From the Dark Ages to Reionization with CMB-S4

Marcelo Alvarez
(LBL)

CMB-S4 Summer Collaboration Meeting
August 12, 2021

The epoch of reionization is mostly uncharted territory

what we know

Universe significantly ionized at z < 6 (**quasar spectra**)

Universe significantly neutral at z > 10 (**large-scale CMB polarization**)

Driven by ionizing radiation from stars (**high-z galaxy and AGN luminosity functions**)

Characterized by ionized bubbles a few to hundreds of comoving Mpc across (**extrapolation**)

what we don't know

What was the mean ionized fraction vs redshift, i.e. the *reionization history*?

How did the sizes and morphologies of the ionized bubbles change with time?

What were the sources of reionization, and how do they differ from galaxies observed later?

How did the first supermassive black holes, with masses as large as 10^9 M_{sun}, form?

Reionization involves a broad range of astrophysical processes

astrophysical processes		model parameters
first star & black hole formation	photon sources	spectral energy distribution
evolution of multiphase ISM		ionizing photon escape fraction
early galaxy formation		luminosity and abundance
energetics of multiphase ISM	photon sinks	cloud size & abundance
radiative feedback on the IGM		clumping factor

Reionization involves a broad range of astrophysical processes

astrophysical processes

first star & black hole formation

evolution of multiphase ISM

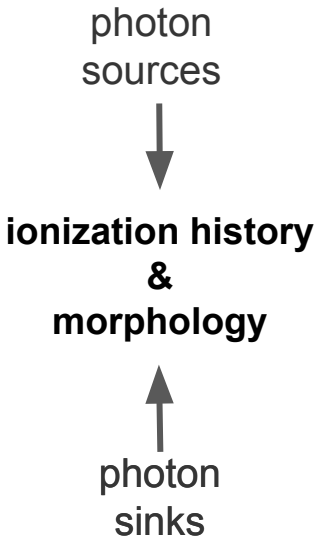
early galaxy formation

model parameters

spectral energy distribution

ionizing photon escape fraction

luminosity and abundance



energetics of multiphase ISM

radiative feedback on the IGM

cloud size & abundance

clumping factor

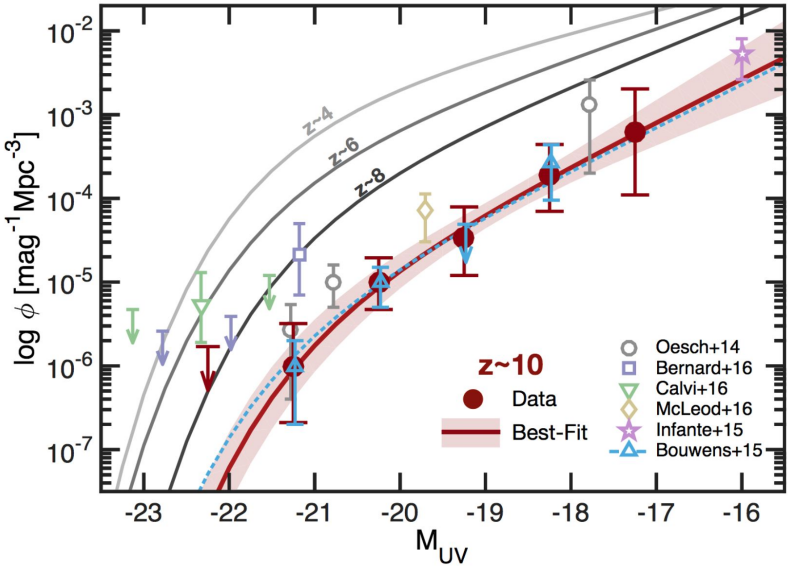
A Diverse Landscape of Observational Probes

electrons
ionization and thermal history, morphology
CMB (**SO, CMB-S4, LiteBIRD**)

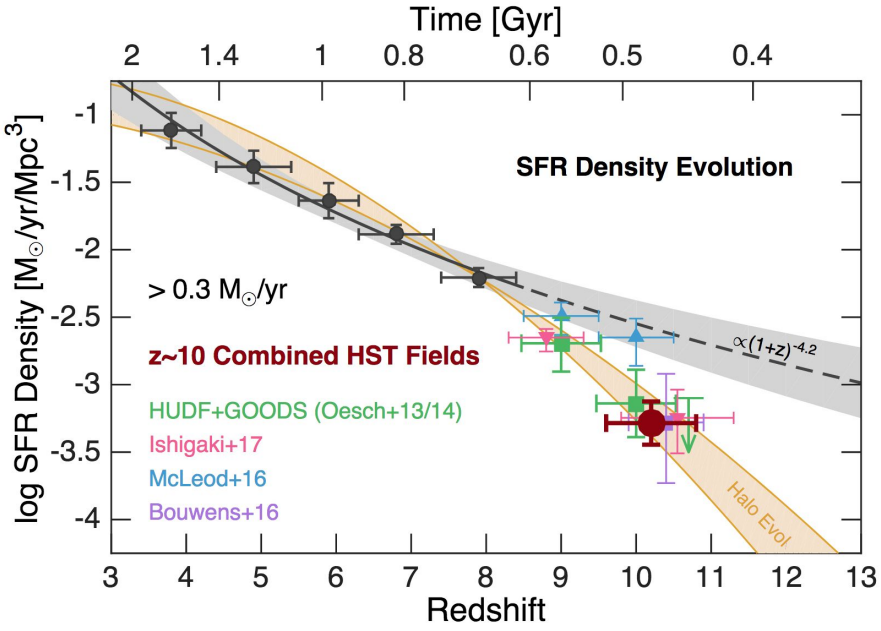
intergalactic hydrogen
ionization and thermal history, morphology
Ly-alpha forest, 21cm (**HERA, SKA**)

galaxy emission
Line intensity mapping (**COMAP, TIME, CONCERTO, FYST, SPHEREx**)
Lyman-break galaxies (**JWST**)

