Highly ionized absorbers at high redshift

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Outline

- Open questions
- Previous surveys (O VI and O V absorbers)
- The VLT O VI sample and the subsamples defined by the expected high/low oxygen abundances
- Line widths of O VI absorbers : constraints on temperature and ionization process
- Line Abundances : confirmation of two different types of O VI absorbers
  - low abundance absorbers : tracers of the low density IGM
  - high abundance absorbers : tracers of outflows close to overdense regions
- $\Omega_{\rm b}$(O VI) and Column density distribution, $f(N)$(O VI)
  - dn/dz, $\Omega_{\rm b}$(O VI) corrected for incompleteness and $\Omega_{\rm b}$(O)
- Gas density of the O VI absorbers under various assumptions
  - the highly metal-rich O VI absorbers are not in hydrostatic equilibrium
- Conclusions

Open questions

- **Where are the baryons at low redshift, $z \sim$ 0-0.5?**
  The baryon budget at low z (stars, interstellar atomic and molecular gas, warm plasma in groups and clusters of galaxies) implies that ~50% of the baryons are still in the form of ionized gas in the IGM. (Fukugita et al. 1998)
- **Where are the metals at high redshift, $z \sim$ 3?**
  - At high z, at least ~90% of the baryons are in the Ly-α forest.
  - only ~10% of the metals expected from star-formation activity in Lyman Break Galaxies (Pettini 1999) have been measured up to now.
- **In both cases, hot and/or highly-ionized gas might be the answer**
  as suggested :
  - low z : hydrodynamic simulations of galaxy formation (e.g. Cen & Ostriker 1999; Davé et al. 2001) and the O VI absorber surveys (this conference).
  - high z : large-scale outflows of metal-rich gas around star-forming galaxies (e.g. Pettini 1999; Bruscoli et al. 2003).

Previous high-ionization absorber surveys

- **O VI absorbers at $z \sim$ 2.0-2.5**
  Surveys of O VI$\lambda\lambda 1031, 1037$ absorption systems have been conducted at the VLT and Keck telescopes. (Carswell et al. 2002 [2 sightlines]; Simcoe et al. 2002, 2004 [7 sightlines]; Bergeron et al. 2002 [1 sightline]).
  - A non-negligible fraction, $\sim 1/3$, of the O VI absorptions associated with the Ly-α forest have line widths $b < 14$ km s^{-1}, thus $T < 2 \times 10^5$ K, which favors a radiative ionization process.
  - A hard UV background flux, small discontinuity at 4 Ryd (Haardt & Madau 1996), reproduces well the observed ionic ratios for –3 $<$ [Z/H] $<$ –0.5.
  - The inferred values of $\Omega_{\rm b}$(O VI) of the above surveys are $\approx 1.1 \times 10^{-7}$ ($\Omega_\Lambda, \Omega_{\rm m}, \Omega_{\rm b}, h =$ 0.7, 0.3, 0.04, 70).
  - A conservative ionization correction, O VI/O=0.16, leads to a mean oxygen abundance of [O/H] $=$ –2.8.
  - The inferred overdensity of the O VI absorbers is $\delta \equiv (\rho/\overline{\rho}) =$ 2 to 40.

Previous high-ionization absorber surveys (cont.)

- **O V absorbers at $z \sim 2.2$**
  Stacked composite absorption spectra from HST-FOS data [4 sightlines] created to search for O V$\lambda 630$ systems associated with the Ly-α forest and other EUV absorption lines (Telfer et al. 2002).
  - Detection of O V over a large range of N(H I) (from Keck data of the Ly-α forest) down to N(H I) $= 10^{13.2}$ cm^{-2}.
  - O IV$\lambda\lambda 544, 788$ lines are only detected in absorbers of high N(H I) ($> 10^{16.0}$ cm^{-2}), which suggests a hard ionizing metagalactic flux.
  - For photoionization, the oxygen abundance in the IGM is [O/H] ≈ –2.2 to –1.3.
  - Comparison with C IV studies suggests a possible overabundance of oxygen relative to carbon, [O/C] ≈ 0.3 to 1.2.

The VLT O VI sample

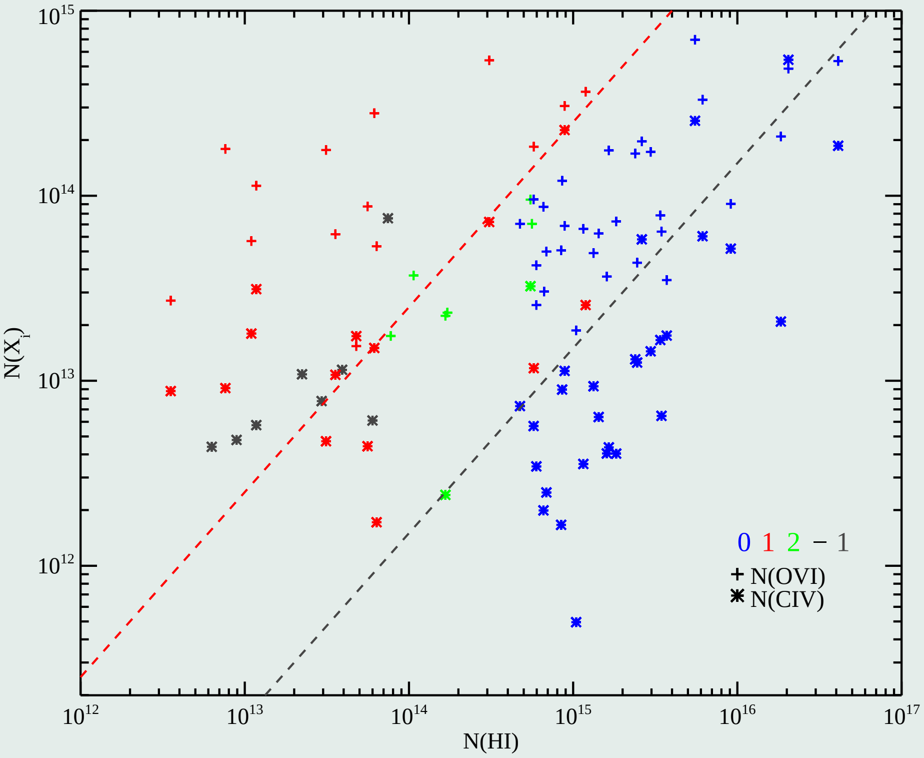
- **The UVES Large Programme (PI : J. Bergeron, 334 hr)**
  - 21 bright QSOs (most with V < 17), of which 19 at $2 < z < 4$, observed with dichroics blue and red,
  - Resolution $=$ 45,000 or $b = 6.6$ km s^{-1},
  - Exposure time per setting per QSO (2 settings per QSO) : 6 to 10 hr,
  - S/N $\sim$ 30, 100 at 3200, 5500 Å respectively.
- **Data reduction (B. Aracil)**
  - Upgrade of the ESO-UVES data-reduction pipeline and continuum fitting
- **Our analyzed sample**
  - 10 QSOs at $2.1 < z < 2.8$ (excluding those in Carswell et al. 2002)
  - data analysis using VPFIT (`http://www.ast.cam.ac.uk/~rfc/`)
  - sample of 136 detected O VI absorbers, $12.7 <$ log N(O VI) < 14.6.
  - 51 individual H I components associated with this O VI sample.

