Is the low density IGM at high z metal-enriched?

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Where are the metals at $z \sim$ 2-3?

- **The missing metals problem**
  - at high z, at least $\sim$90% of the baryons are in the Ly-α forest
  - only $\sim$40% of the metals expected from star-formation activity in high z galaxies have been measured up to now (in IGM, galaxies, damped Lyα absorbers)

    expected metallicity: $\langle[\mathrm{Z/H}]\rangle \sim -1.5$

- **Inhomogeneous metal enrichment of the IGM**
  - relative contribution to the cosmic metals of the general IGM vs metal-rich sites?

    feedback from galactic super-winds:

    important enough to metal-enrich the underdense IGM?
  - spatial distribution of metals - clustering: do they trace large-scale structures?

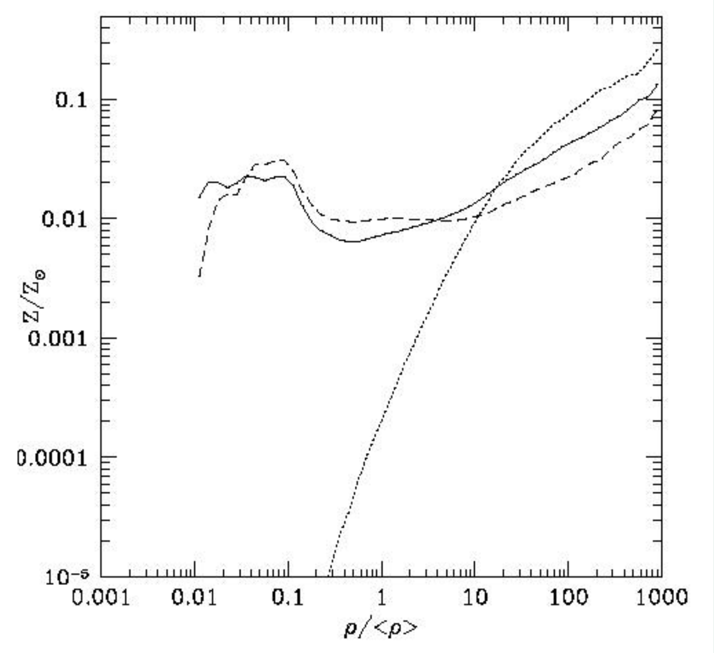
- **main contributor to ionizing radiation field: nuclear burning or accretion?**

  → derived metallicity strongly depends on ionization level

(Pettini 1999 & 2006, Theuns et al. 2002, Cen et al. 2004, Aguirre et al. 2005, Ferrara et al. 2005)

Predicted IGM metallicity at $z \sim 3$

- **Hydrodynamic simulations**
  - wind mass & energy $\propto$ SFR
    (full & dashed lines)
    or
  - no superwind: only low mass galaxies ($M < 10^9 M_\odot$) loose their metals
    (dotted line)

