From the Dark Ages to Reionization with CMB-S4
Summary Talk

Zhilei Xu
(MIT)

CMB-S4 Summer Collaboration Meeting
August 13, 2021

Reionization Overview:
Latest predictions, constraints, & prospects

Jordan Mirocha (McGill)

image credit: Norman, Xu, O'Shea, & Wise

Modeling the Epoch of Reionization

We often think of reionization in the following, highly-idealized, one-zone model:

$$\dot{Q}_{\mathrm{H\ II}} \propto \underbrace{\dot{\rho}_* N_{\mathrm{ion}} f_{\mathrm{esc}}}_{\mathrm{sources}} - \underbrace{\alpha_{\mathrm{H\ II}} n_e}_{\mathrm{sinks}}$$

Each quantity here is potentially very complicated to model and/or infer:

$\dot{\rho}_*$ **star formation rate density:** encodes stellar feedback physics, though averaged over galaxy population

N_{ion} **# of ionizing photons produced per stellar baryon:** encodes stellar atmospheres, IMF, metallicity, binarity

f_{esc} **escape fraction:** encodes topology of interstellar medium, possibly circumgalactic medium

JM Slide

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JM Slide

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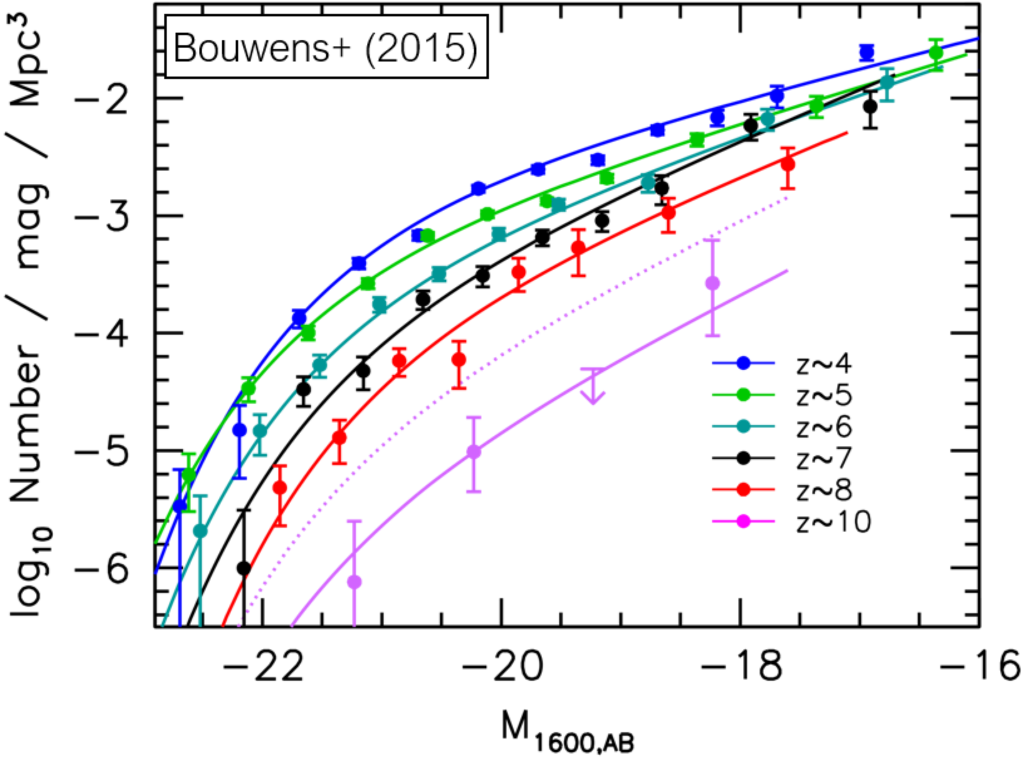

Each quantity here is potentially very

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JM Slide

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Results are model dependent!

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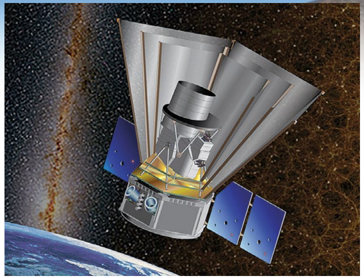
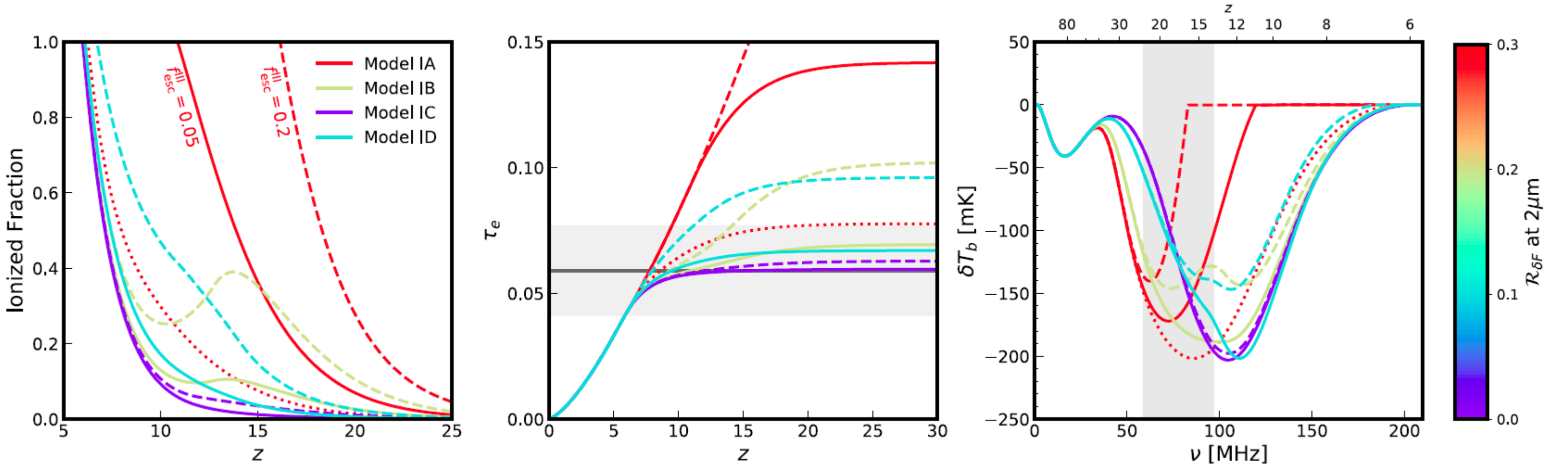
PopIII stars?



SPHEREx

Multi-Probe Prospects

Efficient PopIII star formation drives early reionization, global 21-cm signal, and comprises ~30% of high-z NIRB.



Sun, **J.M.**, et al. (2107.09324)

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Constraining Pop-III reionization at z>15 using the low-ell CMB

(not promising)

Xiaohan Wu (Harvard CfA)

Reionization with Pop-III

- Calculating the reionization history with the simplest Pop-III model:

Pop-III star formation in $10^5 - 10^6\ M_\odot$ halos at z=20–30 with a star formation efficiency

Free parameter:
Star formation efficiency
6 values from 0.0001 to 0.03

Lyman-Werner photons form a background and photo-dissociate H2 → increased minimum halo mass (M_{min}) for Pop-III star formation (e.g. Machacek+01)

Free parameter:
Strength of LW feedback
e.g. fiducial and strong LW

How many ionizing photons emitted by Pop-III stars (+ state-of-the-art Pop-II model)

Reionization history

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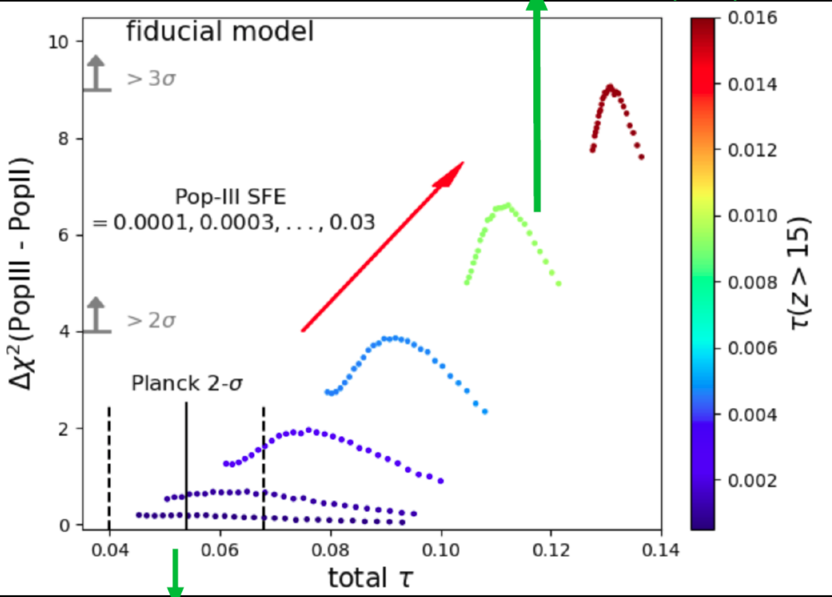
Summary of results

