Multifluid Simulations: Applications to Protoplanetary Disks

Benitez-Llambay, Krapp & Pessah, 2019, ApJS, 241, 25

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The Niels Bohr
International Academy

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Multifluid Equations

Continuity and momentum equations for $i = 1, \ldots, N$ fluid species

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{v}_i) = 0 \,.$$

$$\frac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\, \mathbf{v}_i = -\frac{\nabla P_i}{\rho_i} + \mathbf{a}_i + \frac{\mathbf{F}_i}{\rho_i}$$

$\mathbf{F}_i$ the drag force per unit volume:

$$\mathbf{F}_i = -\rho_i \sum_{j \neq i} \alpha_{ij} \left(\mathbf{v}_i - \mathbf{v}_j\right) \,.$$

Momentum conservation for binary collisions implies

$$\rho_i \alpha_{ij} = \rho_j \alpha_{ji} \,.$$

Implicit Numerical Scheme for the Drag Force

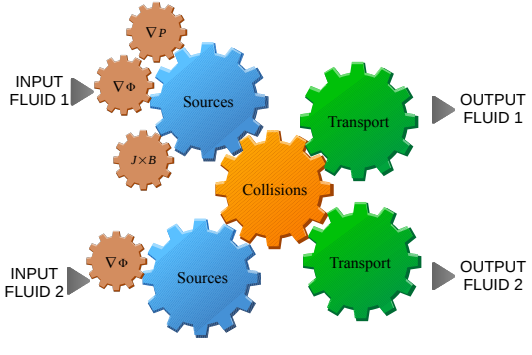
$$\frac{\partial \mathbf{v}_i}{\partial t} = -\rho_i \sum_{j=1}^{N} \alpha_{ij} \left(\mathbf{v}_i - \mathbf{v}_j\right) \quad \Rightarrow \quad \frac{\mathbf{v}_i^{n+1} - \mathbf{v}_i^n}{\Delta t} = -\rho_i \sum_{j=1}^{N} \alpha_{ij}^n \left(\mathbf{v}_i^{n+1} - \mathbf{v}_j^{n+1}\right)$$

- Arbitrary number of (gas and dust) species
- Conserves momentum to machine precision
- Converges to the correct asymptotic equilibrium solution
- Cheaper than analytical method
- Can include non-linear drag forces

A robust and efficient scheme to simulate gas-dust dynamics.

Implementation in FARGO3D

Solve $\dfrac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\,\mathbf{v}_i = -\dfrac{\nabla P_i}{\rho_i} + \mathbf{a}_i + \dfrac{\mathbf{F}_i}{\rho_i}$ using operator splitting technique



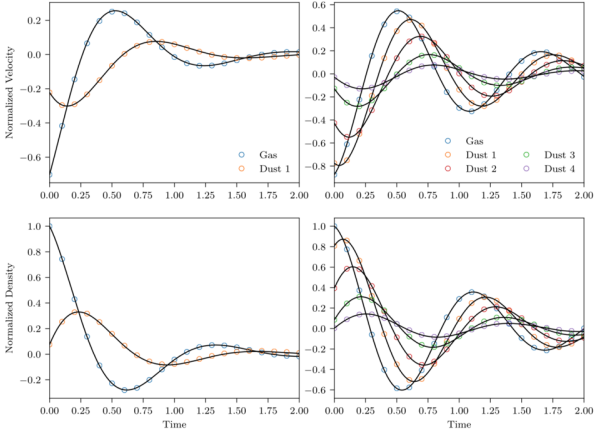
Scheme converges to the correct (analytical) equilibrium solution

(see Benitez-Llambay, Krapp & Pessah, 2019, or Leonardo's poster for details!)