The O VI subsamples

- **A few systems with high ionic ratios, N(O VI)/N(H I) > 0.5,** are present in the samples analyzed by Carswell et al. (2002) and Bergeron et al. (2002).
  They have low H I column densities, log N(H I) < 13.0 (underrepresented in the survey of Simcoe et al. (2004), log N(H I) > 13.6).
- **These systems have high abundances, [O/H] > -1** (or even [O/H] > 0).
  - **They trace highly metal-enriched sites, not the IGM.**
  - They are not present in every sightline : **A large QSO sample is mandatory**
- As several of these O VI absorbers have small line widths, $b < 12$ km s^{-1}, results from photoionization models with [O/H] $= -1$ are used to derive an observational identification criterion :
  - **N(O VI)/N(H I) > 0.25 defines the O VI type 1 subsample**
- A similar criterium is derived for C IV absorbers : **N(C IV)/N(H I) > 0.015**.
  - The **C IV-only type 1 absorbers** are those without O VI detection (O VI either outside the observed range ($z < 2$) or fully blended with strong Lyman lines.)
    There are **18 C IV-only type 1 absorbers**, 11.8 $<$ log N(C IV) $<$ 13.8, with 8 distinct H I components.

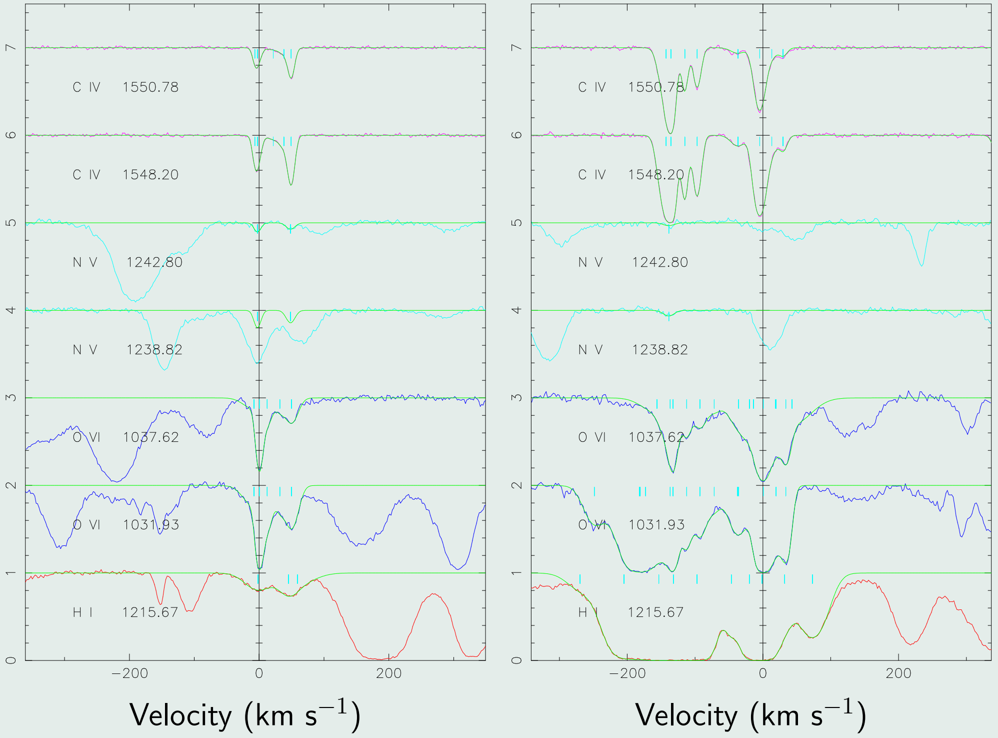
The O VI subsamples

O VI & C IV Column Densities vs H I Column Density



- The O VI subsamples
  - Type 0 : low abundance
  - Type 1 : high abundance O VI and/or C IV
  - Type 2 : less certain O VI
- The C IV only, high [C/H] subsample
  - Type 1 : high abundance
- Red dashed line : N(O VI)/N(H I) = 0.25
- Black dashed line : N(C IV)/N(H I) = 0.015

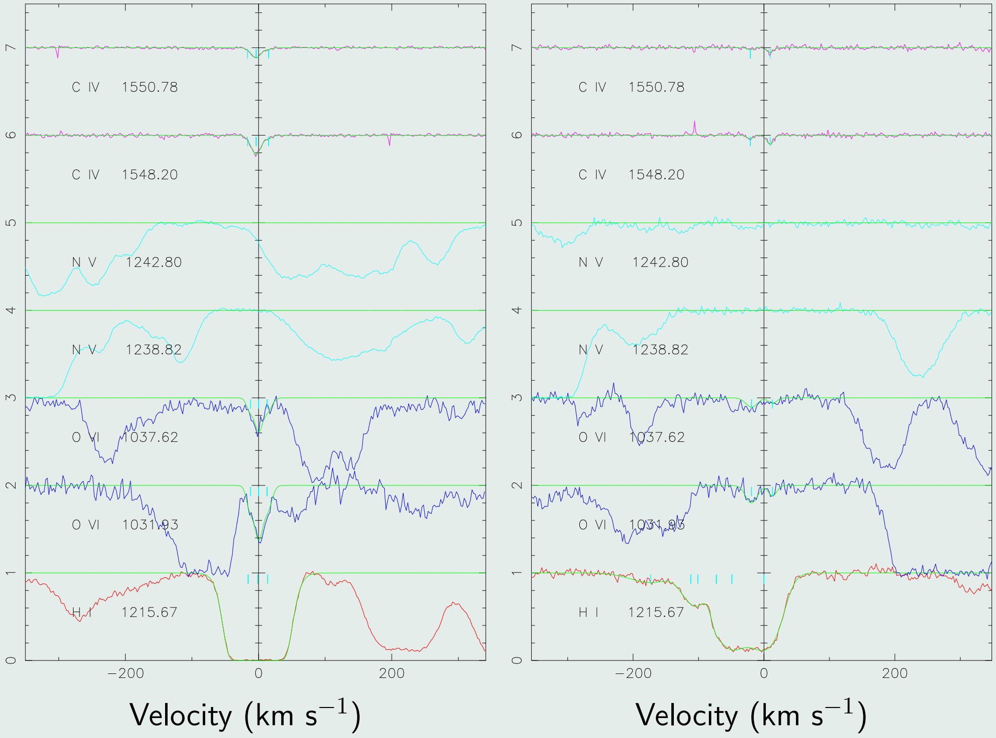
Examples of type 1 O VI absorbers



Weak N(H I) absorbers
z =2.468
(left panel)

