Faint Galaxies and Reionization

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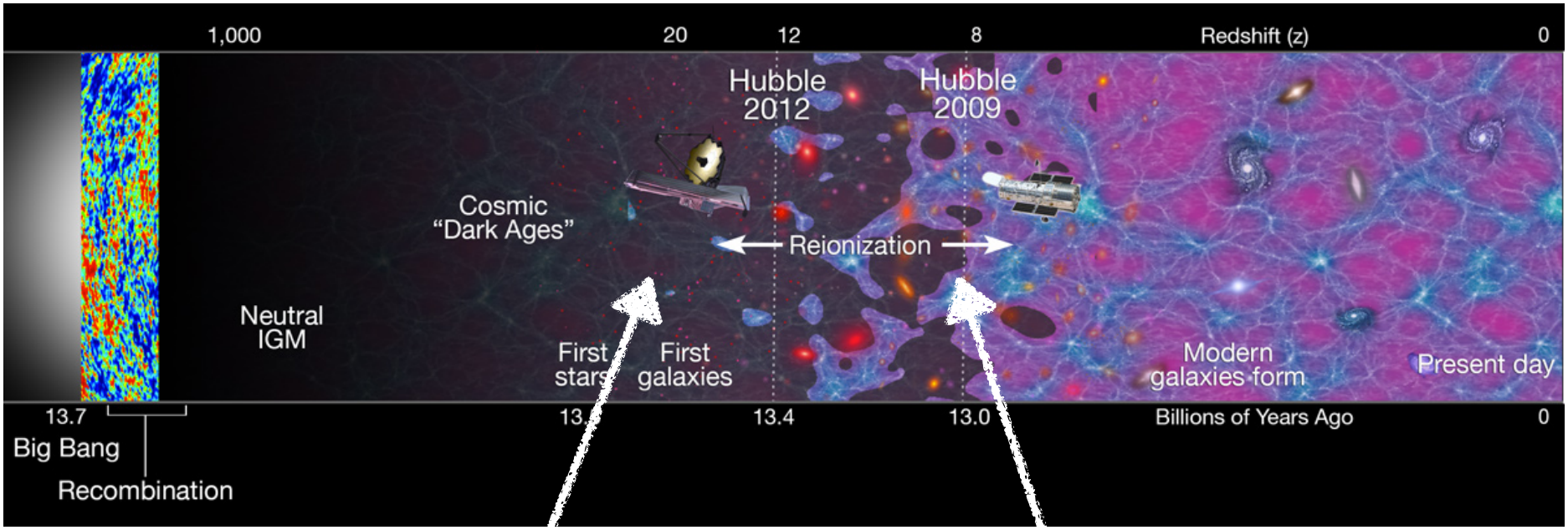
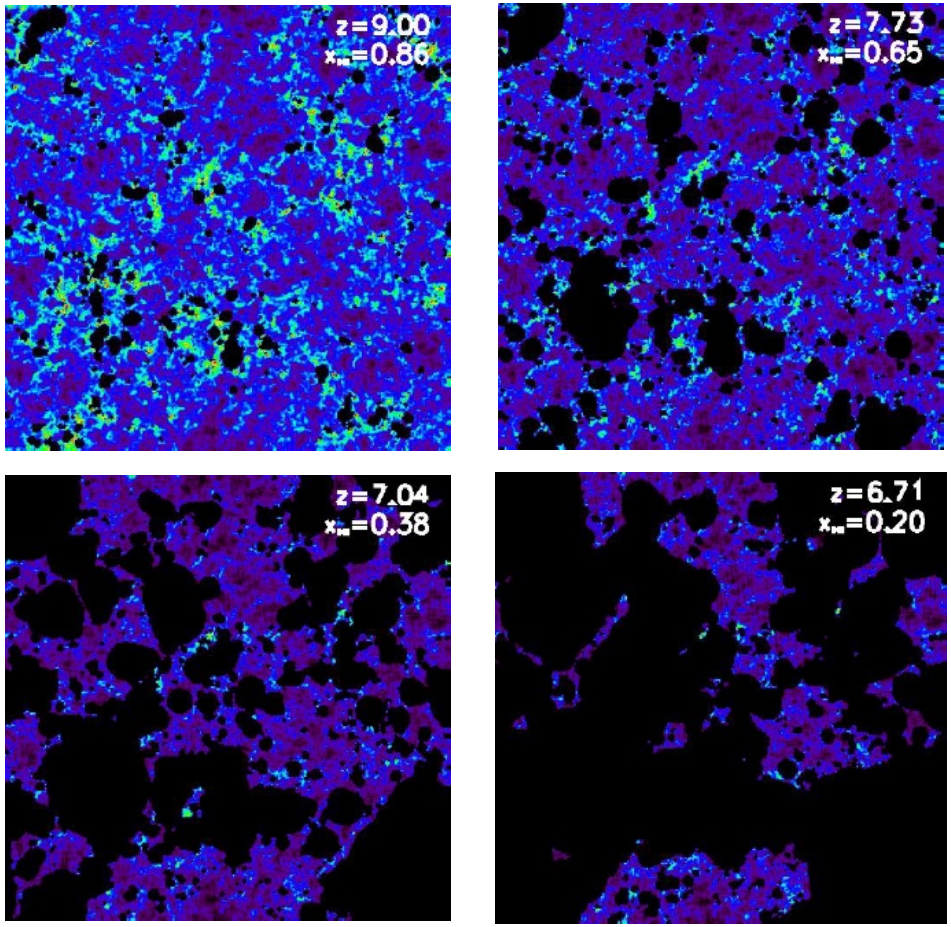
Some Context: The Cosmic Dawn and Reionization



"Cosmic Dawn" Reionization

How do we learn about reionization?

What is reionization?



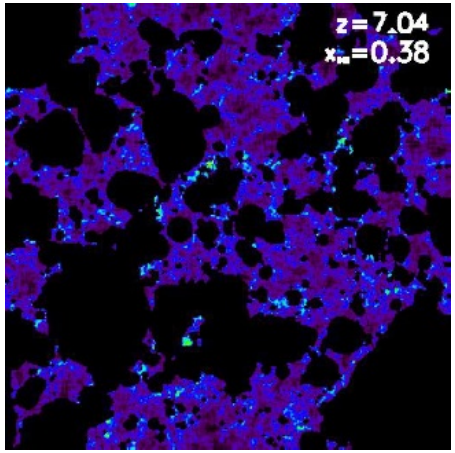
A. Mesinger

- Landmark event of first generation of galaxies
- Affects fuel for future generations of galaxies
- Powerful probe of all those galaxies you CAN'T see

