OXYGEN ABUNDANCES AT HIGH REDSHIFT
FROM ABSORPTION LINES

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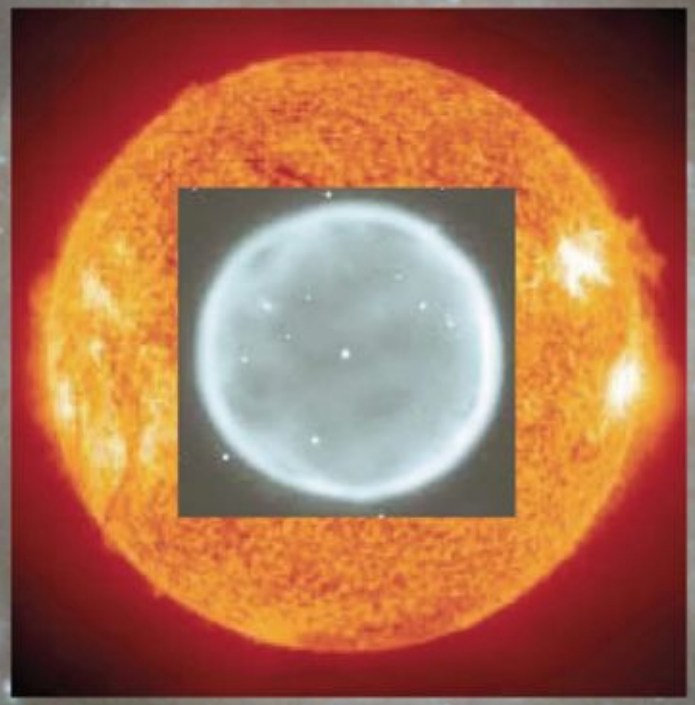


Mapping oxygen in the universe – Tenerife (Spain) – 14-18 May 2012

MEASURING OXYGEN FROM ABSORPTION LINES

Gaseous oxygen can be observed in absorption in the ISM of galaxies on sightlines of luminous background sources

AVAILABLE OXYGEN LINES

Numerous lines of ionized oxygen and of molecules including oxygen atoms exist, but measurements of oxygen are performed on neutral oxygen (OI) resonance lines

➔ all are located in the UV range from 900 to 1400 Å (Morton 91,03)

COLUMN DENSITY MEASUREMENTS

1. derived from equivalent widths via an empirical curve of growth for unsaturated absorption lines
2. determined using the apparent optical depth method (AODM; Savage & Sembach 91)
3. obtained from Voigt profile fitting of absorption lines when high resolution spectra are available (R>40000)

SOURCE OF UNCERTAINTIES

Atomic data: 20% uncertainties in the oxygen oscillator strength values are common

Line spread function shape: in priority affecting the line profile fitting, because of the poorly constrained convolution with the line spread function of the spectrograph

Scattered light at high resolution: leading to uncertain zero flux levels in absorption lines

Continuum: particularly uncertain in crowded spectra with numerous absorption lines

Velocity structure: severe uncertainty in low resolution spectra where the velocity structure of absorption components remains unresolved (Prochaska 06)

MEASURING OXYGEN FROM ABSORPTION LINES

The abundance of oxygen is expressed relative to hydrogen and is defined as:

$$O/H = \log (N(OI)/N(HI))$$

The access to HI lines is mandatory, these lines are in a similar wavelength domain as the OI lines.

GAS-PHASE ABUNDANCES: MAJOR COMPLICATIONS

Dust depletion effects

The measured abundance does not represent the total abundance if a fraction of elements is locked in dust grains

O only very mildly refractory

(Savage & Sembach 96)

Ionization effects

OI is not a good tracer of the oxygen abundance if OI is partly ionized

OI follows HI closely due to charge exchange reactions

(Field & Steigman 71)

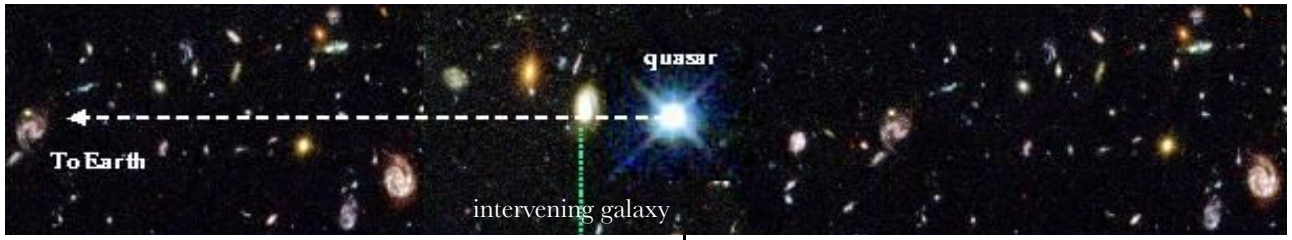
➔ OI/HI accurately determines O/H

ACCESS TO OI AT HIGH-REDSHIFT

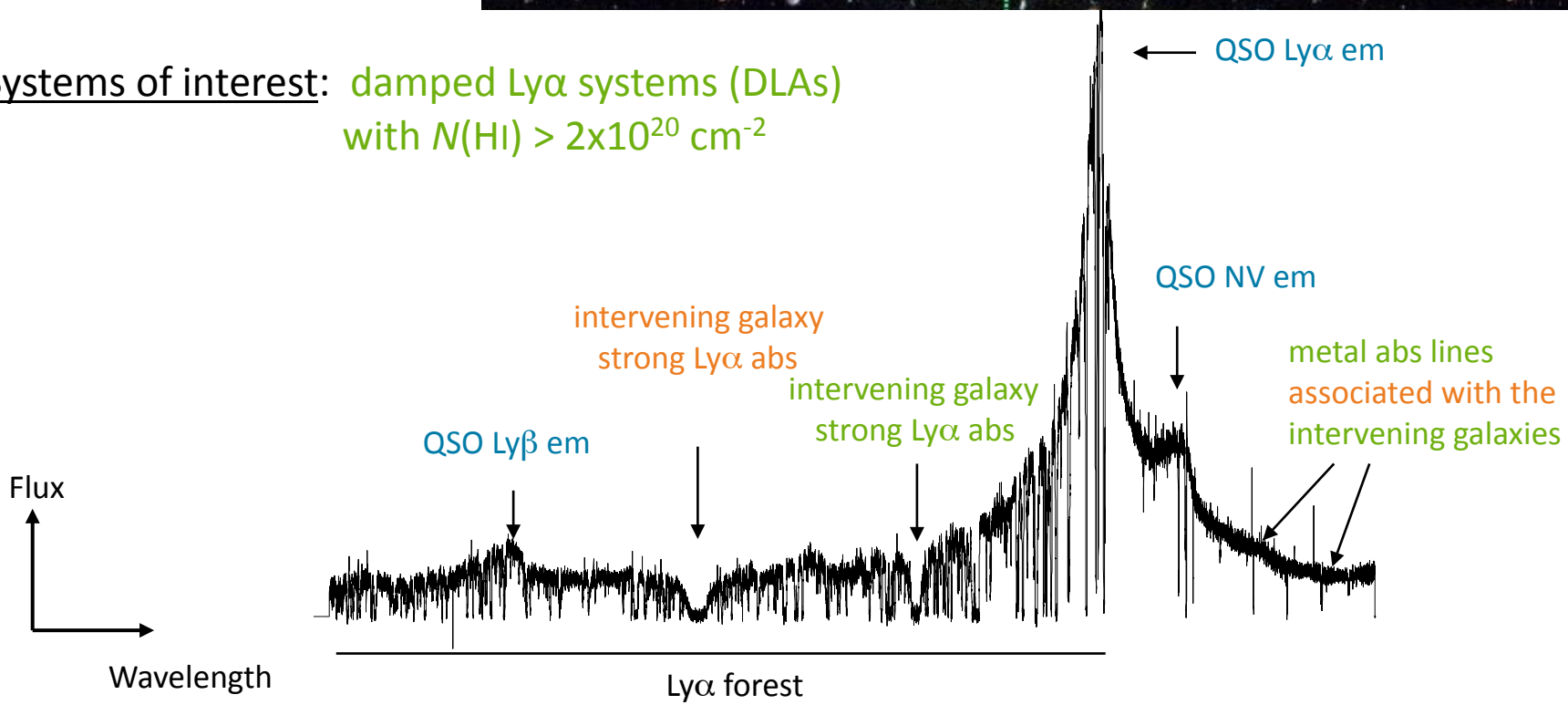
Need the combination of high-resolution spectroscopy on 8–10 m class telescopes and a bright high-redshift background source

