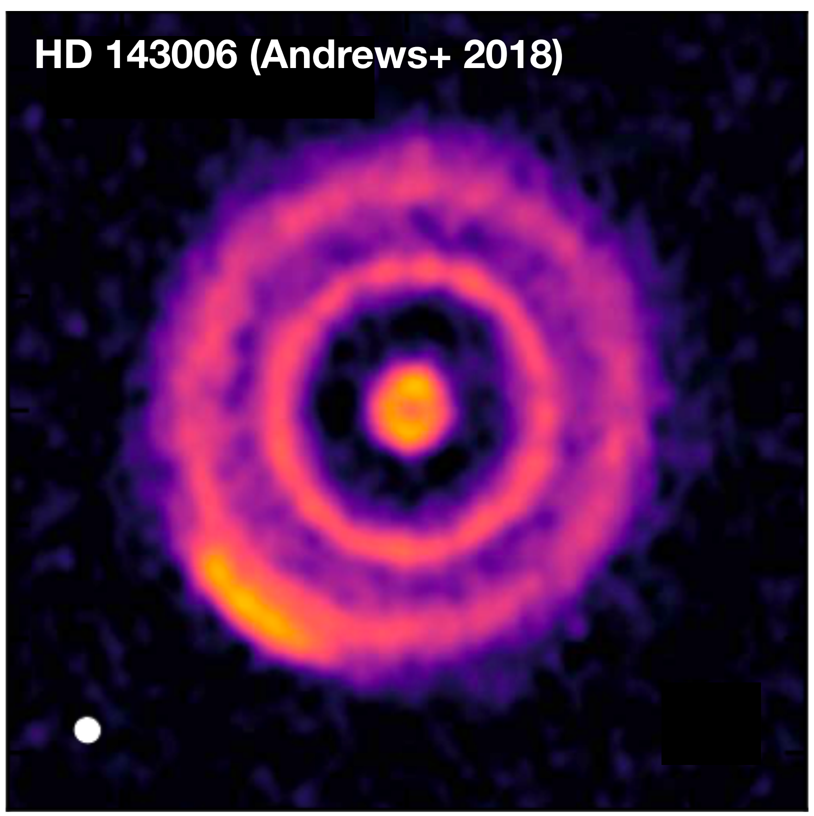
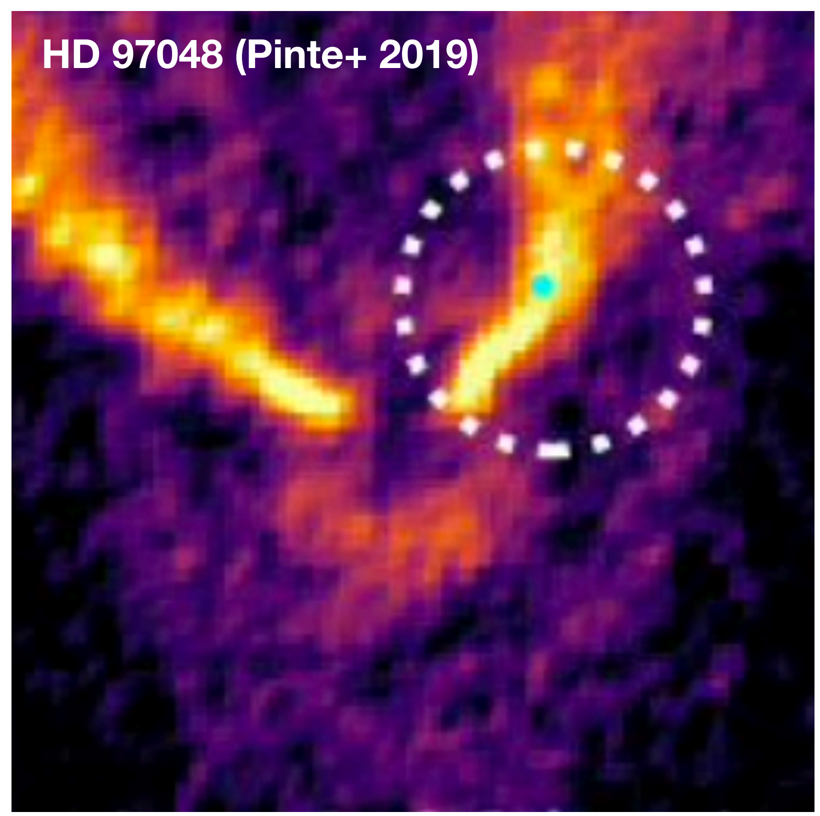
Dynamics and emission of gas and dust in protoplanetary discs

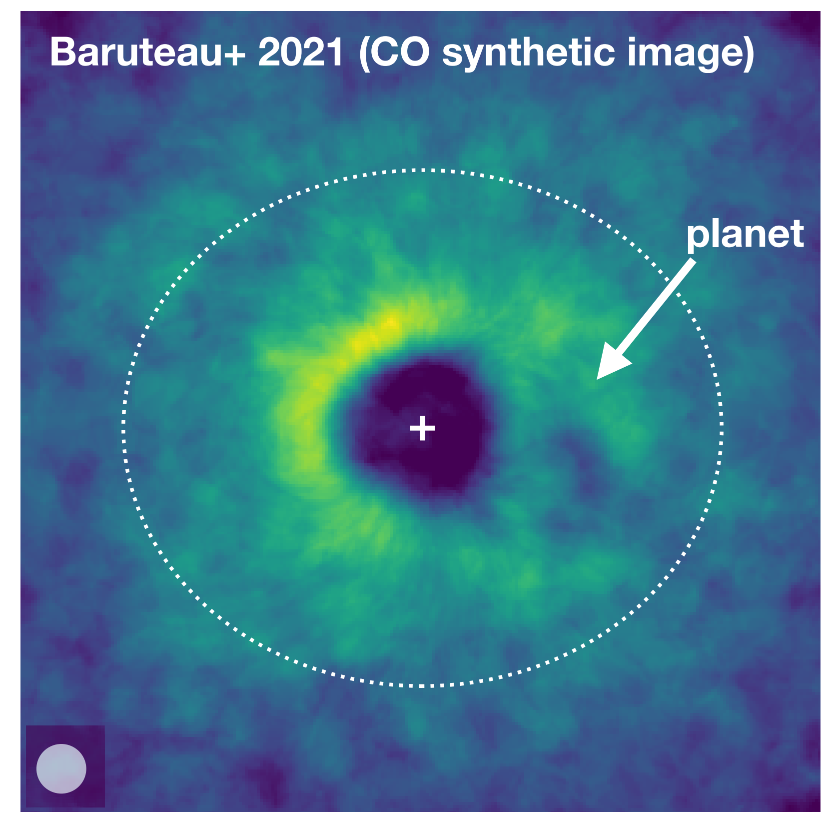
Clément Baruteau (CNRS/IRAP)

&

Gaylor Wafflard-Fernandez, Romane Le Gal, Florian Debras, Andrés Carmona, Asunción Fuente, Pablo Rivière-Marichalar

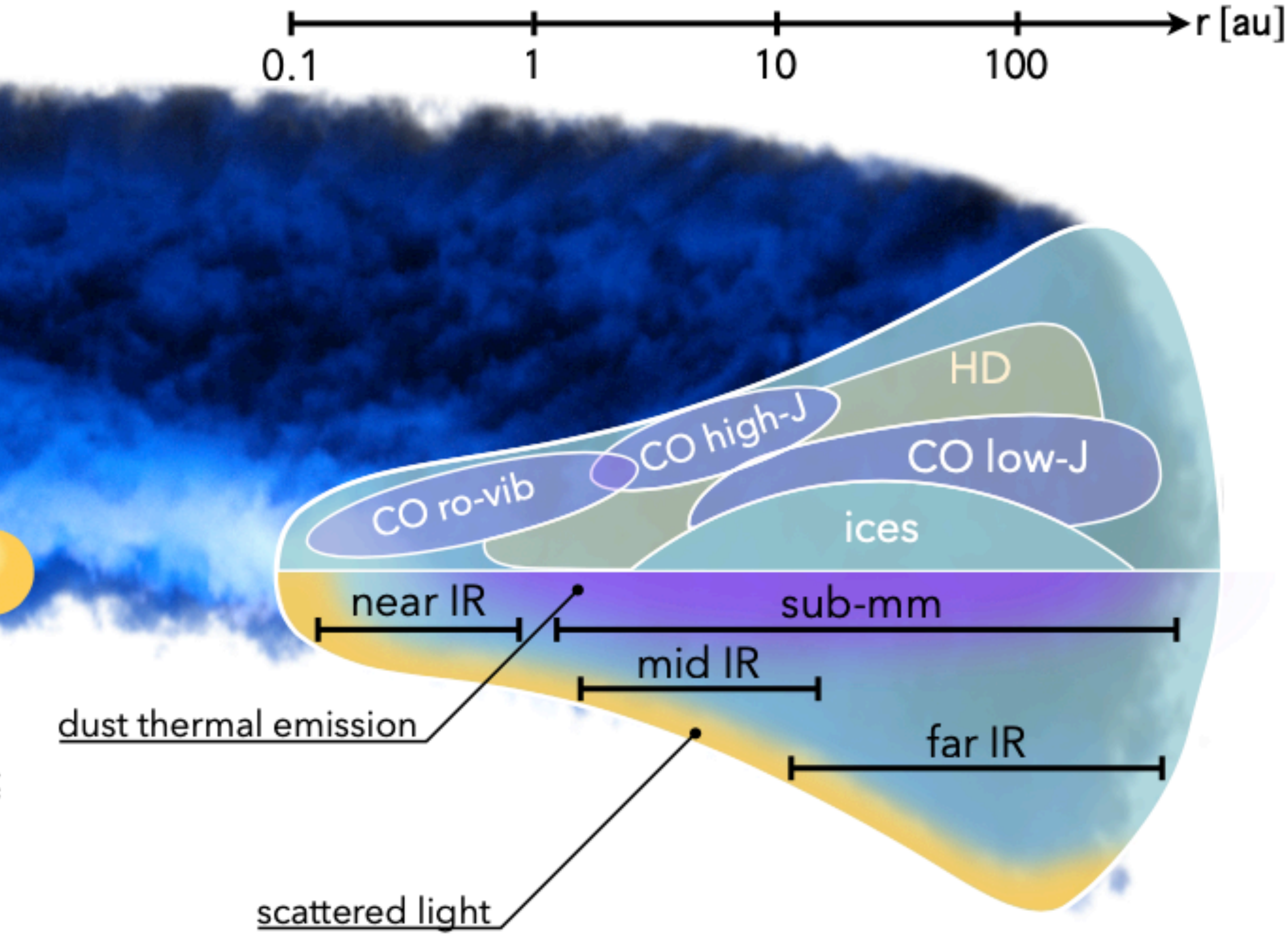






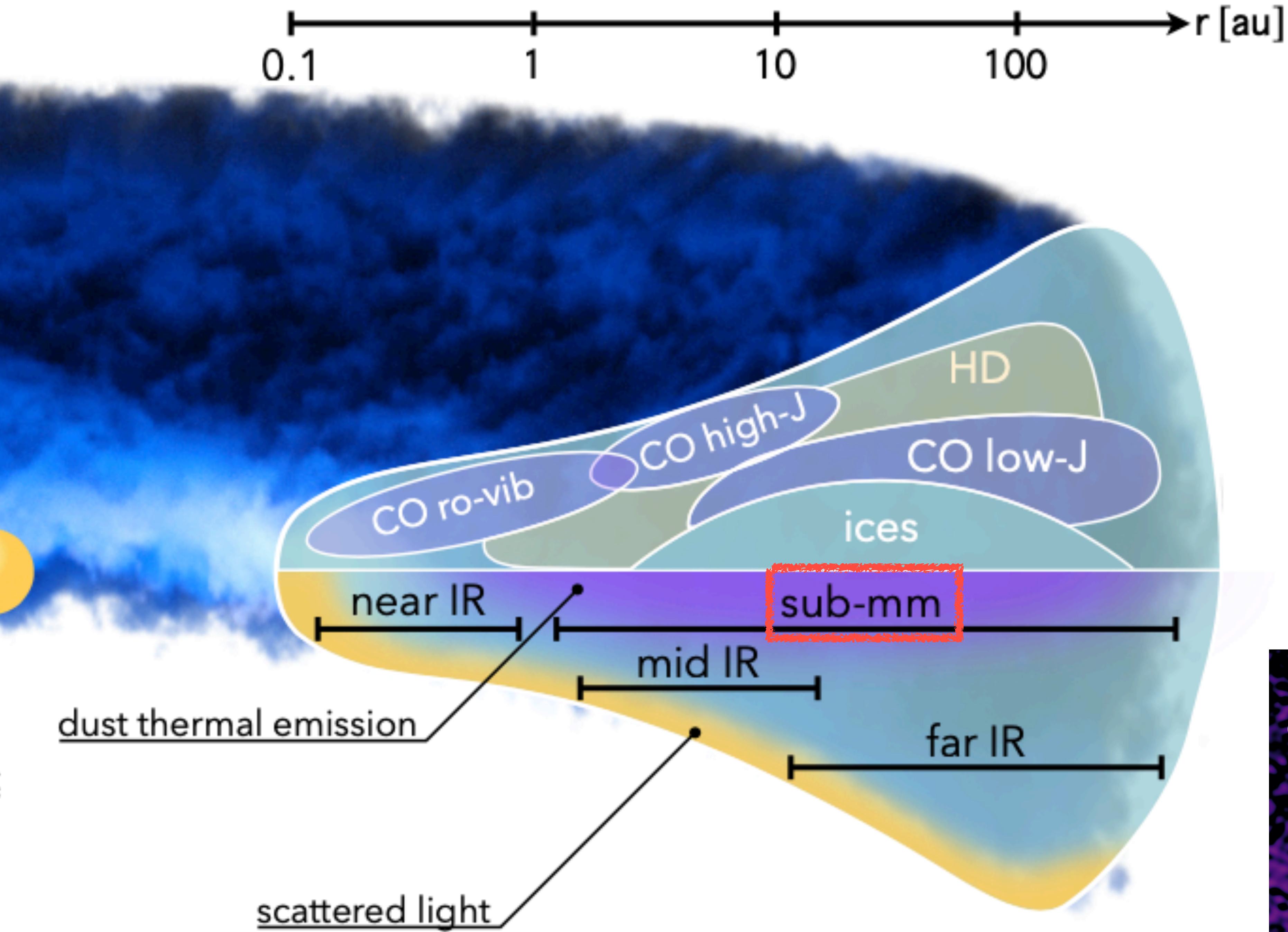
PCMI biennial conference - 28 October 2022

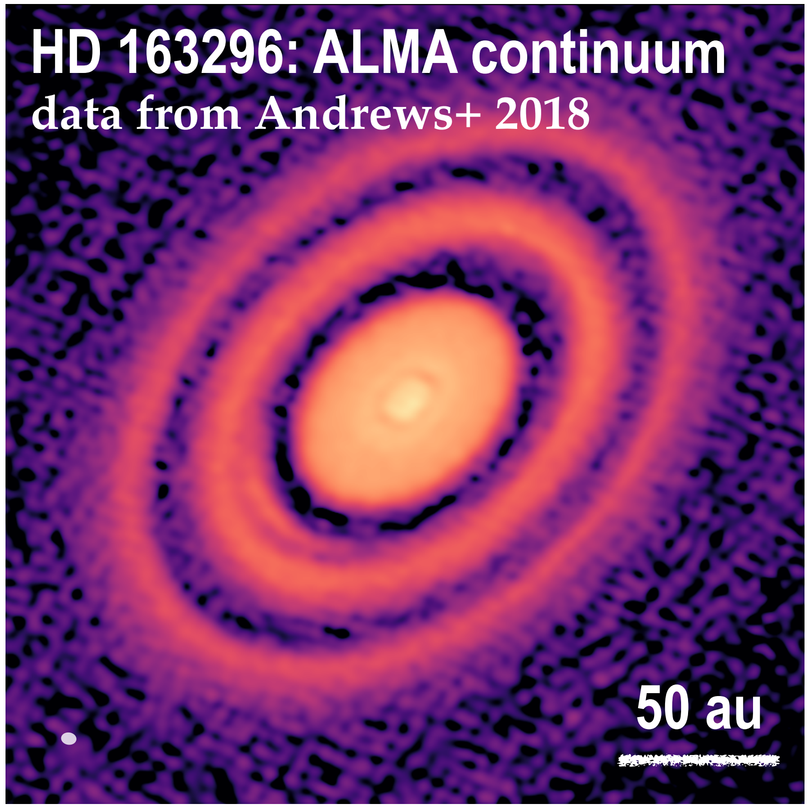
Protoplanetary discs observations



Miotello+ 2022 (PPVII)

Protoplanetary discs observations





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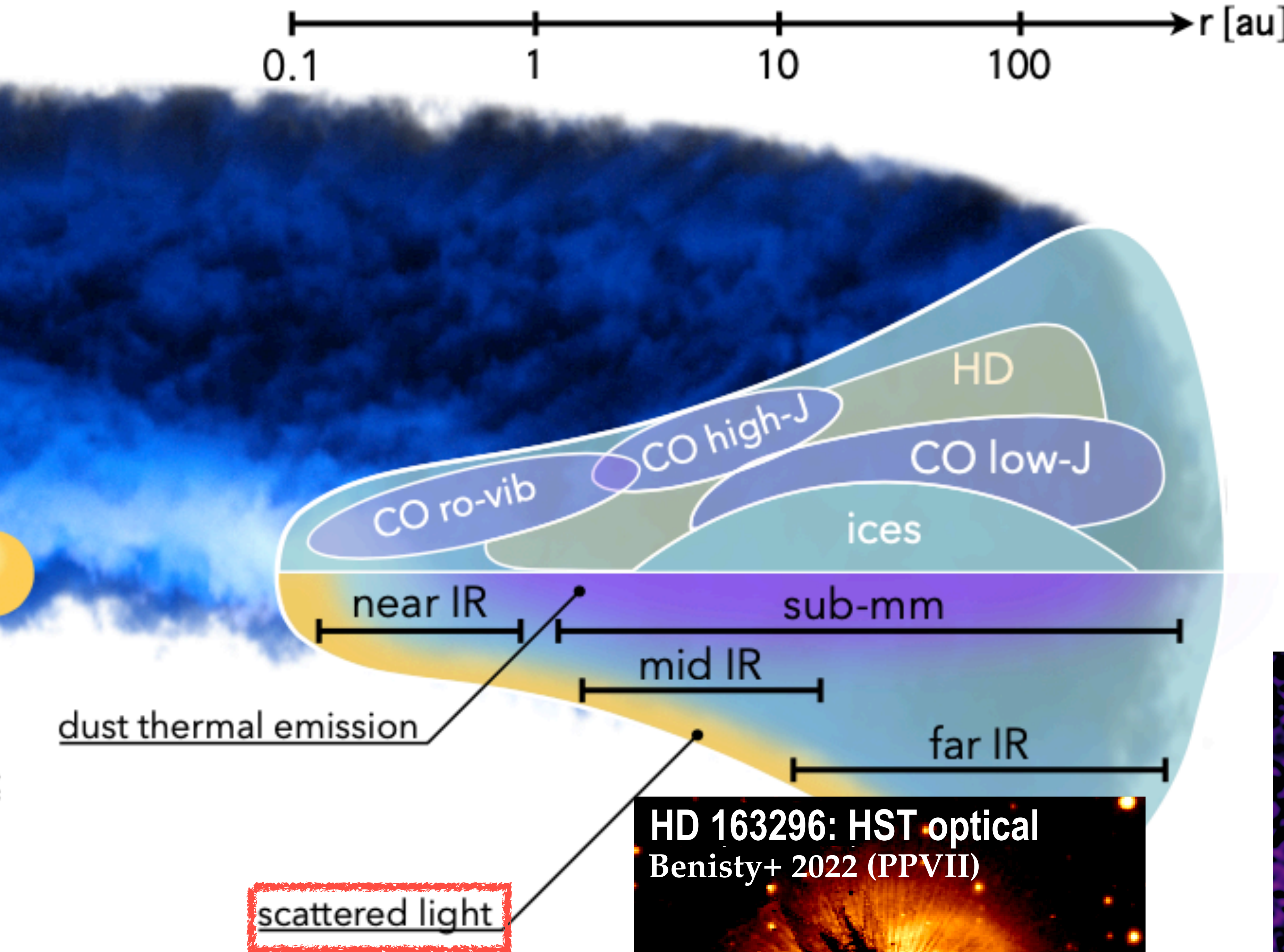

