ALMAで見るz>6の銀河のダスト進化

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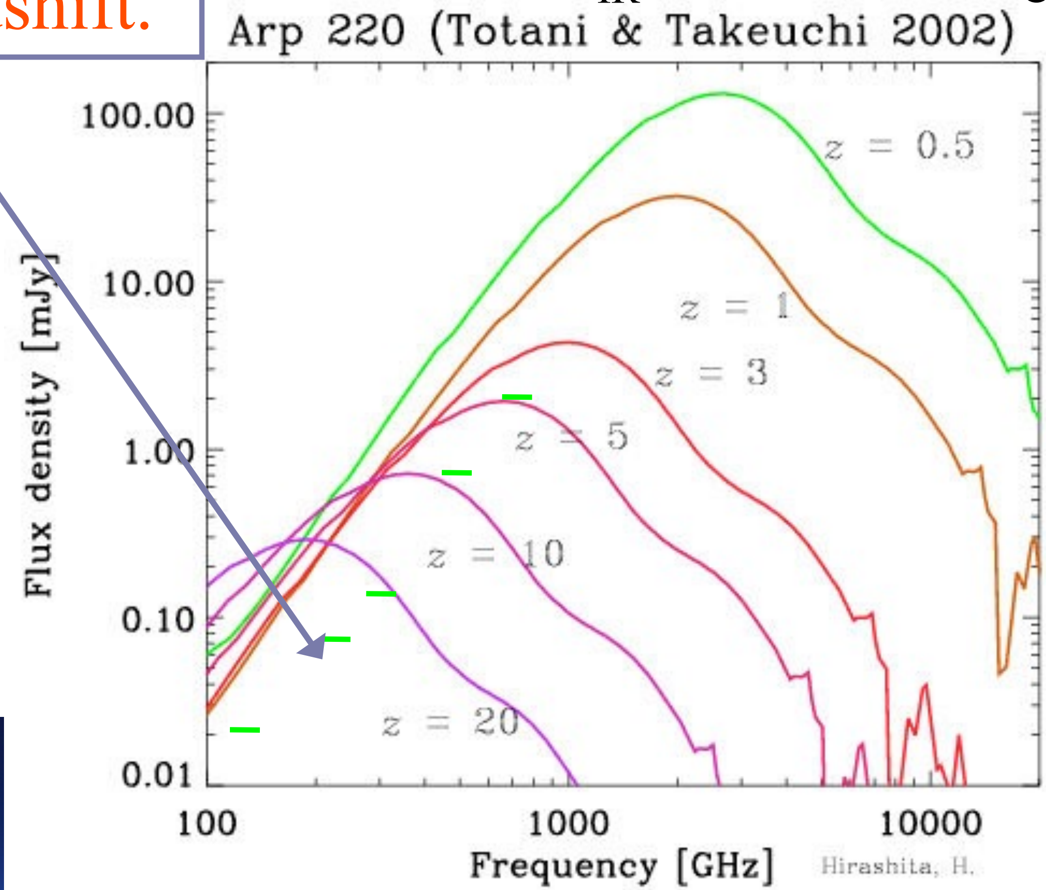
Wang et al. 2017, MNRAS,465, 3475

Submm Observation

ALMA bands are suitable for high redshift.

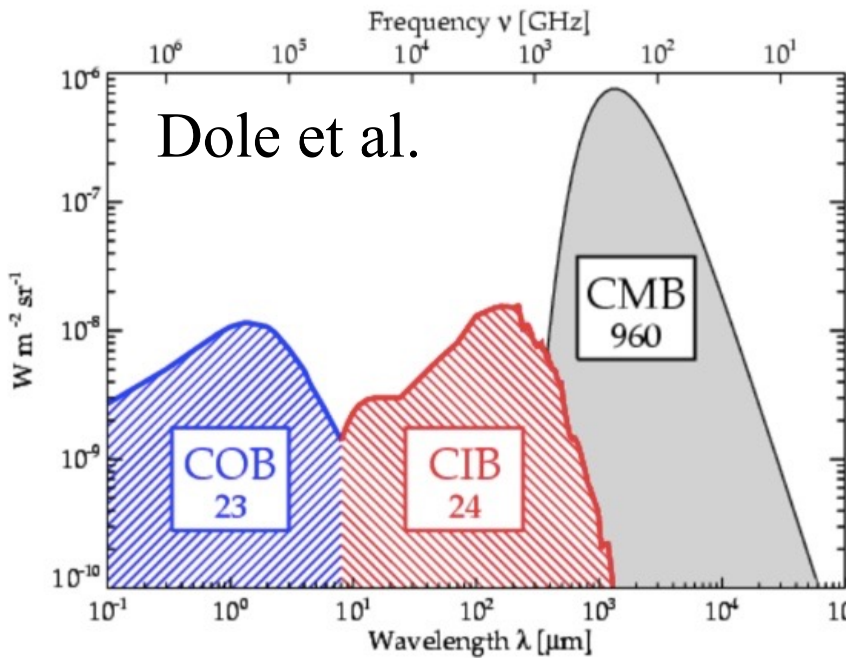
$T_{\mathrm{dust}} = 42$ K

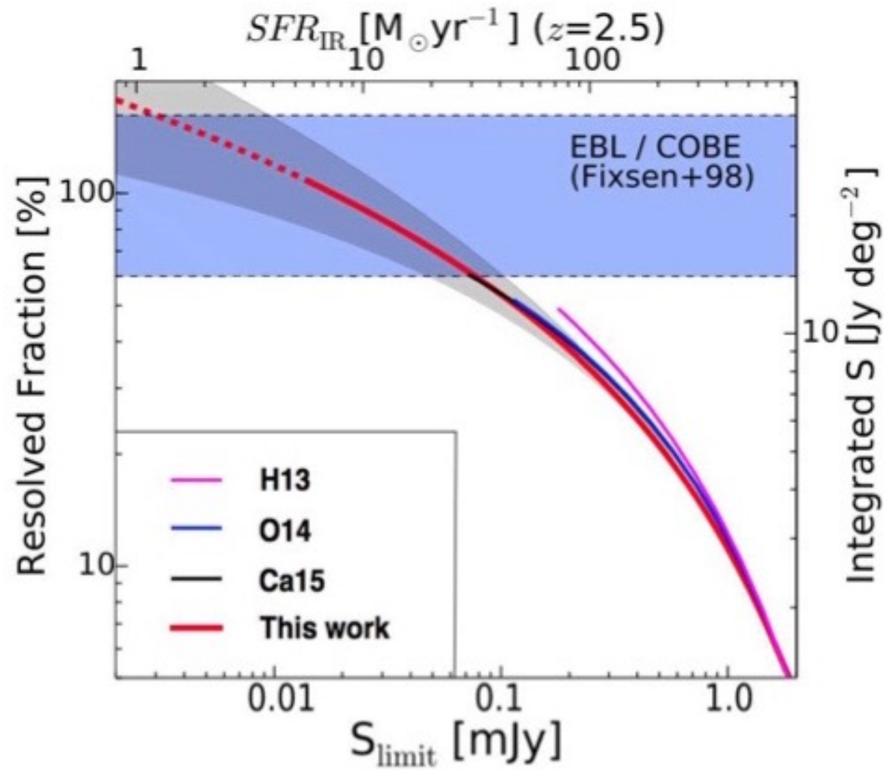
$L_{\mathrm{IR}} = 1.4 \times 10^{12}\ \mathrm{L}_{\odot}$



