The evolution of metals and dust content in galaxies

Roberto Maiolino

University of Cambridge

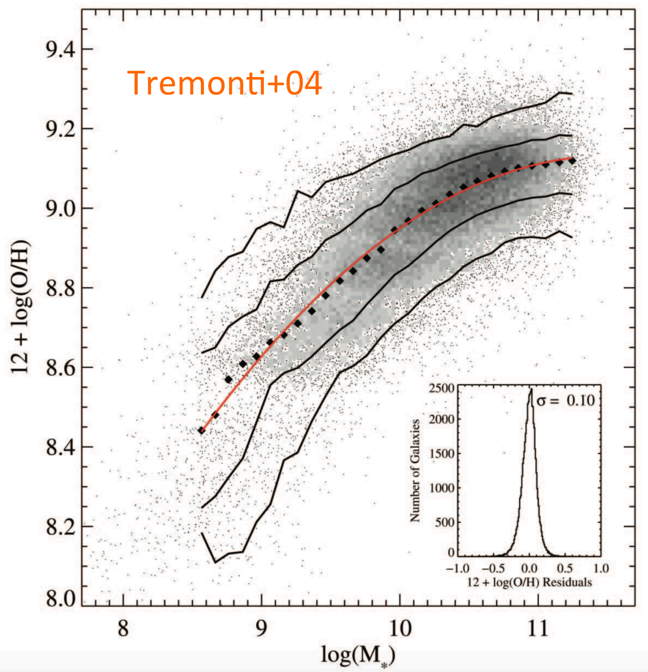
Metallicity
Metal content
Chemical abundances
Dust content
Dust properties

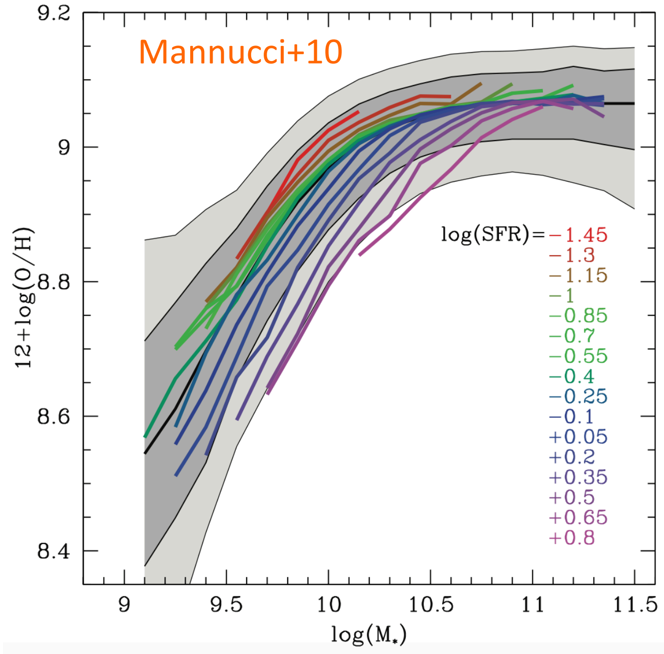
→

Constraints on galaxy evolutionary mechanisms and evolutionary processes:

Gas outflows
Gas inflows
Star formation efficiency
Star formation history
Evolution of stellar populations
...

Mass-Metallicity relation
(and Mass-Metallicity-SFR relation)
typical example of link between metallicity and galaxy evolutionary mechanisms





Explained by ~10^2 models and simulations with different recipes in terms of:

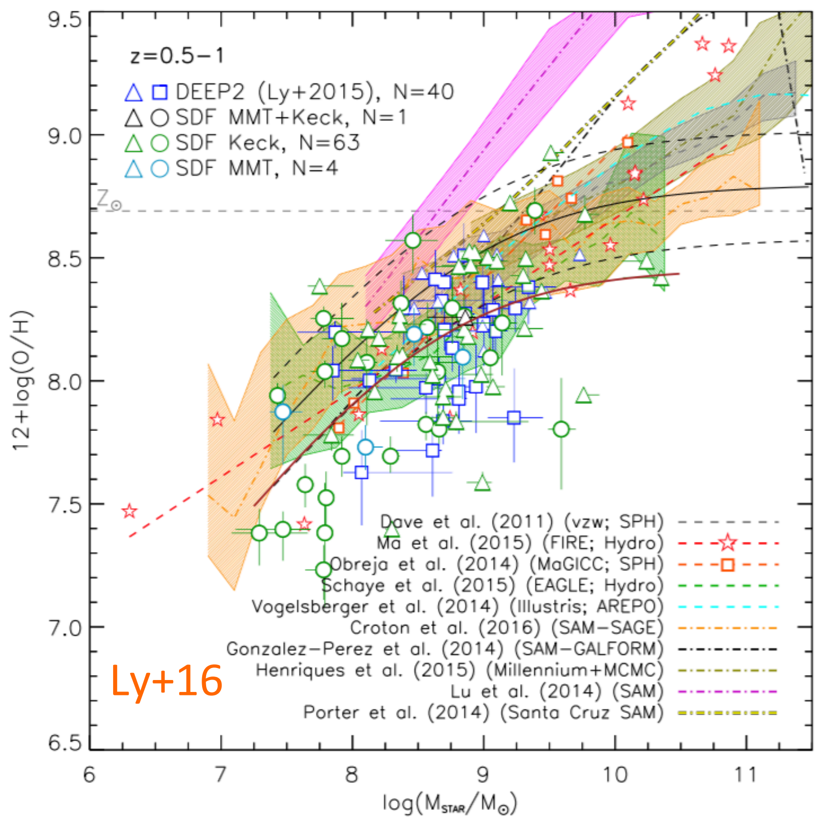
- outflows/feedback
- inflows
- Star formation efficiency
- ...

Dave'+11, Ma+15
Obreja+14, Schaye+15
Vogelsberger+14, Croton+16
Porter+14, Herniquez+14
Kobayashi+08, Tissera+08,
Gonzalez-Perez+14, Lu+14,
Lully+14, Peng+15,....

How to discriminate between different scenarios?

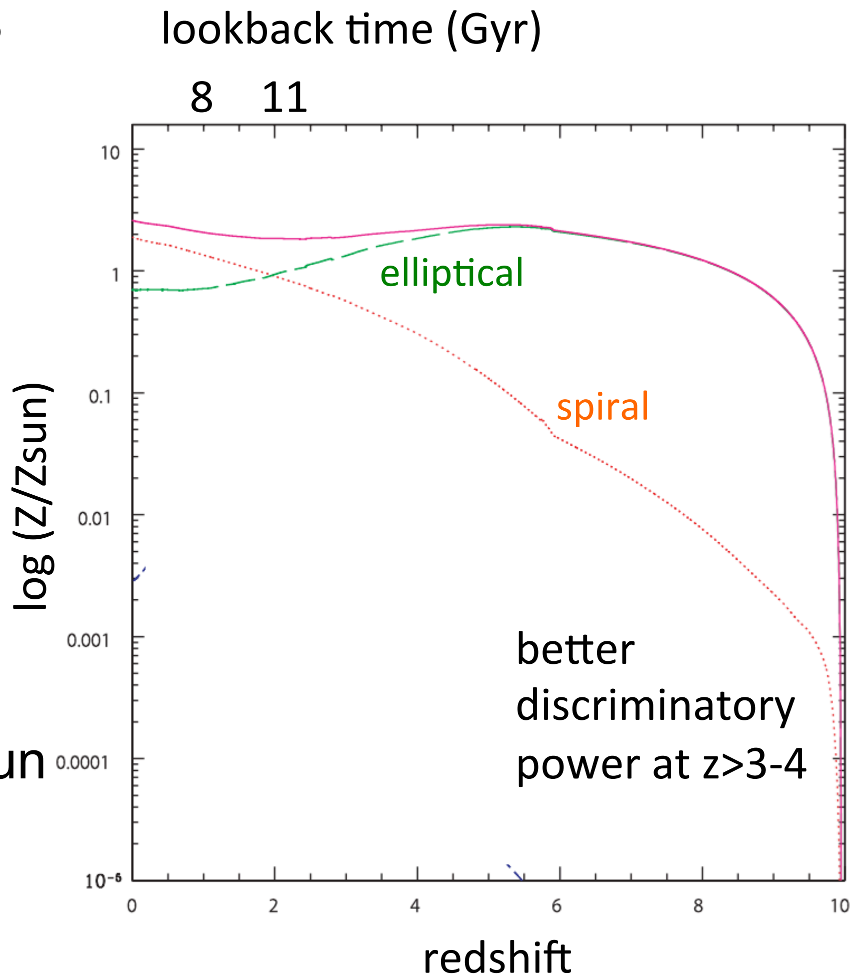
- redshift evolution
- metallicity gradients

Extensive studies of the M-Z relation at high-z, mostly z~1-2
(mostly gas metallicities)



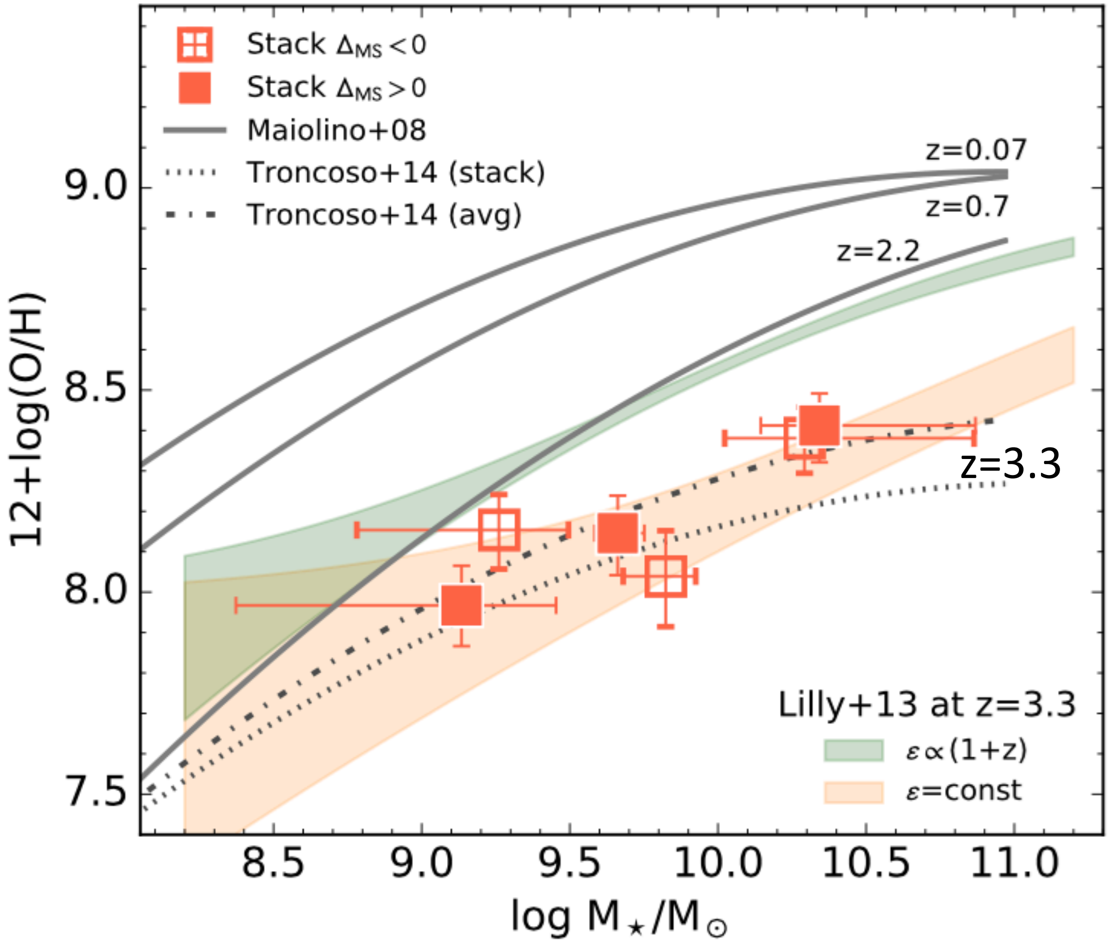
Evolution of the M-Z relation...
but modest
not much useful in disentangling
different models/scenarios

Why?



The metallicity evolution is initially very steep... it takes very little time to evolve from Z=0 to Z~0.3 Zsun
Galaxies spend most of the time at metallicity close to Solar

Push M-Z studies to higher redshift:
z~3 stronger evolution, as expected...



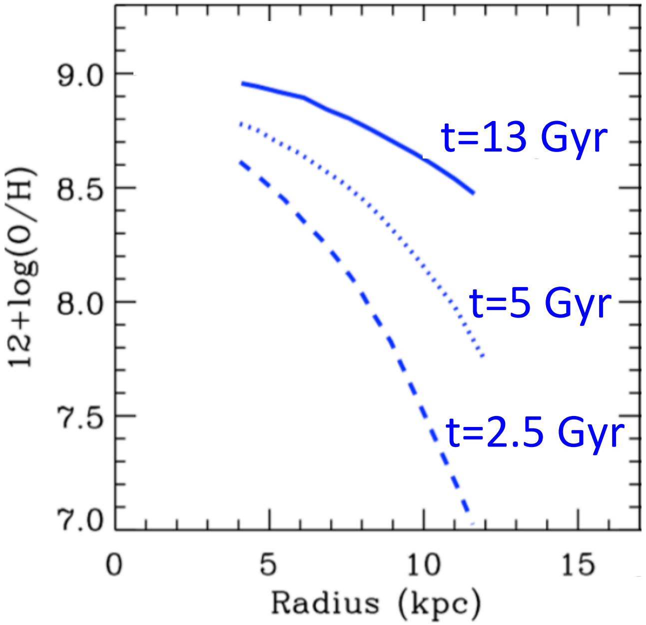
Some intersting constraints on the evolution of star formation efficiency

Onodera+16
Troncoso+14
Maiolino+08

Yet, the bulk of the evolution expected even at higher redshift :
z>4 that's where we can use the full potential of the M-Z relation to explore different scenarios (=> JWST needed)

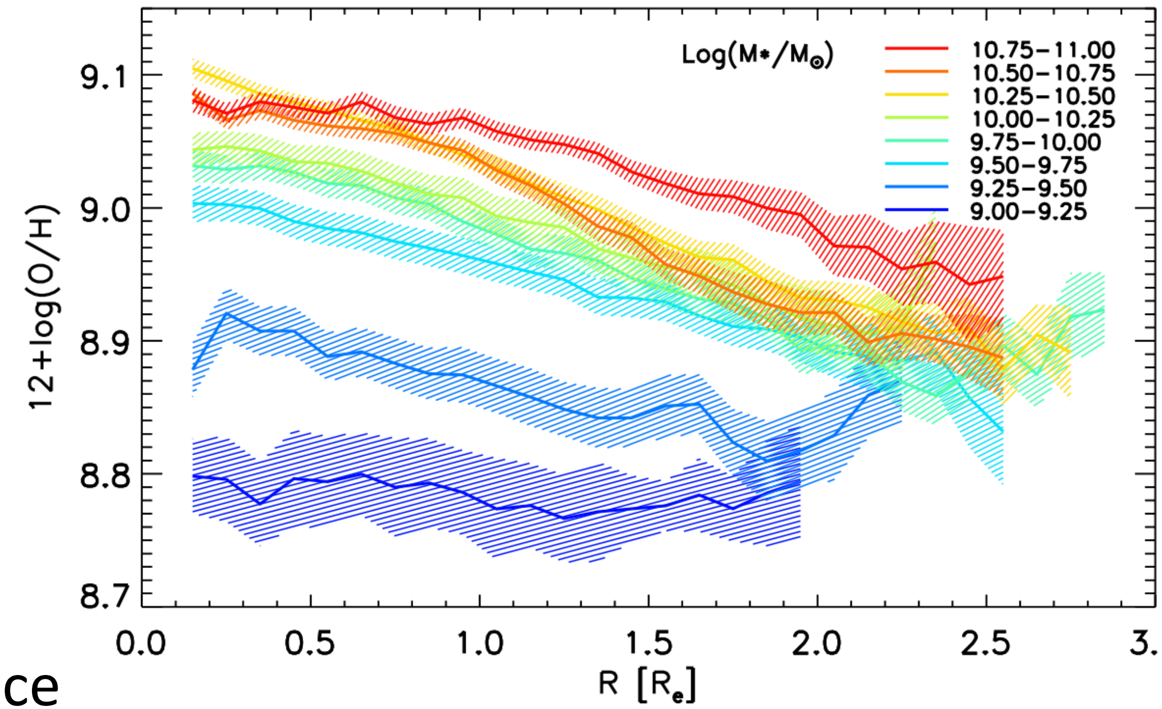
Spatially resolved information: metallicity gradients

Naively expect evolution from steep to shallow
-> following the inside-out build up of stars



Molla'+1997, Gibson+13

Local metallicity gradients
(Manga survey)

