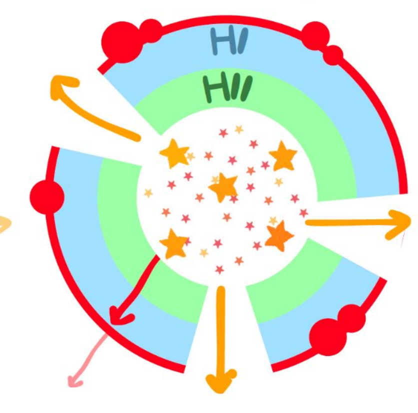
Escape of Lyman radiation from galactic labyrinths

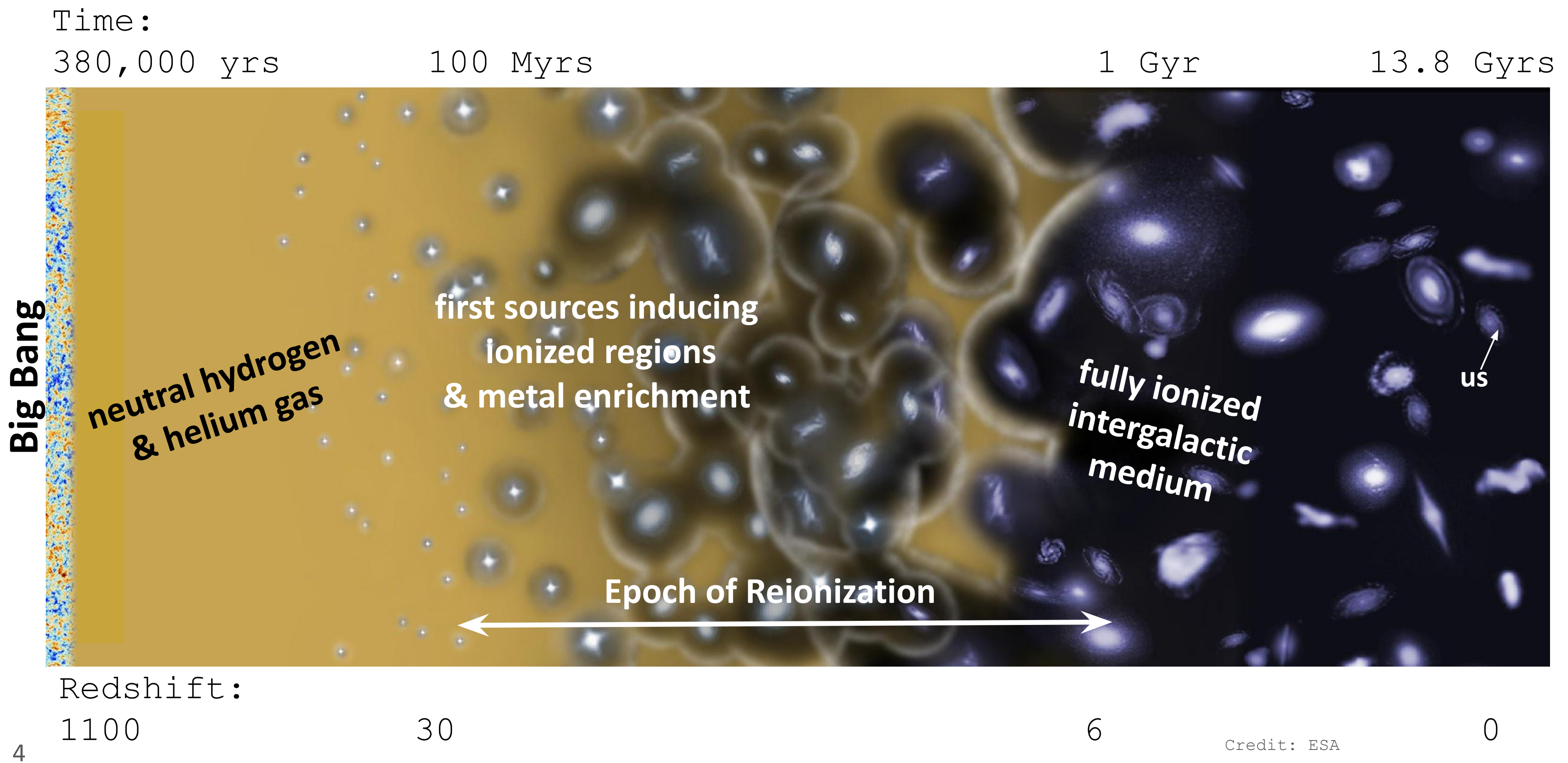


Laura Pentericci (INAF-OAR) & Anne Verhamme (Geneve Observatory)

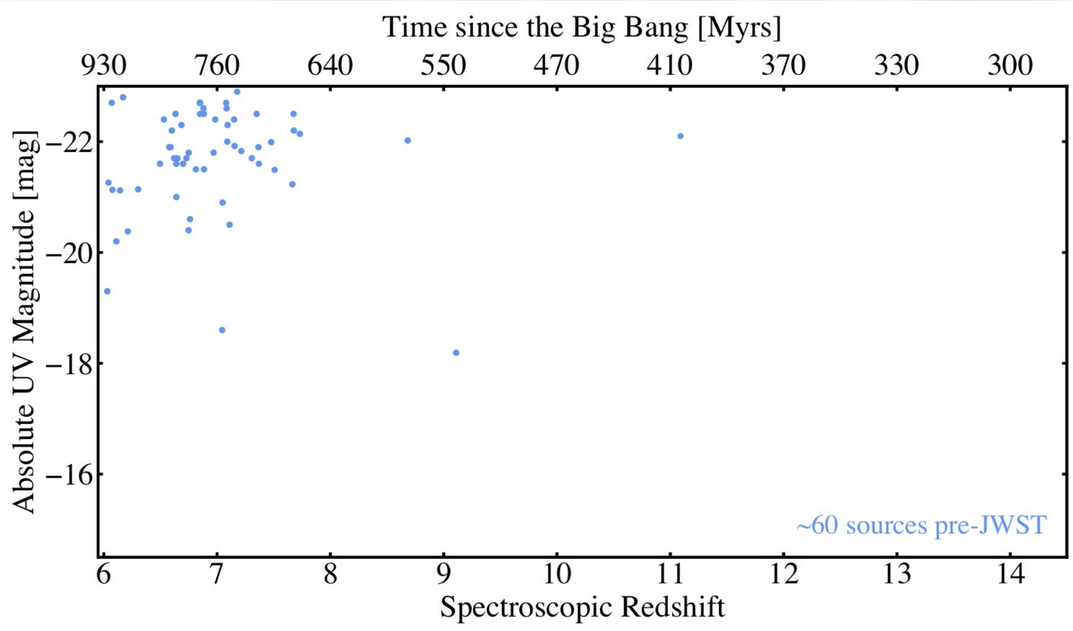
08-11 April 2025, OAC, Kolymbari, Crete

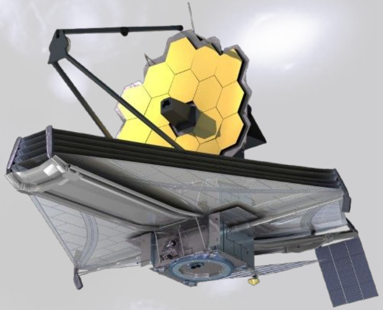
Credit: ESA, NASA, Science RF

Our Universe: 13.8 billion years of history in a picture



The JWST revolution in the exploration of the epoch of reionization





Credit: Guido Roberts-Borsani

results from 20 years of spectroscopic observations

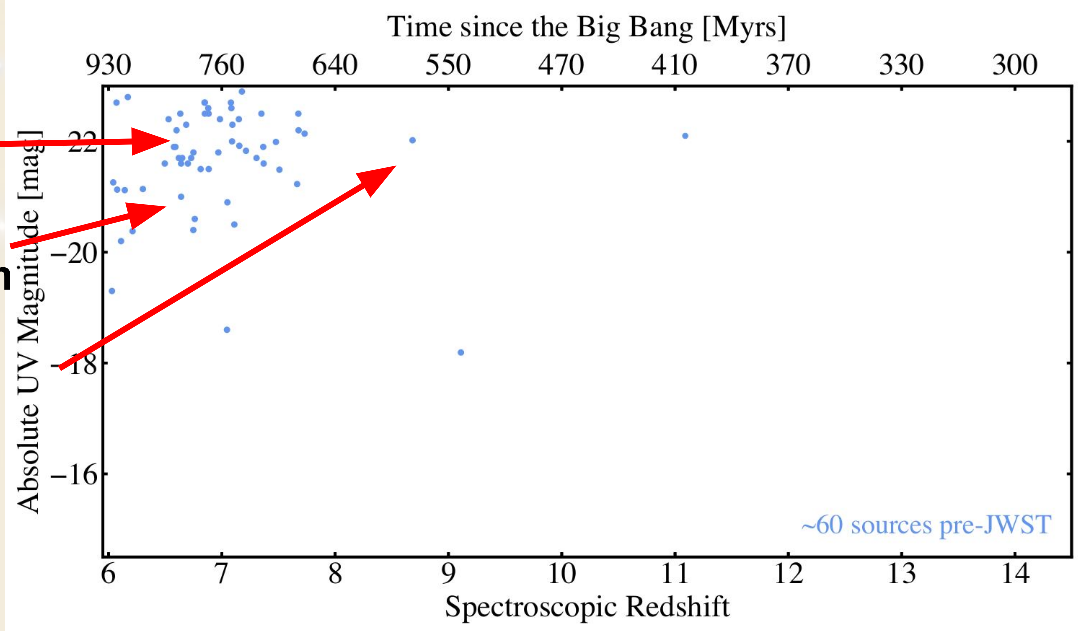
Credit: ESA, NASA, Science RF

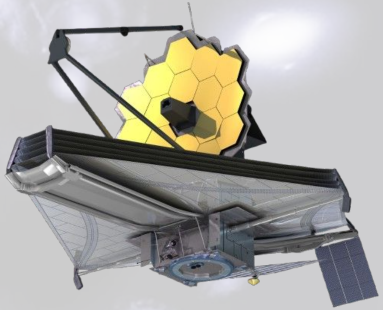
The JWST revolution in the exploration of the early Universe

