First Galaxies and their Local Analogues

Selected Chapters on Astrophysics
November 2025

Lecture 1: Era of Reionization

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EUROPEAN ARC
ALMA Regional Centre || Czech

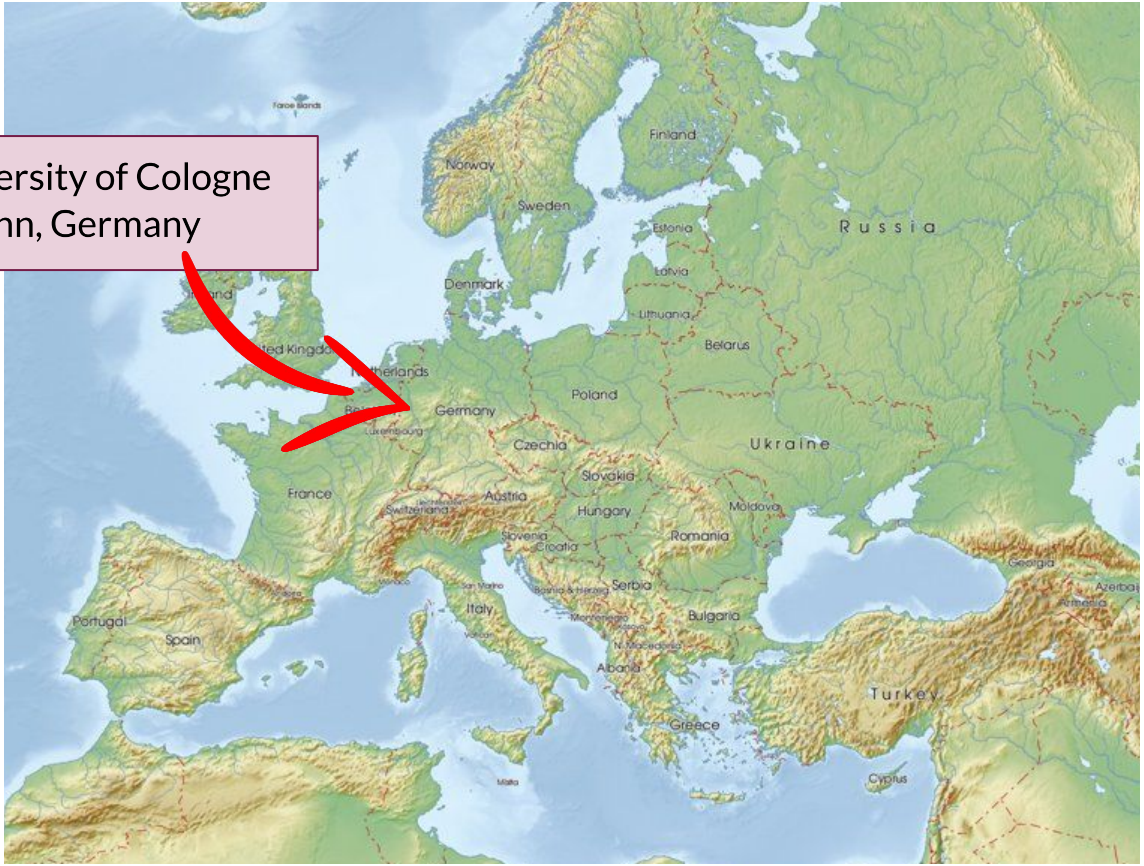
Astronomical Institute of the Czech Academy of Sciences

Who am I?

From Pune, India

Who am I?

Ph. D. from University of Cologne and MPIfR in Bonn, Germany



Who am I?

- Research scientist at Astronomický ústav AV ČR
  - Support Scientist at the Czech node of the European ALMA Regional Center Network
  - AGN Astrophysics (accretion, feeding & feedback, BH-host galaxy connection)
  - Star-forming dwarf galaxies (Green Peas and Blueberries)

Outline of the series

Lecture 1:

- Introduction and Early history of the Universe.
- Signatures of reionization
- First stars, galaxies, black holes

Lecture 2:

- Chasing the redshift frontier
- JWST discovery of early galaxies
- Little Red Dots

Outline of the series

Lecture 3:

- Limitations of studying the first galaxies
- The local analogues (LRD analogues, Green Peas, Blueberries)
- What's in the Future?

Questions, discussion, homework assignment.

Motivation

Ancient Human looking at the stars (José A. Peñas/SINC)

- Who we are?
- Where do we come from?
- Are we alone in the Universe?

Motivation

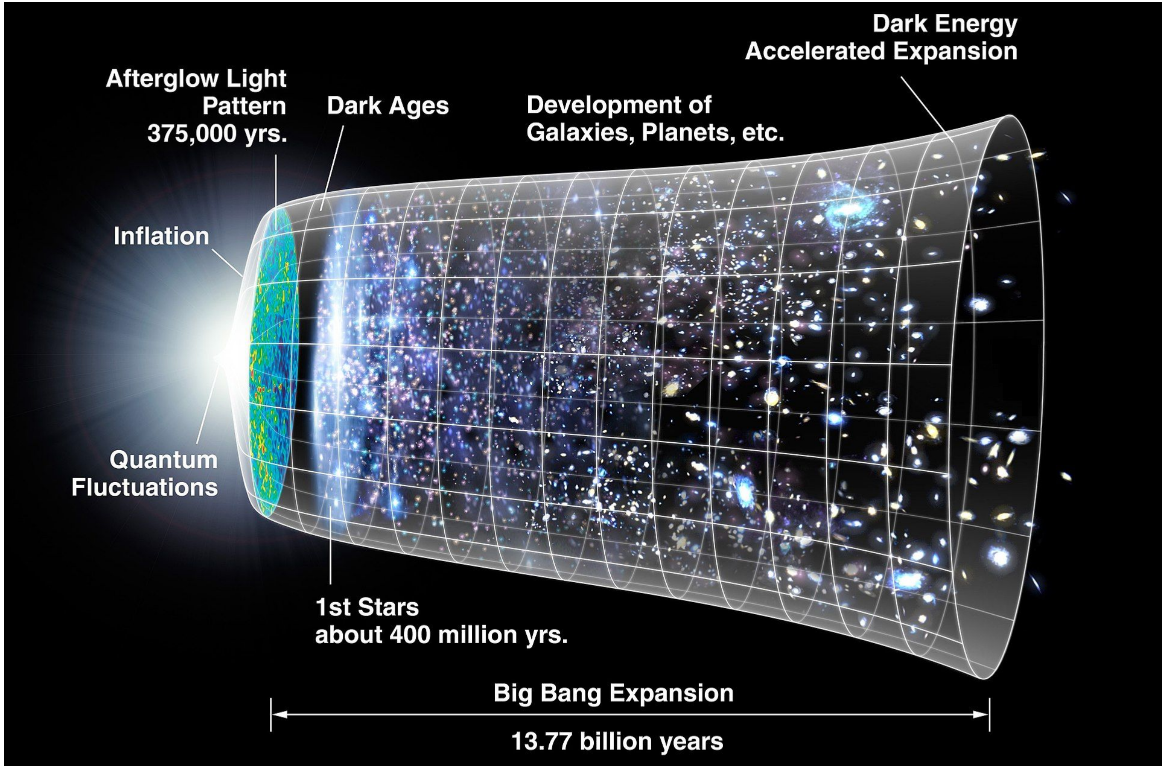
"If you want to make an apple pie from scratch, you must first invent the Universe." - Carl Sagan

Let's start at the very beginning

It all starts with the Big Bang!

"In the beginning, the Universe was created. This had made many people very angry and has been widely regarded as a bad move."

- Douglas Adams, The Restaurant at the End of the Universe

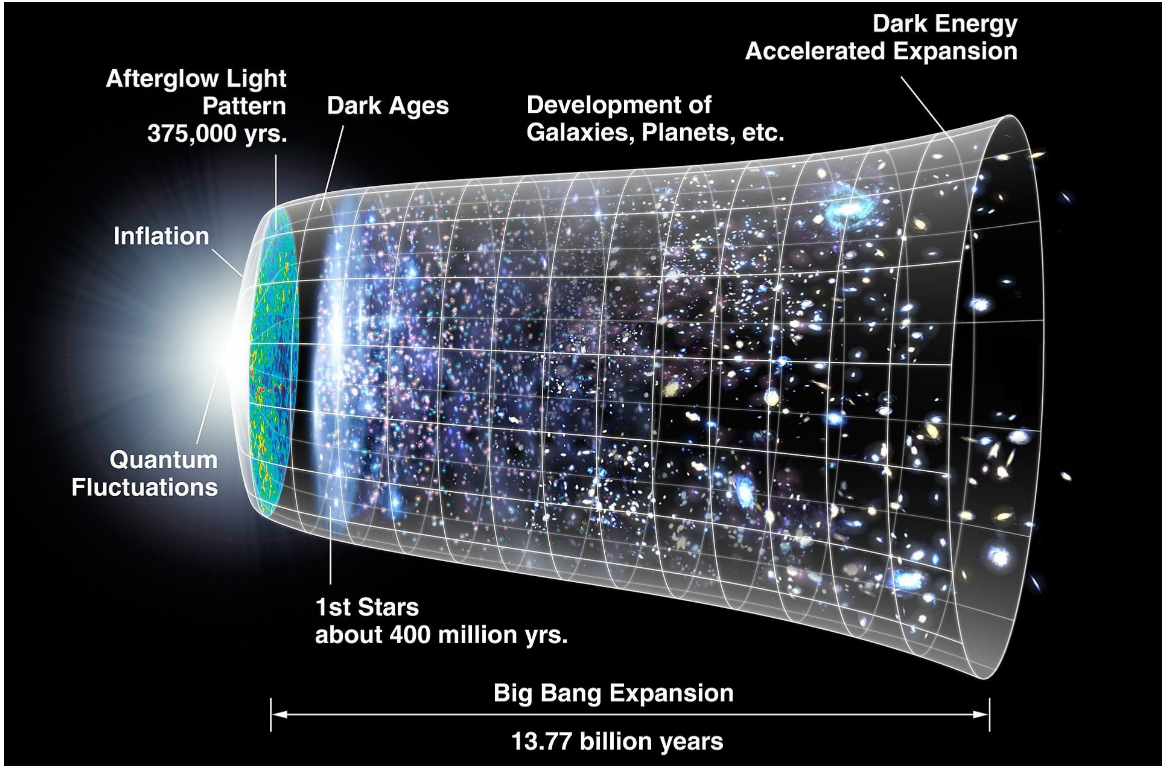


By NASA/WMAP Science Team - Original version: NASA; modified by Cherkash, Public Domain, https://commons.wikimedia.org/w/index.php?curid=11885244

Let's start at the very beginning

Inflationary period

- From 10^{-36} to 10^{-33} seconds.
- Space expanded by a factor of 10^{26}.
- Driven by a type of vacuum energy "inflaton" field.



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From Inflation to CMB

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- Strong and weak nuclear forces separate from EM (< 10^{-12} s).

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From Inflation to CMB

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- Strong and weak nuclear forces separate from EM.
- Quark-gluon plasma → hadrons (protons & neutrons) (10^{-12} to 10^{-5} s).

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From Inflation to CMB

- Inflaton field decays leading to the hot Big Bang.
- Strong and weak nuclear forces separate from EM.
- Quark-gluon plasma → hadrons (protons & neutrons).
- Matter domination over antimatter (*Baryogenesis* 10^{-5} to ~1 seconds).

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- Strong and weak nuclear forces separate from EM.
- Quark-gluon plasma → hadrons (protons & neutrons).
- Matter domination over antimatter.
- Protons and neutrons fused to form the first nuclei (*Big Bang Nucleosynthesis* 3-20 min).

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- Nuclei capture electrons and first atoms form (*Recombination* 20 min to 380,000 years).