Galaxies from the epoch of reionization are distant and faint



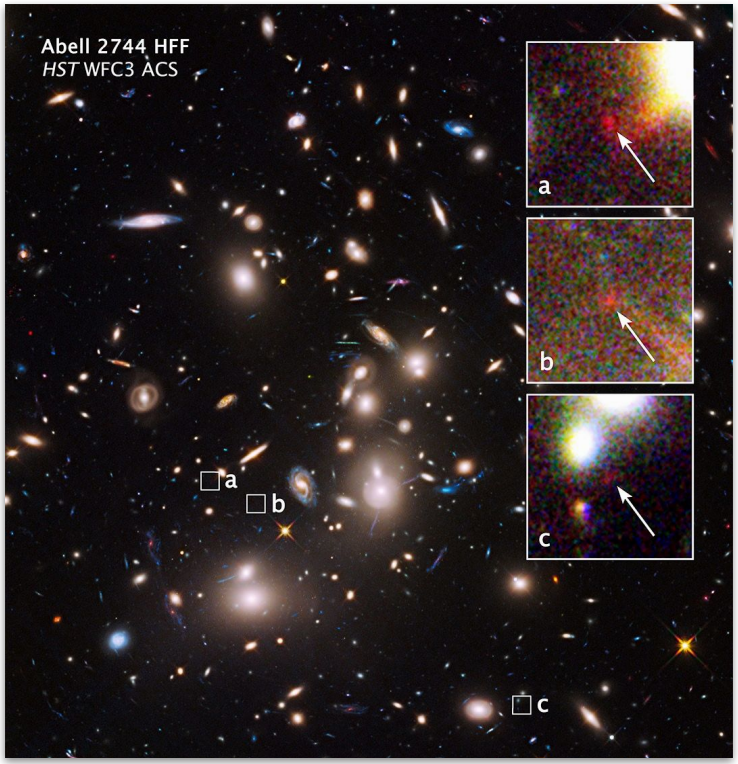
Oesch et al. (2018)



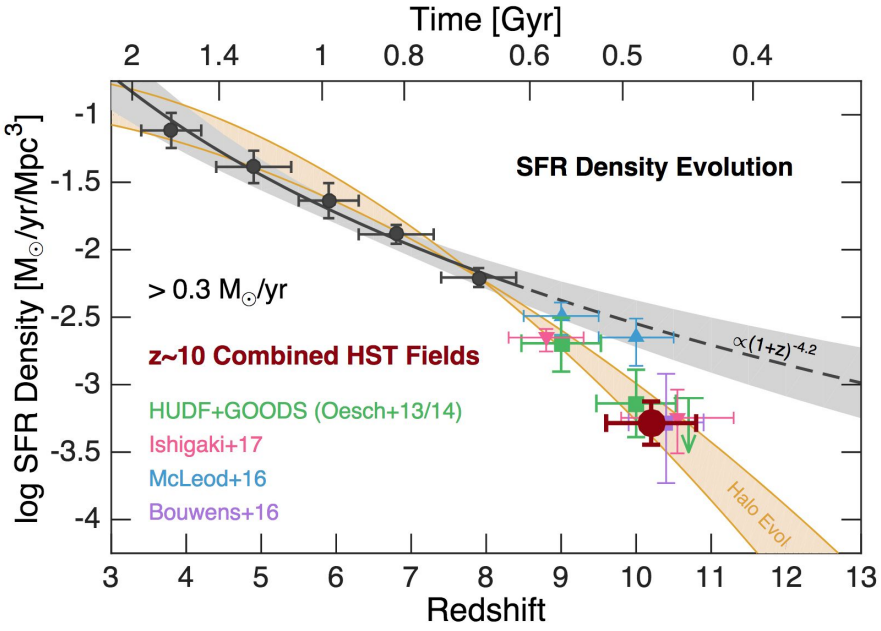
Oesch et al. (2018)

Galaxies from the epoch of reionization are distant and faint

Zitrin et al. (2014)

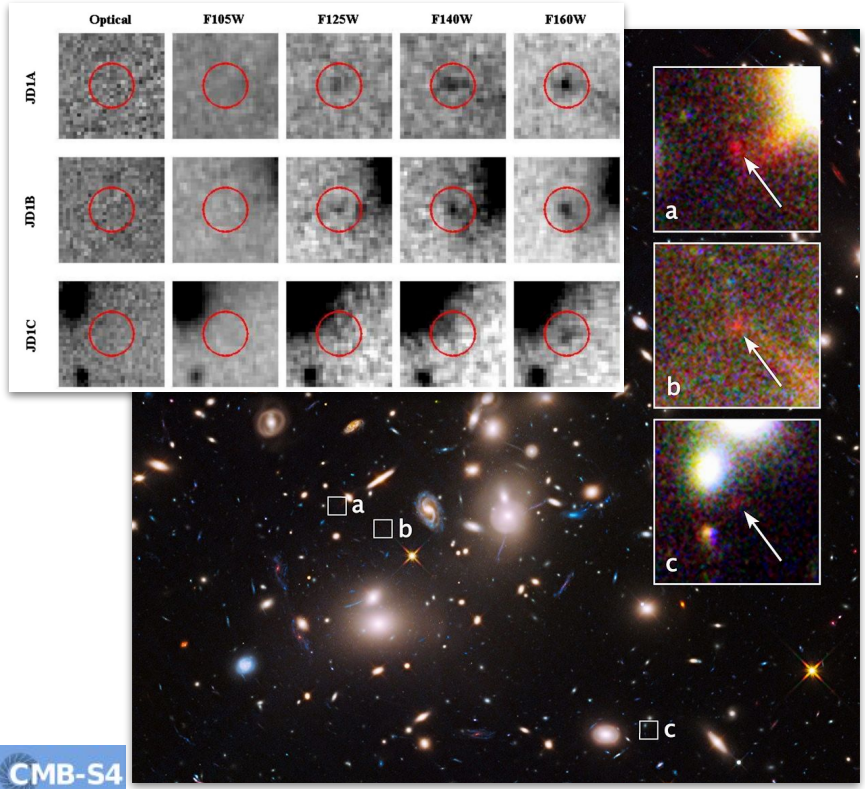


Oesch et al. (2018)