Strong N(H I) absorbers
$z \sim 2.398$
O VI fit with Ly blends
(right panel)

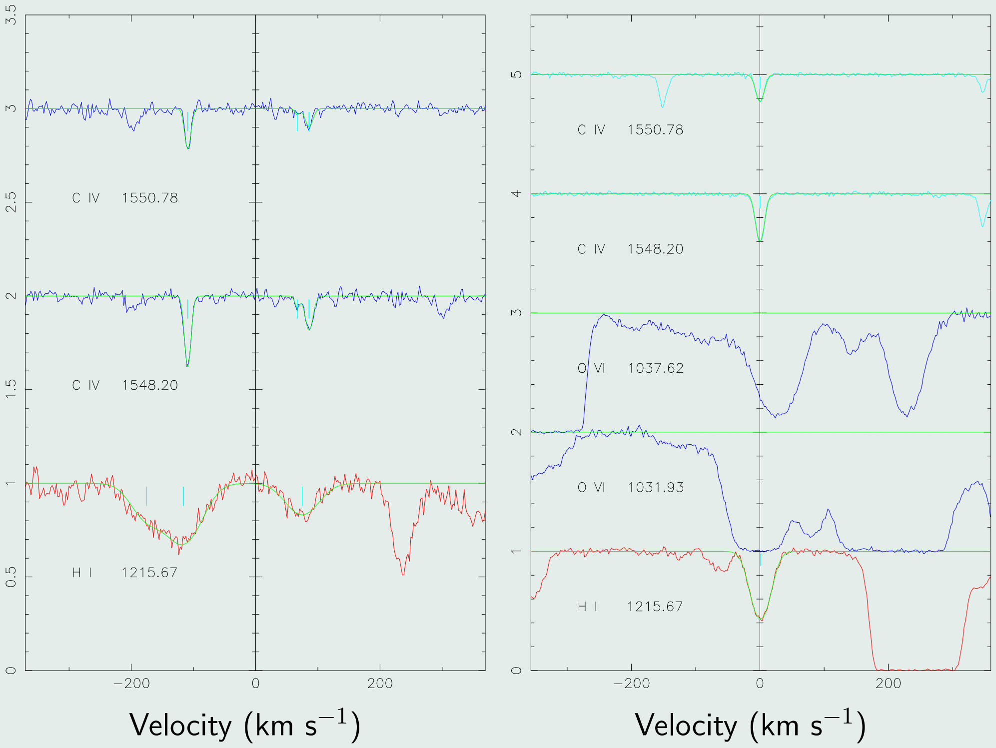
Examples of types 0 and 2 O VI absorbers



Type 0 absorber
$z = 2.089$
(left panel)

Type 2 absorber
$z = 2.314$
(right panel)

Examples of type 1 C IV-only absorbers



Lower z absorbers

$z = 1.727$ & 1.729

O VI outside range

(left panel)

Higher z absorber

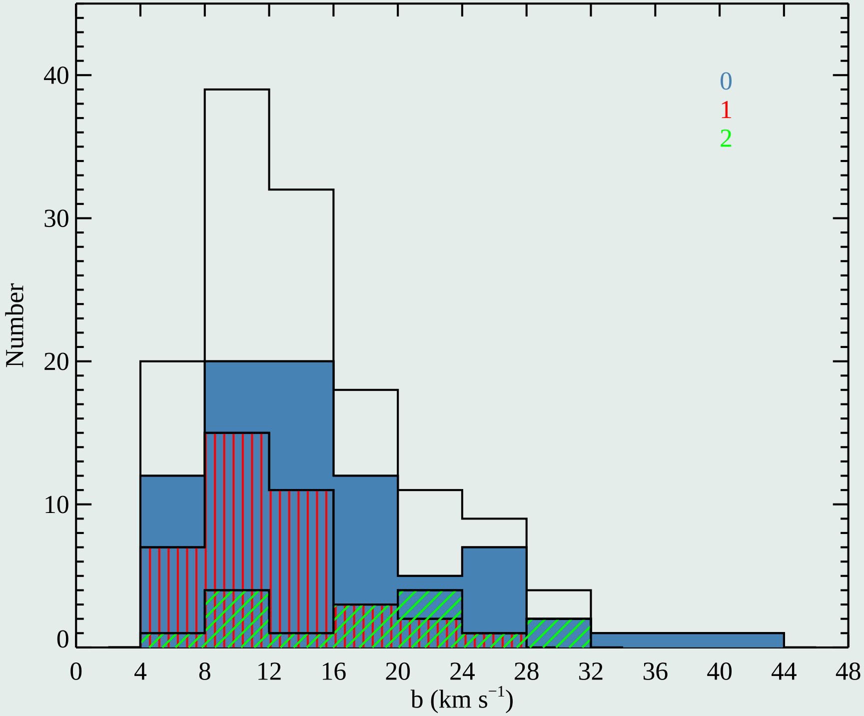
$z = 2.415$

O VI fully blended

(right panel)

Distribution of O VI line widths

- Number of O VI absorbers :
  81, 39, 16 for the types 0, 1, 2
- **The *b* distributions of the types 0 & 1 overlap**
  - but a Kolmogorov-Smirnov test shows that there are different at the 98% confidence level.
- **43% of the absorbers have b<12 km s^{-1} (log T<5.14)**
  → implies photoionization
- Very few O VI absorbers with b>16 km s^{-1} are unambiguously broad systems

