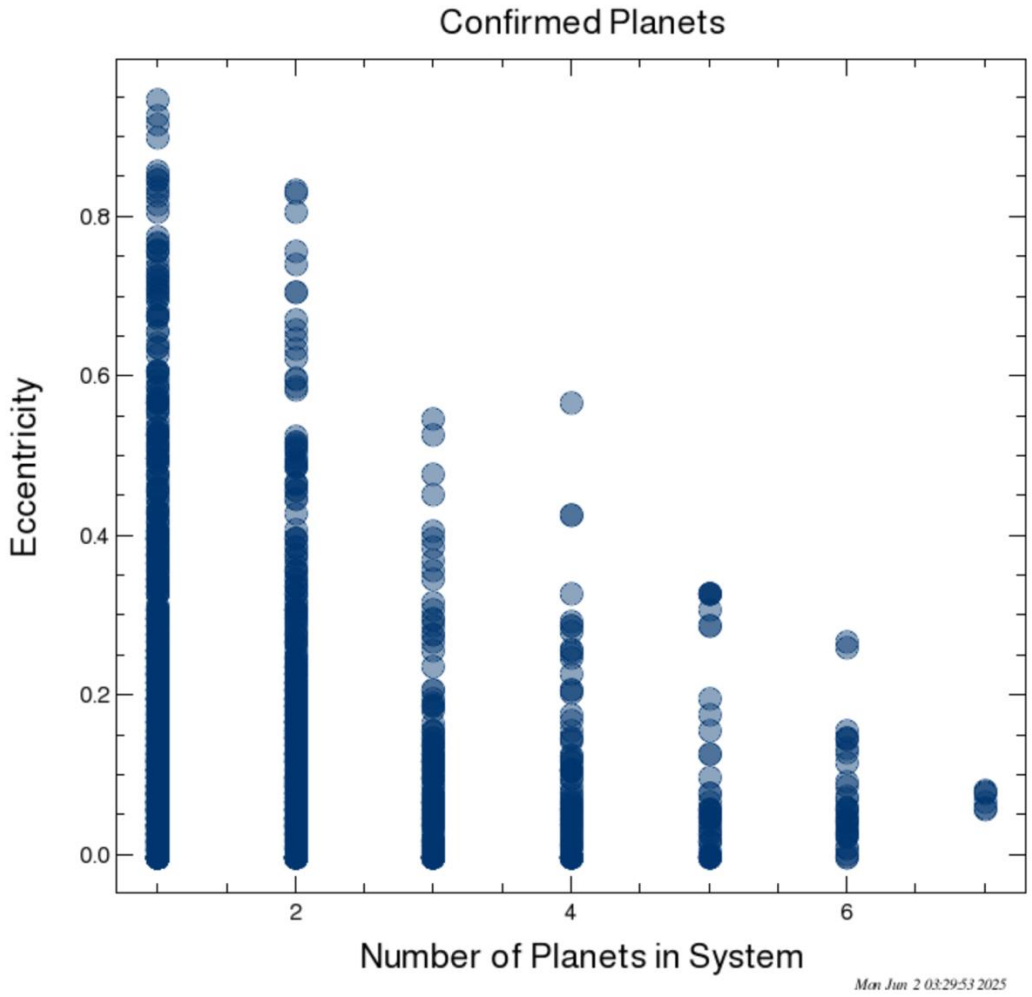
- Two planets, two rings
- Two planets, one ring (and one planet too!)
- Two (or more) stars, one ring
- To ELT (2029) and beyond!

The end of the (planet and star formation) journey



The end of the (planet and star formation) journey



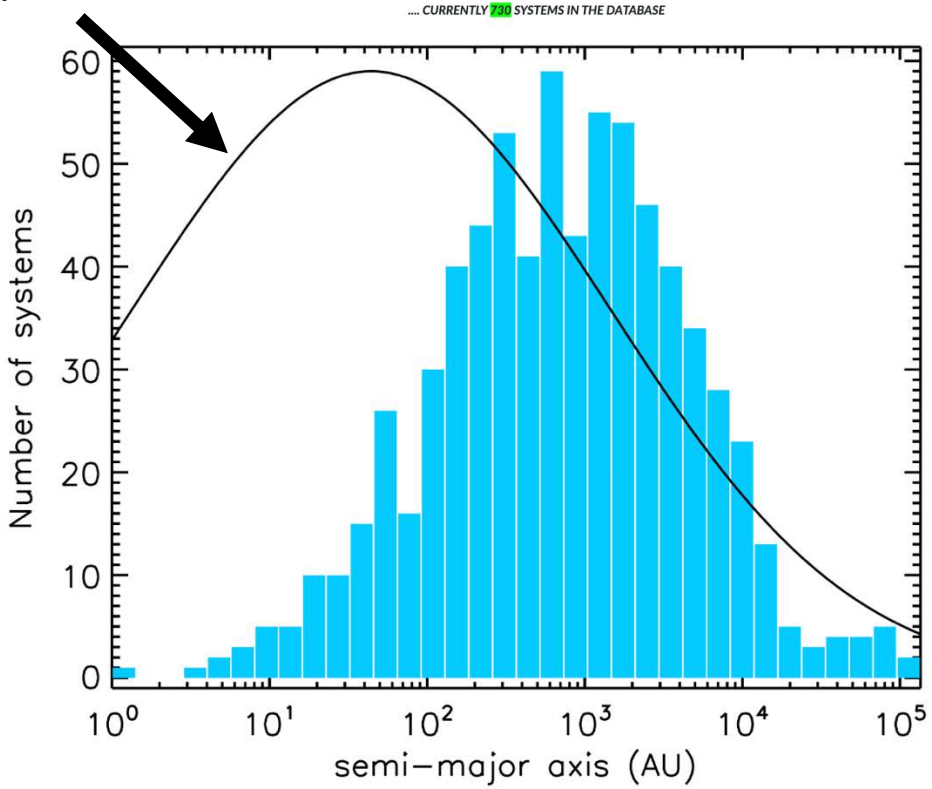


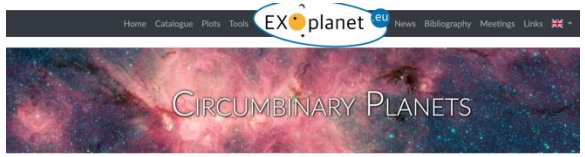
The end of the (planet and star formation) journey

Binary distribution

(This Page is for Planets on S-type orbits that orbit one of the stars. For Circumbinary Planets, click here)

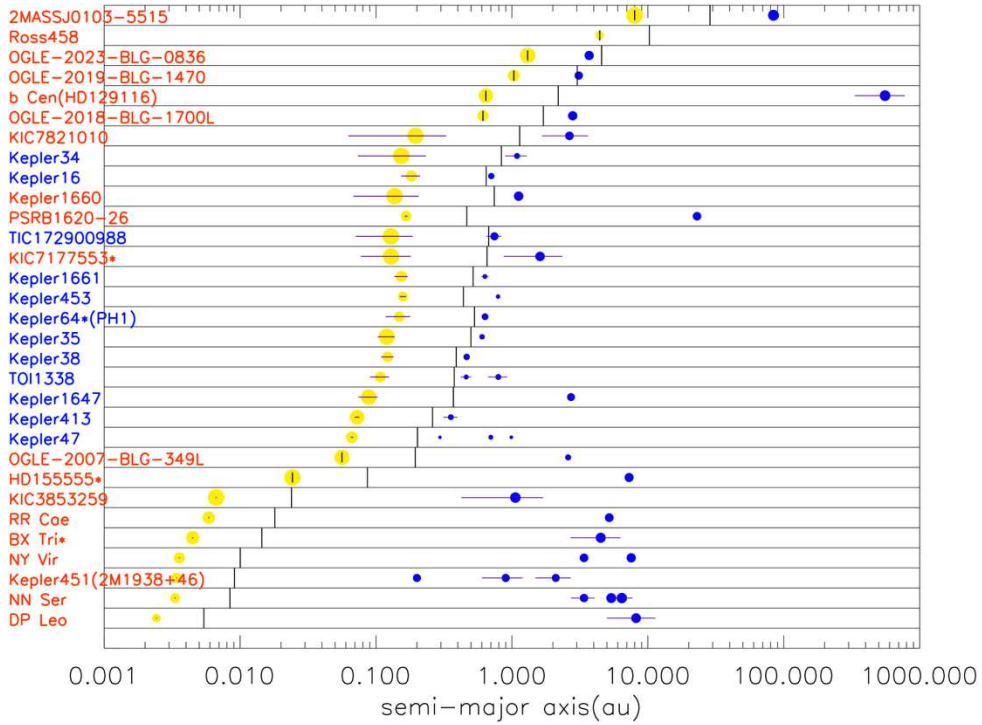
.... currently 730 systems in the database



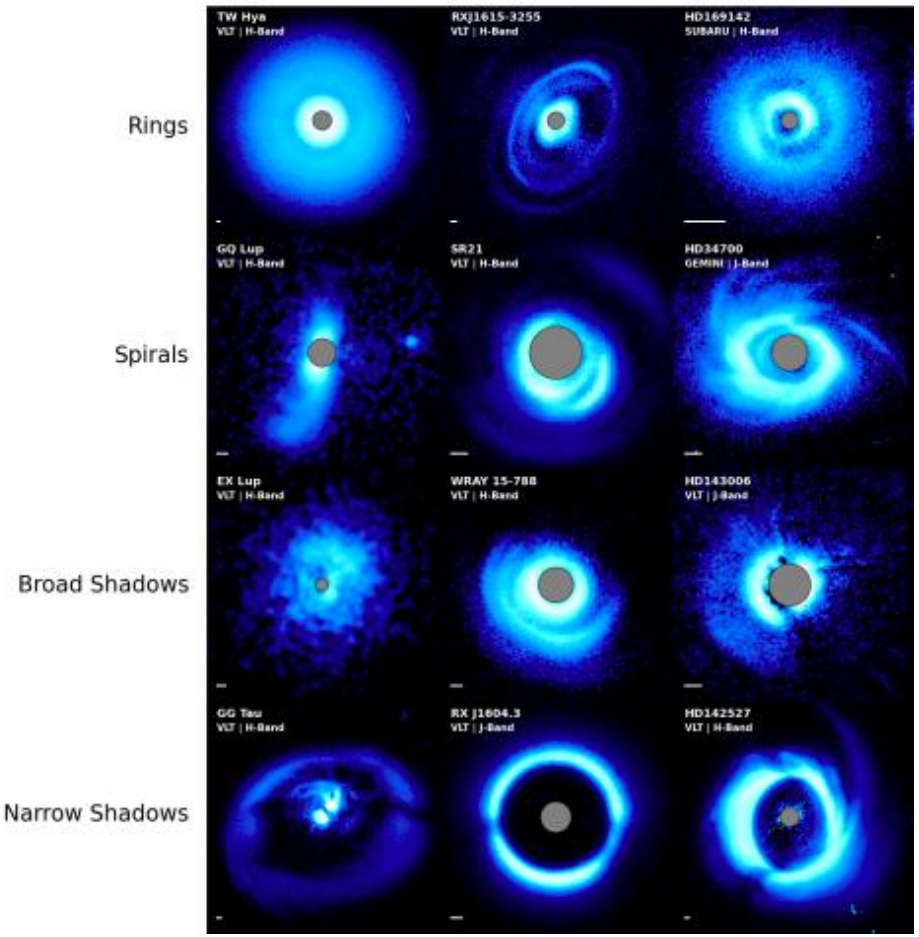


(This Page is for Planets on P-type orbits that orbit both stars. For planets on S-type orbits, click here)

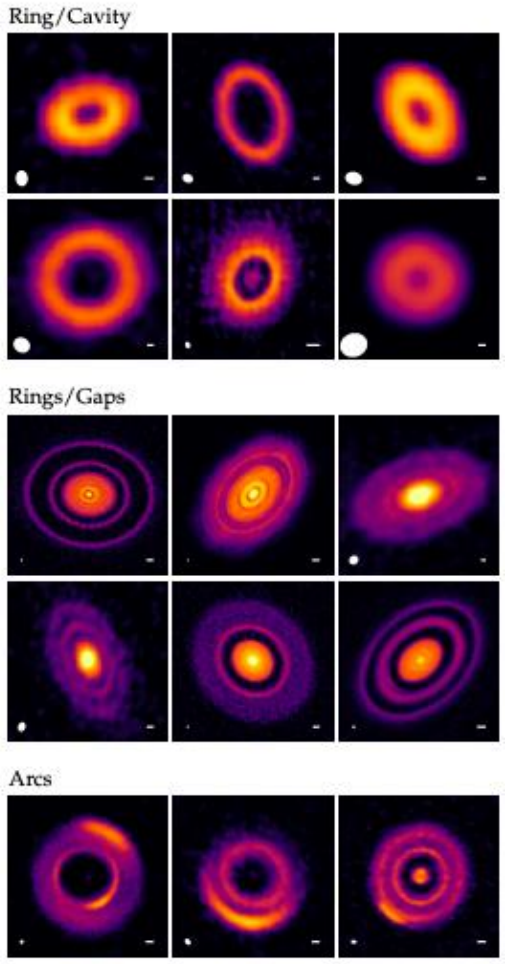
.... currently 31 systems in the database



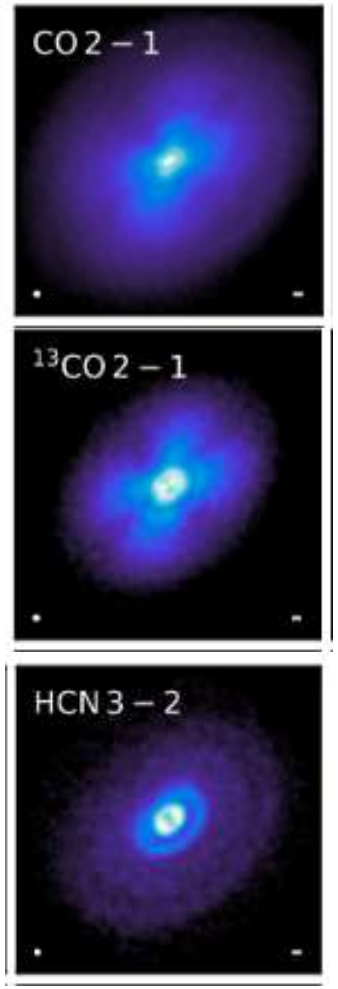
(More than) Ten years of discoveries



Benisty et al. 2022



Andrews 2020



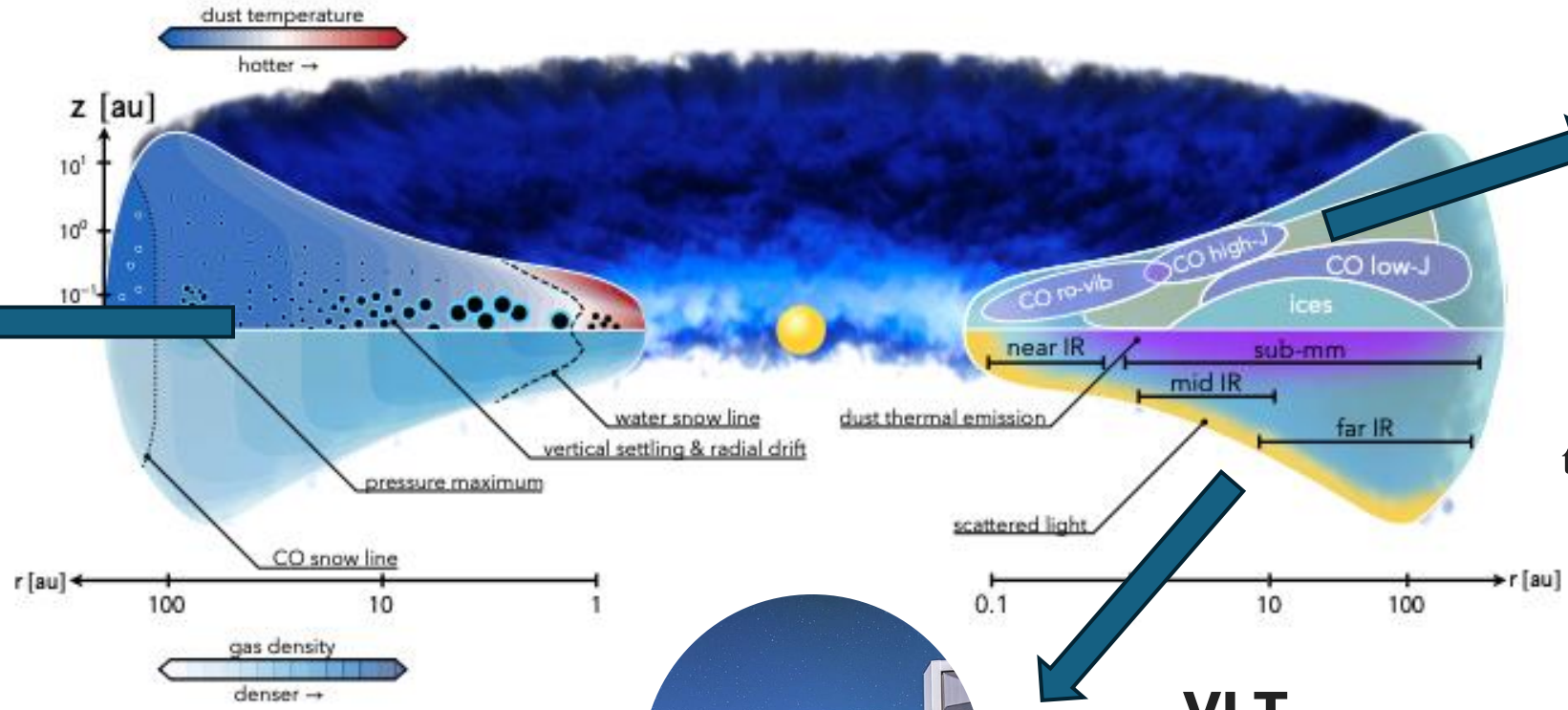
MAPS collab.

