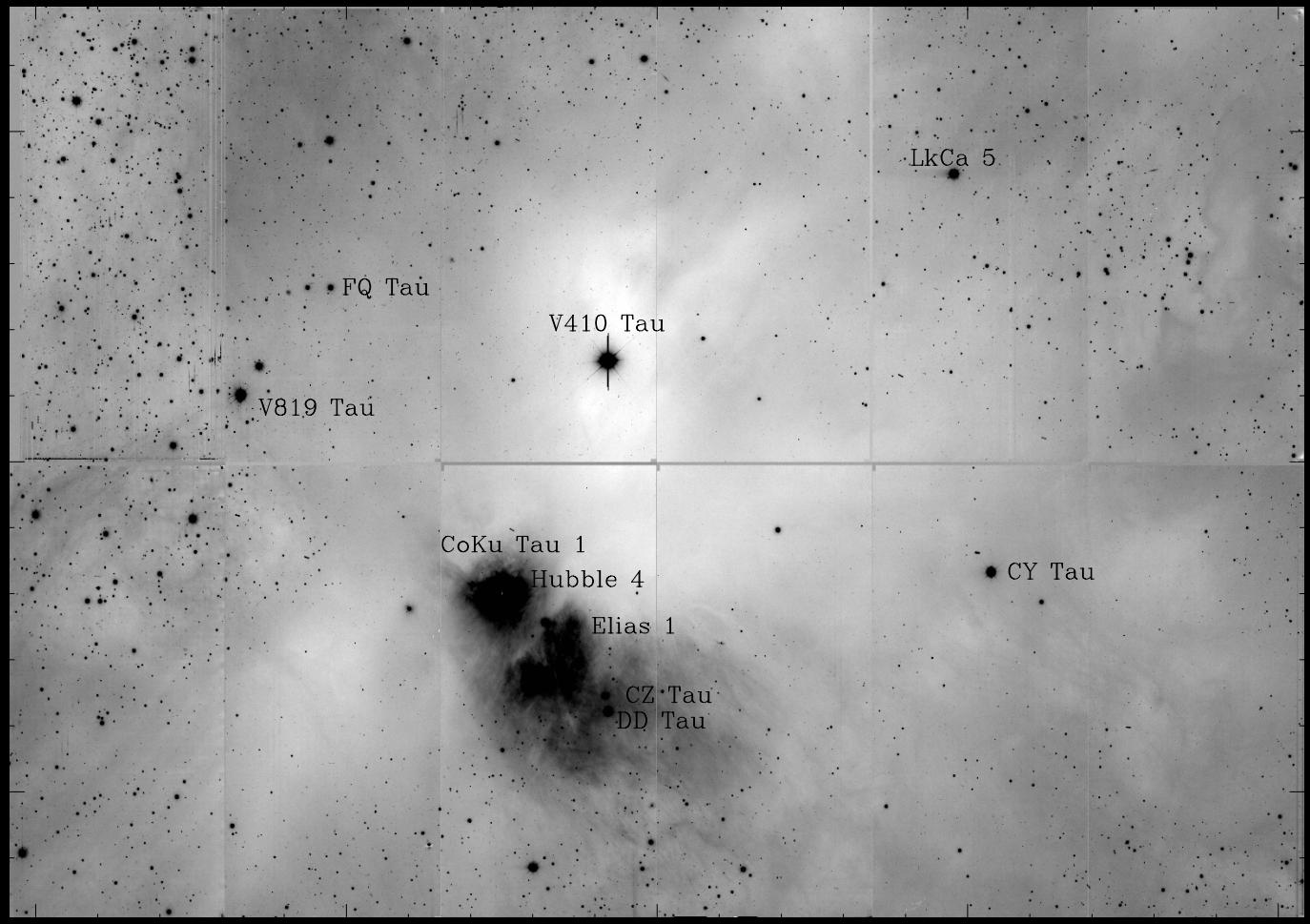
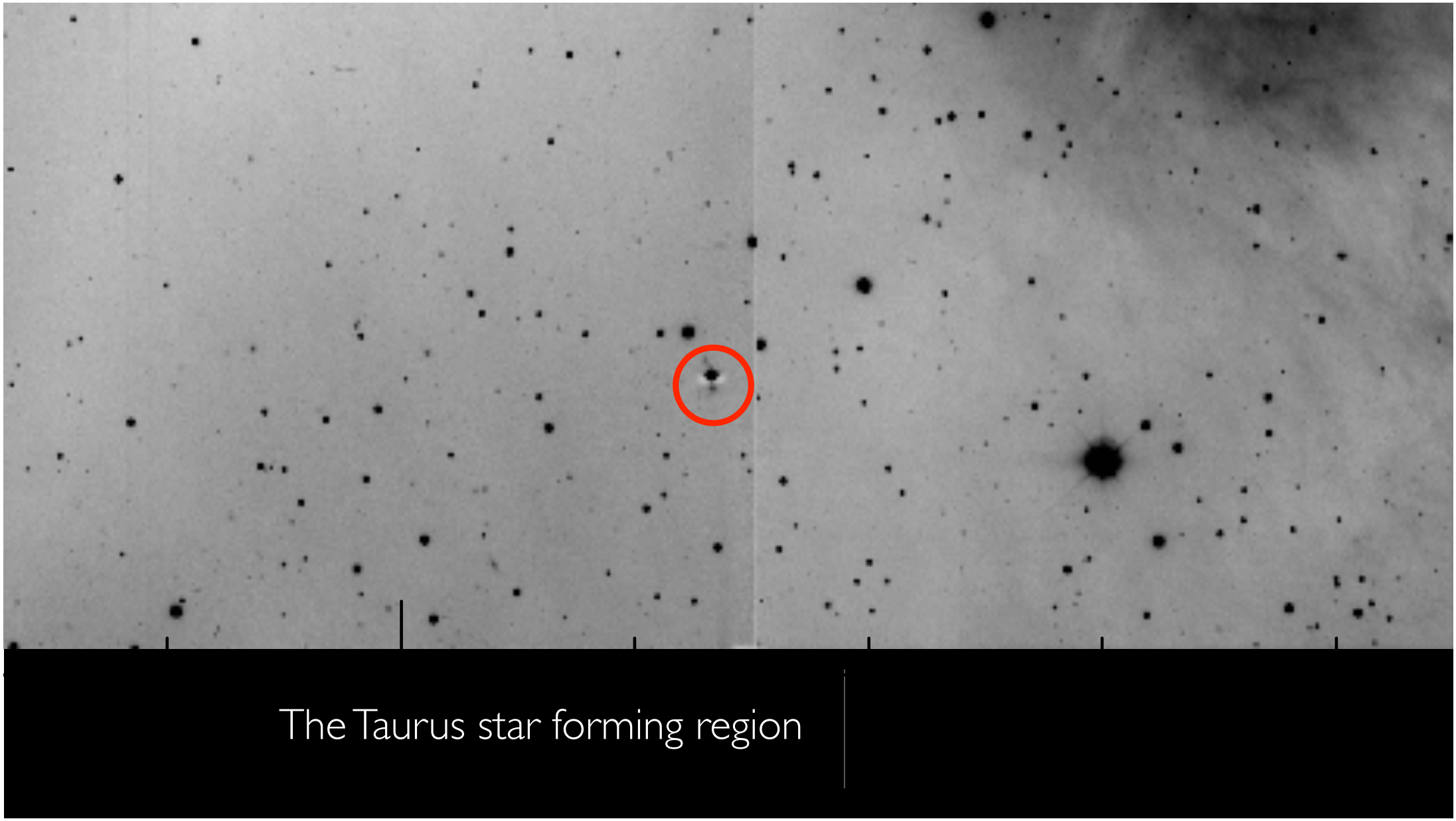
THE CURIOUS CASE OF IRAS04158



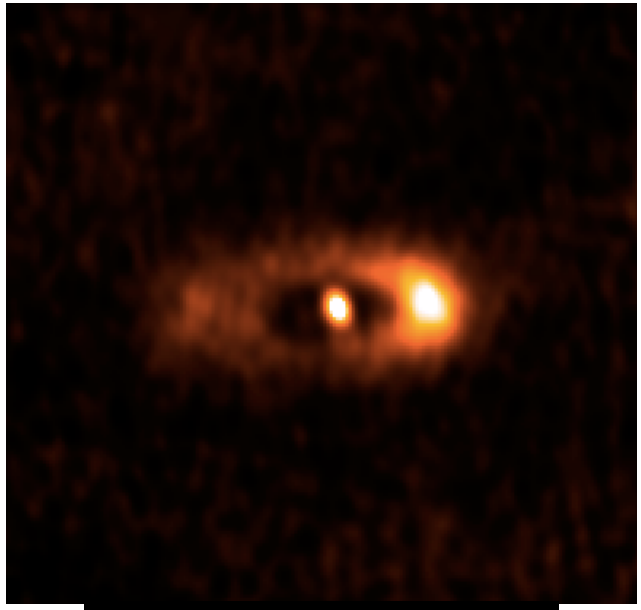
The Taurus star forming region



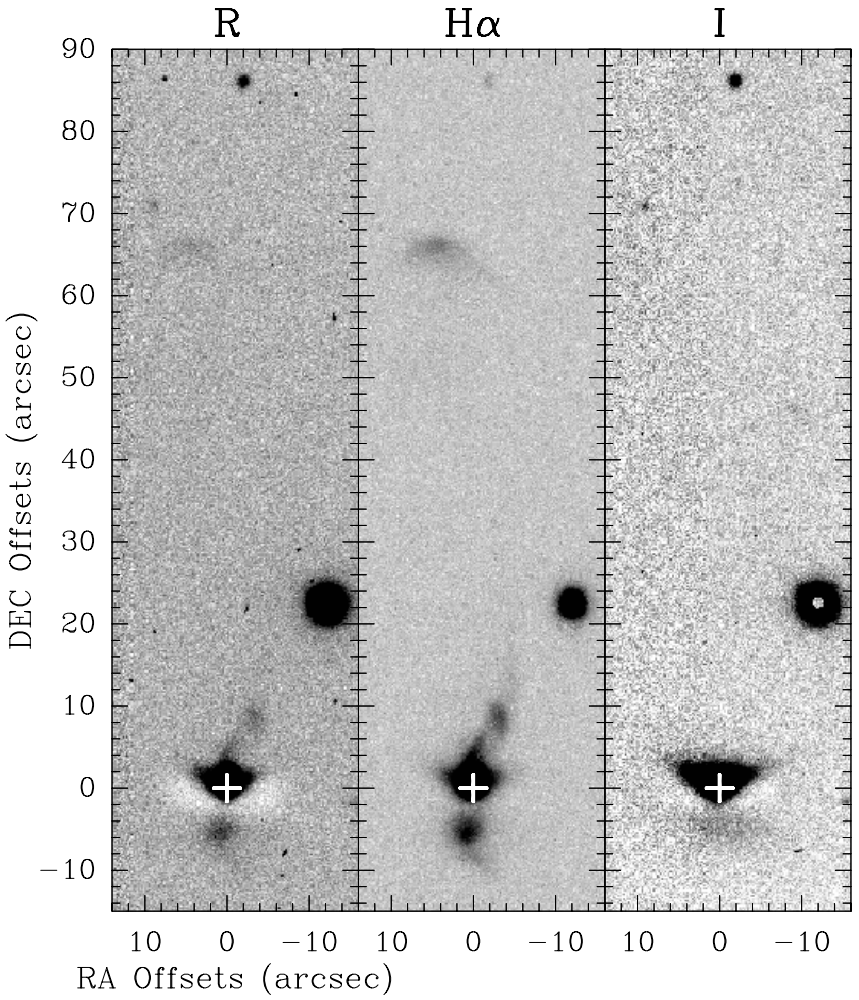
The Taurus star forming region

MEET IRAS04158

- The star has an almost edge on disc...
- ... and a “precessing jet”

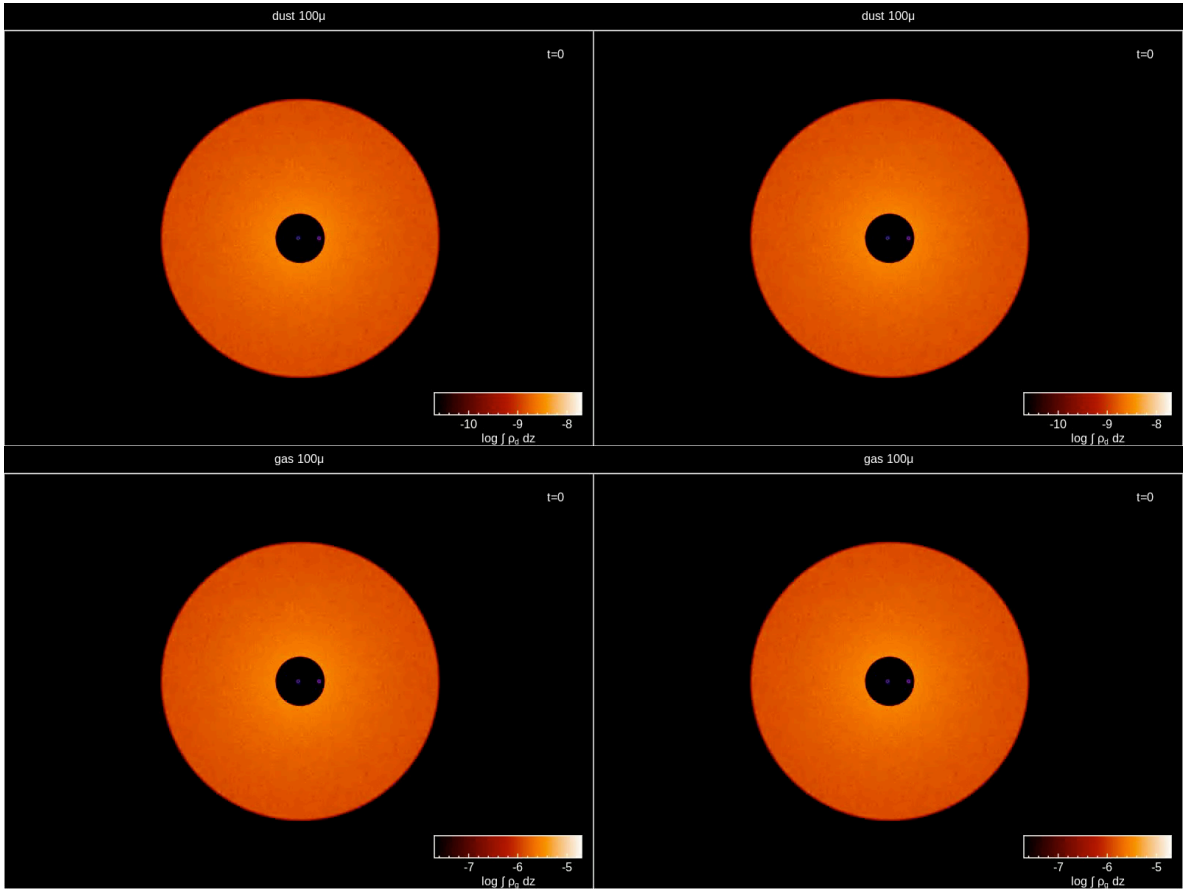


Villenave et al 2020 - ALMA



ASYMMETRIES IN CIRCUMBINARY DISCS

- Ragusa et al



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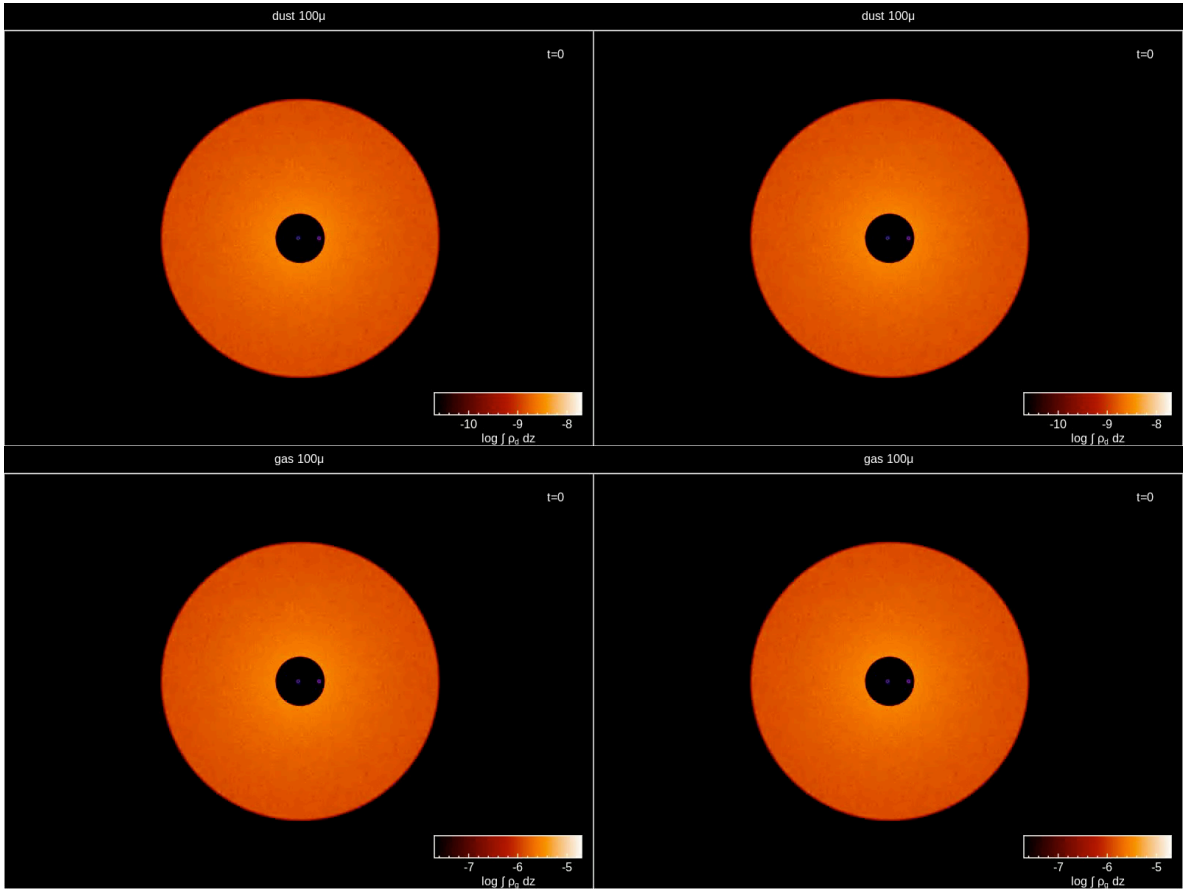

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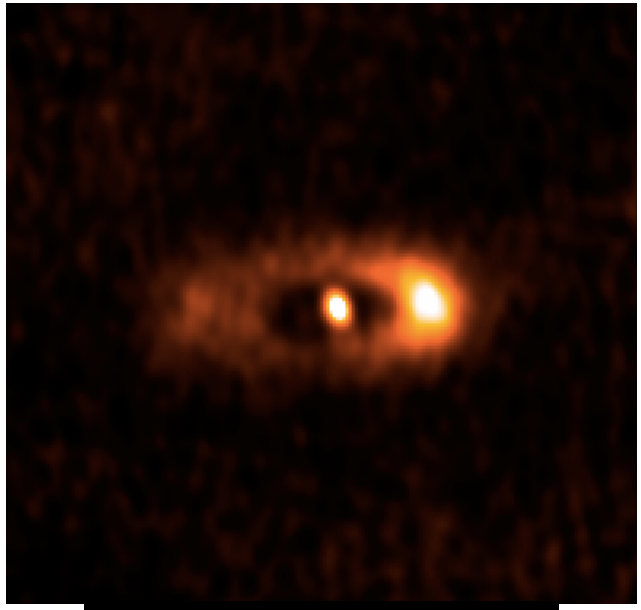

