# The origins and processing of cosmic dust

*Forging connections workshop*
*MSU, June 26 – 29, 2017*

**Lars Mattsson**

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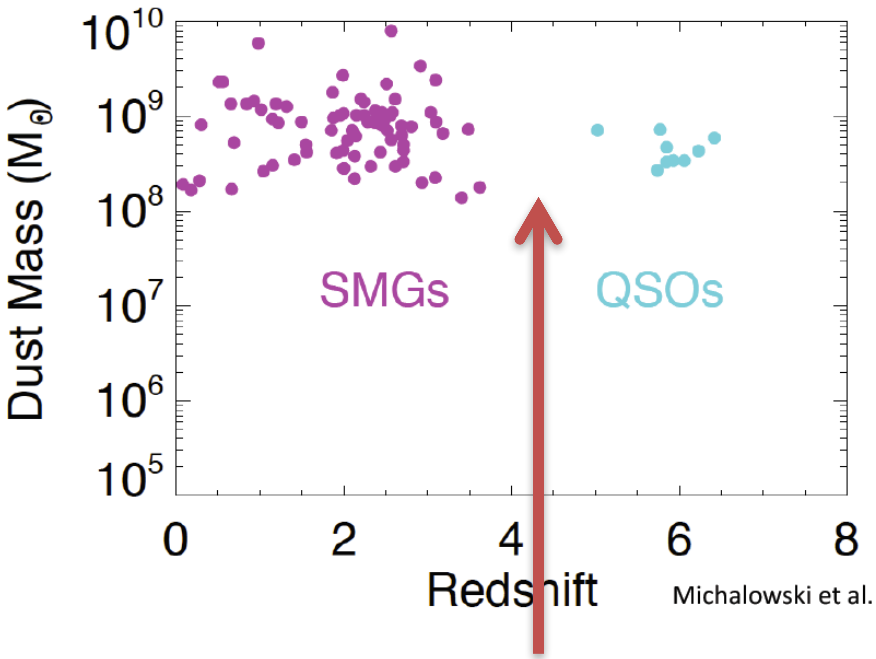
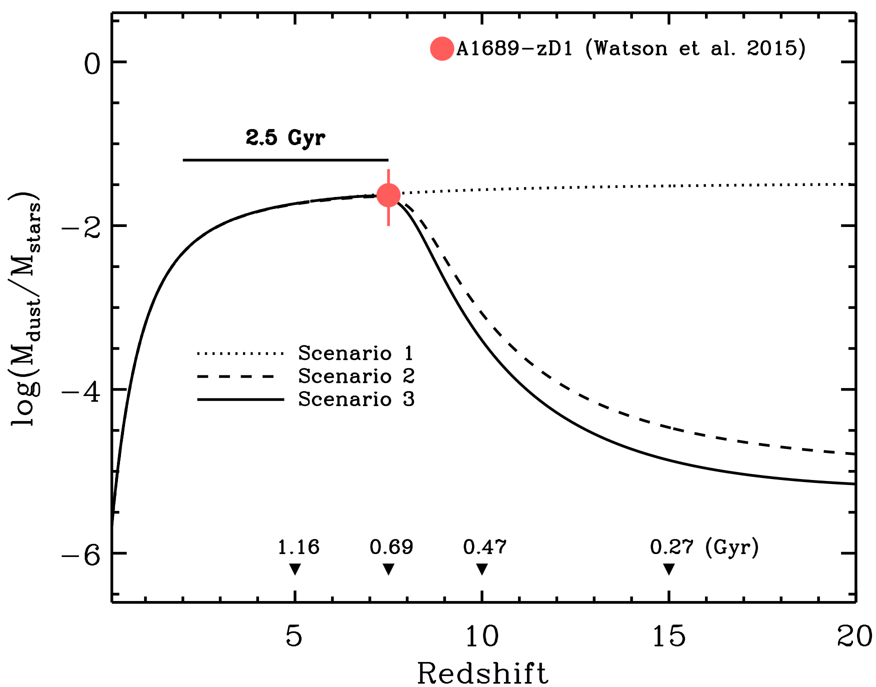
# Large amounts of dust at high redshift




Recent observations populate this gap!




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

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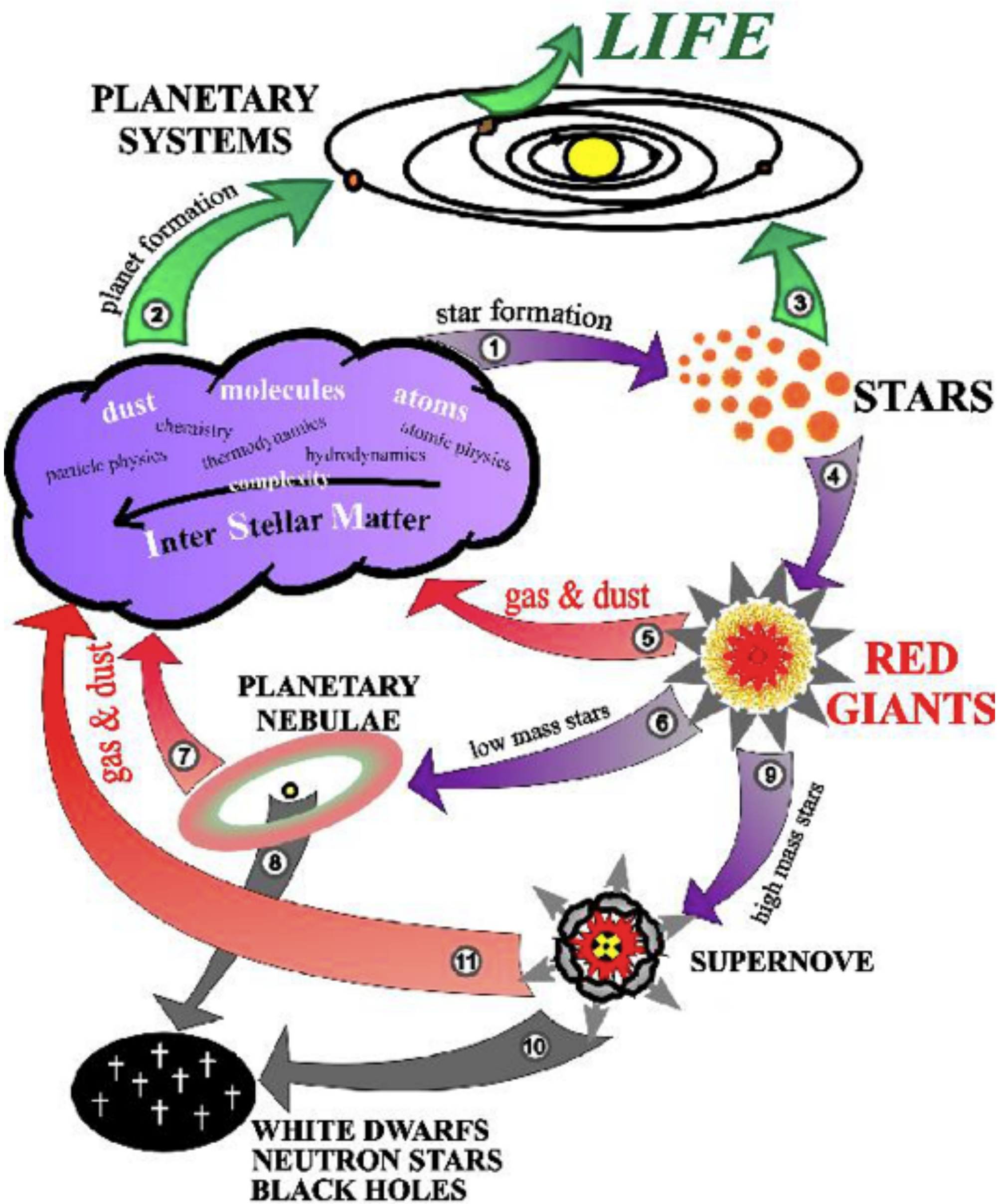
# The cosmic matter cycle

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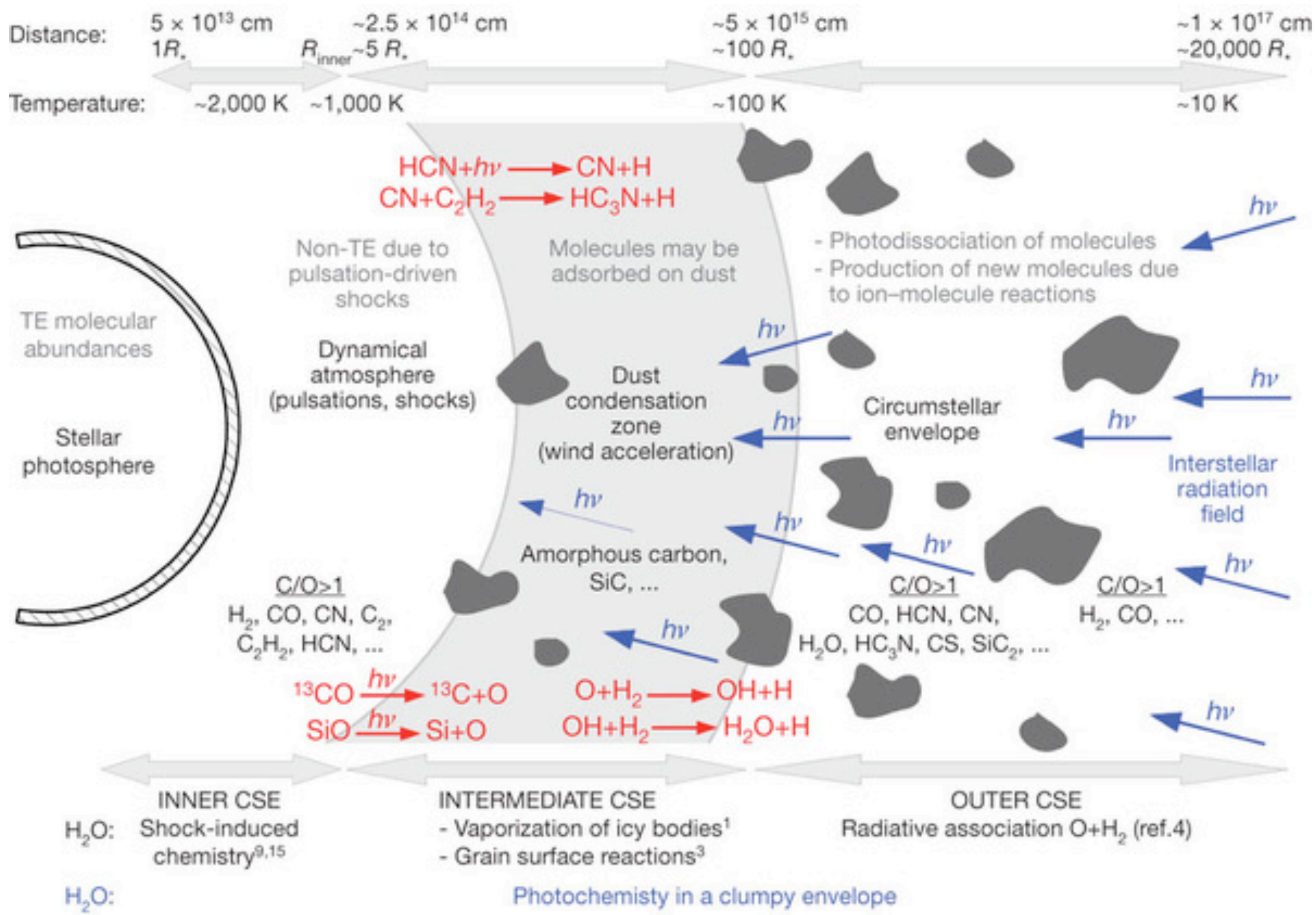
# Dust destruction

- 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?

# AGB stars and dust formation

Grain nucleation – difficult!

Grain growth – easier!




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

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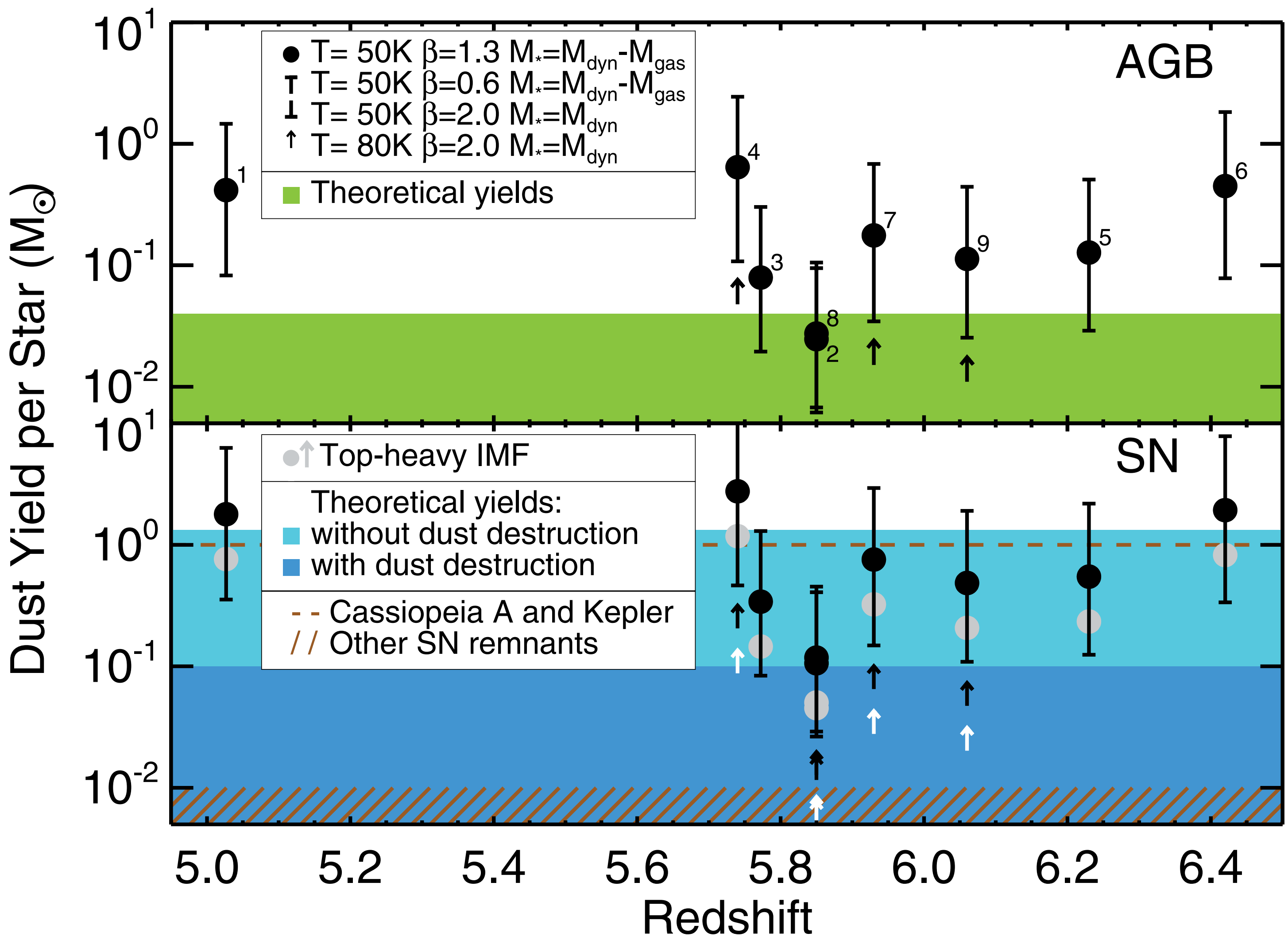
# AGB stars? Nope!




