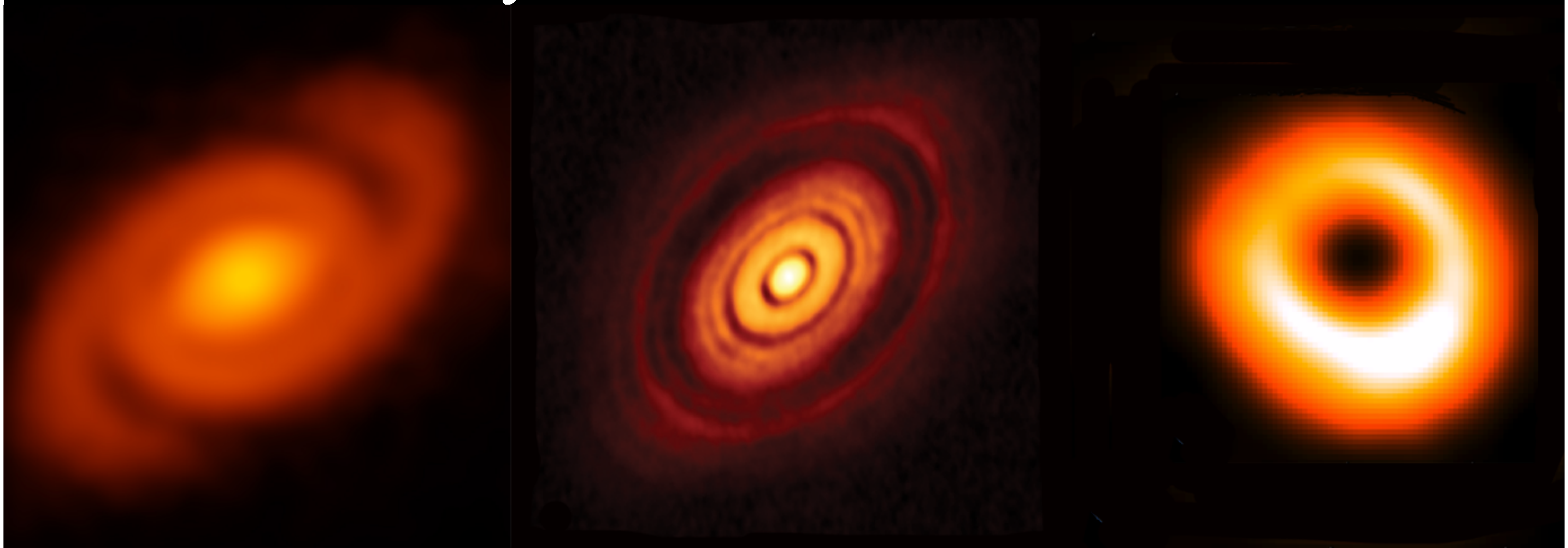
Disc-Planet interaction: Theory confronts Observations



Giovanni Dipierro
University of Leicester

with Richard Alexander, Guillaume Laibe, Luca Ricci, Giulia Ballabio, Nicolas Cuello, Enrico Ragusa, Kieran Hirsh, Leonardo Testi, Giuseppe Lodato and Daniel J. Price

UNIVERSITY OF LEICESTER

Disc substructures!

Spirals

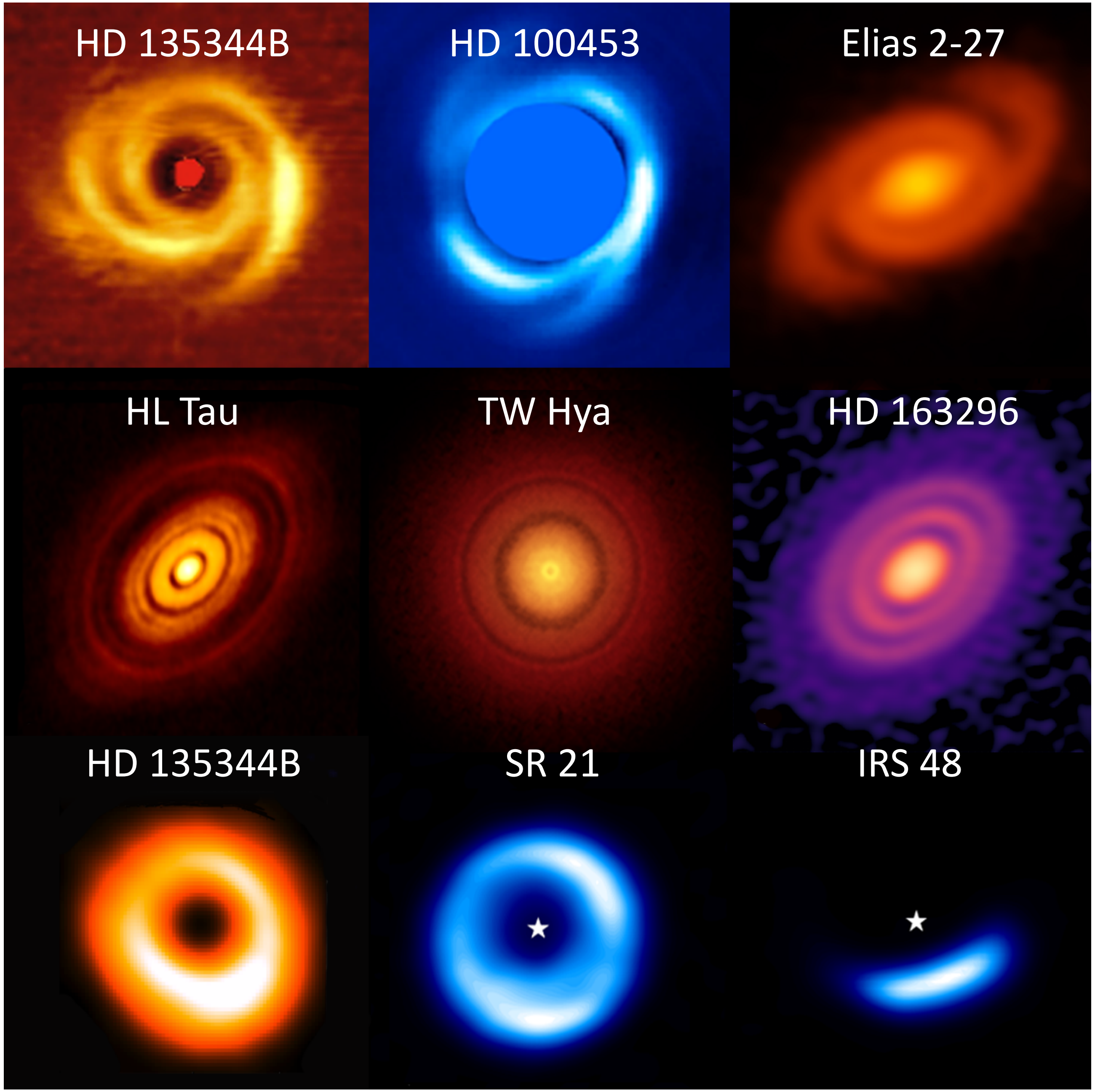
(Garufi +14, Wagner +15, Perez +17)

Gaps

(Alma +15, Andrews +16, Isella +17)

Horseshoes

(Perez +14, van der Marel +13, +15)



Disc substructures!

Spirals
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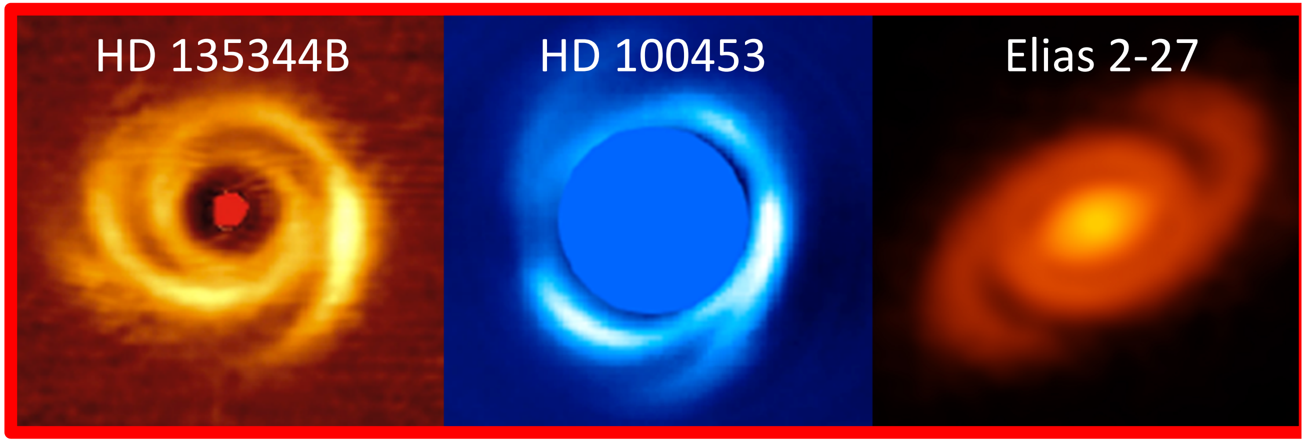


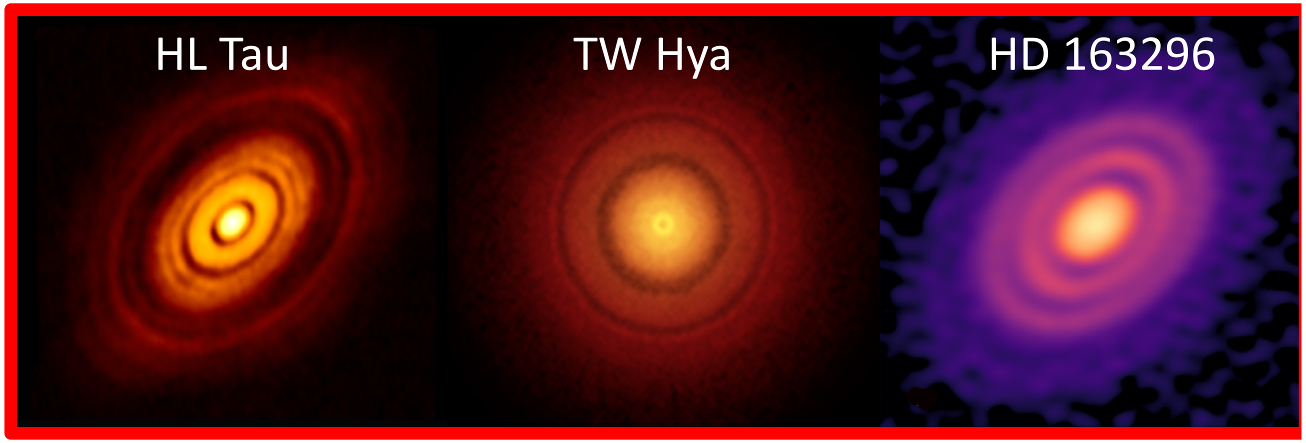
Plausible explanations:

- tidal interaction with embedded protoplanets (Dong +15)
- gravitational instabilities (Cossins +09, Dipierro +15, Hall +16,+18)
- Stellar flybys (Pfalzner et al. 2008, Cuello et al. subm.)

Disc substructures!

