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Dust in z~6 QSOs: Importance of Grain Growth in the Interstellar Medium

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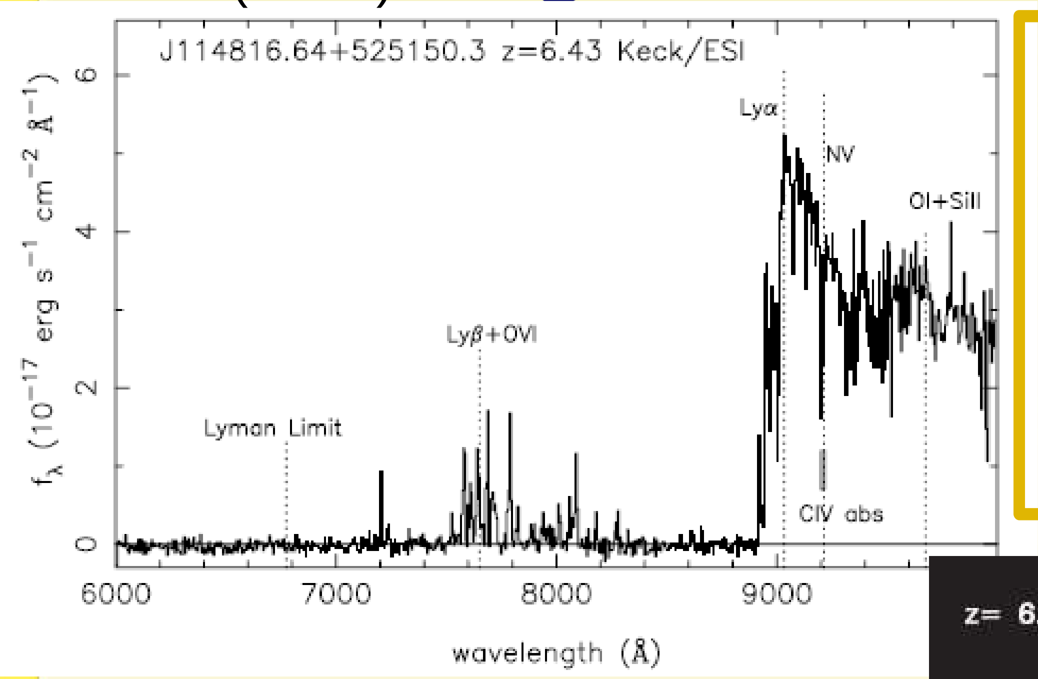
QSO at z=6.42

Fan et al.(2003)

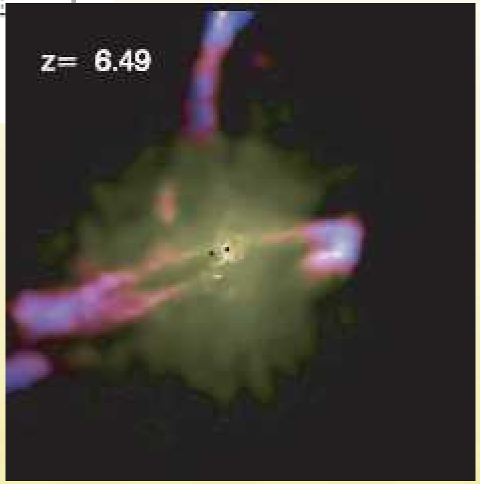


The most distant QSO found by Sloan Digital Sky Survey:

