Toroidal vortices and the conglomeration of dust into rings in protoplanetary discs

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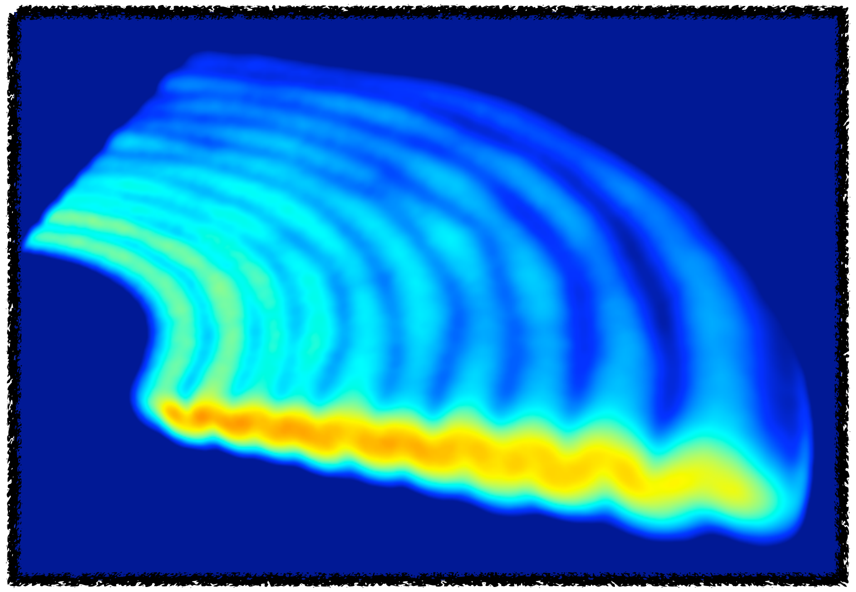

UKEXOM 2016, Exeter

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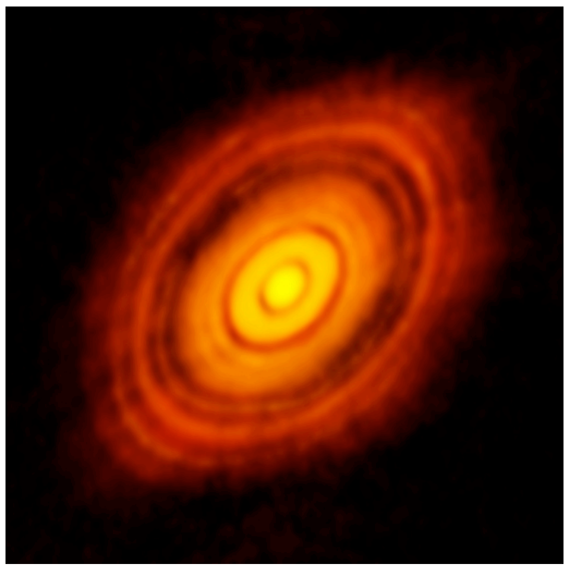
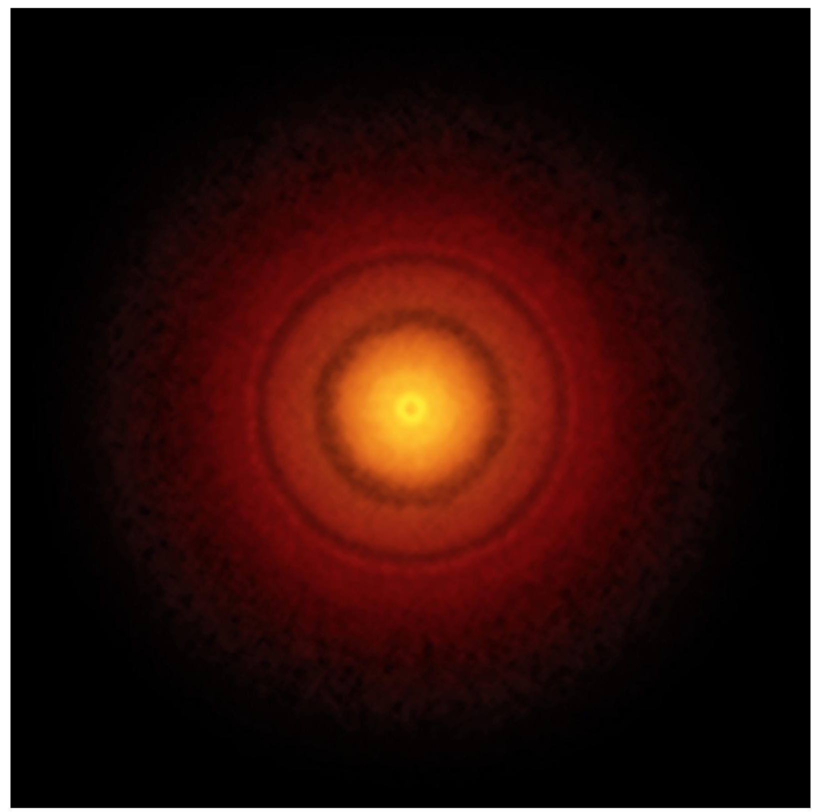
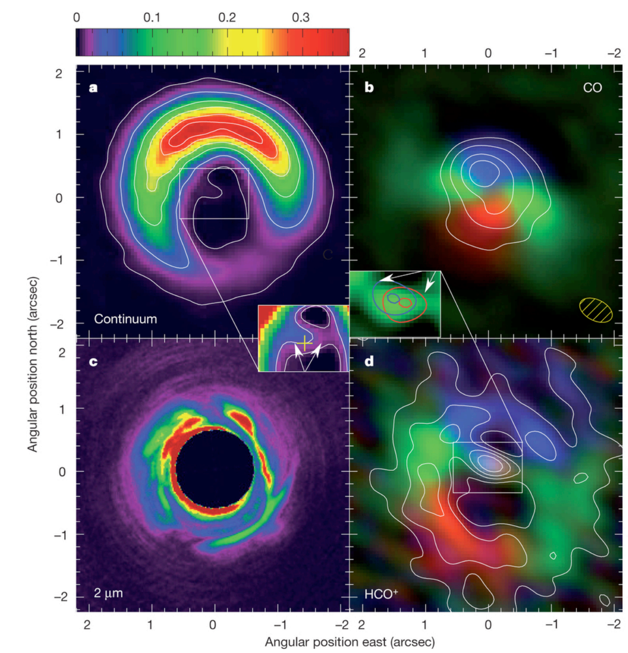
Toroidal vortices in protoplanetary discs



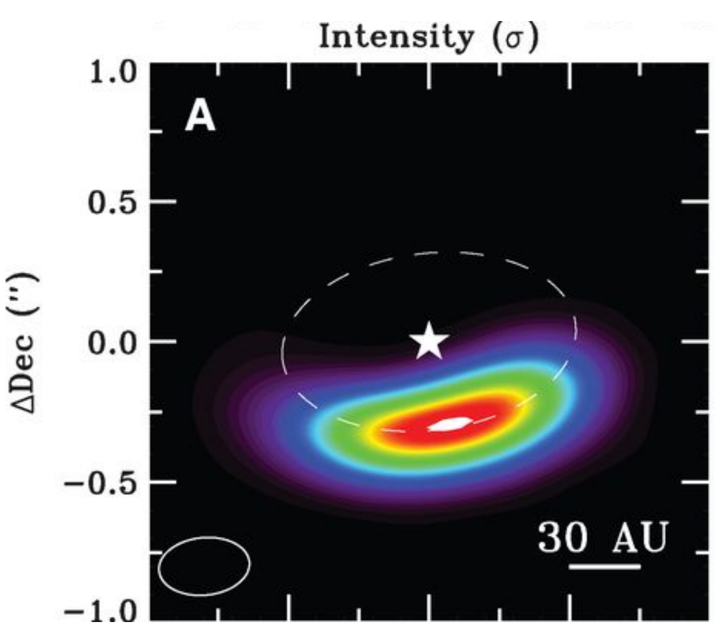
Credit: ALMA (ESO/NAOJ/NRAO)

Credit: S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)



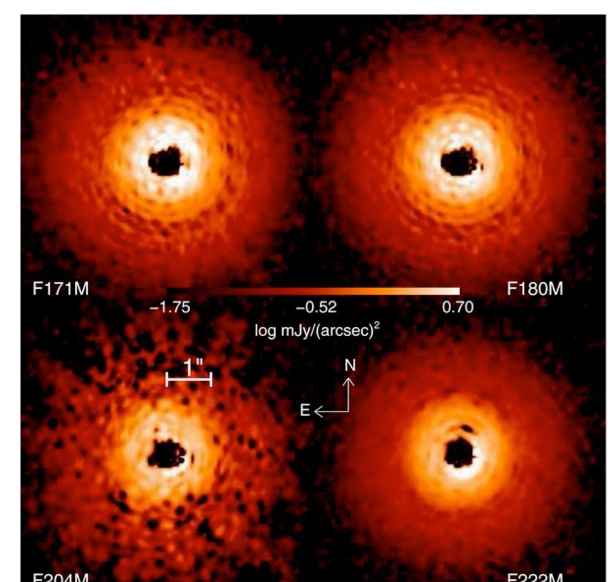


Cassasus et al., Nature, 2013, **493**, 191-194



van der Marel et al., Science, 2013, **340**, 1199

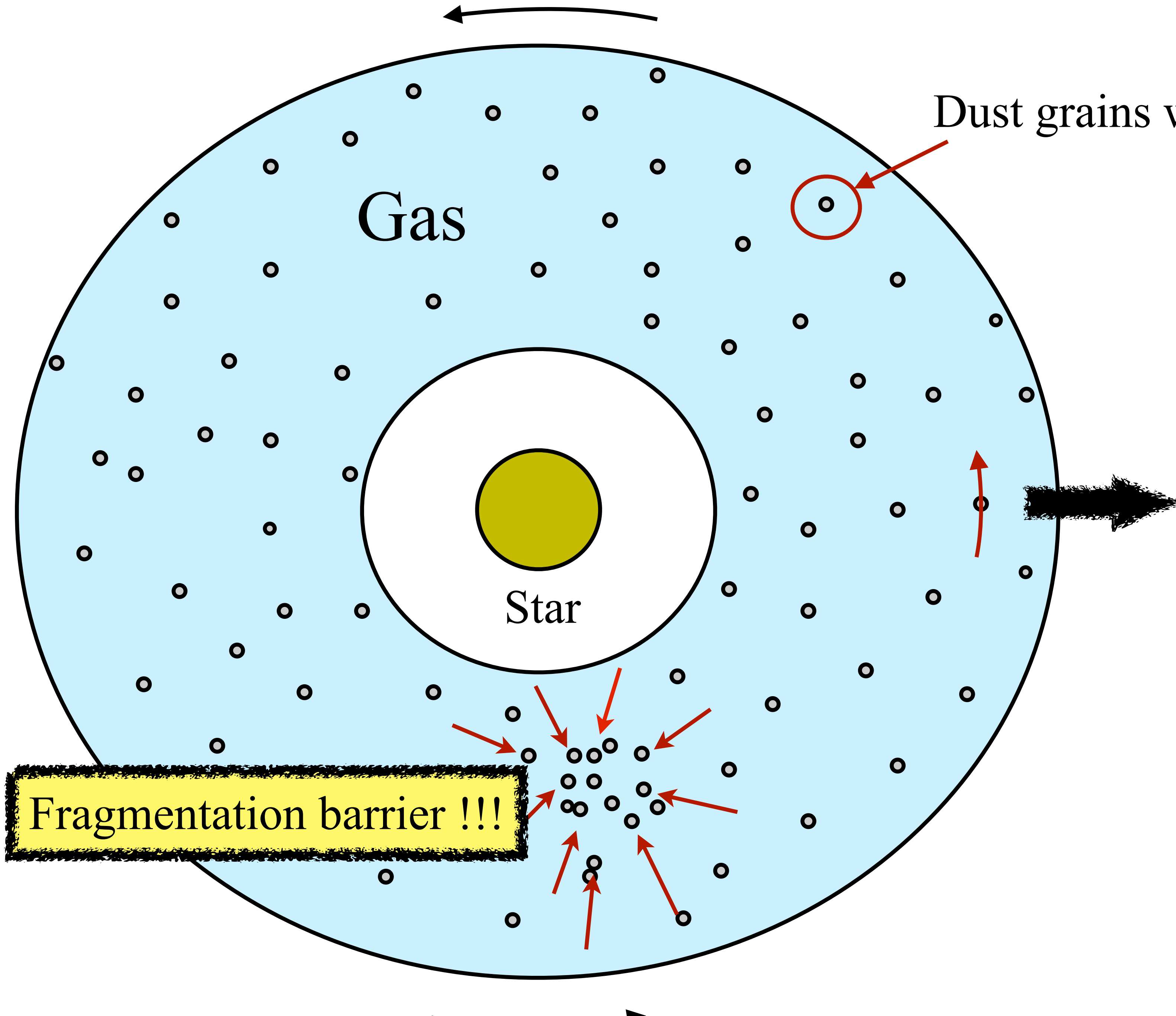
Planets everywhere...
Maybe, but how?