Galaxies and Reionization

Ionizing Photons

IGM Absorption



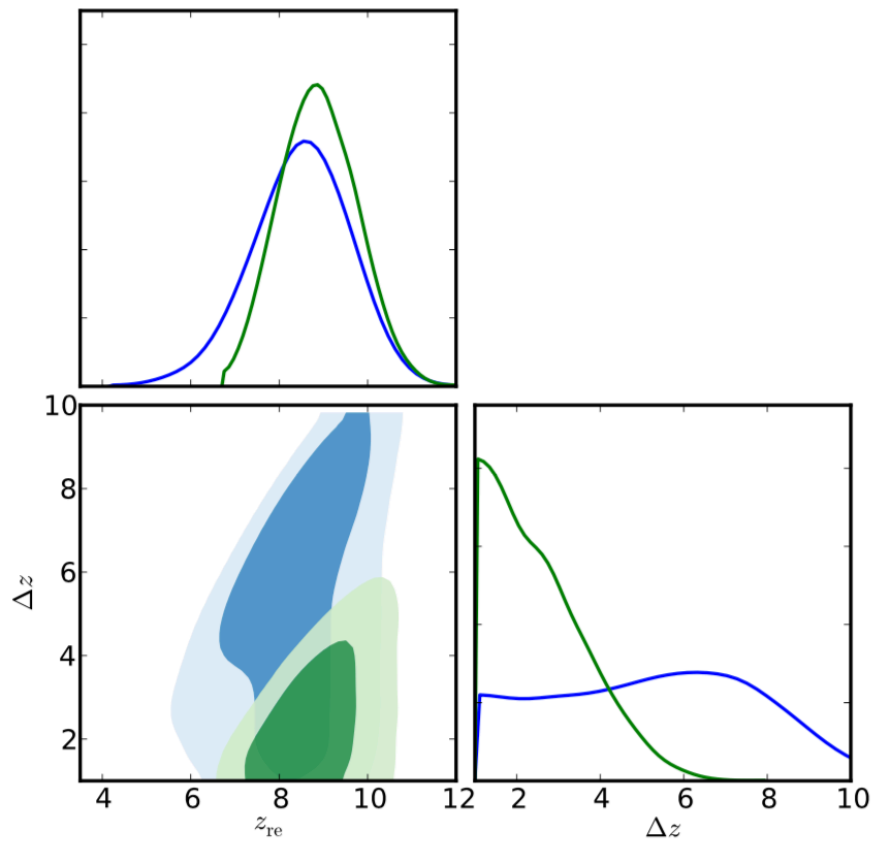
Key Expectations For Reionization

- Ionized structures are LARGE: diameter~50 Mpc (~20 arcmin)
  - Sizes depend on galaxy clustering
- Timing depends on integrated source population
- End phases regulated by IGM absorption (transition to Lyman-α forest)

M. Alvarez

Observations of Reionization: Timing

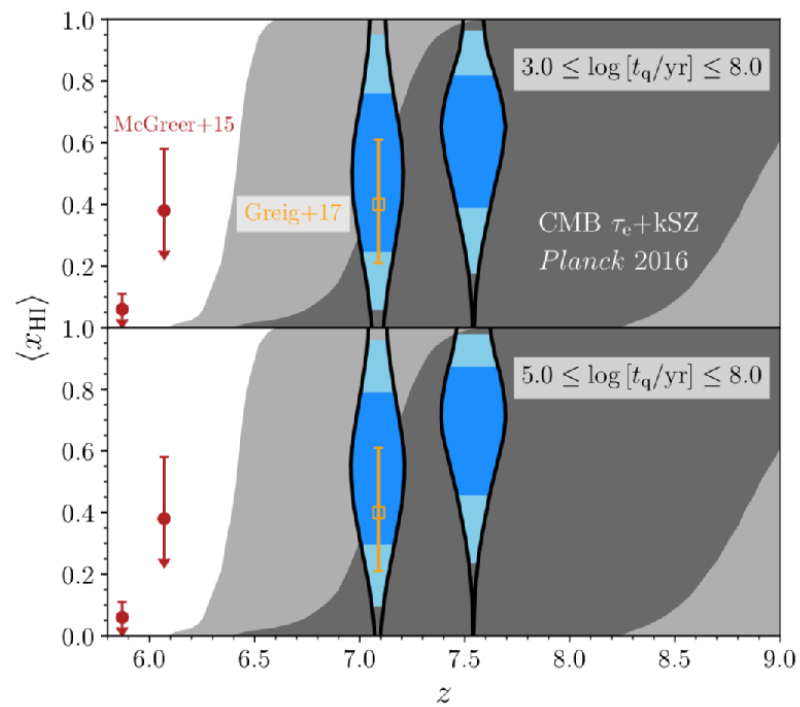
- Free electrons scatter CMB photons
  - Planck measurements suggest reionization ended at z<8 or so



Planck Collaboration (2016)

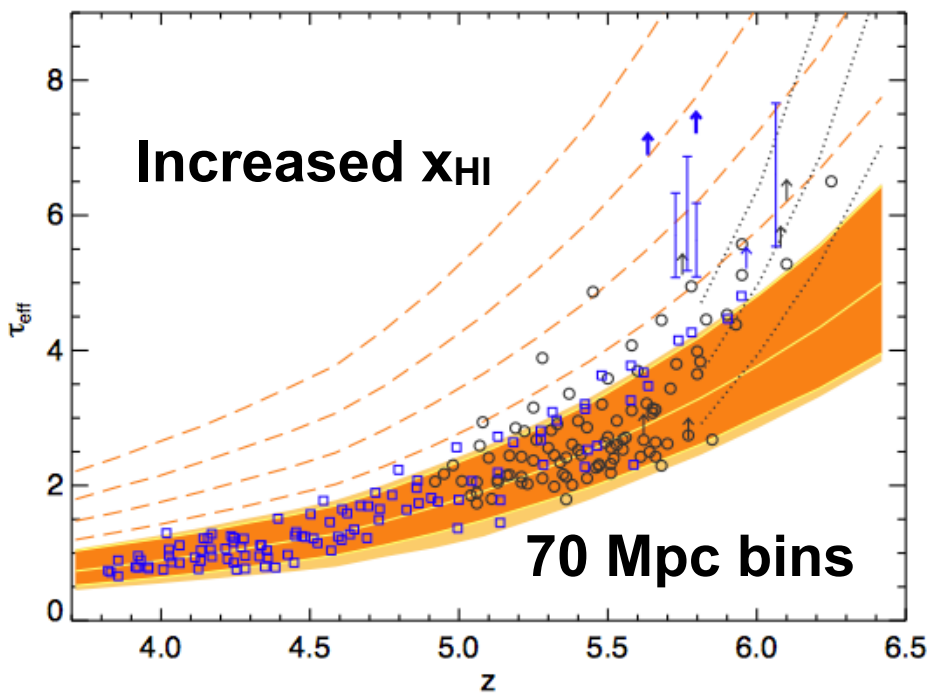
Observations of Reionization: Timing

- Free electrons scatter CMB photons
  - Planck measurements suggest reionization ended at z<8
- Astrophysical measurements are consistent with most of reionization occurring at z<7.5
  - Depend on interpreting IGM Lyman-α absorption (around quasars and galaxies)



Davies et al. (2018)

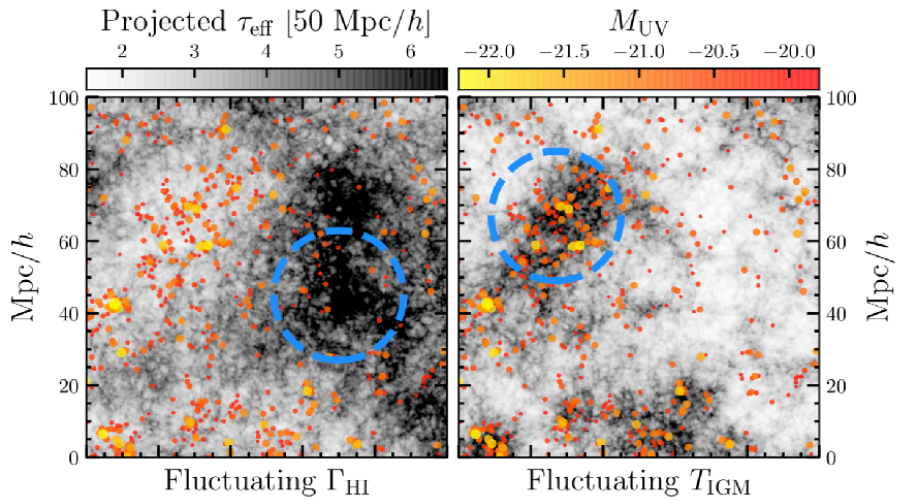
Observations of (Not Quite) Reionization: Structure



Becker et al. (2015)

- Lya forest fluctuates VERY strongly shortly after reionization
- Cannot be explained by a standard model of the ionizing background

Two Potential Explanations, with Opposite Predictions!

