# Simulating Everything in the Milky Way

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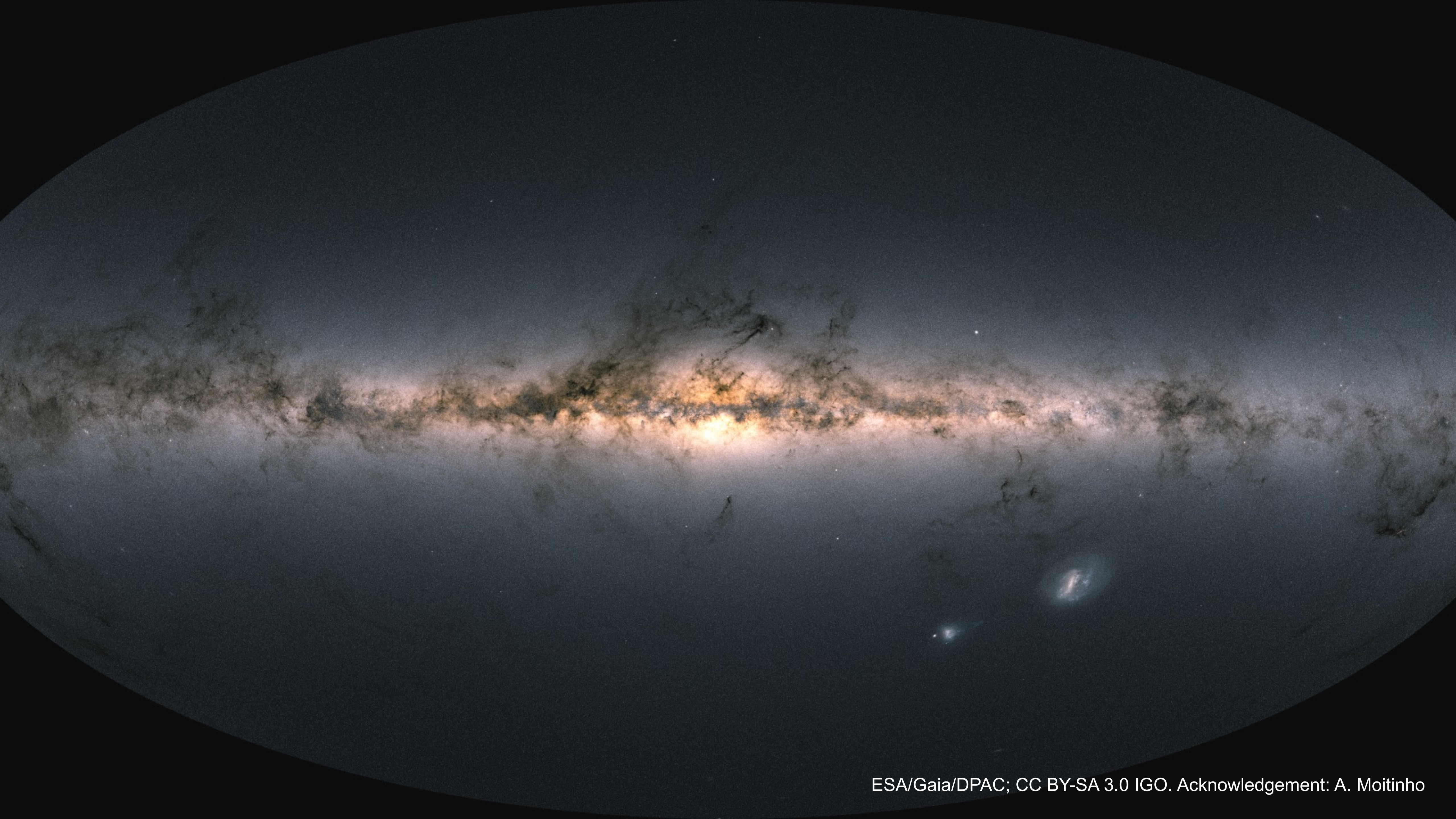

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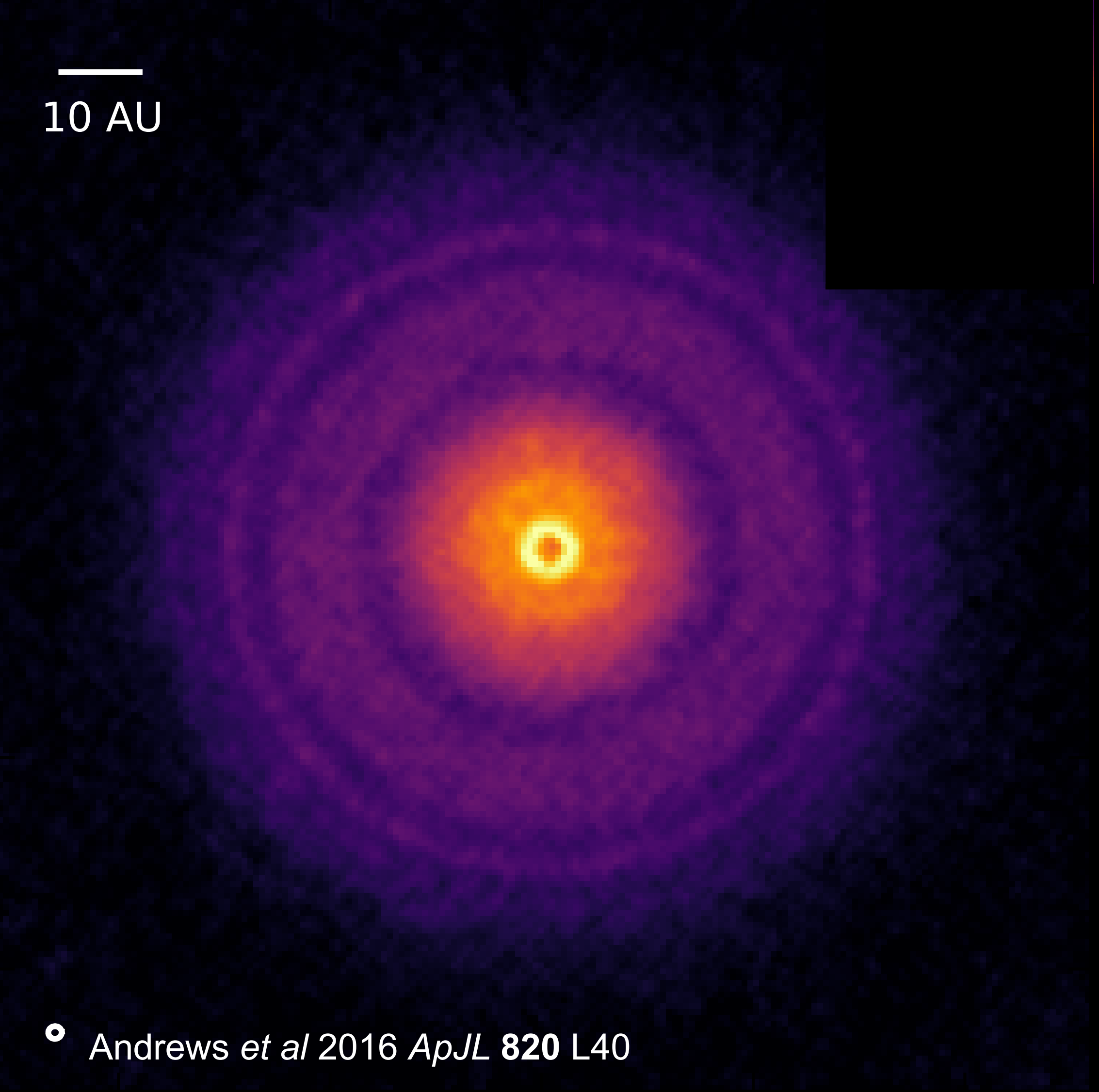
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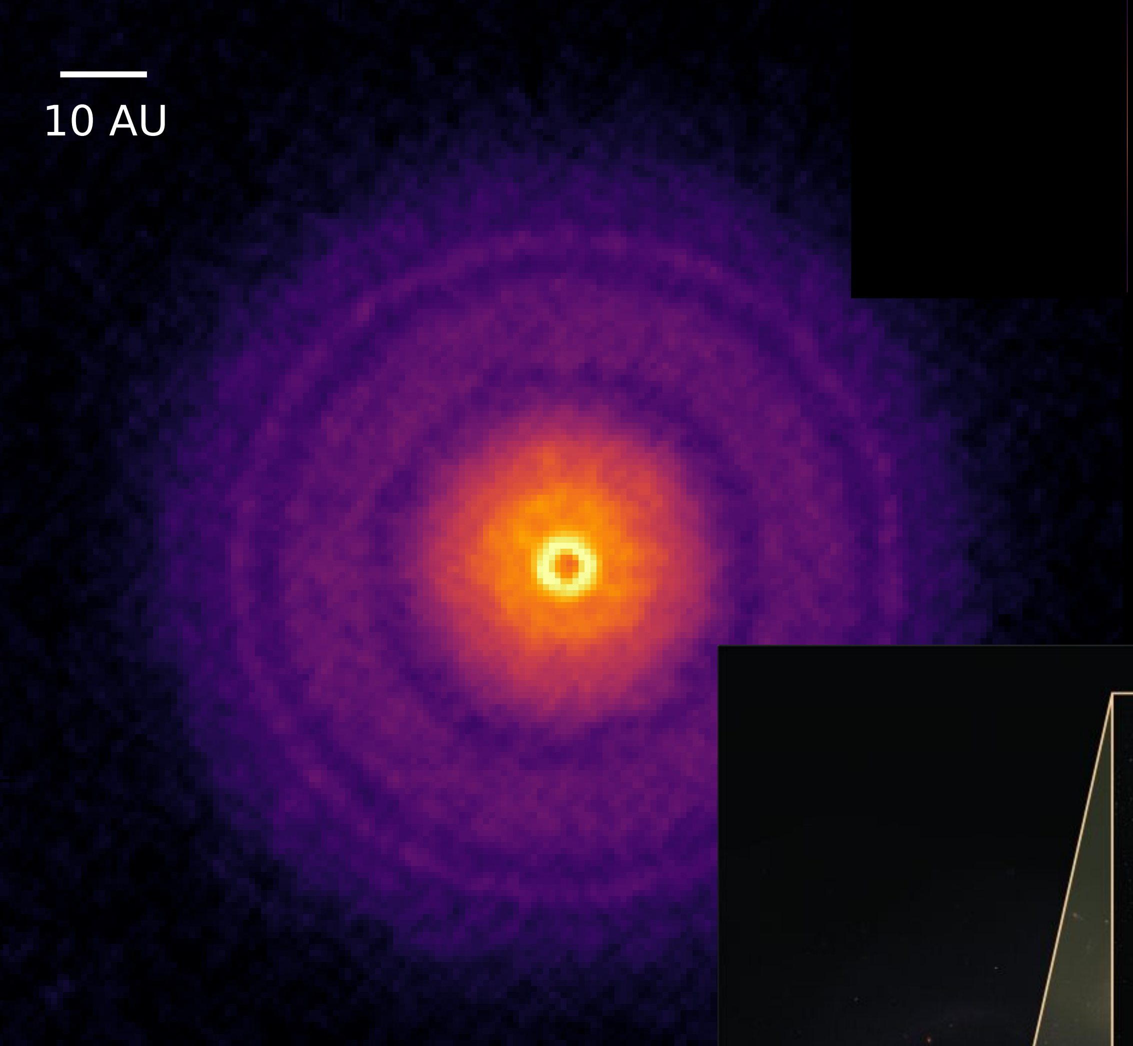