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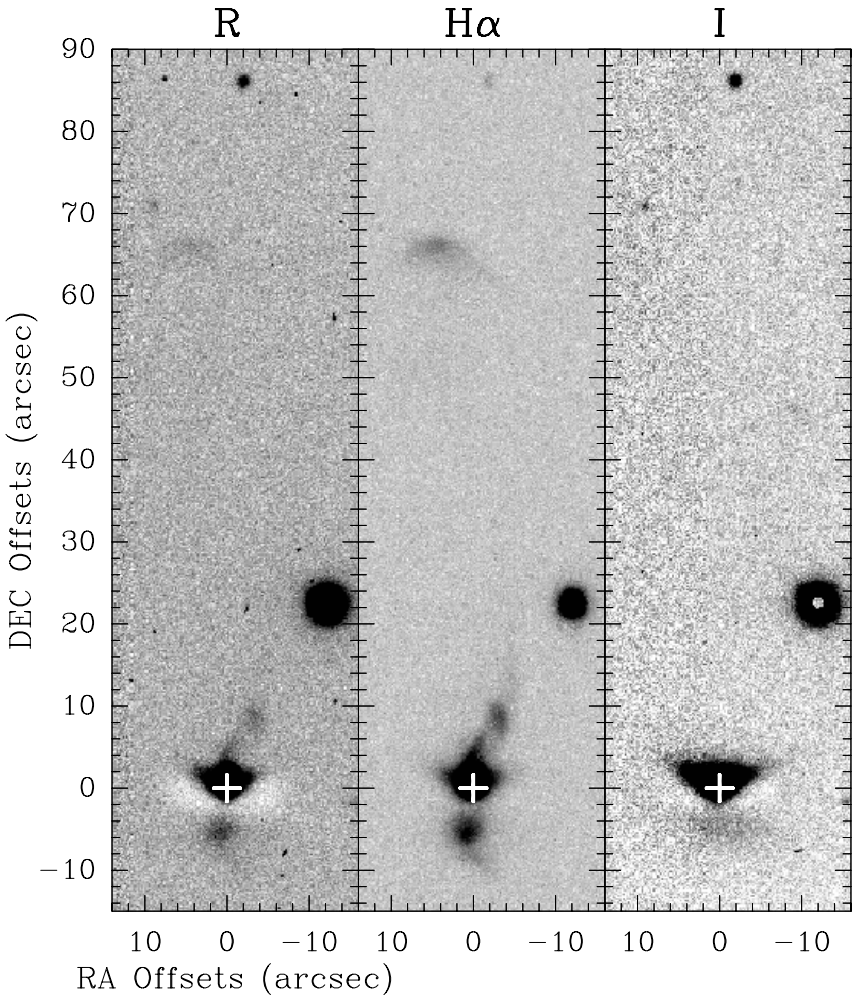

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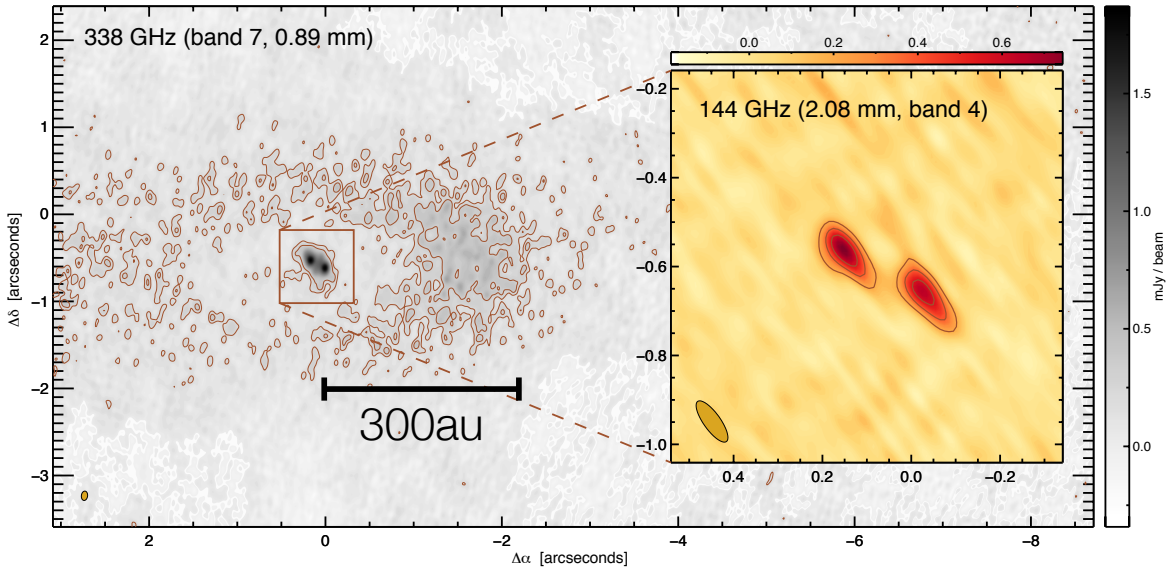
New, hi-res ALMA images



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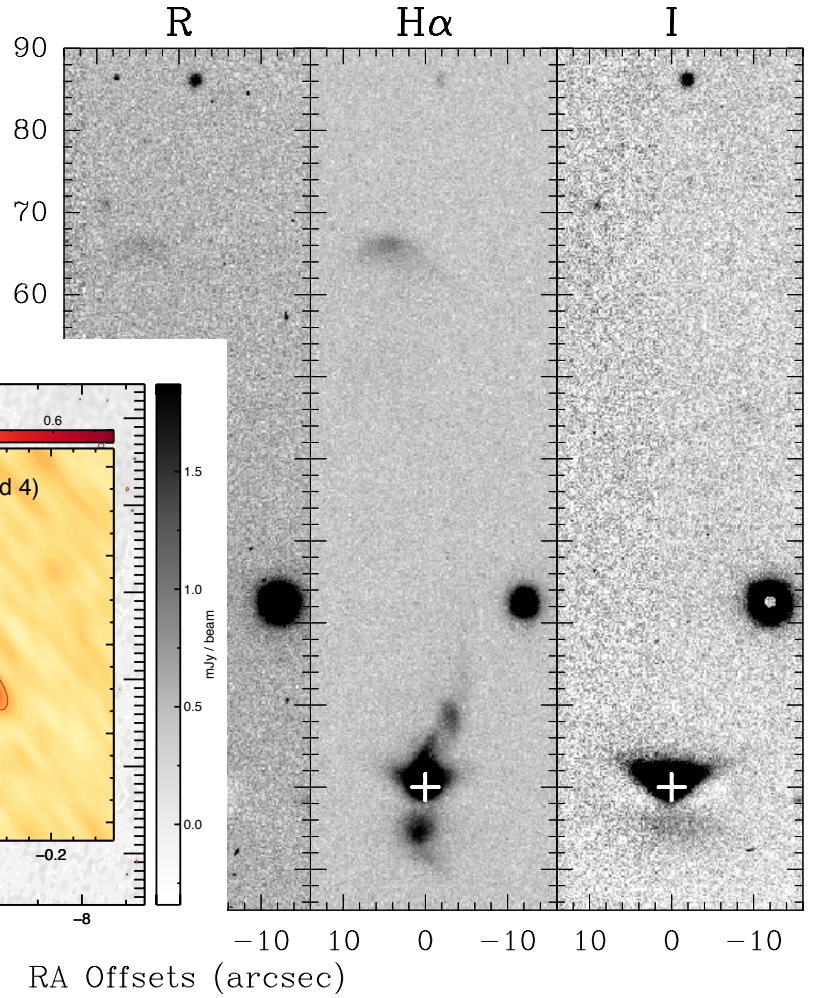
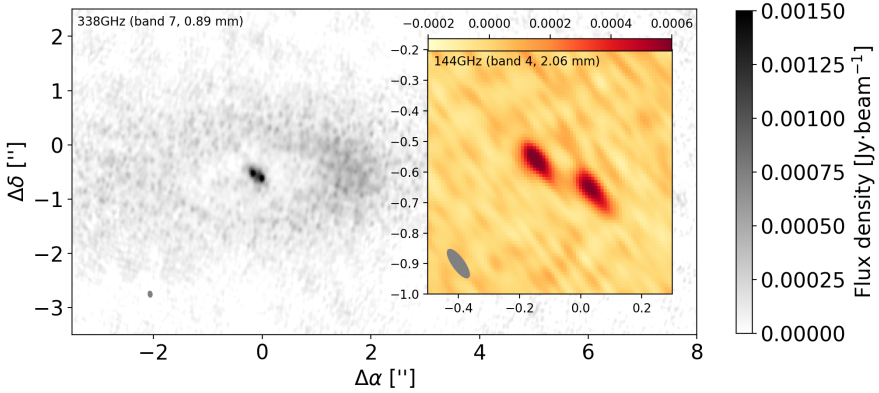
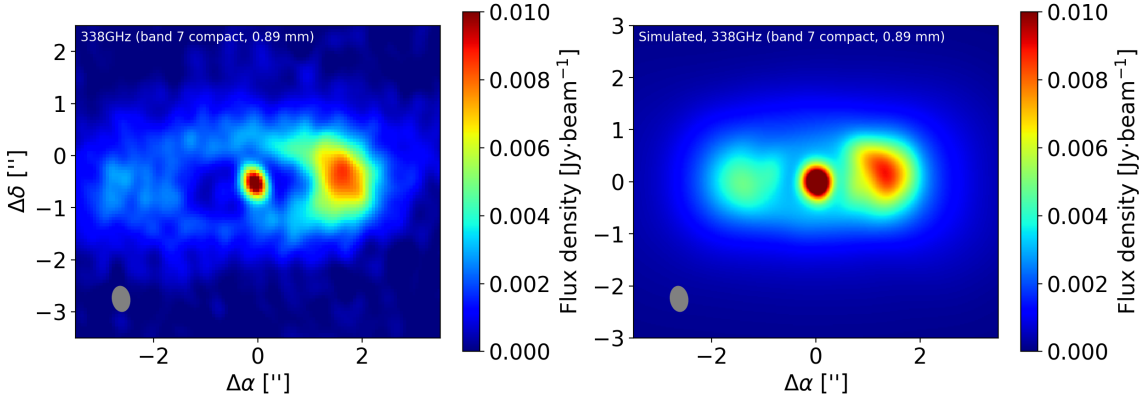


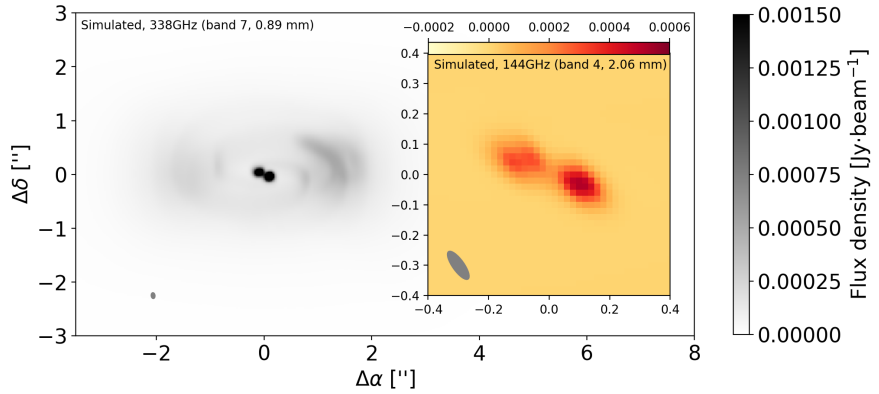
MODELING IRAS04158

Ragusa, GL et al (2021)

- SPH, gas+dust simulations, equal mass eccentric binary (e=0.5), coplanar disc
- Produce synthetic observations using MCFOST for different wavelengths in the dust...

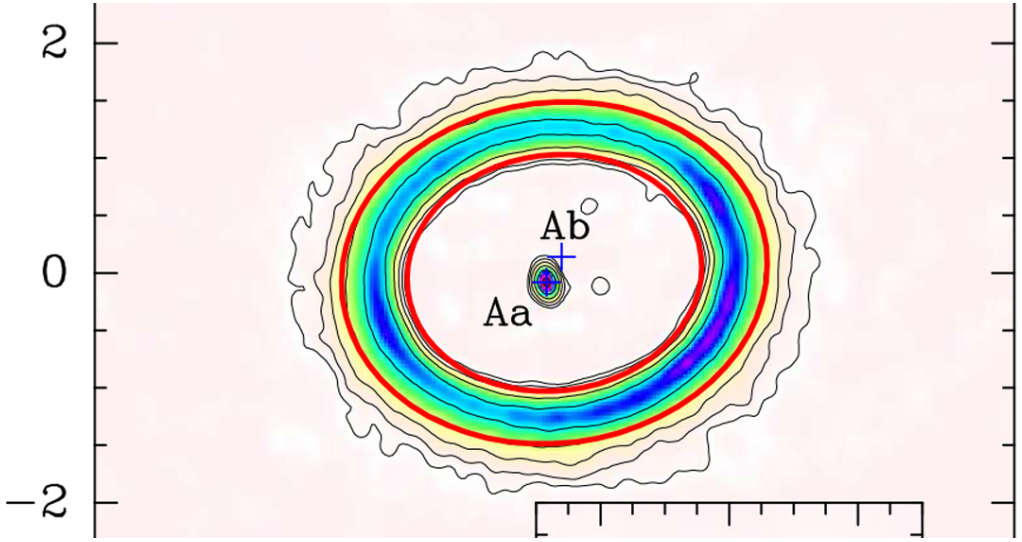


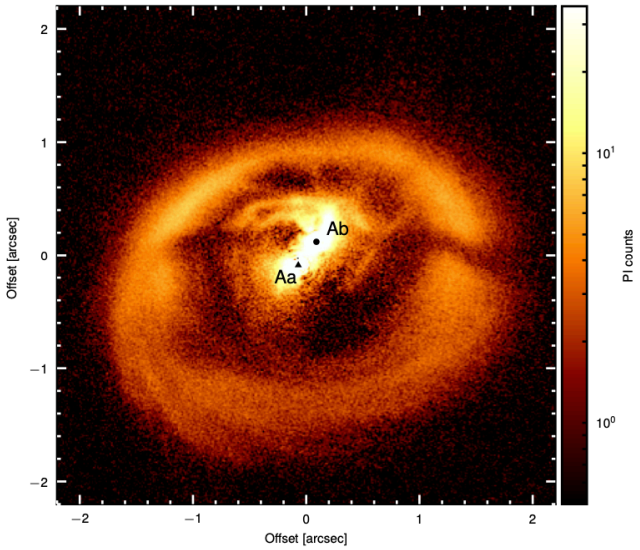




MEET GG TAU

- GG Tau A is a binary (GG Tau Aa and GG Tau Ab) surrounded by a disc





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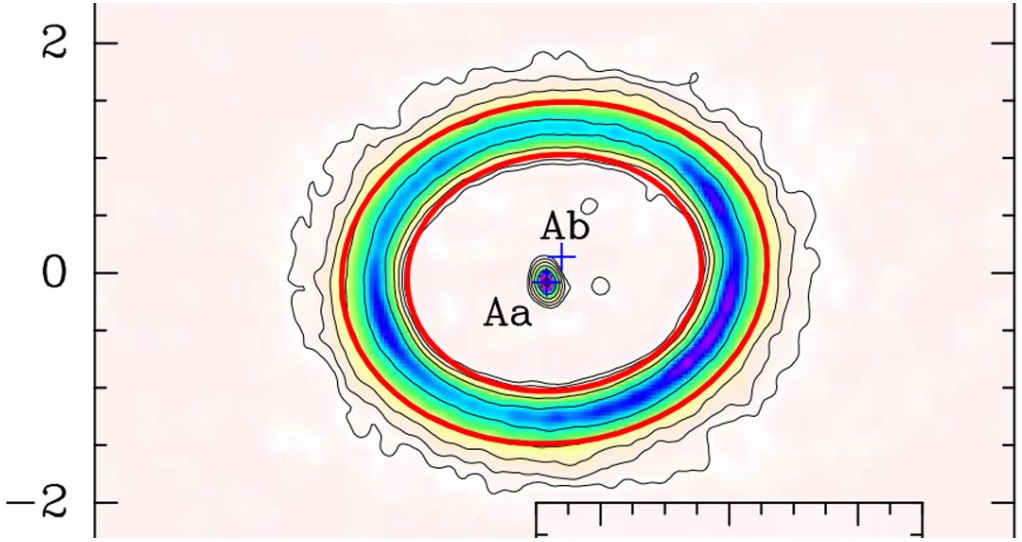

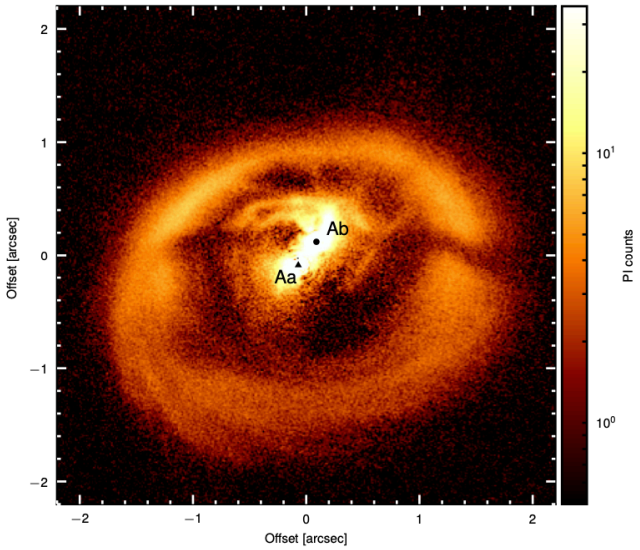

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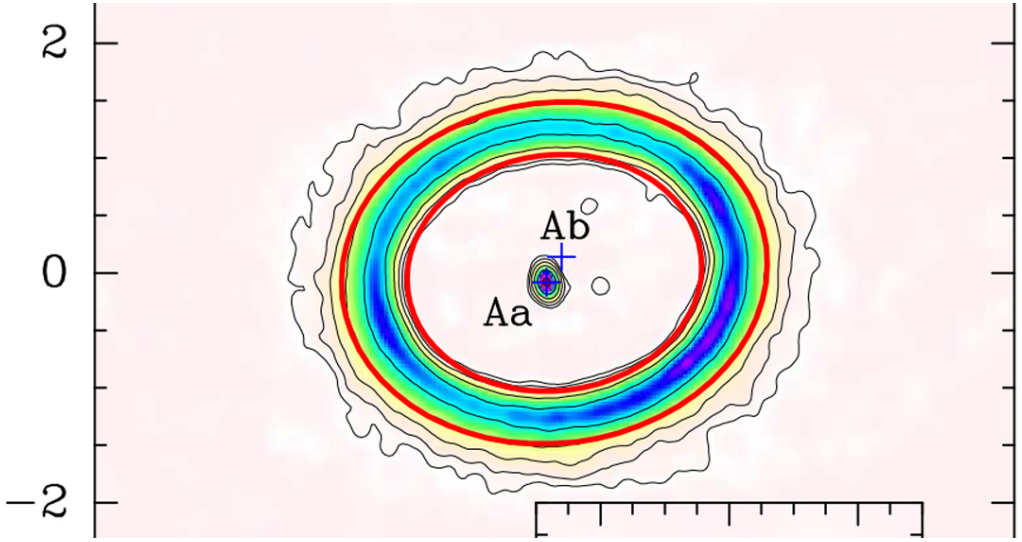

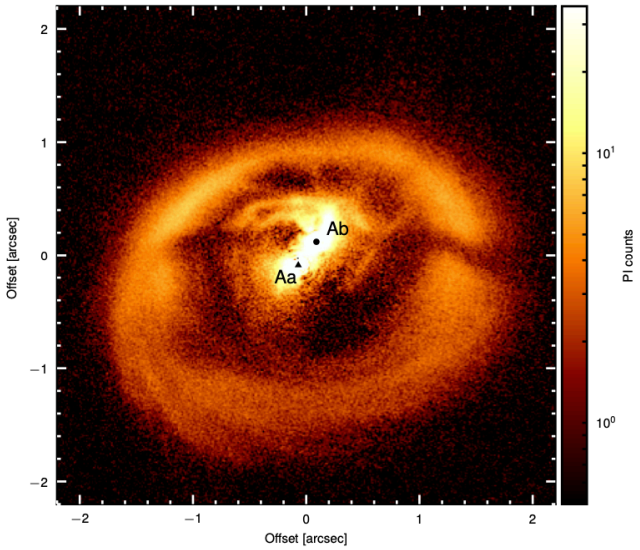

DISC INSTABILITIES AND THE ORIGIN OF "VISCOSITY"

WHAT IS THE ORIGIN OF DISC VISCOSITY?

