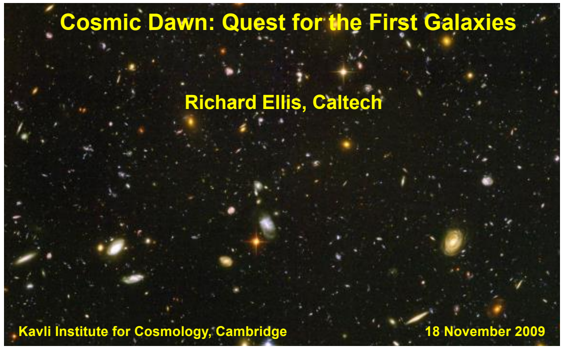
The Quest for Cosmic Dawn

Richard Ellis (UCL)

KICC@10

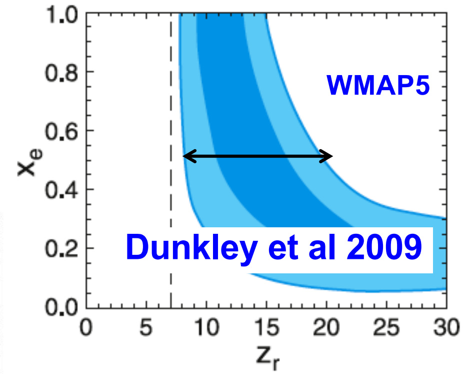
September 18th 2019



Back to 2009…

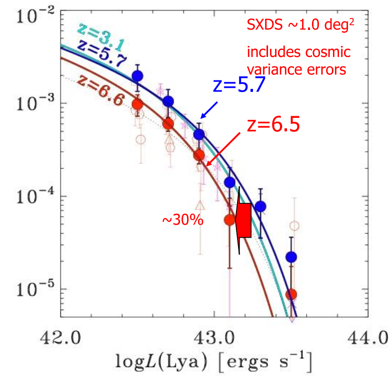
1. **Early reionisation (WMAP)**

Optical depth to scattering:
τ = 0.17 ± 0.08 (WMAP1, 2003)
τ = 0.09 ± 0.03 (WMAP3, 2007)
τ = 0.087 ± 0.017 (WMAP5, 2009)



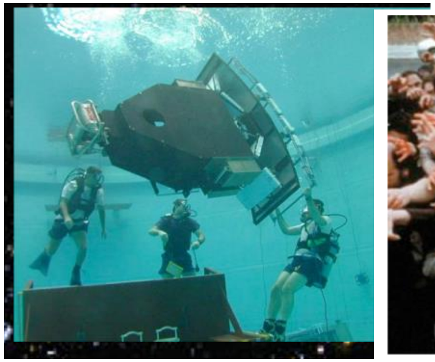
2. **Lyα LF 5.7<z<6.5**

- **Tantalizing fading (0.^{m}3) 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 (2009)

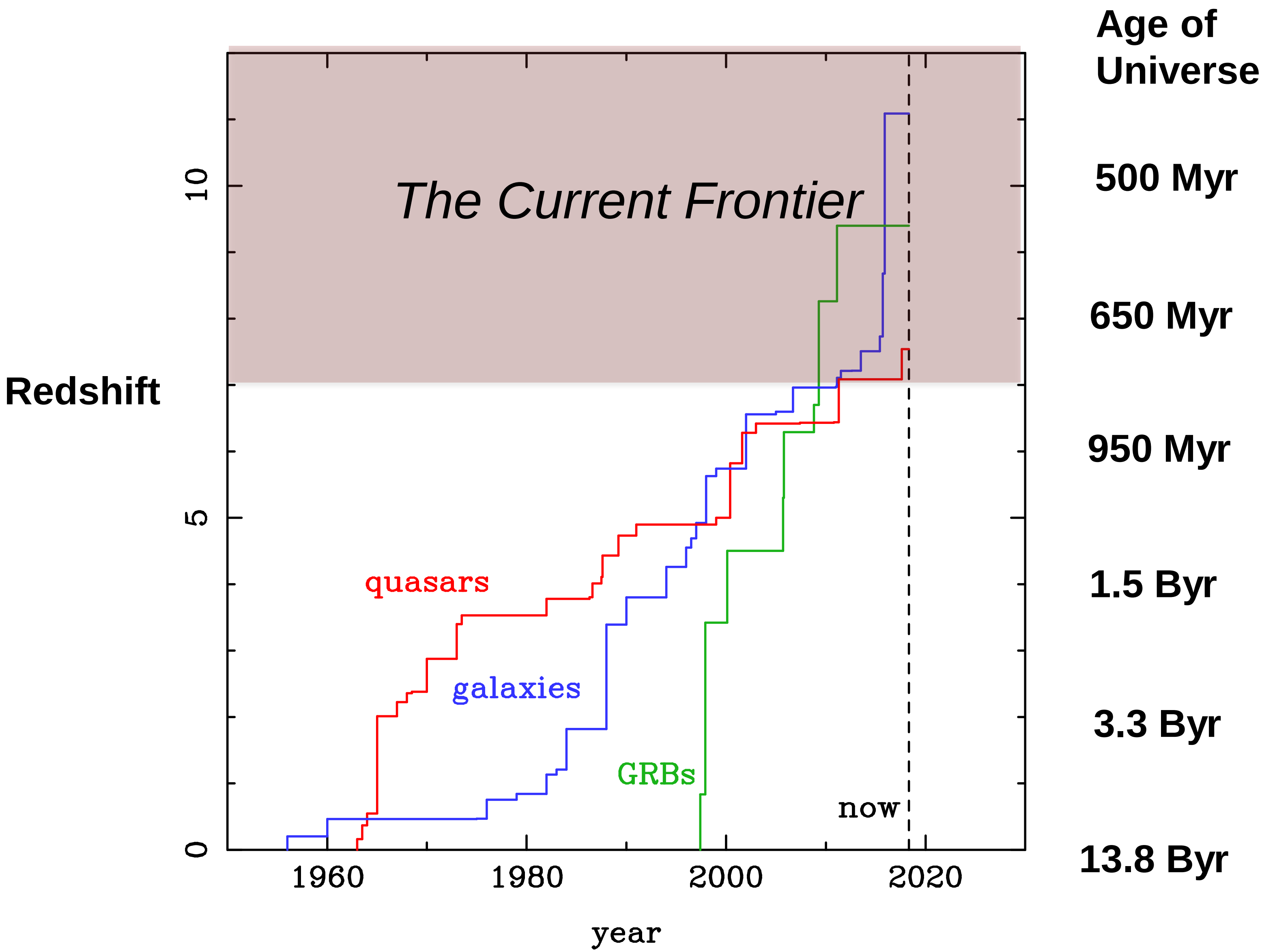
3. **WFC3 revolution began**



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

4. **Great anticipation of JWST (launch 2014) and TMT/ELT (2018)** ☹

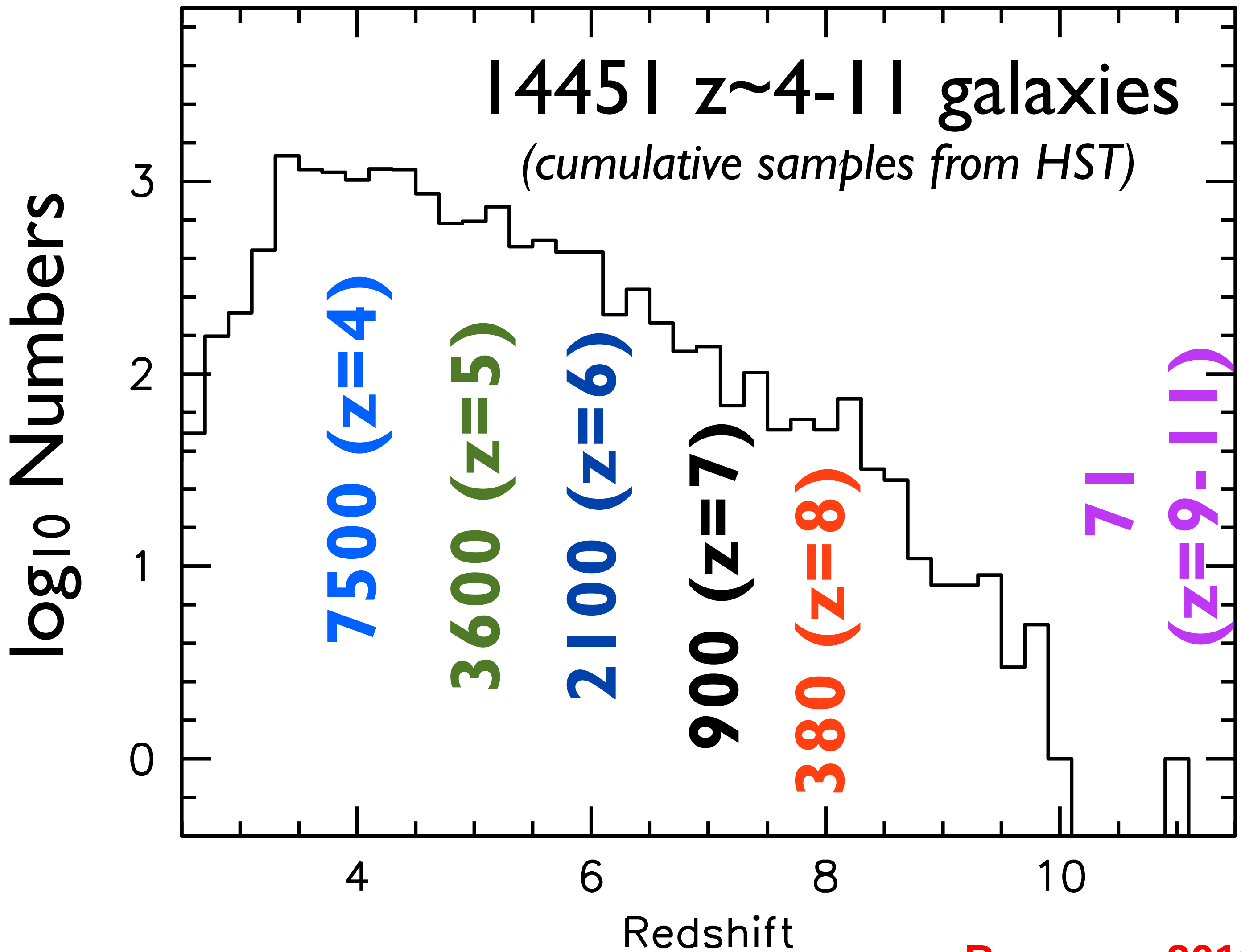
Receding Horizons: The Most Distant Object



Courtesy: Dan Mortlock

Current Census

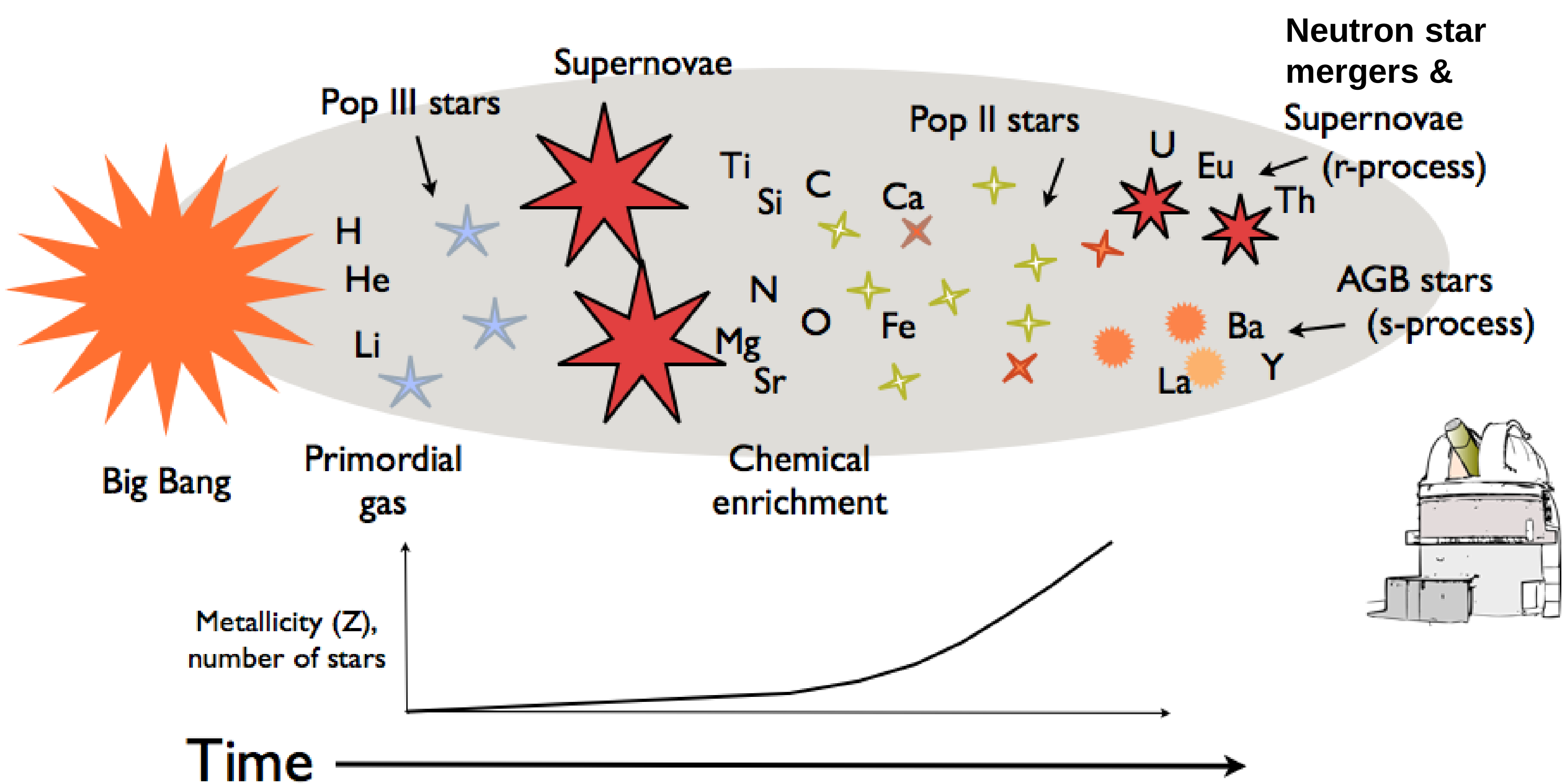
Since Hubble UDF, HST has undertaken wider field comparably deep campaigns (CANDELS) plus a series through lensing clusters (CLASH, Frontier Fields, RELICS)