Detection limits:
100 arcmin^2 survey with 500 h
(Y. Tamura)

Cosmic Infrared Background





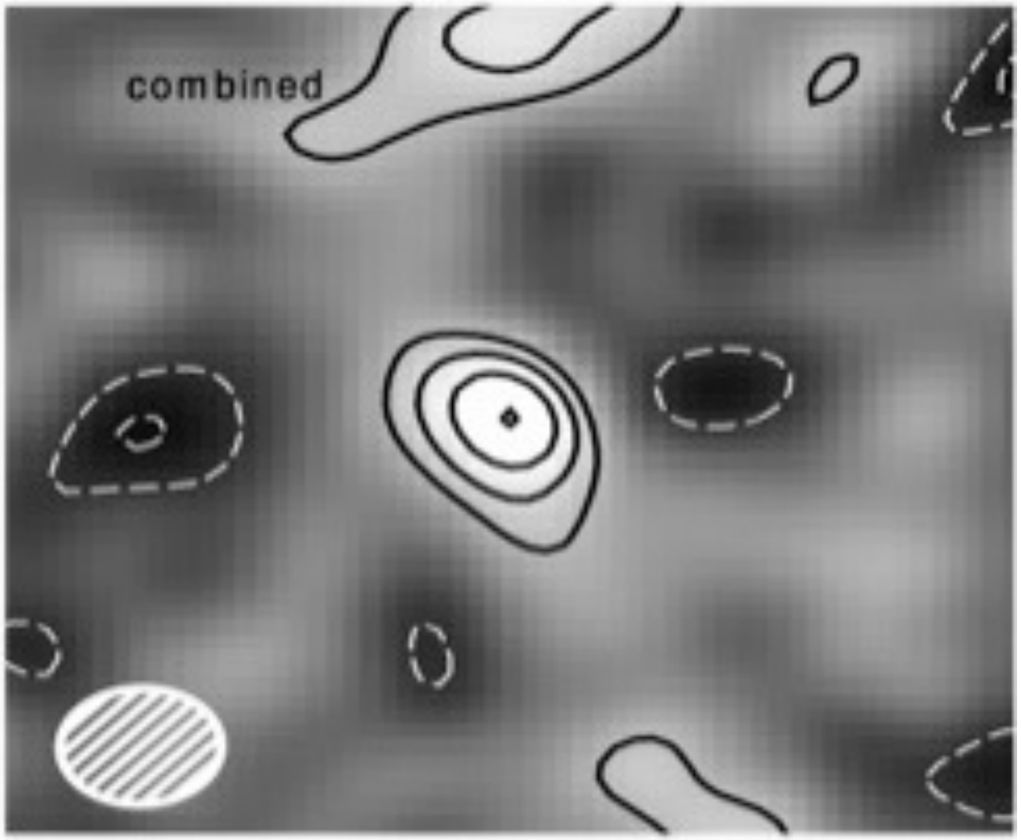
Fujimoto et al. (2016)

Dust emission is as important as stellar optical emission in star formation activities of galaxies.

CIB sources at 1.2 mm have been almost resolved into sources.

Toward Galaxies in the Epoch of Reionization ($z > 6$)

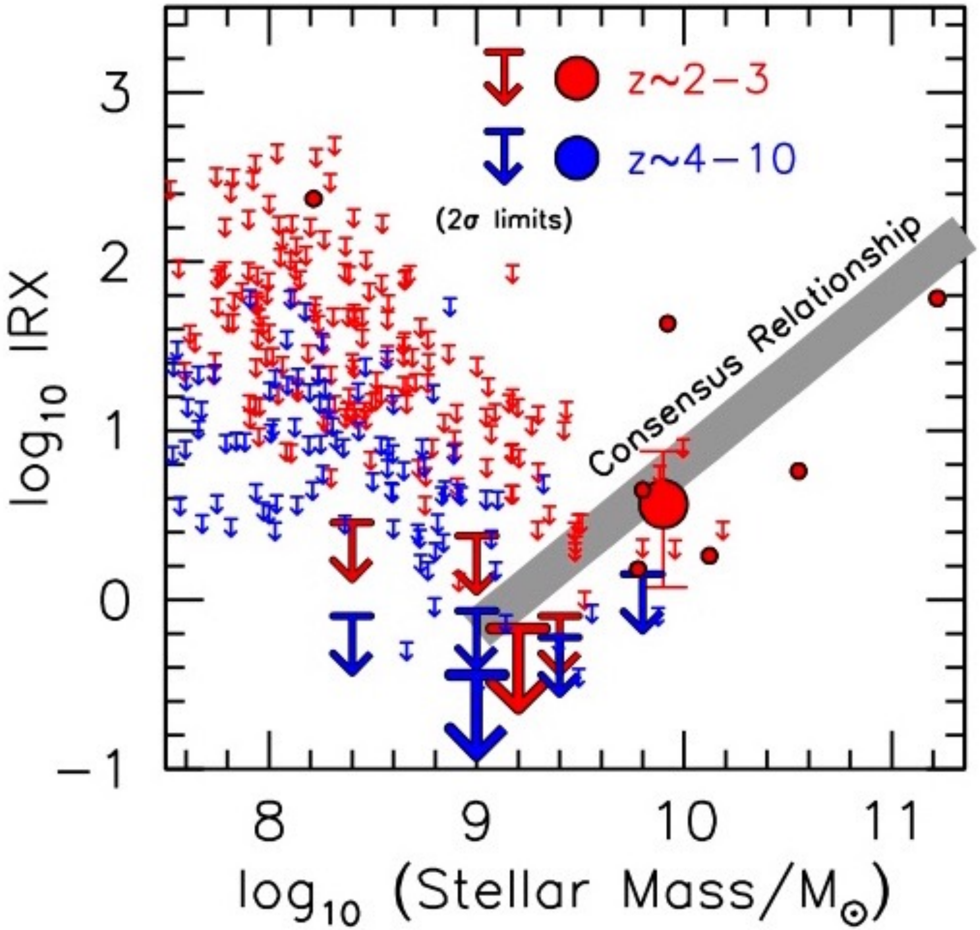
LBG at $z = 7.5$ Detected by ALMA



Watson et al. (2015)
at $z = 7.5$ (lensed LBG)

