The Accuracy of Dusty Turbulence Simulations

PHANTOM

MEMORIAL UNIVERSITY

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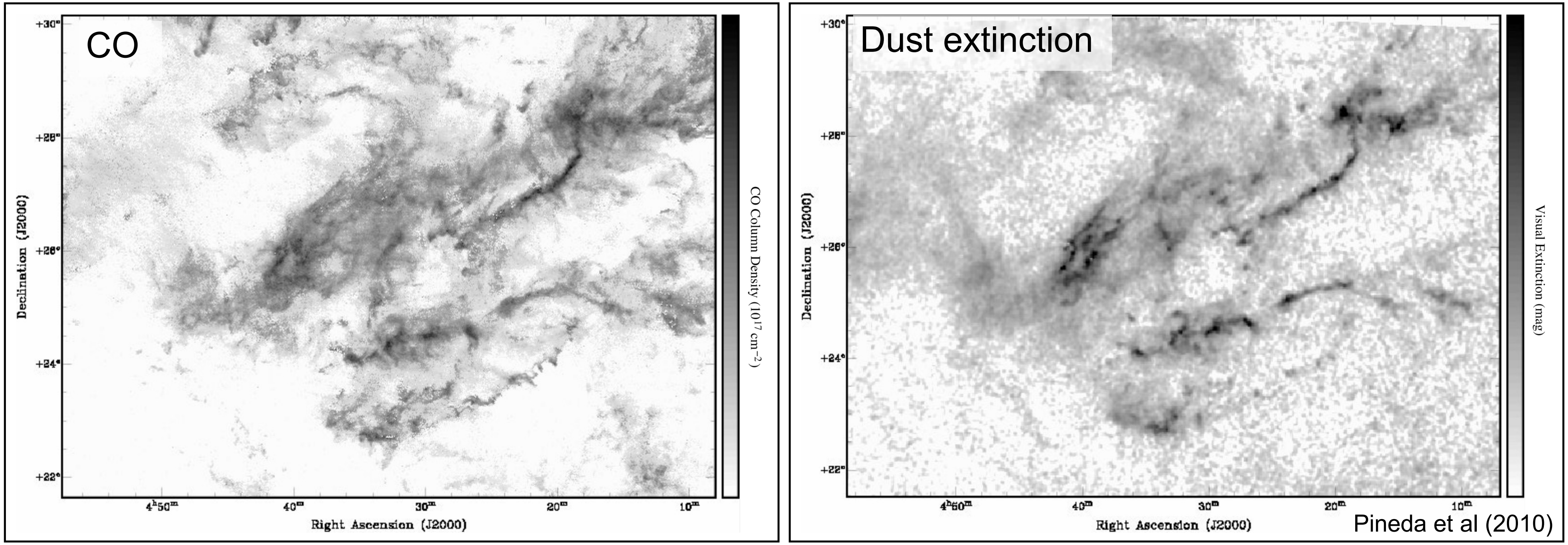
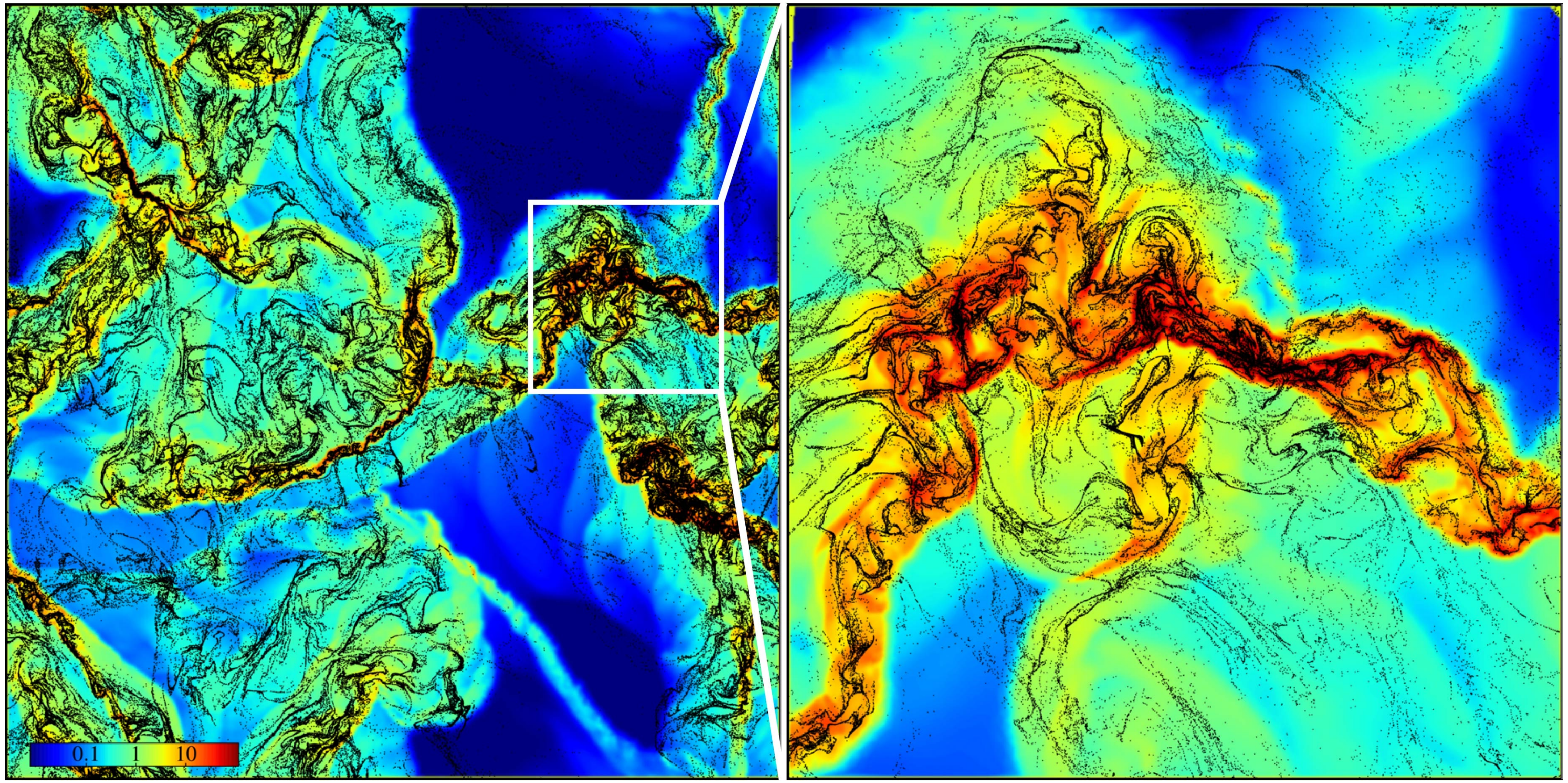
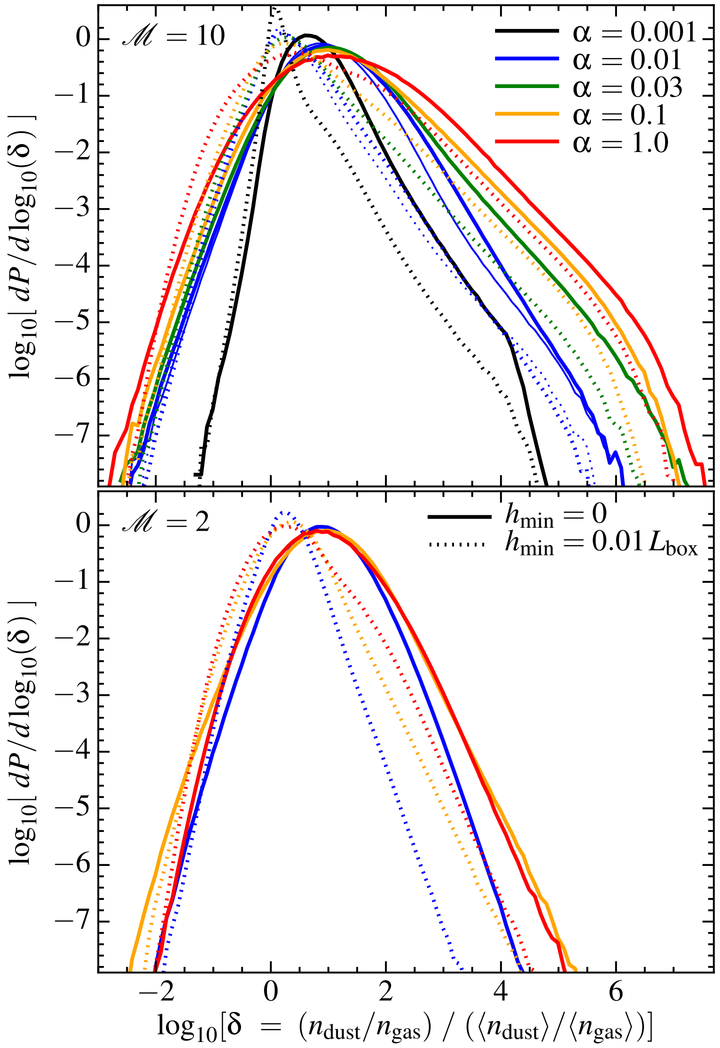
Dusty Turbulence



