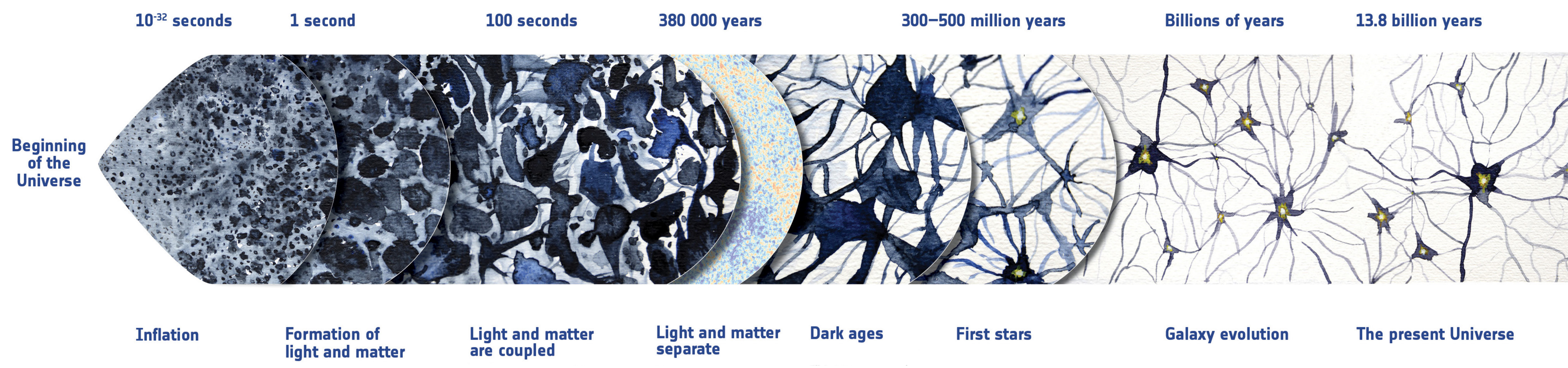

Implications for the Epoch of Reionization in the Local Universe

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Overview

- Reionization constraints from the Cosmic Microwave Background (z > ~6)

"A projected estimate of the reionization optical depth using the CLASS experiment's sample-variance limited E-mode measurement,"

Watts, BW & CLASS, ApJ (2018).

- Local analogs to reionization-era galaxies (z ~ 0.3)

"A new technique for selecting galaxies leaking Lyman-continuum photons: [S II]-deficiency,"

BW, Heckman, Leitherer, et al., ApJ (2019).

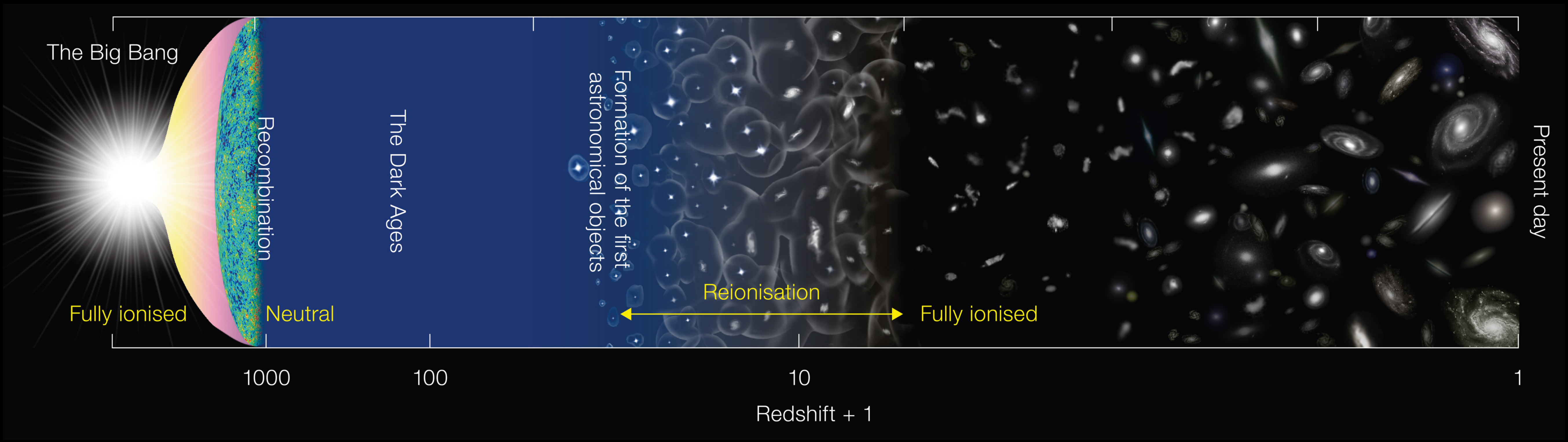
"The Low-redshift Lyman-continuum Survey: [S II]-deficiency and the leakage of ionizing radiation,"

BW, Heckman, & the survey collaboration, submitted to ApJ (2021).

- Starburst-driven outflows (z ~ 0.07)

"A systematic study of galactic outflows via fluorescence emission: implications for their size and structure,"

