Is the Dust-to-Gas ratio constant in molecular clouds?

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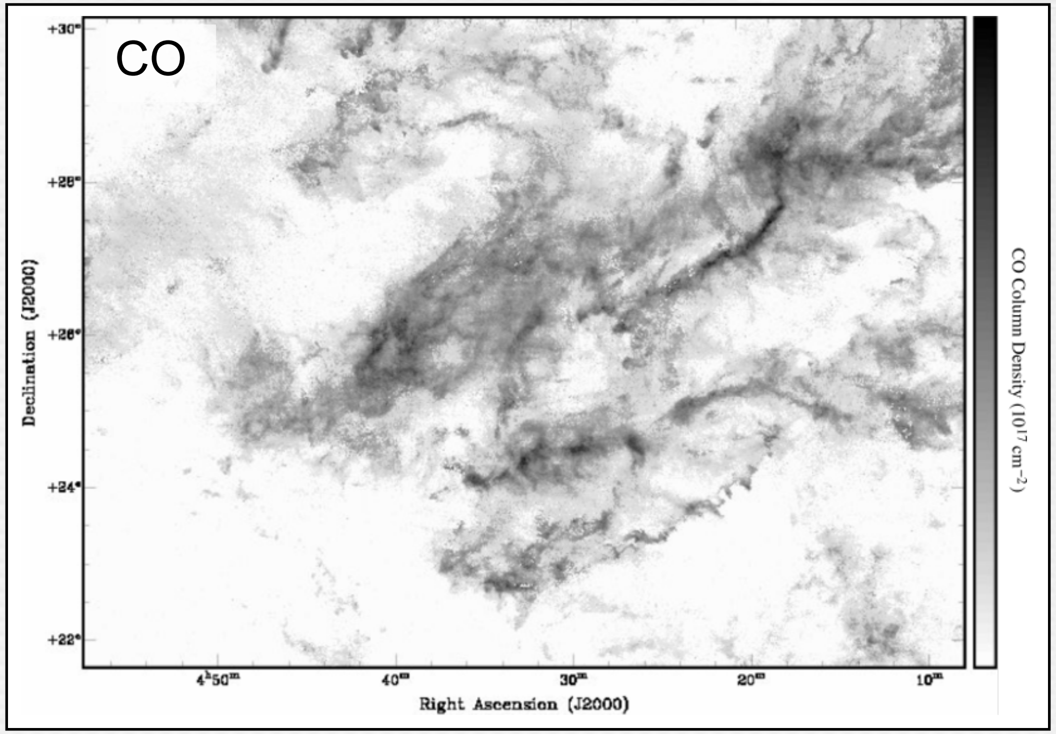
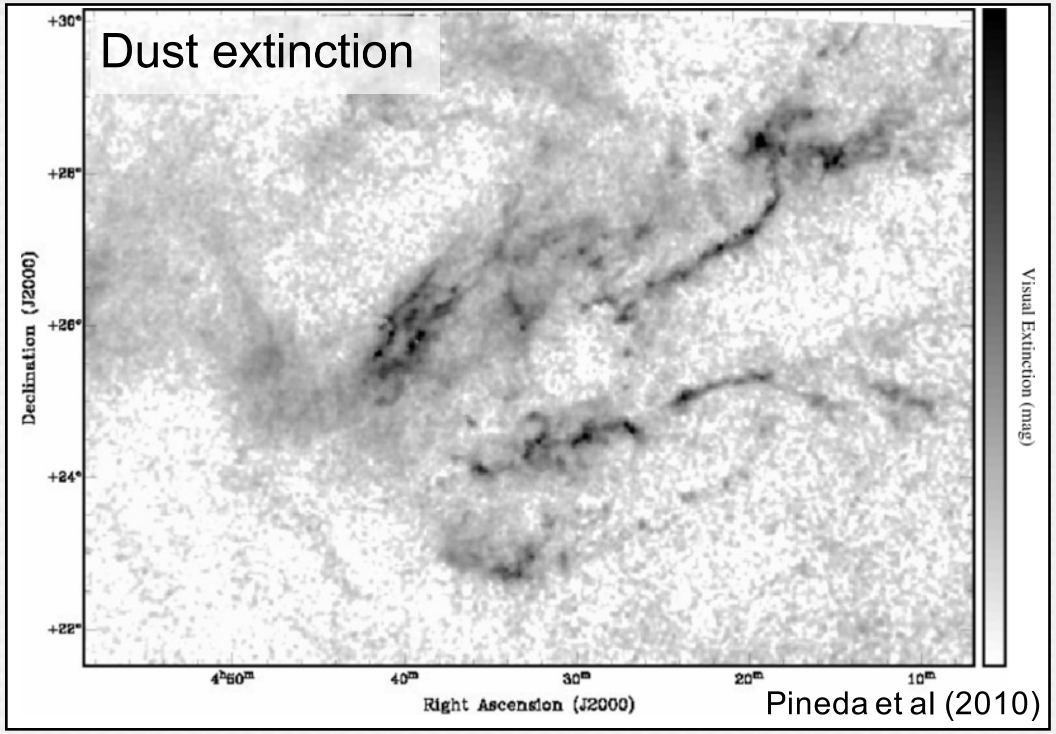
Dust as a Measure of Gas Mass





