First Light: The Earliest Galaxies & their Role in Cosmic Reionization

Richard Ellis (UCL)

Kavli IPMU @ 10 years

October 17th 2017

Happy 10th birthday Kavli IPMU!


Hitoshi Murayama


KAVLI
IPMU

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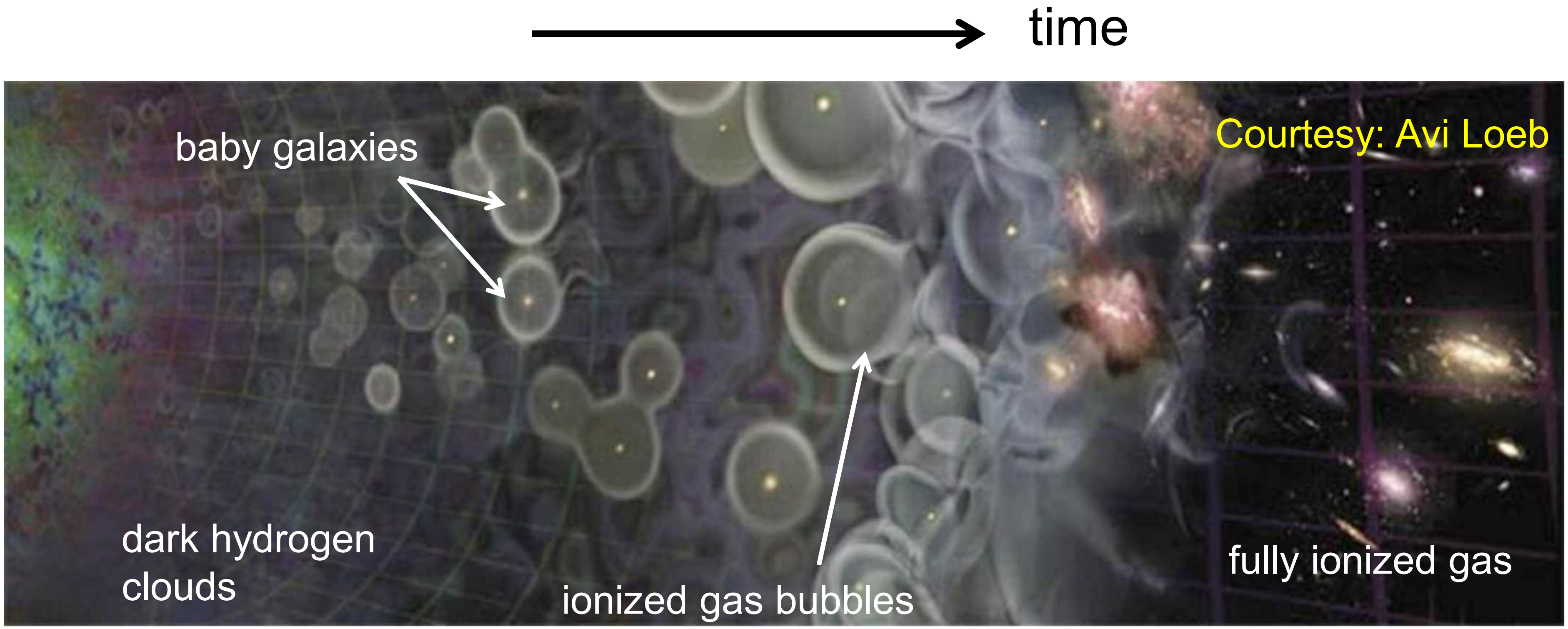
Cosmic Dawn and Reionization



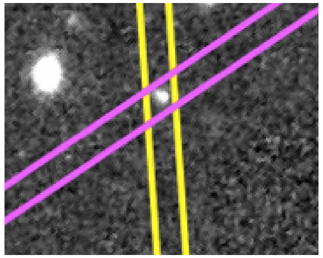
When the first galaxies emerged (**cosmic dawn**), the Universe was bathed in UV light from young stars which produced ionized inbetween the galaxies (**reionization**).

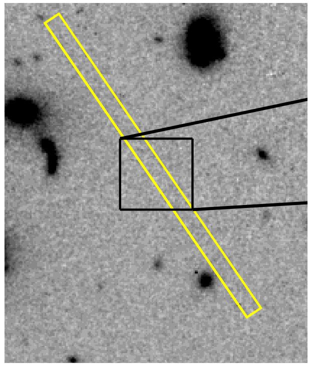
Simulation of Reionization by Galaxies

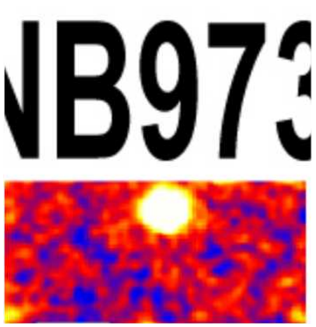
Courtesy: Alvarez & Abel (Stanford)

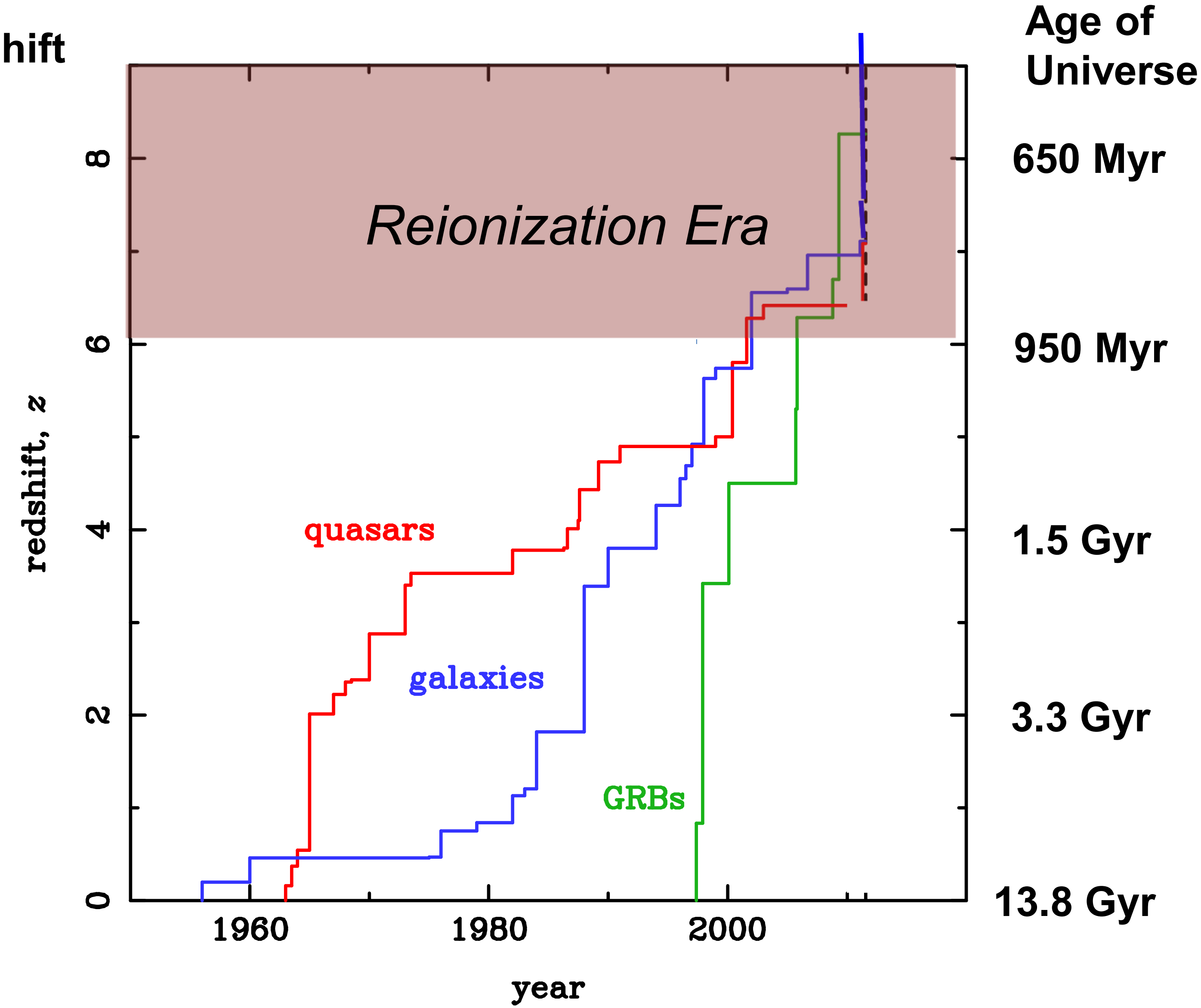
Receding Horizons: The Most Distant Object

Redshift



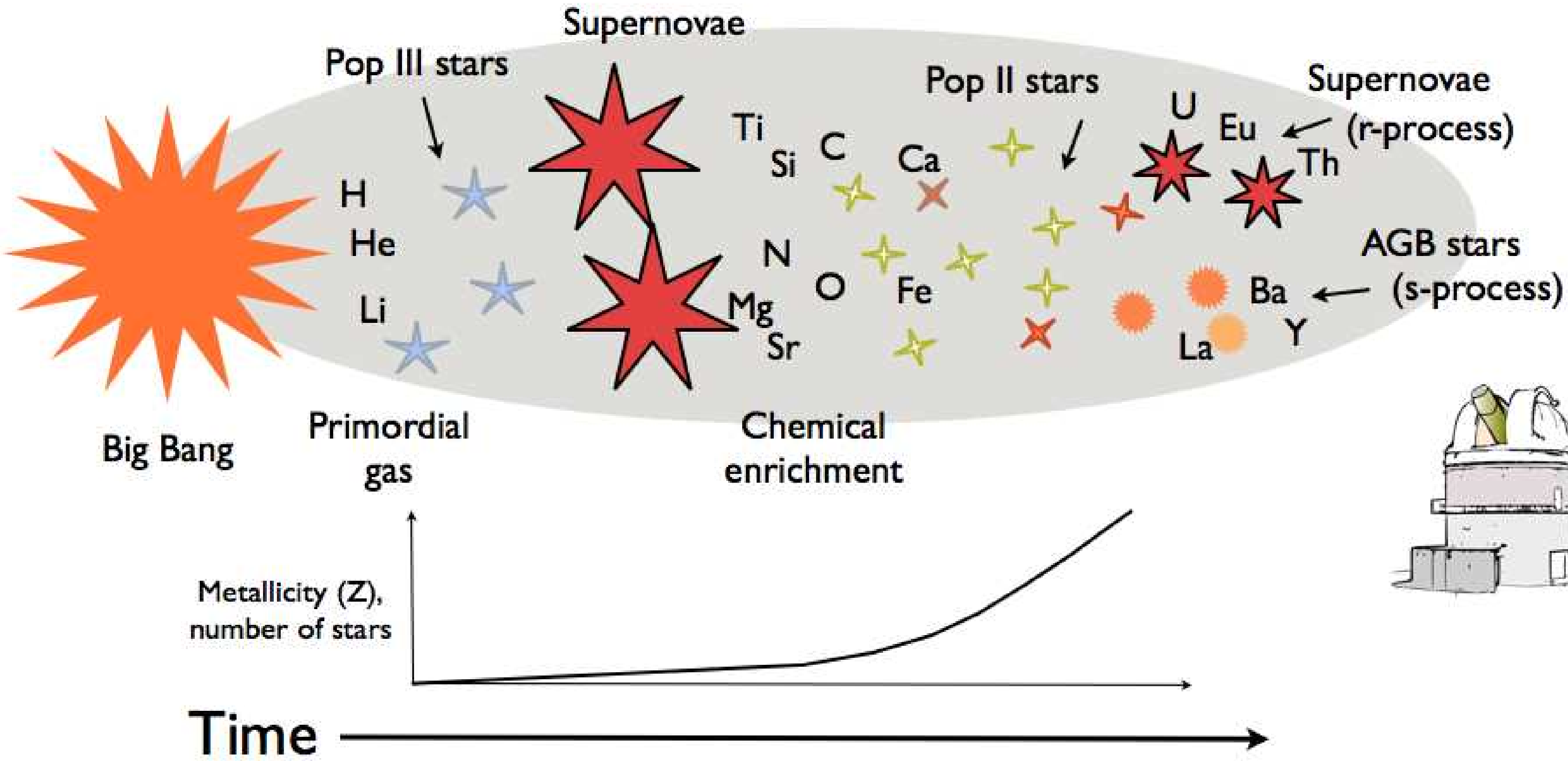






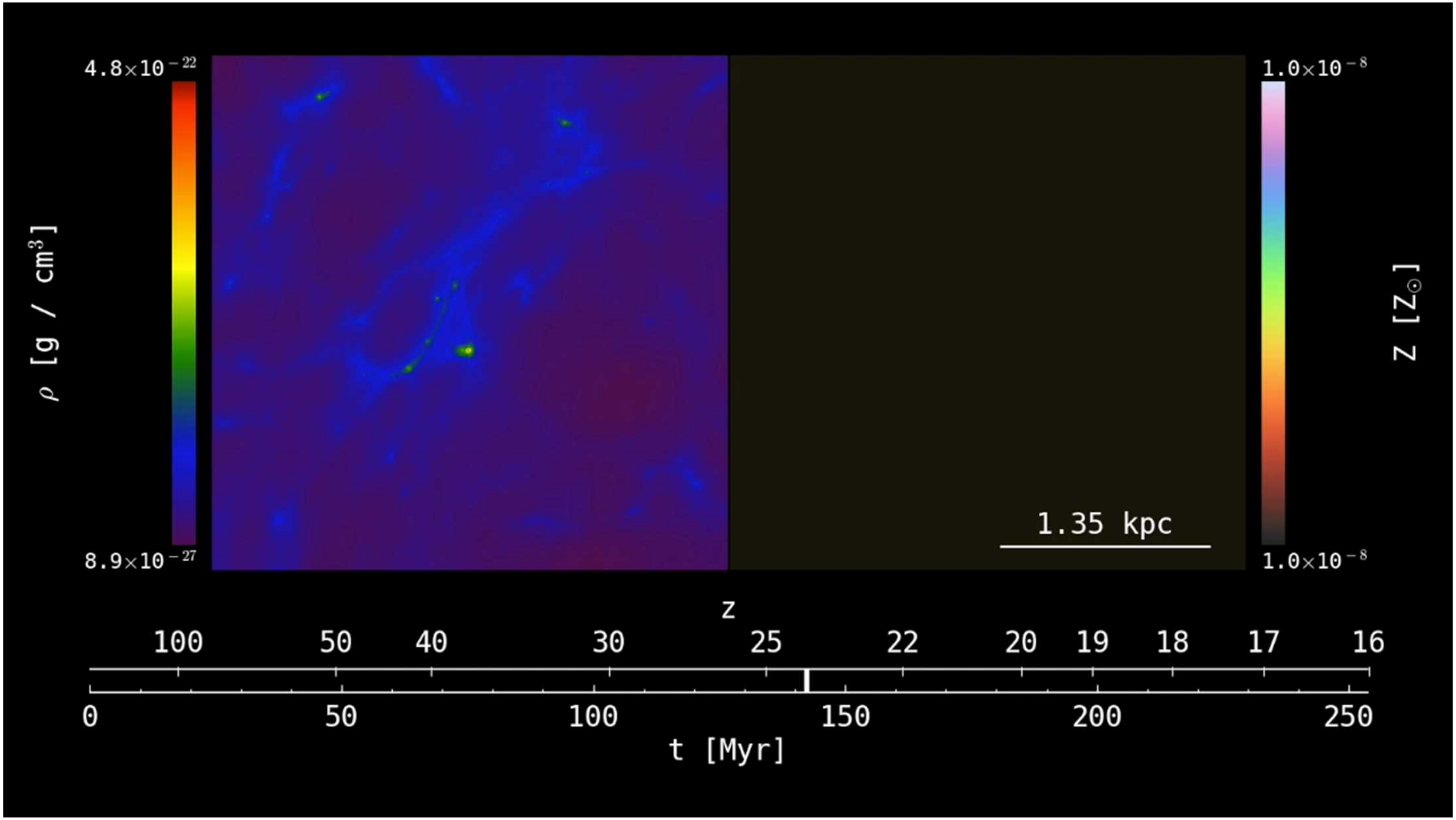
Courtesy: Dan Mortlock

The Holy Grail: Locating the First Galaxies?



