IGM Metallicity
Wide Spread and Cosmic Evolution

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Open questions

- **Where are the metals at high redshift, $z \sim$ 2-3?**
  - at high z, at least ∼90% of the baryons are in the Ly-α forest
  - only ∼10-15% 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: $\langle[\mathrm{Z/H}]\rangle \sim -1.7$ to -1.4
  - inhomogeneous metal enrichment of the IGM:

    relative contribution to the cosmic metals of the general IGM vs metal-rich sites?
  - main contributor to ionizing radiation field: nuclear burning or accretion?

    $\longrightarrow$ derived metallicity strongly depends on ionization level
  - spatial distribution of metals - clustering: do they trace large-scale structures?

- **Hot and/or highly-ionized gas could be the answer**
  - large-scale outflows of metal-rich gas around star-forming galaxies

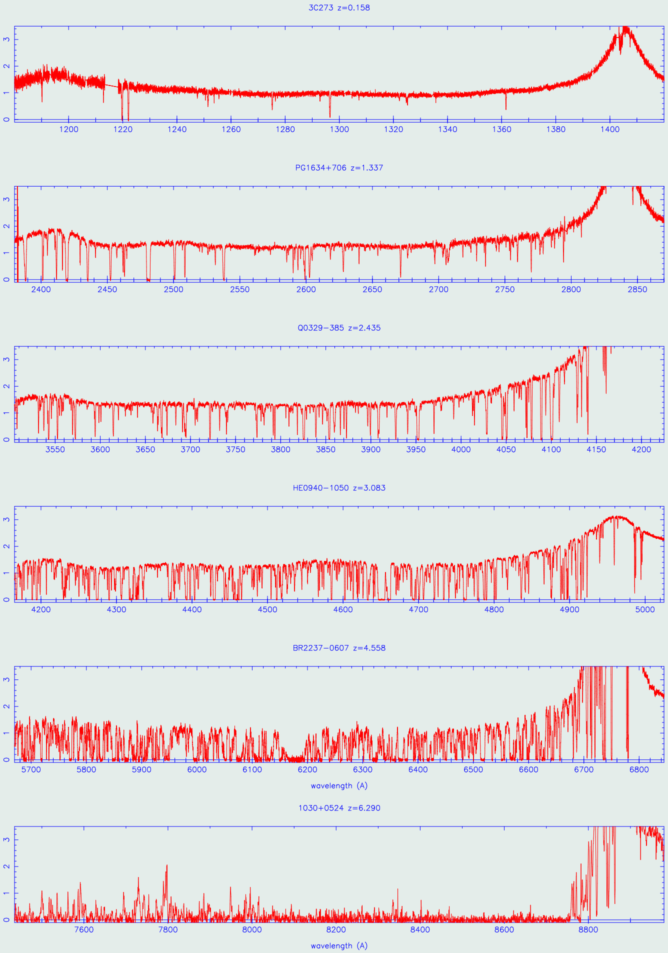
    consistent with numerical simulations which include strong feedback

(Pettini 1999, Theuns et al. 2002, Aguirre et al. 2001 & 2005, Cen et al. 2005, Ferrara et al. 2005)

Open questions/2

- **The reionization epoch, $z \sim$ 7-15**
  - tracable by 21 cm excess brightness and 21 cm absorption spectra
- **Metals at the reionization epoch**
  - no transmitted flux in the Ly-α forest at $z \gtrsim 6$ $(\longrightarrow \mathrm{H\,I/H} \gtrsim 0.01)$
    $\longrightarrow$ observations only of the "metal forest"
    thus no information on the metallicity from optical/NIR alone
  - No clear evidence for evolution of the cosmic metal density at $2 < z < 5$
    $\longrightarrow$ early pollution of the IGM by the first stars and galaxies
    chemical composition at earlier times
- **Search for "bright" very rare background targets at $z \gtrsim 8$**
  - GRBs, population III SNe, QSOs and very luminous radio sources
    dedicated space- and ground-based telescopes

