UNIVERSITY OF CAMBRIDGE

CAVENDISH ASTROPHYSICS
RADIO COSMOLOGY
Science Technology Engineering Mathematics

Astrophysics from the SARAS3 non-detection of the global 21-cm signal

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with
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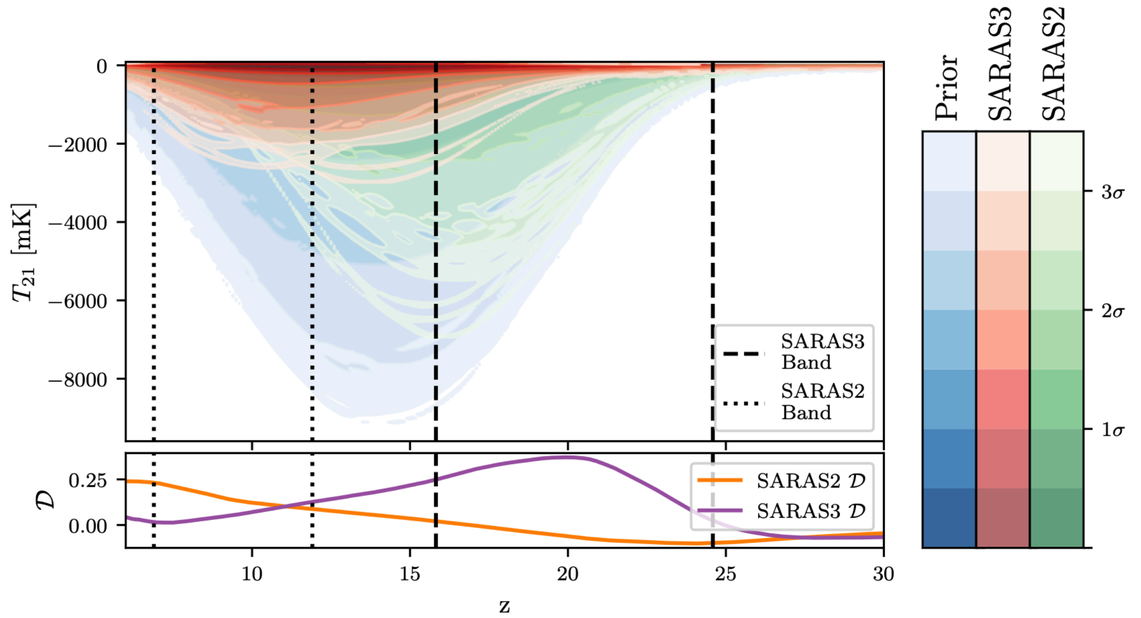
The plan

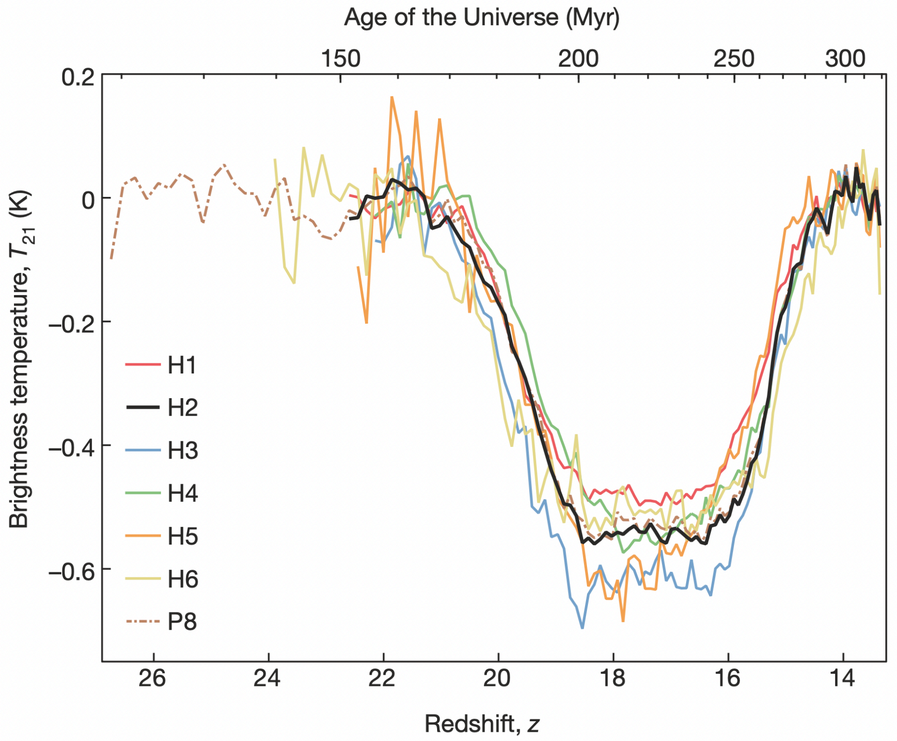
1. Recap the data
2. Introduce the modelling
3. Discuss our results
4. Discuss future work