Lyα

[CIII]158μm

[OIII]88μm





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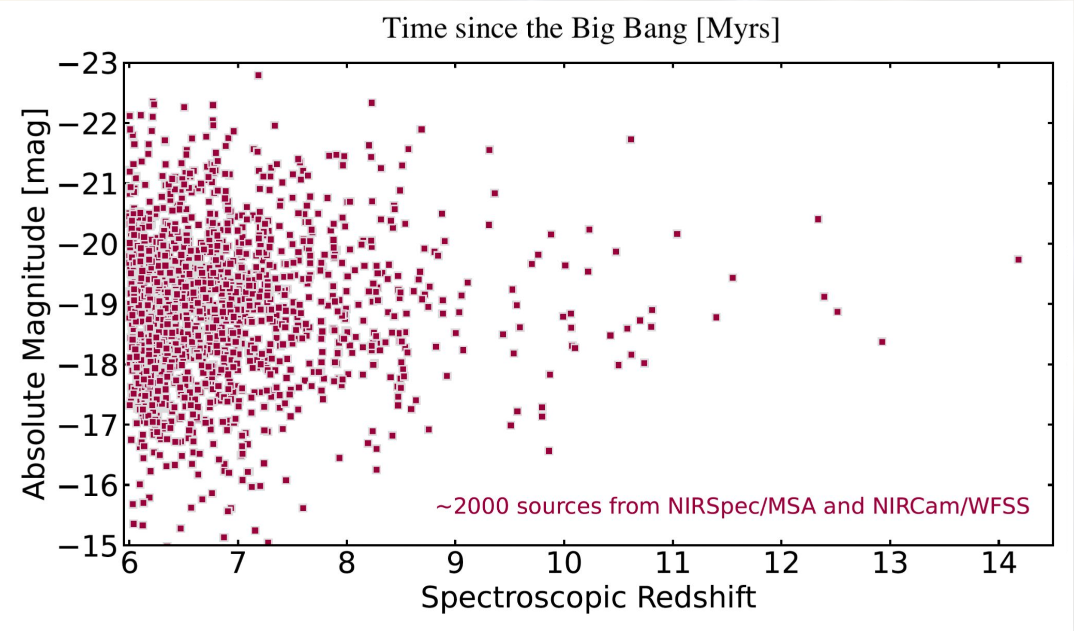
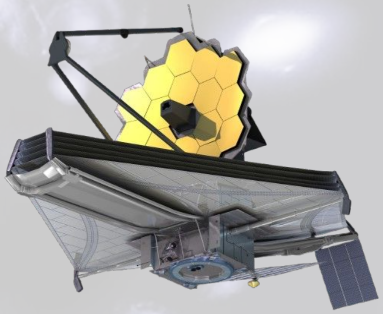




Credit: Guido Roberts-Borsani

After 2.5 years of JWST: much higher redshifts, much fainter magnitudes

The JWST revolution in the exploration of the early Universe

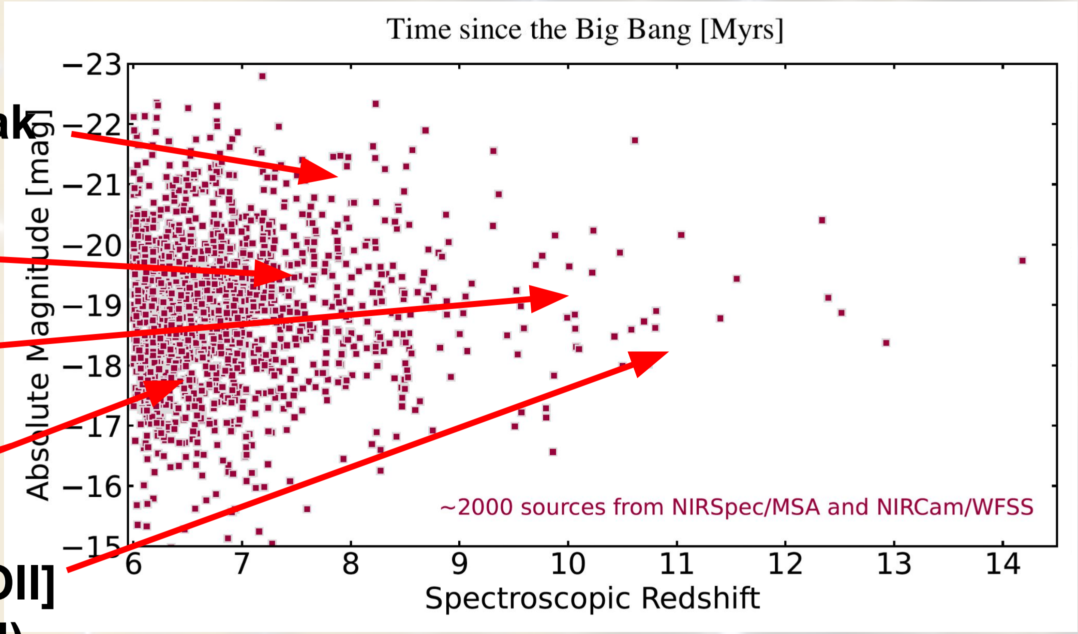
Ly-break

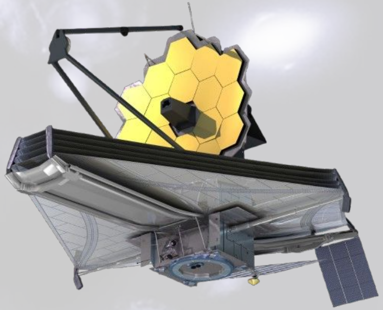
Hα

Hβ

Lyα

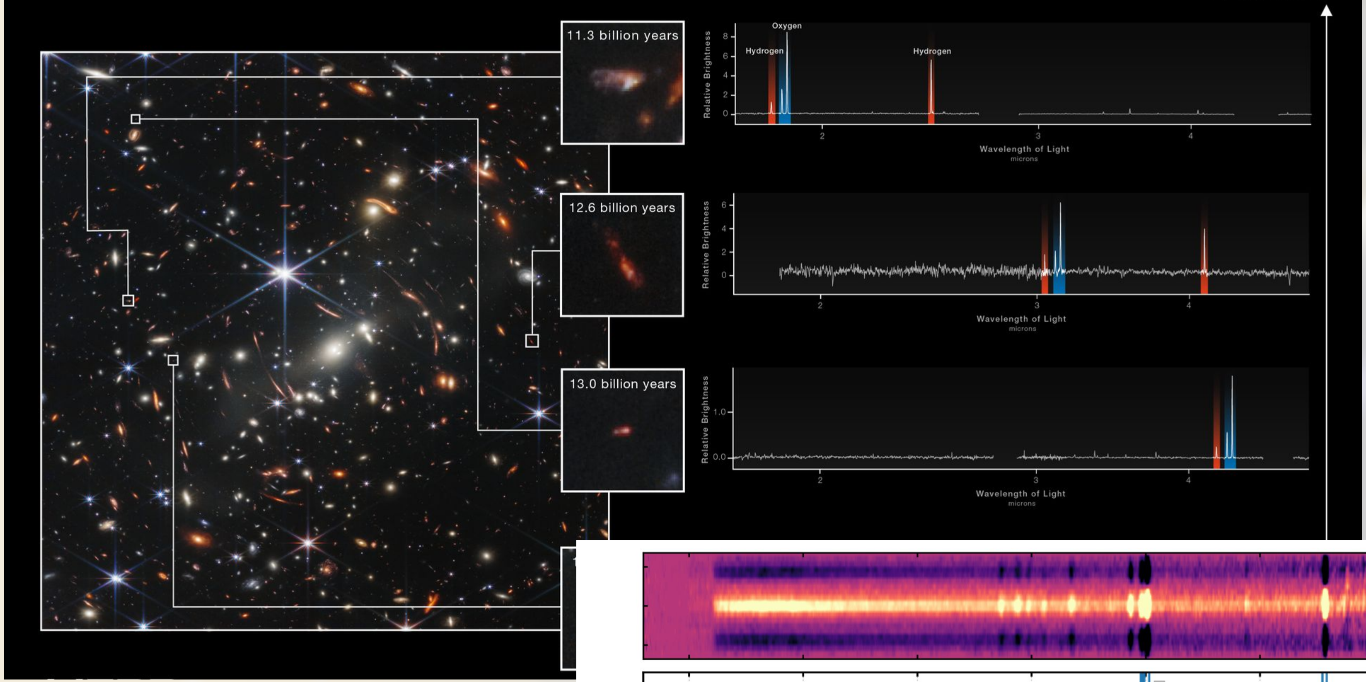
[OIII],[OII] (optical)