- The requirement to satisfy low total tau and endpoint of reionization already *ruled out most of the Pop-III parameter space* (high z structure formation + LW feedback -> hard to get very extended reionization)
- Future CMB surveys is unlikely to help constrain Pop-III models

Pop-III models get distinguishable from Pop-II-only when tau(z>15) > 0.008

$\Delta\chi^2$ of the EE power in the cosmic variance limit



The low total tau does not allow high tau(z>15)

XW Slide

UNIVERSITY OF AMSTERDAM

PERIMETER INSTITUTE

SUVODIP MUKHERJEE

PHYSICAL MODELLING OF PATCHY REIONIZATION

CMB-S4 summer meeting , August 12th 2021

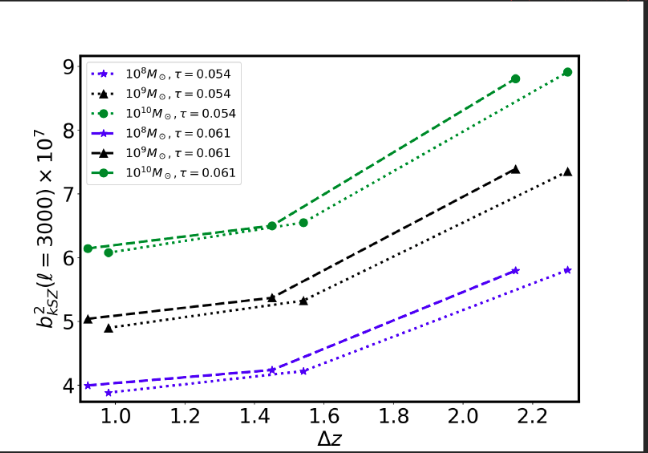
A NEW SCALING RELATION FOR CORRECT INTERPRETATION OF THE KSZ POWER SPECTRUM

Commonly-used relation

$$D^{\rm kSZ}_{l=3000} \approx 2.02\mu{\rm K}^2 \left[\left(\frac{1+\bar{z}}{11}\right) - 0.12\right]\left(\frac{\Delta z}{1.05}\right)^{0.47}$$

New relation

$$D^{\rm kSZ}_{l=3000} \approx 0.65\mu{\rm K}^2 \left(\frac{0.097+\tau}{0.151}\right)\left(\frac{\Delta z}{1.0}\right)^{0.54}\left(\frac{b^2_{\rm kSZ}(l=3000)}{4.0\times 10^{-7}}\right)^{0.92}$$



Paul, Mukherjee, Choudhury, MNRAS 500 (2020) 1, 232-246

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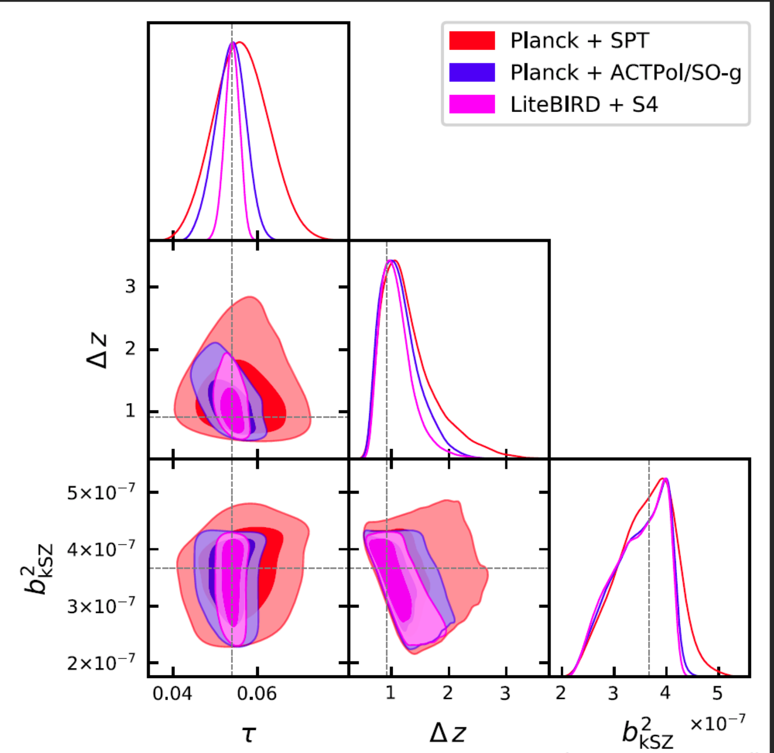
SPT+PLANCK AND FORECAST FOR THE UPCOMING CMB MISSIONS

Choudhury, Mukherjee, Paul, MNRAS-L 501 (2021) 1, L7-L11



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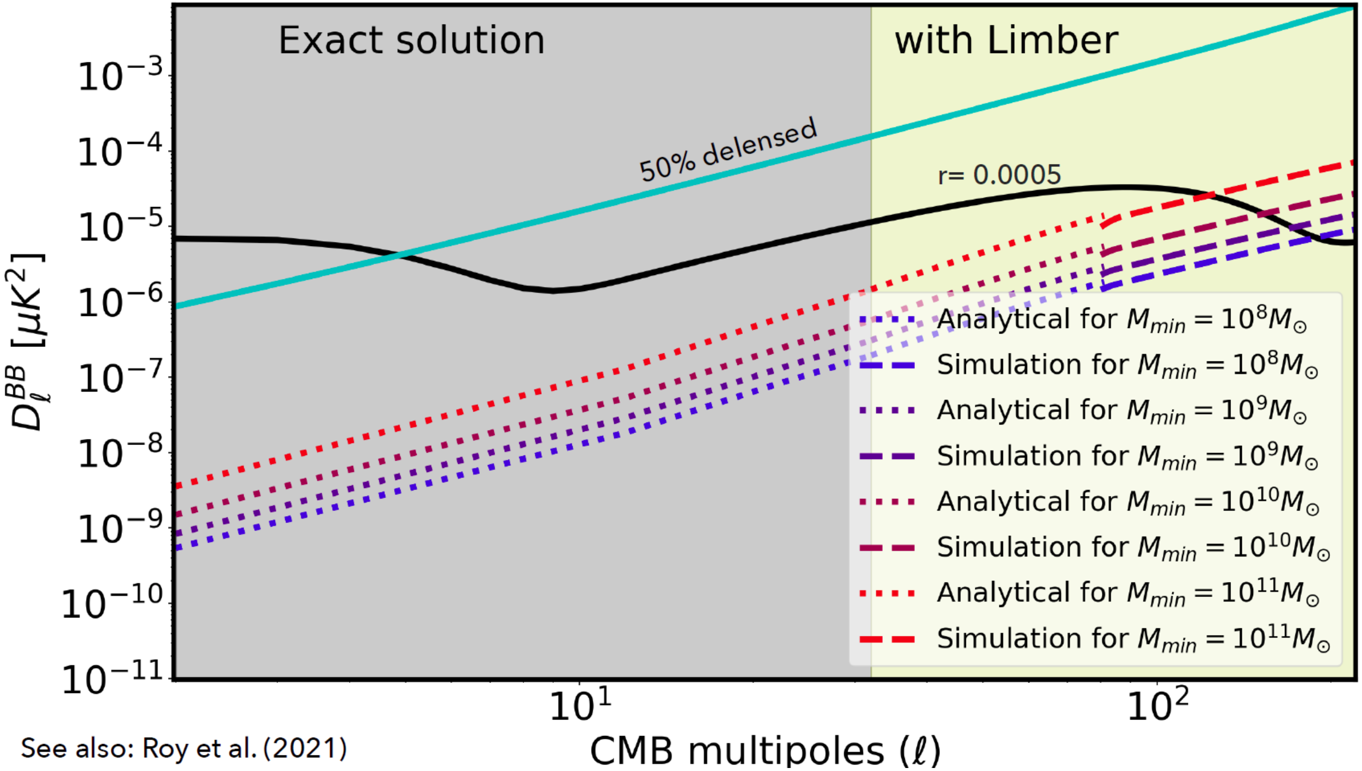
CMB B-MODE POWER SPECTRUM DUE TO PATCHY REIONIZATION

Mukherjee, Paul, Choudhury, MNRAS 486 (2019) 2, 2042-2049



See also: Roy et al. (2021)