- Star-forming molecular clouds are cold (~10 K), with hydrogen & helium effectively invisible.
- Dust is an important tracer of gas structure.

Dusty Turbulence with Gizmo



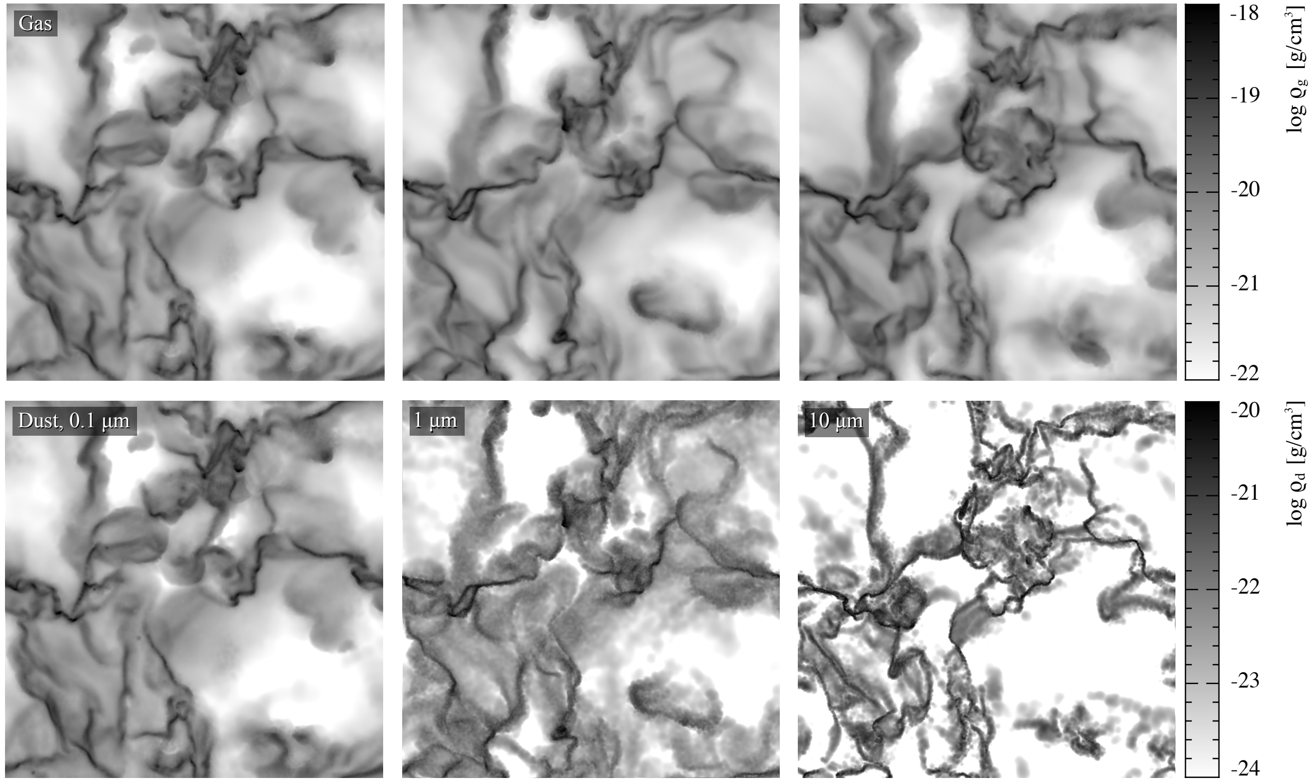


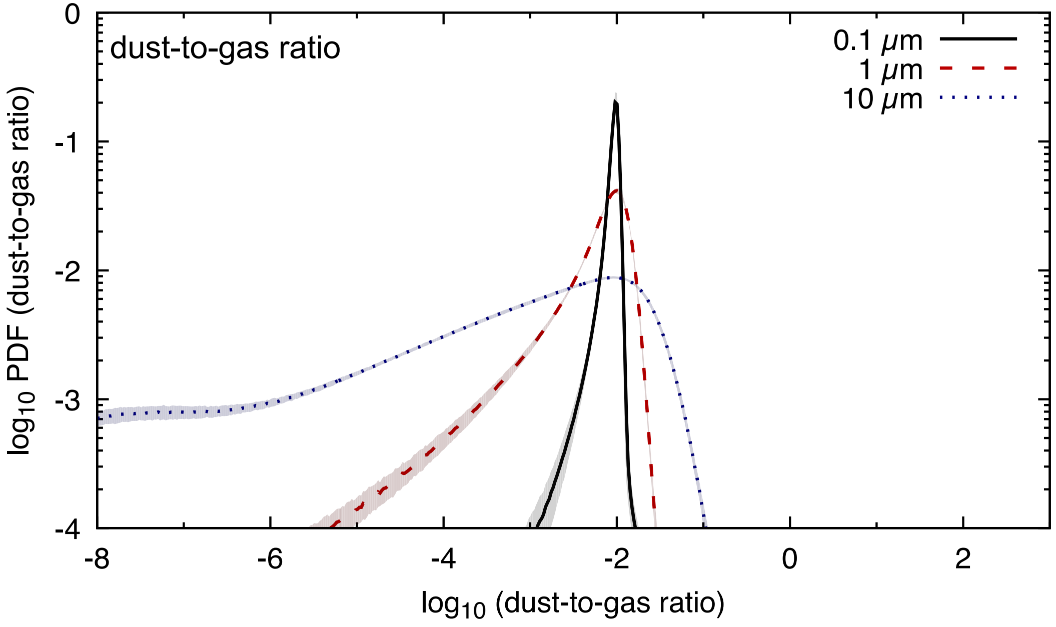
“dust filaments can exist where there is no gas filament at all"

“exhibit dramatic (exceeding factor ~1000) fluctuations in the local dust-to-gas ratio"

Hopkins & Lee (2016); Lee, Hopkins & Squire (2017)

Dusty Turbulence with Phantom





"We find typical fluctuations in the dust-to-gas ratio for 0.1 μm grains of around 10 per cent"

"The large-scale dust column density remains well correlated with the gas column density for all grain sizes."

Tricco, Price, Laibe (2017)

2-Fluid Dust + Gas Method

$$\frac{\partial \rho_{\mathrm{g}}}{\partial t} + \nabla \cdot \left(\rho_{\mathrm{g}} \boldsymbol{v}_{\mathrm{g}}\right) = 0$$

$$\frac{\partial \rho_{\mathrm{d}}}{\partial t} + \nabla \cdot \left(\rho_{\mathrm{d}} \boldsymbol{v}_{\mathrm{d}}\right) = 0$$

$$\rho_{\mathrm{g}} \left(\frac{\partial \boldsymbol{v}_{\mathrm{g}}}{\partial t} + \boldsymbol{v}_{\mathrm{g}} \cdot \nabla \boldsymbol{v}_{\mathrm{g}} \right) = \rho_{\mathrm{g}} \boldsymbol{f} + K(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}}) - \nabla P_{\mathrm{g}}$$

$$\rho_{\mathrm{d}} \left(\frac{\partial \boldsymbol{v}_{\mathrm{d}}}{\partial t} + \boldsymbol{v}_{\mathrm{d}} \cdot \nabla \boldsymbol{v}_{\mathrm{d}} \right) = \rho_{\mathrm{d}} \boldsymbol{f} - K(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}})$$

- Model dust and gas **as two species of particles**.
- Works well when dust and gas are only weakly coupled through the drag term.

- Timestep criterion for dust stopping time + standard CFL condition.
- Spatial resolution on drag length scale.

Laibe & Price 2012a,b

1-Fluid Dust Solver

- **One species of particle** that represents a mixture of dust and gas.
- Barycentric point of view is modeled. Evolving total density + total velocity + velocity drift + dust fraction.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\frac{\nabla P_{\mathrm{g}}}{\rho} - \frac{1}{\rho}\nabla \cdot \left(\frac{\rho_{\mathrm{g}}\rho_{\mathrm{d}}}{\rho}\Delta\boldsymbol{v}\Delta\boldsymbol{v}\right)$$

$$\frac{\partial}{\partial t}\left(\frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{g}}}\right) + \boldsymbol{v} \cdot \nabla\left(\frac{\rho_{\mathrm{d}}}{\rho_{\mathrm{g}}}\right) = -\frac{\rho}{\rho_{\mathrm{g}}^2}\nabla \cdot \left(\frac{\rho_{\mathrm{g}}\rho_{\mathrm{d}}}{\rho}\Delta\boldsymbol{v}\right)$$

$$\frac{\partial \Delta\boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\Delta\boldsymbol{v} = \frac{\nabla P_{\mathrm{g}}}{\rho_{\mathrm{g}}} - \frac{\Delta\boldsymbol{v}}{t_{\mathrm{s}}} - (\Delta\boldsymbol{v} \cdot \nabla)\boldsymbol{v} + \frac{1}{2}\nabla\left(\frac{\rho_{\mathrm{d}} - \rho_{\mathrm{g}}}{\rho}\Delta\boldsymbol{v}^2\right)$$

- Timestep criterion for ***inverse*** dust stopping time + standard CFL condition.
- No spatial resolution requirement.

