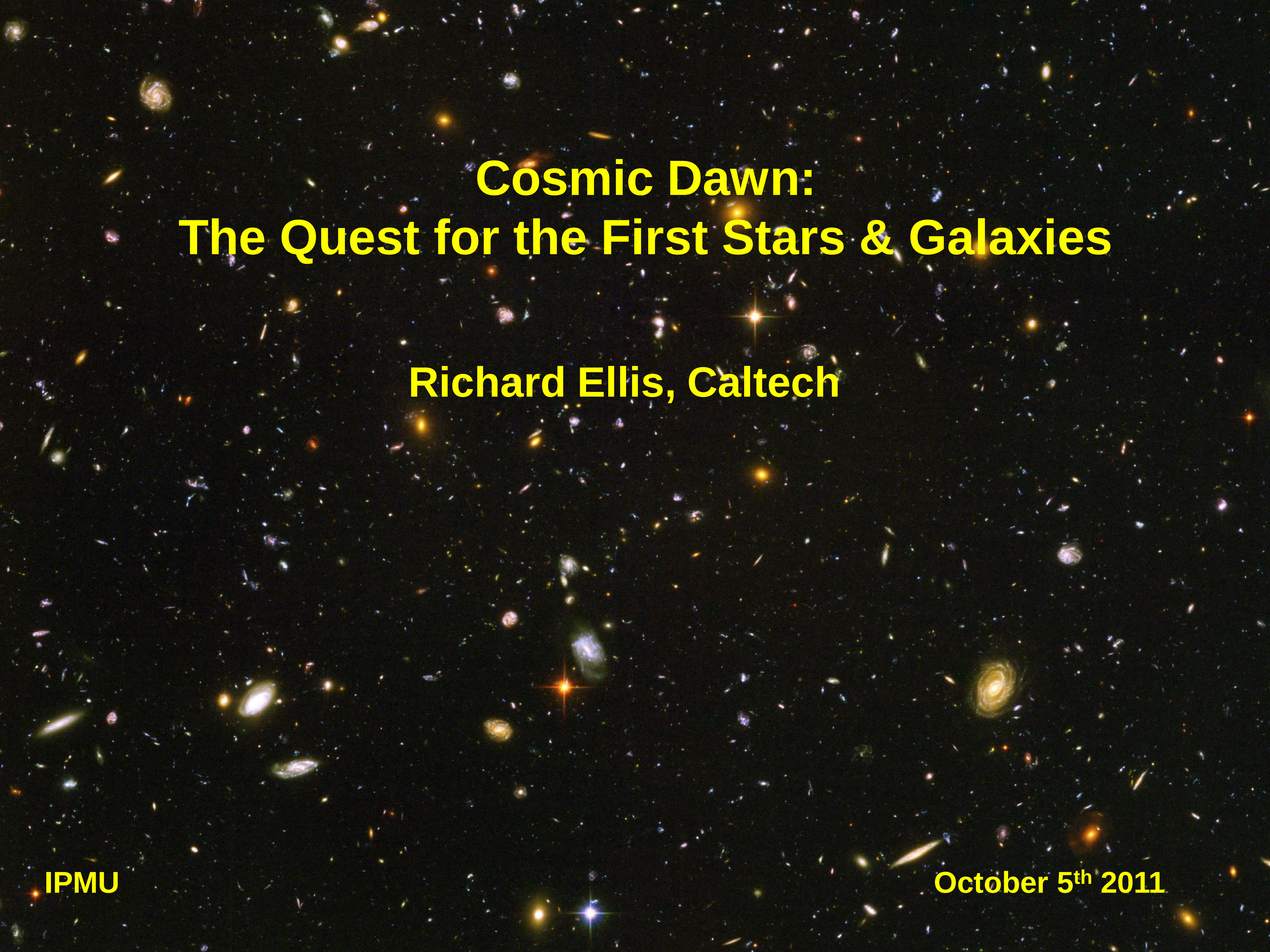


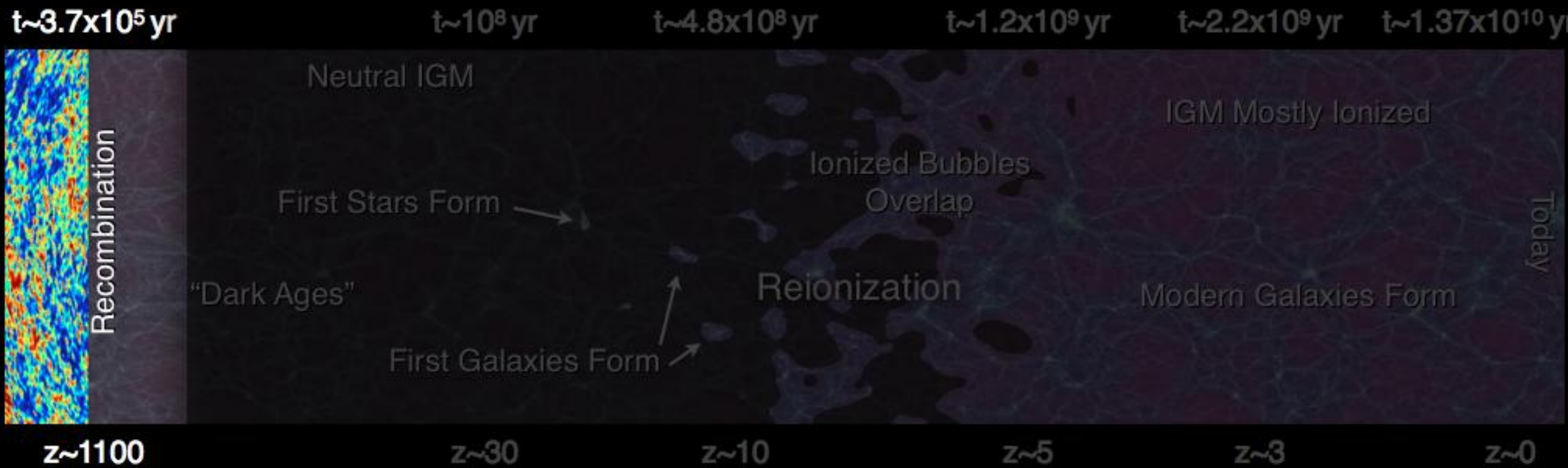
Cosmic Dawn:
The Quest for the First Stars & Galaxies

Richard Ellis, Caltech

IPMU

October 5th 2011

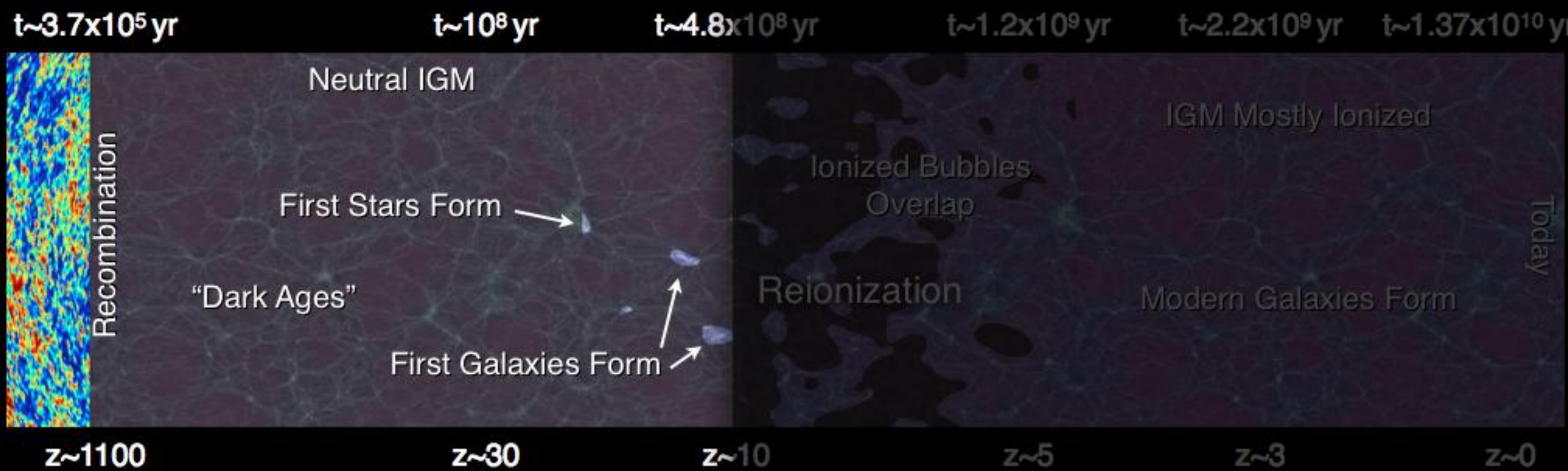
Observable Cosmological History



1) Recombination

Robertson et al., *Nature*, **468**, 49 (2010)

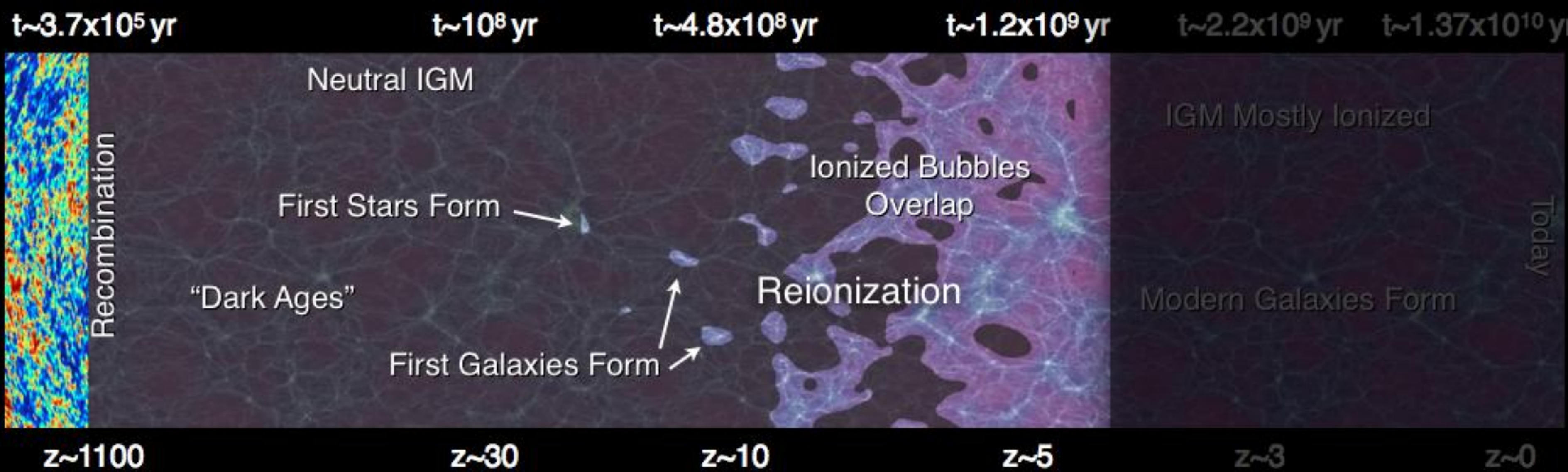
Observable Cosmological History



2) "Cosmic Dawn"

Robertson et al., *Nature*, **468**, 49 (2010)

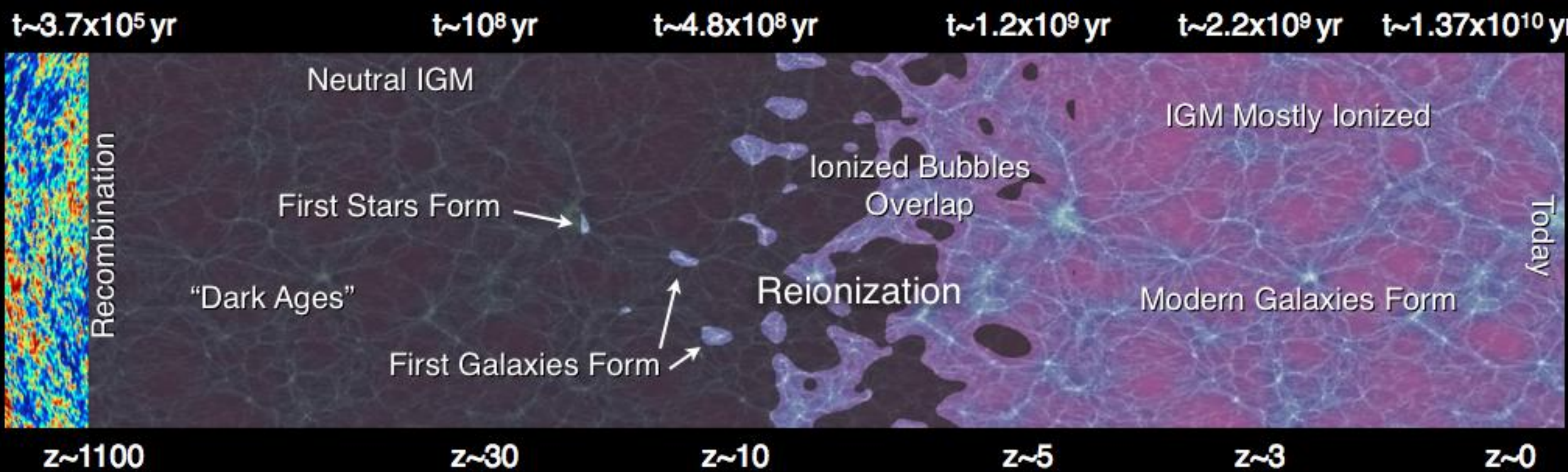
Observable Cosmological History



3) Reionization

Robertson et al., *Nature*, **468**, 49 (2010)

Observable Cosmological History



4) Modern Cosmological History

Robertson et al., *Nature*, **468**, 49 (2010)

The Grand Questions

- Cosmic Dawn: The First Metal-free Stars & Star Clusters:

  - When did they form?
  - How rapidly did later enriched generations form?
  - Visibility issues with James Webb Space Telescope

- Cosmic Reionization: The First Galaxies

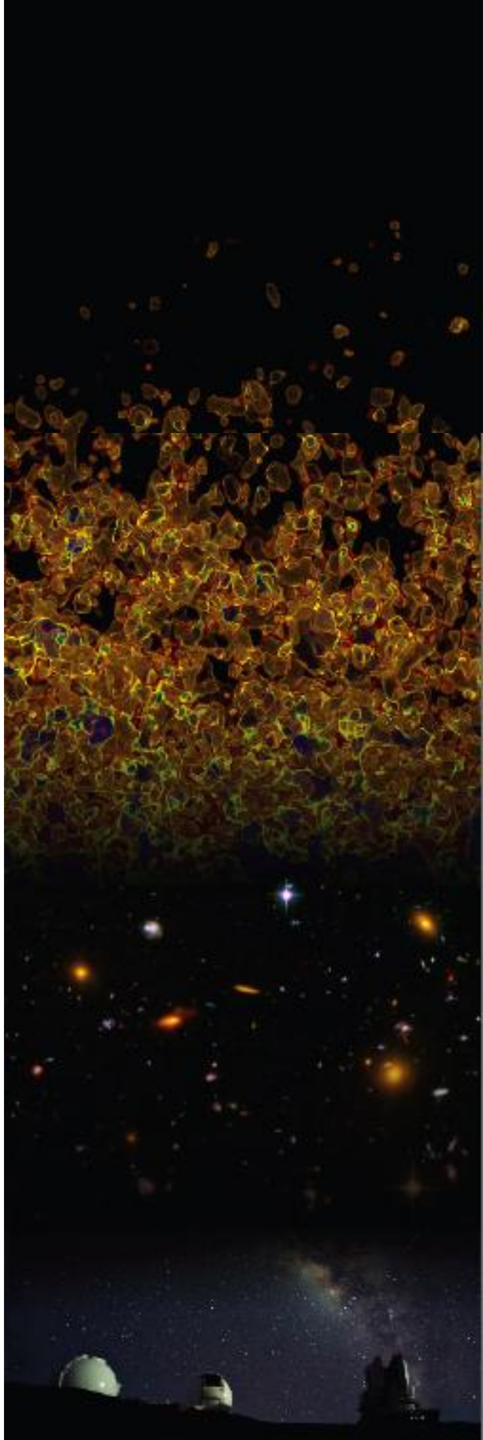
  - When did reionization occur?
  - Were galaxies responsible for reionization?
  - What physical processes governed early assembly and IGM enrichment
  - How do we connect all this to $z < 6$ observations?

Recent review: Nature 468, 49 (2010)

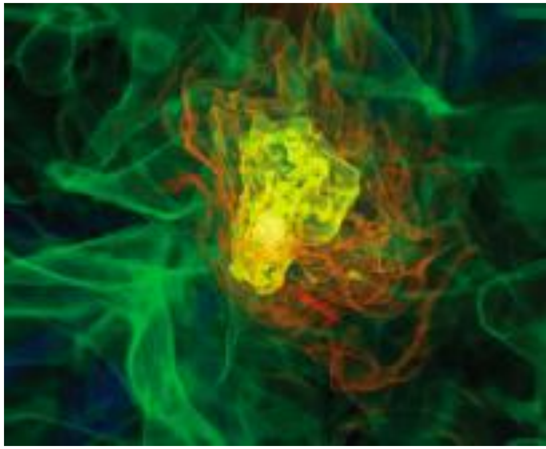
Brant Robertson (CIT), Dan Stark (IoA), Jim Dunlop, Ross McLure (Edinburgh)

Collaborative material from:

Matt Schenker (Caltech**)** Masami Ouchi (Tokyo), Eiichi Egami (Arizona), Jean-Paul Kneib (Marseilles), Johan Richard (Lyon)



Cosmic Dawn: The First Stars



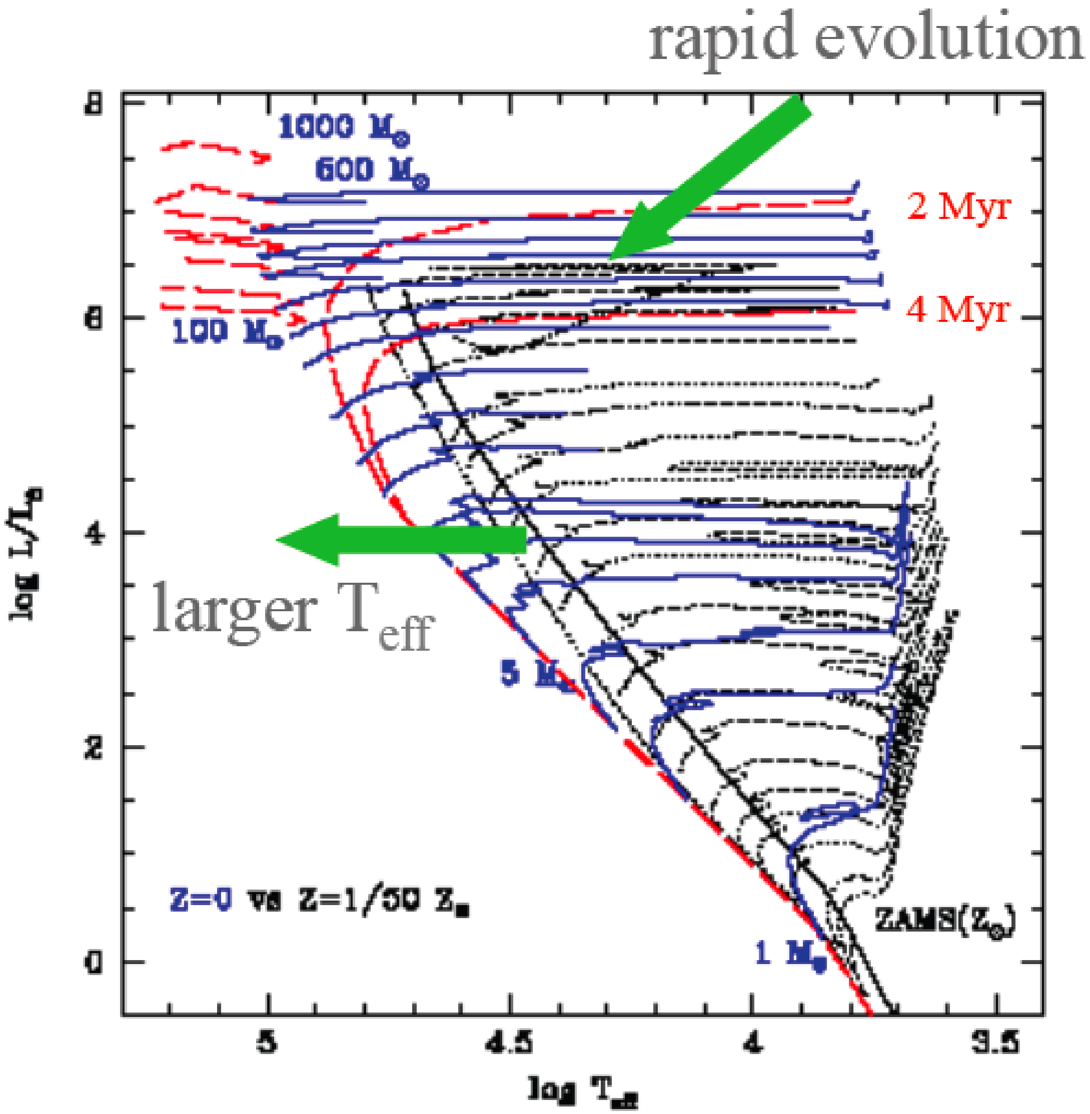
- Early protostars can cool via H_2 which is easily dissociated by radiation (Dekel & Rees 1987)

- AMR/SPH simulations predict the existence of early `Population III' stars (Abel+ 2002, Bromm+ 2002, Yoshida+ 2006)

  - pristene systems (H, He only)
  - very massive and compact (30 - 300 $M_\odot$)
  - extraordinarily hot and luminous (10^6 $L_\odot$)
  - short-lived (~3 million years)

Questions: How long did this Pop III phase last?
What governs the transition from Pop III to Pop II?
What are the observational possibilities for detecting Pop III stars?

Pop III Stars are Hotter and Evolve Rapidly



T_{eff} up to 100,000 K with much stronger/ harder ionizing spectrum

Tumlinson & Shull (2000)

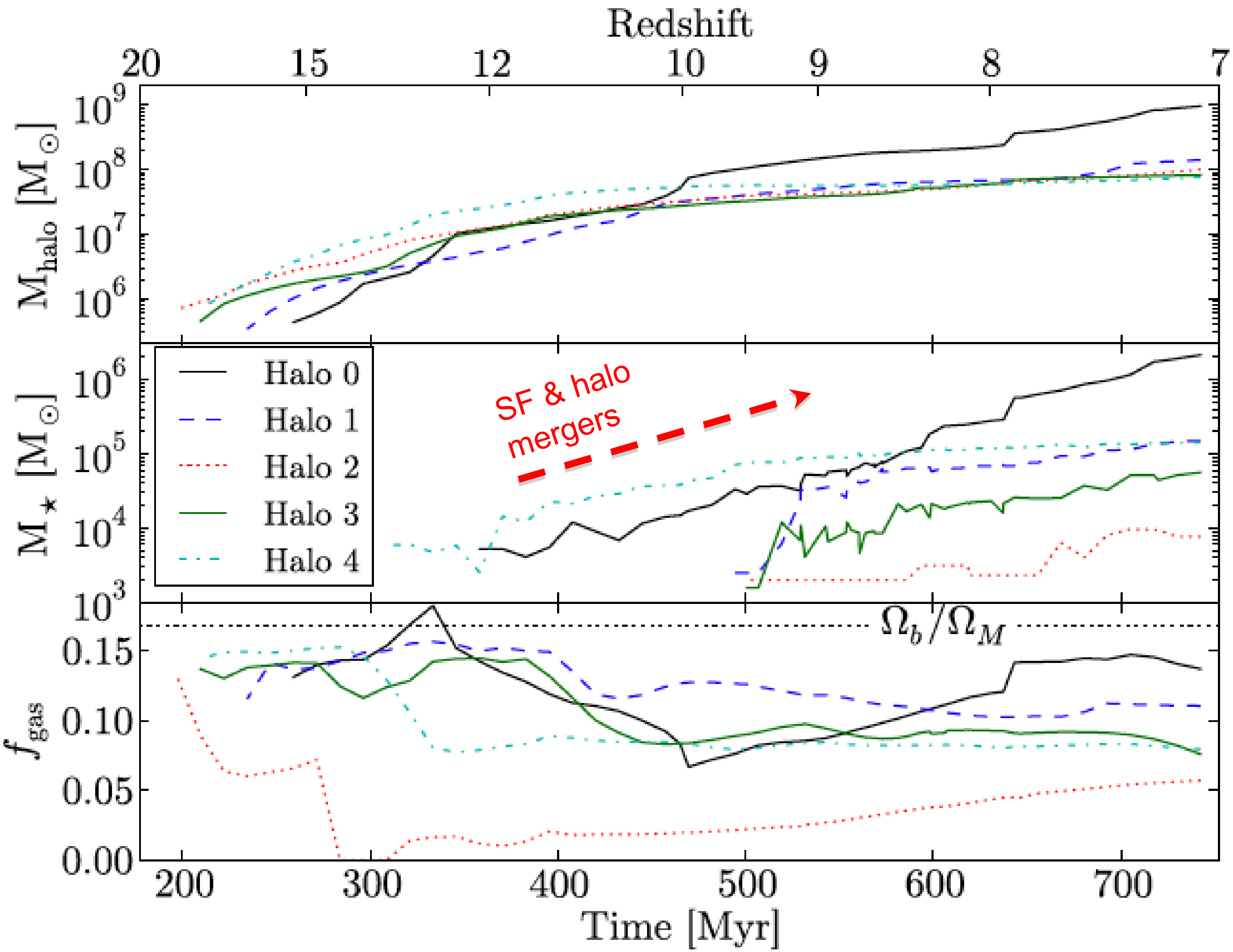
Evolution of First Stellar Systems & Halos

ENZO code (Bryan & Norman 1997, Wise & Abel 2011)

halo mass

stellar mass

gas fraction



Wise et al astro-ph/1011.2632

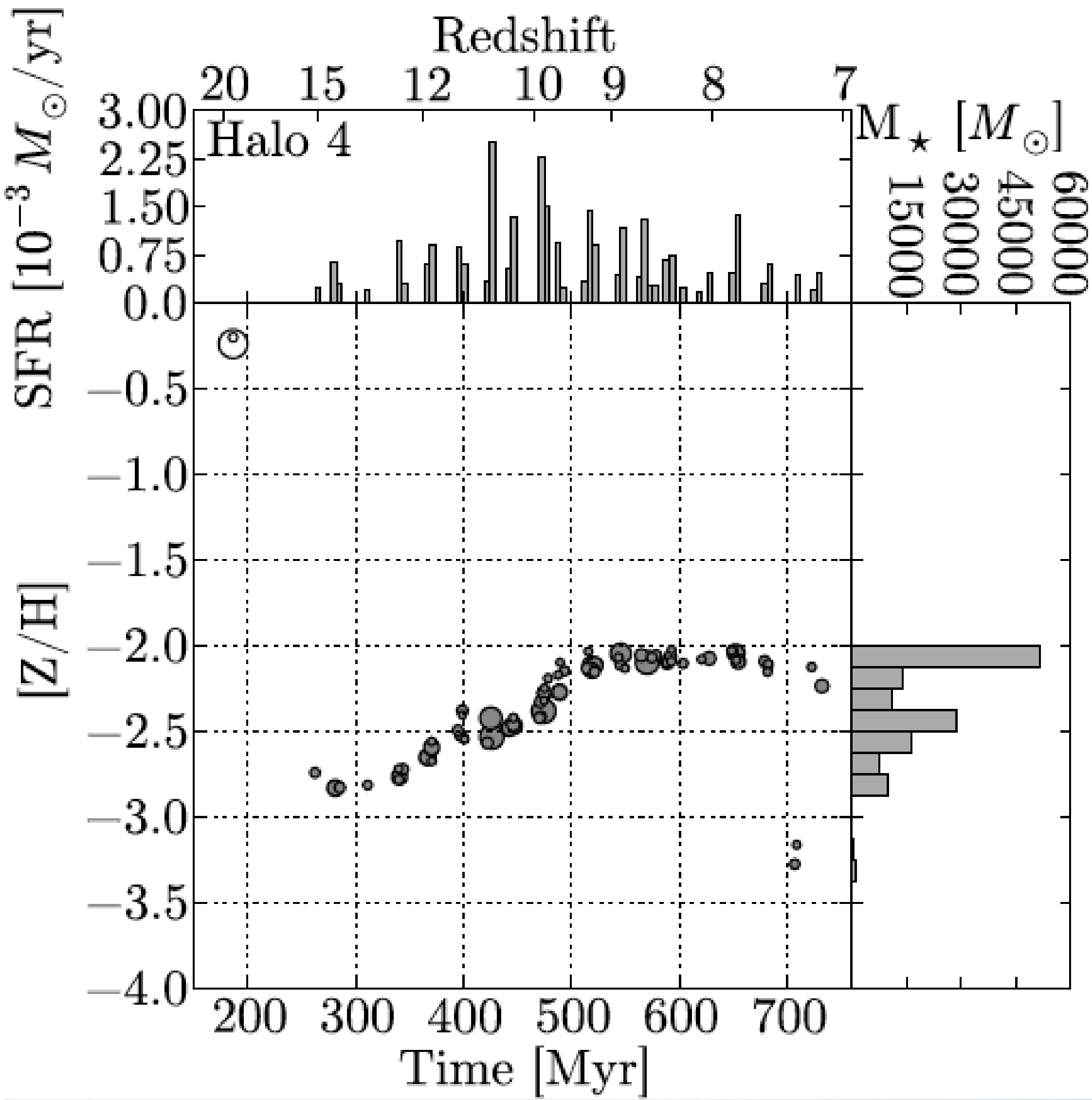
Metal Enrichment History of Single Halo

Halo mass M= 8 10^7 $M_\odot$
(no merger activity)

• Evolution of stellar metallicity is governed by *enriched outflow vs pristene inflow*

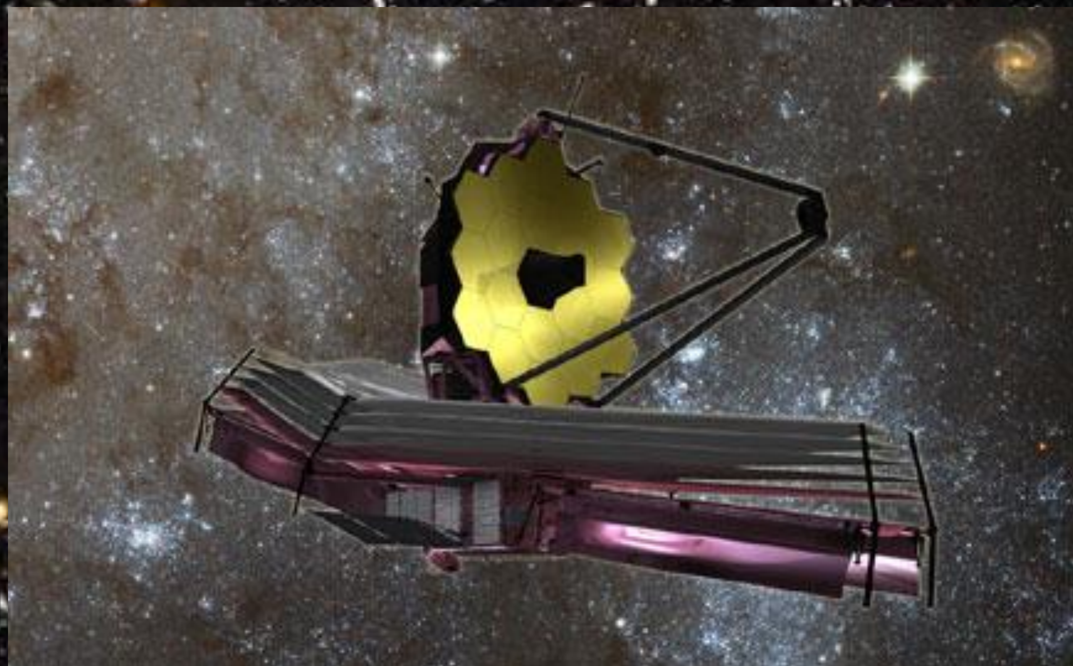
• Evolution is remarkably rapid (e.g. due to one PISN!)

