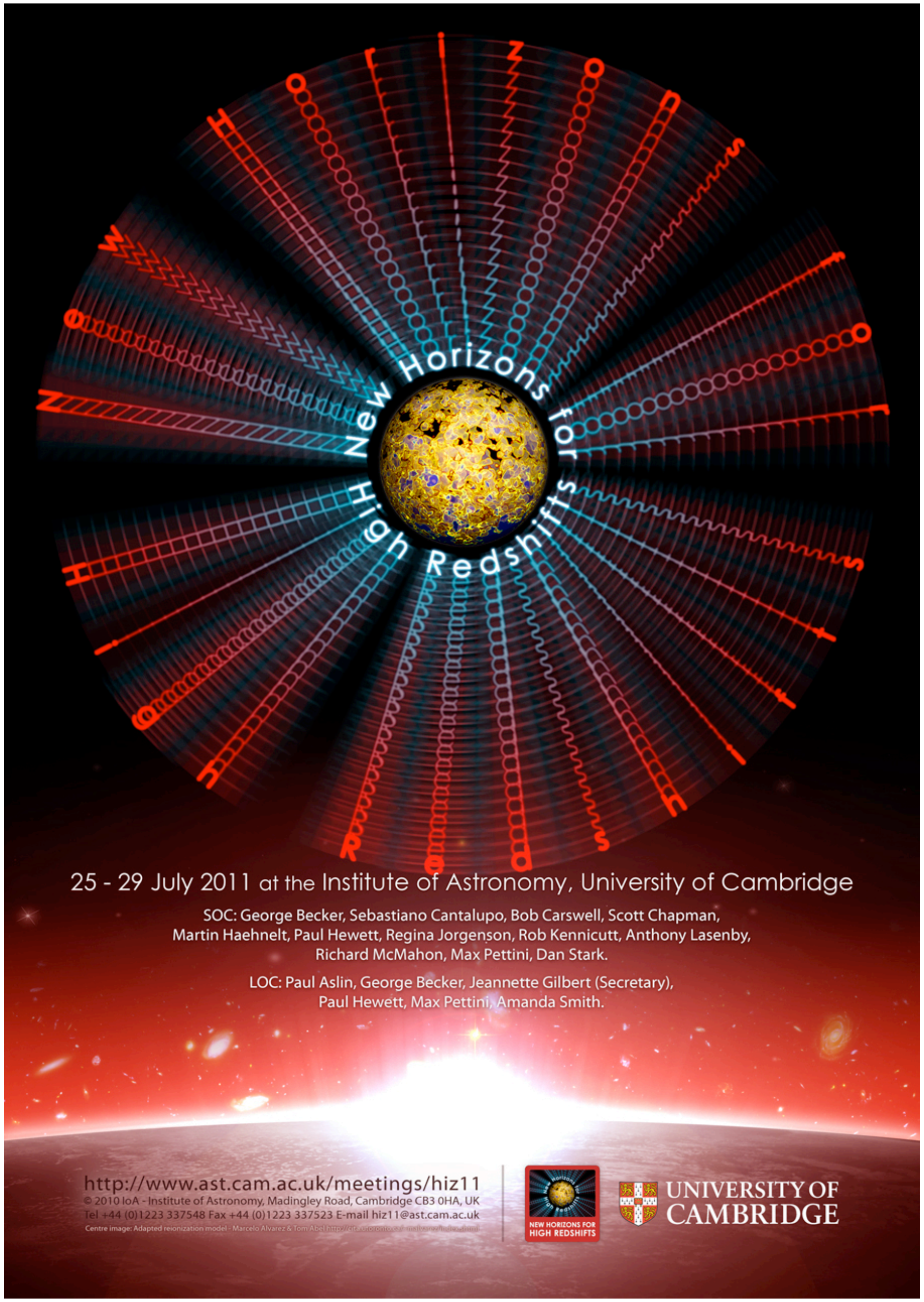
New Horizons for High Redshifts

Conference Summary

IoA UNIVERSITY OF CAMBRIDGE

Richard Ellis (Caltech)

29th July 2011

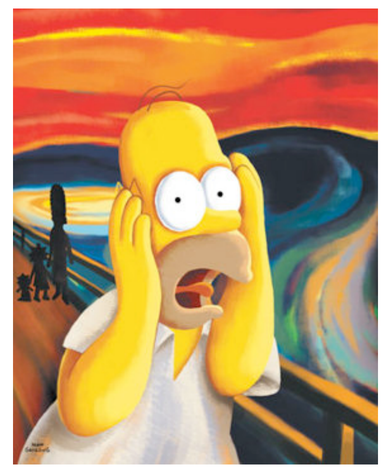


Disclaimer

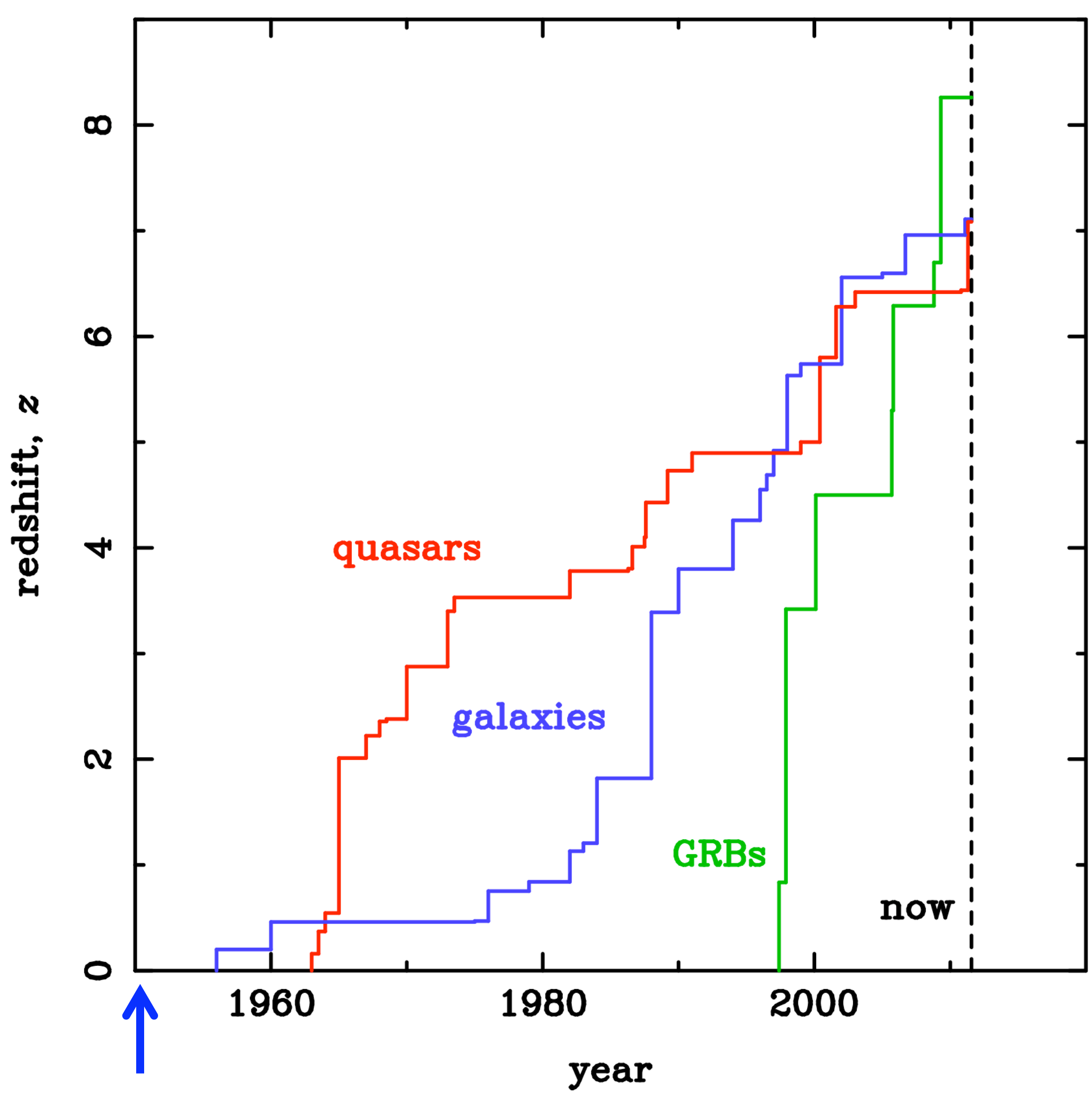
56 talks × 25 slides = 1400 slides

AND 46 posters

All carefully digested, rationalized, inter-compared with results in the literature to give a “lucid, crisp, holistic view of the high redshift Universe and cosmic reionization…..”



Redshift Record (1950 – present)



Courtesy: Dan Mortlock

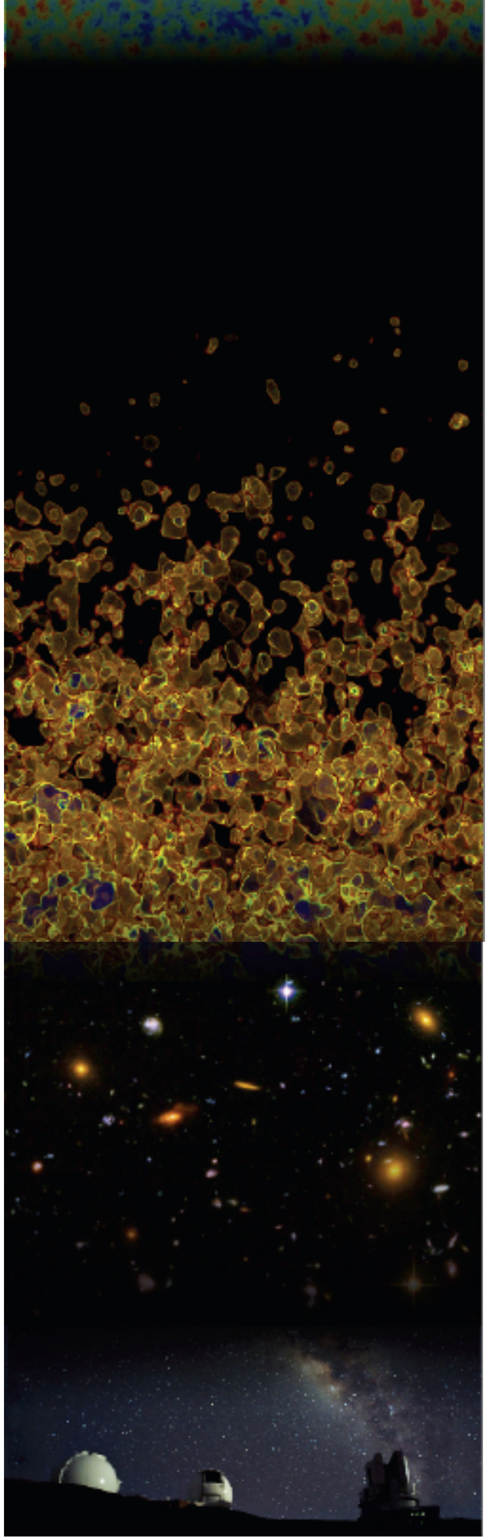
Epoch of RSE formation

Addressing the Grand Questions

Conference web page:

What were the properties of the first stars, galaxies, and AGN? How and when was the IGM reionized? How did interactions between galaxies, QSOs, and the IGM at early times shape the Universe we observe at later epochs? We will address these questions in the context of progress that can be made over the next three to five years. We aim to deliver a more robust understanding of the z= 5-10 Universe that will guide scientific exploitation of next-generation facilities.

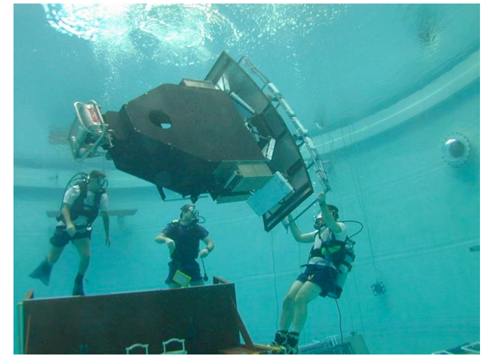
- **When did reionization occur?**
- **Were star-forming galaxies responsible?**
- **What role did AGN play in early evolution?**
- **What are the physical limitations in our understanding of the 5<z<10 Universe (lessons from 2<z<5)?**
- **Prospects and plans in the next 3-5 years?**

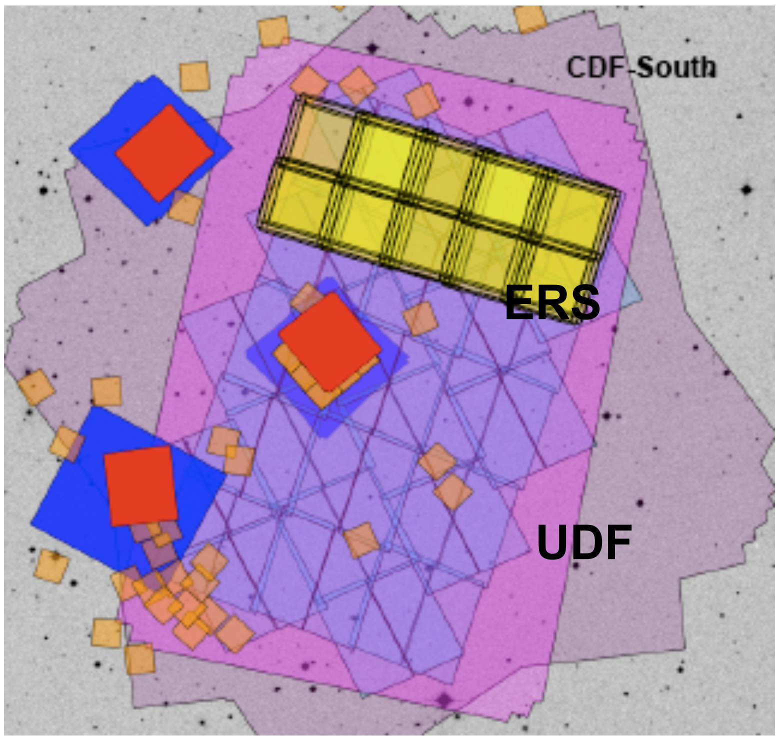


Progress with WFC3

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

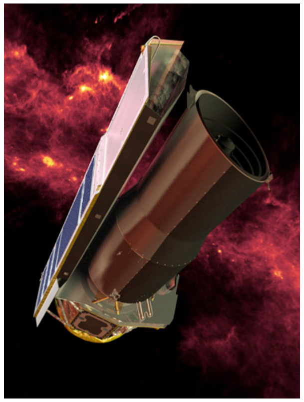
× 40 gain in speed c.f. NICMOS





>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)

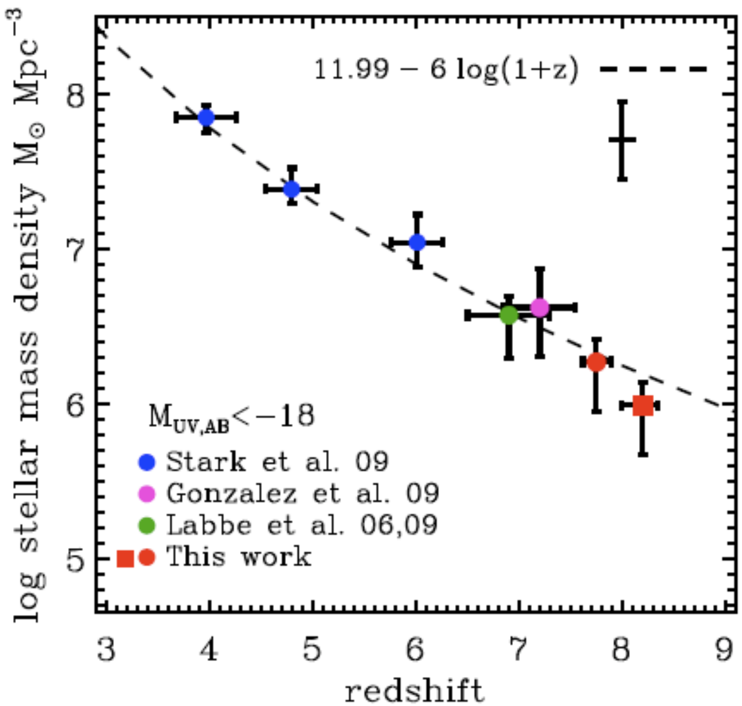
Brighter candidates from parallel surveys and CANDELS fields (**Finkelstein, Trenti**)_



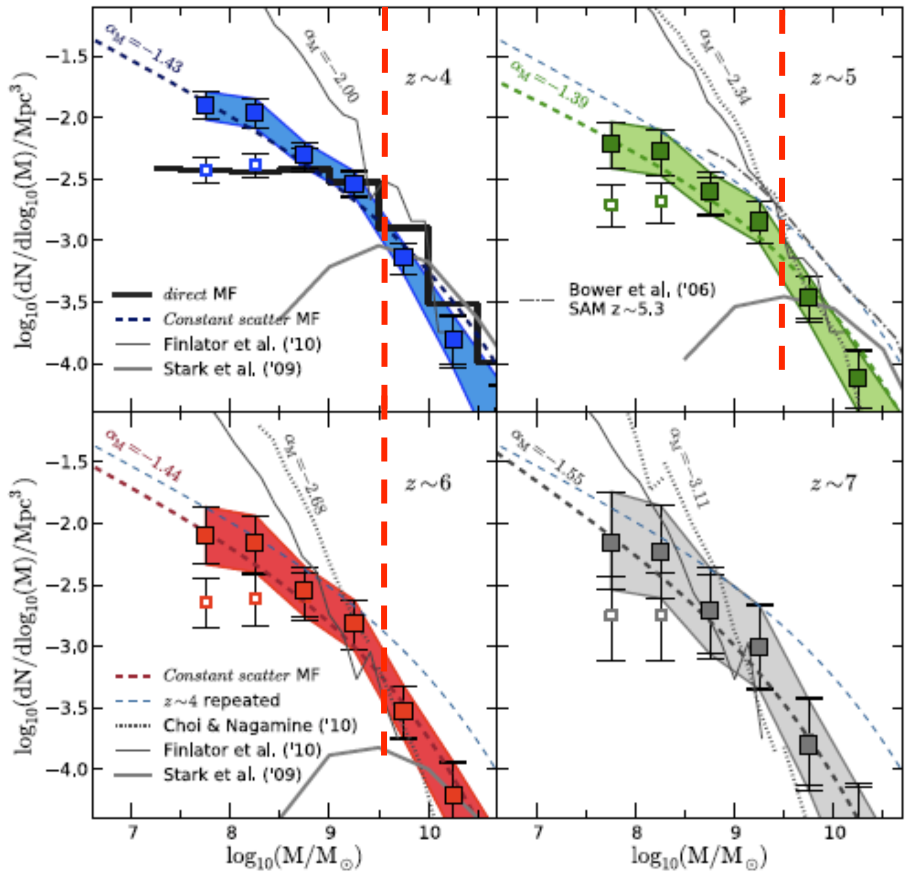
Stellar Masses with Spitzer

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

- Stellar masses & ages at z~5 imply significant earlier star formation
- New steeper mass functions strengthen this result
- Theorists should now try to match these mass functions!



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

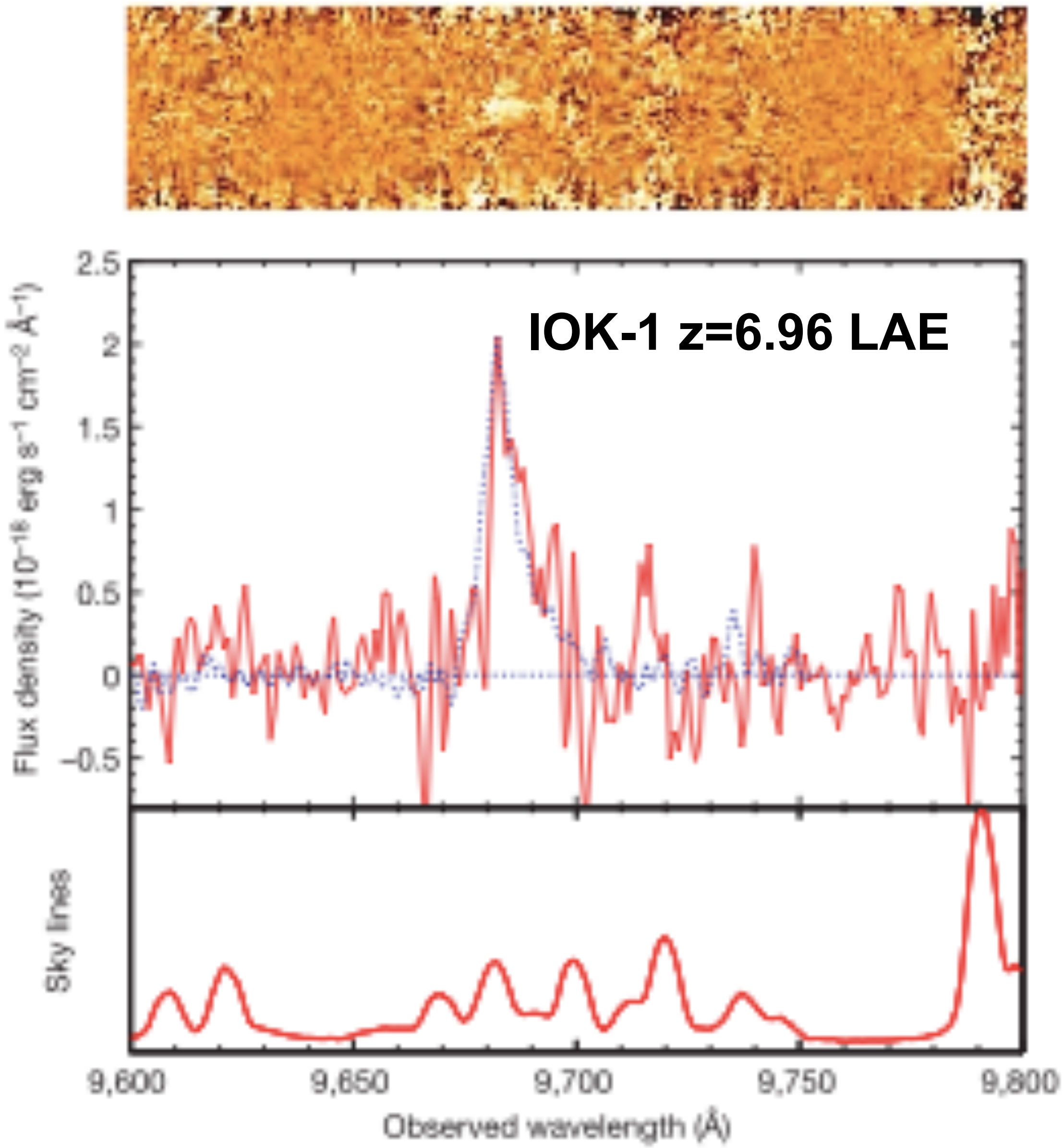


Ivo Labbé + Valentino (poster)

Breaking the z=7 spectroscopic barrier!

