Hints about the Earliest Galaxies

Steve Furlanetto
UCLA
September 16, 2021

The Cosmic Dawn

Robertson et al. (2010)

See also https://cosmicdawn.astro.ucla.edu for more reasons to study this era!

What is reionization?

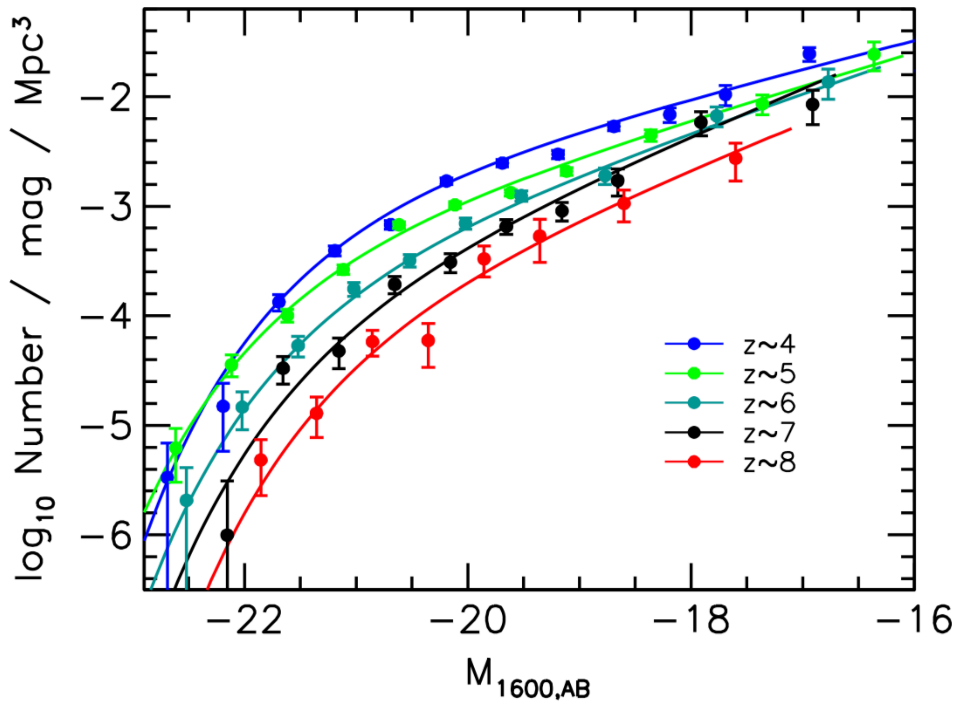
- Landmark event of first generation of galaxies
- Planck and several astrophysical measurements suggest the midpoint of reionization is at z~7, ending at z~6

Outline

- Galaxy physics during the Cosmic Dawn
- Learning from reionization
- Peering into the future: the 21-cm line

Part I:
Galaxies During the Cosmic Dawn

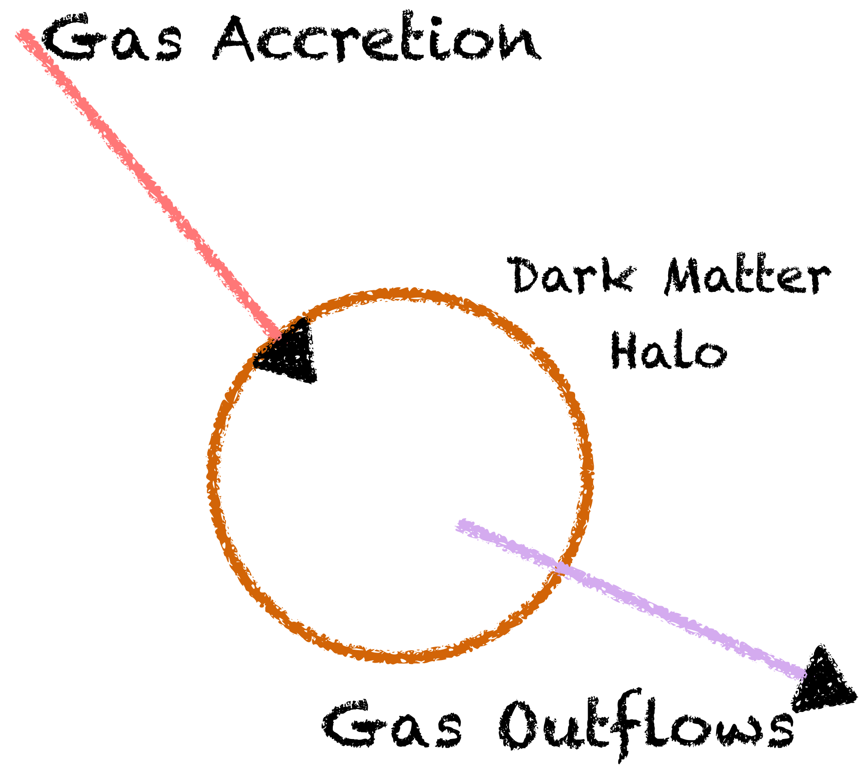
What do we know about galaxies during the Cosmic Dawn?



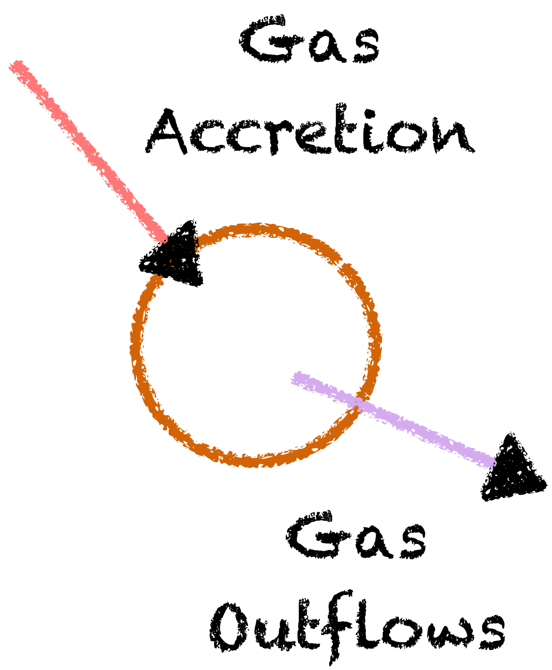
Bouwens et al. (2015)

So how do galaxies form?

- "Minimalist model" inputs
  - Gas accretion
  - Star formation
  - Gas outflows
- "One parameter": mass-loading factor $\eta(M,z)$

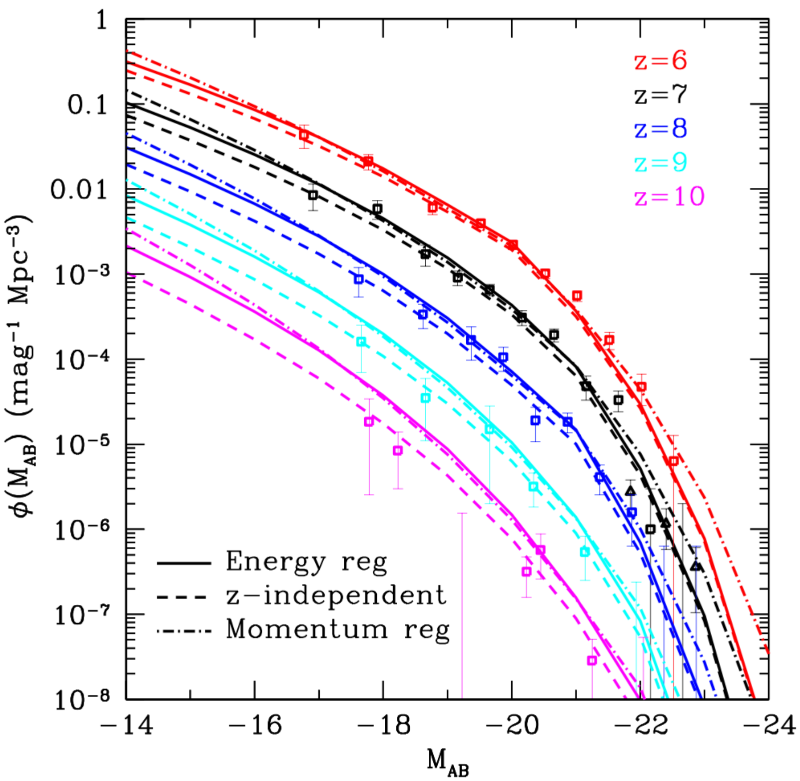


The Physics of Feedback



- Feedback driven by supernova/radiation pressure/etc.
- We can generate a range of reasonable prescriptions...but we are far from a definitive model!

"Minimalist" model of galaxy formation

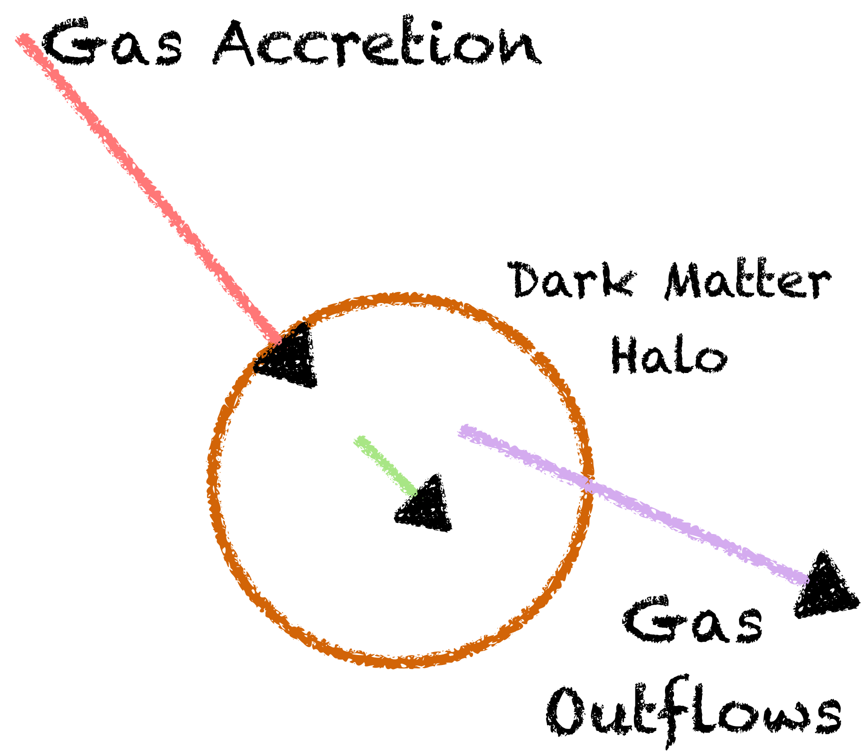


Furlanetto et al. (2017)