1. QUASAR ABSORPTION LINE SYSTEMS

Background sources : bright QSOs with magnitudes between V=16–18.5 and redshifts up to z=7.1



<u>Systems of interest</u>: damped Lyα systems (DLAs) with N(HI) > 2×10^{20} cm^{-2}



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1. QUASAR ABSORPTION LINE SYSTEMS (DLAS)

Background sources : bright QSOs with magnitudes between V=16–18.5 and redshifts up to z=7.1

First dedicated large survey for DLAs: Wolfe et al. 86

Nowadays 937 DLAs are known from the SDSS II (data release 7): Noterdaeme et al. 09

CARACTERISTICS:

- contain most of HI available for star formation in the Universe (Prochaska et al. 05)
- arise in the ISM of protogalaxies
- are the progenitors of present-day spiral and dwarf galaxies (see Wolfe et al. 05 for a review)

2. GAMMA-RAY BURST HOST GALAXIES

Background sources : like QSOs, GRBs provide a bright, albeit transient, light beam with a power-law shape

A systematic spectroscopic survey of GRB afterglows started with the launch of *Swift* in 04

CARACTERISTICS:

- believed to result from the death of a massive star (Woosley & Bloom 06)
- identified exclusively with star-forming galaxies (Le Floc'h et al. 03; Fruchter et al. 06)
- probe the ISM of star-forming GRB host galaxies

3. STRONGLY LENSED LYMAN BREAK GALAXIES

ACCESS TO OI AT HIGH-REDSHIFT

High-quality spectra rich in interstellar metal lines associated with strong Lyα absorption

➔ may lead to accurate abundance measurements of up to 25 elements in DLAs (Prochaska et al. 03; DZ et al. 04,06)

DIFFICULTIES TO MEASURE THE OI ABUNDANCES

- most OI lines have wavelengths below 1215 Å (the wavelength of the Lyα line):
  being located in the Lyα forest, OI lines suffer of heavy line blending with HI lines

- only OI λ1302 and OI λ1355 are usually available redwards of the Lyα forest:
  OI λ1302 has a high oscillator strength –> often saturated –> lower limit
  OI λ1355 has a very low oscillator strength –> often undetected –> upper limit

- OI λ1302 and OI λ1355 lines only accessible in galaxies at $z > 1.5$ and at even higher z for lower wavelength OI lines
  hence redshifted beyond the atmospheric cutoff and accessible from ground-based telescopes

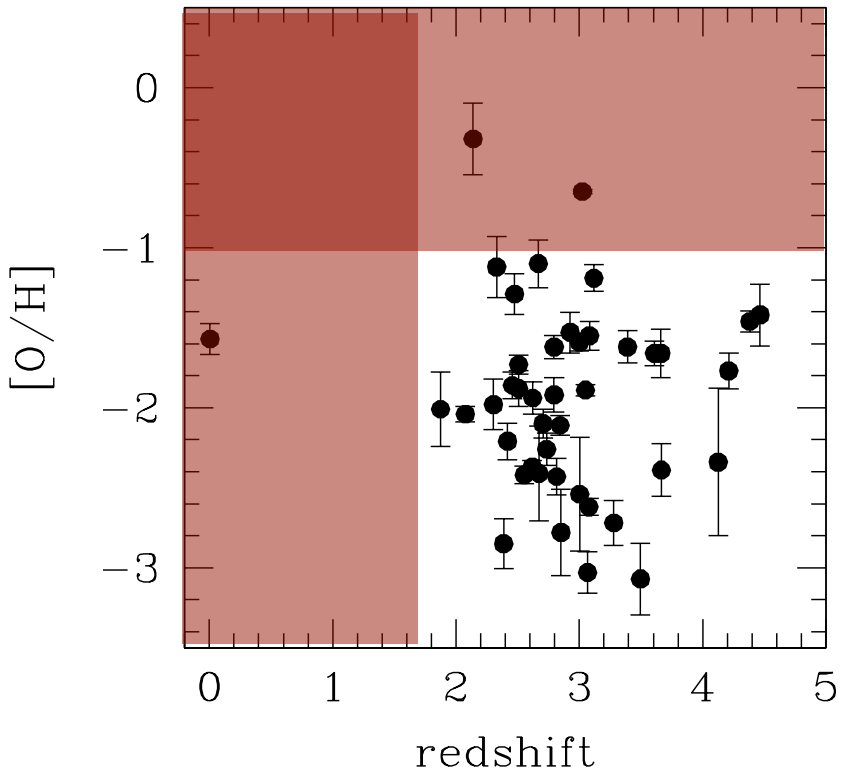
OXYGEN ABUNDANCES AT HIGH-REDSHIFT

QUESTIONS TO BE ANSWERED:

1. What is the current picture of the O/H distribution ?
2. What is the behavior and link of O relative to other chemical elements ?
   And what does that show ?
3. O/H in absorption and in emission measured in the same objects,
   how do the O abundances compare ?

OXYGEN ABUNDANCES AT HIGH-REDSHIFT

1. WHAT IS THE CURRENT PICTURE OF THE O/H DISTRIBUTION ?



DZ compilation

- large O/H dispersion over ~2 dex
- O/H redshift evolution not evident
- all O/H measured at redshifts $z > 1.5$
- most O/H measurements confined to low metallicities [O/H] < −1 (except 2)
  –> reflects a bias against objects with [O/H] > −1 where OI lines are usually saturated

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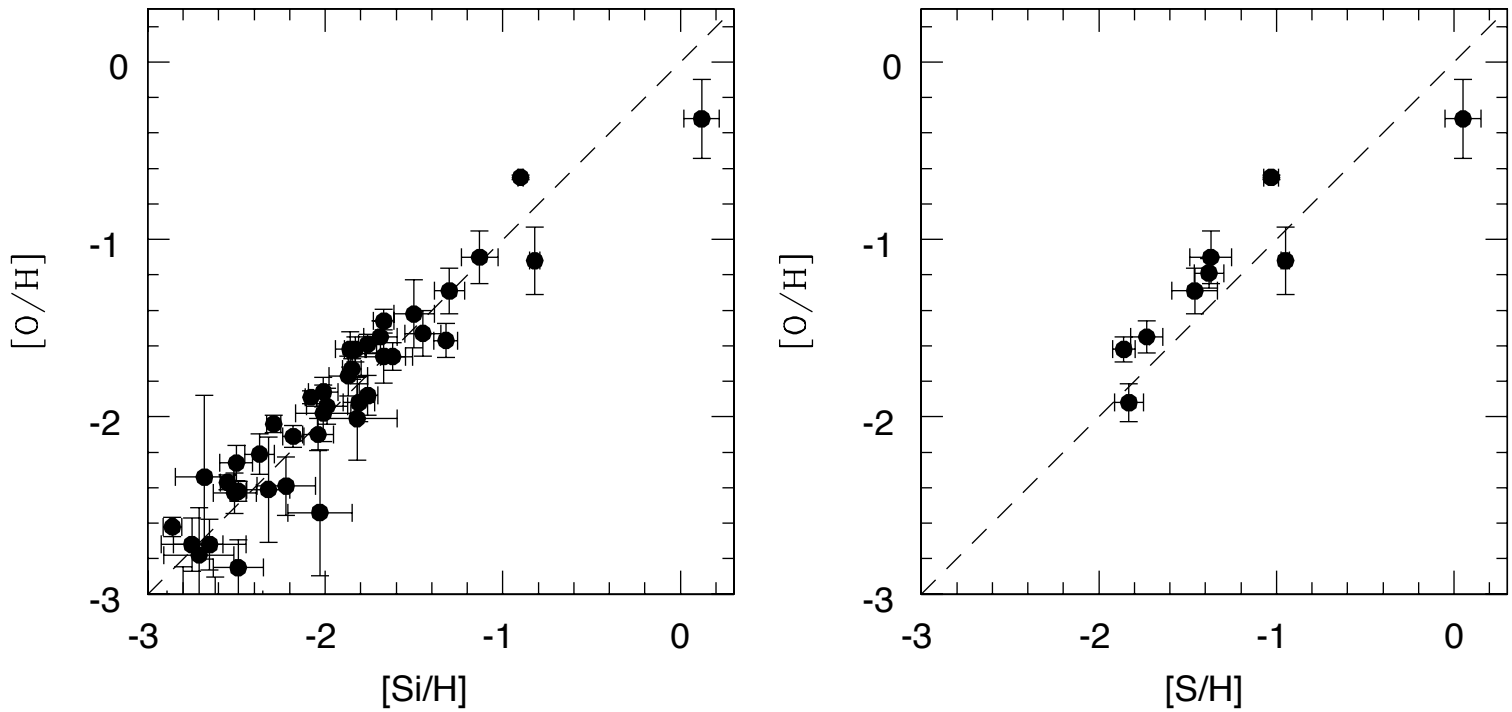