- Collisional viscosity is orders of magnitude too small to allow accretion on the appropriate timescale
- Traditionally, viscosity is associated with the effect of turbulence
- The Shakura-Sunyaev (1973) prescription states that $\nu = \alpha_{\rm SS} c_{\rm s} H$

$$\sigma_{R\phi} = \nu\Sigma(R\Omega') = \alpha_{\rm SS} P \frac{{\rm d}\ln\Omega}{{\rm d}\ln R}$$

- How big should $\alpha_{\rm SS}$ be explain the observed accretion rates?

$$3\pi\nu\Sigma = \dot{M} \quad \longrightarrow \quad \alpha_{\rm SS} = \frac{2}{3}\frac{\dot{M}}{M_{\rm disc}\Omega(R_{\rm c})}\left(\frac{H}{R}\right)^{-2}$$

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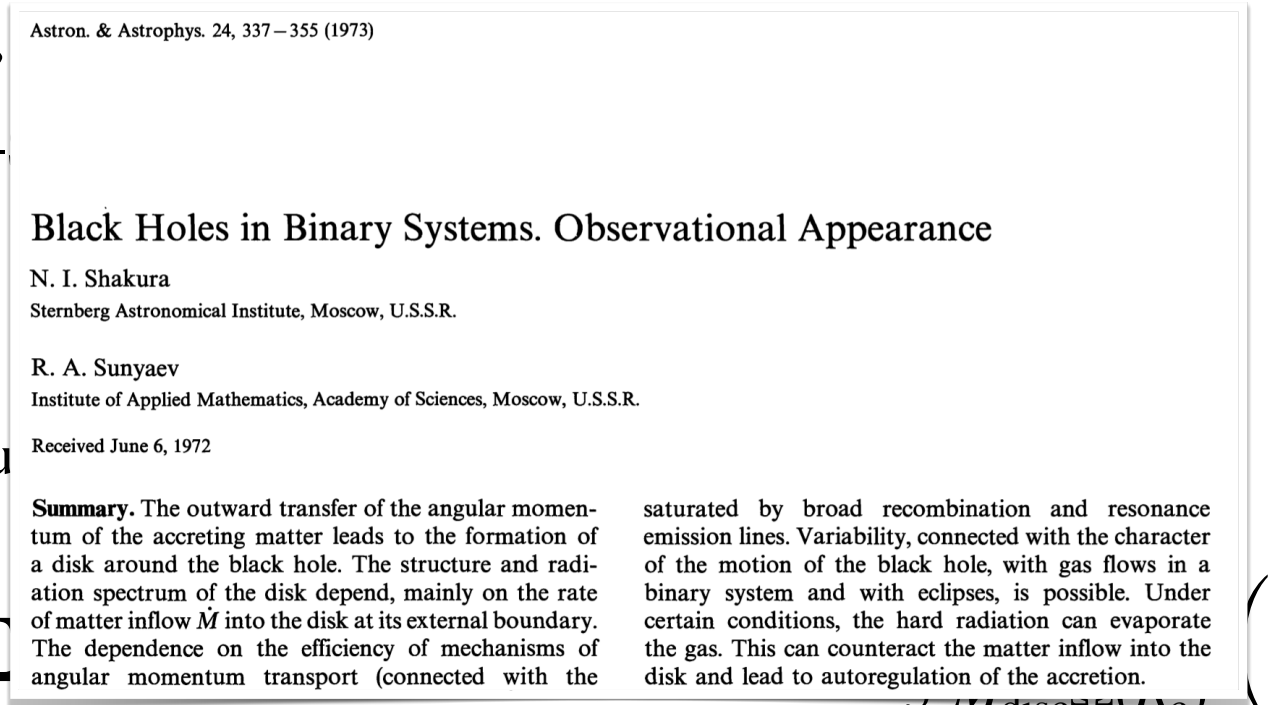

Astron. & Astrophys. 24, 337–355 (1973)

Black Holes in Binary Systems. Observational Appearance

N. I. Shakura
Sternberg Astronomical Institute, Moscow, U.S.S.R.

R. A. Sunyaev
Institute of Applied Mathematics, Academy of Sciences, Moscow, U.S.S.R.

Received June 6, 1972

Summary. The outward transfer of the angular momentum of the accreting matter leads to the formation of a disk around the black hole. The structure and radiation spectrum of the disk depend, mainly on the rate of matter inflow $\dot{M}$ into the disk at its external boundary. The dependence on the efficiency of mechanisms of angular momentum transport (connected with the saturated by broad recombination and resonance emission lines. Variability, connected with the character of the motion of the black hole, with gas flows in a binary system and with eclipses, is possible. Under certain conditions, the hard radiation can evaporate the gas. This can counteract the matter inflow into the disk and lead to autoregulation of the accretion.

$$3\pi\nu\Sigma \qquad \left(\frac{H}{R}\right)^{-2}$$

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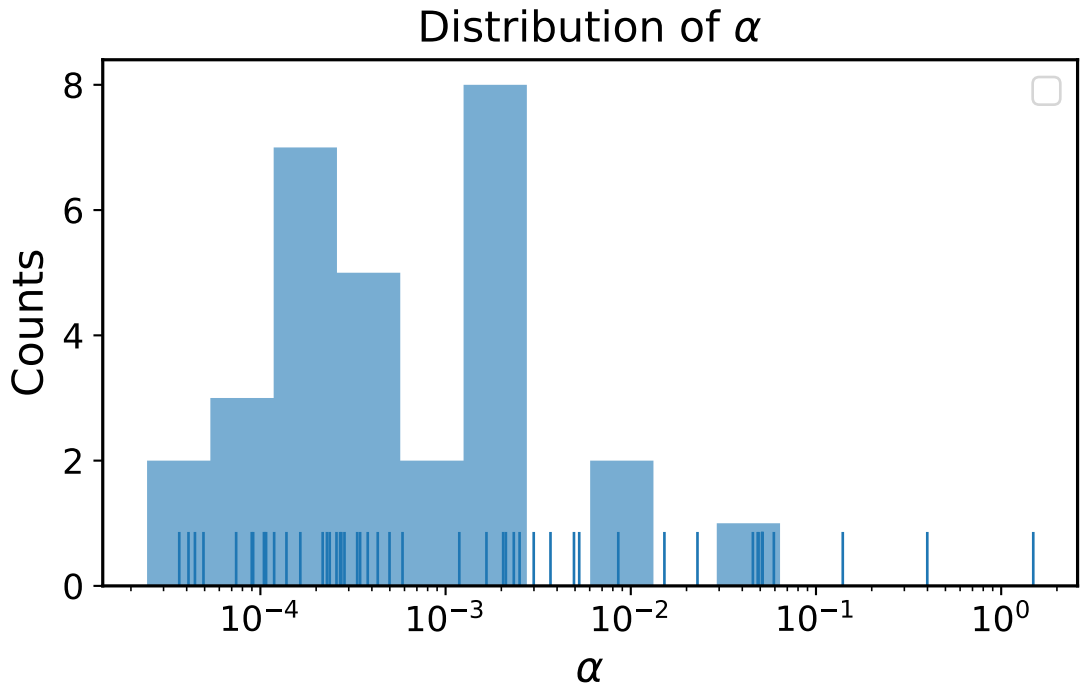
$$\sigma_K$$

- How big should α

$$3\pi\nu\Sigma =$$



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- The Shakura-Sunyaev (1973) prescription states that $\nu = \alpha_{SS} c_s H$
- How big should α_{SS} be explain the observed accretion rates?
- Turbulence can also be inferred from the non-thermal broadening of CO emission lines in the mm-band from ALMA observations (Flaherty et al, 2017-2024)

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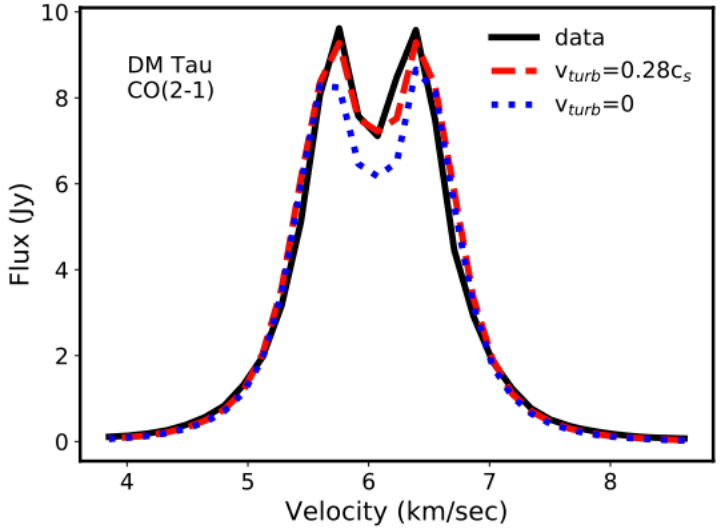
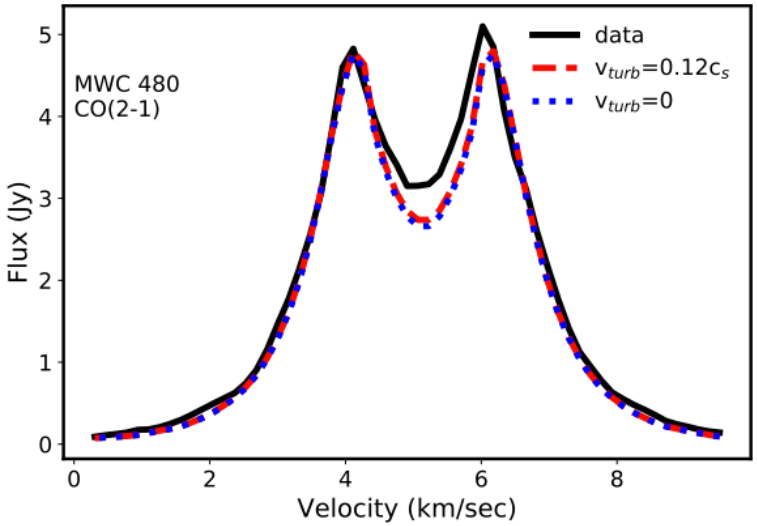


$\alpha = 0.078 \pm 0.002$



$\alpha \lesssim 0.006$

TURBULENT VISCOSITY

- Viscous torques are such that

$$\frac{\partial}{\partial t}\left(\Sigma R v_\phi\right) + \frac{1}{R}\frac{\partial}{\partial R}\left(R v_r \Sigma R v_\phi\right) = \frac{1}{R}\frac{\partial}{\partial R}\left(\nu \Sigma R^3 \Omega'\right)$$

- In an inviscid disc in the presence of turbulence $\vec{v}_{\rm tot} = \vec{v} + \vec{u}$, where $\langle \vec{u} \rangle = 0$

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- If there are other turbulent fields (magnetic field, gravitational field) the stress is

$$\sigma_{R\phi} = \Sigma\left(\langle u_R u_\phi \rangle + \left\langle \frac{B_R B_\phi}{4\pi\rho} \right\rangle + \left\langle \frac{g_R g_\phi}{4\pi G \rho} \right\rangle\right) \approx \alpha_{\rm SS} \Sigma c_{\rm s}^2$$

$$\alpha_{\rm SS} \simeq \left(\frac{\langle u_R u_\phi \rangle}{c_{\rm s}^2} + \left\langle \frac{B_R B_\phi}{4\pi\rho c_{\rm s}^2} \right\rangle + \left\langle \frac{g_R g_\phi}{4\pi G \rho c_{\rm s}^2} \right\rangle\right)$$

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v_φ

bulent velocity, v_φ is the circular keplerian velocity. Thus the efficiency of two of the most important mechanisms of angular momentum transport connected with the magnetic field (which always is present in astrophysical conditions) and turbulence (whose existence in the disk is less definite)

$$-w_{r\varphi} \sim \varrho v_s^2\left(\frac{v_t}{v_s}\right) + \varrho v_s^2\left(\frac{H^2}{4\pi\varrho v_s^2}\right) = \alpha\varrho v_s^2 \qquad (1.2)$$

can be characterized by only one parameter, α. In the case of a turbulent mechanism $\alpha < 1$ always. For $\alpha > 1$ turbulence must be supersonic and leads to rapid heating of the plasma and to $\alpha \leqq 1$. For magnetic transport of angular momentum in the disk, it is likely that $\alpha < 1$. For a wide range of the initial conditions, it is possible that $\alpha \ll 1$. In addition, the parameter α can (and must) be a function of the disk radius[6]). Below, we point out

DISC INSTABILITIES

- The **magneto-rotational instability** (Chandrasekhar 1960): in the presence of a *weak* magnetic field, differential rotation is unstable if: $\frac{\mathrm{d}\Omega^2}{\mathrm{d}\ln R} < 0$



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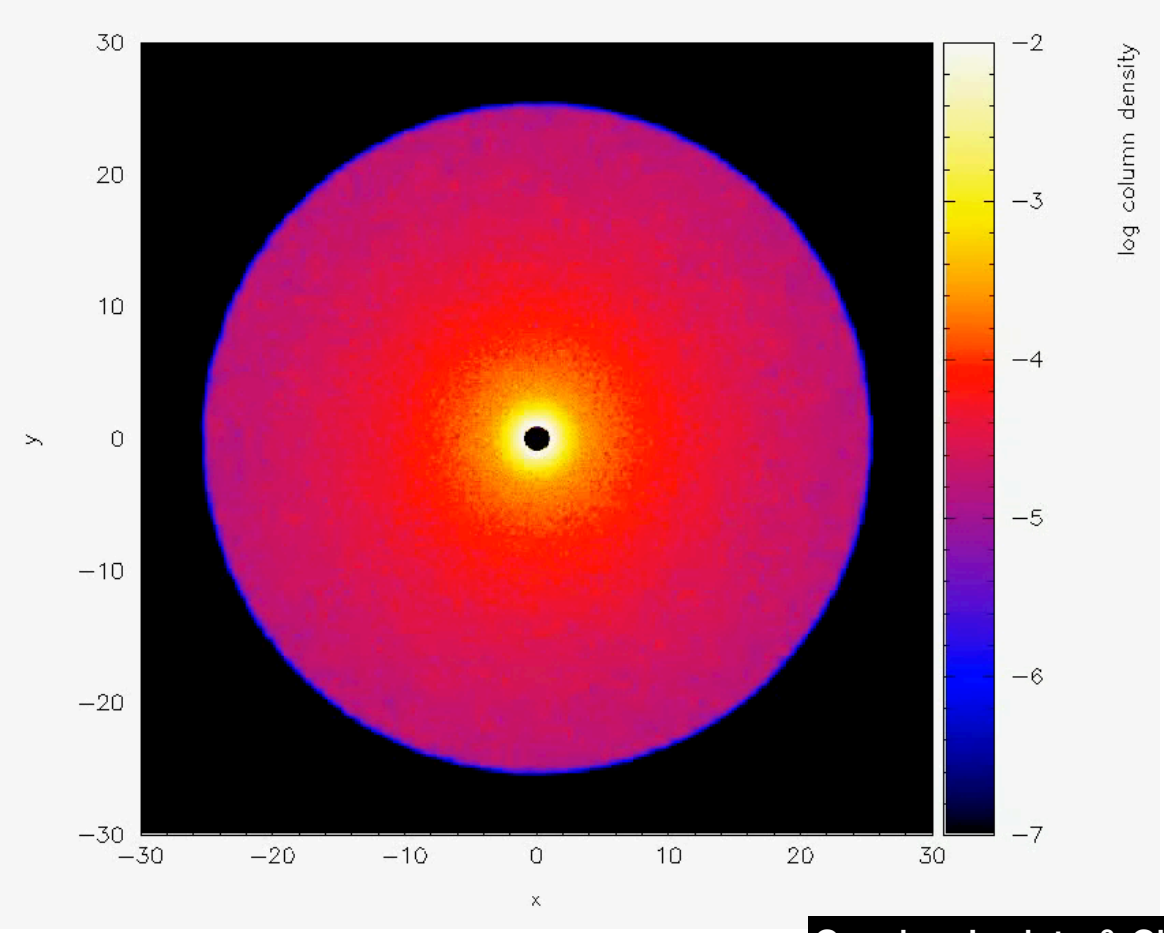
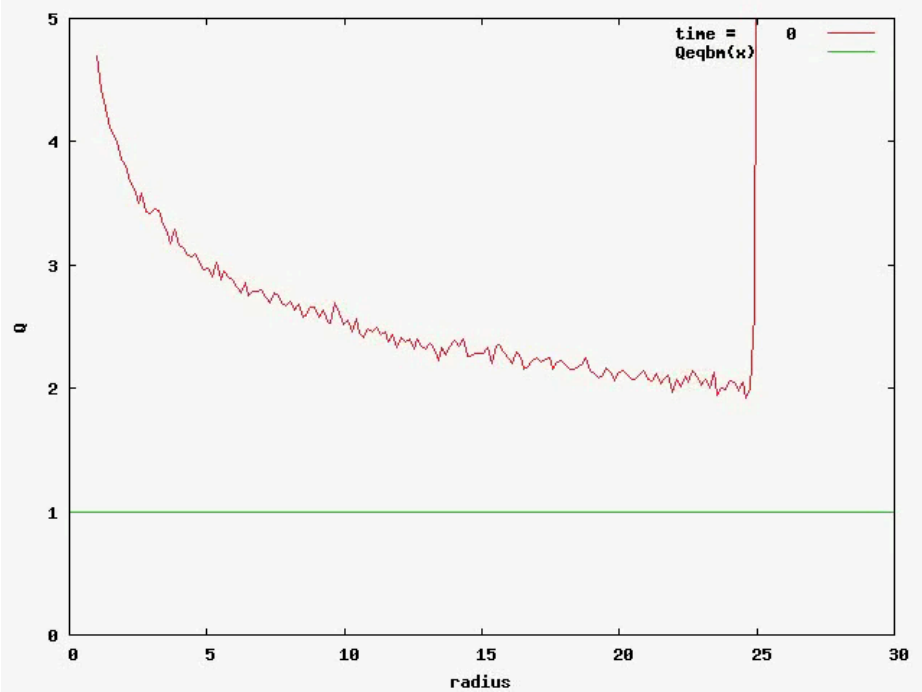
- In protostellar discs, the ionization level is low and non-ideal MHD effect can completely quench the MRI
- The **vertical shear instability** is activated in the presence of vertical shear (which does happen in protostellar discs)
- In the early phase of star formation, **the gravitational instability** can also work, if the disc is massive enough

$$Q = \frac{c_s \kappa}{\pi G \Sigma} \lesssim 1 \quad \longrightarrow \quad \frac{M_d}{M_\star} \gtrsim \frac{H}{R}$$

GRAVITATIONAL INSTABILITY





Cossins, Lodato & Clarke 2009

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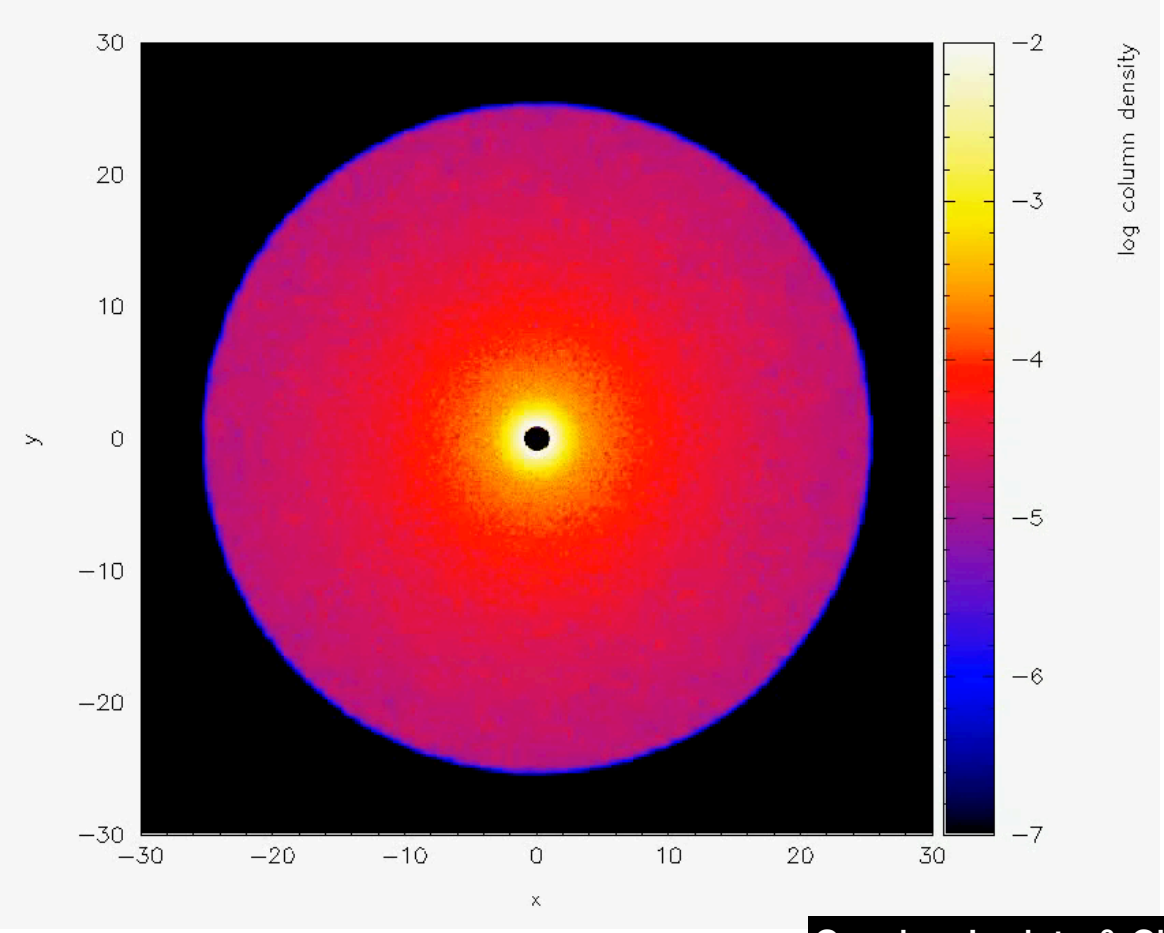

