Rapid production of dust in high-redshift quasars

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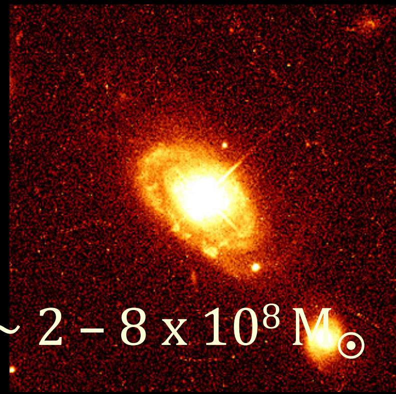
Motivation



- Large amounts of dust in quasars at z ≥ 6 $M_{\mathrm{d}} \sim 2 - 8 \times 10^{8}\ M_{\odot}$
- Dynamical masses $M_{\mathrm{dyn}} \sim 10^{10\text{-}11}\ M_{\odot}$
- Large masses of molecular Hydrogen $M_{\mathrm{H2}} \sim 2 \times 10^{10}\ M_{\odot}$
- Large masses for a super massive black hole $> 10^{9}\ M_{\odot}$
- Very luminous $L_{\mathrm{FIR}} \sim 10^{12\text{-}13}\ L_{\odot}$
- Very high inferred SFRs 500 – 3000 $M_{\odot}$/yr

(e.g., Bertoldi et al. 2003, Walter et al. 2004, Wang et al. 2010, Michalowski et al. 2010)

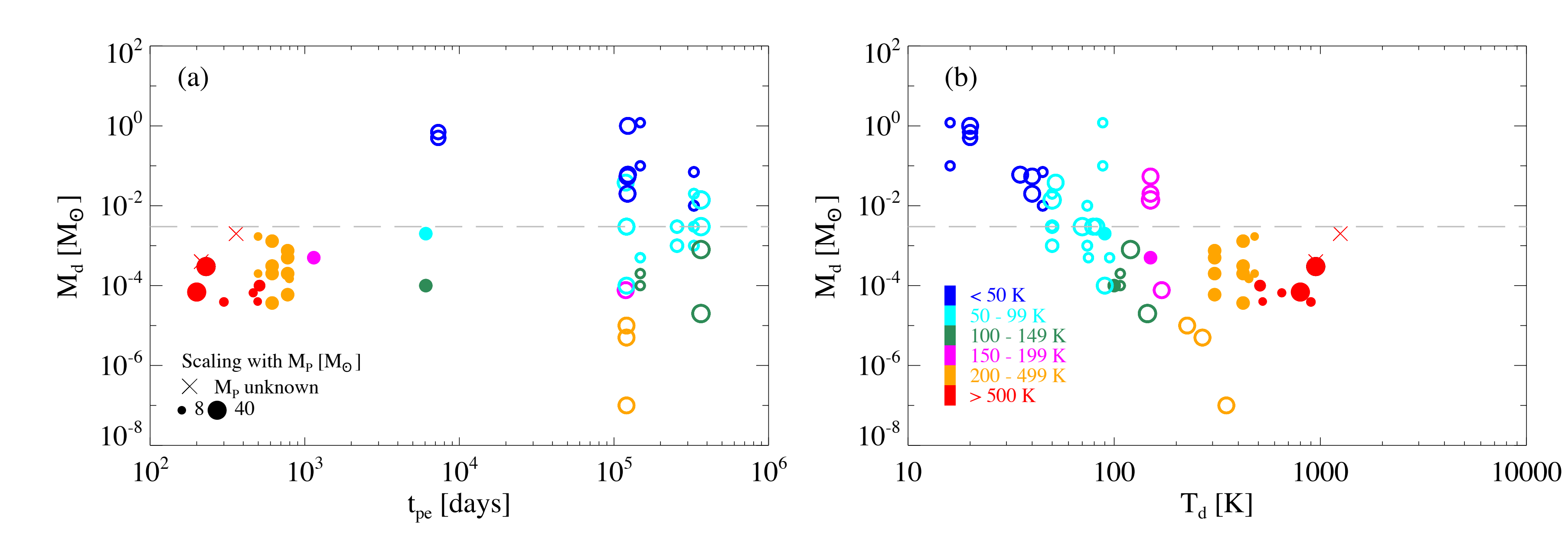
What is the origin of the very large dust masses?