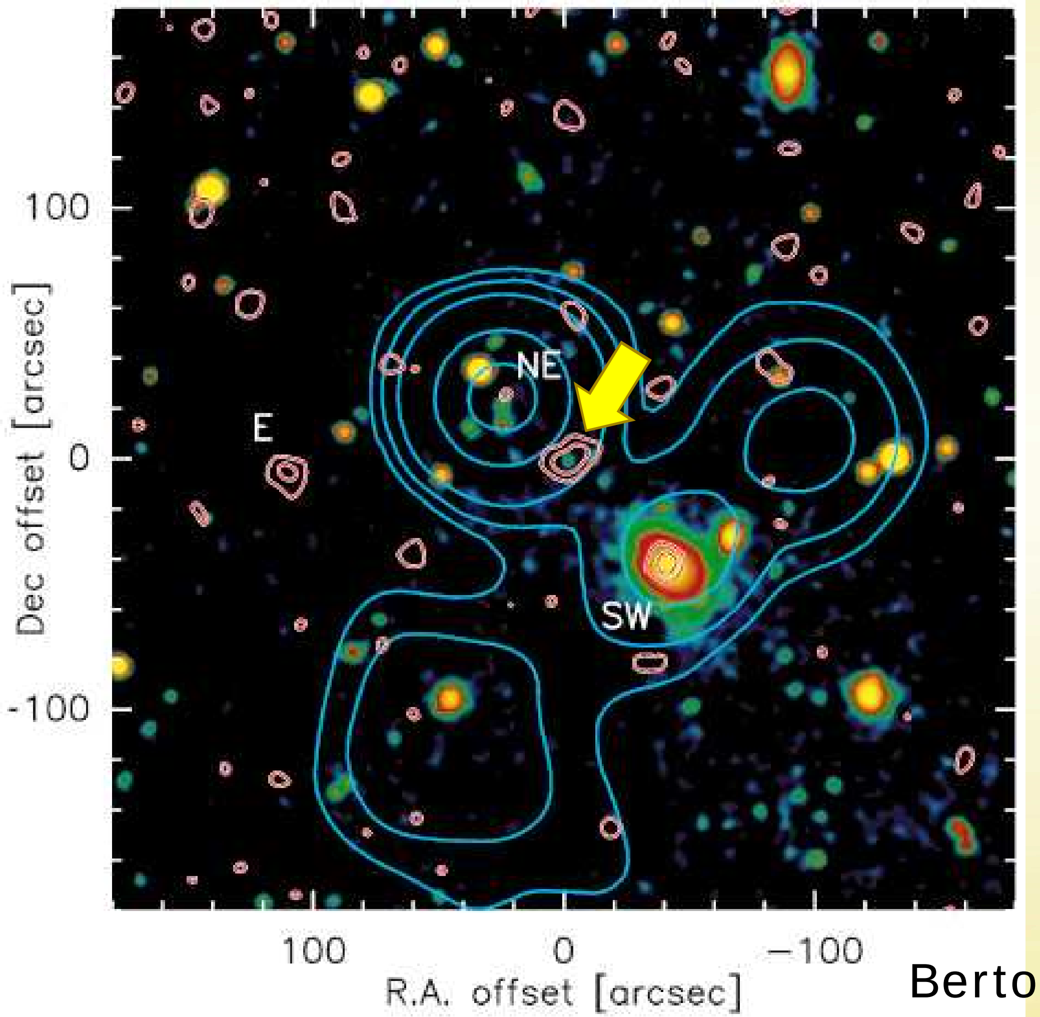
SDSS J1148+5251

Redshift: z=6.42 (Bertoldi et al.2003; CO lines)
Blackhole mass: 3×10^9 Msun (Willott et al.2003;MgII2799)

Cosmic age: 840 Myr at z=6.42
In ΛCDM structure formation scenario, a QSO/SMBH with $\sim10^9$ Msun at z~6 can be formed (Li et al.2007).



A huge amount of dust!



SDSS J1148+5251 (z=6.42)

Blackhole mass: 3×10^{9} Msun (Willott et al.2003)

Dust mass: 2×10^{8} Msun

Gas mass: 3×10^{10} Msun (Dwek et al.2007)

Color(green—red—yellow): SDSS z-band (~9134 A)

Pink: IRAM/MAMBO-2 250 GHz (1.2mm dust continuum)

Blue: VLA 1.4 GHz (21cm)

