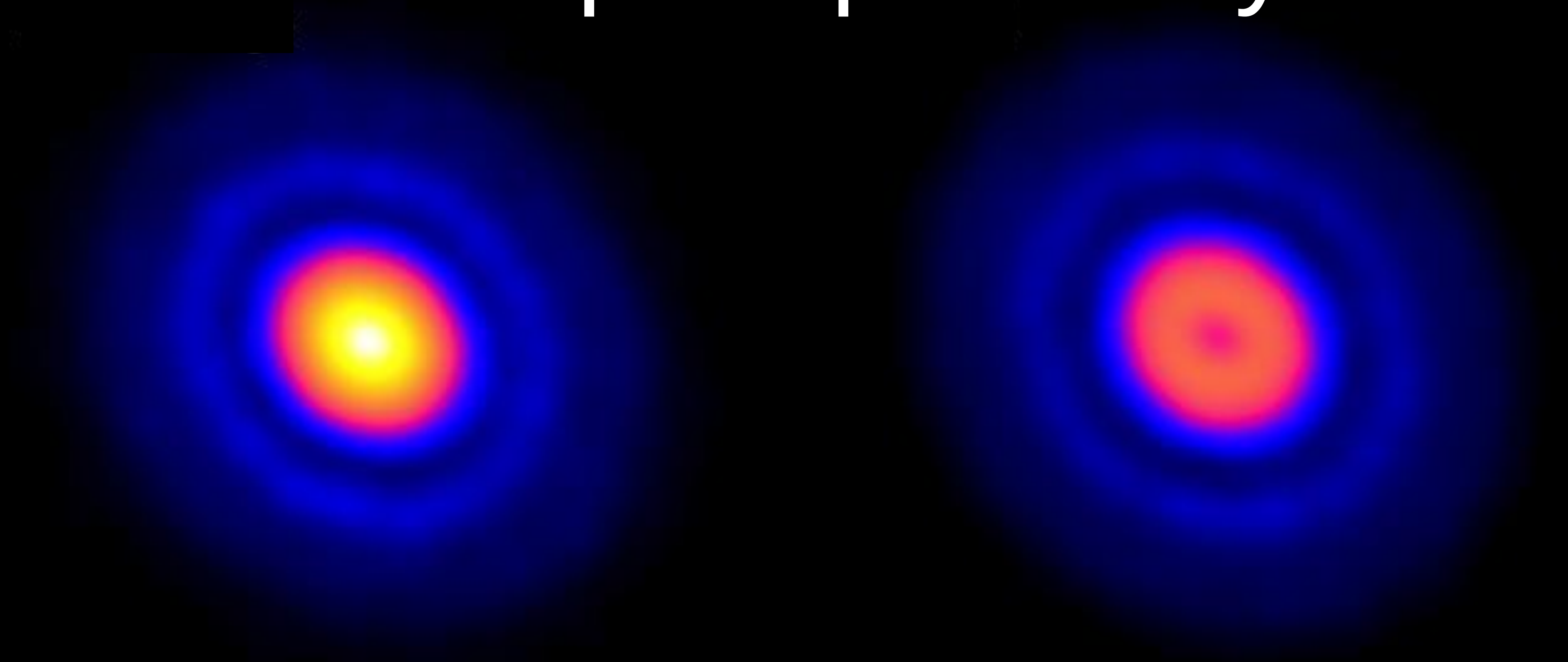
The importance of the dust back-reaction in protoplanetary discs



Richard Alexander

with ***Giovanni Dipierro*** (Leicester), Guillaume Laibe (Lyon), Mark Hutchison (Zürich)

STARRY Conference
Leeds, 18th -21st June 2019

European Research Council
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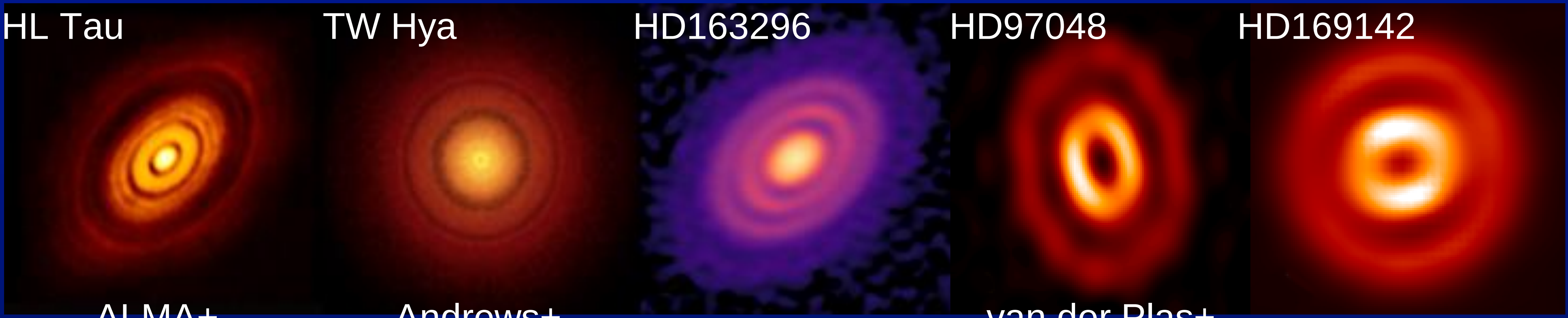
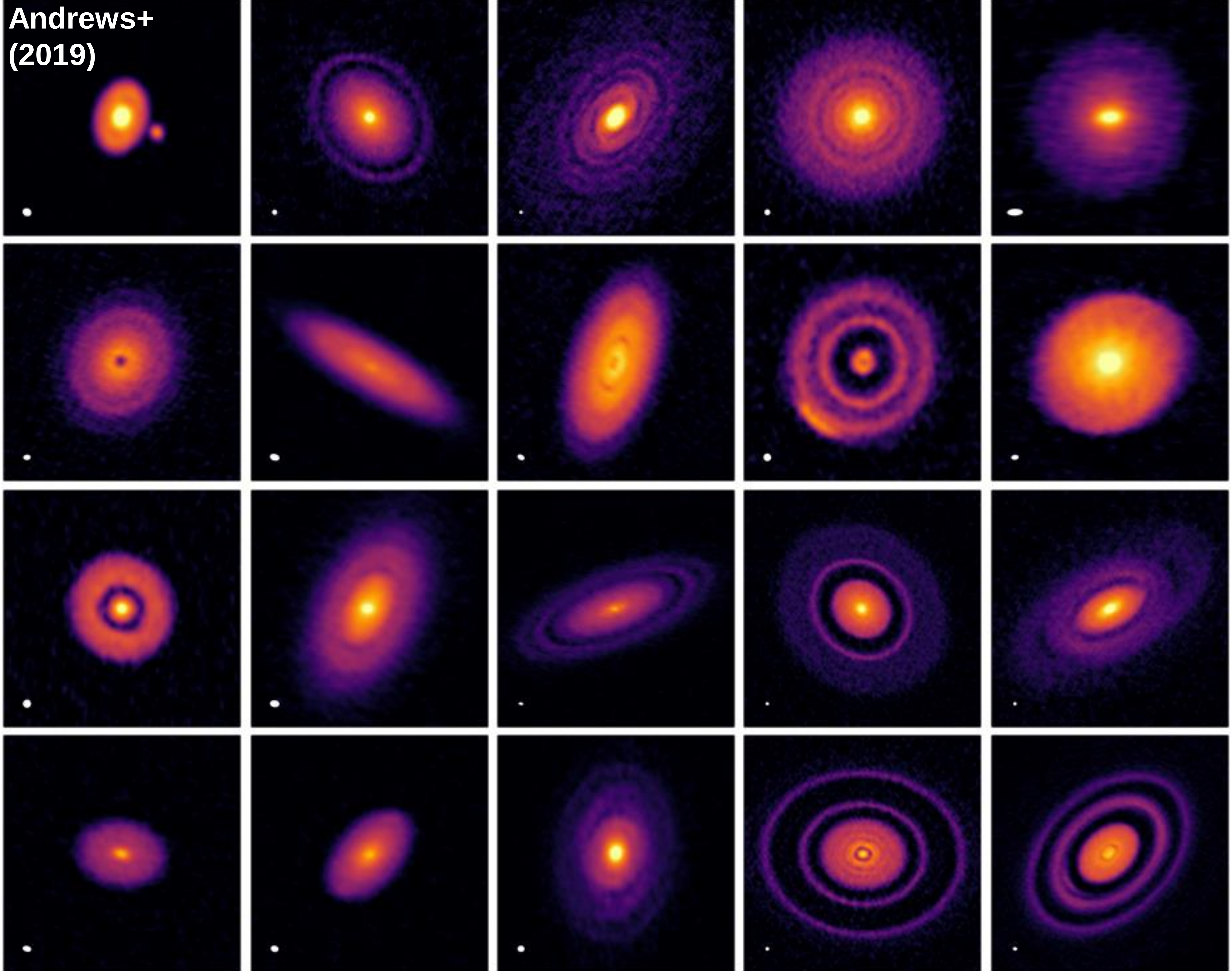
Disc structures are *everywhere*

