Ground-based optical/IR observations with ELTs

Cosmology science case

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Open Questions in Cosmology: the First Billion Years
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Open questions

- Reionization epoch from $z \sim$ 15-20 to $z \sim 6$
  slow/continuous reionization vs 2 re-ionization epochs
  - Growth of black-holes (BHs) and galaxy mass assembly: *large masses at $z \sim 10$?*
    short available time:
    $\Delta t(6 < z < 10) = 4.5 \times 10^8$ yr
    $\Delta t(10 < z < 20) = 2.9 \times 10^8$ yr $\quad (\Omega_\Lambda, \Omega_\mathrm{m}, h = 0.7, 0.3, 70)$
  - Explosive events: Gamma-Ray Bursts (GRBs) and population III supernovae
    search strategy: dedicated space- and ground-based telescopes

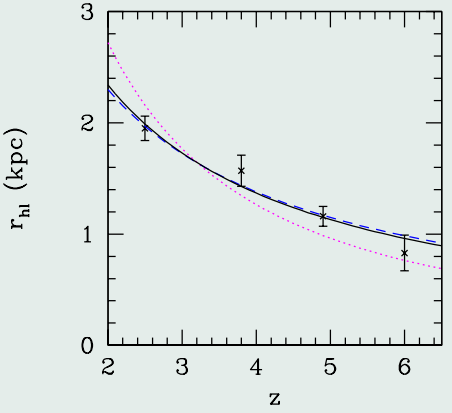
- Metal enrichment of the IGM
  - early metal enrichment at $z \sim$ 7-15: metal forest
    number of bright sources for medium resolution IR spectroscopy?
  - Metallicity of low density regions ($\delta \equiv (\rho/\overline{\rho}) \sim 1$) at $z \sim$ 3-5
    Extremely high S/N, high resolution optical spectroscopy

Galaxies: number and sizes

- Current surveys of $z \sim 6$-10 confirmed/candidate galaxies
  - n (arcmin^{-2}) $\sim$ few hundredths to 1 (few tenths at $z \sim 7$-8)
    down to AB=28.5 (15 nJy): limit for spectroscopy with 100m ELT (R=2000)

  (Bouwens et al. 2004, Shimasaku et al. 2005)

- Observed/predicted sizes of high z galaxies
  - mean half-light radius
    $r_{hl} \propto (1+z)^{-1.05}$
    (Bouwens et al. 2004)
  - angular sizes
    $r_{hl}(z=6) \simeq 1.0$ kpc $= 170$ mas
    $\mathbf{r_{hl}(z=10)} \simeq 0.6$ kpc $= 150$ mas
  - sizes $\gg$ ELT resolution:
    2/7 mas for 100/30 m ELTs