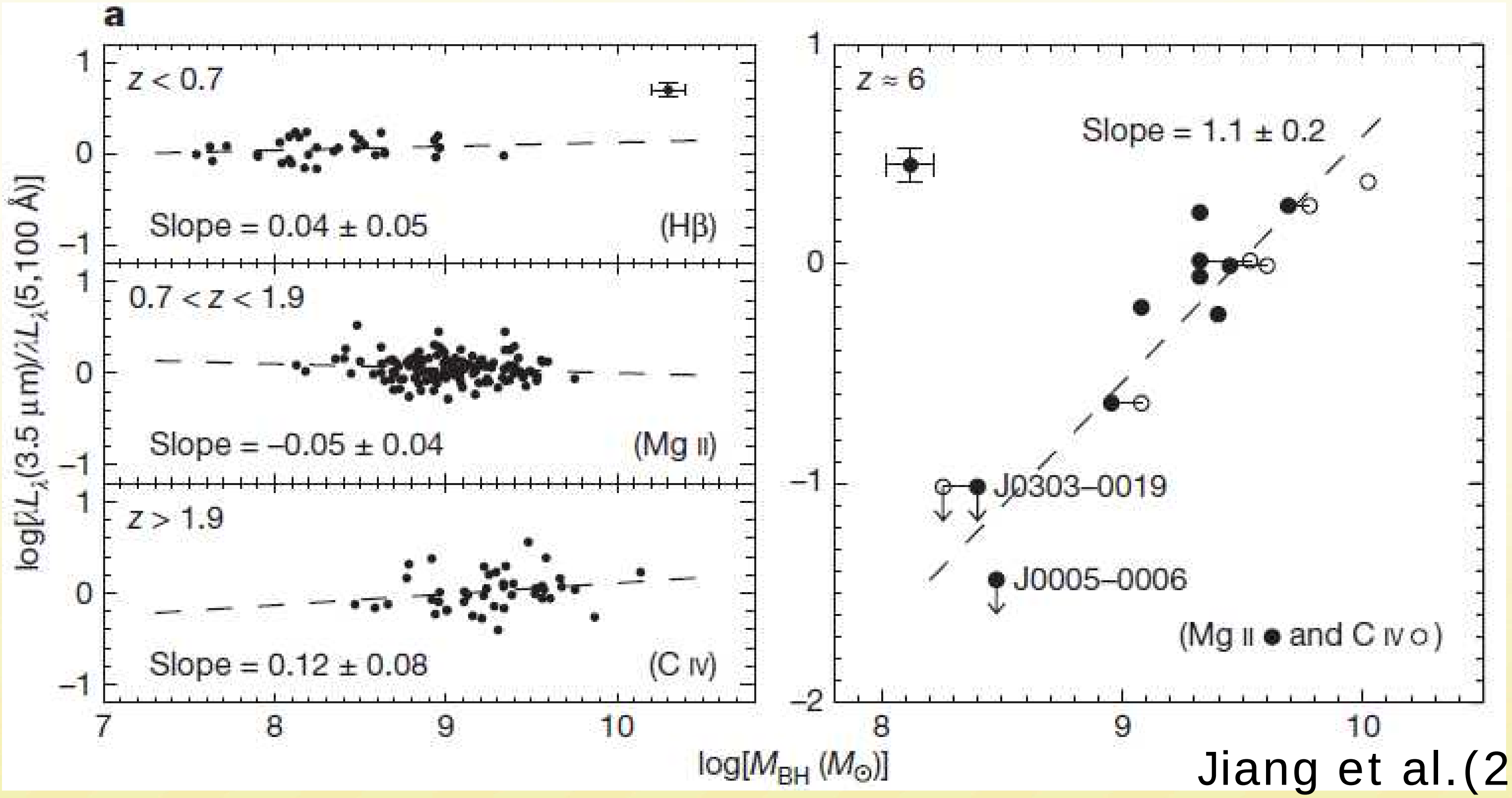
Bertoldi et al.(2003)

Dust-free z~6 QSOs?

A correlation between BH mass and dust abundance is found at z~6!

→ Smaller BHs are before dust production phase?

~Hot dust mass/stellar mass



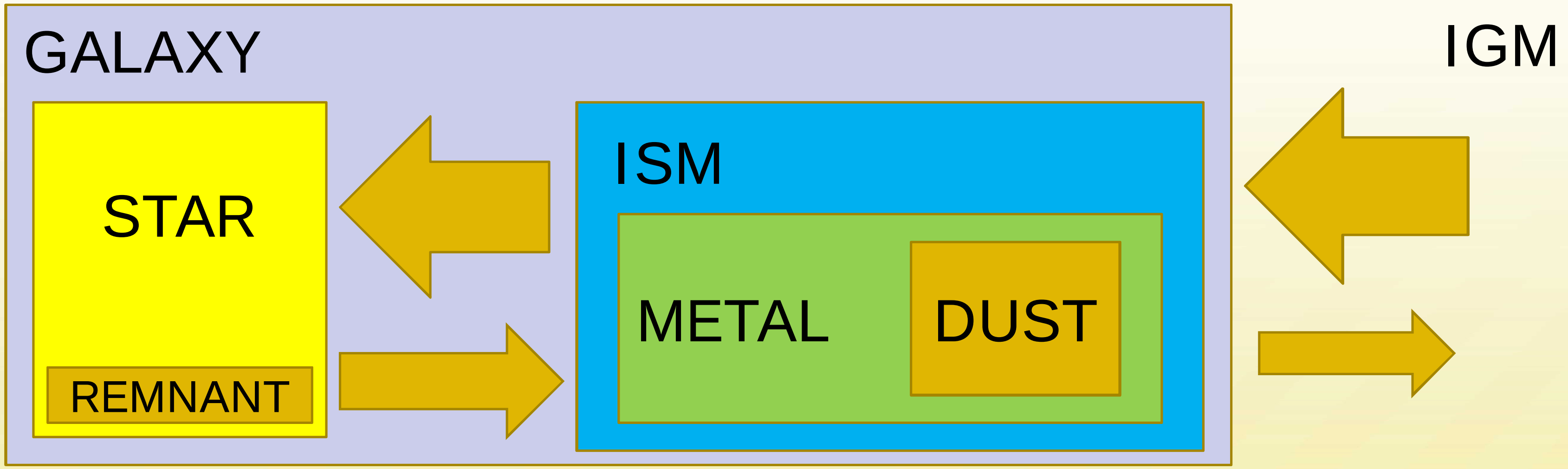
Jiang et al.(2010)