Debes et al., ApJ, 2013, **771**, 45

Toroidal vortices in protoplanetary discs

Gas orbits the star at a sub-Keplerian velocity due to partial support by pressure.



Dust grains with typical sizes: $s \sim \mu\text{m} \rightarrow \text{cm}$

Solids "want" to orbit at the Keplerian velocity. Dust suffers an aerodynamical drag.

$$\vec{F}_{\rm drag} \sim -\frac{\vec{v}_{\rm DG}}{t_{\rm s}}$$

Migration !!!

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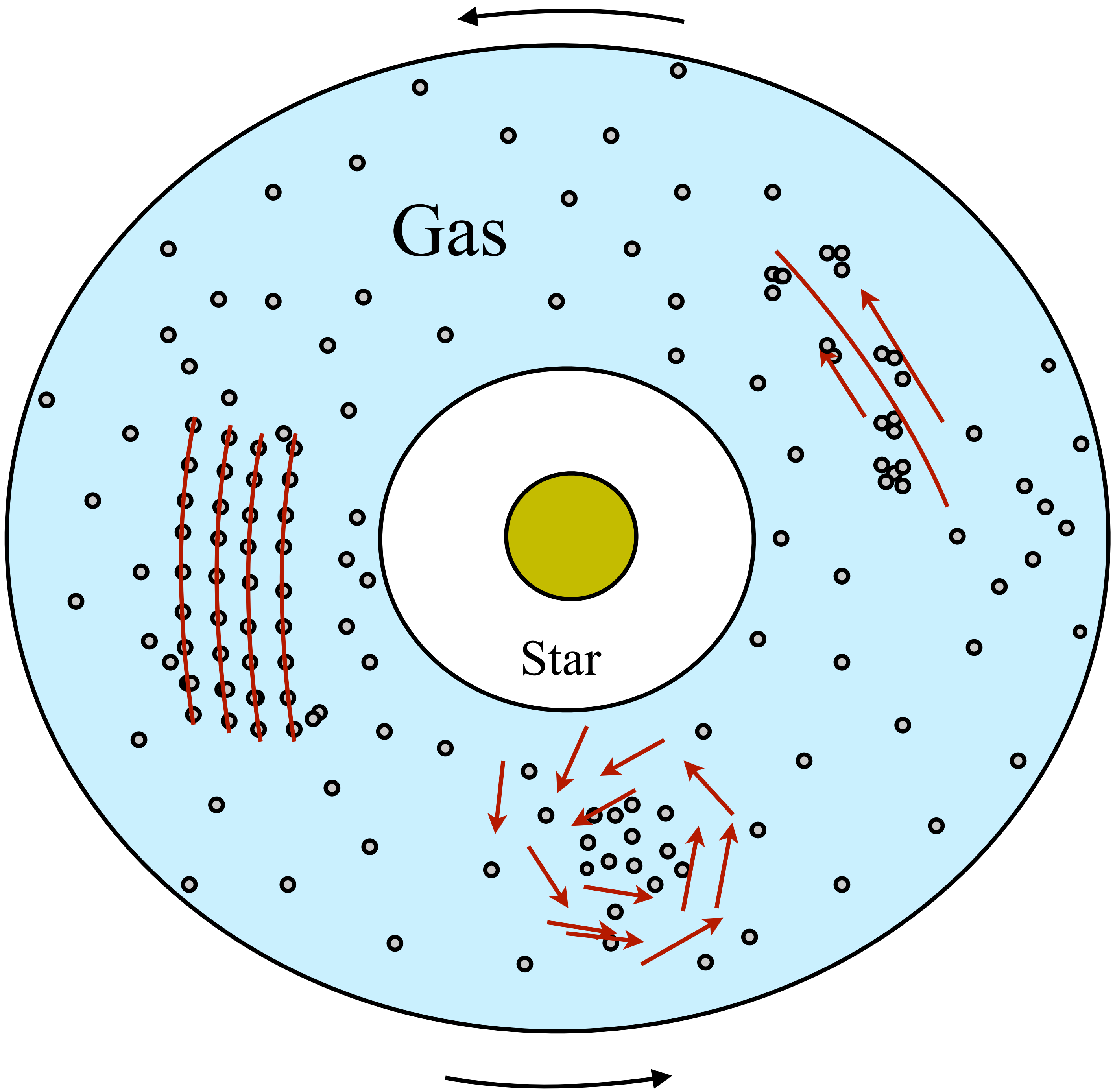
Toroidal vortices in protoplanetary discs



Dust traps

Baroclinic instability
(Klahr & Bodenheimer 2003)

Streaming instability
(Youdin & Goodman 2005)

Fotoelectric instability
(Lyra & Kuchner 2013)

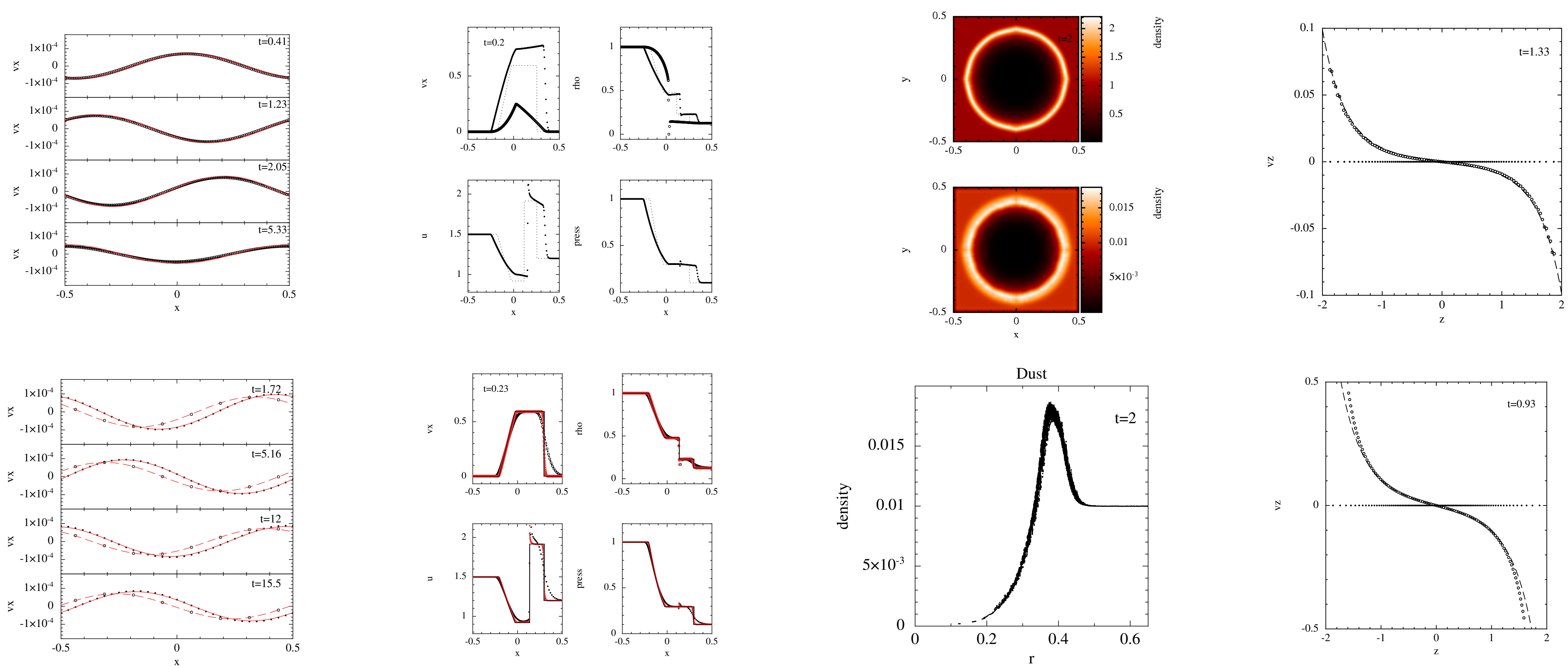
Gravitational instability
(Cameron 1978)

Self-induced dust traps
(Gonzalez et al. 2015)

Toroidal vortices
(Lorén-Aguilar & Bate 2015)

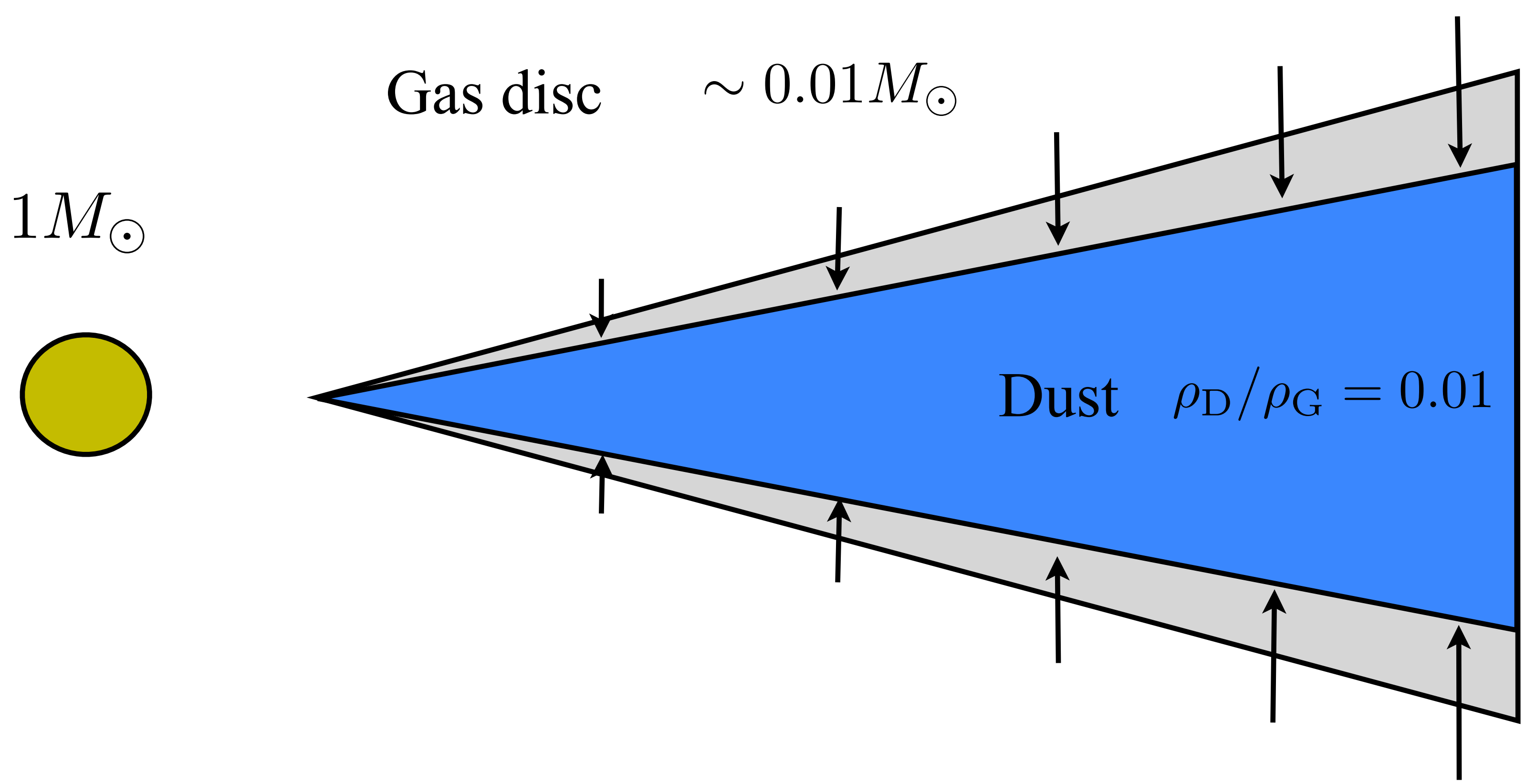
Toroidal vortices in protoplanetary discs