For 5 years the community was only willing to unanimously accept the Subaru z=6.96 LAE as the most distant star-forming galaxy.

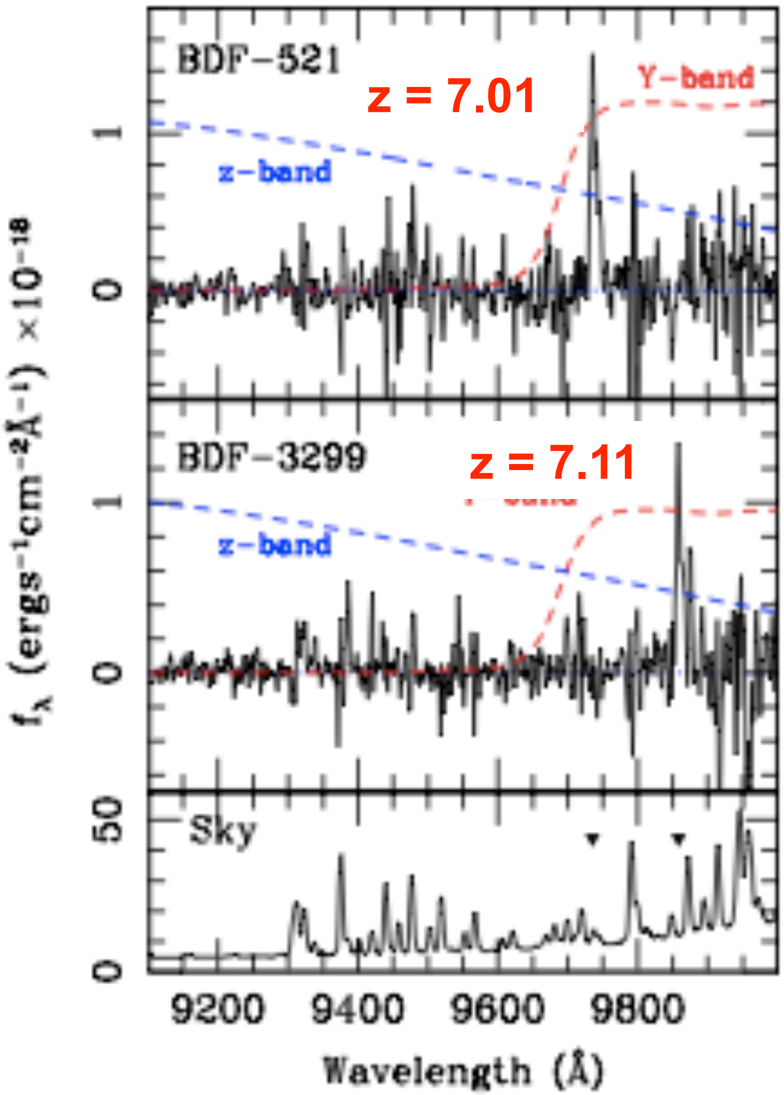
Lyα is placed at the far red end of the optical spectrum – a technical barrier to higher z searches



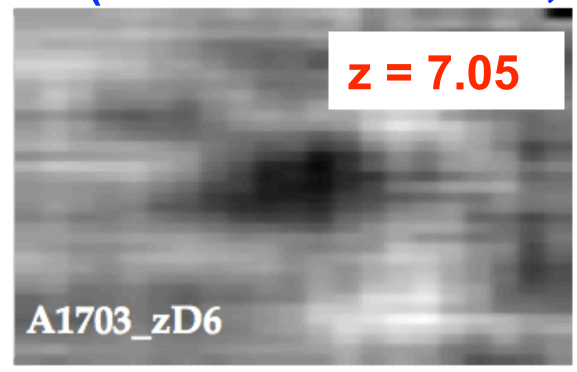
Iye et al (2006)

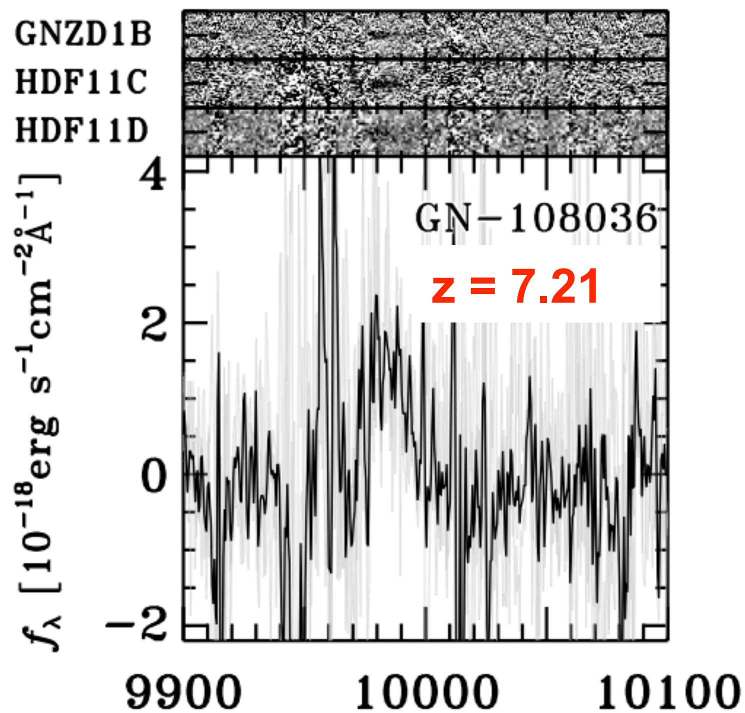
Convincing z > 7 Galaxy Spectra!

Pentericci (Vanzella et al 2011, FORS2)



Stark (Schenker et al 2011, NIRSPEC)





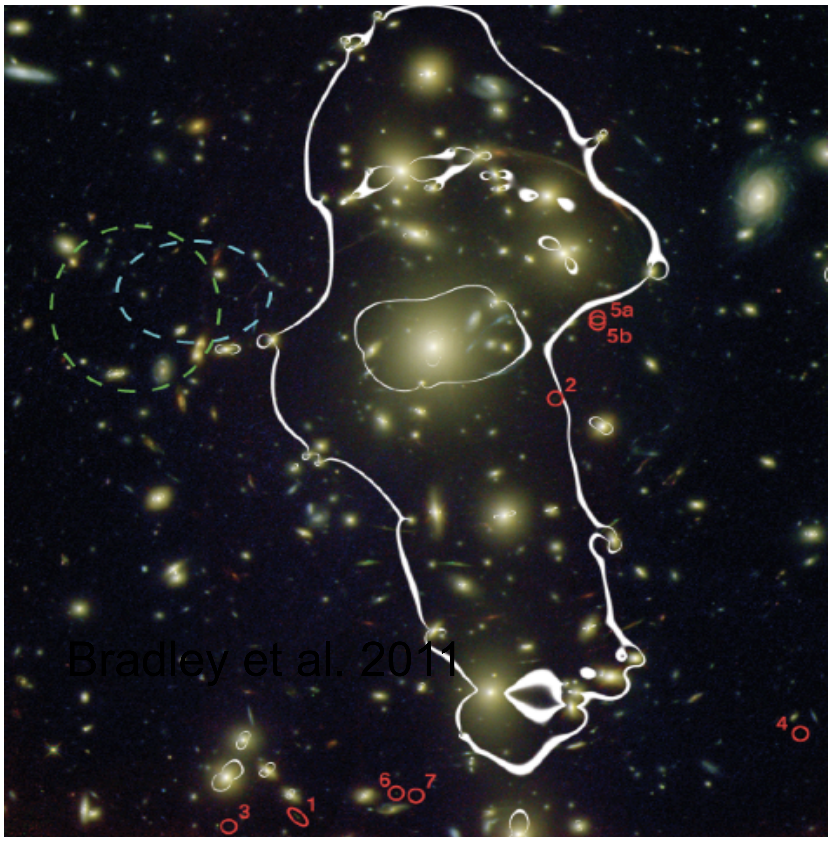
Ono et al 2011 (DEIMOS)

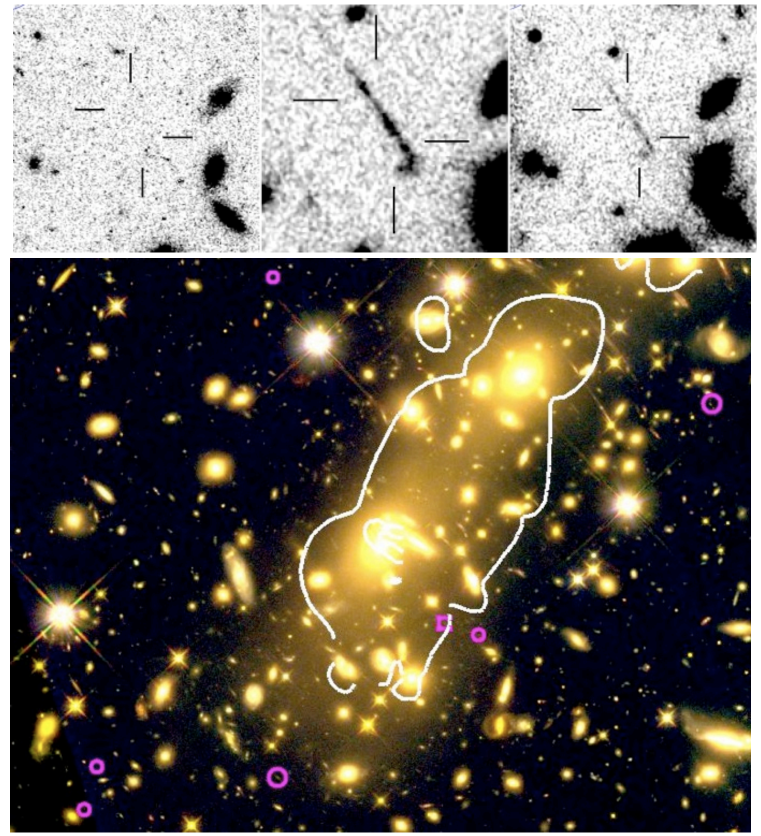
Strong Gravitational Lensing Increasingly Valuable

Enables spectroscopy, probes faint end of LF, resolves z > 6 sources

Abell 1703 z=7.045 mag = ×5

MS0451 z~7.5 mag = ×25



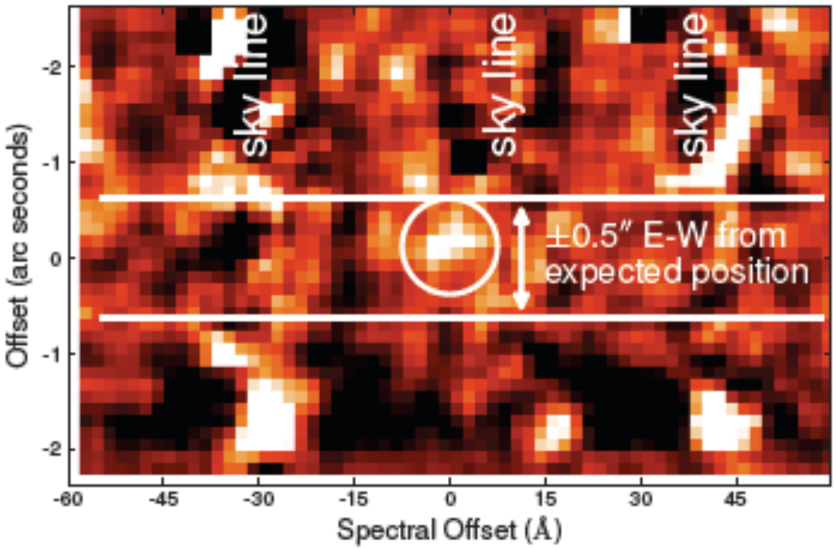


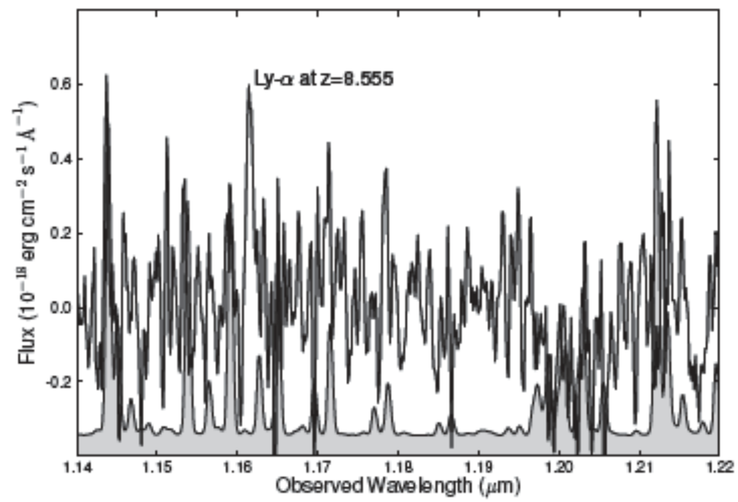
50 well-constrained cluster lenses and several WFC3 campaigns (Hall et al, Bradley et al (CLASH), Kneib et al)

Johan Richard & posters by Ammons, Laporte, Wong

Query on z=8.55 LBG?

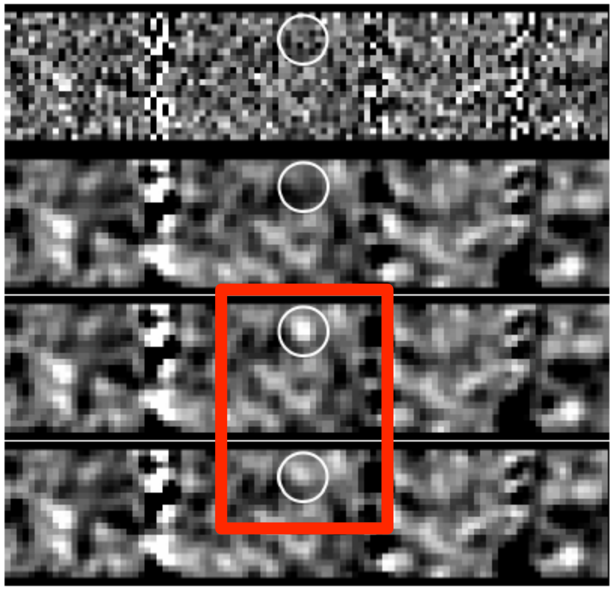
UDFy-38135539 = HUDF-YD3



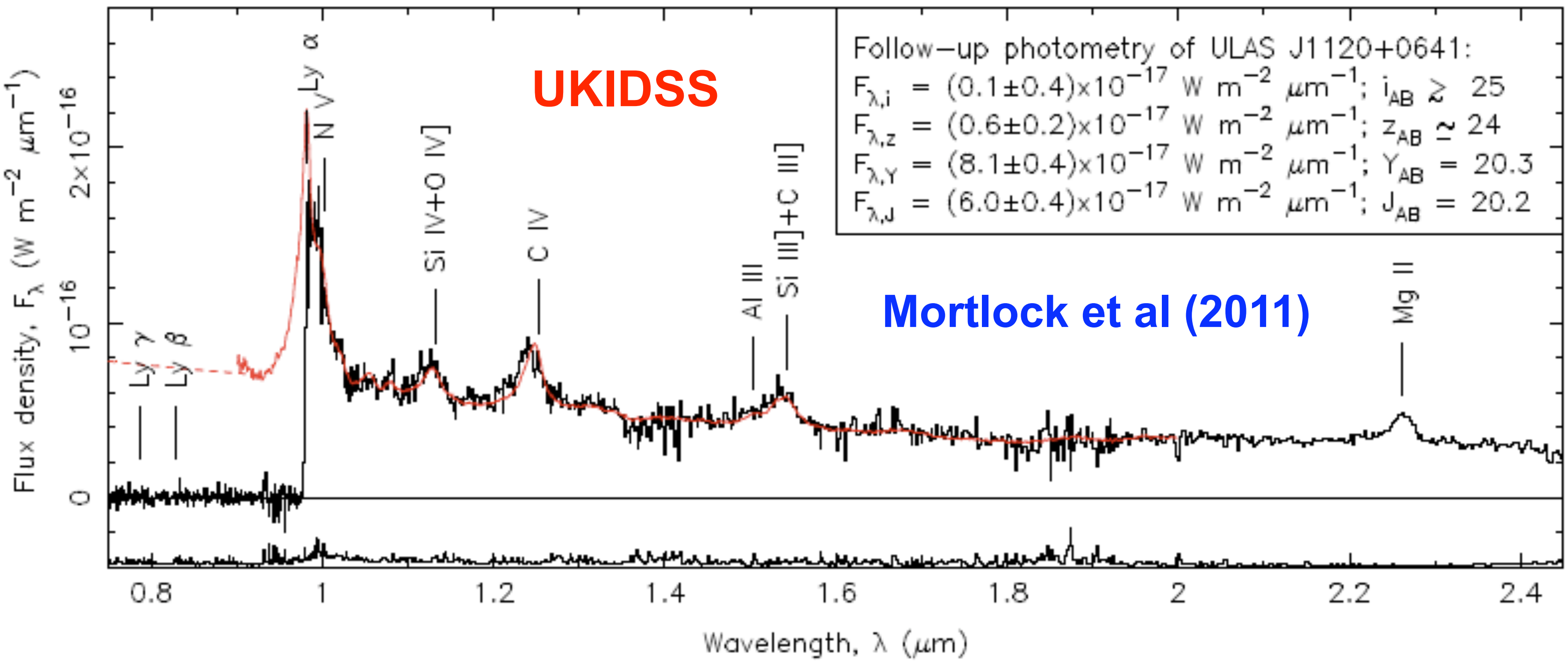


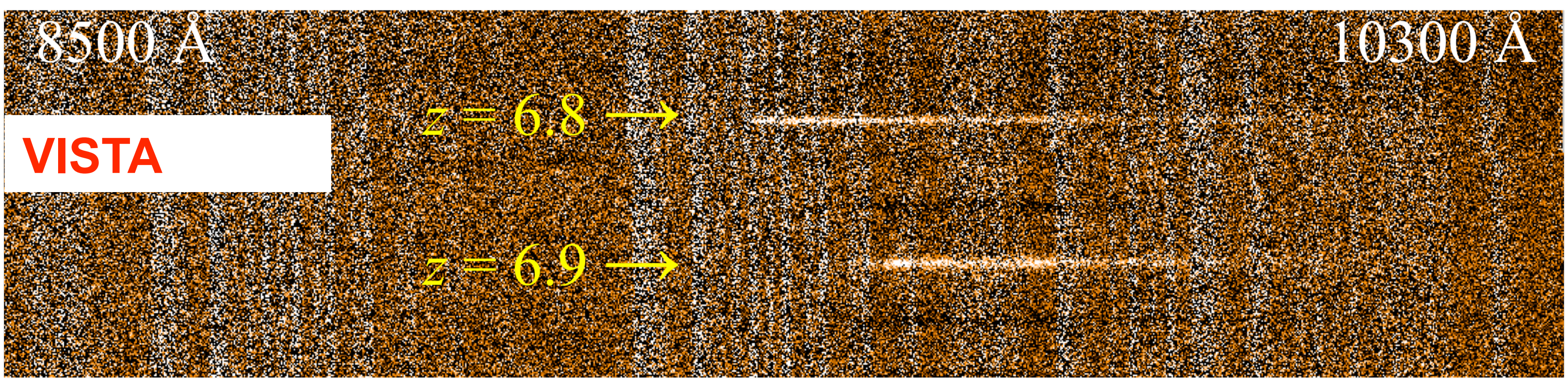
Lehnert et al (2010) VLT SINFONI
14.8 hours R~2000
Claims 6.0σ detection

