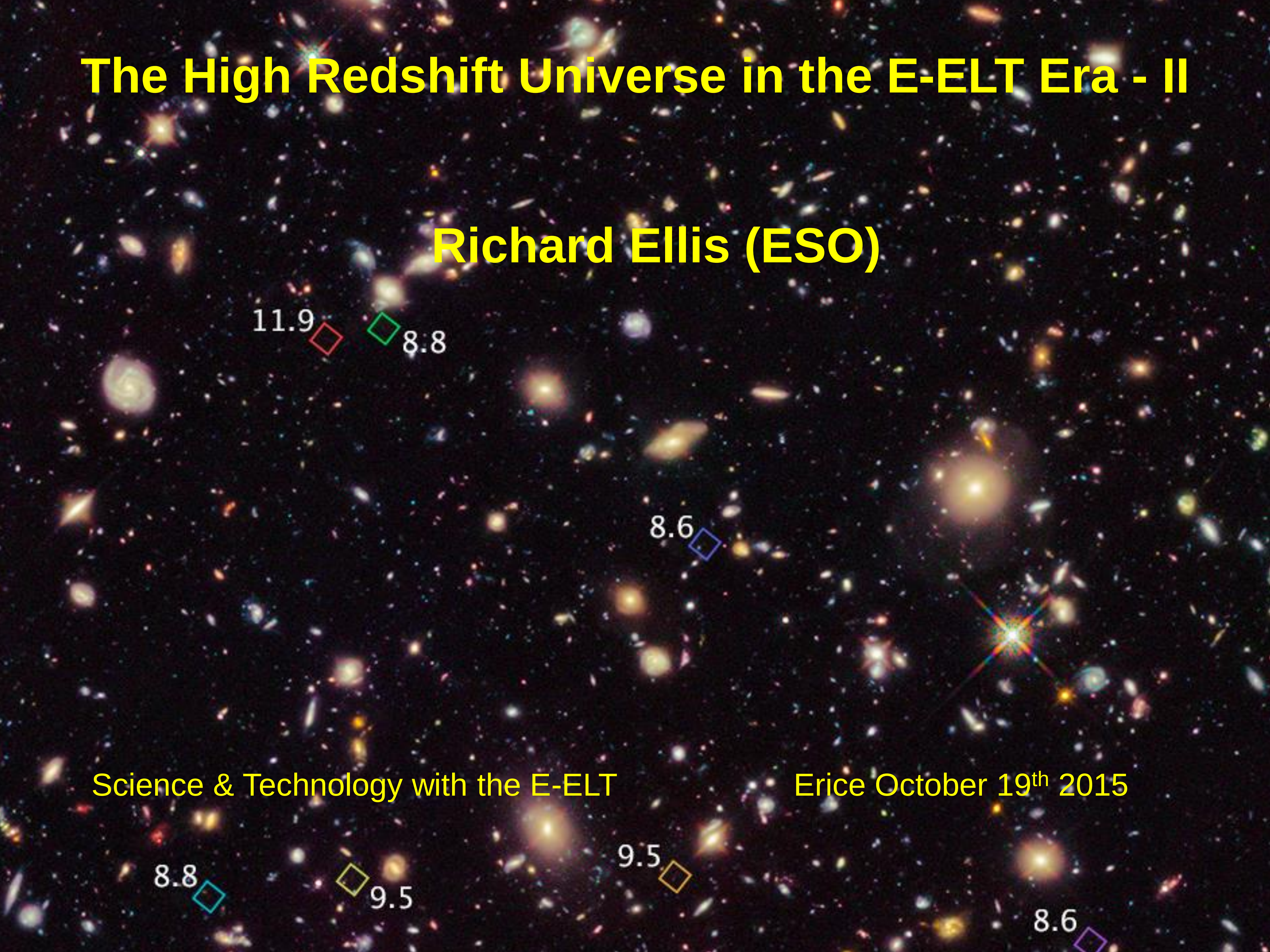
# The High Redshift Universe in the E-ELT Era - II

## Richard Ellis (ESO)




Science & Technology with the E-ELT

Erice October 19th 2015

# Plan

**Lecture 1: Key Questions in Galaxy Evolution & Emerging Techniques**

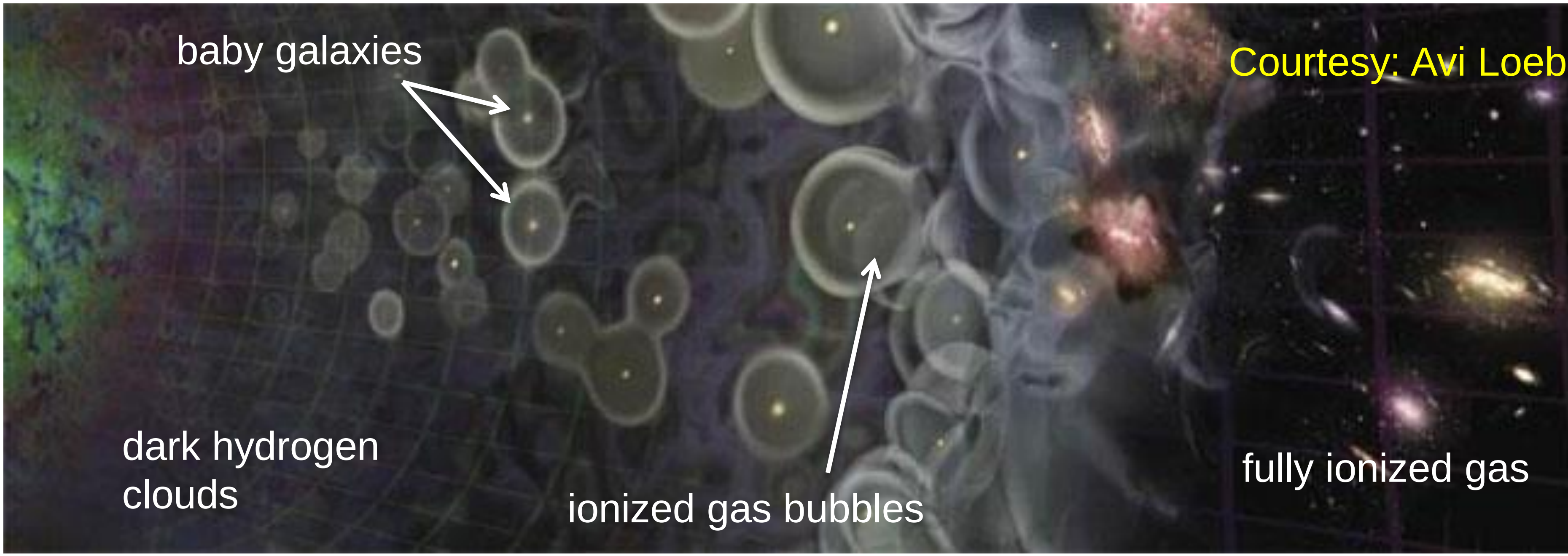
- The Hubble Sequence of Galaxies
- Cosmic Star Formation and Stellar Masses
- Theoretical Concepts: Hierarchical Assembly and Feedback
- The History of Disk Galaxies
- The Formation of Quiescent Galaxies
- Summary of Emerging Techniques in Context of E-ELT

**Lecture 2: Galaxies & Reionisation: Finalizing Cosmic History**

- What is Cosmic Reionisation
- When did Reionisation Occur?
- Were Star-Forming Galaxies Responsible?
- Challenges and Techniques
- JWST – E-ELT synergies

# What is Cosmic Reionisation?

time




When the first galaxies emerged (**cosmic dawn**), the Universe was bathed in ultraviolet light from young stars which produced ionized spheres of electrons and protons inbetween the galaxies (**reionisation**).

This landmark probably occurred 200-800 million years after the Big Bang when the Universe was <5% of its present age (redshifts z~6-20).

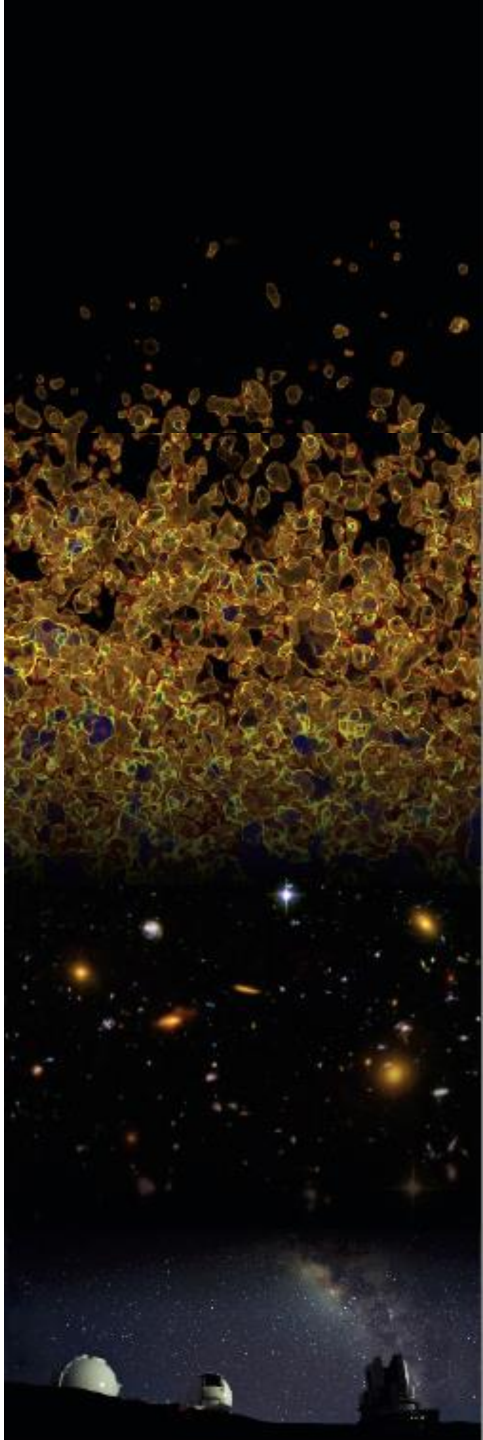
# The Big Questions

- When did reionization occur?
  Constraints from the microwave background; results from current spectroscopy

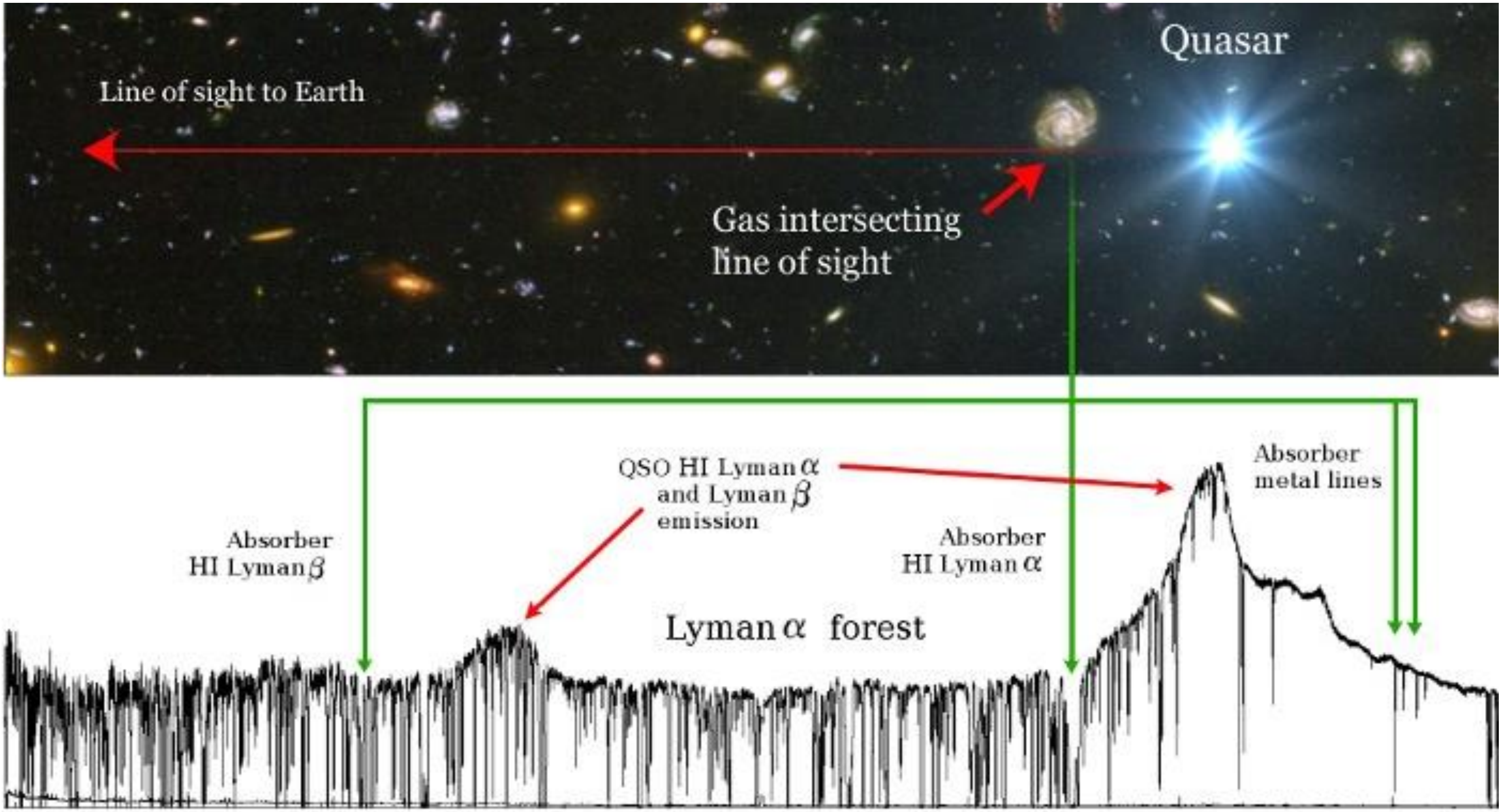
- Were star forming galaxies responsible? Need to study galaxies in the reionization era
  - Abundance of star-forming galaxies
  - Nature of their stellar populations

- Many issues and challenges for E-ELT
  - Lack of spectroscopic confirmations
  - Escape fraction of ionizing photons
  - Nature of ionizing radiation (stellar populations, AGN)
  - Presence of early dust?

- Major driver for both E-ELT and JWST: How will they work together?

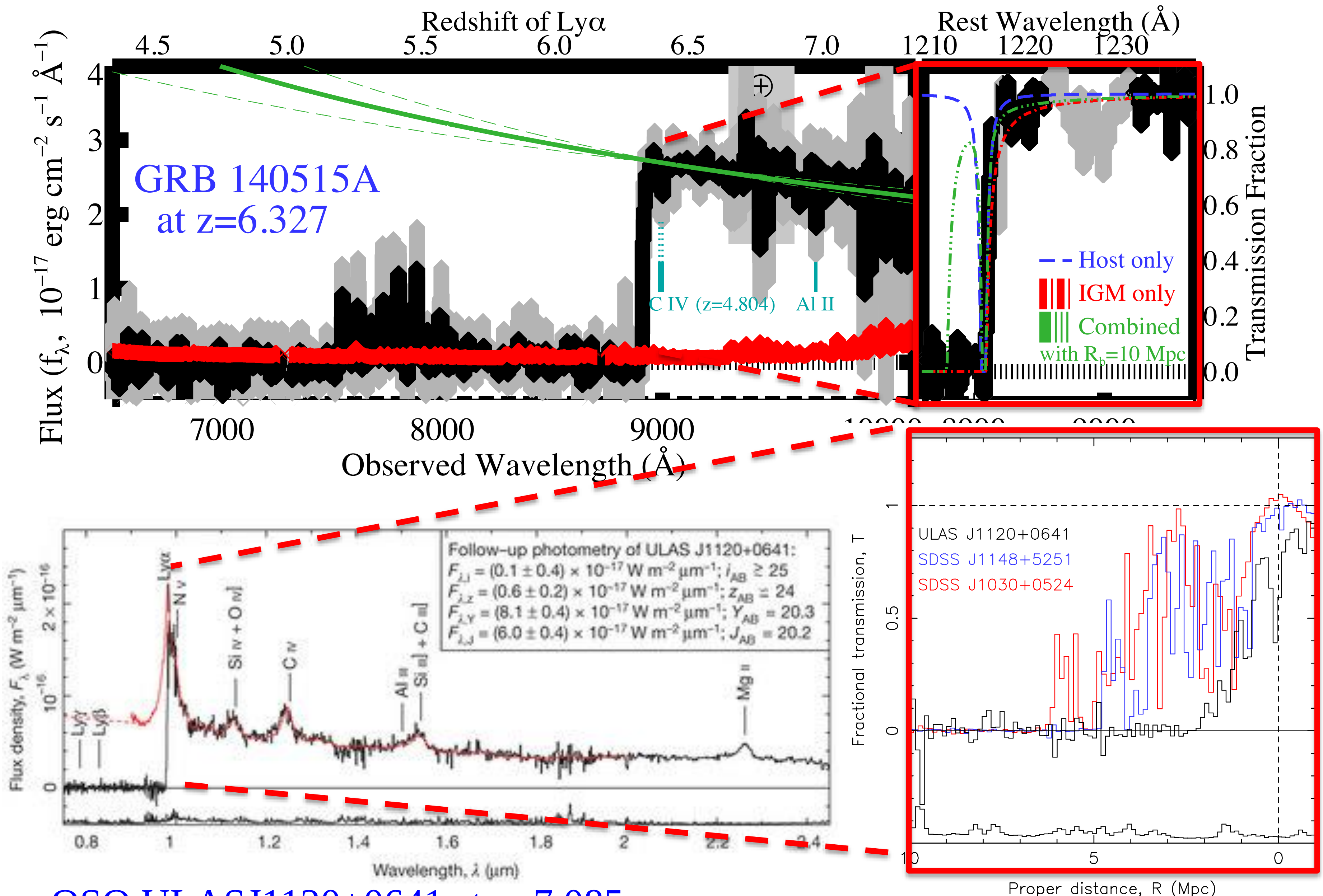


# How to Probe the Intergalactic Medium (IGM)?




High redshift QSOs (and gamma ray bursts) are bright enough to act as beacons illuminating, via absorption line spectroscopy, the presence of neutral hydrogen in the IGM

