Simulating fluid-solid interactions in astrophysical settings

Ryan McKinnon

July 16, 2018

MIT

DOE CSGF

Schematic representation of interstellar medium in a galaxy

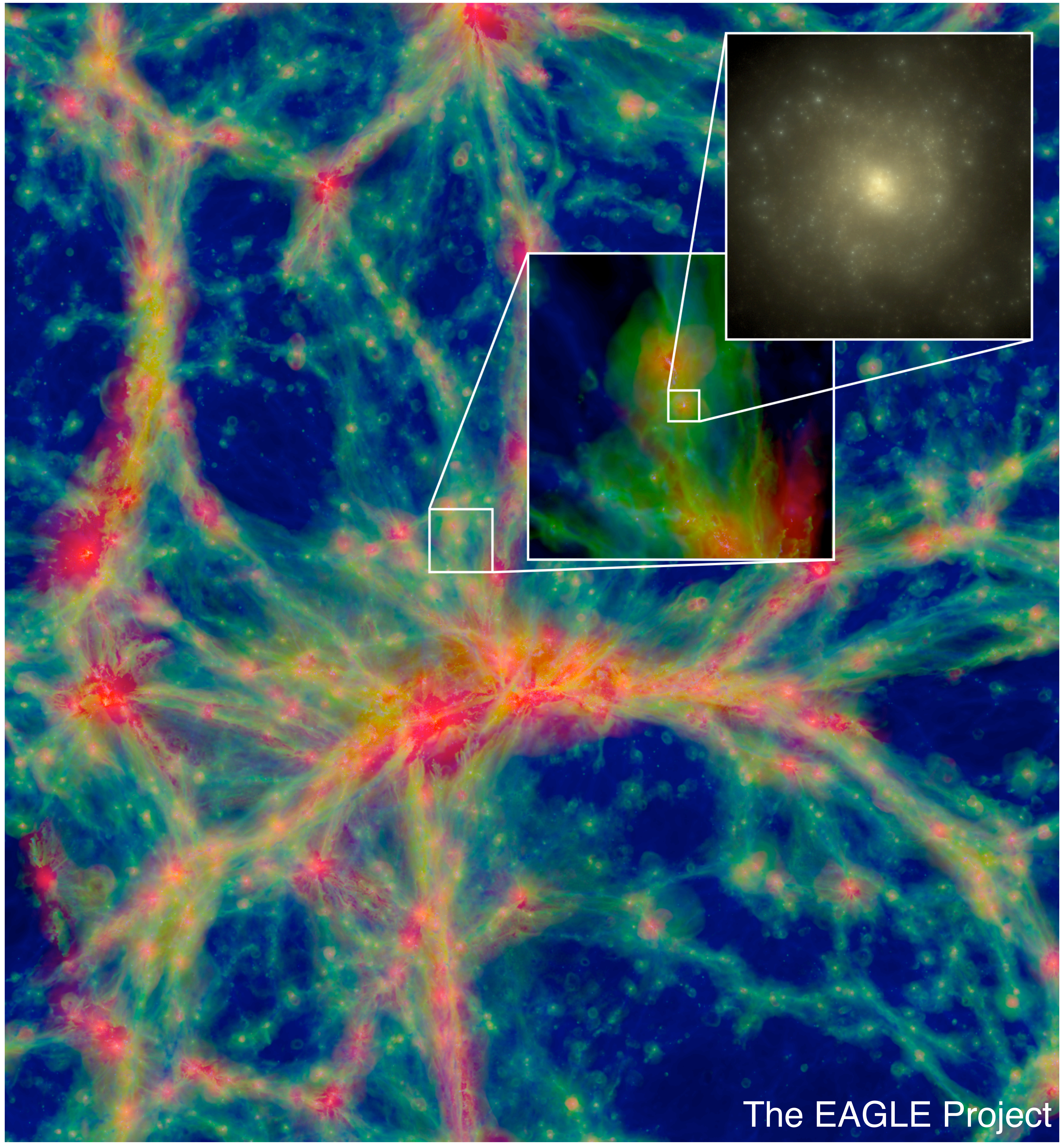
Stars emit visible light, but surrounding gas and dust can obscure galaxy's appearance