- Provides satisfactory fits to luminosity functions!
- At least if we take a "reasonable" feedback model

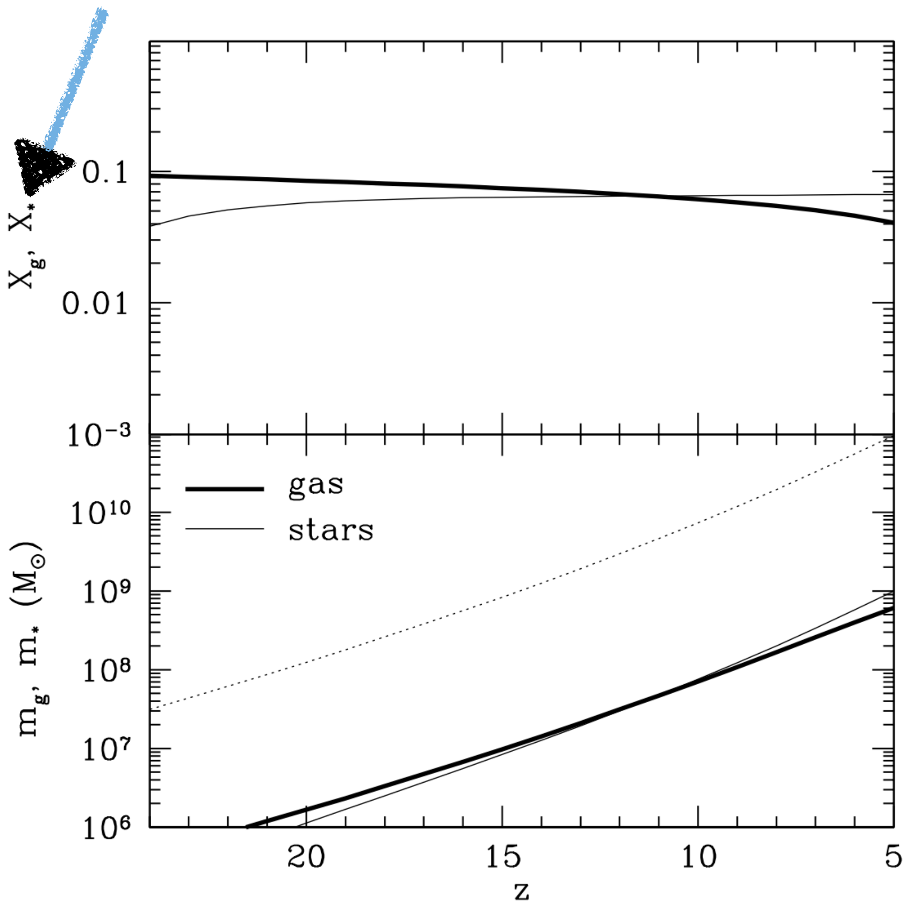
Upgrade #1: An ISM

- “Bathtub/Regulator model” (Bouche et al. 2010, Dave et al. 2012, Lilly et al. 2013, Dekel et al. 2013)
    - Gas accretion
    - Interstellar medium
    - Star formation
    - Gas outflows
- Two parameters
    - Mass-loading factor $\eta(M,z)$
    - Star formation efficiency ε_{ff}



So how do galaxies work?

Fractions relative to cosmic mean

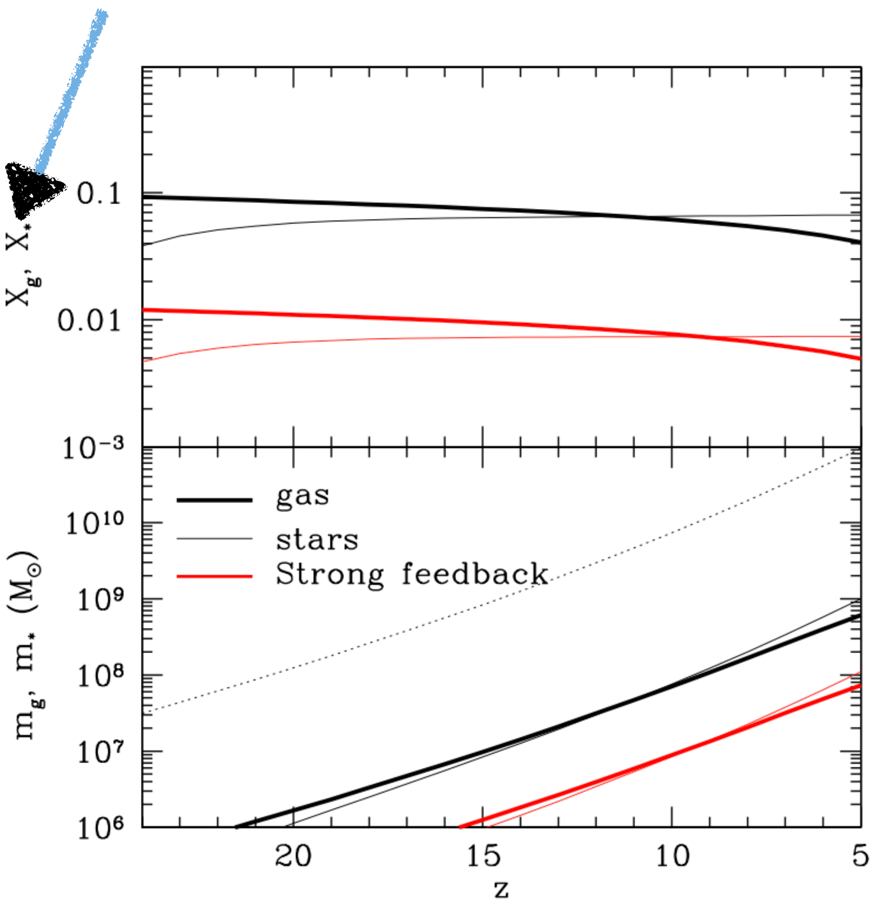


Furlanetto (2020)

- Halos grow exponentially
- Stellar mass grows exponentially as well!

So how do galaxies work?

Fractions relative to cosmic mean

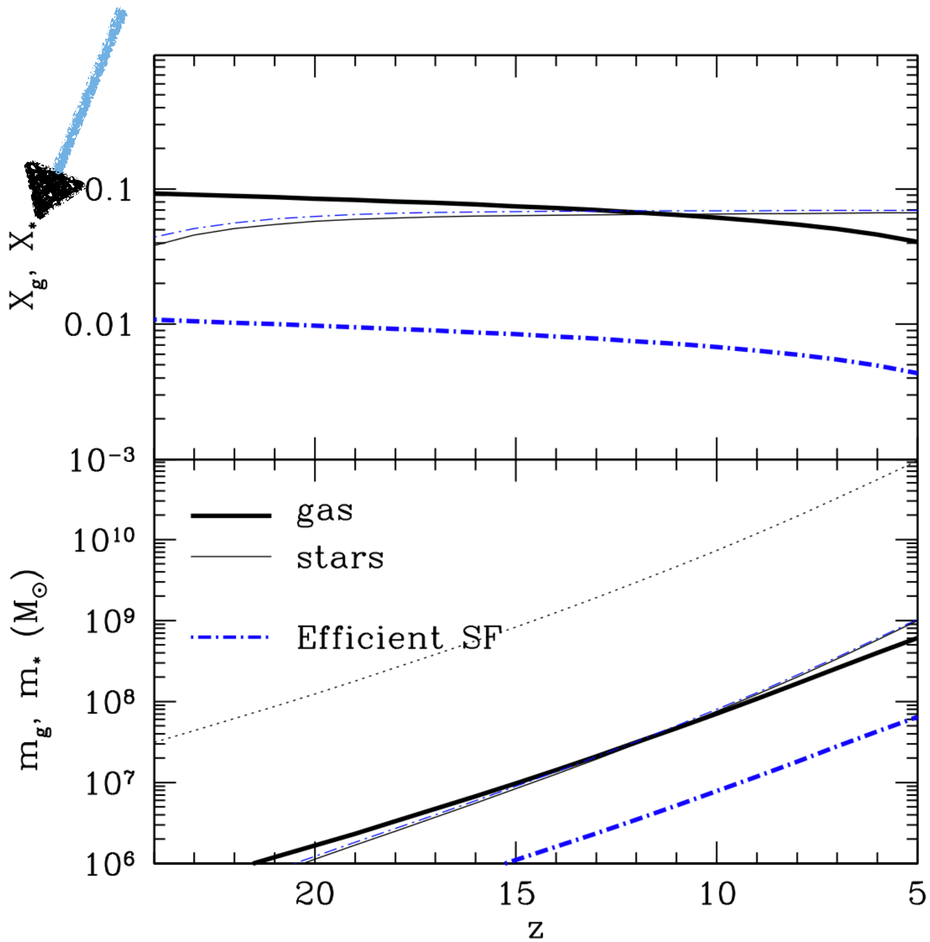


Furlanetto (2020)

Feedback strength controls gas and star formation

So how do galaxies work?