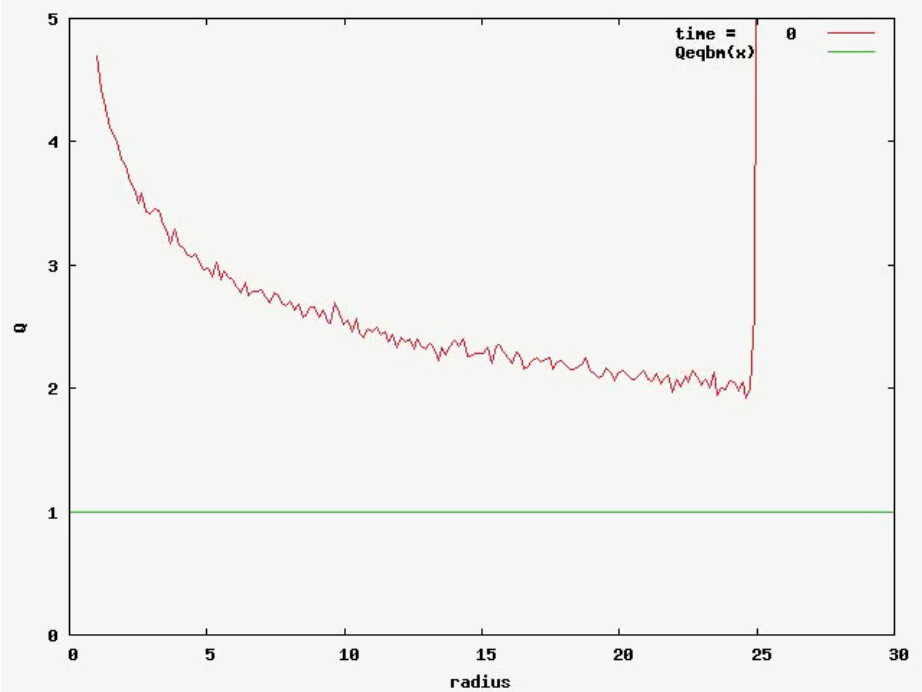

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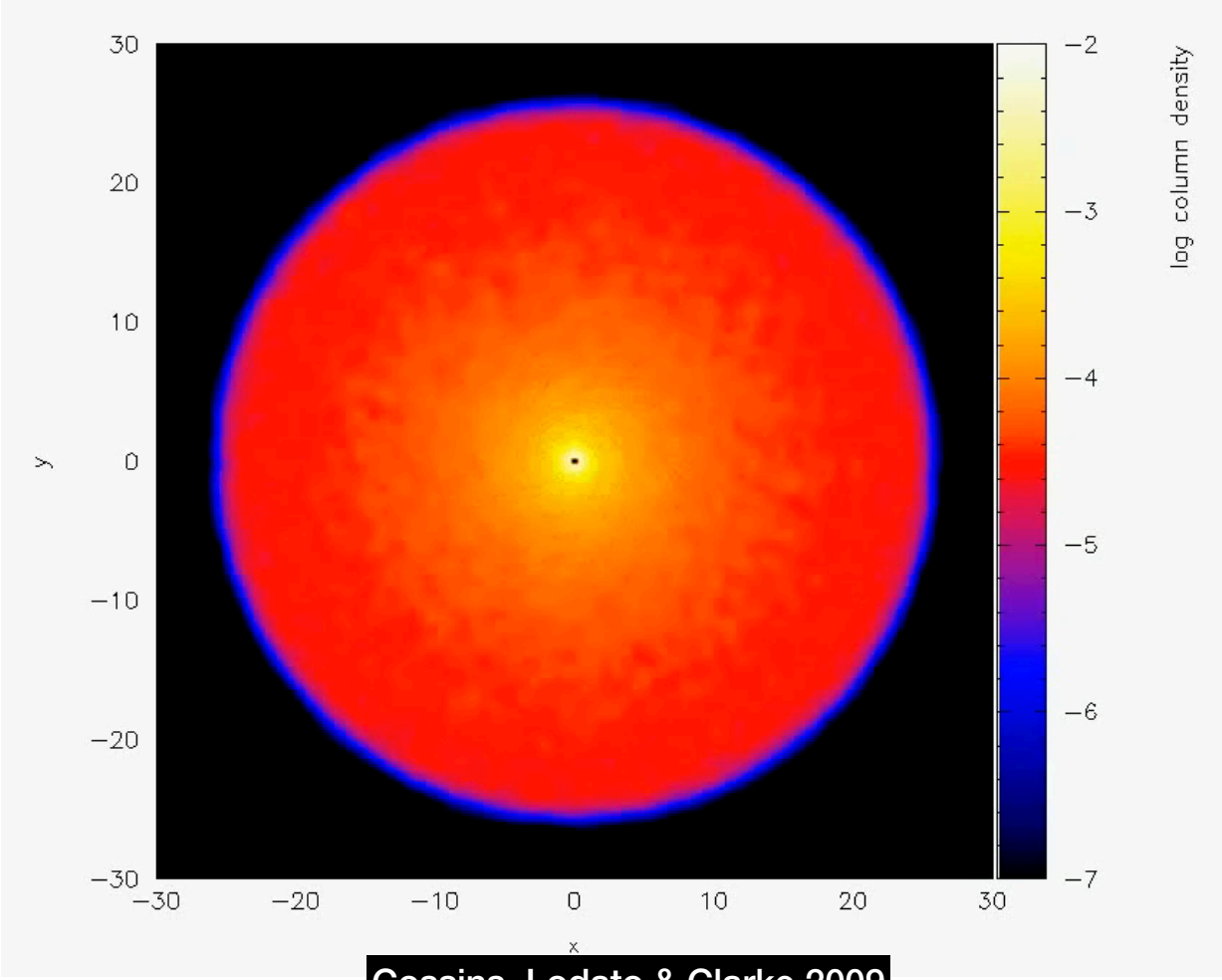

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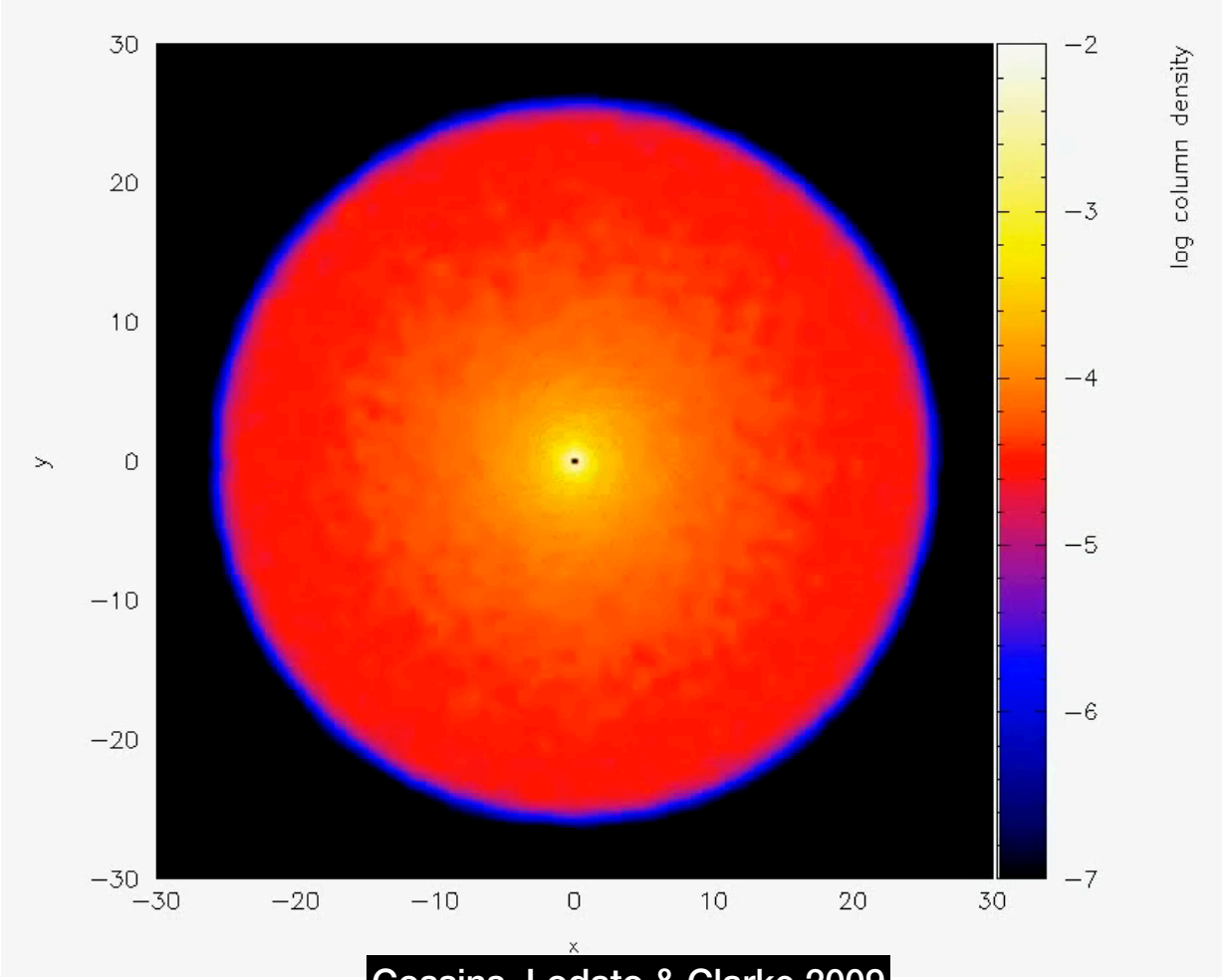

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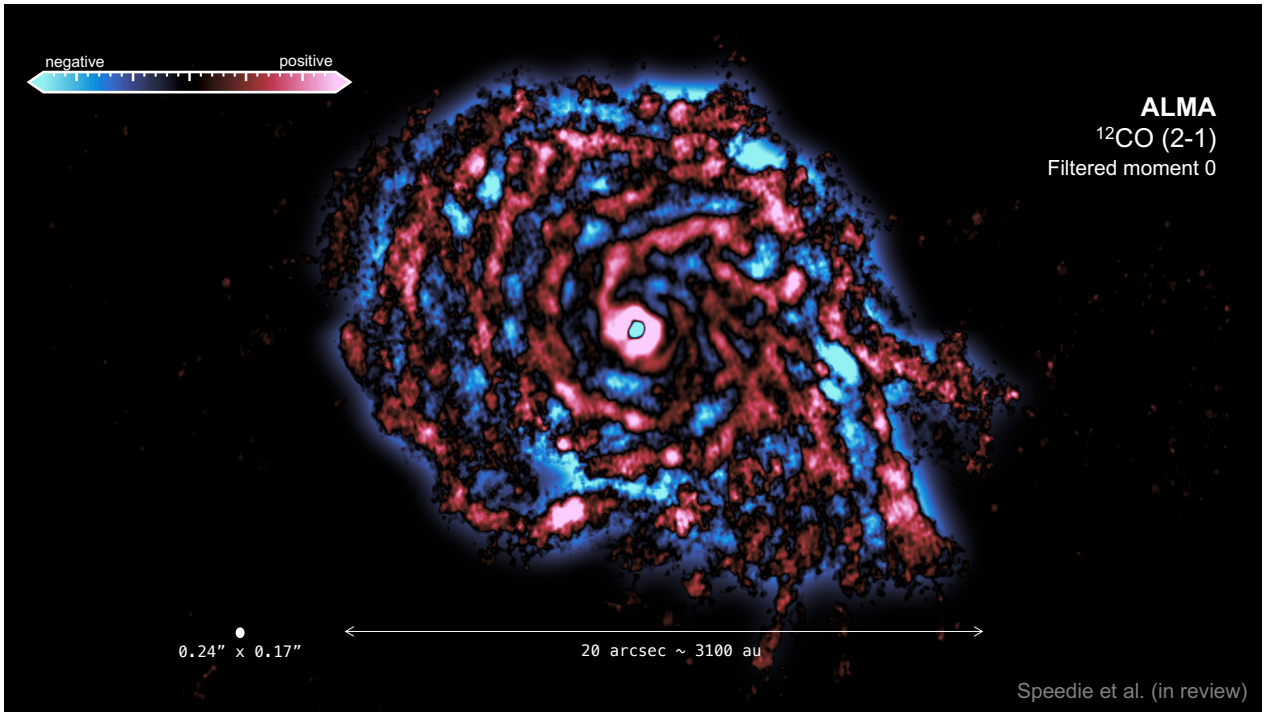
OBSERVING GI DISCS

AB Aur, Speedie et al, Nature, 2025



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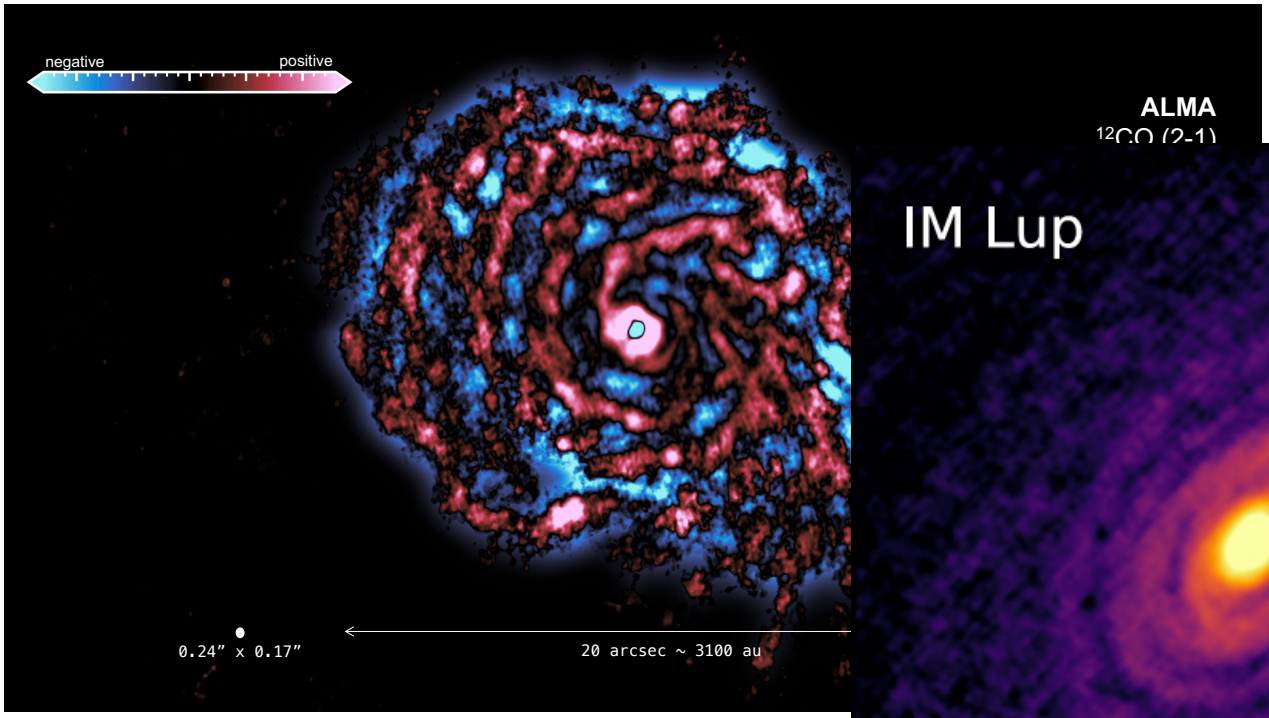