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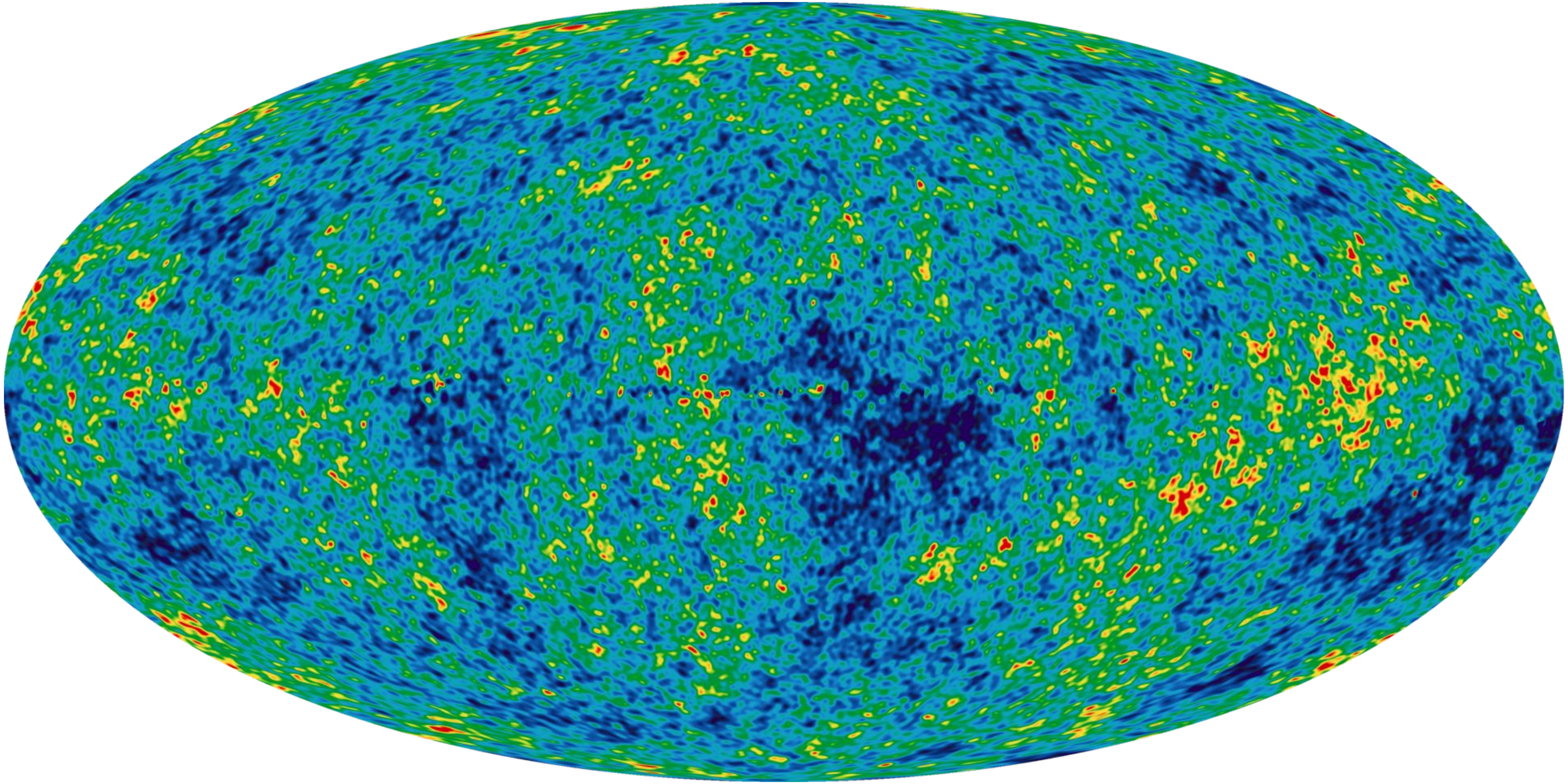
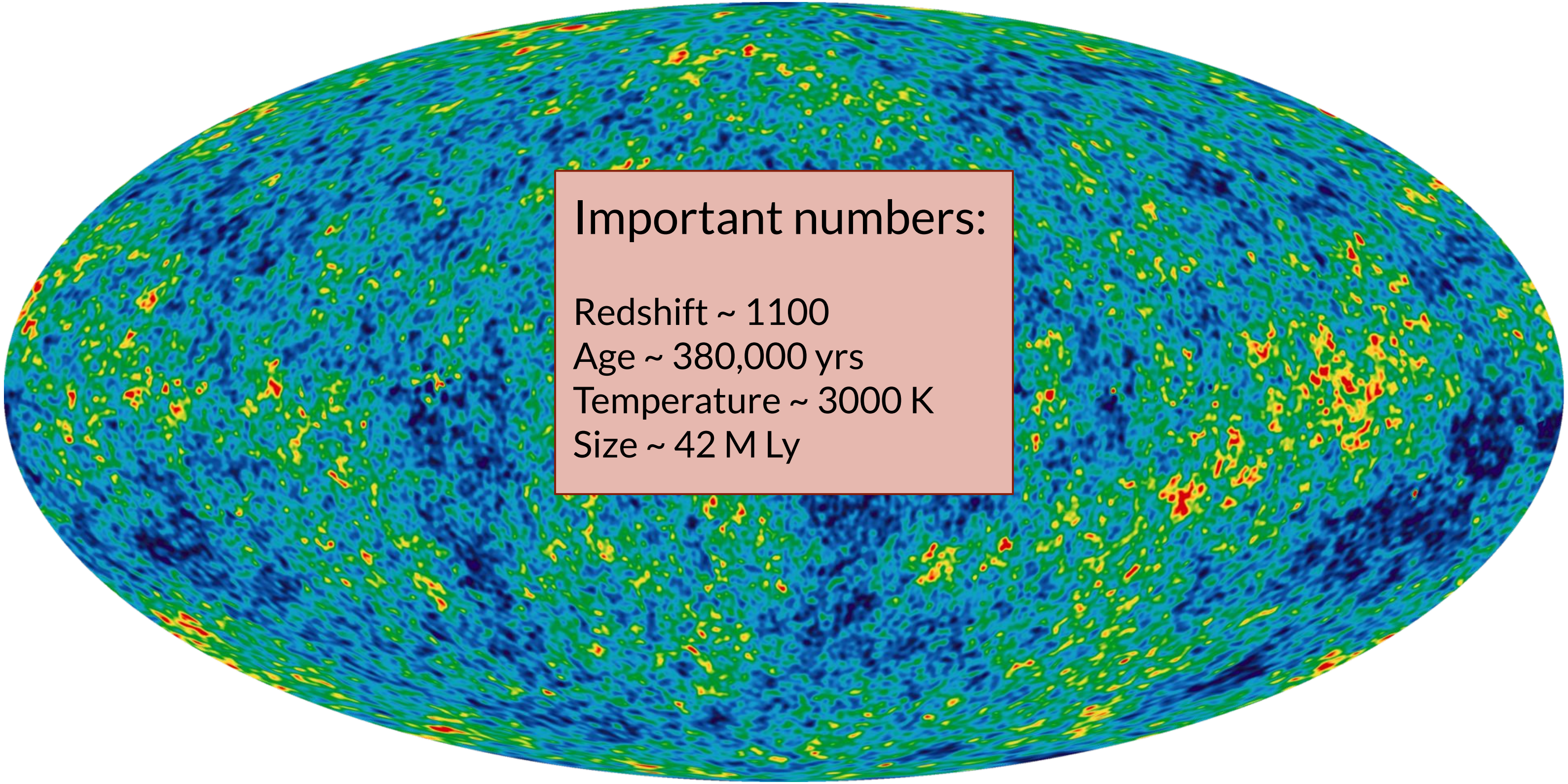
- CMB and photon decoupling ($z \sim 1100$).

Cosmic Microwave Background Radiation



Cosmic Microwave Background Radiation



Important numbers:

Redshift ~ 1100
Age ~ 380,000 yrs
Temperature ~ 3000 K
Size ~ 42 M Ly

The Dark Ages and the Cosmic Dawn

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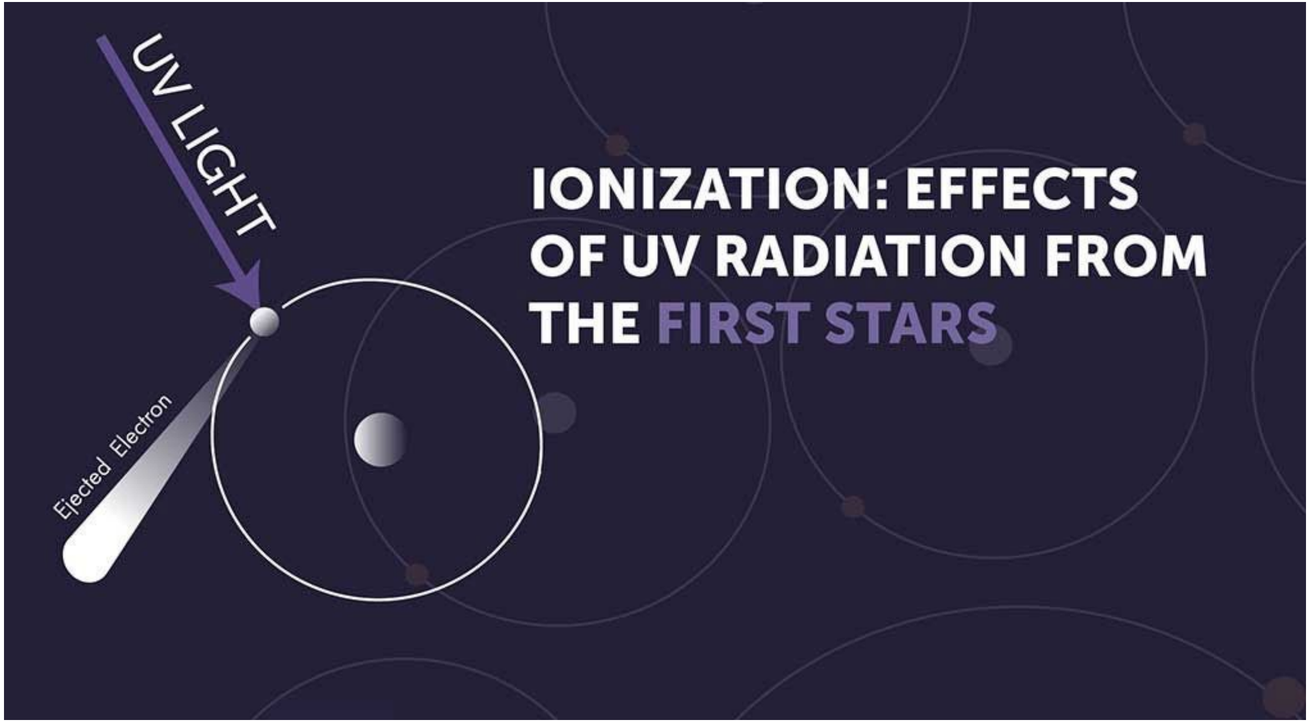
- First black holes?????

