# Is the dust-to-gas ratio constant in molecular clouds?

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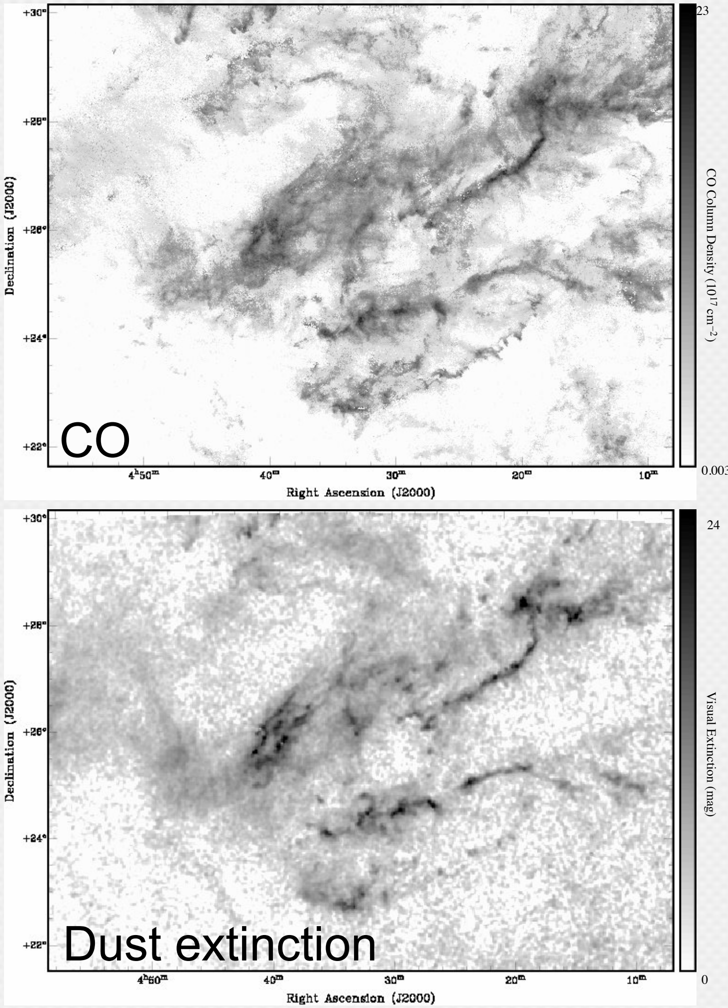
Credit Bruno Gilli/ESO

# Dust in Molecular Clouds

- Molecular hydrogen emits weakly, so bulk of gas is effectively invisible
- 1% dust-to-gas mass ratio used to infer gas mass in dense, cold molecular clouds
- Turn to tracers: other molecules (CO, $N_2H+$), and/or dust
- Dust seems to correlate well with gas




Pineda et al (2010)

# Dust in Molecular Clouds

But is the dust-to-gas ratio in molecular clouds uniformly 1%?

- **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)
- **Ophiuchus A:**
  - Spatial mismatch between gas and dust (Di Francesco+ 2004; Friesen+ 2014)
  - mean 1.1% dust-to-gas ratio, but with local fluctuations of 0.5% to 10% (Liseau+ 2015)

# Dust is not Gas!

- Dust behaves dynamically different than gas
- Could supersonic turbulence cause dynamical variations in the dust-to-gas ratio?

- Analytic estimates for 0.1 micron dust grains in molecular clouds
- For a molecular cloud of typical values:
  - density ~ $10^{-20}$ g/cm$^3$, sound speed ~ 0.2 km/s,
  - 0.1 micron grains, intrinsic grain density ~ 3 g/cm$^3$,
  - Drag stopping timescale ~ $10^3$ yrs << $10^6$ dynamical time of molecular cloud
  - Thus, expect a well-coupled mixture of dust and gas. High drag regime.
- But this assumes cloud is homogenous and *ignores turbulence*!