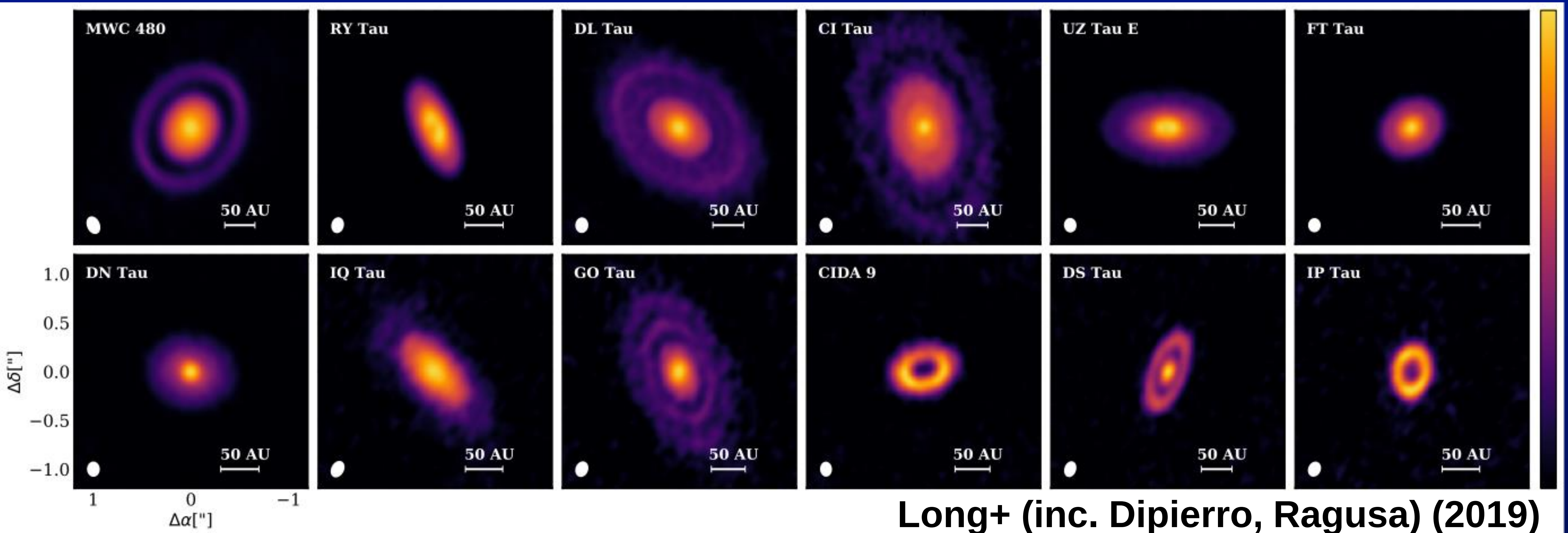


ALMA+ (2015) | Andrews+ (2016) | Isella+ (2017) | van der Plas+ (2017) | Fedele+ (2017)

- We now observe structures (gaps, rings, spirals) in many protoplanetary discs.
- Most of these observations are continuum (IR or mm), where the opacity/emission is dominated by dust.
- Clear evidence for differential dust/gas motion in many discs.