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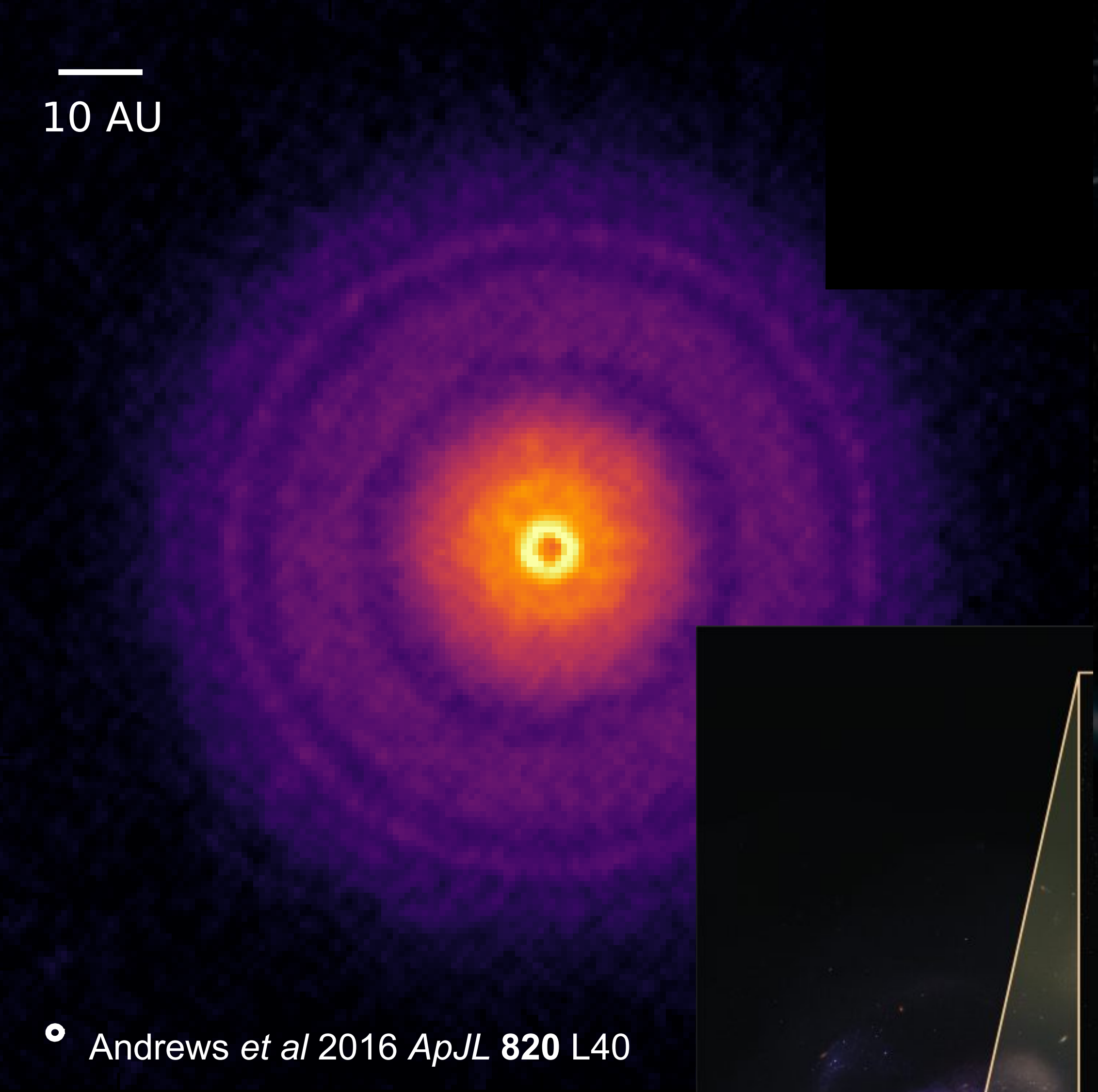
Sophia Dagnello, NRAO/AUI/NSF; NASA, STScI

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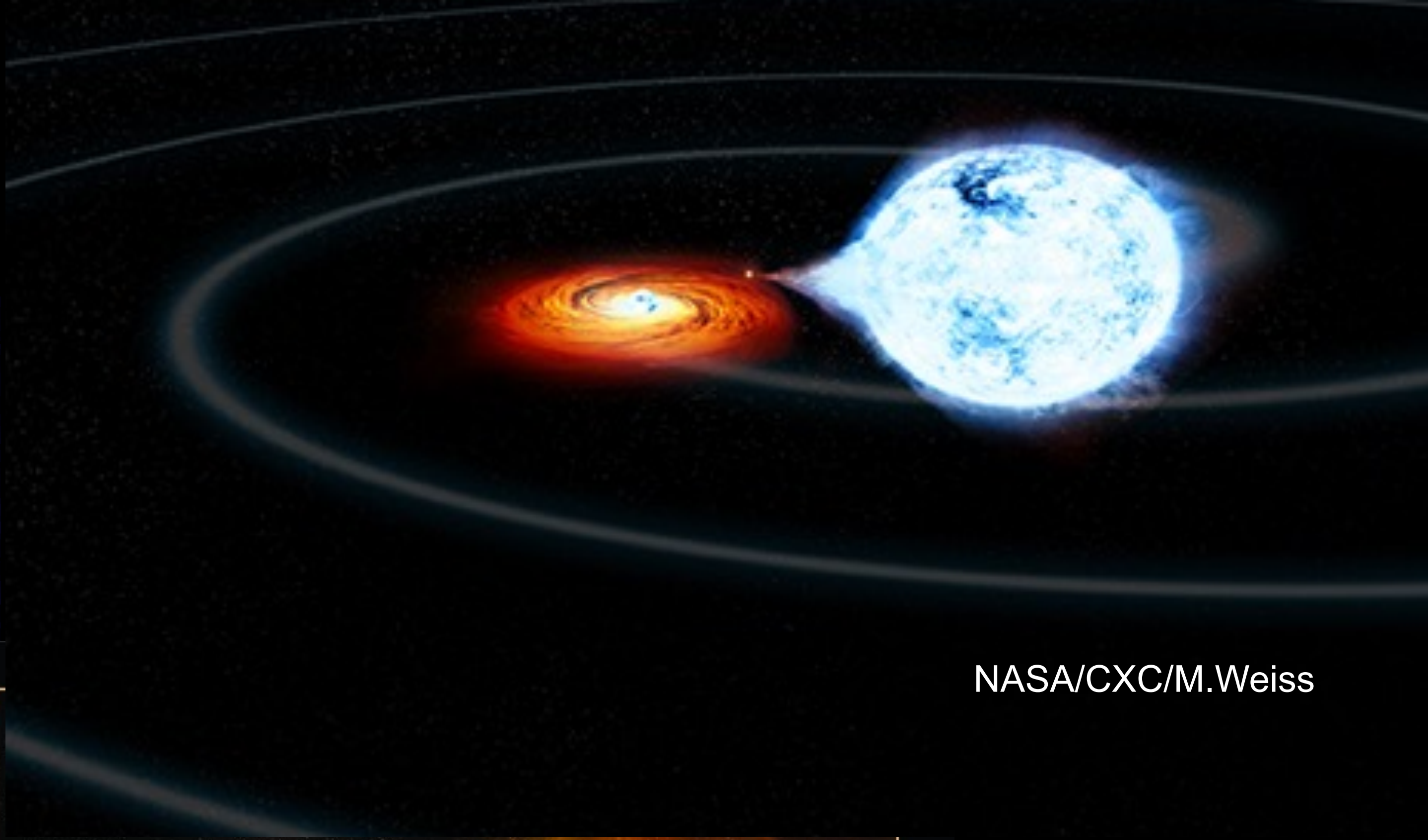