DZ compilation

O is an α-element produced essentially by SNe II as are Si and S

–> the abundances of these 3 elements correlate very well !!!

–> Si or S often used as a proxy of O

OXYGEN ABUNDANCES AT HIGH-REDSHIFT

2. WHAT IS THE BEHAVIOR AND LINK OF O RELATIVE TO OTHER CHEMICAL ELEMENTS ? AND WHAT DOES THAT SHOW ?

A dedicated search of very metal-poor DLAs with metallicities < 1/100 solar in [Fe/H] has been the interest of several research groups, in parallel to local studies of metal-poor stars in the halo of the Milky Way:

PETTINI ET AL. 08; PENPRASE ET AL. 10; COOKE, PETTINI ET AL. 11

O abundances measured in most metal-poor objects offer the possibility to tackle the following questions when analyzed relative to other chemical elements, as proposed by Cooke and Pettini in 2011:

DOES THE BEHAVIOR OF CHEMICAL ABUNDANCE RATIOS BECOMES UNIVERSAL TOWARDS VERY LOW METALLICITIES ?

DO THE MOST METAL-POOR DLAS RETAIN THE SIGNATURES FROM THE EARLIEST EPISODES OF STAR FORMATION ?

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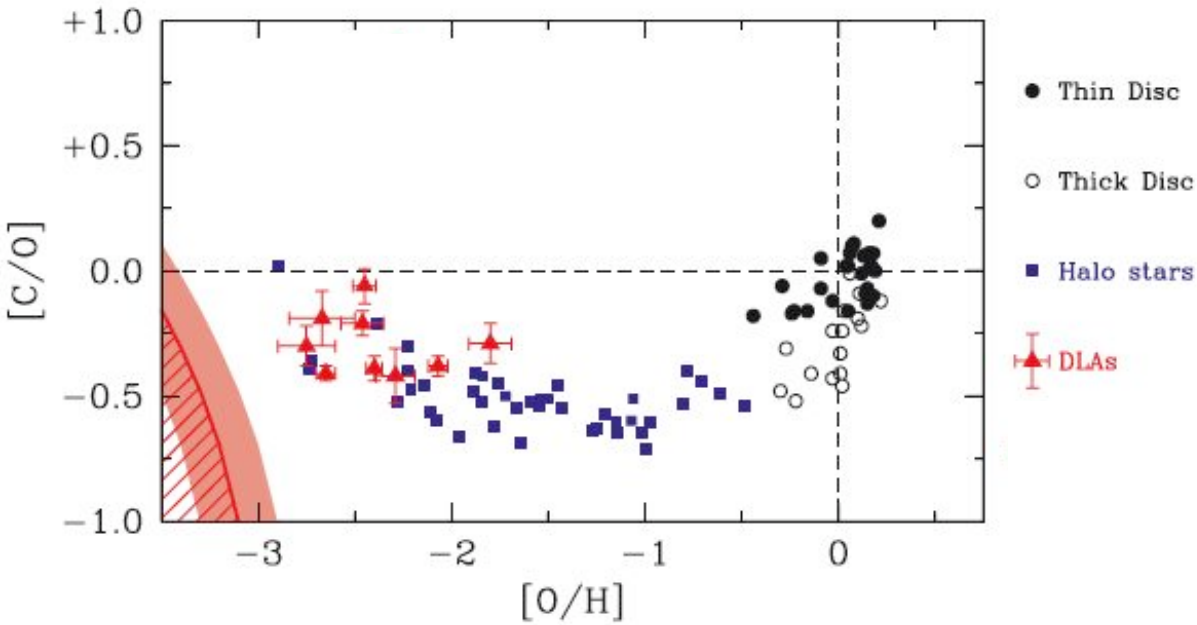

DLAs + halo stars of our Galaxy tell the same story in the metal-poor regime, both show:
near-solar [C/O] when [O/H] < −2

[C/O] evolution when [O/H] > −1 known and understood: linear [C/O] ↗ with ↗ [O/H]

Trend due to the increased, *Z*-dependent, C yields of massive rotating stars, combined with the delayed release of C from low- and intermediate-mass stars (Akerman et al. 04); toward ↘ *Z*, [C/O] is predicted to ↘ or form a plateau

[C/O] evolution when [O/H] < −2: [C/O] ↗ with ↘ [O/H], surprising but confirmed by DLAs

Explanations: 1) leftover signature of high-C producing generation of Pop III stars (Chieffi & Limongi 02; Heger & Woosley 10); 2) pollution from a previous generation of rapidly rotating low-*Z* Pop II stars (Chiappini et al. 06)

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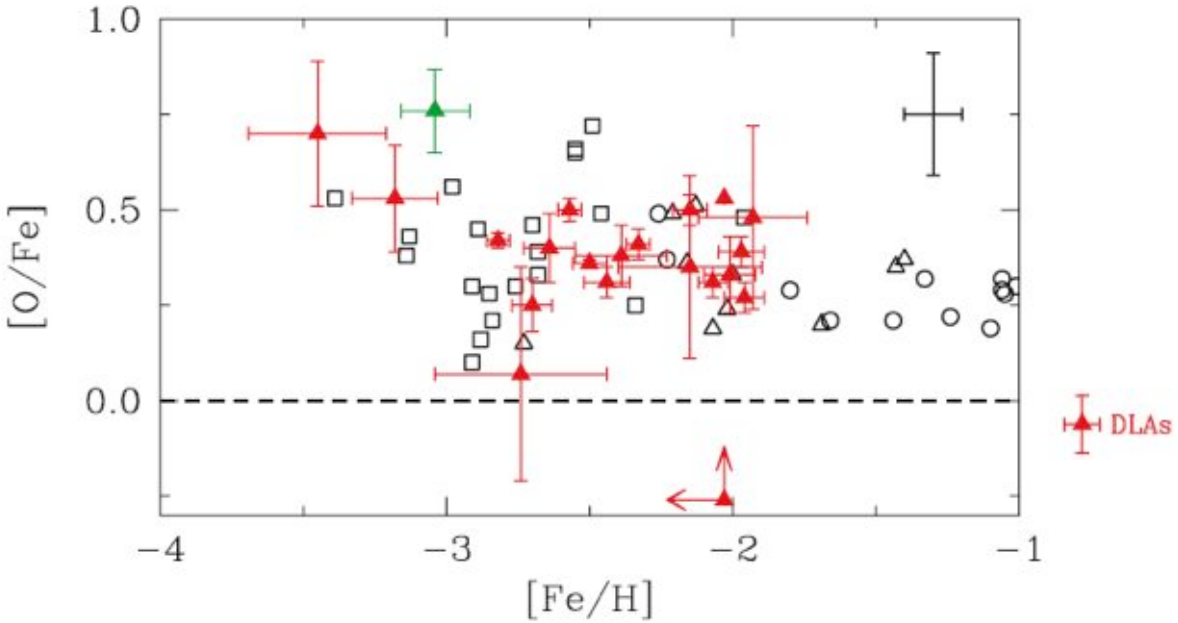