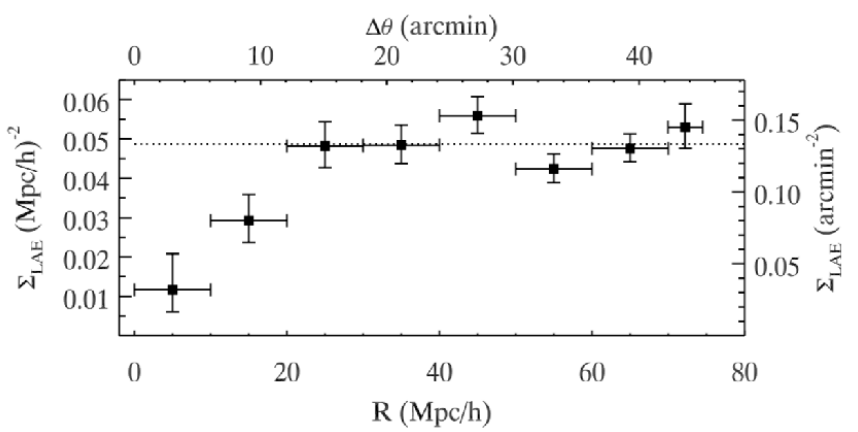


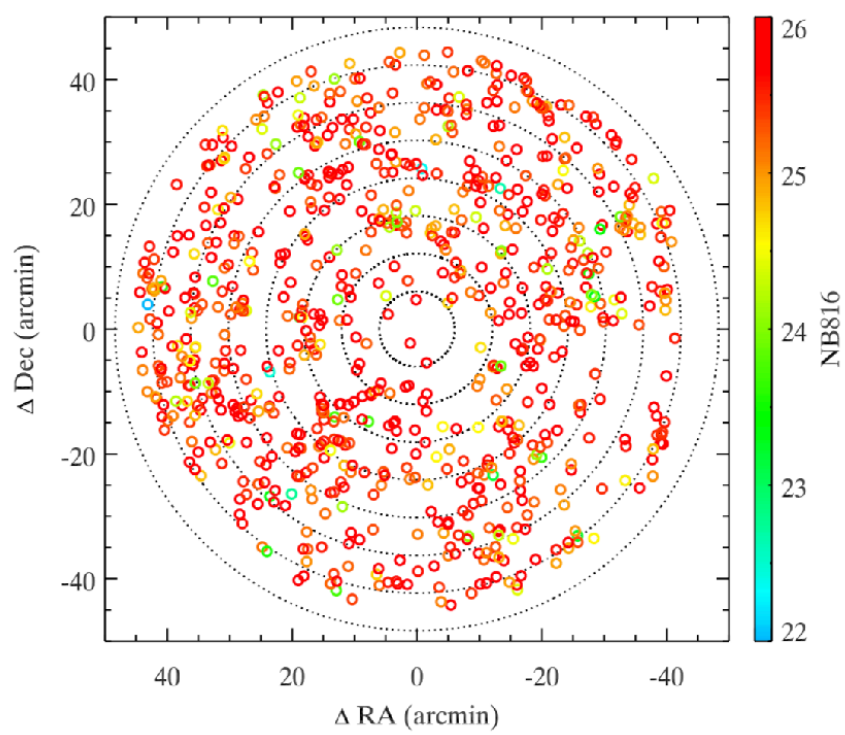
Davies et al. (2018)

- Option #1: a short mean free path triggers large fluctuations in the ionizing background (Davies & Furlanetto 2016) - possibly even ongoing reionization (Kulkarni et al. 2018)
- Option #2: relic temperature fluctuations from extended reionization (D'Aloisio et al. 2016)

Observations!

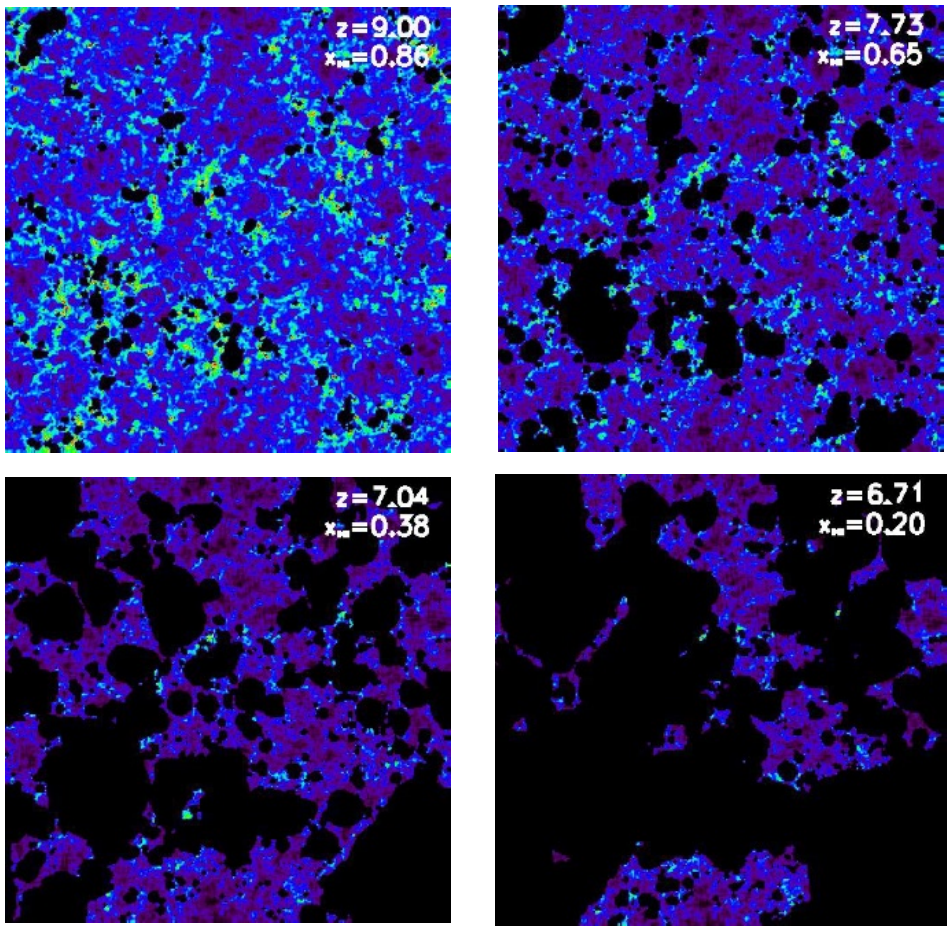
- Used narrowband filter on HyperSuprimeCam (fortuitously matching deepest absorption trough at z=5.7!)
- Clear DEFICIT of LAEs in this area: points toward ionizing background explanation!
- Lessons:
  - Features in ionizing background occur on large scales (>10 Mpc)
  - Redshift information is essential!





Becker et al. (2018)

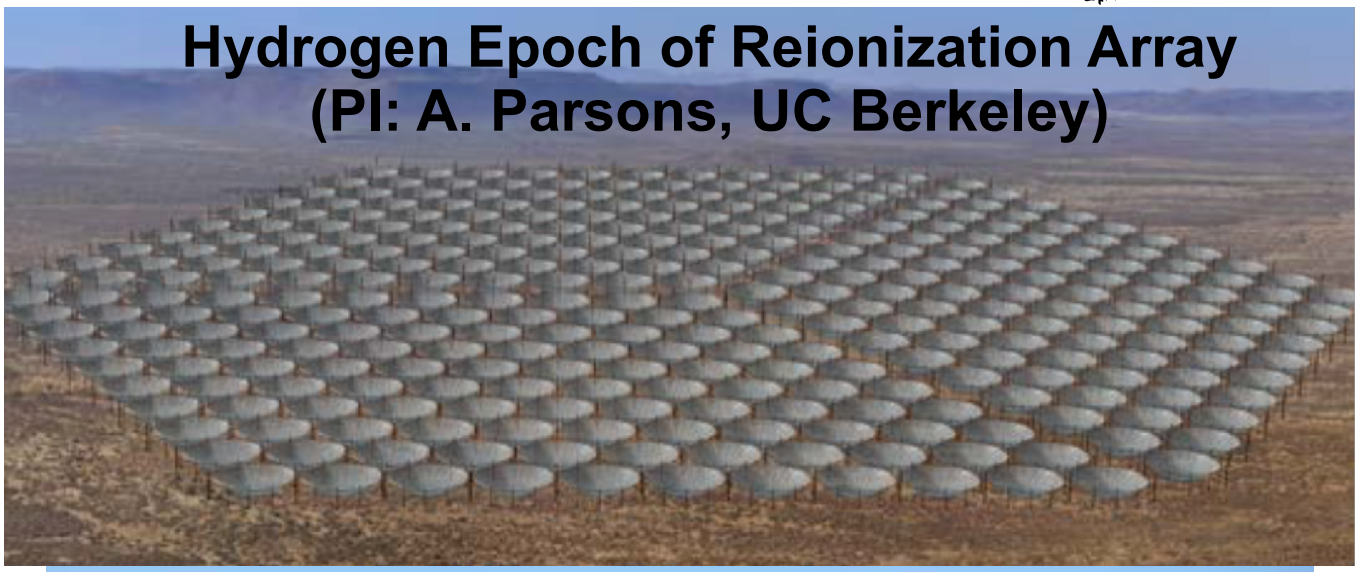
Observing Reionizaiton with the 21-cm Line