Bunker et al (2011) VLT X-Shooter
5 hours R~5100
Expected 3.5-4.5σ detection



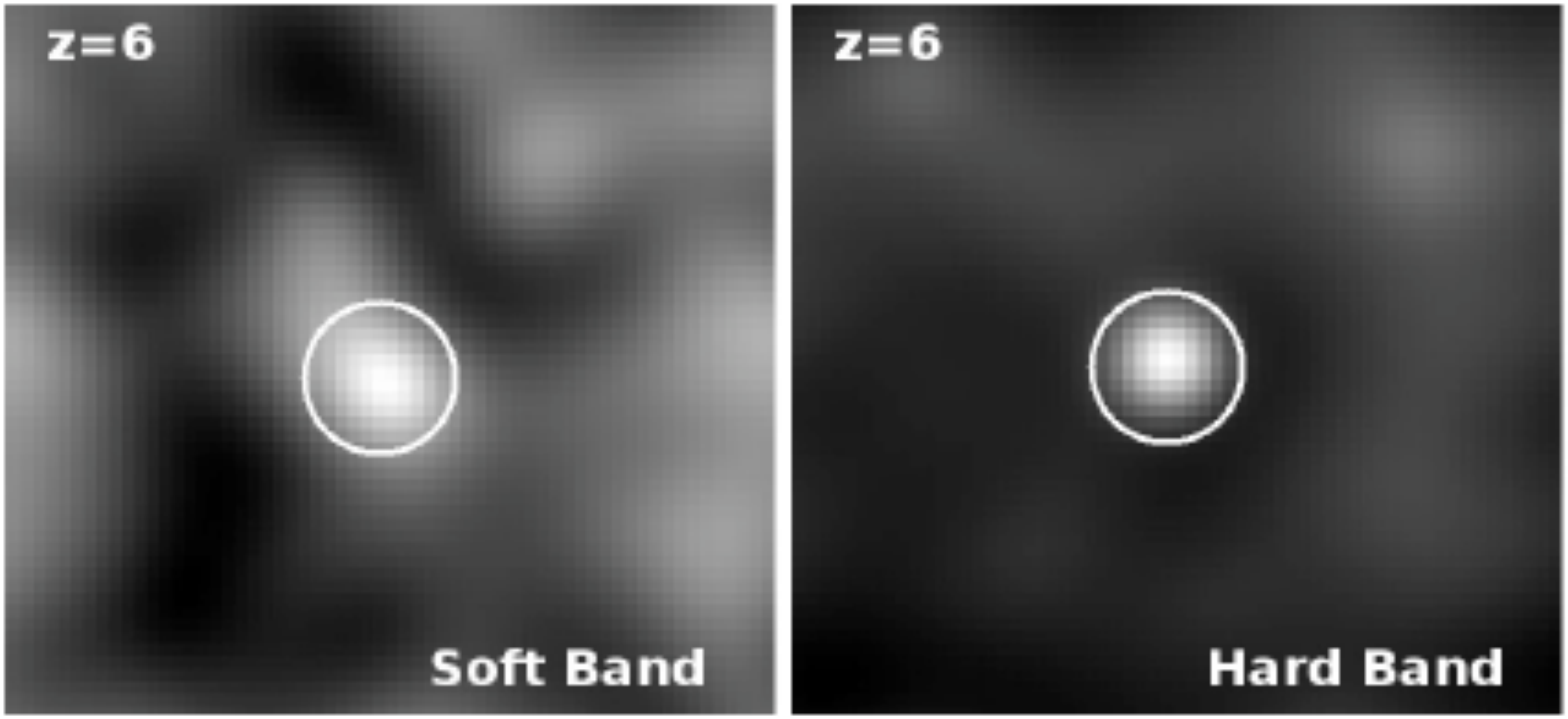
z~7 QSOs!





Bram Venemans (this meeting!)

Obscured AGN in z~6-7 LBGs

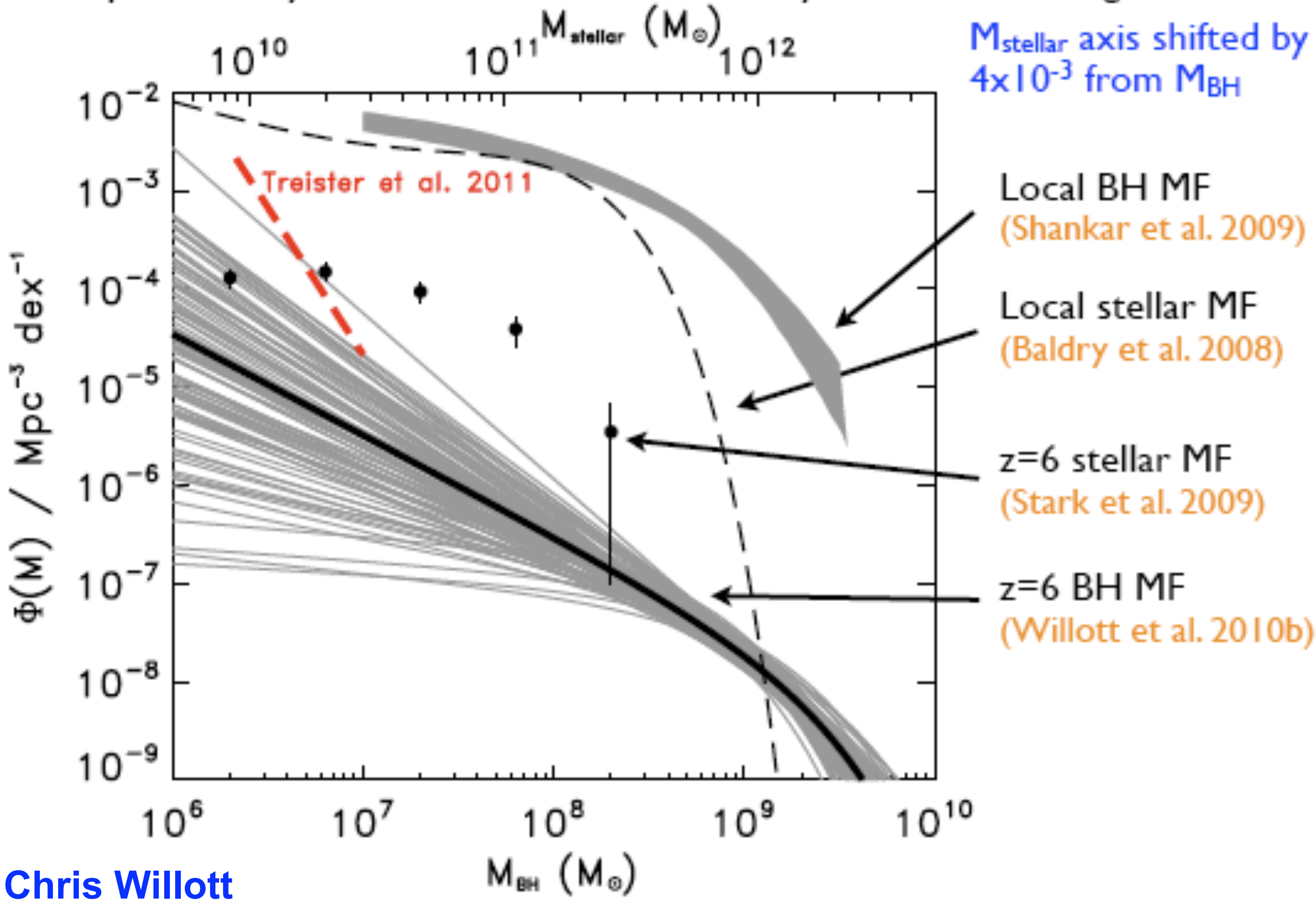


- Stacked 197 z~6 dropouts in CDF-S (4Msec) and CDF-N(2Msec)
- Hard/soft detection ratio implies high column density $N_{HI} > 10^{24}$ cm^{-2}
- Implies self-regulated formation tied to host galaxy assembly and little contribution of AGN to reionization photon budget

Kevin Schawinsky (Triester et al 2011)

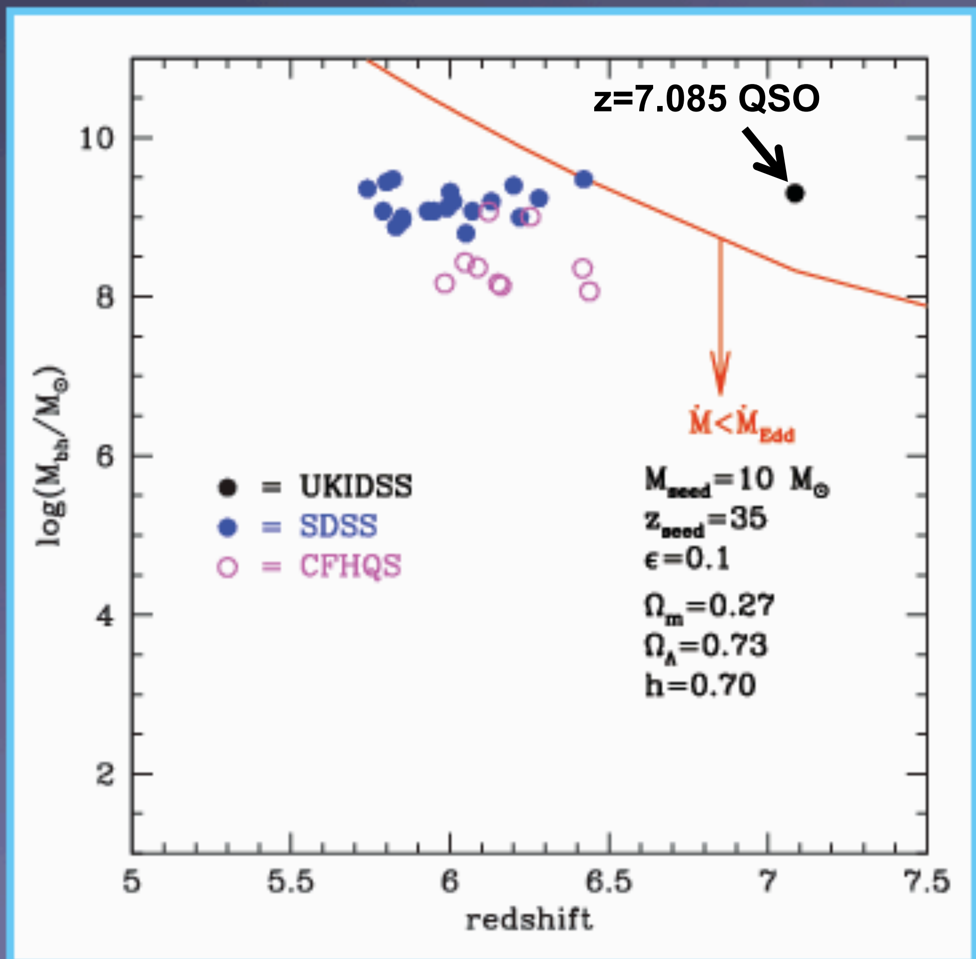
Black Hole Mass Function at z=6

Typical BH mass for Treister et al. X-ray luminosity is 3×10^6 based on 50% contributing at Eddington limit.
Steep luminosity distribution based on no X-ray detections among LBGs.



Chris Willott

Got to Start Early!



e-folding (Edd) time:
$M/(dM/dt) = 4\ (\varepsilon/0.1)\ 10^7$yr

Age of universe (z=6-7)
$(0.8 - 1) \times 10^9$ yr

Must start early!

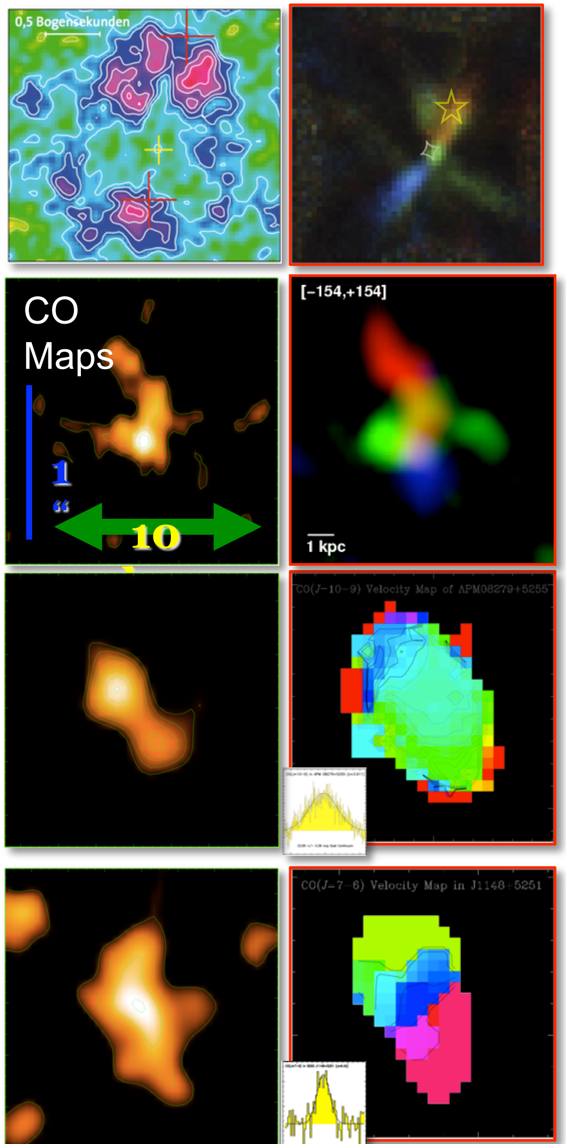
Accretion rate must keep up w/ Eddington at all times

Obvious alternatives:
(1) grow faster or
(2) merge many BHs

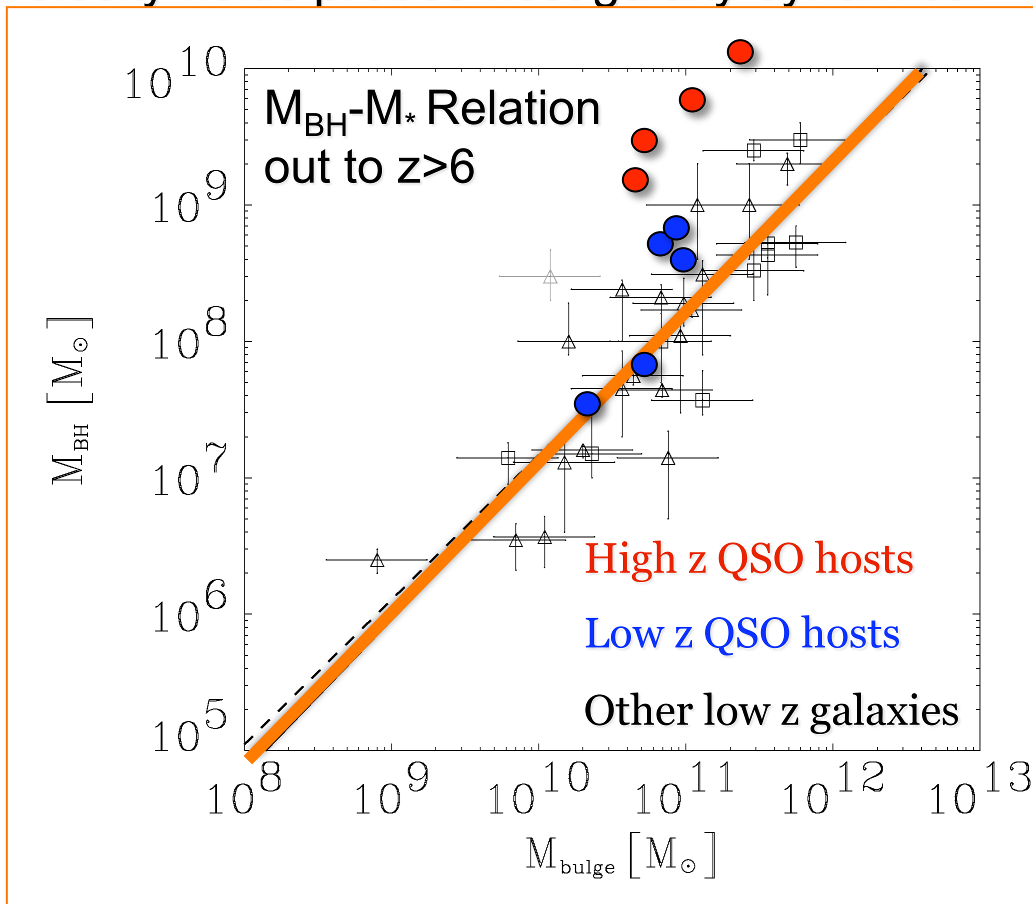
Masses estimated from: Fan et al. (2006); Willott et al. (2010); Mortlock et al. (2011)

Zoltan Haiman

Accelerated growth of black holes at z~6



- z~6 QSOs have massive, heavily enriched host galaxies
- CO velocity fields probes host galaxy dynamics!



ALMA will offer finer resolution (bulges), probe larger samples & lower M_{BH} systems (**Bertoldi)**

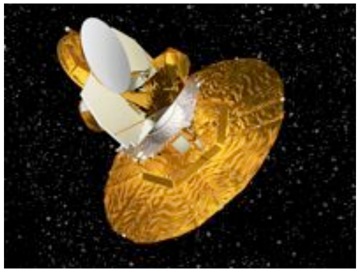
Riechers

When did reionization end?

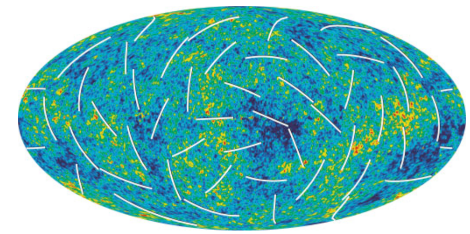
Polarization constraints from WMAP eliminate likelihood of late reionization and point to gradual reionization over $7<z<20$

Exciting progress exploiting sensitivity of Lyα to damping by neutral gas (Miralda-Escude 1998)

- First hints that reionization ended at $z\sim6.5$ from luminosity function of Subaru LAEs now supported by surveys for emission in WFC3/IR + Hawk-I Lyman break samples
- Clustering of LAEs may ultimately be best route, requires HypersuprimeCam
- Promising indications also from $z\sim7.085$ QSO; further examples will help
- Should be prepared for $z>7$ GRBs!

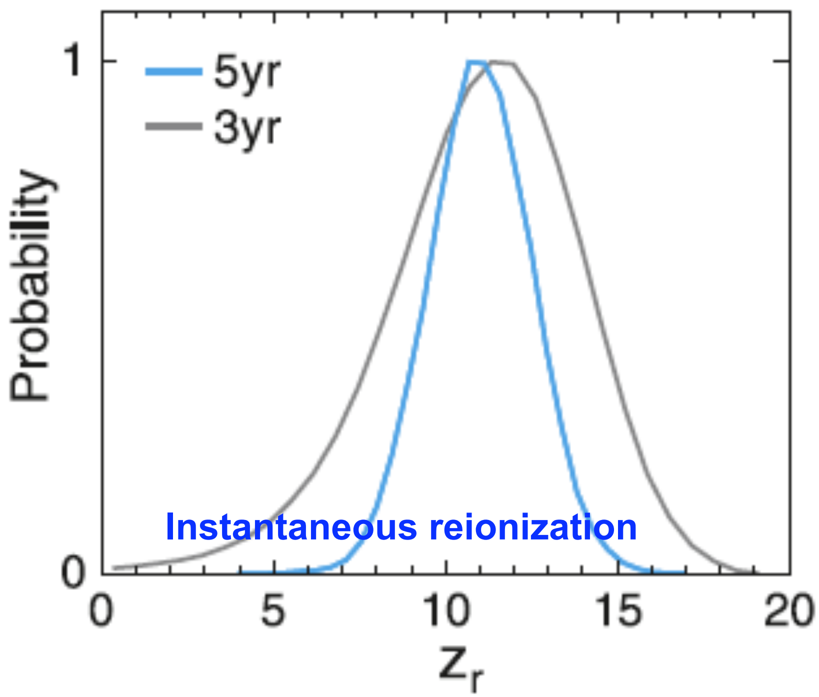


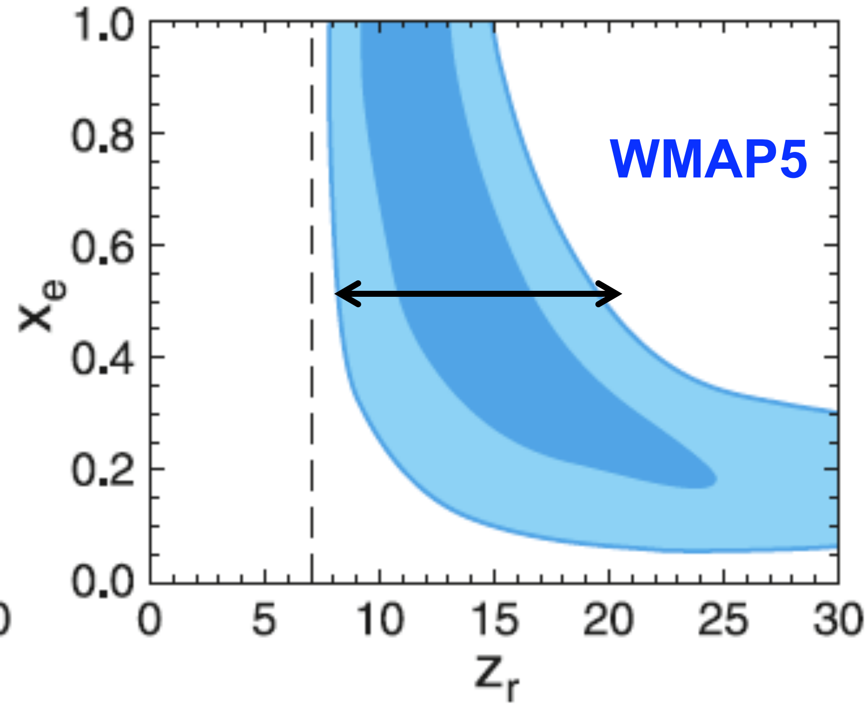
WMAP Polarization



τ = 0.088± 0.015
(WMAP7, 2010)