Stellar mass ~ $2\times10^9\ M_\odot$
SFR ~ $10\ M_\odot$/yr

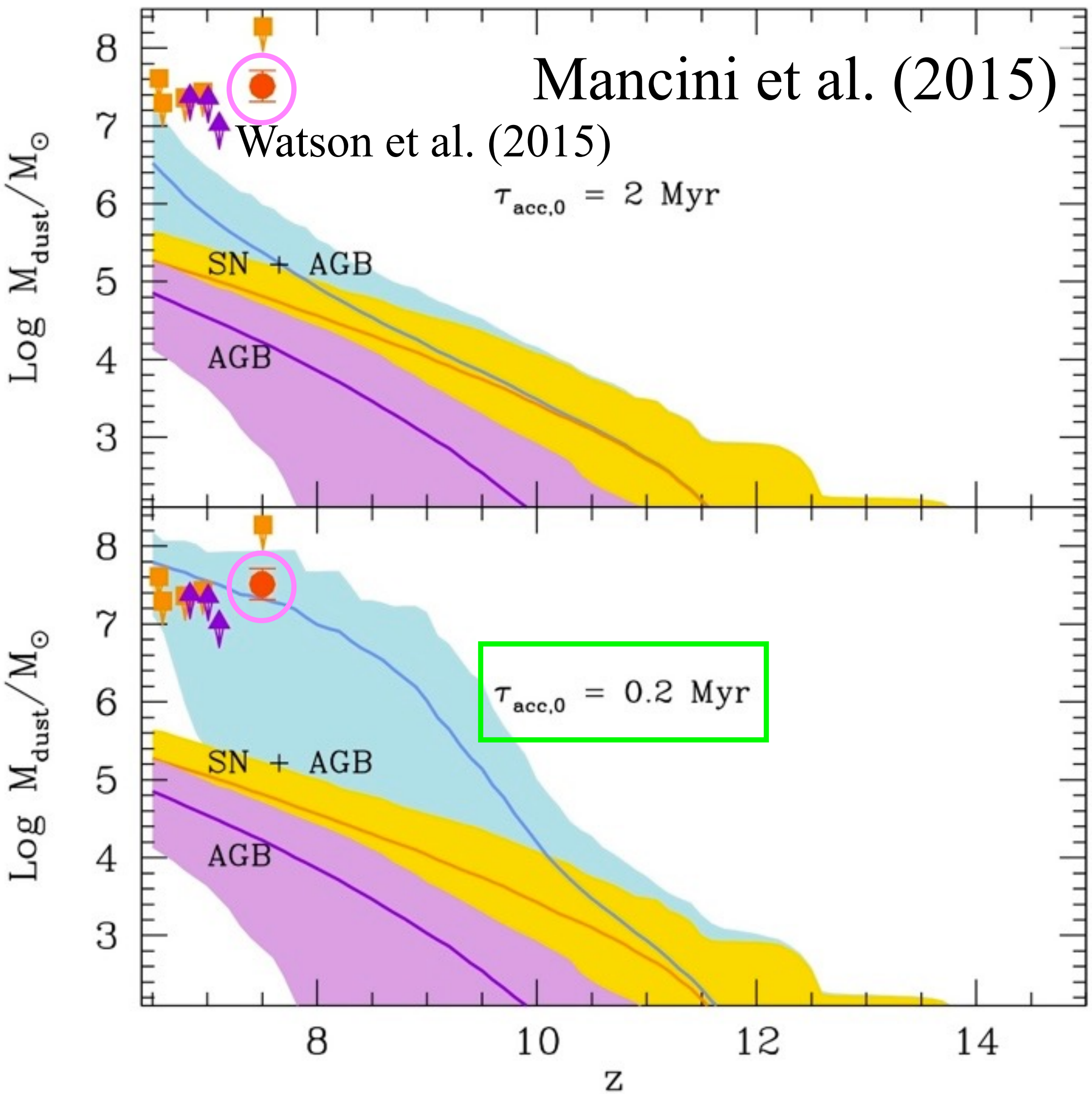
LBGs at High z



Bouwens et al. (2016)

Mostly not detected even by ALMA

Source of Dust at $z > 6$



Dust growth by accretion in the dense ISM is important for the $z = 7.5$ galaxy.

3. Dust Enrichment at High Redshift

"Chemical evolution model" of galaxies
Gas ⇒ Star ⇒ metal/dust injection

Gas

$$\frac{dM_{\rm gas}}{dt} = -\psi + E$$

Metal i

$$\frac{dM_Z}{dt} = -Z\psi + E_Z$$

Dust

$$\frac{dM_{\rm dust}}{dt} = -\mathcal{D}\psi + f_{\rm in}E_Z - \frac{M_{\rm dust}}{\tau_{\rm SN}} + \frac{M_{\rm dust}}{\tau_{\rm acc}}$$