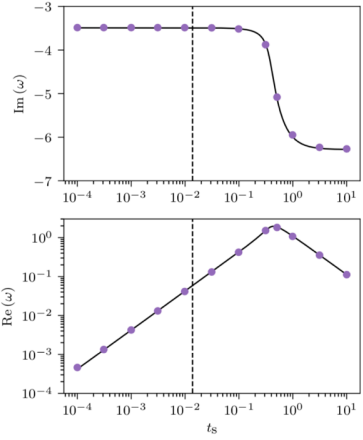
Test-suite

Damping of Dusty Sound Waves

Dusty sound wave - single and multiple dust species



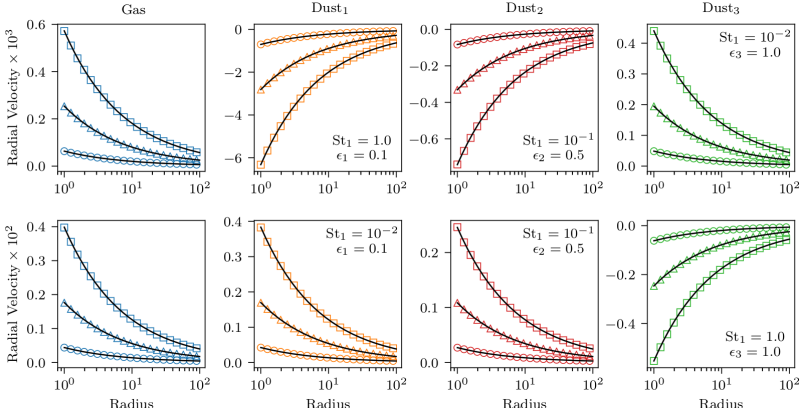
Eigenvalues - single dust



The scheme converges to the correct solution, even in stiff regimes.

New Global Steady State Solutions for Dusty PPDs

- Analytic global axisymmetric steady-state solutions
- Sub-Keplerian gaseous background disk
- Arbitrary number of dust species

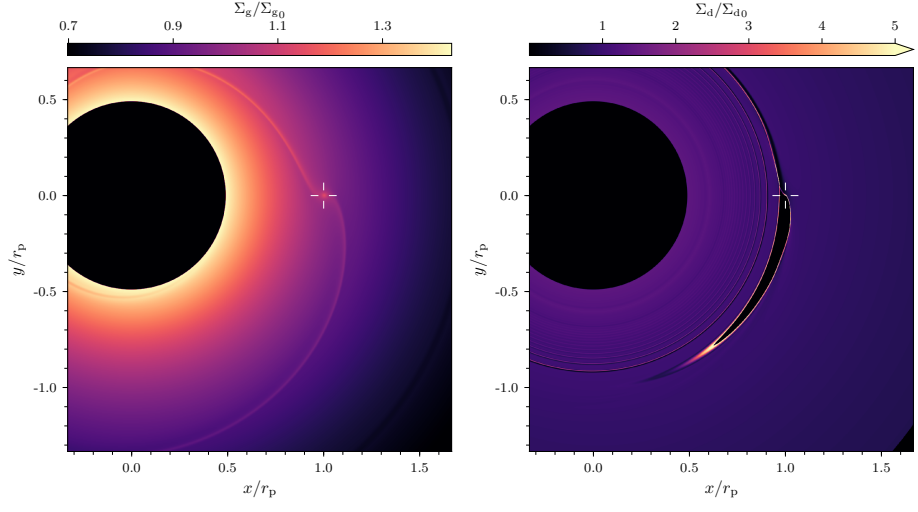


New test bed (and initial conditions) for global simulations of dusty disks

Dust Dynamics in PPDs

Planetary Torques in Dusty Disks - Pablo's talk on Friday

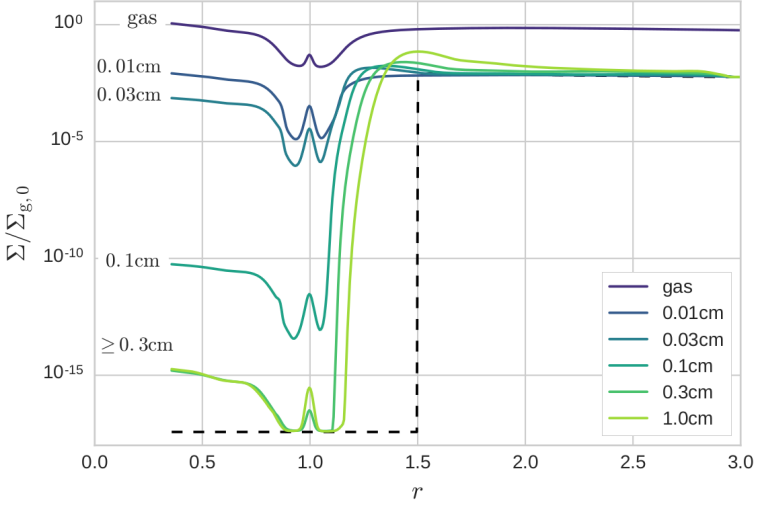
Torques Induced by Scattered Pebble-flow in Protoplanetary Disks.