DLA [O/Fe] values exhibit a plateau with a relatively low scatter in the range −3 < [Fe/H] < −2:

[<O/Fe>] = +0.35 ± 0.09

O enhanced relative to Fe when [Fe/H] < −1, then [O/Fe] ↘ with ↗ [Fe/H]

Behavior resulting from the fact that the largest O yield comes from SNe II explosions, while Fe is largely produced by SNe Ia which explode 1 Gyr later; O/Fe ↘ when SNe Ia kick in

McWilliam 97; Asplund et al. 05; Garcia Perez et al. 06

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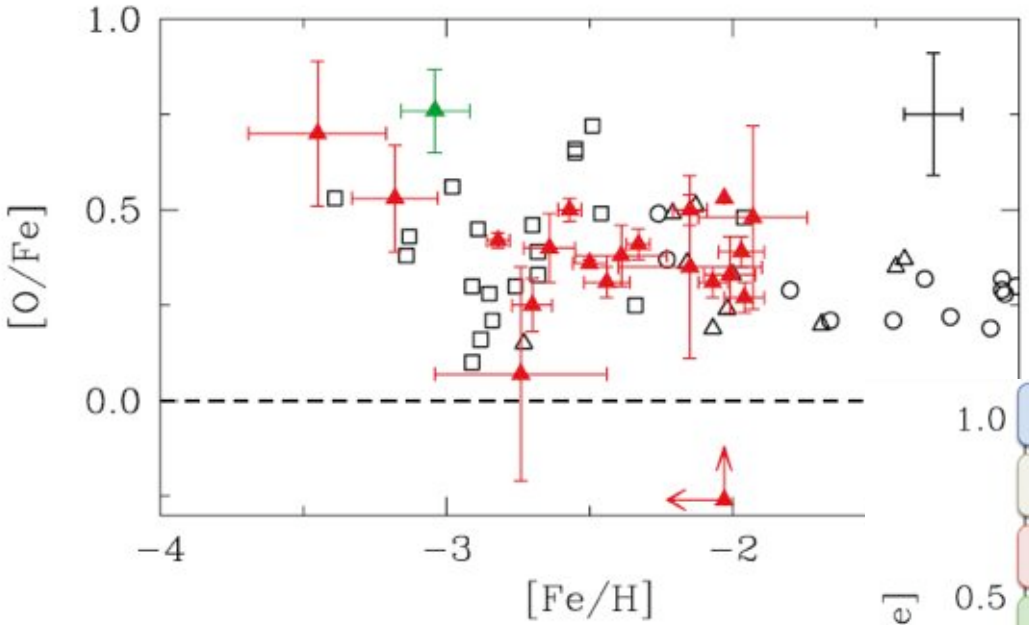

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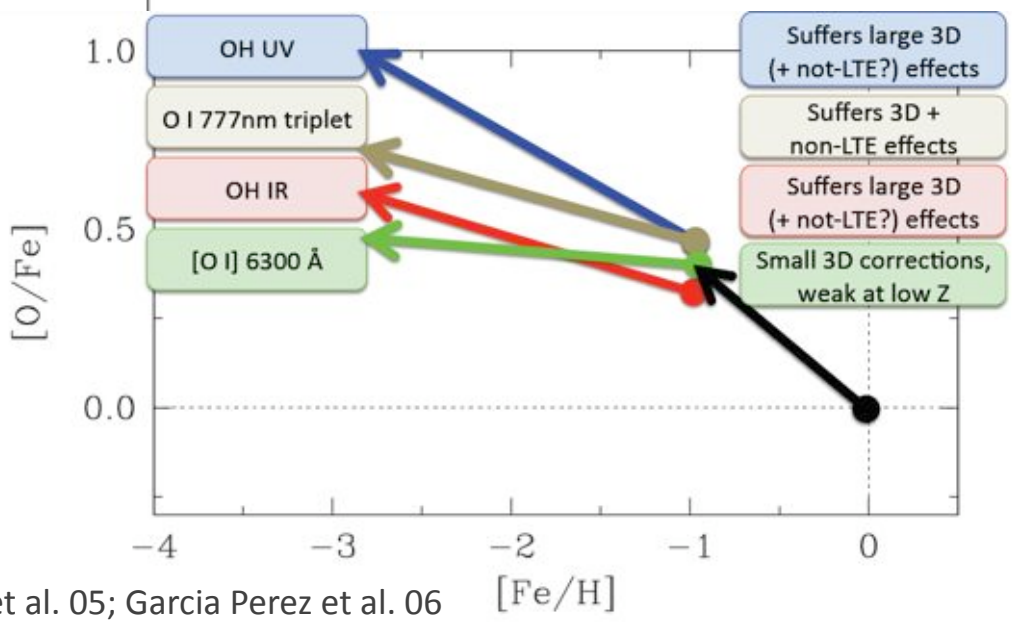
This brings constraints on the long debate on the O/Fe behavior in metal-poor Galactic halo stars

➔ good agreement with O abundances from [OI] λ6300 Å with 3D corrections



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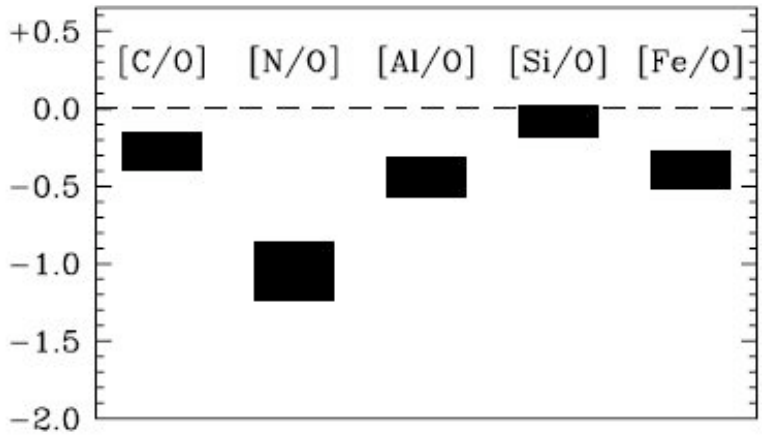
DO THE MOST METAL-POOR DLAS RETAIN THE SIGNATURES FROM THE EARLIEST EPISODES OF STAR FORMATION ?

O is the most appropriate reference element for such a study:

✓ dominant O yield comes from a single source, massive stars

✓ O is the most abundant metal in the Universe

➔ the ratio of a chemical element over O then provides the best handle for determining the properties of the generation of stars from which the 2 elements were synthesized



Cooke et al. 11

Typical very metal-poor DLA
constructed from the mean [<X/O>] ratios
available for all DLAs with [Fe/H] < −2
and for each element X

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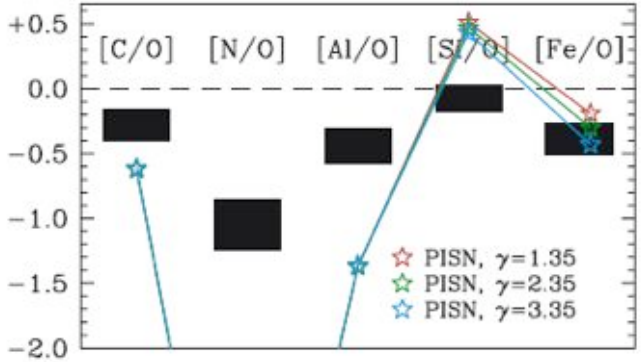