Reionization



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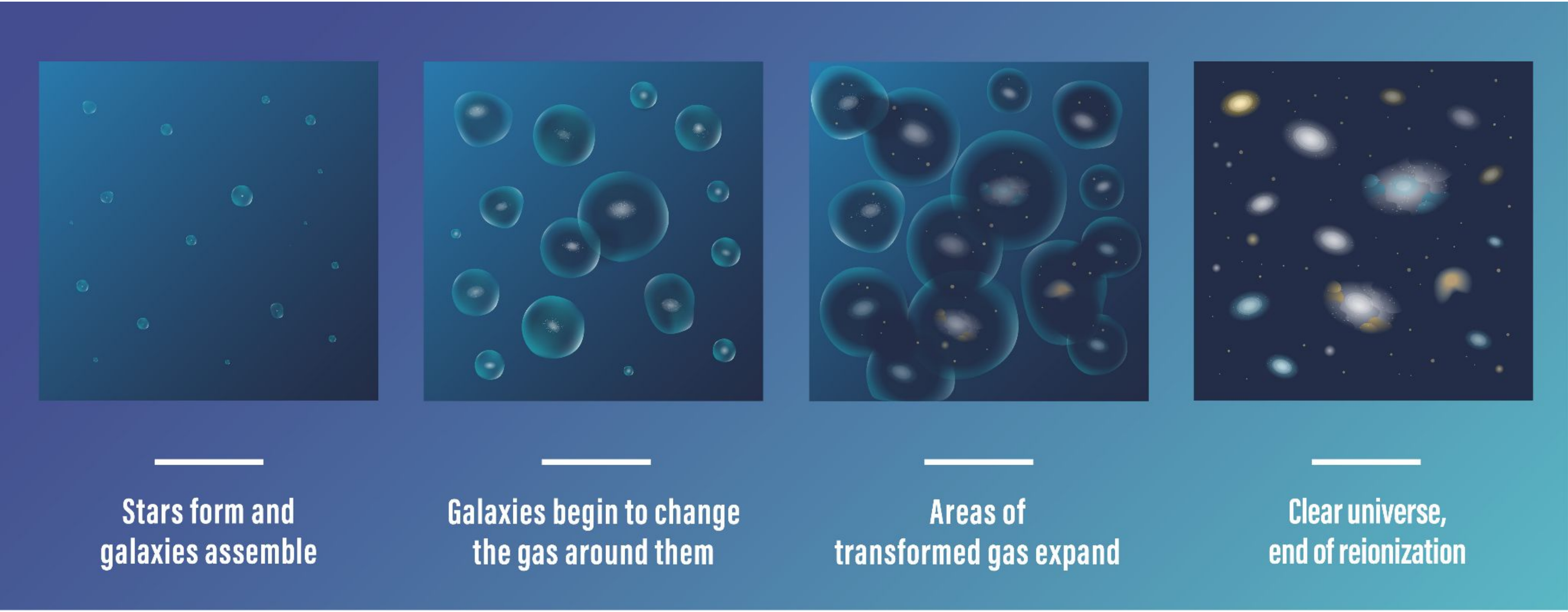
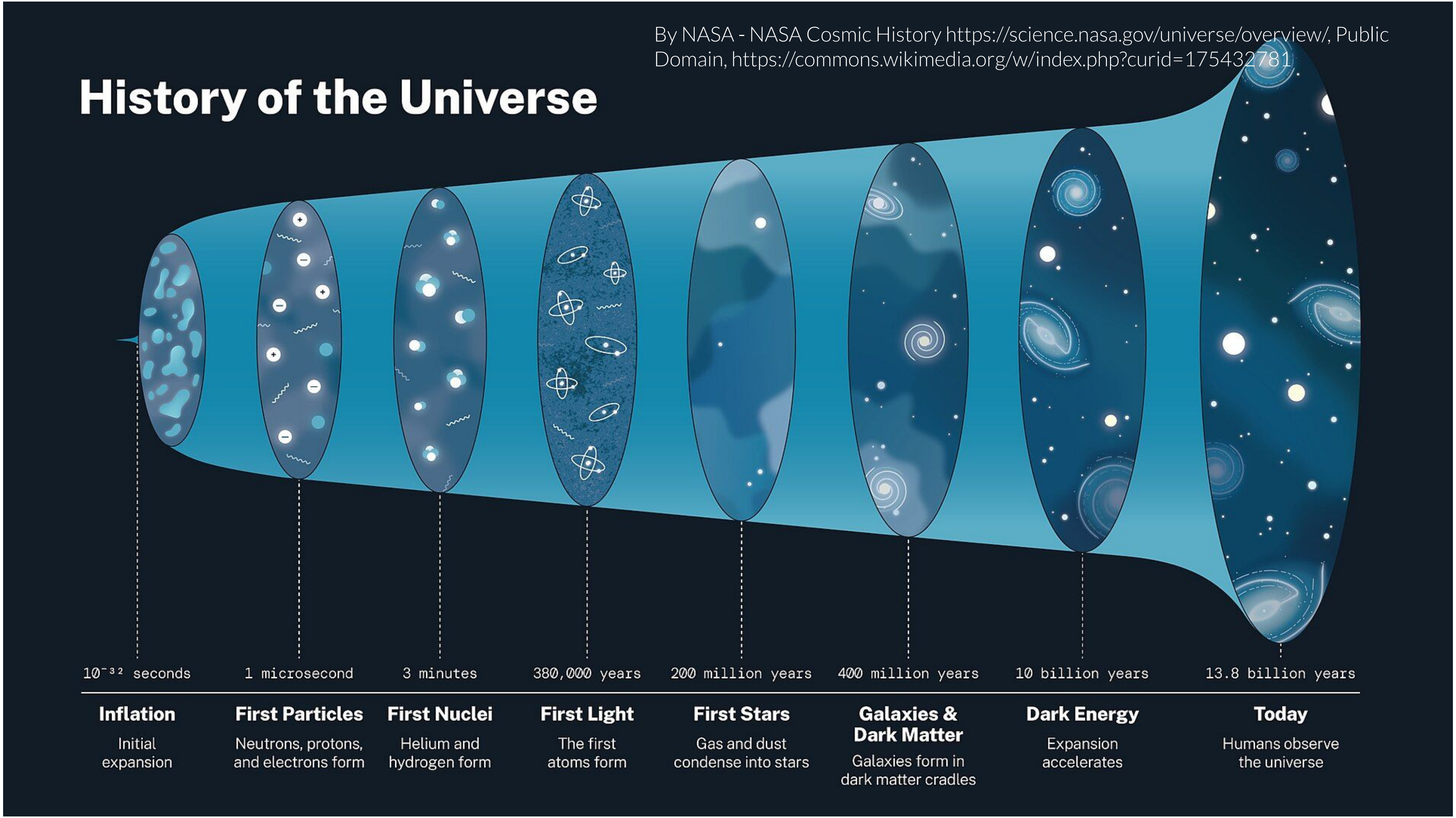
Reionization



NASA, ESA, CSA, Joyce Kang (STScI)

By NASA - NASA Cosmic History https://science.nasa.gov/universe/overview/, Public Domain, https://commons.wikimedia.org/w/index.php?curid=175432781

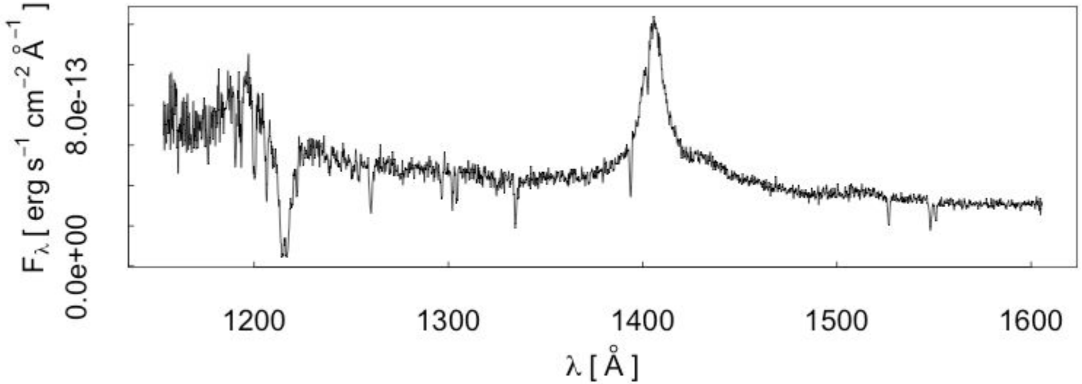


Signatures of Reionization

Discovery of Quasars

Key takeaways from the first discovery of quasars:

- The Universe is fully ionized today.
- Reionization was complete long before z~2.



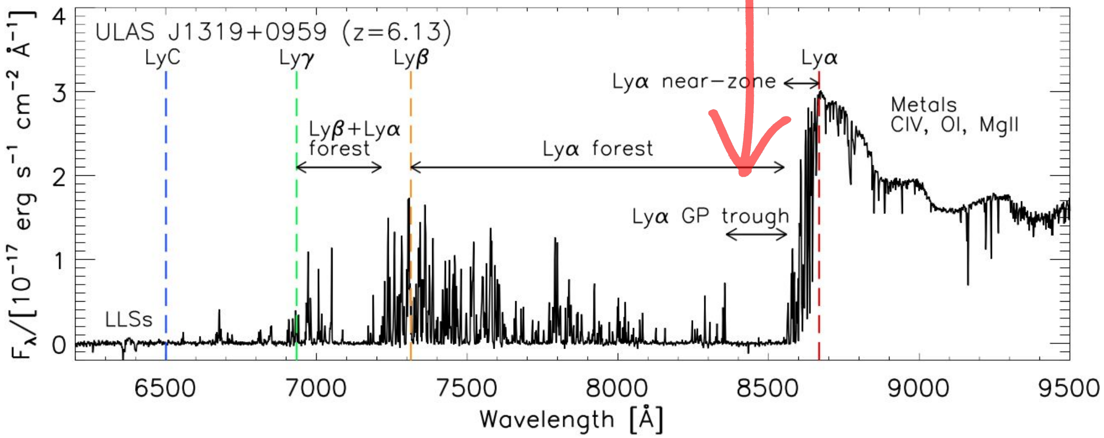
HST spectrum of 3C 273, the first quasar discovered, showing no signs of Lyα absorption.

Gunn-Peterson Trough

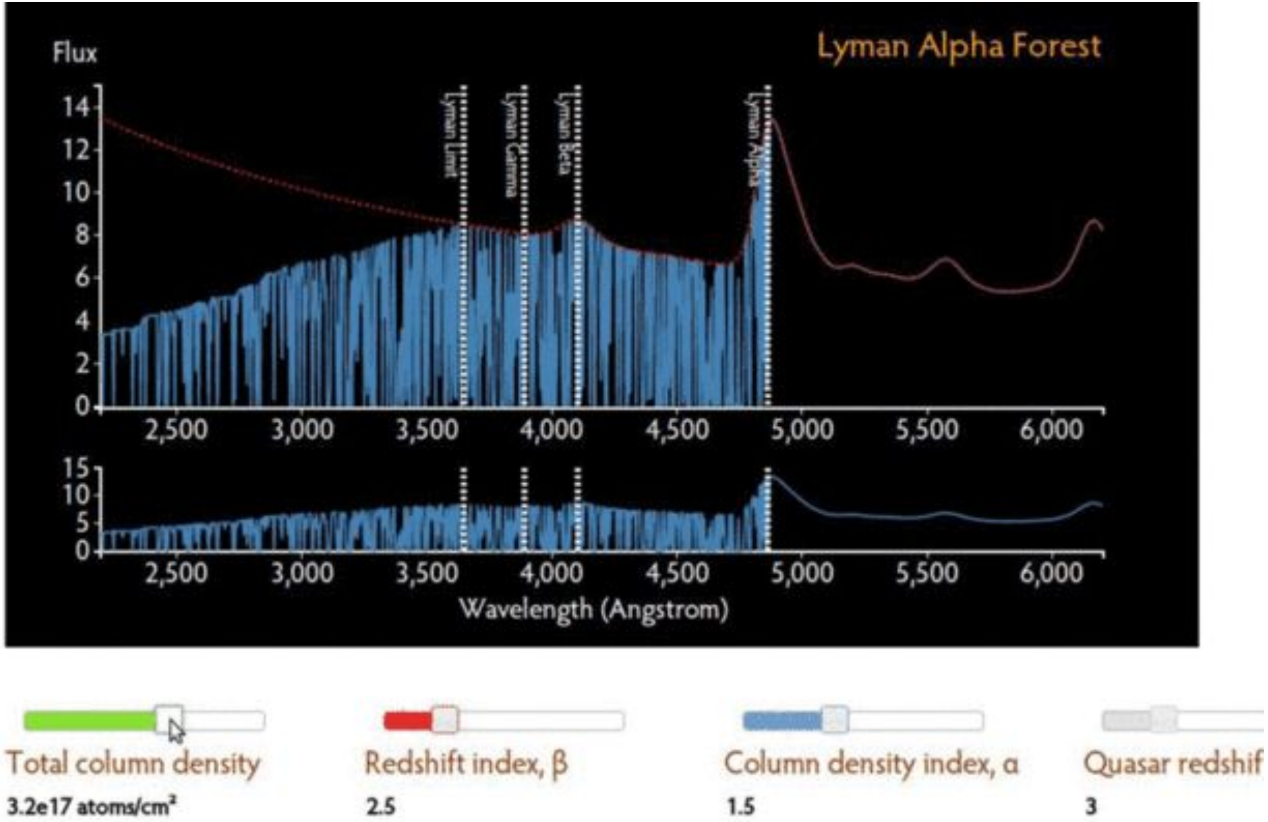
Discovered in 2000s with SDSS which observed z>5 quasars.

A small neutral hydrogen fraction is sufficient to cause a complete flux removal.

Largely neutral IGM absorbs almost all emission from the background source (e.g. quasar)



Spectrum of the quasar ULAS J1319+0959 at z = 6.13 from Becker et al. (2015)

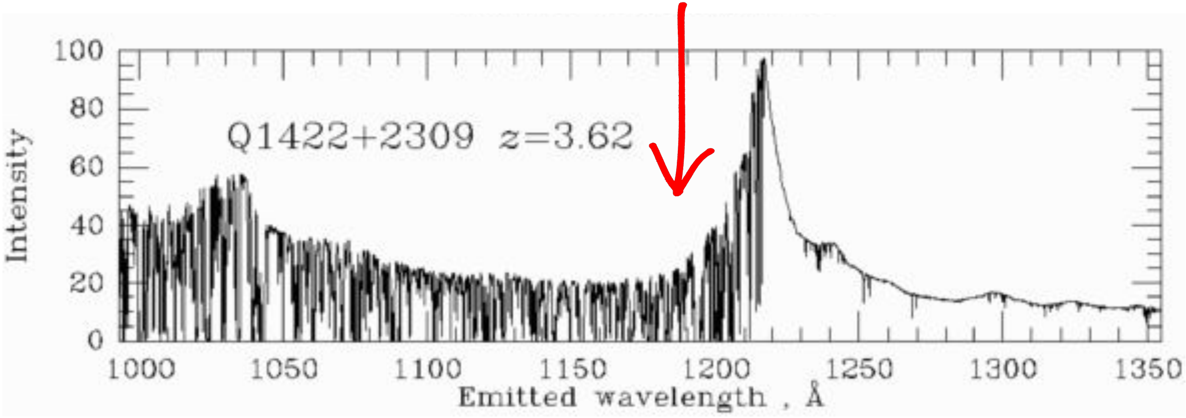


Astrobites.org; https://www.asc.ohio-state.edu/ting.74/lyman_alpha.html

Lyman Alpha Forest

Pockets of neutral hydrogen absorb quasar radiation, creating a forest of absorption lines blueward of Lyα line.

