Clustering and dynamic decoupling of dust grains in turbulent molecular clouds

Phase transitions in astrophysics

Lars Mattsson

Nordita

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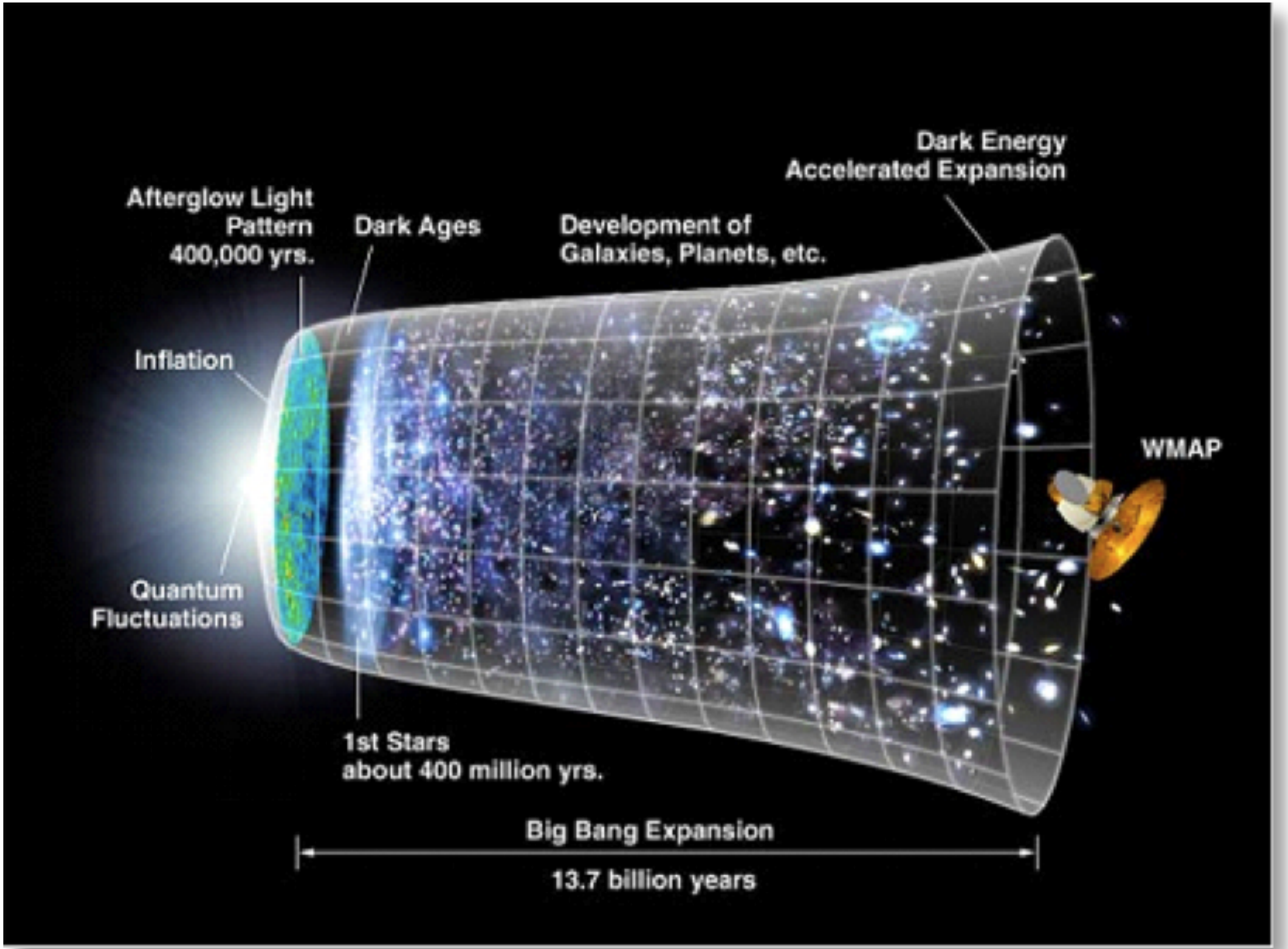
Let's take it from the beginning…



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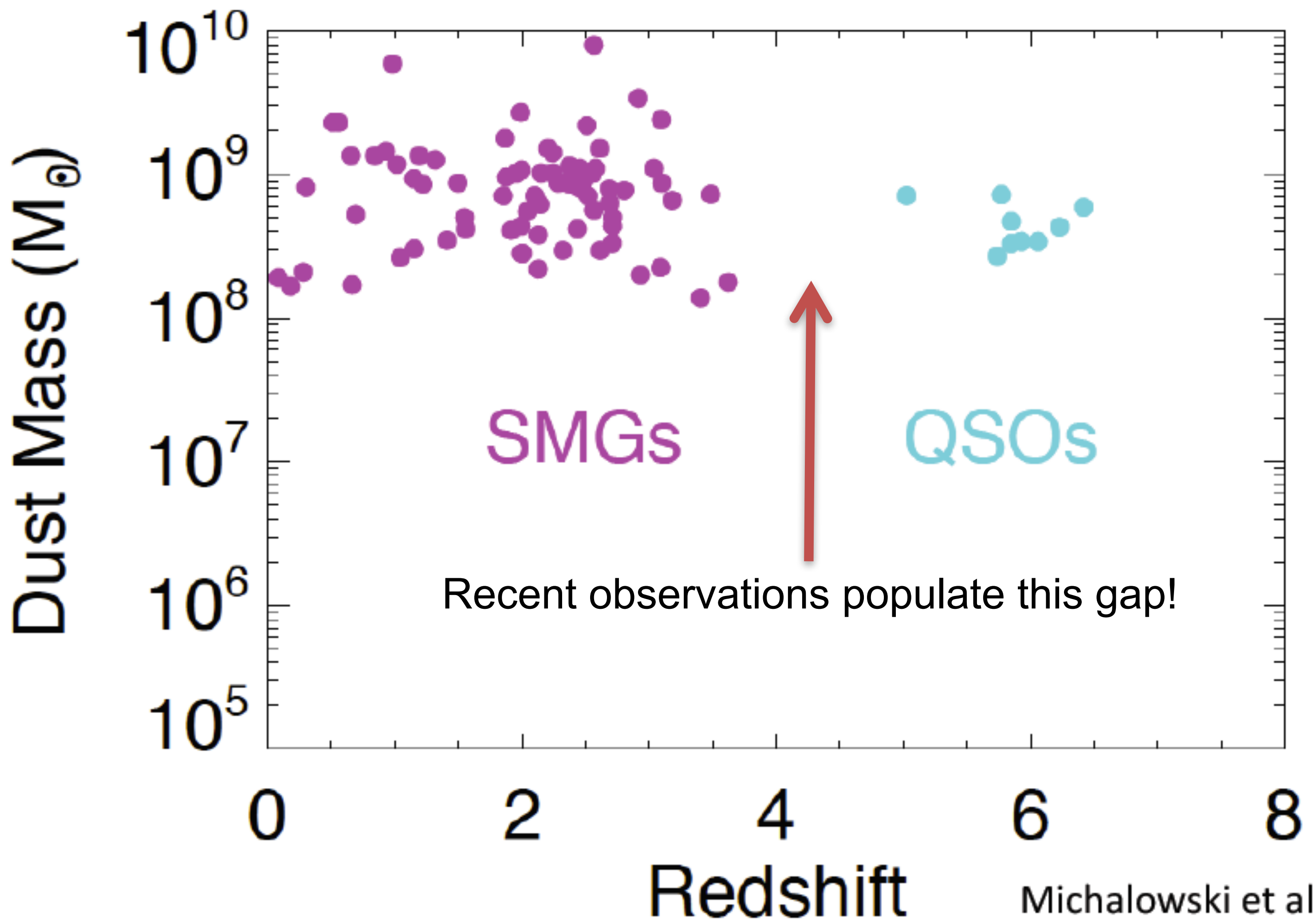
Large amounts of dust at high redshift



Bertoldi et al. (2003, A&A, 406, L55),
Michalowski et al. (2011) and many others….

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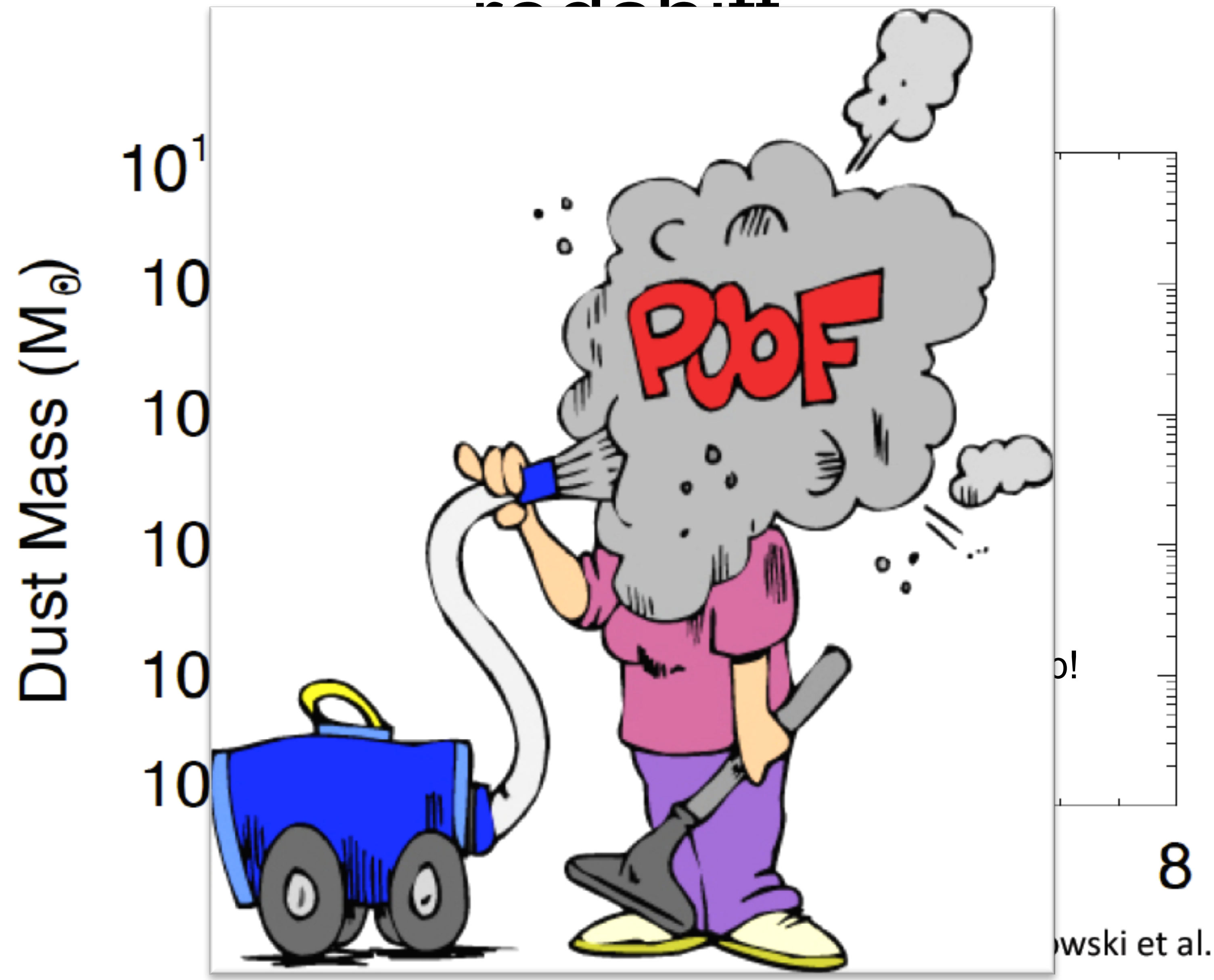

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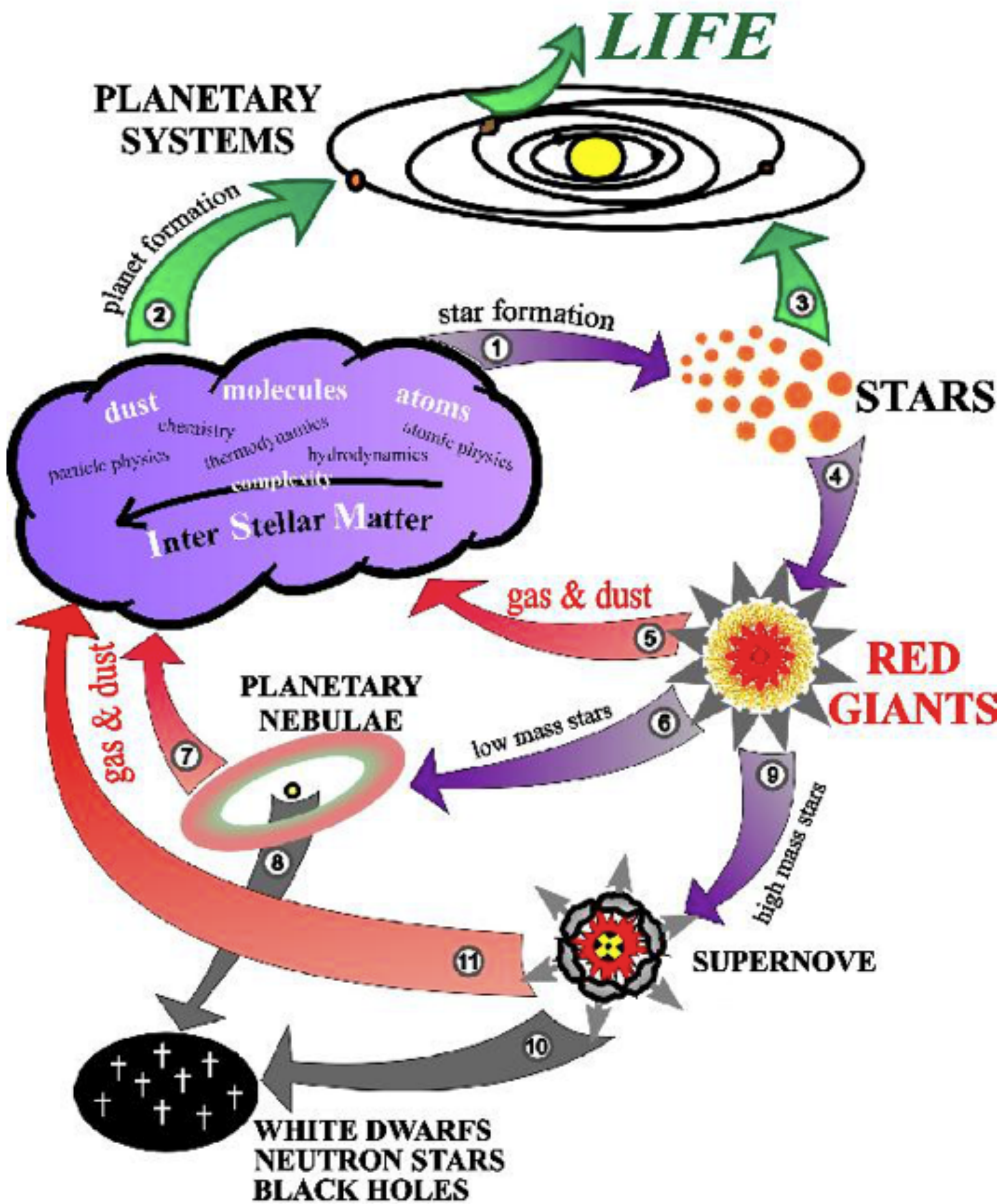
The cosmic matter cycle



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Dust destruction

- Destruction may be induced by passage of SN shocks.
- Fragmentation by passage of SN shocks in combination with more efficient destruction of small grains (Slavin, Jones & Tielens 2004) may lead to a dust destruction timescale which is inversely proportional to the mass density of dust.
- Hydrodynamic instabilities and magnetic fields play an important role also here.
- What happens to the dust grains when a strong shock passes without destruction due to sputtering? Where do the grains end up due to instabilities and the decoupling between dust and gas?