Fractions relative to cosmic mean

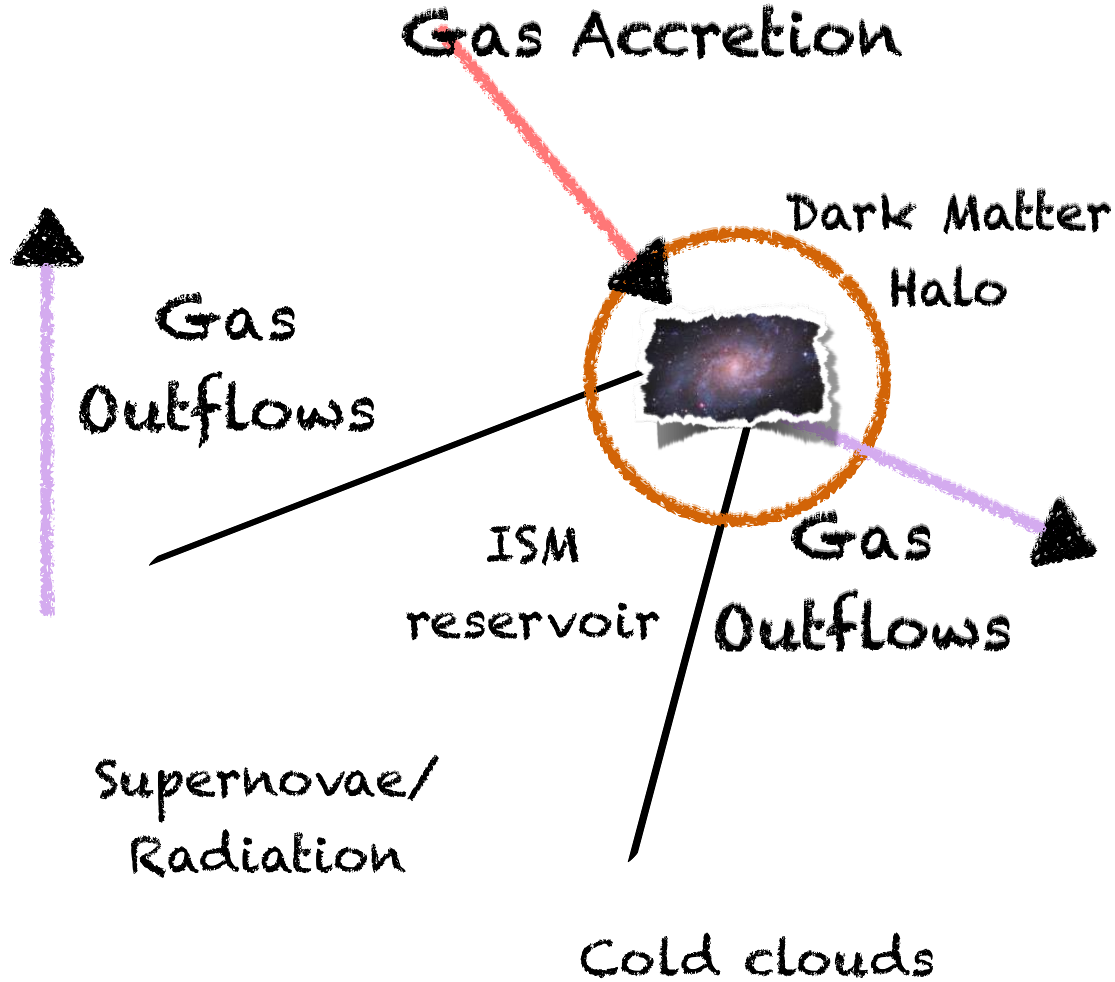


Furlanetto (2020)

- Small-scale star formation efficiency ε_{ff} does NOT affect stellar mass!
  - Does affect gas mass

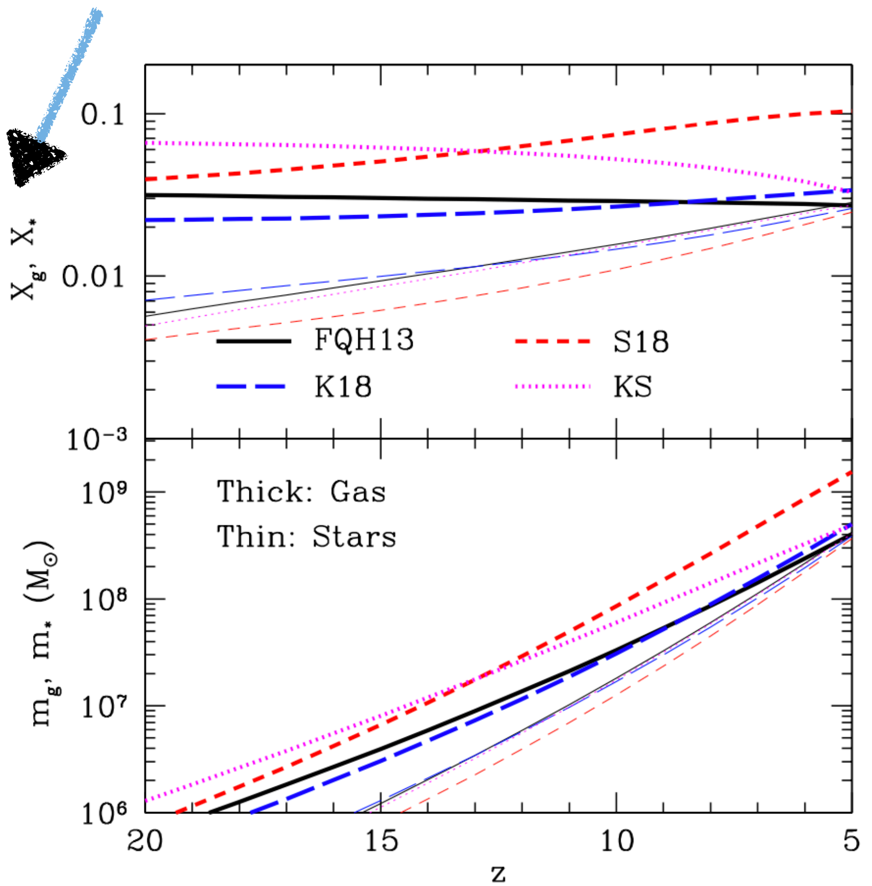
Upgrade #2: Star Formation Models!

- Add star formation laws:
  - Fragmentation
  - Star formation
  - Feedback
  - Turbulent support
- Cycling between ISM phases poorly understood!



“Generic” Predictions for Galaxy Formation

Fractions relative to cosmic mean



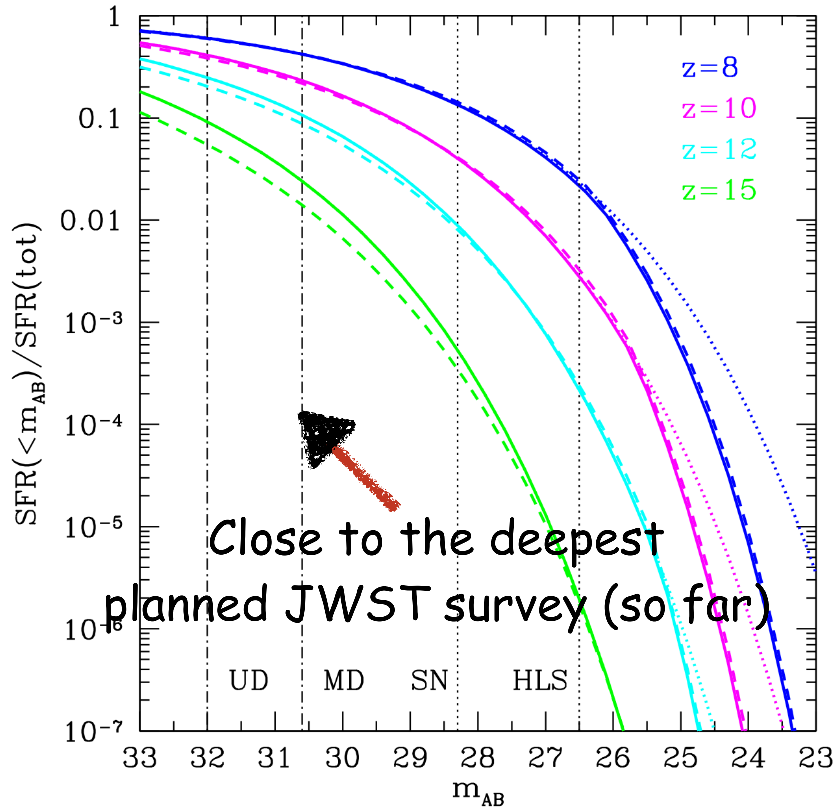
Furlanetto (2020)

- Feedback efficiency controls the stellar mass - star formation law hardly matters!
- Gas mass “self-adjusts” to provide the “correct” stellar mass

see SF laws by Faucher-Giguere/Hopkins/FIRE group; Krumholz group; Semenov &Kravtsov

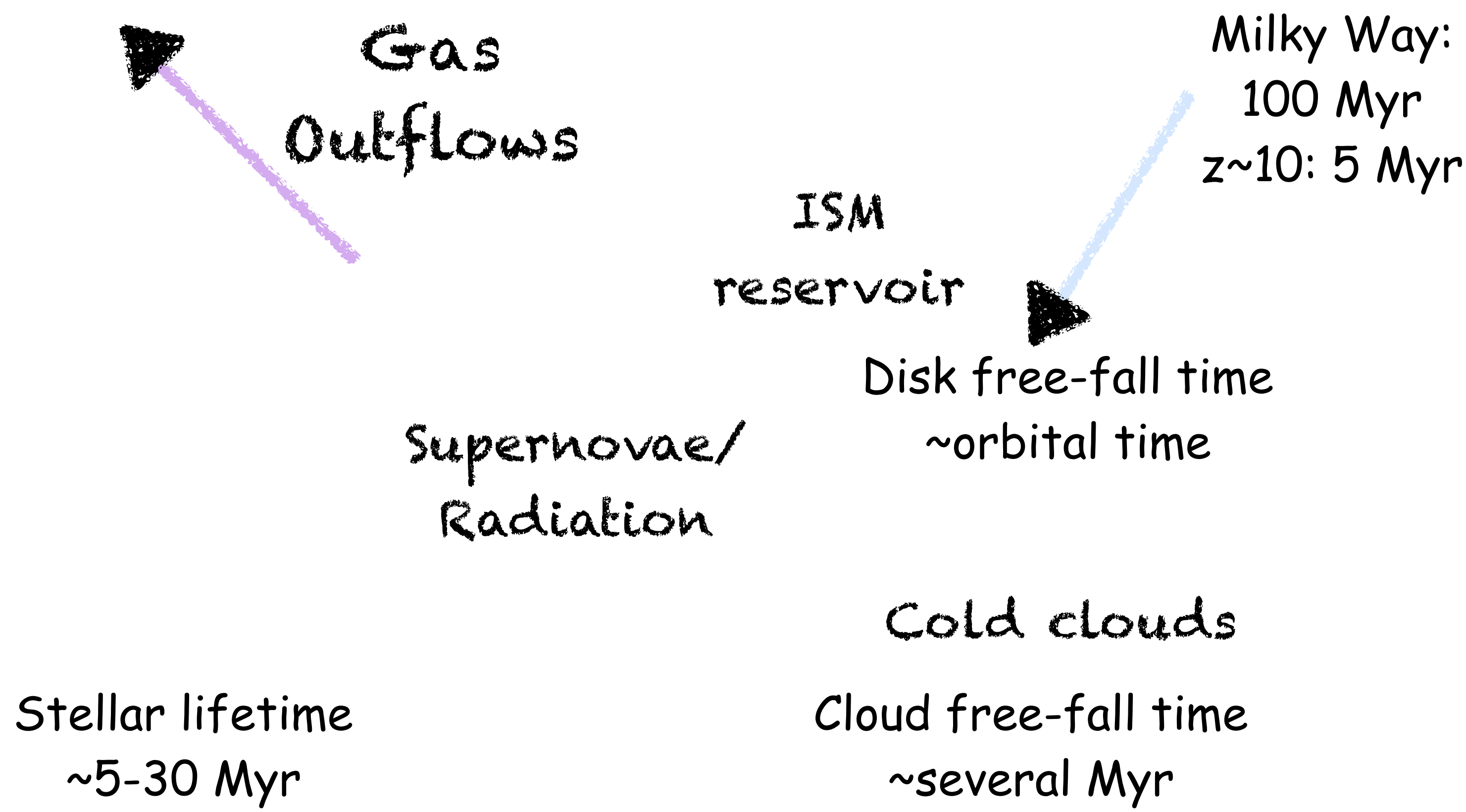
Faint Galaxies

- Only a fraction of the star formation will be directly observable!
- How do we learn about the small, early galaxies?