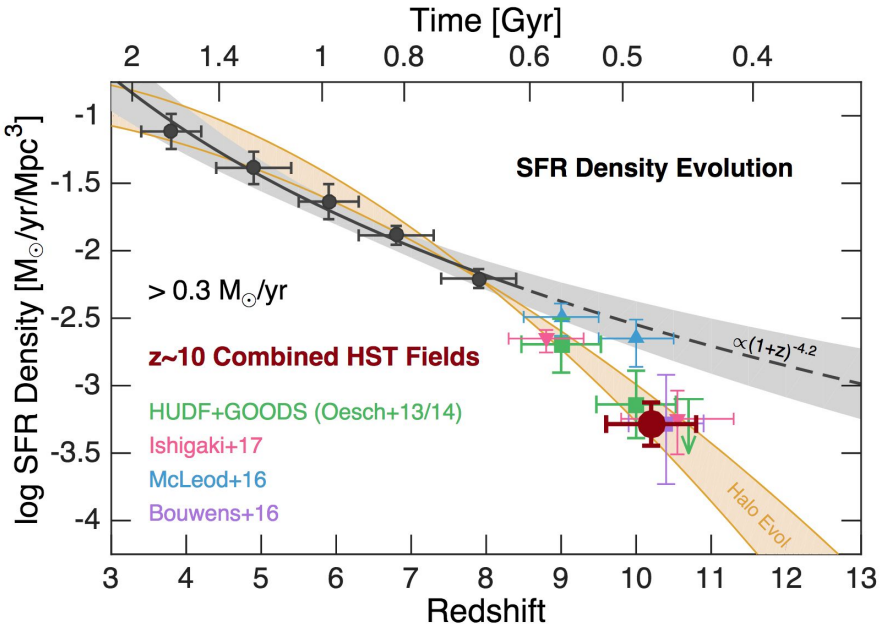


Galaxies from the epoch of reionization are distant and faint

Zitrin et al. (2014)

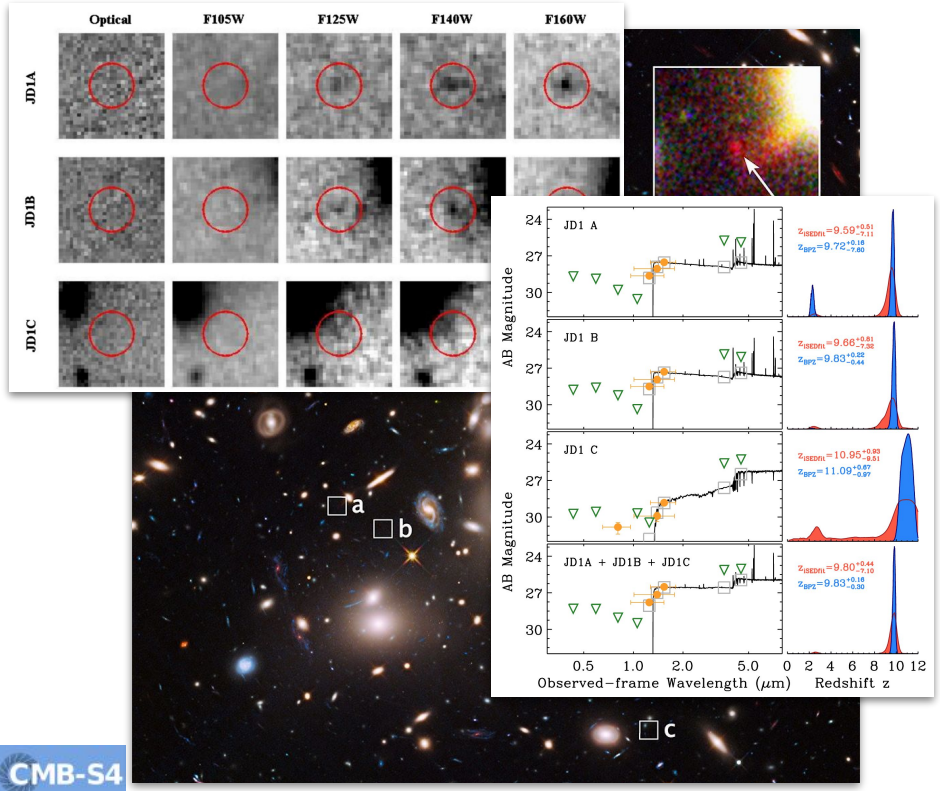


Oesch et al. (2018)