(Michalowski et al. 2010)

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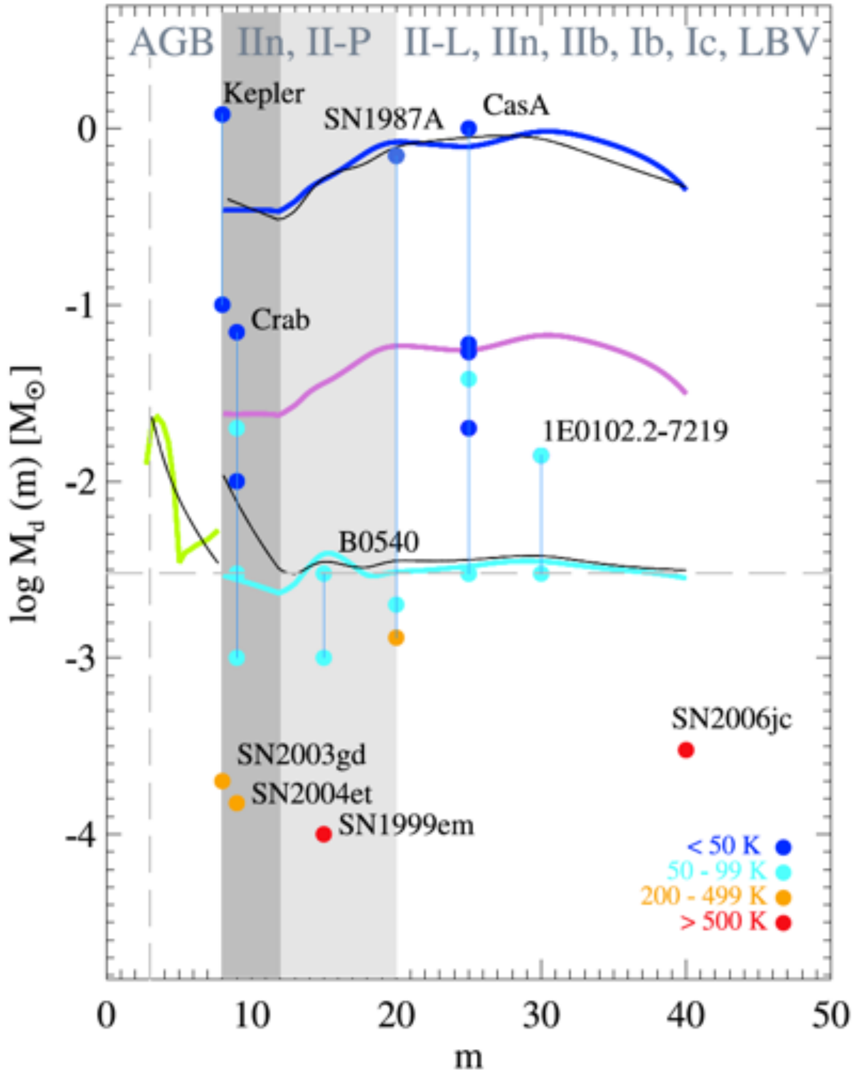
# SN dust works, but…

- 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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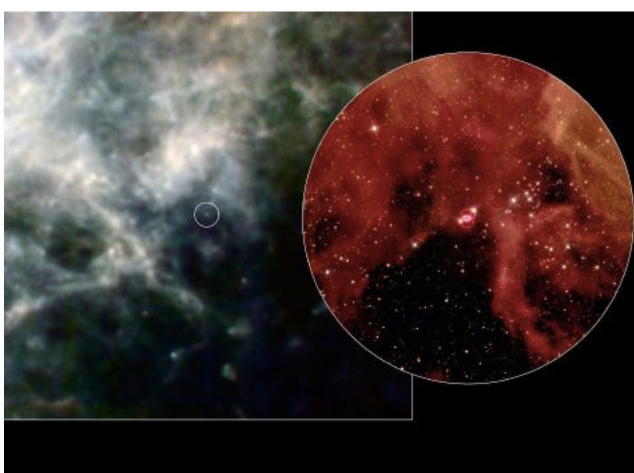
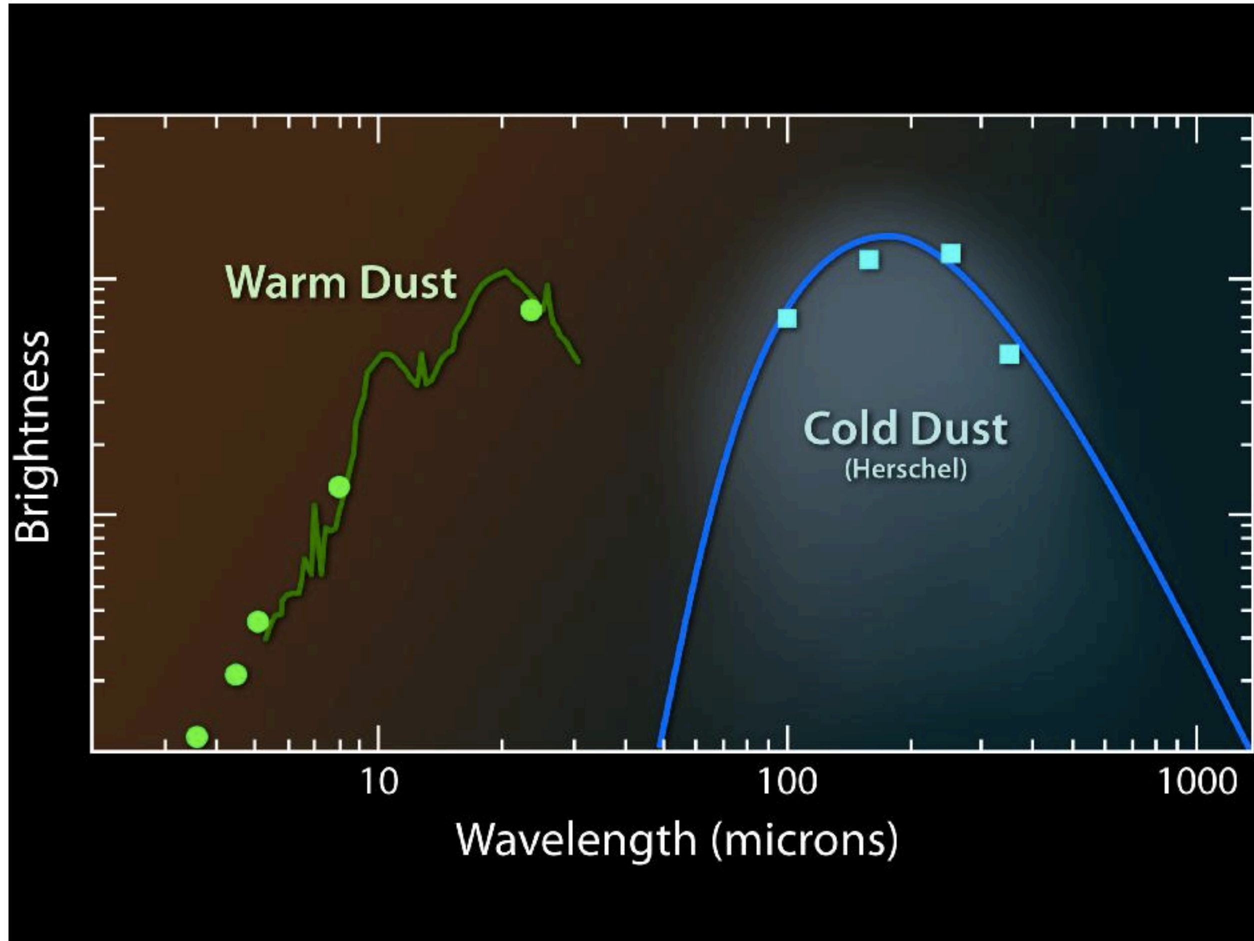
# SN dust works, but…

**SN1987A**

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



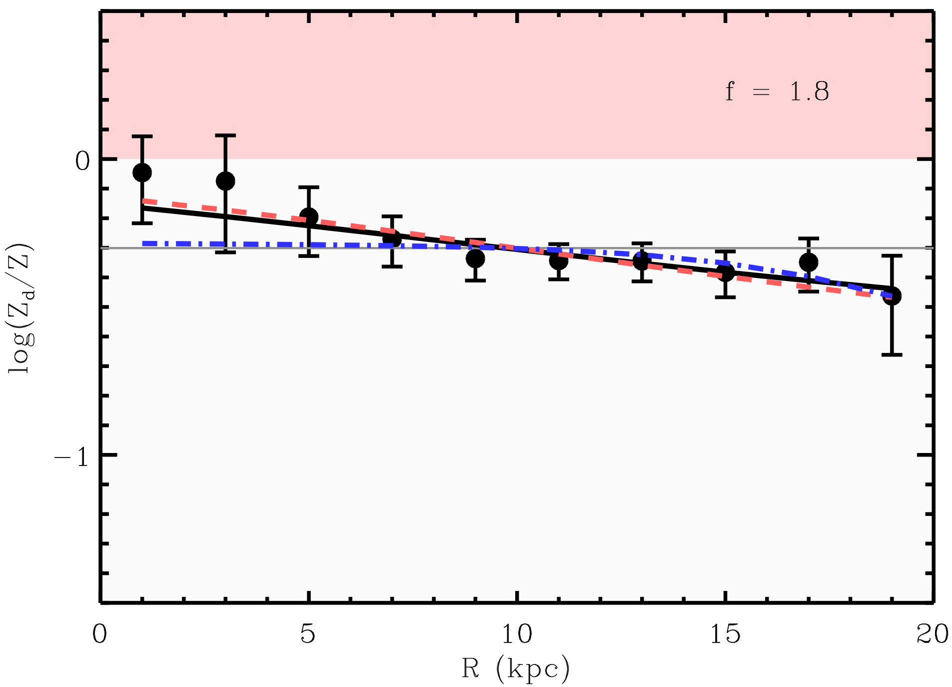


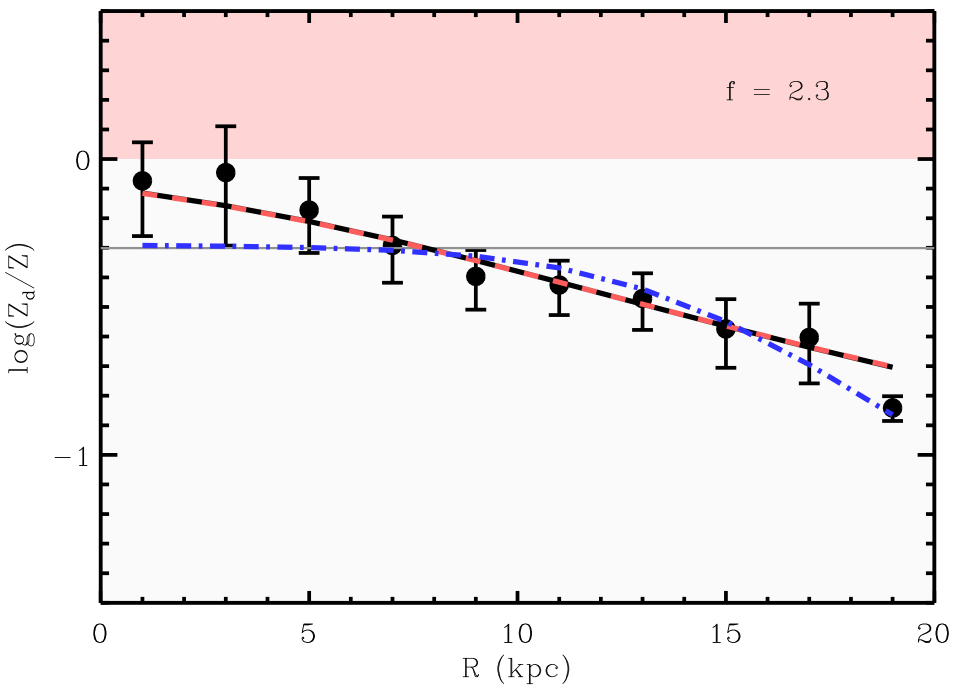

Matsuura et al. (2011, Science, 333, 1258)

# SN 1987 A

- 0.5 – 0.7 $M_{sun}$ of cold dust if there is only C-dust, 2.4 $M_{sun}$ if only silicates (Matsuura et al. 2011).
- The progenitor was a 15 – 20 $M_{sun}$ star.
- An 18 $M_{sun}$ star produces 0.13 $M_{sun}$ of silicon (Woosley & Weaver 1995).
- $A_{silicates} = 121.41 \rightarrow M_{silicates} < 0.56\ M_{sun}$
- $M_C = 0.22\ M_{sun} \rightarrow M_{c\text{-dust}} < 0.22\ M_{sun}$

# Dust-to-metals gradient




Mattsson, Andersen & Munkhammar (2012)
Mattsson & Andersen (2012)
Mattsson et al. (2014)

