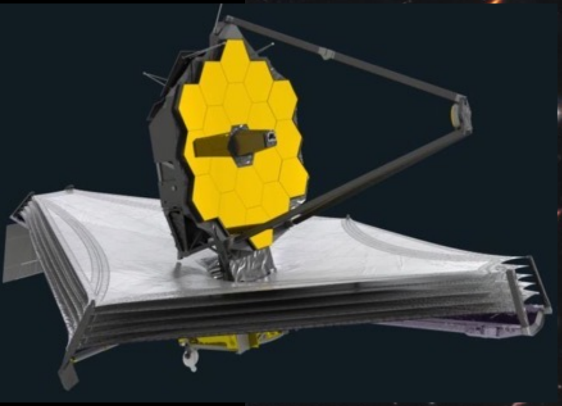
The JWST Revolution:
Cosmic Reionisation & the Redshift Frontier

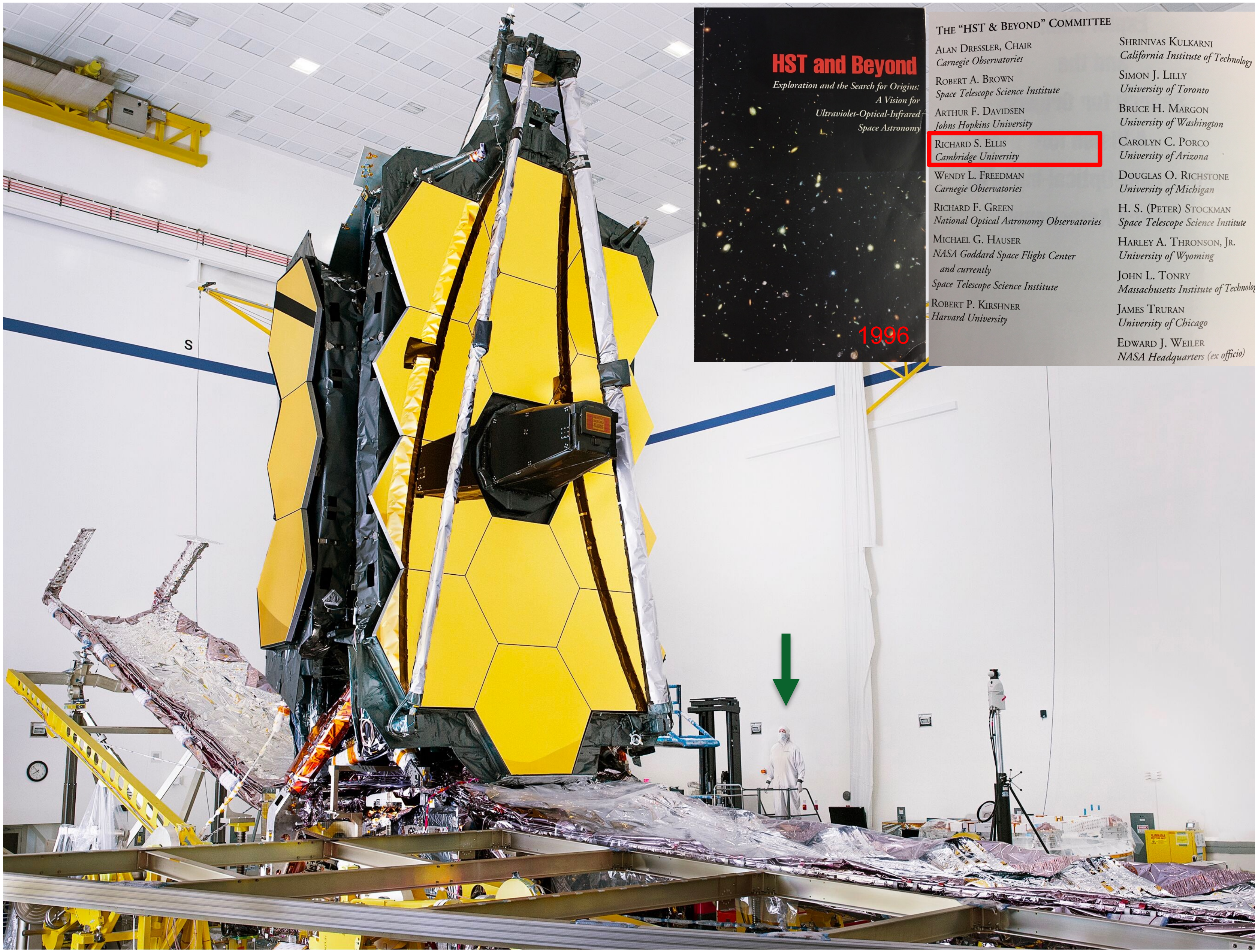


Richard Ellis (UCL)

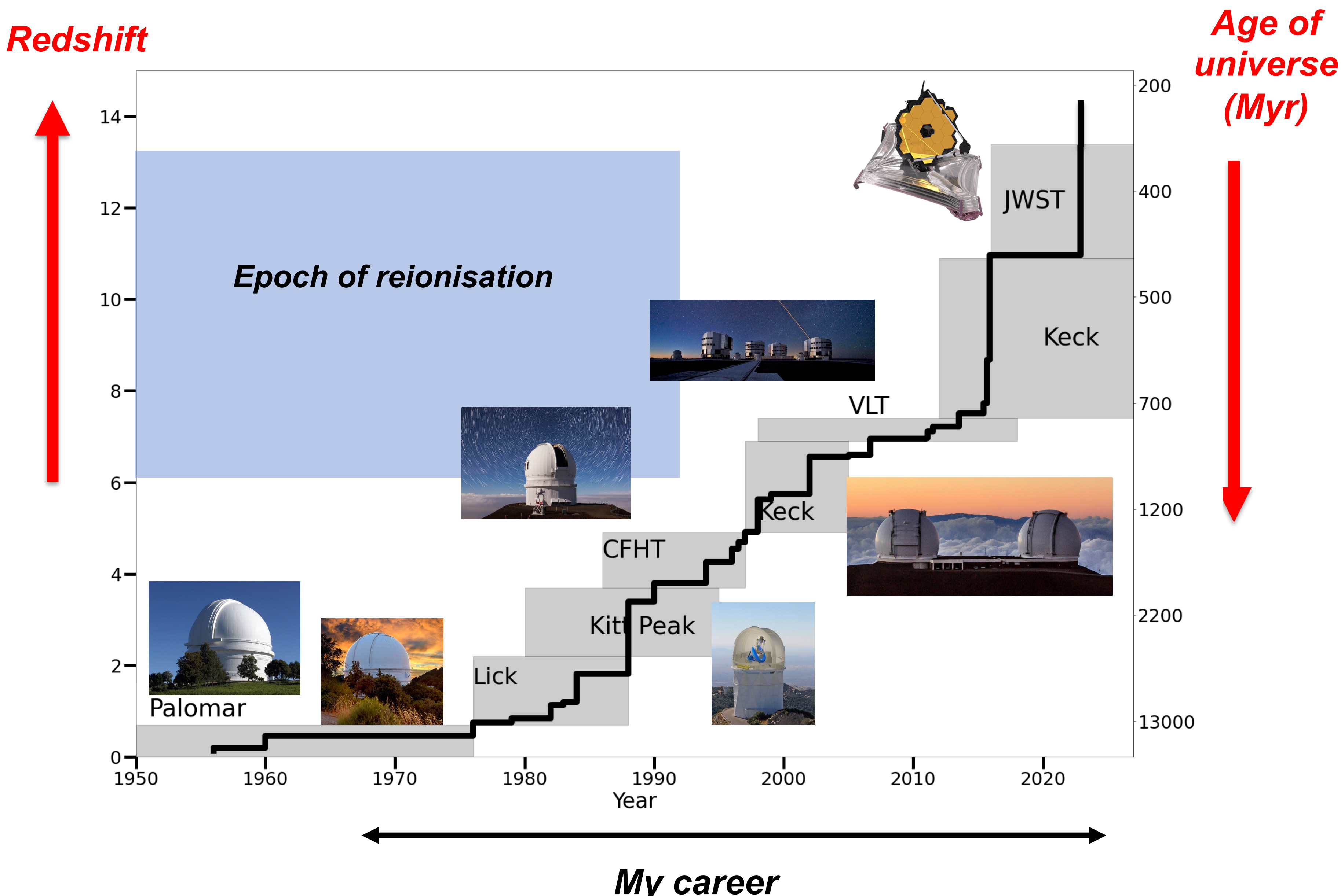
BCCP/Cosmology Seminar

March 18th 2025

The James Webb Revolution



Most distant spectroscopically-confirmed galaxy

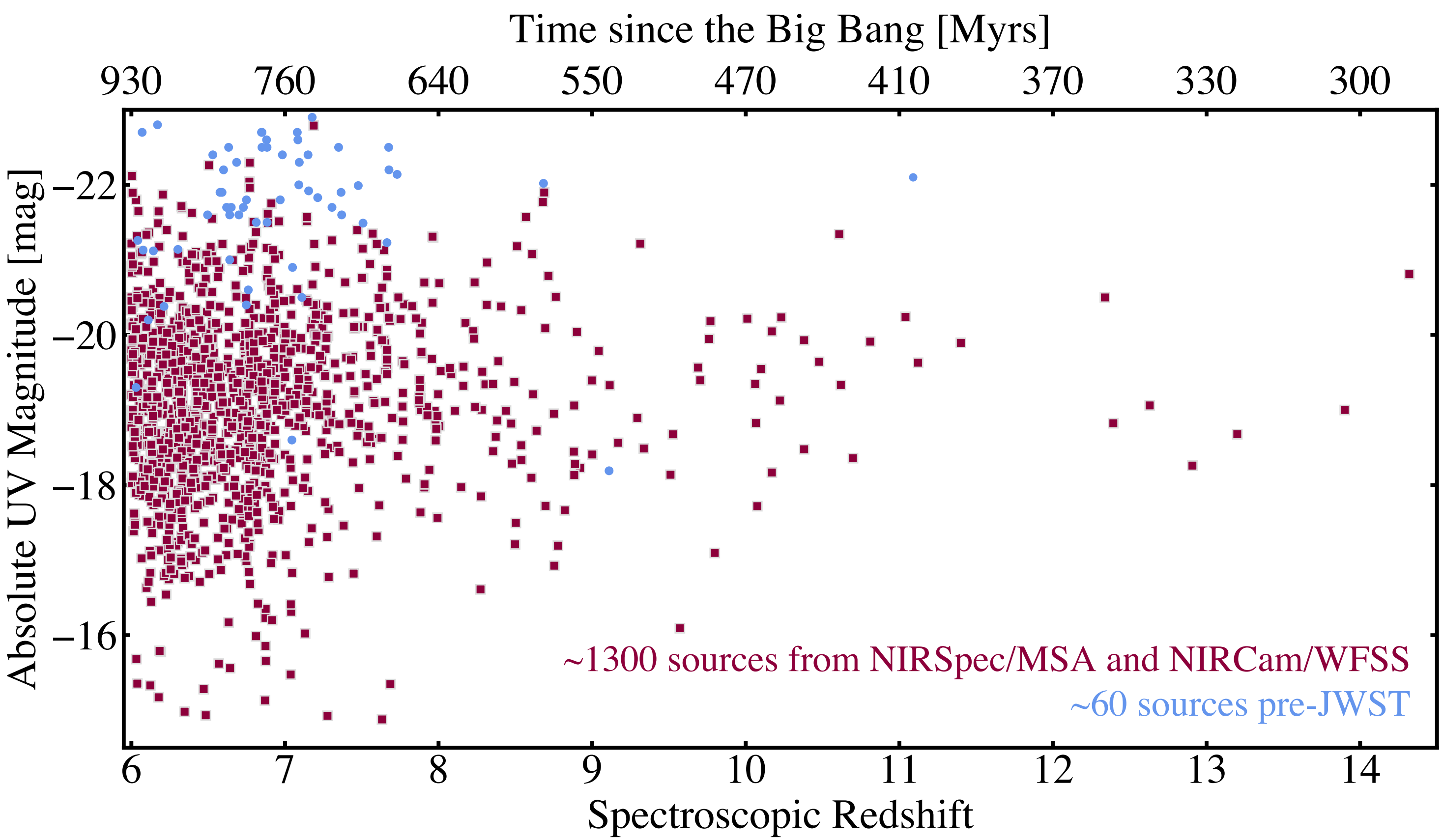


Courtesy: Nicolas Laporte

Redshift Surveys in the Reionisation Era

The primary near-IR instruments prior to JWST for spectra of z>7 galaxies:

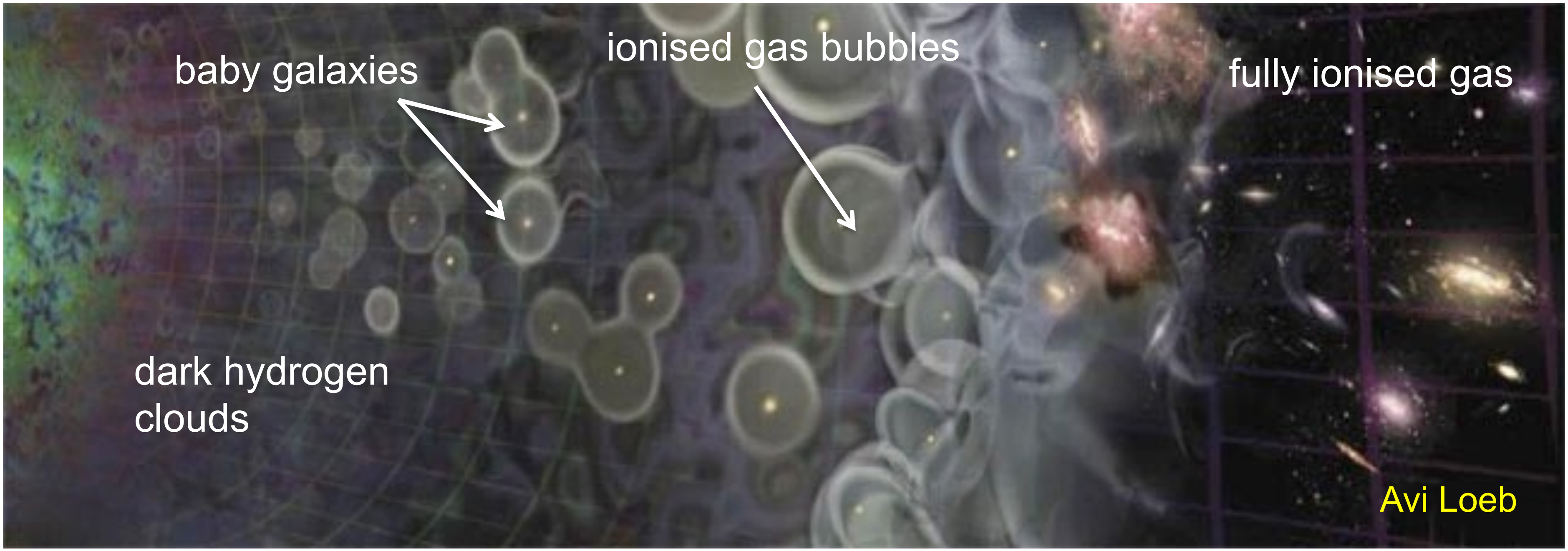
- Keck MOSFIRE, VLT X-shooter, HST WFC3 grism **and ALMA**
- All struggled with either low spectral resolution, airglow or signal/noise issues
- Only ~60 published redshifts z>6 (now with JWST >1300)



Courtesy: Guido Roberts-Borsani

Cosmic Reionisation

time



$t = 3.7\ 10^3$ yr, $z = 1100$:	Recombination & formation of hydrogen
$t \sim 200$ Myr, $z \sim 20$-30:	Hydrogen clouds drawn to DM & collapse
$t \sim 250$ Myr, $z \sim 15$-20:	Nuclear ignition – "cosmic dawn"
$t \sim 250$ Myr – 1 Gyr $15 < z < 5.5$:	UV photons from galaxies (+ AGN?) reionise IGM

Two big questions: When did this happen?
What sources were responsible?

QSOs & end of reionisation

Sarah Bosman

Spectra of 70 QSOs reveal **greater hydrogen opacity** to z~6.

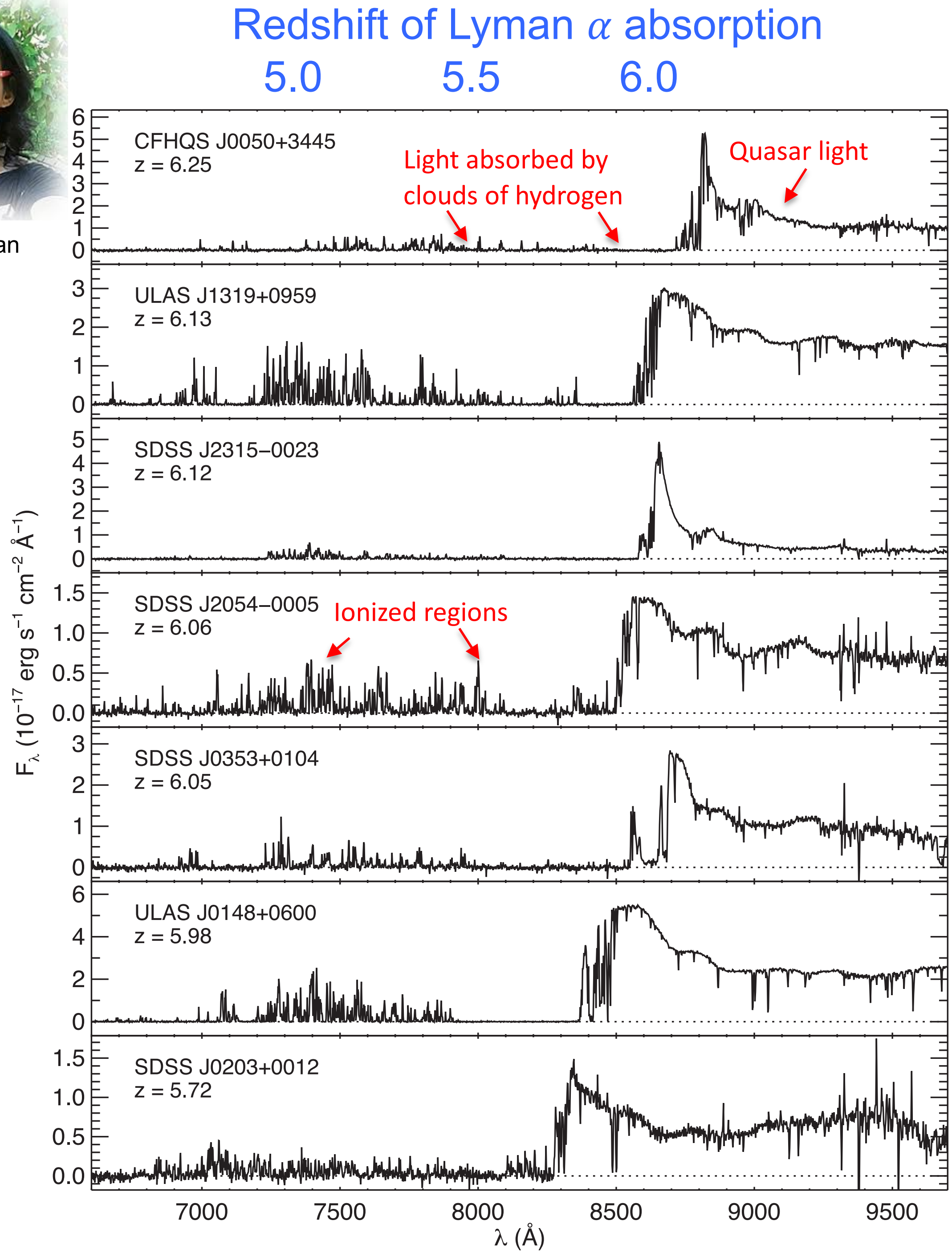
Significant variation across different sightlines suggests a patchy distribution of ionised bubbles

Can quantify the Lyα opacity via the optical depth τ

$$I(\lambda) = I_o(\lambda)e^{-\tau}$$

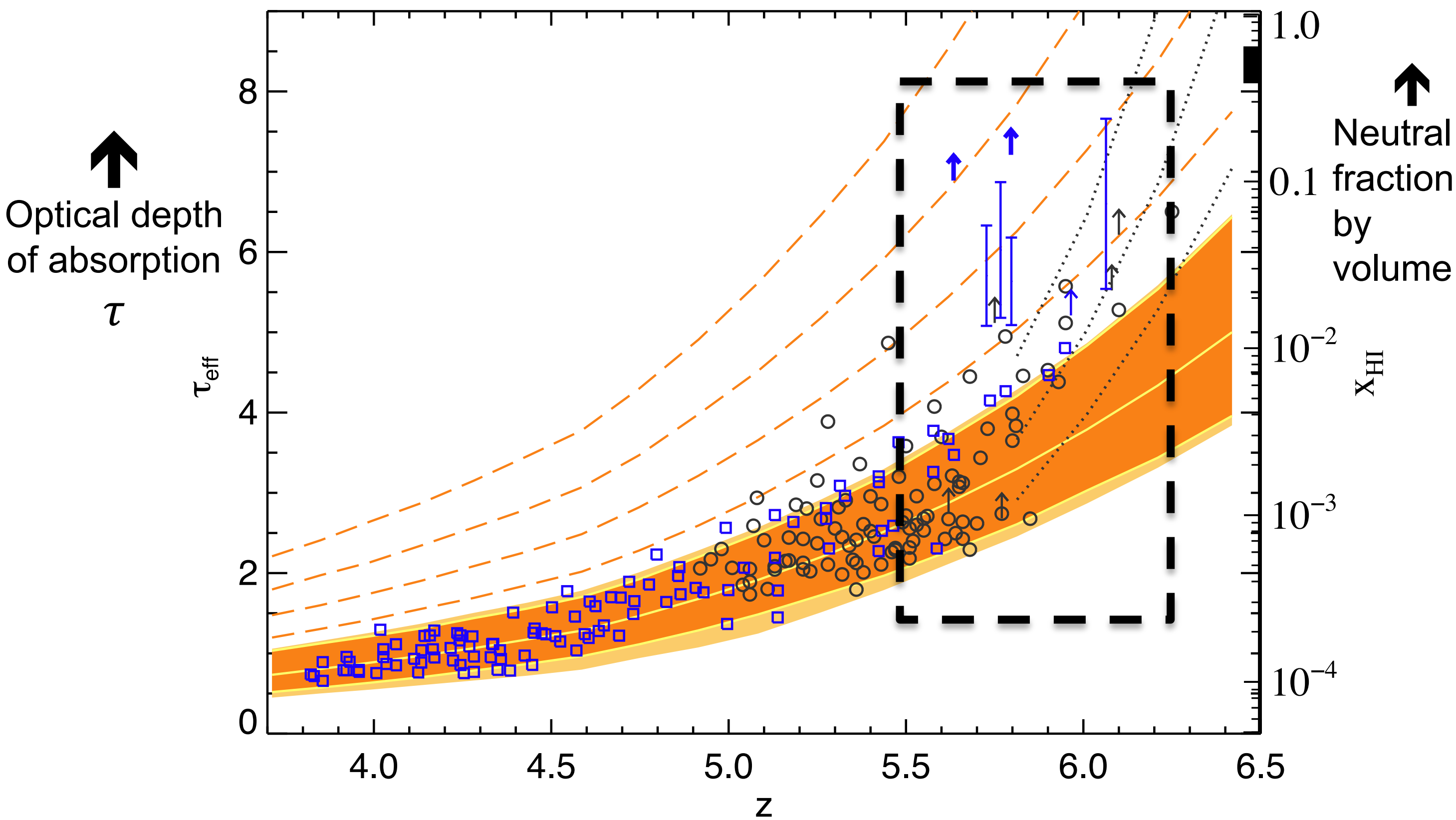
where I_o is the unattenuated continuum and I the observed spectral flux

Bosman et al 2018



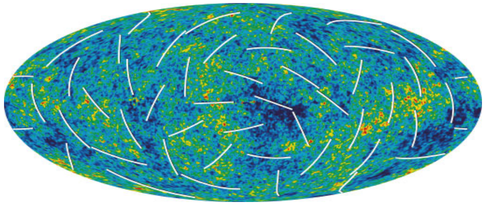
Redshift - Dependent Hydrogen Absorption

Pros: Direct measure of the neutral fraction $X_{HI} = n_{HI} / n_H$
Cons: Few suitable quasars beyond redshift z~6.5
Sensitivity limited to z~6: small amount of hydrogen saturates absorption ($X_{HI} > 10^{-3}$)



- Upturn in opacity at redshifts beyond z~5.5: entering the neutral era
- Significant scatter from one quasar sightline to another: patchy distribution
- NB: other QSO spectral statistics are useful e.g. dark absorption gaps, damping wings

Bosman et al 2018



CMB Polarisation & Reionisation

- Thomson scattering induces polarisation as electrons are anisotropically illuminated by CMB fluctuations

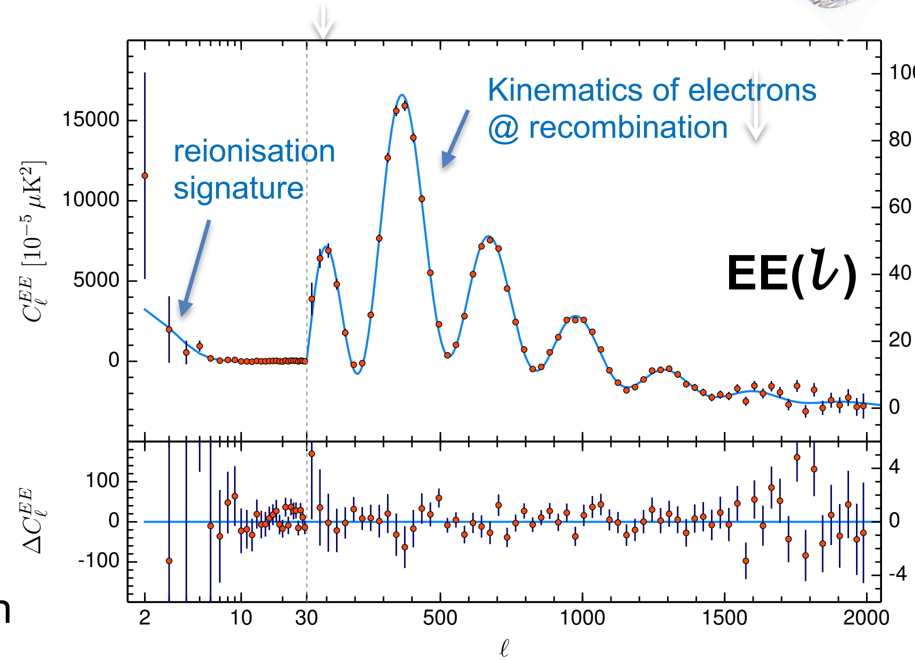
- Reionisation damps TT(ℓ) by an amount degenerate with its intrinsic amplitude but produces an unique EE(ℓ) signal on large scales breaking degeneracy

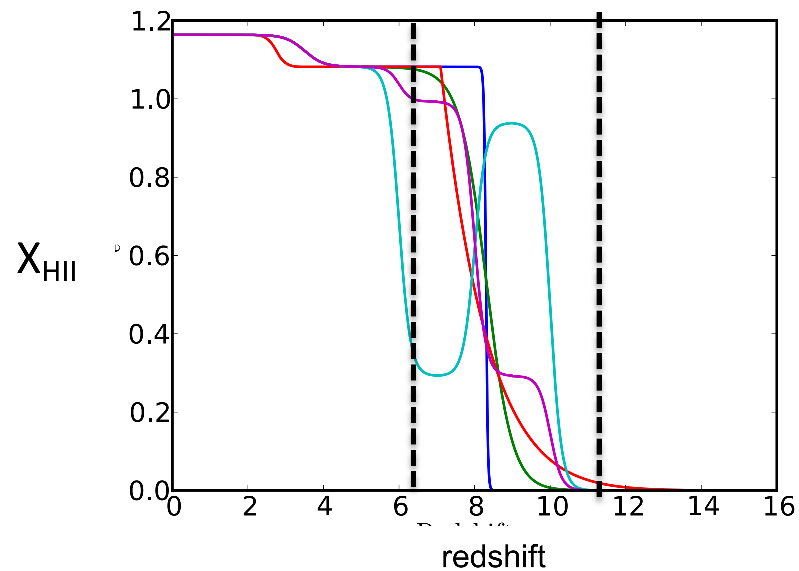
- As an integrated measure, optical depth τ constrains the "median" redshift and duration but not $X_{HI}(z)$

- Planck (2020) indicate τ = 0.057 ± 0.007 implying z_{med} ~7.7±0.7 (age ~650 Myr)

- De Belsunce et al (2021) refined calibration raising τ = 0.063 ± 0.005 (0.5σ)

- Parametric fits to EE, TT, TE indicate reionisation began at z~10-12 & ended at z~6.