What is the origin of dust?

- ~10^8 Msun dust by the cosmic age 840 Myr
- In the present-day Milky Way, Asymptotic Giant Branch (AGB) stars produce the most of 'stardust' (e.g., Draine 2009).
  - Time-scale to evolve to the AGB phase: ~1 Gyr
- Dust supply by SNe of short-lived (<10 Myr) massive stars? (Dwek et al.2007)
  - Dust yield > 1 Msun per 1 SN is required.
  - Theoretical prediction is ~0.1-1 Msun per 1 SN (Nozawa et al. 2007)
  - Observations give <0.01-0.1 Msun per 1 SN
- ~5 Msun stars evolve to AGB phase enough quickly, so these stars can supply enough dust? (Valiante et al.2009)
- How about dust growth in the ISM? (Draine 2009)

Chemical+dust evolution model

- An extension of galaxy chemical evolution model
- Since Dwek & Scalo (1980), there are some groups.
  - In Japan, Hirashita (1999a,b,c,2000), Inoue (2003)



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Chemical+dust evolution model

STAR $$\frac{dM_*}{dt} = S - R$$

ISM $$\frac{dM_{\rm ISM}}{dt} = -S + R + I - O$$

METAL $$\frac{dM_{\rm Z}}{dt} = -ZS + Y_{\rm Z} + I_{\rm Z} - O_{\rm Z}$$

DUST $$\frac{dM_{\rm d}}{dt} = -DS + Y_{\rm d} - \frac{M_{\rm d}}{\tau_{\rm SN}} + \frac{M_{\rm d}(1-\delta)}{\tau_{\rm ac}} + I_{\rm d} + O_{\rm d}$$

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Chemical+dust evolution model

STAR $$\frac{dM_*}{dt} = \frac{M_{\rm ISM}}{\tau_{\rm SF}} - R \qquad S = \frac{M_{\rm ISM}}{\tau_{\rm SF}}$$

ISM $$\frac{dM_{\rm ISM}}{dt} = -\frac{M_{\rm ISM}}{\tau_{\rm SF}} + R + I - O$$

METAL $$\frac{dM_{\rm Z}}{dt} = -\frac{M_{\rm Z}}{\tau_{\rm SF}} + Y_{\rm Z} + I_{\rm Z} - O_{\rm Z}$$

DUST $$\frac{dM_{\rm d}}{dt} = -\frac{M_{\rm d}}{\tau_{\rm SF}} + Y_{\rm d} - \frac{M_{\rm d}}{\tau_{\rm SN}} + \frac{M_{\rm d}(1-\delta)}{\tau_{\rm ac}} + I_{\rm d} + O_{\rm d}$$

