The origins of cosmic dust

Nordita Winter school on the physics of planets

Lars Mattsson

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"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

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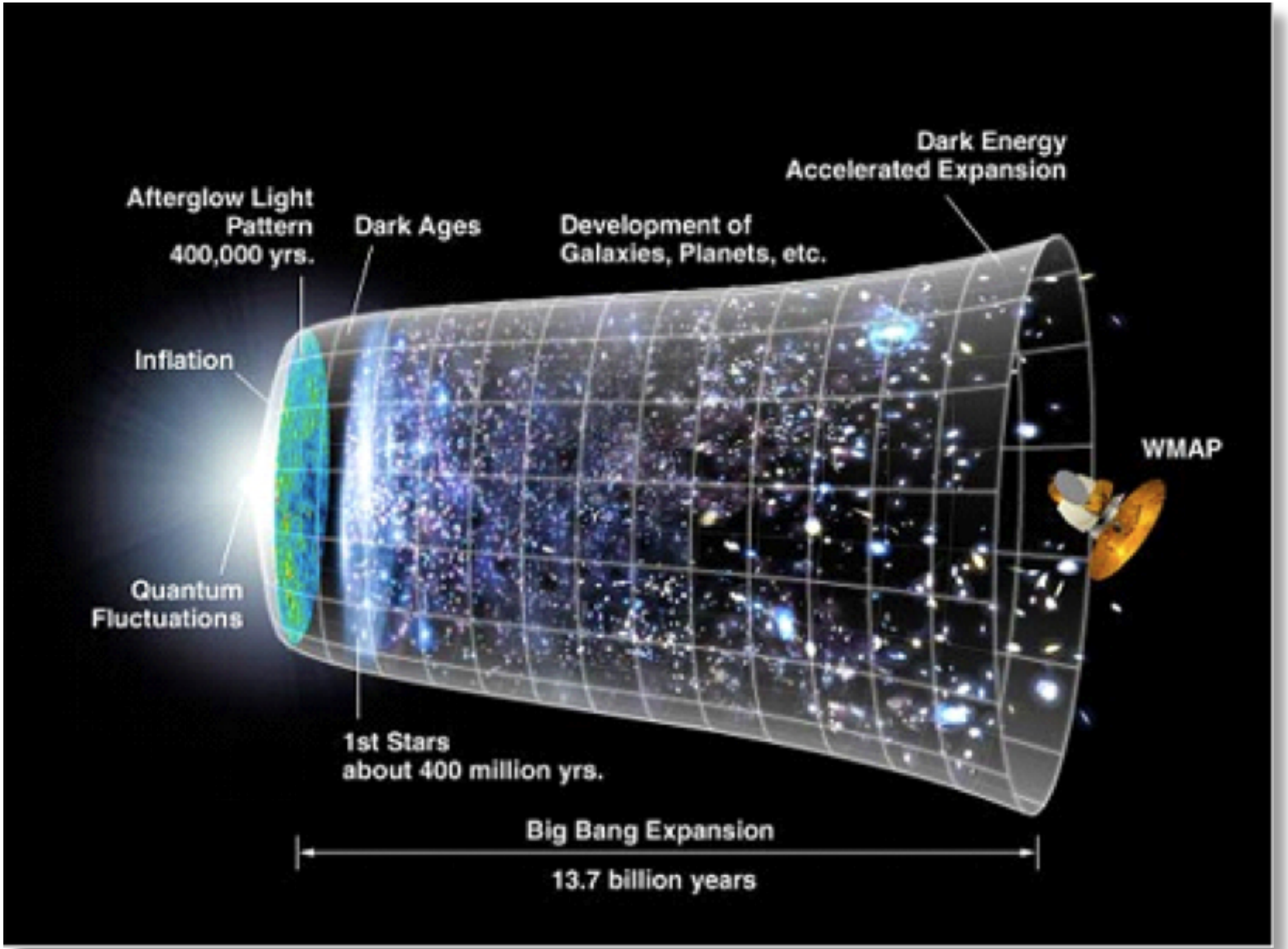
Let’s take it from the beginning…



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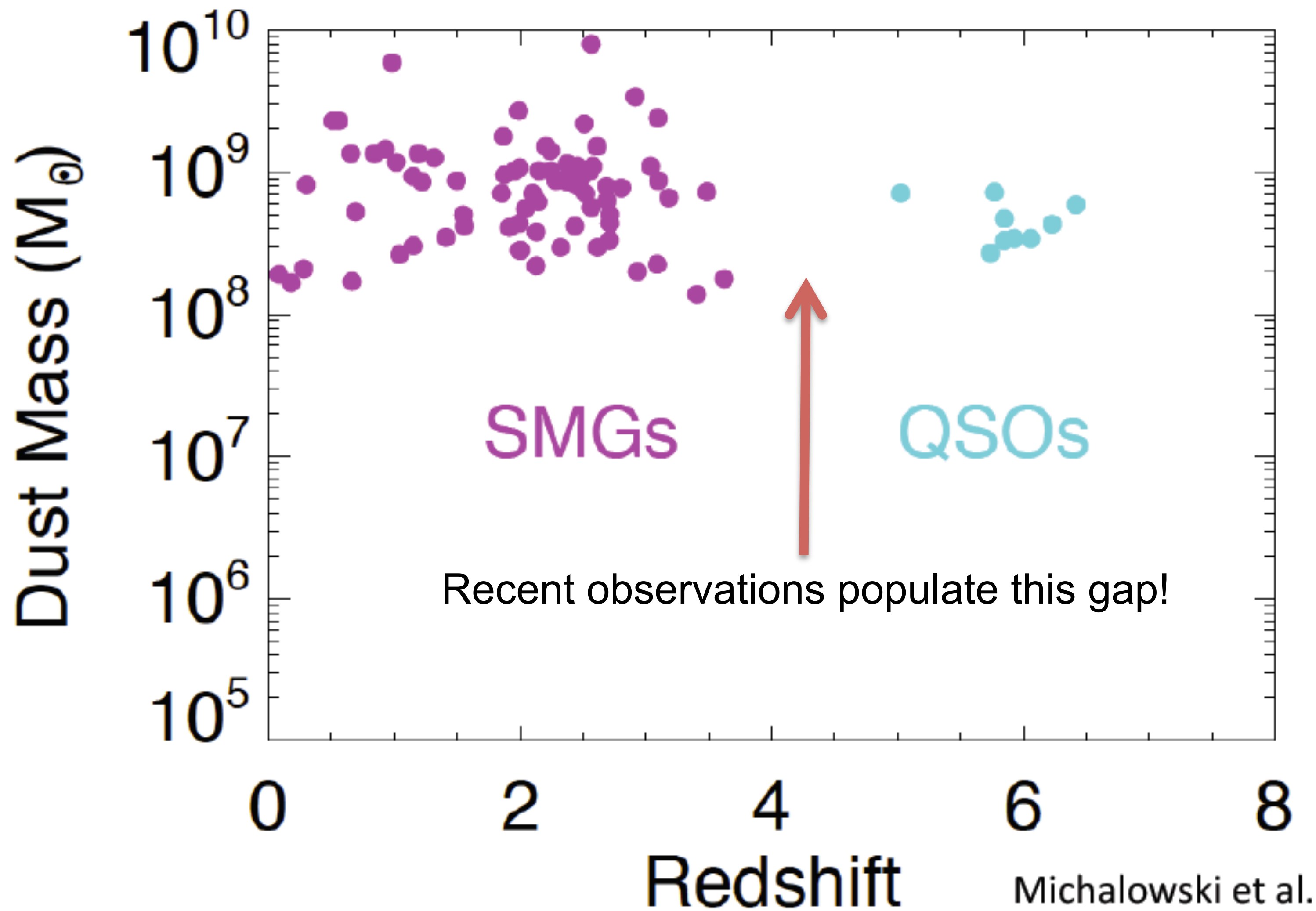
Large amounts of dust at high redshift



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

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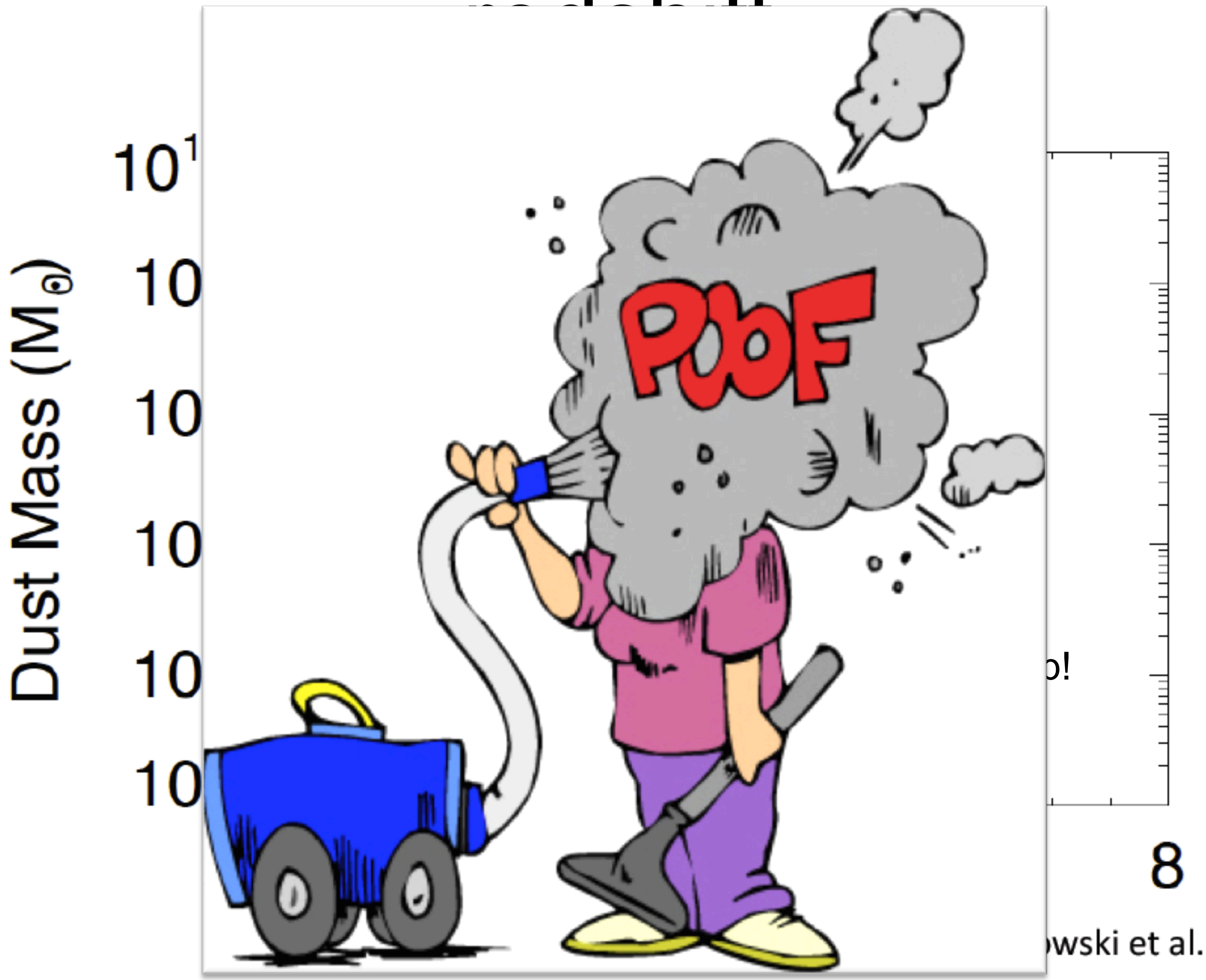

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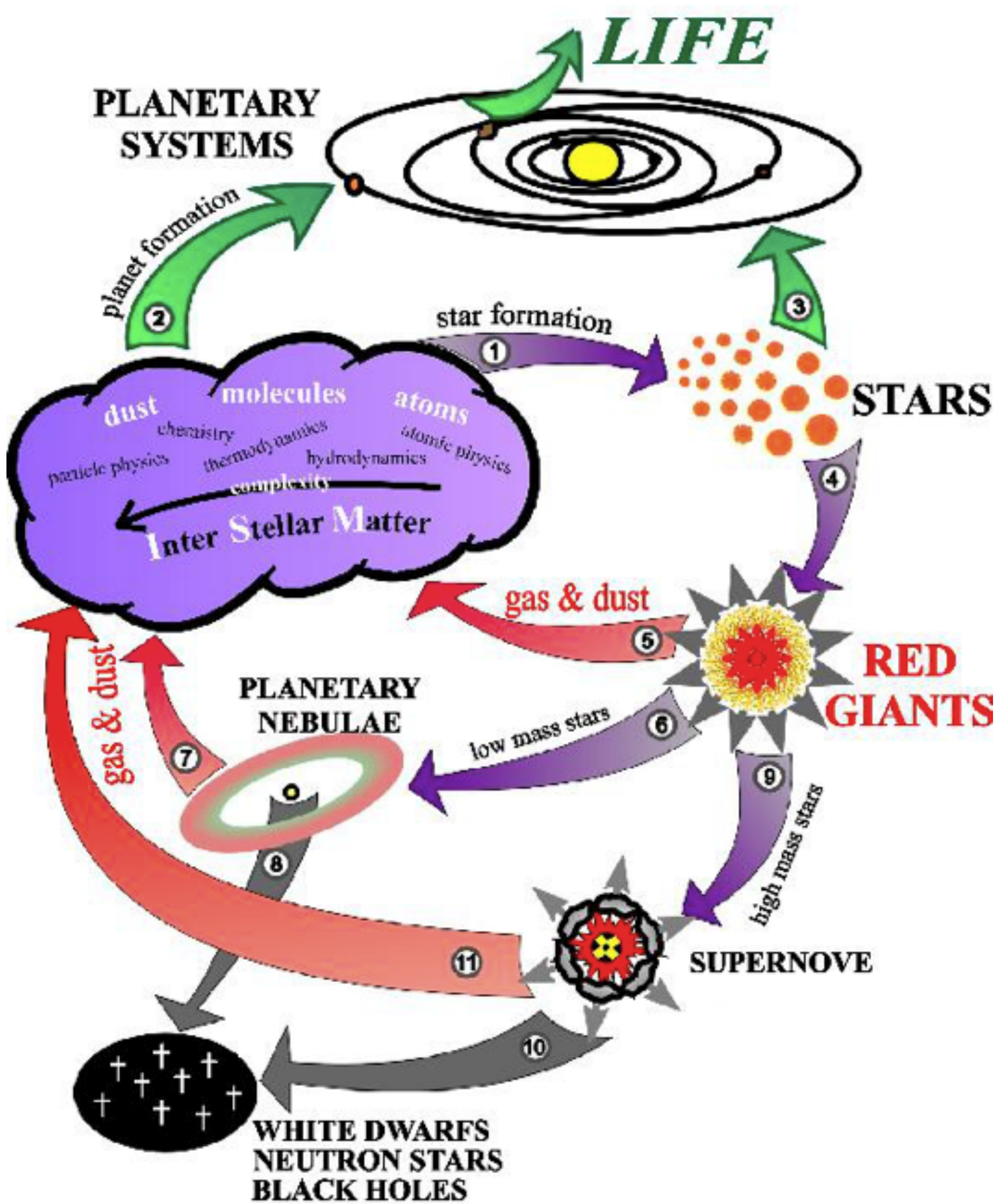
The cosmic matter cycle



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“Chemical evolution”

$$y_i = \frac{1}{\alpha} \int_{m_{\mathrm{lo}}}^{m_{\mathrm{up}}} p_i(m)\, m\, \phi(m)\, dm,$$

$$\Sigma_{\mathrm{g}} \frac{dZ}{dt} = y_Z \frac{d\Sigma_{\mathrm{s}}}{dt} = -y_Z \frac{d\Sigma_{\mathrm{g}}}{dt},$$

$$Z_{\mathrm{d}} = y_{\mathrm{d}} \ln\left(1 + \frac{\Sigma_\star}{\Sigma_{\mathrm{gas}}}\right),$$

Recommended reading: F. Matteucci, “*CHEMICAL EVOLUTION OF THE MILKY WAY AND ITS SATELLITES*” in the proceedings of the 37th Saas-Fee Advanced Course of the Swiss Society for Astrophysics and Astronomy, "*The Origin of the Galaxy and the Local Group*", **astro-ph/0804.1492**

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The effective metal yield for the solar neighbourhood is 0.01 – 0.02

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"Chemical evolution"

$$G(r,t) \equiv \dot{\Sigma}_{\mathrm{gr}}(r,t)\left(\frac{d\Sigma_{\mathrm{s}}}{dt}\right)^{-1},$$

$$D(r,t) \equiv \dot{\Sigma}_{\mathrm{ISM}}(r,t)\left(\frac{d\Sigma_{\mathrm{s}}}{dt}\right)^{-1},$$

$$\Sigma_{\mathrm{g}}\frac{dZ_{\mathrm{d}}}{dt} = y_{\mathrm{d}}\frac{d\Sigma_{\mathrm{s}}}{dt} + Z_{\mathrm{d}}(r,t)\,[G(r,t) - D(r,t)]\,\frac{d\Sigma_{\mathrm{s}}}{dt},$$

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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?