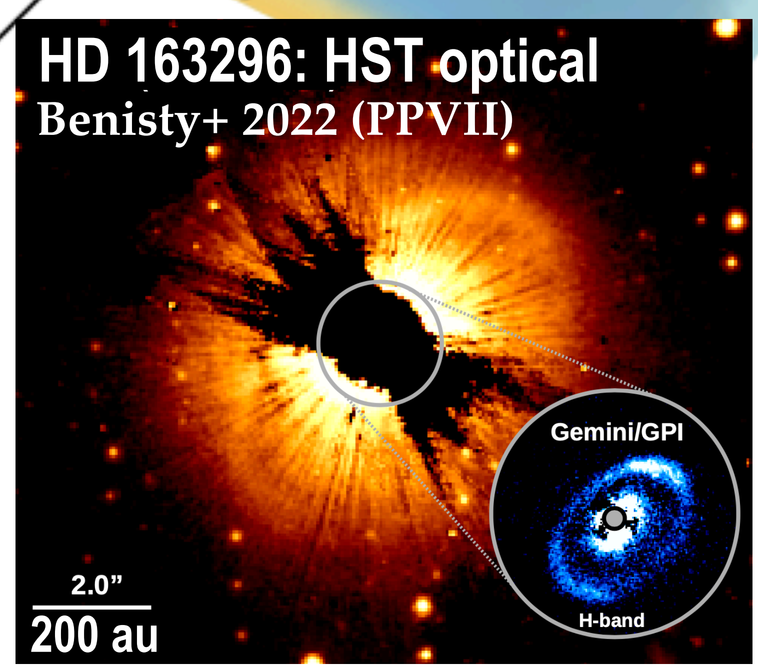

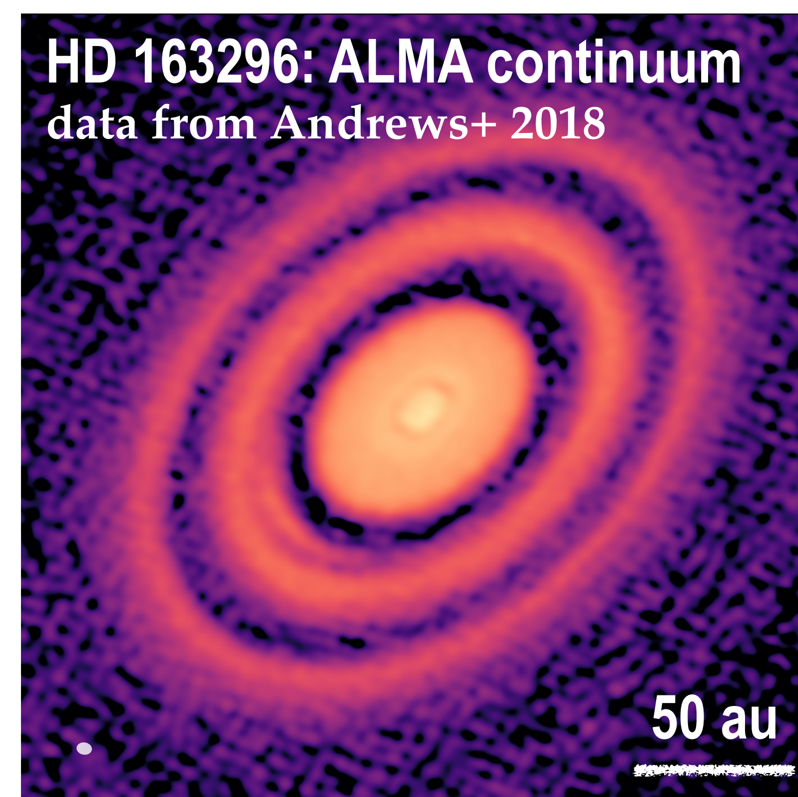

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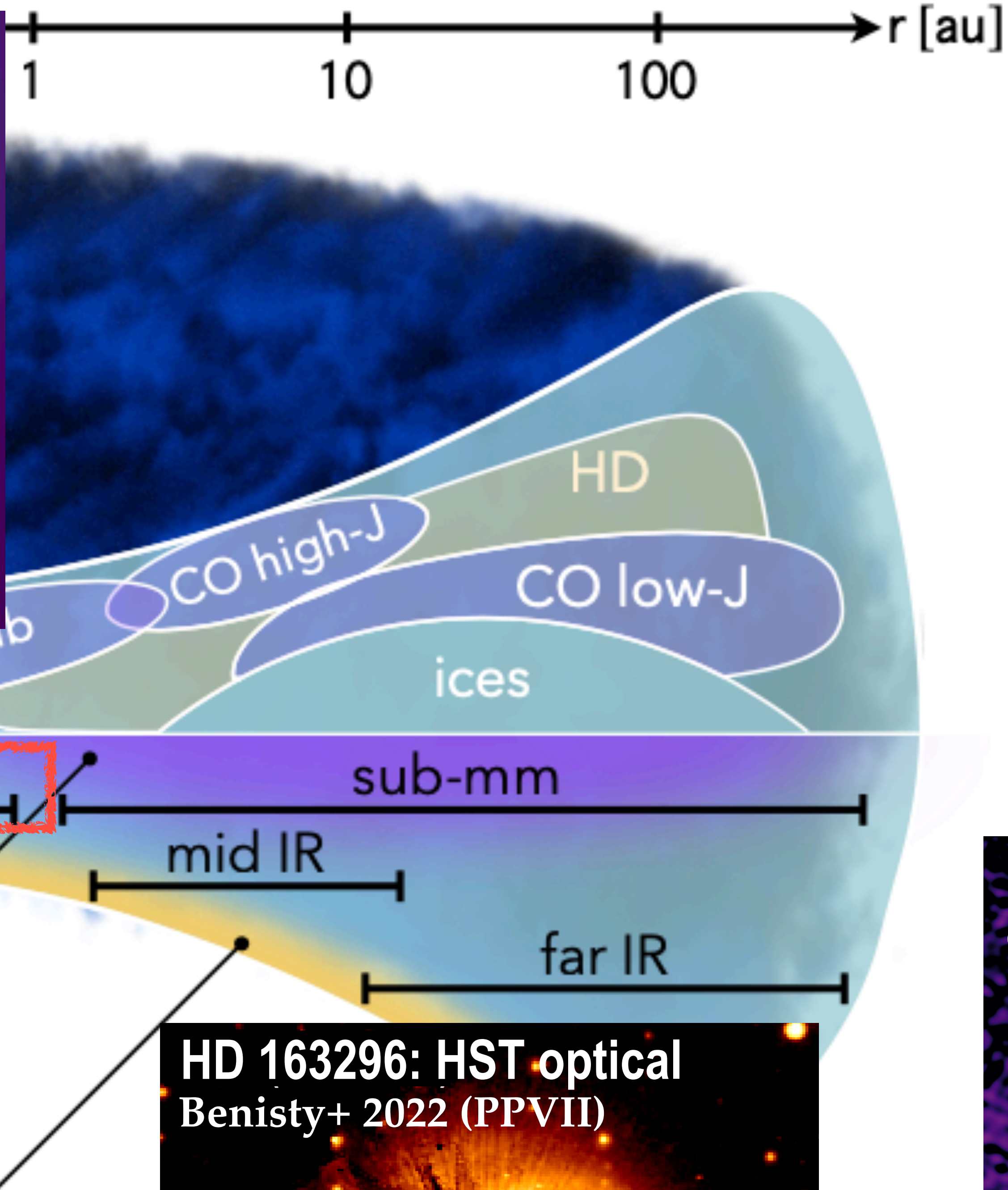
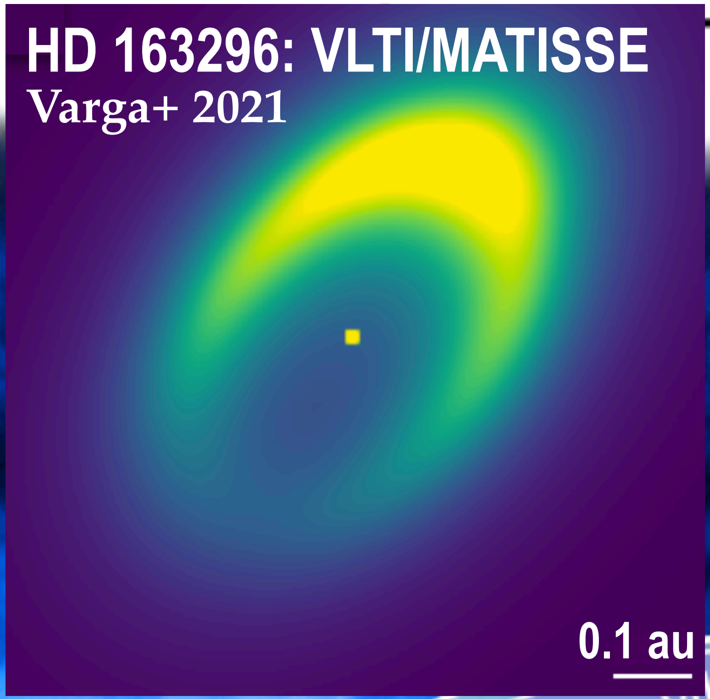
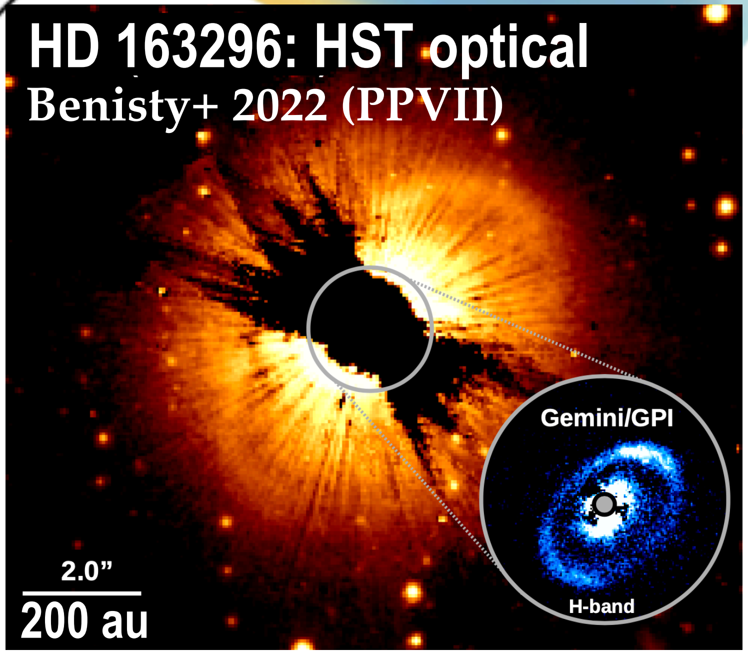
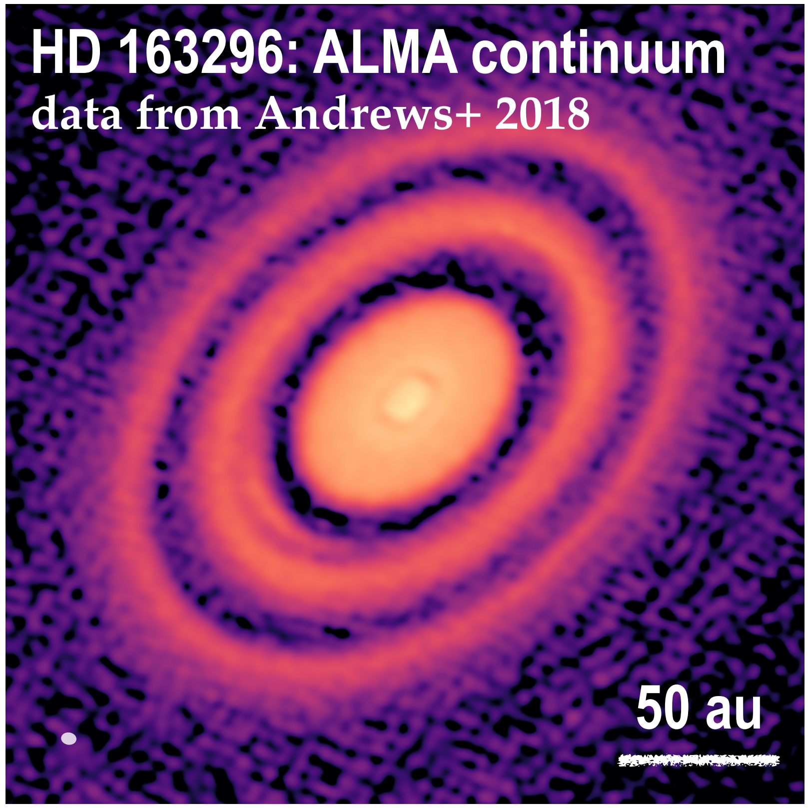
Protoplanetary discs observations









Miotello+ 2022 (PPVII)

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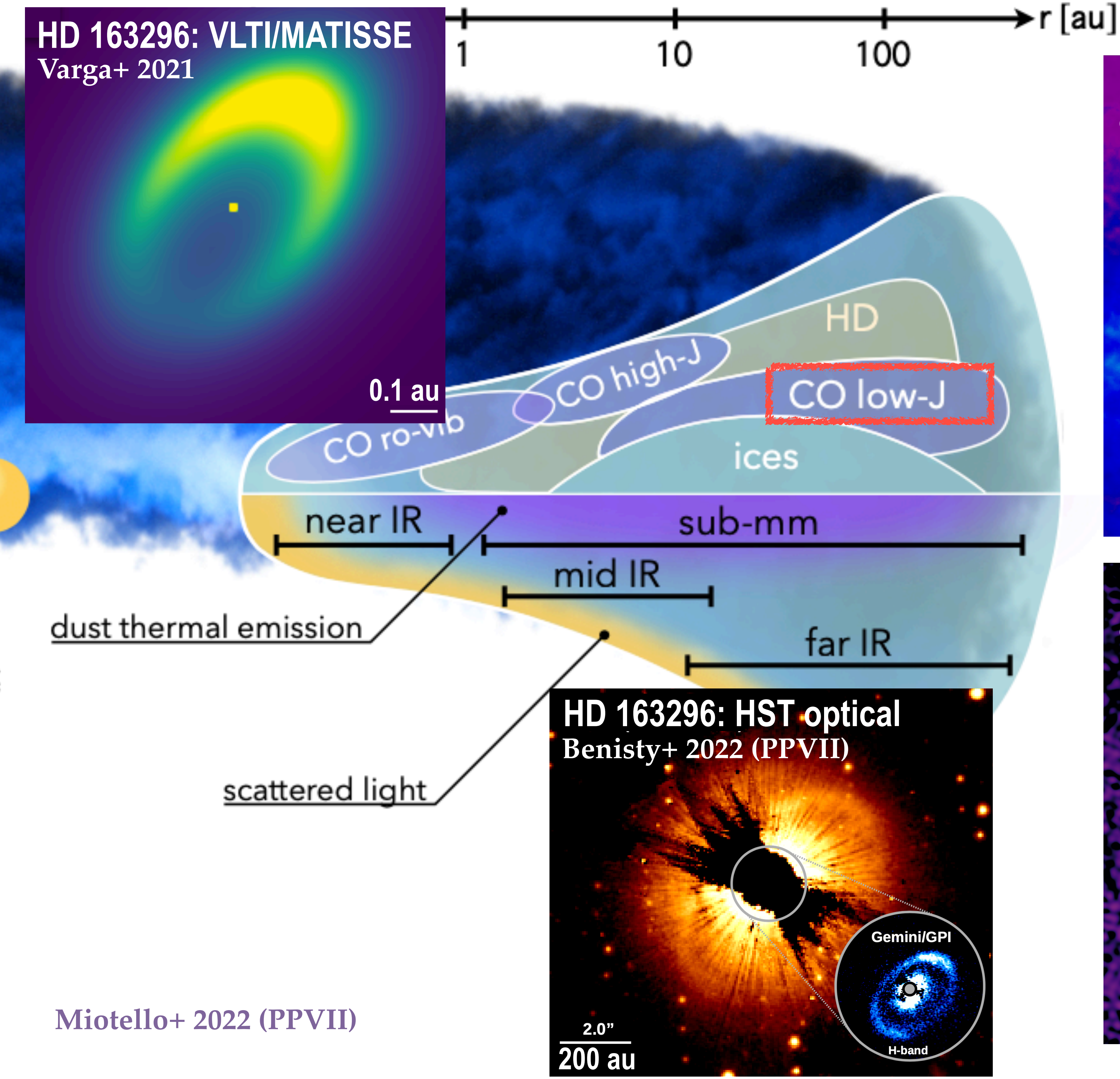

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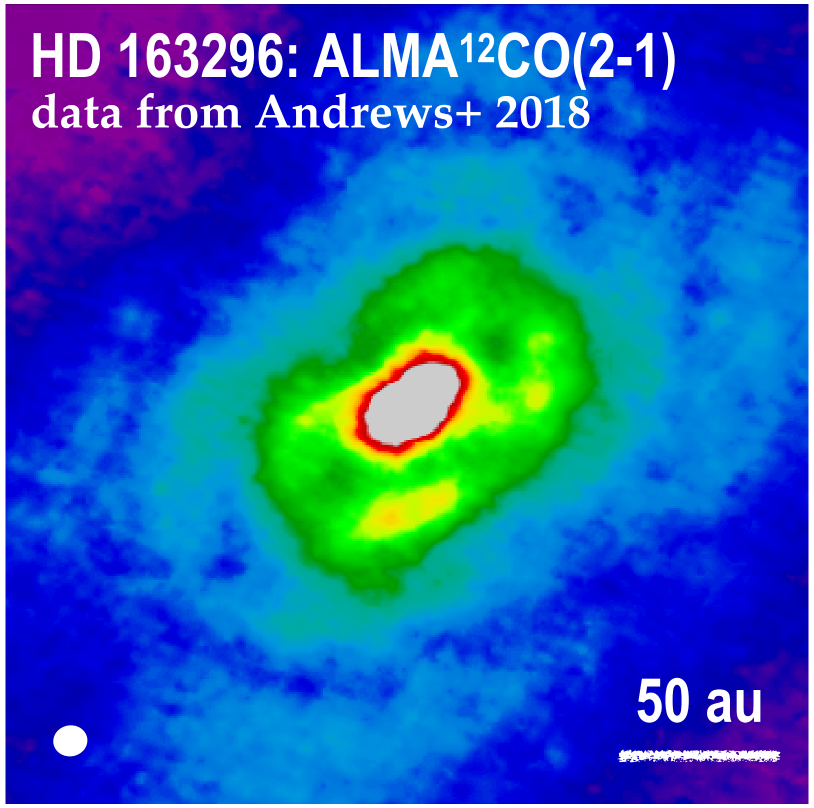