- Stellar sources
  - AGB (0.8 – 8 $M_\odot$) ~10^{-2} $M_\odot$ of dust (Ferrarotti & Gail 2006)
  - RSG (8 – 25 $M_\odot$) (survives?)
  - Supernovae
    - Thermonuclear Type Ia SNe (no dust ?)
    - Core collapse SNe (> 8 $M_\odot$)
  - Luminous blue variable (LBV)

    e.g., η Car : ~ 0.4 $M_\odot$ of dust (Gomez et al 2010)
- Non-stellar sources:
  - Quasar dust, dust grain growth in the ISM ?
- Different model predictions

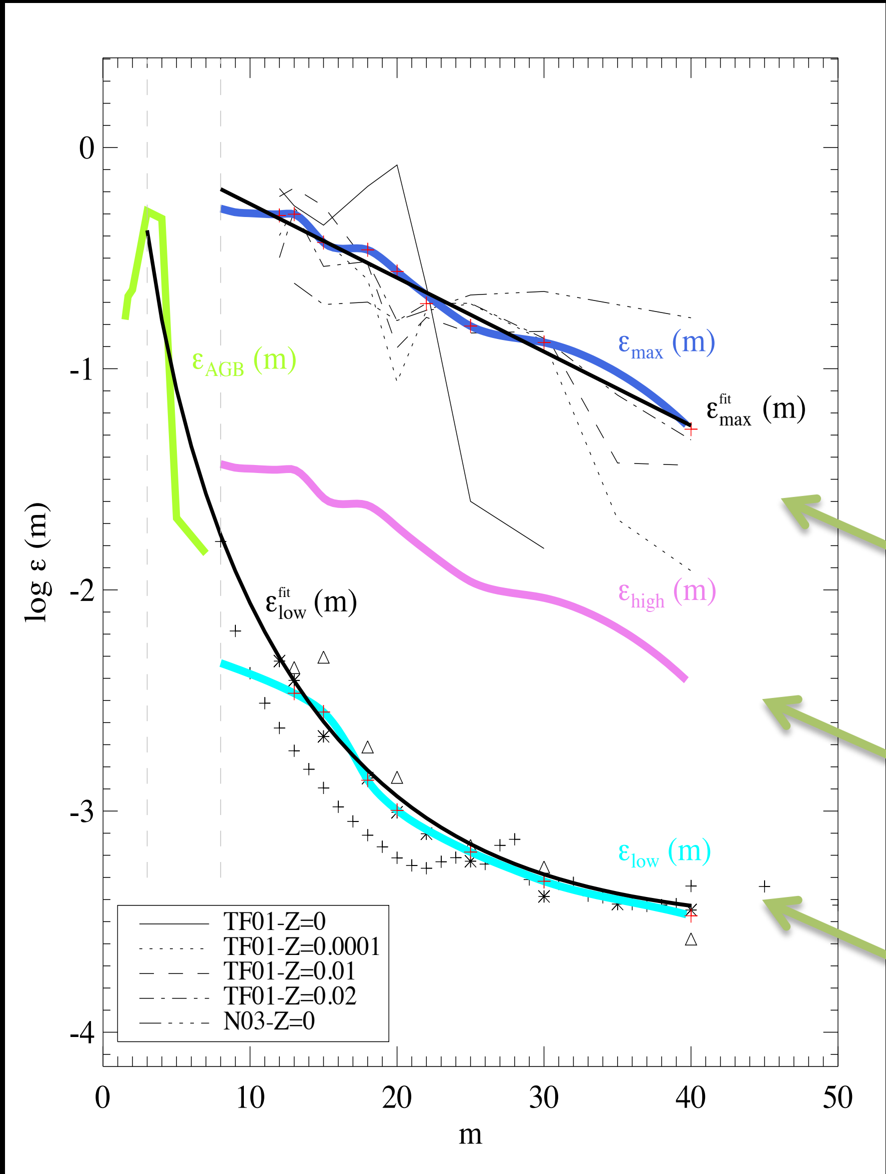
  e.g.: Dwek et al. 2007; Valiante et al. 2009; Pipino et al. 2010, Dwek & Cherchneff 2010