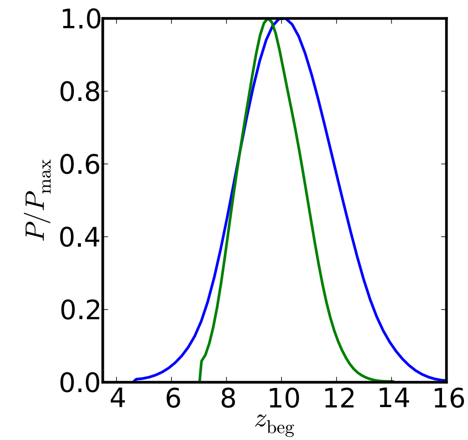




Beginning of Reionisation – Planck view

Planck Consortium : 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 $z \gtrsim 15$.

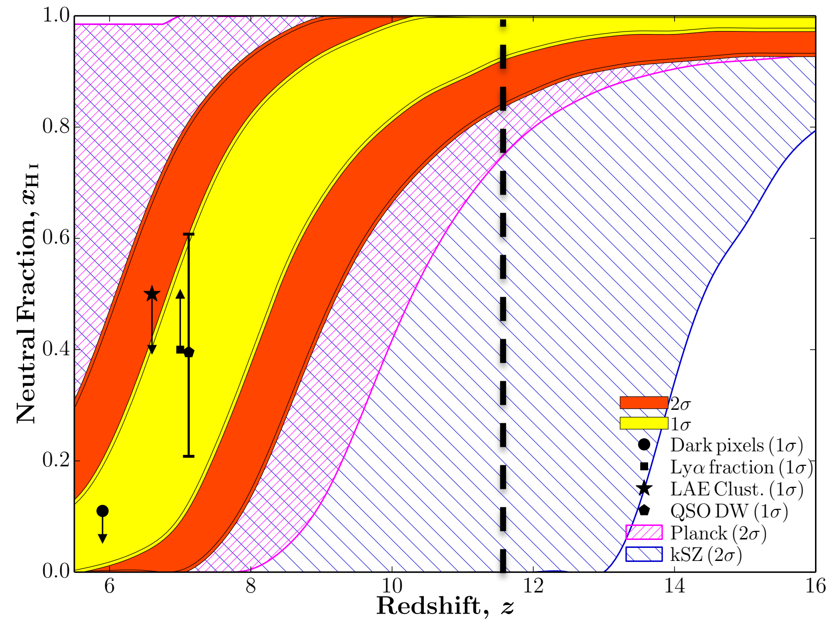


Later modeling taking into account

- Planck CMB τ
- QSO absorption line data
- Galaxy Lyα emission fractions (see later)
- Kinetic S-Z effect

in the context of ΛCDM suggests reionisation may have begun earlier at z~15-20

$x_{HI}(z)$

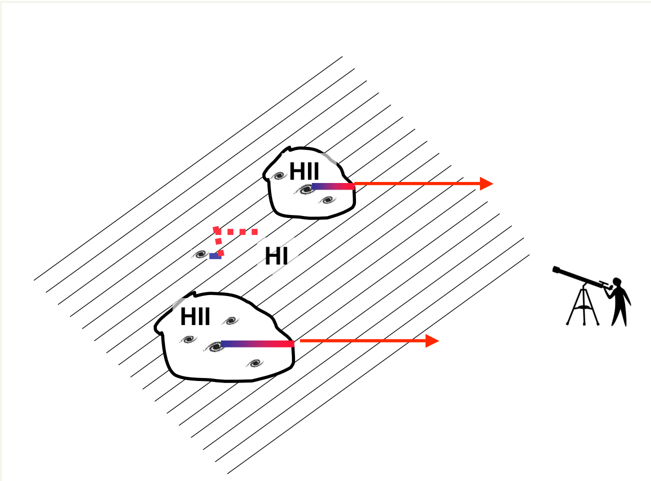


Greig & Mesinger 2016

When Did Reionisation End ? Emission Probes

As a resonant transition Lyman α emission is easily scattered by neutral hydrogen

- In a neutral IGM, line intensity will be greatly reduced
- In ionised bubble, Lyα photons can emerge and be Doppler-shifted out of resonance at a bubble surface



Fractional visibility of Lyα with redshift $X_{Ly\alpha}(z)$ (Stark+2011)

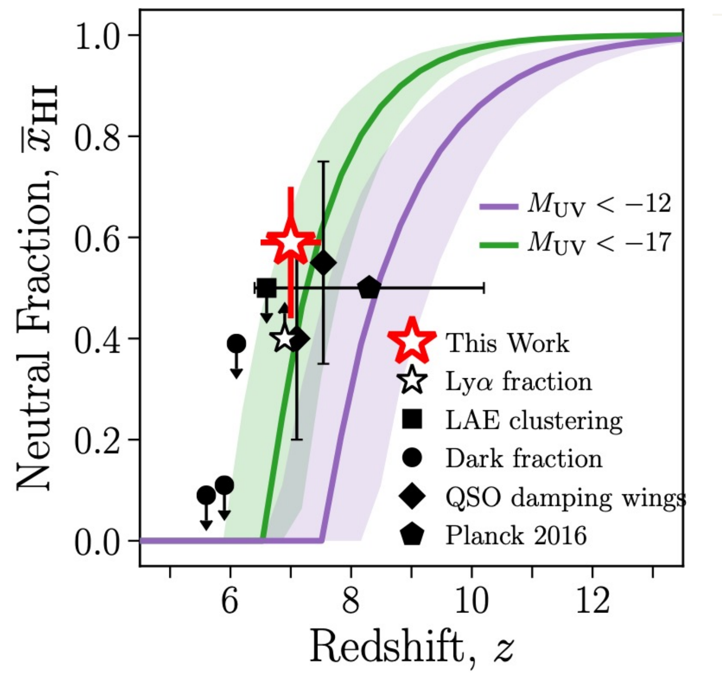
Unfortunately radiative transfer of Lyα photons through a partially neutral IGM is a complex process so inferring $X_{HI}(z)$ from $X_{Ly\alpha}(z)$ is challenging e.g. IGM attenuation will be diminished if gas has significant systemic velocity Δv

Can model these effects assuming demographics of Lyα emission in fully-ionised era @ z~3 (EW, Δv – L_{UV})

Pre-JWST study:

68 z~7 galaxies of which 12 have Lyα detections

Derive X_{HI} (z~7) = 0.59 ± 0.13



Mason et al 2018

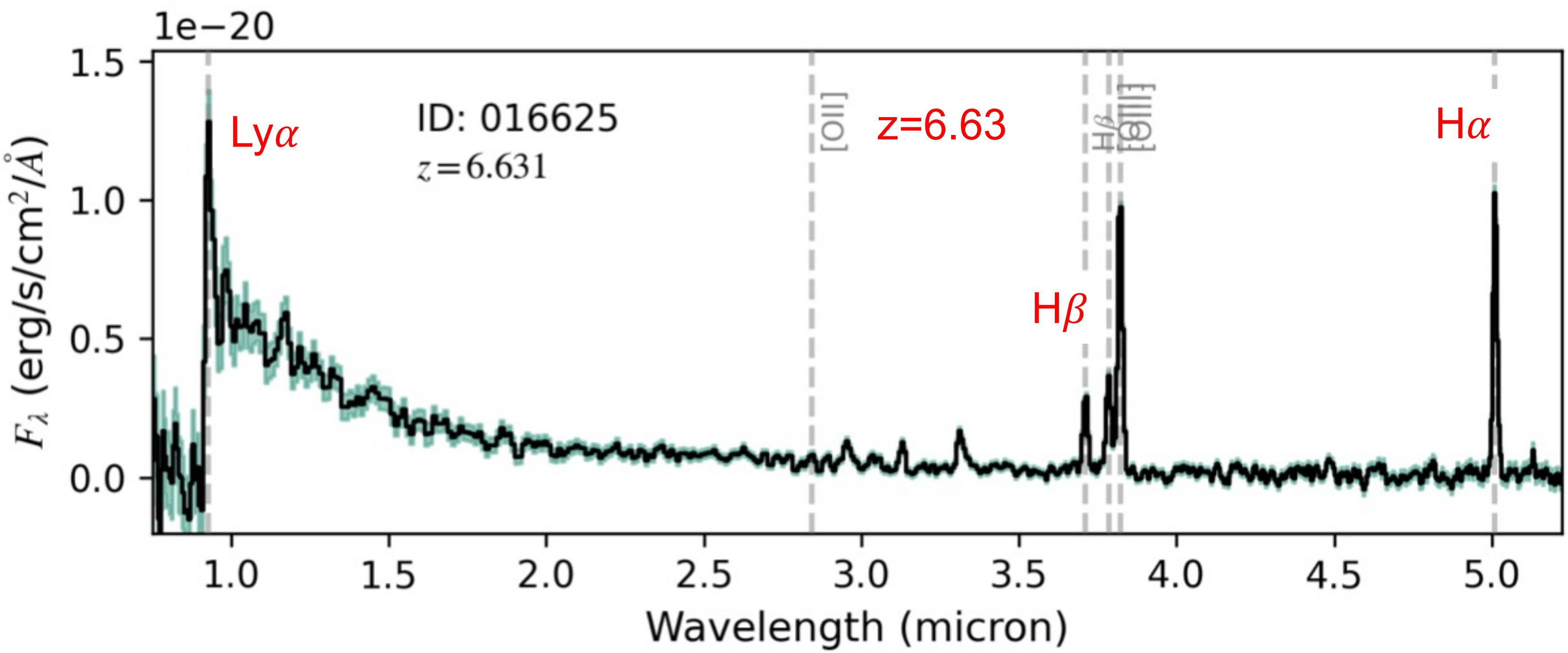
Lyman α studies with JWST - I

As an infrared telescope, JWST provides unique access to Balmer lines **Hα (z<6.6**) and **Hβ (z<9.2)** enabling **escape fraction of Lyα photons $f_{esc}(Ly\alpha)$**.

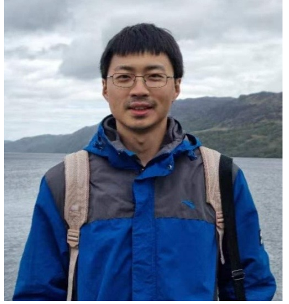
Case B recombination: If n_e=100 cm^{-3}, T_e=10^4K, Lyα / Hα = 8.2

$$So\ f_{esc}(\text{Ly}\alpha) = L(\text{Ly}\alpha)/(8.2 \times L(\text{H}\alpha))$$

Measuring f_{esc}(Lyα) with redshift can extend trends found with ground-based telescopes.



Lyman α studies with JWST - II



Mengtao Tang

Comparison 4.9<z<6.5 sample:

JADES, FRESCO, Keck, VLT
79 galaxies with Lyα and Hα

Derive probability distributions of EWs, f_{esc}(Lyα) and $\Delta v_{Ly\alpha}$ as a function of L_{UV} and [O III] emission

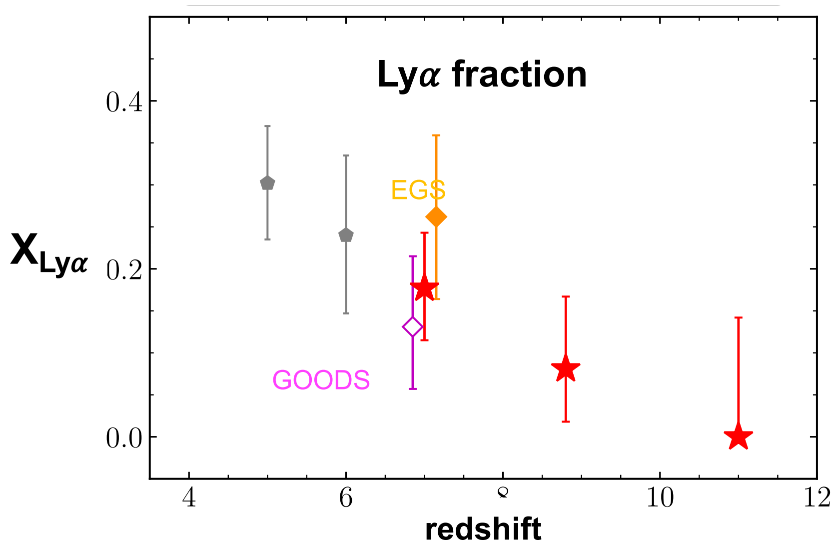
Enables controlled redshift-dependent comparisons

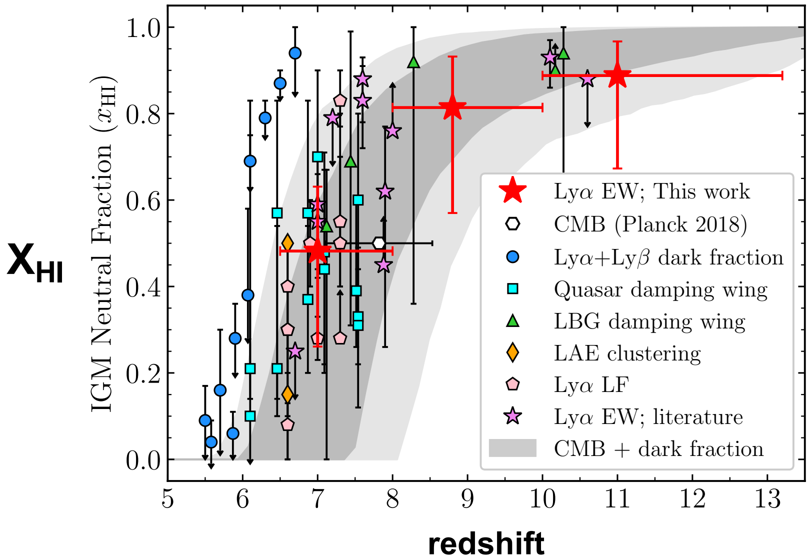
Reionisation sample:

JADES, ERS, GO
210 6.5<z<13 spectra
33 Lyα 6.5<z<10.5

X(Lyα) shows continued decline to z~10 with field-field variations

Can compare with EW distribution @ z~5-6.5 to derive relative $\mathbf{X_{HI}(z)}$ following Mason et al (2018)



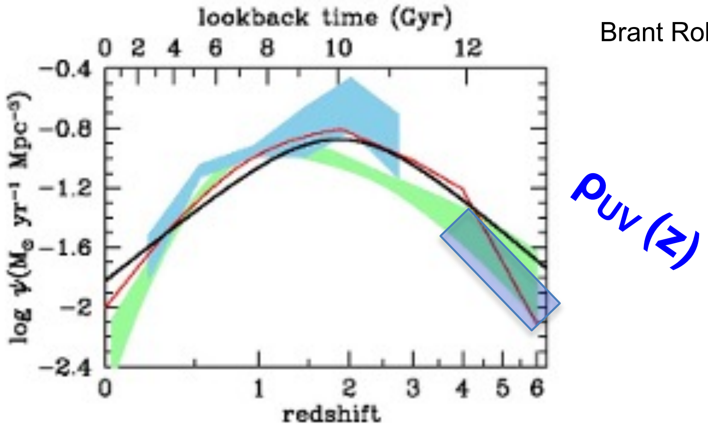


Tang, Stark, RSE et al 2024a,b; see also Kageura et al 2025

Sources of Cosmic Reionisation

Brant Robertson

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



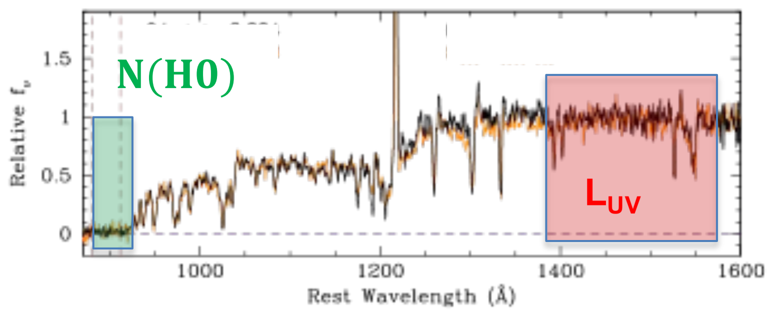
1. Integrated **abundance** of sources: ρ_{UV} (z)

Star-forming galaxies are the most likely candidates but AGN may also contribute

2. **Intrinsic** rate of ionising photons: ξ_{ion}

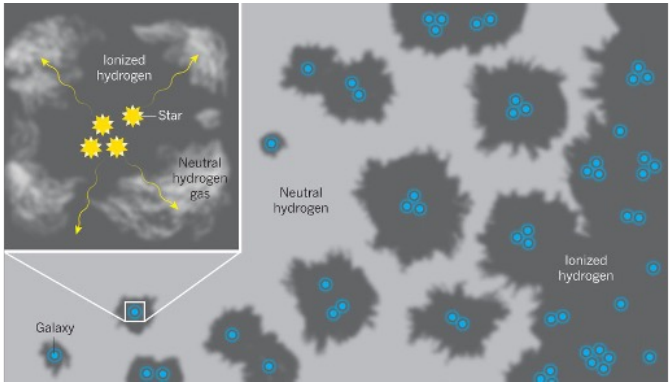
Defined as $\xi_{\rm ion} = \frac{N(\mathrm{H}^0)}{L_{\rm UV}}$ Hz erg^{-1}

Determined from the stellar population or diagnosed using nebular emission lines.



3. **Fraction** escaping to IGM: f_{esc}

Hard to measure LyC escape at z > 4 due to line of sight IGM hydrogen absorption. Direct measures only possible for "analogues" at z~0-3. Indirect measures undertaken at z~6+ (e.g. Lyα)

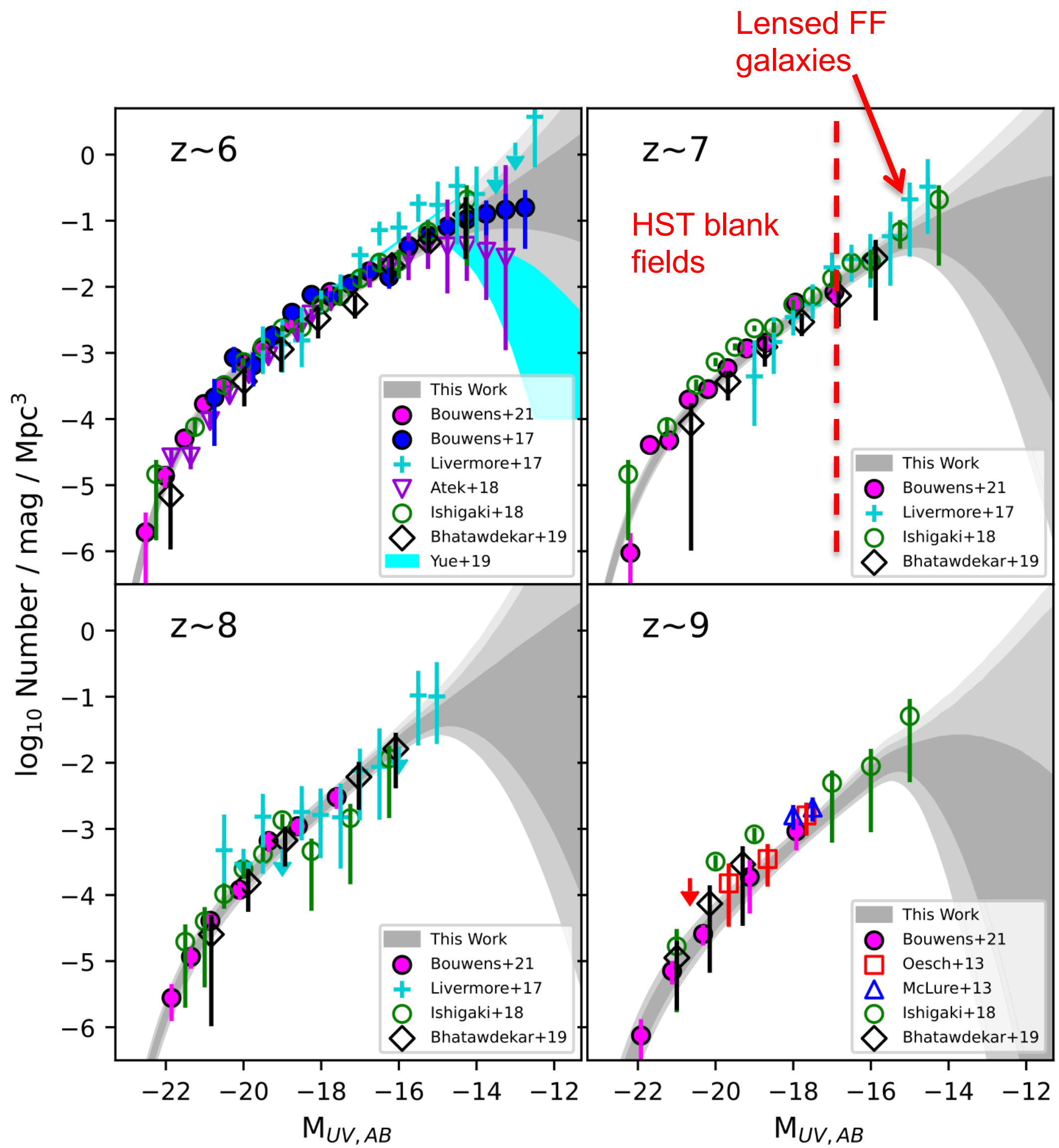


Robertson, RSE et al 2010

HST Measures of UV LF & Integrated ρ_{UV}

Integrated luminosity density: $\rho_L = \int \Phi(L) L \, dL = \Phi^* L^* \, \Gamma(\alpha + 2)$
which diverges if Schechter faint end slope $\alpha \leqq -2$

- Intrinsically faint sources dominate the integral
- So census of lensed faint sources from HST Frontier Fields critical
- HST still provides best constraint via reduced cosmic variance for lensed sources
- Faint end slope steepens from α = -2.05 to -2.34 for z > 7 so integral is formally divergent since no convincing sign of turn down to $M_{UV} \sim -13$
- To this M_{UV} limit ρ_{UV} is constrained to <20%

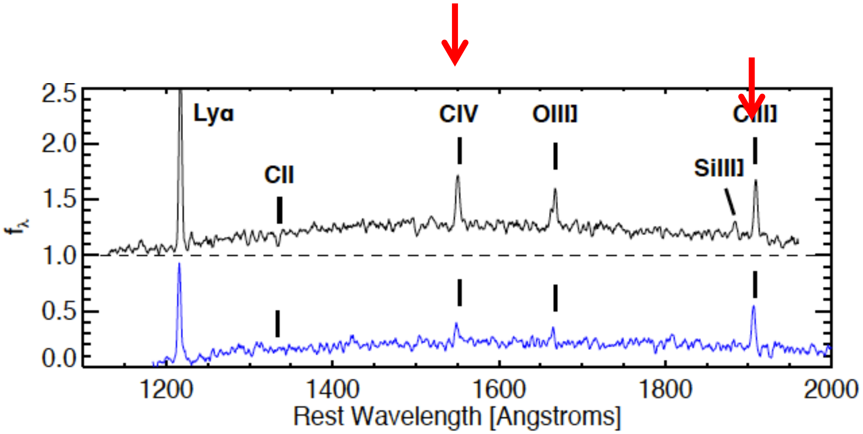


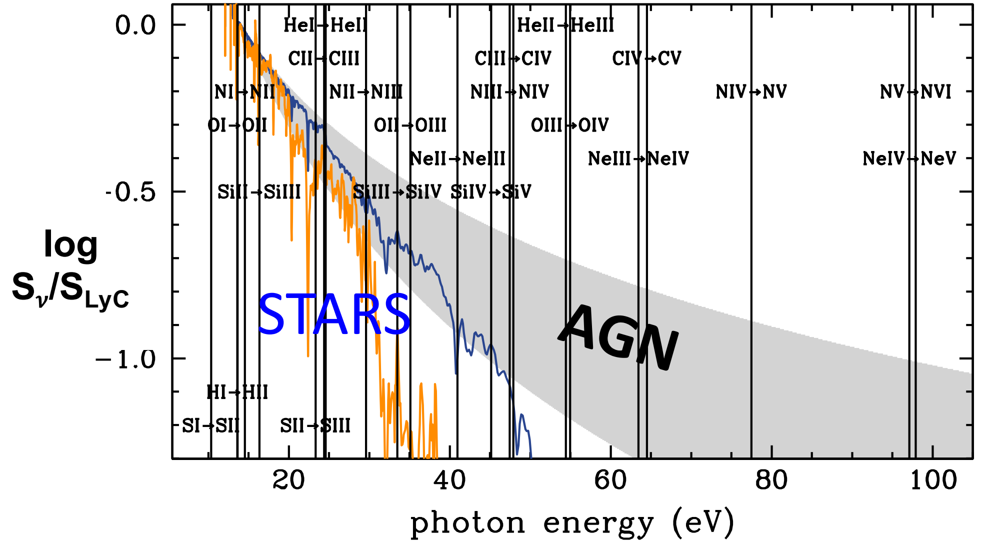
Bouwens, RSE et al 2022

Ionising Photon Production ξ_{ion}

Rest-UV metal lines of high ionisation potential (e.g. CIV, CIII]) interpreted via photoionisation models for stellar populations of different metallicities & AGN