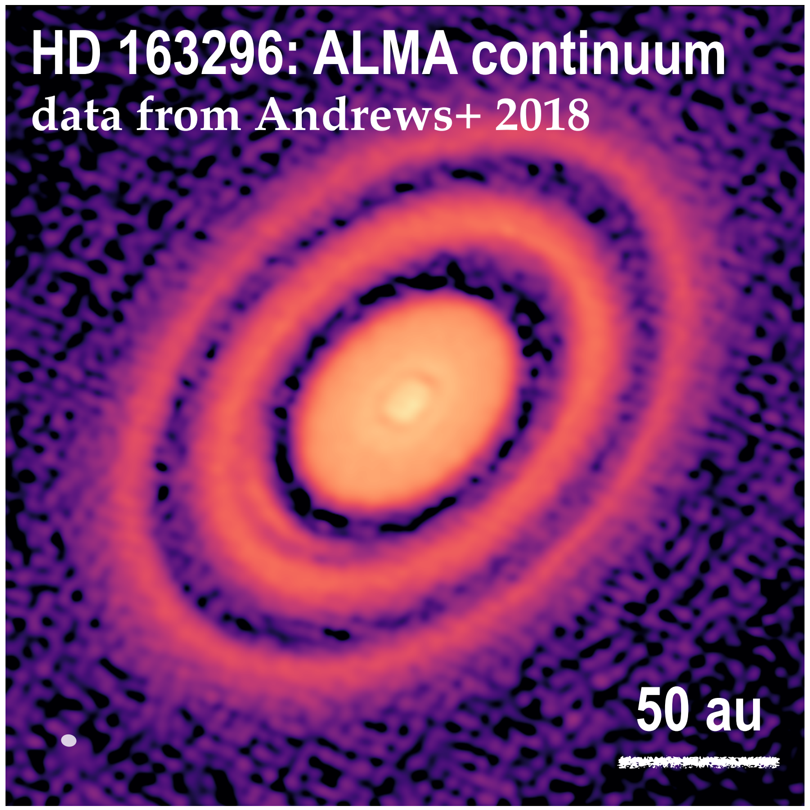

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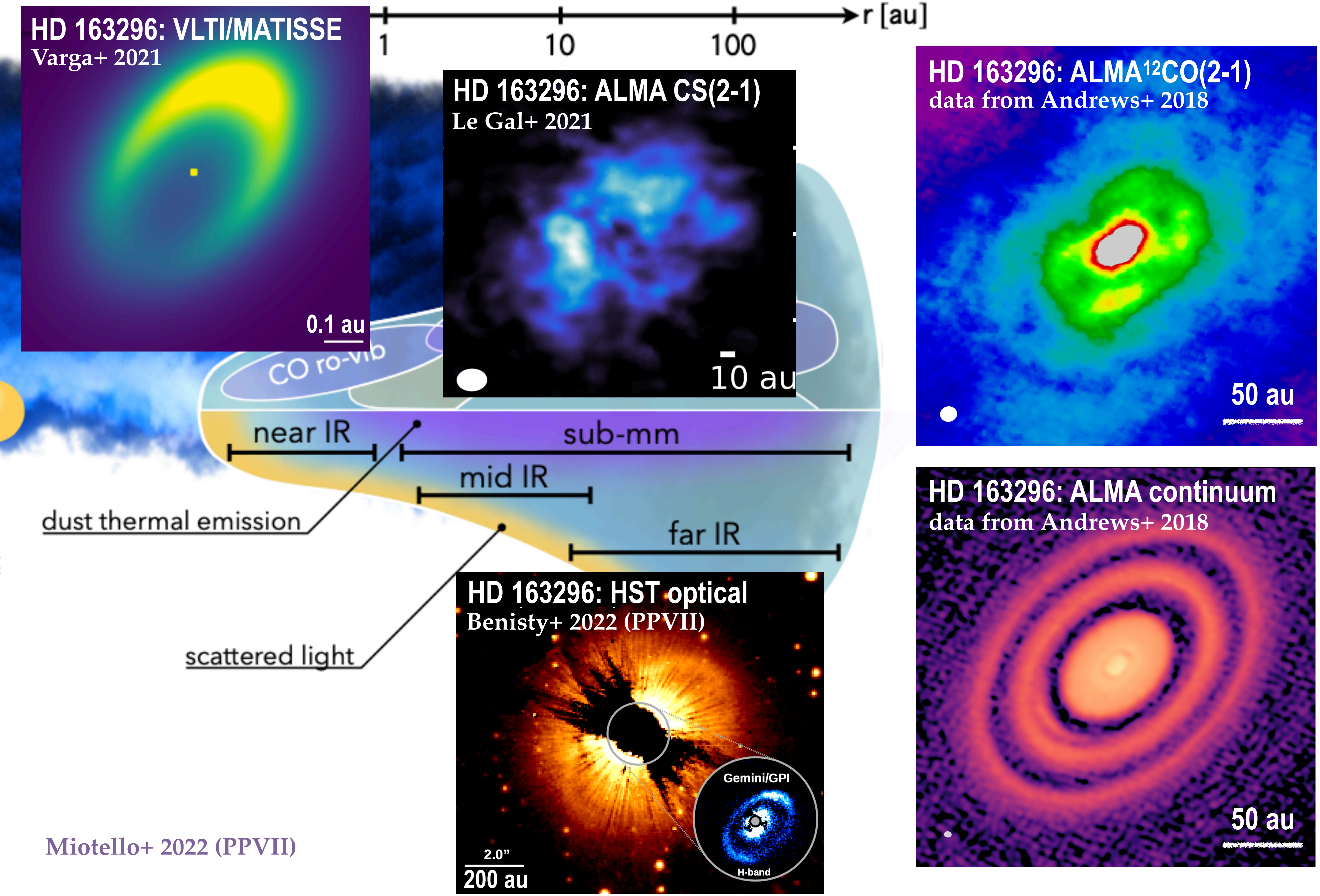
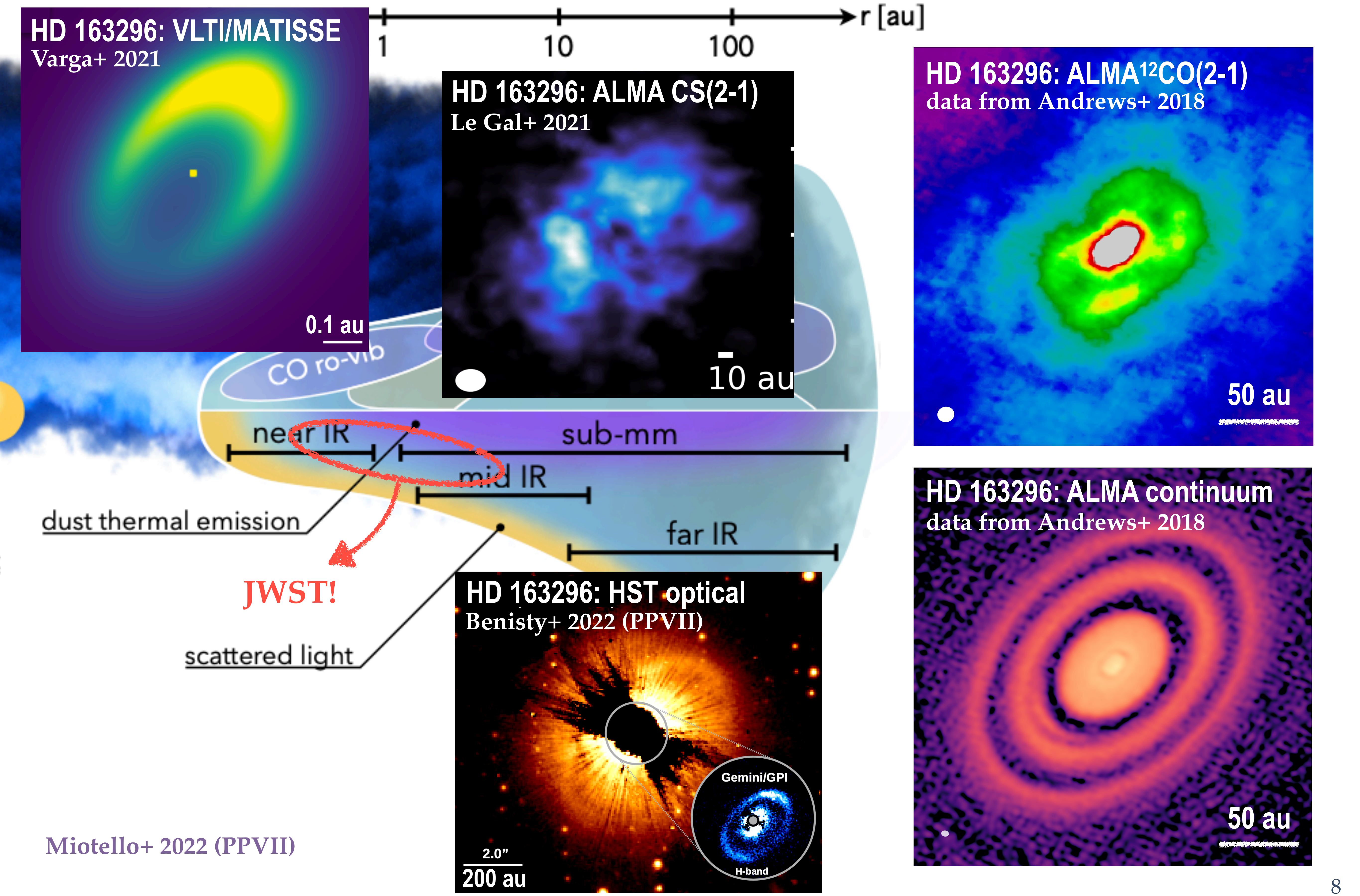
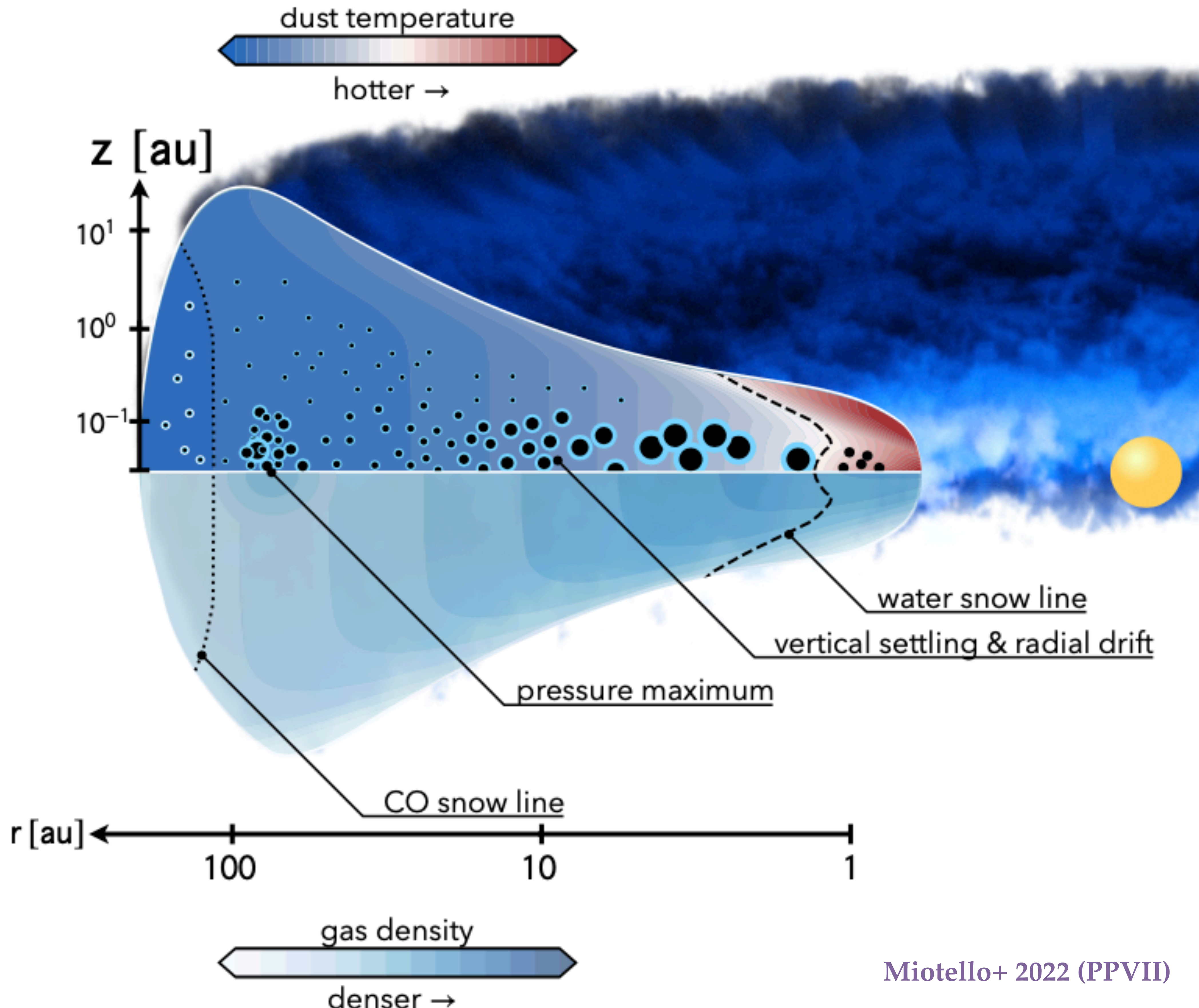


Miotello+ 2022 (PPVII)

Protoplanetary discs observations

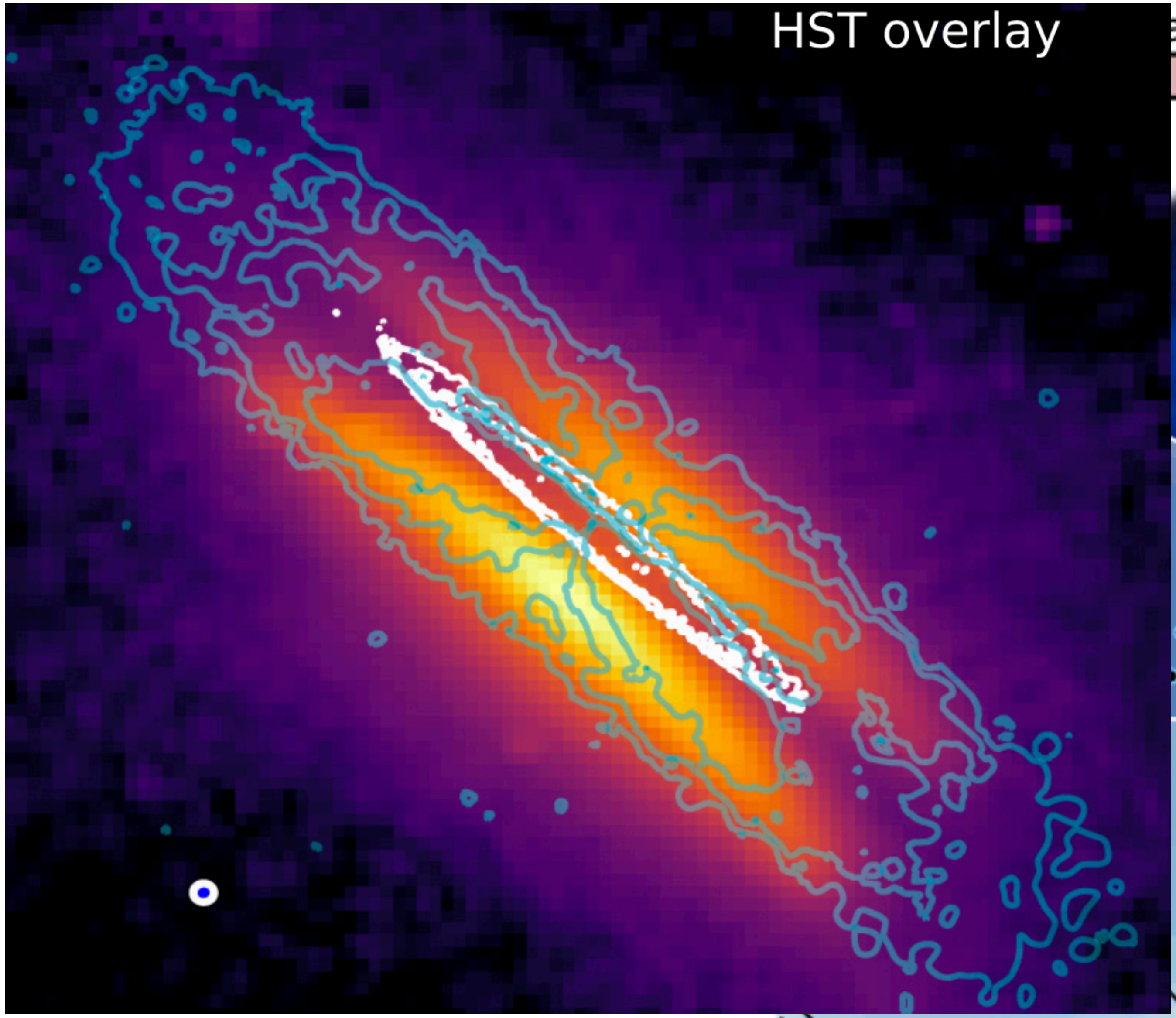


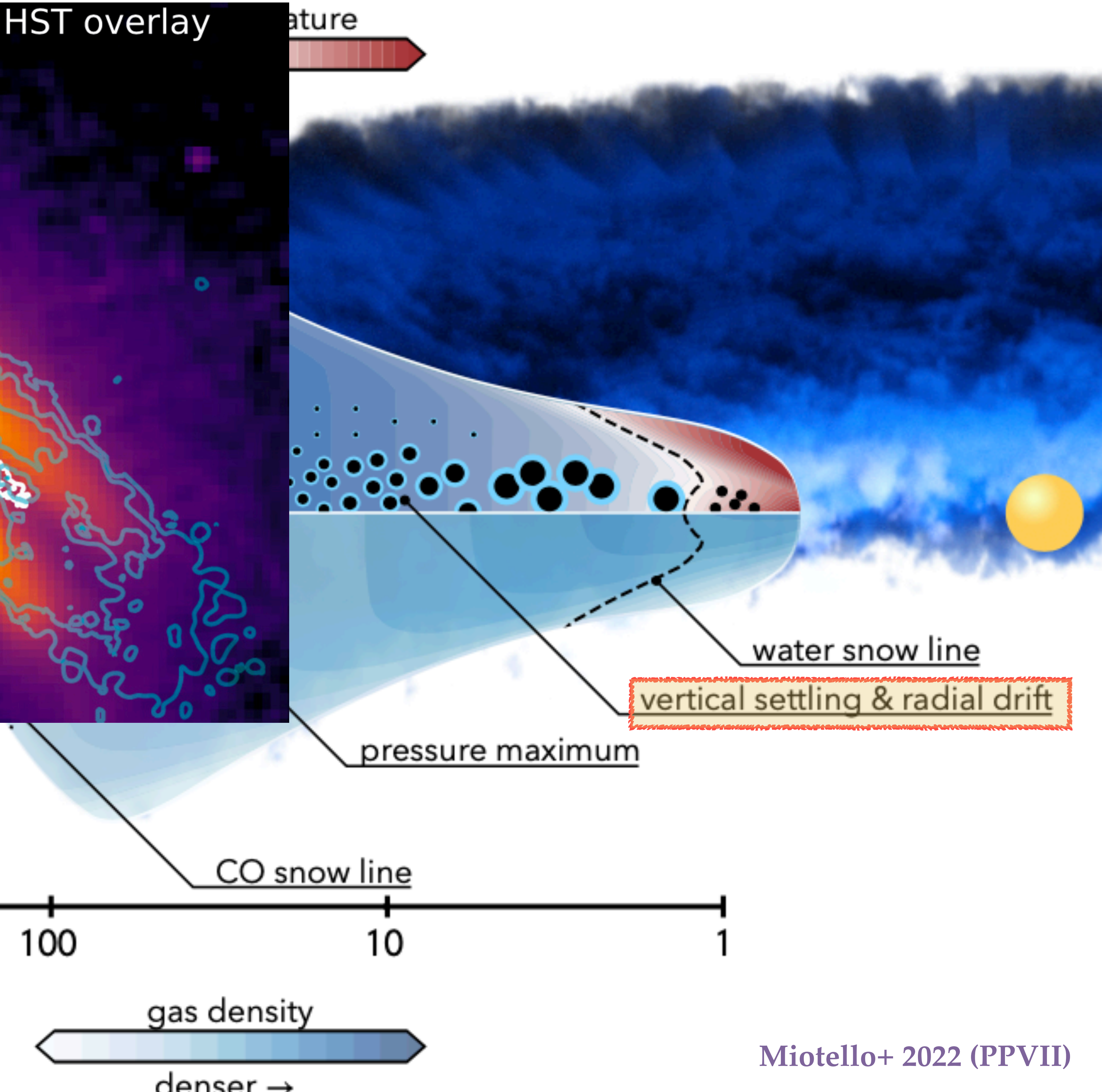
Protoplanetary discs structure



Miotello+ 2022 (PPVII)

