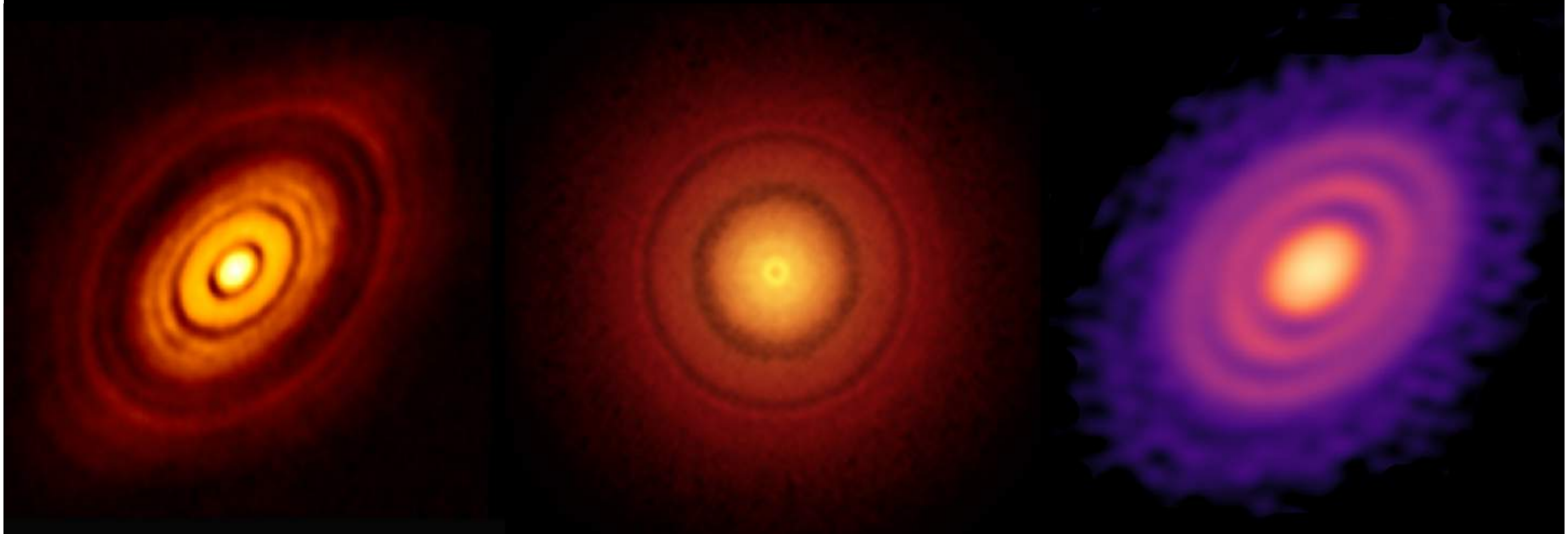
Dust gap opening in protoplanetary discs with PHANTOM



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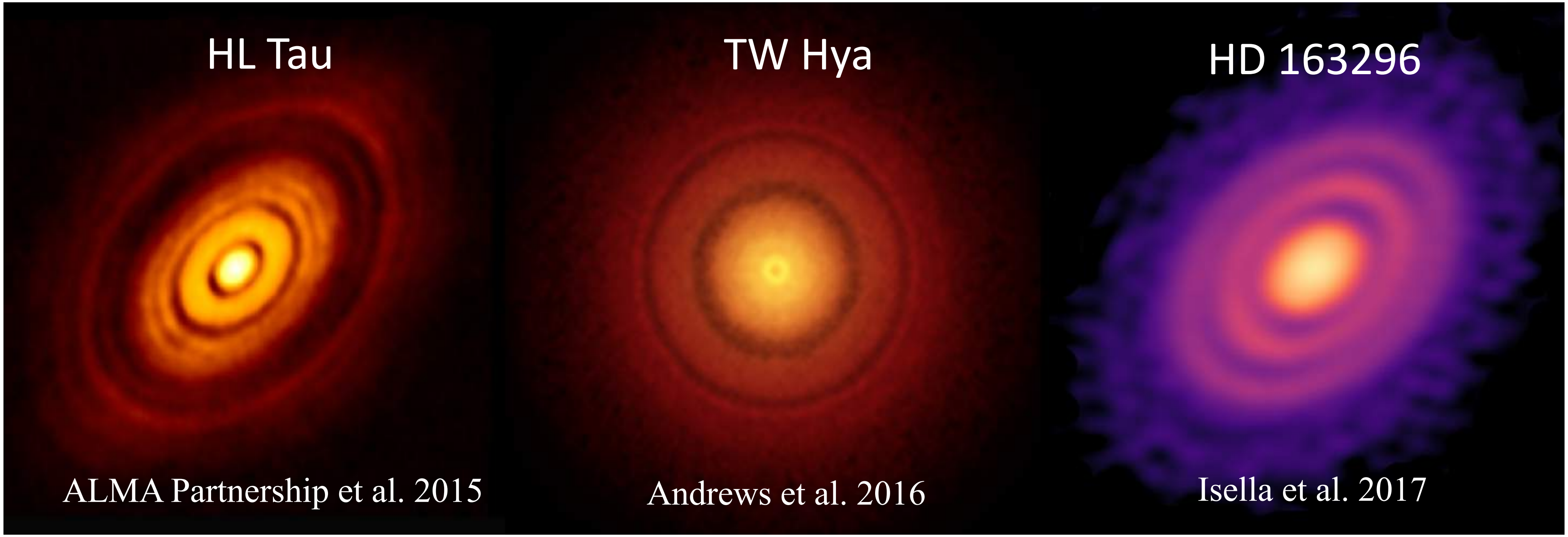
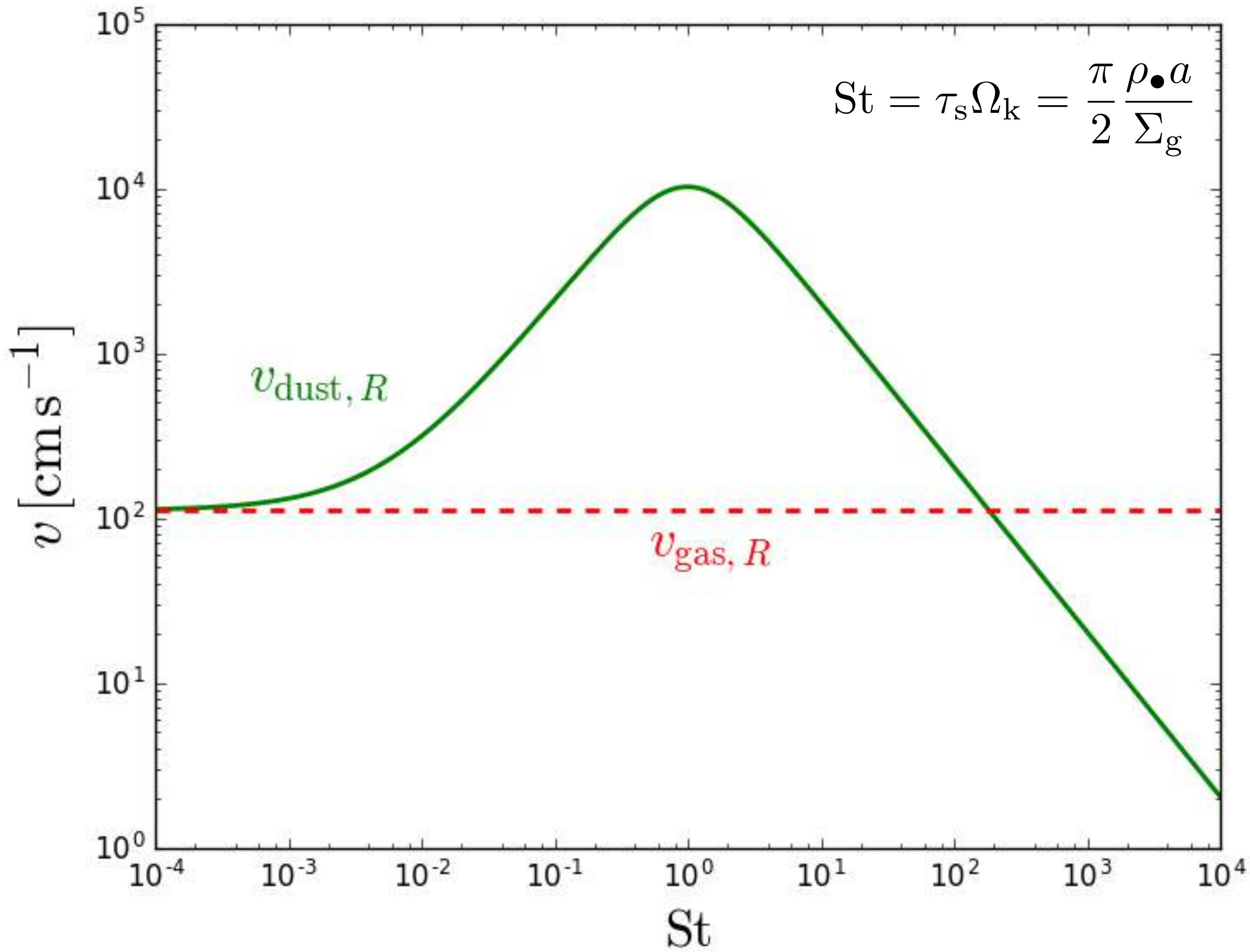
Motivations