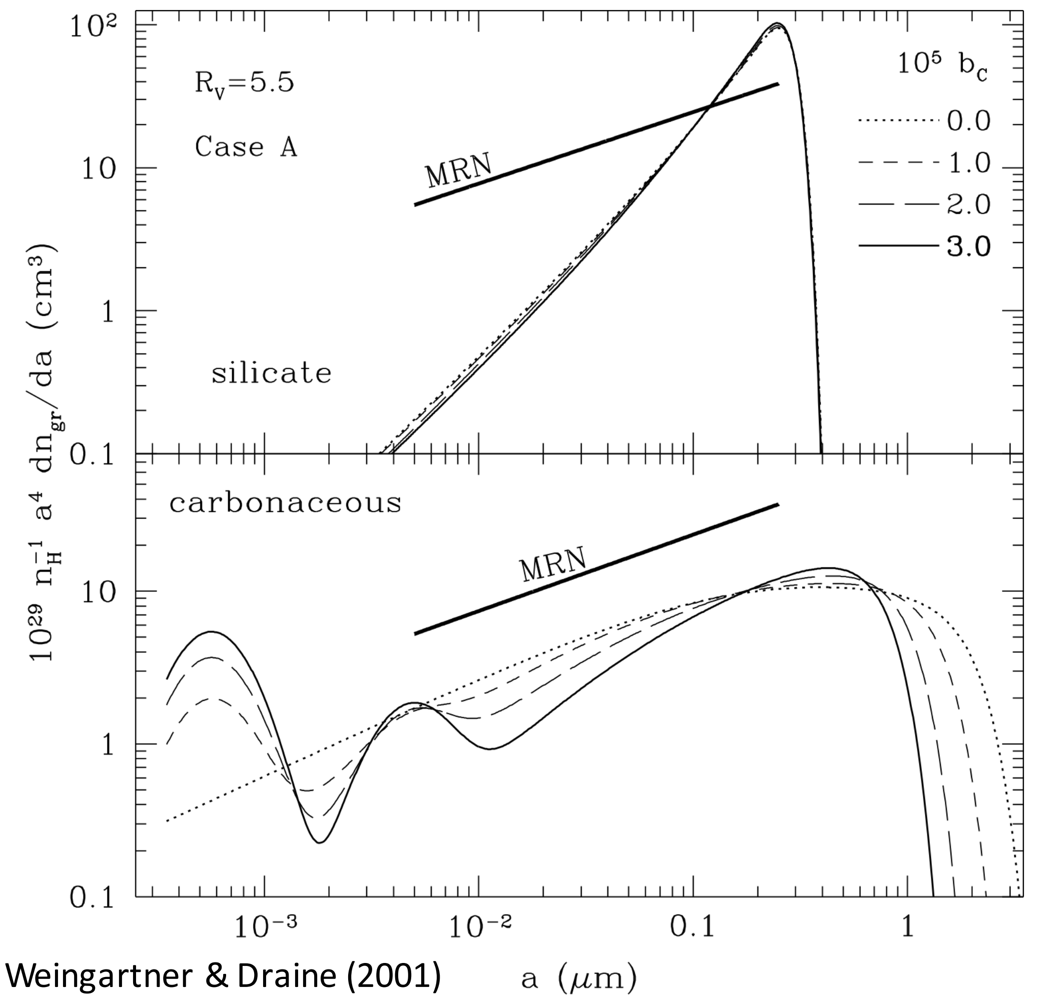
Pineda et al (2010)

- H_2 effectively invisible
- Dust distribution correlates well with molecules
- Use dust or molecular tracers to infer cloud mass
- Requires understanding of the dust properties to have accurate mass measurements

Dust in Molecular Clouds

- **Anomalous extinction laws:**
  - Rv = Av / (Ab – Av) = 3.1 in diffuse clouds (fairly "universal"), but Rv ~ 5 in molecular clouds (Cardelli+ 1989; Weingartner & Draine 2001)
  - Implies molecular clouds have a different grain size distribution
- **Coreshine phenomenon:**
  - higher abundance of large grains (>1 micron) in dense filaments (Pagani+ 2010; Steinacker+ 2010; Lefevre+ 2014)

- e.g., Evans et al 2009 dust re-calibration of c2d data resulted in 40% change of cloud mass



Weingartner & Draine (2001)

Dust is not gas!