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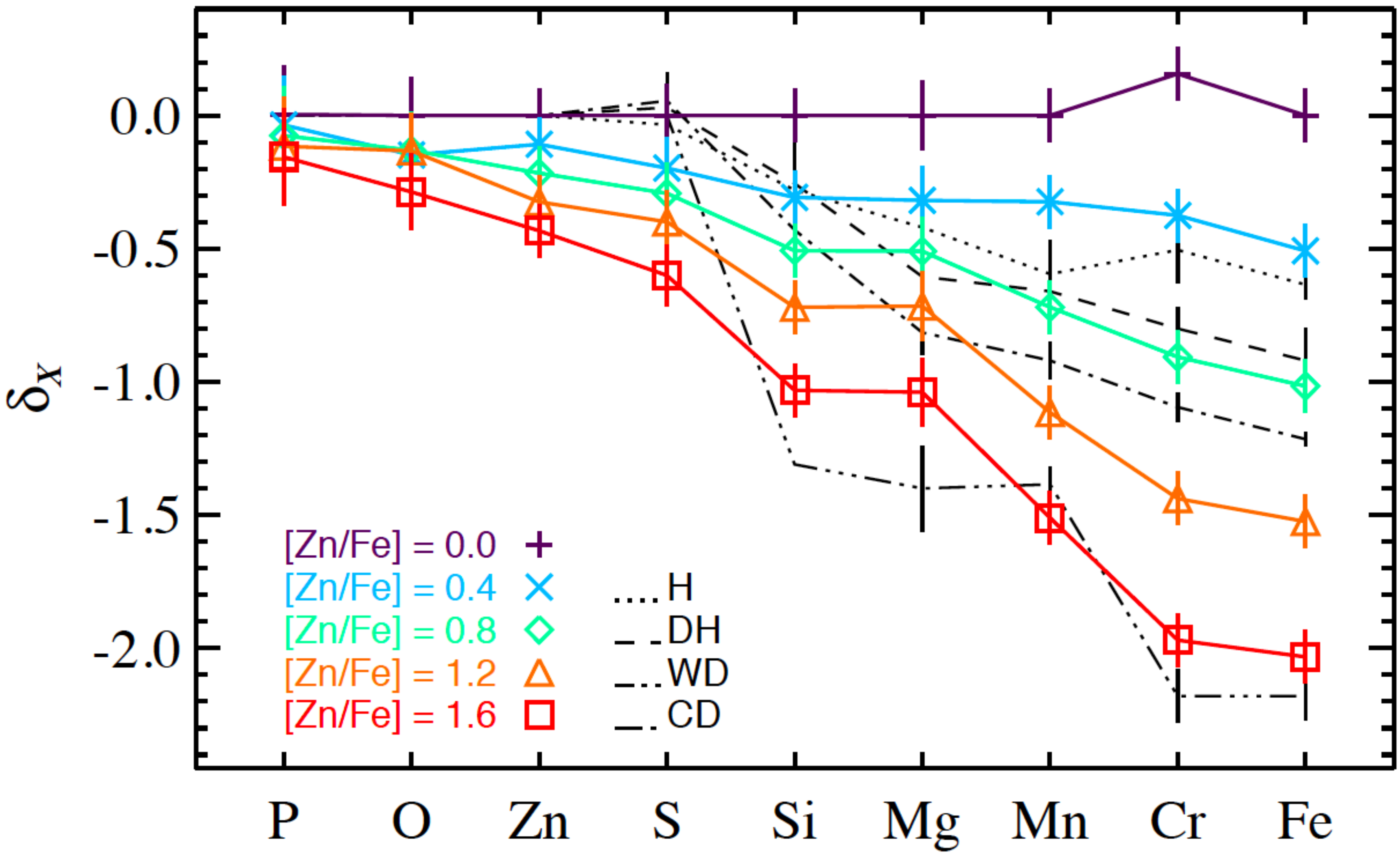
# Condensation!




De Cia et al. (2016); Jenkins (2009)

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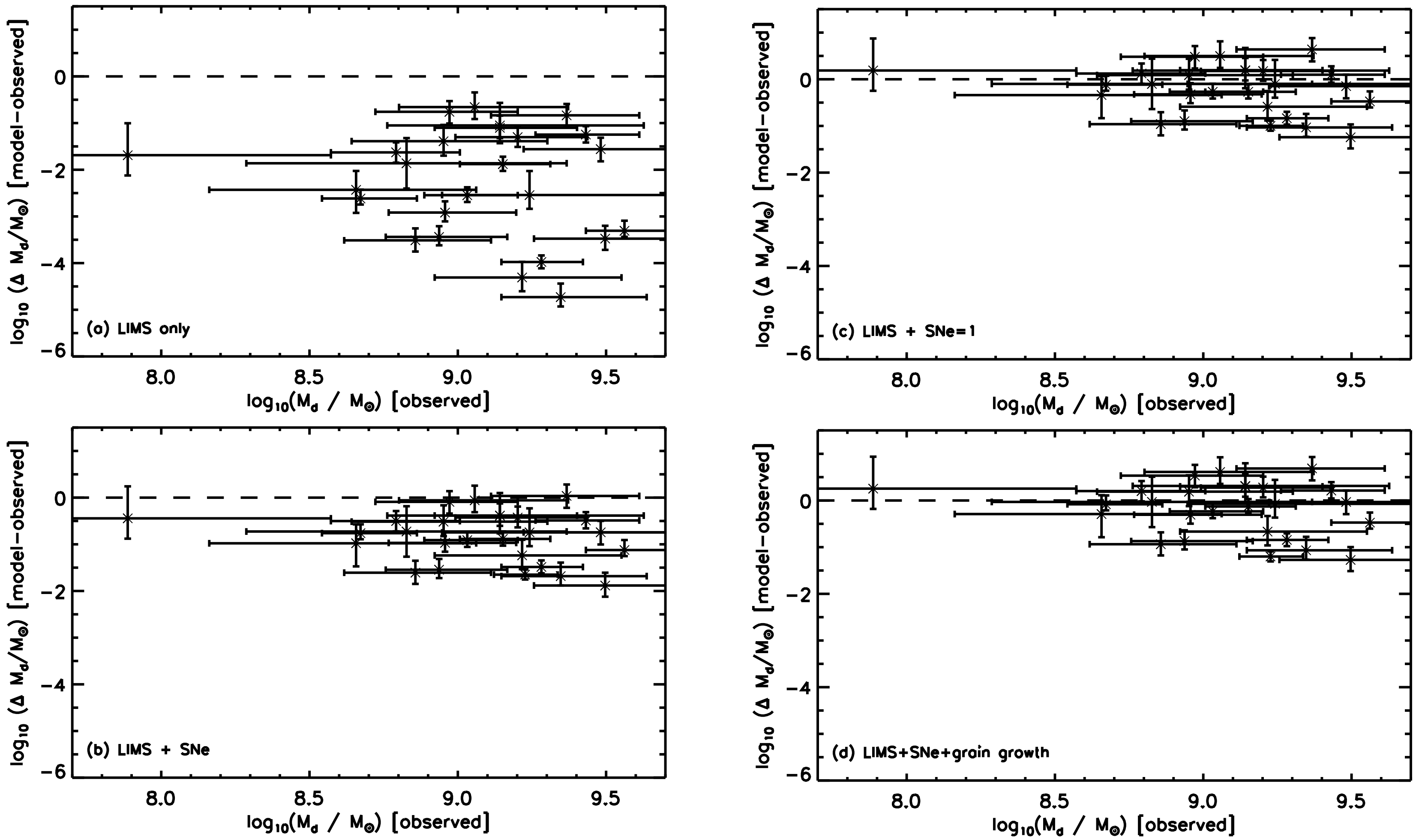
# Dust budget crisis




Rowlands et al. (2014)

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# Conclusions so far

- 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!

# Conclusions so far

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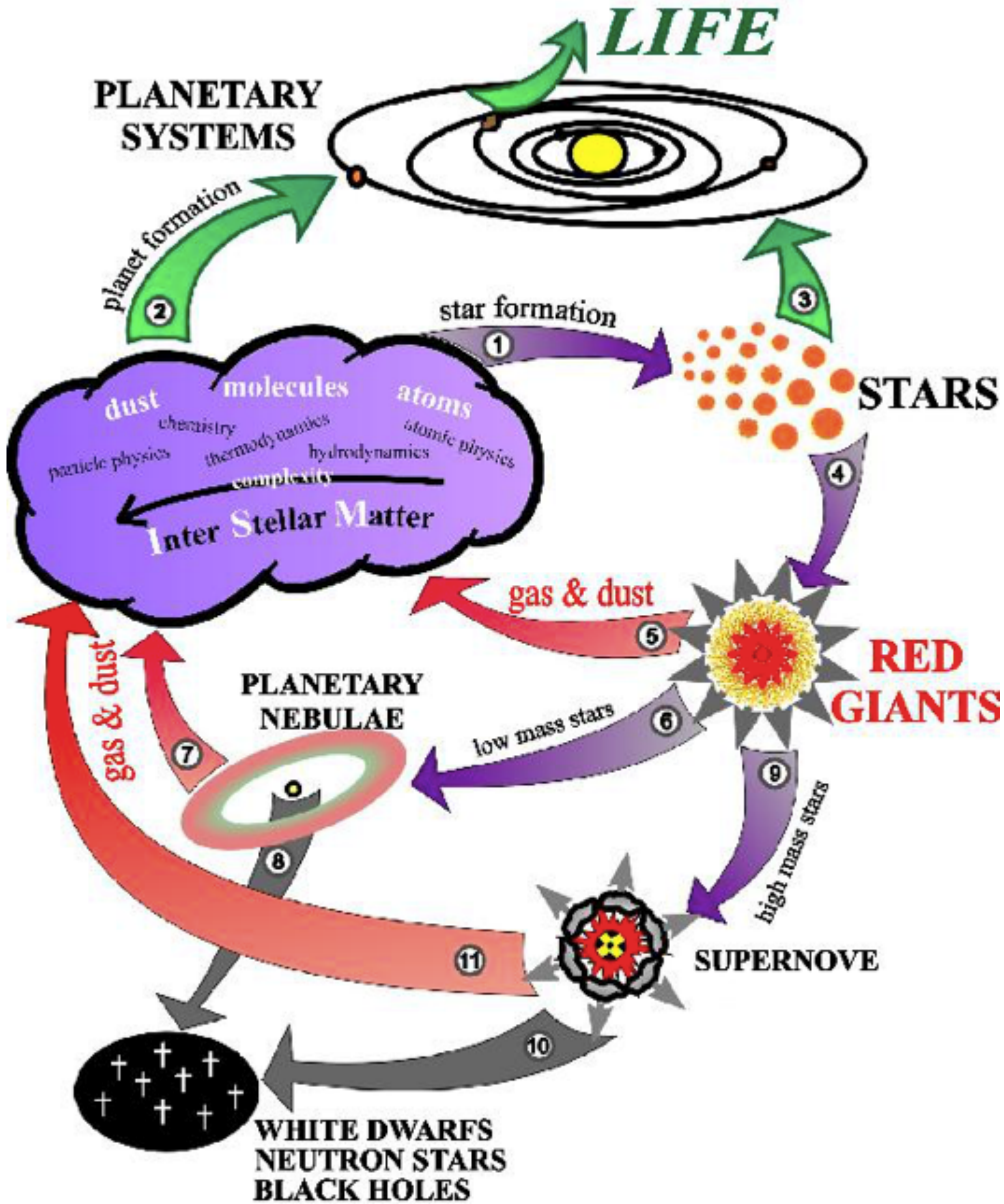
# The cosmic matter cycle

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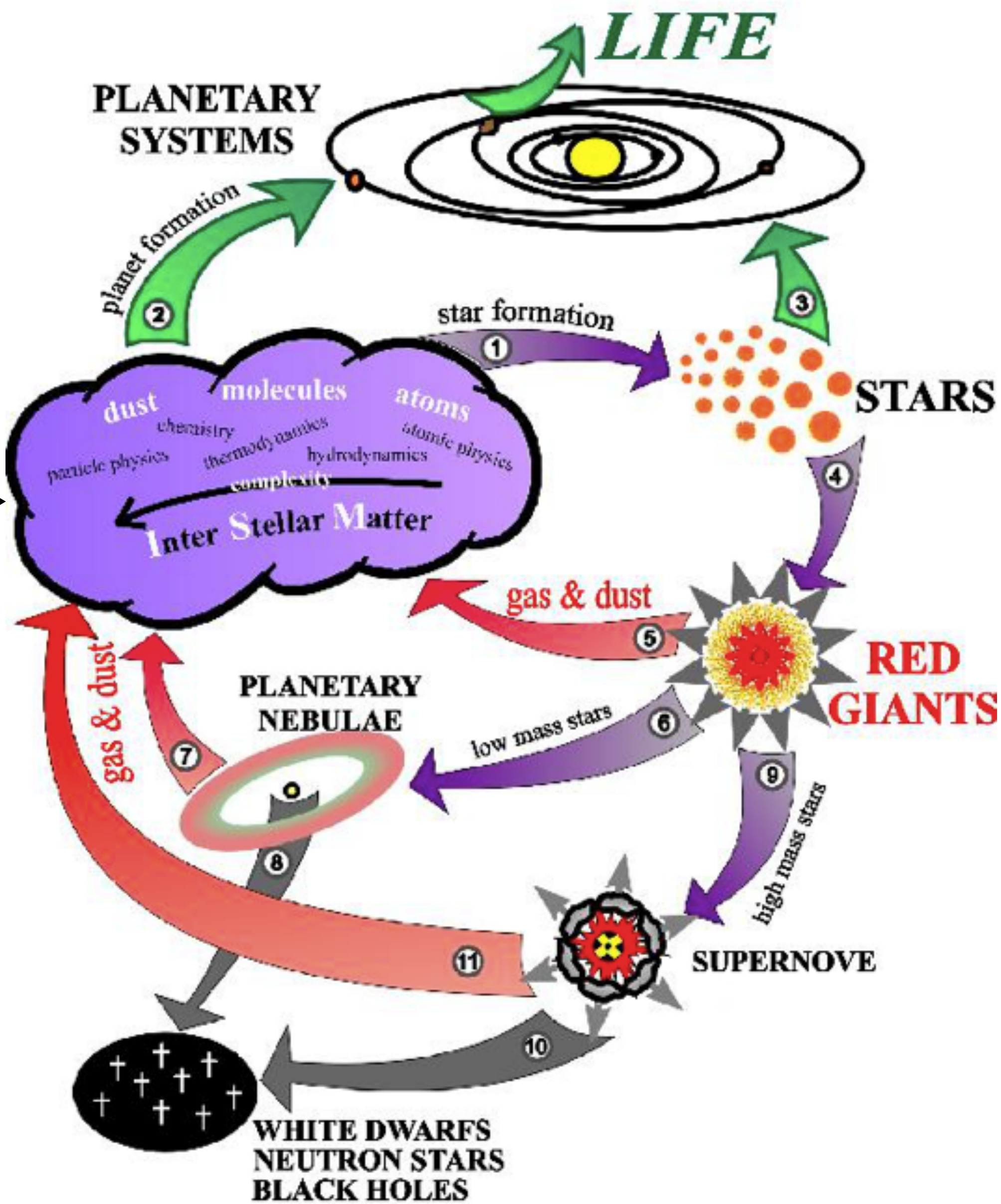
# The cosmic matter cycle

**Turbulence!** →

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# Epstein drag

“Swedish compass”

