Efficient Modelling of Patchy Cosmic Microwave Background Anisotropies:

Anticipated Insights from the CMB-S4 Experiment on the Era of Reionization

Fig Credit: https://kipac.stanford.edu/research/projects/cmb-stage-4

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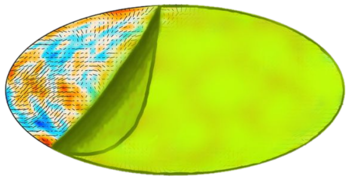
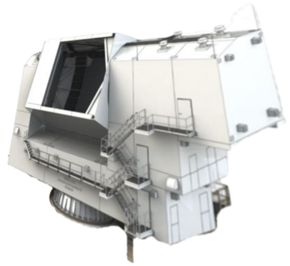
NCRA-TIFR





In collaboration with
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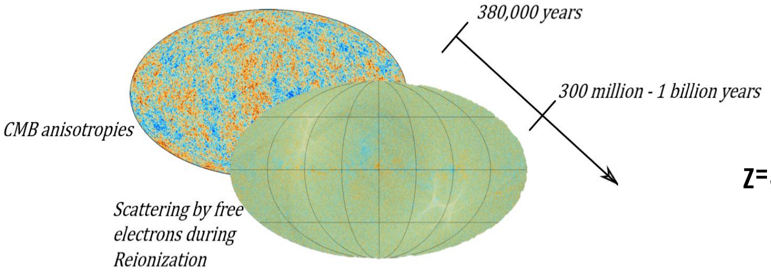
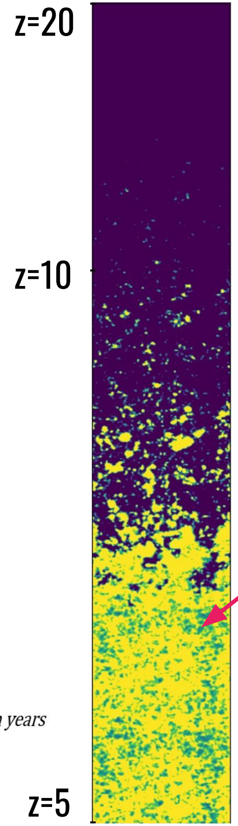
Sourabh Paul (McGill University)

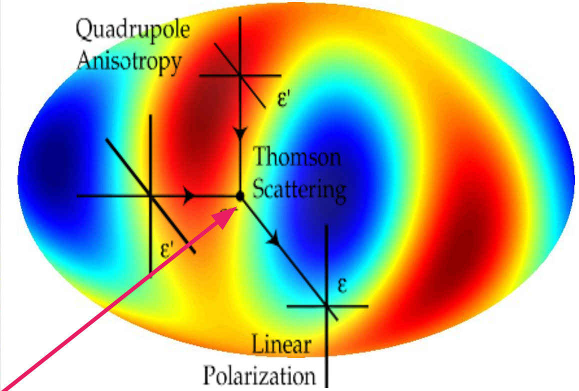
Reionization -CMB connection

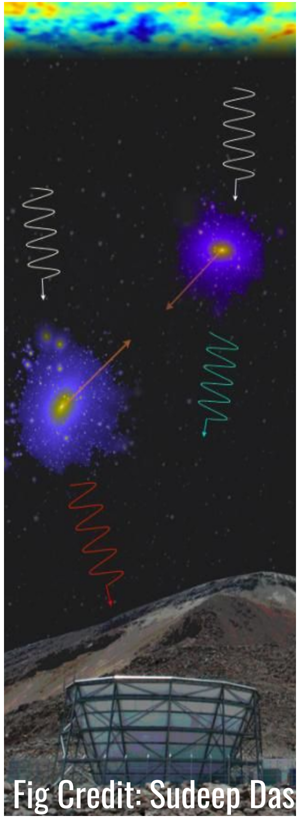
- Reionization is a process whereby hydrogen and helium is ionized by the radiation from first luminous sources.
- CMB photons re-scatters off free electrons in the era of Reionization.