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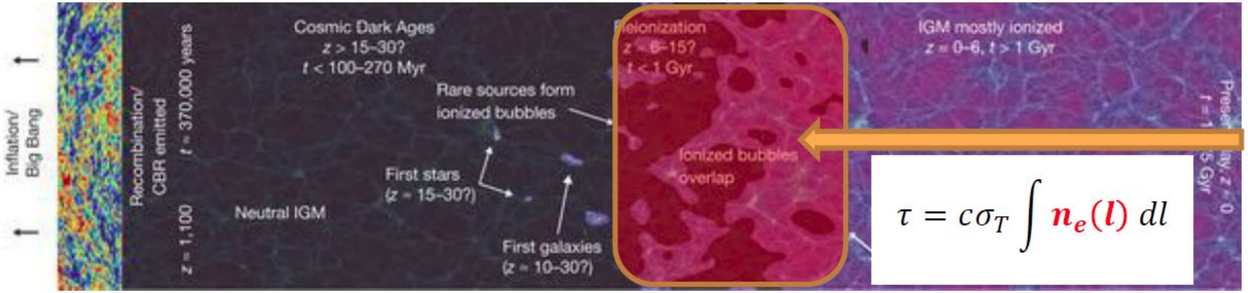
Constraining reionization with the CMB optical depth fluctuation
- Compton-y cross-correlation

Toshiya Namikawa
(Cambridge -> Kavli IPMU)

with A. Roy, B. Sherwin, N. Battaglia, D. N. Spergel

2021-08-12 @ CMB-S4 collaboration meeting

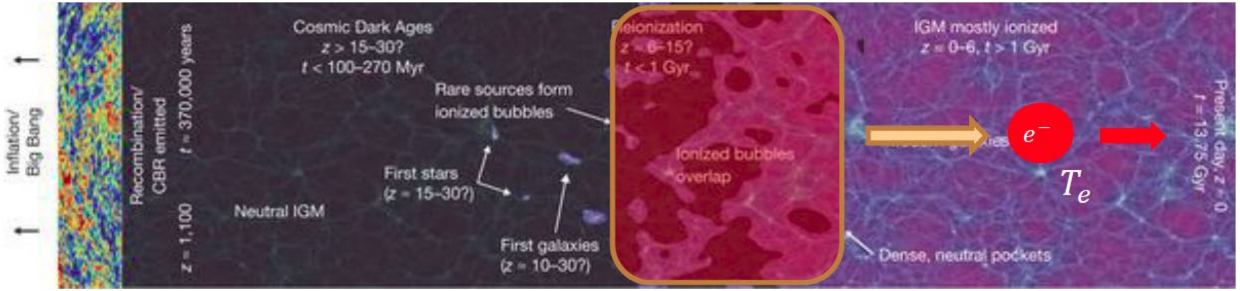
Direction-dependent CMB optical depth



(Robertson et al. 2010)

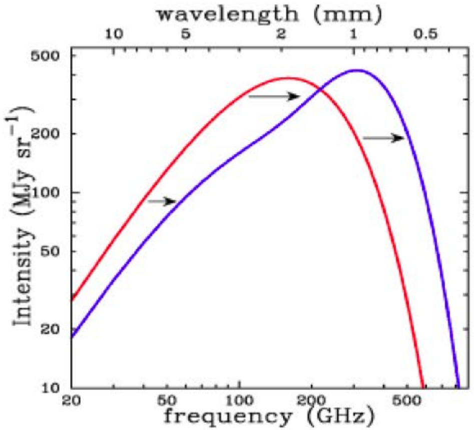
- (Isotropic) CMB optical depth, τ, is often used for cosmological parameter constraints
- However, τ could be anisotropic (originated from fluctuations of n_e)

Thermal Sunyaev Zel'dovich (SZ) effect



(Robertson et al. 2010)

- CMB photons are scattered to higher energies by hot electron gas and the black body spectrum is shifted



The temperature change is characterized by

$$\frac{\Delta T_\nu(n)}{T_{\rm CMB}} = g(\nu)y(n)$$

where the Compton y-parameter is defined as

$$y = \int \frac{k_B \boldsymbol{T_e(l)}}{m_e c^2} \boldsymbol{n_e(l)} \sigma_T c \, \mathrm{d}l$$

(integrated electron pressure)

y is generated at both late-time and reionization

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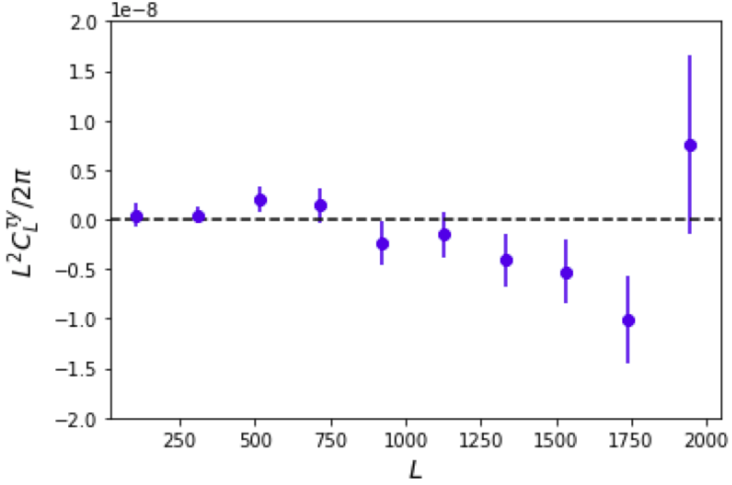
Measurement of optical-depth power spectrum $C_L^{\tau y}$

Planck 2015 data



(Namikawa et al. 2021)

Extracting $\delta\tau$ alone, the measured spectrum becomes consistent with null

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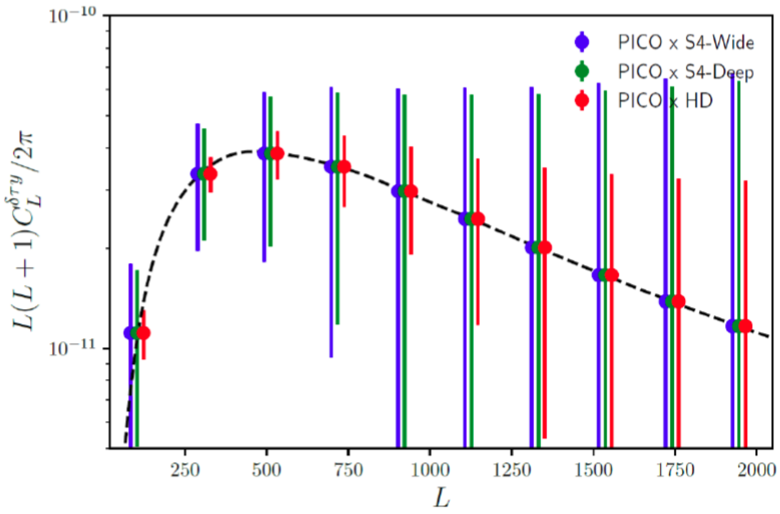
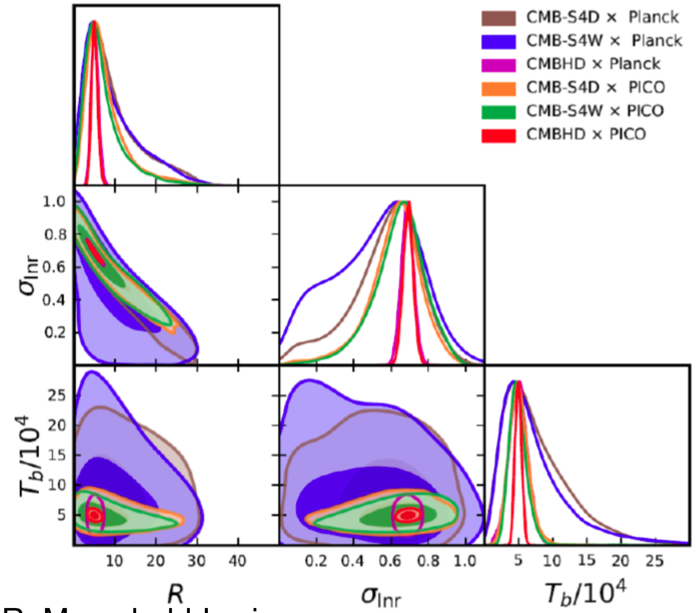
Forecast

Future CMB experiments can improve the signal-to-noise by 2-3 orders of magnitudes, and provide much better constraints on reionization parameters



CMB experiment	f_{sky}	θ [arcmin]	σ_P [μK-arcmin]	α_{del}
S4-Wide	0.4	2.0	1.4	0.2
S4-Deep	0.04	2.0	0.42	0.07
HD	0.5	0.2	0.7	0.1