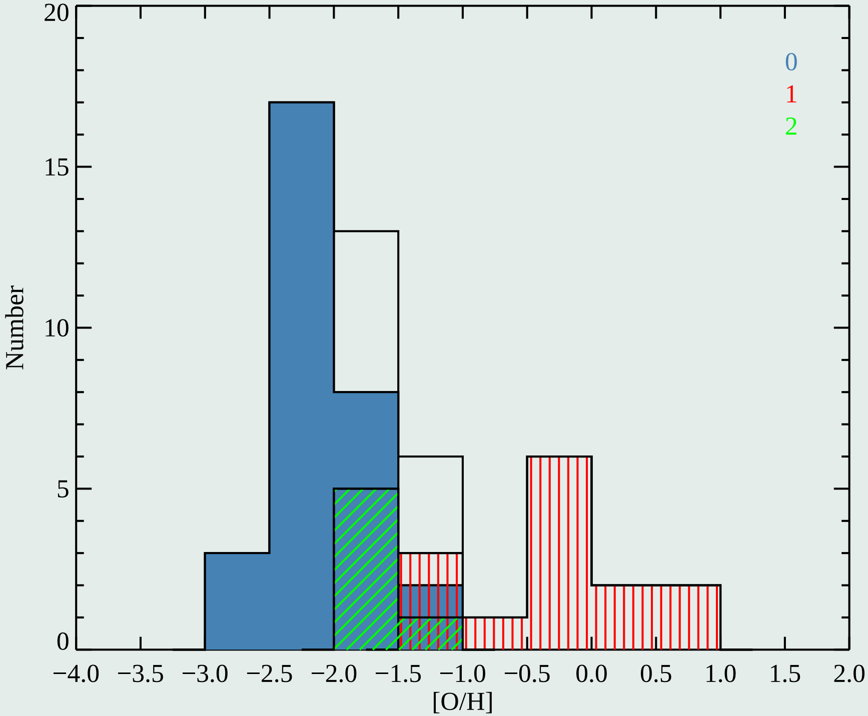


Abundances

- **Radiative ionization process**
  - Photoionization by a hard UV metagalactic flux (Haardt & Madau 1196).
  - Ionization parameter, U, fixed by the ionic ratio (O VI/O)/(C IV/C), assuming [O/C] = 0.
  - is only true if O VI and C IV are in the same phase : should be mostly the case as Si IV is not detected, except in a few systems with high N(H I) ($> 10^{15}$ cm $^{-2}$).
- sample : numbers of O VI-H I systems of 31, 14, 6 for the types 0, 1, 2.
- **Types 0 and 1 : populations with markedly different metallicities**
  - To confirm the difference in metallicity for the types 0 (IGM) and 1 (metal-enriched sites), we investigate other ionization processes for the type 1 population :
    - **Gas temperature fixed** by b(major O VI component) of the system, **plus photoionization** by a hard UV metagalactic flux. The corresponding value of U is then derived (same assumptions as above for (O VI/O)/(C IV/C)).
      No solution for $T \geq 2.0 \times 10^5$ K.
    - **Constant gas density thus constant U** (log U = –0.5 or an overdensity $\delta \approx 10$).
      In a large fraction of the cases, O VI and C IV do not trace the same phase.

Abundances : photoionization case

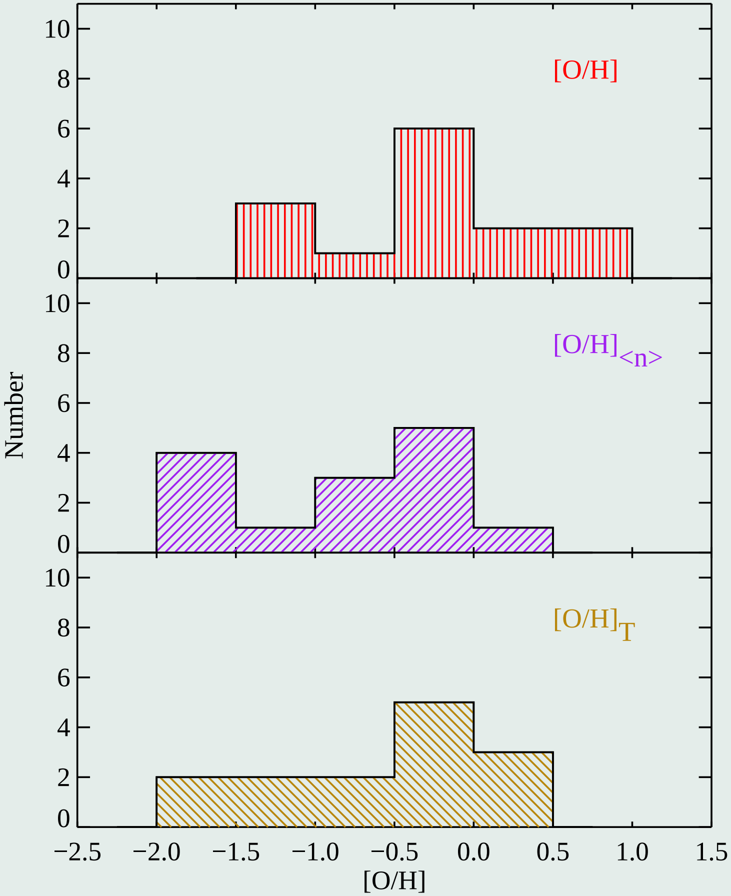
- **[O/H] distribution :** **Confirmed existence of two distinct populations**
  - median [O/H]
    type 0, 1, 2
    −2.07, −0.33, −1.56
- **Type 2 [O/H] distribution** : spans a small range in between those of the types 0 and 1 populations.