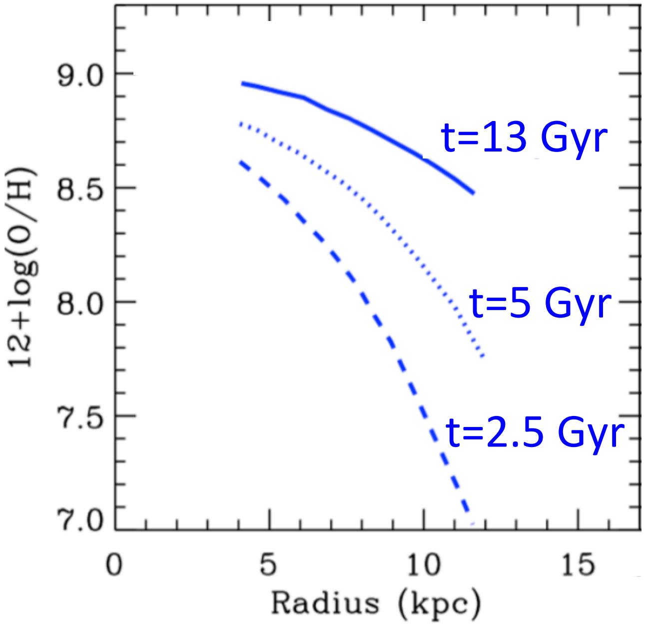


If mass-sequence
is a proxy of gradients evolution,
then ***opposite*** trend than expected

Belfiore+16

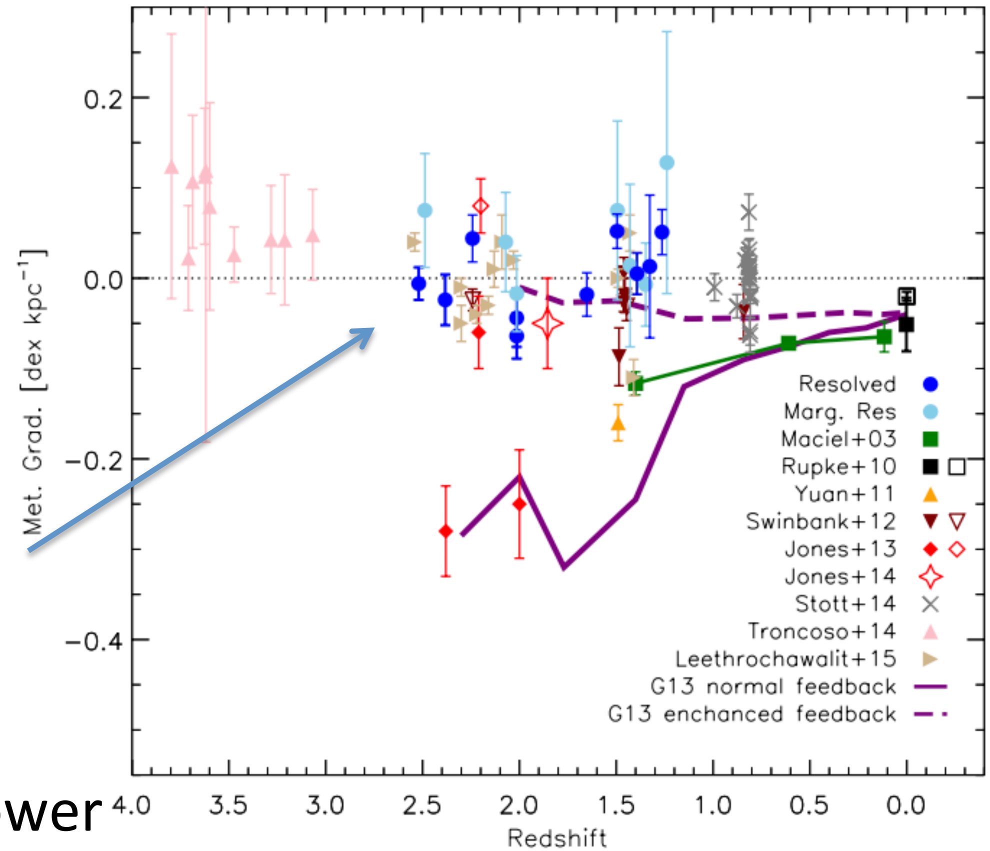
Spatially resolved information: metallicity gradients

Naively expect evolution from steep to shallow in time
-> following the inside-out build up of stars



Molla'+1997, Gibson+13

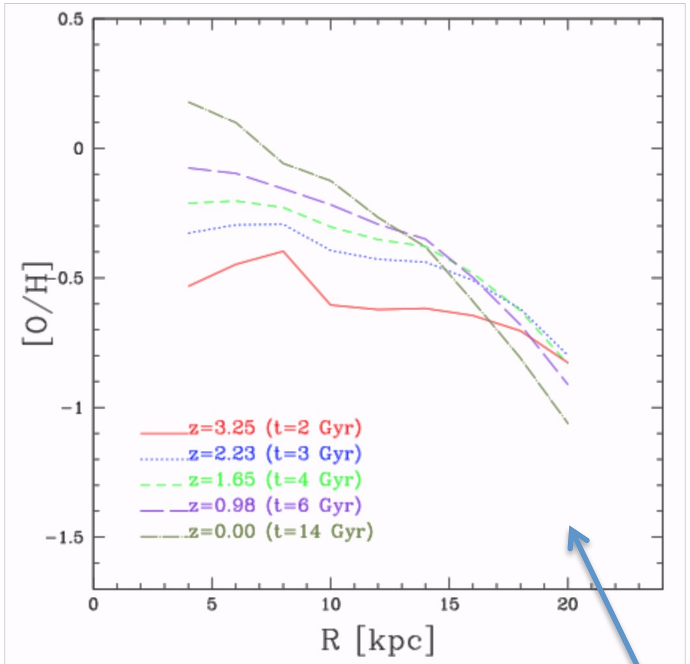
Redshift evolution
of metallicity gradients



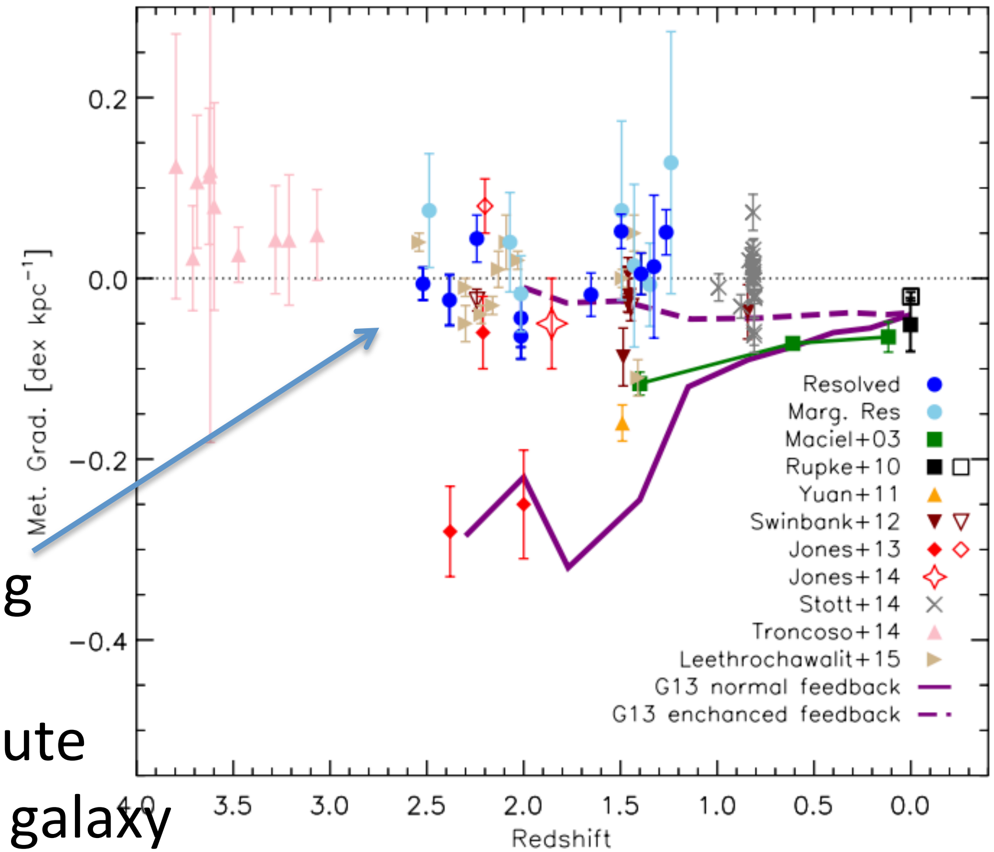
Except for a
few outliers,
high-z gradients
tend to be shallower

Spatially resolved information: metallicity gradients

Naively expect evolution from steep to shallow in time
-> following the inside-out build up of stars



Redshift evolution
of metallicity gradients

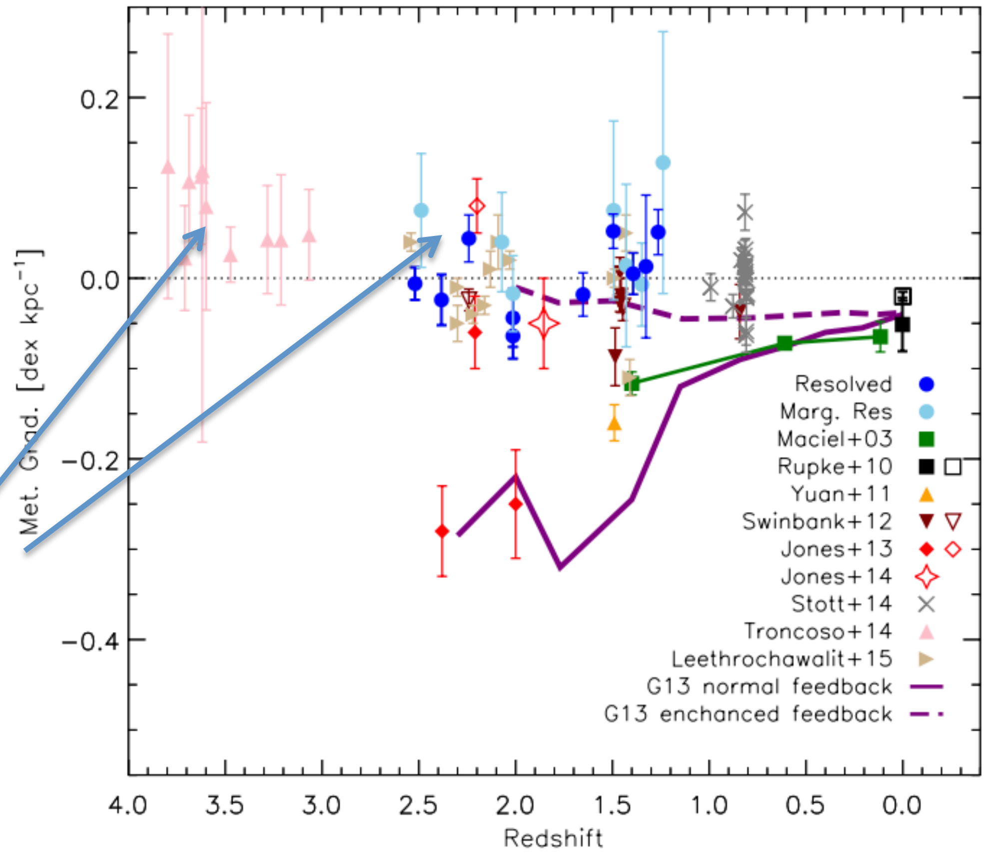


Mott+12
Gibson+13
Chiappini+02

Supporting
scenarios of strong
feedback:
outflows redistribute
metals across the galaxy

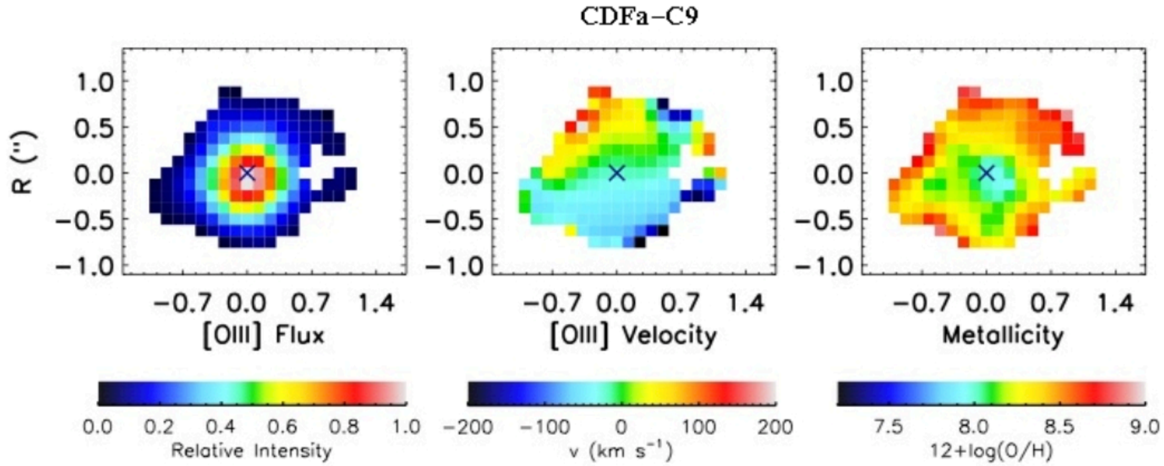
Spatially resolved information: metallicity gradients

Redshift evolution
of metallicity gradients



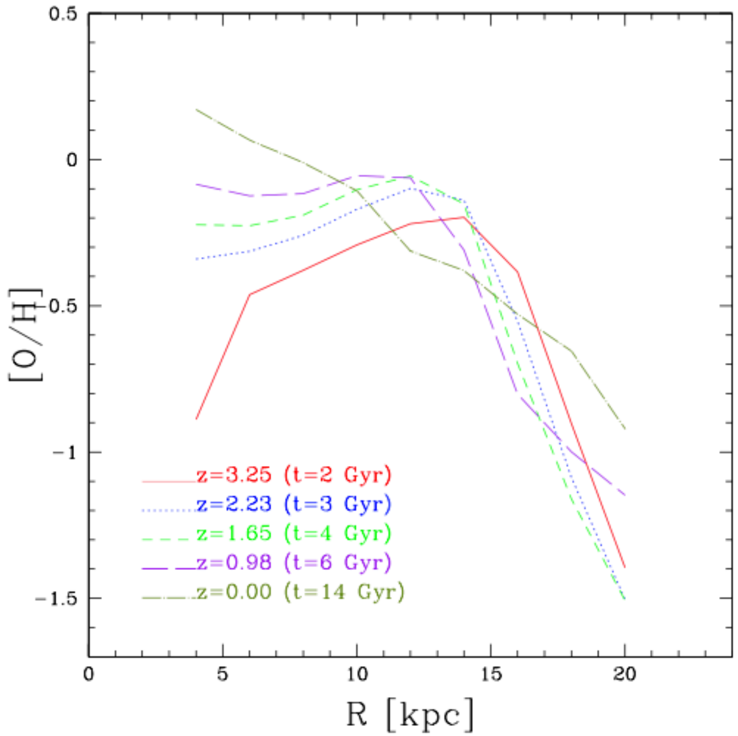
Also inverted
(positive)
gradients

Inverted (positive) gradients:
a few observed locally,
more common at high-z

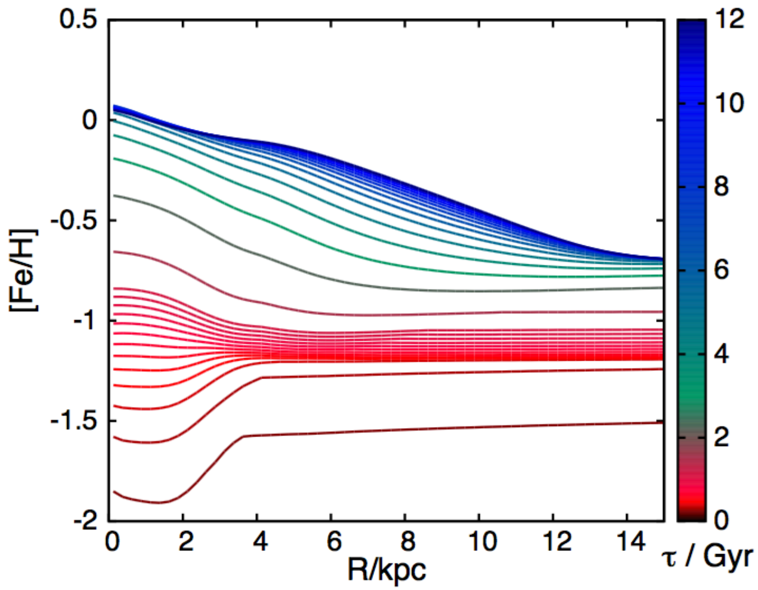


Cresci+10
Troncoso+14

Expected by models:
consequence of gas flows
towards the central regions:
instabilities from interactions
and inflow from cosmic streams