R: Mean bubble size
σ_{Inr}: bubble size distribution
T_b: temperature of ionization bubbles

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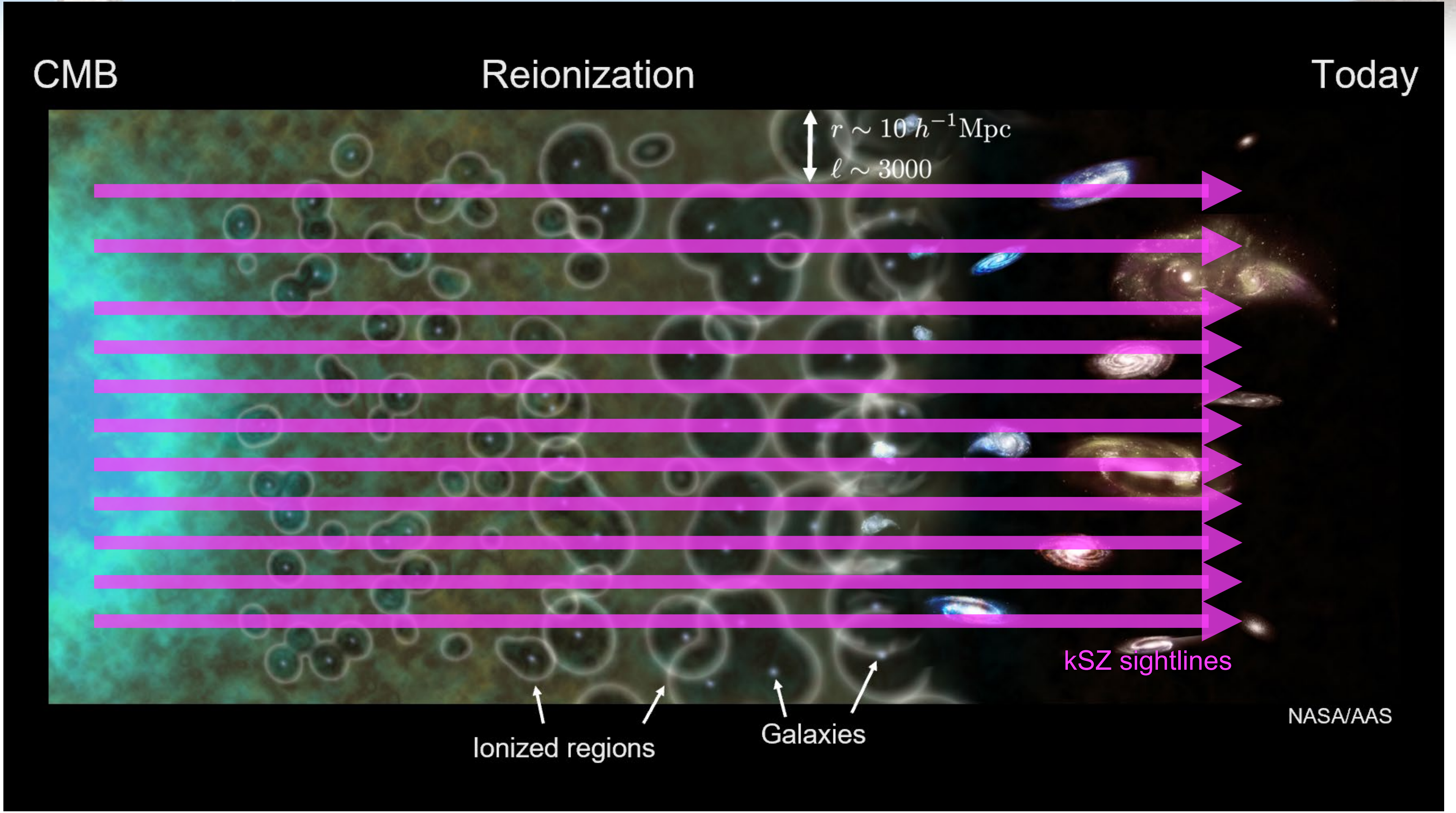
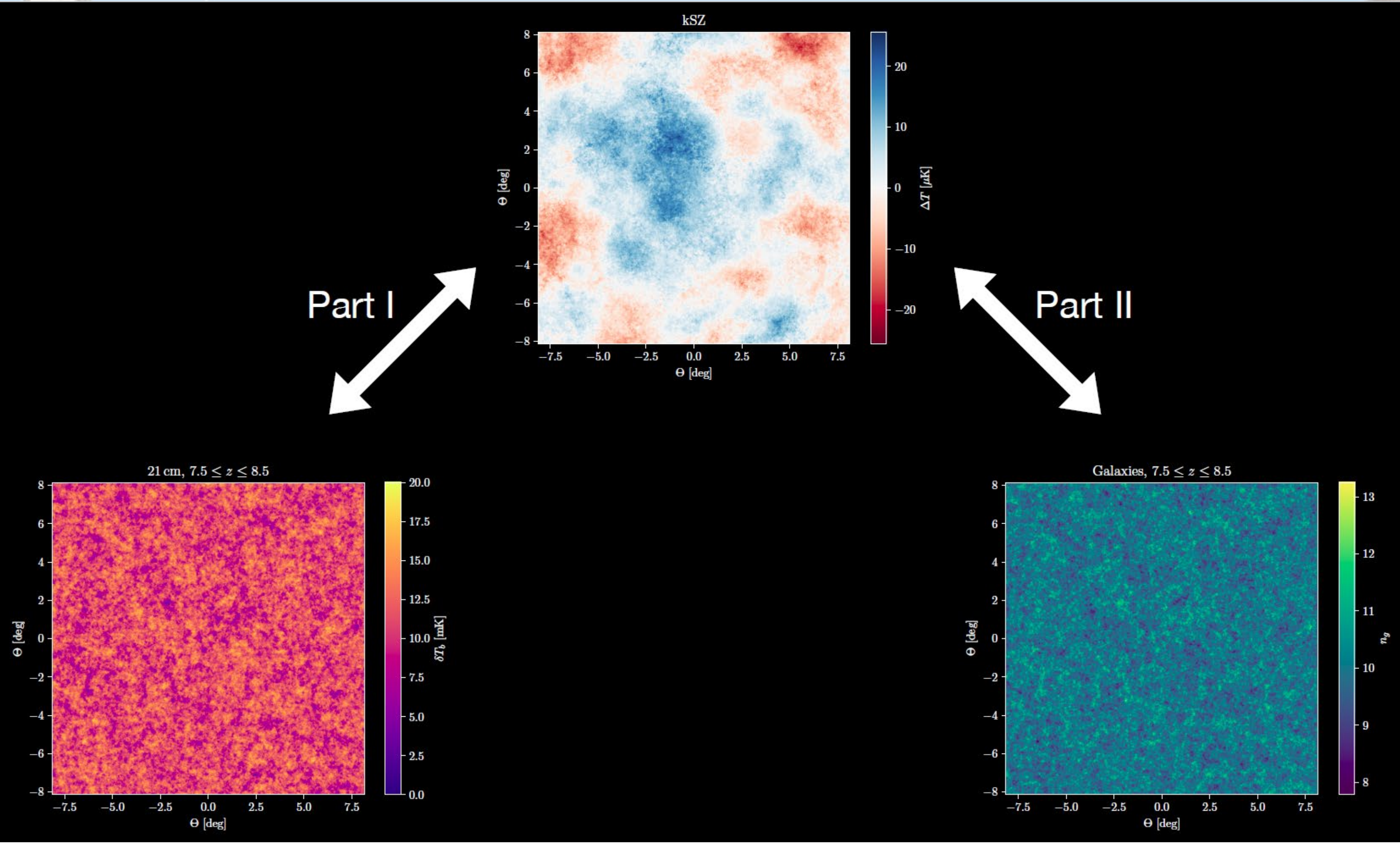
Cross-correlating Patchy kSZ with other Probes of Reionization

Paul La Plante, UC Berkeley
CMB-S4 Summer Meeting
August 12, 2021

In collaboration with: Adam Lidz (Penn), Jackson Sipple (Penn)


CMB
Reionization
Today
$r \sim 10\,h^{-1}\mathrm{Mpc}$
$\ell \sim 3000$
kSZ sightlines
NASA/AAS
Ionized regions
Galaxies