- In 2014 we started investigating a new numerical method (Loren-Aguilar & Bate 2014, Booth, Sijacki & Clarke 2015, Loren-Aguilar & Bate 2015) to follow the evolution of small dust grains in the SPH two-fluid scheme (Monaghan & Kocharian 1995, Monaghan 1997, Laibe & Price 2012)



Loren-Aguilar & Bate 2014

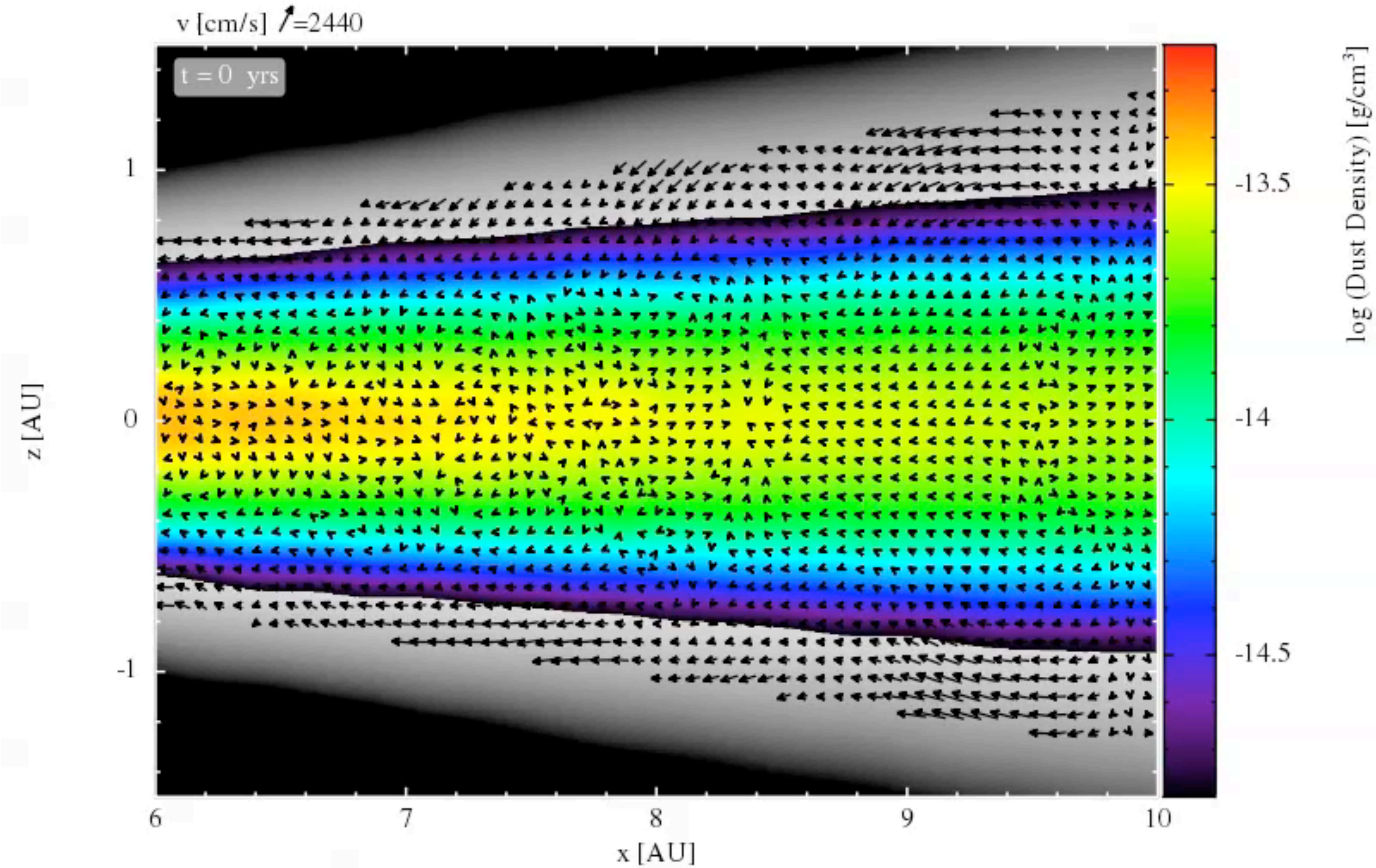
- After testing the method we starting investigating the settling and radial migration of dust grains in a protoplanetary disc.



Locally isothermal EOS => $P = c_s^2(R)\rho_{gas}(R, Z)$

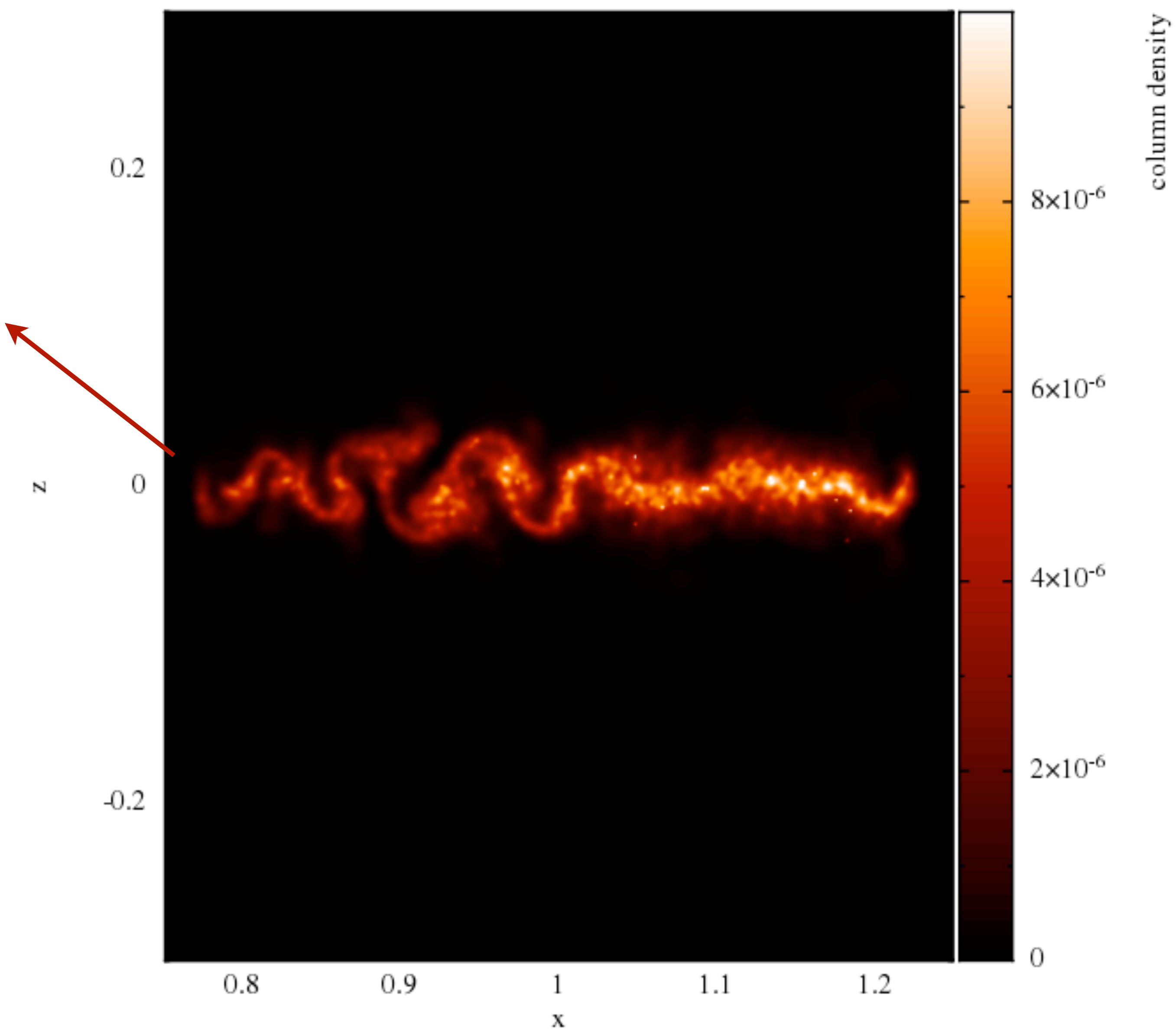
Toroidal vortices in protoplanetary discs

Pablo Lorén-Aguilar & Matthew R. Bate, MNRAS Letters, 2015, **453**, L78



- The possibility of a numerical error was our first concern, so we tested the scenario against standard integration methods, dust-to-gas ratios or resolutions.

High resolution simulations using standard explicit integration methods produce the same result.



Toroidal vortices in protoplanetary discs

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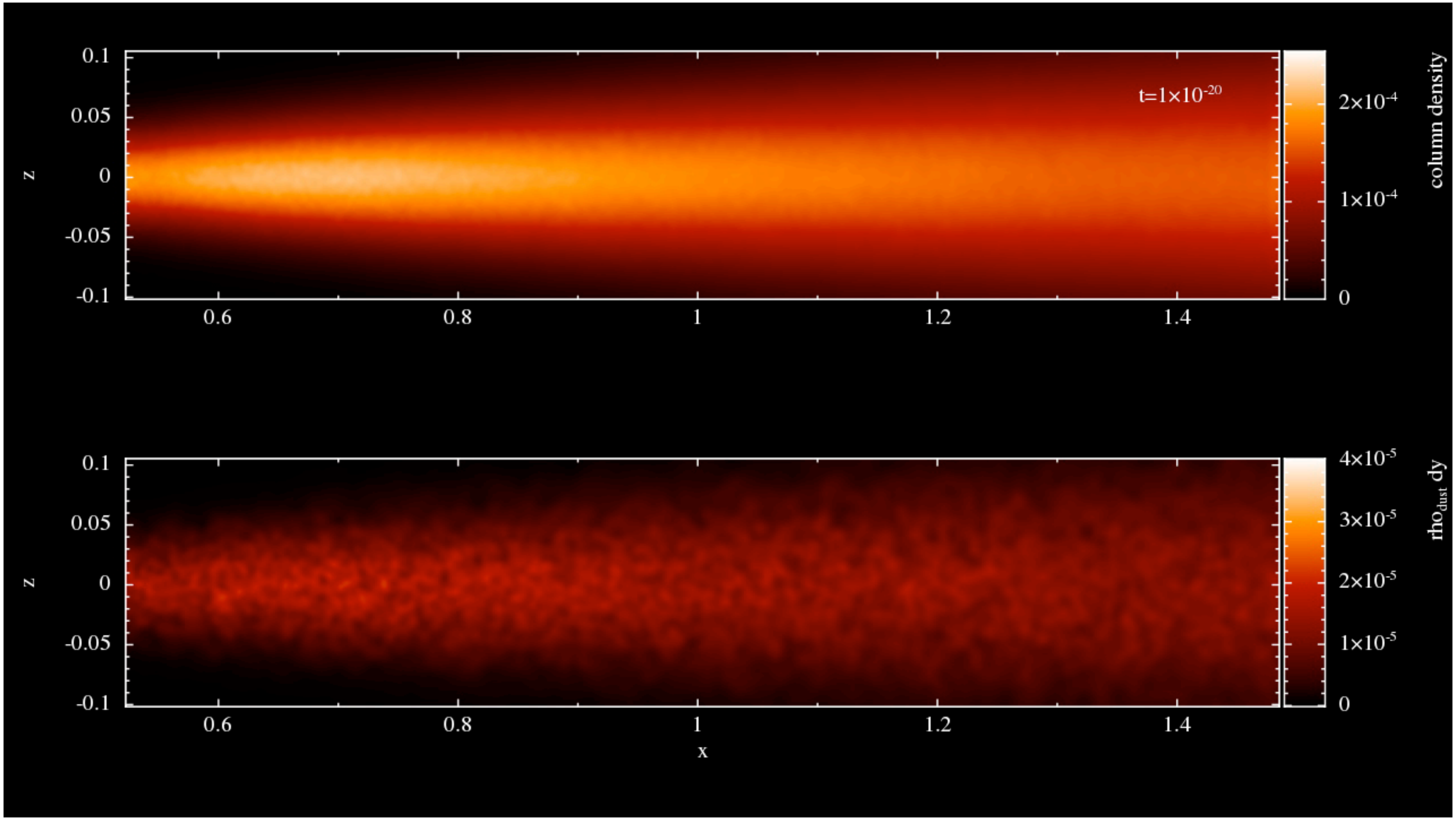
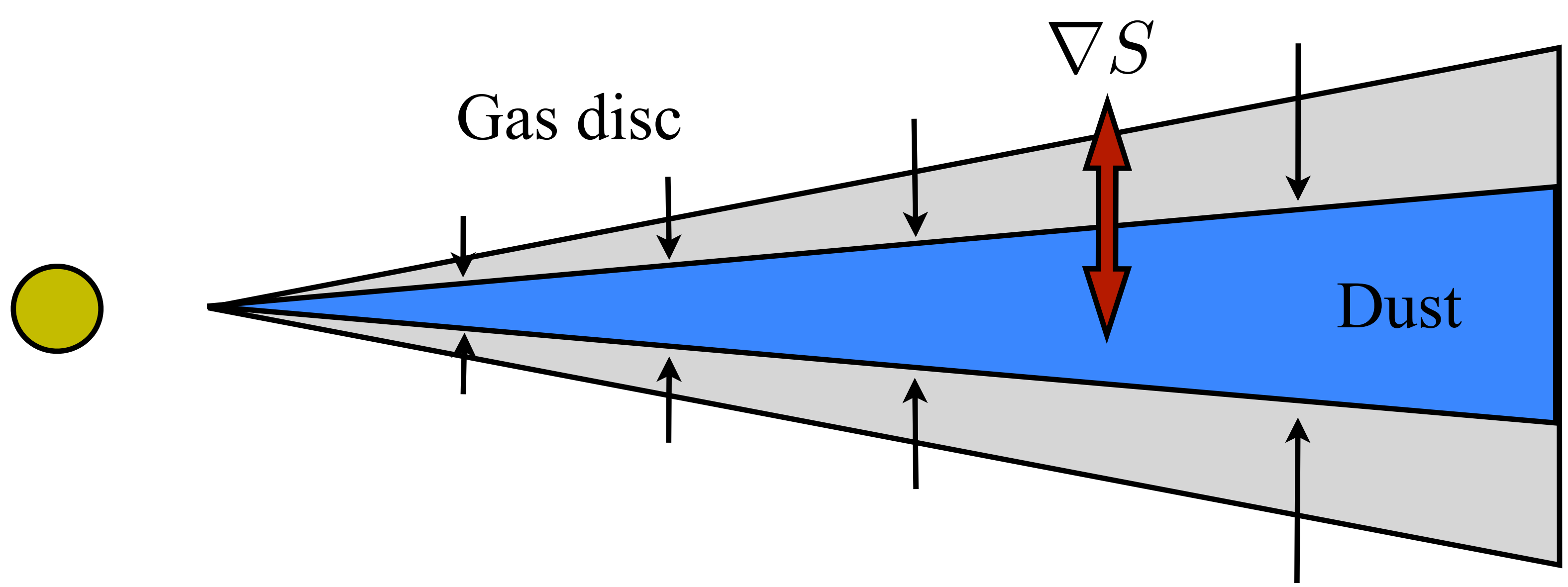