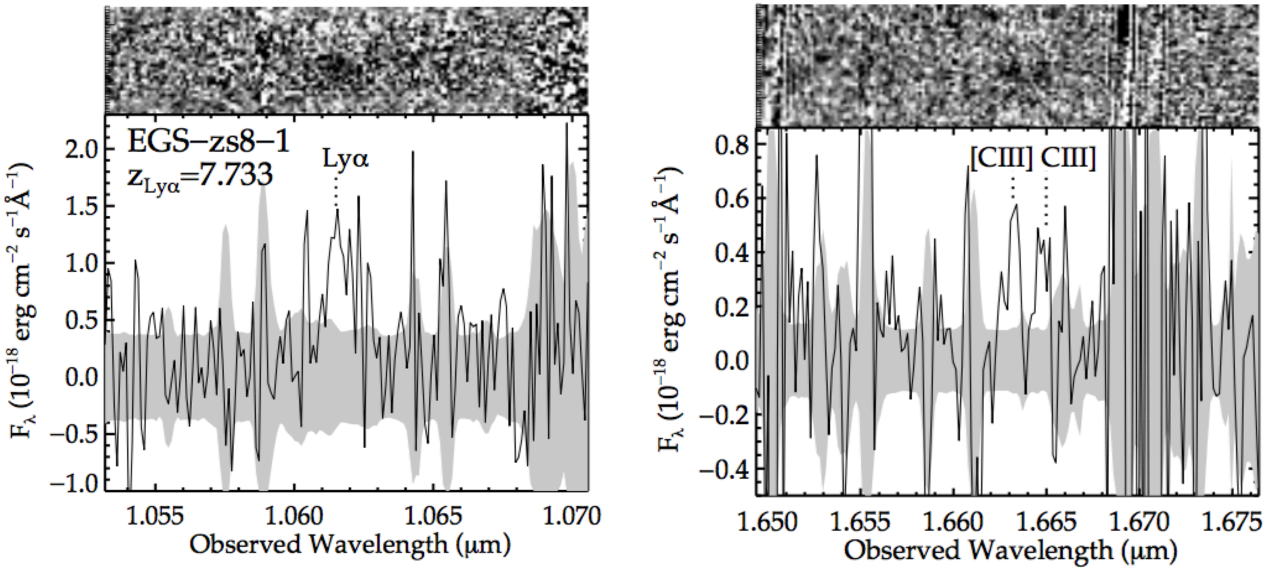


Mott+12



Schonrich+McMilla+16

Metallicity in normal galaxies at z>4-6
from optical/UV nebular lines... still very challenging



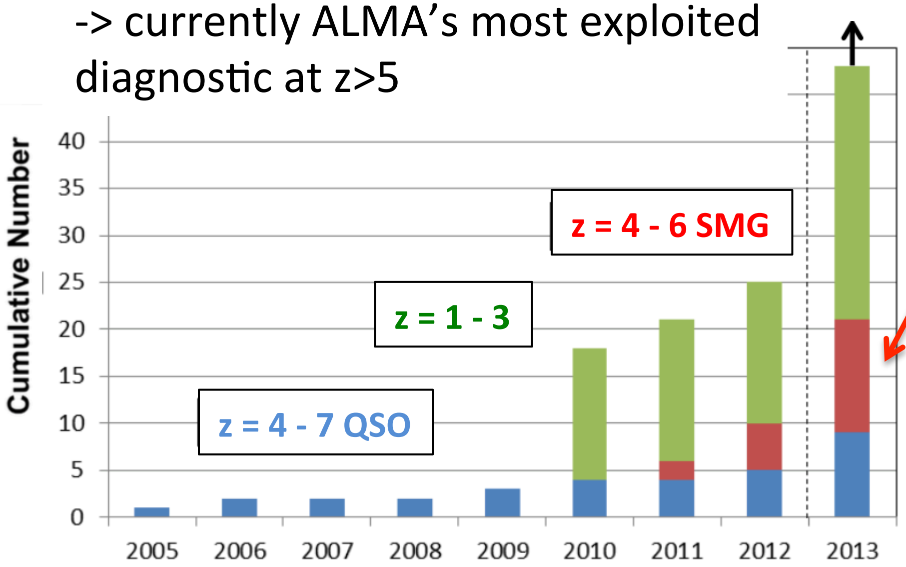
Stark+16

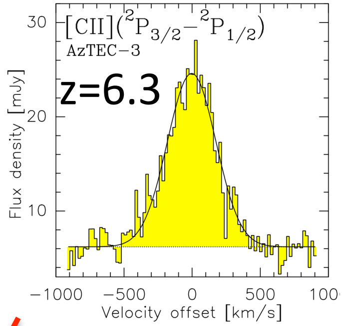
few metal lines detected in emission
...promising for JWST

inferred z~0.1... surprisingly not so low

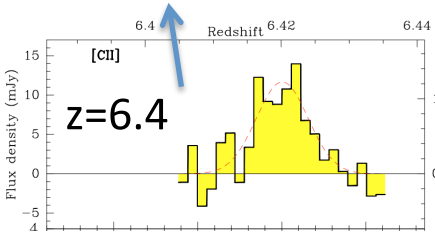
Far-IR fine structure lines: potentially very promising metallicity tracers

[CII]158um generally the brightest line in galaxy spectra
-> currently ALMA's most exploited diagnostic at z>5



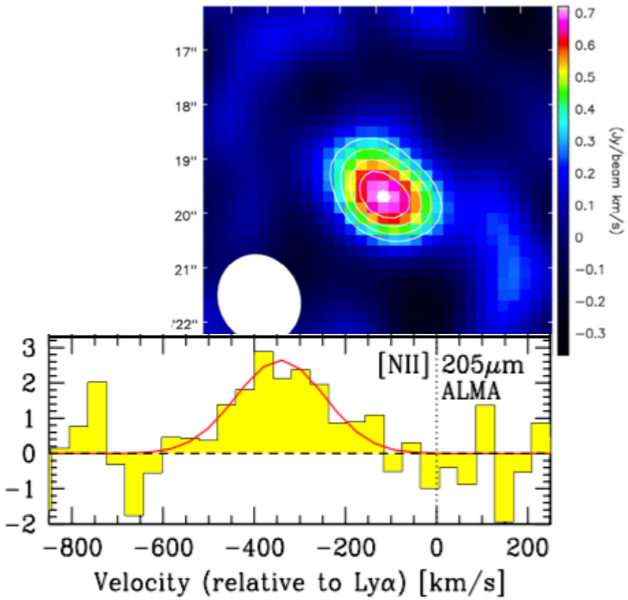


20 min (ALMA)
Riecher+2013



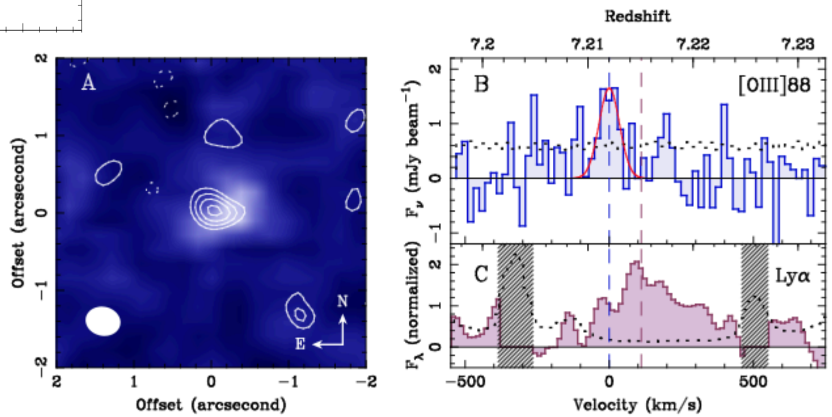
12h (IRAM 30m)
Maolino+2005

[NII]122,205um



Nagao+12, De Carli+13

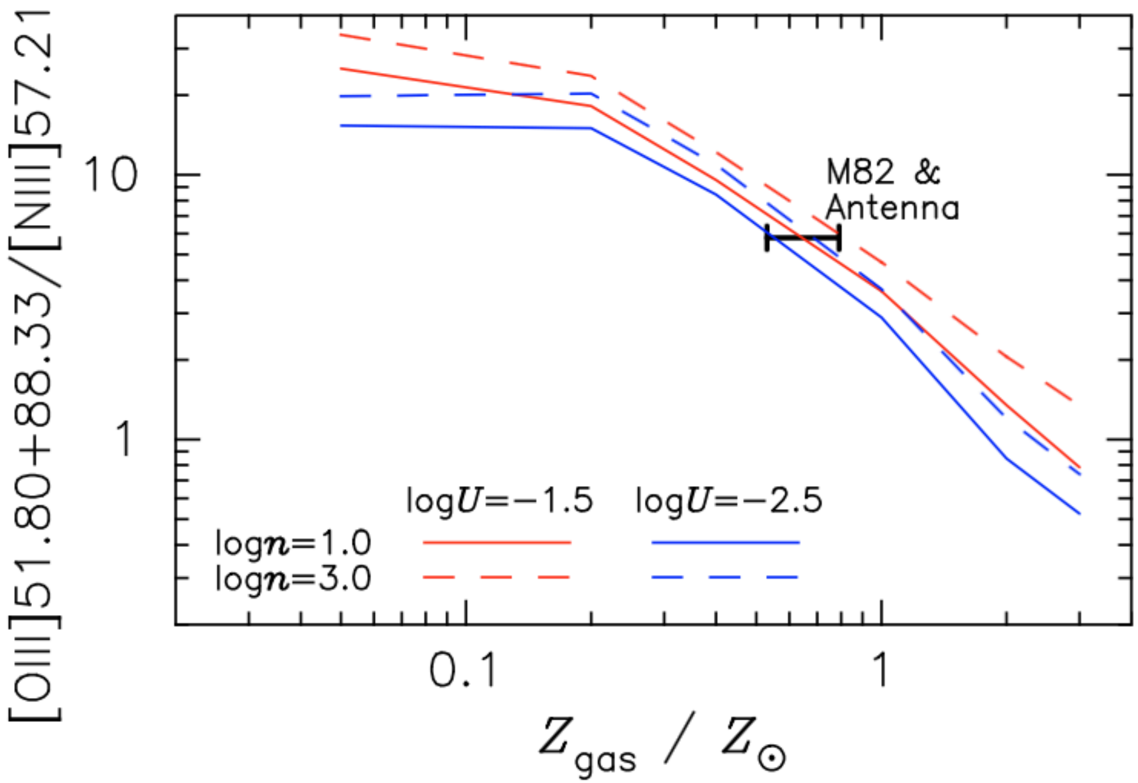
[OIII]88μm



Inoue+16

Far-IR fine structure lines: potentially very promising metallicity tracers

Potentially sensitive metallicity diagnostics

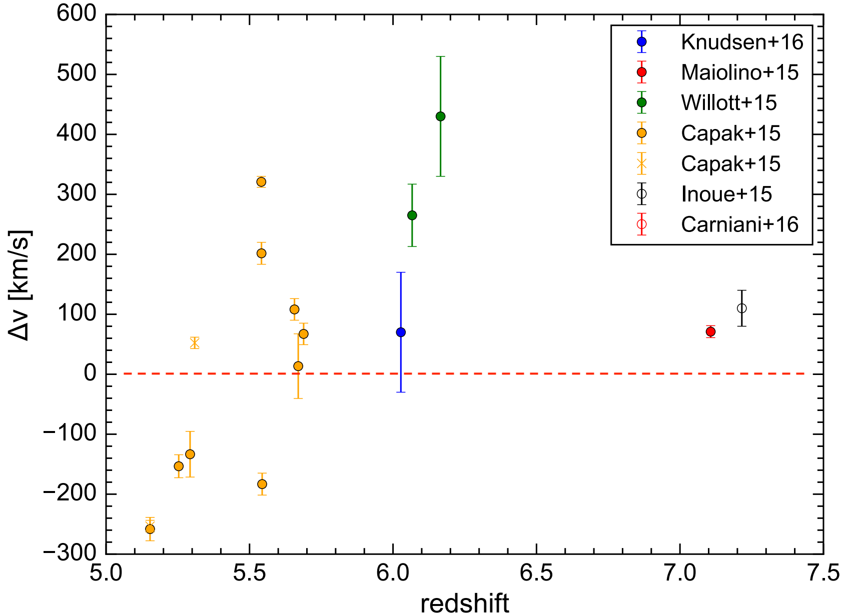


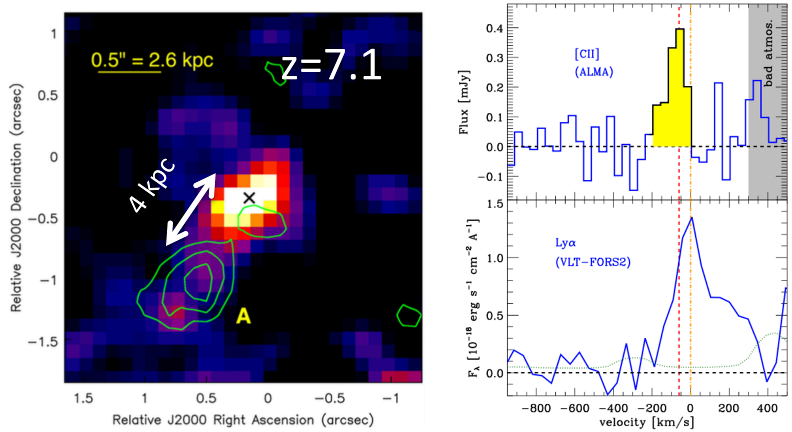
Nagao+11

Detections at z>6 in "normal" galaxies

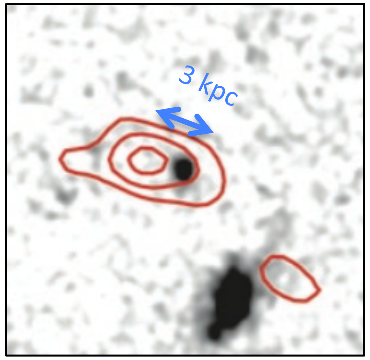
Spatial offset on few kpc scale...

Offset also in velocity





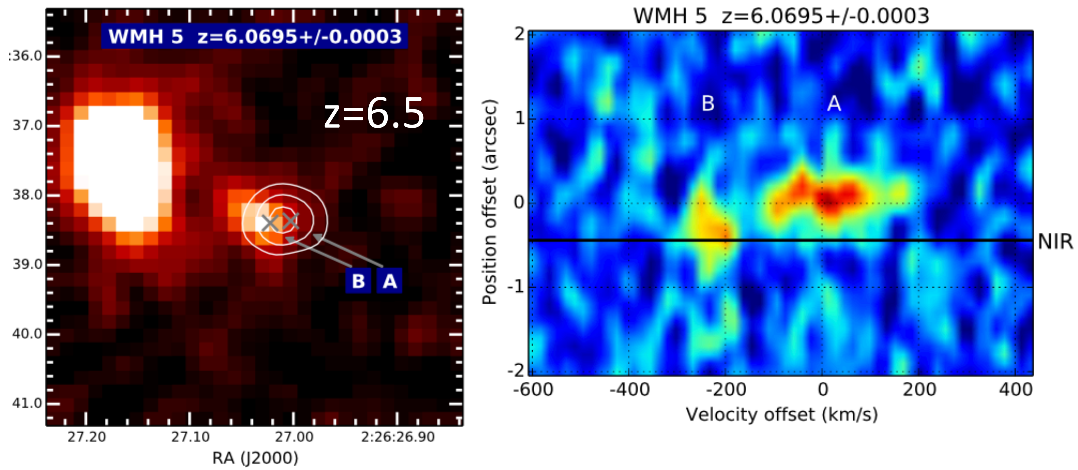
Maiolino+15



z=5.6

Capak+15

Willott+15

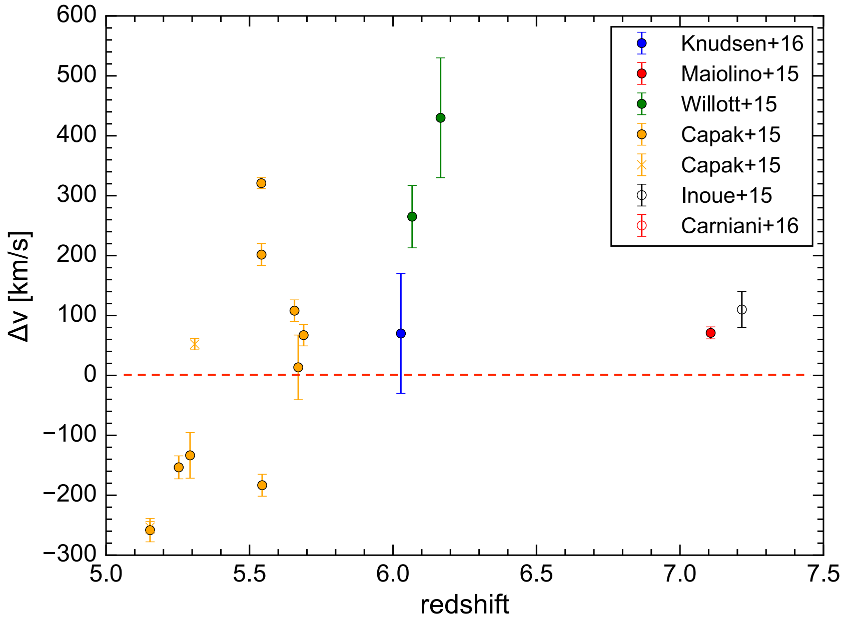


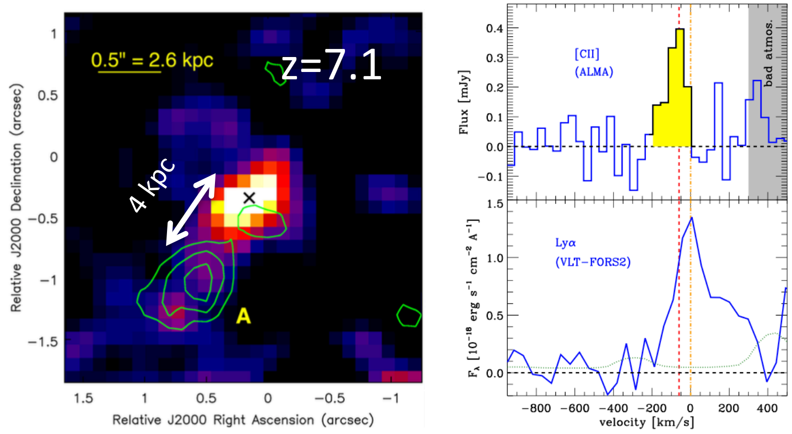
⇒ Often [CII] (and likely [OIII]) does not come from the optically-identified SF galaxy

Detections at z>6 in “normal” galaxies

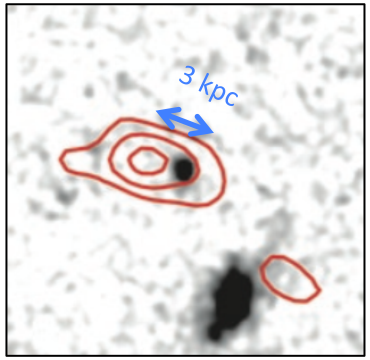
Spatial offset on few kpc scale...