Larson et al 2011
Jarosik et al 2010

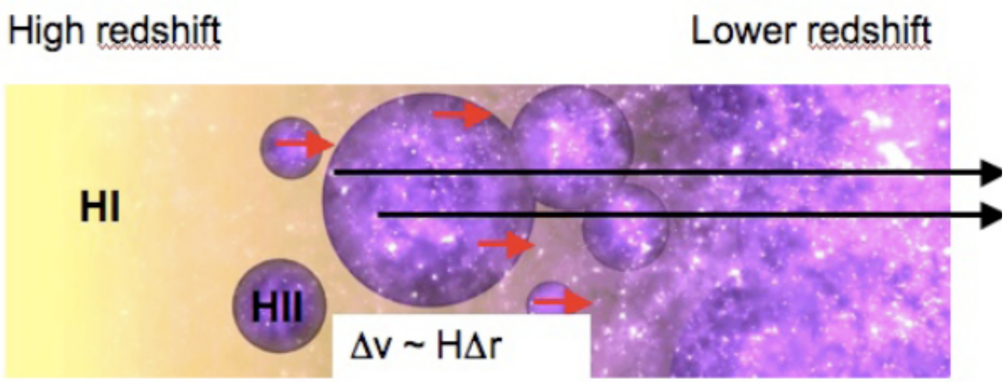


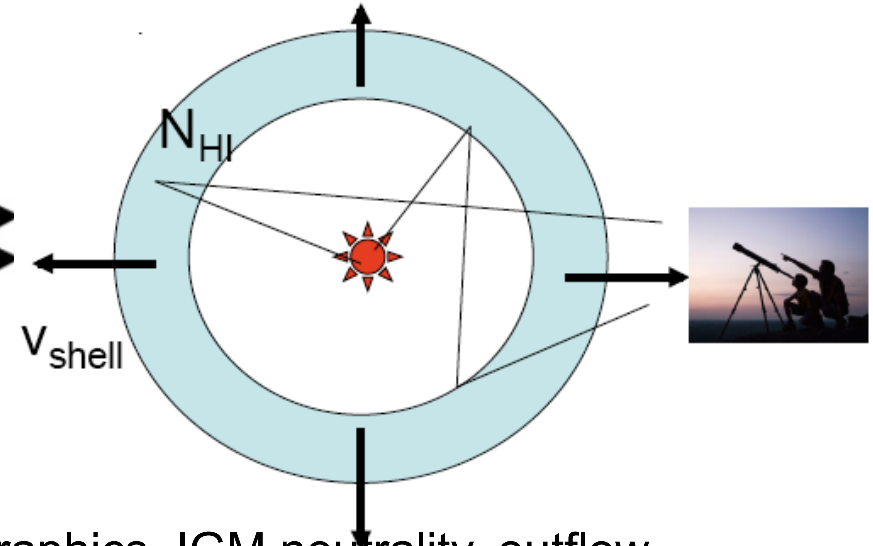


Data rejects instantaneous reionization at z~6-7 so extended
NB: CMB does <u>not</u> pinpoint the responsible cosmic sources

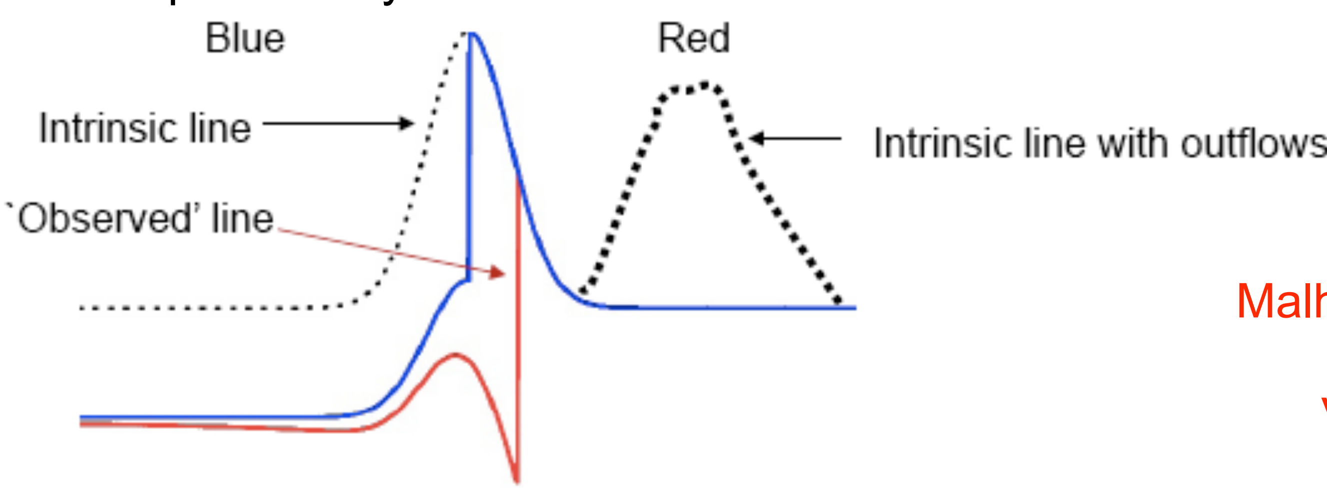
Dunkley

Lyα as a Tracer of Reionization



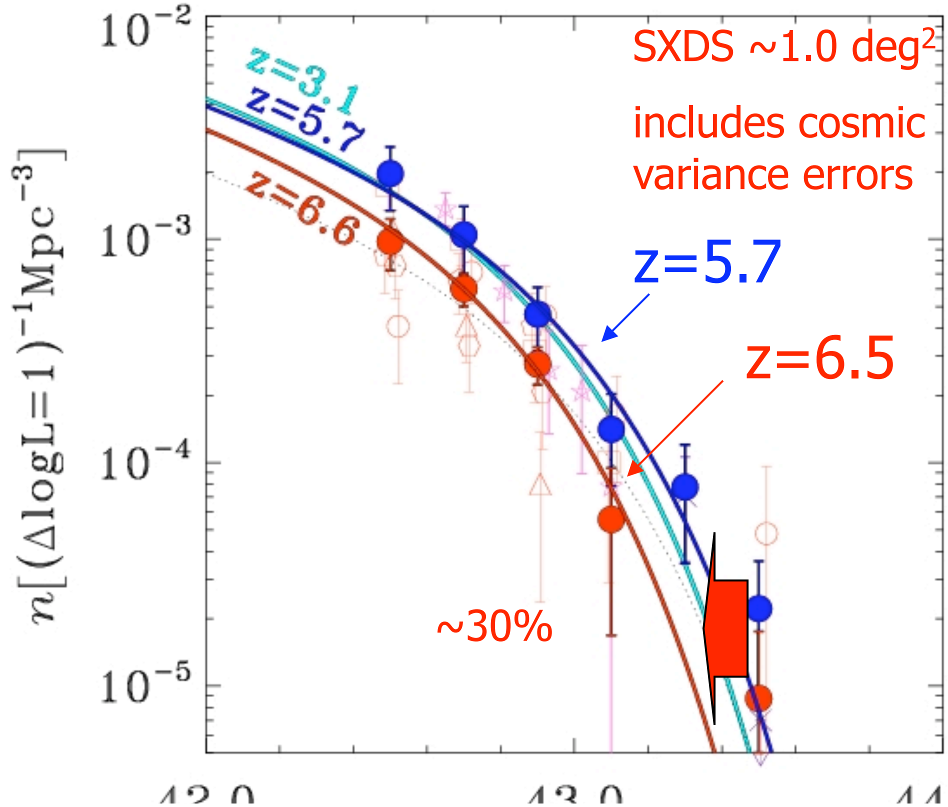


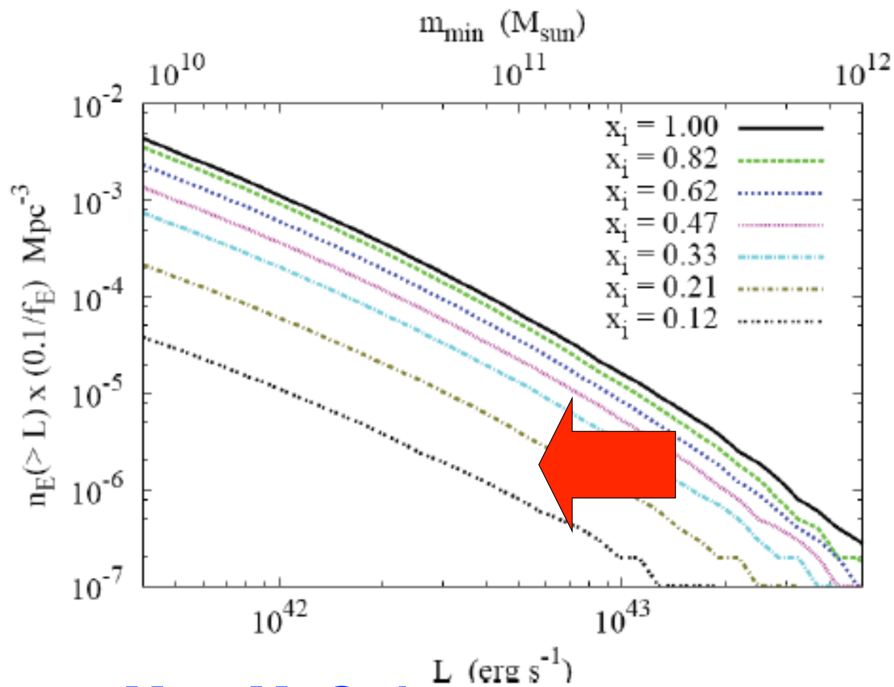
- Detectability of Lyα depends on SF demographics, IGM neutrality, outflow geometry & dust
- Studies of LF of Lyα emitters requires corrections for effects which may change abundances;
- A complementary tracer is relative *fraction* of color-selected LBGs showing Lyα



Miralda-Escude (1998)
Santos (2004)
Malhotra & **Rhoads** (2004)
Dijkstra et al (2007)
Verhamme et al (2008)
Stark et al (2010)

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





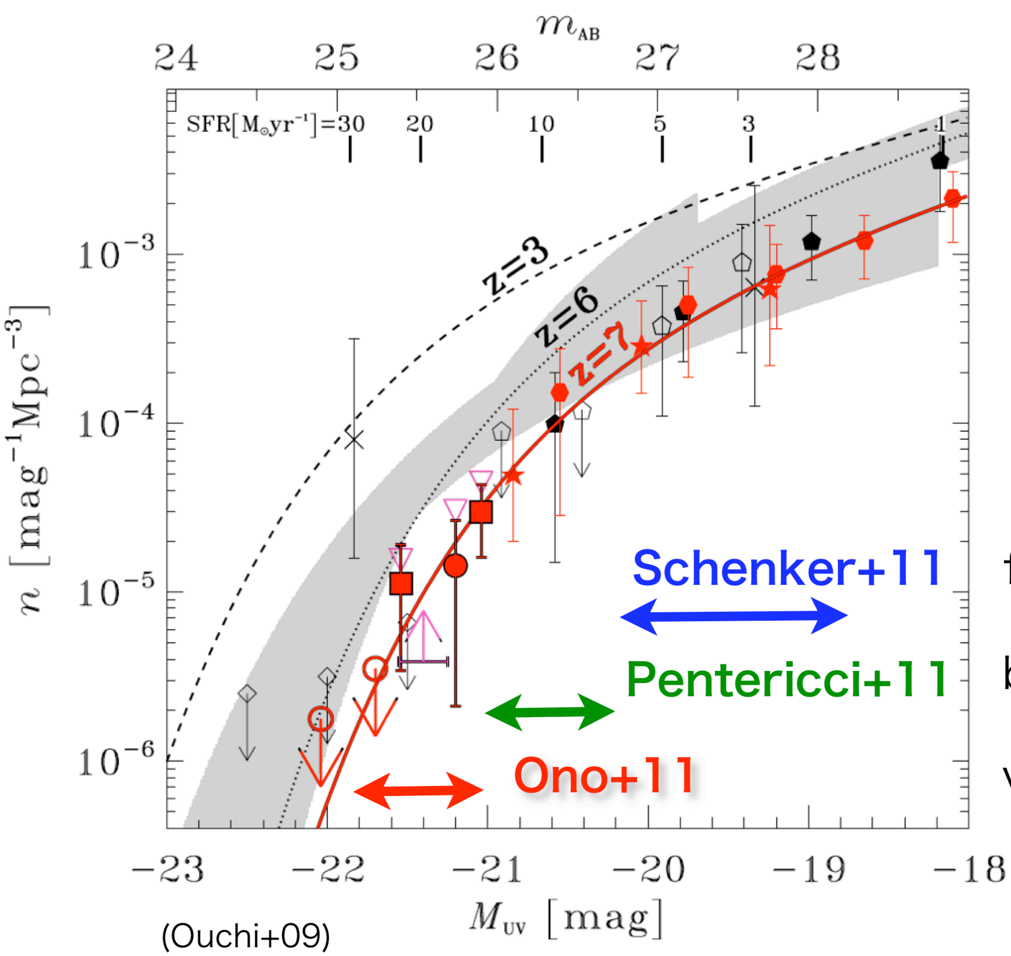
Matt McQuinn

Masami Ouchi (faint z~5.7 data from Henry, incredibly faint data from Rauch)

- **1 deg² SXDS field with 608 photometric and 121 spectroscopic Lyα emitters**
- **Uniform fading (0.ᵐ3) seen in the LF over a small time interval (150 Myr)**
- **Could imply an increase in x_{HI} (e.g. x_{HI} ~0.6 at z~7)**

New surveys for Lyα emission in z~7 LBGs

Difference among the three studies



(Ouchi+09)

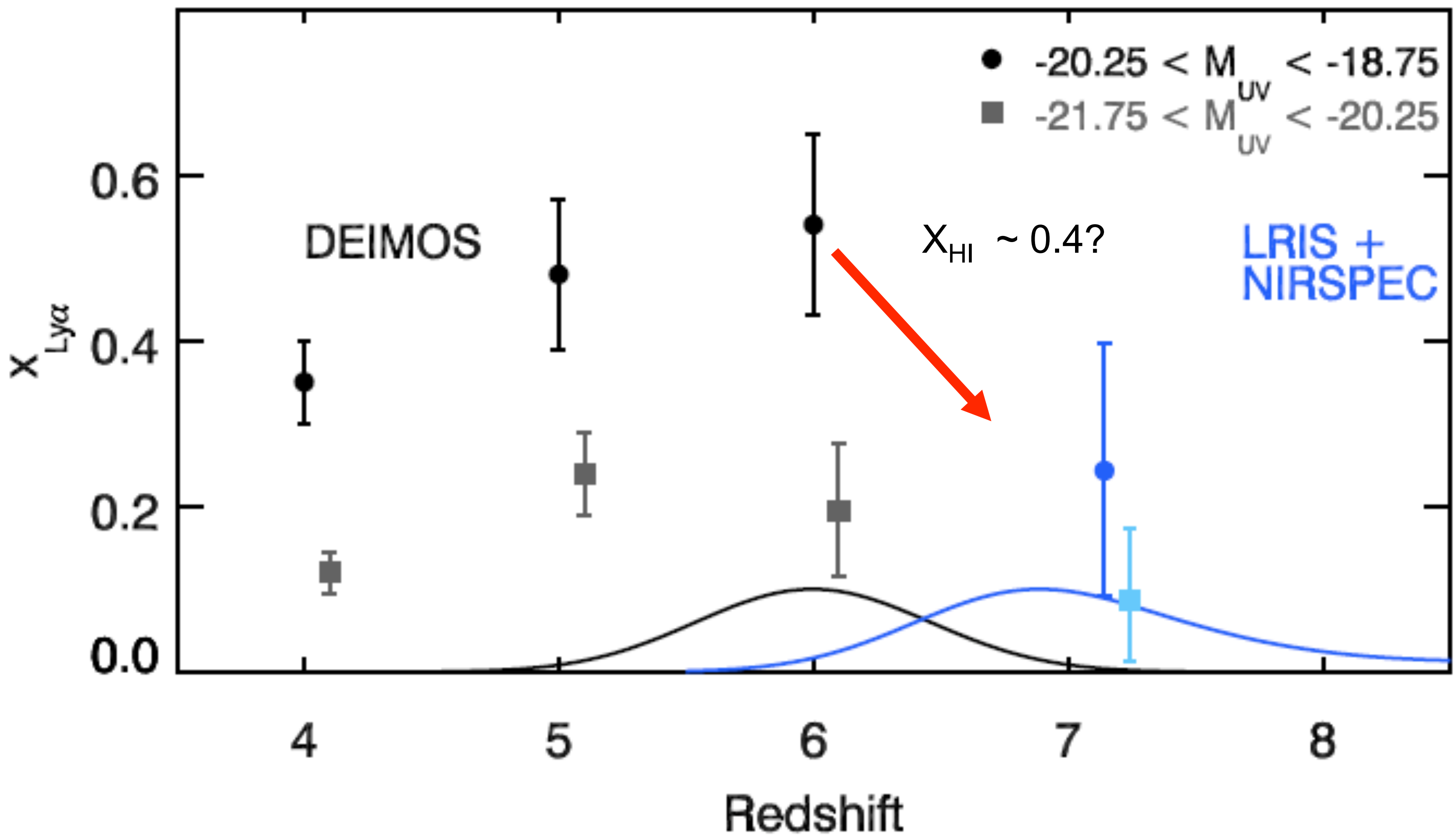
faint z-dropouts

bright z-dropouts

very bright z-dropouts

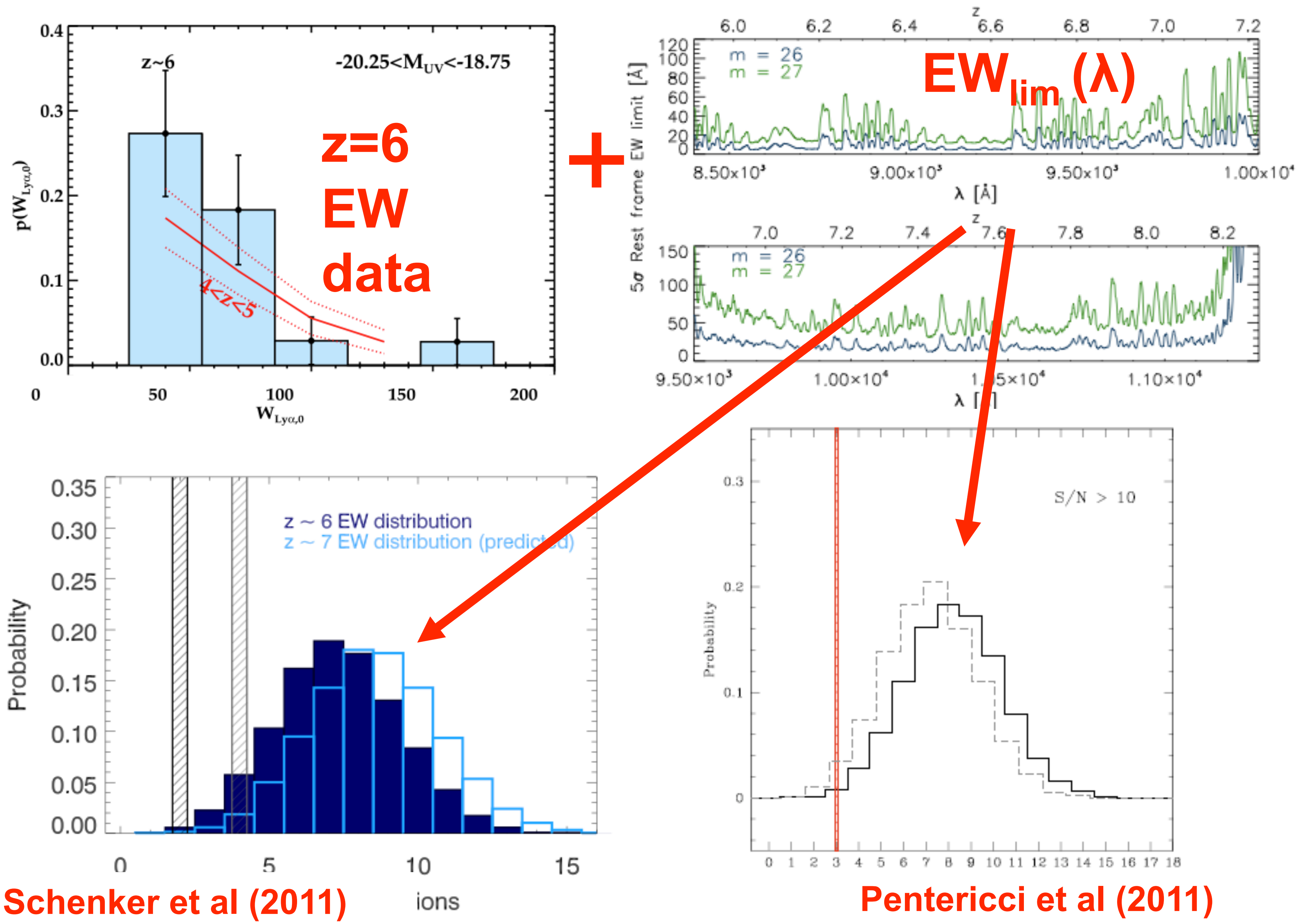
Yoshiaki Ono

Sudden Decline in Lyα Fraction?