• Near-instant enrichment to [Z/H] ~ -3; no low metallicity tail!



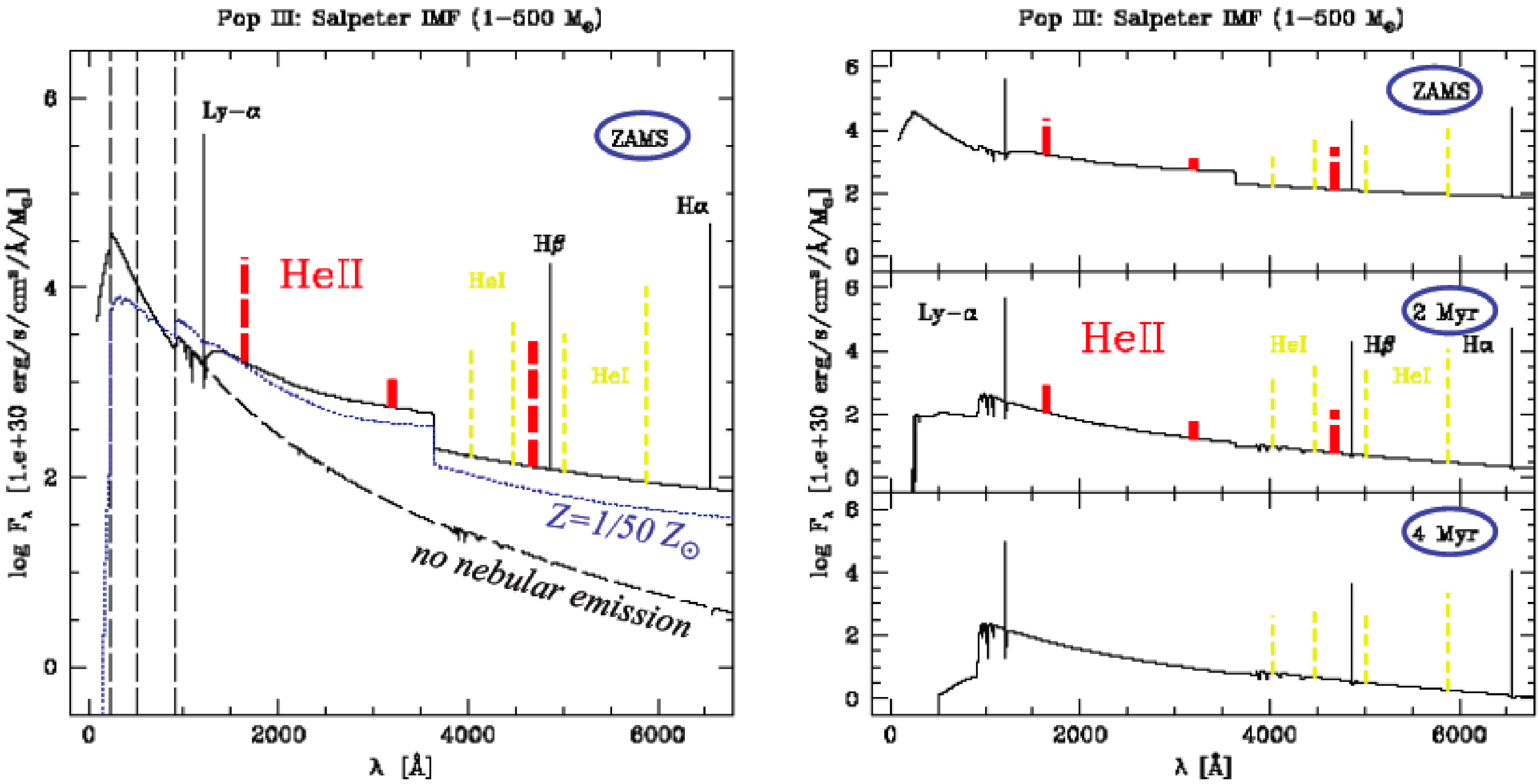
Wise et al astro-ph/1011.2632

James Webb Space Telescope



?

Spectral Signatures of Pop III



Nebular He II line widely discussed as possible probe of Pop III

- Transient feature – may disappear in short period (~ Myr)
- Also produced in WR stars so intense emission essential to detect

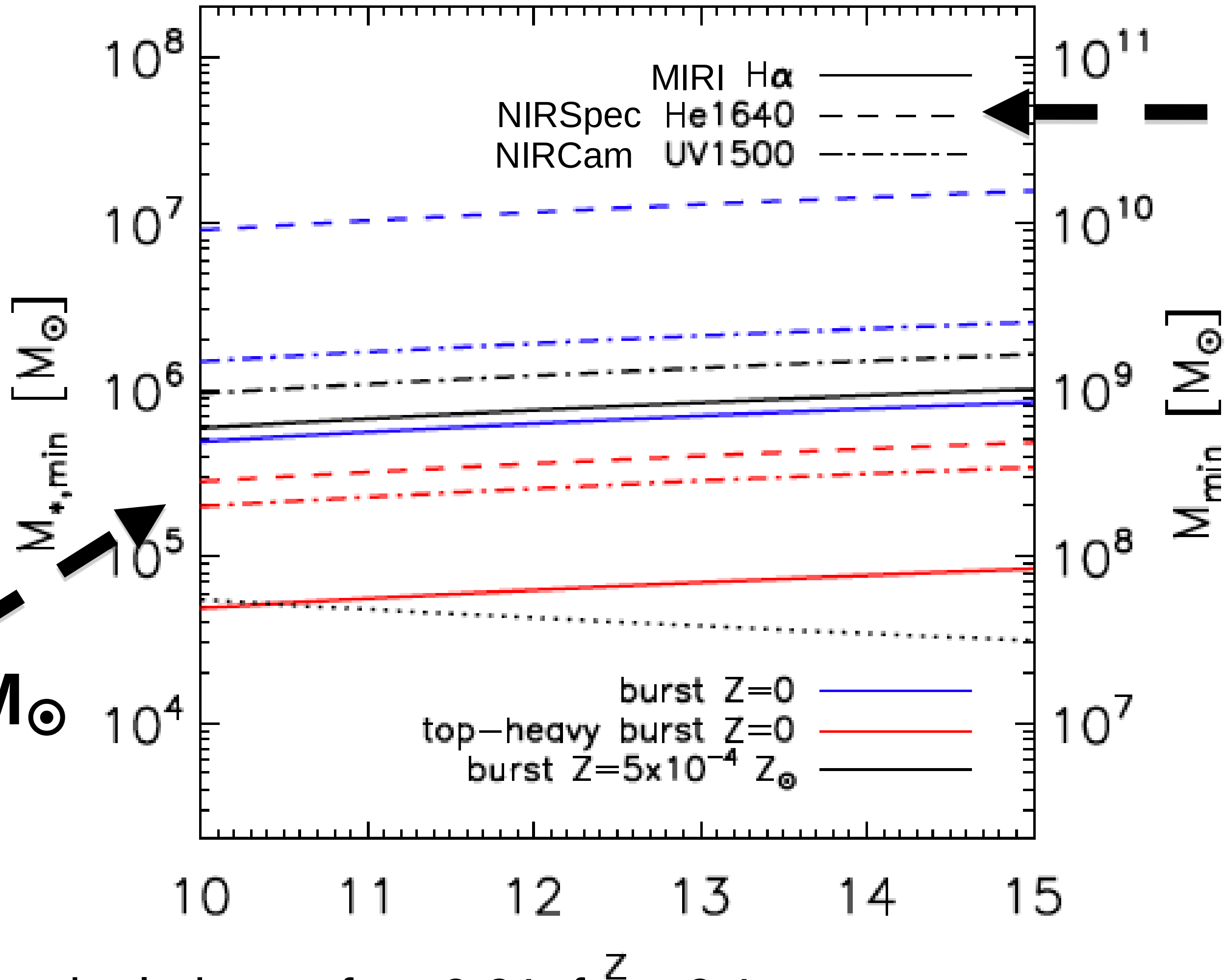
Schaerer 2002

JWST Detection of Pop III galaxy z > 10

stellar mass limit

$t \sim 10^6$ s
S/N~10

$>10^5\ M_\odot$



halo mass limit

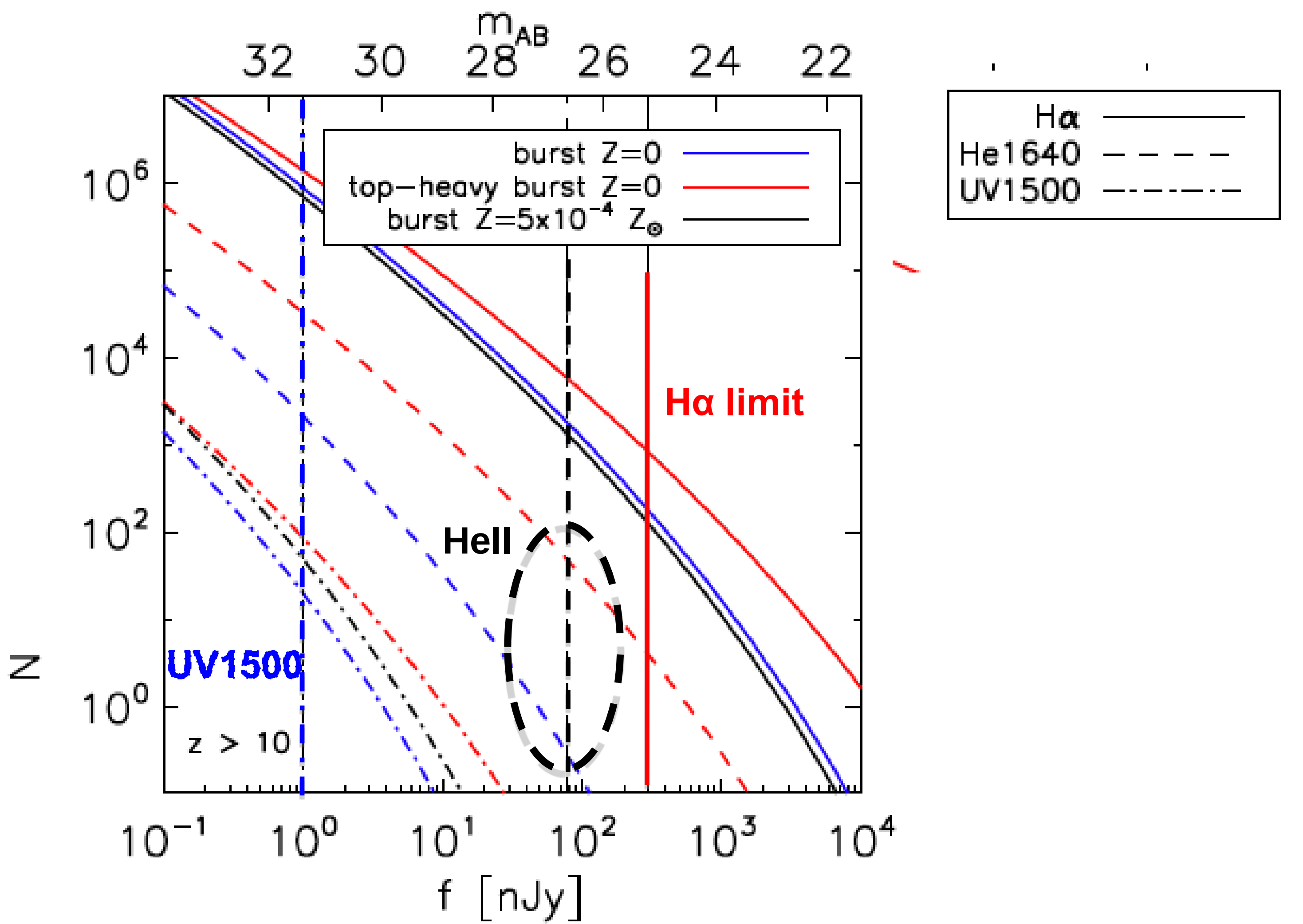
Assumes single burst, f_{gas}~0.01, f_{SFR}~0.1

He 1640 only visible for low mass systems with top-heavy IMFs (Pop III.1)

Pawlik et al 2011 astro-ph/1011.0438

z > 10 JWST Source Counts

Number with S/N~10 in a 10 arcmin^2 field in 10^6 s exposure



Counts very sensitive to presence of zero metallicity systems and top-heavy IMFs but depend also on duration of starburst (<1 to10^3 sources per pointing!)

Pawlik et al 2011 astro-ph/1011.0438

Cosmic Reionization:
The First Galaxies

Did Galaxies Reionize the Universe?

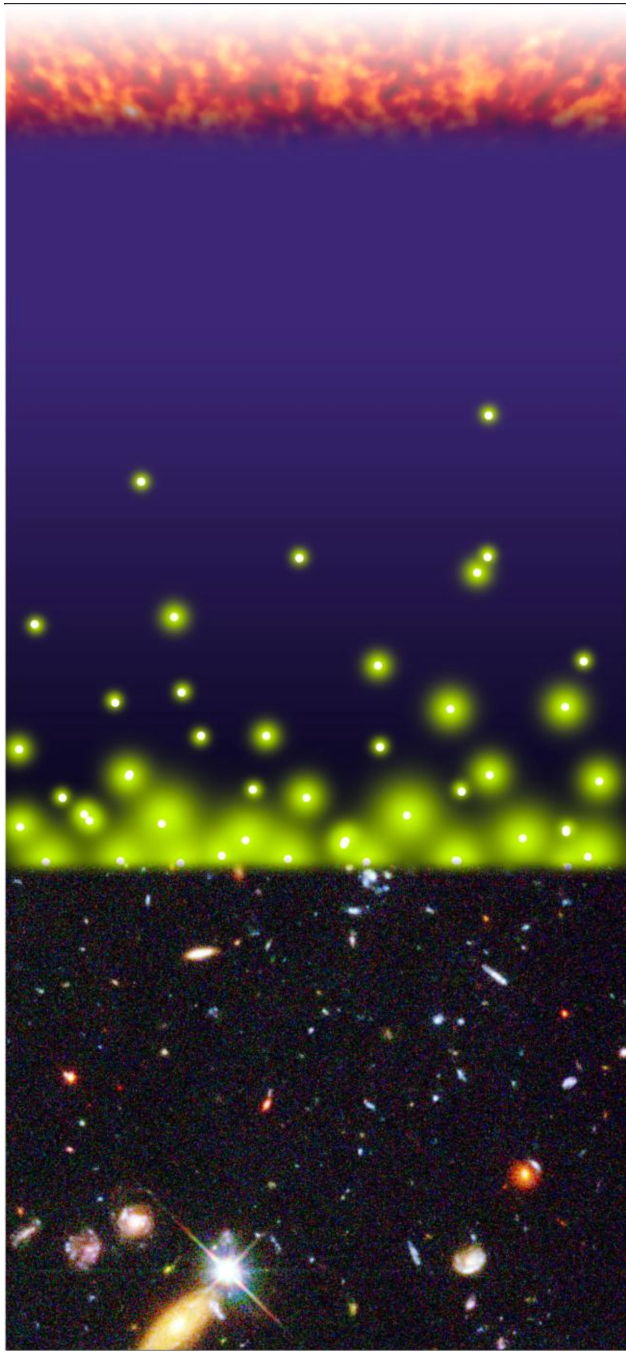
- need enough star-forming galaxies to provide the necessary ionizing photons

- sustained population to overcome recombination

- means for ionizing photons to escape absorbing material within galaxies

What Physical Processes Govern the Emerging Mass and Luminosity Distribution?

- radiative/feedback determines what happens next



Review: Robertson et al (2010) Nature 468, 49

The Present Landscape

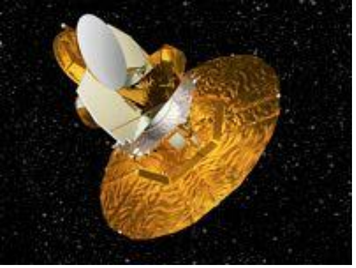
Indirect constraints on when reionization occurred:

- Optical depth to reionization, τ, from the WMAP satellite
- Downturn in ionized carbon abundance at $z > 5$
- Stellar mass densities of $4<z<6$ galaxies: earlier star formation

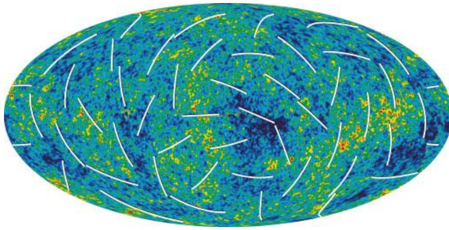
Studies of Early Galaxies

- Two techniques: Lyman alpha emitters and Lyman break galaxies
- The HST WFC3 revolution: new galaxy candidates beyond $z\sim7$
- Tracking Lyman α in distant galaxies spectroscopically
- Other related probes (QSOs, GRBs)

Challenges and prospects for the future

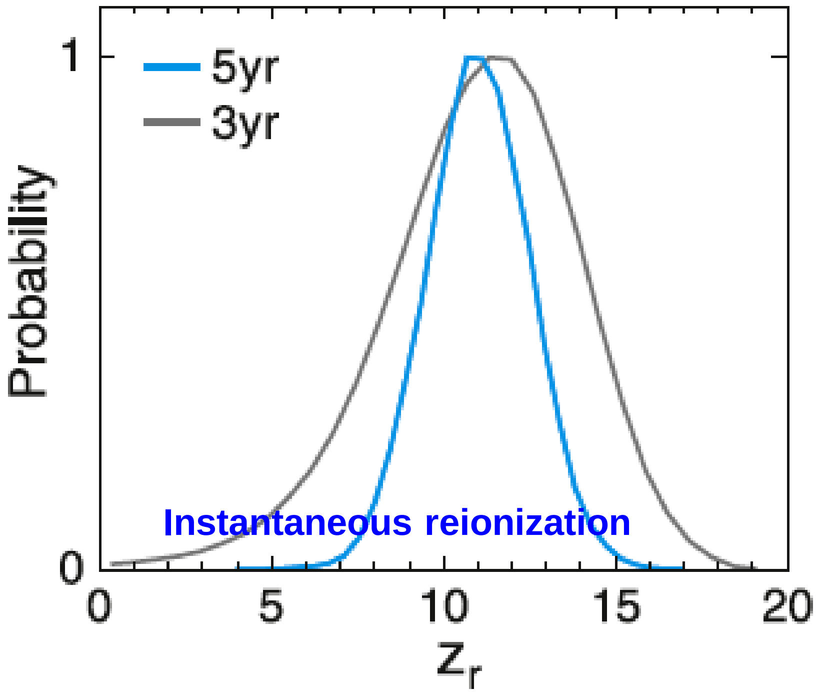


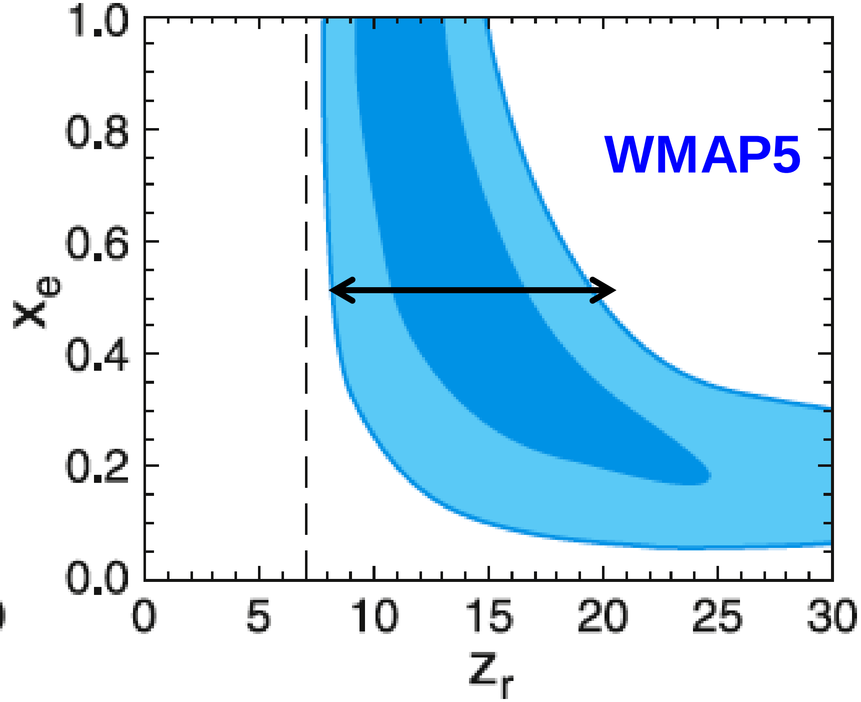
WMAP Polarization



τ = 0.088 ± 0.015
(WMAP7, 2010)

Larson et al 2011
Jarosik et al 2010



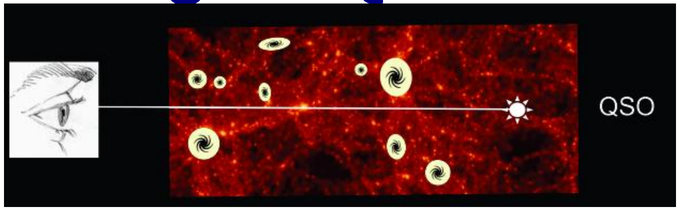


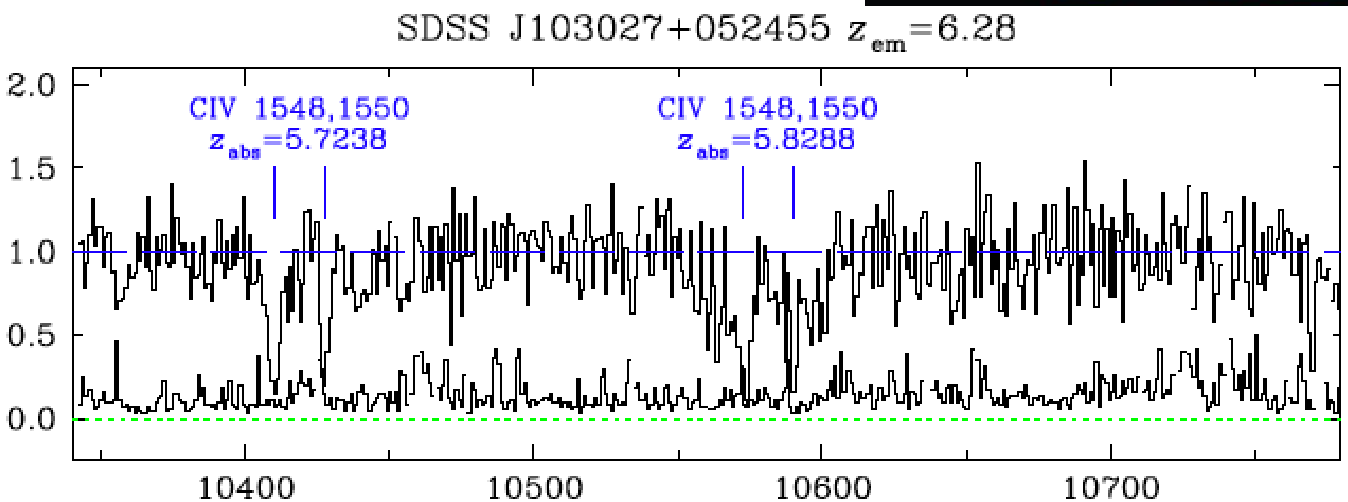
Data rejects instantaneous reionization at z~6-7

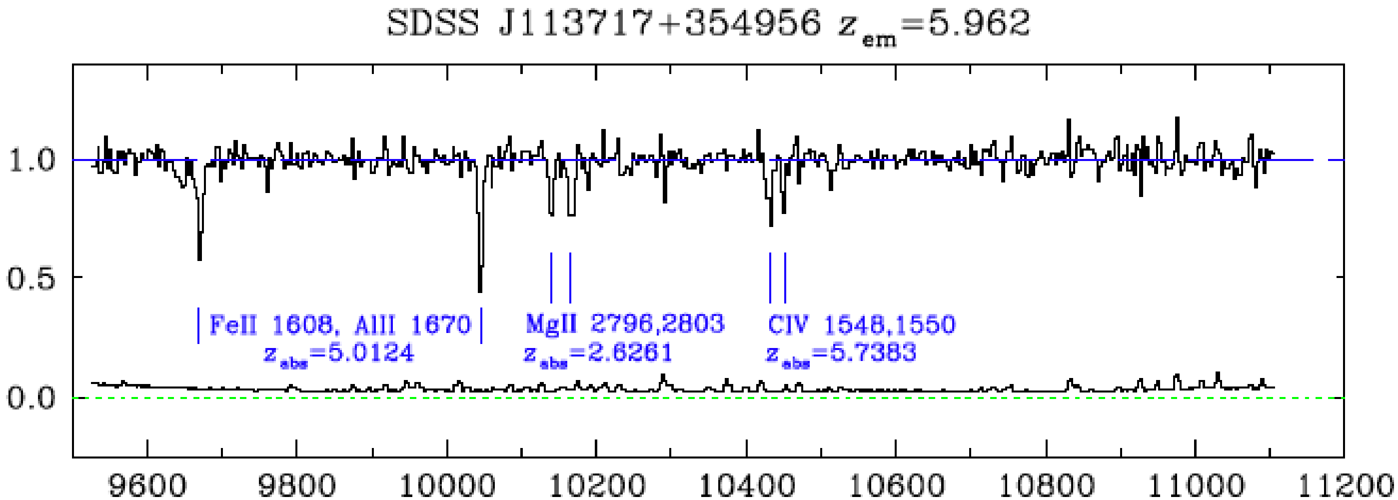
CMB does <u>not</u> pinpoint the responsible cosmic sources