# Supersonic Dusty Turbulence

We modelled the turbulent dynamics of dusty molecular clouds using the SPH code Phantom (Price+ 2017)

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

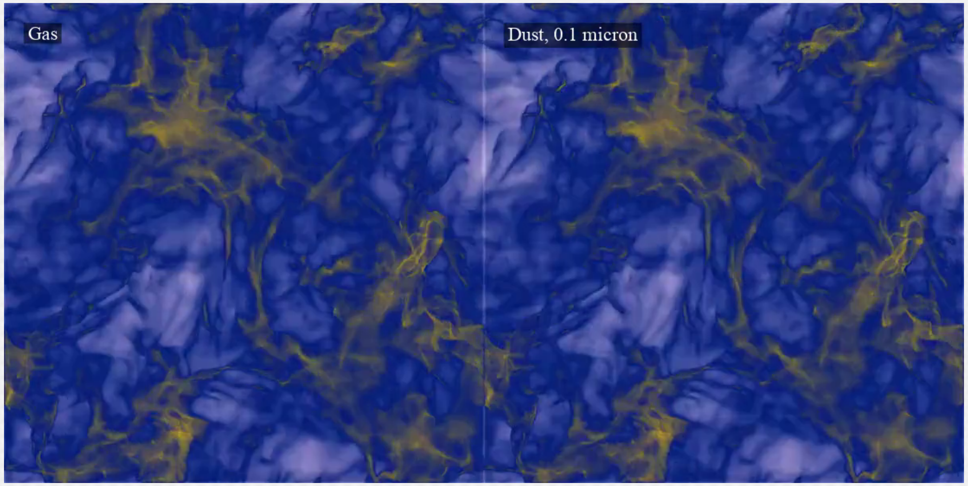
**Initial Conditions:**

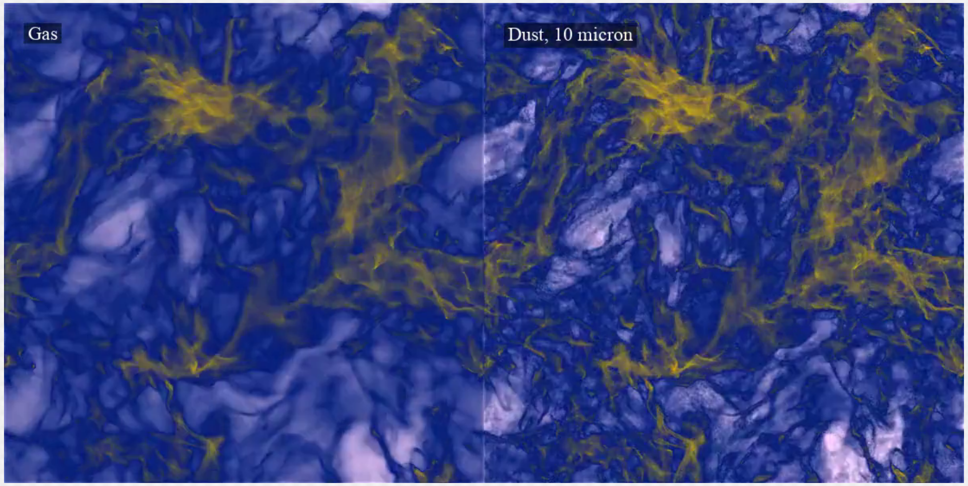
- Density = $10^{-20}$ g/cm$^3$
- Isothermal gas with T = 11.5 K, $c_s$ = 0.2 km/s
- 3 parsec length box
- Driven turbulence on large scales, for ~14 Myr