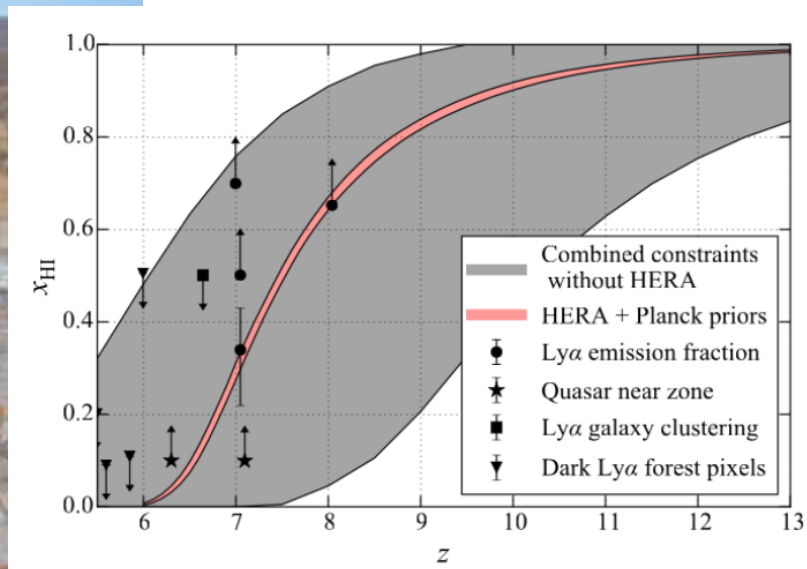
A. Mesinger

- Observe emission or absorption from neutral hydrogen via 21-cm line
  - Disappears during reionization!
- Observed frequencies ~50-200 MHz - hard!

21-cm Surveys: HERA

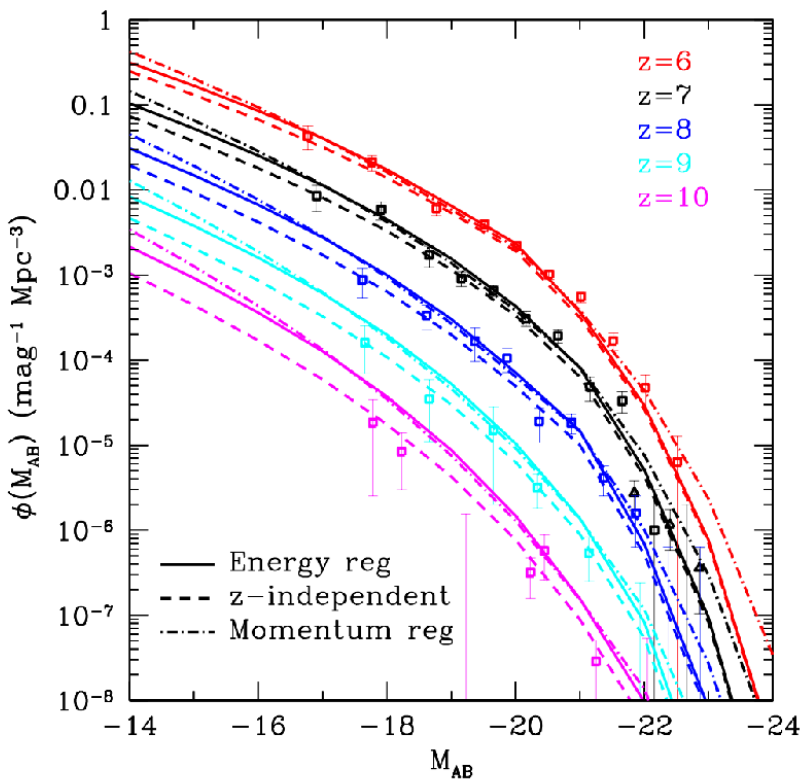


- Now under construction; complete in ~2020
- Will measure statistical fluctuations in the 21-cm field, not make images!



How do we learn about galaxies during the Cosmic Dawn?

Luminosity Functions

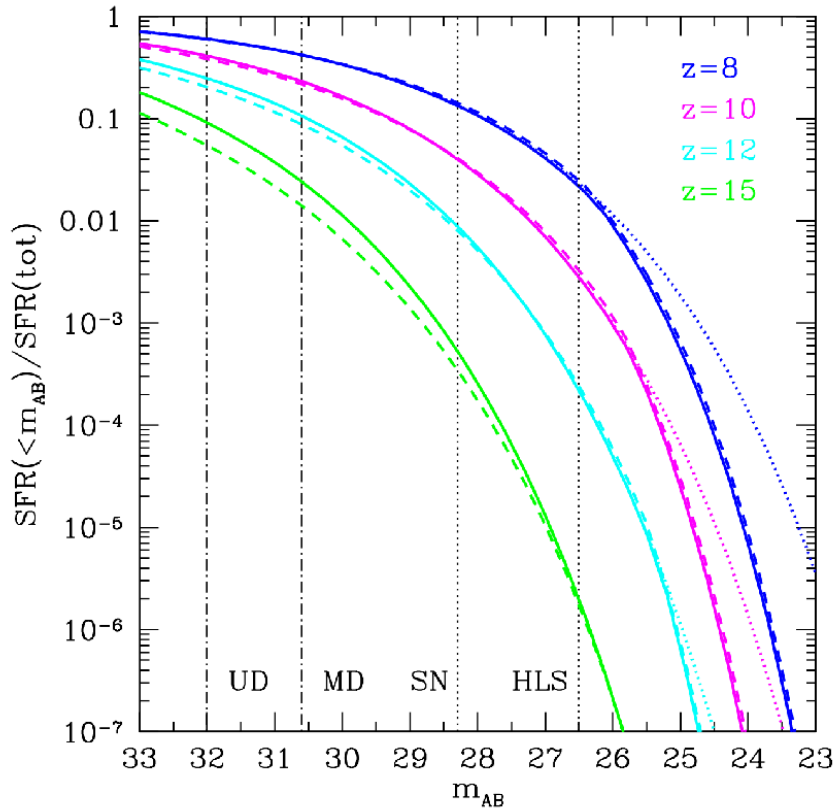


Furlanetto et al. (2017)

- Deep surveys have measured the bright-bright-ism end of the galaxy LF with some precision to z~10
  - Probes of fainter end are more controversial
- This observed LF has no particular surprises: simple galaxy models fit without any real trouble
  - No evidence for new physics!