Quasar hosts at high redshift

- High dust masses: ~ 5 x 10^8 M_{sun}
- Molecular gas masses: ~ 10^{10} M_{sun}
- Total baryon masses: ~ 10^{11} M_{sun}

Stellar dust only, no destruction!

- Simple model: $Z_d = y_d \ln(M_{tot}/M_{gas})$
- Maybe 50% neutral gas: $M_{gas} = 2\ M_{mol}$
- $M_{dust} = y_d\ 2 \times 10^{10}\ M_{sun} \times \ln(5) \rightarrow y_d > 0.015$

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Quasar hosts at high redshift

Hmm... wasn't the effective *metal* yield for the solar neighbourhood 0.01- 0.02 ?!?

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SDSS J1148+525

- Dust mass: ~ 5 x 10^8 M_{sun}
- Molecular gas mass: ~ 2 x 10^{10} M_{sun}
- Dynamical mass: ~ 5 x 10^{10} M_{sun} (M_{tot})

- $M_{dust} = y_{dust}\ 4 \times 10^{10}\ M_{sun} \times \ln(5/4)$

$$\rightarrow y_{dust} > 0.056$$

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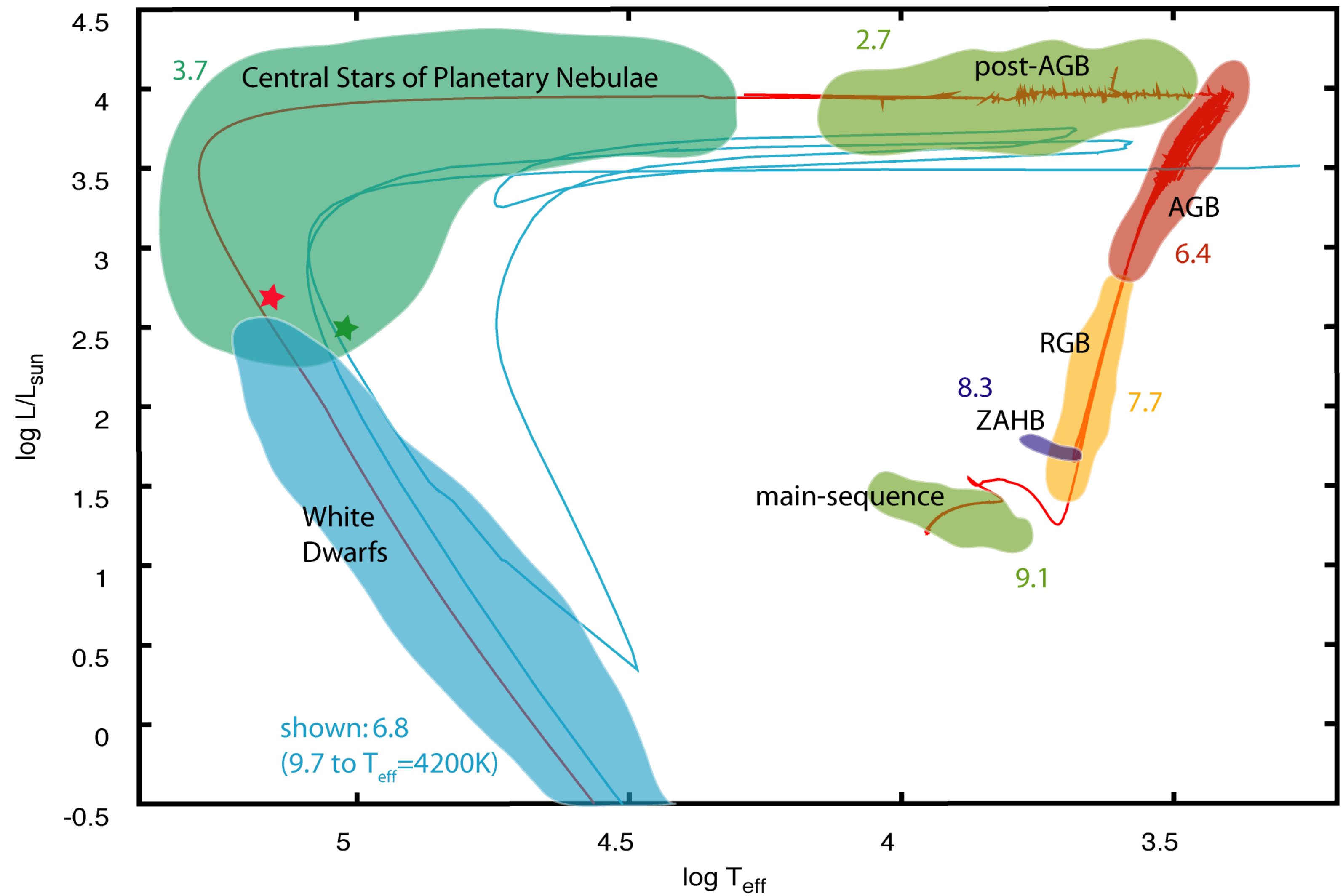
SDSS J1148+525

Eh… what?

AGB evolution and dust formation



(Herwig 2005, ARAA)

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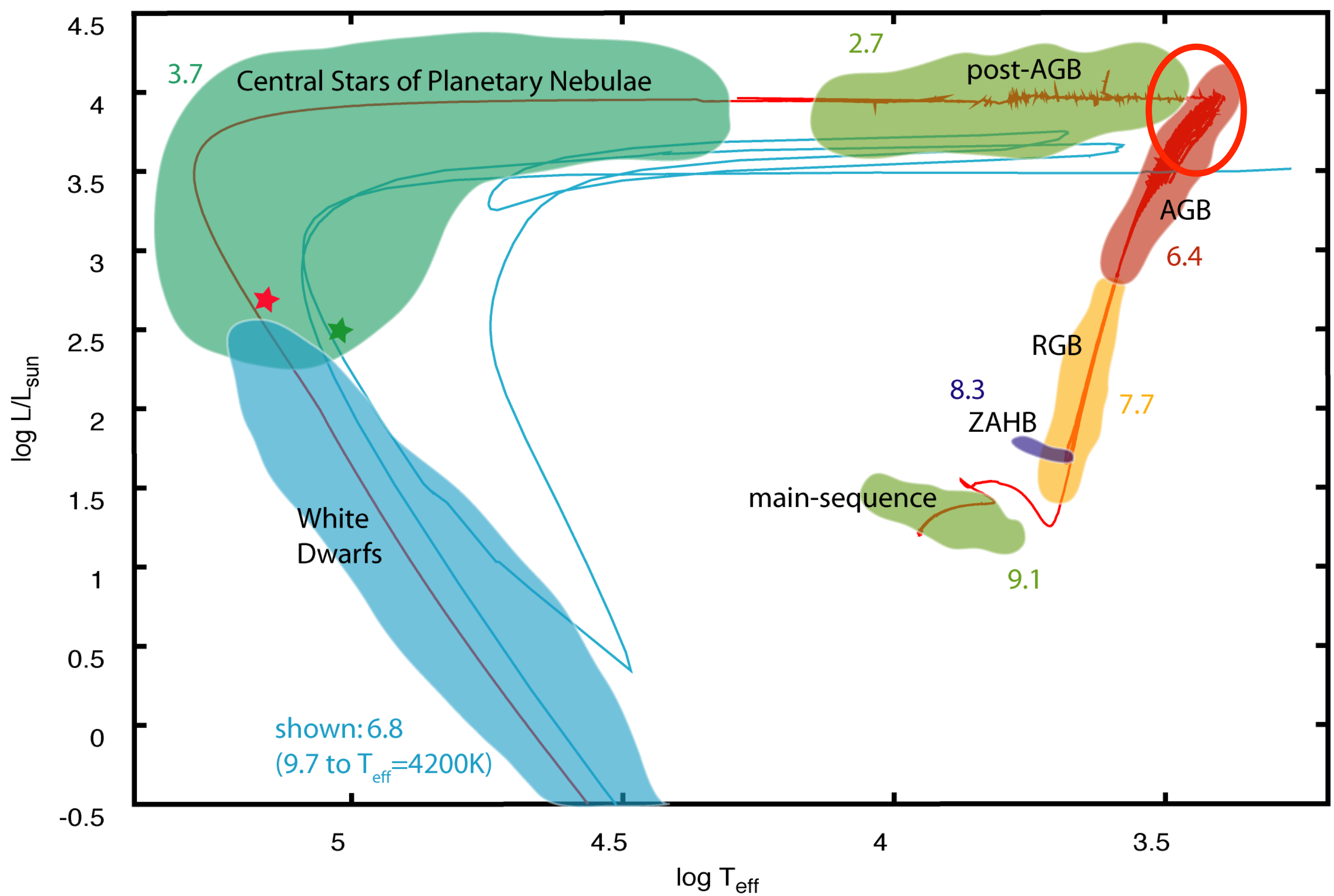
AGB evolution and dust formation



(Herwig 2005, ARAA)

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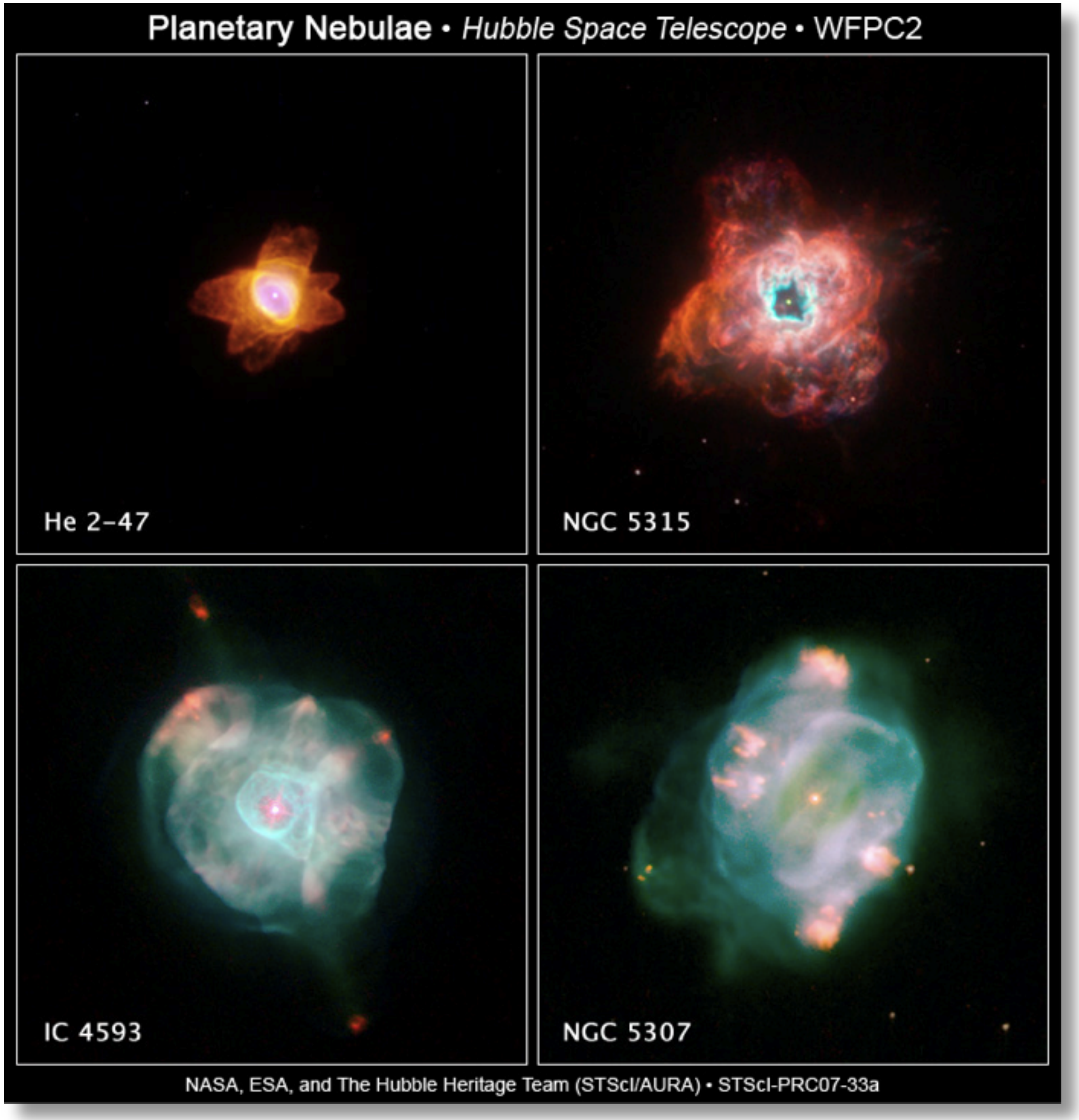
AGB evolution and dust formation



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AGB evolution and dust formation

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AGB evolution and dust formation

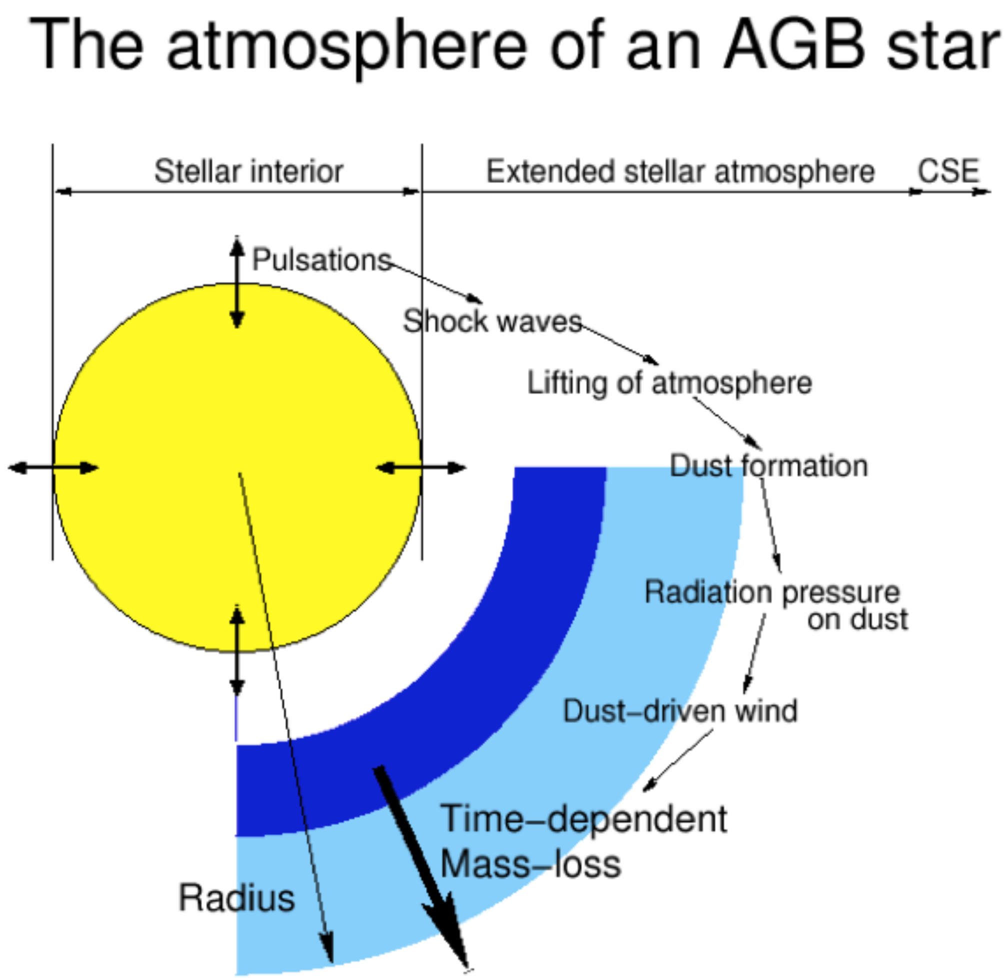

Figure 1. A schematic drawing of the atmosphere of an AGB star and the most important physical processes. (Courtesy of Christer Sandin).

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AGB evolution and dust formation

How would the dust yield be affected by hydrodynamics, feedback etc. ?

$$Y_d = \int_0^{t_{AGB}} f_c(t)\ \tilde{X}_C(t)\ \dot{M}(t)\ dt$$

$$\dot{M}(t) = f(f_c, \tilde{X}_C, \ldots)$$

Stellar evolution models need a physically consistent mass-loss prescription!