Bouwens 2019

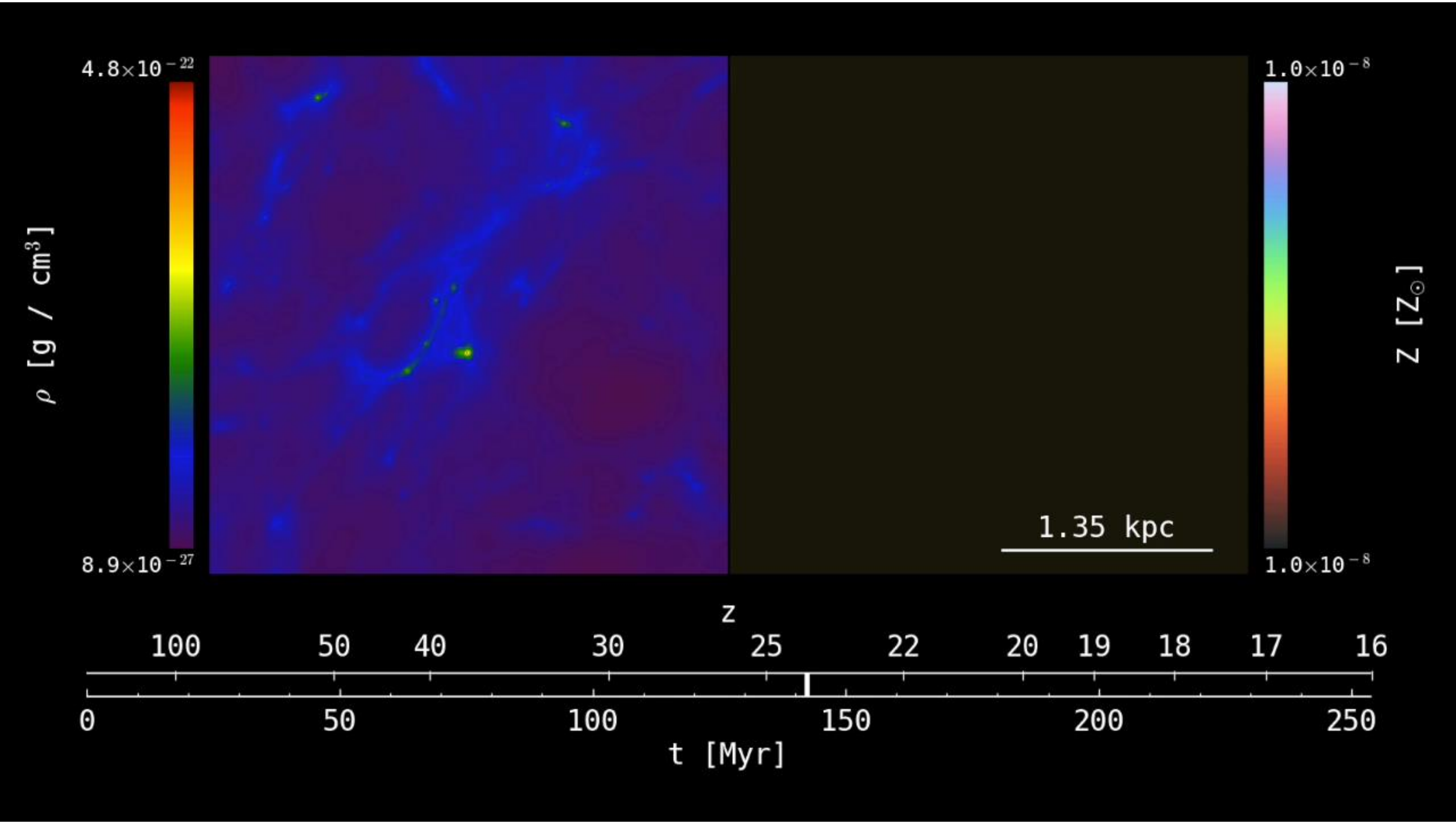
Impressive but only 28 galaxies z>7 and 6 galaxies z>8 are spectroscopically confirmed

The Holy Grail: Locating the First Galaxies?



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

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

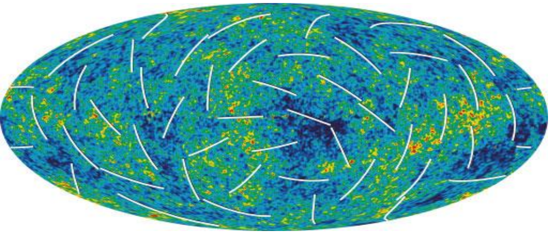


Identifying rare pristene (Pop III) galaxies will be very hard

More practical to tie cosmic dawn to onset of reionisation

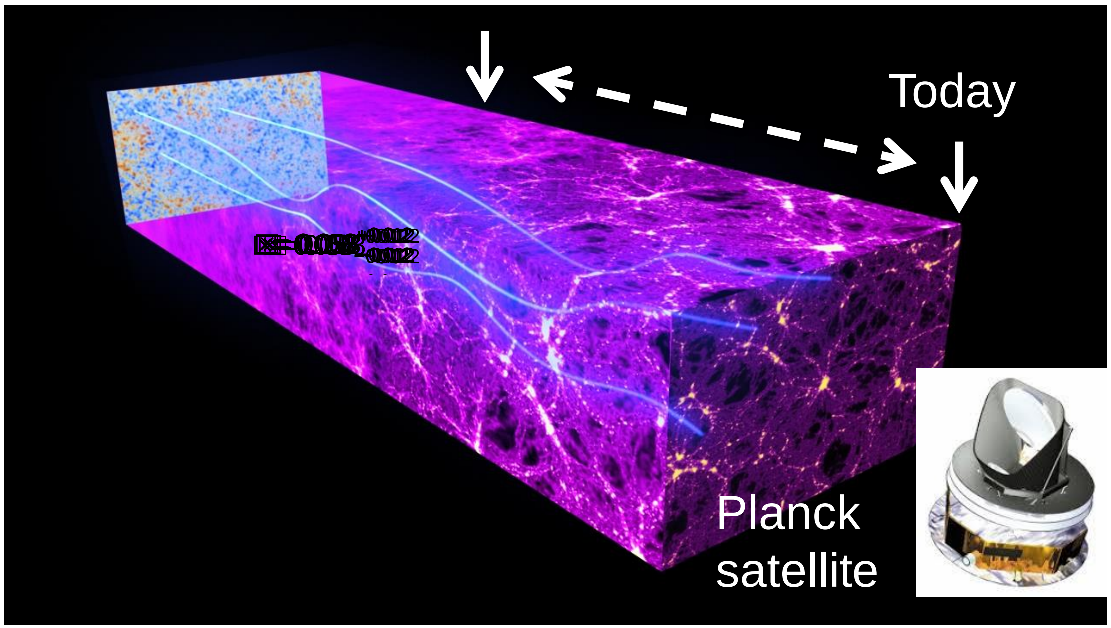
Smith et al (2015) (also Richardson et al 2013, Wise et al 2012, c.f. Cen & Riquelme 2008)

Planck Indicates Late and Fast Reionisation

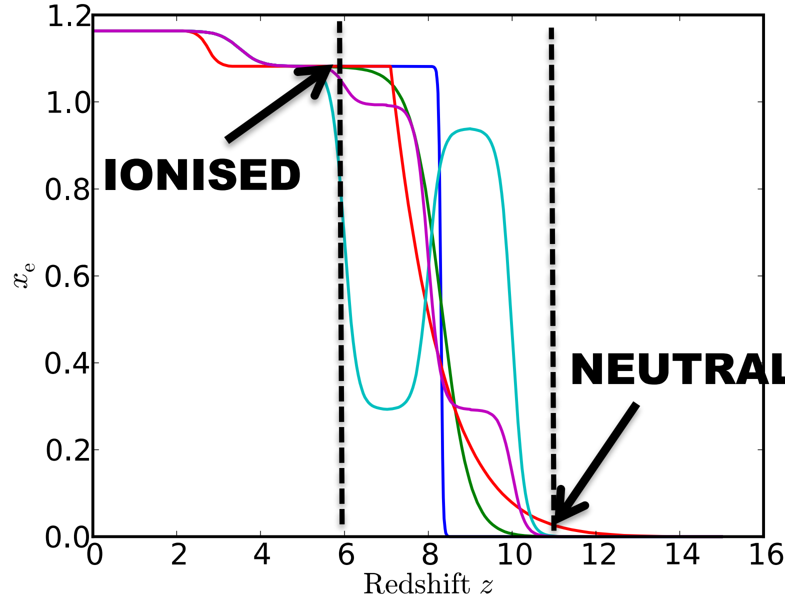


CMB polarisation probes foreground Thomson scattering from the start of reionisation to the present epoch. Optical depth of scattering τ constrains the mean redshift <z> and (model dependent) duration of reionisation

Reionisation begins



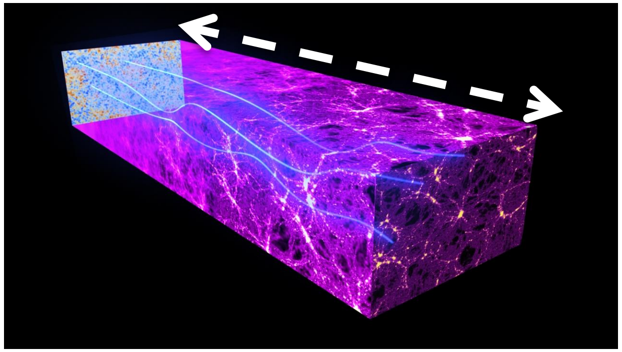
Parametric models consistent with Planck τ



Planck (2019) find τ = 0.0506 ± 0.009 corresponding to <z> ~8.0

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

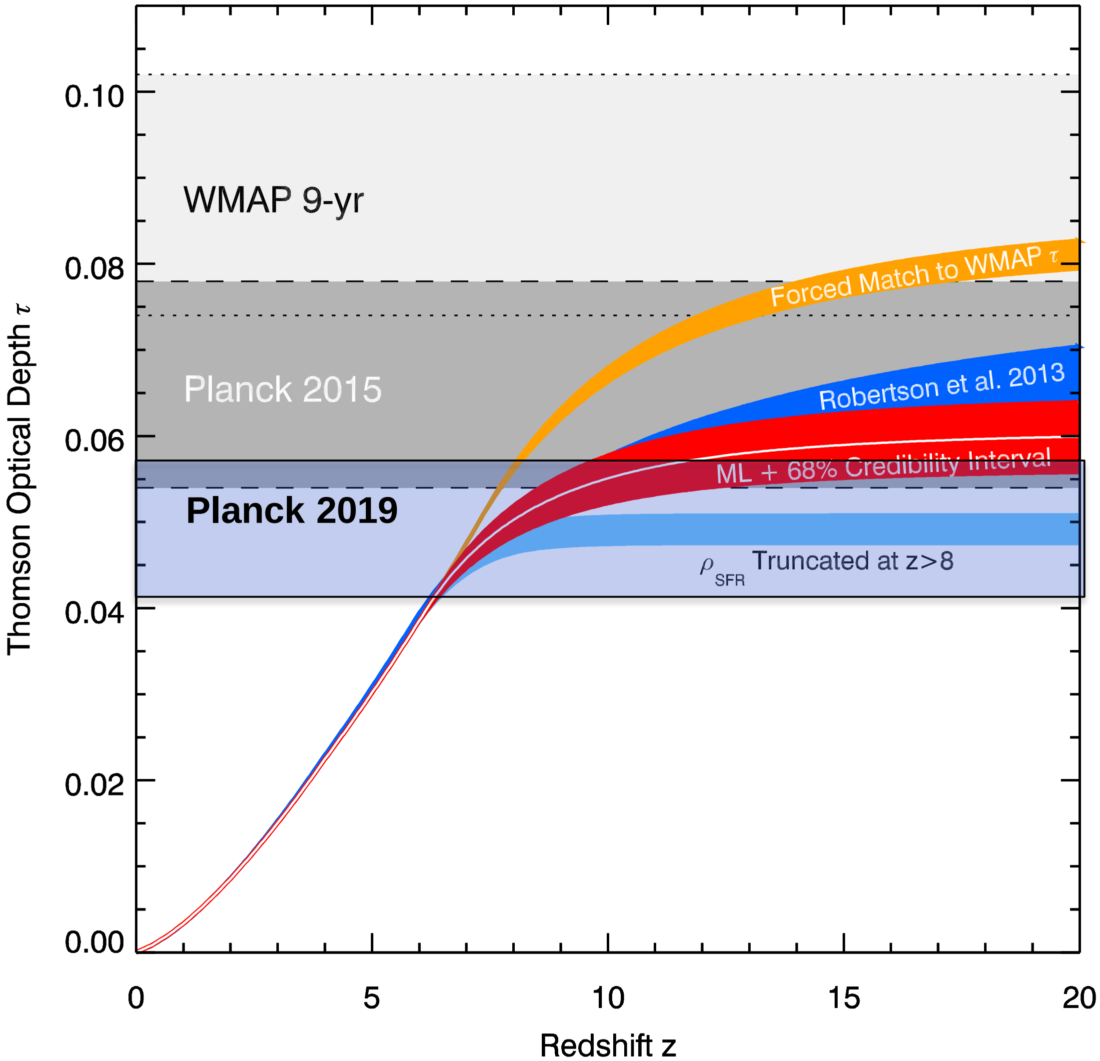
Reconciling Star-Forming Galaxies with Planck