Gaps

(Alma +15, Andrews +16, Isella +17)



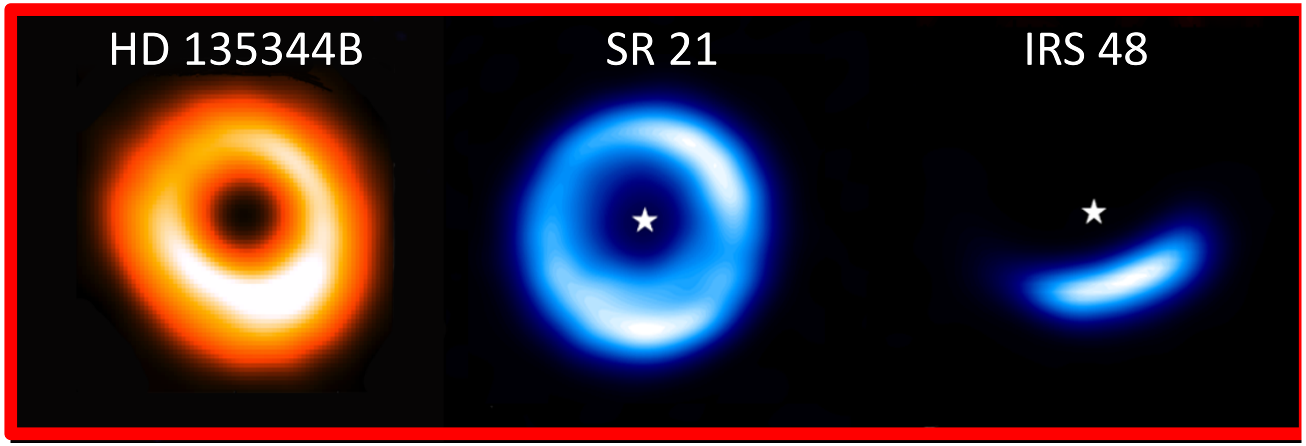
Plausible explanations:

- tidal interaction with embedded protoplanets (Dong +15, Dipierro +15, Picogna + 15, Rosotti +16, Jin +16, Fedele +17)
- self-induced dust pile-ups (Gonzalez +15)
- dead zones (Flock +15, Ruge +16)
- rapid pebble growth around condensation fronts (Zhang +15, Pinilla +17)
- aggregate sintering (Okuzumi +15)
- large scale instabilities due to dust settling (Loren-Aguilar +16)
- secular gravitational instabilities (Takahashi +16)
- large-scale vortices (Barge +17)

Disc substructures!

Horseshoes

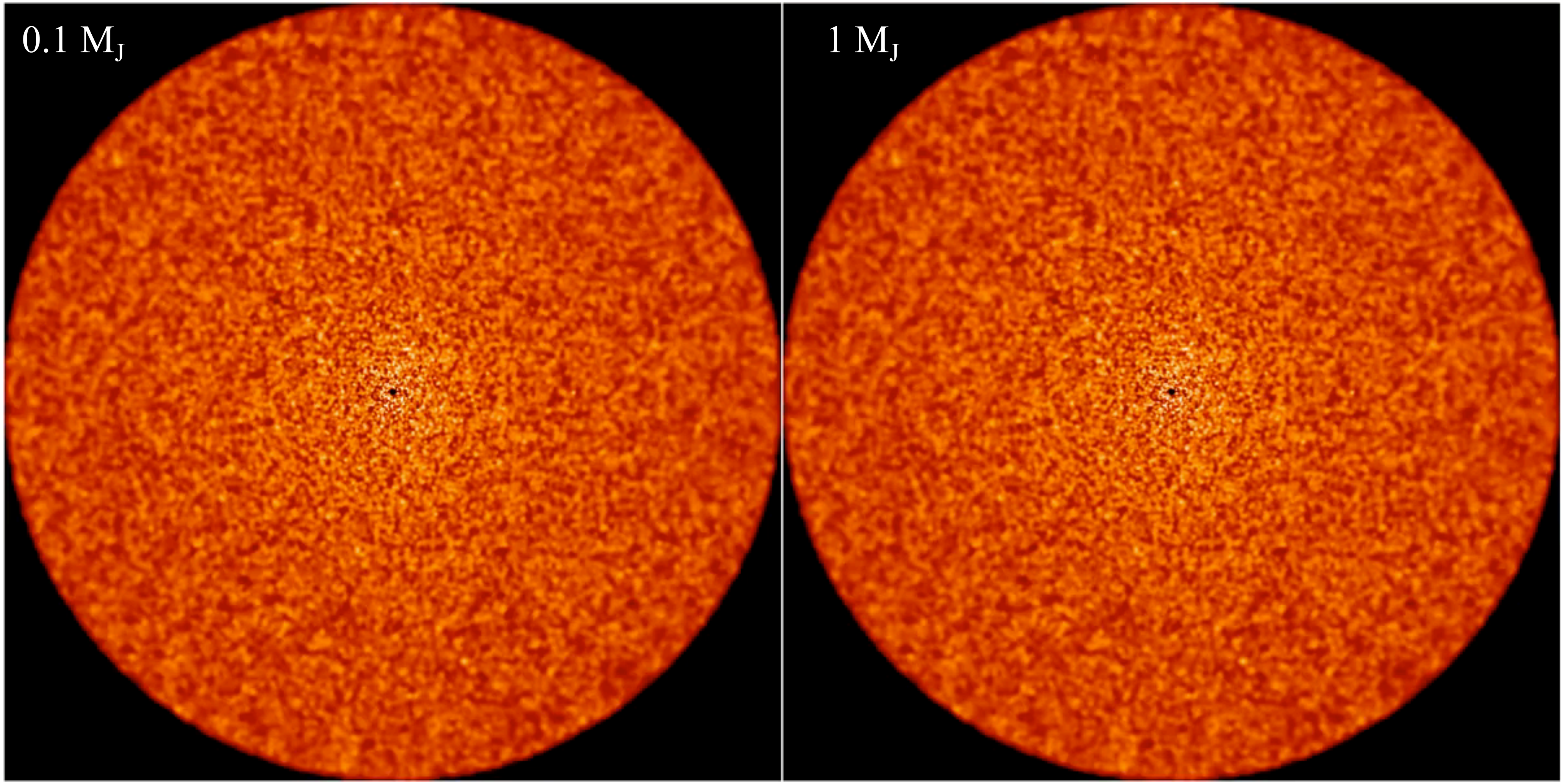
(Perez +14, van der Marel +13, +15)



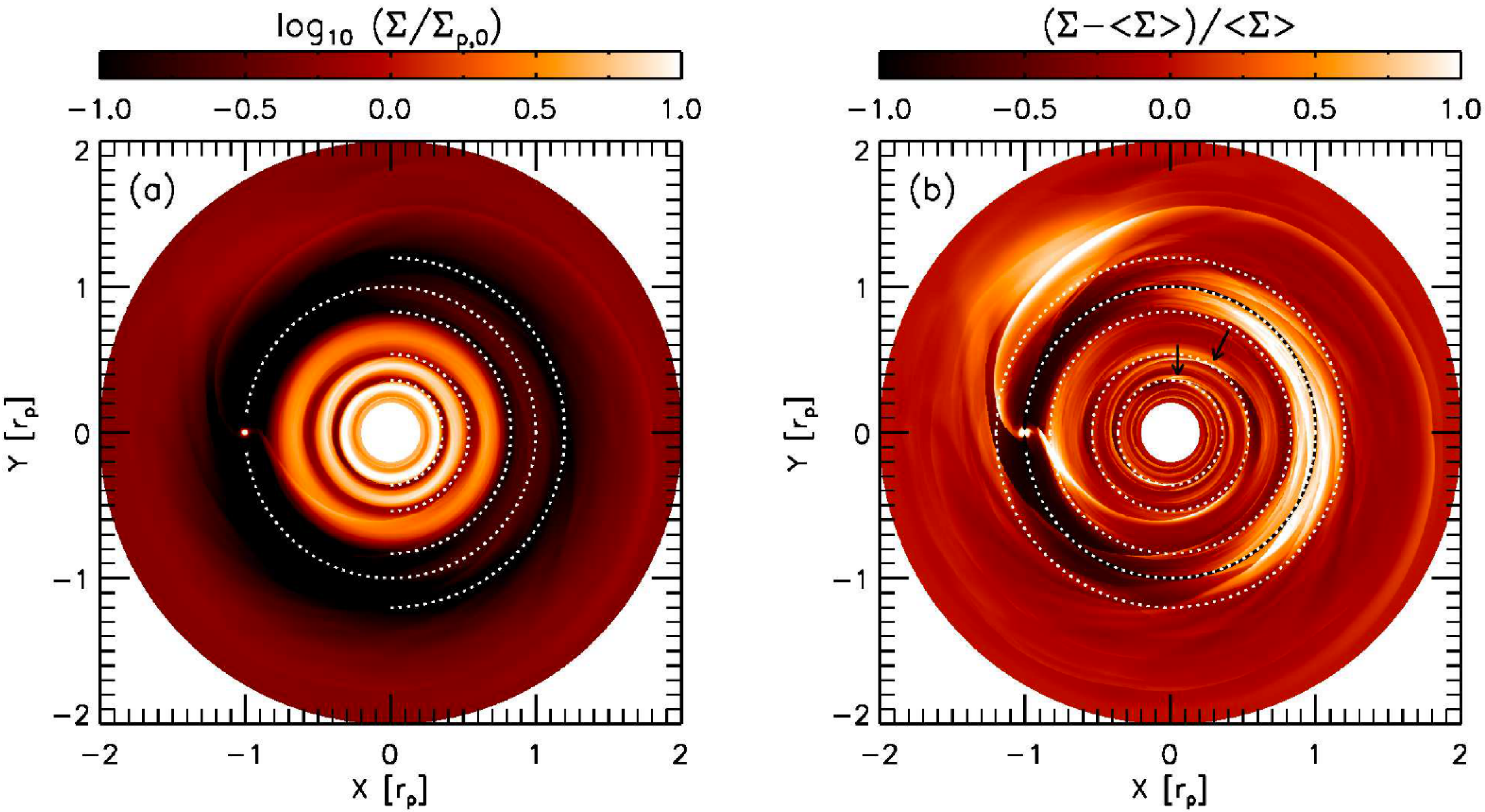
Plausible explanations:

- tidal interaction with high mass perturber in the cavity (Ragusa +17)
- Vortices arising from, e.g., Rossby wave instability at the edge of the gap formed by a young planet or of a dead zone (Regàly +12, Ruge +16)