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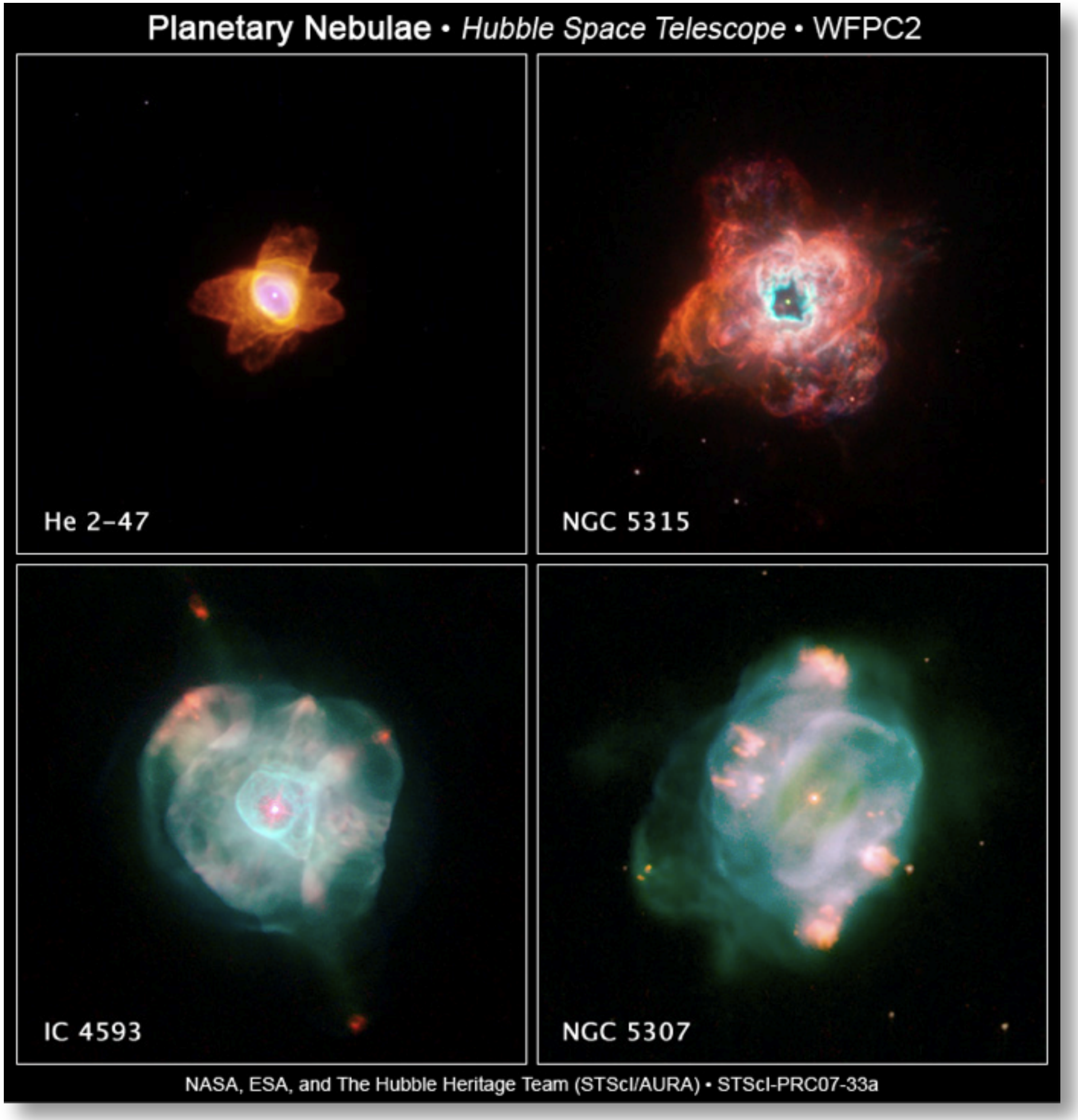
AGB evolution and dust formation



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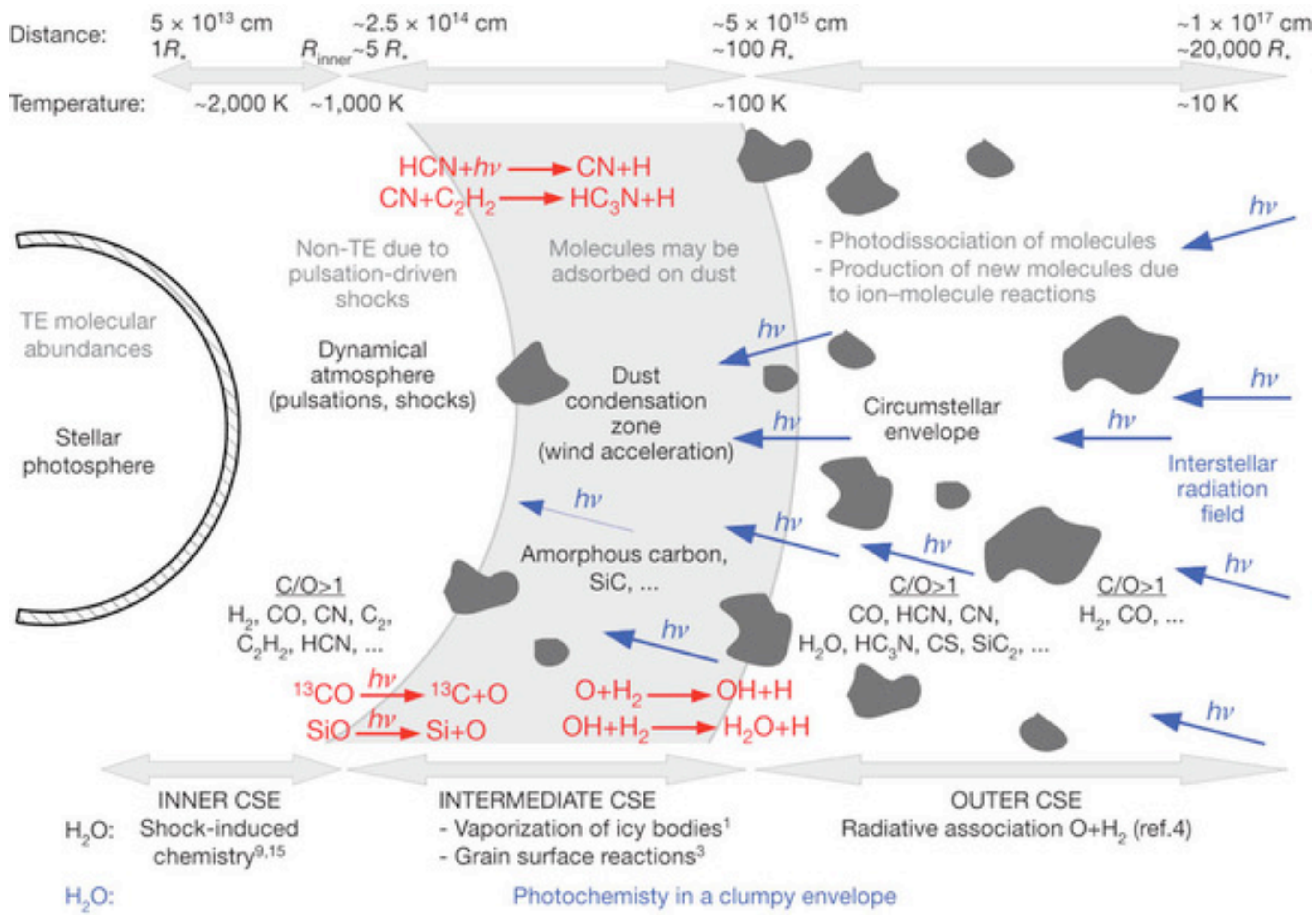
AGB evolution and dust formation

Grain nucleation – difficult!

Grain growth – easier!



Decin et al. (2010, Nature, 467, 64)

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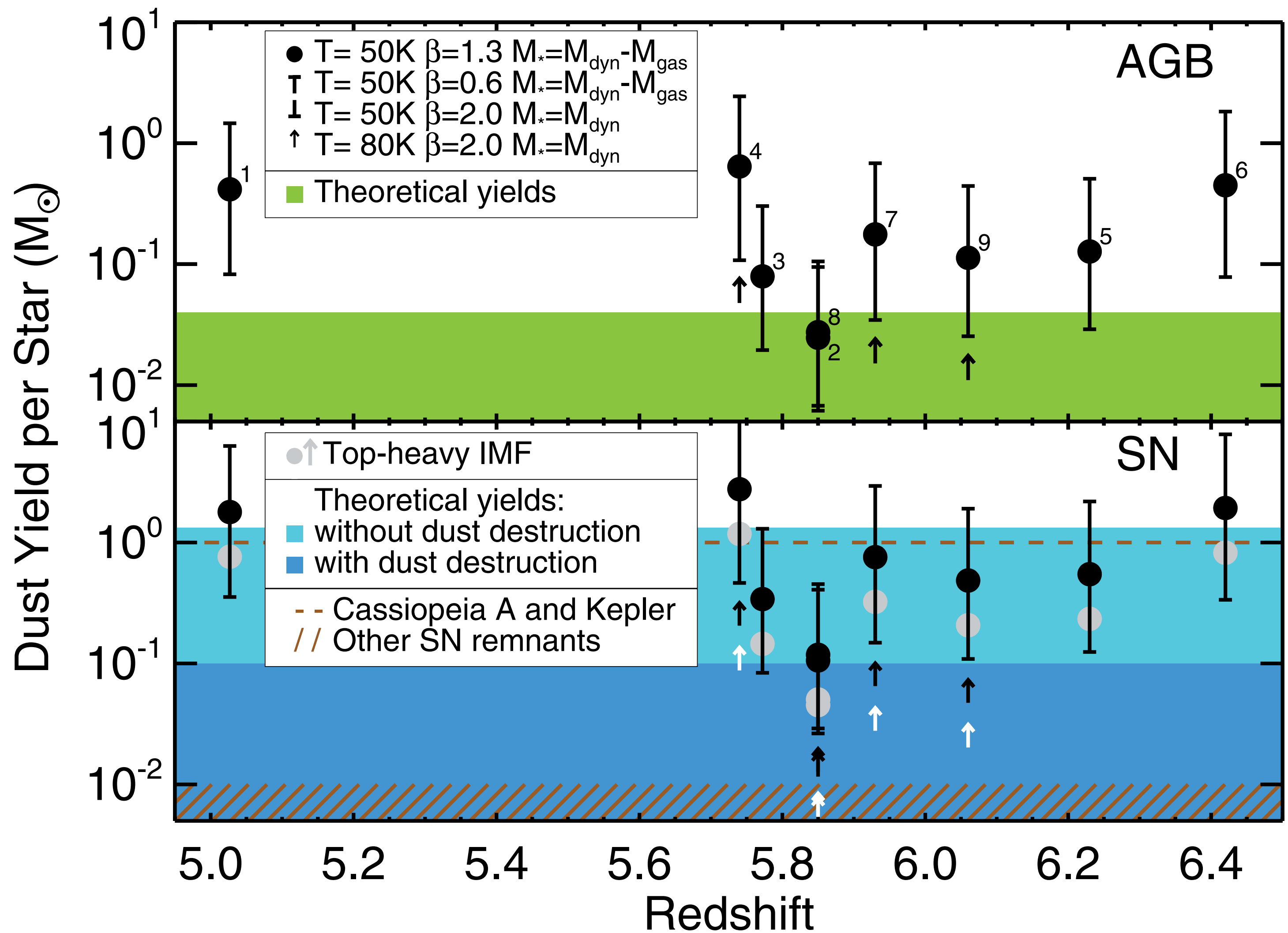
AGB stars? Nope!



(Michalowski et al. 2010)

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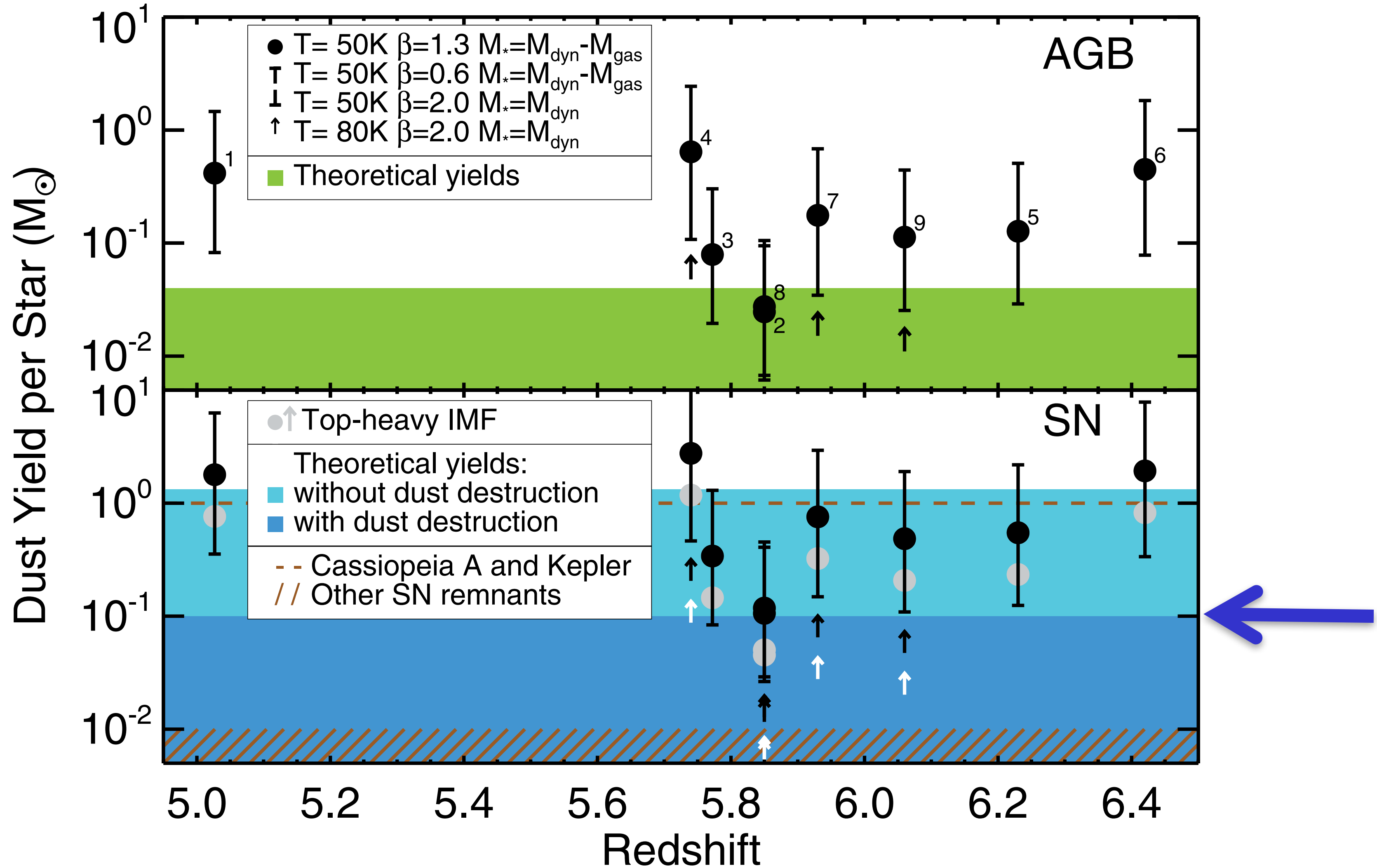

(Michalowski et al. 2010)