The Data

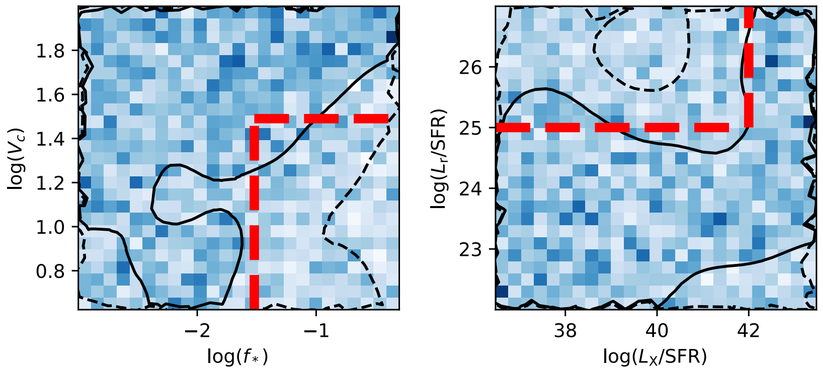
The EDGES

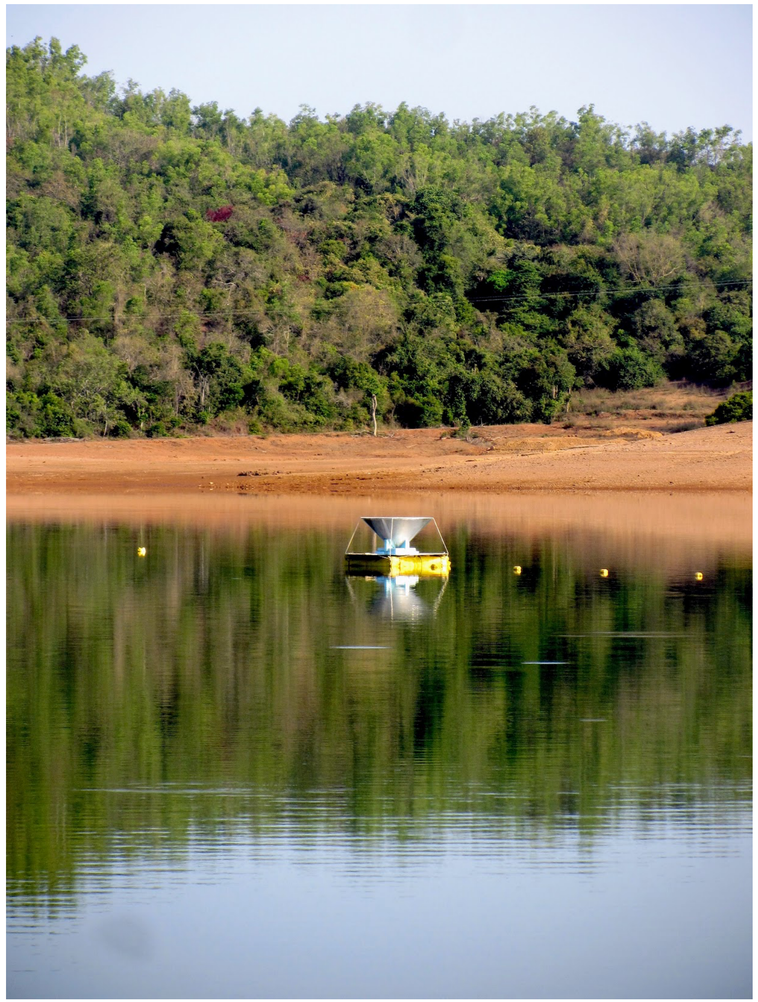
- Reported an absorption feature in Bowman et al. 2018[arXiv:1810.05912]
- First time the residuals were low enough to draw conclusions about cosmological signal
- There are constraints e.g. on the onset of star formation from this work [e.g. Mirocha and Furlanetto 2018 arXiv:1803.03272]
- Standard astrophysical models do not reproduce the shape [Fialkov et al. 2019 arXiv:1902.02438 , Reis et al. 2020 arXiv:2008.04315]
- Concerns about the data analysis and the nature of the cosmological signal [e.g. Hills et al. 2018 arXiv:1805.01421 among others]



