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Joint analysis constraints on the physics of the first galaxies with low frequency radio astronomy data

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With
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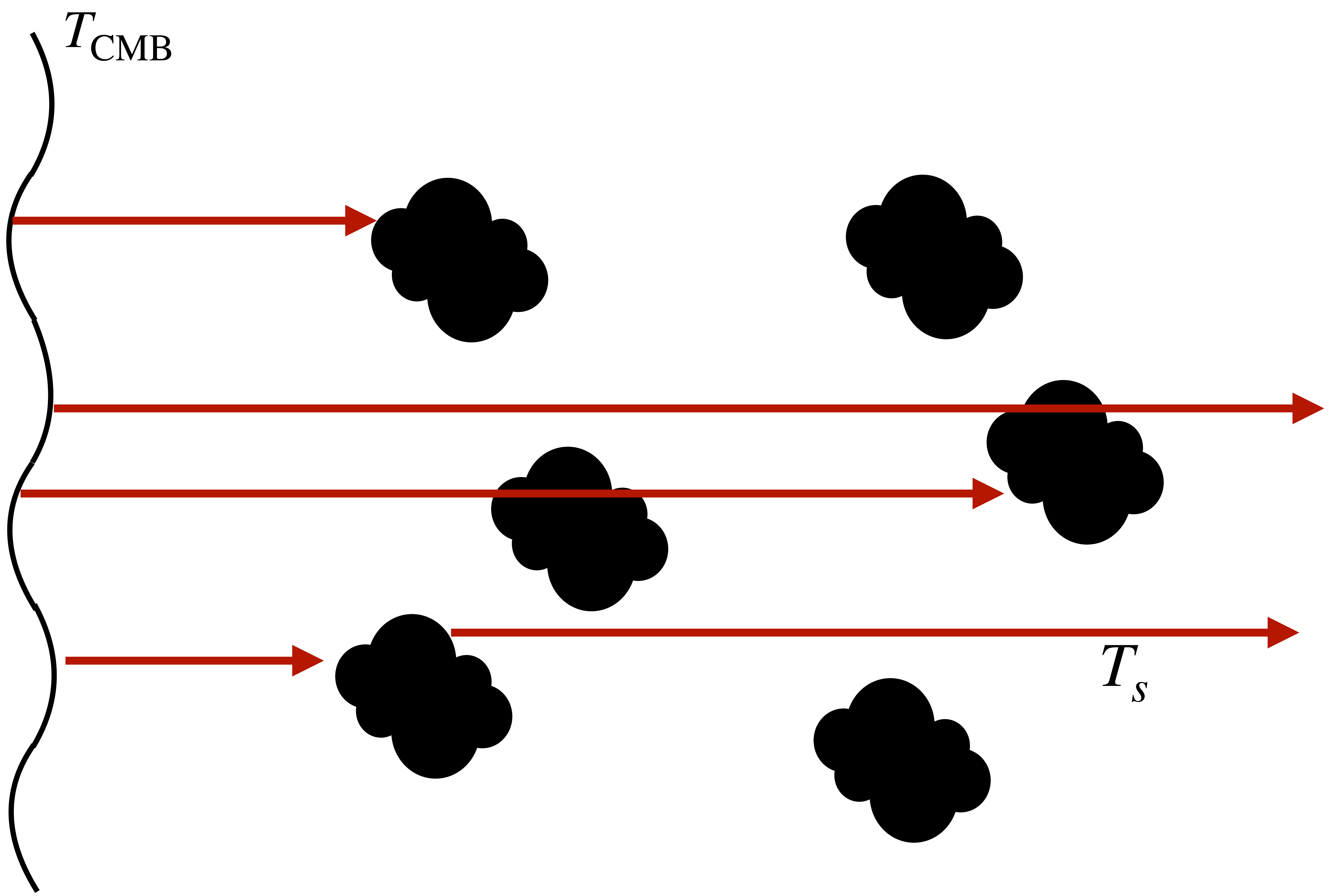
arXiv:2301.03298

Brief overview of 21-cm Cosmology

21-cm Cosmology



- Differential measurement between the radio background and the statistical spin temperature of neutral hydrogen
- Redshift signal in the radio band
- Over $z \approx 5 - 60$
- Experiments come in two flavours looking at sky-averaged properties and spatial variations in the signal

The global 21-cm signal and the power spectrum

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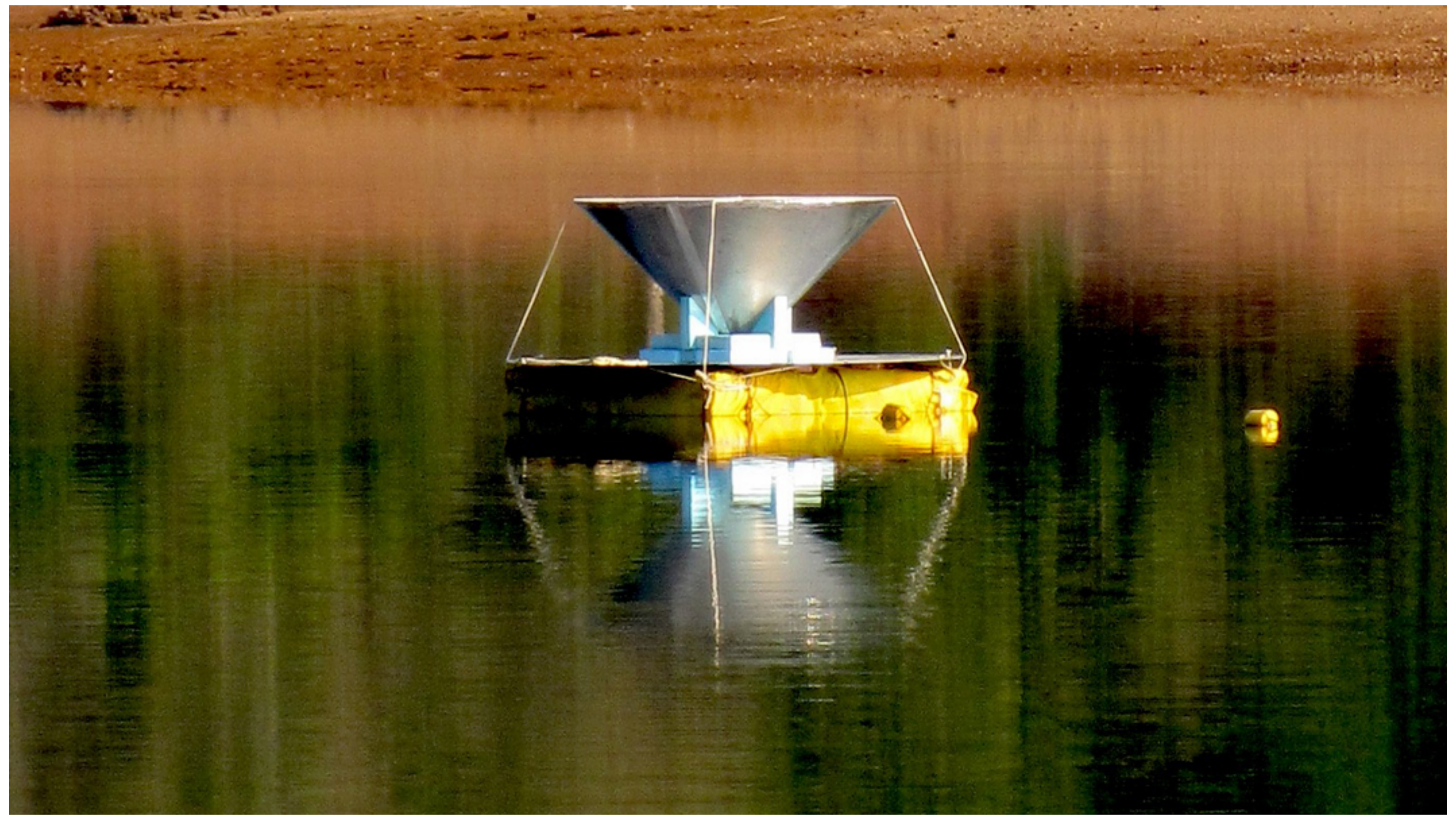
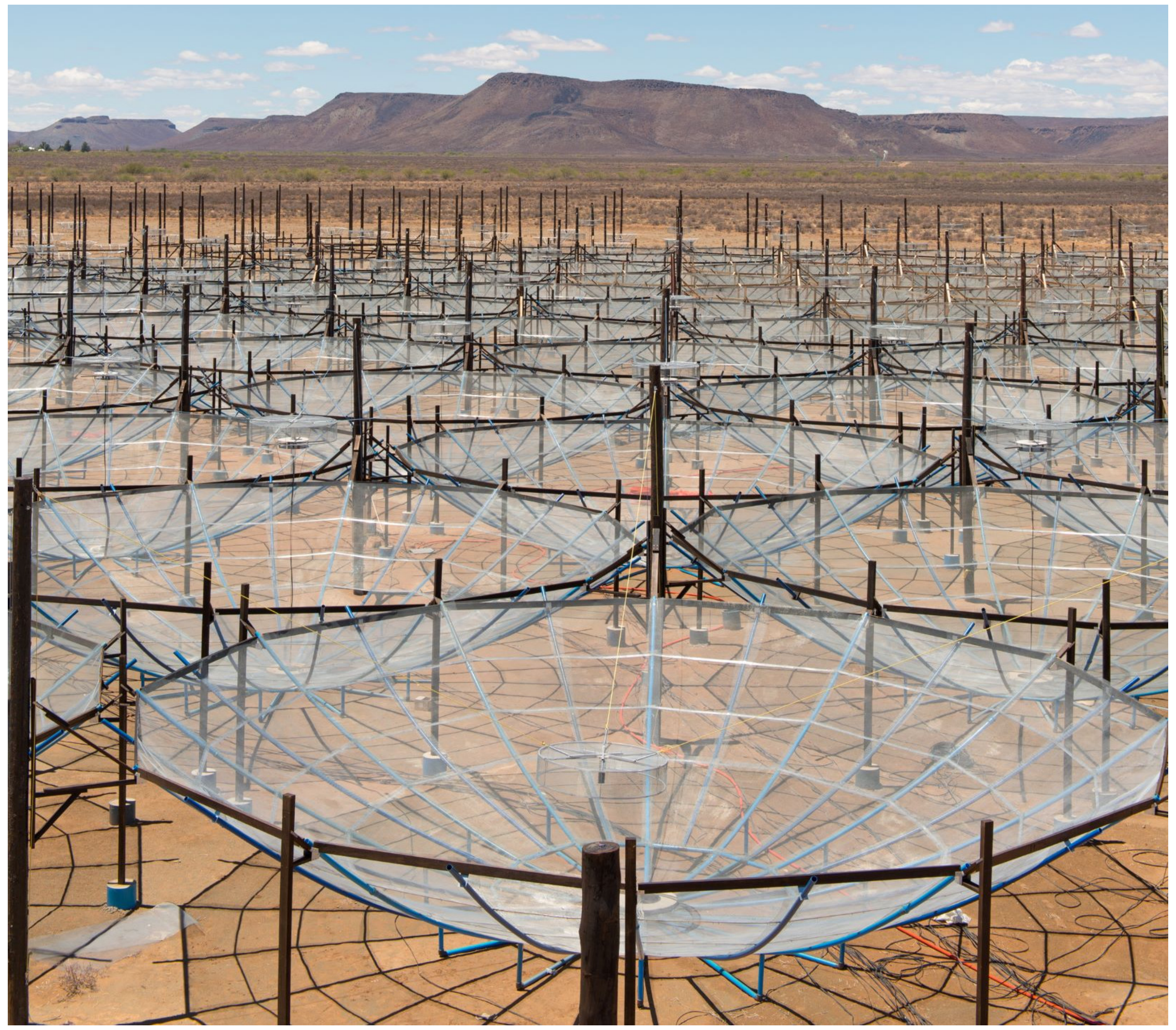