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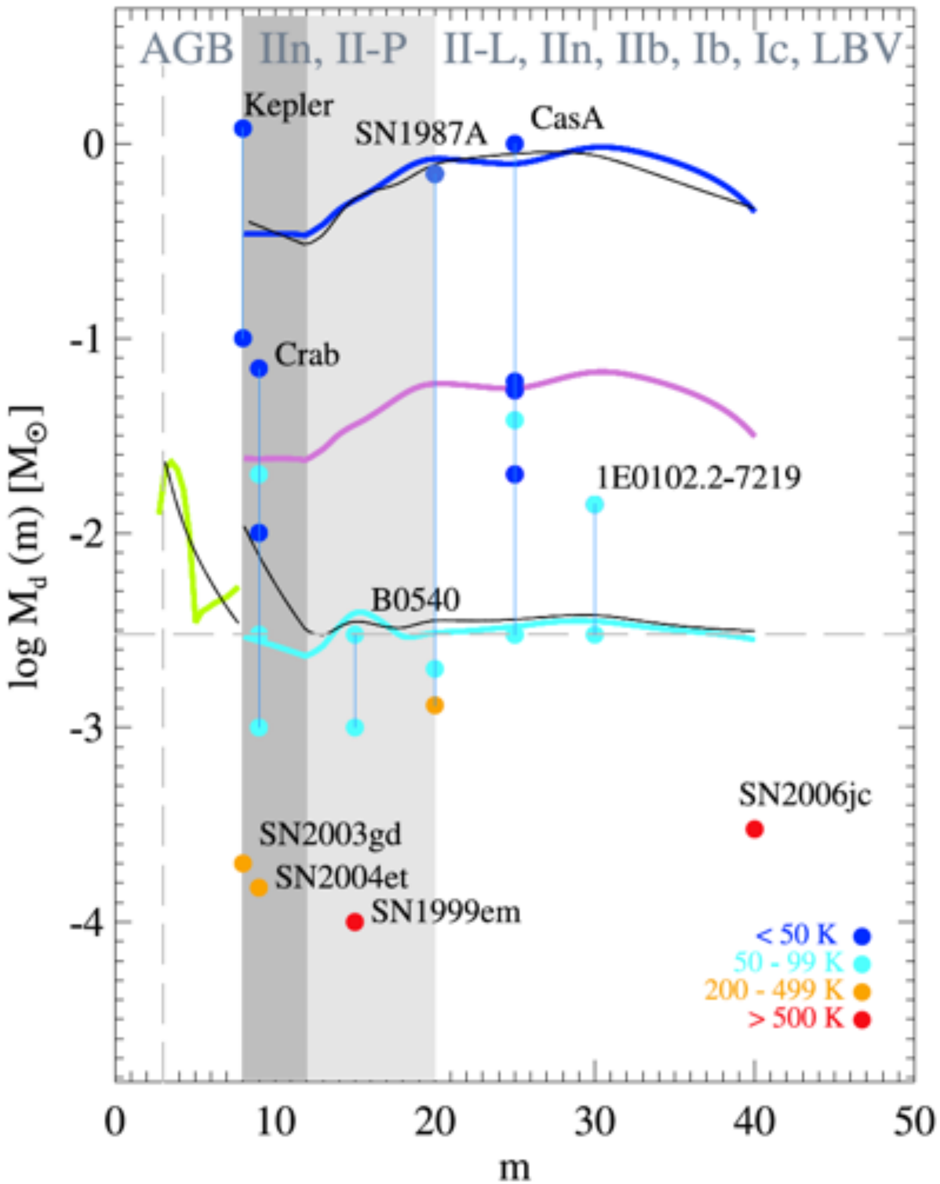
SN dust works, but…

- Very little warm dust observed in SNe, < 10^{-2} M_{sun} (e.g. Wooden et al. 1993; Elmhamdi et al. 2003; Kotak et al. 2009; Meikle et al. 2011)
- But still some controversy over large cold dust masses in SNRs…
- Suggest a constant or declining dust-to-metals ratio, which could be a problem (Mattsson 2011).



Gall et al. (2011, A&AR, 19, 43)

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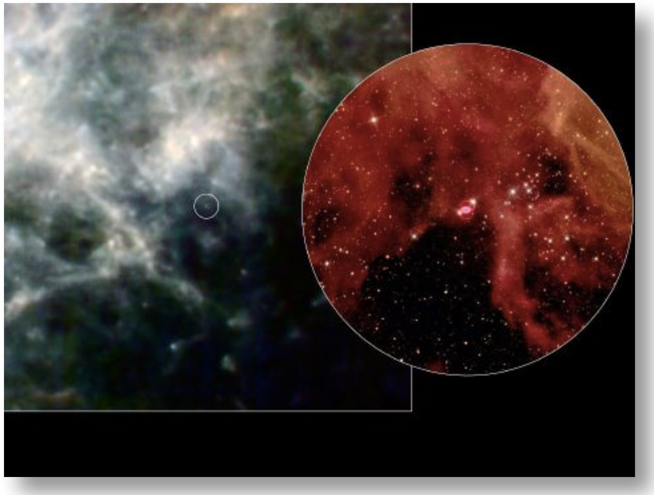
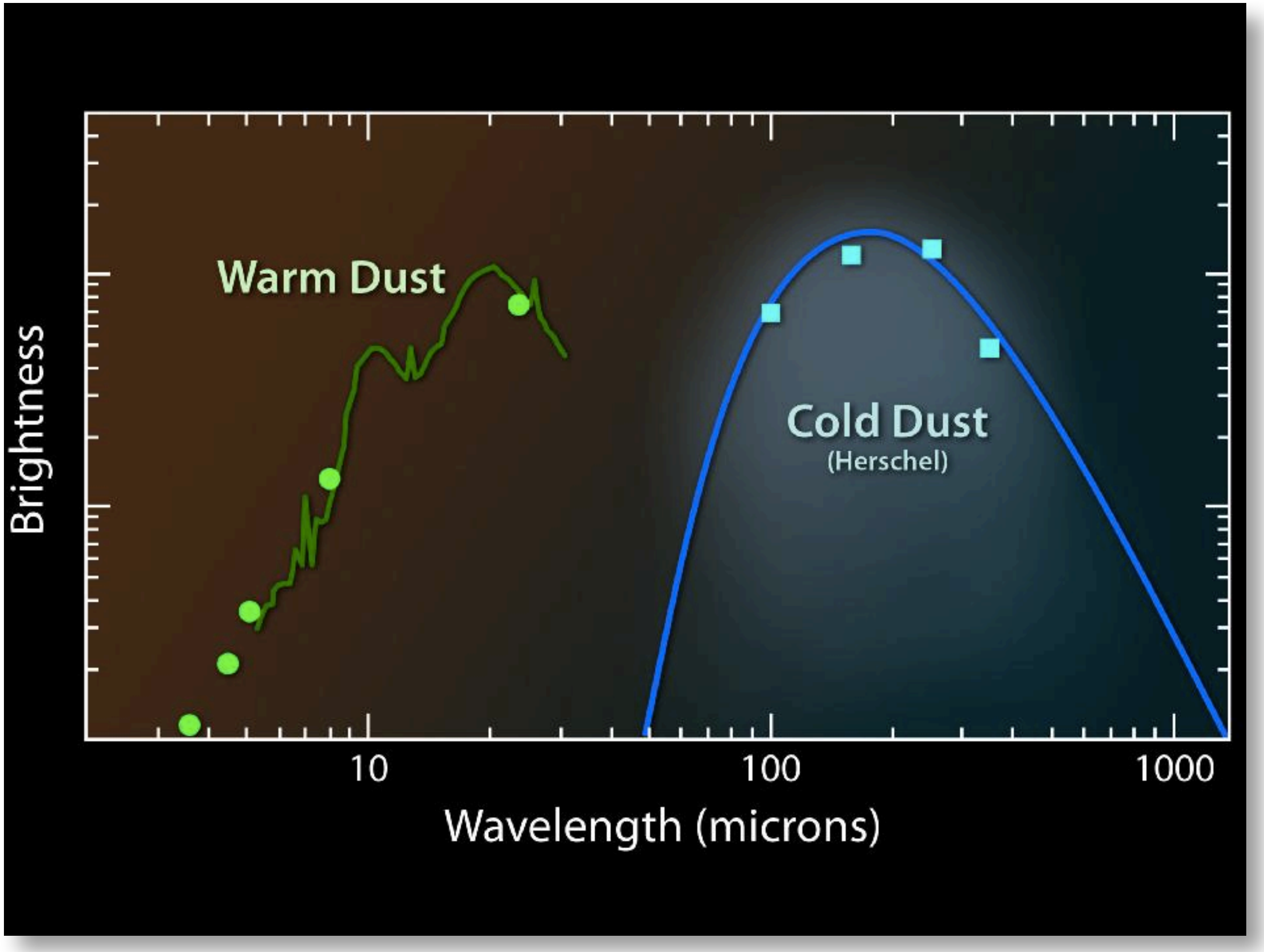
SN dust works, but…

SN1987A

- 100% dust efficiency?
- **All** metals are locked up in dust – no free metals to enter the ISM?





Matsuura et al. (2011, Science, 333, 1258)

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SN 1987 A

- 0.5 – 0.7 M_{sun} of cold dust if there is C-dust, 2.4 M_{sun} if only silicates (Matsuura et al. 2011, Science, 333, 1258).
- The progenitor was a 15 – 20 M_{sun} star.
- An 18 M_{sun} star produces 0.13 M_{sun} of silicon.
- $A_{silicates} = 121.41 \rightarrow M_{silicates} < 0.56\ M_{sun}$
- $M_C = 0.22\ M_{sun} \rightarrow M_{c\text{-}dust} < 0.22\ M_{sun}$

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Anyway…

- Maximum time to build large dust masses: < 400 – 500 Myr.
- SNe can produce dust rapidly, but also destroy dust – A catch 22!
- The universe have been at least as dusty and possibly even more dusty at earlier epochs. But how?
- What source is compensating for the dust destruction? We NEED a replenishment mechanism!

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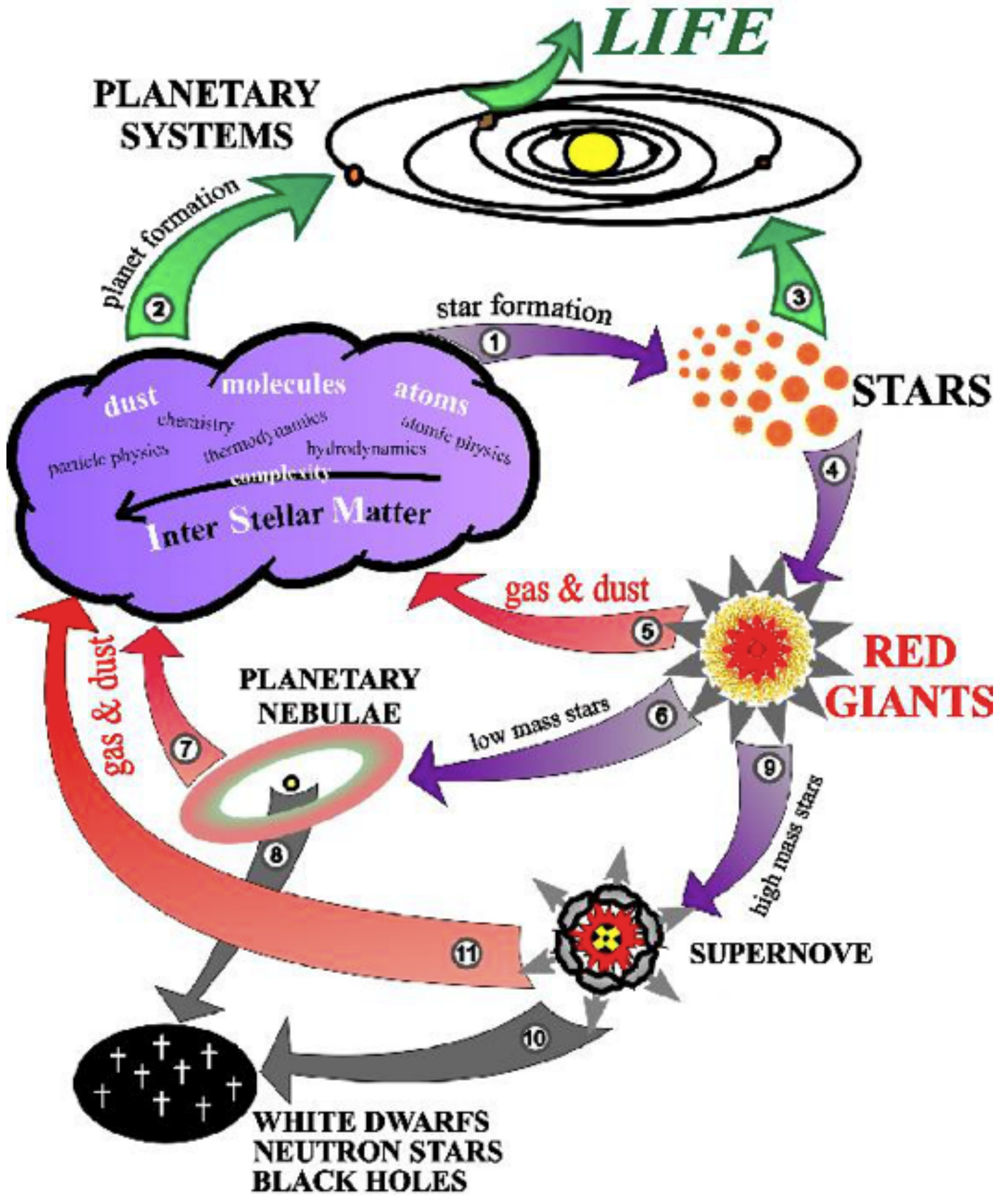
The cosmic matter cycle



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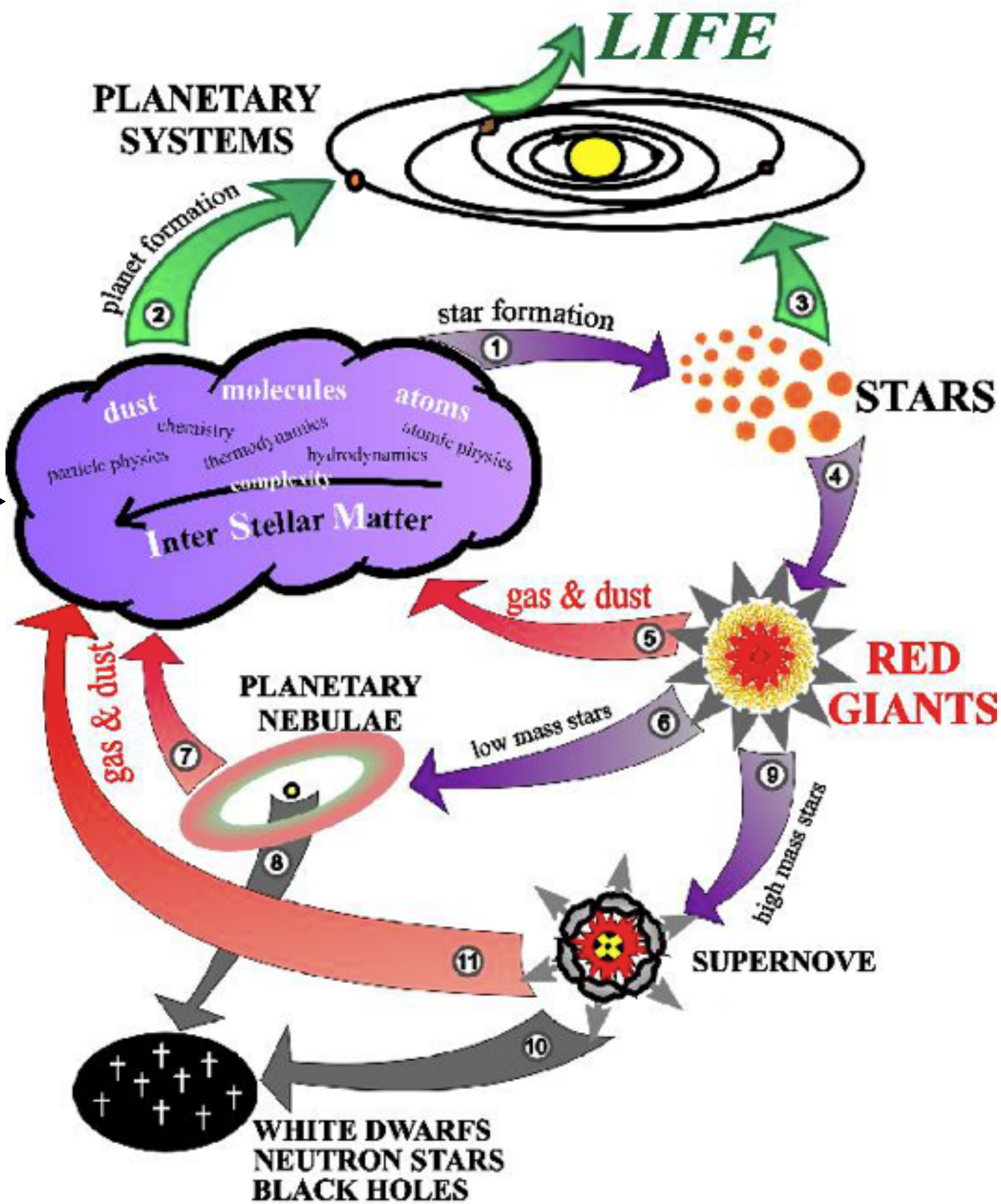
The cosmic matter cycle

Turbulence!