- One can illustrate one possible consequence of the presence of dust by analysing the classical Solberg-Høiland stability criteria for a disc.



$$|\nabla S| \simeq \frac{\partial S}{\partial z} = c_{\rm v}\frac{\partial}{\partial z}\log\left(P/\rho_{\rm gas}^{\gamma}\right) = c_{\rm v}\frac{\partial}{\partial z}\log\left(\frac{P}{\rho^{\gamma}}(1+\epsilon)^{\gamma}\right)$$
$$= -\gamma c_{\rm v}\left[\gamma\Delta\nabla g_{\rm z}/c_{\rm s}^2 - \frac{\partial}{\partial z}\log(1+\epsilon)\right]$$

If St <<1 the gas+dust can be approximately considered as a single "heavy" fluid.

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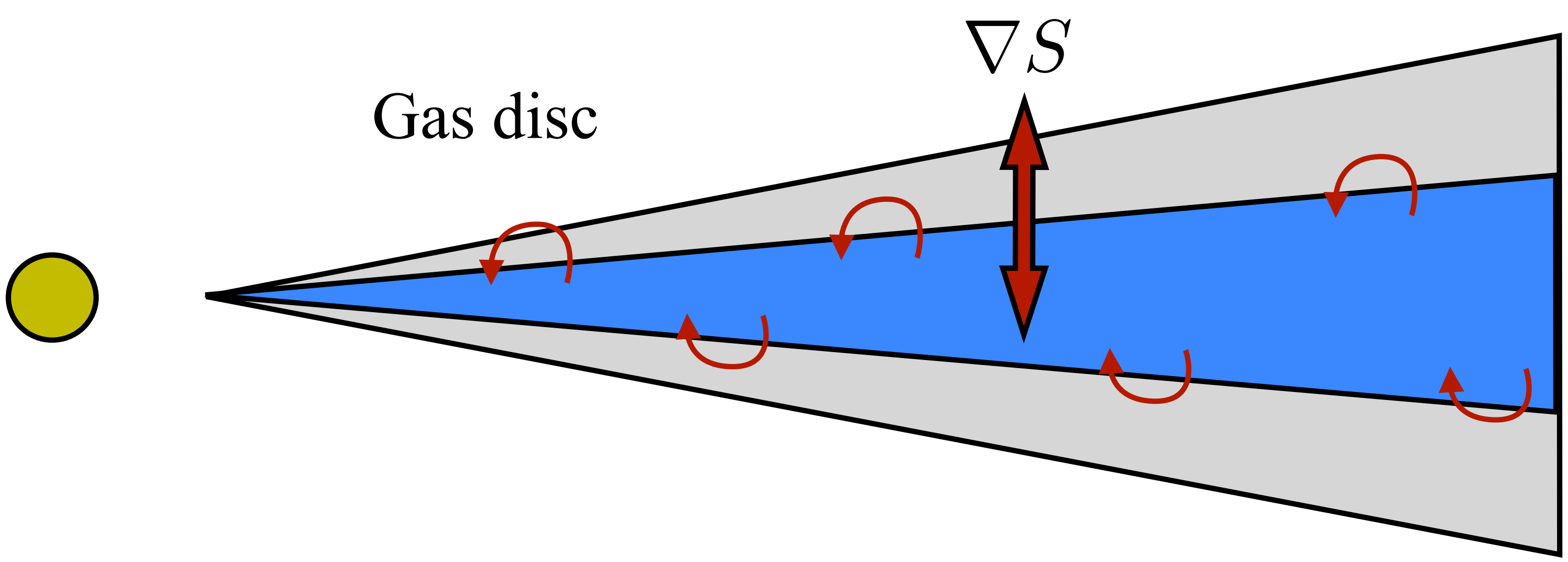

If the entropy gradient is strong enough, disc stability is no longer granted:

$$\frac{1}{r^3}\frac{\partial j^2}{\partial r} - \frac{1}{c_{\mathrm{p}}\rho}\nabla P \cdot \nabla S > 0$$

$$\partial S/\partial z > 0$$

$$\Longrightarrow$$

$$\left|\frac{\partial \epsilon}{\partial z}\right| \gtrsim \frac{z}{H^2}(1+\epsilon)\left[\gamma \Delta\nabla + \left(\frac{H}{z}\right)^2\right]$$

$$\frac{\partial \epsilon}{\partial z} < 0$$

- Another possible source of instability can be obtained by considering (as suggested by Richard Nelson) the impact of the presence of dust in the classical Vertical Shear Instability (Goldreich & Schubert 1967, Fricke 1968, Nelson, Gressel & Umurhan 2013)

$$\frac{\partial j^2}{\partial R} - \frac{k_{\rm R}}{k_{\rm Z}} \frac{\partial j^2}{\partial Z} < 0$$

$$\frac{\partial j}{\partial Z} \approx q \left(\frac{H}{R} \right) \frac{\partial j}{\partial R} \implies \frac{k_{\rm R}}{k_{\rm Z}} > \frac{1}{q} \left(\frac{R}{H} \right)$$

$$c_{\rm s}(R) = c_0 \left(\frac{R}{R_0} \right)^q$$

But if dust is present, this changes...

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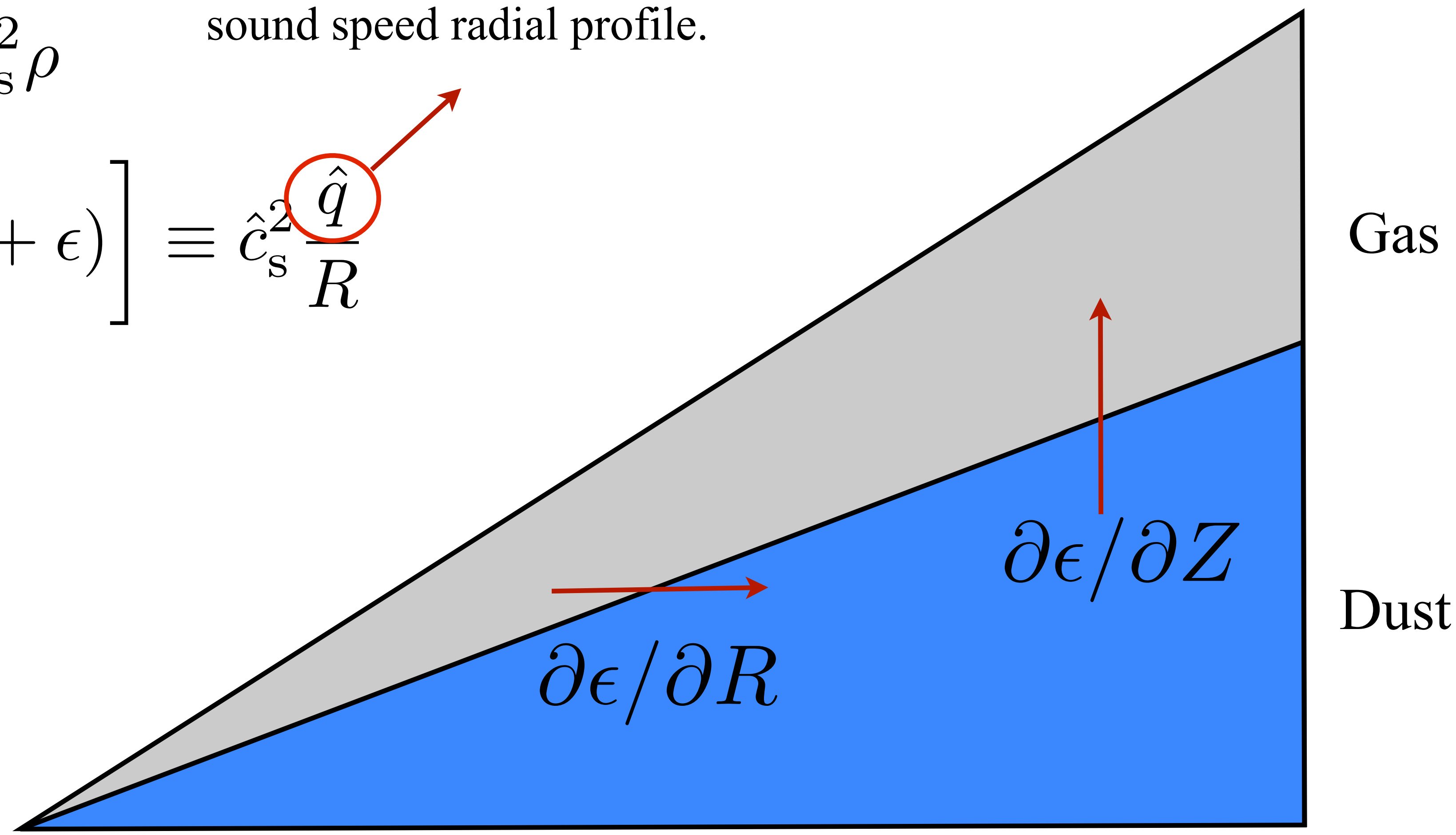
Toroidal vortices in protoplanetary discs

- Another possible source of instability can be obtained by considering (as suggested by Richard Nelson) the impact of the presence of dust in the classical Vertical Shear Instability (Goldreich & Schubert 1967, Fricke 1968, Nelson, Gressel & Umurhan 2013)

