DUST GROWTH AT HIGH REDSHIFT

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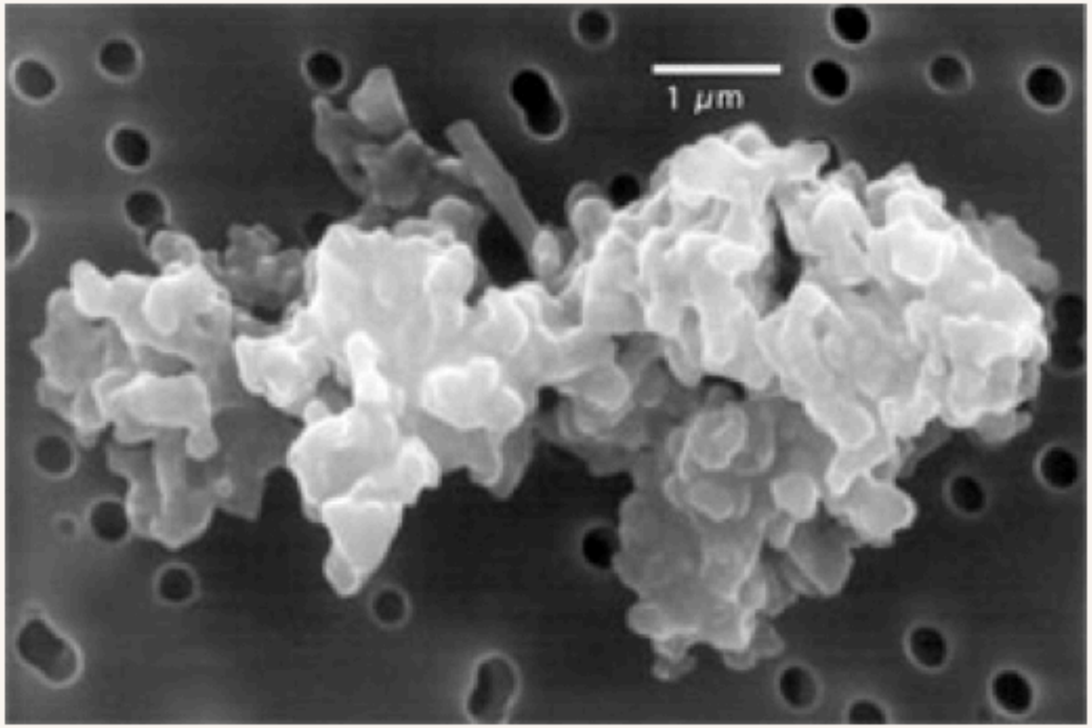
What is interstellar dust ?



A scanning electron microscope image of an interplanetary dust particle. (Courtesy E.K. Jessberger, Institut für Planetologie, and Don Brownlee, University of Washington)

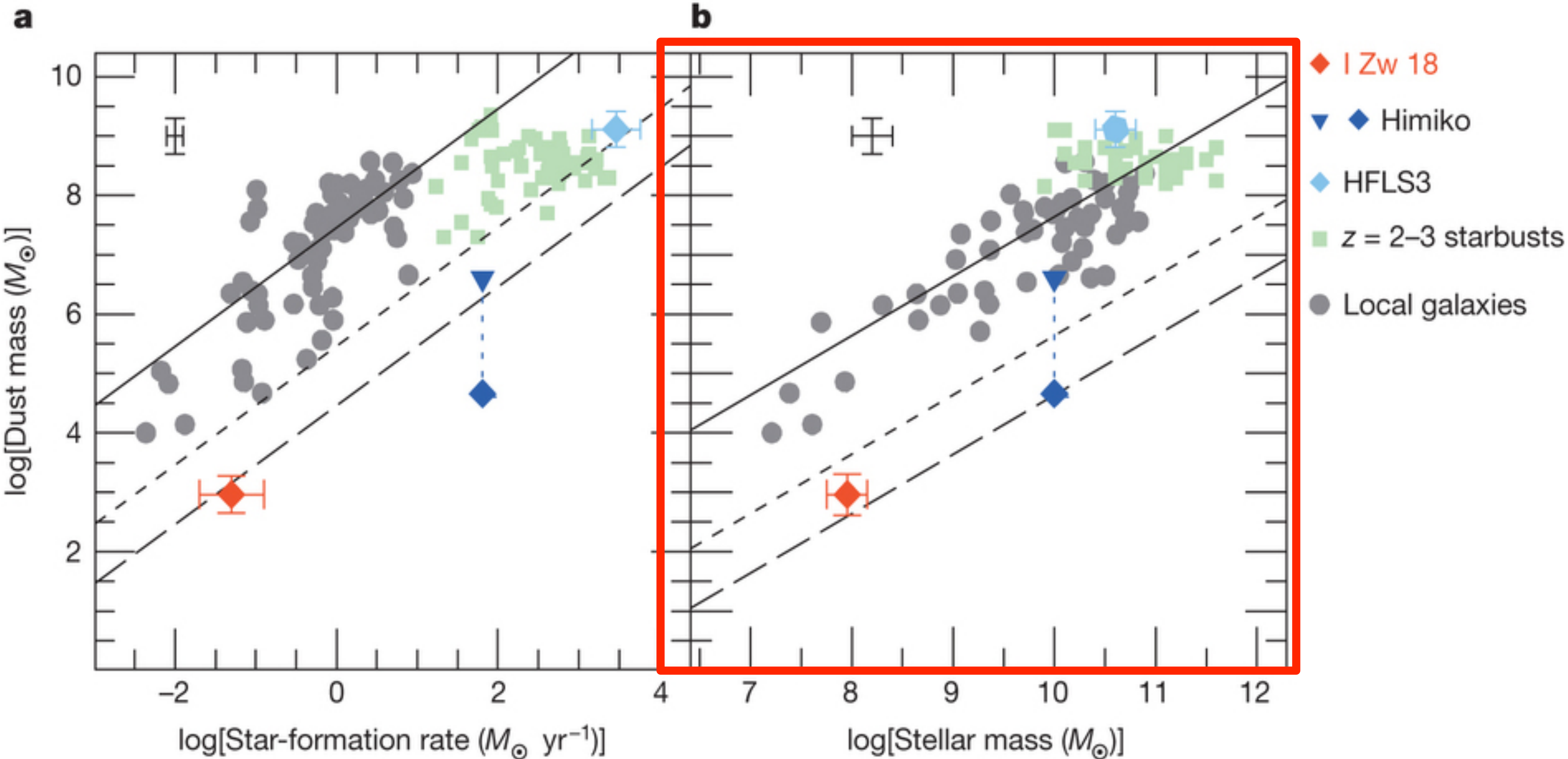
Why care?

- Dust is continuously recycled in galaxies (stars >ISM>molecular clouds>stars)
- Dust grains absorb visible and ultraviolet light which causes them to heat up and radiate in the infrared

Dust in high redshift galaxies

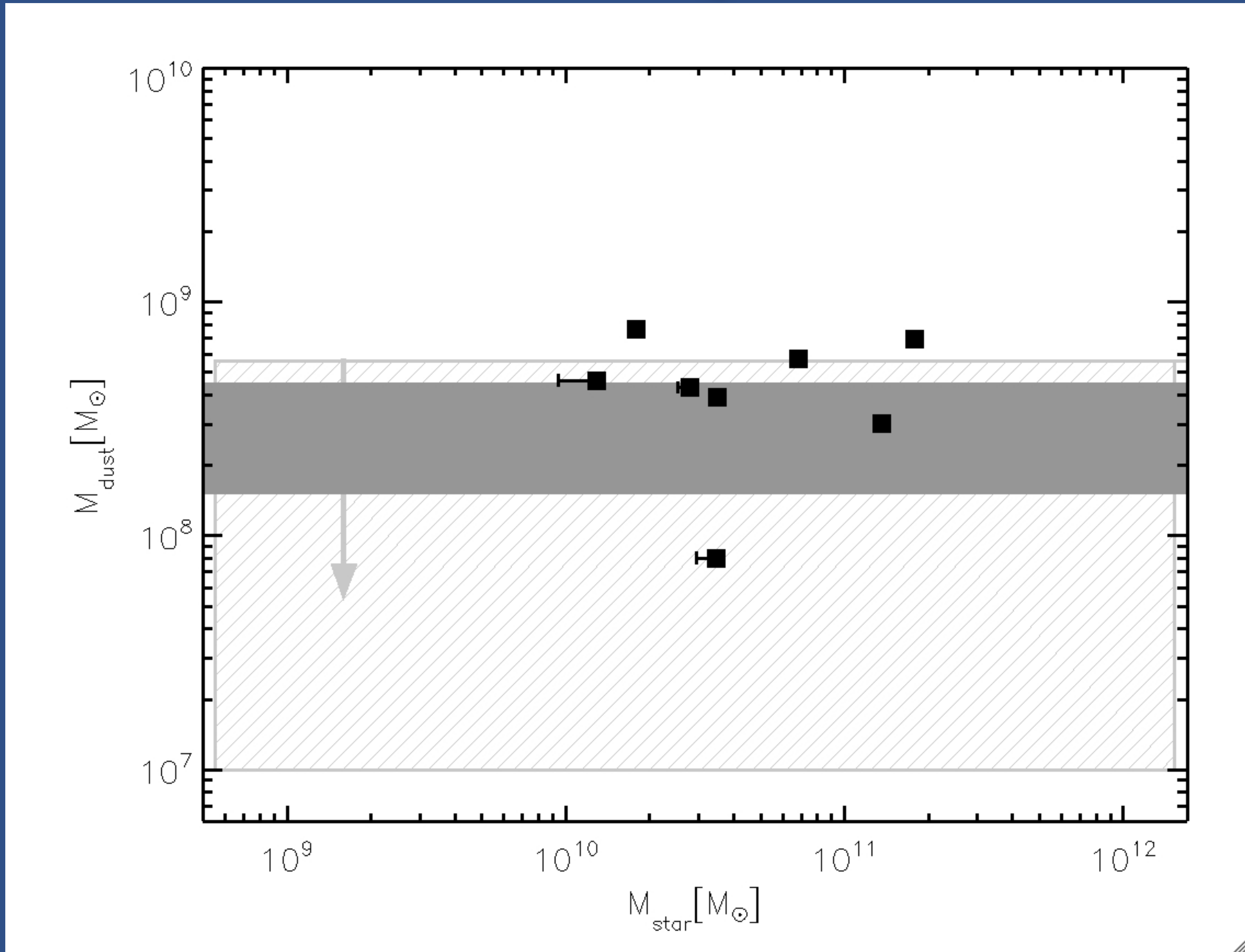
- Recent FIR observations indicate that many QSO hosts at high-*z* contain large amounts of dust ($M_{dust} > 10^8 M_\odot$), larger than in local galaxies
- Such high-*z* systems are also vigorous starbursts (SFR $>10^3 M_\odot$ */yr)*