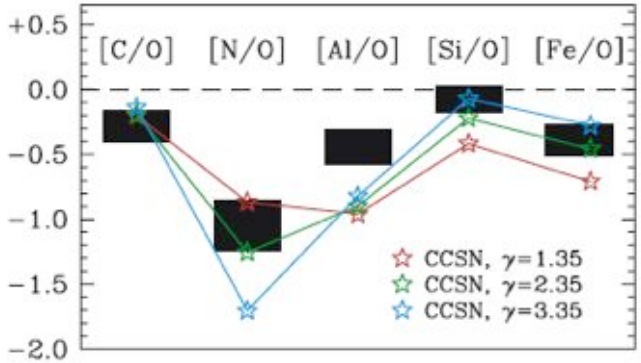
Metal production mechanism

Massive metal-free stars with 140–260 $M_\odot$ that explode as pair-instability SNe (Heger & Woosley 02)

Agreements/ Disagreements

Model ruled out, several metal ratios are wrongly predicted

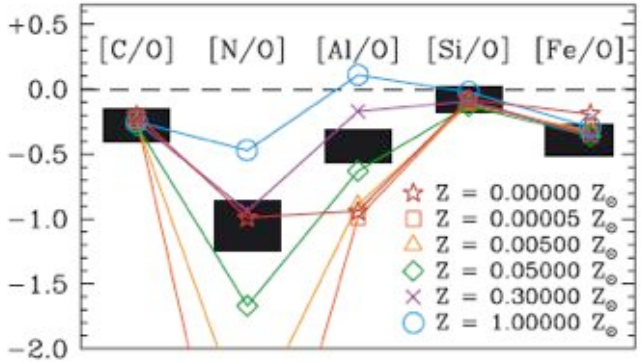
✗



Massive metal-free stars with 10–100 $M_\odot$ that explode as core-collapse SNe (Heger & Woosley 10)

Reasonable agreement with the observed metal ratios; IMF slopes steeper than Salpeter seems to fit the data best

✔



Massive Pop II stars with 13–35 $M_\odot$ covering a range in Z and exploding as core-collapse SNe (Chieffi & Limongi 04)

Good agreement as well, the best fit being obtained for Z = 0.05 and 0.3 $Z_\odot$

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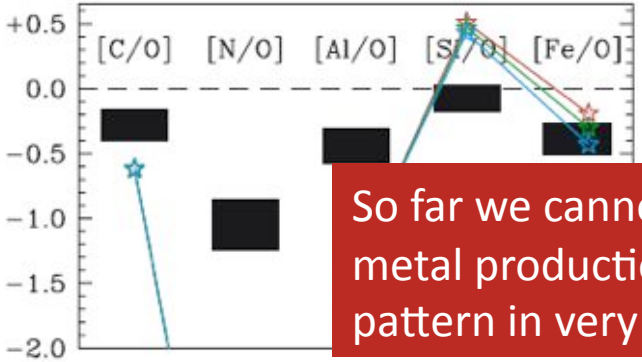
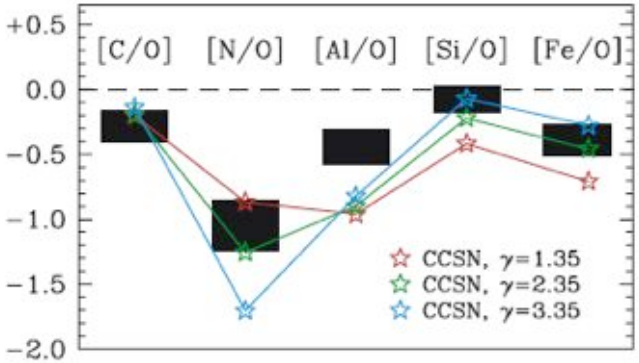


Metal production mechanism	Agreements/ Disagreements
Massive metal-free stars	Model ruled out, several e wrongly

So far we cannot distinguish between Pop II and Pop III metal production mechanisms that lead to the abundance pattern in very metal-poor DLAs

✗



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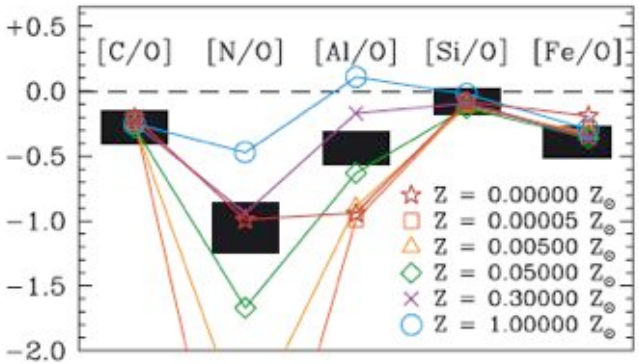

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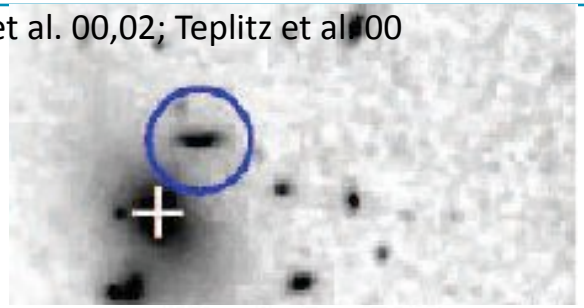
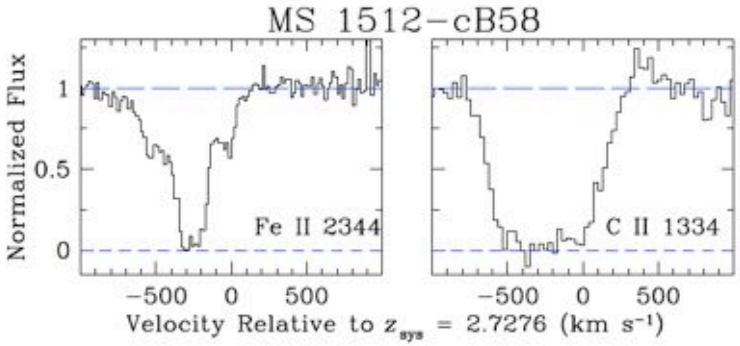
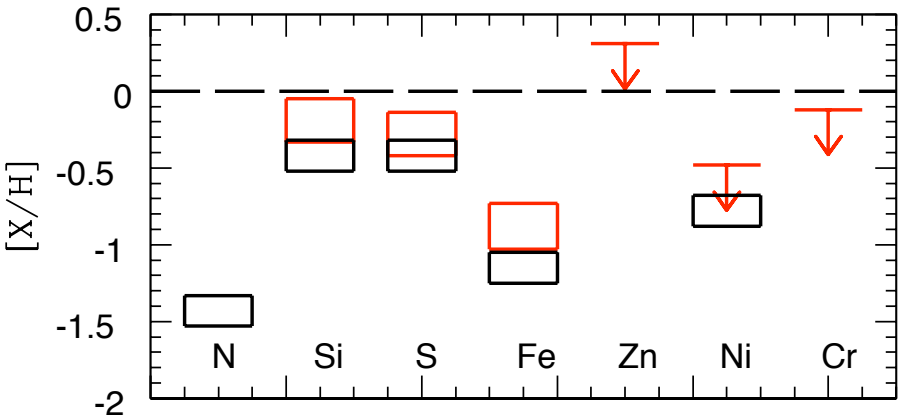
3. O/H IN ABSORPTION AND IN EMISSION MEASURED IN THE SAME OBJECTS, HOW DO THE O ABUNDANCES COMPARE ?