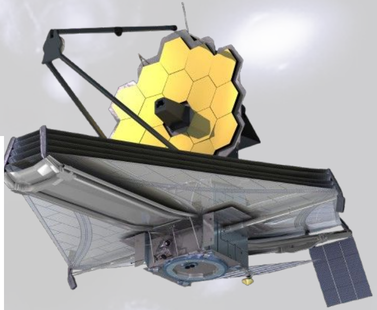


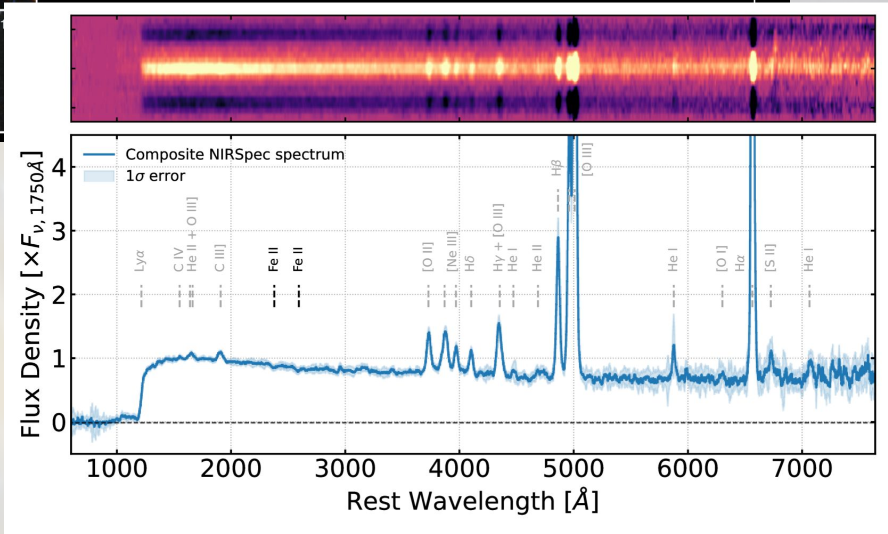
Credit: Guido Roberts-Borsani

After 2.5 years of JWST: much higher redshifts, much fainter magnitudes



Some of the first distant galaxies observed and then confirmed by JWST behind the lensing cluster SMACS 0723





Stacked spectrum of ~500 distant galaxies showing optical and UV emission lines (*Roberts-Borsani+24*)

Credit: ESA, NASA, Science RF

Main achievements with JWST so far (making a long story short!)

galaxies

- Discovery of very distant galaxies and evolution of UV LF and ρ_{UV}
- Accurate physical properties → e.g. stellar masses, dynamical masses
- Detailed ISM conditions → metallicity, ionizing conditions, density, presence of outflows, dust etc
- Spatially resolved studies
- Morphological studies (also thr. lensing)→ mergers, disks/spheroid etc

Credit: ESA, NASA, Science RF

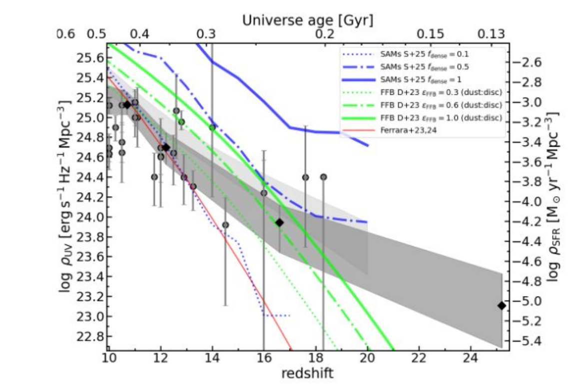
Main achievements with JWST so far (making a long story short!)

IGM

- Lyman α damping wing is normal galaxies
- Spatial correlation between Lyα forest and galaxies
- Discovery of early ionized regions traced by Lyα emitter overdensities
- and many more to come…..

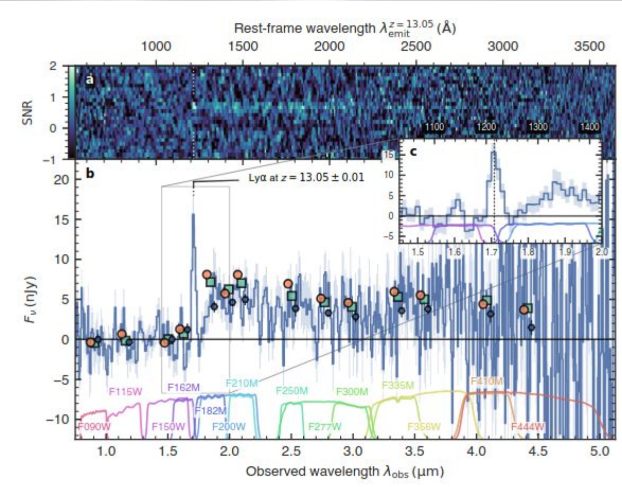
The main surprises of early JWST cycles

Too many bright sources and a slow decline of the UV luminosity density



Perez-Gonzalez+25

Bright Lyα emitters at an epoch when the IGM should be completely neutral

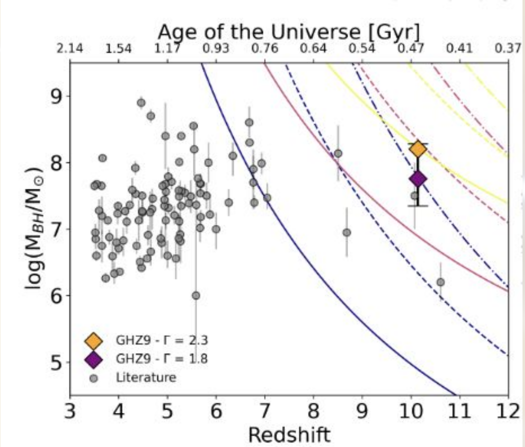


Witstok+25

Credit: ESA, NASA, Science RF

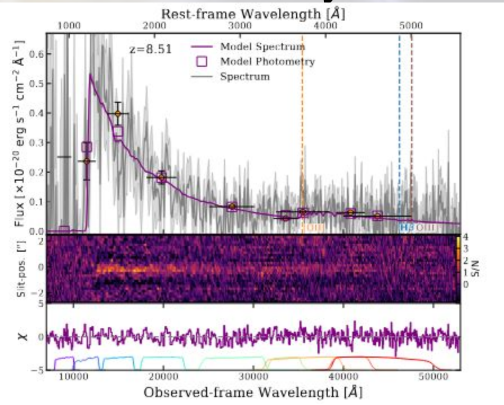
The main surprises of early JWST cycles

Early supermassive BH discovered indicating accelerated evolution of BH mass compared to host galaxy



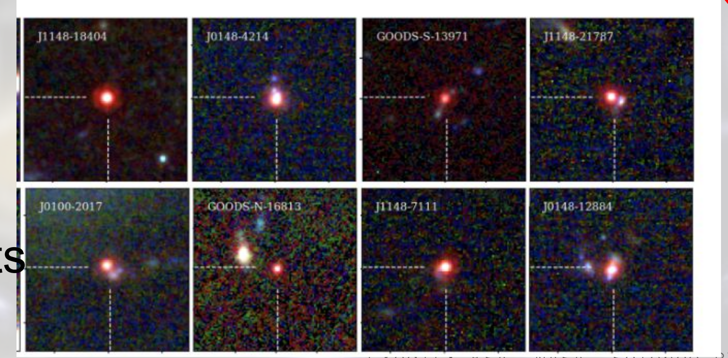
Napolitano+25

The mystery of the extremely blue galaxies with β<-2.6 ..high f_{esc}?