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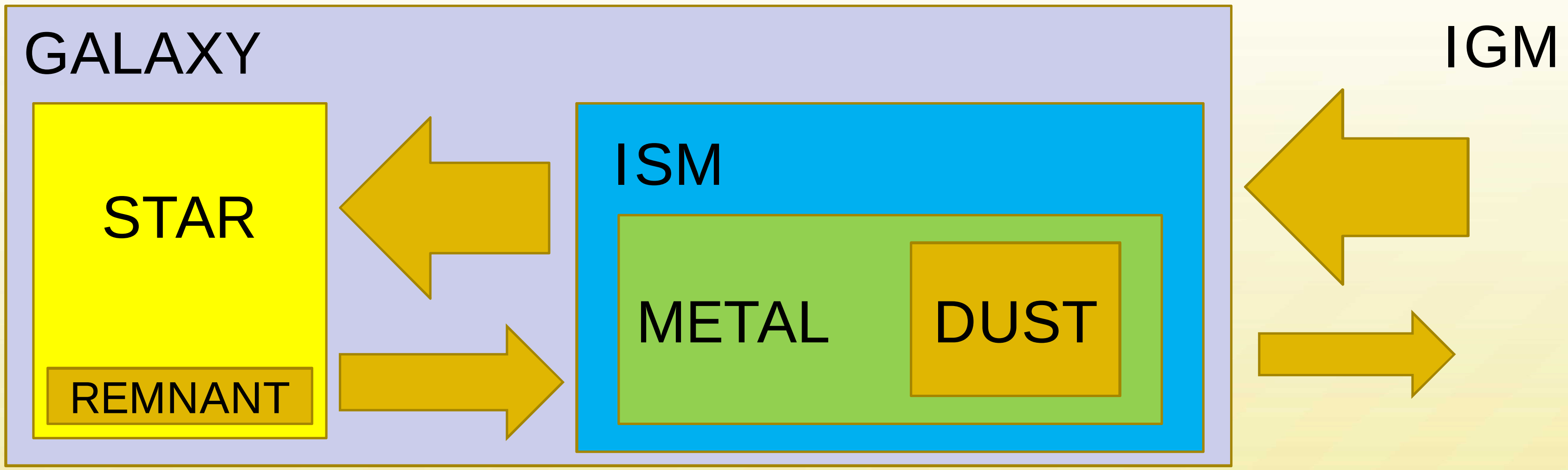
Computational setting

- One-zone, one-phase ISM
- With primordial gas infall, without outflow
- SF timescale = Infall timescale = 1×10^{8} yr
- Total gas reservoir = $1\times10^{12}\ M_{sun}$
- Dust production by SNe and AGB stars ($m_d=1\times10^{-2}\ M_{sun}$)
- Finite stellar life-time



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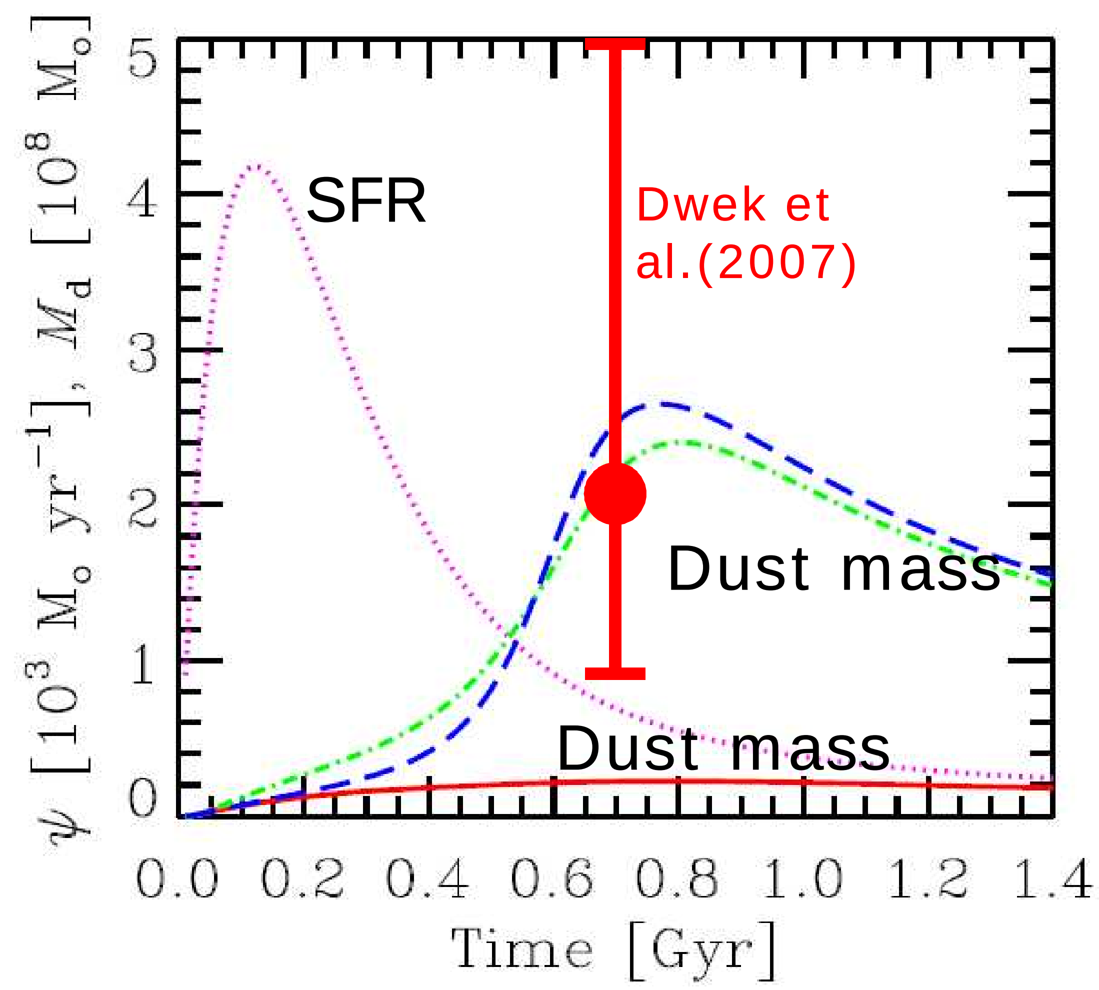
Computational result