Kimihiko Nakajima



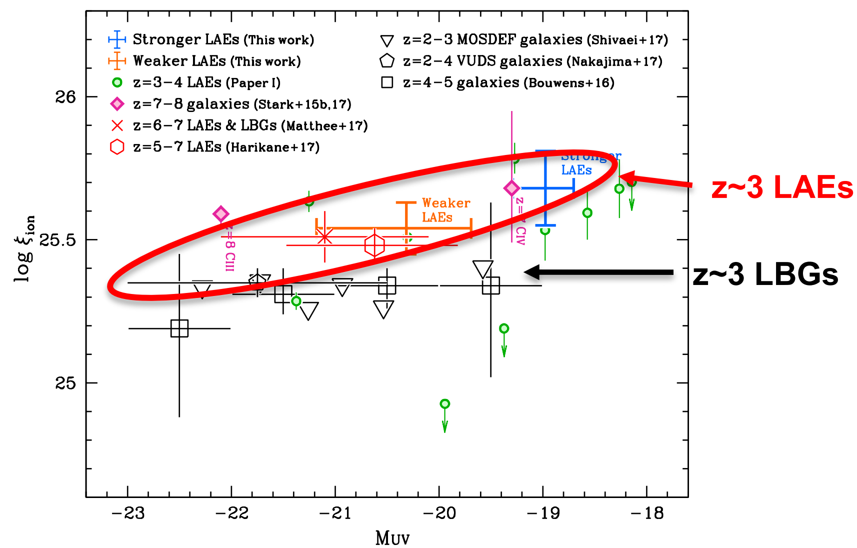


Pre-JWST example:

VLT rest-UV spectra of 100 z~3 Lyα emitters considered to be good analogues of z>7 galaxies

log ξ_{ion} = 25.5 - 25.7 (for f_{esc}=0)

Weak luminosity trend and harder radiation field than z~3 LBGs



Feltre et al 2016; Nakajima, RSE et al 2018

JWST Results for ξ_{ion} - I

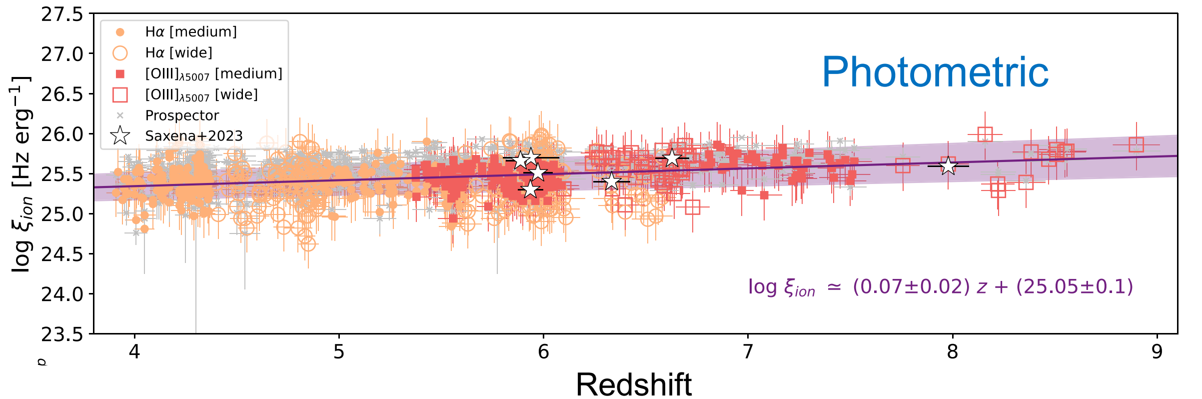
Pre-JWST data suggested ξ_{ion} increased with redshift but samples were very small.

Large JWST analyses have so far determined ξ_{ion} from

(i) photometric measures using medium bands suggest an increase with redshift.

JEMS imaging survey
677 galaxies 4 < z < 9
NIRCam medium/broad bands
sensitive to Hα, [O III]

Simmonds et al 2024

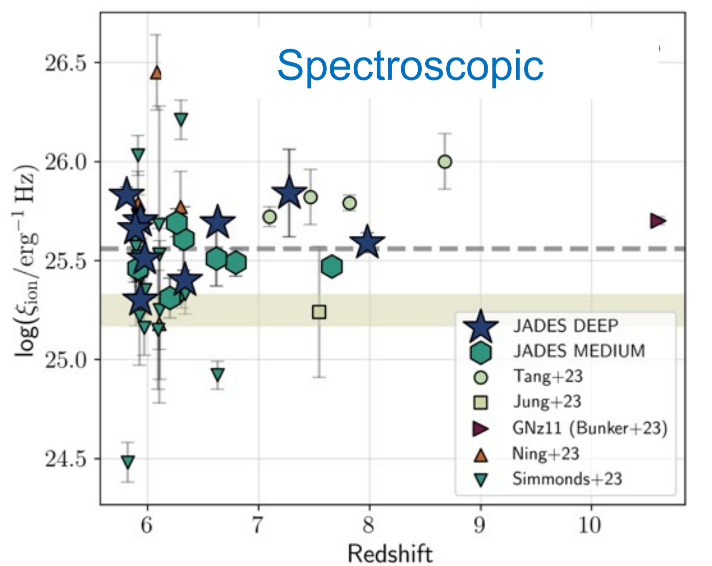


(ii) **spectroscopic data** suggested otherwise

JADES spectra of LAEs
16 galaxies 5.8 < z < 8
Metal poor systems thought to dominate reionisation

log ξ_{ion} ~ 25.6 at all redshifts

Saxena et al 2024



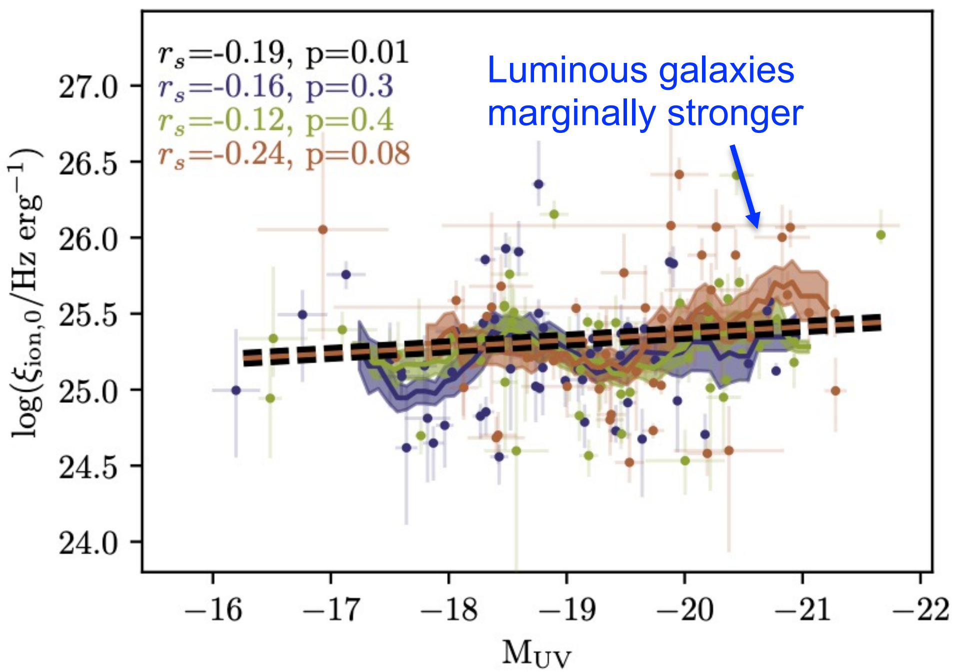
JWST Results for ξ_{ion} - II

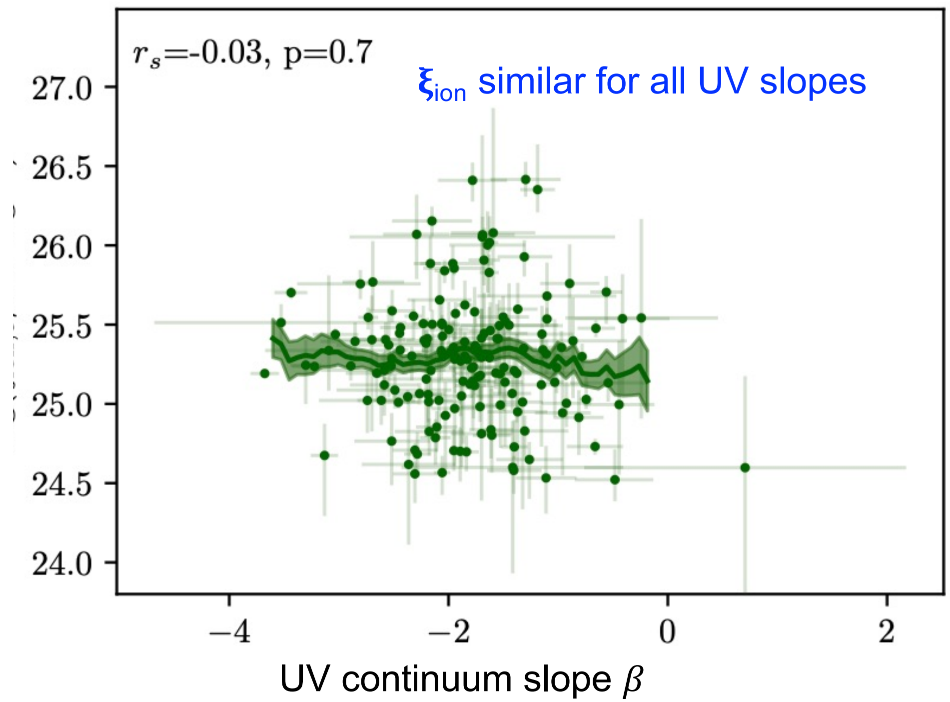
- **Photometric** study also hinted at strong luminosity dependence **ξ_{ion} (M_{UV})** and **UV slope β** trends which, together, suggest galaxies over-produce ionising photons! (Munz et al 2024)

- **Larger spectroscopic sample** provides more accurate measures of possible trends but note samples are not mass-limited.

JADES+CEERS: 167 galaxies 1.1 < z < 6.7 with Hα and Hβ emission

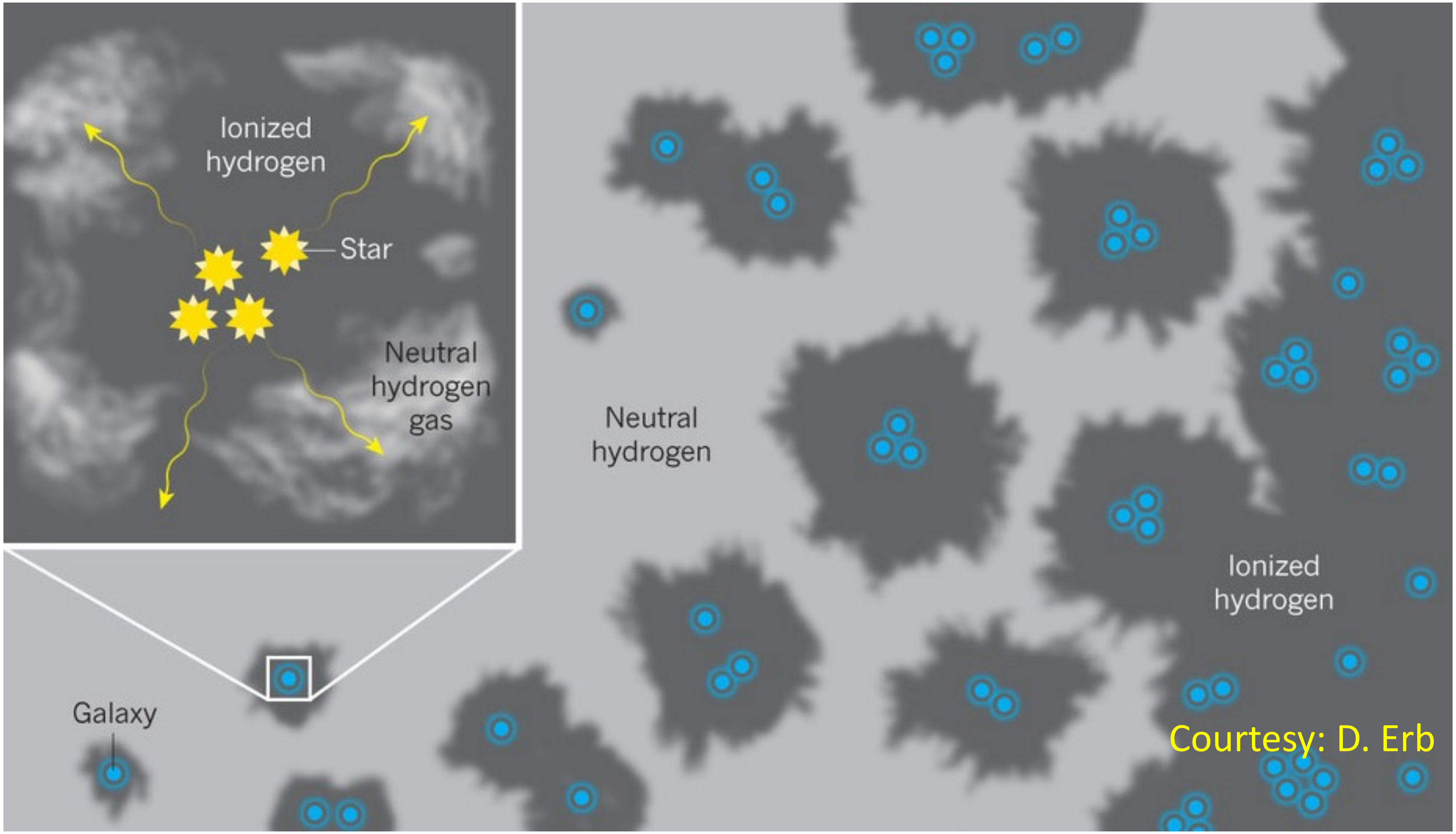
Much weaker **ξ_{ion} (M_{UV})** and **β** trends





Pahl et al 2024; see also Llenera et al 2024

Escape Fraction of Lyman Continuum Photons

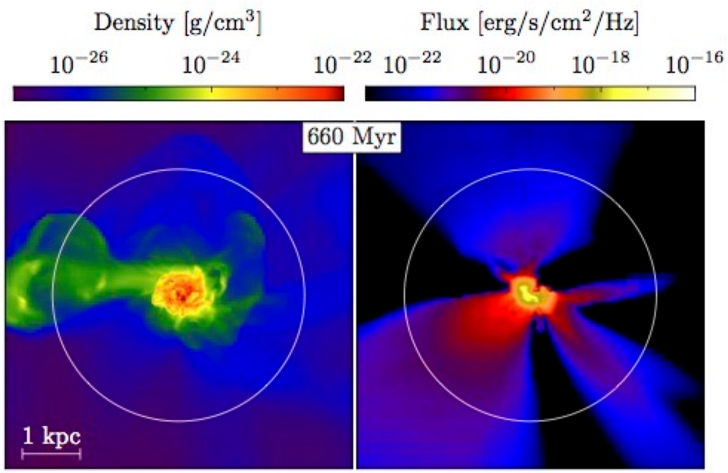


Quantified (inappropriately!) as an average fraction f_{esc}

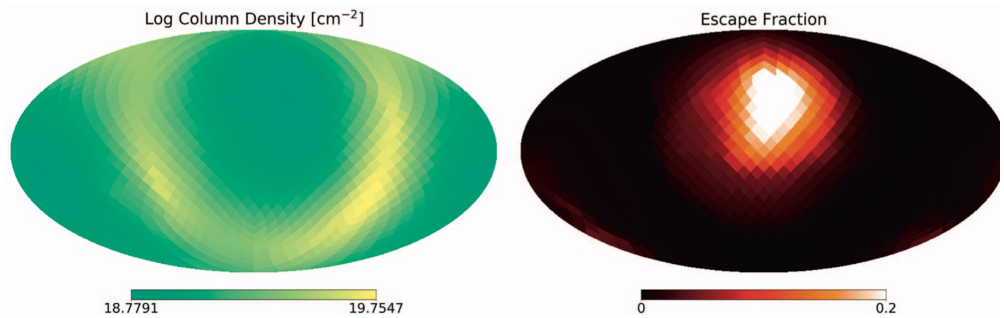
Require $\langle f_{esc} \rangle \geq 10\%$ to maintain reionisation given estimates of ξ_{ion}

Theoretical Perspective

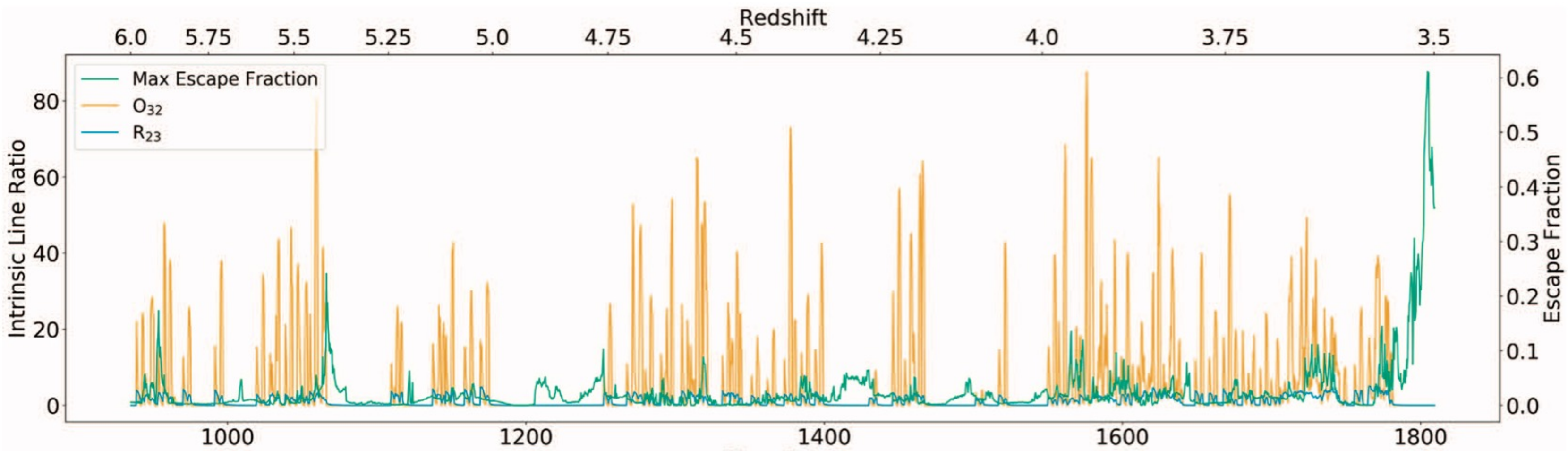
Simulations suggest young SF galaxies are porous with non-zero escape fractions
But emerging LyC radiation is highly time-dependent & anisotropic so expect large variations



Anistropic distribution of ISM HI & resulting f_{esc}



Correlations with specific star formation rate and various ionisation indicators



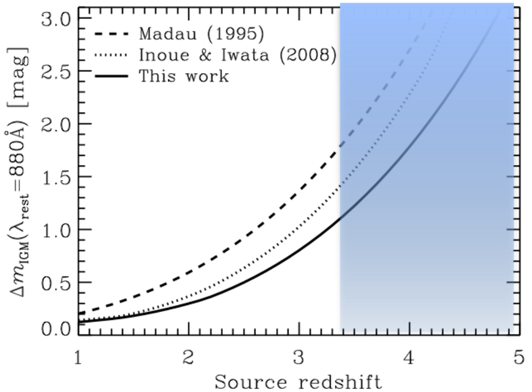
Since galaxies are more compact with more vigorous SF expect f_{esc} to increase with redshift

Wise et al 2014, Sharma et al 2015, Trebitsch et al 2017 Barrow, RSE et al 2020

Observing f_{esc} at High Redshift?

Attenuation of the IGM (mags) at rest-frame λ880 Å as a function of redshift (Inoue et al 2014)

Direct methods are limited to z<3.5



- **Direct rest-frame UV imaging and spectroscopy** – locate flux below LyC
  - straightforward at low redshift
  - challenging at intermediate redshift due to possible foreground contamination
  - not possible beyond z~3.5 due to increased IGM opacity (> 1.0 mag)
- **Recombination line analyses** (e.g. using Balmer lines)
  - provides joint constraint on ξ_{ion} and f_{esc}
  - now possible for 3.5< z < 9 with JWST
- **Statistical association between galaxies and IGM opacity**
  - promising new method and several variants

NB: The theoretical (ideal) definition of f_{esc} is the fraction of the ionising photons produced by stars that escape into the IGM without being absorbed by HI in the ISM. In practice we don't observe the intrinsic rate so often this is termed the (unobservable) absolute value $f_{esc,\,abs}$

In contrast, observers often use a relative value $f_{esc,rel}$

$$f_{\rm esc,rel} = \frac{\langle f_{900}/f_{1500}\rangle_{\rm out}}{(L_{900}/L_{1500})_{\rm int}}$$

observed

stellar synthesis model

Spectroscopic f_{esc} measures at z~3 - I

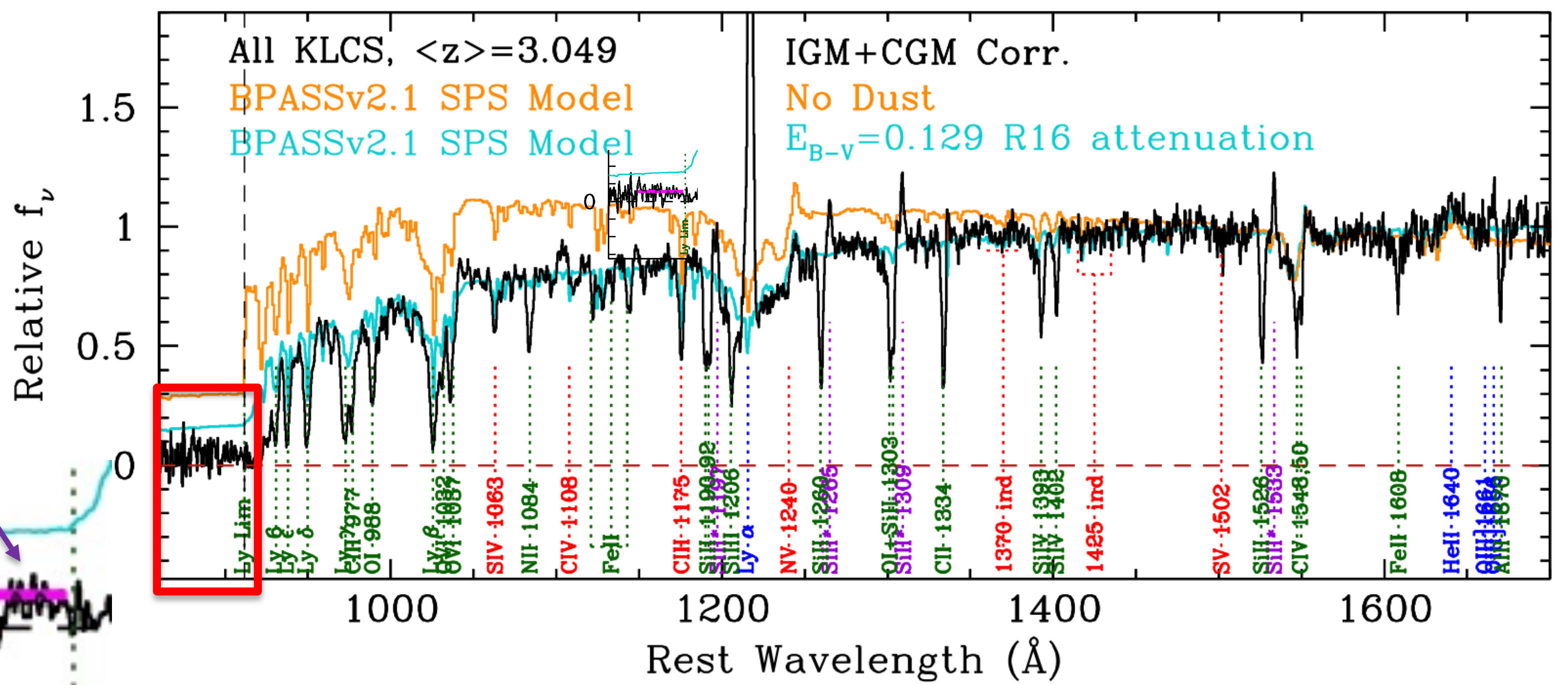
z~3 is a 'sweet spot' since Lyman limit enters optical and IGM opacity is modest

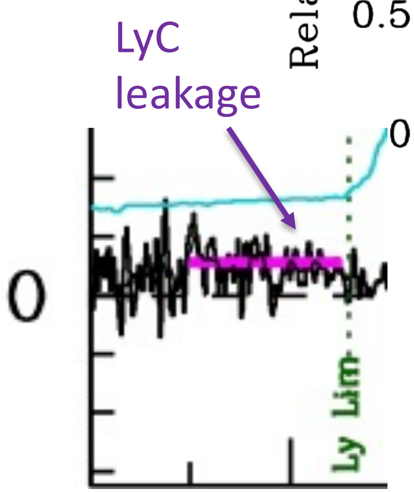
(i) <u>Ground-based spectroscopy:</u>

Keck LRIS spectra of 124 LBGs at <z> ~3.05

LyC signal mostly too faint to be detected individually (15/124 detections)