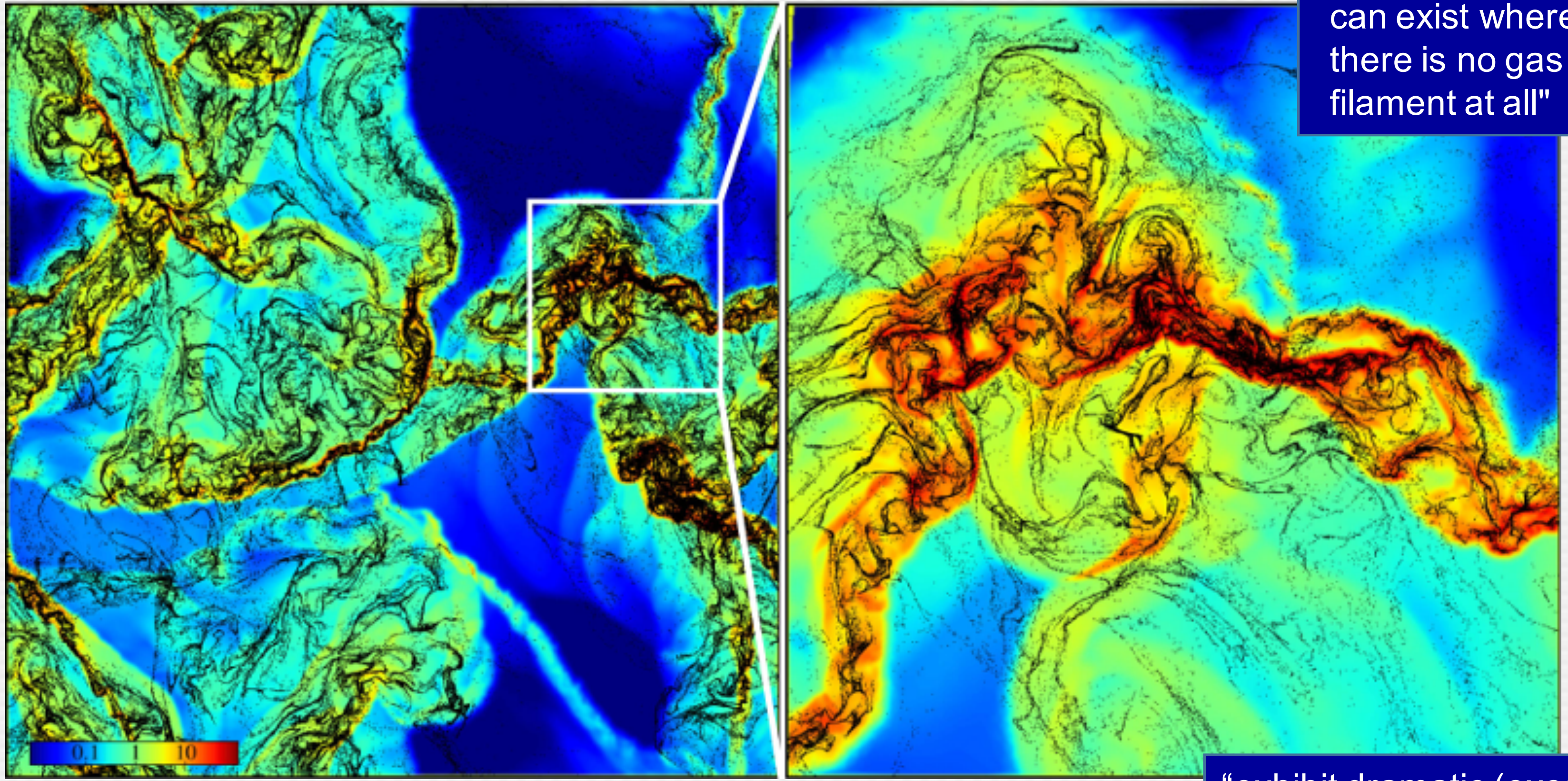
- Dust behaves dynamically different than gas
- But would it have a noticeable effect?
- Let's do some simple napkin math
  - ρ ~ 10^{-20} g/cm^3 (gas density)
  - c_s ~ 0.2 km/s, (sound speed)
  - s_{grain} ~ 0.1 micron (grain size)
  - ρ_{grain} ~ 3 g/cm^3 (intrinsic grain density)

➢ Drag stopping timescale, $t_s \sim \rho_{grain}\, s_{grain} / \rho \sim 10^3$ yrs

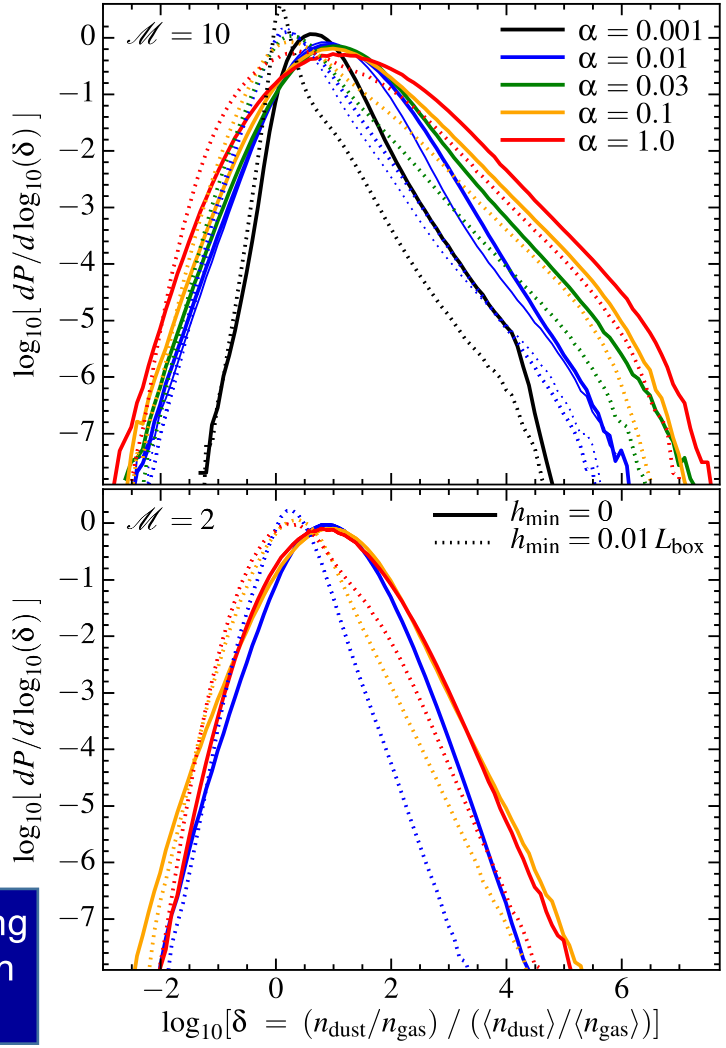
➢ Expect well-mixed and coupled mixture of dust and gas (High drag regime.)

- But this assumes cloud is homogenous and *ignores turbulence*!
- Could supersonic turbulence cause dynamical variations in the dust-to-gas ratio?