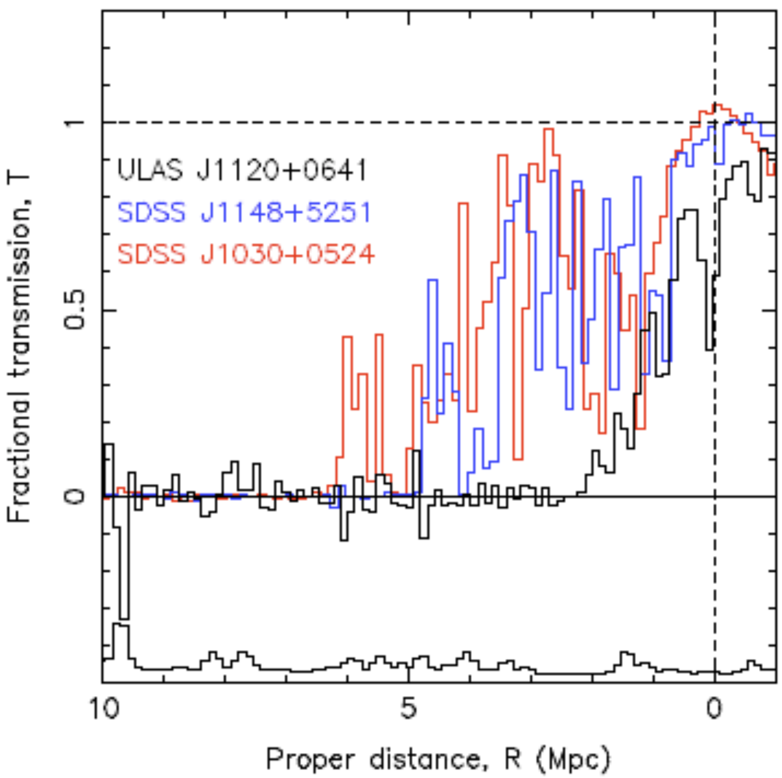
Stark + Schenker (poster)

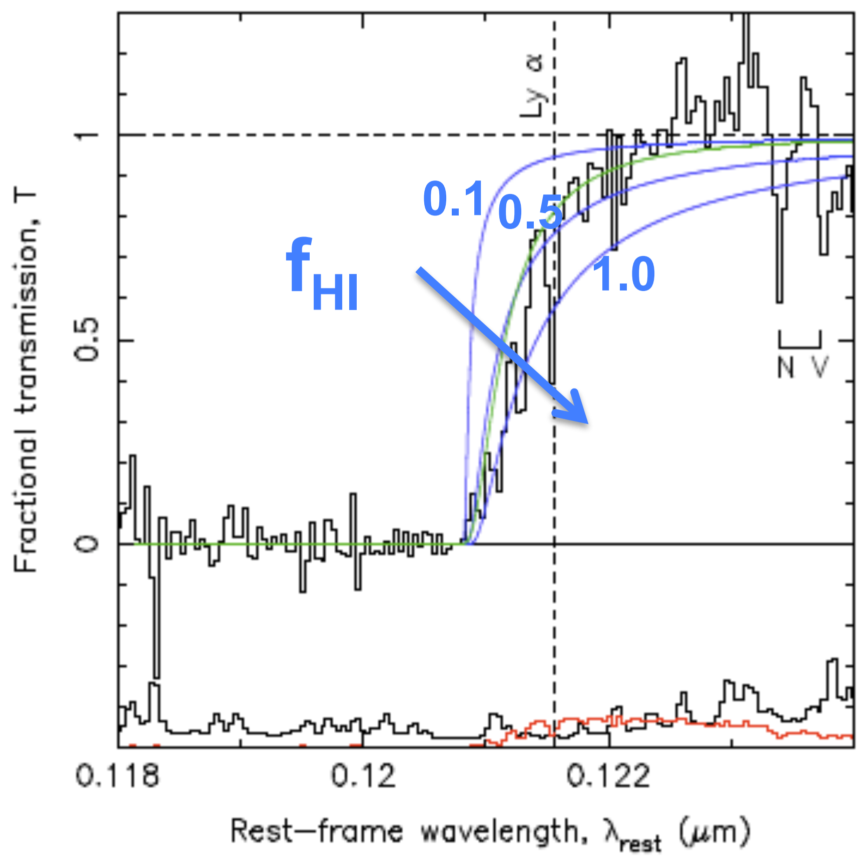
Monte Carlo Simulations More Robust Indicator



Further Evidence: Damping Wing in z=7.085 QSO?

Fit both near-zone radius & damping wing to red side of Lyα (Bolton et al 2011)
Suggests x_{HI} > 0.1 at z~7
A proximate DLA is an alternative explanation but unlikely
Further cases welcome – must be ambitious even with fainter VISTA examples!





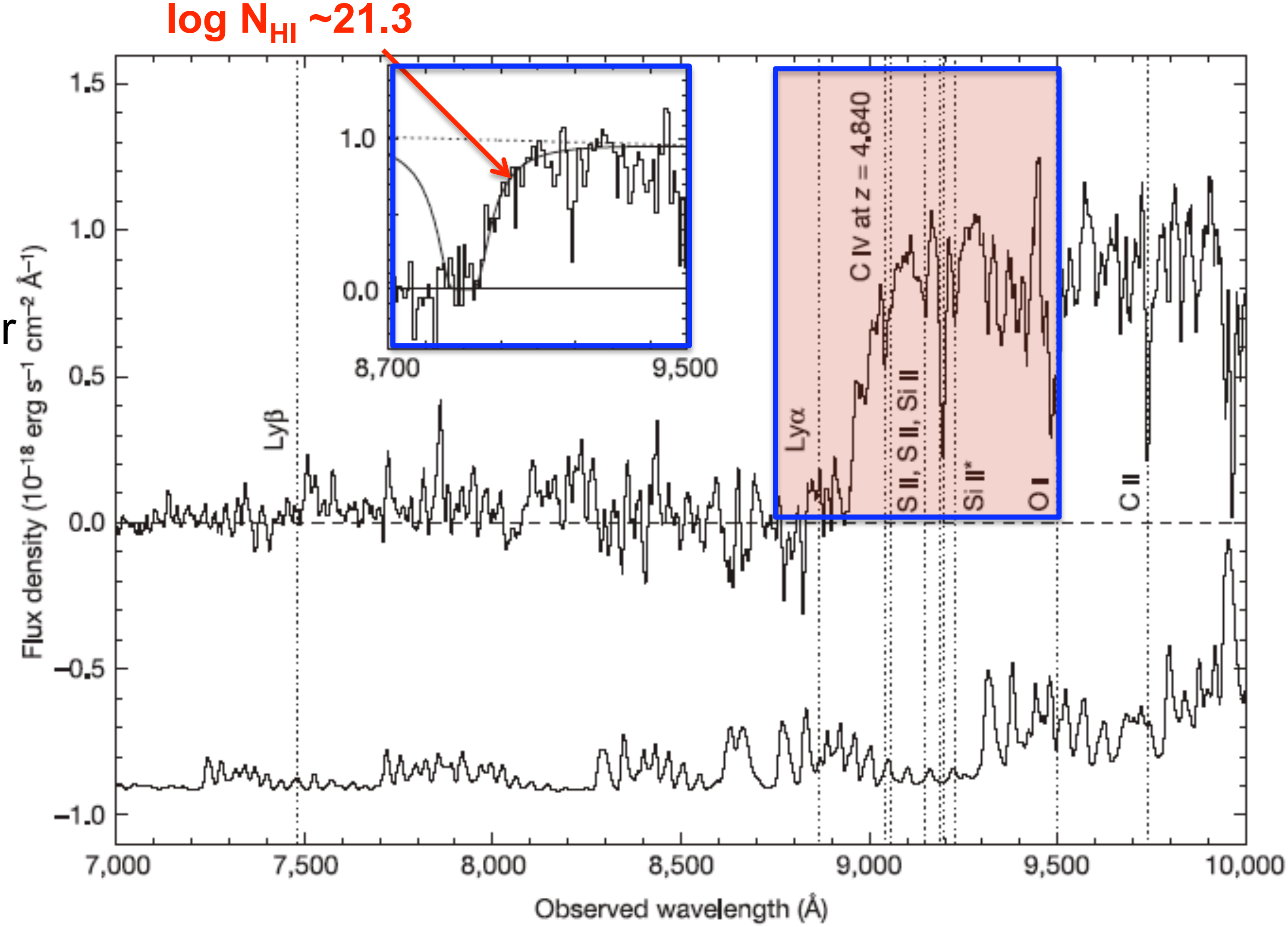
Jamie Bolton

Don't forget GRBs! Need more high z follow-up

GRB050904
z=6.295

Subaru
FOCAS 4.0 hr exposure

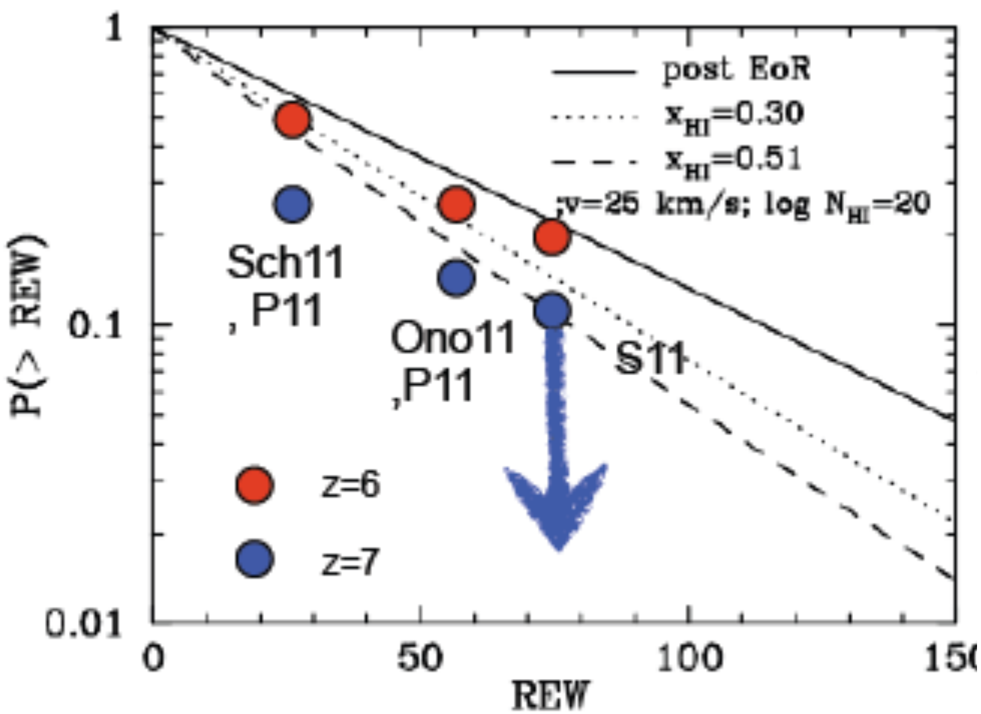
x_{HI} < 0.6



Kawai et al (2006) Nature 440, 184

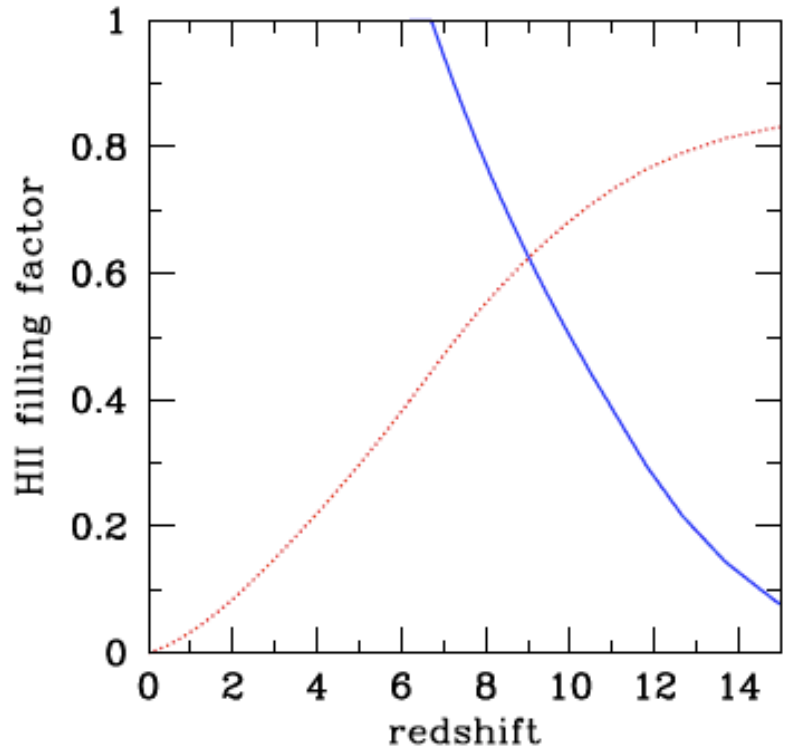
Is such a rapid change in x_{HI} reasonable?

Mark Dijkstra



MD, Mesinger & Wyithe 2011

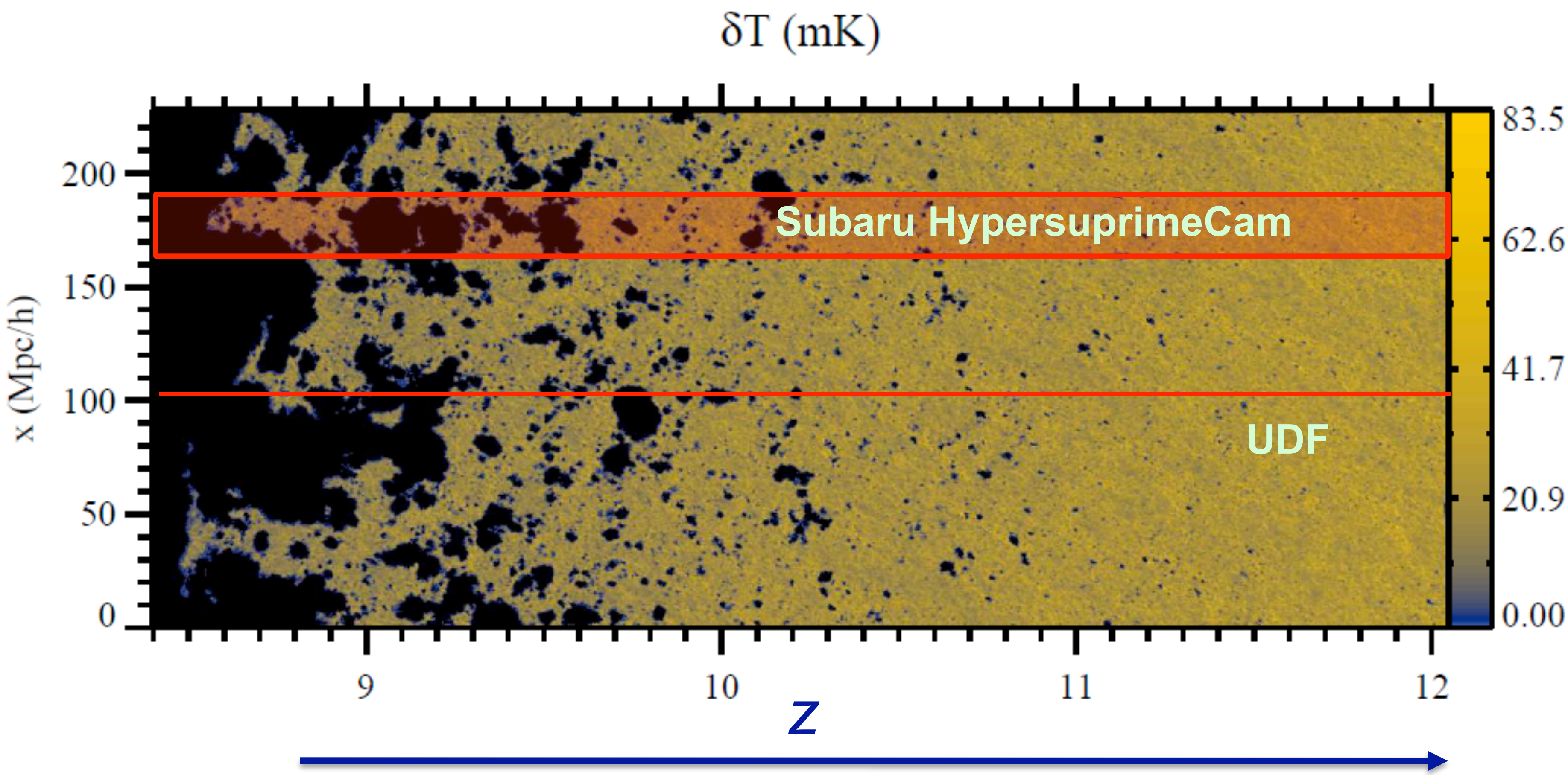
Piero Madau



To explain Lyα data, require rise to x_{HI}~0.4 over 200 Myr which seems surprising

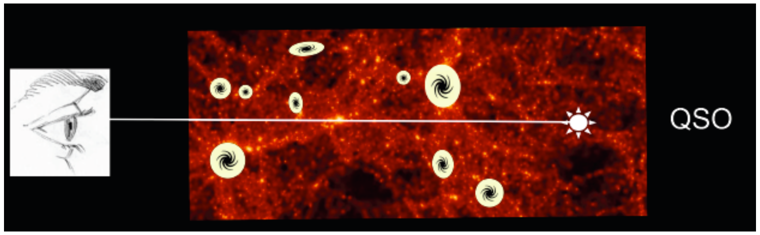
Cosmic variance: Simulated 21cm tomographic map

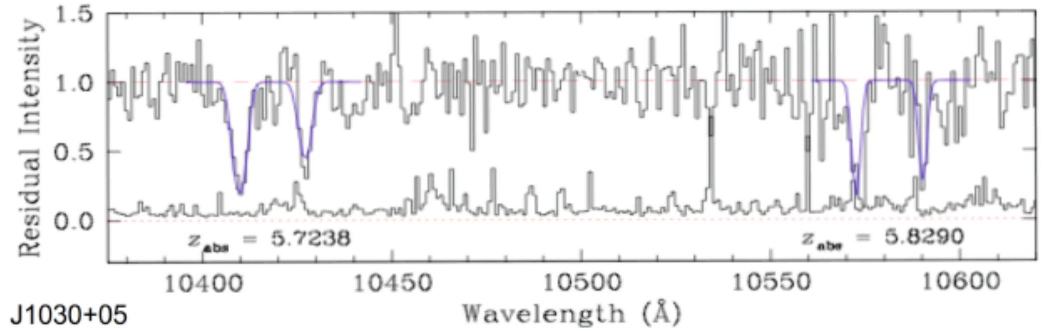
Unfiltered (linear scale)



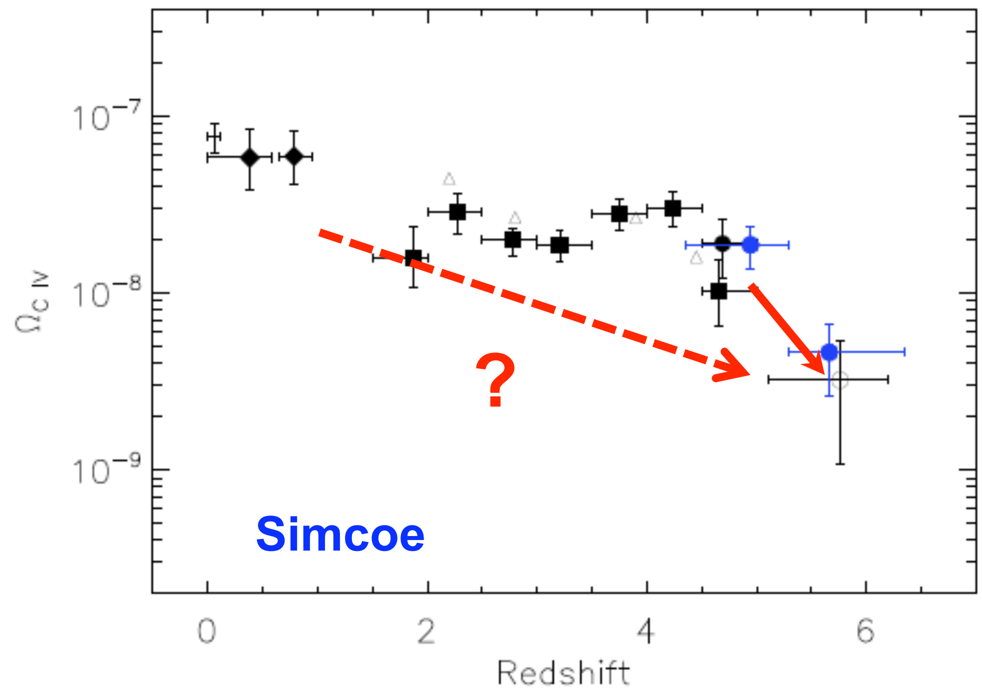
Iliev, Mellema, Shapiro, Pen, Mao, Koda & Ahn 2011,; arXiv:1107.4772