Ionized Carbon Absorbers in High z QSOs

Use QSOs as background beacons to highlight absorbing clouds in the high z intergalactic medium



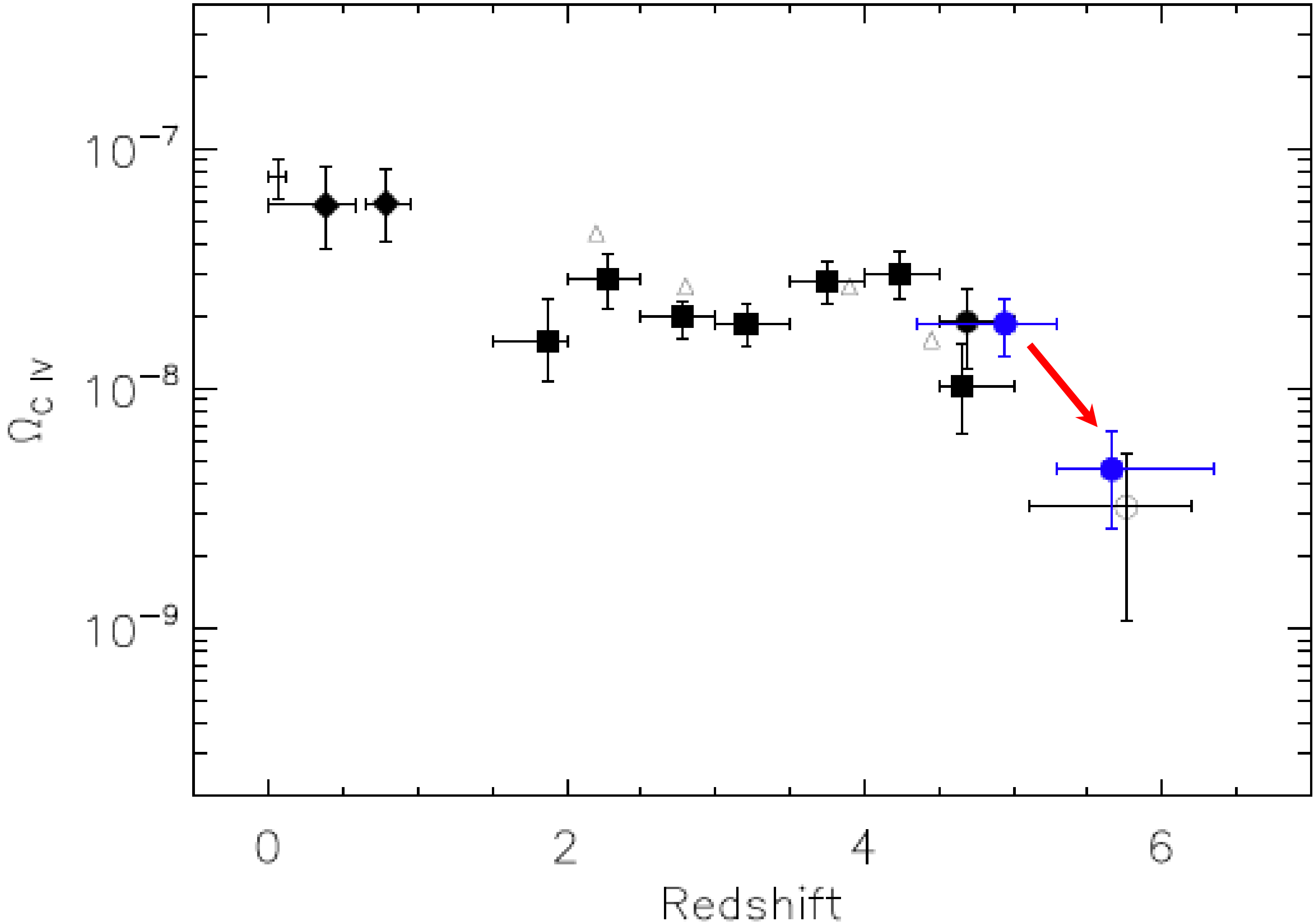




Ryan-Weber et al (2009)

Rapid Drop in Carbon Abundance beyond z~5?

- Near-IR spectra of z > 6 QSOs reveal CIV abundance (Ryan-Weber et al, Simcoe et al)
- Sudden decline over 300 Myr in $\Omega_{CIV}(z)$

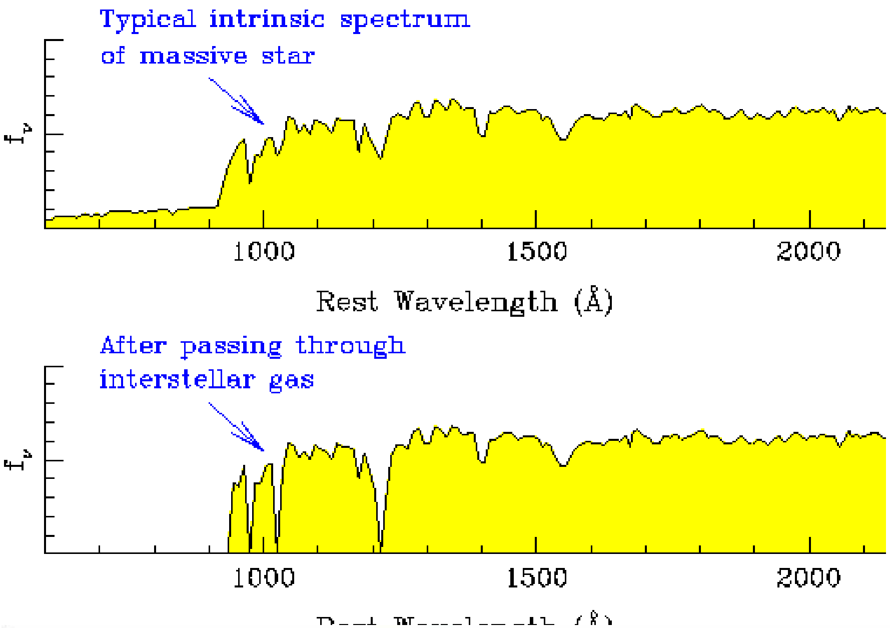


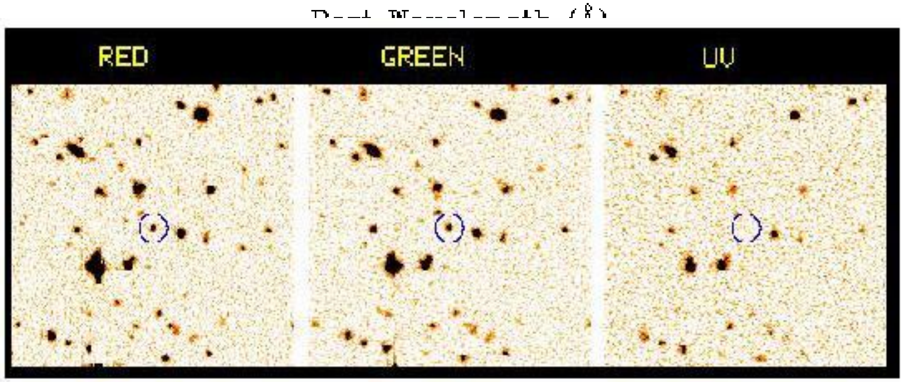
Sudden drop could arise from rapid abundance rise due to early enrichment of galaxy halos <u>or ionization changes?</u>

High Redshift Star Forming Galaxies

Lyman break galaxies (LBGs):

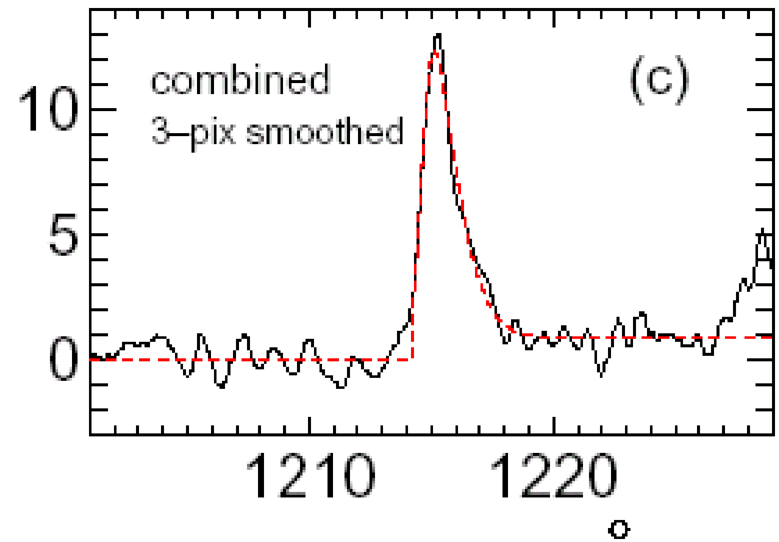
Rest-frame UV continuum discontinuity

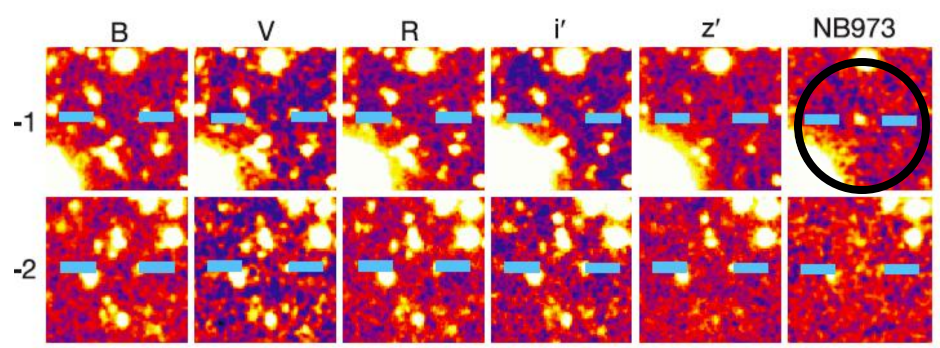




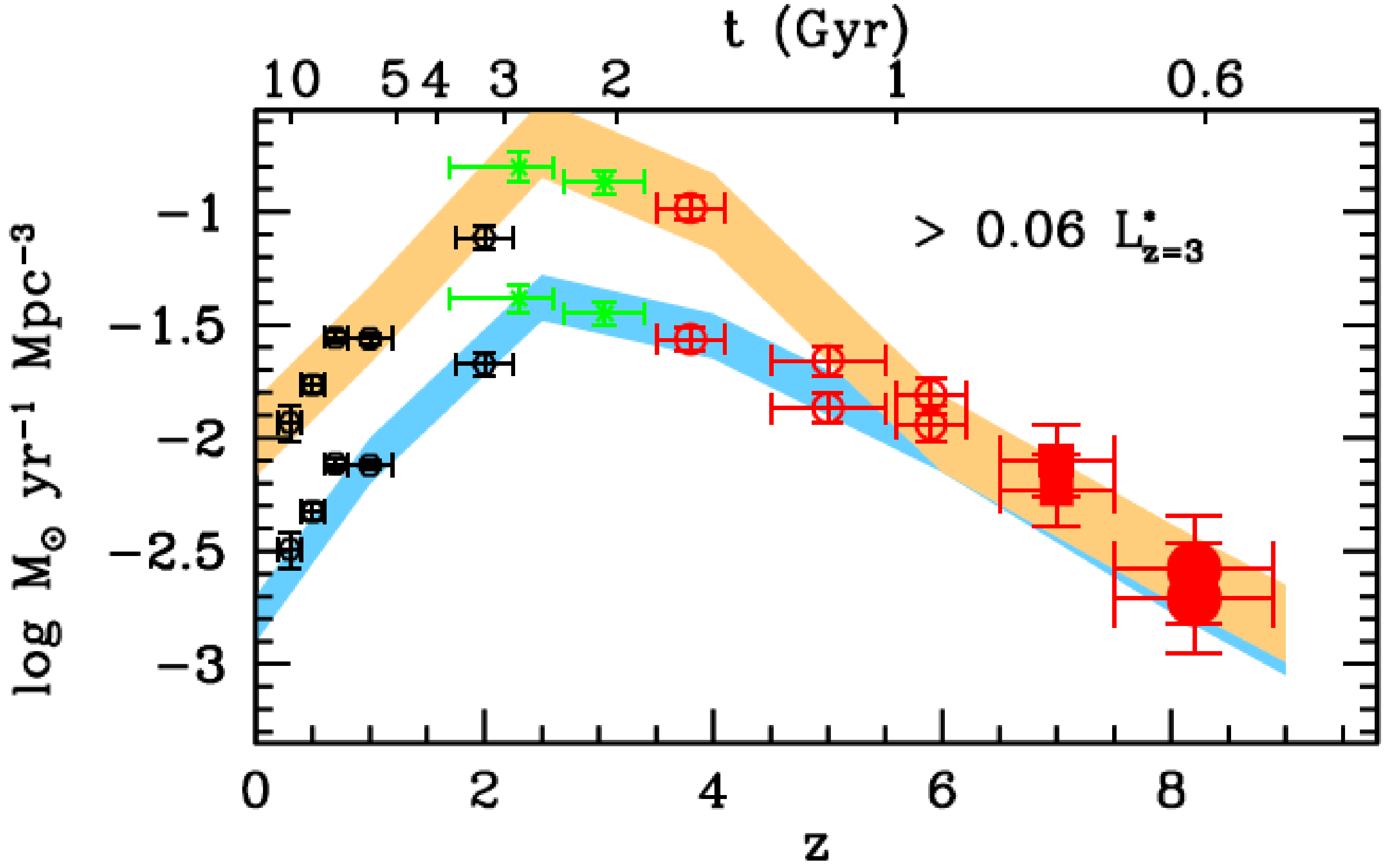
Lyman alpha emitters (LAEs):

Located via narrow band imaging





Star formation density of LBGs



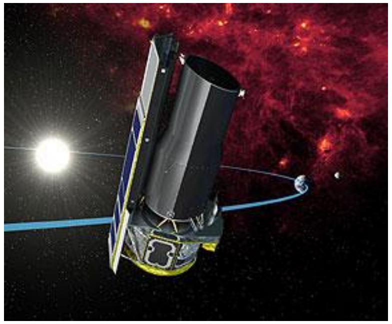
Monotonically declining population to z ~ 6 and beyond

Drop of × 8 in UV luminosity density 2 < z < 6

Appealing indicator: but `observed SF' may be misleading guide

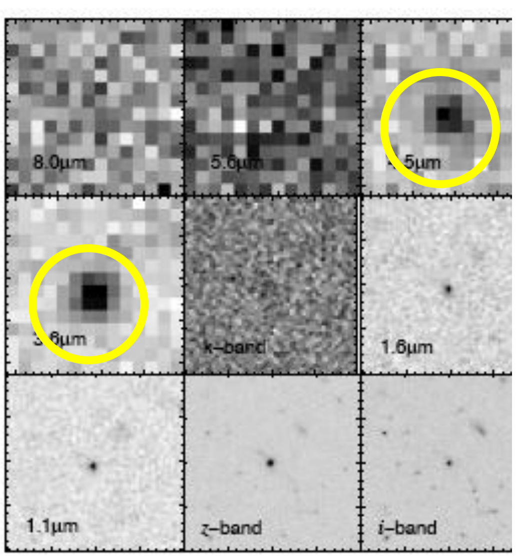
Reddy & Steidel (2009); Bouwens et al (2009, 2011)

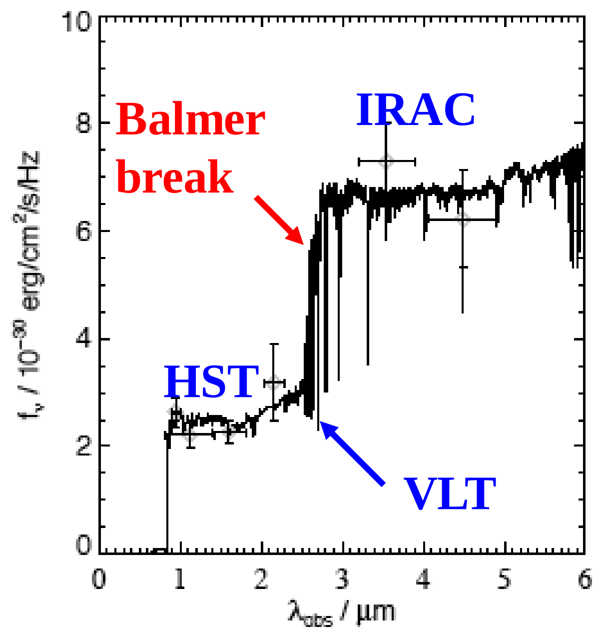
Spitzer Revolution: Stellar Masses & Ages

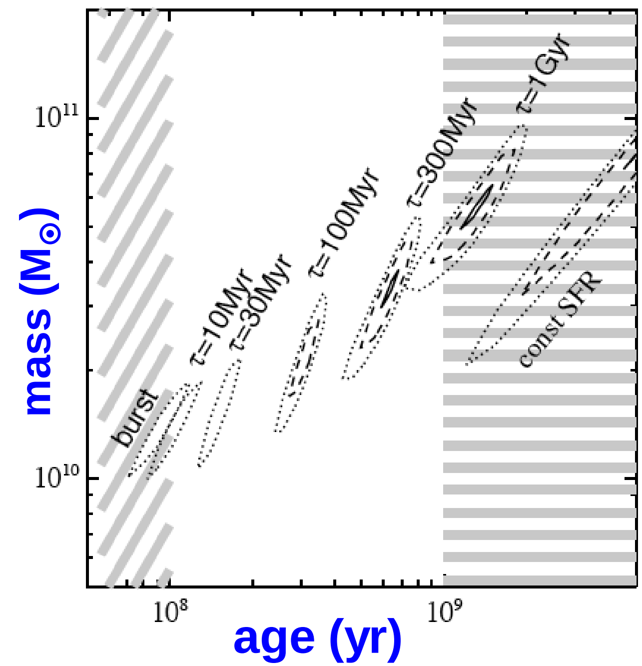


A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their **assembled stellar masses and ages**

SMB03-1: z_{spec}=5.83 IRAC(3.6μm)=24.2 (AB)
stellar mass = 3.4 10^{10} $M_\odot$ age > 100 Myr

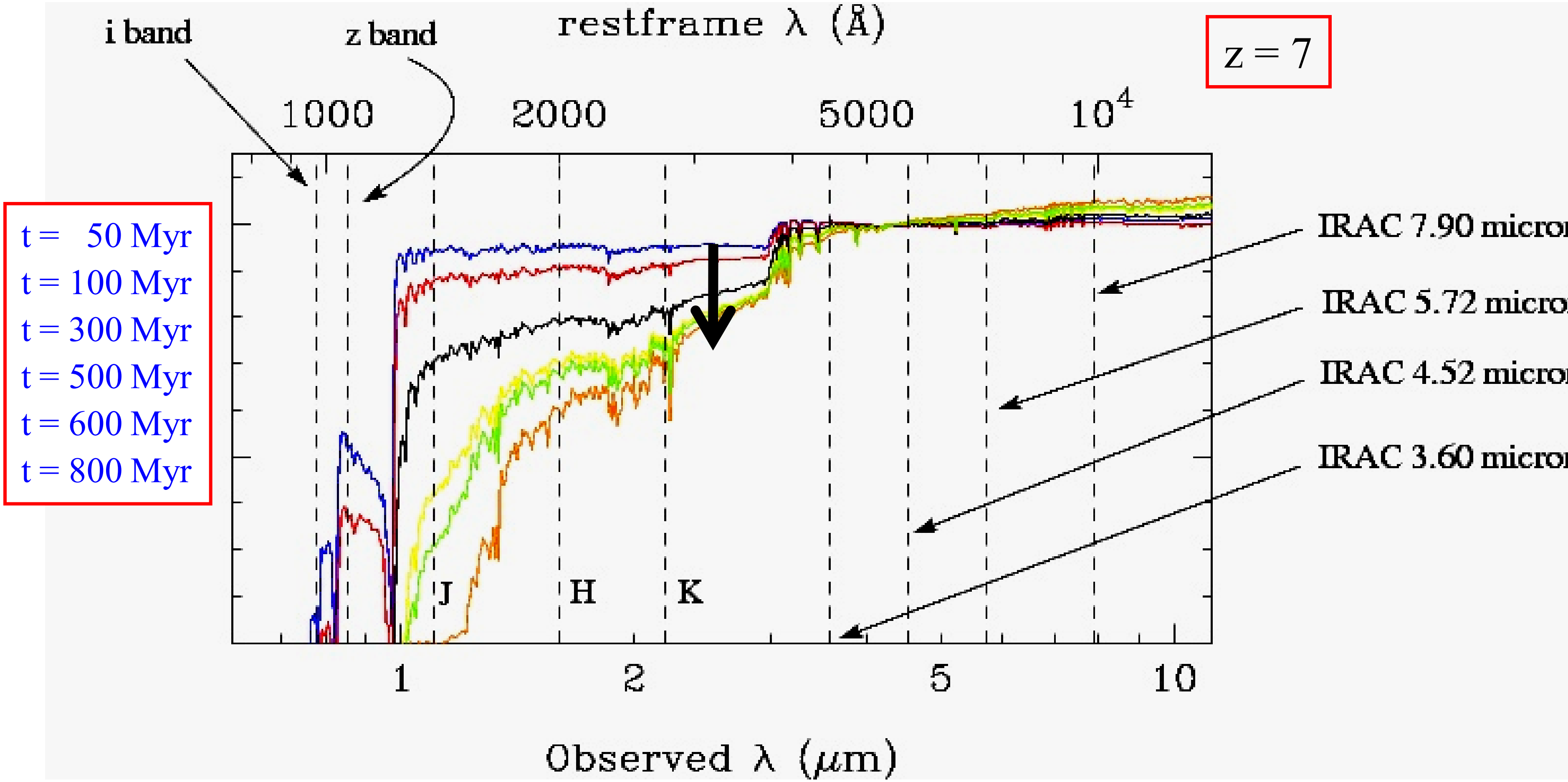






Eyles et al (2005): to produce this mass since z~10 required 5-30 $M_\odot$ yr^{-1}
comparable to the ongoing SFR (6-20 $M_\odot$ yr^{-1})
so should see earlier examples if unobscured

Balmer Break as Age Indicator

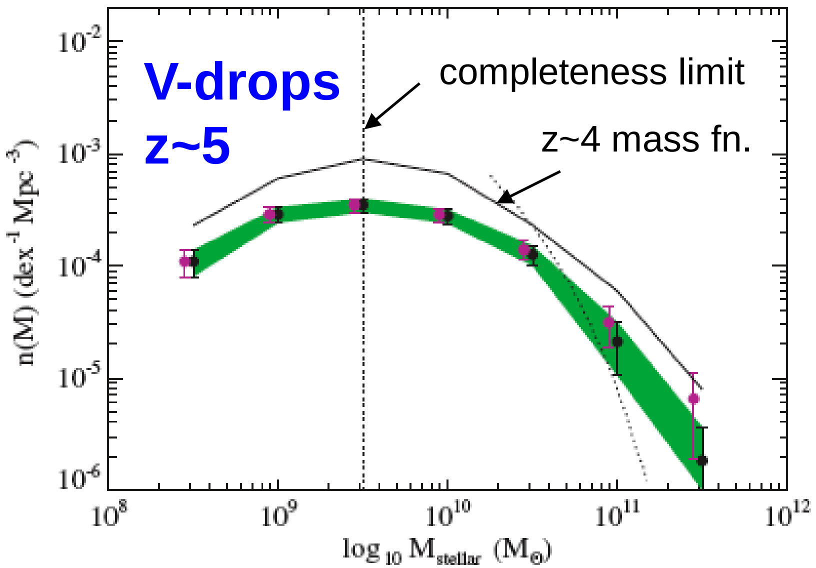


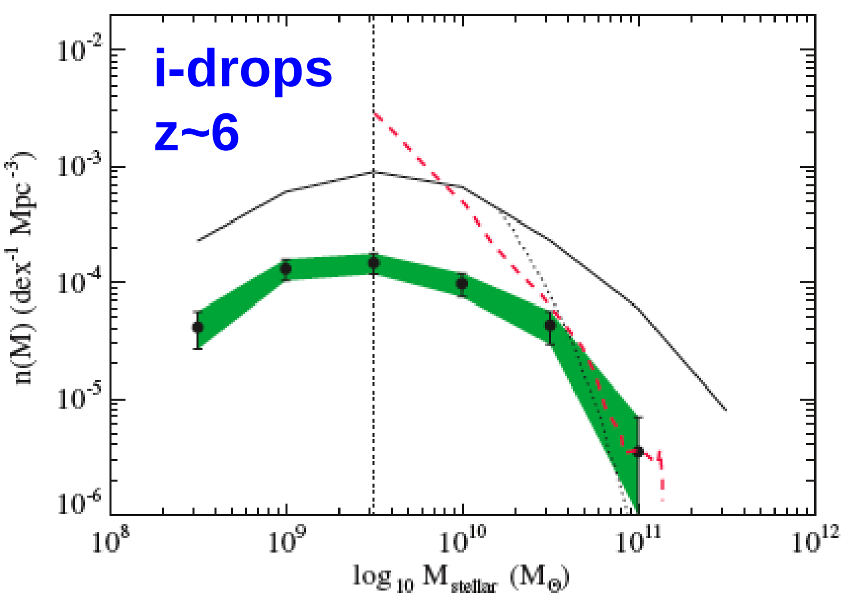
Age is degenerate with star formation history but can infer time-averaged star formation rate and compare this with actual on-going star formation rate

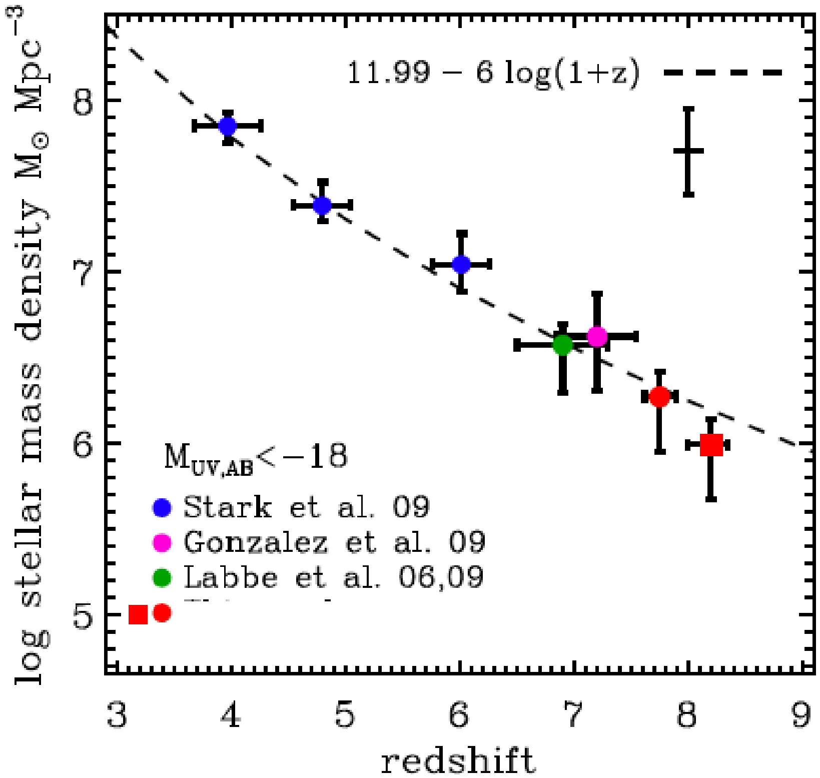
Key concern: do nebular emission lines contaminate the IRAC bands?