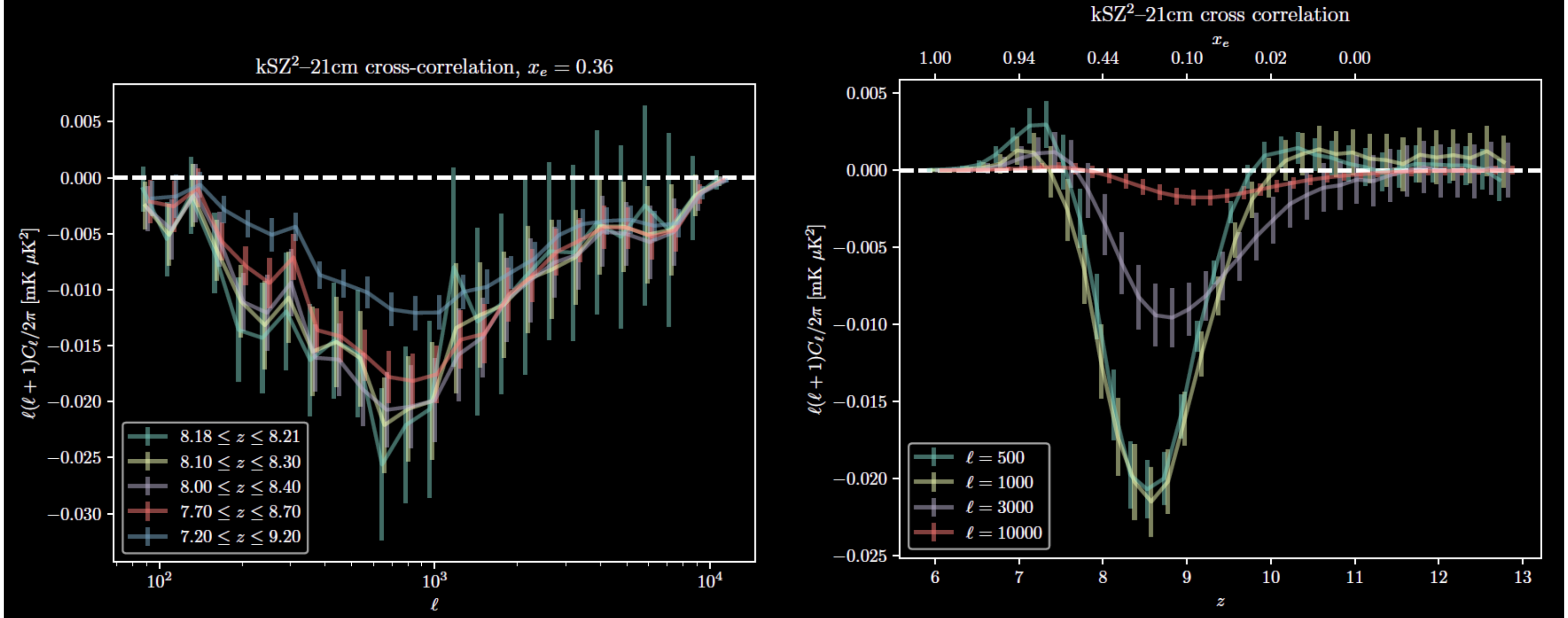


kSZ
Part I
Part II
21 cm, $7.5 \leq z \leq 8.5$
Galaxies, $7.5 \leq z \leq 8.5$
Θ [deg]
ΔT [μK]
δT_b [mK]
n_g

PLP Slide

kSZ² x 21cm
Depends on 21cm window function

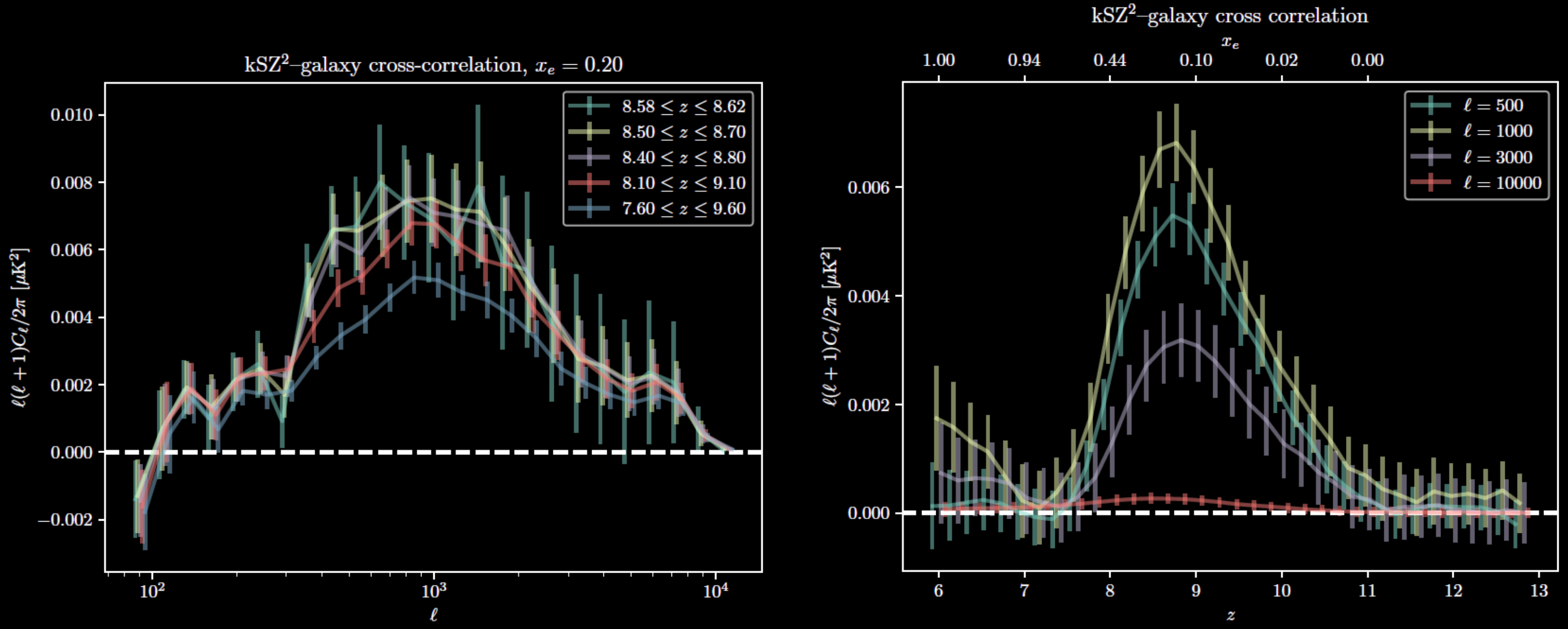
Removing the 21-cm foreground may remove the signals



PLP Slide

kSZ² x galaxies

Also depends on window function



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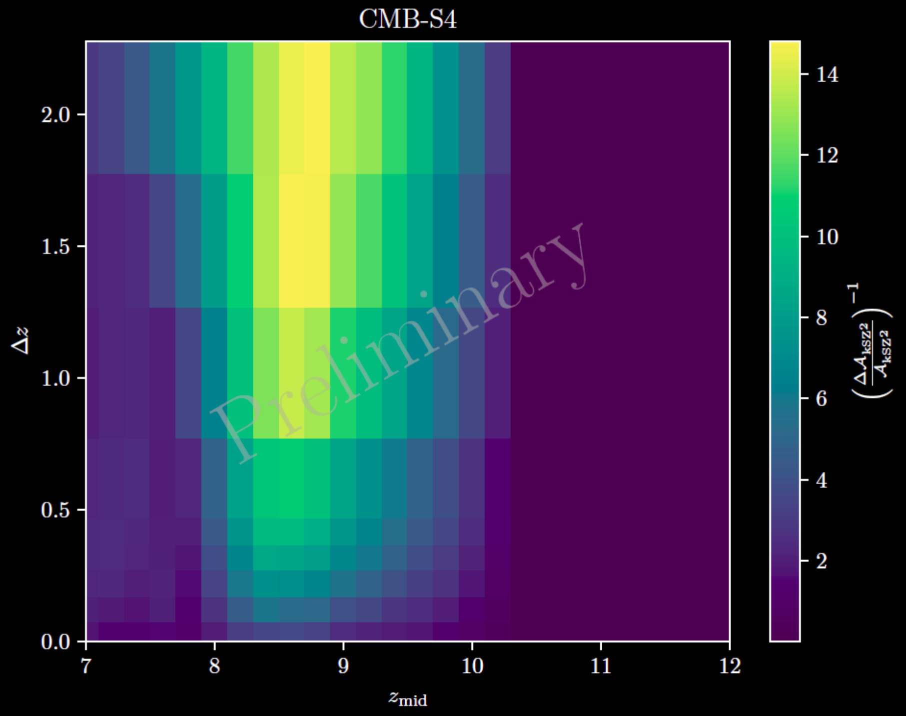
PLP Slide

Big detection with CMB-S4!