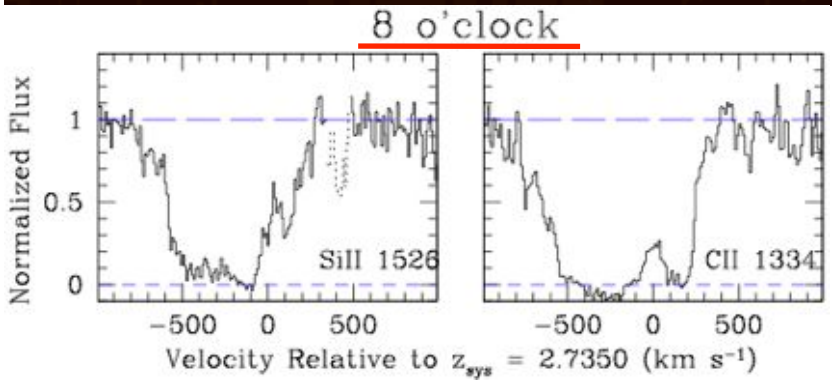
Pettini et al. 00,02; Teplitz et al. 00







Dessauges-Zavadsky et al. 10,11



8 O'CLOCK ARC:

Z_{ISM} = [Si,S/H] = 0.65 ± 0.20 $Z_\odot$

$Z_{HII\ regions}$(N2 index) = 0.53 ± 0.23 $Z_\odot$

MS1512−cB58:

Z_{ISM} = [Si,S,Mg/H] = 0.40 ± 0.20 $Z_\odot$

$Z_{HII\ regions}$(R23) = 0.45 ± 0.20 $Z_\odot$

ISM rapidly polluted by ejecta of OB stars and enriched to the metallicity of HII regions

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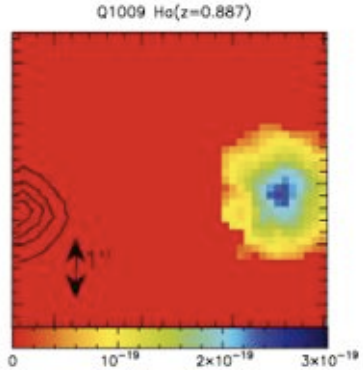
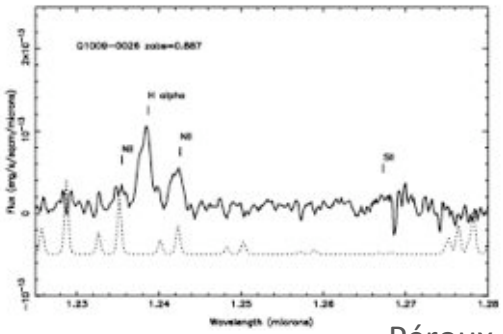
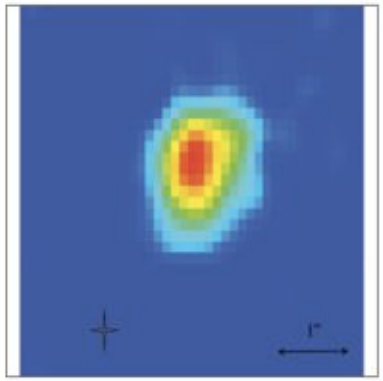


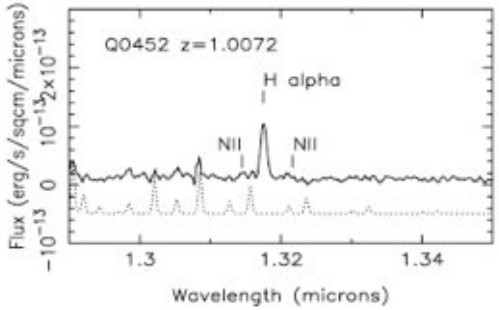


Péroux et al. 11

[Zn/H] = +0.25 ± 0.06
$[O/H]_{N2}$ = +0.04 ± 0.80

–> agree within the error bars



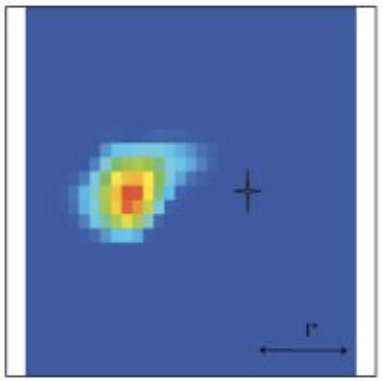


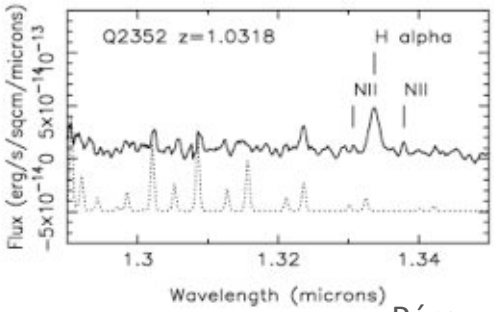
Péroux et al. 12

[Zn/H] = −0.96 ± 0.08 (impact par. = 16 kpc)
$[O/H]_{N2}$ = −0.26 ± 0.21

–> disagree !!!

–> may indicate the presence of metallicity gradient





Péroux et al. 12

[Si/H] = +0.14 ± 0.20
$[O/H]_{N2}$ = −0.26 ± 0.23

–> agree within the error bars

OXYGEN ABUNDANCES AT HIGH-REDSHIFT

2. WHAT DO WE LEARN FROM Si,Fe/H WHEN USED AS THE METALLICITY INDICATOR ?

Si, Fe not used as a proxy of O but as a measure of metal content relative to H in galaxies. Si,Fe/H hence estimates the metallicity, with the advantage that Si,Fe/H cover a much larger redshift range than O/H measurements.

OXYGEN ABUNDANCES AT HIGH-REDSHIFT

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METALLICITY EVOLUTION WITH COSMIC TIME

Very old debate: Pettini et al. 97,99; Savaglio et al. 99; Prochaska & Wolfe 00; Vladilo et al. 00; Prochaska & Wolfe 02; Kulkarni & Fall 02; Prochaska et al. 03; Kulkarni et al. 05; Meiring et al. 06

METALLICITY SCATTER:

- large scatter of ~1 dex per *z*-bin
- roughly constant with *z*

–> combination of gas cross-section selection, metallicity gradients, diff. SF histories

METALLICITY EVOLUTION:

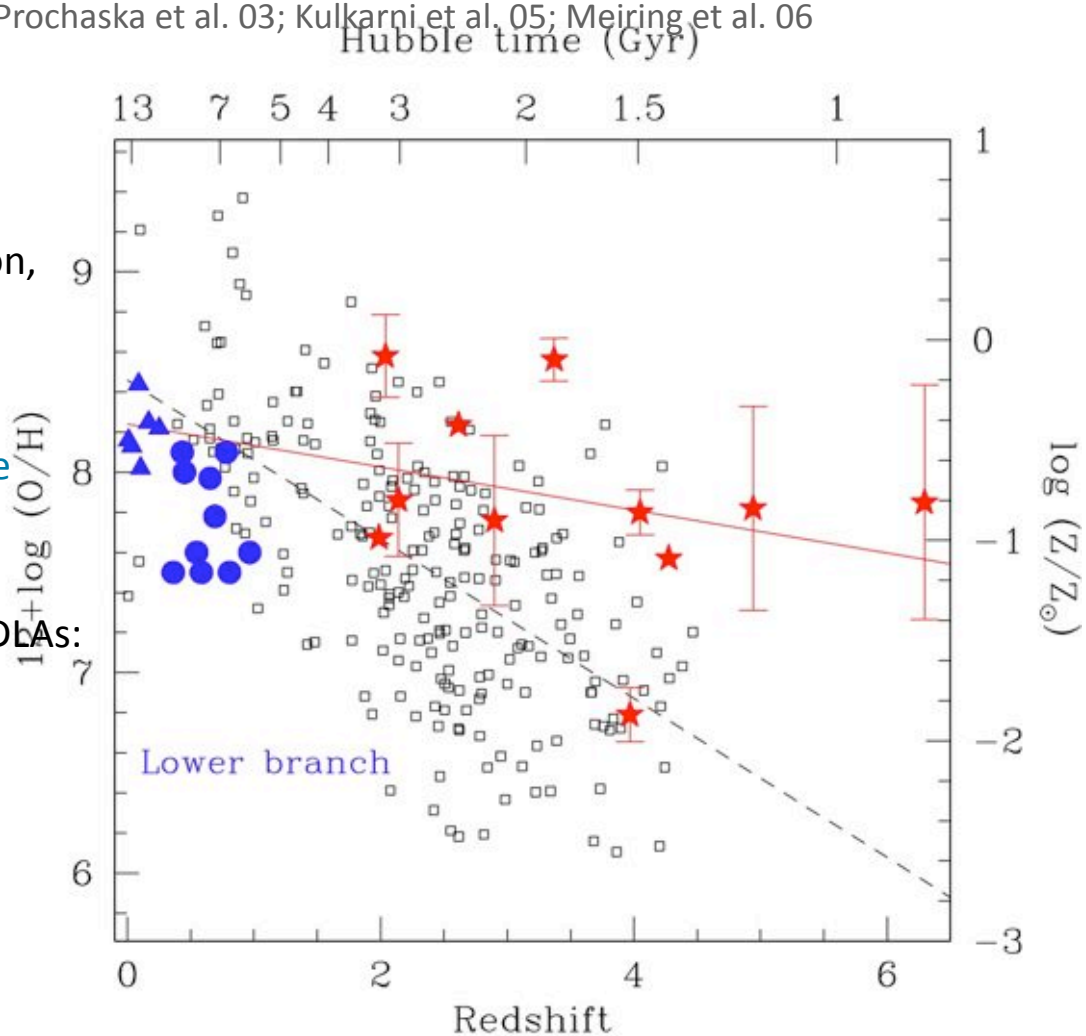
- mild metallicity evolution with cosmic time
- −0.26 dex per *z*-bin (*Z* ↗ ~2x per Gyr)