ESO/NASA/JPL-Caltech/M. Kornmesser/R. Hurt

A lot of physical processes are at play

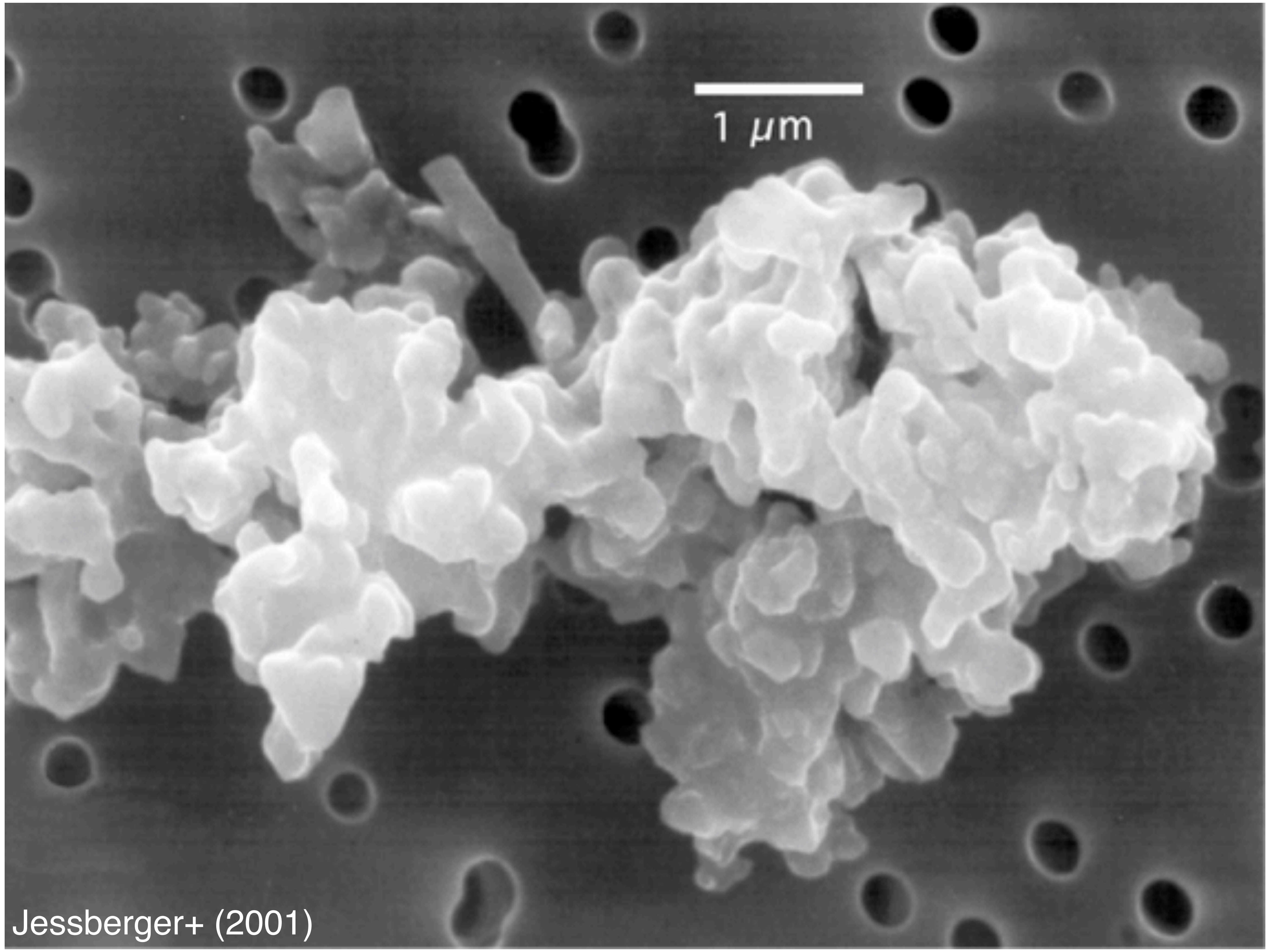
Physics across a wide range of scales

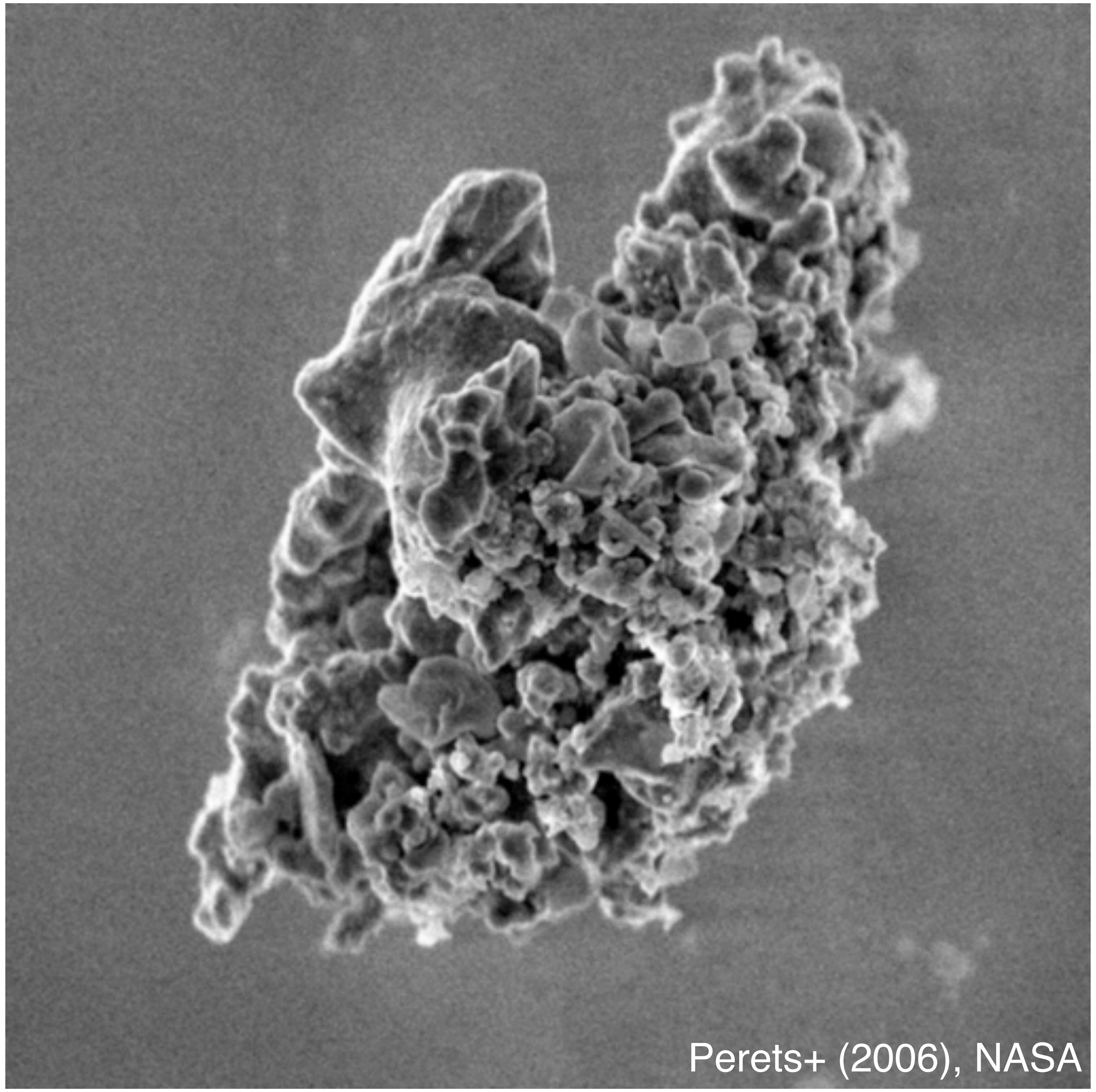
- Gravity
- Hydrodynamics
- Radiation
- Gas cooling, star formation
- Stellar feedback, metal enrichment
- AGN feedback, black hole formation
- Dust grain physics
- Magnetic fields
- Thermochemistry