The SARAS3 Experiment

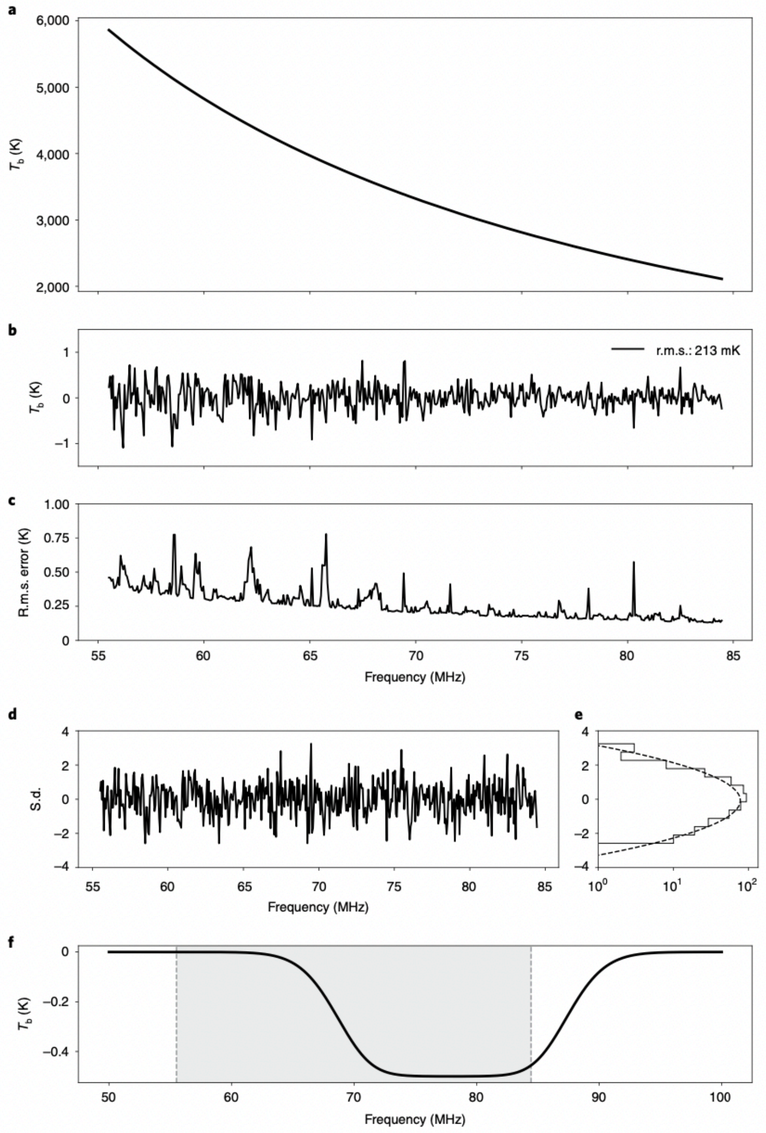
- Reported a non-detection of the EDGES absorption feature at 95.3% confidence in S. Singh et al. 2022 [arXiv:2112.06778]
- Measurements taken from a lake in southern India between $z = 15 - 25$ overlapping EDGES redshift range
- Here we use the reported upper limits to constrain astrophysical scenarios





The SARAS3 Experiment

- 15hrs of observations between $55 - 85$ MHz $(z = 15 - 25)$
- Filtered for RFI and corrections are made for the emission from the water
- Scaled, using a measurement of the total efficiency, to produce a measurement of the temperature of $T_{\rm sky}$