A commonly promoted idea for isolating first generation systems has been to search for <u>chemically pristene</u> examples

Rapid (<60 Myr) SN Enrichment in Early Mini-Halos



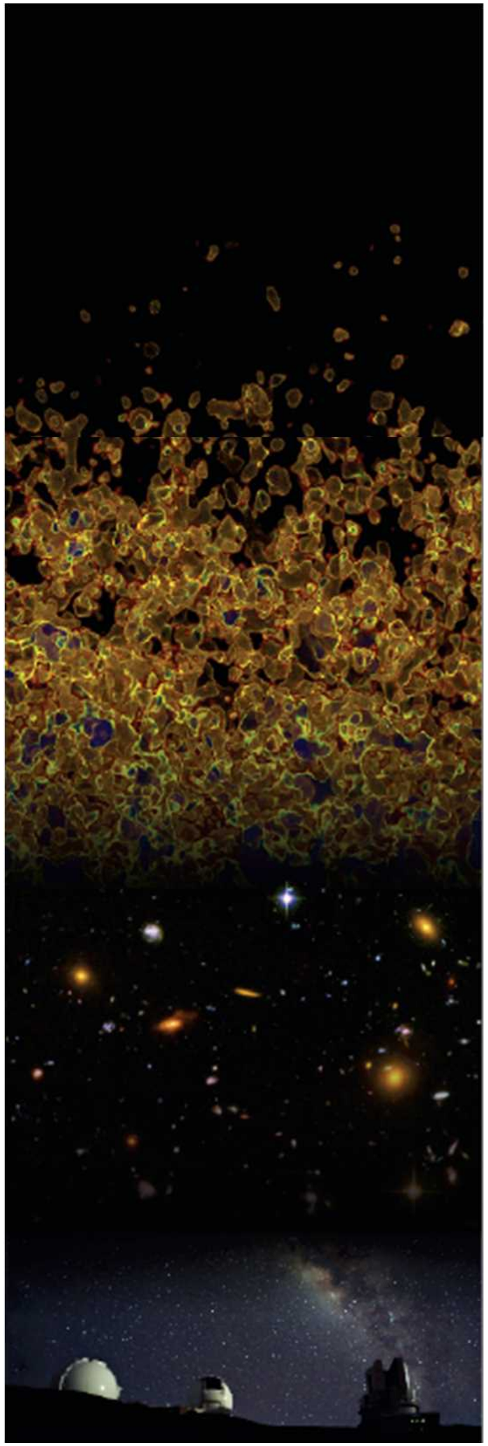
Identifying rare pristene (Pop III) galaxies will be very hard

Smith et al (2015)

(see also Richardson et al 2013, Wise et al 2012, c.f. Cen & Riquelme 2008)

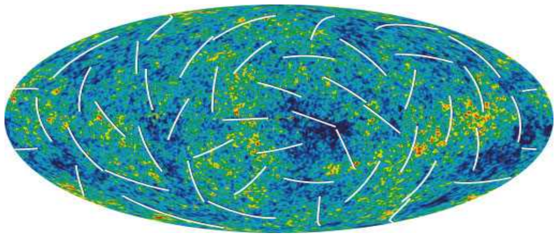
A Statistical Approach

- The birth of galaxies will not be determined via the location of one (or a few) unusual objects with low or zero metal content
- The preferred alternative is to seek a <u>statistical measure</u> associated with their influence on the intergalactic medium
- This requires understanding when reionization began and what was the key role of early galaxies in initiating it



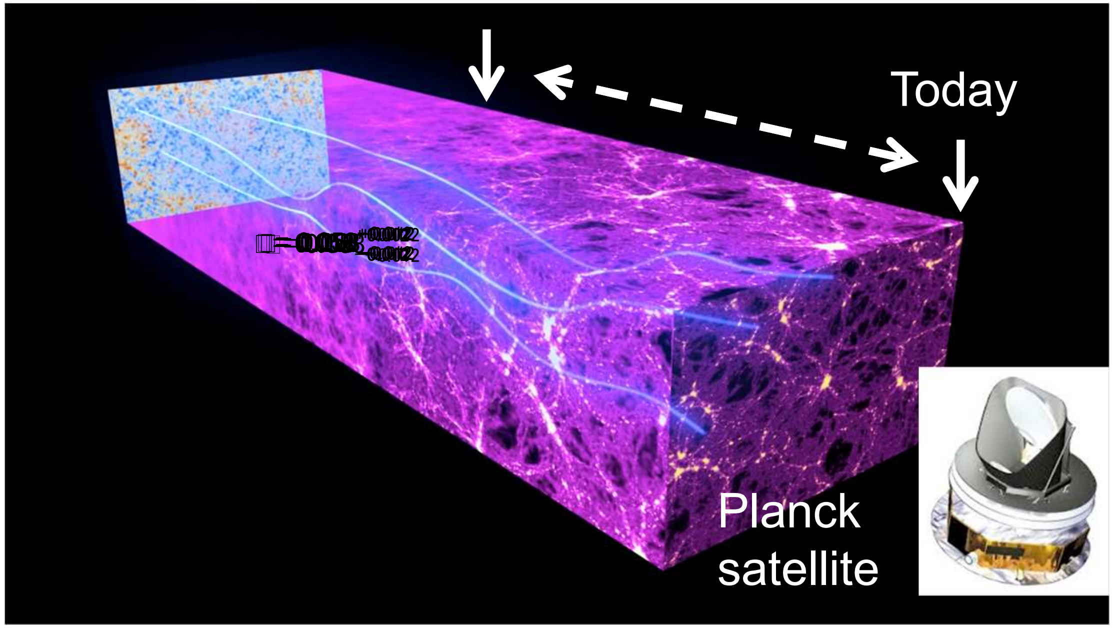
Collaborators: Brant Robertson (UCSC), Dan Stark (Arizona), Jim Dunlop (Edinburgh), , Masami Ouchi (Tokyo), Kimihiko Nakajima (ESO), Nicolas Laporte (UCL), Koki Kakiichi (UCL), Guido Roberts-Borsani (UCL), Tom Fletcher (UCL)

Planck Indicates Late and Fast Reionization

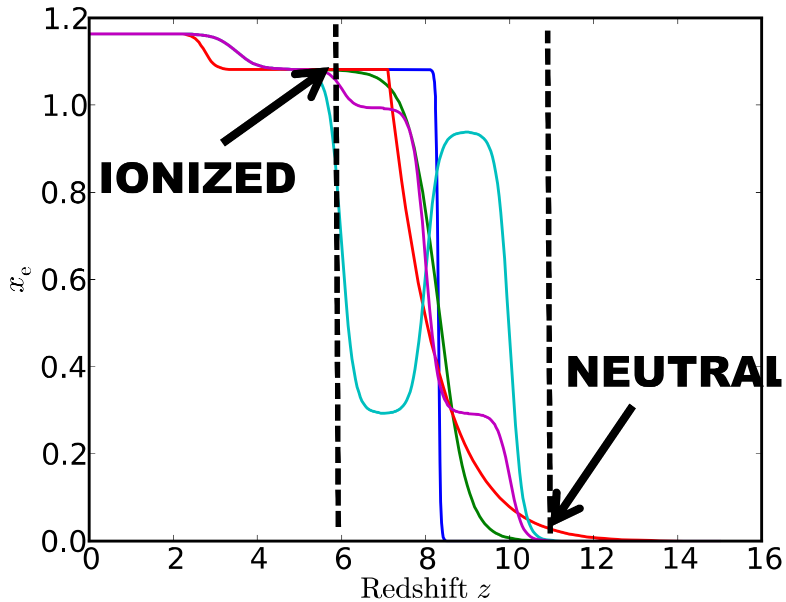


CMB polarization probes foreground Thomson scattering from the start of reionization to the present epoch.
Optical depth of scattering τ constrains the mean redshift <z> and (model dependent) duration of reionization

Reionization begins



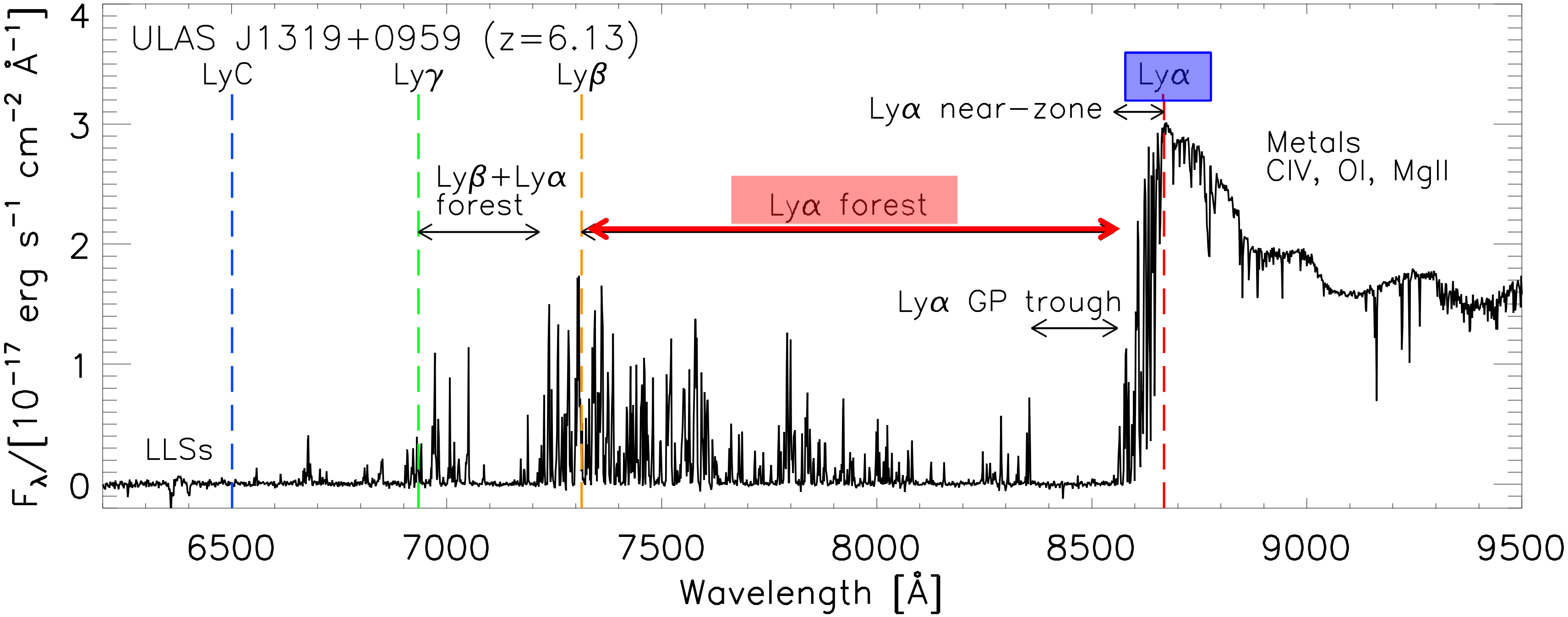
Parametric models consistent with Planck τ



Planck consortium (2016) find τ = 0.058 ± 0.012 corresponding to <z> ~8.3 ± 0.5

Models indicate reionization began at z~10-12 and ended at 6

Probing the Intergalactic Medium via Absorption



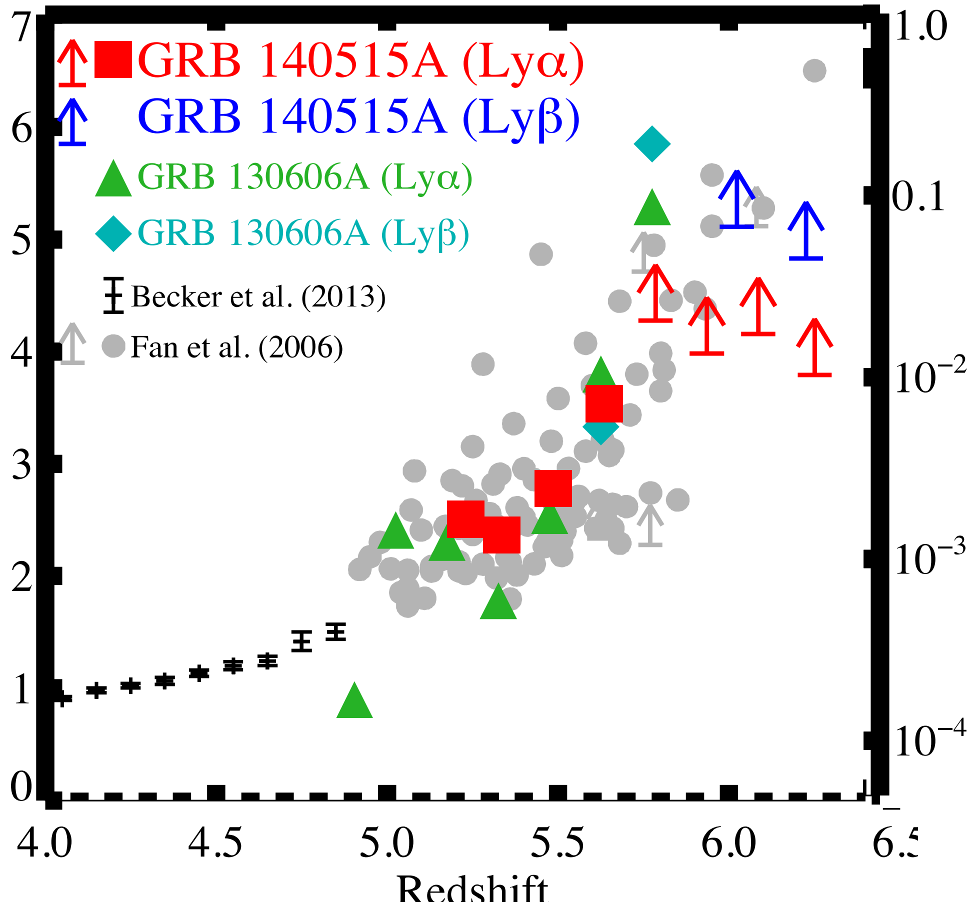
The neutrality of the IGM, quoted fractionally per unit comoving volume, x(HI), can be inferred via the redshift-dependent optical depth of Lyman alpha absorption (Gunn-Peterson effect)

Redshift - Dependent Absorption

- Few suitably luminous sources beyond redshift z~6.5
- Insensitive: small amount of HI saturates absorption ($X_{HI} \sim 10^{-3}$)

Method indicates reionization ended at z~6 (age ~ 1 Gyr)