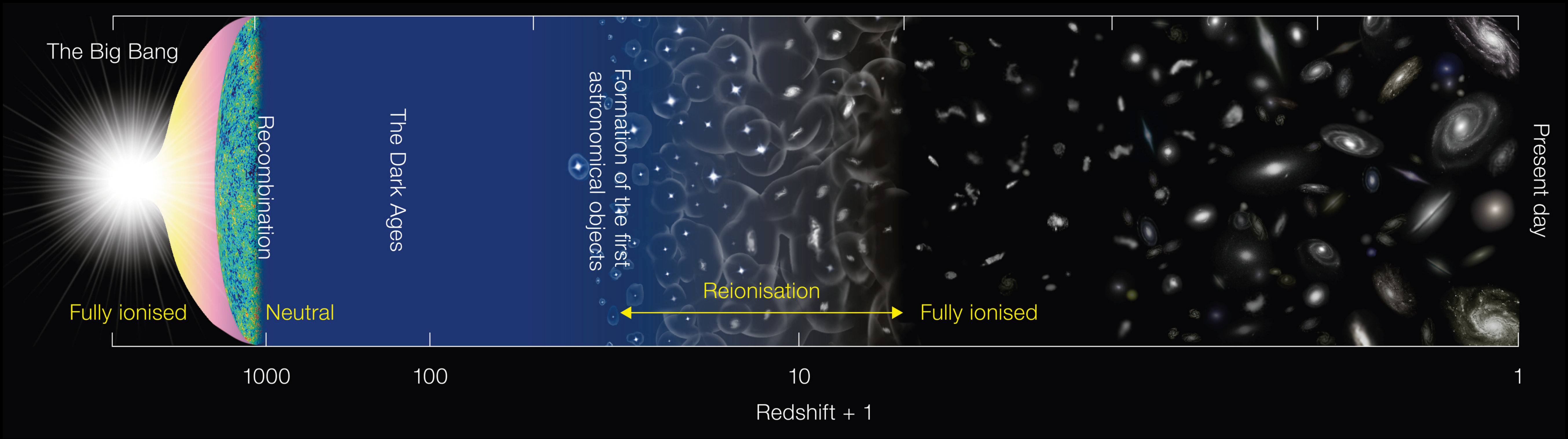
BW, Heckman, et al., ApJ (2020).



When did reionization happen?

- **Spectroscopy of distant quasars:** reionization ends by $z \sim 6$ (e.g., Fan+ 2006)
- **The cosmic microwave background**:
  - mid-point redshift of reionization $z = 7.7 \pm 0.7$ (Planck 2018 VI)
  - future measurements of polarization will tighten the constraint (e.g., CLASS; Watts, BW+ 2018)

Title and above images: ESA, NAOJ

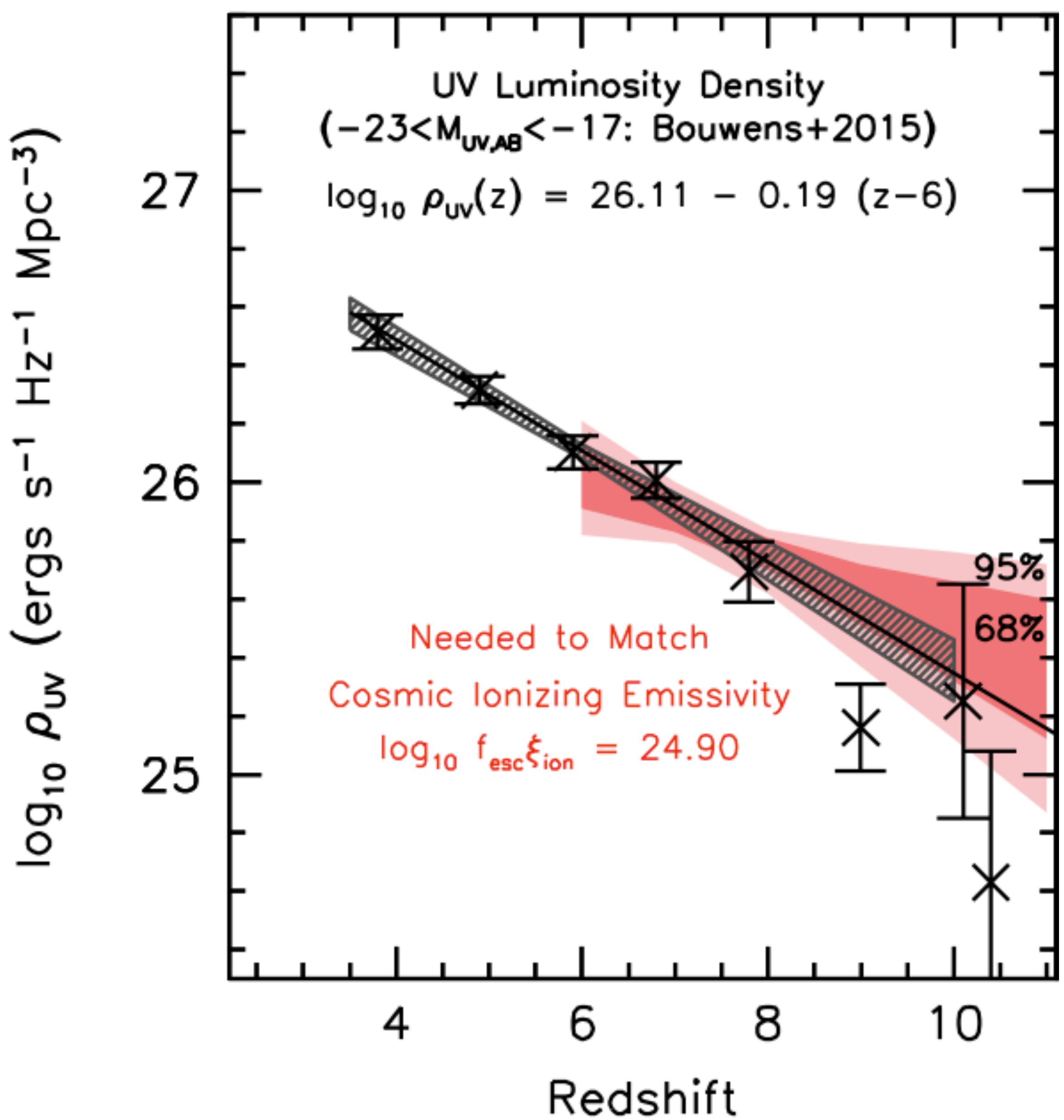


How did reionization happen?

- Where did ionizing (Lyman-continuum; LyC) photons come from?
- How did ionizing photons escape into the intergalactic medium?