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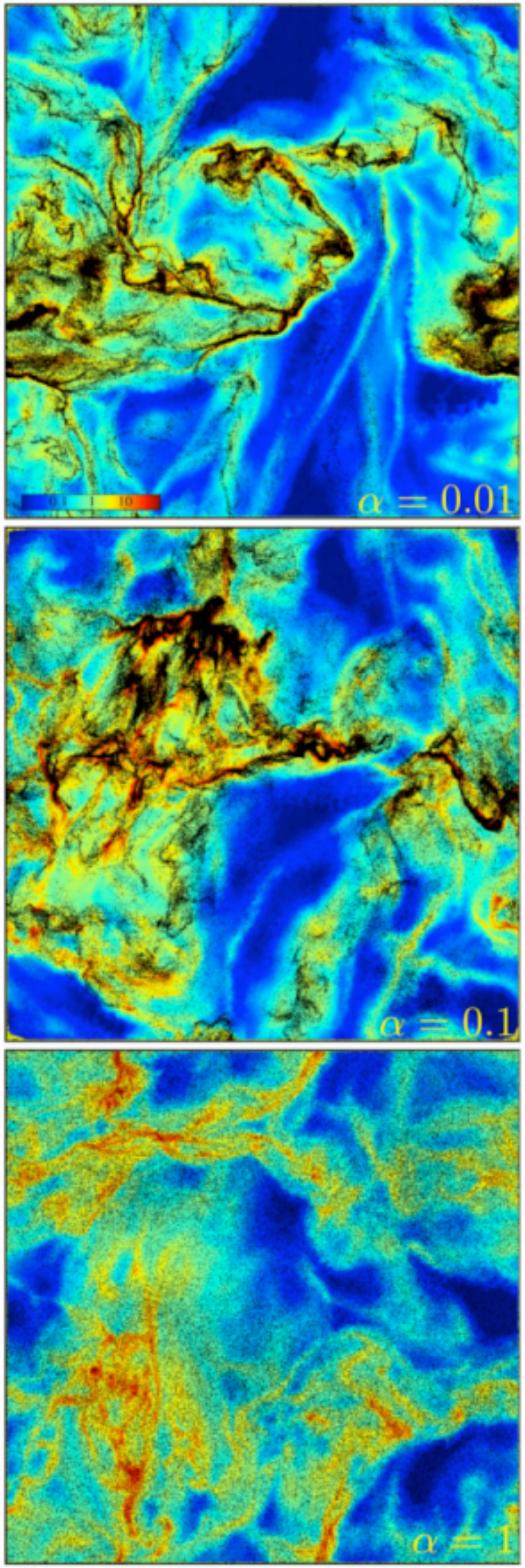


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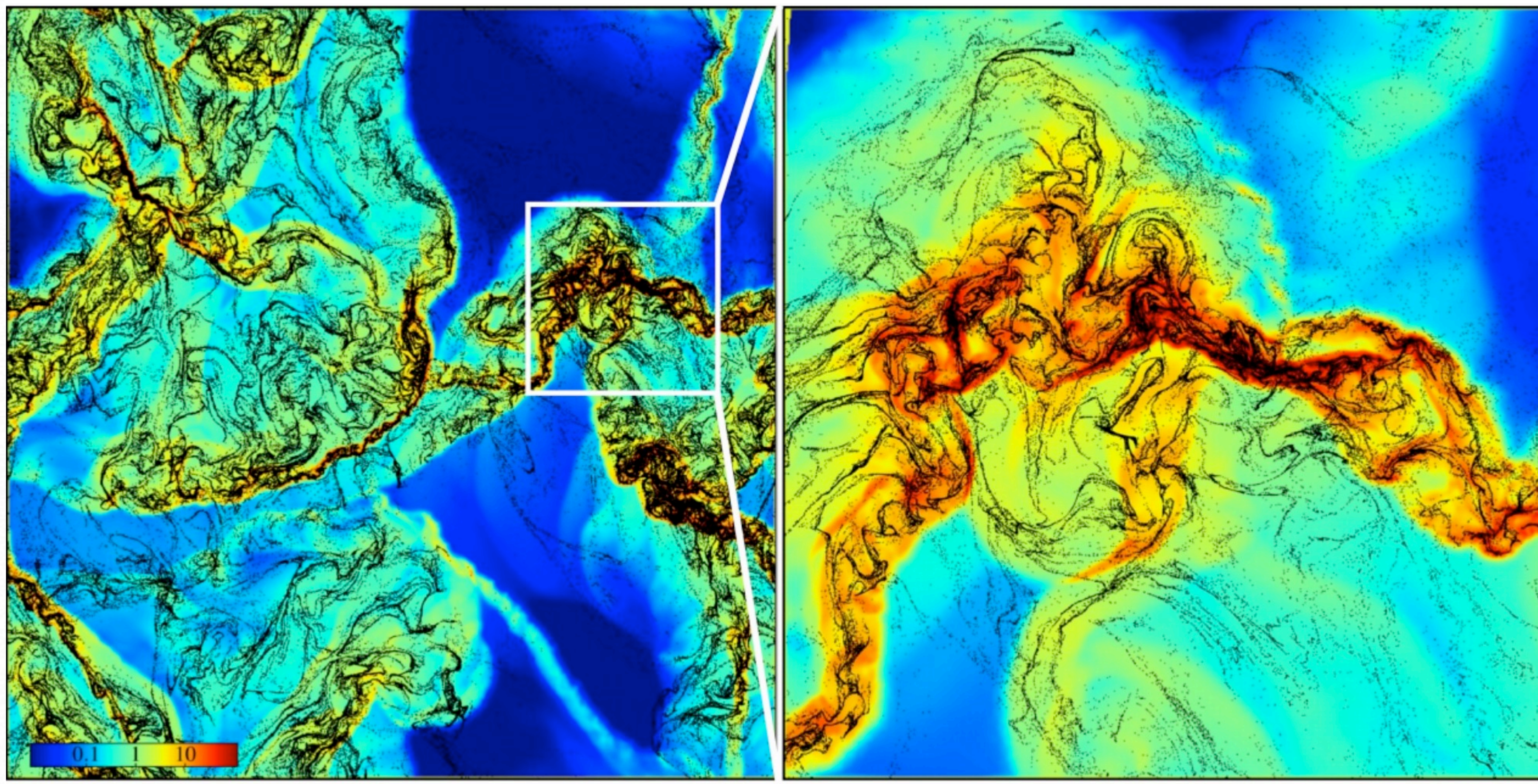


Hopkins & Lee (2016)

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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. (A $1024^3$ isothermal simulation is in progress.)

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# Simulation with PENCIL code

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

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

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

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

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

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# Simulation with PENCIL code

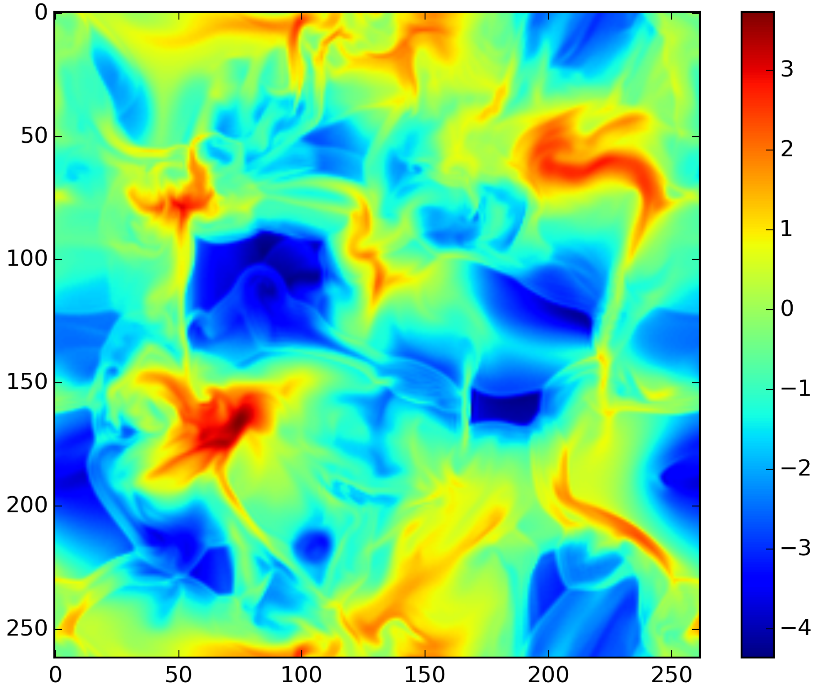
**Table 1**

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

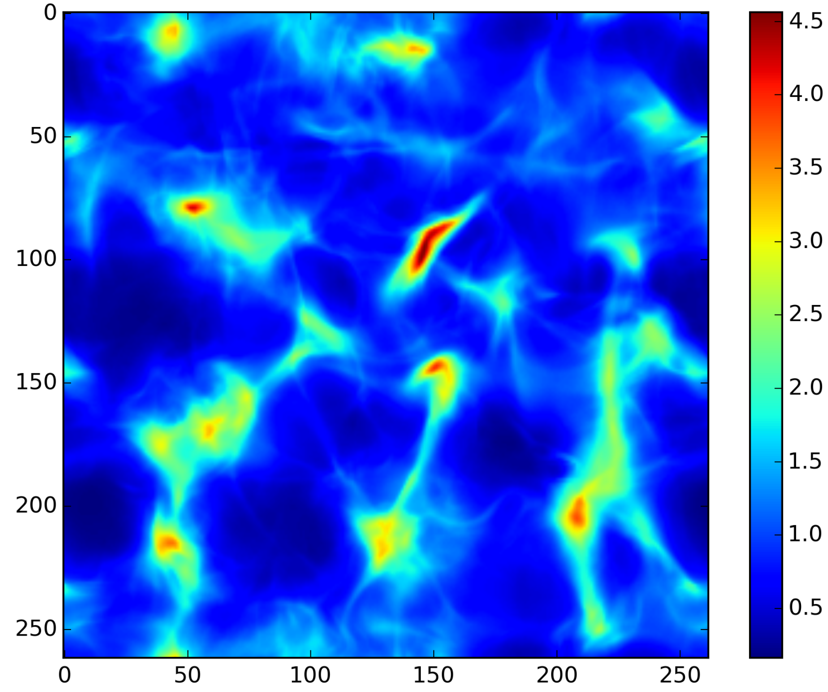
| Properties | GMC | Clump | Core |
|---|---|---|---|
| Size (pc) | 20–60 | 3–20 | 0.5–3 |
| Density ($cm^{-3}$) | 100–300 | $10^3$–$10^4$ | $10^4$–$10^6$ |
| Mass ($M_\odot$) | $10^4$–$10^6$ | $10^3$–$10^4$ | 10–$10^3$ |
| Linewidth ($km\ s^{-1}$) | 6–15 | 4–12 | 1–3 |
| Temperature (K) | 7–15 | 15–40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

# Turbulence in a box

Slice of log(ρ)




Column density (linear)

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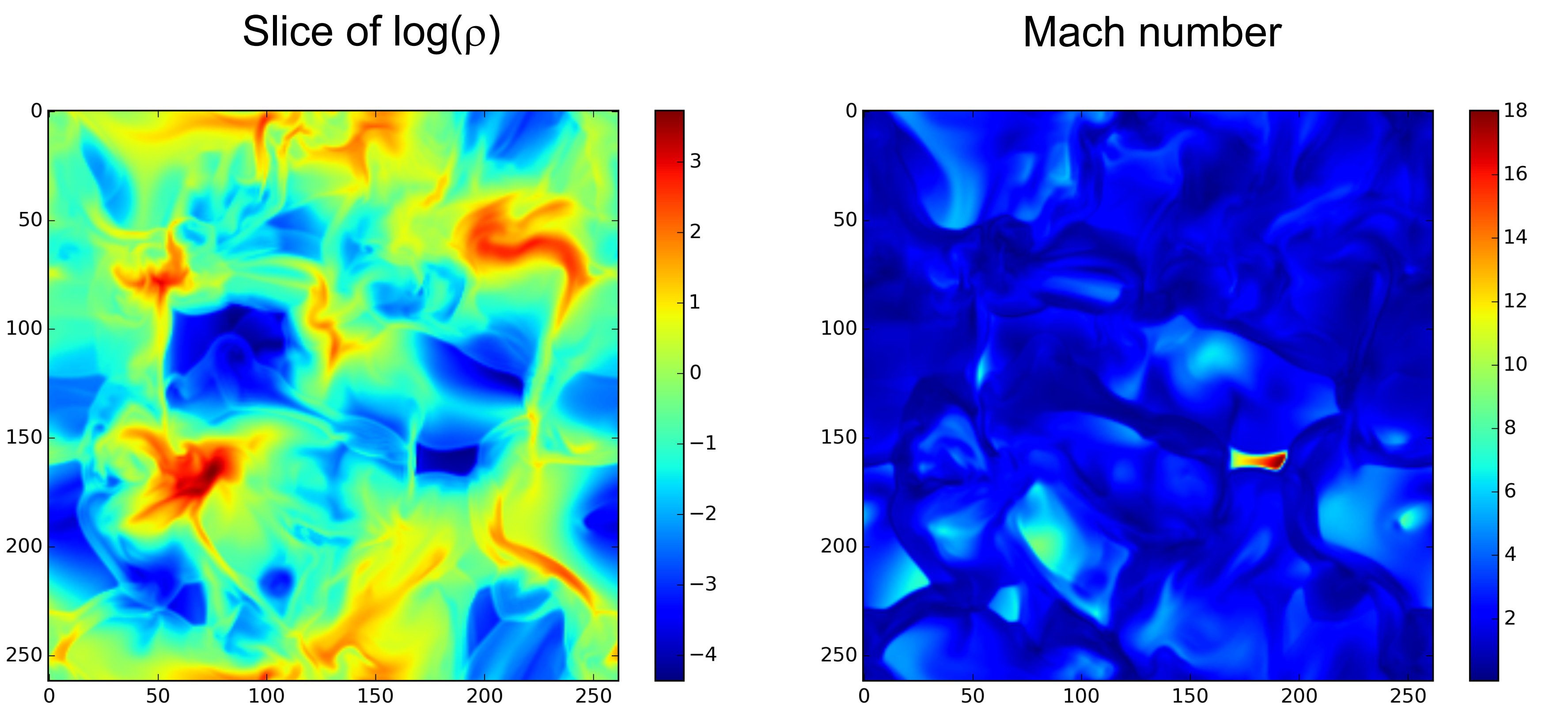