Depending on their ionising output, galaxy demographics from HST matches Planck's optical depth with reionisation from 12 < z < 6

Suggests galaxies reionised universe **provided** their ionising capability is similar to that seen in z~3 Lyα emitters

We find **log ξ_{ion} ~ 25.5 cgs**
$\langle f_{esc} \rangle$ ~10%

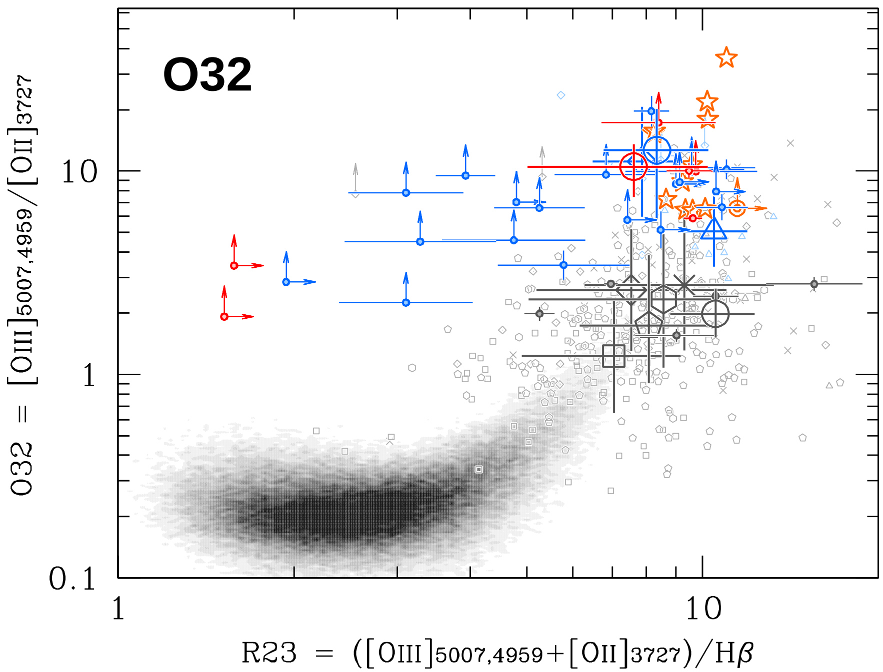


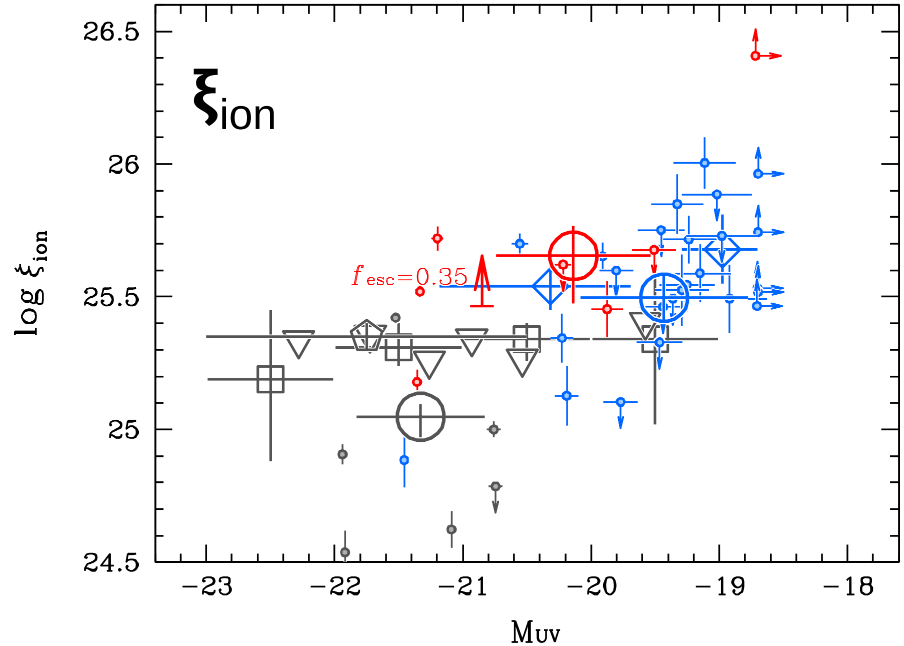
Robertson et al (2015), see also Bouwens et al (2015), Mitra et al (2015)

Ionising Spectrum of z~3 Lyα Emitters

ξ_{ion} = Intrinsic Lyman continuum flux per unit UV luminosity

O32 = [O III] 5007 / [O II] 3727



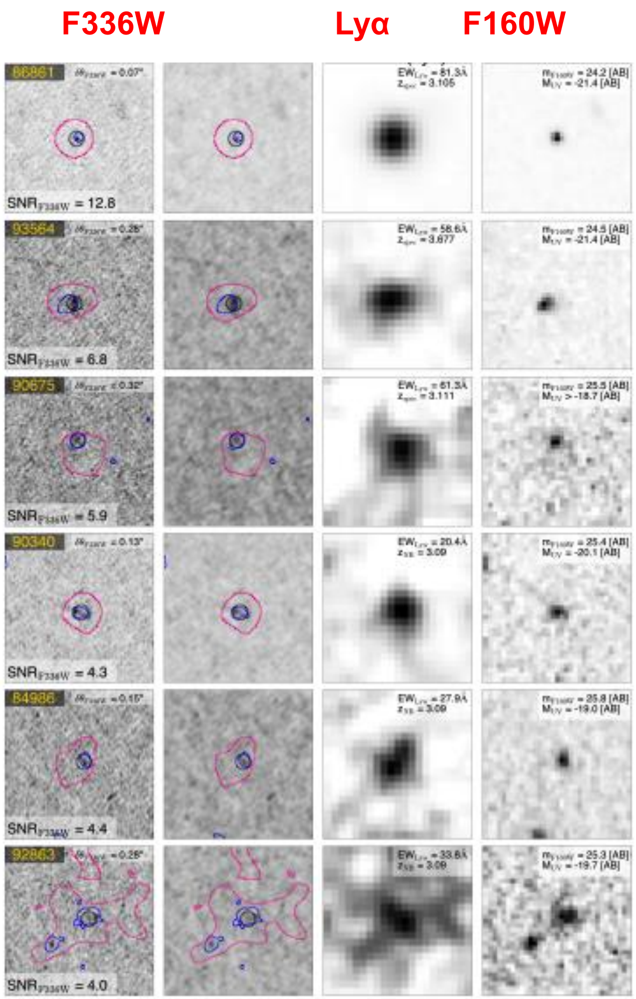


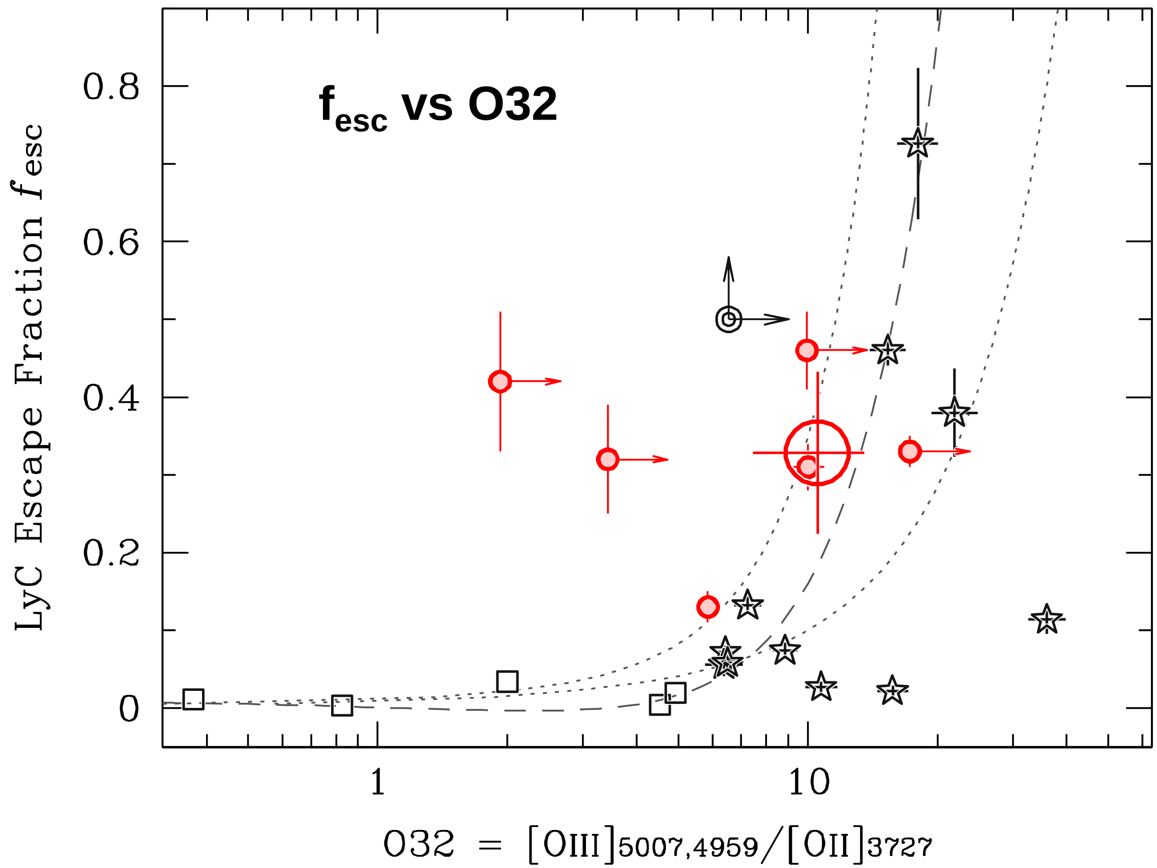
Lyman alpha emitters (leakers/non-leakers) are metal-poor, dust-free & promising analogues of z>7 galaxies with harder radiation fields than Lyman break galaxies (grey)

Nakajima, RSE et al (2018, 2019)

Escape Fraction of z~3 Lyα Emitters

HST LyC imaging of z~3 LAEs: 30% have f_{esc}~15-65% and correlation with O32
Stack of the rest reveals no signal ($f_{esc} < 0.3\%$)
No spectral difference between leakers/non-leakers; **dichotomy due to viewing angle**

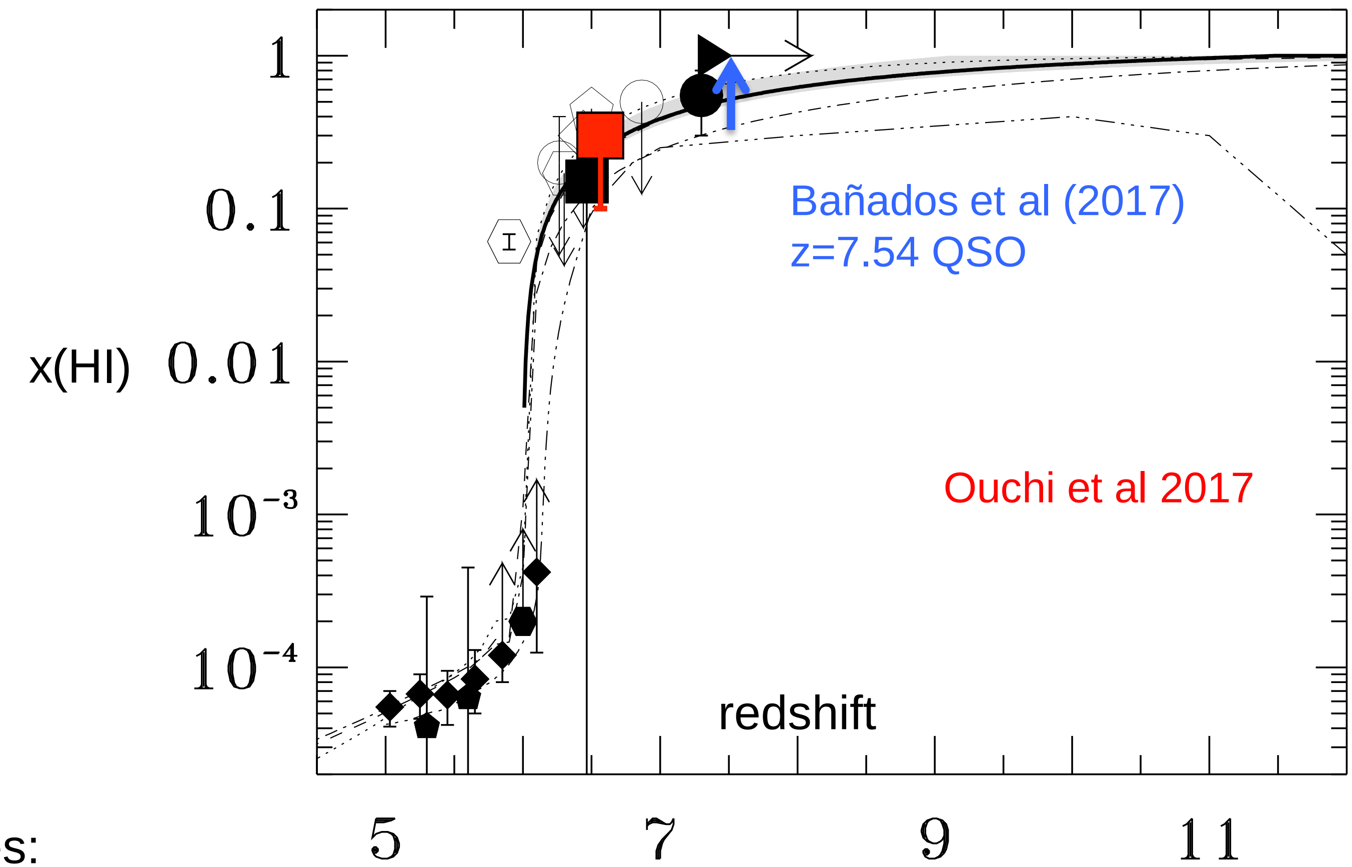




Fletcher, RSE et al (2018)
Nakajima, RSE et al (2019)