**Dust Physics:**

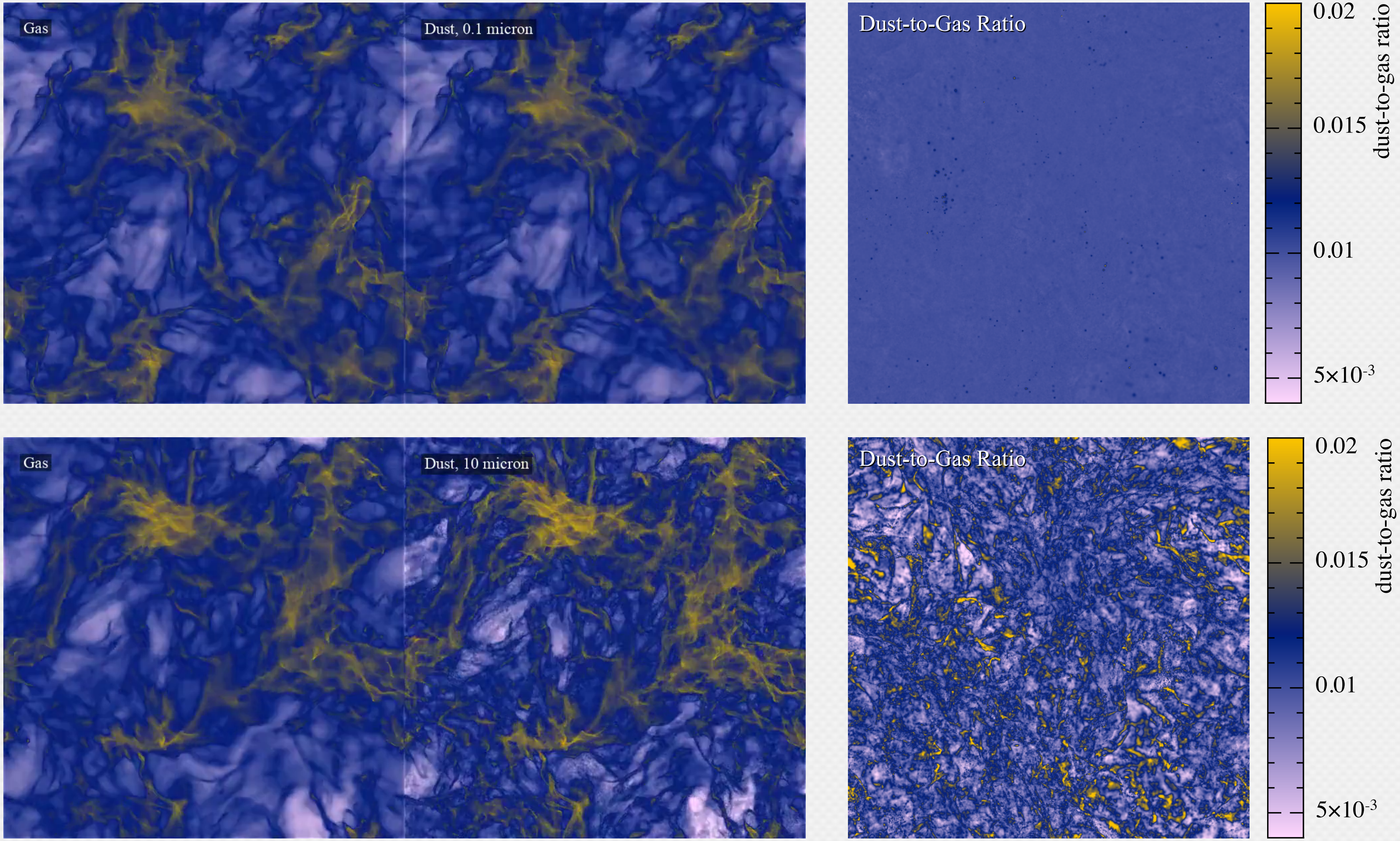
- 3 separate simulations for 0.1, 1 and 10 micron grain sizes
- Initially uniform 1% dust-to-gas ratio