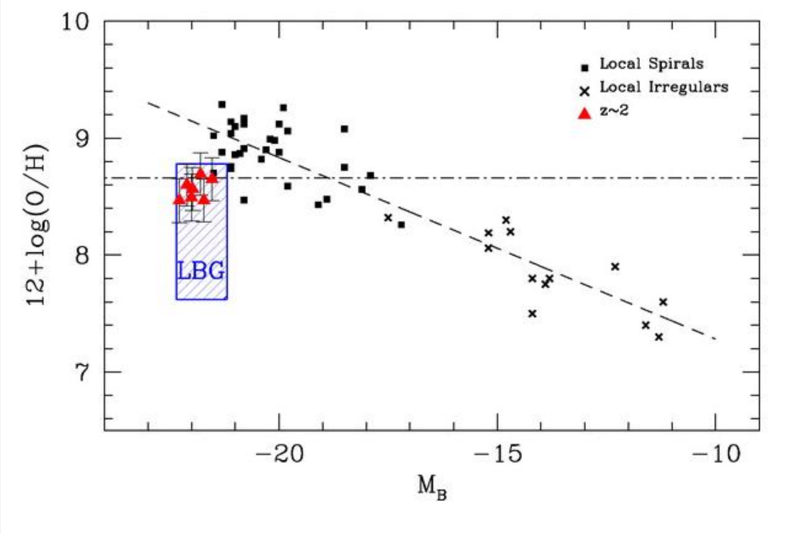


- Spread in $\langle Z/Z_\odot \rangle$ of $\sim$ 40 at $\rho/\langle\rho\rangle = 1$
  - $\langle Z/Z_\odot \rangle > 0.01$: $f_{\mathrm{volume}} \sim 4\%$
- Higher $\langle Z/Z_\odot \rangle$ at $\delta = 1$ than previous teams for superwinds

(Aguirre et al. 2001; Cen, Nagamine & Ostriker 2005)

Metallicity of galaxies at $z \sim$ 2-3

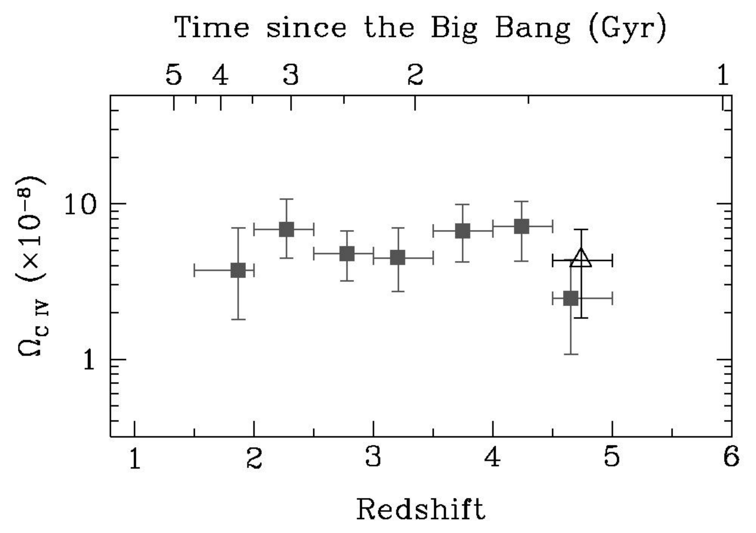
- Optical spectroscopy (H II regions)
  - Local starbursts and spirals : correlation luminosity-metallicity
- Near-IR spectroscopy (ionized gas) : [O II], [O III], Hβ
  - LBGs at $z \sim 3$ **overluminous** for their [Z/H] $\longrightarrow$ low mass-to-light ratio
  - Massive star-forming galaxies at $z \sim 2$: solar metallicities



(Pettini et al. 2001; Shapley et al. 2003)

The C IV cosmic density

- No clear evidence for evolution of the cosmic metal density at $2 < z < 5$
  → early pollution of the IGM by the first stars and galaxies



- $\Omega_b(\mathrm{C\,IV}) = \{H_0 m_C / c\rho_{crit}\}\{\sum N(\mathrm{C\,IV}) / \sum_i \Delta X_i\}$

  m_C: carbon atomic mass, ρ_{crit}: critical density, $\sum_i \Delta X_i$: total redshift path (comoving)

  $\Omega_b(\mathrm{C\,IV}) \sim 5 \times 10^{-8}$ at $2 < z < 5$ - C IV at $z > 5.5$ in NIR

  (Songaila 2001, Pettini et al. 2003)

IGM metal enrichment at $z \sim$ 2-3

- **C IV individual systems**
  - **$\langle[\mathrm{C/H}]\rangle = -2.9$** at $2 < z < 5$
    for $10^{12} <$ N(C IV) $< 10^{15}$ cm^{-2} (assuming $\langle$(C IV/C)$\rangle = 0.30$)