Abundances for the type 1 population

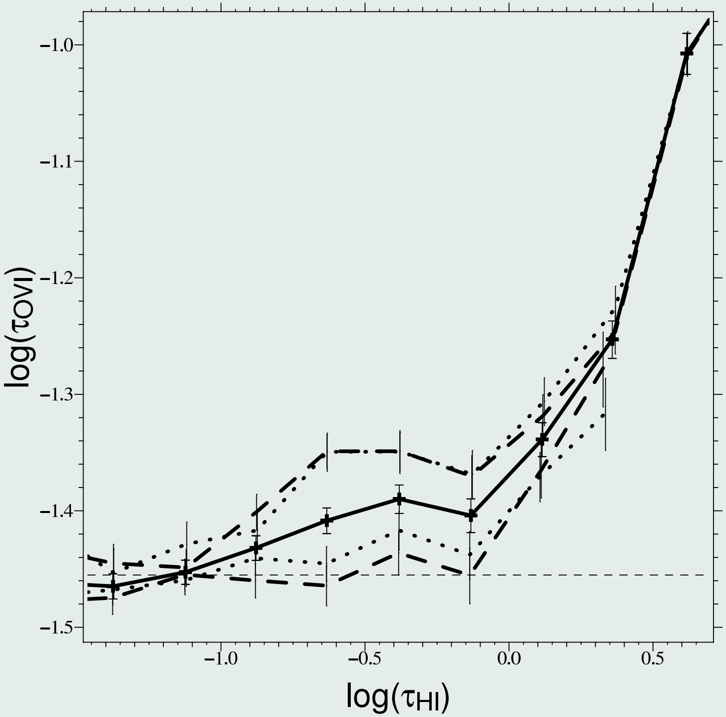
different ionization assumptions

- The three cases shown are :
  - 1. photoionization : U(O VI/C IV) (top panel)
  - 2. photoionization : log U = –0.5 thus fixed gas density (middle panel)
  - 3. T fixed by b(O VI) & photoionization : U(O VI/C IV) (bottom panel)
- Although [O/H] is smaller for cases 2 & 3 than case 1, **it remains far higher than the type 0 value** (case 1)
  - median [O/H]
    type 0 (case 1) : –2.07
    type 1(case 1), 1(case 2), 1(case 3) :
    –0.33 , –0.80, –0.35



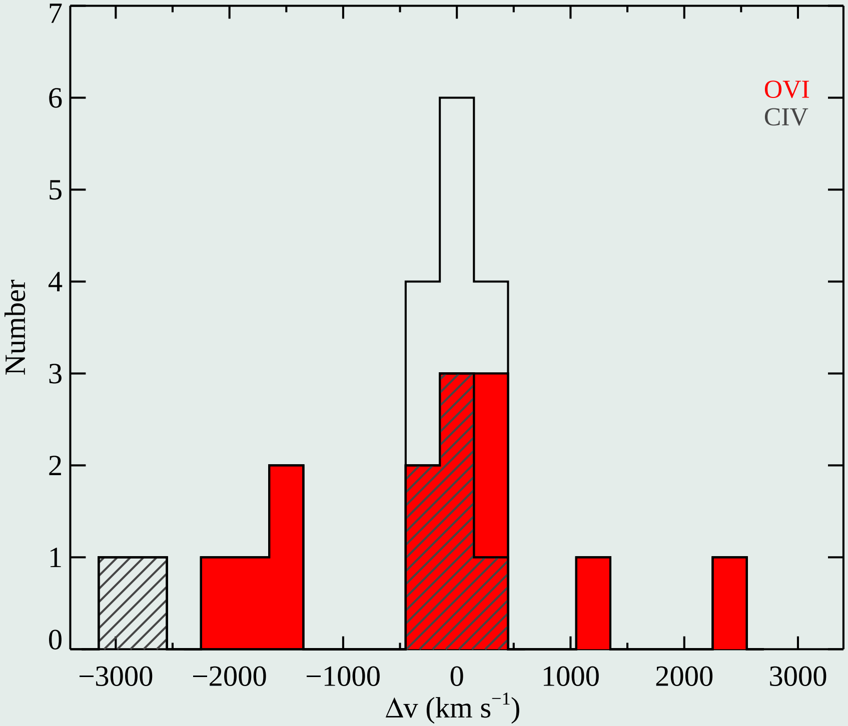
Weak O VI absorption

- From a pixel analysis of UVES-LP QSO spectra, Aracil et al. (2004) found that weak O VI absorption is predominantly detected in the vicinity (small Δv) of strong Ly-α absorption.
  - For $\Delta v \leq 300$ km s^{-1}, a signal is present at $0.2 < \tau(\text{H I}) < 1$ (or $12.9 < \log \text{N(H I)} < 13.6$ for $b(\text{H I}) = 30$ km s^{-1}).
- This suggests that the **O VI absorption arising in regions spatially close to strong Ly-α absorption** may be part of **outflows from overdense regions.**



Type 1 population : Nearest strong H I absorber

- The O VI type 1 population should exhibit the same property as the weak O VI absorptions (from pixel analysis), since there is an overlap in their N(H I) range.
- Distribution of Δv between O VI and C IV type 1 systems and the nearest strong Ly-α system :
  - 57%, 75% of the O VI, C IV type 1 systems have a strong Ly-α system at $\Delta v \leq 450$ km s^{-1}.
- **Pixel analysis and study of individual O VI systems both suggest a link to gas outflows.**



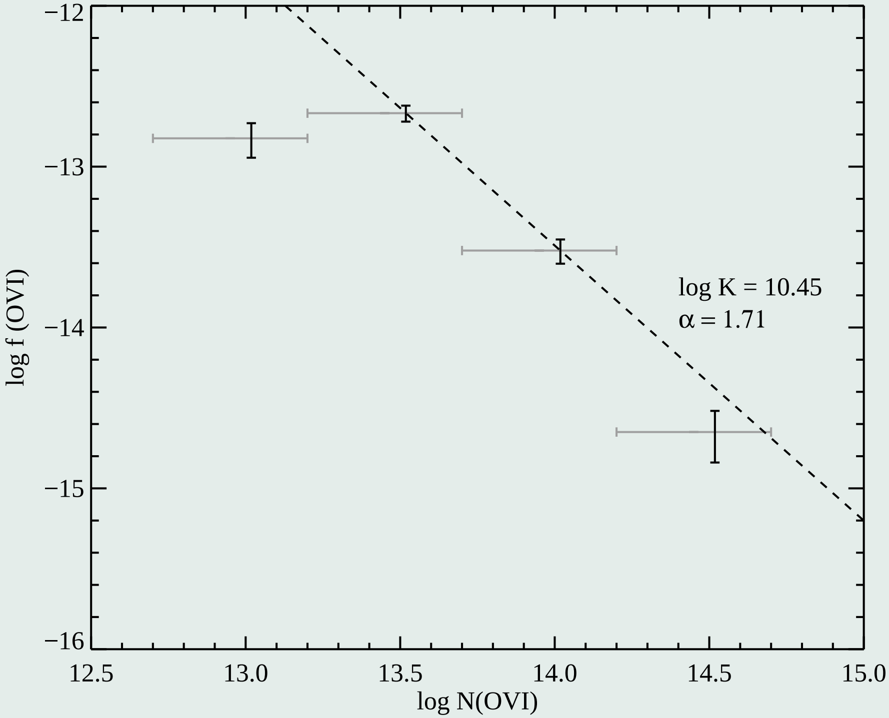
Ω_b(O VI) and the column density distribution

- Ω_b(O VI)
  - $\Omega_b(\mathrm{O\,VI}) = \{H_0 m_O / c\rho_{crit}\}\{\sum N(\mathrm{O\,VI}) / \sum_i \Delta X_i\}$
    $= 2.2 \times 10^{-22}\{\sum N(\mathrm{O\,VI}) / \sum_i \Delta X_i\}$
    H_0: Hubble constant, m_O: oxygen atomic mass, ρ_{crit}: critical density, $\sum_i \Delta X_i$: total redshift path.