Andrews+
(2019)

Disc structures are ***everywhere***

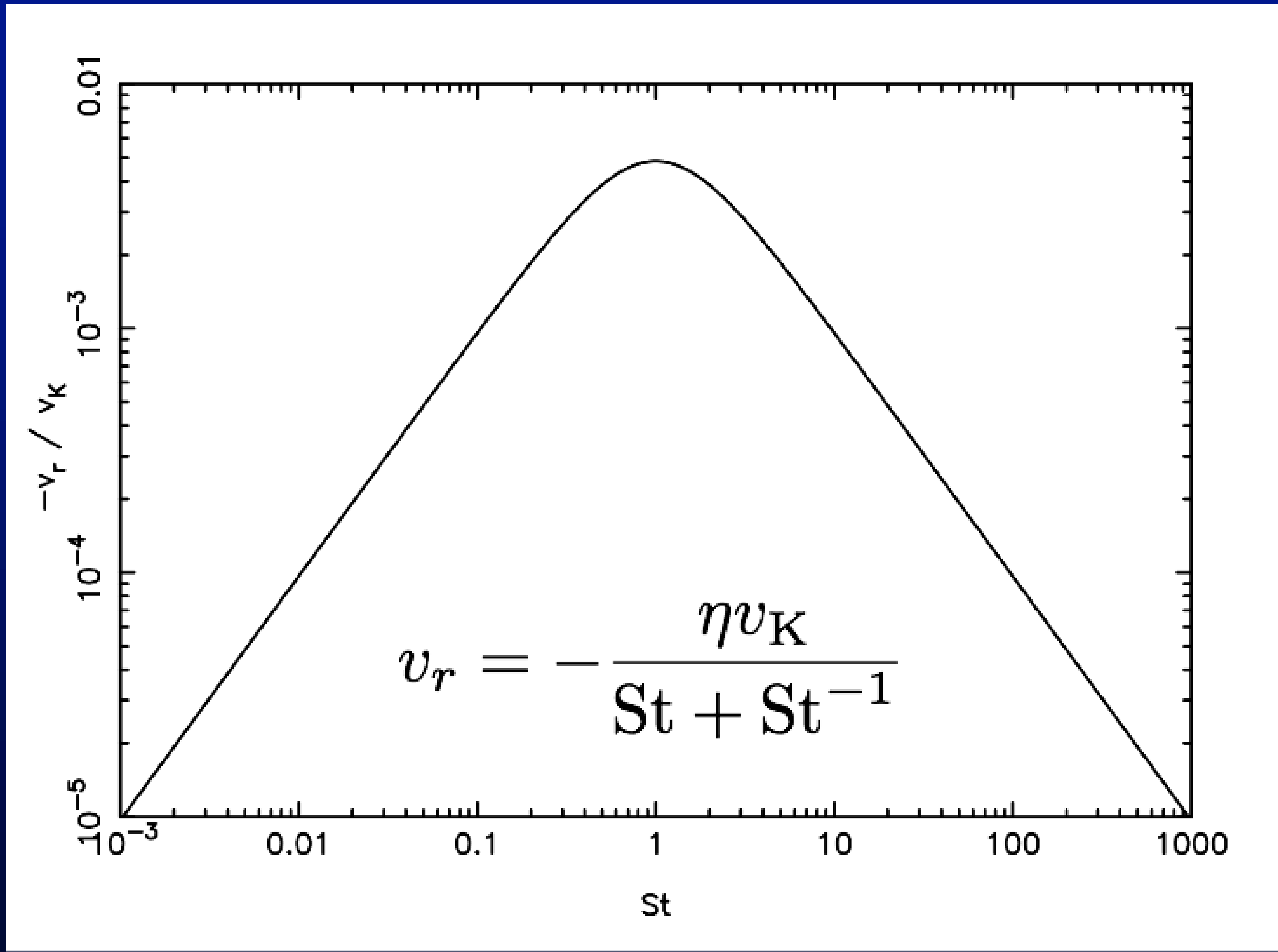


Long+ (inc. Dipierro, Ragusa) (2019)

- Gas data still limited, but increasing evidence that dust-to-gas ratio $\gg 0.01$ over large regions of these discs.
- If dust is not just a trace contaminant, it can have a significant effect on *gas* dynamics.

Dust-gas dynamics recap: radial drift

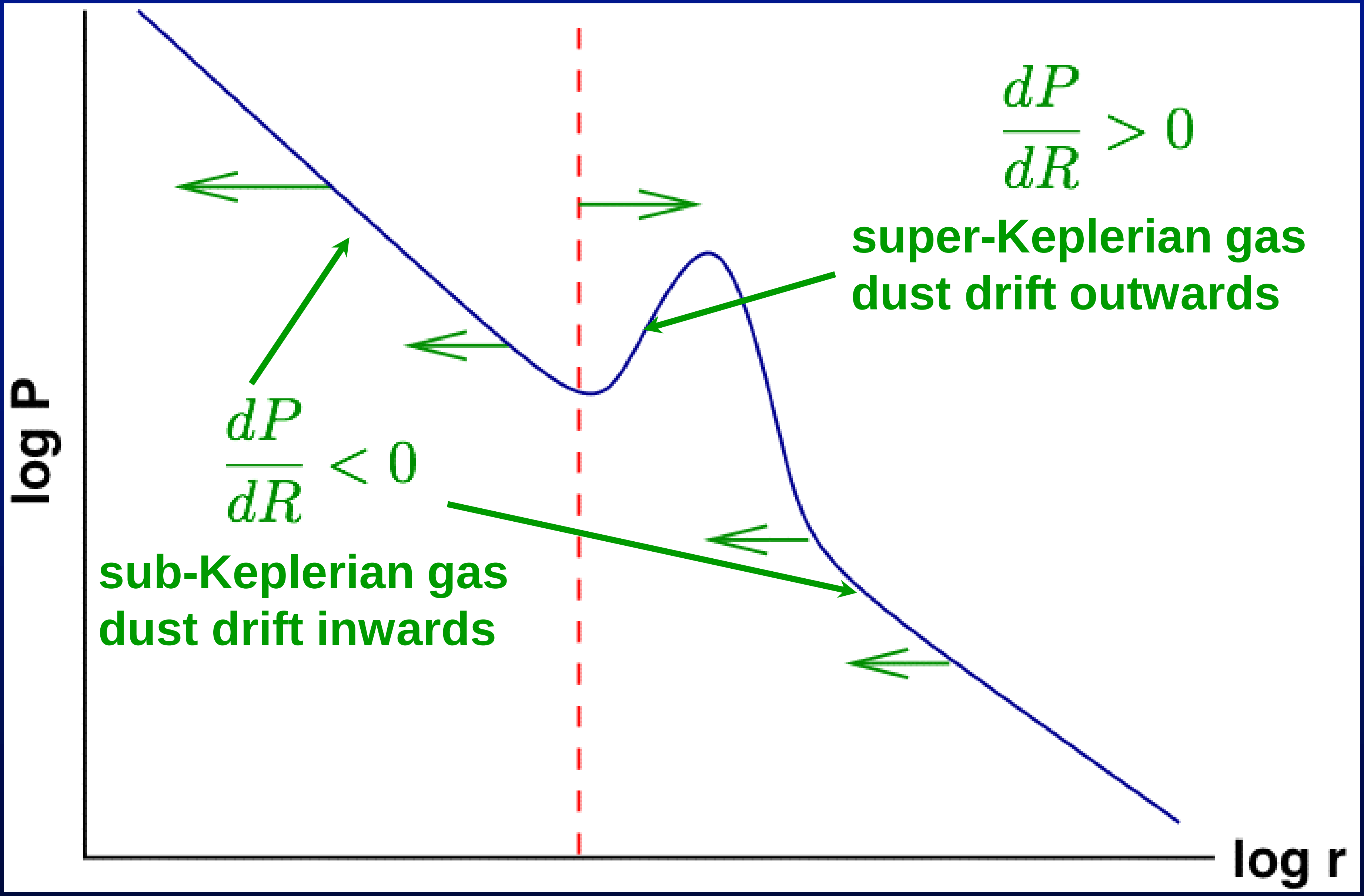
(e.g., Weidenschilling 1977)