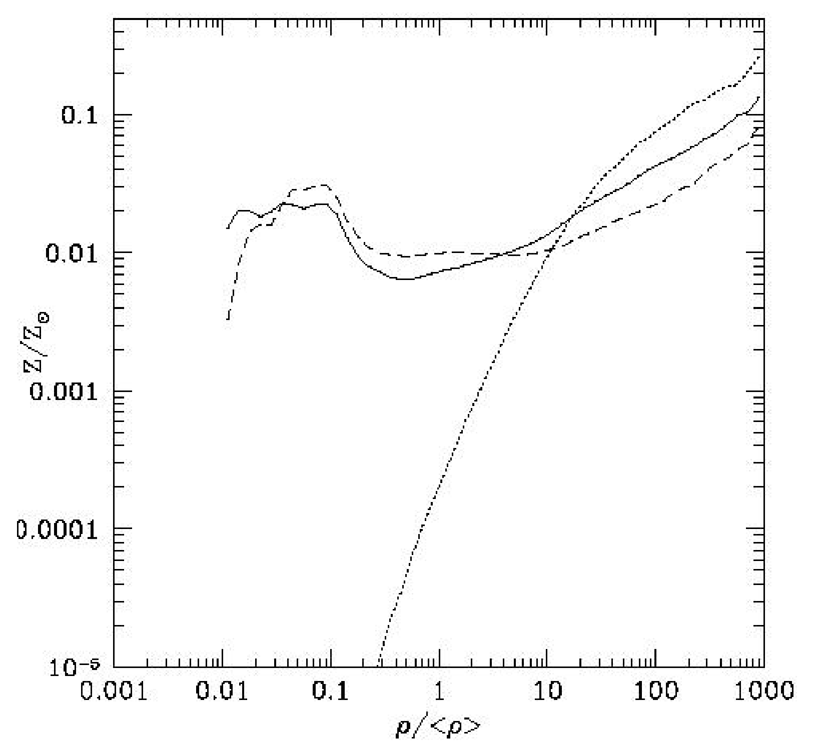
Evolution of the Ly-α forest



Predicted IGM metallicity / 1

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

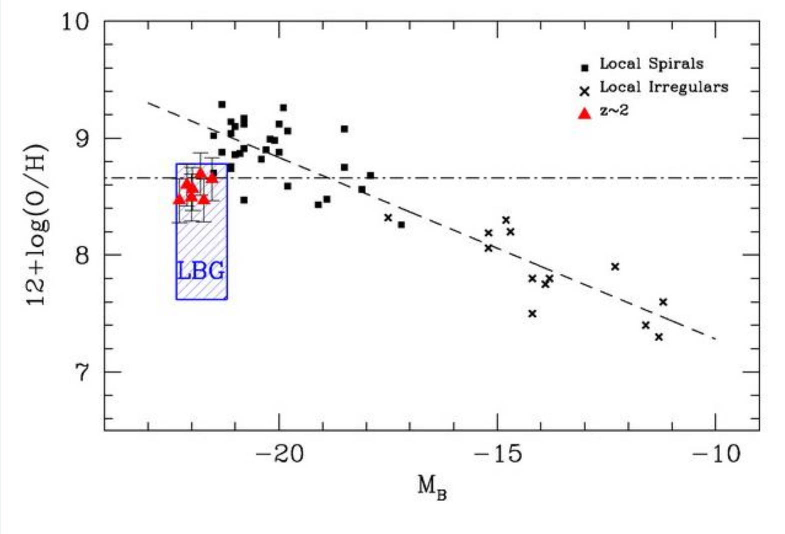
(Aguirre et al. 2001, Cen, Nagamine & Ostriker 2005)



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 metallicity → low mass-to-light ratio
  - Massive star-forming galaxies at $z \sim 2$: solar metallicities

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



High-ionization absorber surveys

- **Best UV tracer of a high-z hot/highly ionized IGM phase**
  - **O VI doublet ($\lambda\lambda 1031, 1037$)** $\longrightarrow$ lies in the Lyα forest
  - problem: ↗ blending with Lyman lines for ↗ z
    limits O VI searches: too high incompleteness for $z >$ 3-3.5
  - coupling O VI, N V, C IV to constrain the ionization level $\longrightarrow$ metallicity
    problem using N V : preliminary results show that [N/C] $\neq$ solar

- **Results of early O VI surveys**
  - $\sim 1/3$ of O VI absorbers have line widths $b < 14$ km s^{-1} or
    $T < 2 \times 10^5$ K $\longrightarrow$ favors a radiative ionization process
  - inferred overdensity of O VI absorbers $\delta \equiv (\rho/\overline{\rho}) = 4$ to 80
  - a few systems have $[\mathrm{O/H}] > -1$ (high ionic ratio N(O VI)/N(H I))
    not present in every sightline and often associated with low N(H I) ($< 10^{13.0}$ cm^{-2})
    $\longrightarrow$ the early surveys were not well suited for their search:
    not enough sightlines or too high N(H I) limit ($> 10^{13.6}$ cm^{-2})

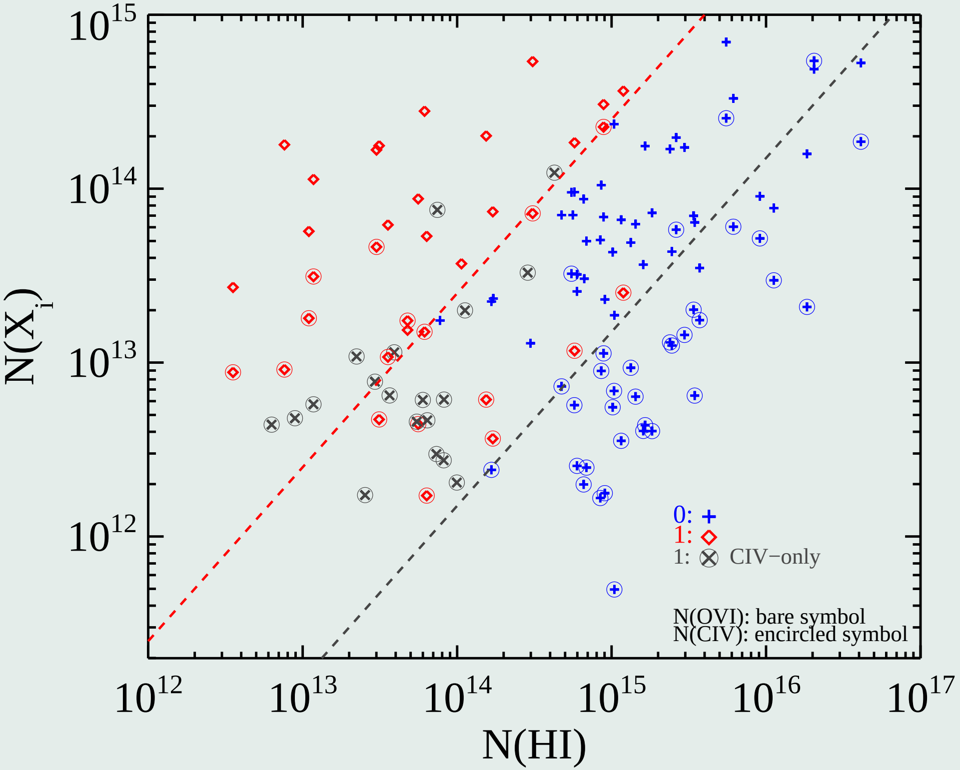
(Carswell et al. 2002, Simcoe et al. 2002& 2004, Bergeron et al. 2002)

The VLT O VI sample

- **The UVES Large Programme**
  - 21 bright QSOs (most with $V < 17$), of which 19 at $2 < z < 4$
  - Resolution: $b = 6.6$ km s^{-1}; λ range: 3050-10000 Å
  - S/N $\sim$ 30/100 at 3200/5500 Å
- **Our analyzed O VI sample**
  - 12 QSOs at $2.1 < z < 2.8$
    → enough sightlines to build a metal-rich sample
  - sample of 152 detected O VI absorbers, $12.7 < \log N(\text{O VI}) < 14.6$
  - 60 individual H I components associated with this O VI sample
- **The O VI subsamples**
  - use photoionization models with $[\text{O/H}] = -1$ to derive observational identification criteria
    - $N(\text{O VI})/N(\text{H I}) > 0.25$: O VI metal-rich/type 1 subsample
    - $N(\text{C IV})/N(\text{H I}) > 0.015$: C IV-only metal-rich/type 1 subsample