Dust grains have little mass but big impact

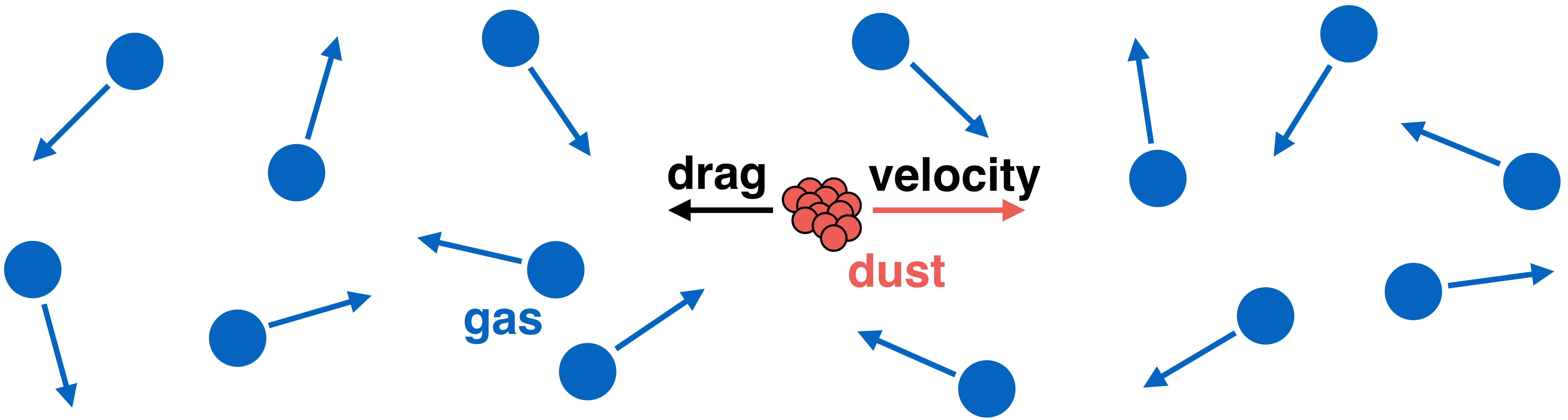
Dust reradiates ~30% of starlight in galaxies but makes up only ~1% of mass





Drag couples dust to hydrodynamic motion

Track dynamics of dust using particles subject to drag (and gravity)



Amounts to including drag force in dust and gas equations of motion

$$\frac{d\mathbf{v}_d}{dt} = -\frac{K_s(\mathbf{v}_d - \mathbf{v}_g)}{m_d} + \mathbf{a}_{d,ext}$$