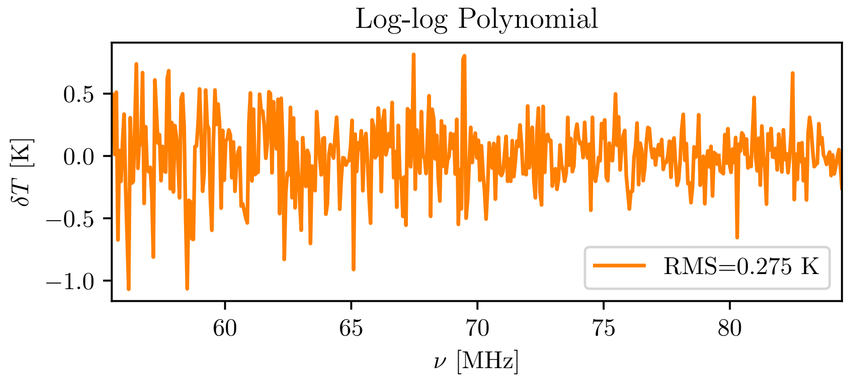
The Modelling

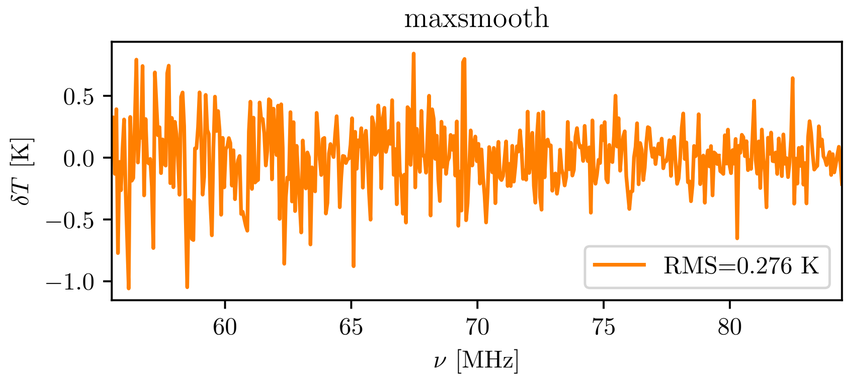
The foreground model

- We use the same log-log foreground model as in the original analysis

$$\log_{10} T_{\rm fg} = \sum_{i=0}^{i=6} a_i \left(\mathscr{R}(\log_{10}\nu)\right)^i$$

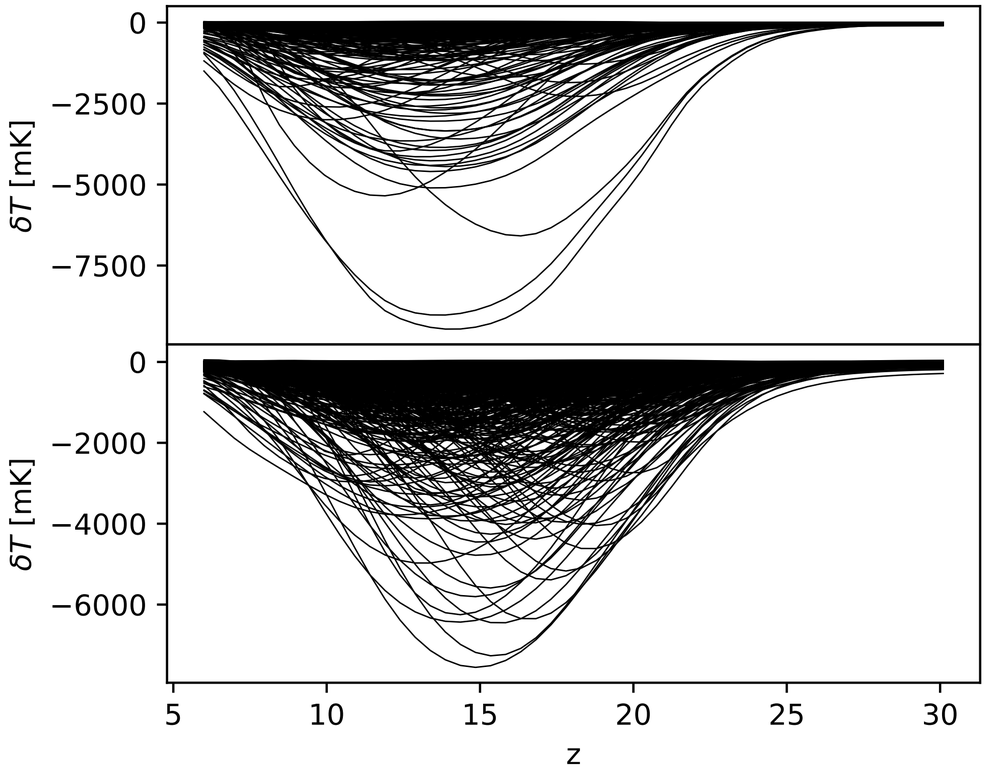
- However, we note that a MSF produces equivalent residuals [*maxsmooth,* Bevins et al. 2021, arXiv:2007.14970]