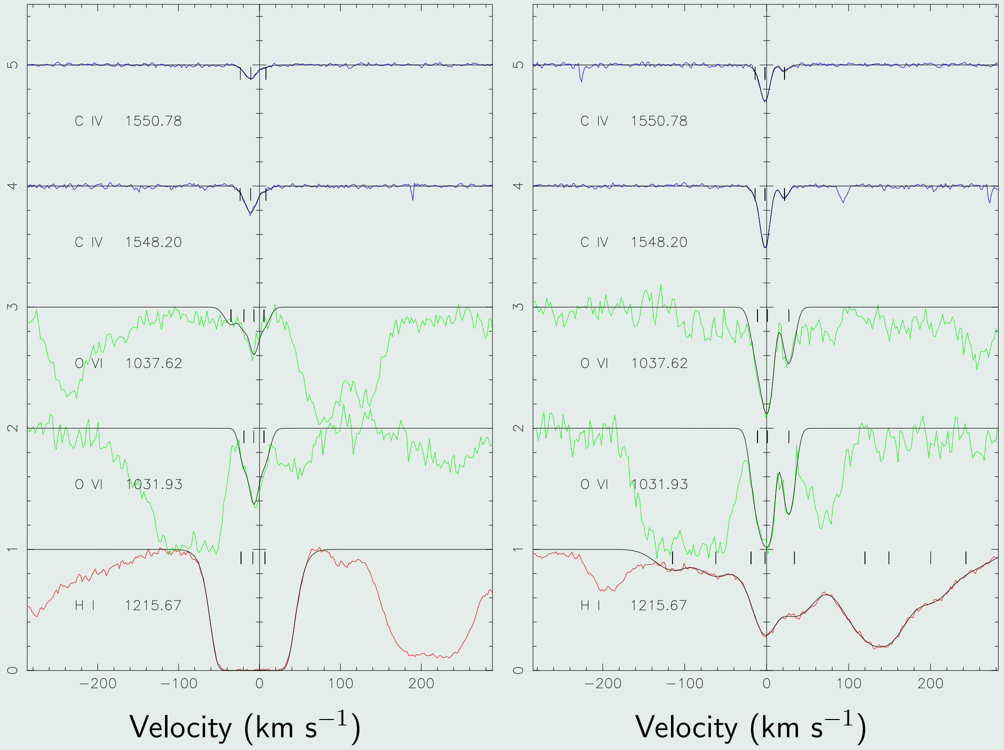
The O VI subsamples

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



- The O VI subsamples
  - – Type 0 : low abundance
  - – Type 1 : high abundance
- The C IV-only subsample
  - – Type 1 : high [C/H]
- Red dashed line : $N(\mathrm{O\,VI})/N(\mathrm{H\,I}) = 0.25$
- Black dashed line : $N(\mathrm{C\,IV})/N(\mathrm{H\,I}) = 0.015$

Metal-poor and metal-rich O VI absorbers



Strong N(H I) absorber

metal-poor

$z \sim 2.1$

(left panel)

Weak N(H I) absorber

metal-rich

$z \sim 2.1$

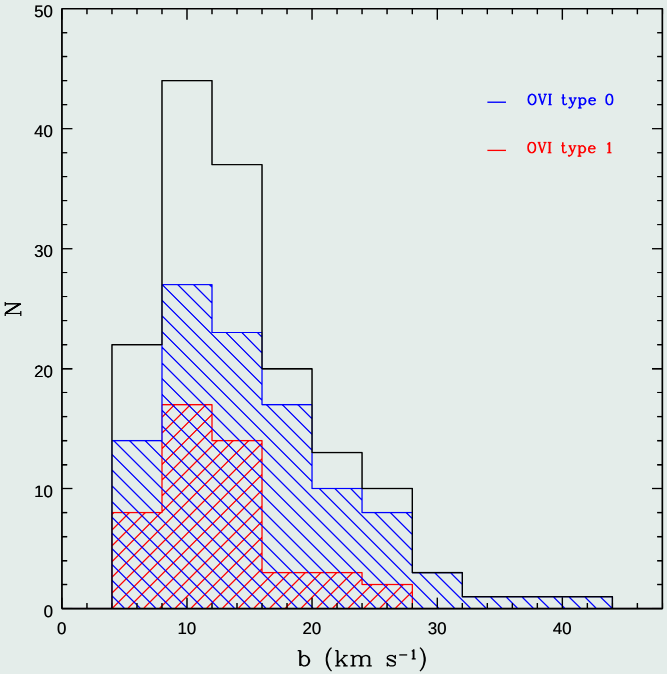
(right panel)

Temperatures

- **O VI line width distribution**
  - absorbers with $b < 12$ km s^{-1} or $T < 1.4 \times 10^5$ K
    - metal-poor : 39%
      high b tail : weak absorbers, low S/N
    - metal-rich : 53%

no unambiguously broad absorbers

⟶ photoionization : dominant process



Abundances

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

- **Metal-rich vs metal-poor populations : markedly different metallicities**
  - difference in metallicity for the metal-poor (type 0: IGM) and metal-rich (type 1: metal-enriched sites) populations confirmed by

    investigating other ionization processes for the metal-rich population :

    photoionization by a hard UV metagalactic flux plus

    - **Gas temperature fixed** by b(O VI) - additional collisional heating source
    - **Constant gas density** - overdensity : $\boldsymbol{\delta \equiv (\rho/\overline{\rho}) \approx 10}$
      - O VI and C IV then usually trace different phases