Stellar Mass Density

$$M_*(z) = \int_{z=5}^{z=10} \rho_*(z) dV(z)$$



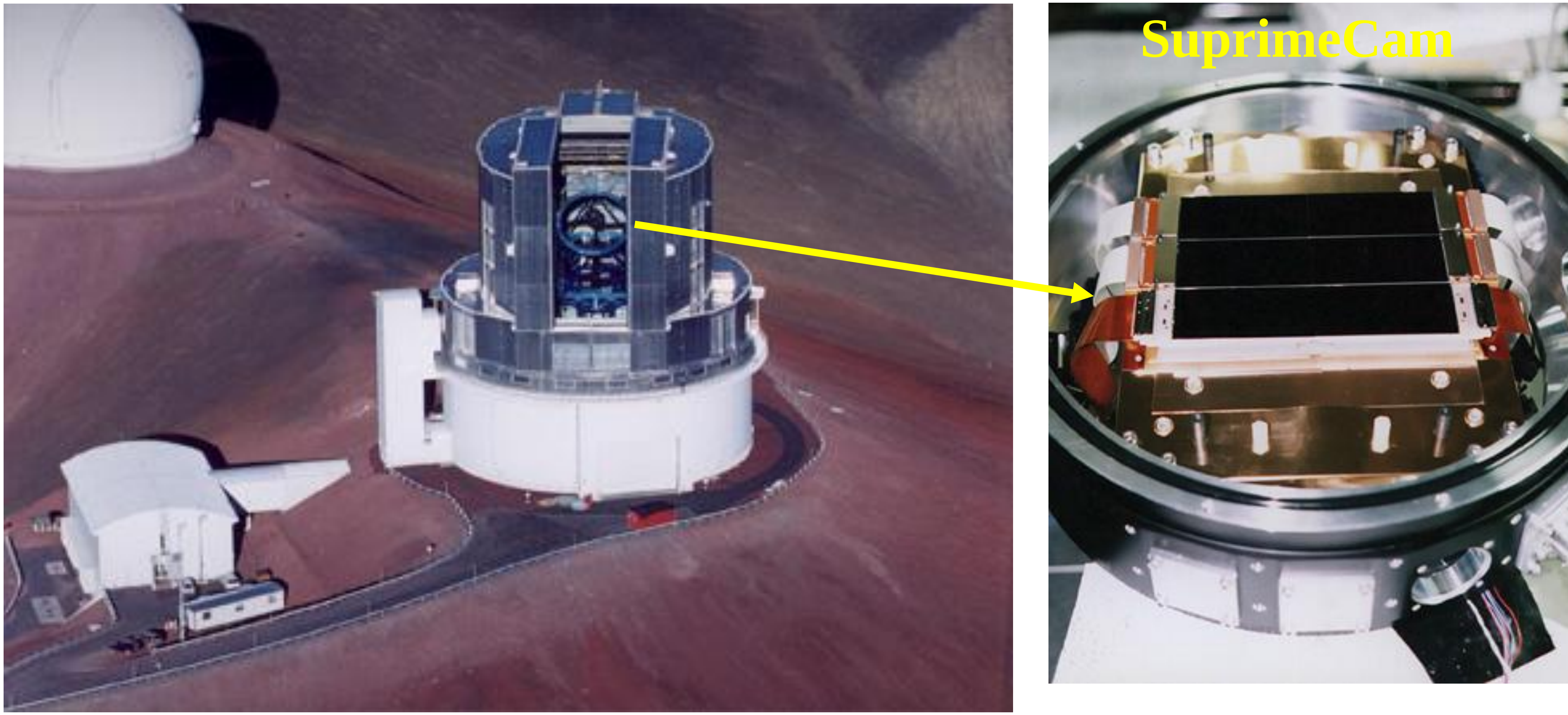




Stellar mass density at z~5-6 implies significant past SF in low luminosity galaxies: perhaps sufficient for reionization?

Stark et al 2007,2009; Labbé et al 2009ab, Gonzalez et al 2010

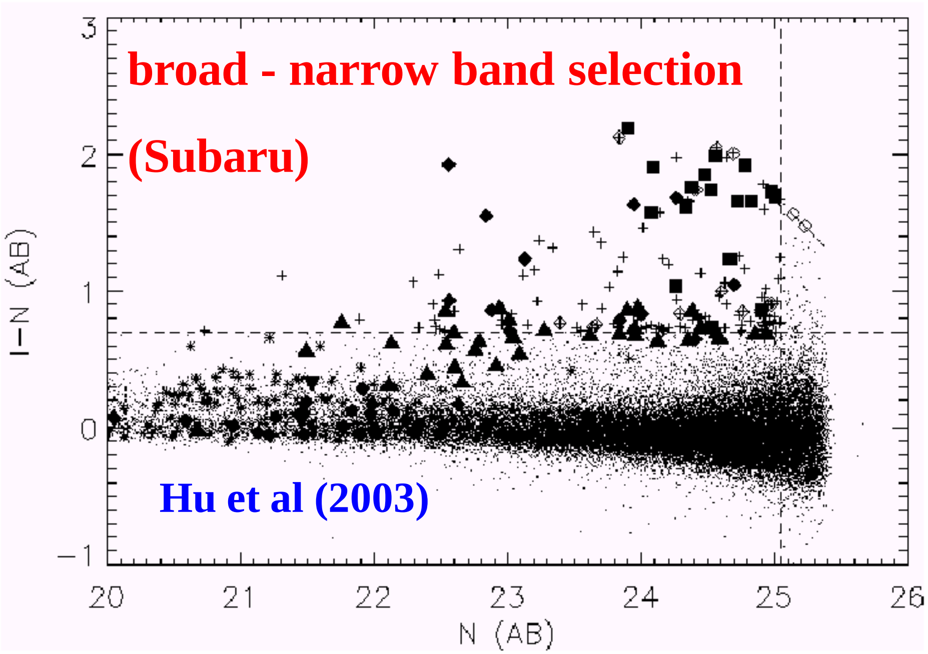
Wide Field Imaging of Lyα Emitters from Subaru

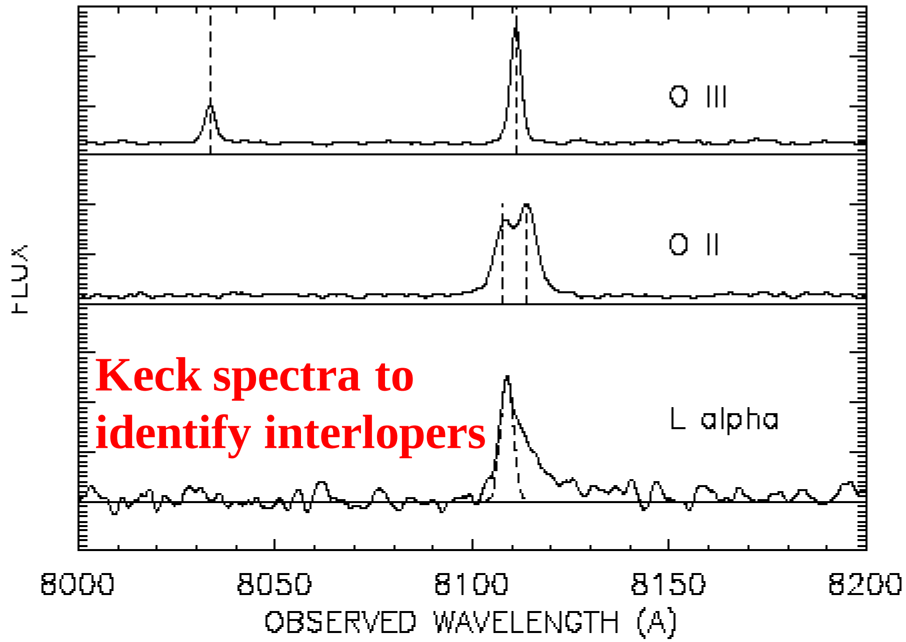


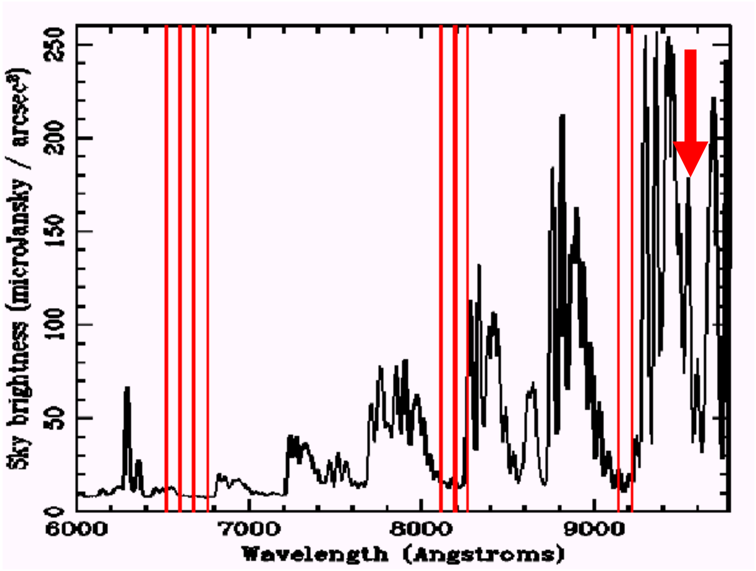
Panoramic imaging with Subaru using narrow-band filters has been used to locate high redshift Lyα emitters (LAEs)

As much as 7% of the total output of a young galaxy can be in this single emission line (so v. efficient for survey work)

Lyman α Emitters: How it Works



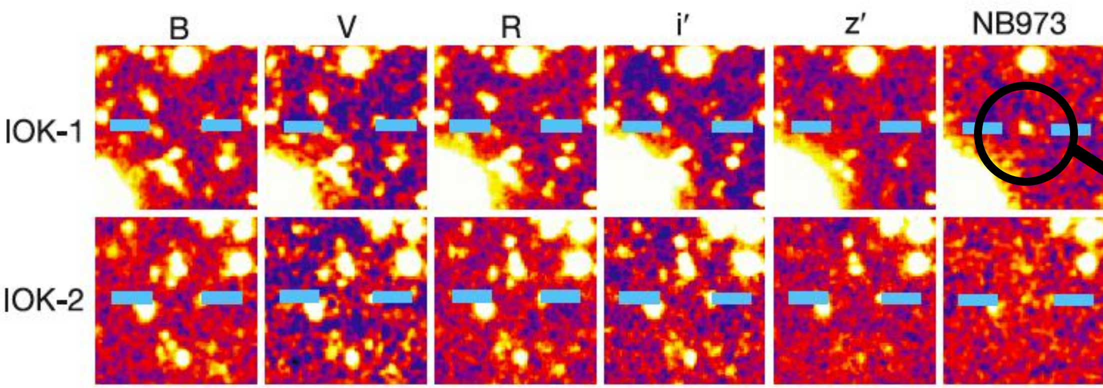


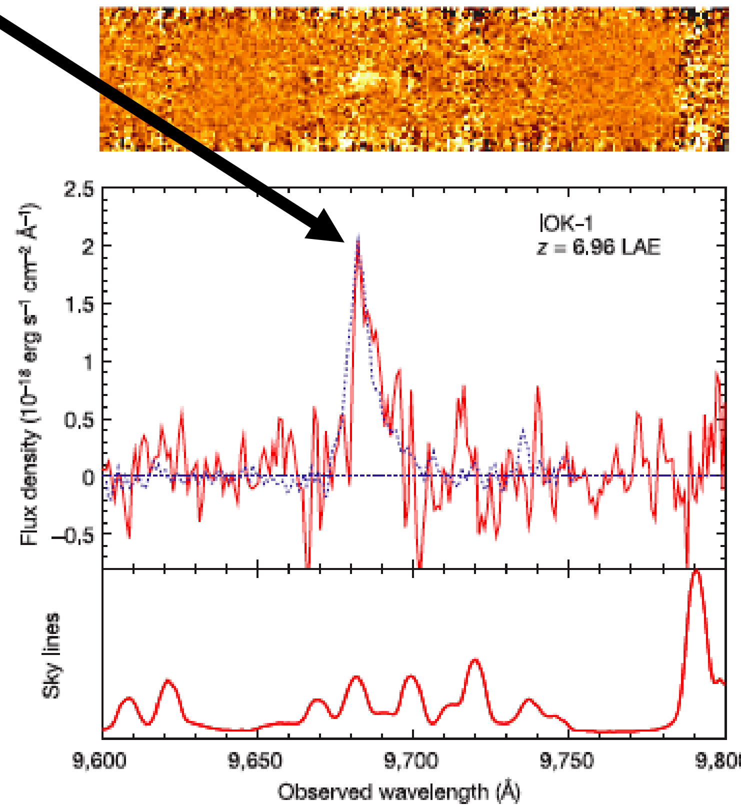


- Selection made in narrow z interval c.f LBGs
- Spectroscopic confirmation often incomplete

A galaxy at a redshift $z = 6.96$

Masanori Iye[1,2,3], Kazuaki Ota[2], Nobunari Kashikawa[1], Hisanori Furusawa[4], Tetsuya Hashimoto[2], Takashi Hattori[4], Yuichi Matsuda[5], Tomoki Morokuma[6], Masami Ouchi[7] & Kazuhiro Shimasaku[2]



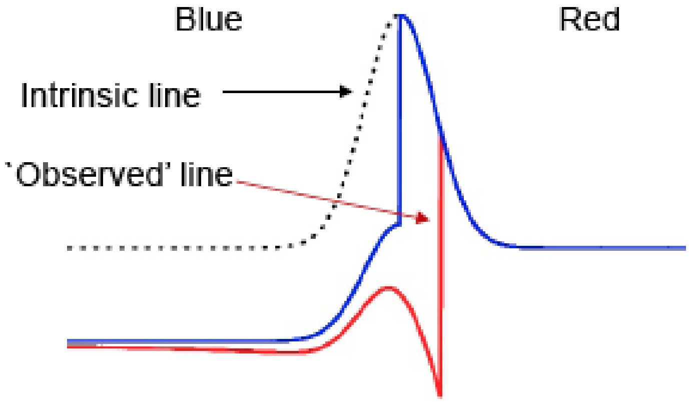


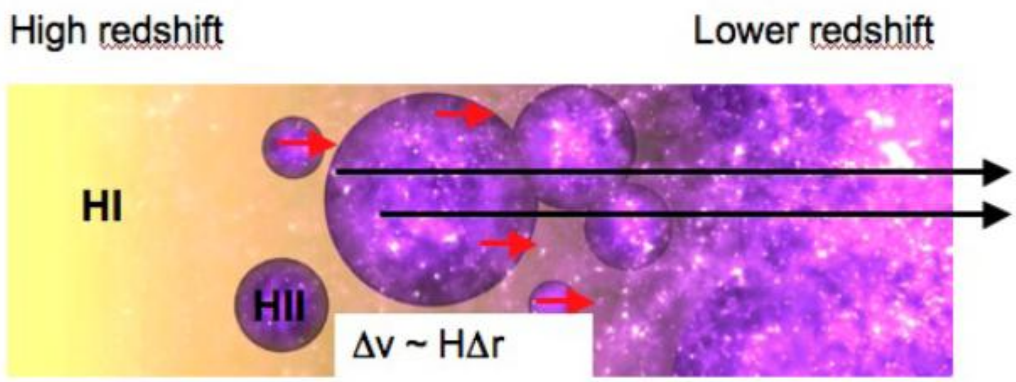
Direct imaging through a narrow band filter with Subaru found 2 candidate z~7 galaxies

One was spectroscopically confirmed at z=6.96

Iye et al Nature 443, 186 (2006)

Lyman α as a probe of the Dark Ages

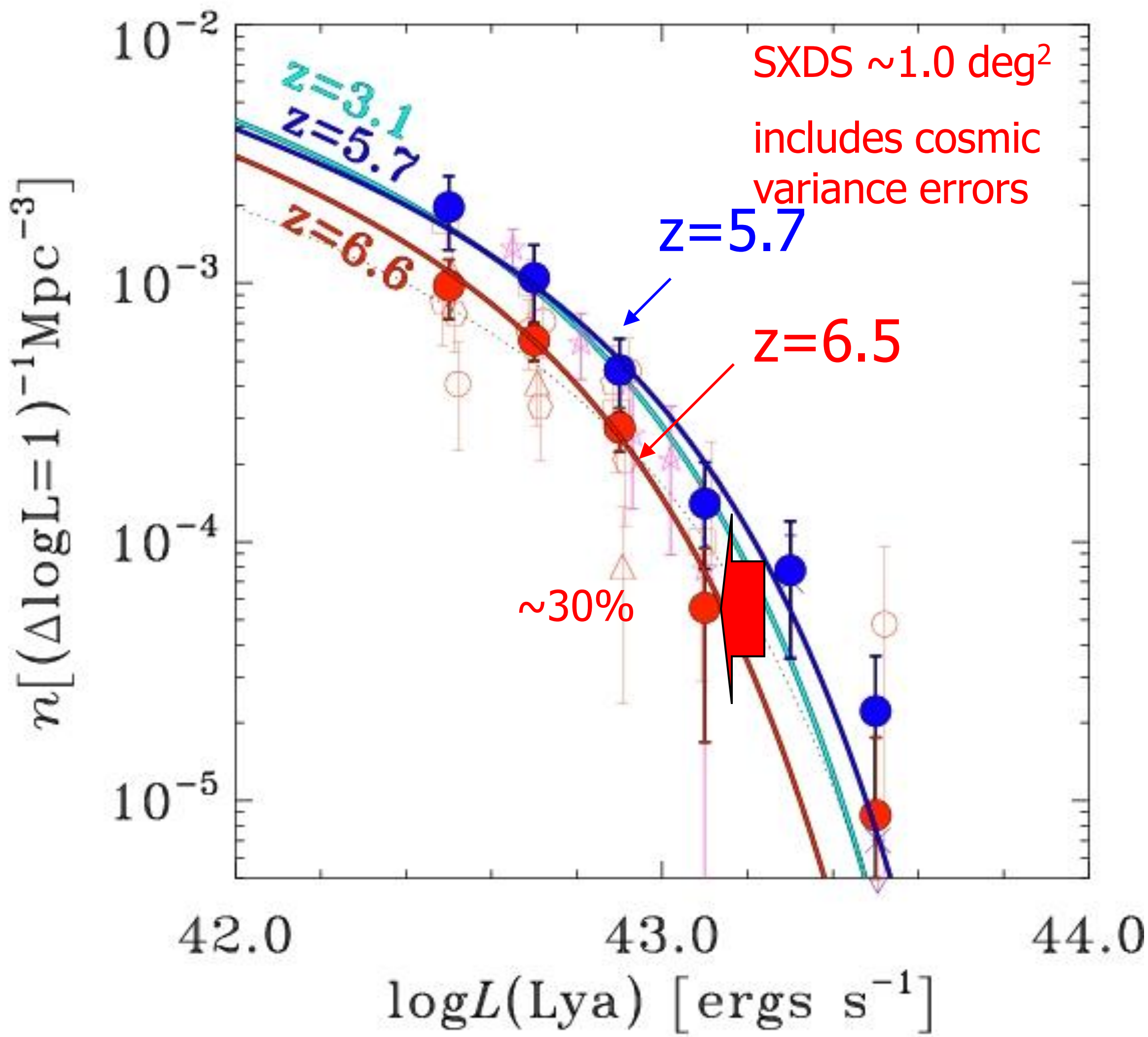




- **Lyman α line is <u>weakened by neutral hydrogen</u> and thus a valuable tracer of its presence**
- **Neutral hydrogen in `Dark Ages' acts as <u>fog</u> obscuring the line emission from young galaxies**
- **A sudden drop in the visibility of line emitting galaxies may indicate we are entering the Dark Ages!**

A Rapid Drop in Lyα Emitters from 5.7<z<6.6?

- 1 deg^2 SXDS field with 608 photometric and 121 spectroscopic Lyα emitters
- Tantalizing fading ($0.^m3$) seen in the LF of Ly α emitters over a small redshift interval 5.7< z< 6.6 (150 Myr)
- Does this mark the end of reionization corresponding to an increase in x_{HI} (e.g. x_{HI} ~0.6 at z~7)?

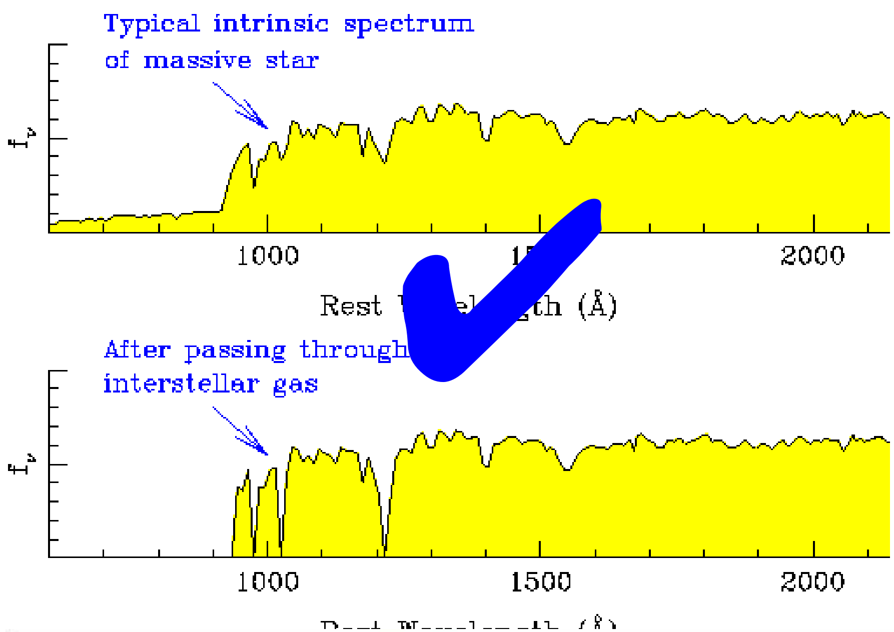


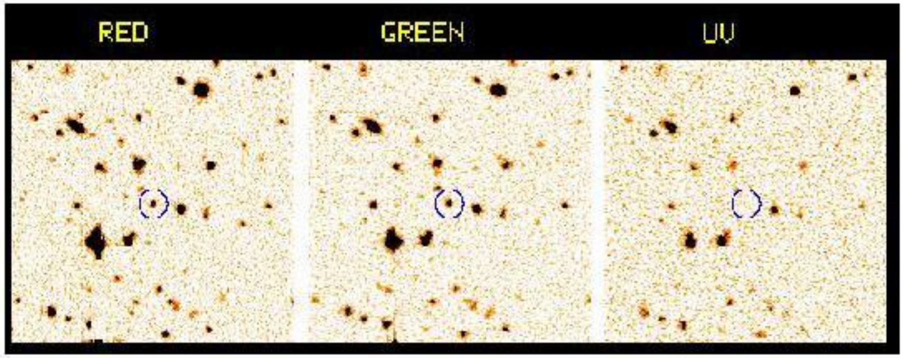
Ouchi et al (2010) Ap J 723, 869

High Redshift Star Forming Galaxies

Lyman break galaxies (LBGs):

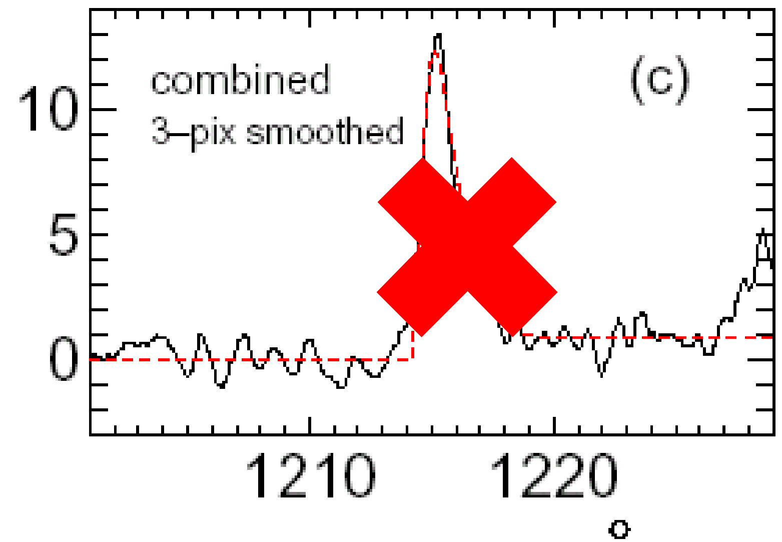
Rest-frame UV continuum discontinuity

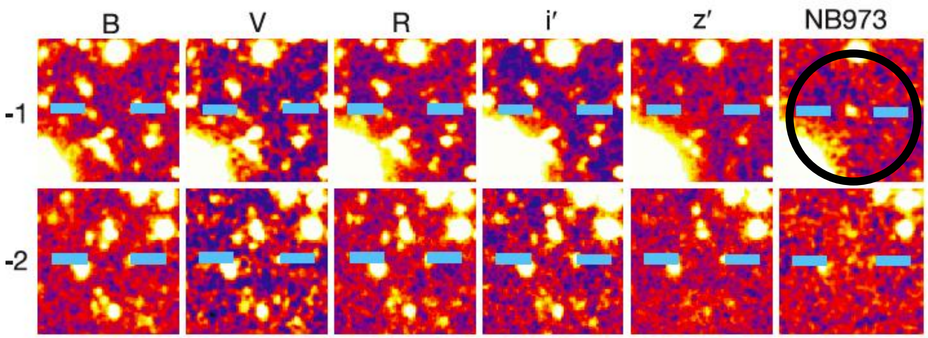




Lyman alpha emitters (LAEs):

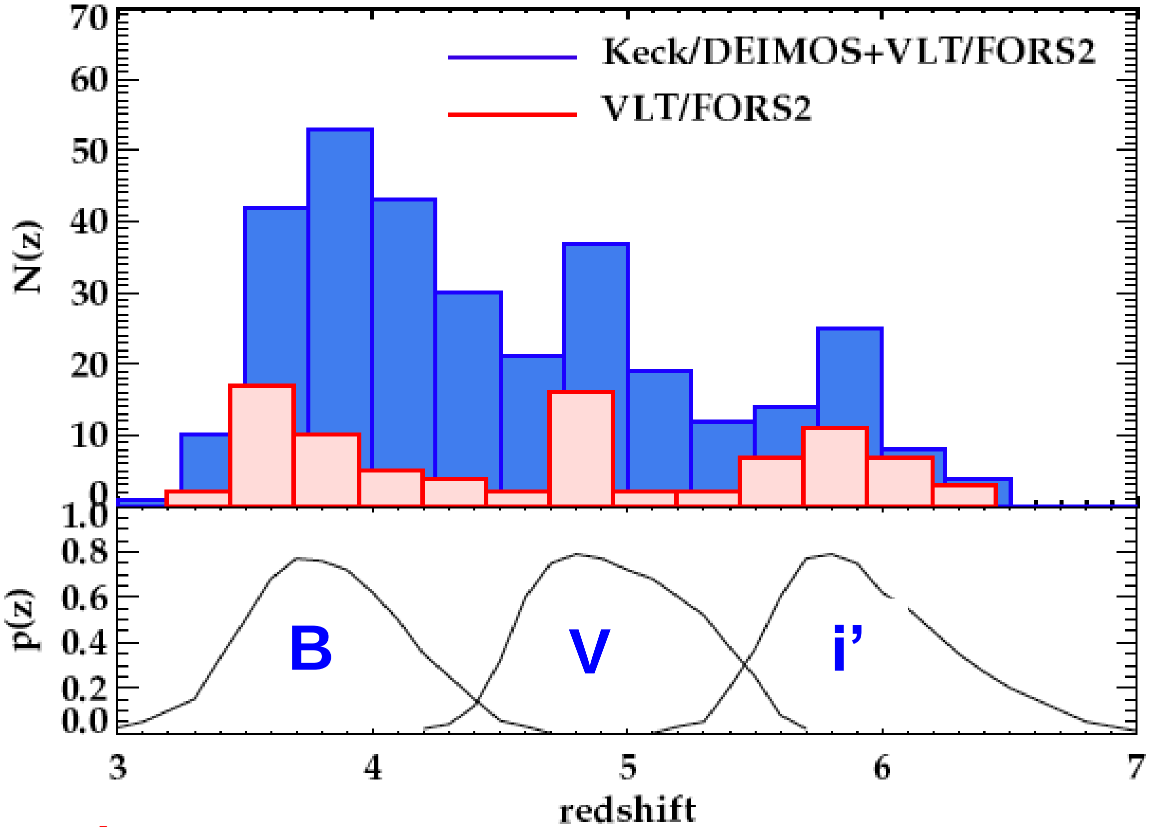
Located via narrow band imaging





Keck Spectroscopic Survey of 4 < z < 7 LBGs

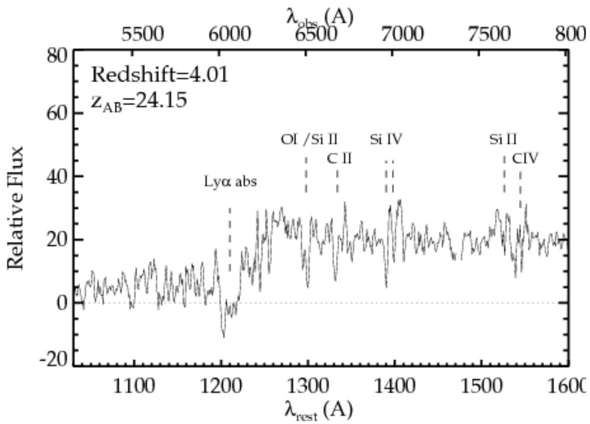
- B, V, i', z drops in GOODS/UDF from Stark et al (09) ACS/IRAC catalog
- 8-16 hr exposures with DEIMOS to m_{AB}=26.5 (emission lines to m_{AB}~27.5)
- Keck/DEIMOS: 361 B + 141 V + 45 I + 17 z-drops = 564 spectra
- VLT/FORS2 retro-selected + same criteria: 195 spectra (Vanzella et al)