Depth of Lyman α absorption



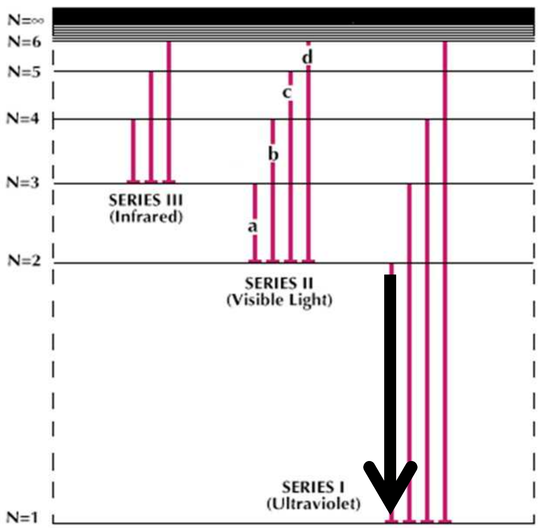
X_{HI}

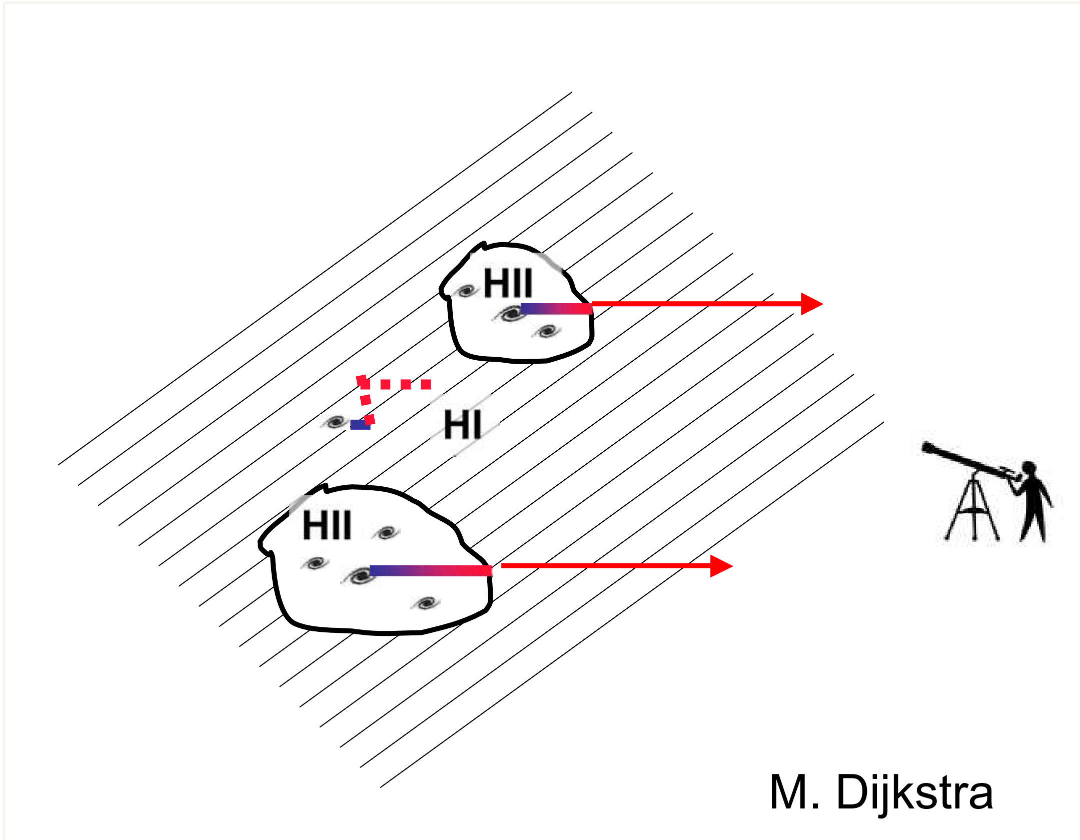
Chornock et al arXiv: 1405.7400; McGreer et al (2015)

Lyα Emission as a Probe of Reionization

Up to 6-7% of galaxy radiation may emerge in Lyα: gas heated by hot young stars

- But resonant scattering by neutral H reduces its visibility
- In a significantly neutral IGM, galaxy must lie in an ionized bubble in order for Lyα to escape
- Expect a drop in the fraction of galaxies revealing Lyα emission as we enter the neutral era



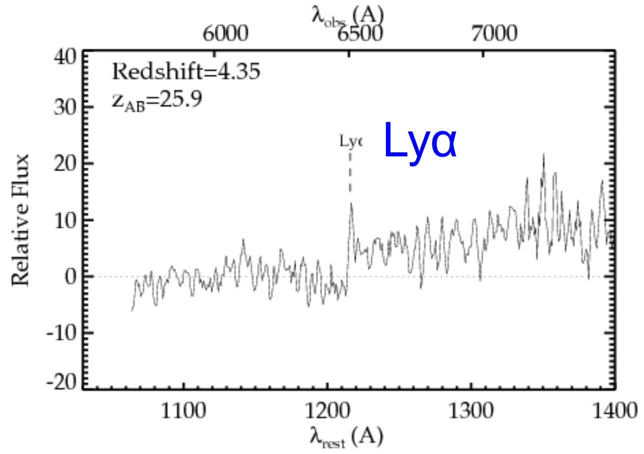


Miralda-Escudé (1998), Santos (2004), Dijkstra+ (2007),

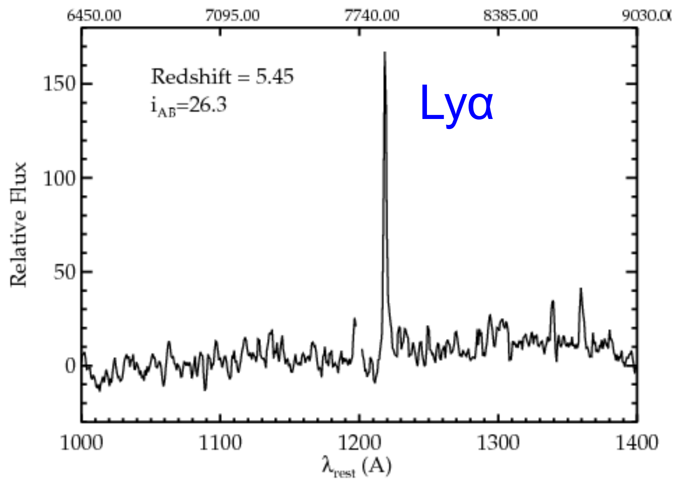
Pushing Keck to the Limit..

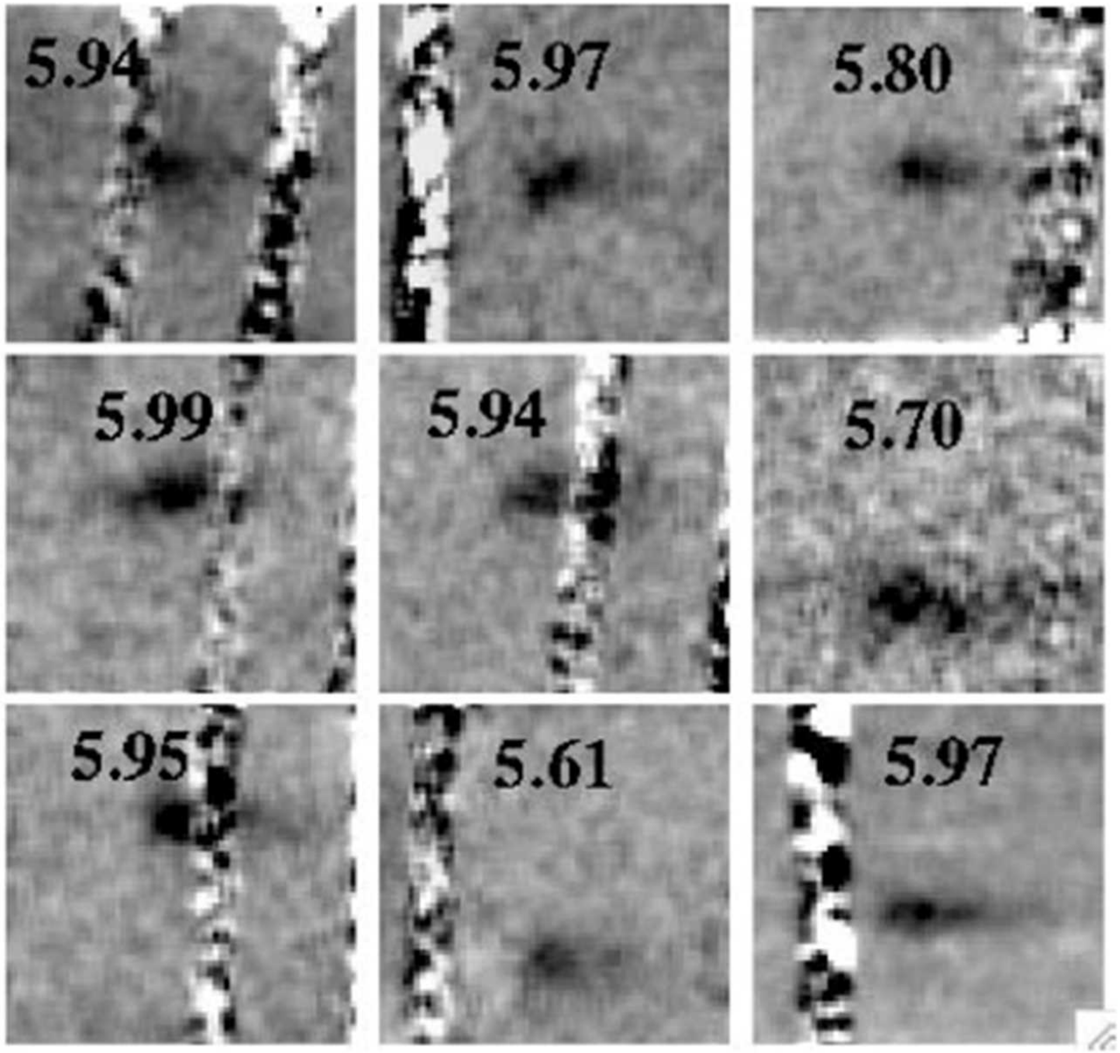
8-12 hour exposures to m~27.5 with frequent detection of Lyα emission

m=25.9, z=4.35



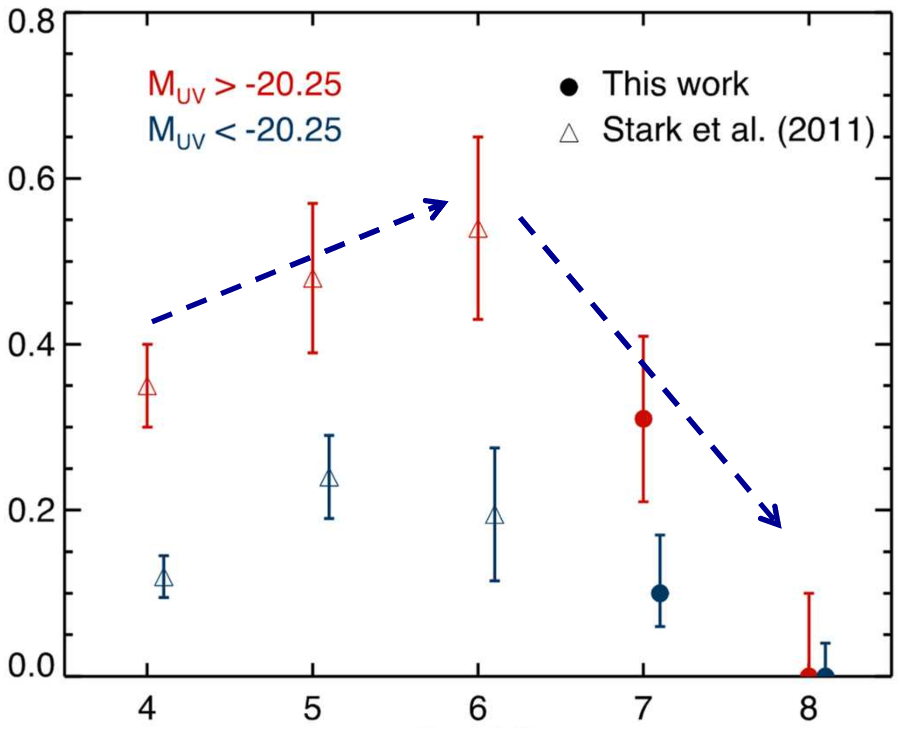
m=26.3,z=5.45





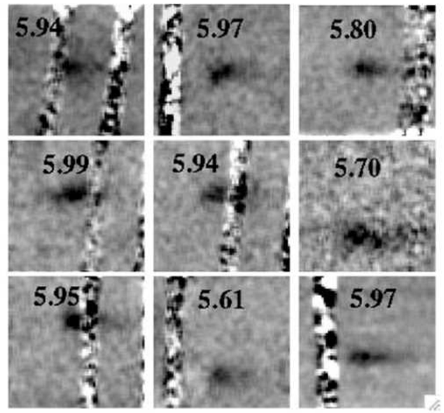
Confirmation: Lyα fraction declines sharply for z > 6

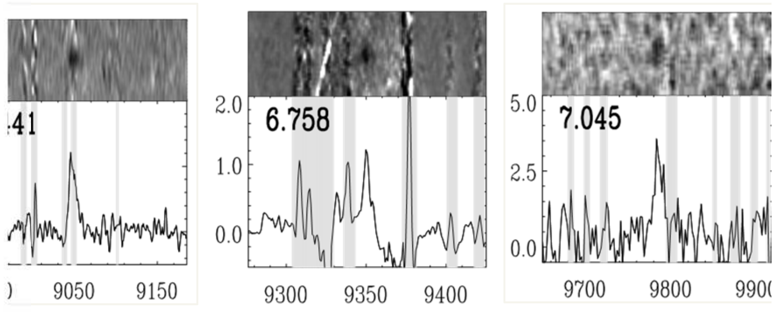
Fraction with Ly α



redshift

50% at z~6 are emitters



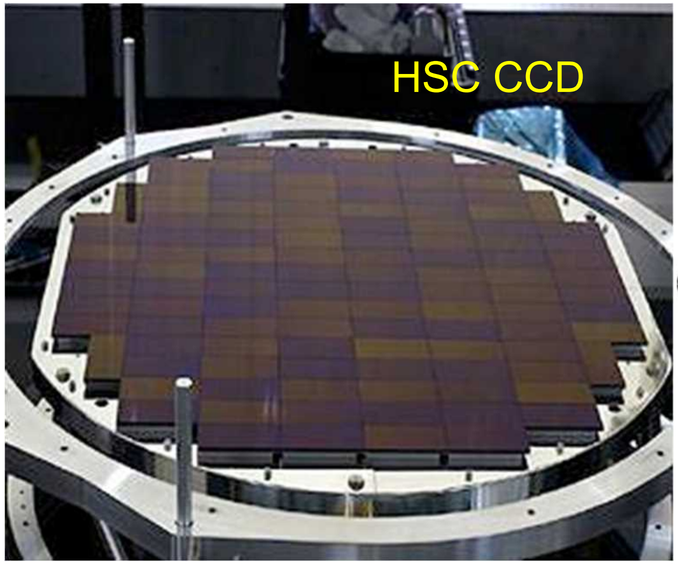


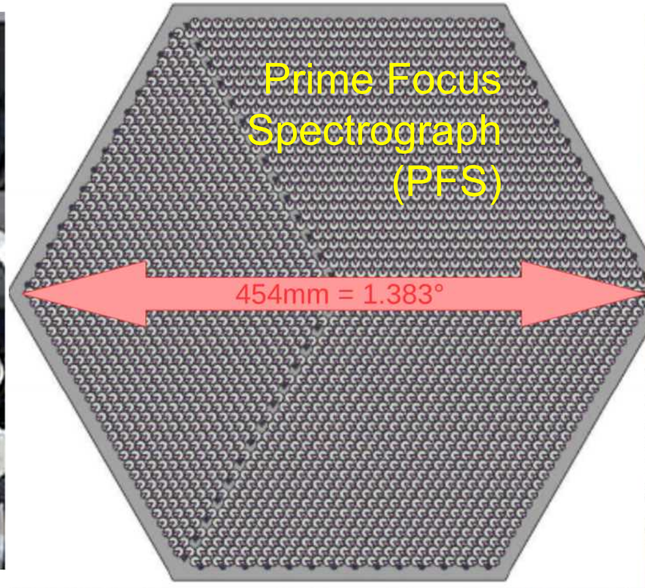
But <10% are emitters @ z > 7

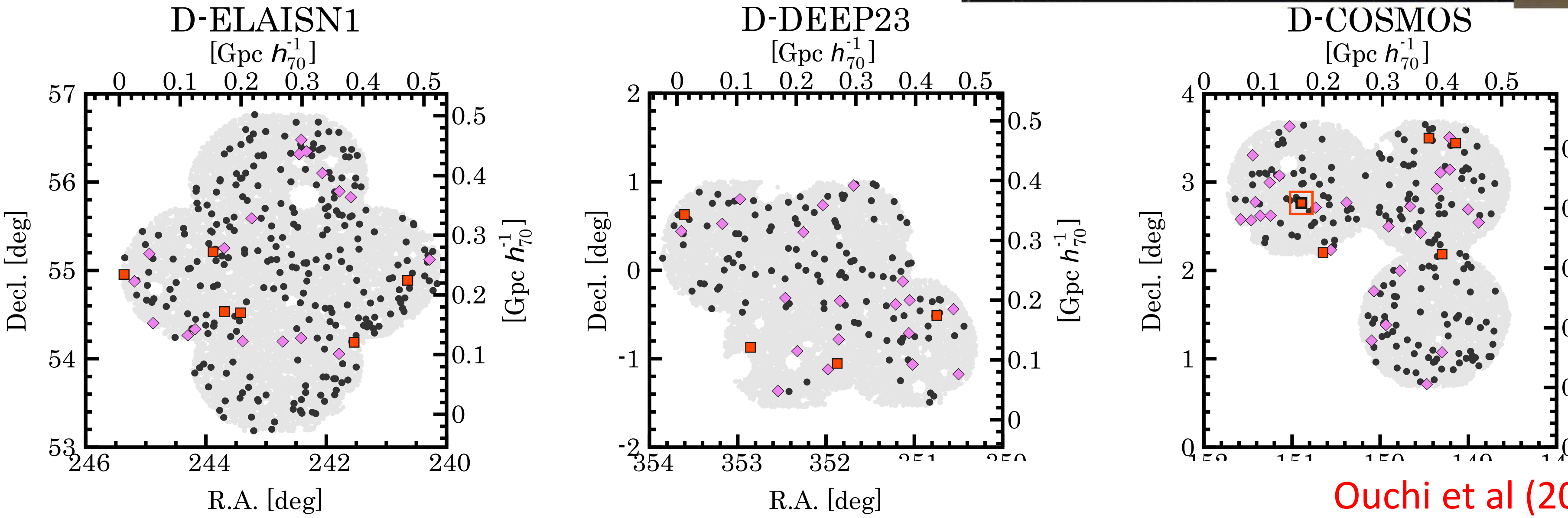
Schenker et al (2012), Ono et al (2012), Schenker et al 2014), Pentericci et al (2014)

Distribution of Lyα Emitters

Subaru HSC is charting > 2000 Lyα emitters in range $5.7<z<7.1$ over 20 deg^2
Constrains evolving sizes of ionized bubbles & longevity of ionizing sources.