- **C IV statistical analysis :** correlation between H I and C IV mean optical depths
  - information only for τ(Lyα or Lyβ)$<$ ln(S/N) $\sim$ 3.5
  - good statistics : information at lower τ(C IV) than from analysis of individual systems
  - median opacities in bins of τ
    → **average** over a range of metallicities for each bin of τ(H I)

  signal down to log $\boldsymbol{\tau}$(C IV)$\simeq -3.0$ → $\langle$N(C IV)$\rangle \sim 10^{10.3}$ cm^{-2}
  and log $\boldsymbol{\tau}$(H I) $\simeq$ 0.2 → $\langle$N(H I)$\rangle \sim 10^{13.7}$ cm^{-2}

  - **$\langle[\mathrm{C/H}]\rangle = -2.8$** with some ↘ of [C/H] with ↘ N(H I)

(Cowie & Songaila 1998; Songaila 2001 & 2005; Pettini et al. 2003; Schaye et al. 2003; Aracil et al. 2004)

Hydrodynamic simulations of the IGM

- **The underdense IGM has low N(H I)**
  - **overdensity : $\delta \equiv (\rho/\overline{\rho}) \propto$ N(H I)$^{0.7}$**

    for $\delta = 1$ and $z = 3$

    $\rightarrow \rho = 2 \times 10^{-5}$ cm^{-3}

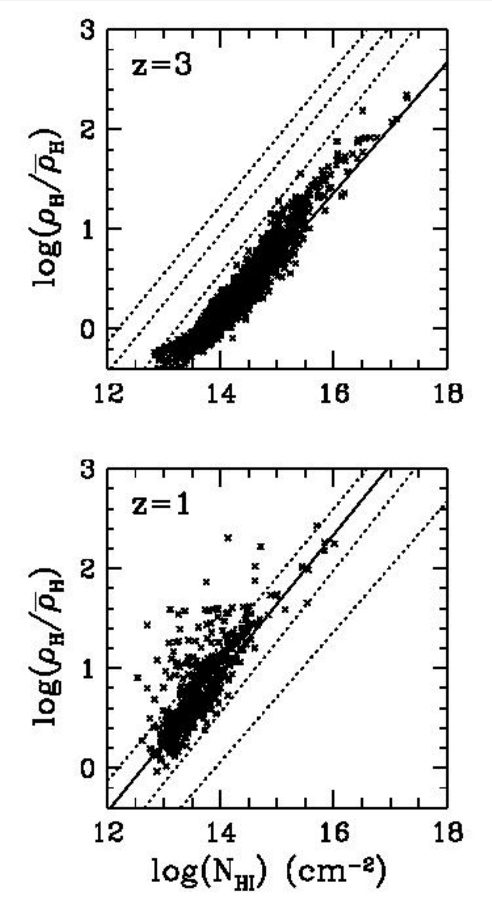
    $\rightarrow$ N(H I) $\sim 10^{13.5}$ cm^{-2}

- **Hydrostatic equilibrium**
  - $t(dyn) \sim t(sound\ crossing\ time)$

    $\rightarrow$ **N(H)** $\sim \boldsymbol{n_{\rm H} L_{\rm Jeans}}$
  - to derive N(H I): assumptions on $T_{\rm gas}$ ($\sim 4 \times 10^4$ K) and photoionization rate
  - $\delta(G) = 4.7 \times 10^{-9}$ N(H I)$^{2/3}([1+z]/3)^{-3}$

    for $\delta(G) = 1$ and $z = 3$

    $\rightarrow$ N(H I) $\sim 10^{13.1}$ cm^{-2}



(Davé et al. 1999; Schaye 2001)