- Drag causes dust to “drift” radially towards pressure maxima.
- For particles with St ~ 1, radial drift is fast (few x100 orbits)

Dust-gas dynamics recap: radial drift

(e.g., Weidenschilling 1977)

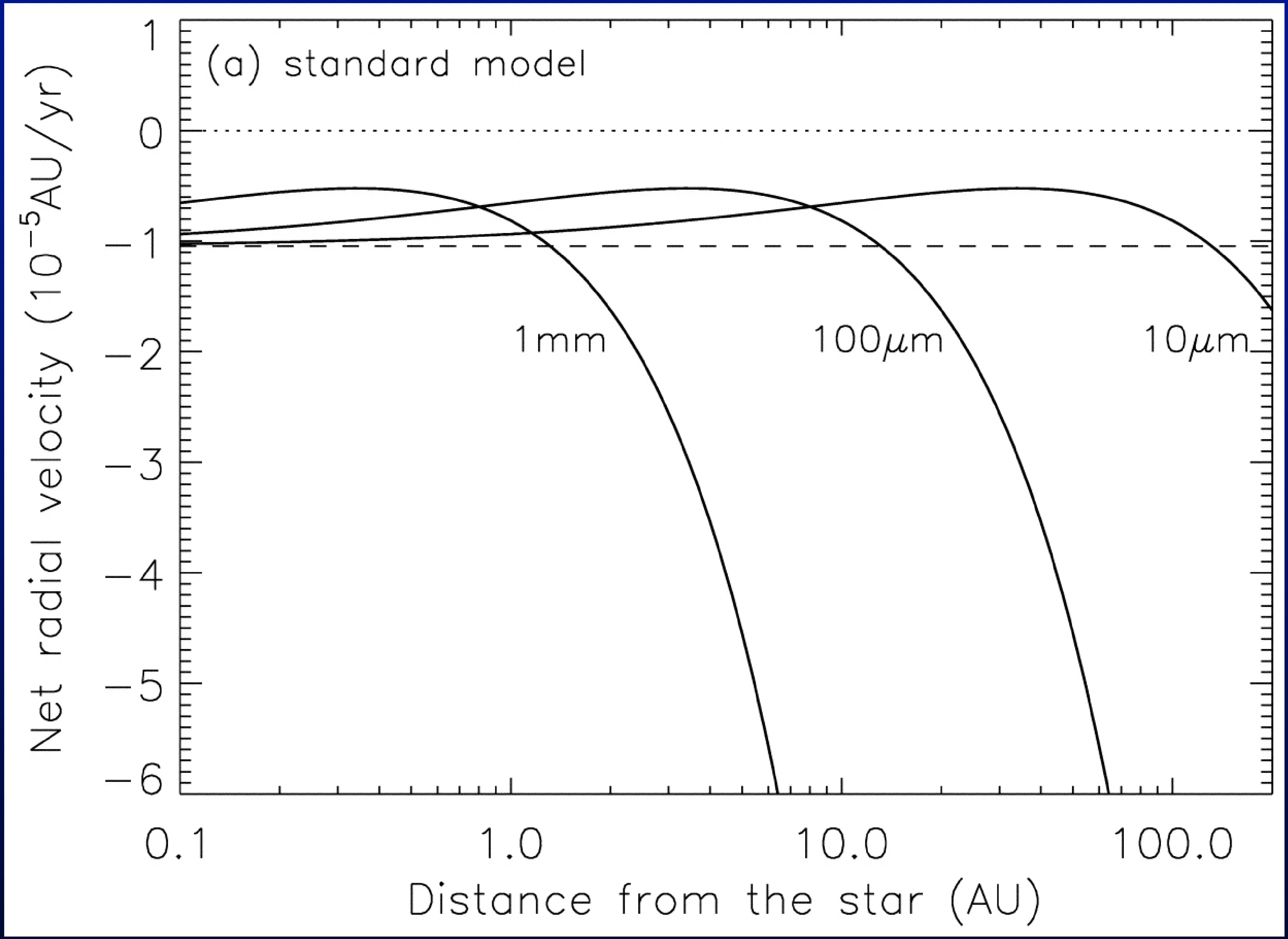


Armitage (2007)

- Drift usually inwards, but can be reversed by disc sub-structures.
- Result is particle “trapping” in local pressure maxima