# Column Dust and Gas Density



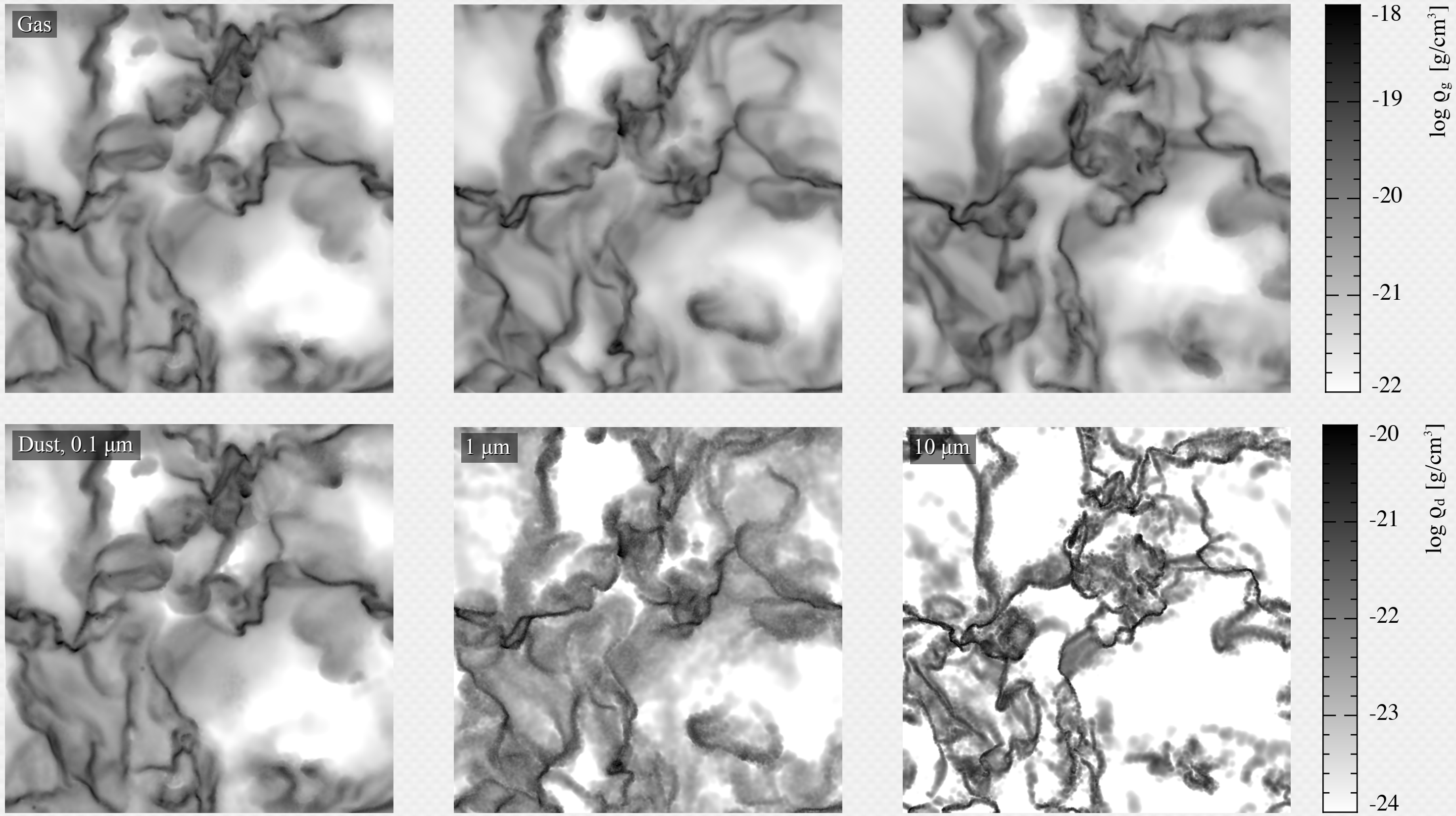



# Column Dust and Gas Density



# Size-sorting of Dust

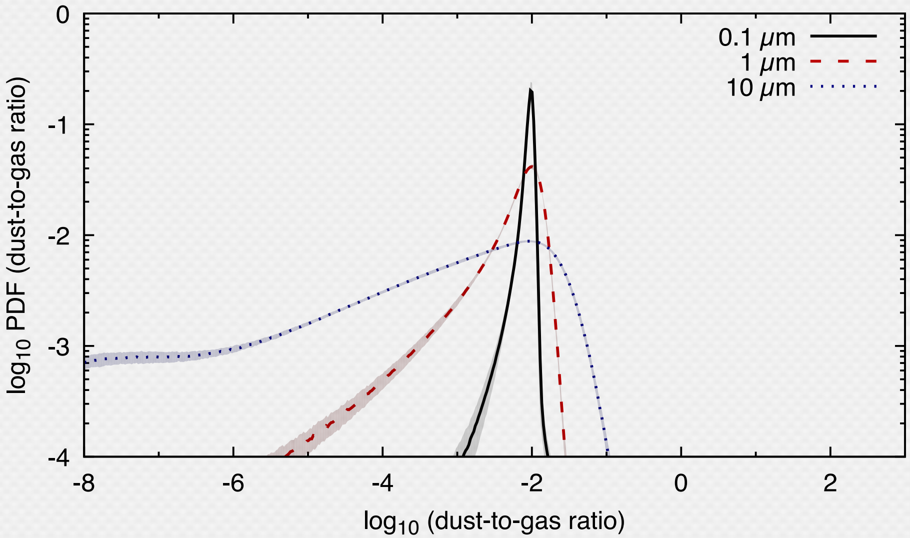
Slices of gas and dust through midplane of the cloud