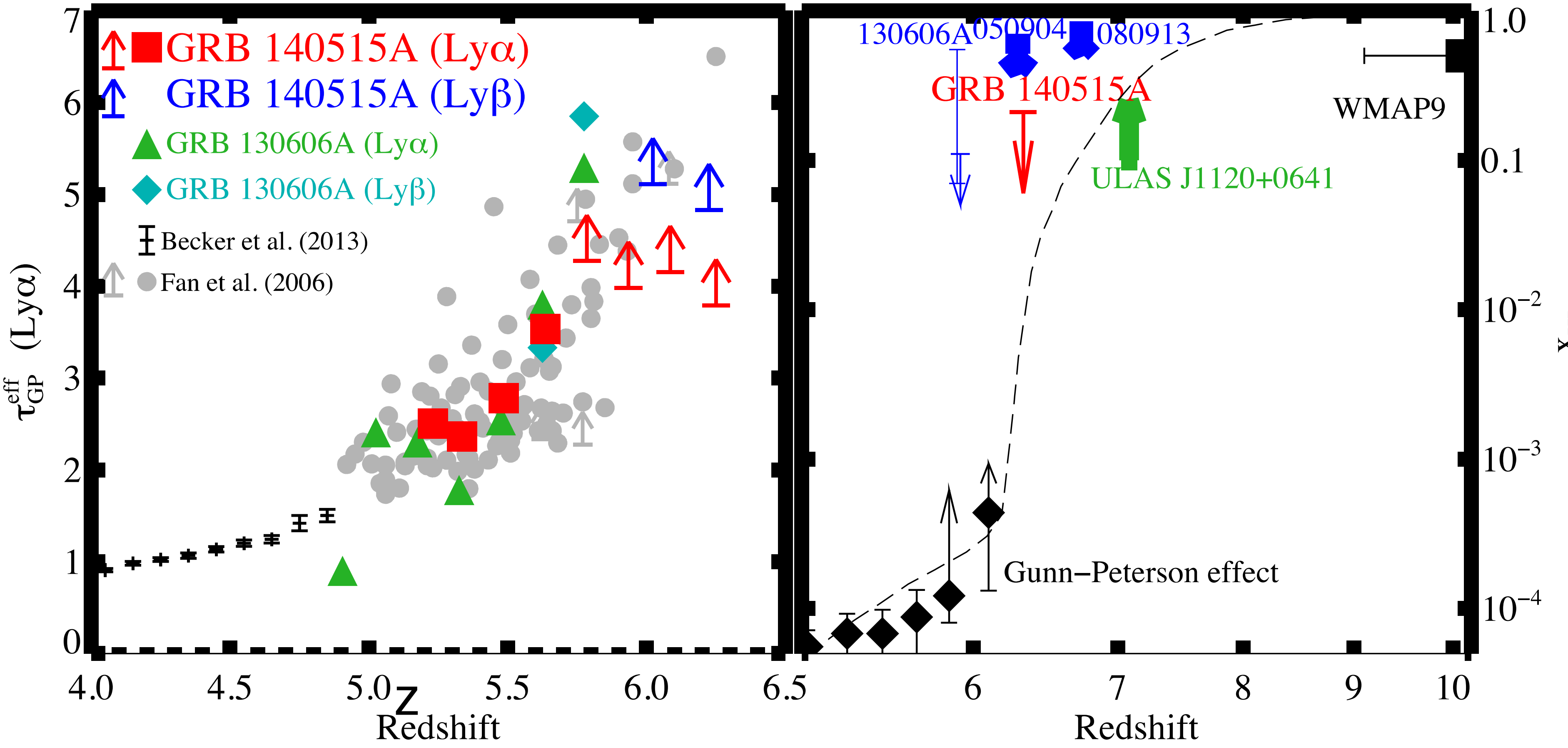
# Absorption Spectra of z > 6 GRBs & QSOs




QSO ULASJ1120+0641 at z=7.085

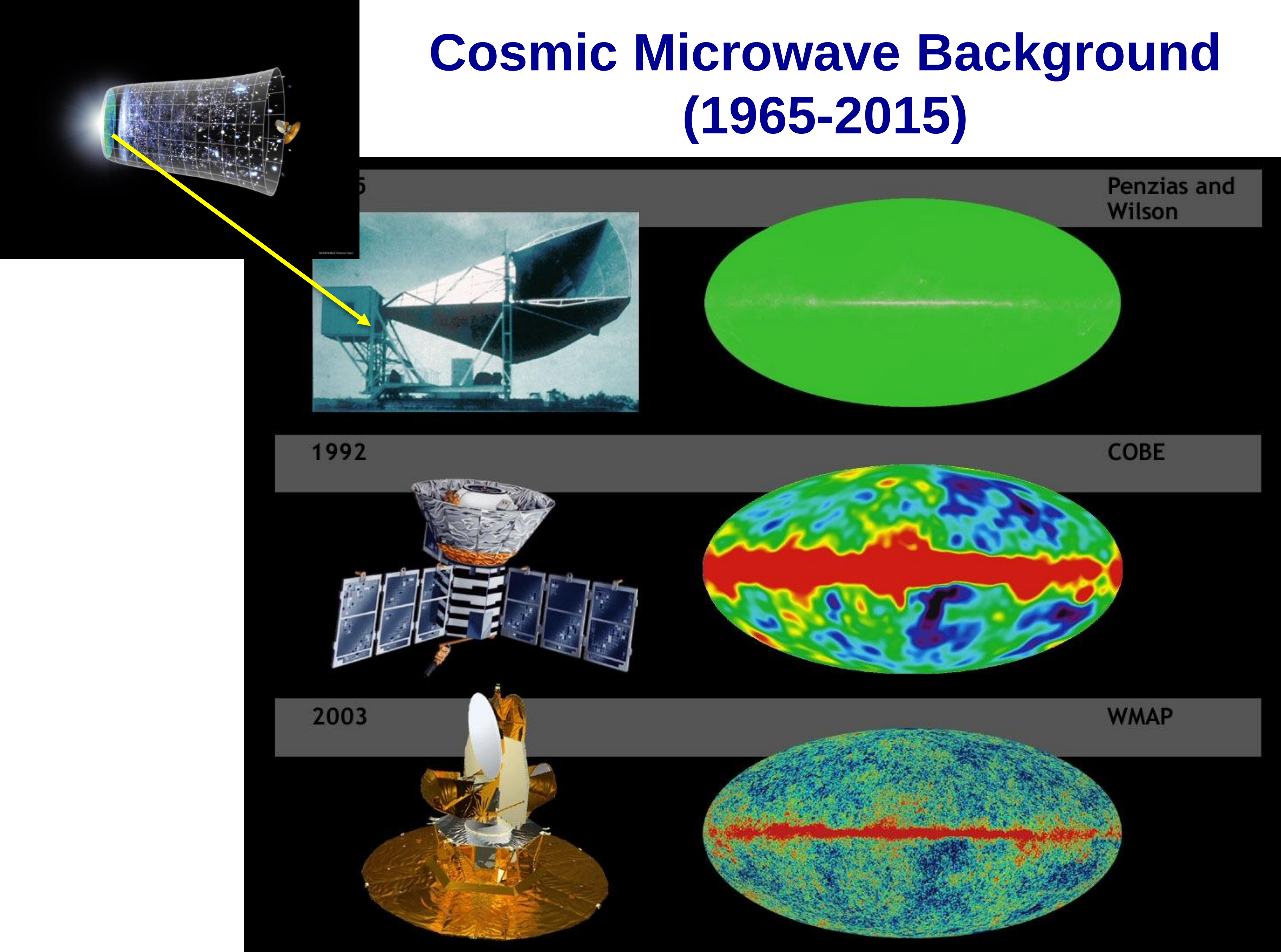
# Redshift-Dependent Absorption

Insensitive: only small amount of HI saturates absorption ($X_{HI} \sim 10^{-3}$)
Modest progress since 2006: few suitable sources beyond z~6

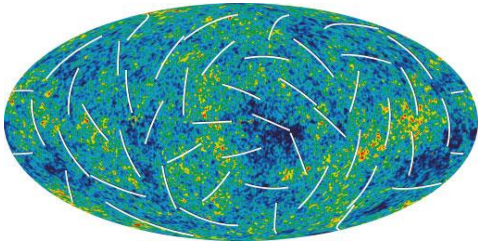


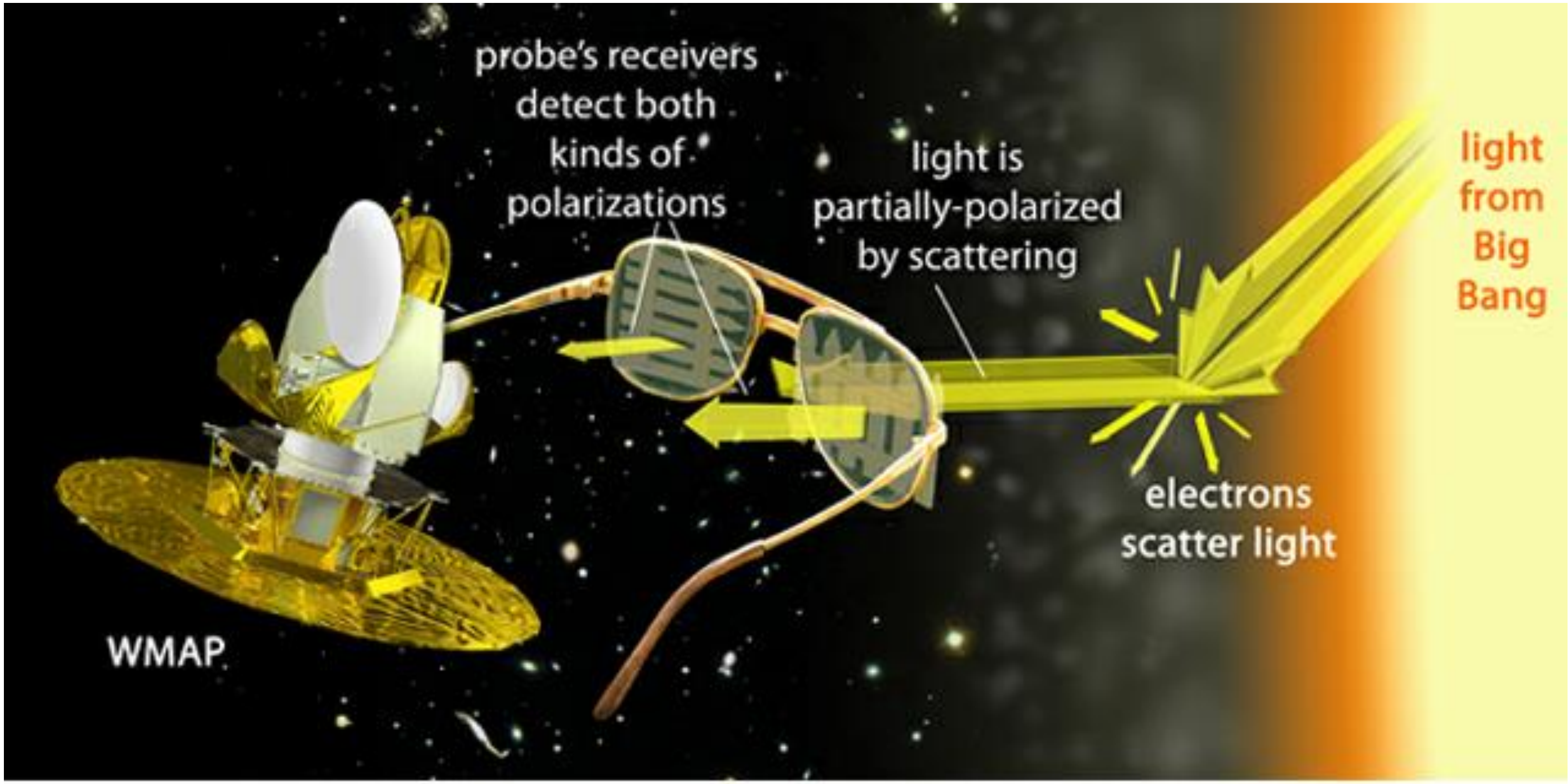

Chornock et al arXiv: 1405.7400
McGreer et al 2015 MN 447, 499

# Cosmic Microwave Background (1965-2015)



# Polarization of Microwave Background





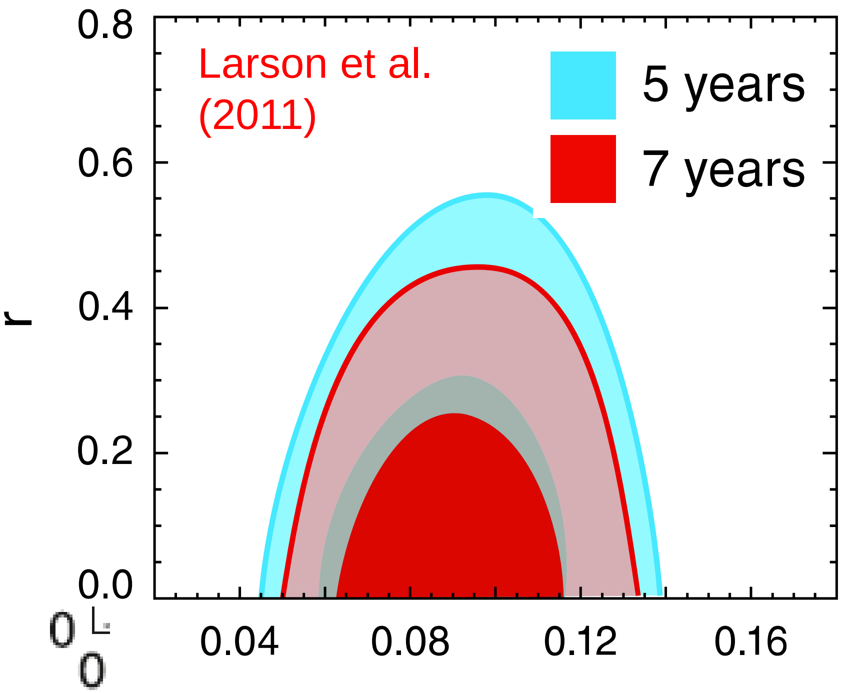

Polarization in microwave background probes electron scattering in the foreground i.e. electrons from the time of reionization

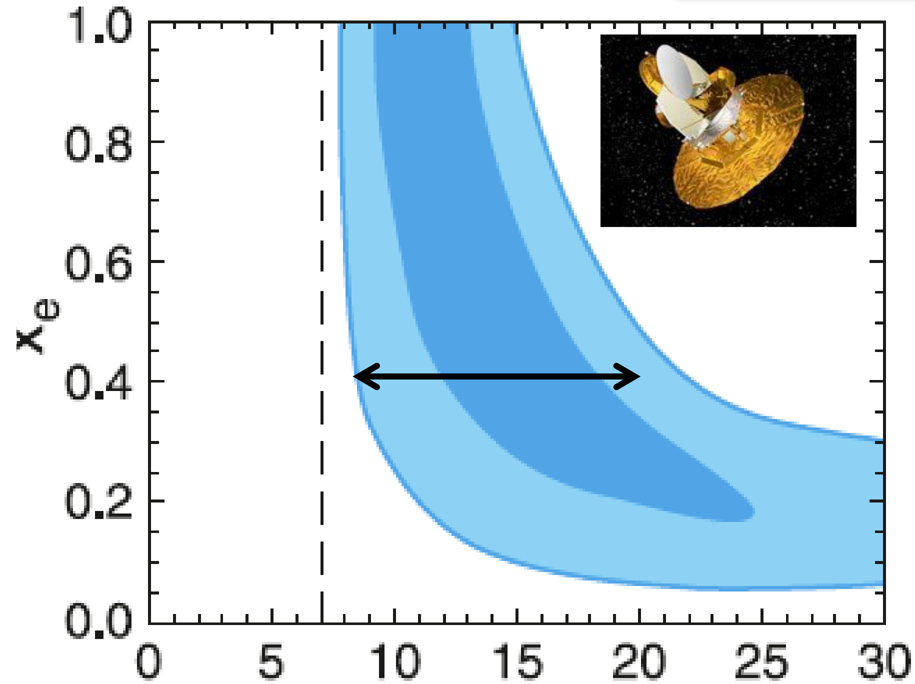
Measured in terms of the optical depth of scattering **T**

# Duration of Reionization - WMAP

WMAP 9yr +eCMB:

$\tau$ = 0.088 ± 0.013 consistent with instantaneous reionization z=10.5 ± 1.1




Stability of this result led us to believe reionization was extended process

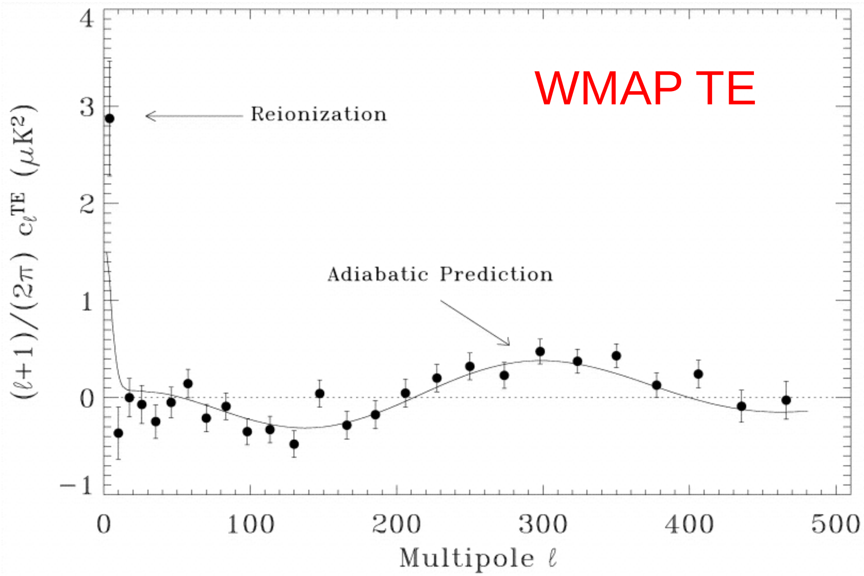
$\tau$ = 0.09 ± 0.03 (WMAP3, 2007)

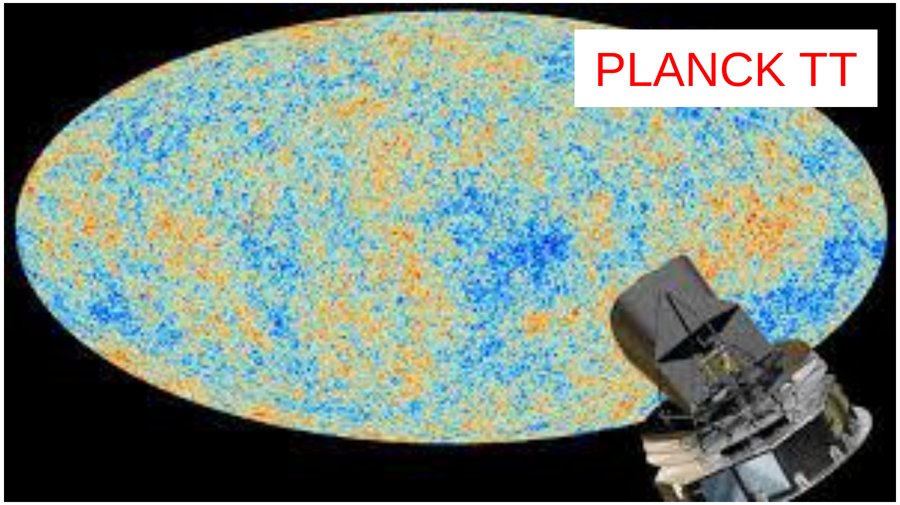
$\tau$ = 0.087 ± 0.017 (WMAP5, 2009)

$\tau$ = 0.088 ± 0.015 (WMAP7, 2010)

Hinshaw et al 2013 Ap J Suppl 208, 19

# Duration of Reionization - Planck




Planck Consortium argue the WMAP τ, derived largely from polarization data, is inherently challenging compared to now superior temperature data from Planck whose degeneracy with the amplitude $A_s$ of dark matter can now be broken via lensing constraints. They derive

$$\tau = 0.066^{+0.013}_{-0.013}, \boxed{z_{re} = 8.8^{+1.3}_{-1.2},} \textit{Planck}\ \mathrm{TT+lowP} \\ \mathrm{+lensing+BAO}$$

Planck Consortium arXiv 1502.01589

# Lyα Emission as a Probe of Reionization

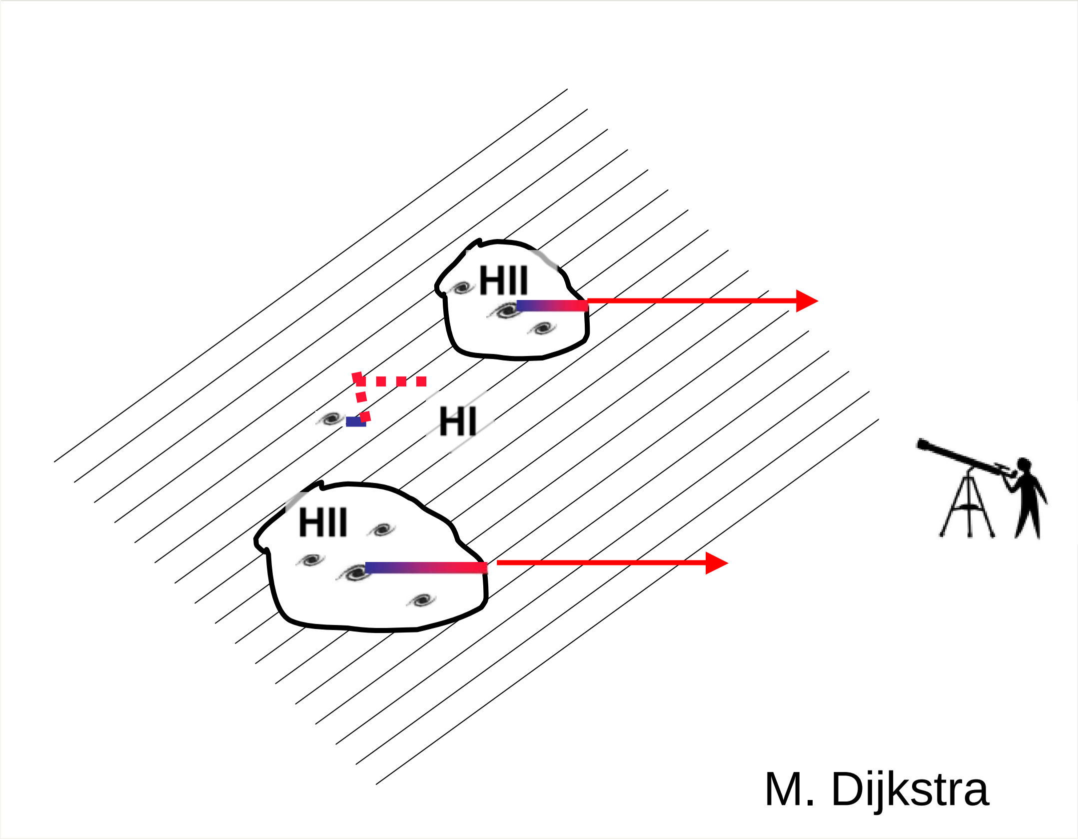
Up to 6-7% of young galaxy light could emerge in Lyα:

- But resonant scattering by neutral gas reduces its visibility

- In a significantly neutral IGM, galaxy must lie in an ionized bubble in order for Lyα to escape

- Expect a sudden drop in the fraction of galaxies revealing line emission as enter the neutral era

- Caveats: dust, outflows etc




Miralda-Escudé & Ress 1998 Ap J 497, 21; Santos 2004 MN 349 1137

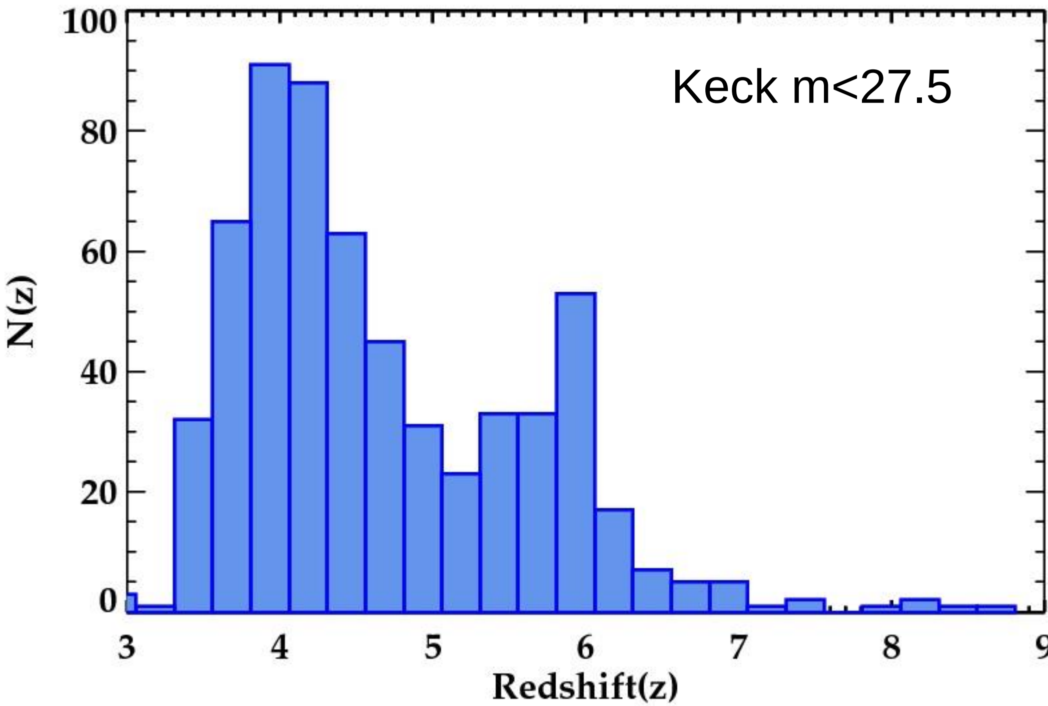
Dijkstra et al 2007 MN 377 1175 , McQuinn et al 2007 MN 381, 75

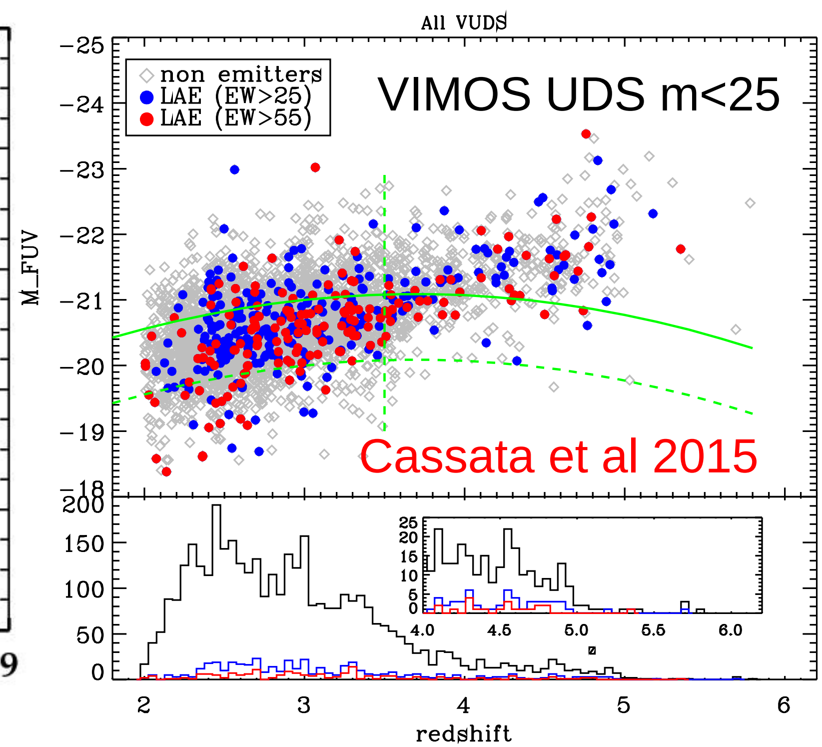
# Keck Spectroscopic Survey 2009-2015

Targets: HST GOODS & CANDELS-UDS $m_{AB}$<27.5

DEIMOS 3<z<6; LRIS-R 6<z<7; MOSFIRE z>7

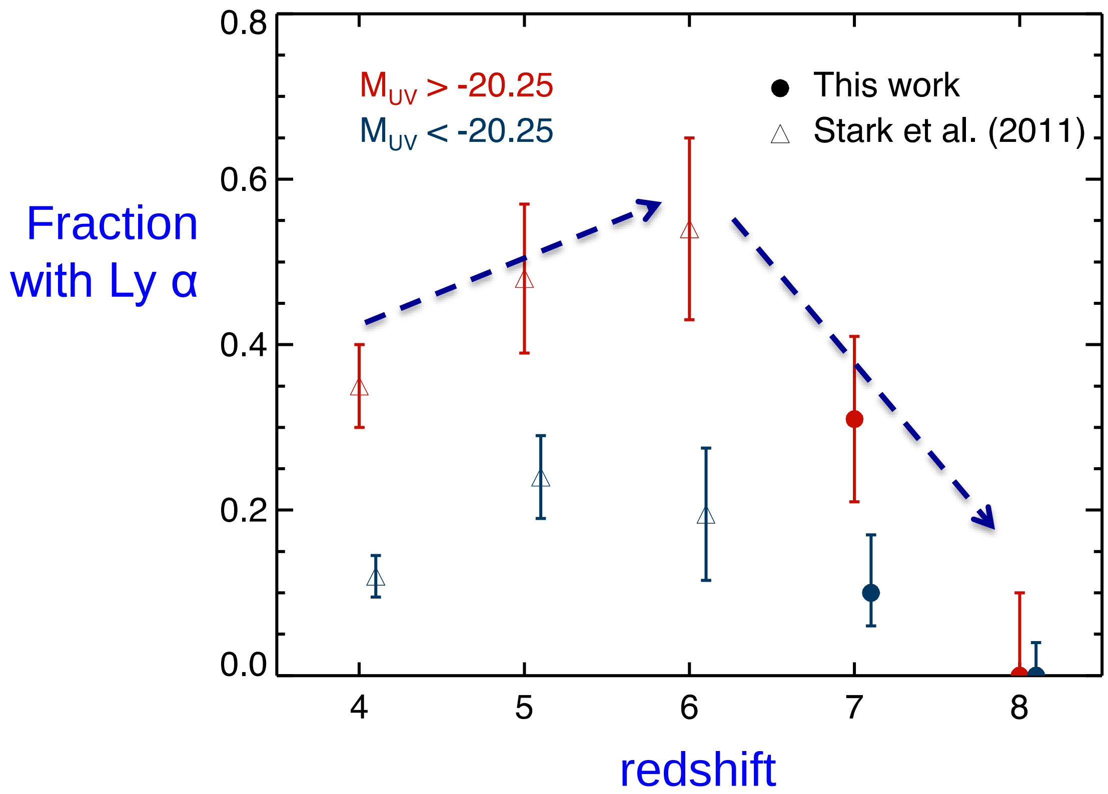
351 B + 201 V + 89 i + 40 z + 5 Y drops = 686 spectra



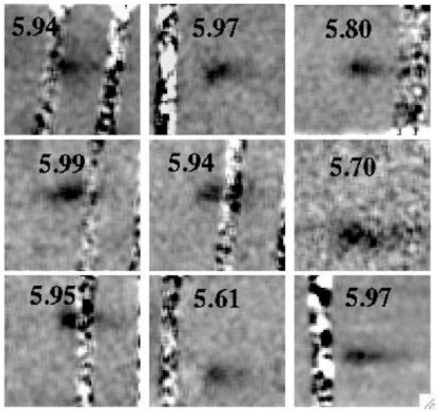



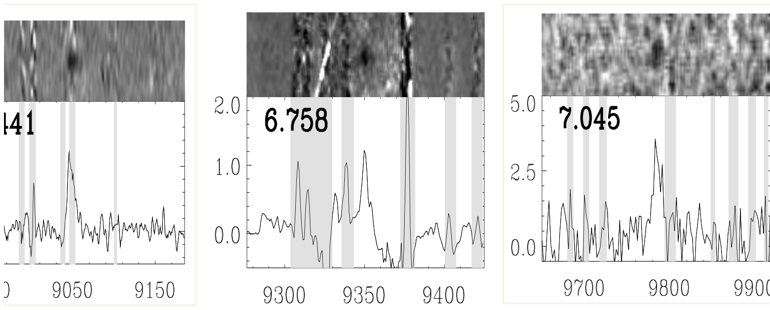

Stark et al (2009, 2010, 2011, 2013, 2015 in prep), Schenker et al (2012, 2014)

# Lyα fraction declines sharply for z > 6




50% at z~6 are emitters




But <10% are emitters @ z > 7

**Schenker et al (2014) – Keck MOSFIRE + UDF, CLASH 7<z<8.2**

also Treu et al (2013) – Keck MOSFIRE + BoRG z~8
Finkelstein et al (2013) – Keck MOSFIRE + CANDELS z > 7
Tilvi et al (2014) – Keck MOSFIRE 7<z<8.2
Pentericci et al (2014) – VLT FORS 6<z<7.3