The End of Cosmic Reionisation

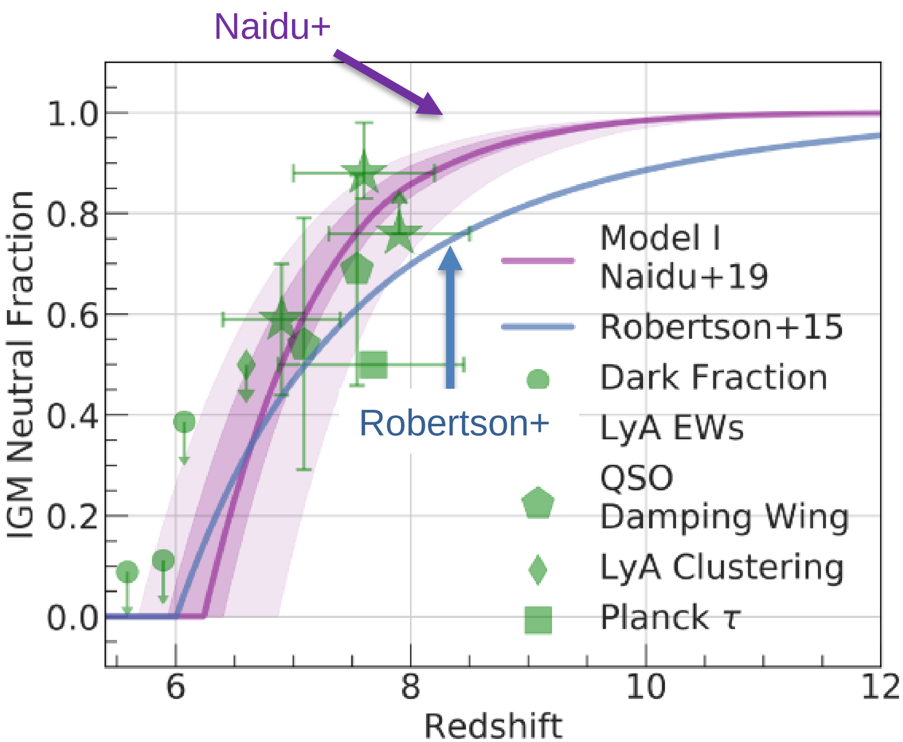
Consistent views from Planck, Gunn-Peterson test and Lyman α fractions?

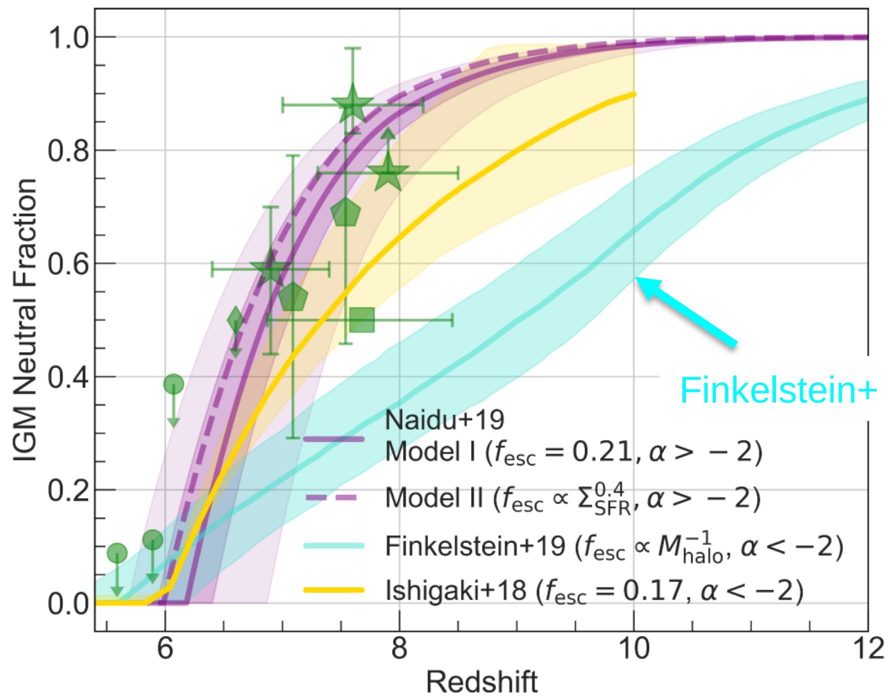


Challenges:
(1) Hard to convert x(Lyα) into x(HI)
(2) Scatter in GP τ_{eff} – origin unclear
(3) No good data beyond z~7

The probes confirm reionisation ended at z~6 but give little additional evidence
Even so, some papers interpret this trend in terms of sources of reionisation

Different Models of Reionisation History





Robertson et al (2015) – classic paper assumed all galaxies have equal ionising capabilities regardless of luminosity and redshift

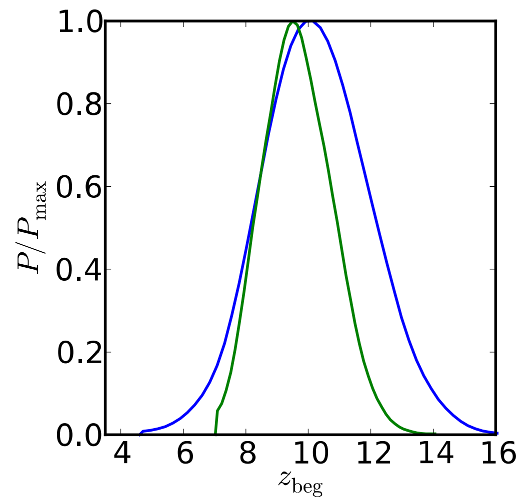
Finkelstein et al (2019) – redshift-dependent contribution; feeble galaxies contribute more early on, hence extended reionisation history

Naidu et al (2019) – contribution is dominated by massive galaxies which form later and hence provide better fit to fast/late evolution of neutral fraction

Cosmic Dawn: The Beginning of Reionisation

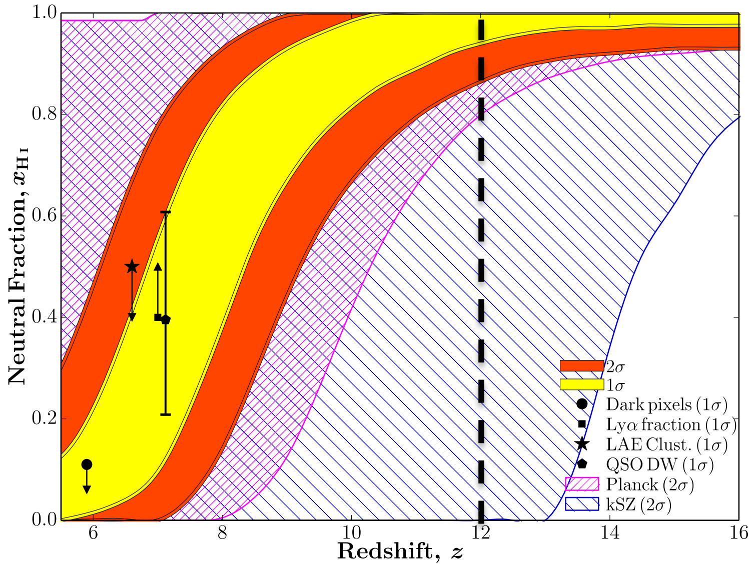
Planck Consortium 2016: Surprisingly bold statement!

The distributions of the two parameters, $z_{\rm end}$ and $z_{\rm beg}$, are plotted in Fig. 12. With the redshift-asymmetric parameterization, we obtain $z_{\rm beg} = 10.4^{+1.9}_{-1.6}$ (imposing the prior on $z_{\rm end}$), which disfavours any major contribution to the ionized fraction from sources that could form as early as $z \gtrsim 15$.



Later modeling within ΛCDM framework suggests otherwise…

$x_{HI}(z)$

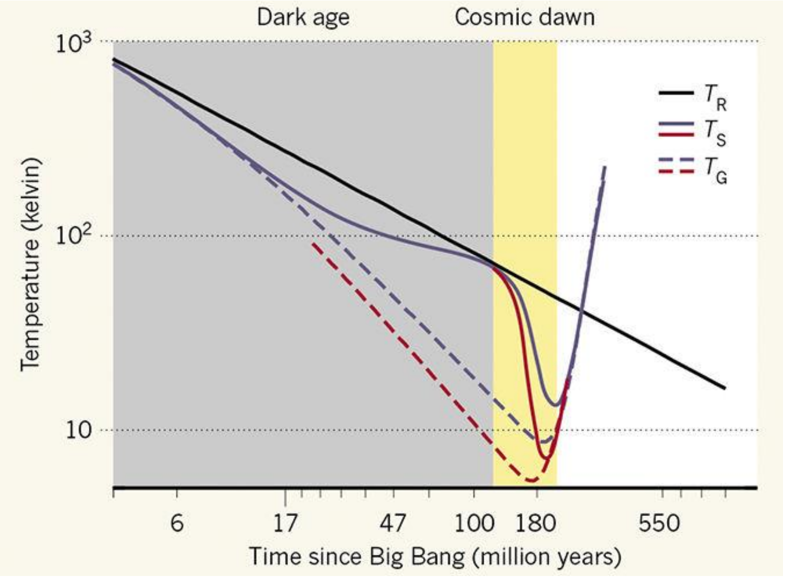


Greig & Mesinger (2016)

Cosmic Dawn @ z~15-20?

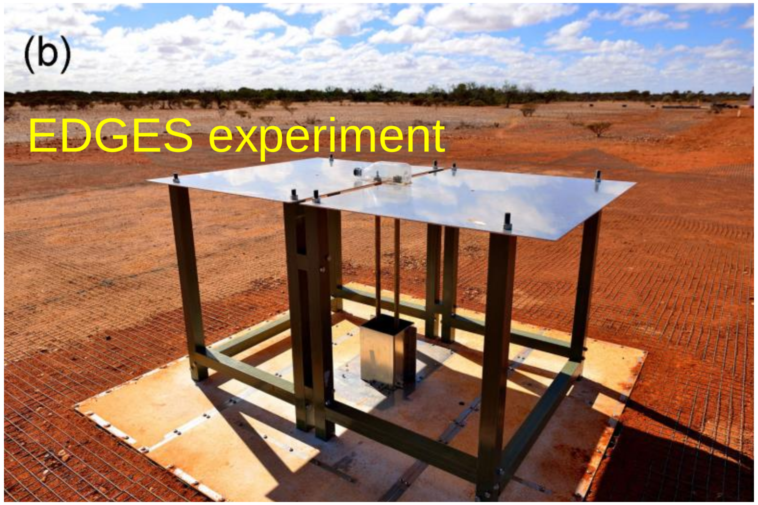
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

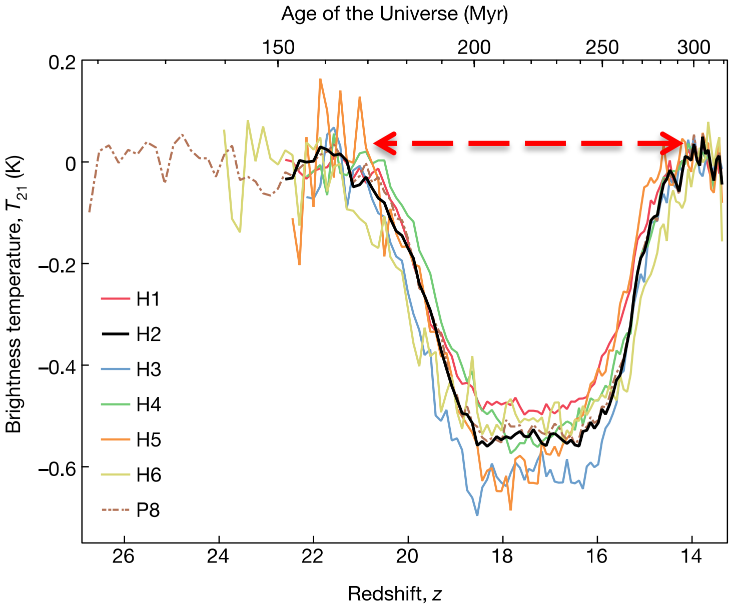
Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]



Wouthuysen-Field coupling of 21cm spin temperature and Lyman alpha radiation from first sources produces 21cm absorption of CMB

EDGES experiment (Bowman et al 2018) claims surprisingly deep 21cm absorption over 15<z<20

