dust in the early Universe

Raffaella Schneider
Sapienza Università di Roma

why the first dust?

i. increase H_2 formation and cooling

ii. lower the Jeans mass in star forming clouds at low metallicity

iii. affect the UV luminosity of the sources of reionization

iv. change the colors of the most distant galaxies

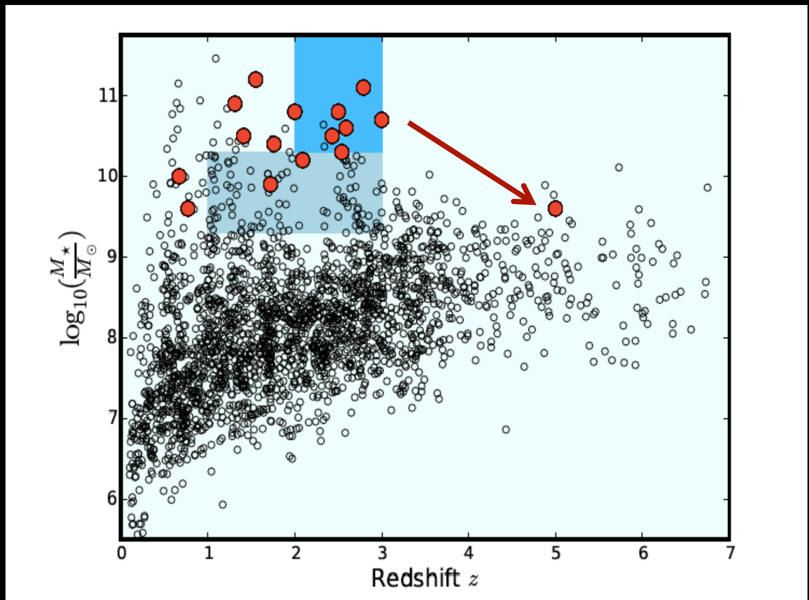
dust changes the colors of the most distant galaxies

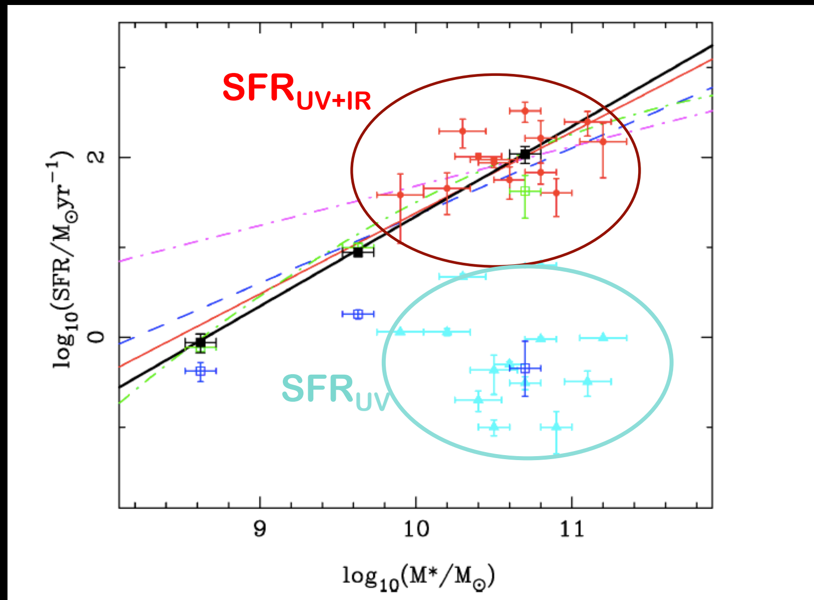
The ALMA view of the Hubble Ultra Deep Field - Dunlop et al. 2016

Credit:NASA/ESA/ESO/J. Dunlop

dust changes the colors of the most distant galaxies

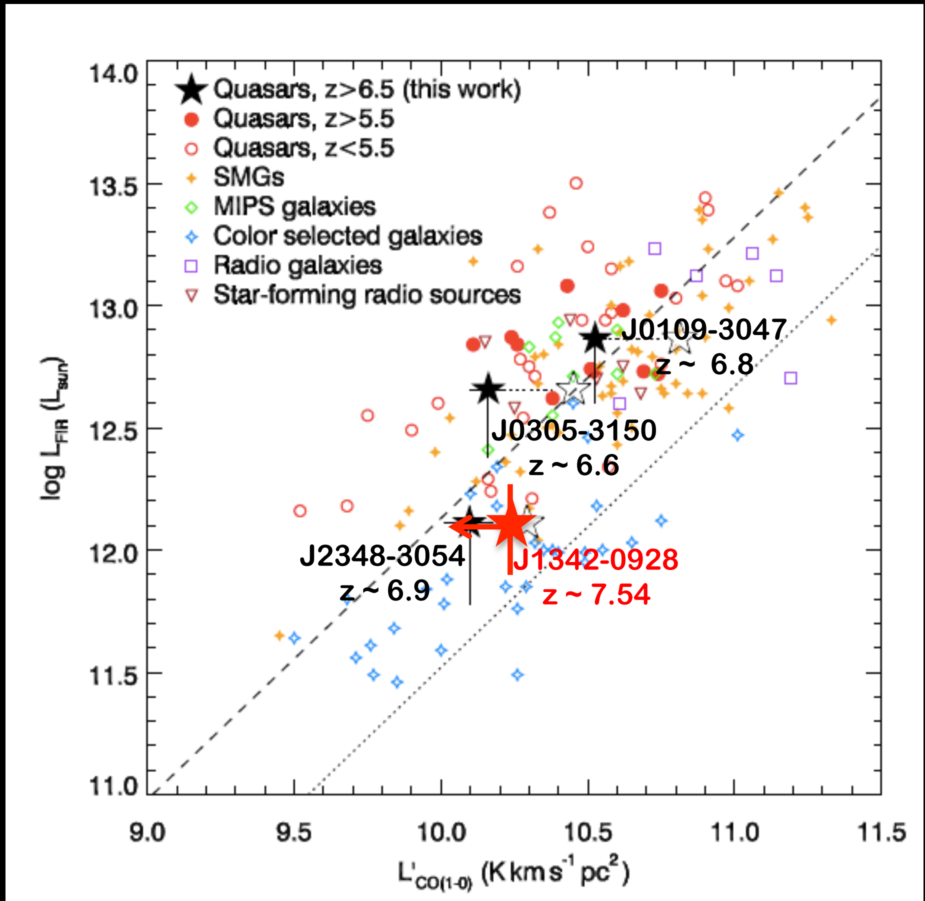
all the objects that ALMA sees appear to be massive star-forming galaxies



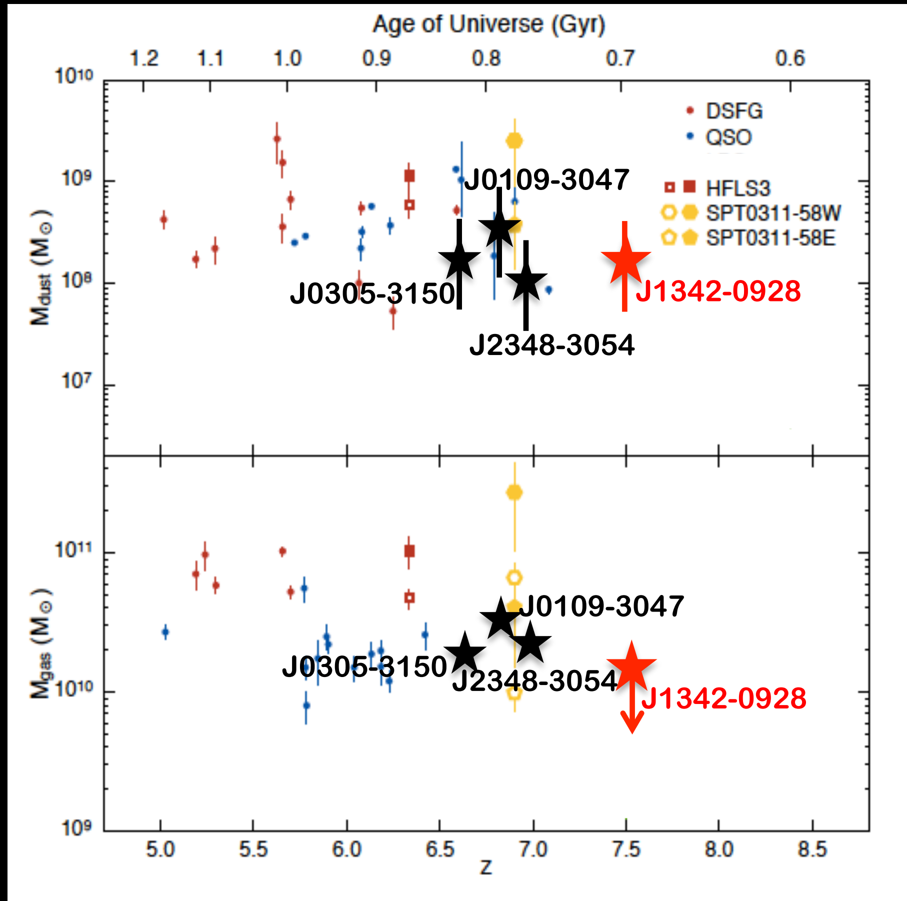


Dunlop et al. 2016

the dust mass in “extreme” galaxies at z ~ 6: dusty SF galaxies and quasar hosts



Venemans et al. 2017a,b



Marrone et al. 2017

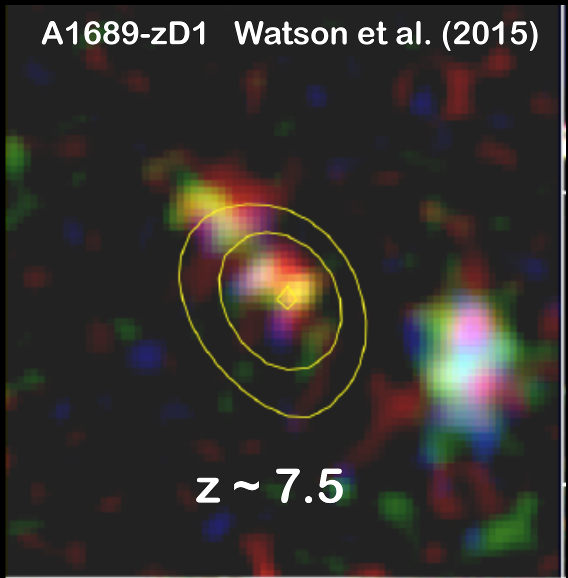
Valiante et al. 2014, 2015

the dust mass in normal star forming galaxies at z > 6

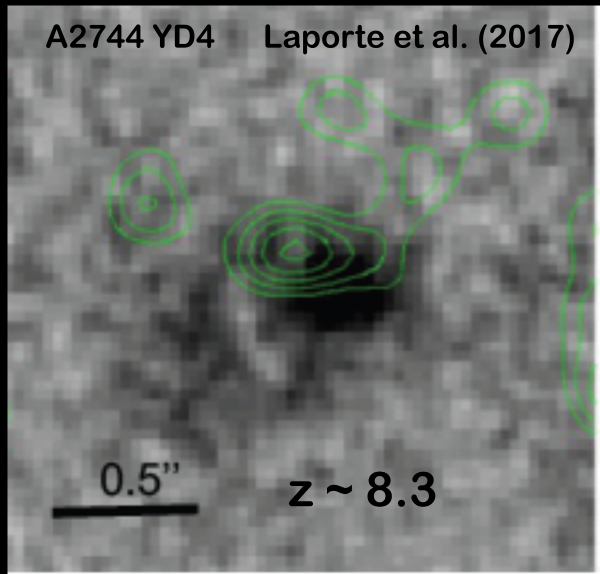
fainter dusty star forming galaxies are hard to detect at high z

but are key to understand what determines the dust content in galaxies

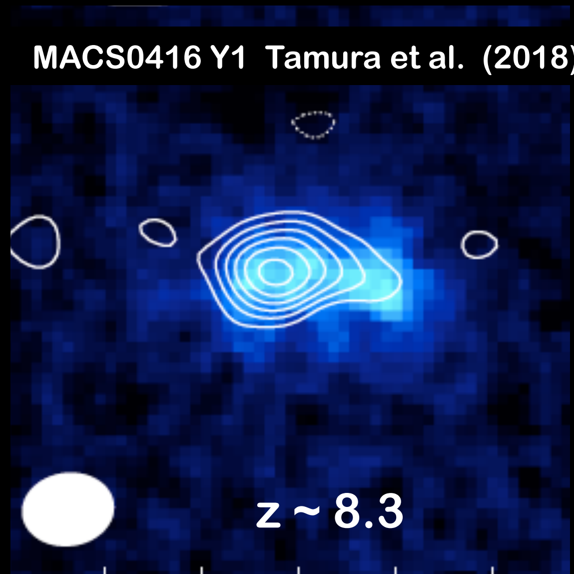
exploiting the power of gravitational lenses