# Can this rapid decline in Lyα be understood?

Converting x(Lyα) to X(HI) is uncertain: ΔX(HI) ~ 0.3-0.5 in 200 Myr

Consistent with fast reionisation inferred from Planck

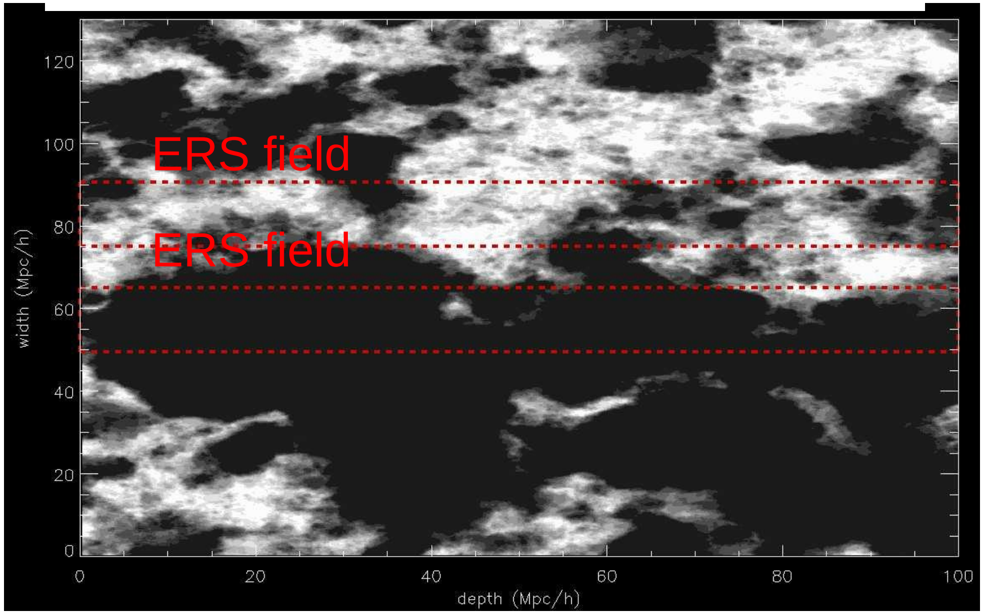
Choudhury et al 2015 MN 452, 261

Mesinger et al 2015 MN 446,566

Other explanations:

- Low z contaminants: requires unreasonably high fraction (>50%)
- Cosmic variance: non-uniform X(Lyα, z) across fields

Simulation for <x(HI)>~0.2



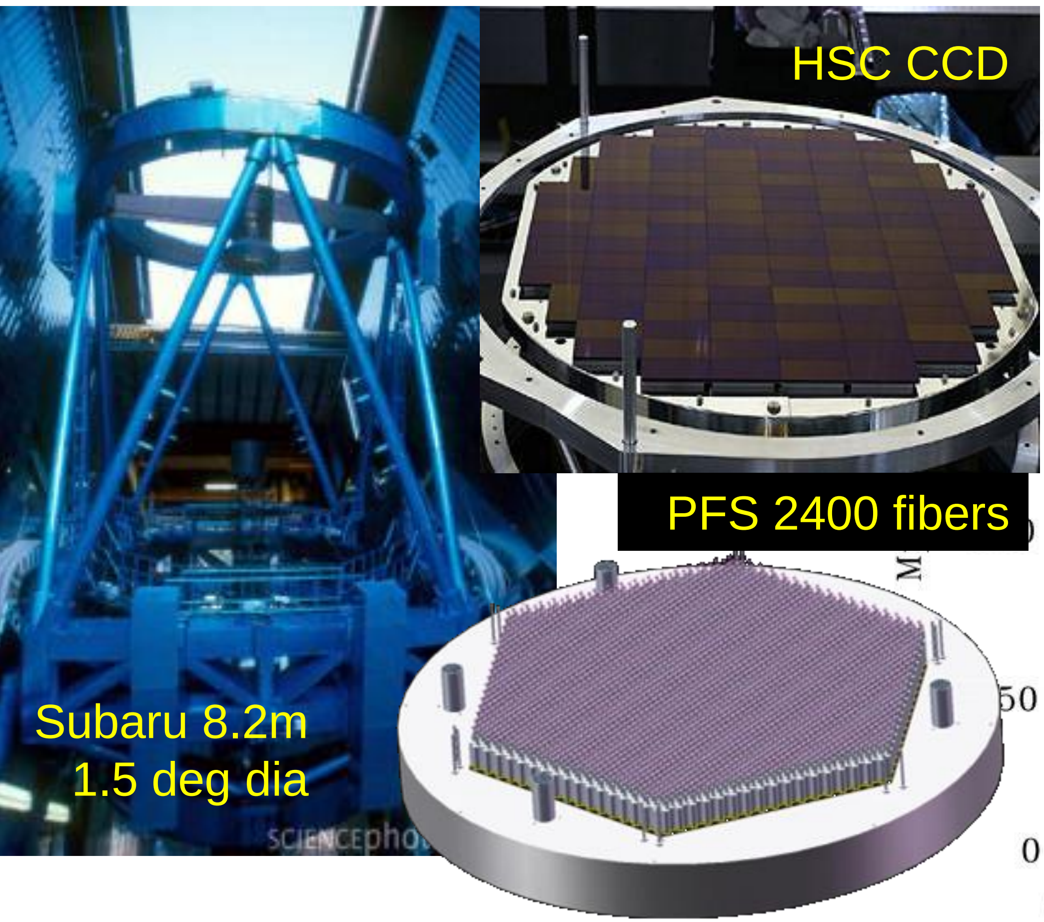

**depth (Mpc)➔**

Taylor & Lidz 2014 MN 437, 2542

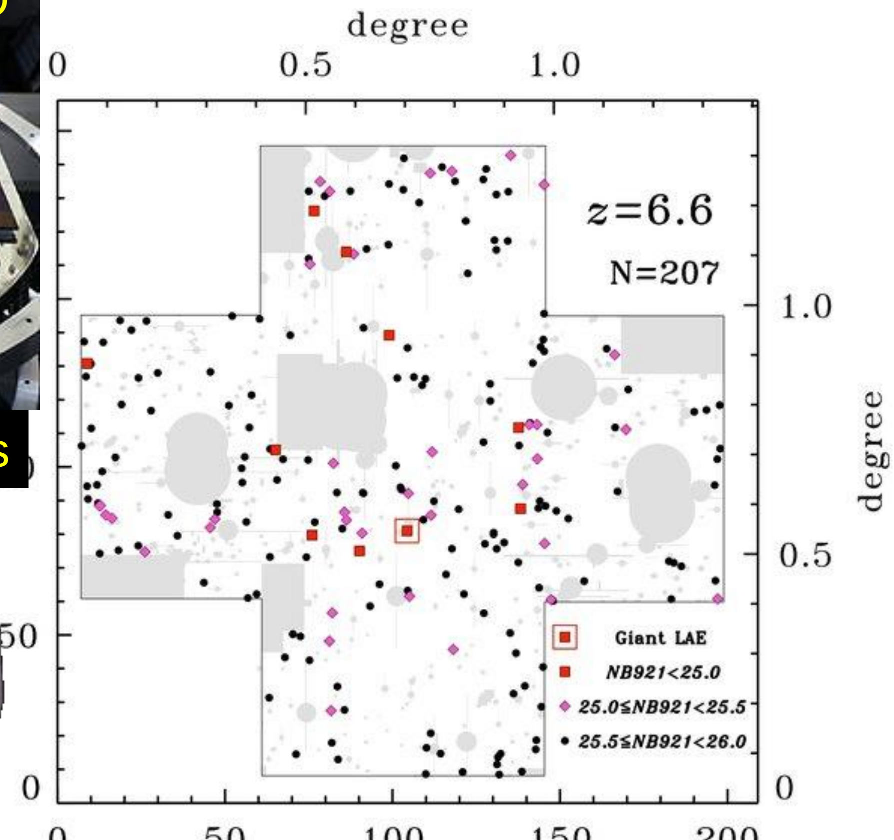
# What's Next: Distribution of Lyα Emitters

Subaru HSC/PFS will chart distribution of Lyα emitters (5.7 < z < 7.1) in possible coordination with LOFAR

Constrains evolving sizes of ionized bubbles & longevity of ionizing sources.




Angular distribution of z~6.6 LAEs via nb imaging with SuprimeCam




Ouchi et al 2010 Ap J 723, 869

# Did Galaxies Reionize Universe?

Ionization rate $\dot{n}_{\rm ion} = f_{\rm esc}\xi_{\rm ion}\rho_{\rm UV}$

Recombination time $t_{\rm rec} = [C_{\rm H\,II}\alpha_{\rm B}(T)(1 + Y_{\rm p}/4X_{\rm p})\langle n_{\rm H}\rangle(1 + z)^3]^{-1}$

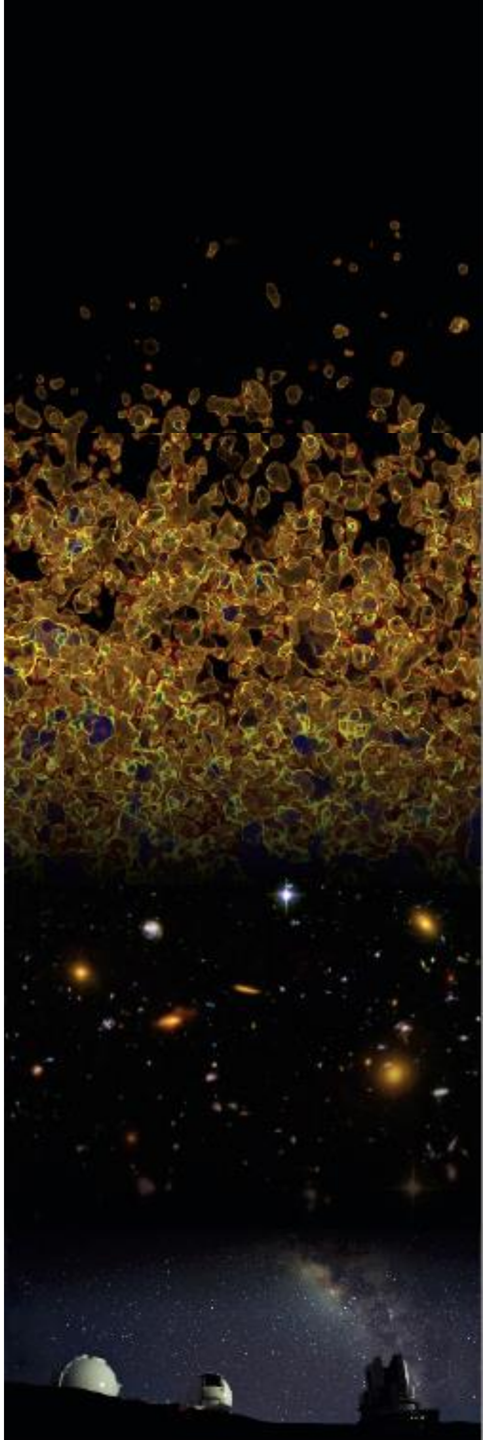
Key observables:

1. Integrated abundance of high z star-forming galaxies especially contribution of low luminosity sources : $\rho_{UV}$

2. Nature of the stellar populations in distant galaxies which determines the rate of ionizing photons: $\xi_{ion}$

3. Fraction of ionizing photons that escape: $f_{esc}$

4. Optical depth of electron scattering to CMB: $\tau$




**Hubble Ultra Deep Field 2012**

*Hubble Space Telescope* WFC3/IR

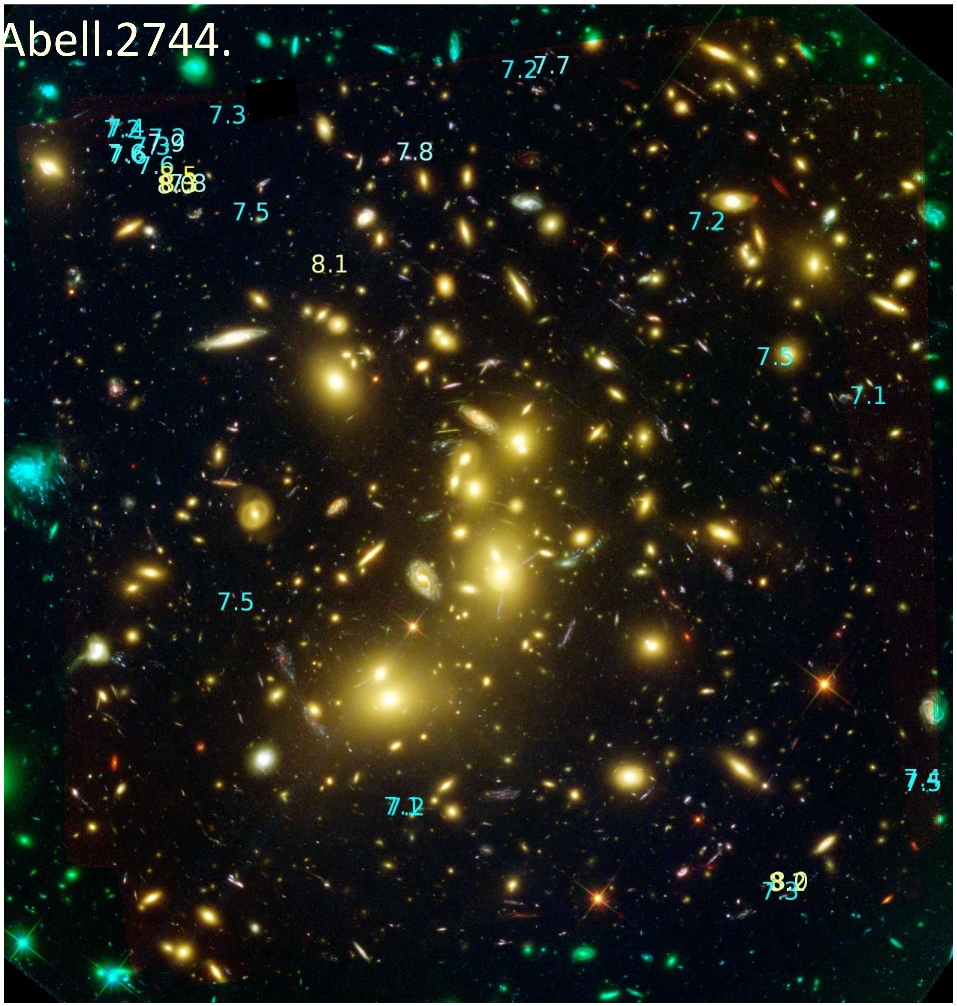
NASA and ESA

STScI-PRC12-48a

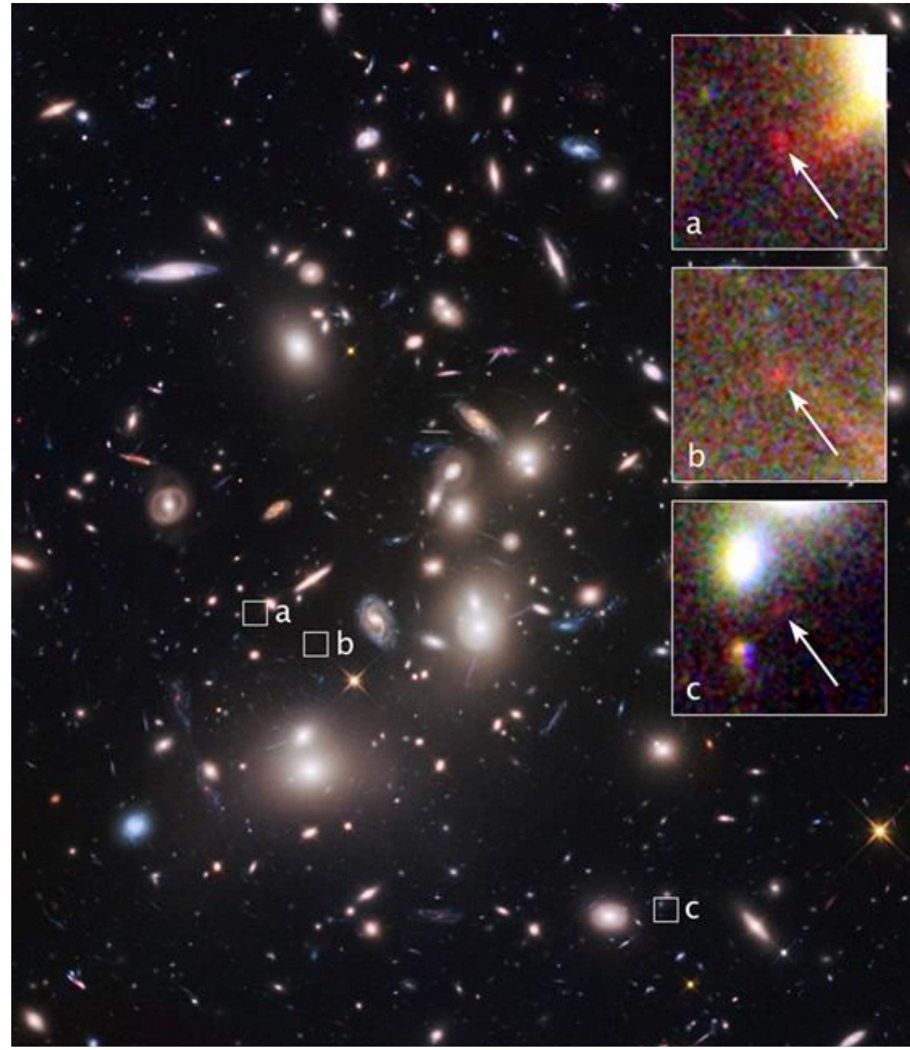
FRONTIER FIELDS

# The Hubble Frontier Fields

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA




z~7-8 lensed galaxies in Abell 2744 (Coe)