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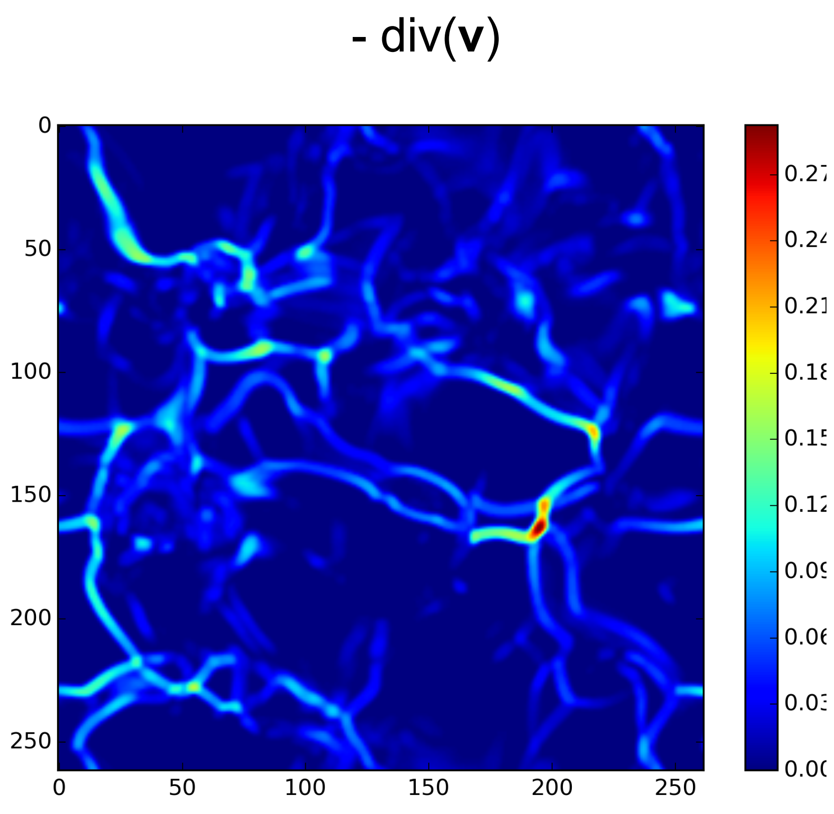


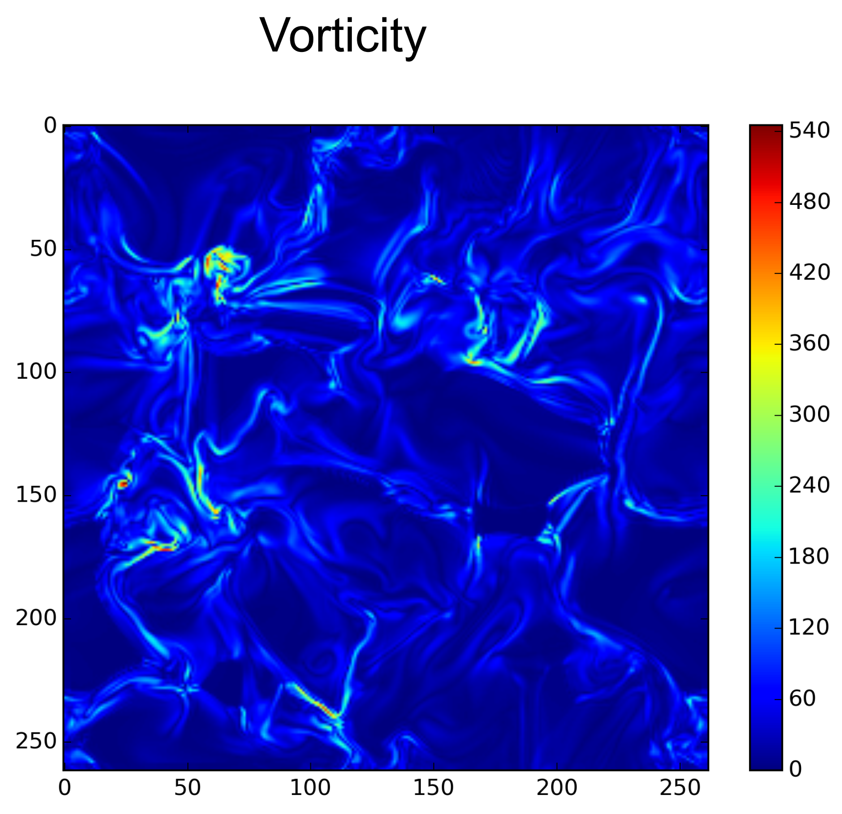


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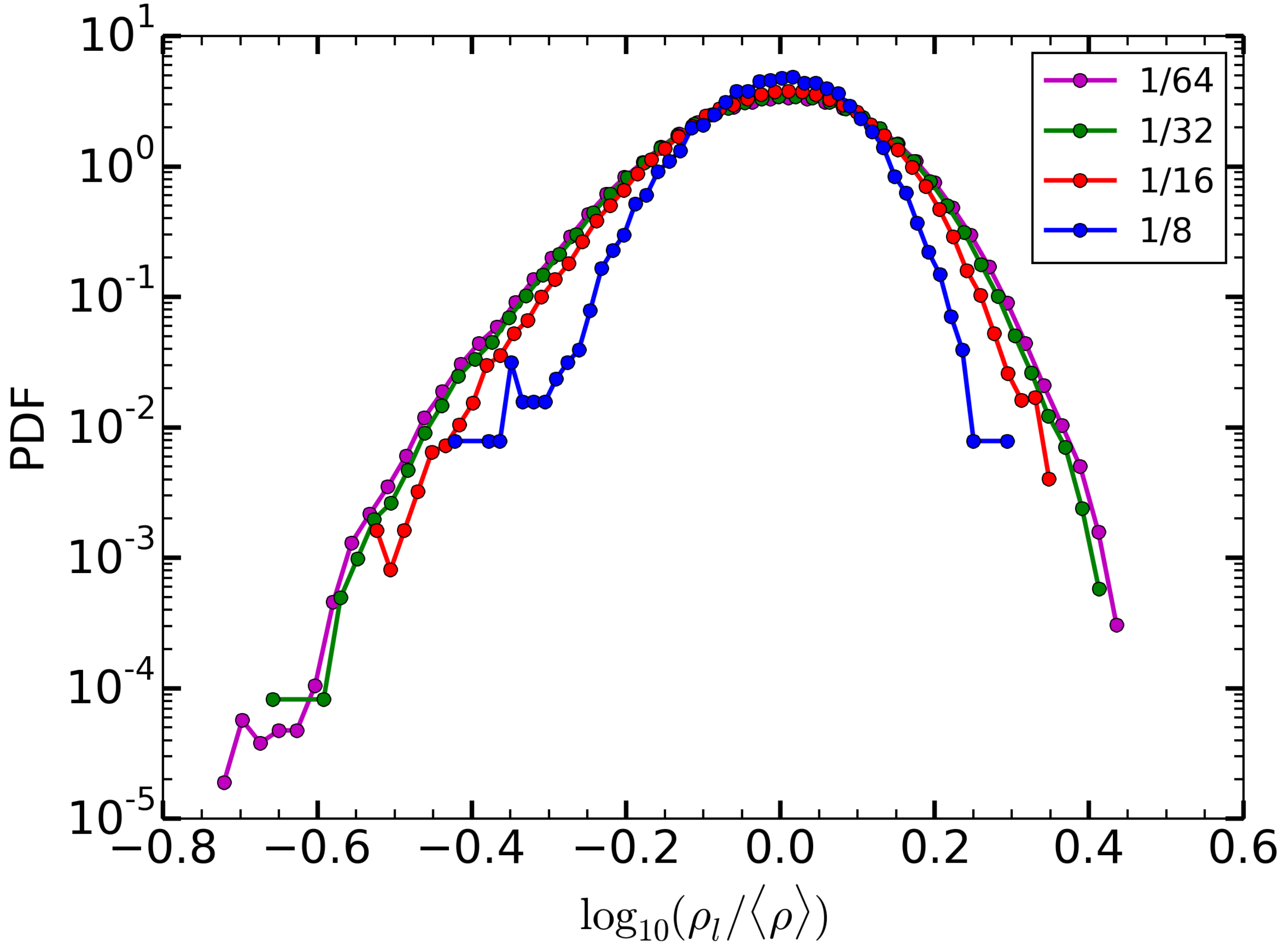
# Gas-density PDF

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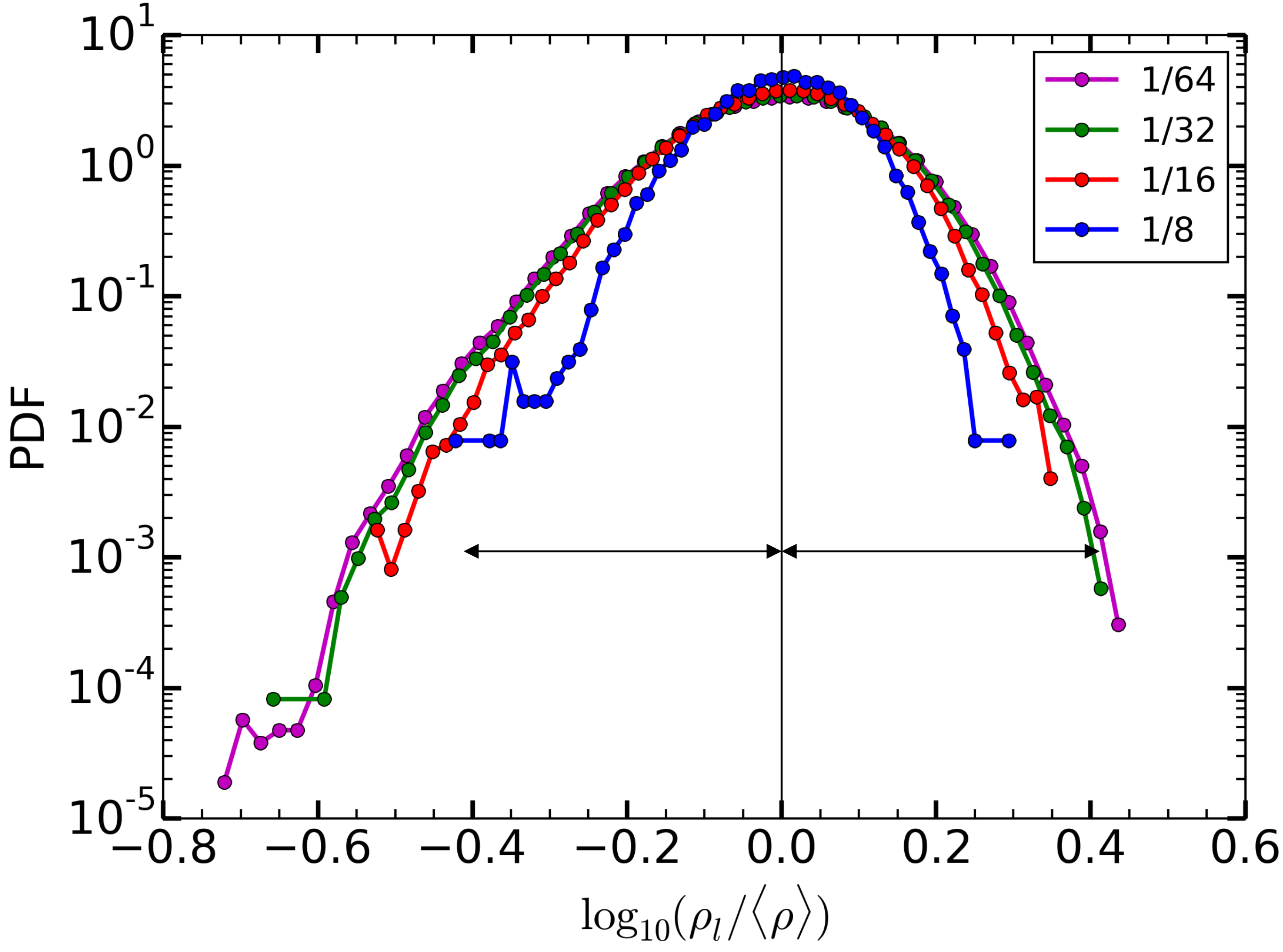


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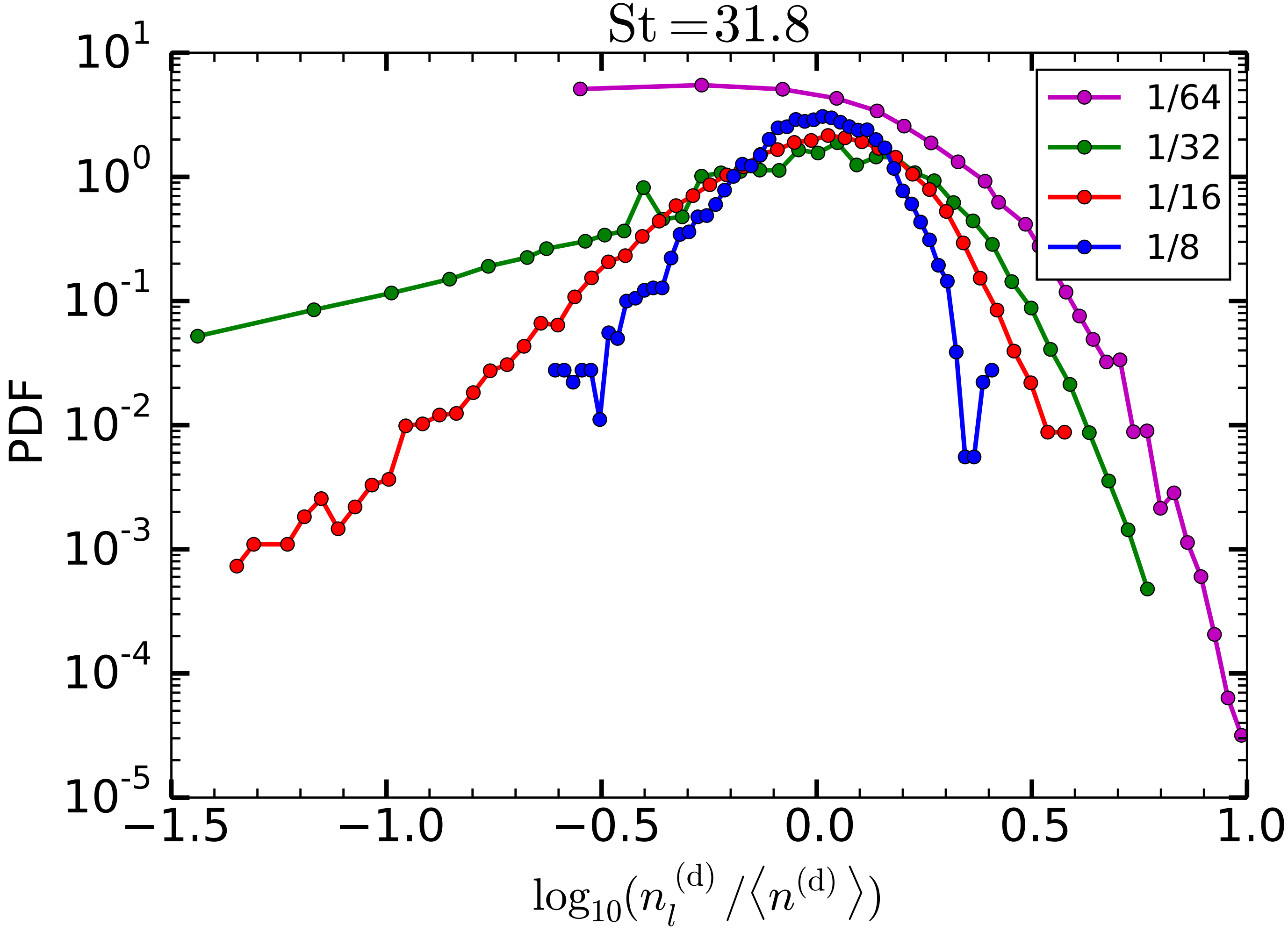
# Dust-density PDF