Dust in high redshift galaxies



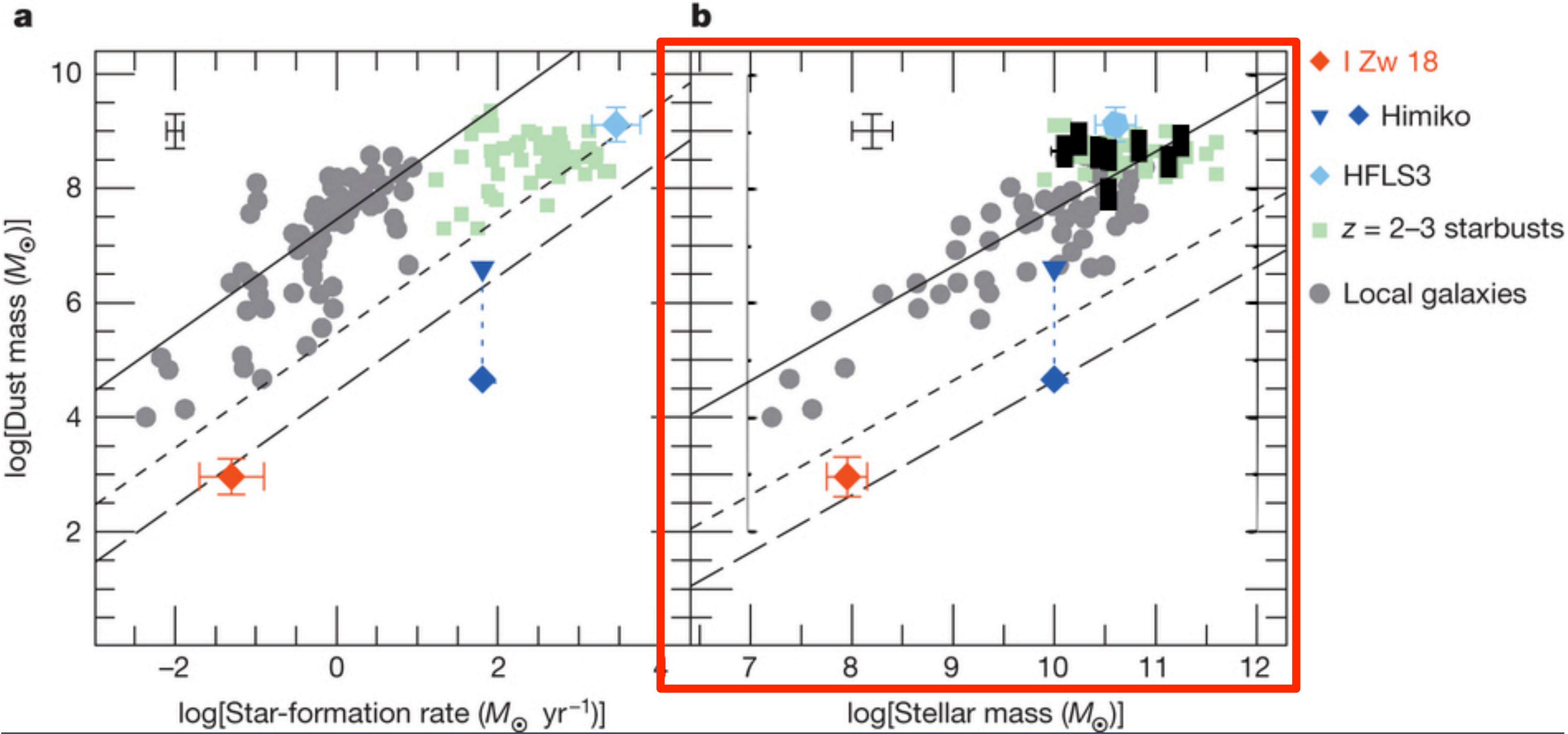
Fisher et al., 2014, Nature, 505, 186

Dust in z>6 QSO hosts



Calura, Gilli, Vignali, et al., 2014, MNRAS, 438, 2765

Dust in high redshift galaxies



Fisher et al., 2014, Nature, 505, 186

Dust in z>6 QSO hosts

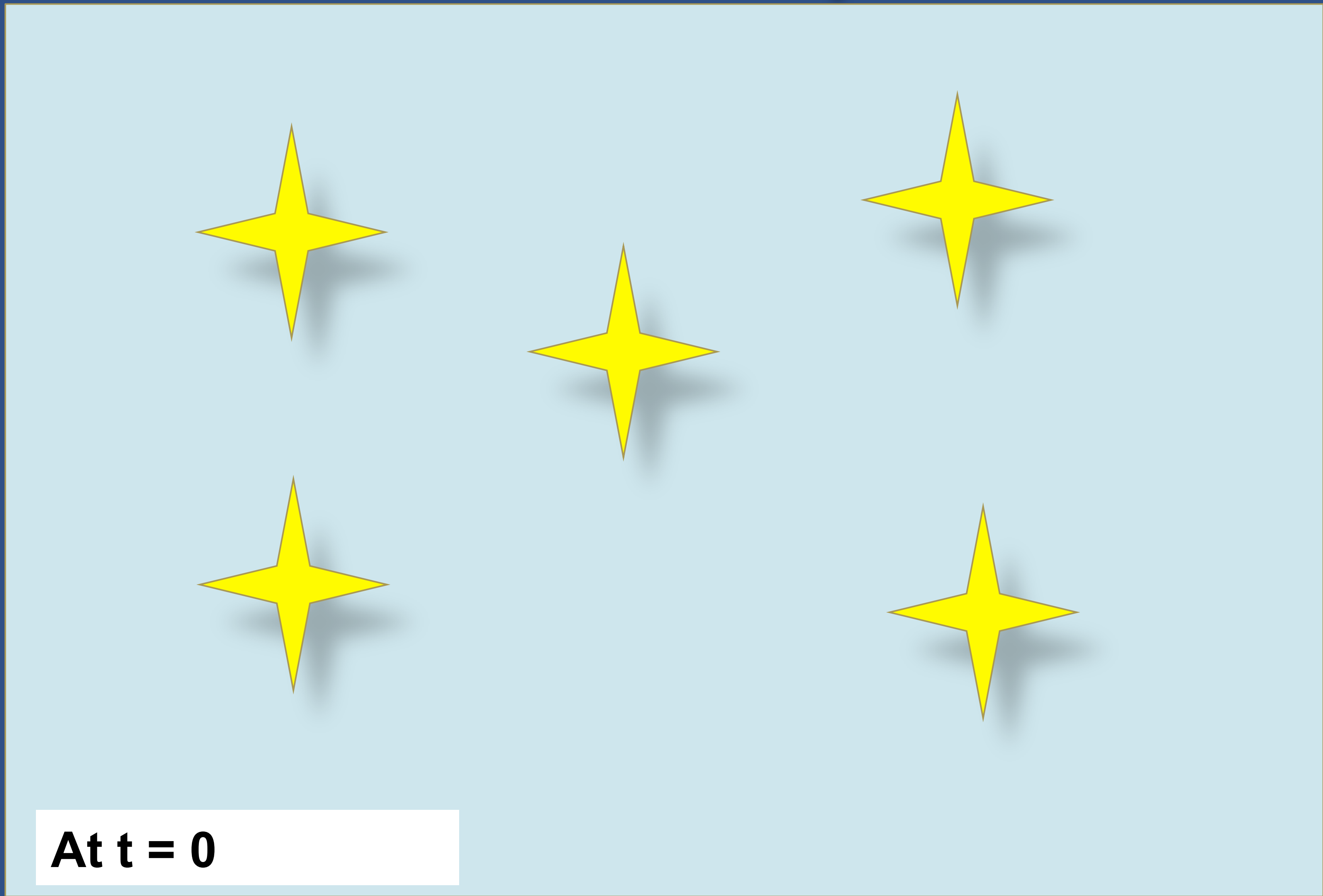
Dust in z>6 QSO hosts

- At z>6 the Universe is ~ 1 Gyr young
- How can the dust mass be accounted for?