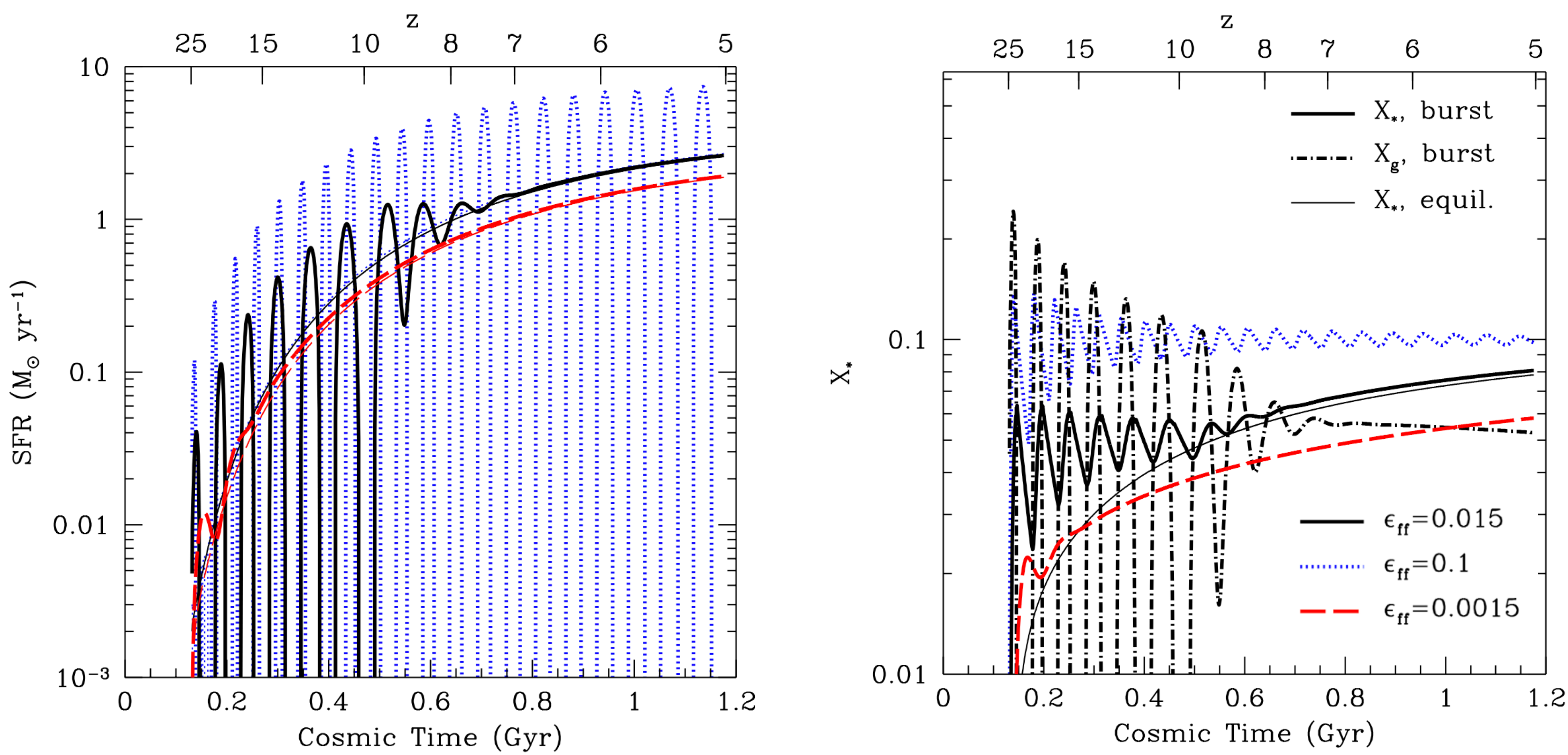
Furlanetto et al. (2017)

An example: bursts



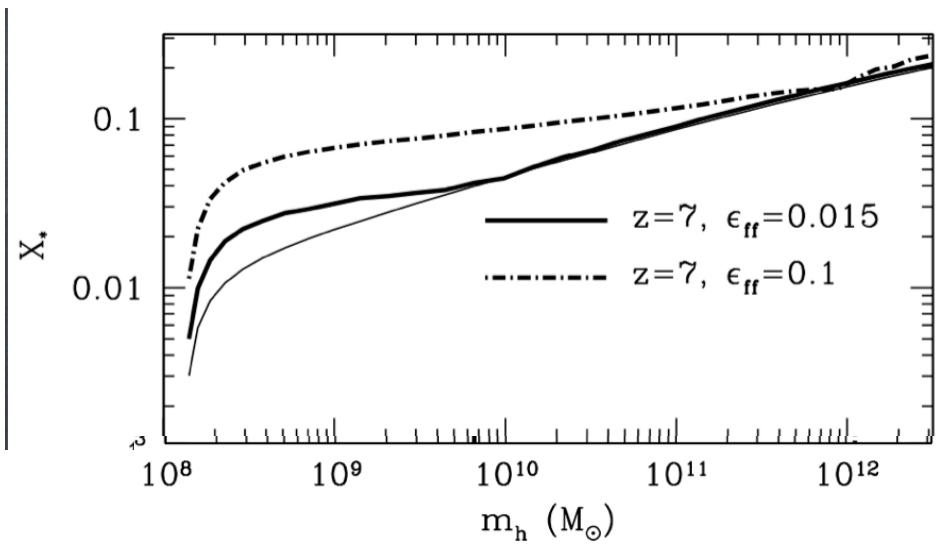
Faucher-Giguere (2018), Orr & Hopkins (2019)

Bursty Star Formation in the Cosmic Dawn



Furlanetto & Mirocha (2021)

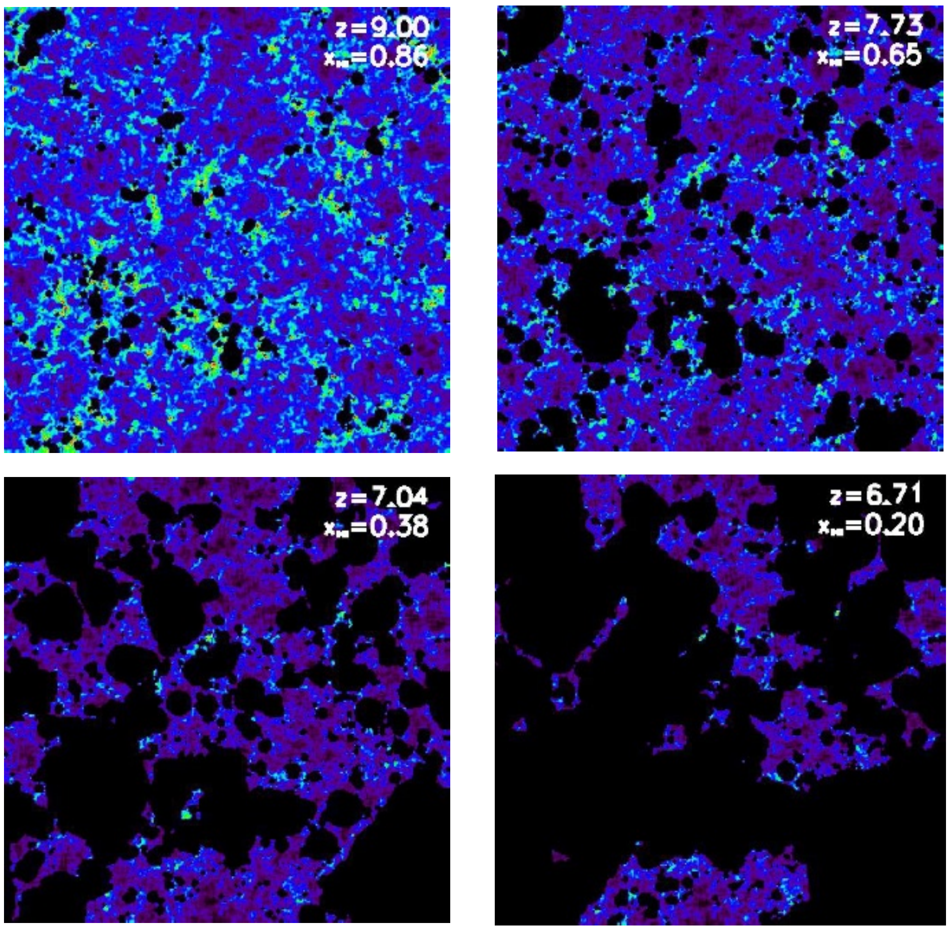
Bursts change our expectations!



Furlanetto & Mirocha (2021)

- Bursts are strongest at small masses, high redshifts
  - Changes scaling expectations!
- But for "normal" parameters no effect on observed (bright) objects!

How can we learn about those faint galaxies?