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Epstein drag

EOM for a particle:

$$m_{\rm gr} \frac{d\mathbf{v}}{dt} = \mathbf{F}_{\rm Epstein} = -\frac{4\pi}{3} a^2 \rho\, v_{\rm th}\, \Delta\mathbf{v}$$

$$m_{\rm gr} = \frac{4\pi}{3} a^3 \rho_{\rm gr}, \qquad \tau_{\rm stop} = \frac{\rho_{\rm gr} a}{\rho\, v_{\rm th}}$$

EOM for dust:

$$\frac{\partial \mathbf{v}_{\rm gr}}{\partial t} + \mathbf{v}_{\rm d} \cdot \nabla \mathbf{v}_{\rm gr} = -\frac{\Delta\mathbf{v}}{\tau_{\rm stop}}$$

Including a correct decoupling of the gas and dust dynamics is crucial!

In ISM simulations one can safely assume the drag is always in the Epstein limit.

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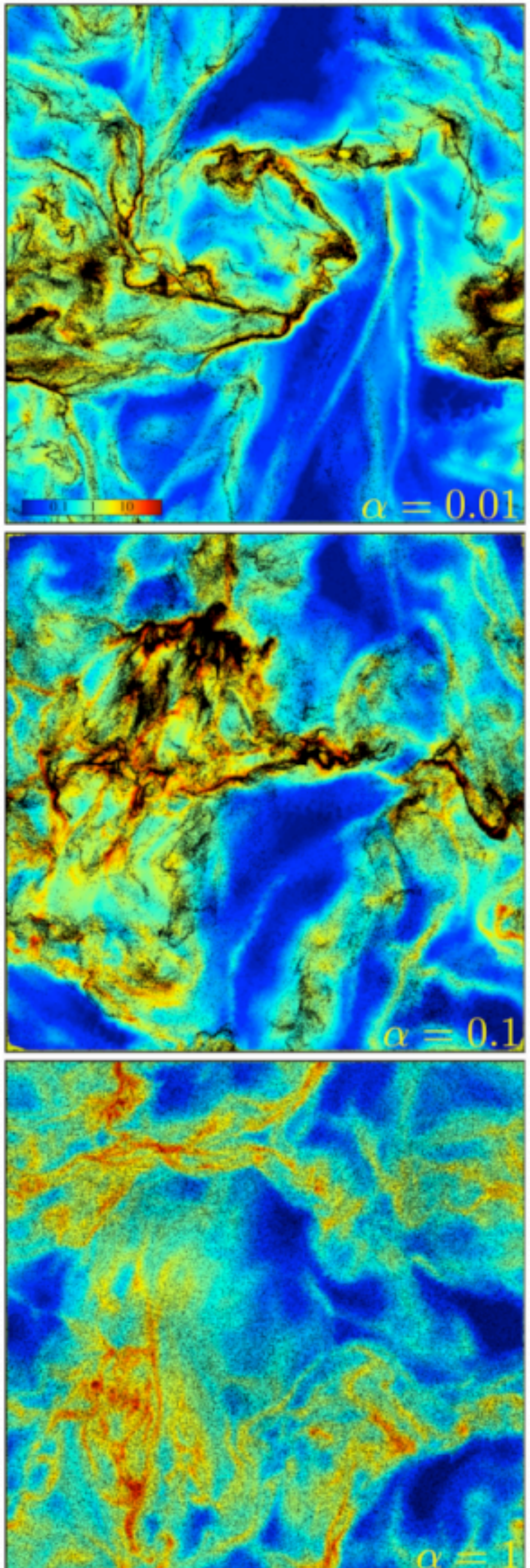
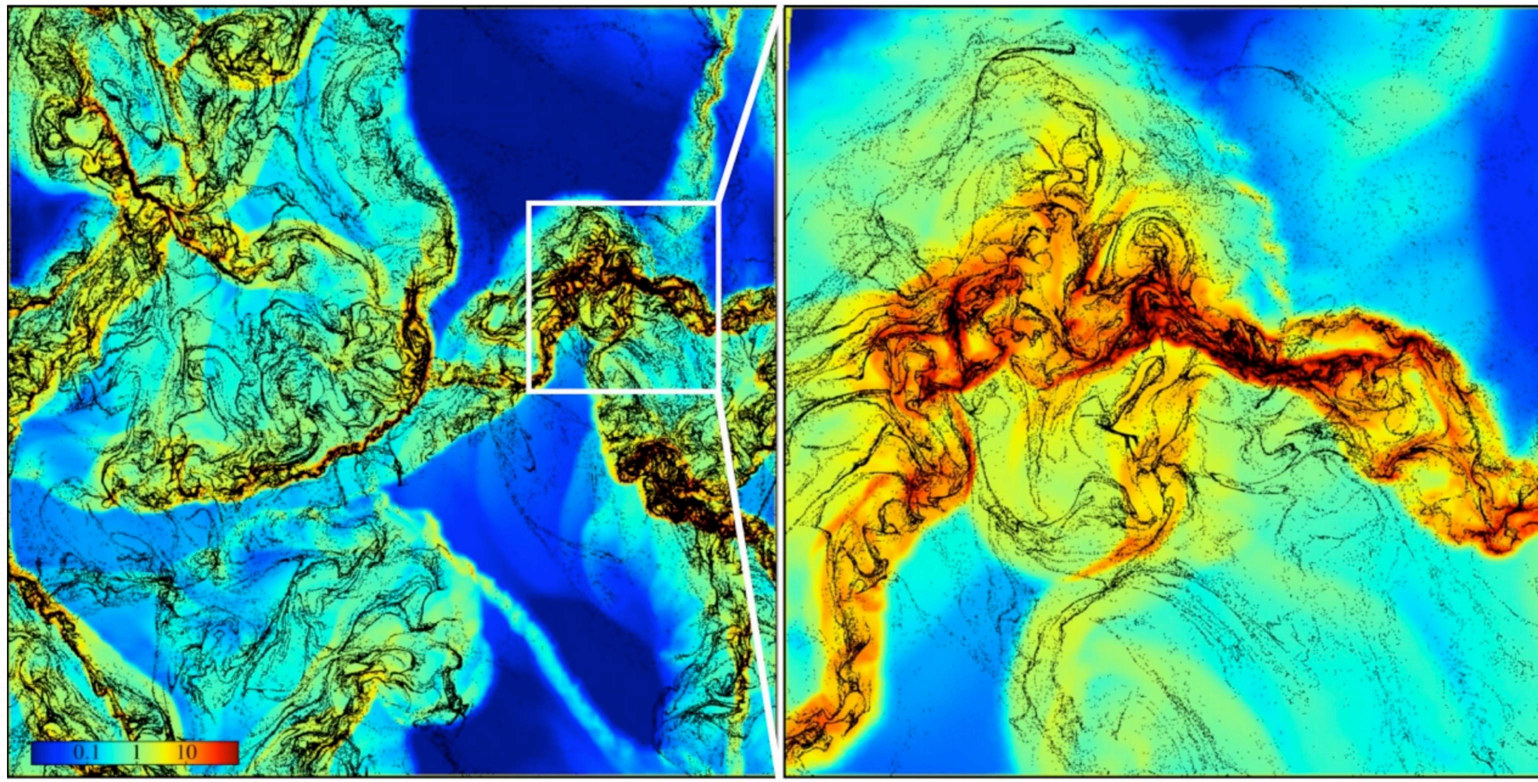
Epstein drag





Hopkins & Lee (2016)

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Epstein drag

“Swedish compass”

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Simulation with PENCIL code

- Central region of cold (T ~10K) molecular gas cloud in ISM.
- Non-isothermal: entropy equation & temperature structure.
- A range of different grain sizes included in dust phase.
- Stochastically forced turbulence.
- "Only" 256^3 resolution because non-isothermal and spectrum of grain sizes.

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Simulation with PENCIL code

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \qquad (1)$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \nabla P + \mathbf{F}_{\mathrm{visc}} + \mathbf{F}_{\mathrm{force}}, \quad \mathbf{F}_{\mathrm{visc}} = \nabla \cdot (2 \nu \rho \mathbf{S}) \qquad (2)$$

$$\rho T \frac{\partial s}{\partial t} + \rho T \mathbf{v} \cdot \nabla s = 2 \nu \rho \mathbf{S}^2 + \mathcal{H} - \mathcal{L}, \qquad (3)$$

$$\frac{\partial \mathbf{v}_{\mathrm{d}}}{\partial t} + \mathbf{v}_{\mathrm{d}} \cdot \nabla \mathbf{v}_{\mathrm{d}} = \frac{\mathbf{v} - \mathbf{v}_{\mathrm{d}}}{\tau_{\mathrm{s}}}$$

$$\tau_{\mathrm{s}} = \frac{\rho_{\mathrm{gr}}}{\rho} \frac{a}{\langle v_{\mathrm{th}} \rangle}$$

Simulation with PENCIL code

Table 1
Properties of Giant Molecular Clouds, Clumps, and Cores (Goldsmith 1987; Cernicharo 1991).

Properties	GMC	Clump	Core
Size (pc)	20–60	3–20	0.5–3
Density (cm^{-3})	100–300	10^3–10^4	10^4–10^6
Mass ($M_\odot$)	10^4–10^6	10^3–10^4	10–10^3
Linewidth ($km\ s^{-1}$)	6–15	4–12	1–3
Temperature (K)	7–15	15–40	30–100

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Some definitions…

- Stokes number: $$\mathrm{St} = \frac{u_0\, t_0}{\ell_0} = \frac{\tau_\mathrm{s}}{\tau_\ell}$$
- Reynolds number: $$\mathrm{Re} = \frac{u_0\, \ell_0}{\nu}$$
- Gas-to-dust ratio: $$g_\ell = \frac{\rho}{\bar{n}_\mathrm{d}^\ell} \Bigg/ \left\langle \frac{\rho}{\bar{n}_\mathrm{d}^\ell} \right\rangle$$

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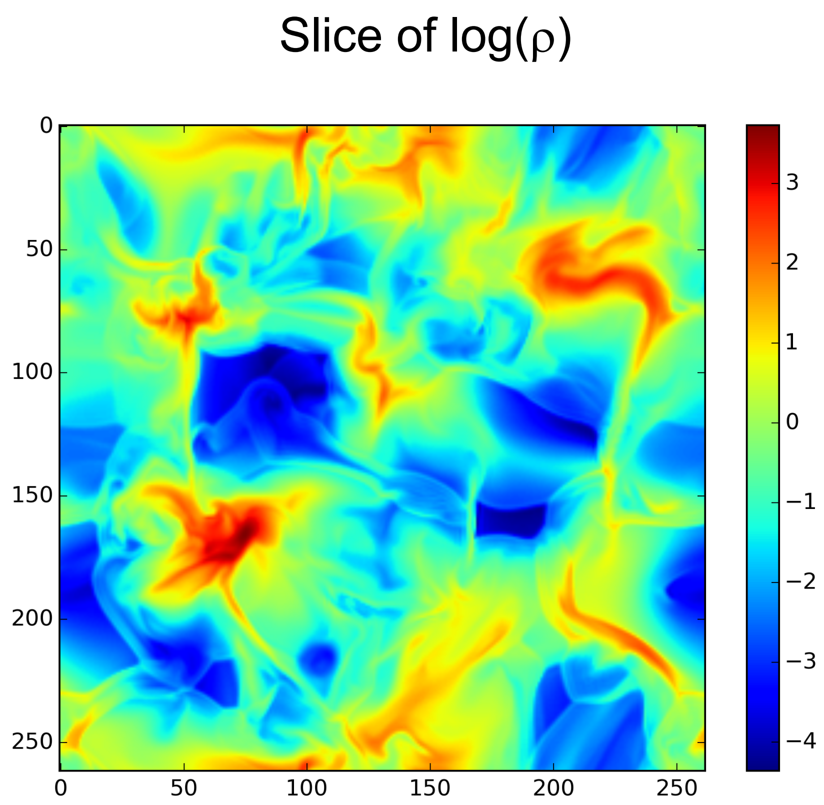
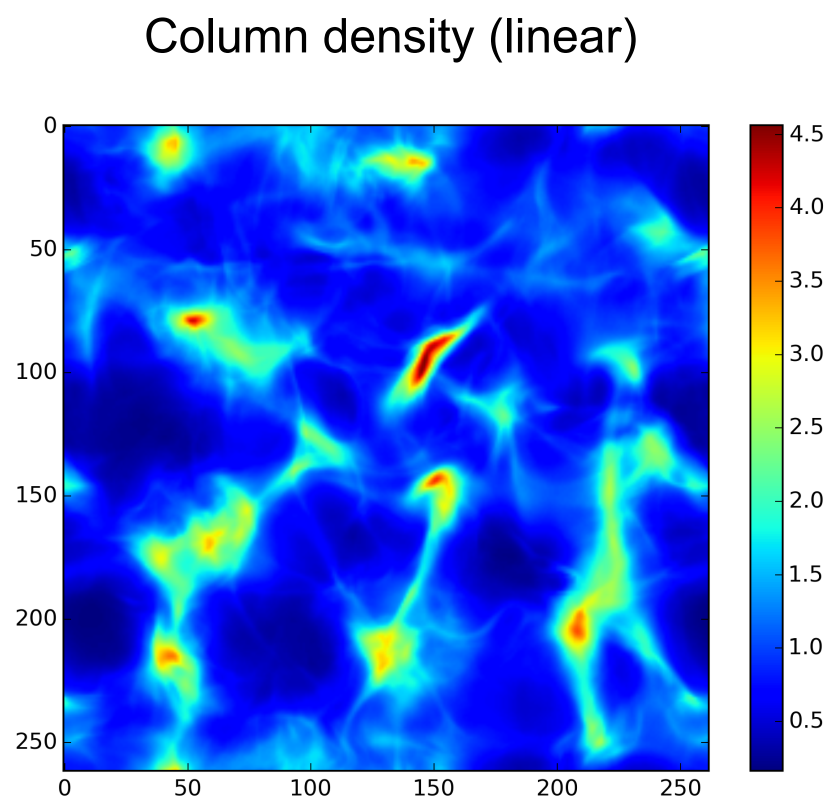
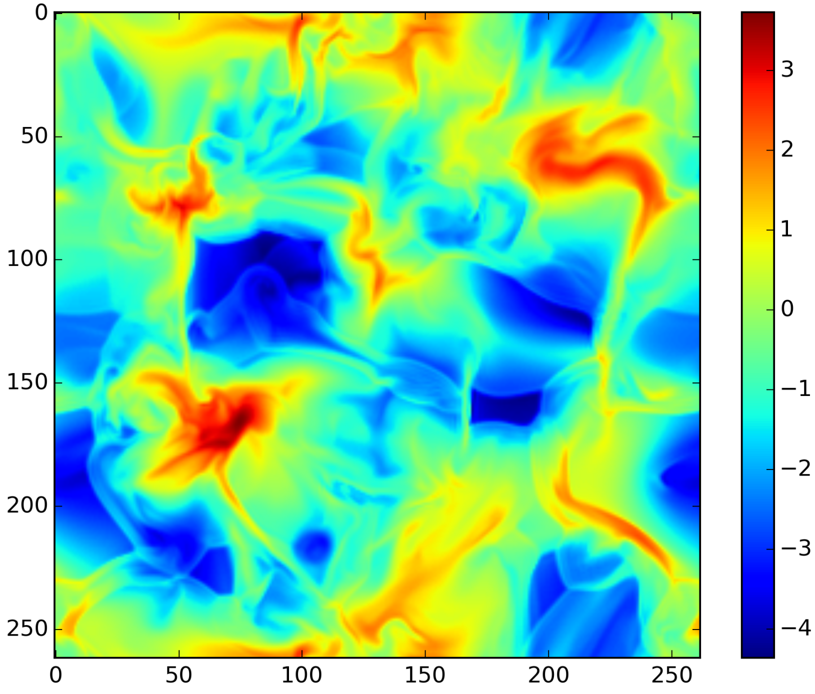
Turbulence in a box