Do the low N(H I) absorbers only probe of the underdense IGM

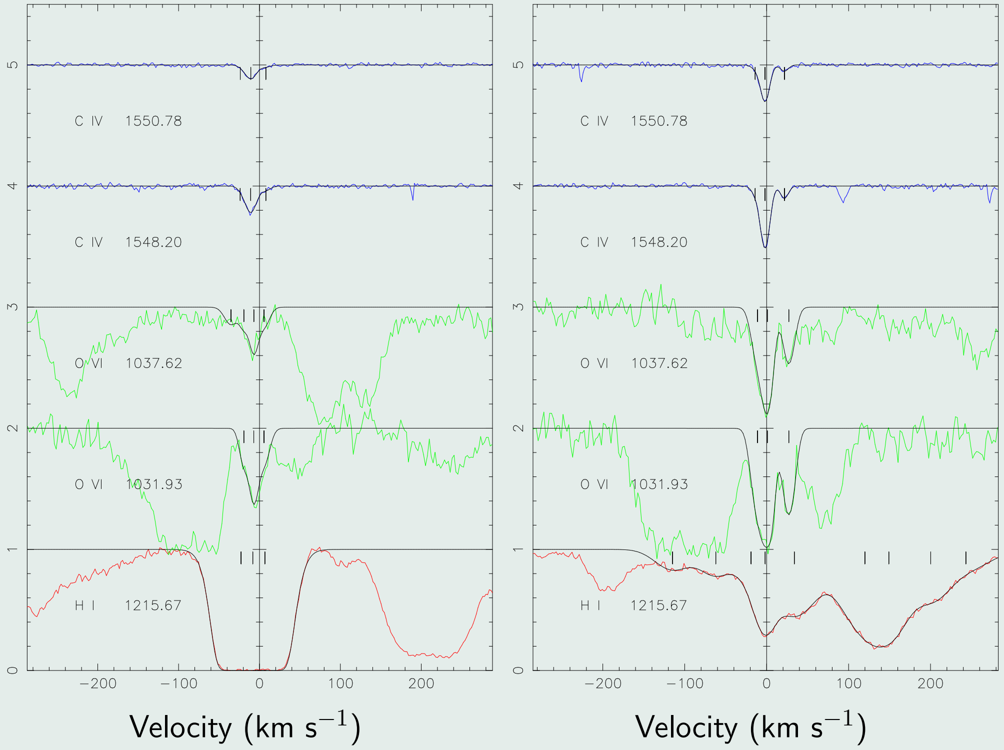
No : existence of 2 populations as shown by the analysis of O VI absorption surveys

- **O VI tracer of a high-z hot/highly ionized IGM phase**
  - O VI doublet ($\lambda\lambda 1031, 1037$) → lies in the Ly$\alpha$ forest
    thus ↗ blending with Lyman lines for ↗ z → O VI searches limited to $z < 3.5$
  - coupling O VI, and C IV : constrain the ionization level → metallicity

- **O VI LP-UVES survey**
  - at good S/N : line widths b(O VI)< 14 km s^{-1} or $T < 2 \times 10^5$ K
    → favors a radiative ionization process
  - inferred overdensity of detected O VI absorbers : $\delta \equiv (\rho/\overline{\rho}) = 4$ to 80
  - O VI subsamples : observational identification criteria
    derived from photoionization models with [O/H] $= -1$
    - ∗ N(O VI)/N(H I) > 0.25 : O VI metal-rich/type 1 subsample
    - ∗ N(C IV)/N(H I) > 0.015 : C IV-only metal-rich/type 1 subsample

(Carswell et al. 2002; Simcoe et al. 2002& 2004; Bergeron et al. 2002; Bergeron & Herbert-Fort 2005)

Metal-poor and metal-rich O VI absorbers



Strong N(H I) absorber

metal-poor

N(O VI)/N(H I) < 0.25

$\boldsymbol{z \sim 2.1}$

(left panel)