Substructures are commonly revealed using different tracers in several (large) sources

(ALMA partnership 14, Andrews et al. 18, Francis&van der Marel 21, Zhang et al. 23, +…)

Zooming into protoplanetary discs

ESO



ALMA

interferometer

thermal and line emission

millimetric

ESO

VLT

SPHERE

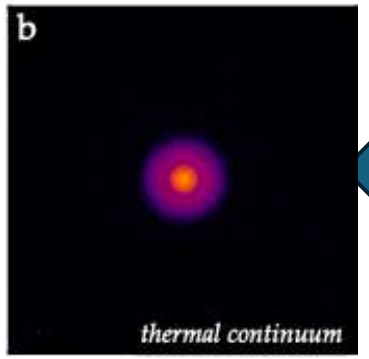
scattered light emission

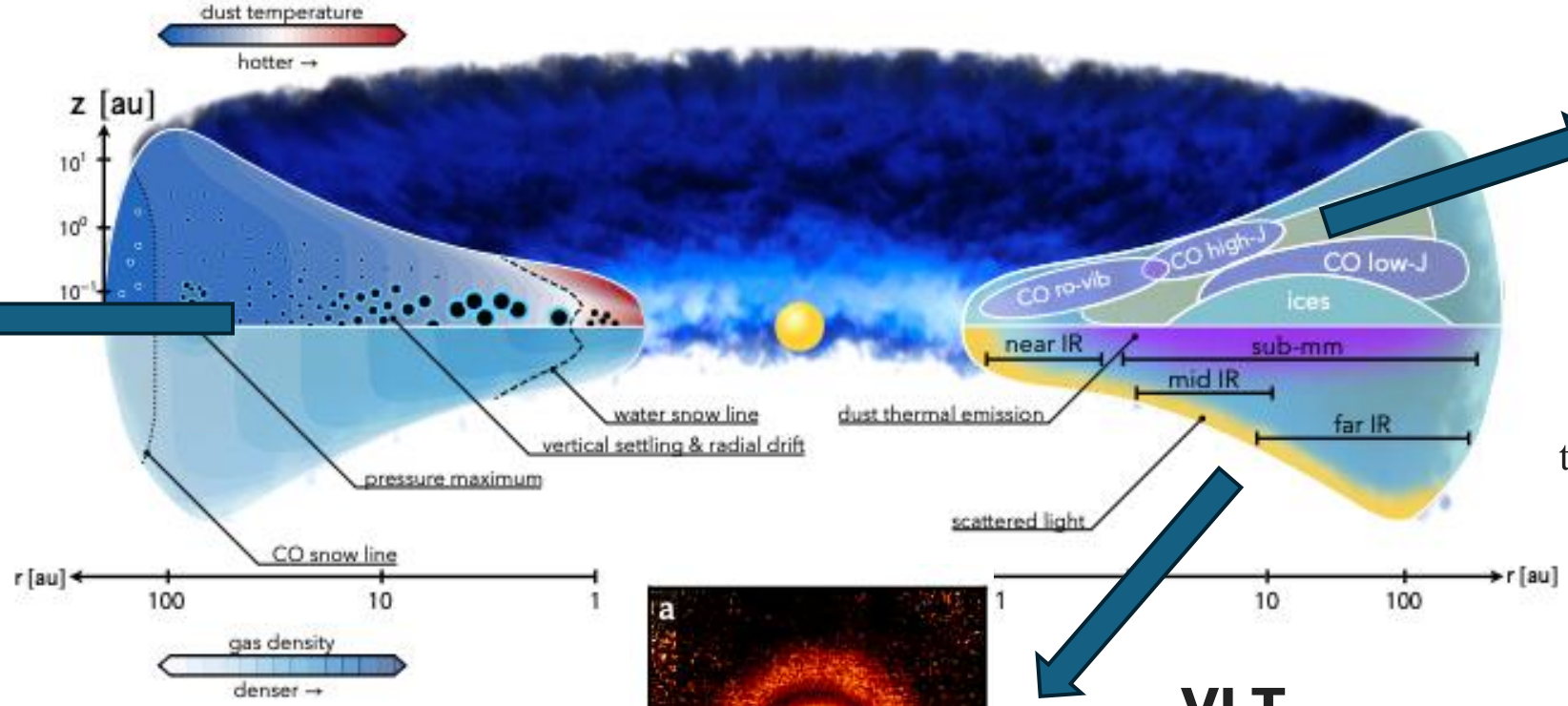
1-2 micron

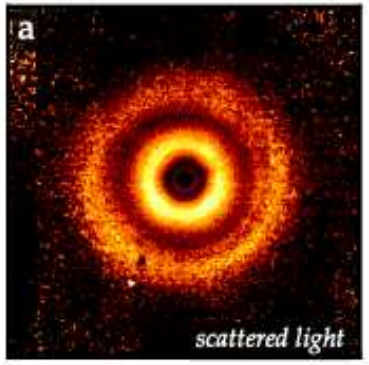
Adapted from Miotello et al., PPVII

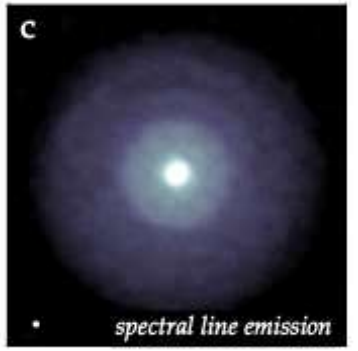
Zooming into protoplanetary discs

ESO









ALMA

interferometer

thermal and line emission

millimetric

VLT

SPHERE

scattered light emission

1-2 micron

Adapted from Miotello et al., PPVII

Andrews 2020

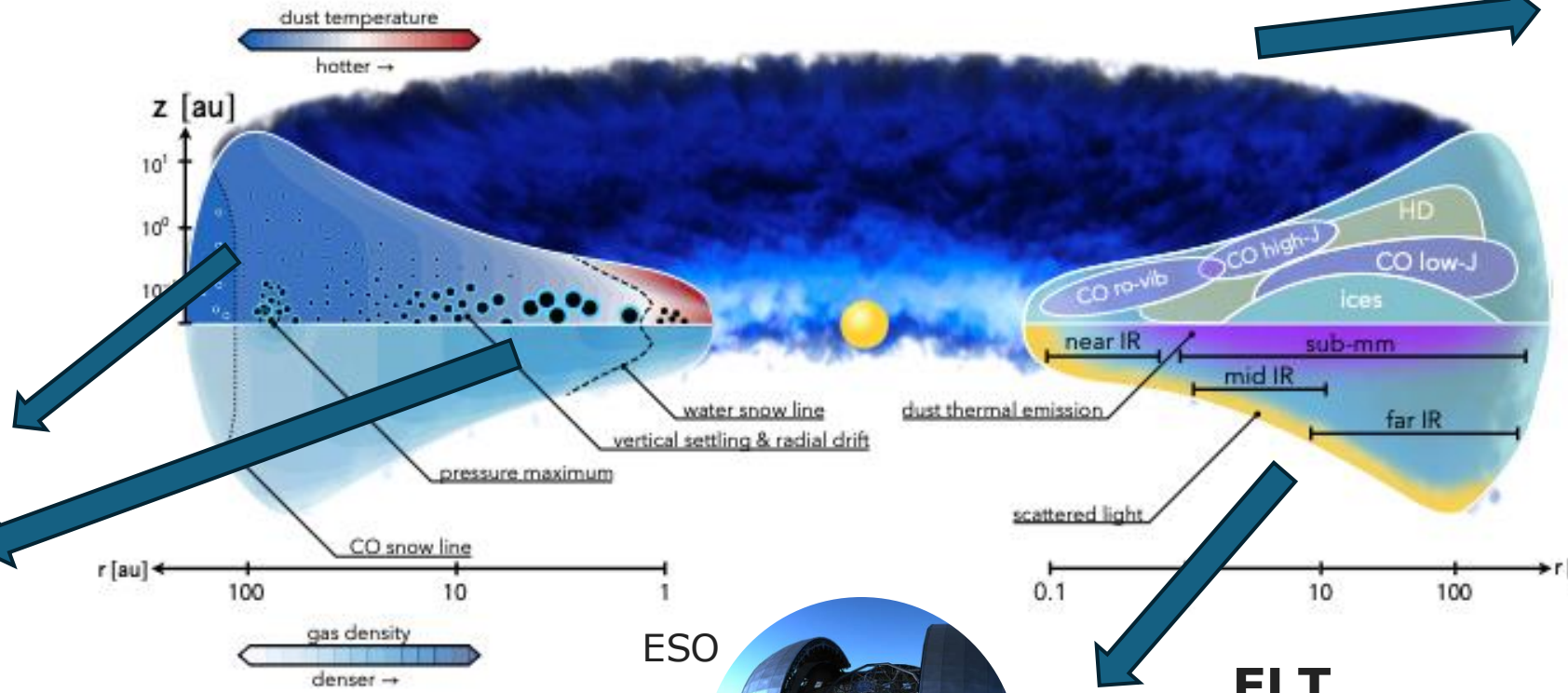
Zooming into protoplanetary discs

VLT

ERIS
scattered light emission
1-5 micron

Maio et al. 2025a
Maio et al. subm.

ESO



SKA

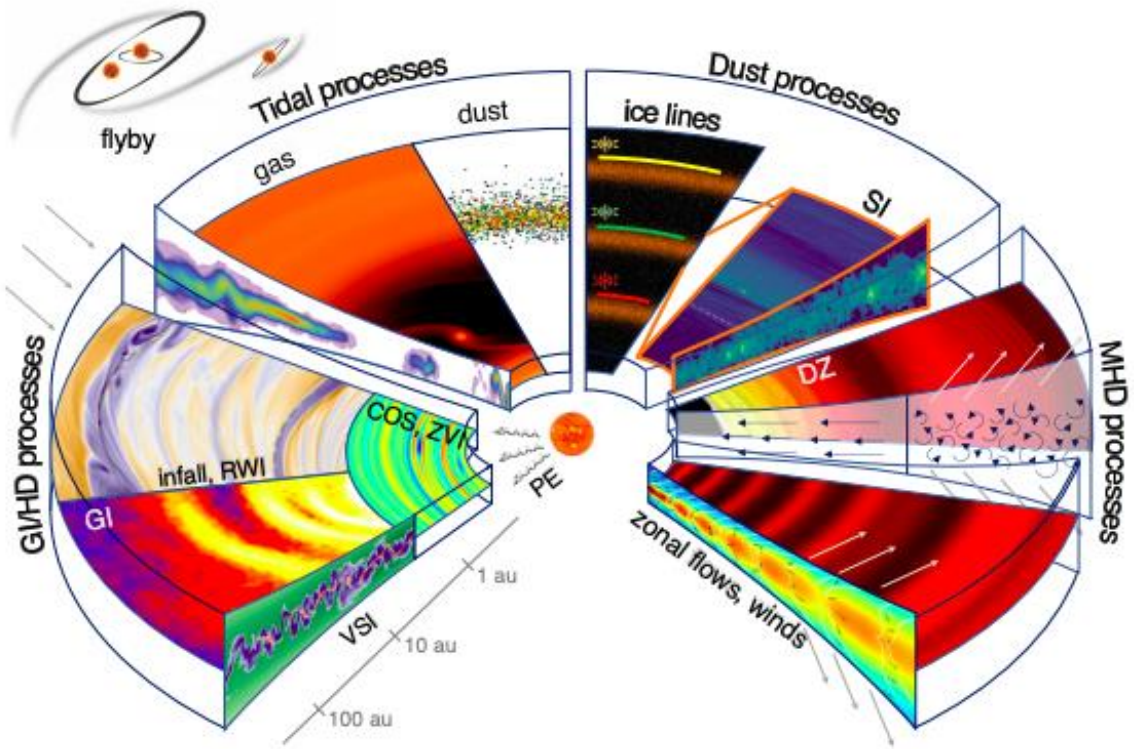
ELT

ESO

Adapted from Miotello et al., PPVII

Andrews 2020

What are we seeing?



Bae et al. 2022

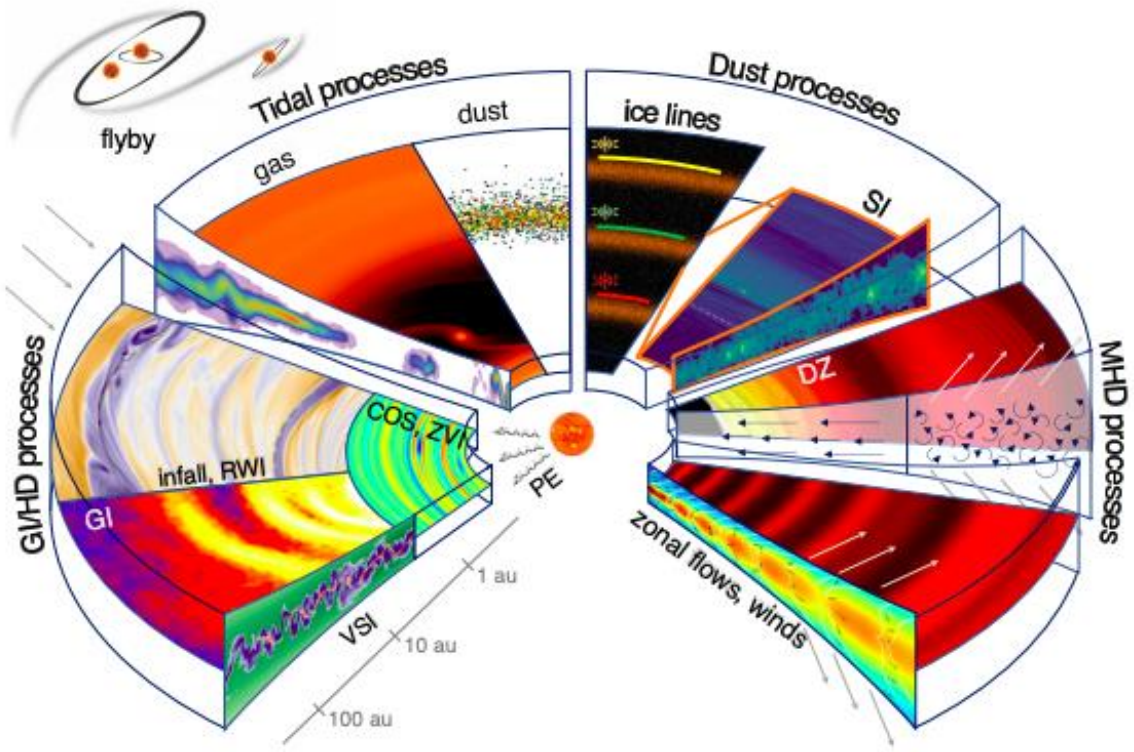
Dust grains trapped in a pressure maxima

(Pinilla et al. 2012, Dullemond et al. 2018, Rosotti et al. 2020 +…)

Induced without a pressure maxima, e.g., due to different opacities, snowlines, MHD effects

(Stammler et al. 2017, Suriano et al. 2019, Lesur et al. 2022)

What are we seeing?



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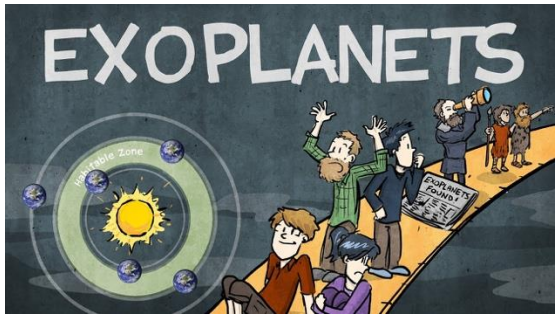
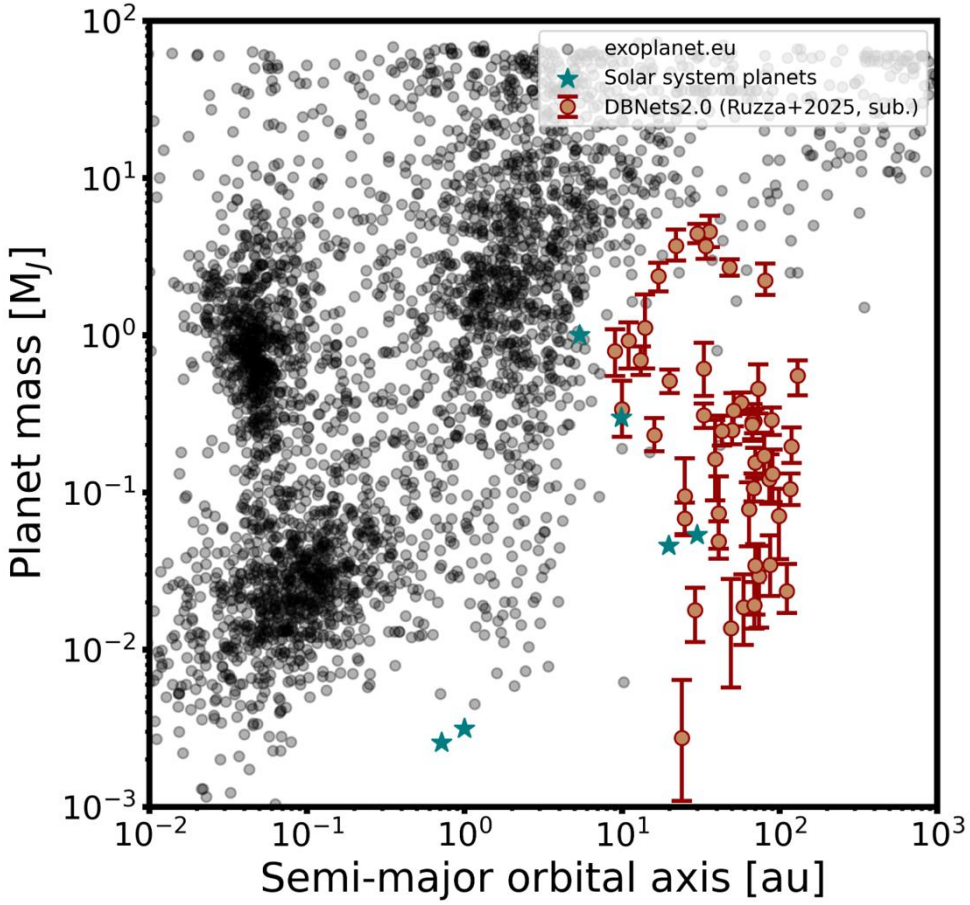


PhD comics

Induced without a pressure maxima, e.g., due to different opacities, snowlines, MHD effects

(Stammler et al. 2017, Suriano et al. 2019, Lesur et al. 2022)

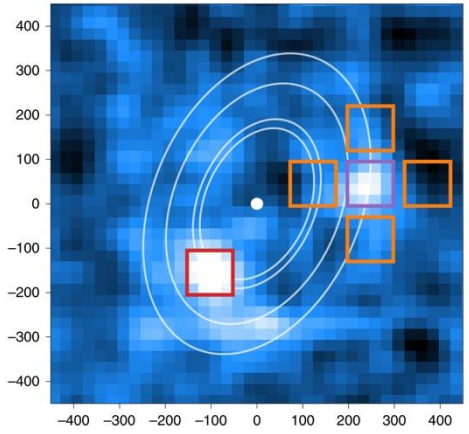
Protoplanets in discs?



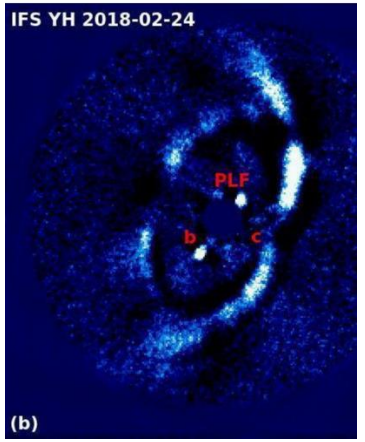
Ruzza et al. 2025 subm.