- Single radiometers looking for a sky averaged signal
    - SARAS [e.g. Bevins et al. 2023 arXiv:2212.00464]
    - EDGES [Bowman et al. 2018 arXiv:1810.05912]
    - REACH [de Lera Acedo et al. 2022 arXiv:2210.07409]

- Interferometers looking to measure the 21-cm power spectrum
    - HERA [e.g. The HERA Col. 2023 arXiv:2210.04912]
    - LOFAR [e.g. Patil et al. 2017 arXiv:1702.08679]
    - MWA [e.g. Trott et al. 2020 arXiv:2002.02575]
    - SKA [e.g. Greig et al 2020 arXiv:1906.07910]

- Probing the same physics corresponding to the epoch when the first galaxies formed through to reionisation ($z \approx 5 - 60$)



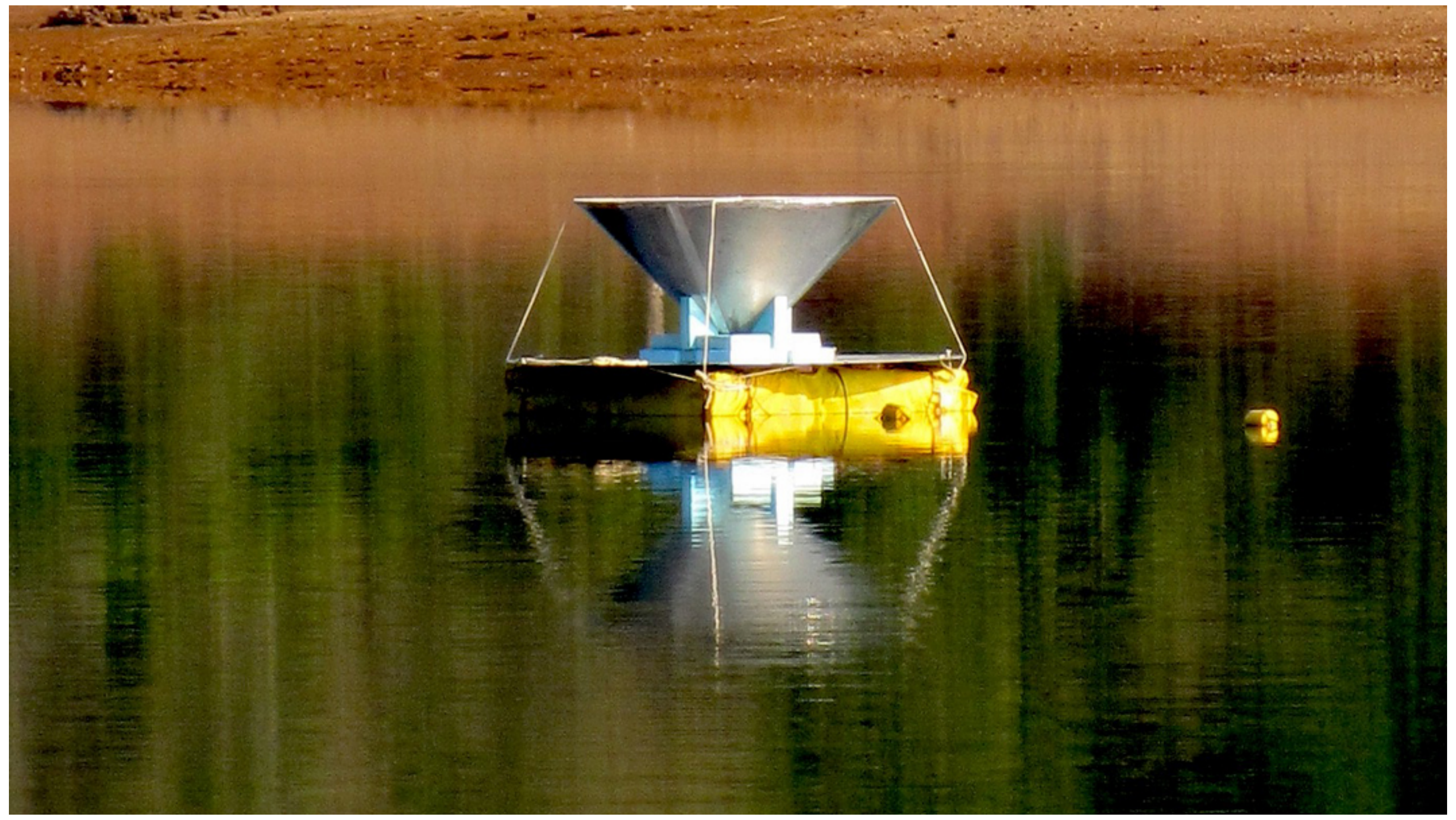
The Goal of this Work

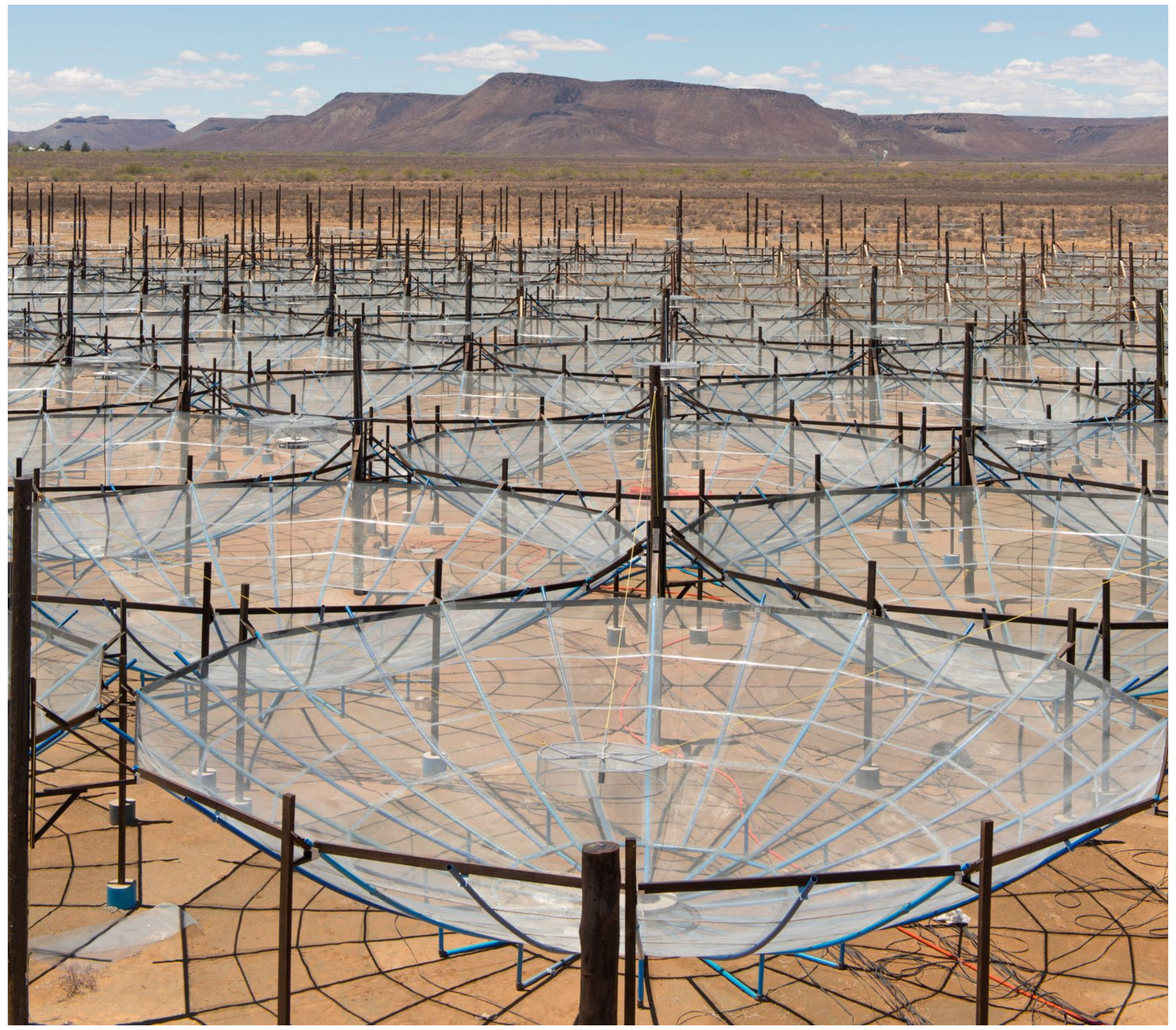
- HERA ($z \approx 8$ and 10) and SARAS3 ($z \approx 15 - 25$) have already been used to constrain the properties of early galaxies

- We want to combine the constraining power of the two instruments

- 18 nights of observations with 39 antennas from the HERA array [The HERA Col. 2023 arXiv:2108.07282]

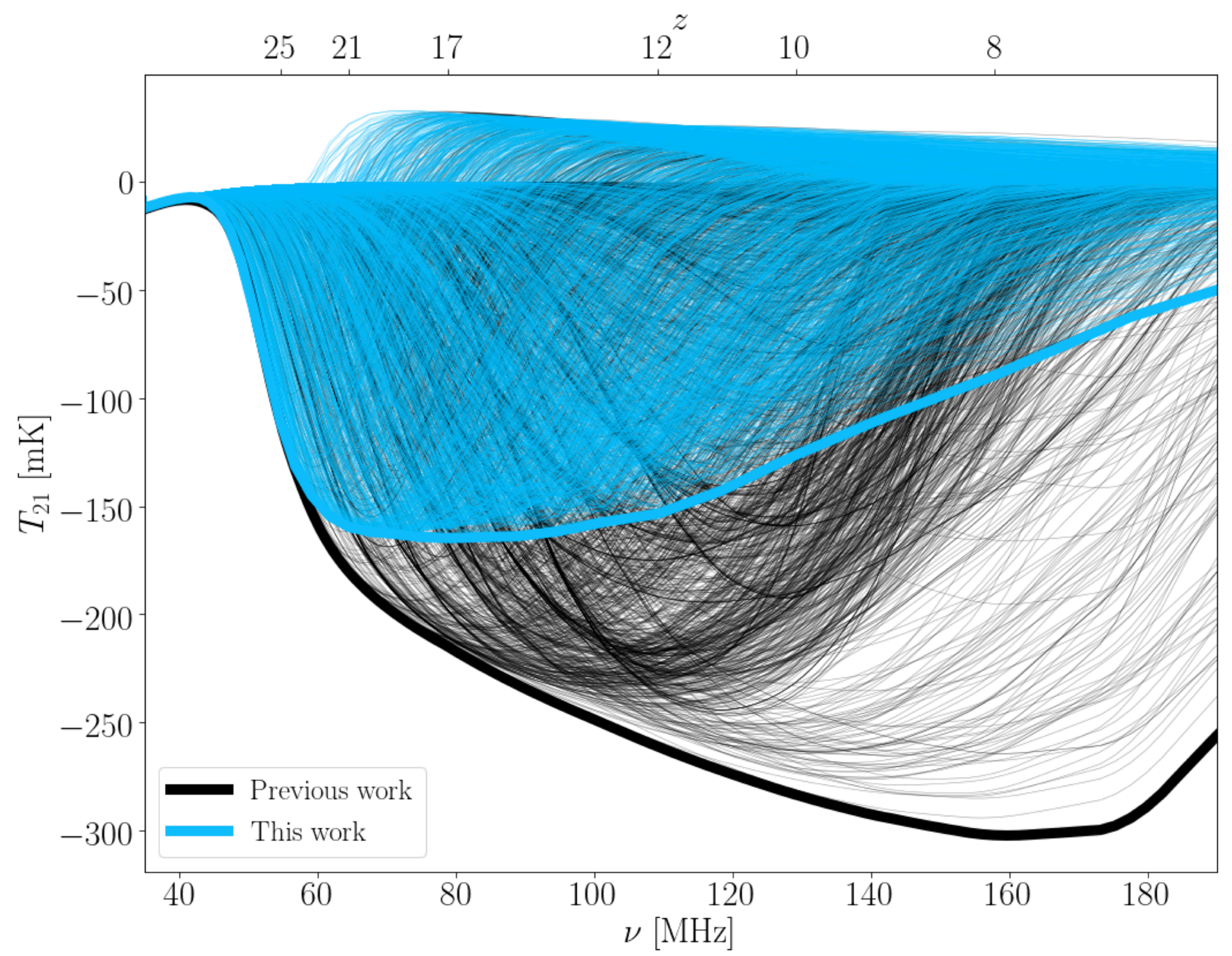
- 15 hours of SARAS3 data [Bevins et al. 2023 arXiv:2212.00464]