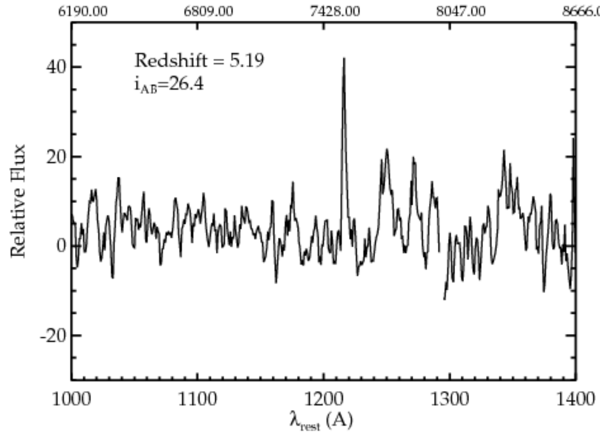
Stark et al (2010) MNRAS 408, 1628

Sample Keck Spectra (R~2500)

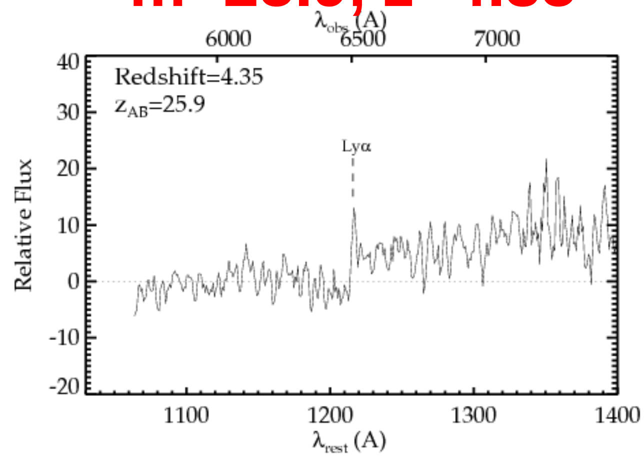
m=24.15, z=4.01



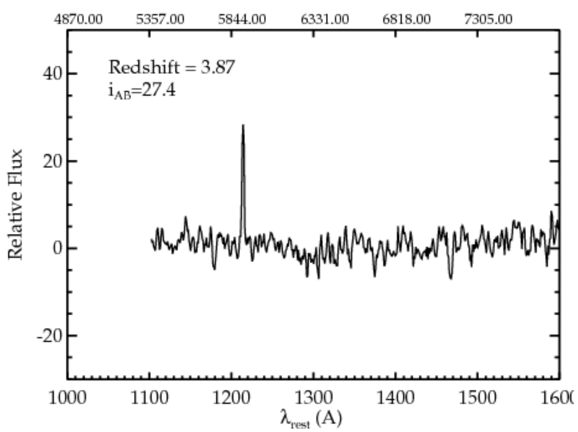
m=26.4, z=5.19



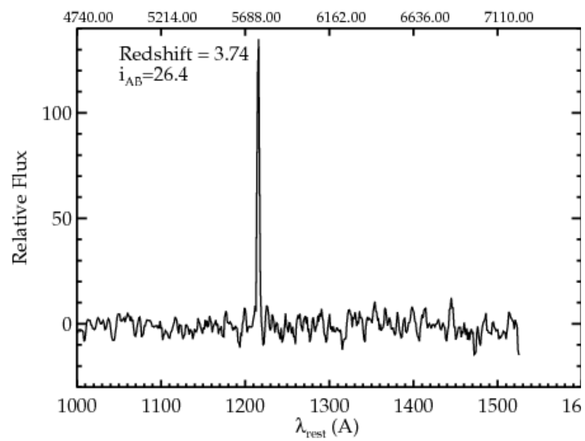
m=25.9, z=4.35



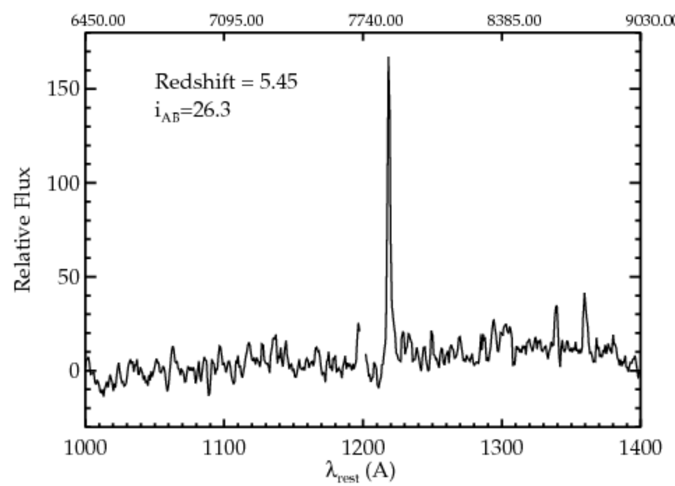
m=27.4, z=3.87



m=26.4, z=3.74

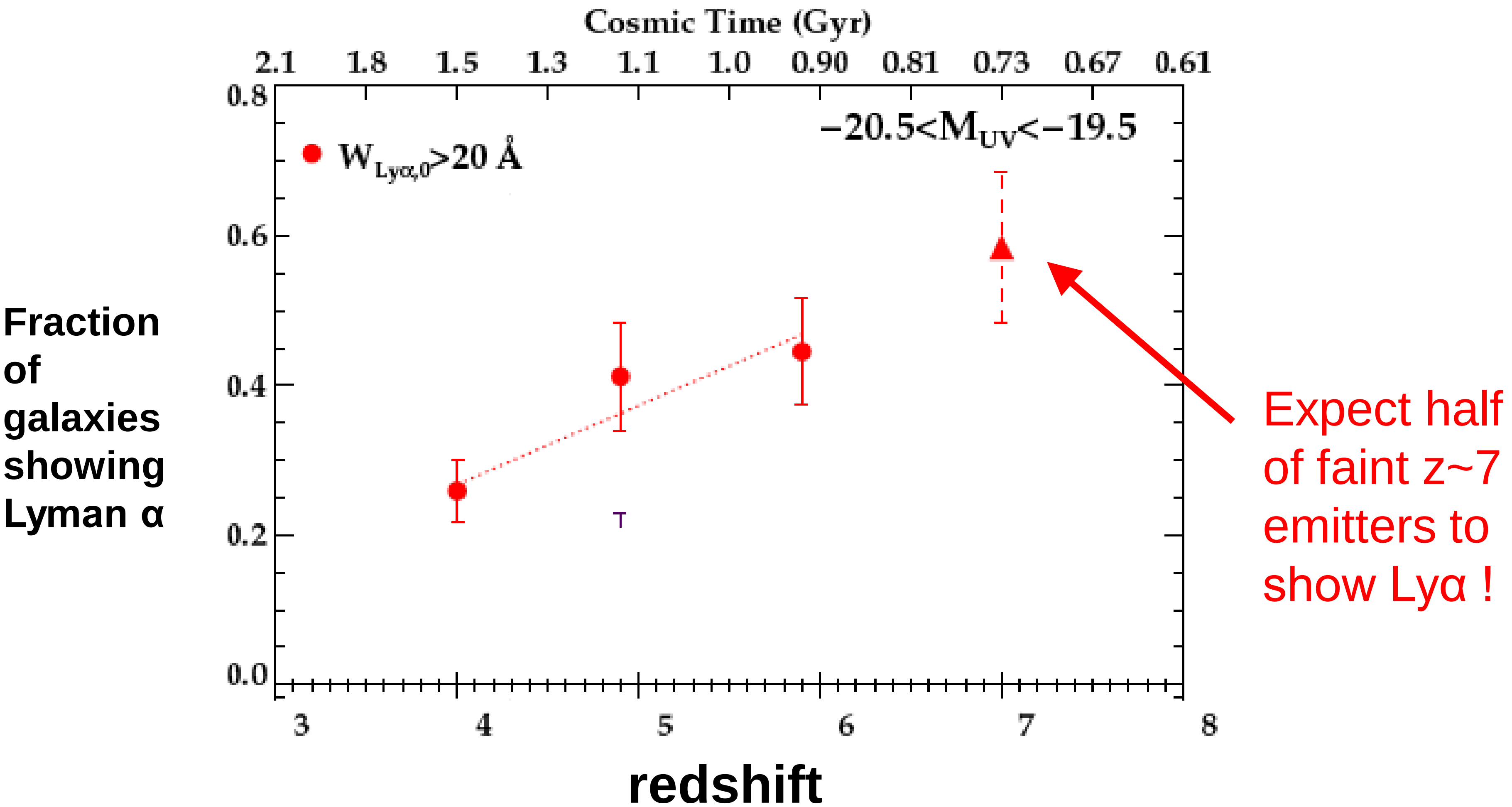


m=26.3,z=5.45



Stark et al (2010) MN 408, 1628

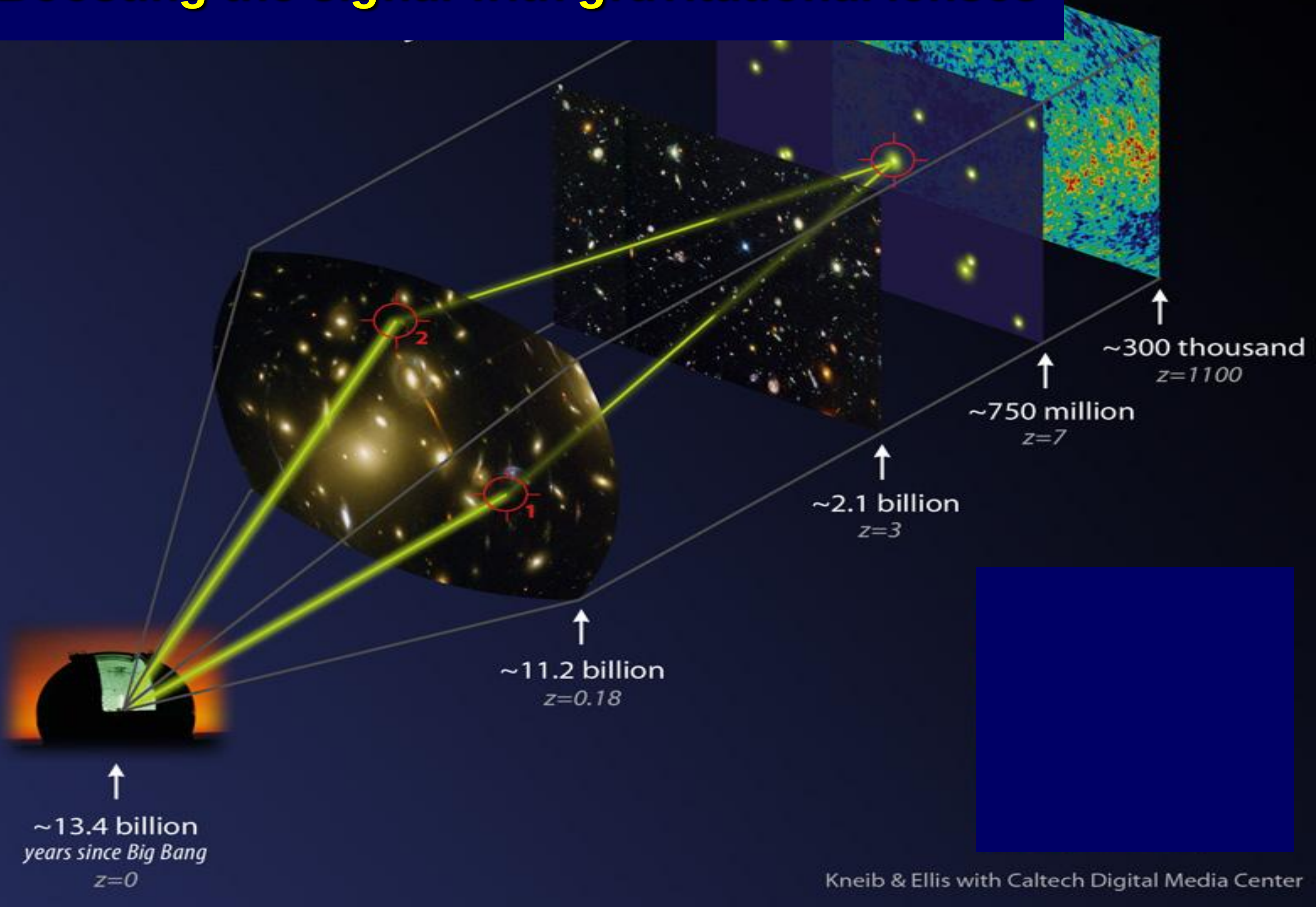
`Lyman α Visibility' versus Redshift



- We see a rising visibility with redshift to z~6
- Suggests should be straightforward to detect emission in z > 7 sources

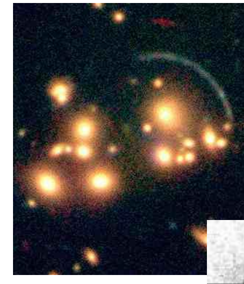
Stark, Ellis & Ouchi (2011) Ap J 728, L2

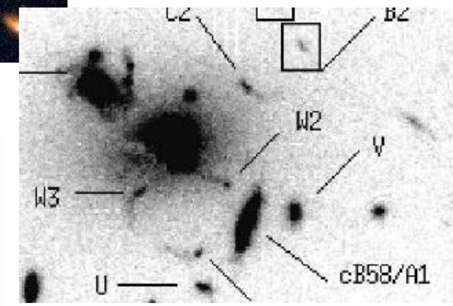
Boosting the signal with gravitational lenses

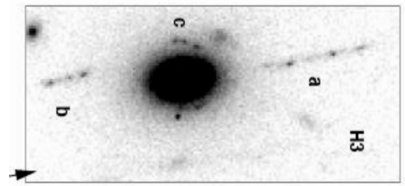


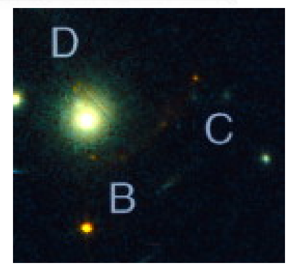
Gravitationally Lensed Galaxies: Record Breakers (1991-2008)

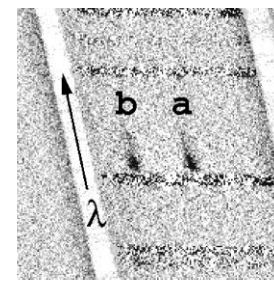
- Cl2244-02 (z=2.237); Mellier et al 1991
- A2218 #384 (z=2.515); Ebbels et al 1996
- MS1512 cB58 (z=2.72); *Yee et al 1996*, Seitz et al 1998
- A2390 (z=4.05); Frye et al 1998, Pellò et al 1999
- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- ***A2218 (z~6.8); Kneib et al 2005***
- ***A1689 (z~7.6); Bradley et al 2008***

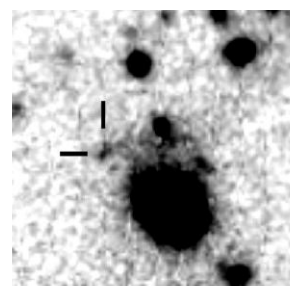


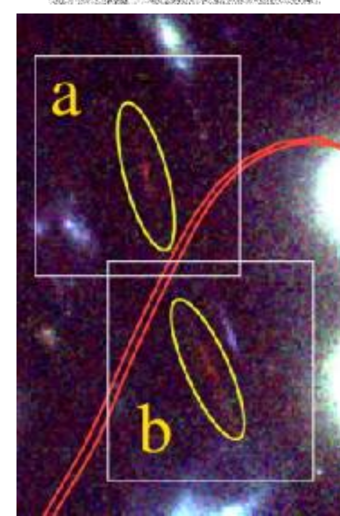






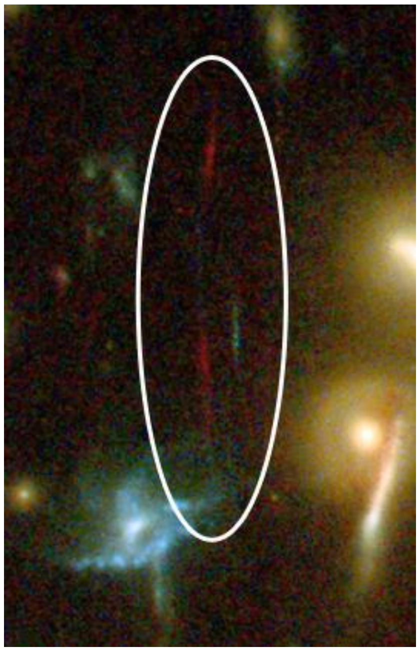


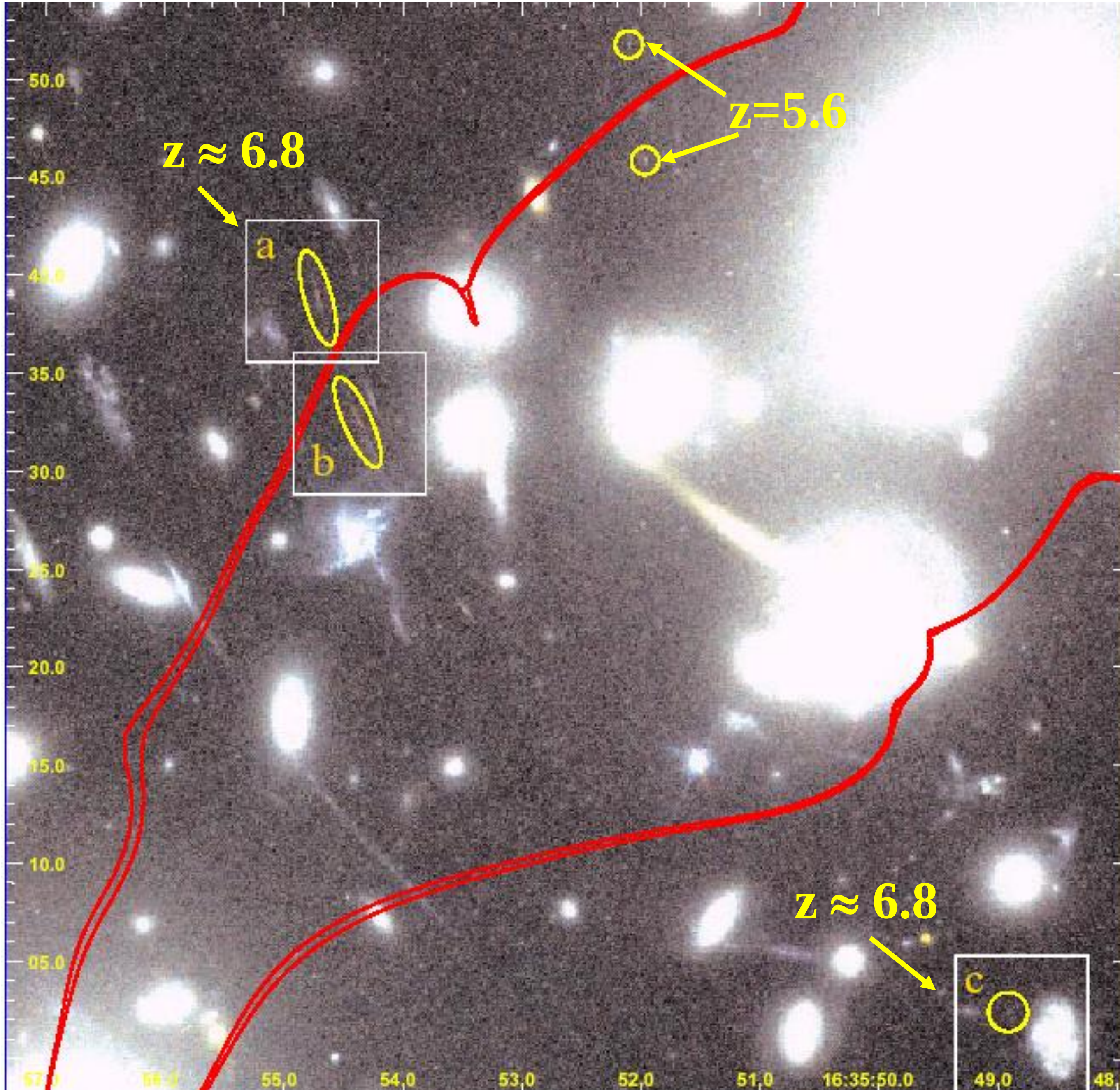




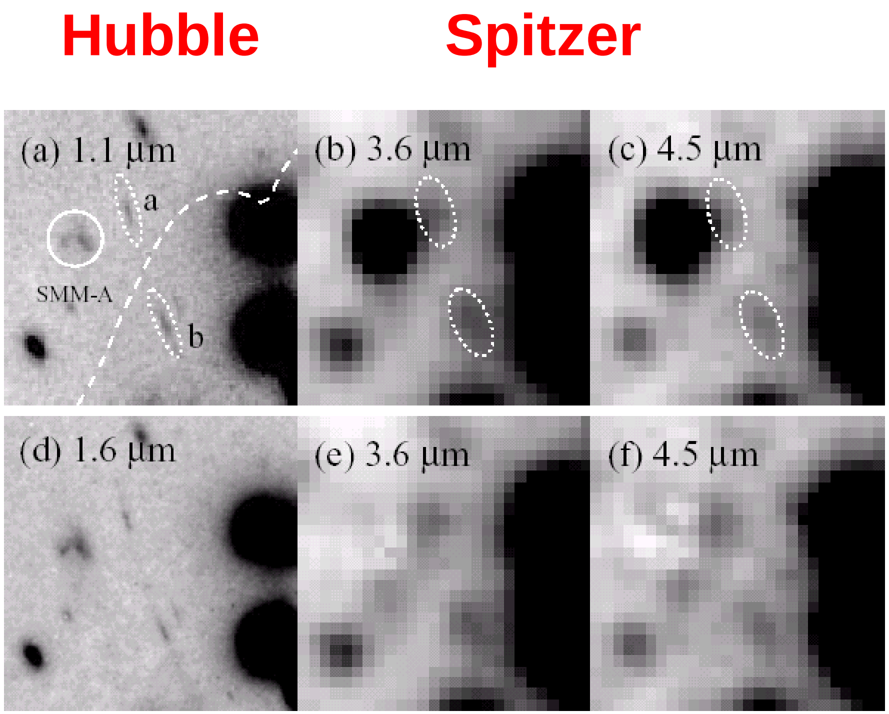
Critical line discoveries in Abell 2218

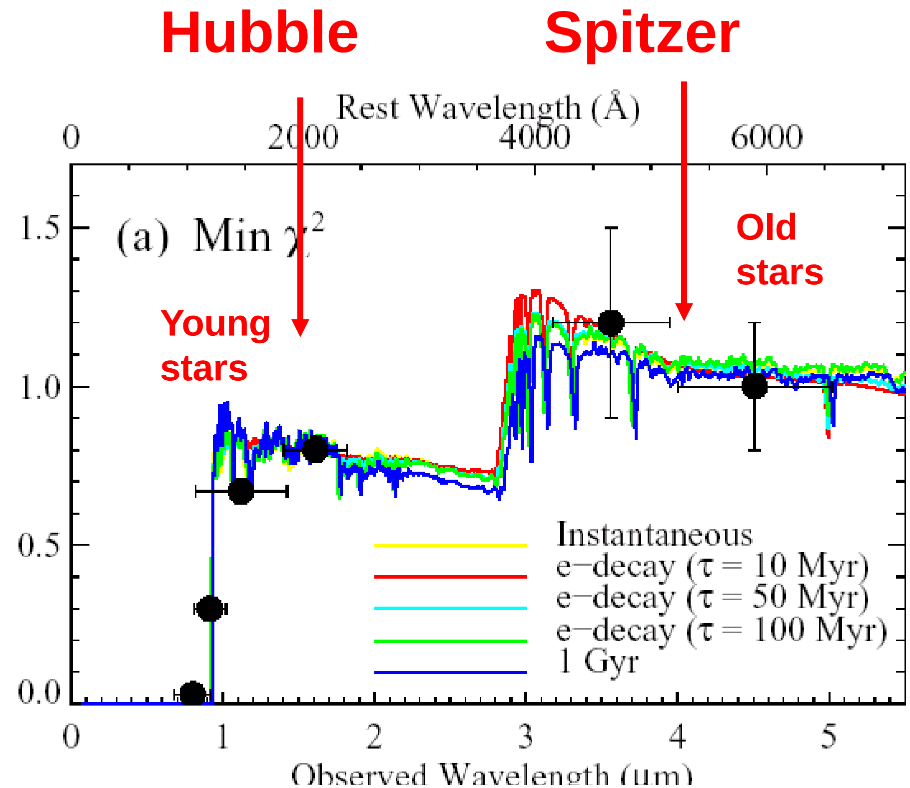
RSE et al 2001, Kneib et al 2004





Deciphering past history of z~6.8 lensed LBG





Multiply-imaged z=6.8 galaxy in cluster Abell 2218; magnification ×25

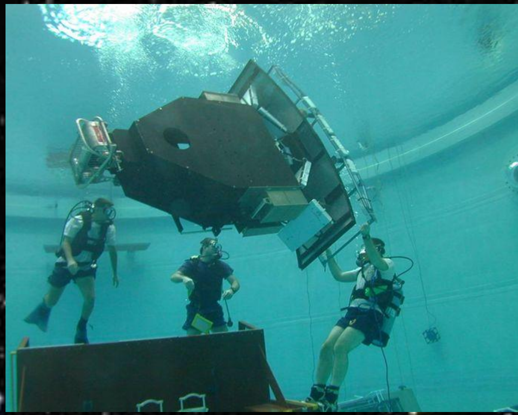
Star formation rate = 2.6 $M_\odot\,yr^{-1}$ Stellar mass ~ 5-10 $10^8\,M_\odot$

Balmer break gives age = 100 – 450 million yrs, so formed at $9 < z_F < 12$

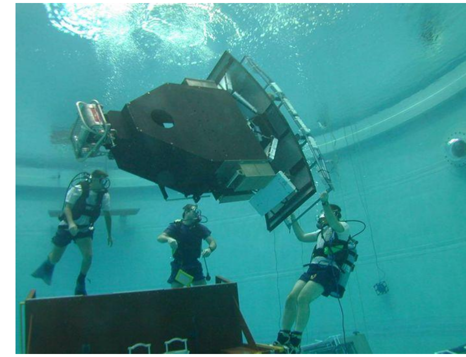
This is already a well-established system 800 Myrs after Big Bang

Egami et al (2005)

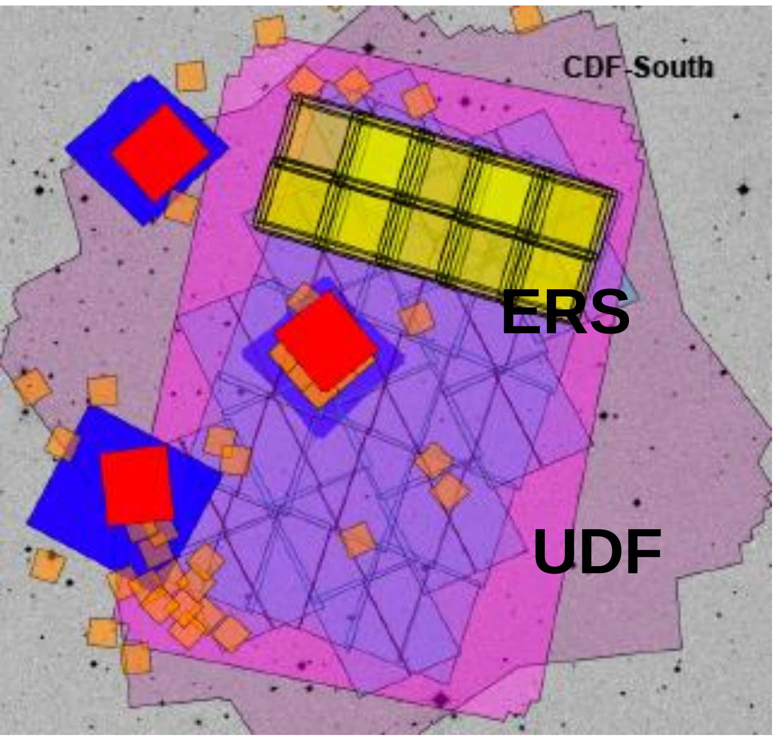
Hubble Ultradeep Field



Progress with WFC3



λλ850 - 1170nm
2.1 × 2.3 arcmin 0.13 arcsec pixel^{-1}



gain in speed c.f
OS

>100 z~7-8 galaxy candidates in UDF & associated fields confirmed by independent groups: **Bouwens** et al (2011), McLure et al (2011), **Bunker** (Wilkins et al 2011)