SFR: dotted line

Dust mass

solid line:

$\varepsilon m_{SN}=1\mathrm{x}10^3\ M_{sun}$

$\tau_{ac,0}=1\mathrm{x}10^7$ yr

dashed line:

$\varepsilon m_{SN}=1\mathrm{x}10^3\ M_{sun}$

$\tau_{ac,0}=5\mathrm{x}10^6$ yr

dot-dashed line:

$\varepsilon m_{SN}=5\mathrm{x}10^2\ M_{sun}$

$\tau_{ac,0}=1\mathrm{x}10^7$ yr

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Comparison of time-scales: 1

In a starburst galaxy (or z~6 QSO)

$$\frac{dM_\mathrm{d}}{dt} = -\cancel{\frac{M_\mathrm{d}}{\tau_\mathrm{SF}}} + \cancel{\frac{M_\mathrm{d}}{\tau_*}} - \frac{M_\mathrm{d}}{\tau_\mathrm{SN}} + \frac{M_\mathrm{d}(1-\delta)}{\tau_\mathrm{ac}}$$

$$\tau_\mathrm{SF} \approx \tau_* \approx 10\tau_\mathrm{SN} \approx \underline{1\times 10^8\ \mathrm{yr}}$$

$$\tau_\mathrm{ac} \approx 3\times 10^7\ \mathrm{yr}\left(\frac{a}{0.1\ \mu\mathrm{m}}\right)\left(\frac{n}{100\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{100\ \mathrm{K}}\right)^{-1/2}\left(\frac{Z}{0.02}\right)^{-1}$$

$$\tau_\mathrm{SF} \approx \tau_* >> \tau_\mathrm{SN} \approx \tau_\mathrm{ac}/(1-\delta)$$

Balance between SN destruction and ISM growth determines the dust amount and dust-metal ratio (δ).

Comparison of time-scales: 2

In the present-day Milky Way

$$\frac{dM_{\mathrm{d}}}{dt} = -\cancel{\frac{M_{\mathrm{d}}}{\tau_{\mathrm{SF}}}} + \cancel{\frac{M_{\mathrm{d}}}{\tau_{*}}} - \frac{M_{\mathrm{d}}}{\tau_{\mathrm{SN}}} + \frac{M_{\mathrm{d}}(1-\delta)}{\tau_{\mathrm{ac}}}$$