Rescattering of CMB during Reionization era







Patchy-τ

Patchy-B mode

Patchy-kSZ

$$\tau^{\rm obs} = 0.054 \pm 0.007$$

Planck 2018

$$D^{\rm kSZ,obs}_{\ell=3000} = 3.0 \pm 1.0 \mu K^2$$

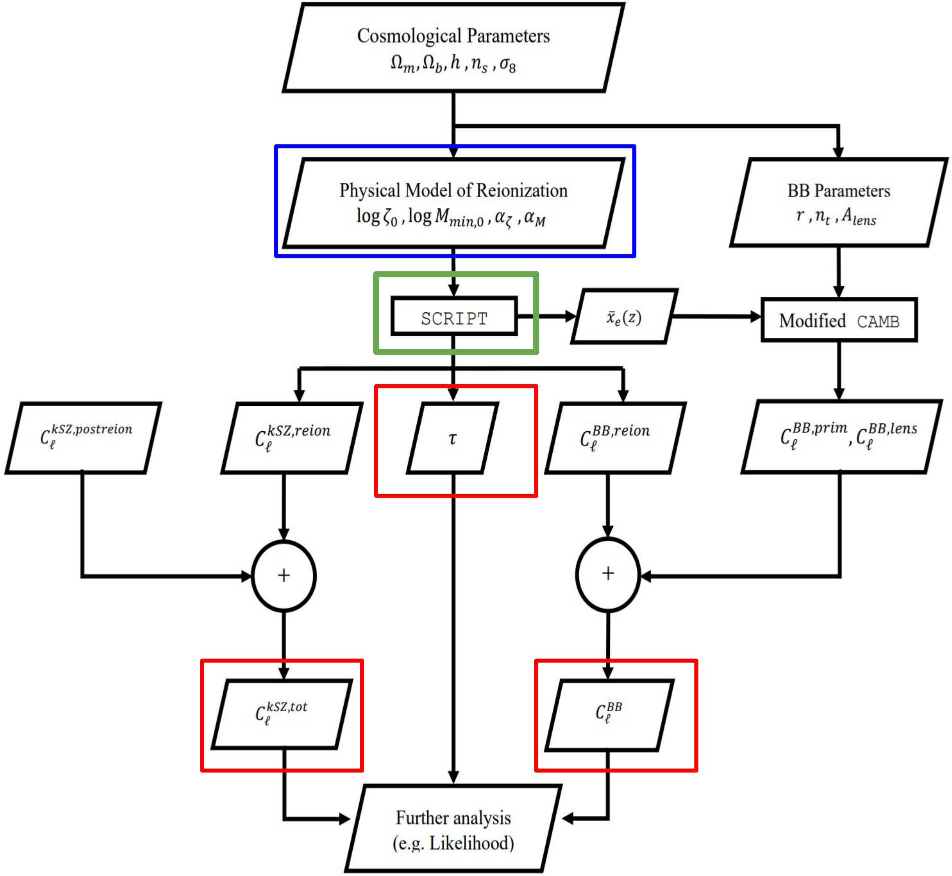
Reichardt 2021

Self-consistent evaluation of CMB Anisotropies with SCRIPT

- SCRIPT is a photon-conserving semi-numerical reionization scheme (*Choudhury & Paranjape 2018*)
- Advantages of SCRIPT:
  - Resolution-independent large-scale ionization maps
  - Generate 21 cm and kSZ maps
  - Vital for parameter estimation due to semi-numerical nature.
- Key Conclusions with current CMB data:
  - Radiative feedback suppresses star formation in haloes $<10^9$ mass at $z \sim 8$
  - As reionization progresses, ionizing efficiency of the sources increases
  - Width of reionization : $\Delta z = 1.19^{+0.27}_{-0.53}$

Jain et al. 2023

SCRIPT: https://bitbucket.org/rctirthankar/script/src/master/



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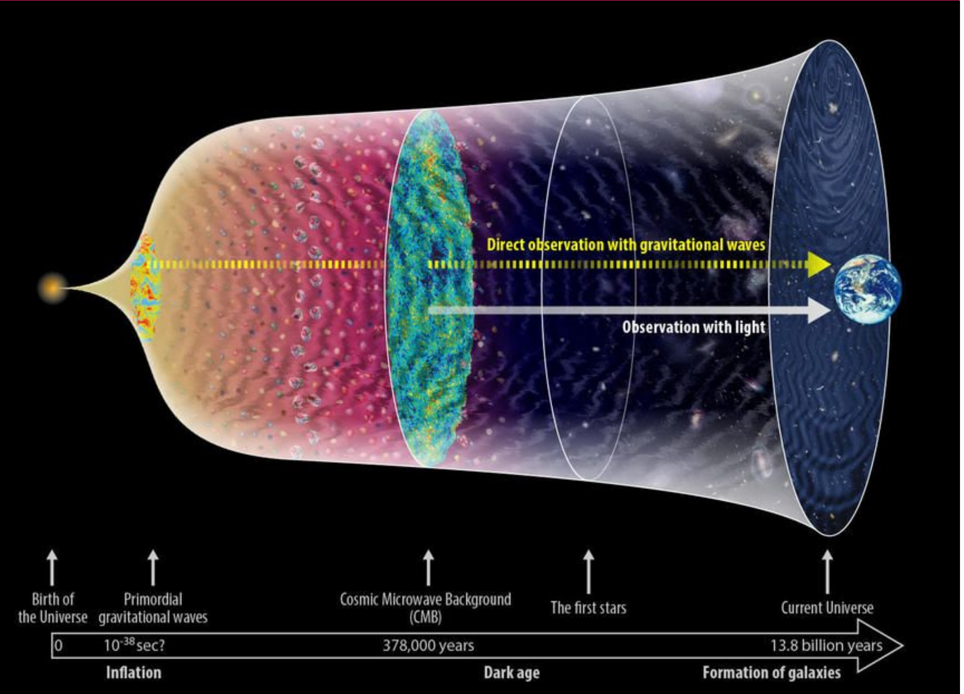
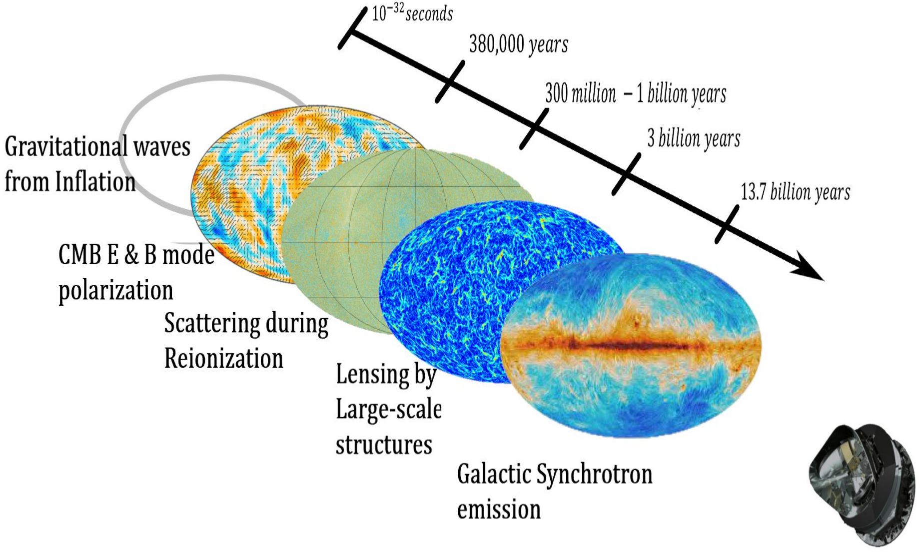
Patchy Reionization Bias On Tensor-to-Scalar ratio r