How to open gaps in mm dust?

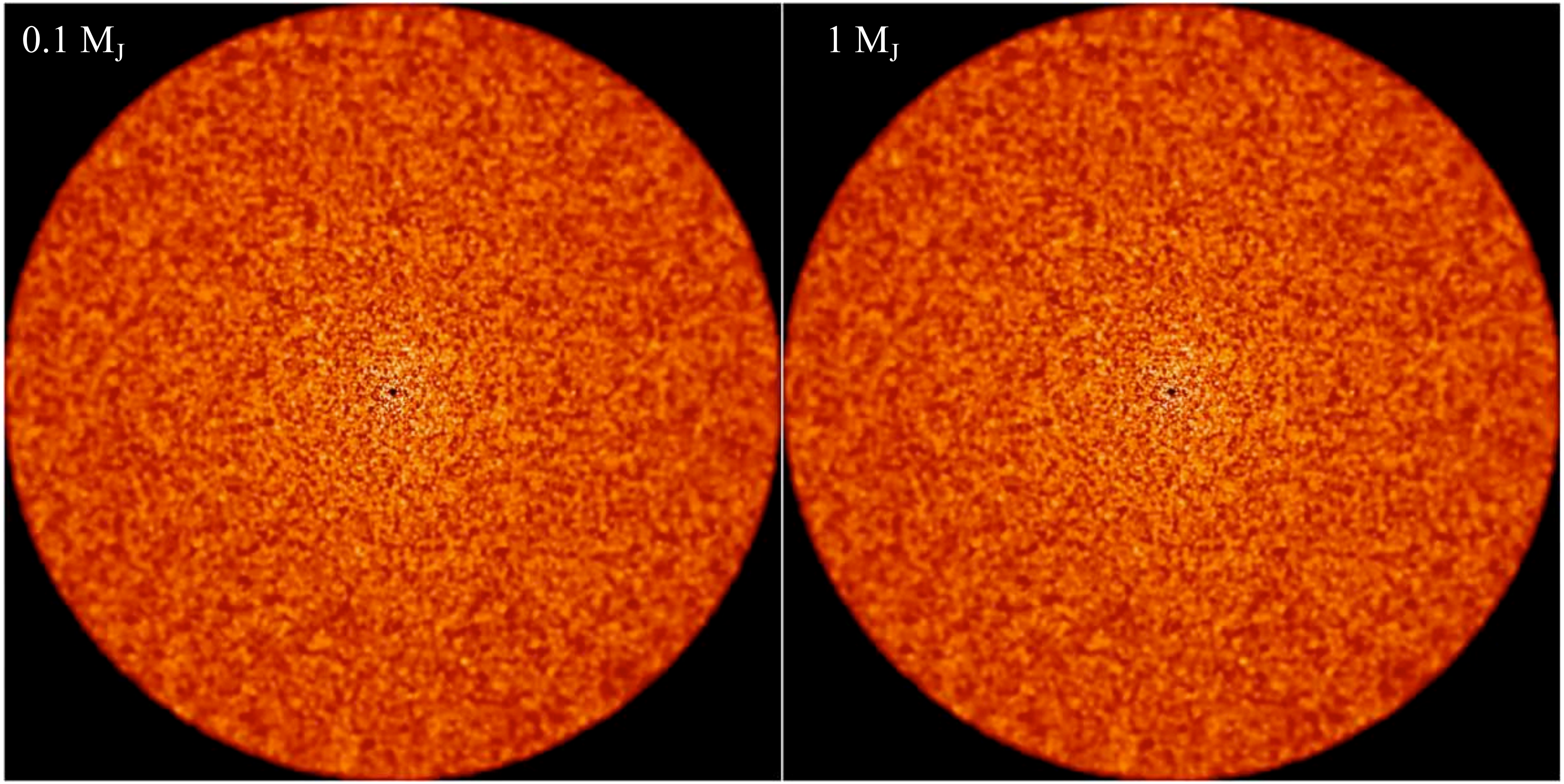
What is the physics behind their morphology?

Dust radial evolution



$$v_{\mathrm{dust},R} = v_\mathrm{drag} + v_\mathrm{drift} = \frac{v_{\mathrm{gas},R}}{1+\mathrm{St}^2} + \frac{1}{\mathrm{St}+\mathrm{St}^{-1}}\frac{1}{\rho_\mathrm{g}\Omega_\mathrm{k}}\frac{\partial P}{\partial R}$$