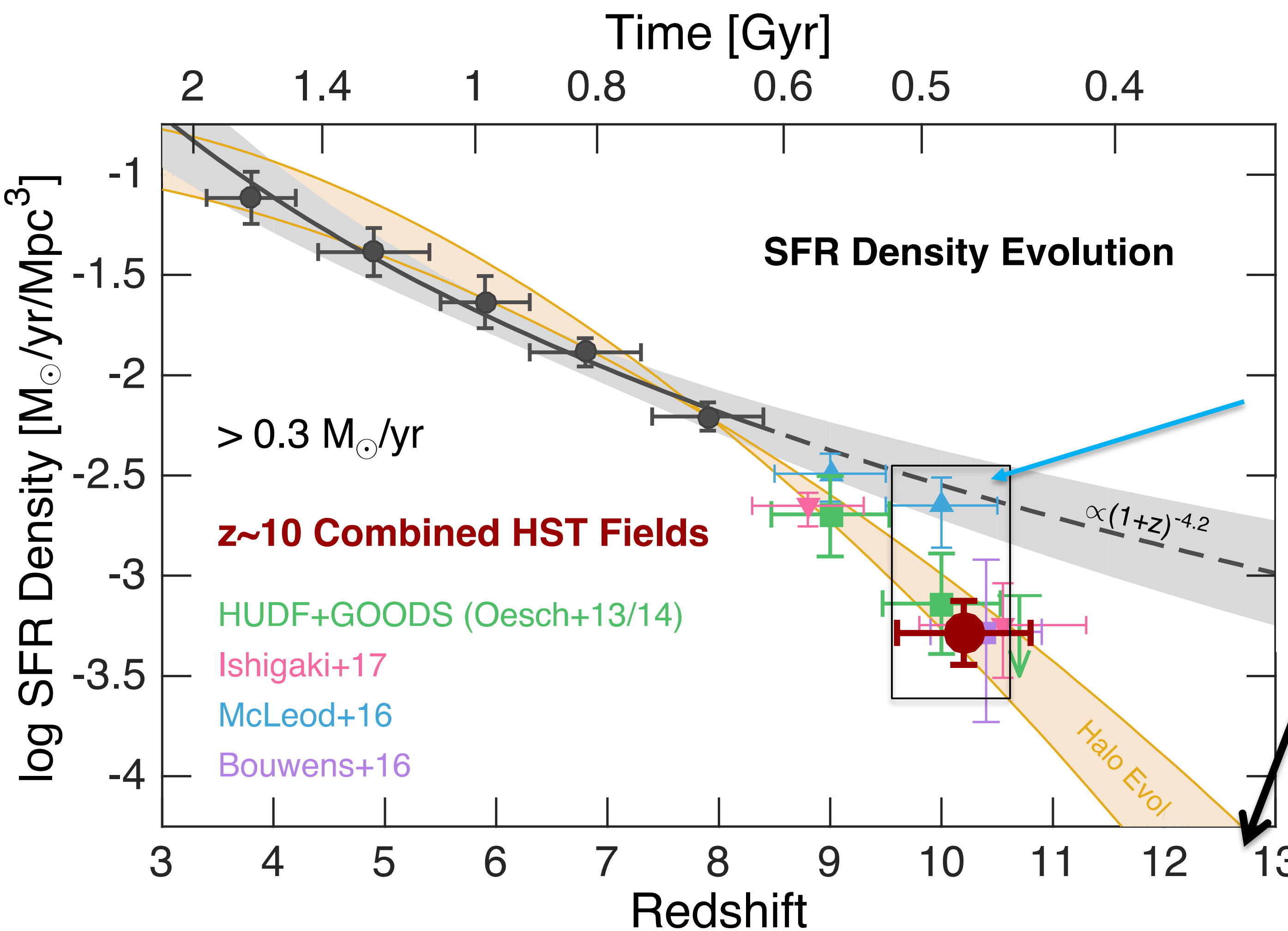




Declining Luminosity Density to z > 10

Data from deep fields (UDF, CANDELS) and lensing clusters (CLASH, Frontier Fields)

- reasonable agreement but seriously sample-limited at z>9
- contentious issue – is there a sharper decline at z>8?



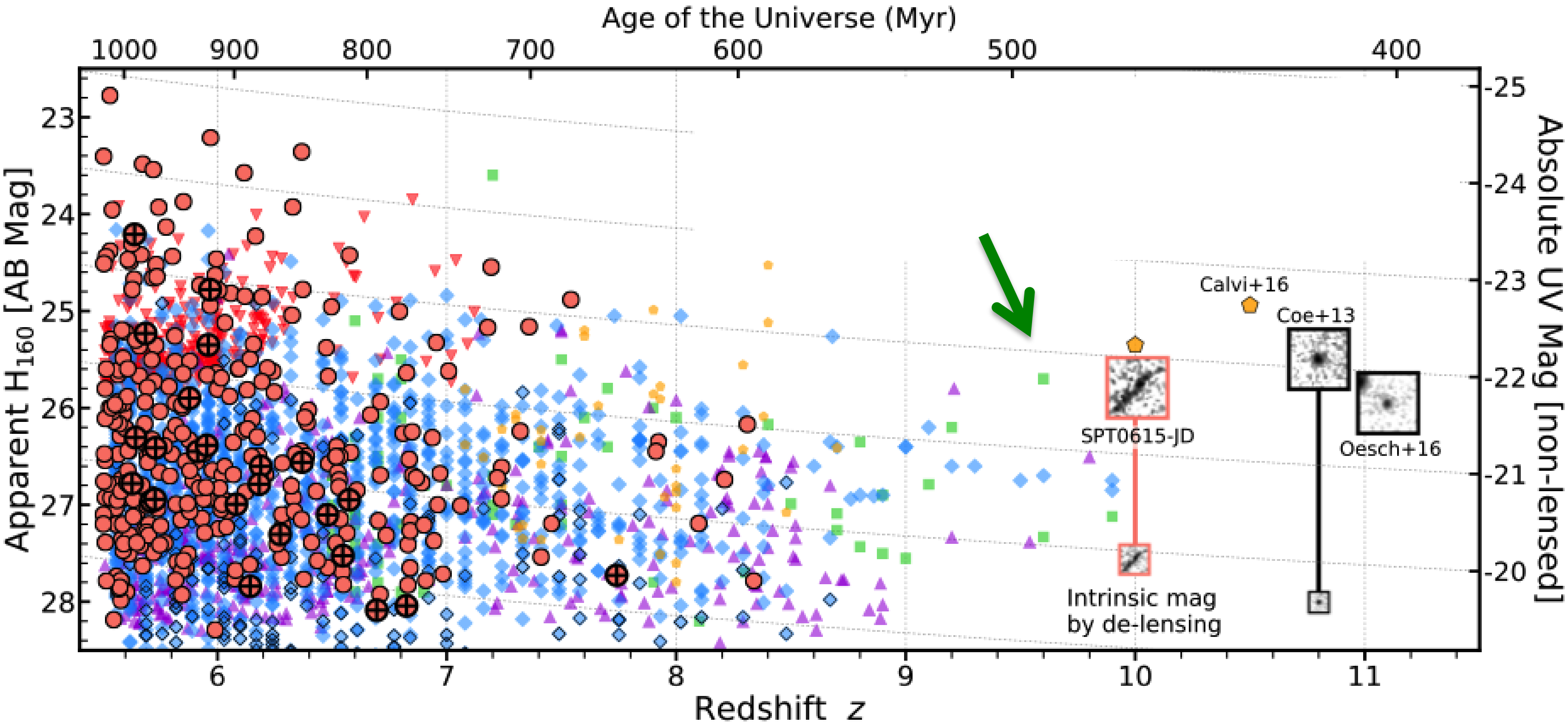
McLeod et al (2016)

Cosmic Dawn?

Oesch et al (2017)

Probing Cosmic Dawn Indirectly?

Current facilities cannot observe sources beyond z~11

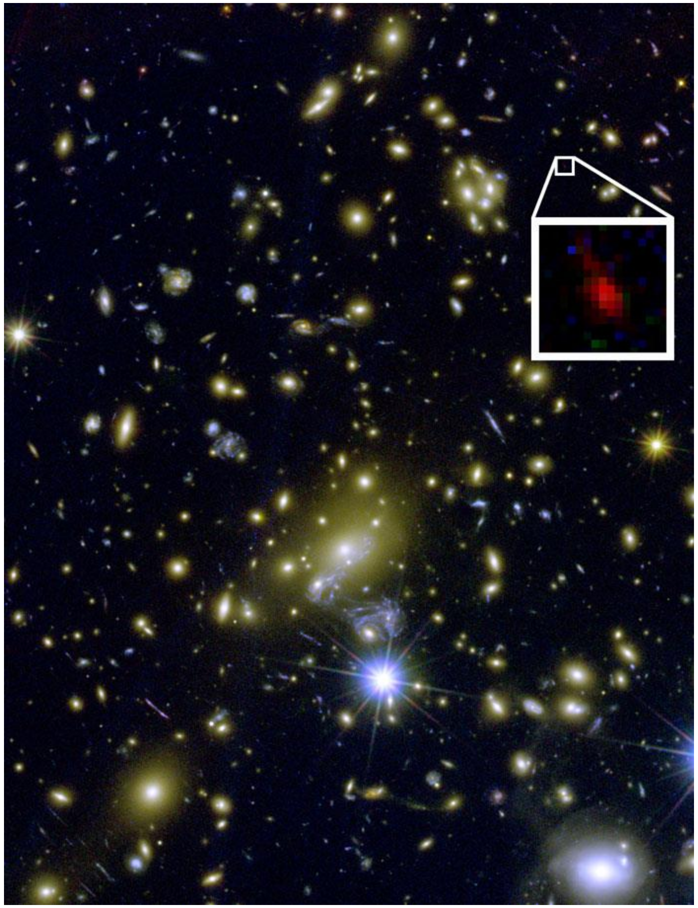


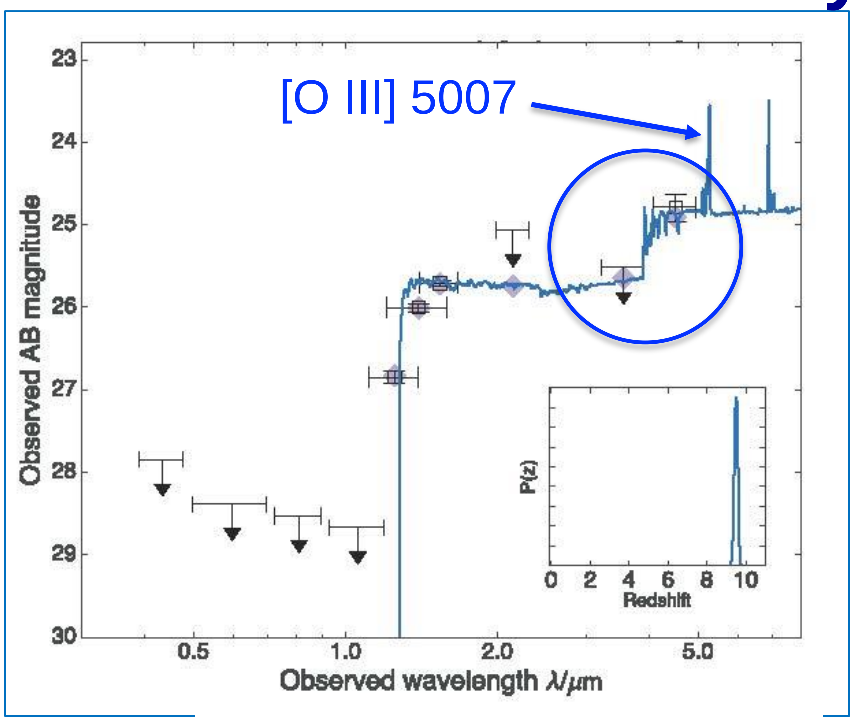
Salmon et al 2018

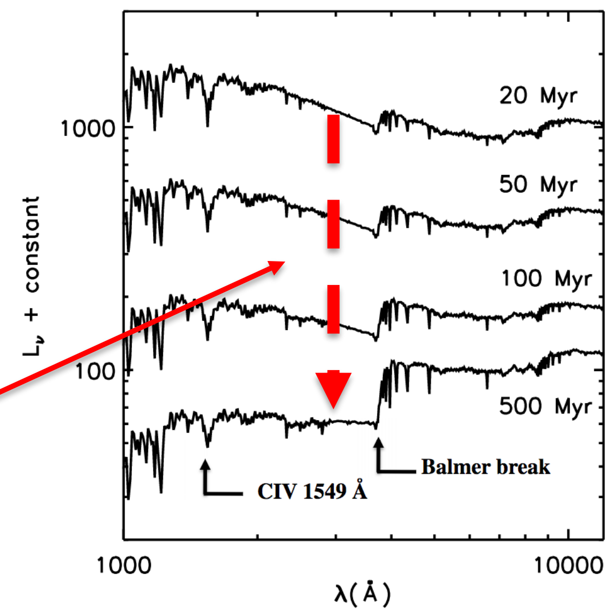
Over 1000 z > 7 HST candidates, but only ~28 spectroscopically confirmed

Can we estimate their ages and earlier star formation histories?

MACS1149_JD1: A Lensed z~9 Frontier Field Galaxy







Earlier workers noted the IRAC 4.5μm excess which, given photometric redshift uncertainties, could arise from nebular [O III] 5007 emission or a Balmer break due to starlight – an age indicator!