Dusty Turbulence with Gizmo



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

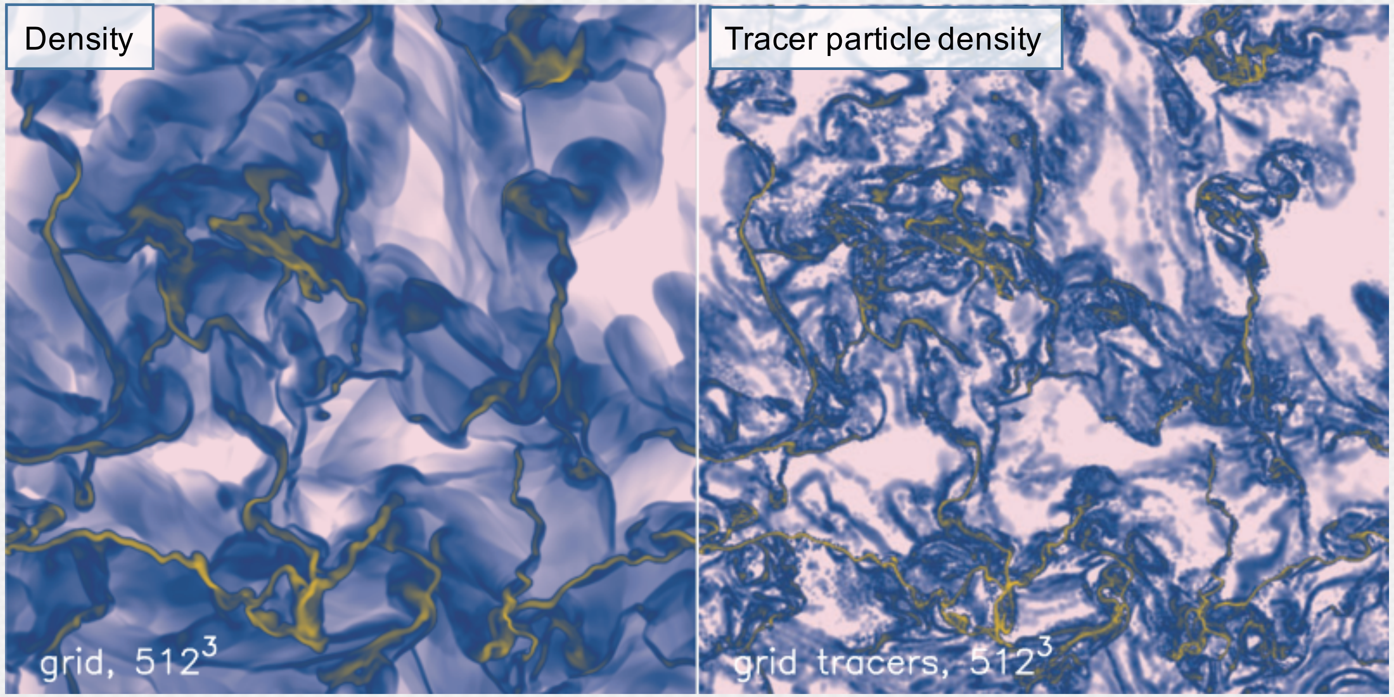


"exhibit dramatic (exceeding factor ~1000) fluctuations in the local dust-to-gas ratio"

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

Dust & Gas Mixtures in High Drag

- Timestep criterion: drag stopping timescale, t_s
- Spatial criterion: *resolve 'stopping length'* of dust grains to be *in the gas*, $l_s \sim c_s * t_s$ (Price & Laibe 2012)
  - For ~ 0.1 micron dust grains in cold, dense molecular clouds, require ~ 1600^3 gas elements (even stricter in dense filaments!)



- Tracer particles in compressible turbulence are known to suffer from numerical artefacts (Price & Federrath 2010; Genel et al 2013)

*"it is notable that a **dense shock structure appears** in the [tracer particles] **that is completely absent** from both SPH and grid density fields"*

"the resulting [density] PDFs show a strong deviation from a lognormal distribution, particularly in the high density tail"

*"the velocity field tracers **display structures that do not exist in the gas distribution**"*

Dust/Gas: Barycentric Point of View

One fluid approach (Laibe & Price 2014a,b; Price & Laibe 2015)

- Change of variables; each element is mixture of dust and gas

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

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

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

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

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

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

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

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

- Ideal when dust and gas well coupled
- No spatial resolution criterion since gas/dust are combined
- Accurate for stopping time short when gas/dust move together

Dust/Gas: Barycentric Point of View

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Gas mass conservation

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

Dust mass conservation

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

Gas momentum conservation

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

Dust momentum conservation

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

Total mass conservation

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

Total momentum conservation

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

Dust/gas ratio

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

Differential velocity

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

- Ideal when dust and gas well coupled
- No spatial resolution criterion since gas/dust are combined
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Supersonic Dusty Turbulence

Modelled turbulent dynamics of dusty molecular clouds using the Phantom SPH code (Price et al, 2017; phantomsph.bitbucket.io)

- Not concerned with grain growth or destruction
- No self-gravity (not trying to make stars) or magnetic fields

Initial Conditions:
- L = 3 parsec, ρ = 10^{-20} g/cm^3 (peak $\rho \sim 10^{-17}$ g/cm^3)
- Isothermal gas with T= 11.5 K, c_s = 0.2 km/s
- Mach 10 turbulence driven on large scales for ~ 14 Myr