Title and above images: ESA, NAOJ

Star-forming galaxies as ionizing sources



Sufficient to reionize the universe as inferred from the UV luminosity function.

But what makes it possible for LyC to escape into the IGM?

- Neutral H column of ~10^{-3} $M_\odot$ pc^{-2} (10^{17} cm^{-2}) absorbs all H-ionizing radiation.

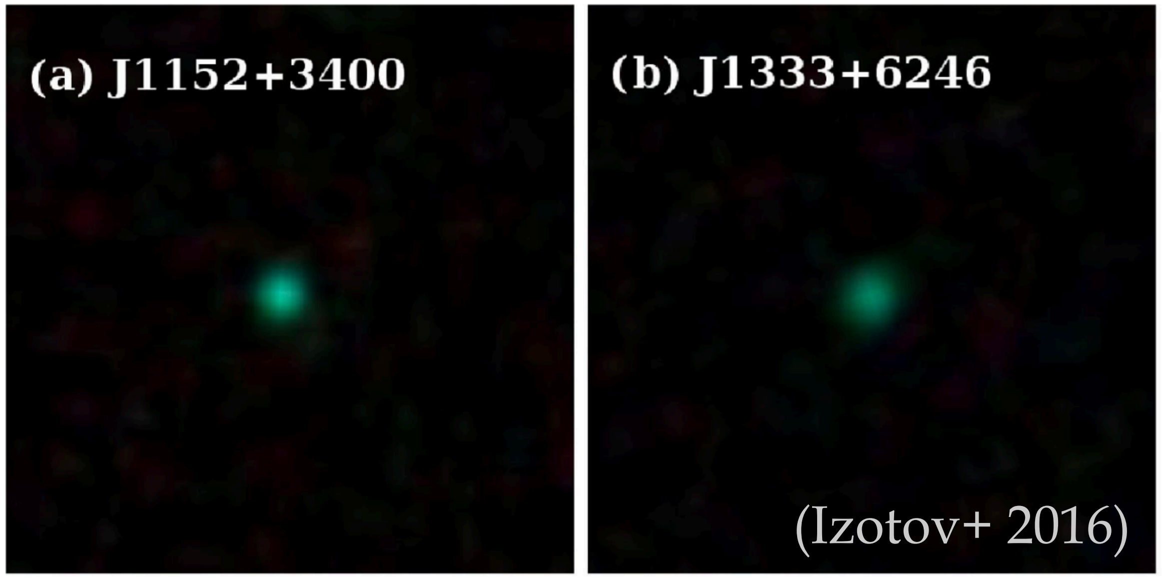
The neural IGM during reionization precludes direct observations of LyC.

(Bouwens+ 2015)

A strategy: studying LyC emitters at low redshifts

~ 10 direct detections in recent years,
e.g., Borthakur+ 2014; Leitherer+ 2016; Izotov+ 2016, 2018.

Benchmark sample: Green-Pea galaxies, characterized by high [O III]/[O II] flux ratios.



Increased sample size →

The Low-redshift LyC Survey
(HST-GO-15626; PI A. Jaskot)

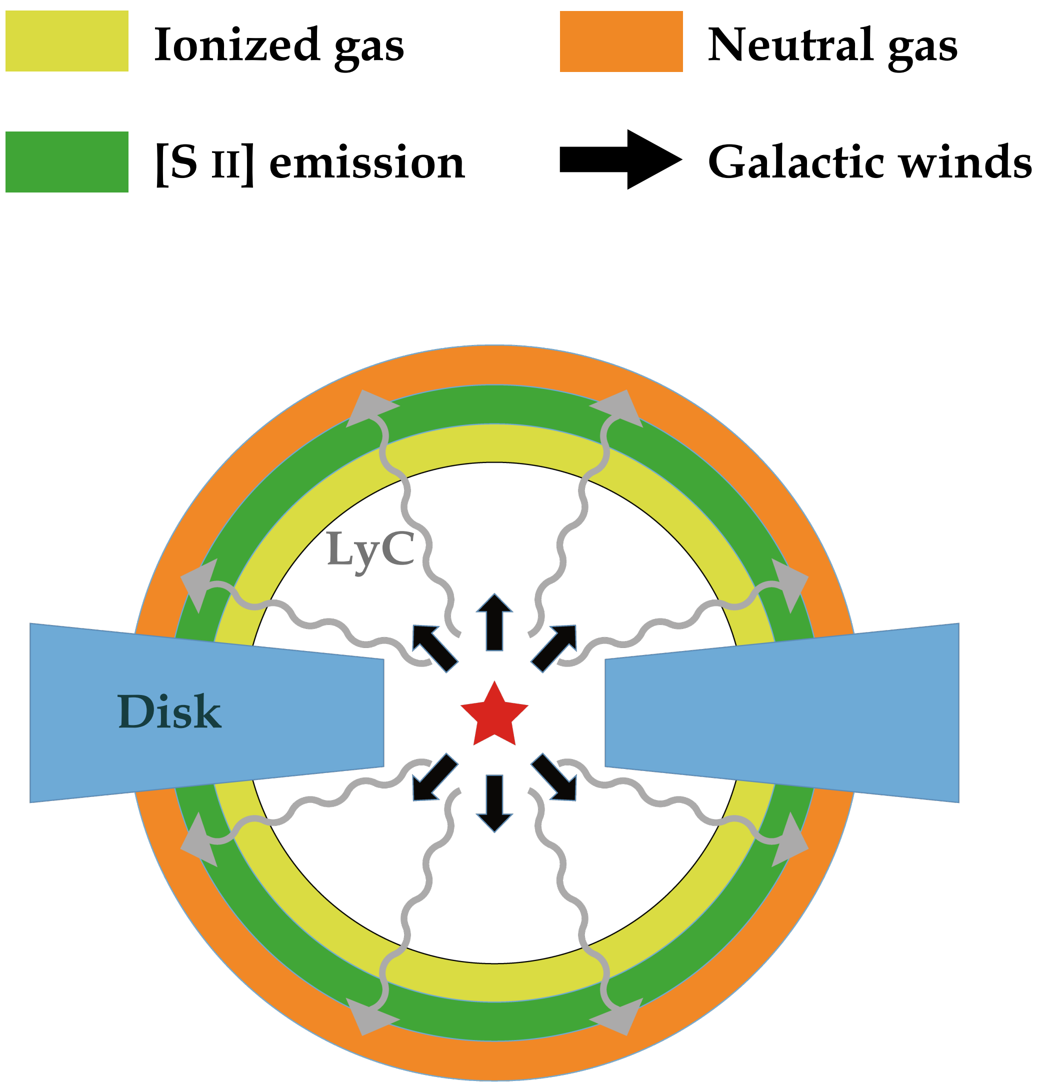
66 star-forming galaxies at $z \sim 0.3$, satisfying at least one of the following criteria:

- [O III]/[O II] flux ratio > 3
- UV spectral slope < −2
- SFR/area > 0.1 $M_\odot\ yr^{-1}\ kpc^{-2}$.

A new LyC signpost: [S II]-deficiency

The ionization potential for producing [S II] (10.4 eV) < that needed for ionizing H I (13.6 eV).

[S II] emission mostly arises in the **partially ionized region**, which is expected to be weak when the **neutral region** is absent to allow LyC to escape.

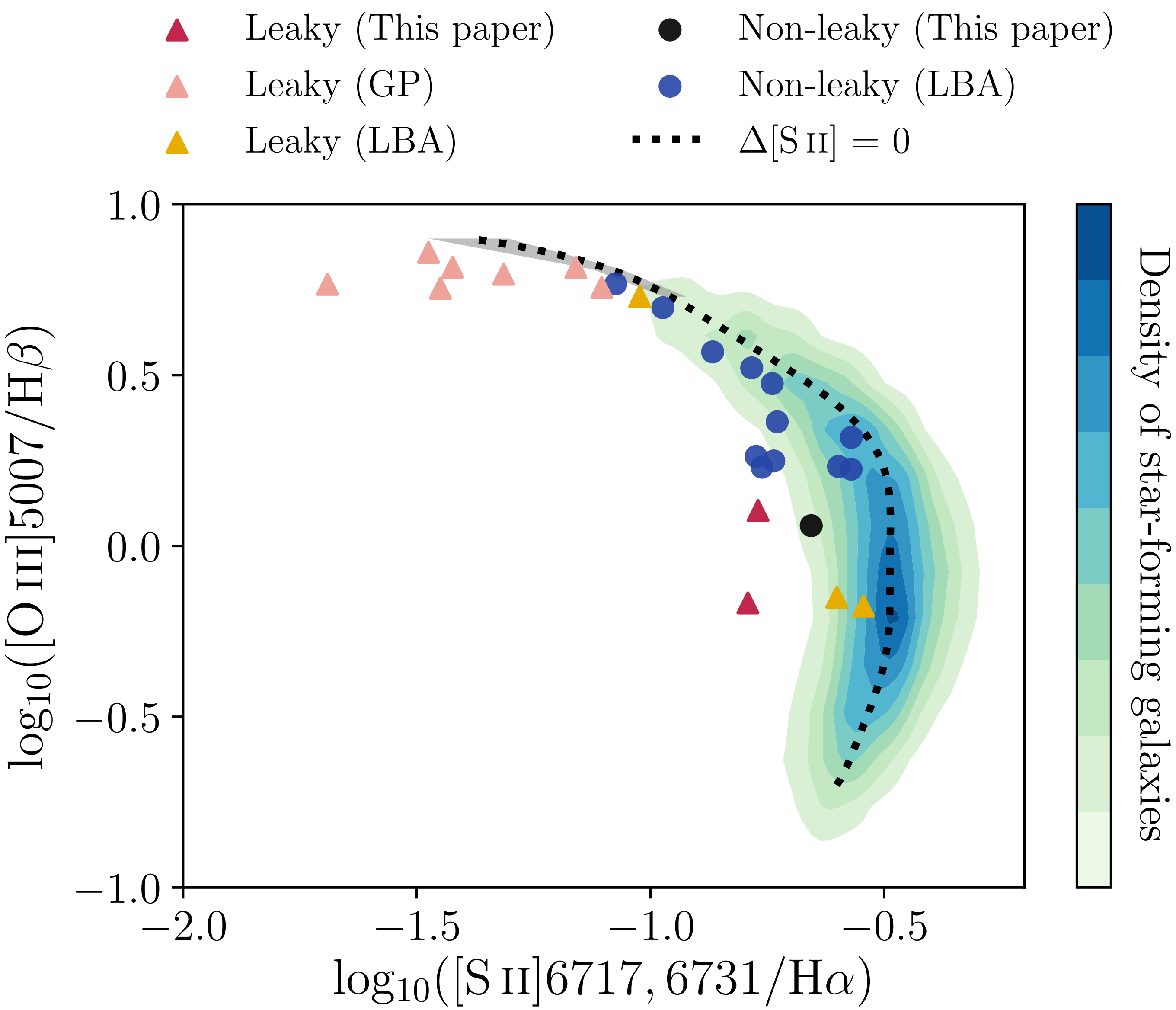


(BW+ 2019, 2021)