A. Mesinger

Reionization depends on the INTEGRATED light from ALL galaxies

Part II:
Lessons from the End of Reionization

The Jigsaw Puzzle of Reionization

Halo Masses

UV Escape Fraction

Unknown! Appears to be <5% at z<4

Stellar Pops

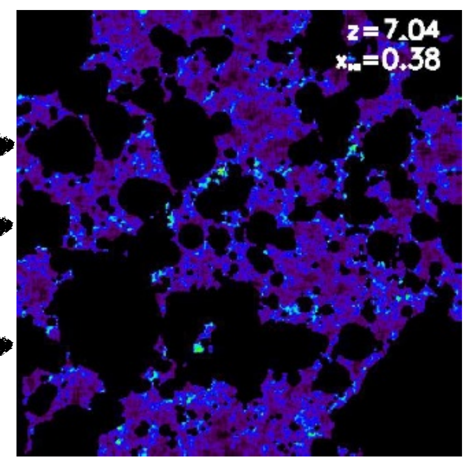
Galaxy X*

IGM Clumps

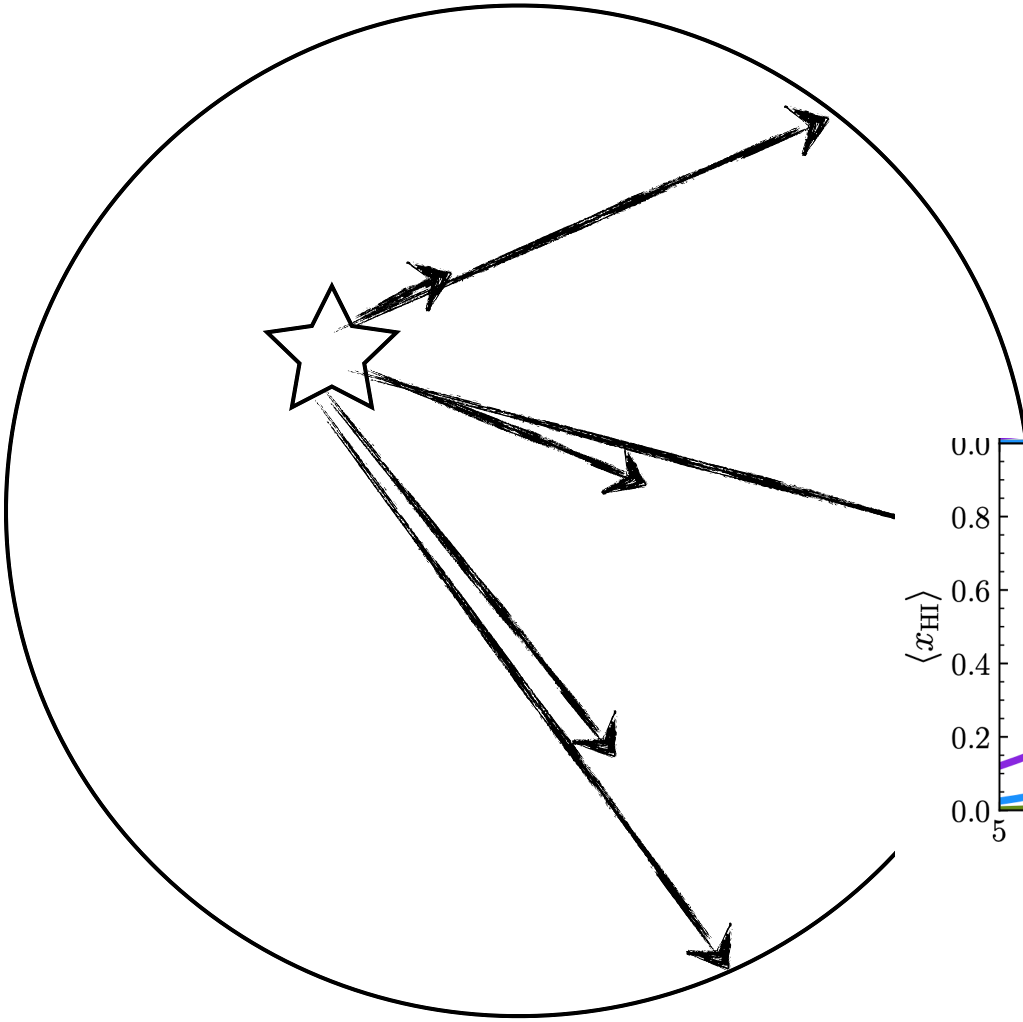
Source models determine timing of reionization

Ionizing Photons

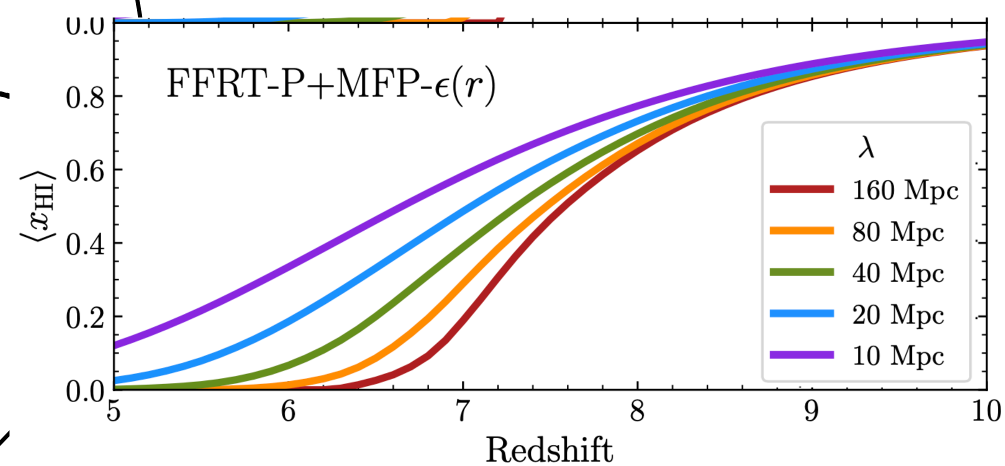
IGM Absorption



How does reionization end?

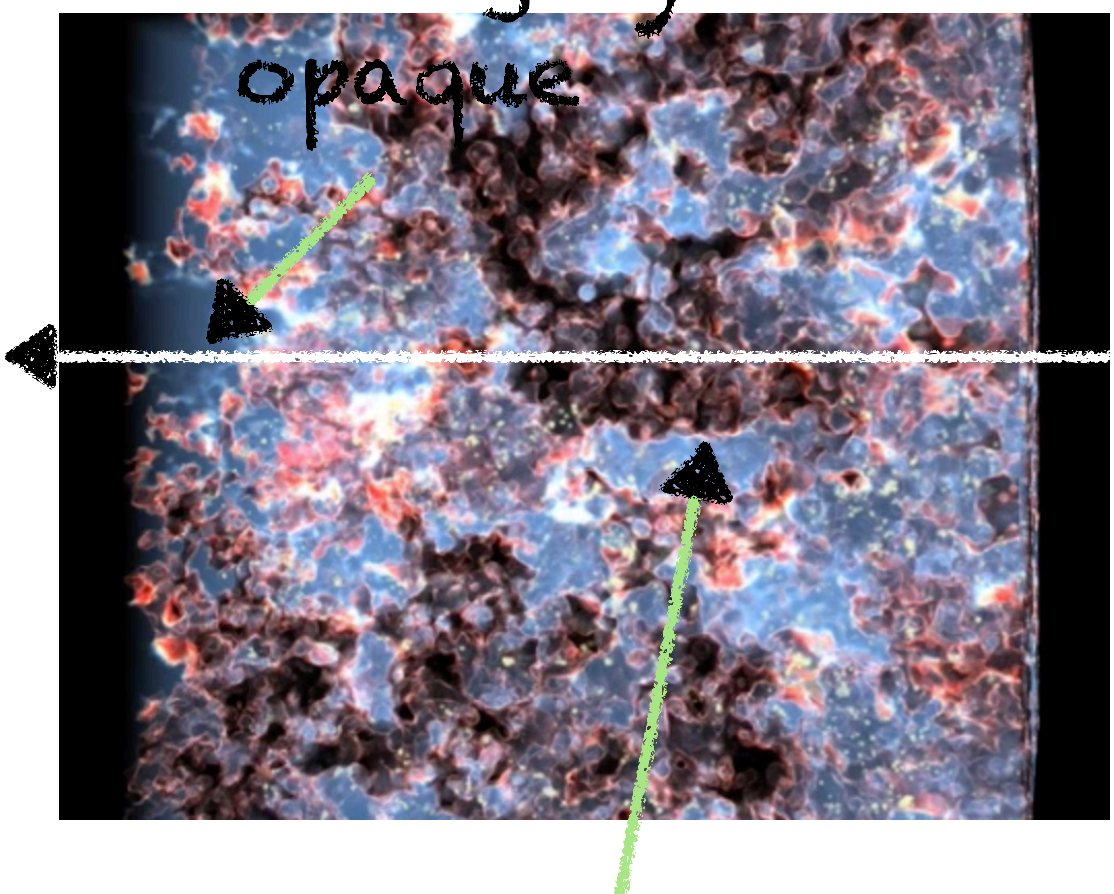


Can we use the timing of reionization to constrain these parameters?



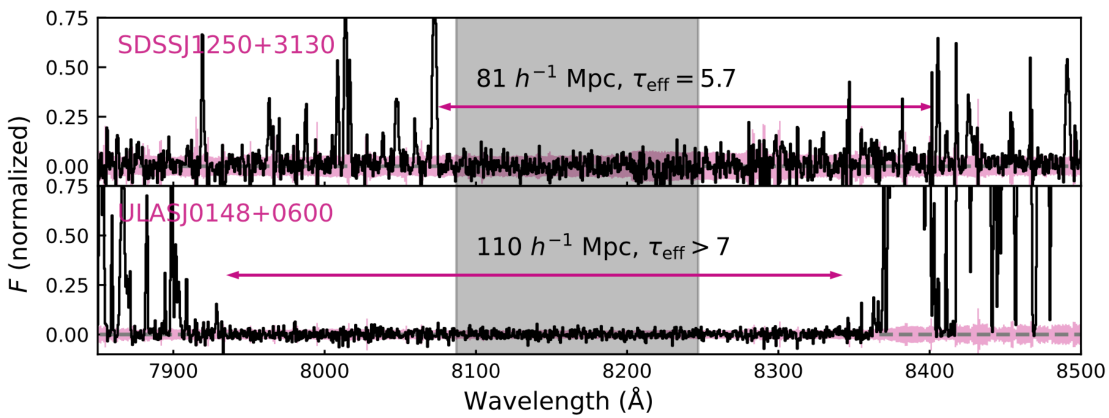
Davies & Furlanetto (2021)

Quasars as a Probe of Reionization



- Lyα forest probes neutral gas along line of sight
- But saturates at even a low neutral fraction
- Most useful for end of reionization!

When, and How, Did Reionization End?