Analysis based on stacked spectra (which may be prone to foreground contamination)





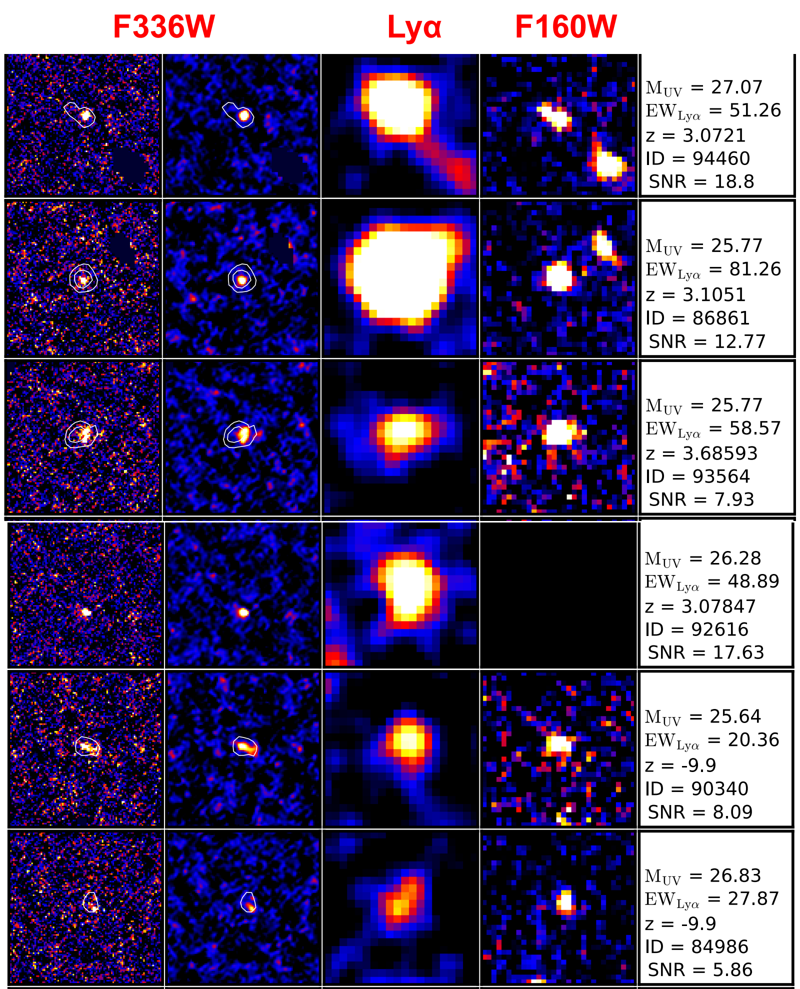
Model-independent f_{900}/f_{1500} = 5.7 ± 6 %

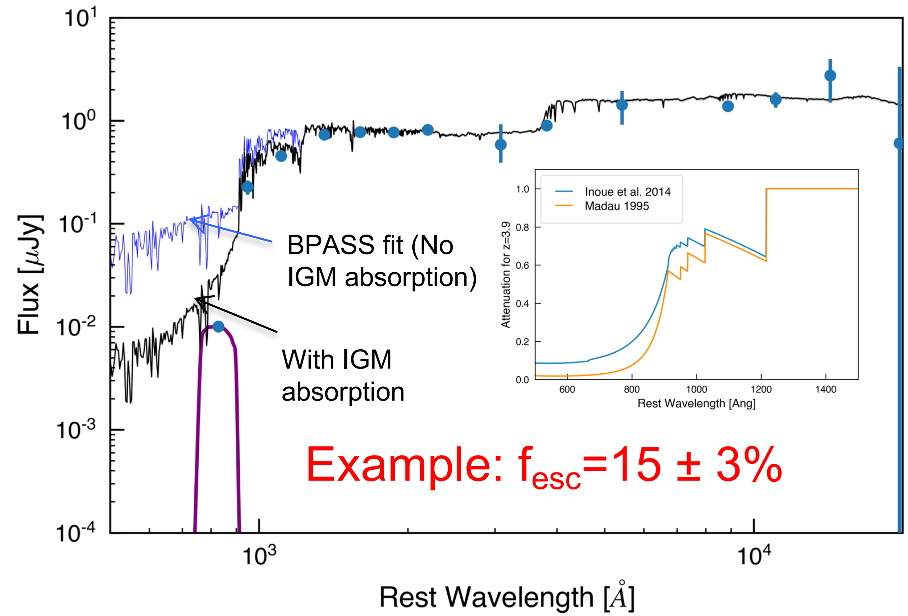
Model-dependent $f_{esc,abs}$ = 9 ± 1 %

Steidel et al 2018

HST UV Imaging of z~3 LAEs

Deep (20 orbits) F336W imaging of 61 z~3 LAEs (PI: B. Robertson)
plus associated F160W, Subaru and Spitzer imaging and Keck/VLT spectroscopy





Methodology:

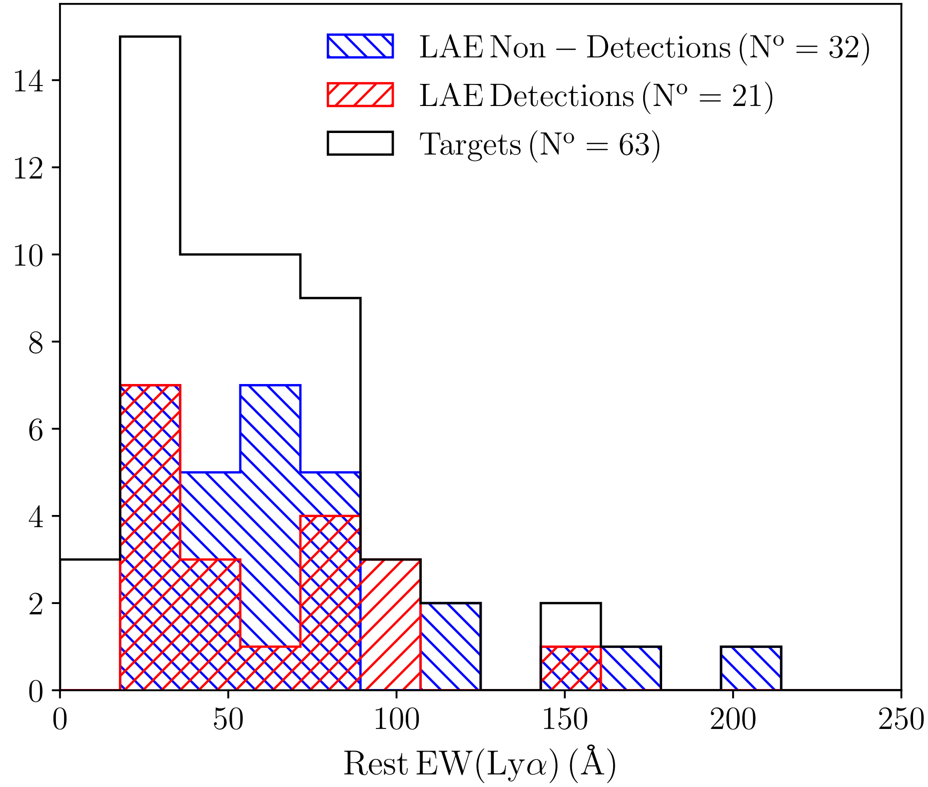
(i) Predict LyC flux using BPASS + nebular emission (calibrated with MOSFIRE [O III]/Hβ fluxes)

(iii) IGM absorption: Adopt Inoue et al (2014) distribution to get f_{esc} likelihood

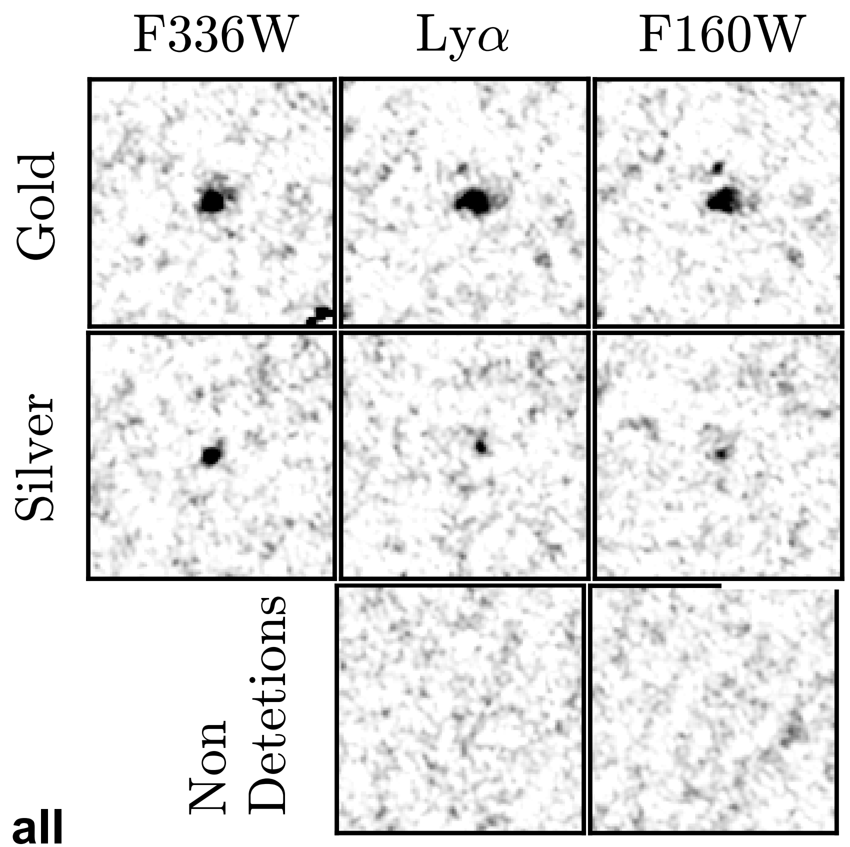
Fletcher, RSE et al 2019

LACES: Puzzling non-detections

32/61 sources have **no F336W** detections to AB=30.2 (3σ, 1.5×PSF)
For a typical individual source this implies f_{esc}< 1.5%
Demographically this population is similar to those with detections [in EW(Lyα) below]
Yet, remarkably, **a stack reveals no signal (corresponding to < f_{esc} > ~ 0.3%**



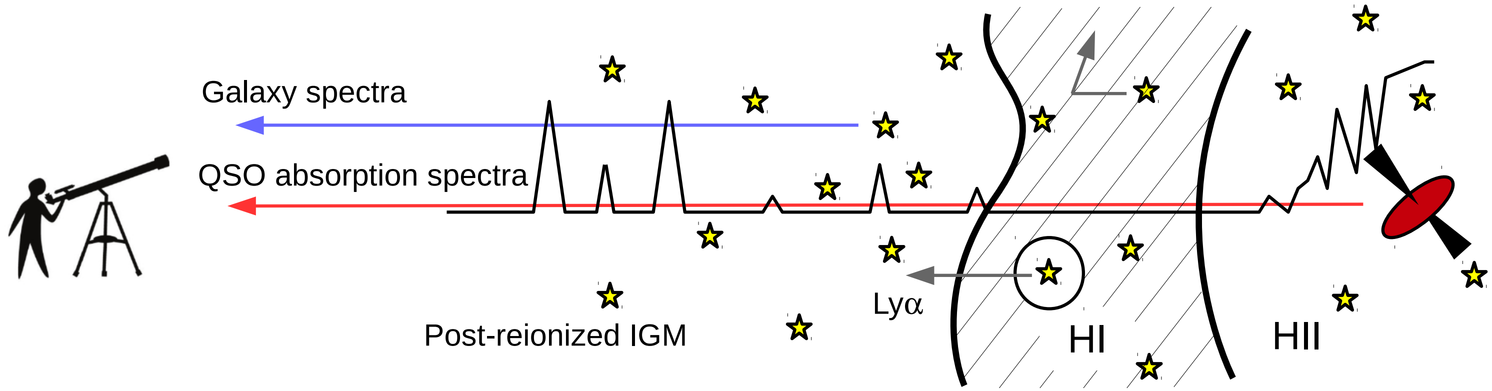
LyC stacks centroided various ways



So LyC radiation is either present or not at all
Anisotropic geometry?

Fletcher, RSE et al 2019

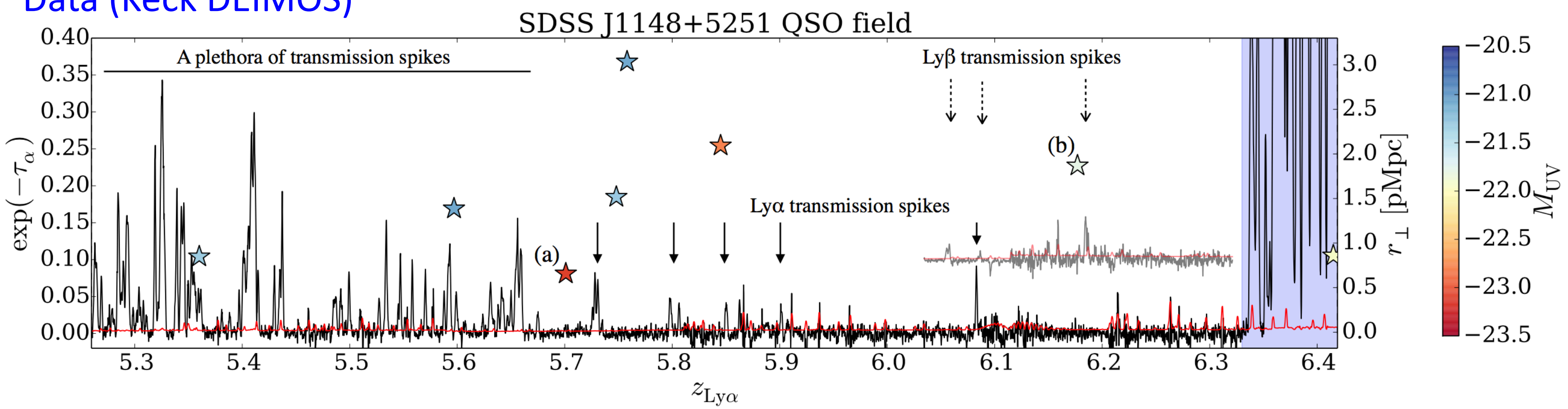
A New Route to the z > 3 Escape Fraction- I



Koki Kakiichi

Balance ionisation state of intergalactic medium deduced from fluctuations in Lyman α absorption in z>6 QSO spectra with contribution from galaxies in same cosmic volume

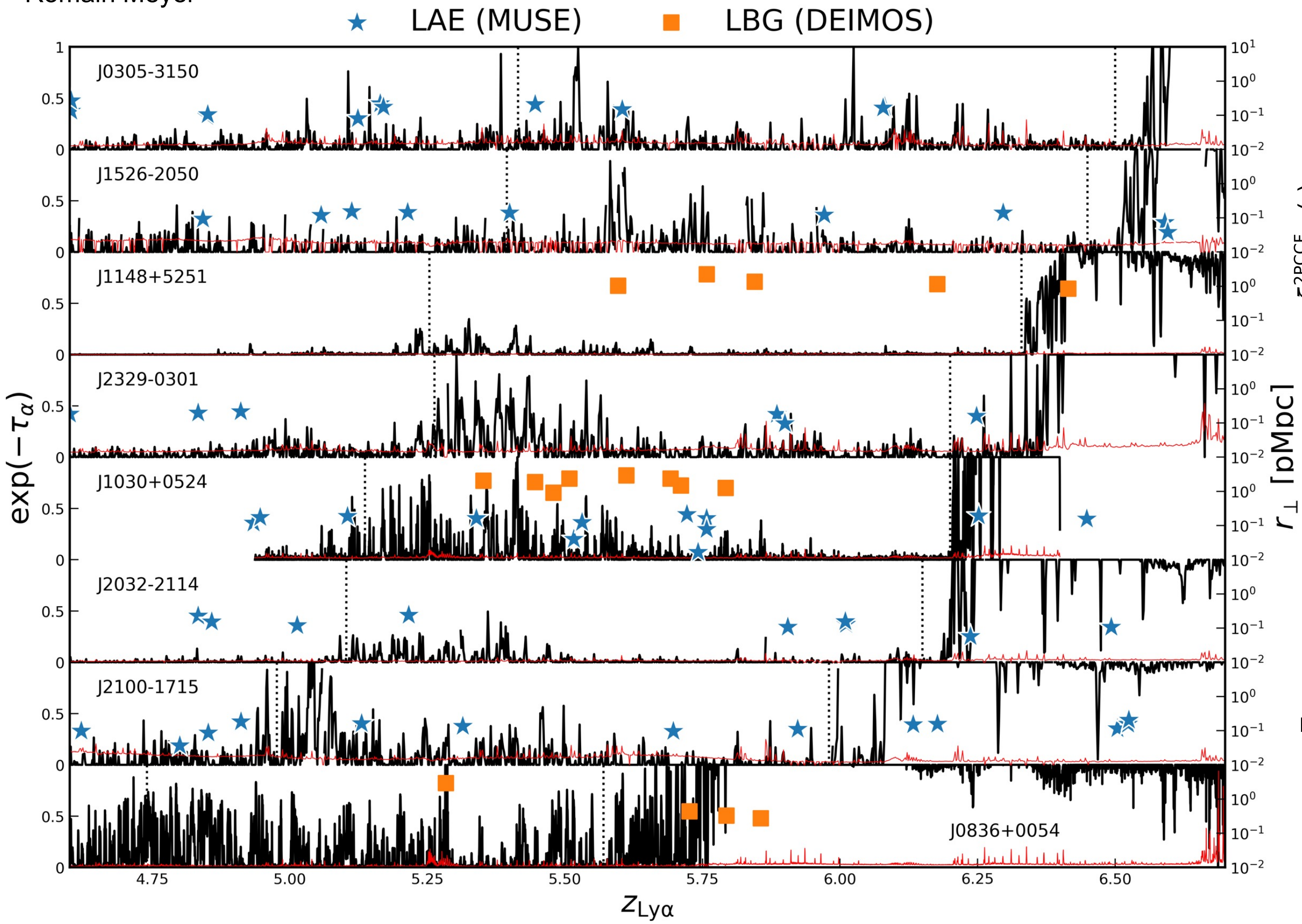
Data (Keck DEIMOS)



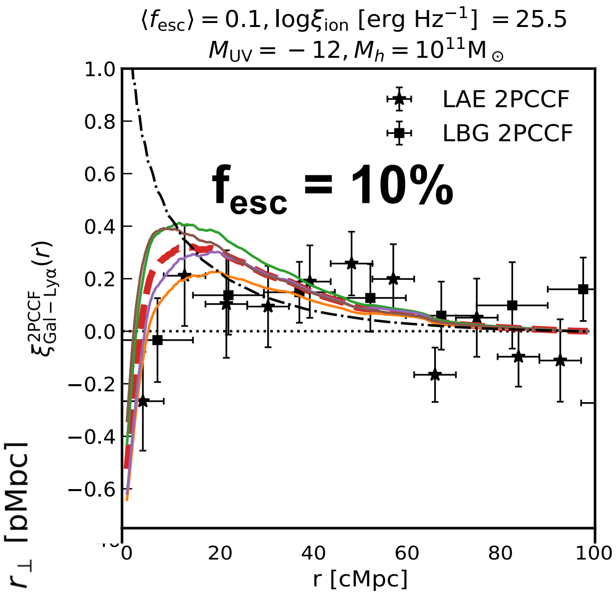
Kakiichi, RSE et al 2018

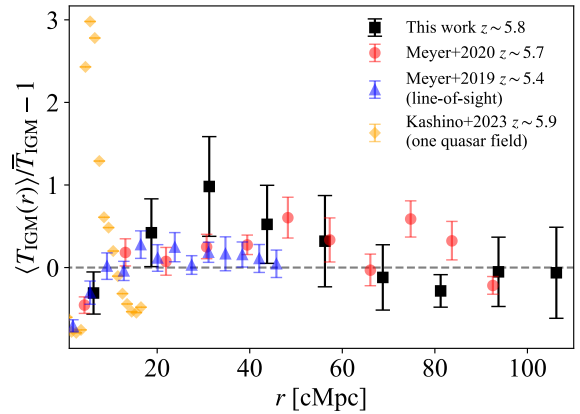
A New Route to the Escape Fraction - II

Romain Meyer



Cross-correlation





Survey of 8 QSO Lyα forest sightlines

DEIMOS (LBGs) + MUSE (LAEs) = 44 sources

Lyα-galaxy cross-correlation suggests $f_{\mathrm{esc}} \simeq 10\%$

Meyer, RSE et al 2020

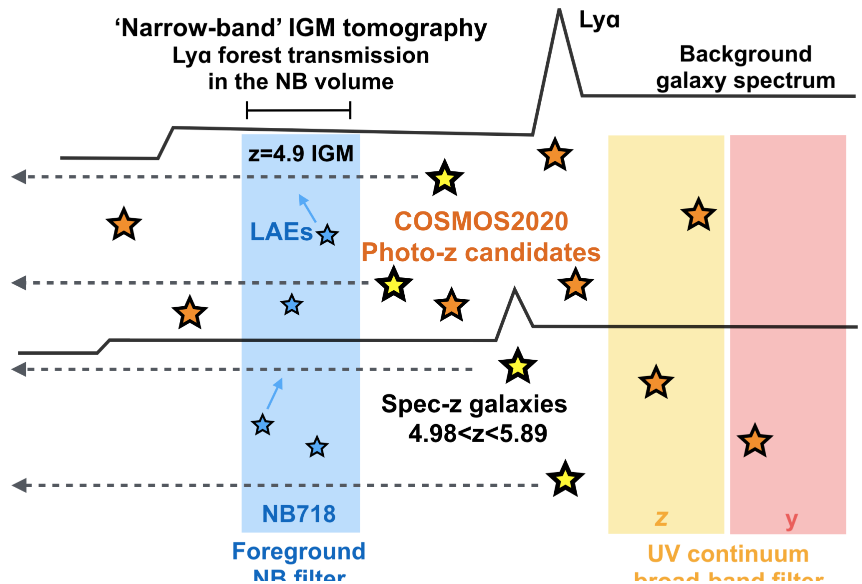
JWST ASPIRE:

5 QSO sightlines 49 [O III] emitters

Kakiichi et al 2025

Even Better Route to the Escape Fraction

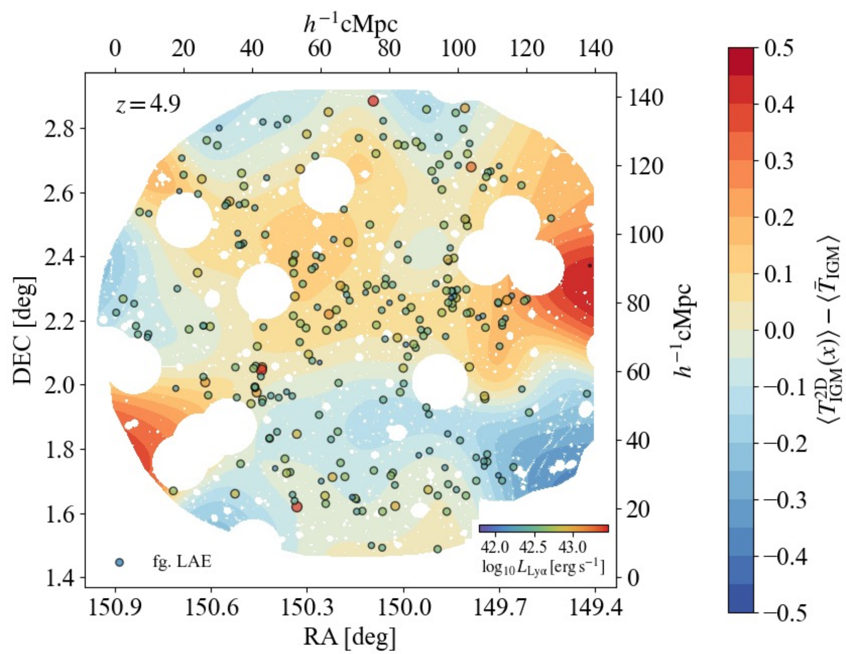
New method



QSO absorption line method is limited to single sightlines. New method uses panoramic Subaru NB filters to measure Lyman α opacity at **fixed absorption redshift** for large sample of background galaxies and locates LAEs in same foreground volume!

Huge increase in number of cross-correlated galaxy-absorber pairs!