SF

Supply from stars

$\psi = M_{\rm gas}/\tau_{\rm SF}$

SF

Destruction by SNe ~ 10^8 yr

Growth in clouds
$\tau_{\rm acc} \propto \mathcal{D}/(nZ)$

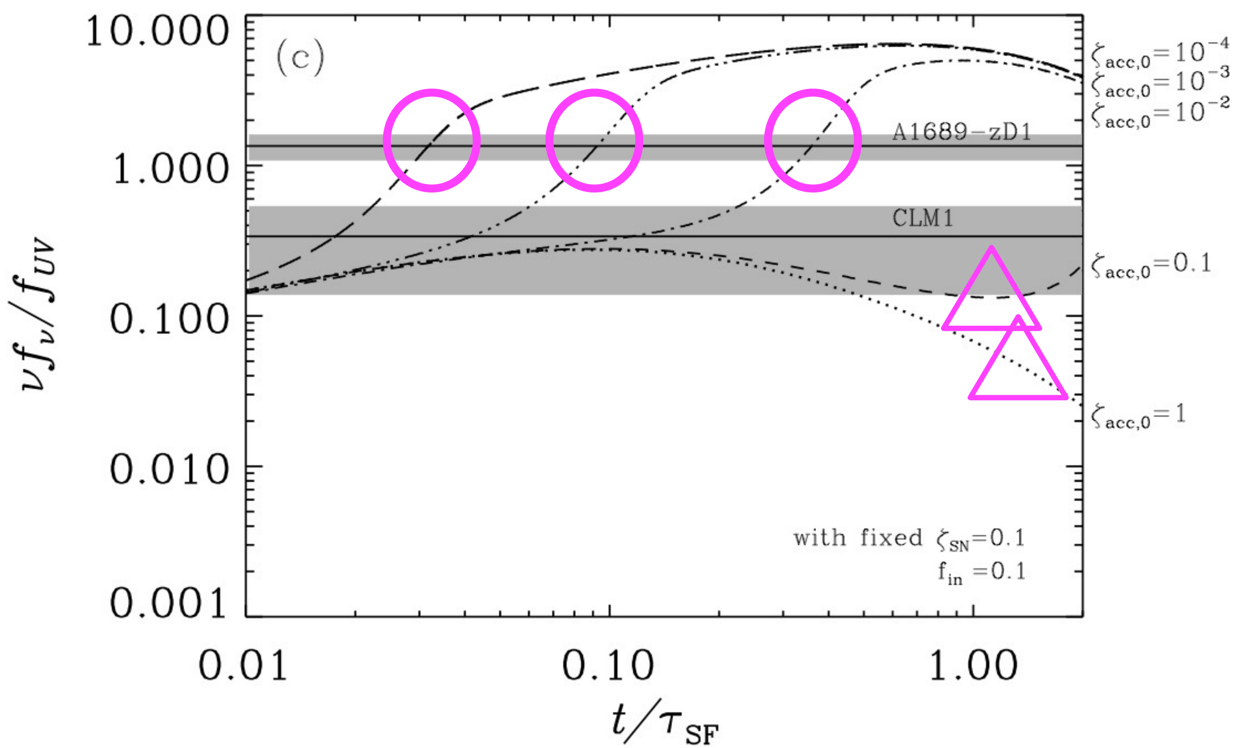
$\zeta_{\rm SN} = \tau_{\rm SN}/\tau_{\rm SF}$
$\zeta_{\rm acc} = \tau_{\rm acc}(Z_{\rm sun})/\tau_{\rm SF}$
$f_{\rm in}$

Analysis Using Dust Evolution Model

Wang, Hirashita & Hou (2016)

(1) One-zone model including dust formation (stellar sources + accretion) and destruction (SNe).
(2) Dust emission is calculated consistently with the stellar radiation field and dust mass.

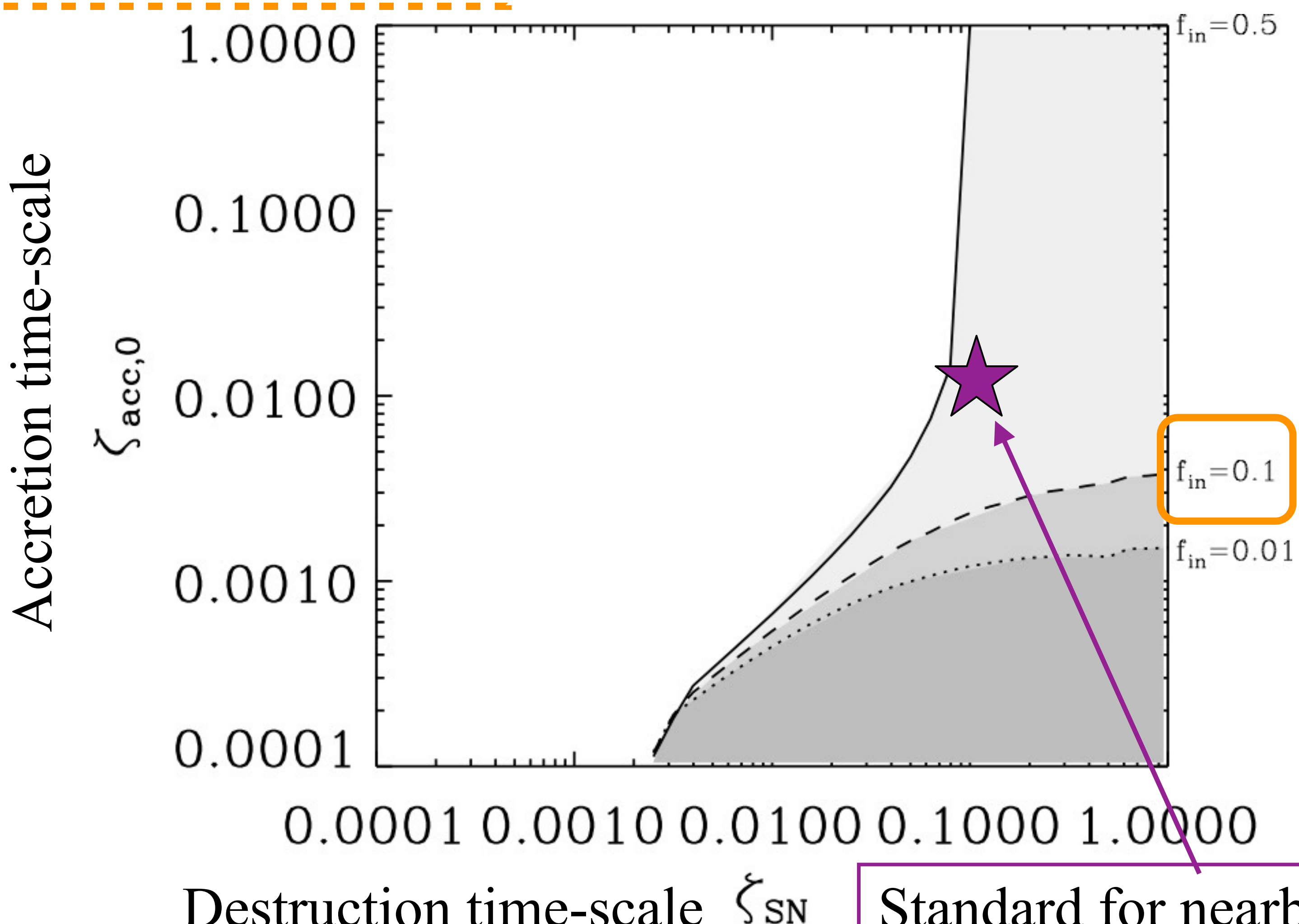
$\zeta_{SN} = \tau_{SN}/\tau_{SF}$
$\zeta_{acc} = \tau_{acc}(Z_{sun})/\tau_{SF}$
f_{in}