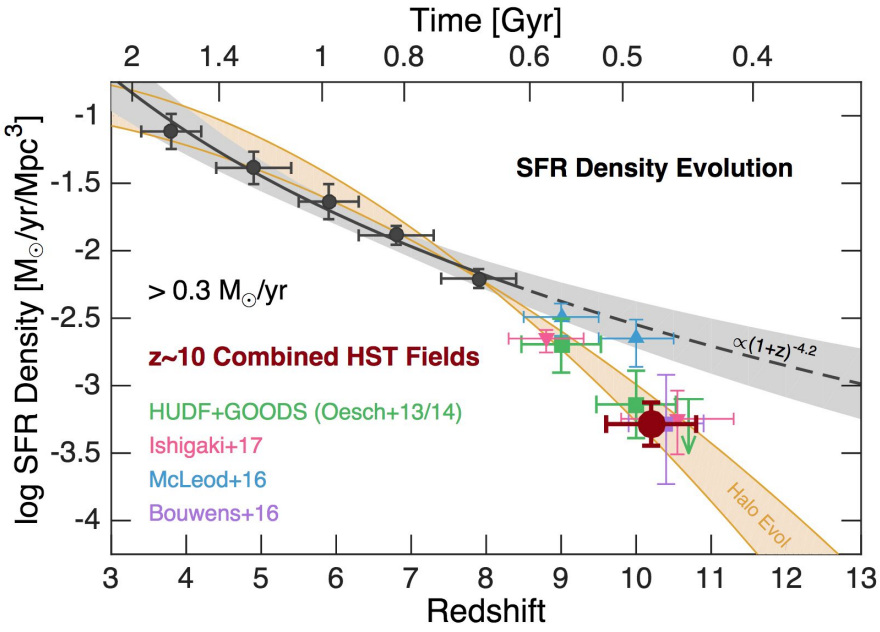


Galaxies from the epoch of reionization are distant and faint

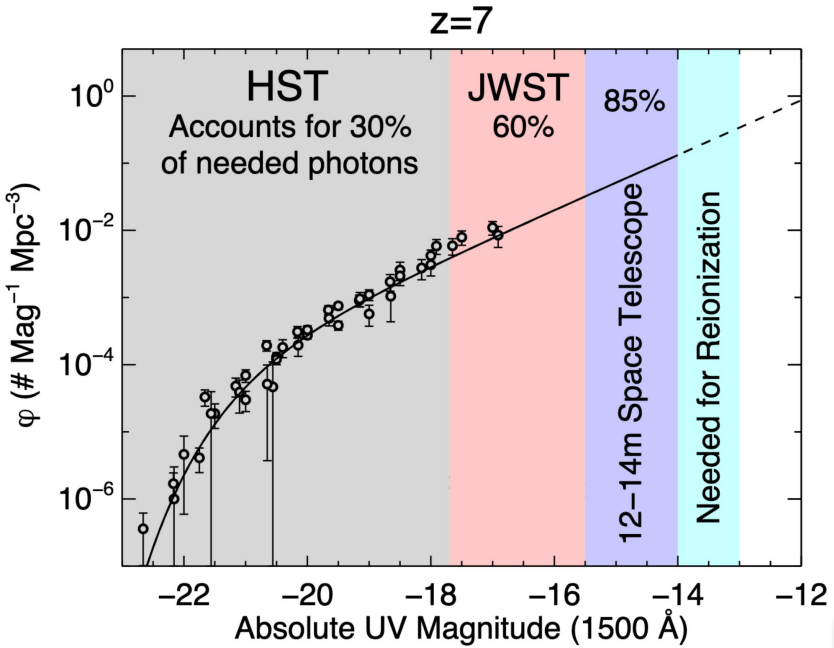
Zitrin et al. (2014)



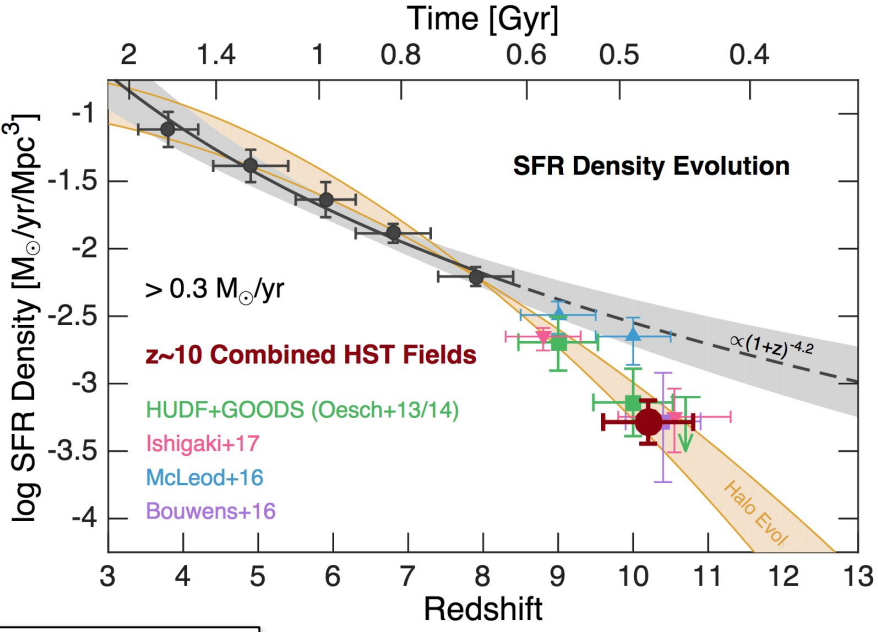
Oesch et al. (2018)



Galaxies from the epoch of reionization are distant and faint



Oesch et al. (2018)



see talk by
Jordan Mirocha

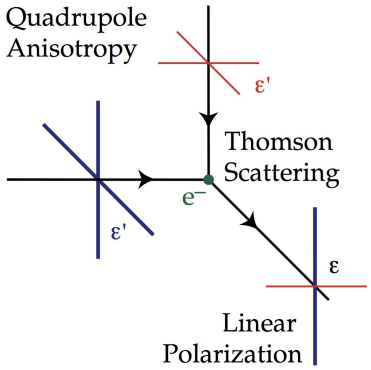
A Diverse Landscape of Observational Probes