Laibe & Price 2014a,b; Price & Laibe 2015

Dust Method Comparison

- Commerçon et al (2023) compared 2-fluid and 1-fluid dusty turbulence using the grid-based code Ramses.

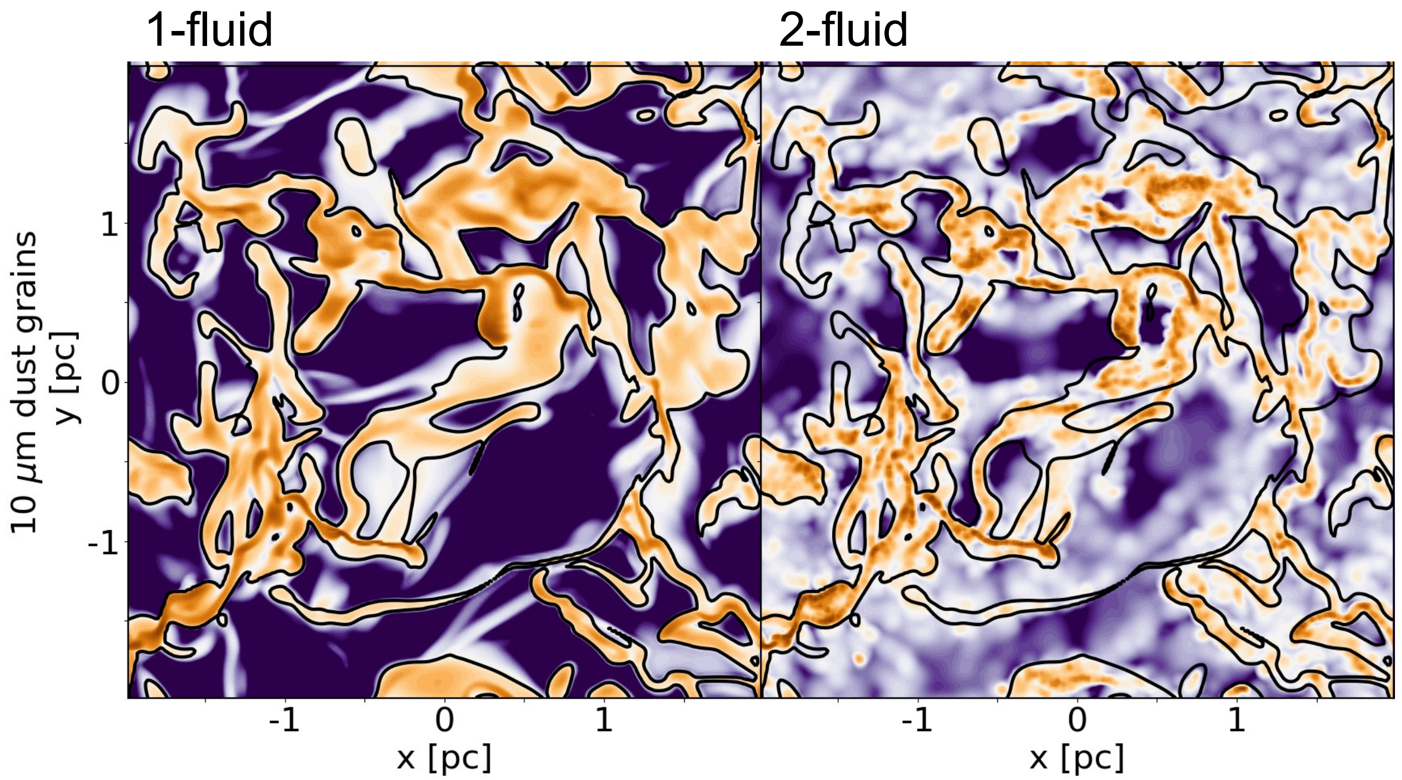
> "*Our results for the two-fluid dust as Lagrangian particles are* ***globally consistent with those of Hopkins & Lee*** *(2016) …*"

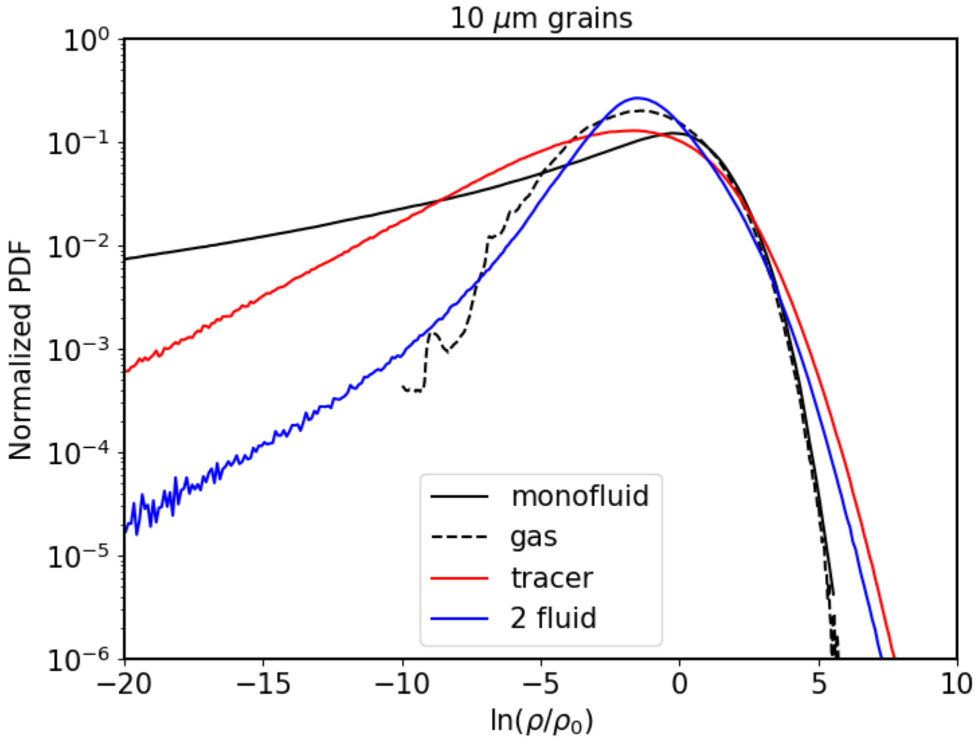
> "*Our [1-fluid] results are in* ***very good agreement with previous work by Tricco et al.*** *(2017).*"

- Previous studies are not inconsistent if you account for differing grain size, grain density, gas density and dynamics.