Baker+25

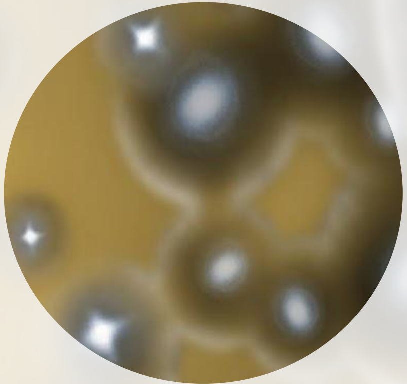
A new population of faint AGN at intermediate/high z: the little red dots



Credit: ESA, NASA, Science R

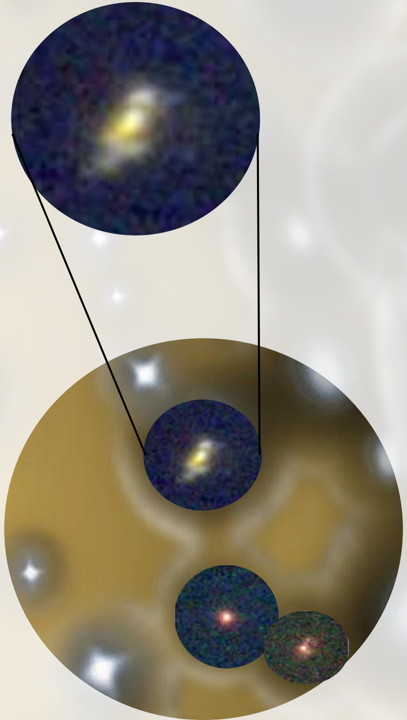
The quest for the sources of cosmic reionization is still wide open

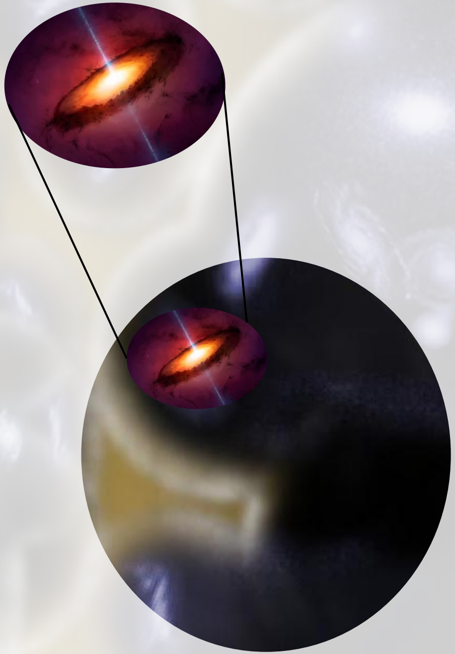
When and how did Reionization happen?



Credit: ESA, NASA, Science RF

The quest for the sources of cosmic reionization is still wide open



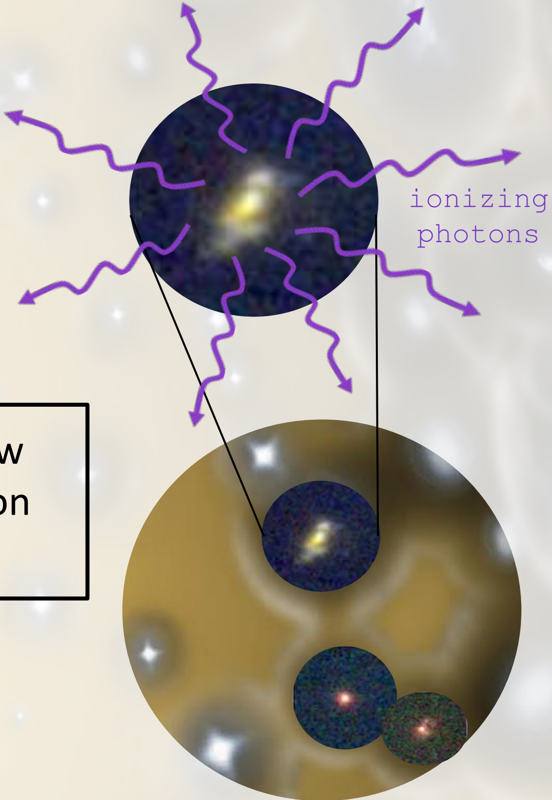


When and how did Reionization happen?

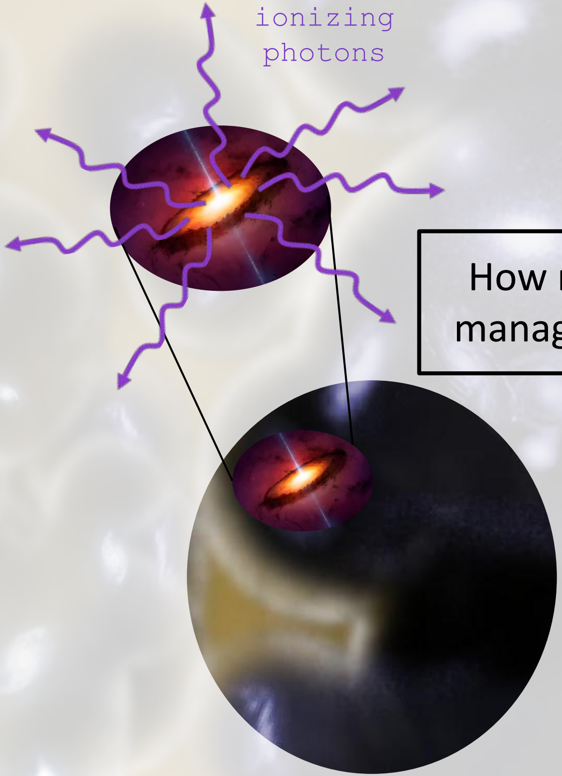
What produced the ionizing photons? Stars, AGN or both?

Credit: ESA, NASA, Science RF

The quest for the sources of cosmic reionization is still wide open



When and how did Reionization happen?



How many photons managed to escape?

What produced the ionizing photons? Stars, AGN or both?

Credit: ESA, NASA, Science RF

The equations governing reionization:

$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_H \rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}},$$

$$\bar{t}_{\rm rec} = [(1+2\chi)\bar{n}_p \alpha_B\, C]^{-1}$$

$$C \equiv \langle n_p^2 \rangle / \bar{n}_p^2$$

clumping factor

Reionization is completed when:

$$\dot{n}_{\rm ion}\bar{t}_{\rm rec} \gtrsim \bar{n}_{\rm H},$$

Credit: ESA, NASA, Science RF

The total ionizing radiation $\dot{n}_{ion}$: the "ingredients"

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

ϱ_{UV}= the total density of UV photons

ξ_{ion} = the photon production efficiency (how many ionizing photons per UV photon)

f_{esc} = the fraction of ionizing photon escaping to the IGM

Credit: ESA, NASA, Science RF

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

ϱ_{UV}= the total density of UV photons

= the photon

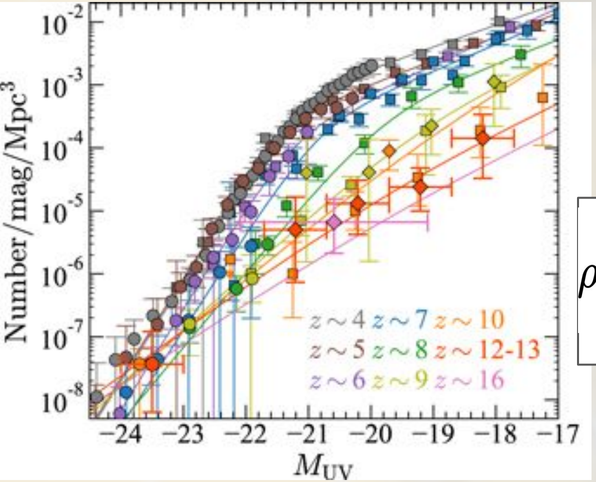
sc = the fraction of
nizing photon
scaping to the IGM

Contribution of galaxies & AGN must be combined

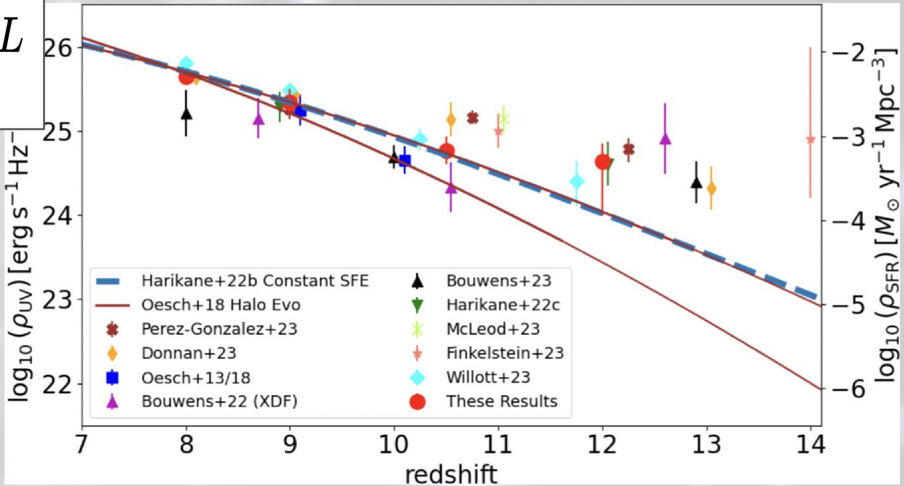
Credit: ESA, NASA, Science RF

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

..now the “easiest” quantity to measure. Some small discrepancy between various studies remain due to selection biases, incompleteness, etc