Constraint from the *z* = 7.5 LBG

Wang, Hirashita, & Hou (2016)

Additional constraint
Z < 0.1 Zsun

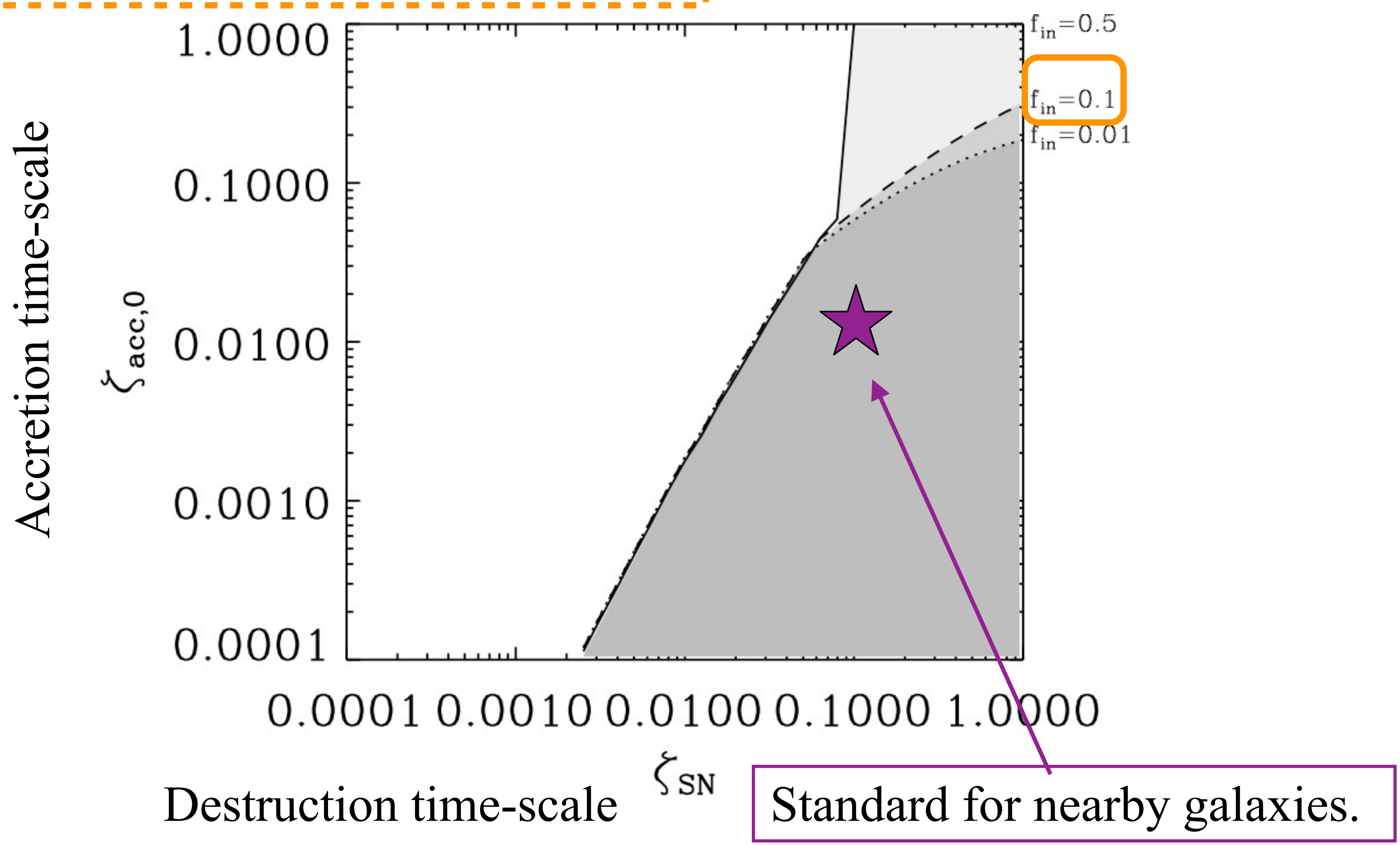


Standard for nearby galaxies.

Constraint from the z = 7.5 LBG

Wang, Hirashita, & Hou (2016)

By allowing for metal-rich solutions



ALMA Detection of LBGs at $z > 6$ Requires…

Wang, Hirashita, & Hou (2016)

(1) Very efficient grain growth by accretion (10–100 times more efficient than nearby galaxies) if their metallicities are $\lesssim 0.1\ Z_\odot$ (Mancini et al. 2015);

(2) They are solar-metallicity objects; or

(3) Very high condensation efficiency in stellar ejecta.

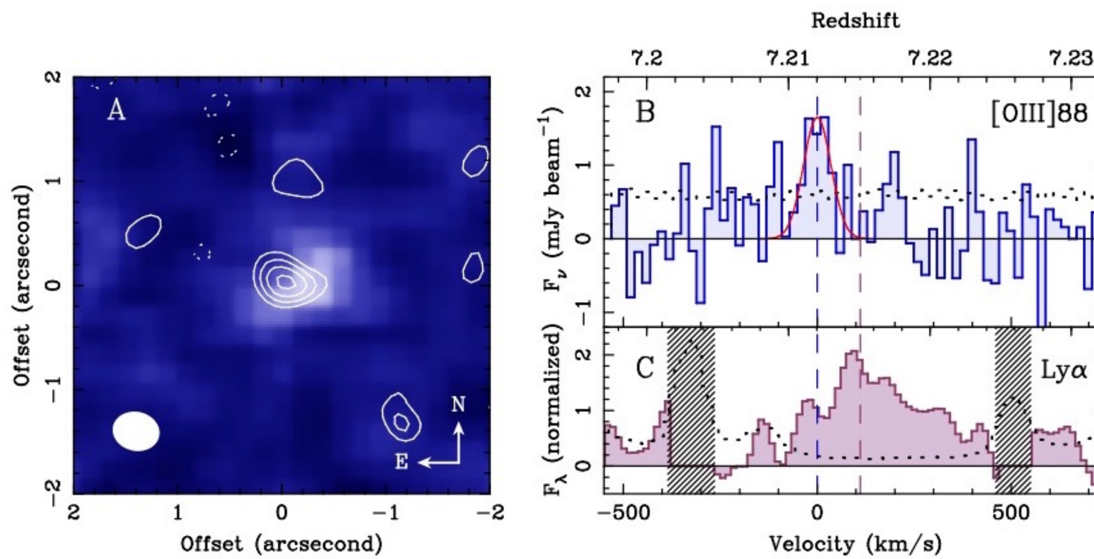
Toward SKA (Era)

(1) Deeper ALMA observations.
(2) Development of dust evolution models and radiation transfer codes. → Escape fraction of ionizing photons.
(3) Relation with gas components ([C II], [O III], CO).