    ⟶ similar mean metallicity than in the above case

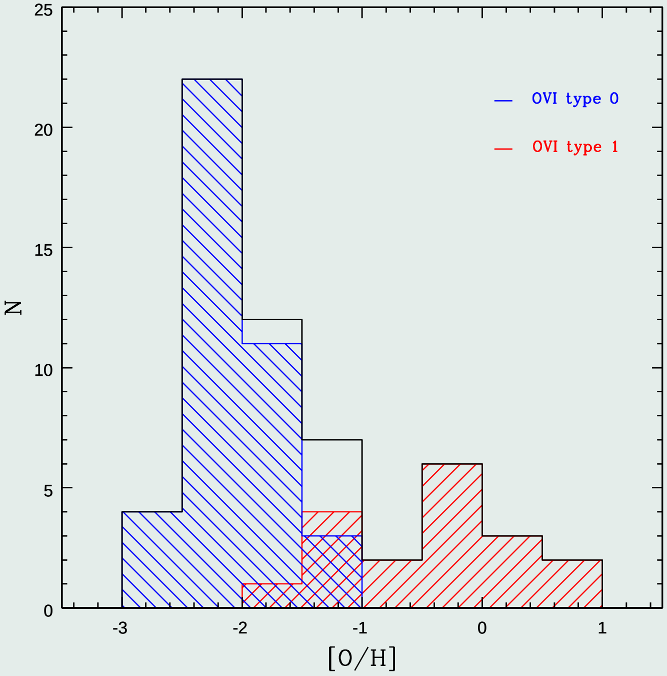
Abundances : results

- **Photoionization : case 1**

  bimodal [O/H] distribution

  → two distinct populations

	median [O/H]	
type	**0**	**1**
	-2.06	**-0.35**



- metal-rich O VI population
  - associated H I

    $10^{12.5} < \mathrm{N(H\,I)} < 10^{15.0}$ 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)

Metal enrichment: statistical approach

Pixel optical depth method

- Correlation of metal-line optical depth with H I optical depth
  - no information for τ(Lyα or Lyβ)> ln(S/N) ~ 3.5
  - good statistics
    - information at lower τ(C IV) than obtained by the analysis of individual systems
    - estimate of incompleteness using simulated spectra
  - median opacities in bins of τ

    ⟶ average over a range of metallicities for each bin of τ(H I)
  - problem due to the different velocity widths ($\propto A^{-0.5}$) in the metal ion and H I

(Cowie & Songaila 1998)

- Correlation between lines of a metal doublet (C IV)
  - avoids the problem of different velocity widths
  - yields the contribution of a given metal to the cosmic density

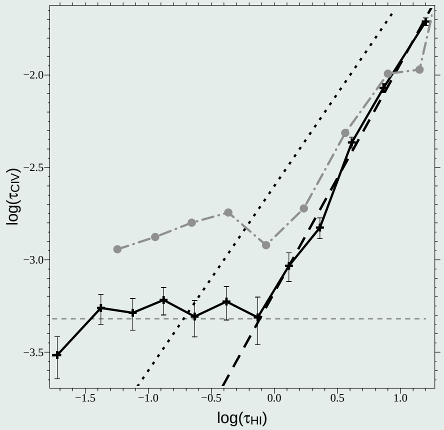
(Songaila 2005)

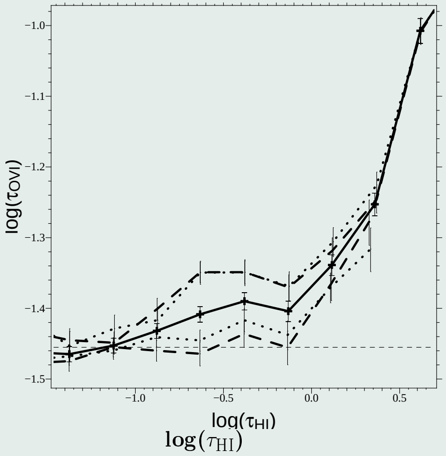
POD : UVES-LP Results - $\langle z \rangle \sim 2.5$

- $\log \tau_{\mathrm{CIV}} = 1.3 \times \log \tau_{\mathrm{HI}} - 3.2$
  previous results: (1) gray line
  (2) dotted line $\log(\mathrm{C\,IV}/\mathrm{H\,I}) = -2.6$

  (Aracil et al. 2004)

- $\log(\mathrm{O\,VI}/\mathrm{H\,I}) \sim -2.0$
  weak O VI absorption is only detected close ($|\Delta v| \leq 400$ km s^{-1}) to strong Ly-α absorption (τ(Lyα >4)



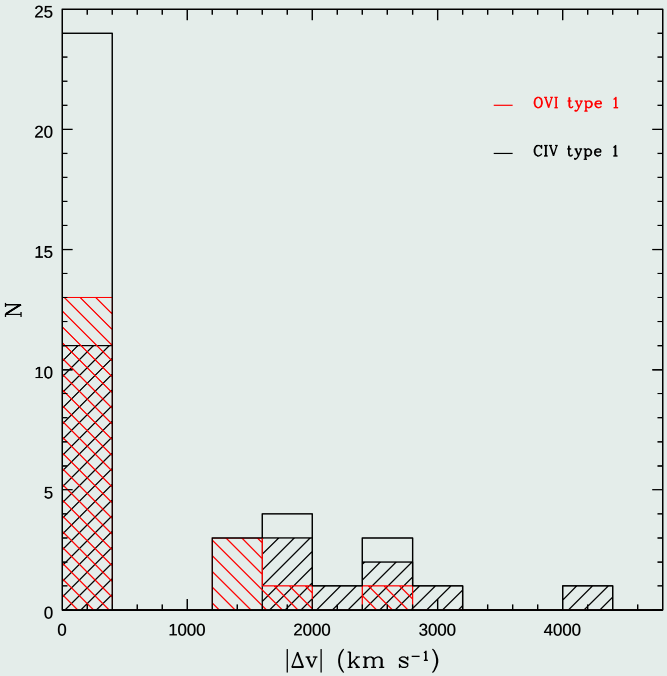


Type 1 population : Nearest strong H I absorber

- The O VI type 1 population and weak O VI absorptions should exhibit similar properties
  overlapping N(H I) range

- Δv between type 1 systems and the nearest strong H I absorption
  - 2/3 of O VI & C IV-only metal-rich systems have a strong Ly-α system, τ(Ly-α) > 4, at $|\Delta v| <$ 400 km s^{-1}

- Study of individual O VI systems and POD analysis both suggest a **link to gas outflows from overdense regions**