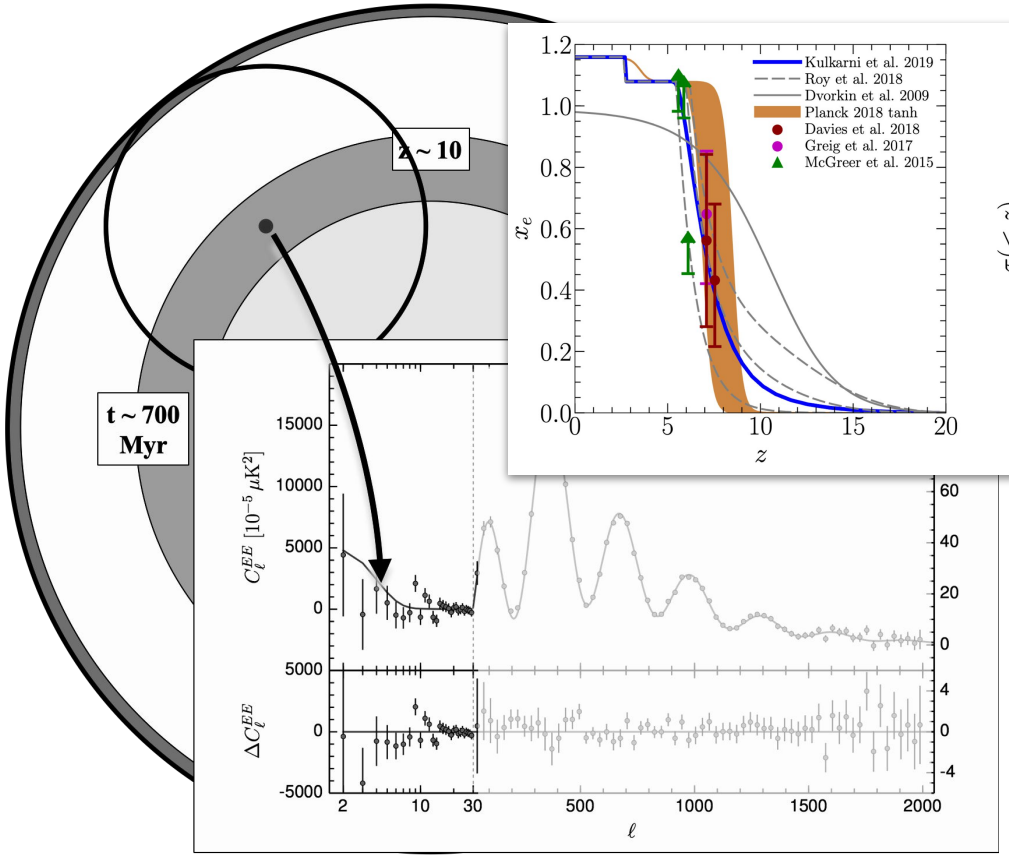
electrons
ionization and thermal history, morphology
CMB (**SO, CMB-S4, LiteBIRD**)

intergalactic hydrogen
ionization and thermal history, morphology
Ly-alpha forest, 21cm (**HERA, SKA**)

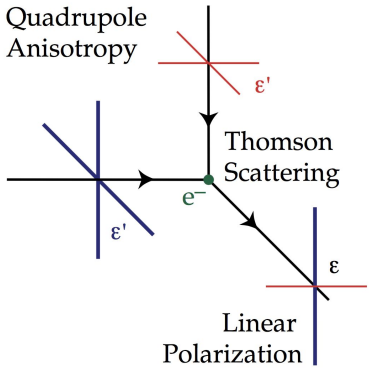
galaxy emission
Line intensity mapping (**COMAP, TIME, CONCERTO, FYST, SPHEREx**)
Lyman-break galaxies (**JWST**)

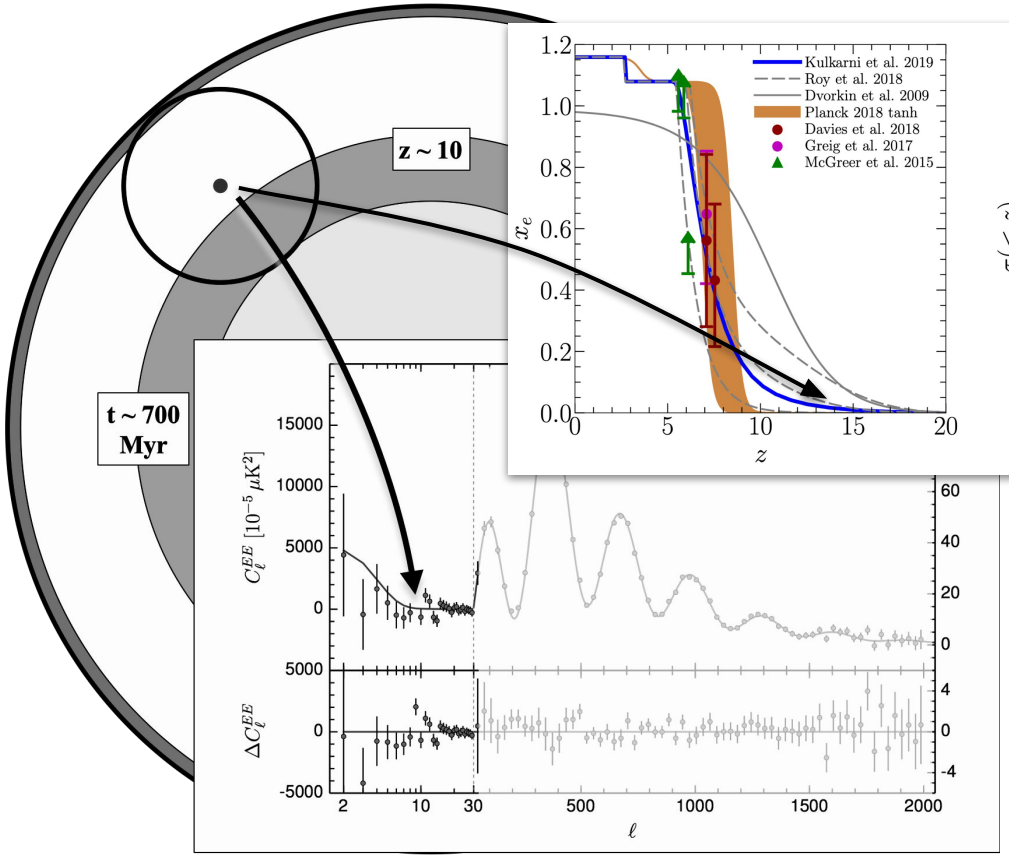
Large scale CMB polarization constrains optical depth





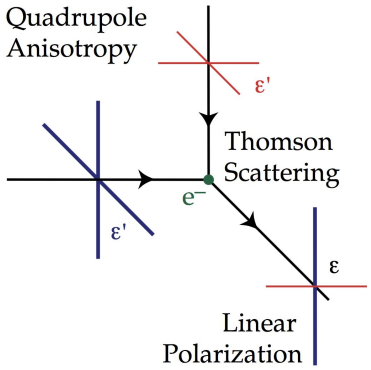
Large scale CMB polarization constrains optical depth and possibly more...