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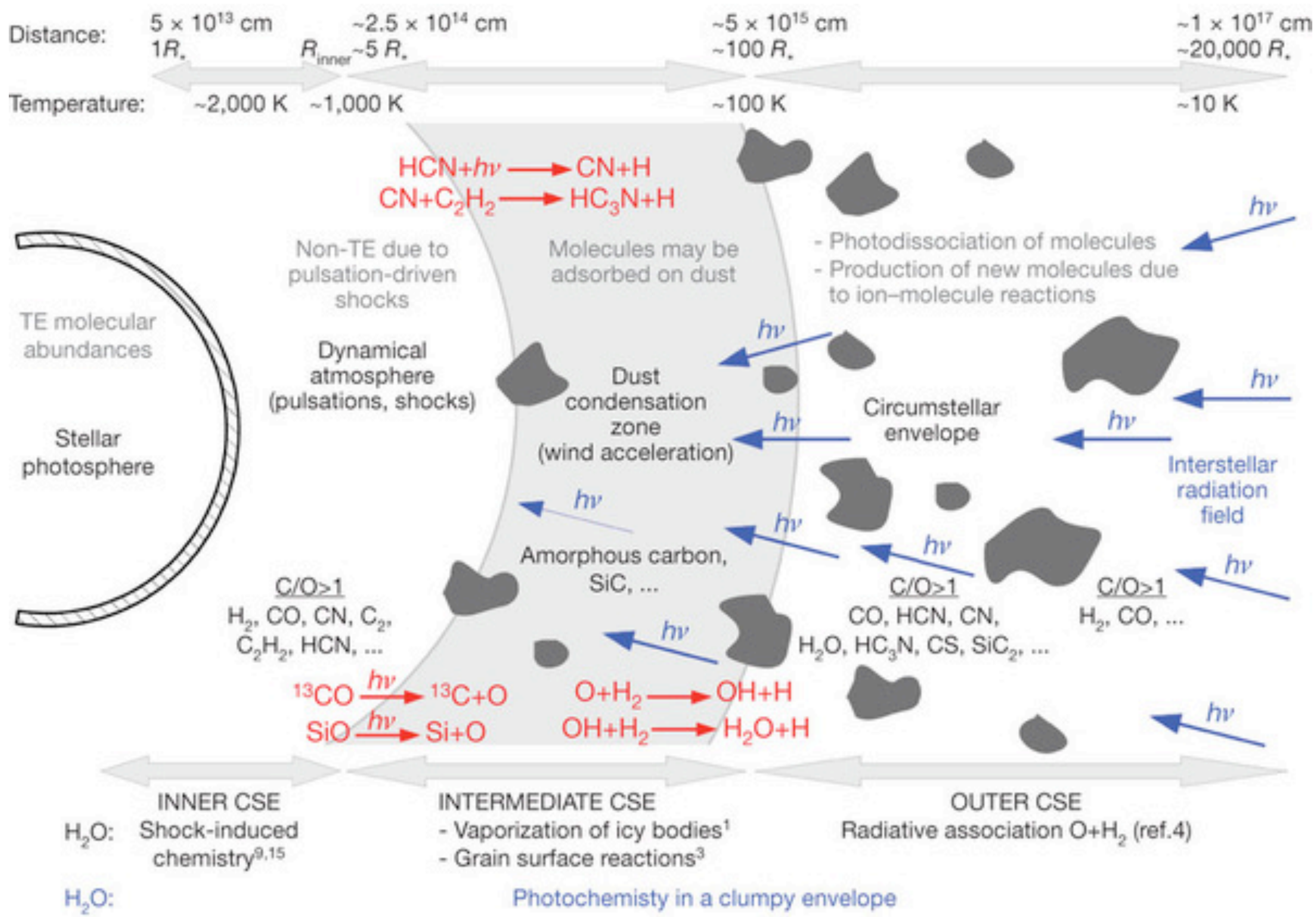
AGB evolution and dust formation

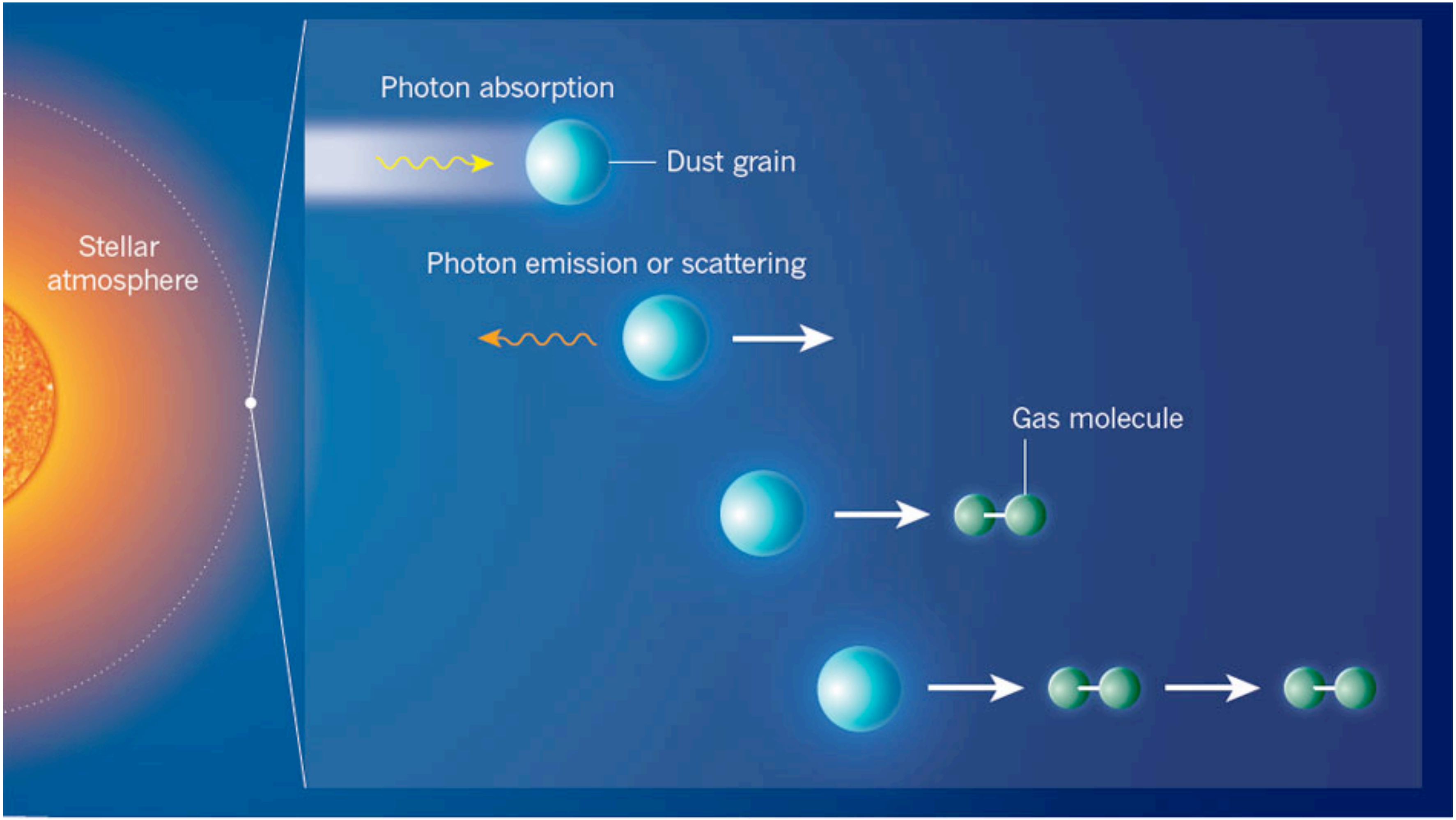
Grain nucleation – difficult!

Grain growth – easier!



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

AGB evolution and dust formation



Dust grains acquire momentum from stellar photons and transfer it to the surrounding gas via collisions.

Höfner (2012, Nature, 484, 172)

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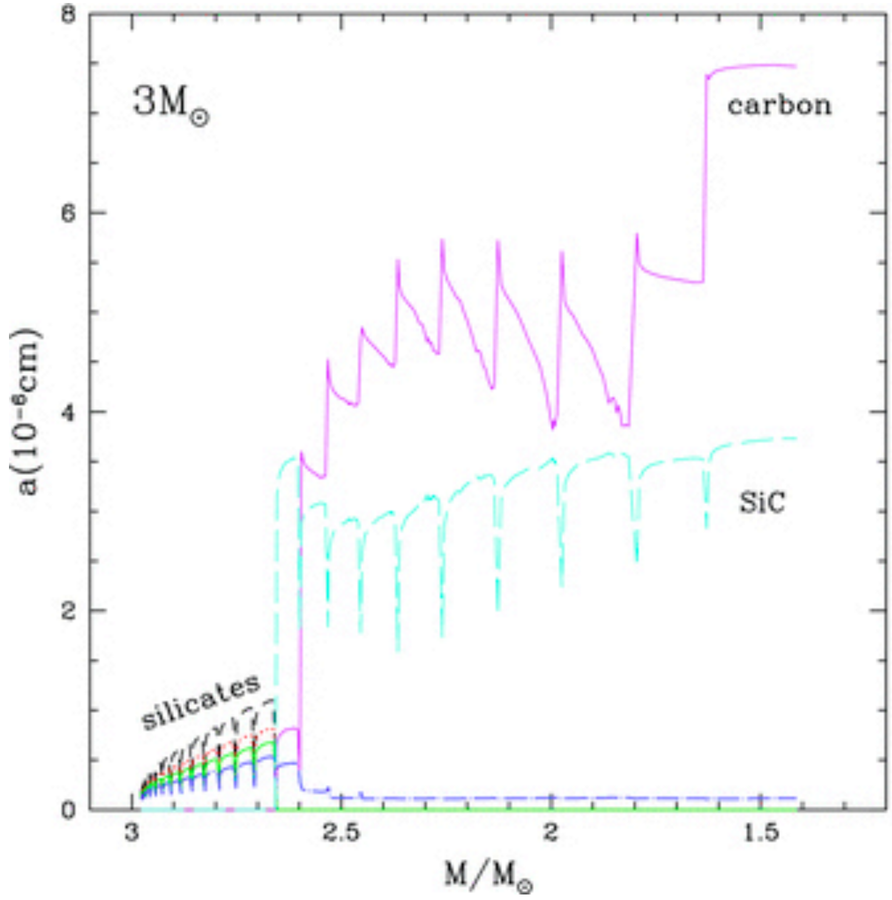
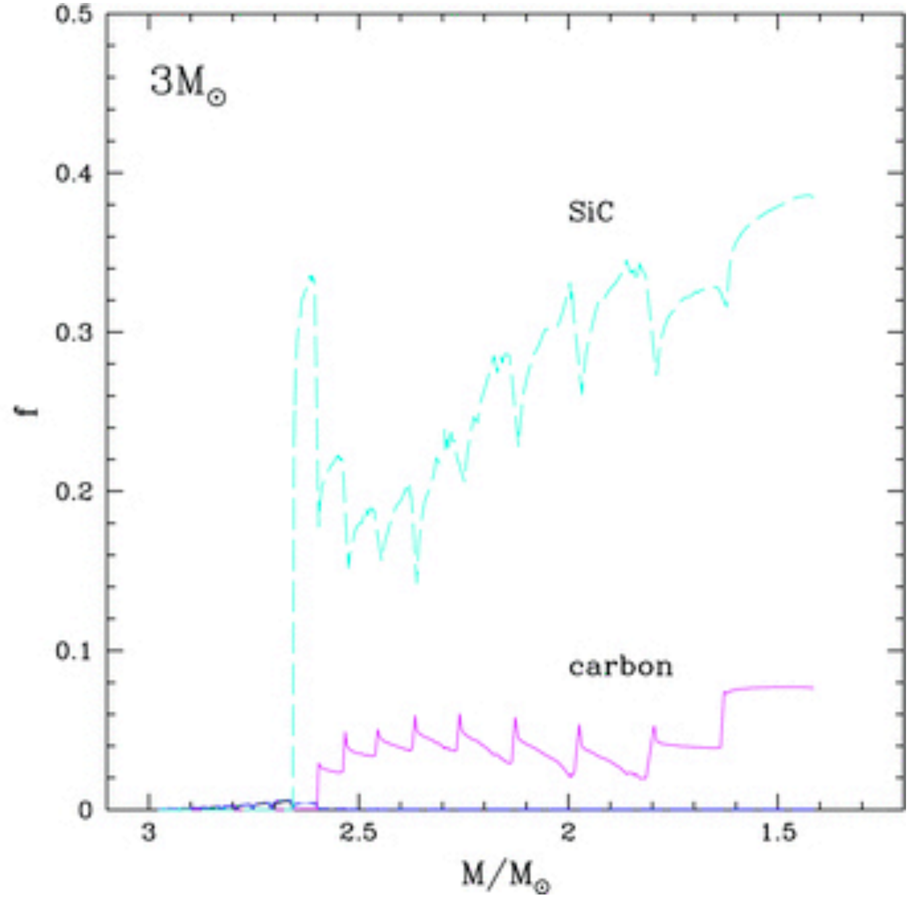
AGB evolution and dust formation





Ventura et al. (2012)

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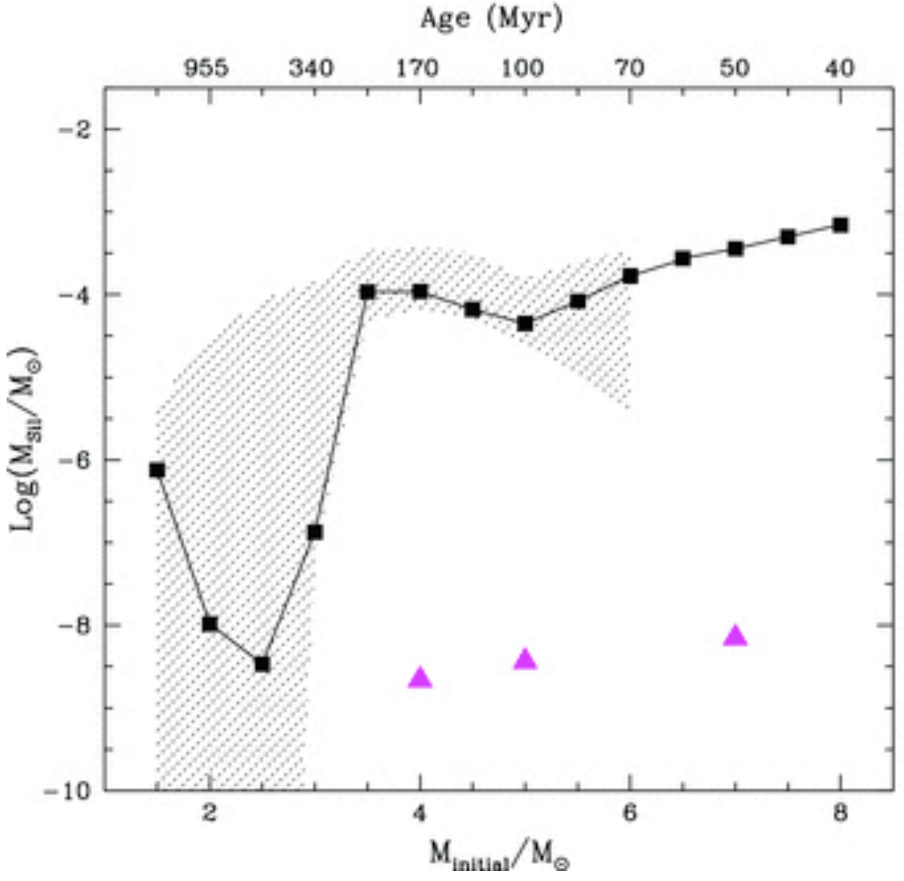
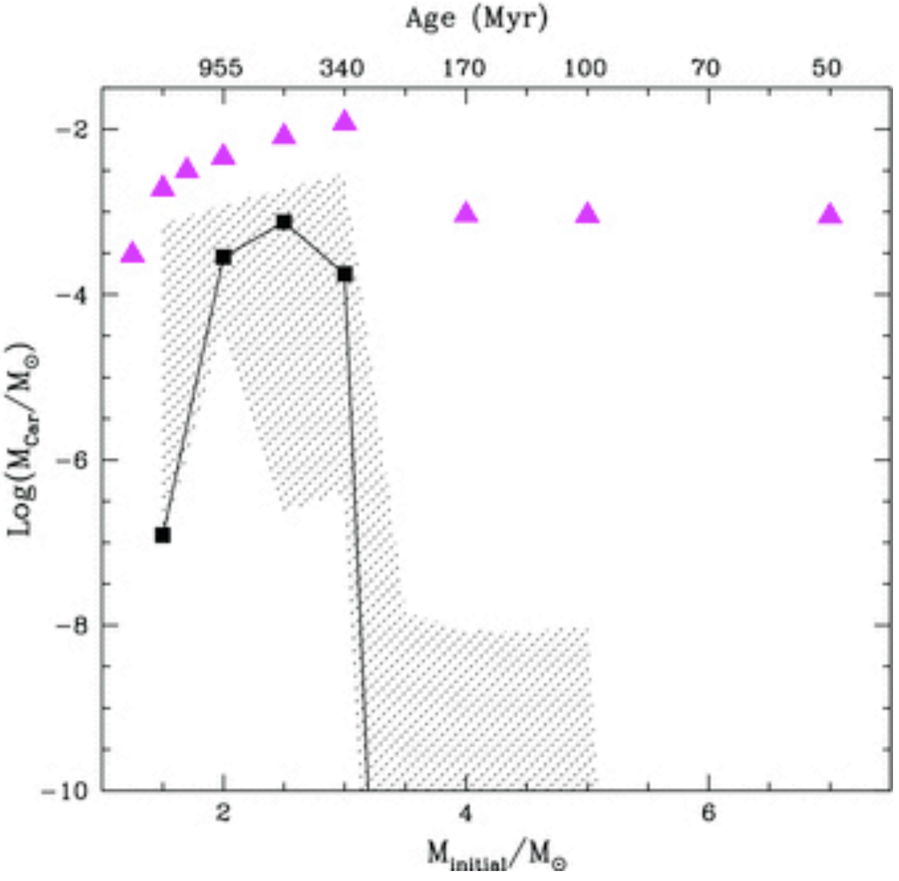
AGB evolution and dust formation