Evidence of dust from SNe



Gall et al. 2011c, A&AR, accepted

Theoretical models: at 600 – 1000 d => 0.1 – 1 $M_\odot$



Dust production efficiency

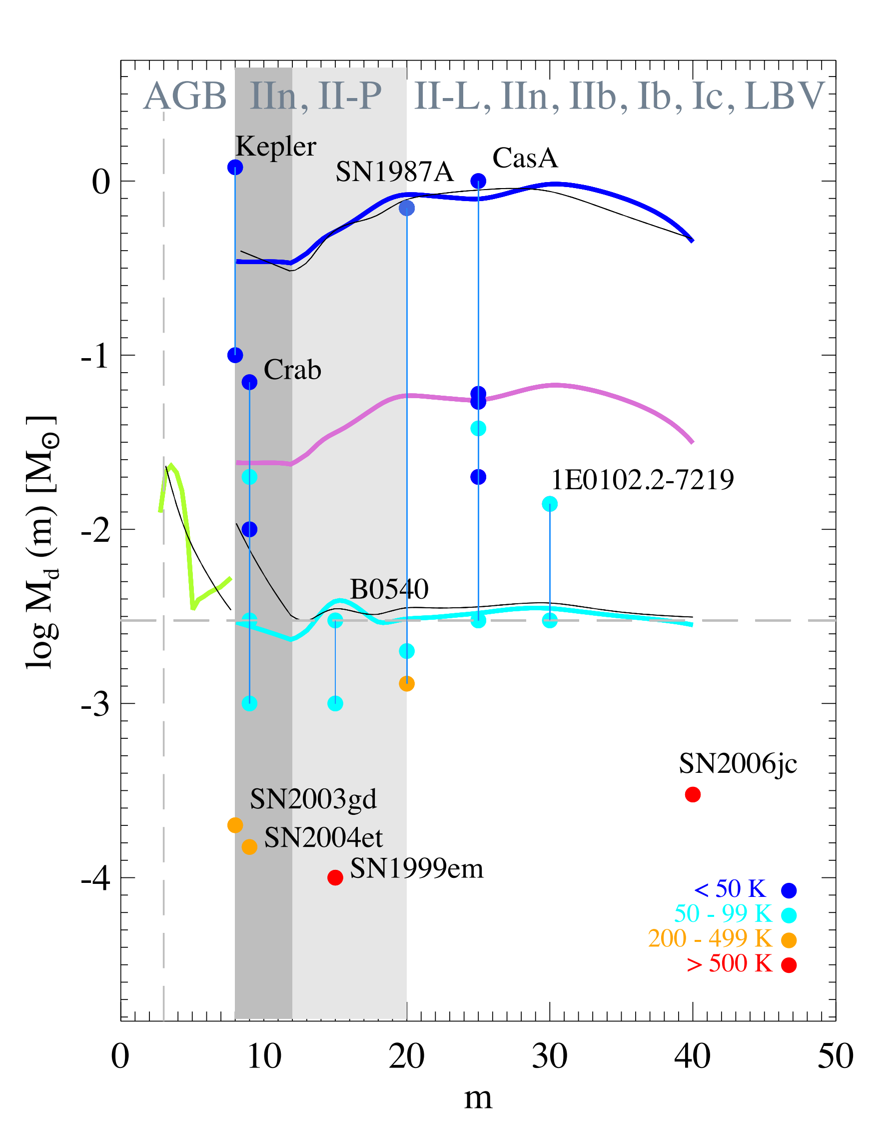
$$\varepsilon(m) = \frac{M_d(m)}{M_Z(m)}$$