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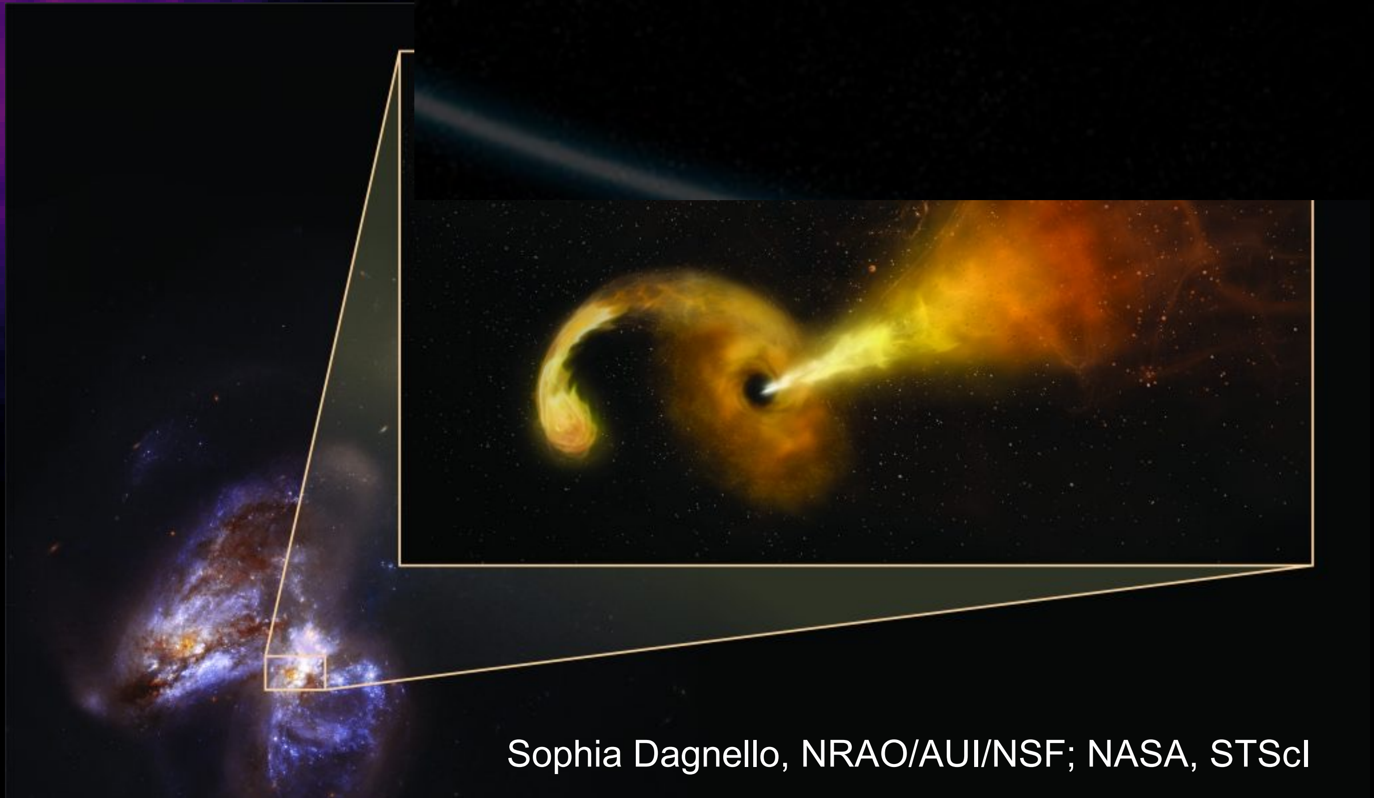

Sophia Dagnello, NRAO/AUI/NSF; NASA, STScI

# Physics Complexity

- Diverse range of physics involved throughout these systems:
  - Dust
  - Magnetic fields
  - Stellar winds
  - Radiation
  - Degenerate matter
  - General relativity
  - …

# Simulating Complex Physics

- Simulating multiple physics is a challenge!

- Some may need to work together rather than in isolation (may have dust + hydro and hydro + magnetic fields, but not charged dust).
- Differing time and/or spatial scales (e.g., radiation is hard to model explicitly).
- Physics solvers may work in some parameter spaces but not others.

# Goals

Our goals:

1. Create the physics implementations to simulate everything within the Milky Way.

2. Create one code that can be used for general study of astronomical systems.

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# Phantom

- Phantom is our high-performance smoothed particle hydrodynamics (SPH) code.
- I am one of the leads of the Phantom collaboration.

- Phantom contains algorithms for gravity, magnetic fields, dust, Navier-Stokes viscosity, galactic potentials, and post-Newtonian gravitational corrections, flux-limited diffusion.
- Has OpenMP + MPI parallelism.

# Phantom

- Phantom is publicly available (released 6 years ago).
- https://phantomsph.github.io/

- We aim for a user-friendly code with good documentation.
- CI/CD pipeline with solid software dev practices.
- Strong community with regular users workshops.
- Used for dozens of research projects (300+ citations of the code paper).

# Available Codes

- There are a number of high-quality astrophysical SPH simulation codes.
  - Gasoline2 (galaxy)
  - Swift (cosmology)
  - Gadget (cosmology)
  - Gizmo (MFM; galaxy formation)
  - StarCrasher, GradSPH, sphNG, and more.

- Phantom’s focus is on stellar, galactic, planetary and high energy astrophysics.

# My Research

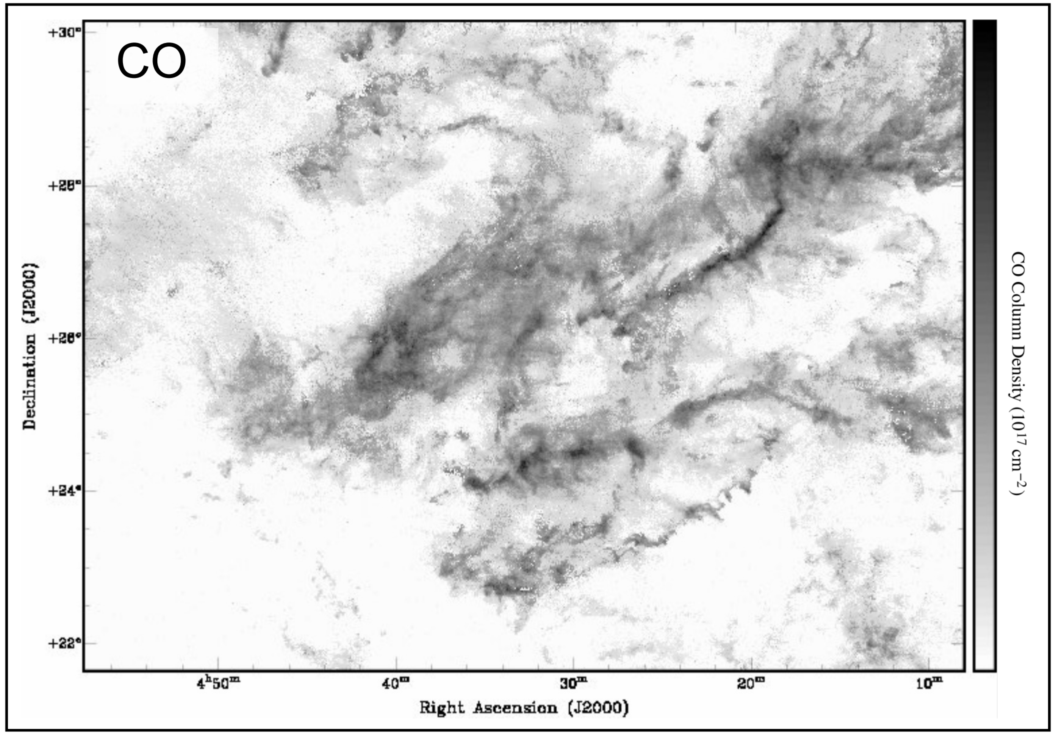
My research interests are in physics algorithms.