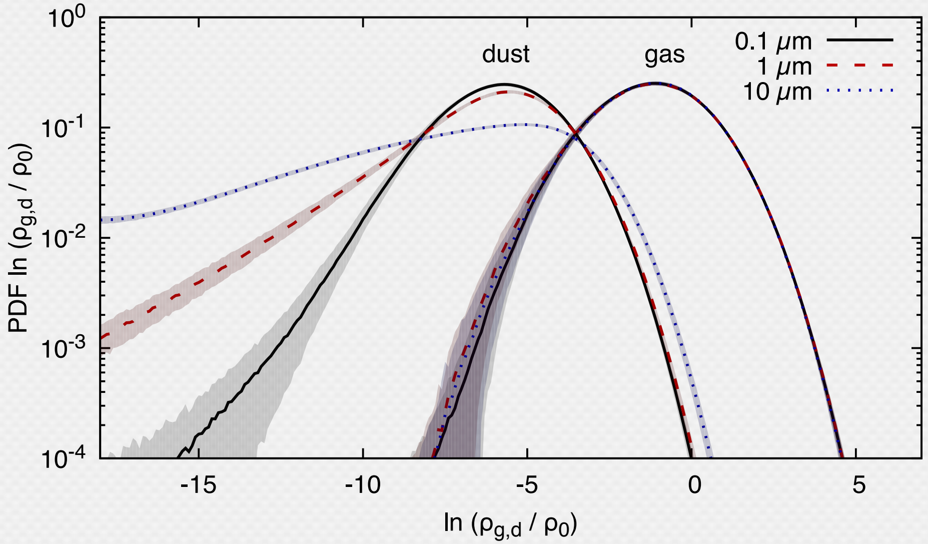

- 0.1 micron grains remain well-coupled to the gas throughout the cloud
- Large grains preferentially concentrated in filaments
- Up to 10x increase of 10 micron grains in dense filaments