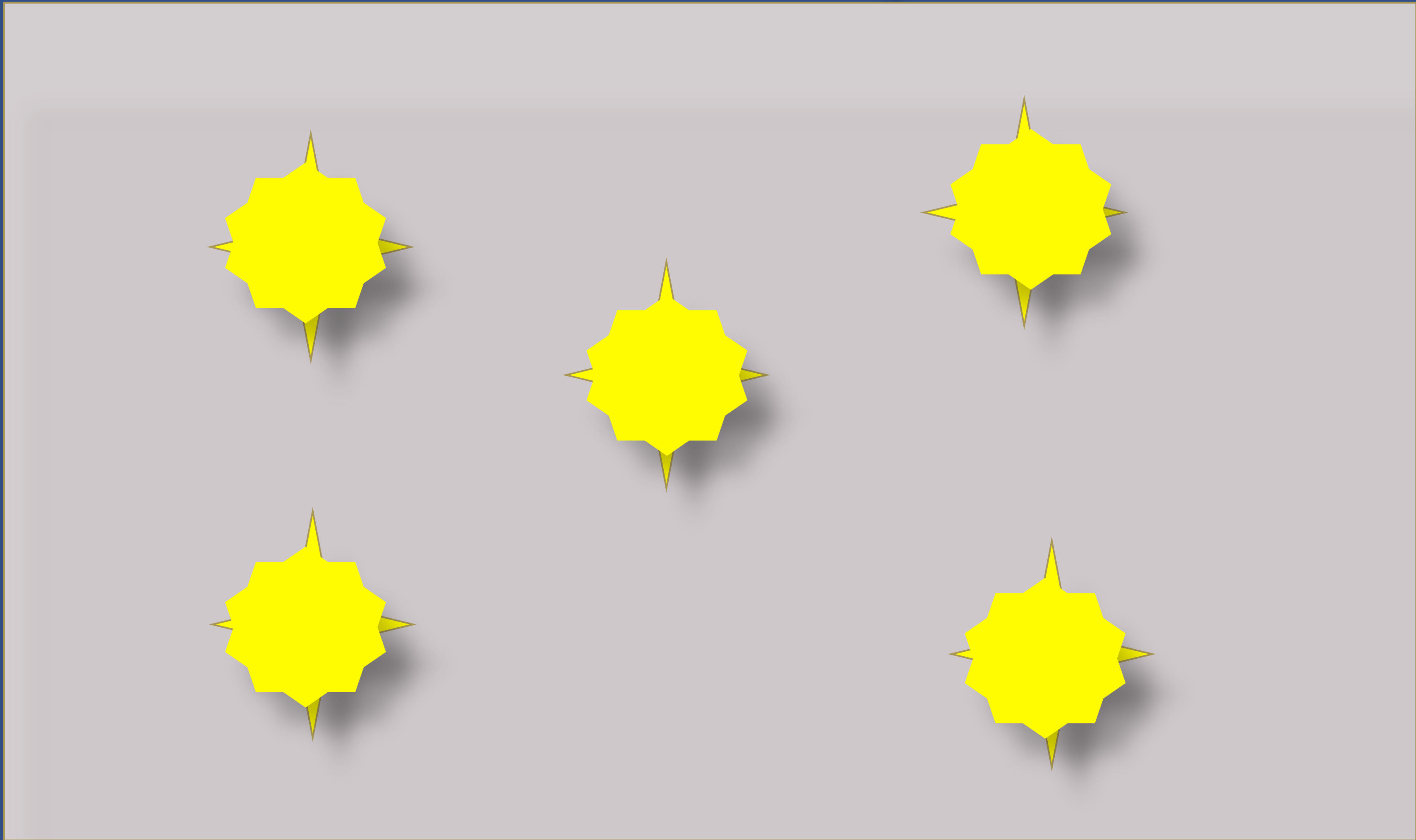
Dust in z>6 QSO hosts

- Massive stars (m> 8 $M_{\odot}$) are the first to die, but weak dust producers (in local SN remnants)
- But Massive stars (as SNe) also destroy dust!
- Also a few AGB stars may play some role
- Another fundamental (but often crudely parametrized in models) process is dust growth in the ISM