    For the adopted cosmological parameters $(\Omega_\Lambda, \Omega_m, h =$ 0.7, 0.3, 70)
    $dX \equiv (1+z)^2\{0.7 + 0.3(1+z)^3\}^{-0.5} \cong \{(1+z)/0.3\}^{0.5}$ when $z > 1$.
  - For our sample of 10 QSOs we obtain :
    Ω_b(O VI)$= 1.51 \times 10^{-7}$
- **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 sample of QSOs with total redshift path $\sum_i \Delta X_i$.
  - Fit of $f(N)$ used to
    (i) estimate the incompleteness correction factor for Ω_b(O VI),
    (ii) derive the number of O VI absorbers per unit redshift.

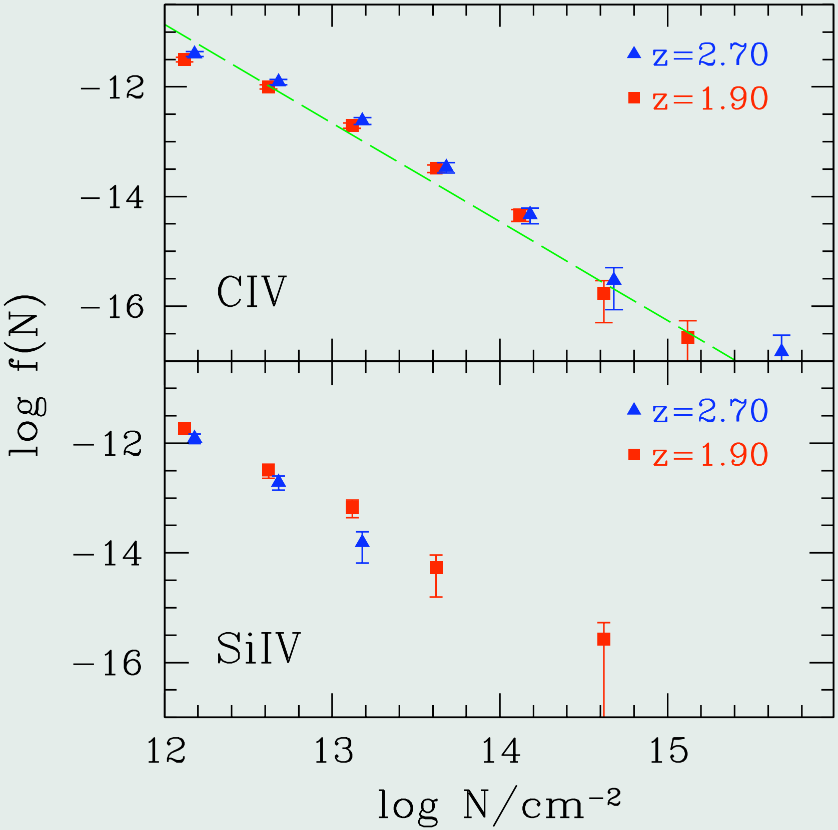
Column density distribution of O VI absorbers

- Assuming a power law distribution : $\boldsymbol{f(N) = KN^{-\alpha}}$ we obtain $\boldsymbol{\alpha = 1.71}$
- The majority of the O VI absorbers have column densities in the range $13.0 <$ log N(O VI) < 14.0.
  - Incomplete, sample variance at log N(O VI) < 13 and > 14.0, respectively.
  - Shifting the ΔN bins by 0.1 dex yields the uncertainty in α $\boldsymbol{\alpha = 1.71\pm^{0.48}_{0.47}}$, which leads to $\boldsymbol{f(N) = 2.3 \times 10^{-13}}$, at log N(O VI) $= 13.5$, with a ∼30% uncertainty.



Column density distribution of C IV absorbers

- For comparison, we show the C IV (and Si IV) column density distribution obtained for 19 UVES-LP QSO spectra (Scannapieco et al. 2005).
  The green dashed line is the fit measured by Songaila (2001) with $\boldsymbol{\alpha = 1.8}$.
- $f(N)$(O VI) at log N(O VI) $= 13.5$ is larger than
  $f(N)$(C IV) at log N(C IV) $= 13.5$
  by a factor 4 & 8
  compared to Scannapieco et al. & Songaila values, respectively.



O VI absorbers : dn/dz

- We now use the derived $f(N)$ to (i) estimate the number density per unit z of O VI absorbers, (ii) correct $\Omega_{\rm b}$(O VI) for incompleteness.
- **O VI : dn/dz**
  - $\boldsymbol{dn/dz = (dX/dz) \int f(N) dN}$
  - using the fit with $\alpha = 1.71$ and log N(O VI) limits of 13.0 and 15.0, we get :
    $dn/dz \approx 73$ at $\overline{z} = 2.2$
  - **at $\overline{z} = 0.1$, $dn/dz \approx 13$** for $w_{\rm r,min} = 50$ mÅ (Sembach et al. 2004).
    For this $w_{\rm r,min}$ (N(O VI) $= 10^{13.6}$), we get **$dn/dz \approx 26$ at $\overline{z} = 2.2$**
  - Comparison between these two values of dn/dz is not straightforward as O VI absorbers may not trace the same population at low and high z.
- **H I : dn/dz**
  - We use the analysis of Kim et al. (2001) to derive dn/dz for (H I).
    The lowest H I column density associated with $\overline{z} = 2.2$ O VI absorbers is
    log N(H I) $= 12.80$.
    We then use a log N(H I) range of 12.8 to 16.0, and get :
    $dn/dz \approx 620$ for H I at $\overline{z} = 2.13$
  - Note : in many cases, we find several O VI components per H I system (unresolved individual H I components).