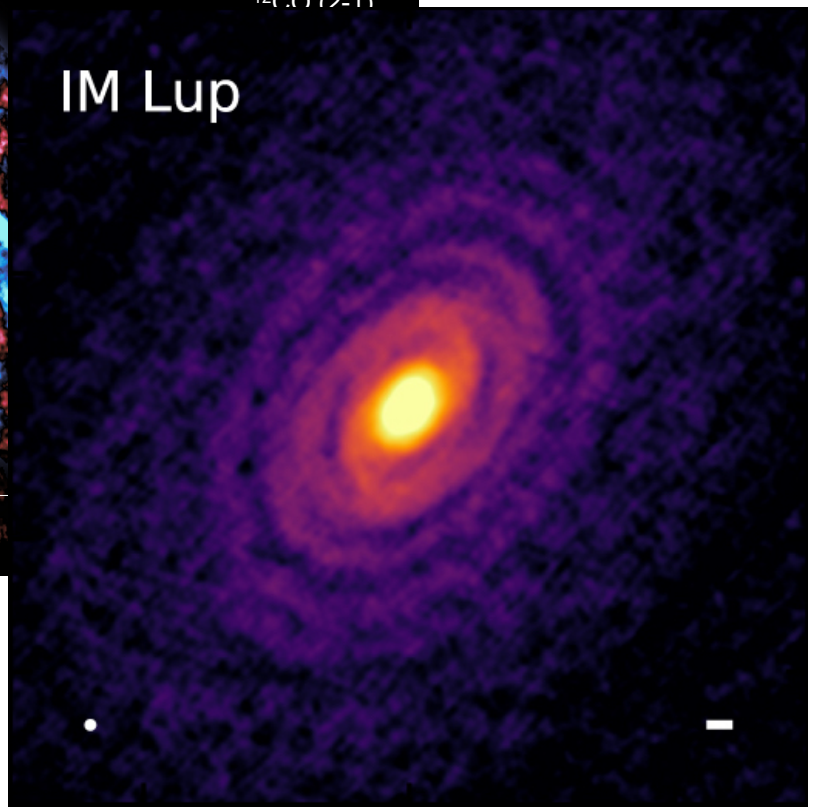

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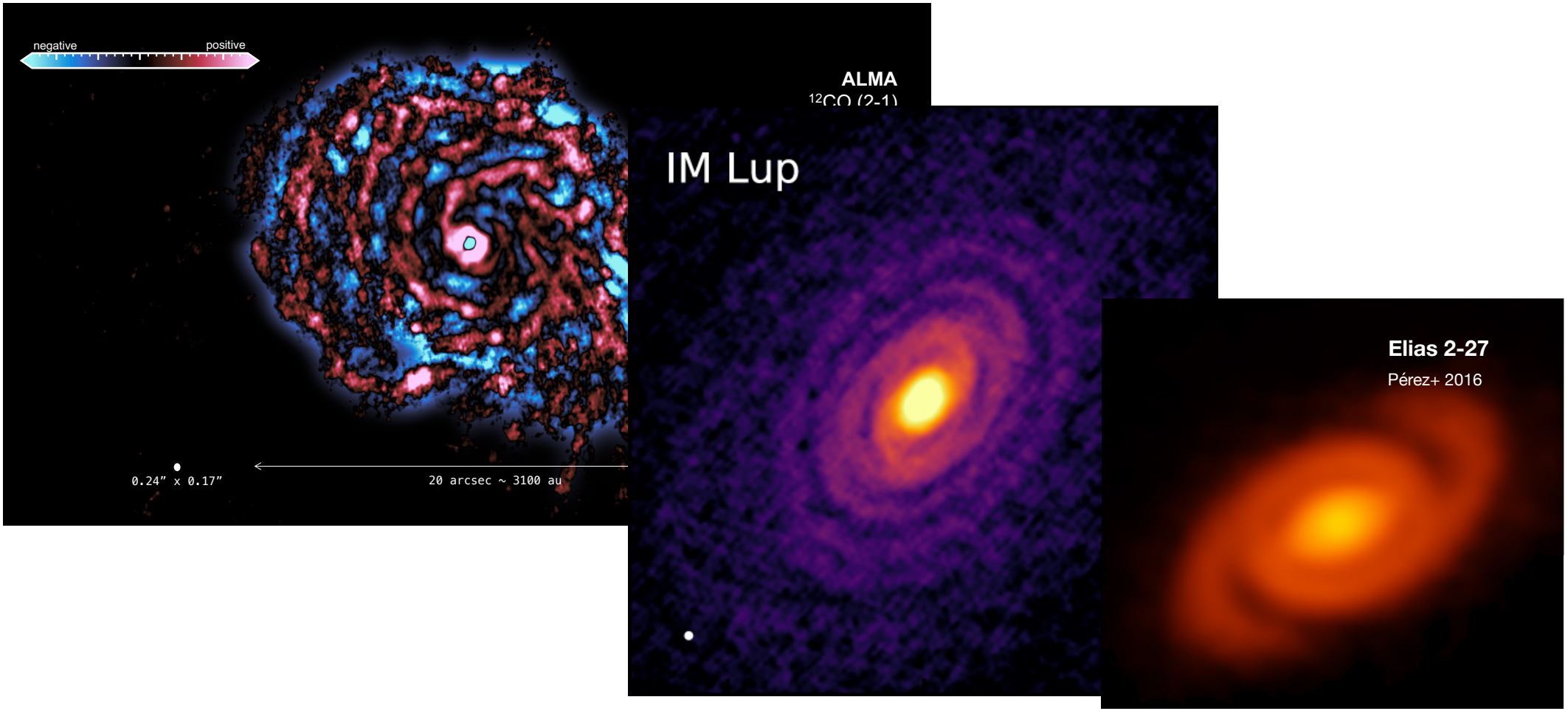
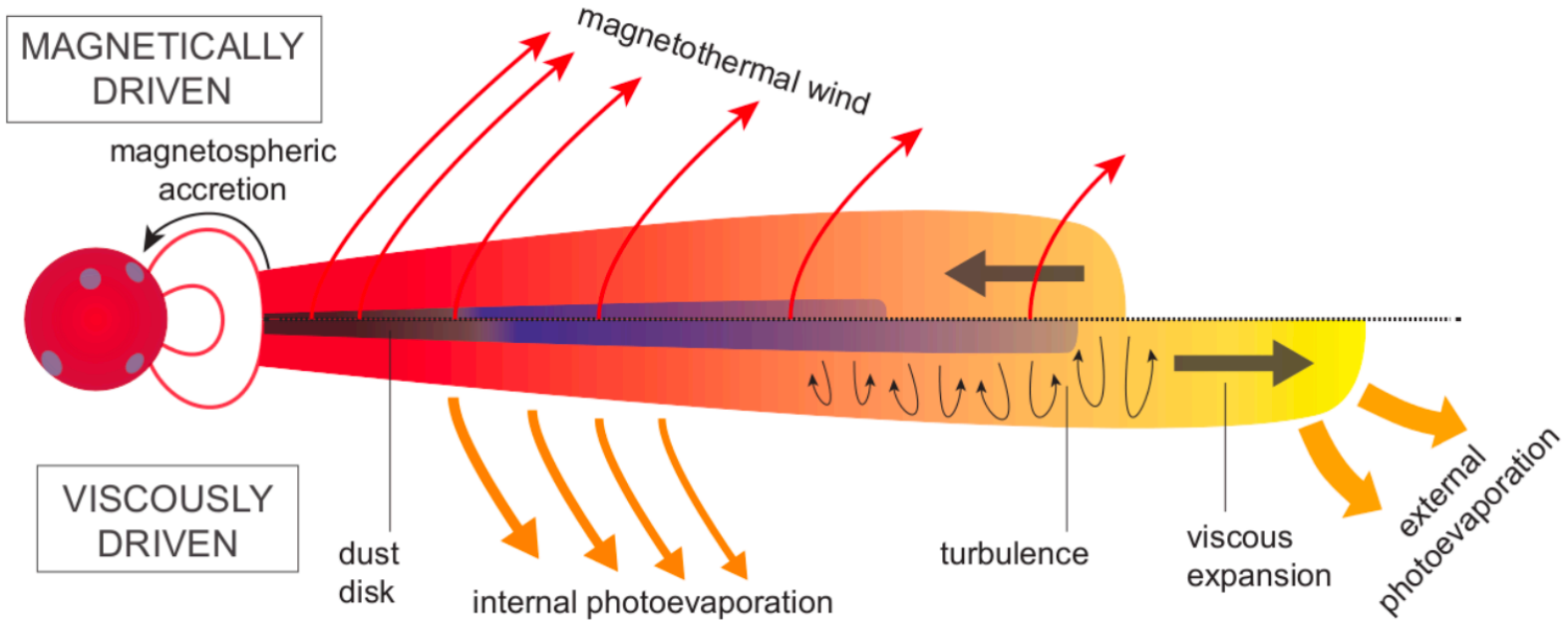


VARIOUS PHYSICAL EFFECTS IN DISC EVOLUTION



Manara et al PPVII 2023

EVOLUTION DUE TO MHD DISC WINDS

Blanford & Payne 1983, Tabone et al 2022

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left\{\frac{1}{R\Omega}\frac{\partial}{\partial R}\left(R^2 \alpha_{\rm SS} \Sigma c_s^2\right)\right\} + \frac{3}{2R}\frac{\partial}{\partial R}\left\{\frac{\alpha_{\rm DW}\Sigma c_s^2}{\Omega}\right\} - \frac{3\alpha_{\rm DW}\Sigma c_s^2}{4(\lambda-1)R^2\Omega}$$

Viscous diffusion

Advection induced by MHD winds

Mass removal by MHD winds

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Blanford & Payne 1983, Tabone et al 2022

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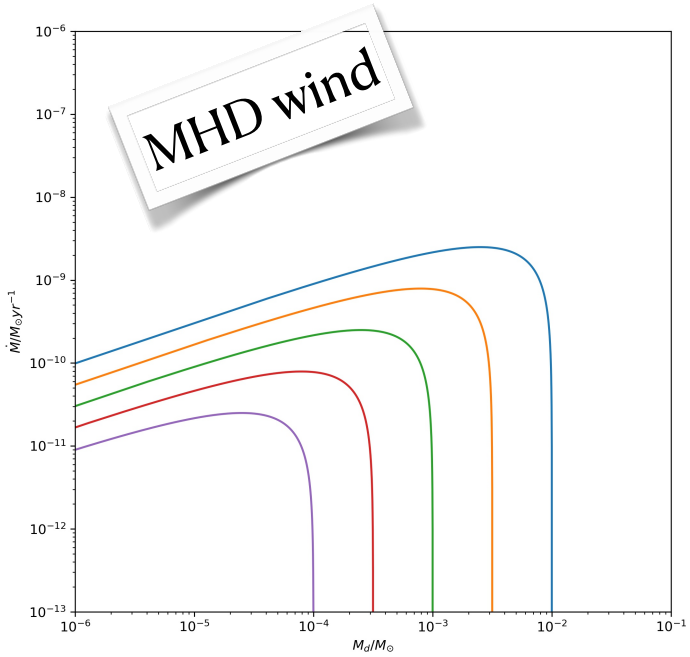

Advection induced by MHD winds

Mass removal by MHD winds

EVOLUTION DUE TO MHD DISC WINDS

Blanford & Payne 1983, Tabone et al 2022

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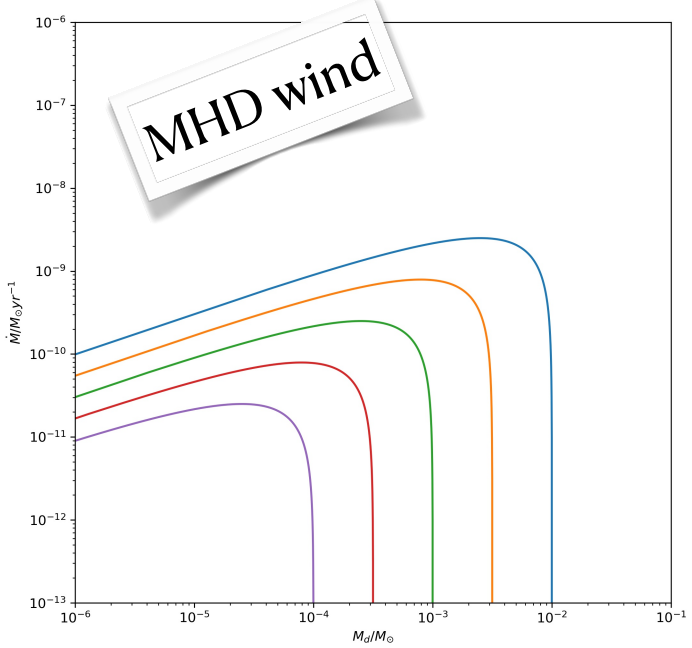

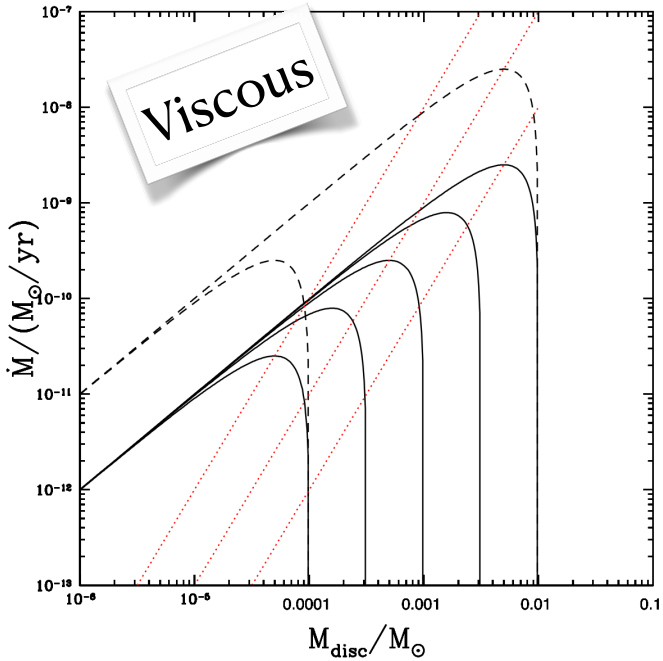

moval winds

DUST DYNAMICS IN DISCS

DUST IN DISCS

- The solid component is essential to produce the rocky planets and the core of giant planets
- Main difference wrt gas: it is *pressureless*
- Key dynamical processes:
  - **Vertical settling**
  - **Radial drift**
- Key physical property: coupling to gas via *drag*

$$\mathbf{F}_{\rm drag} = -\, m_{\rm dust} \frac{\mathbf{v}_{\rm d} - \mathbf{v}_{\rm g}}{t_{\rm stop}} \qquad\qquad St = \Omega t_{\rm stop} = f \frac{\rho_0 s}{\Sigma(R)} \exp \frac{z^2}{2H^2}$$

VERTICAL SETTLING

- Timescale for vertical settling is $t_z = \dfrac{1}{St\Omega}$ (the stronger the coupling - small St - the slower the settling)
- In the presence of turbulence

$$\frac{\partial \rho_d}{\partial t} = D\frac{\partial}{\partial z}\left[\rho_g \frac{\partial}{\partial z}\left(\frac{\rho_d}{\rho_g}\right)\right] + \frac{\partial}{\partial z}\left(St\Omega z \rho_d\right) \qquad \boldsymbol{D \sim \nu}$$

- In a steady state

$$\rho_\mathrm{d} = \rho_{\mathrm{d},0} \exp\left[-\frac{z^2}{2H^2}\left(1 + \frac{\mathrm{St}_0}{\alpha}\right)\right] \qquad H_\mathrm{d} = H\sqrt{\frac{\alpha}{\alpha + \mathrm{St}_0}} < H$$

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Exercise 5: demonstrate that this is the correct solution

RADIAL DRIFT

- Gas orbits at *sub-Keplerian* velocity due to pressure, while dust - to a first approximation - is Keplerian
- Dust feels a head wind, which removes angular momentum and causes faster accretion than gas: radial drift (Weidenshilling 1977)

$$\frac{\mathrm{dv_{d,R}}}{\mathrm{dt}} - \frac{v_{\mathrm{d},\phi}^2}{R} = -\frac{v_{\mathrm{K}}^2}{R} - \frac{v_{\mathrm{d,R}} - v_{\mathrm{g,R}}}{t_{\mathrm{stop}}}$$

$$\frac{\mathrm{d(v_{d,\phi}R)}}{\mathrm{dt}} = -\frac{R(v_{\mathrm{d},\phi} - v_{\mathrm{g},\phi})}{t_{\mathrm{stop}}} \approx \frac{1}{2} v_{\mathrm{K}} v_{\mathrm{d,R}}$$

$$v_\phi^2 = v_{\mathrm{K}}^2 \left[1 - \gamma' \left(\frac{H}{R}\right)^2\right]$$

$$\Delta v = \gamma' \left(\frac{H}{R}\right)^2 v_{\mathrm{K}}$$

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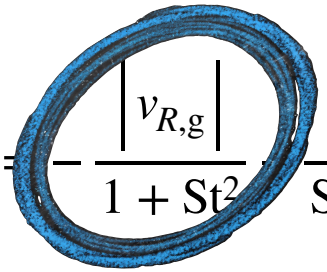

viscous drag

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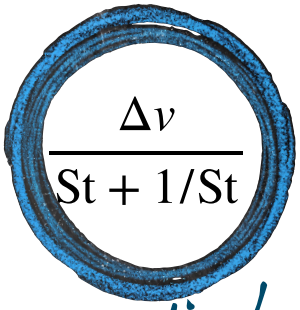

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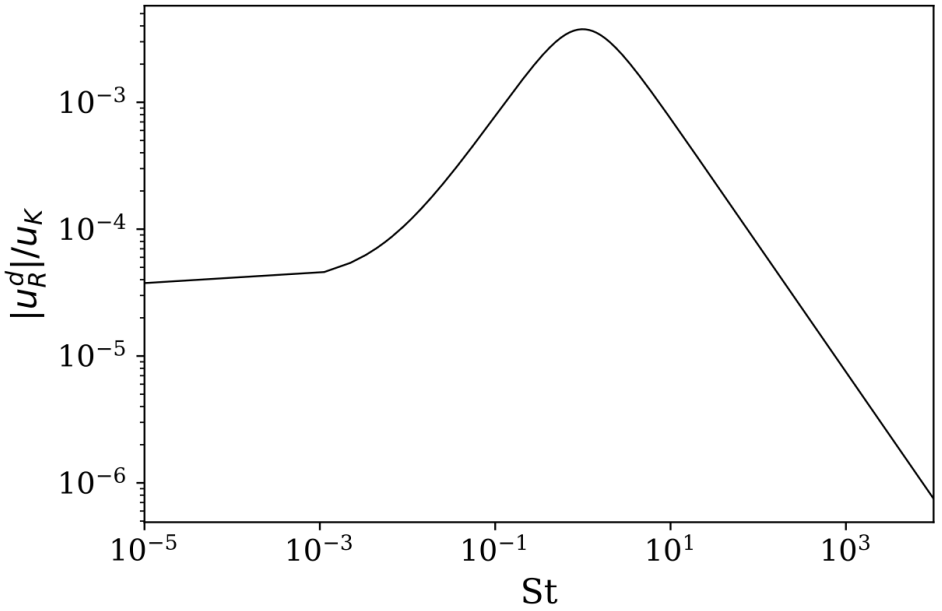
- Dust feels a head wind, which removes angular momentum and causes faster accretion than gas: radial drift (Weidenshilling 1977)
- For St ≈ 1, the radial drift timescale is

$$t_{\text{drift}} = \frac{R}{\Delta v} = \left(\frac{R}{H}\right)^2 \frac{R}{v_{\text{K}}} \approx 100 yrs$$

The “meter size barrier”



DUST TRAPS

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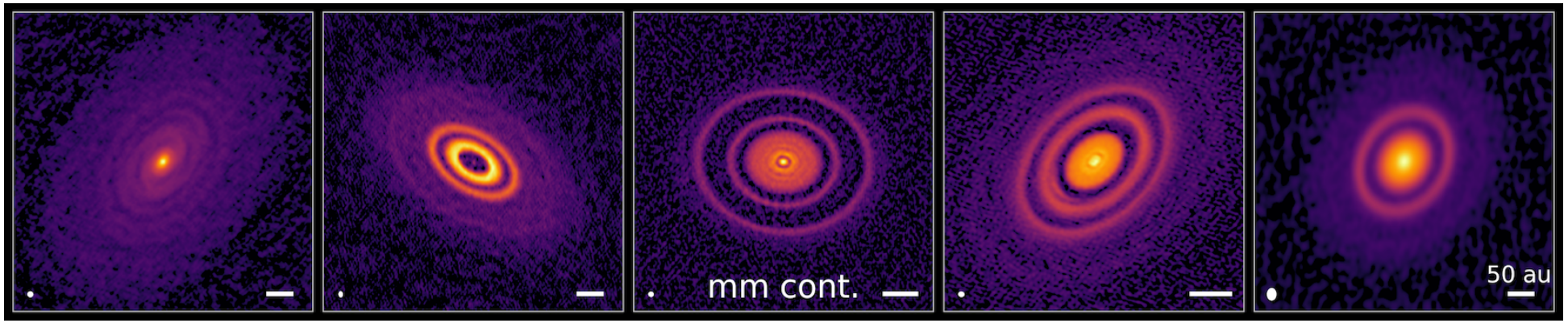

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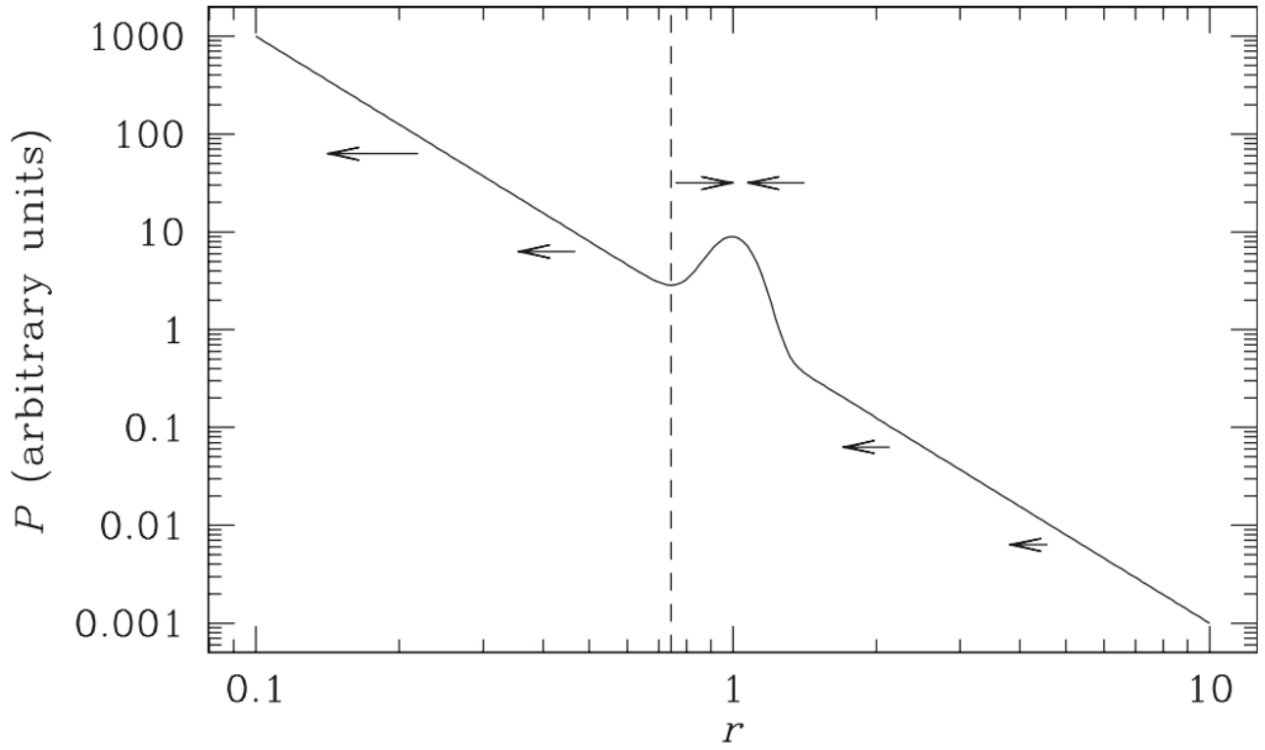


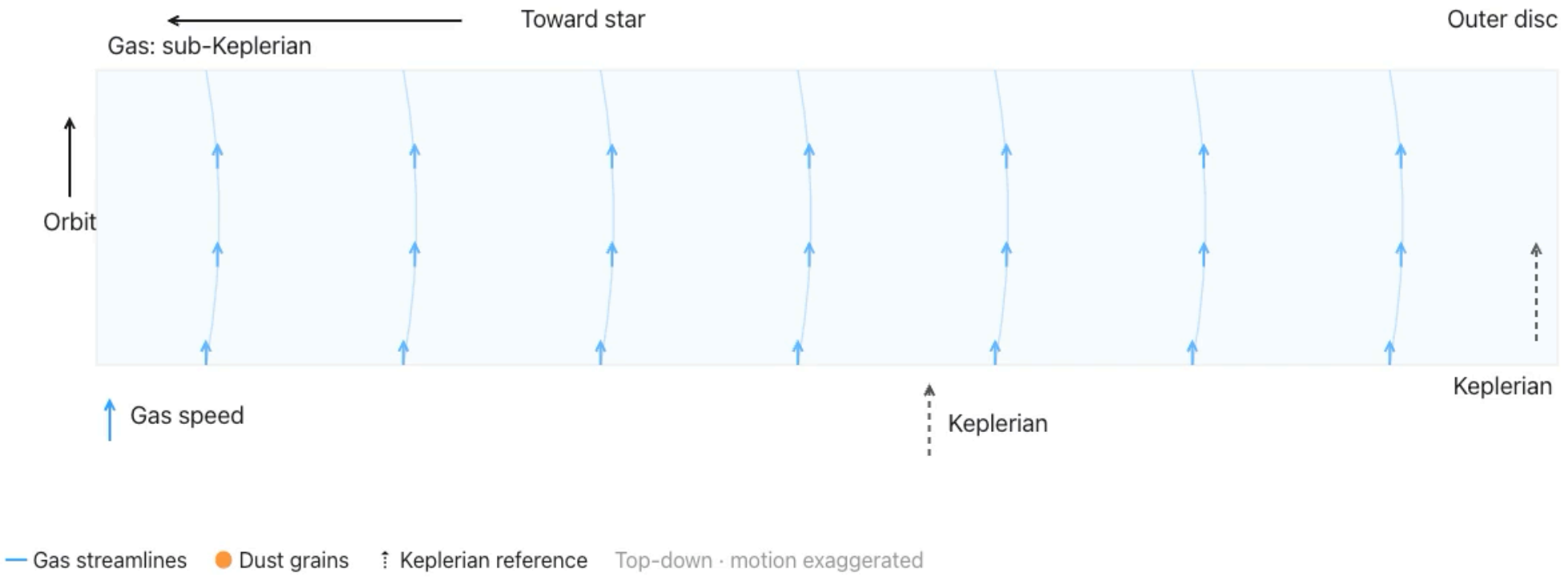
PLANET FORMATION THEORIES

THE CORE ACCRETION MODEL

- Progressive growth of the solid component
  1. From μm to cm sizes through sticking and coagulation - not too difficult and there is evidence for this
  2. From m-sized pebbles to km-sized planetesimals
     - Main obstacles:
       - Fragmentation (determined by velocity dispersion σ and $v_{\text{frag}} \approx 10 km/sec$
       - Meter size barrier
     - Main driver:
       - *The streaming instability* (active at large dust/gas ratio)