A model for dust production

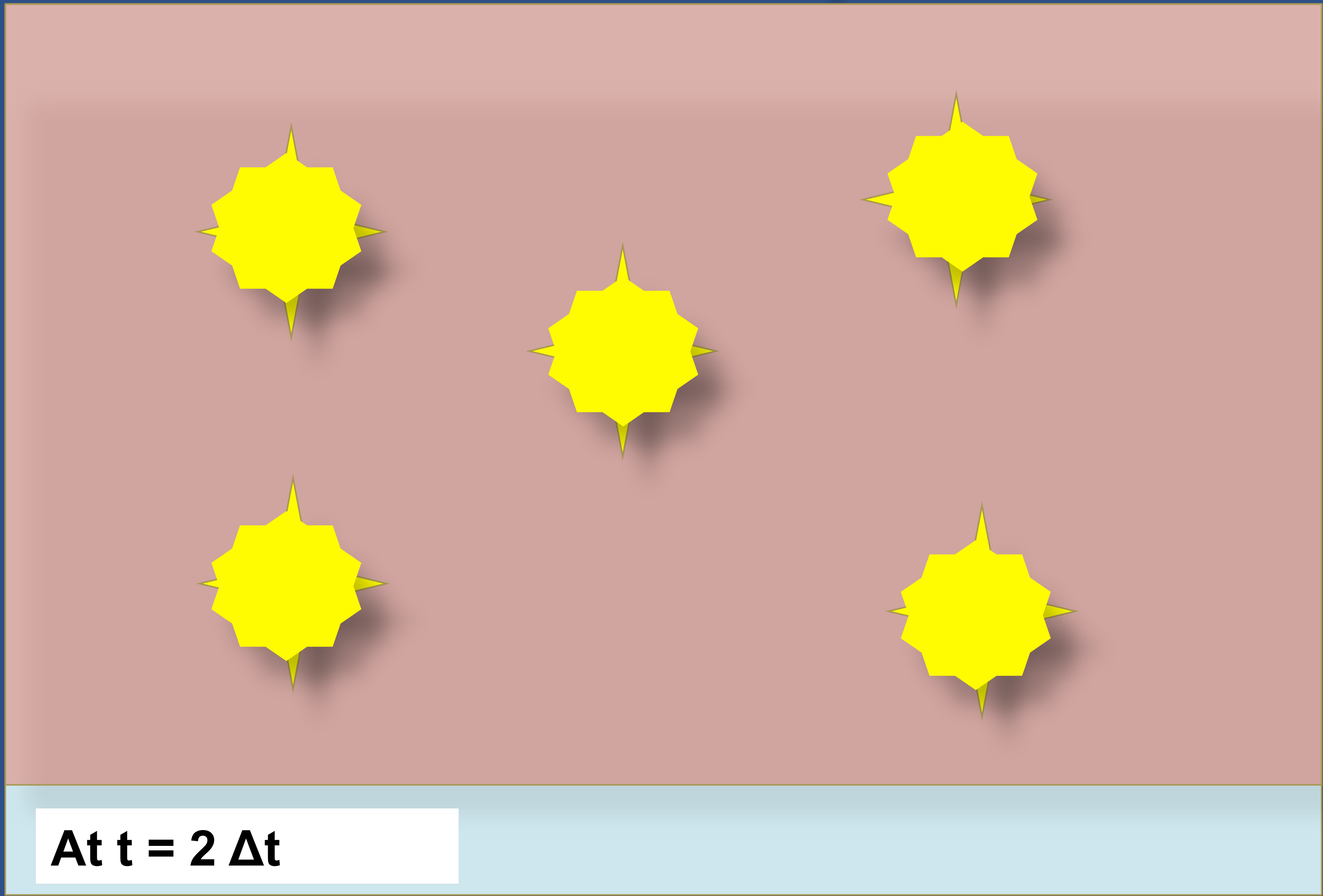


A model for dust production

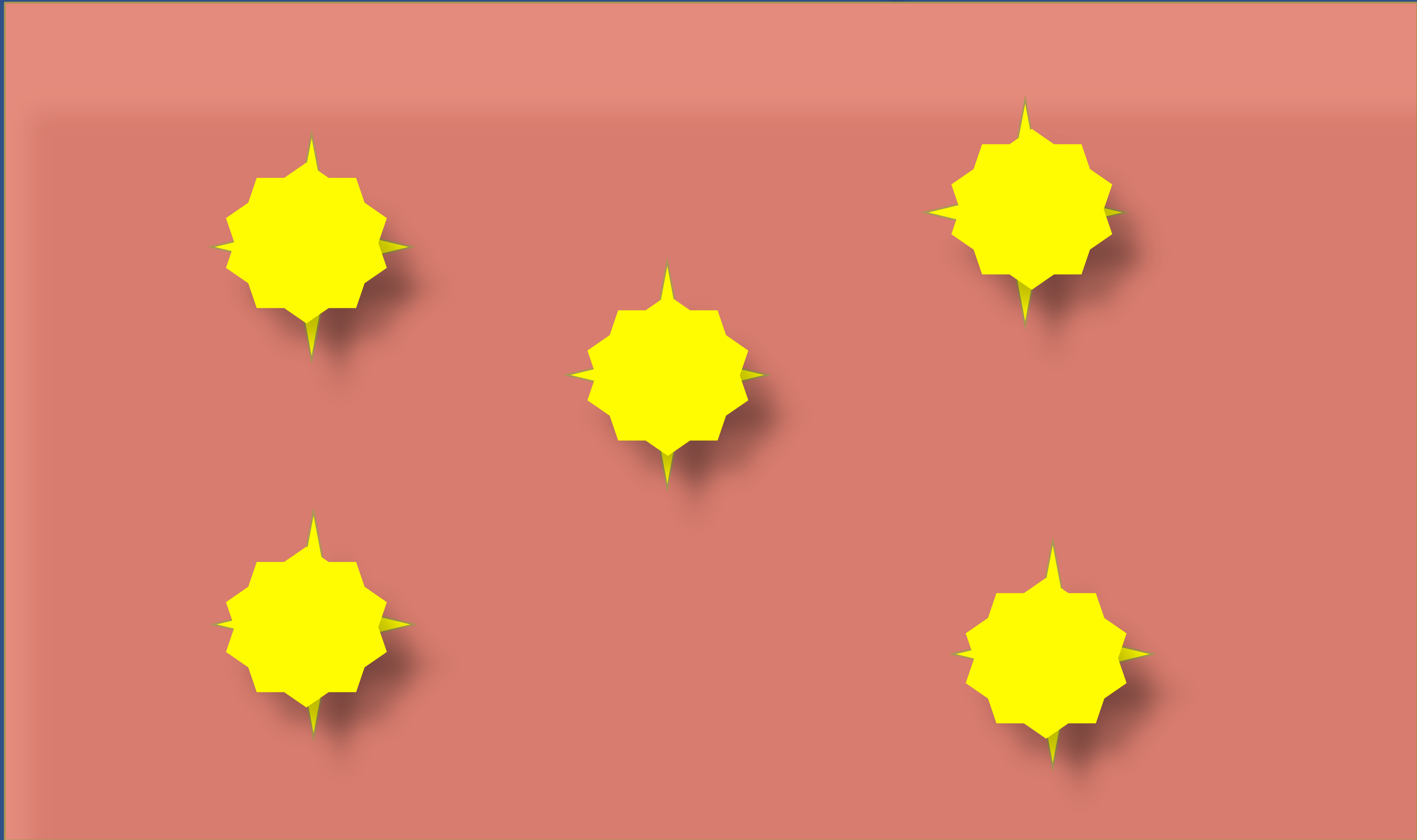


At t = Δt

A model for dust production



A model for dust production



At t = 3 Δt

A model for dust production

Common Refractory elements:

- C
- Si
- Mg
- Fe
- O
- Ca

Basic Quantities

- Star Formation Rate (SFR)

- Stellar Initial Mass function (IMF)

Basic Quantities

- Star Formation Rate $\psi(t)$

  Mass of stars formed btw t and t+**Δ**t

$$[\psi(t)] = M\,T^{-1}$$

Basic Quantities

- Initial Mass Function $\phi(m)$

  Amount of stars formed btw *m* and *m*+*dm*.

In general, normalised as

$$\int_{M_0}^{M_\infty} m\,\phi(m)\,dm = 1$$

$$M_0 \sim 0.1 M_\odot$$

$$M_\infty \sim 100 M_\odot$$

A model for dust production

$\sigma_{d,i}(t)$ is the mass density in dust at time t

Dust Mass fraction: $$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

Initial condition: $$\sigma_{d,i}(t=0) = 0$$

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} =$$

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} = -\psi(t) X_{d,i}(t)$$

Astration (AKA Star Formation)

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} = -\psi(t) X_{d,i}(t) + R_{*,d,i}(t)$$

Stardust production

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} = -\psi(t)X_{d,i}(t) + R_{*,d,i}(t) - \frac{\sigma_{d,i}(t)}{\tau_{dest}} +$$

Dust Destruction

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} = -\psi(t) X_{d,i}(t) + R_{*,d,i}(t) - \frac{\sigma_{d,i}(t)}{\tau_{dest}} +$$

$$+ \frac{\sigma_{d,i}(t)}{\tau_{acc}}$$

Dust Growth or Accretion

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} = -\psi(t)X_{d,i}(t) + R_{*,d,i}(t) - \frac{\sigma_{d,i}(t)}{\tau_{dest}} +$$

$$+\frac{\sigma_{d,i}(t)}{\tau_{acc}} + (\dot{\sigma}_{d,i})_{inf}$$

Infall (commonly zero)

A model for dust production

$$X_{d,i}(t) = \frac{\sigma_{d,i}(t)}{\sigma_{gas}(t)}$$

$$\dot{\sigma}_{d,i} = -\psi(t)X_{d,i}(t) + R_{*,d,i}(t) - \frac{\sigma_{d,i}(t)}{\tau_{dest}} +$$

$$+\frac{\sigma_{d,i}(t)}{\tau_{acc}} + (\dot{\sigma}_{d,i})_{inf} - (\dot{\sigma}_{d,i})_{out}$$

Outflow

Stardust production

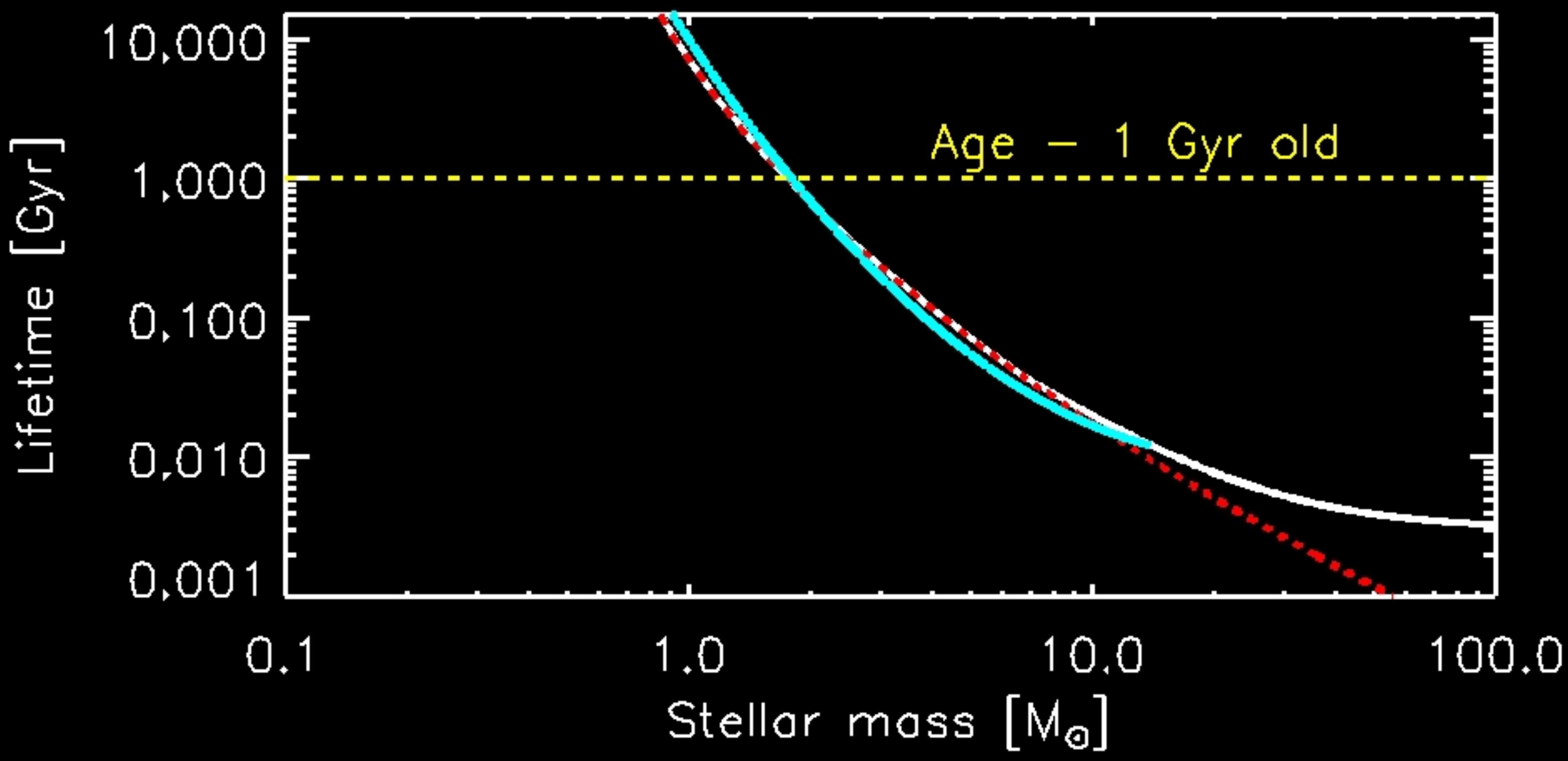
$$R_{*,d,i}(t) = \int_{m_{min,t}}^{100M_\odot} \psi(t-\tau_m) Yield_d(m) \phi(m) dm$$