# Probability Distributions

PDFs of dust-to-gas ratios



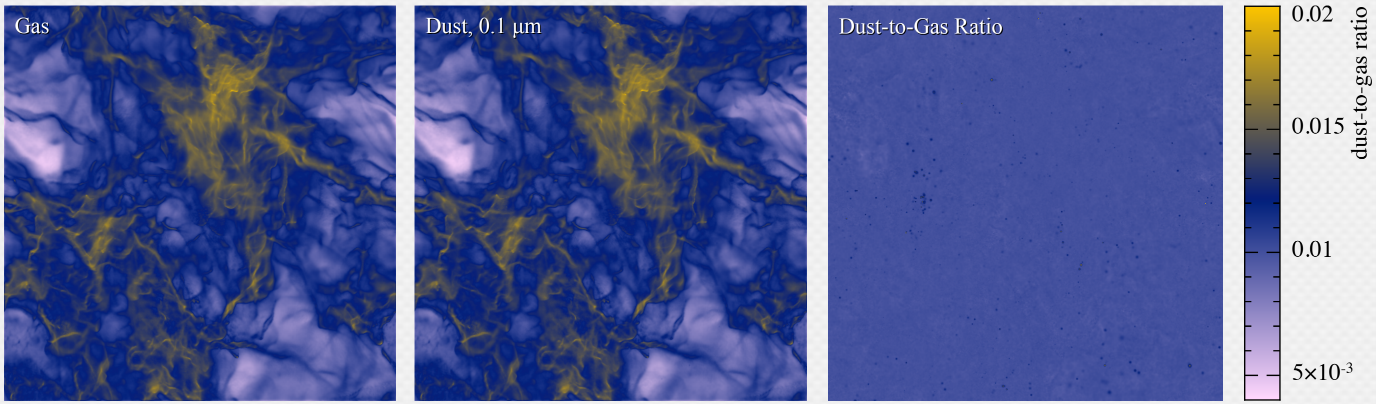

PDFs of gas and dust densities



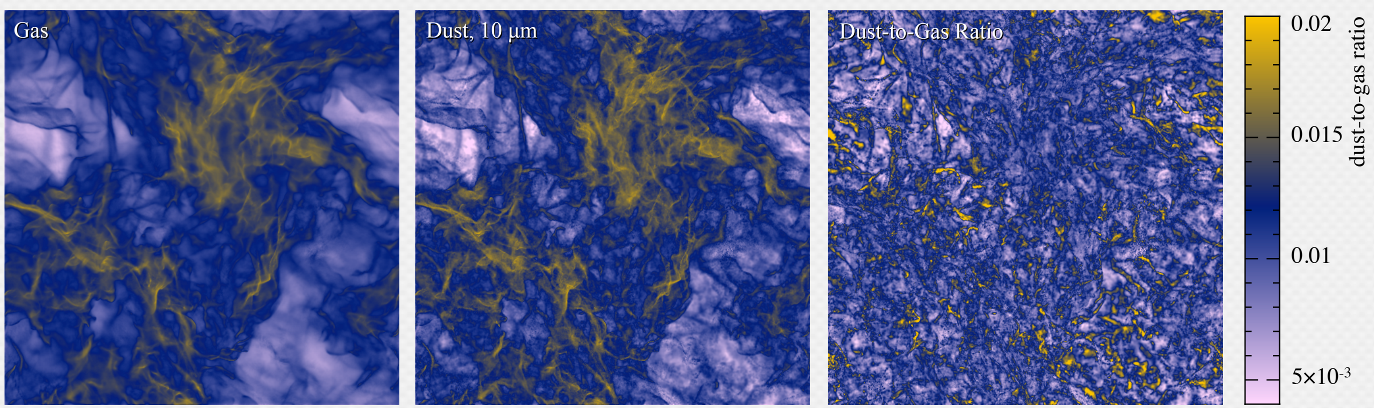

- 0.1 micron grains:
  - Sharply peaked PDF of dust-to-gas ratios at 1%
  - Matching log-normal distribution of gas and dust density
- 1-10 micron grains:
  - PDFs broaden due to ‘size-sorting’
  - Turbulence causes dynamical transfer of dust mass into high density filaments

# Is the dust-to-gas ratio constant?

- **Yes!** For 0.1 micron grains, turbulence has almost no effect




- **No!** For ≥ 1 micron grains, turbulence can induce large variations



# Conclusions

Studied the dynamical effect of supersonic turbulence on distribution of dust in molecular clouds:

- 0.1 micron dust grains:
  - Minimal variation in the dust-to-gas ratio
  - Dust well-coupled to the gas throughout molecular cloud
- 1-10 micron grains:
  - 'size-sorting', concentration of large grains into filaments
  - Up to 10x increase of 10 micron grains in dense filaments
  - Related to coreshine?

# Dust Algorithm

Low Drag: Two fluid approach

- Separate populations of dust and gas
- Evolve gas velocity, dust velocity, gas density, dust density
- Works well when they behave as separate fluids
  - have to resolve drag timescale and lengthscale

High Drag (molecular clouds): One fluid approach

- Combined mixture of dust and gas
- Evolve barycentric velocity, combined density, dust-to-gas ratio
- Works well when they behave similarly
  - does not work well when they start behaving as separate fluids