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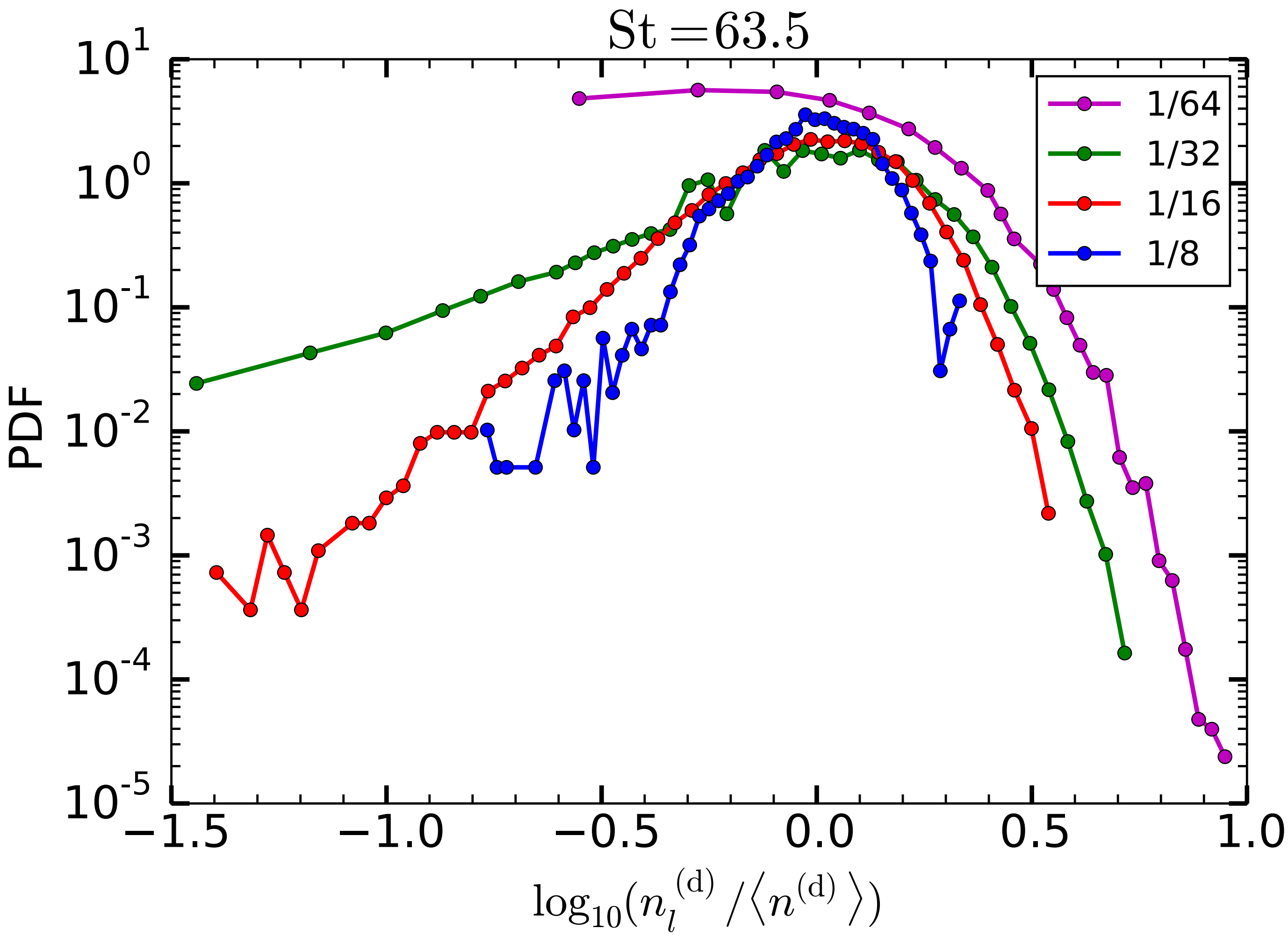


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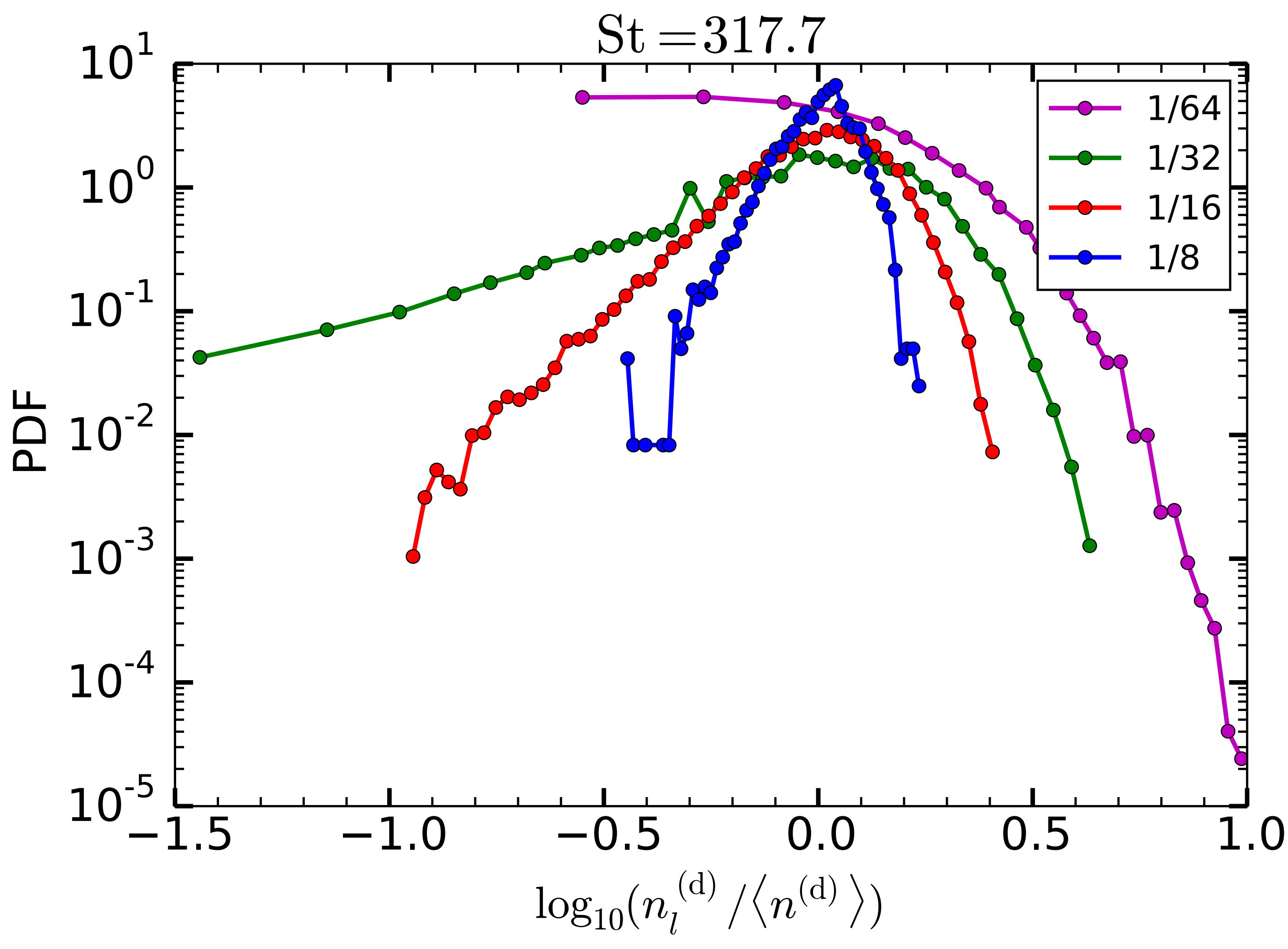


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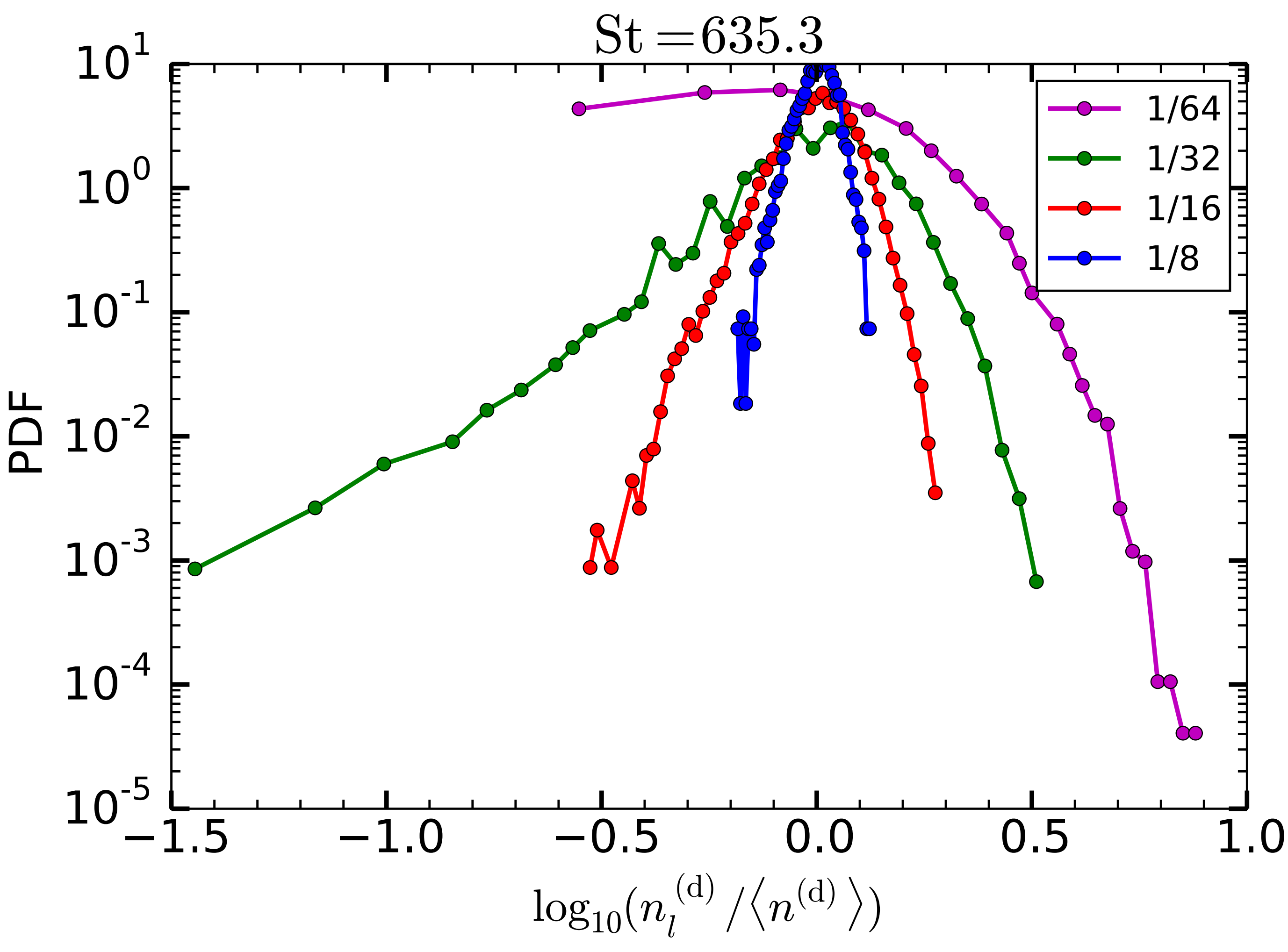

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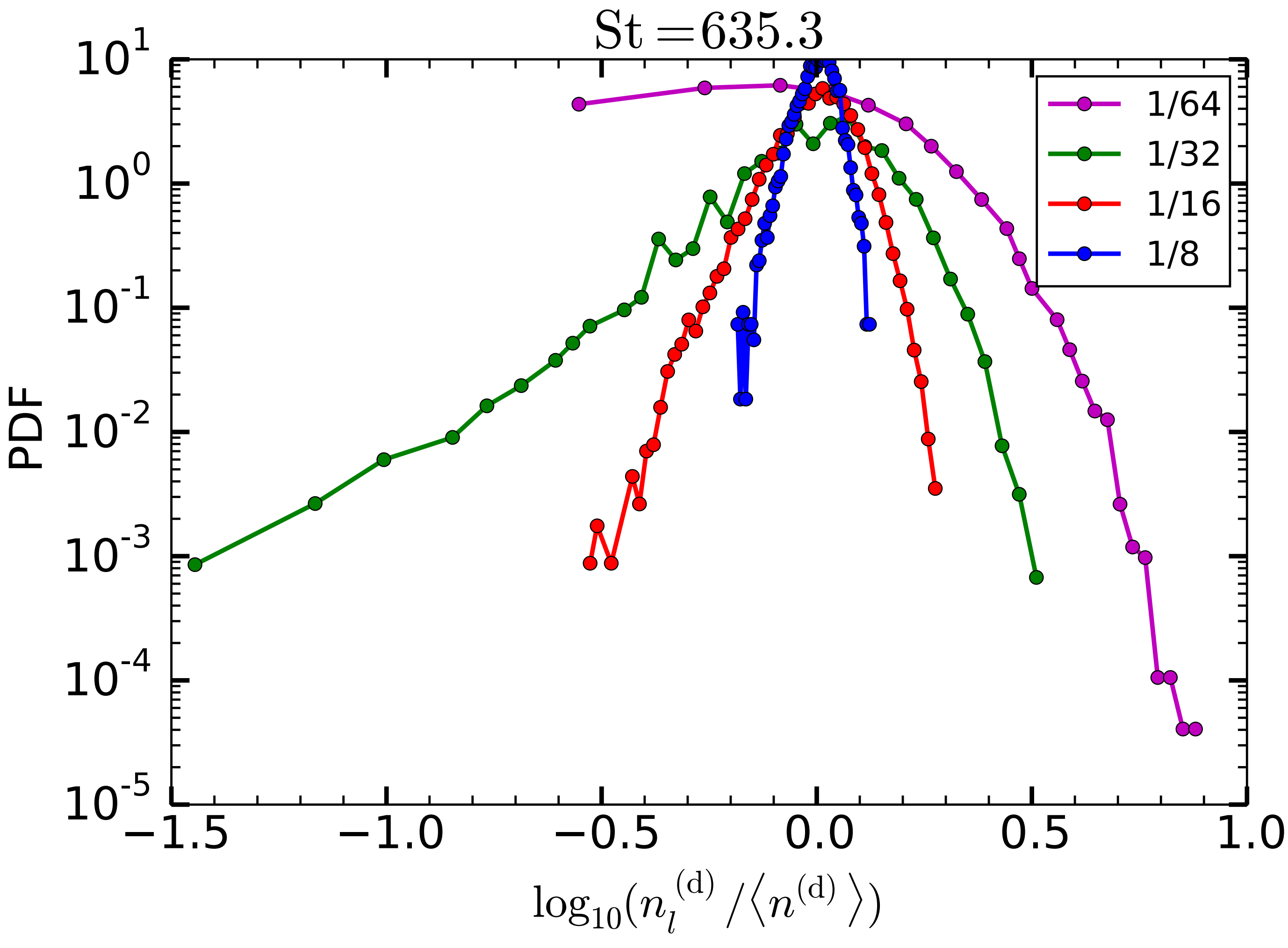