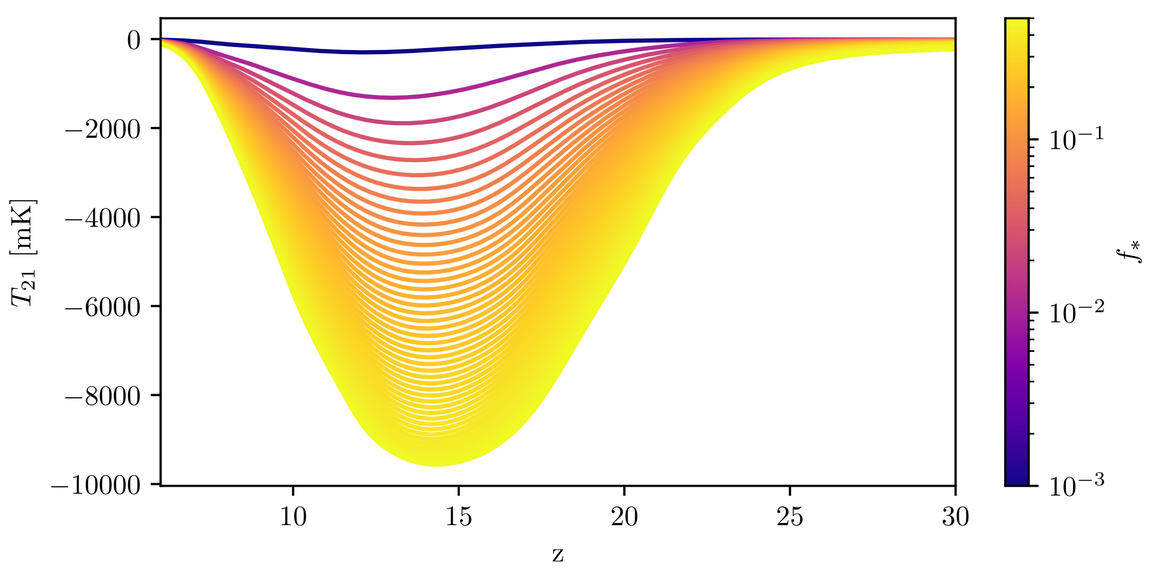


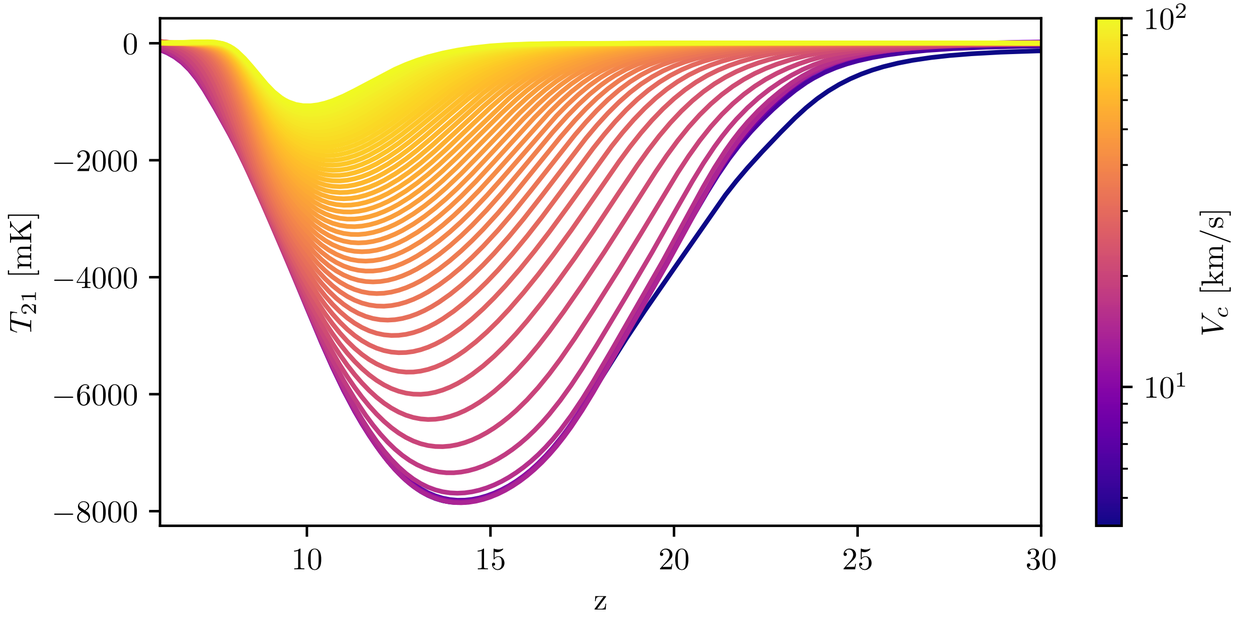
The signal models

- Models from Fialkov and collaborators
- Parametrised by a common set of astrophysical parameters;
  - f_*, the star formation efficiency
  - V_c, the viral circular velocity $\propto M^{1/3}$
  - f_x, the X-ray production efficiency $\propto L_X/\mathrm{SFR}$
  - τ, the CMB optical depth