1. Gravitational Waves (GWs) are prediction of Inflationary waves *(Kamionkowski 2016)*
2. GWs produce B mode polarization.
3. The amplitude of B-mode is tied to the tensor-to-scalar power spectrum ratio r.
4. The latest constraint on r :
   a. $r < 0.035$ (95% C.L.) *(BICEP3 2022)*



Framework to forecast bias on r

Jain et al. 2023

Likelihood function:

$$-2\log\mathcal{L} = \left(\frac{\tau-\tau^{\rm obs}}{\sigma_\tau^{obs}}\right)^2 + \left(\frac{D^{\rm kSZ}_{\ell=3000}-D^{\rm kSZ,obs}_{\ell=3000}}{\sigma^{\rm kSZ,obs}_{\ell=3000}}\right)^2 + \sum_{\ell=\ell_{min}}^{\ell_{max}}\left(\frac{D_\ell^{BB}-D_\ell^{BB,obs}}{\Sigma_\ell}\right)^2$$

$$\text{Template}:\ D_\ell^{BB} = D_\ell^{BB,\rm prim} + A_{\rm lens}D_\ell^{BB,\rm lens} + D_\ell^{BB,\rm reion}$$

$$\text{Template} - D_\ell^{BB,\rm reion}:\ D_\ell^{BB} = D_\ell^{BB,\rm prim} + A_{\rm lens}D_\ell^{BB,\rm lens}$$

To study bias, the idea is the following :

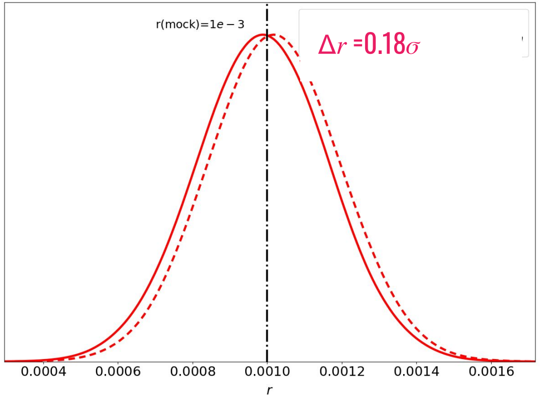
- Inference of r for the model $\text{Template} - D_\ell^{BB,\rm reion}$ corresponds to a biased recovery of r.
- Post inference of r for each model, bias is:

$$\frac{\Delta r}{\sigma} \equiv \frac{\left(r_{\rm Template} - r_{\text{Template}-D_\ell^{BB,\rm reion}}\right)}{\sigma_{r_{\rm Template}}}$$

Template — $\text{Template} - D_\ell^{BB,\rm reion}$

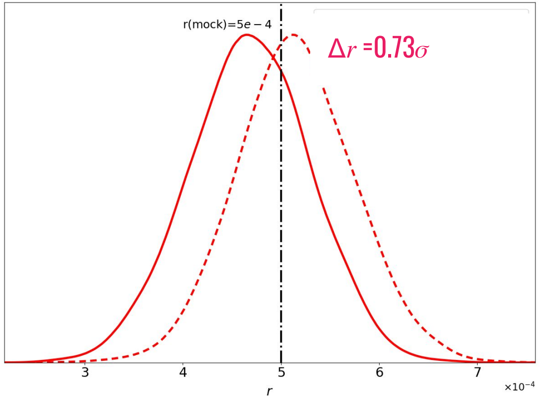
Pessimistic case of bias with CMB-S4

mock r =1e-3
85% delensing
Best-fit reionization model



Optimistic case of bias with PICO:

mock r =5e-4
95% delensing
extreme reionization model

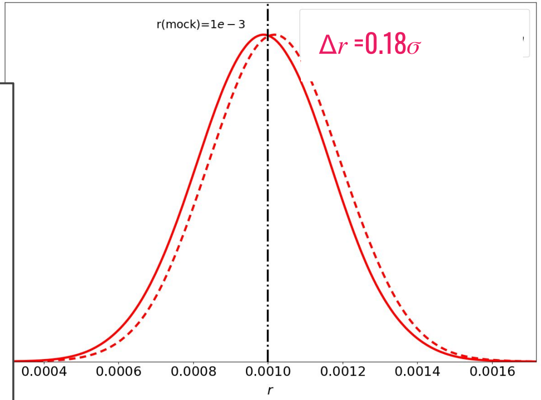


Framework to forecast bias on r

Jain et al. 2023

Template   Template $- D_\ell^{BB,\mathrm{reion}}$

Pessimistic case of bias with CMB-S4



Likelihood function:

$$-2\log\mathcal{L} = \left(\frac{\tau-\tau^{\mathrm{obs}}}{\sigma_\tau^{obs}}\right)^2 + \left(\frac{D^{\mathrm{kSZ}}_{\ell=3000} - D^{\mathrm{kSZ,obs}}_{\ell=3000}}{\sigma^{\mathrm{kSZ,obs}}_{\ell=3000}}\right.$$

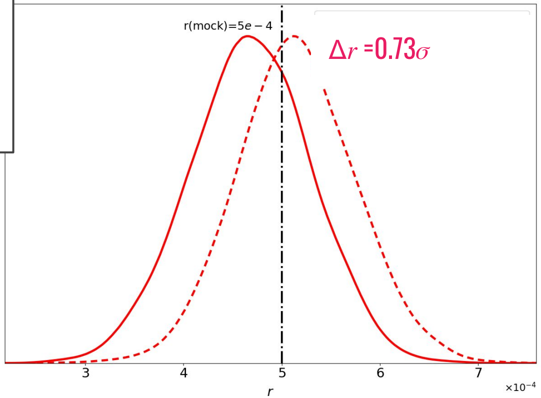
$$\sum_{\ell=\ell_{min}}^{\ell_{max}} \left(\frac{D_\ell^{BB} - D_\ell^{BB,obs}}{\Sigma_\ell}\right)^2$$

$$\mathrm{Template}: \; D_\ell^{BB} = D_\ell^{BB,\mathrm{prim}} + A_{\mathrm{lens}} D_\ell^{BB,}$$

$$\mathrm{Template} - D_\ell^{BB,\mathrm{reion}}: \; D_\ell^{BB} = D_\ell^{BB,\mathrm{prim}} + $$

- Inaccurate B-mode power modelling biases r =1e-3 measurement, lowering detection significance from 5σ to ~4.8σ.
- With extreme reionization and efficient delensing, detection claims for r = 5e-4 influenced by a ~0.73σ bias.
- Combining CMB observables we can constrain patchy reionization and mitigate its impact on the value of r.

c case of bias with PICO:



extreme reionization model

To study bias, the idea is the following :

- Inference of r for the model Templ corresponds to a biased recovery of r.
- Post inference of r for each model, bias as:

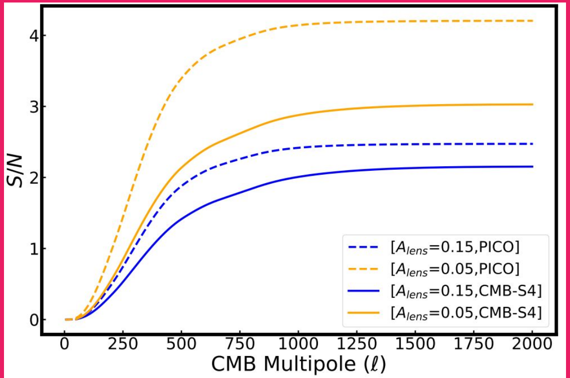
$$\frac{\Delta r}{\sigma} \equiv \frac{\left(r_{\mathrm{Template}} - r_{\mathrm{Template}-D_\ell^{BB,\mathrm{reion}}}\right)}{\sigma_{r_{\mathrm{Template}}}}$$

Detecting Patchy B-mode:

exploiting synergy τ-power spectrum

- Stage-4 CMB experiments will allow near model-independent detection of patchy reionization, exploiting the τ and B-mode power spectrum synergy.
- Infer the signal of both primordial gravitational waves and patchy reionization jointly from the CMB data.

Cumulative signal-to-ratio to detect patchy-τ power at different delensing scenarios corresponding to observations with CMB-S4 and PICO.