Silicates:

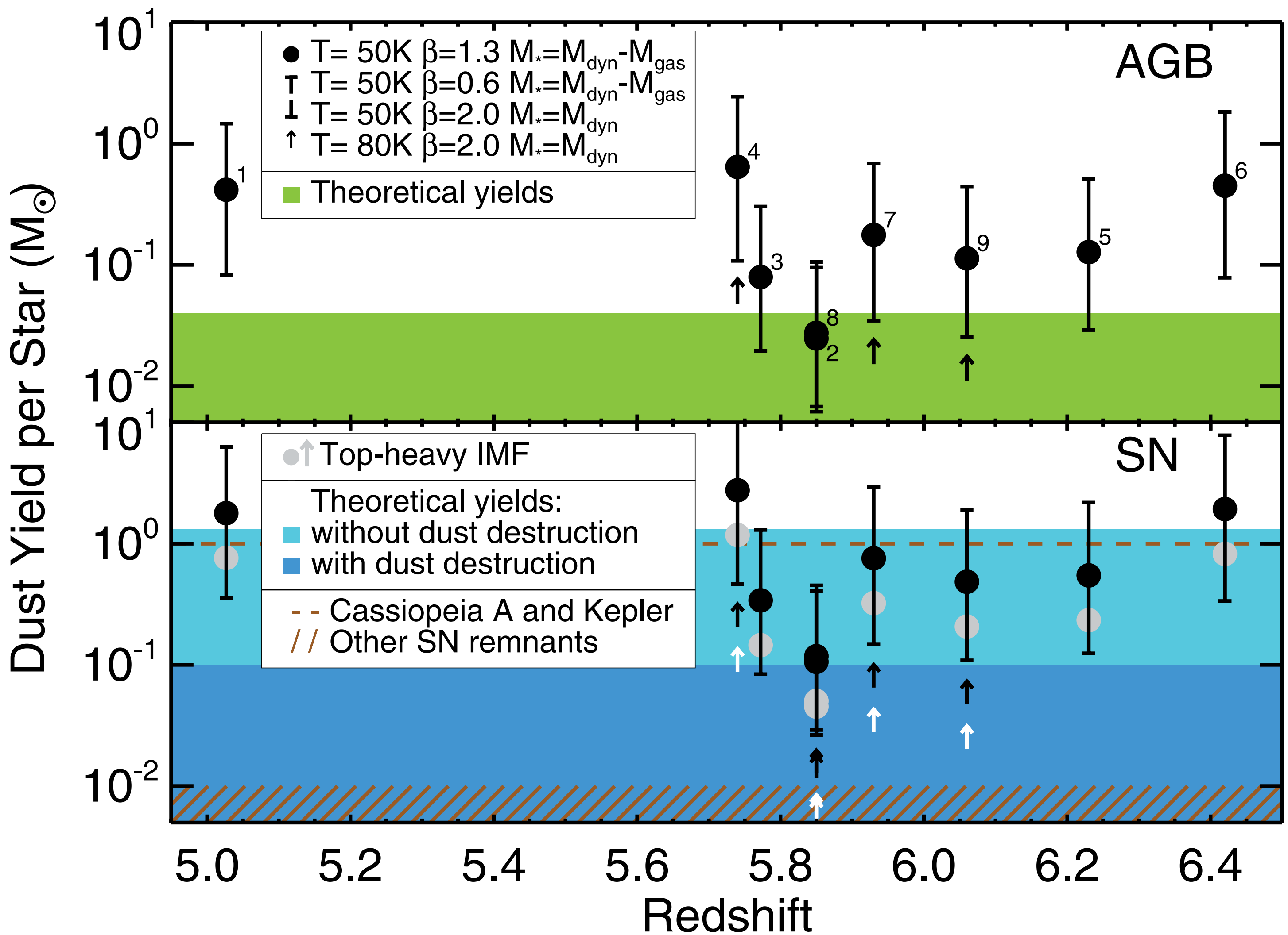


Carbonaceous dust:



Ventura et al. (2012)

AGB stars? Nope!



(Michalowski et al. 2010)

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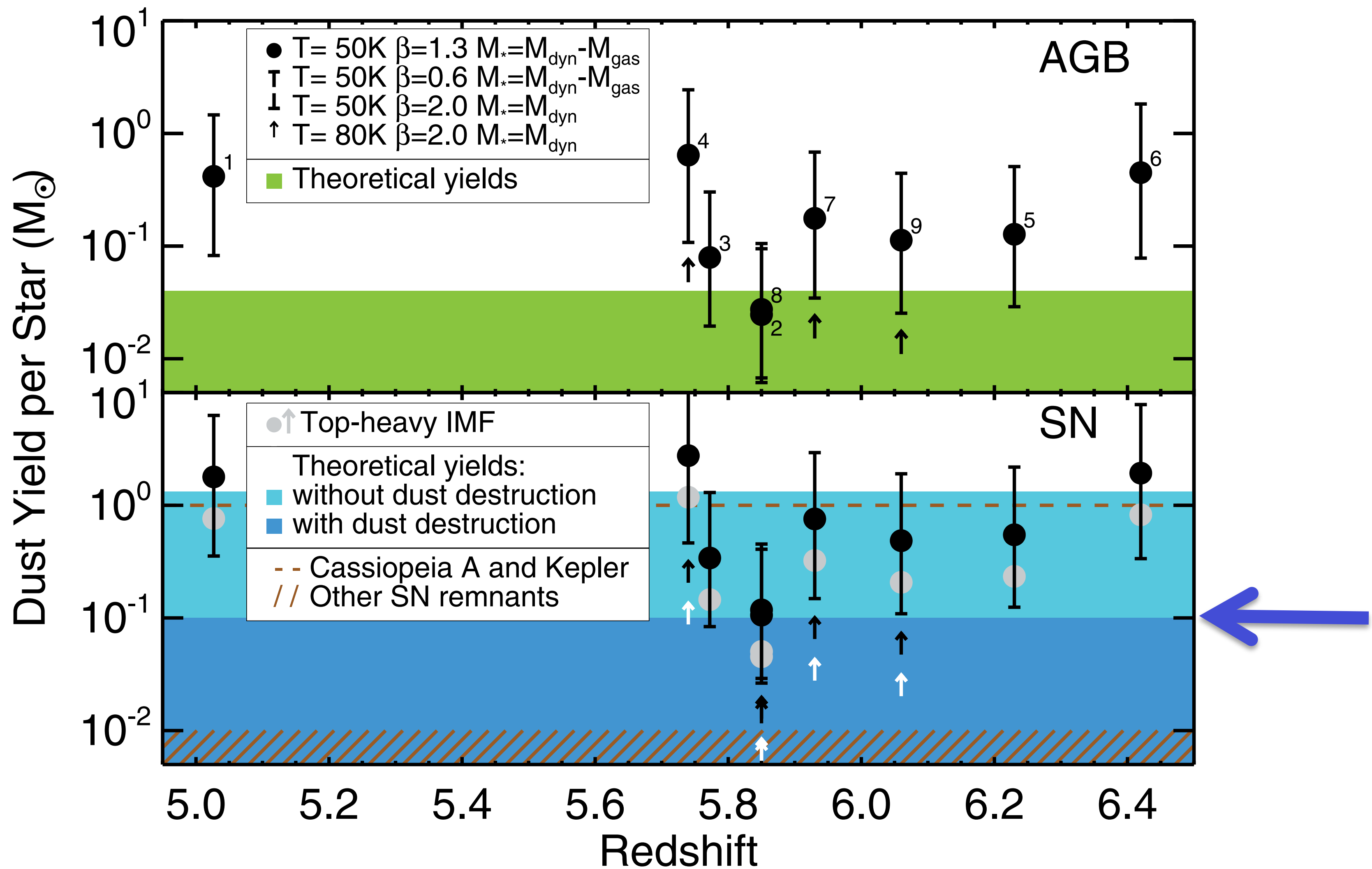
AGB stars? Nope!



(Michalowski et al. 2010)

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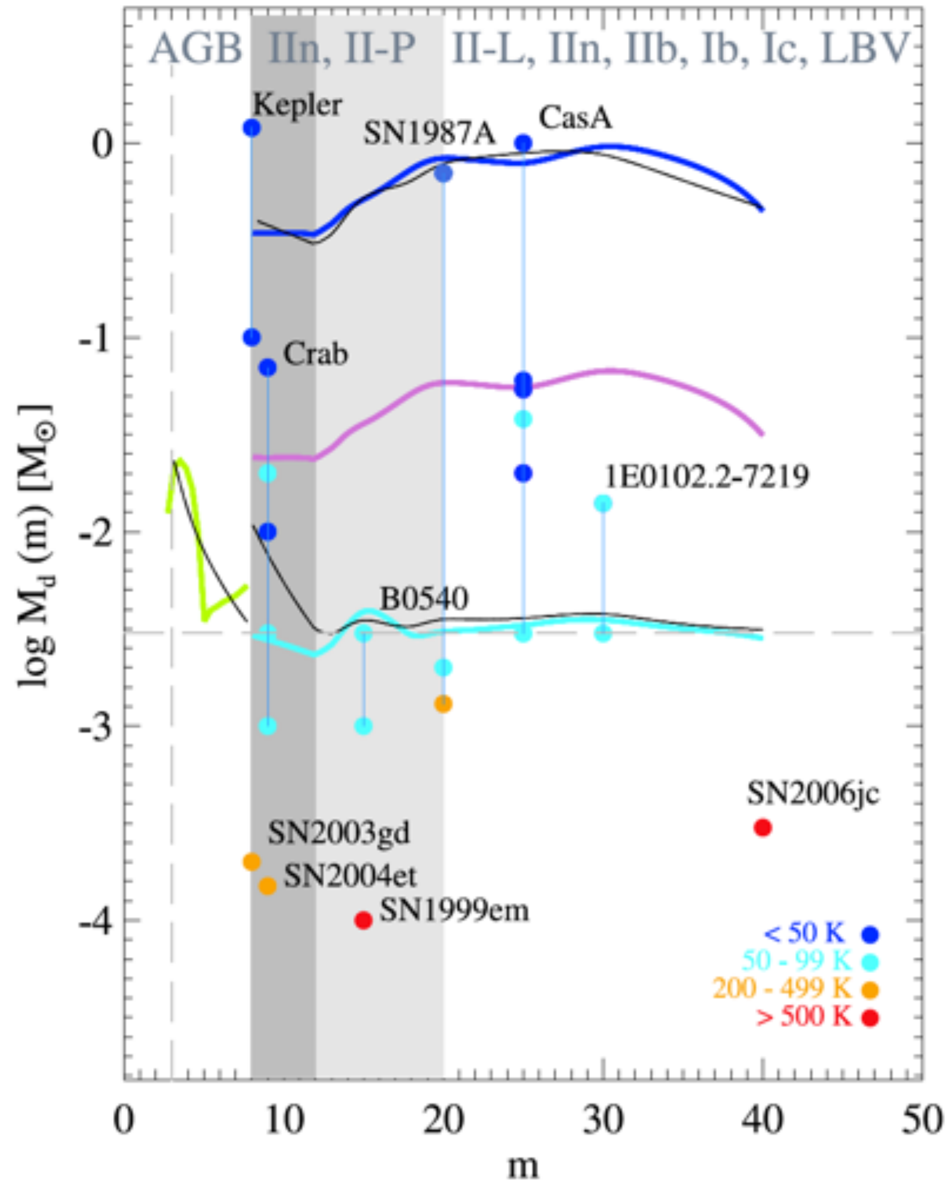
SN dust works, but…

- 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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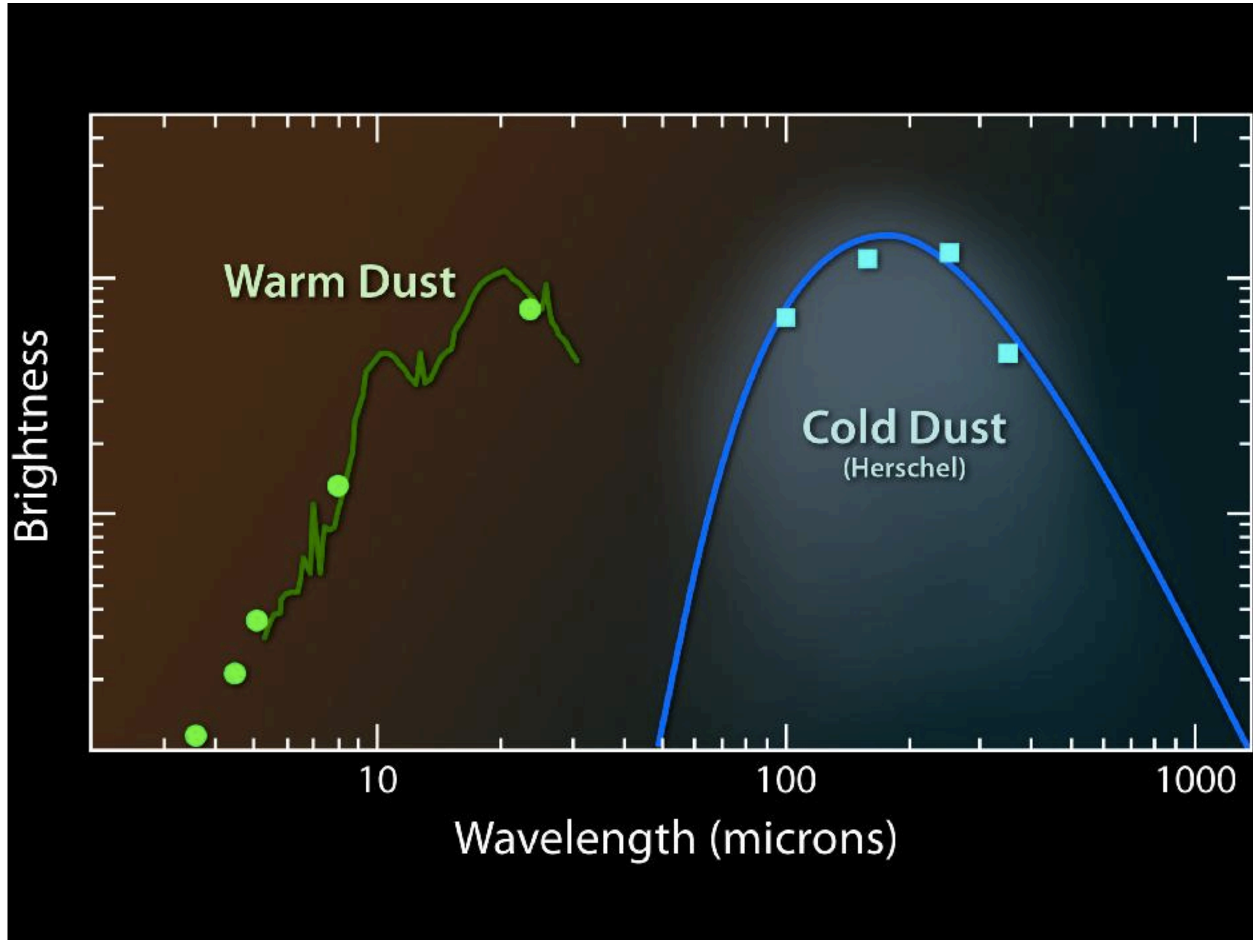
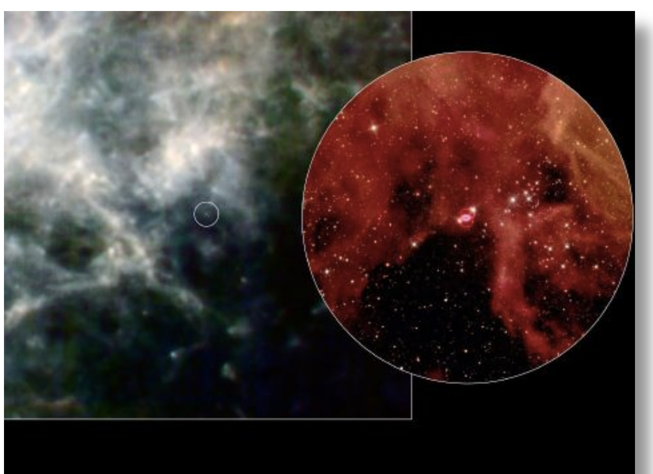
SN dust works, but…

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)

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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.
- $A_{silicates} = 121.41 \rightarrow M_{silicates} < 0.56\ M_{sun}$
- $M_C = 0.22\ M_{sun} \rightarrow M_{c\text{-}dust} < 0.22\ M_{sun}$

Local galaxies

- Do the number add up for local galaxies then? Well, not really...
- NGC 3351:
    - Central dust-to-gas ratio Z_{dust} ~ 0.3
      Upper limit to central log(O/H) ~ -3
    - Assume 1/3 of metals is oxygen (1/2 in Sun).
    - $X_O = 12\ O/H \rightarrow Z = 36\ \ O/H = 0.13$
- All metals condense into dust and then magically multiply...