> "*..we show* ***that there is no tension in terms of the critical size for decoupling*** *between the results reported by Tricco et al. (2017) on one side and Hopkins & Lee (2016) and Mattsson et al. (2019a) on the other.*"

Dust Method Comparison





"For large dust-grain sizes, the density PDFs obtained with the monofluid and the two-fluid formalisms do not agree."

Commerçon et al (2023)

SPH Dusty Turbulence Comparison

- We have further studied the numerical inaccuracies present in the 2-fluid and 1-fluid methods for dusty turbulence.

Initial conditions:

- 3 & 10 μm dust grains. Initially uniform 1% dust-to-gas ratio.
- Only modelling hydrodynamics + dust. (No self-gravity, etc).
- Mach 10 turbulence driven on large scale.
- L = 3 parsec, $\rho = 10^{-20}$ g/cm^3 (peak $\rho \sim 10^{-17}$ g/cm^3).
- Isothermal gas with T = 11.5 K, equivalent to $c_s = 0.2$ km/s.

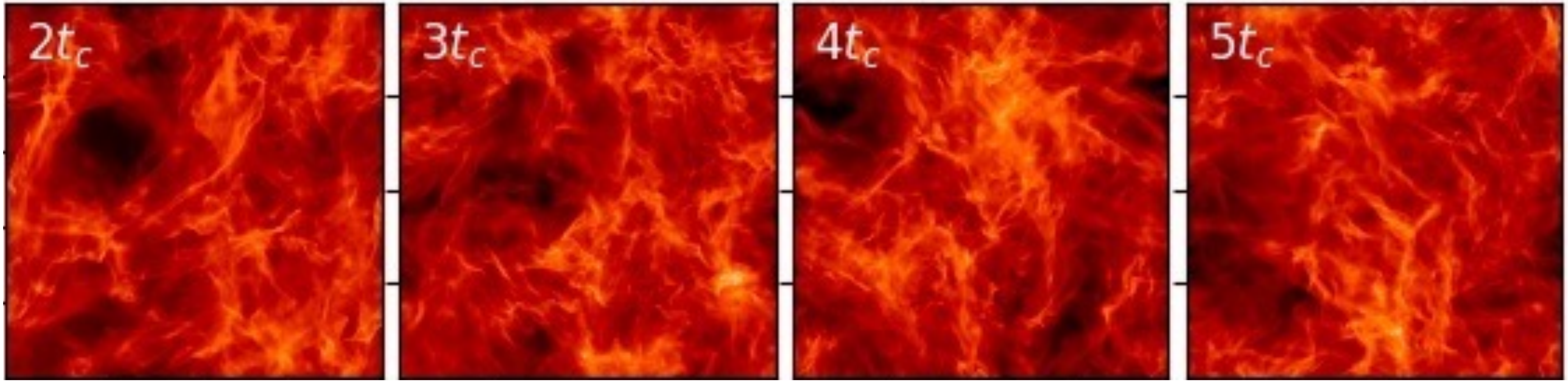
SPH Dusty Turbulence Comparison

- Importantly, all simulations are performed using both the 2-fluid and 1-fluid formalism *in the same code* (Phantom SPH code).

- All other numerical details are exactly the same, including the turbulent driving pattern.
- Any differences can be isolated as due to choice of dust solver.

- Work led by MSc student Narges Vadood.