Offset also in velocity





Maiolino+15



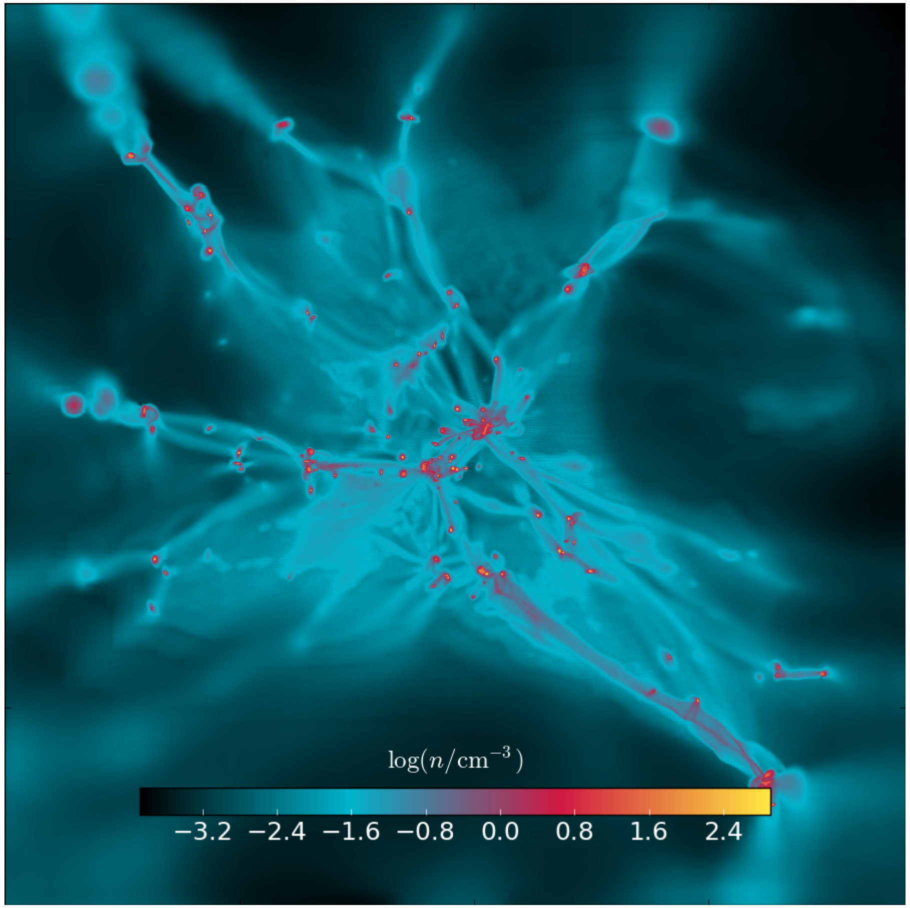
z=5.6

Capak+15

Possible explanations:

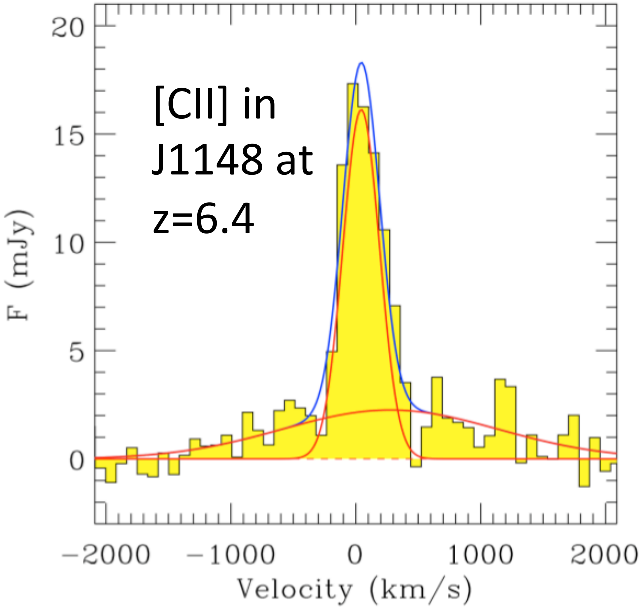
- optical SF galaxy
  - strong feedback that has removed most of the cold ISM
  - very metal poor
- [CII] emitting clumps
  - very dusty star forming companion (but continuum emission unseen)
  - metal enriched outflow
  - metal enriched inflow

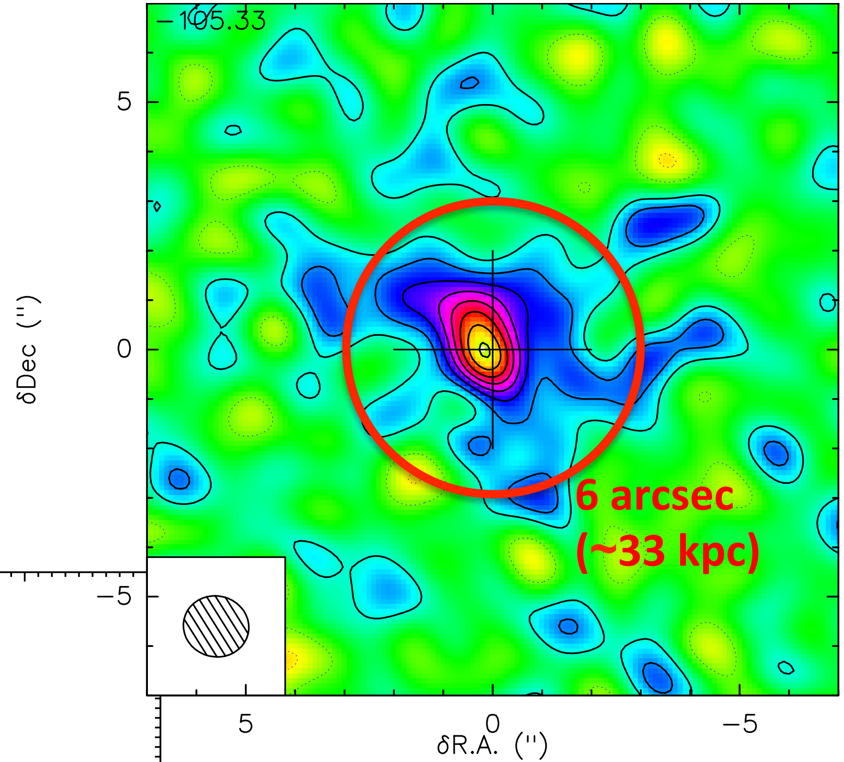
Metal enriched inflows:
expected by models as a consequence of
- pre-enrichment of the IGM by galaxy outflows
- fragmentation, graviational collapse, and star formation in the cosmic streams



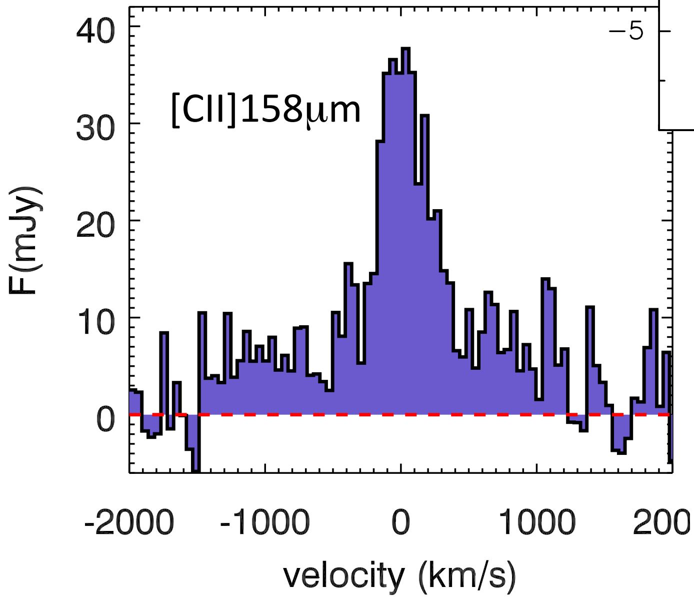
Ceverino+15
Mandelker+16
Pallottini+16
...

Large scale metal enriched massive outflows around z~6-7 QSOs traced by [CII]158μm





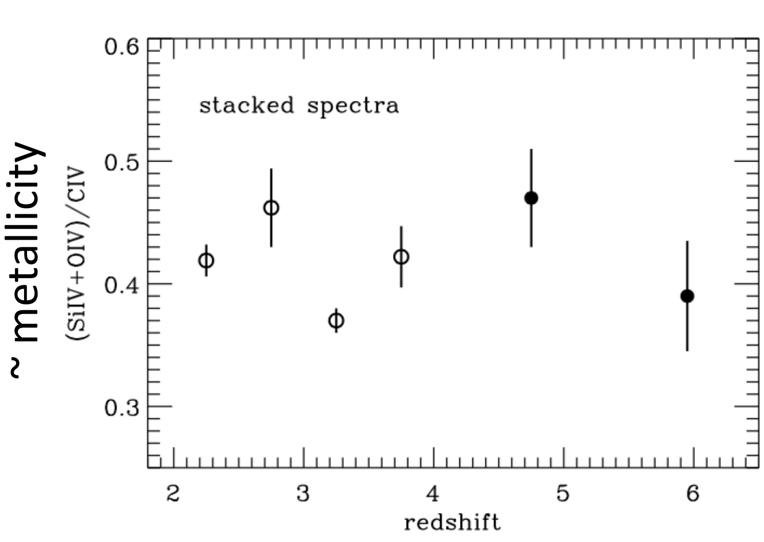
IRAM

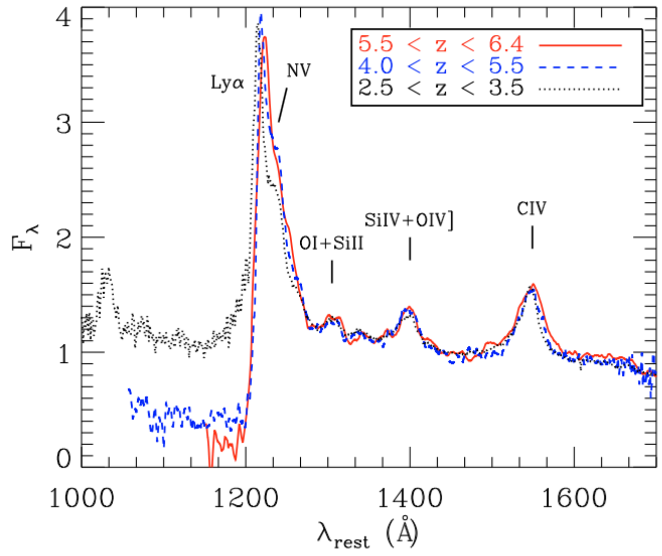


Maiolino+12

Cicone+15

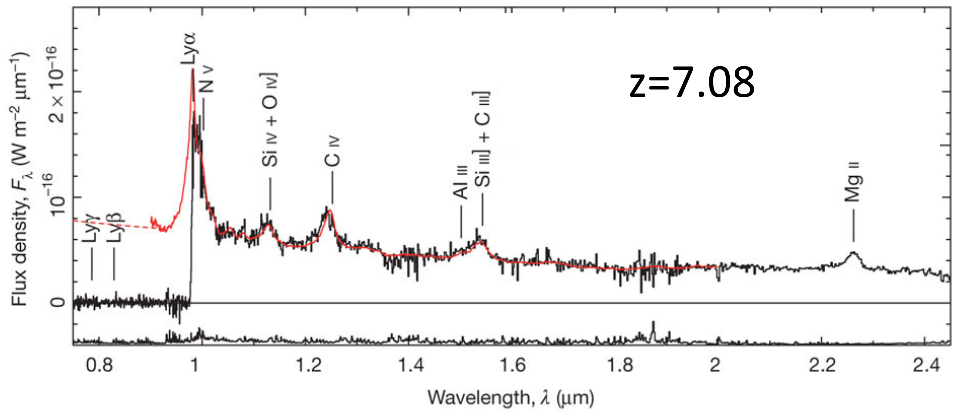
Metals in the nuclear region of QSOs: Lack of evolution





Nagao+06
Juarez+09

No evolution of the metallicity of the nuclear region... is this puzzling?

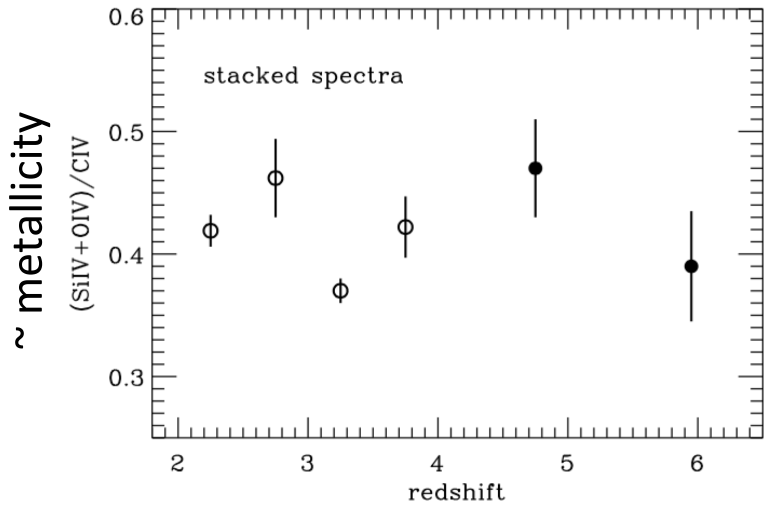


- The "Broad Line Region" has a very small mass ~10^4 Msun -> SN rate less than 10^{-4} yr^{-1} enough to enrich to super solar in less than 100 Myr

Mortlock+12

- QSOs are 6σ overdensity peaks
- Selection effects

Metals in the nuclear region of QSOs: Lack of evolution

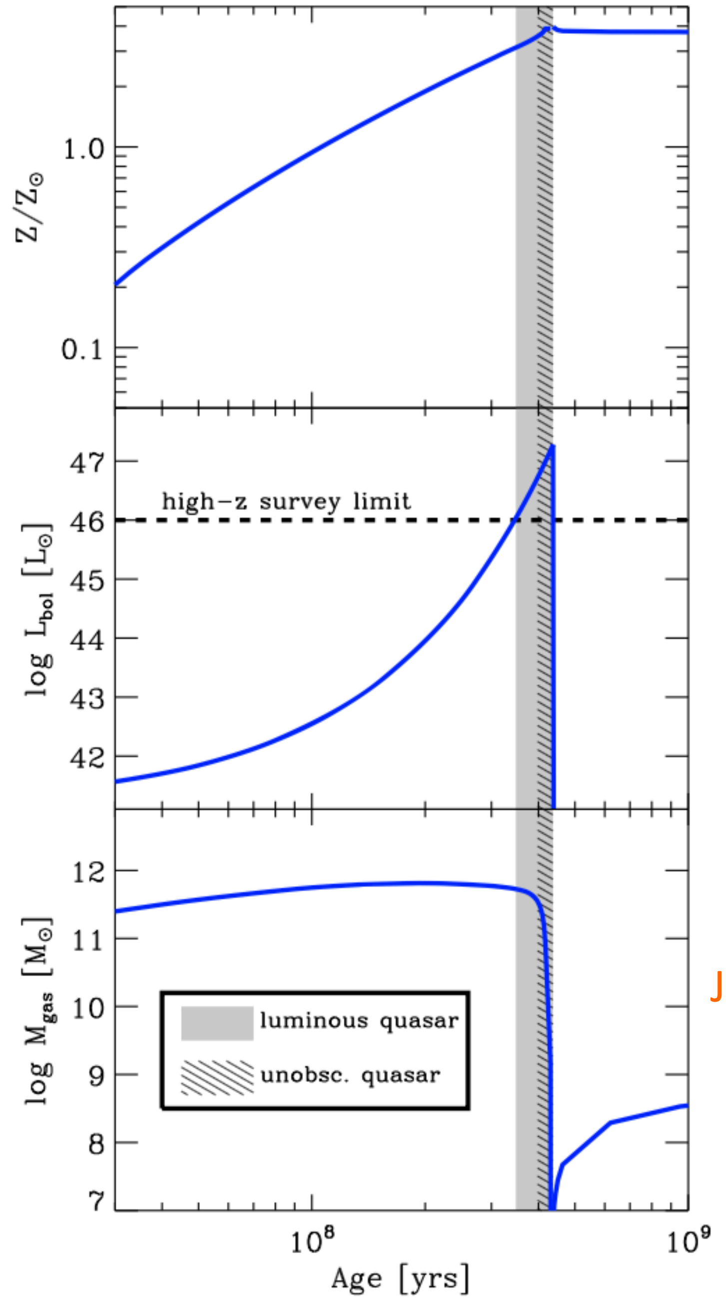


No evolution of the metallicity of the nuclear region... is this puzzling?