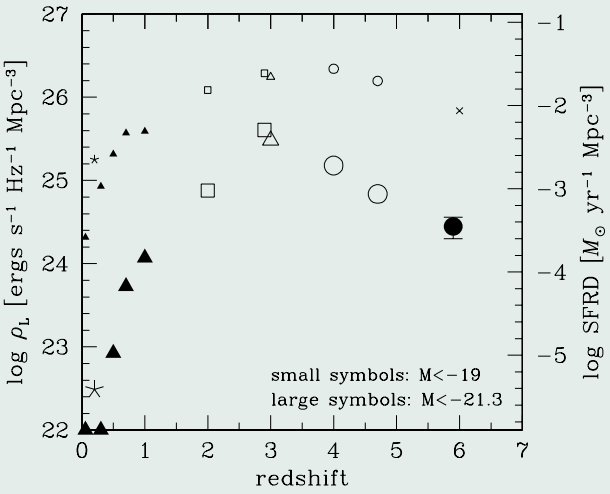
Detection limits

tel	JWST	30m	100m
Imaging	point source,	diffraction limit,	S/N $\sim$ 7, Δt = 1hr
mag	$J_{AB} \sim K_{AB} \sim 29$	$J_{AB} \sim 29$	$J_{AB} \sim 31.5$, $K_{AB} \sim 30$
FoV	$2.2' \times 4.4'$	$\Phi \sim 2'$ (AO/2μ)	$\Phi \sim 2'$ (AO/2μ)
Res (mas)	35	7	2.1
• Spectroscopy	extended source, R $\sim$ 100, 100 mas	R $\sim$ 2000, 25 mas	S/N $\sim$ 20, Δt = 50 hr R $\sim$ 2000, 25 mas
mag	AB(2.6 μ) $\sim$ 27	$J_{AB} - 1 \sim K_{AB} \sim 26.7$	$J_{AB} - 1 \sim K_{AB} \sim 28.0$
• Spectroscopy R$\sim 10^4$	point source,	diffraction limit,	S/N $\sim$ 50, Δt = 100 hr
mag		$R_{AB} \sim 25.5$	$R_{AB} \sim 28.5$, $K_{AB} \sim 26.0$

m_{AB}=29 $\longrightarrow$ f=10 nJy

FUV luminosity density at $z \sim 6$

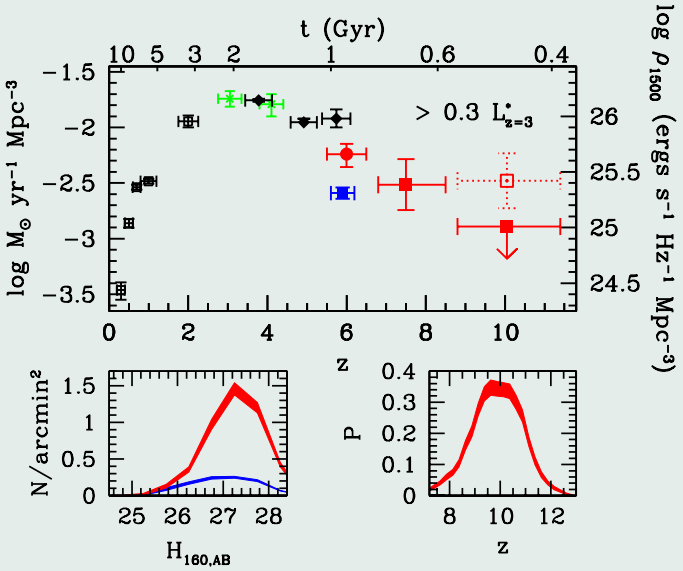
- "Large" area surveys of bright LBGs (Subaru tel.)
  - n $\simeq 1.5 \times 10^{-2}$ arcmin^{-2} down to $z_{884} = 26.2$ ($\sim$ 100 nJy)
- Deeper, small area surveys of faint LBGs (HST)
  - n $\simeq 1.4$ arcmin^{-2} down to $z_{850} = 28.5$



- ρ_L: observed FUV luminosity density
  - $\searrow$ by $\sim$10 for $z \sim 3 \longrightarrow 6$ for M < -21.3 or SFR $= 18$ M$_\odot$ yr^{-1}
  - fainter LBGs (M < -19) shallower $\searrow$
  - contribution to the SFR at $z \sim 6$ $\nearrow$ by 25 from M < -21.3 to < -19

(Bouwens et al. 2004, Dickinson et al. 2004, Shimasaku et al. 2005, Stanway et al. 2005)

Galaxies at $z \sim$ 7-10



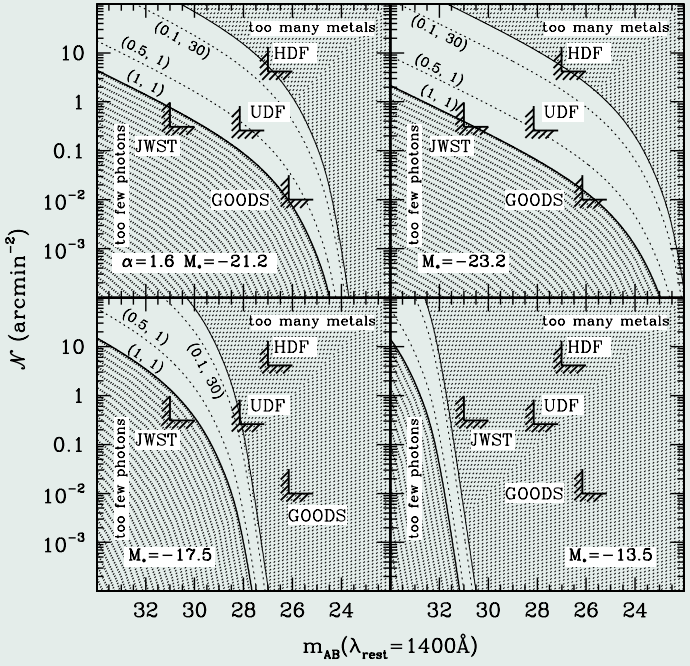
- Searches for high z galaxies
  - a few secure candidates at $z \sim$ 7-8
    down to $H_{1.6\mu} \sim 28$ (HST)
    5 with $H_{1.6\mu} \sim 27$, highly clustered
  - no secure candidates at $z \sim 10$
    down to $H_{1.6\mu} \sim$ 28-28.5 (HST)
  - SFR: strong $\searrow$ for $z \sim 6 \longrightarrow 10$
    for $L > 0.3\ L_{\star,z=3}$