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Local galaxies

WTF?!?

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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Anyway…

- Maximum time to build large dust masses: < 400 – 500 Myr.
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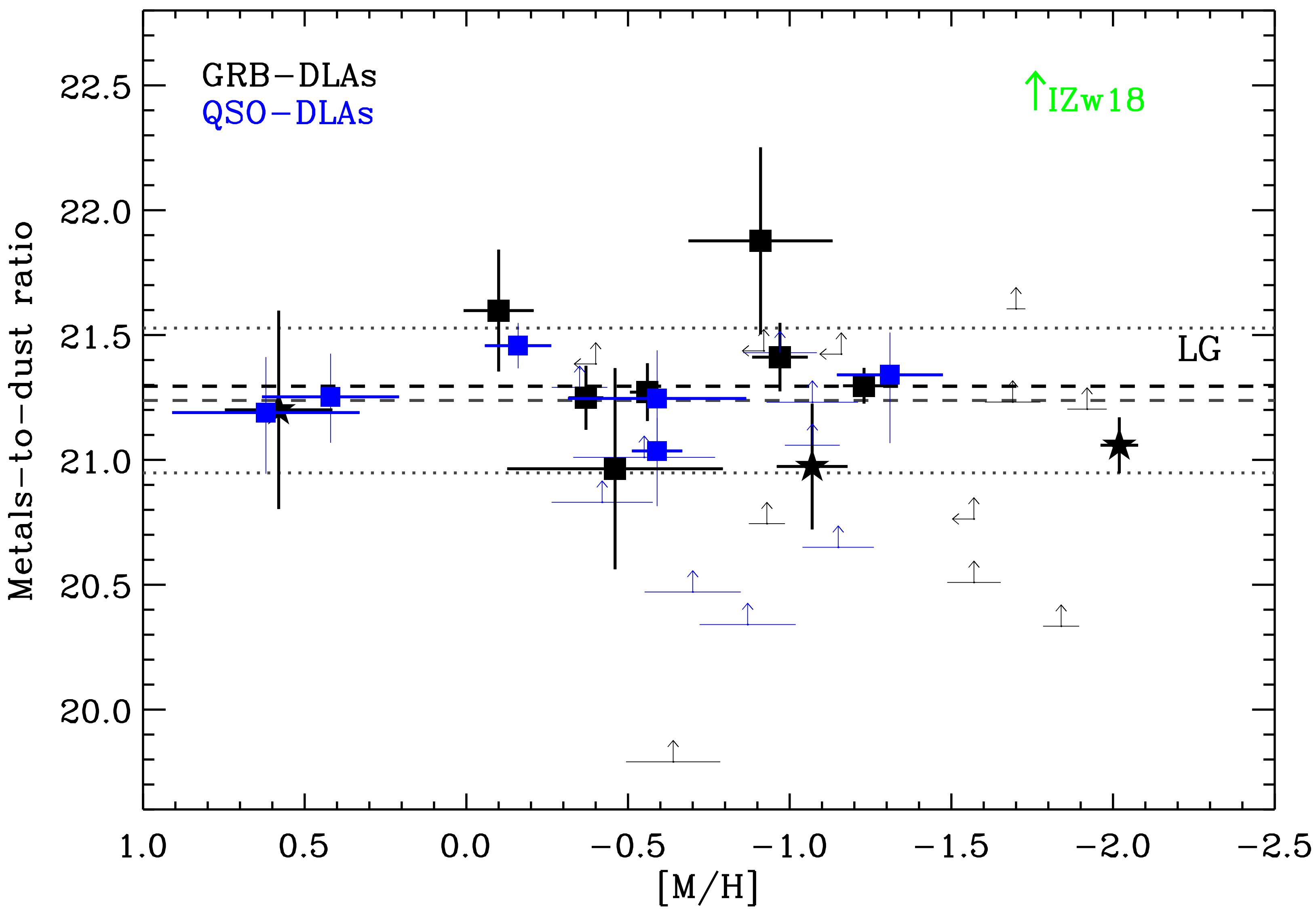
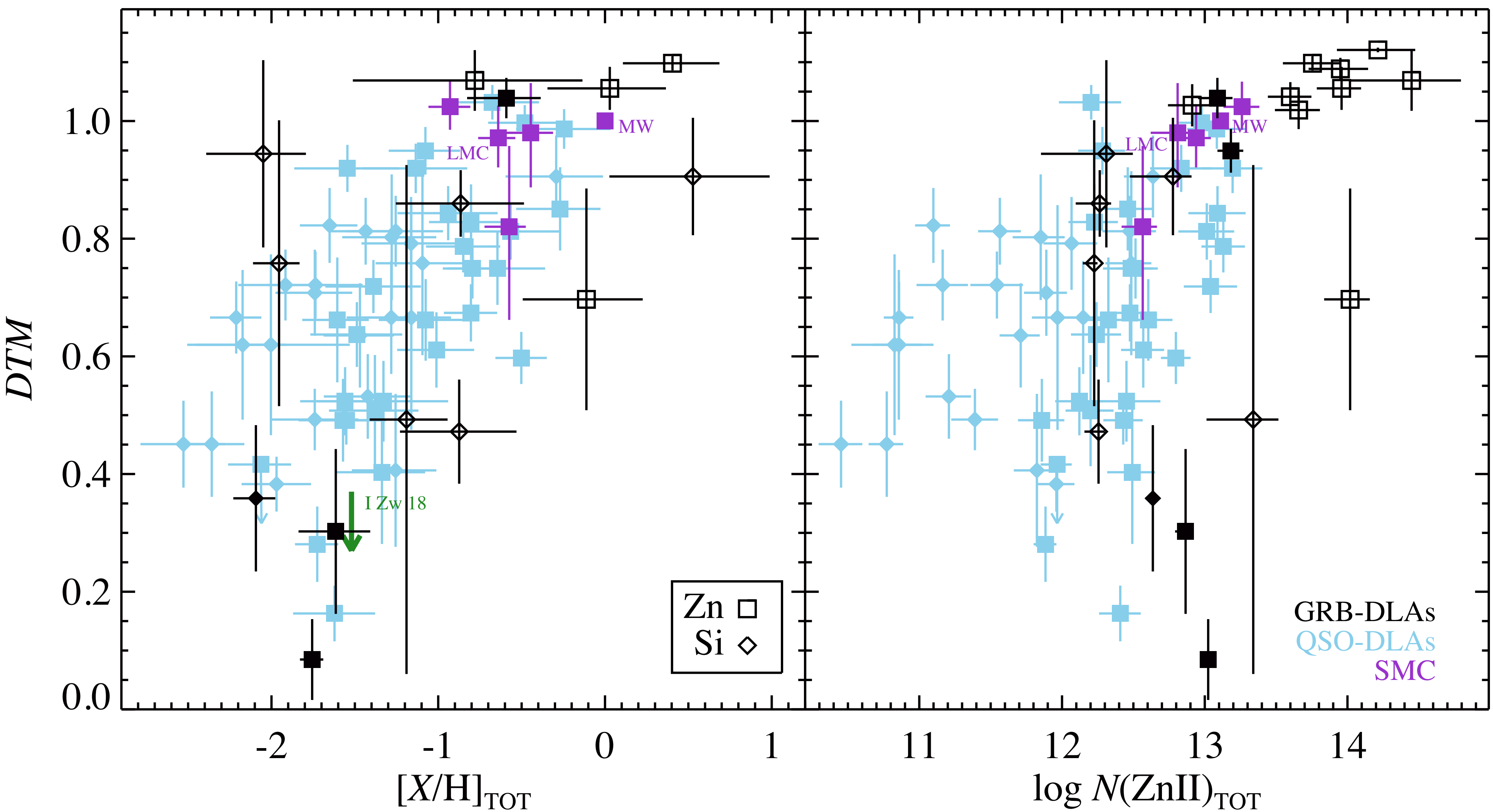
Nearly constant dust-to-metals ratio



AV – dust relation, Zafar & Watson (2013, A&A, 560, A26)

Not so constant dust-to-metals ratio



Dust depletion, De Cia et al.(2013, A&A, 560, A88)

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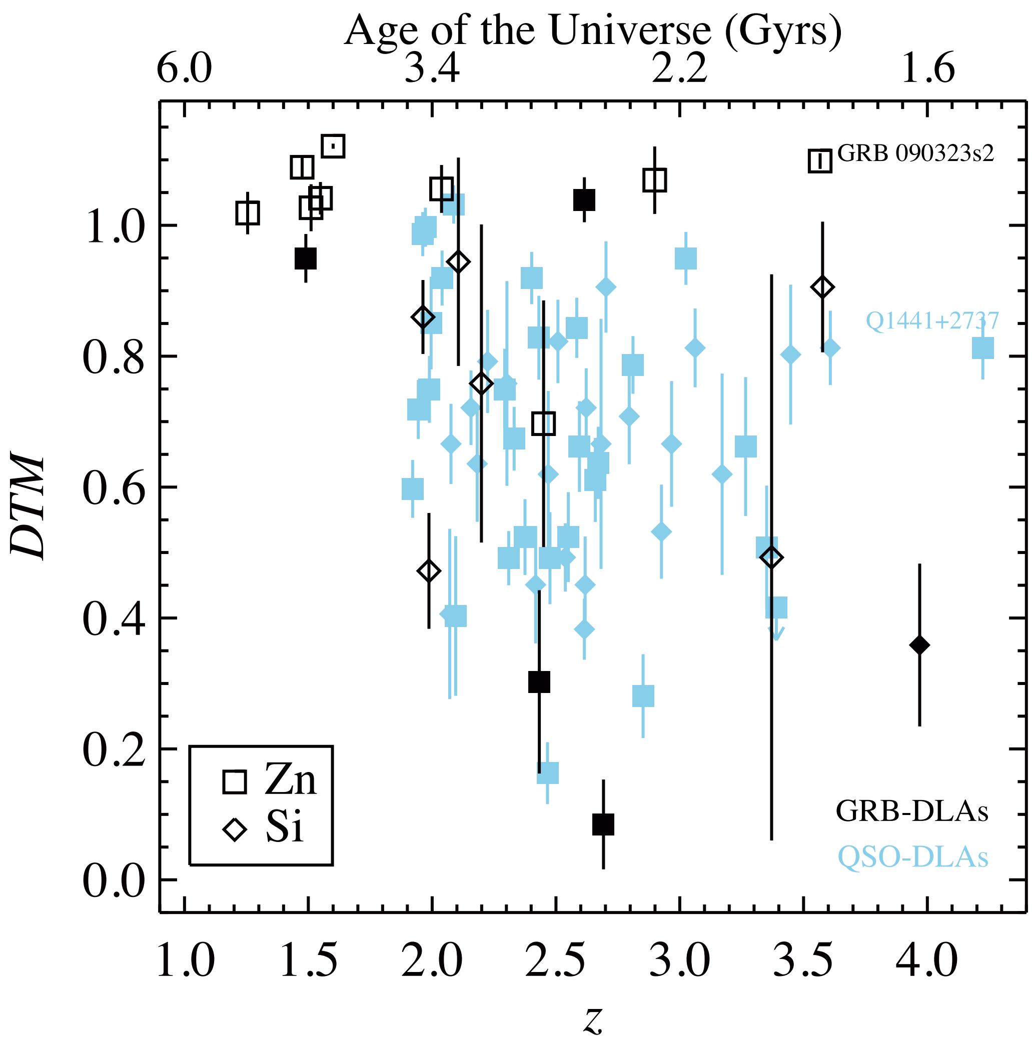
Not so constant dust-to-metals ratio



Towards an equilibrium?

Dust depletion, De Cia et al.(2013, A&A, 560, A88)

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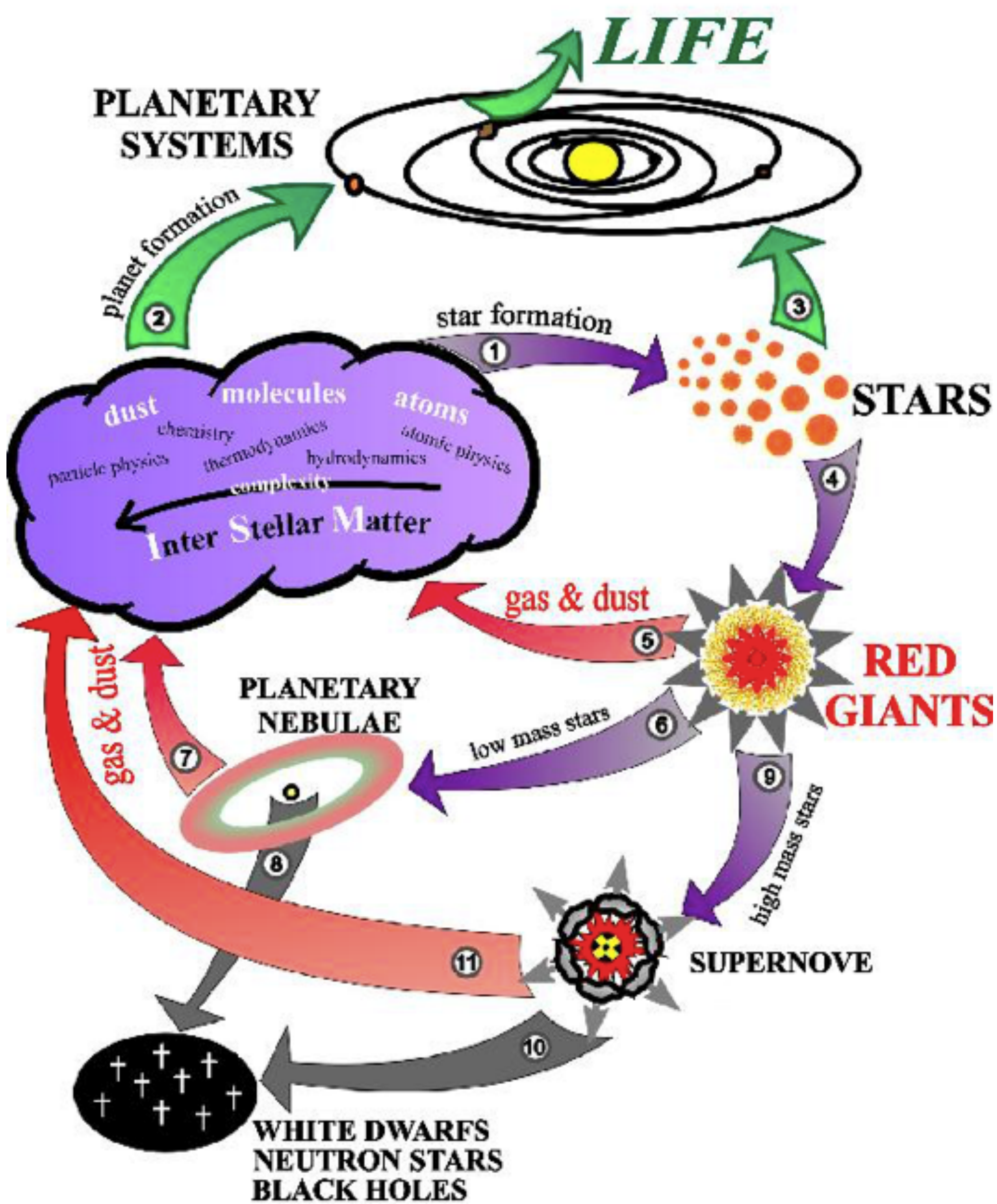
The cosmic matter cycle



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Hypothesis:

- Shock waves from supernovae induce sputtering
  -> timescale depends on SN rate!
- Dust growth (condensation) in molecular clouds
  -> timescale depends on SN rate!
- The growth and destruction rates reach an "equilibrium" creating a constant DTM as time goes by.
- But seed-grain production (or survival, actually) in stars depends on **metallicity**.