Ouchi et al (2017)

Observing galaxies in reionization era : Deep Fields

Deep Field Imaging with HST's Wide Field Camera 3

e.g. Hubble Ultra Deep Field 2012

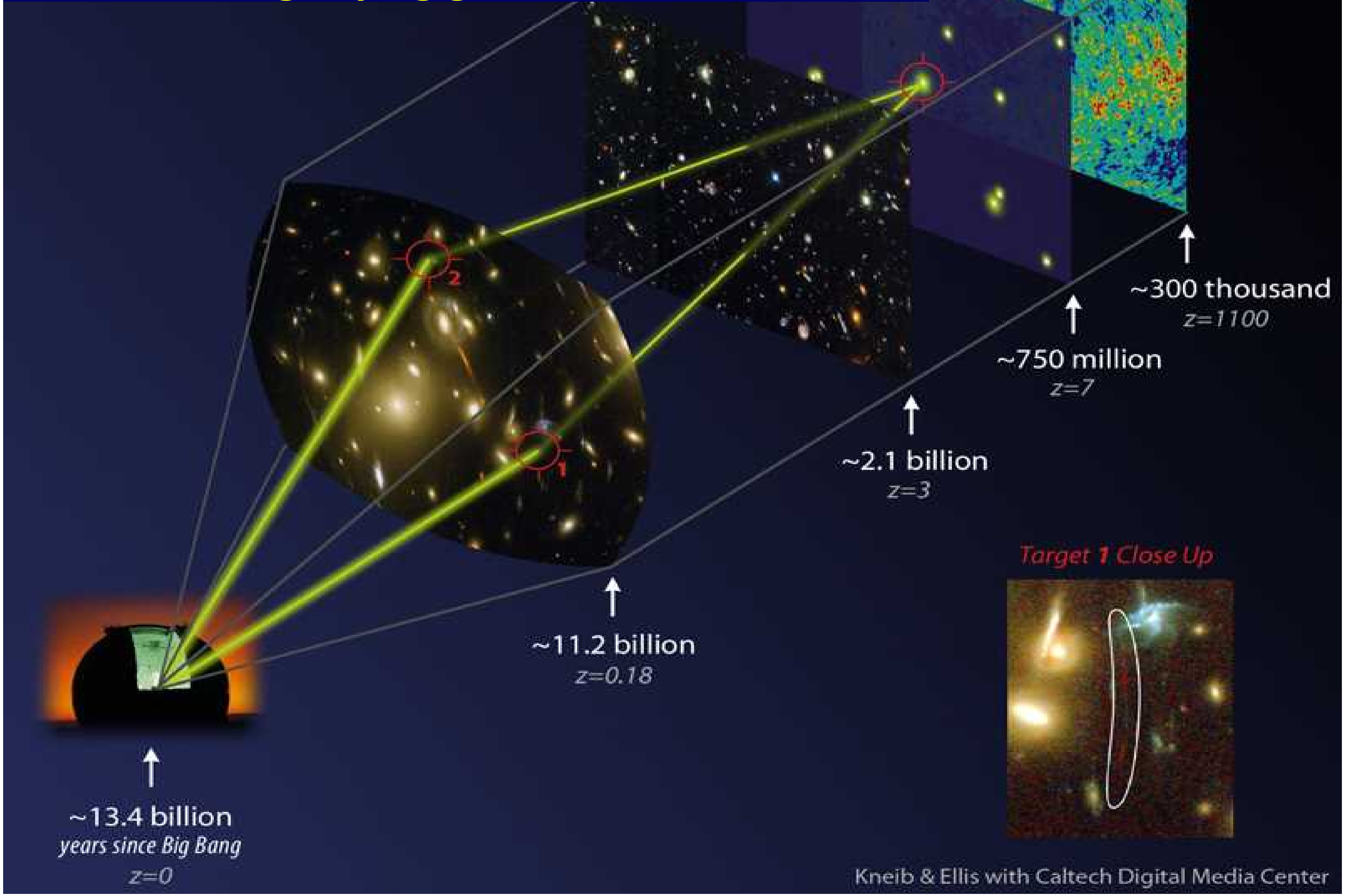
- AB mag ~30+
- first 8.5<z<10 sources
-75 galaxies z>6.5

Plus CANDELS: wider area with IRAC

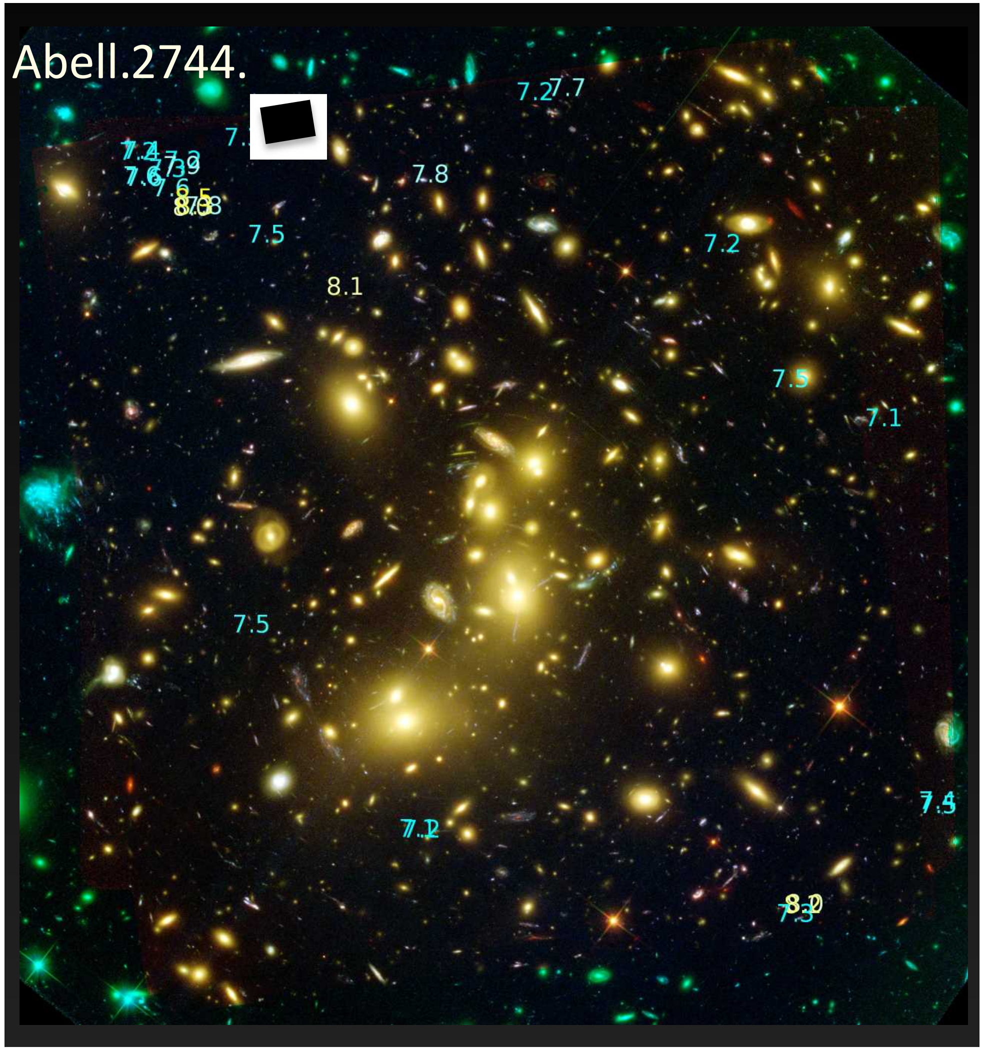
Hubble Ultra Deep Field 2012
Hubble Space Telescope WFC3/IR

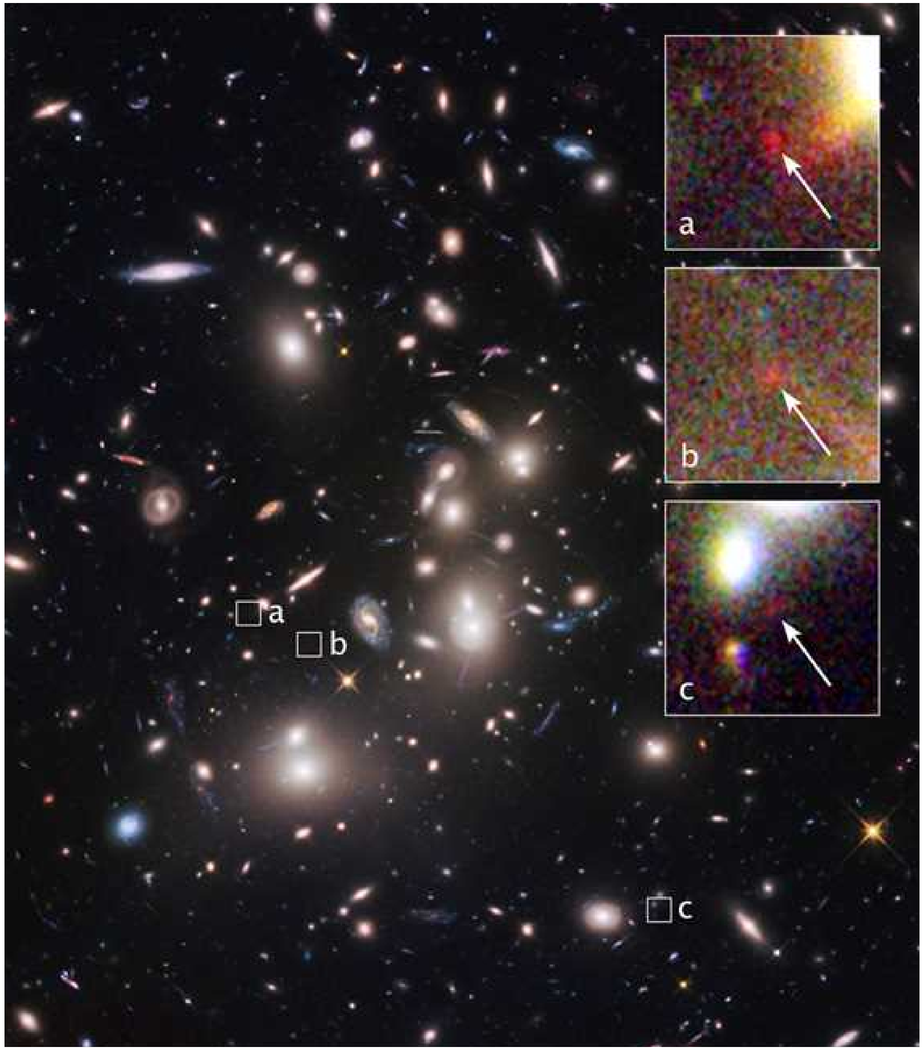
NASA and ESA STScI-PRC12-48a

Gravitational lensing:
A natural magnifying glass..



The Hubble Frontier Fields



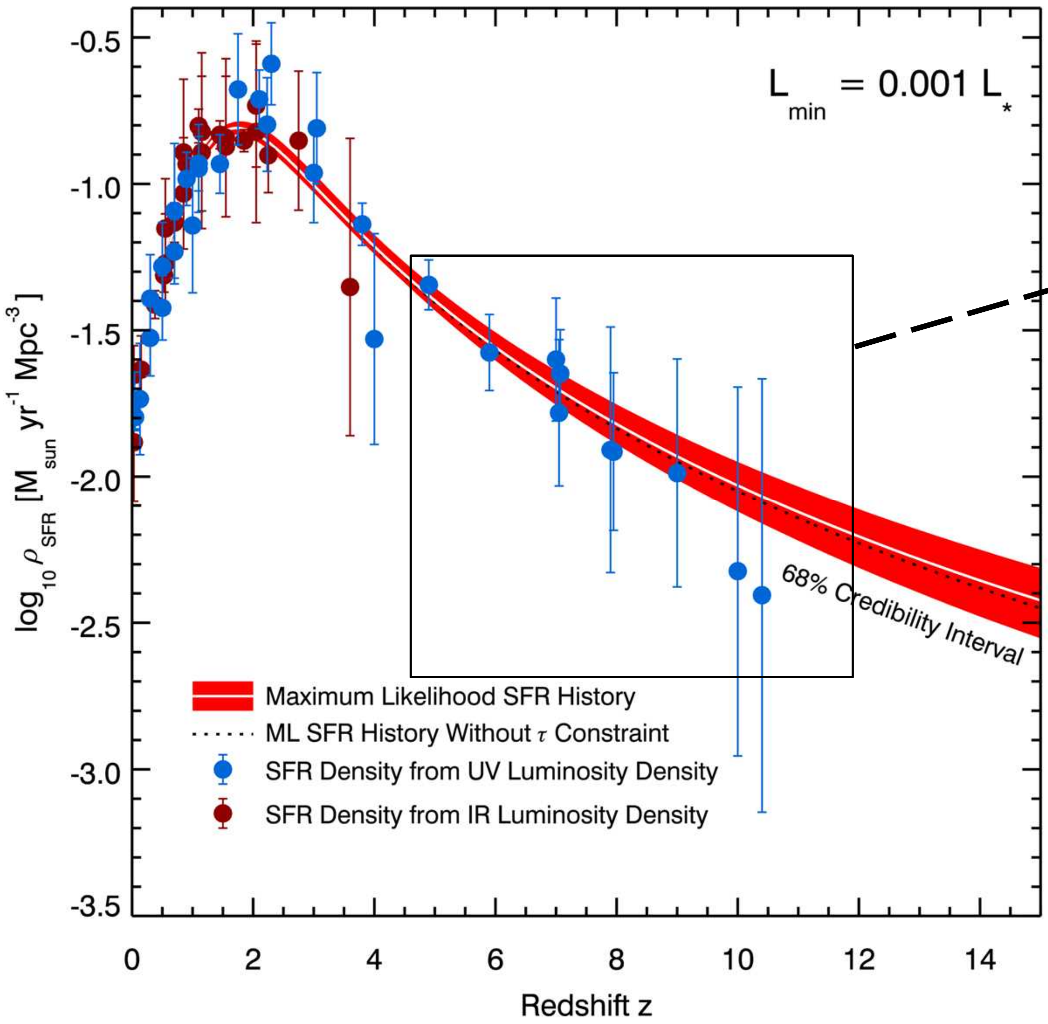


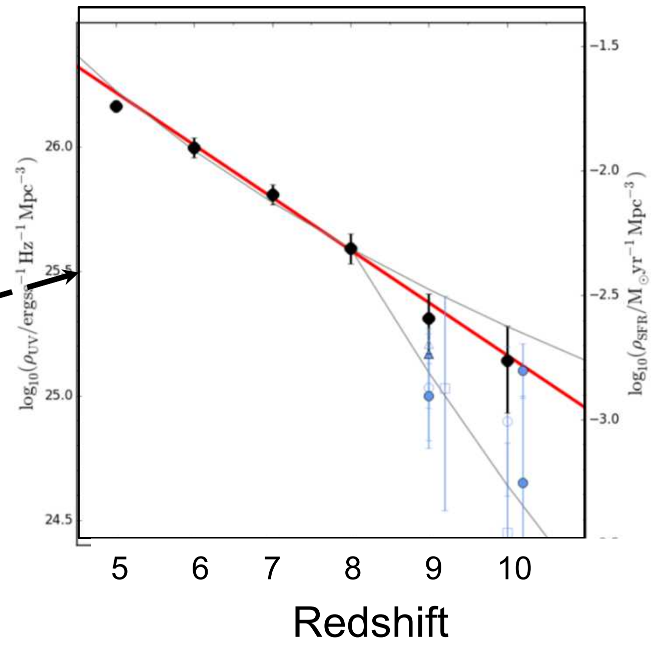
z~7-8 lensed galaxies in Abell 2744 (Coe)