Protoplanetary discs structure



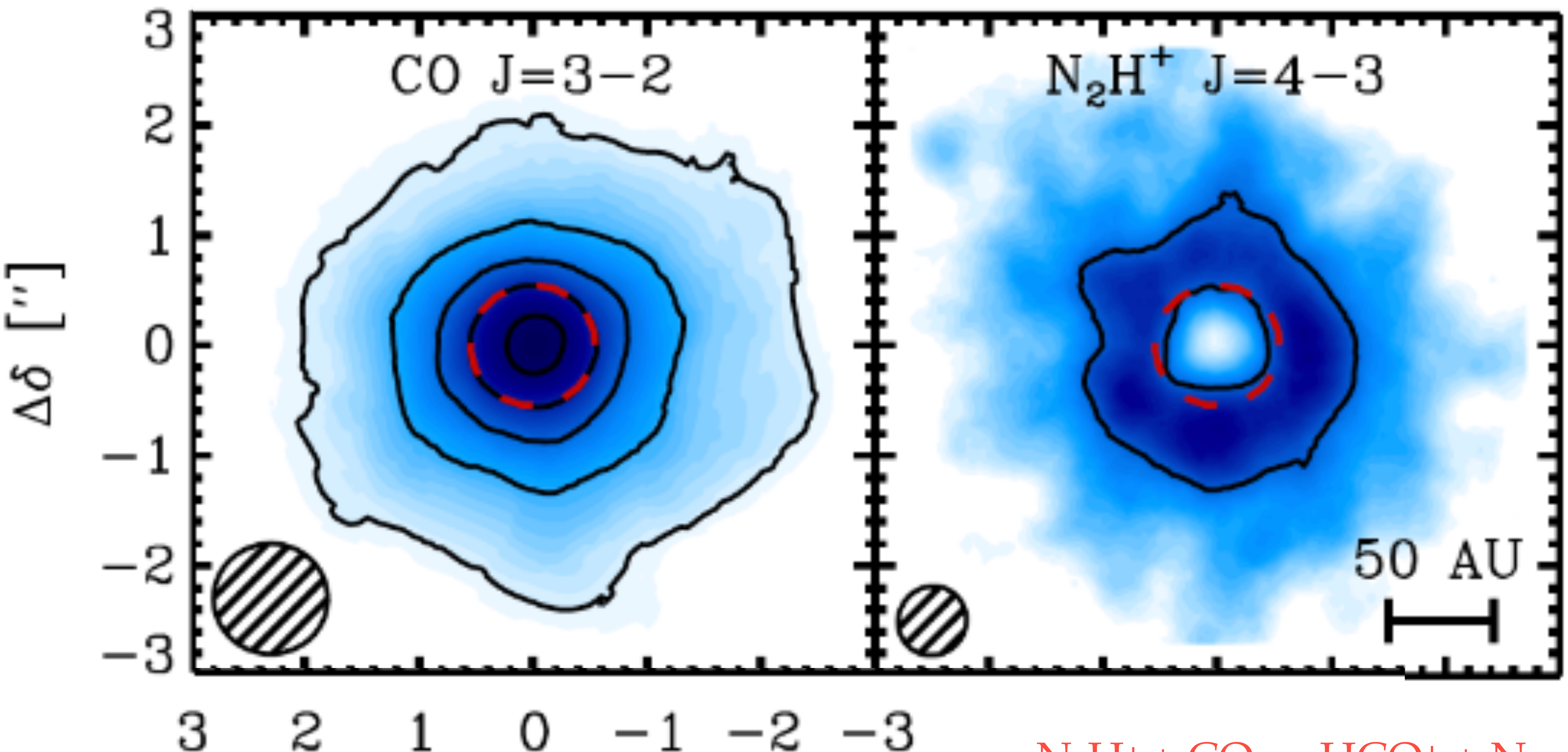


Villenave+ 2022 (Oph 163131 disc)

color: HST scattered light @0.6μm
blue: ^{12}CO(2-1)
white: continuum @1.3mm

Miotello+ 2022 (PPVII)

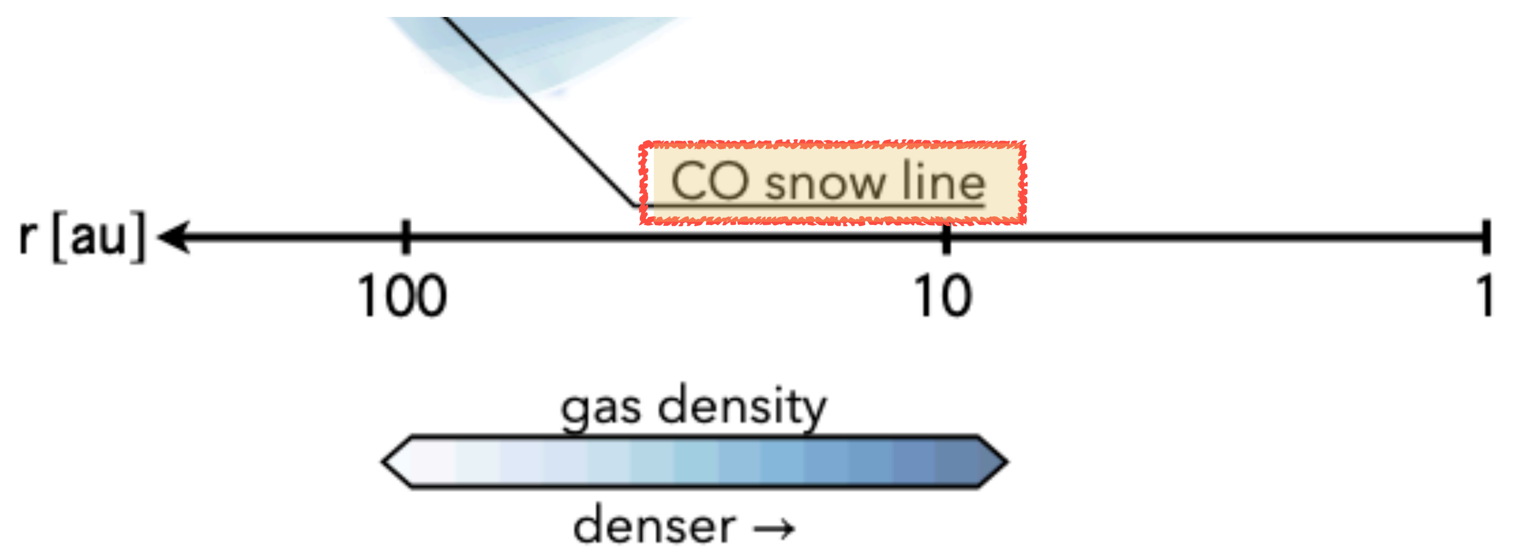
Protoplanetary discs structure



Qi+ 2013
(TW Hya, early ALMA)

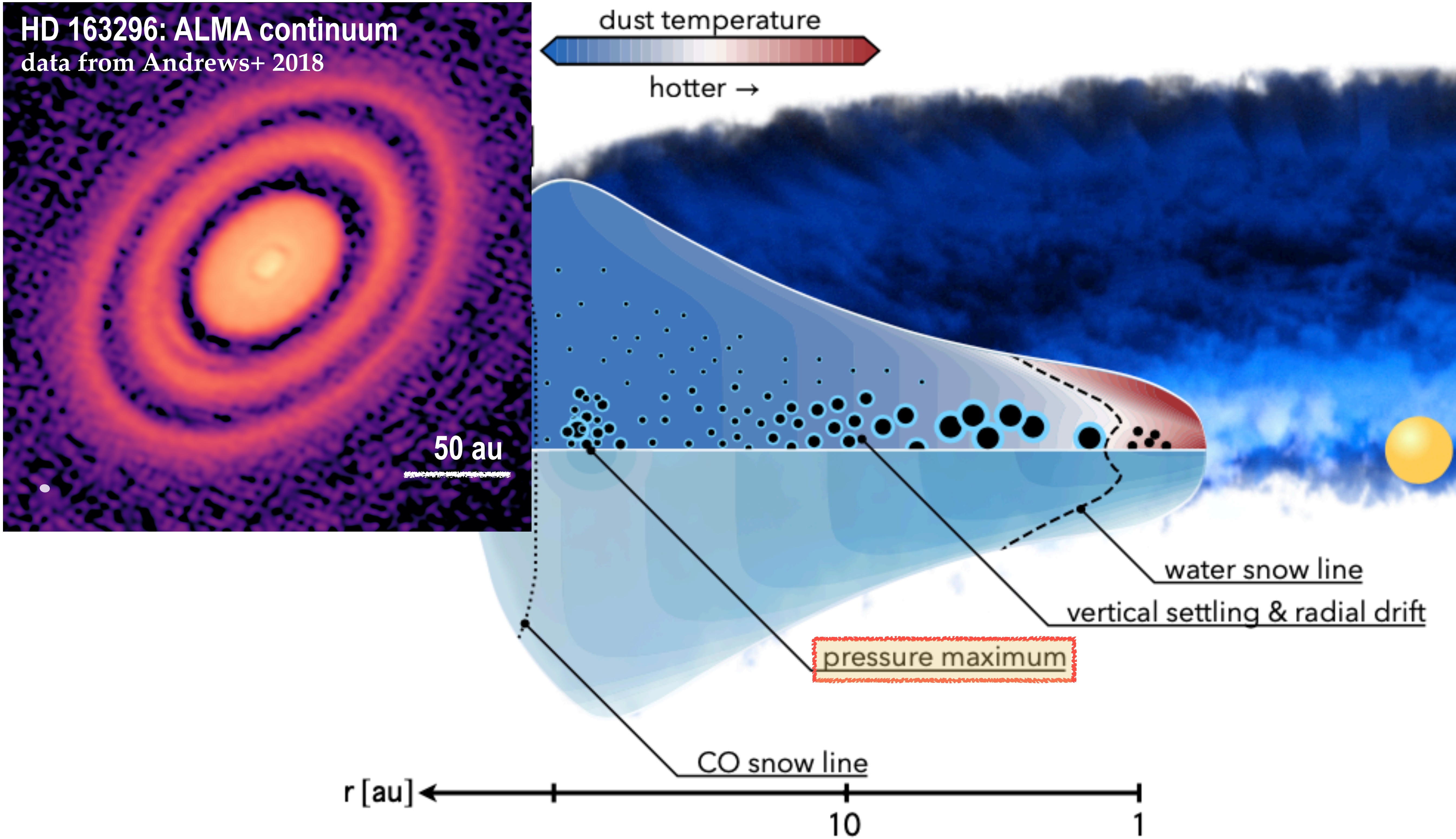
$N_2H^+ + CO \rightarrow HCO^+ + N_2$

- - - CO snowline predicted by theoretical models



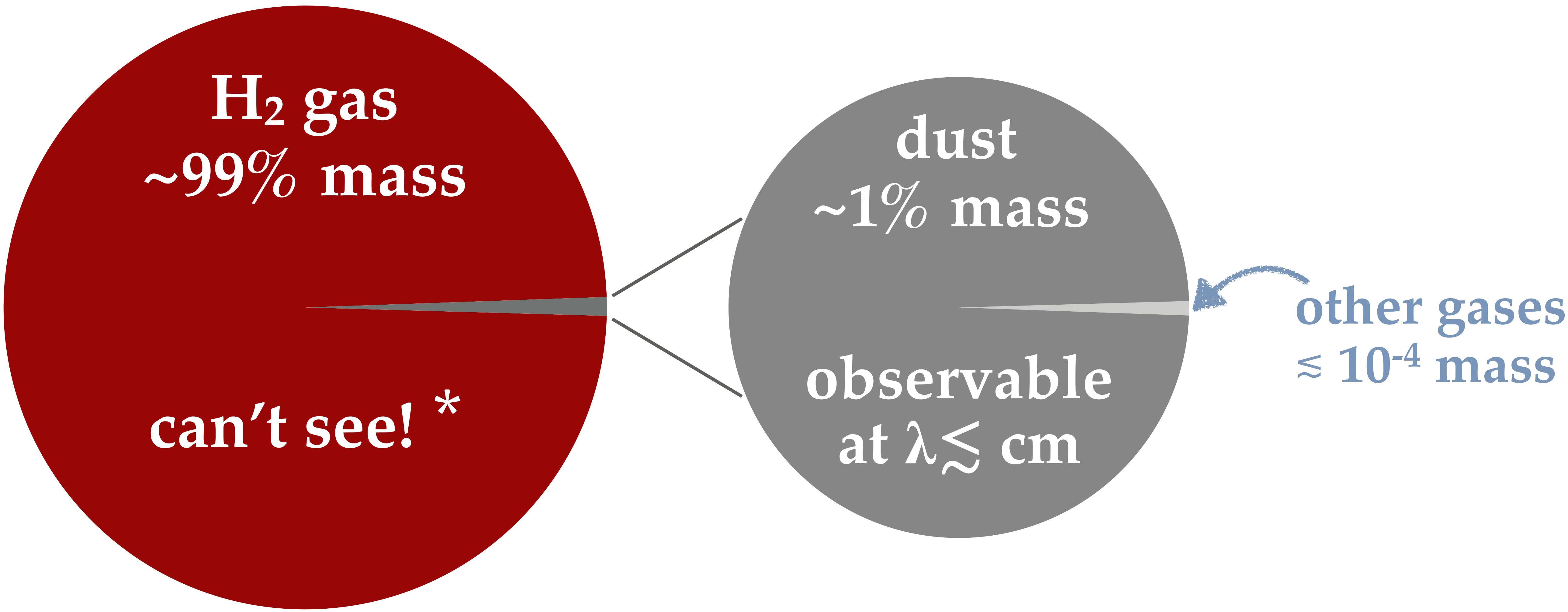
Miotello+ 2022 (PPVII)

Protoplanetary discs structure



Miotello+ 2022 (PPVII)

What is the mass of protoplanetary discs?



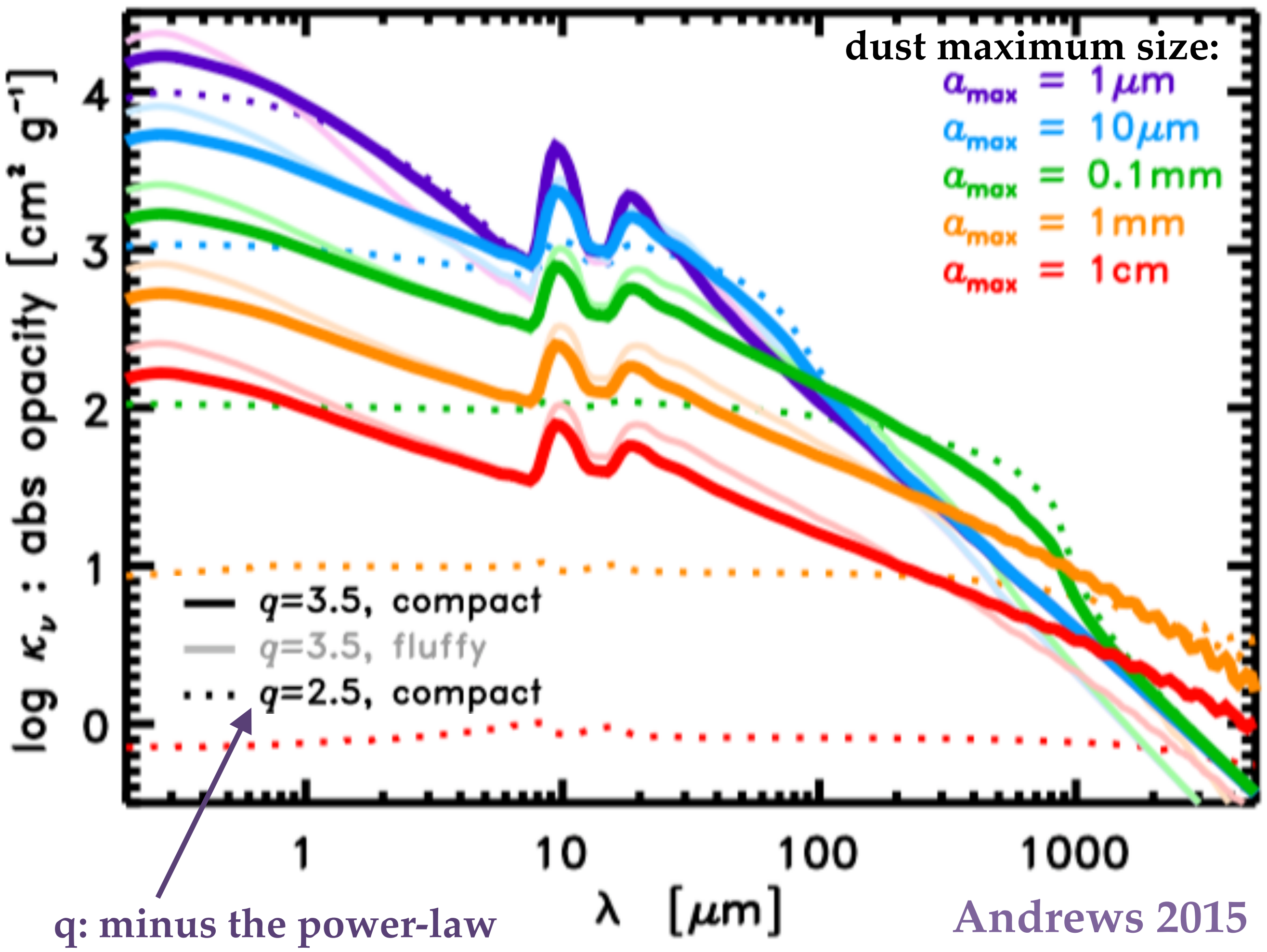
adapted from Kamber Schwarz

* or hardly (e.g., Carmona 2010)

What is the mass of protoplanetary discs?