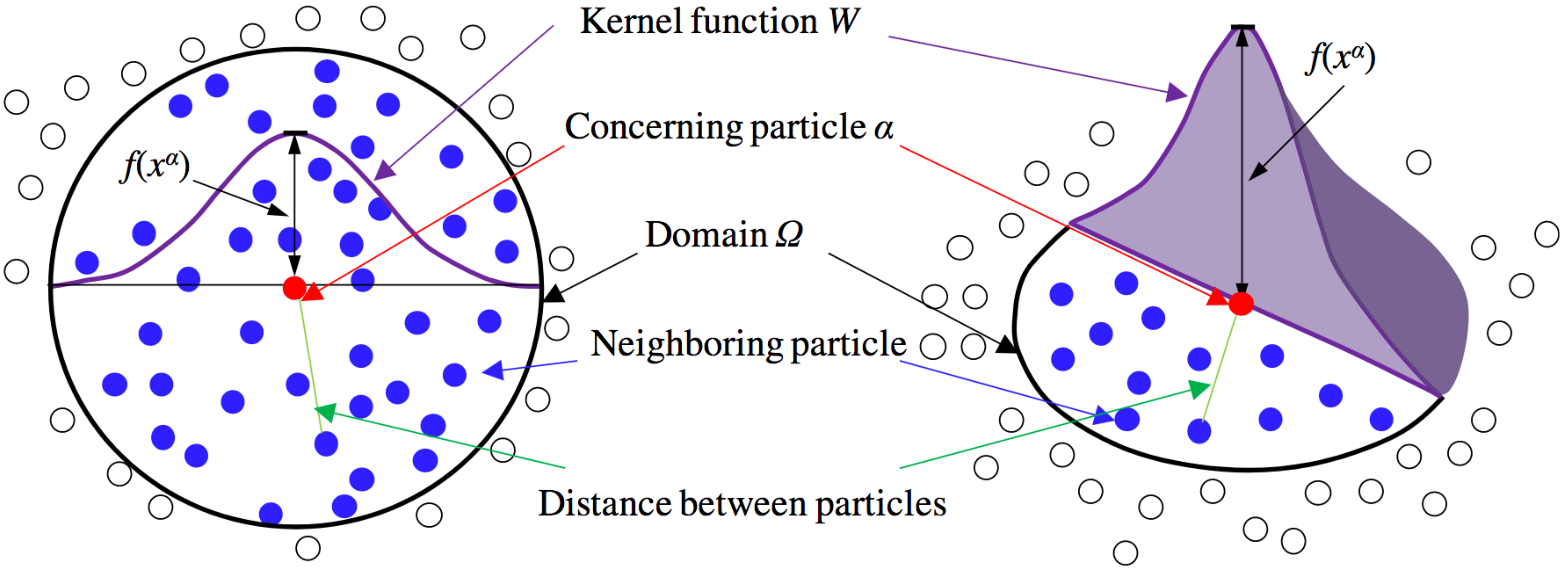
$$\frac{d\mathbf{v}_g}{dt} = -\frac{\nabla P}{\rho_g} + \frac{\rho_d K_s(\mathbf{v}_d - \mathbf{v}_g)}{\rho_g m_d} + \mathbf{a}_{g,ext}$$