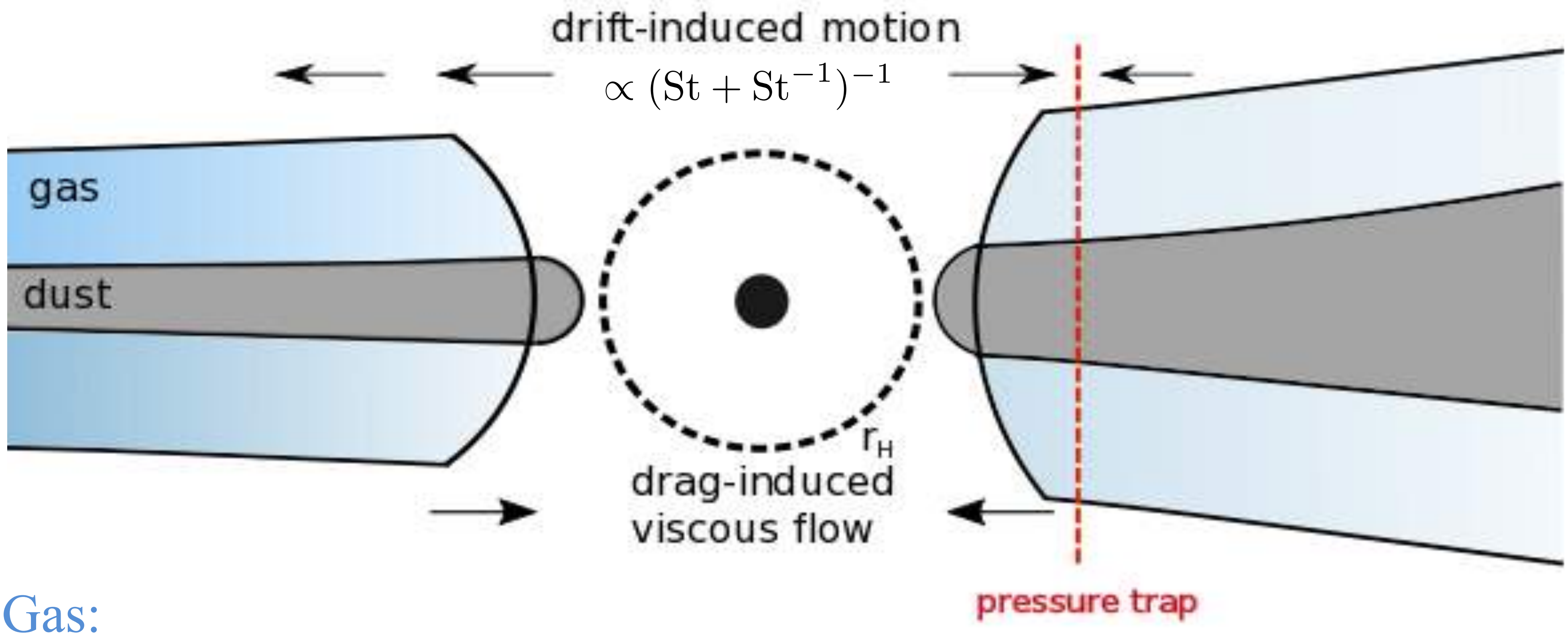
Gap opening process in viscous gas discs



Dust gap-opening: high mass planets

High mass planet: 1 M_j

Dust gap-opening: high mass planets



Gas:

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

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

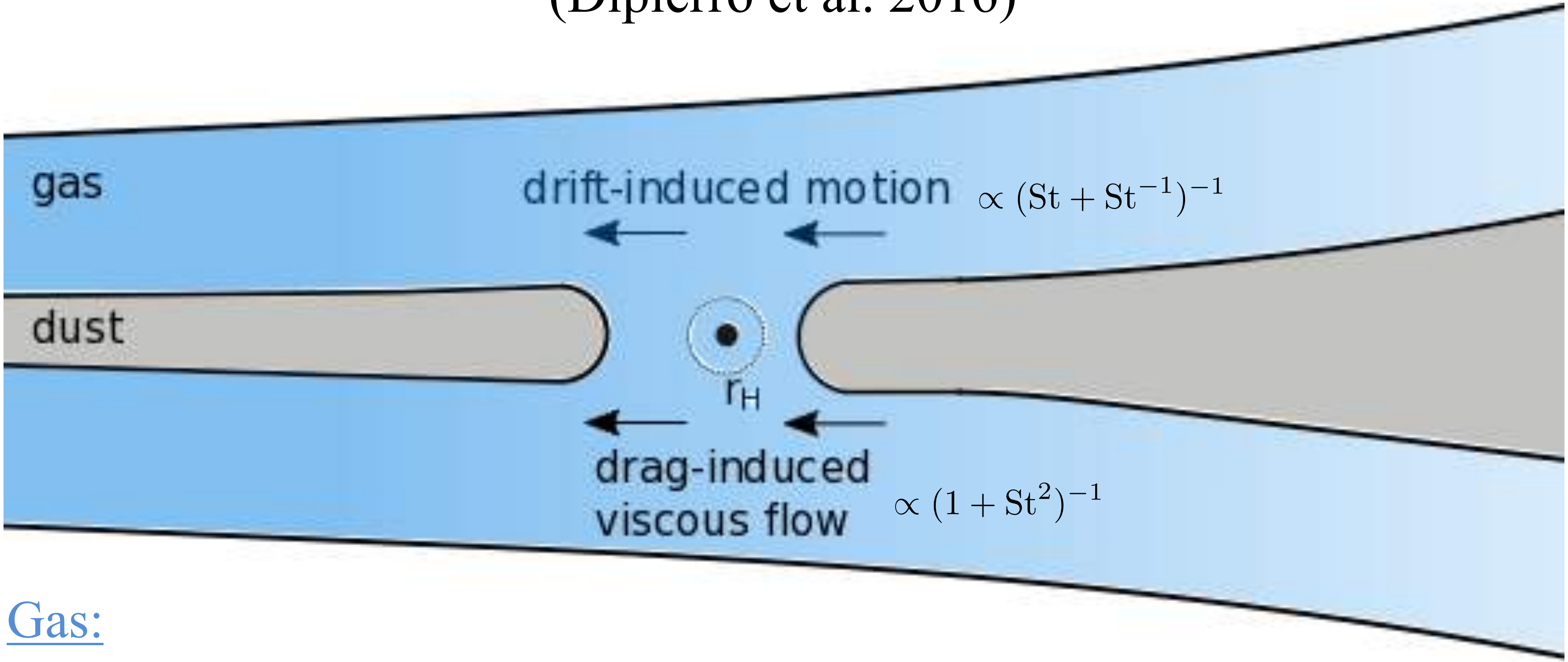
Dust:

- 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: $M_\mathrm{p} \lesssim M_\mathrm{th}\sqrt{37\alpha + 0.01}$

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

Dust gap-opening: low mass planets

Gap opening by low mass planets

Dipierro & Laibe (2017)

$$\frac{\partial \mathbf{v}_{\mathrm{g}}}{\partial t} + (\mathbf{v}_{\mathrm{g}} \cdot \nabla)\,\mathbf{v}_{\mathrm{g}} = \frac{K}{\rho_{\mathrm{g}}}(\mathbf{v}_{\mathrm{d}} - \mathbf{v}_{\mathrm{g}}) - \nabla(\Phi + \Phi_{\mathrm{p},g}) - \frac{1}{\rho_{\mathrm{g}}}(\nabla P - \nabla \cdot \sigma)$$

$$\frac{\partial \mathbf{v}_{\mathrm{d}}}{\partial t} + (\mathbf{v}_{\mathrm{d}} \cdot \nabla)\,\mathbf{v}_{\mathrm{d}} = -\frac{K}{\rho_{\mathrm{d}}}(\mathbf{v}_{\mathrm{d}} - \mathbf{v}_{\mathrm{g}}) - \nabla(\Phi + \Phi_{\mathrm{p},d})$$

where $K = \frac{\rho_{\mathrm{d}}\rho_{\mathrm{g}}}{\tau_{\mathrm{s}}\,(\rho_{\mathrm{d}} + \rho_{\mathrm{g}})}$ $\quad \nabla\Phi_{\mathrm{p}}|_{\theta} = \frac{\Lambda}{r}$ $\quad \Lambda(r) = \mathrm{sgn}(r - r_{\mathrm{p}})\, f\, \frac{(\mathcal{G}M_{\mathrm{p}})^2}{\Omega_{\mathrm{p}}^2}\frac{1}{\Delta^4}$