- from **dust** emission
  - is the dust's **continuum** emission in the (sub-)mm really **optically thin**?
  - is dust **scattering** negligible? **Zhu+ 2019**
  - strong uncertainty in **absorption opacity!**
  - dust **temperature** assumed to be **known**
  - what is the actual **dust/H_2** mass ratio?

$$M_{\rm dust} \approx \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_{\rm dust})}$$



q: minus the power-law exponent of dust size distribution

Andrews 2015

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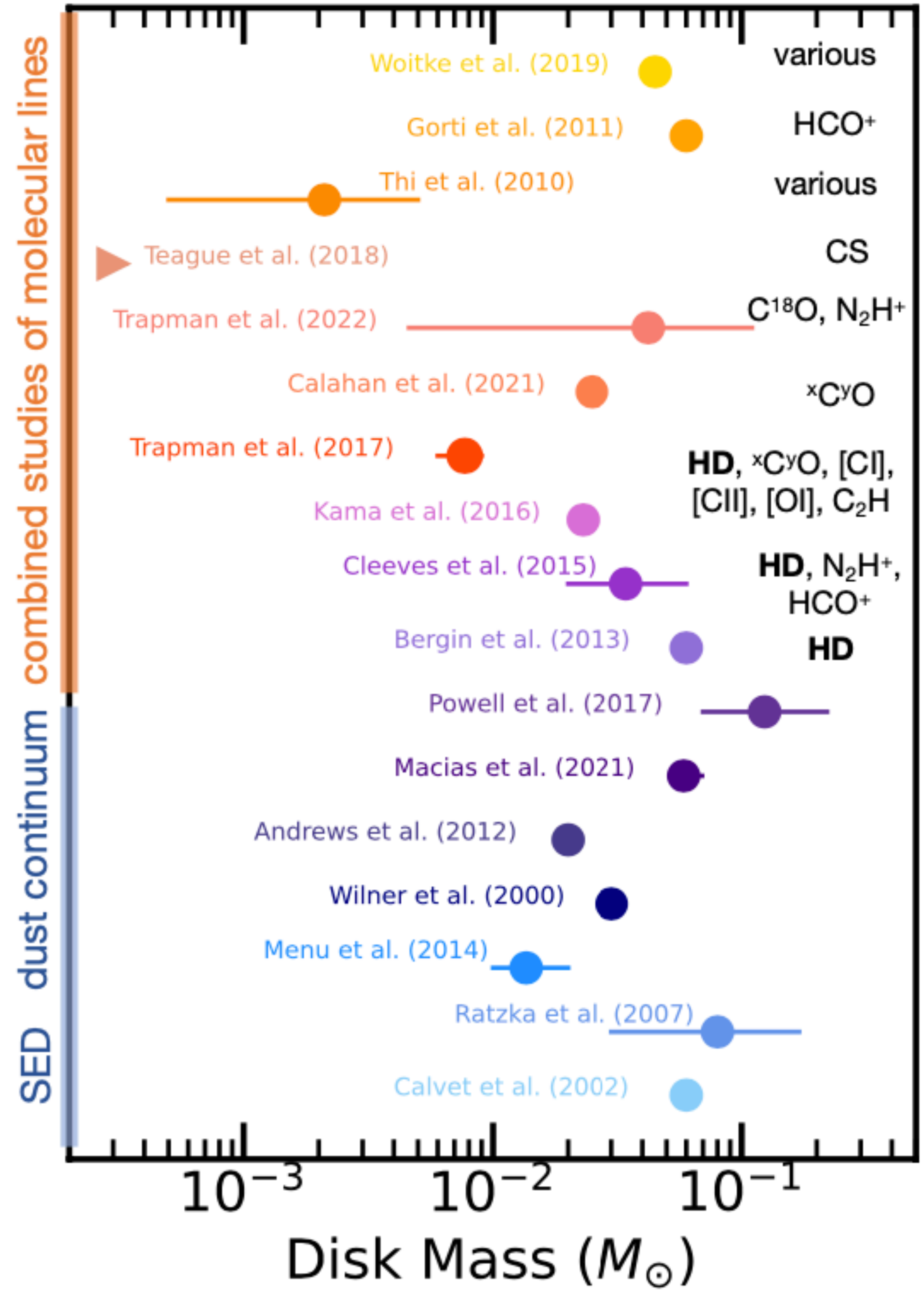
  - strong uncertainty in **absorption opacity!**
  - dust **temperature** assumed to be **known**
  - what is the actual **dust/H_2** mass ratio?

- from **gas** emission
  - **CO** isotopologues: how does **freeze-out** on dust grains impact **CO/H_2** mass ratio?
  - **HD**: does not freeze out but only emits at T>20K; temperature **vertical** structure also **needed**

TW Hya

Miotello+ 2022 (PPVII)

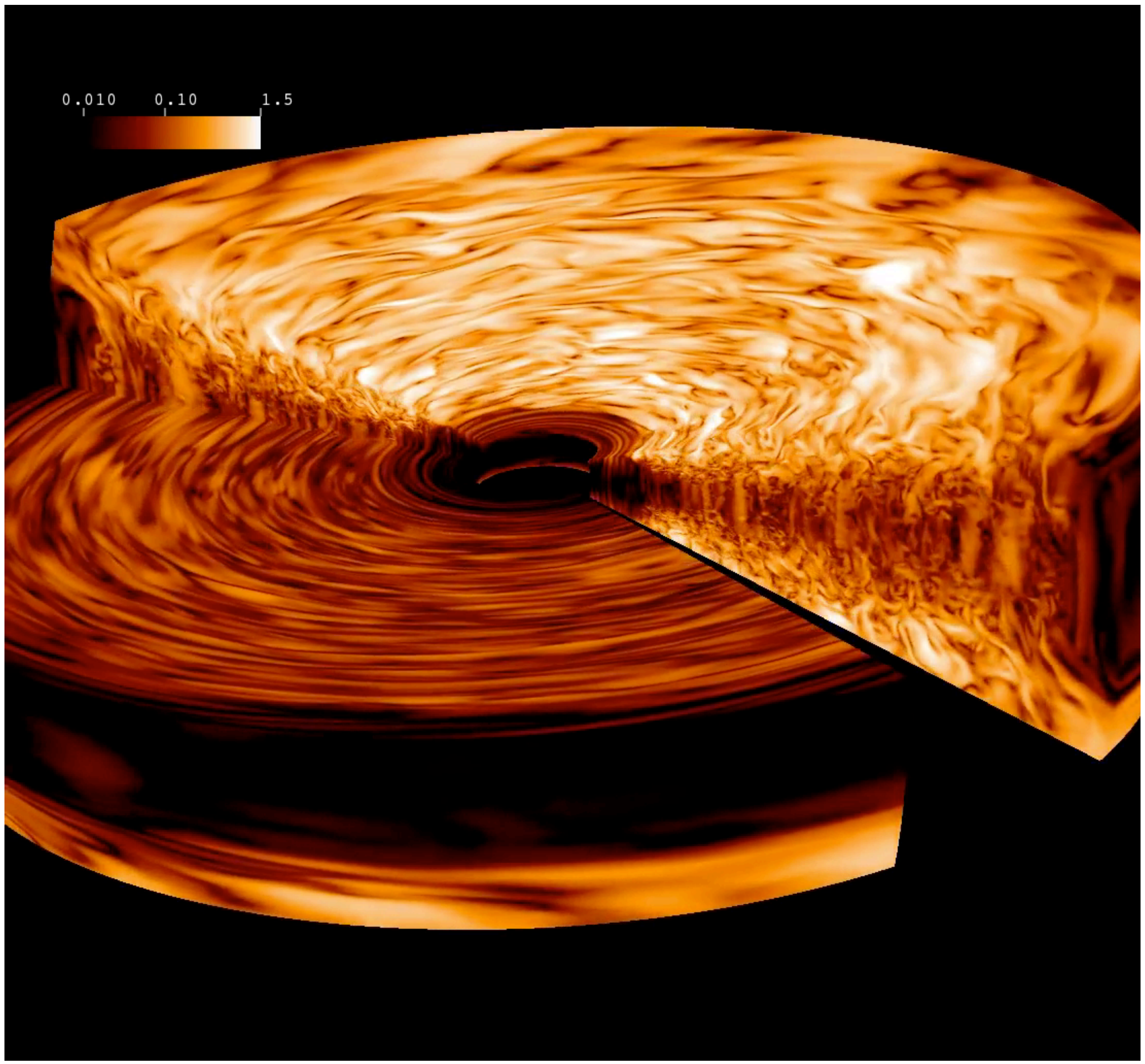


What drives the gas evolution in discs?

- **Turbulent** transport of angular momentum due to the **Magneto-Rotational Instability (MRI)?**
  - linear instability arising in discs dynamically coupled to a **weak** magnetic field

Balbus & Hawley 1991

$$|B|^2/2\mu_0 \lesssim \rho c_s^2$$



Gas Mach number (r.m.s. turbulent velocity in units of the local sound speed). Disc extends from R=0.5 to 1.5 au, r.m.s. turbulent velocity goes from ~1 to ~1000 m/s

Flock+ 2013

- MRI-turbulent disc behaves much like a **viscous** disc
- disc reaches a quasi steady-state with **turbulent** mass **accretion rates** in fair agreement with **observed stellar accretion rates** ($\dot{M} \sim 10^{-8}\ M_\odot\ yr^{-1}$)

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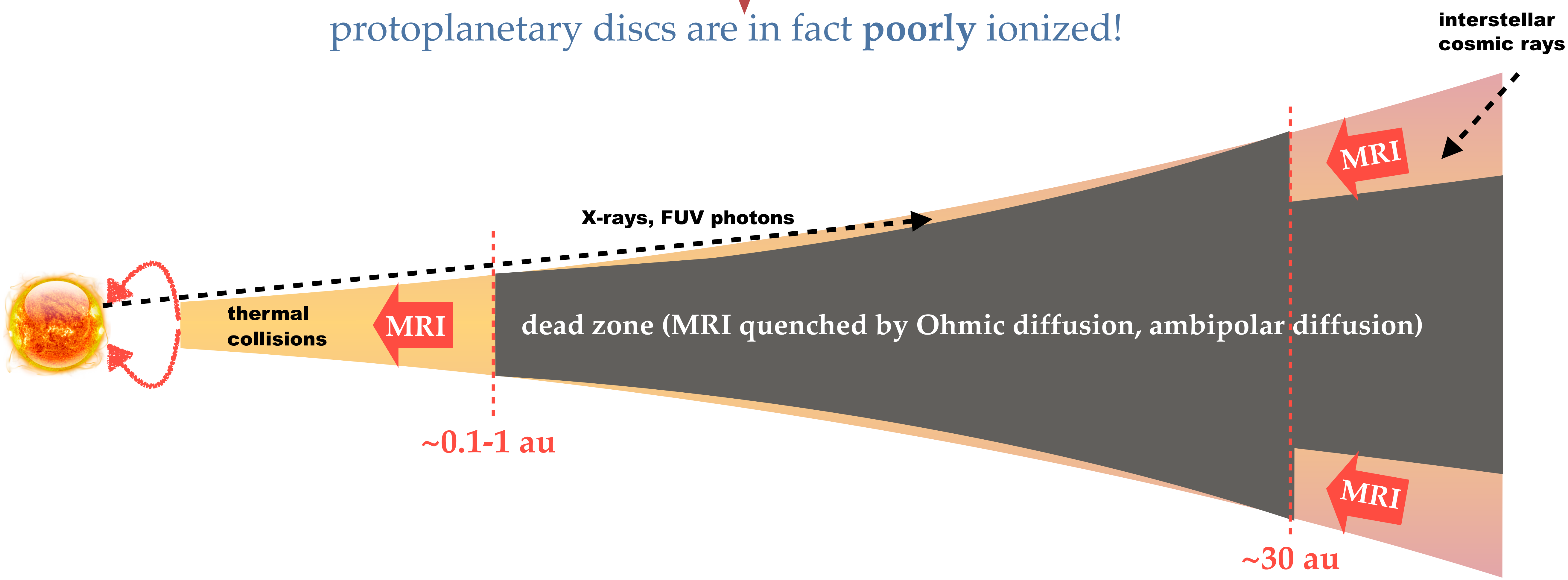
Balbus & Hawley 1991

protoplanetary discs are in fact **poorly** ionized!



→ Ohmic diffusion (electrons-neutrals collisions) and ambipolar diffusion (ions-neutrals collisions) **quench MRI** in a large fraction of the bulk disc

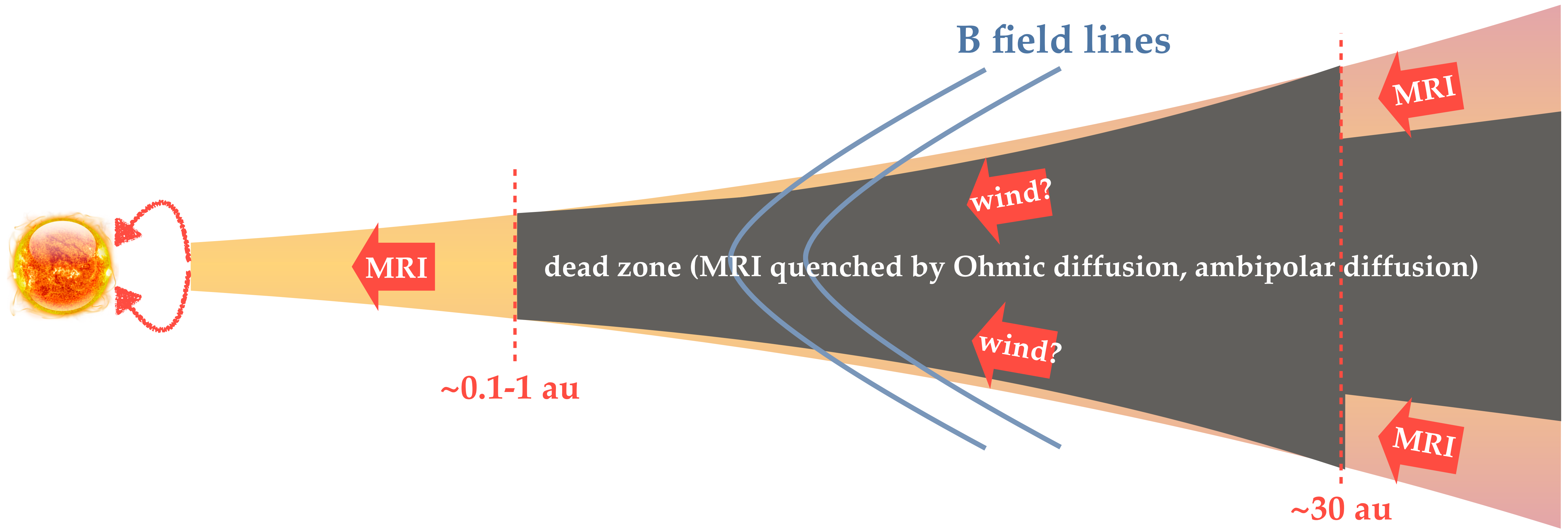
Bai 2013, Simon+ 2013, Lesur+ 2014…

→ overall consistent with **observations** of the (small!) **non-thermal broadening** of molecular gas lines in discs

eg, Flaherty+ 2015

What drives the gas evolution in discs?

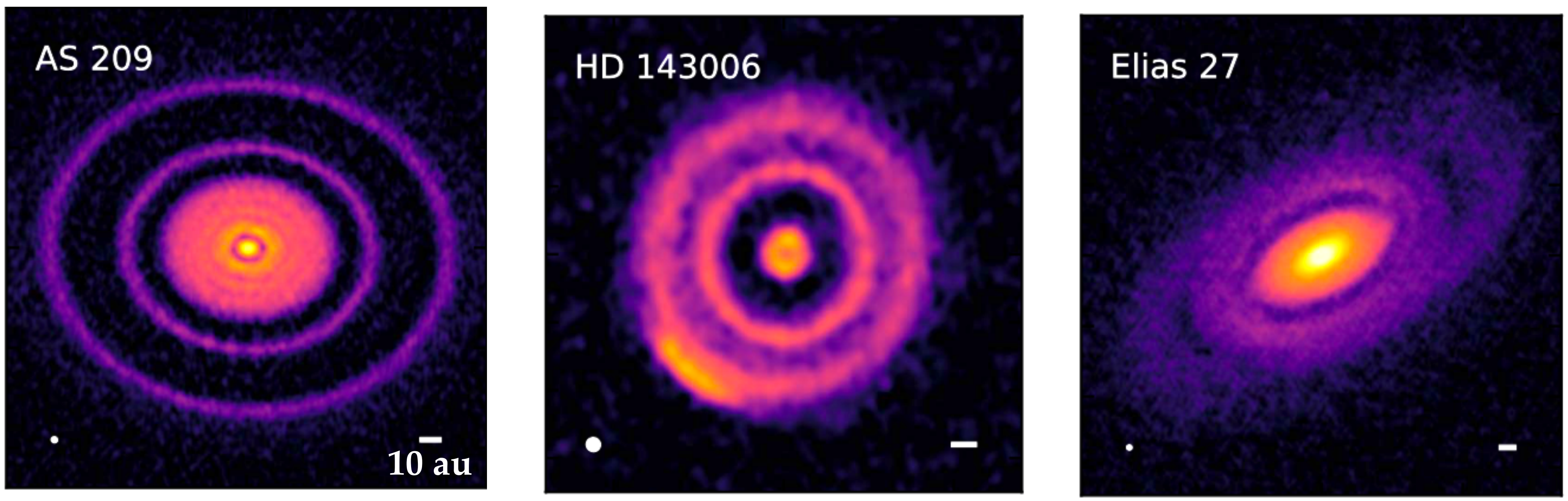
- **Vertical transport (extraction)** of angular momentum by **magneto-centrifugal winds?**
  - **wind**-driven **laminar** accretion if a vertical B field threads the disc
    eg, Blandford & Payne 1982, Béthune+ 2017



  - **observational support** via gas line kinematics? eg, Pascucci+ 2022 (PPVII)
  - **impact** on planet formation and evolution? (global models needed)
  - can other, weaker **hydrodynamical instabilities** become relevant?