M_{star} ~ 2 10^9 M_{sun} SFR ~ 10 M_{sun}/yr
M_{dust} ~ (3 – 6) 10^7 M_{sun}



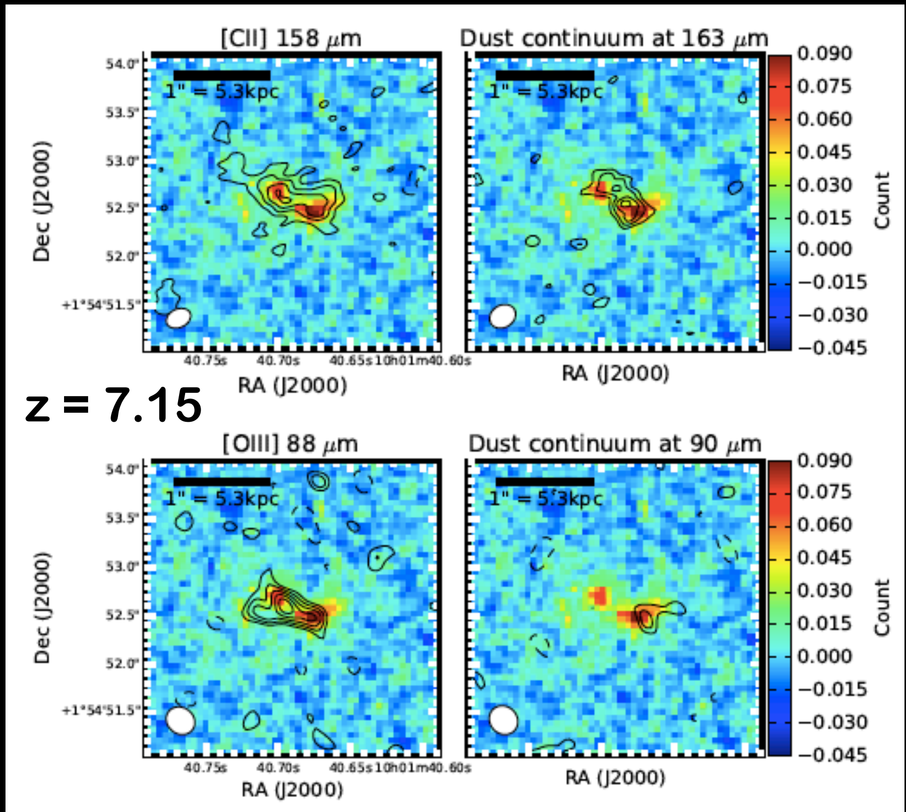
M_{star} ~ 2 10^9 M_{sun} SFR ~ 20 M_{sun}/yr
M_{dust} ~ 6 10^6 M_{sun}



M_{star} ~ 5 10^9 M_{sun} SFR ~ 13 M_{sun}/yr
M_{dust} ~ 4 10^6 M_{sun}

merger-induced disturbed morphologies

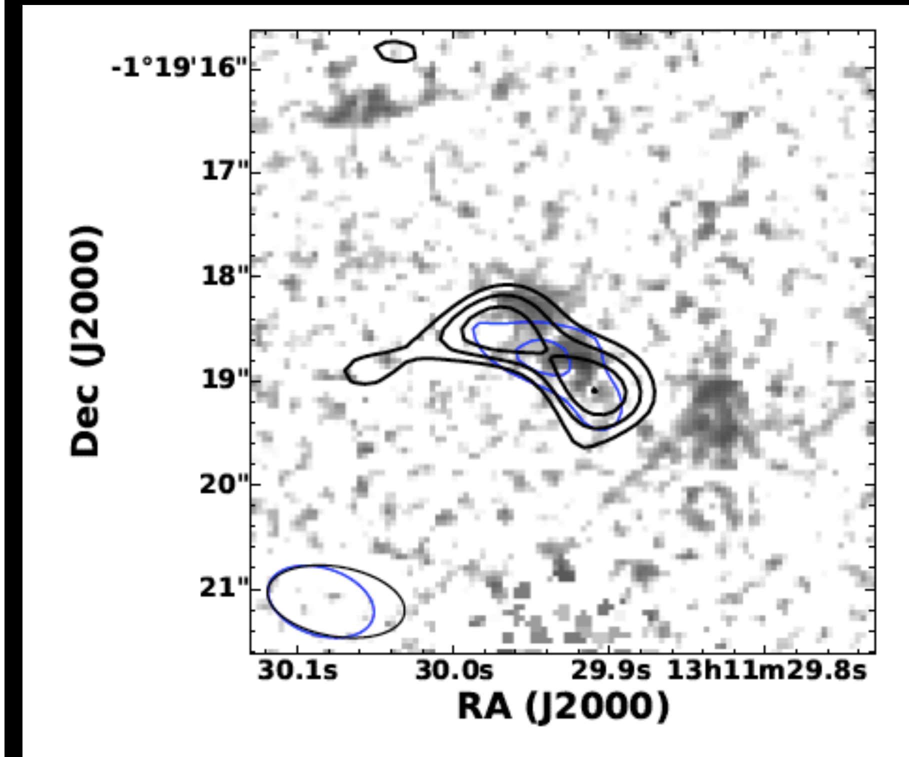
B14-65666 Hashimoto et al. 2018



M_{star} ~ 2.1 10^9 M_{sun} SFR ~ 143 M_{sun}/yr

M_{dust} ~ (1 – 6) 10^7 M_{sun}

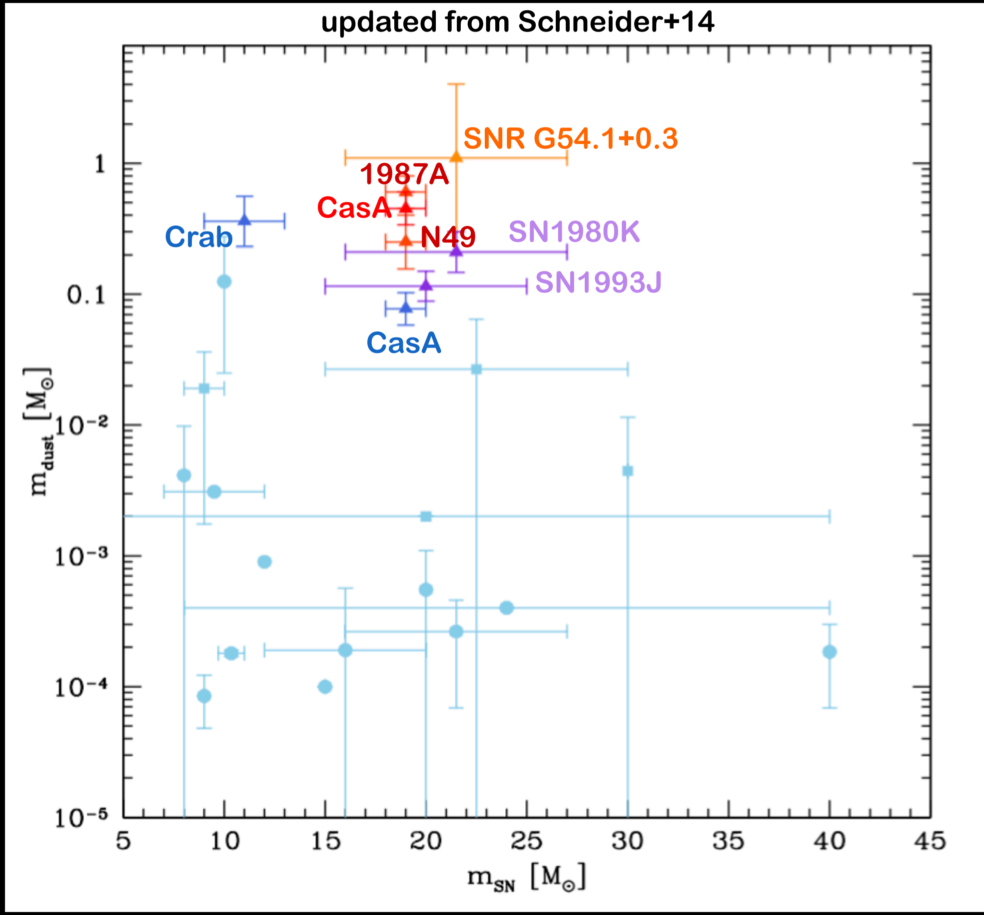
A1689-zD1 Knudsen et al. (2017)



what are the sources of dust?

stellar sources of dust: SNe

observations of SNe and SN remnants show signatures of the presence of dust associated with the ejecta

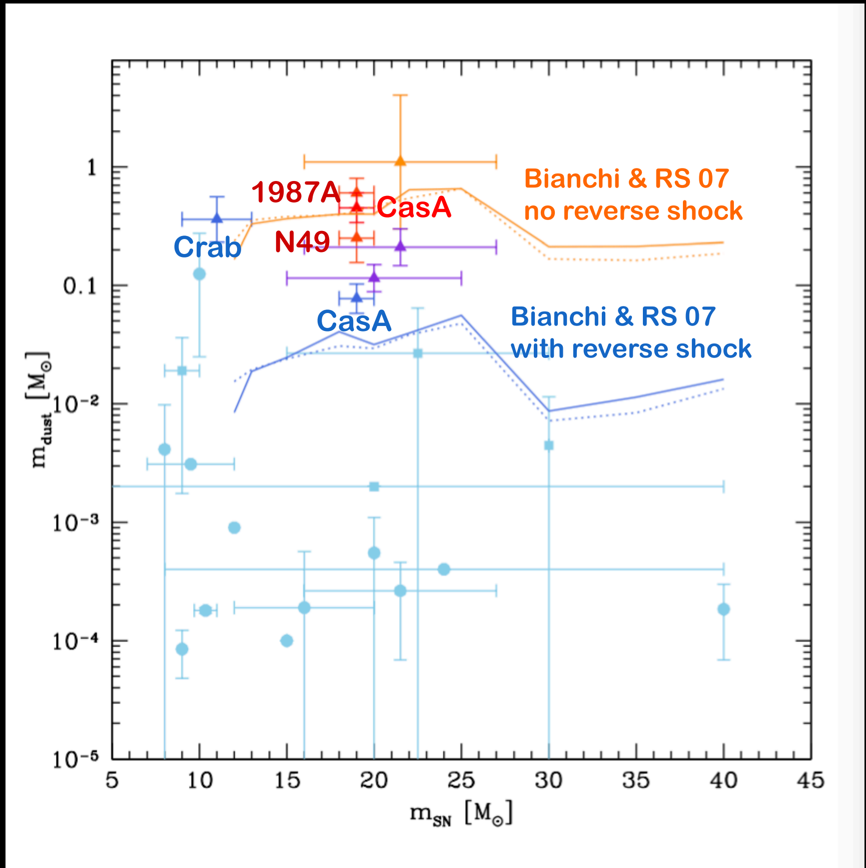


Gall+11 Gomez+12, Dunne+09, Barlow+10, Matsuura+11, Otsuka+10, de Looze+17, Temim+17, Bevan+17

Kozasa & Hasegawa 1987; Todini & Ferrara 2001; Nozawa et al 2003; Schneider, Ferrara & Salvaterra 2004;
Bianchi & Schneider 2007; Chercheneff & Dwek 2010; Fallest et al. 2011; Sarangi & Cherchneff 2013; Marassi+2014, 2015, 2017; Bocchio+2016