stopping time-scale

$$t_s = m_d / K_s \propto a \rho_{grain} / \rho_g c_s$$

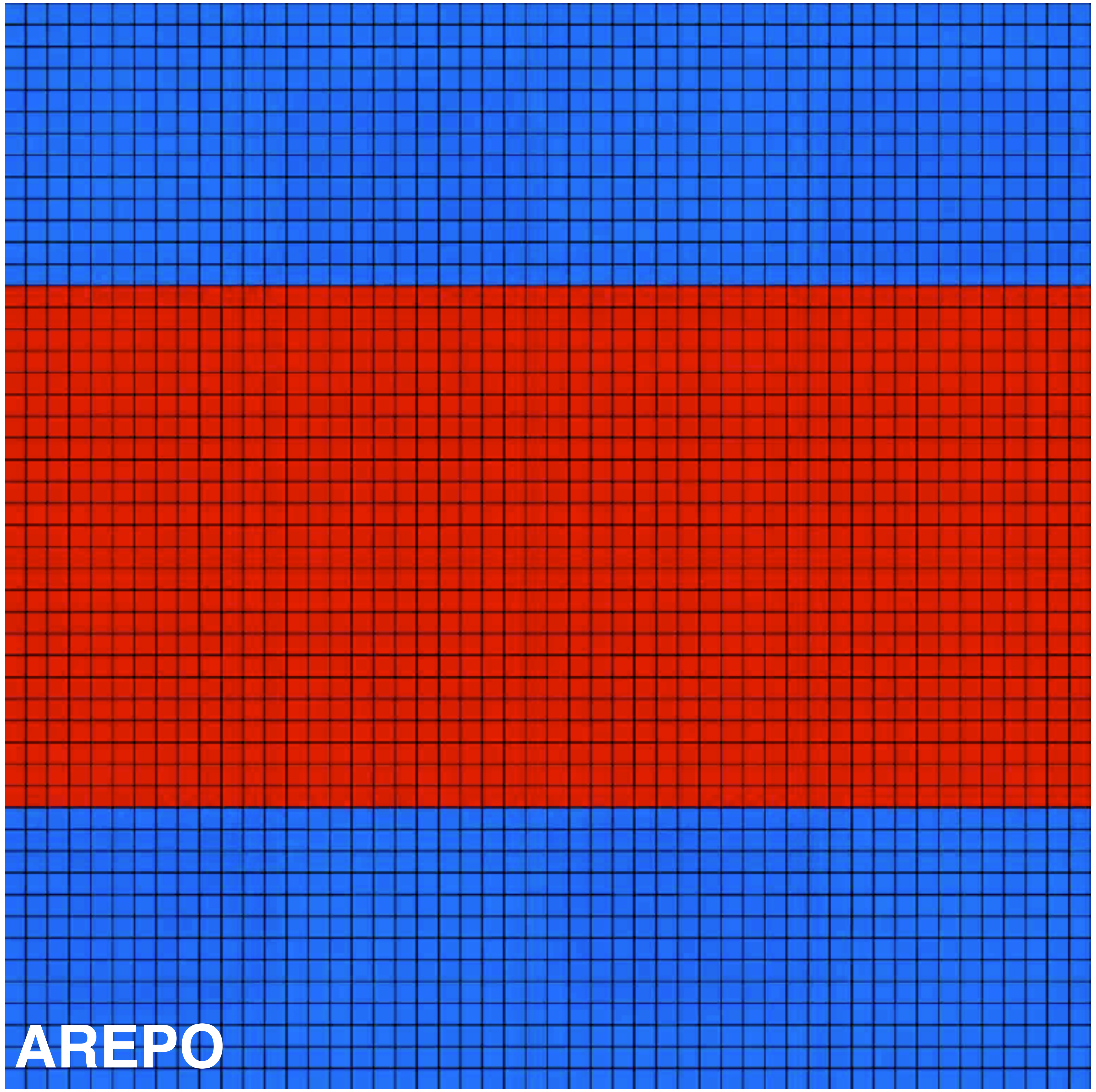
Calculate local quantities using SPH-like interpolation

Estimates of gas density, sound speed, etc. needed to calculate strength of drag force



Dai+ (2016)

Implement dust physics in moving-mesh hydrodynamics code AREPO



Springel (2010)

Demonstration of Kelvin-Helmholtz instability

Hydrodynamics solved using conservative finite volume scheme

Mesh generated by Voronoi tessellation of space, allowed to move with local fluid velocity

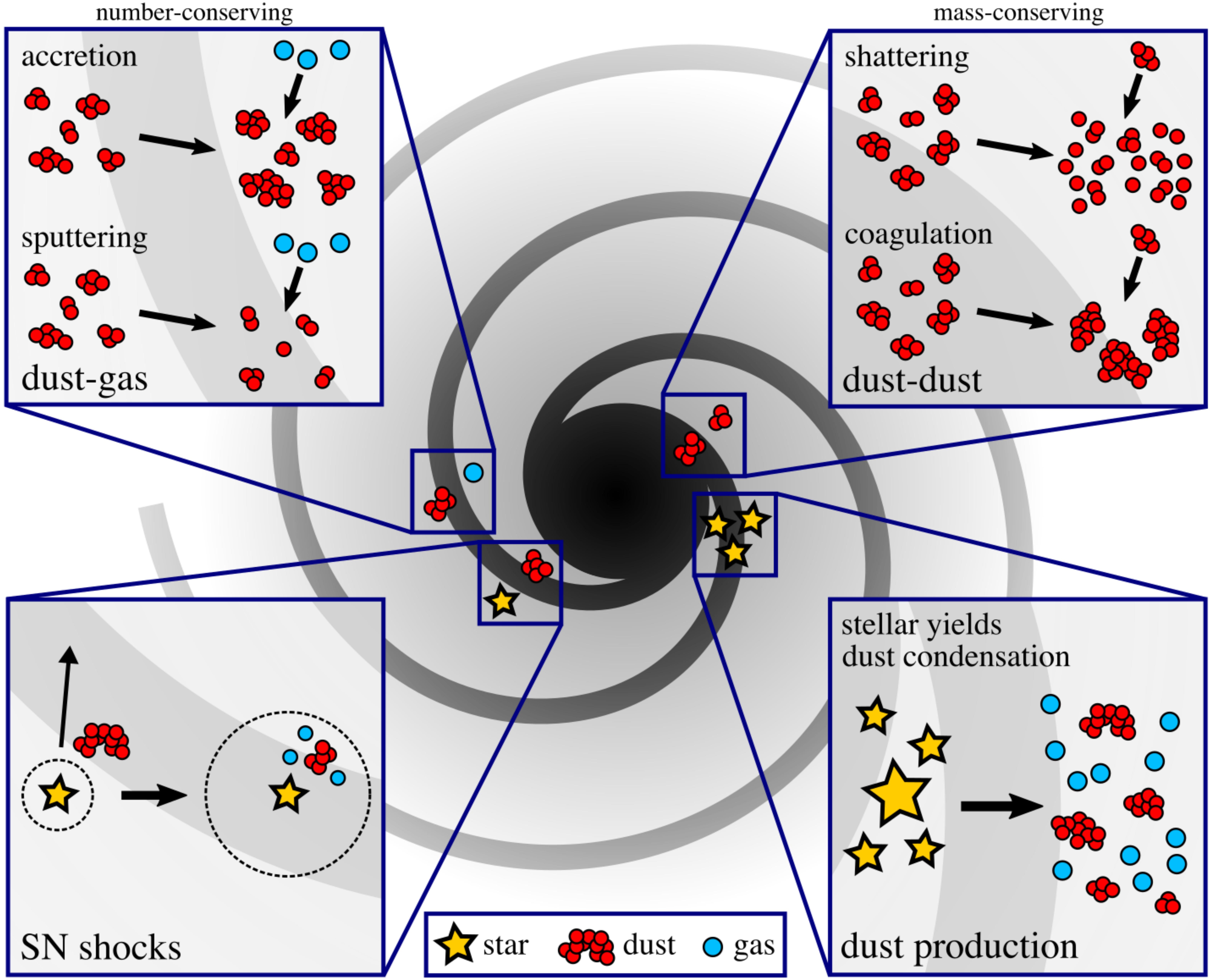
Account for dust dynamics using particles superimposed on mesh motion (McKinnon+ 2018)