We stop seeing the GP trough when the IGM is mostly ionized.

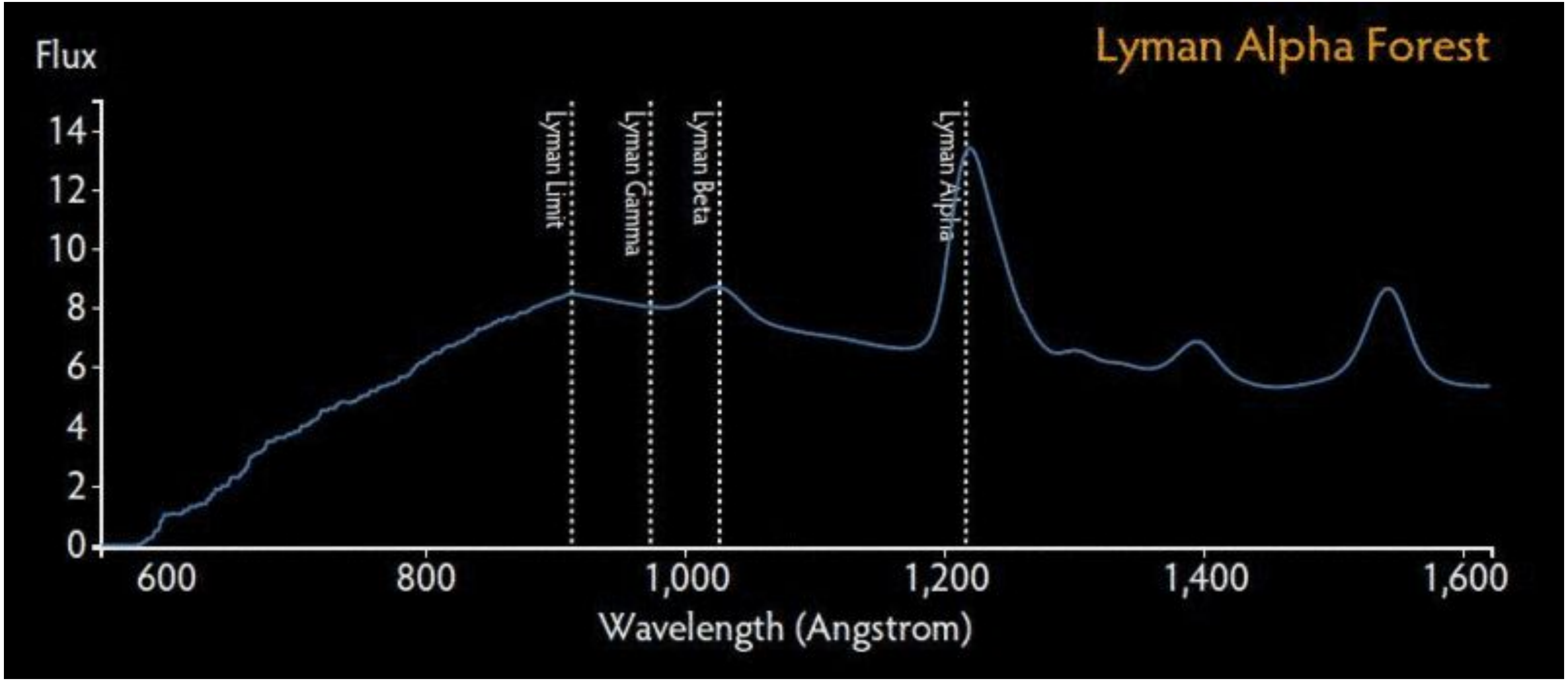


https://www.astro.ucla.edu/~wright/Lyman-alpha-forest.html

The redshift at which GP troughs give way to Lyα forests marks the era when reionization was effectively complete.

Lyman Alpha Forest

A quasar spectrum being continuously redshifted due to cosmic expansion, with various Lyman absorbers acting at different redshifts.



Evidence from CMB

The CMB photons scatter off the ionized electrons in the IGM. This leaves a signature in the polarized signal which you can measure. The optical depth of the Thompson Scattering tells us about the period of reionization.

τ constrains the median redshift z_{mid} and the duration of reionisation.

$$\tau = < n_H > c\sigma_T \int_0^z x_e(z)(1+z)^2 H(z)^{-1} dz$$

A larger value of τ implies an earlier period of reionisation.

Accurately Dating the Reionization

When did it start and when did it end?

- From quasar spectra: End estimated from when the GP trough is not found anymore but Lya forest becomes prominent. The current observations put the end of reionization at $z = 5.6 - 6$.

- From CMB data: Planck observations suggest that reionization started around $z=10 - 12$ and ended at $z=6$. Some advanced models suggest it could have started at $z=16$.

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To ionize hydrogen, the photons need to have an energy E > 13.6 eV (λ < 912 Å).

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Far-UV Lyman Continuum emission

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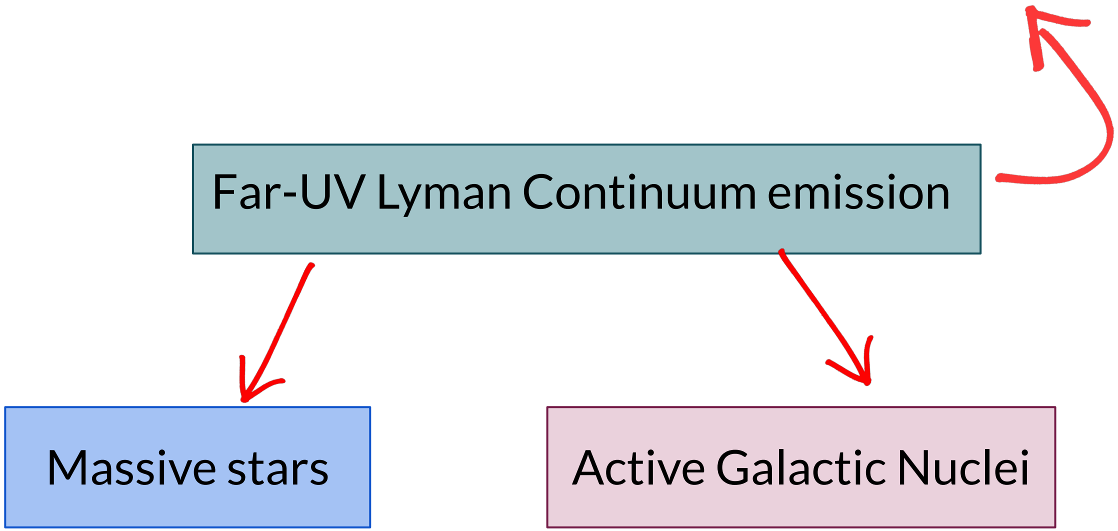


The Reioniozation Budget

The rate of ionizing photons available for reioniozation depends on:

1. The comoving UV luminosity density (how many sources are there).
2. The number of ionizing, LyC photons produced per UV luminosity.
3. The fraction of LyC photons that escape galaxies into the IGM (LyC escape fraction f_{LyC})

UV Luminosity Function

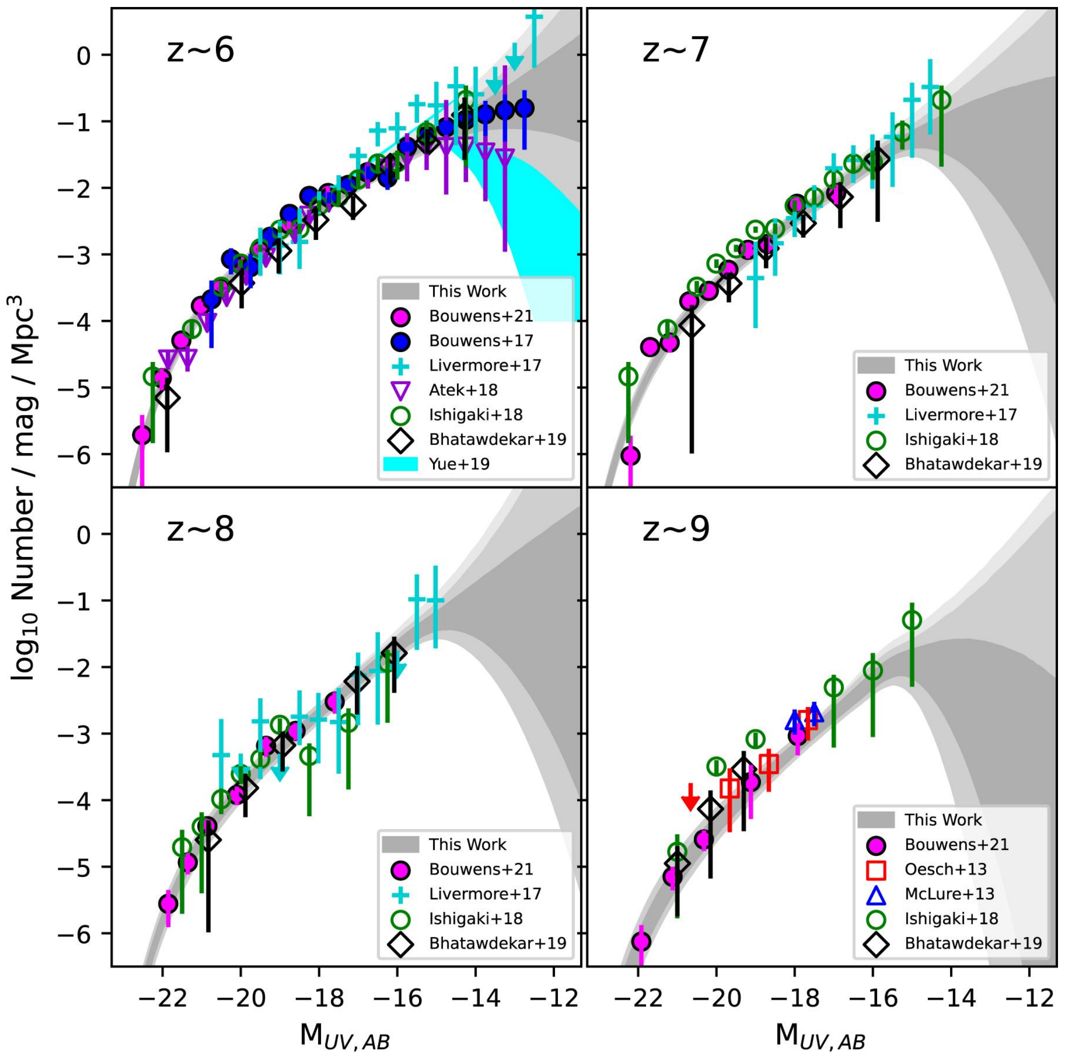
$$\Phi(M_{\mathrm{UV}}, z) = \frac{d^2N}{dV\,dM_{\mathrm{UV}}}$$

where N is the number of galaxies, V is the comoving volume, and MUV is the absolute magnitude.