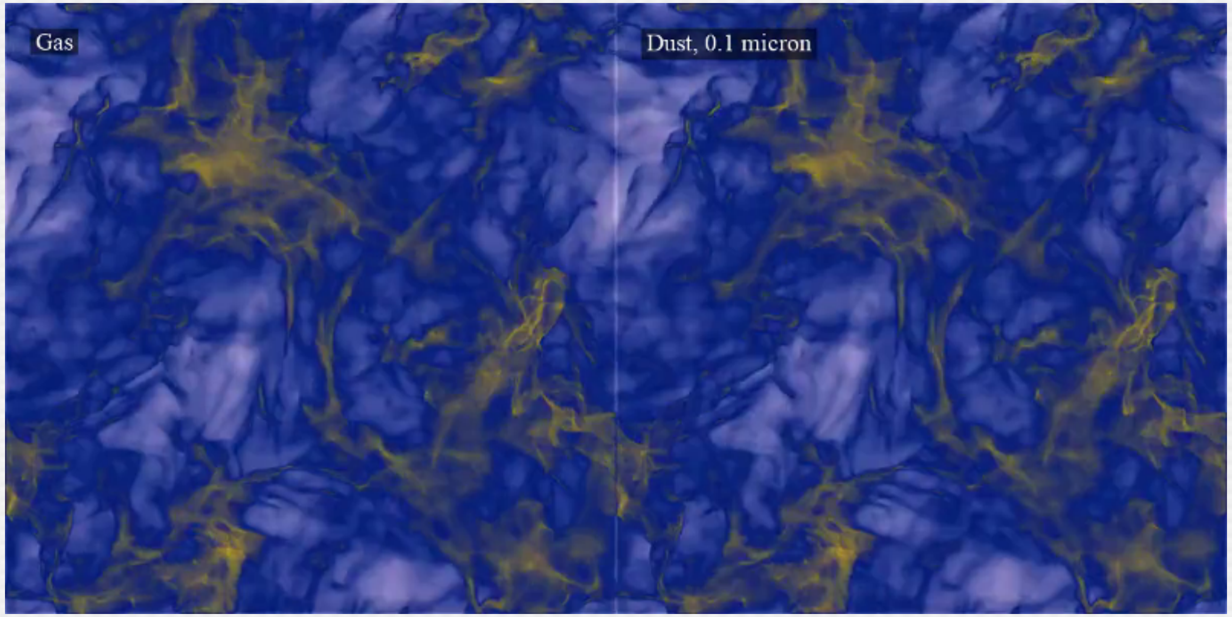
Dust:
- 0.1, 1 and 10 micron dust grains (3 separate simulations)
- Initially uniform 1% dust-to-gas mass ratio
- Includes back-reaction of dust on gas

