Resolving the ionizing photon budget crisis with JWST/NIRCam H II clumping constraints at $z \simeq 6$

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1.Introduction

- EoR : The period btw the first stars/galaxies and the complete reionization of neutral IGM by LyC photons
- The end of EoR is estimated to be z ~ 5-6
- $\dot{n}_{ion}$: the total rate of photon injection into IGM
  - UVLF Φ_{UV}
    - "turnover" ($M_{UV,lim}$)has not yet been found
  - rate $\dot{N}_{ion}$, efficiency $\xi_{ion} = \dot{N}_{ion} L_{UV}^{-1}$ of ionizing photon production
    - ξ_{ion} - M_{UV} relation : positive trend
    - ↑(More recent studies) selection bias ??
  - LyC escape fraction f_{esc}^{LyC}
    - Two theories: density bounded nebulae vs escape via holes
    - Either way, it is challenging to measure f_{esc}^{LyC}
    - LzLCS : β_{UV} - f_{esc}^{LyC} relation (but with large scatter) (J.Chisholm et al 2022)

$$\dot{N}_{\rm ion} = \frac{7.28\times10^{11}}{(1-f_{\rm esc}^{\rm LyC})} L_{\rm H\alpha} \quad [{\rm Hz}],$$

$$\xi_{\rm ion} = \frac{\dot{N}_{\rm ion}}{L_{\nu,{\rm UV}}} \quad [{\rm Hz\ erg^{-1}}],$$

$$\dot{n}_{\rm ion} = \int_{-\infty}^{M_{\rm UV,lim}} \Phi(M_{\rm UV}) f_{\rm esc}(M_{\rm UV}) \dot{N}_{\rm ion}(M_{\rm UV}) dM_{\rm UV}, \qquad (6)$$

- "**Ionizing photon budget problem**" by J.B. Munoz et al.2024
  - JWST : high ξ_{ion} / low-z studies : high f_{esc}^{LyC} for faint galaxies
  - Put together, galaxies not only drive reionization, but **end it too early**.
  - One possible solution : **clumpy** IGM

$$\frac{{\rm d}Q_{\rm HII}}{{\rm d}t} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm HII}}{\langle t_{\rm rec}\rangle}, \quad \langle t_{\rm rec}\rangle = \left[\langle 1+x_{\rm He}\rangle\langle n_{\rm H}\rangle\langle\alpha_{\rm rec}(T_e)\rangle C_{\rm HII,rec}\right]^{-1}$$

- This paper
  - split galaxies at 5.6 < z < 6.5 into **star-forming** and **smouldering** subsets
  - criteria of which is star-formation burstiness $\Phi = SFR_{10}/SFR_{100}$
    - $\Phi > 1$ → star-forming
    - relation btw Φ and $\xi_{ion,0}$:

$$\log_{10}(\xi_{\rm ion,0}/{\rm Hz\ \ erg^{-1}}) = 25.11 + \log_{10}(\Phi_{\rm H\alpha/UV})$$

2. Data and Sample

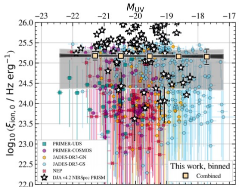
- Photometric data : from JWST/NIRCam, HST/ACS
  - faint end slope by JADES / UVLF's "knee" by PEARLS / bright end by PRIMER
- SED fitting(Bagpipes) : "continuity bursty" SFH with additional low-age bin 0–3, 3-10 Myr
- Selection
  - redshift range : 5.6 < z < 6.5 , 1721 samples
  - ↑LBG and LAE-like selection and SED fitting criteria
- Calculating properties
  - β_{UV} by UV photometry rather than best-fitting SED
  - Burstiness Φ by SED fitting
- Spectroscopy
  - DJA : PRISM/CLEAR catalog
  - 39 of which are cross-matched and selected
- Completeness
  - Mock catalog JAGUAR
  - All scaling relations are computed with 90% Mstellar complete sample