Other Probes of Early SF: CIV in high z IGM



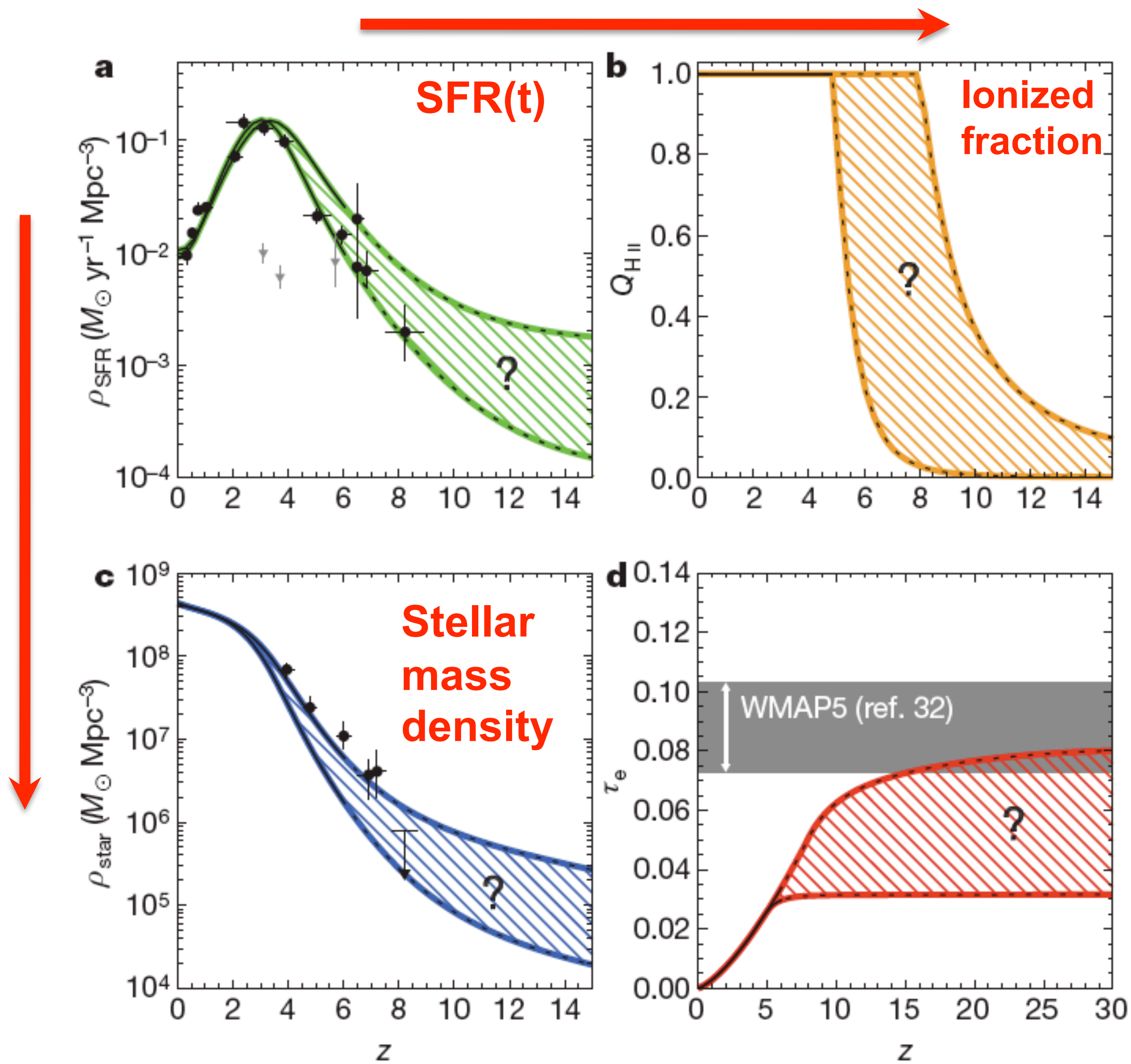


- Near-infrared spectra of z > 6 QSOs reveal CIV absorption from Ryan-Weber et al, **Simcoe** et al, **Cristiani** (D'Odorico et al)
- Sudden decline in $\Omega_{CIV}(z)$ to z~5.8???



Sudden drop (if it holds up) could arise from rapid abundance rise due to early enrichment of galaxy halos or ionization changes?

Did Galaxies Reionize the Universe?



Madau claims no tension but he assumes strong evolution in f_{esc}

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

What could make up the photon shortfall?

Topic discussed at this meeting:

• 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 (**Haiman**)

• Steeper than observed faint end slope of LF (**Trenti, Oesch**)

• Exotic stellar populations (e.g. top heavy IMF) (**Becker**)

• High escape fraction of ionizing photons (**Siana, Nestor, Rauch**..)

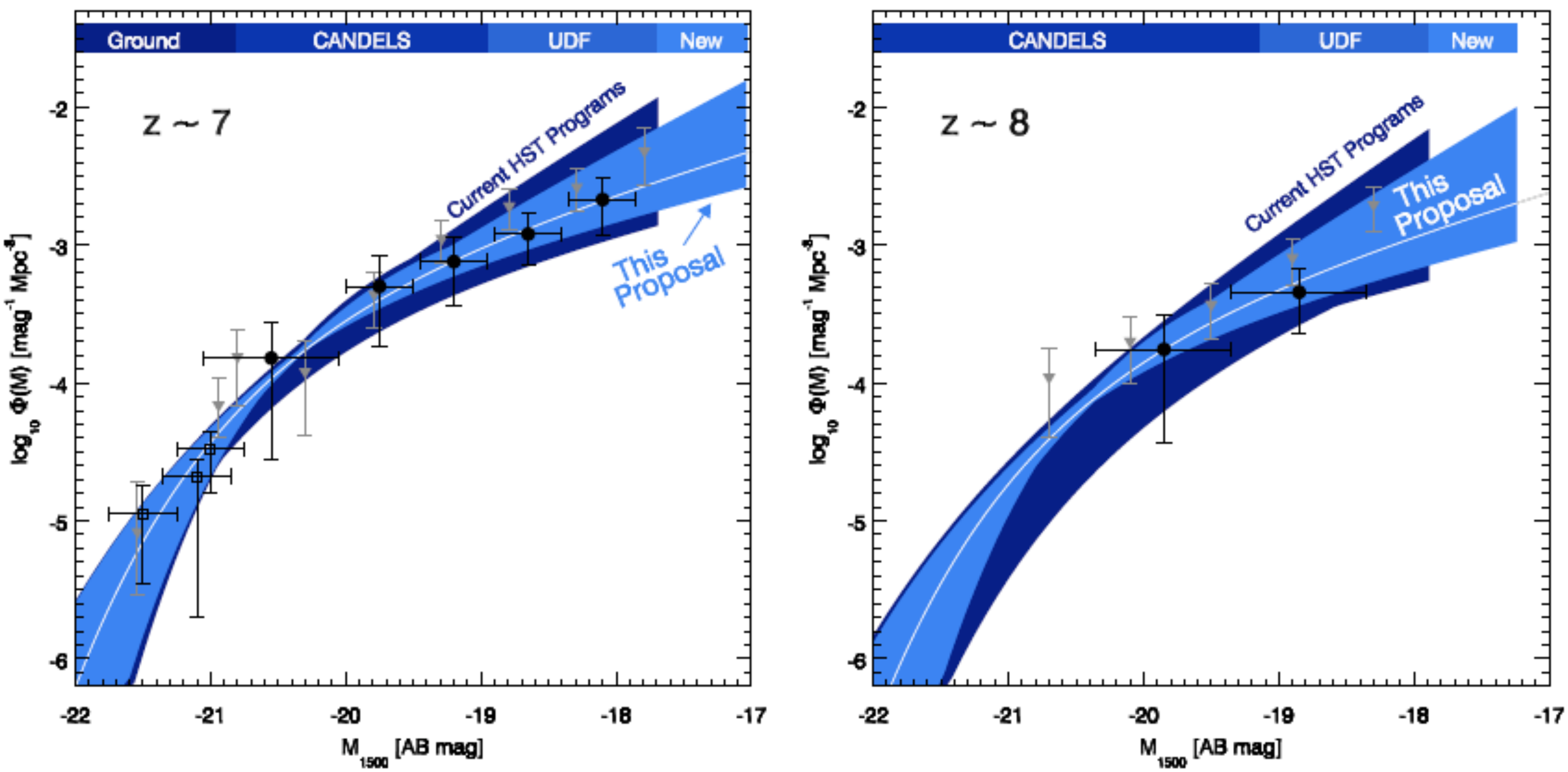
Action items!

• Deeper HST WFC3/IR data to verify faint end LF slopes at z~7-8

• More reliable measures of UV slope β (**Bouwens, Finkelstein**)

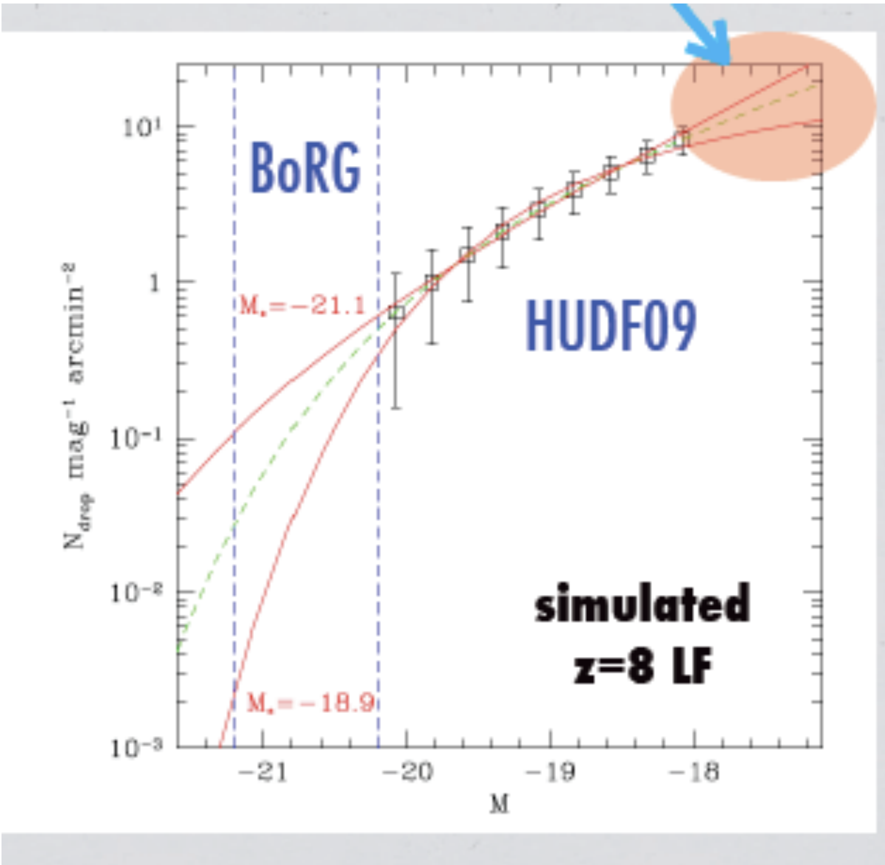
• More good work on 2<z<5 LBG demographics (**Siana, Nestor, Reddy**..)

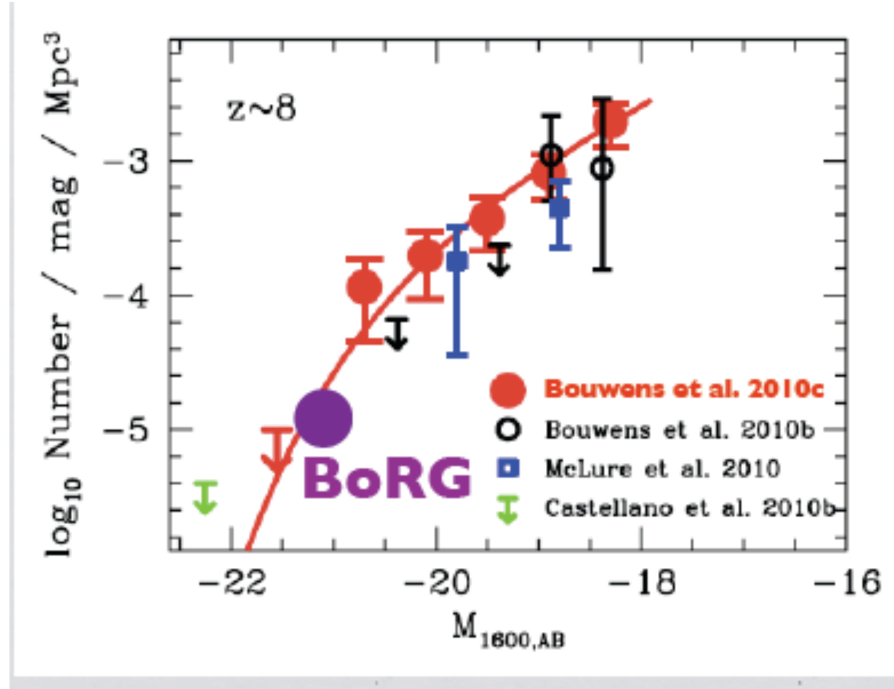
Projected LFs @ z~7-8 with HUDF-IR2



- Very steep LFs (α ~ -2) necessary to close reionization budget (**Trenti, Oesch**)
- 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

Improved Bright End Constraints





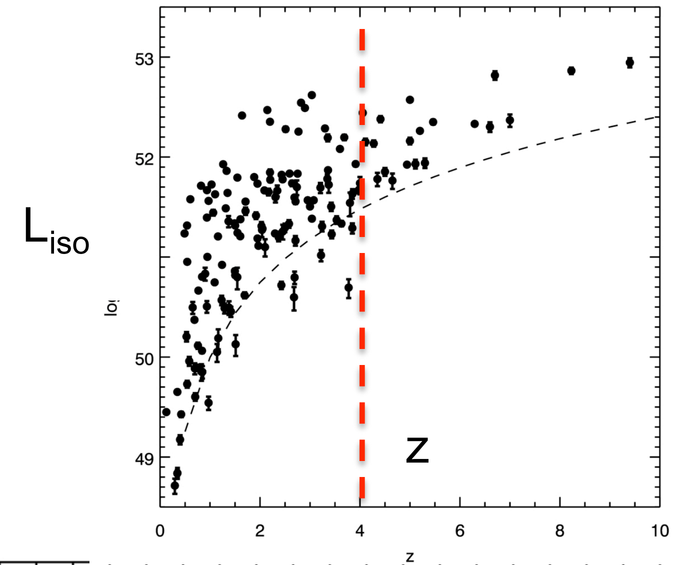
Trenti

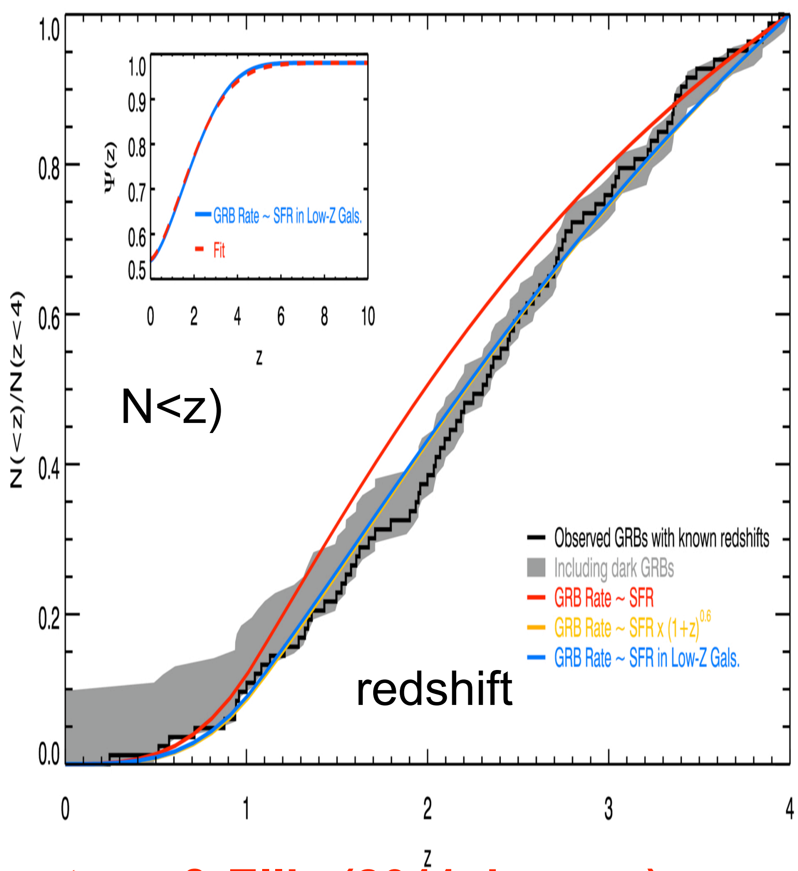
- Ongoing programs (CANDELS, parallel WFC3, Subaru) will provide significant improvements to the bright end of the z~7 and z~8 LF
- This will improve the Schechter fits in conjunction with deeper data (if the form of the LF is assumed)

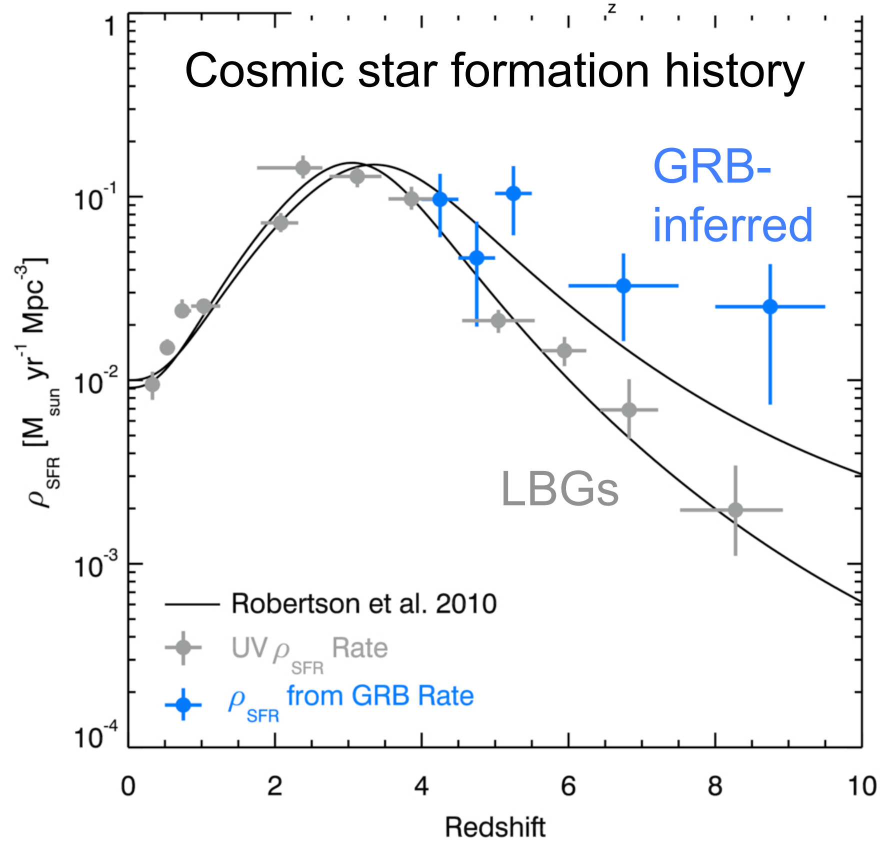
SFH constraints from GRBs

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.

GRBs lie in different stellar pop^{ns} or there's missing SF







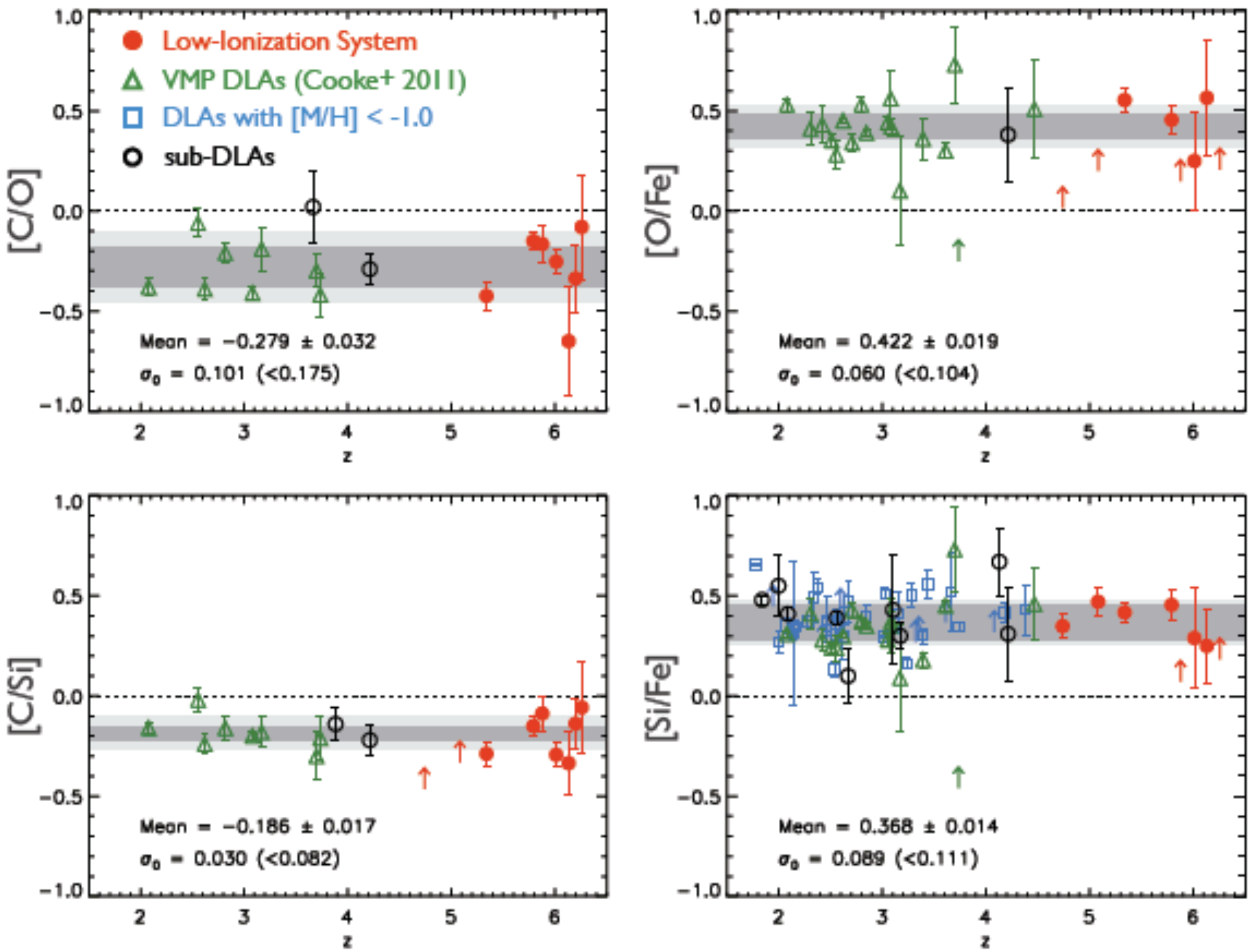
Robertson & Ellis (2011, in prep)

Exotic Stellar Populations z > 6?