–> but the integrated ρ_{SFR} predicts 3-10x the mass density of metals observed in DLAs: "missing metal problem"

METALLICITY FLOOR:

- few DLAs with solar [M/H]
- [M/H] > −3 (exceeds the detection limit)

–> existence of primordial gas in the ISM of high-*z* galaxies ?



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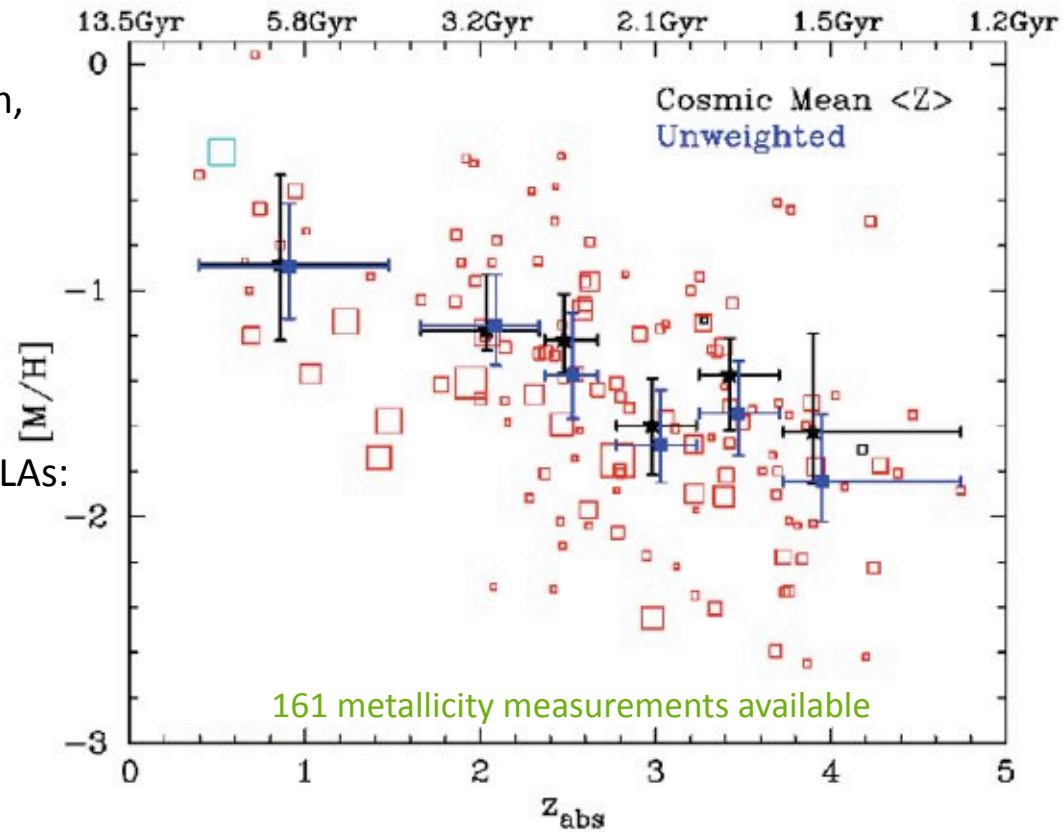
- [M/H] > −3 (exceeds the detection limit)

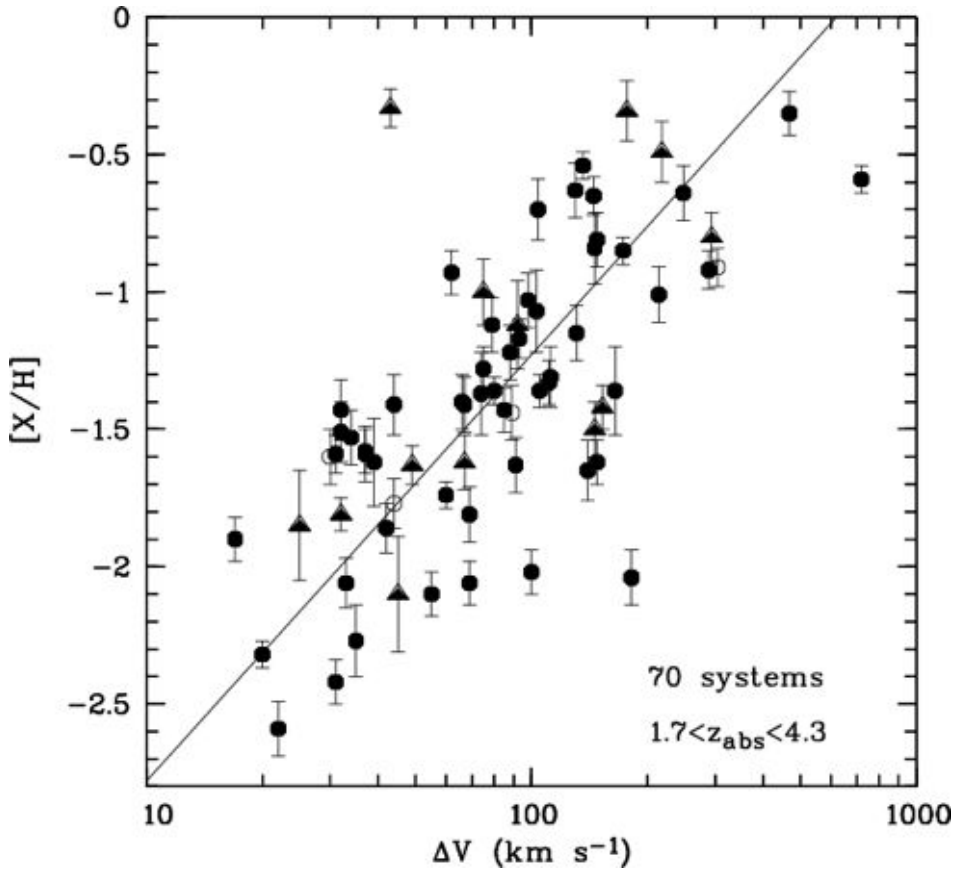
–> existence of primordial gas in the ISM of high-*z* galaxies ?