THE STREAMING INSTABILITY

Youdin & Goodman (2005)



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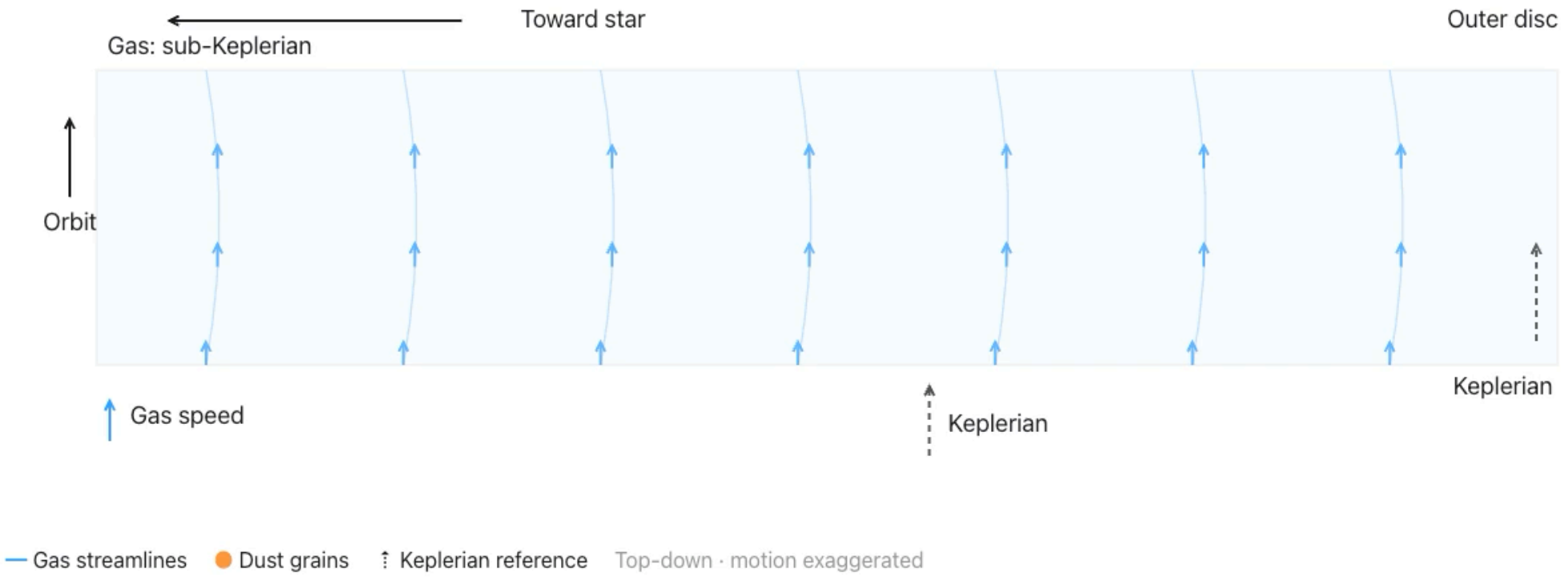

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WISPIT2 - van Cappeleeven et al 2025

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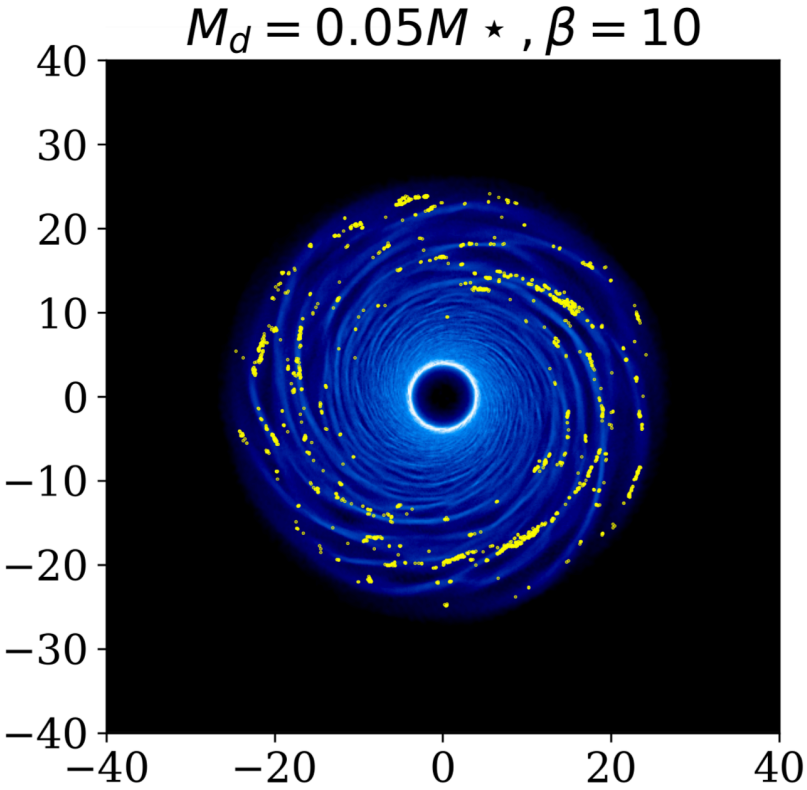

Longarini et al 2025

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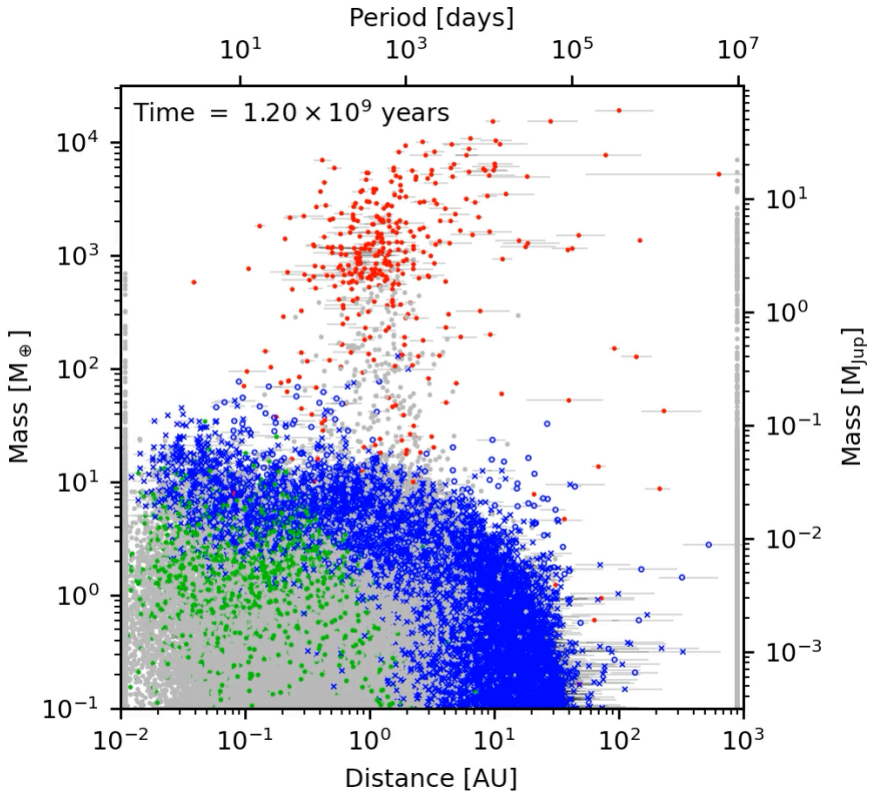
  4. Once a core has become massive enough (a few $M_\oplus$), it can accrete a gas atmosphere and become a giant planet

THE CORE ACCRETION MODEL

- Issues with the core accretion model
  - Planetesimal and core formation remains unclear (streaming instability only works at very high dust/gas ratio)
  - Possible way out: formation occurs in rings (chicken and egg problem)
  - Hard to explain massive planets at large radii with core accretion



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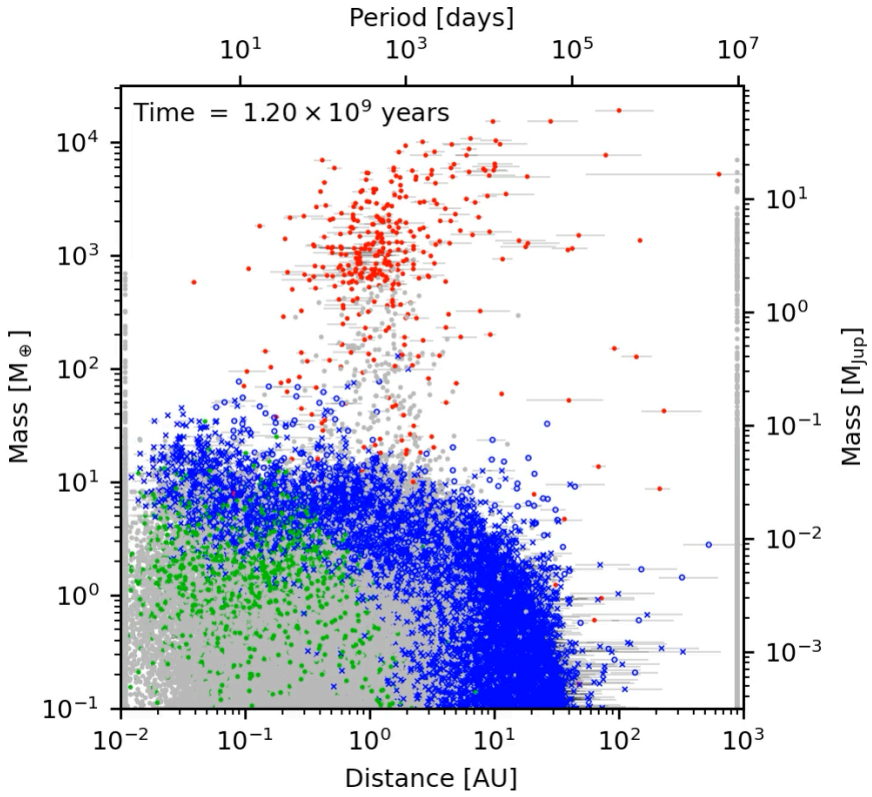
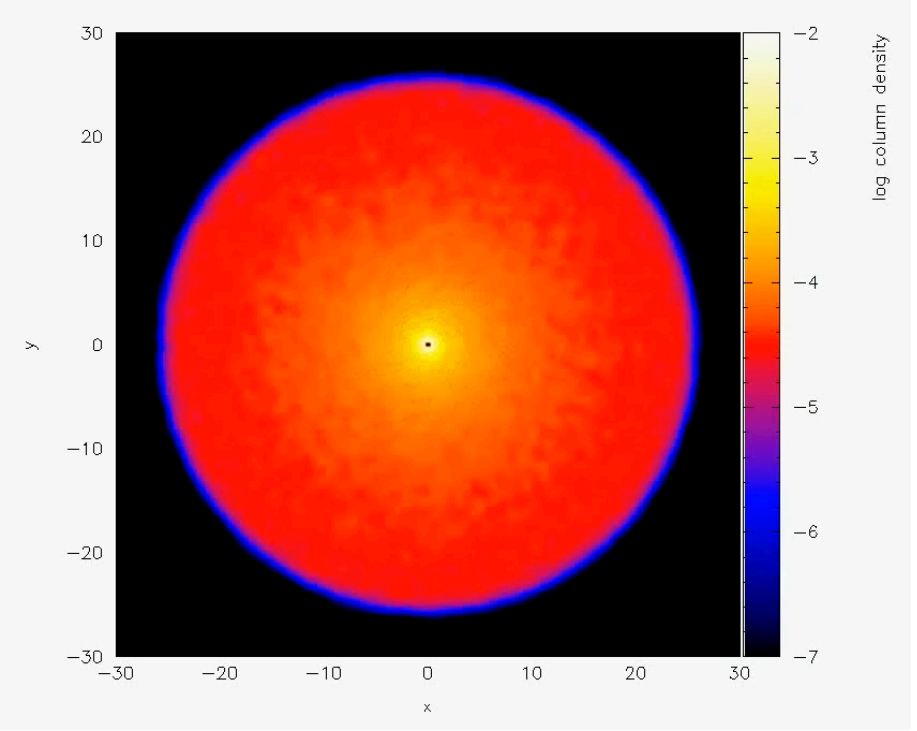


THE GRAVITATIONAL INSTABILITY MODEL

- Directly form giant planets from GI in massive discs
- Issues:
  - Requires fairly massive discs
  - Works only at 50-100au distance from the star
  - Mostly produces very massive planets or brown dwarfs



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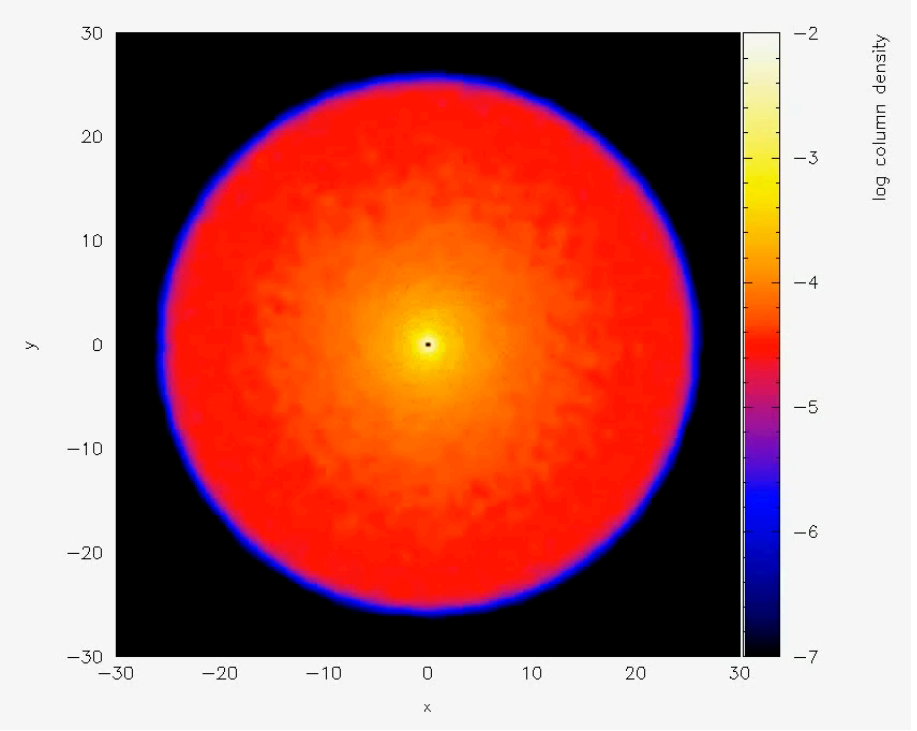
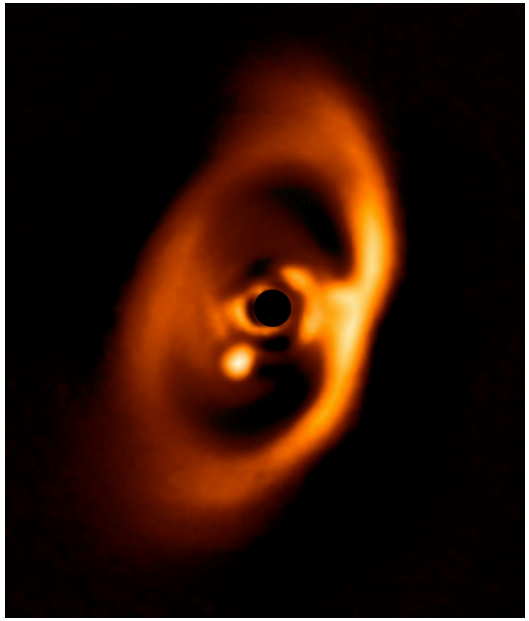


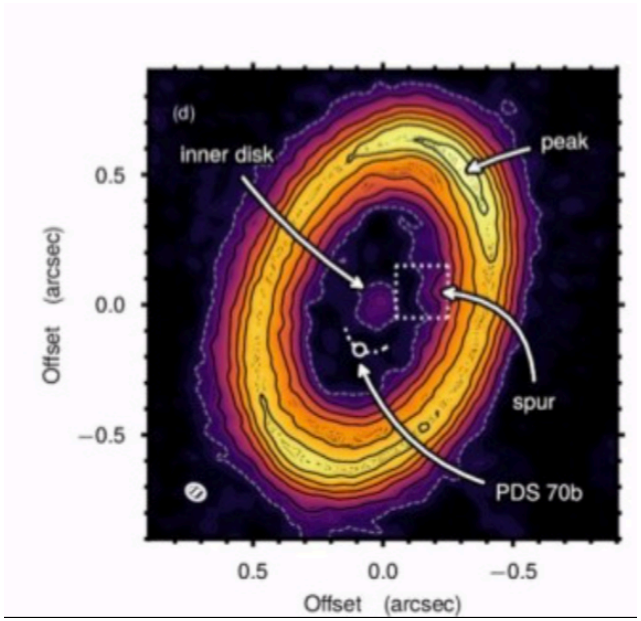
PLANETS IN DISCS

DIFFERENT EVIDENCES FOR PLANETS

1. Direct imaging

PDS 70
Keppler et al (2018, 2019)

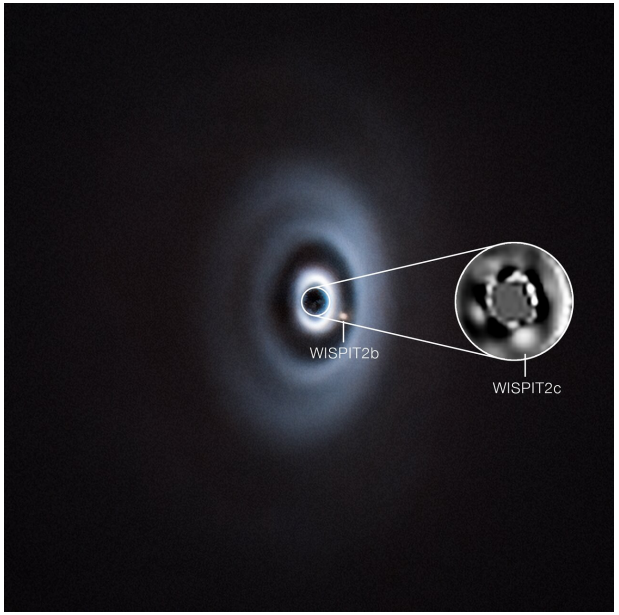




Infrared

Radio

WISPIT 2
van Cappelleven et al (2025)