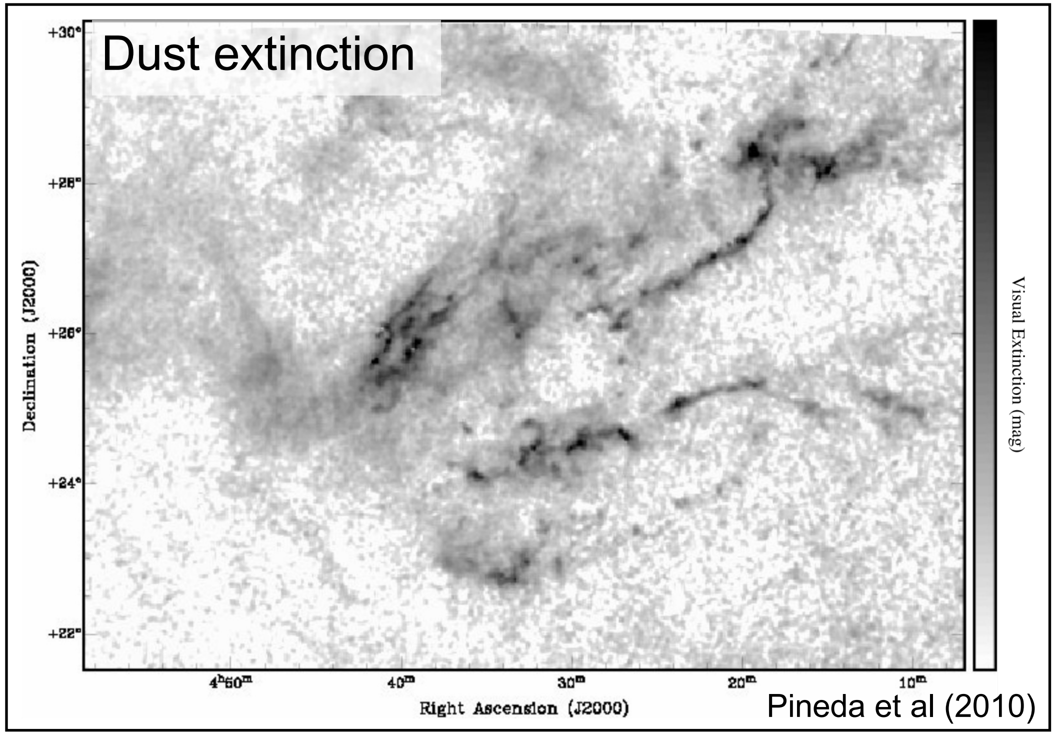
- Under what conditions do current physics solvers break?
- How can current solvers be improved?
- How can we create new solvers for additional physics?

# Dusty Turbulence

Vadood, Tricco (in prep)

# Dusty Turbulence

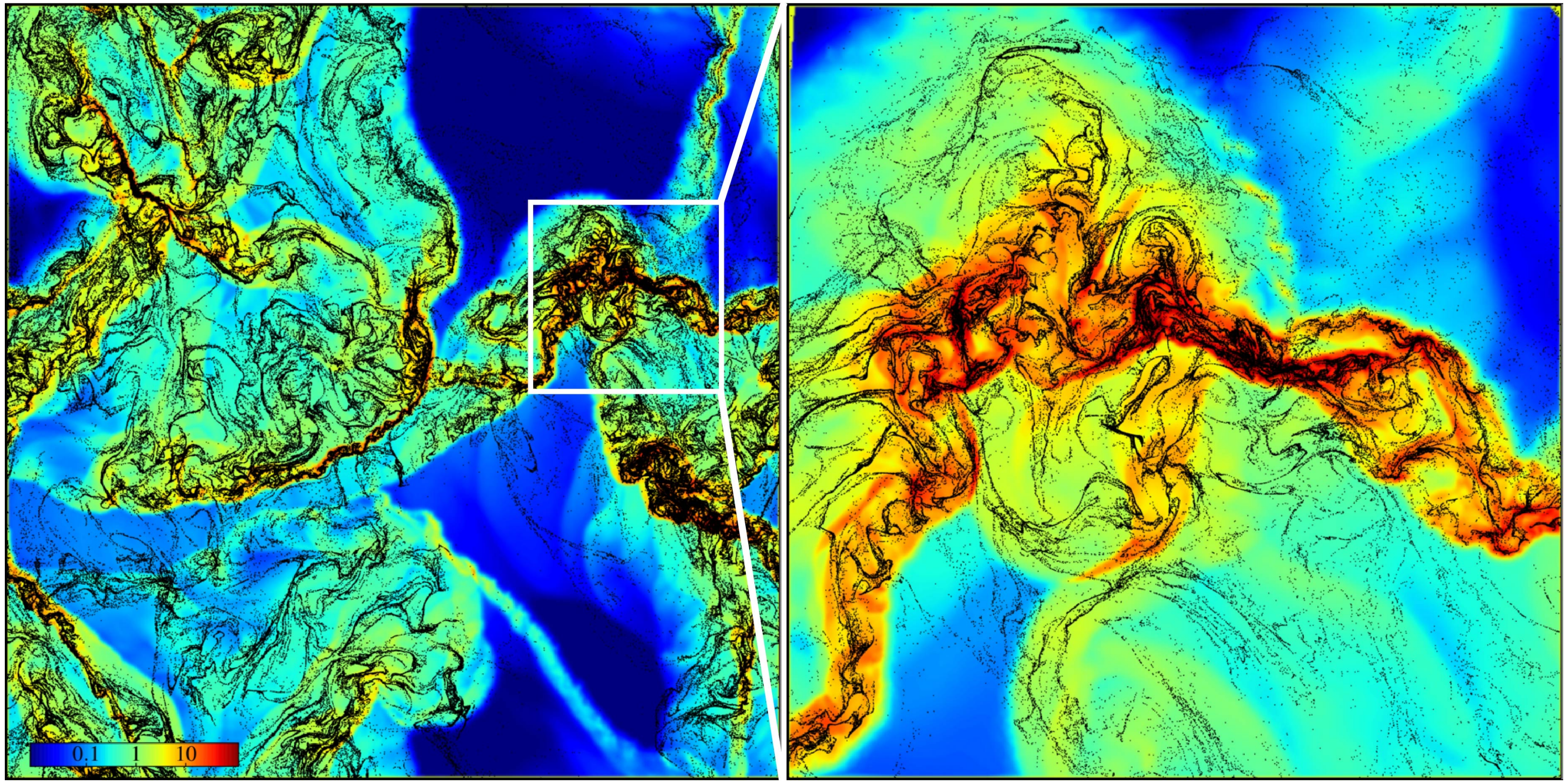


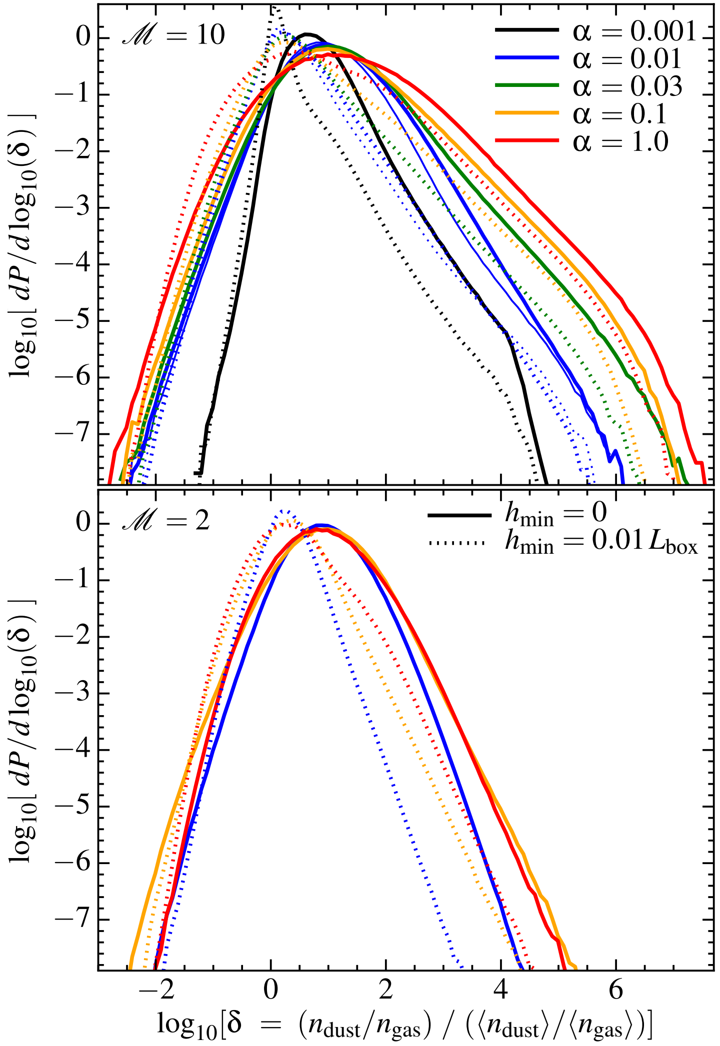




Pineda et al (2010)