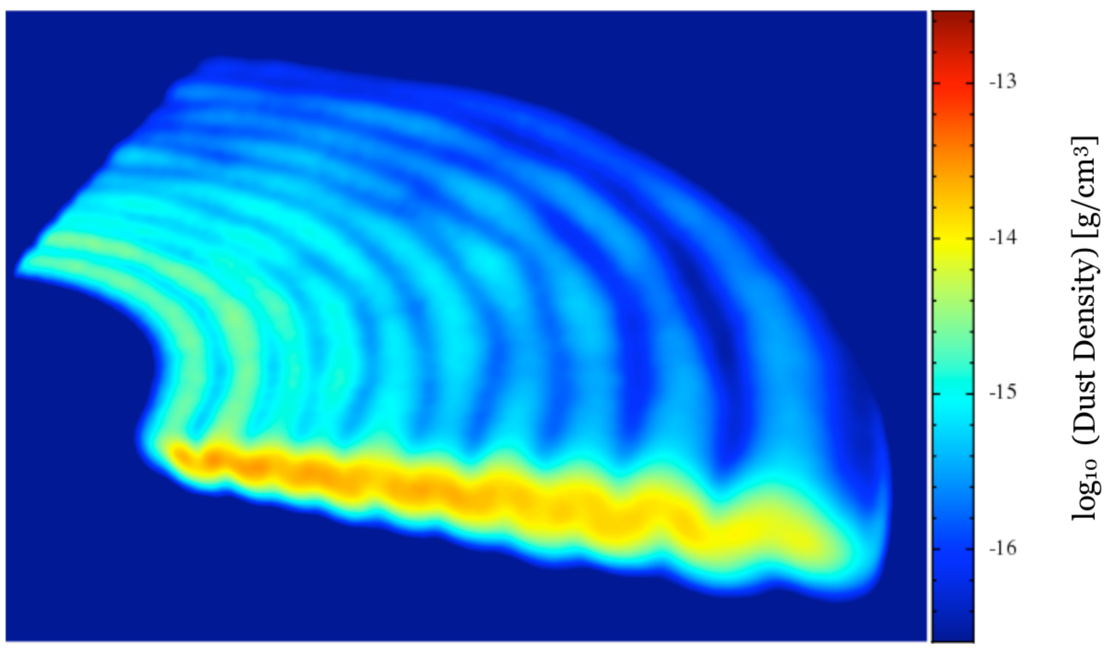
$$P = c_{\rm s}^2 \rho_{\rm gas} = \frac{c_{\rm s}^2}{1+\epsilon}\rho \equiv \hat{c}_{\rm s}^2 \rho$$

$$\frac{\partial \hat{c}_{\rm s}^2}{\partial R} = \hat{c}_{\rm s}^2 \left[\frac{q}{R} - \frac{\partial}{\partial R}\ln(1+\epsilon)\right] \equiv \hat{c}_{\rm s}^2 \frac{\hat{q}}{R}$$

Dust may boost the VSI by modifying the effective sound speed radial profile.



Toroidal vortices in protoplanetary discs



Loren-Aguilar & Bate 2015

• The instability is preferentially triggered by ~ mm grains.

• Smaller grains are too coupled to the gas. They need an extremely long time to settle.

• Bigger grains, of the order of ~ cm, settle extremely fast. If the dust layer is too thin, the conditions become unfavourable for the development of the instability.

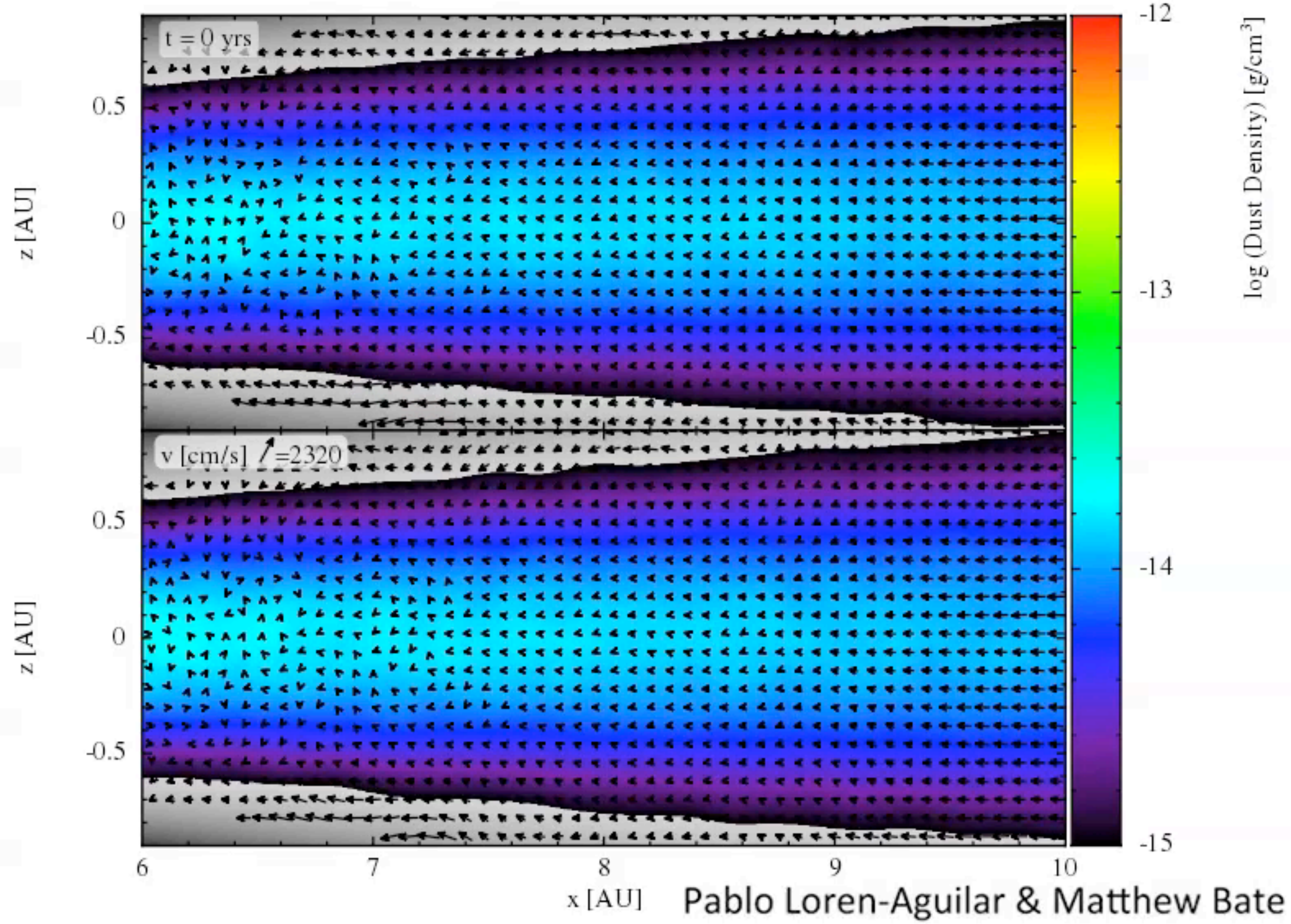
• An increase of the initial dust-to-gas ratio allows the instability to be triggered by bigger grains.

• The wavelength of the instability is roughly proportional to the characteristic height of the dust layer.

• The absence of shear (solid body rotation) "kills" the instability.

Toroidal vortices in protoplanetary discs

Pablo Lorén-Aguilar & Matthew R. Bate, MNRAS Letters, 2016, **457**, L54

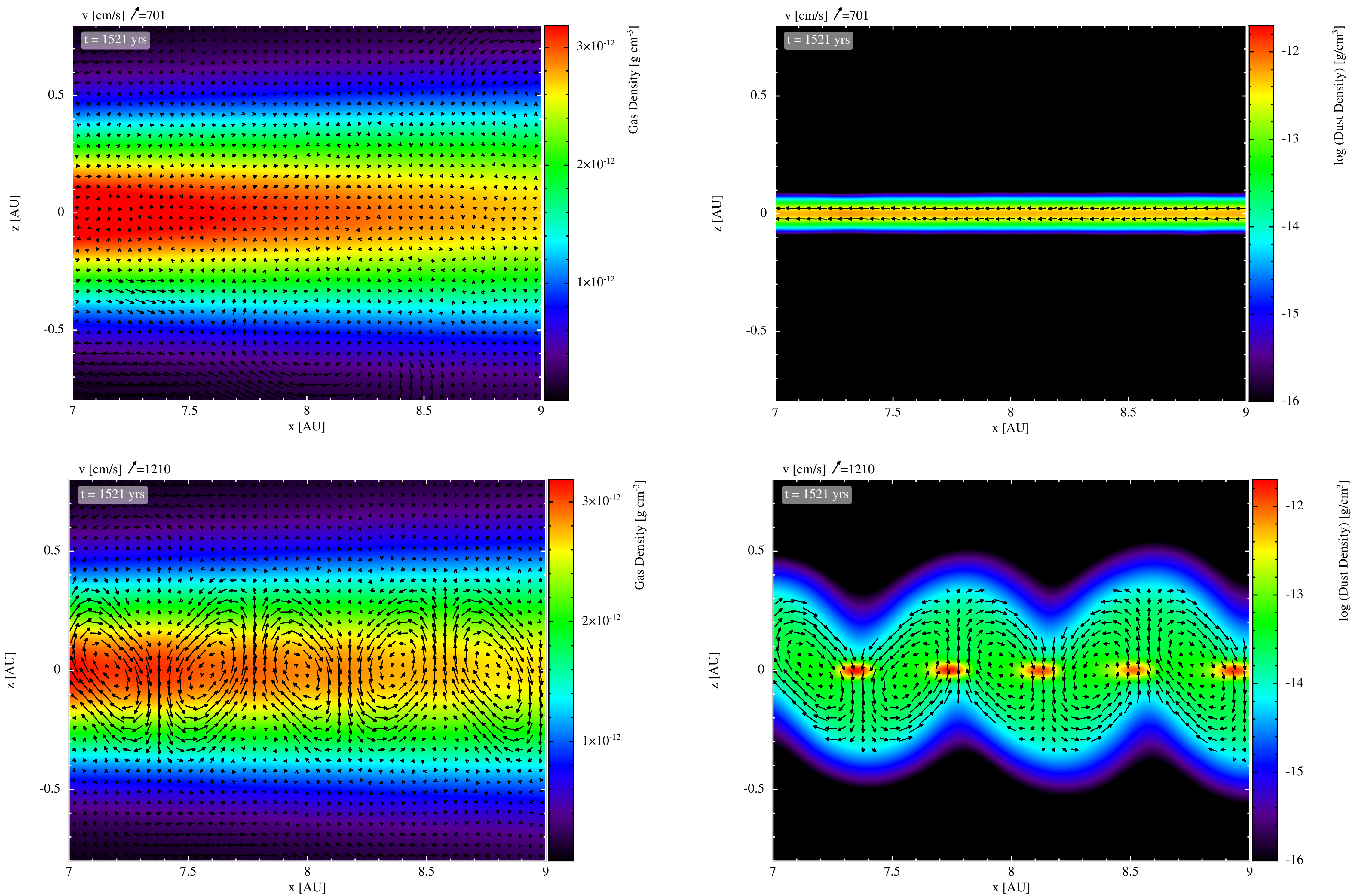


Pablo Loren-Aguilar & Matthew Bate

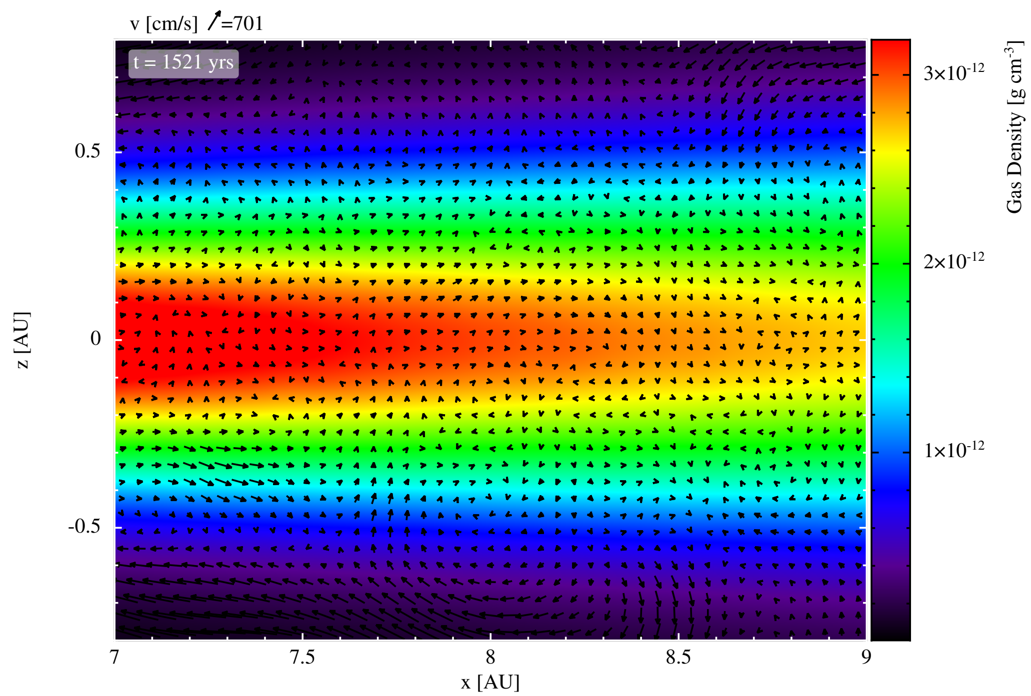
Toroidal vortices in protoplanetary discs