- Big boost from better noise profile
- Caveats:
  - Does not include low-z kSZ
  - Noise might increase with “real-world” component separation
  - Want to understand significance while changing reionization history

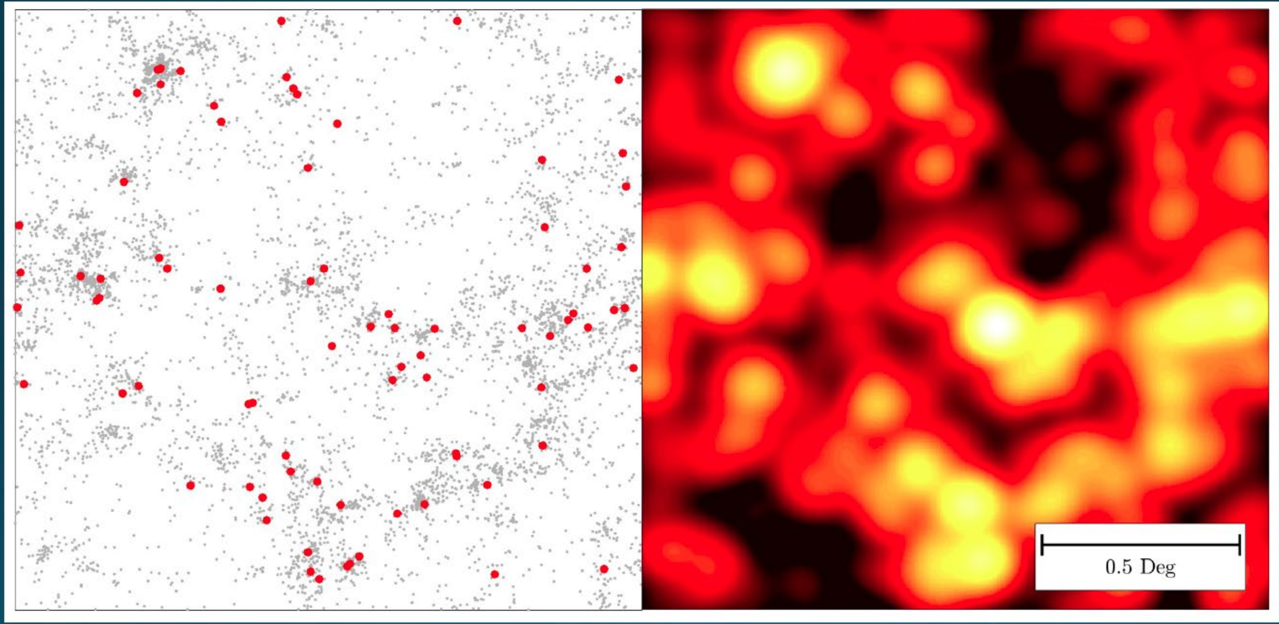


Line Intensity Mapping at Reionization

Patrick C. Breysse (NYU)

CMB-S4 2021 Summer Collaboration Meeting

Line Intensity Mapping



Faint Galaxies Bright Galaxies Line Emission

Galaxy surveys give detailed properties of brightest galaxies

Intensity maps give statistical properties of all galaxies

CO Intensity Mapping

First science result coming up soon!

Carbon Monoxide Mapping Array Project (COMAP)

- Currently mapping CO at z~3
- Partially funded extension to z~7 upcoming
- Maps molecular gas, star formation

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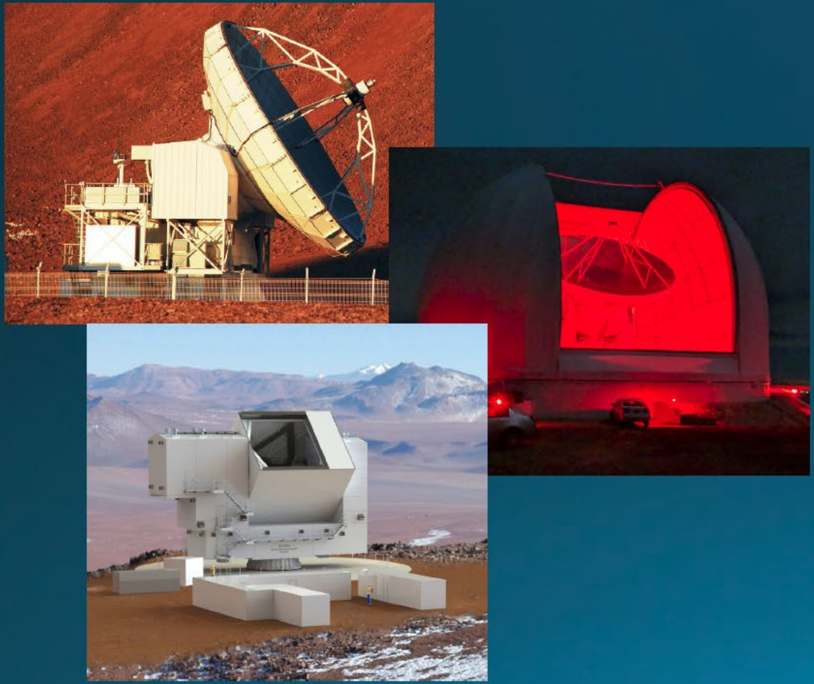
CII Intensity Mapping



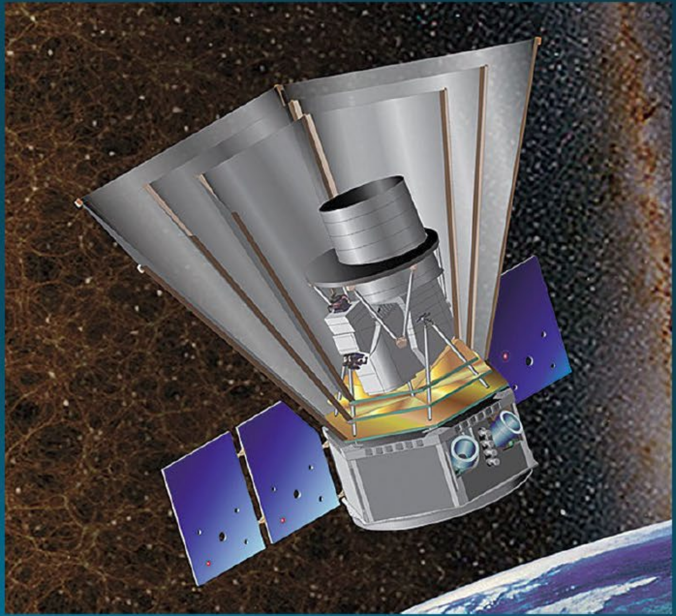
CONCERTO, TIME, and FYST

- All targeting CII 158 μm at z~7
- Widely different spectrograph technologies
- Brighter than CO, but has several foreground lines

Lyman-α Intensity Mapping

SPHEREx midEx Mission

- IR spectrum at every point on the sky, deep fields at poles well-suited for LIM
- Accesses several different lines, inc. EoR-era Lyα



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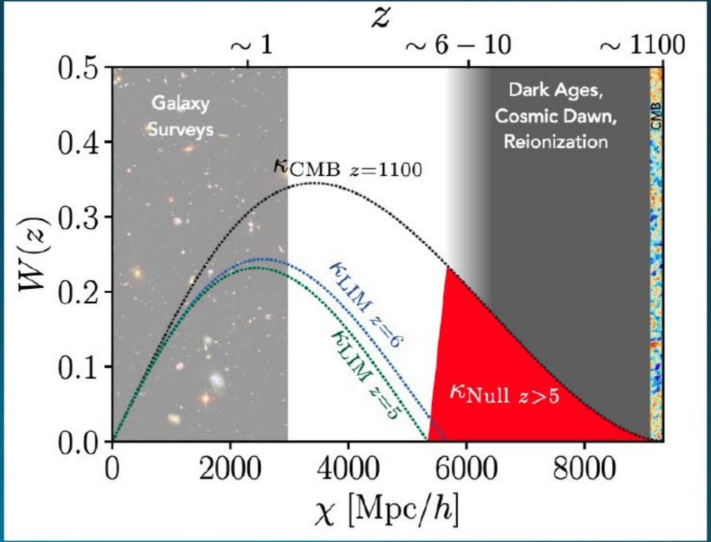
PB Slide

Modeling Limitations

Huge need for theory/modeling effort to understand cross-experiment synergies!

- Example- Dark ages lensing with LIMxCMB
  - Maniyar+ 2021, arXiv:2106.09005
- What other synergies are there?
  - CIB? kSZ? 21cm? ???