Dust-gas dynamics recap: radial drift

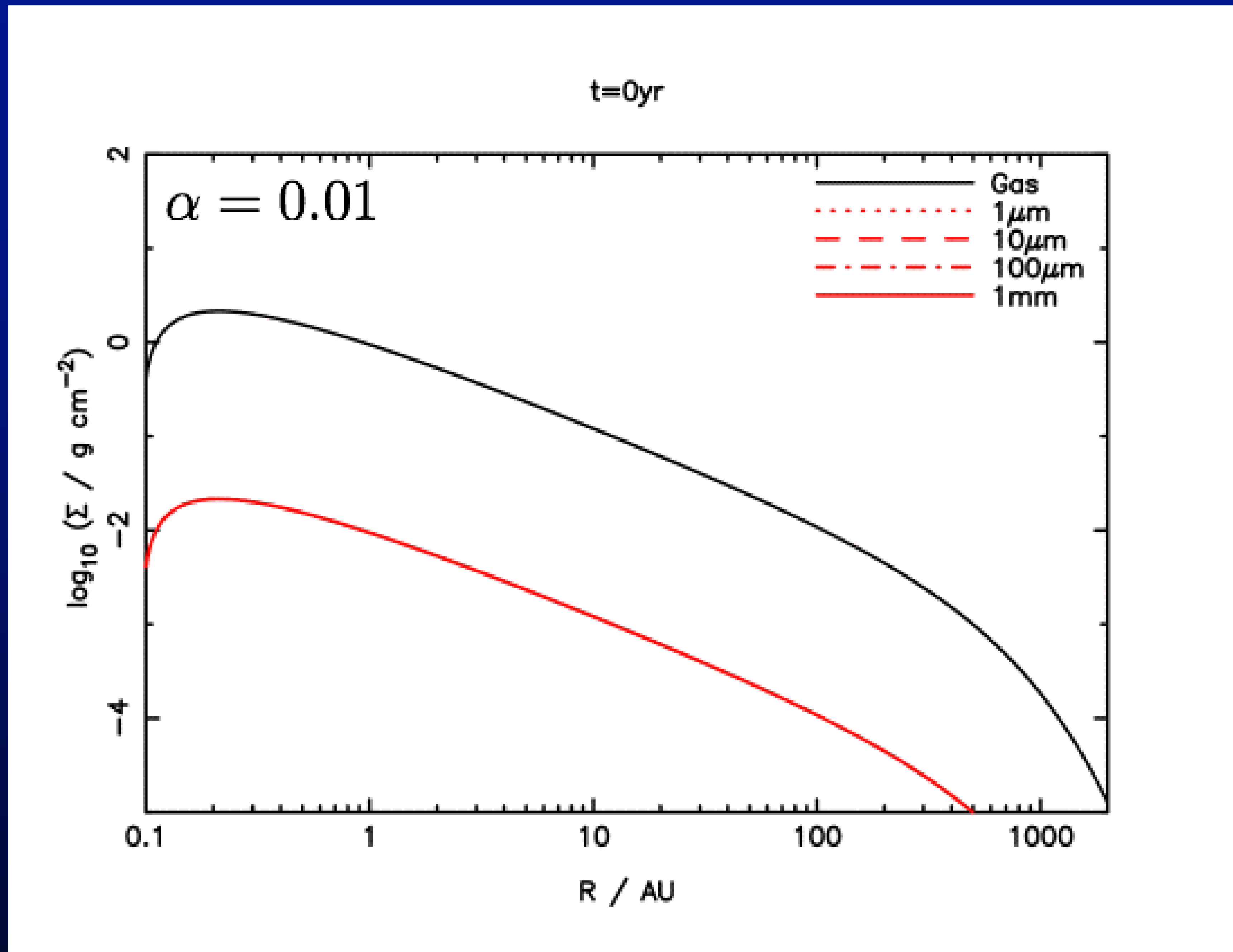
Takeuchi & Lin (2002)



- Secular evolution: “test particle” dust drift in viscous gas discs.
- Particles with St ~ 1 drift inwards rapidly

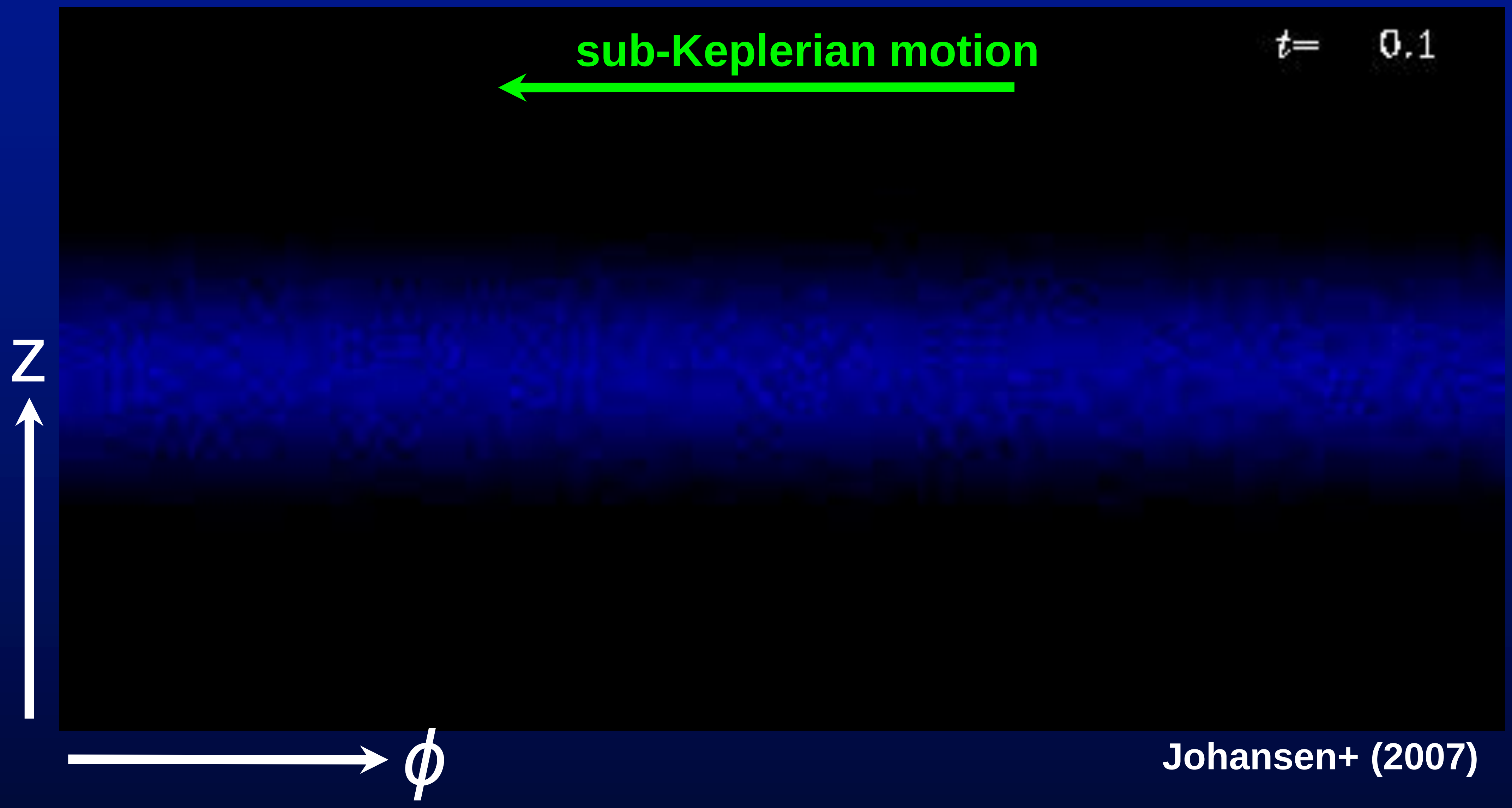
Dust-gas dynamics recap: radial drift

RDA & Armitage (2007)



- Radial drift leads to local enhancements in dust-to-gas ratio.
- "... dust-to-gas ratio becomes large ... model breaks down."

Action and reaction…



Johansen+ (2007)

- Dust “back-reaction” can drive dynamical instabilities.
- But what is the effect on secular time-scales?