Dwek 1998, ApJ, 501, 643

Calura et al., 2008, A&A, 479, 669

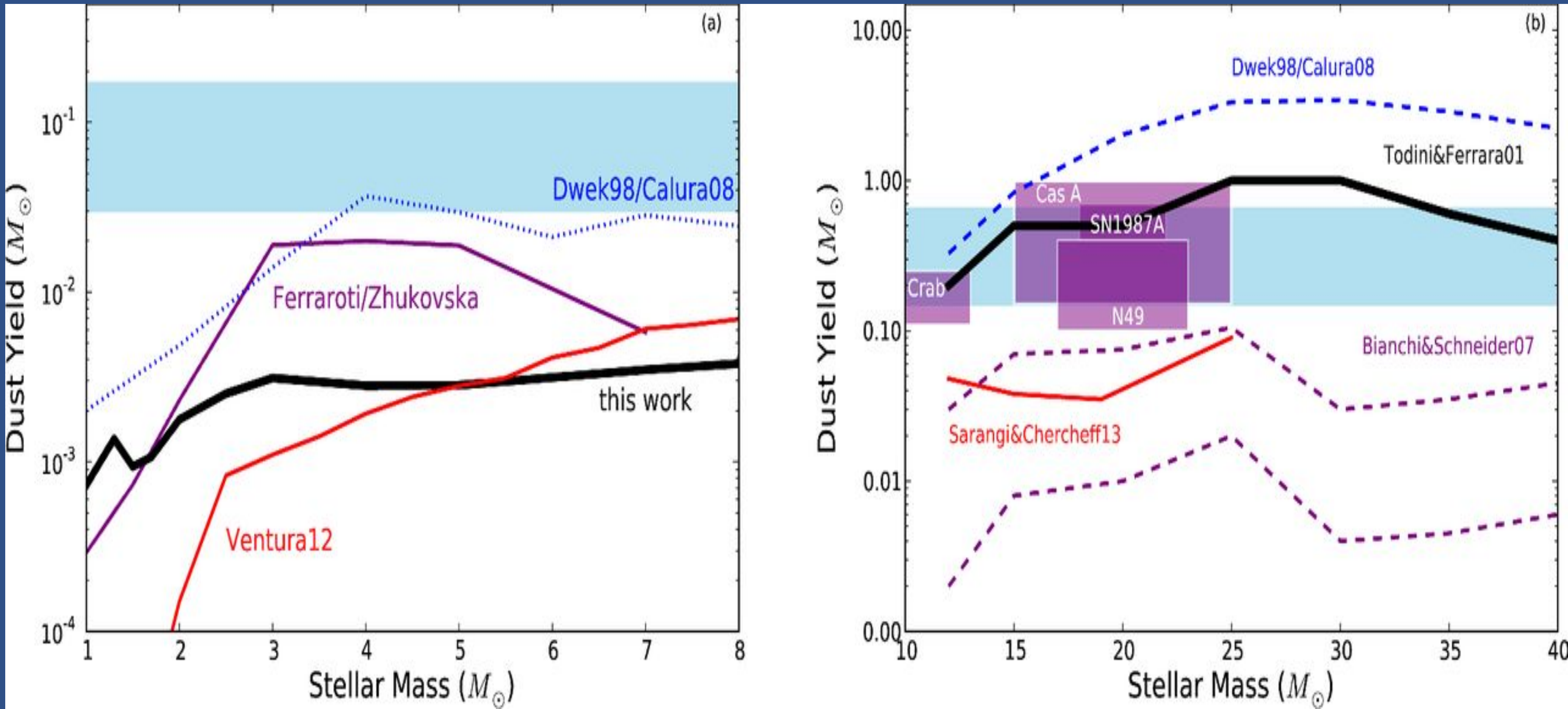
Stardust production

$$R_{*,d,i}(t)$$



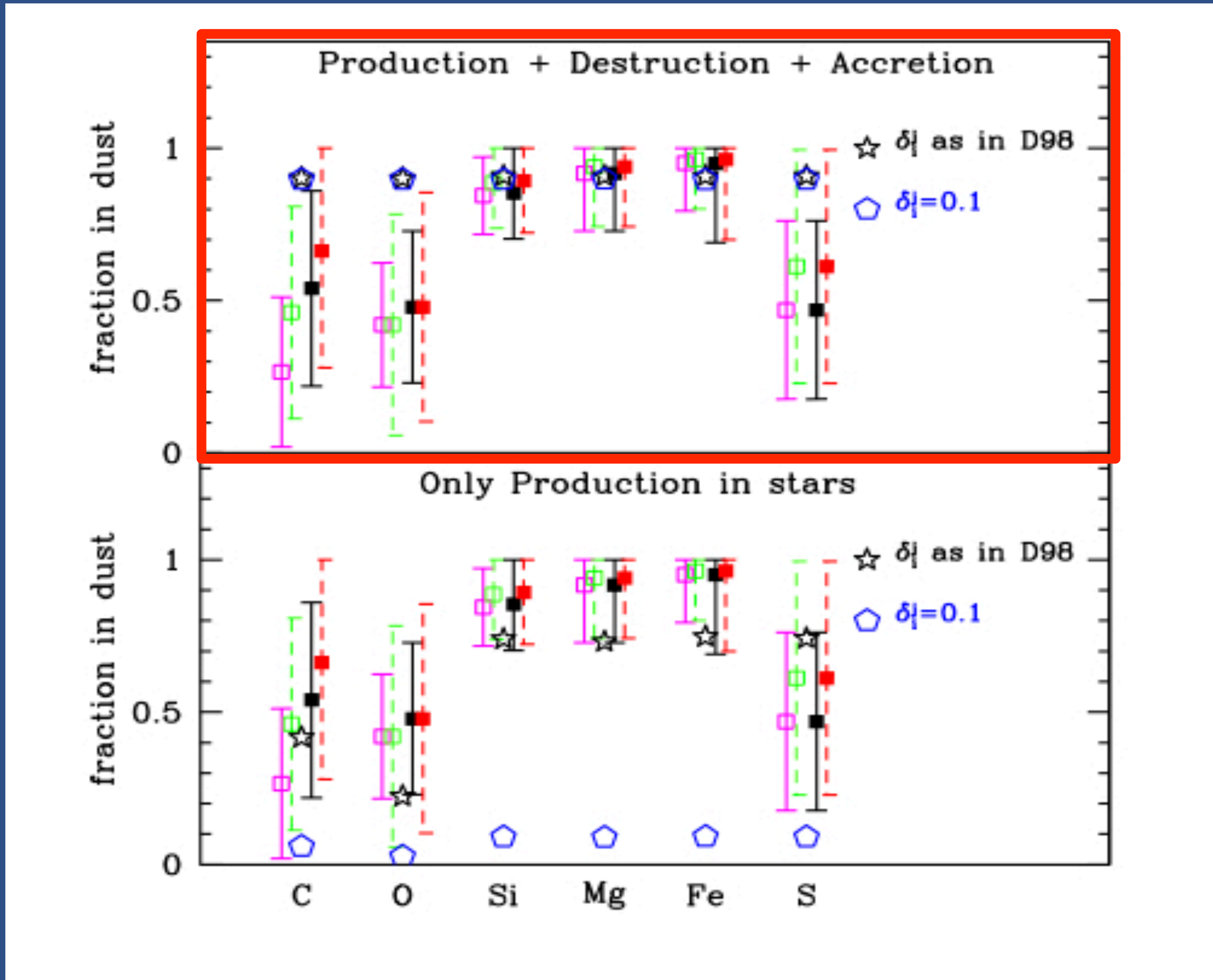
Stardust production

Dust yields vs stellar mass



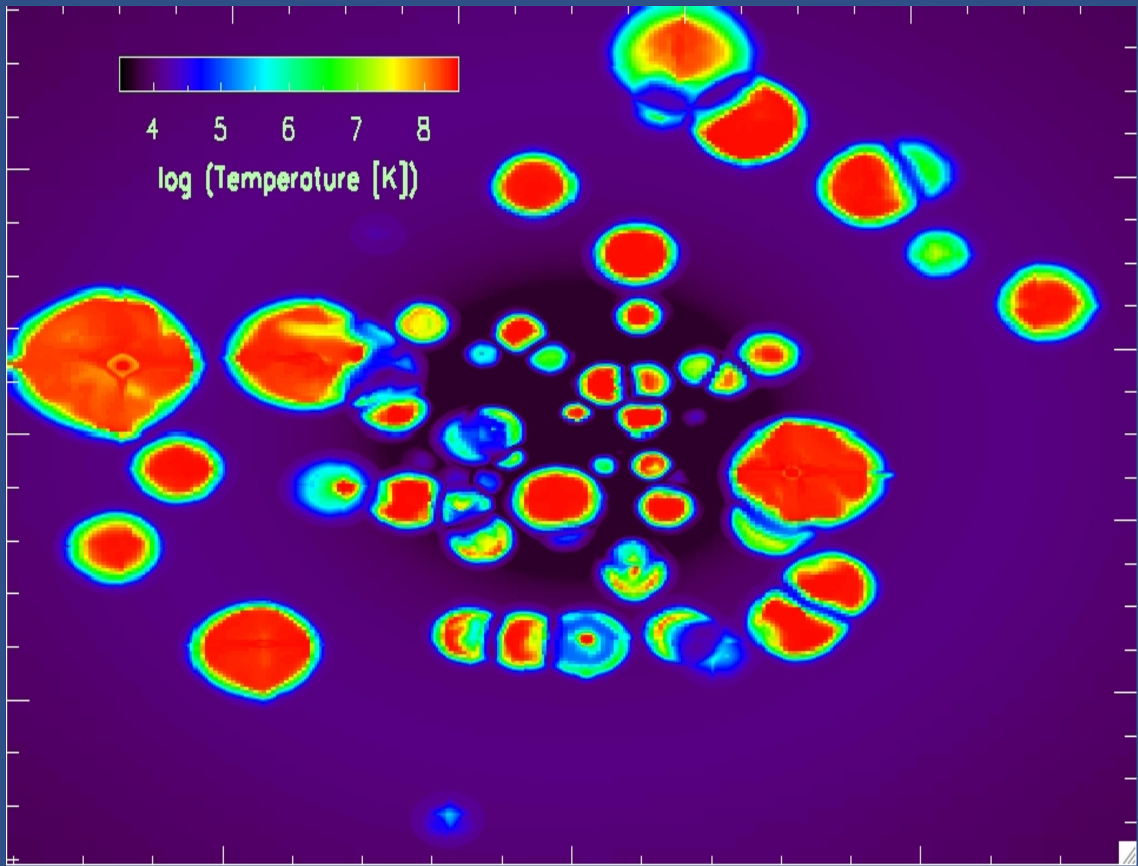
Rowlands et al., 2014, MNRAS, 441, 1040

Stardust production



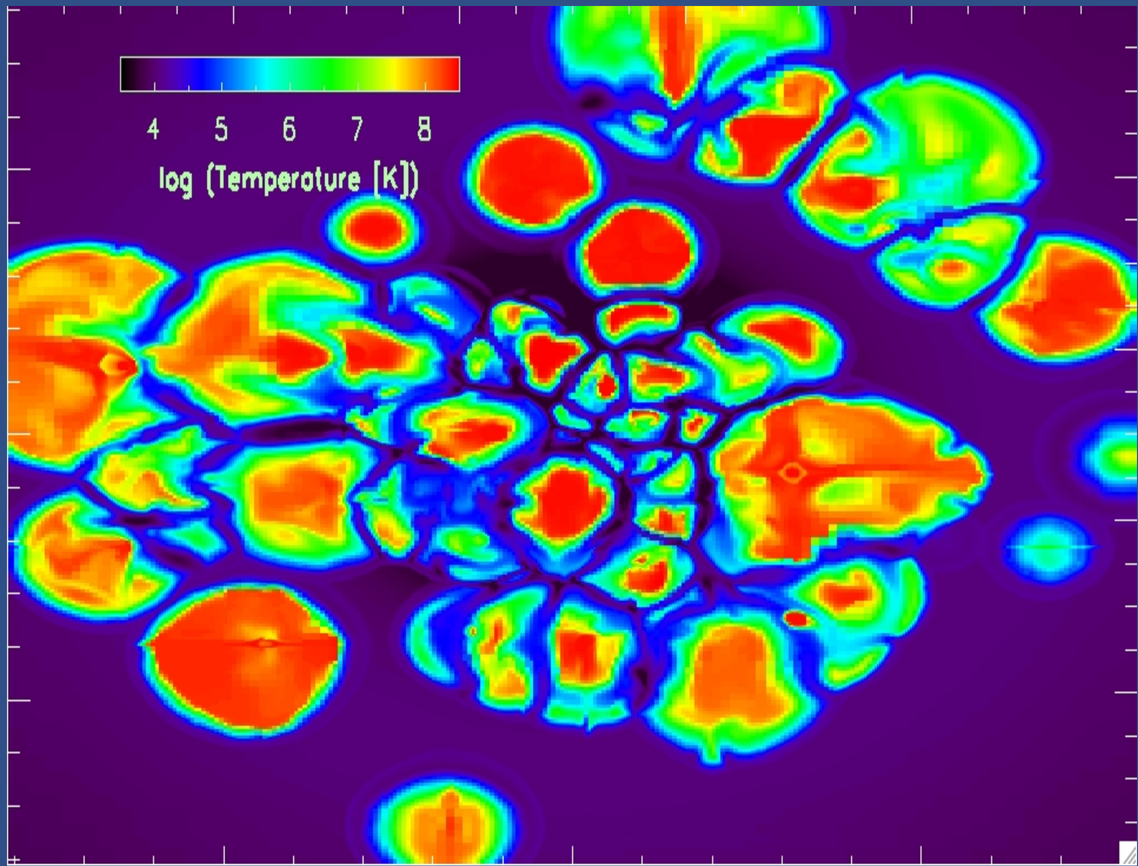
- The dust Yield is loosely constrained (FC+08)

Dust Destruction



It occurs in SN shocks (high Temperatures and high gas/grains velocities)

Dust Destruction



It occurs in SN shocks (high Temperatures and high gas/ grains velocities)

Dust Destruction

Main destruction mechanisms:

- Dust Sputtering (collisions w/ ions)
- Dust Shattering (grain vs grain coll.)

Essentially, the grain material is restored into the ISM (metal enrichment)

Dust Destruction

The process is described by the quantity