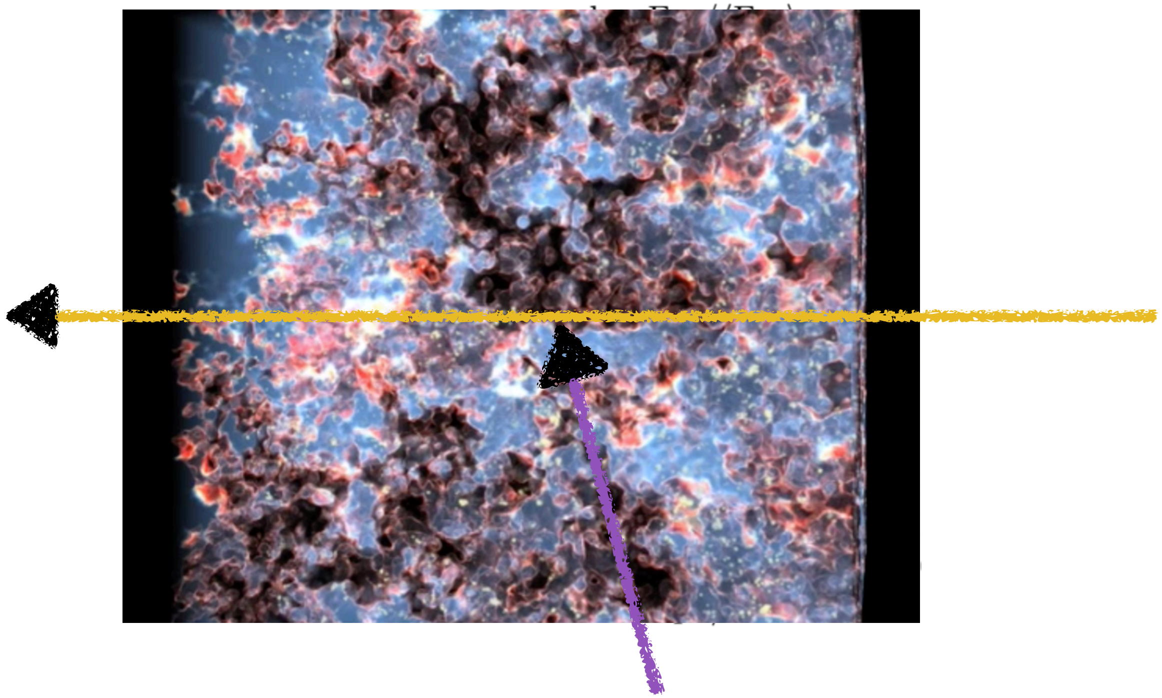


Christenson et al. (2021)

- Conventional wisdom: there's transmission "everywhere" at z<6: reionization is complete
  - Uptick at z>6 indicates end of reionization
- Lyα forest fluctuates VERY strongly at z~5.5
  - Cannot be explained by a standard model of the ionizing background

Fluctuations in the Ionizing Background

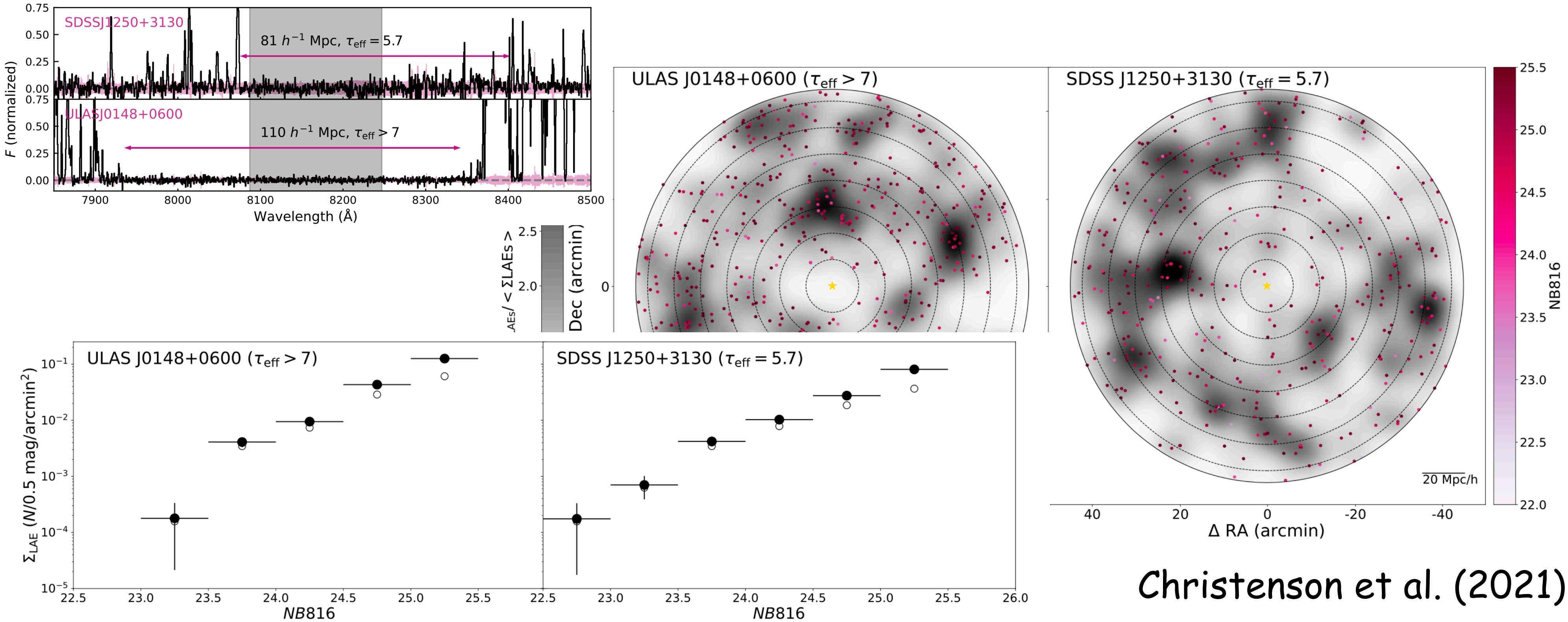
Davies et al. (2018)



Galaxy Void = Opaque Region

- In galaxy void:
  - Emissivity is small
  - Ionizing background decreases
  - Clouds become more neutral
  - Mean free path decreases
  - Ionizing background decreases….
- Natural limit: incomplete reionization! (Kulkarni et al. 2018)

Observation #1: Reionization may end later than expected!

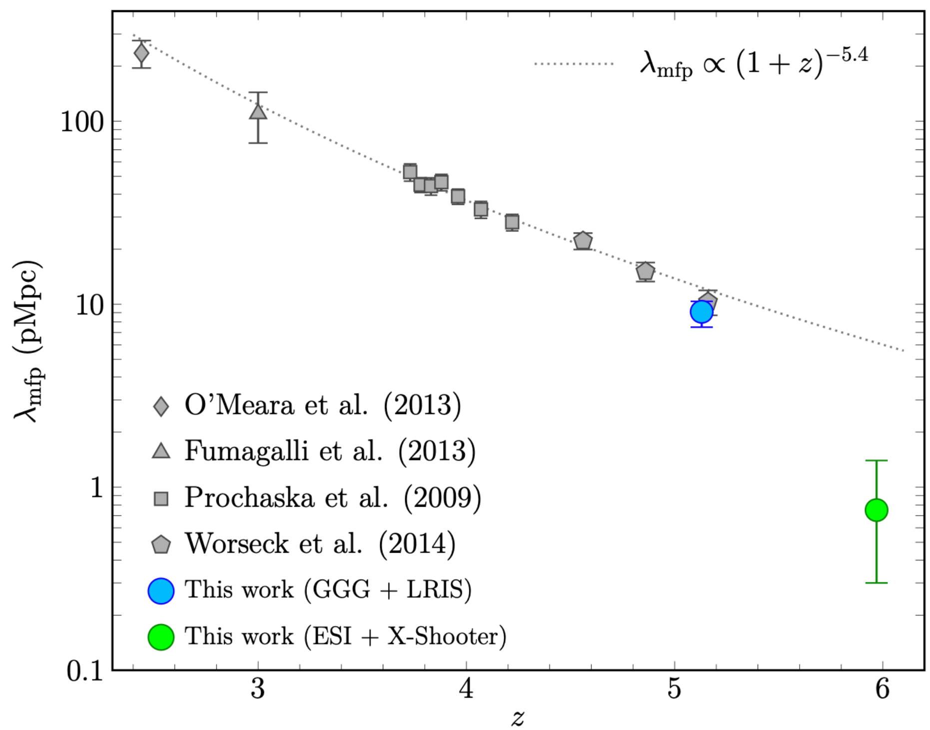


Christenson et al. (2021)

- Used narrowband filter on HyperSuprimeCam (fortuitously matching deepest absorption trough at z=5.7!)
- Deficit of galaxies in opaque regions: ionizing background fluctuations or late reionization?

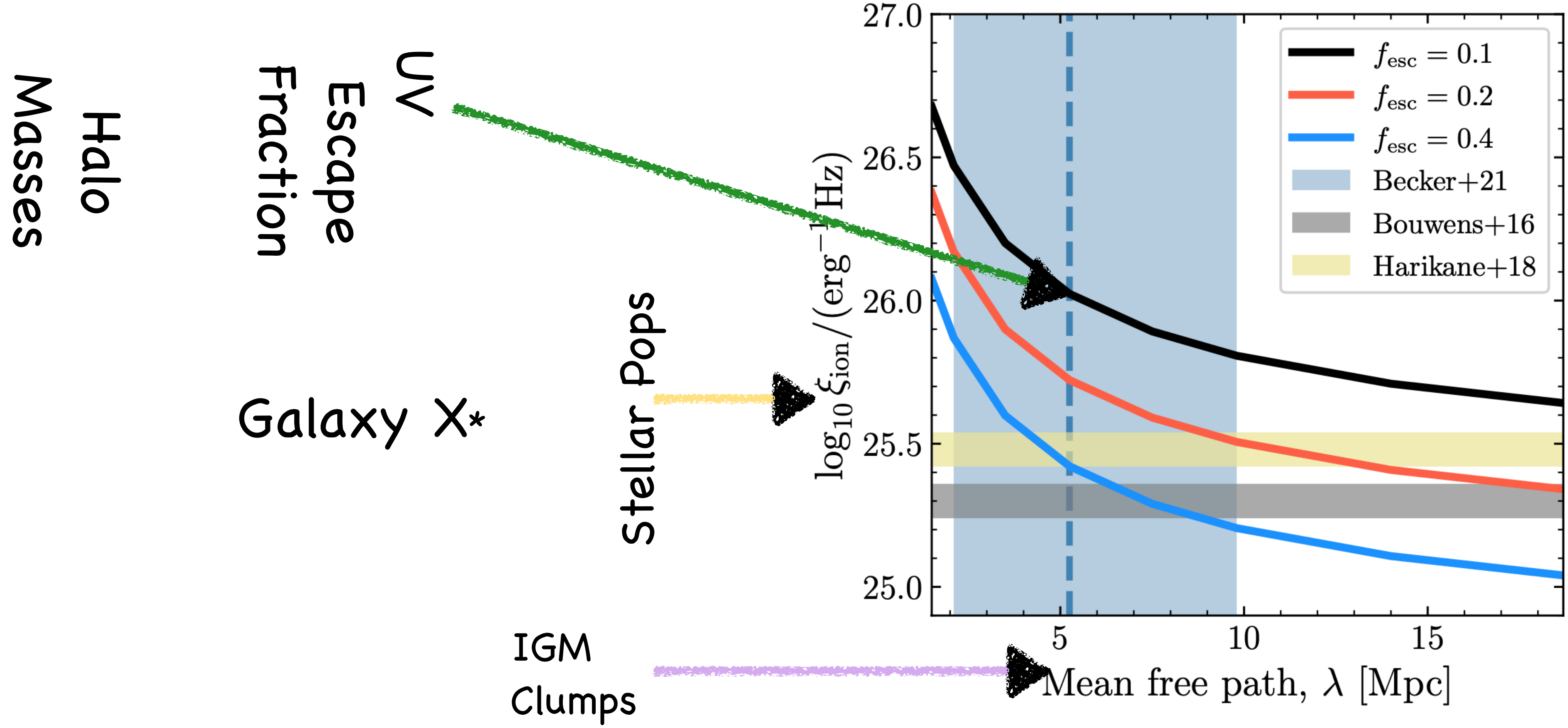
Observation #2: How important are those clumps?