Benítez Llambay, P. & Pessah, M., 2018, ApJL

Dust Filtering by Giant Planets - Morbidelli's talk later today

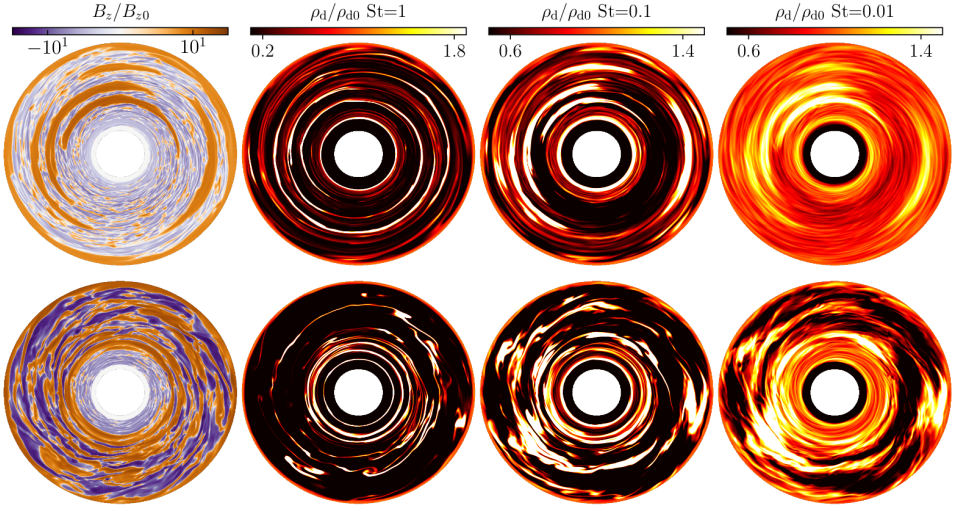
Characterizing the Variable Dust Permeability of Planet-induced Gaps.



Weber, P. et al., 2018, ApJ Haugbølle, T. et al., 2019, ApJ

Dust Trapping in Hall-Dominated PPDs

Dust Segregation in Hall-dominated Turbulent Protoplanetary Disks.

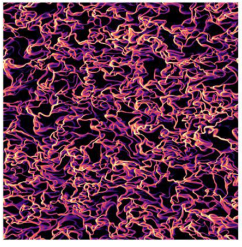


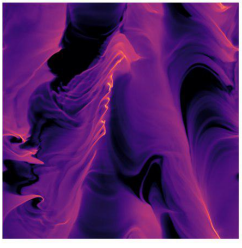
Krapp, L. et al., 2018, ApJ

Comparison with Bai & Stone (2010): Particles vs Fluid

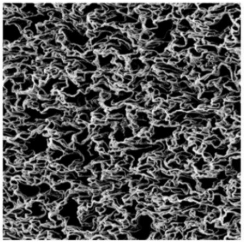
Dust density snapshot.