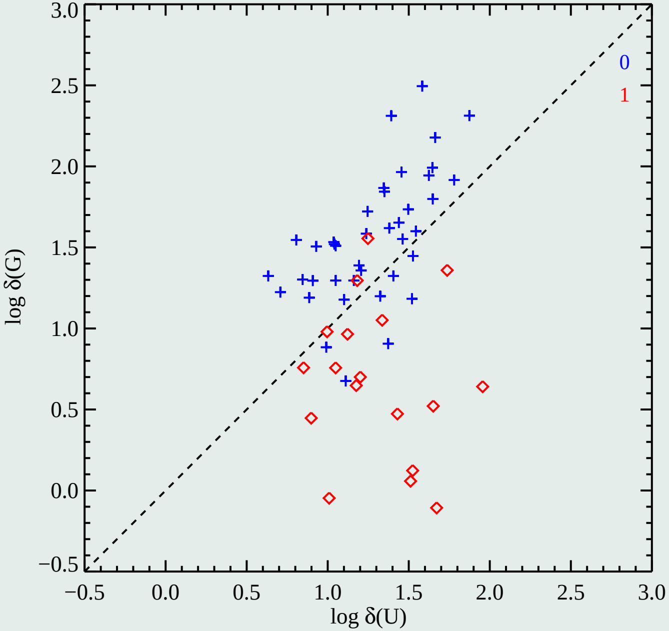
Gas density of O VI absorbers
Further evidence for two O VI populations

- **Gas overdensity of the O VI absorbers,** $\boldsymbol{\delta \equiv (\rho/\overline{\rho})}$ **: assumptions**
  - photoionization : hard UV metagalactic flux → gas density vs ionization parameter
    or
  - hydrostatic equilibrium (+ photoionization) → gas density vs N(H I)
    (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**
  - $t(dyn) \sim t(sound\ crossing\ time) \rightarrow \mathbf{N(H)} \sim \boldsymbol{n_{\mathrm{H}} L_{\mathrm{Jeans}}}$
    to derive N(H I): assumptions on T_{gas} ($\sim 4 \times 10^4$ K) and photoionization rate
  - $\boldsymbol{\delta(G) = 4.7 \times 10^{-9}\ \ \mathrm{N(H\,I)}^{2/3}([1+z]/3)^{-3}}$

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

- Type 0 absorbers
  $\delta(G)$ and $\delta(U)$ are correlated
  with $\delta(G)$ somewhat larger than $\delta(U)$
  - Type 0 absorbers probe the IGM
    hydrostatic equilibrium is roughly valid

- Type 1 absorbers
  $\delta(G)$ and $\delta(U)$ 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



Ω_b(O VI) and O VI column density distribution

- **Ω_b(O VI) : (O VI) cosmic density**
  - $\Omega_b(\mathrm{O\,VI}) = \{H_0 m_O / c\rho_{crit}\}\{\sum N(\mathrm{O\,VI}) / \sum_i \Delta X_i\}$

    $= 2.2 \times 10^{-22}\{\sum N(\mathrm{O\,VI}) / \sum_i \Delta X_i\}$

    m_O: oxygen atomic mass, ρ_{crit}: critical density, $\sum_i \Delta X_i$: total redshift path

    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

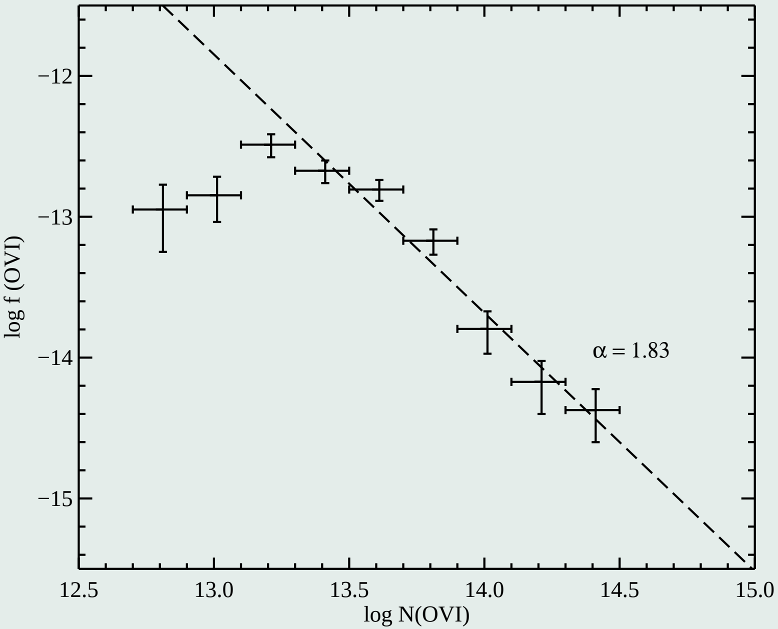
    (i) incompleteness correction factor for Ω_b(O VI) , $\Omega_b \propto \int N f(N) dN$

    (ii) number of O VI absorbers per unit redshift, $dn/dz \propto \int f(N) dN$

Column density distribution of O VI absorbers

- Sample for 12 sightlines
  $\sum_i \Delta X_i = 12.12$
  - power law fit : $\boldsymbol{f(N) = KN^{-\alpha}}$
    $\boldsymbol{\rightarrow \alpha(\mathrm{O\,VI}) = 1.83 \pm 0.15}$
    $\boldsymbol{f(N{=}10^{13.5}){=}1.7 \times 10^{-13}}$
  - log N(O VI)<13: incompleteness
  - log N(O VI)>14.5: sample variance

(Bergeron & Herbert-Fort 2006)



- Comparison with $f(N)$(C IV)
  - **O VI and C IV distributions** have **similar slopes**, but $\boldsymbol{f(N(\mathrm{O\,VI}))/f(N(\mathrm{C\,IV}))}{\sim}\boldsymbol{6}$ at log N $= 13.5$