Definition of [S II]-deficiency

Defined with respect to typical SDSS star-forming galaxies

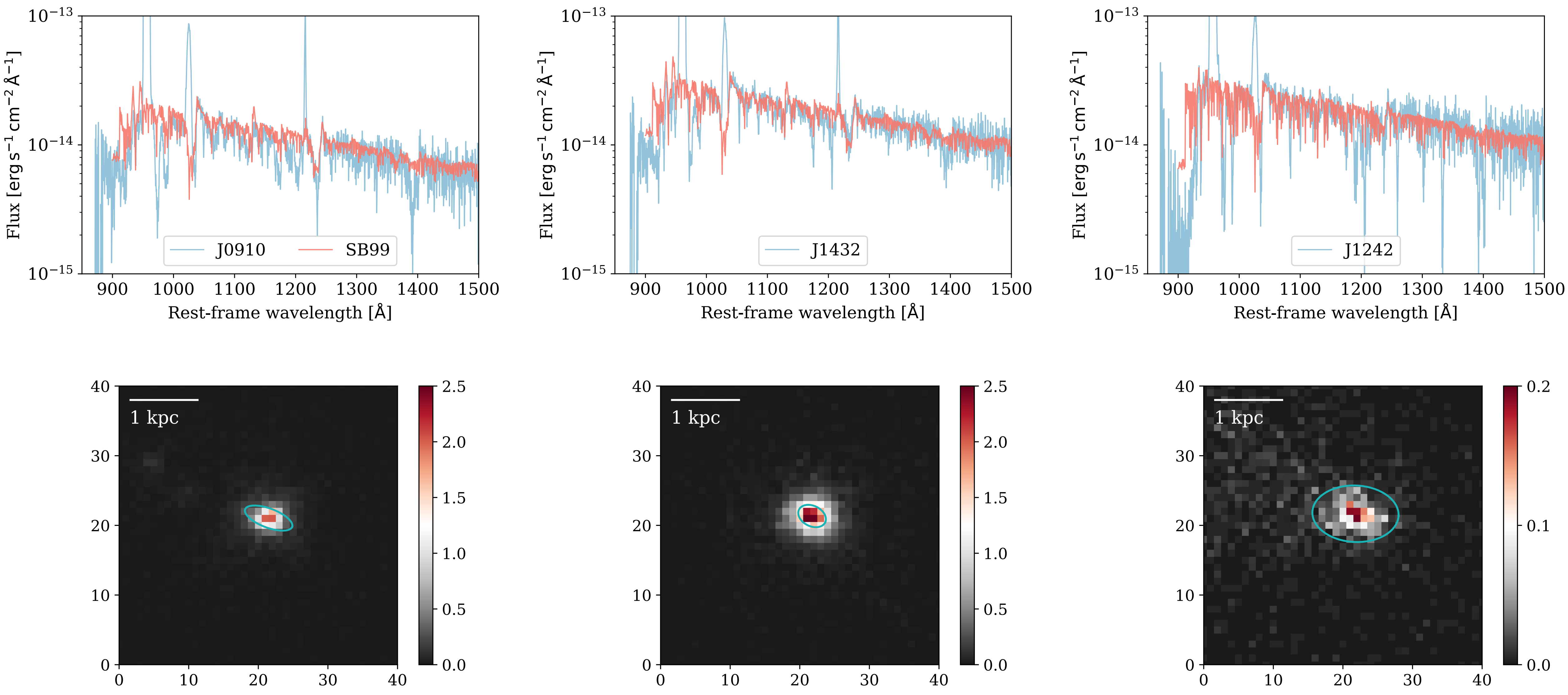
— a galaxy's displacement in log([S II]/Hα) from the ridge line



(BW+ 2019)