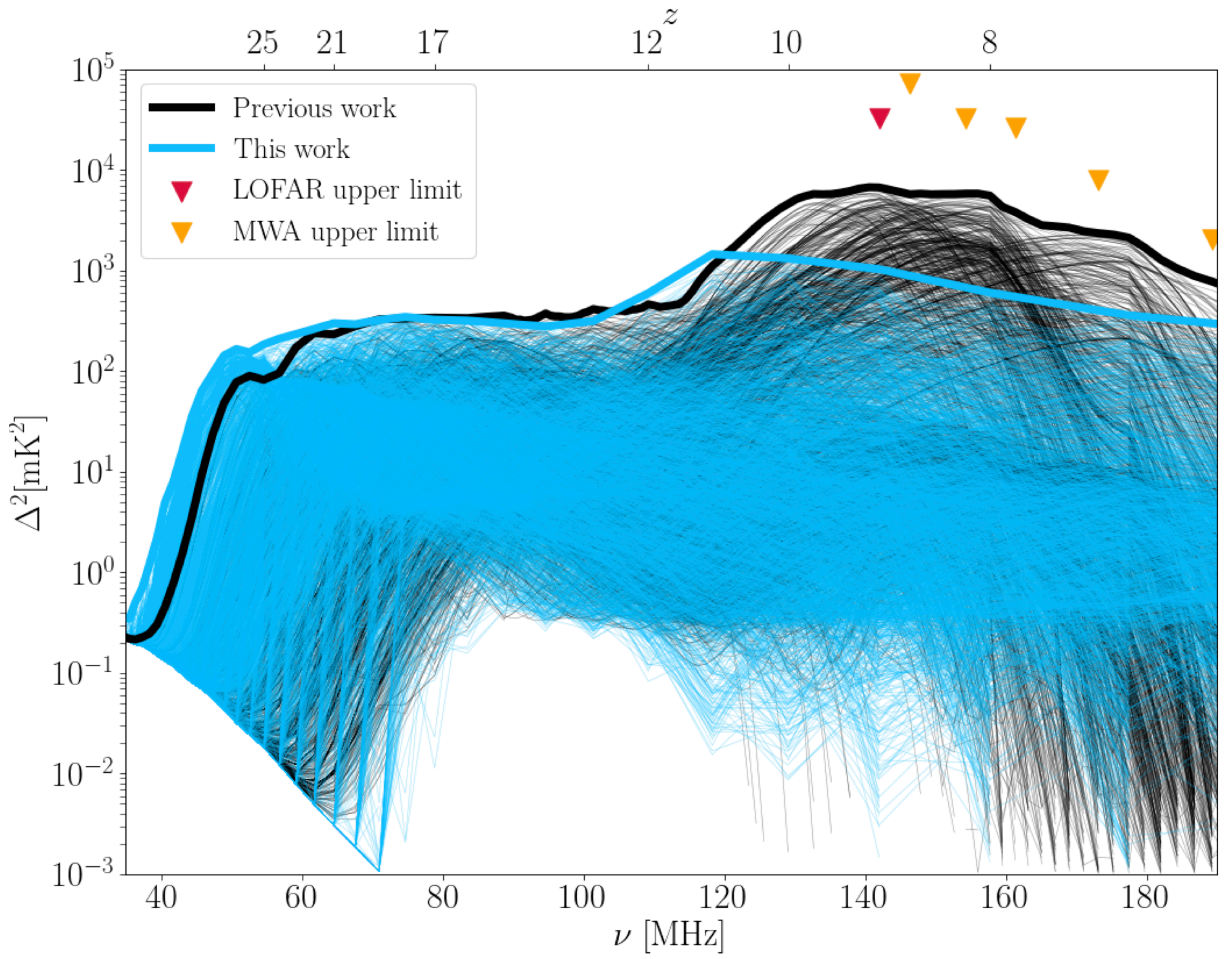


Signal Modelling

- Suite of semi-numerical models developed by Fialkov et al. [e.g. Reis et al. 2021 arXiv:2101.01777, Reis et al. 2020 arXiv:2008.04315]
- Star formation efficiency, f_*, and minimum viral circular velocity, $V_c \propto M_h^{1/3}$
- X-ray luminosity of early galaxies, L_X/SFR, which we model with an X-ray efficiency, f_X
- Dependent on the CMB optical depth, τ
- Excess radio background above the CMB from high redshift radio galaxies given by $L_r/\mathrm{SFR} \propto f_{\mathrm{radio}}$
- $\theta_{21} = \{f_*, V_c, f_X, \tau, f_{\mathrm{radio}}\}$
- Neural network emulators for both signals [e.g. Bevins et al. 2021 arXiv:2104.04336]



Reis et al. 2021 arXiv:2101.01777

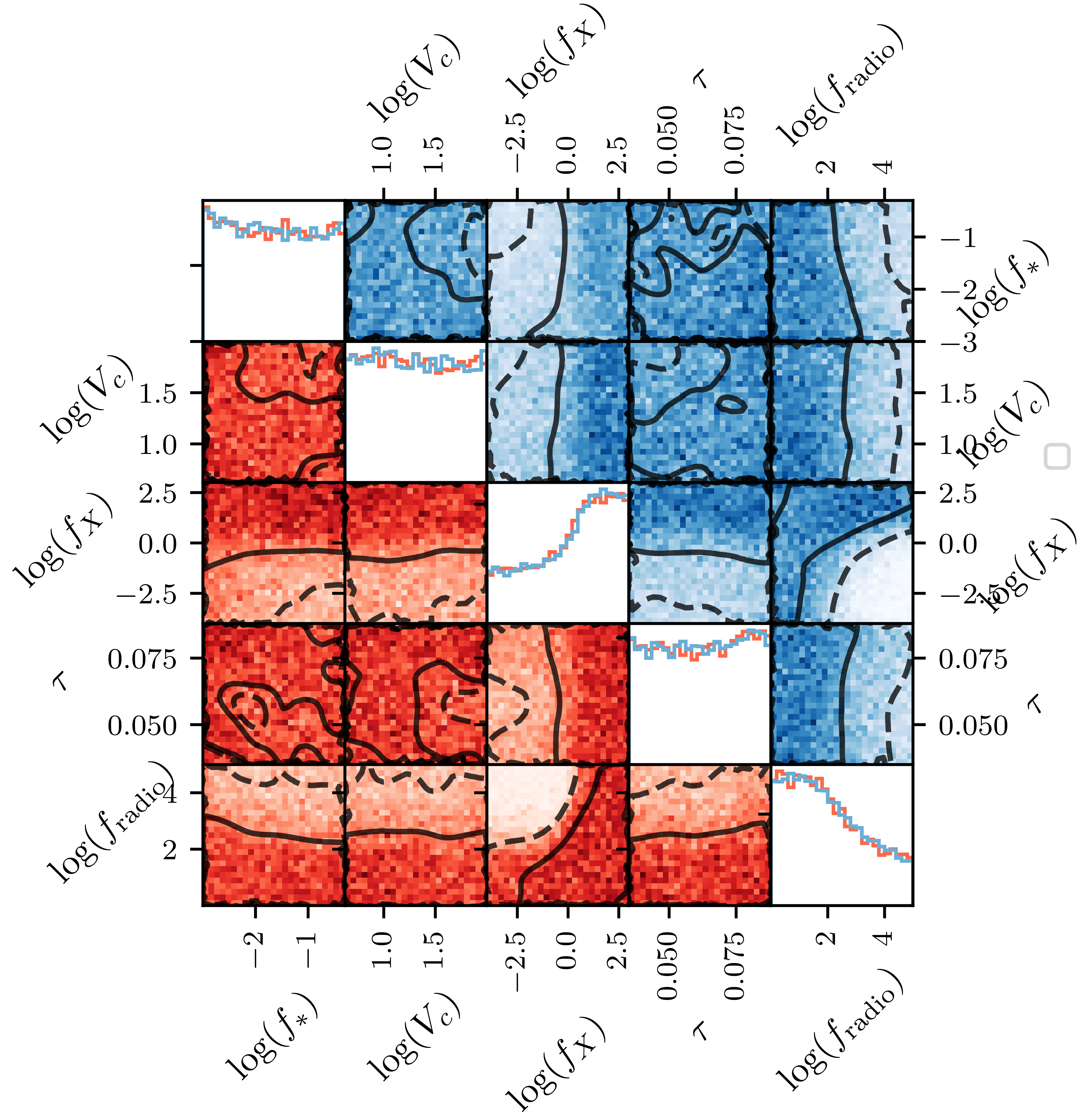


Methodology for Joint Analysis

Methodology: margarine

- Data sets include instrumental effects, θ_I, foregrounds, $\theta_{\rm fg}$, and the 21-cm signal, θ_{21}
- Not interested in θ_I and θ_{fg}
- margarine performs density estimation for a given set of samples using normalizing flows
- Once trained the flows can be used to evaluate probabilities like $\mathscr{P}(\theta_{21}\,|\,D, M)$ and $\pi(\theta_{21})$ and derive $\mathscr{L}(\theta_{21})$
- They can also be used to generate samples [Bevins et al. 2022b, arXiv:2207.11457] and calculate marginal Bayesian statistics [Bevins et al. 2022a, arXiv:2205.12841]

HERA Posterior:



Methodology: margarine

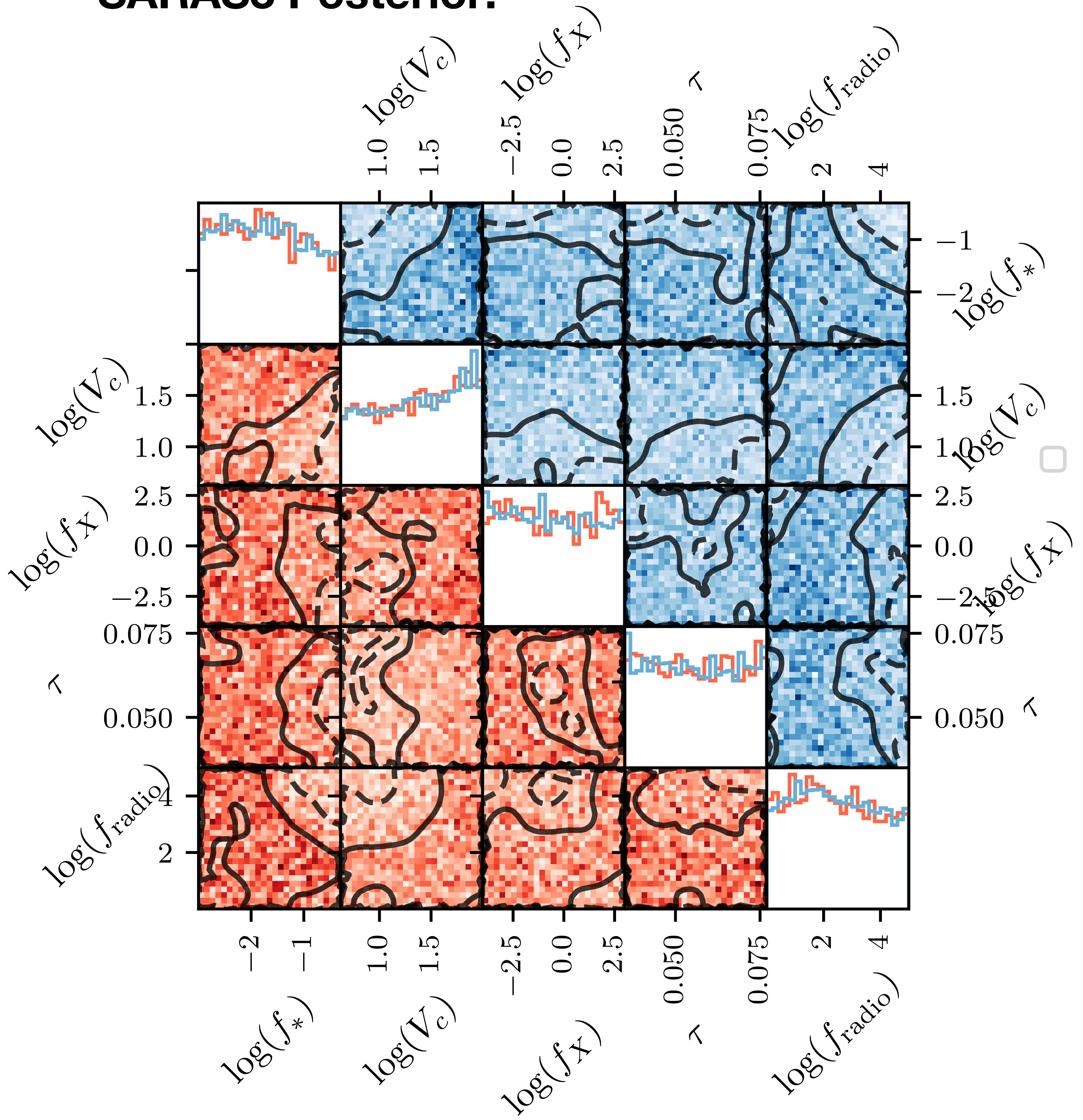
- We an use margarine to evaluate

$$\log(\mathcal{L}_{\text{joint}}(\theta_{21})) = \log(\mathcal{L}_{\text{HERA}}(\theta_{21})) + \log(\mathcal{L}_{\text{SARAS3}}(\theta_{21}))$$

And sample this using Nested Sampling and our signal emulators

- No need to sample nuisance parameters θ_I and θ_{fg}

SARAS3 Posterior:



Constraints

Constraints: Astrophysical properties

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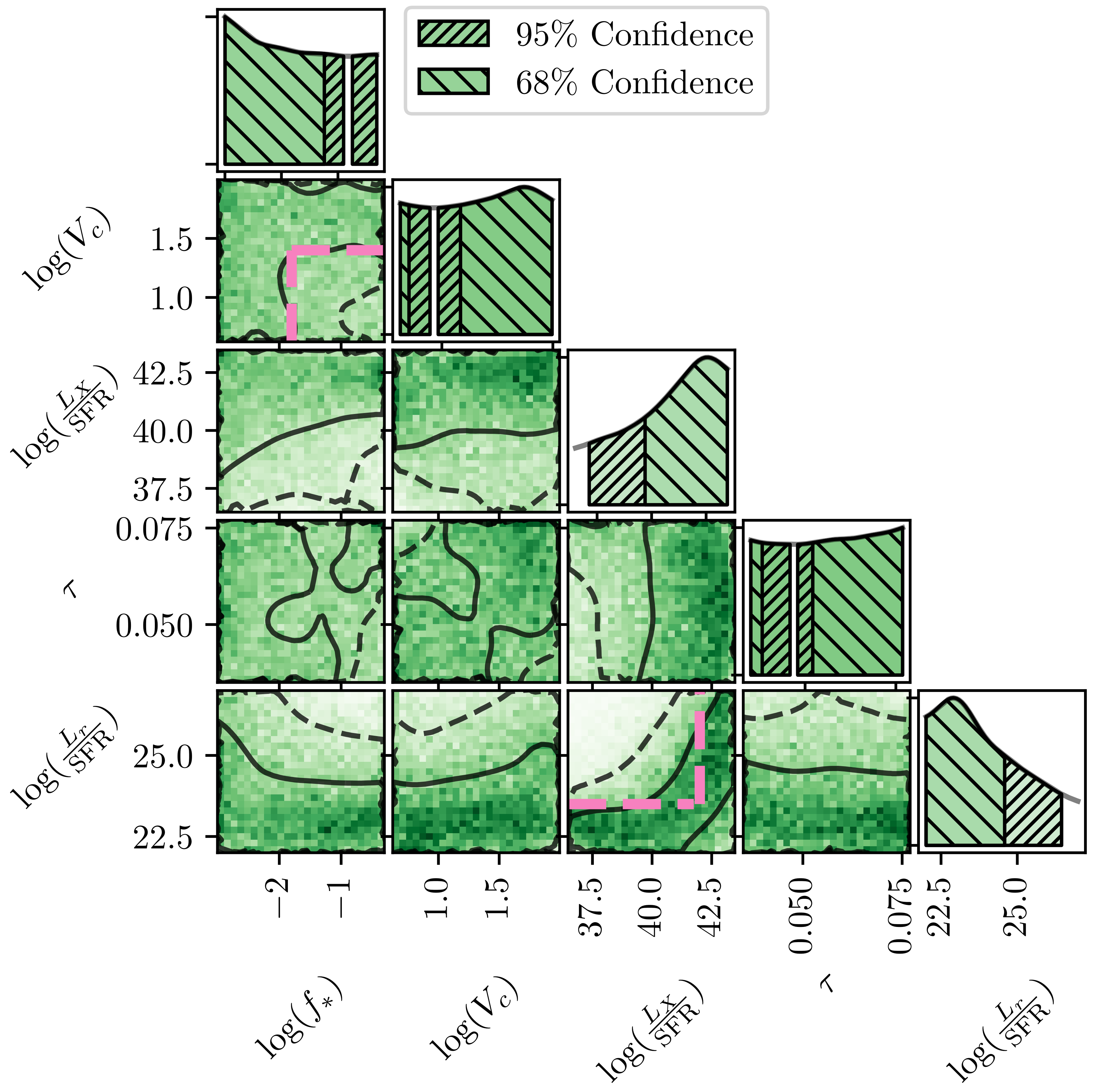
- Constraints are dominated by HERA but SARAS3 provides information about stars at $z \approx 20$

- Our joint analysis disfavours
  - High radio background in combination with low X-ray emission from galaxies
  - At 68% confidence star formation efficiencies $f_* \gtrsim 0.02$ and $M_h \lesssim 4.5 \times 10^7\ \mathrm{M}_\odot$