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Toy Model

Grain growth:

$$\frac{1}{\rho_{\mathrm{d},i}}\frac{d\rho_{\mathrm{d},i}}{dt} = 3 f_{\mathrm{s}} \frac{\langle v \rangle}{a_{\mathrm{eff}}} \frac{\rho_i - \rho_{\mathrm{d},i}}{\rho_{\mathrm{gr}}},$$

$$\tau_{\mathrm{grow}} \propto \frac{1}{Z\rho_{\mathrm{H_2}}}\left(1 - \frac{Z_{\mathrm{d}}}{Z}\right)^{-1}$$

$$\tau_{\mathrm{grow}}^{-1} = \frac{\epsilon Z}{\rho_{\mathrm{g}}}\left(1 - \frac{Z_{\mathrm{d}}}{Z}\right)\frac{d\rho_{\mathrm{s}}}{dt}$$

(See also Inoue 2011)

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Toy Model

Grain destruction (McKee 1989):

$$\tau_{\rm d} = \frac{\rho_{\rm g}}{\langle m_{\rm ISM}\rangle R_{\rm SN}}$$

$$R_{\rm SN}(t) \approx \dot{\rho}_{\rm sfr}(r,t) \int_{8M_\odot}^{100M_\odot} \phi(m)\, dm,$$

$$\tau_{\rm d}^{-1} \approx \frac{\delta}{\rho_{\rm g}} \frac{d\rho_{\rm s}}{dt}$$

(See also Inoue 2011)

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Toy Model

Grain-grain interaction -> shattering.

Collision rate can be defined as:

$$R_{\rm coll} \equiv \sigma_{\rm coll} v_{\rm rel}\, n_{\rm d}, \quad \sigma_{\rm coll} = 2\pi\langle a^2\rangle$$

Collision density: $\frac{1}{2} R_{\rm coll}\, n_{\rm d} \propto Z_{\rm d}^2$ since $n_{\rm d} \propto Z_{\rm d}$

$$\boxed{\tau_{\rm d}^{-1} \approx \frac{\delta}{\rho_{\rm g}} \frac{Z_{\rm d}}{Z_{\rm d,G}} \frac{d\rho_{\rm s}}{dt}}$$

(See also Inoue 2011)

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Toy Model

Grain-grain interaction -> shattering.

Collision rate can be defined as:

$$R_{\mathrm{coll}} \quad \ldots \quad \langle a^2 \rangle$$

Collision ... $n_{\mathrm{d}} \propto Z_{\mathrm{d}}$

Because the destruction timescale is inversely proportional to the dust-to-gas ratio, the growth and destruction of grains will evolve towards an equilibrium!

$$\tau_{\mathrm{d}}^{-1} \approx \frac{\delta}{\rho_{\mathrm{g}}} \frac{Z_{\mathrm{d}}}{Z_{\mathrm{d,G}}} \frac{d\rho_{\mathrm{s}}}{dt}$$

(See also Inoue 2011)

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Toy Model

"Closed box"

"Instaneous recycling"

Equation to solve:

Growth and destruction terms

$$Z\frac{d\zeta}{dZ} = \frac{y_{\mathrm{d}}}{y_{\mathrm{Z}}} + \frac{\zeta Z}{y_{\mathrm{Z}}}[G(Z) - D(Z)] - \zeta.$$

Dust-to-metals ratio!

(See also Inoue 2011)

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Toy Model

If we instead consider our second equation of dust evolution,

$$Z\frac{d\zeta}{dZ} = \frac{y_\mathrm{d}}{y_\mathrm{Z}} + \frac{\zeta Z^2}{y_\mathrm{Z}}\left[\epsilon\left(1-\zeta\right) - \delta'\zeta\right] - \zeta, \quad (17)$$

for the case where the dust-destruction timescale depends on the dust-to-gas ratio Z_d, i.e., $D(Z) = \delta' Z_\mathrm{d}(Z)$, where $\delta' = \delta / Z_{\mathrm{d,G}}$, we obtain a more realistic equilibrium condition. More precisely, we have that $\epsilon(1-\zeta) - \delta'\zeta = 0$, which leads to

$$\frac{\delta'}{\epsilon} = \frac{y_\mathrm{Z}}{y_\mathrm{d}} - 1. \quad (18)$$

This criterion is more useful than Eq. (16), since it does not involve any variable. If we adopt the Galactic dust-to-metals ratio, $\zeta_\mathrm{G} \approx 0.5$, we have $y_\mathrm{d}/y_\mathrm{Z} \approx 0.5$ and thus $\epsilon \approx \delta'$. With $\delta \sim 5 - 10$ and

(See also Inoue 2011)

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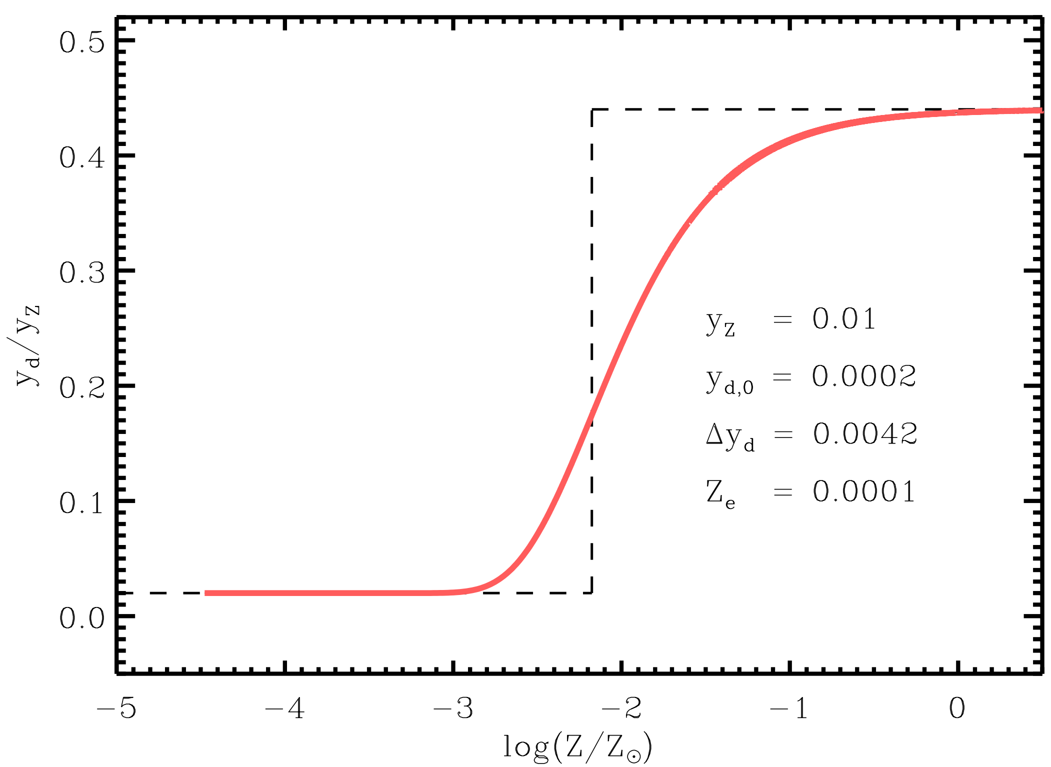
Supernovae: Metallicity dependence needed



$$y_d(Z) = y_{d,0} + \Delta y_d \exp\left(-\frac{Z_e}{Z}\right)$$

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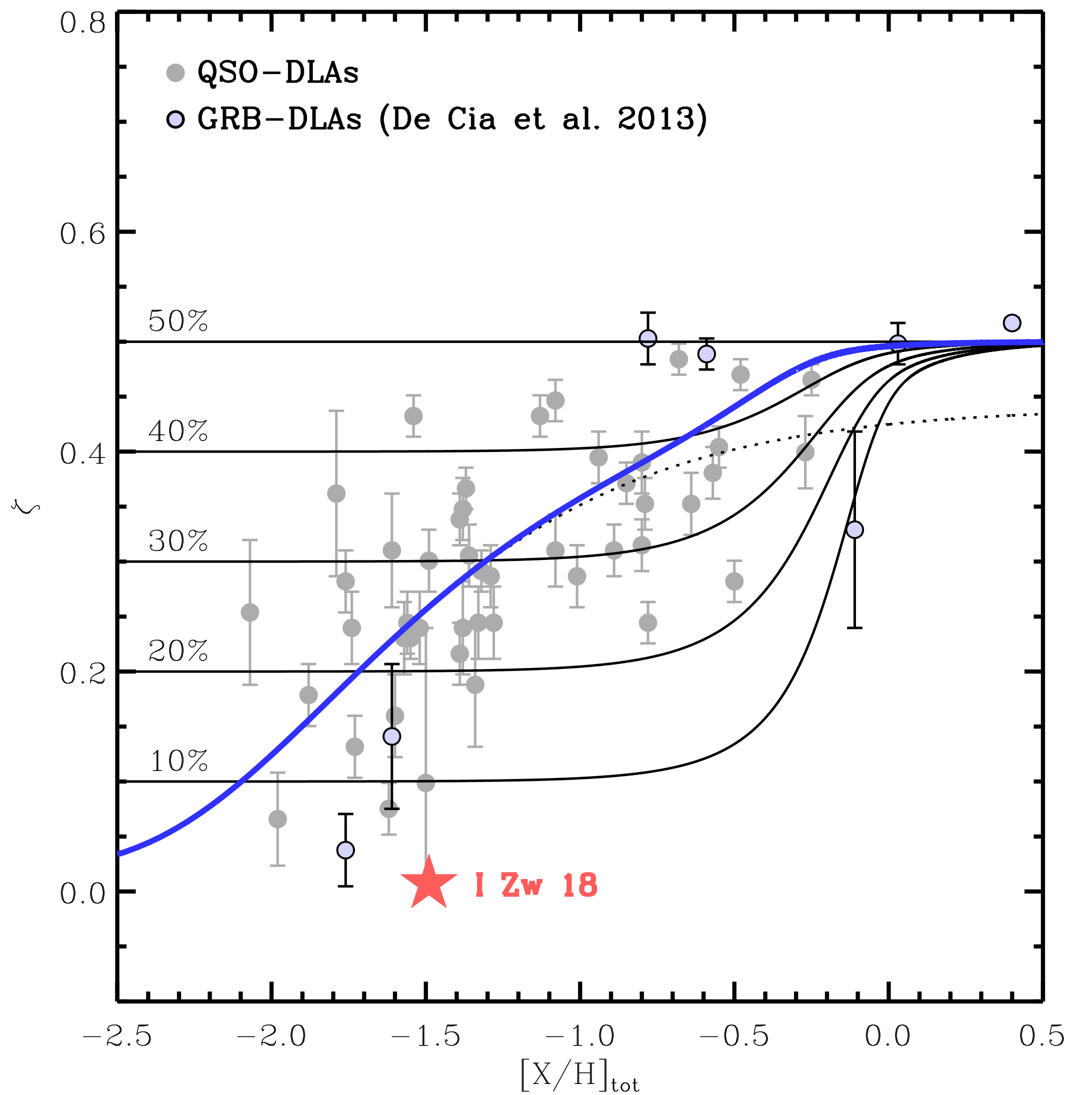
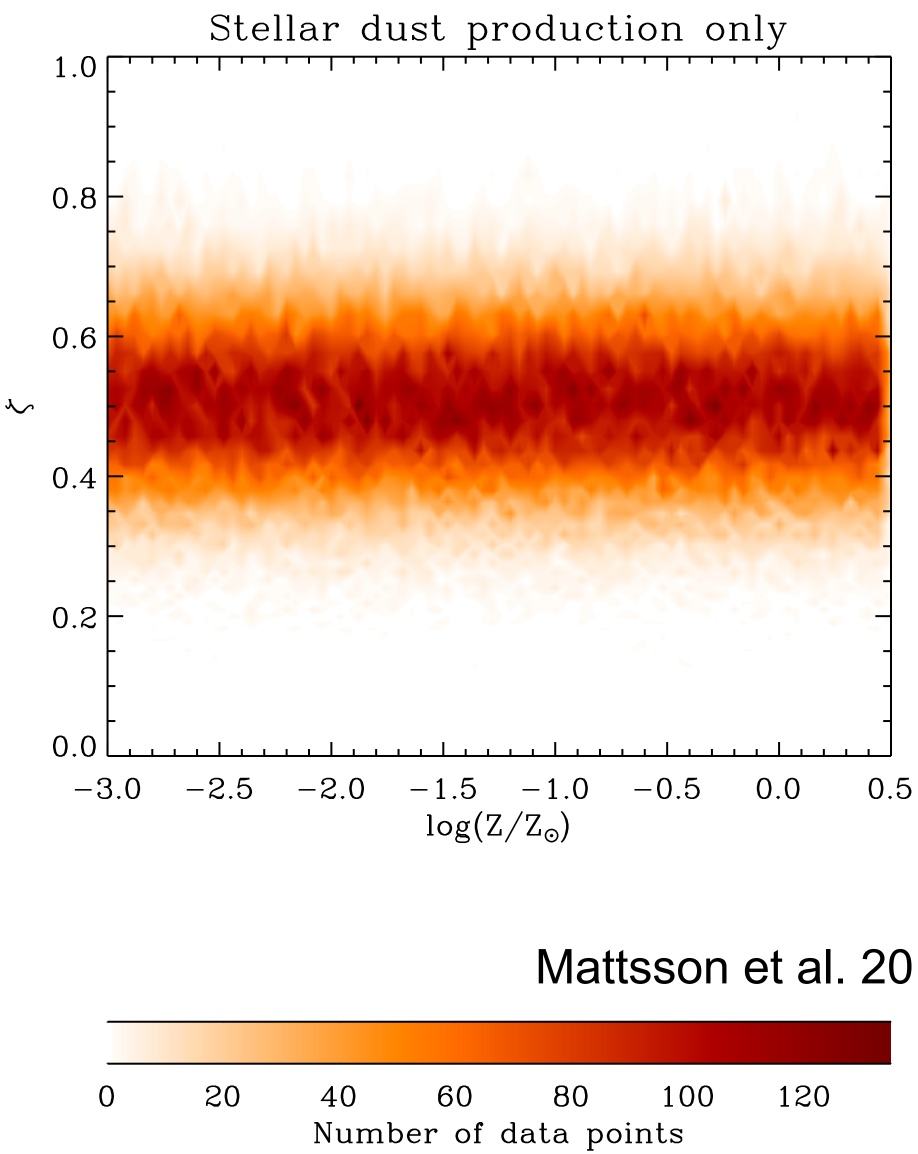
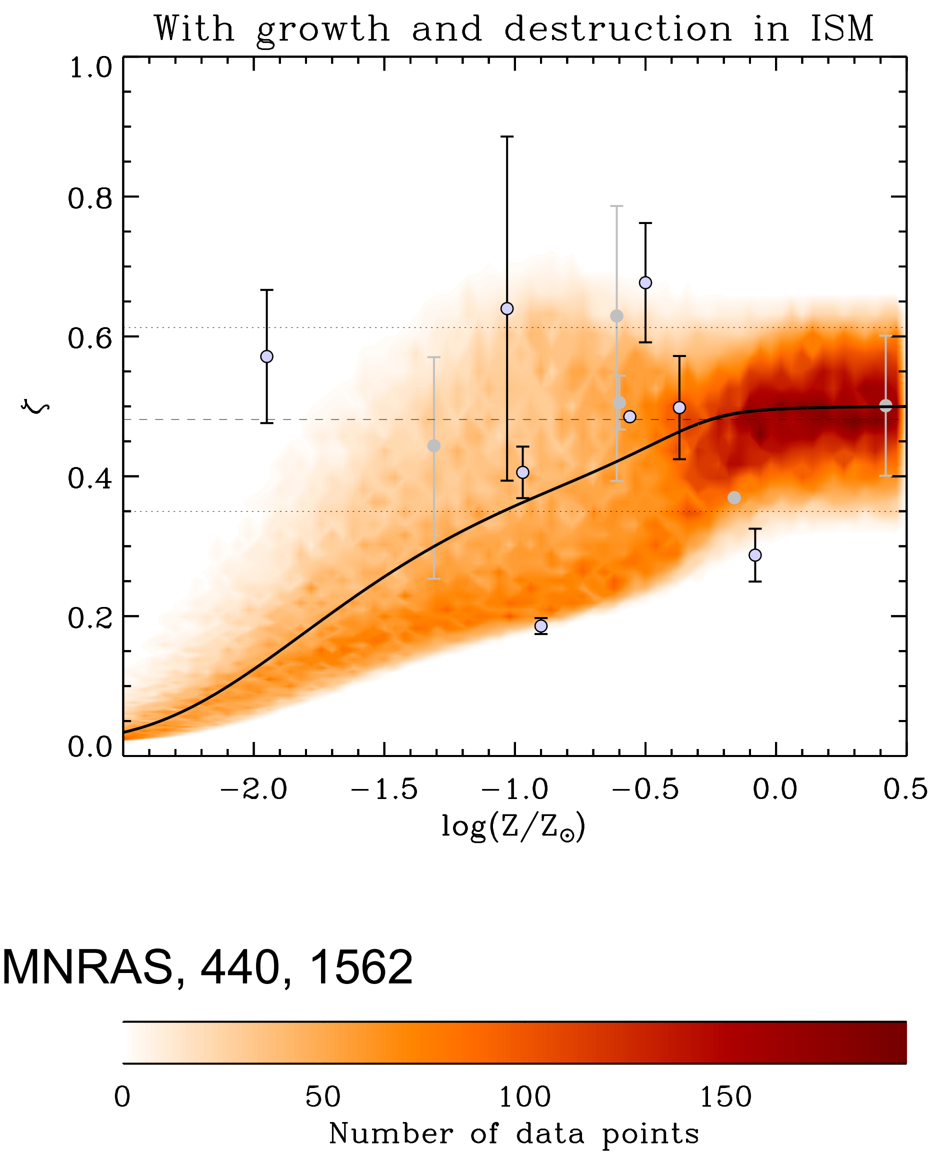
Supernovae: Metallicity dependence needed



Monte Carlo Simulation





Mattsson et al. 2014, MNRAS, 440, 1562

Conclusions, so far…

- Stellar dust production vs. interstellar dust growth is a false dichotomy!
- Supernovae are significant dust producers but the efficiency probably changes with metallicity!
- SN seems a likely stellar source at high z, while AGB stars are minor contributions at best.
- Interstellar dust growth is also important, but stars still need to provide the seeds.