PHANTOMSPH

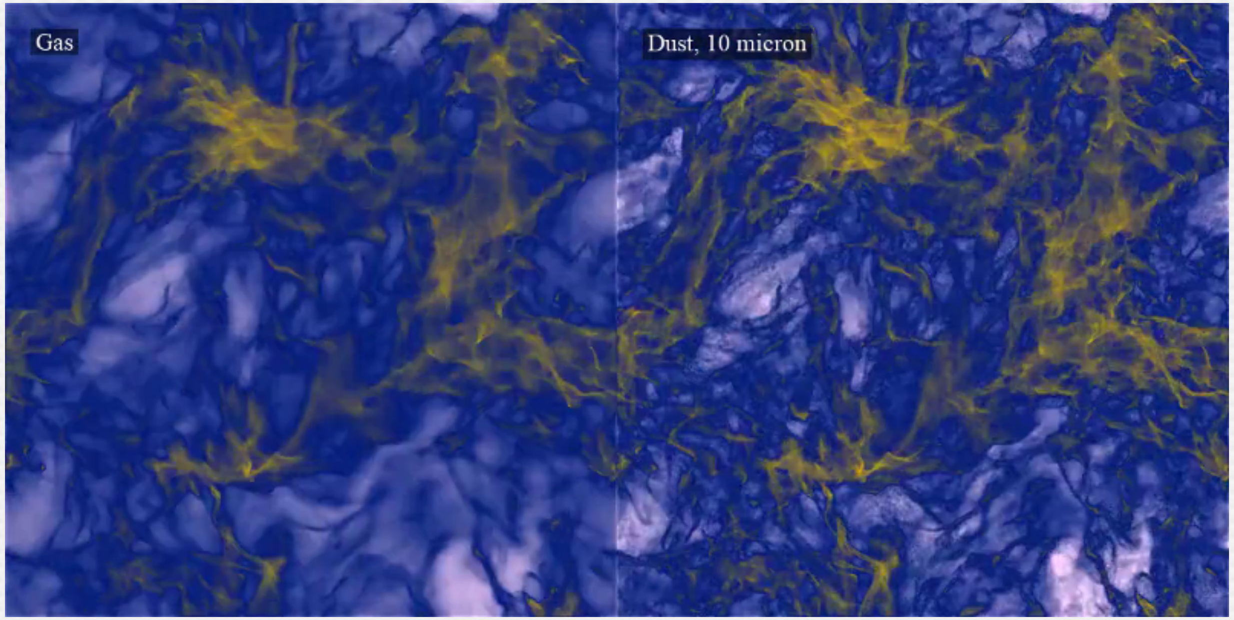
http://phantomsph.bitbucket.io

Column Densities

Gas 0.1 micron dust

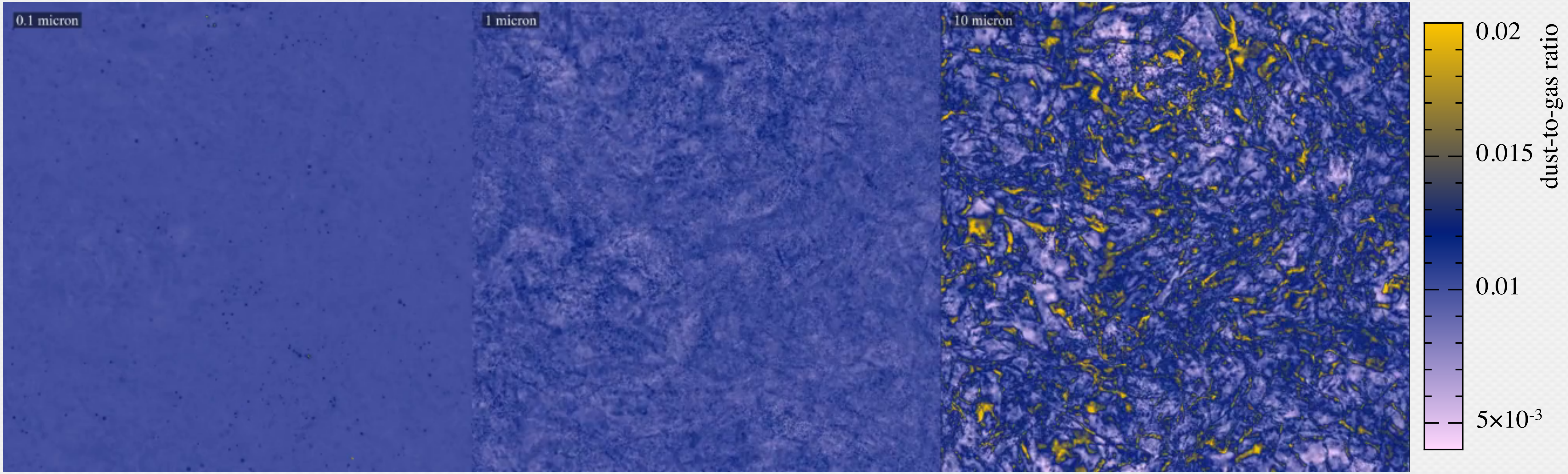


Gas 10 micron dust

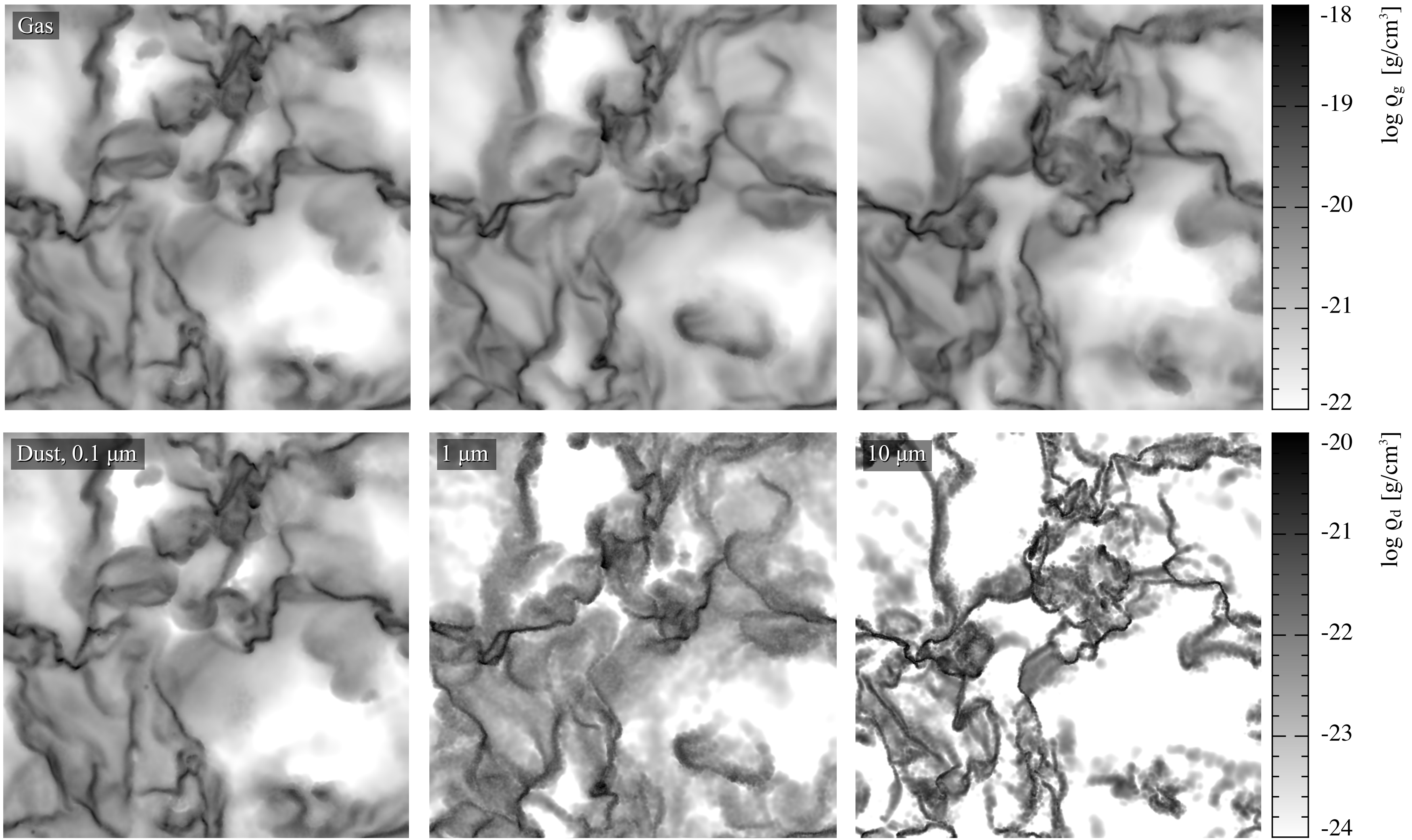


- Large-scale column dust density traces gas column density for all grain sizes
- For 10 micron, local variations in dust column density relative to gas column density