$$\tau_{dest} \propto \epsilon M_{SNR}\, R_{SNe}^{-1}$$

R_{SNe} is the SN rate

$$\epsilon M_{SNR} \simeq 1400 M_{\odot}$$

McKee 1989; Dwek 1998

Dust Growth

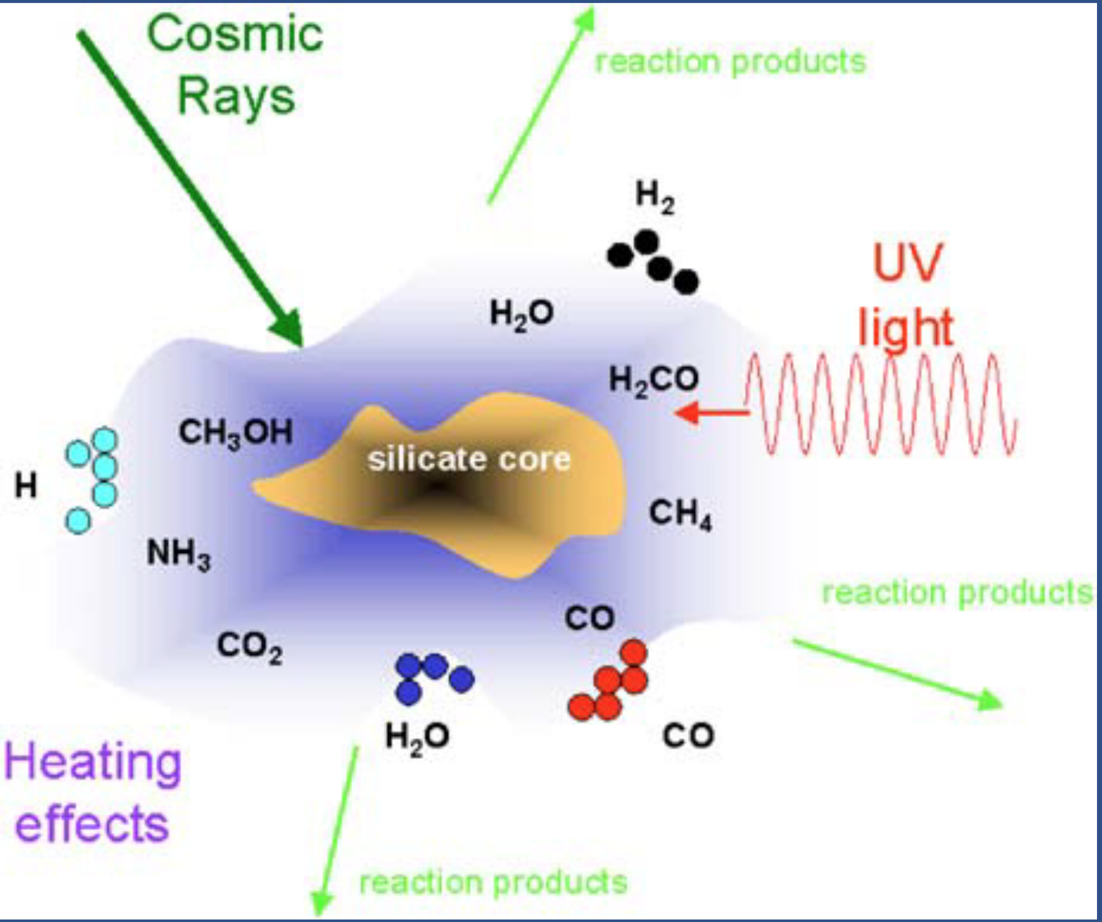
After a dust ‘core’ is produced by stars:

- It can accrete more refractory material

- It can grow an organic ‘mantle’ in molecular clouds

Dust Growth

Interstellar dust silicate core surrounded by an organic mantle



Dust Growth

In molecular clouds $(n_H > 10^3 \ cm^{-3})$

$$\frac{d\sigma(A)}{dt} = const \cdot n_g(A) \cdot n_{dust}$$

The constant includes cross section, sticking coefficient and average velocity (Dwek 1998)

$$n_g(A) \propto n_c(1 - \frac{\sigma_{dust}(A)}{\sigma_{ISM}(A)})$$

Dust Growth

$$\frac{d\sigma(A)}{dt} = \frac{\sigma_d}{\tau_{acc}} = \sigma_d \cdot \frac{[1 - \Delta(A)]}{\tau_0}$$

$$\Delta(A) = \sigma_d(A)/\sigma_{ISM}(A)$$

$\tau_0 \simeq 10^7$ yr (typical molec. Cloud lifetime)

(Dwek 1998)