OXYGEN ABUNDANCES AT HIGH-REDSHIFT

2. WHAT DO WE LEARN FROM Si,Fe/H WHEN USED AS THE METALLICITY INDICATOR ?

VELOCITY - METALLICITY RELATION



Wolfe & Prochaska 98; Ledoux et al. 06;
Murphy et al. 07; Prochaska, Wolfe, DZ et al. 08

CORRELATION:

$[X/H] = 1.55(\pm 0.12) \log \Delta v - 4.33(\pm 0.23)$

DISPERSION:

- sightline impact parameters
- galaxy inclinations
- radial gradients in metallicity

EVOLUTION:

median [X/H] + median Δv ↗ with ↘ z:

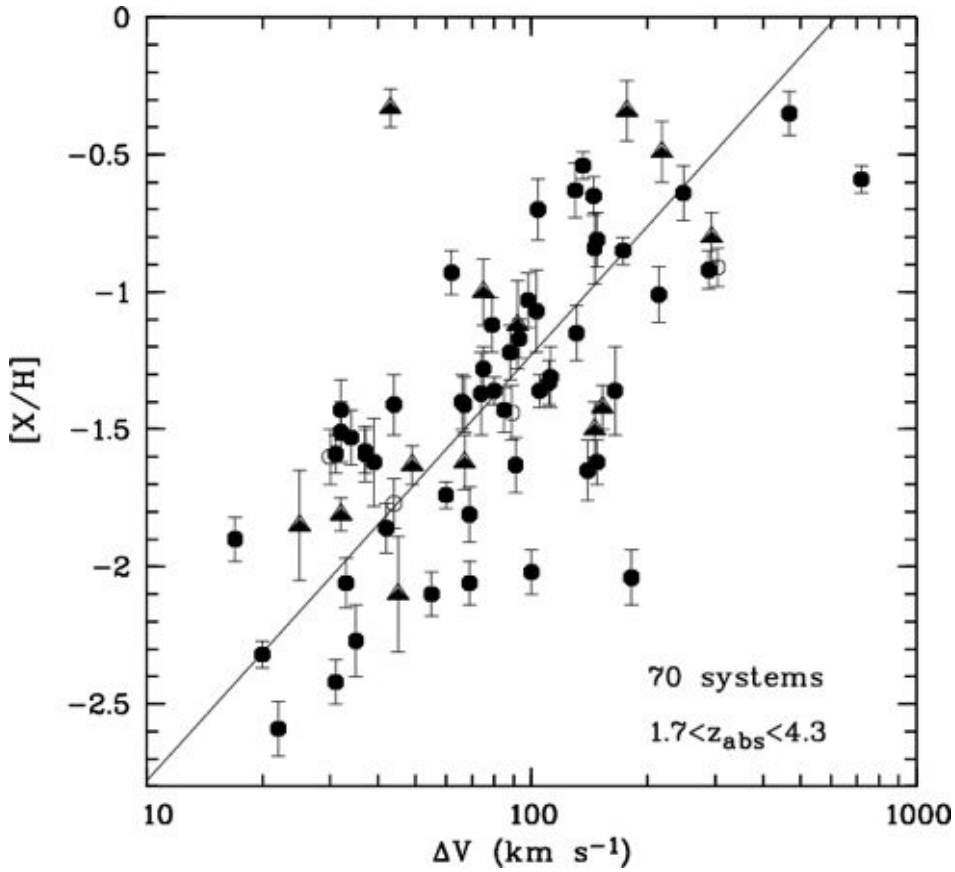
$[X/H] = -1.59$, $\Delta v = 69$ km/s at $z > 2.4$

$[X/H] = -1.15$, $\Delta v = 92$ km/s at $z < 2.4$

OXYGEN ABUNDANCES AT HIGH-REDSHIFT

2. WHAT DO WE LEARN FROM Si,Fe/H WHEN USED AS THE METALLICITY INDICATOR ?

VELOCITY - METALLICITY RELATION ➔ MASS - METALLICITY RELATION ?



Wolfe & Prochaska 98; Ledoux et al. 06; Murphy et al. 07; Prochaska, Wolfe, DZ et al. 08

ARGUMENTS IN FAVOR:

1. Low-ions likely dominated by motions on galactic scales governed by gravity
2. Asymmetries in line profiles favoring rotational dynamics (Prochaska & Wolfe 97)
3. Merging of proto-galactic clumps; Δv indicator of the circular velocity of the DM halo (Haehnelt et al. 98; Maller et al. 01)
4. In local dwarf and LSB galaxies (Dekel & Woo 03):

$$\left.\begin{array}{l}\Delta v \propto M^{0.24} \\ [X/H] \propto M^{0.40}\end{array}\right\} \boxed{[X/H] \propto 1.66 \log \Delta v}$$

remarkable <u>similarity</u> with DLAs

ARGUMENTS AGAINST:

1. $\Delta v > 200$ km/s unrealistic to be explained with a single galactic potential; need of additional velocity field contribution: galactic outflows
2. Individual clouds of a MgII absorber are not virialized in the gaseous haloes of the host galaxies (Bouché et al. 06)

OXYGEN ABUNDANCES AT HIGH-REDSHIFT

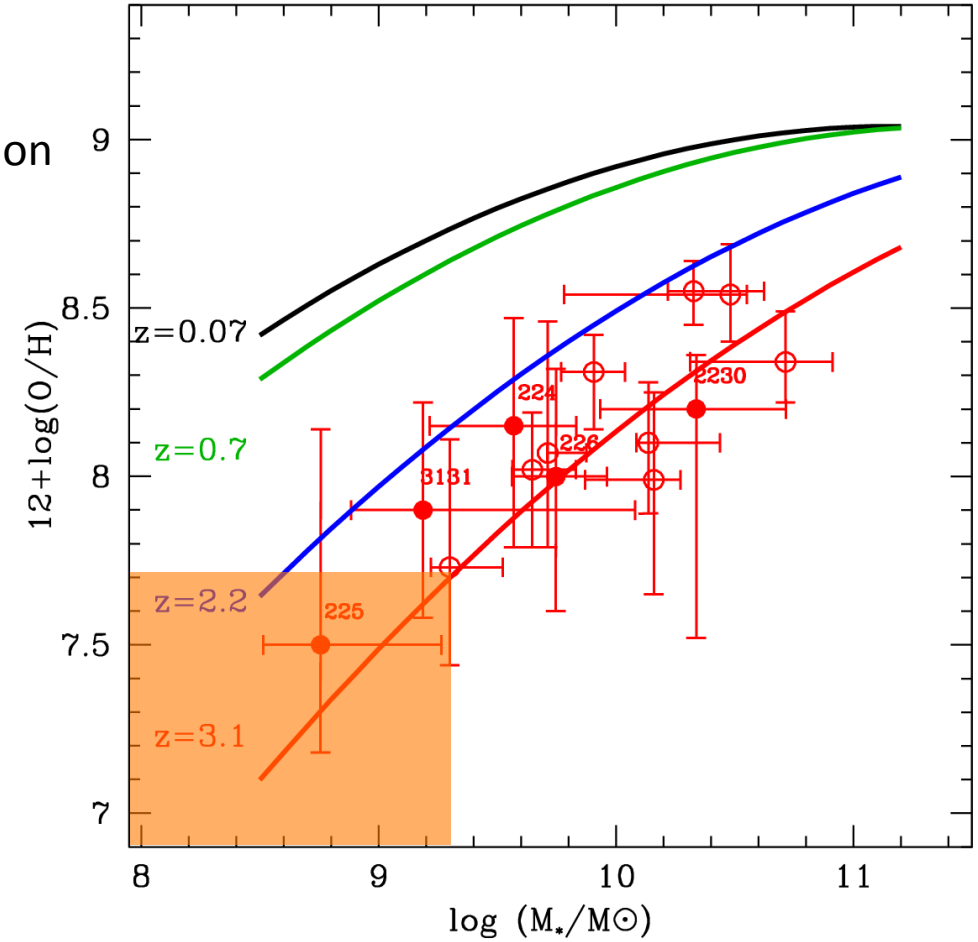
2. WHAT DO WE LEARN FROM Si,Fe/H WHEN USED AS THE METALLICITY INDICATOR ?

VELOCITY - METALLICITY RELATION ➔ MASS - METALLICITY RELATION ?

EXPECTED DLA STELLAR MASSES:

If DLAs follow the mass-metallicity relation determined for SFGs at z = 2–3 :

$10^8 < M/M_\odot < 10^9$



Roberto Maiolino talk (Maiolino et al. 08; Mannucci et al. 09)