Disc planet interaction in high viscous discs

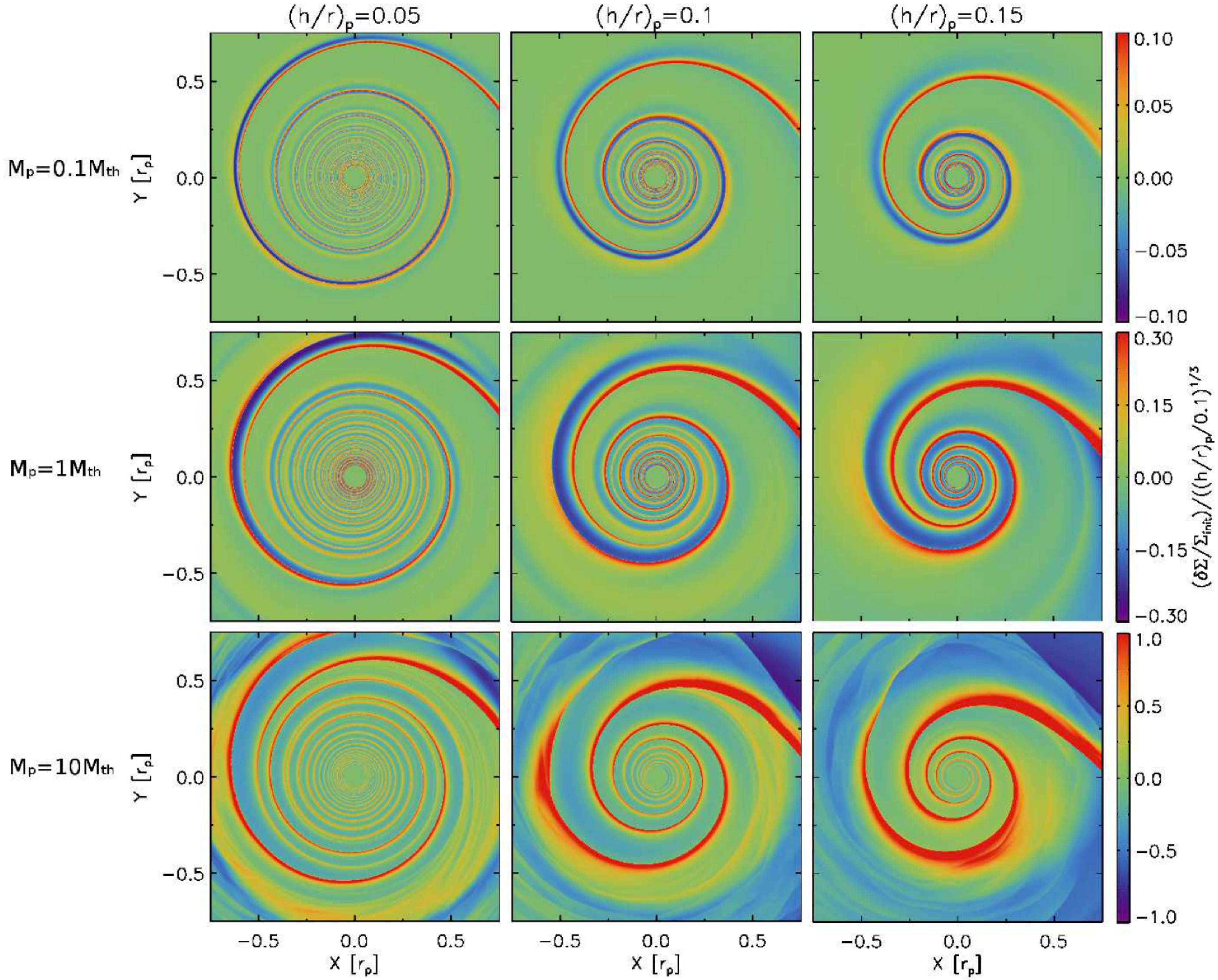


Disc planet interaction in low viscous discs



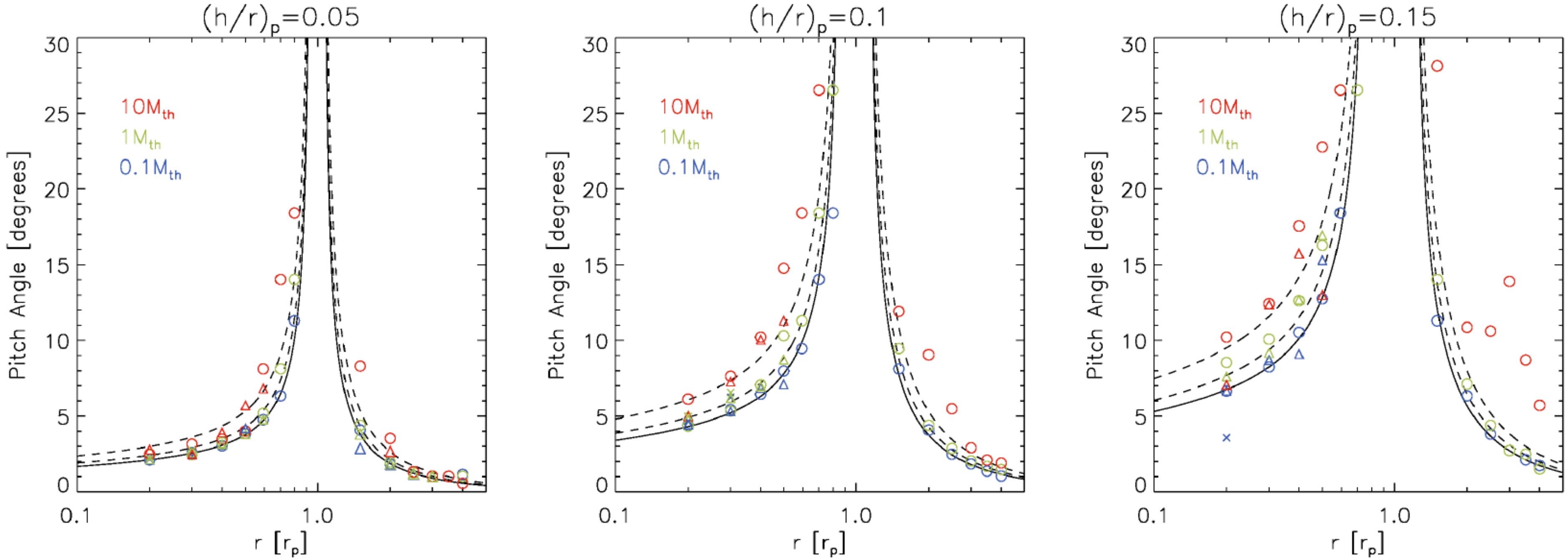
Bae et al 2017

Morphology of the planet-induced spiral

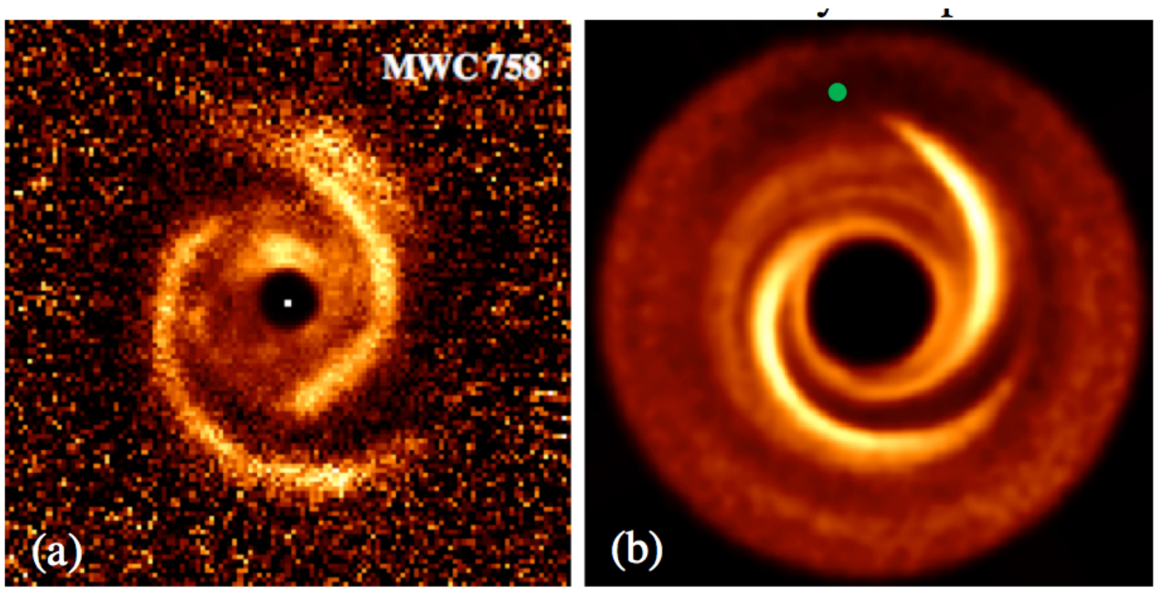


Fung & Dong 2017, Bae et al 2017

Morphology of the planet-induced spiral

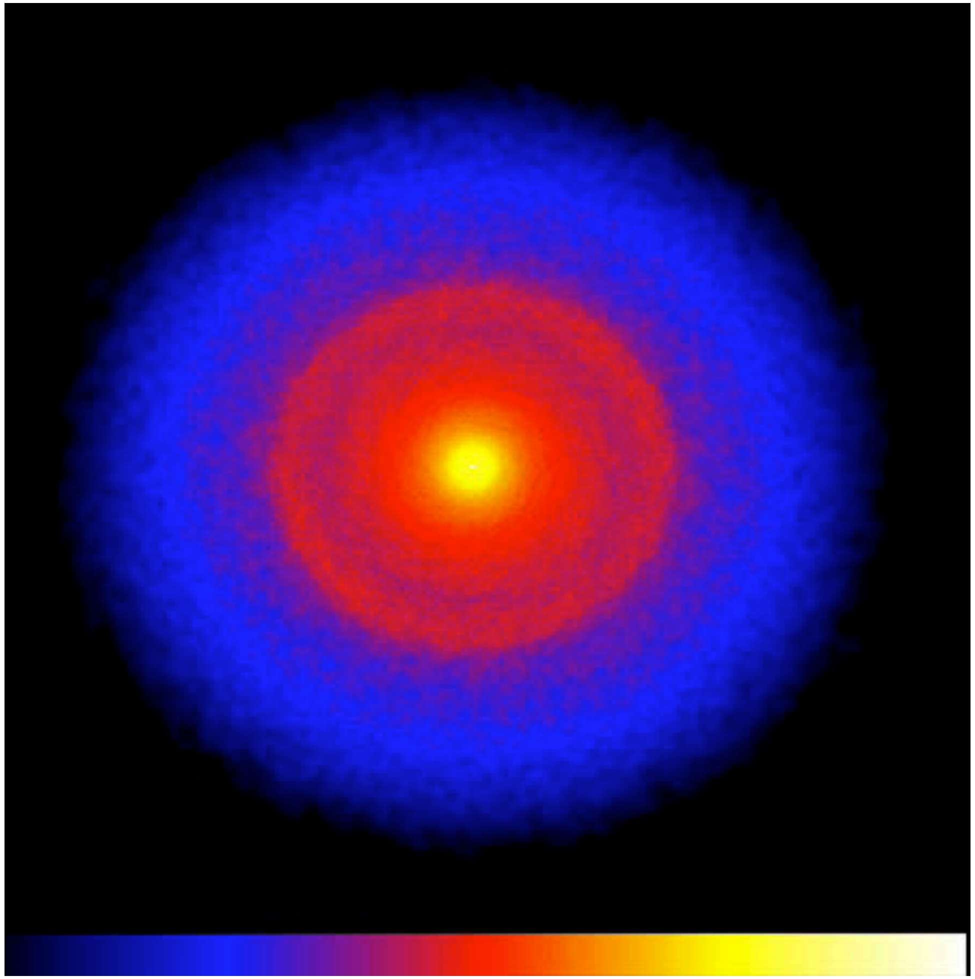


Bae et al 2017



Dong et al 2016

Gravitational instability



Condition for instability:

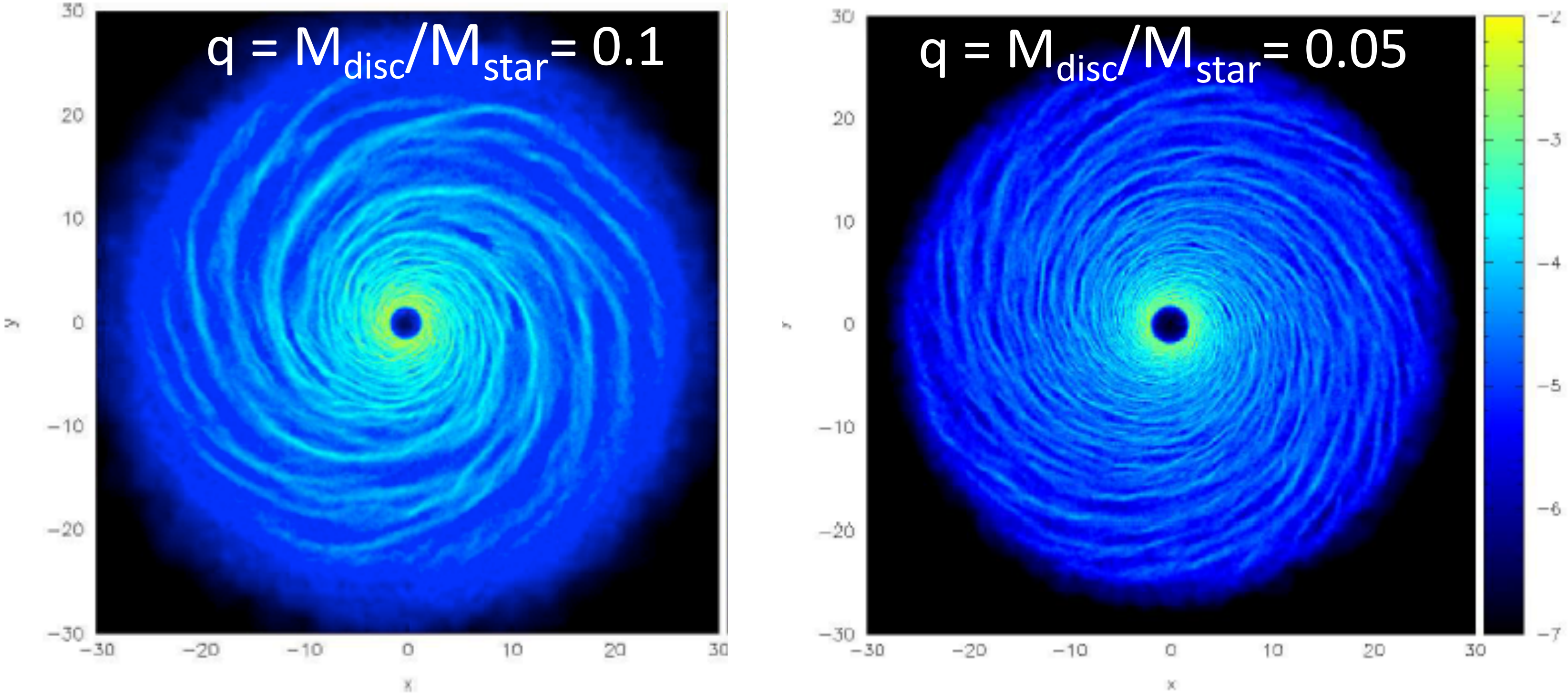
$$Q = \frac{c_s \kappa}{\pi G \Sigma} \leq 1 \quad \Longleftrightarrow \quad M_{\rm disc} \geq \frac{H}{R} M_\star$$

cold and/or massive discs are more likely to be gravitationally unstable.

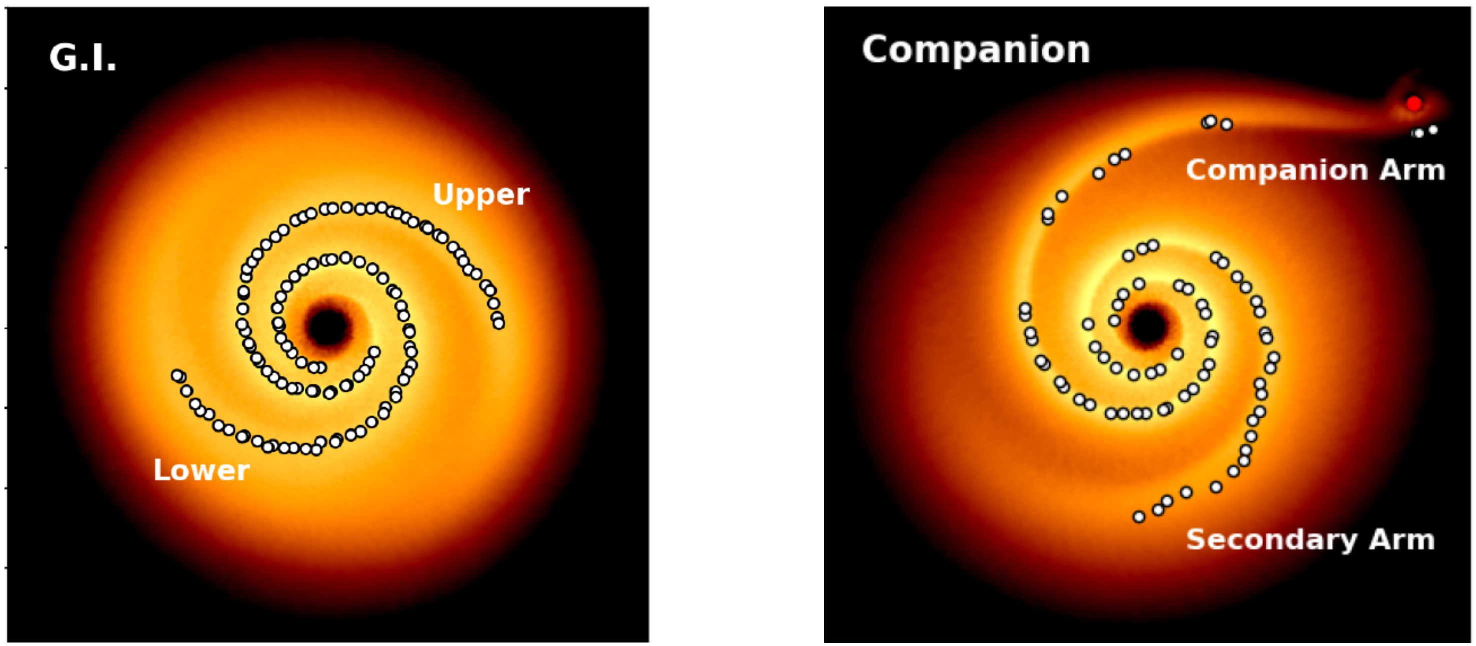
Spiral arms are overdensity, overtemperature and overpressure regions:

- Enhanced density favours and speed up collisional growth
- Solid component may become gravitationally unstable and form bound objects (Rice +04, 06)