Proof of concept: tomographic map of Lyα opacity c.f. LAEs



Major requirements:

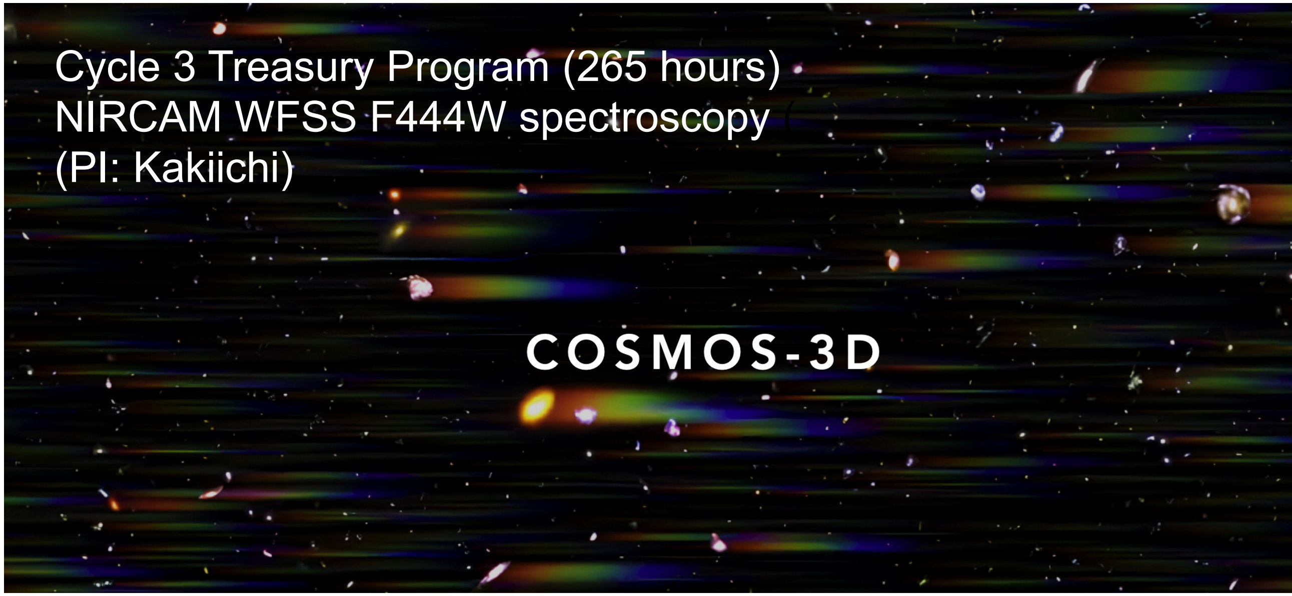
(i) Ultradeep Subaru NB images

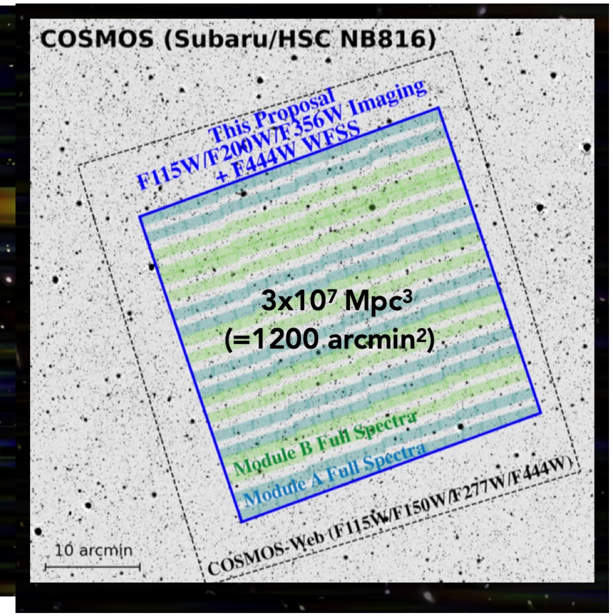
(ii) Spec-z's for all background galaxies!

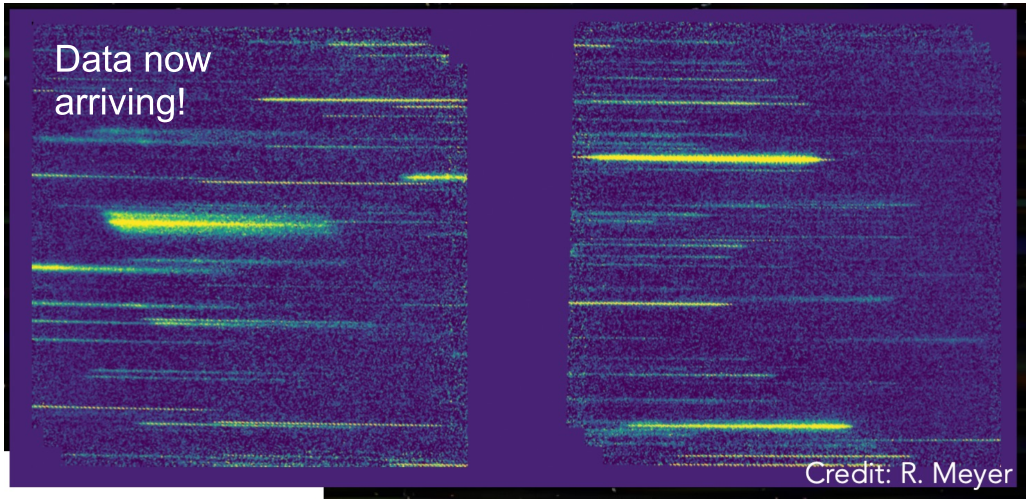
Kakiichi, RSE et al 2022

COSMOS-3D survey

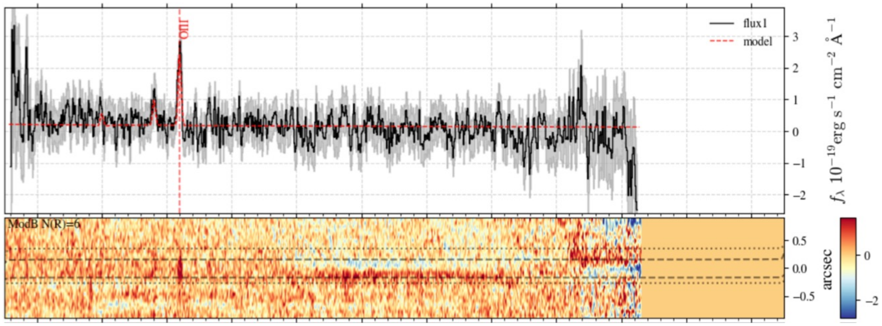
Charting background galaxies in the Subaru NB fields with JWST!







z = 7.22 [O III] emitter



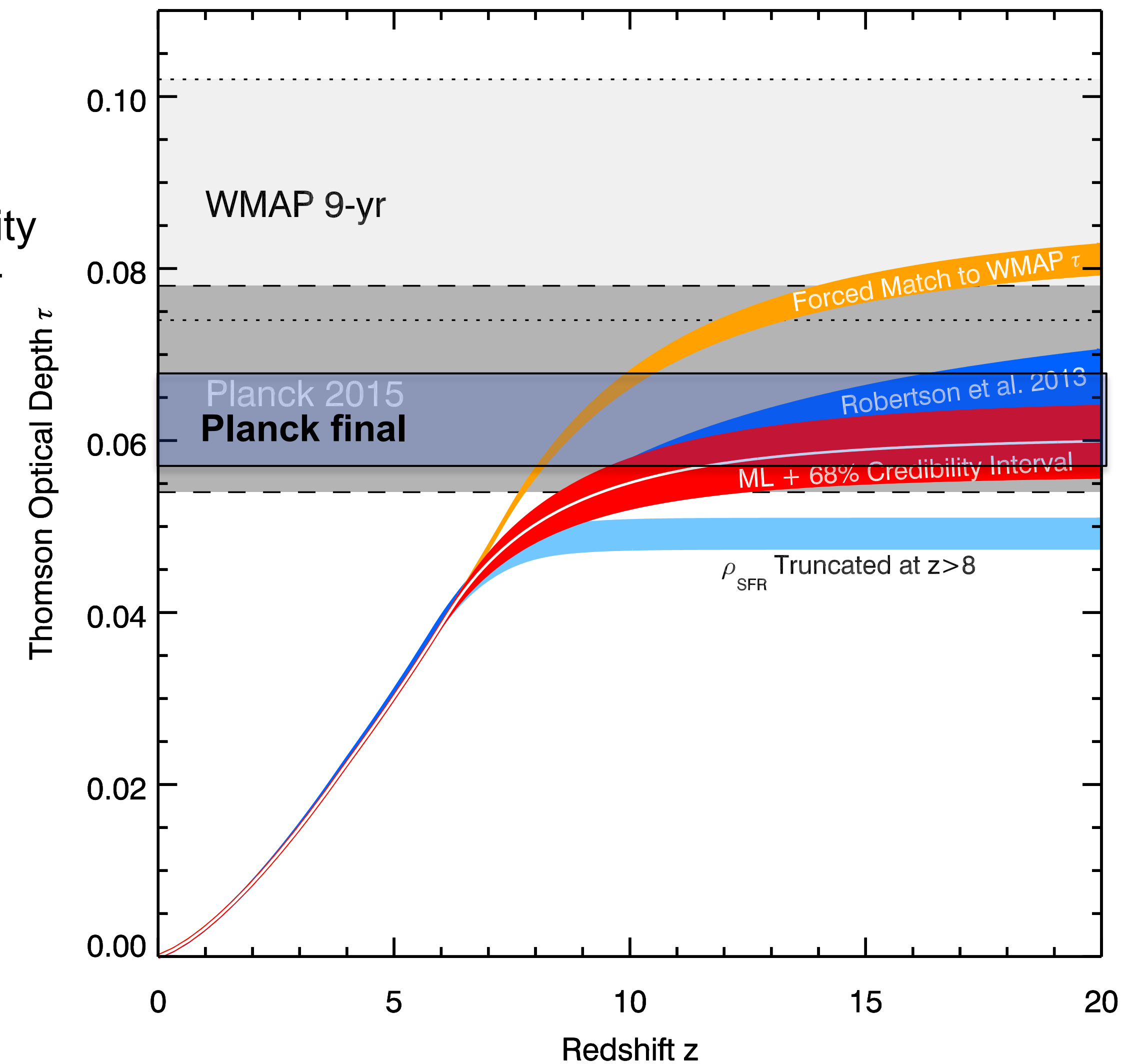
Reconciling HST Demographics with Planck τ

Pre-JWST assumptions that incorporate

- HST-based integrated UV luminosity density of galaxies $\rho_{UV}(z)$ to z~10+
- An average intrinsic ionisation rate **$\langle \log \xi_{ion} \rangle$ ~ 25.5 cgs** and escape fraction **$\langle f_{esc} \rangle$ ~10%** for all star-forming galaxies

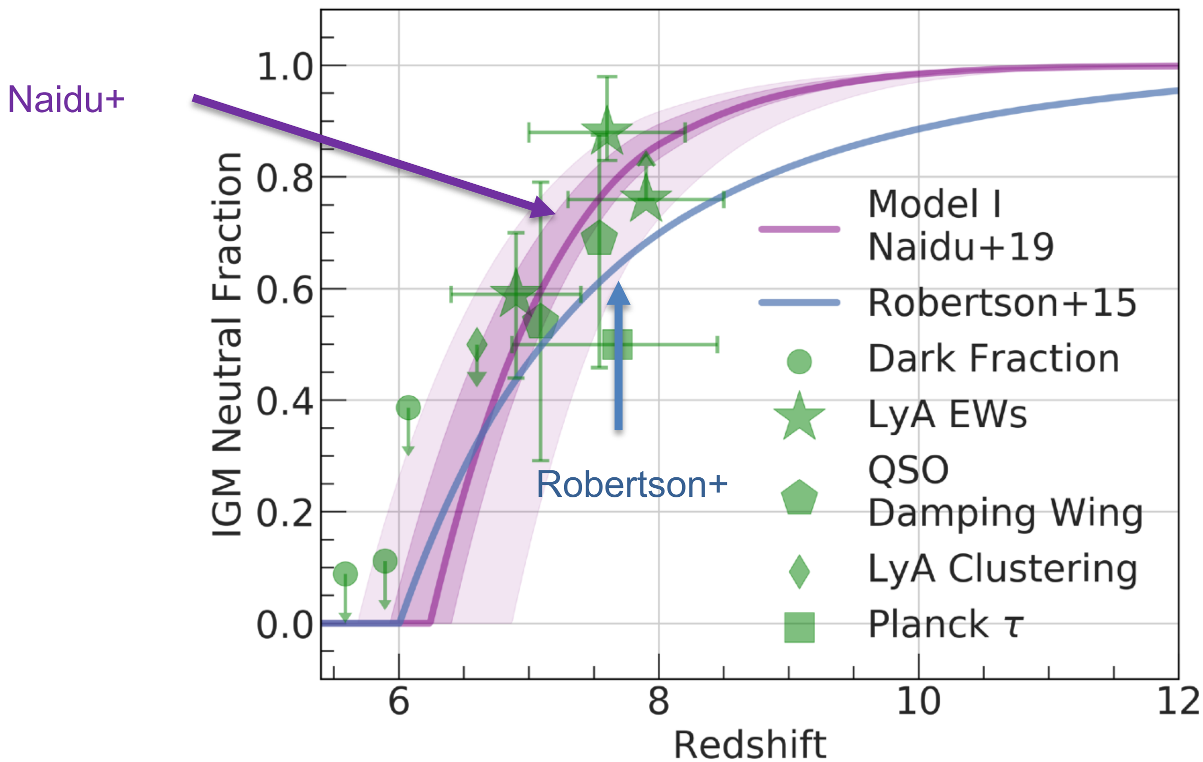
The galaxy demographics from HST matches Planck's optical depth with reionisation from 15 < z < 6

To the accuracy this is possible, with the exception of the escape fraction, these assumptions are broadly supported by the early JWST data



Robertson, RSE et al 2015: see also Bouwens et al 2015, Mitra et al 2015

Pre-JWST Models of Reionisation History



Robertson, RSE et al (2015) – historic paper based on HST galaxy demographics to z~10 fit to Planck $\boldsymbol{\tau}_e$ assuming all galaxies have equal ionising capabilities (ξ_{ion}, f_{esc}) regardless of redshift/luminosity

Naidu et al (2019) – IGM neutral fraction data $X_{HI}(z)$ indicates a **more rapid end to the reionisation process suggesting massive galaxies/AGN contribute**

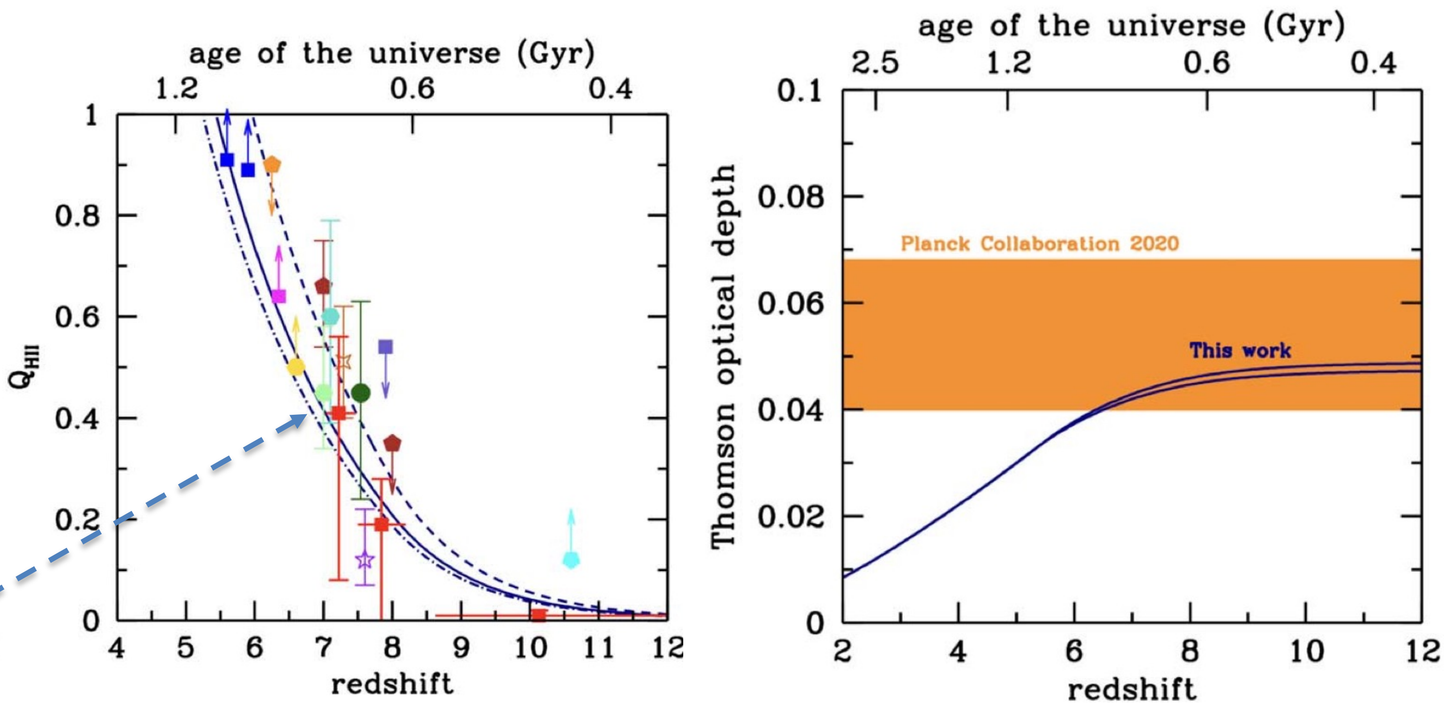
Is it likely that AGN make a significant contribution to reionisation at z < 8?

Possible Role of AGN?

Madau et al have suggested **AGN may dominate the reionisation process!**

They argue the required **f_{esc}~10-20%** from star-forming galaxies is not demonstrated.

Certainly we expect galaxies with AGN to have higher ξ_{ion} and **f** $_{esc}$ than galaxies. But how to estimate the AGN contribution of a galaxy?



Model claims to match the observed reionisation history $Q_{HII}(z)$ and the Planck τ
But with very debatable assumptions:

(i) ρ_{UV} - 15% of galaxies at all z, M_{UV} contain AGN
(ii) **f_{esc}** > 80% for all AGN
(iii) **M_{UV}** – non-thermal component > 50%

Madau et al 2024

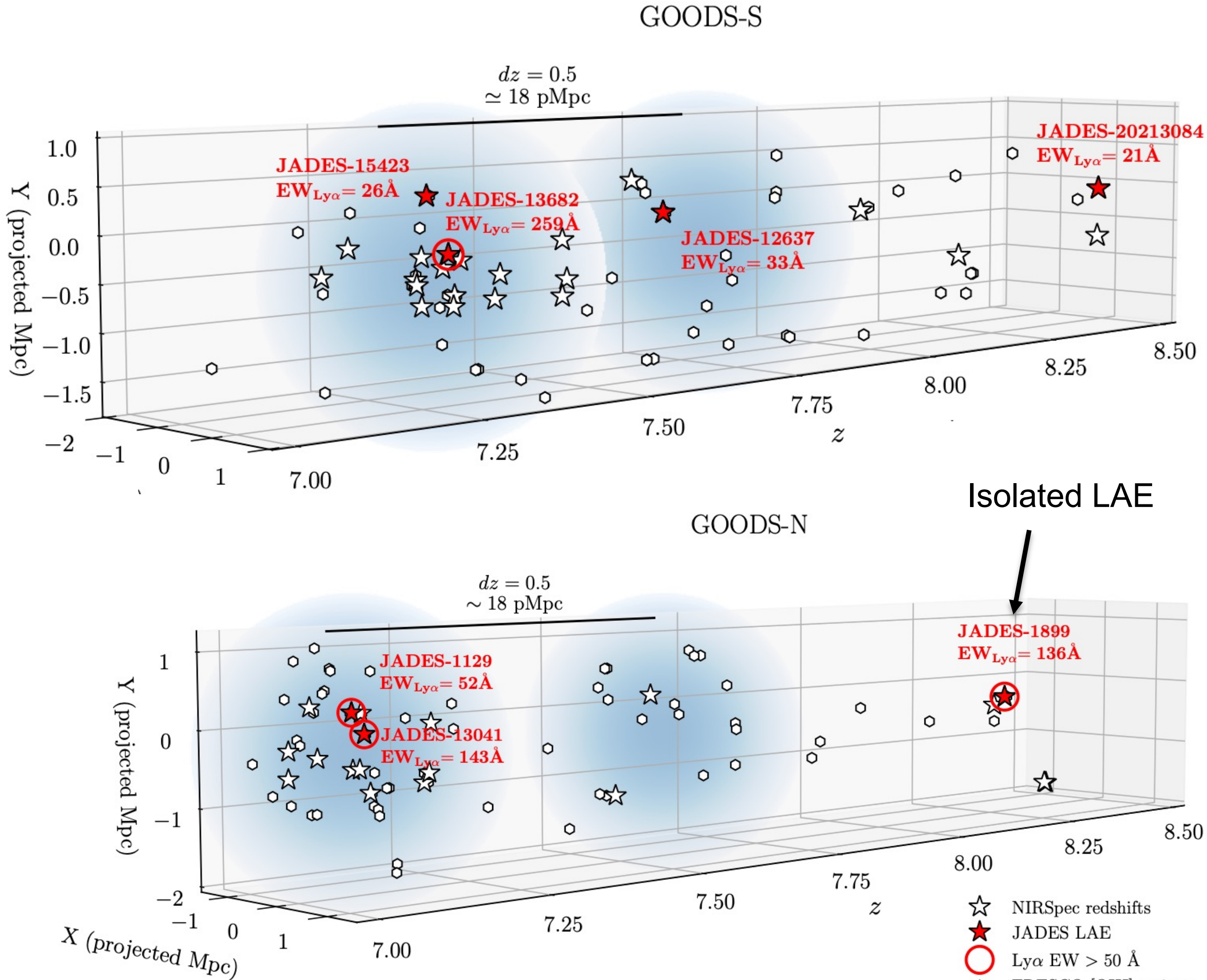
Charting Ionised Bubbles with Lyman α

It's reasonable to assume the escape of Lyα(1216Å) is a proxy for escaping LyC radiation capable of ionising the IGM and hence for tracing ionised bubbles

Use [O III] emitters from FRESCO as reliable indicators of overdensities in both GOODS fields given the blind nature of its NIRCam grism survey

Can see several Lyα emitters are found in these clusters

Isolated examples of high EW (Lyα) may be solely capable of ionising their surroundings.

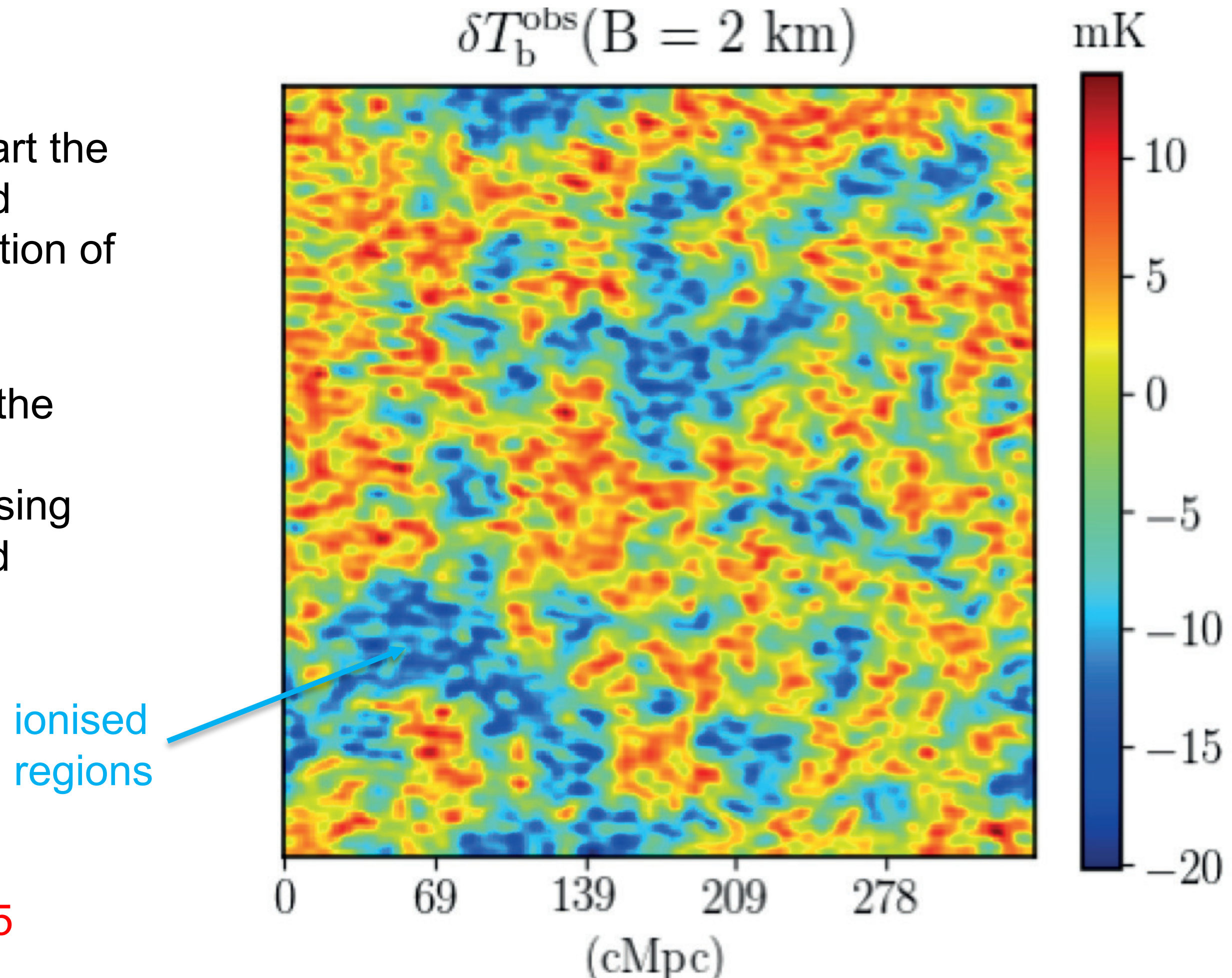


Tang, RSE et al 2024b

SKA 21cm Tomography

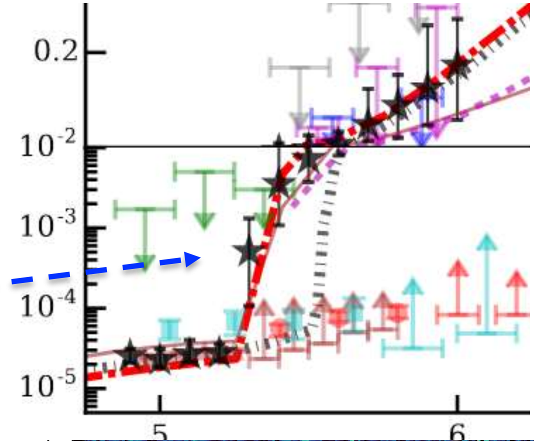
In the longer term (2030+) SKA-Low may be able to chart the contrast between neutral and ionised regions with a resolution of ~ cMpc from 6 < z < 12.

By correlating this map with the positions and redshifts of JWST sources, both the ionising capabilities, bubble ages and escape fractions may be determined.