$$\rho_{UV} = \int_{Lmin}^{Lmax} L\,\Phi\,(L)dL$$

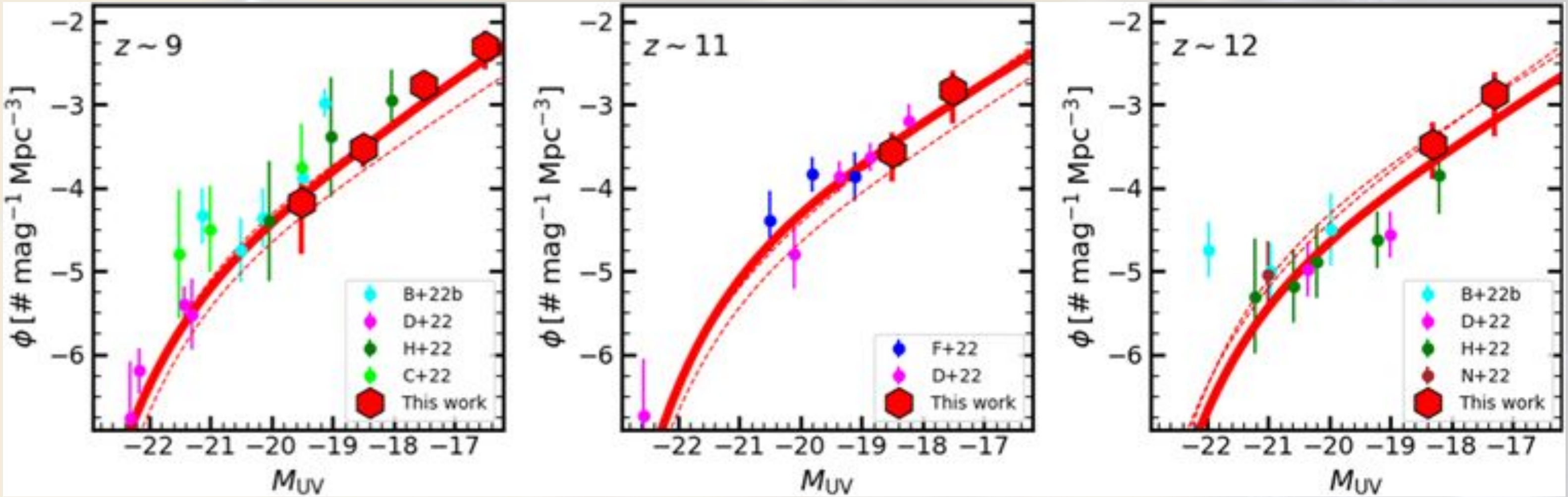


Harikane+23, FInkelstein+23
Atek+23.Castellano+23
and many more

Adams+24, see also Perez-Gonzalez+25

The faint end slope UV luminosity function as seen in the deepest (or lensed) fields (e.g. NGDEEP, CANUCS)

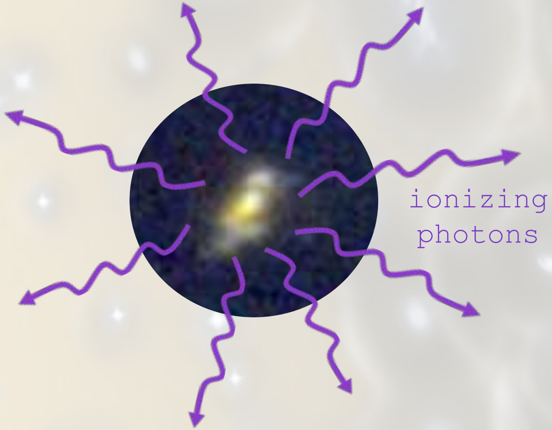
z=9 α =-2.30 z=11 α =-2.14 z=12 α =-2.19

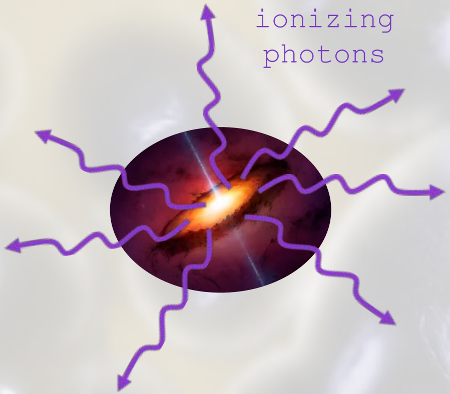


The faint-end slope and absolute magnitude of the knee remain approximately constant, with values $\alpha = -2.2 \pm 0.1$, and $M^* = -20.8 \pm 0.2$ mag (*Perez-Gonzalez+23 see also Adams+24, Leung+24, Chemerynska+24*) → no steepening

Credit: ESA, NASA, Science RF

Determining the other ingredients of reionization is still challenging →
→ our conference !!





- production of Lyman continuum radiation
- transport of Lyman continuum radiation
- escape of Lyman continuum radiation
- the role of AGN
- how can simulations help

Credit: ESA, NASA, Science RF

The escape fraction of ionising photons

In theory, simple and intuitive quantity:

fesc = (nb escaping ionising photons) / (nb of ionising photons produced)

ONE unique value per galaxy // ONE unique value for 'cosmological fesc'

In practice….
'cosmological fesc' is not an observable → galactic fesc over a population

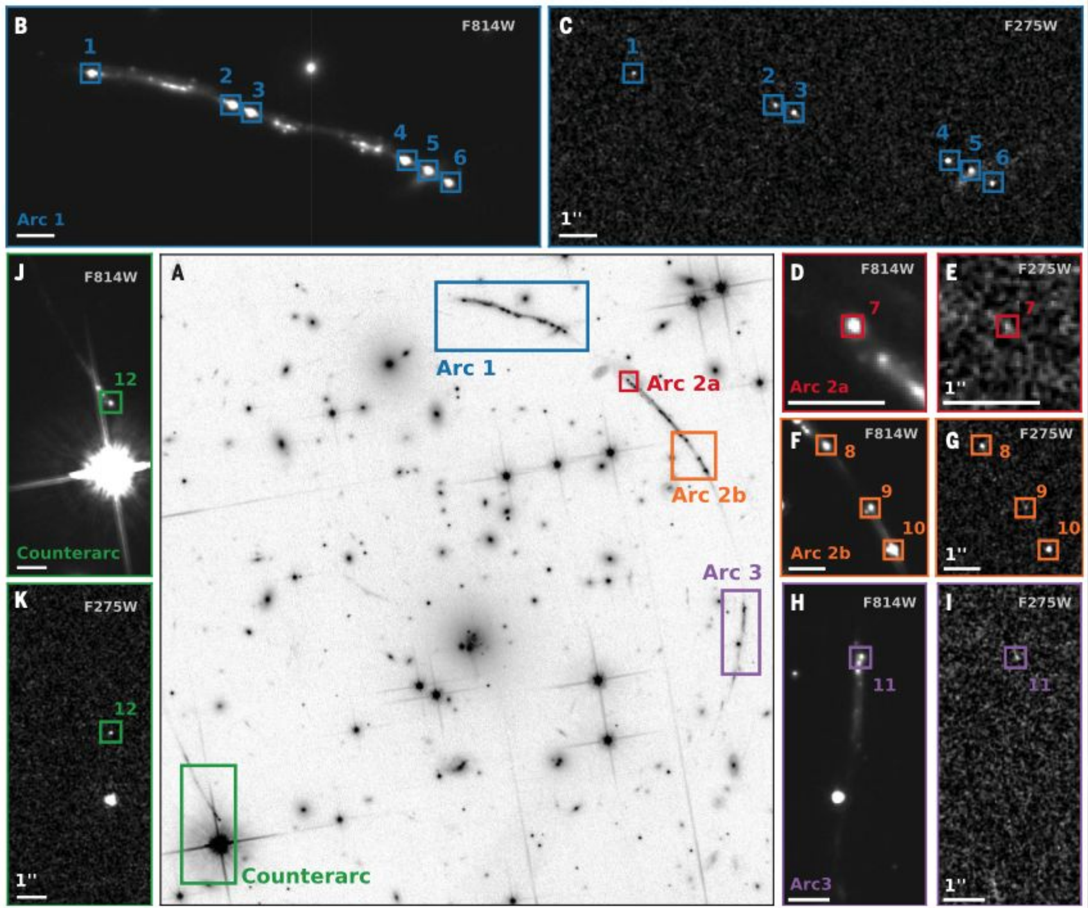
fesc = (nb escaping ionising photons that you observe, along your line of sight) / (nb of ionising photons produced, your best guess/estimate)