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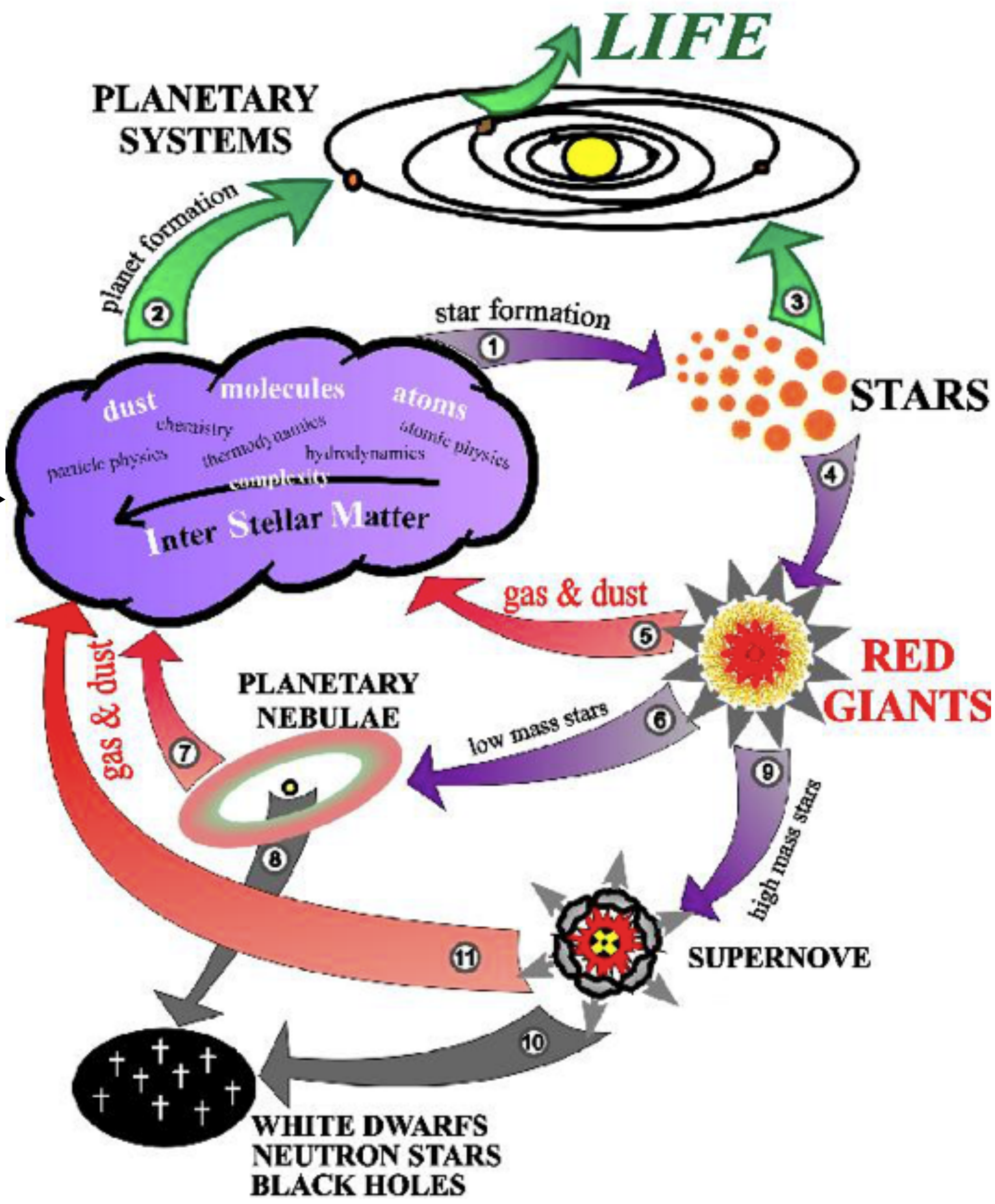
The cosmic matter cycle

Coagulation →



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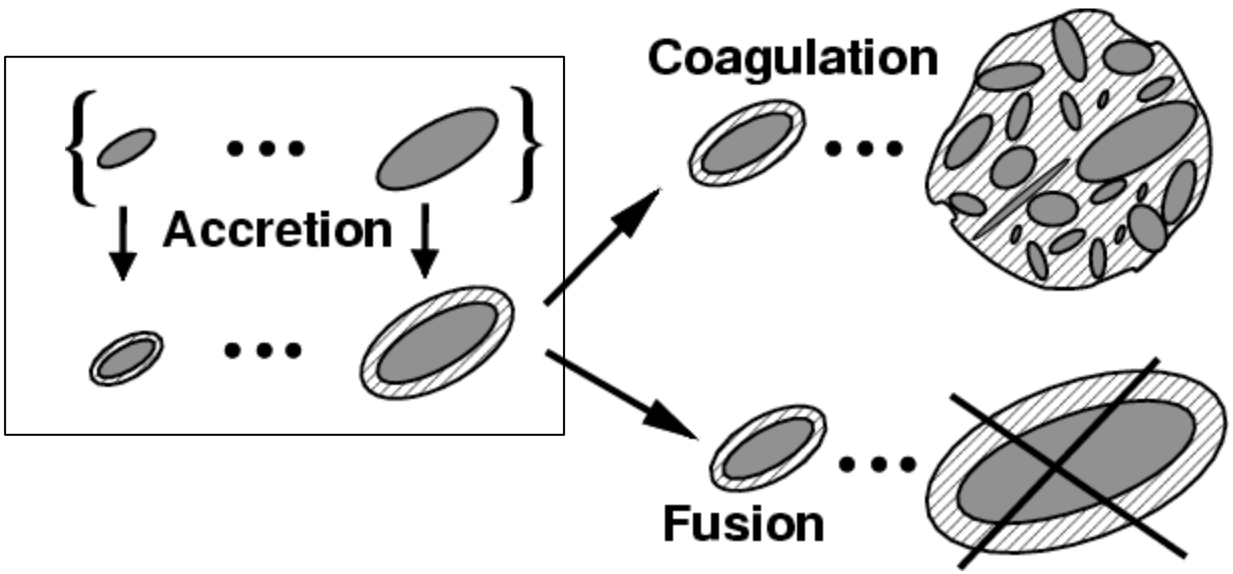
Condensation and coagulation

Condensation equation:

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

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



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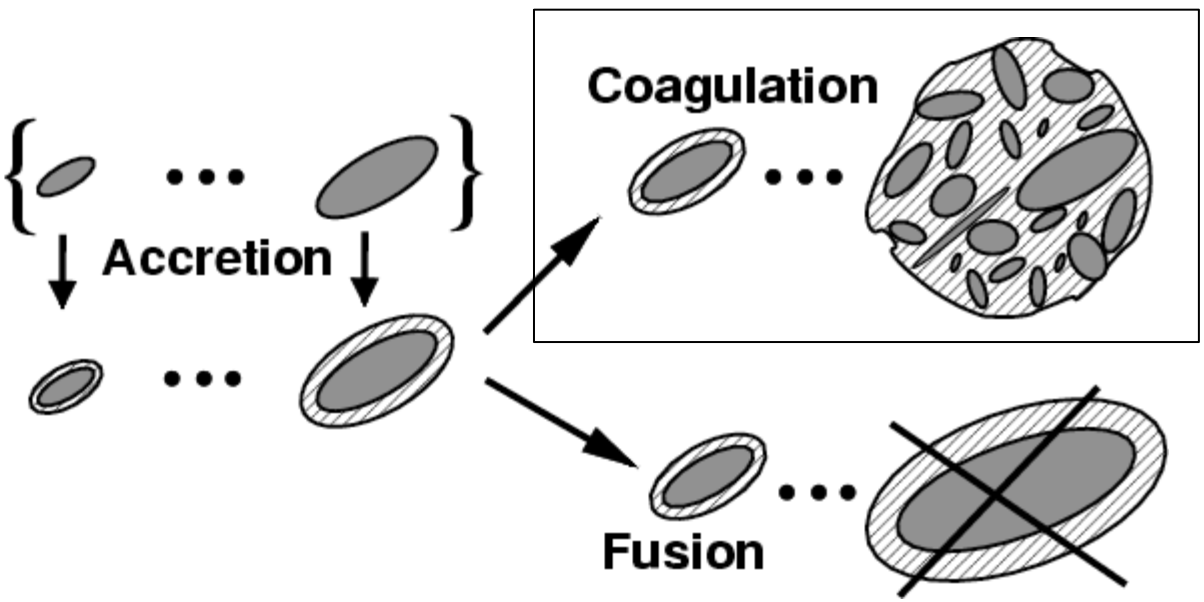
Condensation and coagulation

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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Marian Smoluchowski

(1872 – 1917)

- Found the explanation for Brownian motion in parallel with Einstein. But he got a constant wrong…
- The Svedberg confirmed the erroneous constant with experiments…
- Marian also discovered the “Einstein relation”… but a little too late…
- Derived the coagulation equation… and then he died.

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Condensation and coagulation

- Need to determine sticking probability as a function of other parameters (for both condensation and coagulation).
- What is the correct form of the coagulation kernel?
- What role does the relative gas flow play?
- Gas density fluctuations?
- Drag forces?

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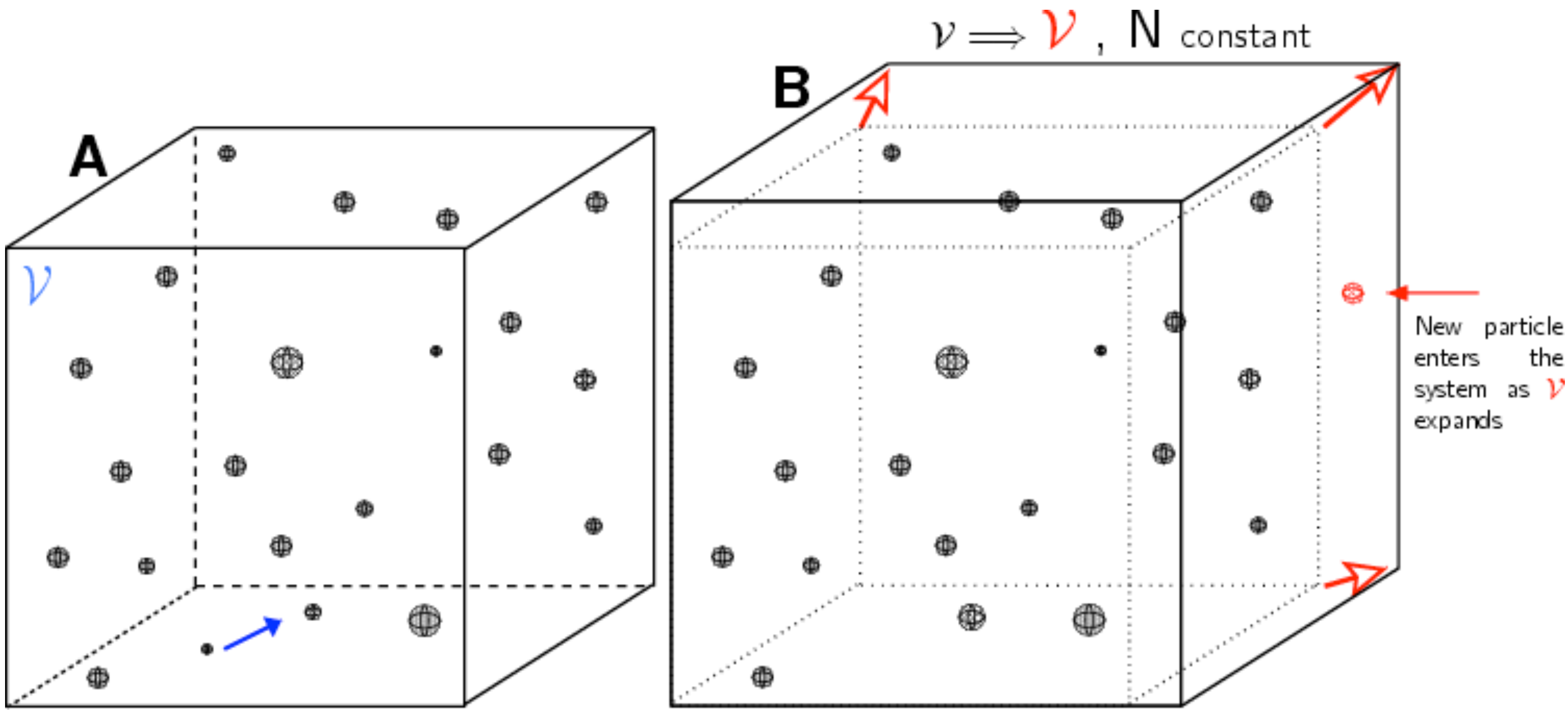
Monte Carlo simulation



Ormel et al. (2007)

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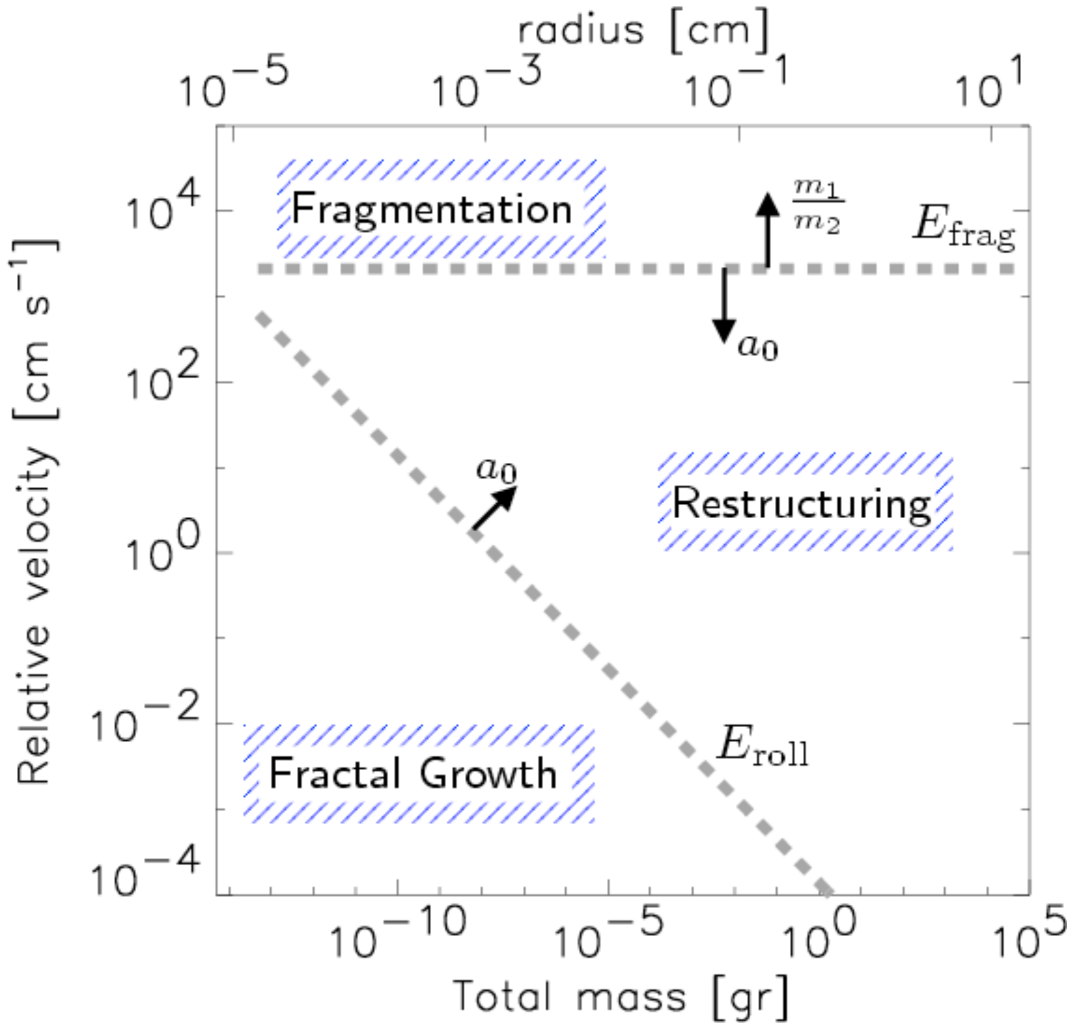
Monte Carlo simulation



The collision regimes as function of total particle mass and relative velocity. Thick dashed lines indicate the critical energies for the onset of rolling and fragmentation. Arrows indicate how the critical energy lines shift with increasing monomer size and mass-ratio.