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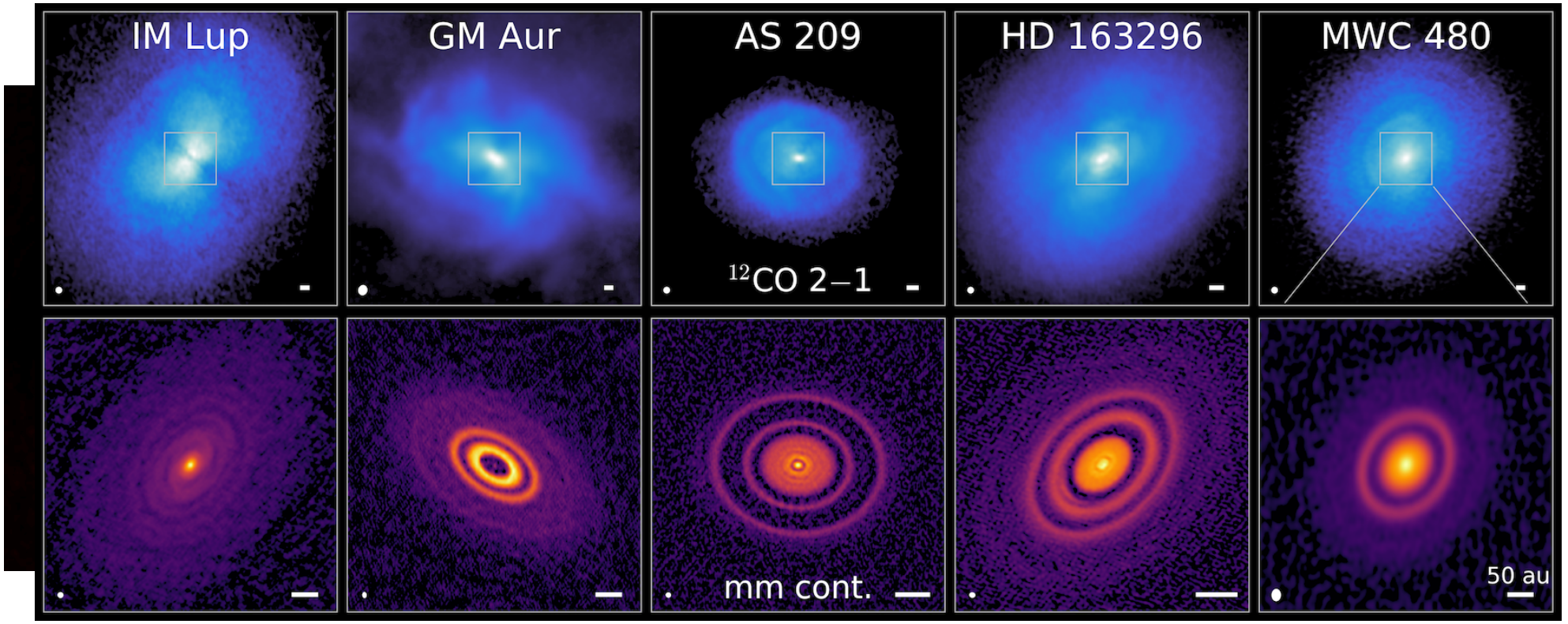

PLANET-DISC INTERACTION

- Planets
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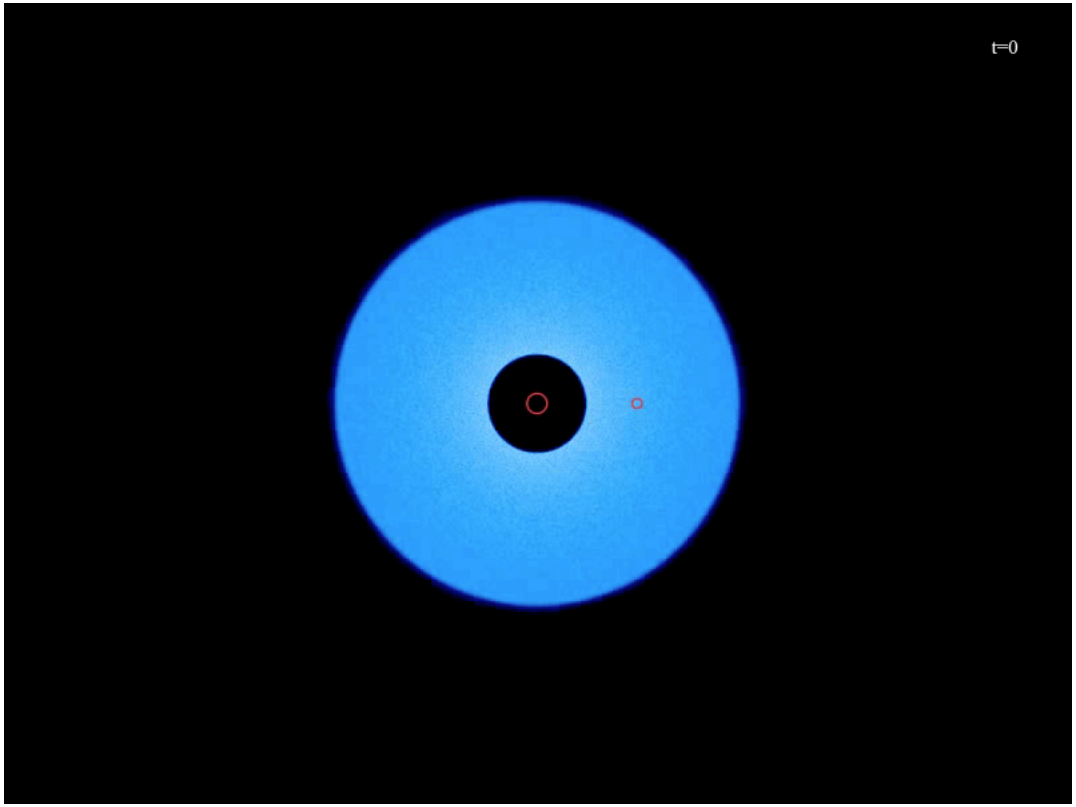

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- Angular momentun exchange can be described through
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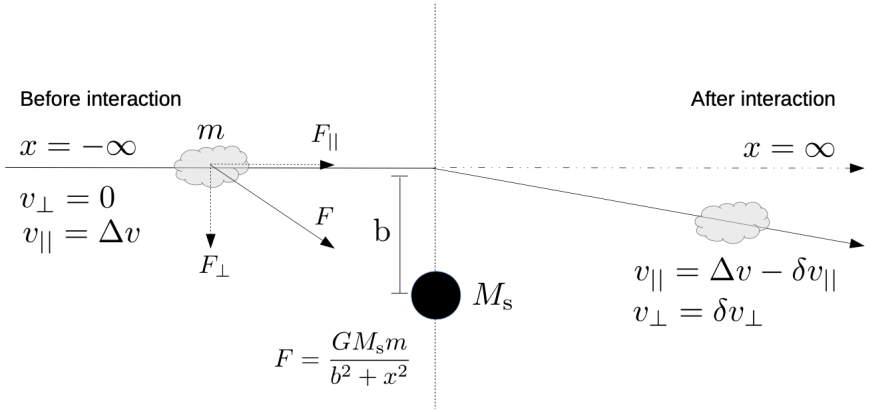
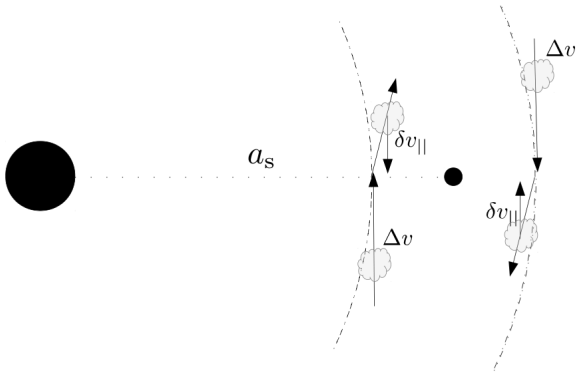
$$\Lambda(R) = \mathrm{sgn}\left(R - a_\mathrm{s}\right) f q^2 \Omega^2(R) a_\mathrm{s}^2 \frac{a_\mathrm{s}^4}{\left(R - a_\mathrm{s}\right)^4}$$

$$q = M_\mathrm{s}/M_\star$$





From Ragusa, PhD Thesis, 2018

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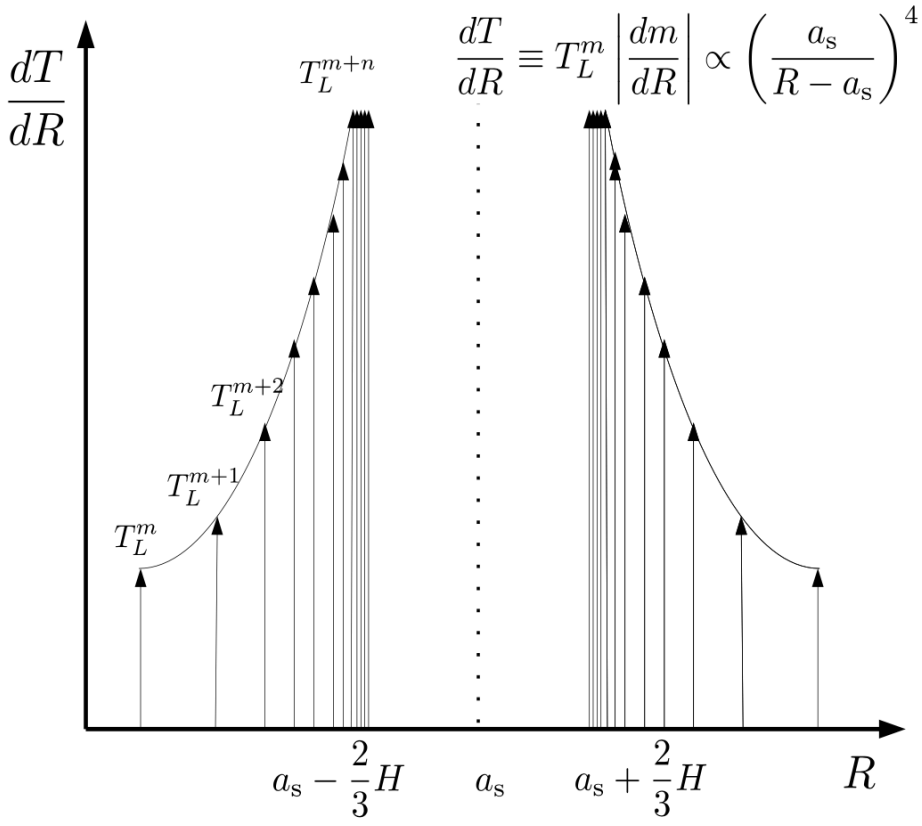

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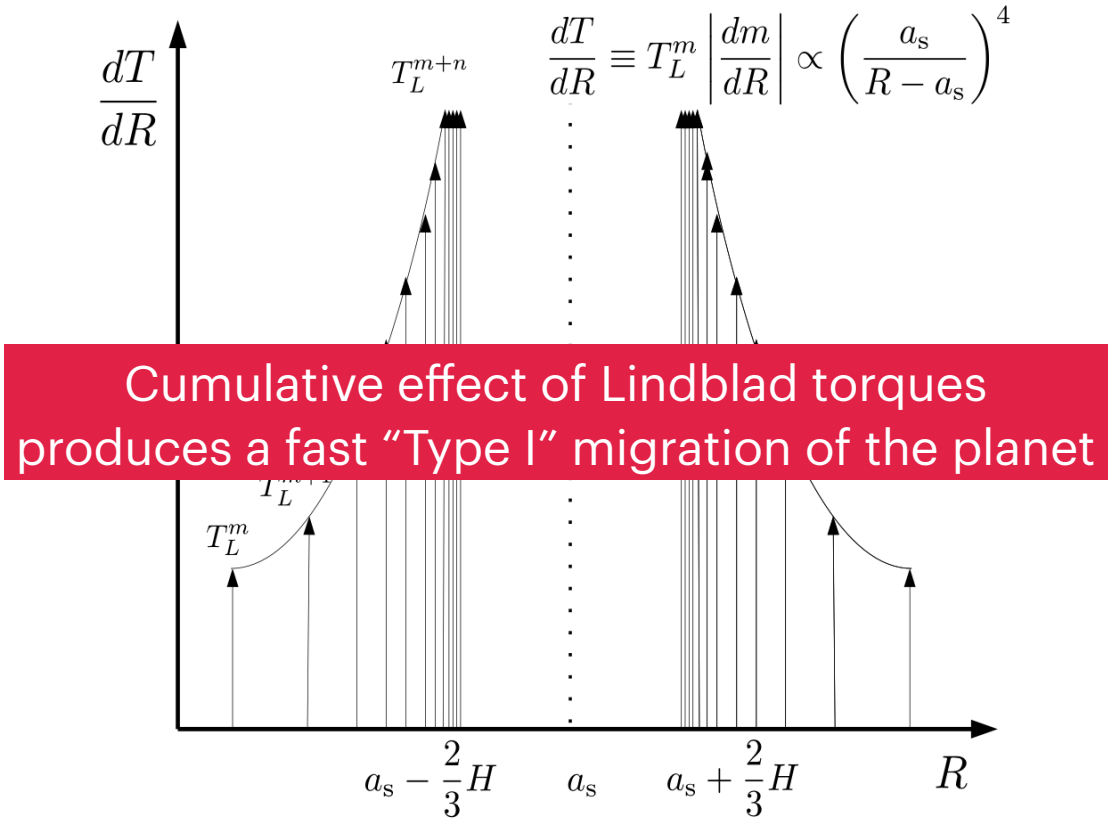
  - Impulse approximation (Lin & Papaloizou 1979)
  - Full theory of angular momentum carried away by the waves (Goldreich & Tremaine, 1979)
    - Wave launched at Lindblad resonances

$$\Lambda(R) = \mathrm{sgn}\left(R - a_\mathrm{s}\right) f q^2 \Omega^2(R) a_\mathrm{s}^2 \frac{a_\mathrm{s}^4}{\left(R - a_\mathrm{s}\right)^4}$$

$$q = M_\mathrm{s}/M_\star$$



Cumulative effect of Lindblad torques produces a fast "Type I" migration of the planet

From Ragusa, PhD Thesis, 2018

PLANET-DISC INTERACTION

Gap opening - Type II migration

- Gap opening criterion by Crida et al (2006)

$$\frac{3}{4}\left(\frac{H}{R}\right)_{a_s}\left(\frac{q}{3}\right)^{-1/3}+\frac{50\nu_s}{\Omega_s a_s^2}q^{-1}\lesssim 1$$

- When a gap is opened, disc-planet coupled evolution is

$$\frac{\partial\Sigma}{\partial t}=\frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(R^{1/2}\nu\Sigma\right)\right]-\frac{2}{R}\frac{\partial}{\partial R}\left[\frac{\Lambda\Sigma}{\Omega}\right]$$

$$t_{\rm II}=\frac{1+B}{B}t_\nu(a)$$

$$\dot{a}=-\frac{4\pi}{a_s M_s\Omega_s}\int_{R_{in}}^{R_{out}}\Lambda\Sigma R\ \mathrm{d}R$$

$$B=\frac{4\pi a^2\Sigma(a)}{M_s}$$

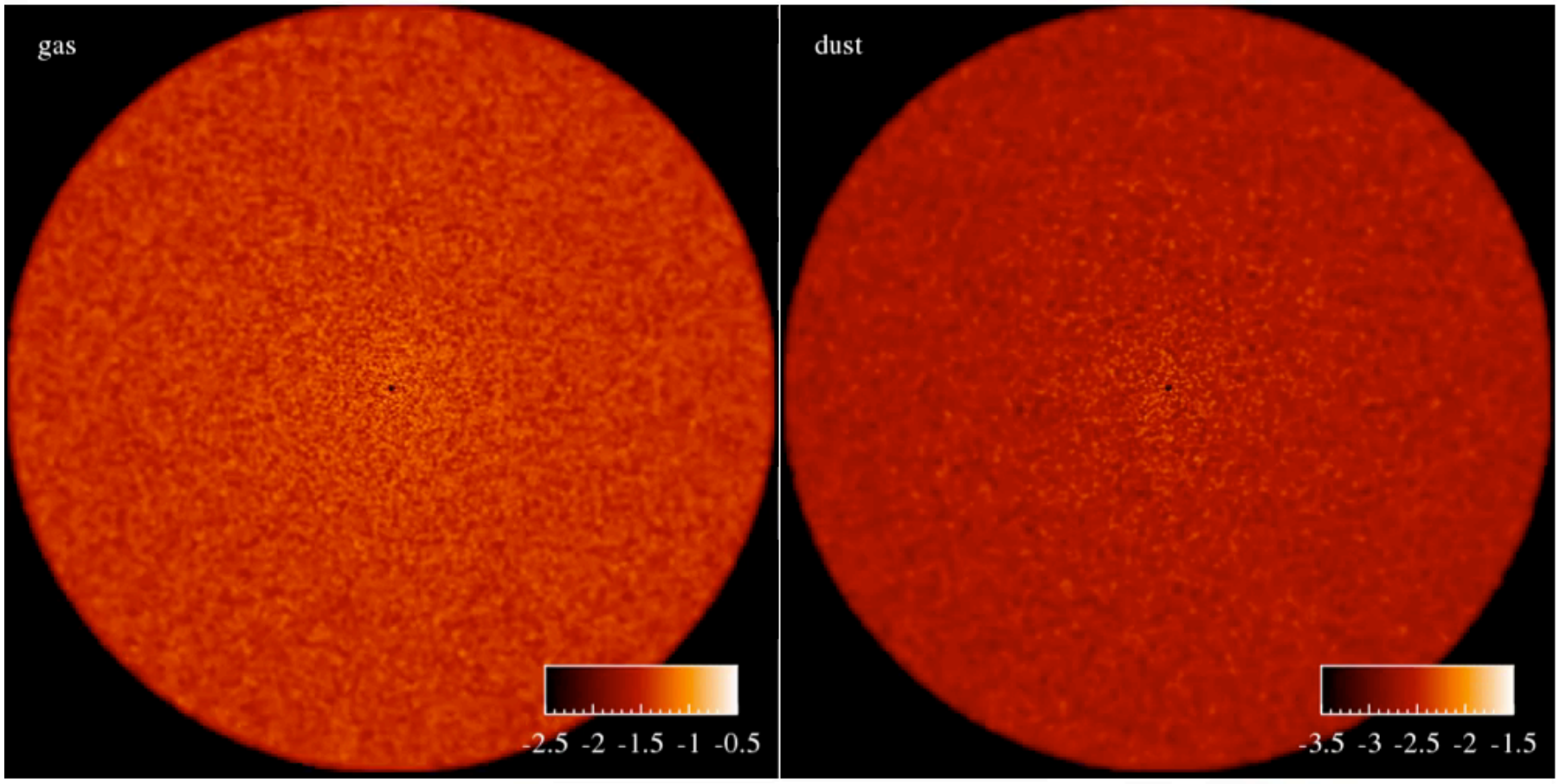
However, for very massive planets Type II migration can be reversed (Scardoni et al 2025)

PLANET PROPERTIES FROM DISC GAPS

- Given the morphology of substructures, one can retrieve the disc and planet properties
  - By complex hydrodynamical simulations (e.g. Dipierro et al 2015,...)