Lodato et al. 2019

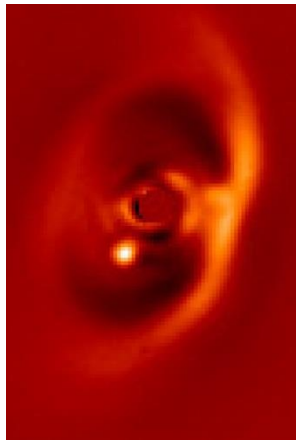
Haffer et al. 19



Mesa et al.19

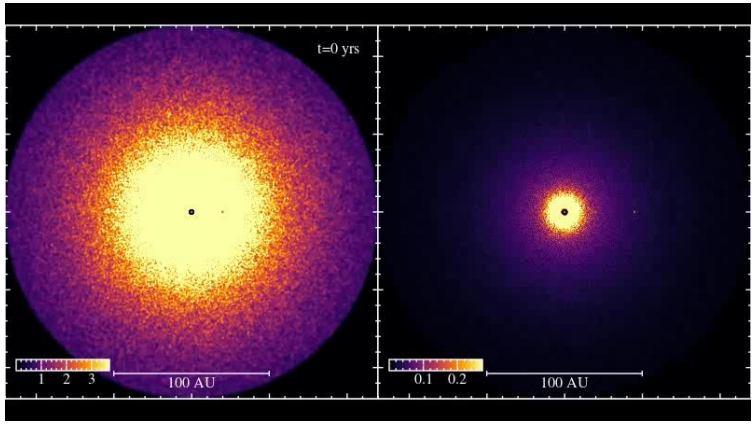


Benisty et al. 21



Muller et al. 18

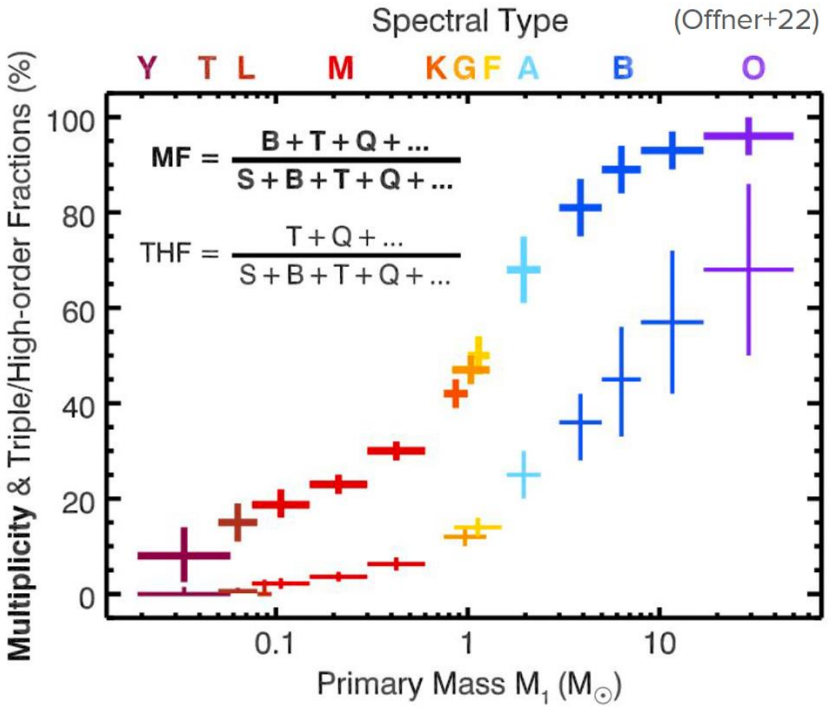
Gas

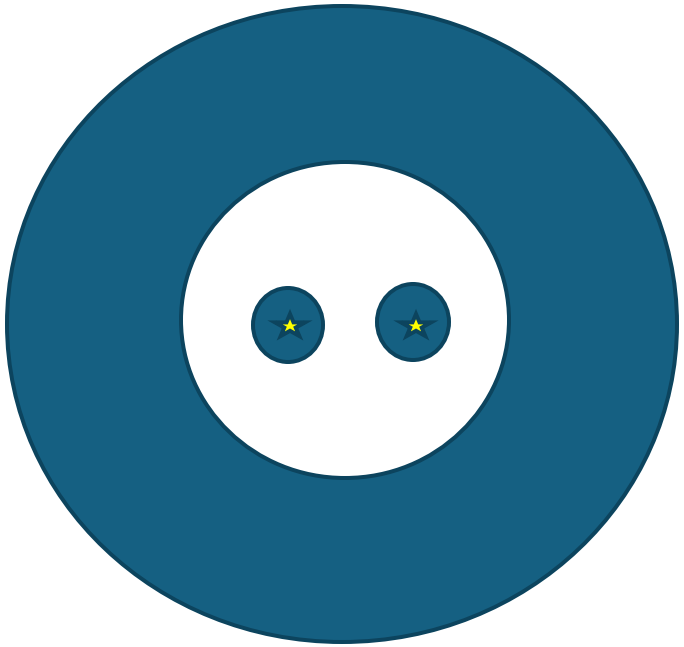


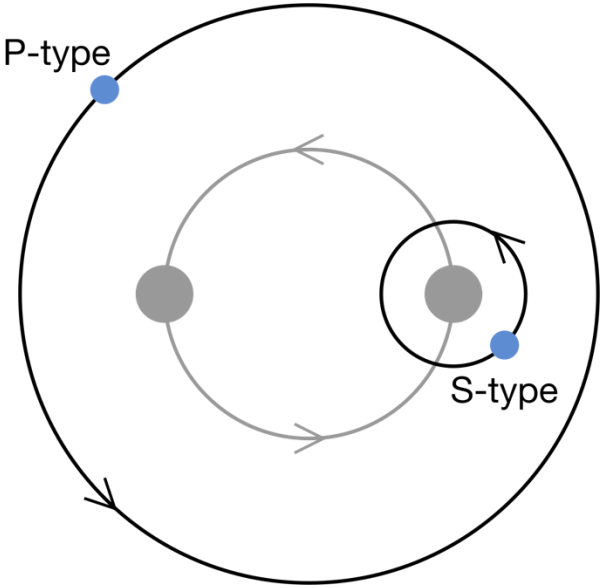
Dust

Toci et al. 2020a

Multiplicity in protoplanetary discs







Where are the perturbers?

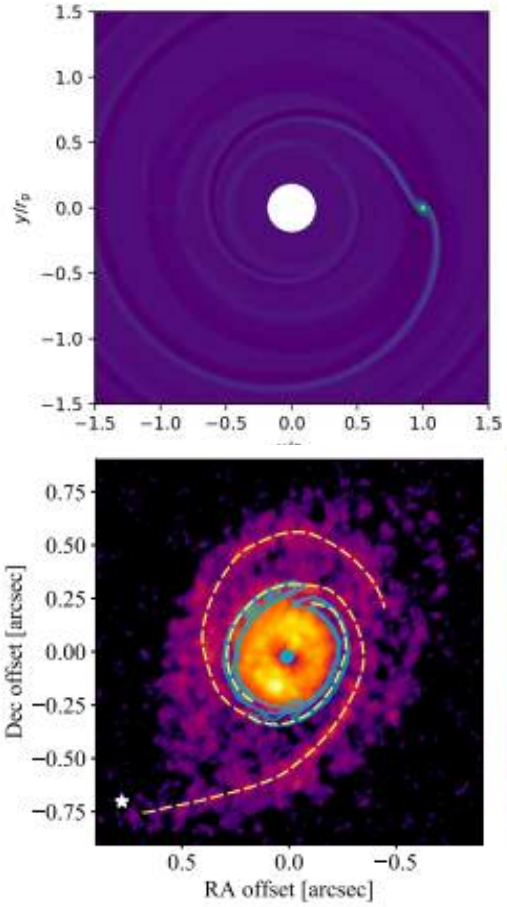
- Can we produce the substructures we observe with planet (perturber) disc interaction?

- Are the substructures we are observing generated by protoplanets (perturbers) interacting with their disc?

- Can we learn something on the planets (perturbers) generating the substructures?

See the 'invisible'

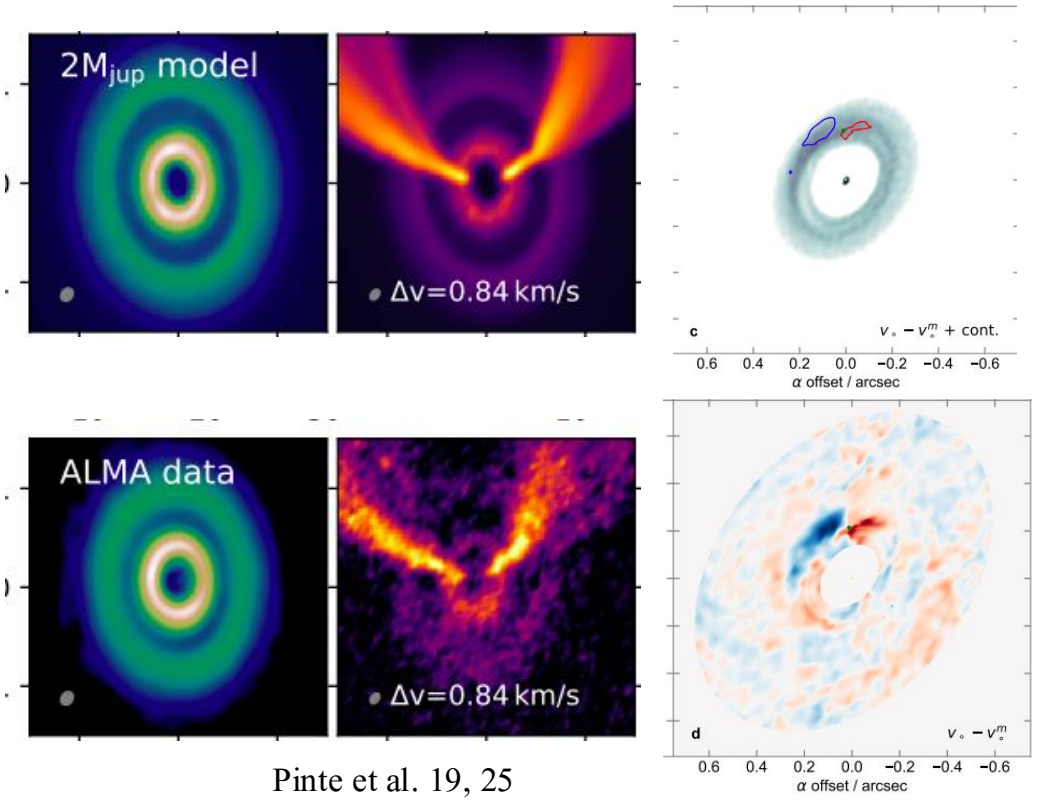
Spirals



Pardekooper et al. PPVII

Rosotti et al. 19

Kinematics

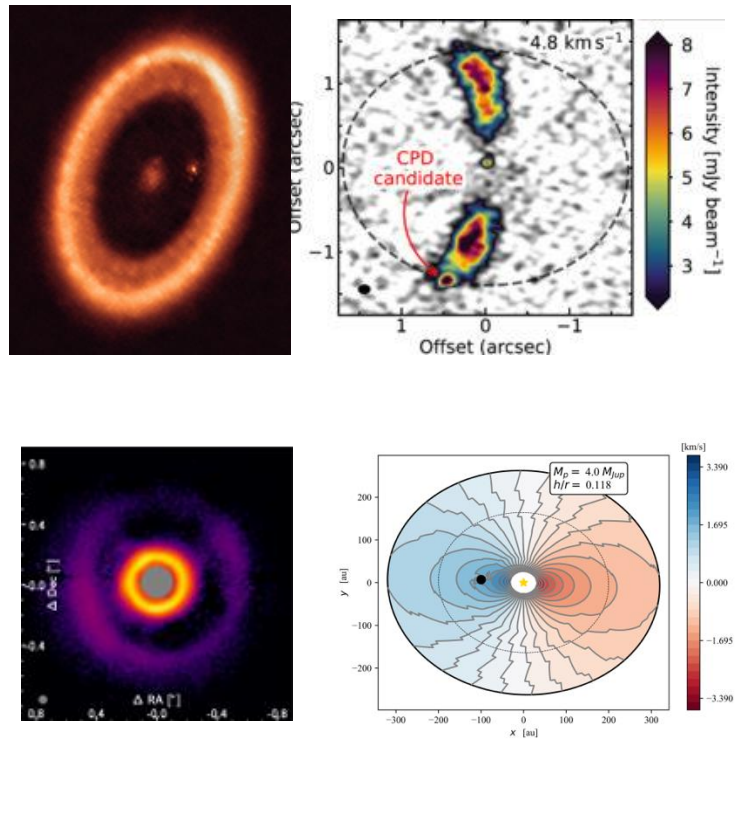


Pinte et al. 19, 25

Casassus&Perez 19, Izquierdo et al. 2023

EXOALMA Collaboration!

Circum-planetary



Benisty et al. 21

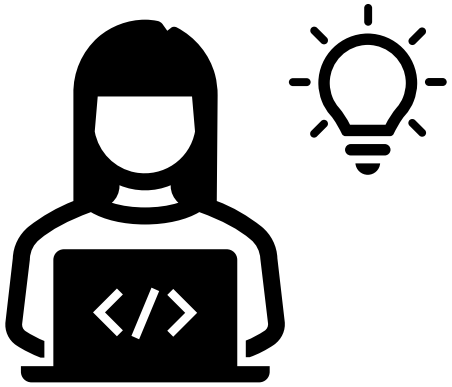
Bae et al. 22, Fedele et al. 23

Hammond et al. 23

A bridge between communities

Physics

(Hydrodynamics, Magnetohydrodynamics, chemical networks, planet-disc interaction, self-gravity, photoevaporation. . A few examples in discs)



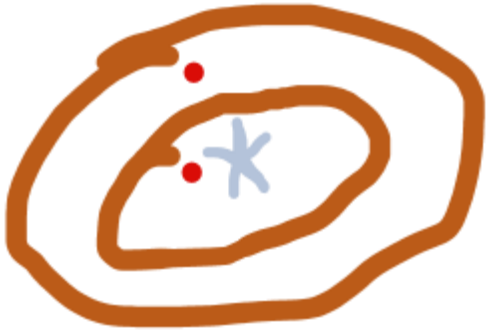
PHANTOM
+
MCFOST

From: PhDcomics.com

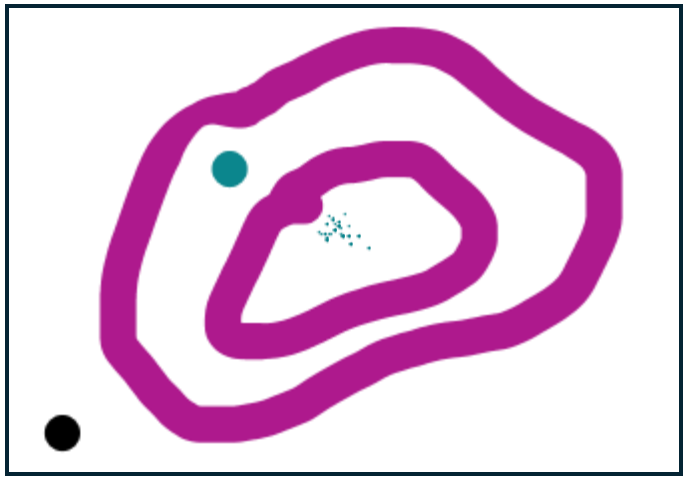
Observations

(continuum, molecular lines, scattered light)

From models to synthetic observations

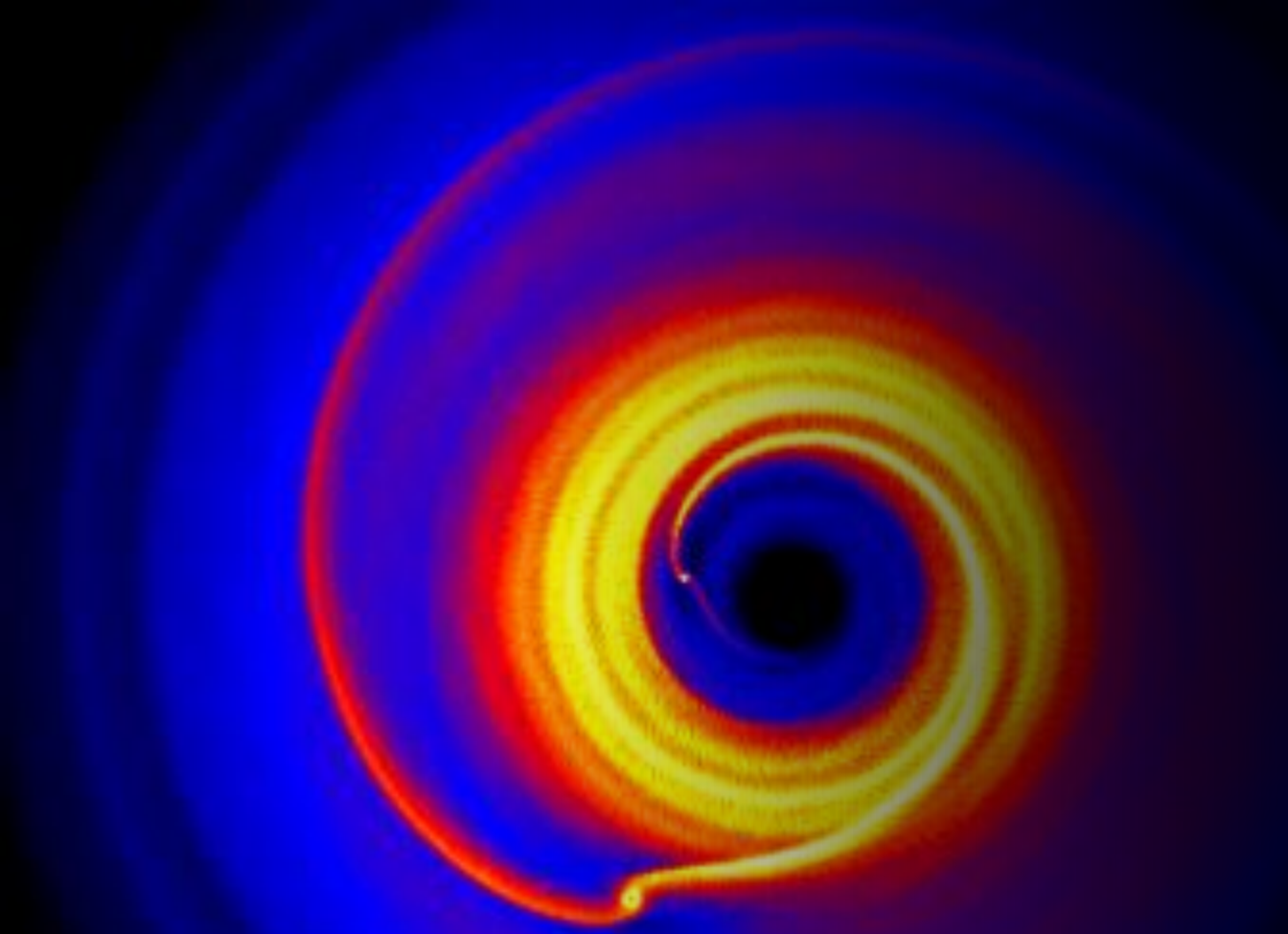


Your cool simulation



Your amazing synthetic flux

Simulations → Radiative transport codes → Synthetic images → Comparison with observations



Two perturbers

Discs with cavities

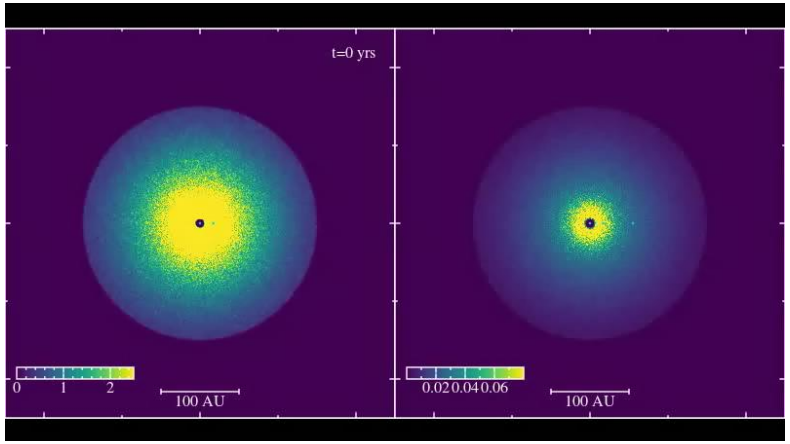
Ringed discs

Wide and deep gaps

Unique signatures

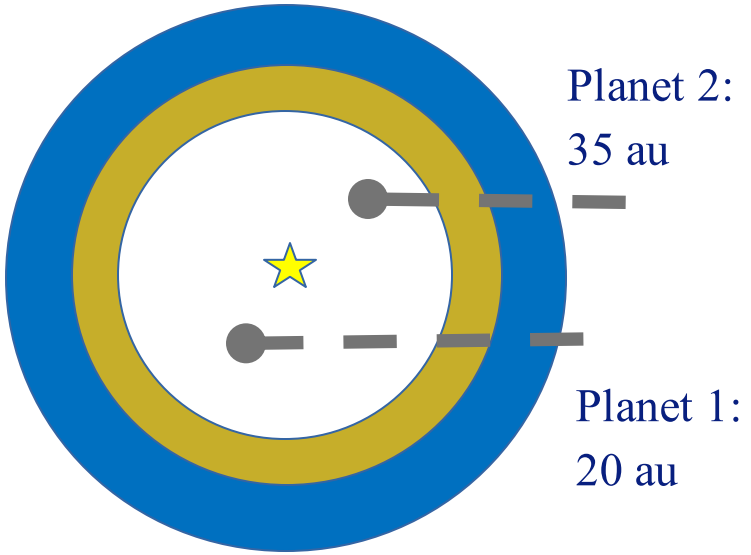
Hope for direct detection!