$\varepsilon_{max}(m)$
from theoretical models

$\varepsilon_{high}(m)$
with destruction of 93%

$\varepsilon_{low}(m)$
from observations

Gall et al. 2011c, A&AR, accepted



Dust mass

$$M_d(m) = \varepsilon(m) M_Z(m)$$

Gall et al. 2011c, A&AR, accepted

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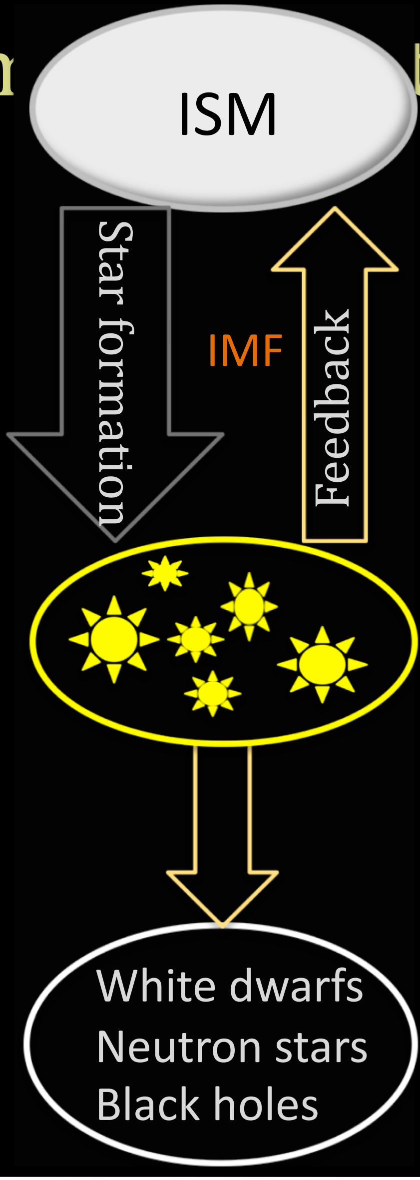

ISM
Star formation
IMF
Feedback
White dwarfs
Neutron stars
Black holes

Chemical Evolution

- Star formation

$$\psi(t) = \psi_{\rm ini}(t)\left[\frac{M_{\rm ISM}(t)}{M_{\rm ini}}\right]^k$$

- IMF

$$\int_{m_1}^{m_2} m\phi(m)dm = 1$$

- AGB, SN rates

$$R_{\rm i}(t) = \int_{m_{\rm L(i)}}^{m_{\rm U(i)}} \psi(t-\tau_m)\phi(m)dm$$

- Injection rates

$$E(t) = \int_{m_{\rm L(i)}}^{m_{\rm U(i)}} Y(m)\psi(t-\tau_m)\phi(m)dm$$

- Dust

$$\frac{{\rm d}M_{\rm d}(t)}{{\rm d}t} = E_{\rm d,SN}(t) + E_{\rm d,AGB}(t) - E_{\rm D}(t)$$

$$E_{\rm D}(t) = \eta_{\rm d}(t)(\psi(t) + M_{\rm cl}(t)R_{\rm SN}(t) + \Psi_{\rm SMBH})$$

- Gas

$$\frac{{\rm d}M_{\rm g}(t)}{{\rm d}t} = E_{\rm g}(t) + \eta_{\rm d}(t)M_{\rm cl}(t)R_{\rm SN}(t) - (1-\eta_{\rm d}(t))(\psi(t) + \Psi_{\rm SMBH})$$