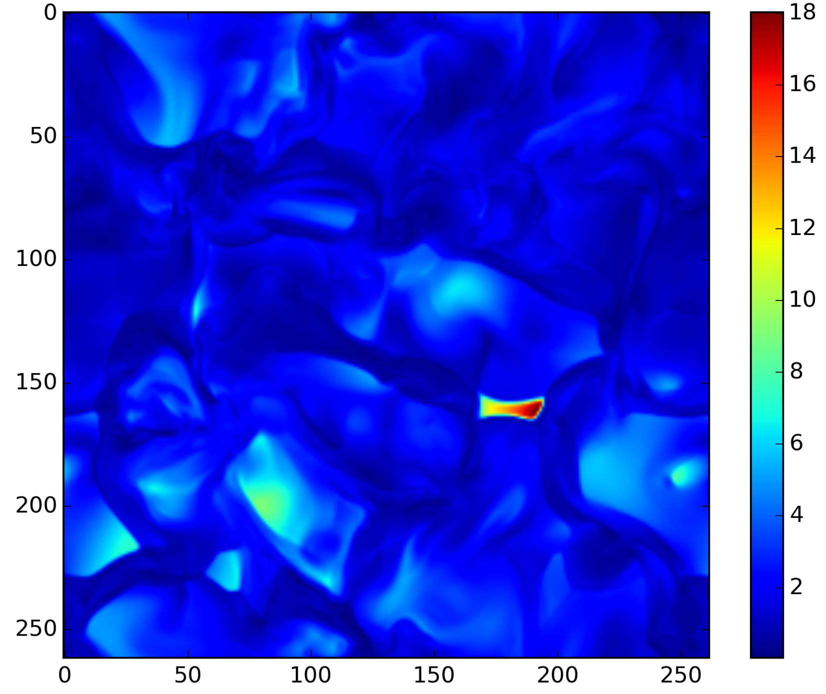


Turbulence in a box

Slice of log(ρ)



Mach number



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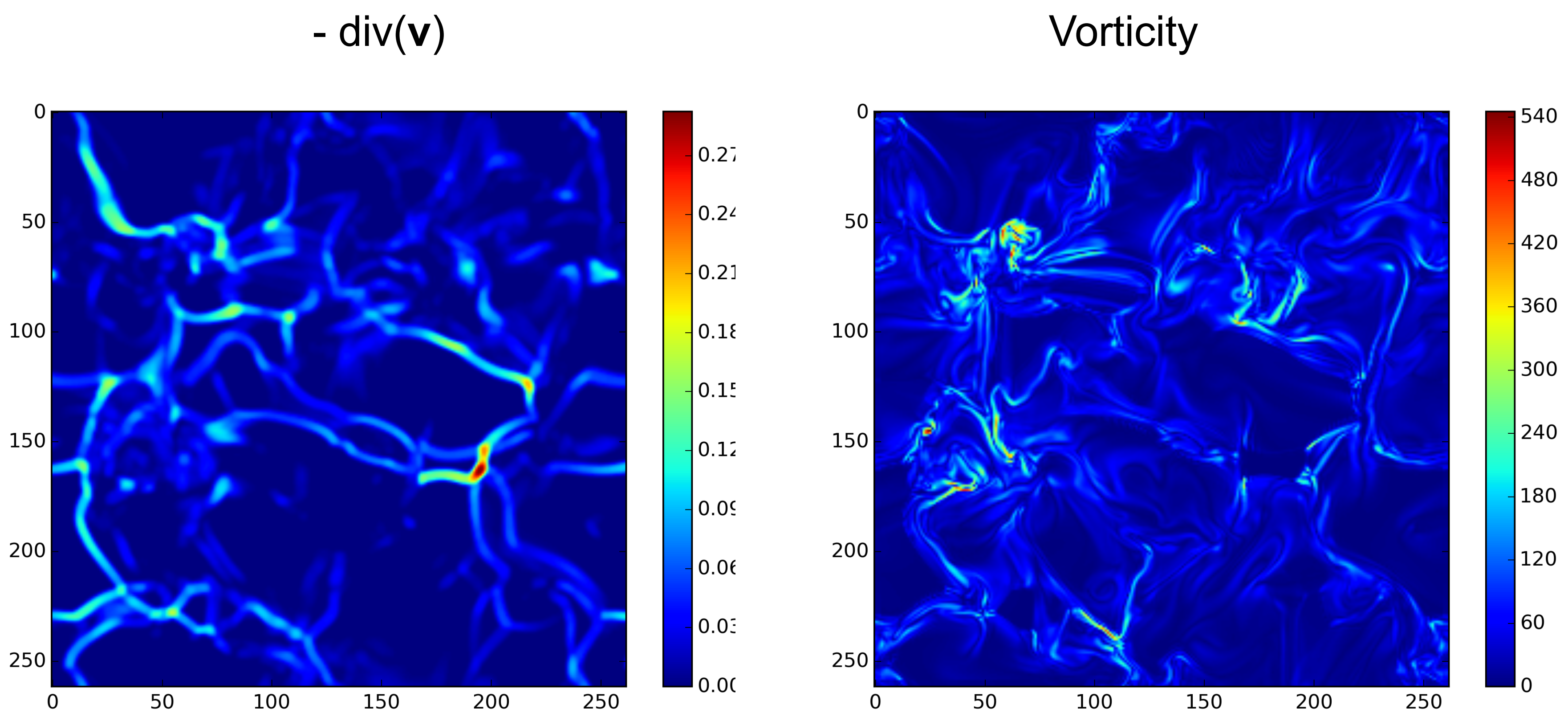

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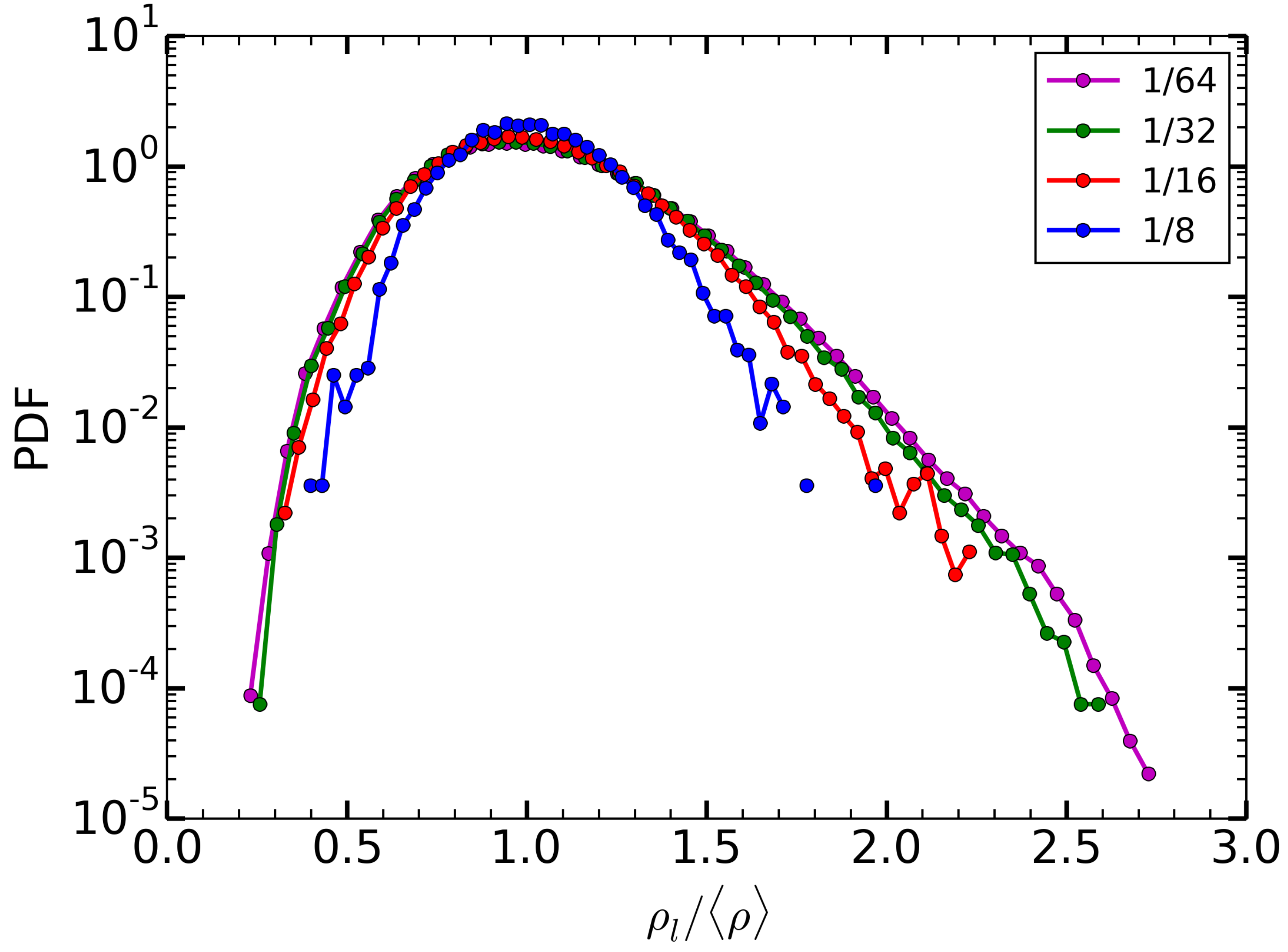
Gas-density PDF



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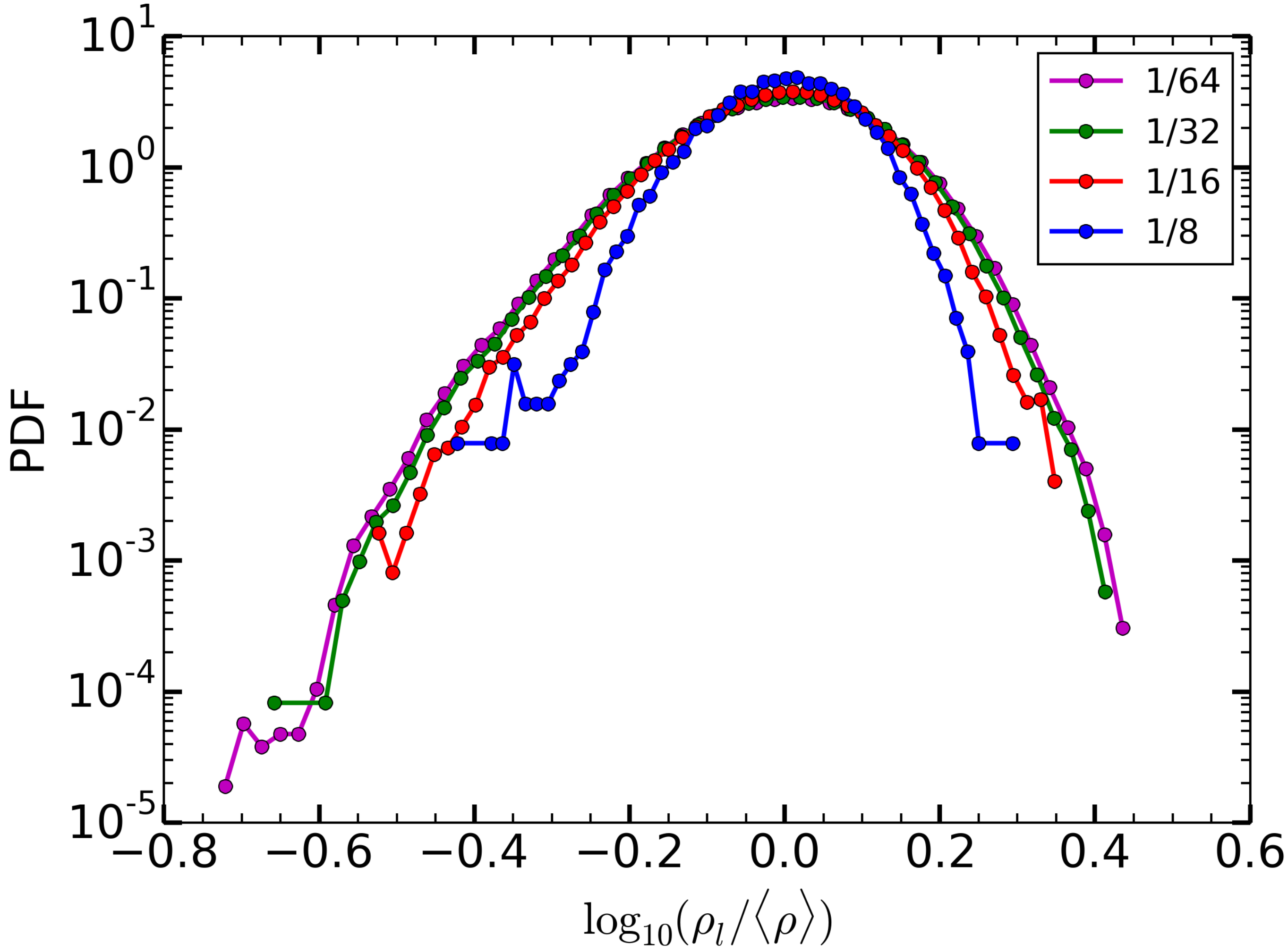

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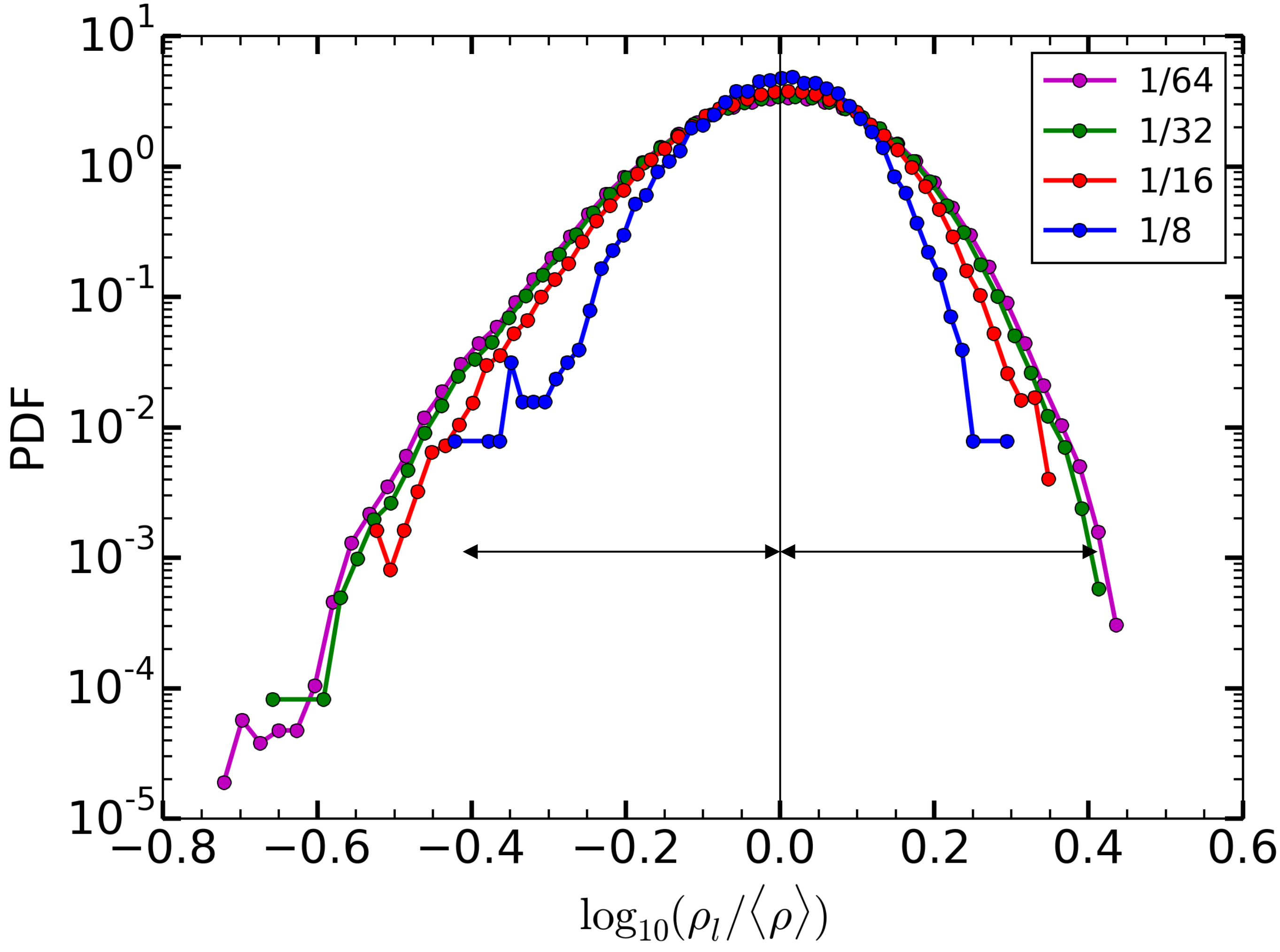