Hubble WFC3 High z Stampede

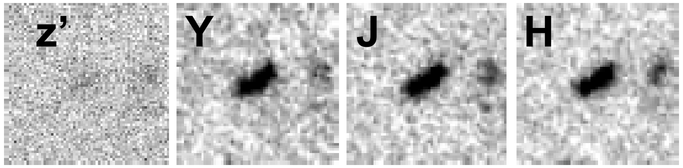
WFC3/IR: 850 - 1170nm
2.1×2.3 arcmin field of view
0.13 arcsec pixel^{-1}
10 times survey power of NIC3

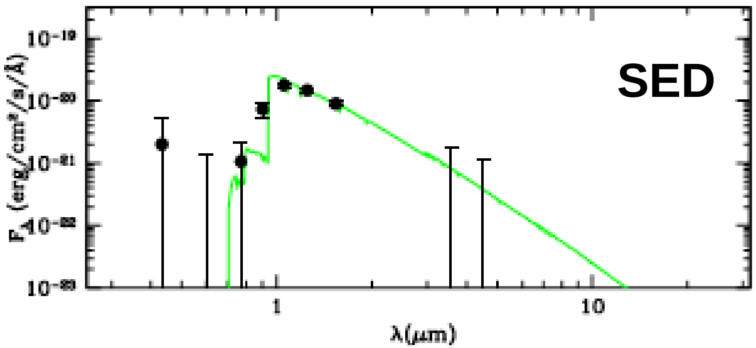
UDF 4.7 arcmin^2
60 orbits in YJH
Reaches m_{AB}~29 (5σ)

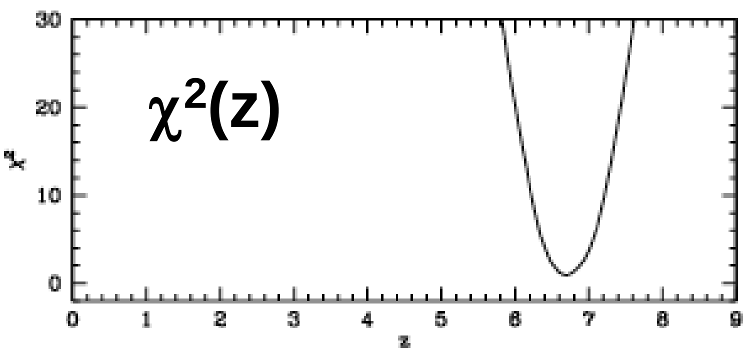
2009 Sep – Dec articles

Bouwens et al 0909.1803
Oesch et al 0909.1806
Bunker et al 0909.2255
McLure et al 0909.2437
Bouwens et al 0910.0001
Yan et al 0910.0077
Labbé et al 0910.0838
Bunker et al 0910.1098
Labbé et al 0911.1365
Finkelstein et al 0912.1338

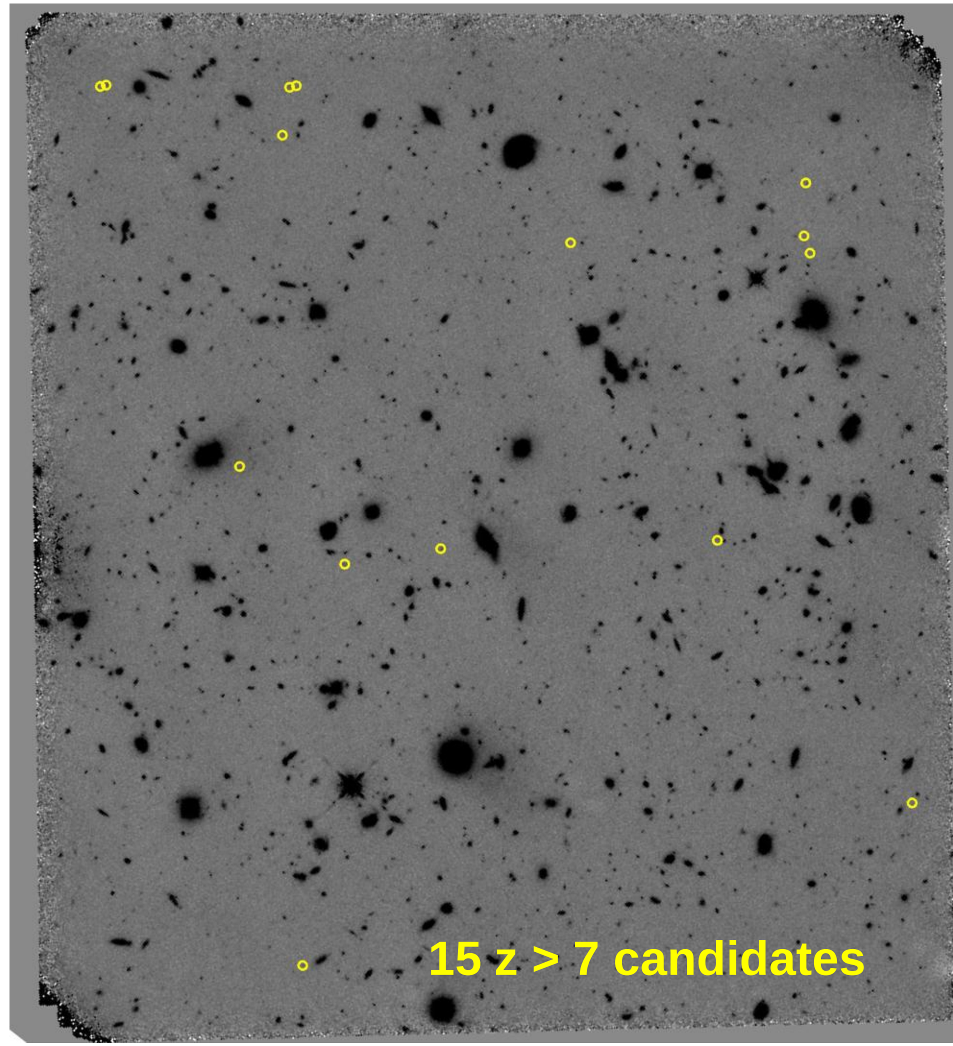
z >7 candidates from WFC3 UDF campaign







688: $z_{est} = 6.70\,(6.50 - 6.90)$



3 IR filters c.f. 2 leads to more secure photometric redshifts and reliable UV continuum slopes

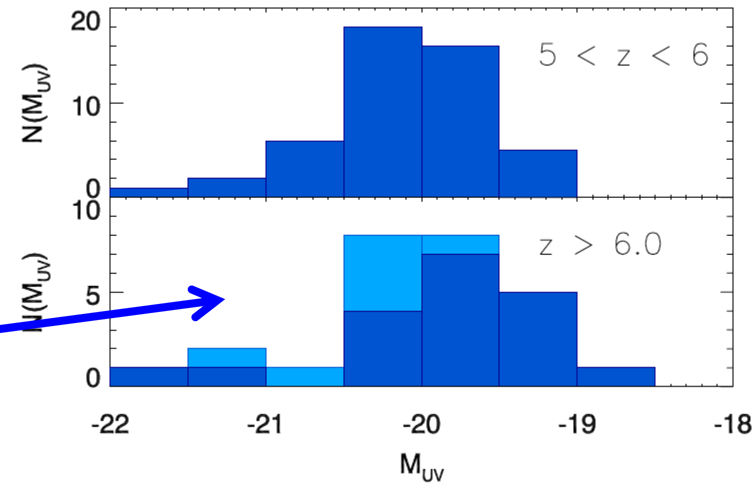
McLure et al (2009, 2010)

Spectra of 26 WFC3 selected LBGs $6.3<z_{photo}<8$

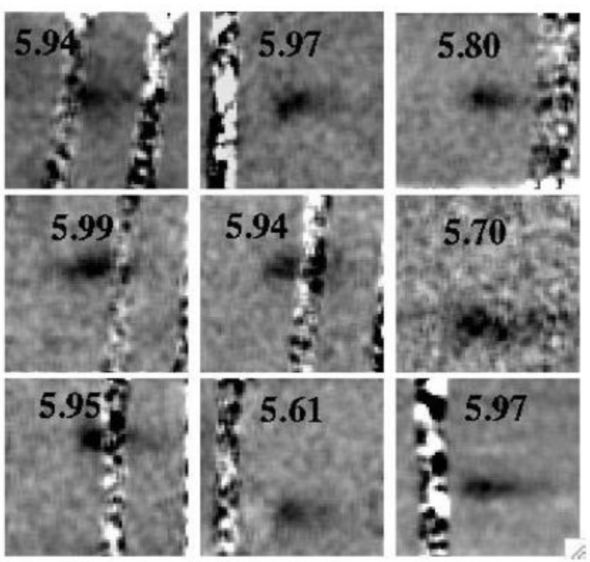
Keck NIRSPEC/LRIS-R spectra of 19 z>6.3 WFC3-IR LBGs from UDF, ERS, lensing clusters

Plus 7 Hawk-I/WFC3-IR FORS-2 spectra from Fontana et al (2010)

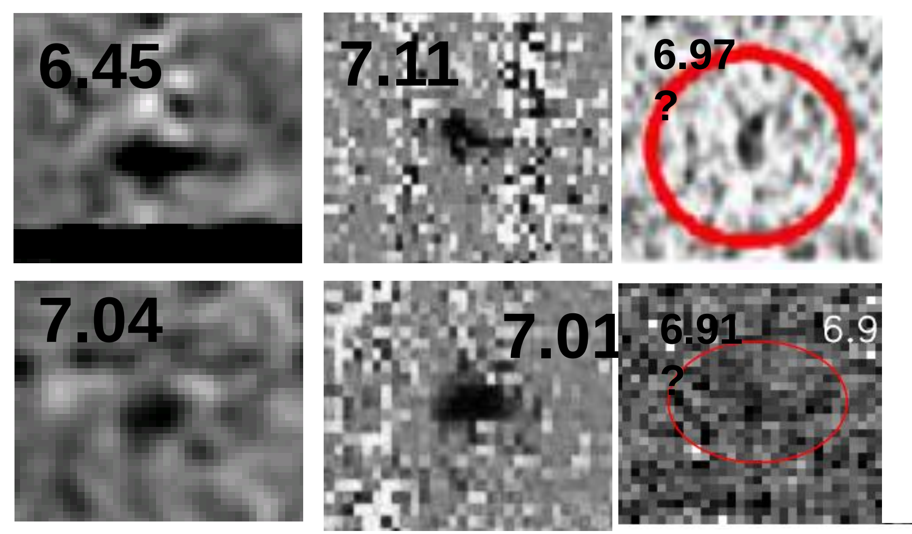
Luminosity distribution c.f. 5<z<6 sample



z~6 emitters

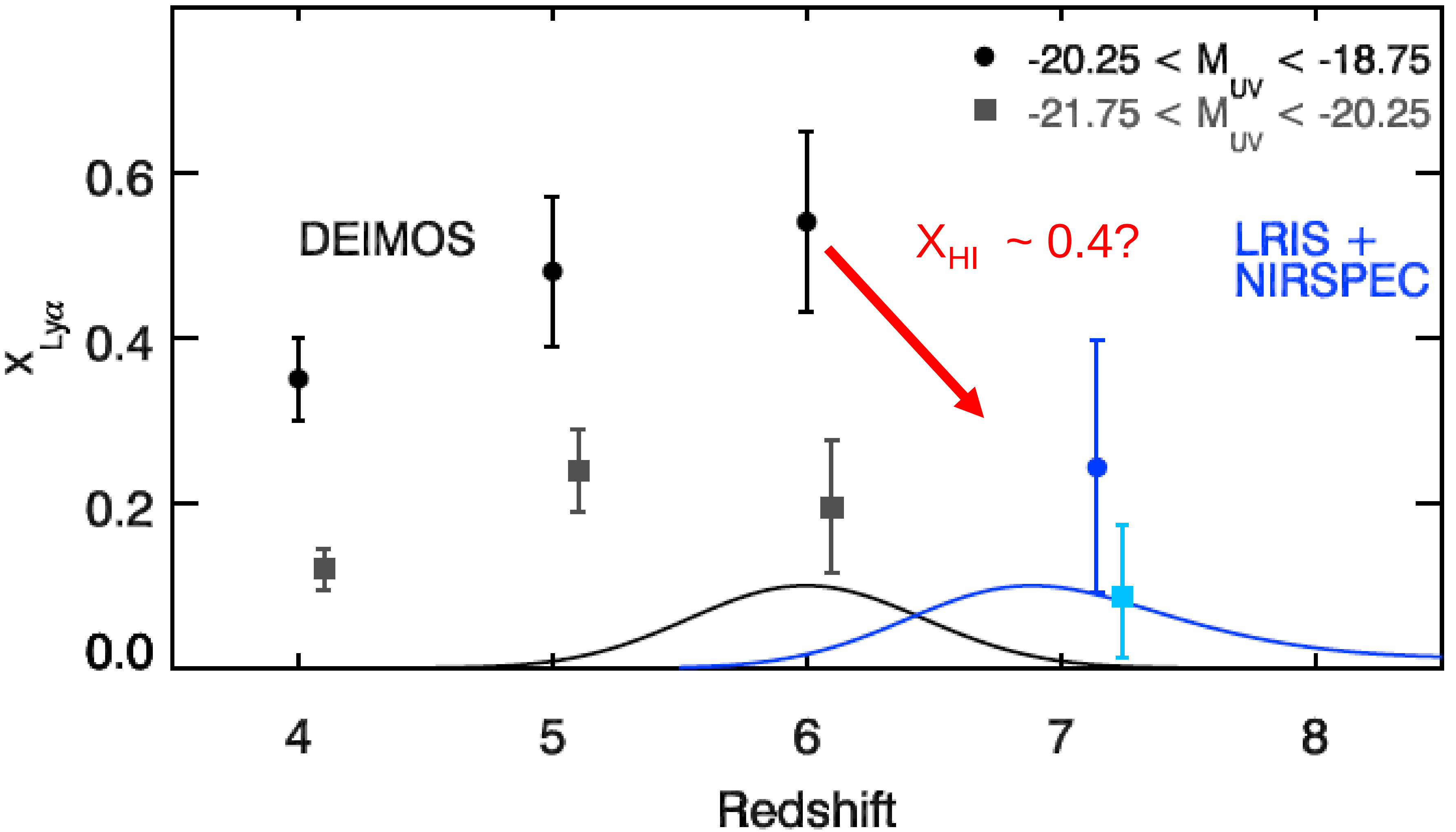


New z > 6.3 emitters



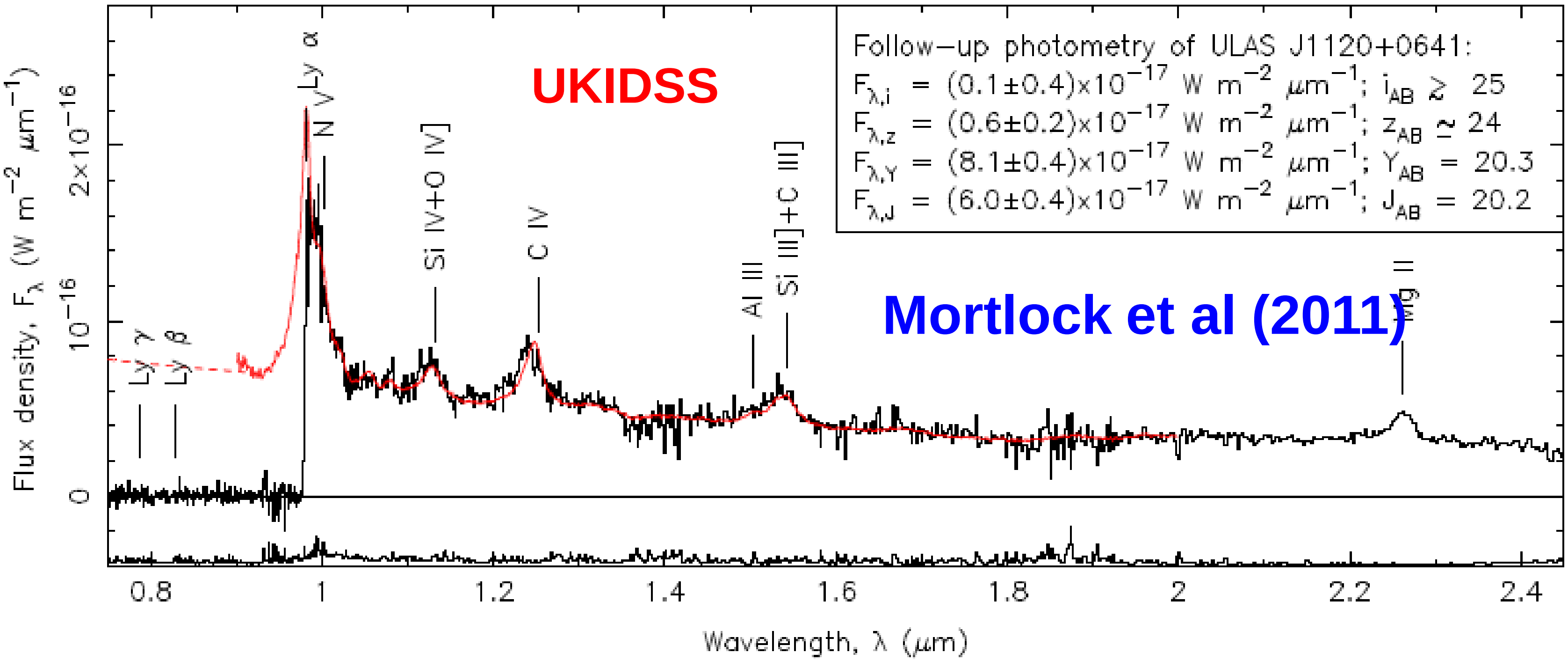
Schenker et al (2011) astro-ph/1107.1261

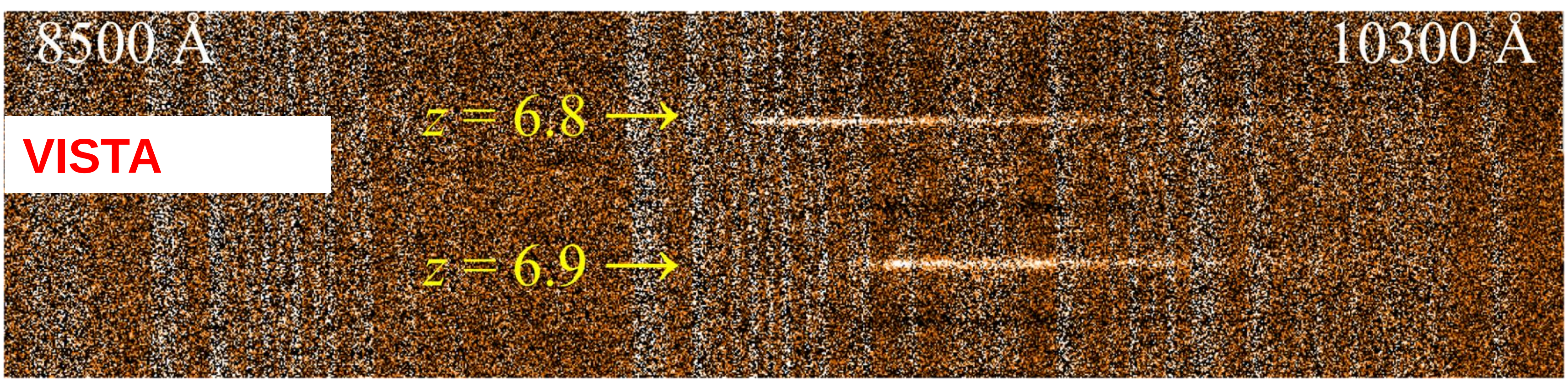
Sudden Decline in Lyα Fraction in LBGs



Schenker et al (astro-ph/1107.1261)
also Pentericci et al (astro-ph/1107.1376), Ono et al (astro-ph/1107.3159)

z~7 QSOs!

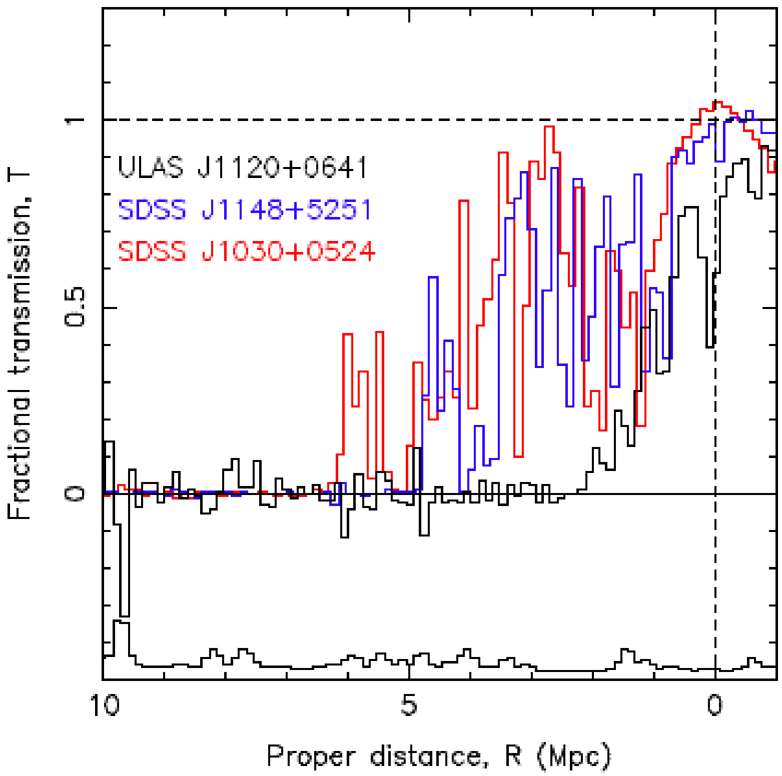


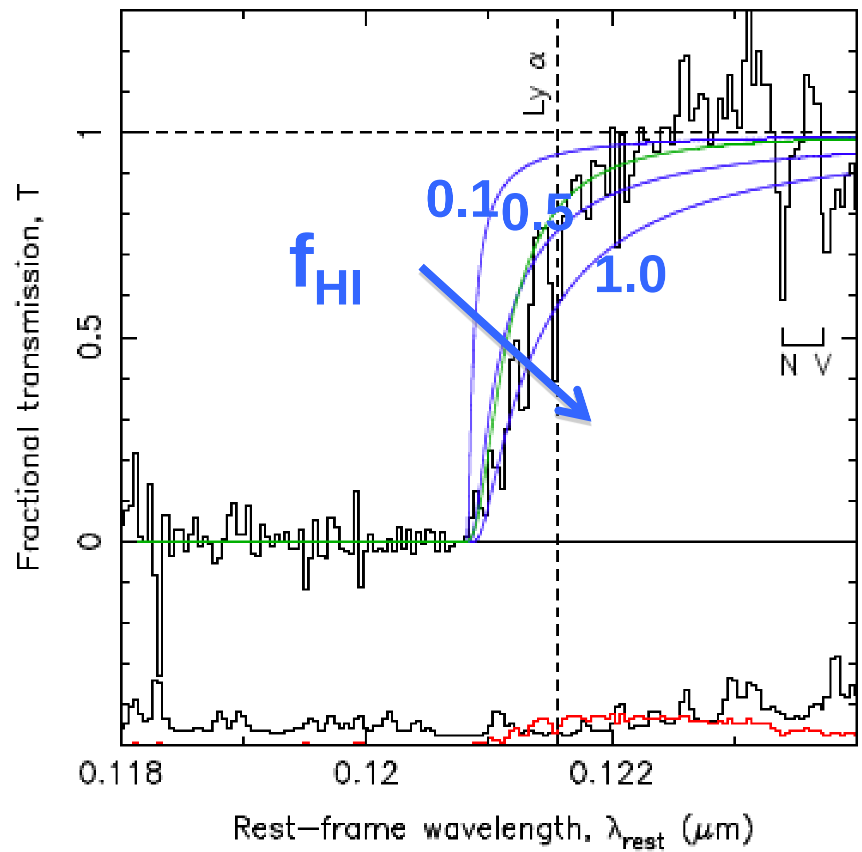


Venemans et al (in prep)

Further Evidence: Damping Wing in z=7.085 QSO?

Fit both near-zone radius & damping wing to red side of Lyα
Suggests x_{HI} > 0.1 at z~7
A proximate DLA is an alternative explanation but unlikely





Bolton et al (2011)

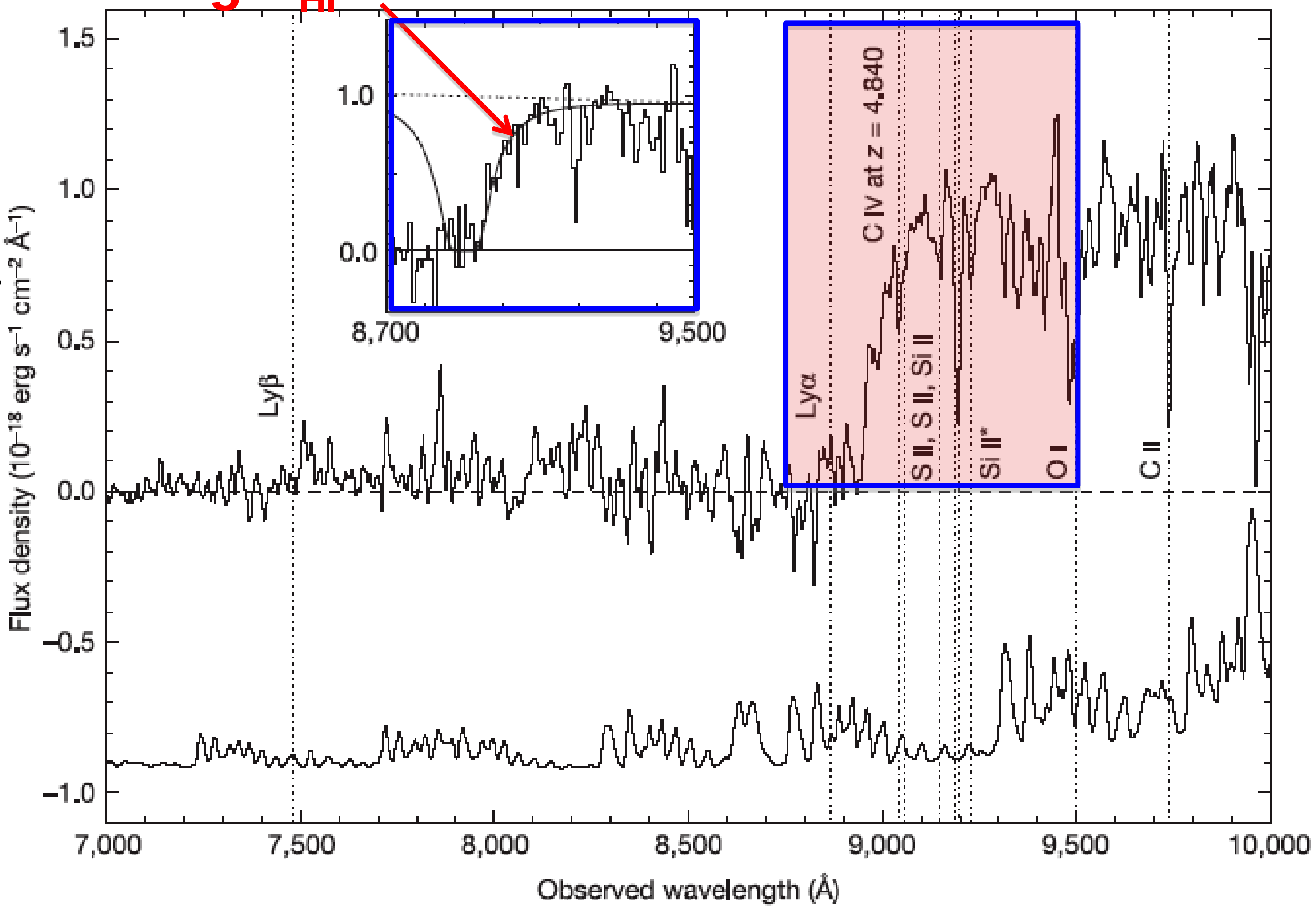
Gamma Ray Bursts

GRB050904
z=6.295

Subaru
FOCAS 4.0 hr exposure

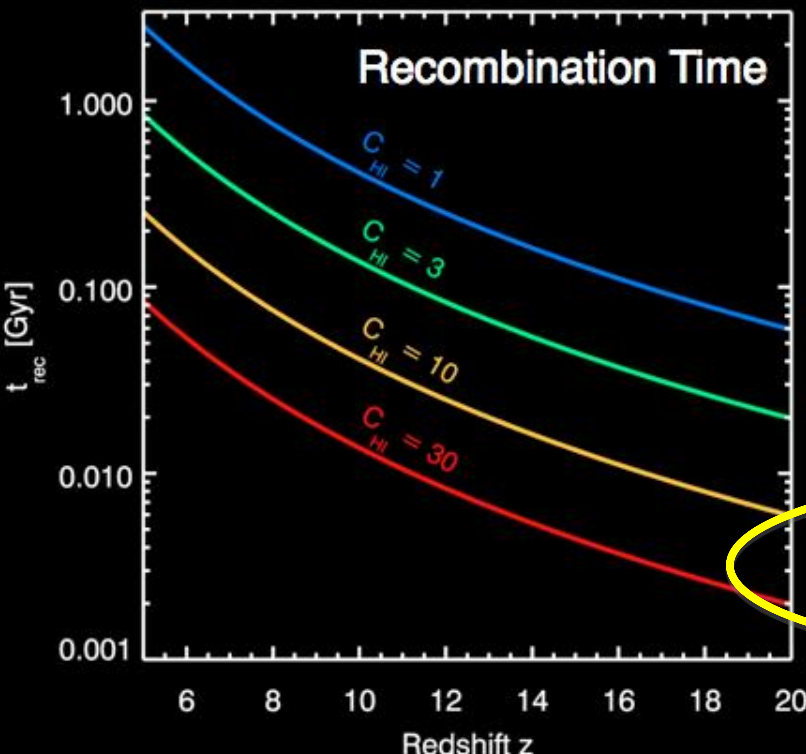
$x_{HI} < 0.6$

log N_{HI} ~21.3



Kawai et al (2006) Nature 440, 184

How Does Cosmic Reionizaton Occur?