Double giants in discs

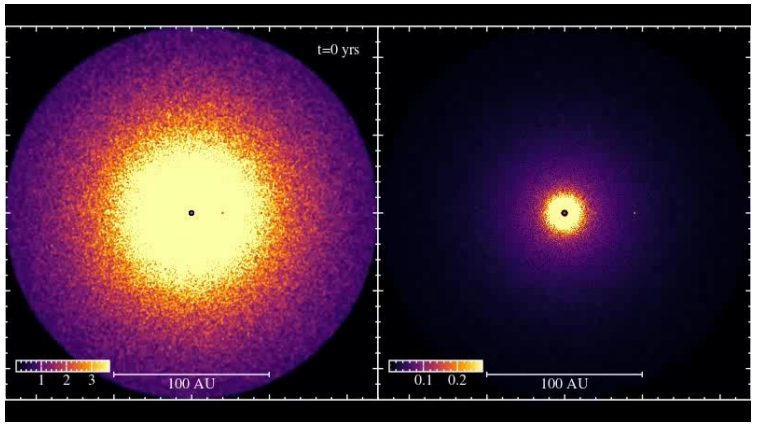


Toci et al. 2020a

PDS70



Gas **Dust**



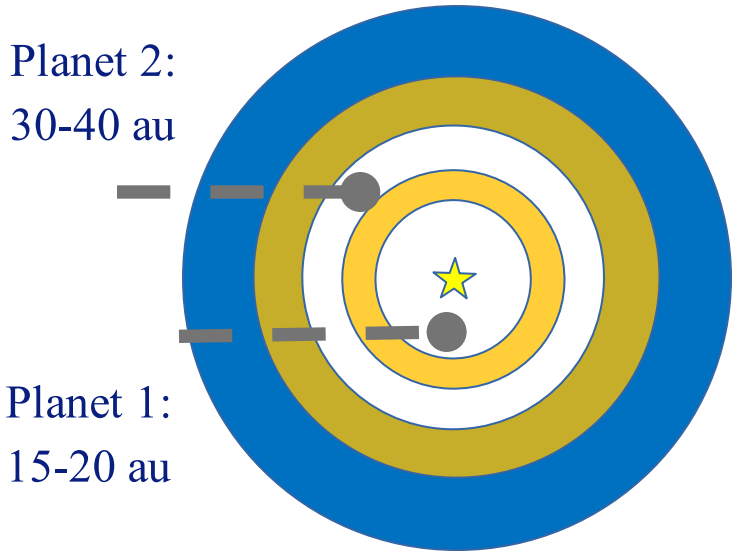
Toci et al. 2020b

Toci et al. MNRAS 2020b

See also: Bae et al. 2019

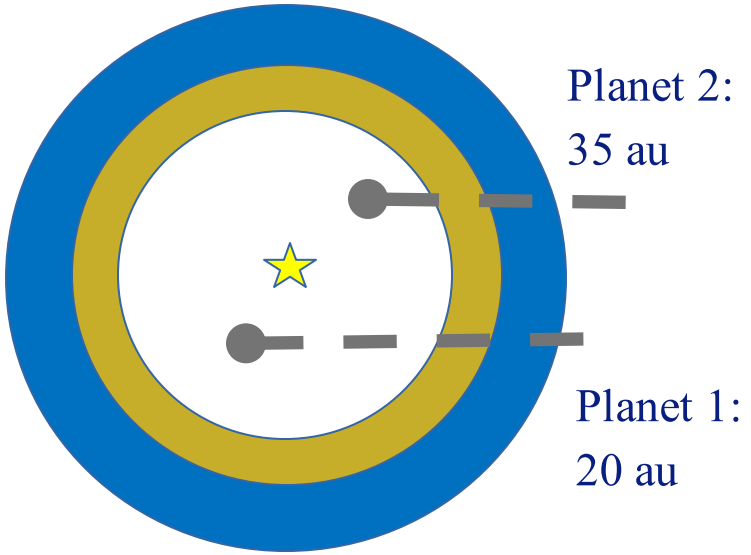
Different morphologies

HD169142



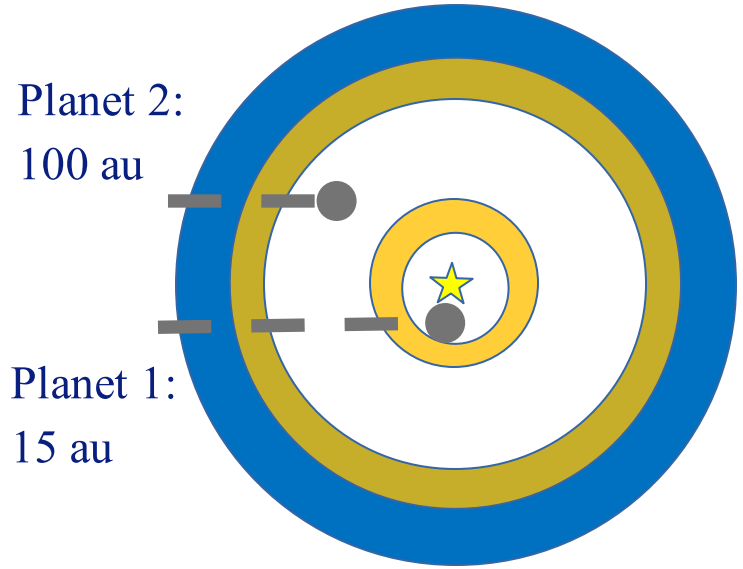
Toci et al. APjL2020

PDS70



Toci et al. MNRAS 2020b

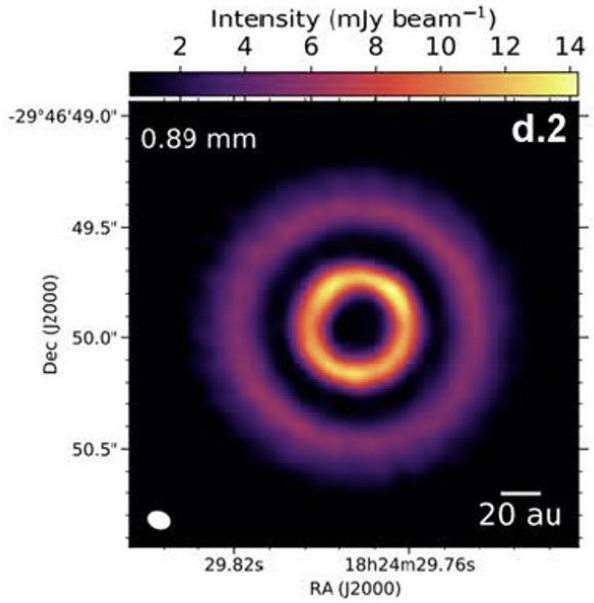
HD100546



Fedele, **Toci** et al. A&A 2021

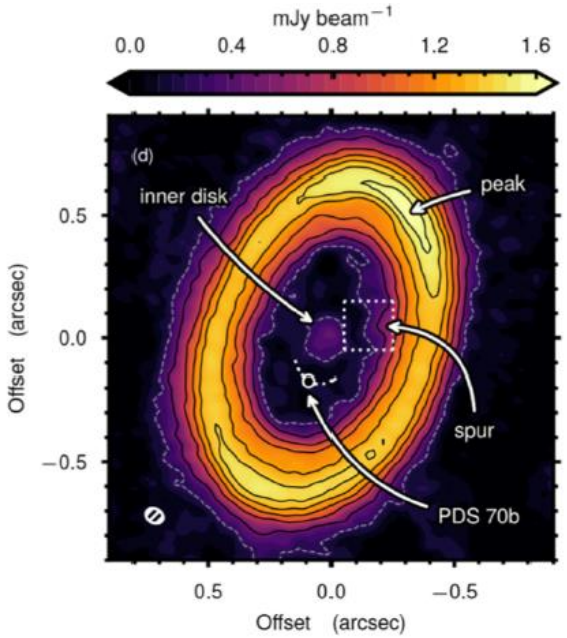
Different morphologies

HD169142



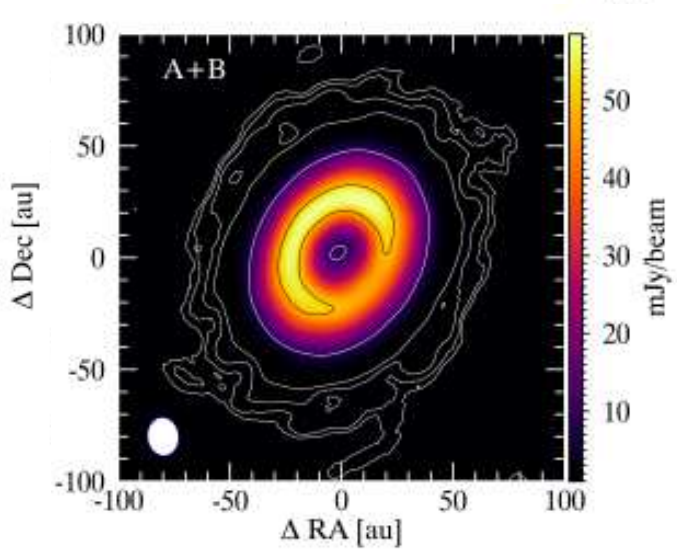
Toci et al. APjL2020
Macias et al. 2018

PDS70



Toci et al. MNRAS 2020b
Keppler et al. 2019

HD100546



Fedele, **Toci** et al. A&A 2021

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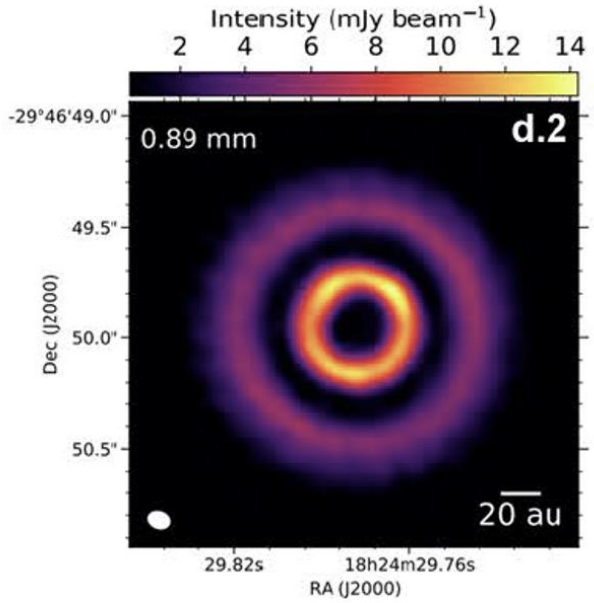

Toci et al. APjL2020
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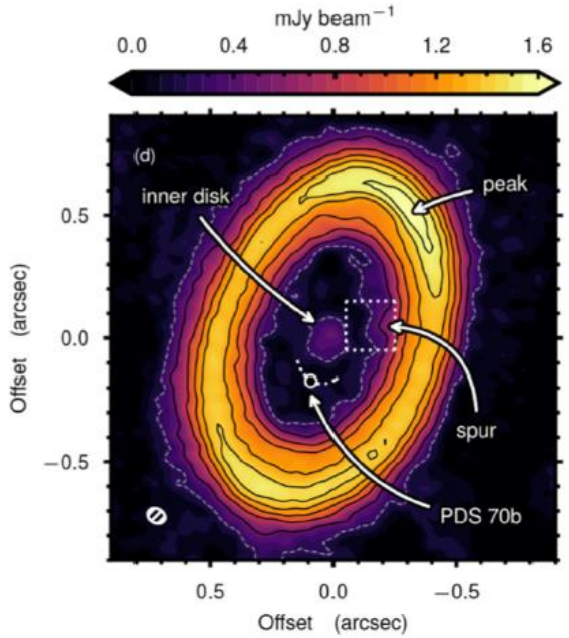

Toci et al. MNRAS 2020b
Keppler et al. 2019

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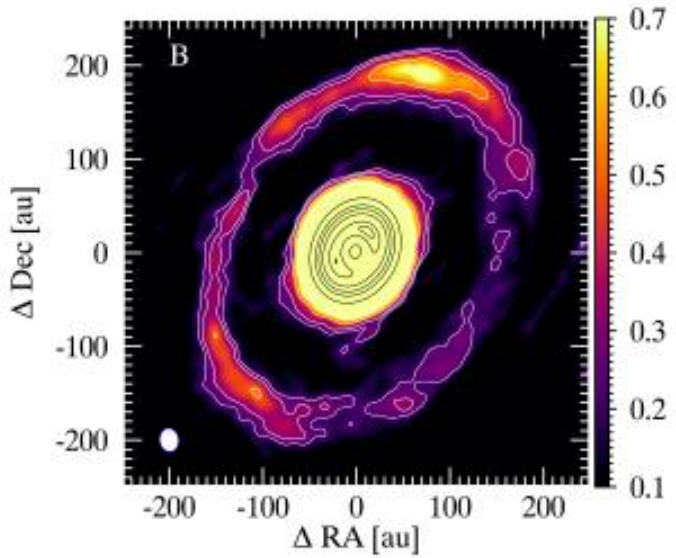
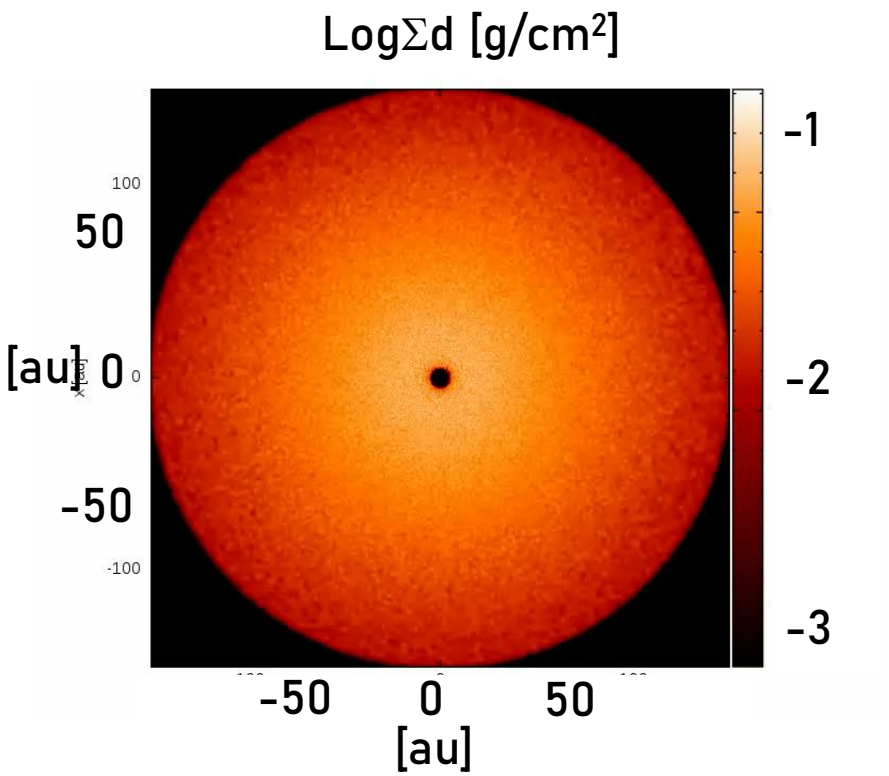
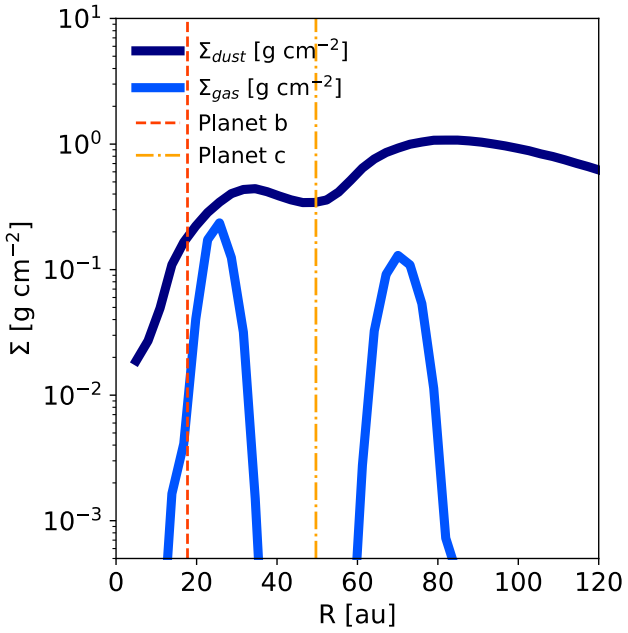


Fedele, **Toci** et al. A&A 2021

Dust properties

HD169142

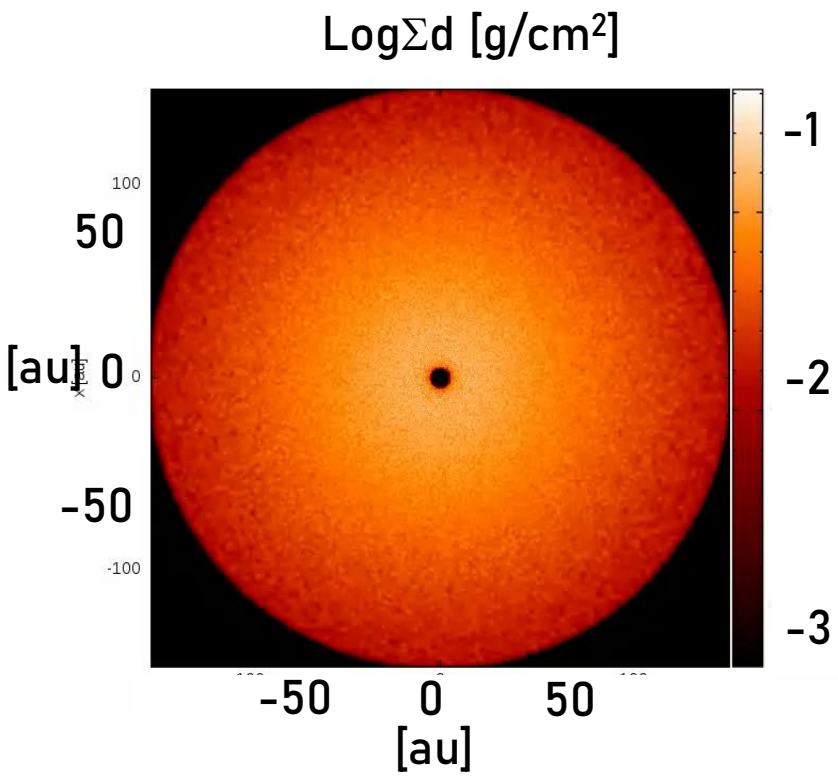




Toci et al. 2020a

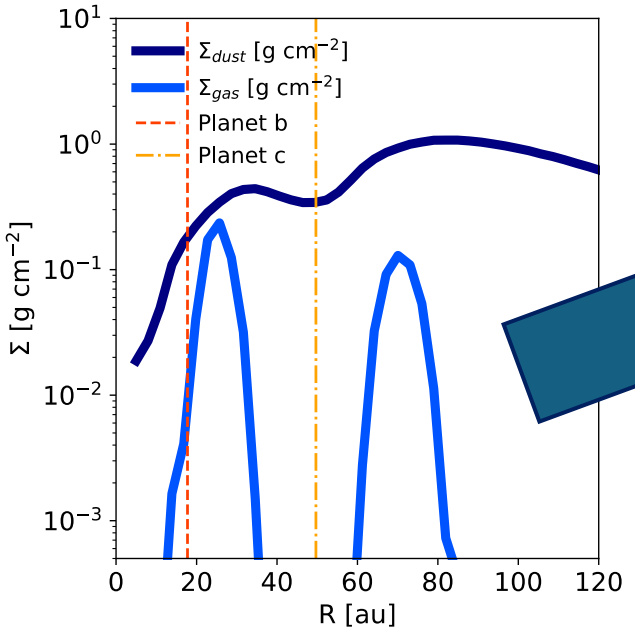
Dust properties

HD169142

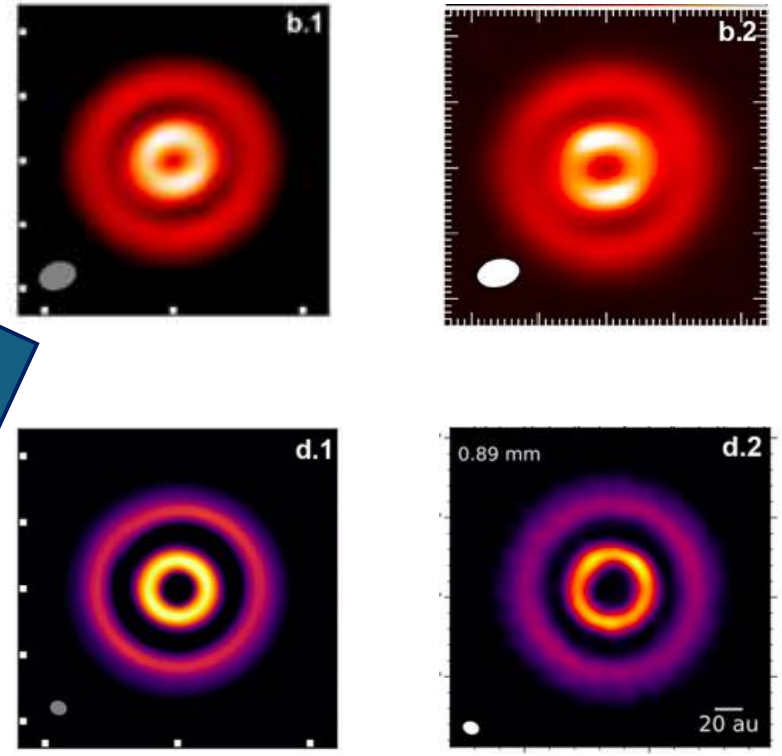


Toci et al. 2020a

Radiative transfer
Thermal structure
Chemical structure (opacities)
Noise(s)