Faint Galaxies

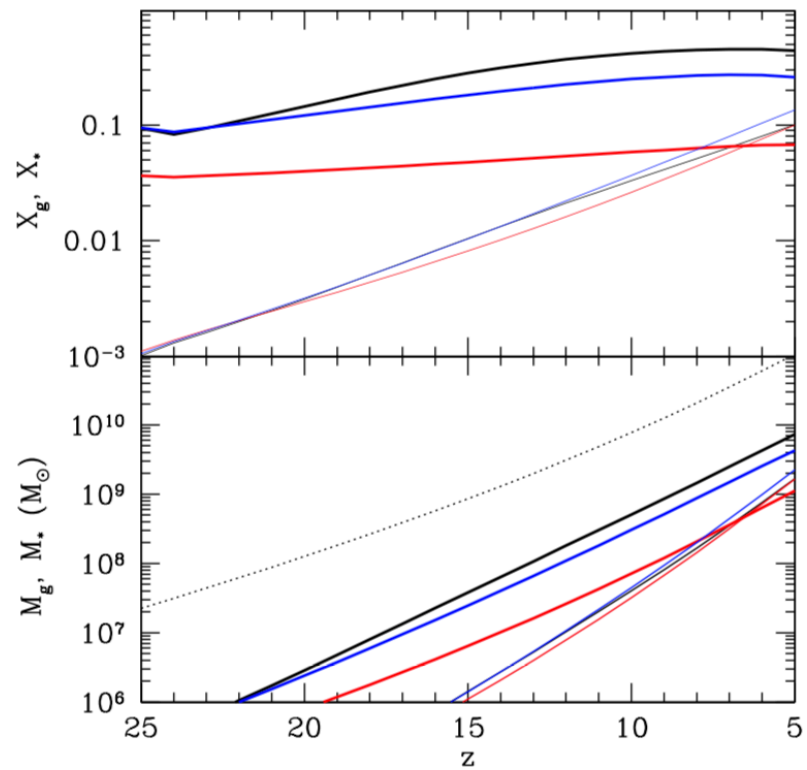
- BUT key is in the faint end: dominates total emission!
- This is ALSO where we might expect new physics
  - Pop III sources?
  - Bursty dwarf galaxies?
  - Globular clusters?
  - Who knows?



Furlanetto et al. (2017)

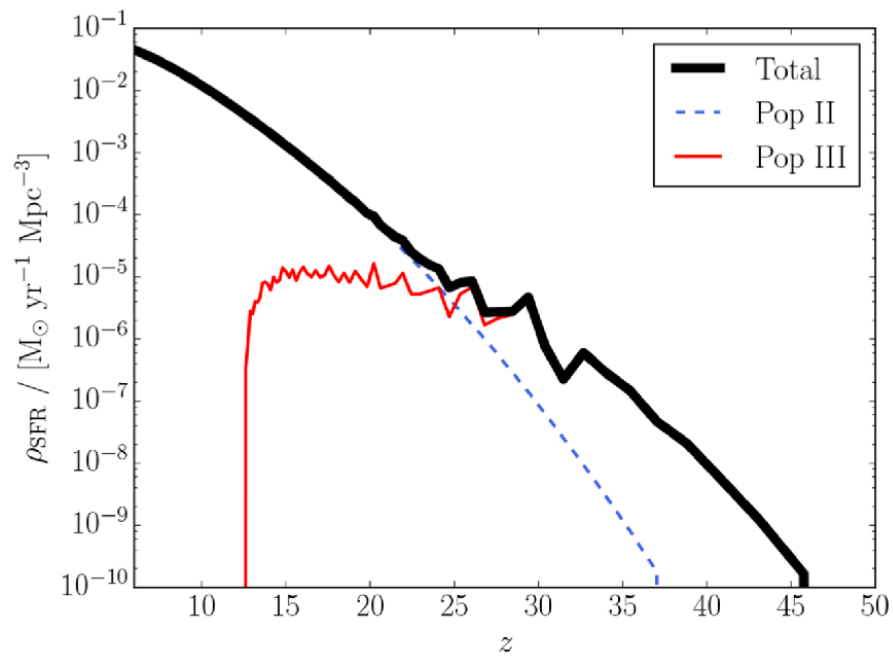
Galaxies Take a "Long" Time to Grow!

- Super-simple model of "smooth" galaxy formation
- Final product: halo of mass 10^{11} M_{sun} at z=5, or M_{AB}~-20
- Can begin forming stars using conventional methods at z~25!



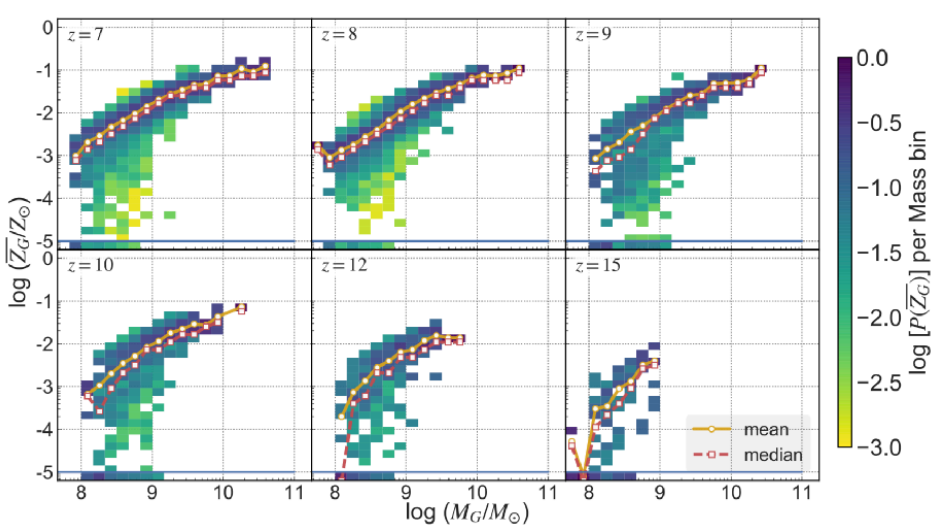
Key Physics: Pop III -> Pop II Transition

- How does "normal" galaxy formation establish itself?
- Pop III phase likely…
  - Brief (in any given halo)
  - Bursty
- Star formation in small halos is regulated by Lyman-Werner background from massive galaxies
- Need to probe very faint sources!



Mebane et al. (2018)

Signatures of New Physics in Bright Galaxies?

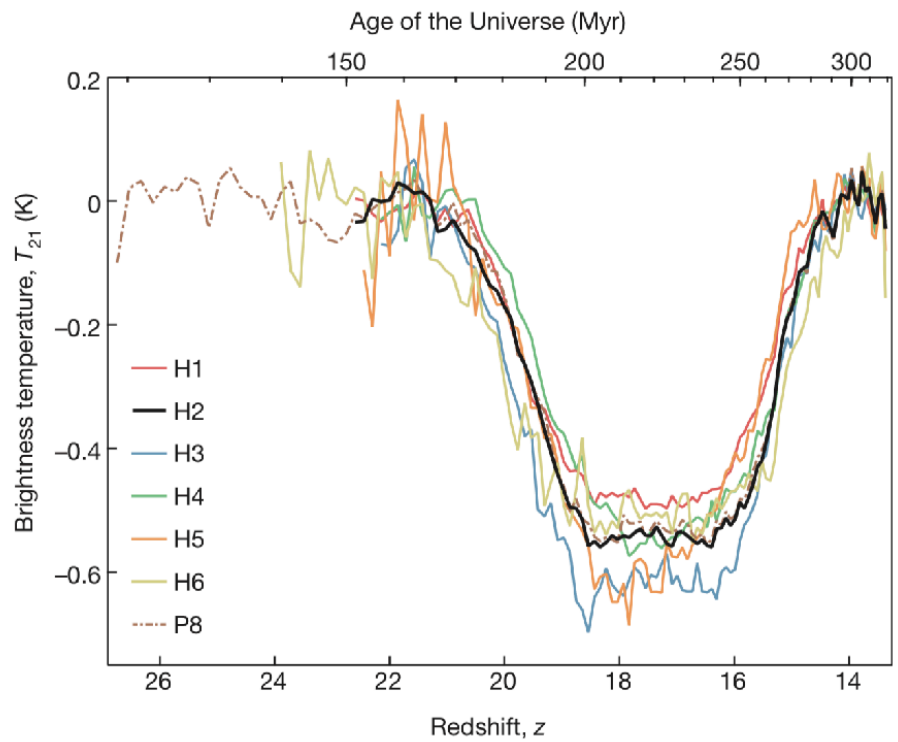


Sarmento et al. (2018)

- Can we learn about these early stars by looking in detail at bright objects?
- Incomplete mixing means Pop III stars continue to form?
- Unusual emission lines
- Burstiness
- Etc.