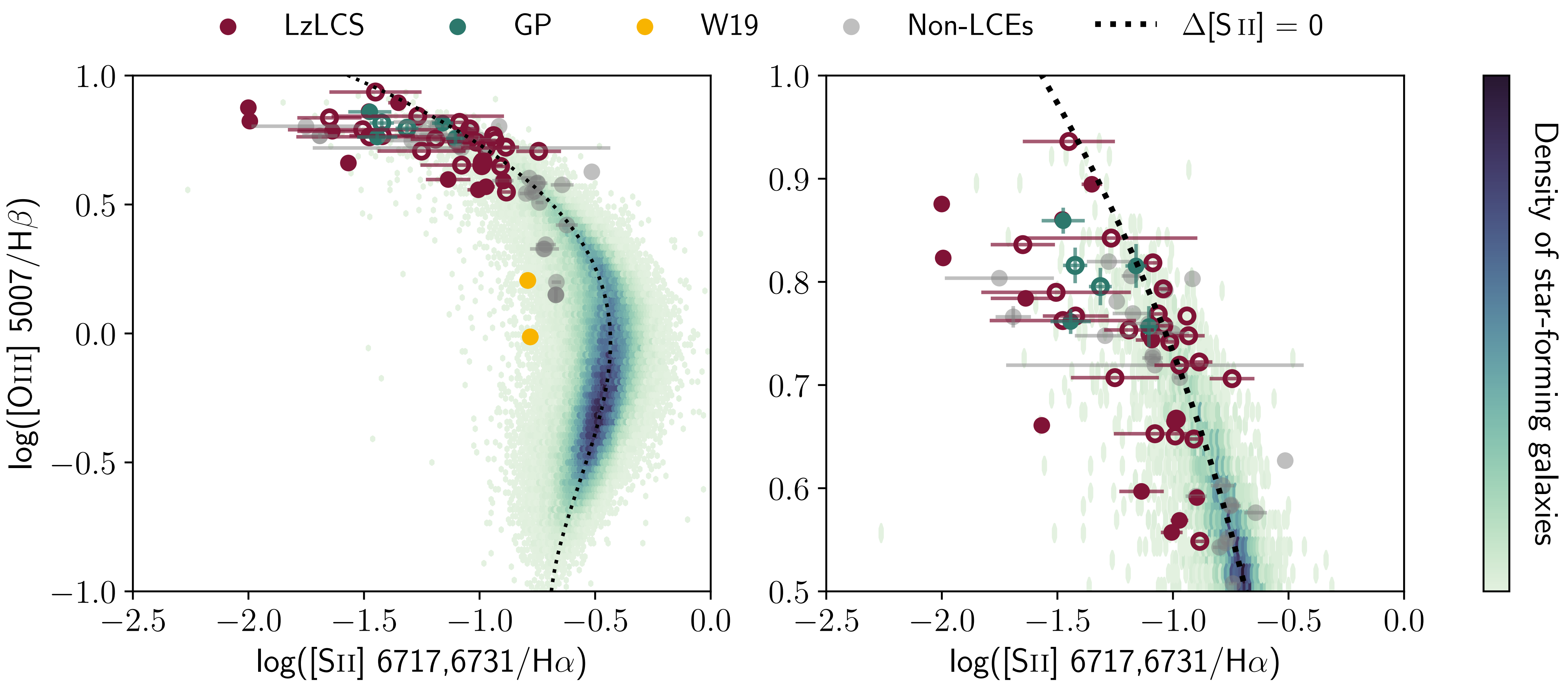
Results from a pilot HST program

Two out of the three [S II]-weak-selected star-forming galaxies are confirmed to be LCEs.



(BW+ 2019)