Morphology of the GI-induced spiral

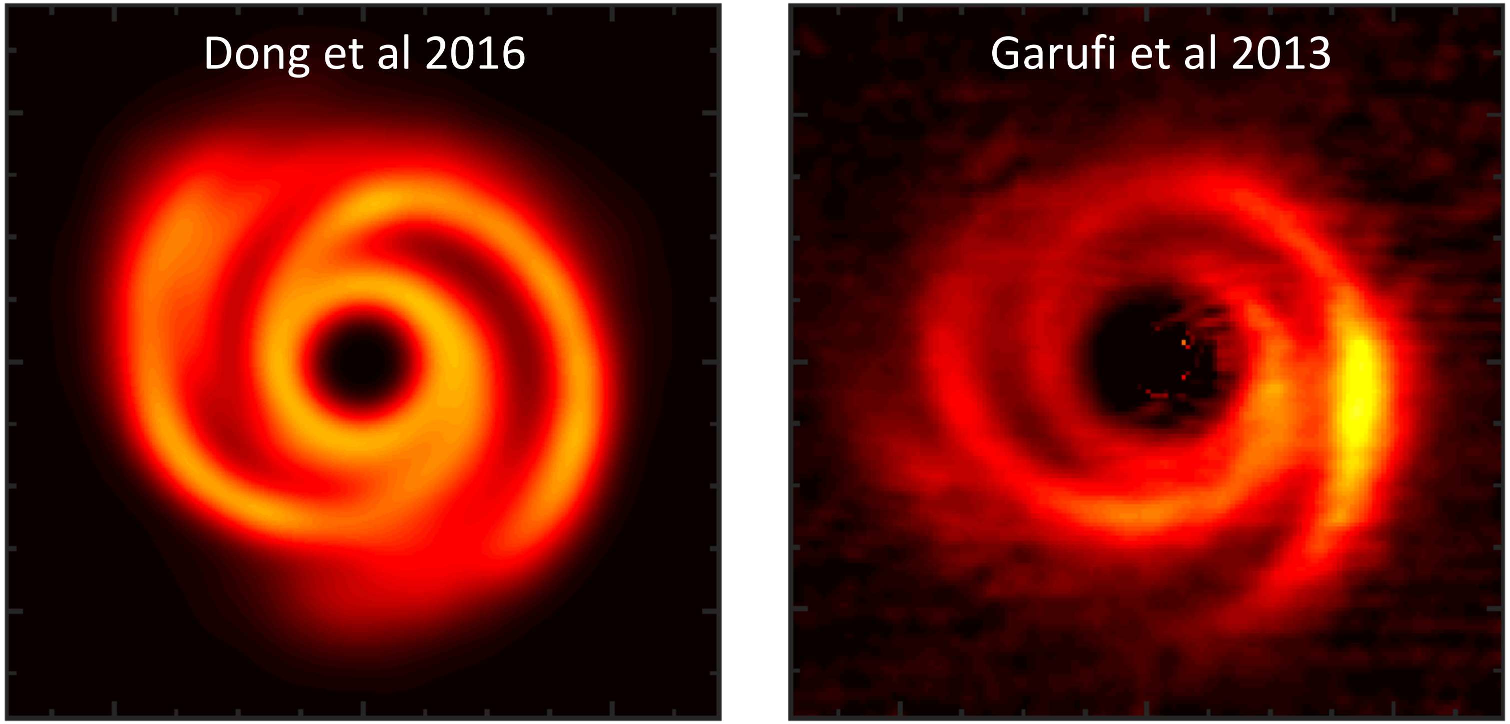


Cossins et al 2009

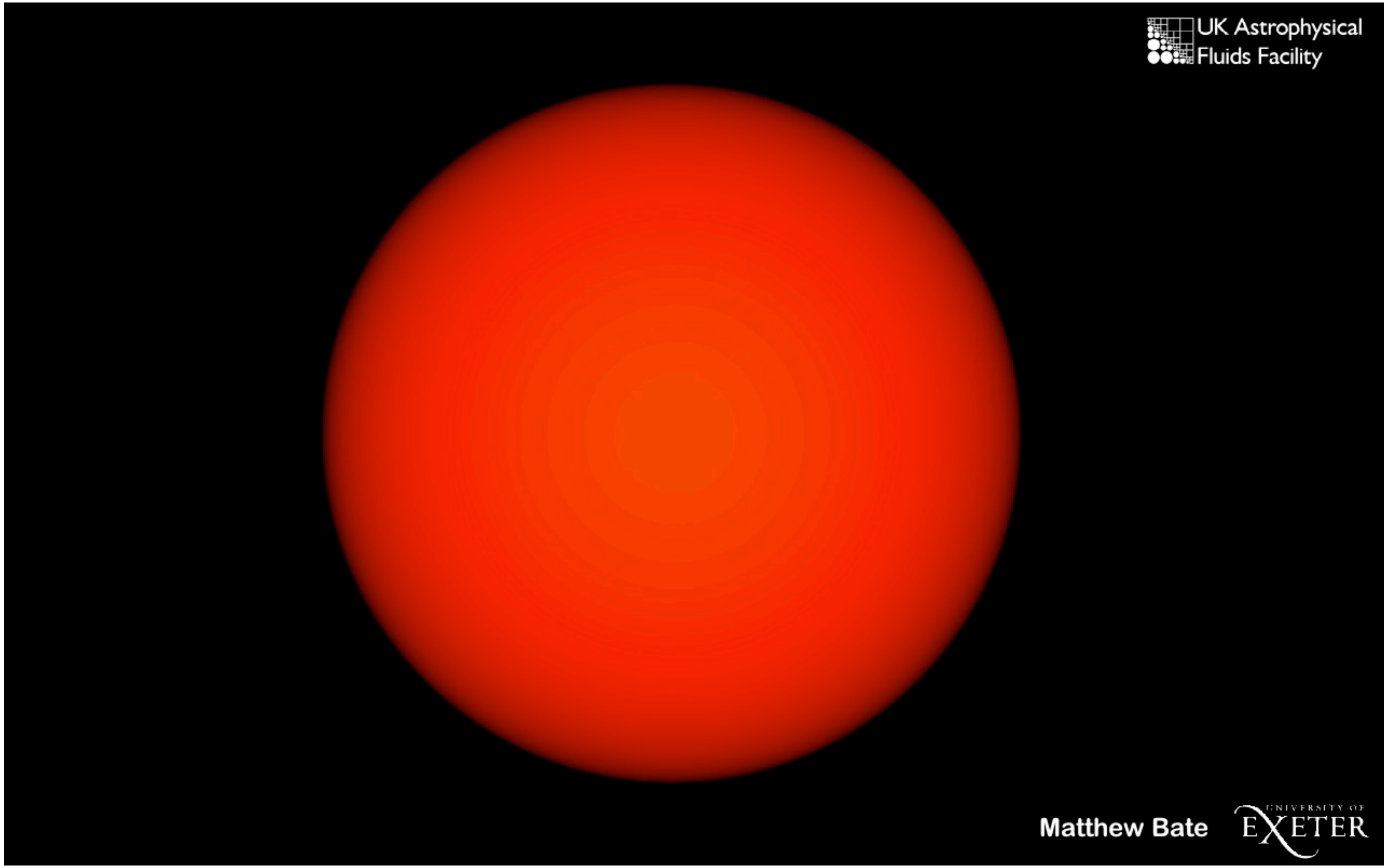


Forgan et al 2018

SAO 206462

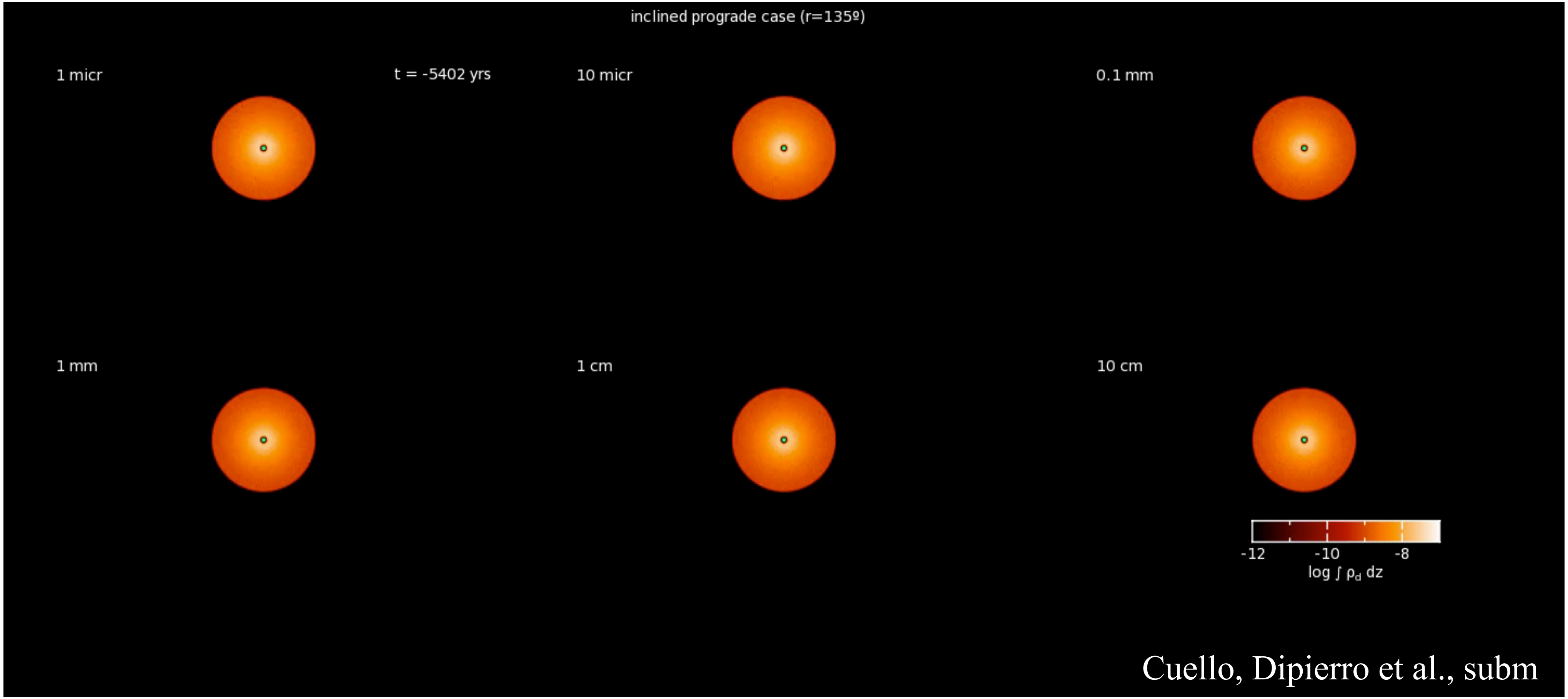


Spiral induced by stellar flybys

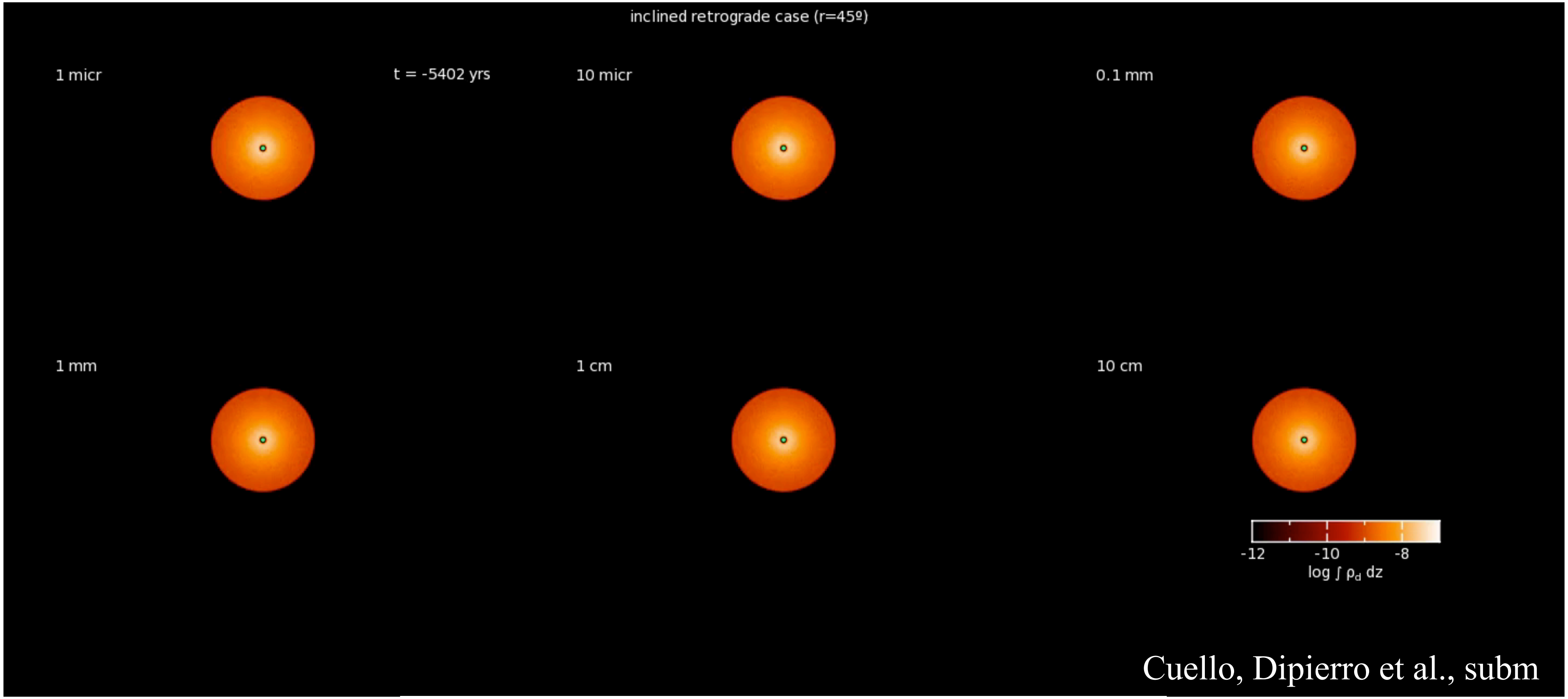


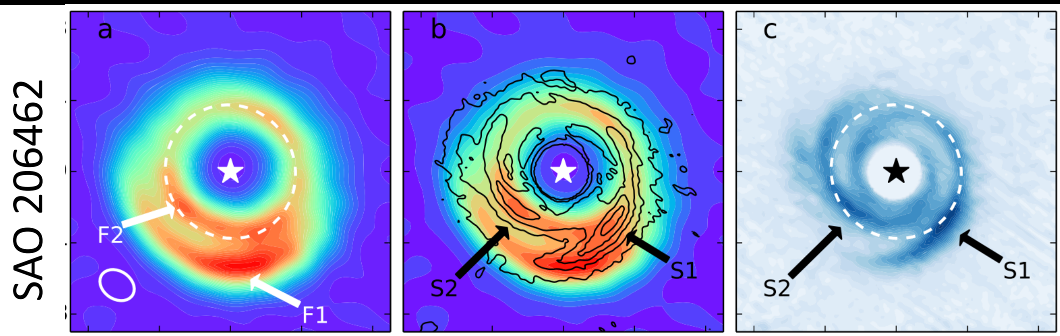
- Stars form in regions of enhanced ambient gas and stellar densities compared to the Galactic field (Lada +03).
  - The protoplanetary discs surrounding the newly formed stars might be influenced by this environment
    - The more massive is the perturber, the stronger is the effect on disc size (Pfalzner et al. 2008)
- Penetrating encounters destroy most of the disk, whereas distant encounters mainly have a strong influence in the outer regions of the disc (Bhandare et al 2016)