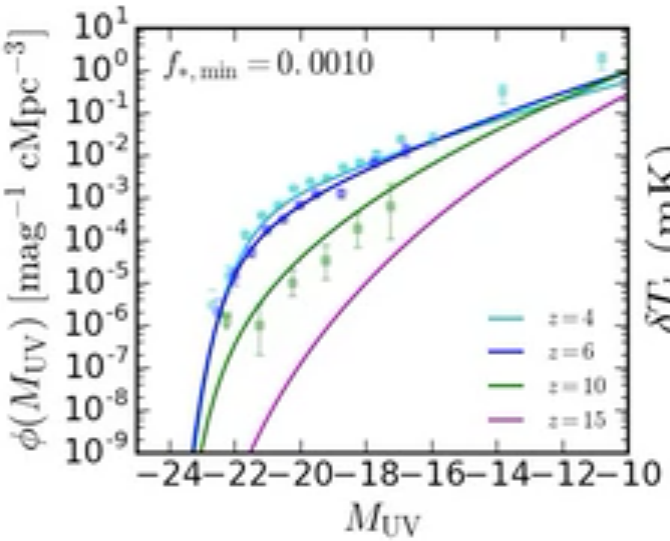
Probing the Earliest Phases of Galaxy Formation

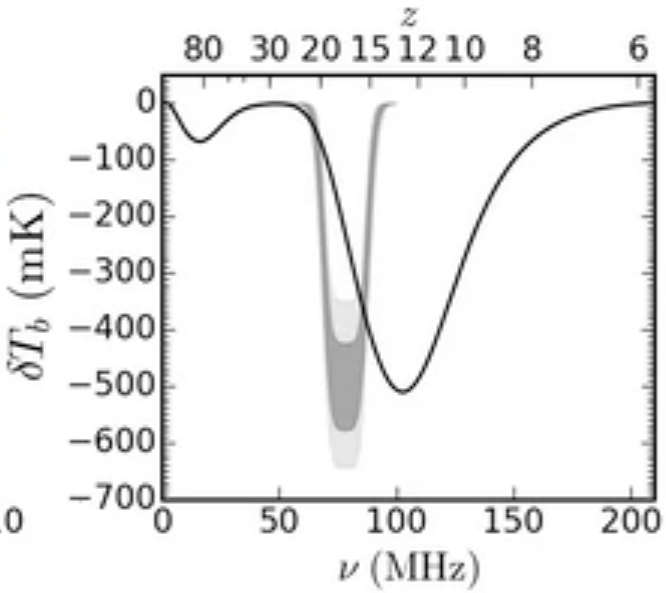
- Bowman et al. (2018) claimed the first detection of the redshifted 21-cm signal with the EDGES experiment
  - Highly controversial and requires confirmation!!!
- IF confirmed, important implications for galaxy formation!



Bowman et al. (2018)

EDGES and Galaxies

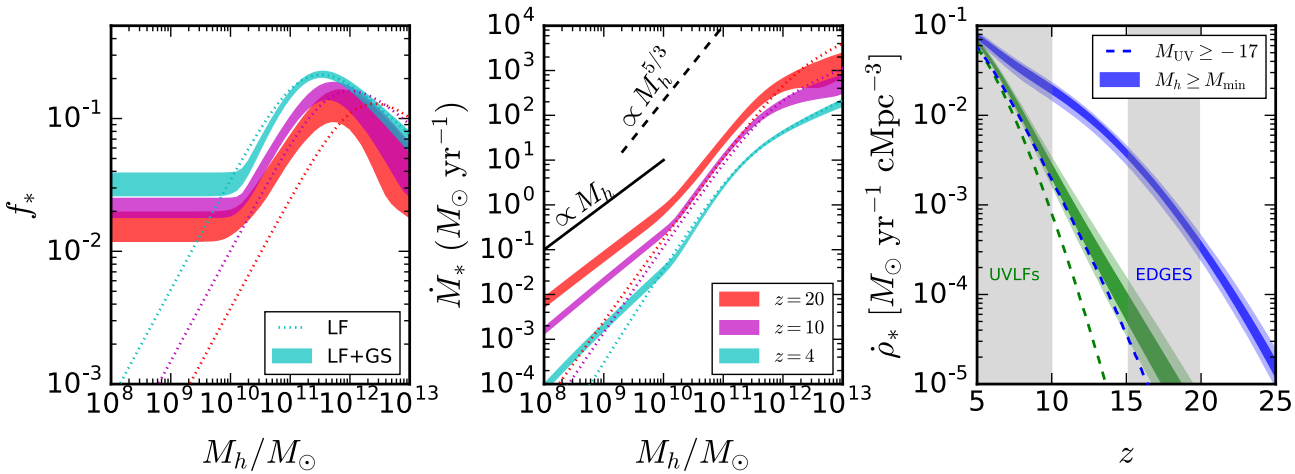




Mirocha & Furlanetto (2019)

- Timing is most important for galaxy formation
- Early signal requires EITHER
  - More efficient star formation at higher redshifts
  - More efficient star formation in (very) small halos
  - (Or both)
- Shape still difficult to reproduce…steepness requires very massive sources (Kaurov et al. 2018)

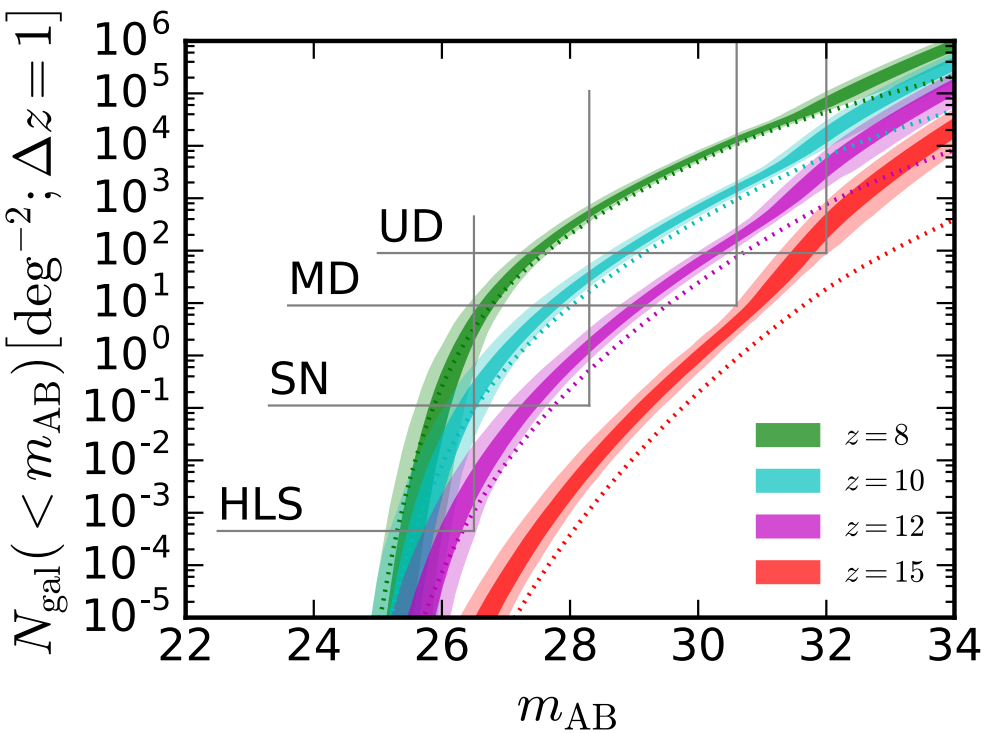
EDGES and Galaxies



Mirocha & Furlanetto (2019)

- Requires substantial differences from theoretical expectations and UV LFs
- BUT new physics may end at some intermediate time…
- Alternate classes of sources?
  - Globular clusters?
  - Pop III stars?
  - AGN?