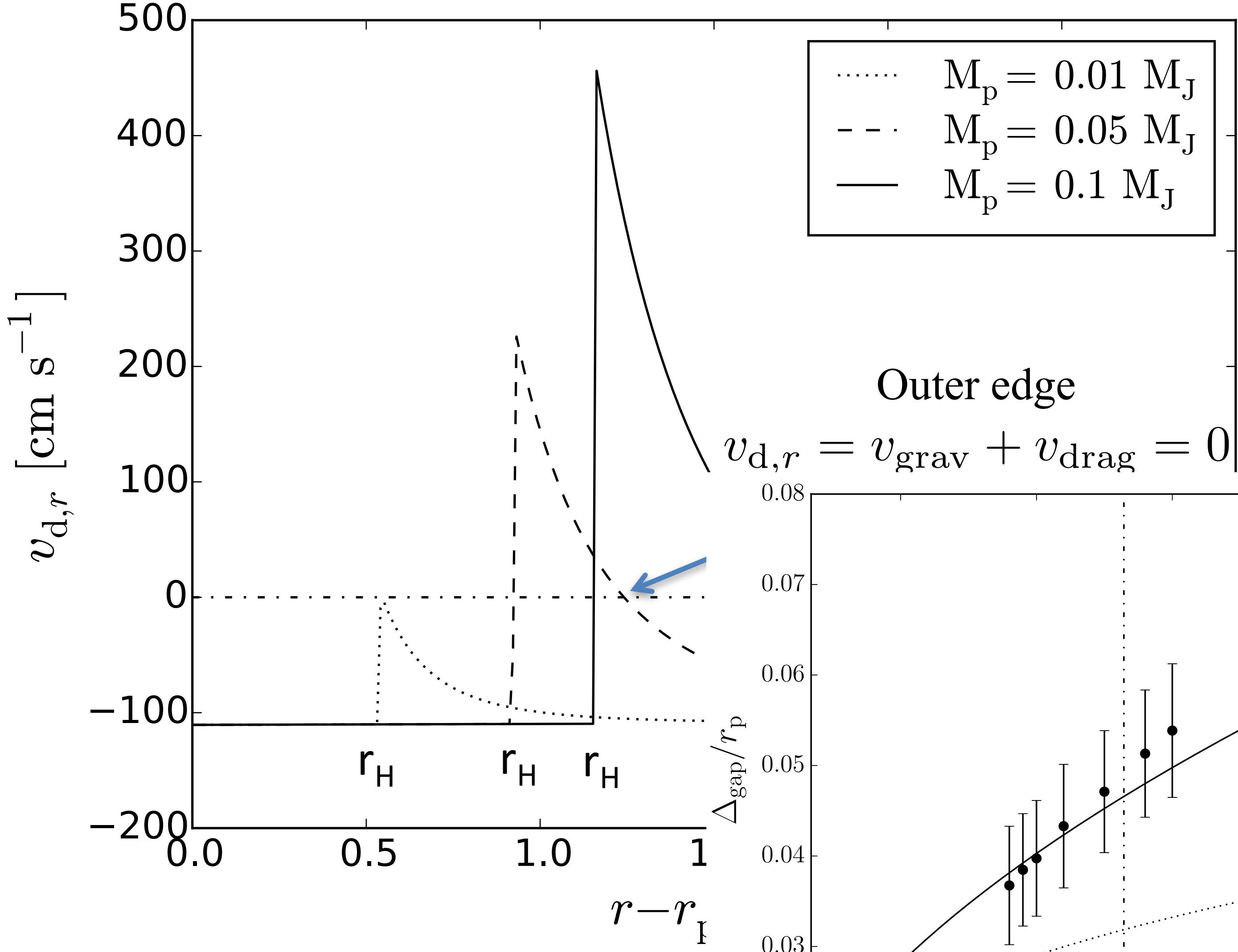
Goldreich & Tremaine 1979

Different prescriptions for the tidal torque in gas and dust:

$\Delta_{\mathrm{g}} = \max(|r - r_{\mathrm{p}}|\,, H, r_{\mathrm{H}})$ $\qquad \Delta_{\mathrm{d}} = \max(|r - r_{\mathrm{p}}|\,, r_{\mathrm{H}})$

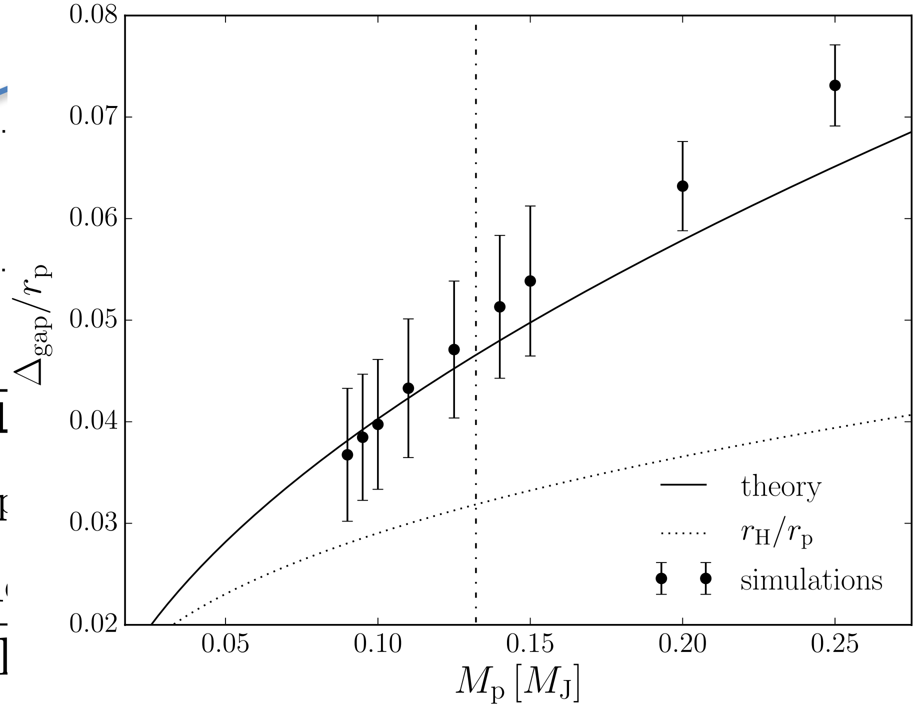
Outer gap edge

Dipierro & Laibe (2017)



Outer edge

$$v_{\mathrm{d},r} = v_{\mathrm{grav}} + v_{\mathrm{drag}} = 0$$



$$v_{\mathrm{d},r}(r_{\mathrm{p}} + \Delta_{\mathrm{gap}}) = 0 \longrightarrow \frac{\Delta_{\mathrm{gap}}}{r_{\mathrm{p}}} \sim \left|\frac{\partial \mathrm{l}}{\partial \mathrm{l}}\right.$$

Gap opening criterion for dust gaps

Dipierro & Laibe (2017)