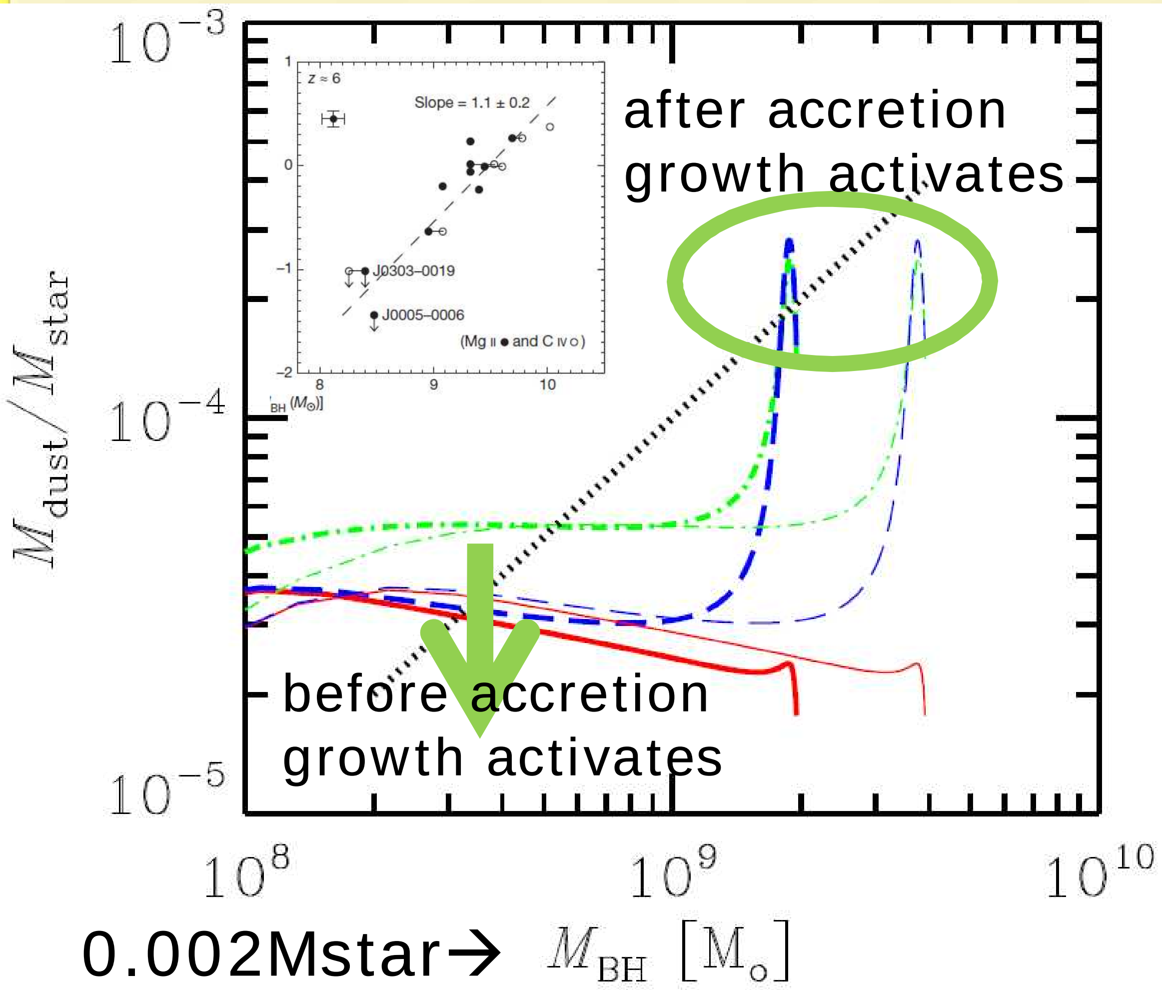
$$\tau_{\mathrm{SF}} \approx \tau_{*} \approx 10\tau_{\mathrm{SN}} \approx 5\times10^{9}\ \mathrm{yr}$$

$$\tau_{\mathrm{ac}} \approx 3\times10^{7}\ \mathrm{yr}\left(\frac{a}{0.1\ \mu\mathrm{m}}\right)\left(\frac{n}{100\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{100\ \mathrm{K}}\right)^{-1/2}\left(\frac{Z}{0.02}\right)^{-1}$$

$$\tau_{\mathrm{SF}} \approx \tau_{*} >> \tau_{\mathrm{SN}} \approx \tau_{\mathrm{ac}}/(1-\delta)$$

Balance between SN destruction and ISM growth determines the dust amount and dust-metal ratio (δ).

Dust-free QSO?



thick: M=1x10^{12} Msun
thin: M=2x10^{12} Msun

Dust mass

solid line:
εm_{SN}=1x10^3 M_{sun}
$\tau_{ac,0}$=1x10^7 yr

dashed line:
εm_{SN}=1x10^3 M_{sun}
$\tau_{ac,0}$=5x10^6 yr

dot-dashed line:
εm_{SN}=5x10^2 M_{sun}
$\tau_{ac,0}$=1x10^7 yr

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Summary

- Dust growth in the ISM can account for the observed huge amount of dust in z~6 QSOs.
- Dust amount is determined by the balance between SN destruction and ISM growth after the ISM growth becomes effective:
  → A universal mechanism to determine the dust mass.
- 'Dust-free' QSOs recently found at z~6 may be in the phase before the ISM growth becomes effective.