Theoretical modeling

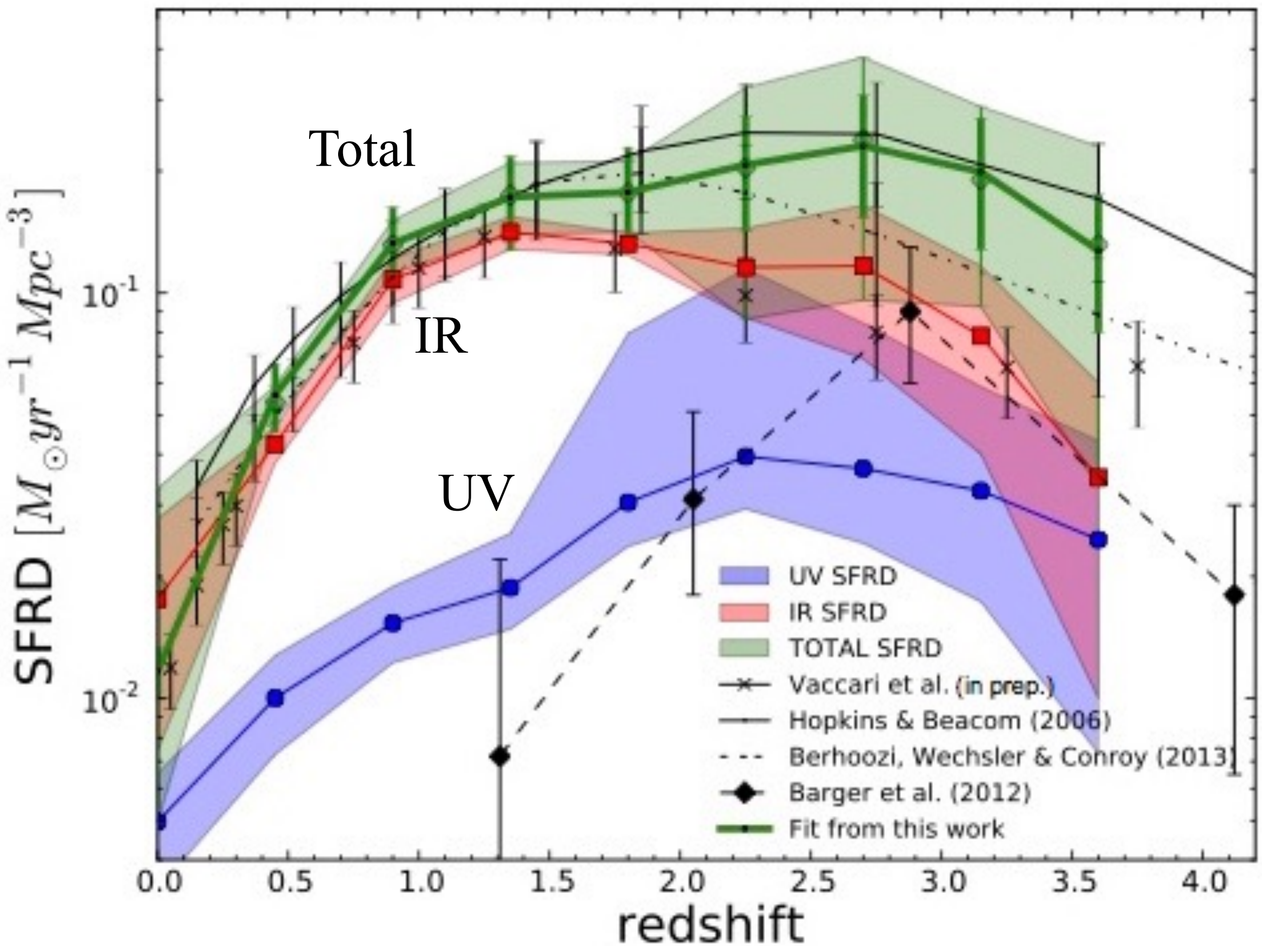
Relation to H I.

Inoue et al. (2016)



Thank you.

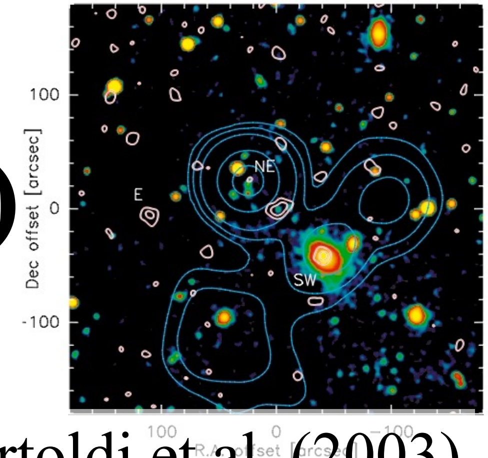
SFR Traced by Dust Emission



Star formation rate traced by FIR dust emission becomes more and more important as we go to the epoch of SFR peak.

Burgarella et al. (2013)
See also Takeuchi et al. (2005)

A Lot of Dust at $z > 5$
(10^9 yr after the Big Bang)



Bertoldi et al. (2003)