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

Census of Star Forming Galaxies

Reasonable agreement between blank & lensed surveys

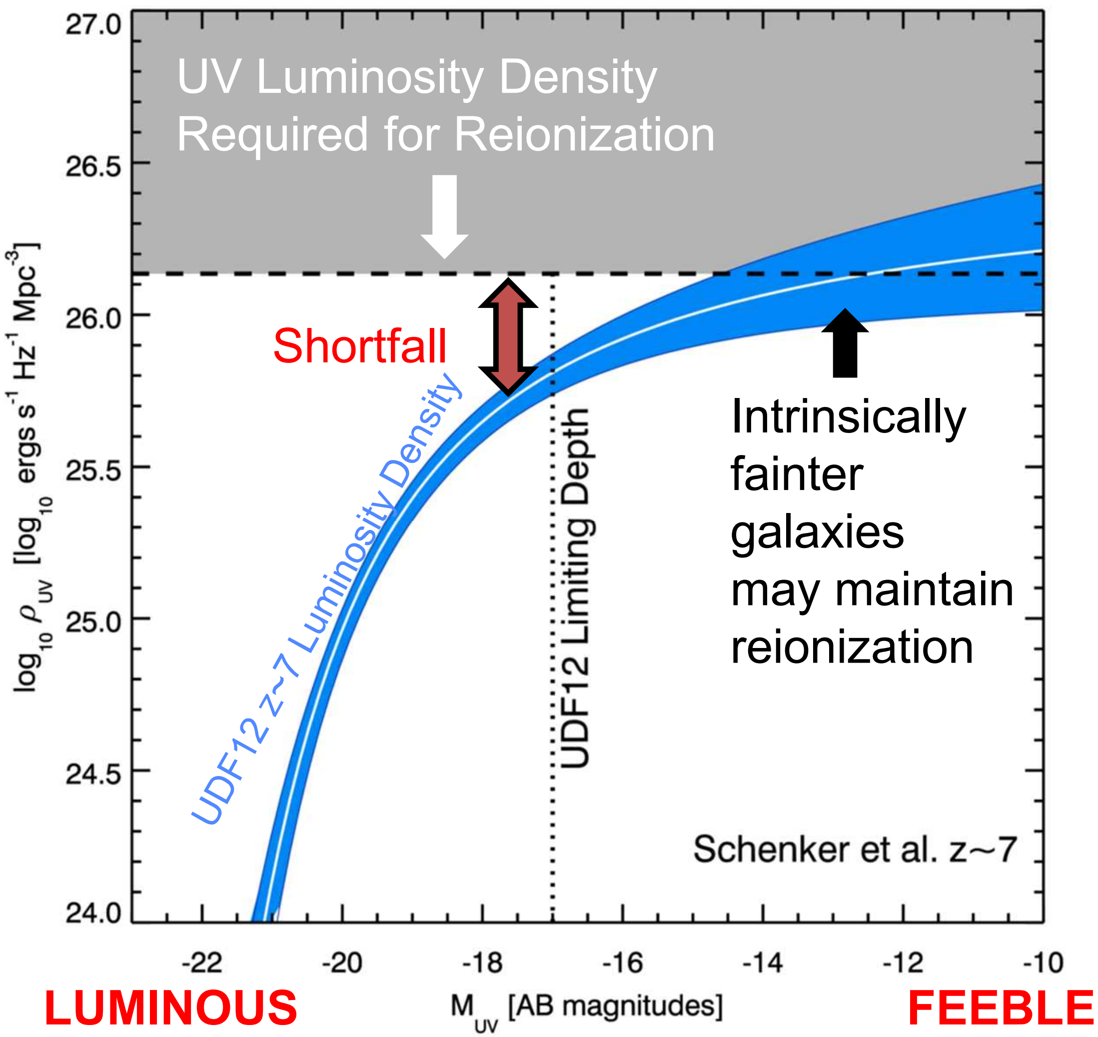




~35 objects with z>8.5 indicates no steepening of decline in numbers beyond a redshift z > 8

Robertson et al (2015), McLeod et al (2016)

The Luminosity Function: An Illustration



- Even with the deepest imaging we only see a luminous proportion of the galaxy population at early times
- The **observed population of z~7-8 galaxies** may not produce enough radiation to reionize intergalactic hydrogen
- But the constrained **faint end slope** of the luminosity function allows us to imagine that **feeble, so far unseen galaxies** might be sufficient

Robertson et al (2013)

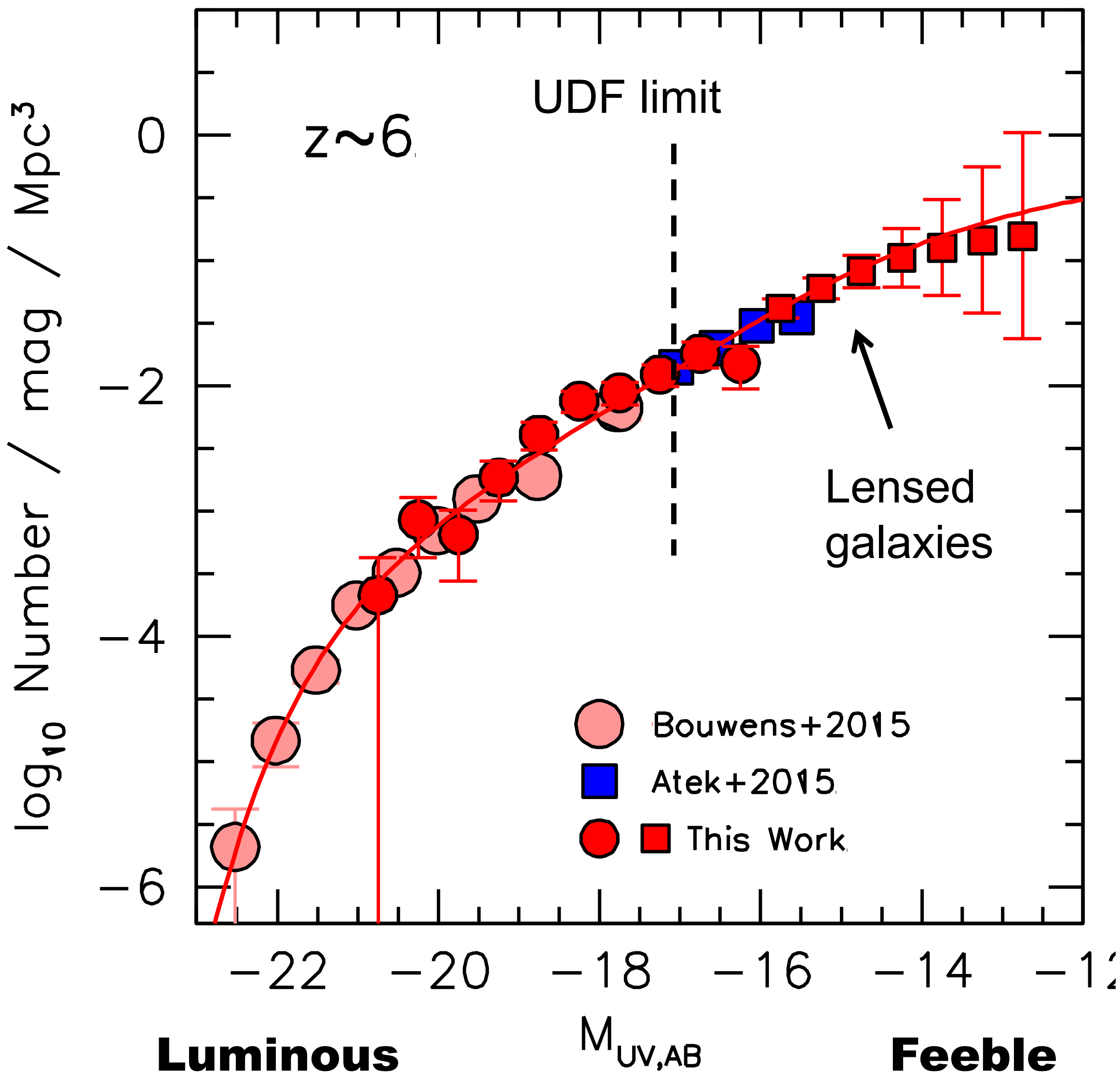
Lensing Probes Contribution of Feeble Sources

UDF12 probed to M_{UV}=-17

Lensed data reaches feeble sources to M_{UV}=-15

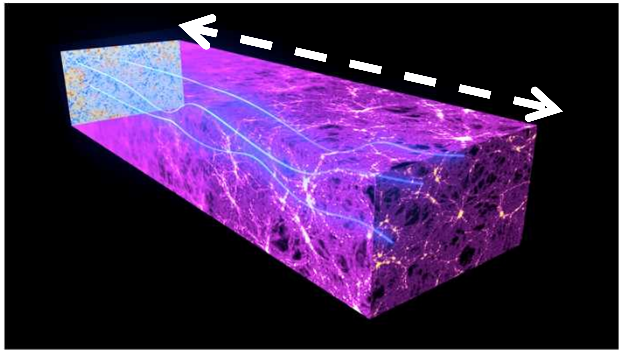
The key issue is the `*faint end slope*' which measures the integrated effect of feeble sources.

Uncertainty on integrated luminosity density ρ_{UV} is ~20%



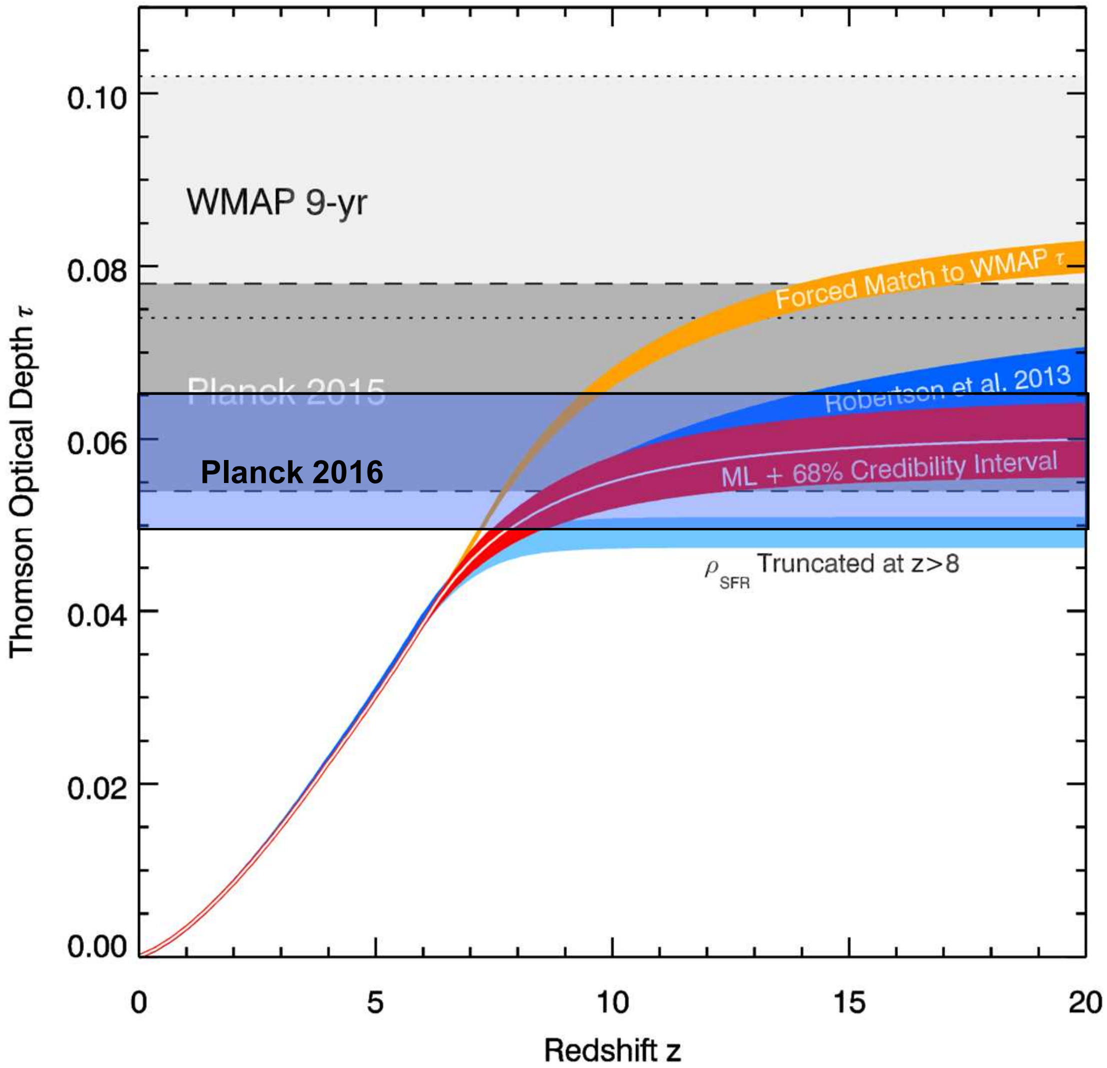
Schenker et al (2013), Atek et al (2015), Bouwens+RSE et al (2016)

Reconciling Star-Forming Galaxies with Planck



Depending on their ionizing output, the demographics of early galaxies from HST matches Planck's optical depth of electron scattering with reionization contained with 12 < z < 6

Focus thus turns to demonstrating the validity of these assumptions about the ionizing output of early galaxies



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

So Did Galaxies Reionize Universe?