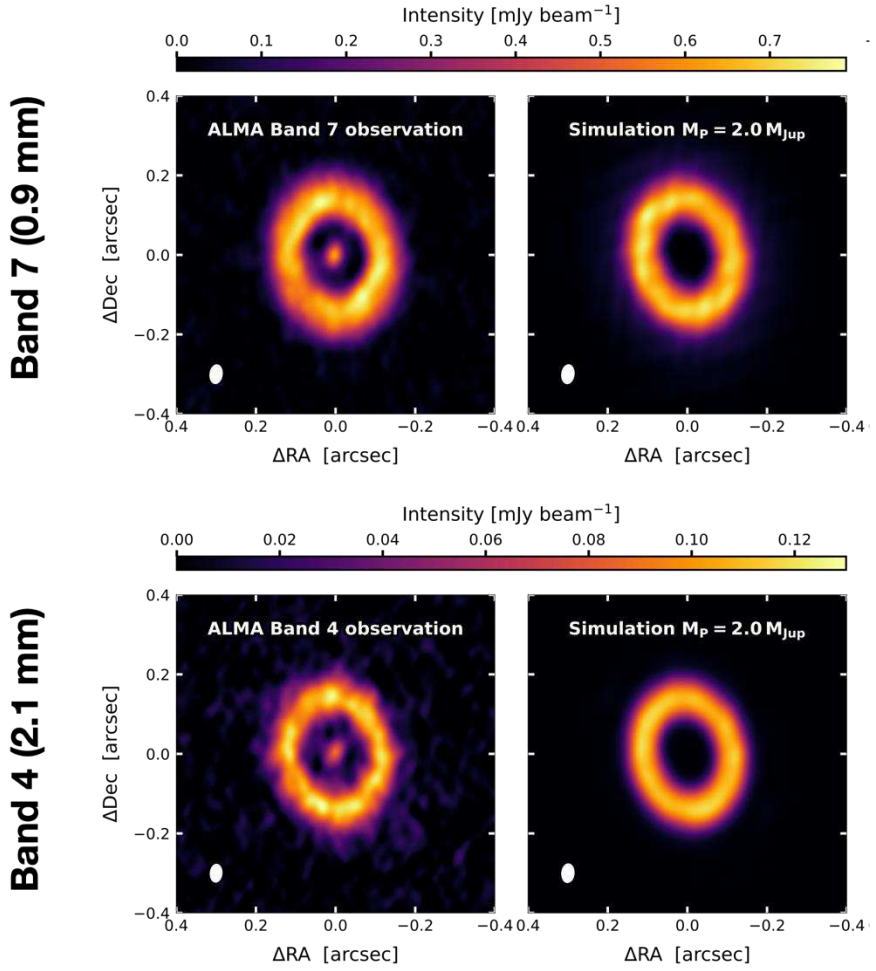
What can we learn?
Mass and position of the planet, dust properties, kinematics

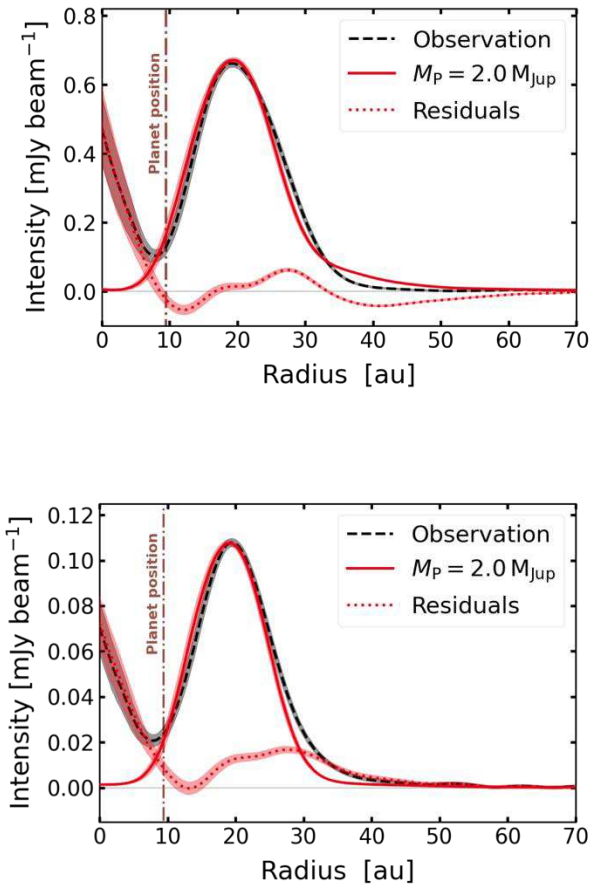


Fedele et al. 2017, Macias et al. 2019

Dust properties and spectral index

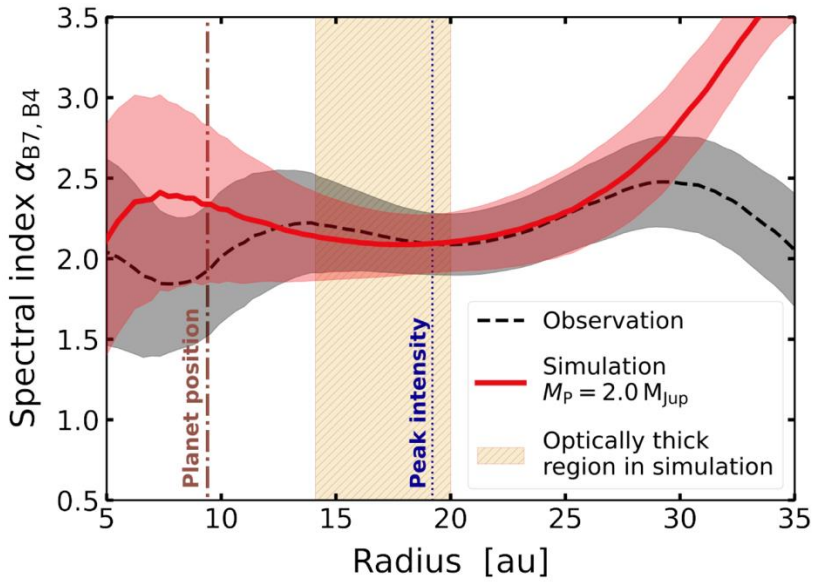
CIDA 1





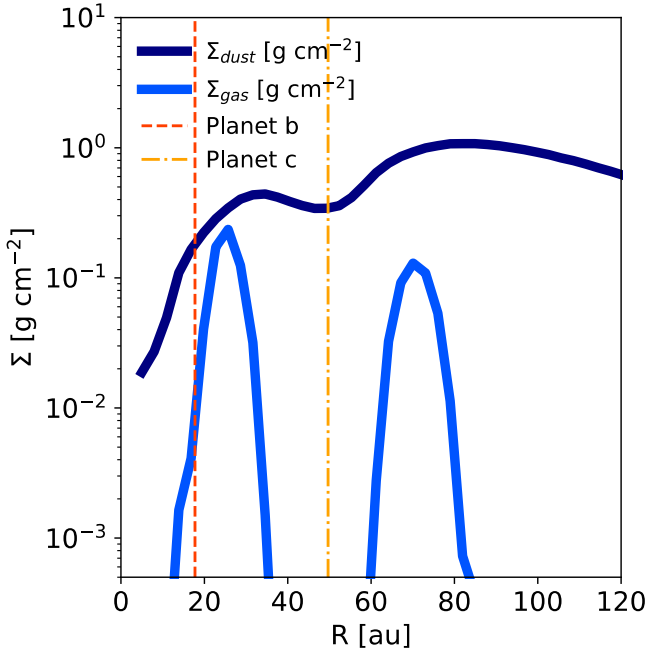
What can we learn?

Mass and position of the planet, dust properties, kinematics

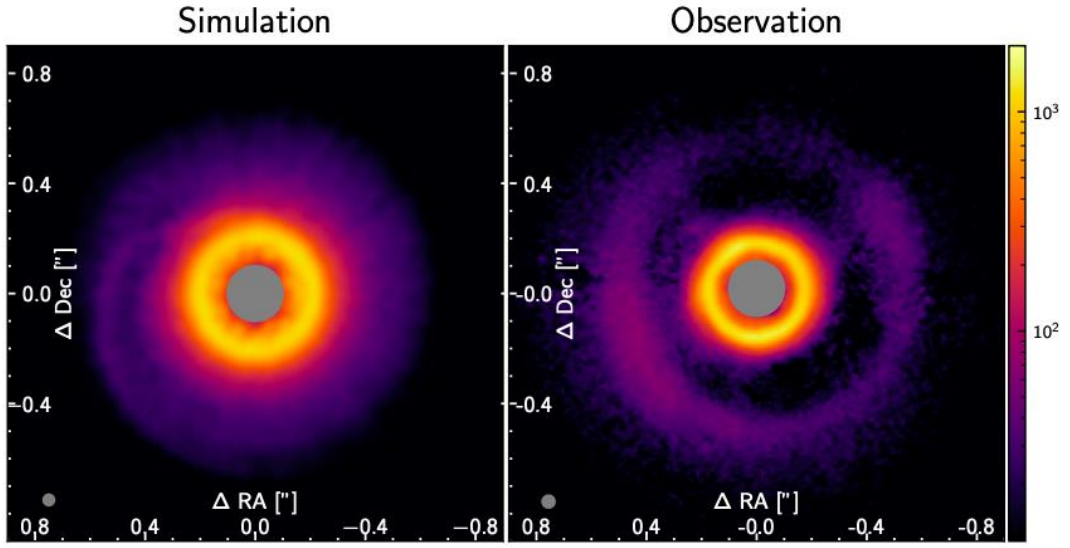


Predict observable to test

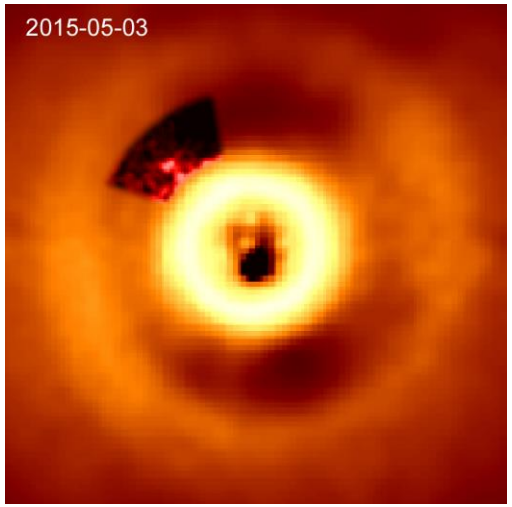
HD169142



Toci et al. 2020a



Hammond et al. (inc. **Toci**) 2023

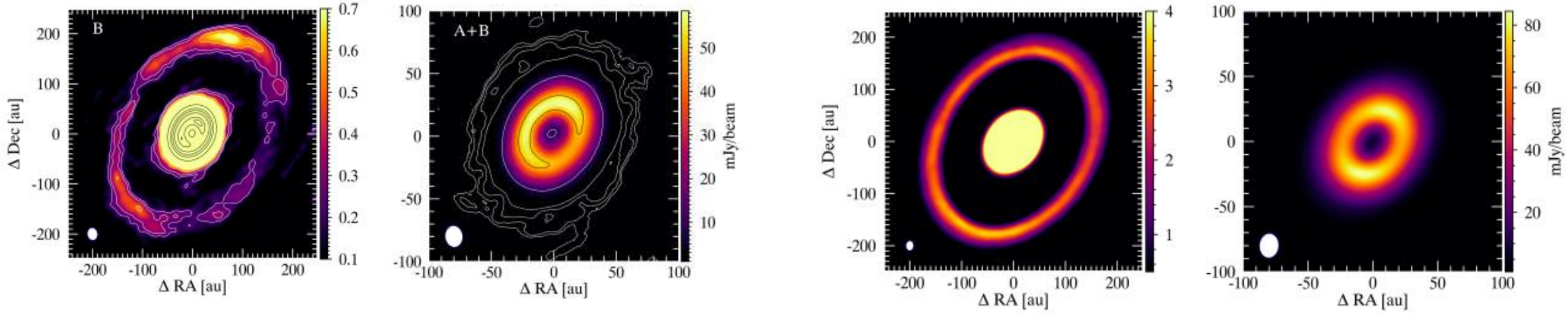


Gaps properties and planets predictions

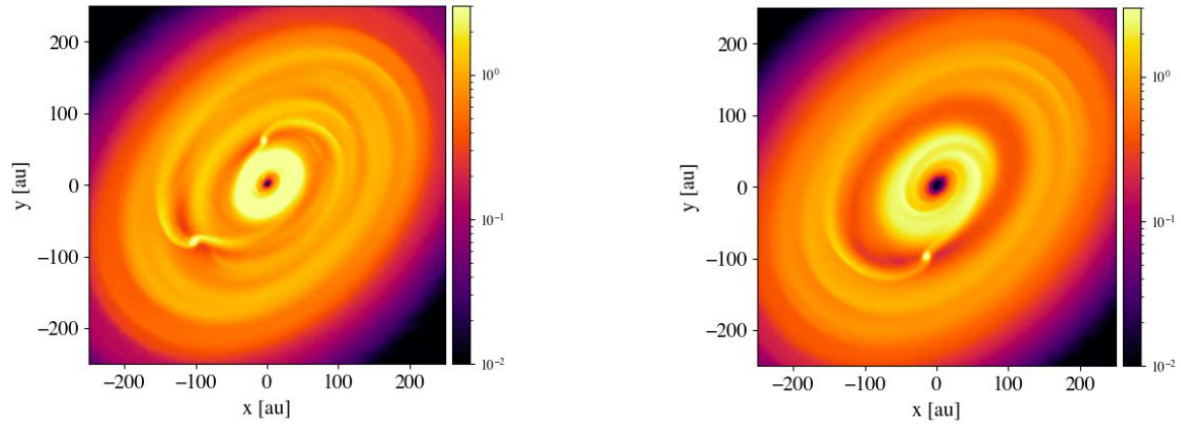
Mass & position of planets

Multiwavelenghts comparison: predict new observables (HD 100546)

HD100546

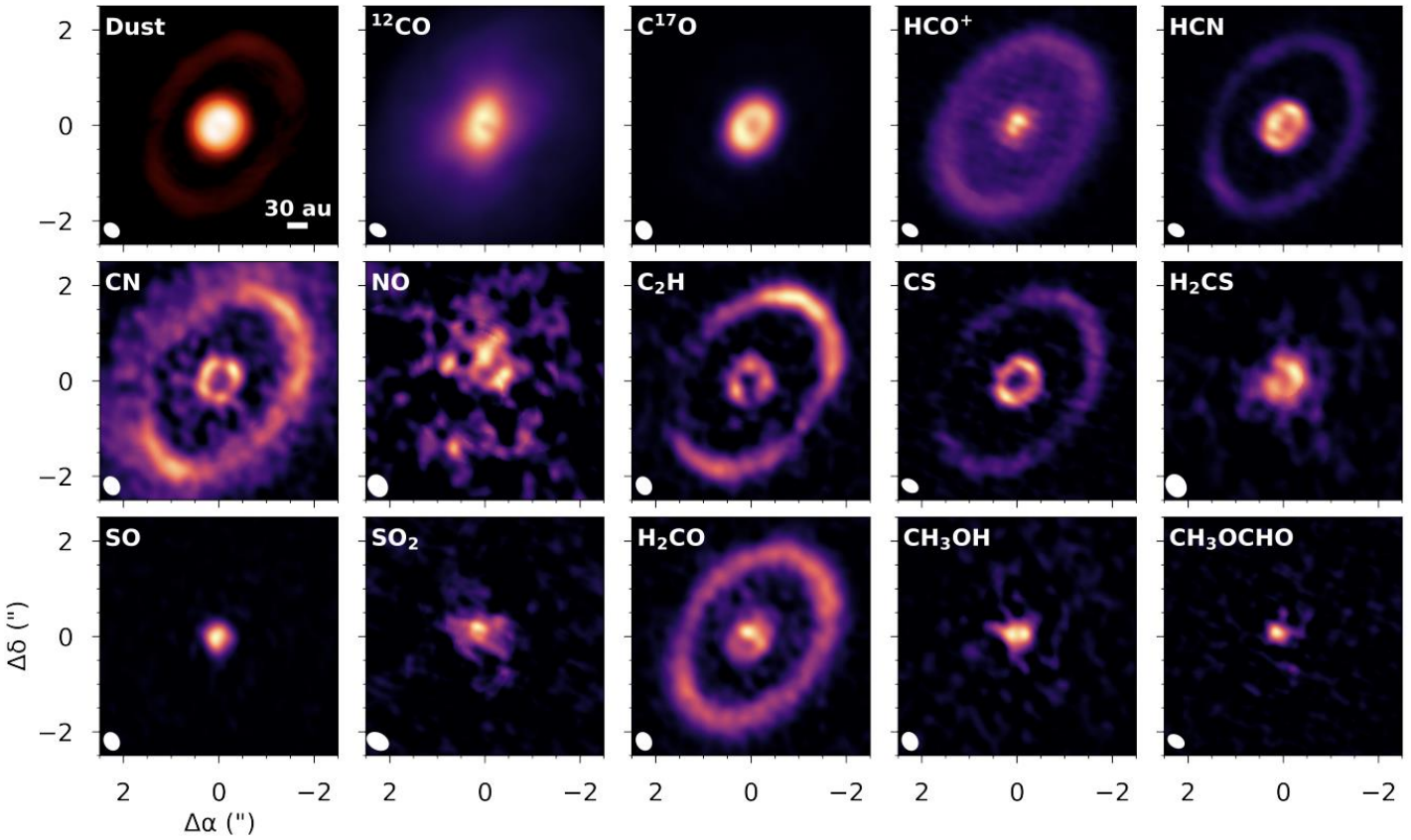


How many planets?