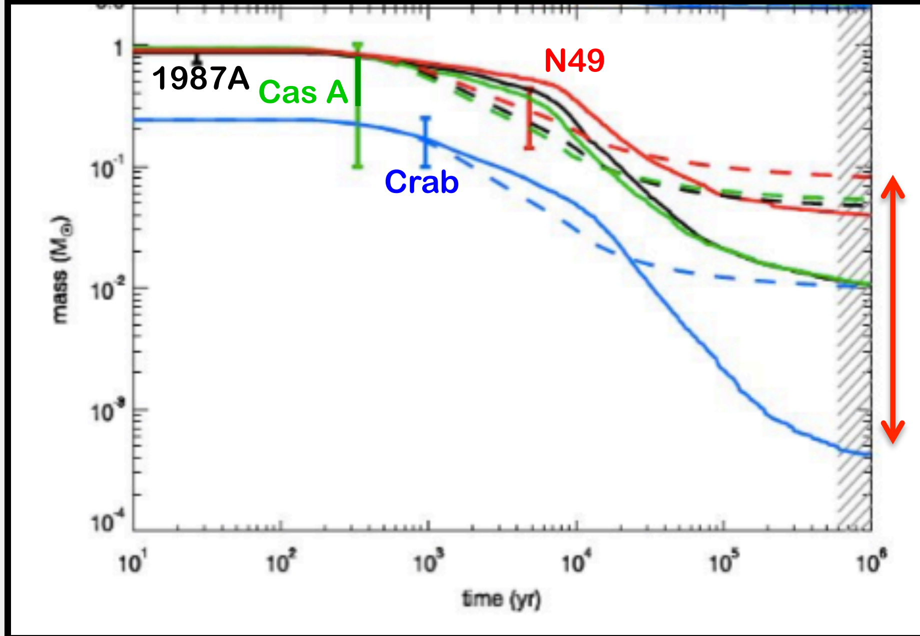
SN dust yields: comparison with observations

updated from Schneider+14



Gall+11 Gomez+12, Dunne+09, Barlow+10, Matsuura+11, Otsuka+10, de Looze+17, Temim+17, Bevan+17

Marassi+14,15; Bocchio+16



Nozawa et al 2006, 2007; Bianchi & Schneider 2007; Silvia et al. 2010, 2012; Marassi et al. 2014, 2015; Bocchio et al. 2016; Micelotta+2016

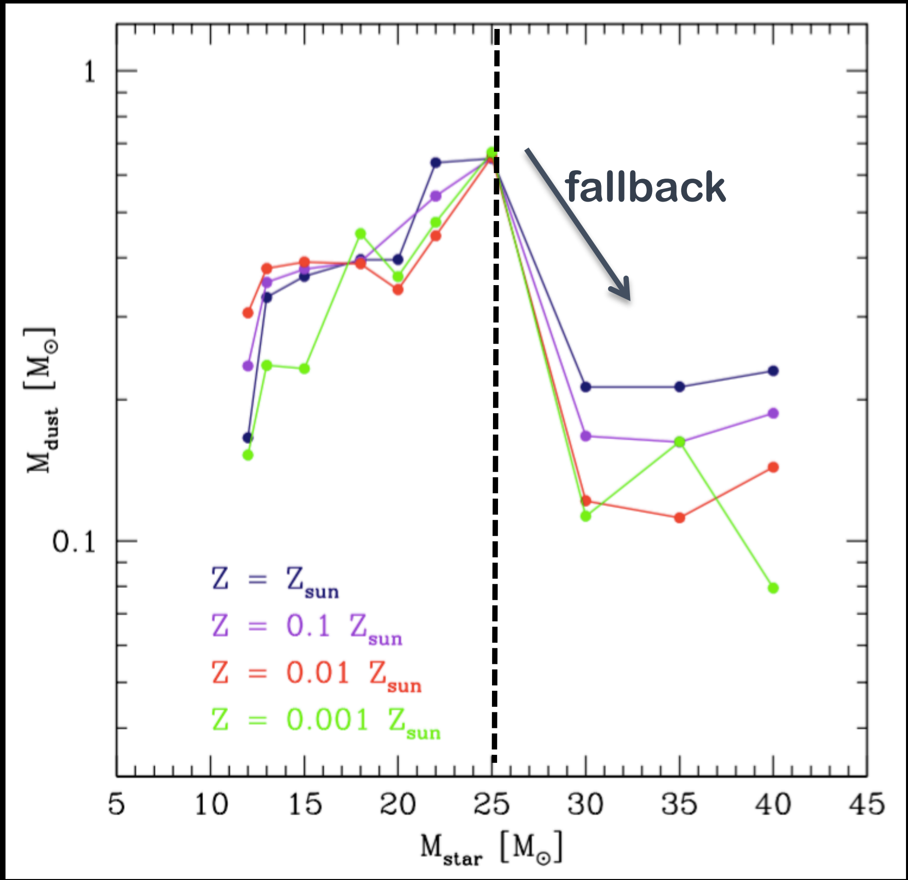
theoretical SN dust yields are in broad agreement with available data

the mass of SN dust that will enrich the ISM << than observed in SN remnants with t_{age} < 10^4 yr

SN dust yields: dependence on metallicity

Kozasa & Hasegawa 1987; Todini & Ferrara 2001; Nozawa et al 2003; Schneider, Ferrara & Salvaterra 2004;
Bianchi & Schneider 2007; Chercheneff & Dwek 2010; Fallest et al. 2011; Sarangi & Cherchneff 2013; Marassi+2014, 2015

fixed energy explosion models (1.2 10^{51} erg) and fully mixed ejecta



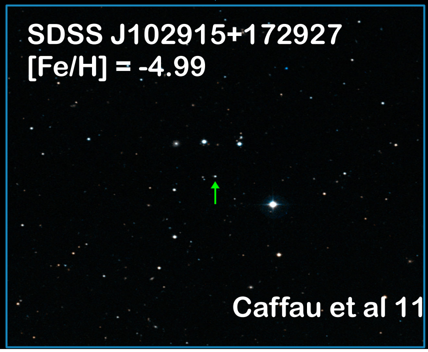
Bianchi & Schneider (2007)

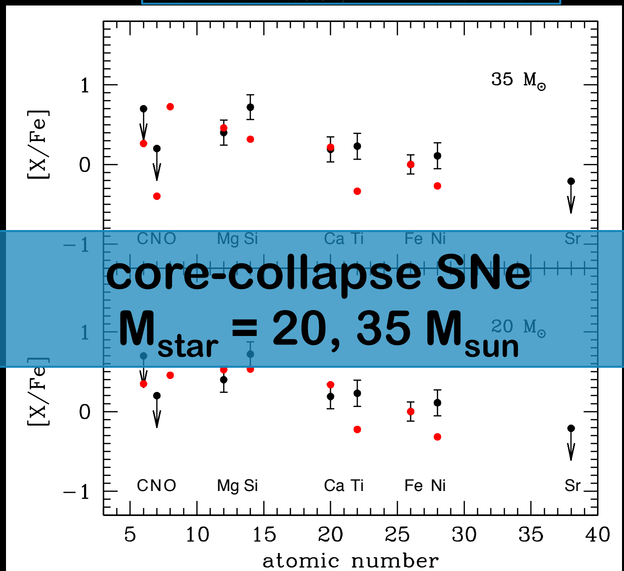
Pop III supernova yields:

constraints from stellar archaeology

C-normal and C-rich stars

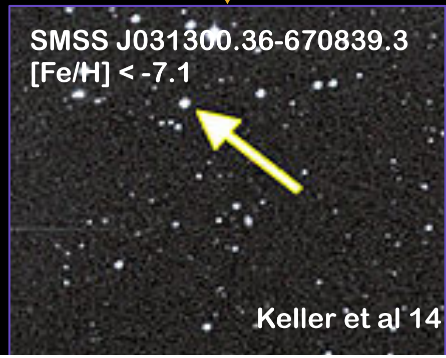
see also Chiaki+2015,2017

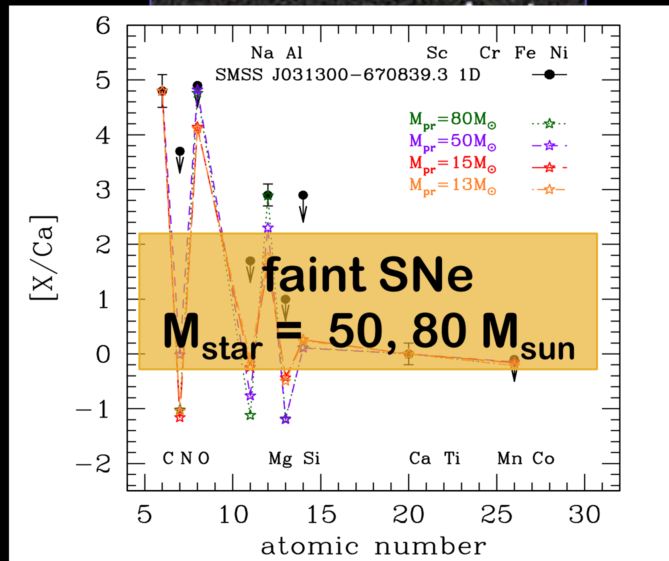




core-collapse SNe
M_{star} = 20, 35 M_{sun}

Schneider et al. 2012





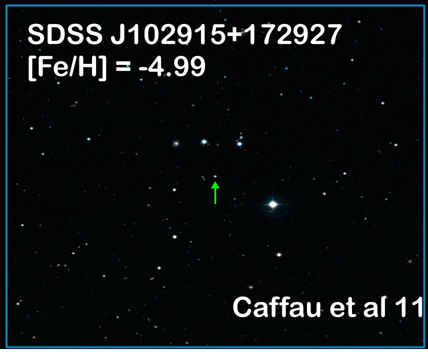
faint SNe
M_{star} = 50, 80 M_{sun}

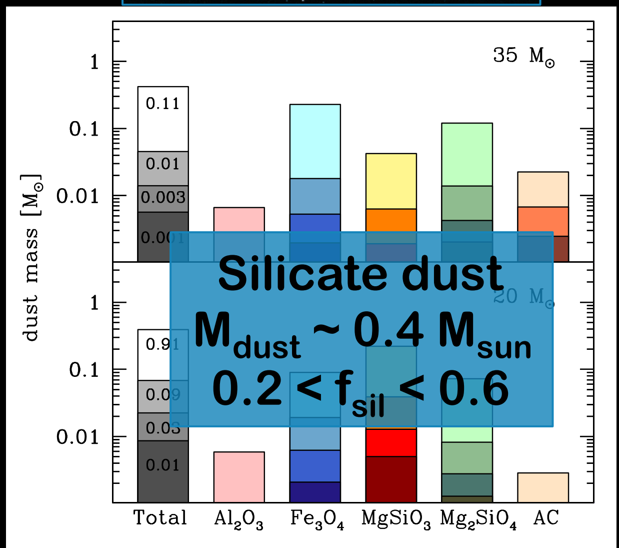
Marassi et al. 2014

Pop III supernova yields:

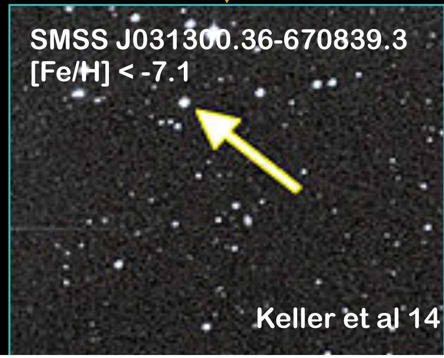
constraints from stellar archaeology

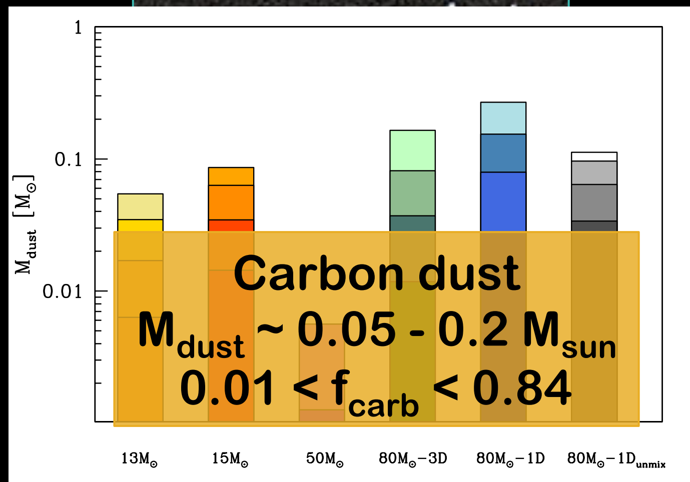
C-normal and C-rich stars





Schneider et al. 2012





Marassi et al. 2014

stellar sources of dust: AGB

their role in the early Universe depends on the mass- and metallicity-dependence of the dust yields