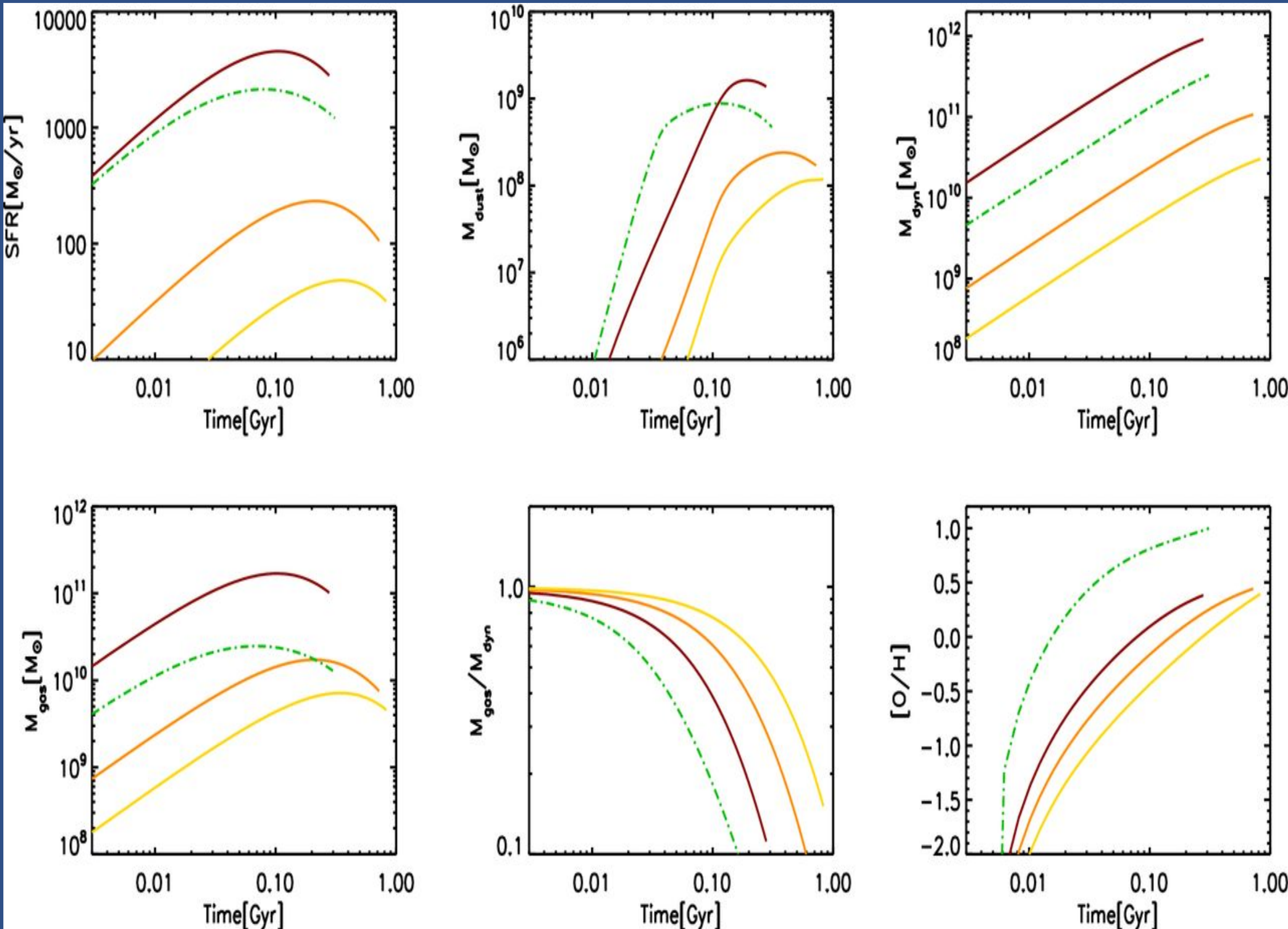
A model for Starbursts

- Conservation equation
- *IMF*
- Schmidt-Kennicutt law for star formation

$$\psi(t) = \nu \cdot M_{gas}(t)$$

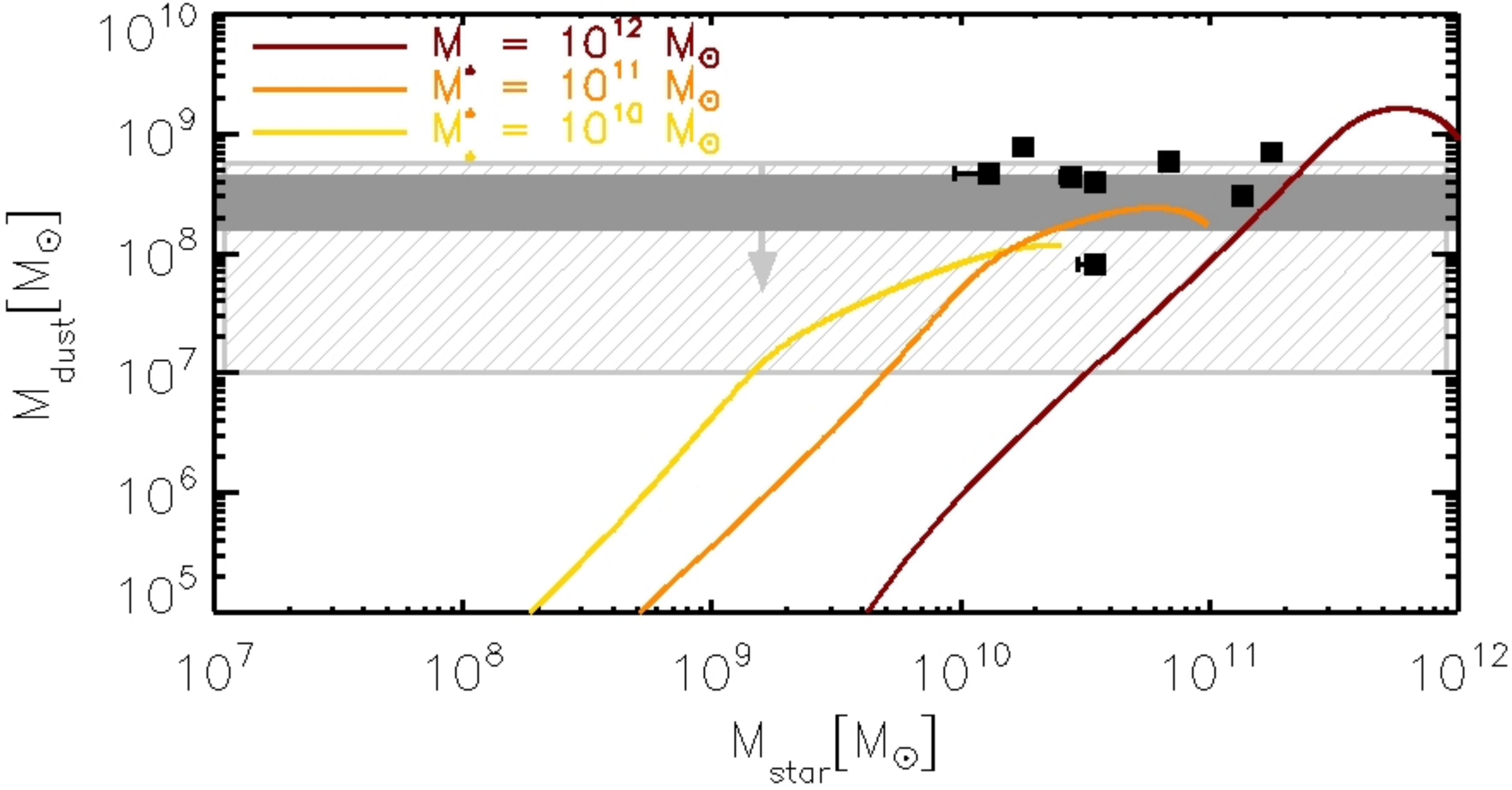
Schmidt 1959; Kennicutt 1998

A model for Starbursts

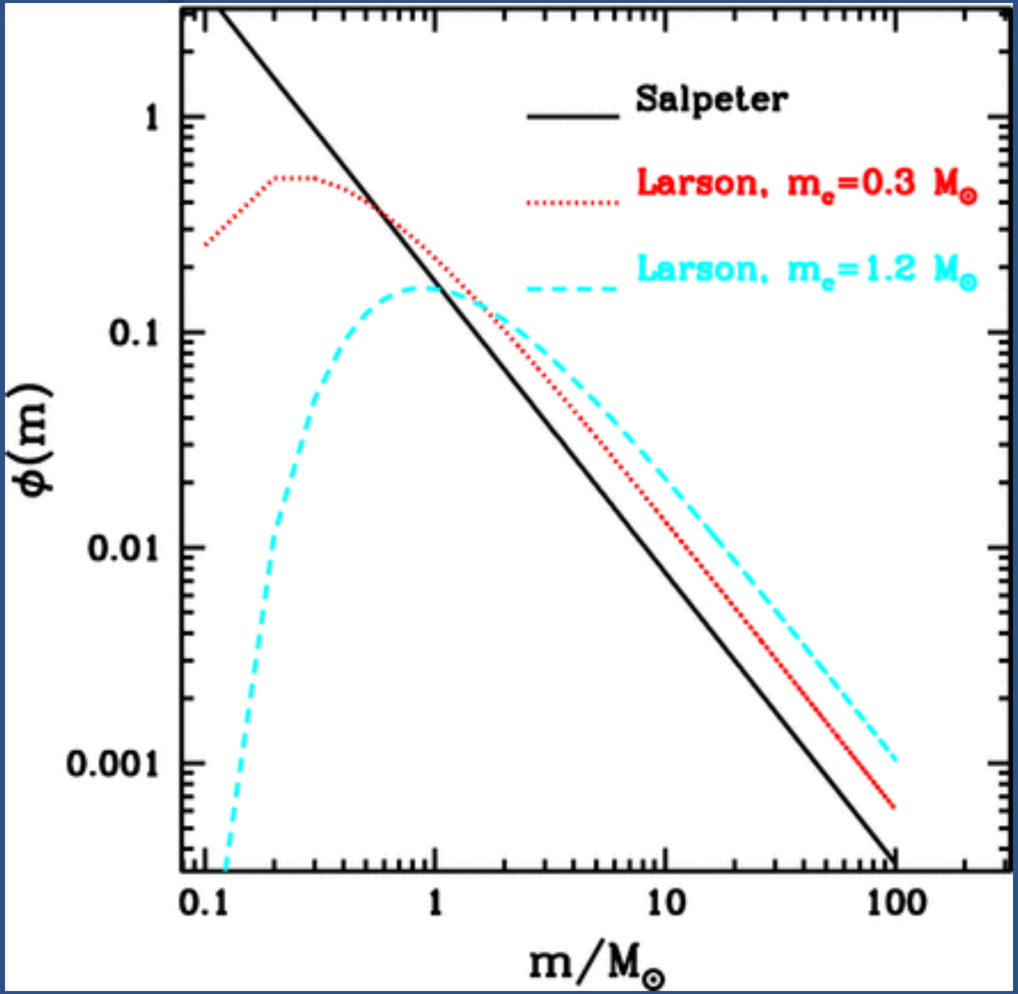


Calura, Gilli, Vignali, et al., 2014, MNRAS, 438, 2765

Observations vs Model



Impact of the IMF



$$\phi_L(m) \propto m^{-1.35}\, e^{-m_c/m}$$

Top-Heavy IMF at high redshift

- Larger Temperatures > Larger Jeans Mass

$$M_J \simeq (2\ \mathrm{M}_{\odot}) \left(\frac{c_s}{0.2\ \mathrm{km\ s}^{-1}} \right)^3 \left(\frac{n}{10^3\ \mathrm{cm}^{-3}} \right)^{-1/2} .$$