Column Dust-to-Gas Ratio



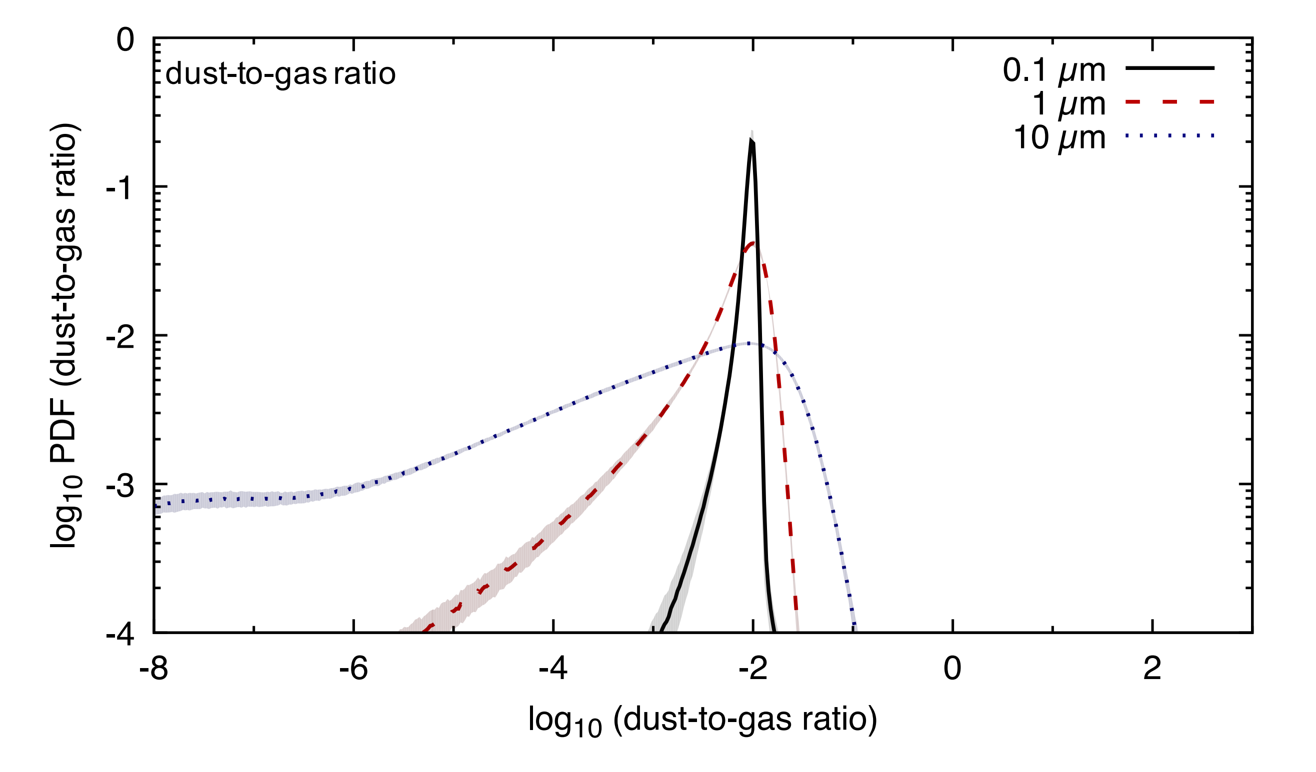
- Almost no variation in dust-to-gas ratio for 0.1 micron grains
- Large, 10 micron grains typical variations of ~2-3x (max ~10x)



Slices through midplane of cloud

Dust/Gas Ratio Distribution

- ~0.1 micron grains:
  - Sharply peaked PDF of dust-to-gas ratios at 1%
  - Dust density distribution matches gas (well-coupled throughout cloud)
- 1-10 micron grains:
  - PDFs broaden with increasing grain size due to 'size-sorting'
  - Turbulence causes dynamical transfer of dust mass into high density filaments