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

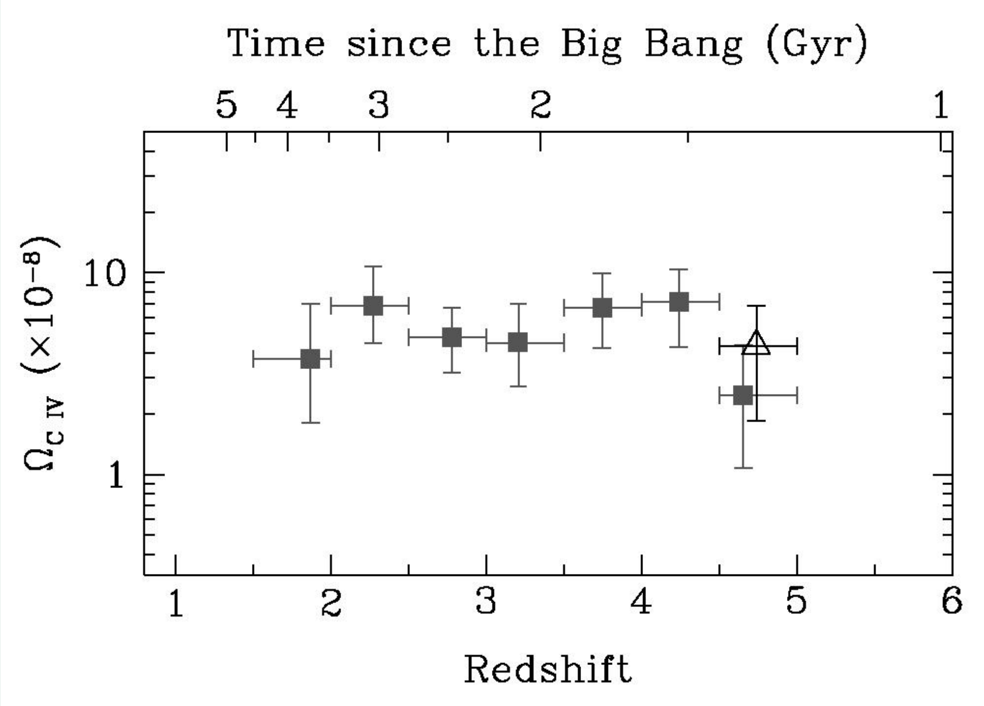
O VI absorbers : corrected Ω_b

- Ω_b(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 restricting the integration range to 13.0< log (N(O VI)) < 15.0

    yields : $\Omega_b(\mathrm{O\,VI}) \approx (2.2 \pm 0.2) \times 10^{-7}$
    i.e. an incompleteness correction factor of 1.5 at $\overline{z}$=2.2
- Ω_b(O)
  - using a conservative ionization correction factor, (O VI/O) = 0.15, yields
    $\Omega_b(\mathrm{O}) = 1.5 \times 10^{-6}$ or
    $\log\ (\Omega_b(\mathrm{O})/\Omega_b(\mathrm{O})_\odot) \equiv \langle[\mathrm{O/H}]\rangle = -2.4$
    with the solar abundances of Anders & Grevesse (1989)
- **The above value of Ω_b(O) is a lower limit, as we have to include broad 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)

C IV and O I at $z \sim$5-6

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



- O I absorbers ($10^{13.7} <$ N(O I) $< 10^{15.0}$ cm^{-2}) recently detected at $z \sim$6 (optical)
Ω_b(O I) $\sim 7 \times 10^{-8}$ at $z \sim 6.0$ i.e. 1/3 of Ω_b(O VI) at $z \sim 2.5$

(Songaila 2001, Pettini et al. 2003, Becker et al. 2005)

IGM metal enrichment

summary current status

- Metallicity at $z \sim$ 2-5 : assuming a metal production of 1/30 solar
  - O VI individual systems : distinguish metal-rich/metal-poor systems whatever N(H I)
    - $\langle[\mathbf{O/H}]\rangle = \mathbf{-2.4}$ at $z \sim 2.5$
      for $10^{13} <$ N(O VI) $< 10^{15}$ cm^{-2} (assuming $\langle$(O VI/O)$\rangle = 0.15$)
  - C IV individual systems
    - $\langle[\mathbf{C/H}]\rangle = \mathbf{-2.9}$ 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 : H I + C IV
    signal down to log τ(C IV)$\simeq -3.0$ → $\langle$N(C IV)$\rangle \sim 10^{10.3}$ cm^{-2}
    - $\langle[\mathbf{C/H}]\rangle = \mathbf{-2.8}$ with some ↘ of [C/H] with ↘ δ $(10^{-0.5} < \delta < 10^{2})$
  - **No clear evidence for cosmic evolution of $\Omega_{\rm b}$(C IV) for $2 < z < 5$**
    → early metal enrichment

(Songaila 2001 & 2005, Pettini et al. 2003, Schaye et al. 2003, Aracil et al. 2004, Bergeron & Herbert-Fort 2005)

Probing IGM metal enrichment with ELTs

- Where are the missing metals at $z \sim$ 2-5?
  - A hot phase traced by O VII-O VIII : possibly detectable with future X-ray satellites
  - The lower density IGM, $\boldsymbol{\delta \sim 1}$: detectable with future ELTs
    - [Z/H] : hydrodynamic simulations with/without galactic superwinds

      $\rightarrow$ 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 of 100 in the detection limit of individual C IV doublets

- Metal forest at $z \sim$ 7-15
  - IGM absorption signatures: C IV C II O I Si II

    detectable in the NIR for $z <$ 12.5 14.7 15.1 15.7 $(\lambda < 2.1\mu)$
    - *column densities*
    - *clustering*
  - O I absorbers at $z \sim \mathbf{6}$ detected in QSOs and one GRB (+ C II, Si II)

    (Becker et al. 2005, Kawai et al. 2005)

Background sources/1

- GRBs and population III SNe
  - GRBS : mean afterglow fluxes 1.5 to 0.05 μJy at $z \sim 10$
    1 to 10 days after explosion (K$_{\mathbf{AB}}$ 23.6 to 27)
    brightest afterglow : 20 × mean fluxes
    GRB050904: $z = 6.3$, J$_{\mathbf{AB}} \simeq$ 20 1 day lag ($z_{\mathbf{sp}}$: Subaru 3.4 day lag)
  - population III SNe (pair instability - M = 140-260 M$_\odot$) : K$_{\mathbf{AB}} \sim$ 25 at $z \sim$ 10-15
    with possible time lag of weeks between discovery and ELT spectroscopy