Spiral induced by stellar flybys in gas and dust



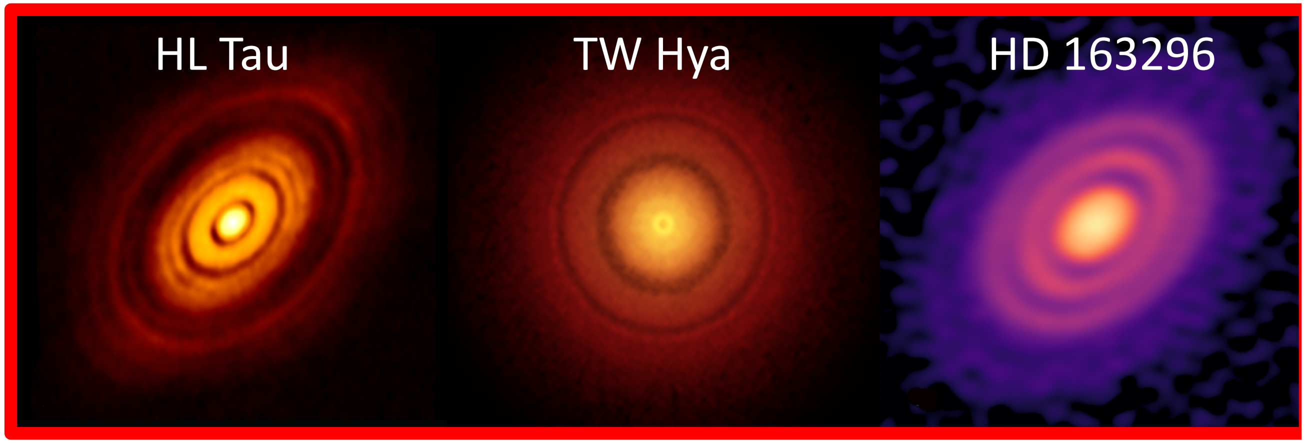
Spiral induced by stellar flybys in gas and dust





Gaps

(Alma +15, Andrews +16, Isella +17)



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Dust gap-opening: high mass planets

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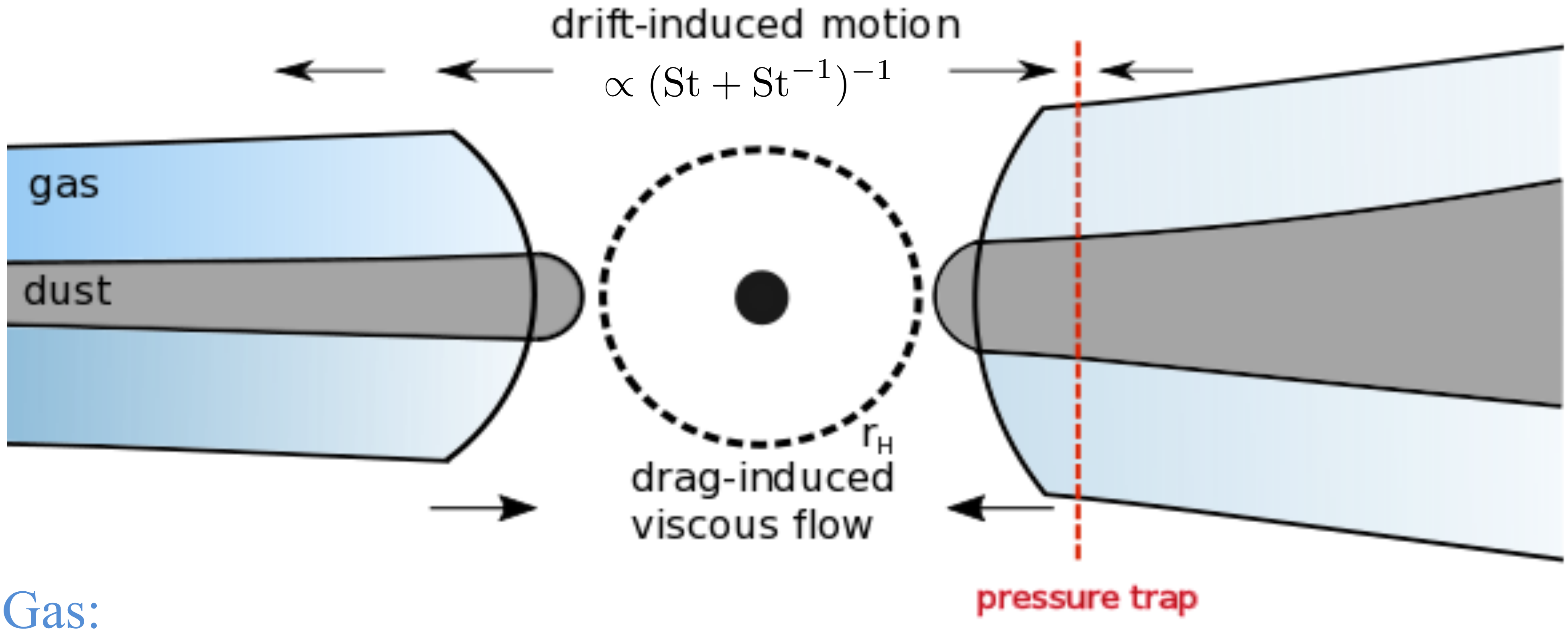


Gas:

- Criterion for the creation of pressure maxima (found numerically in 2D and 3D simulations):

$M_\mathrm{p} \gtrsim M_\mathrm{th}\sqrt{37\alpha + 0.01}$ with $M_\mathrm{th} = 3M_\star \left(\frac{H}{R}\right)^3$ (Ataiee et al 2018)

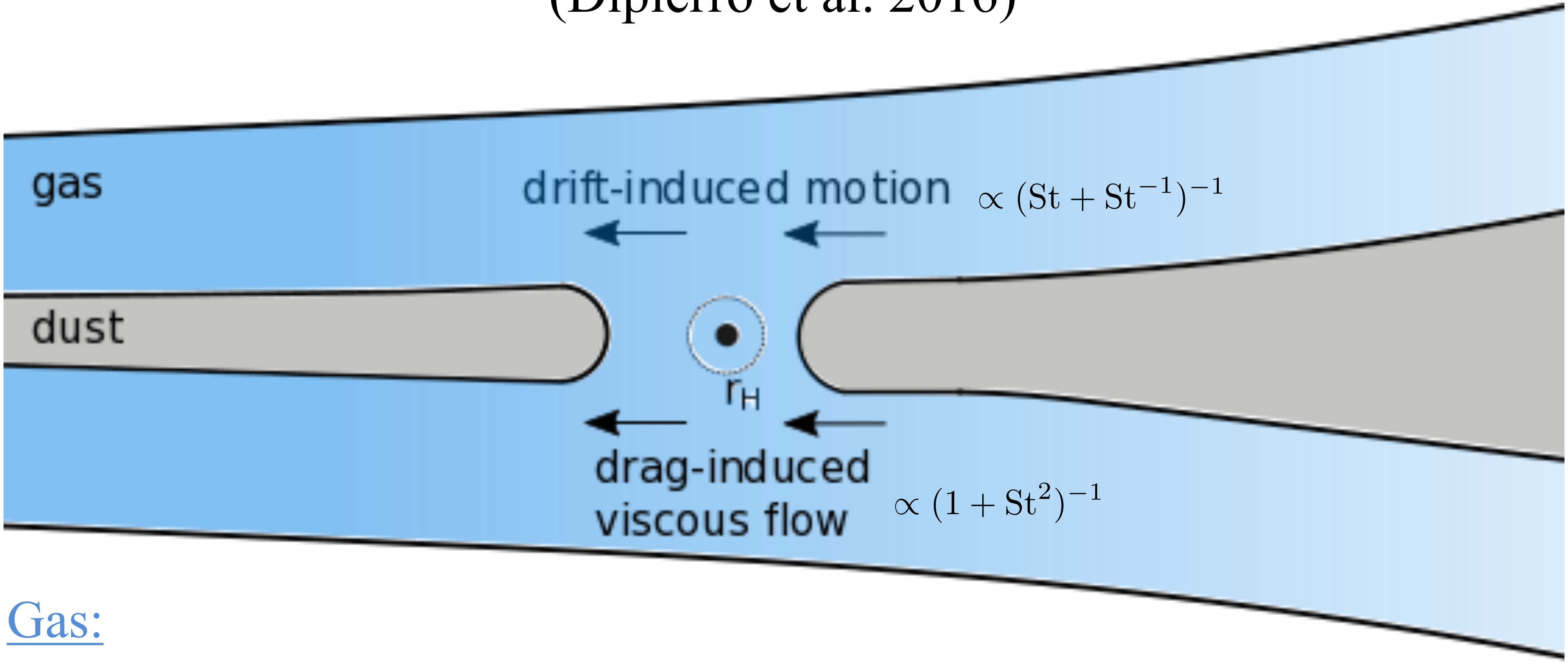
Dust:

- Small dust (St<<1): follows the gas: gap of width ~ 2 - 4 H (Duffel et al. 2013)
- For St ~ 1: dust trapping at the gap edges: deep gap (Pardekooper & Mellema 2004/6, Zhu et al 2014)

Role of the drag : assist gap opening from both inside and outside the planet orbit

Dust gap-opening: low mass planets

Dust gap-opening: low mass planets
(Dipierro et al. 2016)



Gas:

Unperturbed by planet: $M_\mathrm{p} \lesssim M_\mathrm{th}\sqrt{37\alpha + 0.01}$ (Rosotti +16, Dipierro & Laibe 2017)

Dust:

St < 1: follows the gas (no gap)

St ~ 1: drag tends to close the gap most efficiently

Drag: *assist* gap opening from *inside* and *resist* it from *outside* the planet orbit

Gap opening criterion for dust gaps

Dipierro & Laibe (2017)