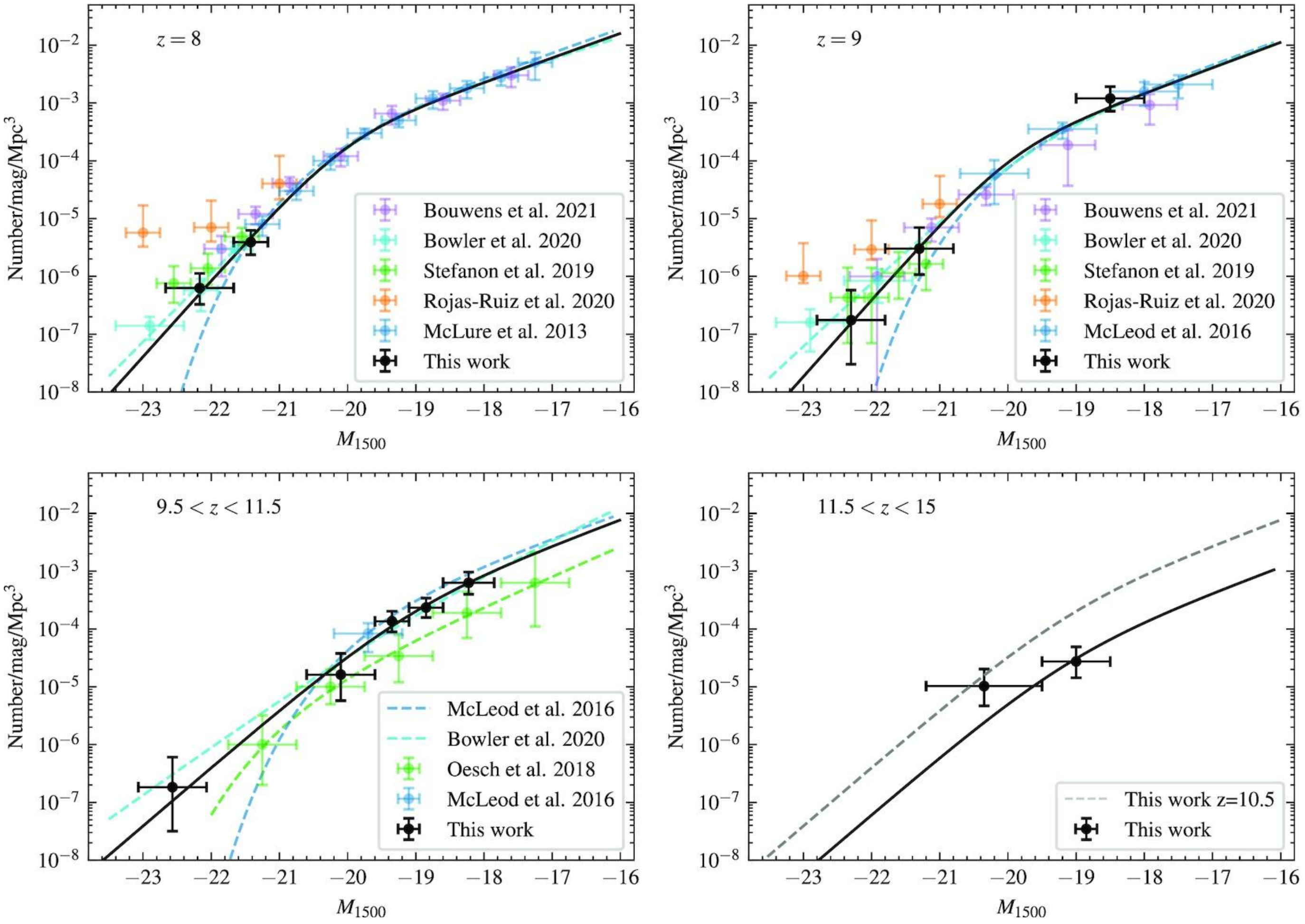
$$\Phi(L)\frac{dL}{L^*} = \Phi^*(\frac{L}{L^*})^{-\alpha} exp(-\frac{L}{L^*})\frac{dL}{L^*}$$

Often expressed as a double power law aka Schechter function

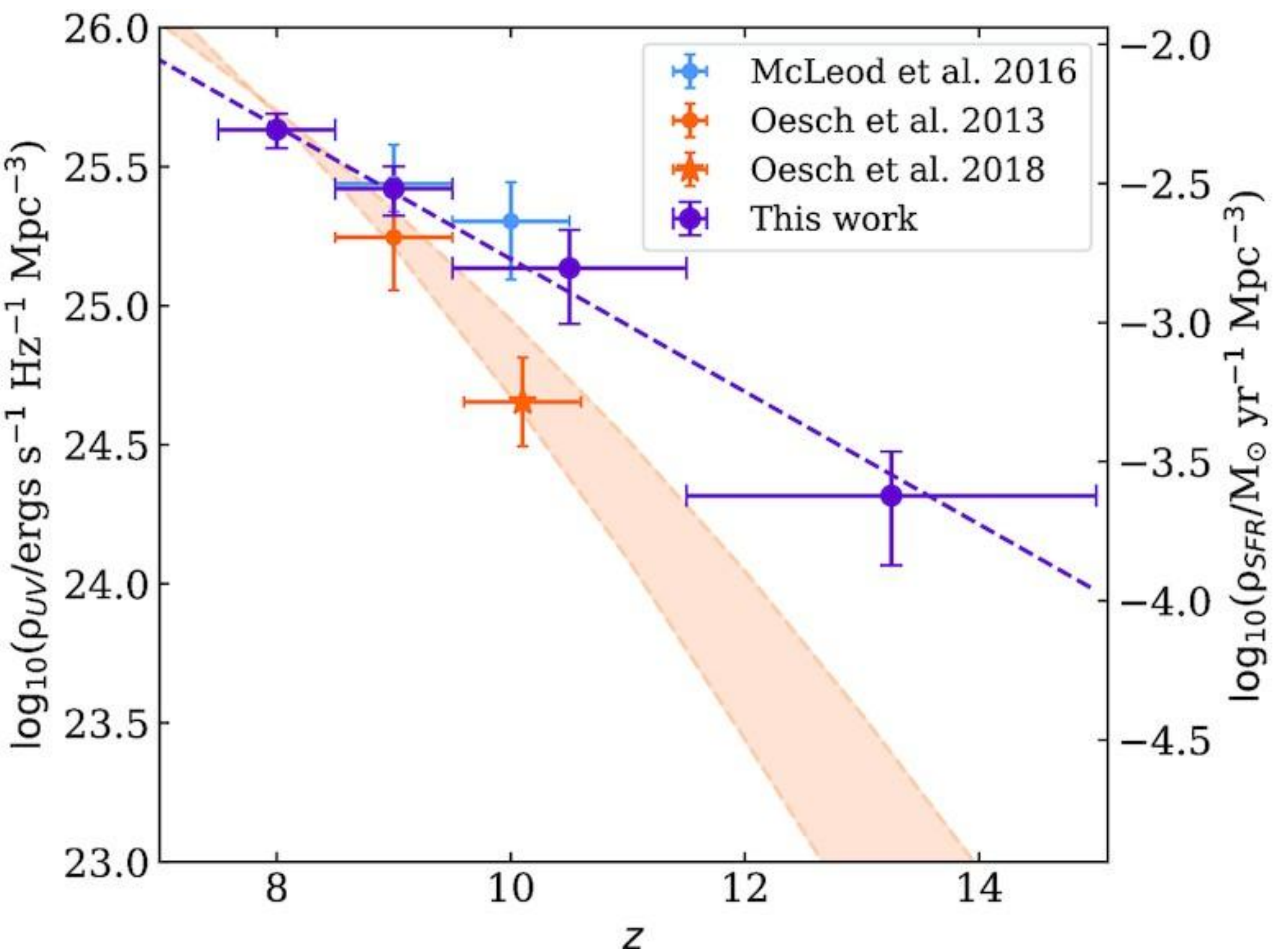
UV Luminosity Function



Redshift-dependent UV luminosity function of galaxies combining HST's deep fields and the six lensing Frontier Field Clusters (Bouwens et al., 2022).

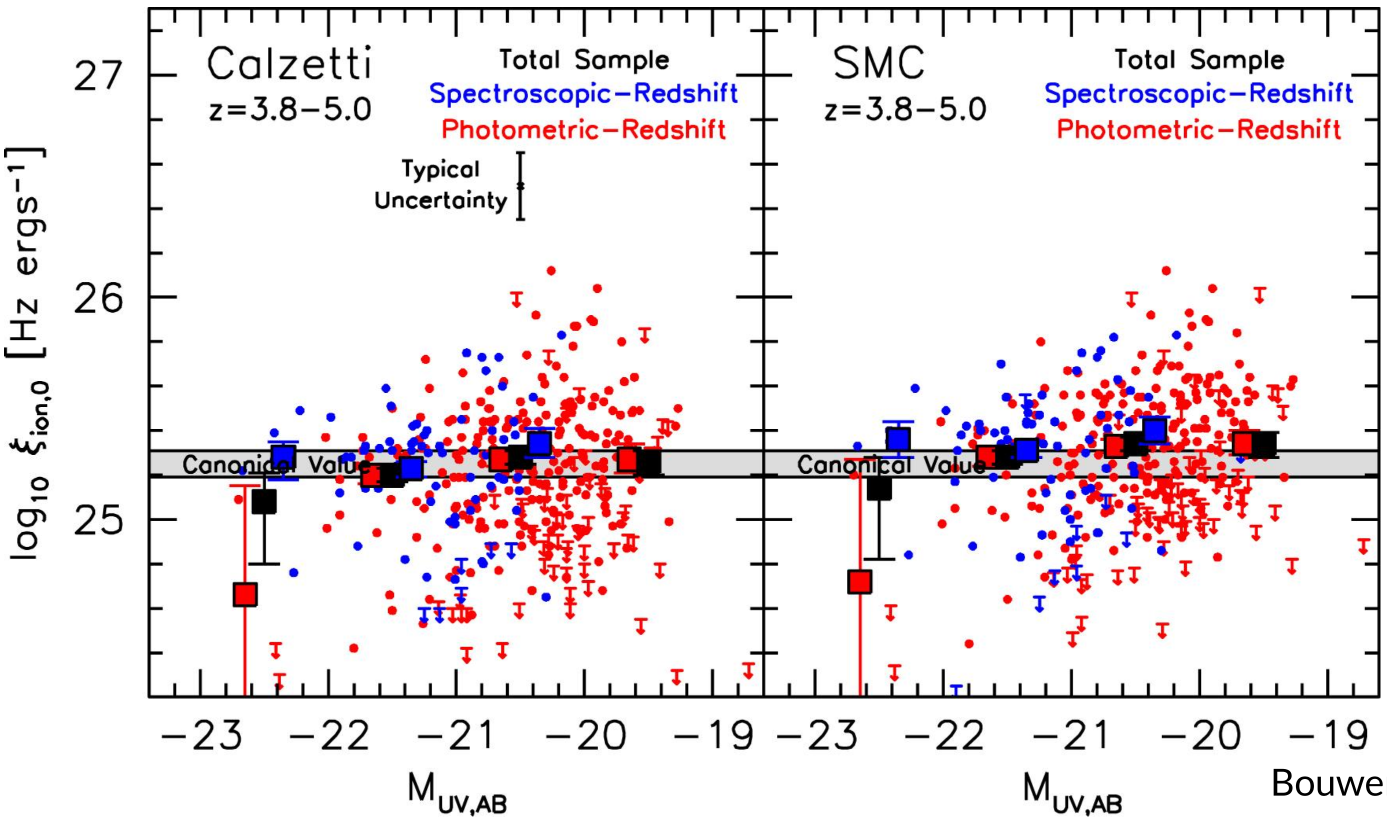


Donnan et al. (2022)



Donnan et al. (2022)

Ionising Productivity ξ_{ion}



Bouwens et al. (2016)

Escape Fraction

Direct method

$$f_{esc}^{abs} = \frac{(L_{LyC}/L_{UV})_{obs}}{(L_{LyC}/L_{UV})_{int}} \times T_{IGM}$$

LyC escape fraction.

Name	Monochromatic flux density[a]									
	I_{mod}[b] (900 Å)	I_{mod}[b] (1500 Å)	I_{obs}[c] (900 Å)	I_{obs}[c] (1500 Å)	I_{esc}[d] (900 Å)	22 μm/ 1500 Å[e]	f_{esc}^{rel}[f] (LyC)	f_{esc}[g] (LyC)	f_{esc}[h] (LyC)	f_{esc}[i] (LyC)
J0925+1403	4.40	5.84	$0.235^{+0.021}_{-0.020}$	1.55	$0.343^{+0.038}_{-0.037}$	1.08	0.236	0.072 ± 0.008[j]	0.064	0.046
J1152+3400	3.30	3.14	$0.428^{+0.037}_{-0.034}$	1.36	$0.502^{+0.043}_{-0.040}$	–	0.335	0.132 ± 0.011	0.132	0.116
J1333+6246	1.52	2.05	$0.083^{+0.023}_{-0.022}$	0.75	$0.090^{+0.025}_{-0.024}$	–	0.149	0.056 ± 0.015	0.064	0.055
J1442−0209	4.59	3.99	$0.198^{+0.027}_{-0.028}$	1.50	$0.367^{+0.050}_{-0.052}$	1.44	0.154	0.074 ± 0.010	0.090	0.032
J1503+3644	3.19	3.24	$0.160^{+0.018}_{-0.017}$	1.80	$0.195^{+0.021}_{-0.019}$	1.54	0.090	0.058 ± 0.006	0.069	0.050

Izotov et al., (2016)