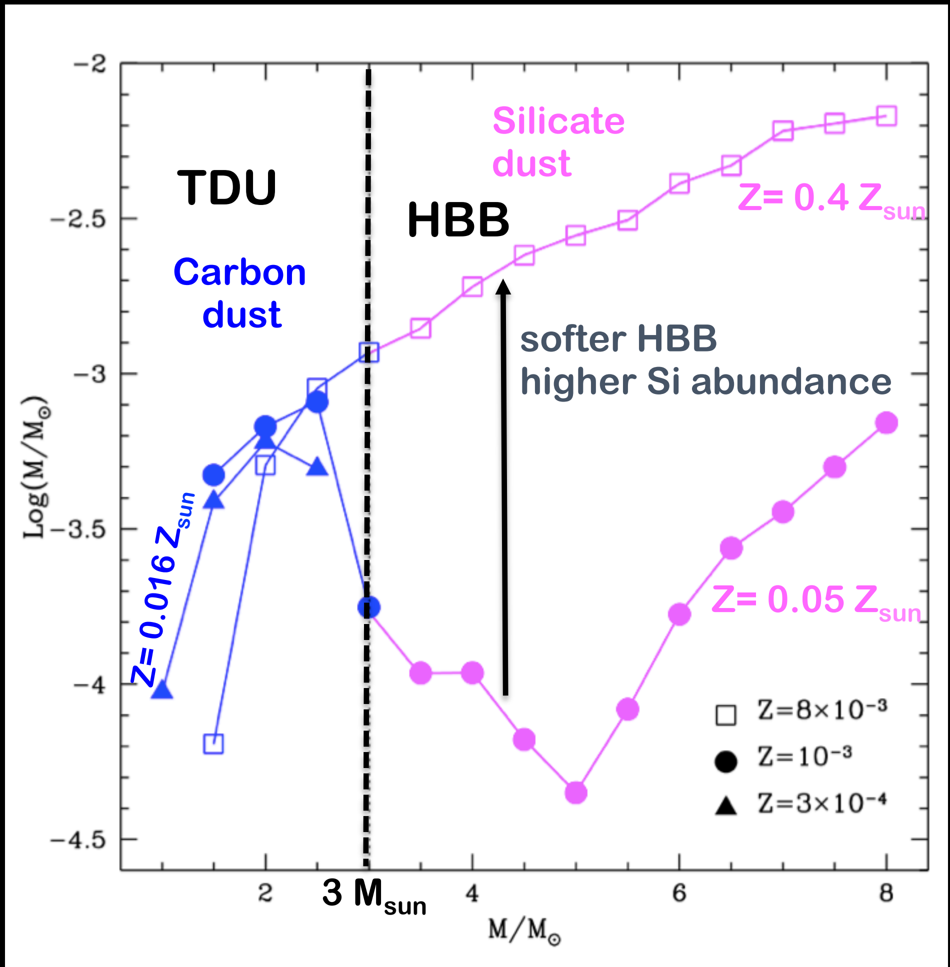
Ferrarotti & Gail 01; 02; 06; Zhukovska+08; Nanni+13; Ventura+12a,b; Di Criscienzo+13; Dell'Agli+14; Ventura+14 ; dell'Agli+15

- stationary spherically symmetric wind
- grain growth (olivine, pyroxene, quartz, iron, corundum, silicon carbide, carbon)
- numerical integration of stellar models (ATON code, Ventura+98)
  - Third Dredge Up: surface C enrichment
  - Hot Bottom Burning: C (and O) surface depletion

Grid of AGB/SAGB stars with $1\ M_{sun} \leq M \leq 8\ M_{sun}$ and $0.01\ Z_{sun} \leq Z \leq Z_{sun}$

dust yields from AGB stars: mass and metallicity dependence

Ventura+12b; Di Criscienzo+13



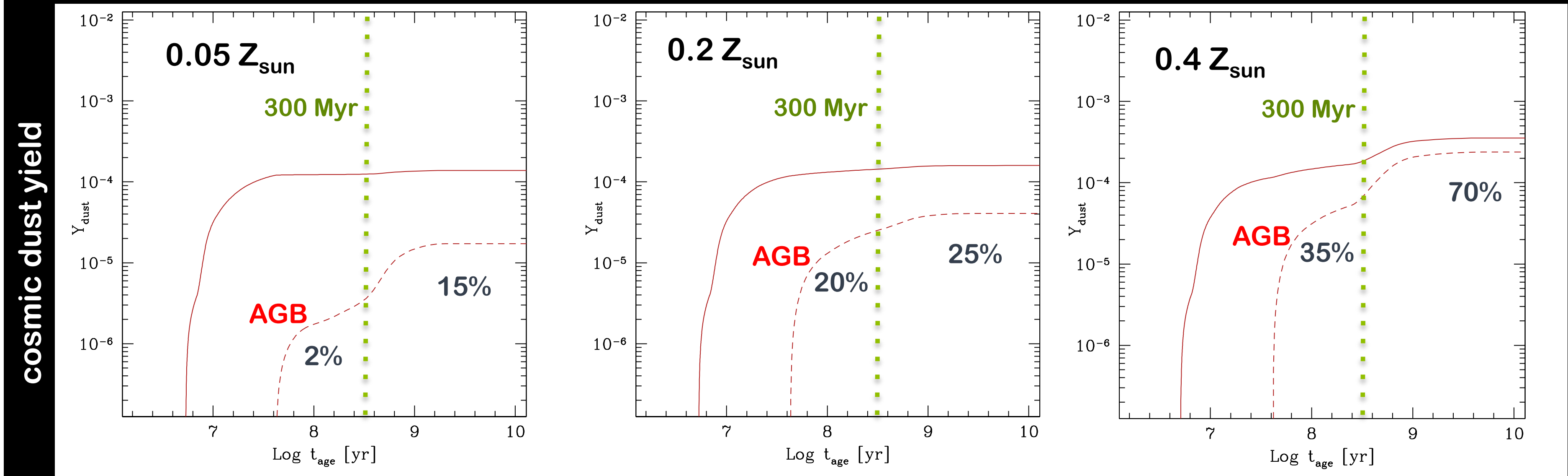
- ✓ Silicates are produced by > 3 M_{sun} stars
- ✓ Silicate dust production increases with Z
- ✓ No silicates are produced when Z < 0.05 Z_{sun}
- ✓ Carbon dust is produced by < 3 M_{sun} stars and does not depend on Z
- ✓ When Z < 5 10^{-3} Z_{sun} HBB is present even at M < 2 M_{sun} → no AGB dust

the contribution of AGB and SN to early dust enrichment

all stars are formed in a single burst at t = 0 with a Salpeter IMF:

AGB dust yields from ATON code (Ventura+12,13)

SN yields from Bianchi & Schneider (2007)



with ATON yields, AGB contribution to the total dust budget becomes > 30% only when the Z > 0.2 Z_{sun} and becomes dominant in 500 Myr

when Z ≤ 0.2 Z_{sun} AGB dust is always sub-dominant wrt to SN dust

the contribution of AGB stars to early dust enrichment

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AGB dust yields from ATON code (Ventura+12,13)

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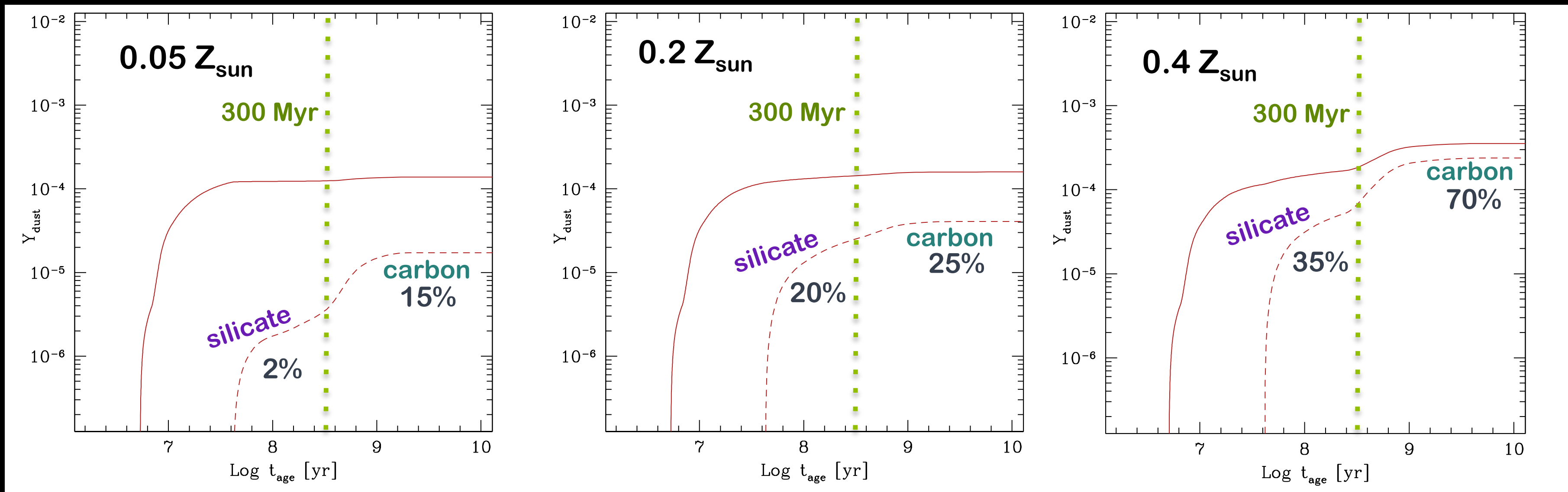


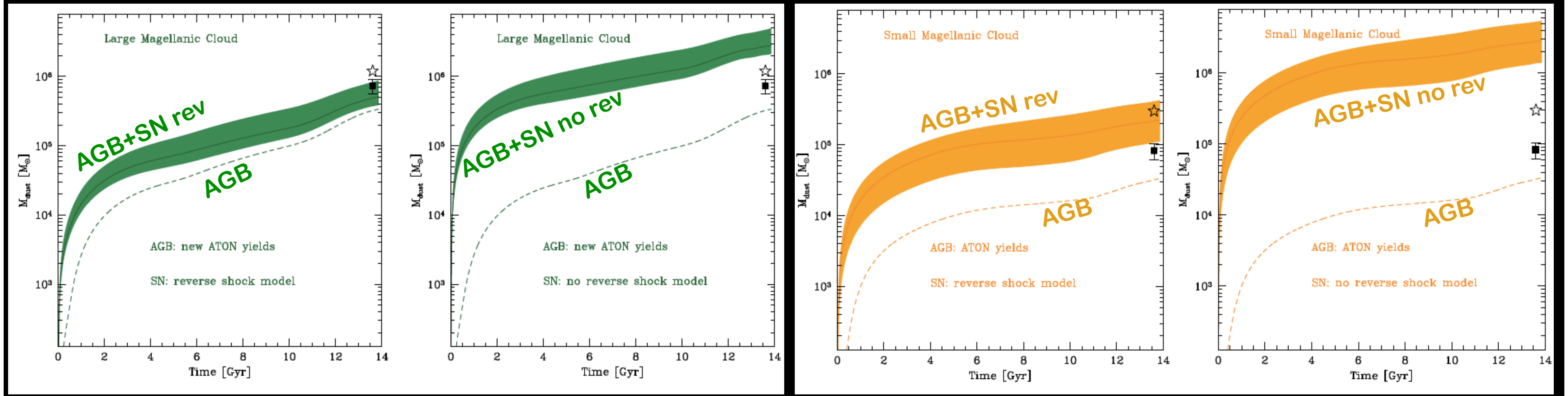
if SN at low Z produce mostly silicate dust, we expect to see only silicate features in young (< 300 Myr) starbursts and the presence of carbon features (PAHs) may be an indication of the growing AGB contribution to the total dust mass at > 300 Myr

Can SNe and AGBs reproduce the observed dust mass and dust-scaling relations in nearby galaxies?

Zhukovska+14; Schneider+14; Ginolfi+17; Popping+17

stellar dust in the Magellanic Clouds

Large Magellanic Cloud Schneider+2014 Small Magellanic Cloud



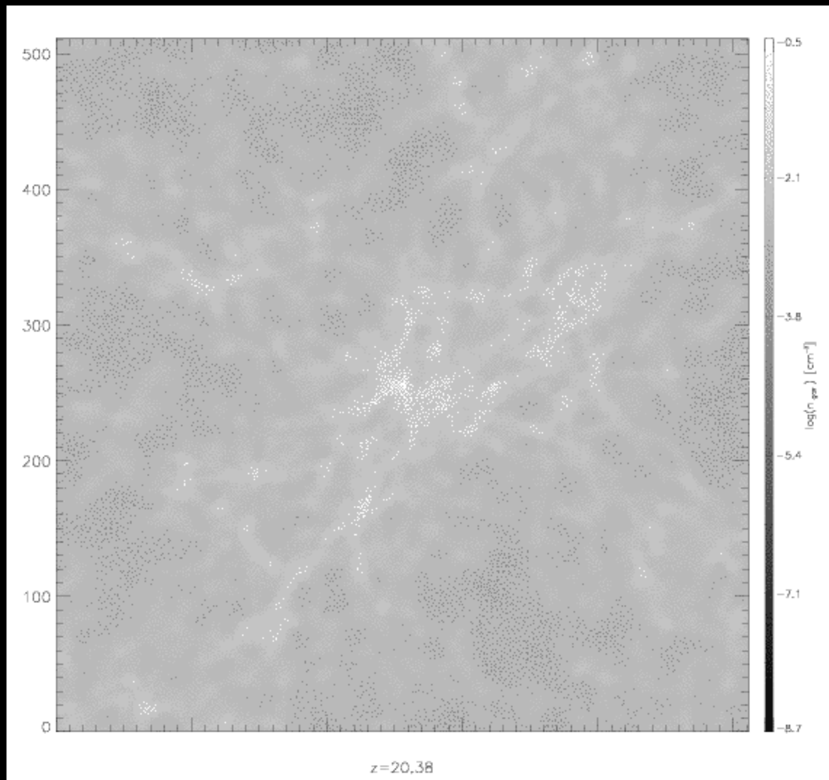
Data: Skibba et al. (2012) ☆ Gordon et al. (2014) ●

the existing dust mass in the ISM of the Magellanic Clouds can have a stellar origin unless significant destruction of the newly formed dust in SN reverse shock or in the ISM takes place

where does Galactic dust come from?