O VI absorbers : corrected Ω_b

- Ω_b(O VI)
  - $\Omega_b = 2.20 \times 10^{-22} \int N f(N) dN$
  - using again the fit with $\alpha = 1.71$ and log N(O VI) limits of 13.0 and 15.0, we get :
    Ω_b(O VI) $\approx 3.5 \times 10^{-7}$
    i.e. an incompleteness correction factor of 2.3 at $\overline{z} = 2.2$.
- Ω_b(O)
  - using a conservative ionization correction factor, (O VI/O) $= 0.16$, yields
    $\Omega_b(\mathrm{O}) = 2.2 \times 10^{-6}$
  - Using the solar abundances of Anders & Grevesse (1989), we get
    $\Omega_b(\mathrm{O})/\Omega_b(\mathrm{O})_\odot = 0.9 \times 10^{-2}$
- **The above values of dn/dz and Ω_b(O) are lower limits, as we have not yet included the O VI absorbers without associated H I absorption.**
  This requires a statistical analysis of "pseudo" O VI doublets in simulated spectra of the Ly-α forest (work in progress).

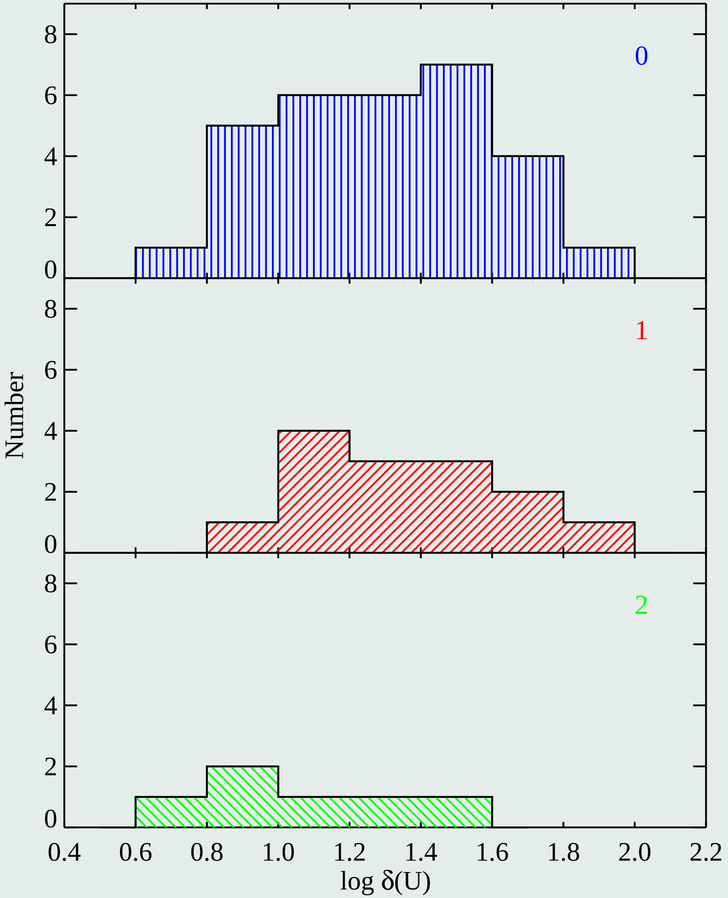
Gas density of O VI absorbers

- **The gas overdensity of the O VI absorbers, $\delta \equiv (\rho/\overline{\rho})$, is estimated for two cases :**
  - photoionization by a hard UV metagalactic flux,
  - hydrostatic equilibrium (Schaye 2001).
- **Photoionization**
  - U is fixed by the O VI/C IV ionic ratio (assuming [O/C] solar) $\overline{\rho}$ is the mean baryonic density at each z(O VI)
  - $\boldsymbol{\delta(U) = 4.0\ U^{-1}([1+z]/3)^{-3}}$.
- **Hydrostatic equilibrium**
  - For $\Omega_{\rm b}/\Omega_{\rm m} = 0.15$, a gas temperature $T = 4 \times 10^4$ K and a photoionization rate Γ(H I) $\approx 1.5 \times 10^{-12}$ s^{-1}, we get :
  - $\boldsymbol{\delta(G) = 4.8 \times 10^{-9}\ \ \mathrm{N(H\,I)}^{2/3}([1+z]/3)^{-3}}$.

Absorber density : photoionization case

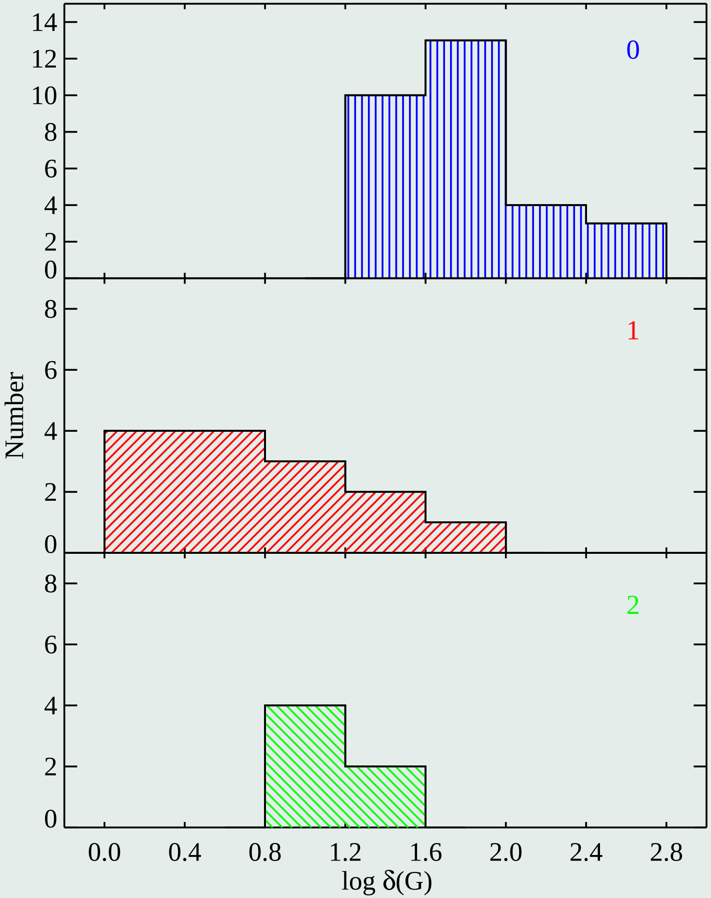
- Distribution of $\delta(U)$.
  - The median values of $\delta(U)$ for the type 0 (metal-poor) and type 1 (metal-rich) are equal :

    $\boldsymbol{\delta(U) \approx 22}$,
    and $\sim$ 40% smaller for the type 2.
- The ranges of $\delta(U)$ are very similar for the types 0 and 1 populations.
  - a Kolmogorov-Smirnov test shows that they have the same $\delta(U)$ distribution at the 97% confidence level.