- The "Broad Line Region" has a very small mass ~10^4 Msun -> SN rate less than 10^{-4} yr^{-1} enough to enrich to super solar in less than 100 Myr

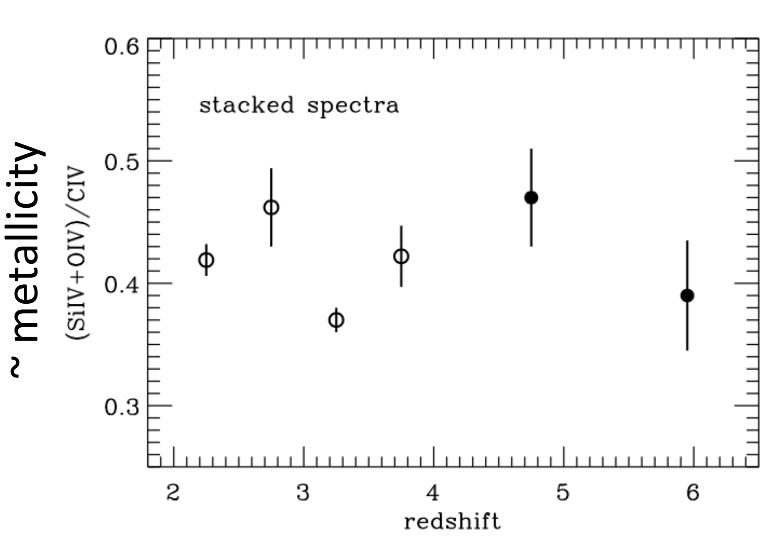
- QSOs are 6σ overdensity peaks

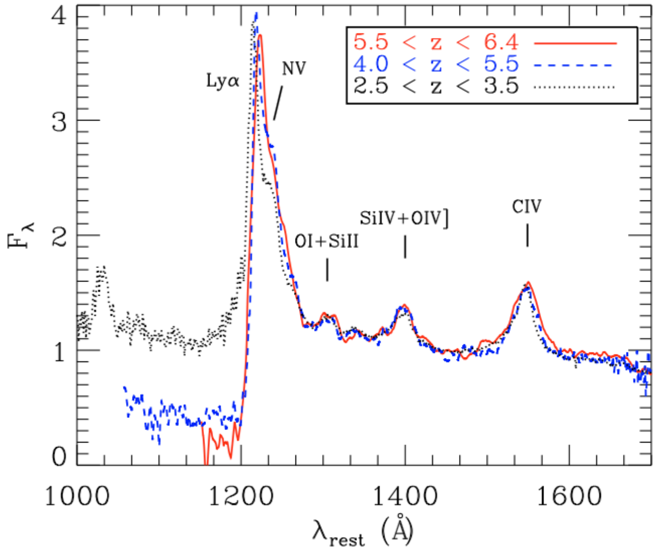
- Selection effects



Juarez+09

Metals in the nuclear region of QSOs: Lack of evolution





Nagao+06
Juarez+09
Mortlock+12

No evolution of the metallicity of the nuclear region... is this puzzling? → Not really

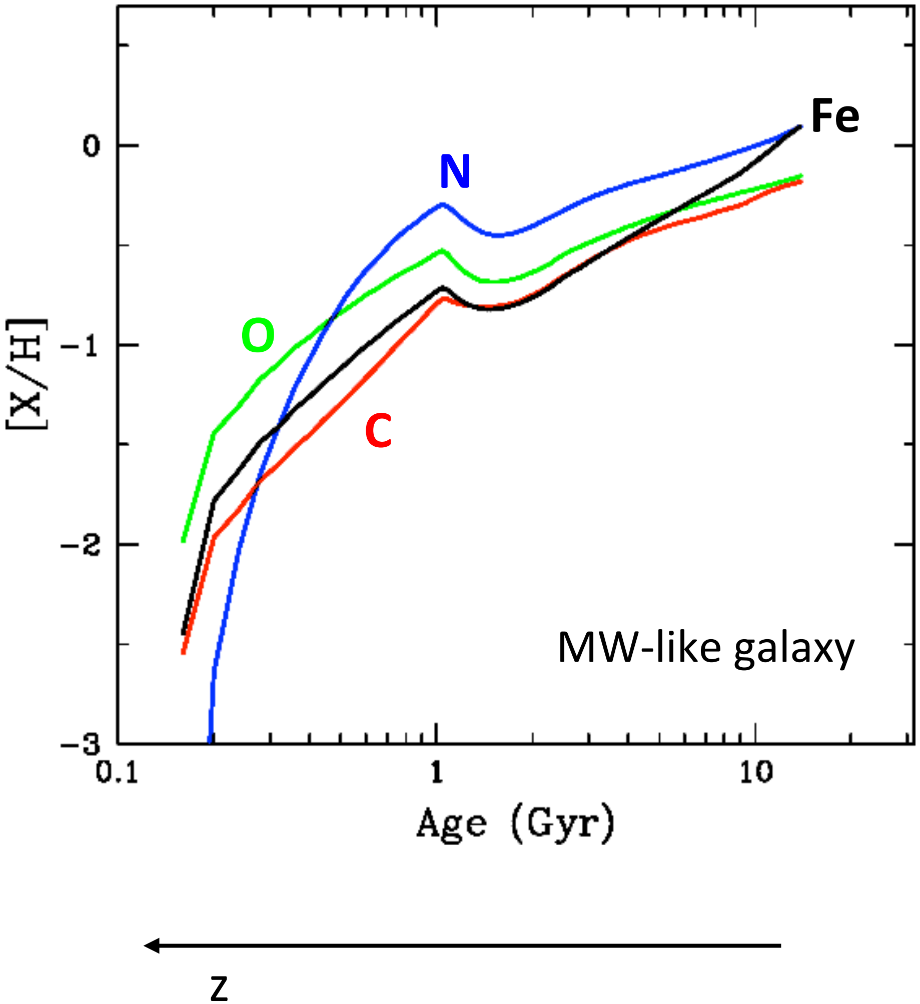
- The “Broad Line Region” has a very small mass ~10^4 Msun -> SN rate less than 10^{-4} yr^{-1} enough to enrich to super solar in less than 100 Myr

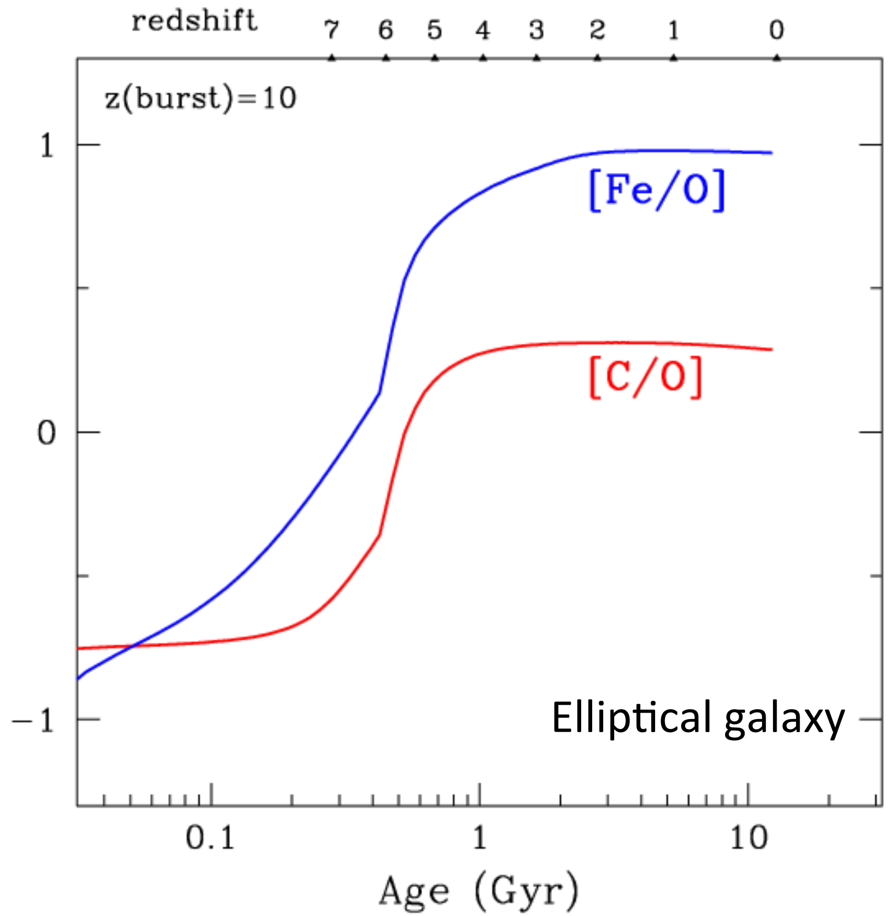
- QSOs are 6σ overdensity peaks

- Selection effects

More worrying is the lack of evolution of elemental abundances Fe/α, C/O, N/O...

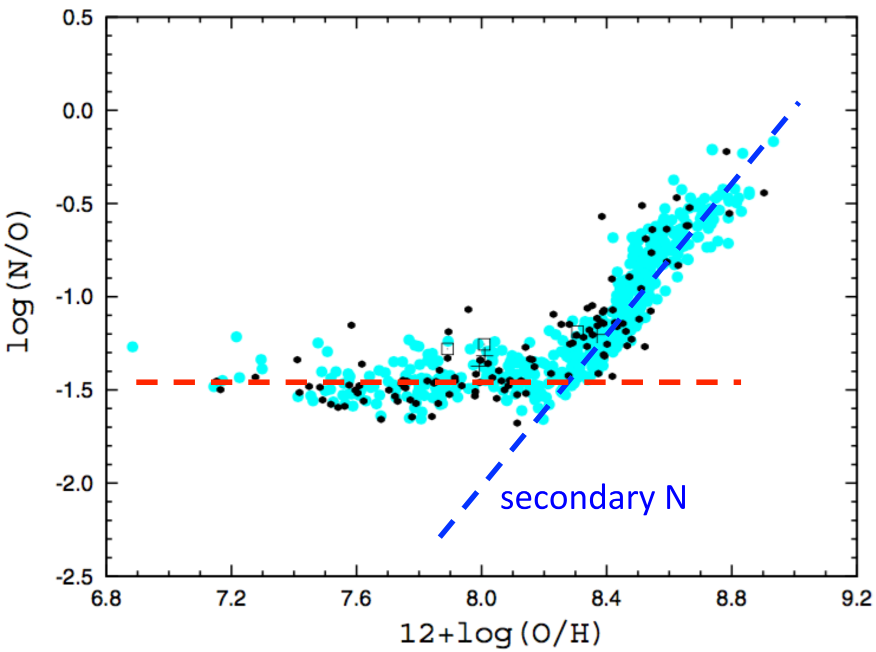
Abundance ratios, Fe/α, C/O, N/O, as “clocks” of star formation



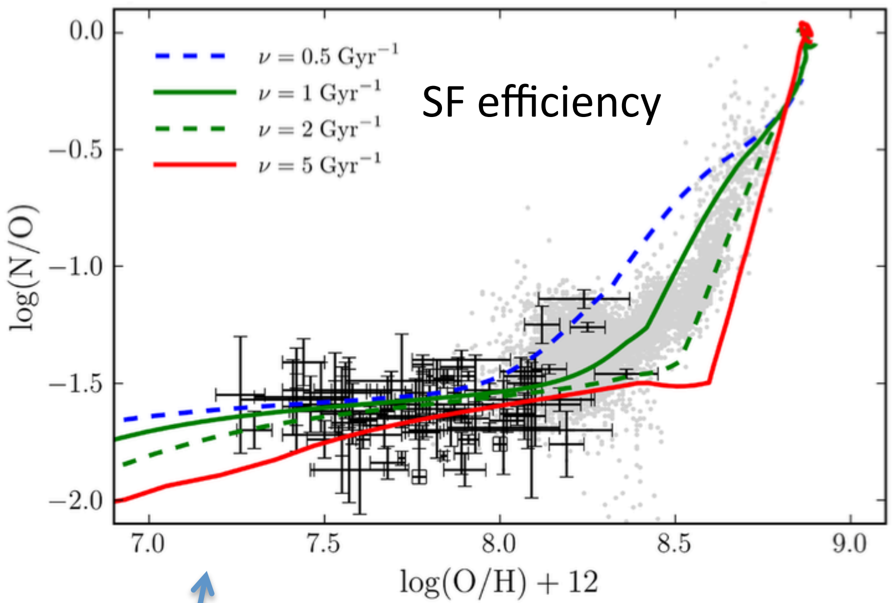


Signature of such “clock” seen in the abundance ratio versus metallicity diagrams

The case of Nitrogen: additional interesting feature of having a “secondary” component



Pilyugin+10

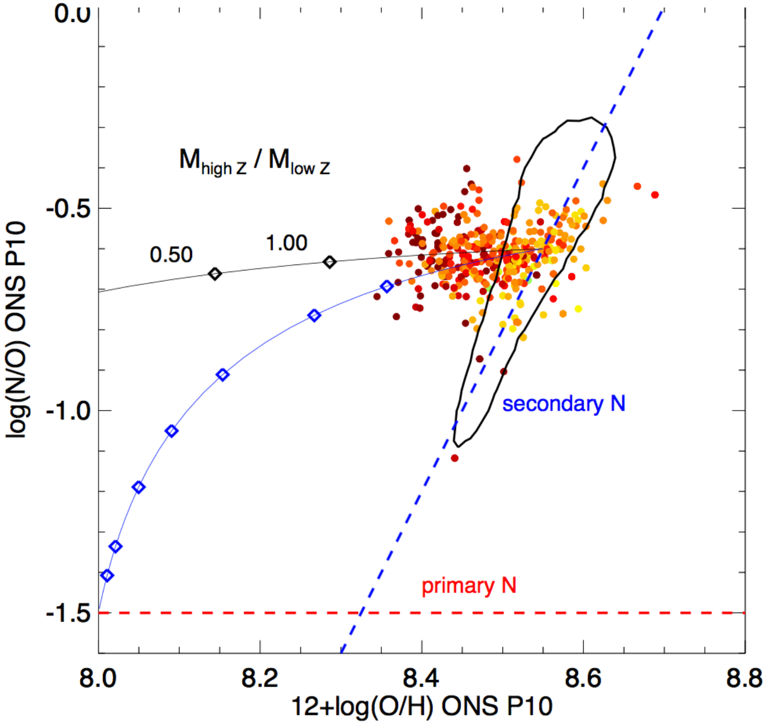


Vincenzo+16

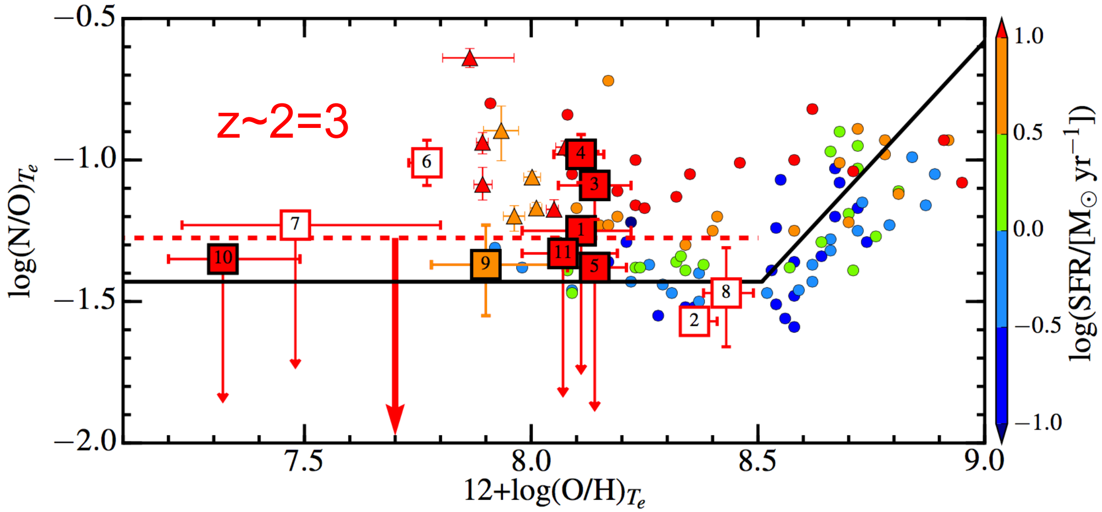
effect of different star formation efficiency
=> different evolutionary timescales

Deviations from “standard” pattern are diagnostics of peculiar evolutionary stages