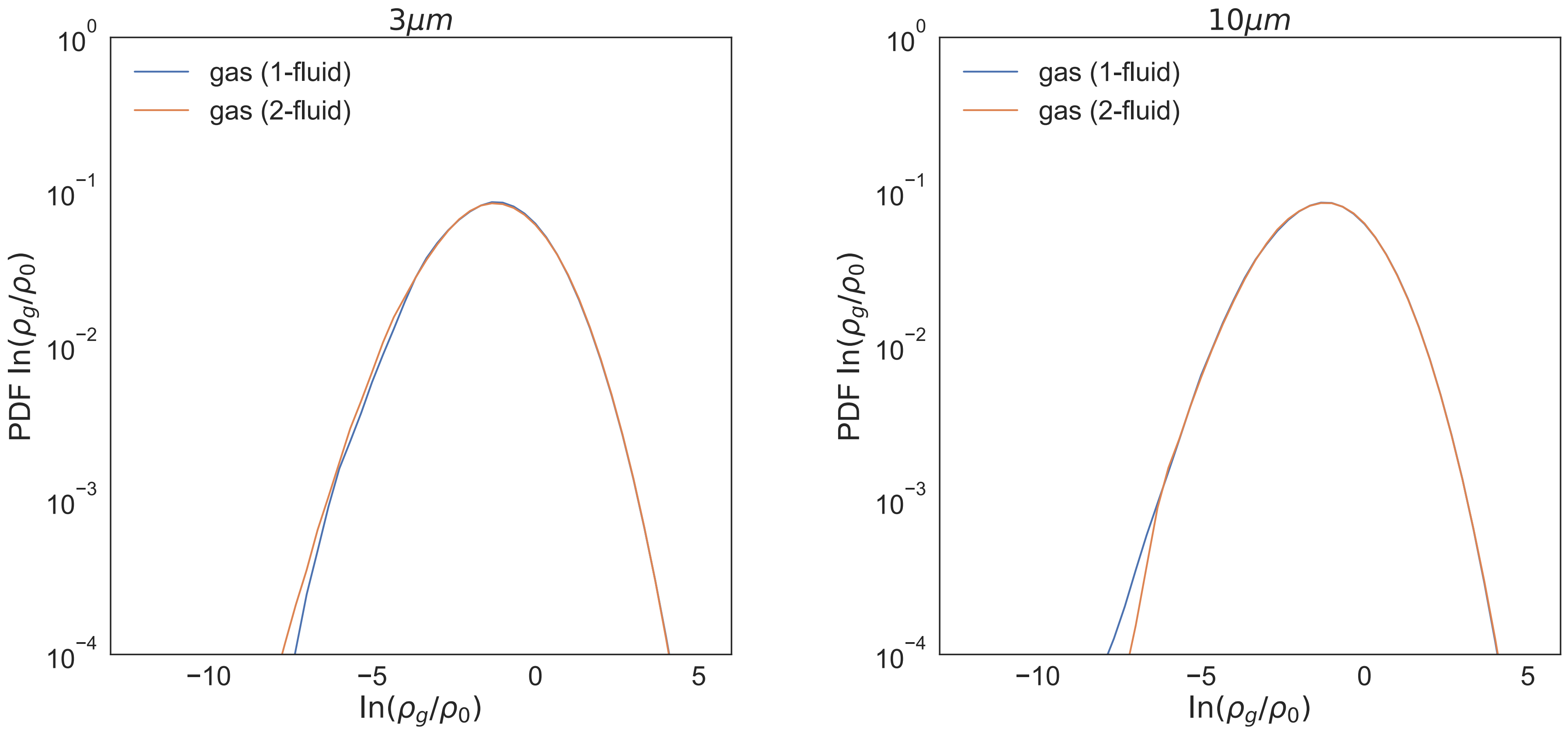
Gas Density Evolution



- Column gas density evolved over ~2M years.
- Turbulence is driven (sustained) and undergoes turbulent energy cascade from large to small scales.

Vadood, Tricco (in prep)

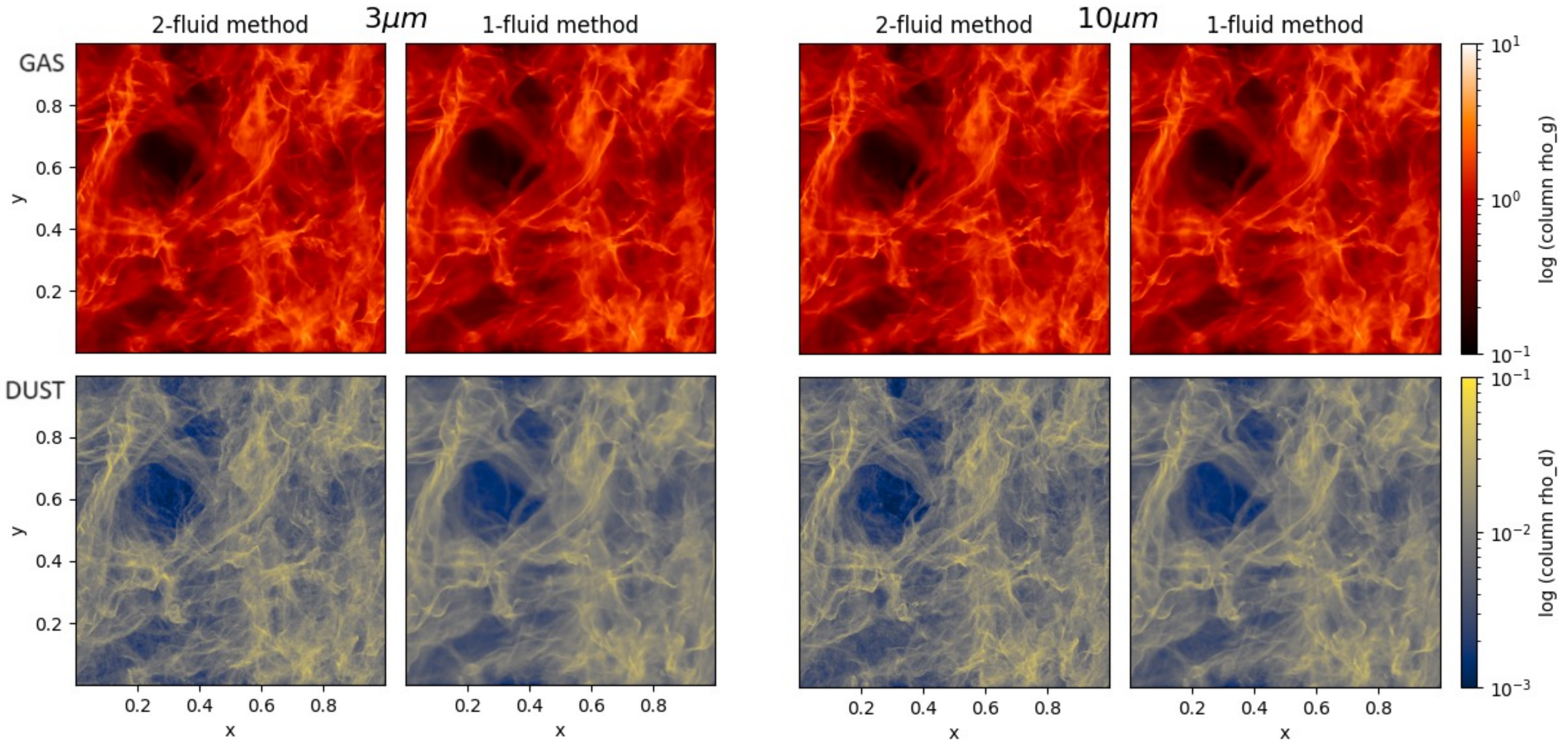
Gas Density PDFs



- Gas density PDFs exhibit log-normal shape, as is expected for supersonic, isothermal turbulence.