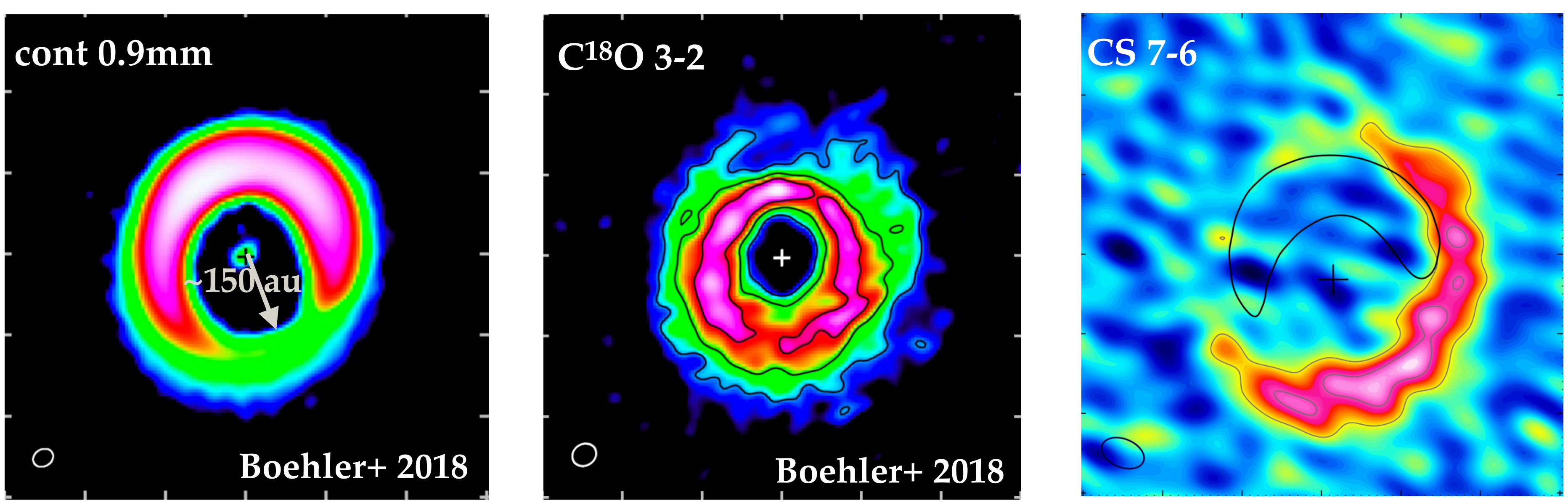
What causes sub-structures in discs?

- sub-structures seem **ubiquitous** in the **gas** and **dust emissions**
  - dark and bright **rings**, crescent-like **asymmetries**, **spirals**…



selected ALMA discs

Andrews+ 2018



van der Plas+ 2014

HD 142527 disc

What causes sub-structures in discs?

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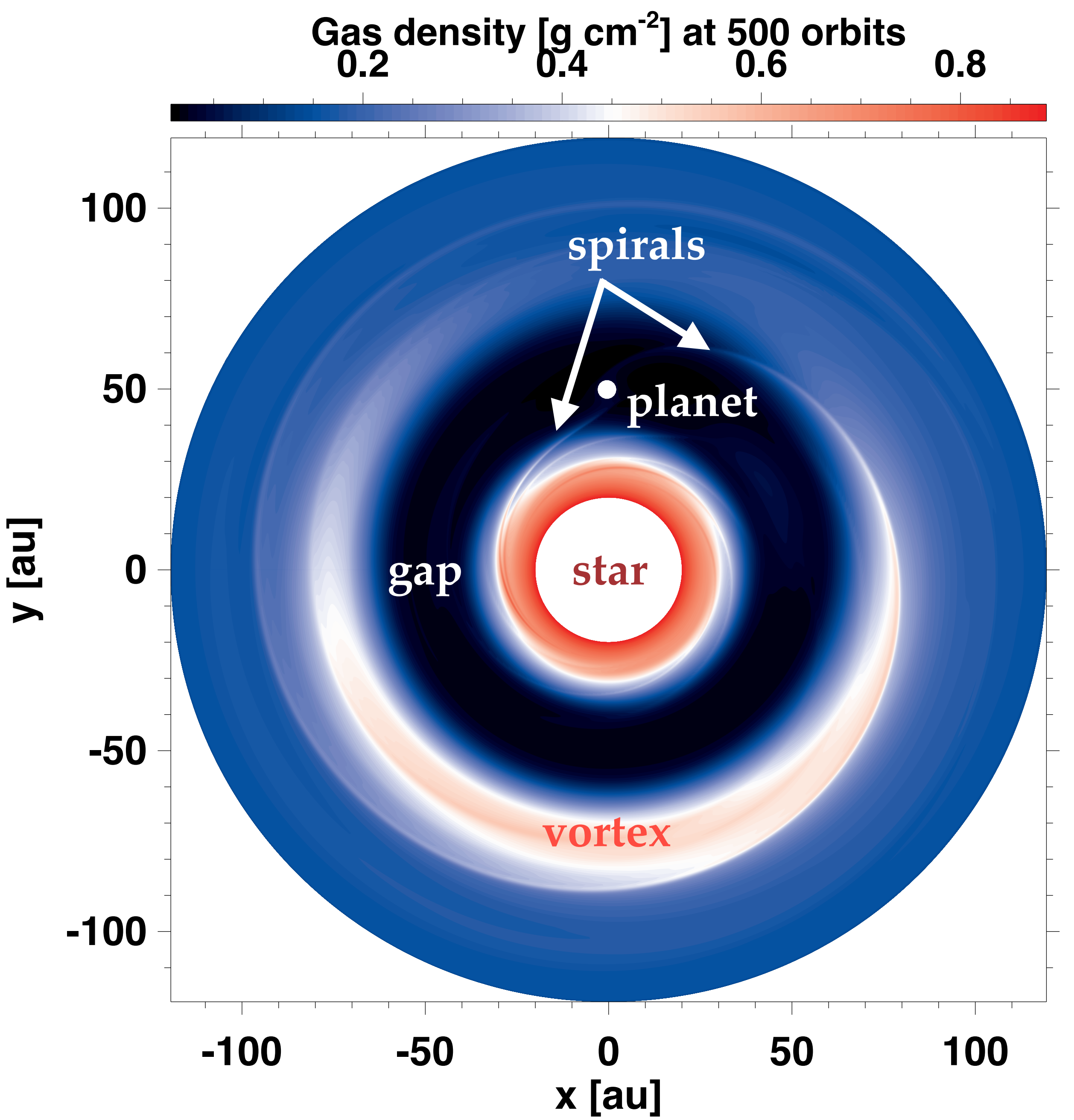

hydrodynamical simulation of a Jupiter-mass planet embedded in a protoplanetary disc

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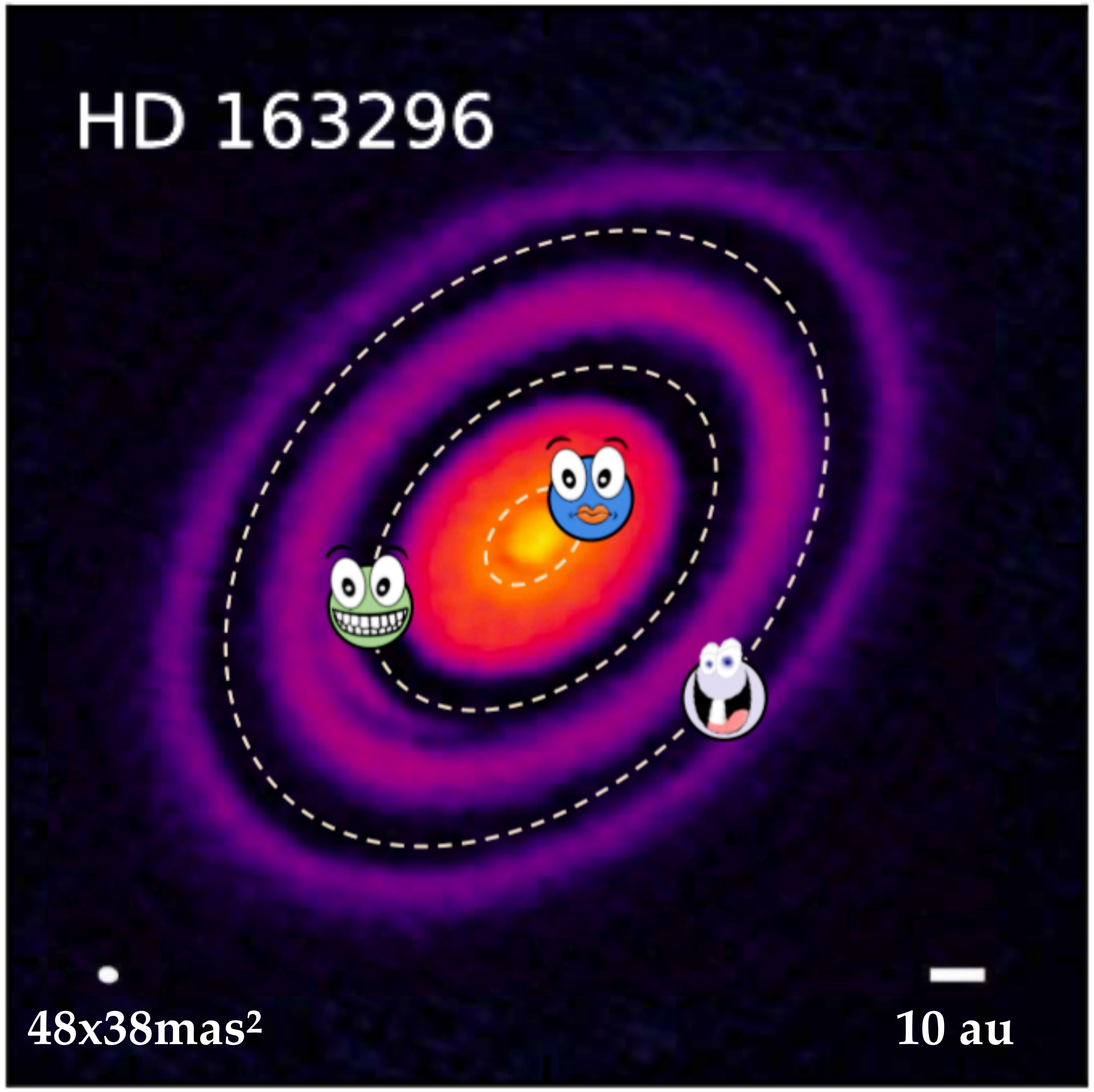
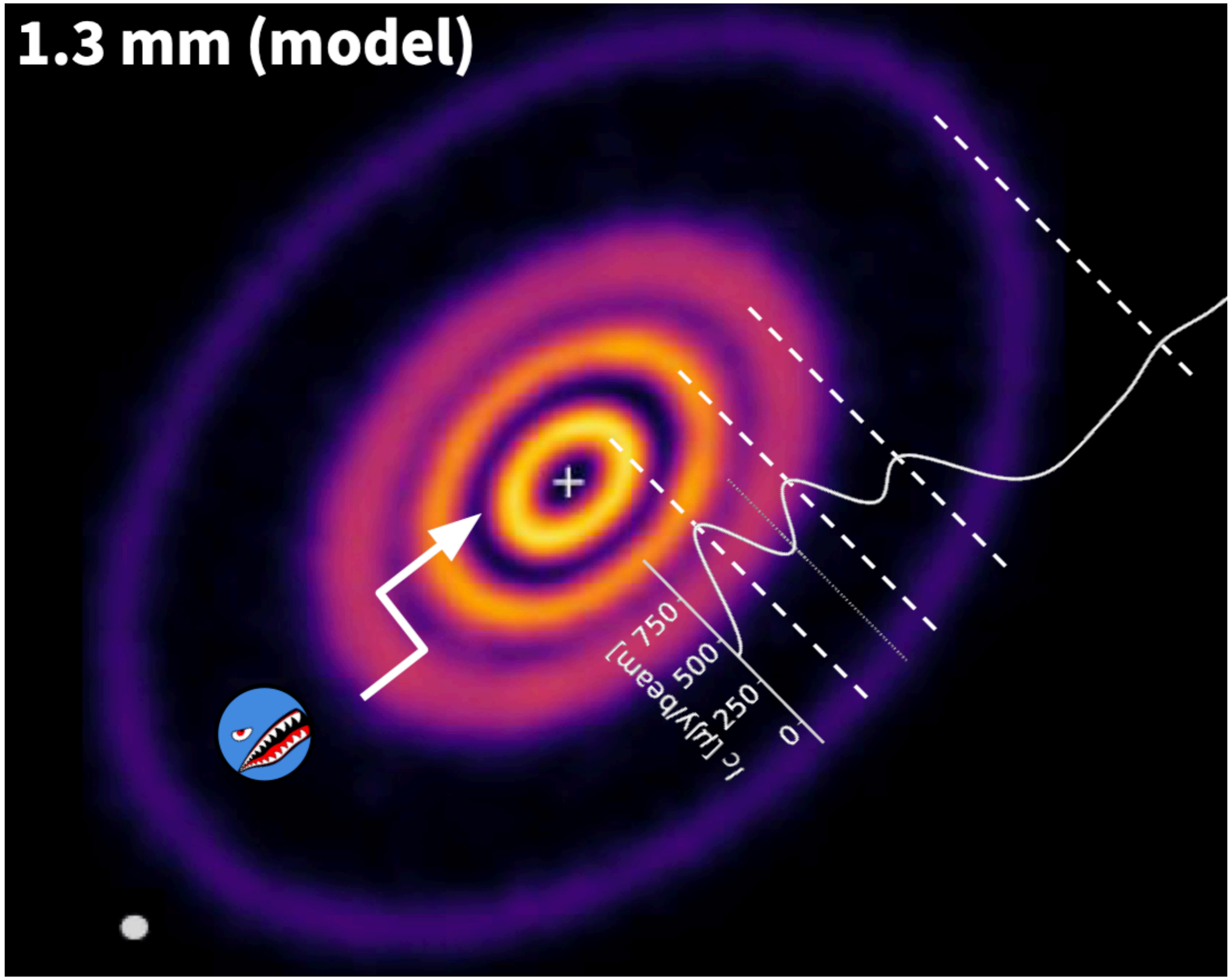


Andrews+ 2018 (ALMA@1.3mm)



Wafflard-Fernandez & Baruteau 2020

Credit: Gaylor Wafflard-Fernandez

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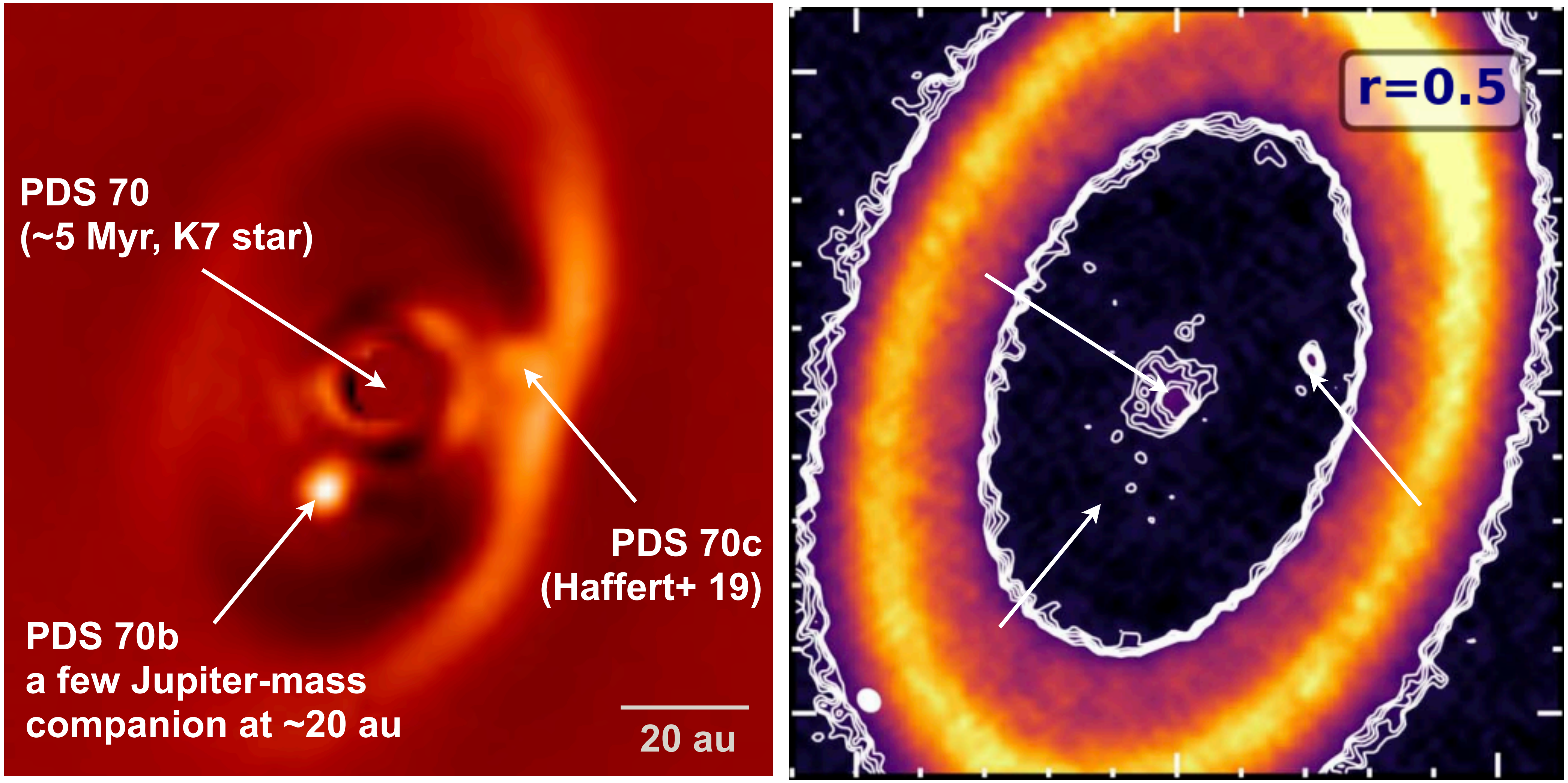

protoplanetary disc around PDS 70 imaged by SPHERE (@~2.1μm, left, Müller+ 2018) and by ALMA (@~0.9mm, right, Benisty+ 2021)