- Detection limits : 4σ limit for R$=10^4$ & S/N=50
  - N(C II)$_{\mathbf{min}} \simeq \mathbf{4} \times \mathbf{10^{12}}$ cm^{-2} and N(O I)$_{\mathbf{min}} \simeq \mathbf{1} \times \mathbf{10^{13}}$ cm^{-2}
    → metal-enriched sites only
  - *clustering signatures down to* 30 km s^{-1}
  - **for the brightest GBRs** (R$=4 \times 10^4$ & higher S/N)
    → factor 4-10 lower column densities
    plus velocity scale and temperature estimate

GRBs and population III SNe

type	z	$\lambda_{\rm obs}$	m$_{\rm AB}$/flux(nJy)	R	lag(day)	S/N	Δt(hr)	S/N	Δt(hr)
						100m		30m	
average GRB	10	K	23.6/1500[†]	10^4	1	40	1.8	15	15
average GRB	10	K	27.4/40	10^4	10	15	90	-	-

[†] **brigthest GRBs : 20 times brighter & similar fluxes after 10 days**

type	z	$\lambda_{\rm obs}$	m$_{\rm AB}$/flux(nJy)	R	S/N	Δt(hr)	R	S/N	Δt(hr)
					100m			30m	
pop III SNe	9	J	24.4/650	10^4	40	1.7	2000	40	8
pop III SNe	12	H	24.8/440	10^4	40	4.0	2000	40	50
pop III SNe	16	K	25.2/300	10^4	40	14	2000	20	70

Time lag discovery → ELT follow-up : weeks

Background sources/2

- QSOs
  - massive BH at $z \sim 10$?
    - $z \sim 6$ QSOs : BH masses $\sim$ (1-3)$\times 10^9$ M$_\odot$ for L = L$_{\rm Edd}$
      progenitors: BH growth : *Eddington rate and accretion efficiency = 0.15*
    → **M = (1-3)×10^6 M$_\odot$ at z = 10** → **10^3 M$_\odot$ progenitor at z = 20-30**
  - merging of thousands of 10^3 M$_\odot$ BHs ?
  - *primordial BH ?*
  - number density - main problem : search strategy of *very rare objects*
    results of current NIR searches will help (e.g. UKIDSS)
  - **M$_{\rm BH}$ > *a few* 10^5 M$_\odot$** → J$_{\rm AB}$/K$_{\rm AB}$ < 29/28
- Detection limits : 4σ for R=2000 & S/N=50
  - **N(O I)$_{\rm min}$ $\simeq 5 \times 10^{13}$ cm^{-2}**
    → sub-DLAs from metal-enriched sites
  - *clustering signatures down to* 150 km s^{-1}

QSOs

type	z	$\lambda_{\rm obs}$	R	$m_{\rm AB}$/flux(nJy)	S/N	Δt(hr)	$m_{\rm AB}$/flux(nJy)	S/N	Δt(hr)
					100m			30m	
QSO	9	J	2000	27.4/40[†]	40	1.7	26.2/120[‡]	40	8
QSO	12	H	2000	27.8/27[†]	40	4.0	26.6/80[‡]	40	50
QSO	16	K	2000	28.2/18[†]	40	14	27.0/55[‡]	20	70

[‡] $$\begin{aligned} \nu_{rest} \times L_{\nu_{rest}} &= 3 \times 10^{44}\ \mathrm{erg\ s^{-1}\ at}\ \lambda_{\rm rest} = 1300\text{Å} \\ &\sim 30\ \nu_{rest} \times L_{\nu_{rest}}\ (10^{8}\mathrm{M}_\odot\ \text{galaxy at same}\ z) \\ &\sim 10^{-2.5}\ \nu_{rest} \times L_{\nu_{rest}}\ (z = 6\ \text{SDSS QSO}) \end{aligned}$$

- Minimum $\mathrm{M_{bh}}$

$R = 2000$, S/N=20, $\Delta t = 50$ hr with a 100m telescope

$z = 9$: $\mathrm{J_{AB}}$=29.1/8.3nJy & Eddington limit ⟶ $\mathrm{M_{bh}} = 1.5 \times 10^{5}\mathrm{M}_\odot$
$z = 12$: $\mathrm{H_{AB}}$=28.2/19nJy & Eddington limit ⟶ $\mathrm{M_{bh}} = 5.0 \times 10^{5}\mathrm{M}_\odot$
$z = 16$: $\mathrm{K_{AB}}$=27.6/33nJy & Eddington limit ⟶ $\mathrm{M_{bh}} = 1.3 \times 10^{6}\mathrm{M}_\odot$

Probing the dark ages

- One of the 5 SKA Key science projects (observations of the redshifted H I 21 cm line)
  together with - Origin and evolution of Cosmic Magnetism
  - Galaxy evolution, cosmology and dark energy

- Reionization
  - whole sky 21 cm absorption/emission
    first sources of Lyα radiation and heating of the gas
  - 21 cm discrete absorptions from start of reionization to nearly complete reionization
    spectra of very powerful background radio sources

- Structure formation
  - maps of neutral gas
    through multifrequency observations
  - growth of structures
    fluctuations of 21 cm brigthness temperature

- Simulations : HORIZON project with participation to DEISA "extreme computing initiative"

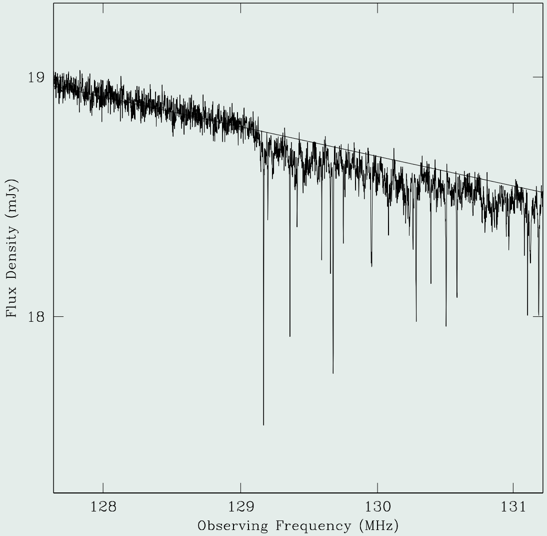
Simulated 21 cm absorption spectrum

- **intervening H I absorption**

  Highly luminous background souce at z=10 with S(120 MHz)=20 mJy

  (Carilli et al. 2002, Haiman et al. 2004)