$$c_s = \sqrt{\gamma k T / m}$$

- Lower Metallicity > Less cooling (less fragmentation)

Larson 1998

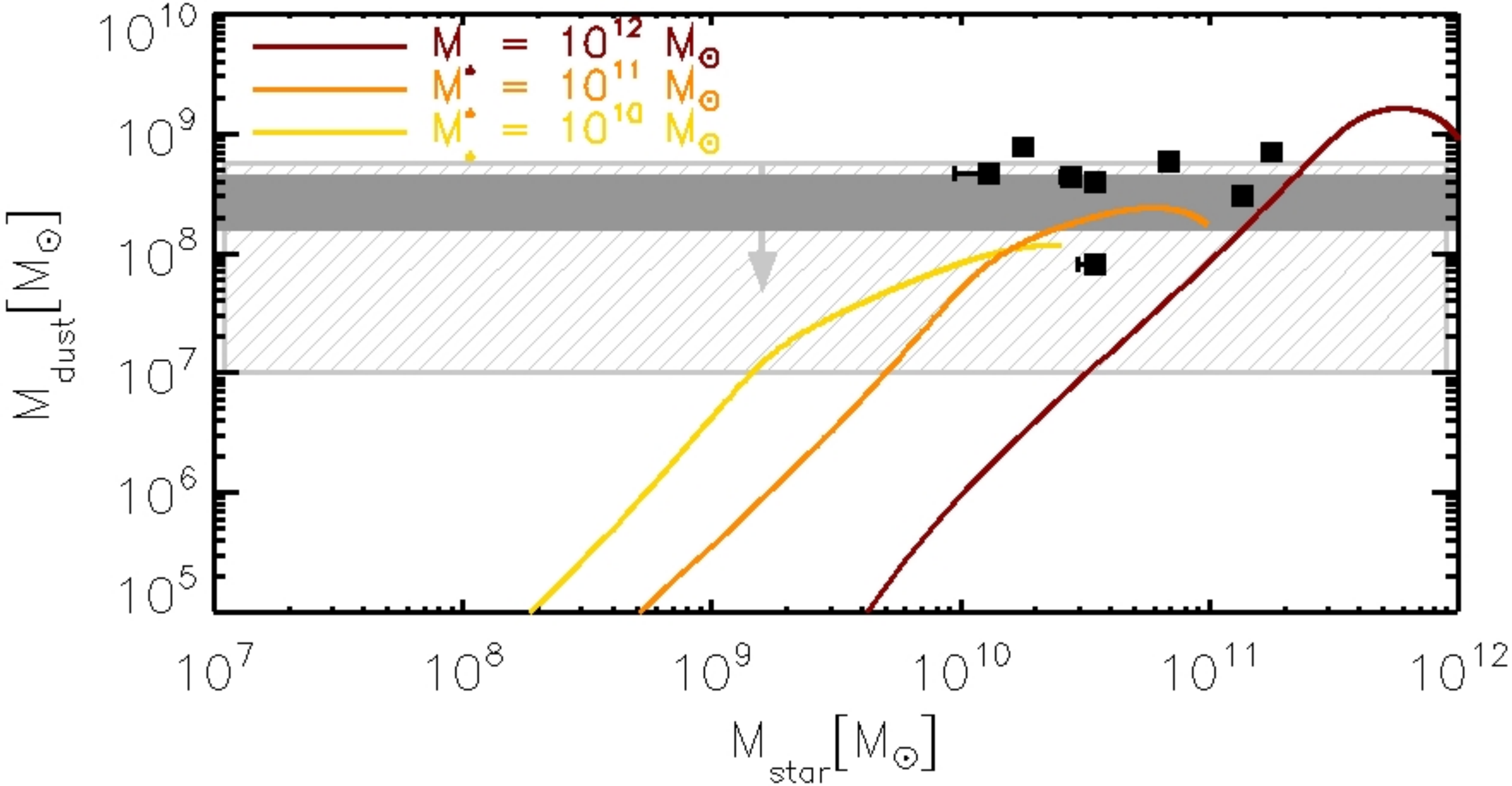
Top-Heavy IMF at high redshift

- Observed evolution of the optical Luminosty density

- FIR Background

Larson 1998

Observations vs Model



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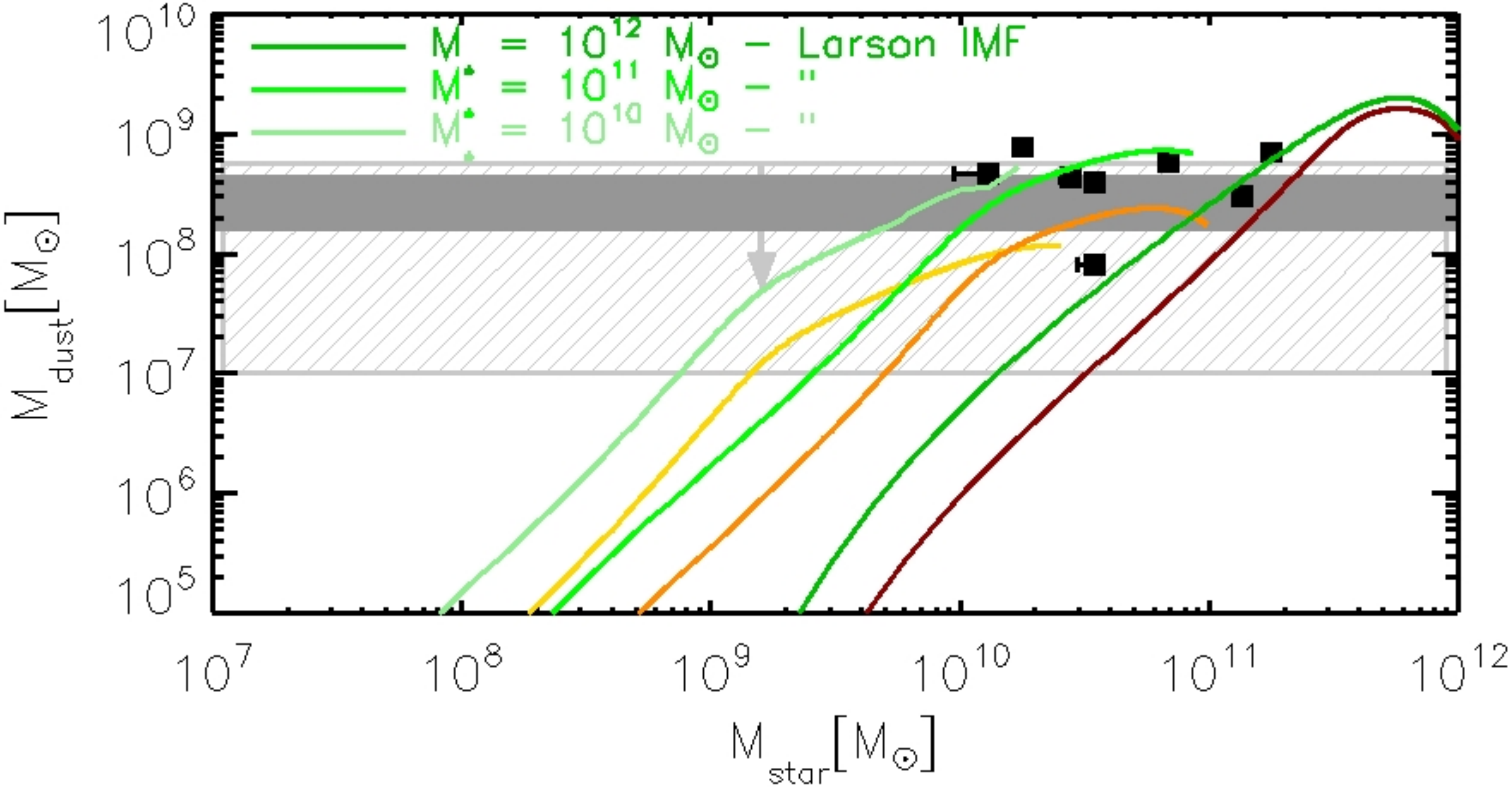

Conclusions

- A model for dust evol. must include prod. by stars, destruction and accretion

- IMF matters a lot: large dust masses @ high-z reproduced w/ TH IMF