EDGES and Galaxies

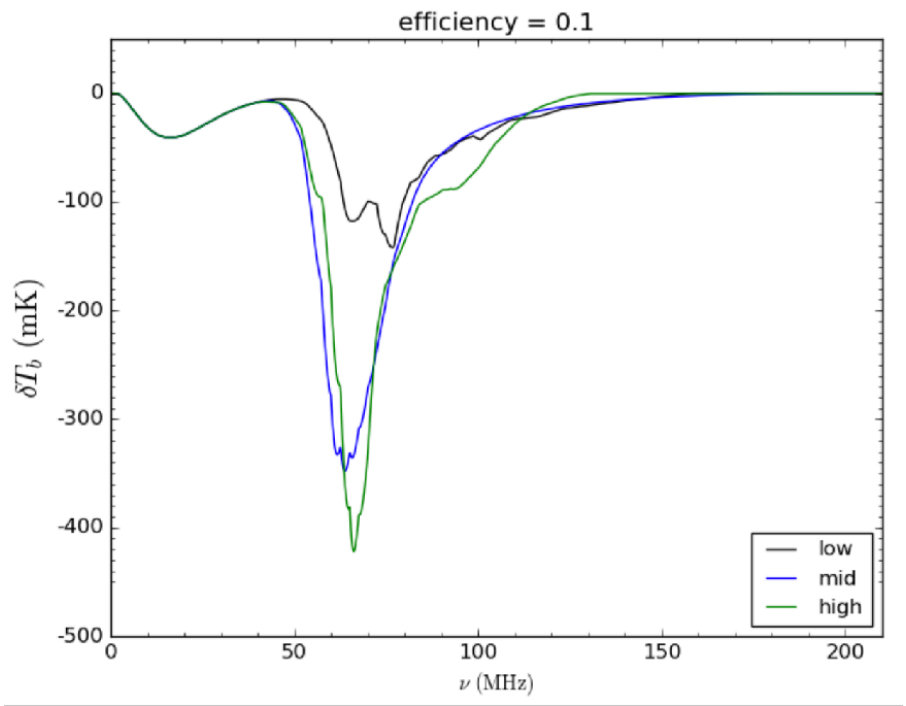


- Potentially observable with ultra deep fields

Mirocha & Furlanetto (2019)

What are these extra stars?

- Can reasonably get enough Pop III star formation to turn on the 21-cm background (see also Schauer et al. 2019)
- Requires fast heating as well - substantial, rapidly accreting black hole remnant population!
- Just one example of a potential explanation!

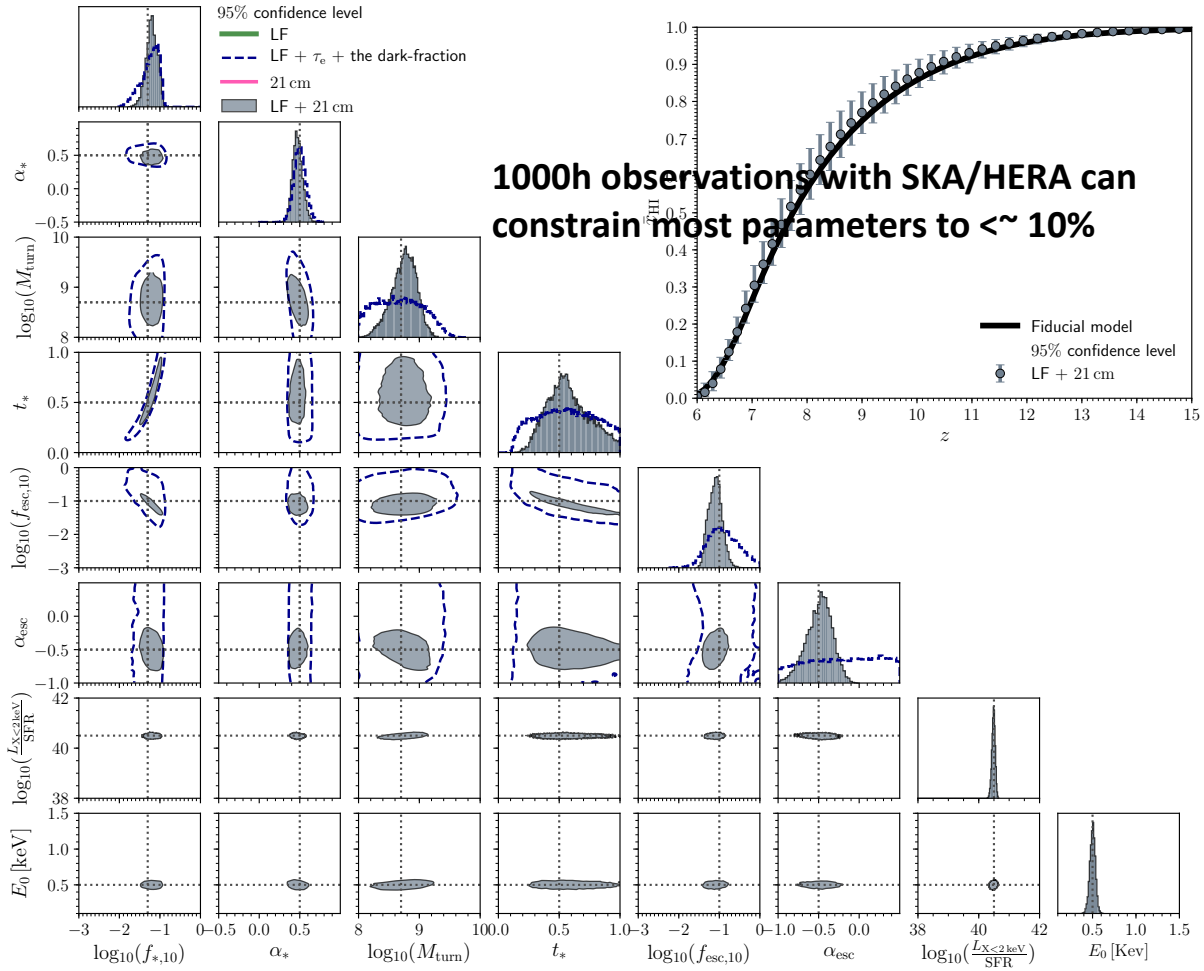


Mebane et al. (in progress)

How do we connect the two?

Improved Source Modeling

- Reionization (and other radiation backgrounds) depend on source parameters!
- Most can be constrained from 21-cm; some improve significantly with LF information
- BUT constraints highly dependent on parameterization!



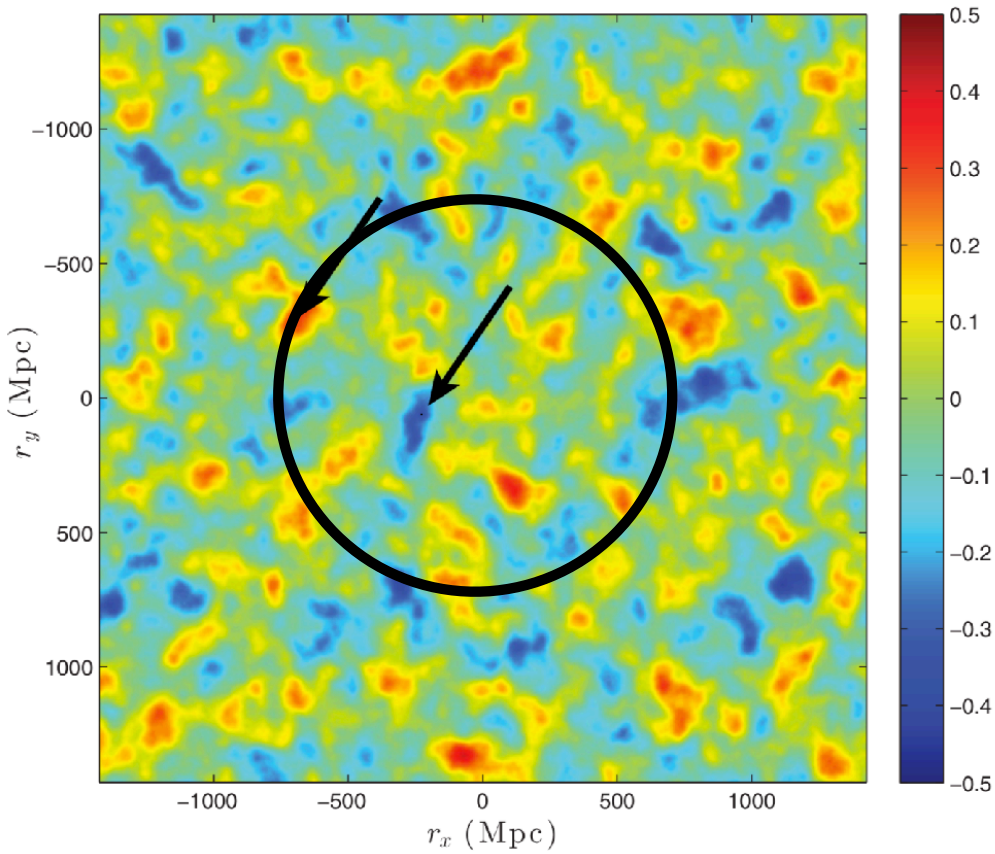
1000h observations with SKA/HERA can constrain most parameters to <~ 10%

Park et al. (2018)

How do we interpret observations of invisible galaxies?