Relative abundances consistent with low z metal poor absorbers & metal poor halo stars

Small scatter suggests bulk of stars that enriched were Pop II

Implies: Pop III phase short?



Becker + posters by Penprase, Ryan Cooke

Pop III Models: Metal Enrichment History

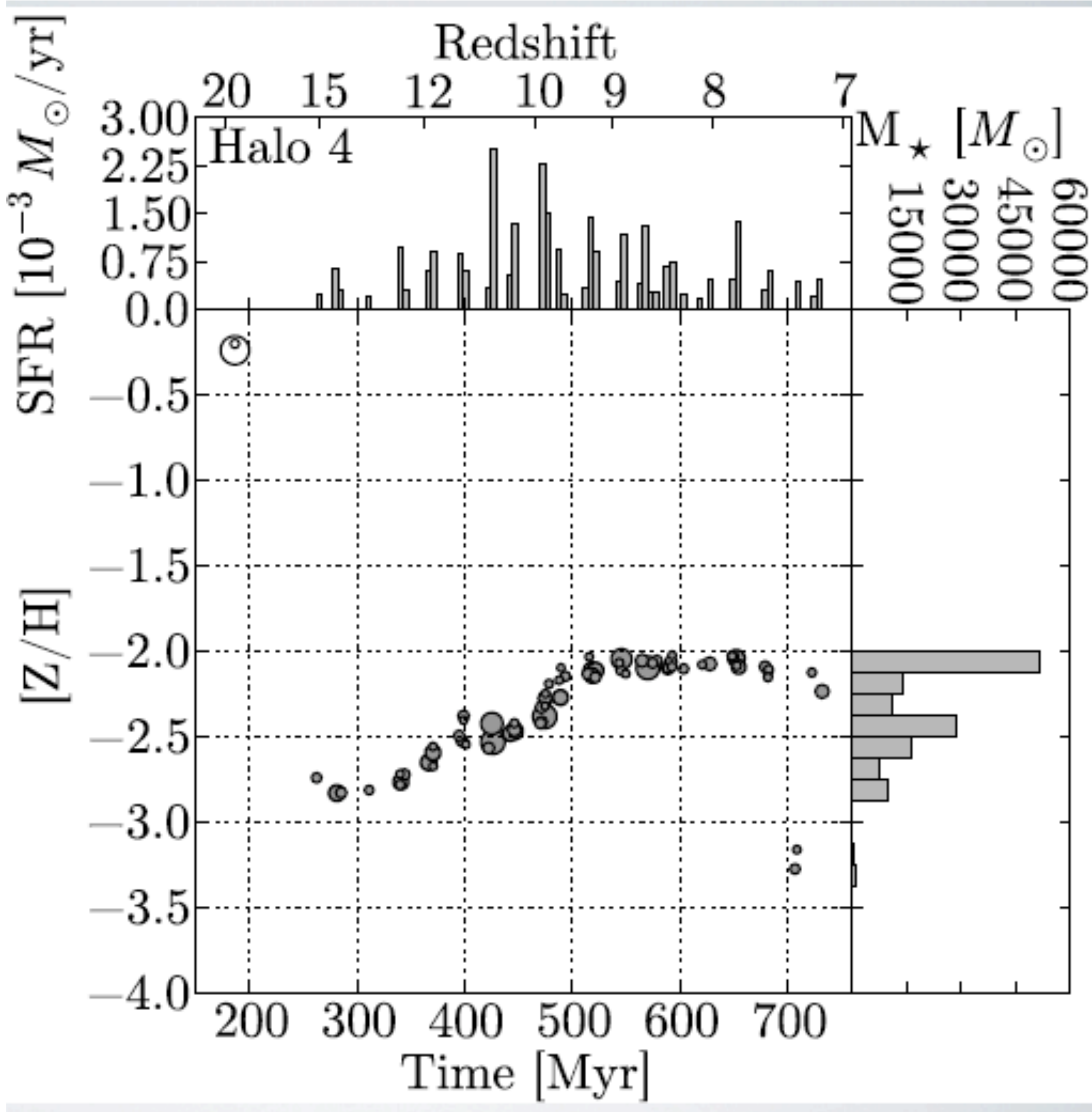
ENZO code (Bryan & Norman 1997, Wise & Abel 2011)

Halo mass M= 8 10^7 $M_\odot$

• 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

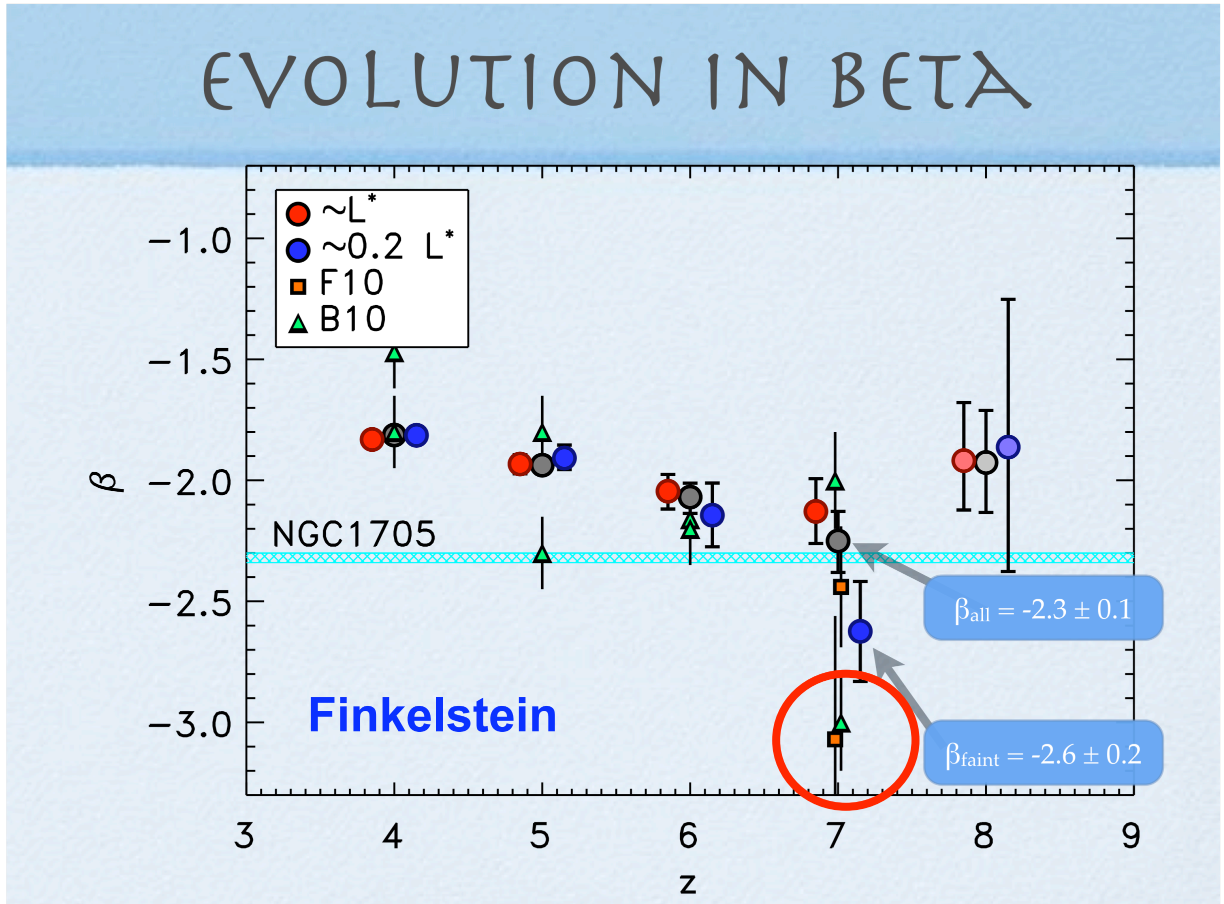
Steep UV Continua: `β-gate'?

WFC3 data measure slope β of the stellar continuum where $f(\lambda) \propto \lambda^{\beta}$: $\beta \rightarrow -3$!

Could imply very young, metal poor or even Pop III contributions

Early claim by Stanway et al (2004); see also Wilkins et al (2011) discussed by **Bunker**

Bouwens update: $\beta = -2.7$

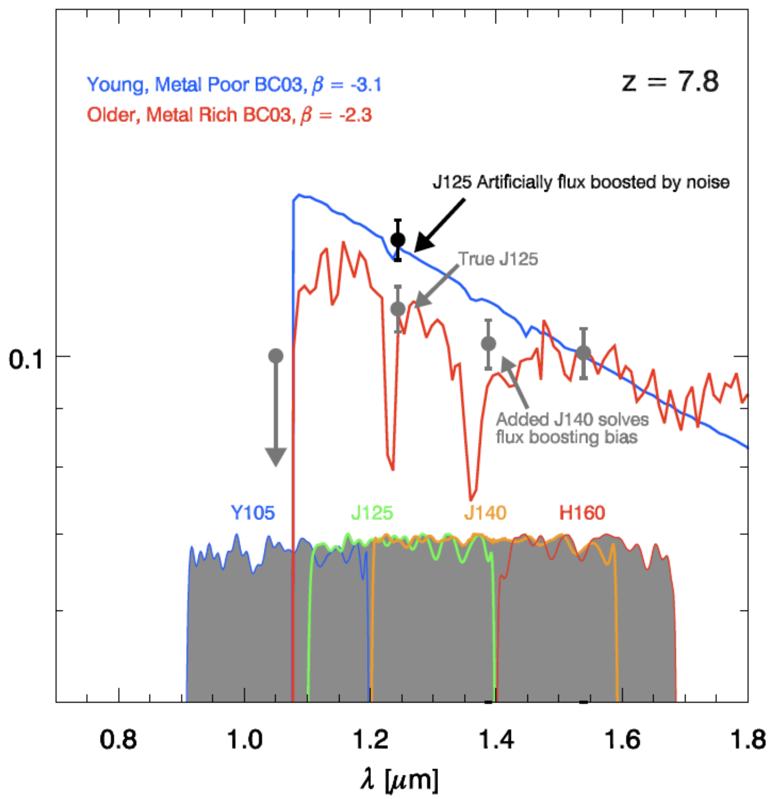


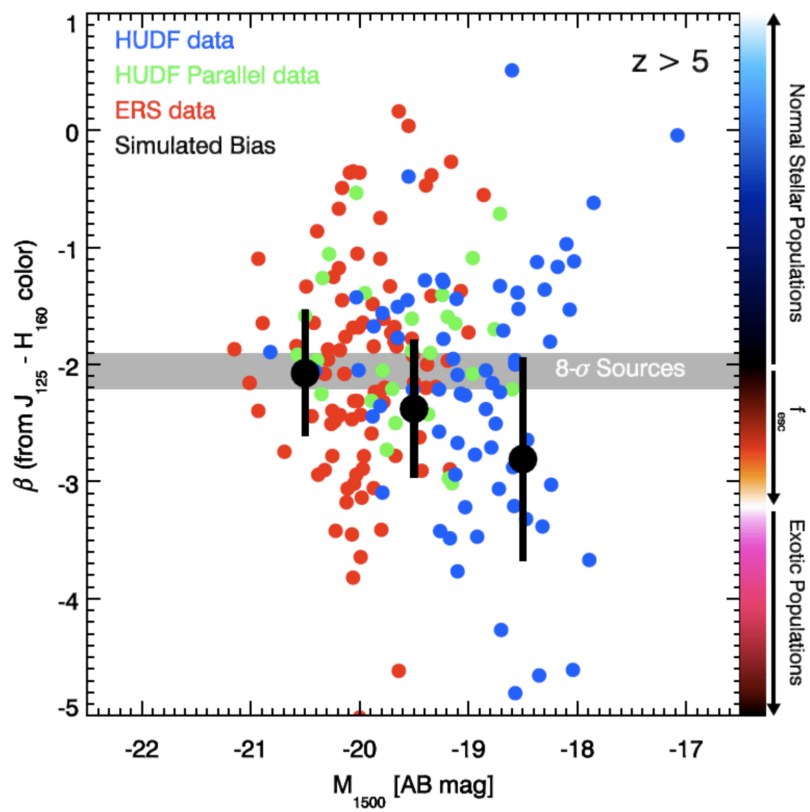
Agree higher z and low L galaxies are slightly bluer (less dusty - Stanway)
But evidence for uncomfortably steep slopes limited to faint z~7 LBGs

Validity of UV slopes in Faintest Data?

β estimated from (J-H) using noisy photometric data

- Boosting in J due to noise biases β to bluer, more extreme values
- Boosting in H affects photo-z solution, placing object at z~2
- Bouwens claims boosting has only marginal effect on traditional color-color methods of drop out selection
- **Deeper HST data with additional J140W filter will clarify**

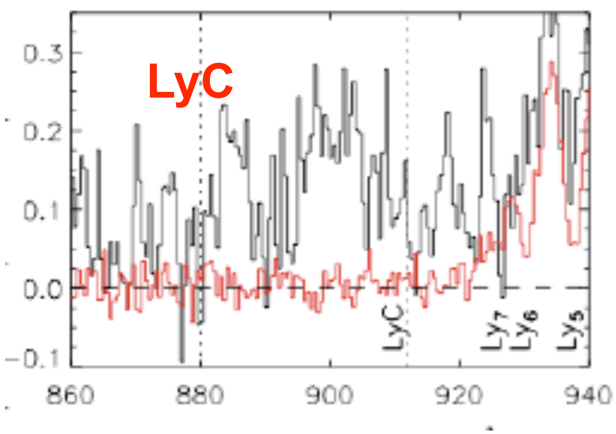




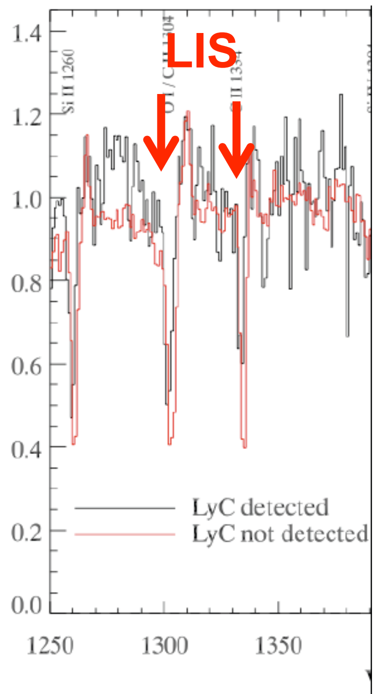
Dunlop et al astro-ph/1102.5005

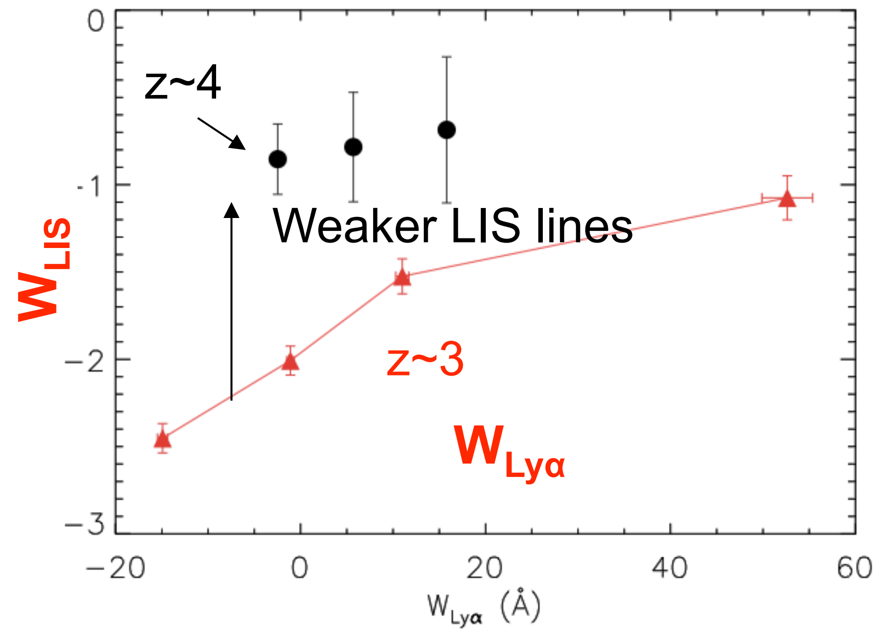
Does f_{esc} increase with z?

Keck spectra reveal LyC is seen in faint blue LBGs where low ionization lines are shallower implying reduced covering fraction (Steidel et al 2011, in prep)



Siana





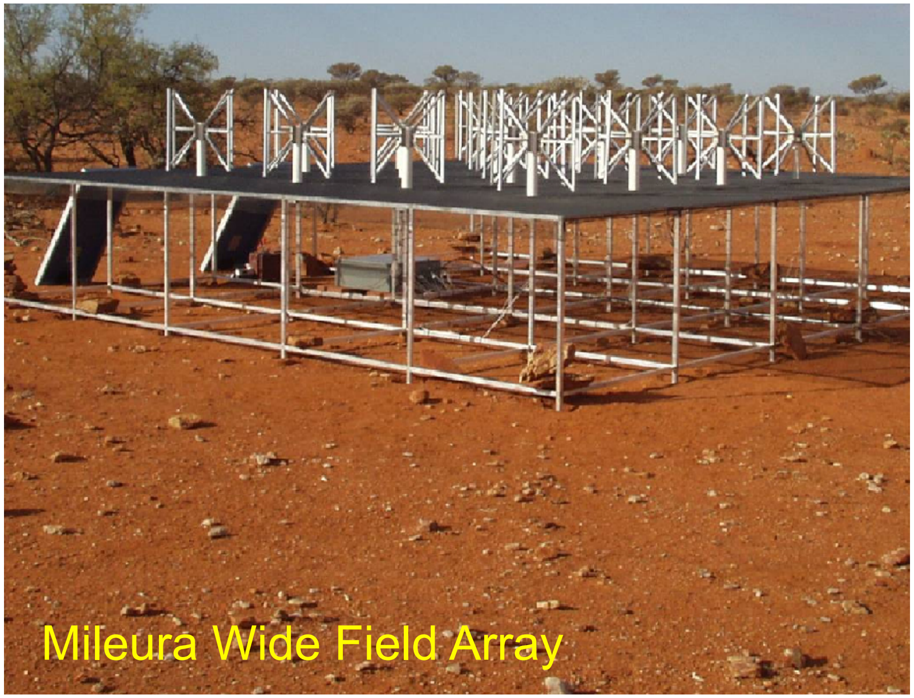
Stark, Jones

Stack of ~120 z~4 Keck DEIMOS spectra shows weaker low ionization lines which may imply increased f_{esc} (although other interpretations are possible).