many different values per galaxy: depending on wavelength, direction, time…

Credit: ESA, NASA, Science RF

escape fraction varies spatially

Rivera Thorsen+19



Credit: ESA, NASA, Science RF

escape fraction varies spatially

Mauerhofer+21

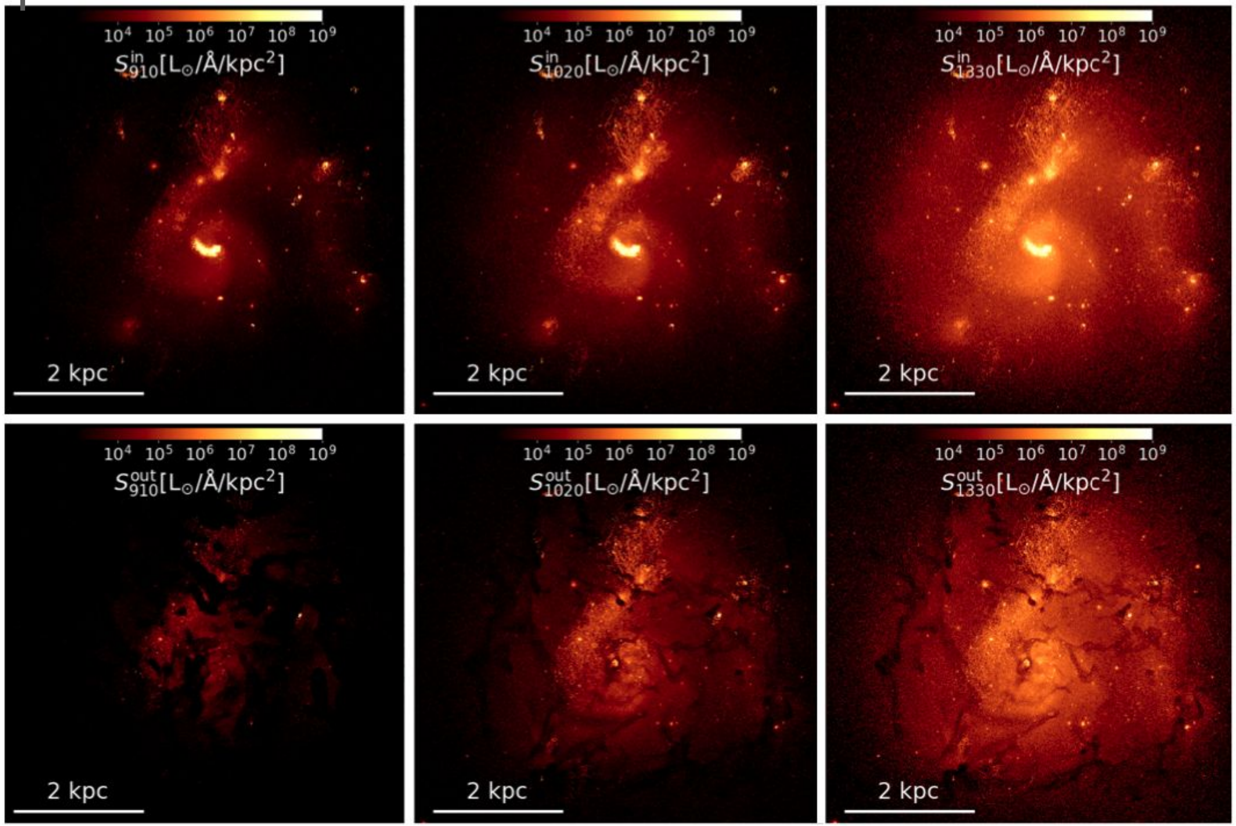


Fig. 14. Surface brightness maps of output C (z = 3.0). *Upper left*: intrinsic surface brightness at 910 Å. *Upper middle*: intrinsic surface brightness at 1020 Å. *Upper right*: intrinsic surface brightness at 1330 Å. *Lower left*: surface brightness at 910 Å after H^0 and dust absorption. *Lower middle*: surface brightness at 1020 Å after dust extinction. *Lower right*: surface brightness at 1330 Å after dust extinction.