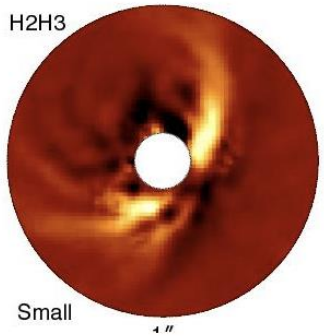
Fedele, **Toci** et al. A&A 2021

Gaps properties and planets predictions

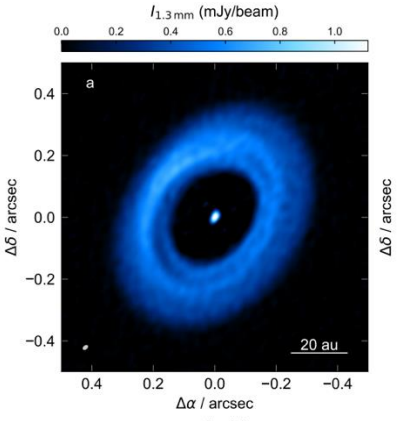


Booth et al. 2024

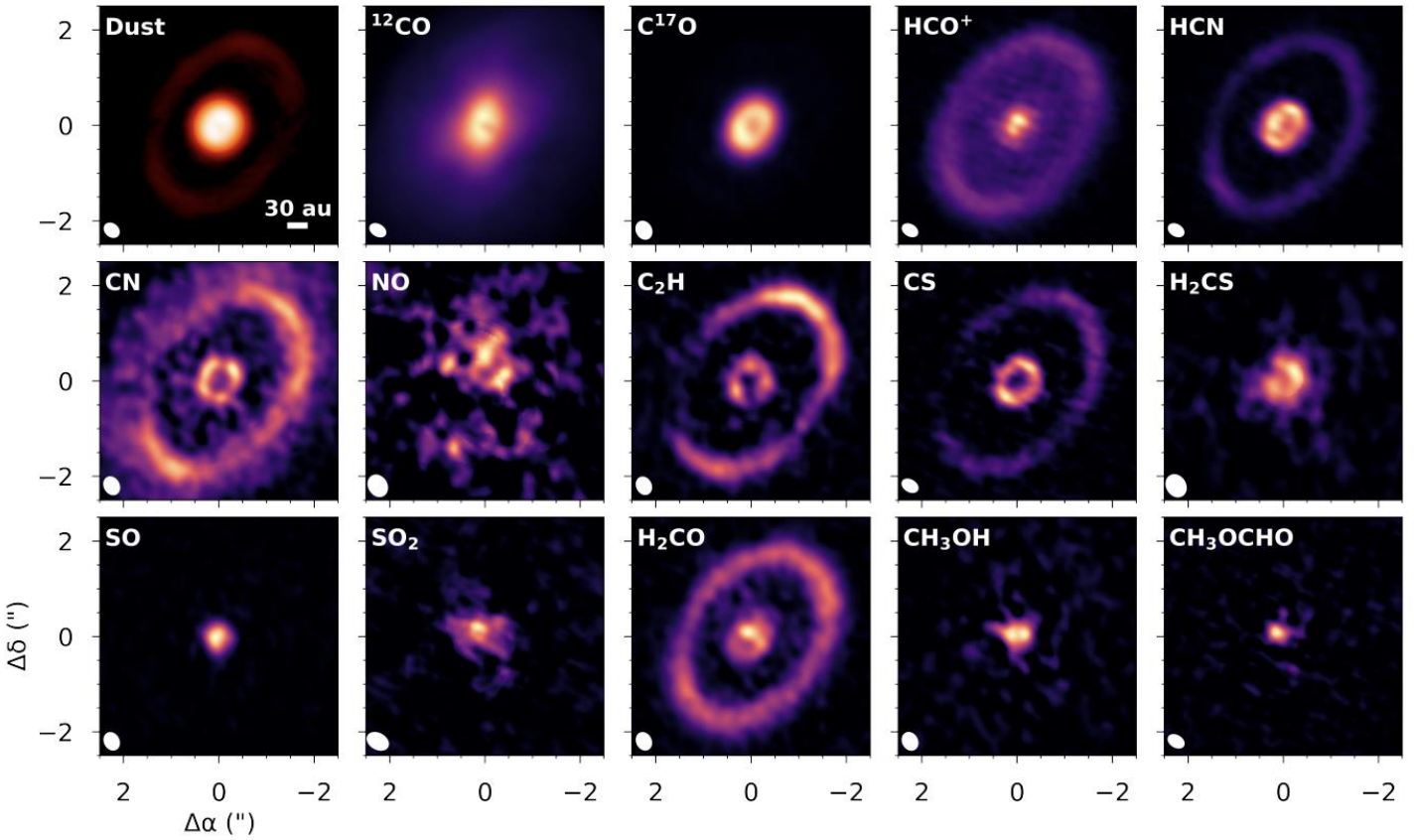
Garufi et al. 2016



Perez et al. 2019



Gaps properties and planets predictions



Booth et al. 2024

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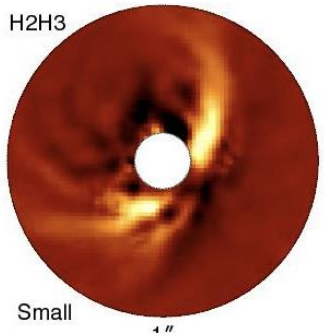
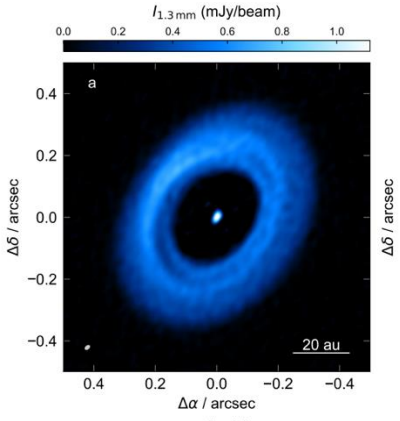
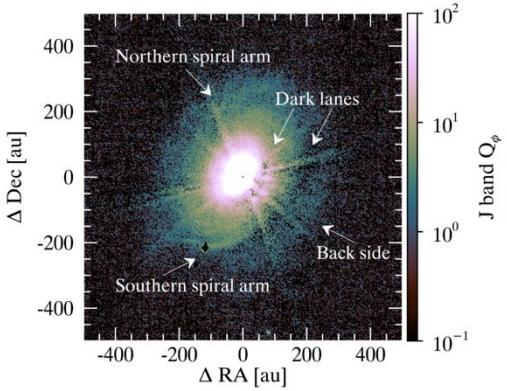
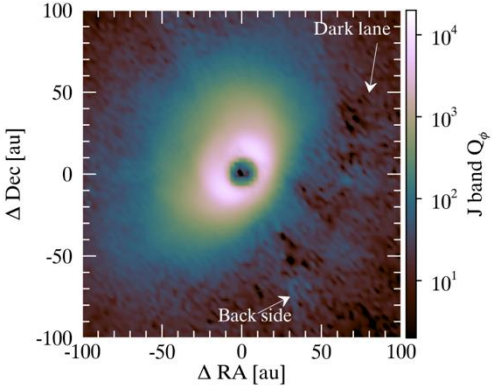


Perez et al. 2019

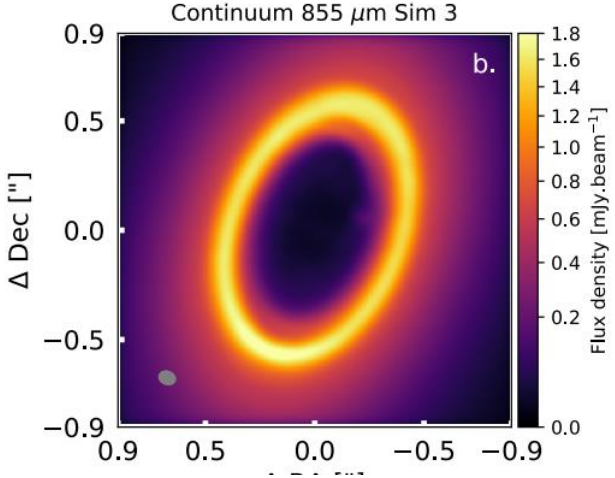


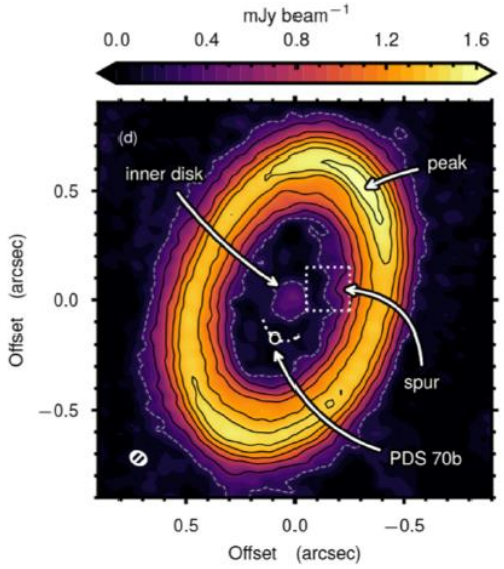


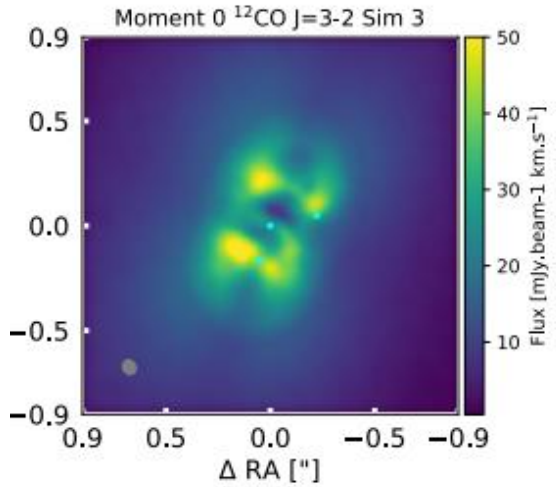


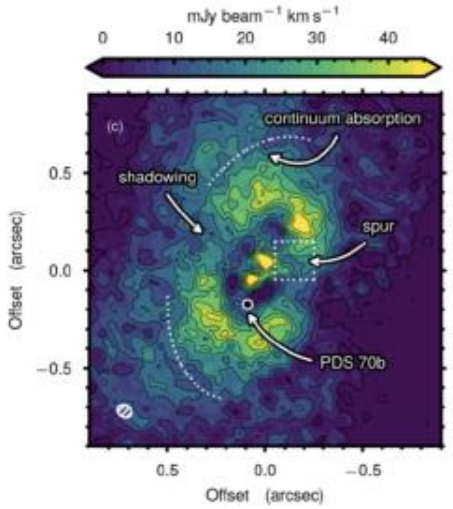
Fedele et al. 2021

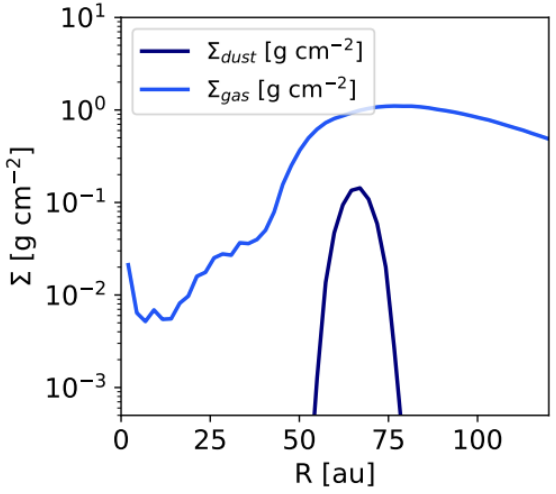
Multi-wavelength is better than one





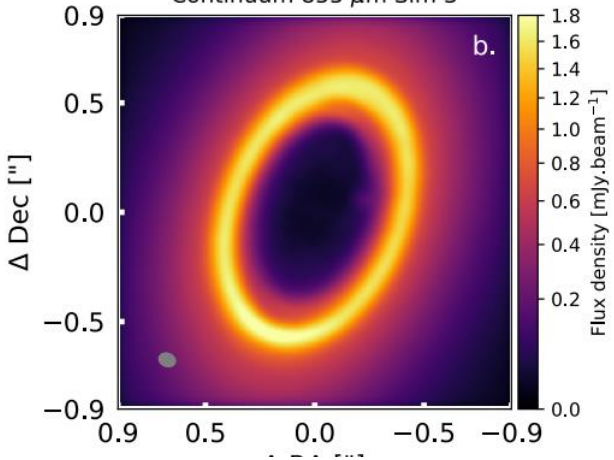


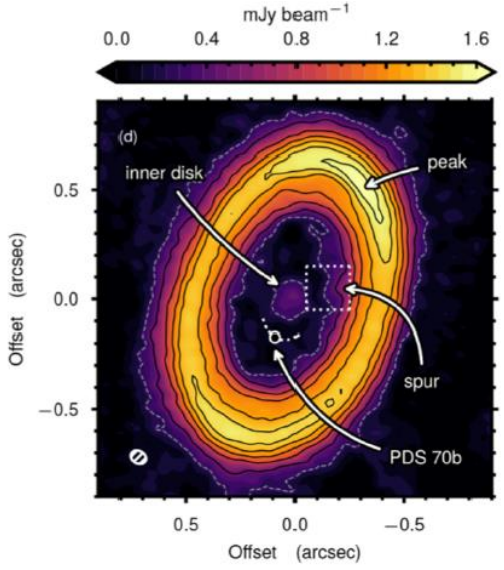


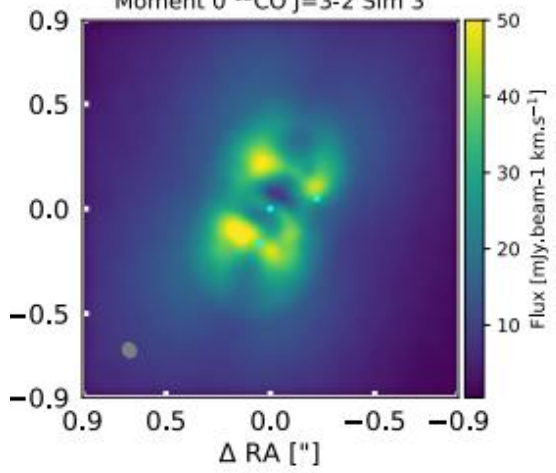


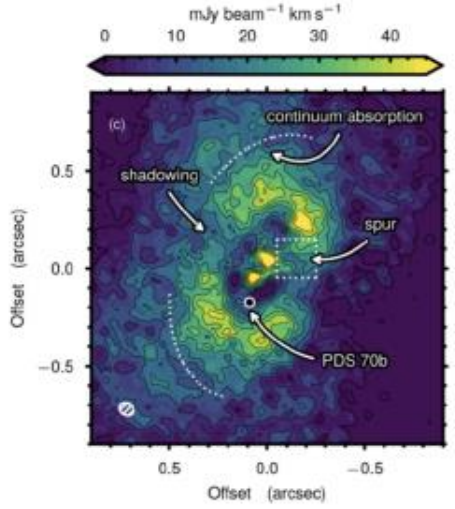
Hydrodynamical model: **Toci** et al. 2020b, Observations: Keppler et al. 2019, Mueller et al. 2018, Christiaens et al. 23

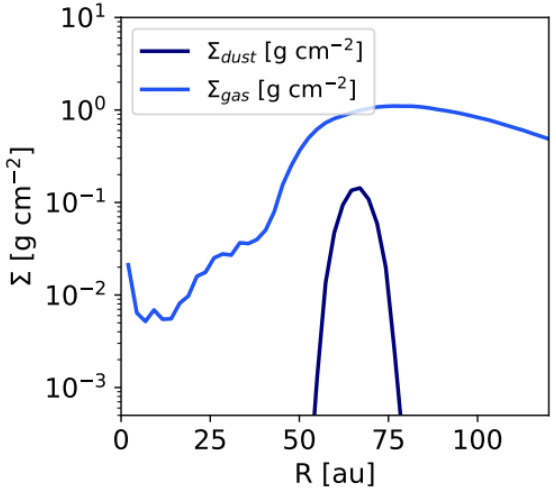
Who's accreting more. Tidal locking & co.

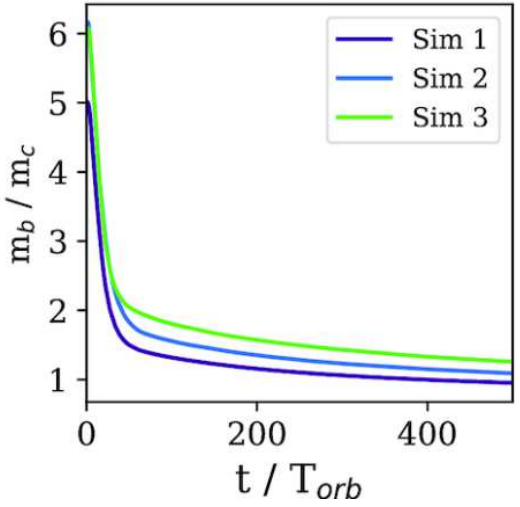


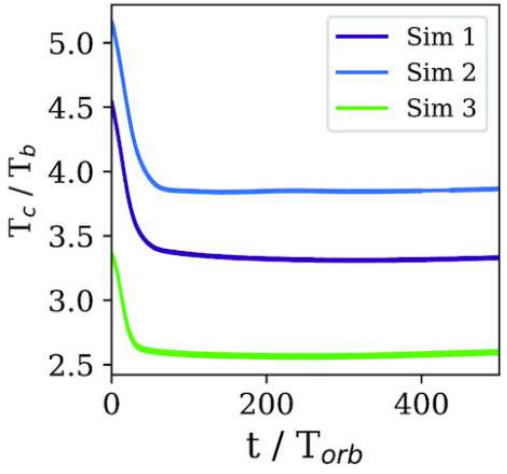


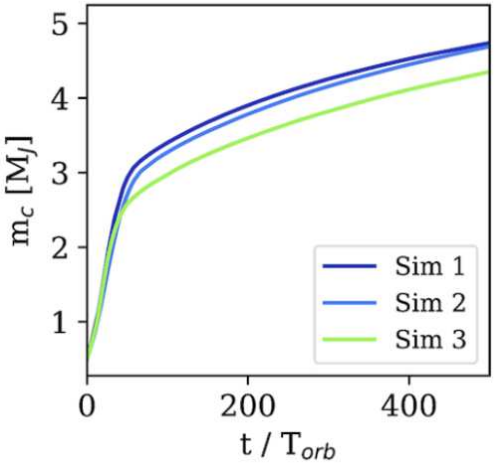






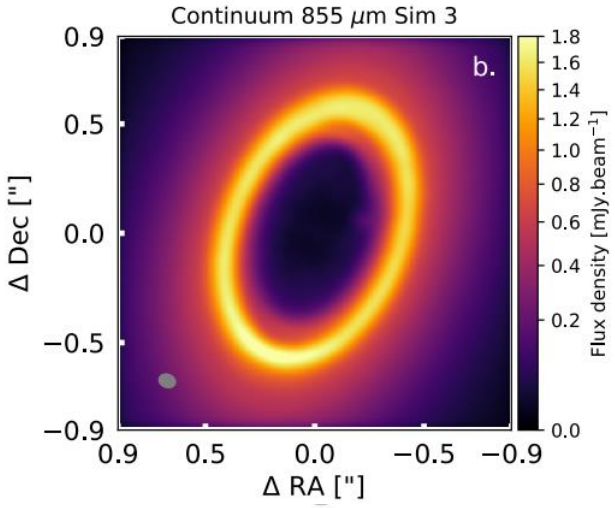


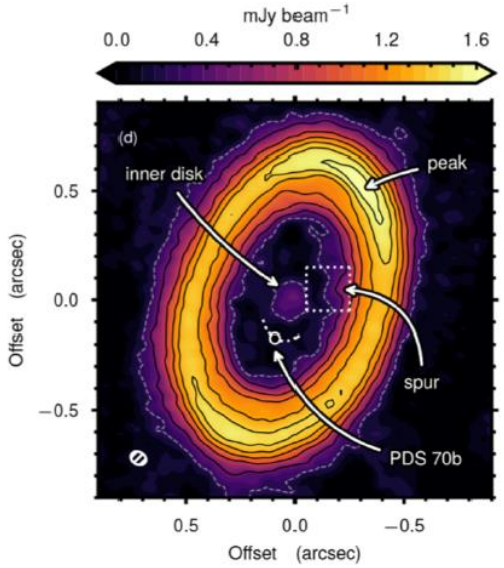


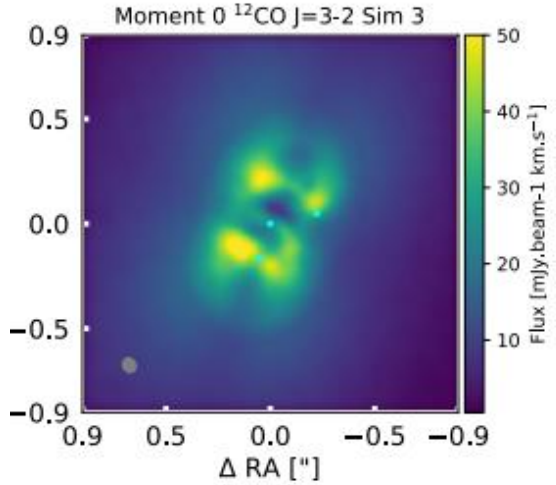


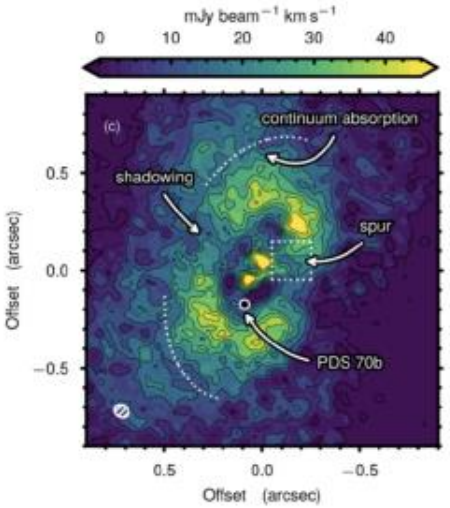
Hydrodynamical model: **Toci** et al. 2020b, Observations: Keppler et al. 2019, Mueller et al. 2018, Christiaens et al. 23