Weak N(H I) absorber

metal-rich

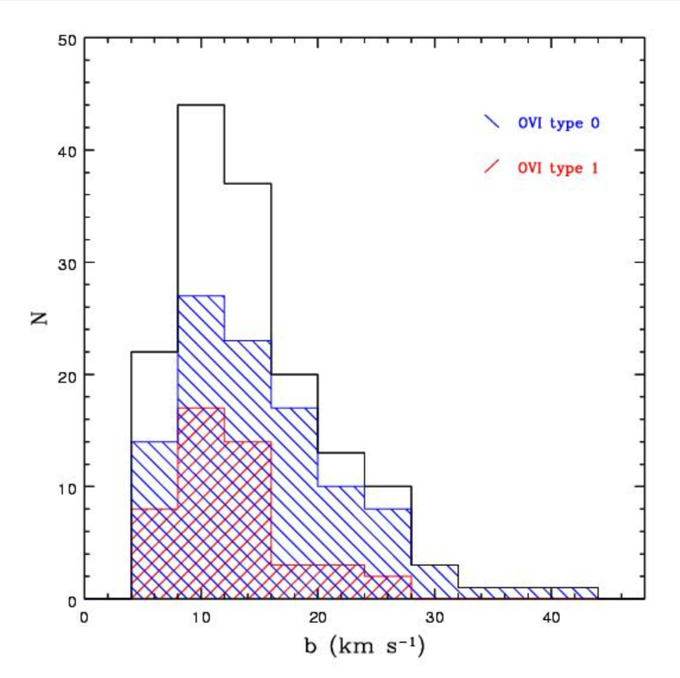
N(O VI)/N(H I) > 0.25

$\boldsymbol{z \sim 2.1}$

(right panel)

Temperatures

- **O VI line width distribution**
  - absorbers with $\boldsymbol{b} < \mathbf{12}$ km s^{-1} or $\boldsymbol{T} < \mathbf{1.4} \times \mathbf{10^5}$ K
    - metal-poor : 39%
      high b tail : weak absorbers, low S/N
    - metal-rich : 53%
  - no unambiguously broad absorbers
    ⟶ photoionization : dominant process



Gas density

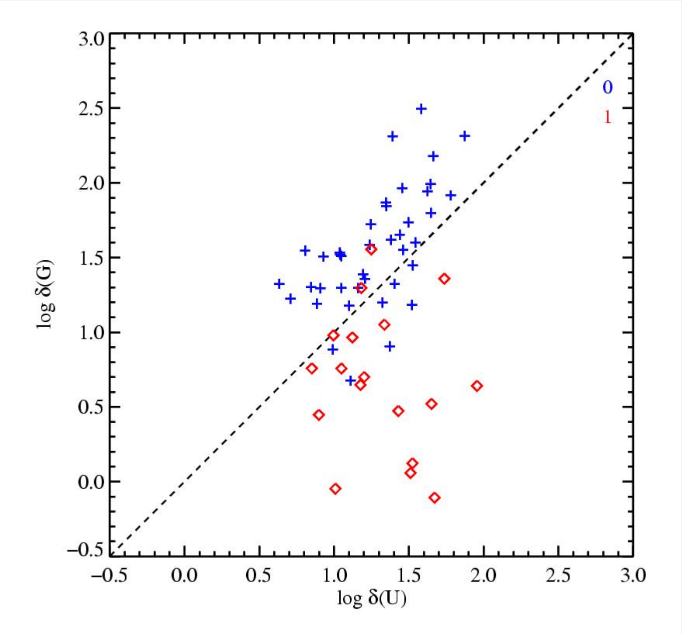
- **Radiative ionization process**
  - assumptions
    - hard UV metagalactic flux (main contribution at $z \sim 2.5$: QSOs)
    - O VI and C IV co-spatial (Si IV usually not detected)
    - [O/C] $= 0$

- **Ionization parameter**
  - U is fixed by the O VI/C IV ionic ratio
    gives ρ : the baryonic density at each z(O VI)
  - $\boldsymbol{\delta(U) = 4.0\ U^{-1}([1+z]/3)^{-3}}$
  - **if low N(H I) absorbers trace the underdense IGM**
    the assumption of hydrostatic equilibrium should be roughly valid :
    $\boldsymbol{\delta(U) \simeq \delta(G) = 4.7 \times 10^{-9}\ \ \mathrm{N(H\,I)}^{2/3}([1+z]/3)^{-3}}$

Overdensity : $\boldsymbol{\delta(G)}$ vs $\boldsymbol{\delta(U)}$

- **Metal-poor** (type 0) absorbers
  $\boldsymbol{\delta(G)}$ and $\boldsymbol{\delta(U)}$ are correlated
  with $\delta(G)$ somewhat larger than $\delta(U)$
  - Type 0 absorbers probe the IGM
    hydrostatic equilibrium is roughly valid