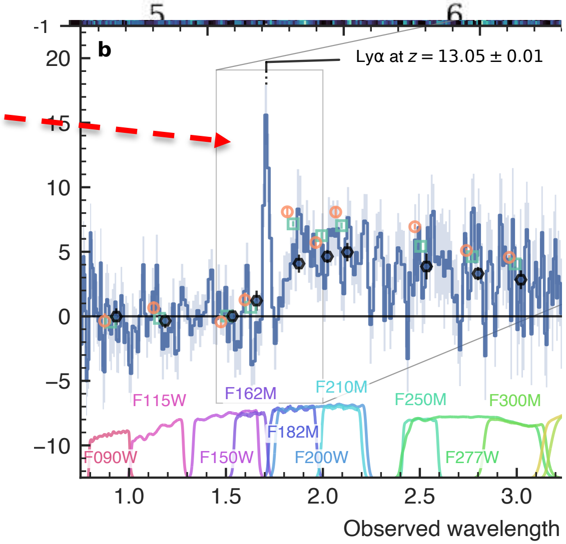
Koopmans et al 2021;
Gagnon-Hartman et al 2025

Reionisation: Synopsis & Prospects

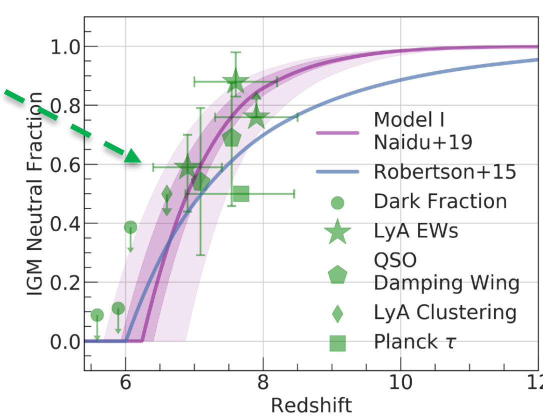


When: QSO data shows declining opacity below z~6 to z~5.3
NB: Defining “the end” is academic i.e. $x_{HI} \simeq 0$?

Planck can’t rule out ionisation beyond z~12
Detection of Lyα at z=13 (Witstok+24) confirms
No constraints yet beyond z~15
Absence of z>15 galaxies consistent with N (z < 15)



How: No strong luminosity trends in ionising parameters?
Would suggest feeble galaxies dominate
Fundamental limitation is poorly-known f_{esc}
JWST AGN numbers higher but still modest contribution?
Key result is rapid change in x_{HI} for z<7.5 – late AGN?

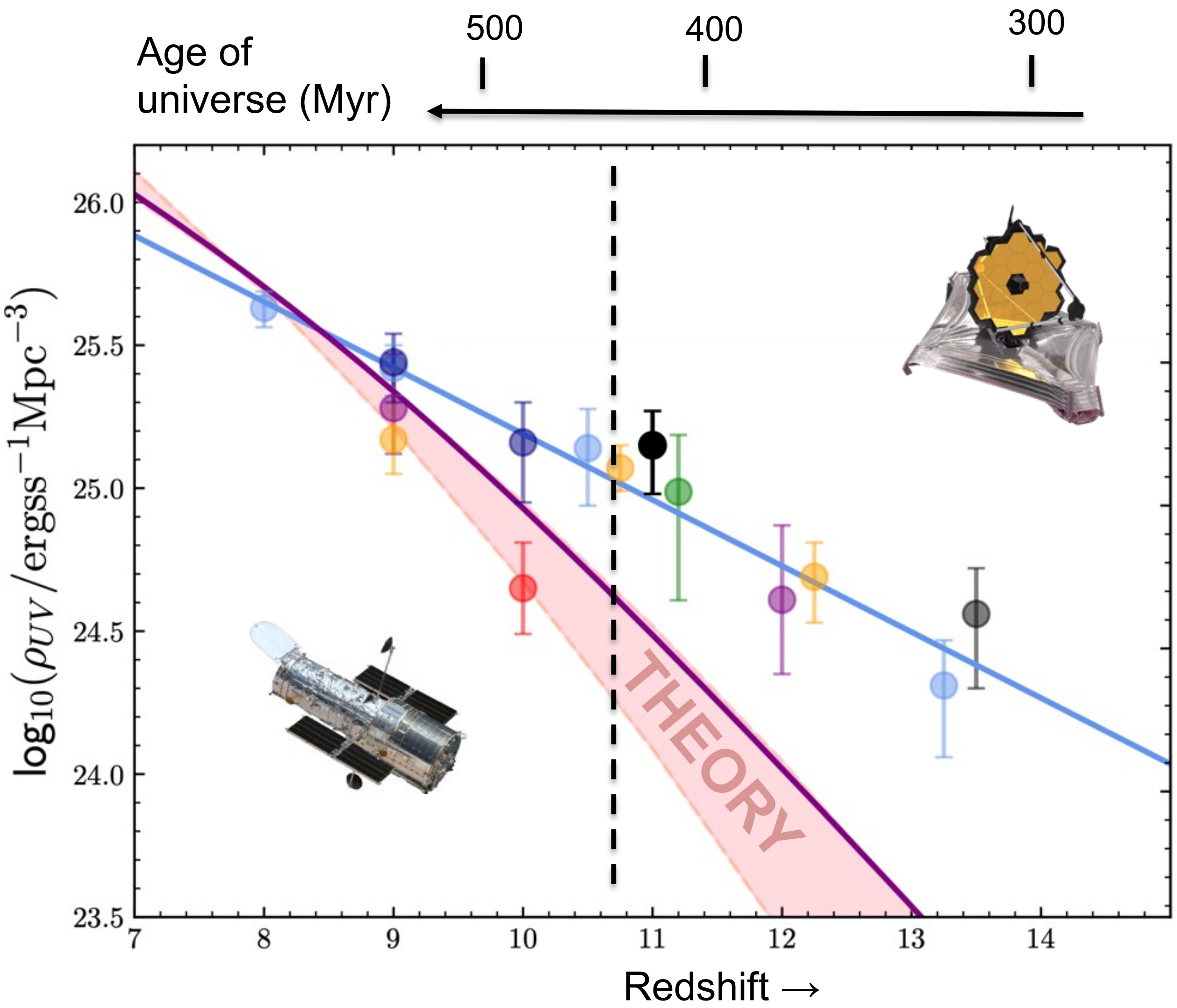


Future: Need to determine escape fraction for larger samples
with a range of masses, spectral classes etc
Methods connecting directly with IGM opacity more effective
SKA may ultimately contribute via 21cm tomography

Redshift Frontier: Early JWST Census to z~14

Derek McLeod

Immediate result: galaxies to z~13, ruling out rapid decline @ z>8



Unlike HST data to z~8 JWST data inconsistent with stars forming from gas clouds with a constant efficiency.

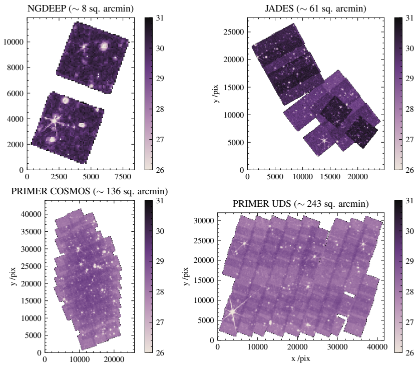
Galaxies beyond z>10 are too luminous!

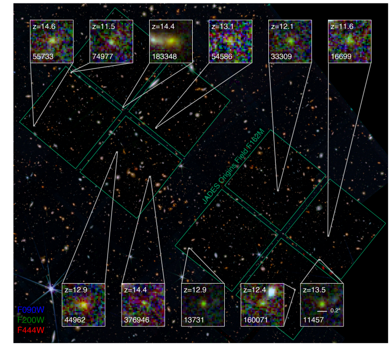
e.g. McLeod, RSE et al 2023

See also: Naidu+22; Castellano+22; Finkelstein+22; Harikane+22; Bradley+22; Atek+22; Adams+22,;Yan+22,;Donnan+22; Bouwens+22

Subsequent Developments – Wide vs Deep

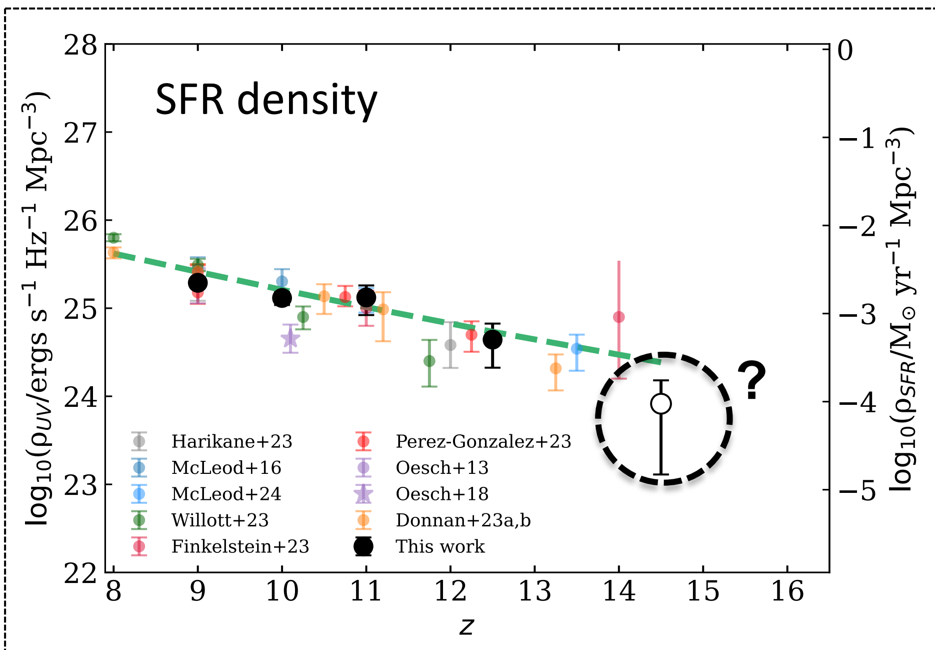
Callum Donnan



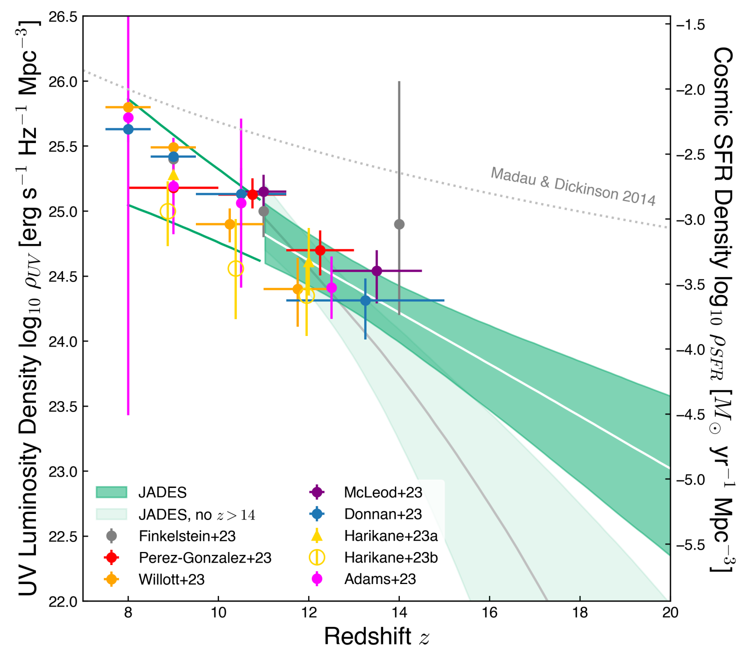


PRIMER+others ~400 arcmin² (10×ERS fields)
Tiered wide+deep gives ΔM_{UV}~ 4 mag range @ z~11
2548 galaxies z_{phot} > 8.5 with robust prior for p(z)
SFR density remains high with hint of decline at z~14.5

JADES Origins Field: ultra-deep (m_{AB}~30.5)
Two fields 9.05 arcmin² exposed for ~7 days
Probe 12<z<20 via 14 JWST filters+HST
Located 8 galaxies 11.5<z<14.4
No z>15 galaxies - consistent with decline



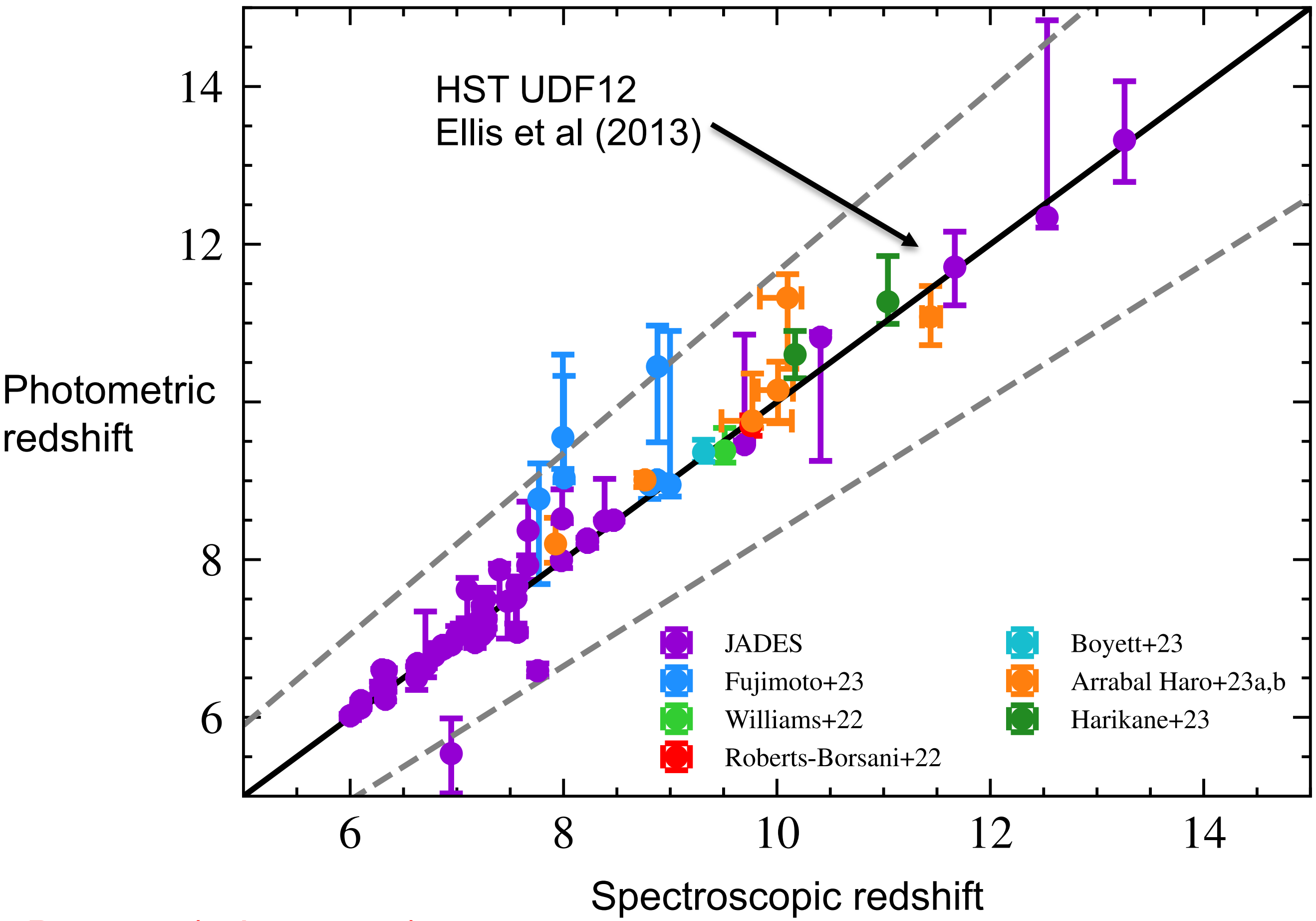
Donnan, RSE et al 2024



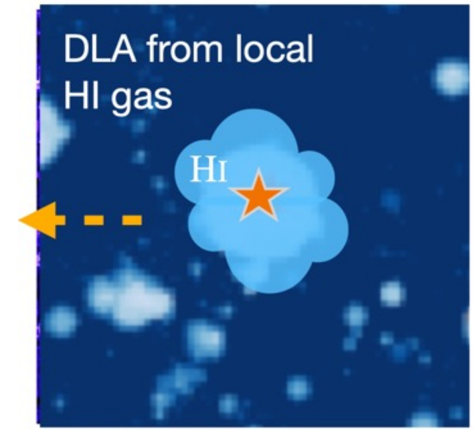
Robertson et al 2024

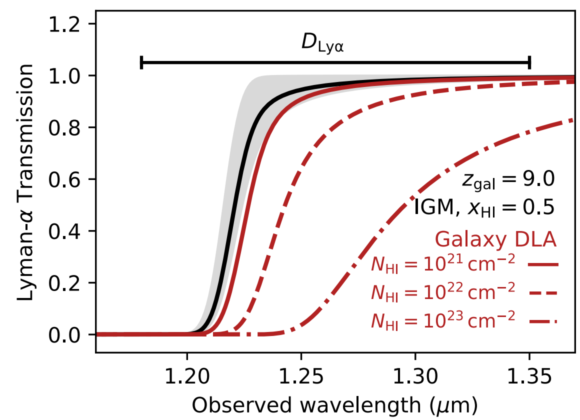
JWST Spectroscopic Confirmations so far…

With a few exceptions, there is generally remarkably good agreement between JWST multi-band photometric redshifts and subsequent spectroscopic measures. There is a small bias *Δz* ~ 0.10-0.15 to higher photometric redshifts due to *in-situ* H absorption



Donnan (priv. comm)





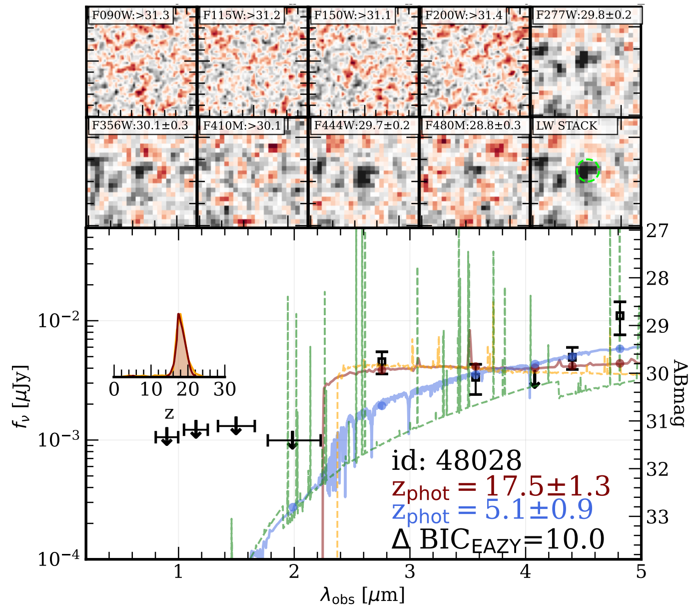
Heintz et al 2024

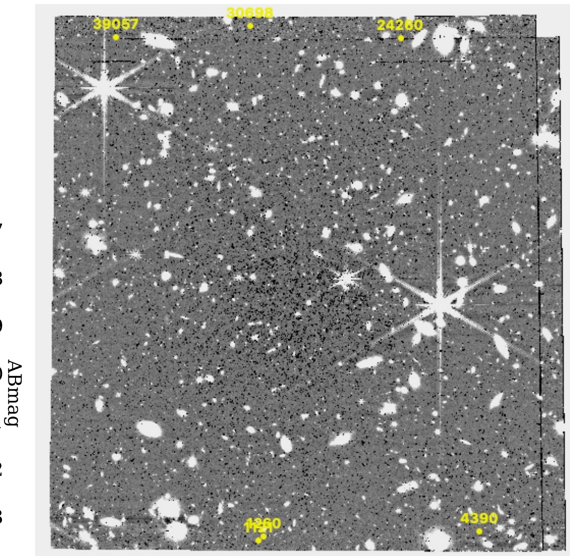
Recent Claims for z > 16 galaxies

The GLIMPSE survey has proposed 5 z>15.9 candidates based on deep NIRCam photometry

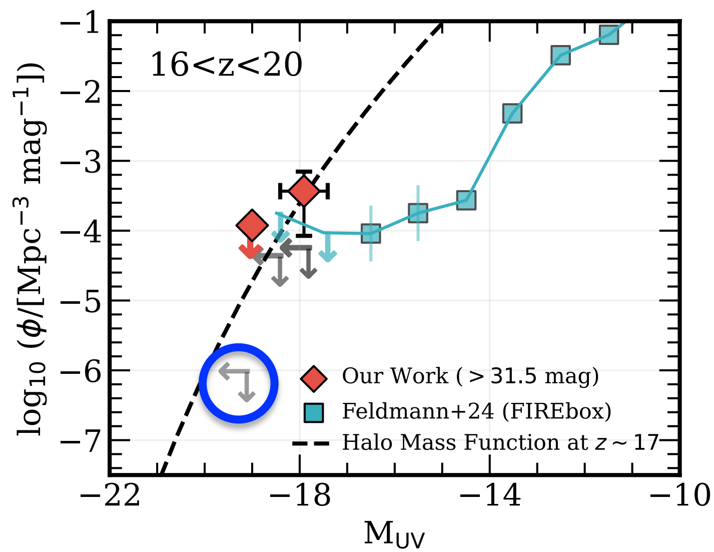
Some cautionary remarks:

- The redshift range 16<z<18 is tricky due to the possibility of strong optical emission from z~5 galaxies at 2-4μm (a la Donnan et al)
- The candidates lie near the edges of the imaging frames where the photometry is perhaps less reliable



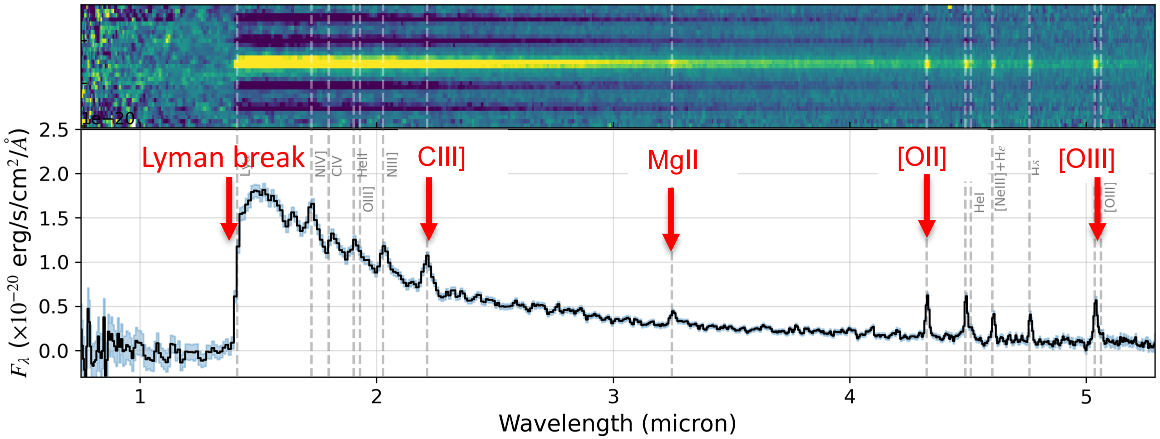


The implied comoving density is in tension with limits provided by the JADES Origins Field to a similar depth (lensing magnification would be minimal at the periphery of Abell S1063



Kokorev et al 2024

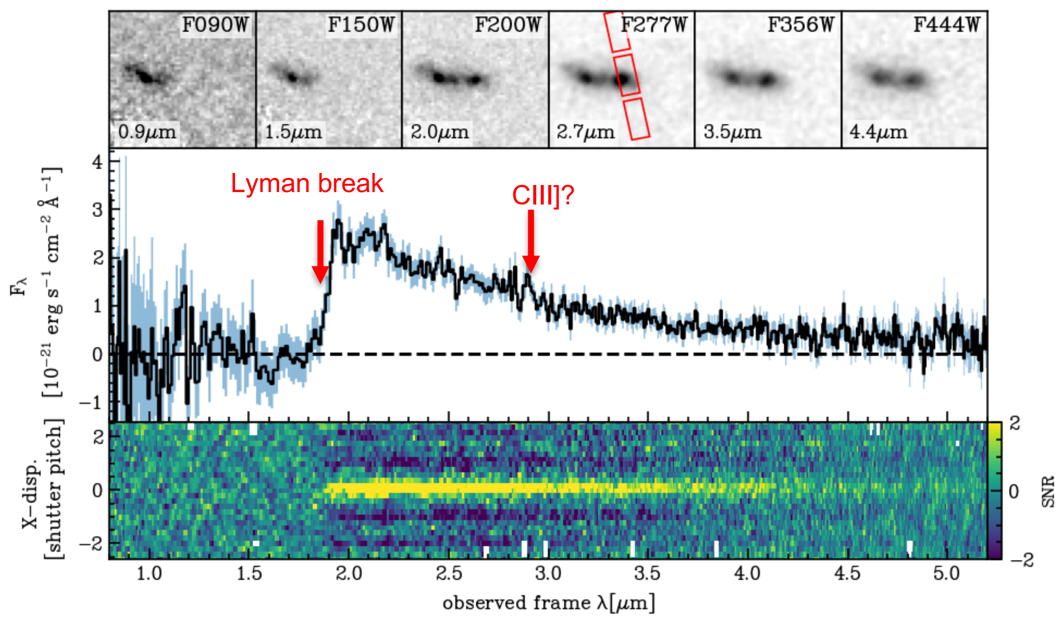
Properties of super-luminous z>10 galaxies



GN - z11:

Originally claimed via HST Lyman break (Oesch et al 2016)

z_{spec}= 10.60
M_{UV} ~ -21.5
radius ≈ 100pc
M* ~ $10^{8.7}$ $M_\odot$
SFR ~ 25 $M_\odot$ yr^{-1}



JADES-GS-z14.0: current record holder

Originally disfavoured by the JADES team as it's 0.4 arcsec from a foreground z~3.5 galaxy, but perseverance paid off!