- 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



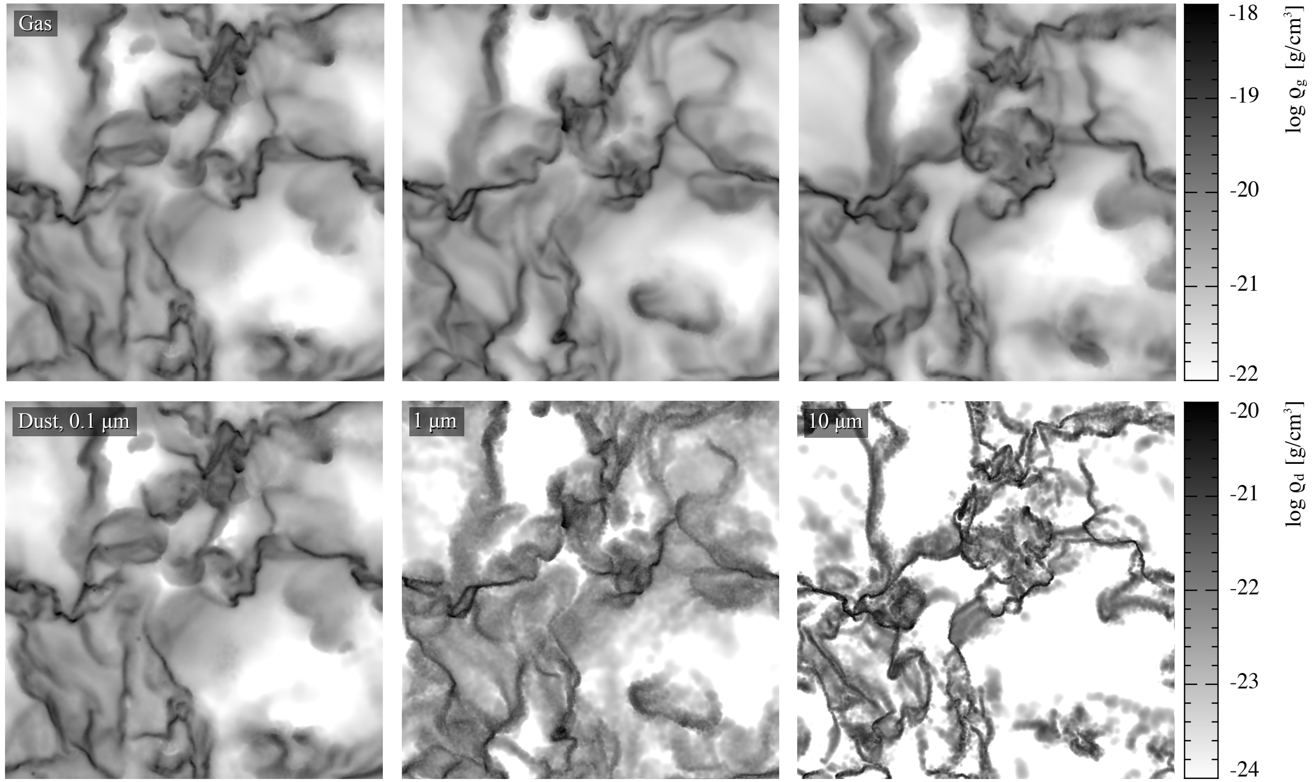



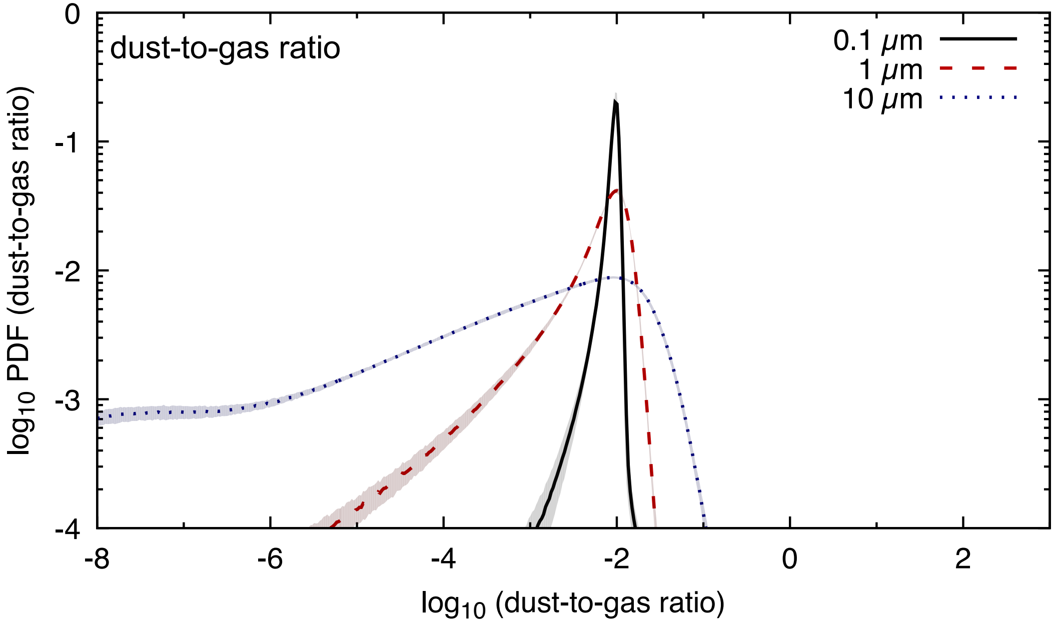

“dust filaments can exist where there is no gas filament at all"

“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

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

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

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

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

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

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

Laibe & Price 2012a,b

# 1-Fluid Dust Solver

- Particles are a mixture of dust and gas.
- Barycentric point of view is modeled. Evolving total density + total velocity + velocity drift + dust fraction.

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

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

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

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

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

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

# Two Dust Solvers

- **2-fluid** models gas + dust individually.
  - Assume they move independently. Difficult to solve when they are move together.
  - Works well for large grains.

- **1-fluid** models gas + dust as a combined mixture.
  - Assume they move together. Difficult to solve when they move separately.
  - Works well for small grains.

# Dust Method Comparison

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

- 1-fluid method grid for mixed gas + dust.
- 2-fluid method used grid for the gas + Lagrangian tracer particles for the dust.