Jain et al. (in prep)

Model B-mode signal: Measures patchiness in the reionization B-mode

$$C_\ell^{BB} = C_\ell^{BB,prim} + A_{lens} C_\ell^{BB,lens} + \boxed{A_\tau} C_{\ell,\mathrm{fid}}^{BB,\mathrm{reion}}$$

Constraining A_τ with projected τ and B-mode data:

$$-2\log\mathcal{L} = \left(\frac{\tau - \tau^{\mathrm{obs}}}{\sigma_\tau^{obs}}\right)^2 + \sum_\ell \left(\frac{\bar{C}_\ell^{BB} - C_\ell^{BB}}{\Sigma_\ell^{BB}}\right)^2.$$

Analytical relation between patchy-B mode and the τ-power spectrum: *(Dvorkin et al. 2010)*

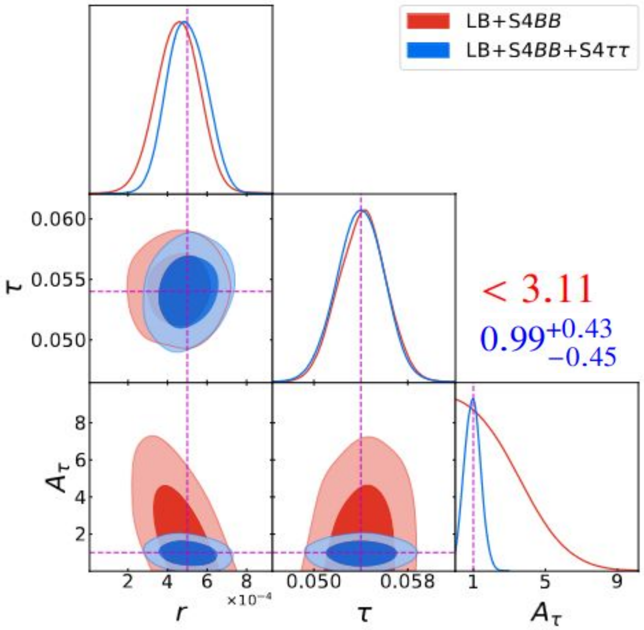
$$\boxed{C_\ell^{BB,\mathrm{reion}}} \approx \frac{3}{100} \boxed{C_\ell^{\tau\tau}} Q_{\mathrm{rms}}^2 e^{-2\tau}$$

Constraining A_τ with projected polarization data:

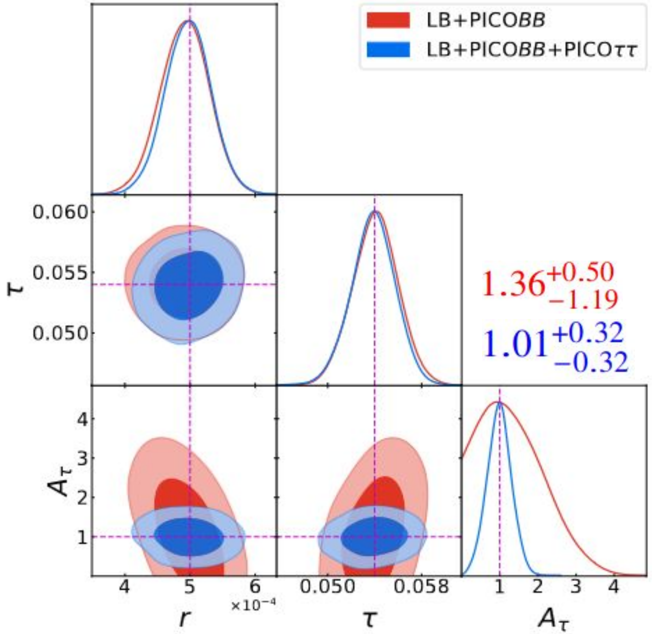
$$-2\log\mathcal{L} = \left(\frac{\tau - \tau^{\mathrm{obs}}}{\sigma_\tau^{obs}}\right)^2 + \sum_\ell \left(\frac{\bar{C}_\ell^{BB} - C_\ell^{BB}}{\Sigma_\ell^{BB}}\right)^2 \boxed{+ \sum_\ell \left(\frac{\bar{C}_\ell^{\tau\tau} - C_\ell^{\tau\tau}}{\Sigma_\ell^{\tau\tau}}\right)^2}$$

Forecasts on A_τ with Stage-4 CMB experiments

Jain et al. (in prep)