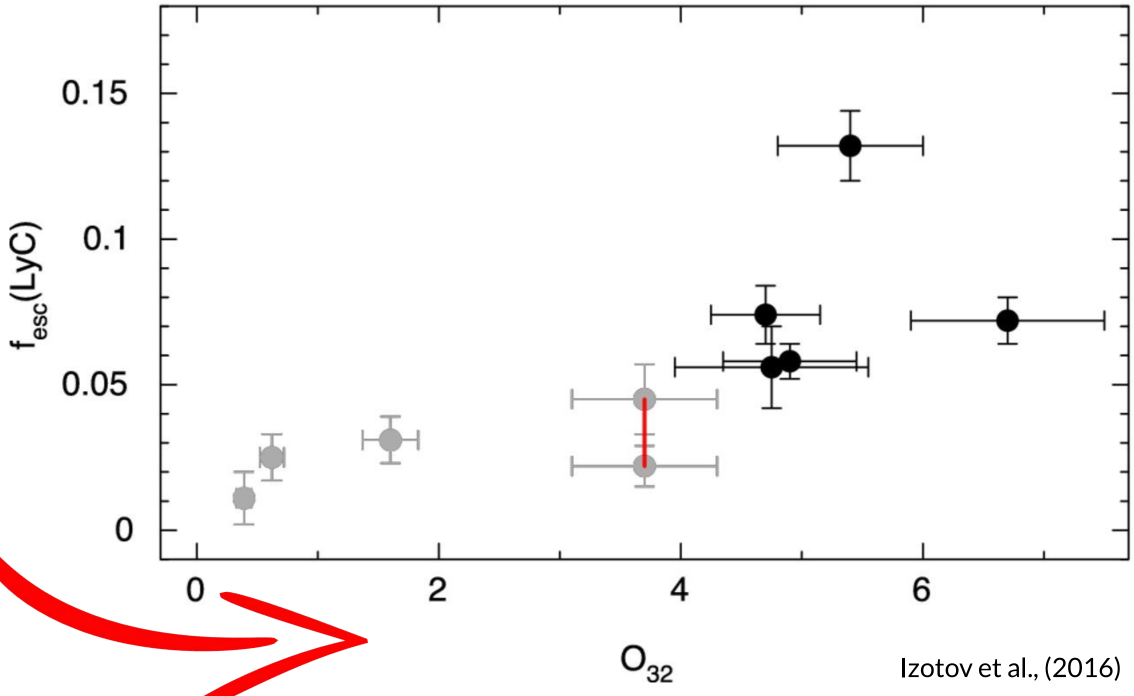
Escape Fraction

Direct method

$$f_{esc}^{abs} = \frac{(L_{LyC}/L_{UV})_{obs}}{(L_{LyC}/L_{UV})_{int}} \times T_{IGM}$$

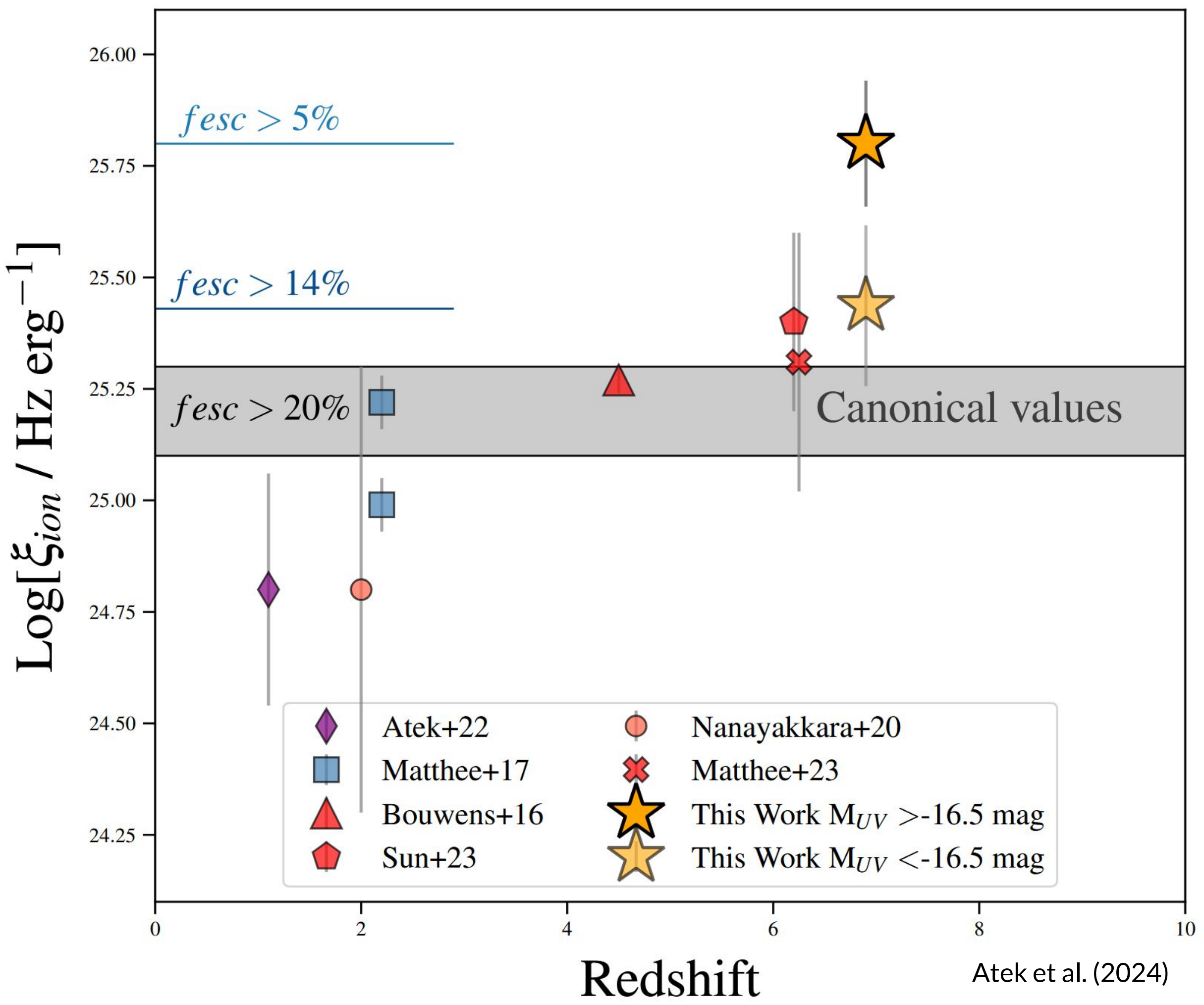
Indirect method

Ratio of the emission lines [OIII] $\lambda 5007$ Å to [OII] $\lambda 3727$ Å

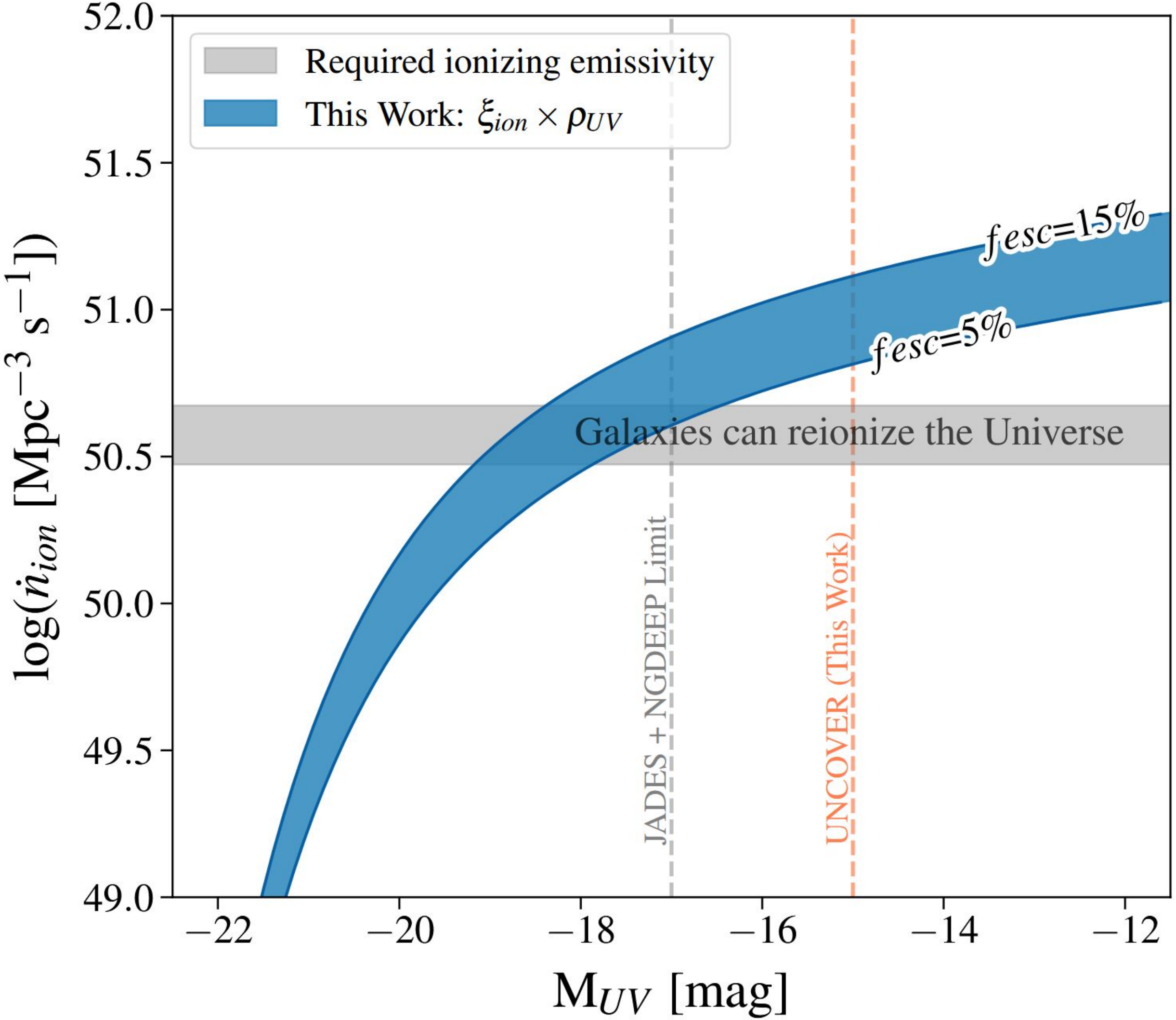


Izotov et al., (2016)

JWST Results

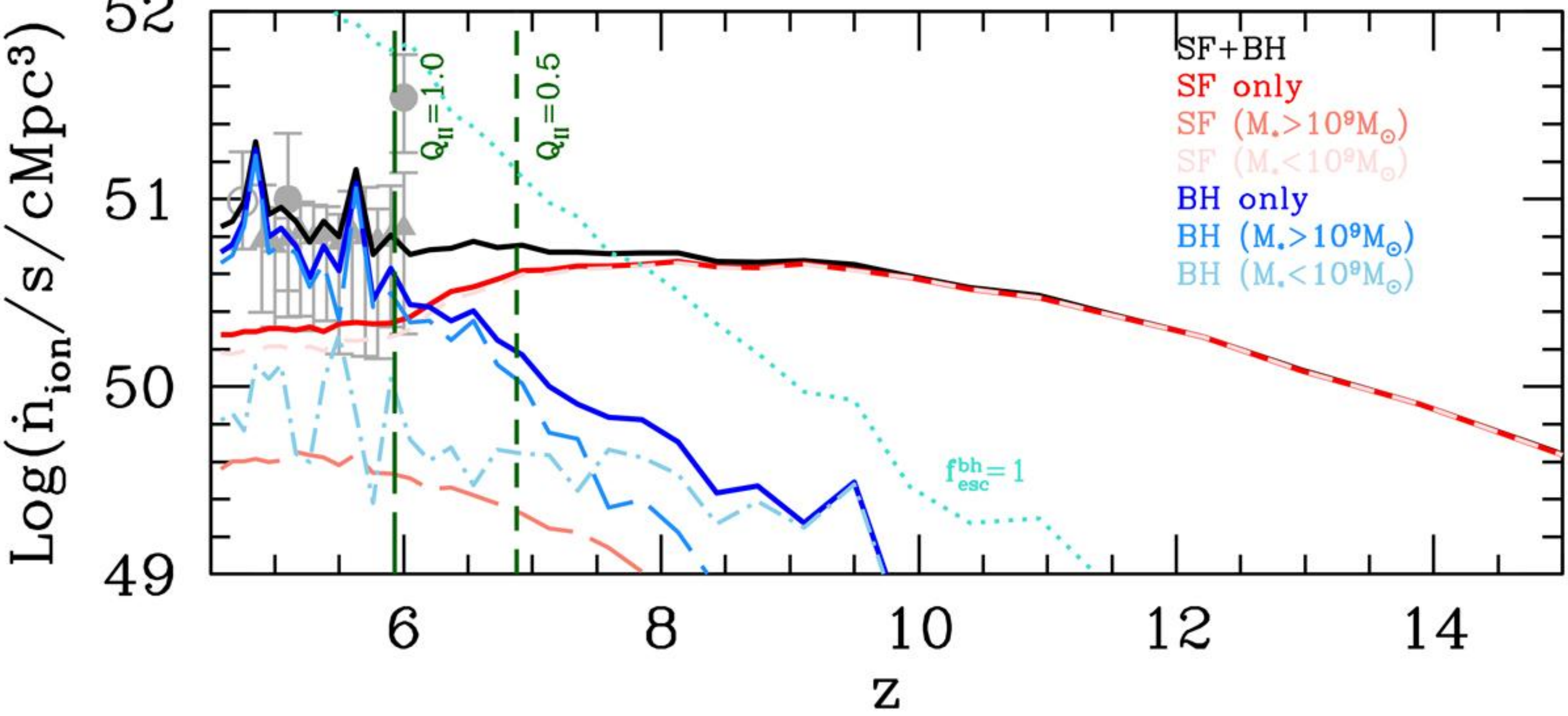


Atek et al. (2024)



Atek et al. (2024)

Who is responsible for Reionization?