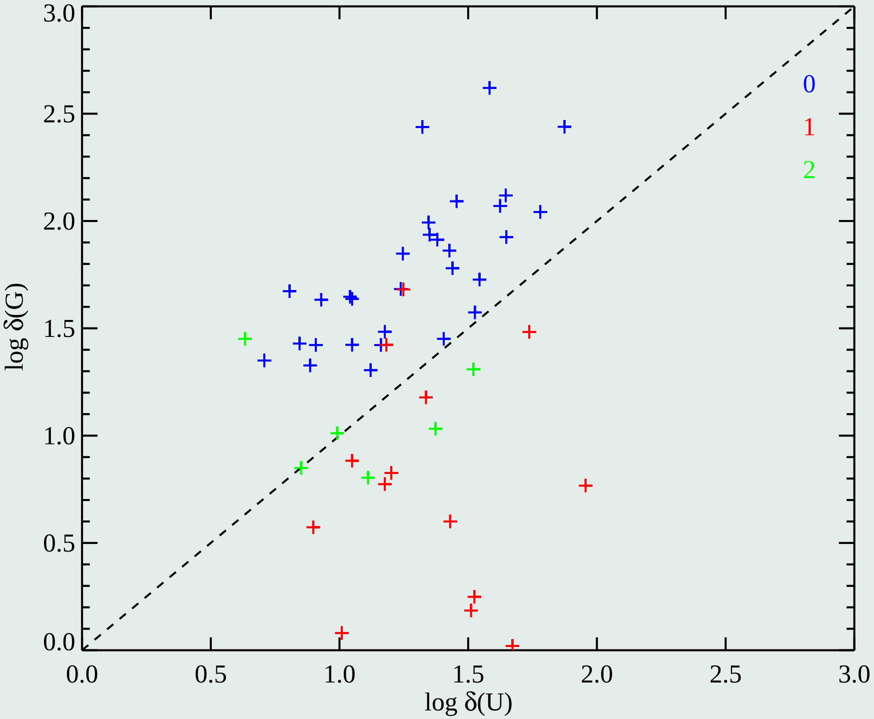
Absorber density : hydrostatic equilibrium case

- Distribution of $\delta(G)$.
  There is a marked difference between the type 0 and type 1 populations.
  - The median values of $\delta(G)$ are 53 and 6 for the type 0 and type 1 absorbers, respectively;
    that for the type 2 is 11.
- The range of $\delta(G)$ for ≈80% of the type 1 absorbers does not overlap with the type 0 absorbers.



Overdensity

- Different nature of the types 0 and 1 populations : $\delta(G)$ vs $\delta(U)$.
- For the type 0 absorbers, $\delta(G)$ and $\delta(U)$ are correlated, and $\delta(G) > \delta(U)$ may suggest that a large fraction of H I is not in the O VI phase.
  - Type 0 absorbers probe the IGM and hydrostatic equilibrium is roughly valid.
- For the type 1 absorbers, $\delta(G)$ and $\delta(U)$ are uncorrelated:
  - hydrostatic equilibrium does not apply. Type 1 absorbers do not trace the IGM, but rather gas outflows in the vicinity of overdense regions.



Conclusions

- **O VI absorbers comprise two populations that trace :**
  - **The IGM - low metallicity absorbers (type 0) : $[\mathrm{O/H}] < -1.5$,**
  - **Gas outflows from overdense regions** with strong star-formation activity - **high metallicity absorbers (type 1) : $[\mathrm{O/H}] > -1.0$.**
- **Populations well defined by a simple observational criterion :**
  $N(\mathrm{O\,VI})/N(\mathrm{H\,I}) < 0.25$: type 0
  $N(\mathrm{O\,VI})/N(\mathrm{H\,I}) > 0.25$: type 1
- **[O/H] of the type 1 population remains high : median $[\mathrm{O/H}] \approx -0.4$** regardless of detailed ionization assumptions.
- **$\sim$ 60% of the type 1 absorbers have a strong H I at $\Delta v < 450$ km s^{-1};** also found for weak O VI absorbers from pixel analysis.
  - supports outflows

Conclusions (cont.)

- **Our O VI sample is large enough to derive a rough column density distribution, $f(N) = KN^{-\alpha}$:**
  - $\alpha = 1.71 \pm^{0.48}_{0.47}$ and
  - $f(N) = 2.3 \times 10^{-13}$ at $N(\mathrm{O\,VI}) = 10^{13.5}$ cm^{-2}, ∼30% uncertainty.
- **dn/dz, $\Omega_\mathrm{b}(\mathrm{O\,VI})$ and $\Omega_\mathrm{b}(\mathrm{O})$**
  for $10^{13} < N(\mathrm{O\,VI}) < 10^{15}$ cm^{-2}
  - $dn/dz = 73$ (66-106) at $\overline{z} = 2.2$: $f(N)$ fit
  - $\Omega_\mathrm{b}(\mathrm{O\,VI}) = 1.5 \times 10^{-7}$: O VI sample (incomplete)
    $\Omega_\mathrm{b}(\mathrm{O\,VI}) = 3.5$ (2.6-6.7) $\times 10^{-7}$: $f(N)$ fit
  - $\Omega_\mathrm{b}(\mathrm{O}) = 2.2 \times 10^{-6} = 0.009\ \Omega_\mathrm{b}(\mathrm{O})_\odot$: $f(N)$ fit
- **Gas overdensity** $(\delta \equiv (\rho/\overline{\rho}))$
  - $\delta(U)$: 4 to 100 ($U \equiv$ photoionization)
    $\delta(G)$: 1 to 600 ($G \equiv$ hydrostatic equilibrium)
  - Hydrostatic equilibrium roughly valid for type 0 population : low metallicity/IGM, but not for type 1 (high metallicity) population : strengthens further the outflow suggestion.

Prospectives

- **Search for O VI doublets with very weak H I**
  - coupled to a statistical analysis of simulated spectra.
- **Better constrain $\Omega_{\mathrm{b}}(\mathrm{O})$** : increase the sample
  - Complete the analysis of the UVES-LP $z_Q < 3$ sample (5 more)
  - Include "partially" blended O VI doublets
- **Link observational results to models of radiatively cooling gas** (Heckman et al. 2002; Furlanetto et al. 2004)
- **High metallicity absorbers : identification of associated starburst galaxies** (imaging & spectroscopy)