GAS AND DUST SIMULATIONS

Dipierro et al 2015



Three planets: *0.2M_{Jup}* (*@13.2au*), *0.27M_{Jup}* (*@32.3au*), *0.55M_{Jup}* (*@68.8au*)

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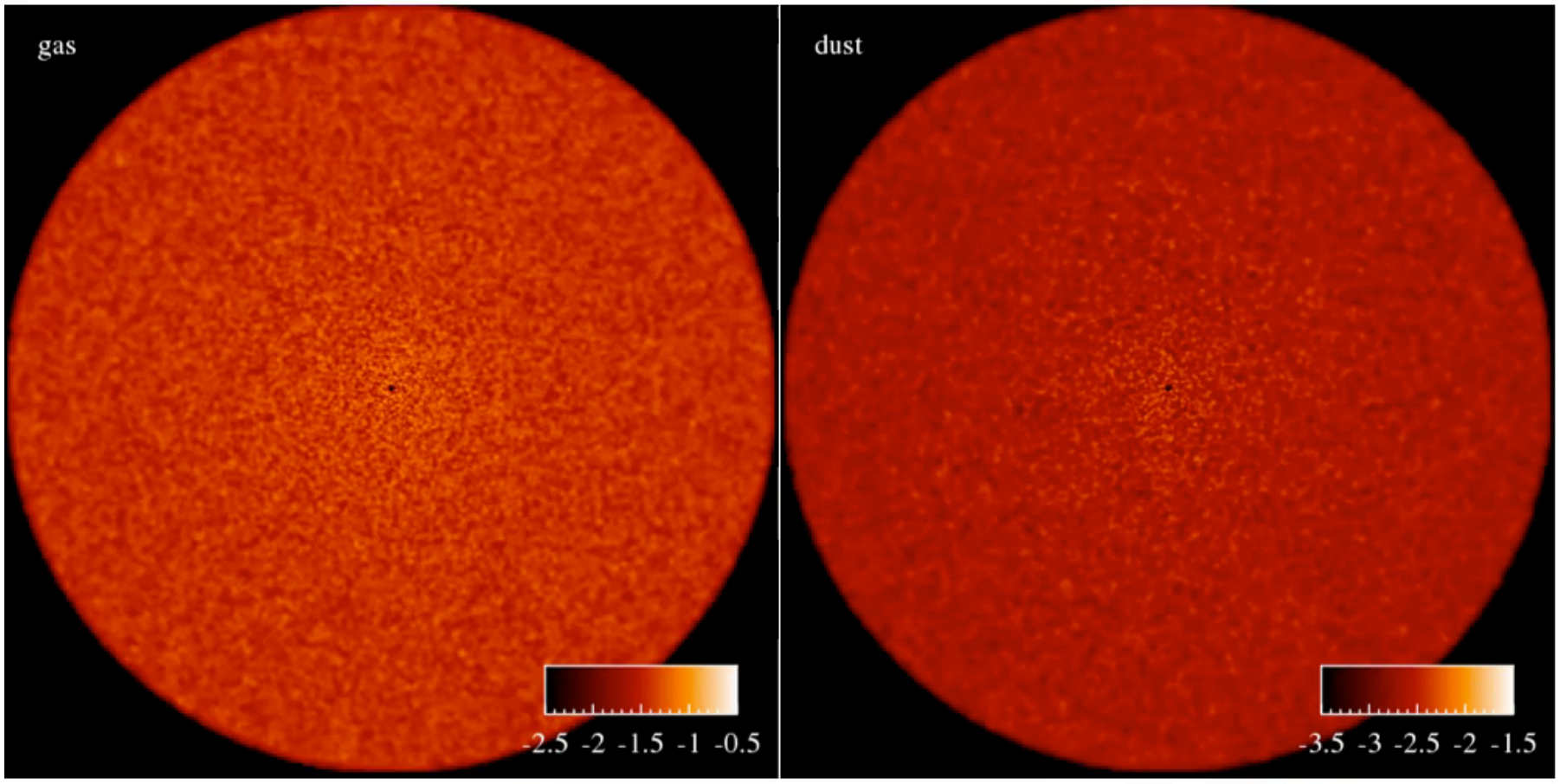

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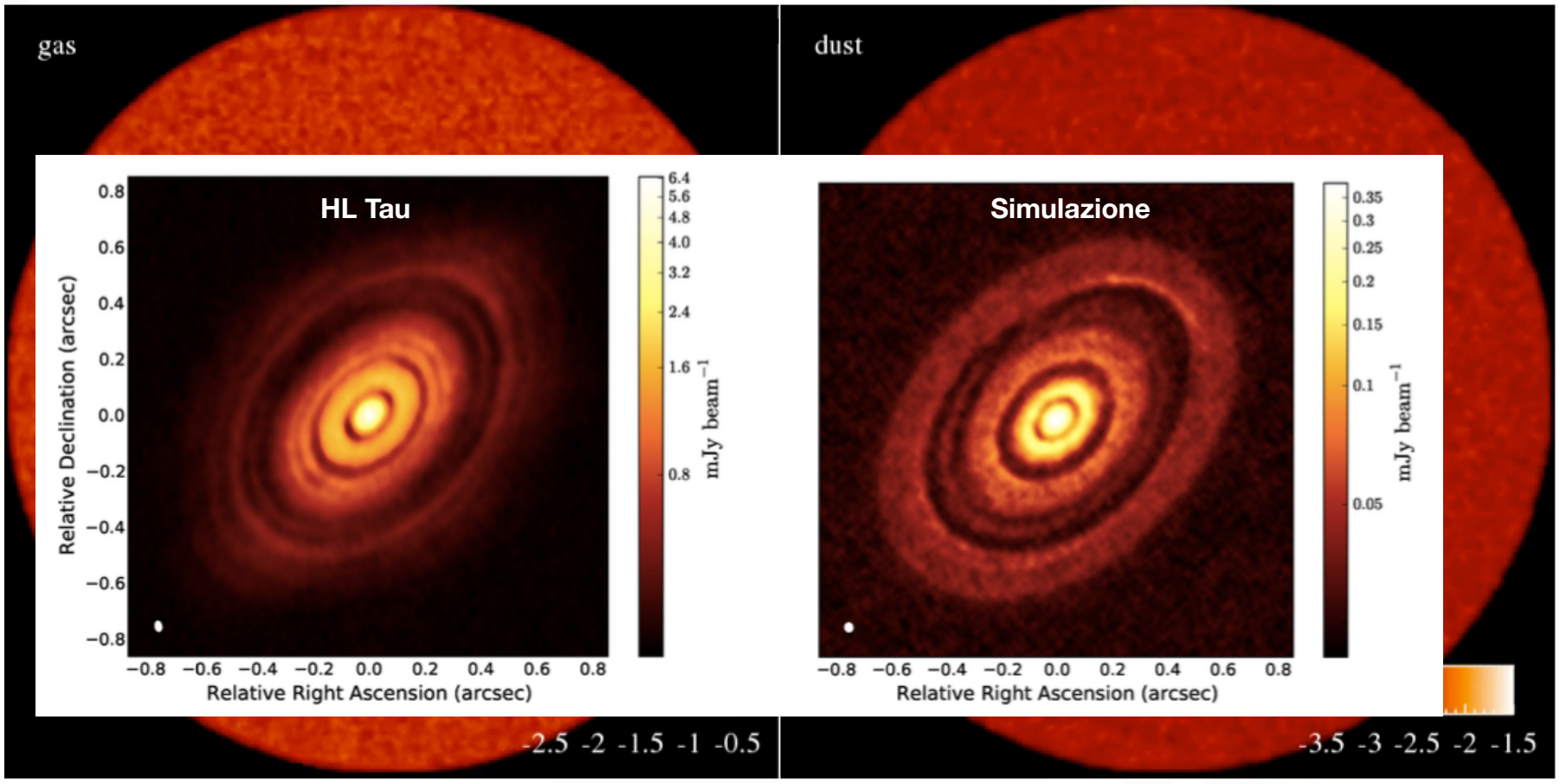

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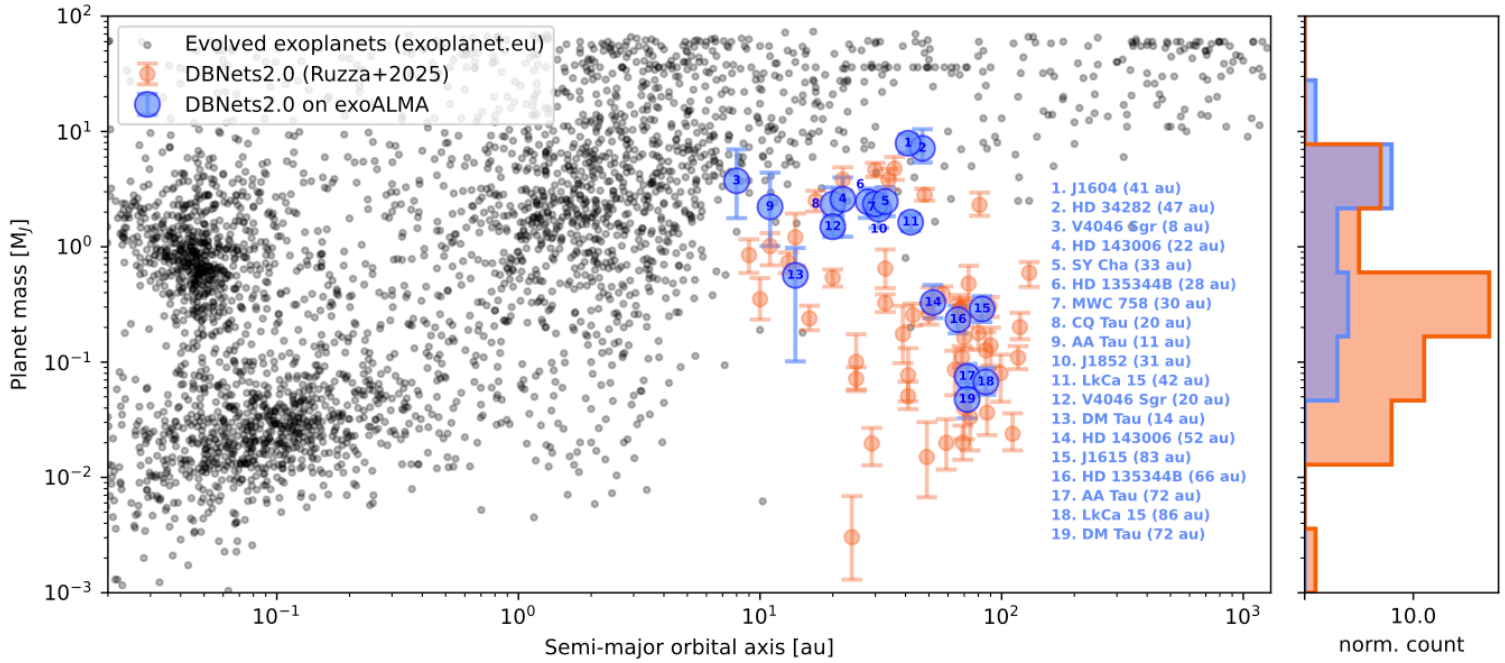
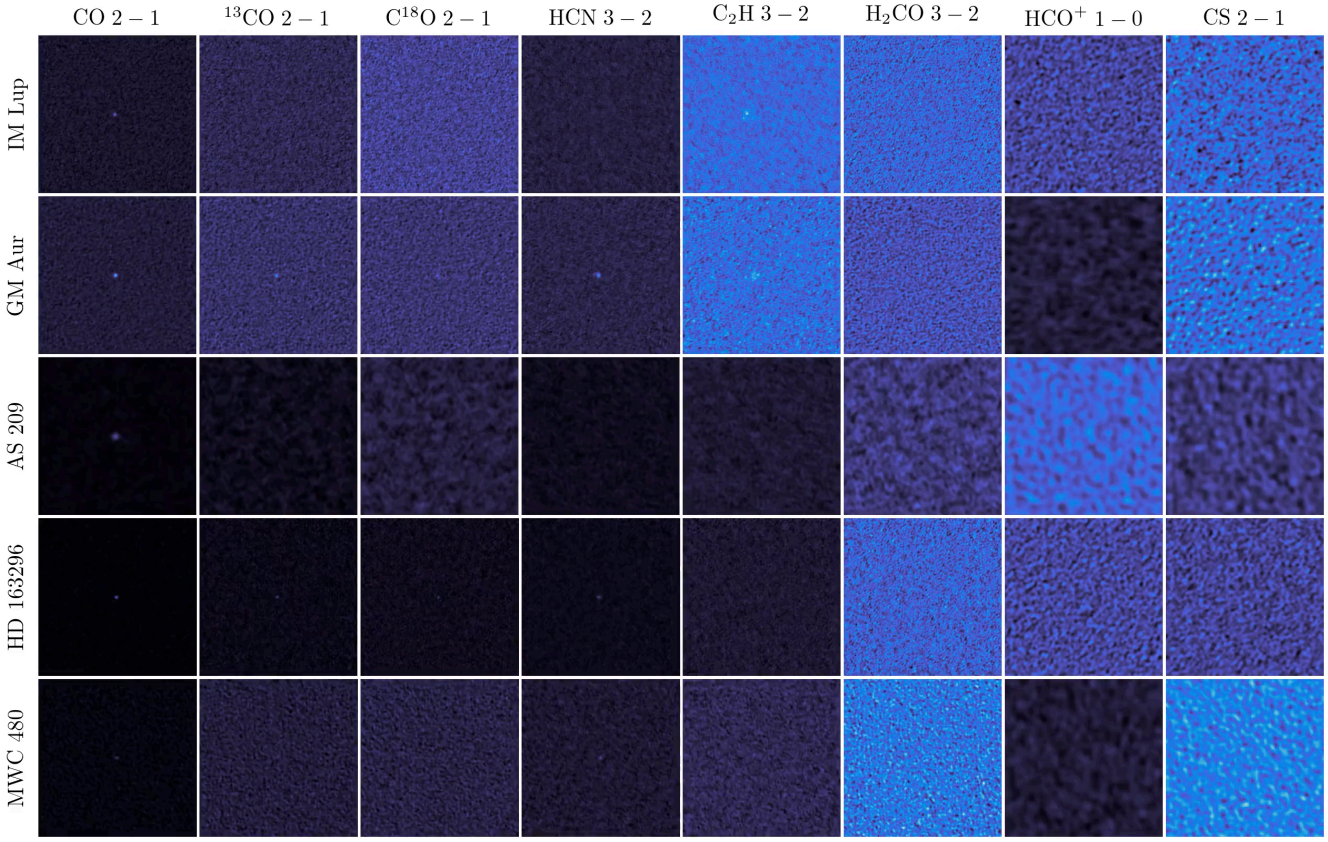
PLANET PROPERTIES FROM DISC GAPS

- Given the morphology of substructures, one can retrieve the disc and planet properties
  - By complex hydrodynamical simulations (e.g. Dipierro et al 2015,...)
  - By Machine Learning techniques (Ruzza et al 2024,2025,2026): DBNets2.0



KINEMATIC EVIDENCE OF PLANETS

- The spiral density wave produced by a planet also shows up as velocity perturbations



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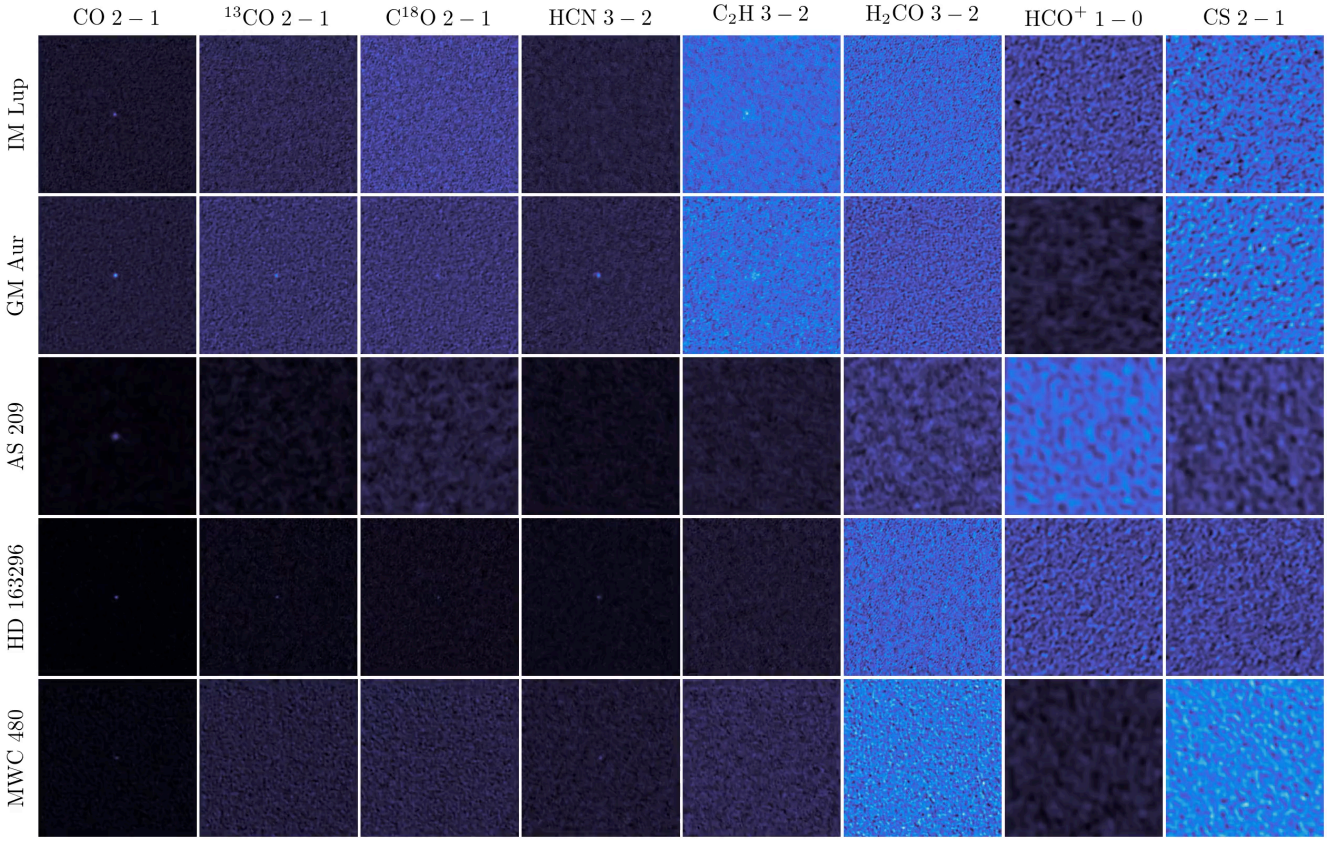

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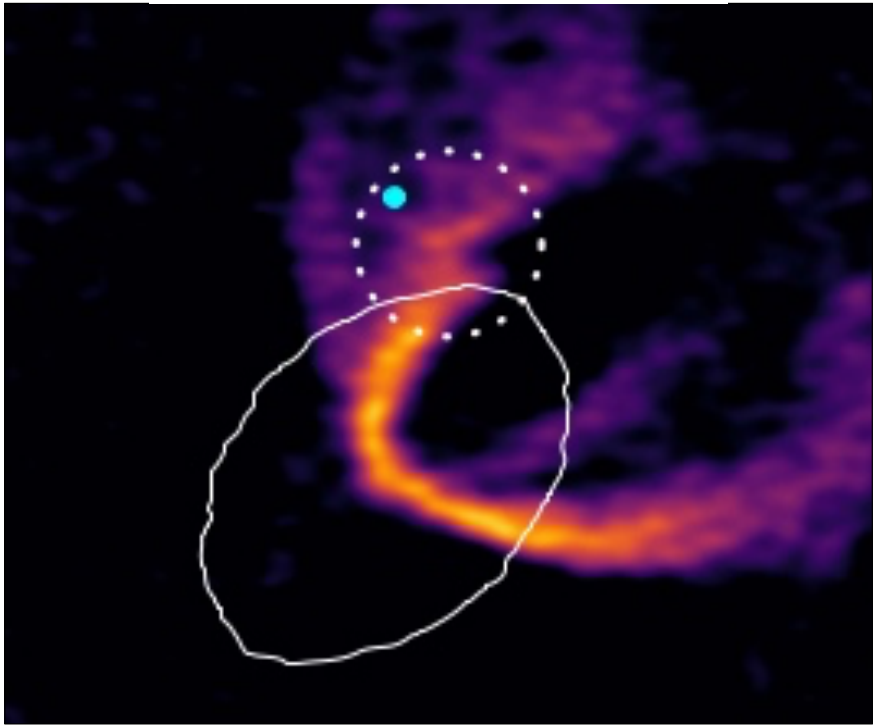
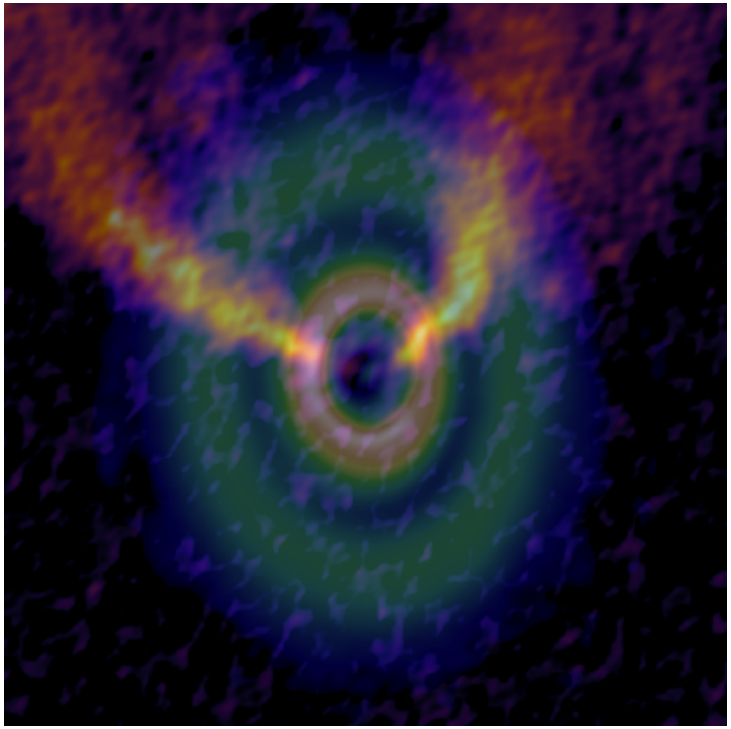
HD 163296 - Pinte et al 2018



HD 97048 - Pinte et al 2019



CONCLUDING REMARKS

- Protostellar discs are a wonderful laboratory to study physical processes relevant in many different astrophysical contexts (e.g. AGN discs, BH mergers and GW emission, ...)
  - Accretion and angular momentum transport
  - Disc instablities (MHD, hydro,...)
  - Interaction of disc and satellite/companion
- Protostellar discs offer a wealth of observables often unavailable in more distant sources to test our models against observations
- ... and, they are also essential to answer a cool astrophysical question: *how do planets form*!
- Many additional effects ignored here but worth of investigation
  - Disc warping
  - Interaction with a central (or external) binary
  - Interaction with environment (infall, external photoevaporation, etc...)