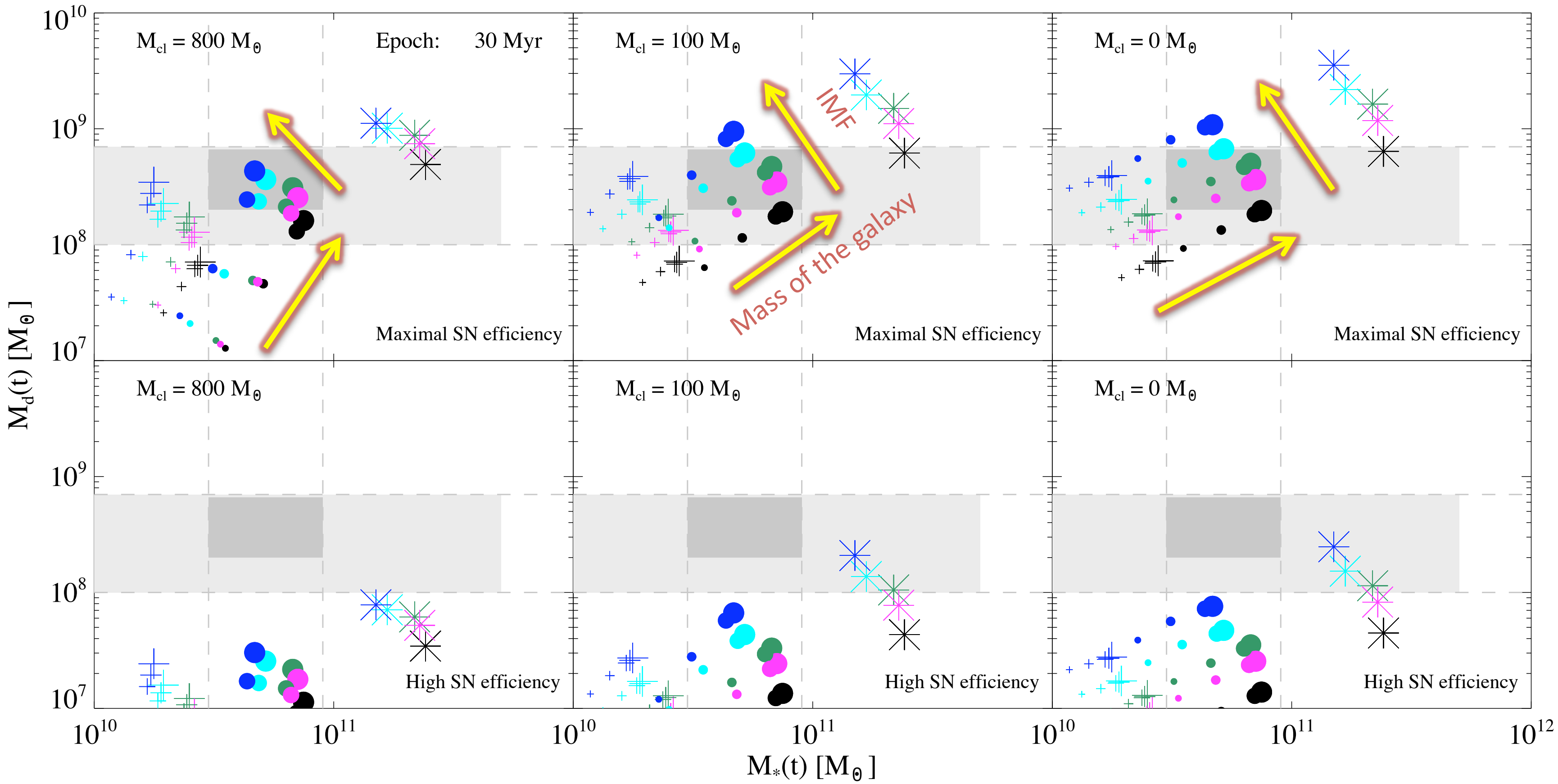
- Metals

$$\frac{{\rm d}M_{\rm Z}(t)}{{\rm d}t} = E_{\rm Z}(t) - \eta_{\rm z}(t)(\psi(t) + \Psi_{\rm SMBH})$$