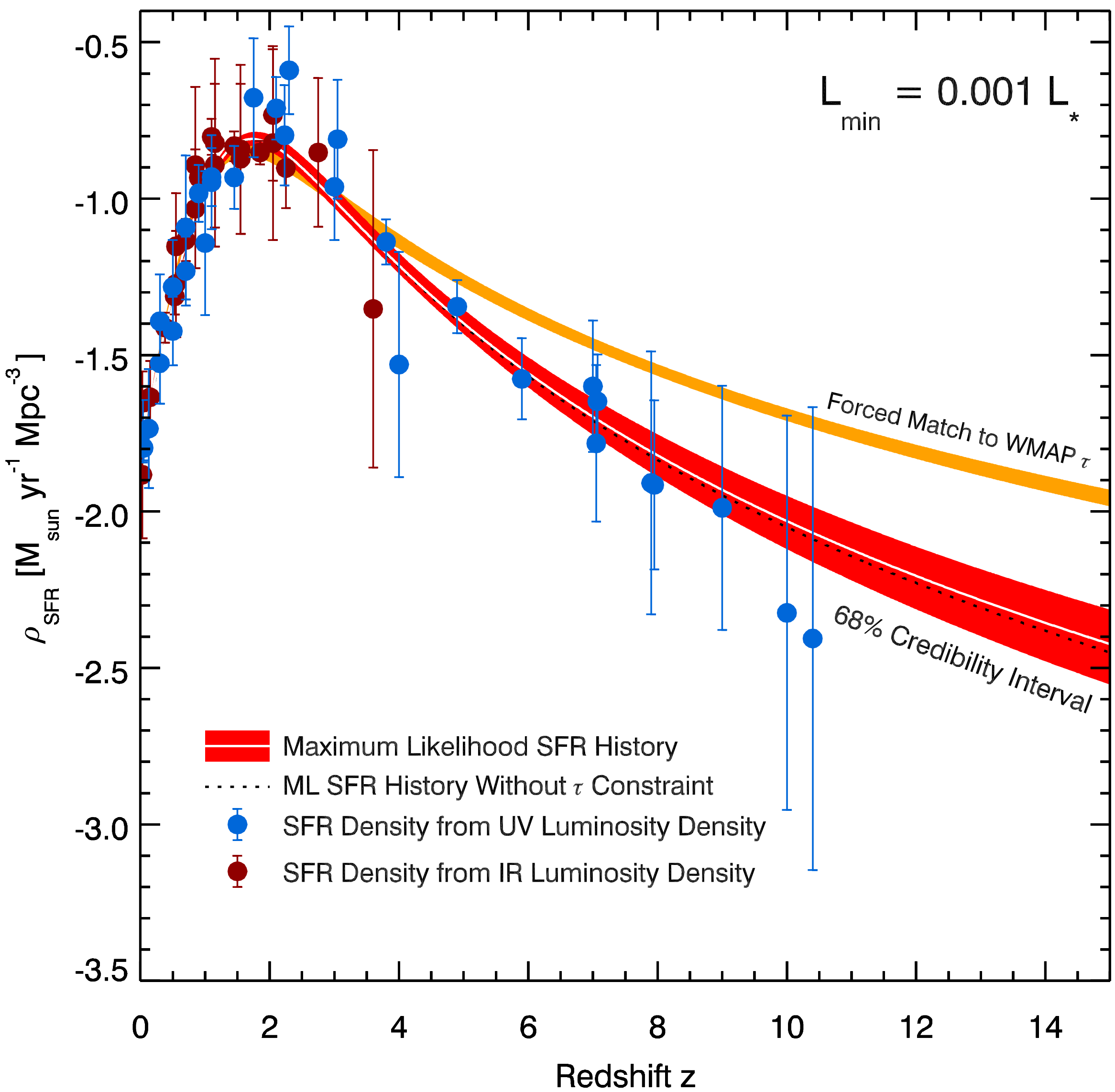



Triply-imaged z~10 galaxy (Zitrin et al 2014)

# Star Formation History

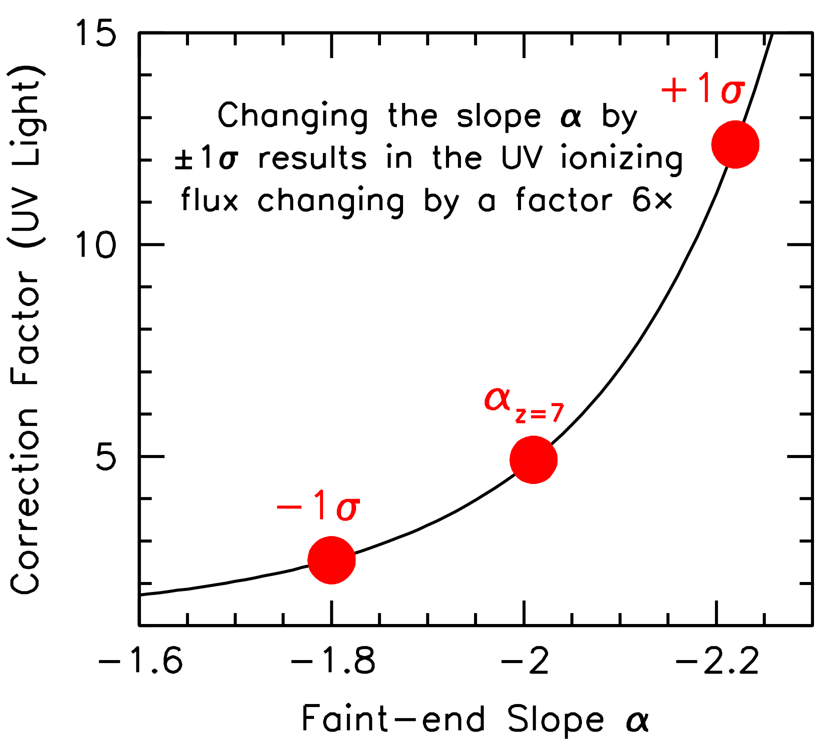
Census of galaxies now reaches to z~10 utilizing both blank fields and lensed surveys.

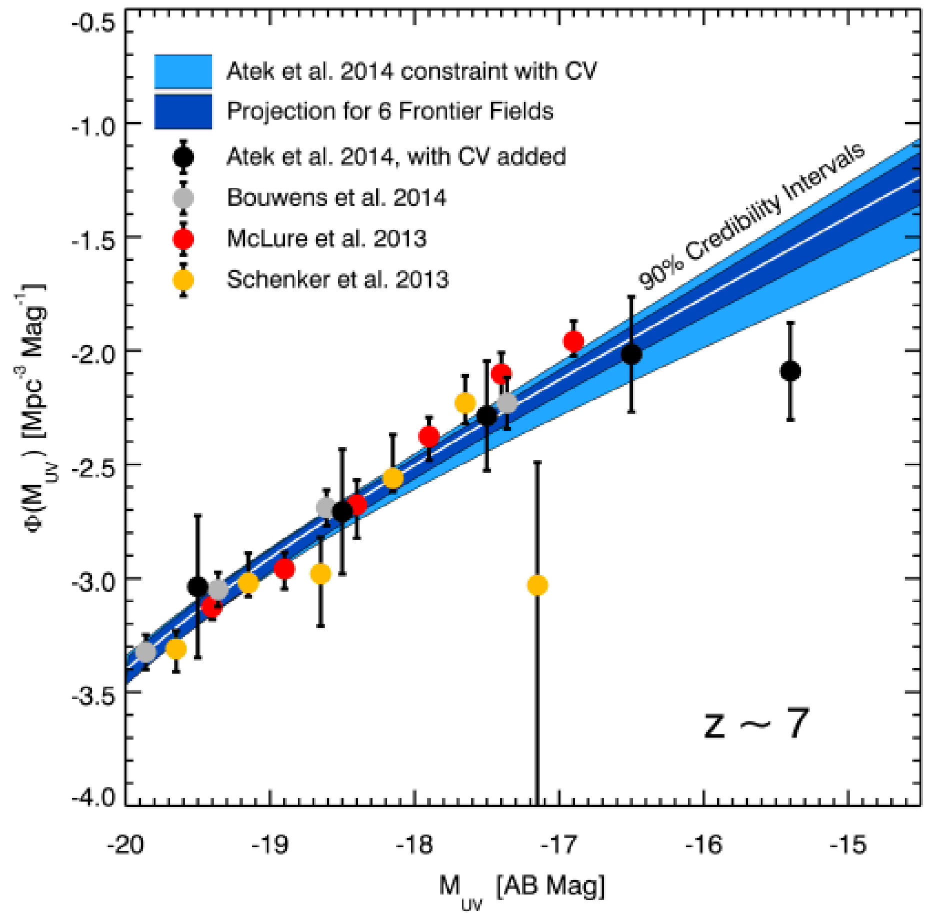
Adopting Madau & Dickinson (2014) formalism with all HST data up to Jan 2015 (including cosmic variance estimates) in Planck cosmology




Robertson et al 2015 Ap J 802, L19

# Slope and Extent of High z Luminosity Functions




UDF12 indicated α = -1.87 ± 0.18 @ z~7 to $M_{UV}$=-17

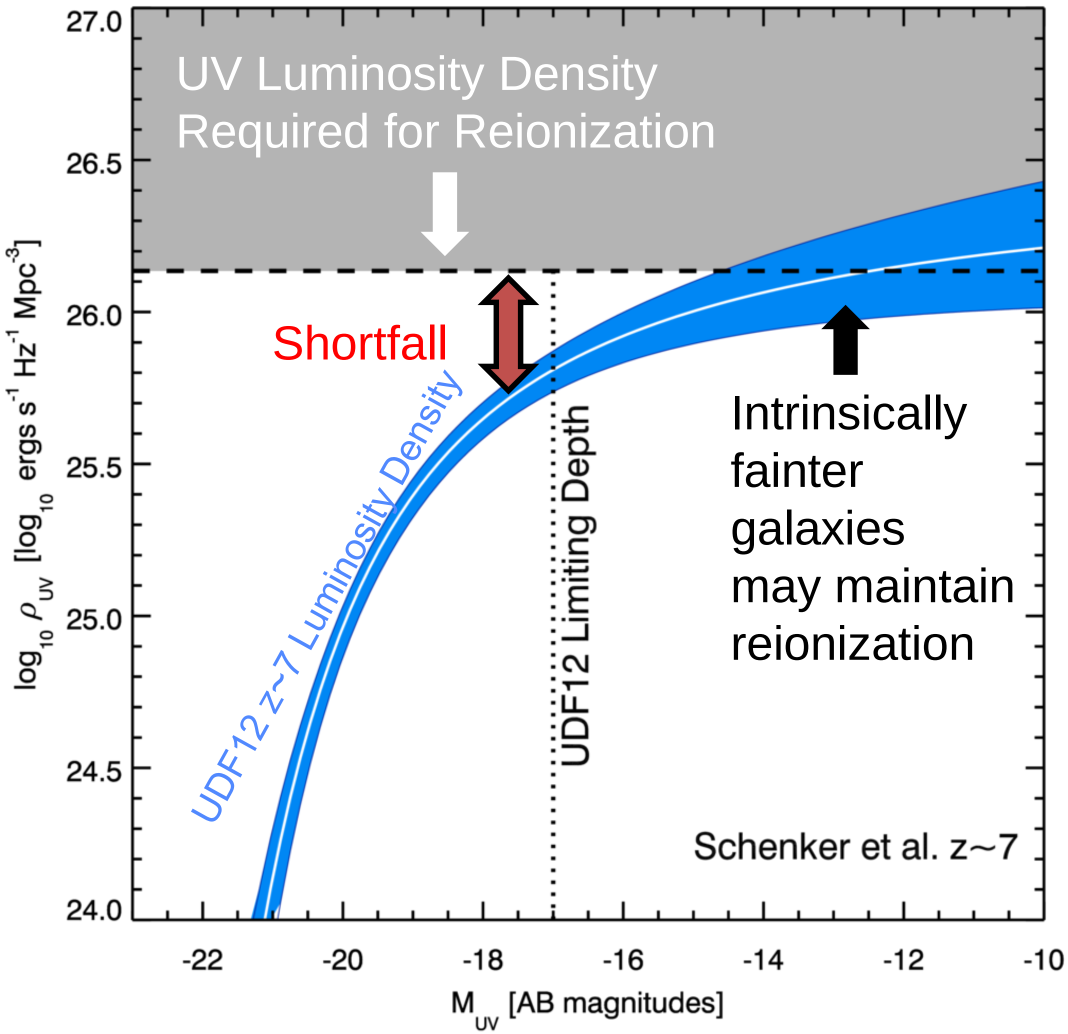
Early Frontier Field data shows potential of extending 1-1.5 mag fainter

Including cosmic variance, 6 FF clusters could reduce α uncertainty to ± 0.05

This would reduce uncertainty on integrated ρ (< $M_{UV}$=-13) from ×2 to 30%

Bouwens et al (2012), Schenker et al (2013), Atek et al (2014) Robertson et al (2014)

# UDF12 Reionization Constraints: A Simple Illustration




- Assuming Schenker et al LF, for a given $\xi_{ion}$ and $f_{esc}$, the <u>**observed population of z~7-8 galaxies**</u> does not produce enough radiation to reionize intergalactic hydrogen
- But the constrained faint end slope of the luminosity function allows us to imagine that **fainter, yet unseen galaxies (extrapolating to $M_{UV}$~-13)** might be sufficient to maintain reionization

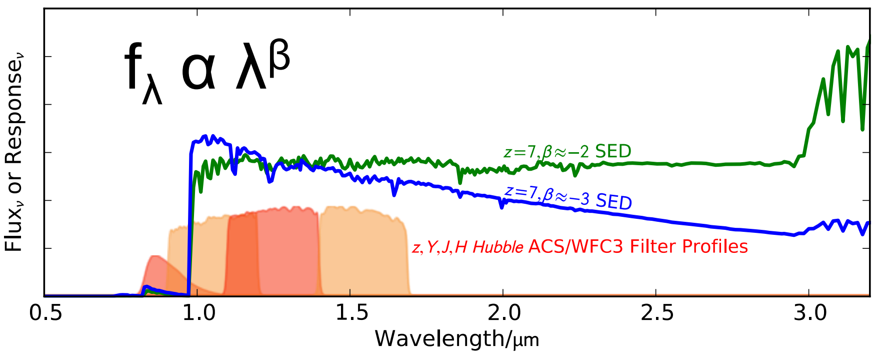
Robertson et al 2013 Ap J 768, 71

# Ionizing Spectrum?

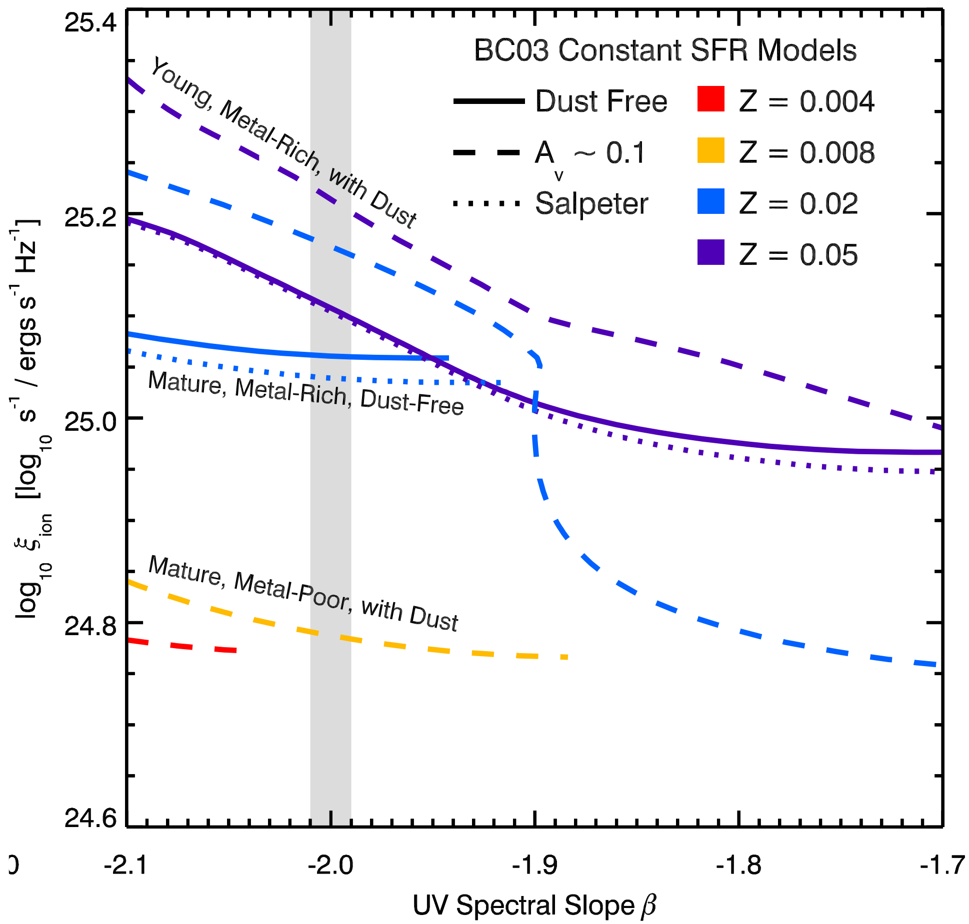
UV continuum slope β distinguishes between:

(i) metal-poor galaxies with steep UV continua, i.e. **large $\xi_{ion}$**

(ii) metal-enriched systems with flatter spectral slopes, i.e. **lower $\xi_{ion}$**