  - very few sources
    expected at $z > 8$ & S > 10 mJy :
    $\mathbf{10^{-2}}$ deg^{-2} (M$_{\mathbf{BH}}$ > $\mathbf{10^7}$ M$_\odot$)
    GRB radio afterglows : too faint
    possibly hypernovae : flux up to 1 mJy?
  - metallicity
    coupling O I/ELT to H I/SKA absorptions
    for discrete strong absorbers

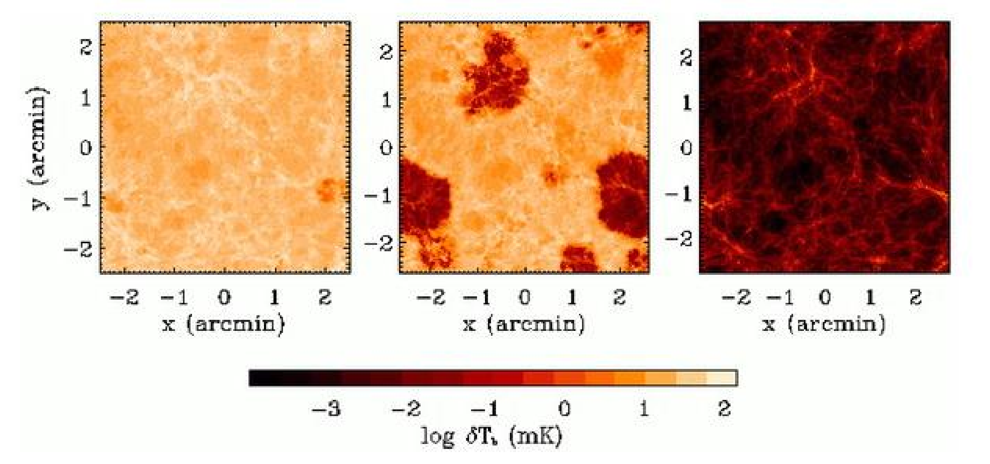


- SKA observations of powerful radio galaxies

  10 days, resolution : $\Delta\nu = 1$ kHz

H I 21 cm brigthness fluctuations

- Maps of 21 cm brigthness temperature (5×5 arcmin^2) at $z =$ 12.1, 9.2 and 7.6 (left to right) with a width $10h^{-1}$ comoving Mpc and depth $\Delta\nu =$ 0.1 MHz
  assuming a late, single epoch of reionization and $T_S \gg T_{CMB}$
  HII regions have negative brigthness temperatures relative to ⟨H I signal⟩
  ⟶ information on the the sources responsible for reionization



(Furlanetto et al. 2004, Zaldarigga et al. 2004)

Angular power spectrum of 21 cm fluctuations

- **Predicted power spectrum**

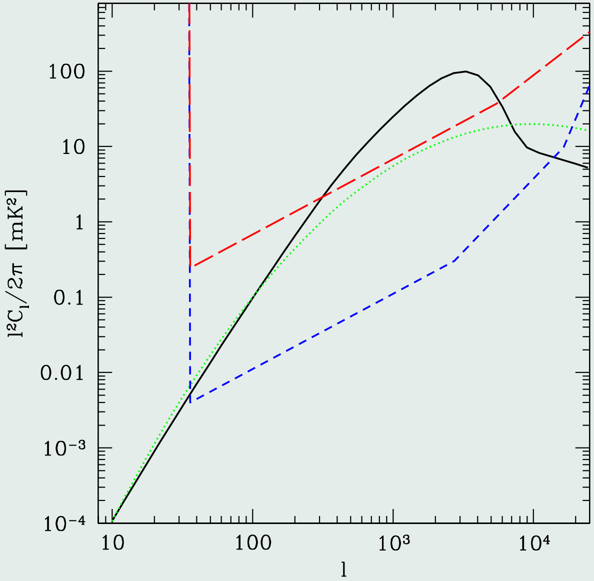
  during reionization at z=10
  peak at a few arcmin (black curve)

  fully neutral medium (dotted curve)

- SKA sensitivity (short dash line)

- LOFAR sensitivity (long dash line)

  (Furlanetto & Briggs 2004, Zaldarriaga et al. 2004)



Conclusions

- **IGM metal enrichment**
  - highly inhomogeneous
  - O VI absorbers
    - bimodal distribution of [O/H] at $\langle z \rangle \sim$ 2-2.5 : IGM proper & metal-enriched sites ($\langle$[O/H]$\rangle \simeq -0.35$) (progenitors of galaxy clusters)
    - photoionization : dominant process
    - large fraction of τ(H I)< 1 O VI absorbers trace metal-rich sites
    - Can the IGM proper be enriched by superwinds?

→ probing [Z/H] in $\delta \leq 1$ regions at $z \sim 3$ (C IV) with ELTs

- **Metal cosmic density**
  - O VI populations : ∼15% of metals expected from SF activity
    2.5 times higher than derived for Carbon (C IV)
  - in LBGs + DLAs : ∼10% of expected metals

→ missing metals : probing a hotter phase ($T > 3 \times 10^5$ K) with XEUS, Constellation X

Prospectives

- **IGM metallicity at $z \gtrsim 7$**
  - search for O I and C II in the NIR (high N(H I)) → ELTs
  - search for H I 21 cm absorption (close to the onset of reionization) → SKA
  - clustering of absorbers : low vs high mass star/galaxy formation sites?

- **Search for very rare, bright sources at the reionization epoch**
  - GRBs, pop III SNe : dedicated space- and ground-based telescopes
  - QSOs, bright galaxies - few deg^2 surveys → 8-10 m telescopes, JWST, ELTs
  - radio sources - few 10^2 deg^2 surveys → LOFAR, SKA

- **Simulations of galaxy and structure formation**