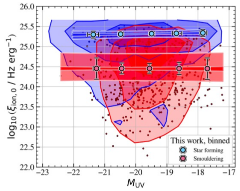
3. Production Efficiency

$\dot{N}_{\rm ion,0} = (1-f_{\rm esc}^{\rm LyC})\dot{N}_{\rm ion}; \quad \xi_{\rm ion,0} = (1-f_{\rm esc}^{\rm LyC})\xi_{\rm ion}.$

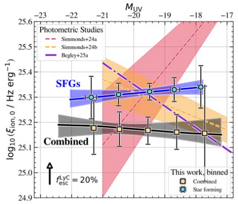
Instead of $\dot{N}_{ion}$and ξ_{ion} , $\dot{N}_{ion,0}$ and $\xi_{ion,0}$ are used.
SED fitting (Bagpipes) calculates both of them

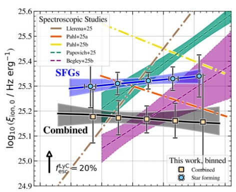
- $\xi_{ion,0}$ vs M_{UV}

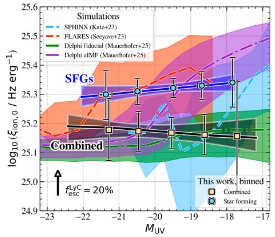


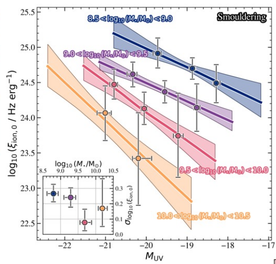


consistent with HST canonical value









<u>Photometric</u>

- Simmons2024a : positive trend
- Simmons2024b : 90% completeness cut

<u>Spectroscopic</u>

- wildly differing : potentially from MSA selection function
- positive trend : bursty, faint galaxies tend to be detected

<u>Simulations</u>

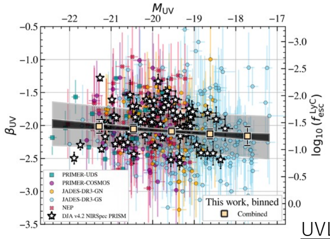
- combined sample is consistent with fiducial setup DELPHI
- SFG sample best matches the FLARES
- for SPHINX and DELPHI eIMF, exotic starburst populations dominate the sample

<u>Smouldering</u>

- $\xi_{ion,0}$ is decreasing function of $M_{\star}$: massive → self-regulated
- scatter σ_{ξ} is also decreasing function of $M_{\star}$
  - scenario for high mass smouldering : density bounded nebulae

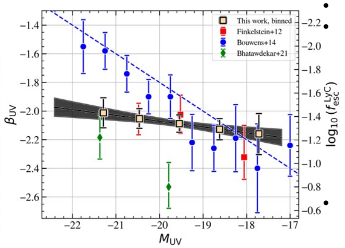
4.Reionization Budget Constraints

- β_{UV} vs M_{UV}

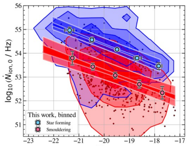


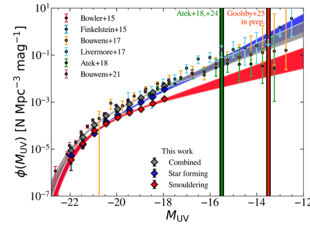
mild negative trend
shallower slope than HST studies

- due to the SPS template ?
- due to bright ultra-blue sources confirmed spectroscopically
- Using the relation(J.Chisholm et al 2022) they find fairly moderate $\langle f_{esc}^{LyC} \rangle \simeq 5\%$ at $M_{UV} \simeq -19$