First Upper Limits from HERA on the 21 cm Power Spectrum

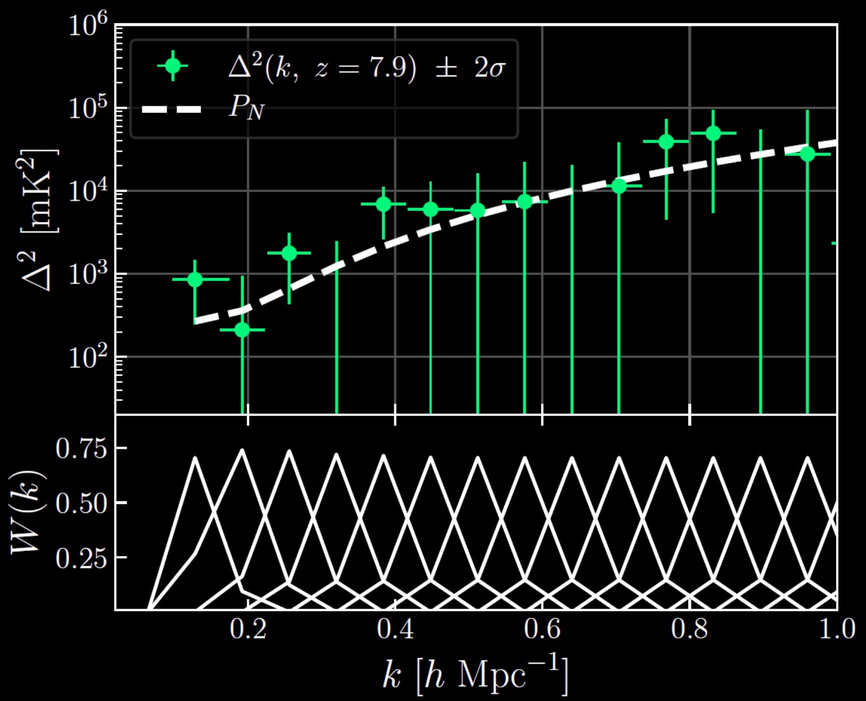
Josh Dillon
UC Berkeley

JD Slide


CAL POLY POMONA
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
Queen Mary University of London
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory
SKA AFRICA SQUARE KILOMETRE ARRAY
NRAO
HERA
The Hydrogen Epoch of Reionization Array
Penn University of Pennsylvania
McGill UNIVERSITY
BROWN
HARVARD
UNIVERSITY OF KWAZULU-NATAL
RHODES UNIVERSITY Where leaders learn
UNIVERSITY of the WESTERN CAPE
GORDON AND BETTY MOORE FOUNDATION
NSF

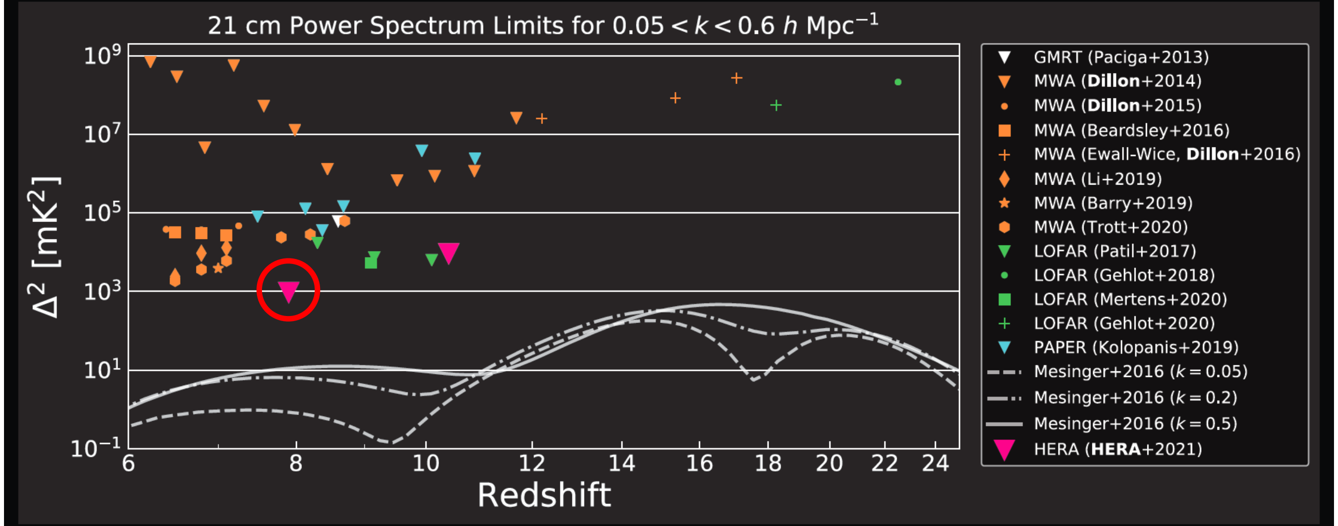
JD Slide

Working outside the foreground-dominated region, we get our power spectrum upper limit.



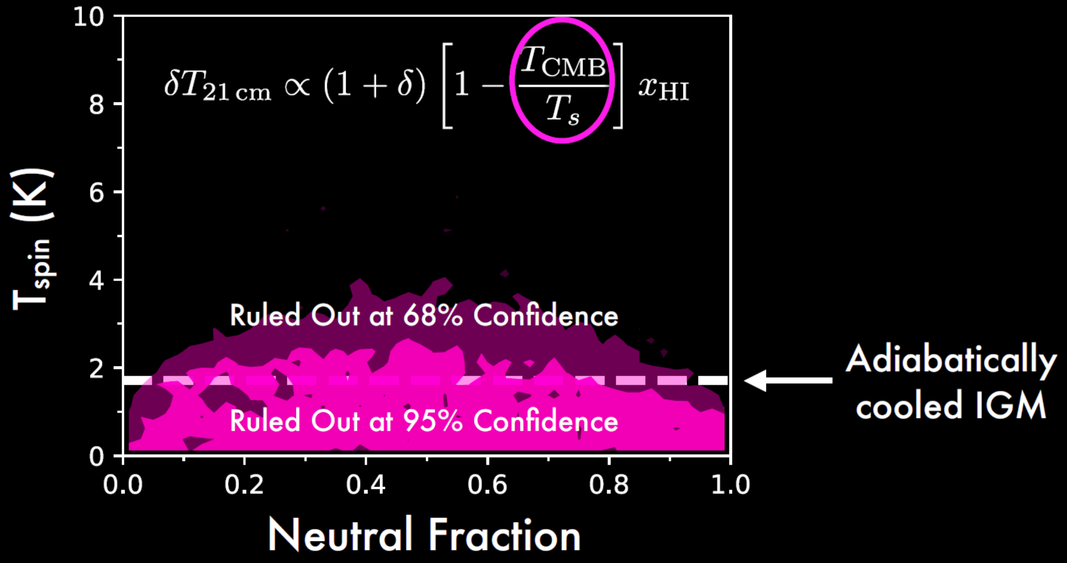
HERA Collaboration (2021)

Our first (and world-leading!) limit with just 18 nights and a very conservative analysis.



HERA Collaboration (2021)

We can already largely rule out an IGM unheated by X-rays at z = 7.9, though this is not at all surprising.



PRELIMINARY!

HERA Collaboration (in prep.)

We'll have way more sensitivity with a full season (~100 nights) and the full array, and should easily rule EDGES in or out.