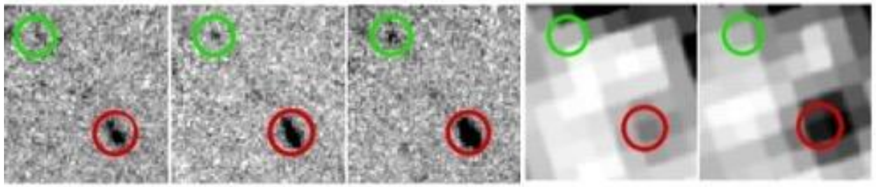
Zheng et al (2012, 2017), Hoag et al (2018)

[O III] Contamination versus Balmer break

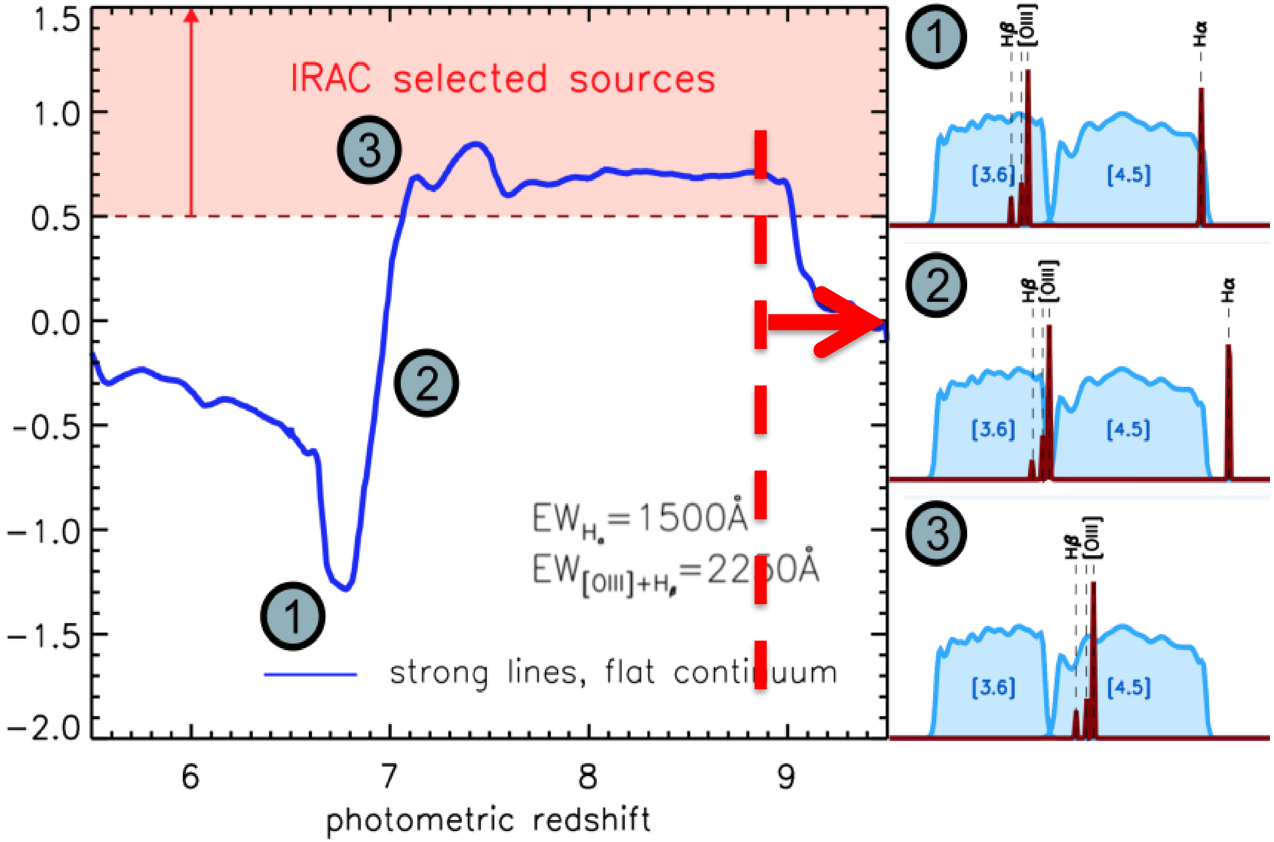
The interpretation of the so-called IRAC excess in MACS1149_JD1 depends critically on its redshift!

UV: young stars

optical: old stars



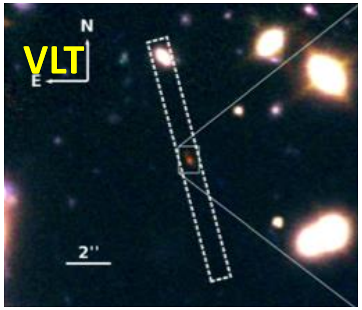
[3.6]-[4.5]μm IRAC colour

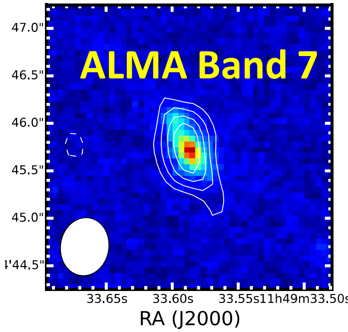


Beyond a redshift z=9.0, [O III] moves out of the IRAC 4.5μm band

Courtesy: Guido Roberts-Borsani

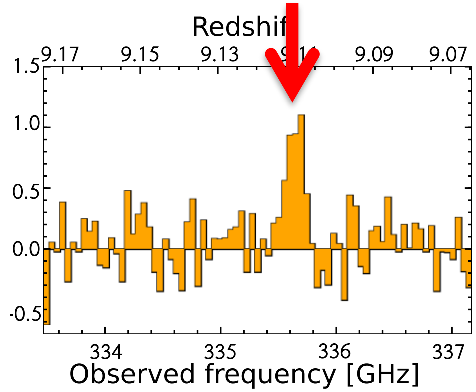
MACS1149_JD1: z=9.1096 is >200 Myr old



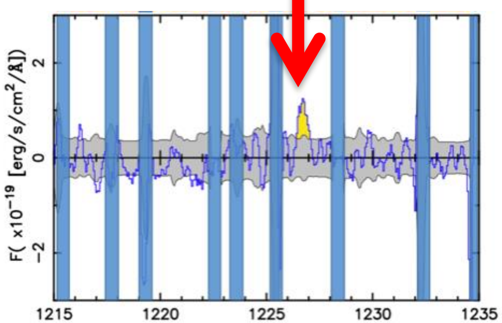


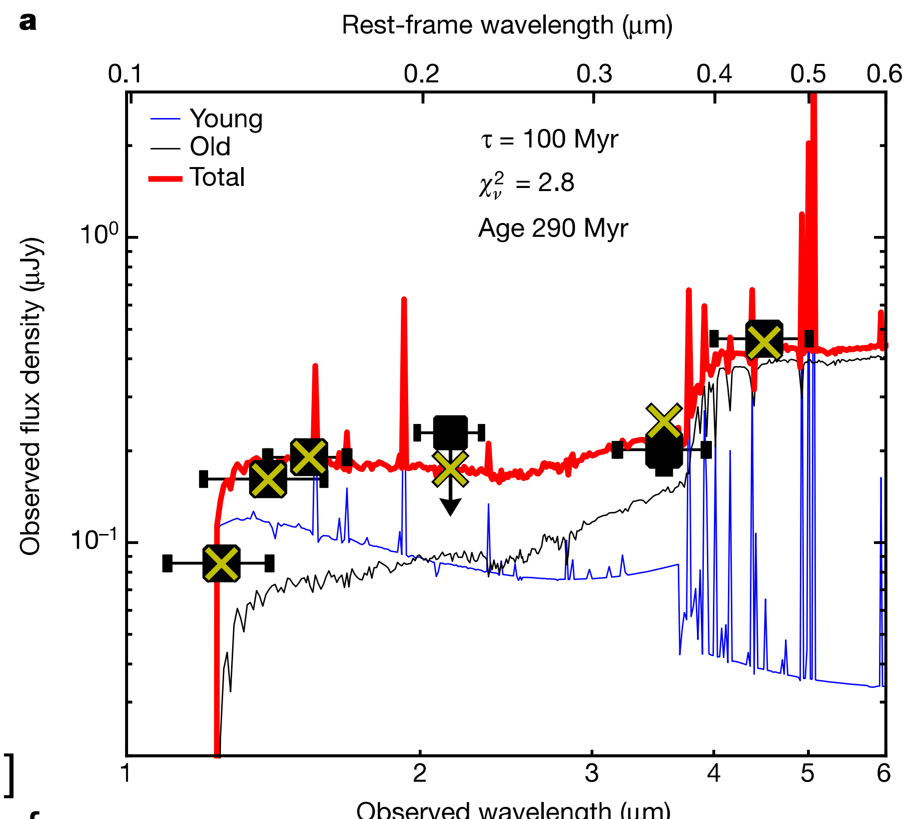
Spectroscopic confirmation from ALMA/VLT demonstrates IRAC excess is **due to starlight** not nebular emission. Balmer break provides a valuable **age indicator**

ALMA [O III] 88μm (7.5σ)



VLT Lyα (4.0σ)



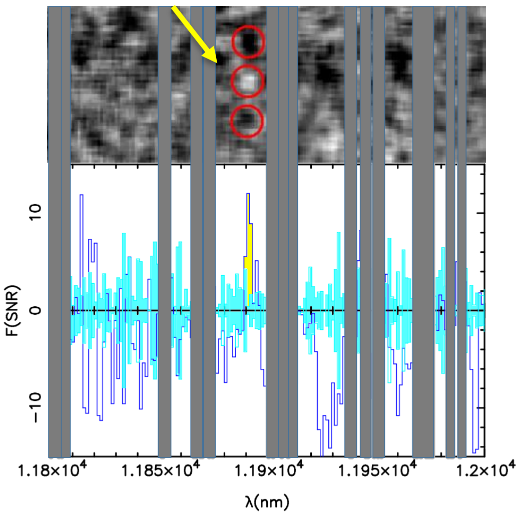


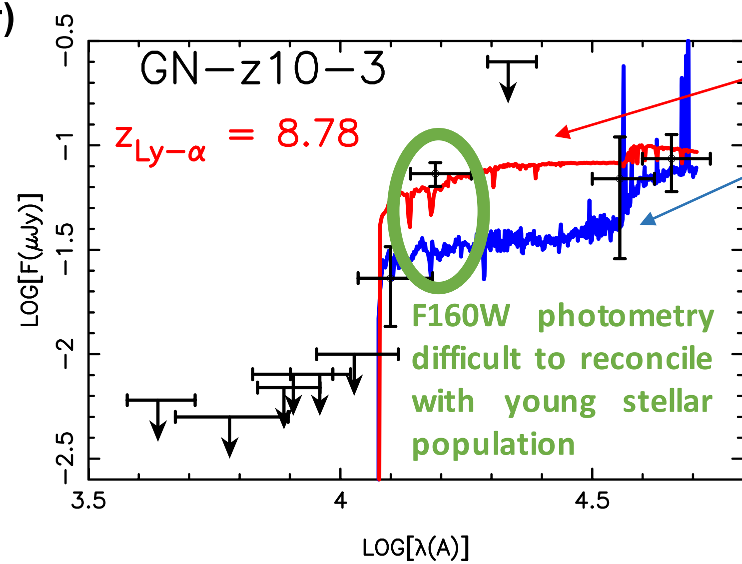
To reproduce Balmer break, UV SED/[O III] 88 μm & dust continuum upper limit, most of rest-frame optical light is due to ~10^9 $M_\odot$ of stars 290 Myr old **→ z_F~15 ± 2**

Hashimoto, Laporte, RSE et al (2018)

Spectra of More Balmer Break Candidates….

Keck 6hrs: Lyα @ z=8.78 (6σ)



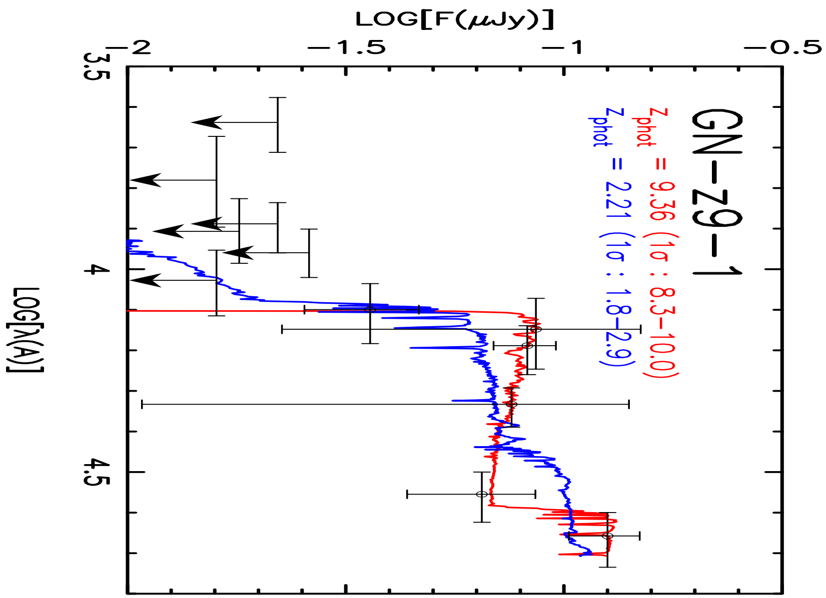


Old stellar population

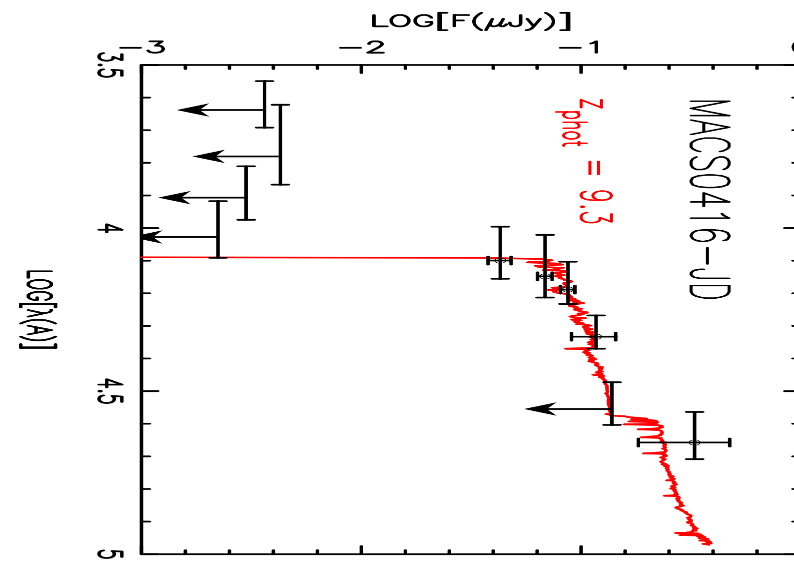
Young stellar population

GN-z10-3 has Lyα at z=8.78. Although IRAC excess could be due to [O III], a young stellar population is ruled out by prominent F160W flux:
Age ~ 290 Myr z_F ~15