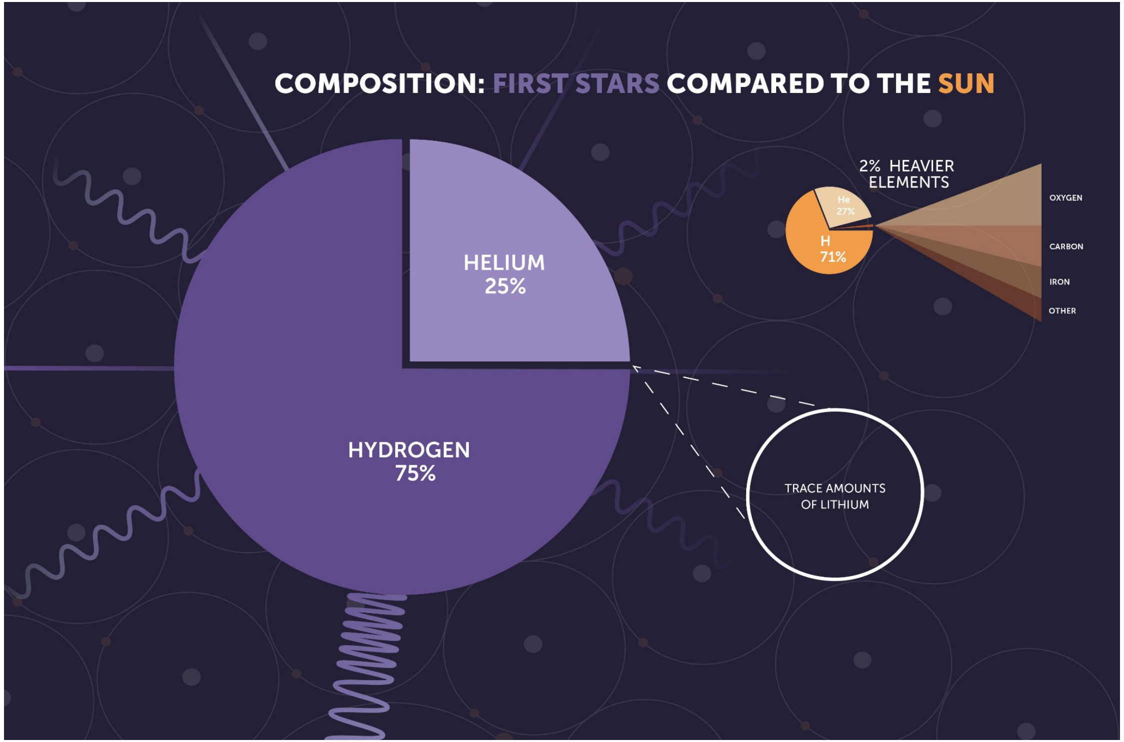


Dayal et al. (2025)

First Stars

Population III stars

- Pure hydrogen and helium, no heavier elements (metal free).



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First Stars

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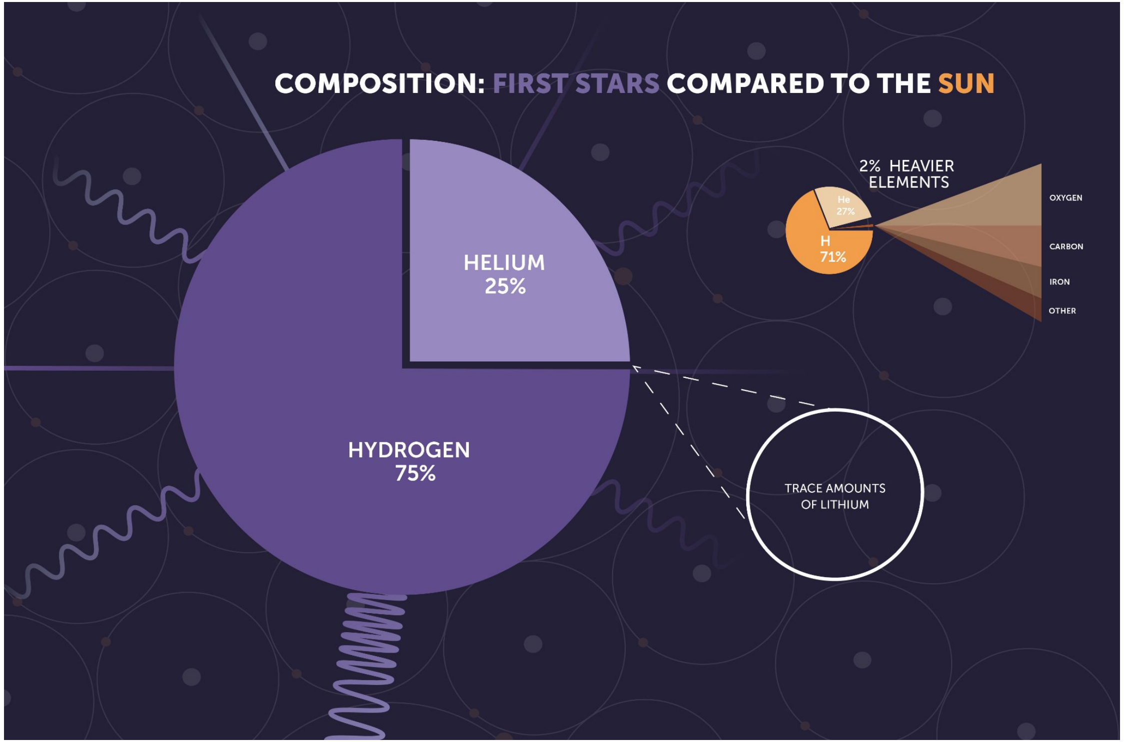
- Very massive: 10-300 M_{sun}
  Rough upper limit of 700 M_{sun}



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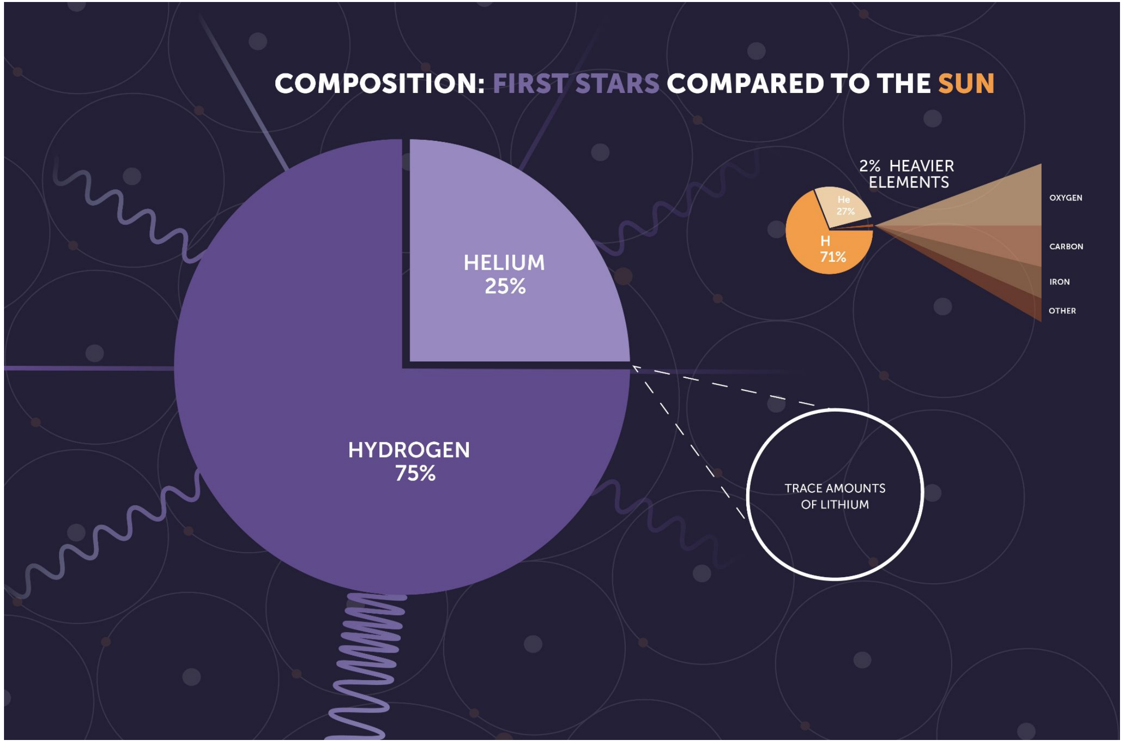

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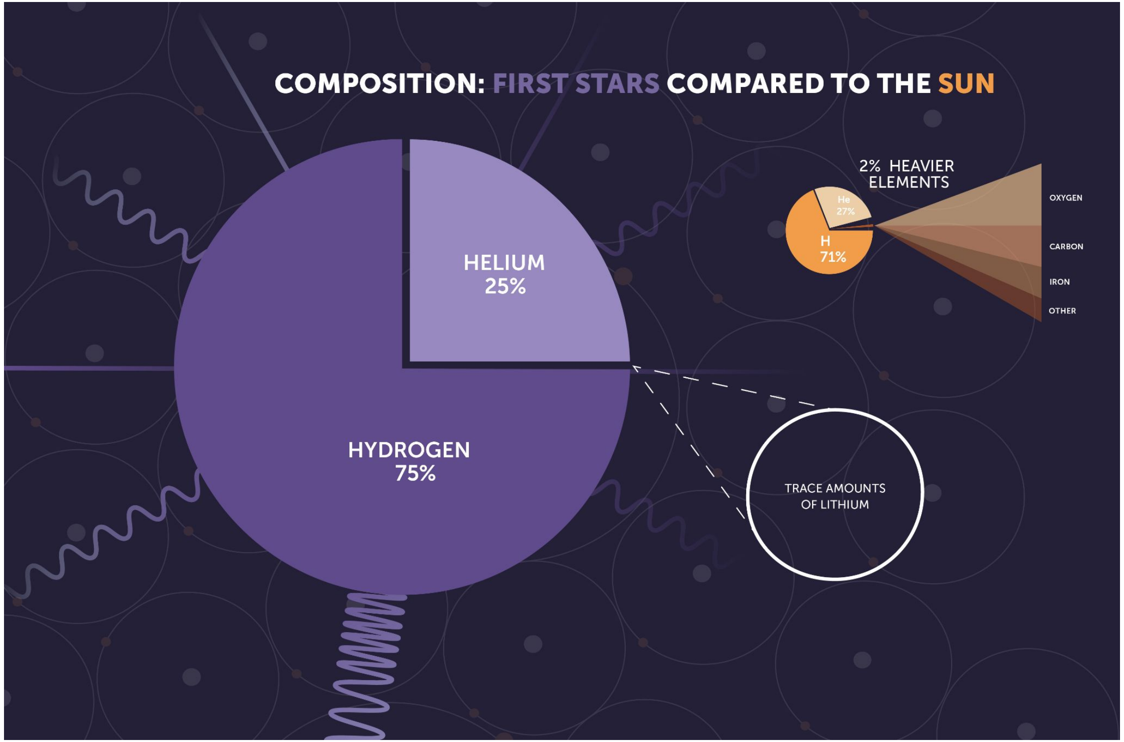

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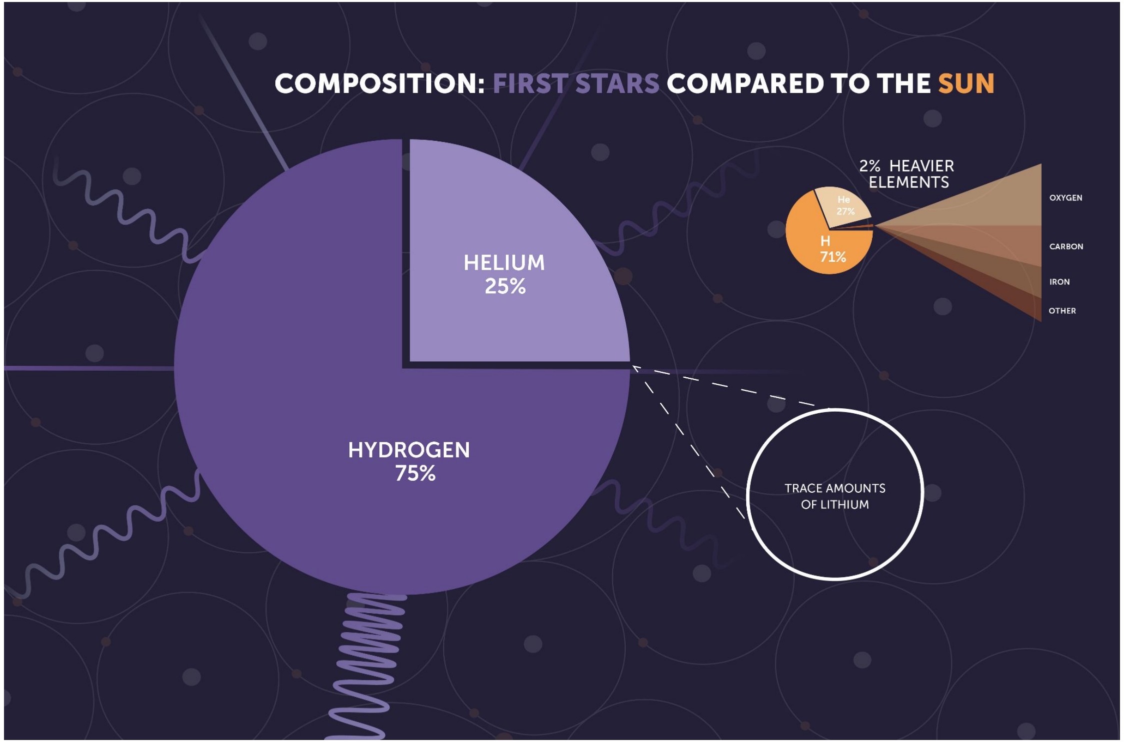
- Lower mass stars lived long enough to forge iron in their cores and went off as supernova