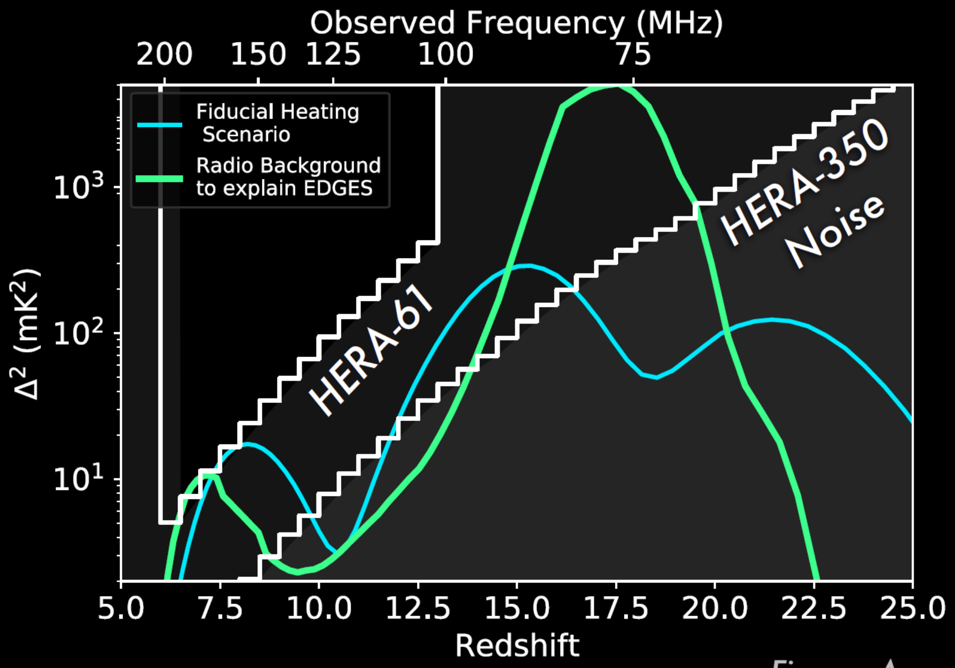
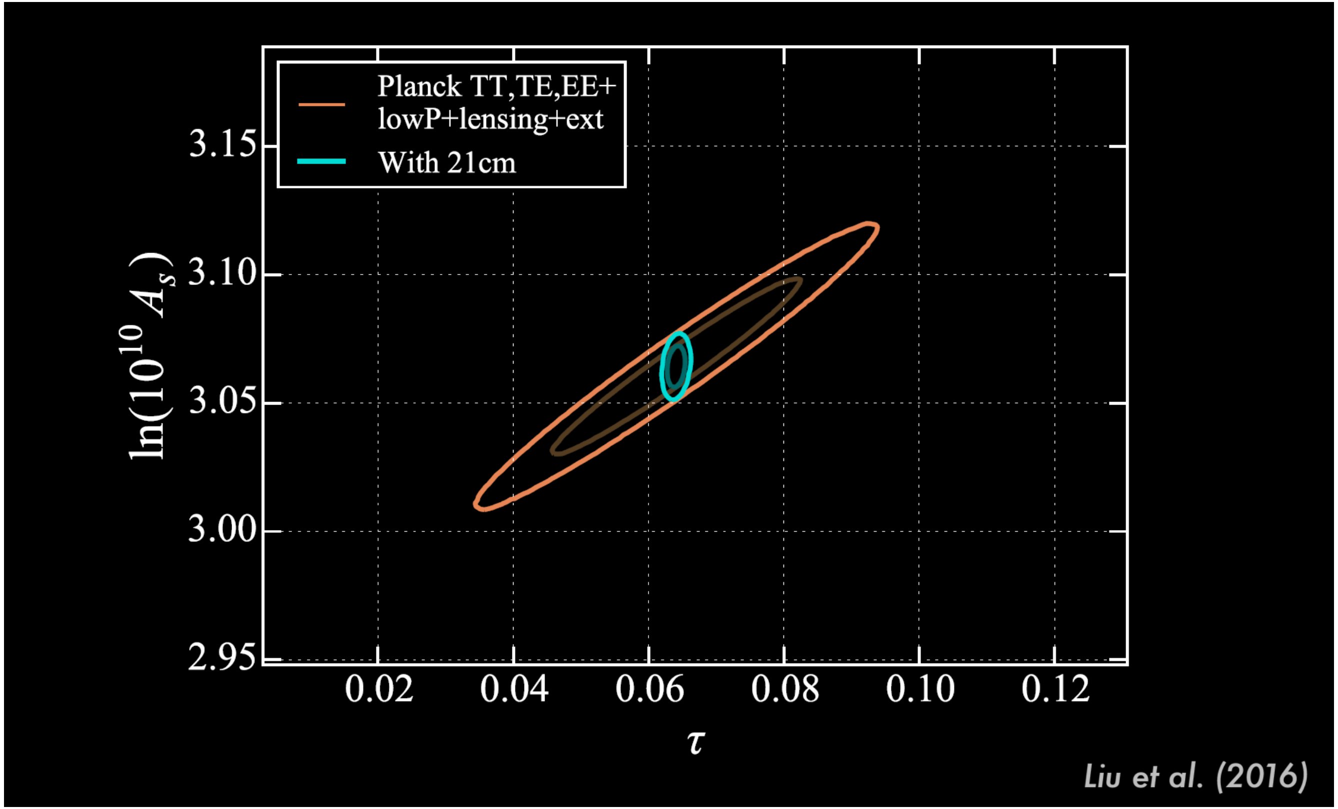
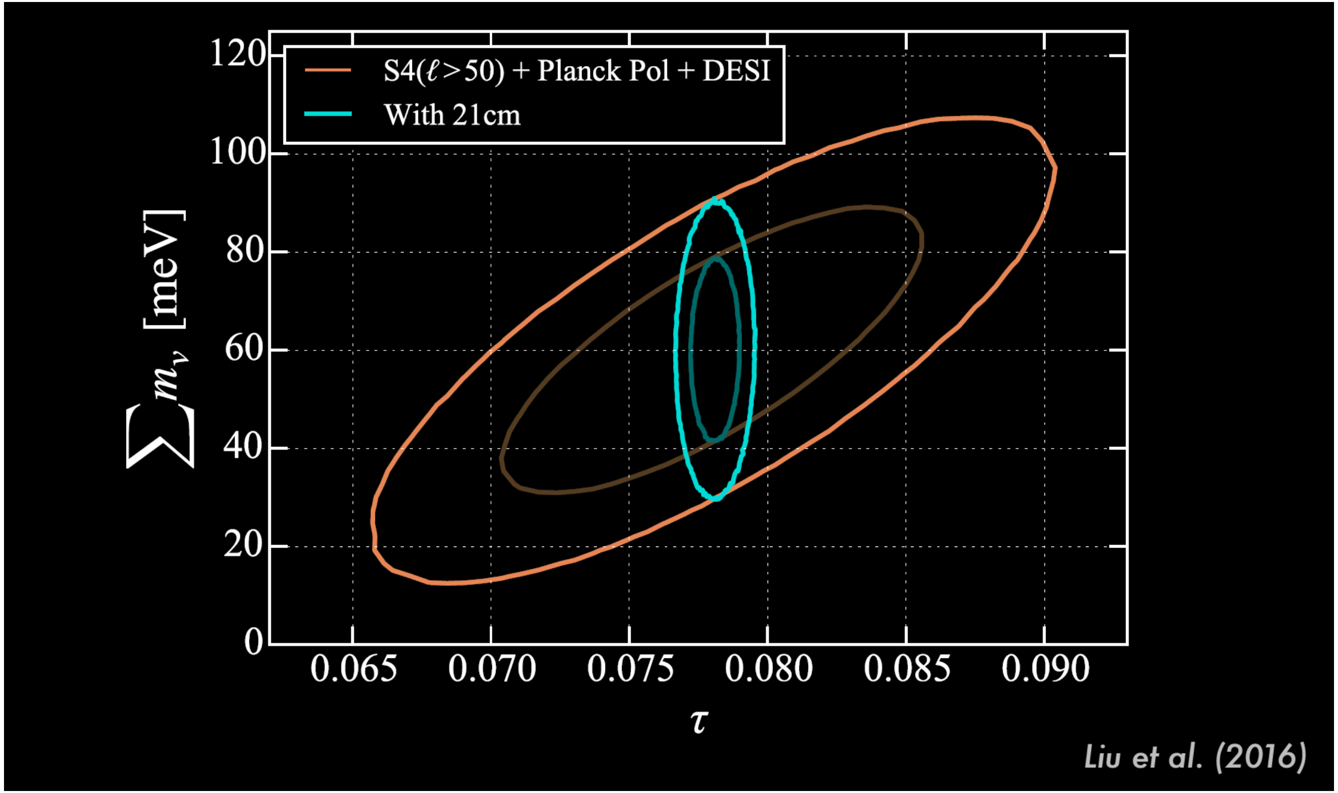


Figure: Aaron Ewall-Wice


Planck TT,TE,EE+
lowP+lensing+ext
With 21cm
3.15
3.10
3.05
3.00
2.95
$\ln(10^{10}A_s)$
0.02
0.04
0.06
0.08
0.10
0.12
τ
Liu et al. (2016)

JD Slide



S4(ℓ>50) + Planck Pol + DESI
With 21cm
$\sum m_\nu$ [meV]
120
100
80
60
40
20
0
0.065
0.070
0.075
0.080
0.085
0.090
τ
Liu et al. (2016)

Discussion

- How will CMB f_{sky} affect the cross-correlation with external tracer?
  - Roman Space Telescope covers 5% of the sky
  - Hard to predict for intensity mapping since there is so little known about the signal
- Coordinates between experiments and modeling
  - Including realistic prediction of instrument modeling and noise
  - Astrophysical modeling is generally difficult, including galaxy modeling and intensity mapping modeling
- Session note link

We thank all the speakers who contributed to the session!

Jordan Mirocha, Suvodip Mukherjee, Xiaohan Wu, Patrick Breysse, Paul La Plante, Toshiya Namikawa, and Josh Dillon