Further DEIMOS spectra over 4<z<6 will clarify

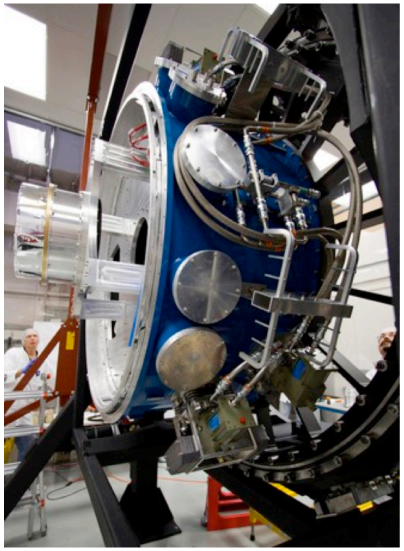

The Future
Atacama Large Millimeter/submm Array (Bertoldi, Richer)

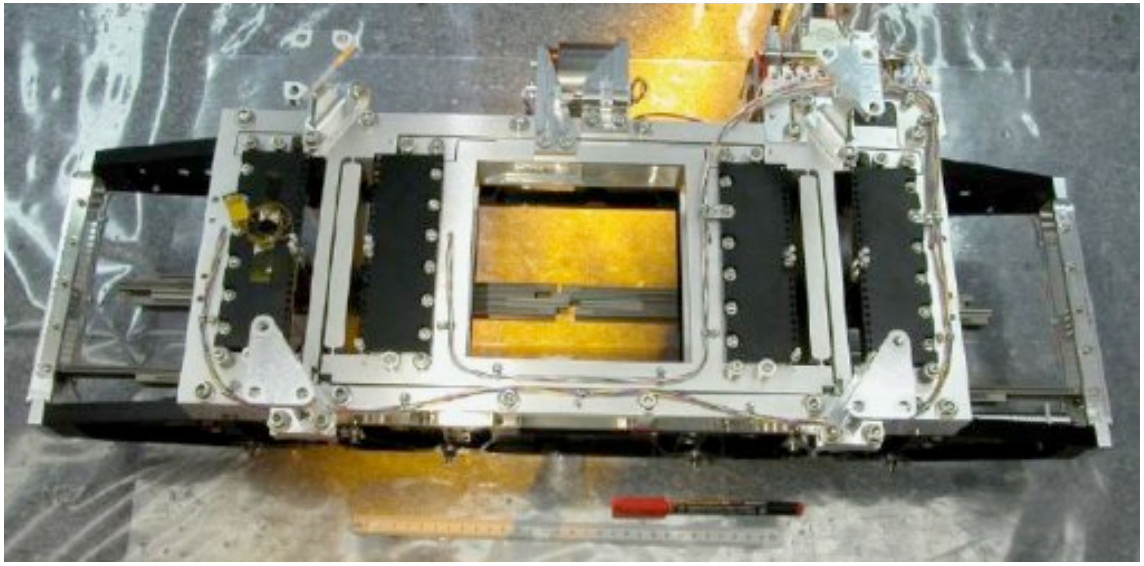
Mapping reionization through 21cm emission

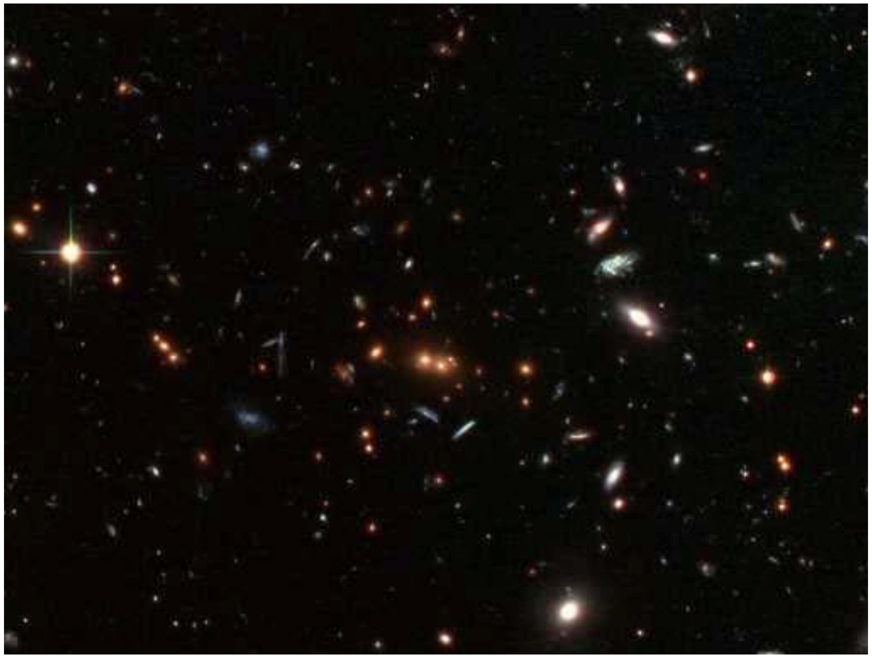


Zaroubi, Pober, Pritchard, Meiksin

MOSFIRE (Keck I)







Cryogenic Multi-slit IR spectrograph

6.1 x 3.1 arcmin spectroscopic field

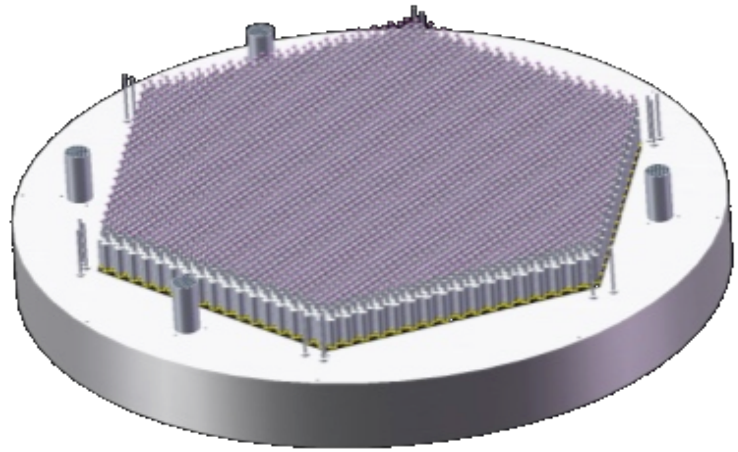
$\lambda\lambda$0.97 - 2.45 microns

R ~3300 for 0.7 arcsec slit

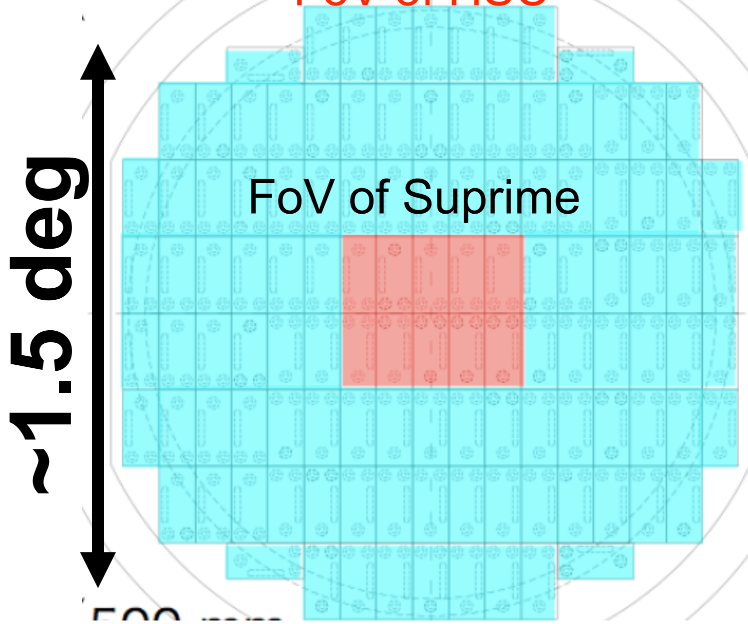
45 slits via configurable slit unit (<5mins)

Subaru Wide Field Instrumentation

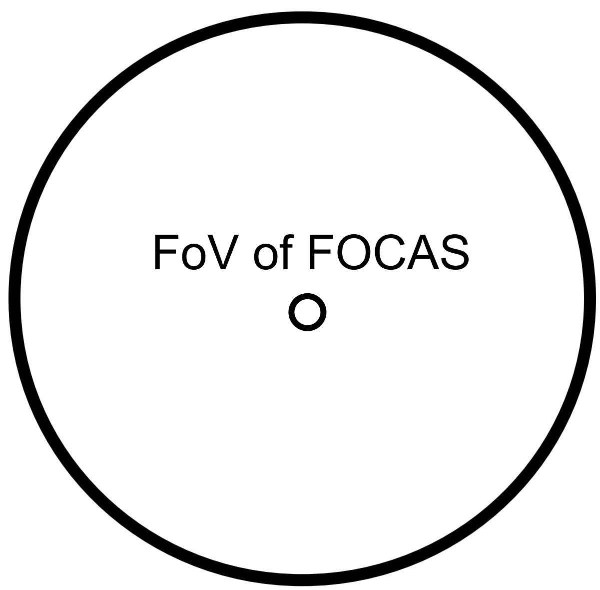
2400 fiber positioning system

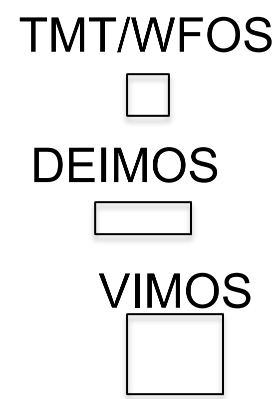


FoV of HSC

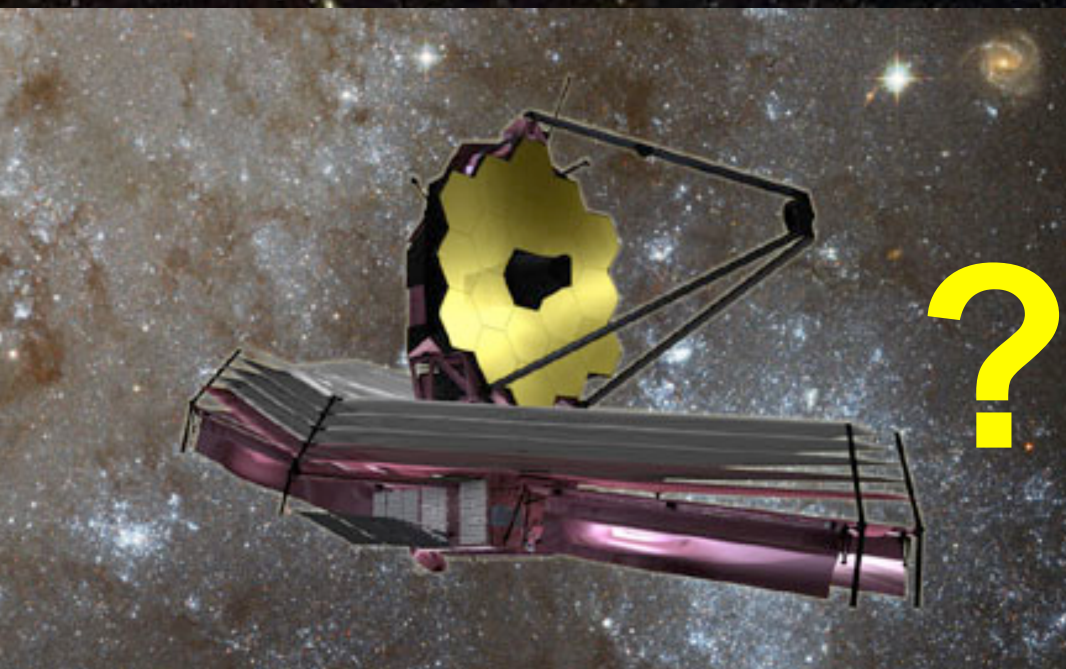


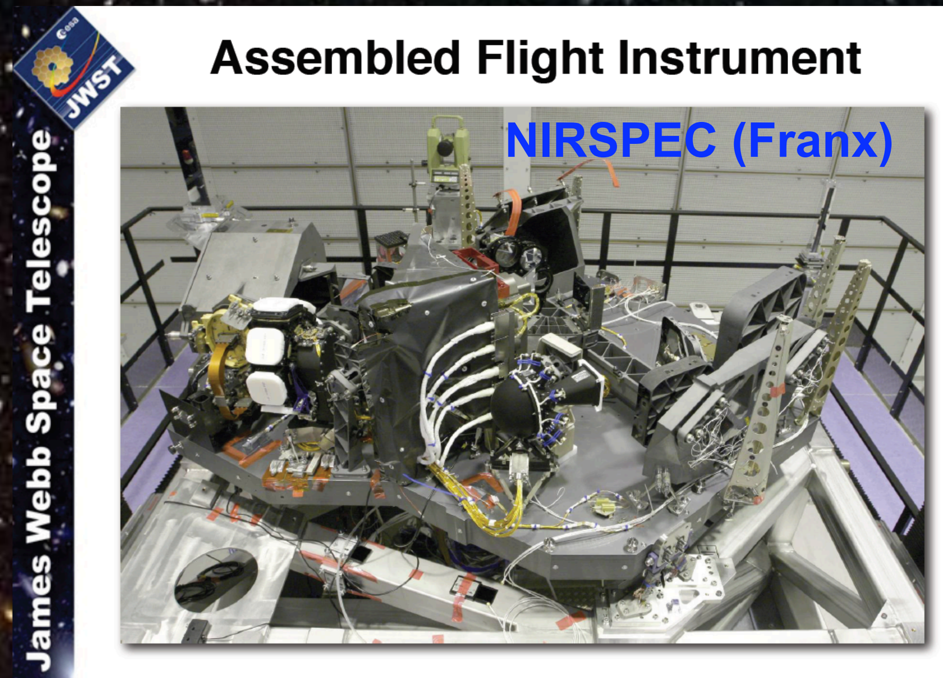
FoV of PFS





James Webb Space Telescope

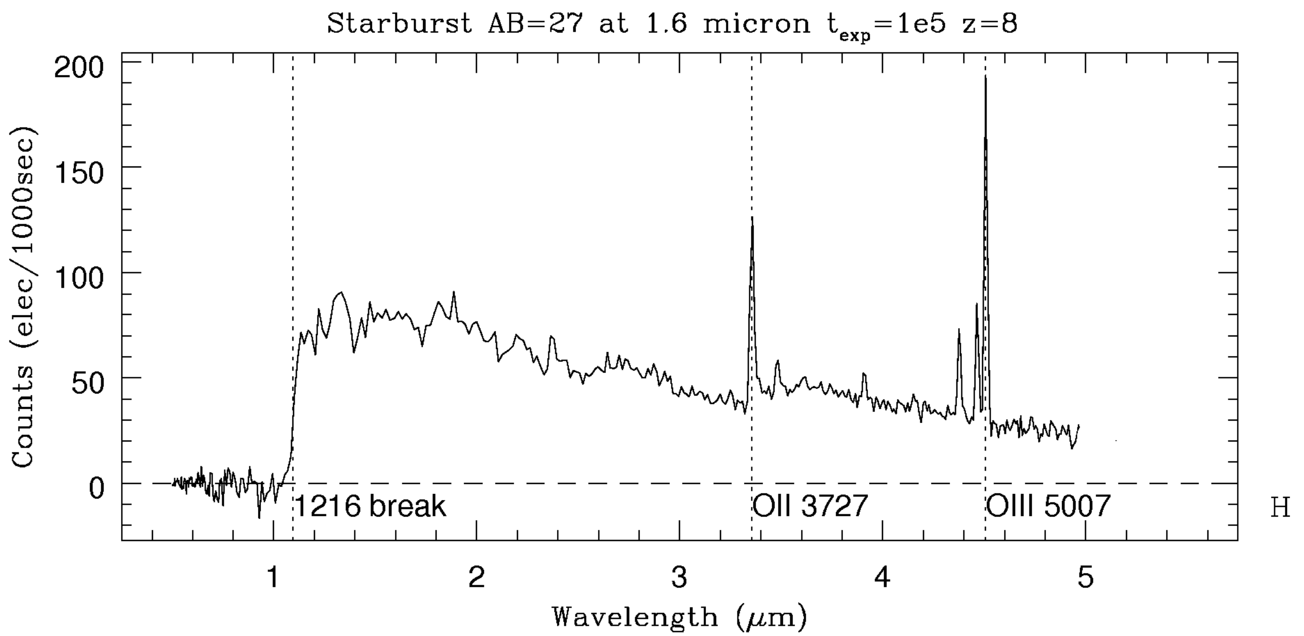




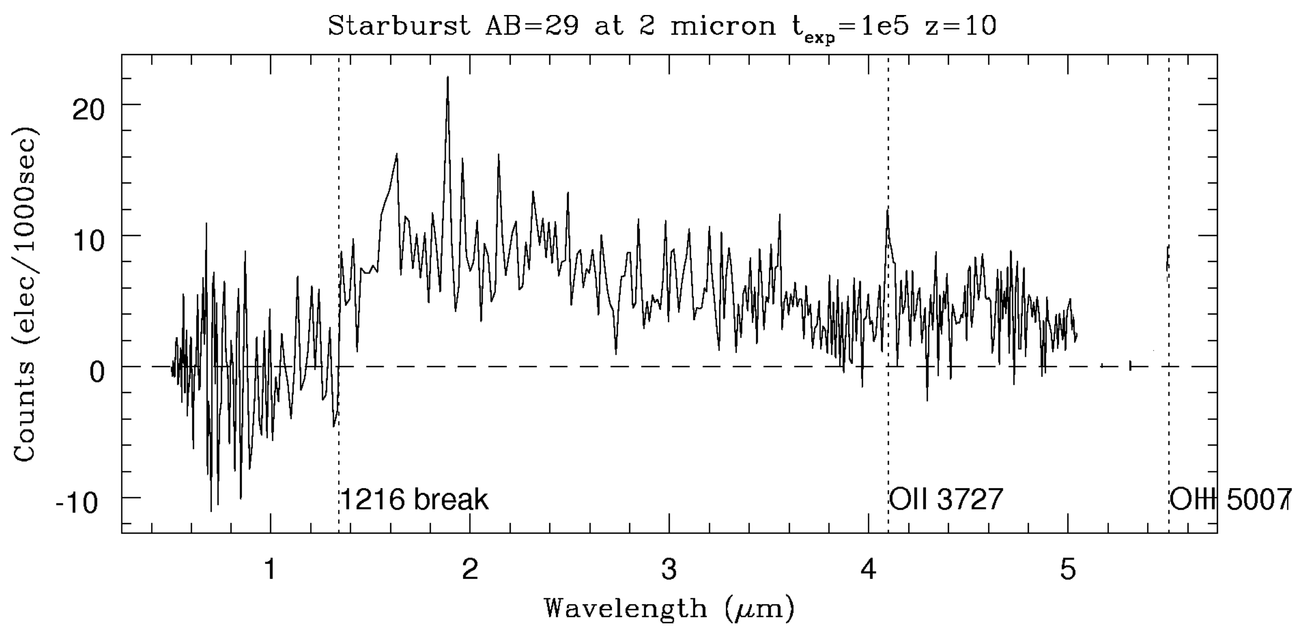
Mike Shull

Simulated NIRSPEC spectra

AB=27 z=8
enabling full nebular/stellar decontamination and gas phase metallicities (**Maiolino, Schaerer**)

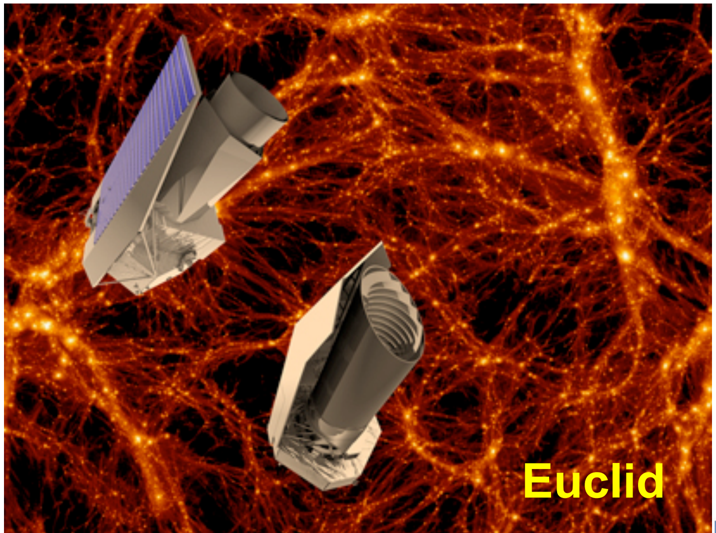


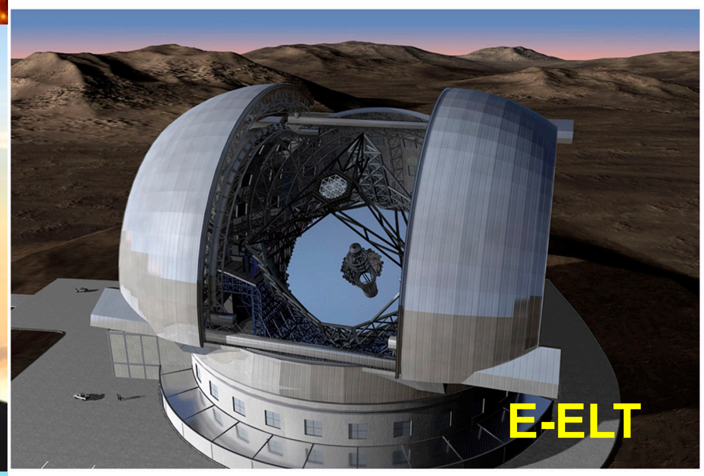
AB=29 z=10
(current UDF limit)

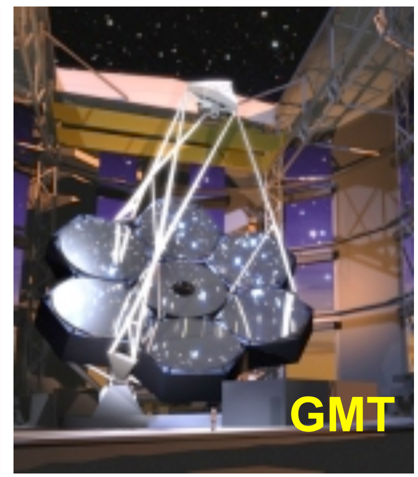


Franx

Other Prospective Goodies







Thanks for a great meeting!

Scientific Organising Committee
George Becker
Sebastiano Cantalupo
Bob Carswell
Scott Chapman
Martin Haehnelt
Paul Hewett
Regina Jorgenson
Rob Kennicutt
Anthony Lasenby
Richard McMahon
Max Pettini
Dan Stark

Local Organising Committee
Paul Aslin
George Becker
Jeannette Gilbert (sec)
Martin Haehnelt
Paul Hewett
Max Pettini
Amanda Smith