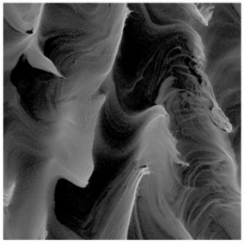
Benítez-Llambay et al. (2019)





Bai & Stone (2010)

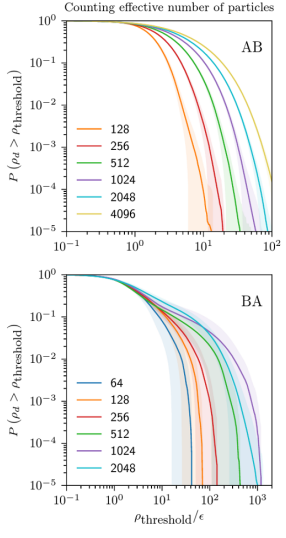




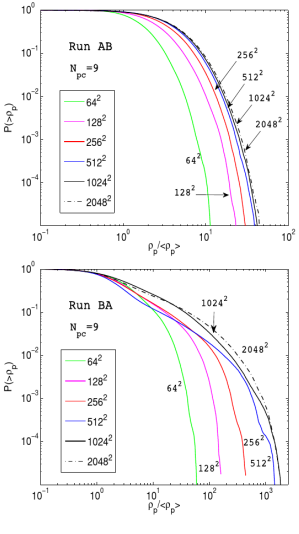
Comparison with Bai & Stone (2010): Particles vs Fluid

Cumulative density distribution

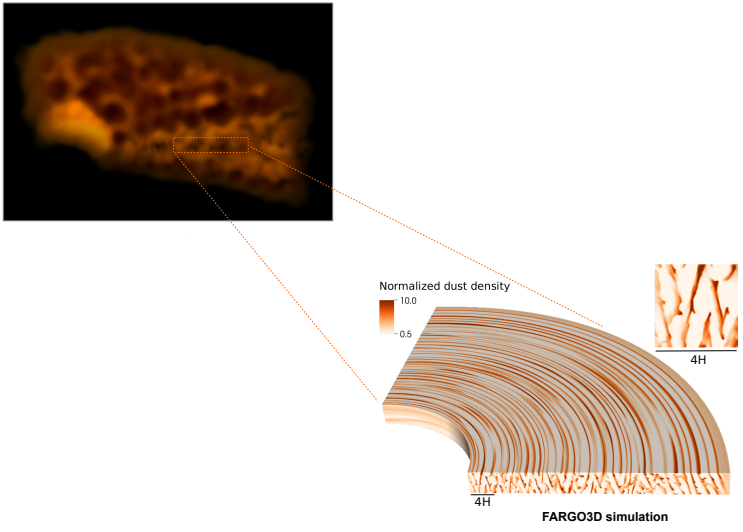
Benítez-Llambay et al. (2019)



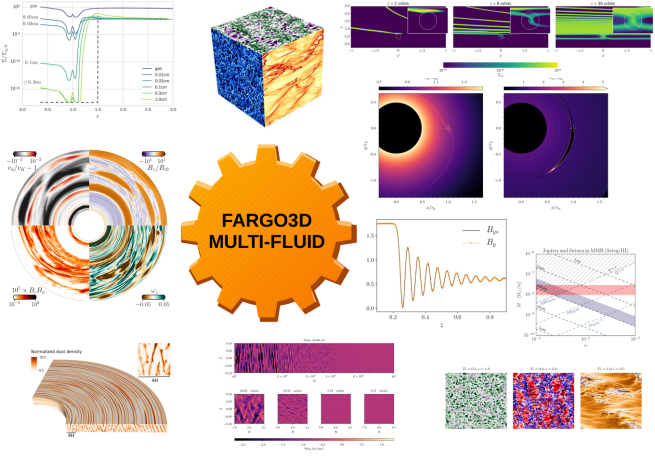
Bai & Stone (2010)



Streaming Instability - Global PPDs Simulations - wait for Leonardo's talk!



Recent Publications with FARGO3D



- Weber et al. (ApJ, 2018)
- Benítez-Llambay, & Pessah (ApJL, 2018)
- Krapp et al. (ApJ, 2018)
- Haugbølle et al. (ApJ, 2019)
- Benítez-Llambay et al. (ApJS, 2019)
- Krapp et al. (ApJL, 2019)

Take Home Message

A robust, precise, and perhaps one of the most efficient schemes to simulate multi-species systems (to first order in time)

Don't take our word for it. Download FARGO3D and see for yourself!

FARGO3D – Public Repository – https://bitbucket.org/fargo3d