- **Metal-rich** (type 1) absorbers
  $\boldsymbol{\delta(G)}$ and $\boldsymbol{\delta(U)}$ are uncorrelated
  - hydrostatic equilibrium does not apply
    Type 1 absorbers do not trace the general IGM,
    but rather **gas outflows**
    in the vicinity of metal-rich sites



Abundances : results

- **Photoionization**

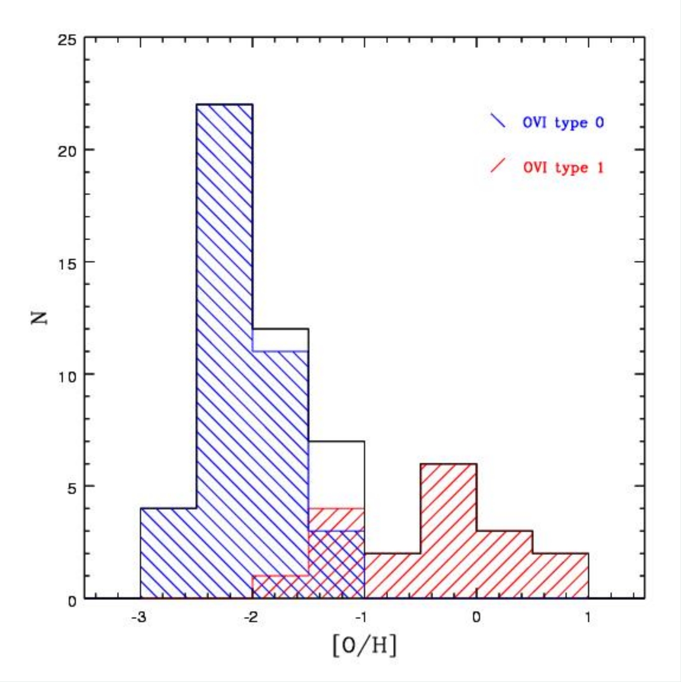
  bimodal [O/H] distribution
  → two distinct populations

  median [O/H]

type	**0**	**1**
	metal-poor	metal-rich
	$\mathbf{-2.06}$	$\mathbf{-0.35}$

- **Metal-rich O VI population**
  - associated H I
    $\mathbf{10^{12.5}} < \mathrm{N(H\,I)} < \mathbf{10^{15.0}}\ \mathrm{cm}^{-2}$
    or $0.1 < \tau(\mathrm{H\,I}) < 30$
  - contributes ∼40% to cosmic [O/H]
  - its ⟨metallicity⟩ ∼ [Fe/H] of galaxy clusters at $z \sim$ 0.3-1

(Bergeron & Herbert-Fort 2005, 2007)



Ω_b(O VI) and O VI column density distribution

- **O VI cosmic density**
  - $\Omega_b(\mathrm{O\,VI}) = \{H_0 m_O / c\rho_{crit}\}\{\sum N(\mathrm{O\,VI}) / \sum_i \Delta X_i\}$
    $= 2.2 \times 10^{-22}\{\sum N(\mathrm{O\,VI}) / \sum_i \Delta X_i\}$

    cosmological parameters ($\Omega_\Lambda, \Omega_m, \Omega_b, h$ =0.7, 0.3, 0.04, 70)

    $dX/dz \equiv (1+z)^2\{0.7+0.3(1+z)^3\}^{-0.5} \cong \{(1+z)/0.3\}^{0.5}$ when $z > 1$ (comoving)
  - result : $\Omega_b(\mathrm{O\,VI}) = 1.5 \times 10^{-7}$