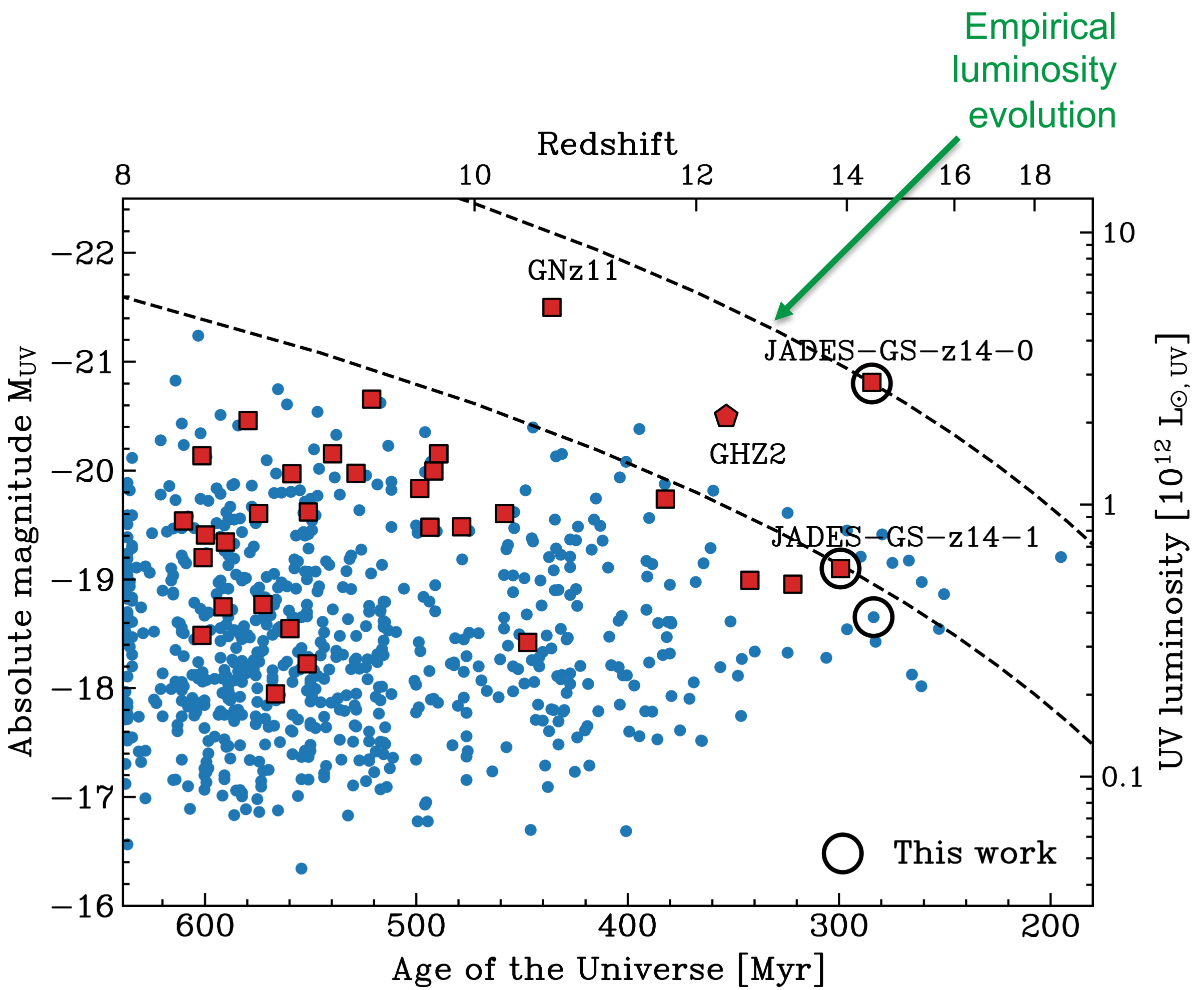
z_{spec}= 14.1 (ALMA)
M_{UV} ~ -20.81
radius ≈ 200pc
M* ~ $10^{8.7}$ $M_\odot$
SFR ≤ 20 $M_\odot$ yr^{-1}

Bunker et al 2022; Carniani et al 2024

See also: Curtis-Lake+22; Arrabal Haro+23; Harikane+23; Wang+23; Atek+23; Hainline+24

What's going on?

The discovery of four spectroscopically-confirmed z>10 super-luminous galaxies in such small cosmic volumes is a tantalising indication that **new time-specific physical processes may be responsible,** perhaps related to the onset of cosmic dawn



Carniani et al 2024

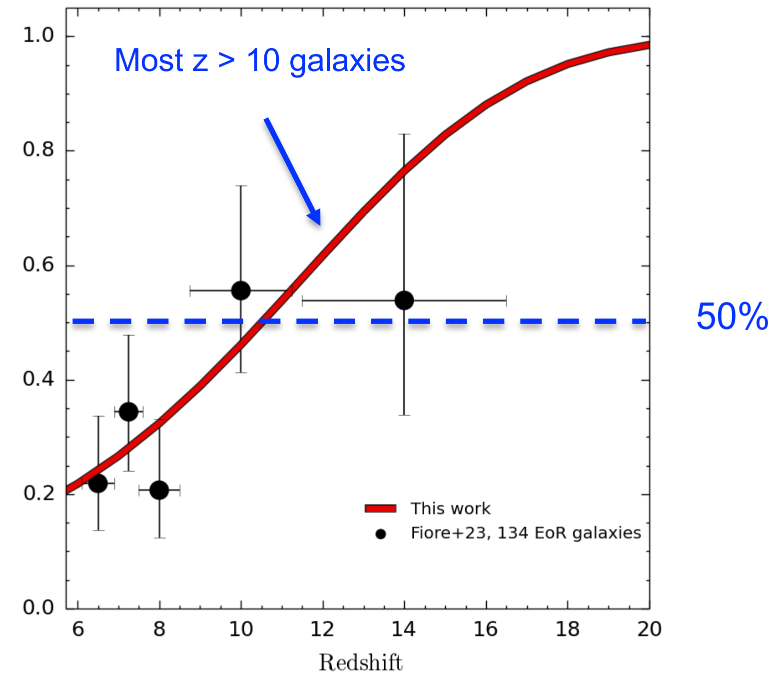
Many explanations!

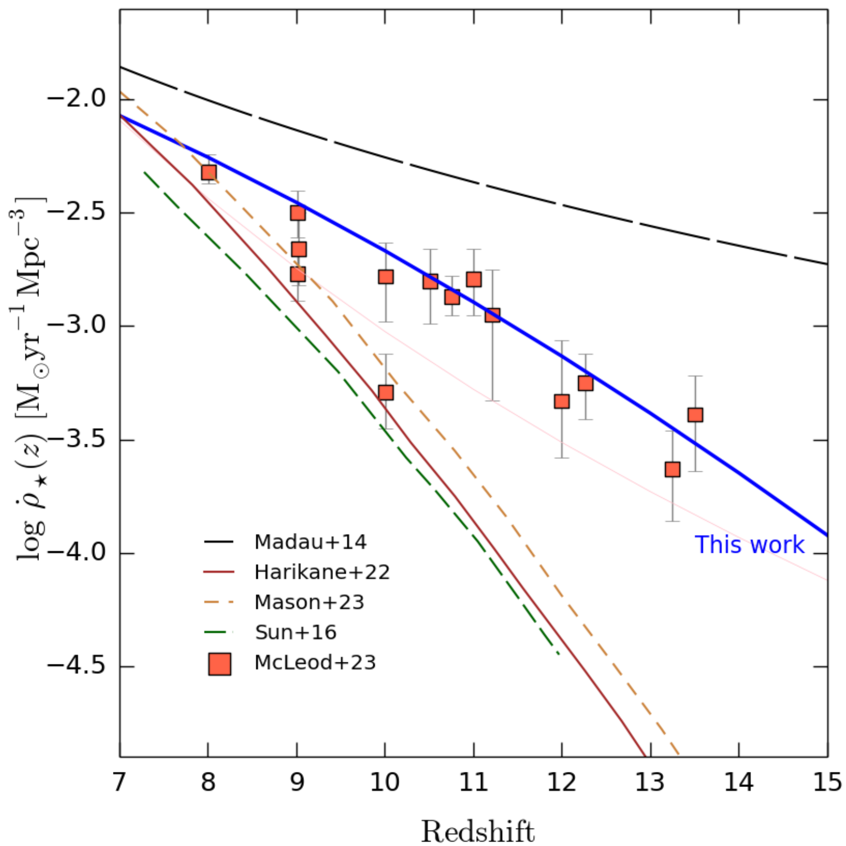
- **ejected dust?**
- (Ferrara+23)
- **ineffective feedback?** (Dekel+23)
- **biased detection via bursty SF?**
- (Shen+23,24, Gelli+24,Kravtsov+24)
- **top-heavy IMF/low Z**?
(Harikane+23, Menon+24)

Dust-free galaxies at z > 10?

Ferrara (2022, 2023) proposes that at z >10 increased specific SFR leads to radiation pressure-driven outflows expelling dust. This reproduces JWST SFR density observations and model matches limited outflow data

Fraction of critical outflows derived from sSFR distribution



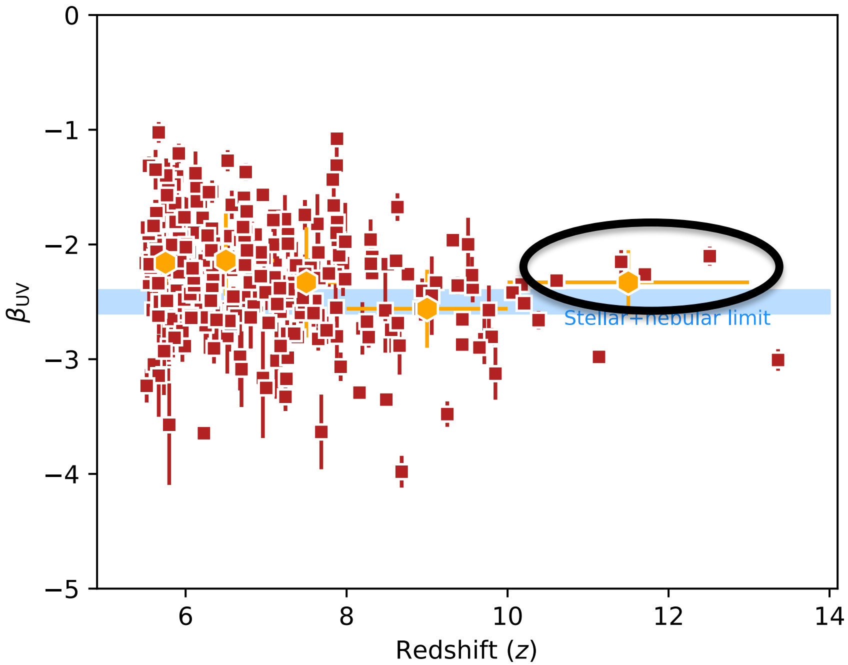


Do we see a marked change in dust-content of z>10 galaxies?

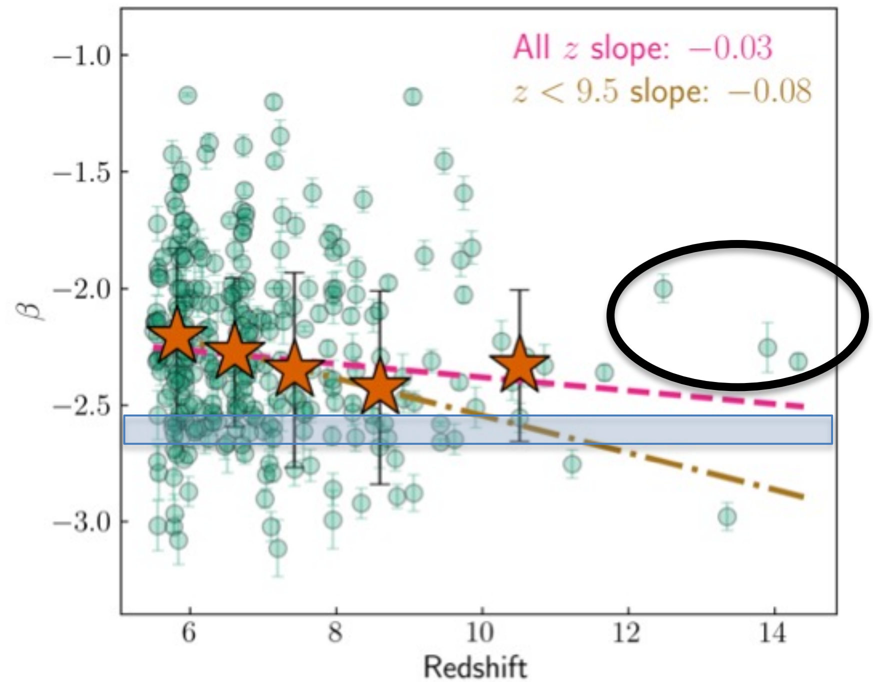
Only available diagnostic is the **UV continuum slope β**

Spectroscopic measures of the UV slope β

Heintz et al 2024: archival sample
494 5.5<z<13 NIRSpec prism

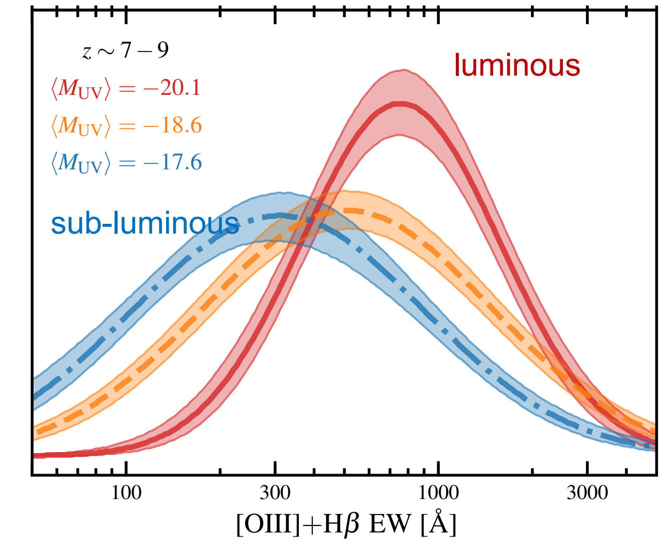


Saxena et al 2024: JADES
295 5.5<z<14 NIRSpec prism



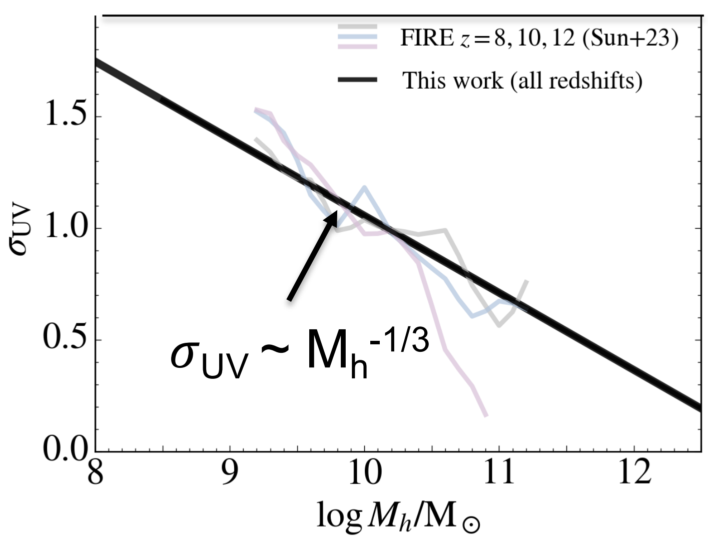
- No evidence of significant steepening in UV slope at z~10
- Possible redder trend at z > 10 which may arise from increased nebular contribution?

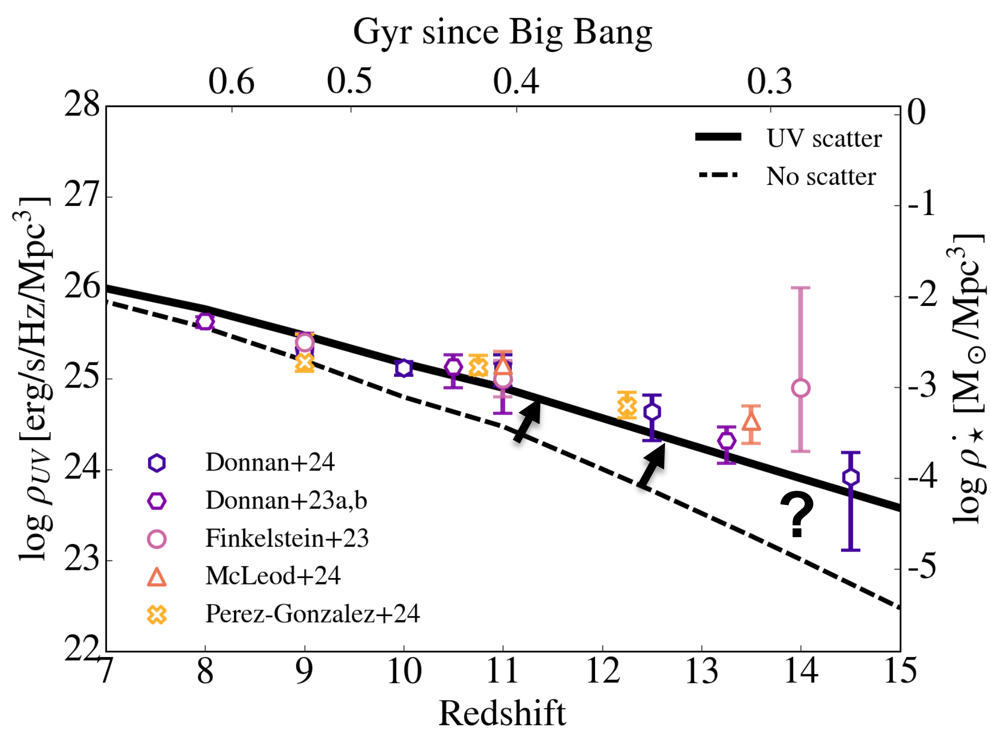
Bursty Star Formation?



Endsley et al 2023

Low luminosity galaxies at z~7-9 have **weaker emission lines** consistent with SFR downturn. Luminous ones could be "up-scattered" by bursts. FIRE simulations indicate scatter σ_{UV} in $M_{UV} - M_{halo}$ relation is larger for low luminosity galaxies. Incorporating such a scatter increases the visibility of sub-luminous systems but may be insufficient to match data at highest redshifts





Gelli et al 2024 (see also Mason et al 2023, Shen et al 2023, Kravstov & Belokurov 2024)

UV boost from very massive stars?

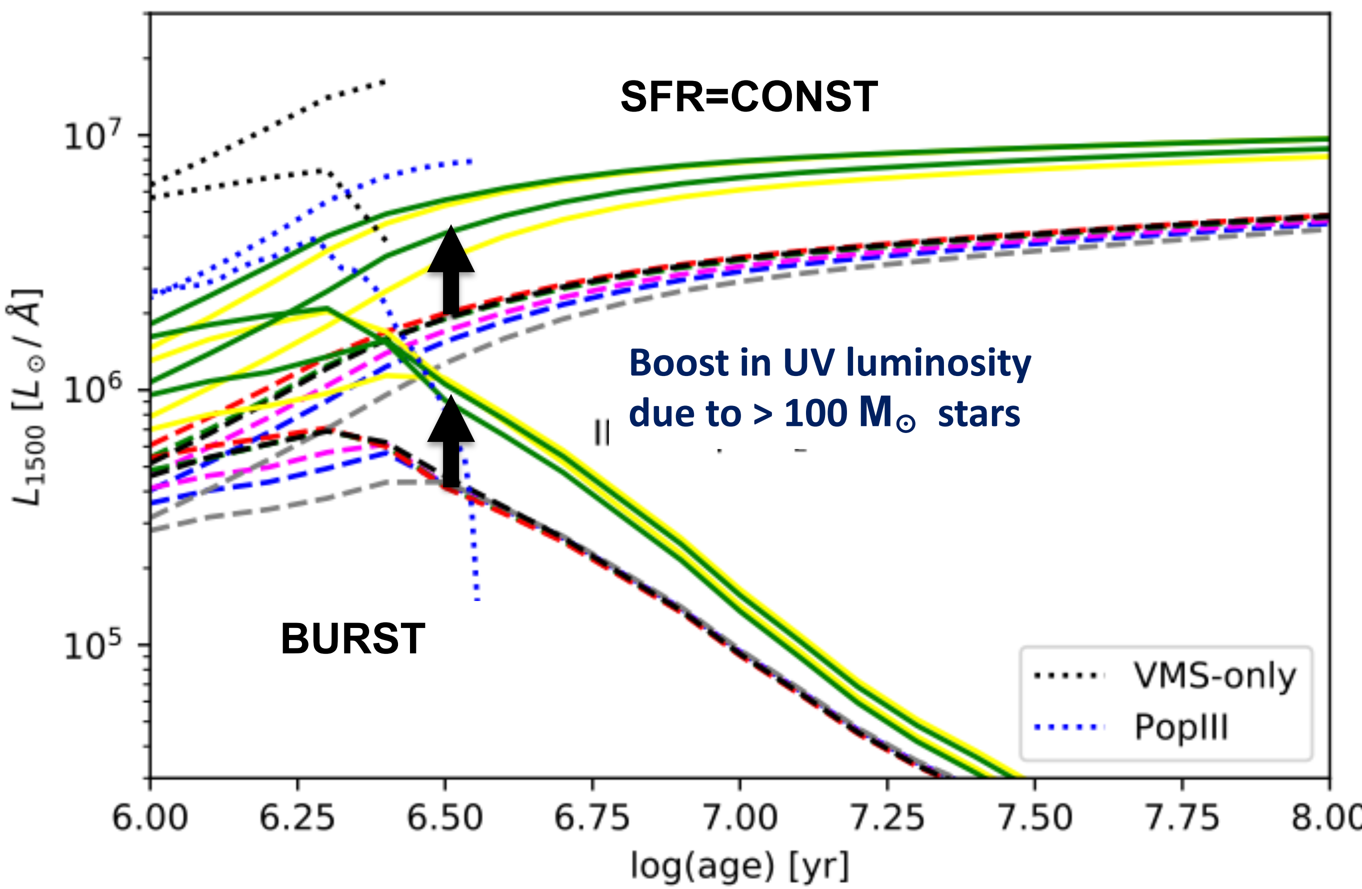
Growing evidence from strong He II 1640 Å emission for 100-400 $M_\odot$ WR stars in LMC, nearby SF galaxies & lensed z~2 galaxies

Their presence provides a significant boost to both **stellar and nebular UV continuum for ages < 10 Myr.**

Models predict

L_{UV} boost × 6
ξ_{ion} boost × 1.5
EW (He II) ~ 7 Å

Some examples of He II in z>10 spectra but presence is not ubiquitous



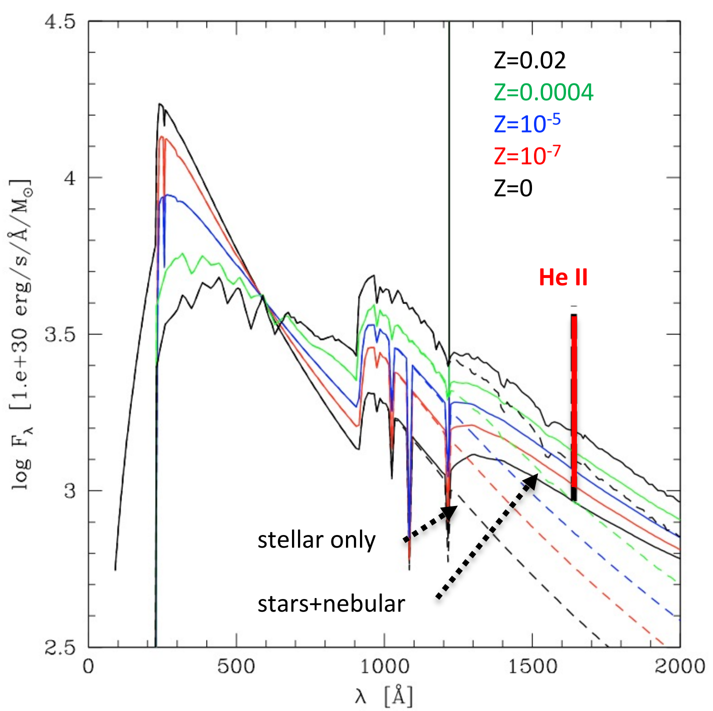
Schaerer et al 2024, also Katz et al 2024, Harikane et al 2023, Menon et al 2023

Cosmic Dawn: Pop III galaxies

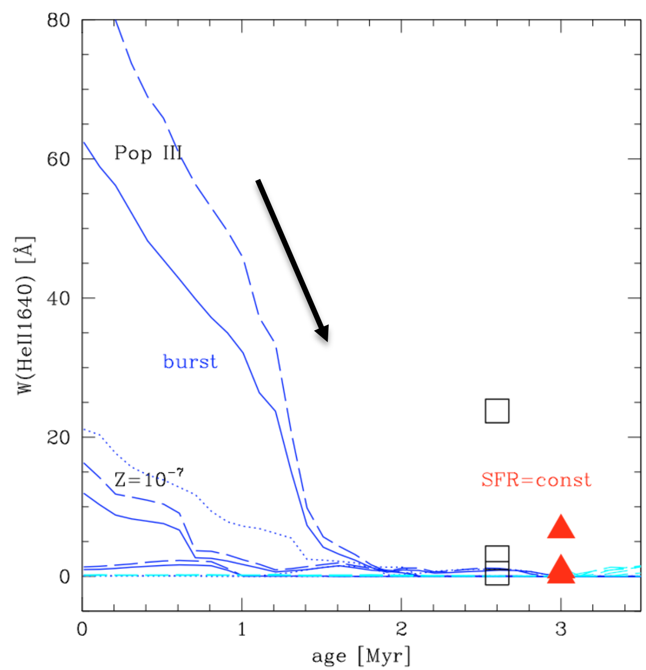
Daniel Schaerer: Metal-free stellar population synthesis calculations

- For galaxy formation: cooling timescale < dynamical timescale
- Pop III stars formed by H_2 cooling in halos with T_{vir}~10^3 K (so atomic cooling ineffective)
- Simulations indicate a fragmentation scale that yields stellar masses > 100 $M_\odot$
- Nebular continuum dominant (so emission lines weakened)
- He II recombination lines λ1640 Å - key signature for very low metallicities
- Rapid decline in He II visibility will be a challenge in identifications
- Pair-instability SNe* from 140 <$M/M_\odot$< 250 stars $\gamma \rightleftharpoons e^+ + e^-$ reducing pressure