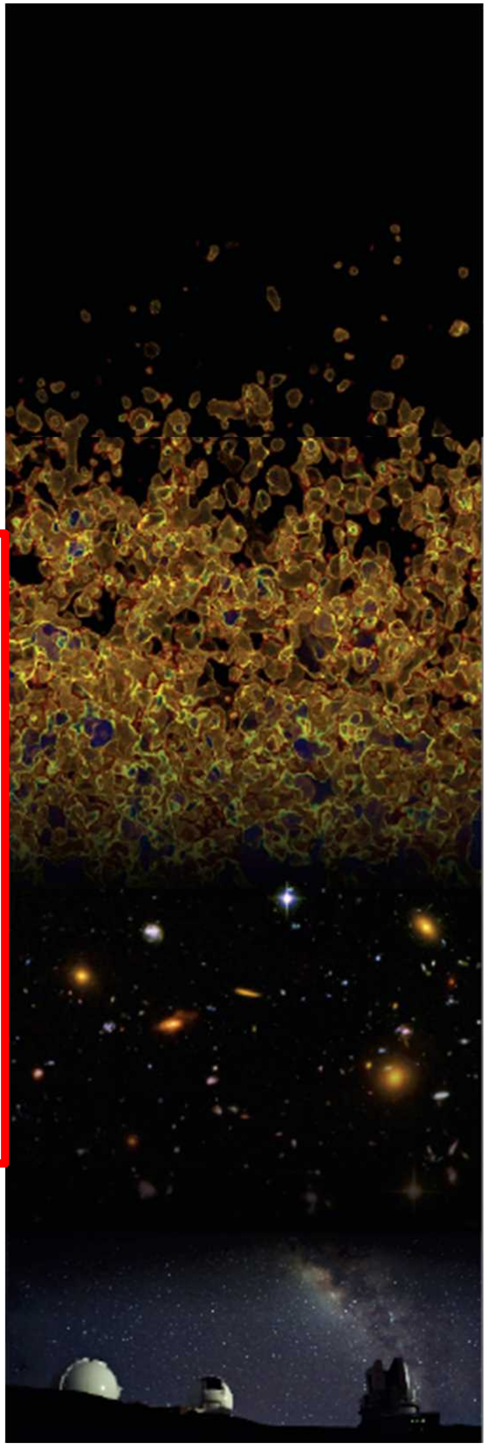
Ionization rate $$\dot{n}_{ion} = f_{esc}\xi_{ion}\rho_{UV}$$

Key observables:

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

2. Nature of the stellar populations in distant galaxies which determines the rate of ionising photons: ξ_{ion}

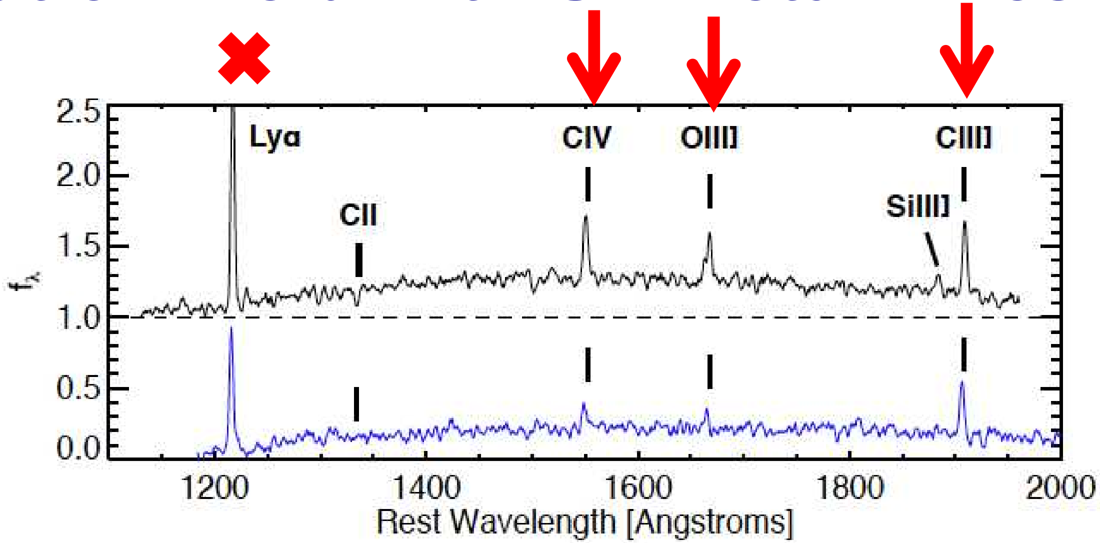
3. Fraction of ionizing photons that escape: f_{esc}

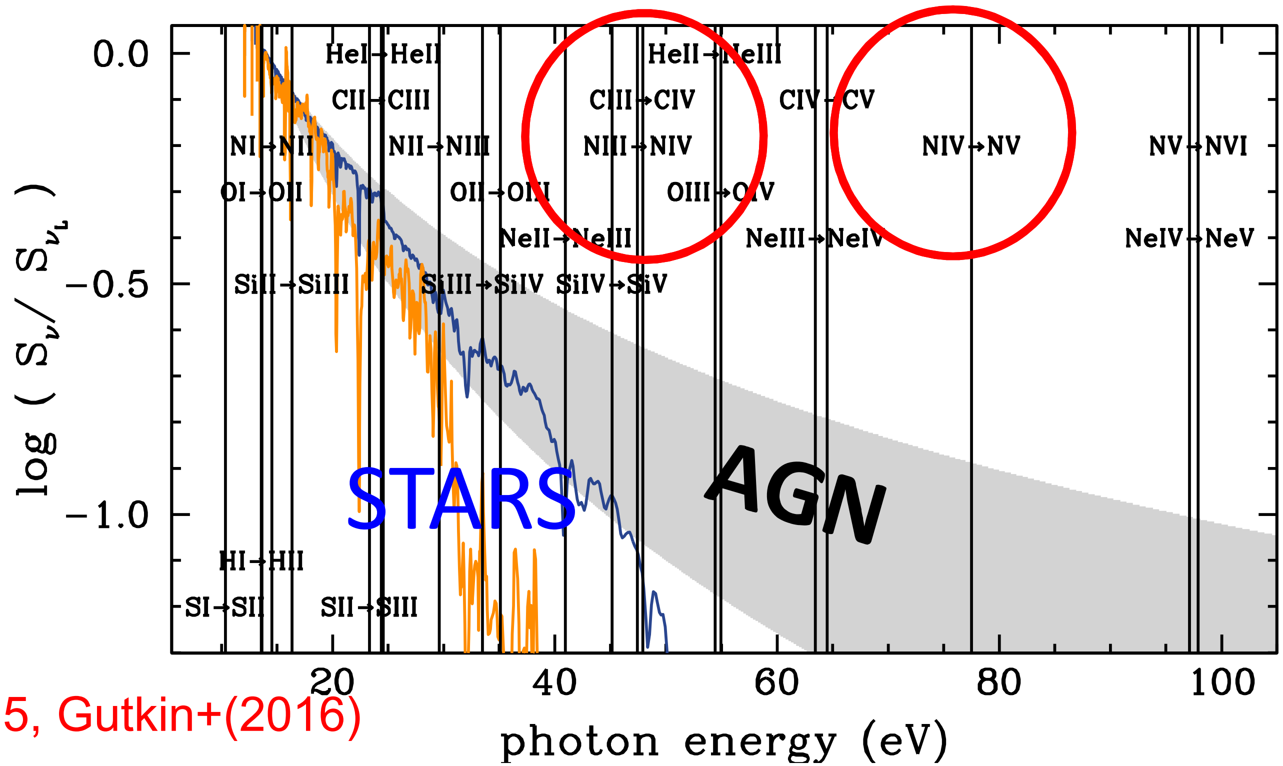


Diagnosing the Radiation Field with UV Metal Lines

Ionizing radiation could be thermally product from hot stars or non-thermal from active nuclei containing black holes

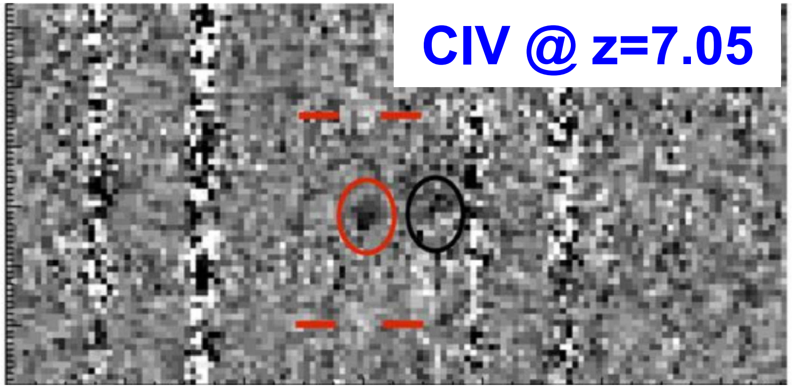
UV metal lines of high ionization potential (CIV, NV) probe the nature of the radiation field

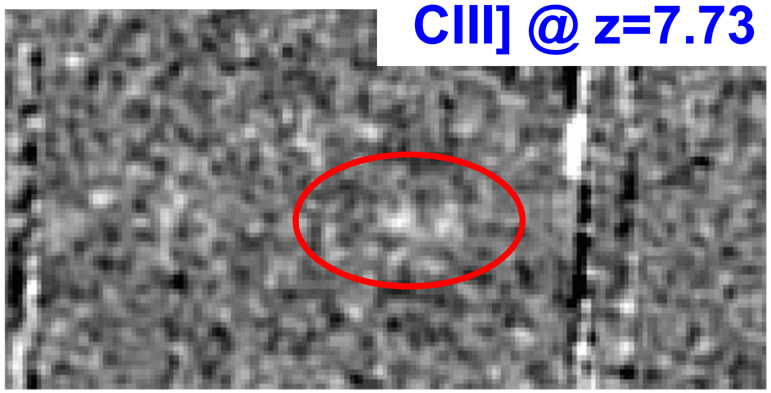


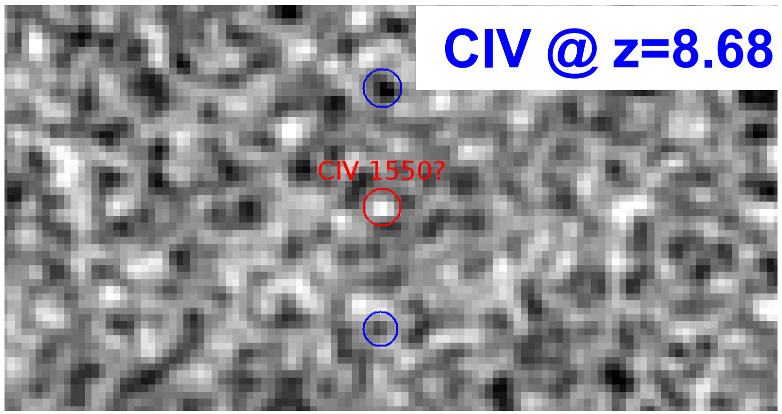


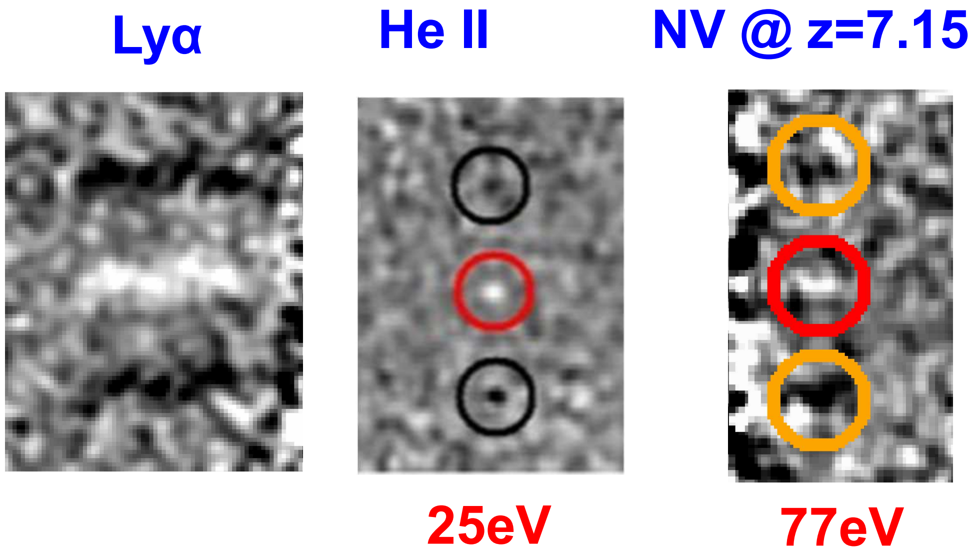
Stark+(2014), Feltre+(2015, Gutkin+(2016)

High ionization lines in z > 7 sources





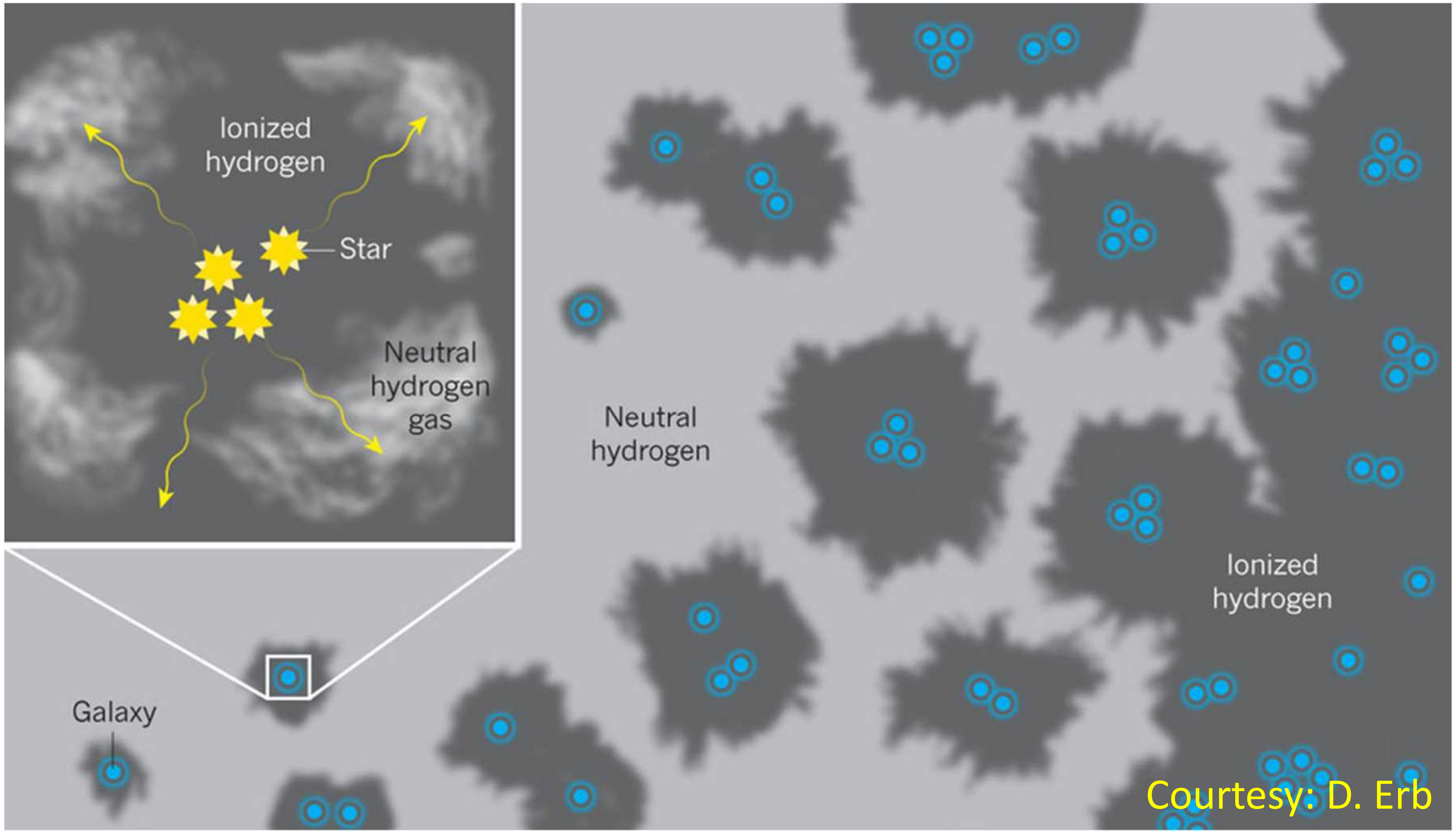




Keck/MOSFIRE and VLT/X-Shooter exposures (up to 18 hours) reveal evidence of hard radiation fields arising from metal-poor massive stars and, in one convincing case, an active nucleus harboring a massive black hole

Stark et al 2015, 2017, Laporte et al 2017

How Much Ionizing Radiation Escapes into the IGM?