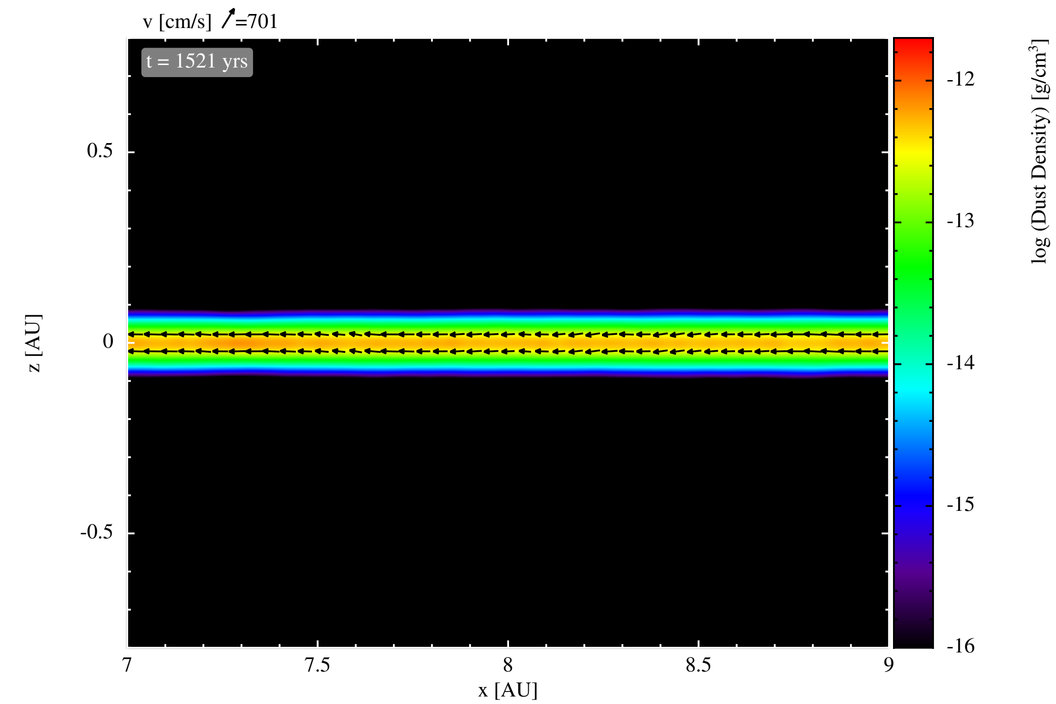
Single dust population
(50 cm)

Two-fold dust population
(1 mm & 50 cm)