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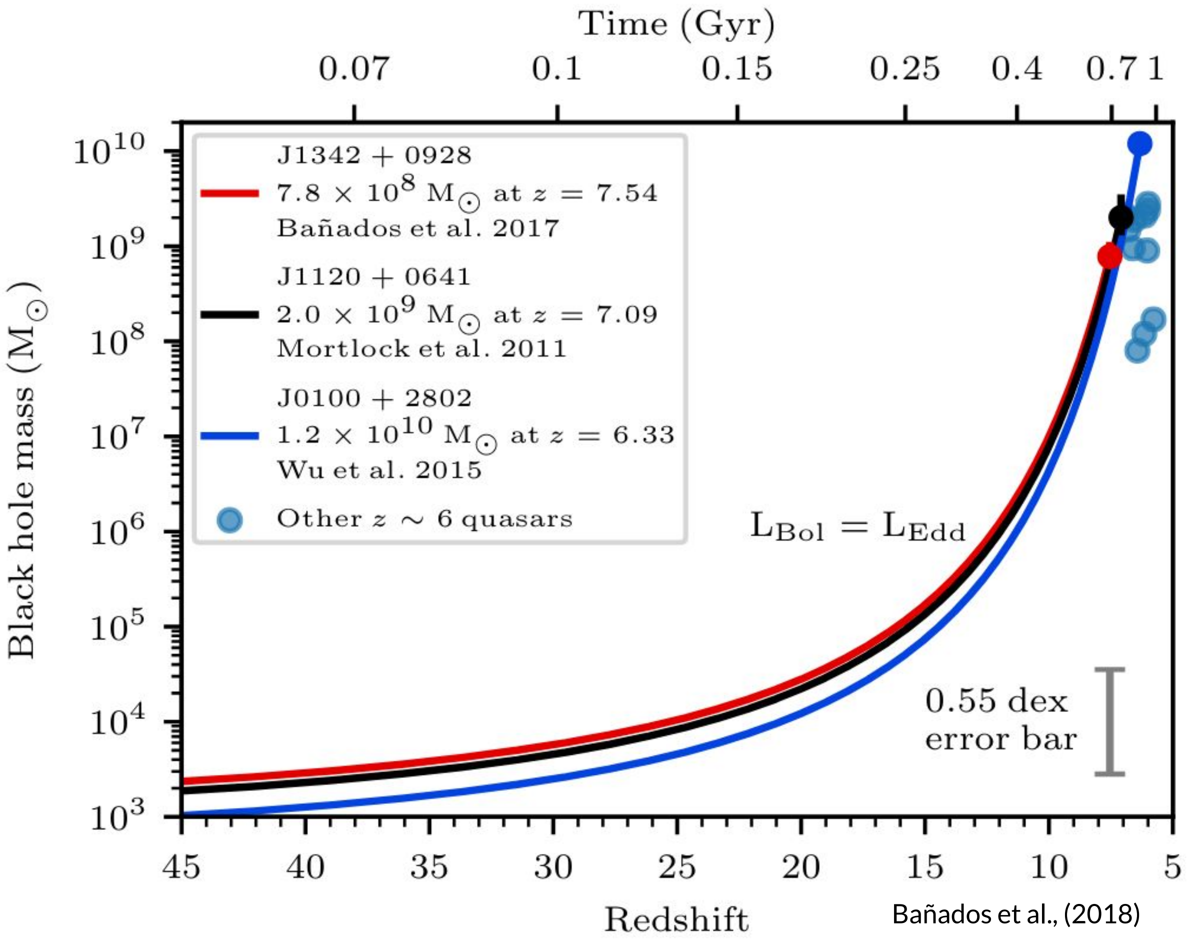
First Black Holes

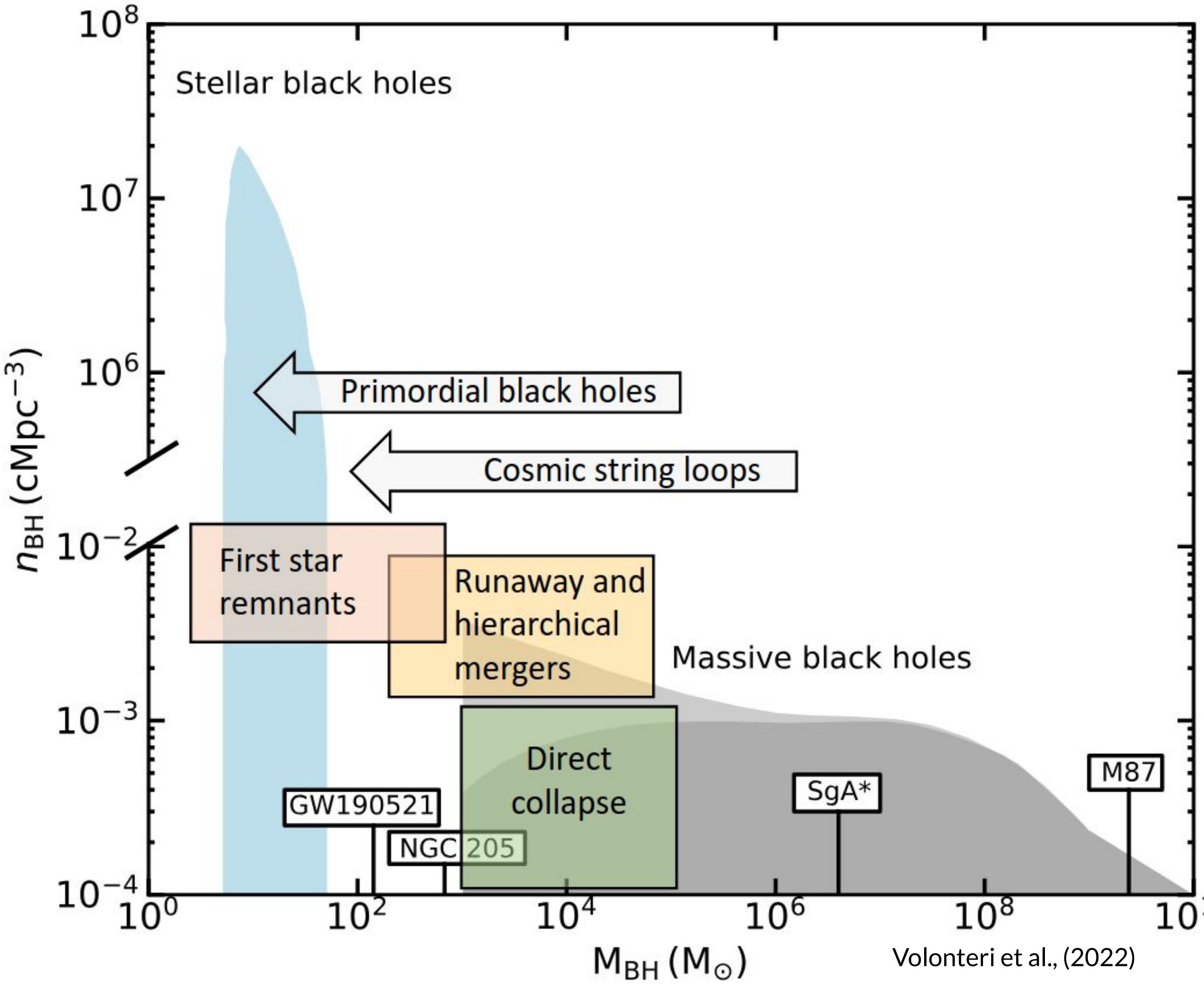
Pre-JWST detection of massive BHs



Bañados et al., (2018)

First Black Holes

Different MBH formation scenarios



Volonteri et al., (2022)

First Black Holes

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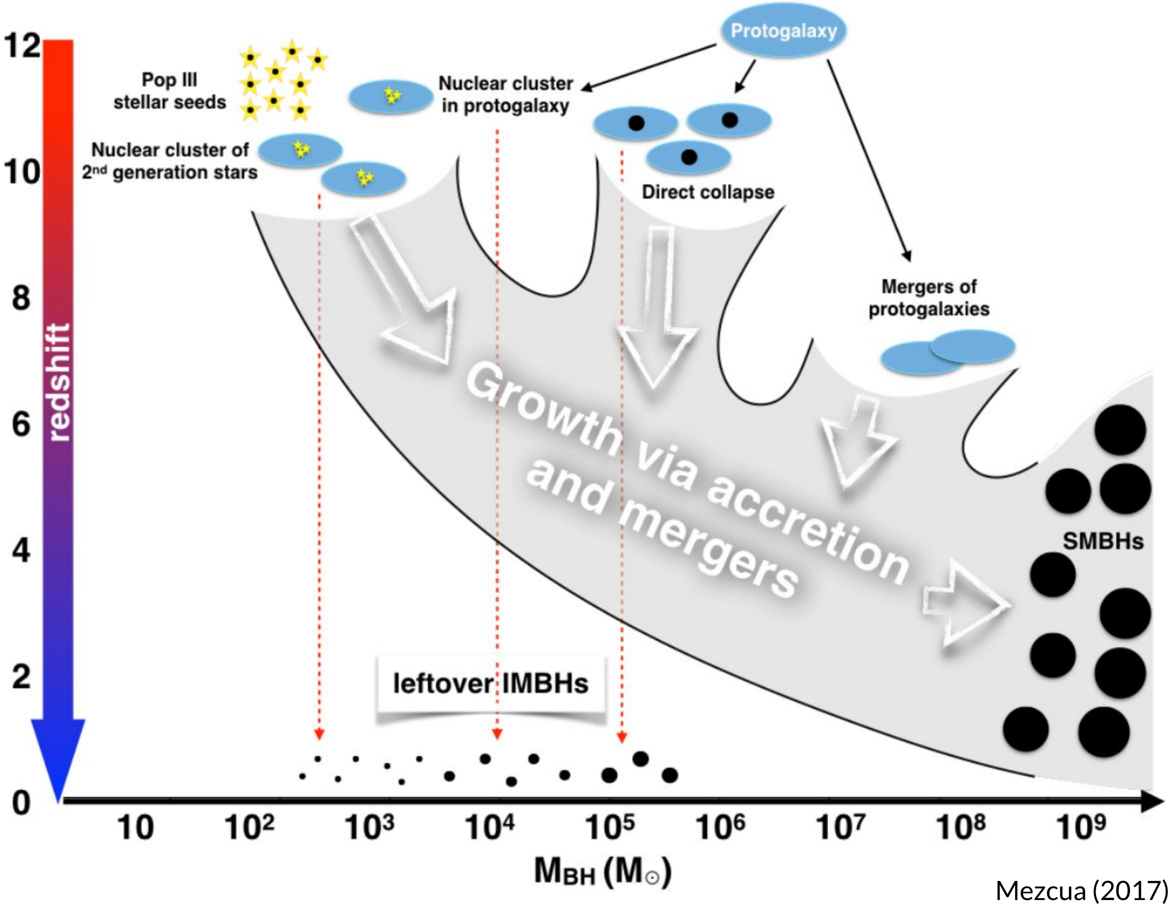

Mezcua (2017)

First Galaxies

Stay tuned for the next lecture!

Summary

- Multiple analyses find that ξ_{ion} values are higher than expected from pre-JWST results.
- The galaxies most efficient at producing ionizing photons are young, highly star-forming, and normally expected to have low metallicities and be dust-poor.
- High escape fractions may not be necessary to complete reionization.
- Discovery of several z>10 galaxies, incl. z>14 suggests the process of reionization may have started earlier than previously thought, just a few hundred million years after the Big Bang.
- There is still a debate about the exact start, end and the mid-point of the reionization, and about the relative contributions of various sources.