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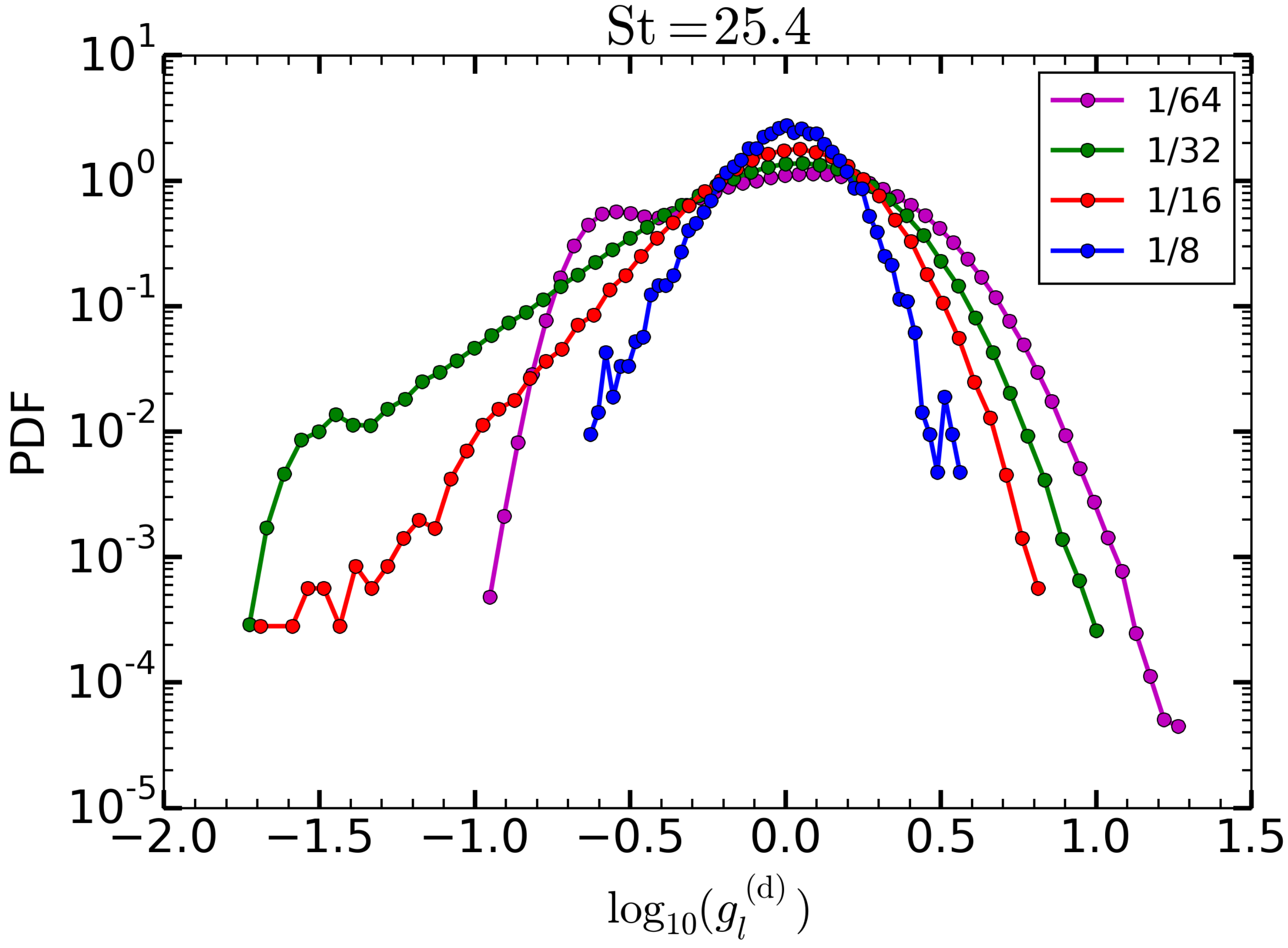
# Dust-to-gas PDF

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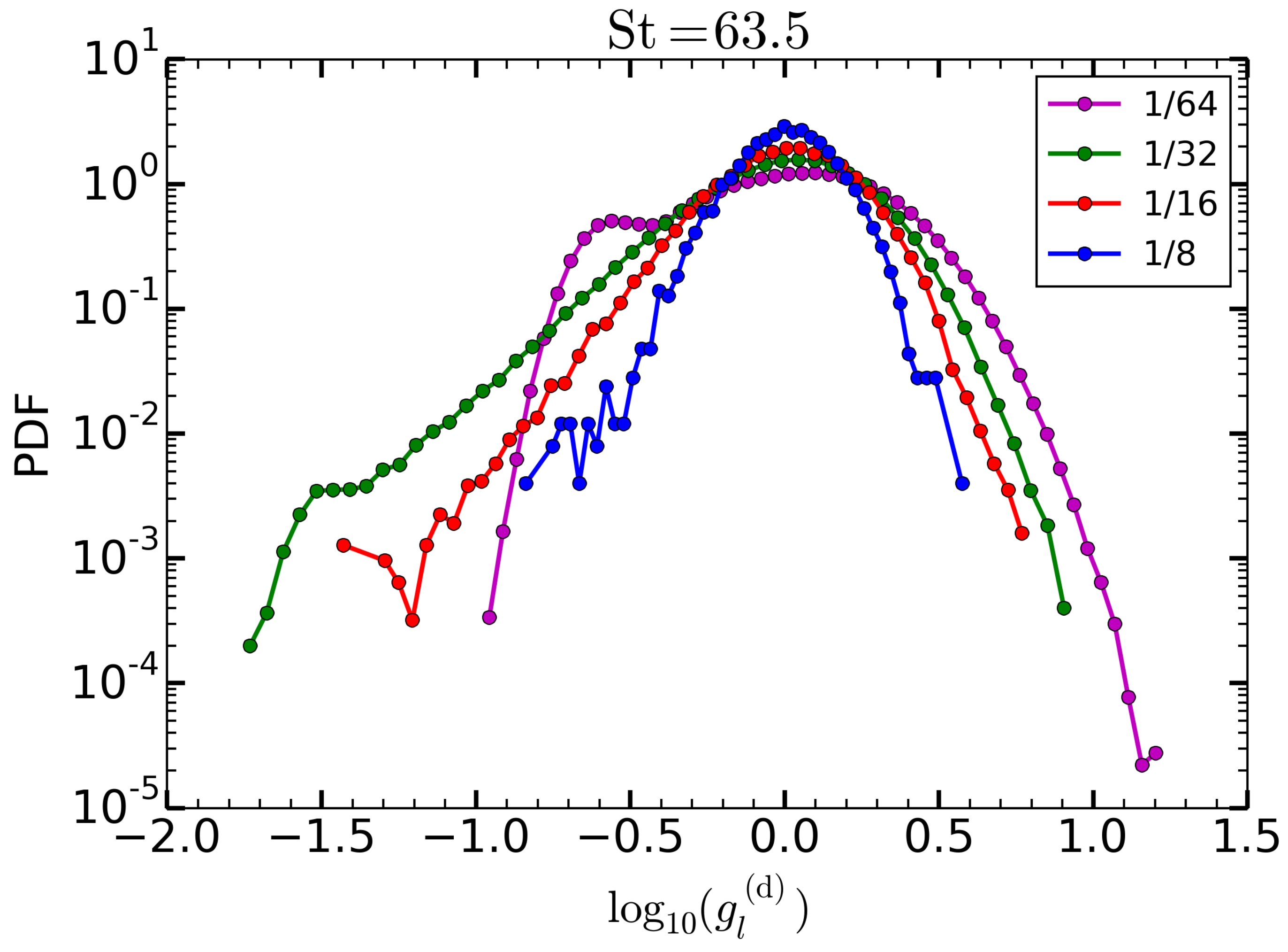


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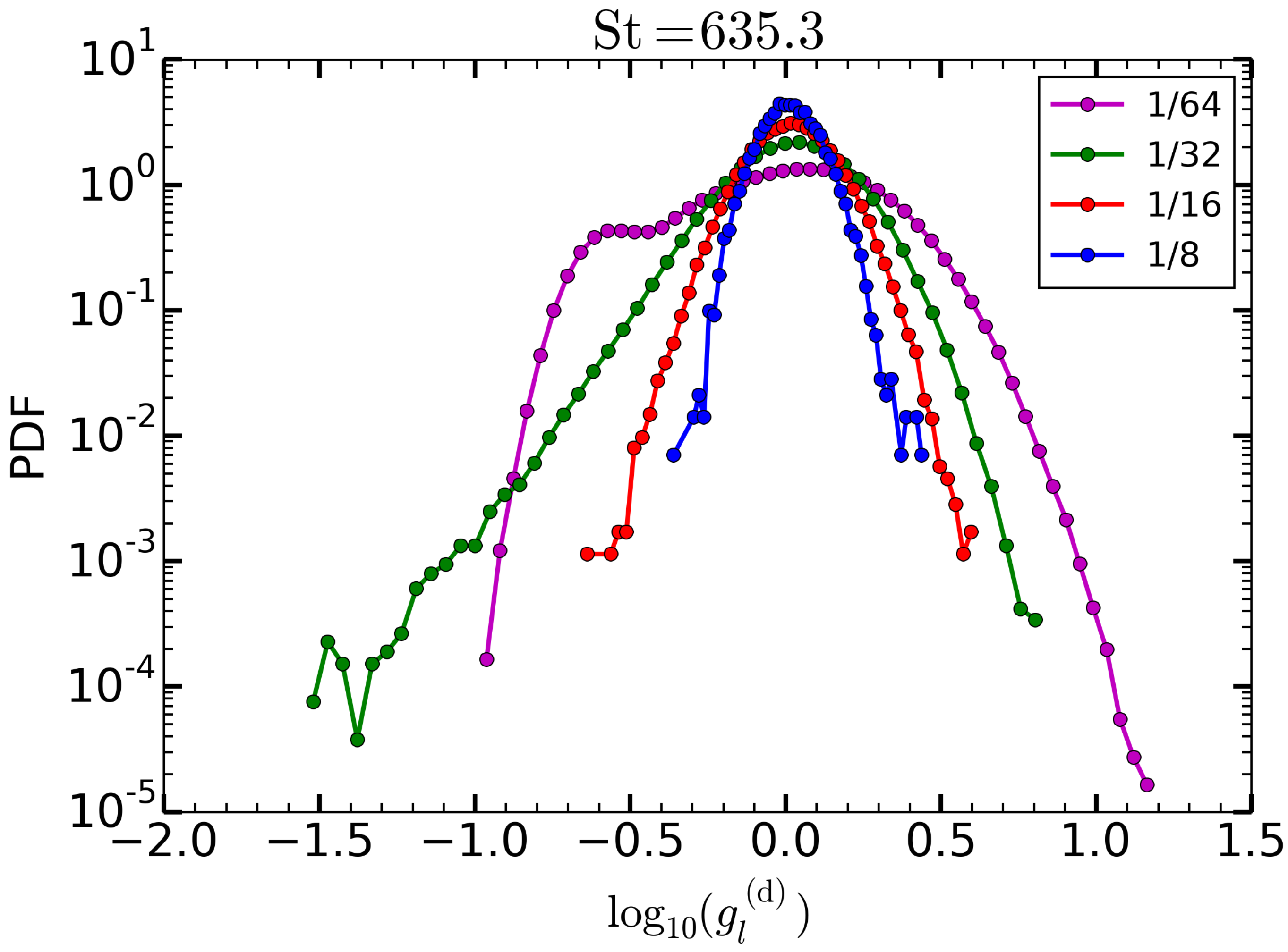
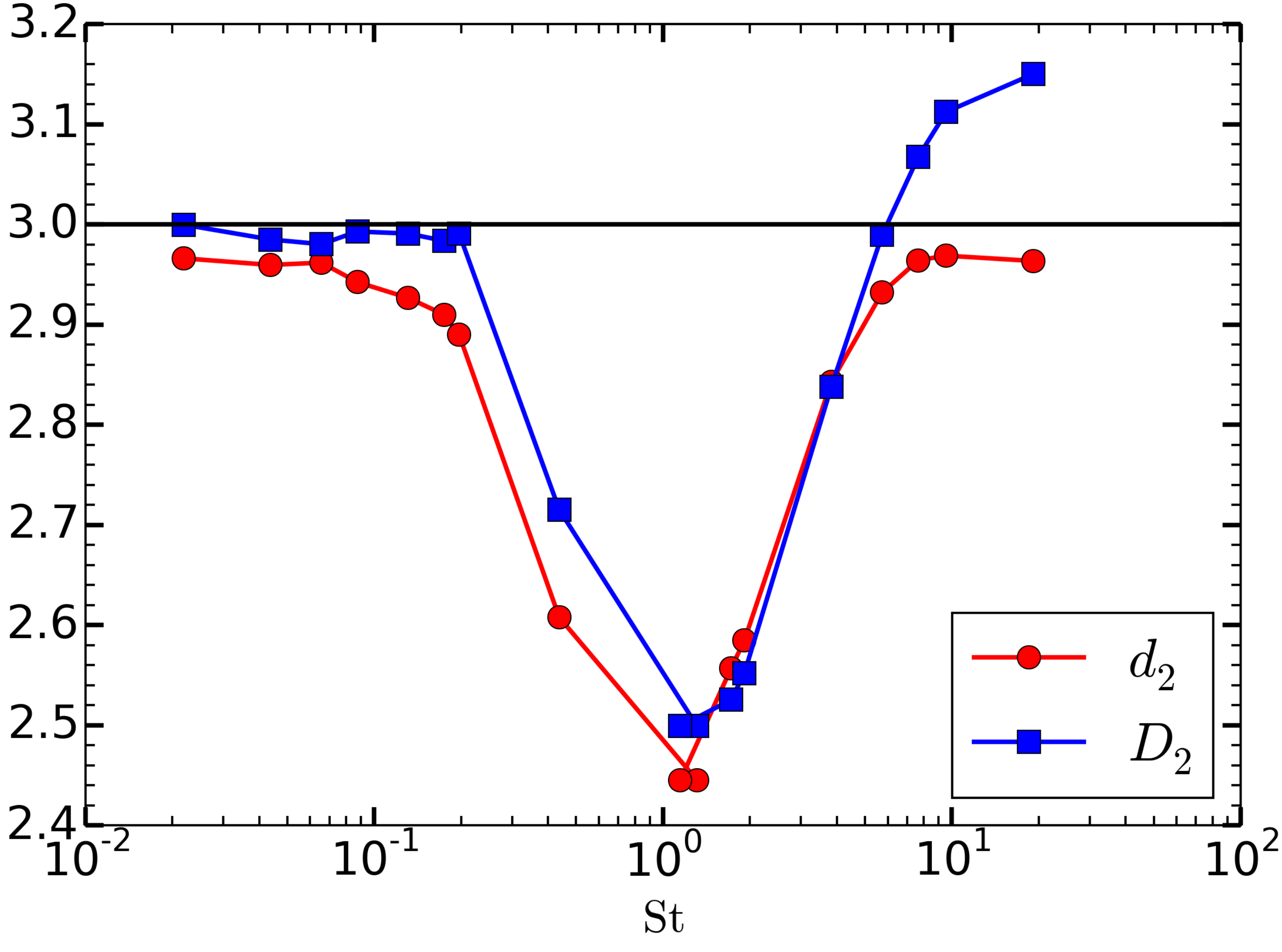