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

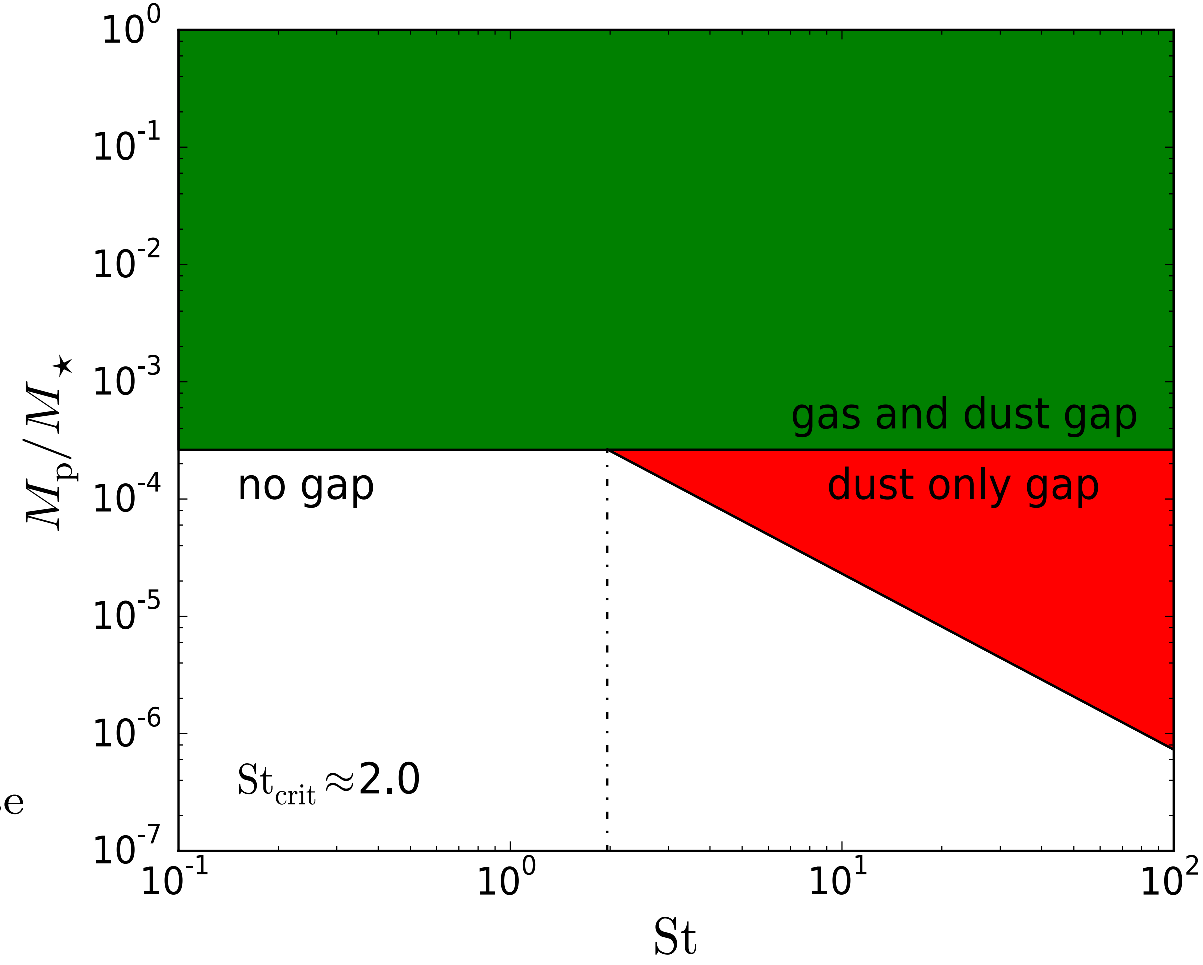
$$t_{\rm open} = \frac{\Delta J}{|{\rm dJ/dt}|} \sim \left(\frac{M_{\rm p}}{M_\star}\right)^{-1/3} \Omega_{\rm k}^{-1}$$

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

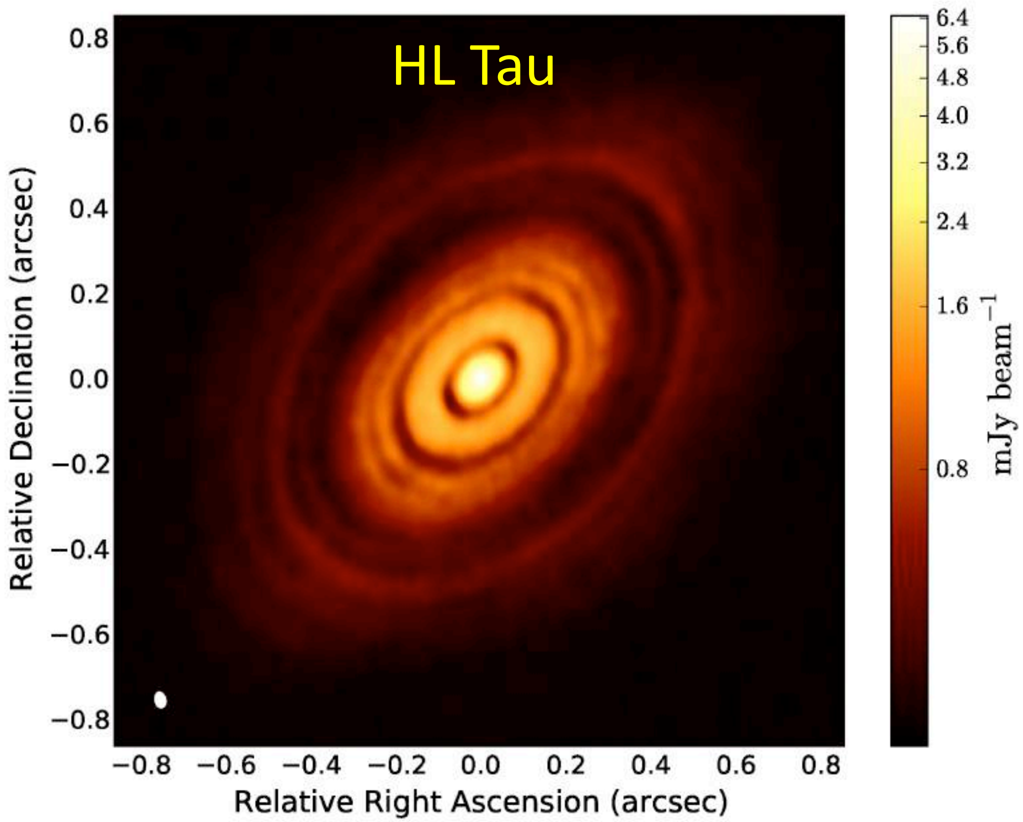
$$t_{\rm close} = \frac{r_{\rm H}}{v_{{\rm d},r}} = \frac{(1+\epsilon)(1+{\rm St}^2)}{-\zeta {\rm St} + (6+3\zeta)\,\alpha}\frac{v_{\rm k}}{c_{\rm s}^2} r_{\rm H}$$