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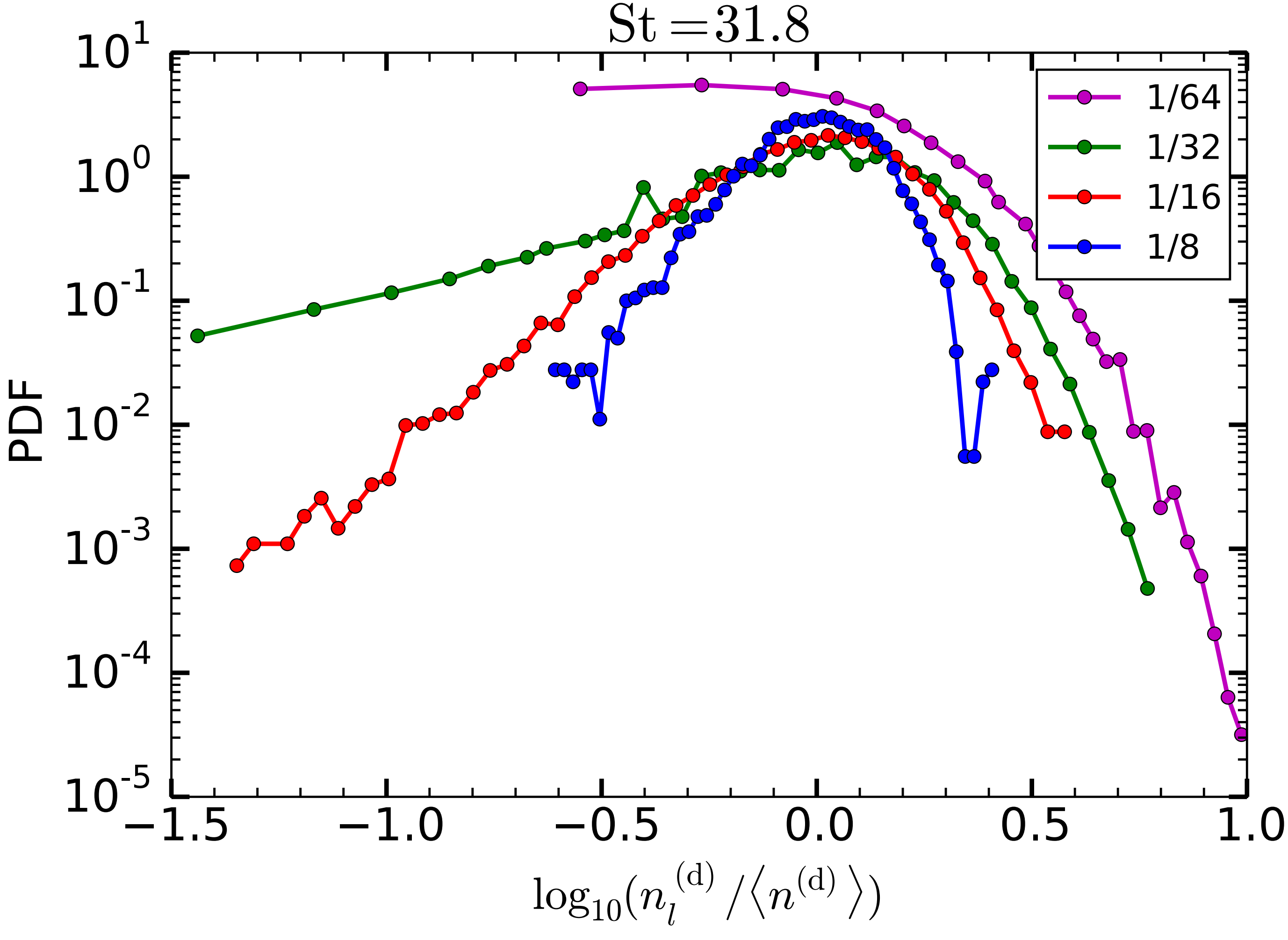
Dust-density PDF



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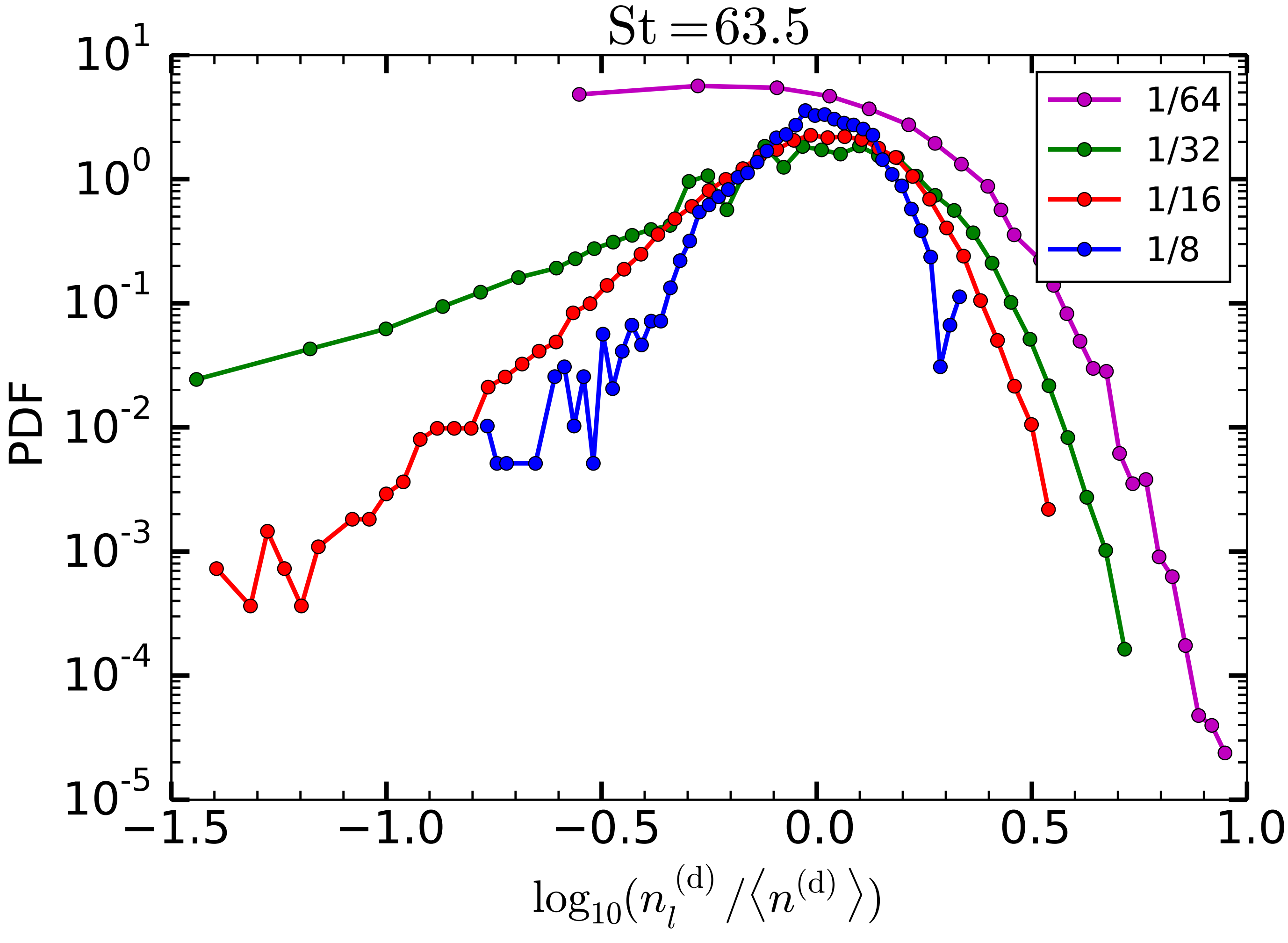

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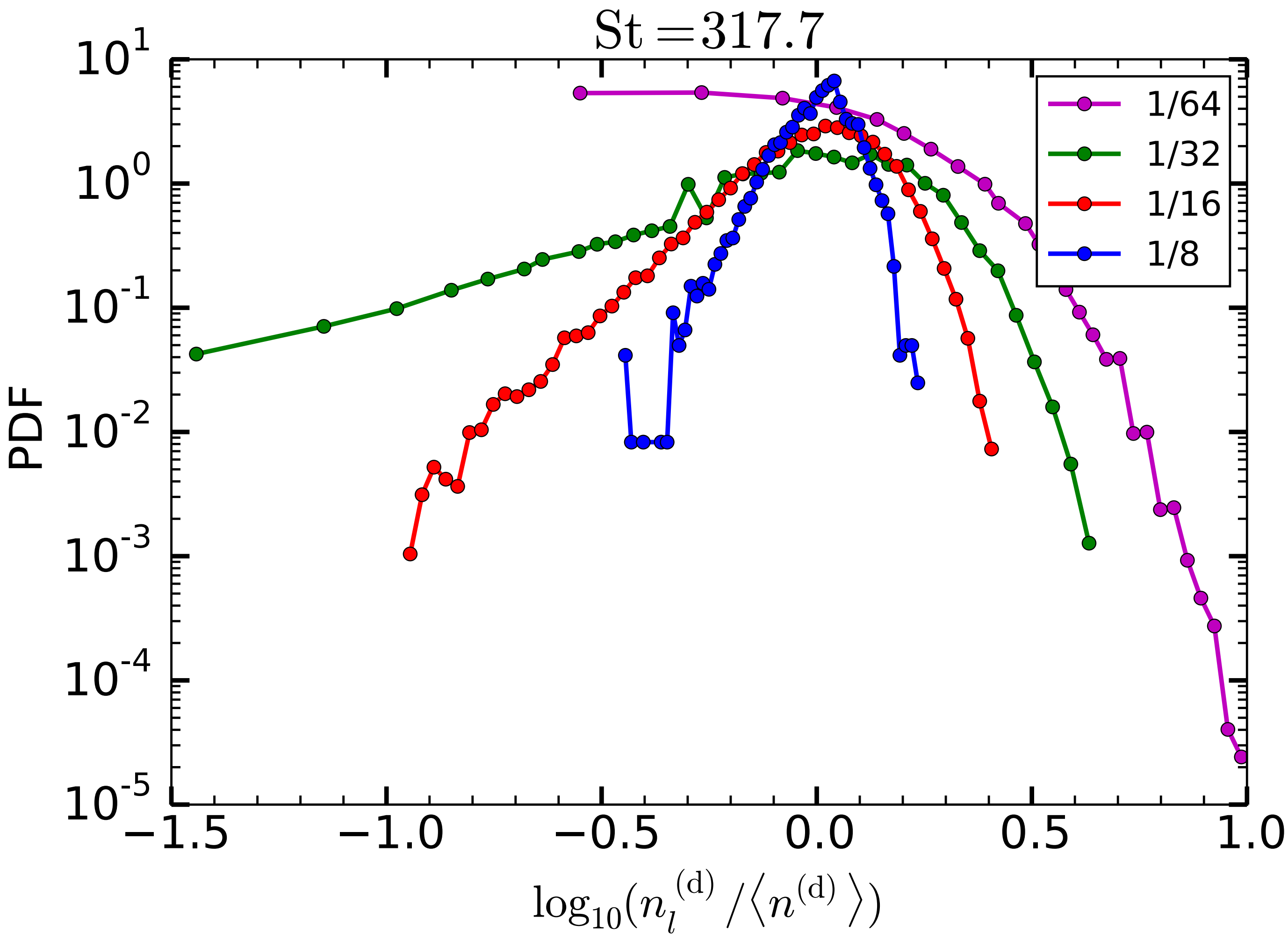

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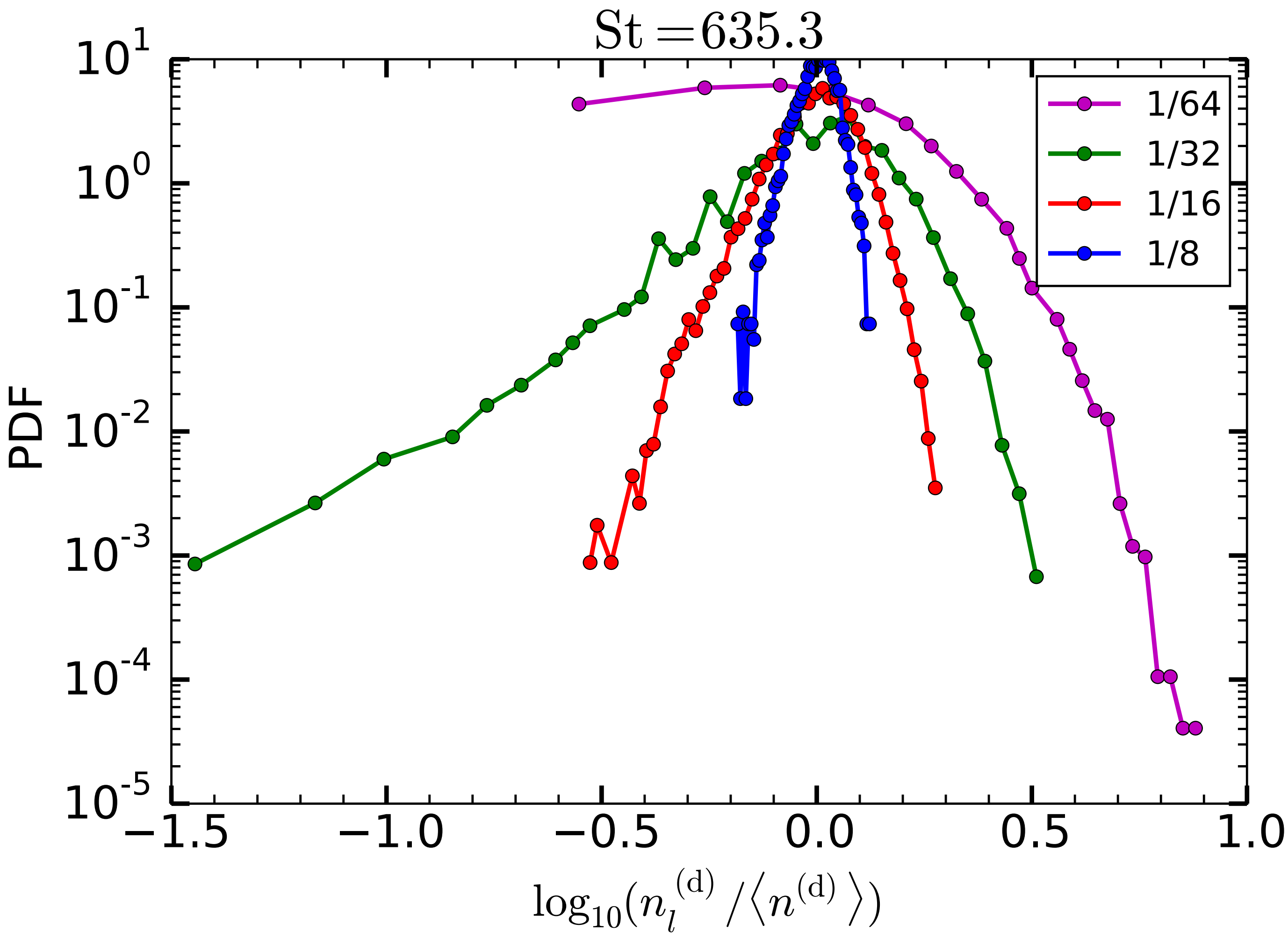