Parameter-space of the model

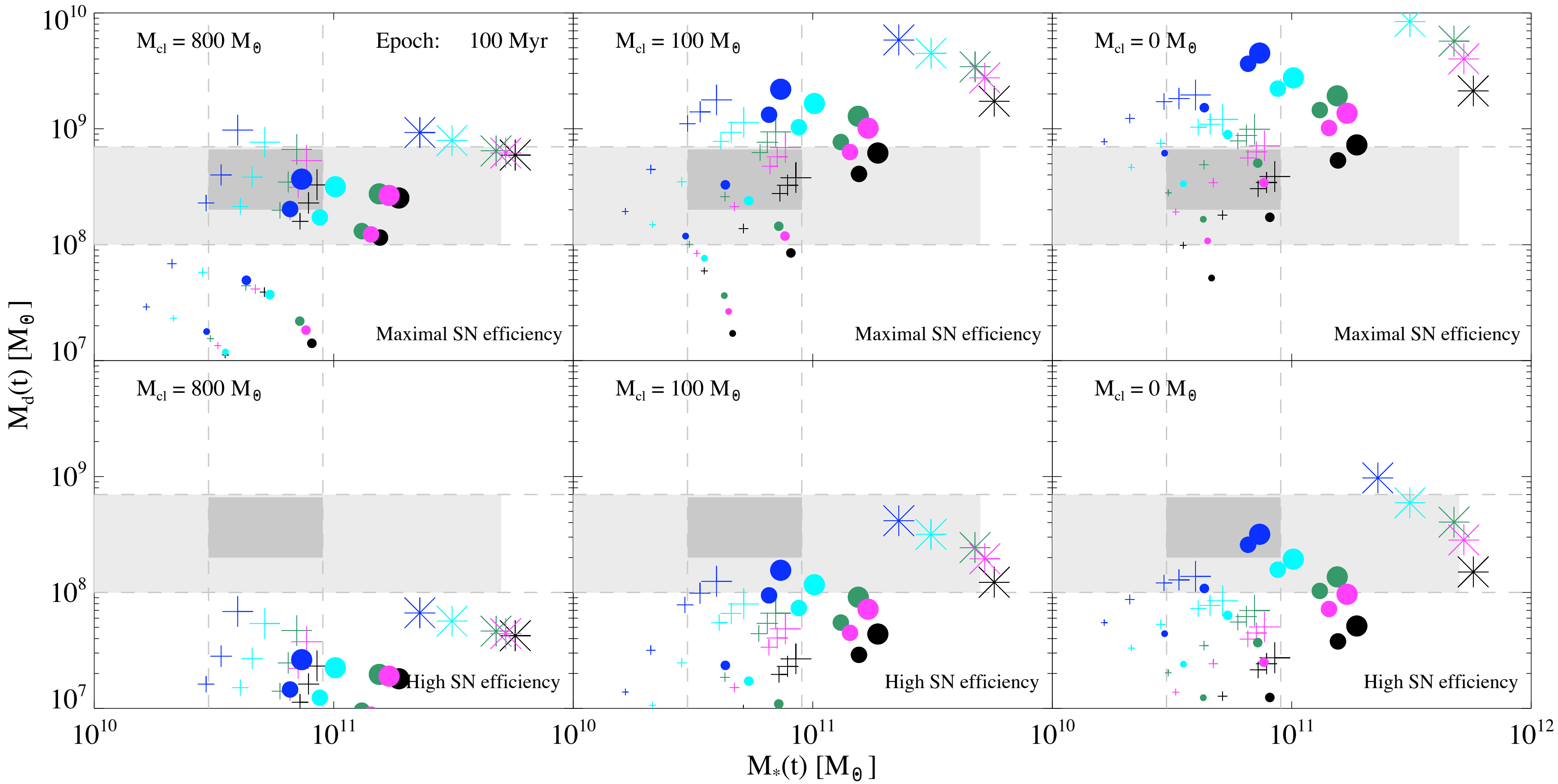
- Mass of the galaxy: $1.3 \times 10^{12}\,M_\odot$, $5 \times 10^{11}\,M_\odot$, $3 \times 10^{11}\,M_\odot$, $1 \times 10^{11}\,M_\odot$, $5 \times 10^{10}\,M_\odot$
- Star formation rate: $1\text{-}3 \times 10^{3}\,M_\odot/yr$
- Dust destruction through SN shocks: $M_{cl} = 0, 100, 800\,M_\odot$
- Dust production efficiency: $\varepsilon_{max}(m)$, $\varepsilon_{high}(m)$, $\varepsilon_{low}(m)$
- 5 different IMFs
- Different stellar yields: Woosley & Weaver (1995), Nomoto et al. (2006), Eldridge et al. (2008)
- Differentiation between diverse SN types: II-P, II-L, Ib/c
- Evolution up to 1 Gyr