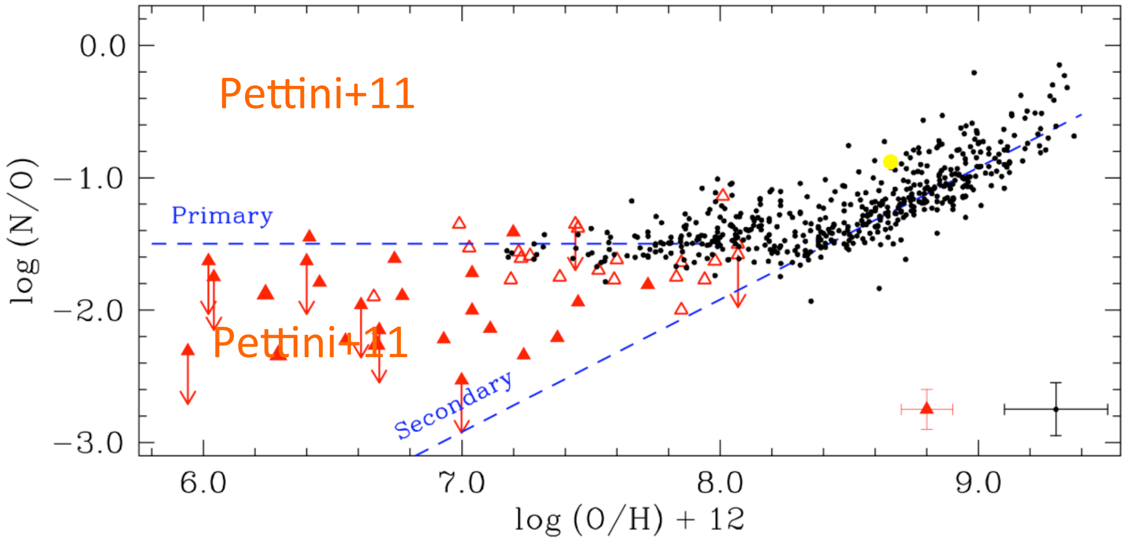
Map within (Manga) local galaxy



Belfiore+15

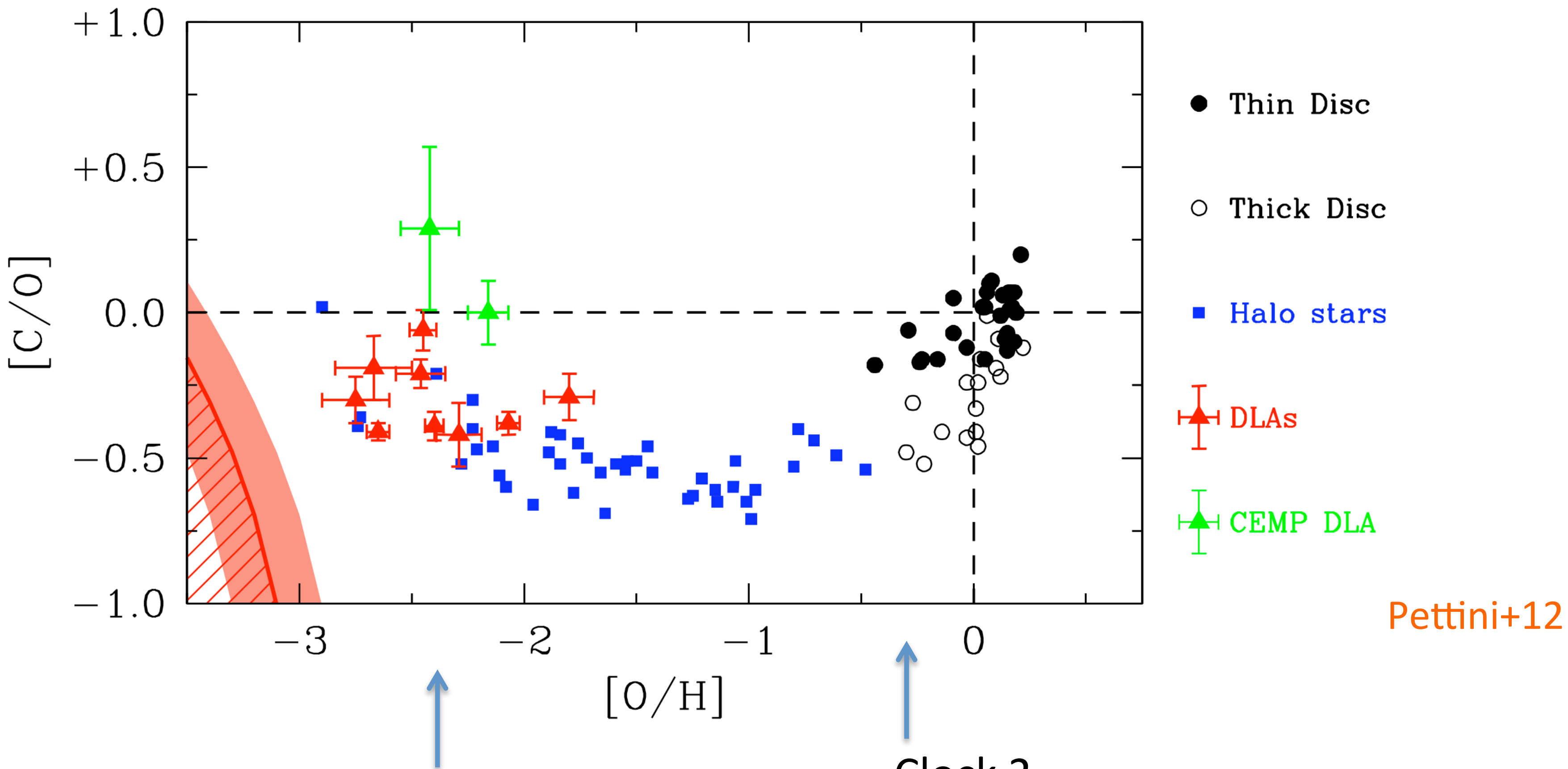


Koyama+16



- Dilution from pristine inflows
- Mixing within galaxies
- Star formation timescale
- Peculiar yields

Evolution of the C/O abundance ratio

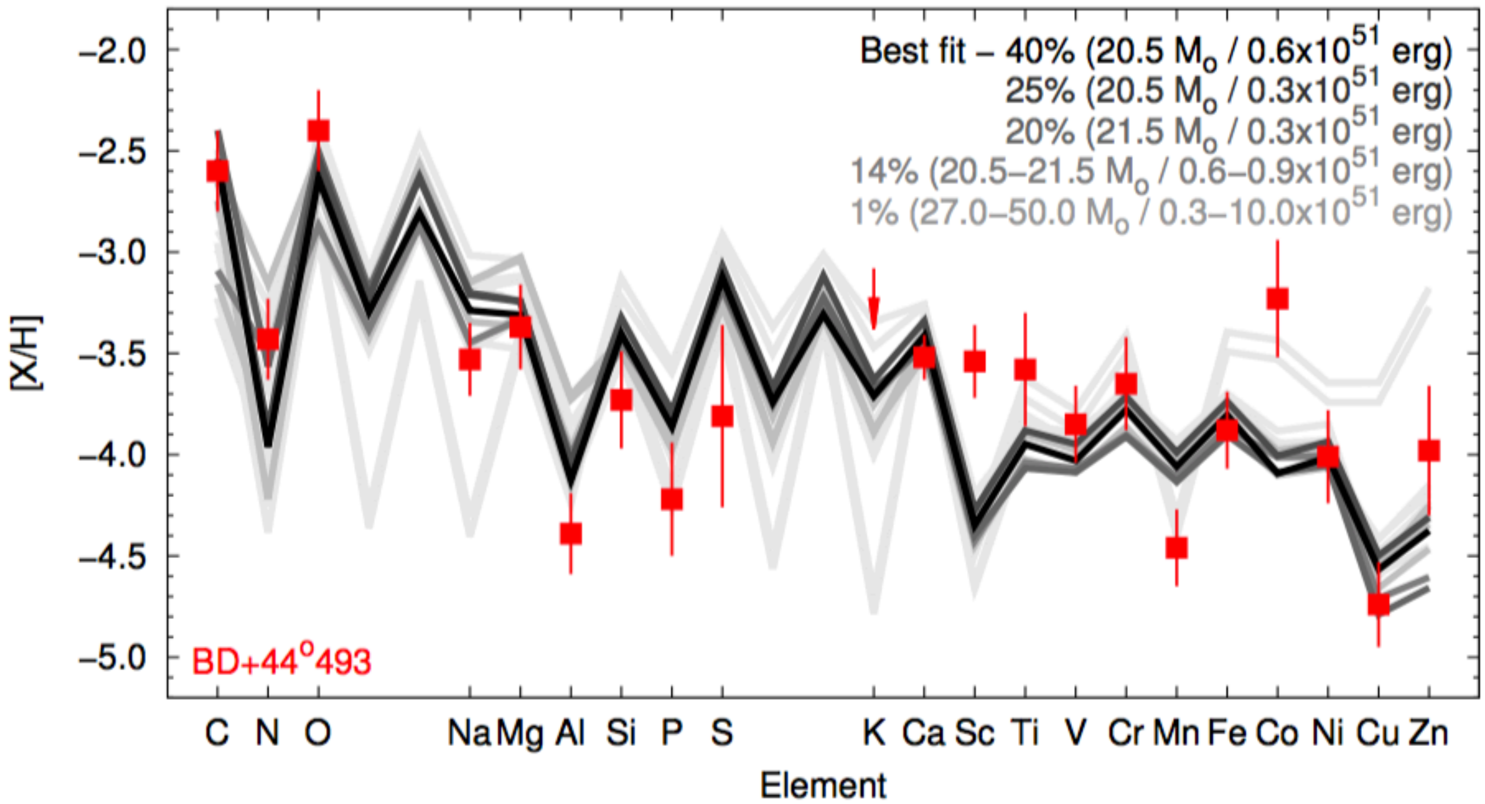


Clock 1
popIII – PopII transition?

Clock 2
massive-intermediate stars transition

High-z DLA and astro-archeology most promising tool to identify the fingerprint of PopIII

Astro-archeology really constraining
the properties of first generation of stars



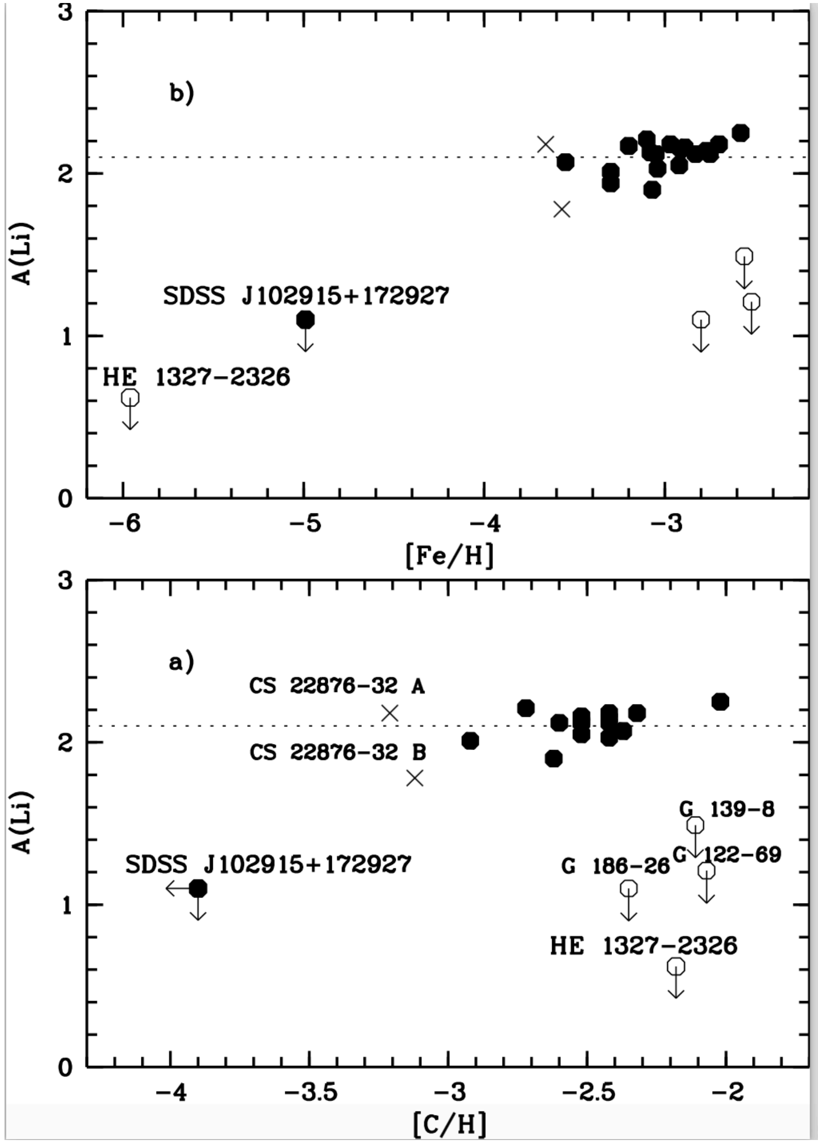
Roederer+16

Mass of PopIII progenitor: 20 Msun
Faint SN

Analysis of high-z absorbes approaching the same level of accuracy

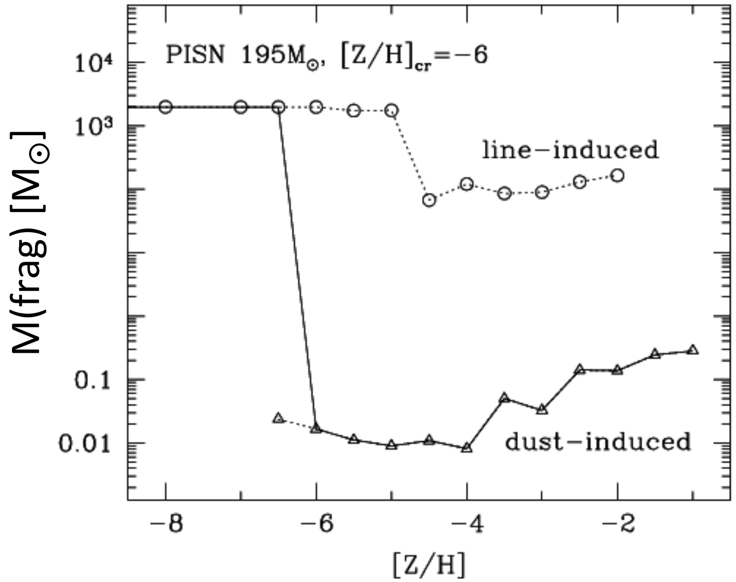
The star(s) that should not exist

Low mass star with metallicity below the “critical value” for fragmentation



Caffau+11

Explained with extra-cooling (-> fragmentation) provided by the first dust grains injected into the ISM by the first SN explosions



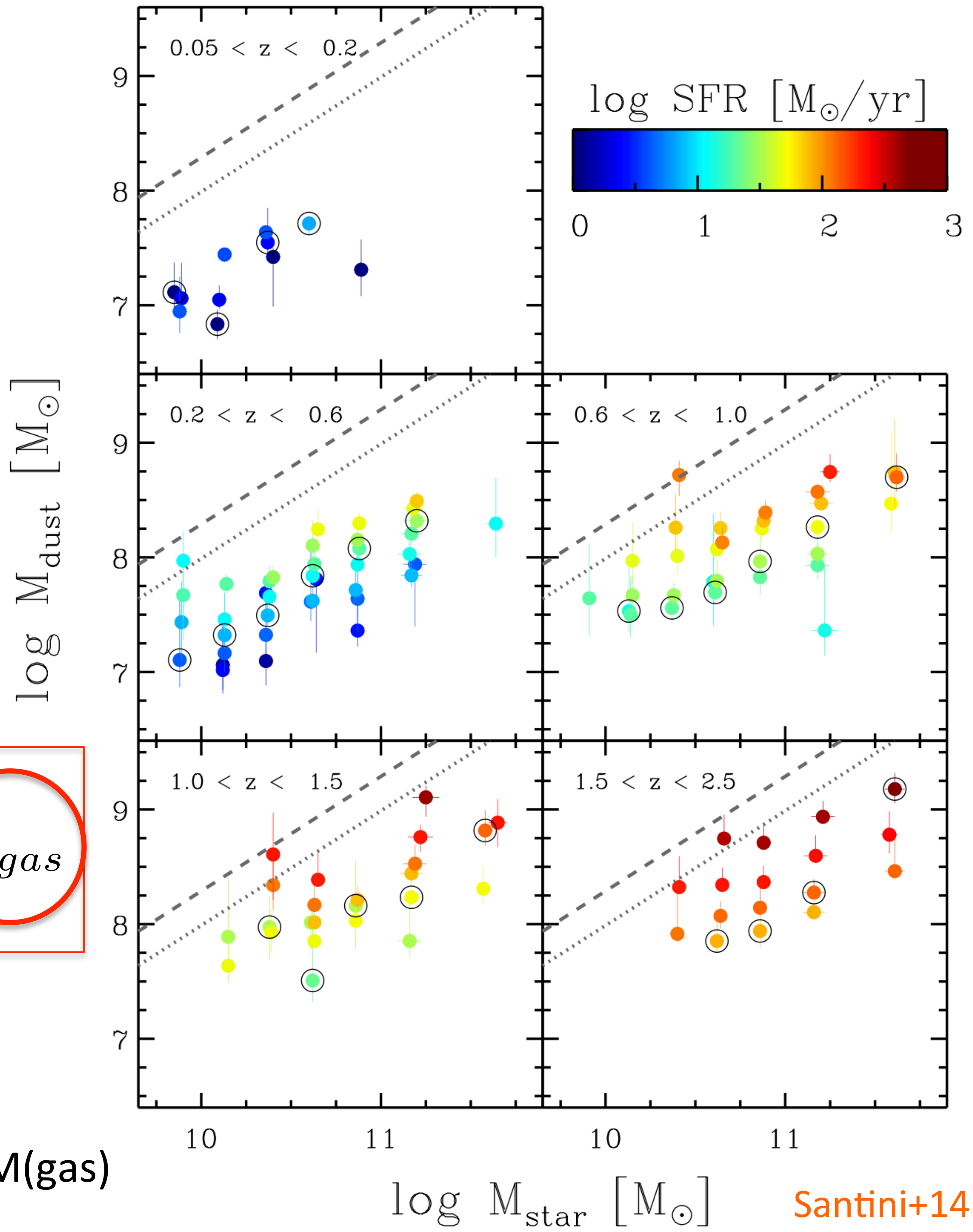
Dust enrichment by first generation of stars crucial for the formation of first low mass stars