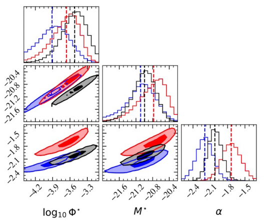
- $\dot{N}_{ion,0}$ vs M_{UV}

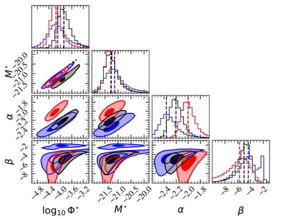




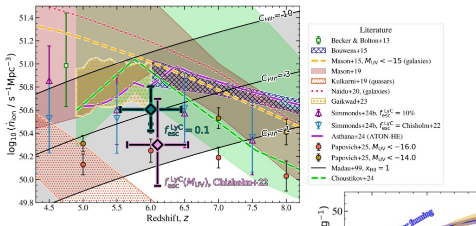
<u>UVLF</u>

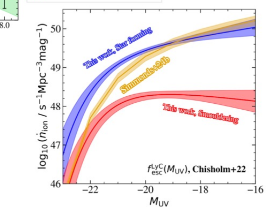
- computed by 1/Vmax method
- fit with a Schechter function
  - Φ, α is consistent with previous research
  - Among subsets, $M_{\star}$ is consistent
  - The largest difference is α (-2.2 for SFG, -1.7 for smouldering)
- also fit with a DPL
  - a bimodal solution for β_{SFG}
  - α remain consistent
- Information Criterion(Akaike, Bayes)
  - favour towards Schechter

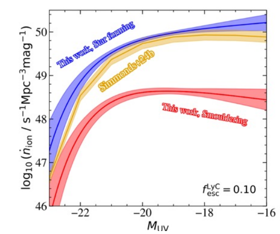




- $\dot{n}_{ion}$
  - $M_{UV,lim} = -17$ is assumed
  - f_{esc}^{LyC} in two ways
    - fixed 10%
    - J.Chisholm (2022) $f_{esc}^{LyC}(M_{UV})$
  - smouldering subsets account for < 10%





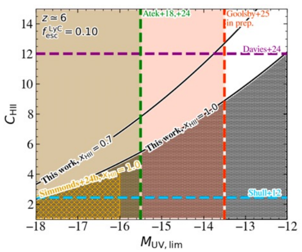


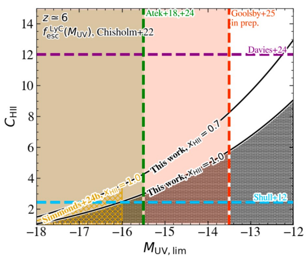
5.IGM Clumping

- formulation for reionization equilibrium

$$Q_{\rm HII} = \frac{\dot{n}_{\rm ion}(1+z)^3}{\langle n_{\rm H}\rangle^2 \langle \alpha_{\rm rec}(T_e)\rangle C_{\rm HII,rec}} \frac{4(1-Y)}{(4-3Y)}.$$

- For given Q_{HII}, $C_{HII,rec}$ is uniquely obtained.
  - $C_{HII,rec}$ is a function of $M_{UV,lim}$ through $\dot{\boldsymbol{n}}_{\boldsymbol{ion}}$





- similar results to C.Simmonds (2024b) at $M_{UV,lim} \leq -17$
- differences become large when extrapolating to fainter $M_{UV,lim}$
- $M_{UV,lim}$ estimated by simulations
  - -16.0 by J.Jaacks (2013)
  - -12 ~ -10 by Angel(2016); Mutch(2016); Poole (2016)
  - -12 ~ -11 by Ocvirk(2020); Dawoodbhoy(2023)
- New record : GLIMPSE survey by Goolsby(in prep)
  - no turnover as faint as $M_{UV,lim} = -13.5$
  - adopting this limit leads to $C_{HII,rec} \simeq 8.8$ for $f_{esc}^{LyC} = 0.10$
  - $C_{HII,rec} \simeq 6.2$ for $f_{esc}^{LyC}(M_{UV})$
- Favourability of Davies(2024) model over Shull(2012)
  - evaluated by the Bayes factor
  - For $M_{UV,lim} = -13.5$, both favour Davies(2024)
- $Q_{HII} = 0.7$
  - To favour Davies(2024) model, required turnover is $M_{UV,lim} > -15.7$, $M_{UV,lim} > -13.7$, respectively.
  - they conclude a moderate favourability of Davies(2024)
- Two scenarios for the topology of reionization
  - "inside out" : reionized from the most to the least-dense regions
    - At the end of EoR, the least dense void reionized very quickly
    - This might violate the assumption $dQ_{HII}/dt = 0$
    - Numerical simulations favour it.
  - "outside in" : the opposite
- Their elevated $C_{HII,rec}$ measurements could (in part) due to more "inside out"