That pesky third law…

Dipierro+ (2018b)

Dust drift:

$$v_r = -\frac{\eta v_{\rm K}}{{\rm St} + {\rm St}^{-1}} \simeq -{\rm St}\left(\frac{H}{R}\right)^2 v_{\rm K}$$

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Dipierro+ (2018b)

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$$u_{\mathrm{dust}} = -\epsilon\, v_r \simeq \epsilon\,\mathrm{St}\left(\frac{H}{R}\right)^2 v_{\mathrm{K}}$$

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$$\frac{|u_{\rm dust}|}{|u_{\rm visc}|} \simeq \frac{\epsilon\, {\rm St}}{\alpha}$$

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$$u_{\rm visc} \simeq -\alpha\left(\frac{H}{R}\right)^2 v_{\rm K}$$

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The dust "back-reaction" on the gas can be stronger than the viscous accretion stress.

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Back-reaction:

$$u_{\mathrm{dust}} = -\epsilon\, v_r \simeq \epsilon\, \mathrm{St}\left(\frac{H}{R}\right)^2 v_{\mathrm{K}}$$

Gas accretion:

$$u_{\mathrm{visc}} \simeq -\alpha\left(\frac{H}{R}\right)^2 v_{\mathrm{K}}$$

$$\frac{|u_{\mathrm{dust}}|}{|u_{\mathrm{visc}}|} \simeq \frac{\epsilon\, \mathrm{St}}{\alpha}$$

DSHARP survey (Dullemond+) measured values of St/α in the range ~1–30, in regions with $\epsilon \gg 0.01$ …

Dust-gas dynamics revisited…

Dipierro+ (2018b)

arXiv:1806.10148

Fully-coupled gas-dust dynamics

Dipierro+ (2018b)

$$\frac{\partial u_r}{\partial t} = \sum_i \frac{K_i}{\rho_{\rm g}}(v_{i,r} - u_r) - \frac{1}{\rho_{\rm g}}\frac{\partial P}{\partial r} + 2\Omega_{\rm k} u_\phi$$

$$\frac{\partial u_\phi}{\partial t} = \sum_i \frac{K_i}{\rho_{\rm g}}(v_{i,\phi} - u_\phi) - \frac{\Omega_{\rm k}}{2} u_r + \frac{1}{\rho_{\rm g}} \nabla \cdot \sigma|_\phi$$

Gas

$$\frac{\partial v_{i,r}}{\partial t} = -\frac{K_i}{\rho_{{\rm d},i}}(v_{i,r} - u_r) + 2\Omega_{\rm k} v_{i,\phi}$$

$$\frac{\partial v_{i,\phi}}{\partial t} = -\frac{K_i}{\rho_{{\rm d},i}}(v_{i,\phi} - u_\phi) - \frac{\Omega_{\rm k}}{2} v_{i,r}$$

Dust

Fully-coupled gas-dust dynamics

Dipierro+ (2018b)

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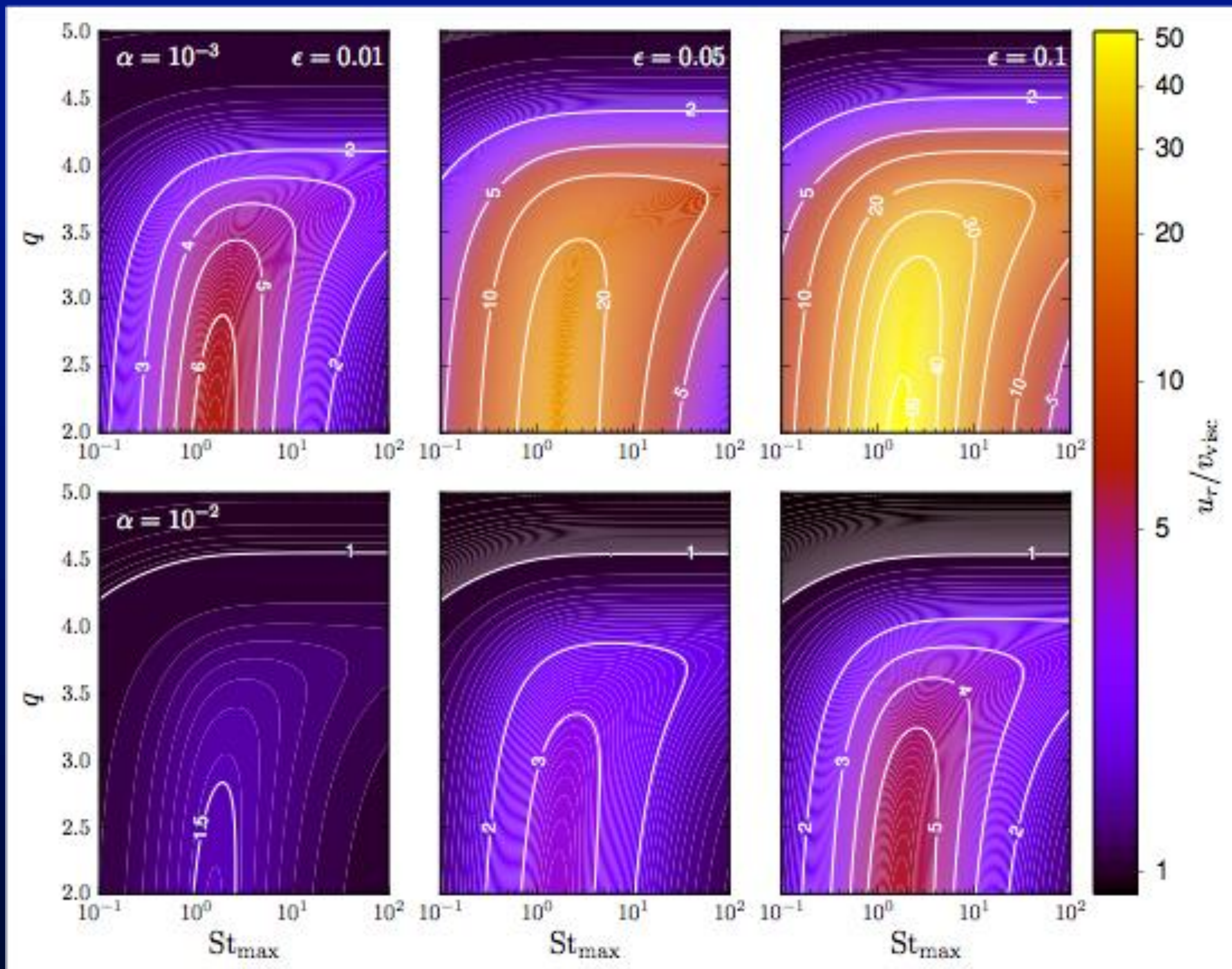
$$\frac{\partial v_{i,\phi}}{\partial t} = -\frac{K_i}{\rho_{{\rm d},i}}(v_{i,\phi} - u_\phi) - \frac{\Omega_{\rm k}}{2} v_{i,r}$$

Dust

Assume a power-law grain size distribution, and compute steady-state solutions for gas + entire dust distribution.