Keck 6hrs: possible Lyα z>9 (marginal)



VLT 10hrs: in progress (Aug/Sep)



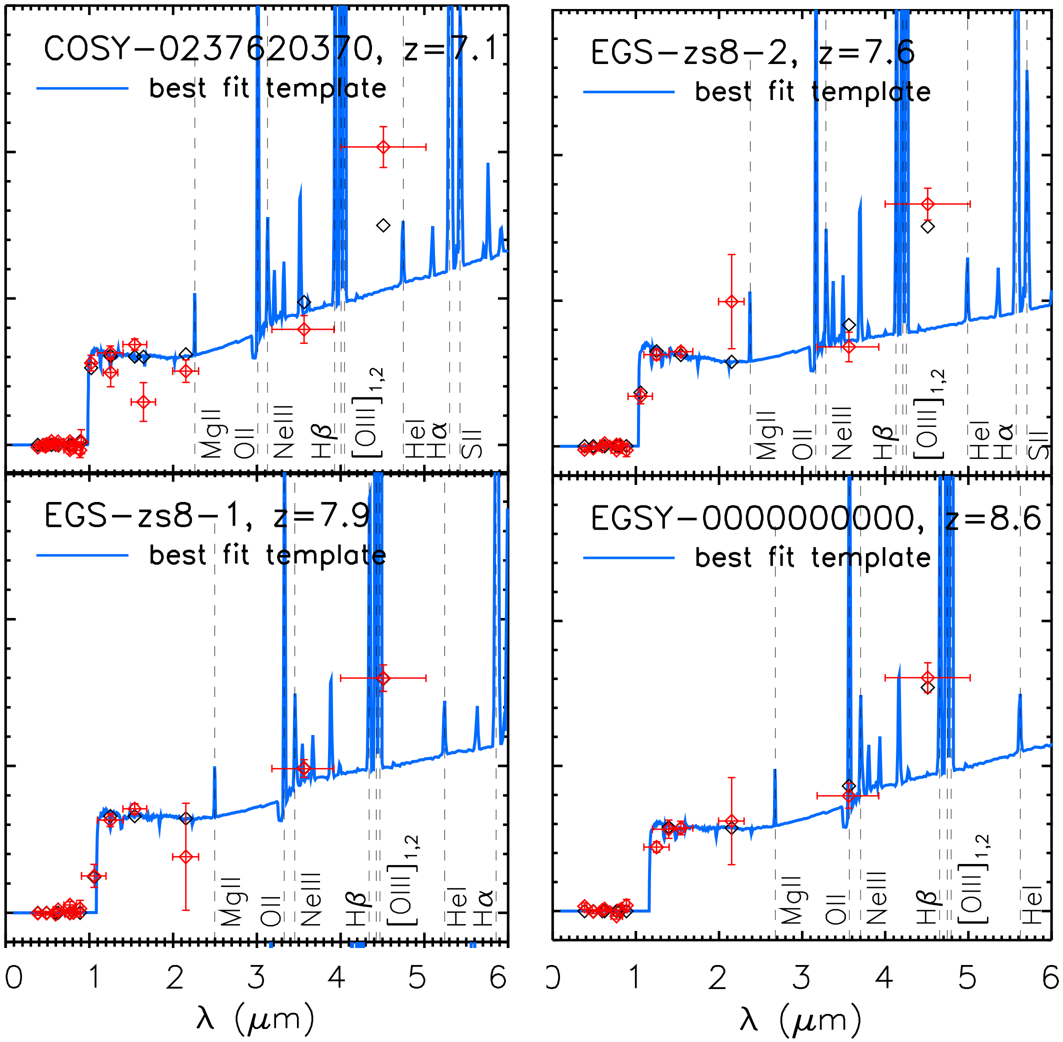
Laporte, Meyer, RSE in prep

Revisiting the Origin of the IRAC Excess

Many luminous 7 < z < 9 galaxies have a strong excess in the 4.5μm Spitzer IRAC band.

4 such objects (H~25) located in CANDELS fields; all spectroscopically-confirmed

How sure are we that this excess arises solely from [O III]/Hβ emission given we see similar excess at z >9 where these lines are redshifted beyond the band?



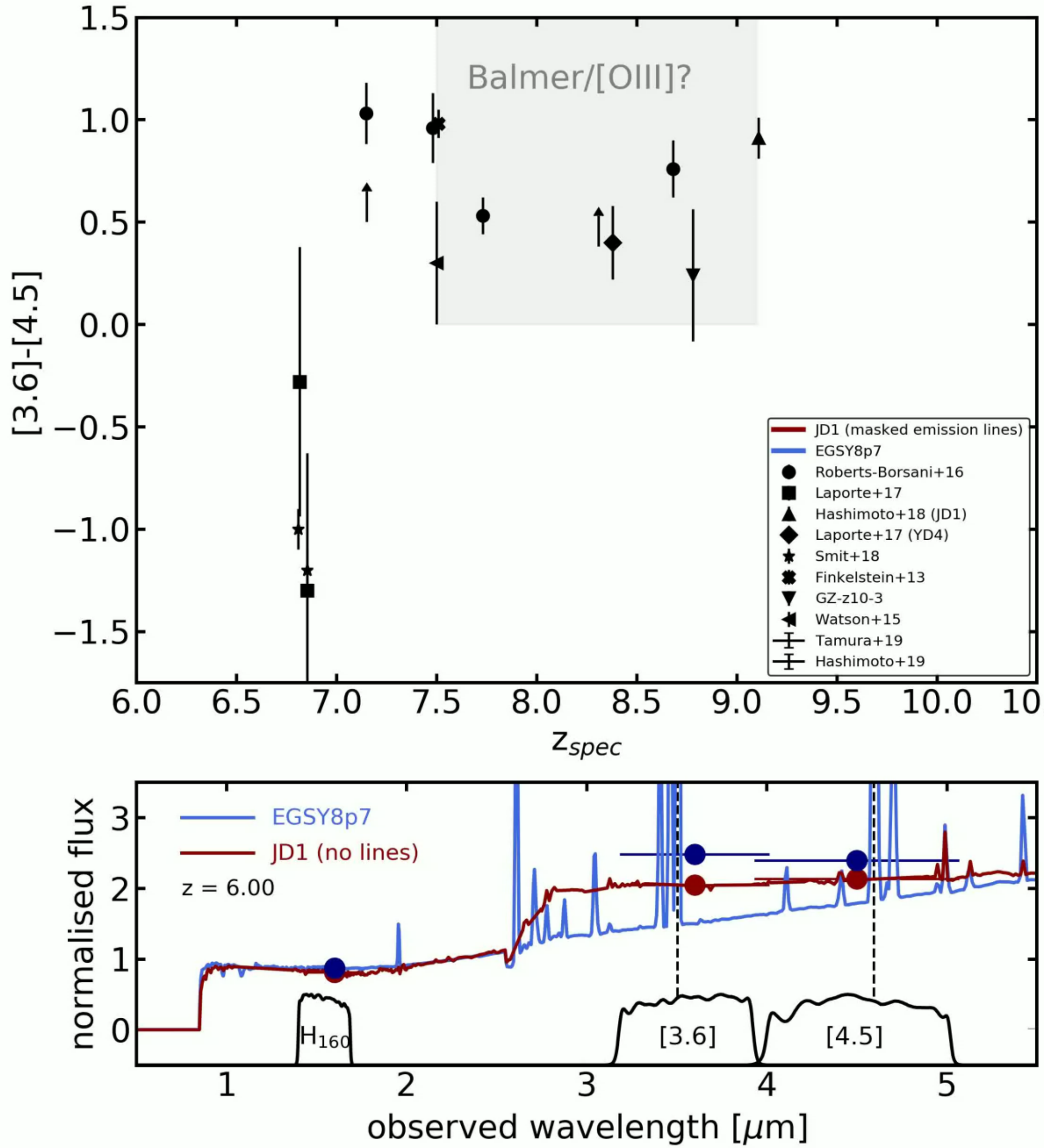
Roberts-Borsani et al (2015)

IRAC Excess: [O III] emission or starlight?

Perhaps surprisingly, a Balmer break SED (MACS1149_JD1 with no lines) can, within the observational uncertainties, also explain the IRAC excess colours for 7.5<z<9.0 spectroscopically-confirmed sources with IRAC data!

NB: **Not** implying [O III] does not contribute but rather than the ages and stellar masses of these sources may be underestimated

Roberts-Borsani, Laporte, RSE in prep



Atacama Large Millimetre Array (2015 -)

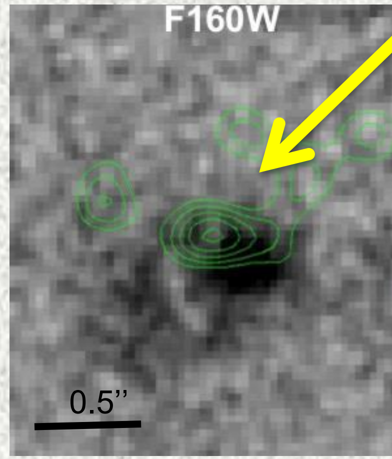
ALMA interferometer with up to 15 km baselines has Hubble resolution for tracing early dust

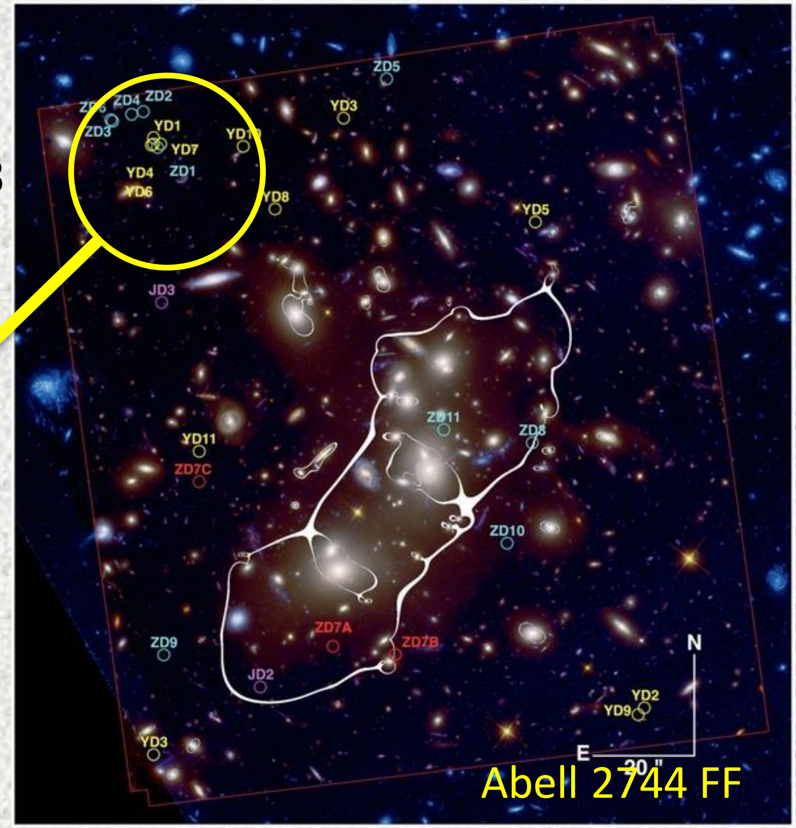
ALMA/C. Padilla

Dust at z=8.38

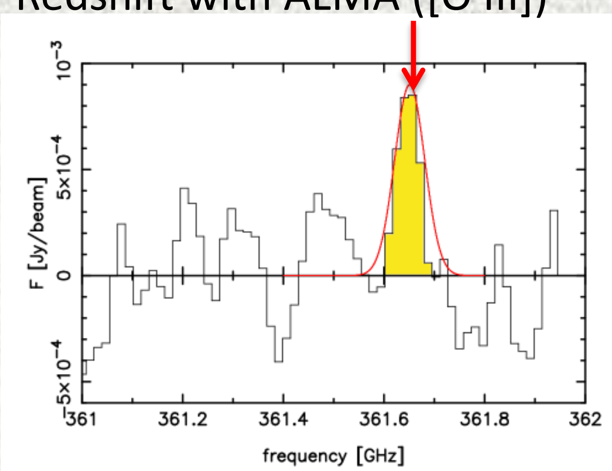
ALMA Band 7 ~1mm dust at z=8.38

If early dust grains were formed mostly in SNe, the mass could provide a crude estimate of earlier chemical enrichment and star formation





Redshift with ALMA ([O III])

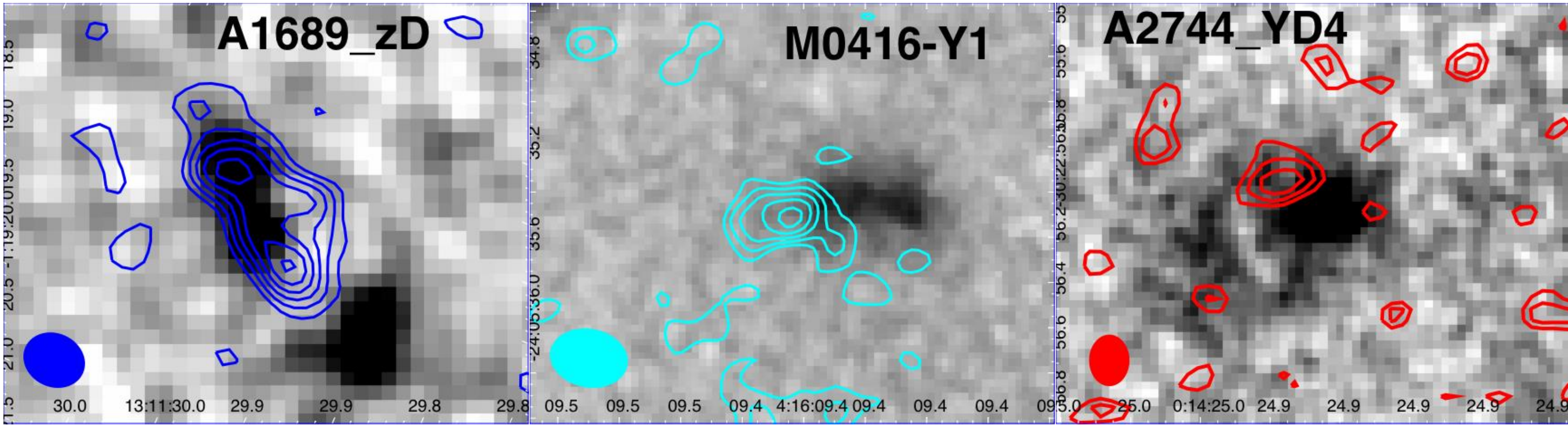


Stellar mass 2 × 10^9 $M_\odot$
SFR ~ 20 $M_\odot$ yr-1
Dust mass ~6 × 10^6 $M_\odot$