Quasars

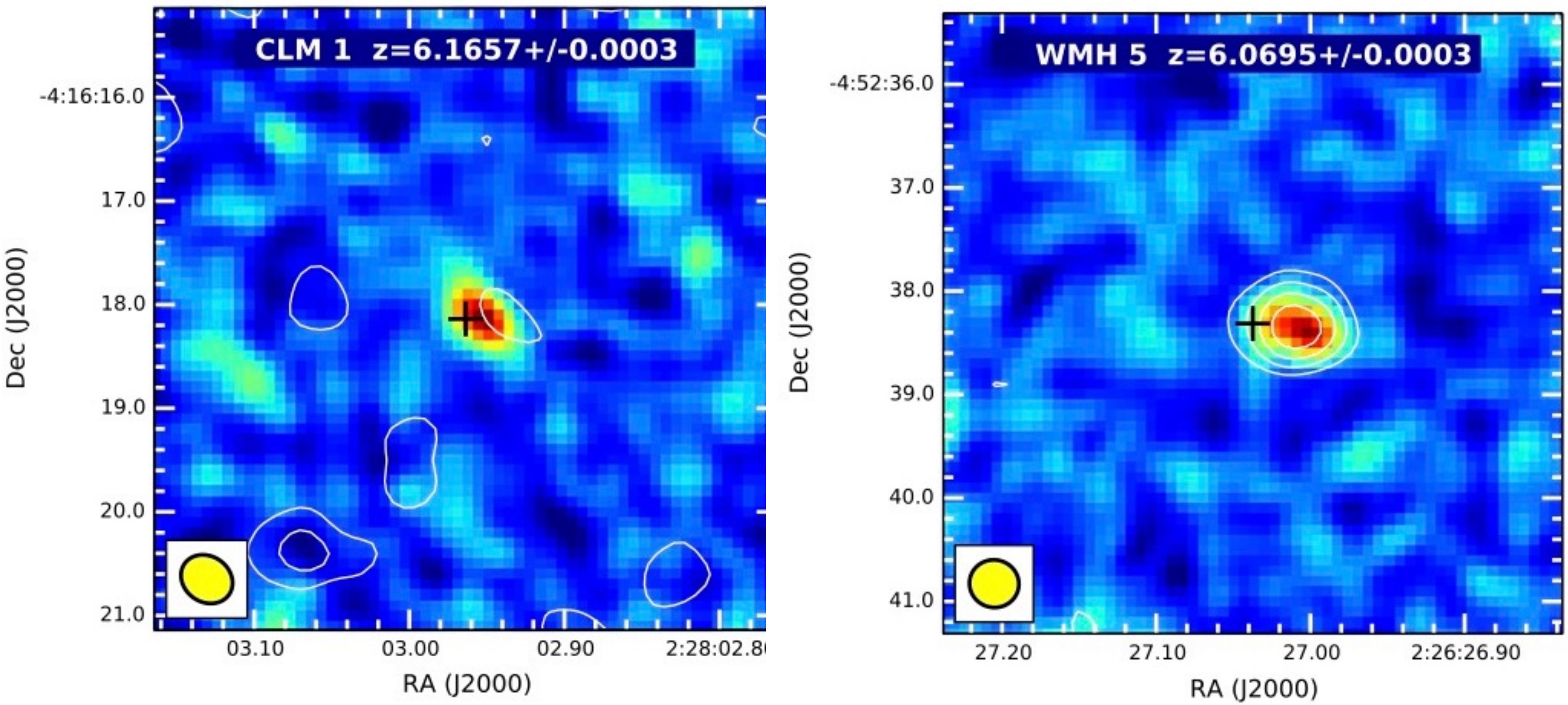
age < 1 Gyr

No.	QSO	z	M_{dust} ($10^8\ M_\odot$)	M_{gas} ($10^{10}\ M_\odot$)	$M_{dyn} \sin^2 i$ ($10^{10}\ M_\odot$)	$\frac{M_{gas}}{M_{dust}}$	T_{dust} (K)
1	J0338+0021	5.03	7.1 ± 0.6	2.2[a]	3.0[a]	31	45.6[d]
2	J0840+5624	5.85	4.7 ± 0.9	2.5[b]	24.2[b]	53	...
3	J0927+2001	5.77	7.2 ± 1.1	1.8[b]	11.8[b]	25	51.1[d]
4	J1044–0125	5.74	2.7 ± 0.6	0.7[b]	0.8[b]	26	...
5	J1048+4637	6.23	4.3 ± 0.6	1.0[b]	4.5[b]	23	<40[e]
6	J1148+5251	6.42	5.9 ± 0.7	1.6[c]	4.5[c]	27	55.0[f]
7	J1335+3533	5.93	3.4 ± 0.7	1.8[b]	3.1[b]	53	...
8	J1425+3254	5.85	3.3 ± 0.7	2.0[b]	15.6[b]	60	...
9	J2054–0005	6.06	3.4 ± 0.8	1.2[b]	4.2[b]	35	...

Michałowski et al. (2010)

LBGs at *z* ~ 6

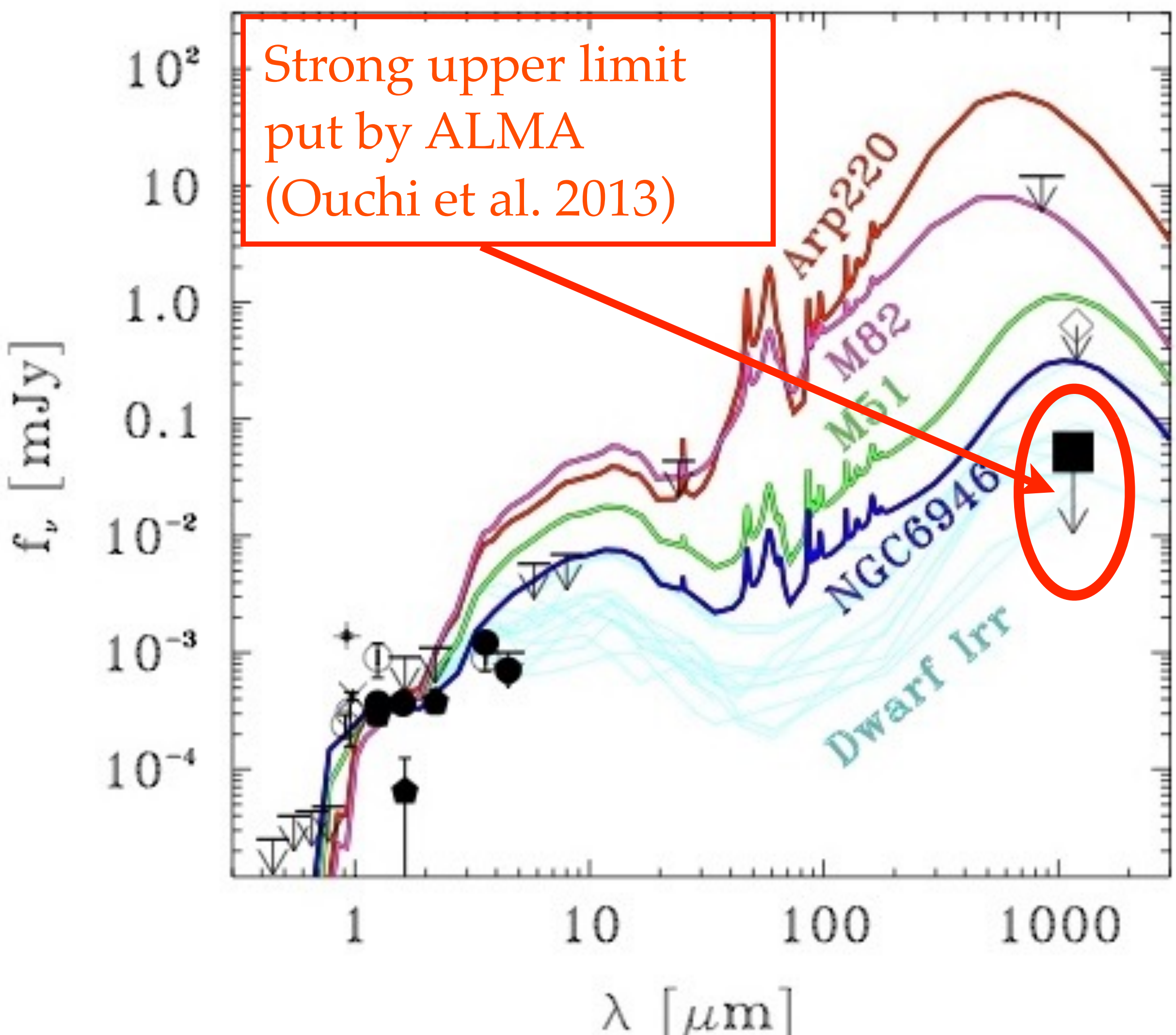
Willott et al. (2015)