Fully-coupled gas-dust dynamics

Dipierro+ (2018b)



Viscosity - α

d/g ratio - ϵ

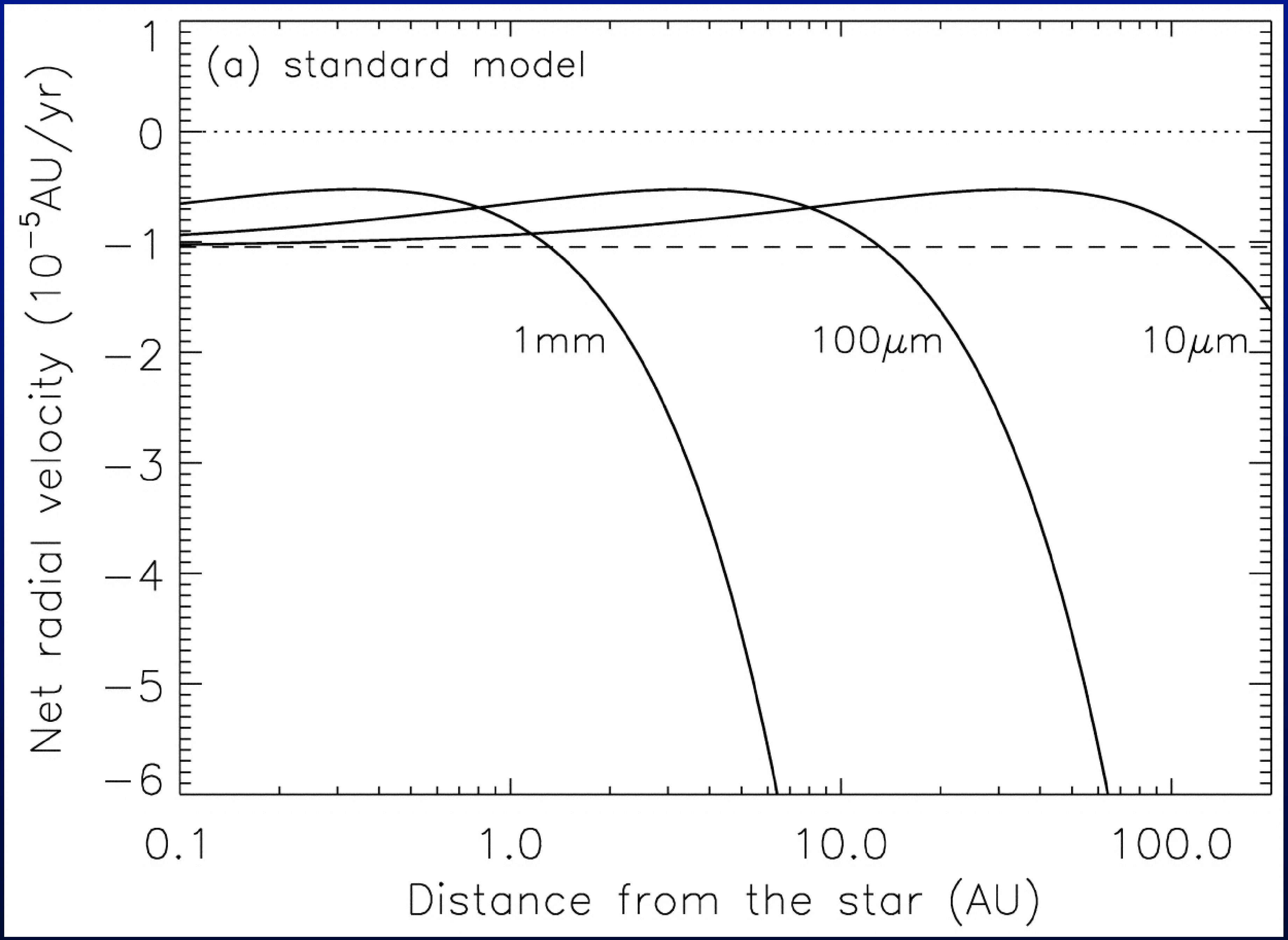
Size distrib. -

$$\frac{\mathrm{d}n}{\mathrm{d}s} \propto \left(\frac{s}{s_{\max}} \right)^{-q}$$

- Back-reaction dominates for low viscosity or high dust/gas ratio.
- Significant effect on gas dynamics even for “normal”