GAMESH: semi-analytical galaxy formation model +
dark matter simulation coupled to the radiative transfer code CRASH

Graziani et al. 2015, 2017



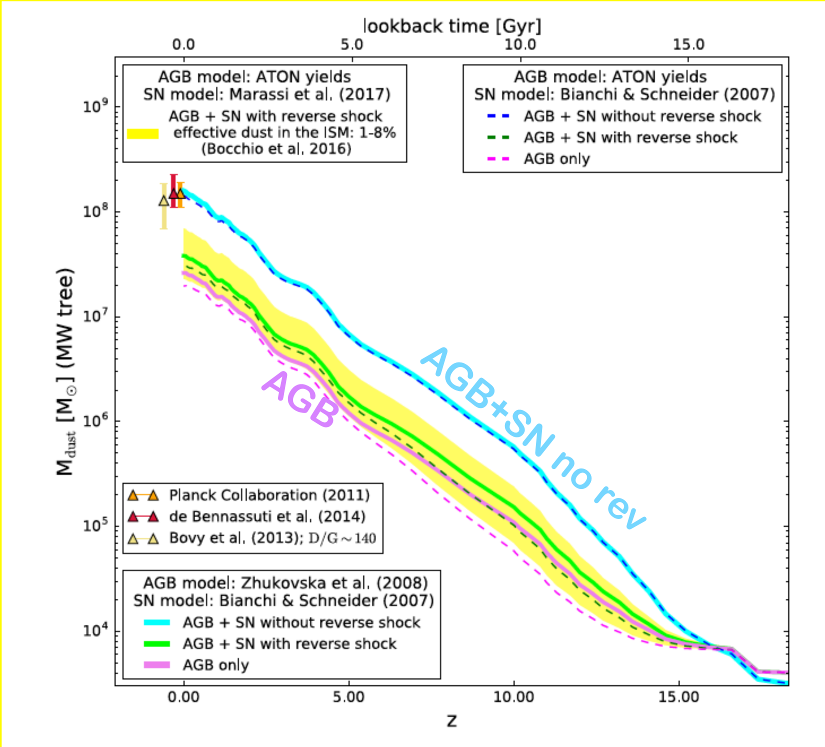
Dark matter simulation of the Milky Way galaxy in Planck cosmology GCD+ code with multi-resolution technique (Kawata & Gibson 2003):

Low-res spherical region of $R_l \sim 20\ h^{-1}$ Mpc taken from a low-res cosmological simulation

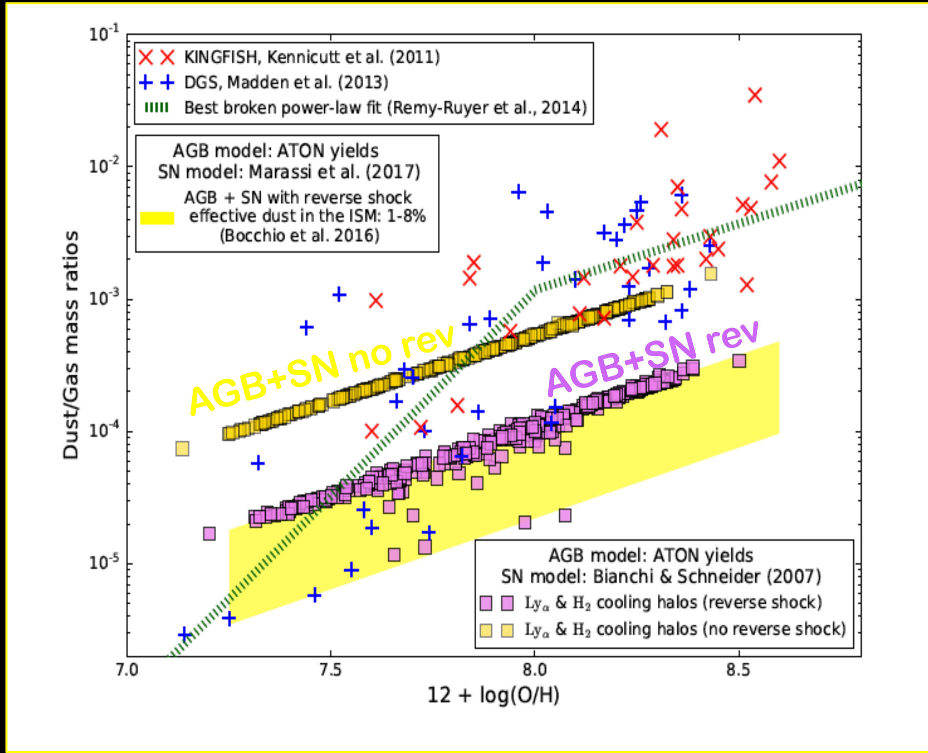
High-res spherical region of $R_h \sim 2\ h^{-1}$ Mpc with $M_p = 3.4 \times 10^5\ M_{sun}$

where does Galactic dust come from?

stellar dust production along the build-up of the MW



dust-to-gas mass ratio vs metallicity: stellar dust sources



Ginolfi+17

(1) SN always dominate dust production wrt AGB stars

(2) the injected and surviving dust mass with reverse shock is a factor 4-5 smaller than observed in the MW

(3) models with stellar dust only can not reproduce the observed scaling relations between the dust-to-gas mass and the metallicity

these conclusions are independent of the adopted dust yields

Remy-Ruyer et al. 2014; Asano+2013; Zhukovska+2014; Schneider+14; Feldman+15; Popping+16

Can SNe and AGBs reproduce the observed dust mass in distant galaxies?

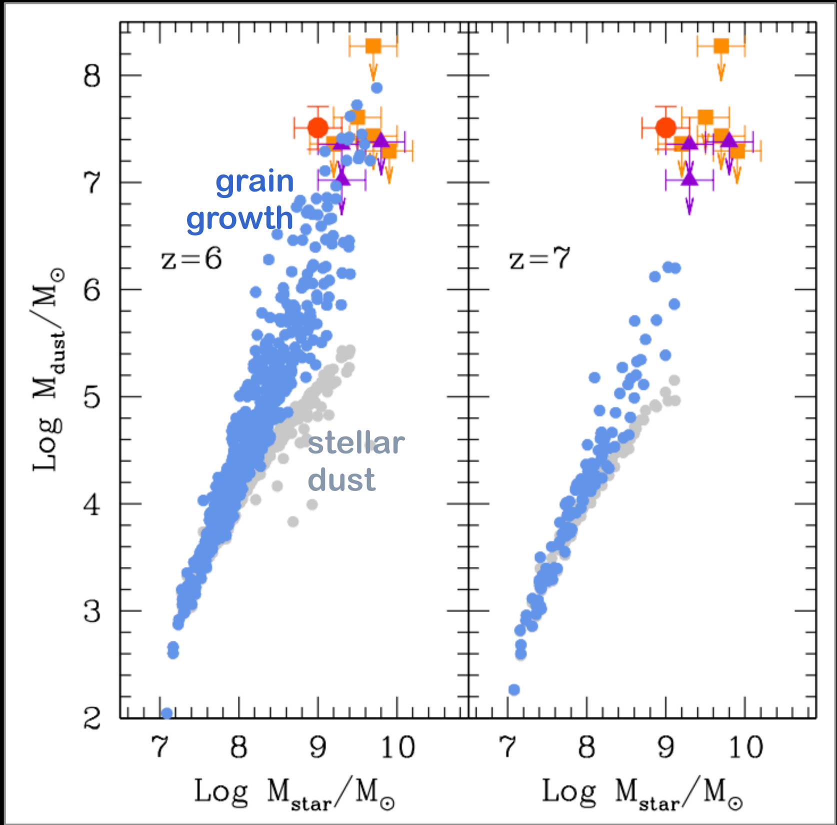
Valiante et al. 2009, 2011, 2014; Gall et al. 2010, 2011; Dwek & Cherchneff 2011; Mattsson 2011; Pipino et al 2011; Calura et al. 2013; Rowlands+2014; Michałowski+2015; Shimizu+14; Mancini+2015, 2016; Khakaleva-Li & Gnedin 2016; Grassi+ 2016

the dust mass in z ~ 6 "normal" SF galaxies

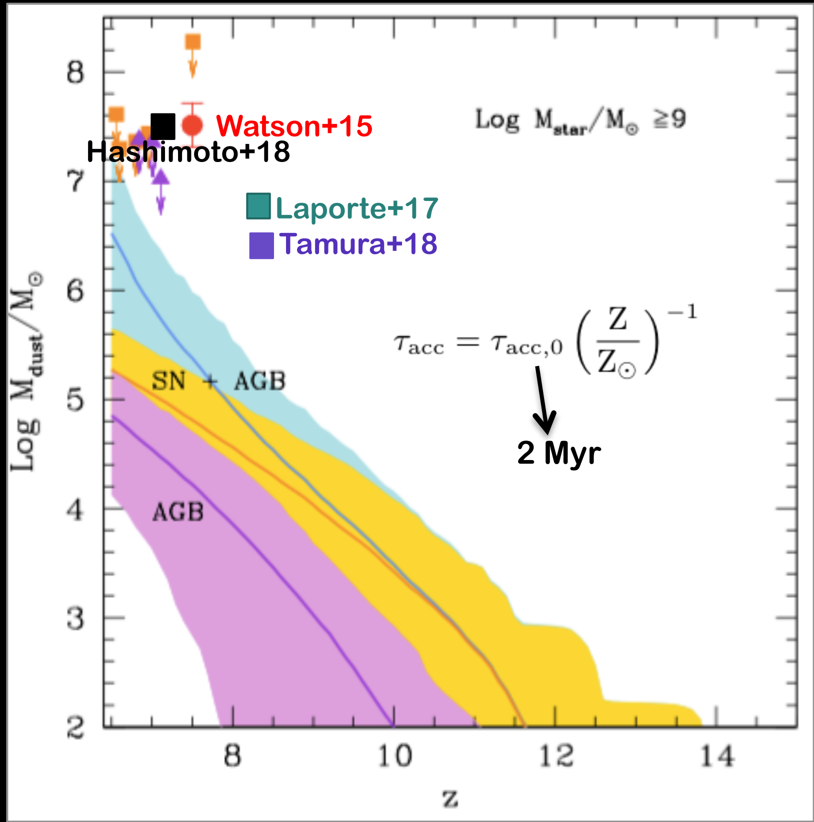
Ouchi+2013; Kanekar+2013; Ota+2014; Schaerer+2014; Maiolino+2015; Watson+2015, 2016

semi-numerical approach: SFR, metal and gas masses from a cosmological simulation
dust mass evolution in post-processing

dust vs stellar mass:
simulation results vs observations



dust evolution of the most massive galaxies



Mancini et al. (2015)

see also Zhukovska et al. 2016

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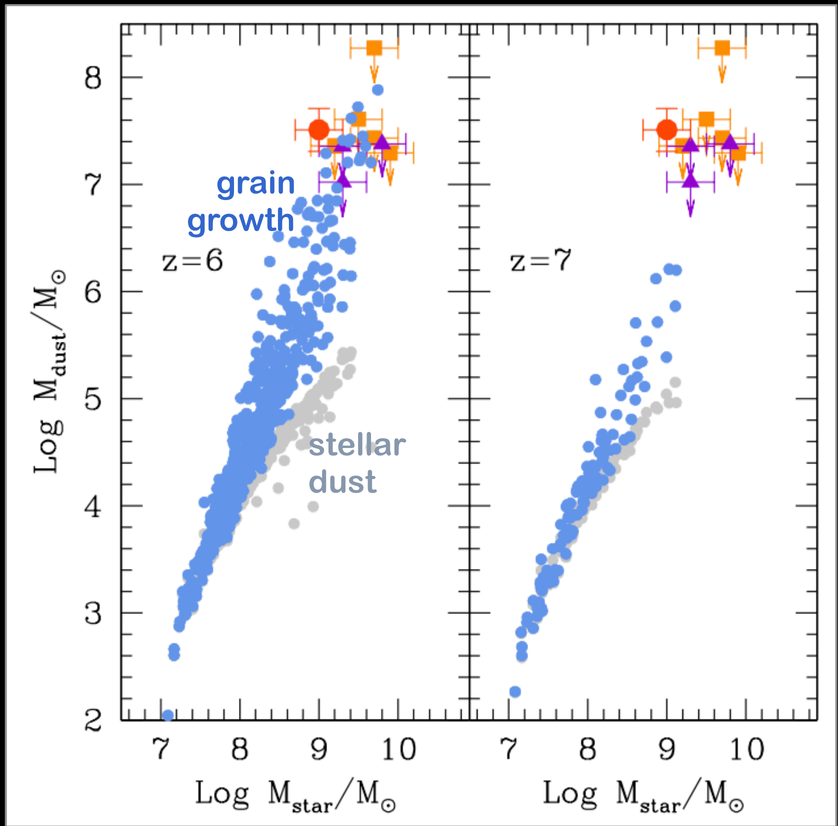