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

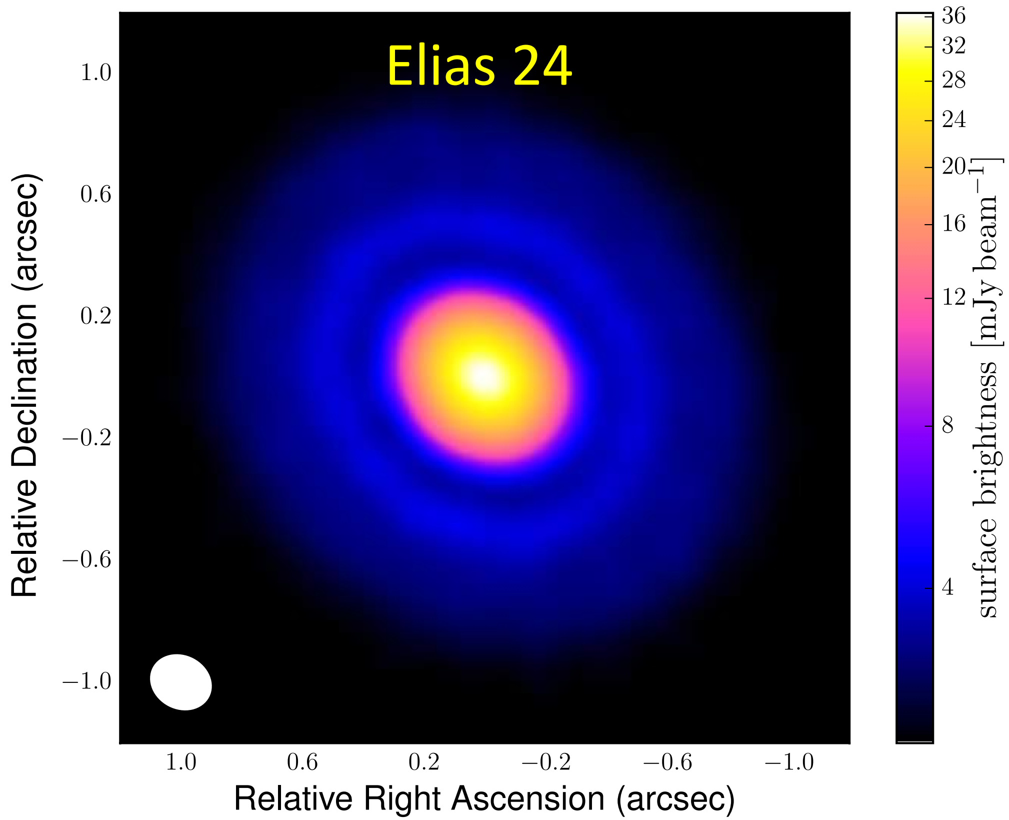
$$\frac{M_{\rm p}}{M_\star} \sim {\rm St}^{-3/2}\left(\frac{H}{r_{\rm p}}\right)^3$$



Application to Elias 24 and HL Tau

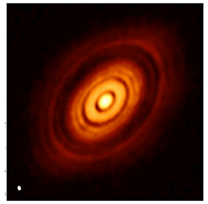


ALMA Partnership +15



Dipierro +18

HL Tau

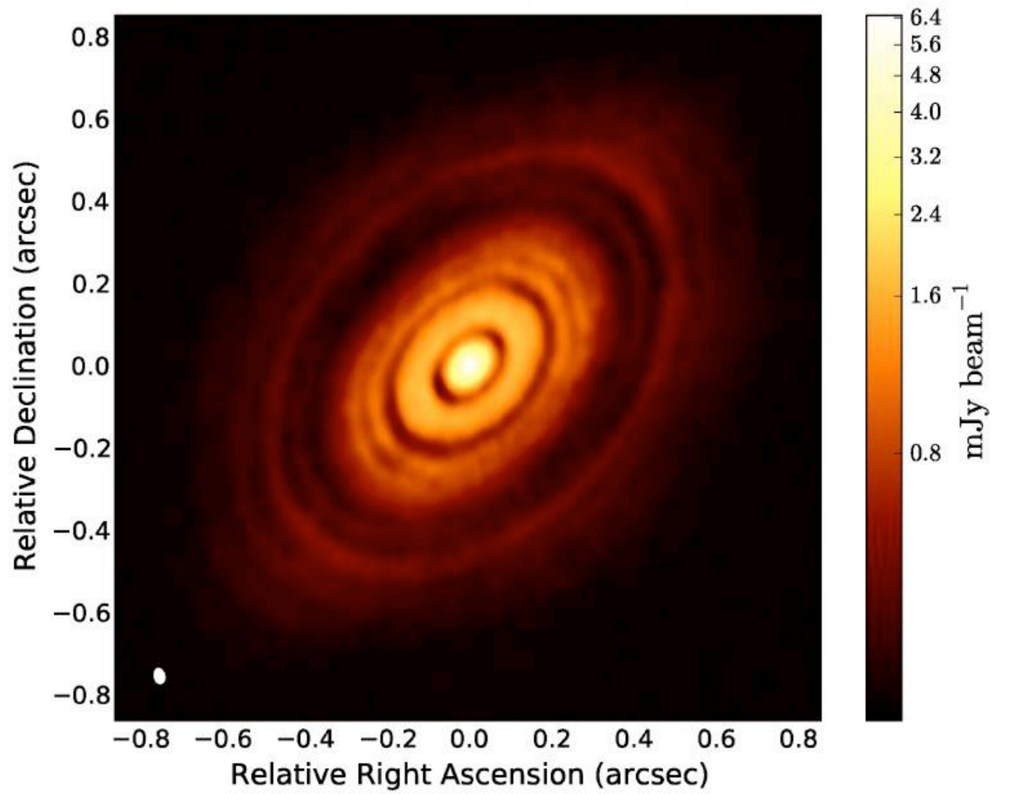


3D SPH dust/gas simulation:

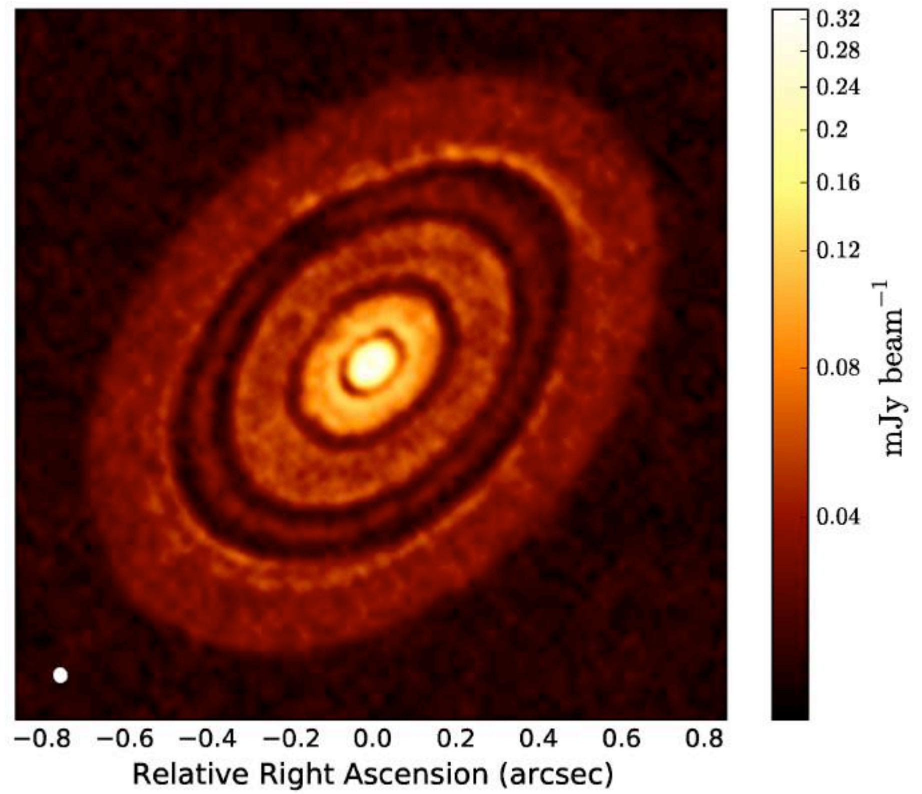
- 3 planets with mass 0.08, 0.1 and 0.5 M_J at 13.2, 32.3 and 68.7 AU