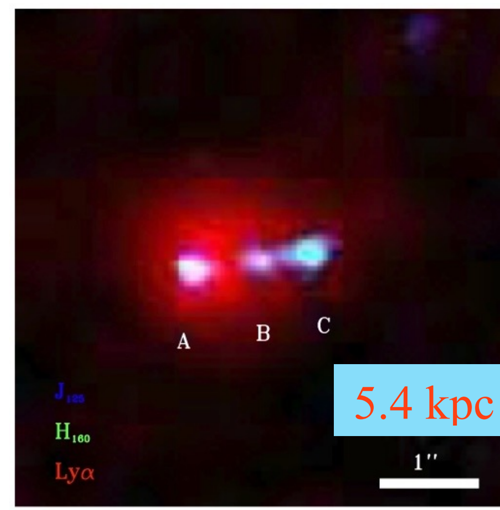
Color: [C II] 158 μm, Contour: dust continuum
Cross: center of NIR

Poor Dust Content in Lyα Emitters

Ouchi et al. (2013)



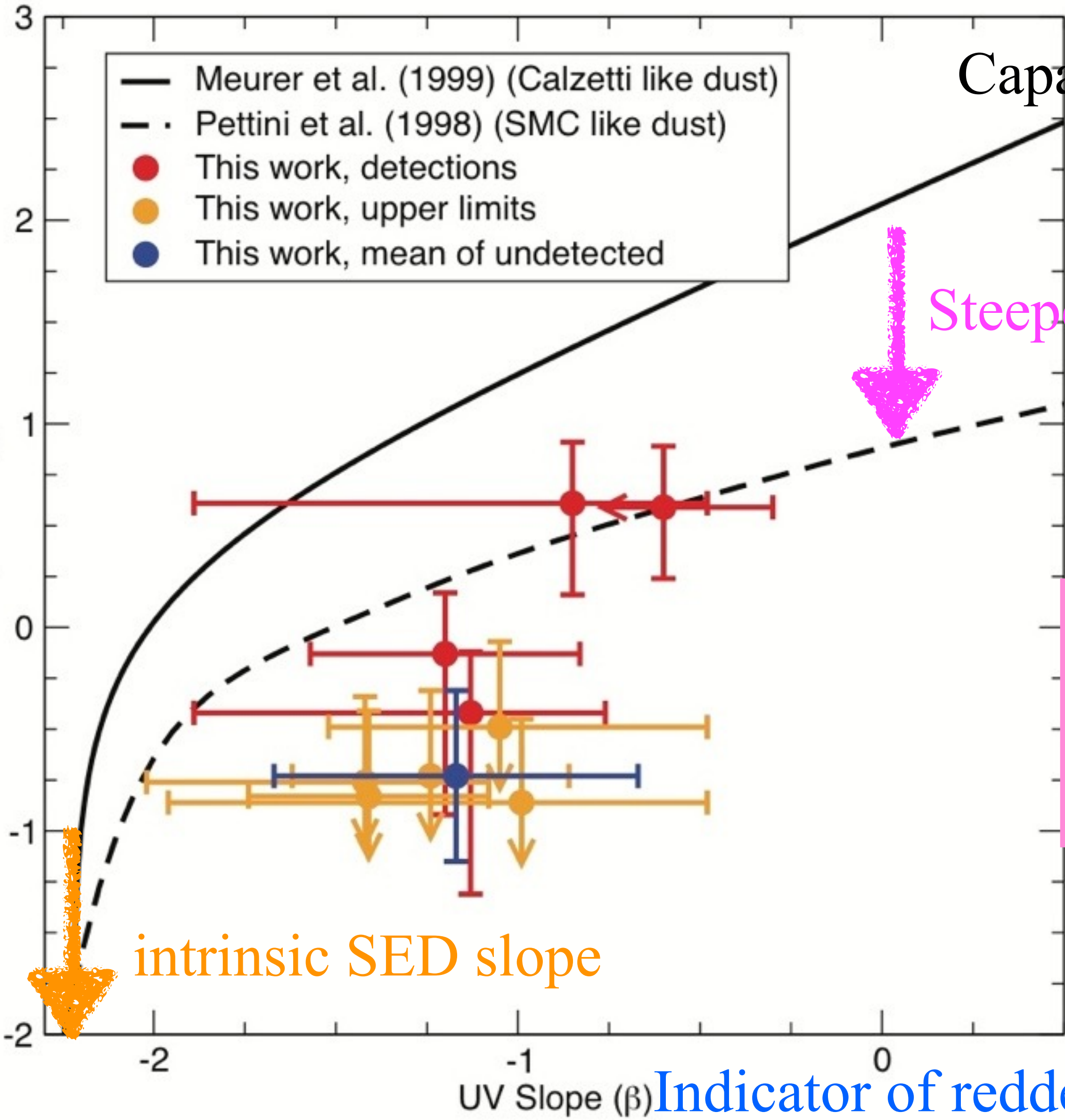
"Himiko"
Giant Lyα Emitter
at $z = 6.6$
(age ~ 100–300
Myr)



Inefficient FIR emission compared with nearby galaxies.

LBGs at z = 5–6

Capak et al. (2015): z = 5–6



Indicator of total dust absorption

Indicator of reddening by dust

4/9 typical (1–4 L^*)LBGs are detected by ALMA