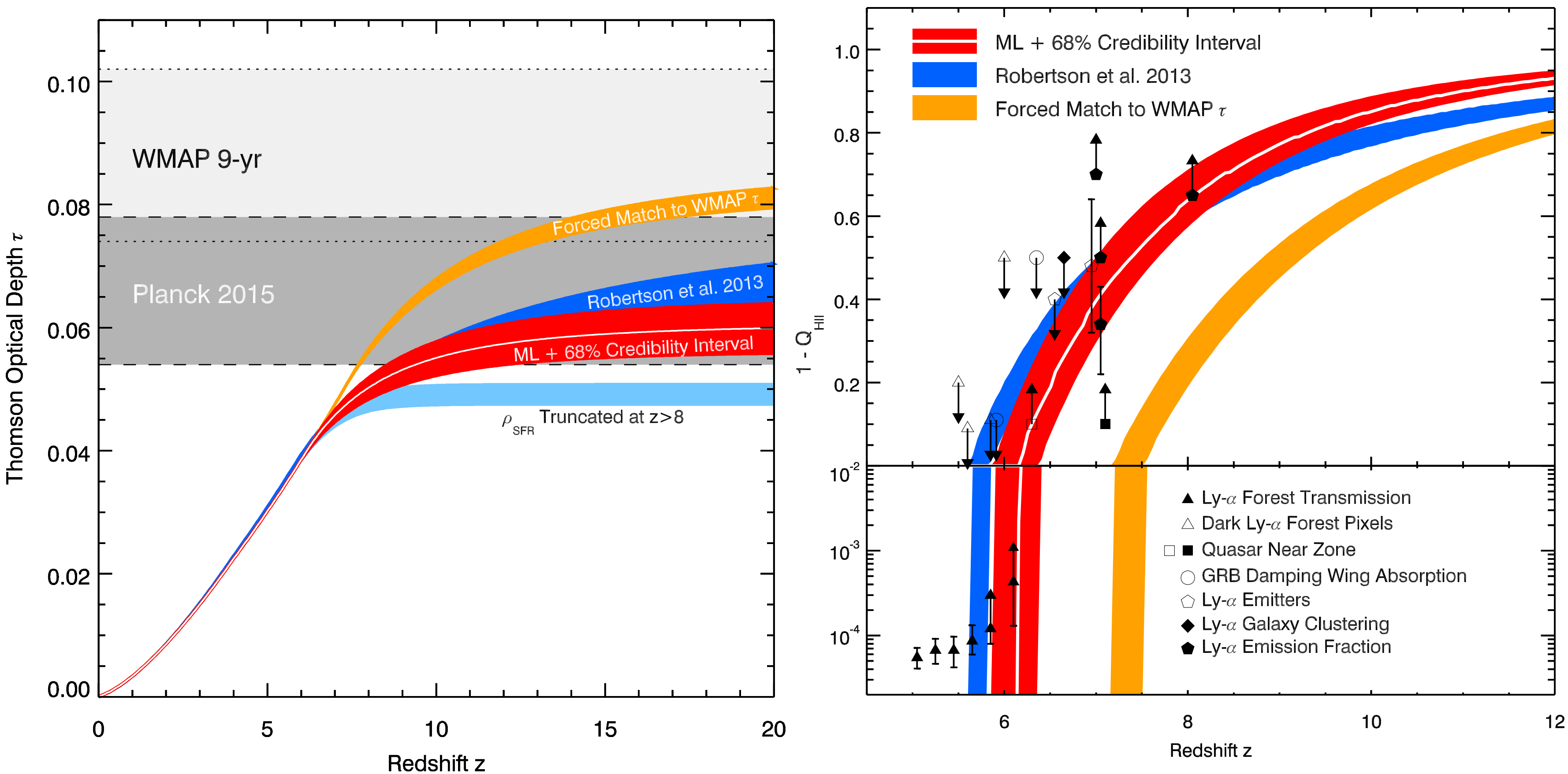



Although the UV continua of z~7-8 galaxies show a uniform slope **β=-2** consistent with population of mature (>100 Myr) enriched stars, ambiguities remain depending on composition, dust and IMF.




Dunlop et al 2013 MN 432, 3520

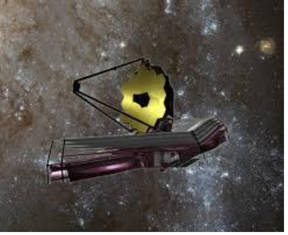
# Reconciling Current Data with Planck τ



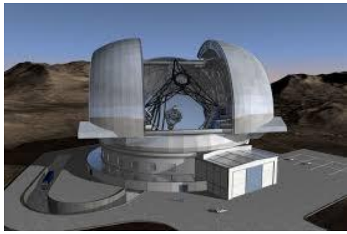

Adopting $f_{esc}$ = 0.2, $\xi_{ion}$ consistent with β= -2, a LF extending to $M_{UV}$=-13 can match Planck data with reionization largely contained with 10 < z < 6

If correct, major implications for JWST and 21cm tomography surveys!

Robertson et al (2015), see also Bouwens+(2015), Mitra+(2015)



# Outstanding Challenges



- Escape fraction of ionizing photons $f_{esc}$
  - maintaining ionization at z~7-8 from galaxies needs high value!
  - low ionization absorption in galaxies (`covering fraction')
- Spectroscopic prospects
  - if Lyα is suppressed what are the alternatives?
- Production rate of ionizing photons per unit SFR $\xi_{ion}$
  - galaxy colors (β) are a poor guide to early stellar populations
  - prefer diagnostic spectroscopy e.g. high ionization metal lines
  - role of AGN?
- Dust at high redshift?
  - Crucial ALMA observations would affect above conclusions!
- Synergies between JWST and E-ELT

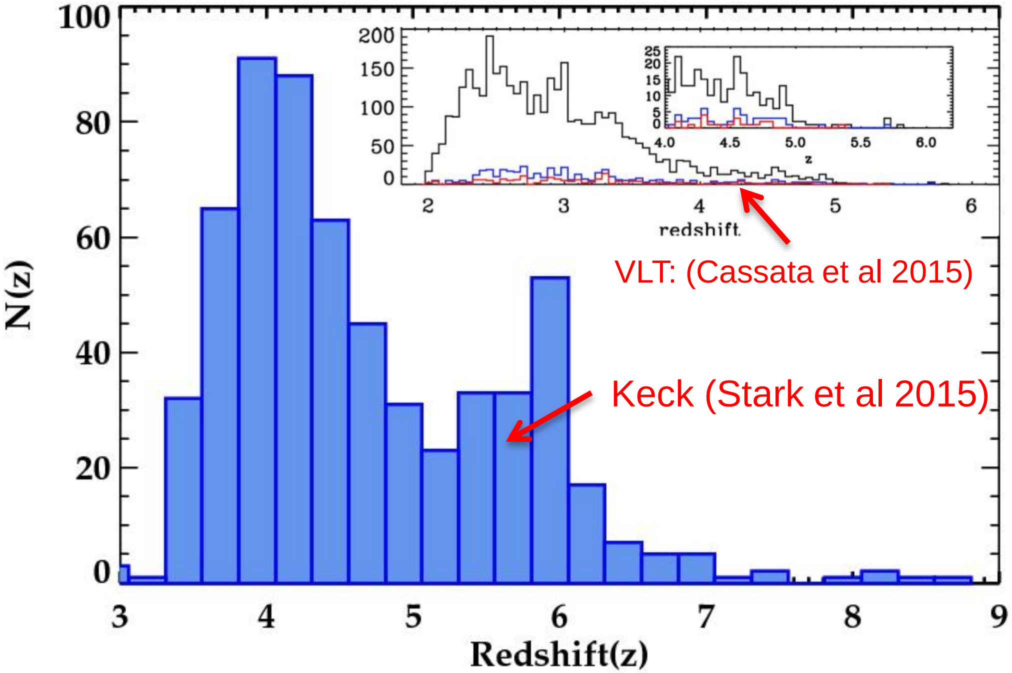
# Ground-Space Synergy 1993-2015

Hubble Space Telescope

Ground-based 8-10m telescopes

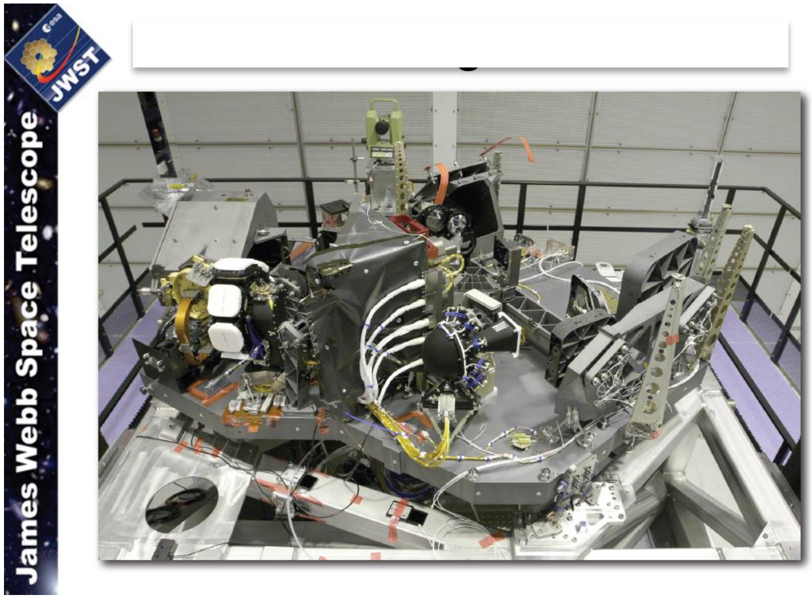
Precision/resolved optical/NIR imaging

Spectroscopy (redshifts, physical properties)

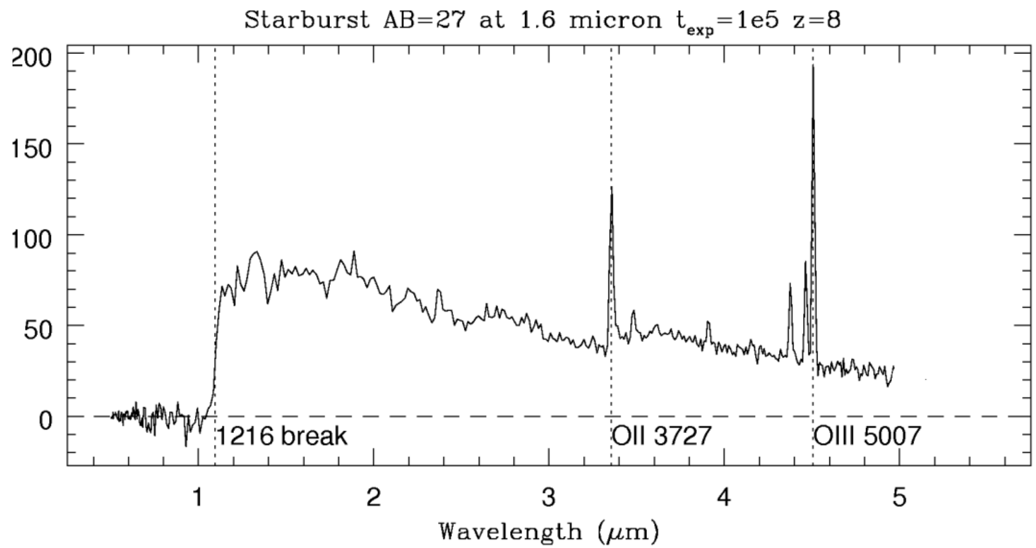


# Ground-Space Synergy 2020s: JWST Spectra

**NIRSpec**




**z=8 galaxy; 25 hour exposure**




JWST spectroscopy will measure stellar continuum & composition of gas in z < 9 galaxies using optical lines longward of 2 microns beyond reach of E-ELT – and it will be available sooner (first ERS proposals 2017!)

# Ground-Space Synergy 2020s: E-ELT AO Imaging

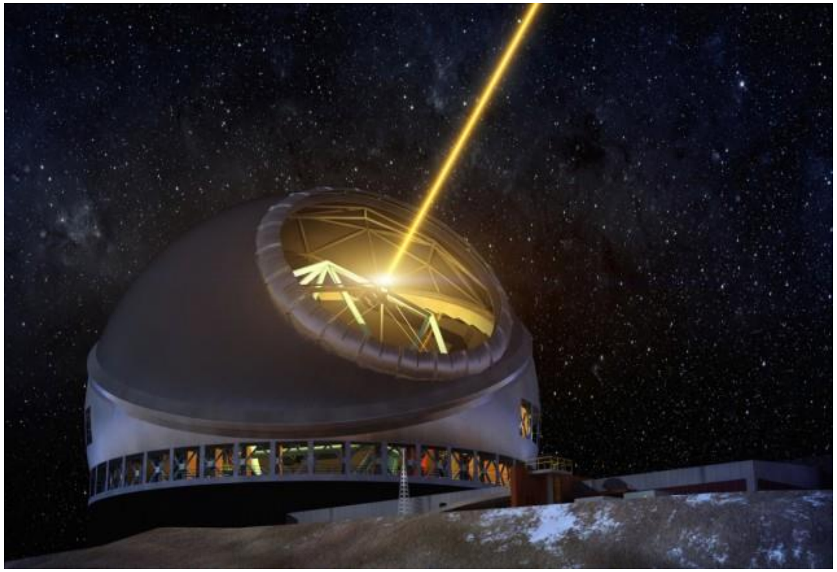
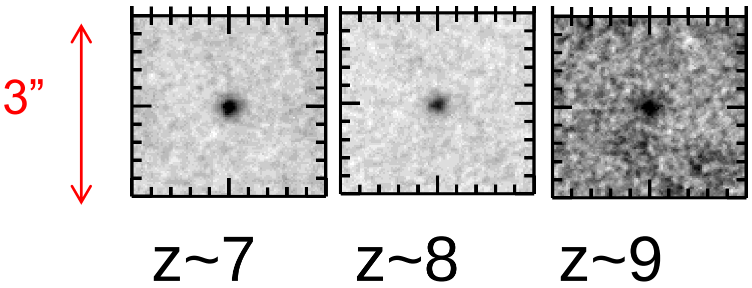
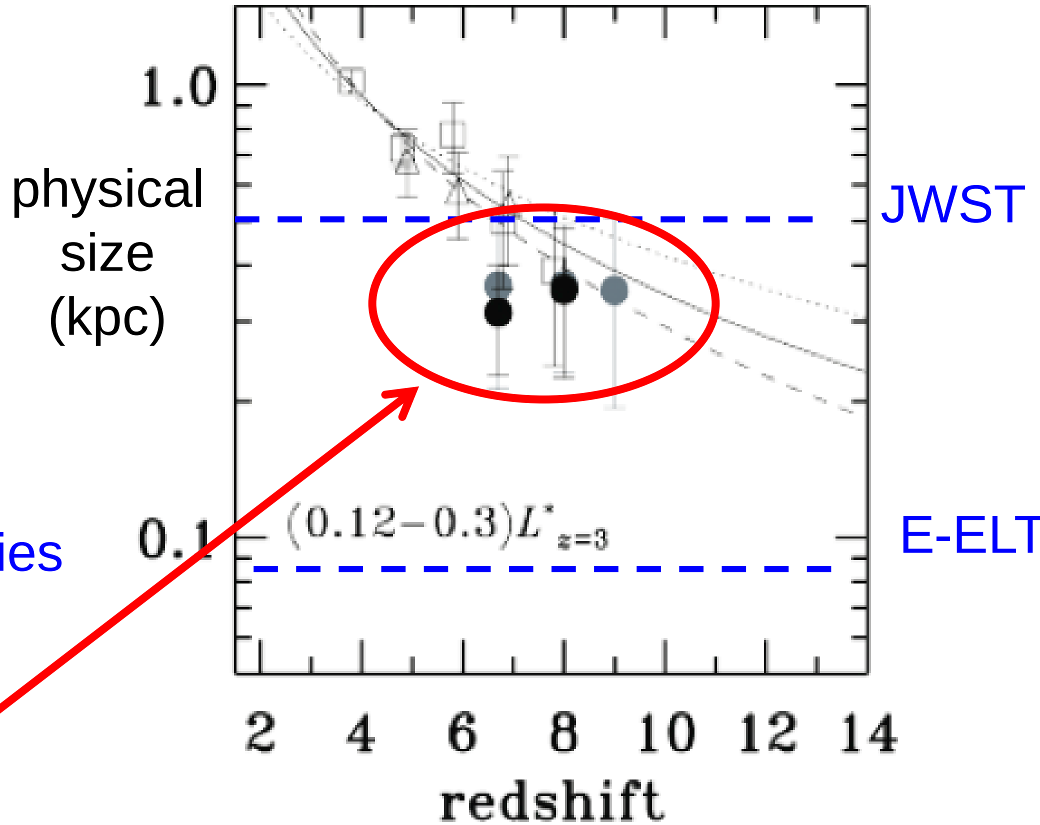