(Schneider+06,+13 Tsuribe et al. 06, Omukai et al. 05)

Cosmic evolution of the dust content in galaxies

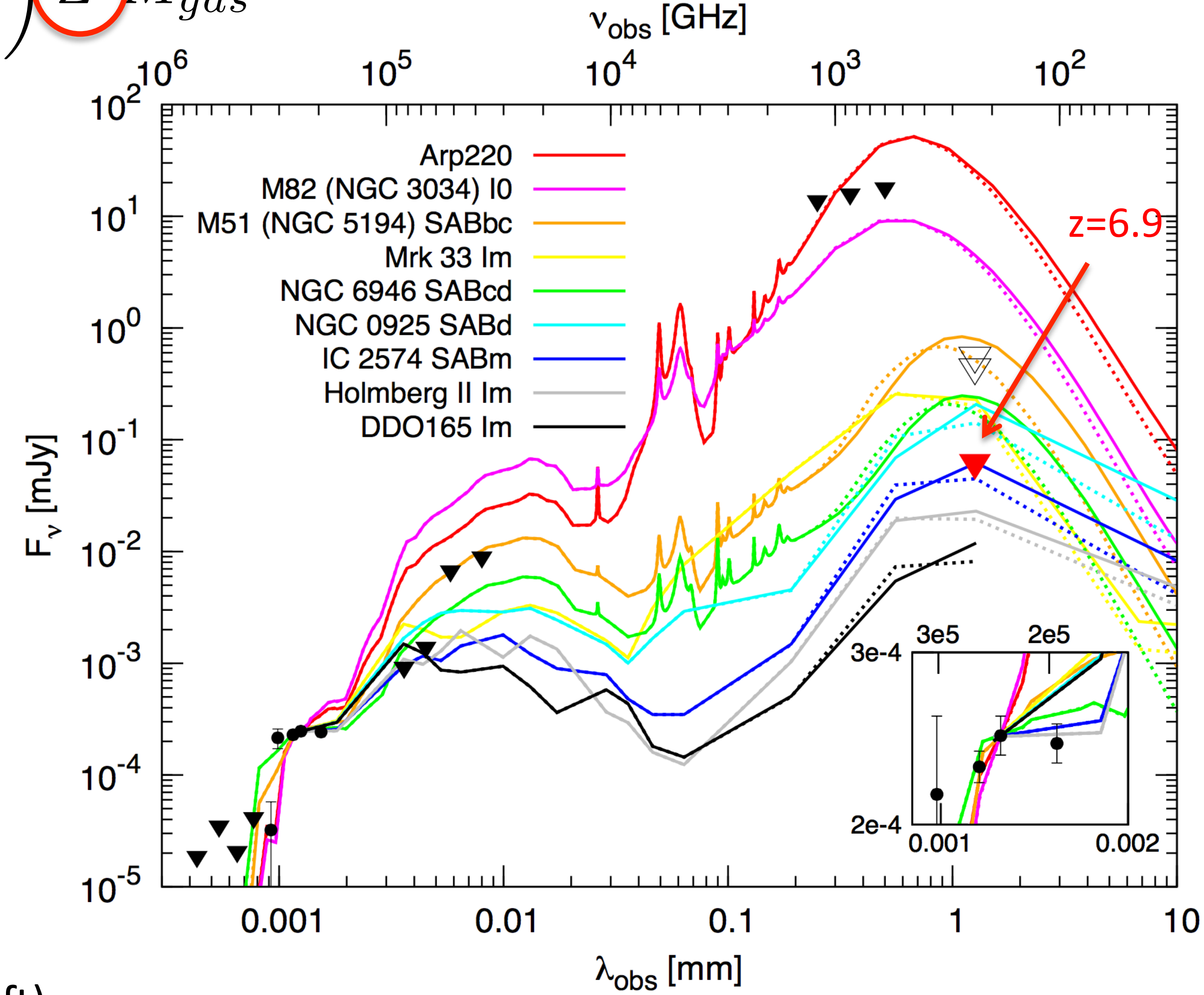
$$M_{dust} = \left(\frac{M_{dust}}{M_{metals}} \right) Z \, M_{gas}$$

Out to intermediate redshift
the evolution of M(dust) is
mostly driven by the evolution of M(gas)



Santini+14

$$M_{dust} = \left(\frac{M_{dust}}{M_{metals}}\right) Z M_{gas}$$



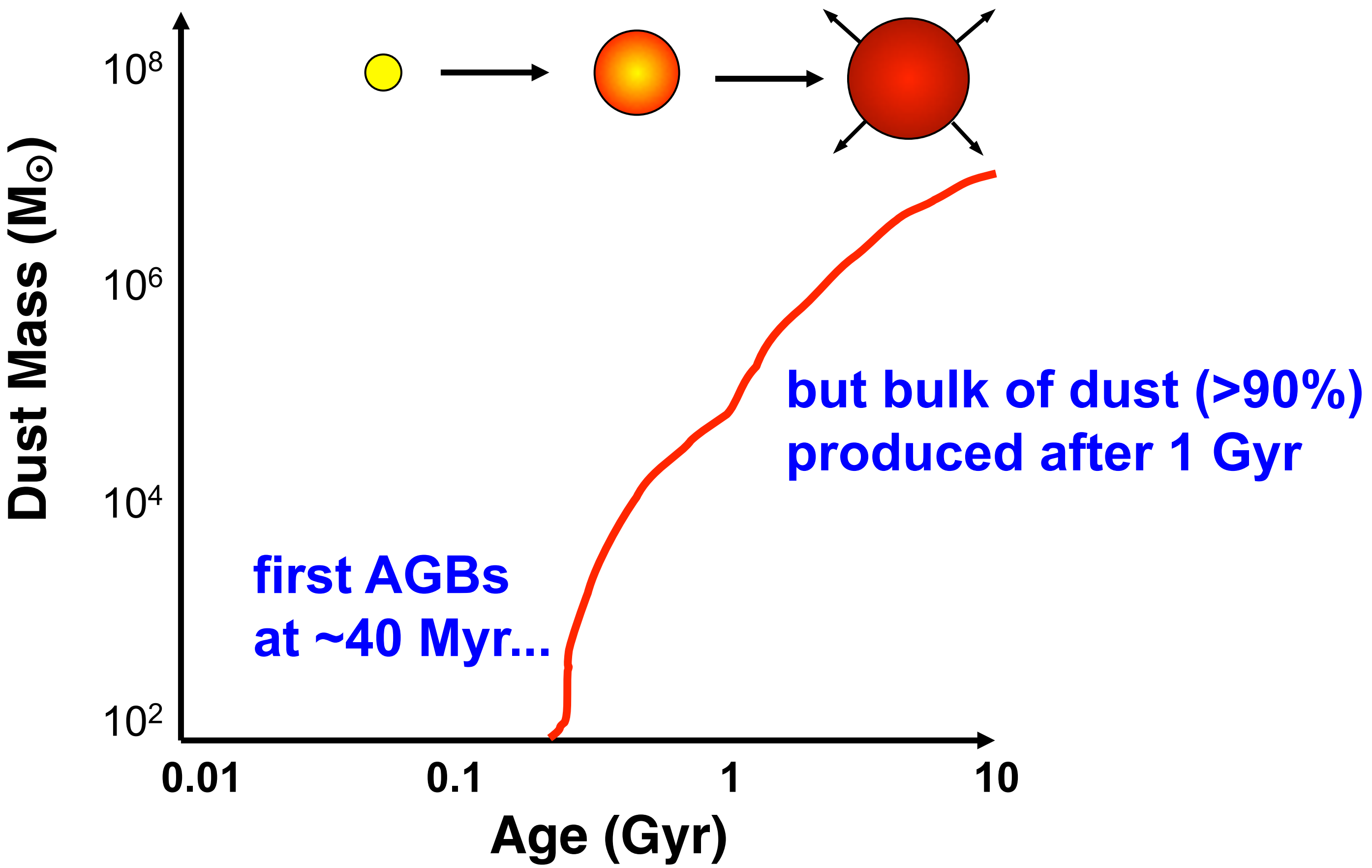
Of course looking at
low metallicity galaxies
(low mass or high redshift)
the "metallicity" terms
plays a significant role

Ota+14
Walter+12
Maiolino+15
Schaerer +15

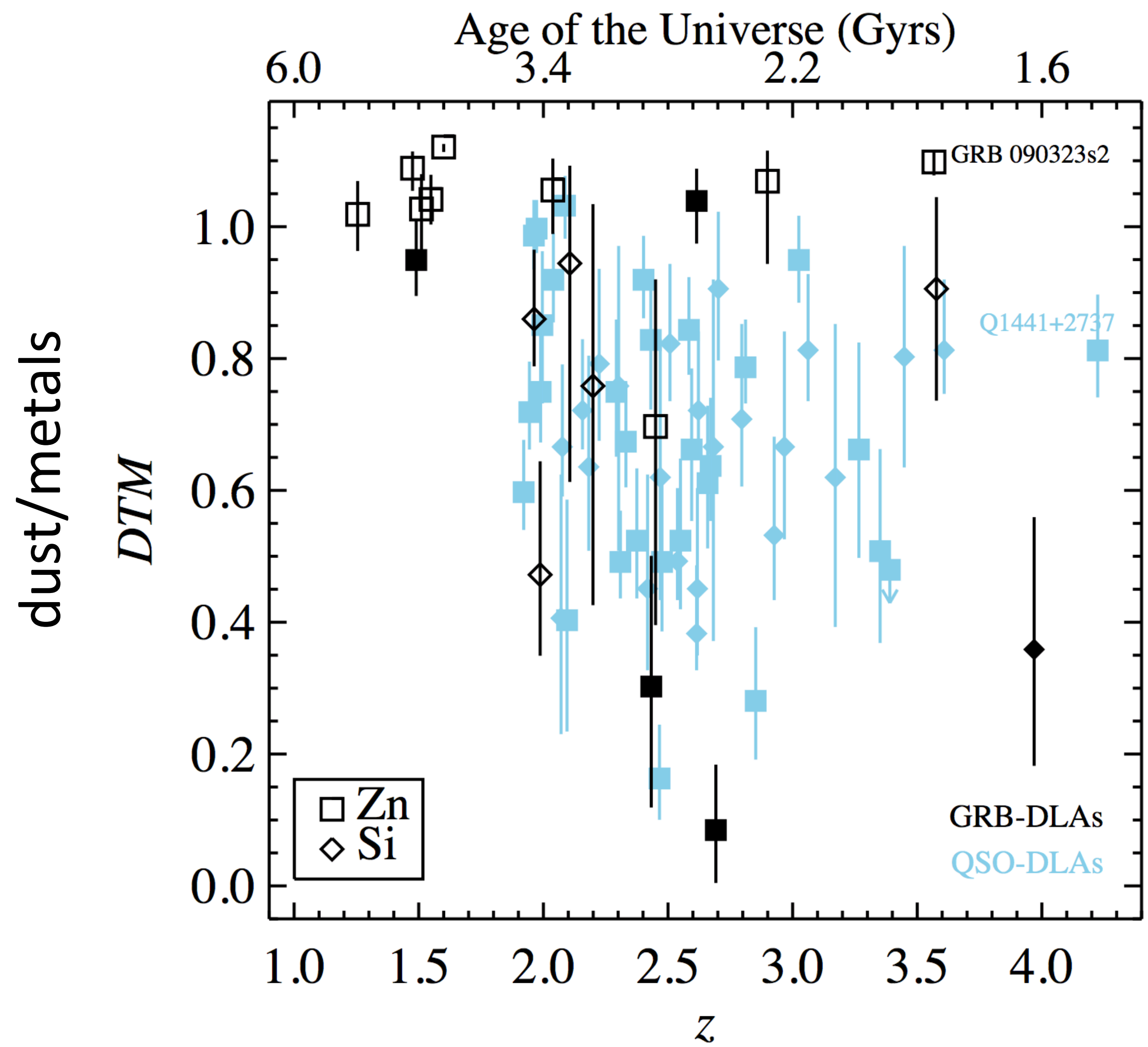
Yet, at very high redshift
or in very un-evolved system
also the dust production
mechanism (i.e. M_{dust}/M_{metals}) has an effect

$$M_{dust} = \left(\frac{M_{dust}}{M_{metals}}\right) Z\ M_{gas}$$

In the local universe dust is mostly
produced by evolved low mass stars (AGBs)



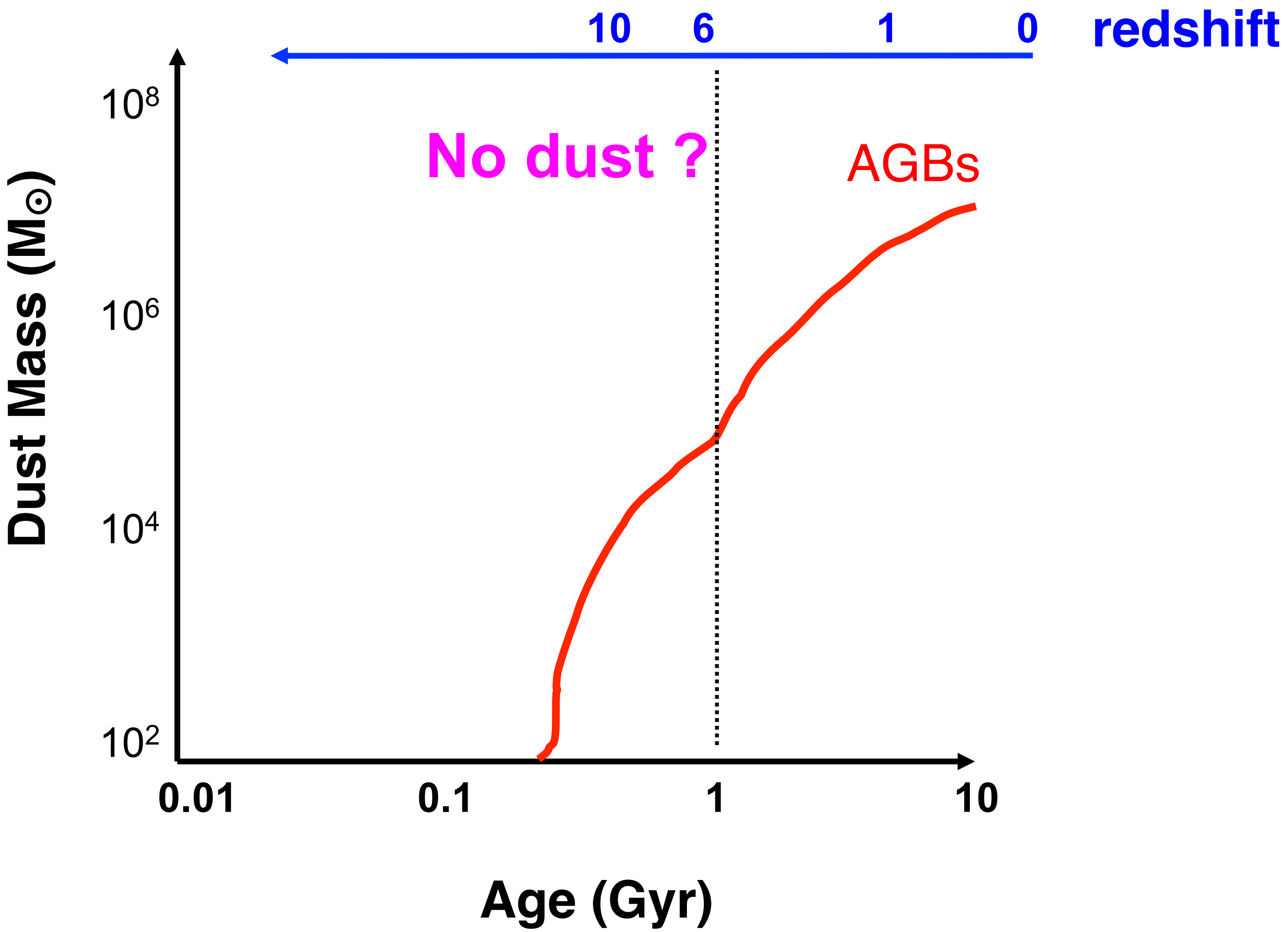
Minimum timescale for dust production likely responsible for the observed evolution of the dust/metals ratio