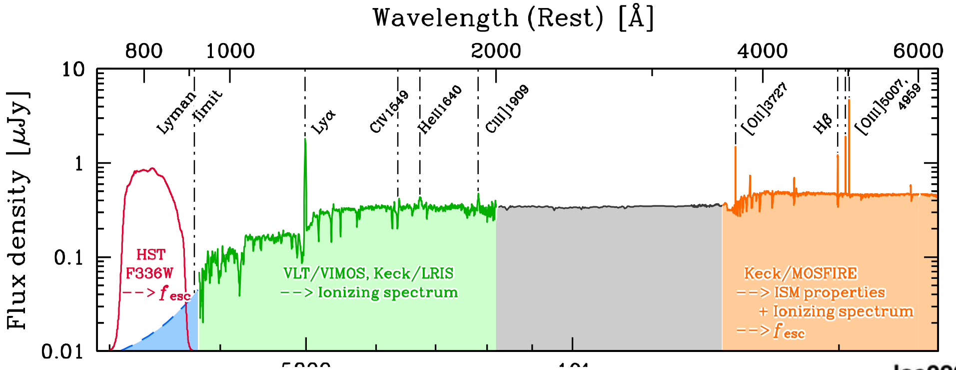


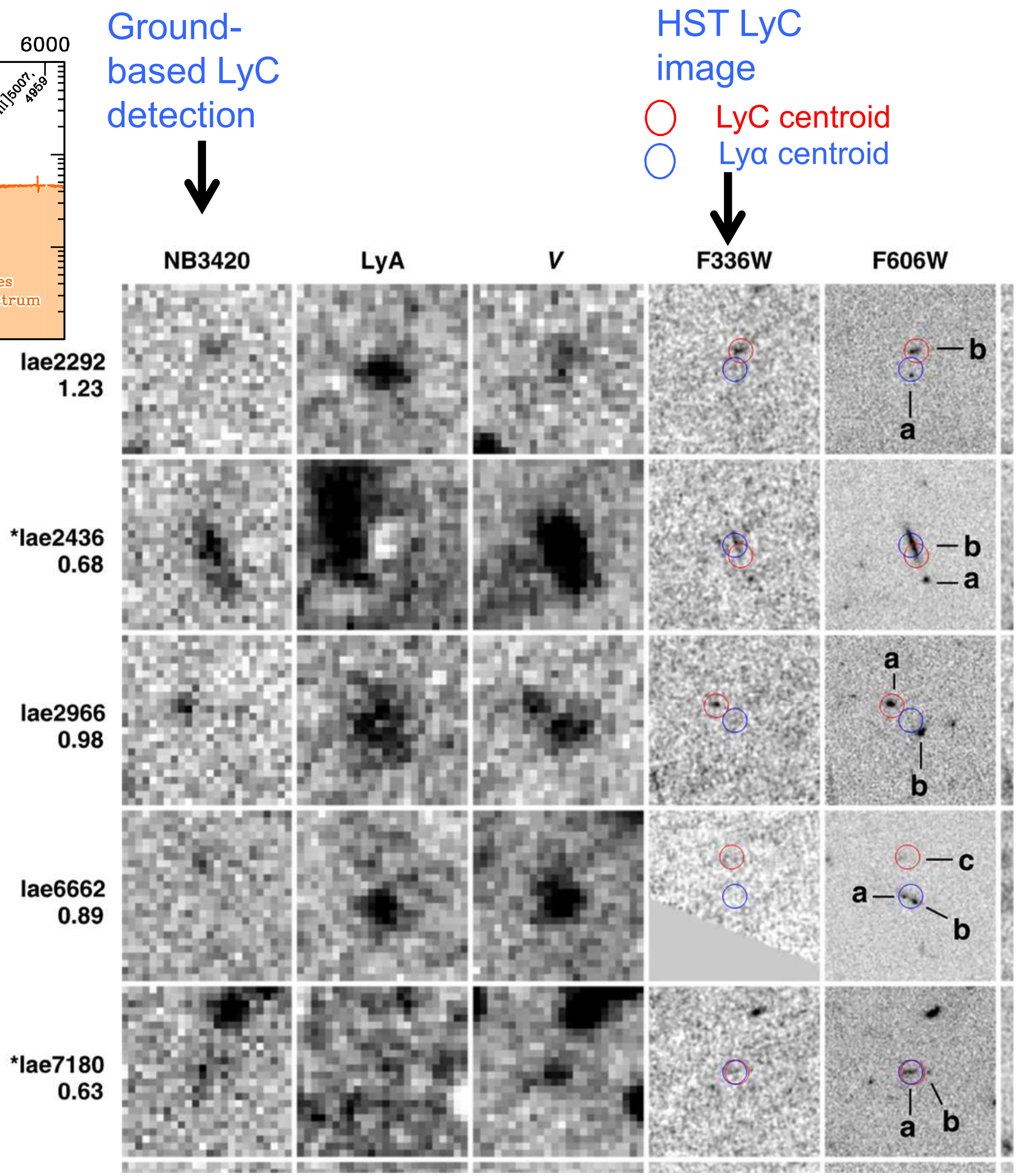
Quantified as a fraction f_{esc}

Require $f_{esc} > 10\%$ to maintain reionization

Numerical simulations suggest young galaxies are compact and porous due to intense star formation which produces strong radiation pressure

Challenges of Measuring f_{esc} at z~2-3





At z~2 direct imaging below Lyman limit is practical, but for promising candidates selected from ground-based images, subsequent Hubble imaging and spectroscopy reveals contamination from lower redshift galaxies.

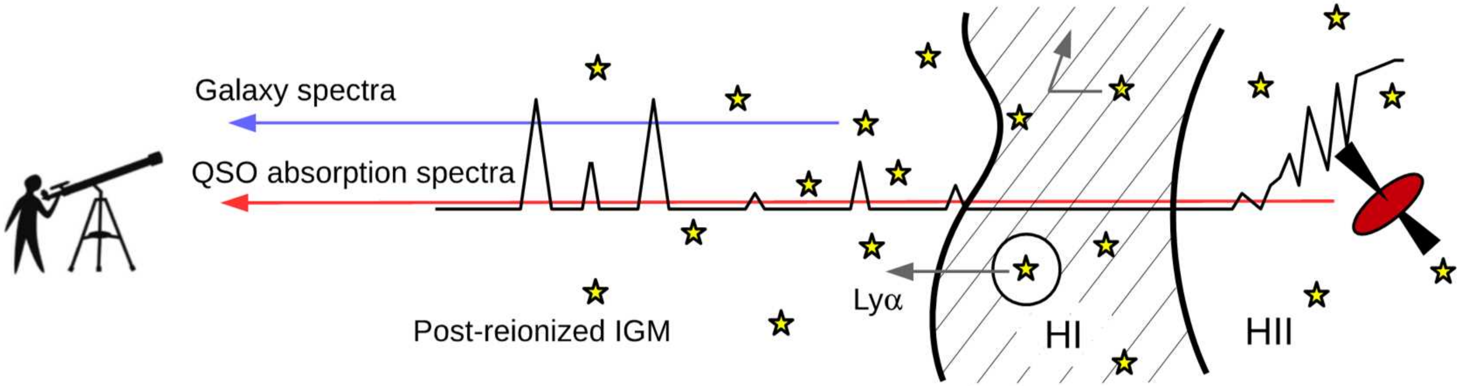
Implies f_{esc} < 2-5%

AT z > 6 DIRECT METHODS CAN'T BE APPLIED

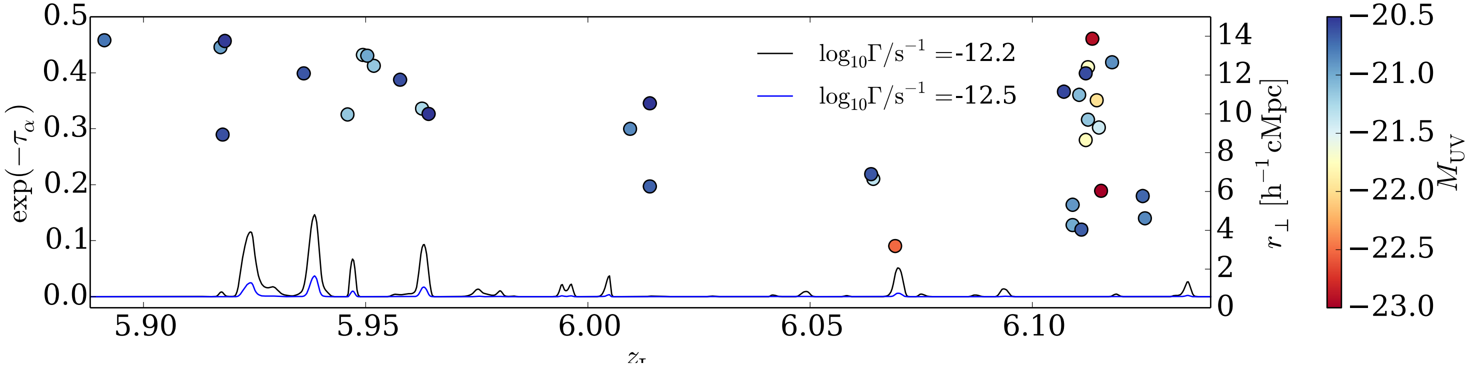
Mostardi +l (2015), see also Guaita +(2016)

A New Route to the Escape Fraction - I

Balance ionization state of the IGM deduced from fluctuations in Lya absorption in z>6 QSO spectra with contribution from galaxies of known luminosity, redshift and line-of-sight distance in the same cosmic volume



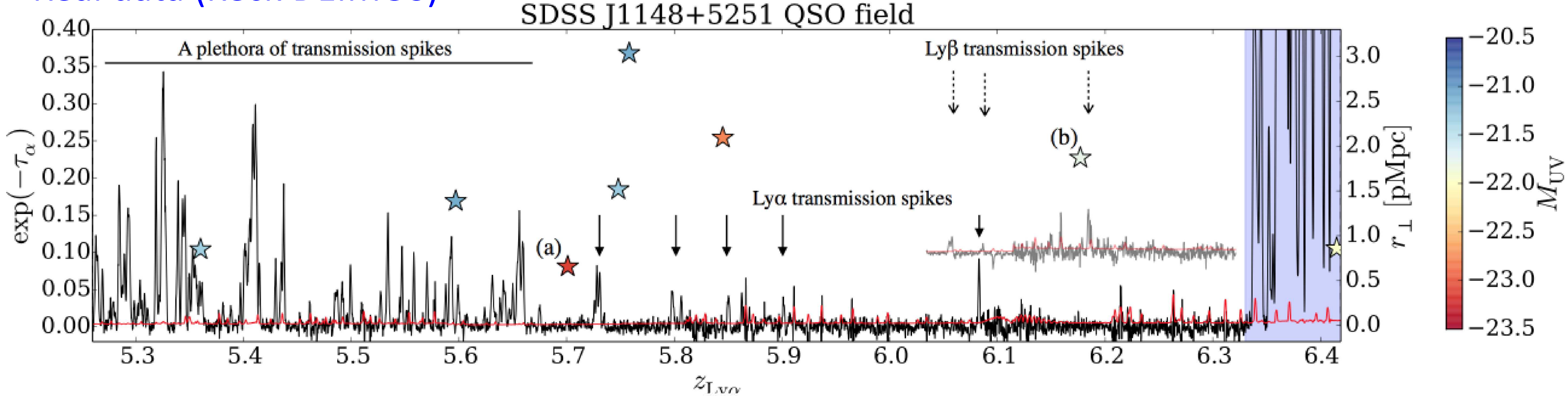
Simulation



Kakiichi + 2017 (in prep)

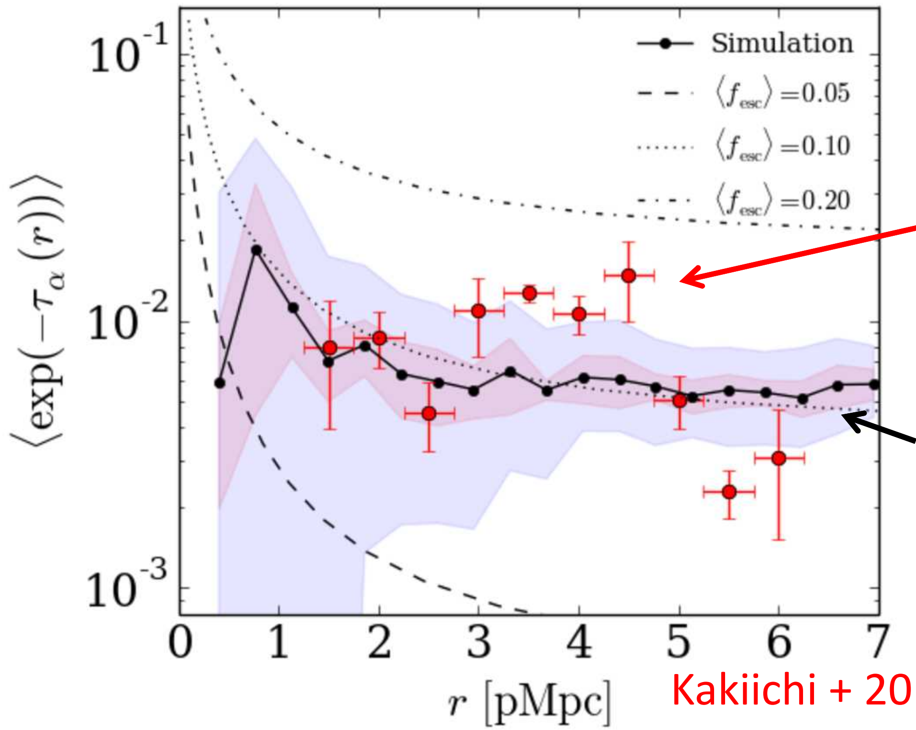
A New Route to the Escape Fraction - II

Real data (Keck DEIMOS)



First results indicate a positive correlation between fluctuations in Lyα absorption and star-forming galaxies on 2-5 Mpc scales

According to analytic and hydrodynamical simulations, the effective escape fraction is ~10% (significantly larger than at lower redshift)



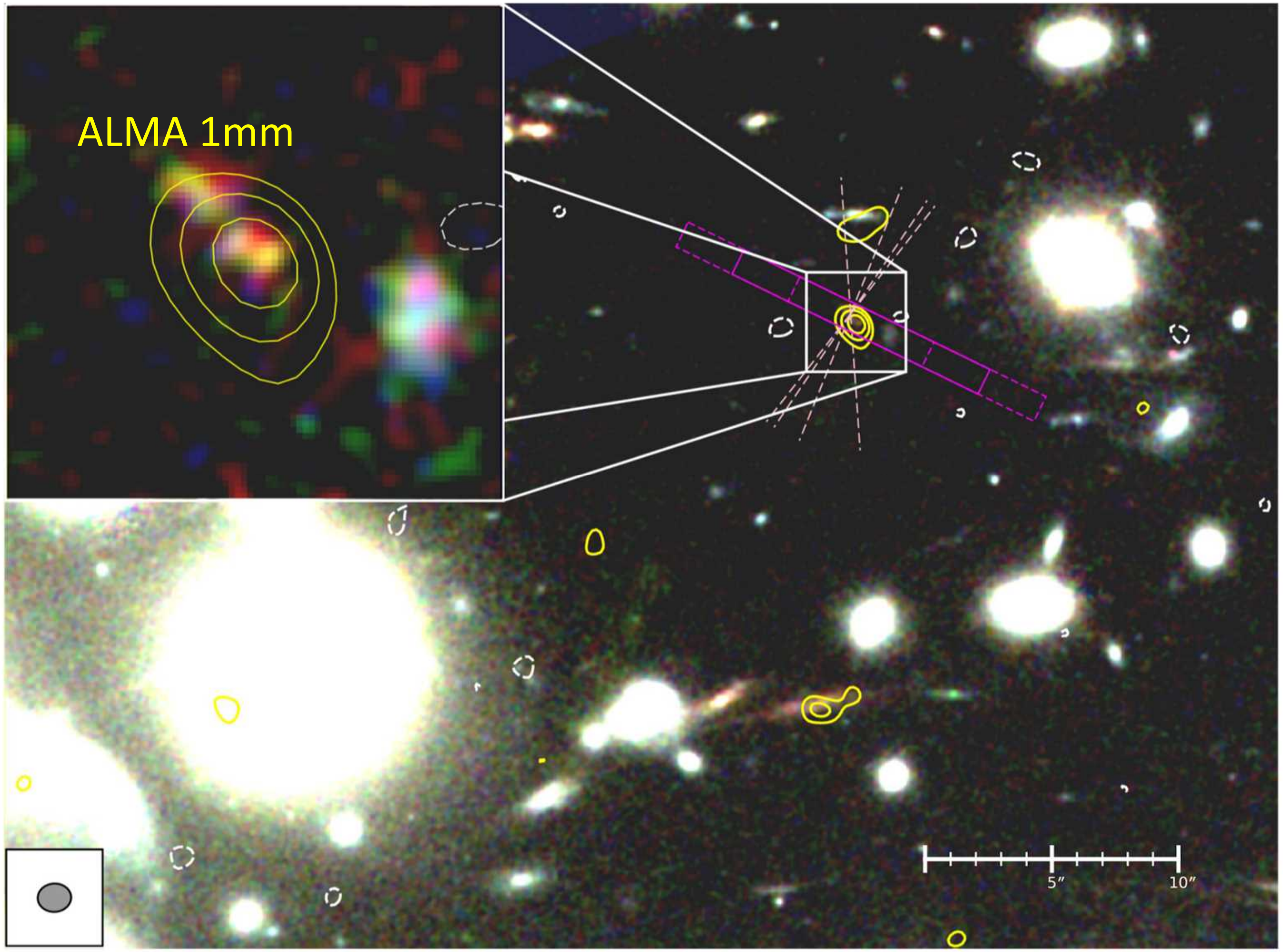
Kakiichi + 2017 (in prep)