Bottleneck problems

- Ice-condensation as intermediate step in the formation of planetesimals (e.g. Ros & Johansen 2013).
- The “metal-budget crises” for growing very large dust grains (e.g. in SN remnants).
- Mitra, Wettlaufer & Brandenburg (2013) have demonstrated that “perfect sticking” coagulation aided by turbulent motion lead to phase of runaway growth towards planetesimals.

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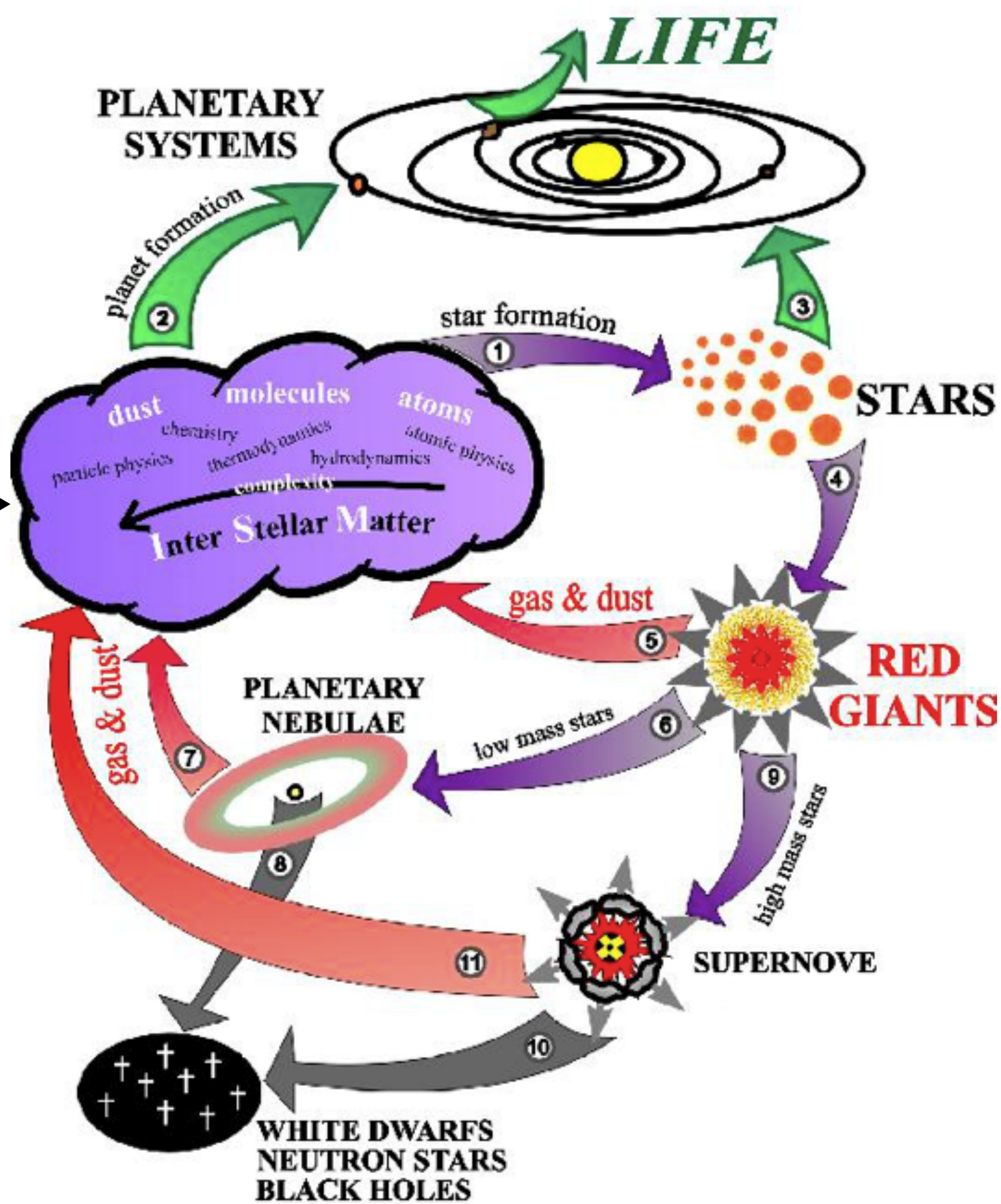
The cosmic matter cycle

Turbulence!



Epstein drag

EOM for a particle:

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

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

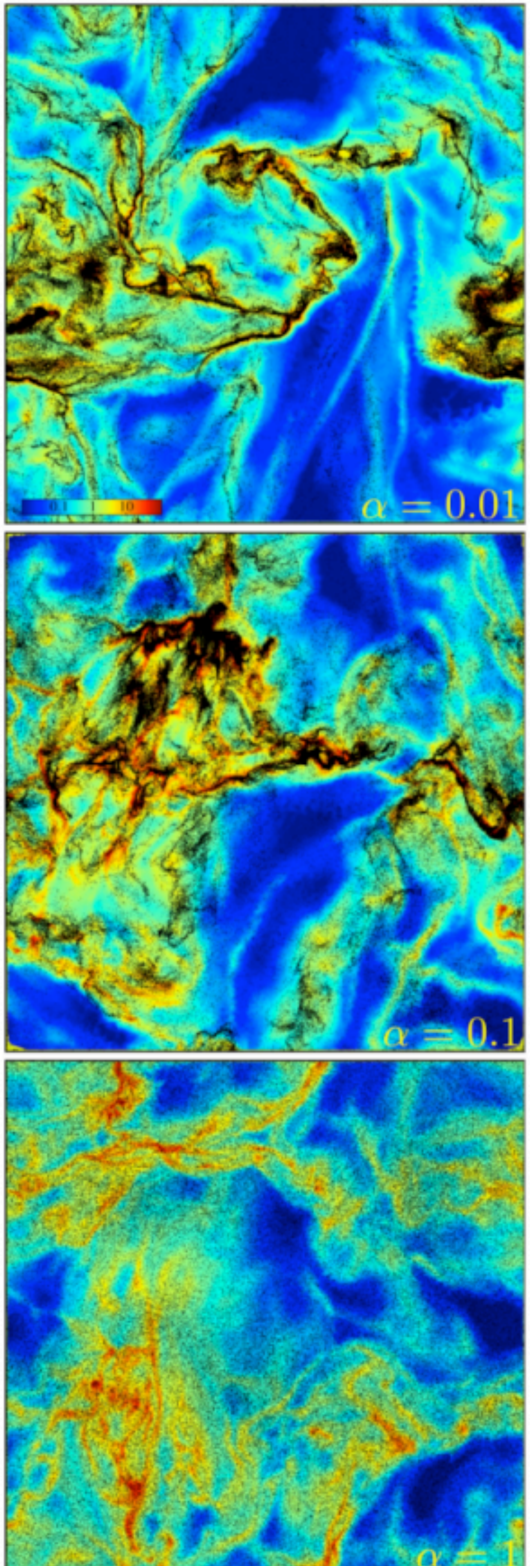
EOM for dust “fluid”:

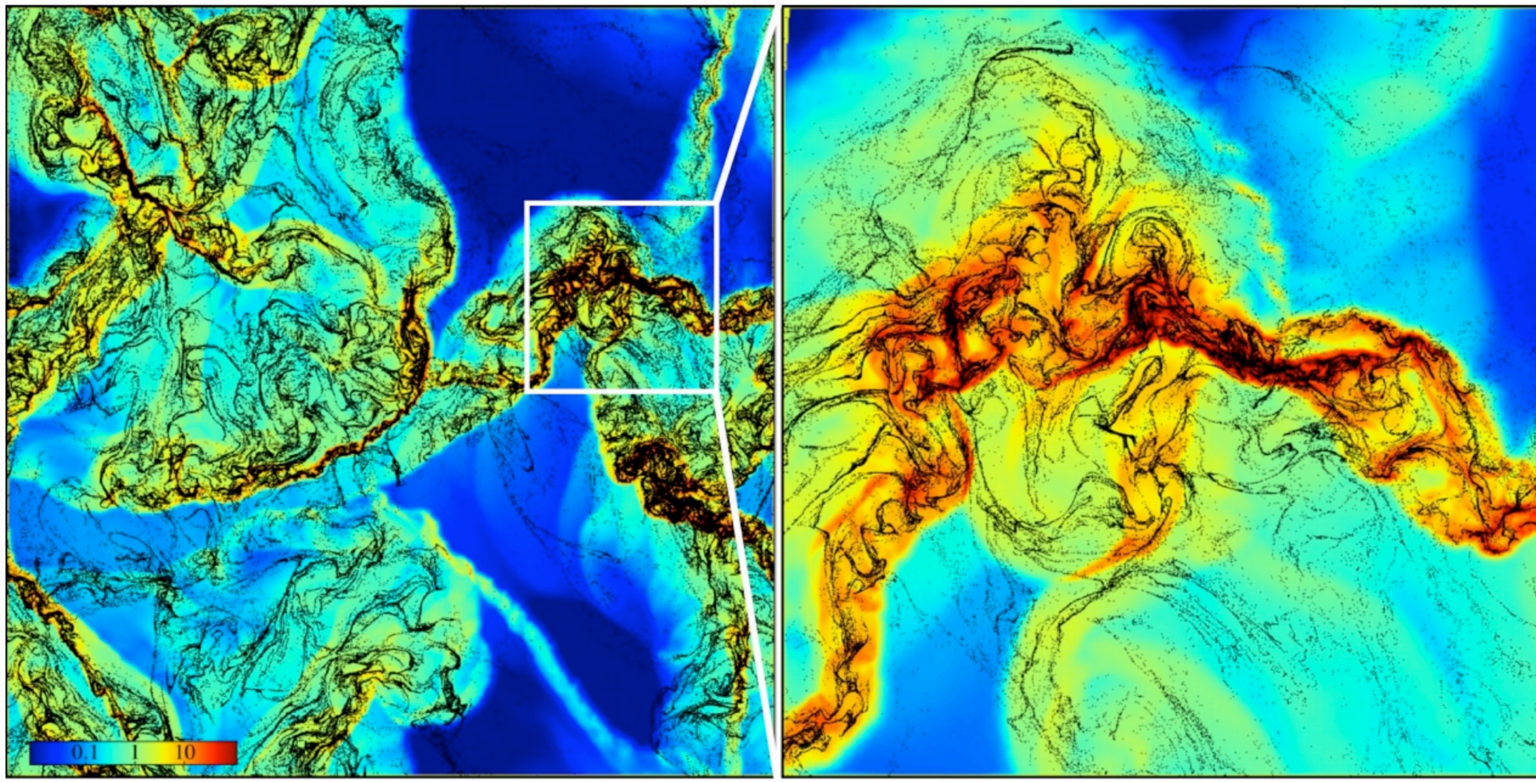
$$\frac{\partial\mathbf{v}_{\mathrm{gr}}}{\partial t} + \mathbf{v}_{\mathrm{d}}\cdot\nabla\mathbf{v}_{\mathrm{gr}} = -\frac{\Delta\mathbf{v}}{\tau_{\mathrm{stop}}}$$

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

However, for ISM simulations one can safely assume the drag is always in the Epstein limit.

Epstein drag





Hopkins & Lee (2016)

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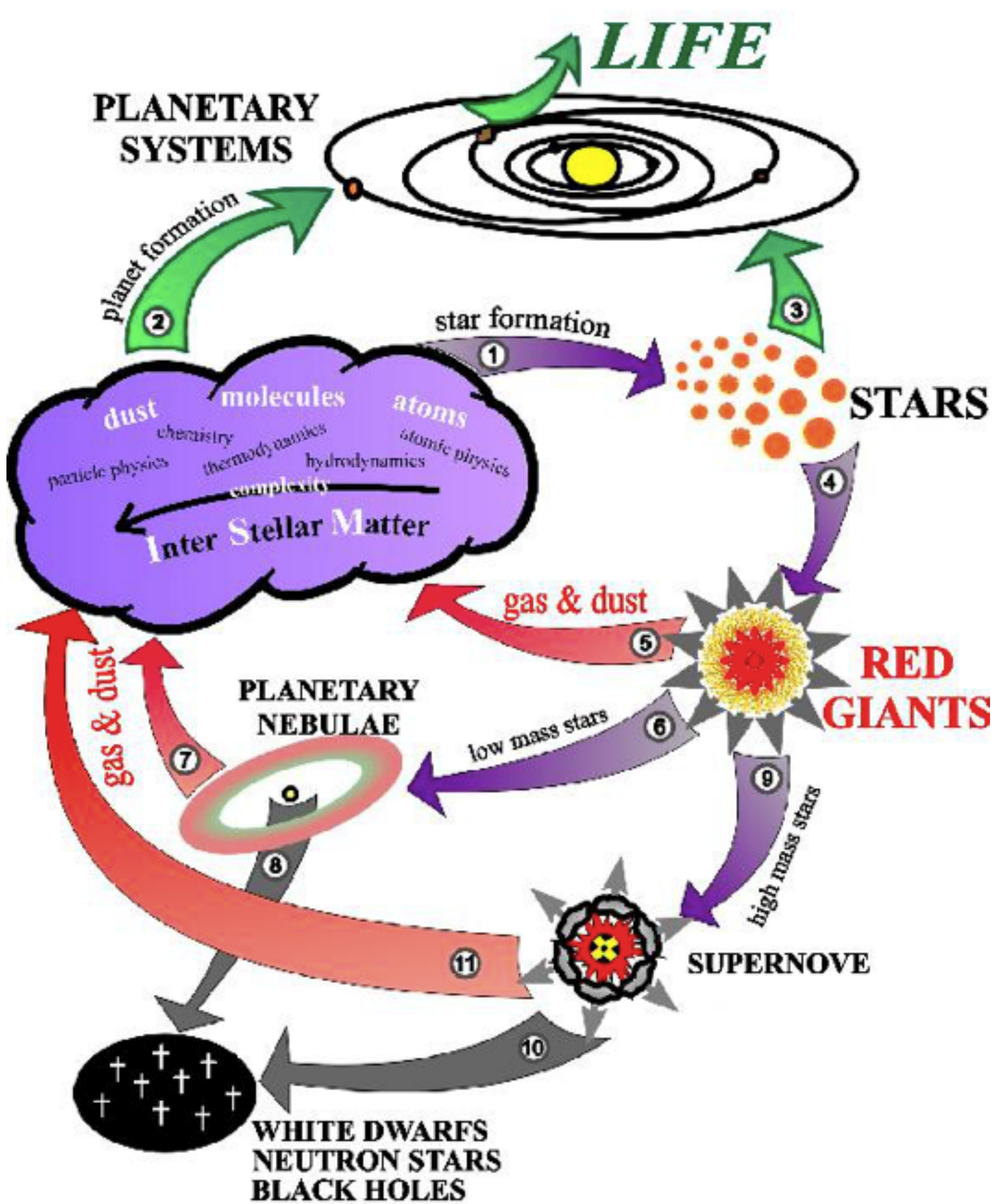
The cosmic matter cycle



Conclusions

- Stars produced the first dust grains, but most of the interstellar dust may have condensed in MCs.
- We now that SNe make a significant contribution, but the exact numbers are very uncertain.
- AGB stars may be least important channel!
- Under all circumstances, interstellar dust condensation is needed as a replenishment mechanism.
- The origins of cosmic dust is a mixed bag. Unfortunately it comes without a declaration of contents…

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