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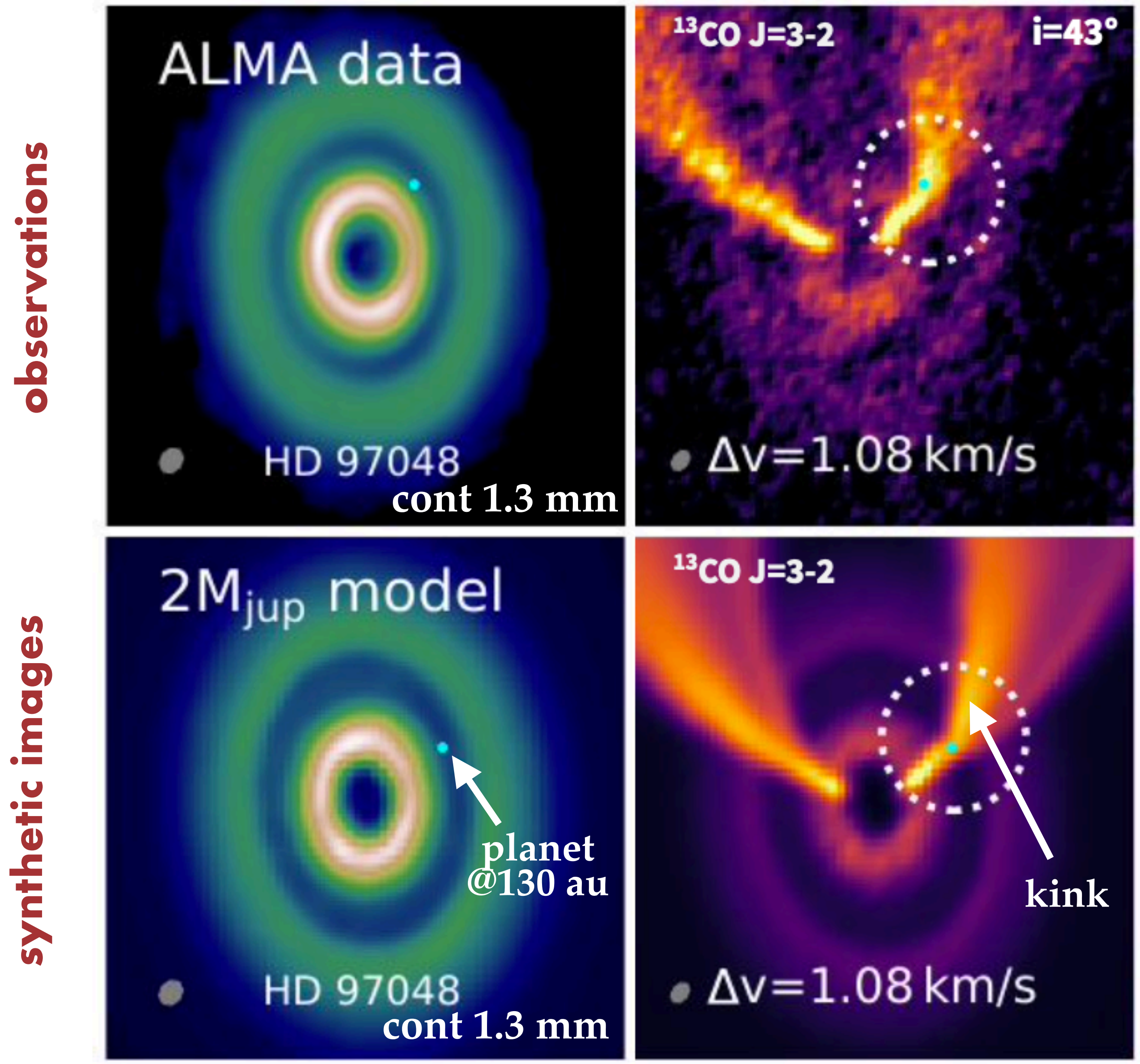
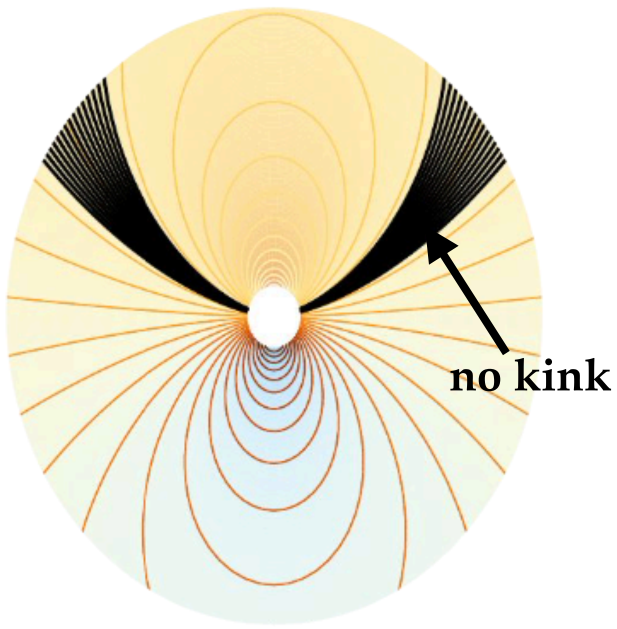


Pinte+ 2019



No planet

Credit: Gaylor Wafflard-Fernandez

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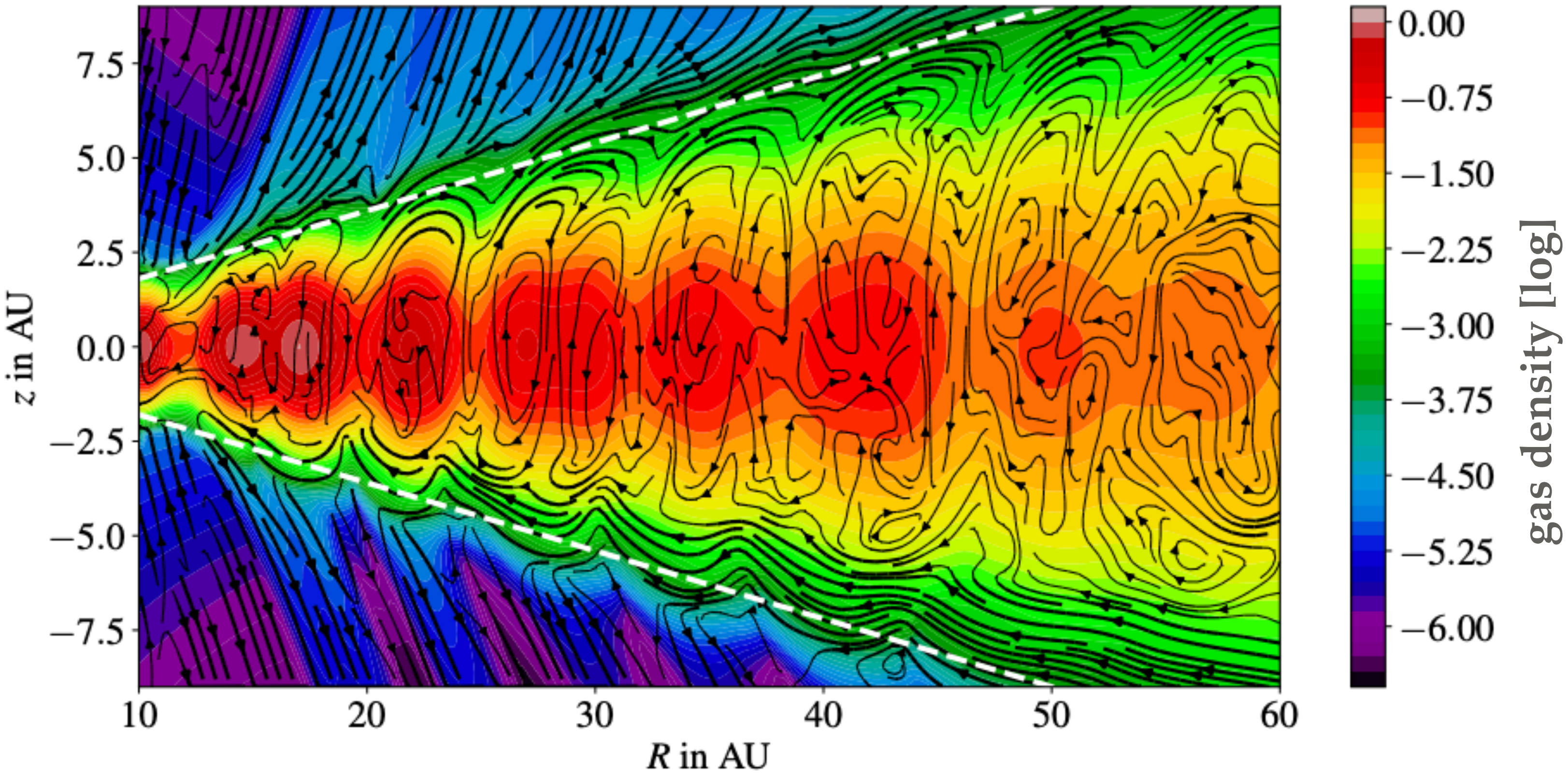
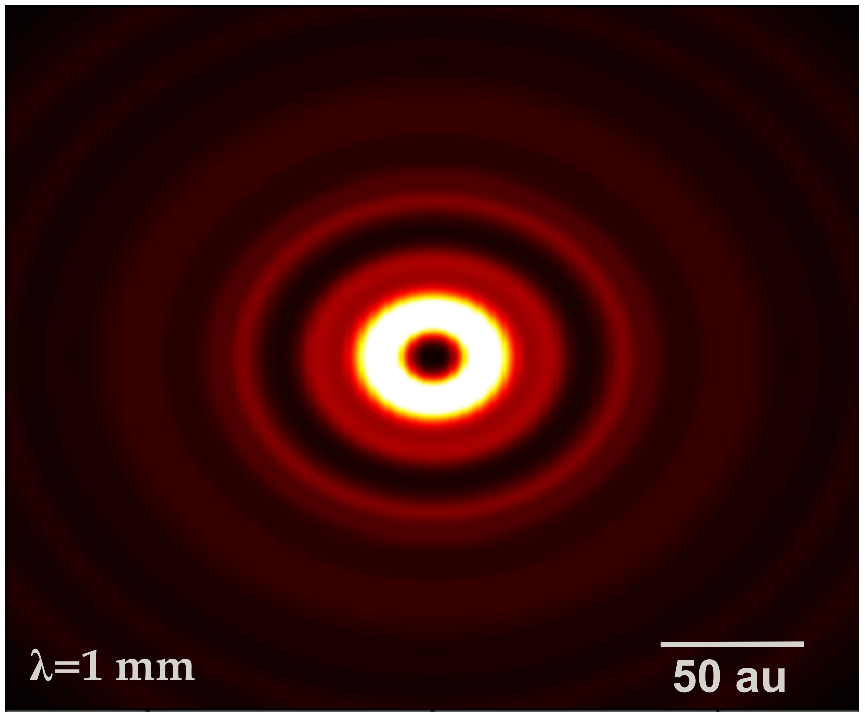
  - **rings** via **zonal flows** in low-turbulent discs?





Riols+ 2020

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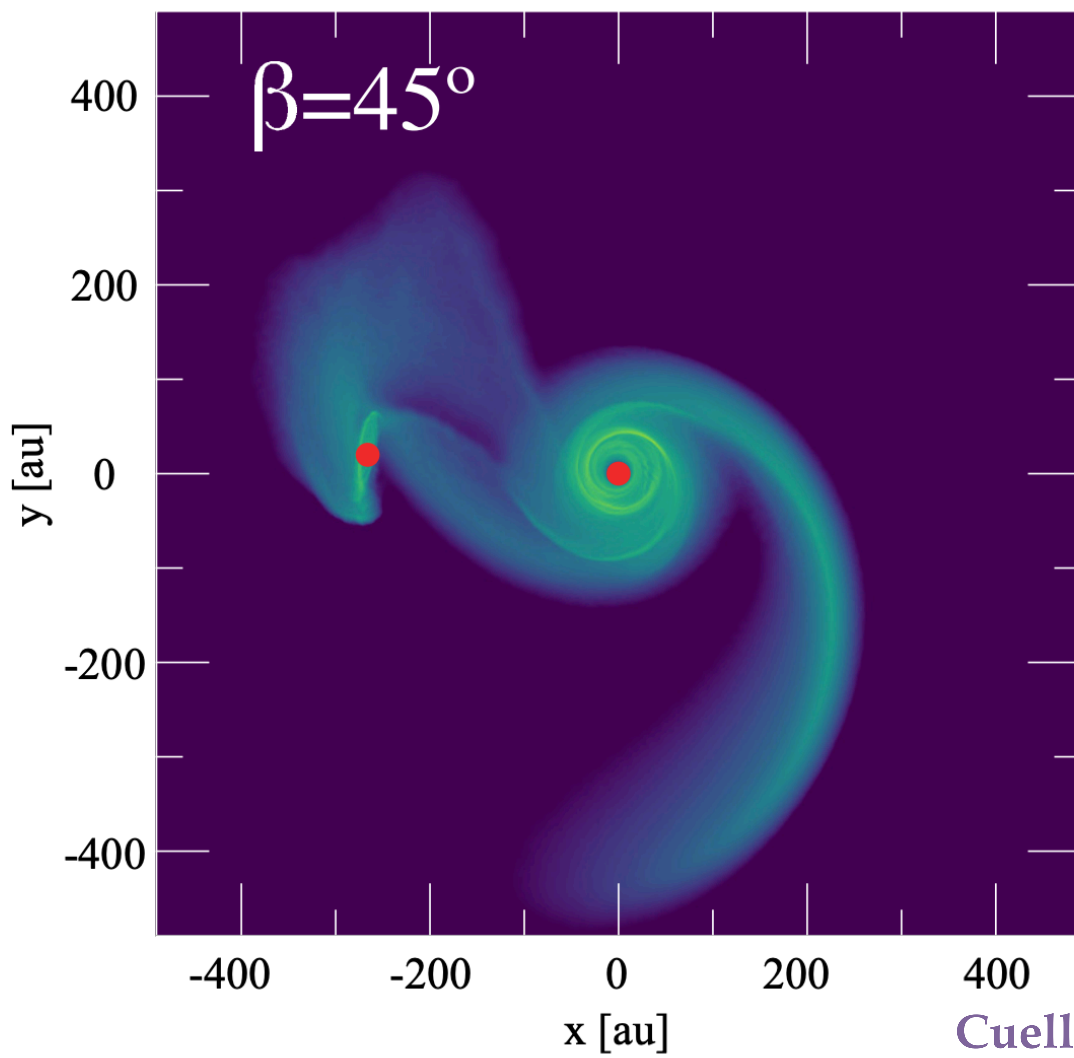

Cuello+ 2022

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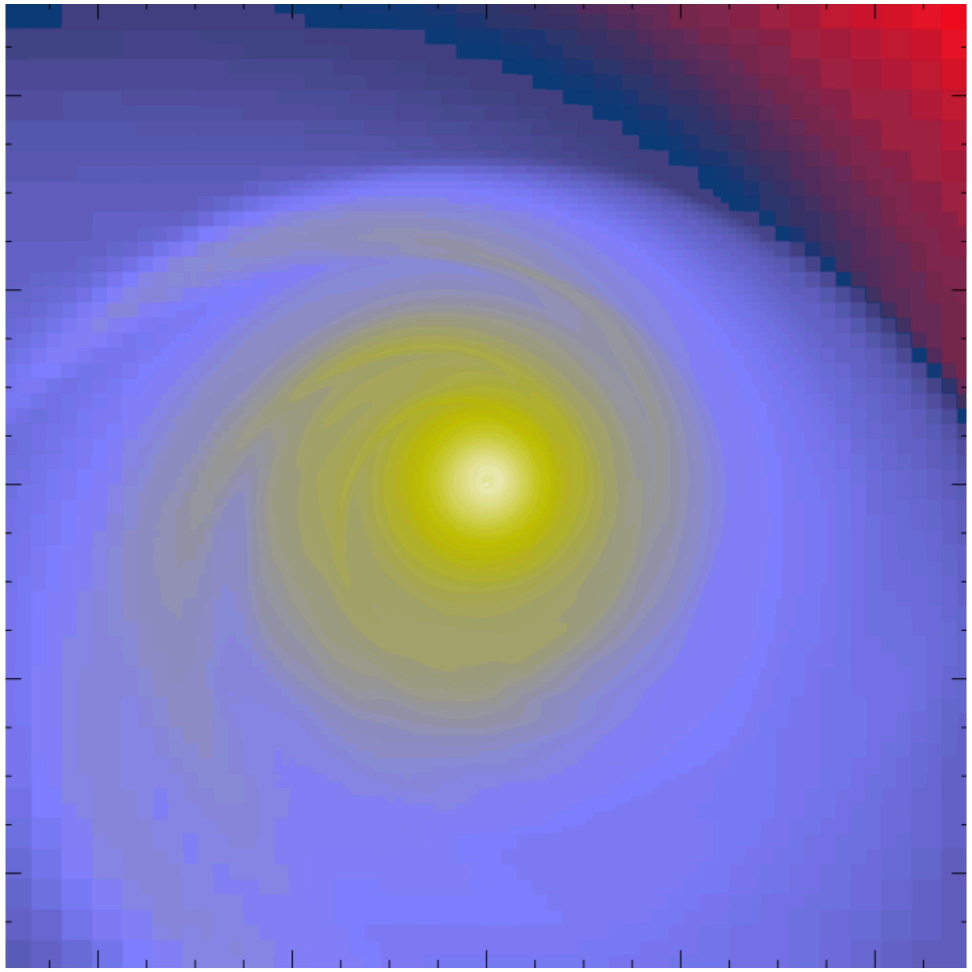
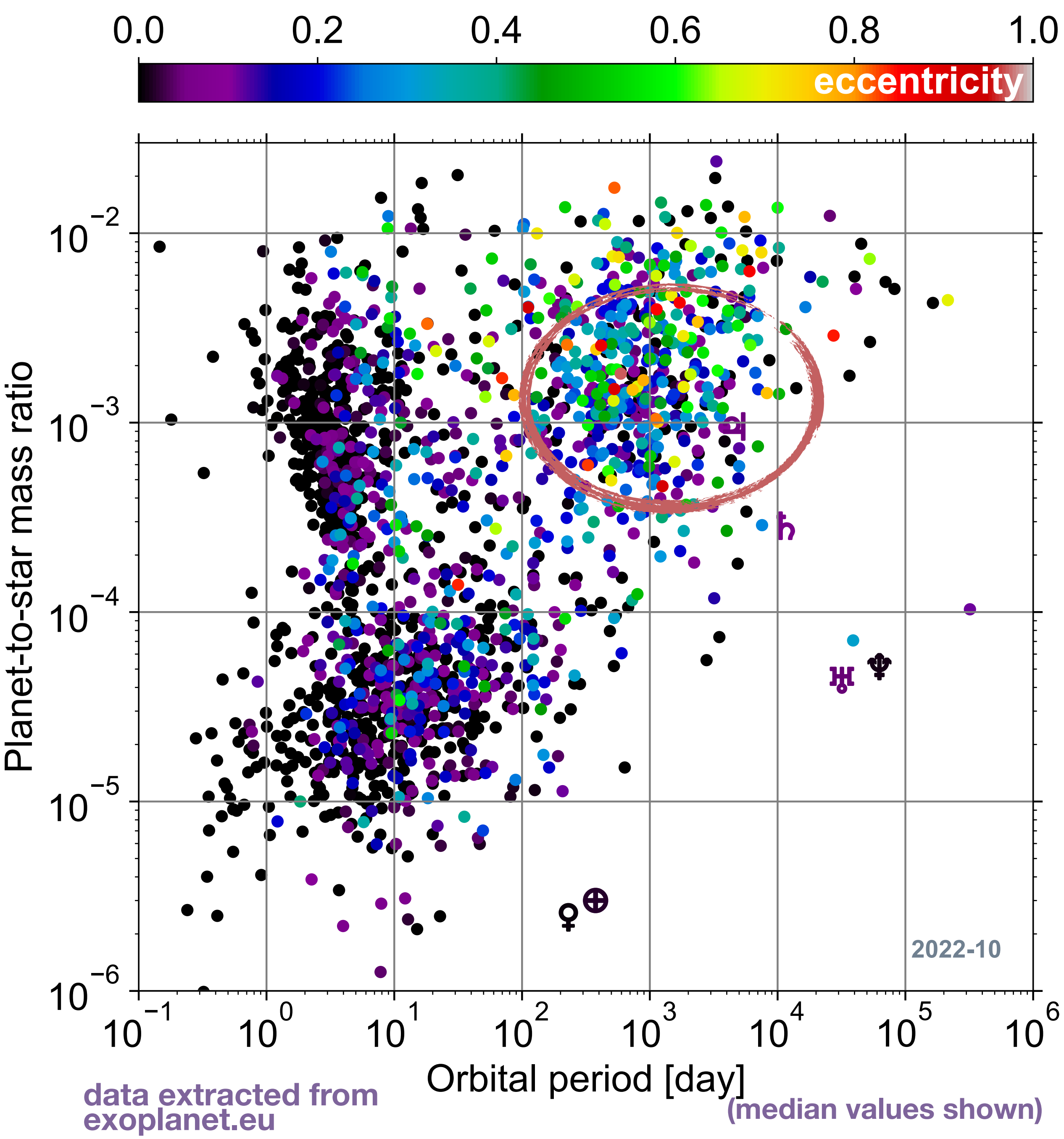
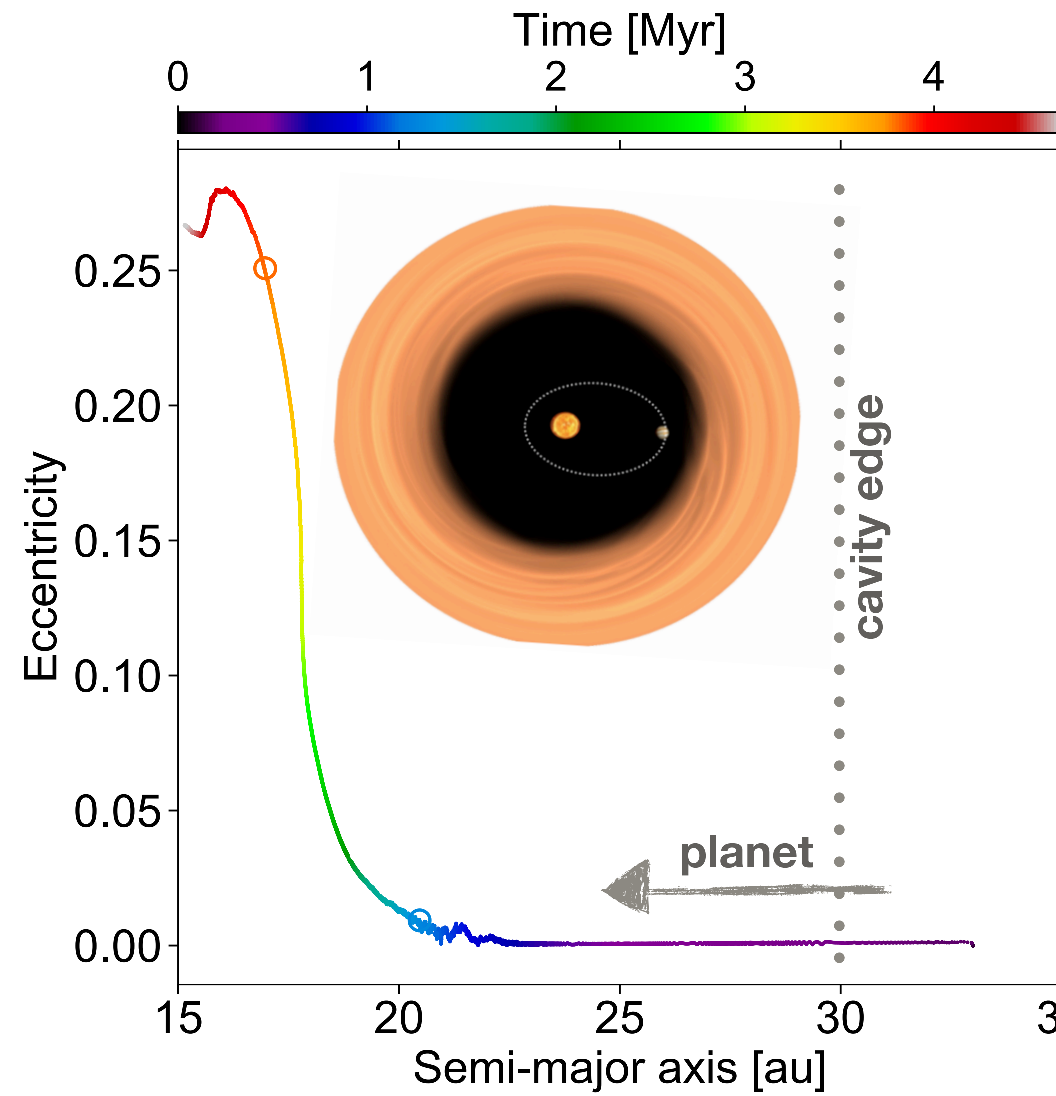
  - **rings** via **zonal flows** in low-turbulent discs? **spirals** via stellar flybys, by remnant accretion of molecular cloud?