# Clustering

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

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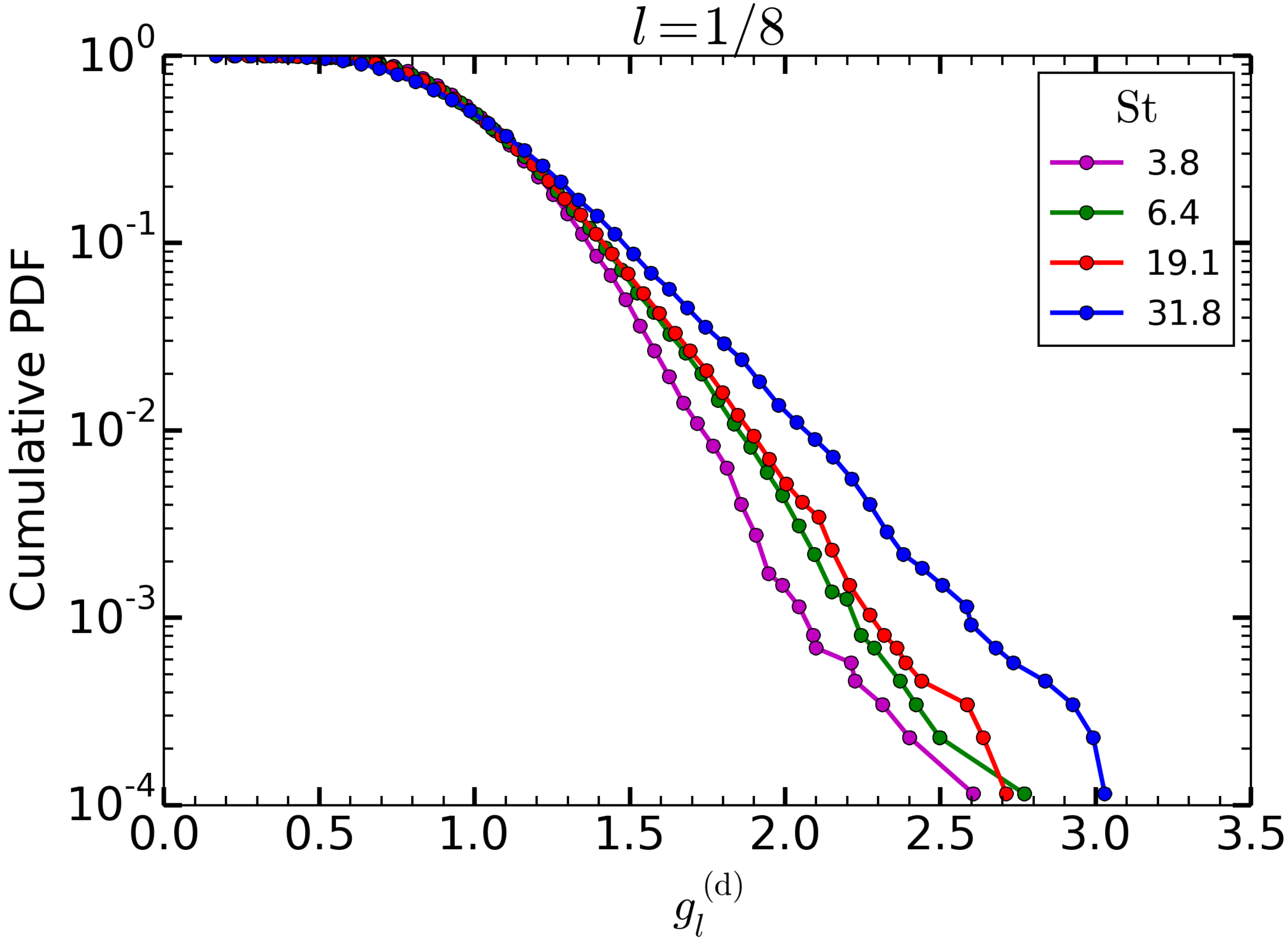


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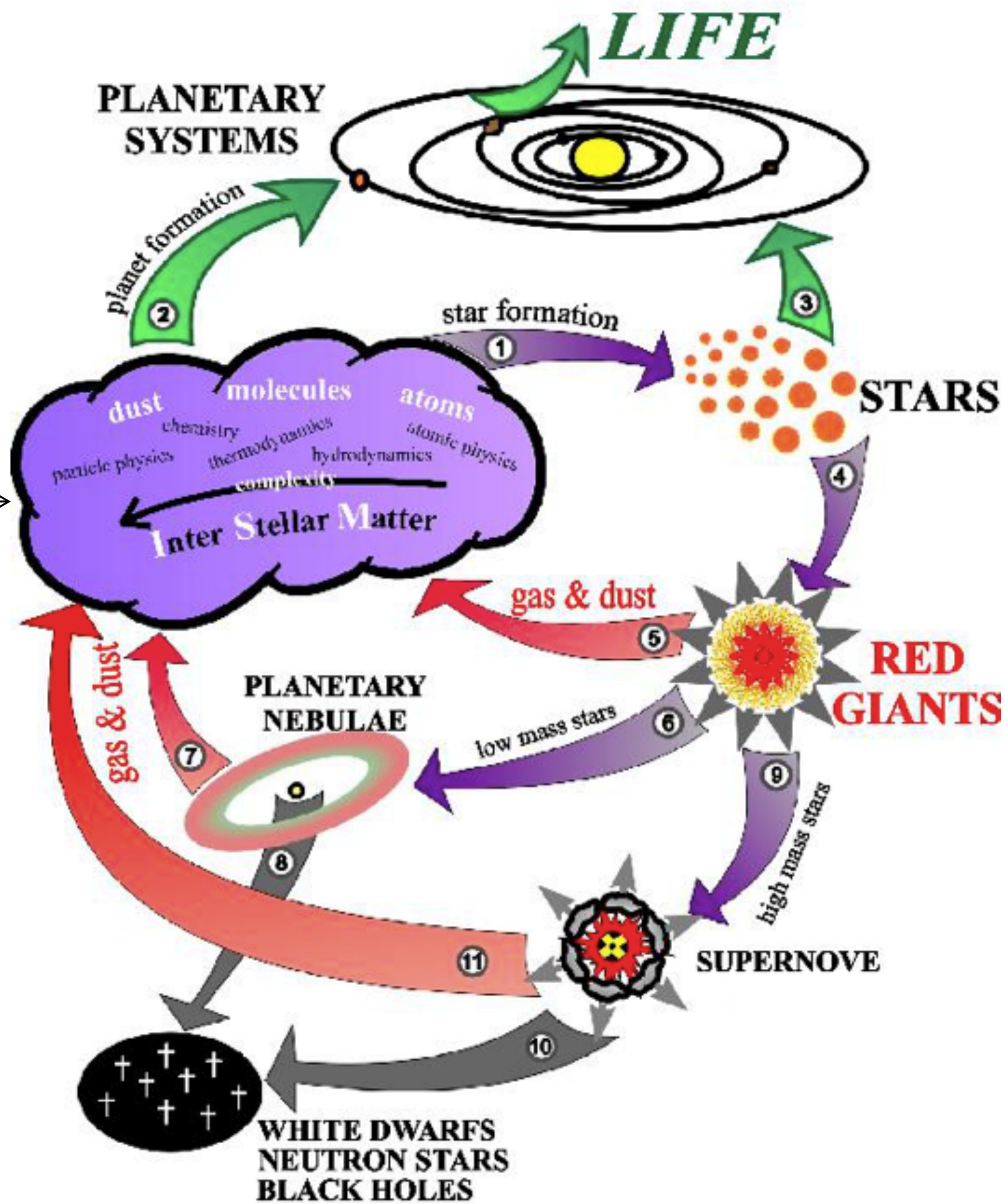
# The cosmic matter cycle

**Coagulation & condensation**

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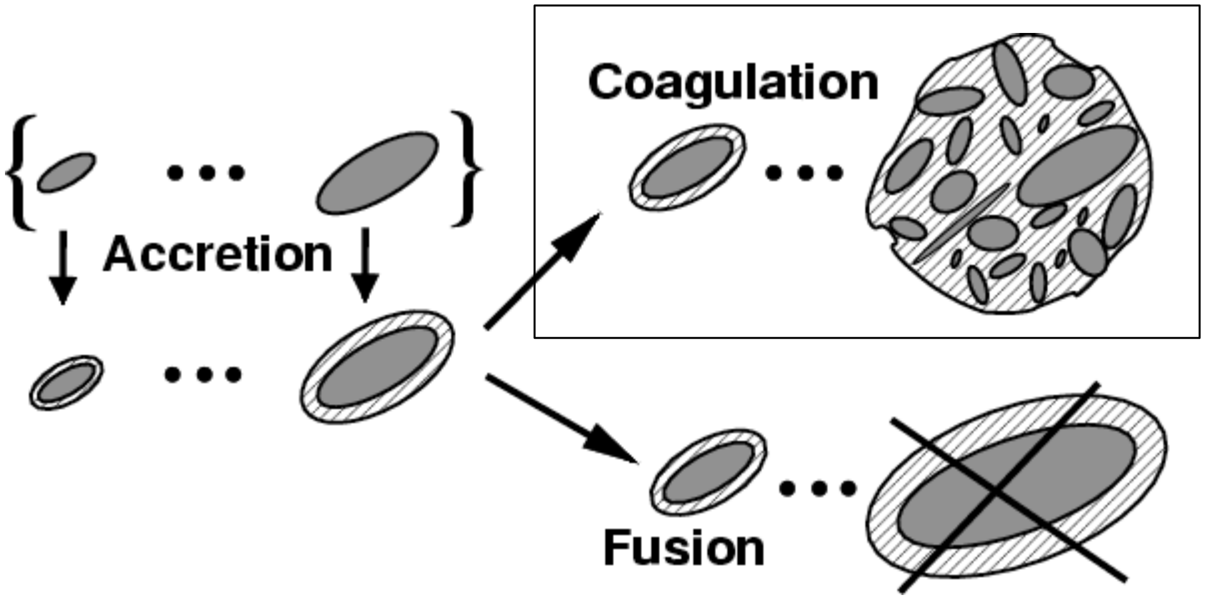
# Coagulation

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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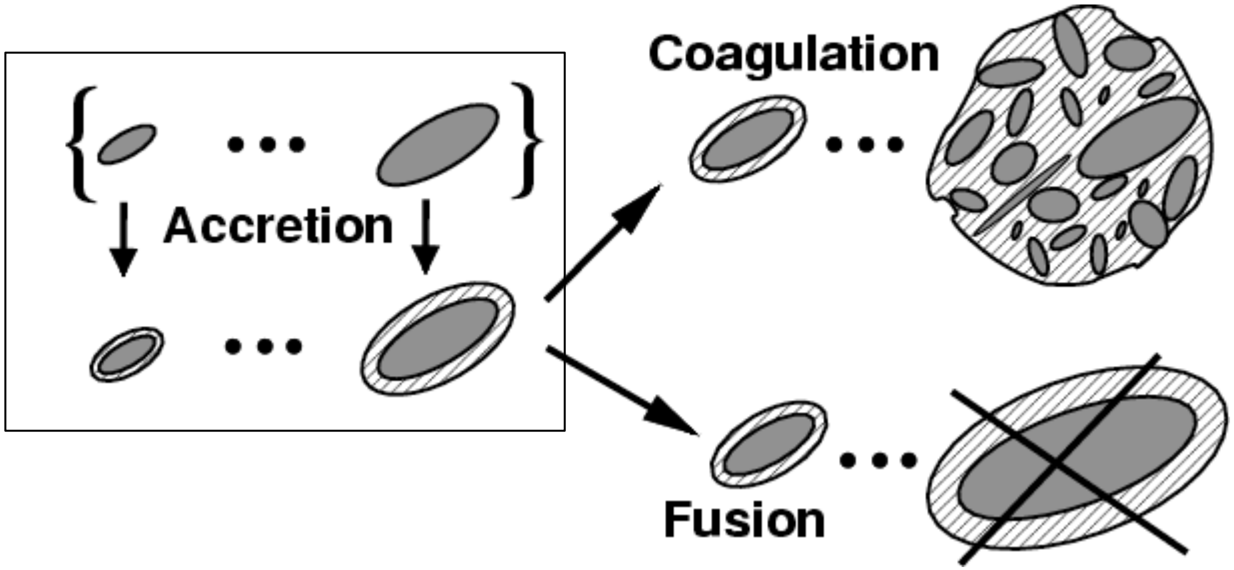
# Condensation

Condensation equation:

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

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

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# Compressibility: condensation

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

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

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

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

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

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# Compressibility: 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:

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

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

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# 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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