Demonstration of drag in Sod shock tube

Strength of drag affects how closely dust dynamics follow gas dynamics

McKinnon+ (2018)

Stars, dust, and gas coevolve within galaxies



McKinnon+ (2018)

Similarities to population balance equations

Smoluchowski coagulation equation describes collisional evolution of many-sized particles

$$\frac{\partial n(x,t)}{\partial t} = \underbrace{-\int_\Omega K(x,y)n(x,t)n(y,t)\,\mathrm{d}y}_{\textbf{consumption}} + \underbrace{\int_\Omega K(x-y,y)n(x-y,t)n(y,t)\,\mathrm{d}y}_{\textbf{production}}$$

Wide variety of applications in statistical physics, chemical physics, aerosols, colloids, etc.

A New Moment Method for Solving the Coagulation Equation for Particles in Brownian Motion

The Self-Preserving Particle Size Distribution for Coagulation by Brownian Motion[1]

MODELING COAGULATION AMONG PARTICLES OF DIFFERENT COMPOSITION AND SIZE

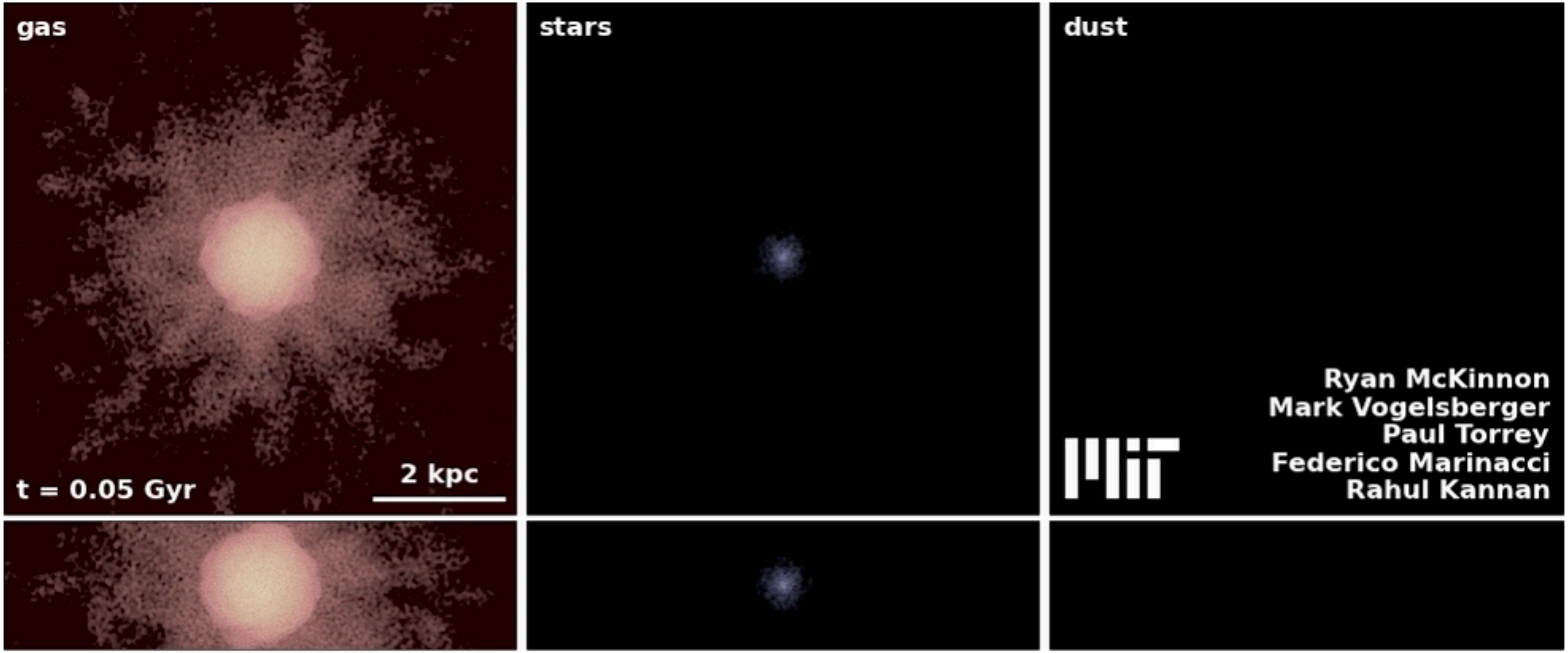
Well-posedness of Smoluchowski's coagulation equation for a class of homogeneous kernels