Ionization Fraction Evolution

$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = \frac{1}{\langle n_{\mathrm{HII}} \rangle} \frac{\mathrm{d}n_{\mathrm{ion}}}{\mathrm{d}t} - Q_{\mathrm{HII}} C_{\mathrm{HII}} \frac{\langle n_{\mathrm{HII}} \rangle}{a^3} \alpha_{\mathrm{B}}(T)$$

Comoving H density

Scale factor

Case B recombination coefficient

Ionizing Photon Density

$$\frac{\mathrm{d}n_{\mathrm{ion}}}{\mathrm{d}t} = f_{\mathrm{esc}} \zeta_Q \rho_{\mathrm{SFR}}$$

Escape fraction

Ionizing photon production rate

Comoving star formation rate density

$$t_{\mathrm{rec}} = [(1 + 2\chi_{\mathrm{He}}) \langle n_{\mathrm{HII}} \rangle \alpha_{\mathrm{B}}(T) C_{\mathrm{HII}}]^{-1}$$

Helium fraction

Clumping Factor $C_{\mathrm{HII}} \equiv \dfrac{\langle n_{\mathrm{HII}}^2 \rangle}{\langle n_{\mathrm{HII}} \rangle^2}$

~1-6 (Pawlik et al. 2009)

Robertson et al (2010)

Madau et al. 1998, Bolton & Haehnelt 2007

Requirements for Reionization by Galaxies

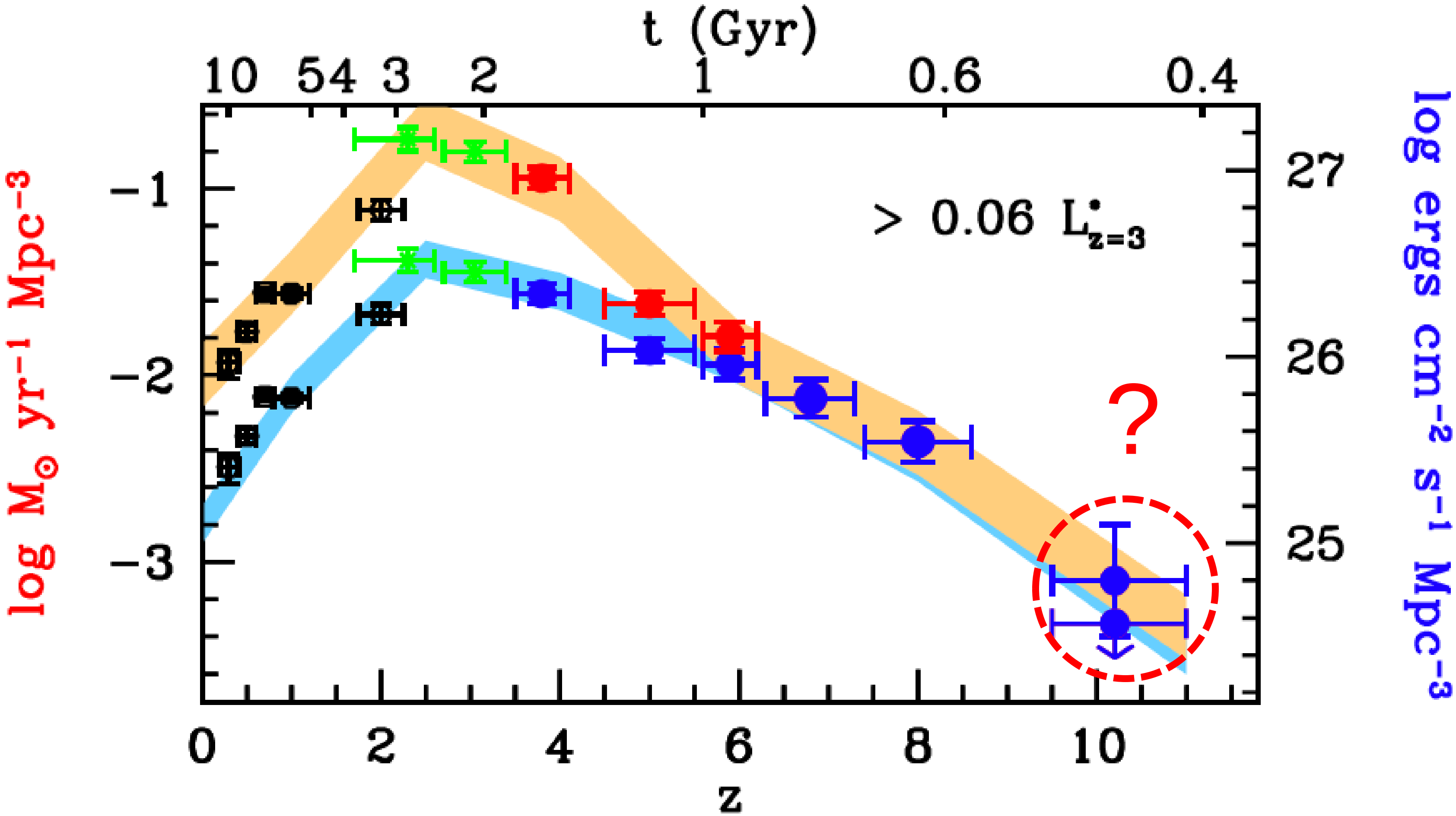
3 basic requirements to test hypothesis:

- A sustained output from star-forming galaxies over $7<z<10$ (continuity in SF trends over $\Delta t \sim 300$ Myr)
- A steep faint end slope ensuring high fraction of UV photons arises from abundant sub-luminous sources ($\alpha < -1.8$), i.e. $\boldsymbol{\rho}_{\mathbf{SFR}}$
- A good understanding of the stellar populations, for example: is there a increased number of massive stars at high z such as might be expected in very metal poor young systems? i.e. $\boldsymbol{\zeta}_{\mathbf{Q}}$
- A high escape fraction of ionizing photons $\mathbf{f}_{\mathbf{esc}}$

Prospects for resolving ambiguities in next 2-3 years is promising via

- first UDF campaign (Cy 18, Illingworth 105W, 125W, 160W)
- shallower CANDELS MCT campaign (Faber/Ferguson)
- deeper targeted UDF campaign (Cy 19, Ellis, 105W, 140W, 160W)

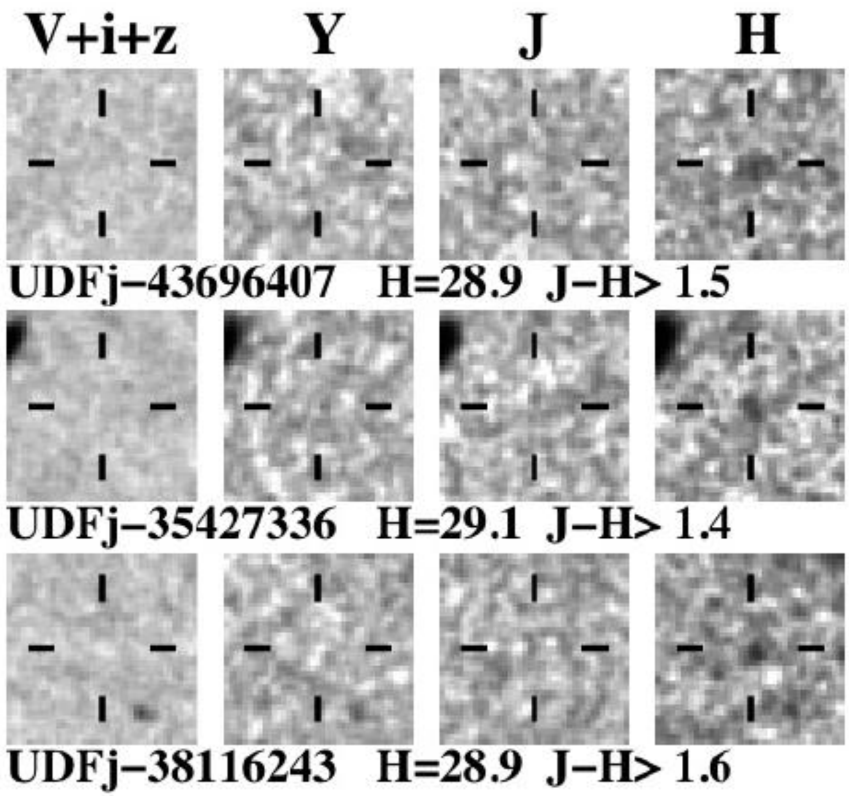
Sustained Output from SF Galaxies 3 < z < 10

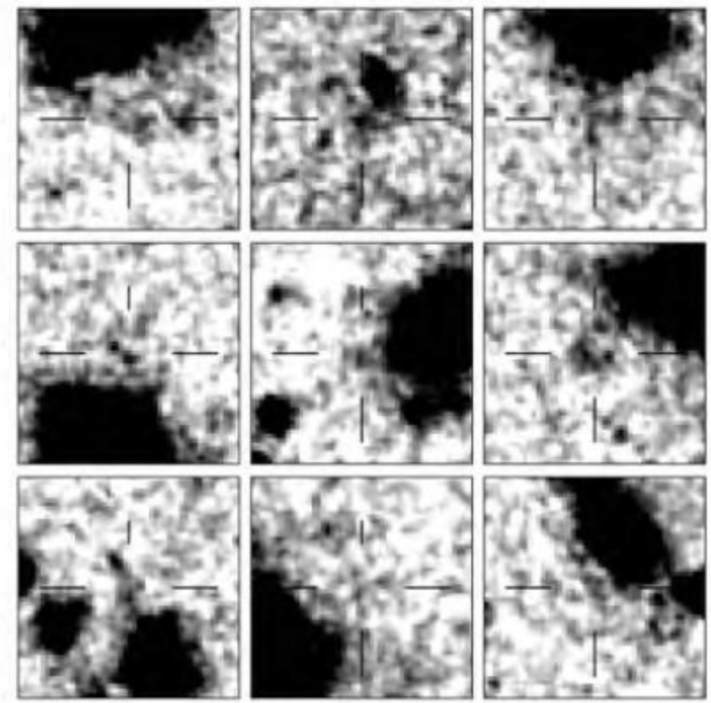


66 z~7 and 47 z~8 candidates in deep HUDF + parallel fields (AB~29, 4 arcmin^2) & shallower ERS area (AB~27.5, 40 arcmin^2)

Bouwens et al astro-ph/1006.4360

An aside: z~10? Bouwens et al vs Yan et al





Bouwens et al 0912.4263

Yan et al 0910.0027

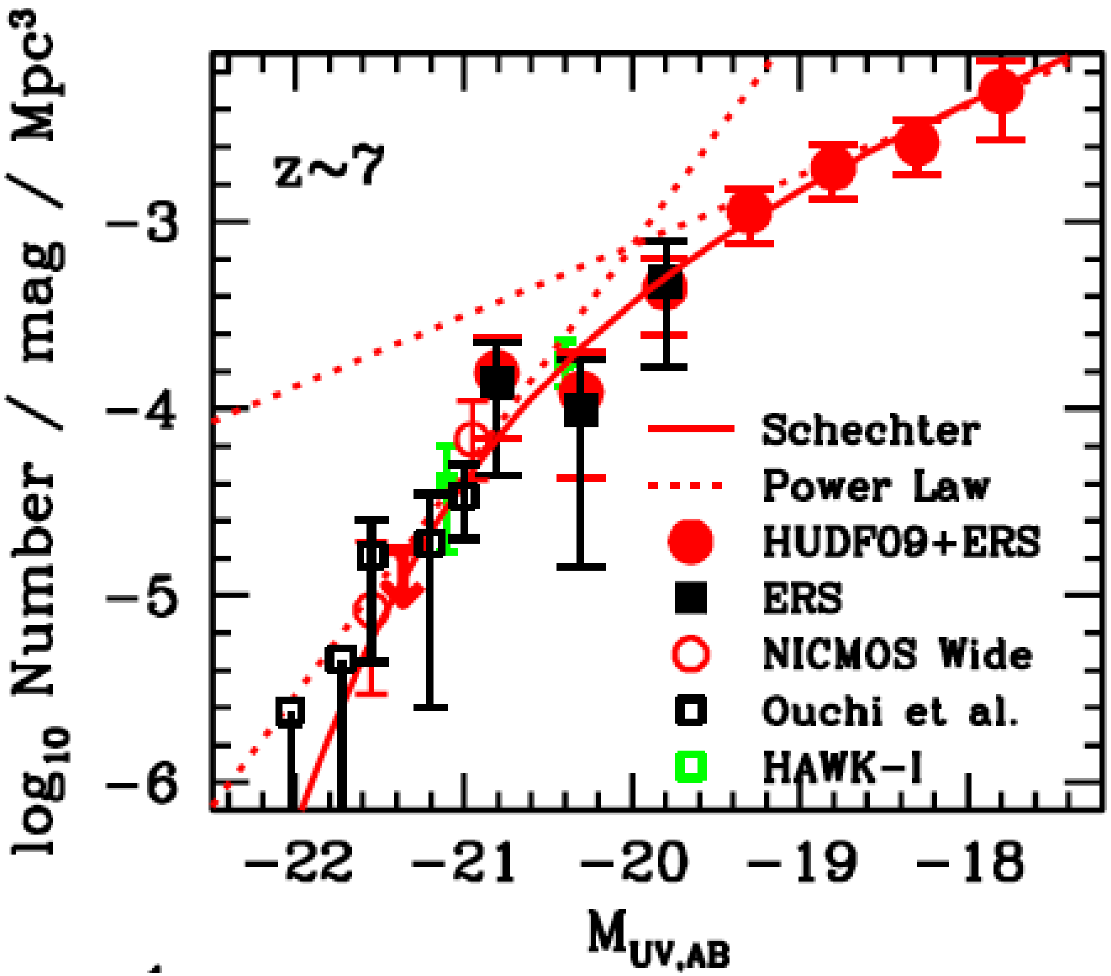
Bunker et al: no convincing J-drop candidates to H~28.5

Yan et al: 20 J-drops to H~29

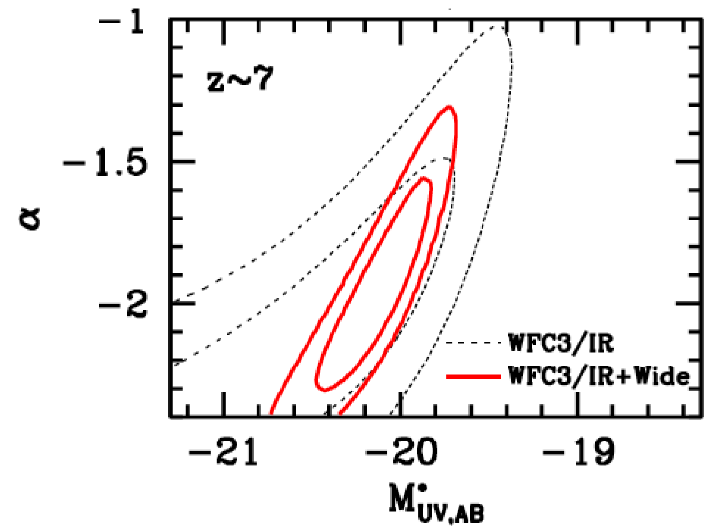
Bouwens et al: 3 J-drops to H~29

One band detections and not a single candidate in common!

Steep Luminosity Functions @ z~7



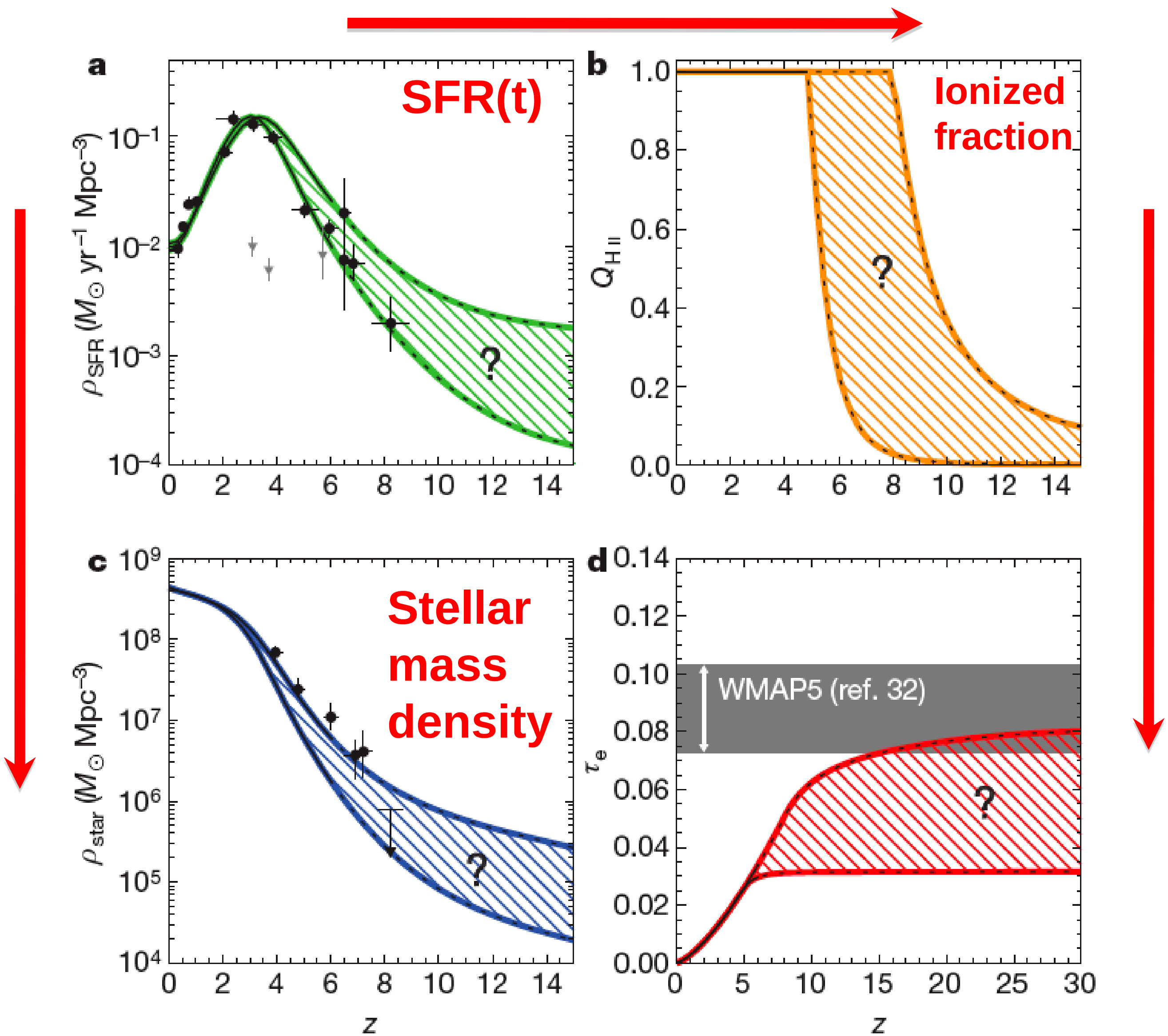
Utilizing deep + shallow WFC3/IR plus Subaru



Steep faint end slope: low star formers <1 $M_\odot$ yr^{-1} dominant

Ouchi et al 2009 Ap J 706, 1136; Bouwens et al astro-ph/1006.4360 plus many earlier papers (Oesch, Bunker, McLure…) also poster by Yan

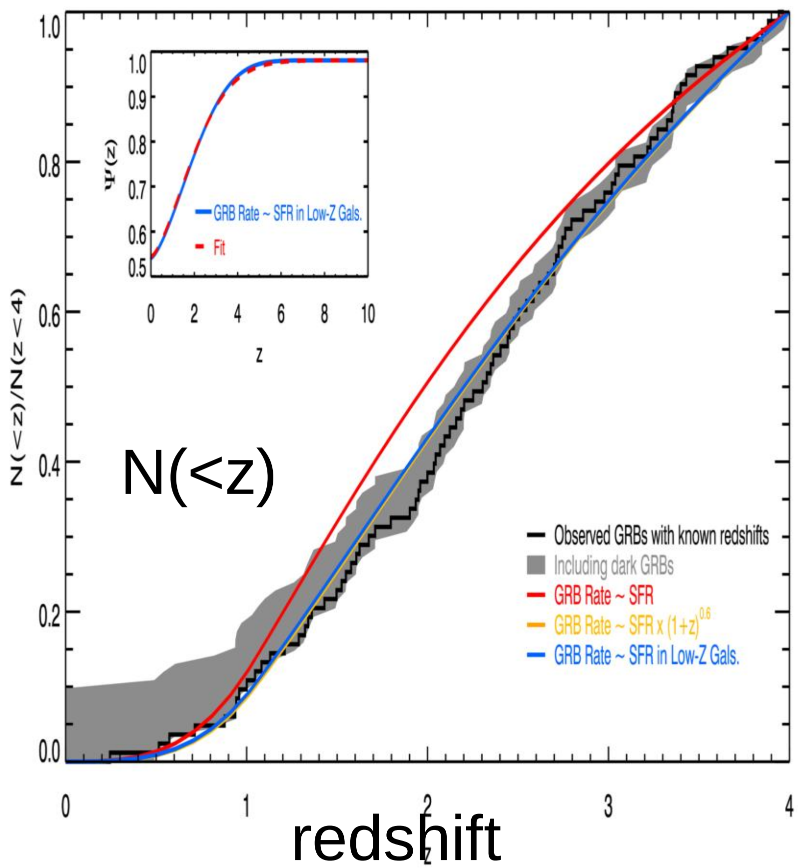
Did Galaxies Reionize the Universe?

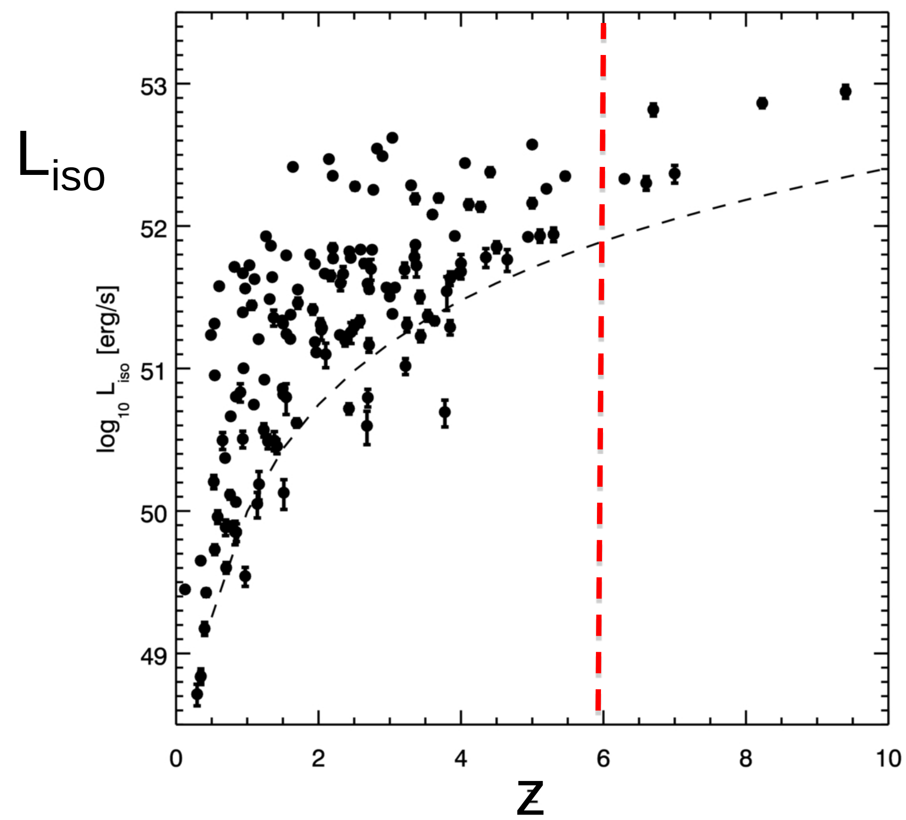


Robertson et al (2010) : some tensions even assuming f_{esc}=0.2, C_{HII} = 2

Constraining Early Star Formation from GRBs

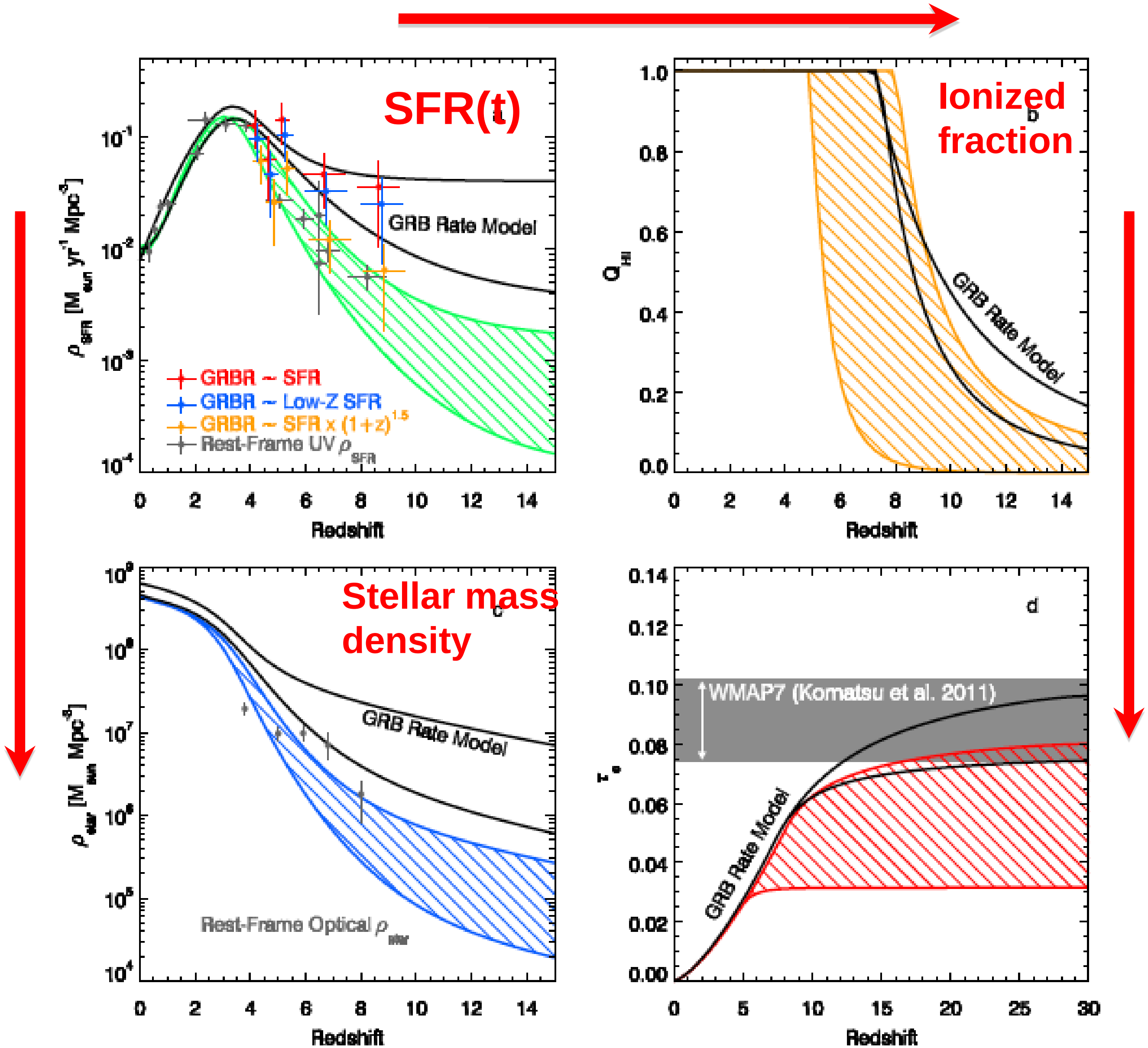
N(<z) for 152 GRBs (plus dark sample) matches integral of SFH 0<z<4 (best fit for low metallicity sources following z-dependent MMR).
Allows us to interpret rate of GRBs with z>6.