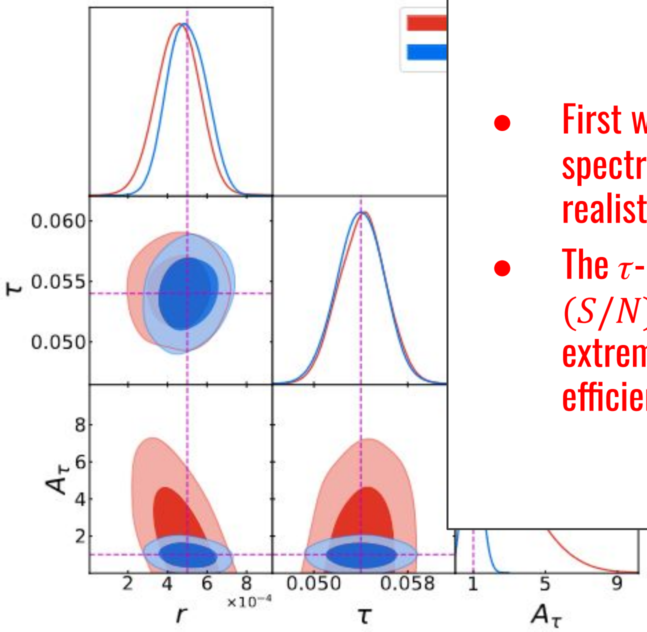
LB+CMB-S4 data sets: A_τ/σ_{A_τ} = 2.25



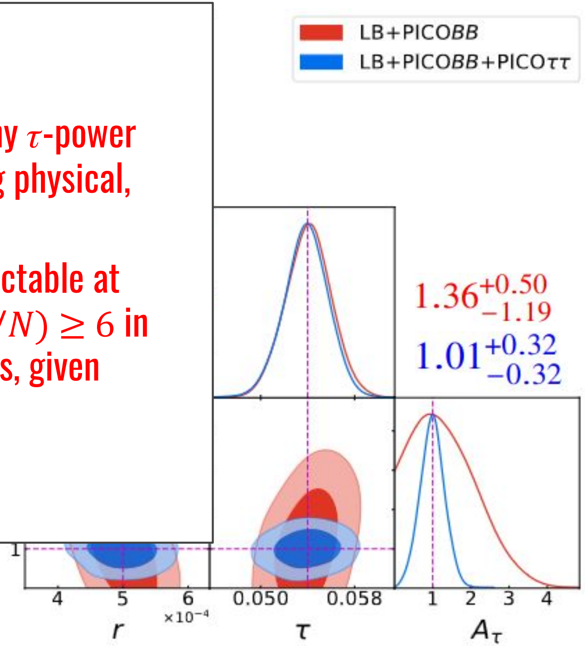
LB+PICO data sets: A_τ/σ_{A_τ} = 3.16

Forecasts on A_τ with Stage-4 CMB experiments

Jain et al. (in prep)



- First work to assess the patchy τ-power spectrum's detectability using physical, realistic reionization models.
- The τ-power spectrum is detectable at $(S/N) \sim 3$, improving to $(S/N) \geq 6$ in extreme reionization scenarios, given efficient delensing.



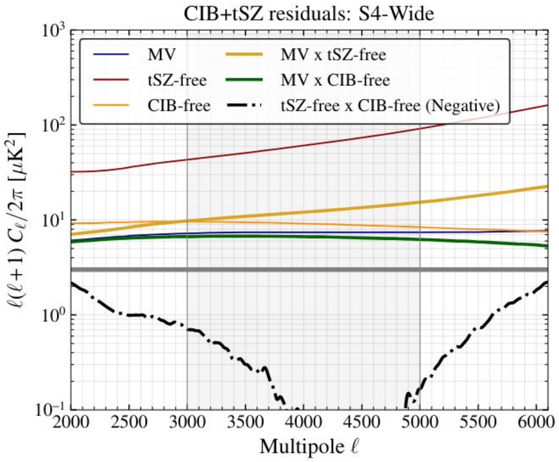
LB+CMB-S4 data sets: A_τ/σ_{A_τ} = 2.25

LB+PICO data sets: A_τ/σ_{A_τ} = 3.16

Forecasting Reionization details with kSZ: *Jain et al. (in prep)*

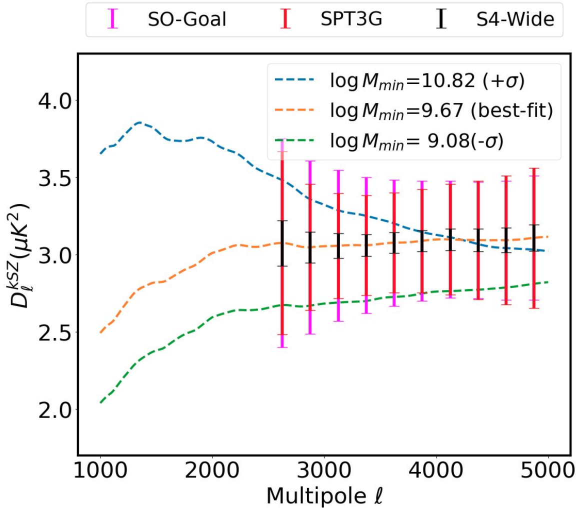
updates with Cross-Internal Linear Combination

- Detection of patchy kSZ will enable crucial insights into patchy reionization era.
- Bias from tSZ and CIB foreground in kSZ, critical for Stage-4 CMB experiments, can't be overlooked *(Raghunathan & Omori 2023)*
- Cross-ILC technique (*Raghunathan & Omori 2023*) aimed at robustly extracting the kSZ signal, minimizes residual bias from CIB and tSZ.
- Despite a lower SNR compared to standard minimum variance ILC, this technique greatly mitigates CIB and tSZ systematics.



The CIB+tSZ residual shown in black dash dotted curve is almost an order of magnitude lower than kSZ (grey line at $3\mu K^2$) for $\ell \in [3500, 5000]$.