- The clumpiness slowly increases with redshift to z~5
- And then drops off a cliff by z~6!



Becker et al. (2021)

Implications of a short mean free path



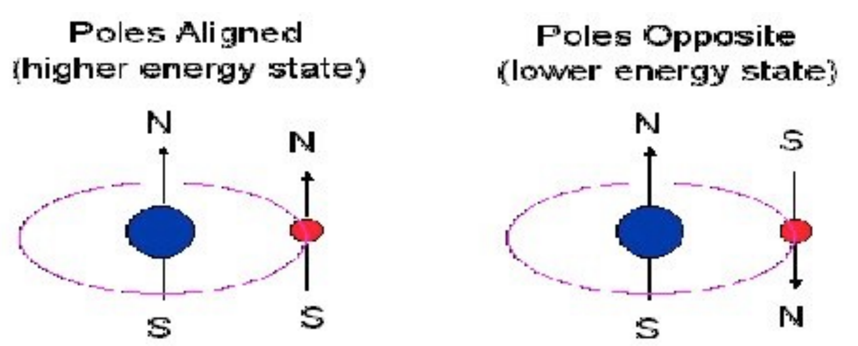
Davies et al. (2021)

Part III:
The Next Steps…

The JWST Revolution

- Several deep galaxy programs already approved!
- Will extend galaxy measurements to z~12!
- AND measure large-scale structure
- See my short talk later, and several forthcoming Trapp & Furlanetto papers!

The 21-cm Line

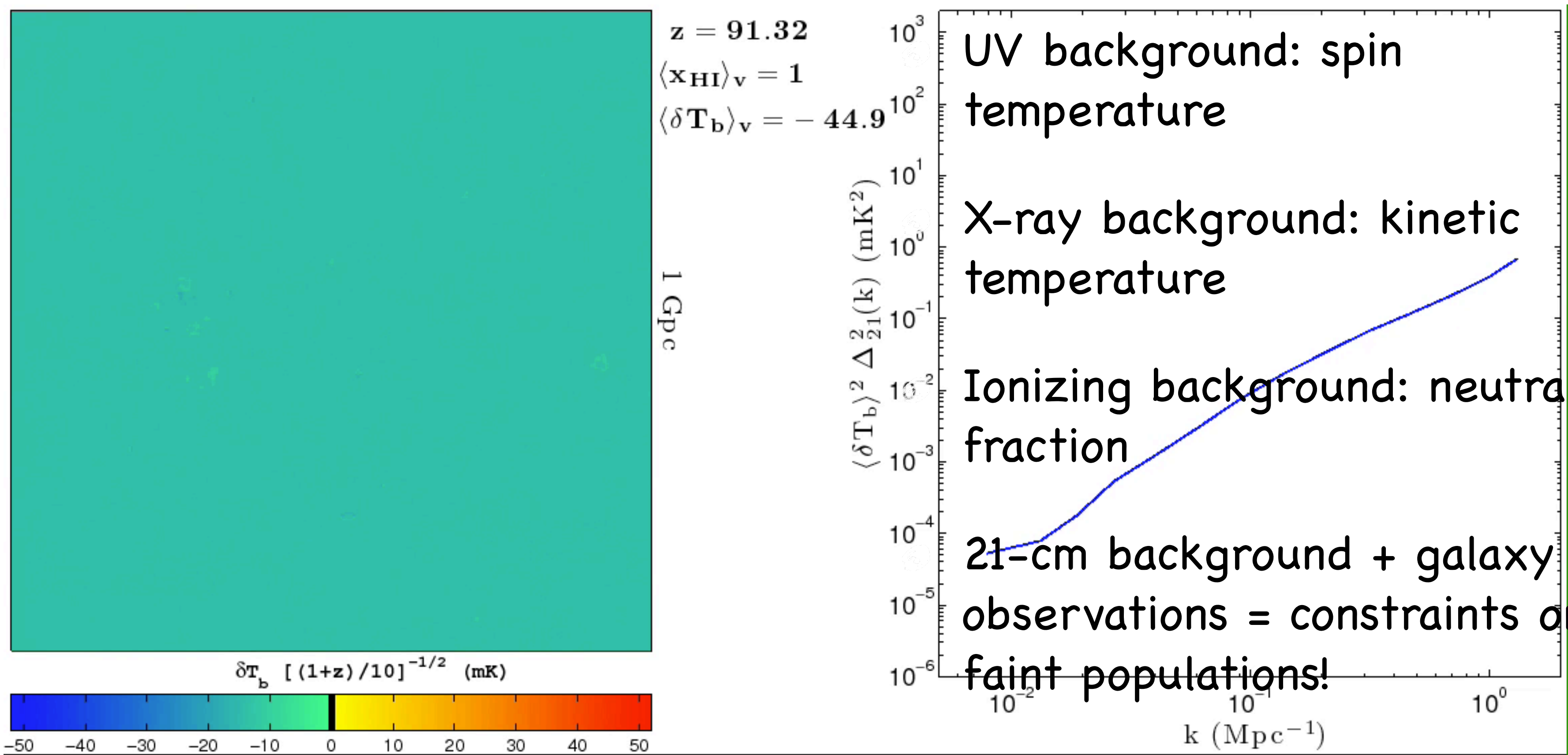


- Protons and electrons both have spins and hence magnetic moments
- Transition between alignments corresponds to 21-cm (1420 MHz) photon

The Advantages of the 21-cm Line

- Observe emission or absorption from neutral hydrogen via 21-cm line
  - Observed frequency -> redshift
- Observed frequencies ~50-200 MHz - hard!
- First detection (maybe) from EDGES; Bowman et al. 2018

The Four Phases of the 21-cm Signal



UV background: spin temperature

X-ray background: kinetic temperature

Ionizing background: neutral fraction

21-cm background + galaxy observations = constraints on faint populations!

Mesinger, Furlanetto, & Cen (2011)

The Jigsaw Puzzle of the 21-cm Signal

Halo Masses

UV Escape Fraction

Galaxy

1. $f_{*,10}$, the normalization of the stellar mass–halo mass relation, evaluated at $M_h = 10^{10} M_{\odot}$

2. $\alpha_{\star}$, the power law index of the stellar mass–halo mass relation

3. $f_{\mathrm{esc},10}$, the normalization of the ionizing escape fraction–halo mass relation, evaluated at $M_h = 10^{10} M_{\odot}$

4. α_{esc}, the power law index of the ionizing escape fraction – halo mass relation

5. M_{turn}, the characteristic halo mass scale below which the abundance of active galaxies is exponentially suppressed

6. t_*, the characteristic star formation time scale, expressed in units of the Hubble time

7. $L_{\mathrm{X}<2\,\mathrm{keV}}/\mathrm{SFR}$, the soft-band X-ray luminosity per unit SFR

8. E_0, the minimum X-ray energy of photons capable of escaping their host galaxies

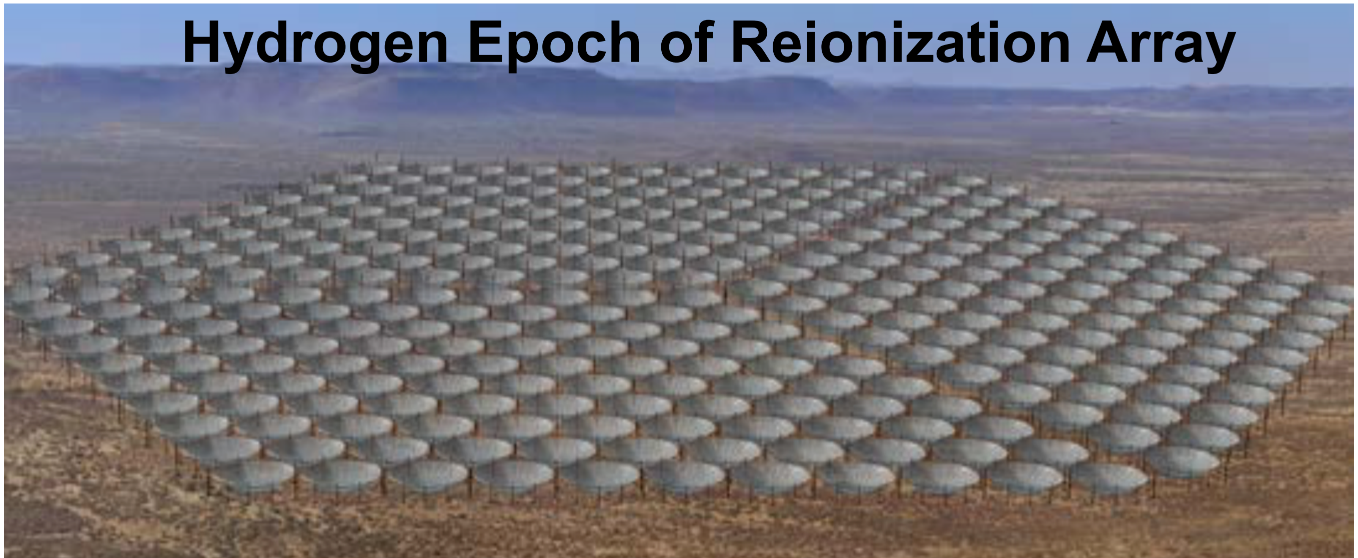
9. α_{X}, the energy power law index of the X-ray SED