overestimated

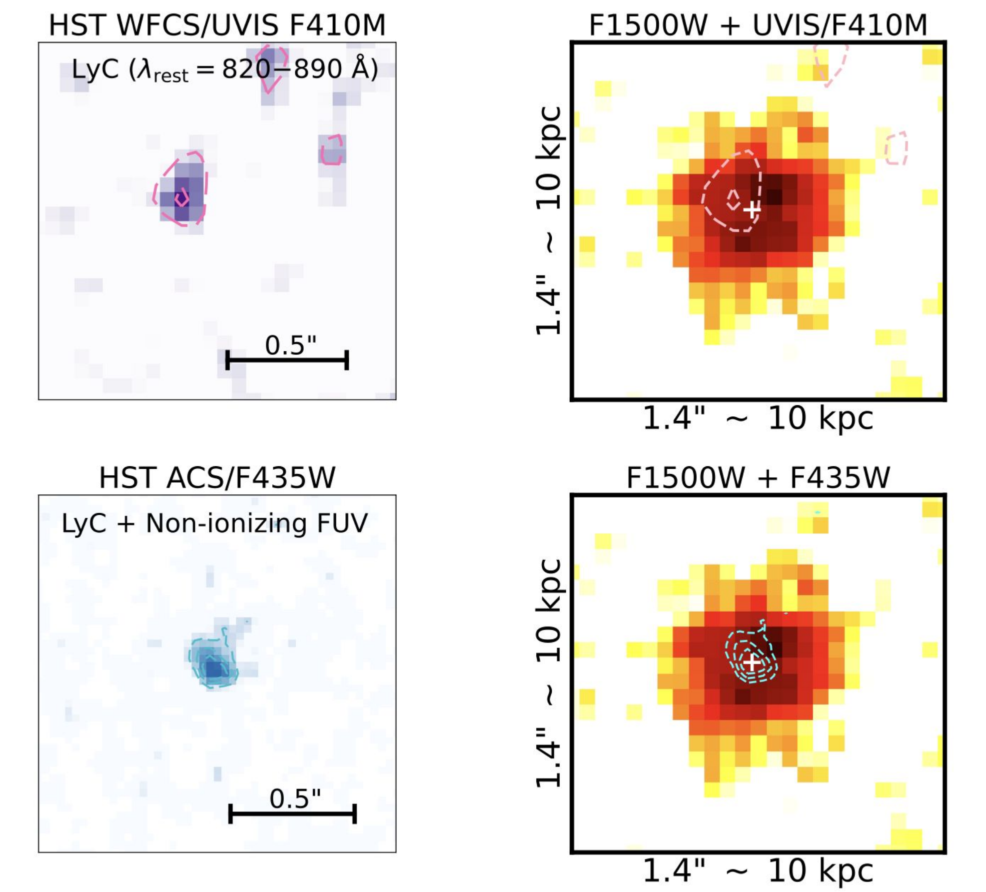
fesc = escaping / intrinsic

underestimated

Credit: ESA, NASA, Science RF

escape fraction varies spatially

Ji+25



LyC escape from a dusty galaxy

Ion 1, LCE at z~3.6

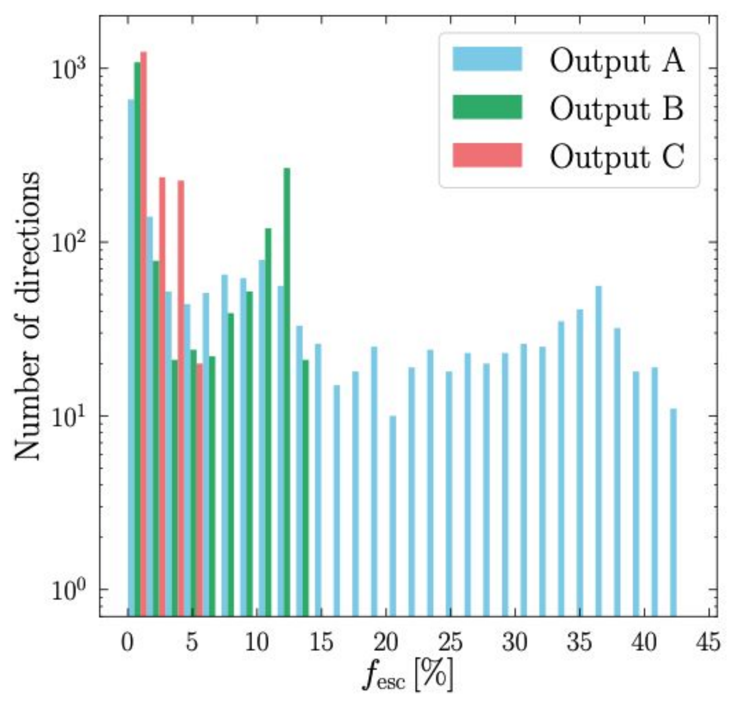
LyC + UV emission with HST

dust emission with JWST/MIRI

Credit: ESA, NASA, Science RF

escape fraction varies with direction and time

Mauerhofer+21



Choustikov+24

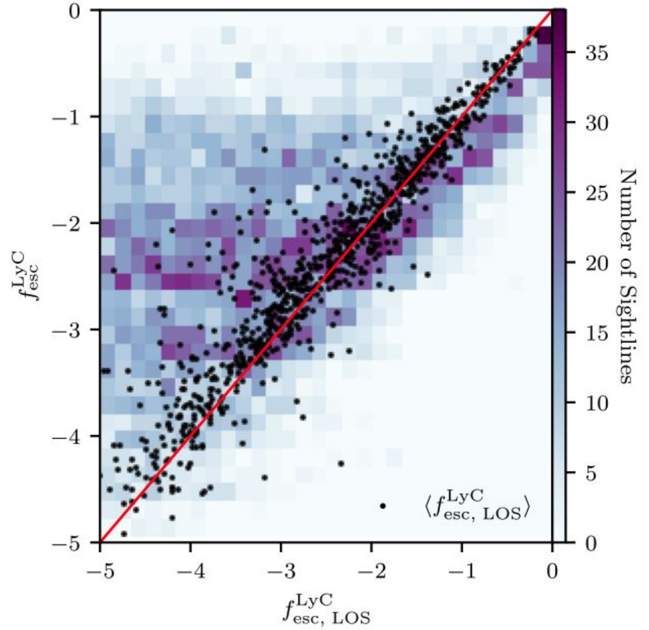
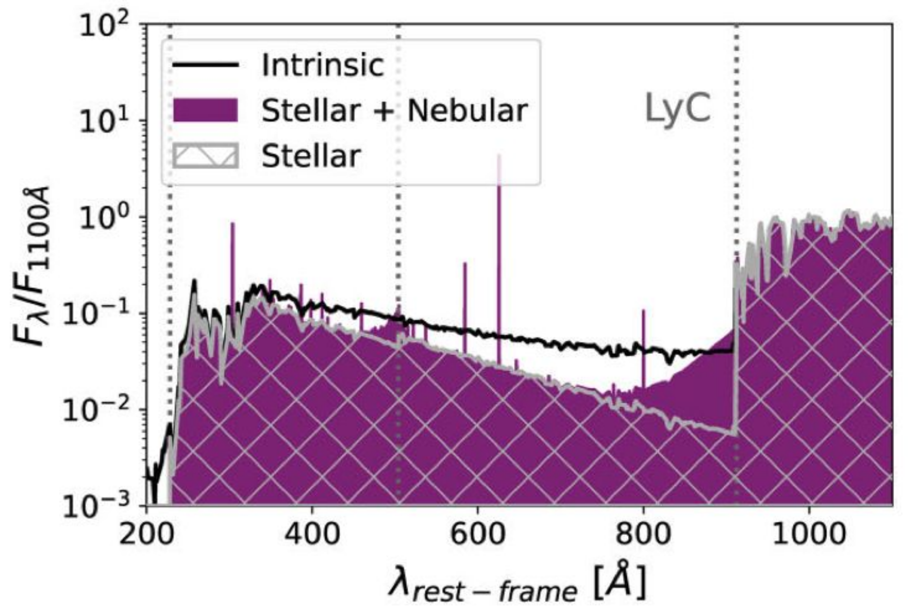
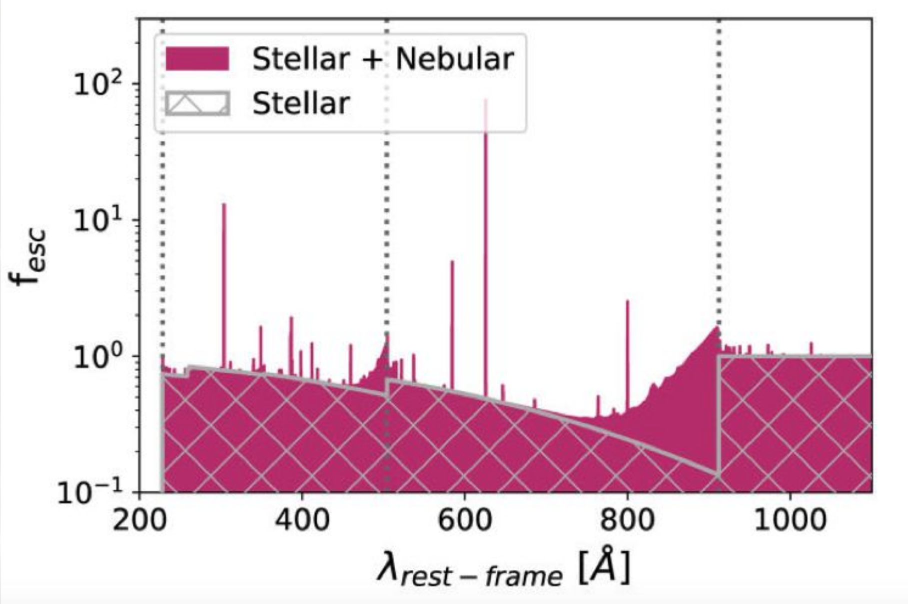


Figure B1. Histogram of global LyC escape fractions, f_{esc}^{LyC} against the 10 line-of-sight LyC escape fractions, $f_{esc,\ LOS}^{LyC}$ measured for each galaxy. We also include the angle averaged line-of-sight values for each true global value as black points. The one-to-one relation is shown in red.

escape fraction varies with wavelength !