Image stacks for faint Hubble galaxies



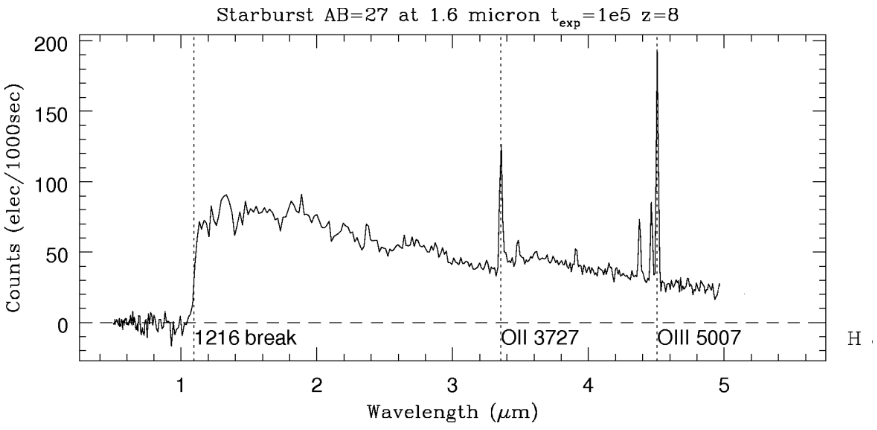

AO will enable E-ELT to outperform JWST in image quality

Unique advantage in rest UV studies of physically-small distant galaxies

# Probing the ionizing radiation

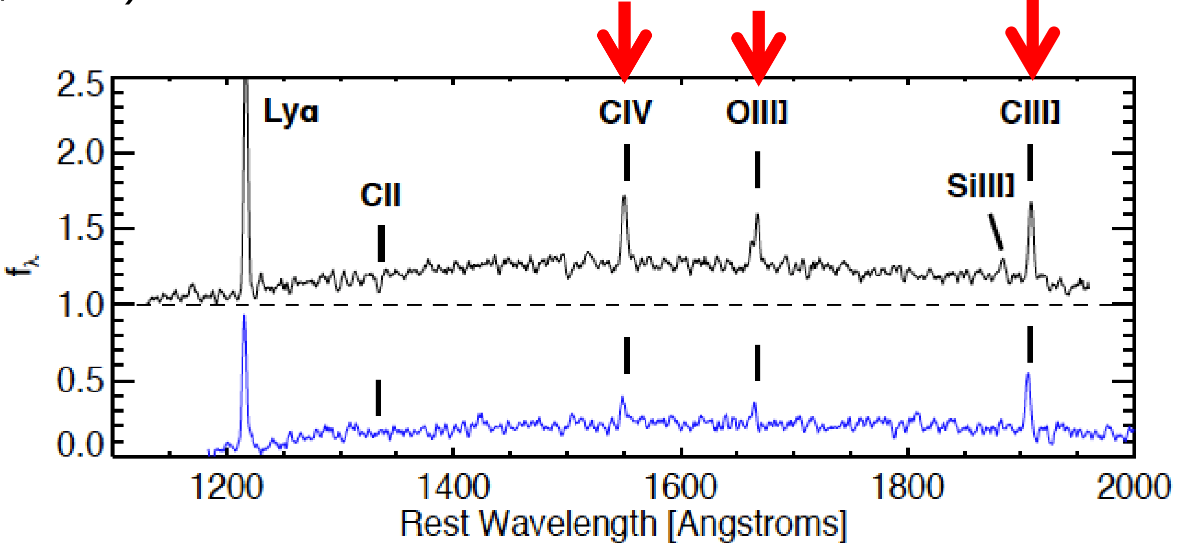
- JWST will probe the familiar rest-frame optical lines [O II], Hβ, [O III] to z~9

NIRSPEC z~8 20 hrs



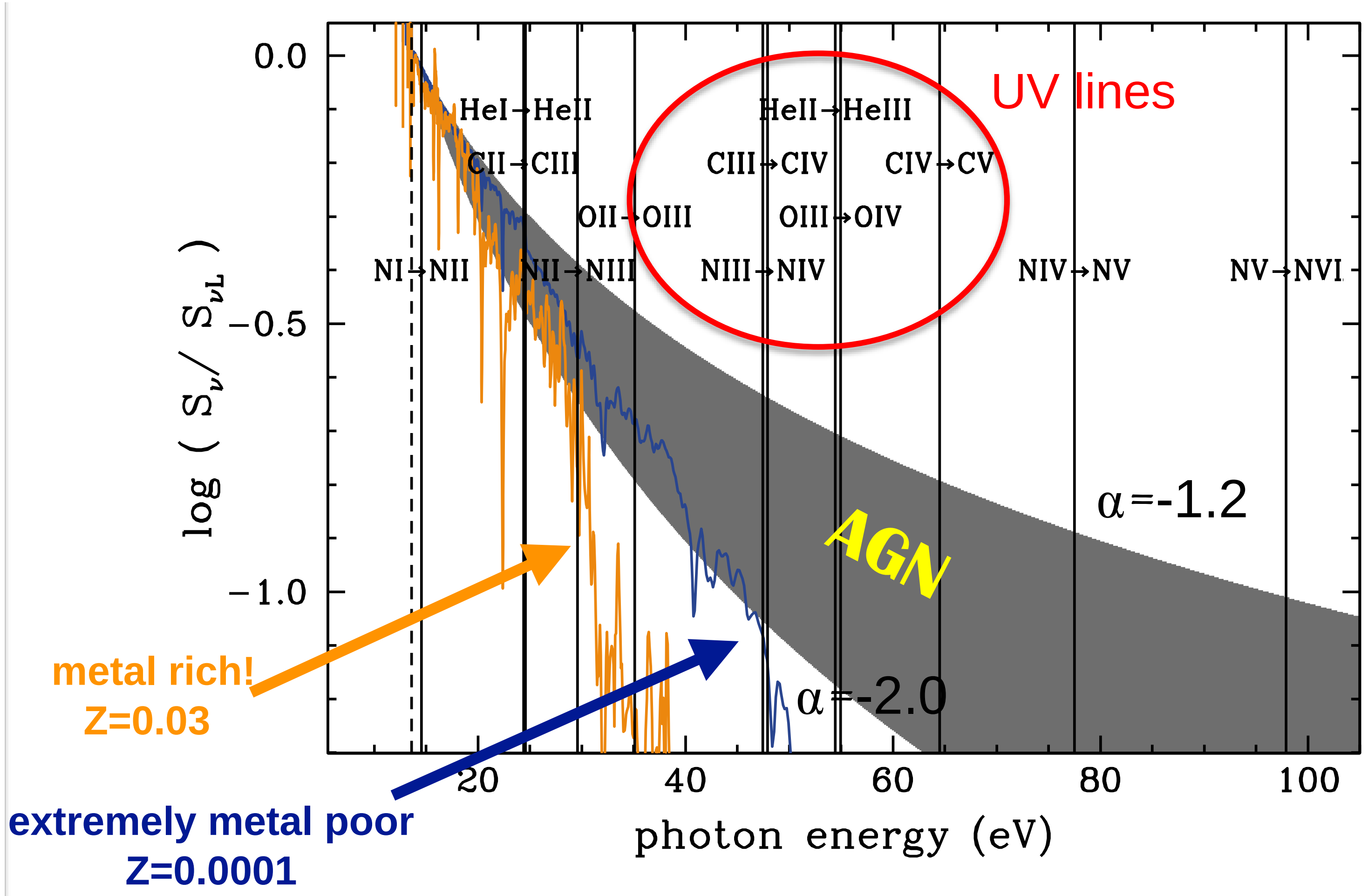

- E-ELT will access more efficiently the rest-frame UV lines with higher ionization potentials that can be utilised to test the nature of the ionising radiation (contribution of hot stars, AGN)

CIV 1548 Å 48 eV
O III] 1664 Å 35 eV
CIII] 1909 Å 24 eV




Stark et al 2014 MN 445, 4200

# Important UV Emission Lines



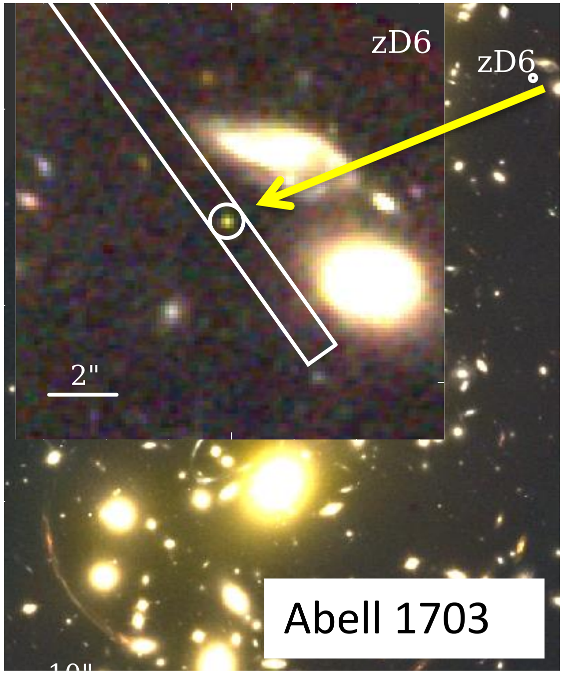

Feltre+15

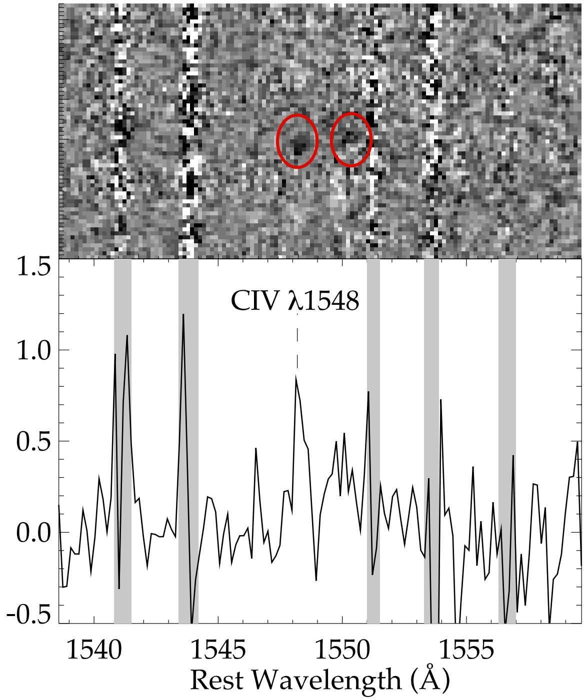
Two grids of photoionization models predicting nebular emission line ratios:

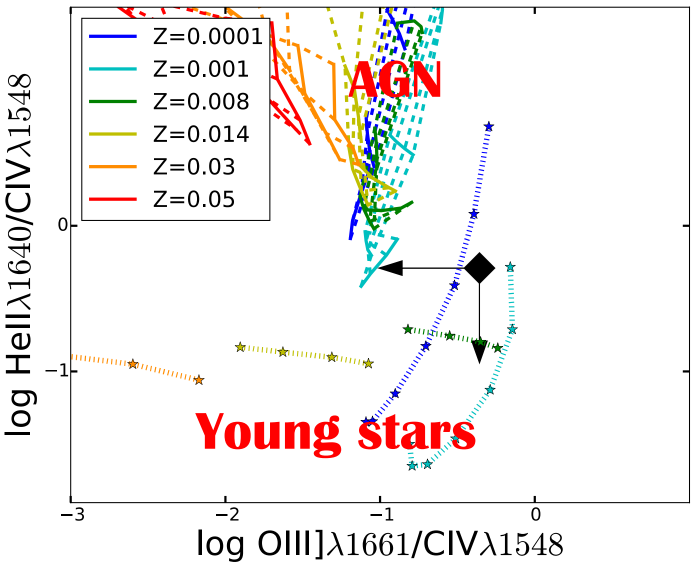
Young stars: CB15 (new tracks, WR stars) + CLOUDY

AGN-driven: Power law F(ν) ~ $\nu^\alpha$ + CLOUDY

# Illustration: CIV Doublet in z ~ 7.045 Galaxy



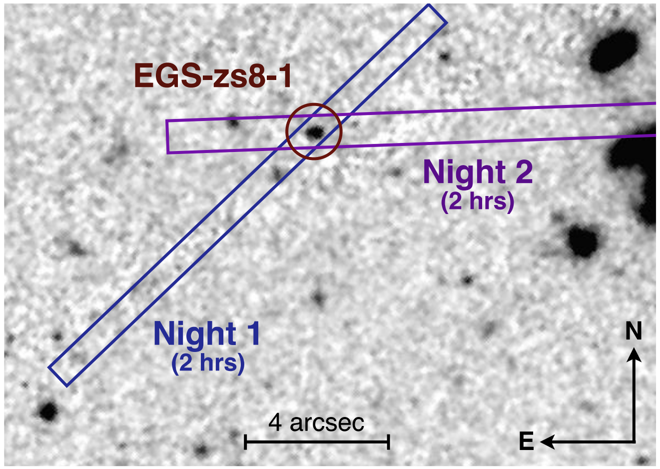



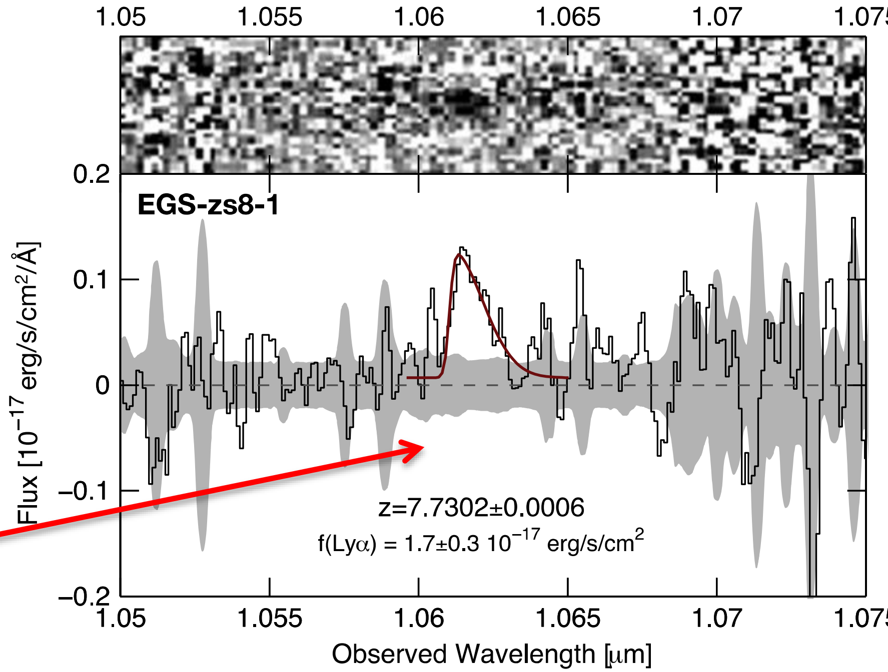

CIV / Lyα ratio much stronger than in z~2 sample – what does this mean?

- High ionization parameter ($U_S = \rho_\gamma/\rho_{gas}$): log $U_S$ ~ -1.35
- Low metallicity: ~0.01 solar

Stark et al 2015 MN 454,1393

# CIII] at z=7.73

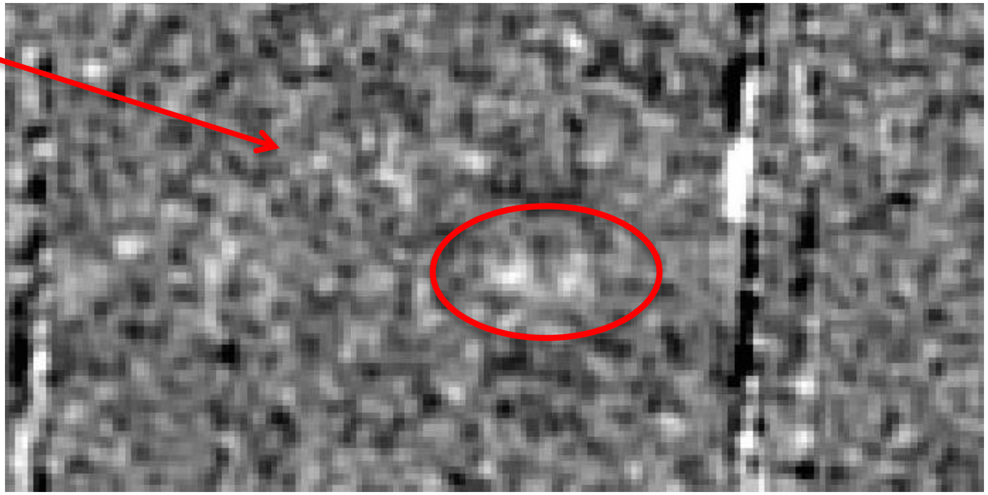



Lyα at z=7.73 Oesch et al (2015)

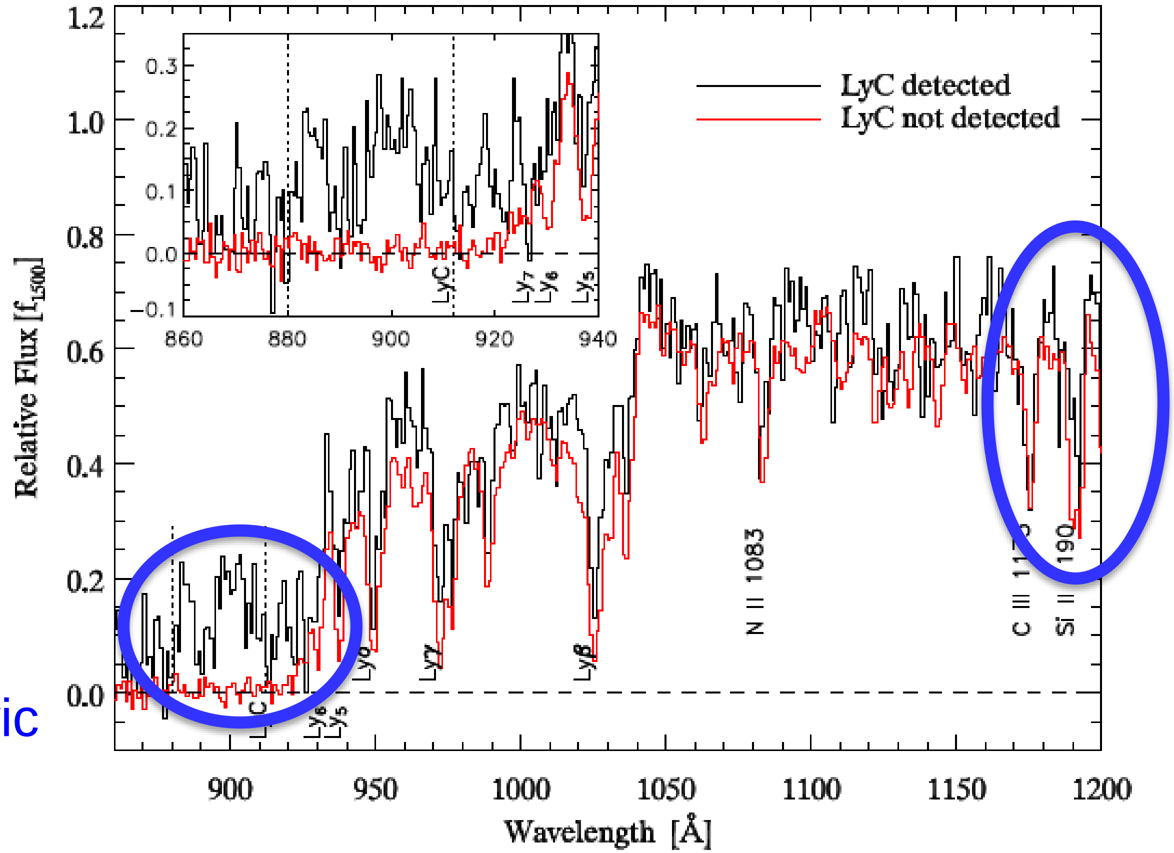
Detection of CIII] doublet – April/June 2015

CIII] 1909/1905 line ratio is a valuable indicator of the electron density and hence, together with UV luminosity can constrain the production rate of ionizing photons.