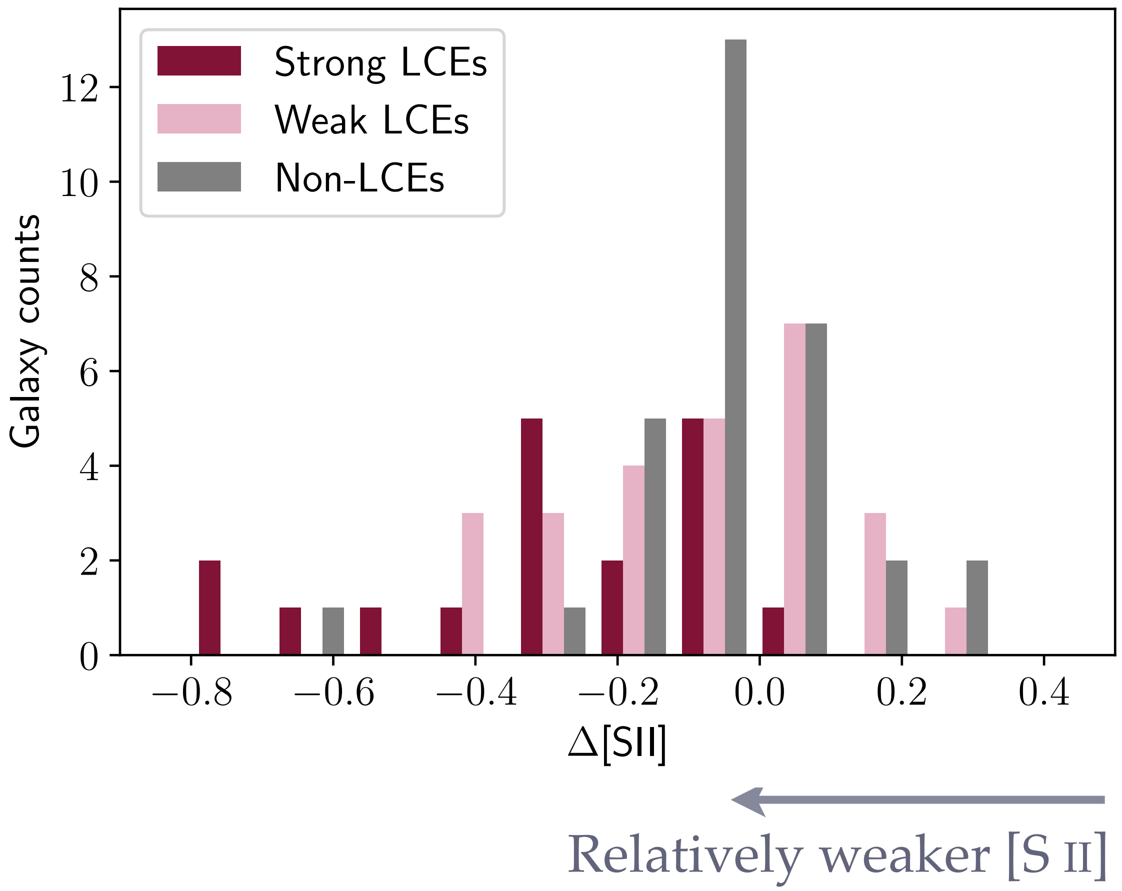
Results from the Low-z LyC Survey

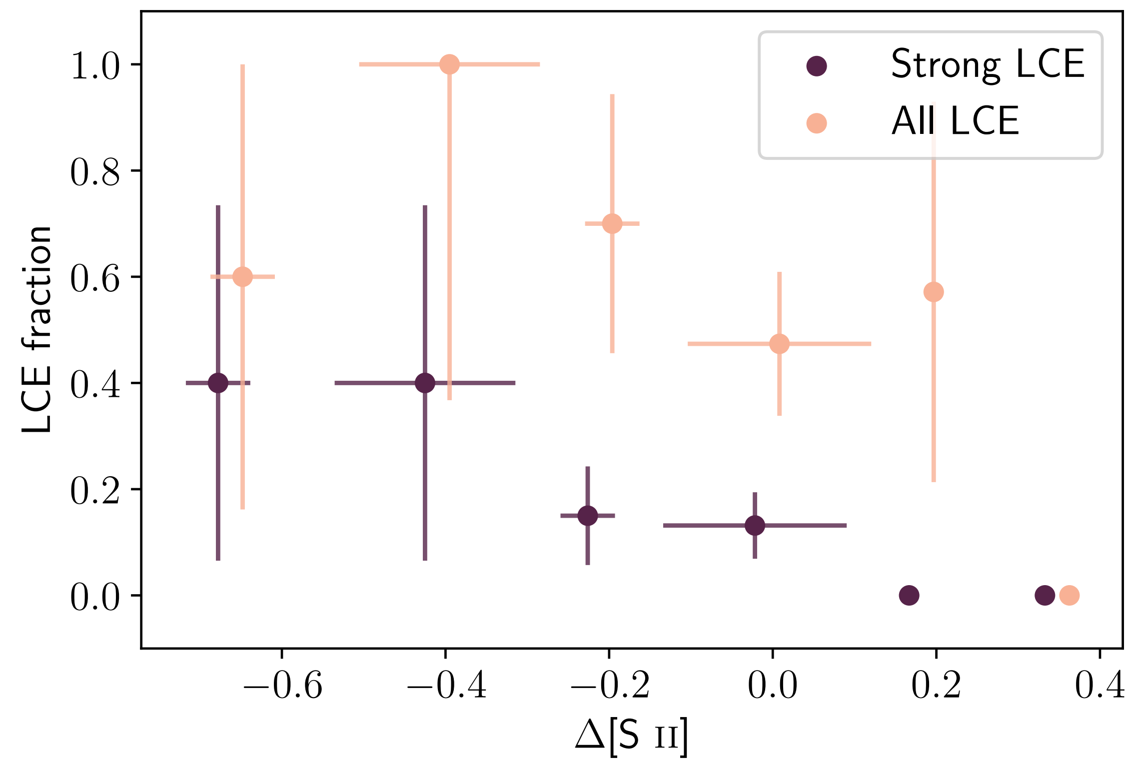


(BW+ 2021)

Statistical tests

[S II]-deficiency diagnostic can reliably select candidates of LyC emitters.





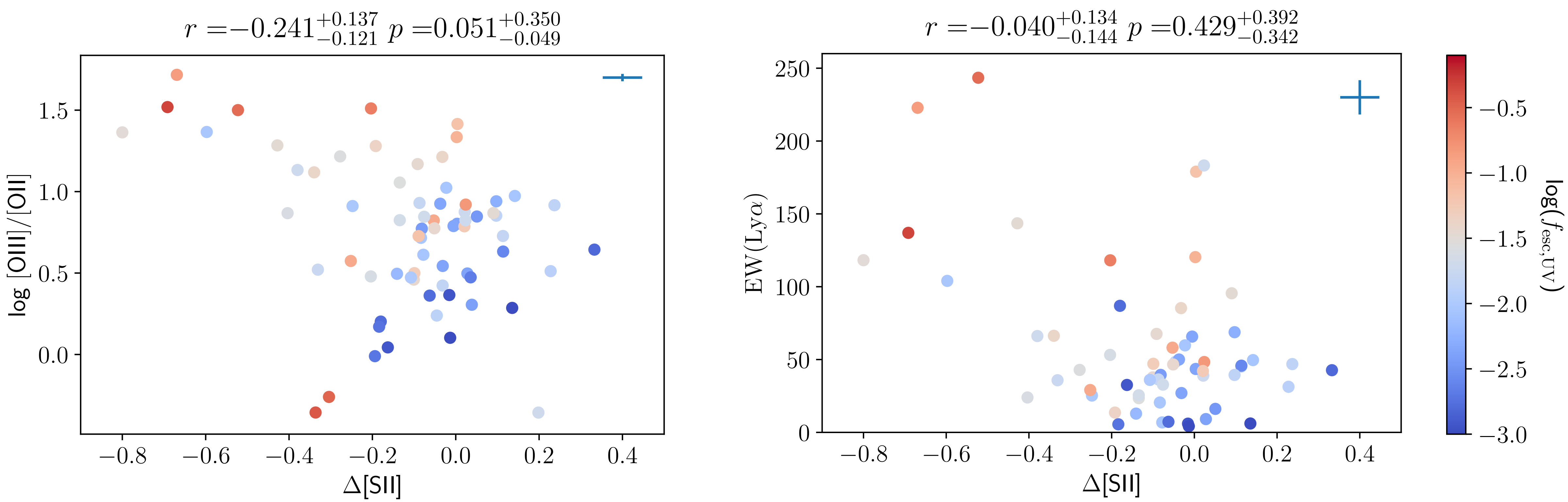
Distributions of LCEs differ from that of non-LCEs along the axis of [S II]-deficiency.

Fractions of LCEs detected increase as [S II]-deficiency becomes more prominent.

(BW+ 2021)

Comparisons to other LyC diagnostics

Correlations btw [S II]-deficiency and other diagnostics are weak, indicating that it provides independent information on LyC leakage.