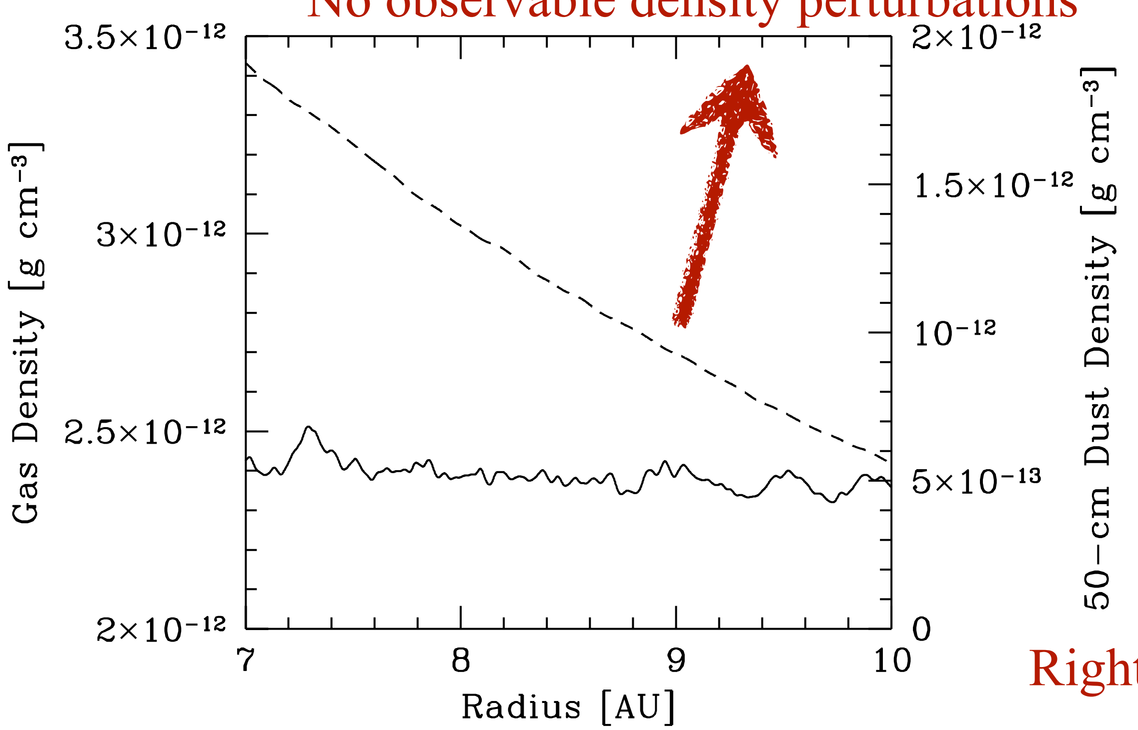


Toroidal vortices in protoplanetary discs

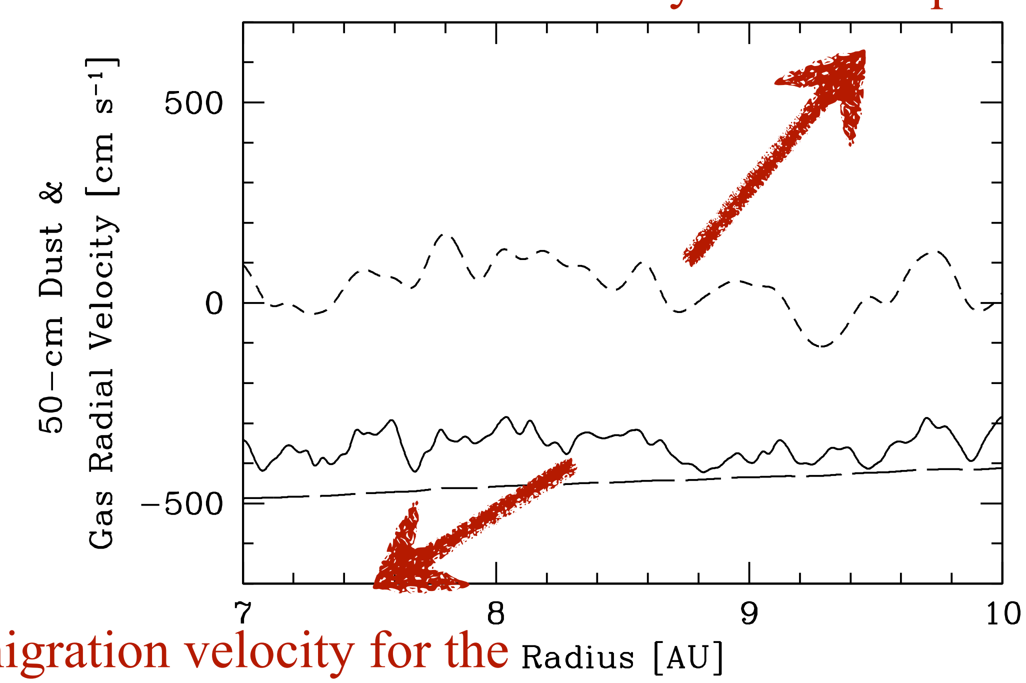




No observable density perturbations

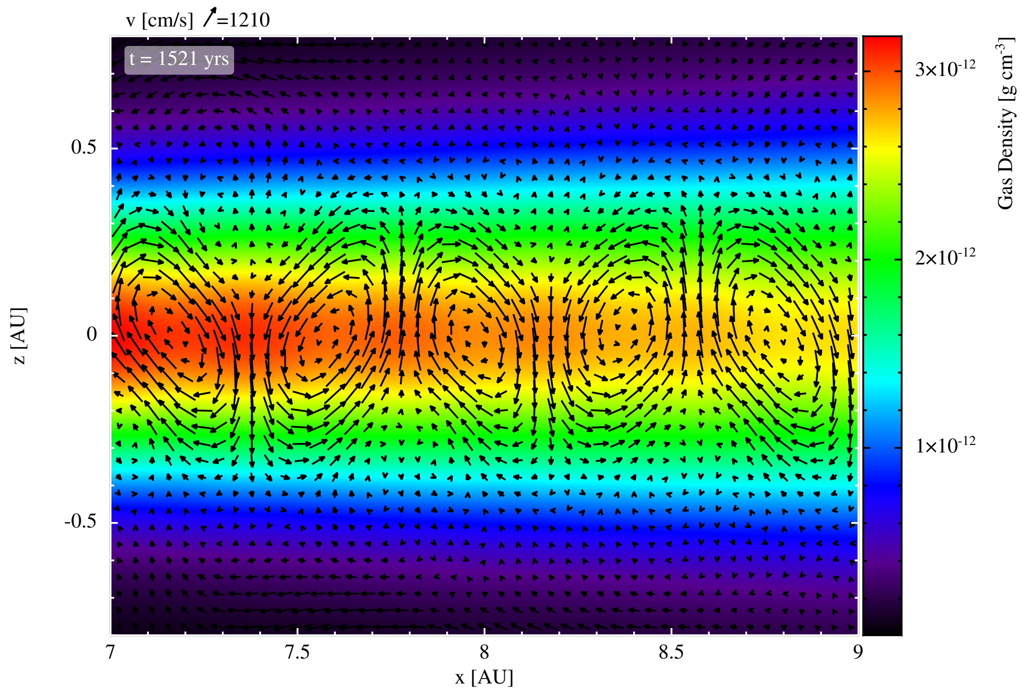


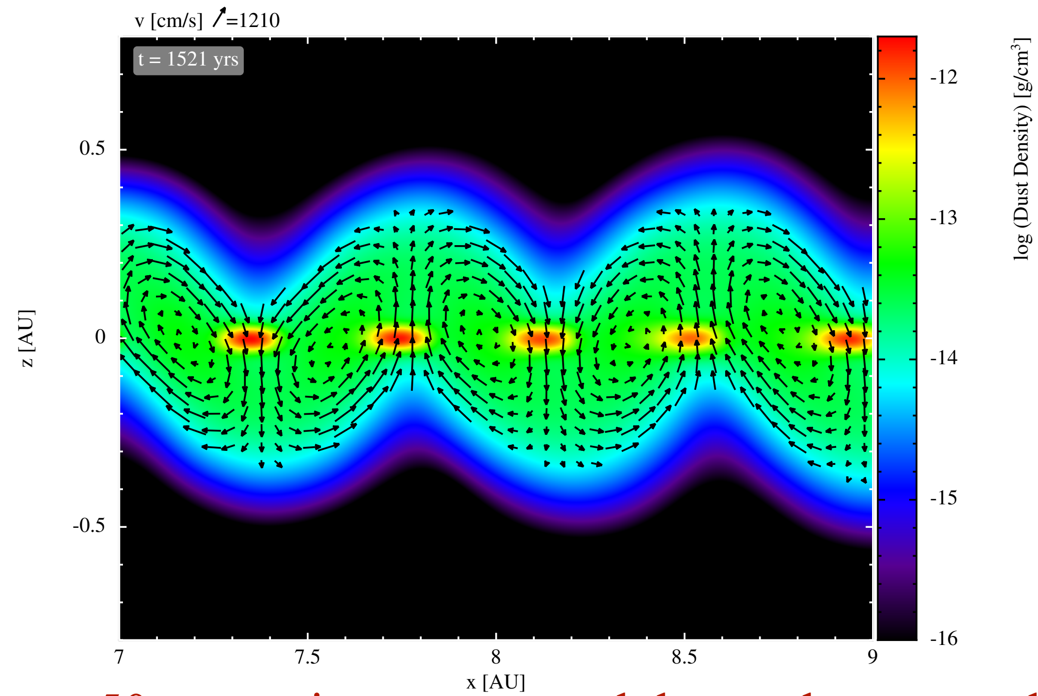
Gas in hydrostatic equilibrium



Right migration velocity for the dust

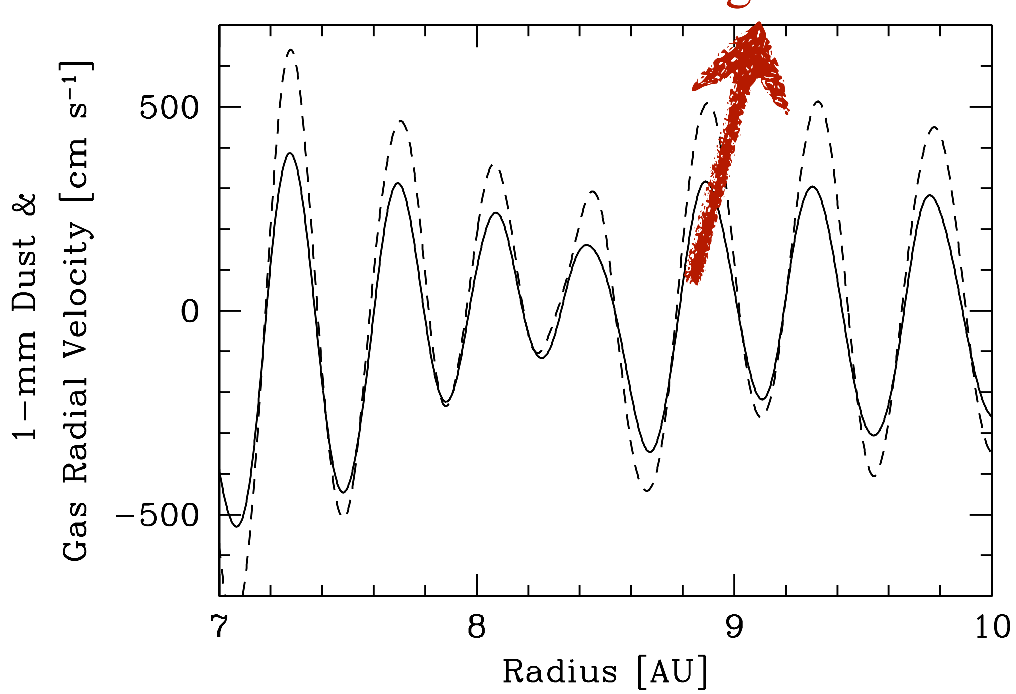
Toroidal vortices in protoplanetary discs

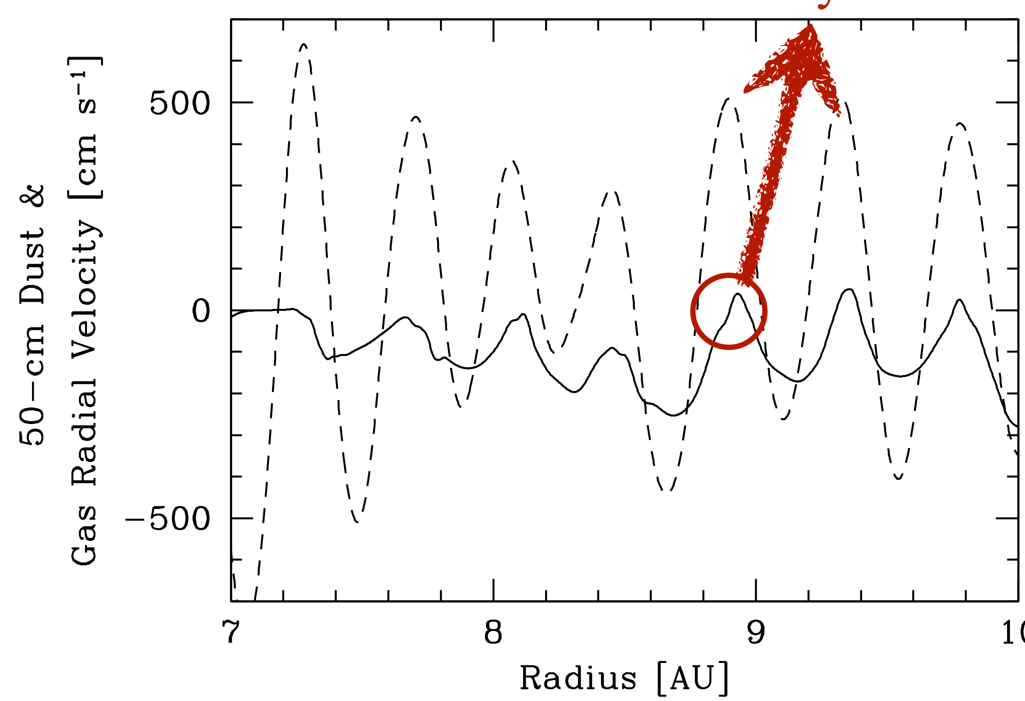




1 mm grains and gas move together due to the strong drag

50 cm grains are stopped due to the outward gas radial velocity





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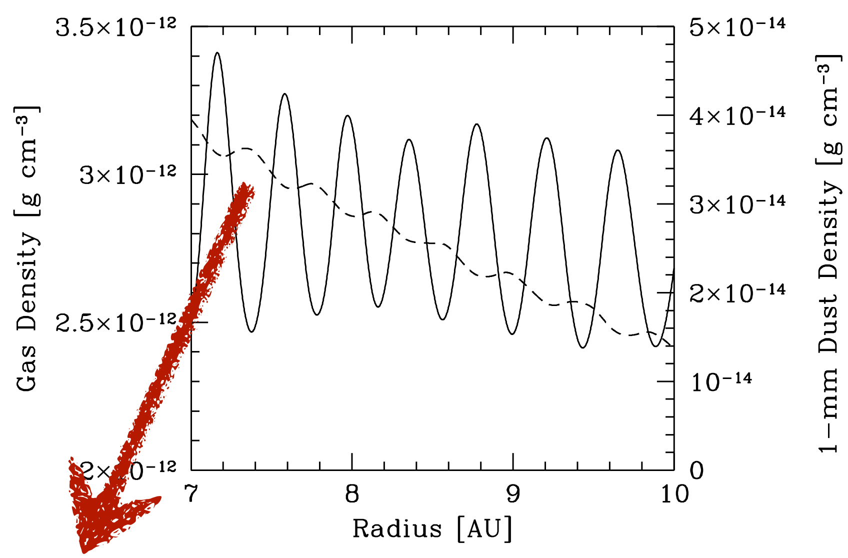
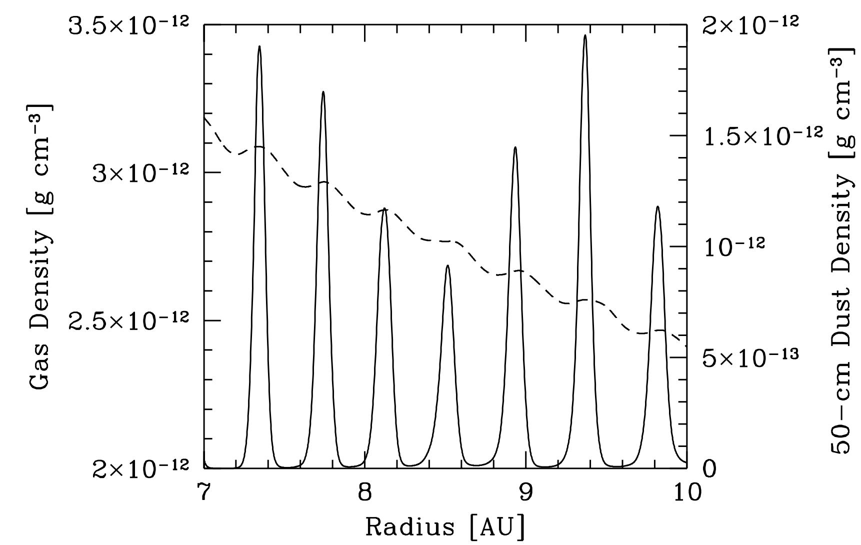
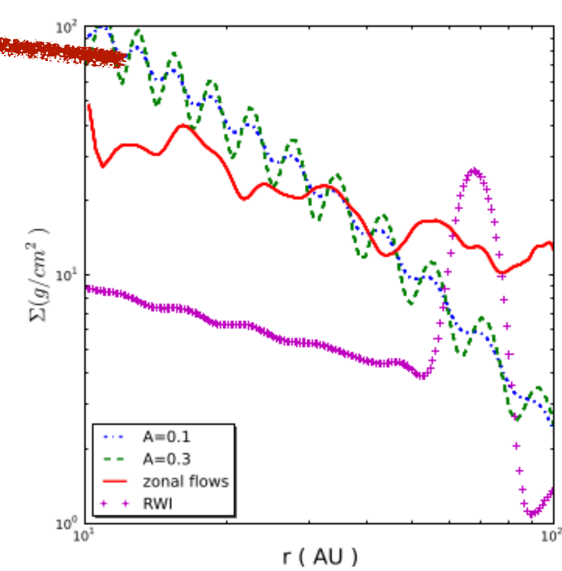
Toroidal vortices in protoplanetary discs

- Given the accuracy of present observations of protoplanetary discs, we should be able to start thinking in searching for the presence of the vortices.





Interesting similarities



The results presented here suggest that the presence of pressure bumps with a width of the order of the disk scale-height and an amplitude of 30% of the gas surface density of the disk, provide the necessary physical conditions for the survival of larger grains in a disk with properties summarized in Table 1. Comparisons between the observed fluxes of the Taurus, Ophiucus and Orion Nebula Cluster star forming regions with the results of the models ratify that the effect of the radial drift is reduced allowing particles to grow. Figure 8 shows how models with these kind of disturbances reproduce much better mm-observations than models with full or without radial drift.

Pinilla et al. 2012

- Given the accuracy of present observations of protoplanetary discs, we should be able to start thinking in searching for the presence of the vortices.

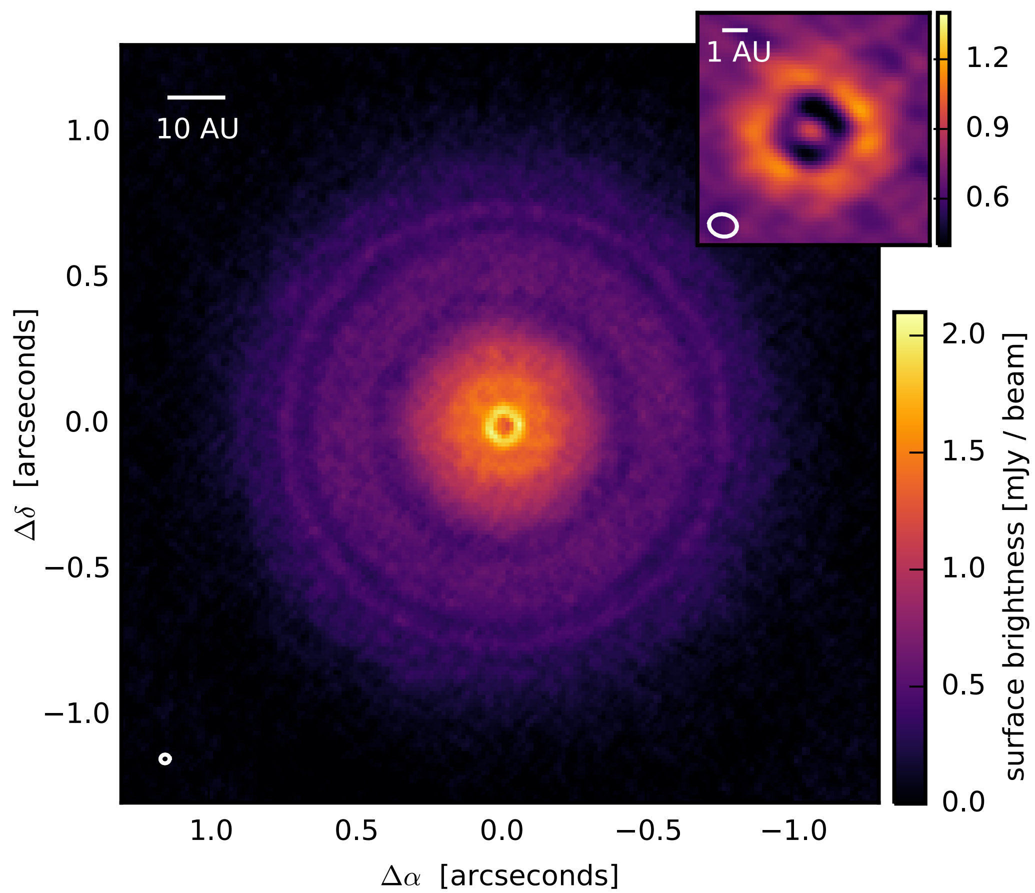


Figure 1. A synthesized image of the 870 μm continuum emission from the TW Hya disk with a 30 mas FWHM (1.6 AU) circular beam. The RMS noise level is $\sim$37 μJy beam^{-1}. The inset shows a 0.2″-wide (10.8 AU) zoom using an image with finer resolution (24×18 mas, or 1.3×1.0 AU, FWHM beam) to highlight the central unresolved source, 1 AU dark annulus, and 2.4 AU bright ring.