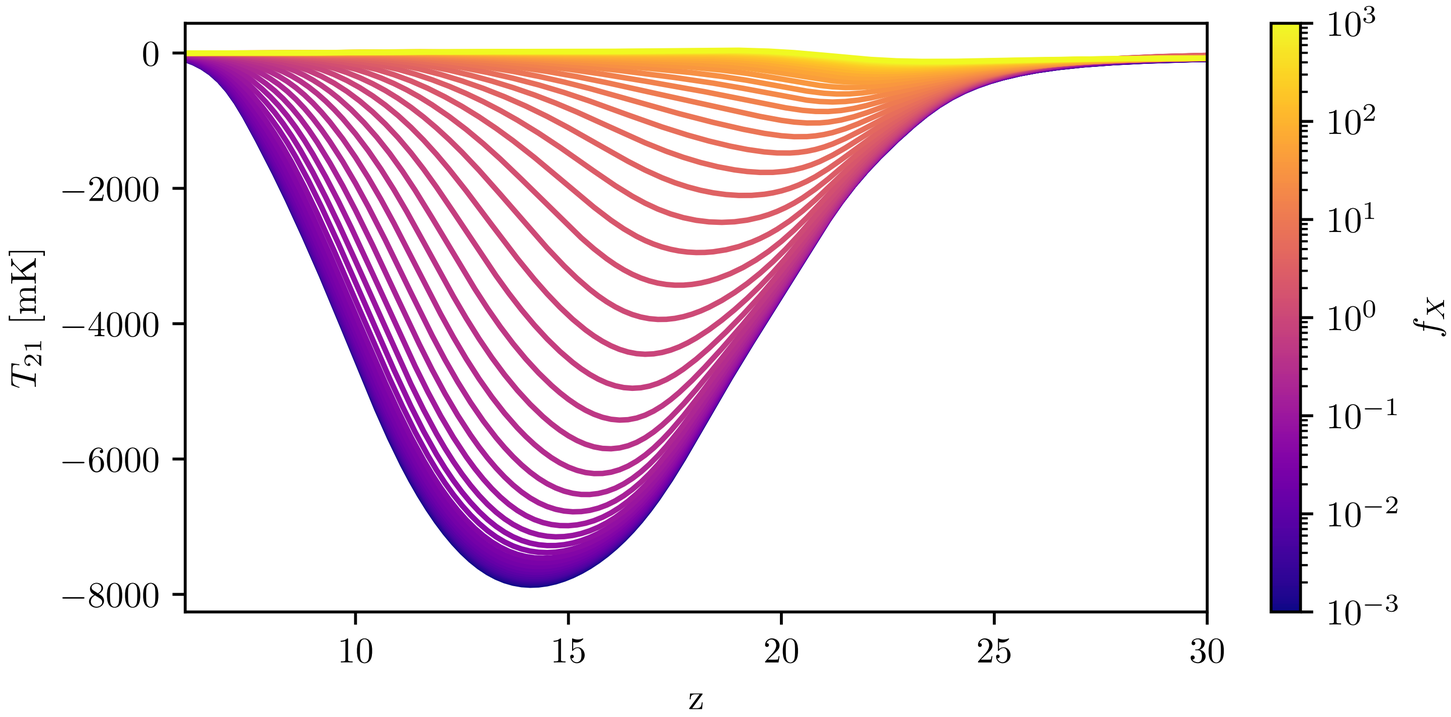
The effects of Star Formation





Low V_c and high f_* →high star formation rates → deep 21-cm signals

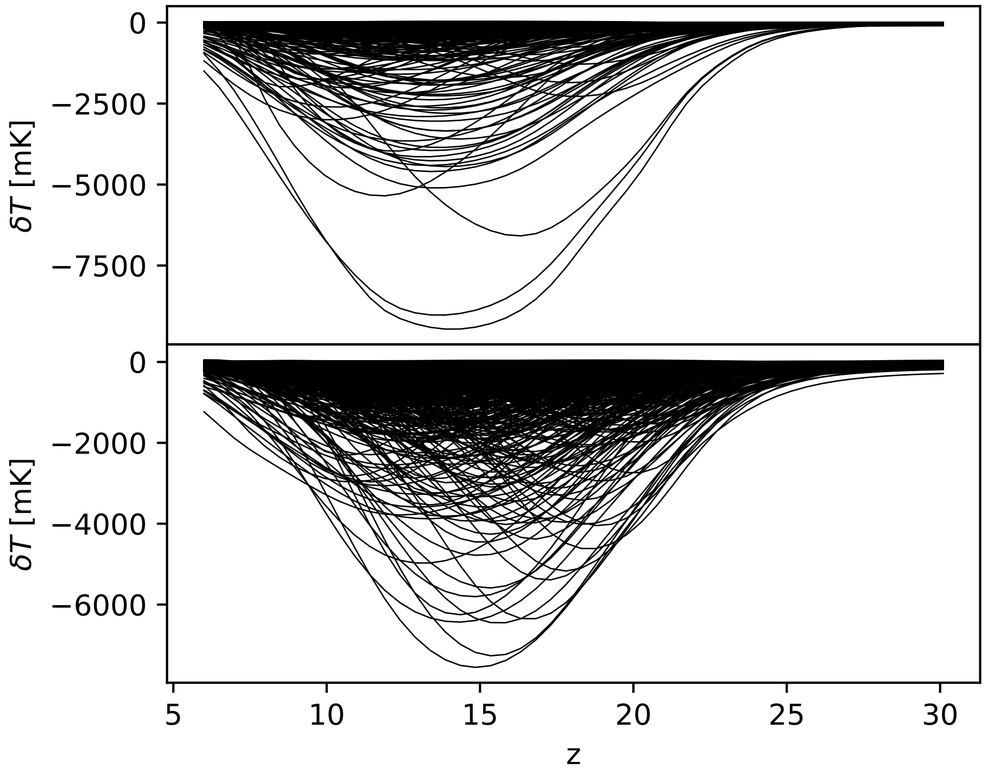
The X-ray Luminosity



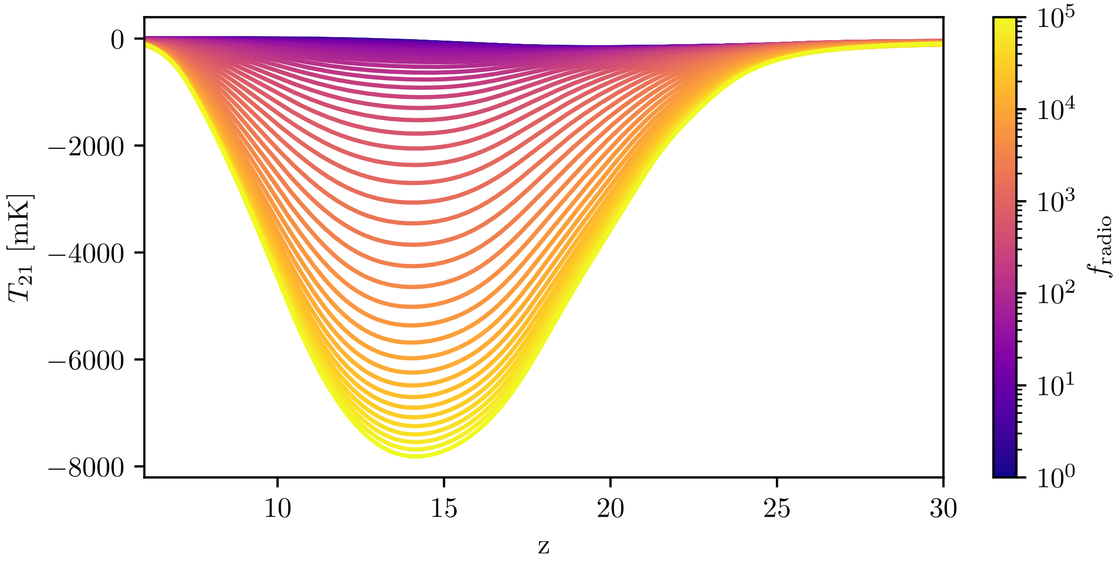