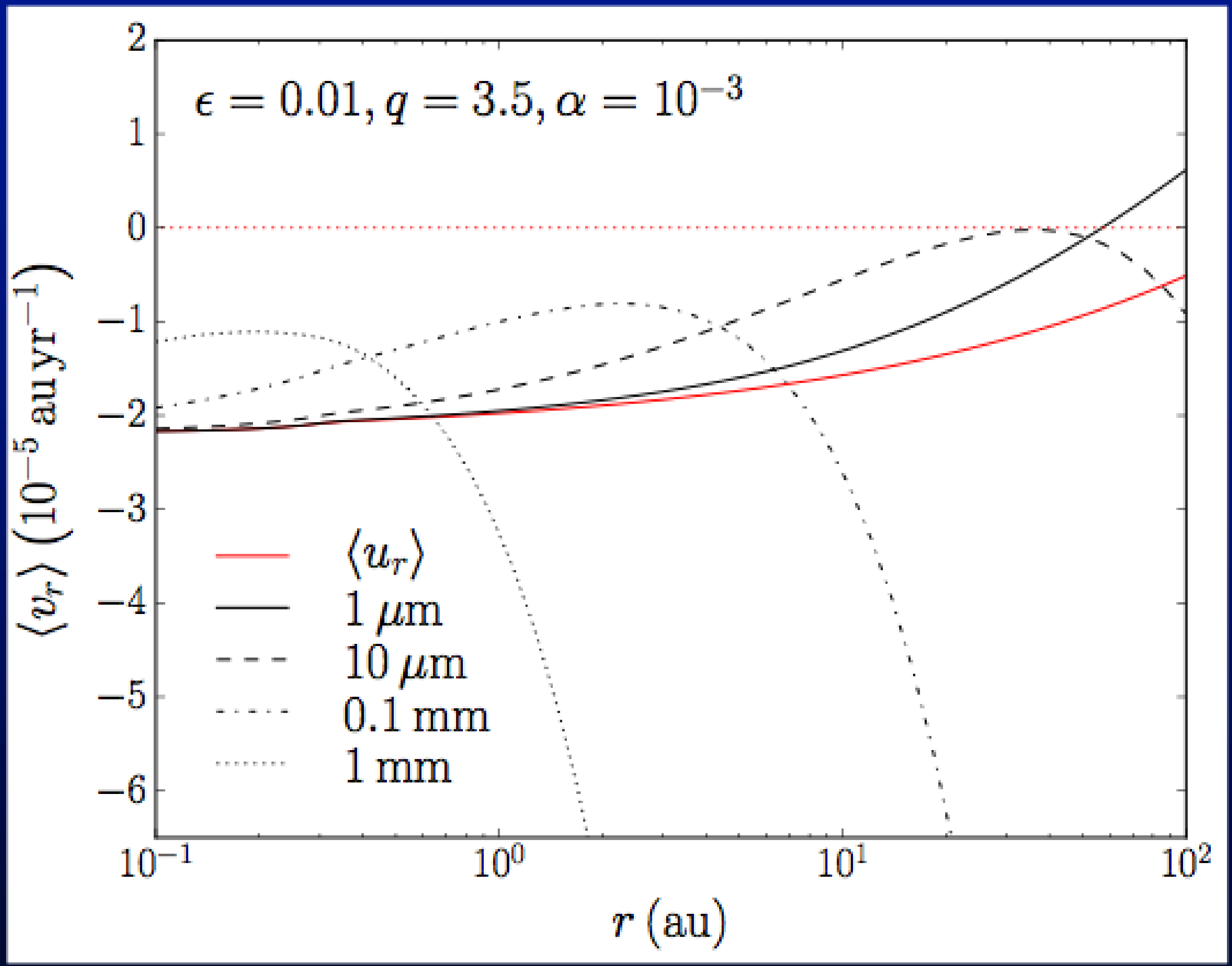
No back-reaction

Takeuchi & Lin (2002)



With back-reaction

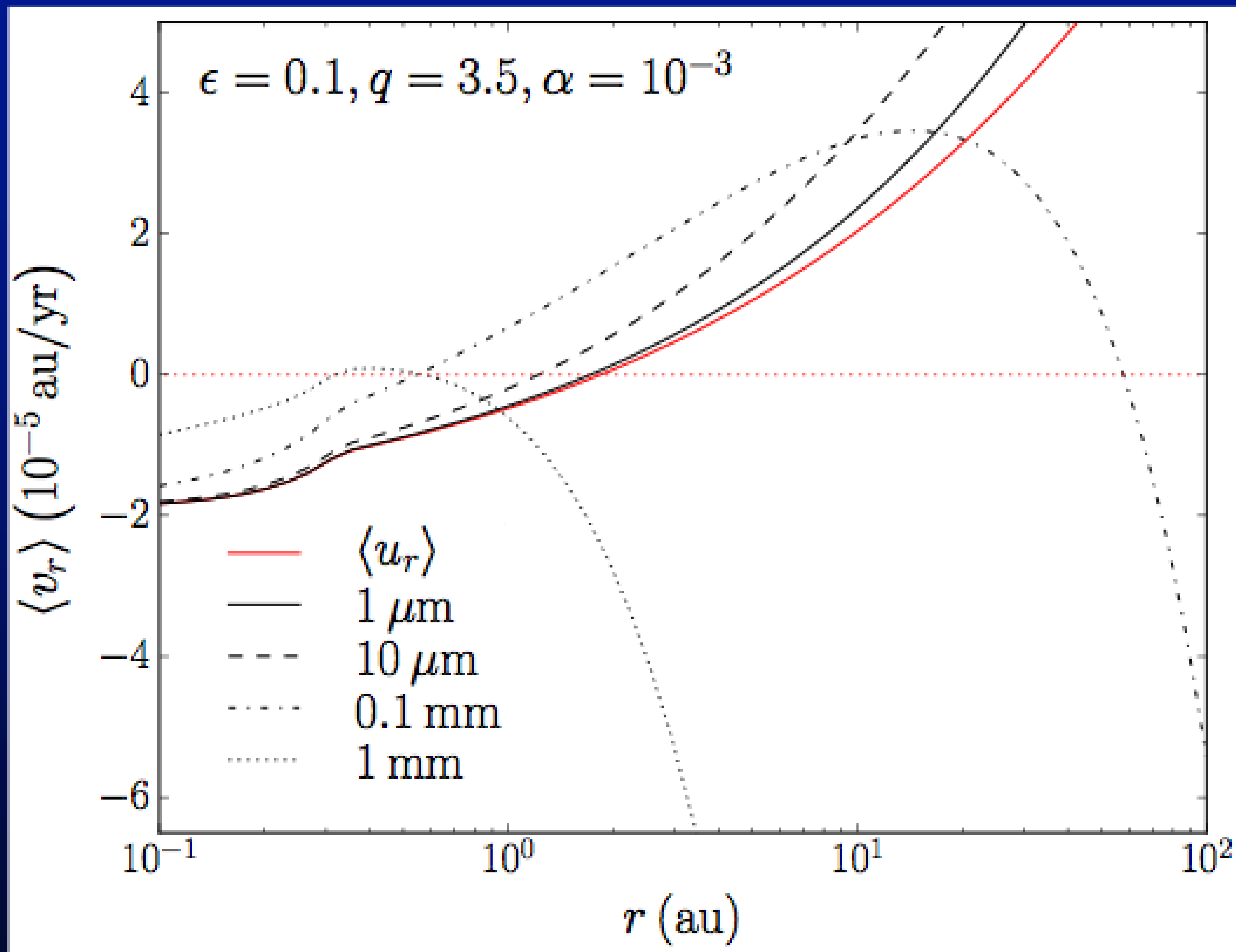
Dipierro+ (2018b)



- Back-reaction changes gas flow even in “typical” disc models.
- If $\epsilon \gtrsim 0.05$ the gas velocity in the outer disc is *outwards*

With back-reaction

Dipierro+ (2018b)



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Summary

Dipierro+ (2018b)

- First self-consistent models of coupled dust-gas dynamics to include back-reaction for multiple species in viscous discs.
- Results with distribution of grain sizes differ significantly from single-size models (Kanagawa+ 2017).
- Back-reaction affects the gas dynamics strongly even for canonical disc parameters.
- For low viscosity and/or increased dust-to-gas ratio, the dust back-reaction completely dominates the radial motion of gas.
- Differential motions can create structures in outer disc.