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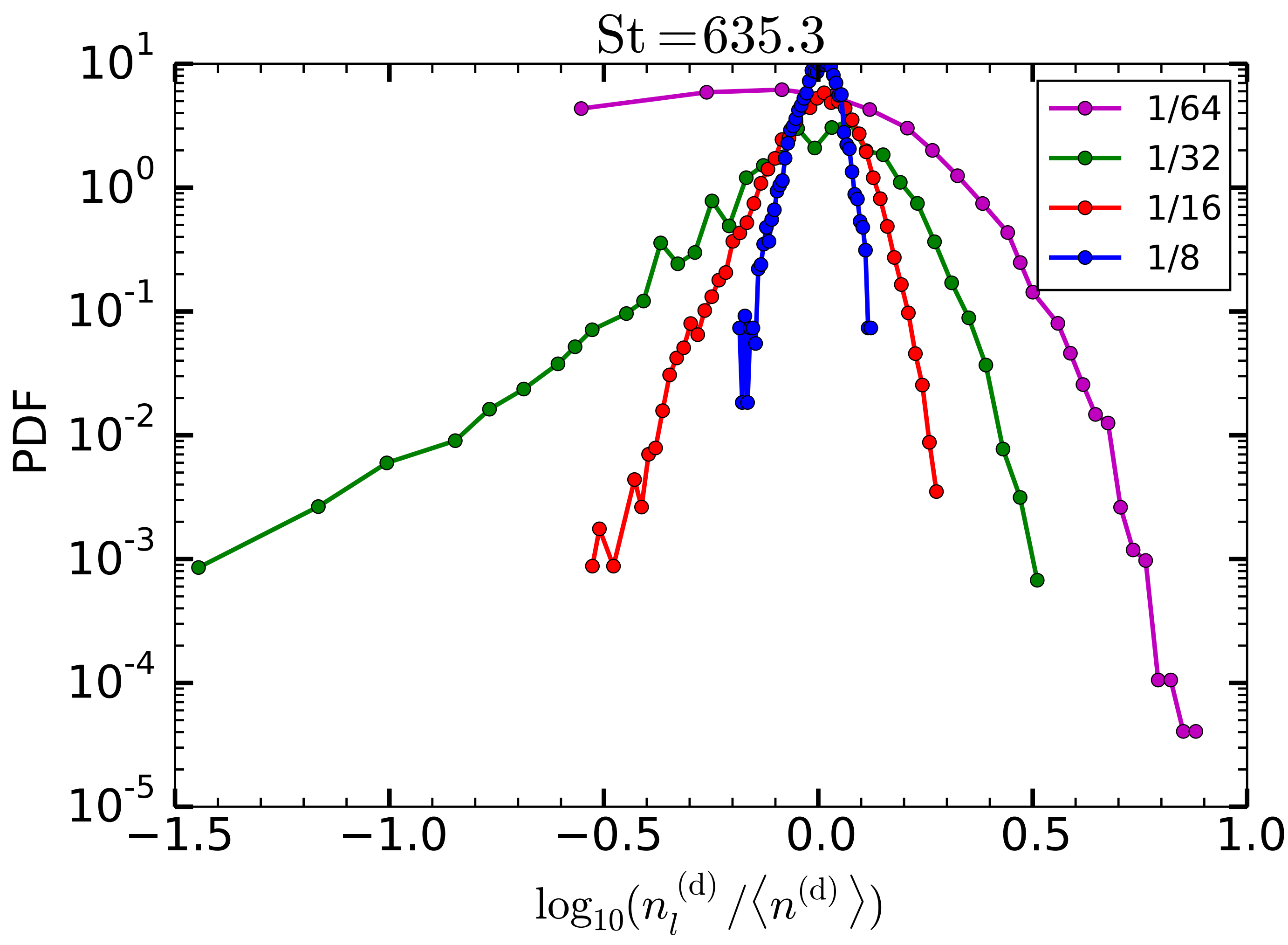

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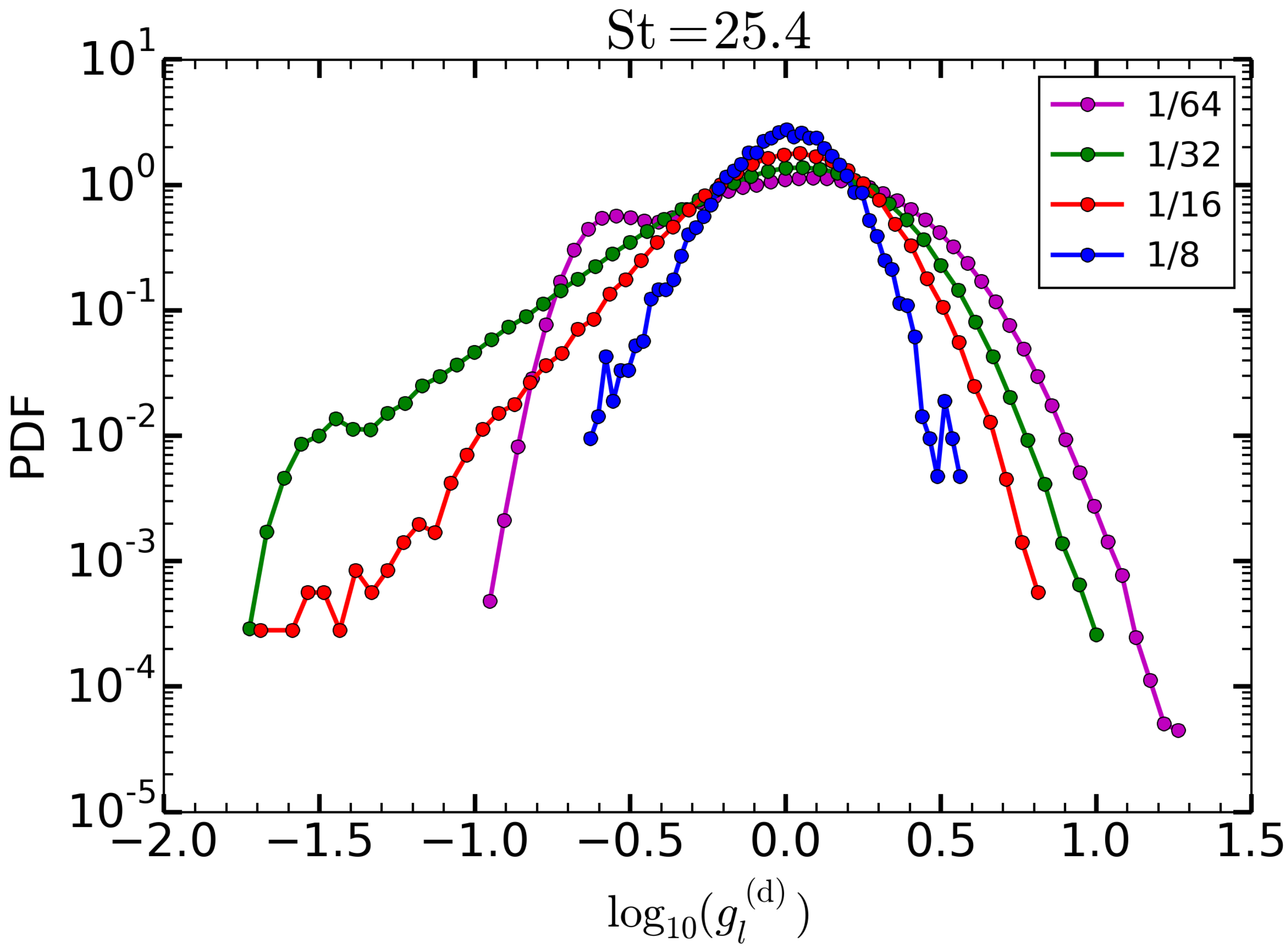
Dust-to-gas PDF



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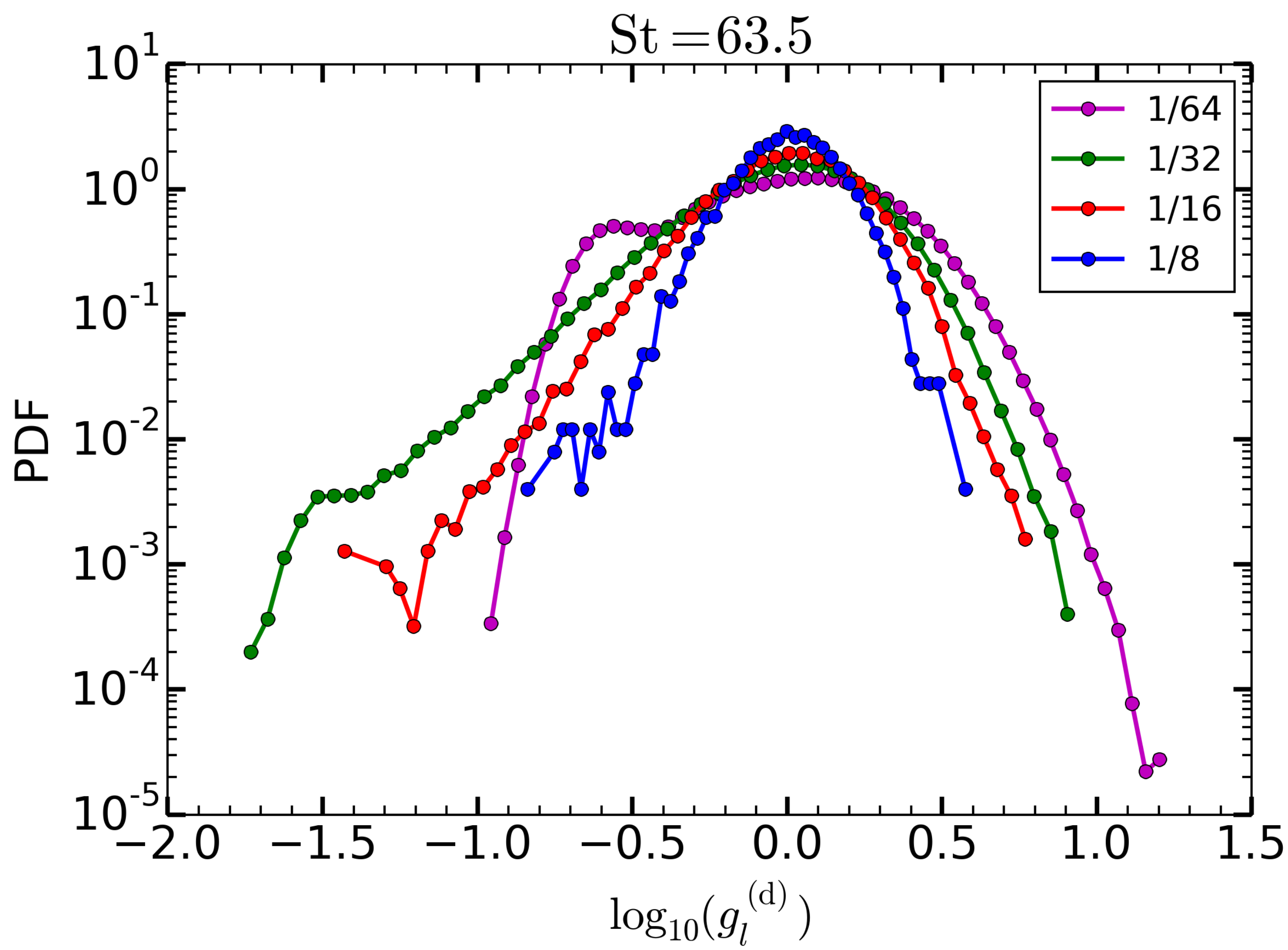
Dust-to-gas PDF



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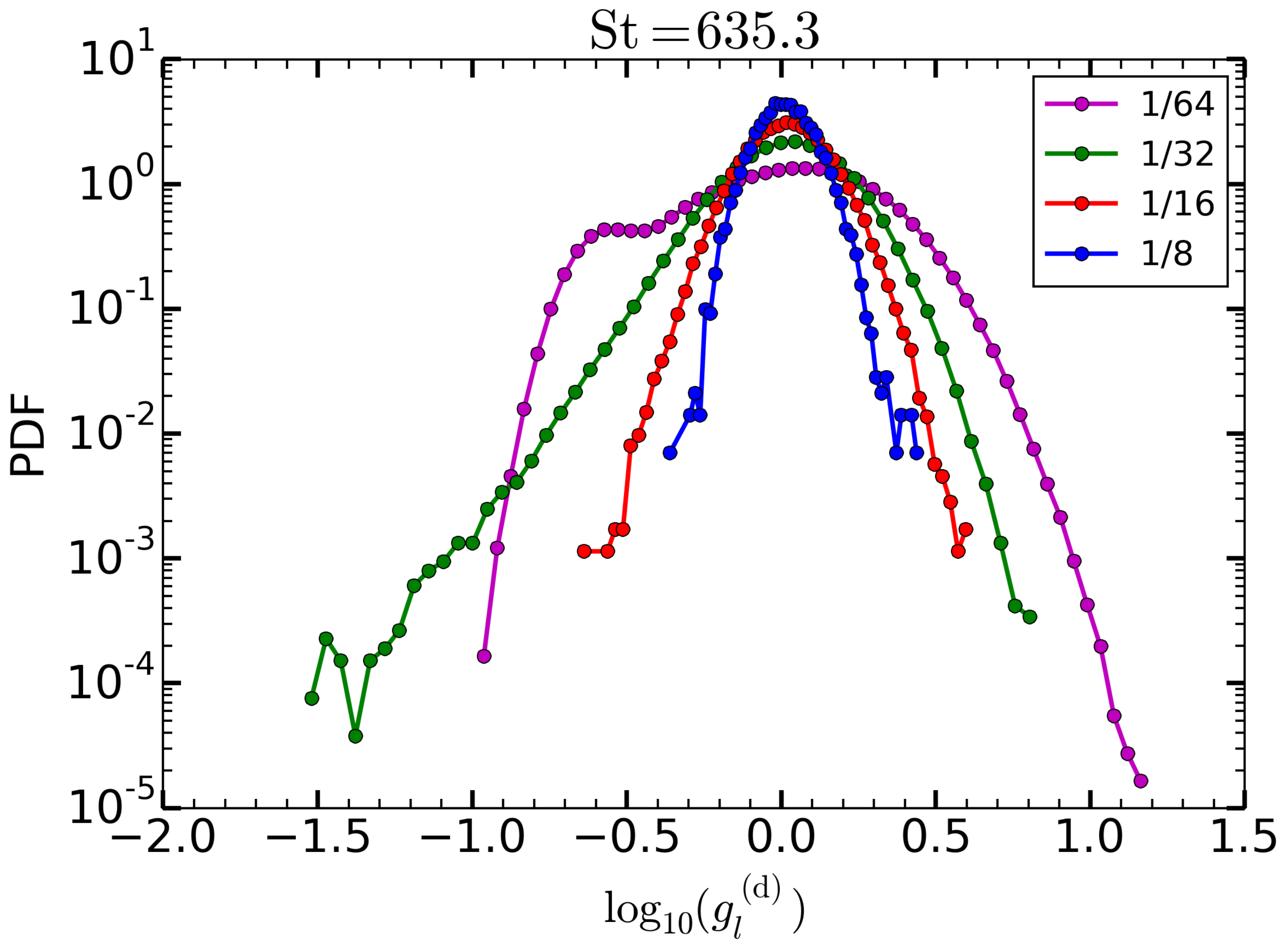

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Clustering

Bec et al. (2007, PRL, 98, 084502):

Below the Kolmogorov length scale η where the velocity field is differentiable, the motion of inertial particles is governed by the fluid strain, and the dissipative dynamics leads their trajectories to converge to a dynamically evolving attractor. For any given response time of the particles, their mass distribution is singular and generically scale invariant with fractal properties at small scales [8,11]. To characterize particle clusters at these scales, we measured the correlation dimension $\mathcal{D}_2$, which is estimated through the small-scale algebraic behavior of the probability to find two particles at a distance less than a given r: $P_2(r) \sim r^{\mathcal{D}_2}$.