(Bouwens et al. 2004, 2005)

- Searches for high z lensed galaxies
  - a few secure candidates at $z \sim$ 7-8
    for $J_{1.6\mu} \sim$ 24-25 (HST)
  - one infirmed candidate at $z \sim 10$
    $H_{1.6\mu} \sim 25$ (HST)

(Hu et al. 2002, Egami et al. 2005, Kneib et al. 2004, Pello et al. 2004)

Predicted surface density of high z galaxies



- Reionization sources
  - end reionization $z_f = 6$ & $\Delta z = 1$
    - minimum surface density *depends mainly of* Δz *not* z_f

    LF: various $M_{\star,1400}$ & $\alpha = -1.6$

    $M_{\star,1400} = -21.2$ at $z \sim$ 3-4

    [Stiavelli et al. 2004 - parameters: escape fraction (f), IGM clumpiness factor (C)]

- Predicted number density at $m_{AB} \sim 29$

  $z > 6$, f=0.5, C=1
  - $M_{\star,1400}$=−21.2: ∼1 source arcmin^{-2}
  - $M_{\star,1400}$=−17.3: ∼0.2 source arcmin^{-2}

Future searches/studies of high z galaxies

- High number density (surveys of 1 deg^2 scale), and sizes $\sim$ 150 mas
  - JWST - NIRCam: R=35 mas ($\sim$ 1px at $\lambda < 2.3\ \mu$), $m_{AB,NIR} \sim 29$
    - 1 month canpaign
  - ELTs
    - sensibilities *similar* (30 m) or *higher* (100 m) than JWST
    - too high spatial resolution $\longrightarrow$ **increase px scale** (camera: small focal ratio)

- LF: Evolution of $L_\star$
  - little evolution between $z = 3$ and 5
    - $M_{\star,1400} = -21.2$ gal at $z \sim 10 \longrightarrow J_{AB} \sim 27.3$

- strong clustering $\longrightarrow$ observations of many fields

ELT requirements for studying high z galaxies

- Searches
  - JWST
    - imaging ($m_{AB} \sim 29$)
      low Res spectroscopy ($m_{AB} \sim 27$) : z *estimate*
  - ELTs
    - imaging - large FoV (a few arcmin^2 with moderate AO correction) and large px scale (25 mas) ($J_{AB} \sim$ 29-31 for 30-100 m ELTs)

- Intermediate resolution spectroscopy
  - metals, kinematics
  - NIR, R=2000, S/N up to 100, optimal with OH suppressor
    - multiple IFUs over a total FoV of several arcmin^2
    - $M_{\star,1400} = -21.2$ gal at $z \sim 10$ ($J_{AB} \sim 27.3$) observable with 30-100 m ELTs
      fainter objects observable with $> 50m$ *ELTs*