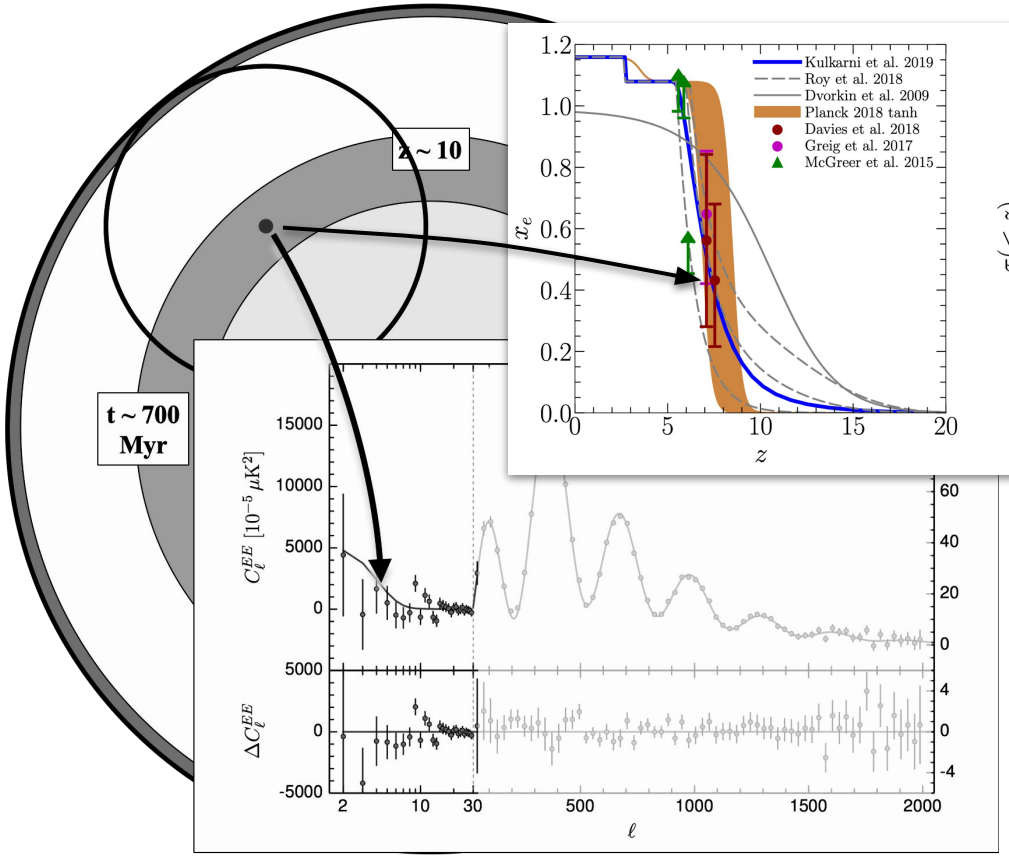




see talk by **Xiaohan Wu**

Large scale CMB polarization constrains optical depth and possibly more...