Laporte, RSE et al (2017)

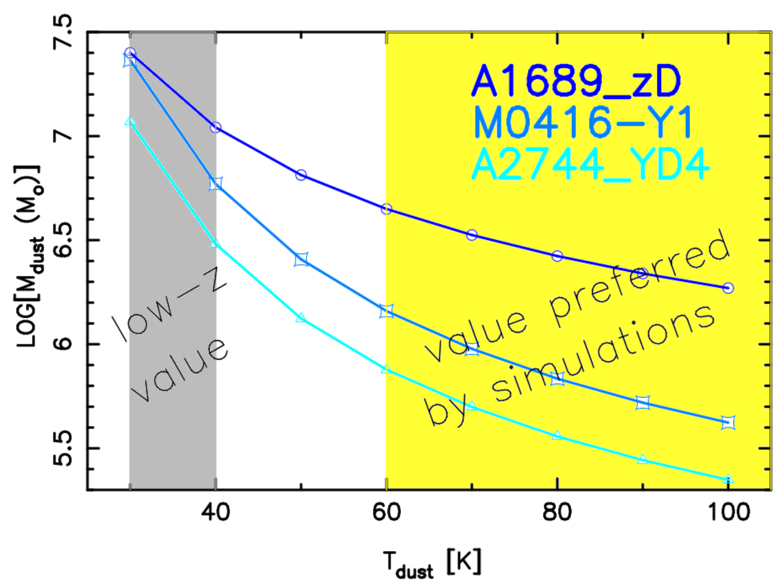
Three Dust Detections at z>7.5

z=7.5 (Watson et al 2015) **z=8.31 (Tamura et al 2019)** **z=8.38 (Laporte et al 2017)**



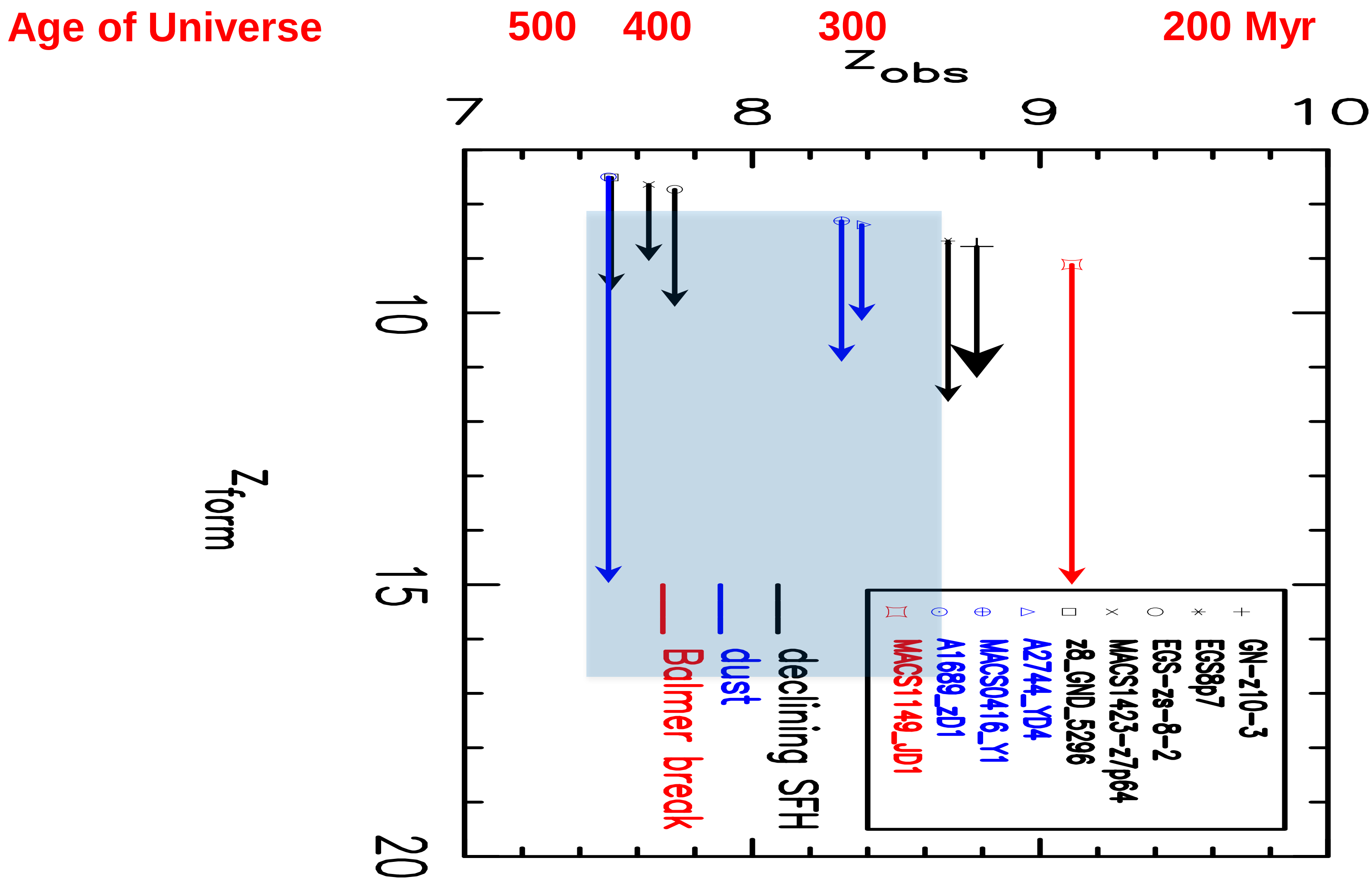
Major uncertainties are

- T_{dust} leading to large mass uncertainties
- Past SF history (uniform/rising/declining with time?)
- Amount of dust ejected or not detected (nonetheless a valuable lower limit)
- Continued dust production via sputtering in ISM?

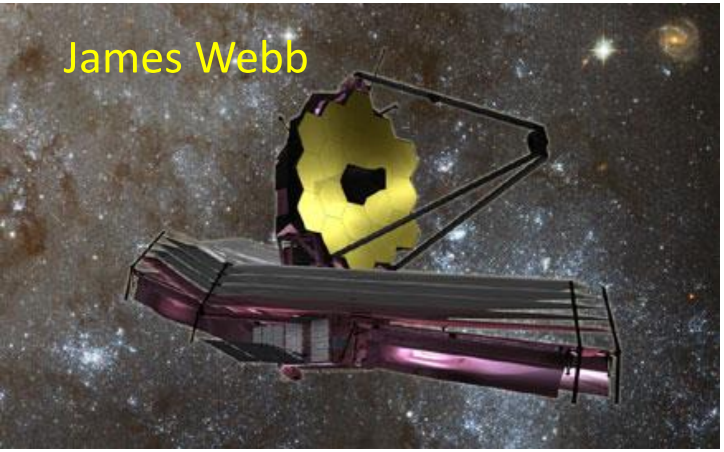


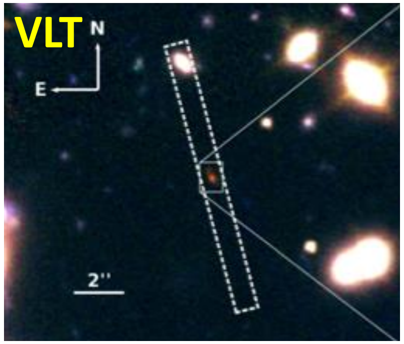
Probing Cosmic Dawn: The Latest

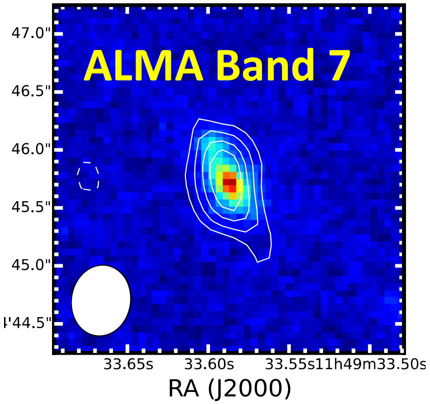
Although highly uncertain, using dust masses and stellar ages we get a first glimpse of evidence for earlier star formation to redshifts z~11-15



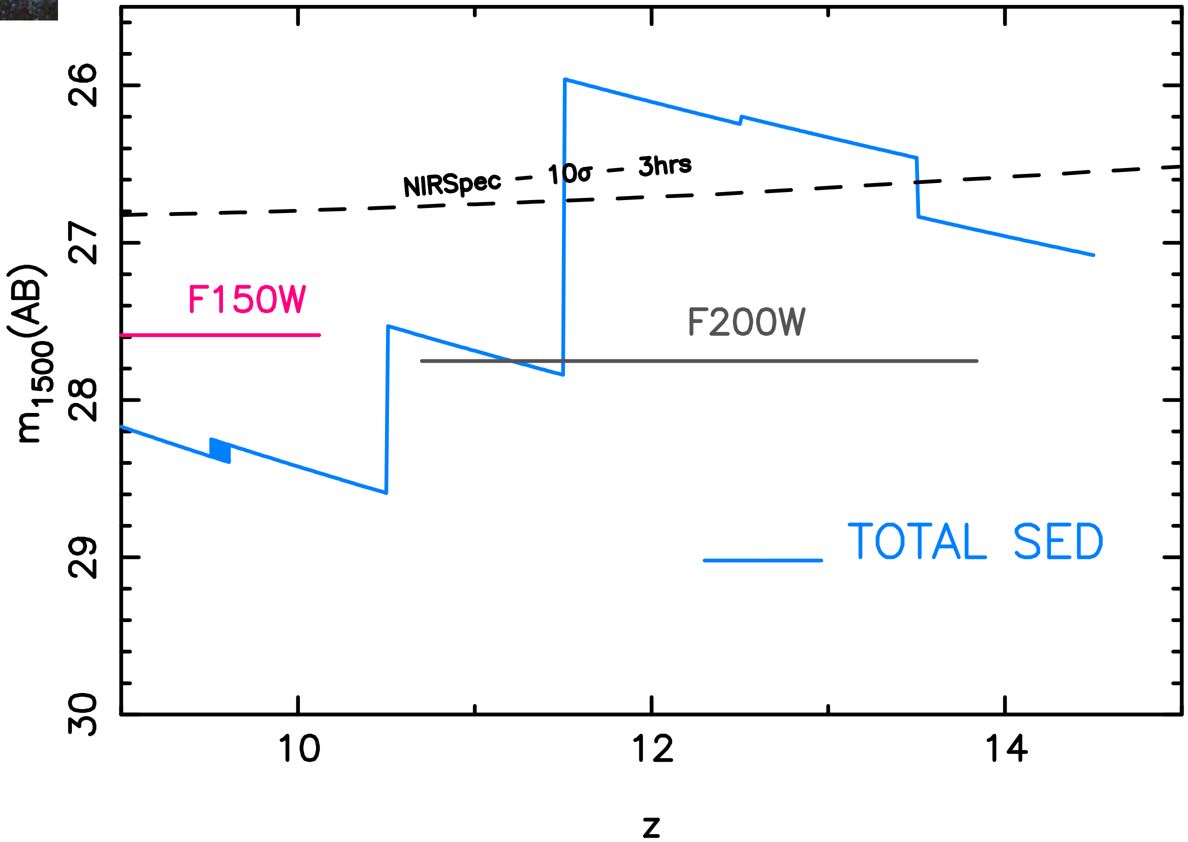
Direct Detection of Progenitors?







Predicted early evolution of the UV brightness of MACS1149_JD1 according to the best SED fit at z=9.1 compared to imaging limits with NIRCAM (10σ 20 mins) and spectroscopic limits with NIRSpec (10σ 3 hours)



Summary

- Good progress in determining the demographics of star-forming galaxies to z~10 from deep fields and via lensing clusters
- Census (numbers, LFs) can be made consistent with Planck optical depth if ionising radiation is hard and escape fractions are ~10% as suggested in metal-poor analogues: Lyman alpha emitters at z~3
- The most distant spectroscopically-confirmed z>8 sources with metal lines, dust continua and Balmer breaks point to star formation as early as z~15
- In the best studied cases the prospects are good for directly studying the earlier phases of activity with JWST

JD1 Questions/Caveats

How uncertain is the age, e.g. as a function of assumed SF histories?

- Unable to reproduce the Balmer break with constant or rising SFHs

Do the stellar population diagnostics come from same spatial location?

- Hard to convincingly determine due to low IRAC resolution
- Velocity offset between Lyα and [O III] 88μm may imply two components

Could IRAC ch2 excess be due to extremely intense Hβ/[O III] 4959A?

- Only for very young SF; intense [O II] would produce `inverted Balmer break'

Is JD1 an outlier in terms of structure formation?

- Most models predict rising SFHs over $8<z<15$ and lower stellar masses
- Katz et al (2019) can reproduce the basic properties in hydro simulations