# Escape Fraction of Ionizing Photons $f_{esc}$ @ z~2

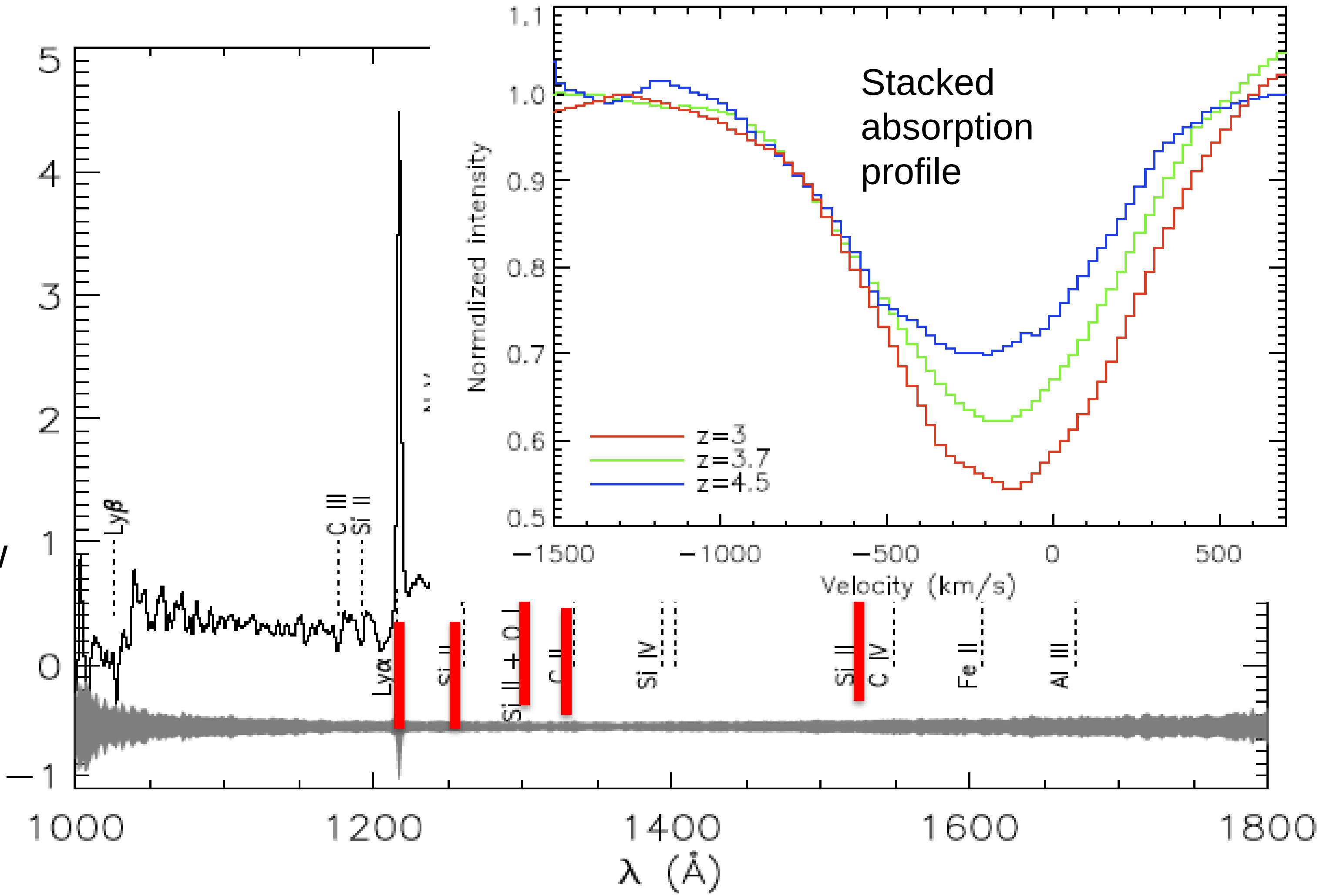
Escaping ionizing radiation at z=3 (Bogosavljevic thesis)




Weaker low-ionization absorption in sources with escaping ionizing flux

- $f_{esc}$ estimated via spectroscopic or UV imaging below Lyman limit (e.g. Nestor et al 2013)
- Impractical for high z galaxies due to intervening absorption by Lyα forest
- Consider low-ionization absorption lines which trace the HI covering fraction whence $f_c = 1 - f_{esc}$

# Outflowing Neutral Gas as probe of $f_{esc}$



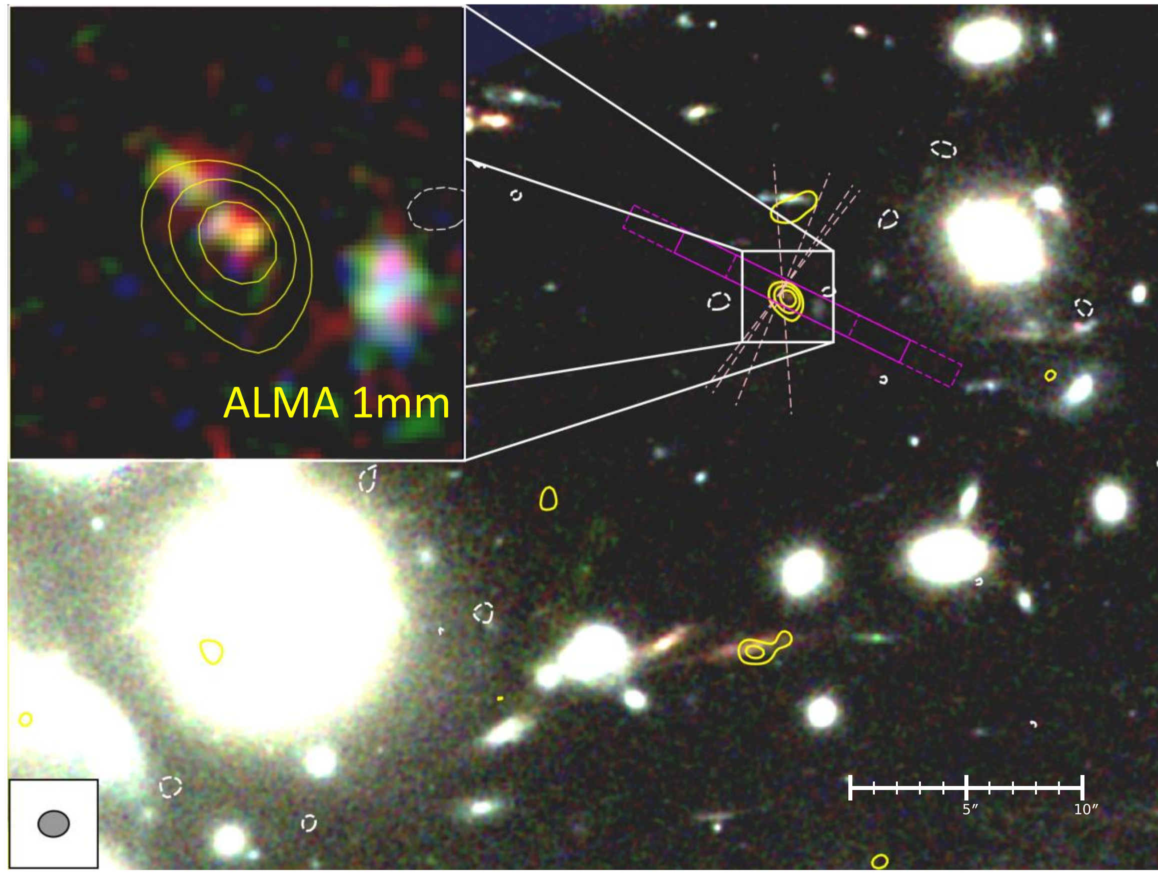

By stacking spectra we can detect weak low ionization absorption from neutral outflowing gas

EW of low ionization line gives <u>covering fraction</u> of neutral gas $f_c = 1 – f_{esc}$

Jones et al 2013 Ap J 779, 52

# ALMA: Dust at High z?

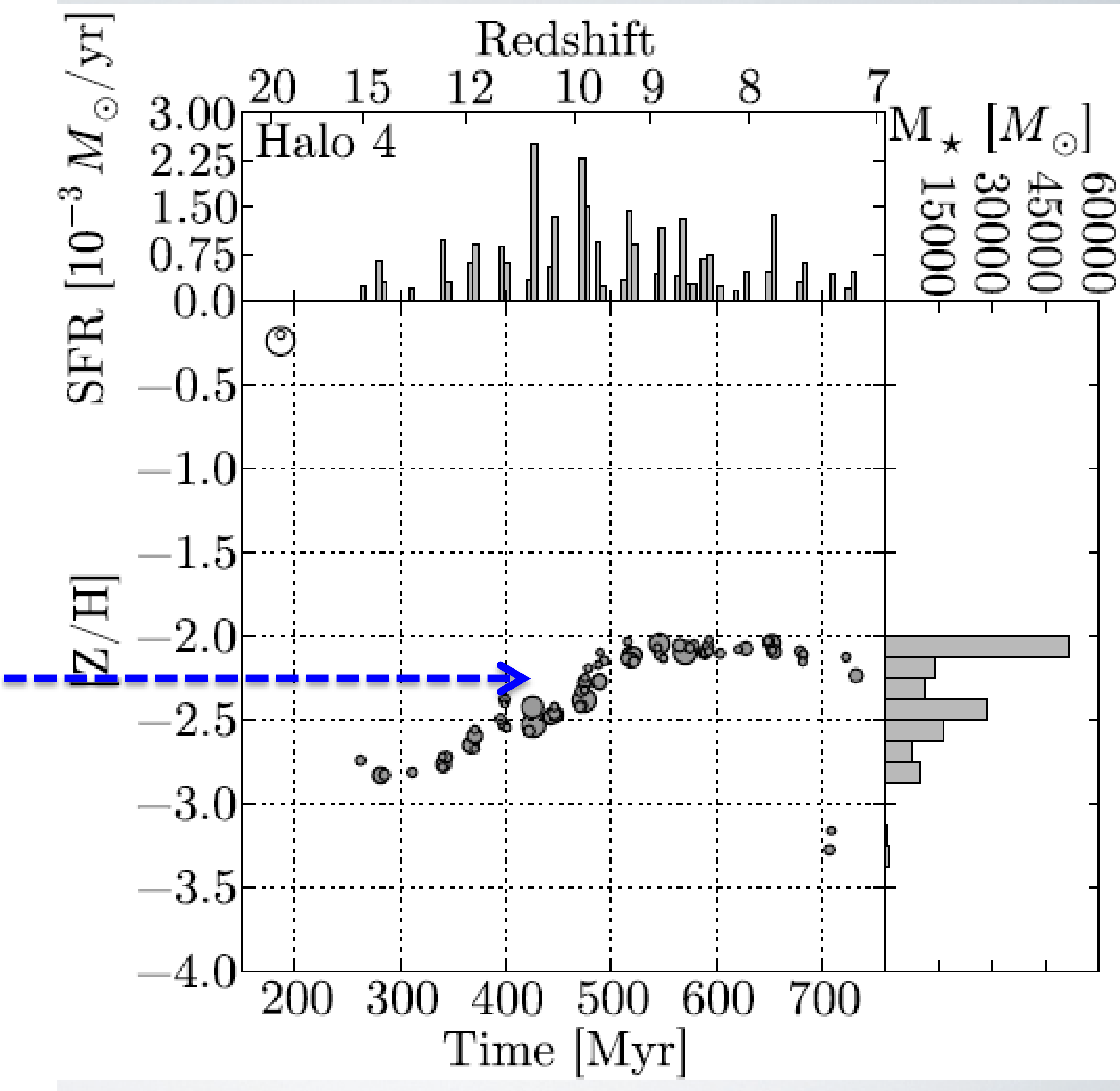
- Lensed galaxy A1689_zD1 z=7.5 (Bradley et al 2008); magnification ~×9
- Low mass (log M*~9.2) with blue UV slope
- ALMA band 6 (1mm) detection confirmed via 3 independent exposures (log $M_{dust}$ ~8)




Watson et al (2015)

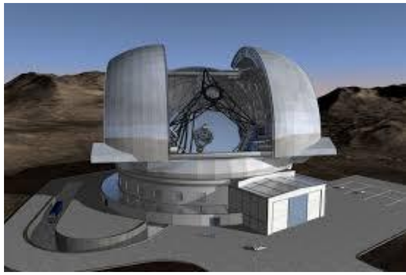
# Detecting a Pristene Pop III Galaxy?

- Consider halo mass ~ 8 $10^7$ $M_\odot$
- Metallicity evolution governed by competition between enriched outflow vs pristene inflow
- Find rapid enrichment (< 200Myr) to [Z/H] ~ -3; no low metallicity tail




Wise et al (2012)

# So How to Plan for the E-ELT?



- If Planck data is correct, early galaxies primarily lie in the redshift range $6<z<12$ which is very good news for E-ELT as most diagnostic UV lines are within reach

- First light AO instruments also give E-ELT a competitive advantage c.f. JWST (early galaxies are small)

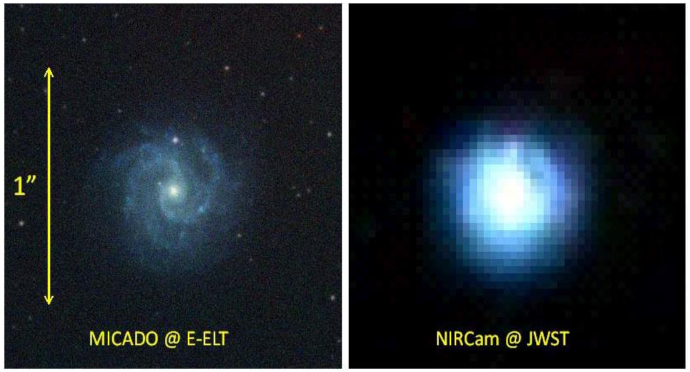
- However JWST will have a head start of a few years (2019 c.f. 2022+)

- Key survey strategies:

  - faint end of the luminosity function (photometric counts beyond m~30)
  - nature of the ionizing spectrum (detailed rest-frame UV spectra)
  - escape of ionizing photons (high s/n absorption line spectra)
  - correlation of ionized bubbles with radiating sources

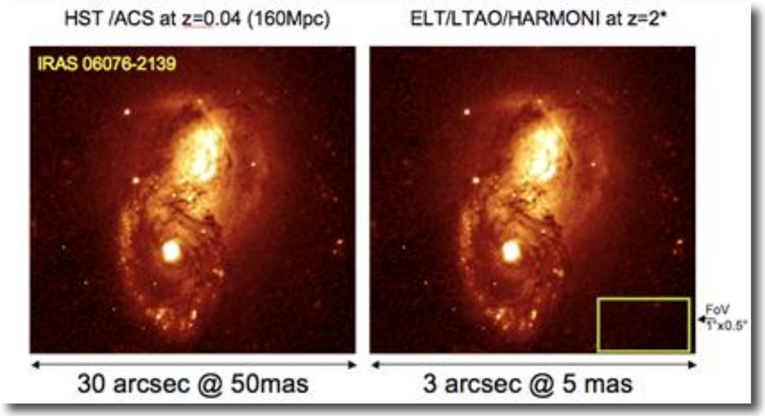
# Attributes of Optical/NIR E-ELT Instruments

ELT-CAM (MICADO)



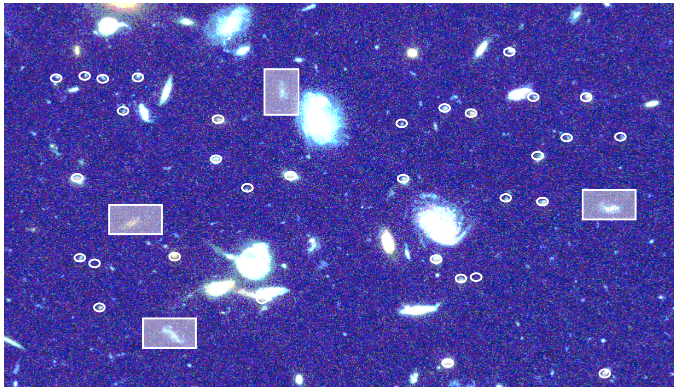

Deep imaging in selected areas to probe the rest-frame UV LF

ELT-IFU (HARMONI)




Diagnostic spectroscopy of ionizing radiation using rest-frame UV metal lines

ELT-MOS (MOSAIC)



High spectral resolution studies of stacked z~5-7 sources to probe covering fraction of low ionizing and neutral gas