Dust and stellar mass at 30 Myr



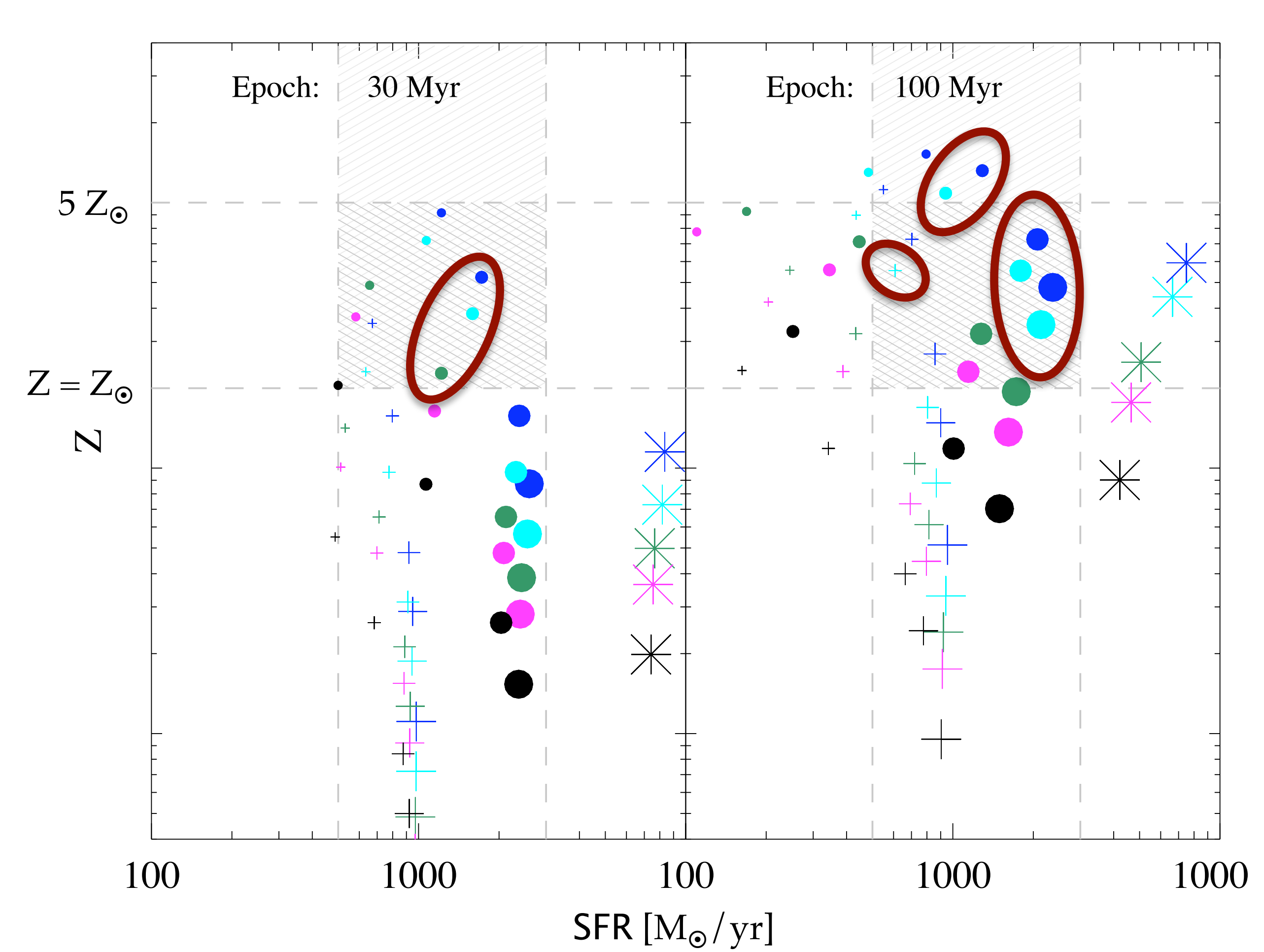
Gall et al. 2011b

Dust and stellar mass at 100 Myr



Gall et al. 2011b

Star formation rate and metallicity



Gall et al. 2011b

A few examples

- Quasar J1148+5251 ($z = 6.4$)

	Calculated ~	From observations
Dust mass [$10^8 M_\odot$]	3.1 – 5.1	5.9 ± 0.7
SFR [$M_\odot$/yr]	1600	2380
Stellar mass [$10^{10} M_\odot$]	3.5	~ 3.3
Metallicity [$Z_\odot$]	2	$> Z_\odot$

Epoch: 30 Myr

SN efficiency: max

Mass : $10^{11} M_\odot$

SFR_{ini}: $3 \times 10^3 M_\odot$

A few examples

- Quasar J1148+4637 (z = 6.23)

	Calculated ~	From observations
Dust mass [$10^8 M_\odot$]	3.5	4.3 ± 0.6
SFR [$M_\odot$/yr]	610	650
Stellar mass [$10^{10} M_\odot$]	2.8	< ~ 9.0
Metallicity [$Z_\odot$]	3.4	> $Z_\odot$

Epoch: 100 Myr — Mass : $10^{11} M_\odot$

SN efficiency: max — SFR_{ini}: 1 x $10^3 M_\odot$

A few examples

- Quasar J2054+0005 (z = 6.06)

	Calculated ~	From observations
Dust mass [10^8 $M_\odot$]	2.7	3.4 ± 0.8
SFR [$M_\odot$/yr]	1150	1180
Stellar mass [10^{10} $M_\odot$]	4.7	< ~ 9.0
Metallicity [$Z_\odot$]	4.4	> $Z_\odot$

Epoch: 70 Myr

SN efficiency: max

Mass : 10^{11} $M_\odot$

SFR_{ini}: 3 x 10^3 $M_\odot$

Conclusions

- Rapid dust production when SFR of starburst ≥ 10^3 $M_\odot$/yr
- Required dust masses reached at epochs 30 – 170 Myr
- Favored mass of galaxy 1 – 3 x 10^{11} $M_\odot$
- Dust contribution from AGB stars is negligible
- Very high supernova dust production needed
- Models with moderate dust destruction and high SN efficiency favored at later epochs
- Best agreement with observations for models with IMFs biased towards higher stellar masses

THANK YOU!