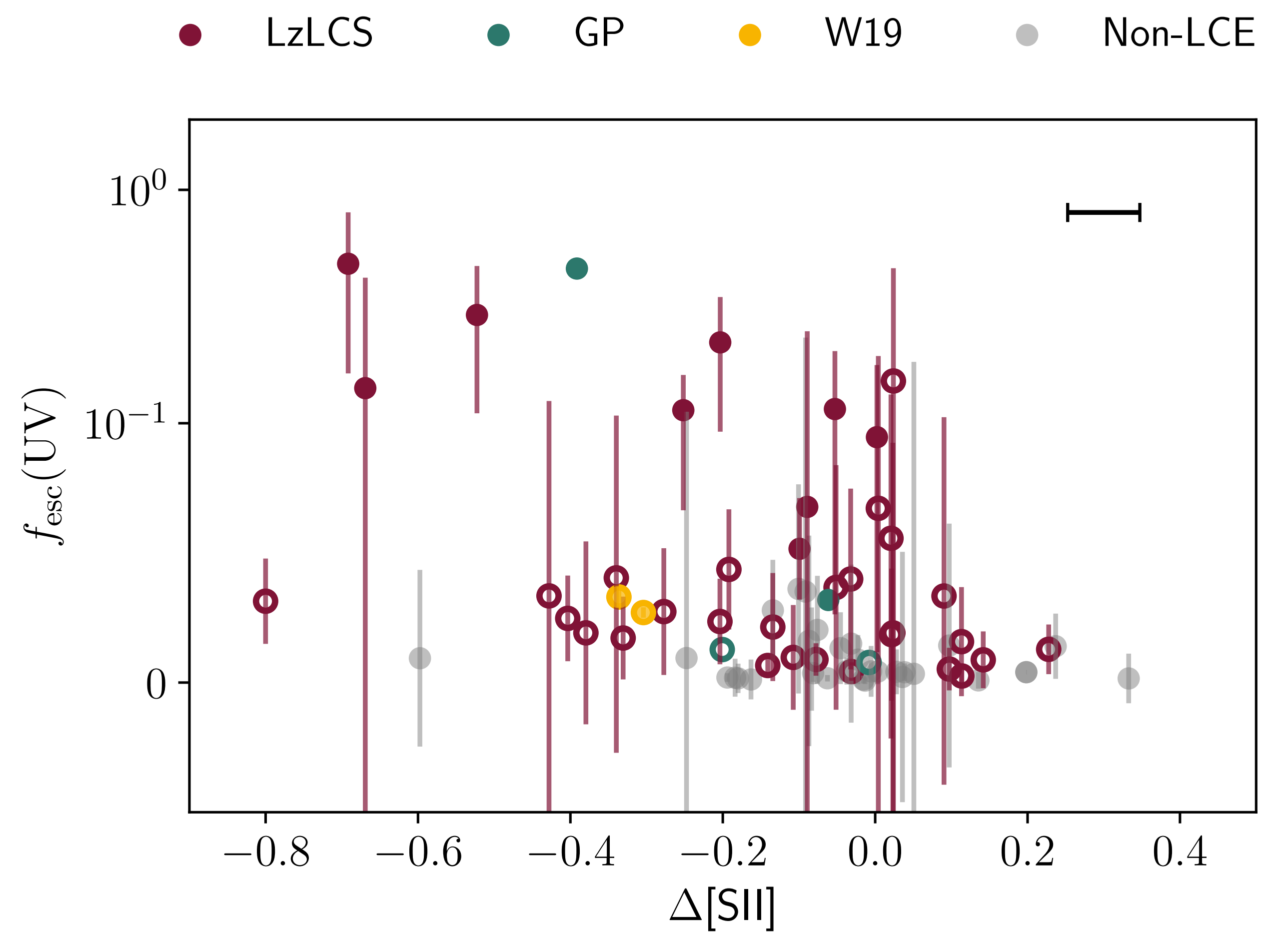


(BW+ 2021)

Escape fractions

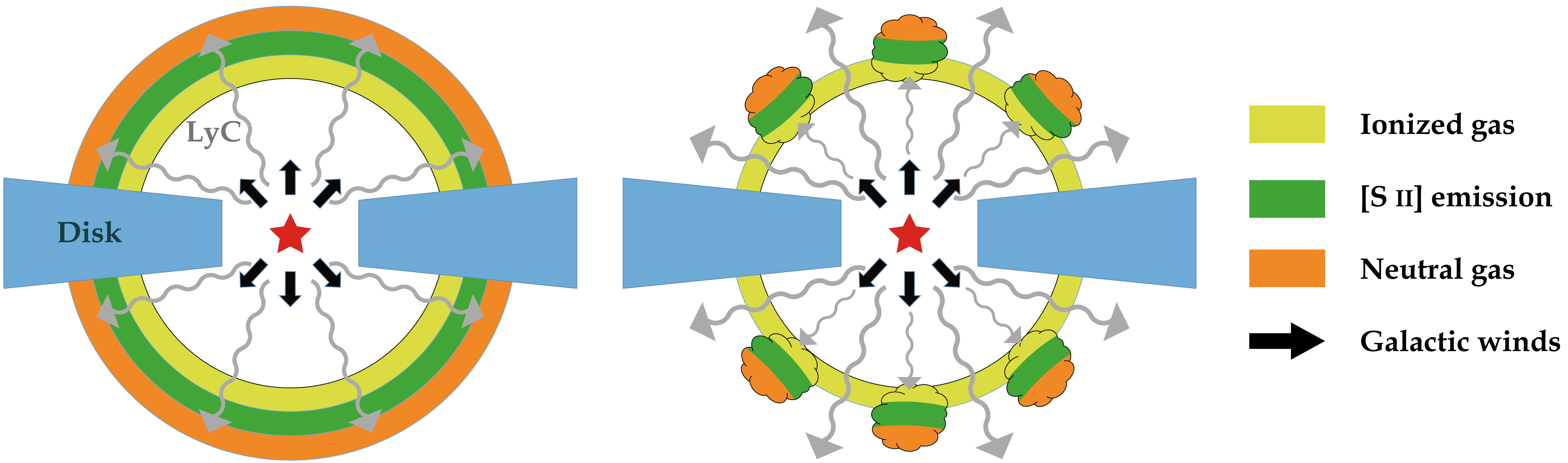
The escape fraction (f_{esc}) is very important for understanding reionization, but remains poorly constrained.

The weak correlation with significant scatter suggests that it is not obvious to infer f_{esc} from numerical values of [S II]-deficiency.



(BW+ 2021)

Photoionization models



(BW+ 2021)

The weak correlation may indicate:

- line-of-sight variations caused by porous H I regions (e.g., Steidel+ 2018; Nakajima+ 2020)
- anisotropically escaping LyC photons (e.g., Cen & Kimm 2015)

Conclusions

How did reionization happen?

◉ Where did ionizing (Lyman-continuum; LyC) photons come from?

- **Star-forming galaxies** are the best candidates;
- We have selected LyC-emitting galaxies based on **[S II]-deficiency** — a sign of gas that is optically thin to ionizing radiation;
- [S II]-deficient candidates tend to be strong LyC emitters.

◉ How did ionizing photons escape into the intergalactic medium?

- Only a weak correlation is found between numerical values of [S II]-deficiency and LyC escape fraction.
  - line-of-sight variations caused by porous H I regions;
  - anisotropically escaping LyC photons.