Vadood, Tricco (in prep)

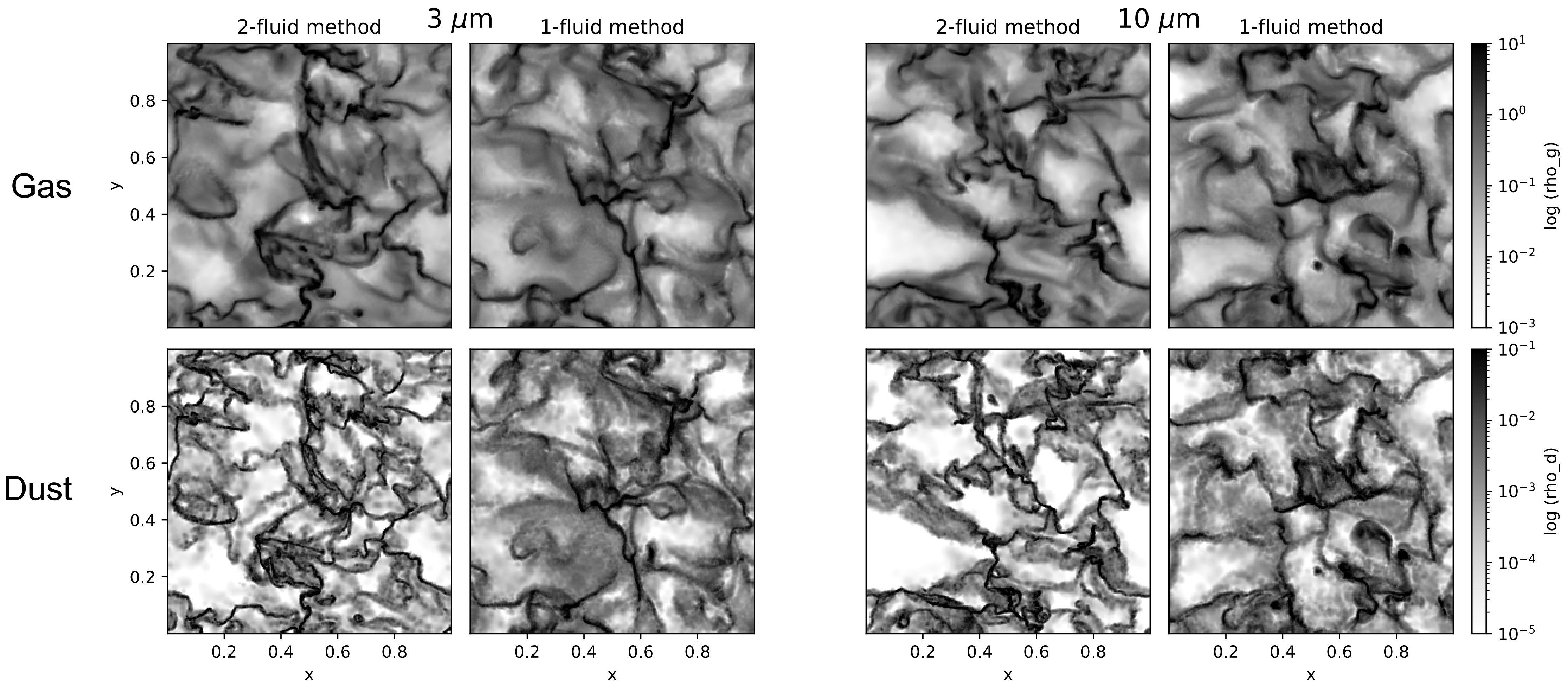
Column Gas / Dust Density



Early time! Column gas (top) and dust (bottom) densities start off qualitatively similar.

Vadood, Tricco (in prep)

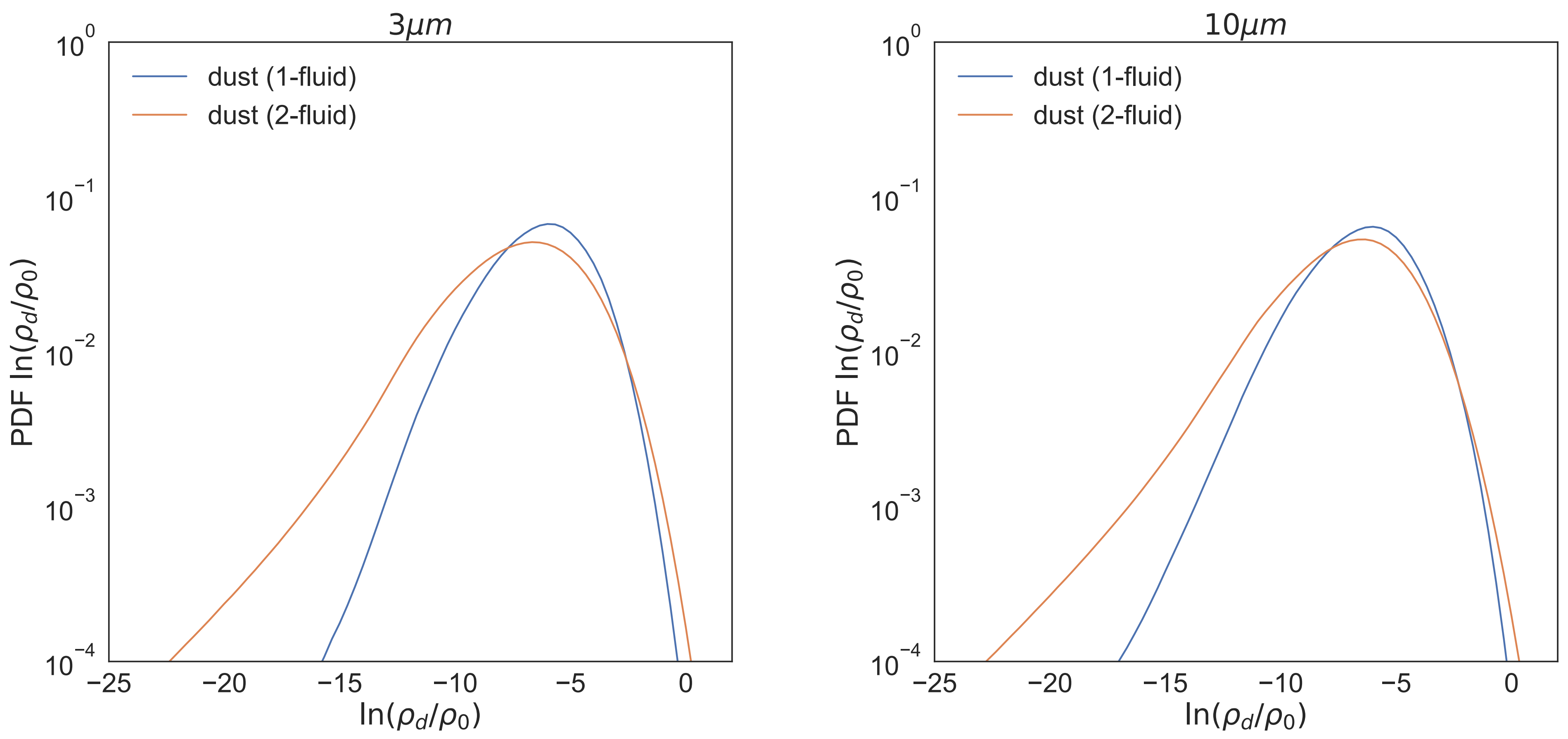
Planar Slices of Gas / Dust



Evolved time density slices: Dust evacuation from low-density gas areas is more pronounced with 2-fluid method.