Time required to evacuate all the dust contained between r_p and $r_p + r_H$

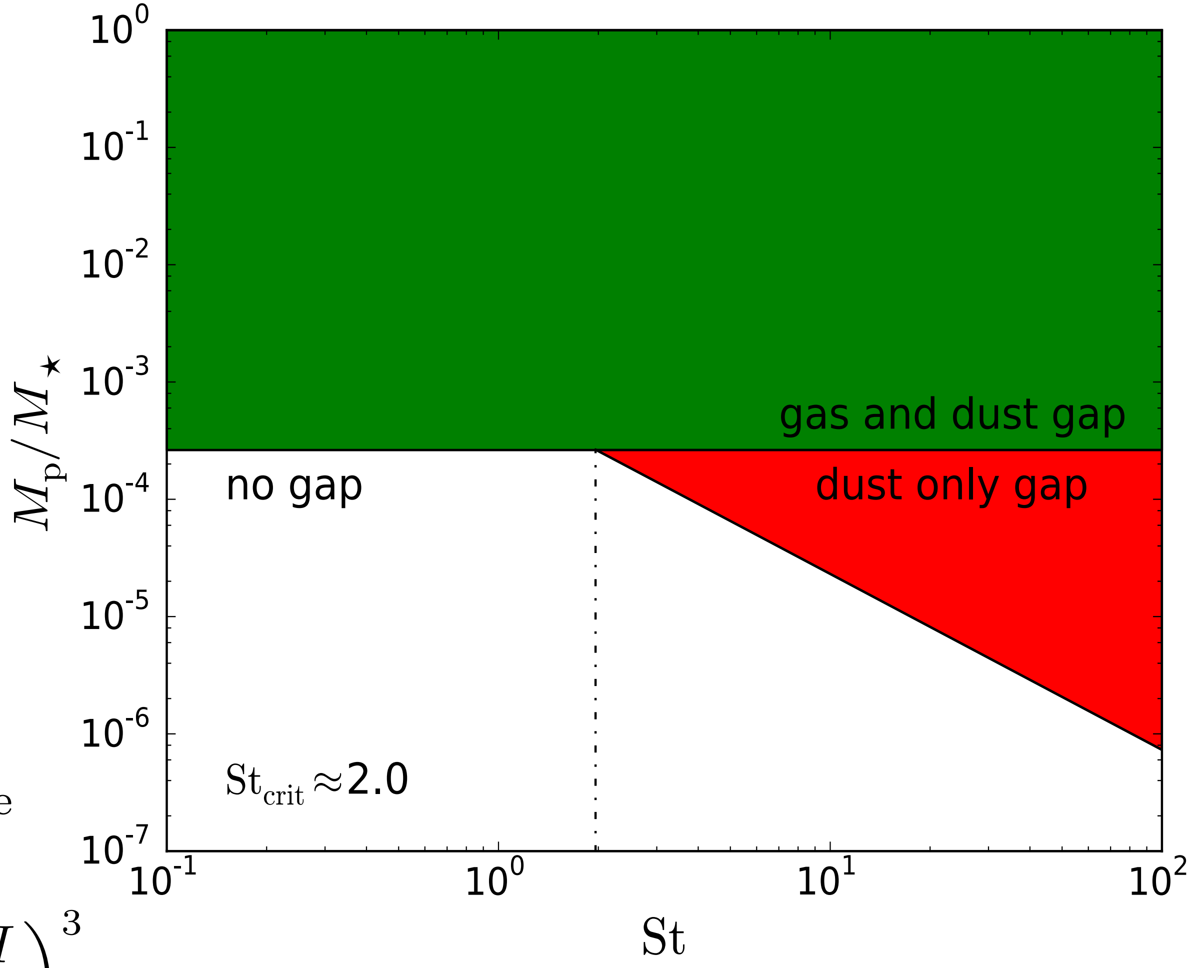
$$t_{\rm open} = \frac{\Delta J}{|{\rm dJ/dt}|} \sim \left(\frac{M_{\rm p}}{M_\star}\right)^{-1/3} \Omega_{\rm k}^{-1}$$

Time required to fill the gap by the radial inward drift induced by drag

$$t_{\rm close} = \frac{r_{\rm H}}{v_{{\rm d},r}} = \frac{(1+\epsilon)(1+{\rm St}^2)}{-\zeta {\rm St} + (6+3\zeta)\,\alpha} \frac{v_{\rm k}}{c_{\rm s}^2} r_{\rm H}$$

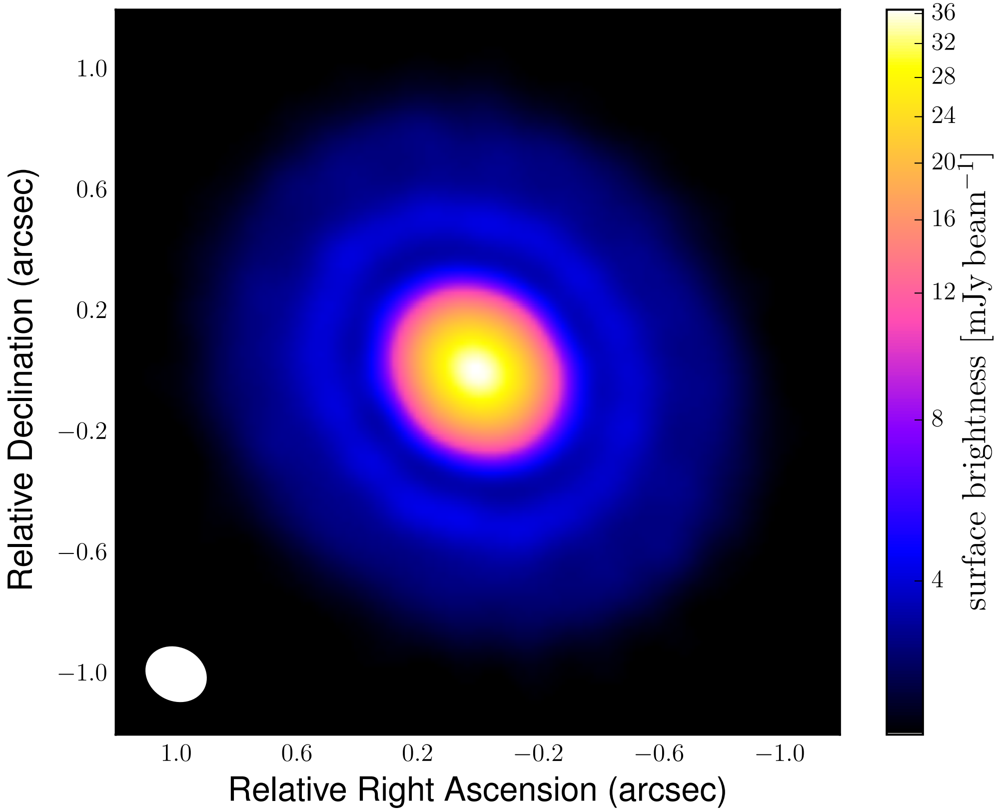
Refilling condition: $t_{\rm open} \leq t_{\rm close}$

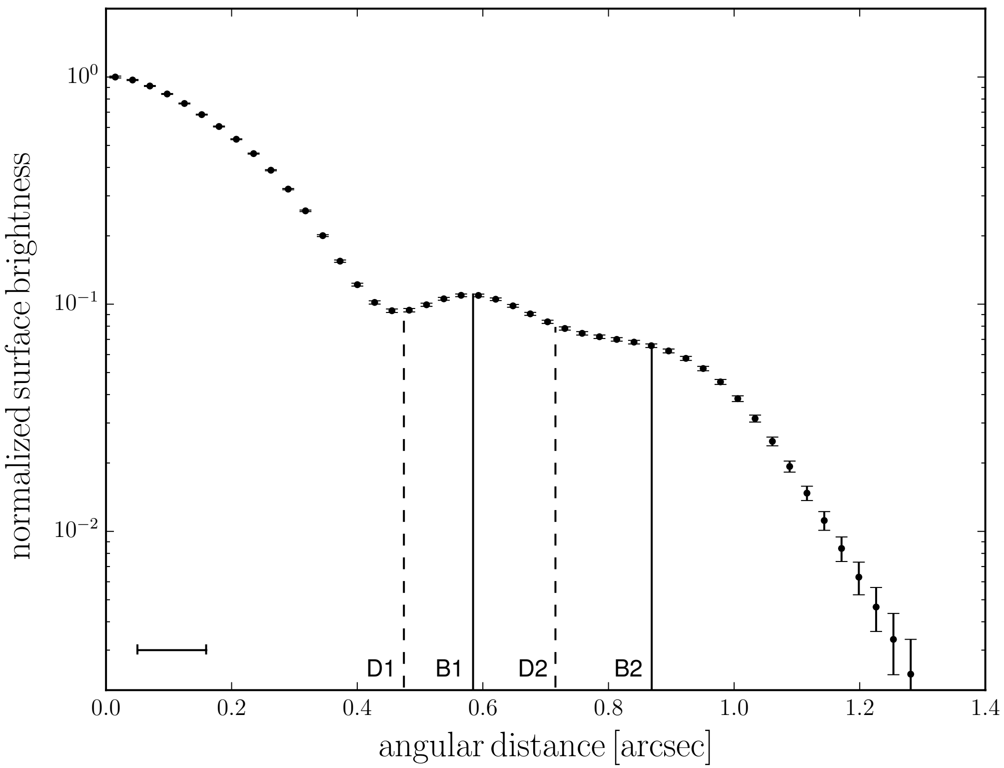
$$\frac{M_{\rm p}}{M_\star} \gtrsim 1.38 \left|\frac{\partial \log P}{\partial \log r}\right|_{r_{\rm p}}^{3/2} {\rm St}^{-3/2} \left(\frac{H}{r_{\rm p}}\right)^3$$



Elias 24

Dipierro et al. (2018)

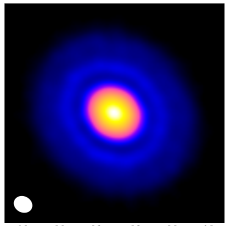


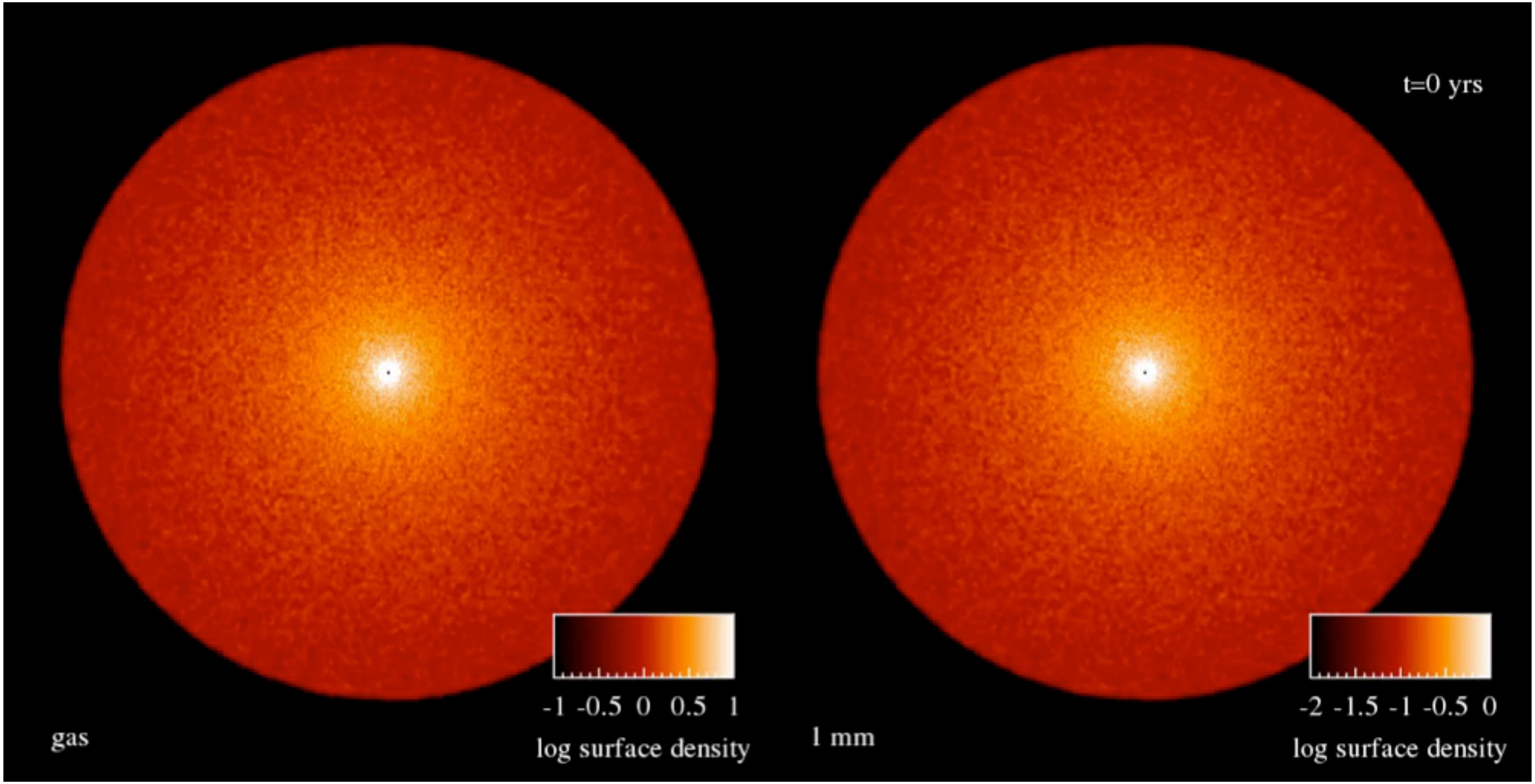


ALMA Cycle 2 observations of the 1.3 mm dust continuum emission with an angular resolution of 0.2" (~ 28 au)