UV Emission

Radio emission

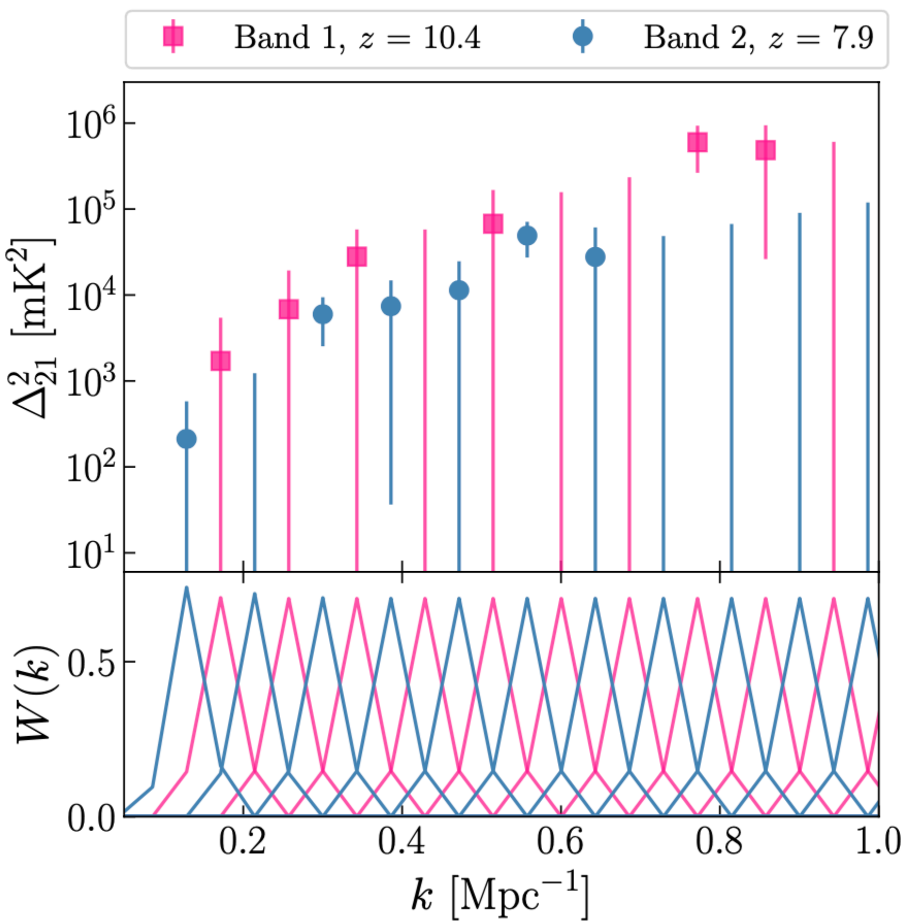
Black Holes

21-cm Surveys: HERA



Now under construction; complete…soon

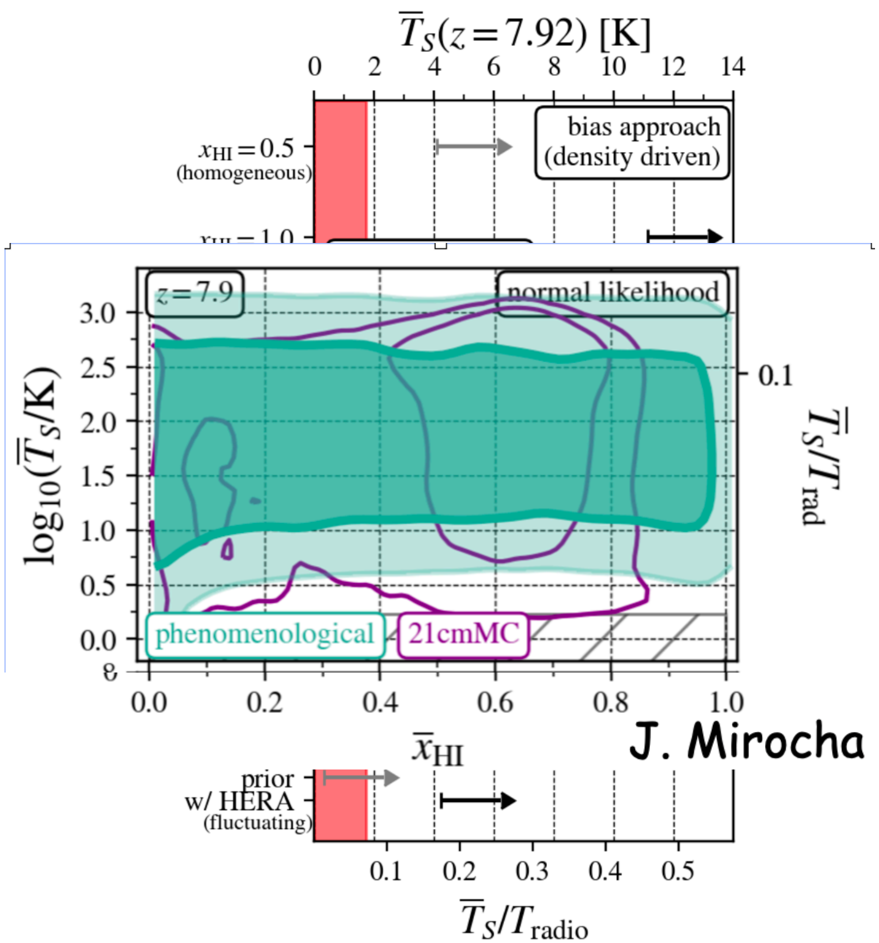
The First Limits from HERA!



HERA Collaboration (2021), N. Kern

- Upper limits from first observing campaign (39 antennae, 18 nights)
- Most stringent upper limits on the spin-flip signal to date!

IGM Heating at z~8!

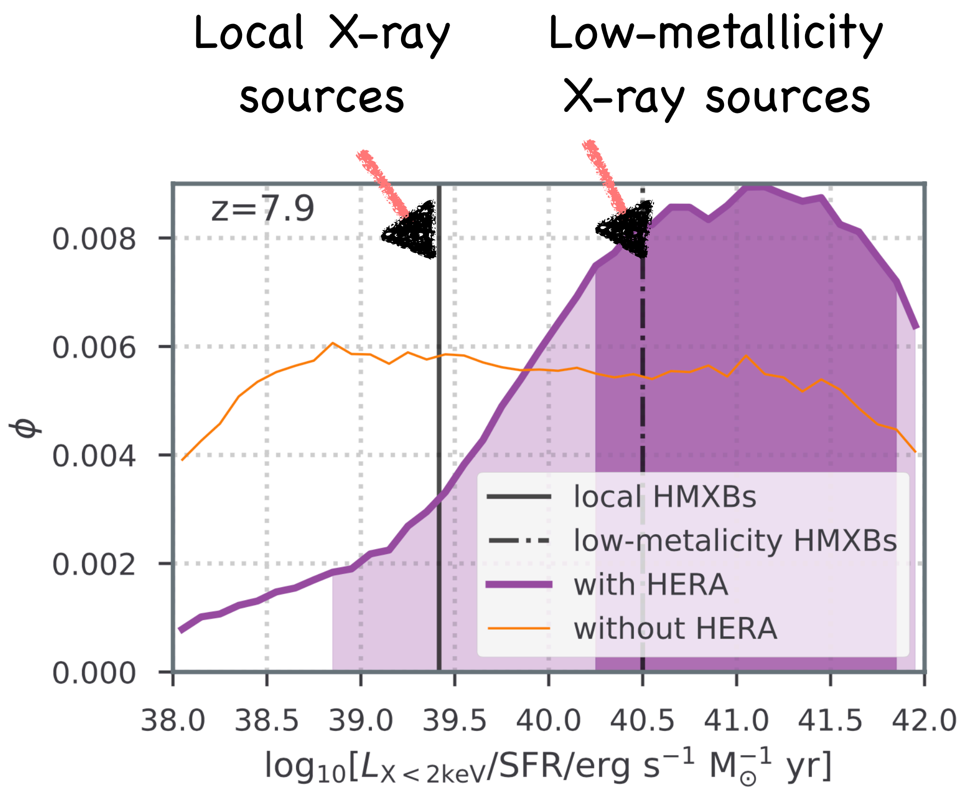


HERA Collaboration (2021)

Key result: IGM must be above the adiabatic cooling limit at z~8!

True of four independent approaches, marginalized over all other astrophysics

IGM Heating at z~8!

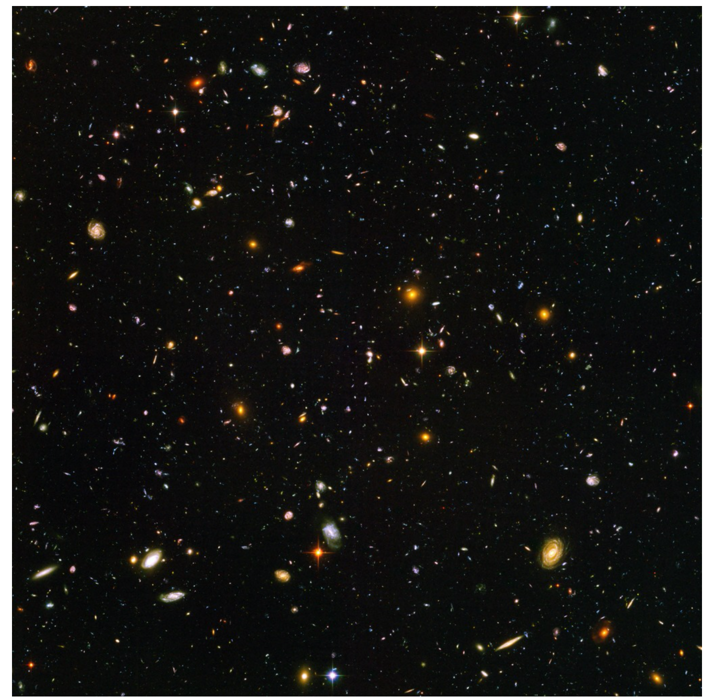


HERA Collaboration (2021), Y. Qin & A. Mesinger

If the heating is interpreted as X-rays from galaxies, suggests substantial high-mass X-ray binary population!

So where do we stand?

- So far, during the Cosmic Dawn…
  - Bright galaxies work just as we might expect
  - But reionization measurements suggest there are unknowns with the unseen galaxies!
  - And theory suggests there are many things that can change in smaller and earlier galaxies!



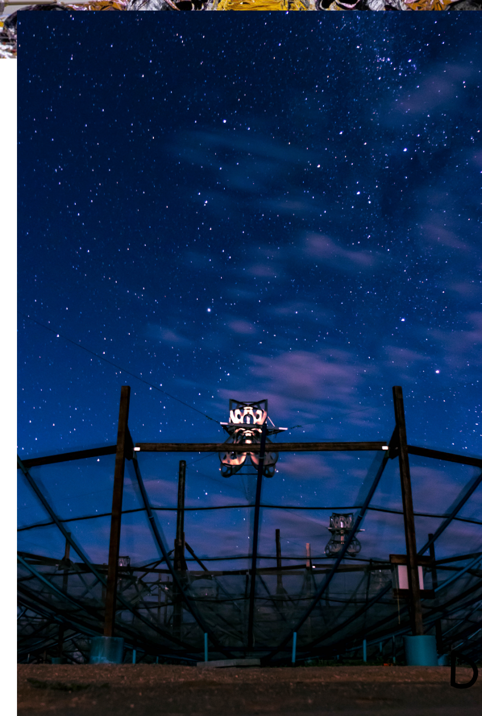
HST UDF

See also https://cosmicdawn.astro.ucla.edu for more reasons to study this era!

And what's next?

In the (near!) future…

- Galaxy measurements will improve dramatically
- 21-cm limits are already telling us new physics
- 21-cm and IGM measurements, in combination with direct galaxy measurements, will reveal much more about the faint population



D. Storer

See also https://cosmicdawn.astro.ucla.edu for more reasons to study this era!