Gas and Dust Density Distributions

- ~0.1 micron grains:
  - Sharply peaked PDF of dust-to-gas ratios at 1%
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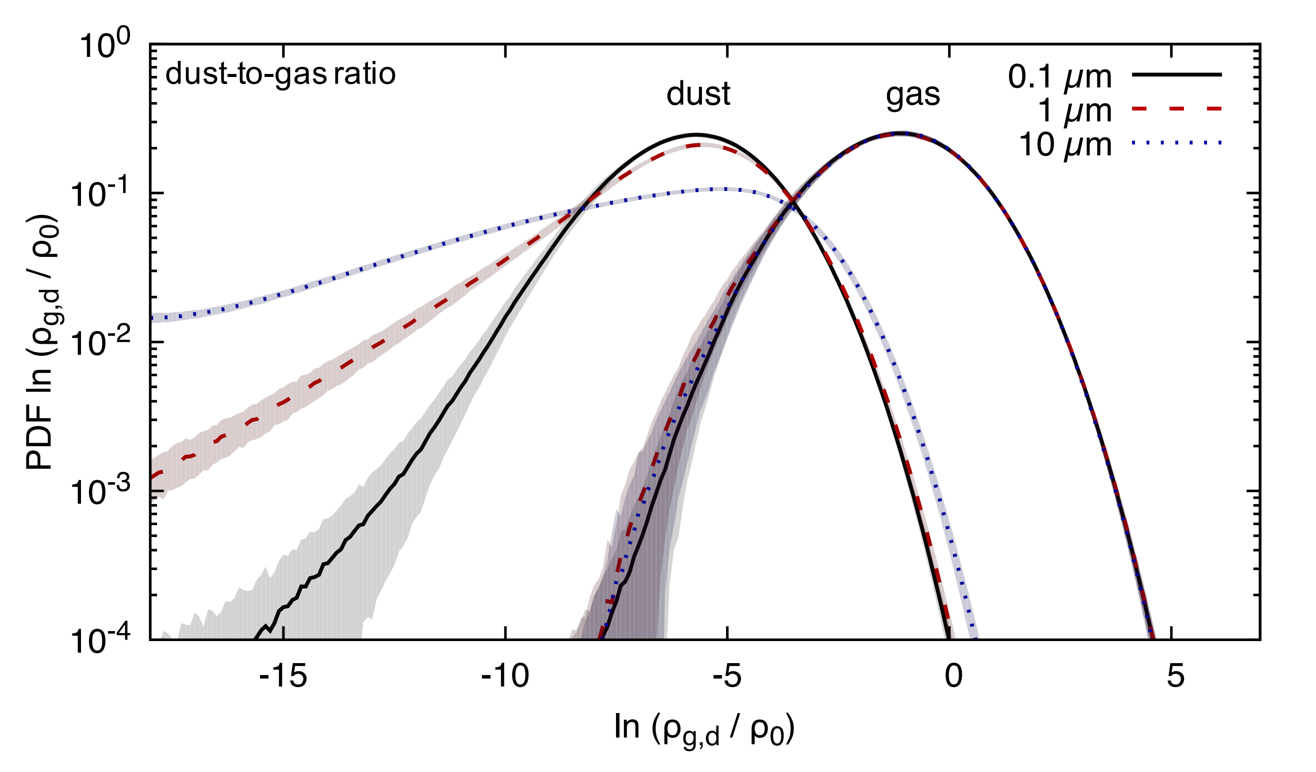
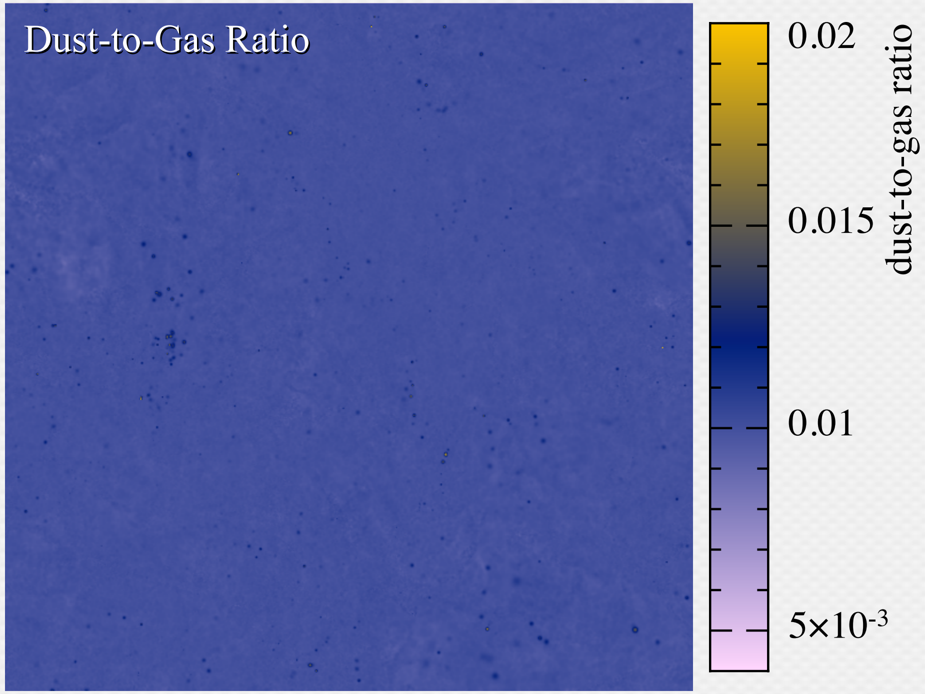
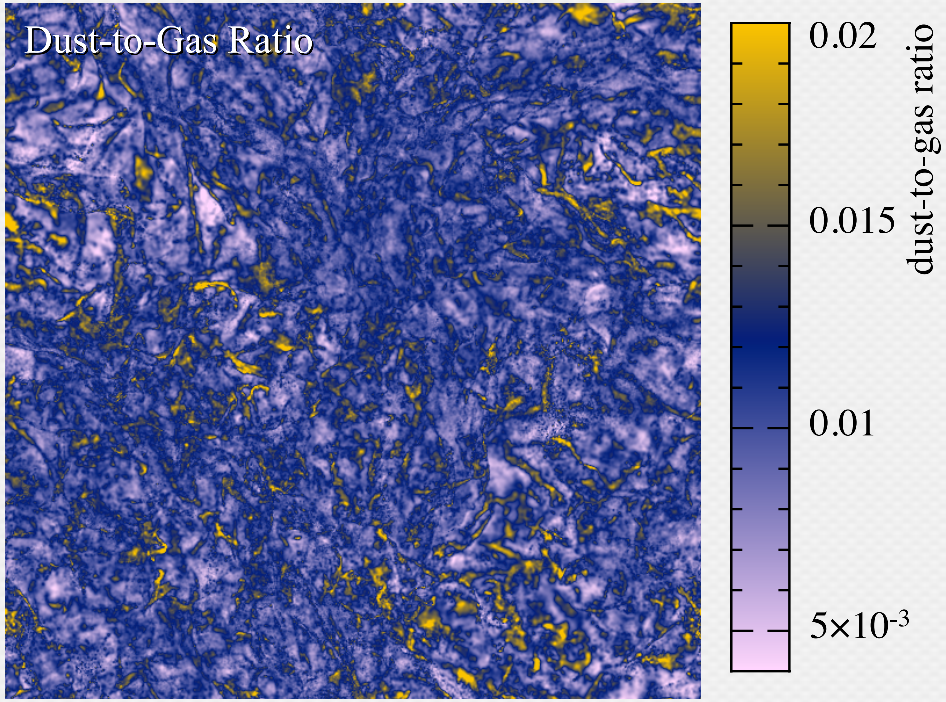


Is the Dust-to-Gas Ratio Constant?

- **Yes!** For ~0.1 micron grains, turbulence almost no effect since dust is well-coupled to gas throughout the cloud



- **No!** For ≥ 1 micron grains, turbulence causes typical variations ~2-3x



Summary

- We find that 0.1 micron dust grains remain well-coupled to the gas throughout a molecular cloud
- We do not find orders of magnitude fluctuations for ~0.1 micron dust grains, contrary to Hopkins & Lee (2016)
- Local, small-scale variations of dust-to-gas ratio for large grains (>1 micron) can occur, with typical increases of ~40% up to 2-3x
- A maximum of 10x increase for 10 micron dust grains (max dust-to-gas ratio of 1:10)
- 'size-sorting': preferential concentration of large grains into filaments due to changes in dust-stopping times between filaments and lower density gas
    - May be relevant for coreshine
- These are dynamical effects – not grain growth!