# Dust Method Comparison

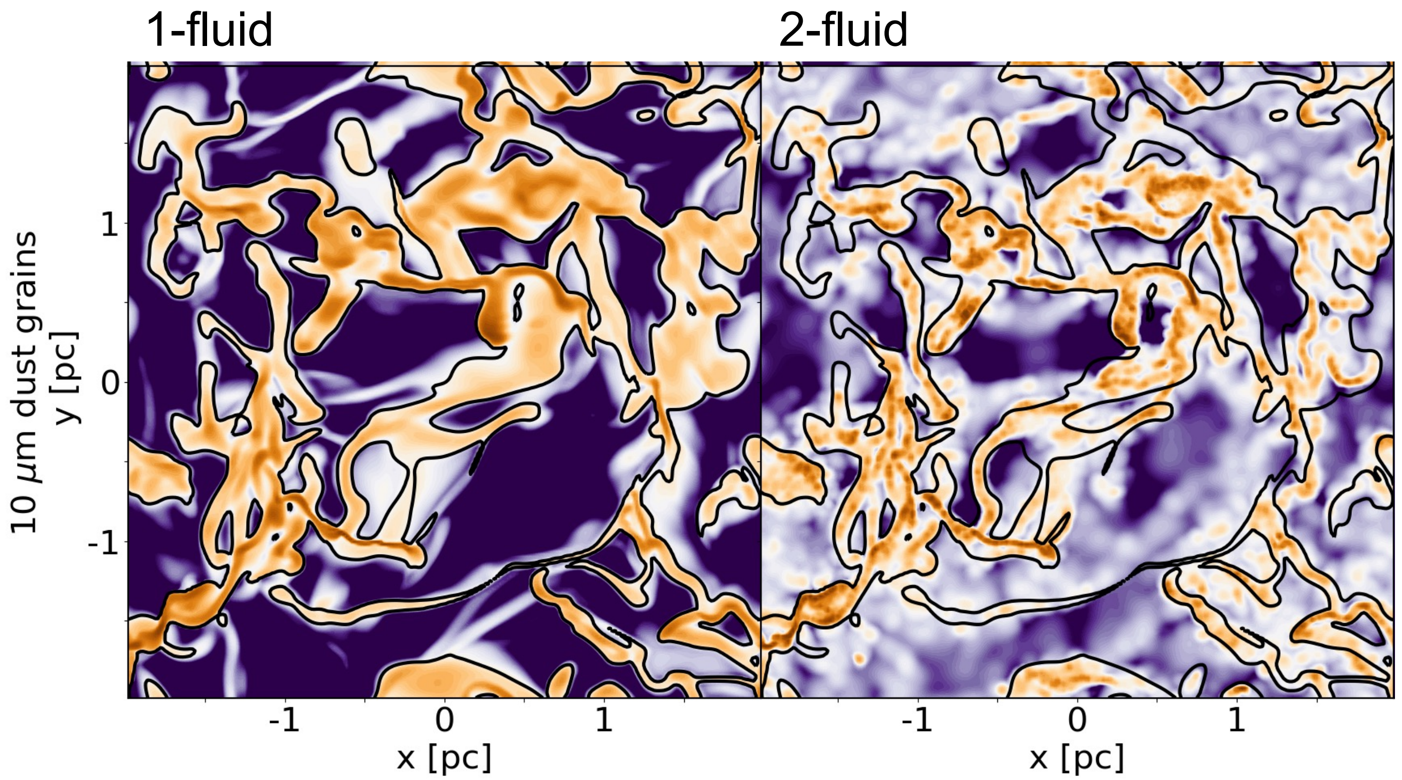
“Our results for the two-fluid dust as Lagrangian particles are **globally consistent with those of Hopkins & Lee** (2016) at very low α, with the largest variation of the dust ratio observed in the regions of low gas density."

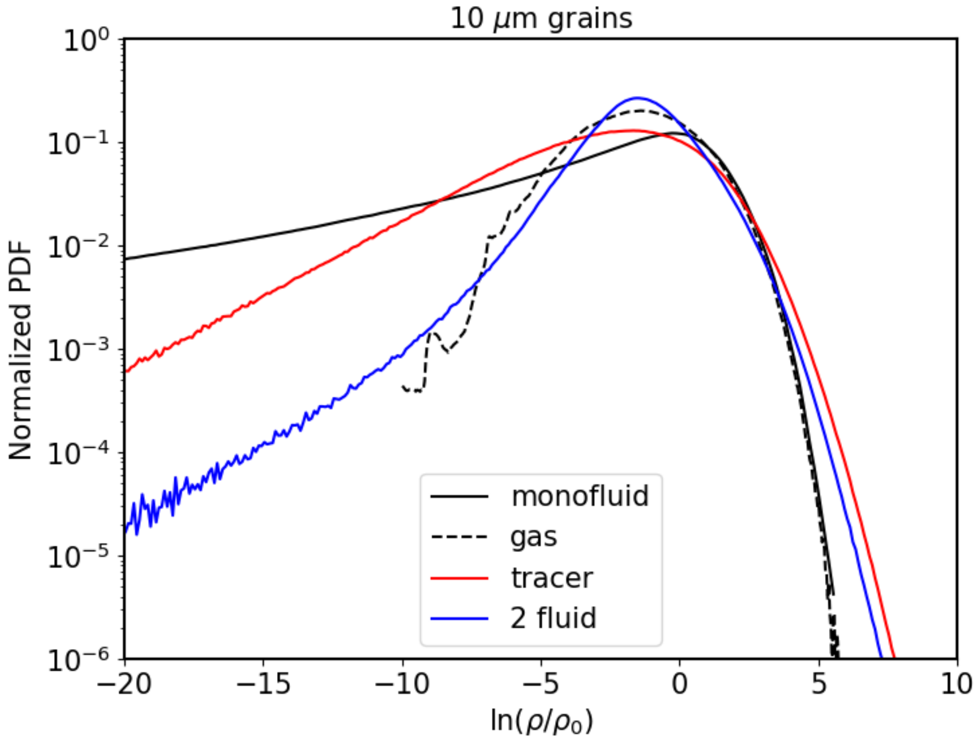
“Our [1-fluid] results are in **very good agreement with previous work by Tricco et al.** (2017). "

“..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. “

Commerçon et al (2023)

# 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.

- 3 and 10 micron 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.

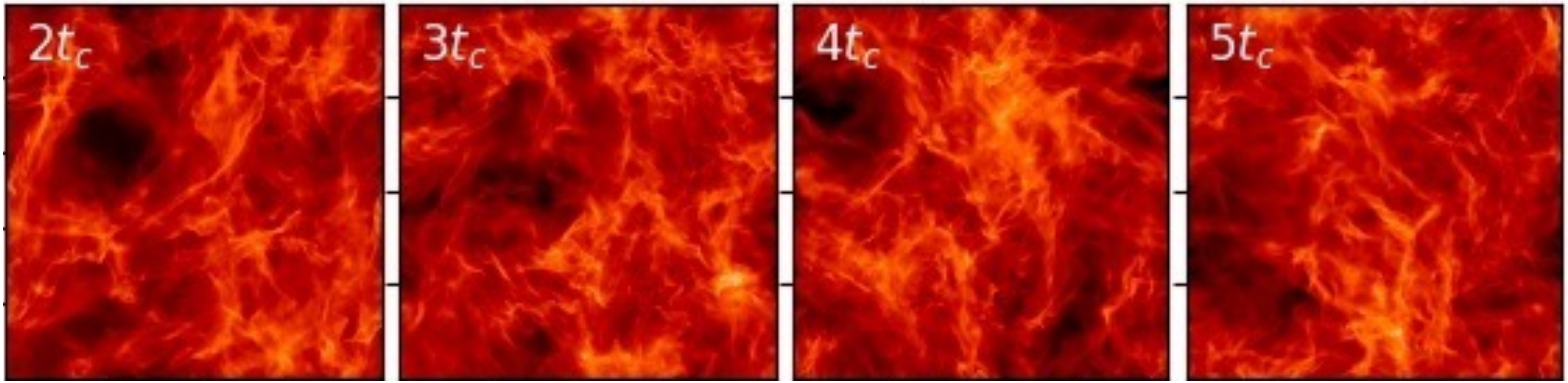
# SPH Dusty Turbulence Comparison

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

- Can isolate any differences as being due to just the dust solver.
- All other numerical details are exactly the same, including the turbulent driving pattern.

- Work led by MSc student Narges Vadood.