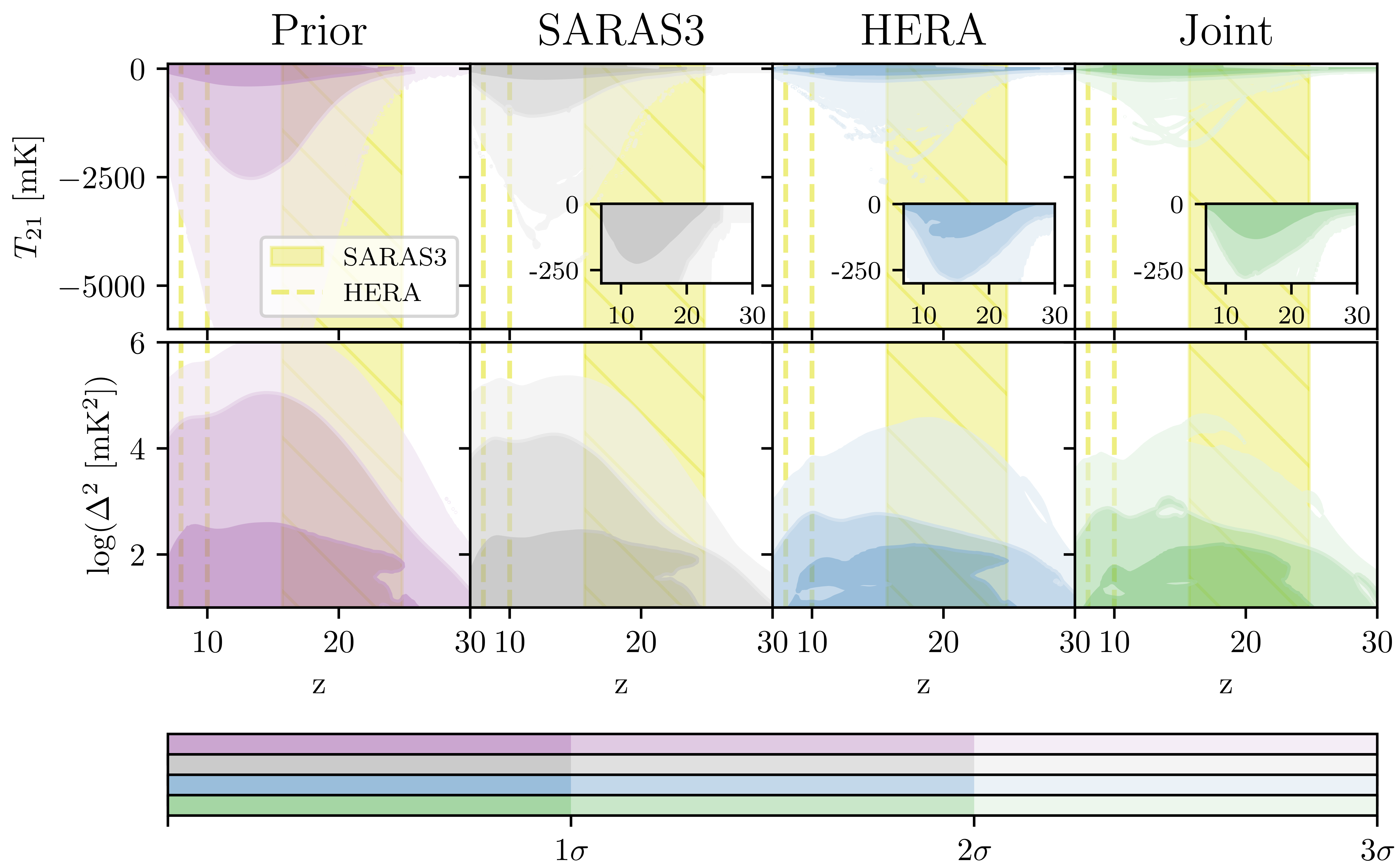


Signal Magnitudes

- 3σ constraint on global signal reduced from -2630 mK to -1770 mK at $z = 15$ and for the power spectrum from $10^{3.7}$ mK² to $10^{3.2}$ mK² at $z = 25$

- 3σ limit on the power spectrum is close to the expected sensitivity of NenuFAR from 1000 hours of observations [Mertens et al. 2021 arXiv:2109.10055]

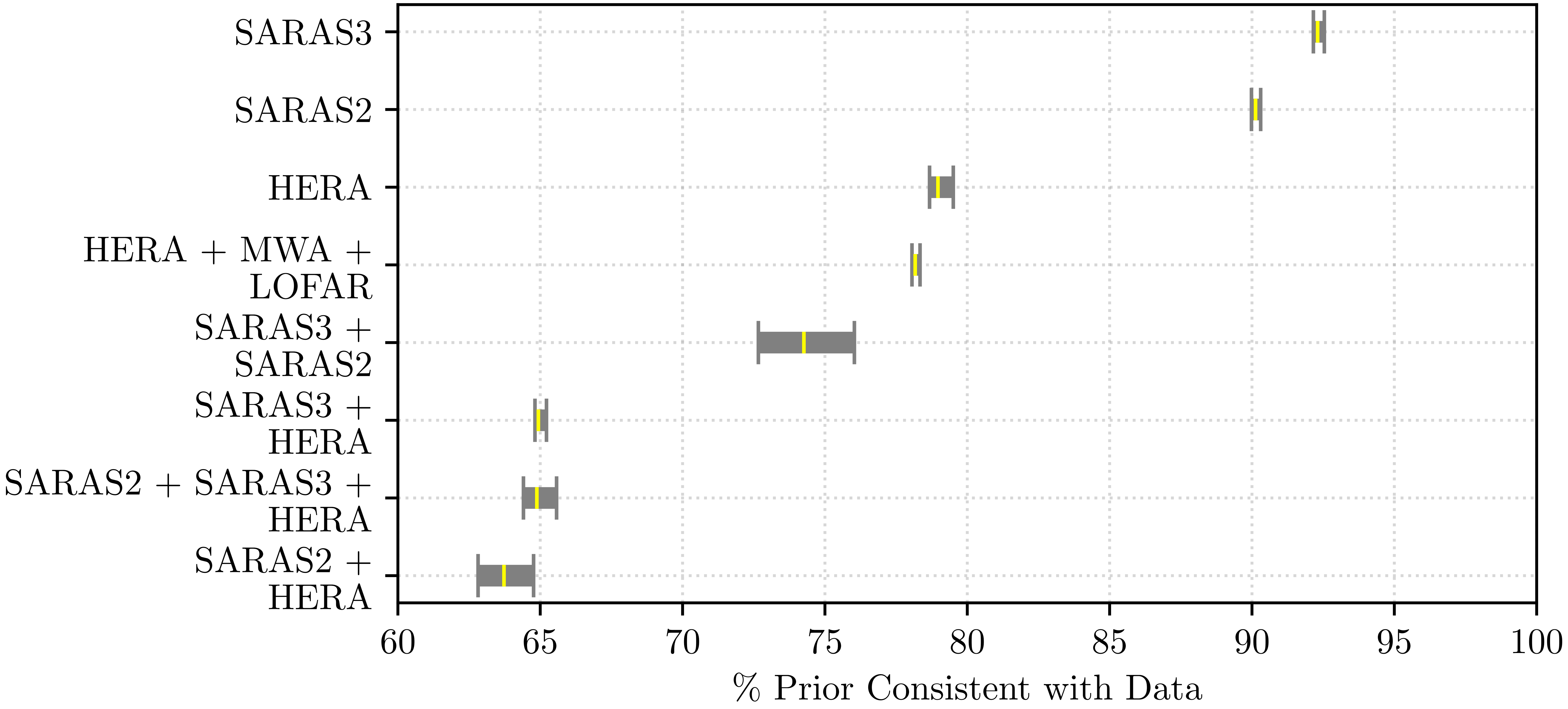
- 2σ limit on the global signal is ≥ -277 mK close to expectations for models with $T_r = T_{\rm CMB}$ [Reis et al. 2021 arXiv:2101.01777]



Constraining Power

- Use $\mathtt{margarine}$ to assess KL-divergence in θ_{21} parameter space and calculate

$$\% = 100 \times \exp(-\mathcal{D}) \approx 100 \times \frac{V_{\mathcal{P}}}{V_{\pi}}$$



Conclusions

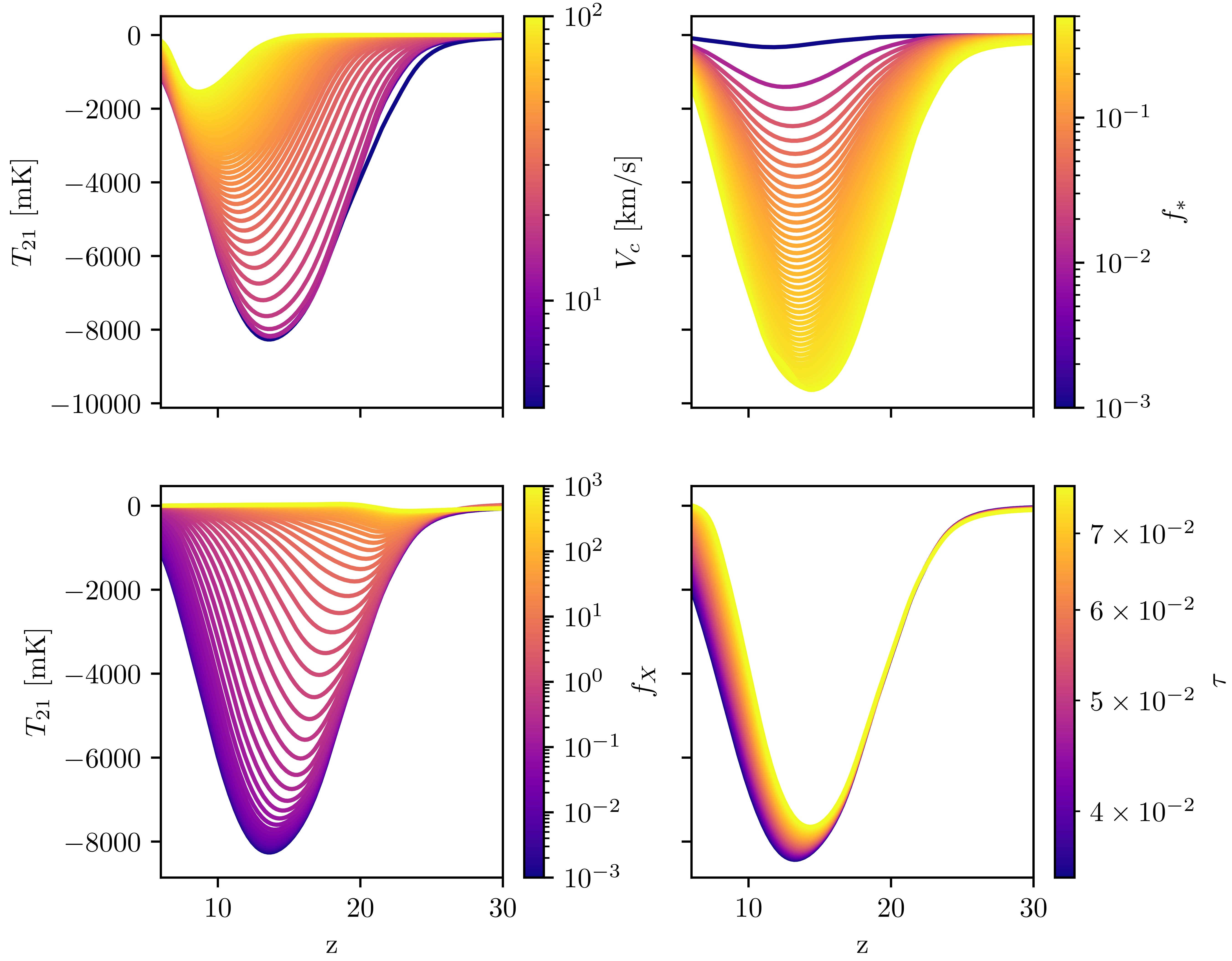
- Through our joint analysis of HERA and SARAS3 we have improved constraints on the properties of the first galaxies and the magnitude of the 21-cm signal