Low mass regime

Intermediate mass regime



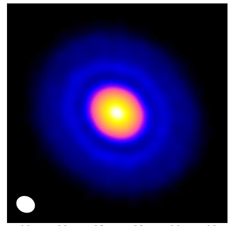
ALMA Partnership et al. 2015

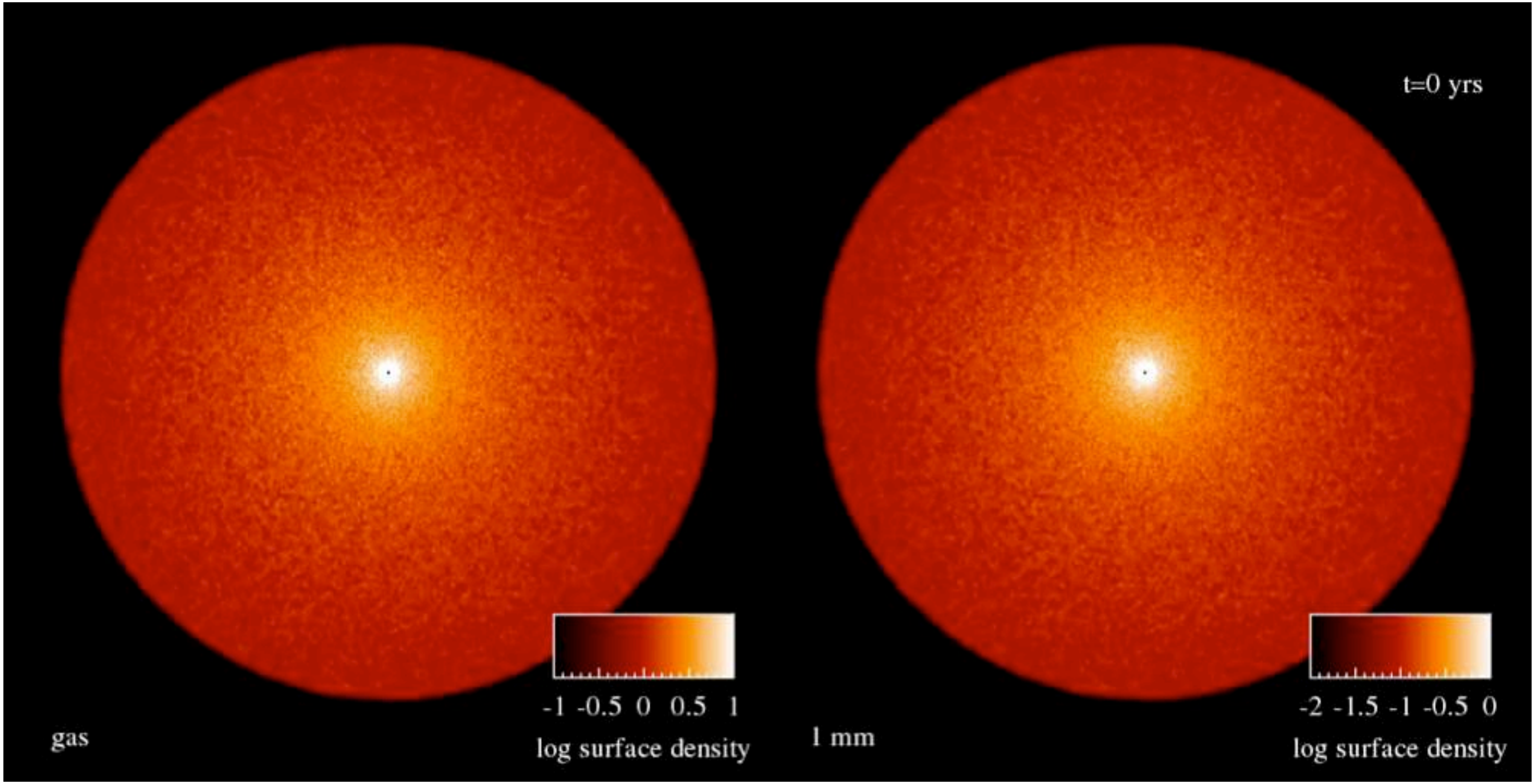


Dipierro et al. 2015

3 planets with mass 0.08, 0.1 and 0.5 M_J at 13.2, 32.3 and 68.7 AU

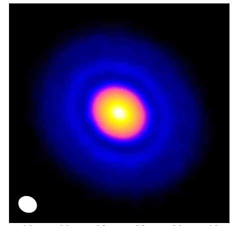
3D dust/gas simulations

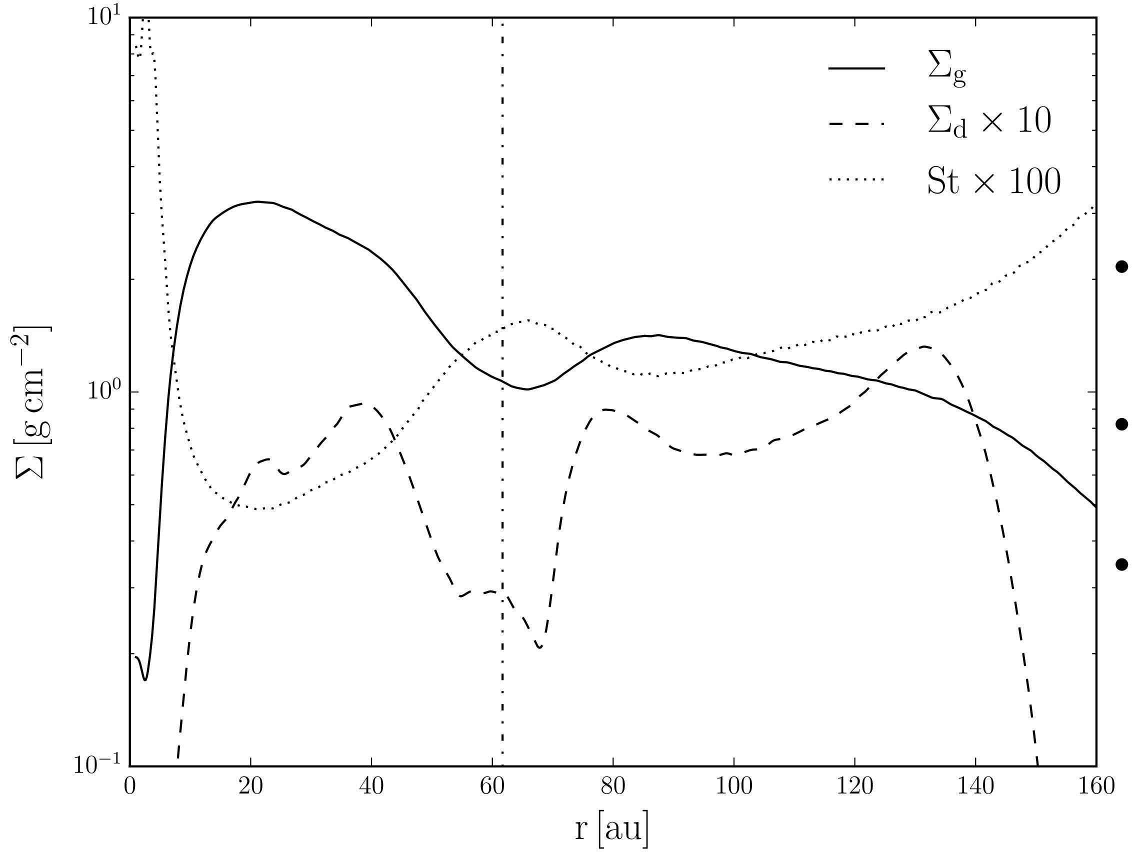




Initial conditions: $\Sigma_{g-d} \propto r^{-0.7}$ with dust mass of mm grains 0.0017 $M_{\odot}$, dust to gas ratio 0.1
Planet with initial mass 0.15 M_J , initially located at 65 au
After 85 orbits (at 65 au) the planet reaches a mass 0.7 M_J and migrates from 65 to 61.7 au

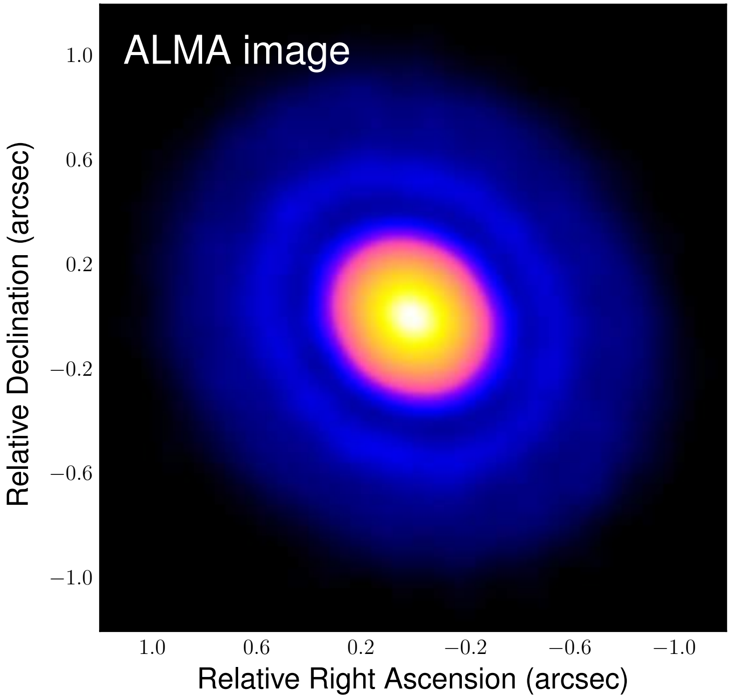
Disc structure

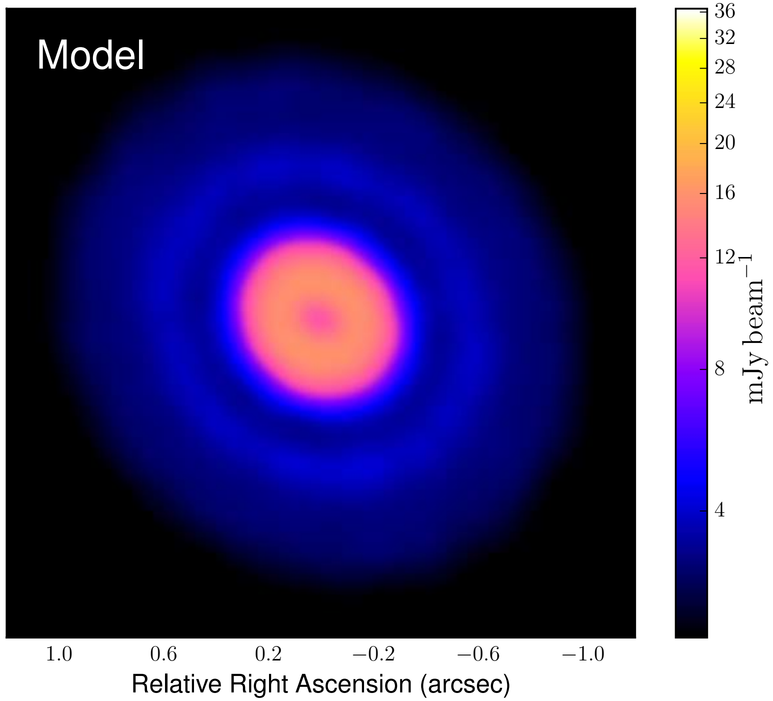


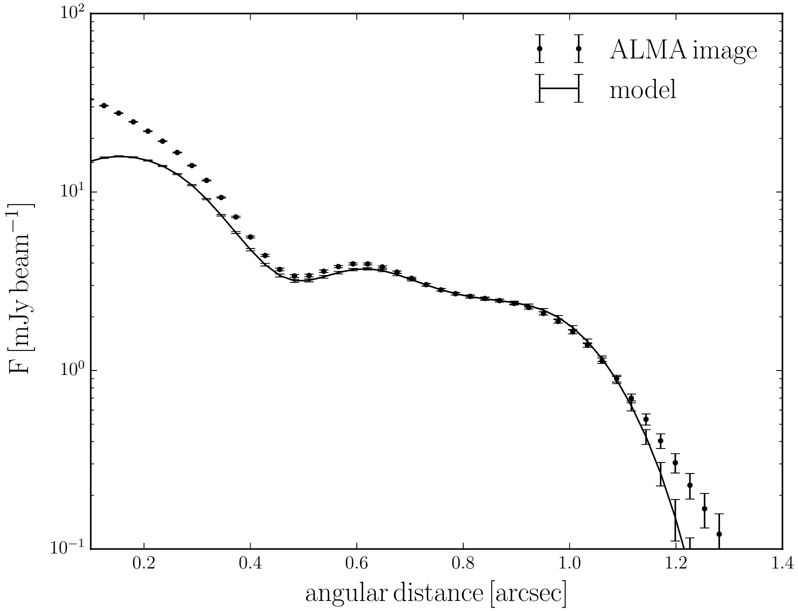


- Planet's co-orbital gas surface density drops to ~ 60% of its initial value.
- mm grains accumulates at the pressure maximum
- non uniform gas distribution across the outer disc regions leads to a gradient in the dust radial velocities

ALMA simulated observation







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

- 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:

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

Estimate of the location of the outer edge of the dust gap:

$$\frac{\Delta_{\rm gap}}{r_{\rm p}} \simeq 0.87 \left|\frac{\partial \log P}{\partial \log r}\right|_{r_{\rm p}}^{-1/4} {\rm St}^{1/4} \left(\frac{H}{r_{\rm p}}\right)^{-1/2} \left(\frac{M_{\rm p}}{M_\star}\right)^{1/2}$$

- Major features of HL Tau and Elias 24 are well reproduced by assuming the presence of planets with mass in the range [0.1,0.8] M_J