High z QSOs

- SDSS $z \sim 6$ QSOs
  - survey limit $z_{AB} < 20.2$ complete sample down to $z_{AB} \sim 19.9$ or $M_{1450} = -26.4$
    $n \simeq 2.0 \times 10^{-3}$ deg^{-2}
  - only preliminary results from a survey twice as deep
  - BH masses $\sim$ (1-3)$\times 10^9$ $M_\odot$
    * BH growth : *Eddington rate and accretion efficiency = 0.15*
      the SDSS $z \sim 6$ BHs (assuming $L = L_{Edd}$) have
      $\longrightarrow$ $M = (1\text{-}3) \times 10^6$ $M_\odot$ at $z = 10$
- SDSS $z \sim 5$ QSOs
  - number density $\nearrow$ by 3 for $\searrow$ in flux of 2 (same at $z \sim 4$)
    extrapolation to fainter sources : LF not known
- QSOs vs LBGs
  - at $z \sim 2$, 3 & 4, fraction of QSOs among the selected LBG candidates = 3%
    * $\longrightarrow \sim 1$ QSO deg^{-2} at $z \sim 6$ down to $z_{884} = 26.2$
      from the Subaru bright LBG survey

QSOs, GRBs and population III SNe at the reionization epoch

- $z \sim$ 7-15 QSOs
  - massive BH at $z \sim 10$?
    - at least the progenitors of SDSS $z \sim 6$ QSOs : a few $\mathbf{10^6}$ $M_\odot$
  - merging of thousands of $\mathbf{10^3}$ $M_\odot$ BHs ?
  - *primordial BH ?*
  - number density ?
    - main problem : search strategy of *very rare* objects
      results of current NIR searches will help (e.g. UKIDSS)
  - spectroscopy (R=2000) : $J_{AB}/K_{AB} < 29/28$ targets $\longrightarrow$ $M_{BH} > \boldsymbol{a few\ 10^5}$ $M_\odot$

- GRBs and population III SNe : **bright sources**
  - GRBS : mean afterglow fluxes 1.5 to 0.05 μJy at $z \sim 10$
    1 to 10 days after explosion (K_{AB} 23.6 to 27)
  - population III SNe (pair instability - M = 140-260 $M_\odot$) : $K_{AB} \sim 25$ at $z \sim$ 10-15
    with possible time lag of weeks between discovery and ELT spectroscopy

IGM metal enrichment

- Metallicity at $z \sim$ 3-5 - current status
  - search for individual systems : N(C IV) $> 10^{11.5}$ cm^{-2}
  - *pixel optical depth method* : statistics of H I and C IV optical depths
    * at $\langle z \rangle \sim 2.5$ signal down to $\tau_{\rm HI} \simeq 1$ or N(H I) $= 10^{13.6}\ b_{30}$ cm $^{-2}$
    with $\langle$N(C IV)$\rangle = 10^{9.3}\ b_8$ cm $^{-2}$ *(contribution of a few higher [Z/H] systems?)*

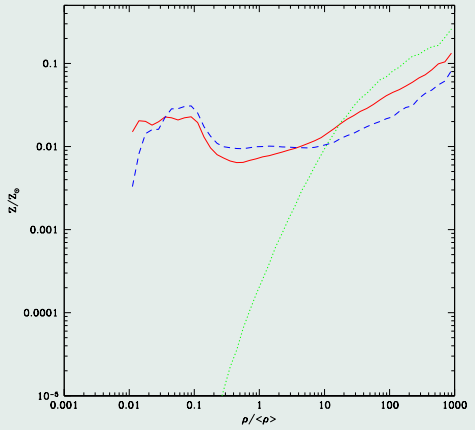
    (Aracil et al. 2004)
- Metallicity at $z \sim$ 3-5 down to $\delta \equiv (\rho/\overline{\rho}) \sim 1$
  - N(C IV) $\sim$ a few 10^9 cm^{-2} : assuming
    * N(H I) vs number density : *hydrostatic equilibrium* case (Schaye 2001)
    * *photoionization* by the UV metagalatic flux (Haardt & Madau 2001)
    * Z/H $= 10^{-3.5}$ solar
  - detecting such small C IV columns densities $\longrightarrow$ huge S/N of 10^4
    when using bright QSO (high spectral resolution) and $\langle$tens of systems$\rangle$