Mancini et al. (2015)

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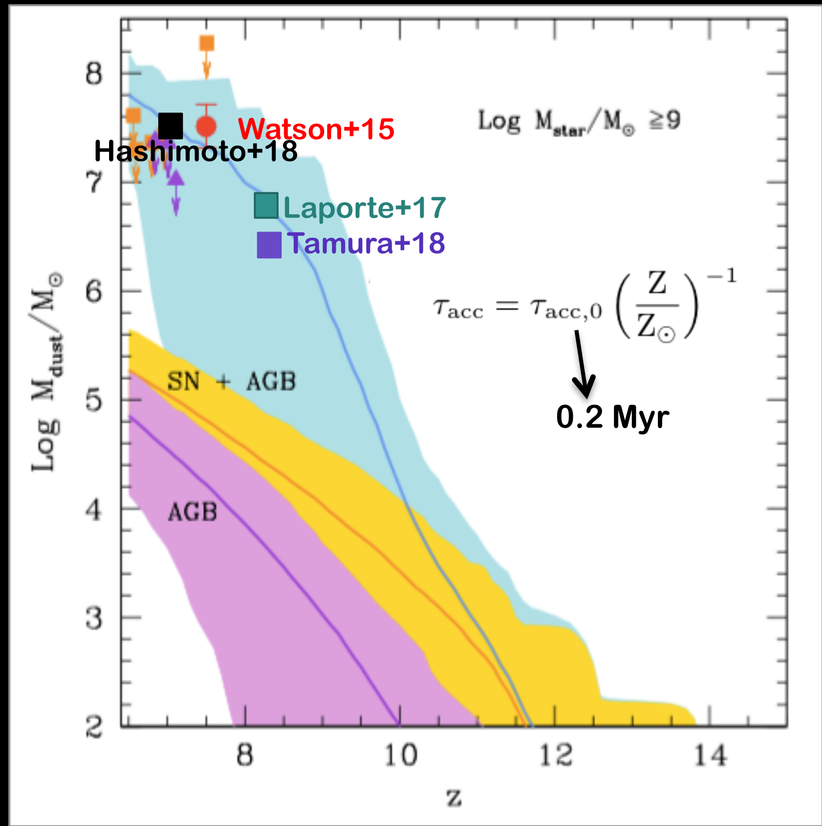


efficient grain growth is required to
account for the observed dust mass

where does grain growth occur?

$$\tau_{acc} = \tau_{acc,0} \left(\frac{Z}{Z_{sun}}\right)^{-1}$$

$$\tau_{acc,0} = 2\text{ Myr} \left(\frac{< a >}{0.1\mu m}\right)\left(\frac{n}{1000 cm^{-3}}\right)^{-1}\left(\frac{T}{50\text{ K}}\right)^{-1/2}$$

molecular clouds:

$n \sim 1000$ cm^{-3} $T \sim 10 - 20$ K   the grains form icy mantles, growth is problematic (Ferrara+16, Ceccarelli+18)

if $\tau_{acc,0} = 2$ Myr then <a> = 0.1 μm

if $\tau_{acc,0} = 0.2$ Myr then <a> = 0.01 μm

cold neutral medium

$n \sim 30$ cm^{-3} $T \sim 100$ K   the grains can grow, enhanced collision rate due to Coulomb focusing (Zhukovska+18)

if $\tau_{acc,0} = 2$ Myr then <a> = 0.004 μm = 4 nm

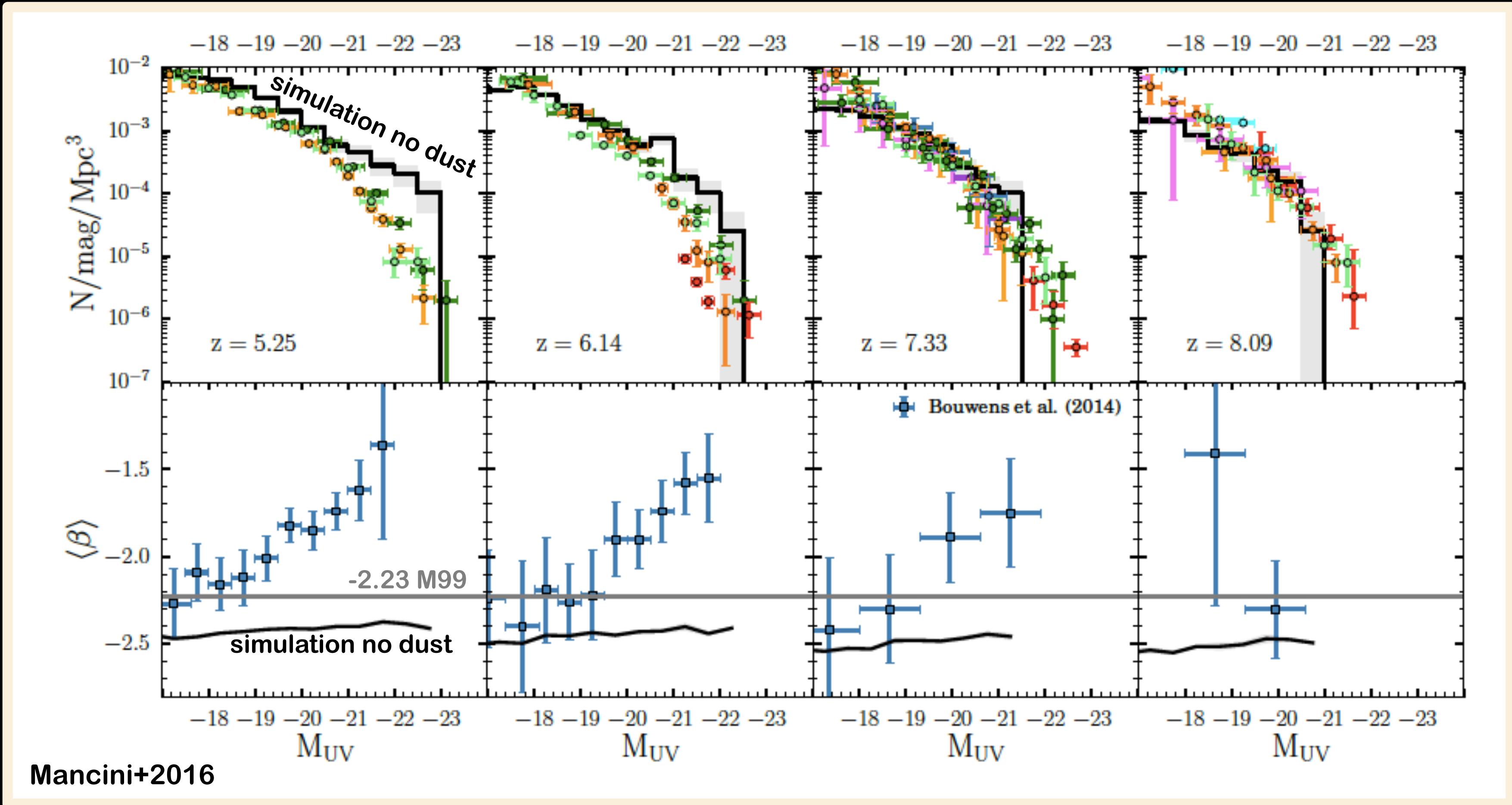
if $\tau_{acc,0} = 0.2$ Myr then <a> = 0.0004 μm = 0.4 nm

high redshift galaxy colours

dust affects the UV luminosity function, the beta-slope $F_\lambda \sim \lambda^{-\beta}$ at [1500 – 3000]Å

and the IRX = Log F_{IR}/F_{1500}

high redshift galaxy colours



at z ~ 5 observations require significant dust extinction at all luminosities brighter than M_{UV} ~ - 18

intrinsic colours are much bluer than observed and bluer than the value adopted by the Meurer+99 (M99) relation

Wilkins+12; Salvaterra et al. (2013); Dayal et al. (2013); Finkelstein et al. (2015a) and Khakhaleva-Li & Gnedin (2016)

high redshift galaxy colours

dust affects the UV luminosity function, the beta-slope $F_\lambda \sim \lambda^{-\beta}$ at [1500 – 3000]Å and the IRX = Log F_{IR}/F_{1500}

Given the dust masses predicted by the semi-numerical model, explore the combination of attenuation and dust distribution that can fit:

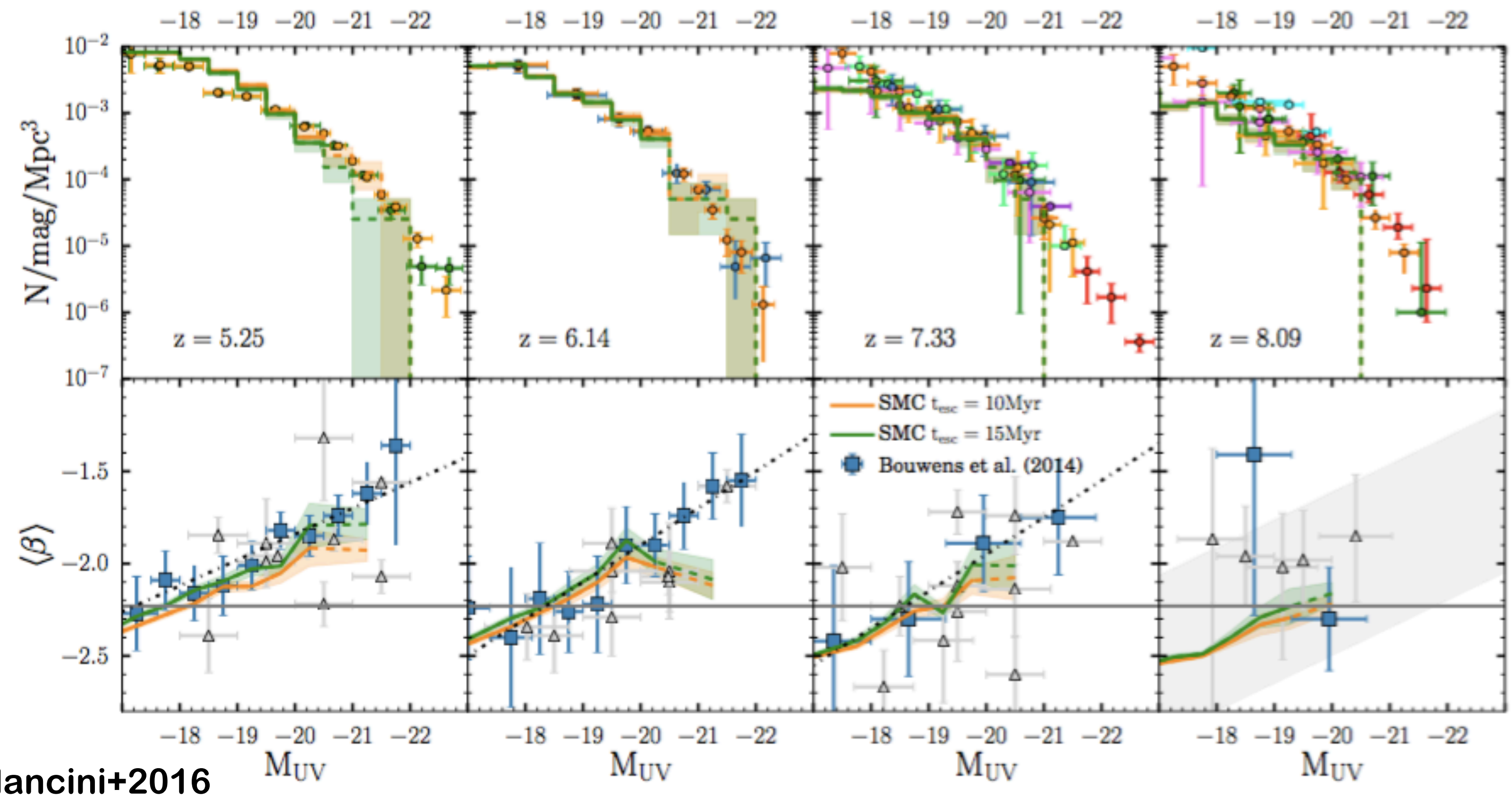
1) UV luminosity function
2) colour-magnitude relation (β vs M_{uv})