- dark and bright rings at 0.47” and 0.58” with a ratio of the continuum intensity of ~ 0.8.
- change of concavity at ~ 0.7” and ~0.9"

Elias 24



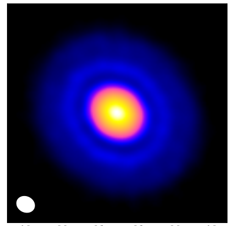


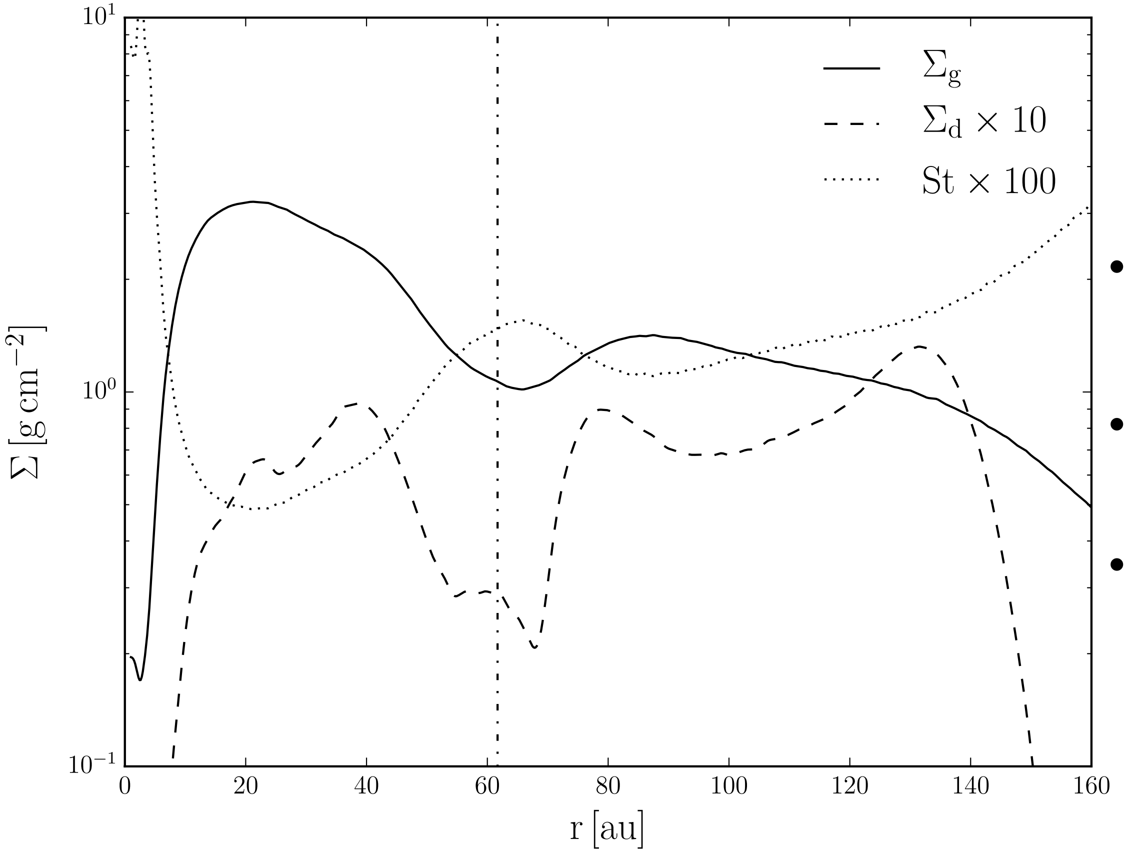
Initial conditions: $\Sigma_{g-d} \propto r^{-0.7}$ with dust mass of mm grains 0.0017 $M_{\odot}$, dust to gas ratio 0.1

Planet with initial mass 0.15 M_J, initially located at 65 au

After 85 orbits (at 65 au) the planet reaches a mass 0.7 M_J and migrates from 65 to 61.7 au

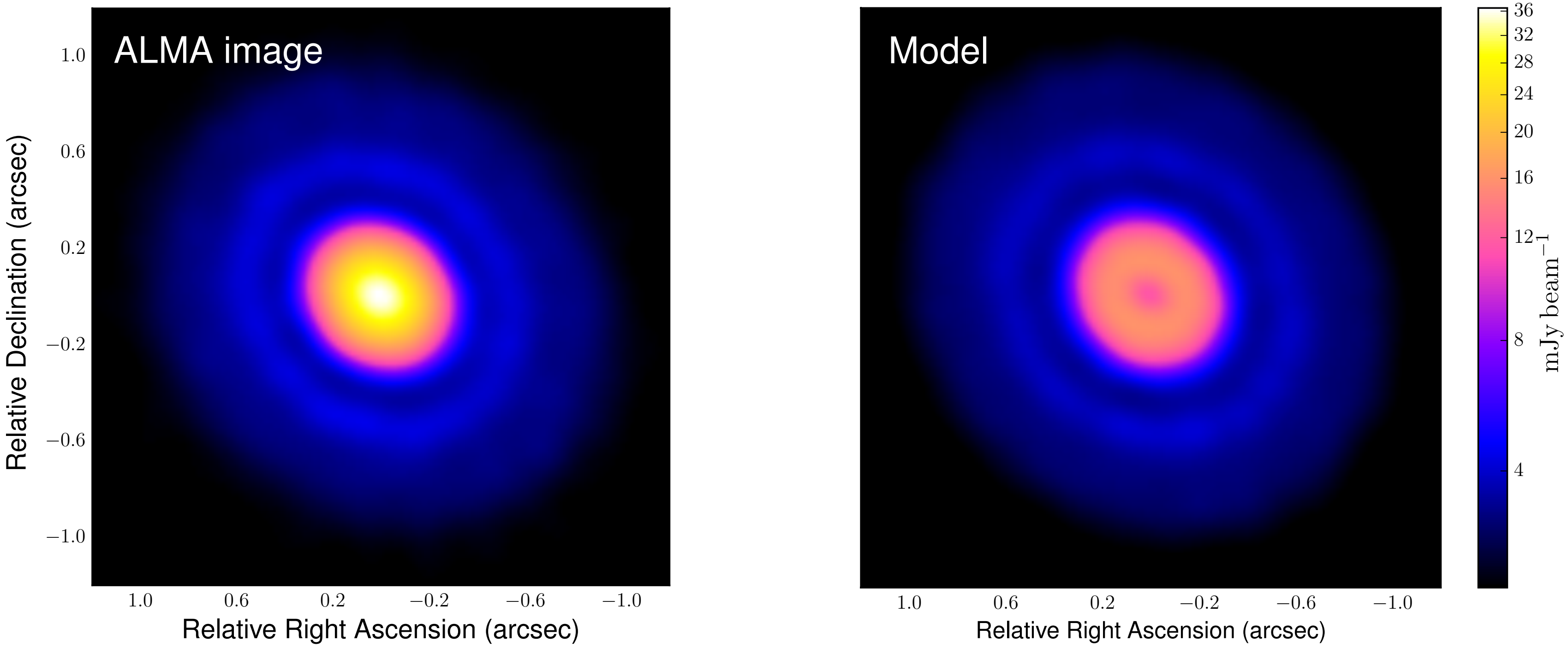
Elias 24

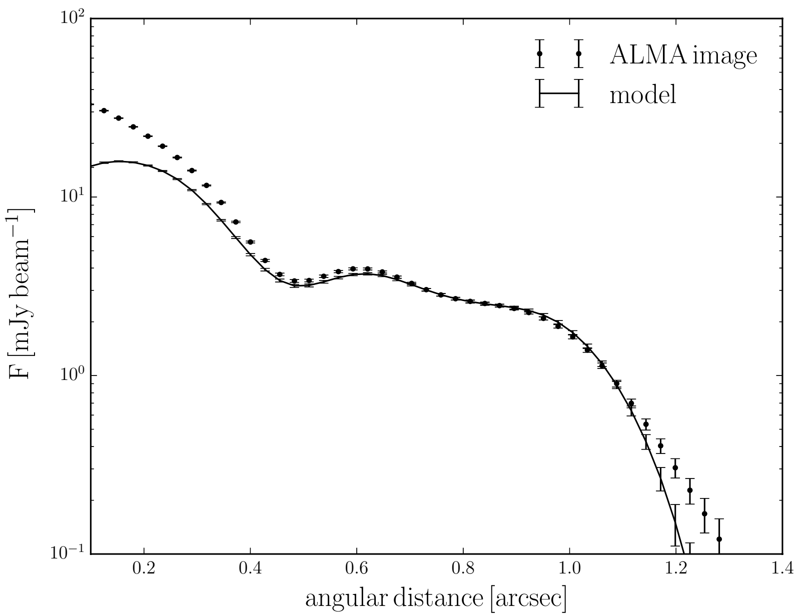




- Planet's co-orbital gas surface density drops to ~ 60% of its initial value.
- mm grains accumulates at the pressure maximum
- non uniform gas distribution across the outer disc regions leads to a gradient in the dust radial velocities

Elias 24





Reasonable match to the gap and ring like structure observed in Elias 24

Change of concavity at ~0.7" is explained by the differential radial motion of large dust grains from the outer radius

Conclusions

- The morphology of the spiral structure (in gas) can be used to constrain the mechanism responsible for their formation
- For planet-induced spiral, the pitch angle can be used to constrain the mass of unseen planet but requires accurate disc gas temperature measurements
- Dust gaps do not necessarily indicate gas gaps (see also Rosotti+2016)
- Low mass planets open gaps in the dust: *resisted* by drag outside and *assisted* by drag *inside*, while high mass planets open dust gaps assisted by drag

Grain size-dependent criterion for dust gap opening in discs:

$$\frac{M_{\rm p}}{M_\star} \gtrsim 1.38 \left| \frac{\partial \log P}{\partial \log r} \right|_{r_{\rm p}}^{3/2} {\rm St}^{-3/2} \left(\frac{H}{r_{\rm p}} \right)^3$$

- Major features of Elias 24 (and other sources, e.g. Dipierro +15, Isella +16, Fedele +17) are well reproduced by assuming the presence of planets with mass in the range [0.1,0.8] M_J at large distances (~10 au) from their star.


Thanks for your attention!