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‘Stardust’ production

$$Y_{\mathrm{d}}(t) = \int_{m(t)}^{m_{\mathrm{u}}} m_{\mathrm{d}}(m, Z[t-\tau_{\mathrm{lf}}(m)])\Phi(m)S(t-\tau_{\mathrm{lf}}[m])dm$$

Stellar dust yield
(SNe and AGBs)

$$\langle m_{\mathrm{d}} \rangle \approx 10^{-2}\ M_{\mathrm{sun}}$$

(Nozawa et al.2007, Zhukovska et al.2008)

Instantaneous recycling approximation (or a constant SFR):

$$Y_{\mathrm{d}}(t) \approx S(t)\langle m_{\mathrm{d}} \rangle \int_{m_{\mathrm{t}}}^{m_{\mathrm{u}}} \Phi(m)dm$$

$$\approx 10^{-3} S(t) = \frac{M_{\mathrm{ISM}}}{\tau_{\mathrm{SF}} 10^{3}} = \frac{M_{\mathrm{d}}}{\tau_{*}}$$

(for Salpeter IMF)

$$\boxed{\tau_{*} \equiv \tau_{\mathrm{SF}}\left(\frac{D}{10^{-3}}\right)}$$

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Destruction by SN shocks

$$\left[\frac{dM_{\rm d}}{dt}\right]_{\rm SN} = \varepsilon D m_{\rm SN} R_{\rm SN} = \frac{M_{\rm d}}{\tau_{\rm SN}} \qquad \tau_{\rm SN} \equiv \frac{M_{\rm ISM}}{\varepsilon m_{\rm SN} R_{\rm SN}}$$

(e.g., McKee 1989)

SN occurrence rate:

$$R_{\rm SN}(t) = \int_{8M}^{40M} \Phi(m) S(t - \tau_{\rm lf}[m]) dm$$

$$\approx 10^{-2} S(t) = 10^{-2} \frac{M_{\rm ISM}}{\tau_{\rm SF}}$$

$$\boxed{\tau_{\rm SN} \approx \frac{\tau_{\rm SF}}{10}}$$

Effective shocked mass:

$$\varepsilon m_{\rm SN} \approx 10^3 M_{\rm sun}$$ (e.g., McKee 1989)

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Growth in the ISM

$$\left[\frac{dM_{\rm d}}{dt}\right]_{\rm ac} = N_{\rm d}\pi\langle a^2\rangle s_{\rm Z}\rho_{\rm Z}^{\rm gas}\langle \upsilon_{\rm Z}\rangle = \frac{M_{\rm d}(1-\delta)}{\tau_{\rm ac}}$$

Dust particle number:

$$N_{\rm d} = \frac{3M_{\rm d}}{4\pi\langle a^3\rangle\sigma}$$

Density of gas-phase metals:

$$\rho_{\rm Z}^{\rm gas} = \rho_{\rm Z} - \rho_{\rm d} = Z\rho_{\rm gas}(1-\delta)$$

δ: depletion factor
(dust-metal mass ratio)

$$\tau_{\rm ac} \equiv \frac{4\langle a^3\rangle\sigma}{3\langle a^2\rangle s_{\rm Z}\rho_{\rm gas}\langle \upsilon_{\rm Z}\rangle Z}$$

(σ=3 g/cm^3, s_Z=1, ^{56}Fe case)

$$\approx \underline{3\times10^7\ \rm yr}\left(\frac{a}{0.1\,\mu\rm m}\right)\left(\frac{n}{100\,\rm cm^{-3}}\right)^{-1}\left(\frac{T}{100\,\rm K}\right)^{-1/2}\left(\frac{Z}{0.02}\right)^{-1}$$

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A universal mechanism?

- Both in the current Milky Way and in z~6 QSO, the balance between SN destruction and ISM growth is likely to determine the dust amount.
  → a universal mechanism?
- How about the composition and size distribution?
  - What kind of dust species grow by the accretion process?
  - What is the effect of different "seeds"?
- What about the accretion time-scale? More rapid? (Draine 2009)
  - Effect of charge? (Weingartner & Draine 2001)
  - ISM turbulence? (Yan et al.2004)