Vadood, Tricco (in prep)

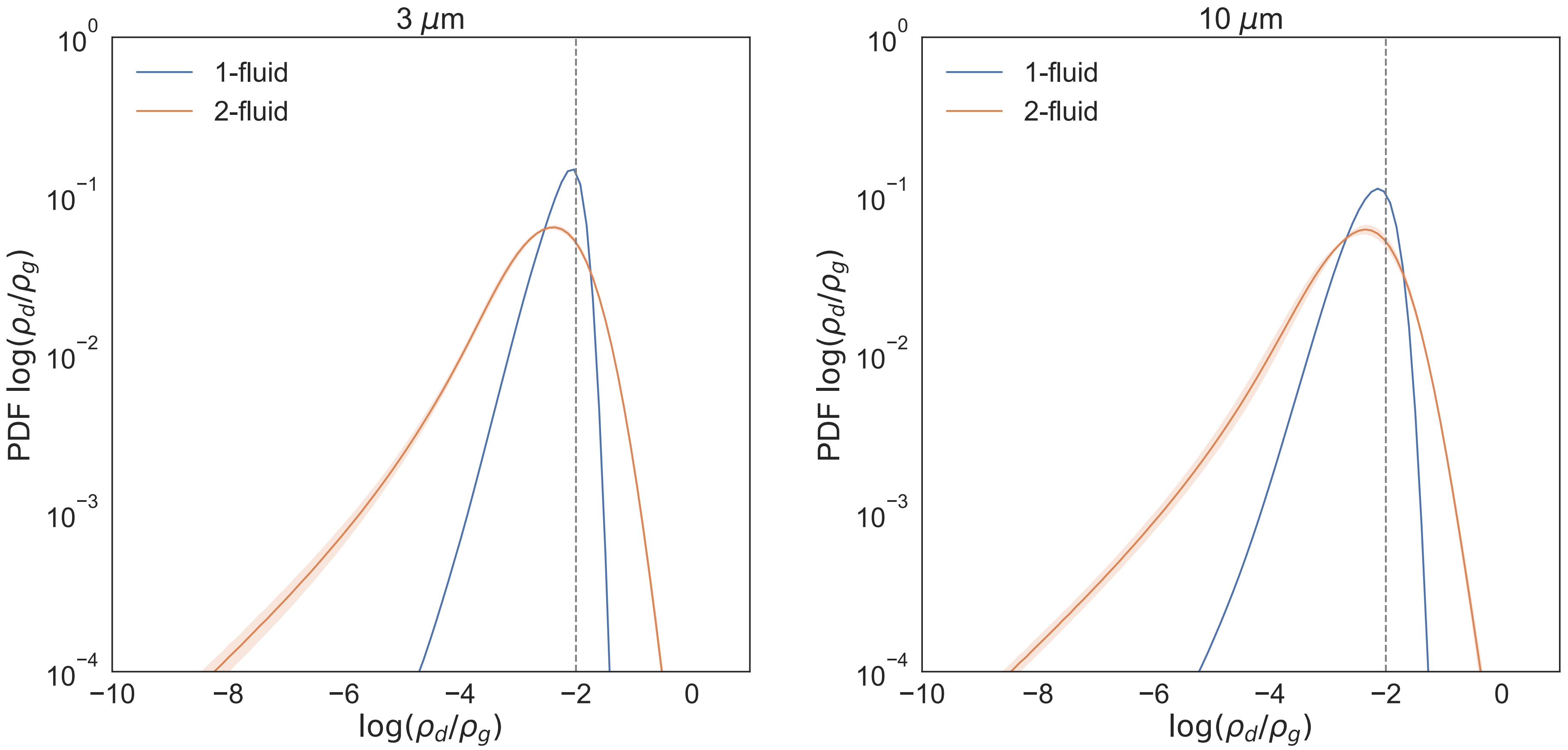
Dust Density PDFs



Time-averaged 2-fluid dust density PDFs are broader than 1-fluid.
2-fluid reaches to lower dust density and also (slightly) higher densities.

Vadood, Tricco (in prep)

Dust-to-Gas Ratio PDFs



2-fluid shows much greater variation in dust-to-gas ratios.

1-fluid dust-to-gas maximum increase is ~2-3x, whereas 2-fluid is ~20-30x.

Vadood, Tricco (in prep)

Dust-to-Gas Ratio PDFs

- 2-fluid results are similar to Commerçon et al (2023).
- But 1-fluid densities and dust-to-gas ratios are narrower.

- Difference in results is likely due to limiter applied to 1-fluid simulations in Phantom.
- Limiter is used to conserve dust mass in low-density regions.

- WIP – critical threshold appears to be around Stokes number, the ratio of dust stopping time to dynamical time.

Conclusion

- **1-fluid:**
  - Works well for tightly coupled dust-gas (dense filaments).
  - Accurate high-end tail for dust density & DTG ratio PDFs.
  - Expect at most ~2-3x increase in dust-to-gas ratios.
- **2-fluid:**
  - Works well for weakly coupled dust-gas (low density areas).
  - Accurate low-end tail for dust density & DTG ratio PDFs.
  - Substantial decreases in DTG ratio in low density regions.

- Need to be careful about choice of algorithm, and any numerical assumptions that are made, when simulating dusty turbulence.

PHANTOM

https://phantomsph.github.io/

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1st North American Phantom Users Workshop

Where: Memorial University of Newfoundland
Signal Hill Campus
St. John's, NL, Canada

When: July 8—12, 2024

Website: phantomsph.github.io/na2024

Registration still open until next week!