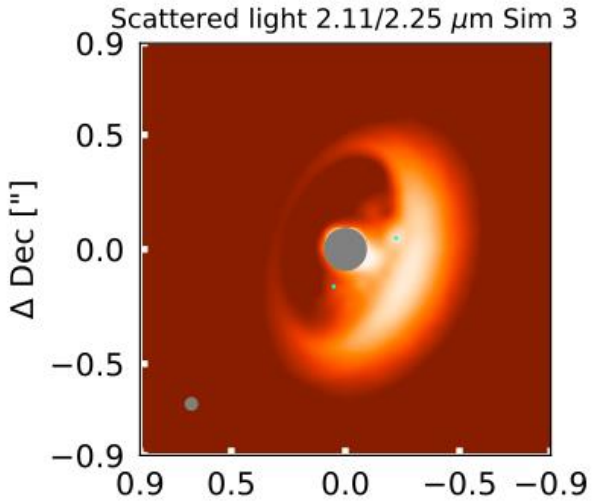
Multi-wavelength is better than one

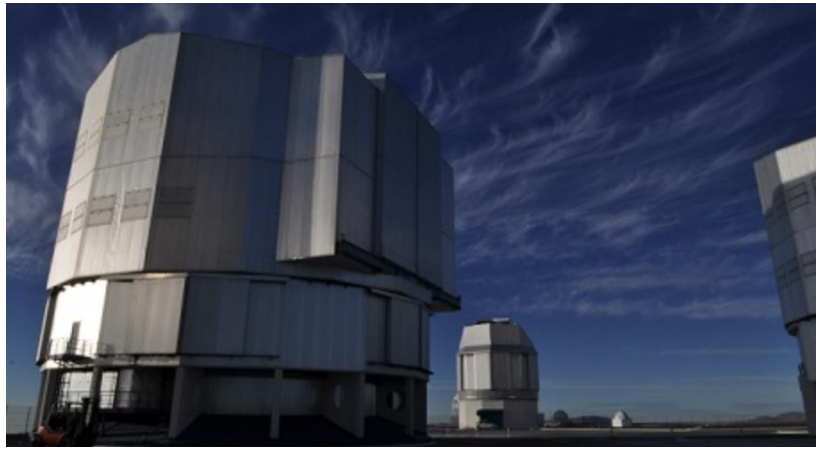












Hydrodynamical model: **Toci** et al. 2020b, Observations: Keppler et al. 2019, Mueller et al. 2018, Christiaens et al. 23

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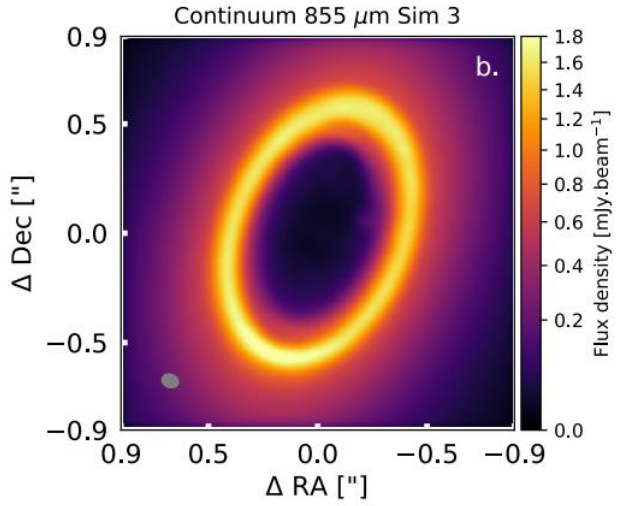
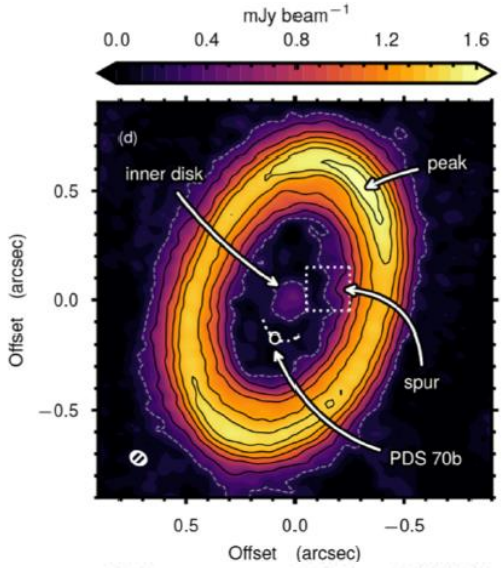
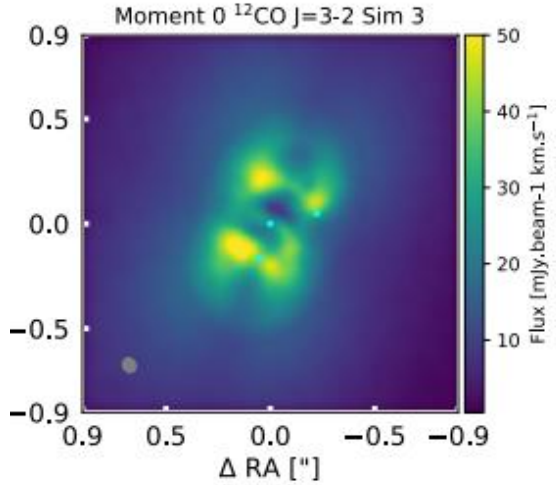
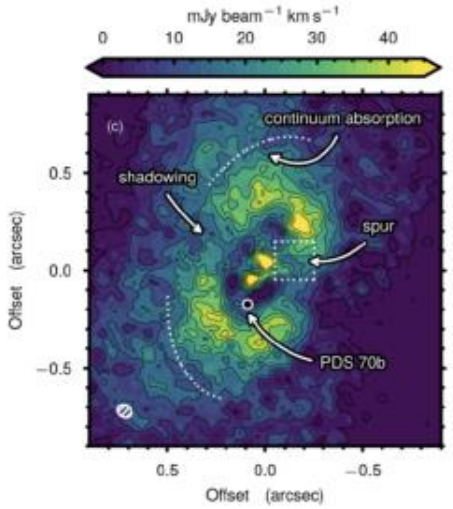
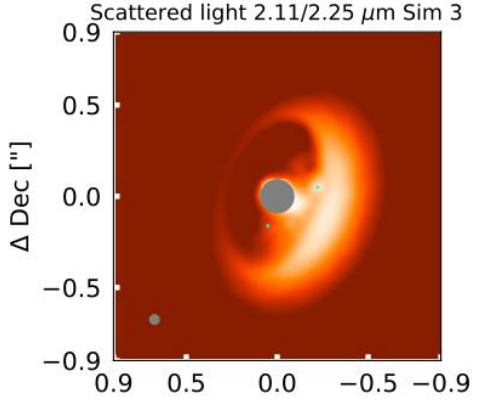


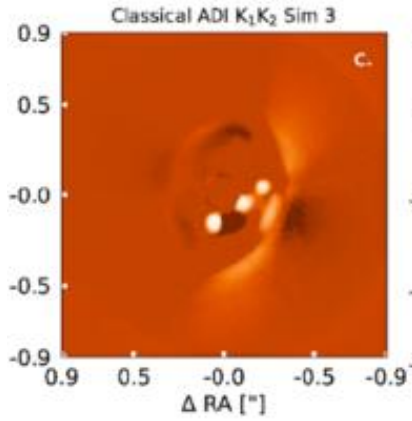




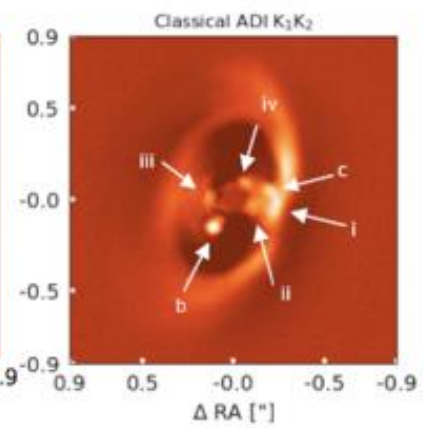




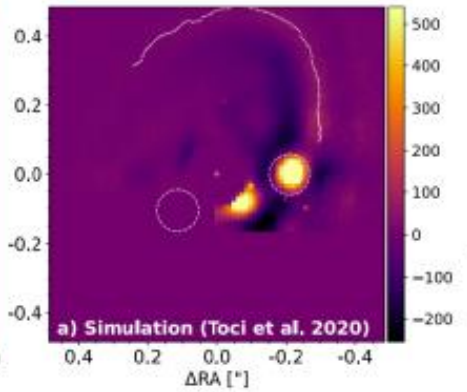
ADI on model



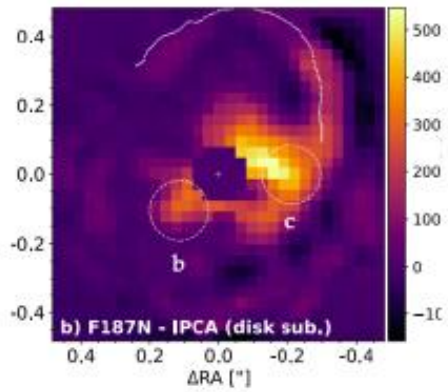
ADI on VLT image



JWST prediction

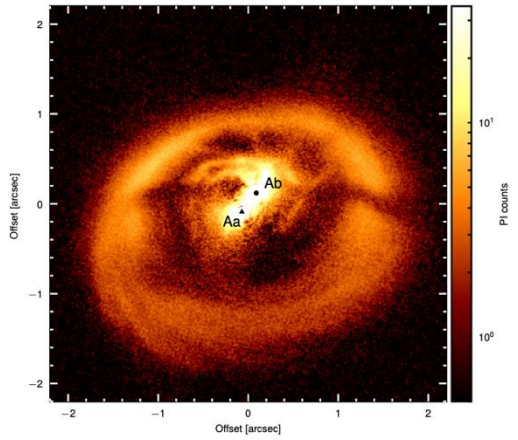


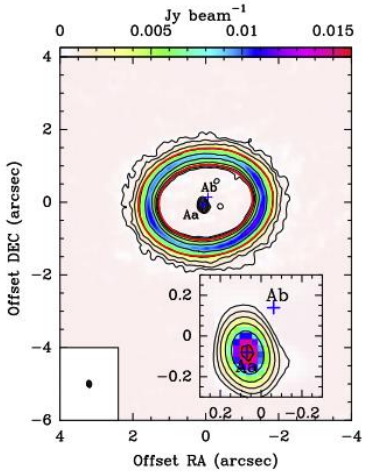
JWST observation



Hydrodynamical model: **Toci** et al. 2020b, Observations: Keppler et al. 2019, Mueller et al. 2018, Christiaens et al. 23

The orbits of binaries





Astrometry

Kohler et al. 2011

Two possible configurations for the primary binary

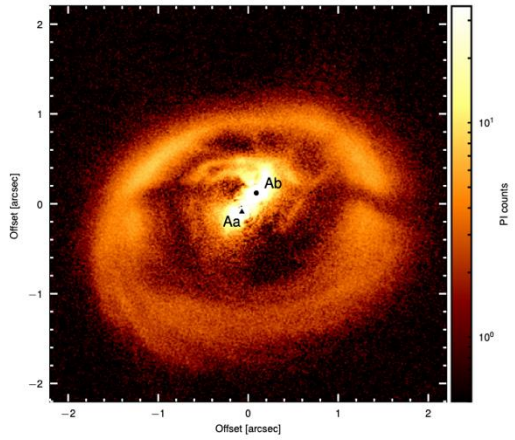
Coplanar (a=35 au)

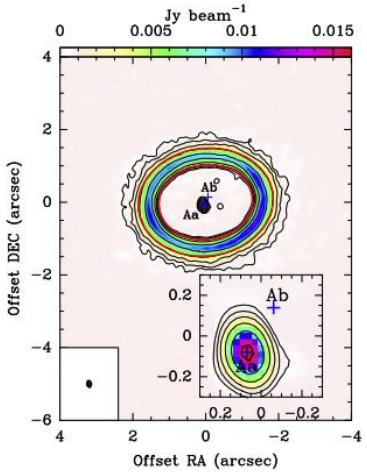
Misaligned (a=60 au)

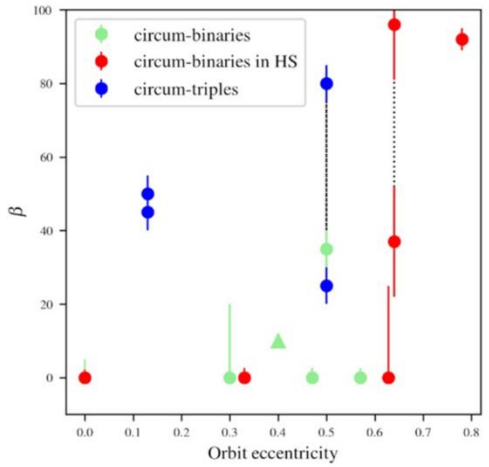
Secondary configuration: unknown (a=1-2 au)

Toci et al. 2024,
Observations:
Kohler et al. 2011
Phuong et al. 2020,
Keppler et al. 2020

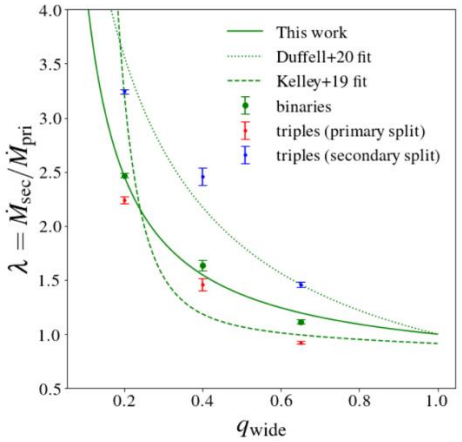
The orbits of binaries







Ceppi et al. 22



Ceppi et al. 23

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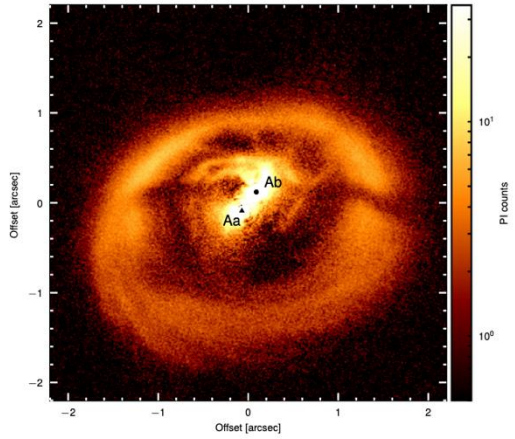
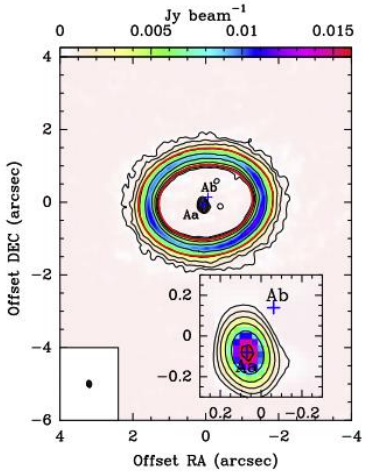
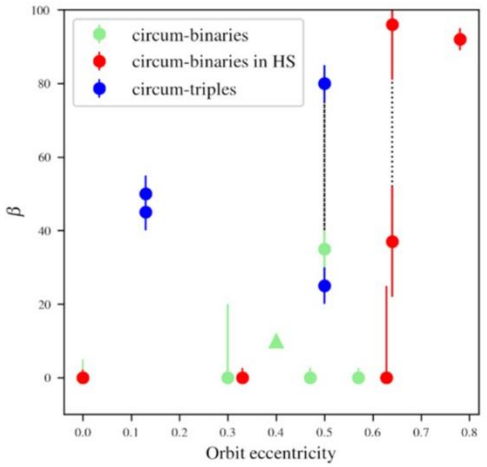
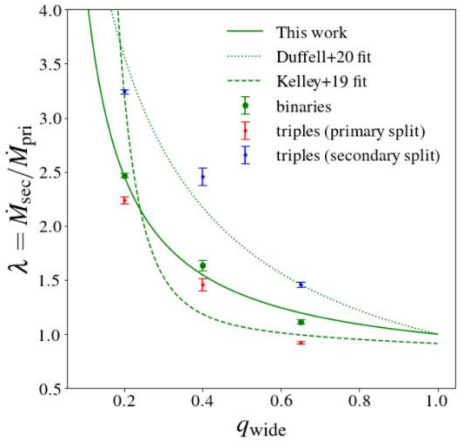
The orbits of binaries







Ceppi et al. 22



Ceppi et al. 23

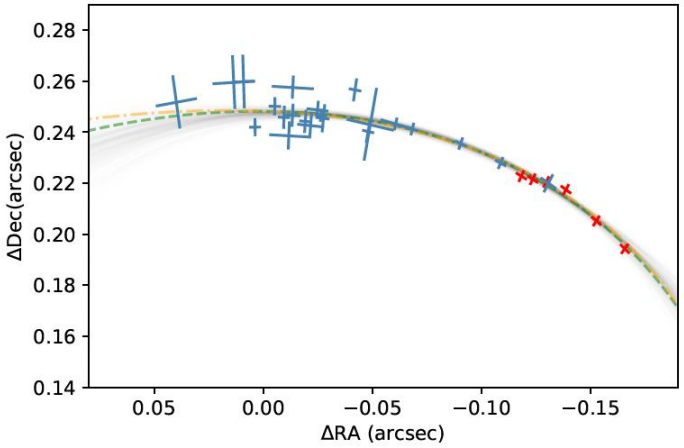
Astrometry

20 years of astrometry

No conclusive answer on the orbits of the primary

Toci et al. 2024

Duchene al. 2024



Secondary configuration:

T = 8 yr , e = 0.5, inclined (38 or 95 deg)

M1,2 = 0.75Msun (equal masses)

Observations:

Kohler et al. 2011

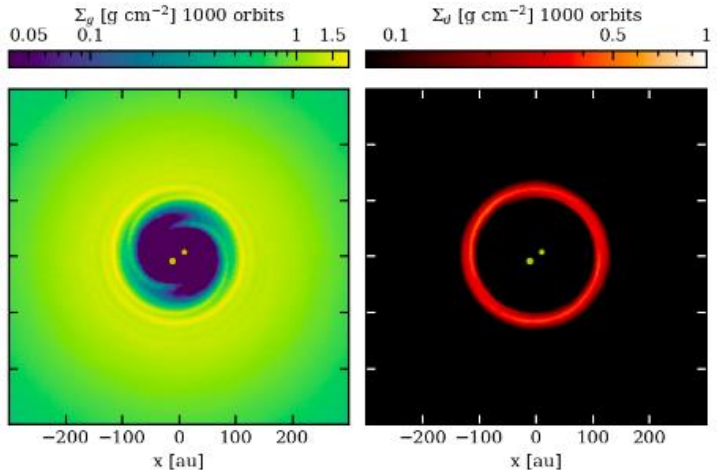
Phuong et al. 2020,

Keppler et al. 2020

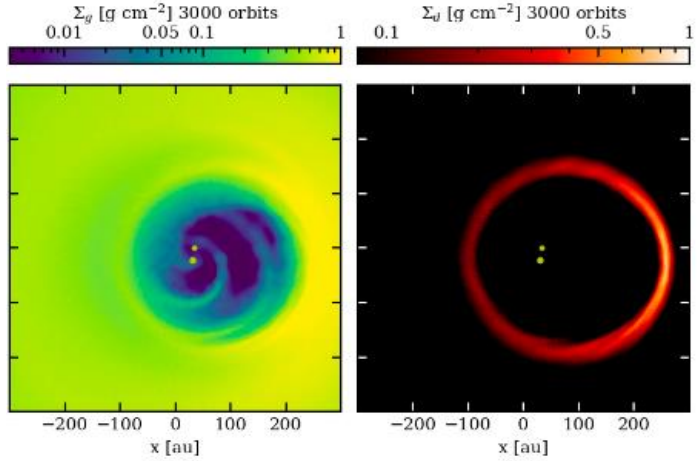
Eccentric cavities or circular cavities?