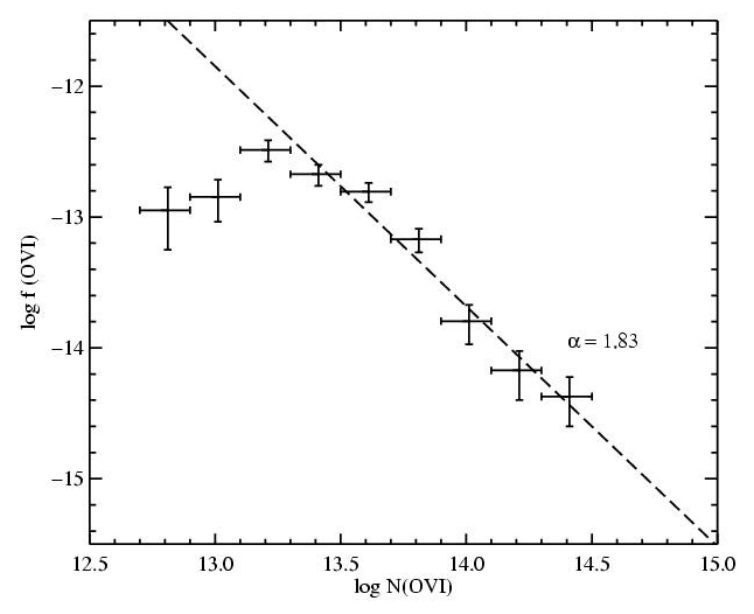
- **O VI column density distribution**
  - $f(N)dNdX = \{n/(\Delta N \sum_i \Delta X_i)\}dNdX$

    n : number of O VI absorbers in a column density bin ΔN centered on N for a total redshift path $\sum_i \Delta X_i$
  - Fit of $f(N)$ used to derive
    (i) incompleteness correction factor for Ω_b(O VI) , $\Omega_b \propto \int N f(N) dN$
    (ii) number of O VI absorbers per unit redshift, $dn/dz \propto \int f(N) dN$

Column density distribution of O VI absorbers

- **Power law fit :** $f(N) = KN^{-\alpha}$
  $\rightarrow \alpha$(O VI)$= 1.83 \pm 0.15$
  - log N(O VI)<13: incompleteness
  - log N(O VI)>14.5: sample variance

(Bergeron & Herbert-Fort 2007)



- **Comparison with** $f(N)$**(C IV)**
  - **O VI and C IV distributions** have **similar slopes**, but
    $f(N$(O VI)$)/f(N$(C IV)$)\sim6$
    at log N $= 13.5$

(Songaila 2001 & 2005, Scannapieco et al. 2005)

Cosmic density of O VI absorbers

- $\Omega_b(\mathrm{O\,VI})$
  - $\Omega_b = 2.20 \times 10^{-22} \int N f(N) dN$
  - using the slope and normalization parameter of the power-law fit and restricted to $13.0 < \log\,(N(\mathrm{O\,VI})) < 15.0$

    yields : $\Omega_b(\mathrm{O\,VI}) \approx (2.2 \pm 0.2) \times 10^{-7}$

    → incompleteness correction factor of 1.5 at $\bar{z}$=2.2
- $\Omega_b(\mathrm{O})$
  - with an ionization correction factor : $(\mathrm{O\,VI/O}) = 0.15$

    $\longrightarrow\ \Omega_b(\mathrm{O}) = 1.5 \times 10^{-6}$ or

    $\log\,(\Omega_b(\mathrm{O})/\Omega_b(\mathrm{O})_\odot) \equiv \langle[\mathrm{O/H}]\rangle = -2.4$
  - $\langle[\mathrm{O/H}]\rangle = \langle[\mathrm{C/H}]\rangle + 0.5$

    for $12.0 < \log\,(N(\mathrm{C\,IV})) < 15.0$

    → if the missing metals are in the IGM : over 2/3 of them are still undetected
  - **must detect much weaker (including broad) C IV absorbers**

Probing IGM metal enrichment with ELTs

- **The C IV forest ELT project $(1.5 < z < 3.5)$**
  - the lower density IGM at $z \sim 3$
    - [Z/H] : hydrodynamic simulations with/without galactic superwinds
    - at $\delta \sim 1 \rightarrow$ N(C IV) $\simeq \mathbf{10^{10.4}}/\mathbf{10^{8.8}}$ cm^{-2} for [Z/H] $\simeq -2.1/-3.7$