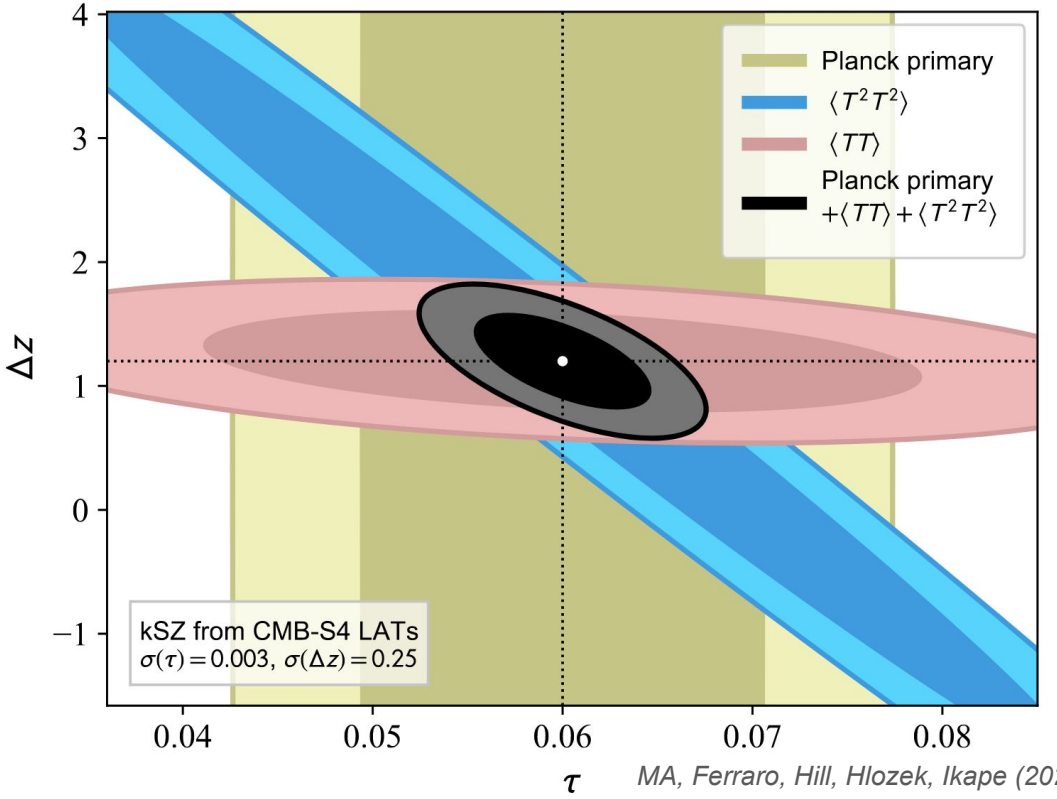


see talk by **Xiaohan Wu**

CMB probes patchiness of reionization through electron scattering

SOURCE		OBSERVABLE
CMB monopole patchy electrons + peculiar velocity	kinetic SZ ⟷	temperature $\ell \gtrsim 500$
CMB temperature quadrupole patchy electrons	"scattering" ⟷	polarization $\ell \gtrsim 50$
CMB primary anisotropies patchy tau	"screening" ⟷	temperature + polarization $\ell \gtrsim 50$

CMB probes patchiness of reionization through electron scattering



MA, Ferraro, Hill, Hlozek, Ikape (2020)

CMB-S4 has the statistical power to constrain the optical depth to ~5% accuracy

assuming we can model patchiness well enough and that non-patchy contribution is negligible.

CMB probes patchiness of reionization through electron scattering

see talks by
Suvodip Mukherjee
Paul La Plante
Toshiya Namikawa

SOURCE		OBSERVABLE
CMB monopole patchy electrons + peculiar velocity	kinetic SZ ⟷	temperature $\ell \gtrsim 500$
CMB temperature quadrupole patchy electrons	"scattering" ⟷	polarization $\ell \gtrsim 50$
CMB primary anisotropies patchy tau	"screening" ⟷	temperature + polarization $\ell \gtrsim 50$

A Diverse Landscape of Observational Probes

electrons
ionization and thermal history, morphology
CMB (**SO, CMB-S4, LiteBIRD**)

intergalactic hydrogen
ionization and thermal history, morphology
Ly-alpha forest, 21cm (**HERA, SKA**)

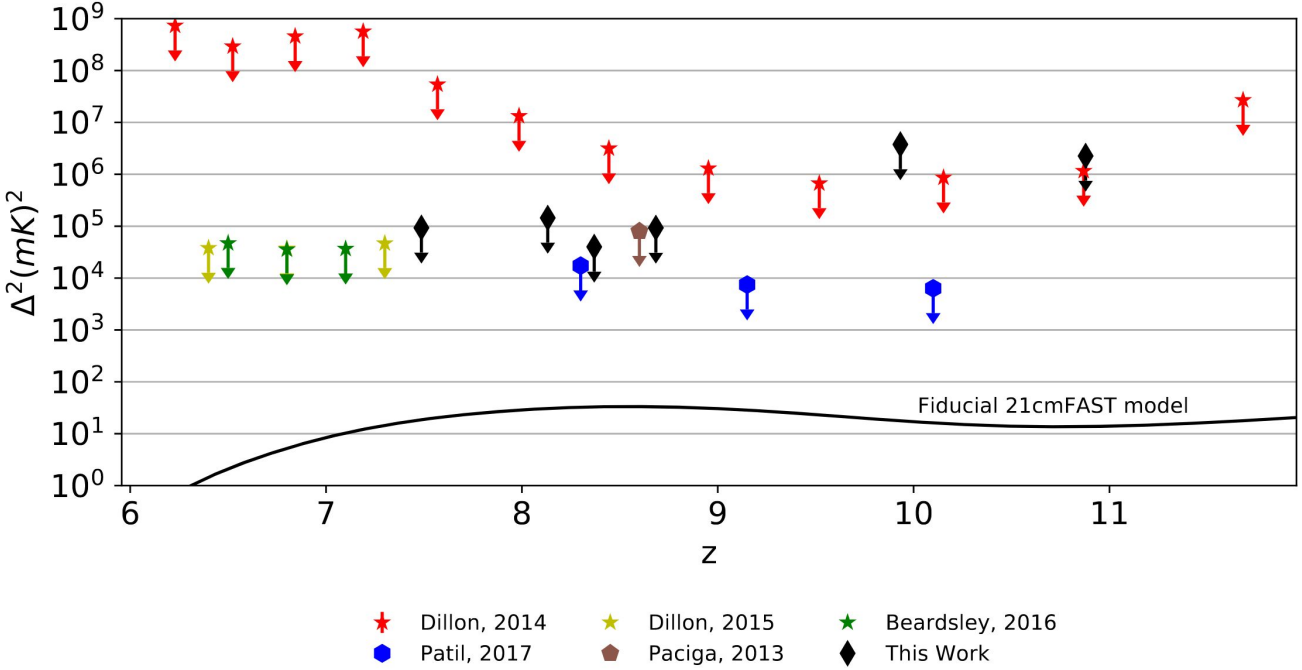
galaxy emission
Line intensity mapping (**COMAP, TIME, CONCERTO, FYST, SPHEREx**)
Lyman-break galaxies (**JWST**)

The 21cm transition probes neutral hydrogen during reionization

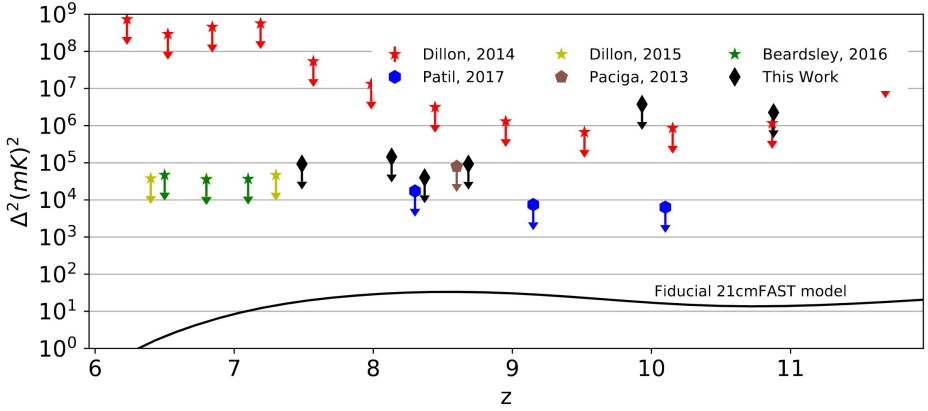
Kolopanis et al. (2019)