Integrated spectrum for 0< $Z/Z_\odot$ < 0.02



Rapid decline in He II visibility

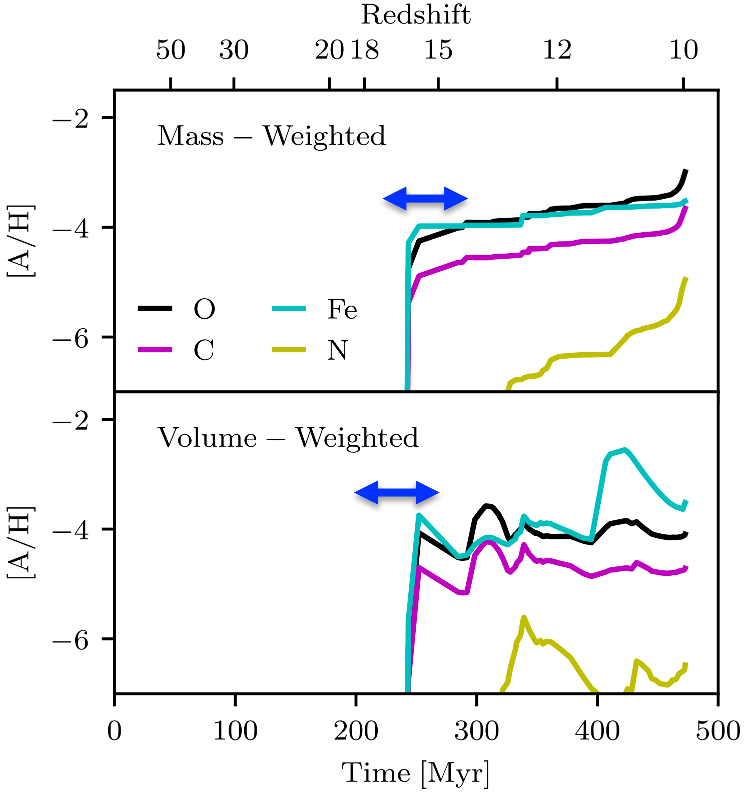


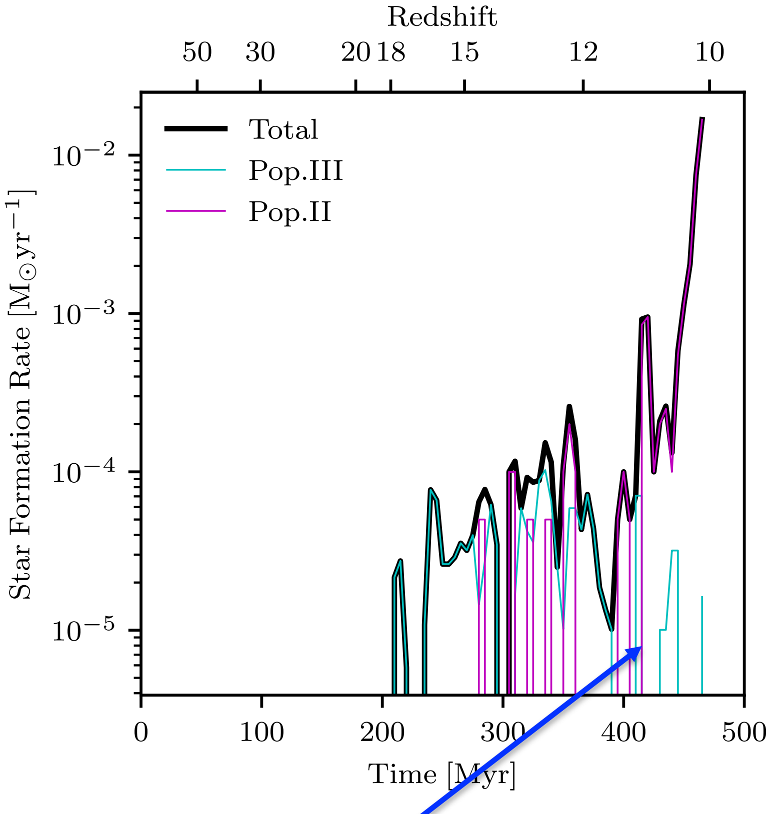
Schaerer 2002, 2003

Recent Simulations

Zoom simulation of Pop III to Pop II transition for a 3. 10^8 $M_\odot$ halo @ 0.8pc resolution for various IMFs using on-the-fly radiative transfer plus non-equilibrium chemistry & cooling


Harley Katz





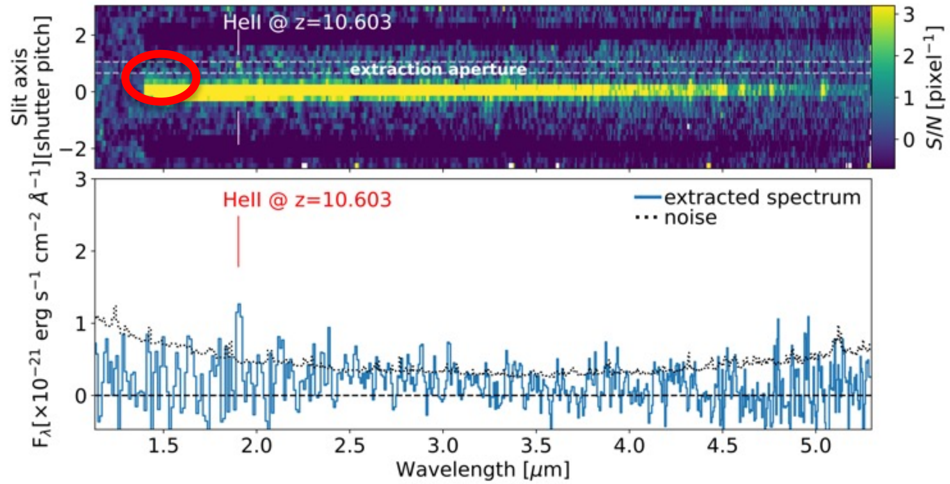
Metal enrichment proceeds rapidly (~5 Myr) after first Pop III SNe

Pop III star formation co-exists with Pop II (declines by z~10 in this source)

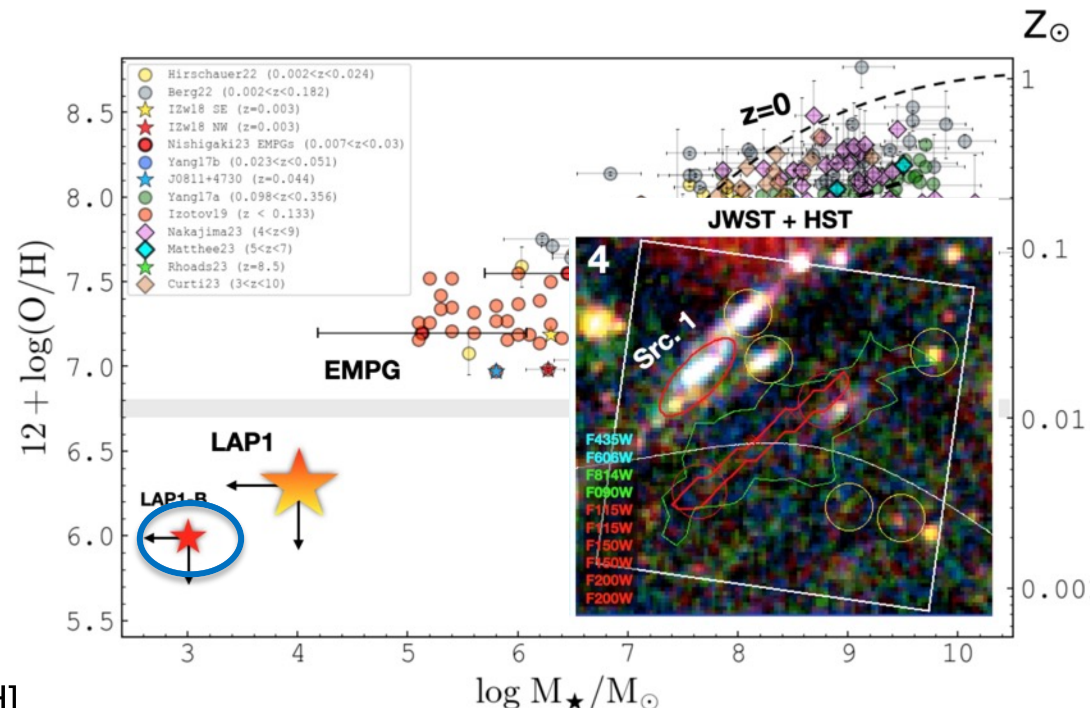
Katz, RSE et al 2023 (also Zackrisson et al 2024, Venditti et al 2024, THESAN/Zier et al 2025)

JWST Pop III claims

Maiolino+ claim isolated He II 1640 Å in vicinity of GNz-11 @ z=10.6. Pop III source with $M_{stars} \sim 6.\ 10^5\ M_\odot$ claimed via EW~170 Å and absence of metal lines



Vanzella+ IFU spectra of a highly-magnified μ > 100 z=6.6 source LAP1-B straddling critical line of a Frontier Field cluster MACS0416. Absence of [O III] places upper limit of **$Z < 0.003\ Z_\odot$** for a $M \sim 10^3\ M_\odot$ system



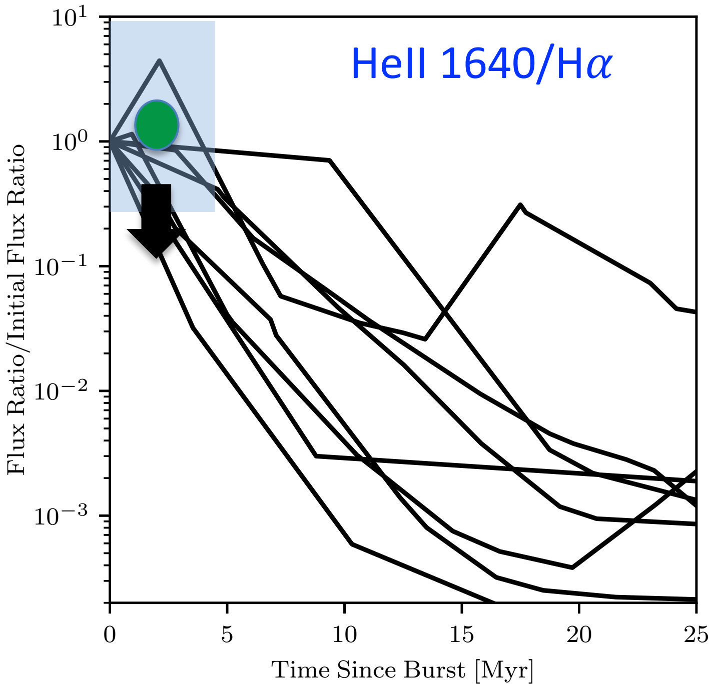
NB1: **Wang et al (2024)** claim a Pop III candidate with an anomalous He II 1640 (EW~21 Å) in an enriched z=8.16 galaxy

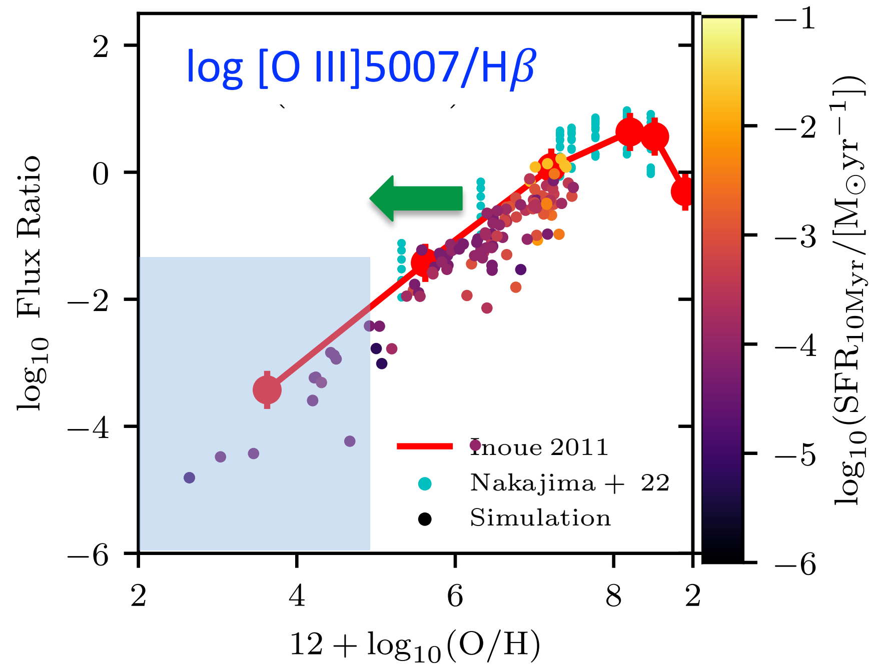
NB2: **Fujimoto et al (2025)** claim a Pop III candidate at z=6.50 with He II and upper [O/H] limit inferred from NIRCam photometry

Maiolino et al 2023, Vanzella et al 2023

Burden of proof for Pop III is high!

Simulations suggest require log He II/Hα > - 0.5 and log [O III] / Hβ < -1.5





He II 1640 Å, a favourite Pop III diagnostic, fades faster than Hα (×100 in 5 Myr!)

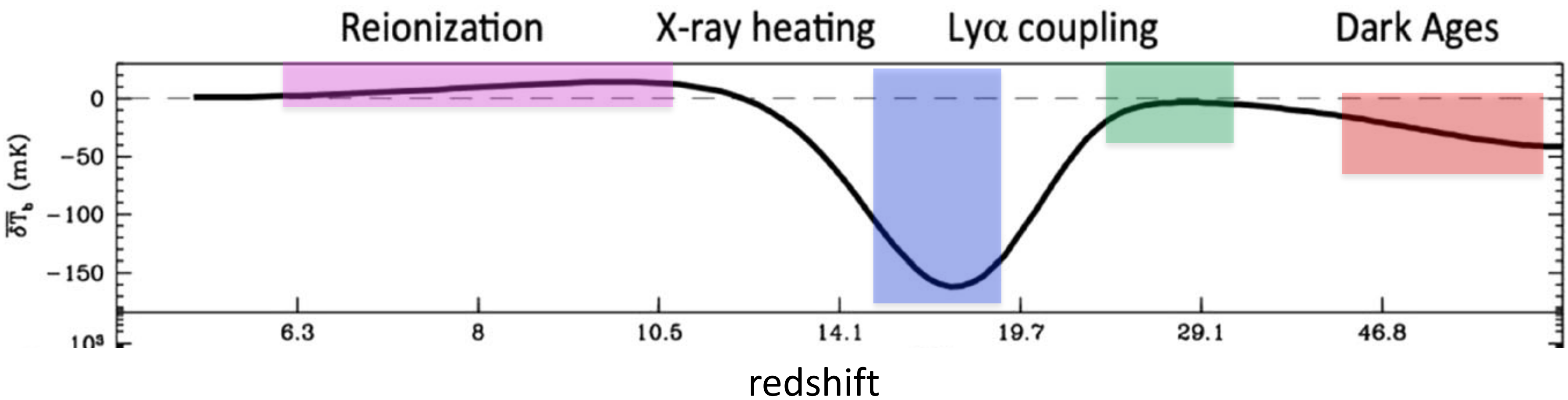
[O III] 5007 Å, the most prominent metal line, remains weak initially even in Pop II, so claiming metal-free halos will need long JWST exposures

Vanzella et al 2023 ×100 magnified ~30pc clump at z~6.6 with Z_{gas} < 0.003

Maiolino et al 2023 z=10.6 ~1 kpc system adjacent to GN-z11 @ z=10.6

Katz, RSE et al 2022 (see also Schaerer 2002, 2003; Inoue 2011; Nakajima & Maiolino 2022)

21cm brightness temperature & cosmic dawn



- In dark ages, cosmic expansion cools gas $\rho \propto a(t)^{-3}$ faster than radiation $T_{rad} \propto a(t)^{-1}$ while atomic collisions maintain $T_s \sim T_{gas}$: 21cm seen in absorption against CMB
- By z~30 decreasing gas density renders atomic collisions ineffective $T_s \sim T_{rad}$: no signal
- At cosmic dawn, IGM is heated penetrating dense ISM so $T_s \sim T_{gas}$: absorption
- Eventually $T_s > T_{rad}$ as the radiation continues to cool: emission throughout reionisation era

Pritchard & Loeb 2012; Koopmans et al 2021

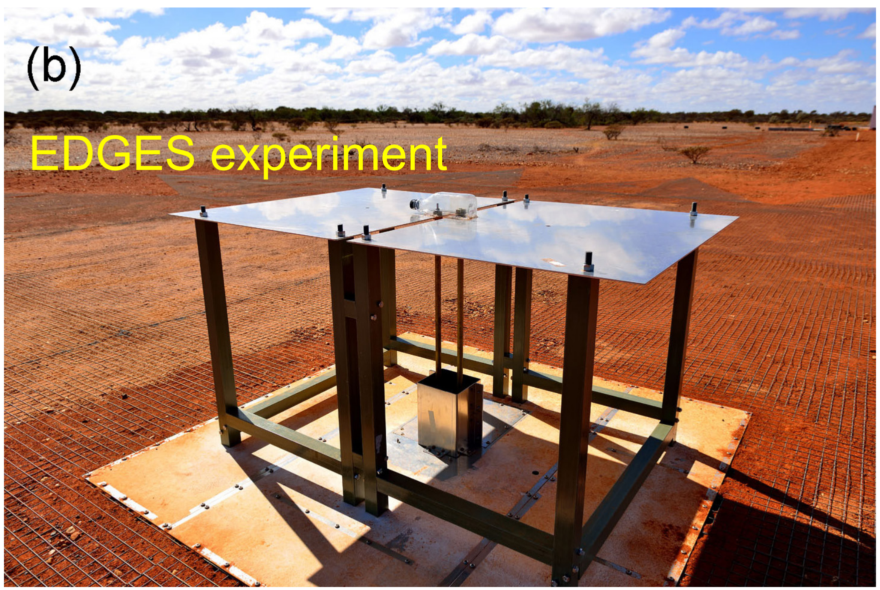
Cosmic Dawn @ z~15-20?

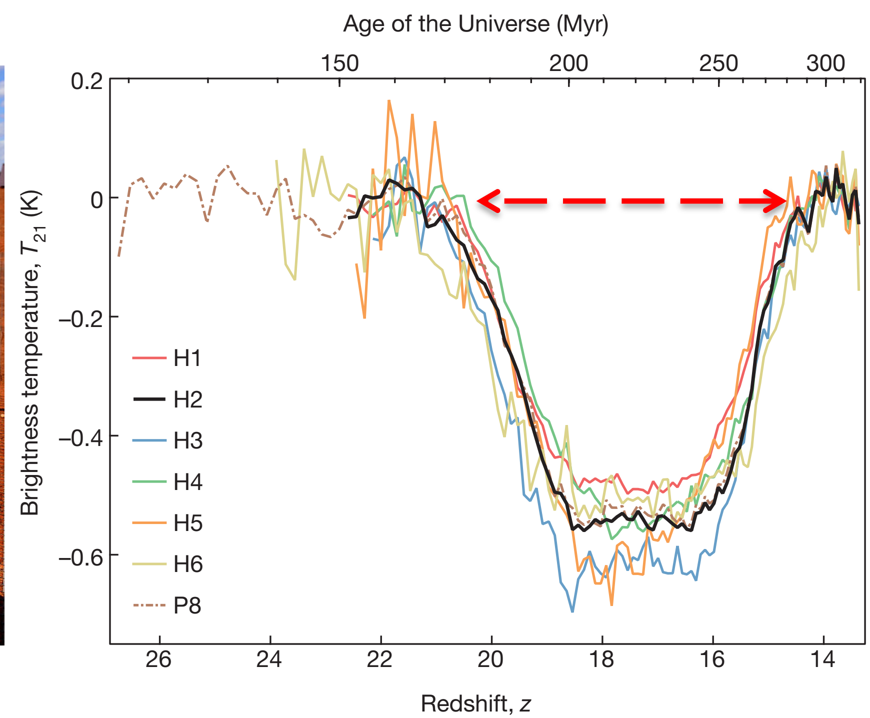
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

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 stars produces 21cm absorption of CMB

All-sky EDGES receiver detects surprisingly deep 21cm absorption over 15<z<20





Bowman et al 2018

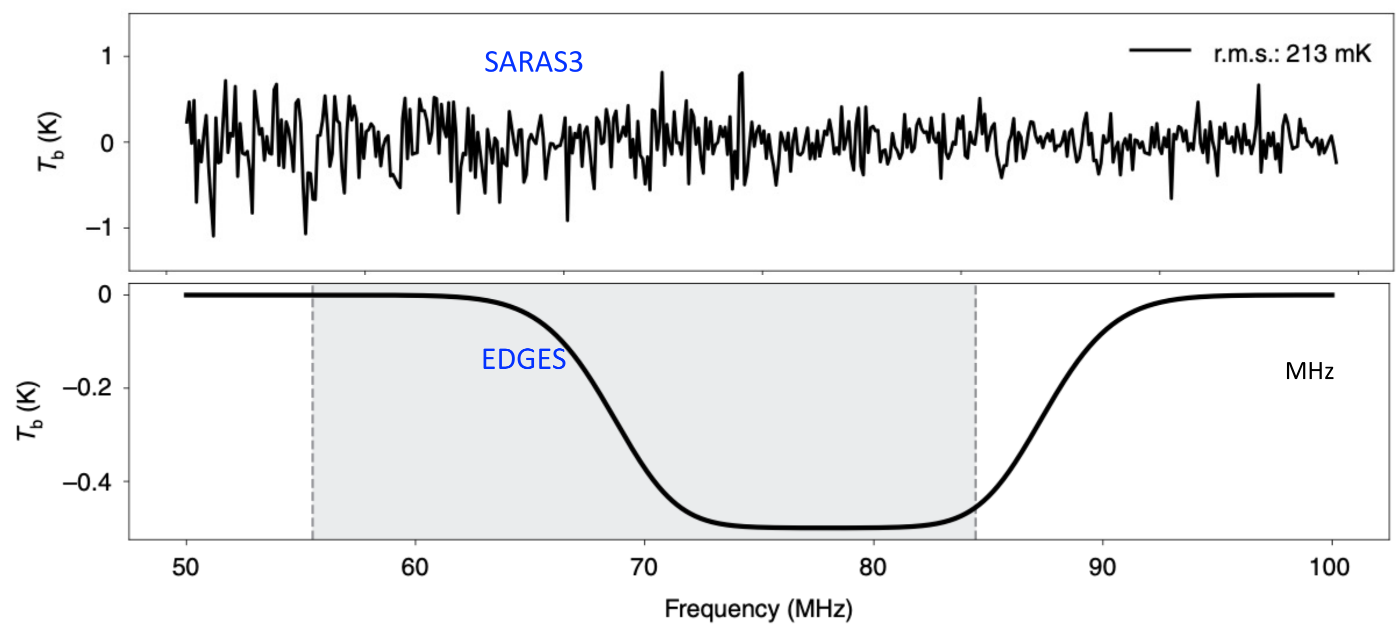
Verifying the EDGES claim?

The EDGES claim has been disputed on two accounts

- The absorption dip is ~2 × deeper and broader than expected theoretically suggesting either excess radio background or non-standard thermal history
- Correction for foreground synchrotron and free-free radio emission (10^5 × stronger than the expected signal) may be incorrectly applied

c.f. exchanges in Hills et al 2018 vs Bowman et al 2018

One independent radio telescope (SARS3) fails to reproduce the EDGES signal:



Singh et al 2022

Redshift Frontier: Synopsis & Prospects

Census at z > 10:

- JWST has pushed the redshift frontier to z=14.1 (297 Myr after Big Bang)
- HST's horizon was z=11.6 (UDF) (389 Myr)
- Pre-JWST had 1 z>10 spec-z (GN-z11); JWST has 25 (and rising e.g. CAPERS+Cy 4)
- Exploring 15<z<20 has failed to deliver credible candidates but areal coverage small
- Conceivably "cosmic dawn" is at z~15-20 (c.f. suggestions from age-dating @ z~9)

Pop III claims and recognising primordial galaxies

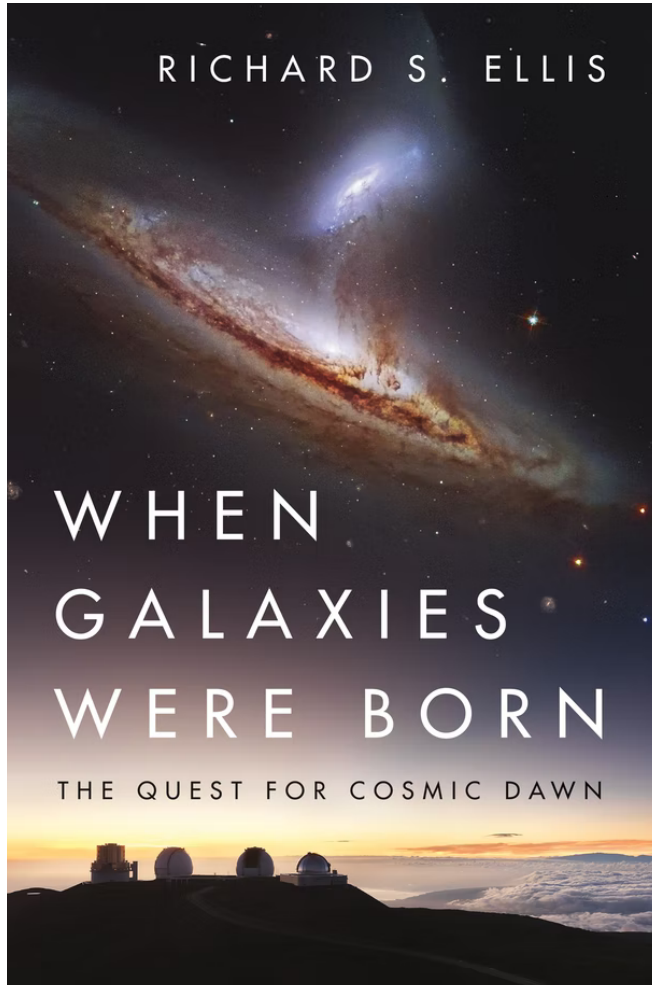
- Simulations suggest a true Pop III system is a very brief phase (~3-5 Myr)
- Examples of Pop III regions may be found mixed with Pop II (less interesting?)
- Burden-of-proof via He II/H and no metals would require very deep spectra
- Better to proceed statistically as well as utilise SKA 21cm absorption

What then?

- Primordial star clusters/massive stars may plausibly exist at earlier times
- Beyond JWST, possibly we can explore z > 20 for ionised regions with SKA-Low?

Regardless of what transpires, the future is exciting!

Postscript



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