      $\rightarrow$ must gain a factor $\gtrsim 10$ in the detection limit of individual C IV doublets

      $\rightarrow$ spectroscopy at a resolution $\boldsymbol{R \sim 5 \times 10^4}$ and $\mathbf{S/N \simeq 1000}$
    - *clustering level of weak C IV absorbers : do they trace large-scale structures?*
  - the hotter IGM phase
    - occurence of broad C IV systems : $b \sim$ 12-20 km s^{-1} or $T > 10^5$ K

      $\rightarrow$ extremely well defined ct level : exquisite correction of order response
    - *could be the reservoir of the missing metals*

- **Abundances : complementary survey**
  - associated Lyα lines : ELT, and VLT for $z < 2.15$ C IV absorbers
    - *ionization level* : mainly constrained by O VI (in the forest, at z<2.7 → VLT), Si IV and possibly N V (but [N/C] $\neq 0$ in many cases)

Sample selection

- **Minimum number of background targets**
  - sample and cosmic variance : at least ∼20-30 targets
  - target brightness
    - QSOs with V < 16.5 and $2.2 < z < 4.0$: **too few targets** in either the north (17) and the south (6)
    - QSOs with V < 17.0 and $2.2 < z < 4.0$: 30 at dec $< +20$ deg of which only 17(5) at $z > 2.4$ (3.0)
    - GRBs : **fading too quickly**
      GBR050904 (z=6.3) would have at z=2.5, 1.0/3.2 hr after burst : AB=15.3/17.0
      GRB990123 (z=1.6) had already 1.0 hr after burst : AB=16.4
- **implied wavelength range**
  - **3800-4200 Å wavelength range mandatory :** for obtaining a significant C IV absorber sample (>100-150) at $z > 2.0$ extrapolating the $f(N(\mathrm{C\,IV}))$ power law distribution at lower N(C IV)
  - most of the associated Lyα lines are then detectable with the same ELT spectrograph

Requested observing time

- **Setting**
  - telescope 42 m
  - **high spectral resolution $R = 5 \times 10^4$**
  - spectrograph : single setting for the whole wavelength range
  - equivalent slit width : 300 mas and binning : 2 spectral px
  - laser tomography
- **Exposure time**
  - V(AB) = 17 and S/N = 1000 → t = 18 hr
  - similar result without AO but larger slit width
  - **Total exposure time (min of 20 targets) : 360 hr**
- **Abundances**
  - for IMG regions with $\delta \sim 1$ can probe **metallicities down to 1/100 solar**
    5σ detection limit at $z = 2.5$: N(C IV) $\simeq 10^{10.3}$ cm^{-2} or $w_{\rm obs} = 0.3$ mÅ
    - *constrain the IGM volume fraction affected by superwinds*

Feasibility of the project with a 25-30 m?

- **Sample**
  - targets no fainter than V $= 16.5$
    for a minimum sample of $\mathbf{10}(17)$ objects at $\boldsymbol{z} > \mathbf{2.5}(2.2)$ and dec > -10 deg
    and $\mathbf{2}(6)$ objects at $\boldsymbol{z} > \mathbf{2.5}(2.2)$ and dec $< +10$ deg
  - implies an all-sky survey in the south, e.g. with VST,
    to detect all the southern V < 16.5 QSOs
- **Exposure time**
  - S/N $= 1000$ at $R = 5 \times 10^4$ and same setting as for the 42 m case
  - exposure time $= 22/32$ hr for a $30/25$ m telescope
- **Possible problems**
  - overall efficiency : $< 25\%$? (c/ e.g. UVES)
  - S/N : systematics (e.g. detector noise) that may limit the maximun exposure time
- **Conclusions**
  - science may be not fully feasible with a 25-30 m telescope
  - need more detailed characteristics of the high-resolution spectrograph