↓

the best-fit model is then used to interpret the properties of the IRX-β relation

the effects of dust on the UV colours at z ~ 5 - 8

Shimizu+2014; Filkenstein+15; Mancini, RS+2015, 2016; Khakaleva-Li & Gnedin 2016; Graziani+2017

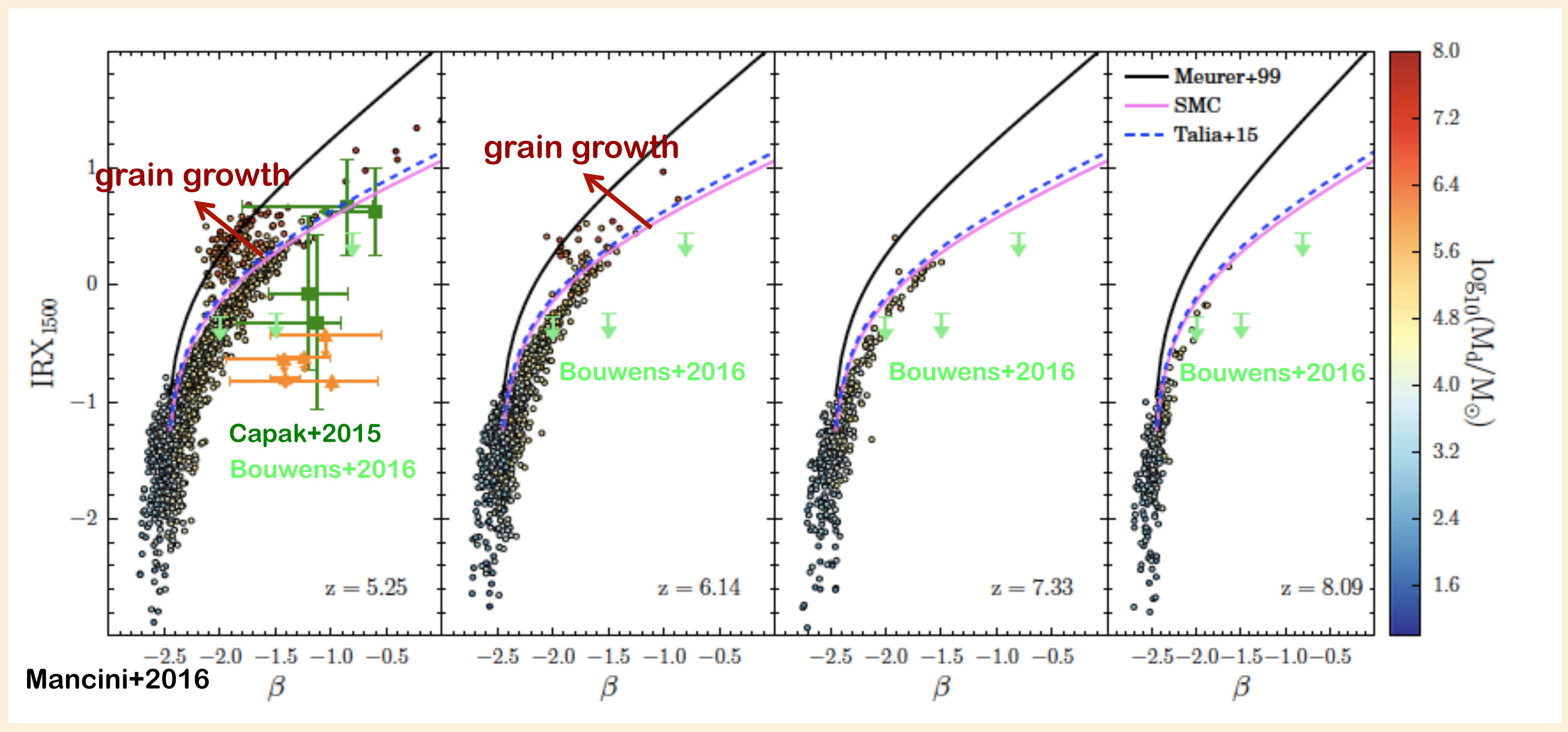


Mancini+2016

observed trends suggest a steep (SMC-like) extinction curve in the wavelength range 1500Å - 3000Å, and that stars with age < 15 Myr are embedded in their dense molecular natal clouds where they suffer a larger dust extinction

the IRX - β relation

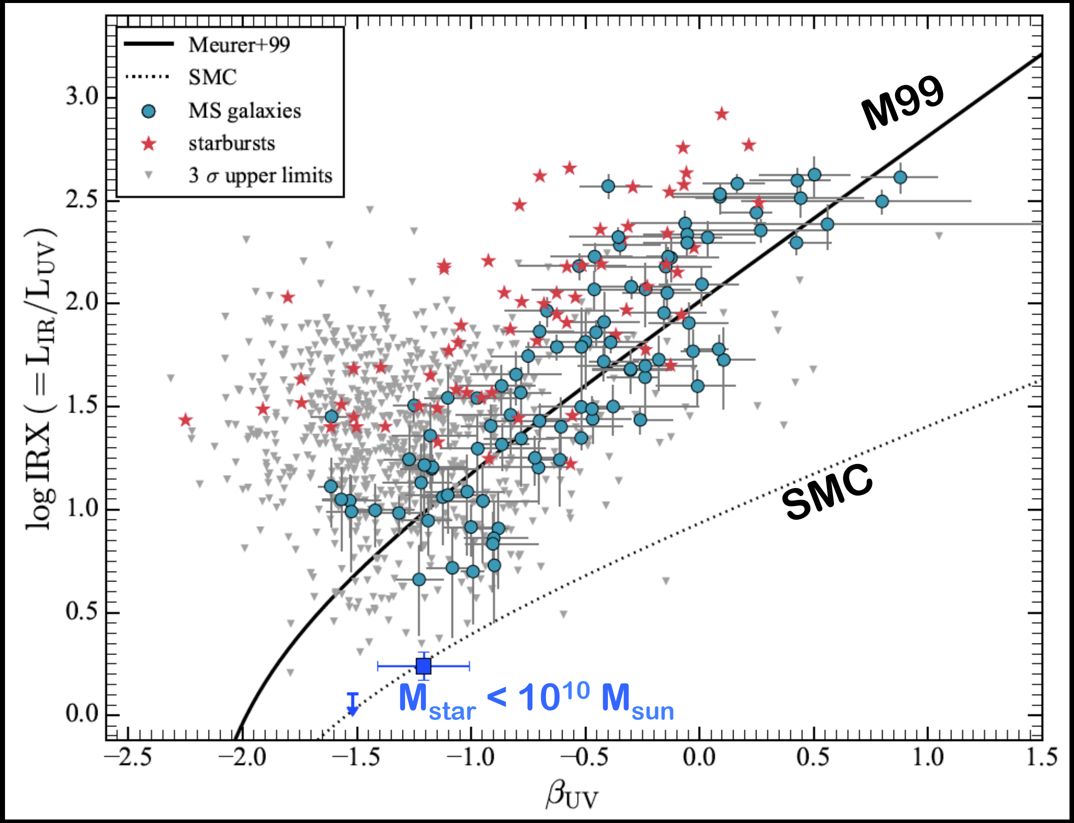
Mancini, RS+2016; Khakaleva-Li & Gnedin 2016; Cullen+17; Narayan+17; Popping+17



lower stellar mass and less chemically mature galaxies have smaller IRX than implied by the M99 relation

massive and dustier galaxies, where grain growth in the ISM increases the mass of dust, shift on the M99 relation and introduce a considerable scatter in the IRX at a given colour

the IRX – β relation of z ~ 2.5 - 4 galaxies



Fudamoto+2018

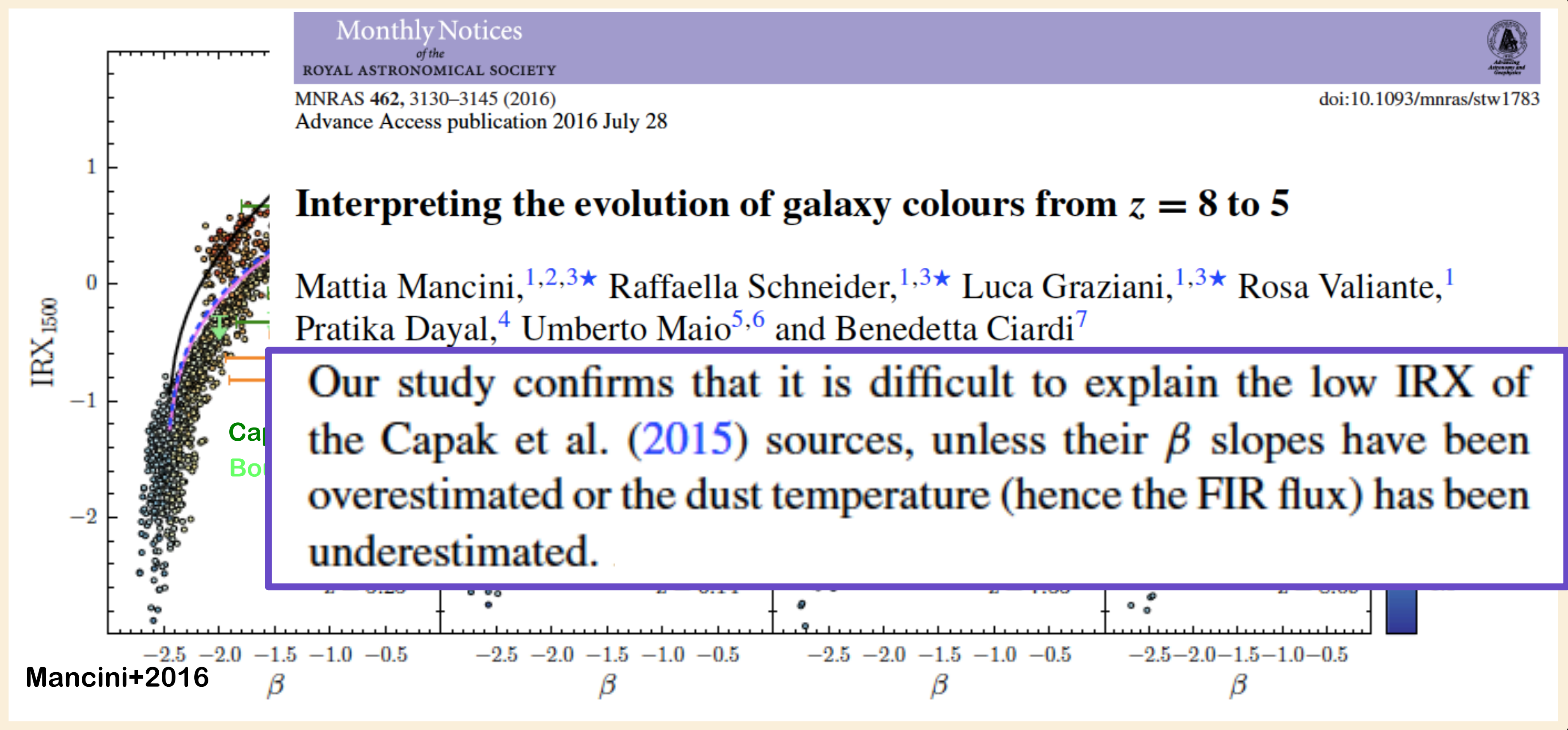
Main sequence galaxies show an IRX-beta relationship at z~2.5-4.0 that is perfectly consistent with that of local starburst galaxies (Meurer+99)