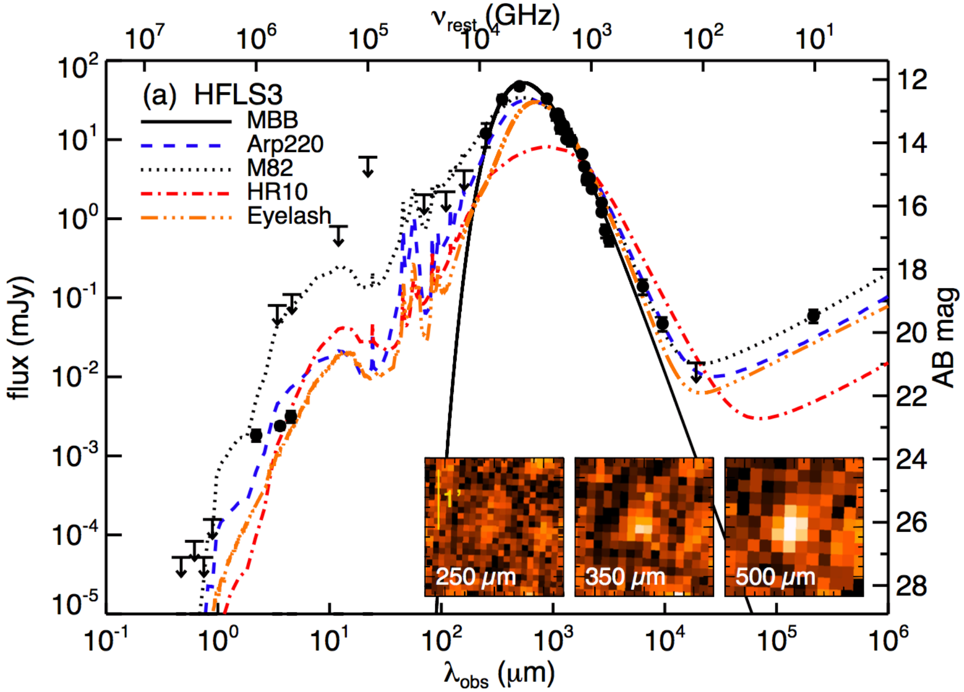
De Cia+14

Dust at z>6

Age of the Universe < 1 Gyr:
short of time to produce dust with AGBs

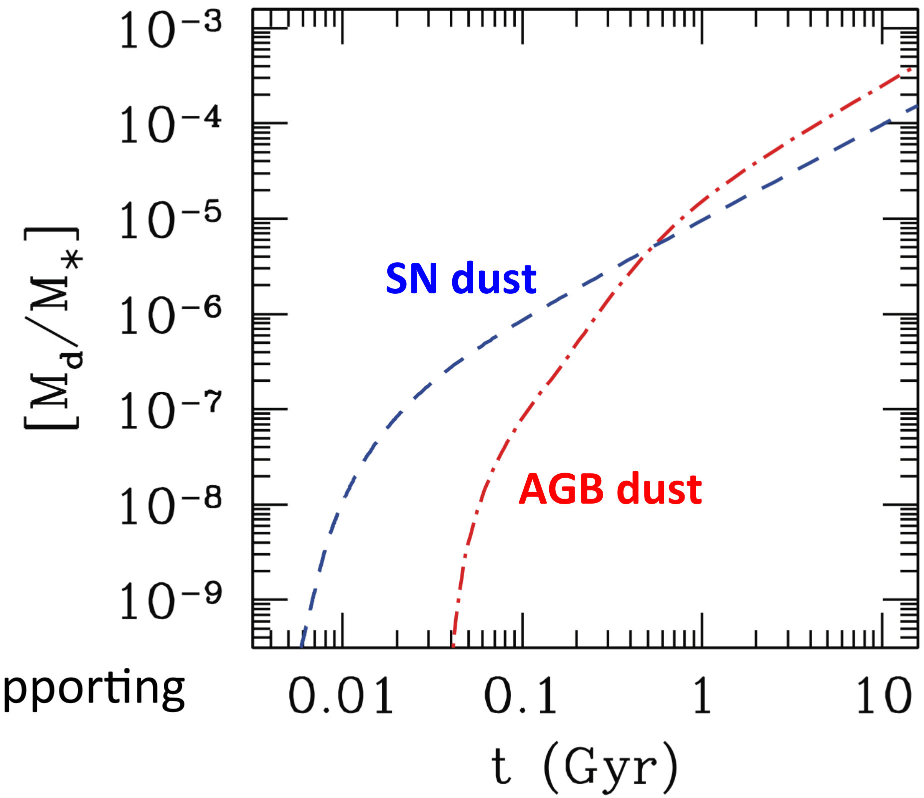


Yet very high dust masses discovered at z>6-7 in SMGs and QSO hosts



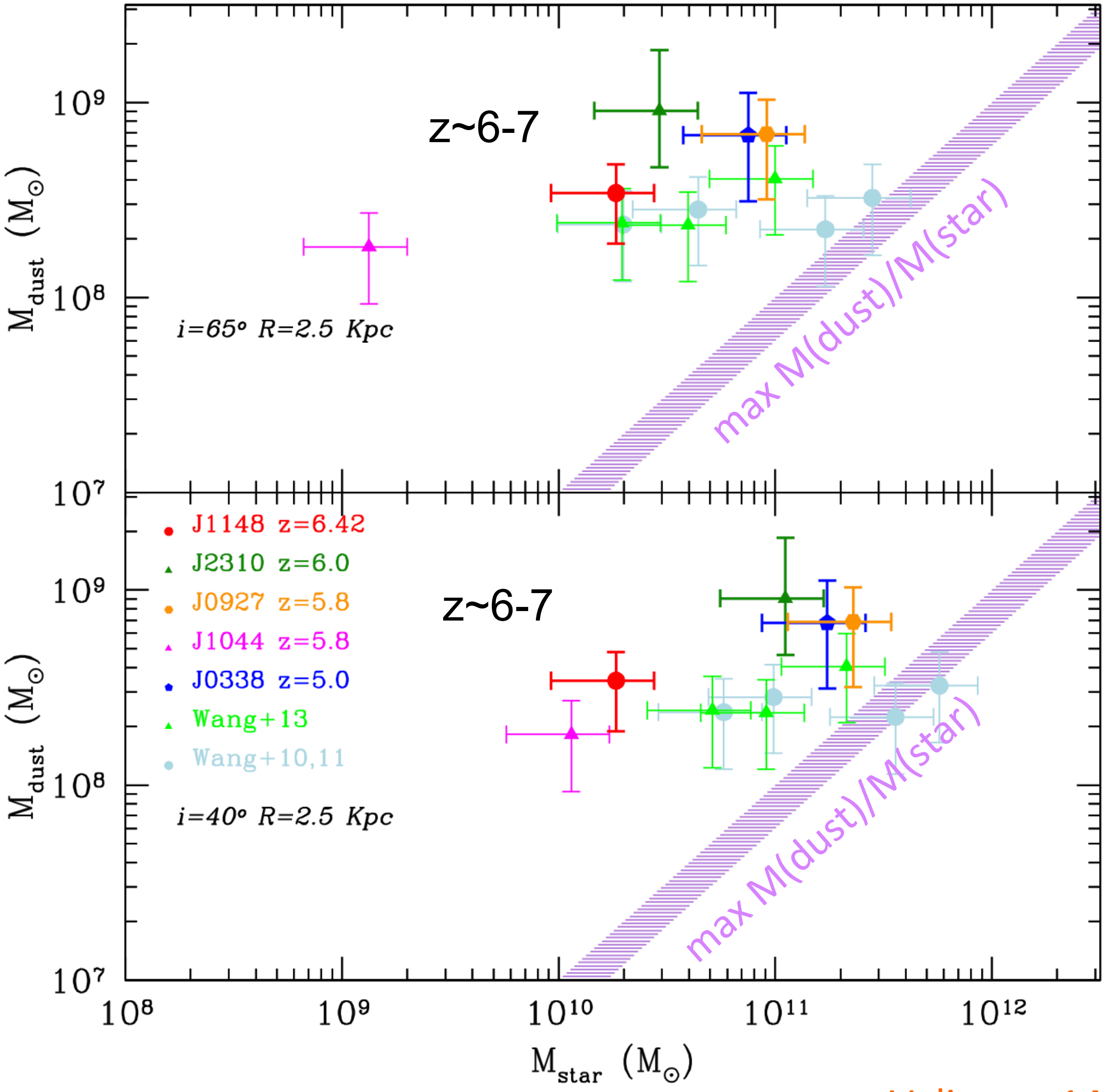
Beelen et al. 2006
Bertoldi et al. 2003
Priddey et al. 2003
Robson et al. 2005
Riechers+2013
Weiss+2014

Dust formed in the ejecta of SNe as additional dust production mechanism on short timescales



High-z xtinction curves supporting contribution by SN dust

Yet, several cases of uncomfortably high dust masses compared with the stellar masses (inferred from dynamical measurements)

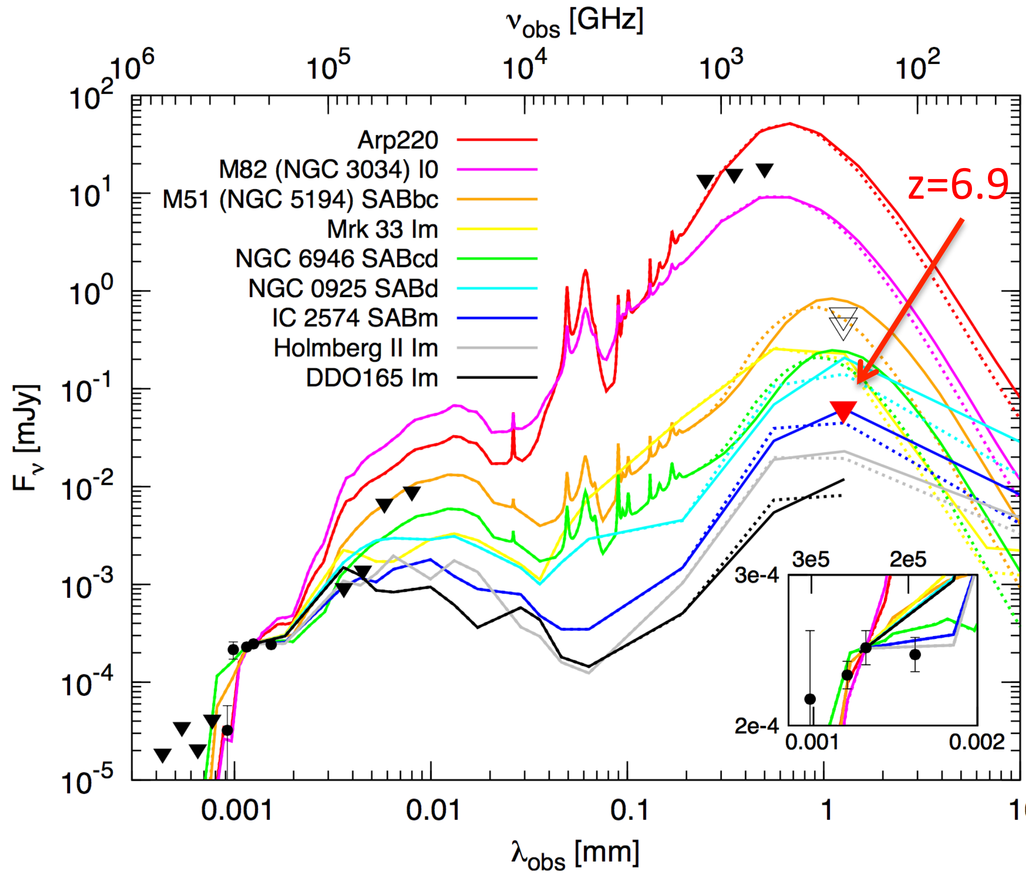


Either:
- dynamical masses wrong by orders of magnitude

or
- different IMF in the early Universe

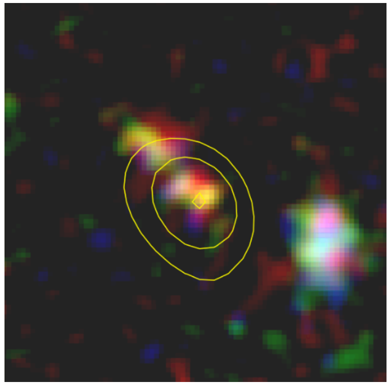
Valiante+14

In “normal” galaxies dust masses are generally very low (non detections or weak ALMA detections...)

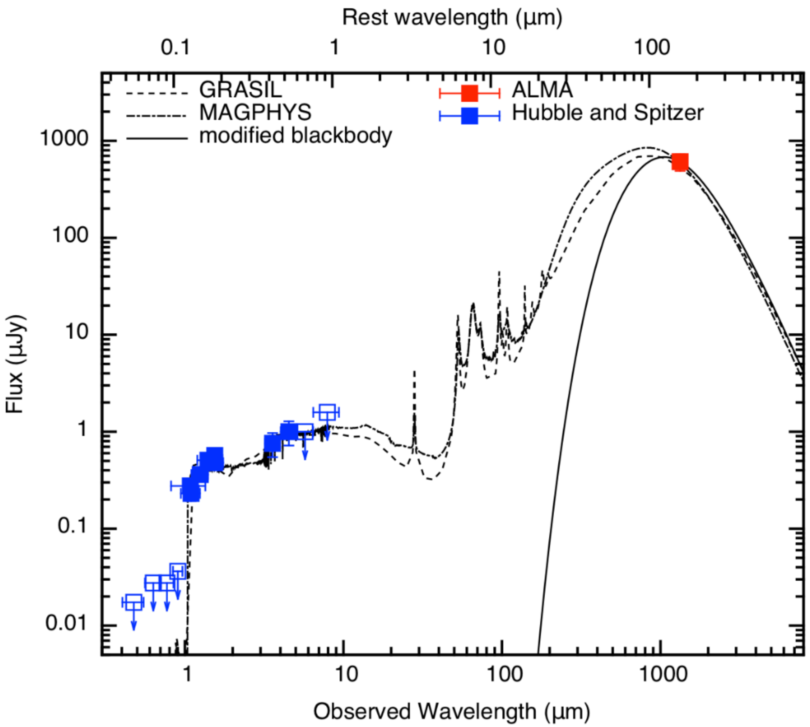


Low dust content as expected for their early evolutionary stage and low metal content

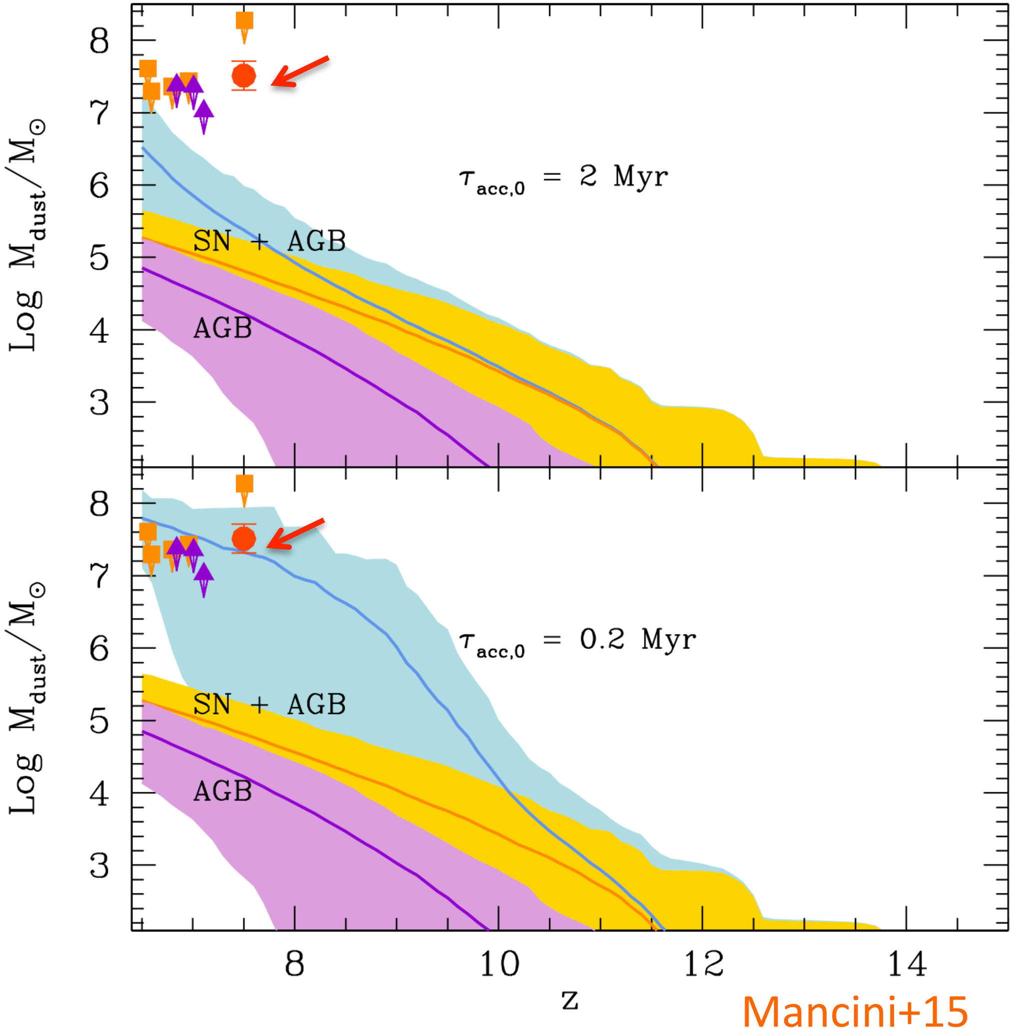
Detection of large amount dust in a normal (lensed) galaxy at z~7.5



Watson+15



really difficult to explain:
requires extremely fast
dust accretion timescales in the ISM



Mancini+15

Summary

- The investigation of the metallicity, chemical abundances and dust content in local and distant galaxies is providing key information to understand the formation and evolutionary processes in galaxies

- Several important questions and puzzling issues are still open

- Major progress is expected in the coming few years, especially thanks to JWST, ALMA in full operation and the extremely large telescopes

Thank you!