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Clustering

Bec et al. (2007, PRL, 98, 084502):

$$g(r) \propto r^{-2}\frac{dP}{dr} \propto r^{d_2}$$

$$w^2 \equiv \frac{x^2}{\eta^2} + \frac{v^2}{u_{\rm rms}^2}, \quad g(w) \propto w^{D_2}$$

Below t… he veloc-
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their mas… ly scale
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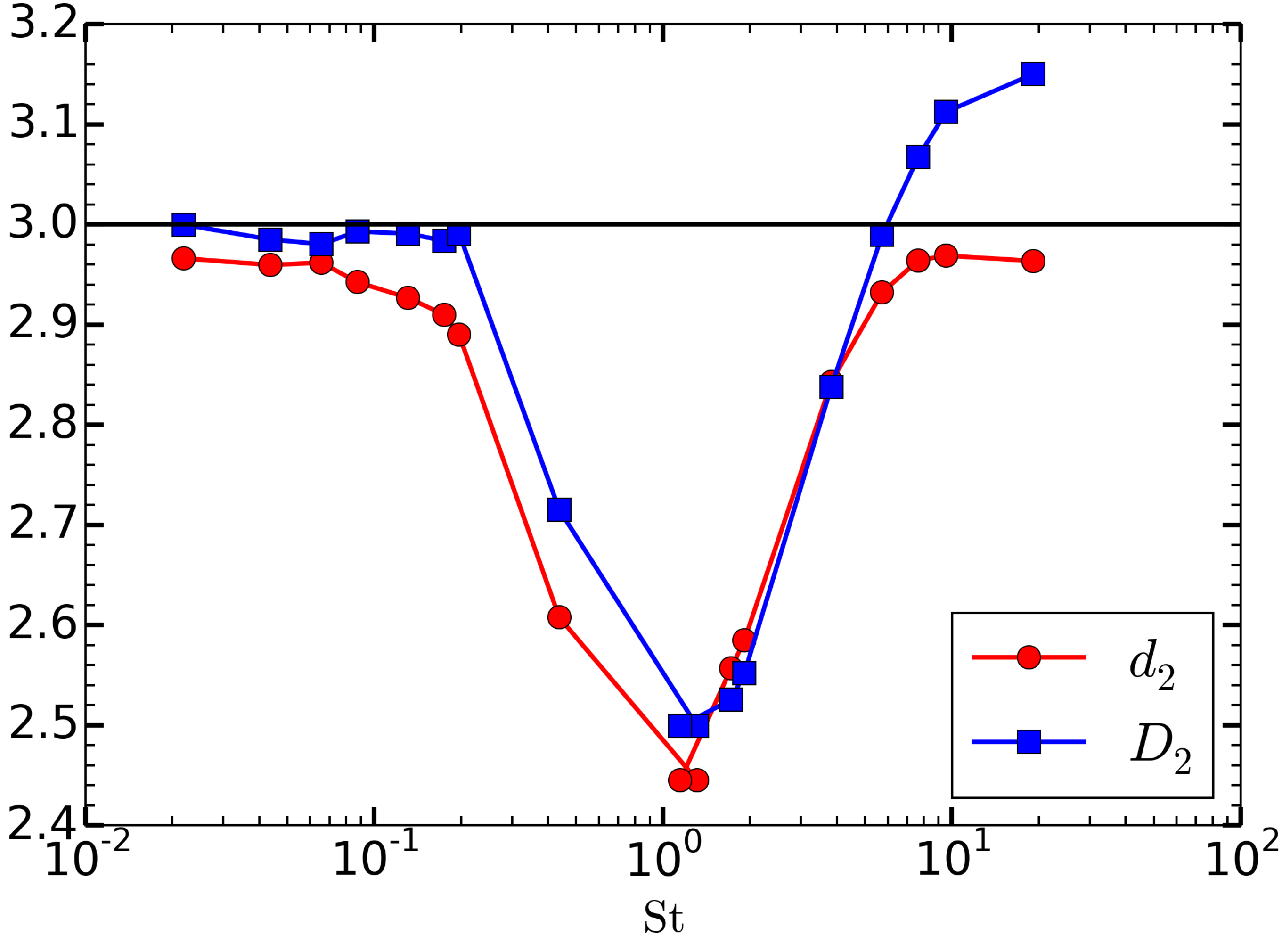

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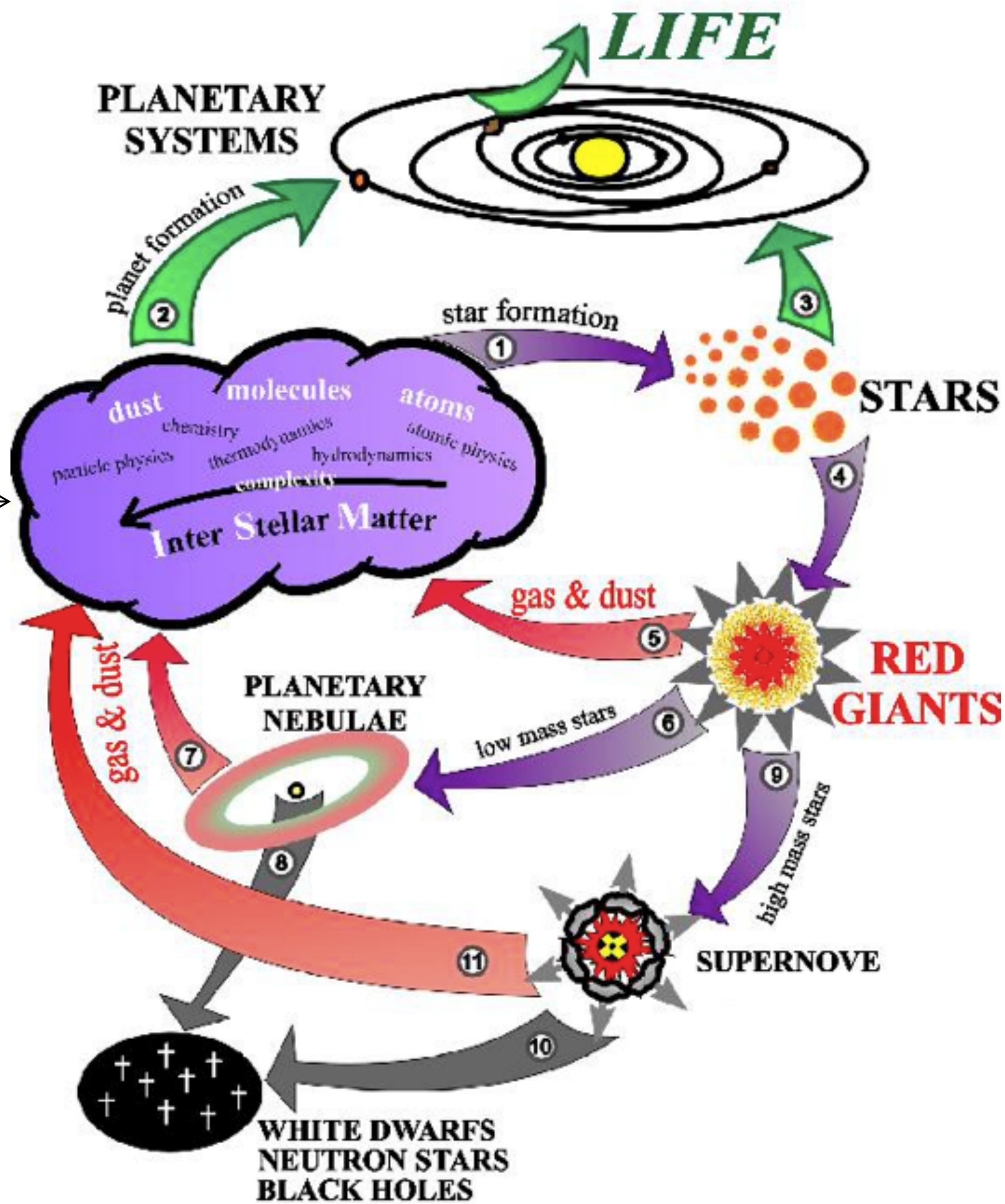
The cosmic matter cycle

Coagulation
&
condensation



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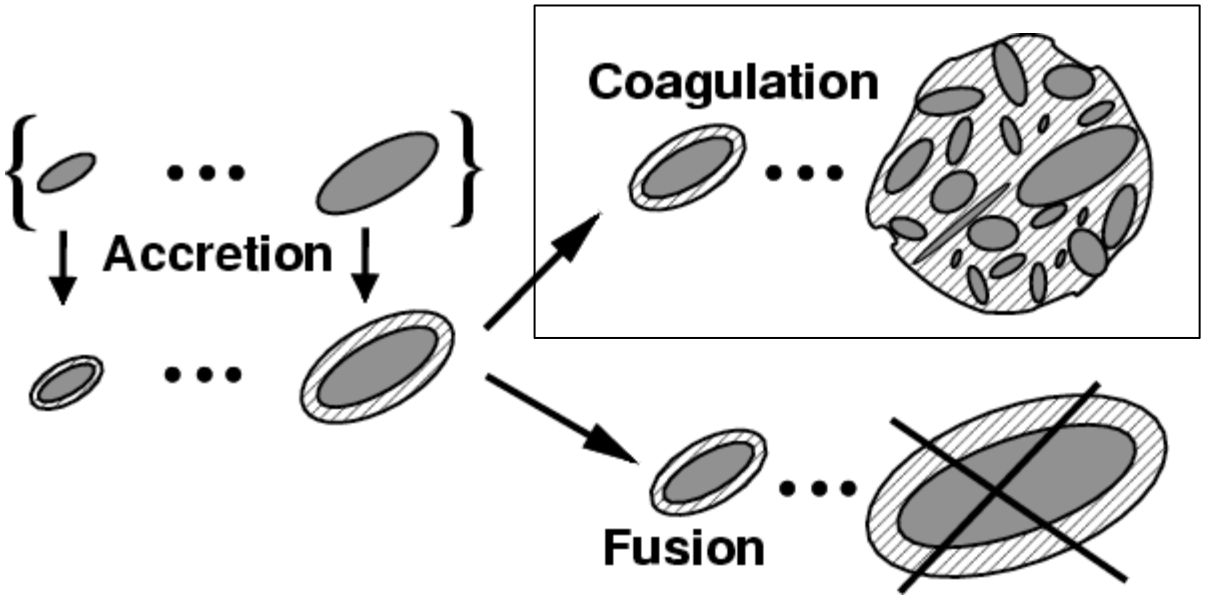
Coagulation

Smoluchowski (coagulation) equation:

$$\frac{\partial f}{\partial t} = \frac{1}{2}\sum_{j=1}^{i-1} C(m_i - m_j, m_j)\, f(m_i - m_j, t)\, f(m_j, t) - \sum_{j=1}^{\infty} C(m_i, m_j)\, f(m_i, t)\, f(m_j, t),$$

$$\frac{\partial f}{\partial t} = \frac{1}{2}\int_0^m C(m - m', m') f(m - m', t) f(m', t)\, dm' - f(m, t)\int_0^\infty C(m, m')\, f(m', t)\, dm',$$



(+ **fragmentation** as a “reverse process”)

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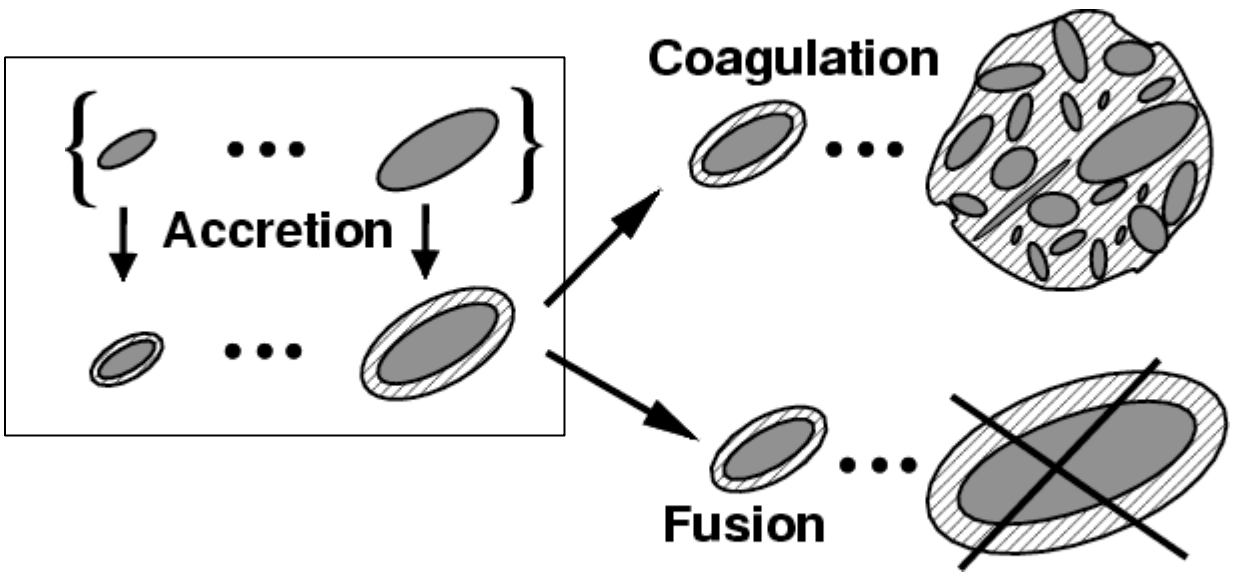
Condensation

Condensation equation:

$$\frac{dm}{dt} = 4\pi\, a^2\, \alpha_{\rm s}\, \langle v_{\rm mol}\rangle\, \rho_{\rm mol}(t),$$

$$\xi_{{\rm c},k}(t) = \frac{da}{dt} = \alpha_{\rm s}\, \langle v_{\rm mol}\rangle\, \frac{A_{{\rm eff},\,j}}{A_k}\, \frac{\rho_k(t) - \rho_{\rm d}(t)}{\rho_{\rm gr}},$$



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Condensation

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

$$\frac{\partial \rho_{\mathrm{d}}}{\partial t} + \nabla \cdot (\rho_{\mathrm{d}}\, \mathbf{v}_{\mathrm{d}}) = [\text{cond. source term}]$$

Lagrangian frame:

$$(\nabla \cdot \mathbf{v})_{\mathrm{L}} = \left(\left.\frac{\partial v_1}{\partial x_1}\right|_{\mathbf{r}(t)} + \left.\frac{\partial v_2}{\partial x_2}\right|_{\mathbf{r}(t)} + \left.\frac{\partial v_3}{\partial x_3}\right|_{\mathbf{r}(t)} \right)_{\mathrm{L}}$$

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Condensation

$$\mathcal{K}_\ell(t) = \int_0^\infty a^\ell f(a,t)\, da.$$

$$\frac{d\mathcal{K}_\ell}{dt} = \ell\xi(t)\,\mathcal{K}_{\ell-1}(t)$$

With dynamics (Lagrangian, dust-gas velocity coupling):

$$\frac{d\mathcal{K}_\ell}{dt} = \ell\xi(t)\,\mathcal{K}_{\ell-1}(t) - \mathcal{K}_\ell(t)\,(\nabla\cdot\mathbf{v})_\mathrm{L}$$

$$\frac{d\langle a^\ell\rangle}{dt} = \frac{1}{\mathcal{K}_0}\left(\frac{d\mathcal{K}_\ell}{dt} - \frac{\mathcal{K}_\ell}{\mathcal{K}_0}\frac{d\mathcal{K}_0}{dt}\right)$$

$$\frac{d\langle a^\ell\rangle}{dt} = \ell\,\xi(t)\,\langle a^{\ell-1}\rangle$$

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Condensation

$$\mathcal{K}_\ell = \bar{\mathcal{K}}_\ell + \mathcal{K}'_\ell, \quad \xi = \bar{\xi} + \xi'$$

$$\bar{Q}(t) = \frac{1}{2\tau} \int_{t-\tau}^{t+\tau} Q(t')\, dt'$$

Results in the following averaged equations:

$$\frac{d\bar{\mathcal{K}}_\ell}{dt} = \ell \bar{\xi}\, \bar{\mathcal{K}}_{\ell-1} + \ell \overline{\xi' \, \mathcal{K}'_{\ell-1}} - \overline{\mathcal{K}'_\ell \, (\nabla \cdot \mathbf{v})'_{\mathrm{L}}}$$

$$\overline{(\nabla \cdot \mathbf{v})_{\mathrm{L}}} = 0, \quad \overline{\mathcal{K}'_0 \, (\nabla \cdot \mathbf{v})'_{\mathrm{L}}} = 0.$$

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Condensation

$$\rho_{\rm d}(t) \equiv \frac{4\pi\rho_{\rm gr}}{3}\int_0^\infty a^3 f(a,t)\,da.$$

$$\mathbf{v}_{\rm d}(t) \equiv \frac{4\pi}{3}\frac{\rho_{\rm gr}}{\rho_{\rm d}(t)}\int_0^\infty a^3 f(a,t)\,\mathbf{v}_{\rm d}(a,t)\,da$$

$$\rho \equiv \rho_{\rm g} + \rho_{\rm d}, \qquad \mathbf{v} \equiv \frac{\rho_{\rm g}\mathbf{v}_{\rm g} + \rho_{\rm d}\mathbf{v}_{\rm d}}{\rho}$$

$$\frac{\xi}{\xi_0} = \frac{X_i\rho - \rho_{\rm d}}{\rho_0} = \left[\frac{X_i\bar{\rho}_{\rm g} - (1-X_i)\bar{\rho}_{\rm d}}{\rho_0}\right] + \left[\frac{X_i\rho'_{\rm g} - (1-X_i)\rho'_{\rm d}}{\rho_0}\right]$$

Condensation

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> 0

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Conclusions

- Stars produced the first dust grains, but most of the interstellar dust may have condensed in MCs.
- Under all circumstances, interstellar dust condensation is needed as a replenishment mechanism.
- Compressible turbulence leads to gas-dust separation and clustering of grains:
    - **Coagulation rate increases due to the clustering.**
    - **Condensation rate can be affected in various ways and may effectively decrease due to the separation.**

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