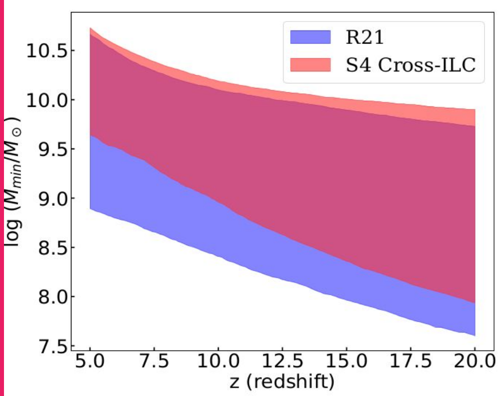
Raghunathan & Omori 2023



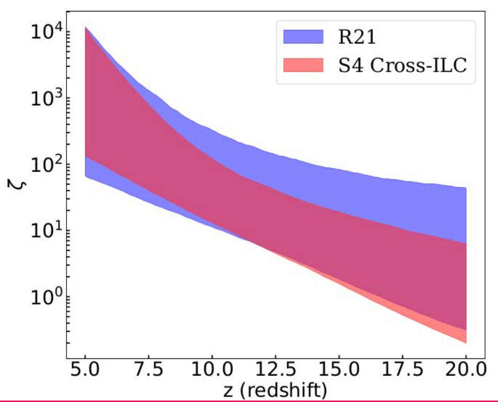
kSZ power with Cross-ILC error bars

Reionization forecast for CMB-S4

Jain et al. (in prep)

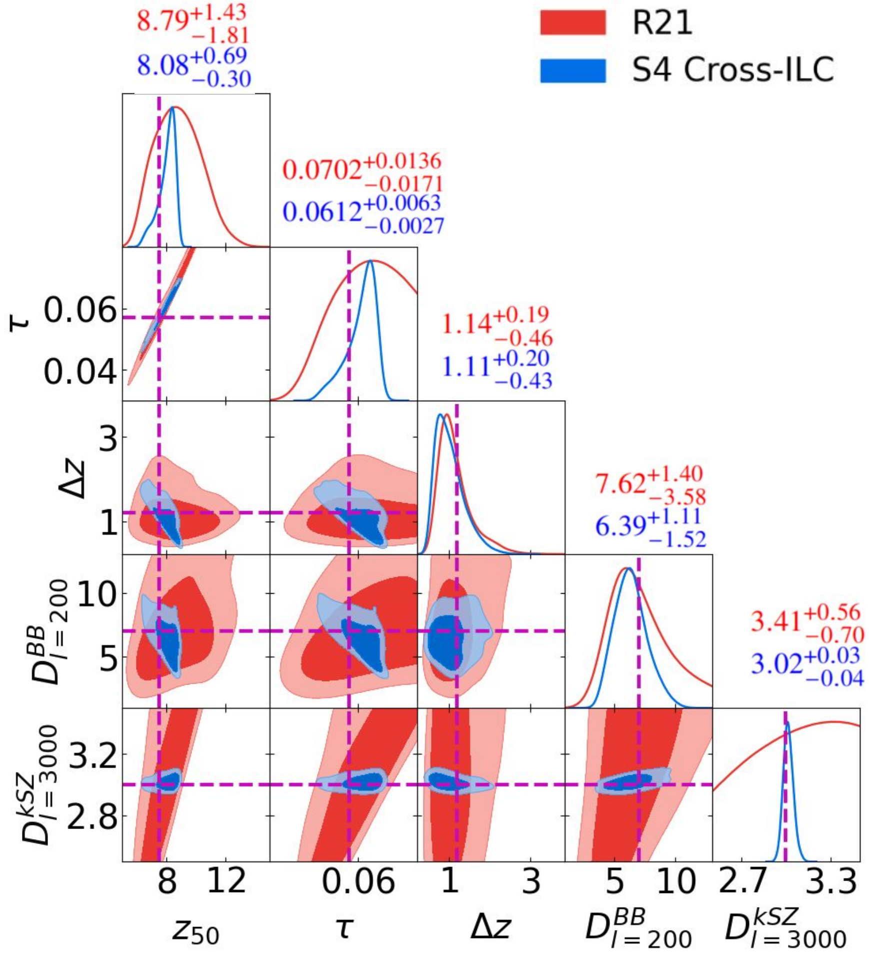


Comparison of the 68% spread in the evolution of the minimum mass of halos for models corresponding to R21 and S4 Cross-ILC



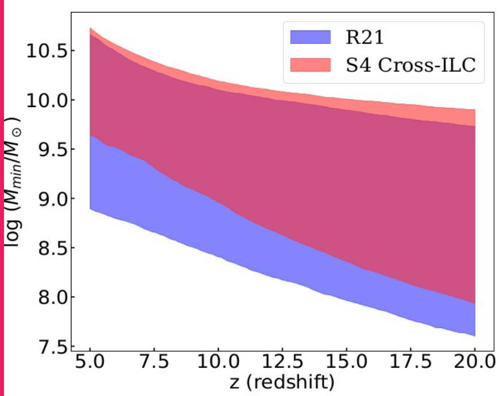
Comparison of the 68% spread in the evolution of the ionizing efficiency of the sources for models corresponding to R21 and S4 Cross-ILC

R21: $D_{\ell=3000}^{\mathrm{kSZ,obs}} = 3.0 \pm 1.0\mu K^2$ *Reichardt 2021*



Reionization forecast for CMB-S4

Jain et al. (in prep)