Tail Distribution of Large Clusters from the Coagulation Equation

Cluster size distribution in chemically controlled cluster–cluster aggregation

Simulate idealized disk galaxy with grain size evolution

Track spatial distribution, size distribution of dust grains self-consistently

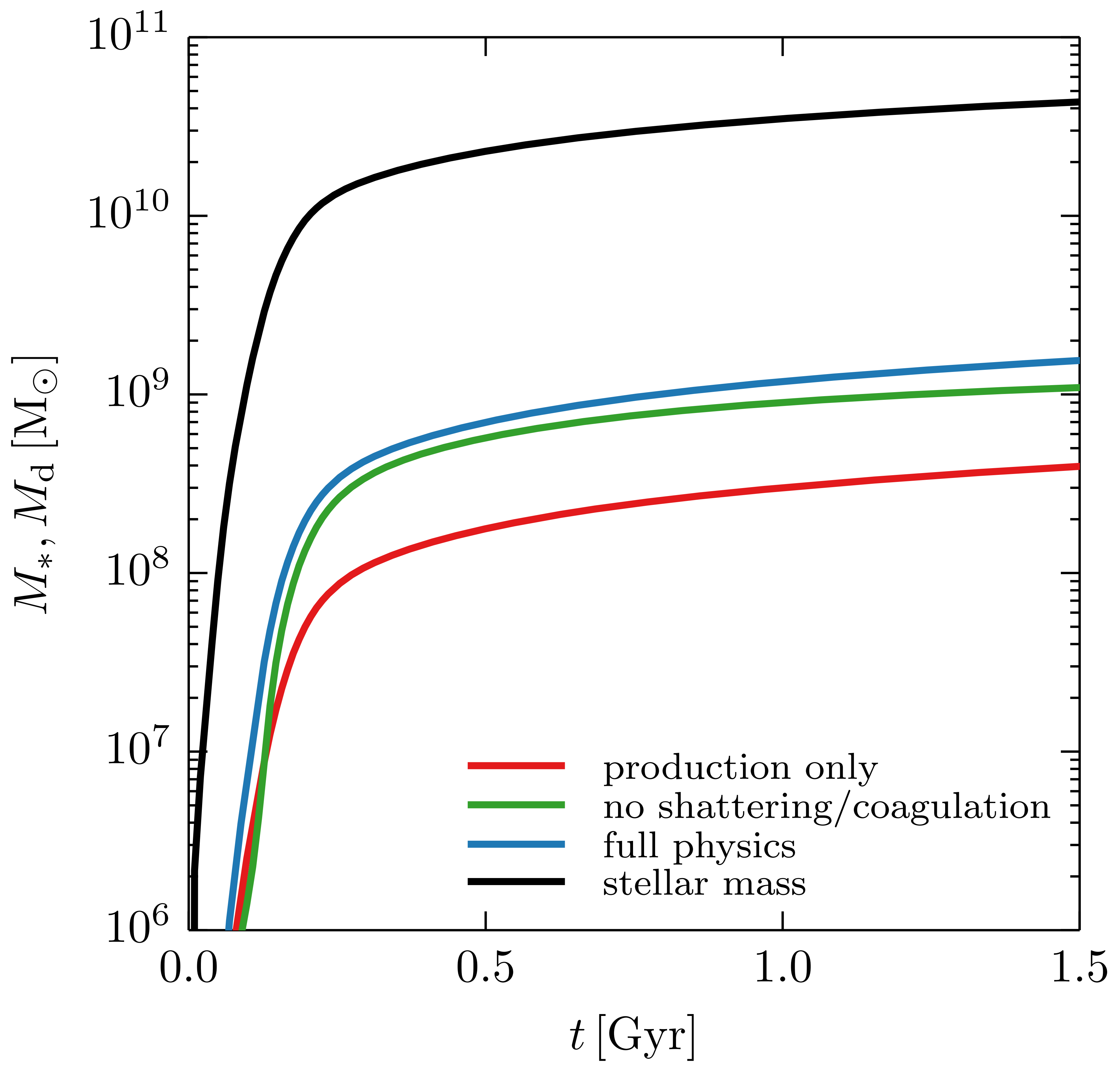


McKinnon+ (2018)