Hennebelle+ 2017

How did most warm Jupiters become eccentric?





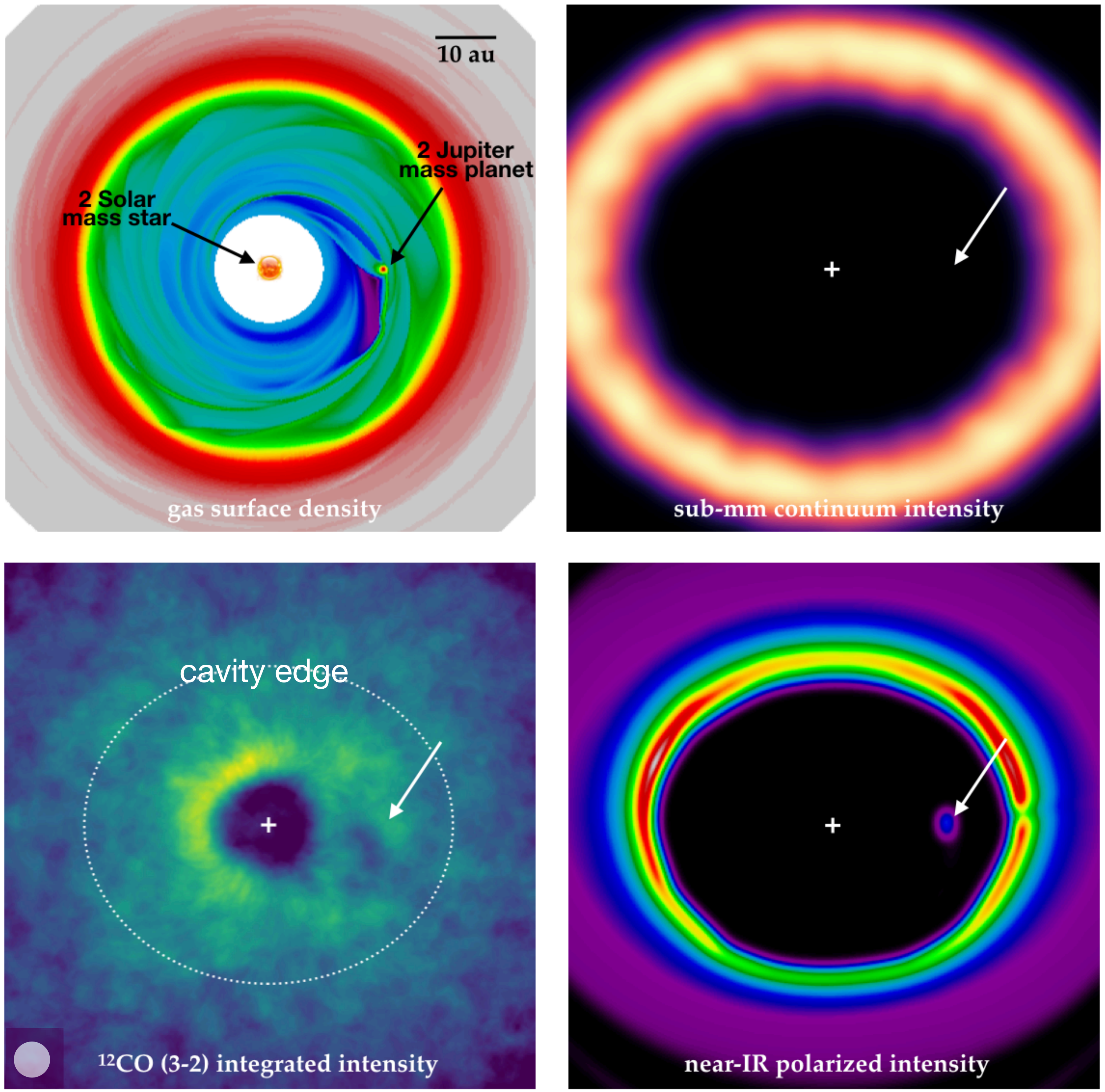
- Planets more **massive** than Saturn can acquire a **large eccentricity** (up to 0.4) when **migrating** into a low-density **gas cavity** in their protoplanetary disc

- A **generic** way to form **eccentric warm Jupiters**?

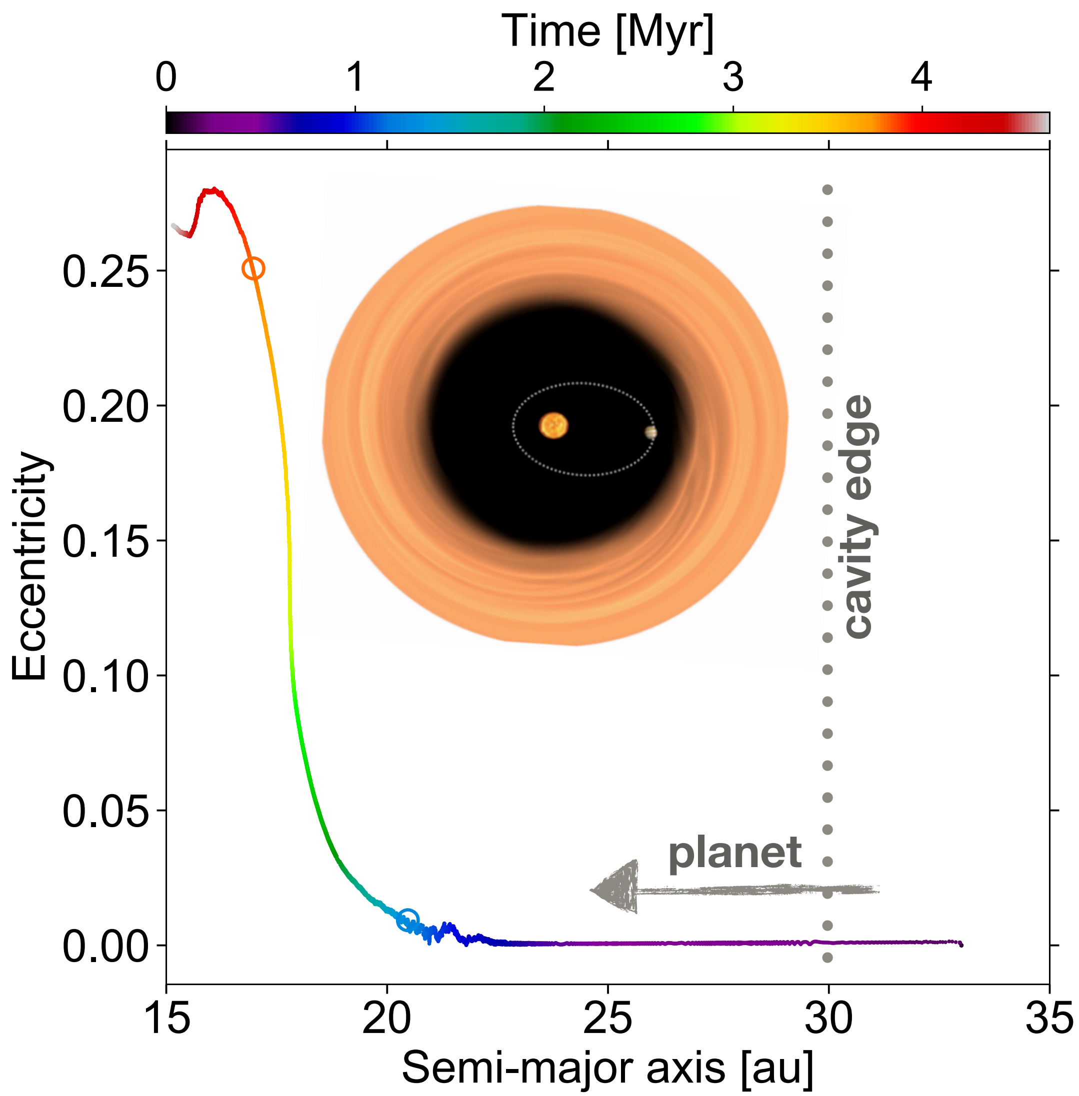
Debras, Baruteau & Donati 2021

- 50% of exoplanets with orbital **periods** > 100 days and with **masses** between that of Saturn and 5x that of Jupiter have **eccentricities** in **[0.1-0.4]**

How did most warm Jupiters become eccentric?



Baruteau, Wafflard-Fernandez, Le Gal et al. 2021



- 2D gas+dust **hydrodynamical** simulations post-processed by 3D **radiative transfer** calculations
  - uniform CO/H_2 ratio, simple photodissociation model
  - d=100pc, i=30°, 50mas beam, 1mJy/beam rms noise per channel map

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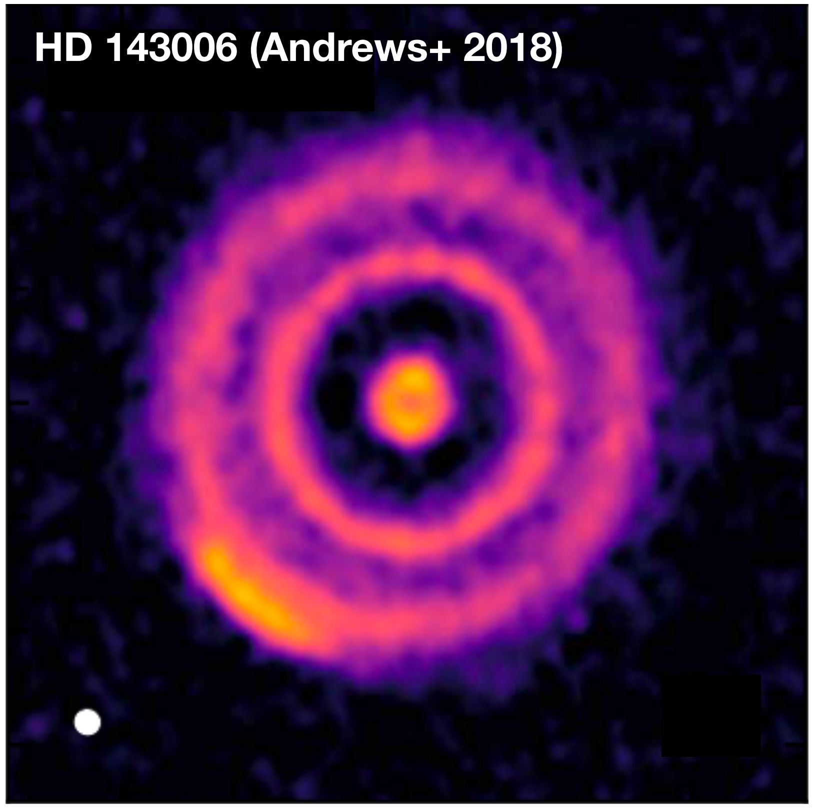

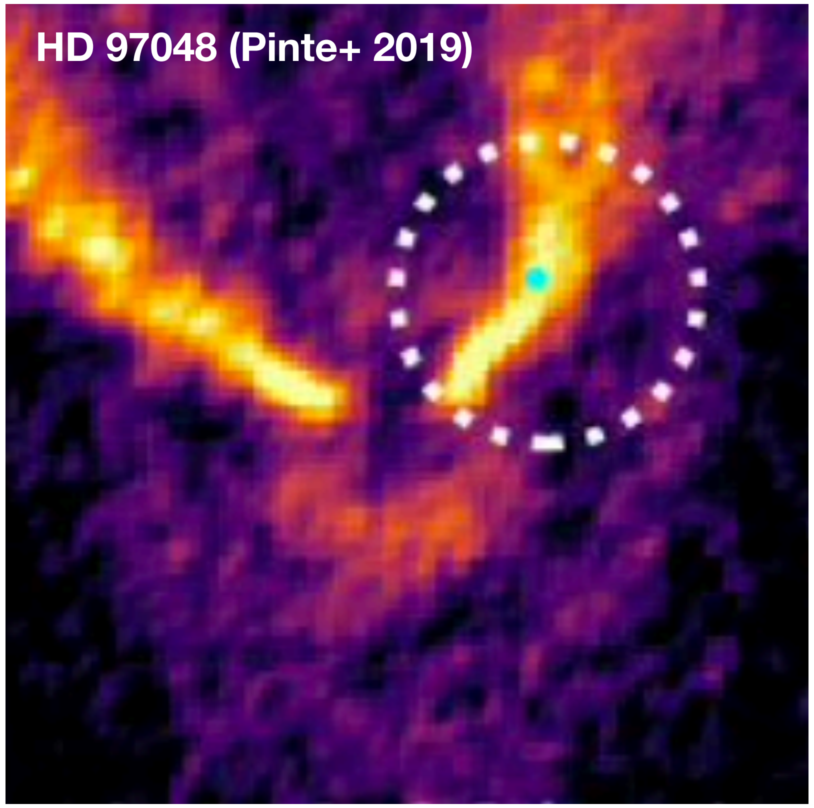

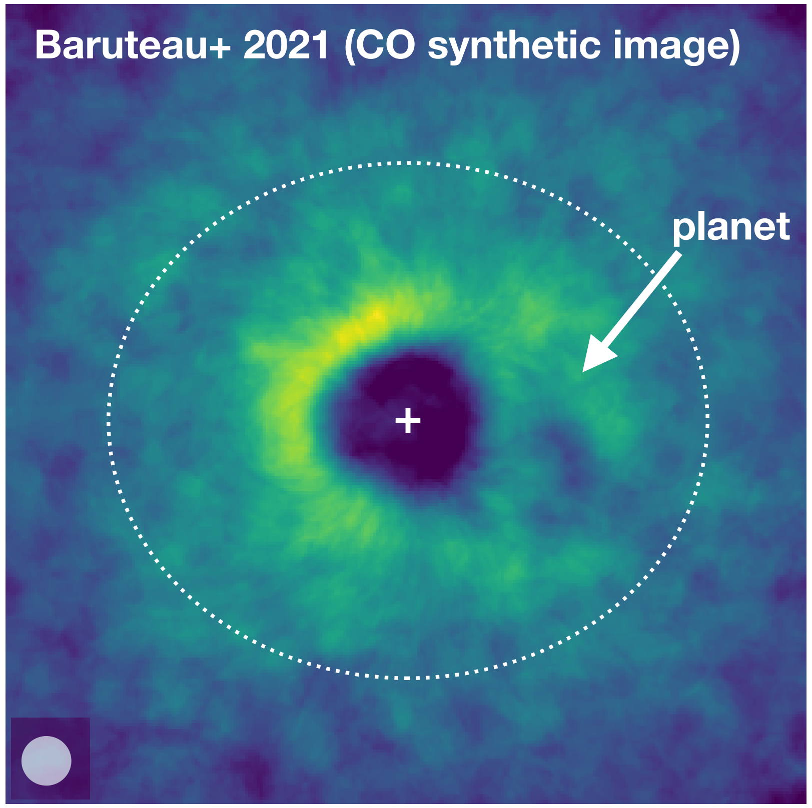

PCMI biennial conference - 28 October 2022

... thanks!