Starburst galaxies (defined to have a star formation rate 3×SFR MS) have generally larger (~0.5 dex) IRX values

evidence that $M^* < 10^{10} M_{sun}$ galaxies have lower IRX and an SMC-like IRX – β relation

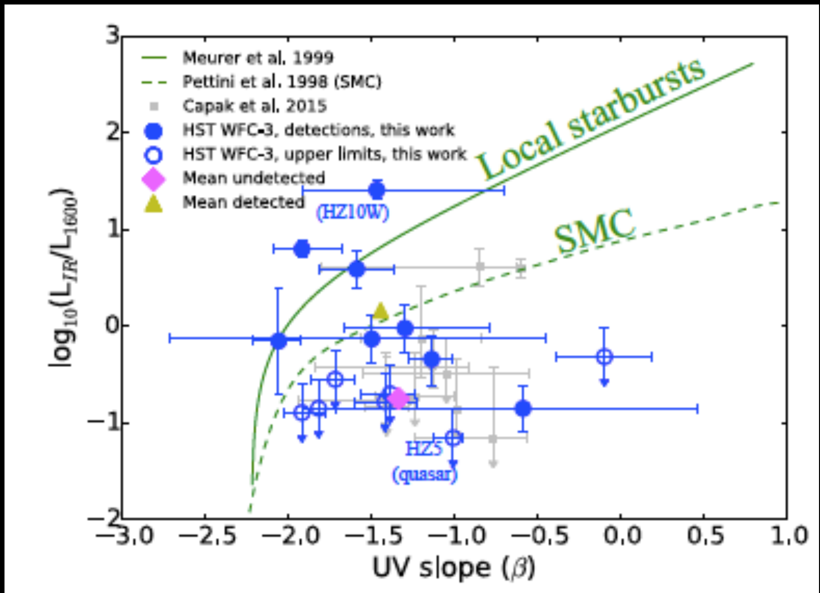
the IRX - β relation

Mancini, RS+2016; Khakaleva-Li & Gnedin 2016; Cullen+17; Narayan+17; Popping+17



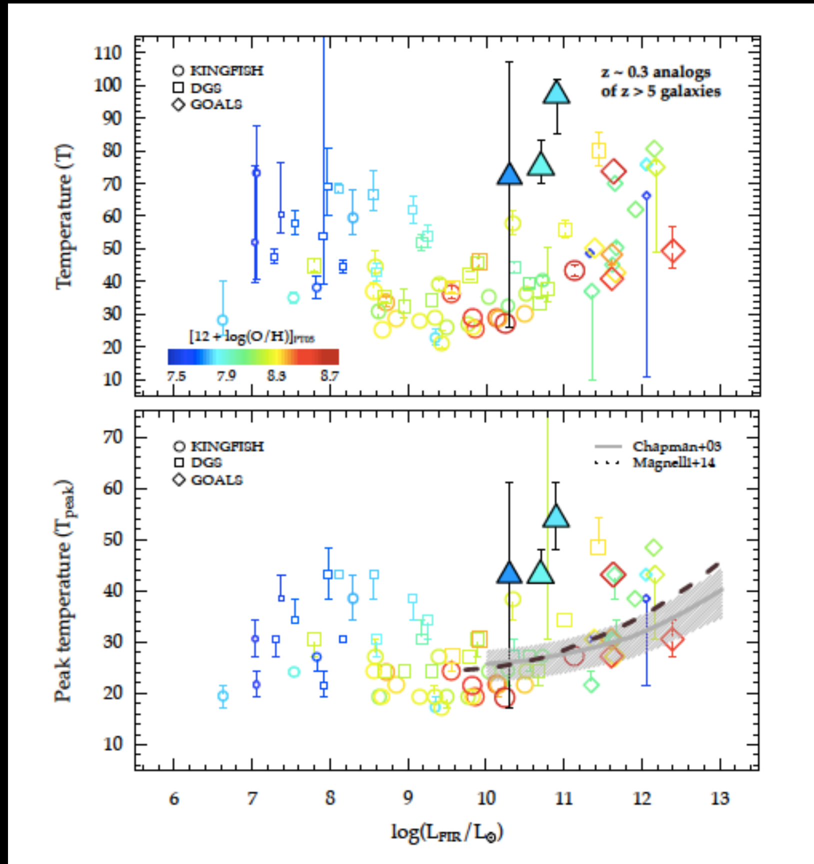
revisiting the IRX – β relation of z ~ 5.5 galaxies

Barisic et al. 2017



bluer UV spectra slopes are found
using new HST/WF3 imaging

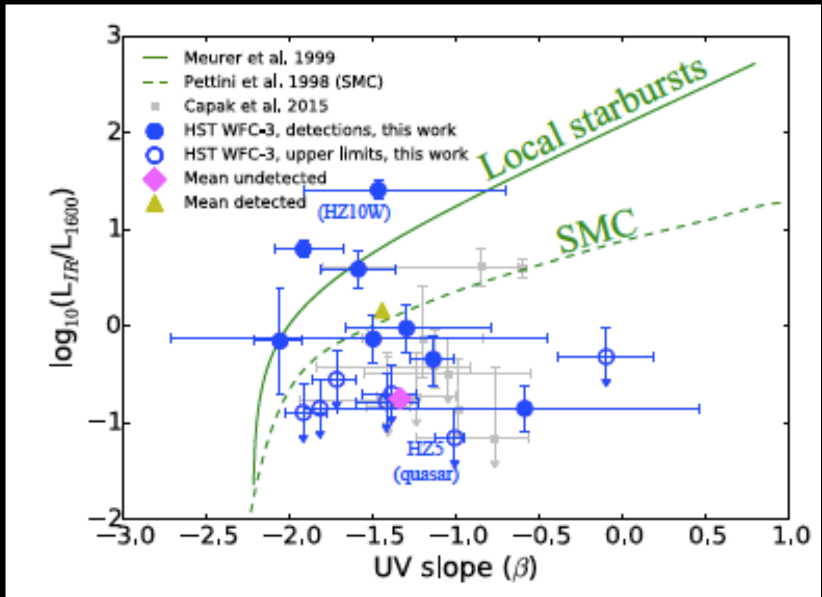
Faisst et al. 2017



Local low-Z systems and z~ 0.3 analogues
of z ~ 5.5 show warmer temperatures (40K – 60K)
than usually assumed (20K - 30K)

revisiting the IRX – β relation of z ~ 5.5 galaxies

Barisic et al. 2017



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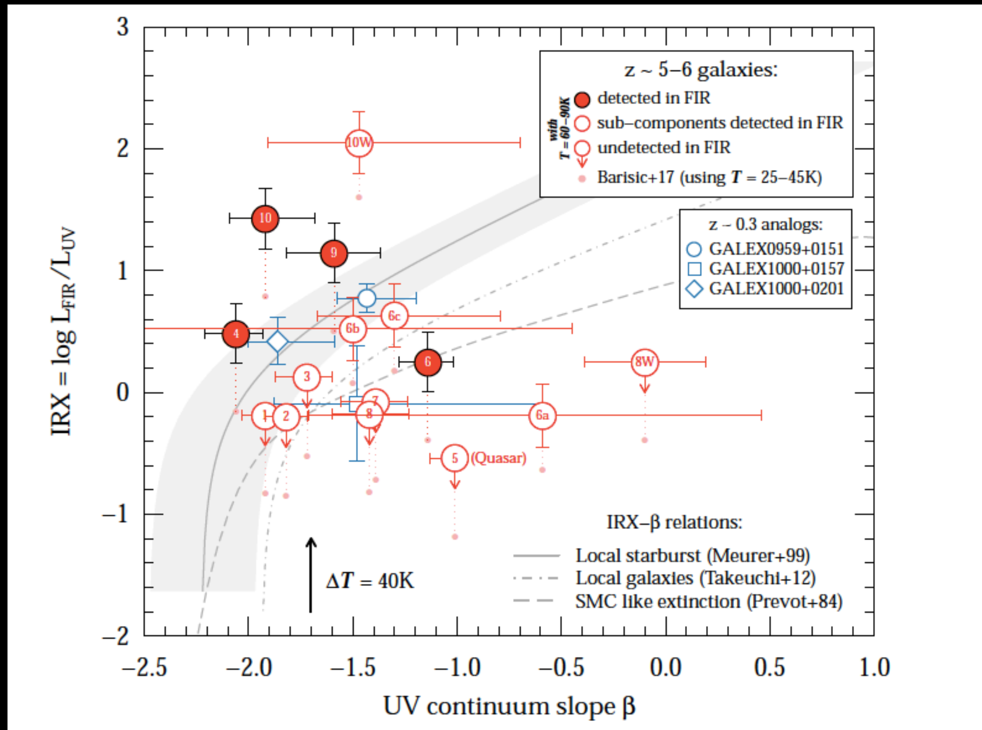
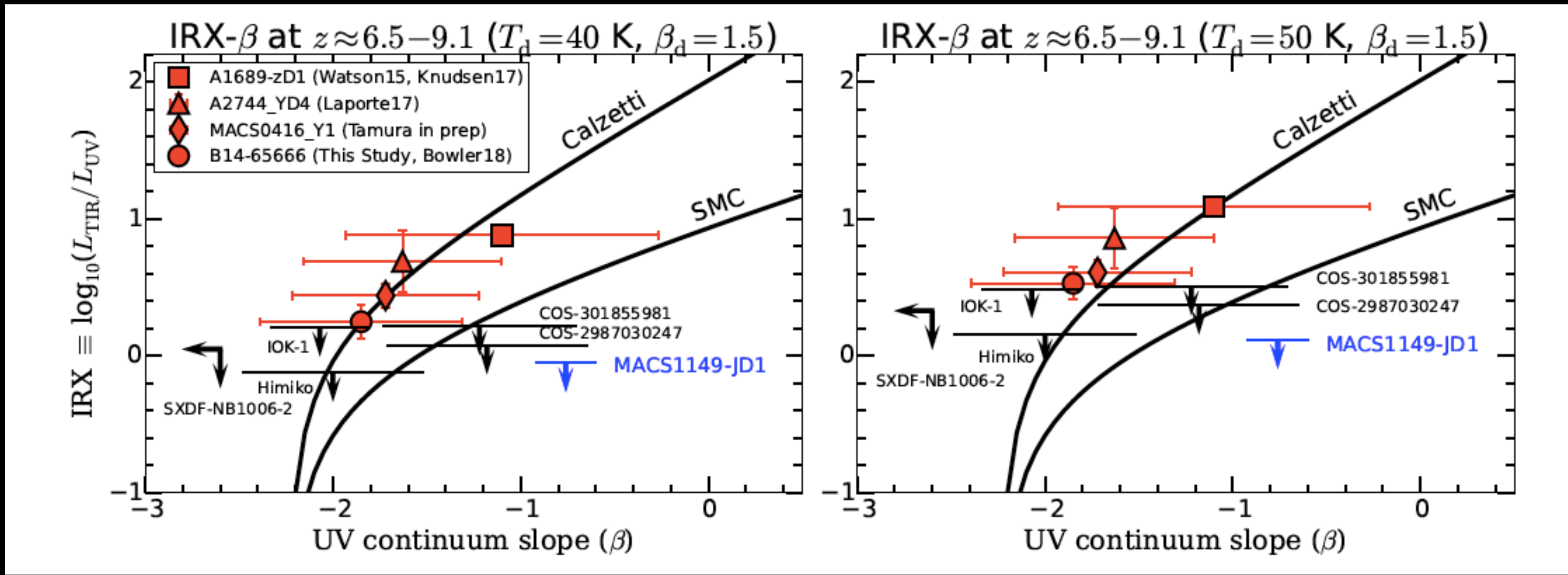


with increased T_{dust}, inferred L_{IR} rise and reduce the tension between dust attenuation models and observations

the IRX – β relation of z ~ 7 - 9 galaxies



Hashimoto+2018

the 4 galaxies at z > 6.5 with dust continuum detections are all consistent with a Calzetti attenuation curve

this is consistent with their inferred dust masses that require grain growth

Summary

- comparison between models and data suggests that effective SN dust yields may be 1/10 -1/100 than currently observed

- the relative importance of SN and AGB stars depends on metallicity-dependent AGB yields (and SFH, IMF….)

- observed dust masses and dust scaling relations in local galaxies can not be reproduced by stellar sources only: this is independent of the reverse shock effect and adopted stellar dust yields

- dust mass in high-z SMGs, quasars hosts, and normal SF galaxies require efficient grain growth in the ISM

nearby galaxies offer the opportunity to understand the micro-astrophysical processes responsible for dust evolution in the ISM and apply our knowledge to the more distant Universe