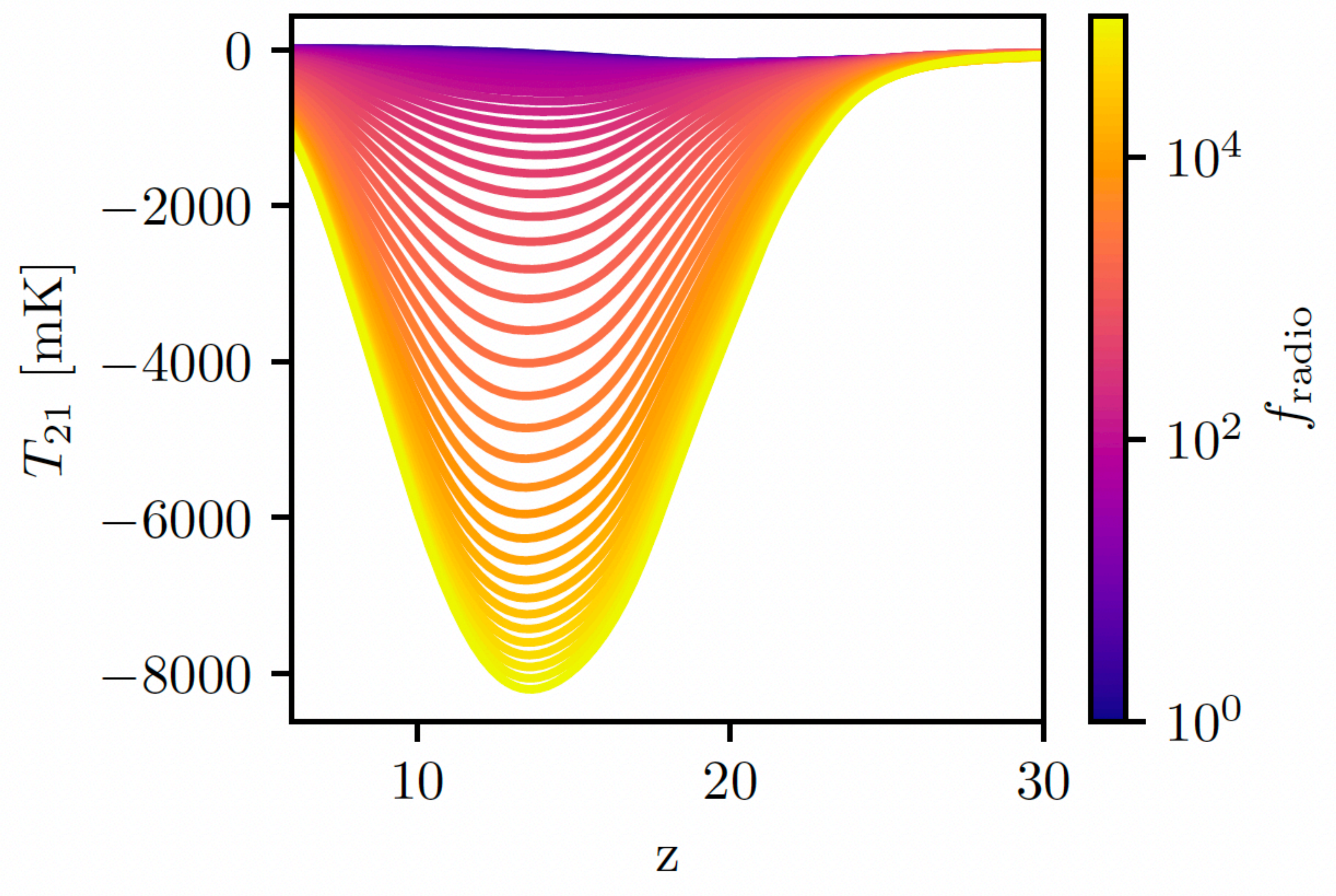
- Further, we have pioneered a new method for performing joint analysis with normalizing flows (`margarine` is available at https://github.com/htjb/margarine)

- The limits from 21-cm cosmology are currently being updated by

  - Simon Pochinda; adding in X-ray background constraints from Chandra+ and distinguishing constraints on PopII and PopIII star formation efficiencies
  - Thomas Gessey-Jones; Constraining a potential radio background from cosmic strings


The 21-cm signal





Methodology

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$$\log(\mathcal{L}_{\mathrm{joint}}(\theta_{21})) = \log(\mathcal{L}_{\mathrm{HERA}}(\theta_{21})) + \log(\mathcal{L}_{\mathrm{SARAS3}}(\theta_{21}))$$

$$\mathcal{L}(\theta_{21}) \equiv \frac{\int \mathcal{L}(\theta_{21}, \alpha)\pi(\theta_{21}, \alpha)d\alpha}{\int \pi(\theta_{21}, \alpha)d\alpha} = \frac{\mathcal{P}(\theta_{21}|D,\mathcal{M})\mathcal{Z}}{\pi(\theta_{21})}$$

Need to be able to evaluate $\mathscr{P}(\theta_{21}\,|\,D, M)$ and $\pi(\theta_{21})$ for a set θ_{21}

Methodology

$$\mathcal{P}(\theta|D,\mathcal{M}) = \frac{\mathcal{L}(\theta)\pi(\theta)}{\mathcal{Z}} \qquad \theta = \{\theta_I, \theta_{fg}, \theta_{21}\}$$

$$\log(\mathcal{L}_{\mathrm{joint}}(\theta_{21})) = \log(\mathcal{L}_{\mathrm{HERA}}(\theta_{21})) + \log(\mathcal{L}_{\mathrm{SARAS3}}(\theta_{21}))$$

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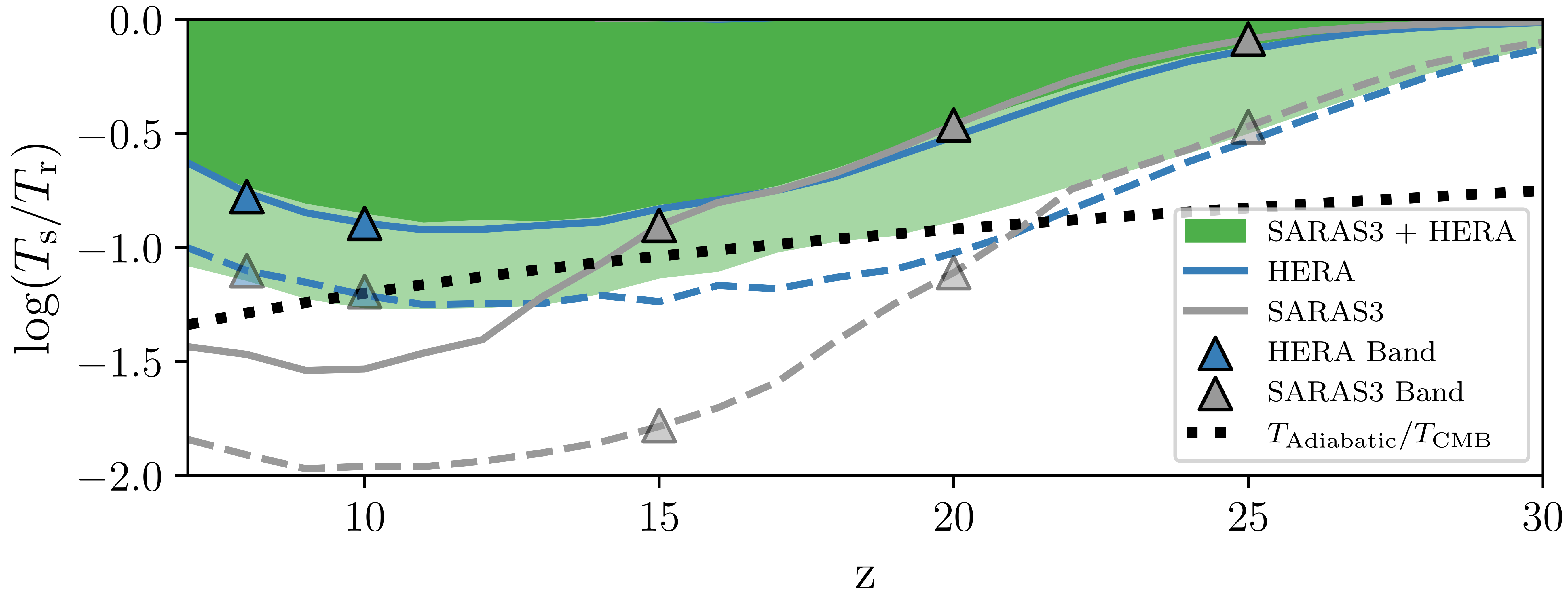
For an individual experiment we have…

$$\theta = \{\theta_I, \theta_{fg}, \theta_{21}\} \rightarrow \{\theta_{21}\} \boxed{\rightarrow \mathrm{MARGARINE} \rightarrow} \log(\mathcal{P}(\theta_{21}|D,\mathcal{M}) \rightarrow \log(\mathcal{L}(\theta_{21}))$$