Radio interferometers such as HERA and SKA search for the 21cm signal from reionization at ~100 - 200 MHz

These observations promise to measure the power spectrum and map out the ionized bubbles in 3D, but are extremely challenging, with only upper limits so far



The 21cm transition probes neutral hydrogen during reionization

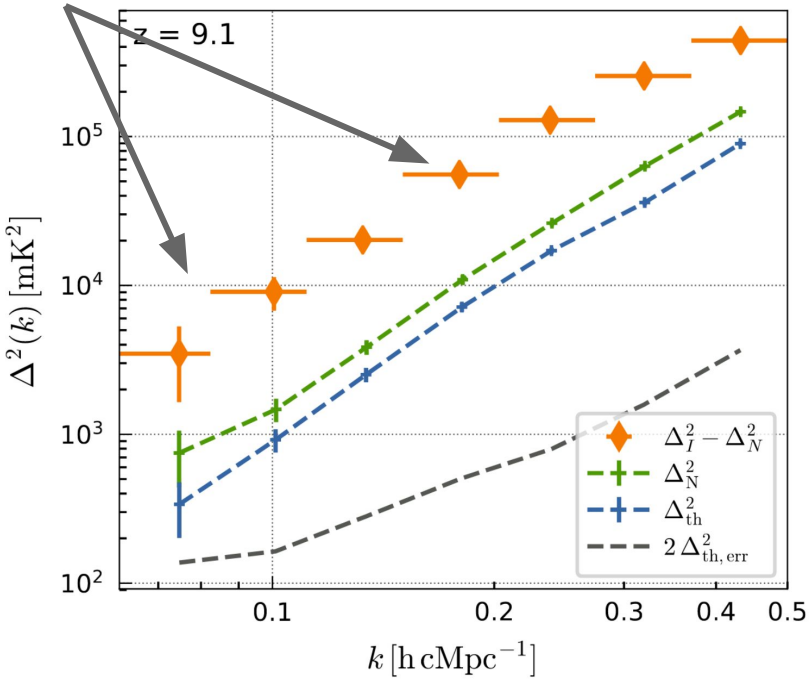


Kolopanis et al. (2019)

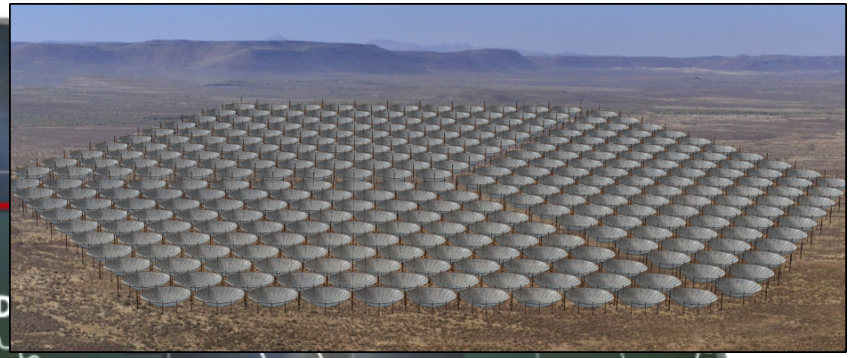
See talk by **Josh Dillon**

Most recent LOFAR Upper Limits

Mertens et al. (2020)



The CMB-S4 large area survey overlaps with 21cm surveys: is there a detectable cross-correlation?



See talk by
Paul La Plante

A Diverse Landscape of Observational Probes

electrons
ionization and thermal history, morphology
CMB (**SO, CMB-S4, LiteBIRD**)

intergalactic hydrogen
ionization and thermal history, morphology
Ly-alpha forest, 21cm (**HERA, SKA**)

galaxy emission
Line intensity mapping (**COMAP, TIME, CONCERTO, FYST, SPHEREx**)
Lyman-break galaxies (**JWST**)

see talk by
Patrick Breysse

Talks in Dark Ages to Reionization Parallel Session

11:20–11:40 **Jordan Mirocha**: *Overview of high-z sources*

11:40–11:55 **Suvodip Mukherjee**: *Physical modeling of patchy reionization*

11:55–12:10 **Xiaohan Wu**: *The high-redshift tail of reionization & low-ell CMB*

12:10–12:25 **Patrick Breysse**: *Status of reionization-era line intensity mapping*

~20 minute break

13:45–13:00 **Paul La Plante**: *Cross-correlating patchy kSZ with other probes*

13:00–13:15 **Toshiya Namikawa**: *Optical depth - Compton-y cross-correlation*

13:15–13:30 **Josh Dillon**: *First upper limits from HERA on 21cm power spectrum*

13:30–14:00 **Discussion**

Talks in Dark Ages to Reionization Parallel Session

11:20–11:40 **Jordan Mirocha**: *Overview of high-z sources*

11:40–11:55 **Suvodip Mukherjee**: *Physical modeling of patchy reionization*

11:55–12:10 **Xiaohan Wu**: *The high-redshift tail of reionization & low-ell CMB*

12:10–12:25 **Patrick Breysse**: *Status of reionization-era line intensity mapping*

~20 minute break

12:45–13:00 **Paul La Plante**: *Cross-correlating patchy kSZ with other probes*

13:00–13:15 **Toshiya Namikawa**: *Optical depth - Compton-y cross-correlation*

13:15–13:30 **Josh Dillon**: *First upper limits from HERA on 21cm power spectrum*

13:30–14:00 **Discussion**

summary talk by
Zhilei Xu