Robertson & Ellis (astro-ph/1109.0990)

A Gamma Ray Burst Version?



High number of z>6 GRBs implies more SF than HST has seen and matches WMAP τ but seriously overproduces Spitzer measured stellar mass

Robertson & Ellis (astro-ph/1109.0990)

What could make up the photon shortfall?

- Some component of WMAP τ (~0.02?) may come from first generation of massive stars; not all has to arise in $7<z<10$ galaxies
- Steeper than observed faint end slope of LF?
- Exotic stellar populations (e.g. top heavy IMF)?

Failing this, we'd have to consider a second source of reionizing photons

Future Prospects

- HST + WFC3:

  - Deeper UDF campaign will probe fainter sources and clarify UV slope

- Continued improvement in 4<z<7 spectroscopic surveys:
  much to learn about demographics of LBGs/LAEs including spatial mapping of populations (Subaru PFS + Keck DEIMOS)

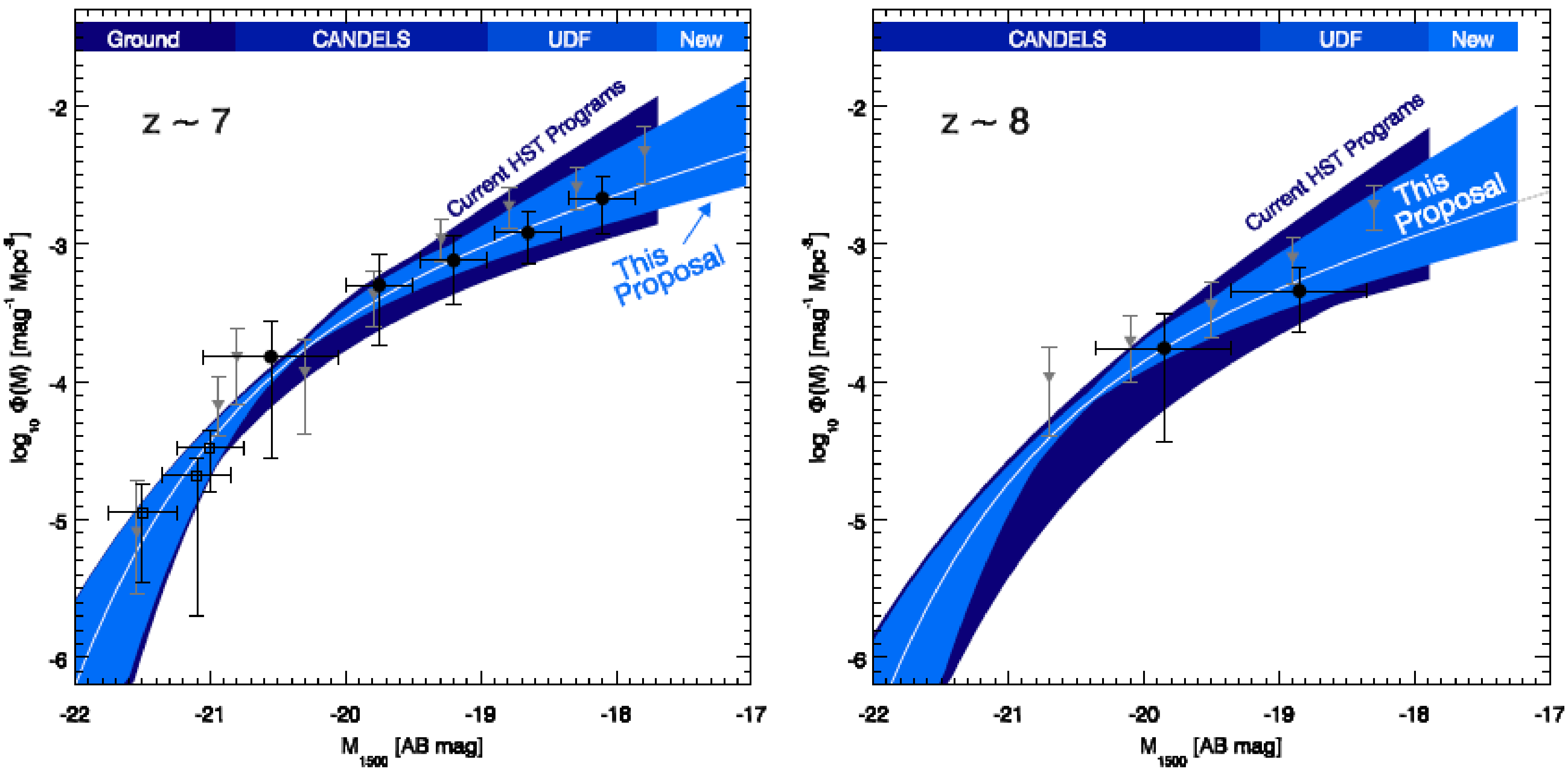
- Multi-slit IR spectrographs for following existing and other z>7 candidates

  - MOSFIRE on Keck (2012A)

- JWST (2018??) and..not too far off..(2020)..TMT

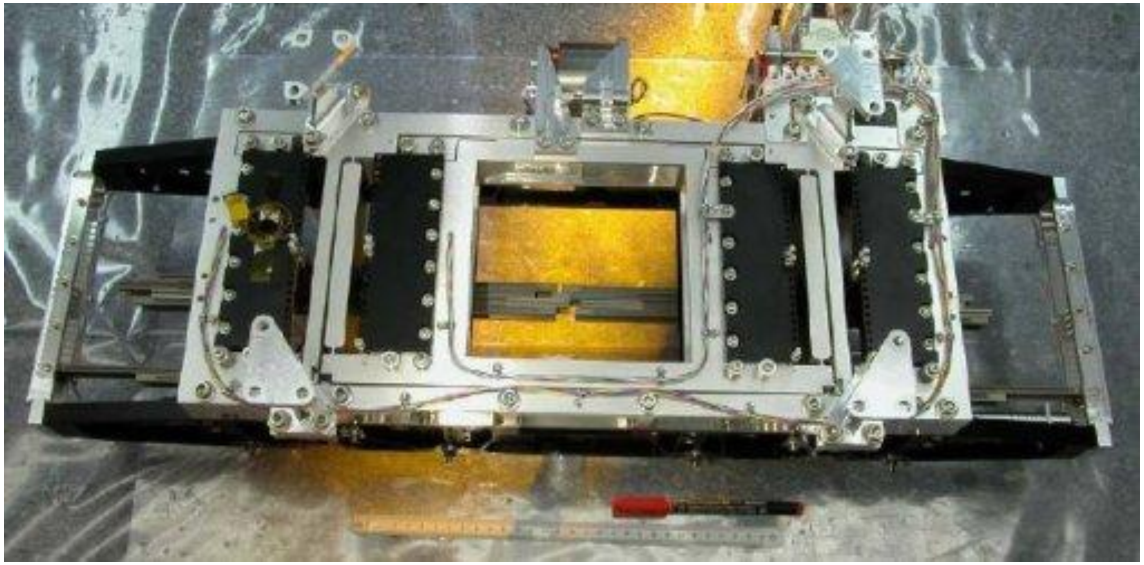
LOTS TO LOOK FORWARD TO!

Projected LFs @ z~7-8 with New HST campaign



- Very steep LFs (α ~ -2) necessary to close reionization budget
- Statement is highly dependent on assumed f_{esc}
- Current uncertainty in faint end slope Δα ~ 0.2-0.3 (Bouwens, McLure)
- New UDF program (128 orbits) will provide improved faint end constraints

MOSFIRE (Keck I) – Jan 2012



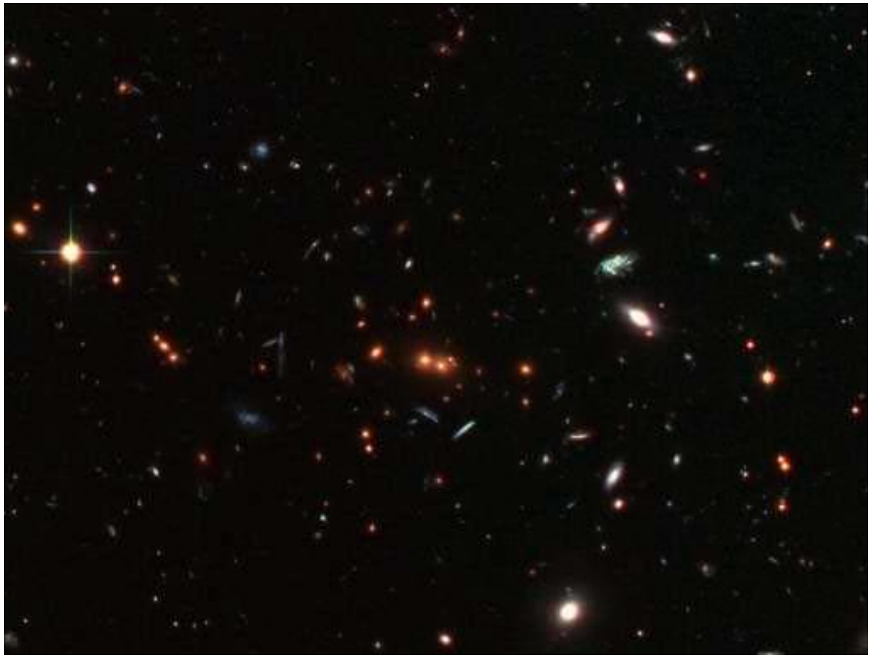
Cryogenic Multi-slit IR spectrograph

6.1 x 3.1 arcmin spectroscopic field

$\lambda\lambda$0.97 - 2.45 microns

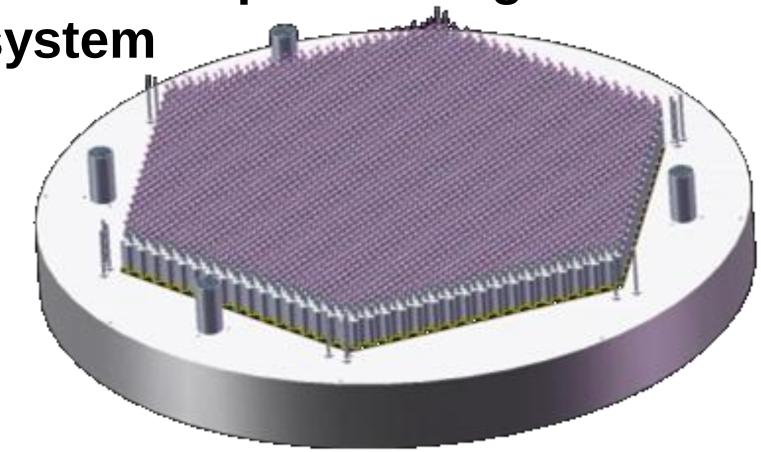
R ~3300 for 0.7 arcsec slit

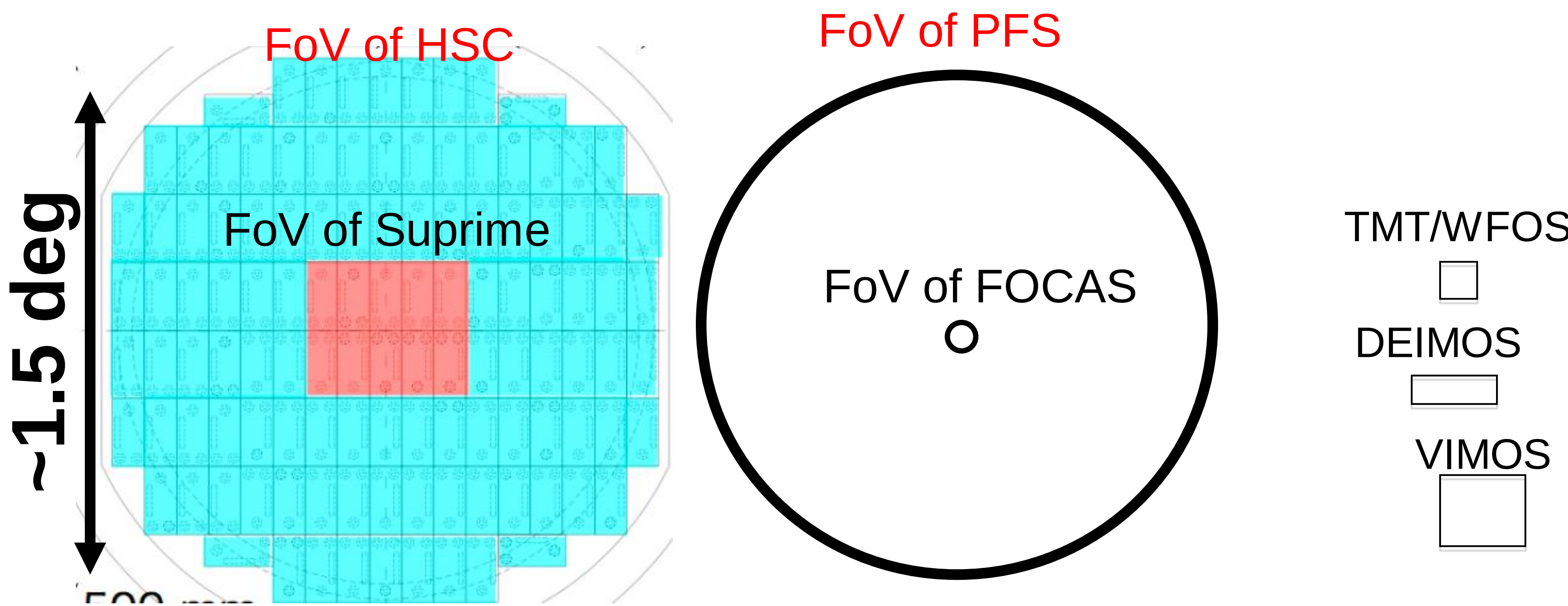
45 slits via configurable slit unit (<5mins)



Subaru Wide Field Instrumentation

2400 fiber positioning system





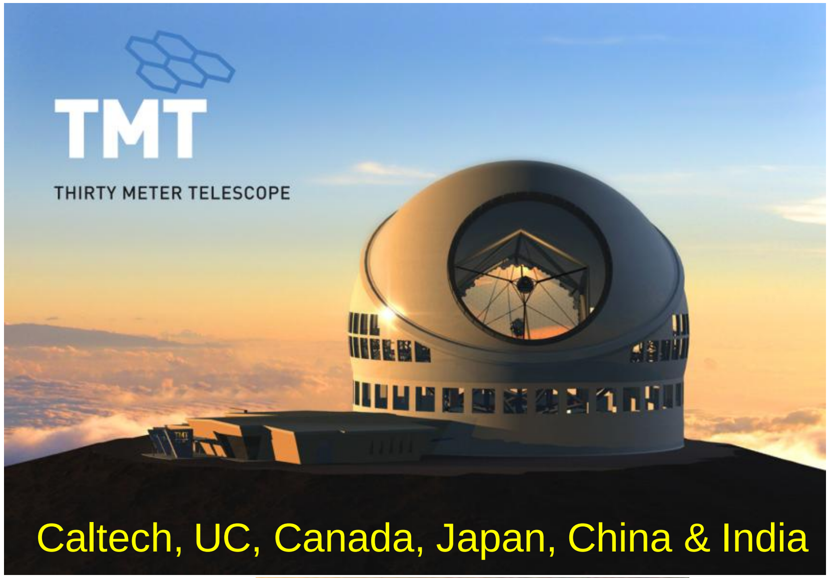
AO impacts JWST-TMT Synergy

TMT with AO will have <u>better resolution</u> than JWST (*not a dream: Keck AO has better resolution than HST*)

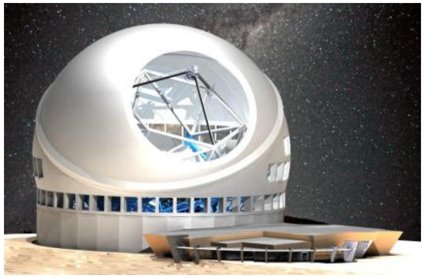
– together with large aperture significantly changes space-ground synergy

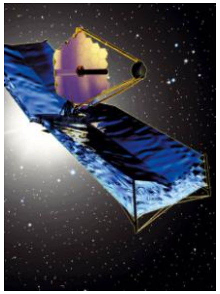
First sources & cosmic reionization:

- TMT is key to locating more abundant, fainter, smaller sources (AO gives $\times$10-100 gain over JWST depending on angular size).
- JWST probes to higher z in mid-IR

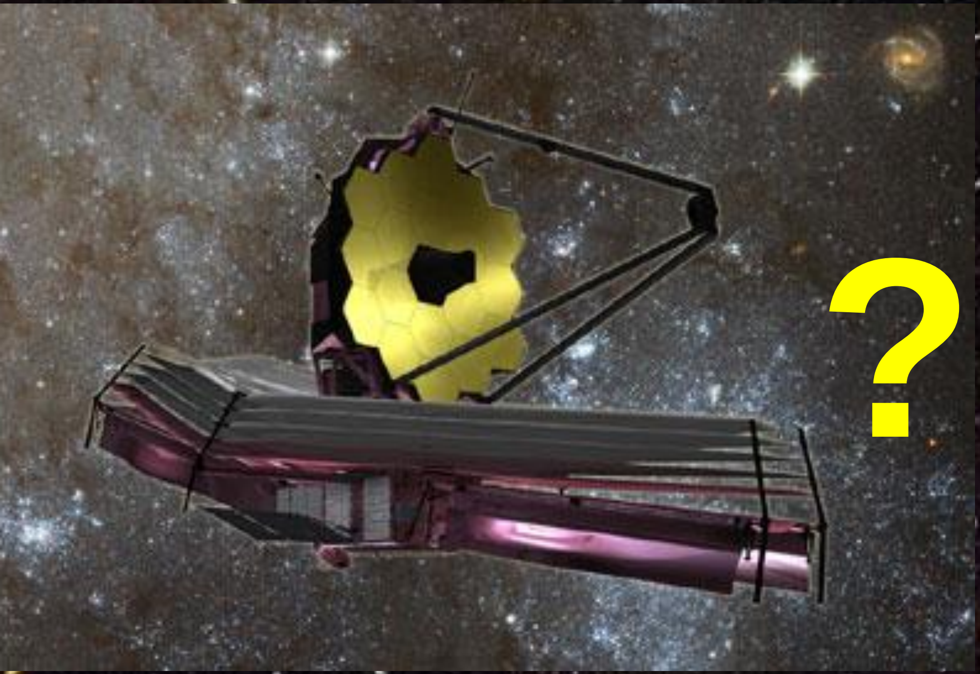


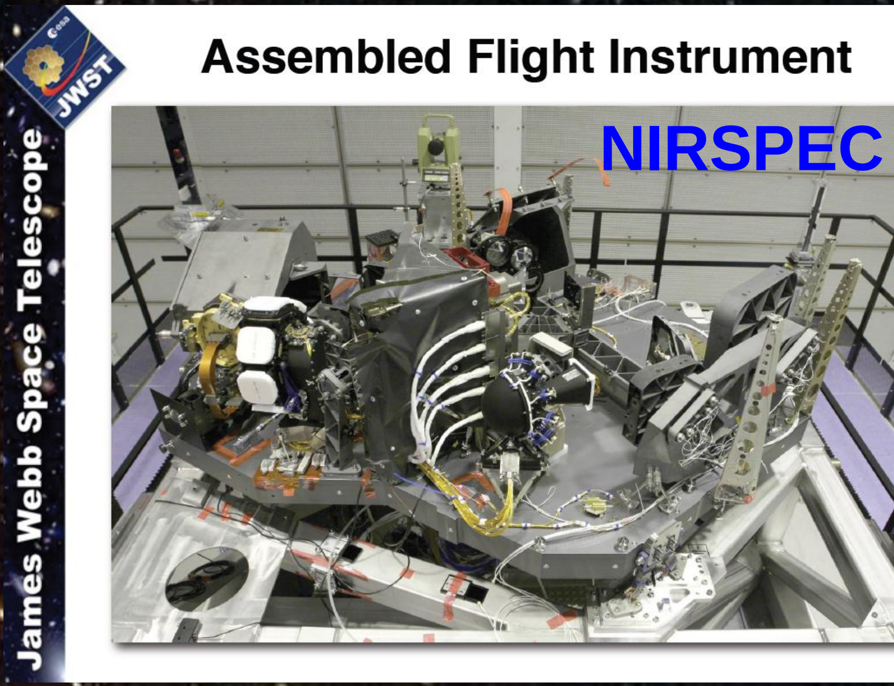
Lensed galaxies at z ~6
Unlensed sizes ~ 150pc or < 30mas!





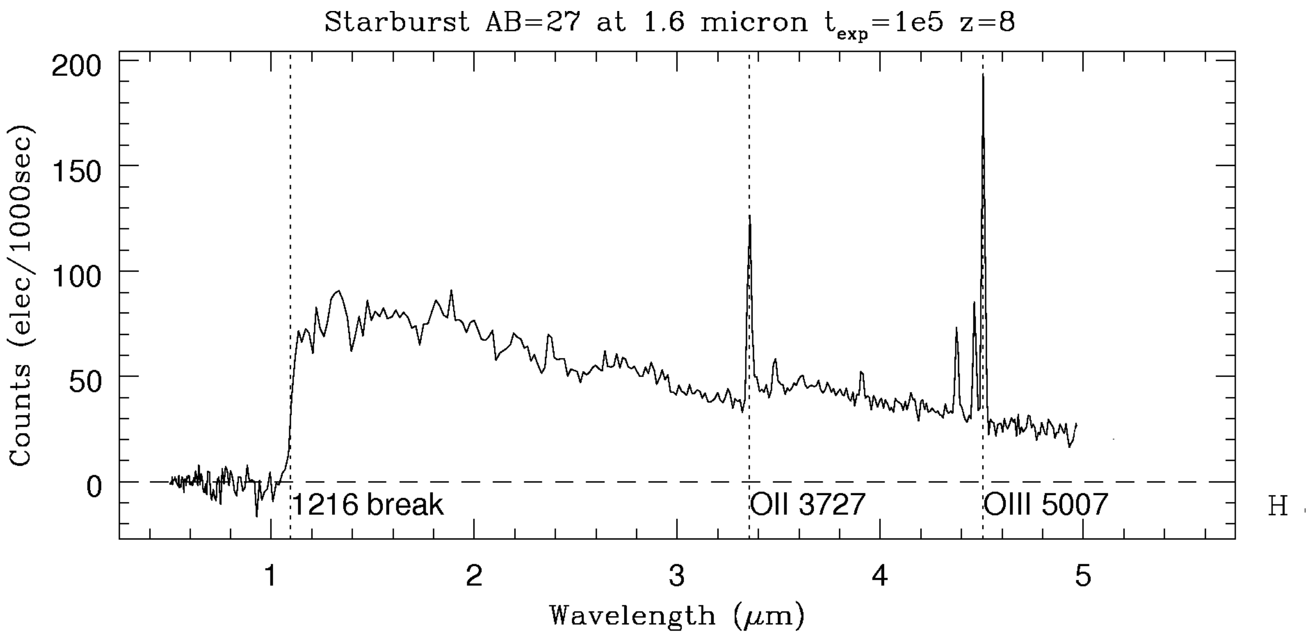
James Webb Space Telescope



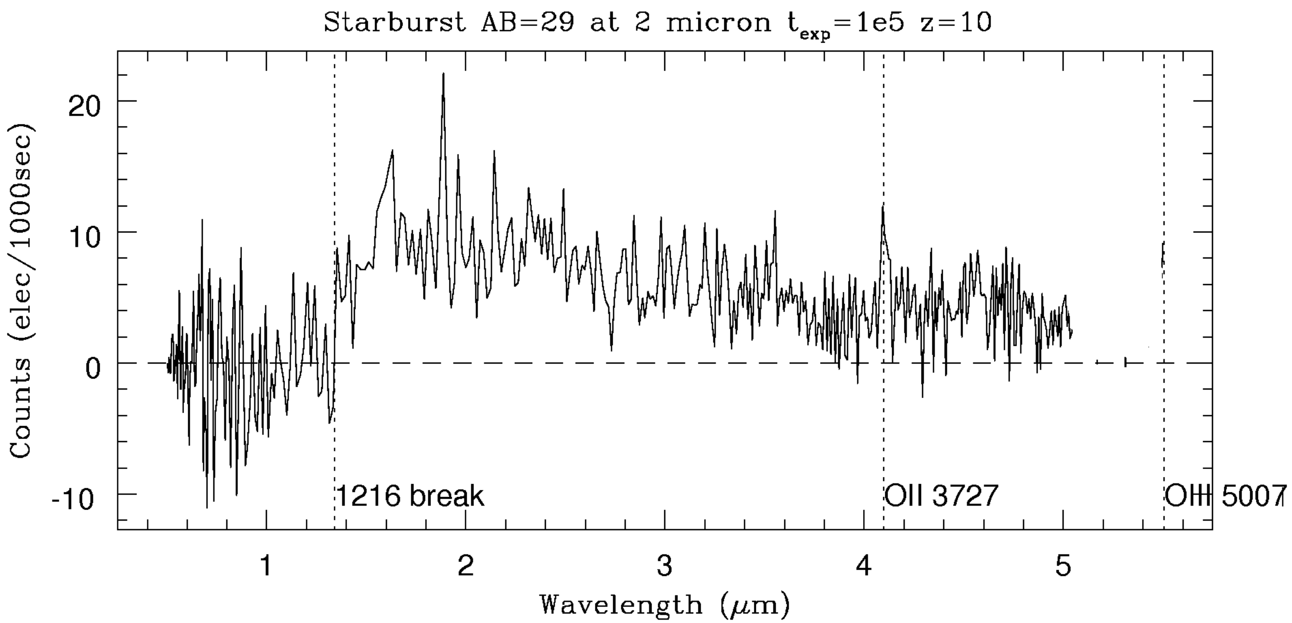


Simulated NIRSPEC spectra

AB=27 z=8 enabling full nebular/stellar decontamination and gas phase metallicities



AB=29 z=10 (current UDF limit)



Conclusions & Future Prospects

- Exciting time in the study of $z>7$ galaxies with HST, Spitzer and large telescopes still in the vanguard
- Dramatic progress with deep IRAC observations: from a couple of $z\sim6$ detections in 2005 now to comprehensive measures of the stellar mass density over $4<z<7$
- WFC3 has led to rapid progress:
  - continuity of SF trends over 300 Myr
  - dominant fraction of sub-luminous galaxies
- Rapid decline in visibility of Lyman α over $6.5<z<8$ suggests neutral era begins in this redshift range
- Many uncertainties but good prospects for improved data which will address possible deficiency of galaxies as source of reionizing photons
- Key role of future large telescopes in exploiting adaptive optics and efficient multi-object spectrographs in concert with JWST and large samples of $7<z<10$ which can still be delivered by HST