- Statistical constraints will be highly dependent on parameterization!
  - True of 21-cm, luminosity functions, intensity mapping, etc.
- What is a sensible parameterization of (for example) Pop III star formation?
  - Needs to be connectable to physics we can model, but not locked into any one scenario
  - Ideally has some way to suggest forward progress when we realize the model is broken!
- "Orthogonal" observations will offer one approach
- Or drill down to the details, where ELTs will shine!

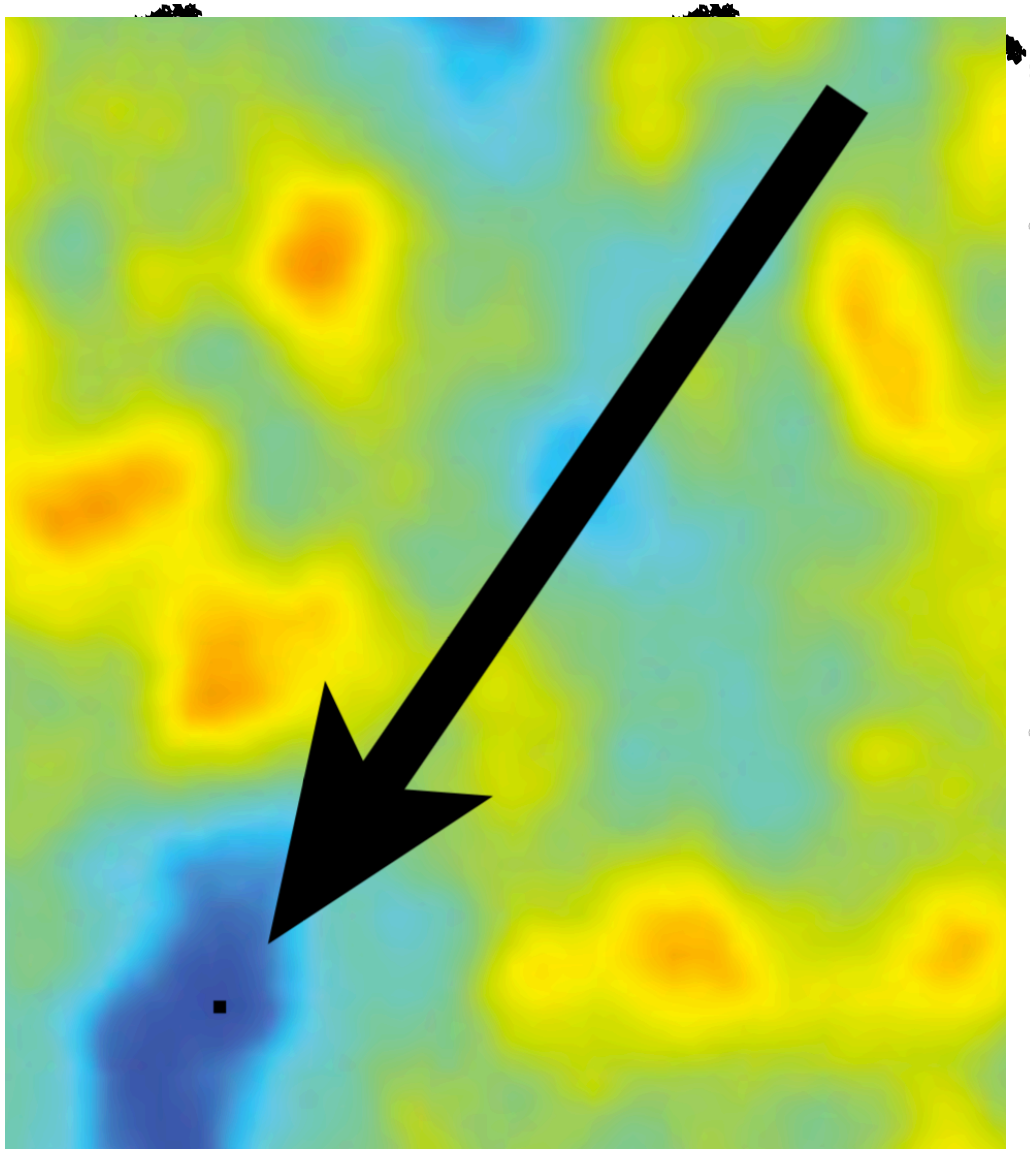
Challenges of Cross-Correlation



Beardsley et al. (2015)

- 21-cm surveys have VERY POOR angular resolution!
  - Not SO bad because features in reionization are also large
  - Current plans call for throwing out nearly all modes with angular information
- Detailed cross-correlation requires deep observations (>10^5 galaxies), excellent redshifts (<3% errors), and a large areal coverage (>30 square degrees)

Challenges of [illegible]relation



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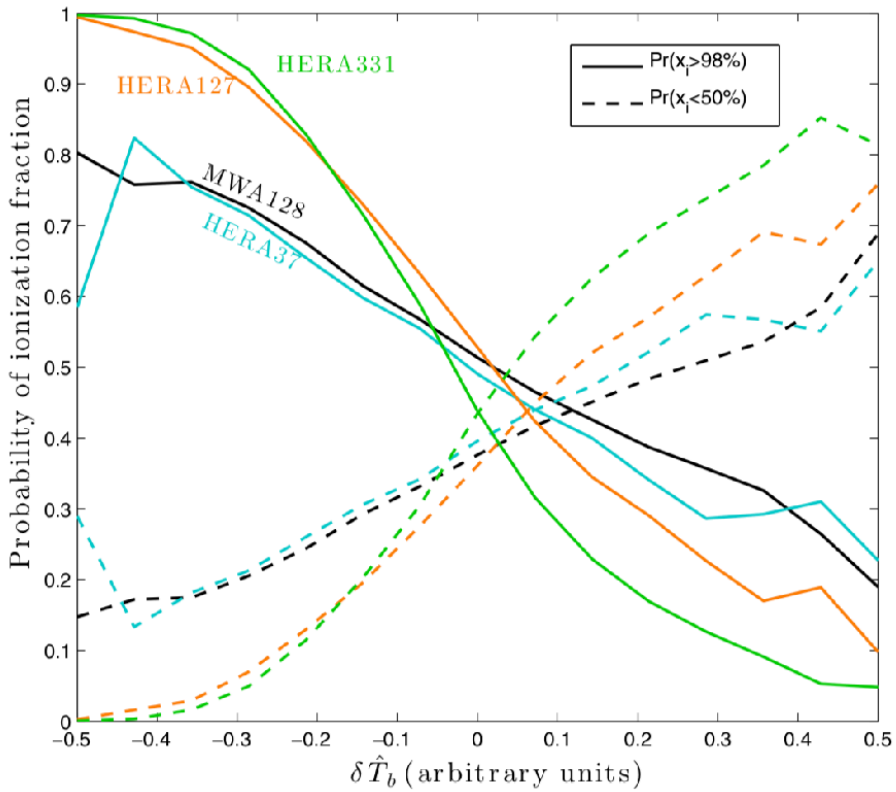
Cross-Correlation Can Provide Statistical Constraints on Galaxy Environment



Beardsley et al. (2015)

- HERA (and other near-future instruments) CAN offer statistical constraints on ionization fraction over ~arcmin scales
- Act as "source finder" for ELTs at very high redshifts?

Conclusions

- Reionization measurements require large-scale probes BUT can inform galaxy measurements
- We EXPECT the physics of galaxy formation to change… but only in very small halos!
- An understanding of early galaxies will require complementary information constraining observable galaxy populations AND integrated emission
  - Also can inform (and be informed by!) environmental studies