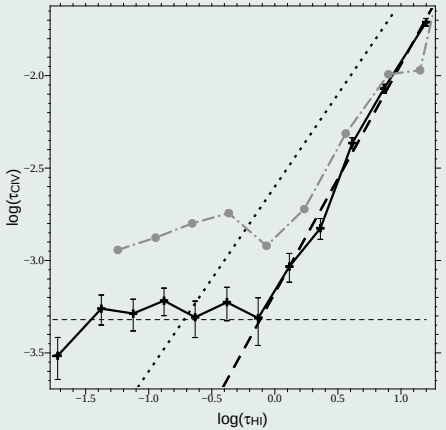
    (The science case for the european ELT 2005)
  - test case for models with galactic winds : predict higher metal enrichment :
    abundances up to 10^{-2} solar at $\delta \sim 1$

    (Cen et al. 2004)

Metal enrichment - predictions vs observations

- Λ CDM hydrodynamic simulations with injected energy in the IGM
  $\longrightarrow$ stimulating galactic winds
  Cen et al. 2004 : with galactic winds (red and blue curves) and without (green curve)
- Metallicity from the optical depth method - $\log \tau_{\rm CIV} = 1.3 \times \log \tau_{\rm HI} - 3.2$
  Aracil et al. 2004 : dotted line $\log {\rm C\,IV/H\,I} = -2.6$





IGM early metal enrichment

- Metal forest at $z \sim$ 7-15
  - IGM absorption signatures: C IV, C II, O I Si II
    detectable in the NIR for $z \leq$ 12.5, 14.7, 15.1, 15.7 $(\lambda < 2.1\mu)$
    * *column densities*
    * *clustering*
  - detection limits: GRBs and population III SNe
    * 4σ limit for R=10^4 & S/N=50:
      $N(C\,II)_{min} \simeq 4 \times 10^{12}$ cm^{-2} and $N(O\,I)_{min} \simeq 1 \times 10^{13}$ cm^{-2}
      $\longrightarrow$ metal enriched sites
    * *clustering signatures down to* 30 km s^{-1}
    * for the brightest GBRs (R=4×10^4 & higher S/N):
      $\longrightarrow$ factor 4-10 lower column densities and velocity scale + temperature estimate
  - QSOs: for$M_{BH} > 10^5$-10^6 $M_\odot$ (R=2000 & S/N=50)
    * column density limits 5 times higher than above
    * *clustering signatures down to* 150 km s^{-1}

ELT requirements for studying the IGM

- Searches for sources with other telescopes
  - JWST
  - *dedicated* ground- and space- base telescopes (rare faint sources & transient objects)
- Intermediate/high resolution spectroscopy
  - NIR, R=2000, S/N up to 100 (CCDs), optimal with OH suppressor
    multiple IFUs over a total FoV of several arcmin^2
    - QSOs + the brigther LBGs at $z > 7$ ($m_{AB} \sim$ 27-28)
    - *brightest sources only observable with 30 m ELTs*
  - NIR, R=10000, S/N up to 100 (CCDs): single target
    - ⟨luminosity⟩ GRBs + population III SNe at $z > 7$ ($m_{AB} \sim 25$)
- Very high resolution spectroscopy: single target
  - optical & NIR, R=40000, S/N=1000 up to 10000 $\longrightarrow$ photon counting detectors
    - brightest GRBs (S/N=100) at $z > 7$ (lag=1 day, $m_{AB} \sim 20$)
      and bright QSOs at $z \sim$ 3-5 ($m_{AB} \sim$ 16-17)
    - *80-100m ELTs*

Conclusions and challenges

Reionization : galaxies vs BHs

- Models : LF at $z \sim 6$
  $\longrightarrow$ test : on-going "large" area, deep surveys (e.g. CFHTLS, Subaru)
- Models : SFR & mass range ($> 10^5$ $M_\odot$) at $z \sim 10$
  - Observations - census : JWST + ELTs
    - physical properties : ELTs mandatory *(multiple IFU spectrograph)*
    $\longrightarrow$ challenges : dedicated large px scale camera
    QSO (galaxies) surveys : tens of deg^2 (several deg^2)

metal enrichment of the IGM

- Simulations : importance of galactic winds at high z
  pollution of $\delta \sim 1$ regions
  - Observations : dedicated searches/telescopes for transient sources
    $\longrightarrow$ challenges : reaction times of days (GRBs), weeks (pop III SNe)
    extremely high Res spectrograph (opt-NIR) - ELTs mandatory