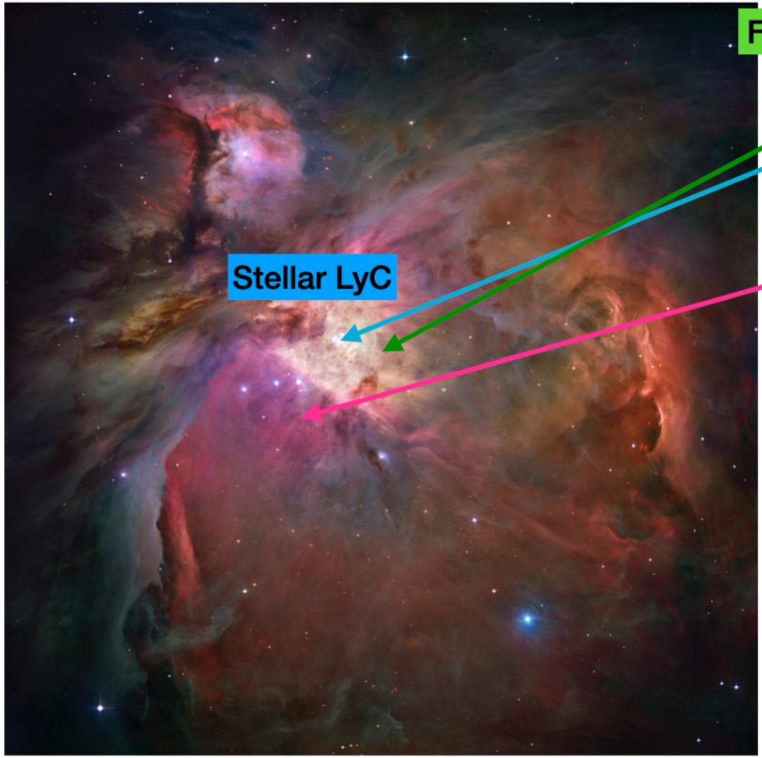
Simmonds+24

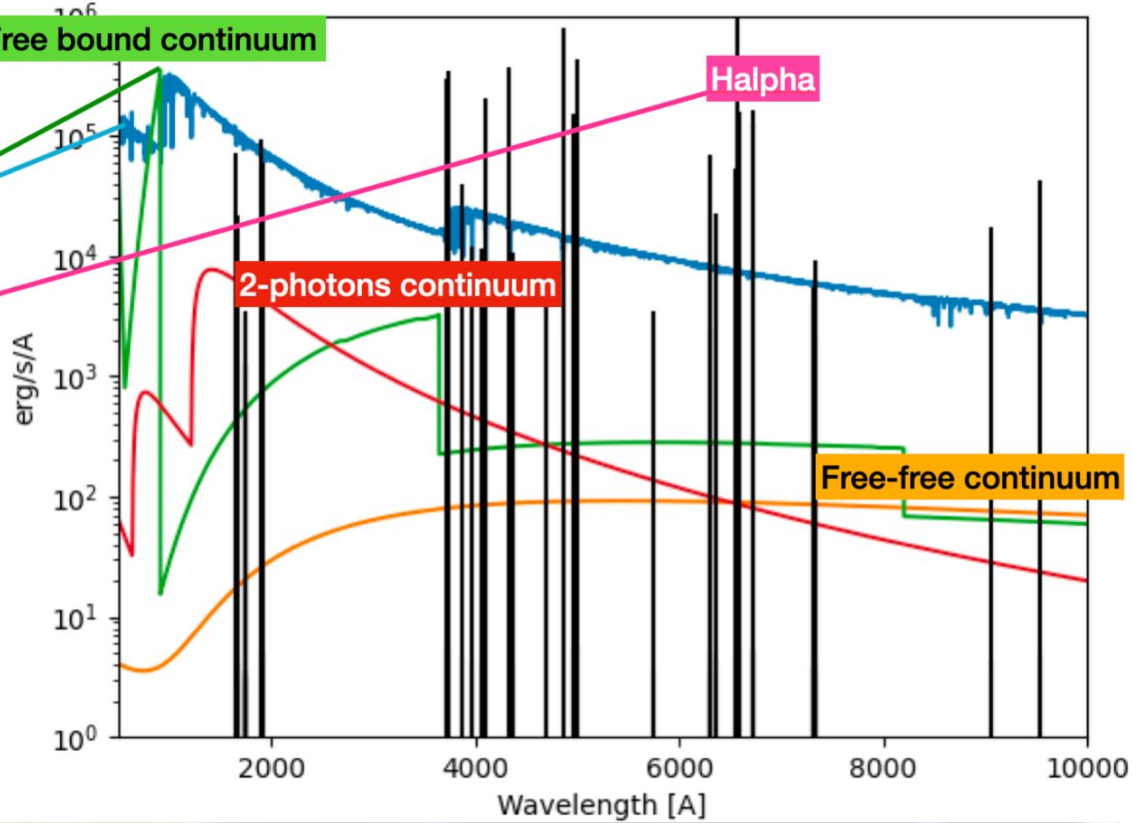




LyC nebular emission

Cooling emission from ionised gas that recombines

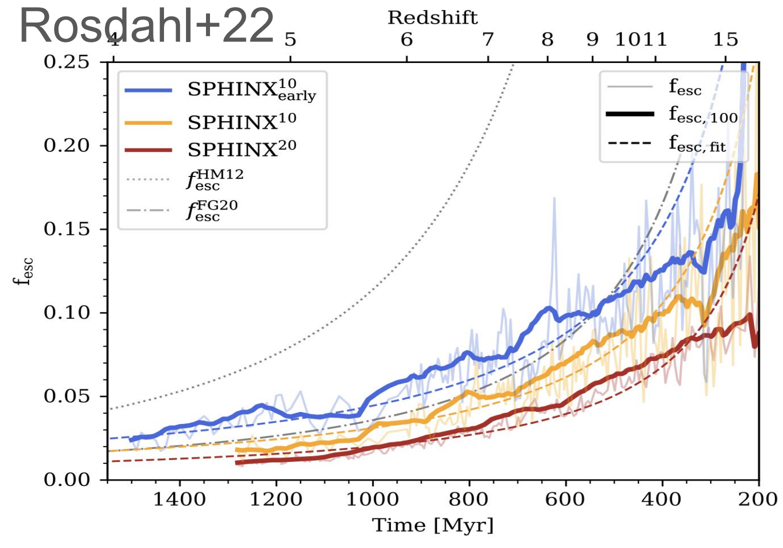




~~The~~ escape fraction**S** of ionising photons

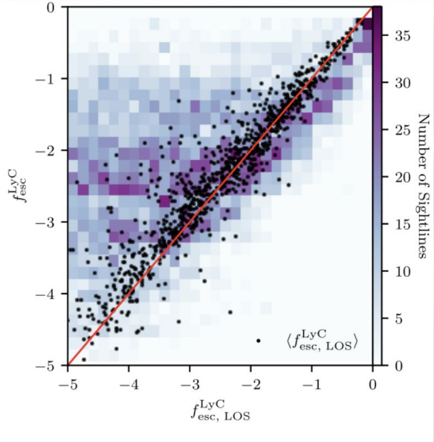
- cosmic escape fraction

Rosdahl+22

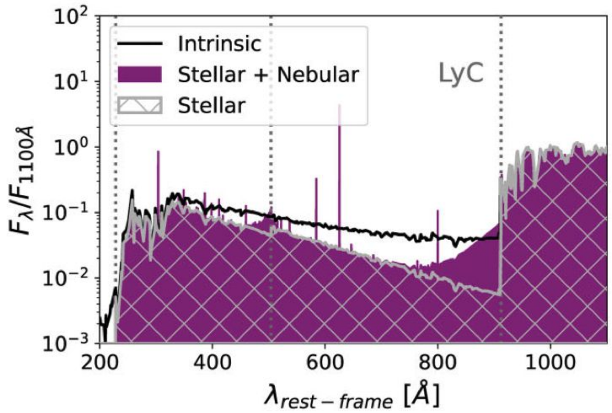


- galactic escape fractions:
  - 3D or LOS
  - over which wavelength range

Choustikov+24



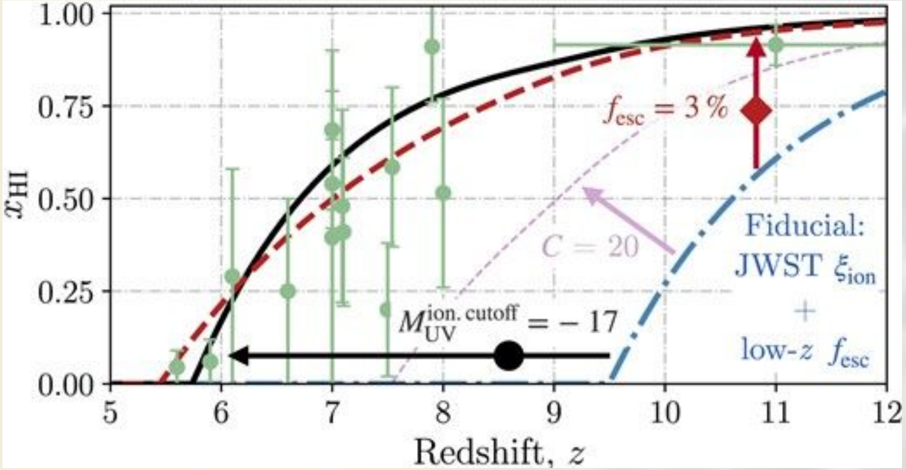
Simmonds+24



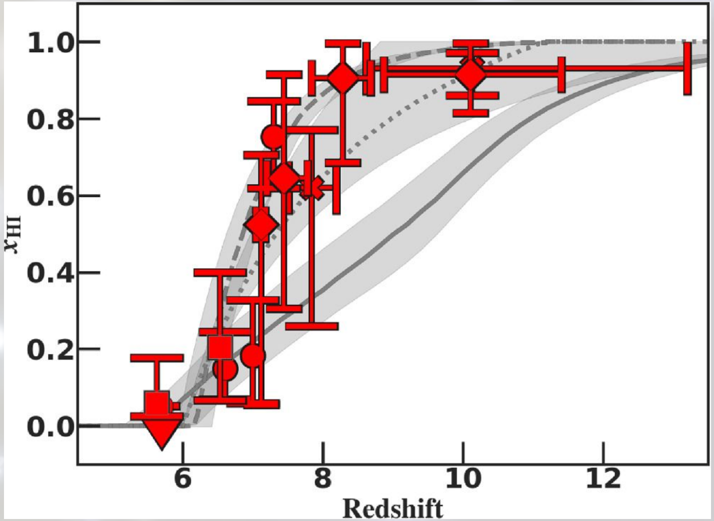
- complicated to estimate, and to link with Reionisation history
- any other idea to estimate/parametrise ionising photons budget ?

$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_H \rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}},$$

Matching the inferred $\dot{n}_{ion}$ to the evolving Q_{HI} determined by independent IGM probes (Lyα fraction, clustering, LF, QSO DW, galaxies DW etc)



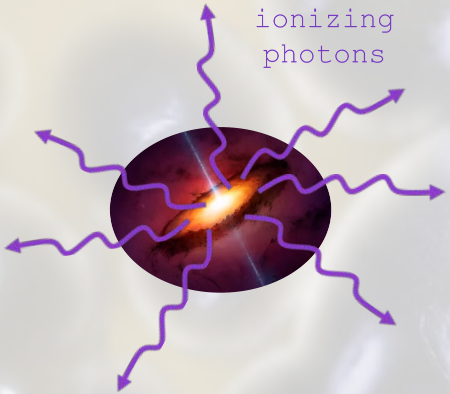
Munoz+24

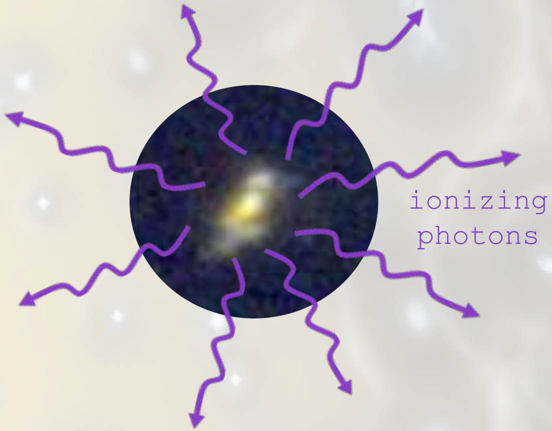


Umeda+25

Credit: ESA, NASA, Science RF

Determining most of the ingredients of reionization is still challenging → → our conference !!





- production of Lyman continuum radiation
- transport of Lyman continuum radiation
- escape of Lyman continuum radiation
- the role of AGN
- how can simulations help

Credit: ESA, NASA, Science RF