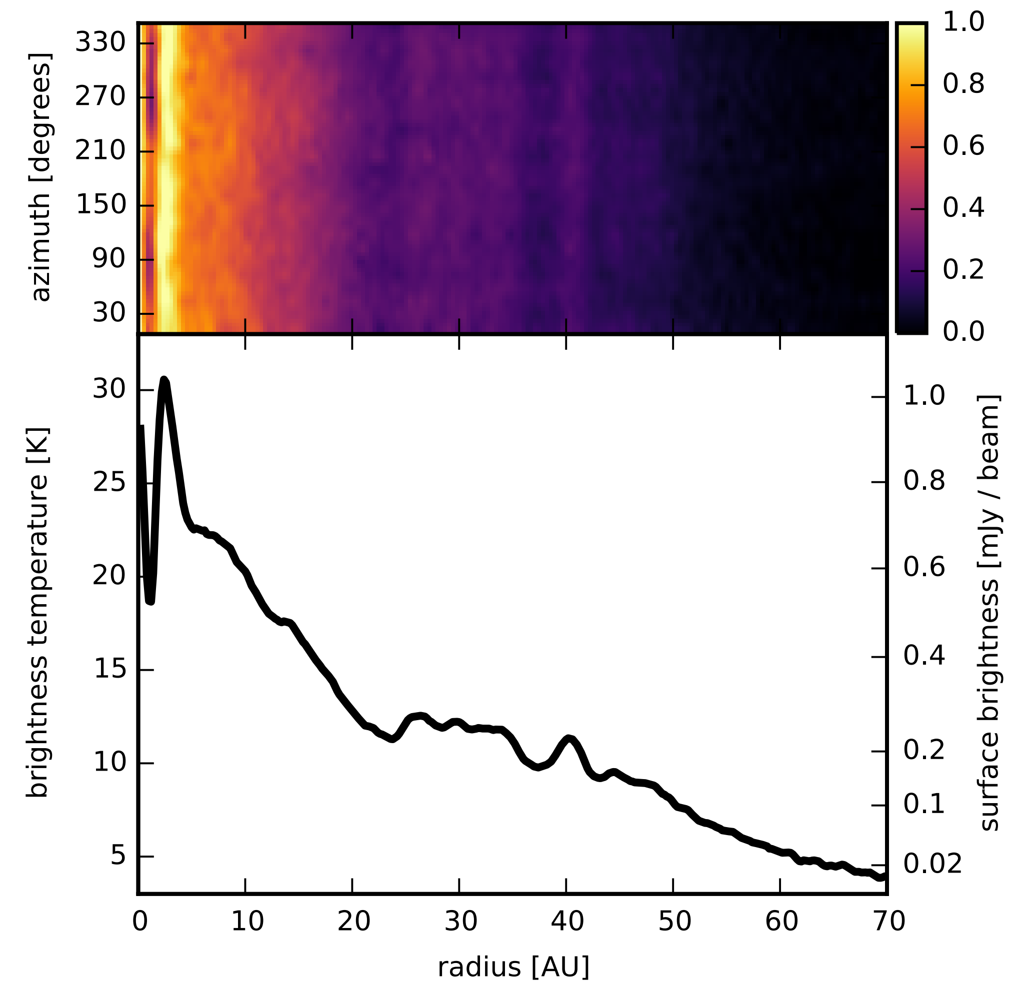
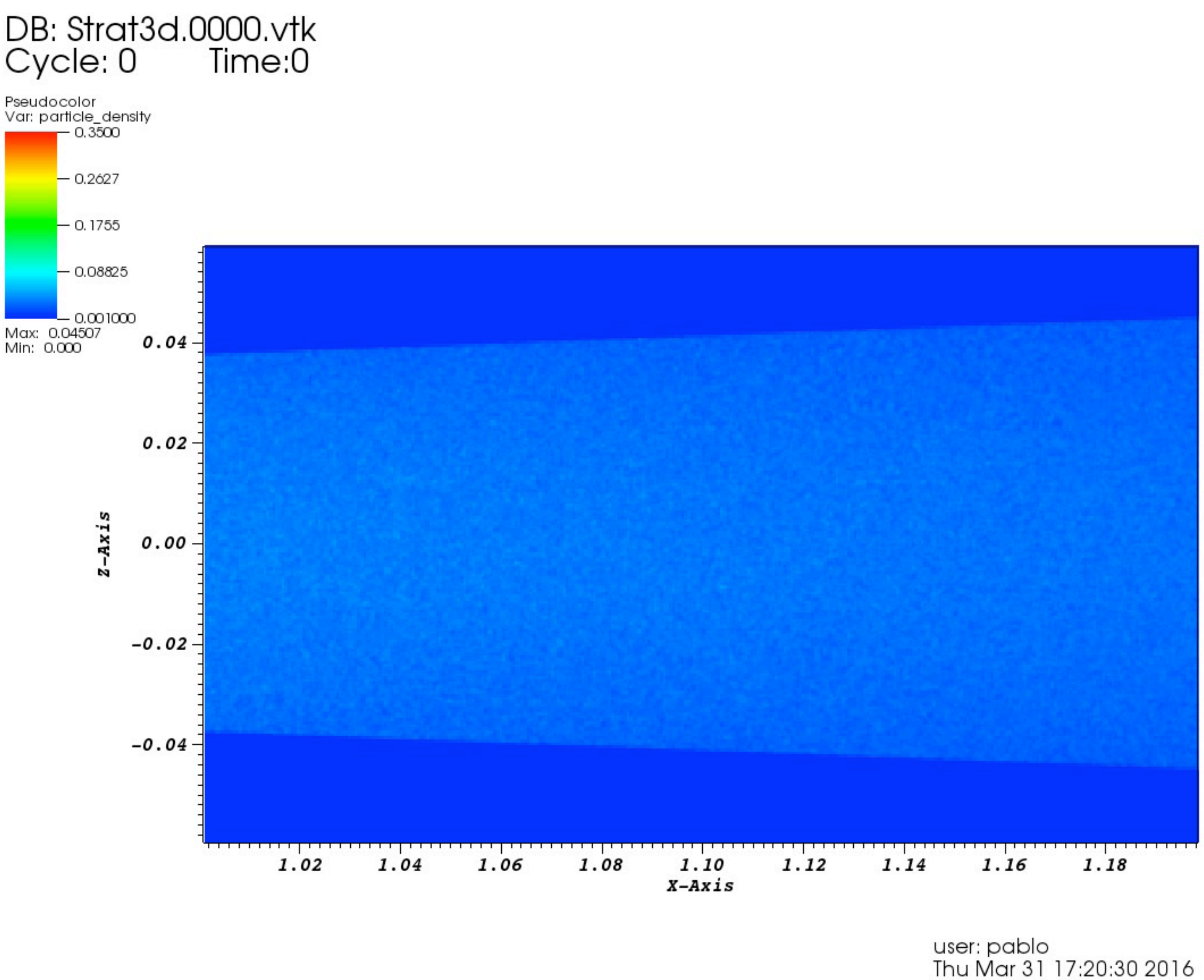


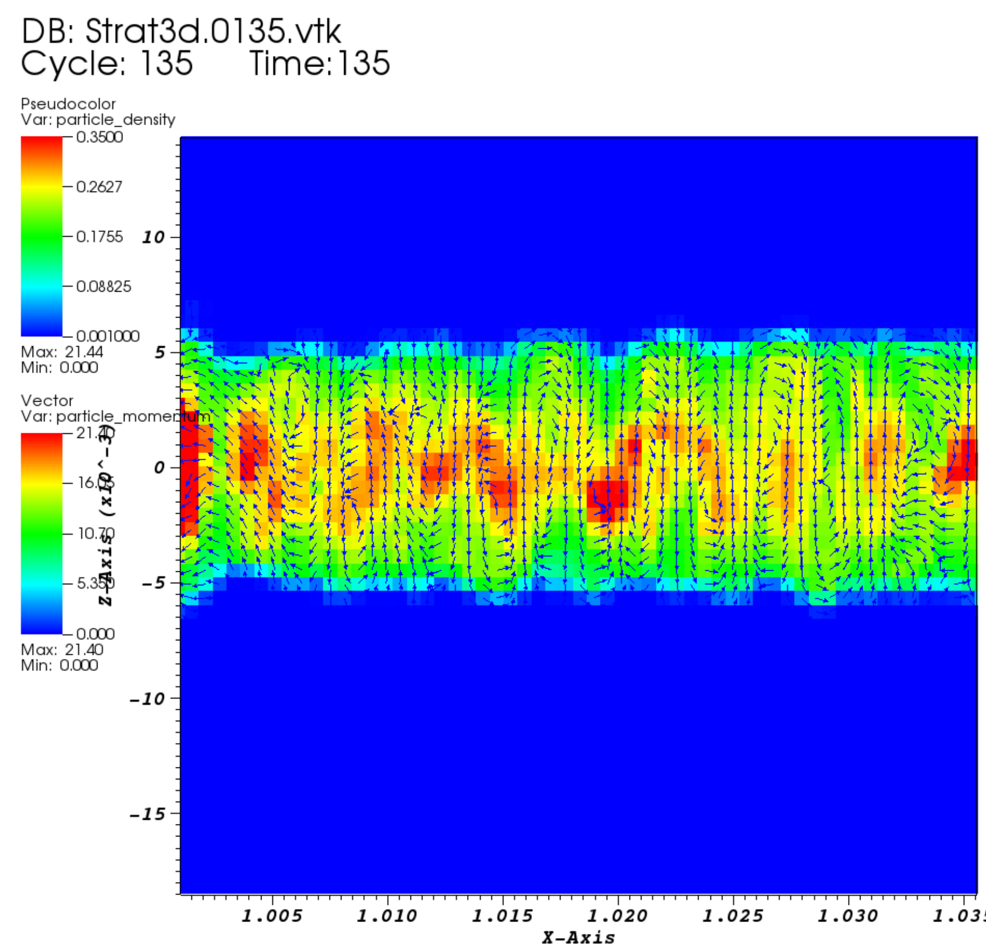
Figure 2. (*top*) The high resolution (24 × 18 mas beam) synthesized image described in Sect. 2, deprojected into a map in polar coordinates to more easily view the disk substructure. (*bottom*) The azimuthally-averaged radial surface brightness profile.

Andrews et al. 2016

Toroidal vortices in protoplanetary discs

• We have recently started a new project, trying to reproduce the instability using another numerical technique. We are using a modified version of the Athena code in order to simulate the process of dust settling in global protoplanetary discs (Disclaimer: this is *extremely* ongoing work)





Conclusions

- The instability is preferentially triggered by intermediately coupled grains (~ mm).

- An increase of the initial dust-to-gas ratio allows the instability to be triggered by bigger grains.

- The wavelength of the instability is roughly proportional to the characteristic height of the disc.

- Simulations suggest that the presence of the instability can stop the radial migration of bigger grains.

- The best theoretical explanation so far seems to be a “dusty version” of the VSI. A detailed theoretical model will arrive soon (-ish).

- Given the accuracy of present day observations, we should be capable to search for the the presence of the instability.