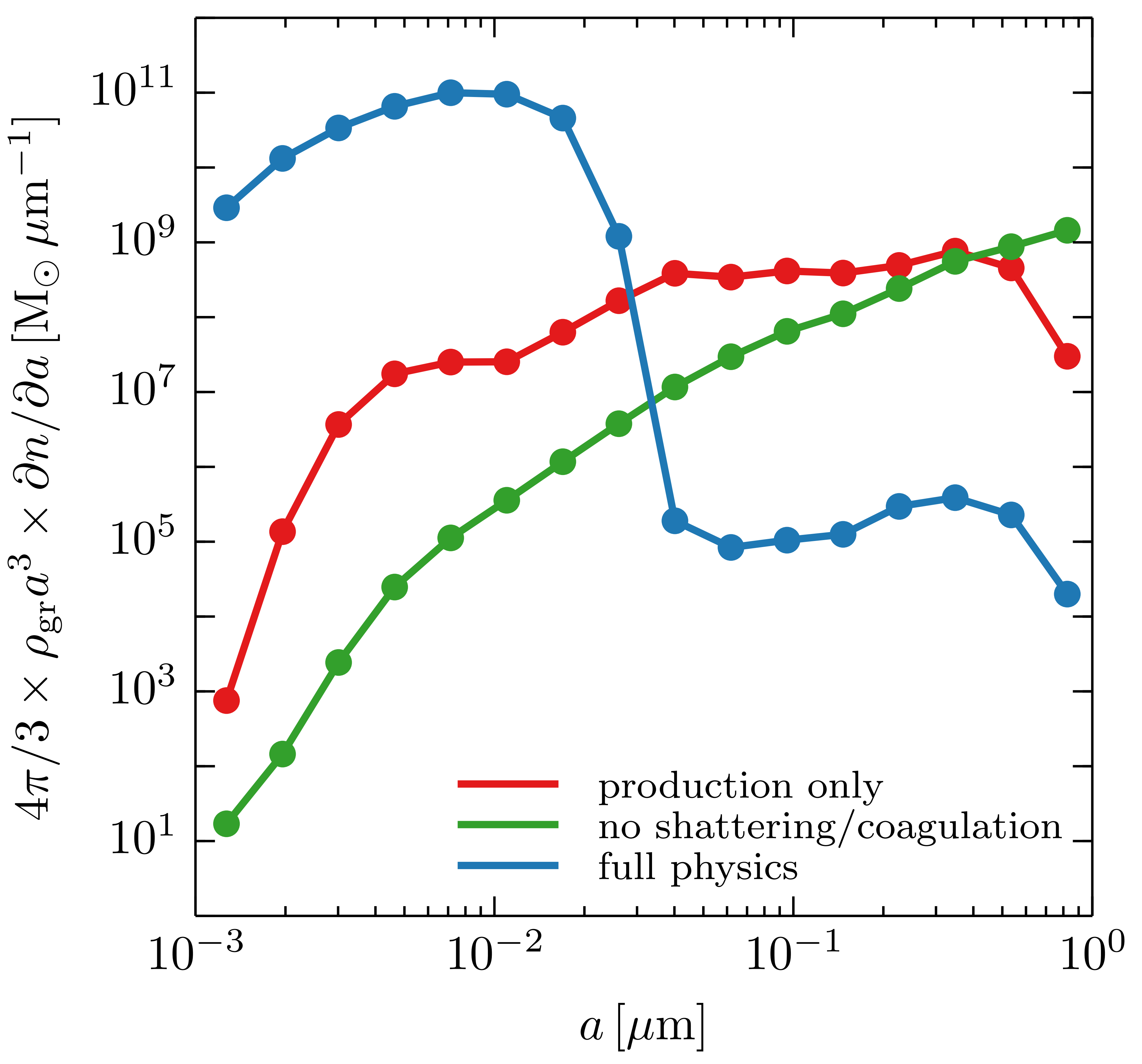
Grain physics models predict different size distributions

Overall dust mass is similar, but distributed among grains of various sizes

Evolution of total dust mass



Comparison of grain size distributions



dust from stars only **dust from stars, dust-gas collisions** **dust from stars, dust-gas collisions, dust-dust collisions**

McKinnon+ (2018)

Summary

Galaxy formation is complicated!

Modeling solid dust grains in a fluid galaxy presents a challenge:

- Grain dynamics affect grain sizes, and
- Grain sizes affect grain dynamics

These simulations enable valuable predictions about faraway, hard-to-observe galaxies!

NASA/JPL-Caltech/K. Gordon (University of Arizona)