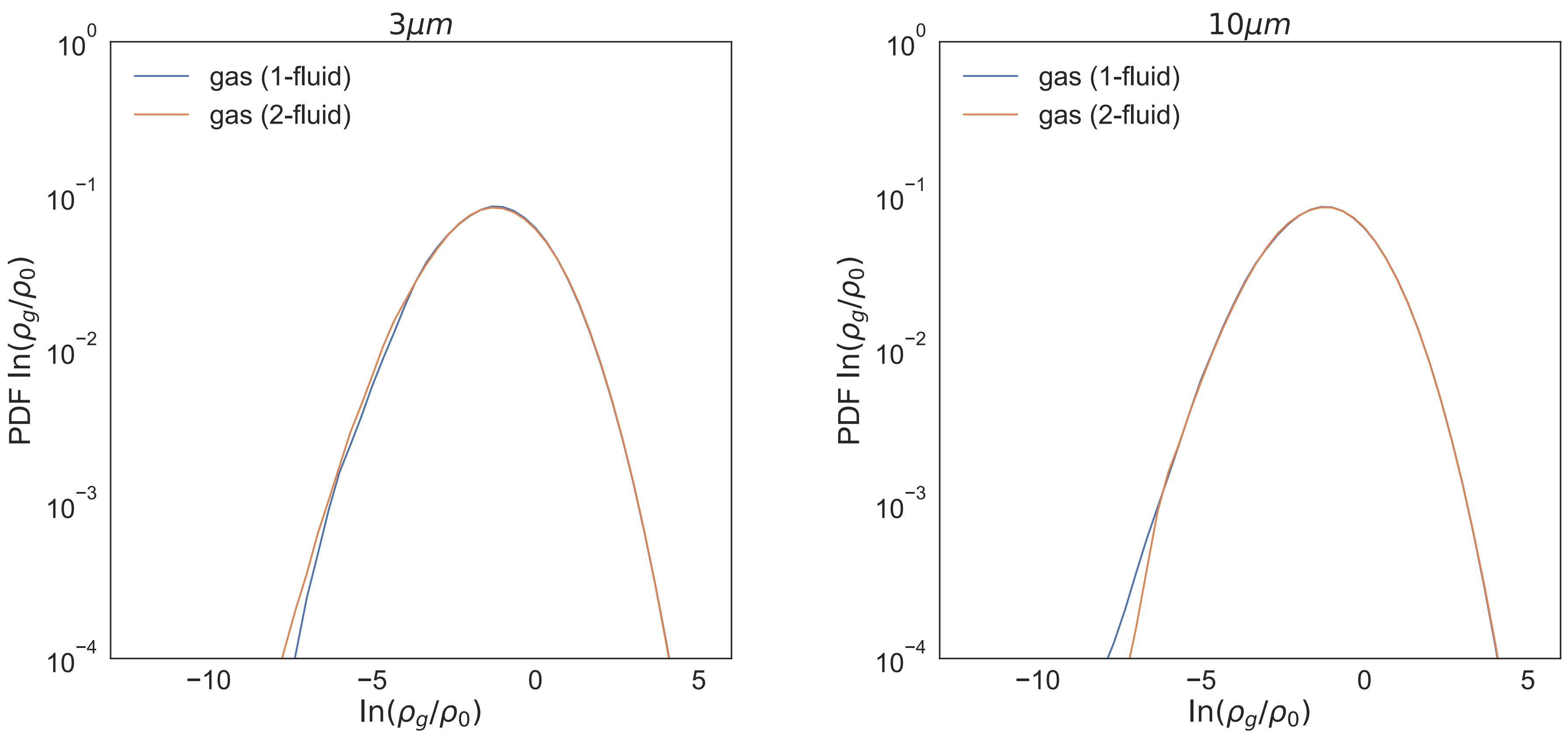
# Gas Density Evolution




- 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)

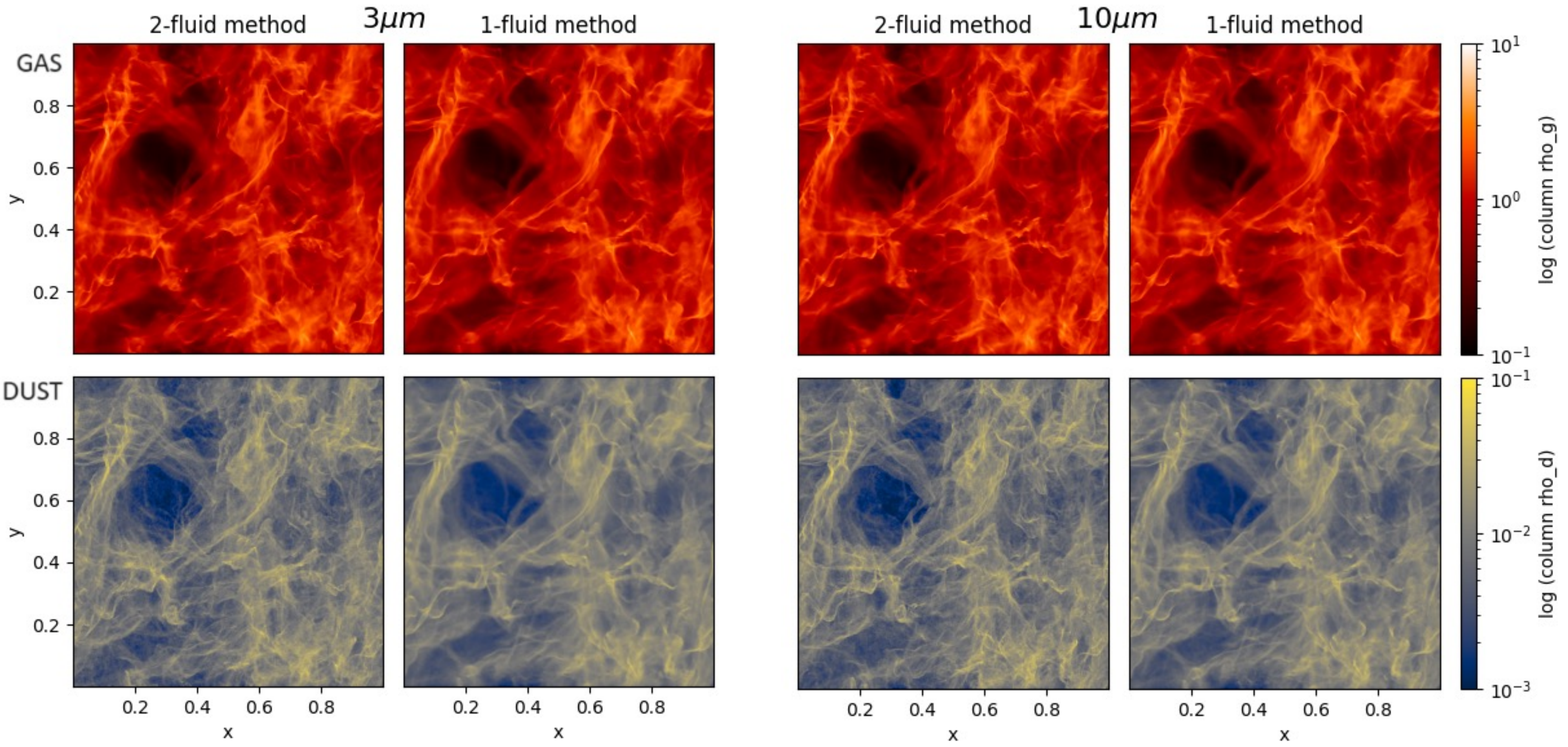
# Gas Density PDFs




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

Vadood, Tricco (in prep)

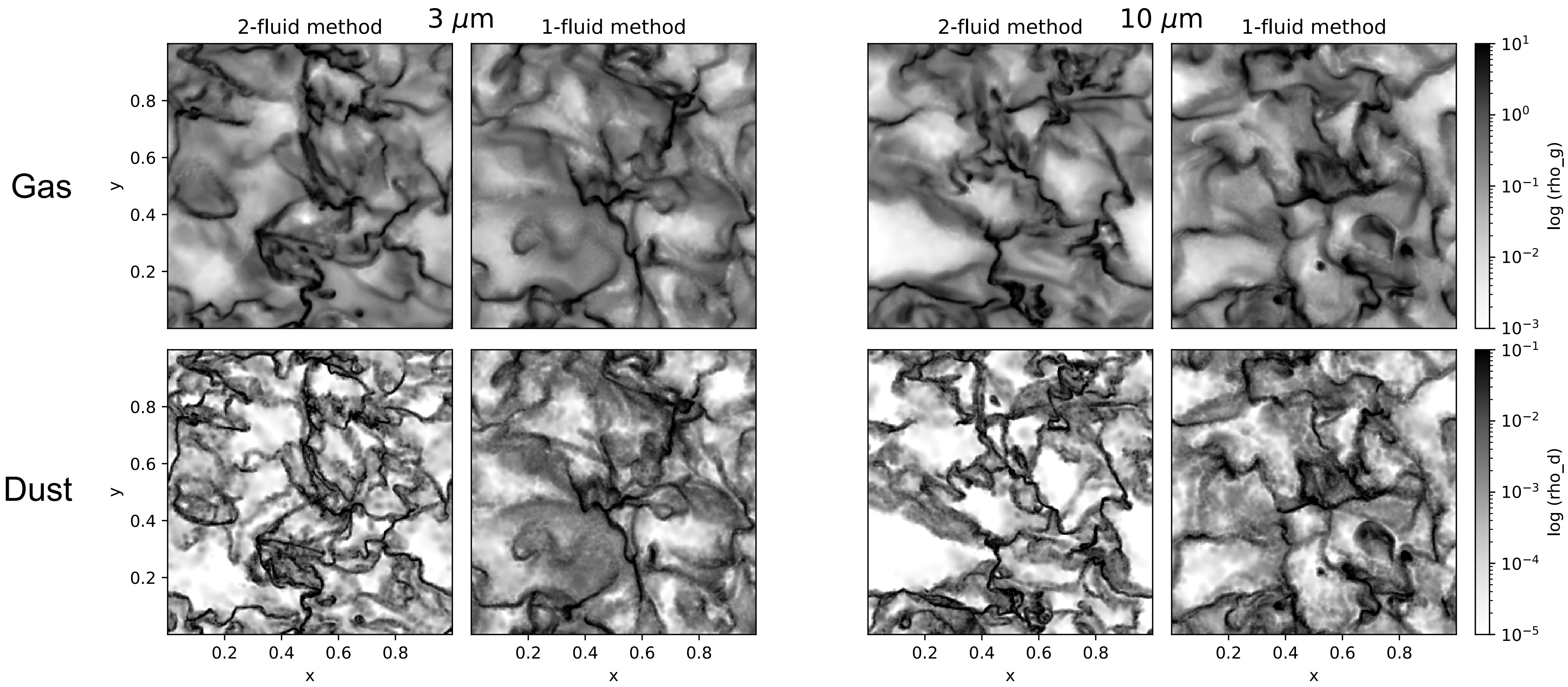
# Column Gas / Dust Density




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

Vadood, Tricco (in prep)