Same configuration, different time-scales

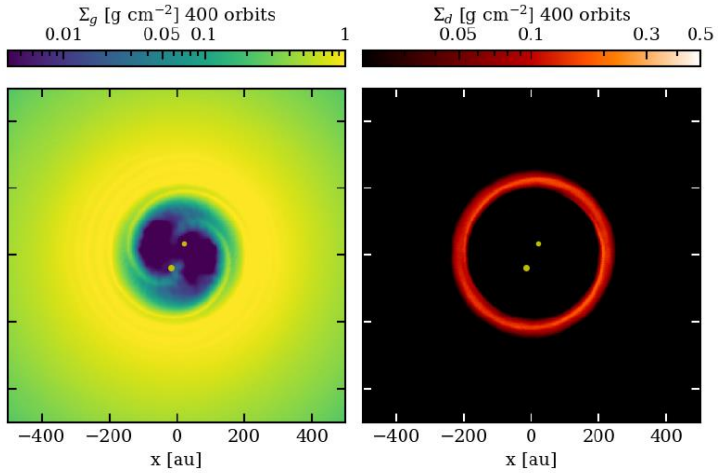
Coplanar case



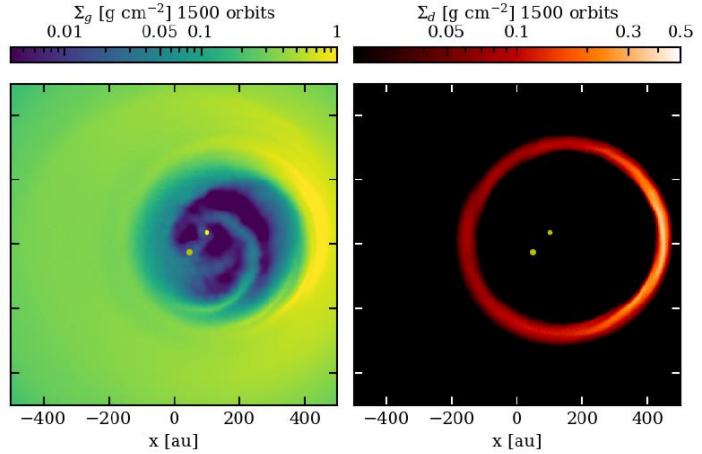
Coplanar after e growth



Misaligned case

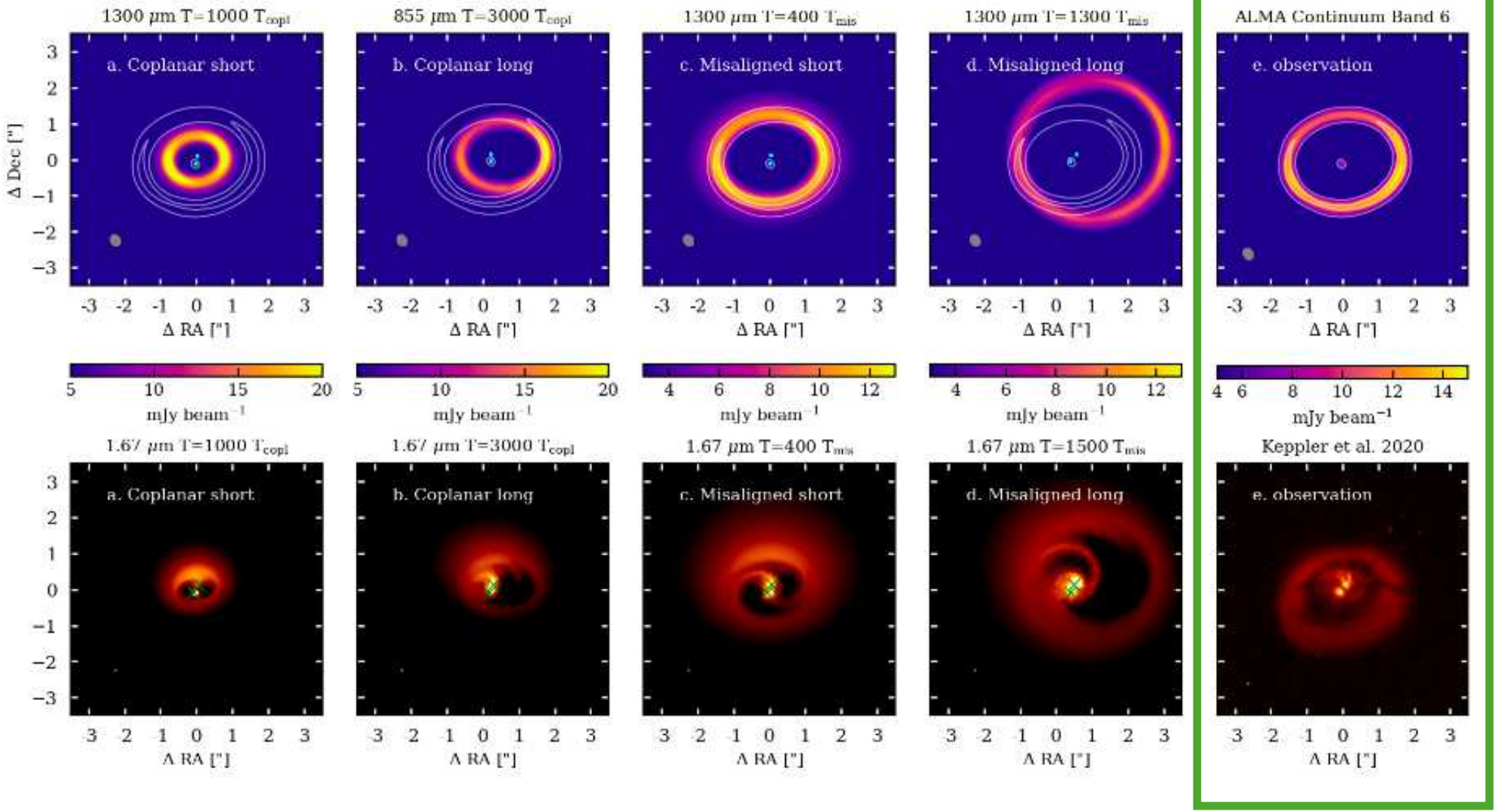


Misaligned after e growth



Theoretical prediction, again

observations



Where are the perturbers?

Can we produce the substructures we observe with planet (perturber) disc interaction?

Yes (but not only, e.g., winds?)

Are the substructures we are observing generated by protoplanets (perturbers) interacting with their disc?

Yes (but not only, e.g., winds?)

Can we learn something on the planets (perturbers) generating the substructures?

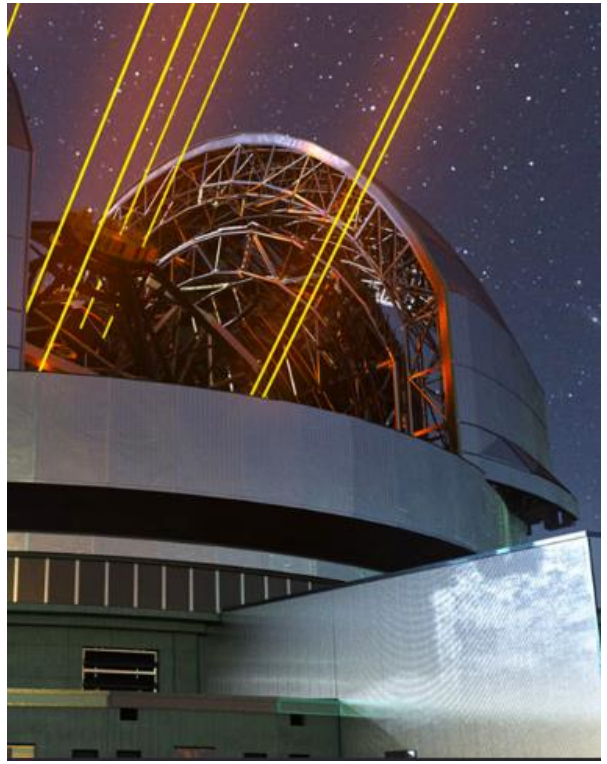
Yes (but not only, e.g., winds?)

To the future and beyond

SKA (interferometry, cm size)

Ilee et al. 2020

Wu & Speedie et al. in prep.



MICADO/MORFEO
(imager, 2 μm size)

To the future and beyond

MICADO/MORFEO @ELT (μm size)

Atmospheric background
As a function of wavelength

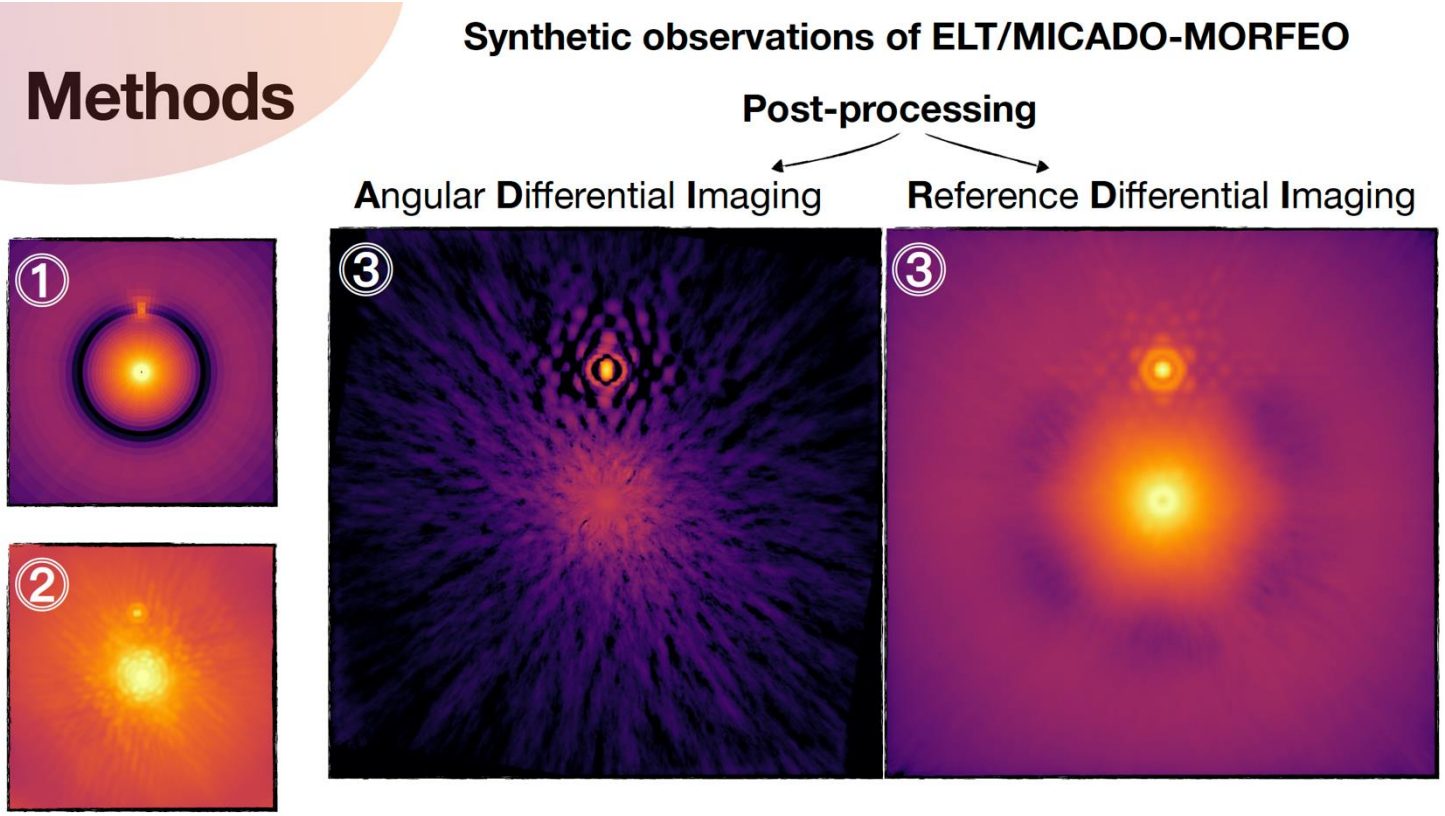
Lyot coronagraph

PSF sequence
90 images, 10s each, NCPA

Detector noises
Shot noise, Readout noise

COMPASS/MYSTHIC software
Baudoz+2019

Methods



Detectable:

Jupiter planets in open gaps (AO is good)

Gaps for bright star, not too close (contrast), not too far away (gap is not empty)

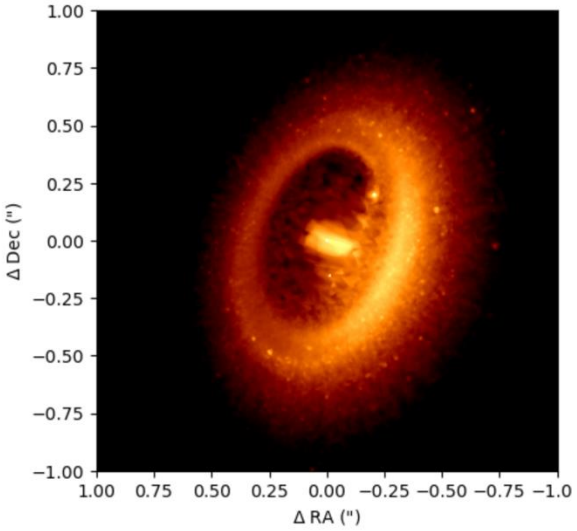
Alaguero and the Jediex collab. in prep

Toci and the JediEx collaboration in prep.

Testing the limits

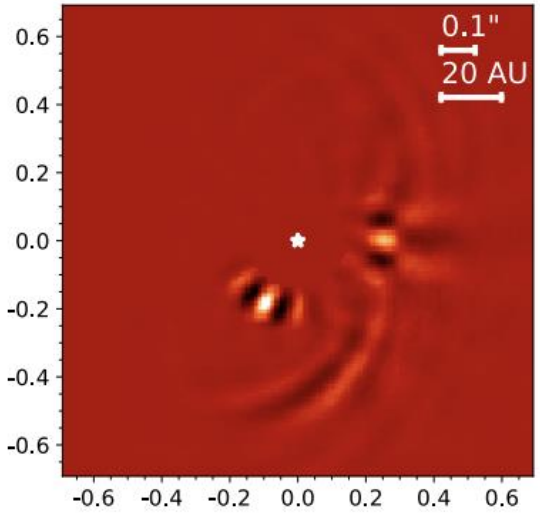
Model

(Toci et al. 2020)



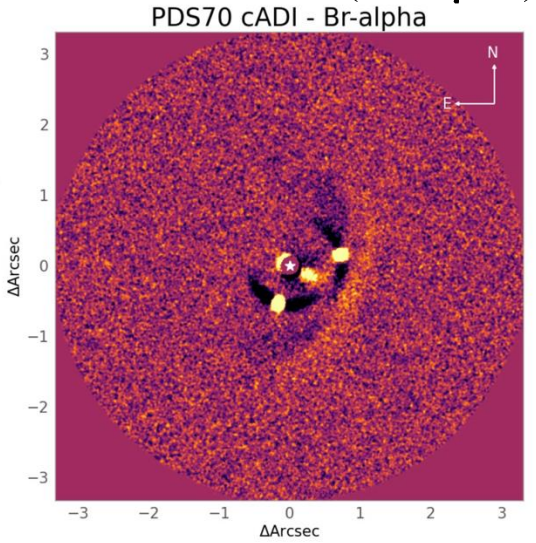
SPHERE

PCA on model (2.2 μm)



ERIS

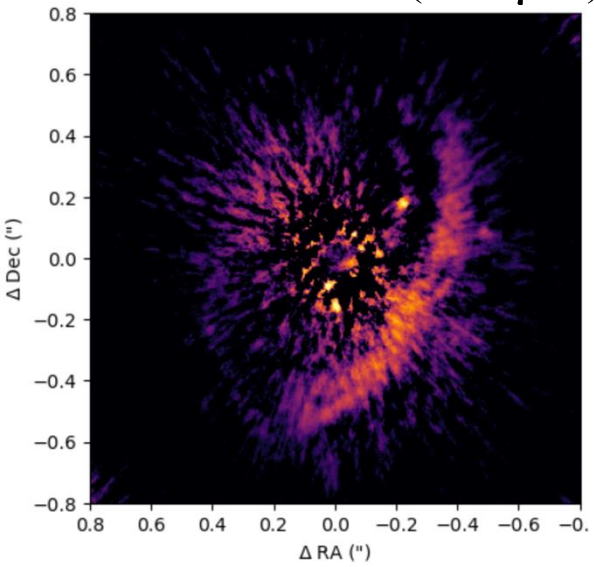
ADI on model (4.78 μm)



Maio et al. 2025c in prep.

MICADO

PCA on model (1.65 μm)



Alaguero and the Jediex collab. in prep

Toci and the JediEx collaboration in prep.

Future perspectives

- Increase the resolution: SHAMROCK and APR
  (e.g., testing GG Tau with increased resolution)

- Accurate temperature layers: PHANTOM + MCFOST
  (e.g., testing GG Tau with different temperature structures)

- Chemical complexity: PHANTOM + KROME
  (e.g., testing molecular emission of GG Tau)

Take home message

- Planet-perturber interaction fundamental to understand observations obtained with current AND future facilities
- Protoplanets and binaries are there, we just need to understand how to see (and characterize) them!
- Phantom can help us in finding good candidates for protoplanets detection

Thank you!