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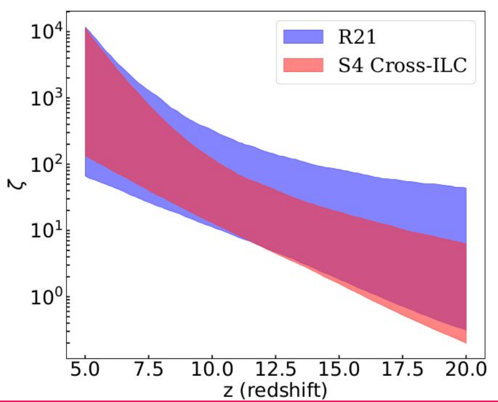

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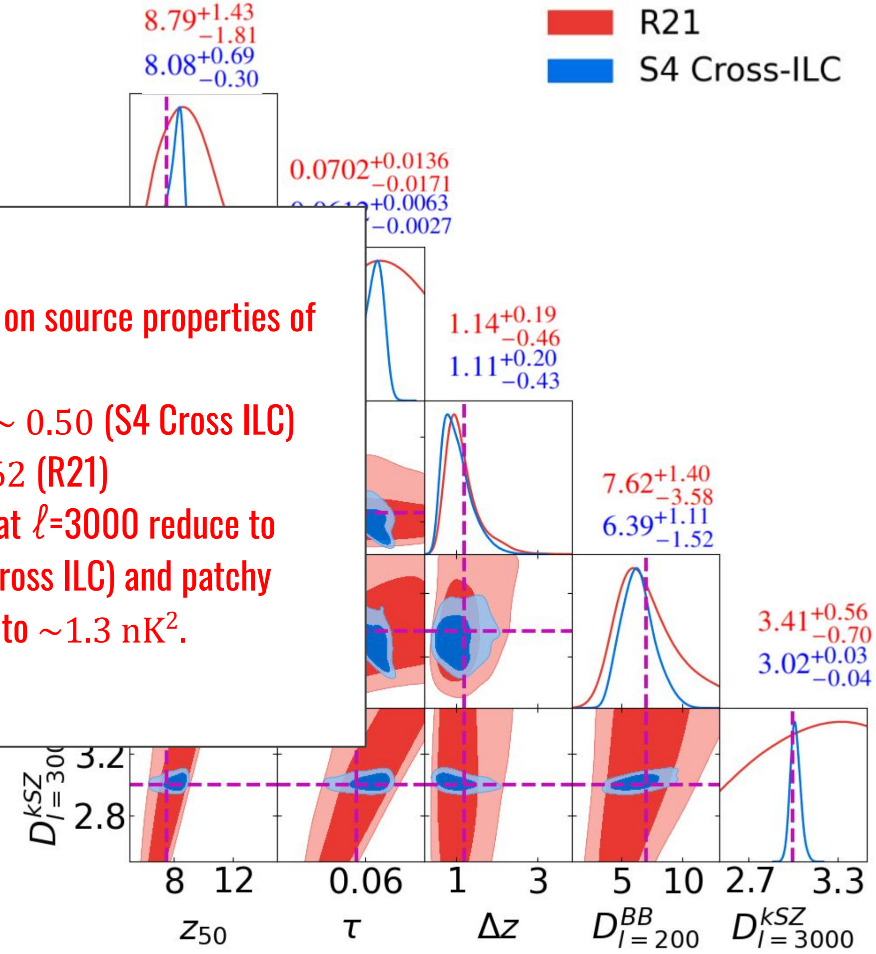

- Tighter constraint on source properties of reionization
- Error bars on $z_{50} \sim 0.50$ (S4 Cross ILC) compared to ~ 1.62 (R21)
- Error bars on kSZ at ℓ=3000 reduce to $\sim 0.04\ \mu K^2$ (S4 Cross ILC) and patchy B-mode at ℓ=200 to ~ 1.3 nK^2.

Summary:

SCRIPT is a photon-conserving semi-numerical reionization scheme https://bitbucket.org/rctirthankar/script/src/master/ (Choudhury & Paranjape 2018)

PATCHY REIONIZATION BIAS ON TENSOR TO SCALAR POWER SPECTRUM RATIO: (Jain et al. 2023)

1. Ignoring patchy B-mode could undermine 5σ detection claims, with extreme bias scenario up to $\sim 0.73\sigma$ for $r = 5\text{e-}4$.
2. Our model, using CMB observables, can constraint patchy reionization and consequently mitigate its impact on r.

DETECTING PATCHY B-MODE WITH STAGE-4 CMB EXPERIMENTS: (Jain et al. in preparation)

1. Patchy τ and B-mode power spectrum synergy may enable first 3σ detection of patchy reionization B-mode signal, potentially up to 7σ for extreme reionization scenarios.
2. Detection of patchy B-mode is cardinal to achieve unbiased measurement on r .

UPDATED REIONIZATION FORECASTS WITH CROSS ILC TECHNIQUE: (Jain et al. in preparation)

1. Our model can predict the kSZ power spectrum shape.
2. Informed by power spectrum shape and Cross-ILC error bars, our model forecasts tight error bars on both homogeneous and patchy properties with CMB-S4 kSZ measurement.