New Kid on the Block
Atacama Large Millimetre Array (2015 -)
ALMA interferometer in Chile with up to 15 km baselines has Hubble resolution for tracing early dust
ALMA/C. Padilla

ALMA's Unique Role – Tracing Early Dust

ALMA Band 6 continuum for z=7.5 galaxy (log M_{dust} ~8)

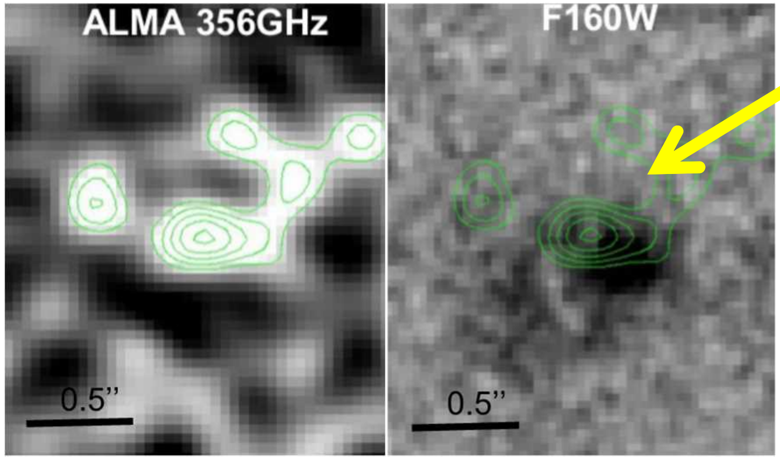
Dust grains are produced in supernovae explosions and so the amount of dust provides a valuable `clock' to estimate when chemical enrichment began

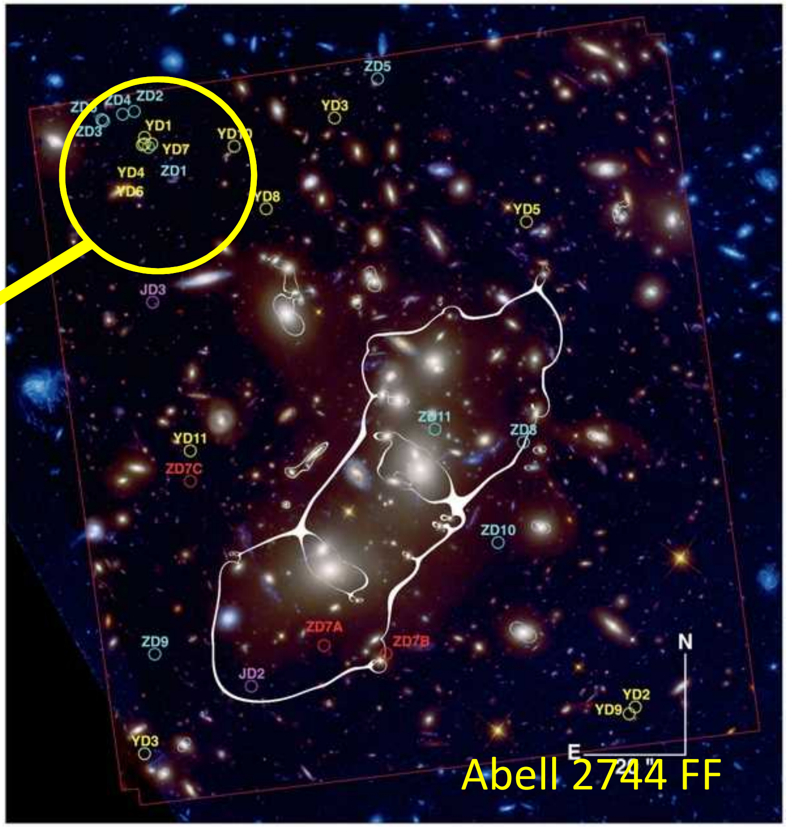


Watson et al (2015)

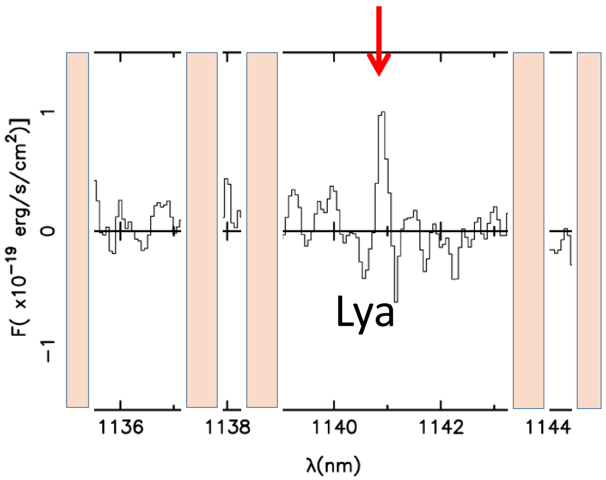
Emergence of Dust at z=8.38

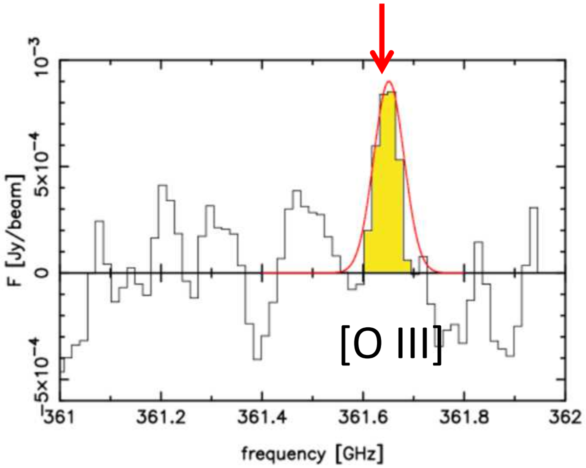
ALMA Band 7 ~1mm dust at z=8.38





Redshift with X-shooter (Lyα) and ALMA ([O III])





Stellar mass 2 × 10^9 M$_\odot$
SFR ~ 20 M$_\odot$ yr-1
Dust mass ~6 × 10^6 M$_\odot$

Consistent with SN production since z~12

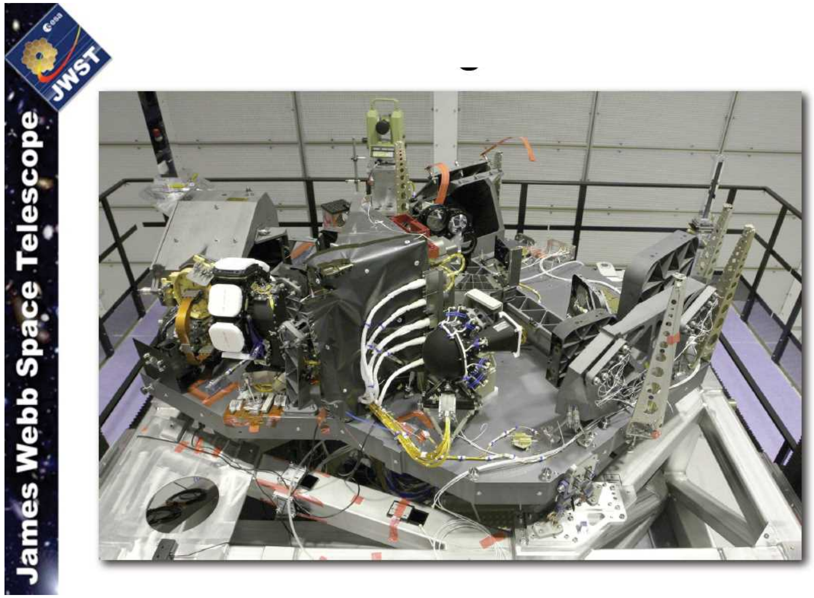
Laporte + (7017)

The Future

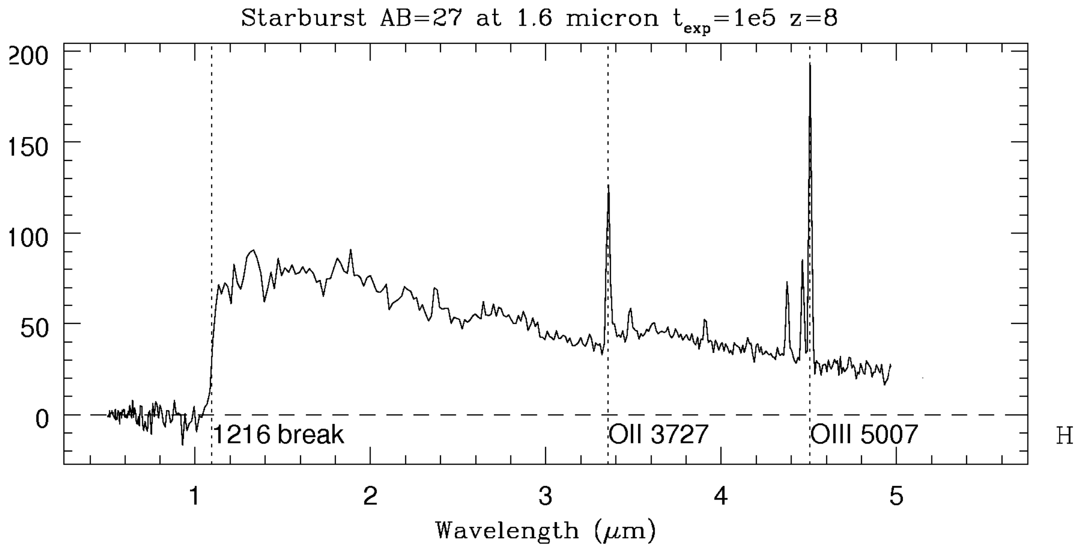

TMT
THIRTY METER TELESCOPE
SPDO / Swinburne Astronomy Productions

Spectroscopy with James Webb (2019 -)

NIRSpec Instrument



z=8 galaxy; 25 hour exposure



JWST spectroscopy will detect the stellar continuum and measure composition of gas and the nature of ionizing radiation in redshift 8-12 galaxies using rest UV and optical lines ([O II], [O III], Hα) beyond reach of ground-based telescopes

Ground-Space Synergy 2020s: ELT AO Imaging

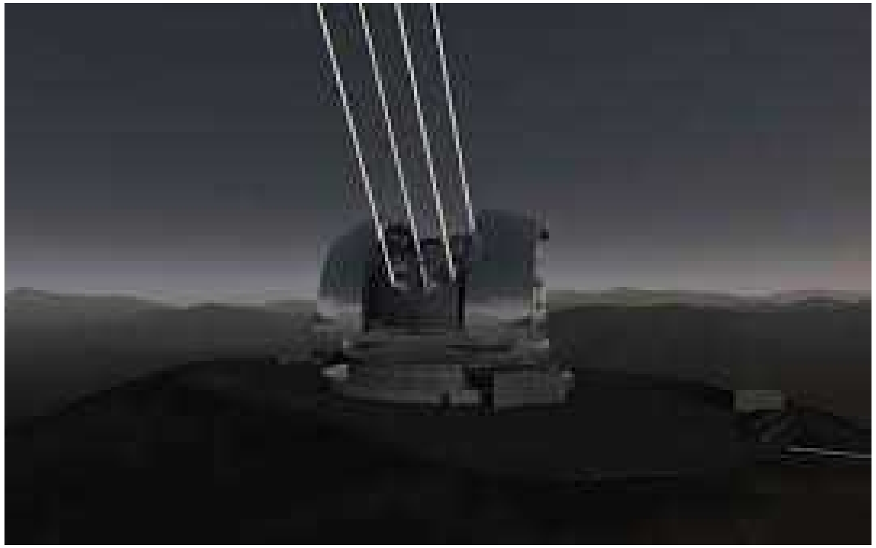
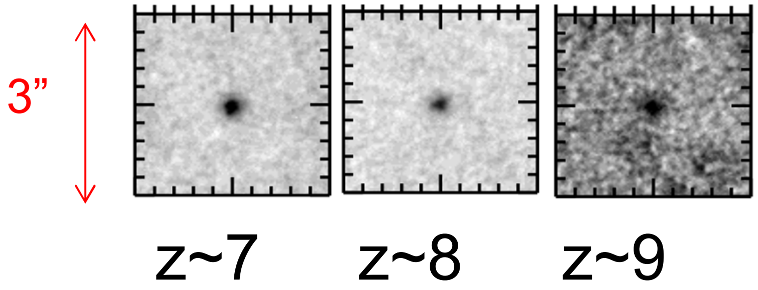
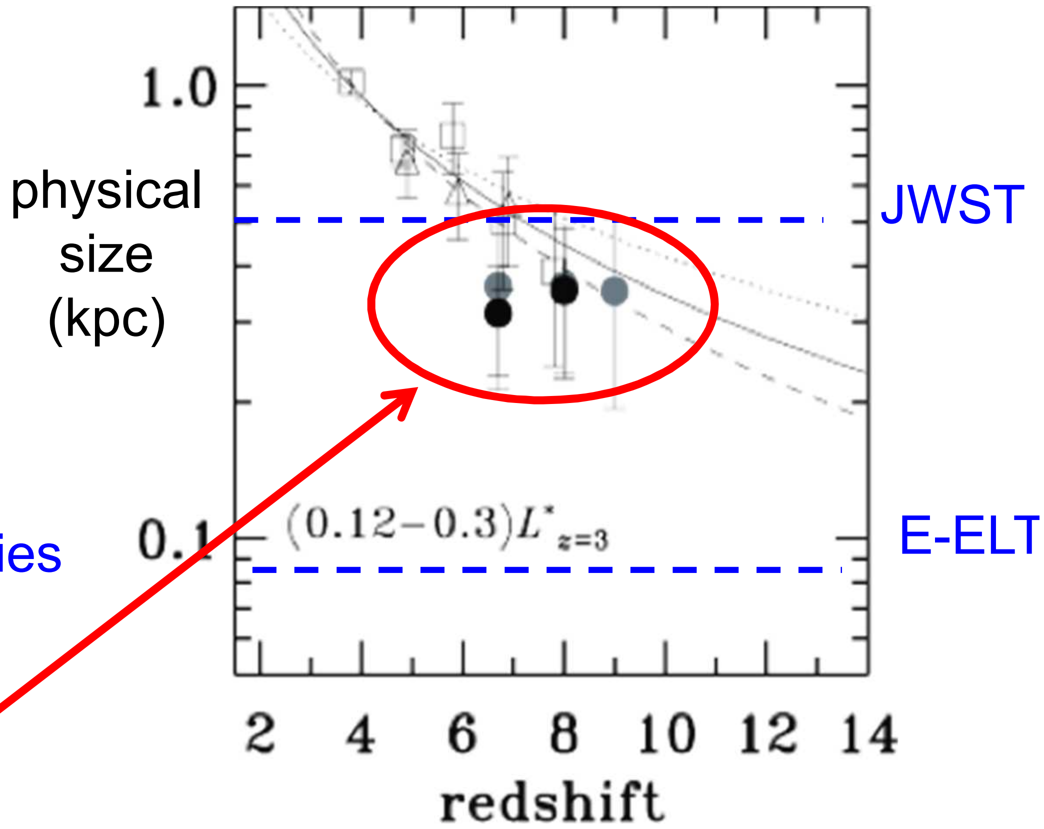


Image stacks for faint Hubble galaxies





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

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

Conclusions

- Planck is main evidence for `late reionization' since measures of Lyman alpha in absorption/emission are either insensitive or too complex to interpret quantitatively

- Soon will see new constraints on late reionization from Subaru HSC distribution of LAEs and 21cm pathfinders (e.g. LOFAR)

- Two outstanding issues regarding the role of galaxies;
  - Production rate of ionizing photons per unit SFR; tests our understanding of massive stars and role of AGN
  - Escape fraction of ionizing photons; direct measures not possible in reionization era even with JWST

- Dust at high redshift! Crucial to secure more ALMA continuum measures

- Evidence is all pointing to first light at redshifts z~12-15; within sight of upcoming facilities

EXCITING TIMES AHEAD!