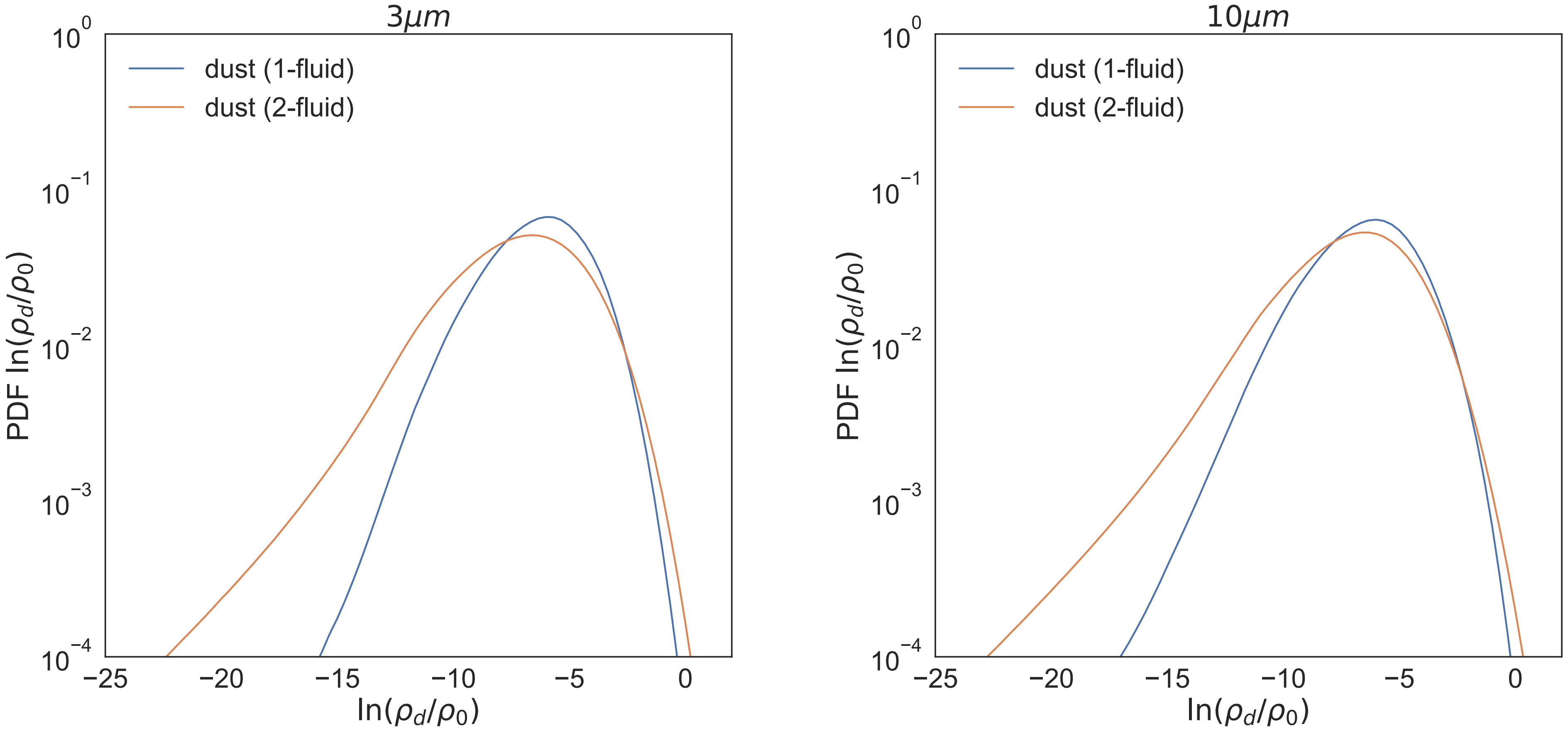
# Planar Slices of Gas / Dust




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

Vadood, Tricco (in prep)

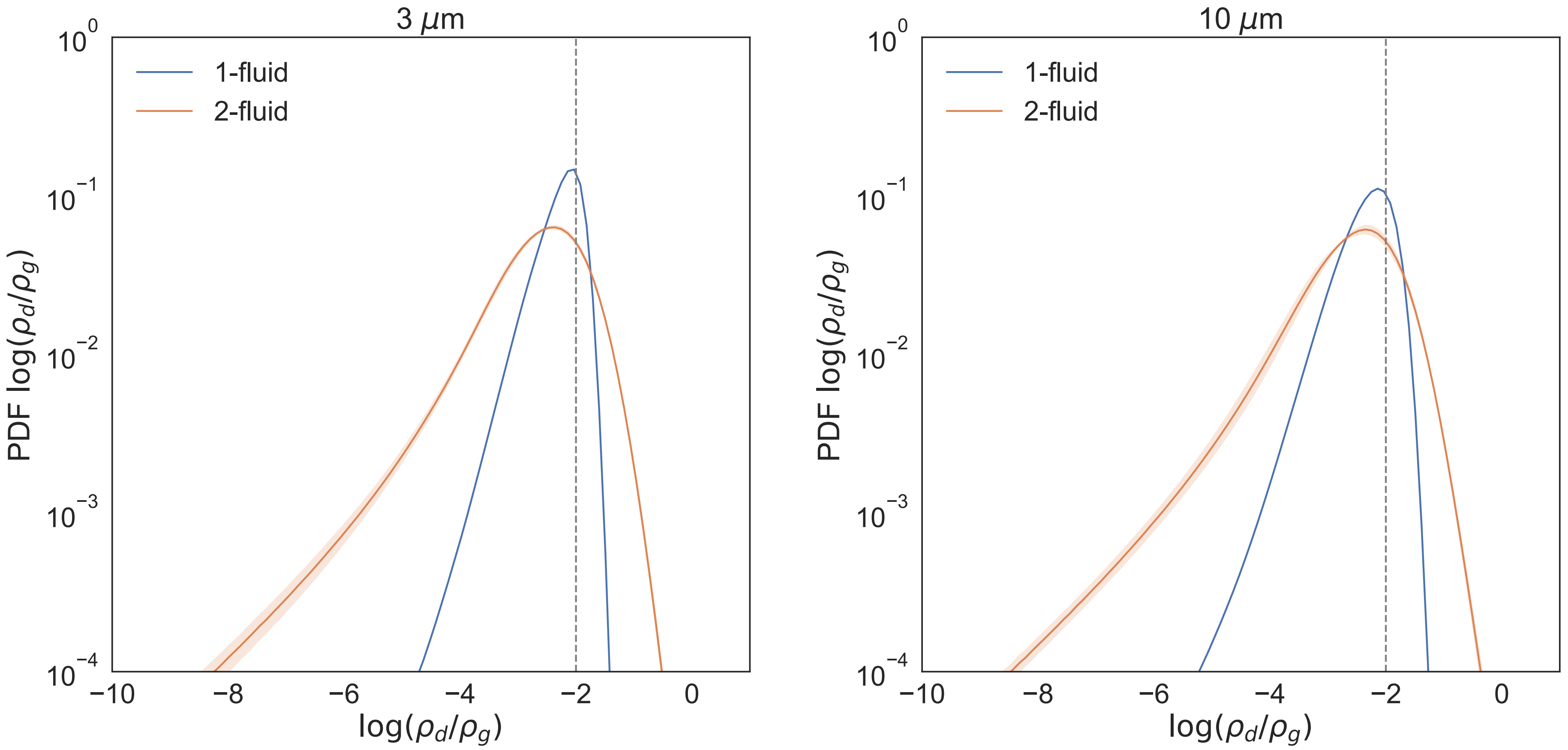
# Dust Density PDFs




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

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

- Continuing to dive deeper into analysis of numerics.
- Difference likely due to 1-fluid limiter used in Phantom to avoid numerical inaccuracies in low-density regions.
- WIP – critical threshold appears to be around Stokes number, the ratio of dust stopping time to dynamical time.

# Conclusion

- I am interested in the pedantic numerical details of multi-physics SPH algorithms.
- This often involves testing the boundaries of these algorithms to validate their accuracy and applicability.

- Our goal is for Phantom to contain the algorithms needed to simulate everything within the Milky Way.

- Next Phantom Users Workshop is in St. John's this July!
- Registration open: https://phantomsph.github.io/na2024/