Constraints: Gas Properties

- 21-cm directly related to the ratio of the spin temperature, $T_s(\theta_{21})$, and radio background temperature, $T_r(\theta_{21})$
- Deeper the ratio then deeper the sky-averaged signal
- Improved constraints at high-z
- Greater confidence across a range of redshifts

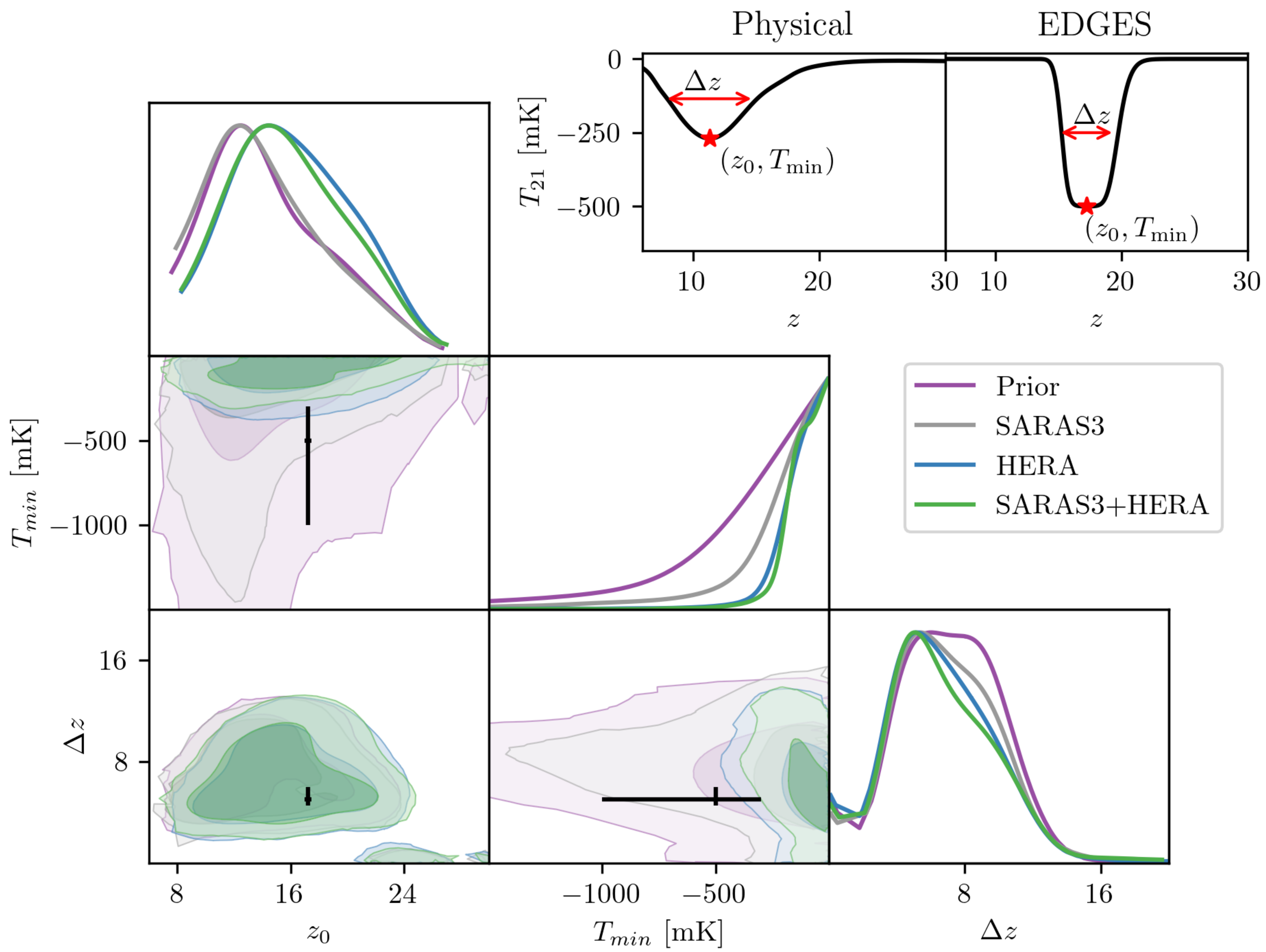


Implications for EGDES

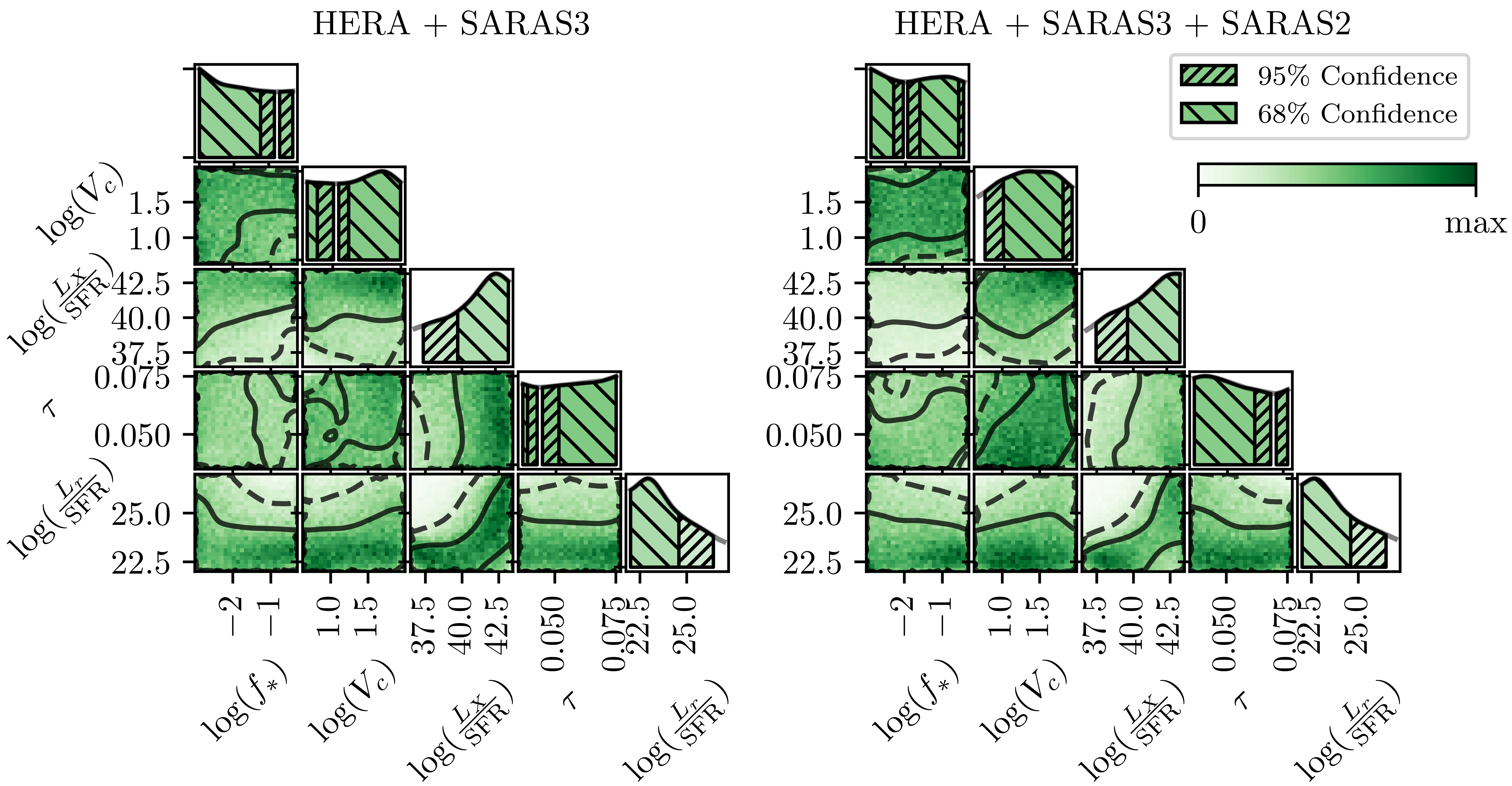
- EDGES made a controversial detection of the sky averaged 21-cm signal in 2018 [Bowman et al. 2018 arXiv:1810.05912]

- Translate constraints on the astrophysical parameters to constraints on the depth, $T_{\rm min}$, central redshift, z_0, and width of the signal, Δz

- We find that the joint analysis rules out signals with the same depth as EDGES with 2σ significance



Other Global experiments: SARAS2



Other Interferometers: MWA and LOFAR