Low f_X → inefficient X-ray heating → deep 21-cm signals

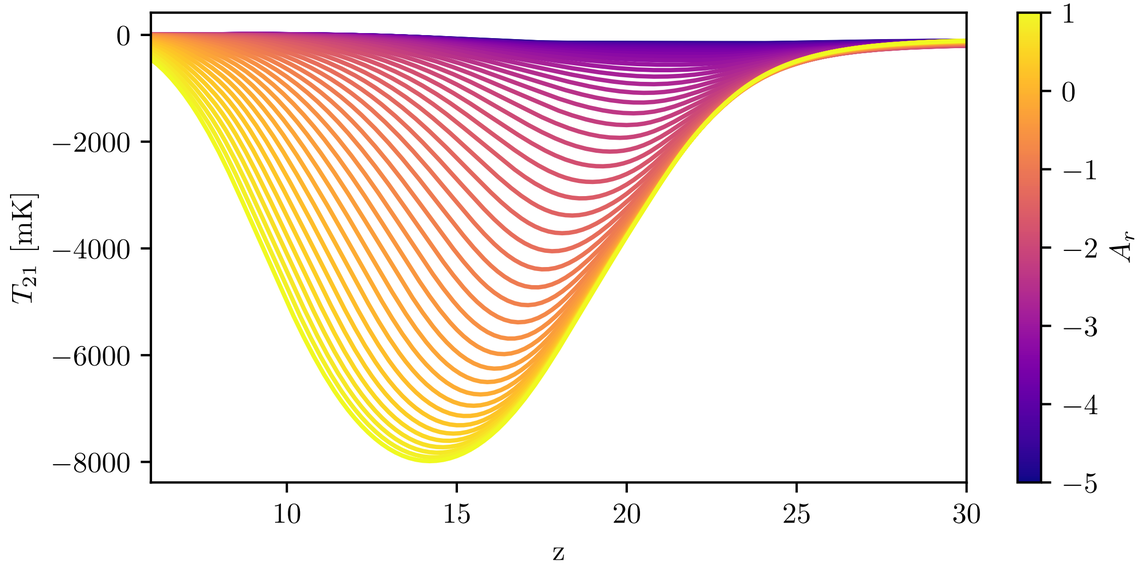
The signal models

- And two different parameterisations of an excess radio background;
  - From high redshift radio galaxies via $f_{\rm radio} \propto L_r/{\rm SFR}$ at 150 MHz [Reis et al. 2020, arXiv:2008.04315]
  - And separately from a phenomenological synchrotron source via A_r [Fialkov and Barkana 2019, arXiv:1902.02438]
- Originally motivated by EDGES but they don't account for implied rapid star formation and rapid X-ray heating



The Radio backgrounds

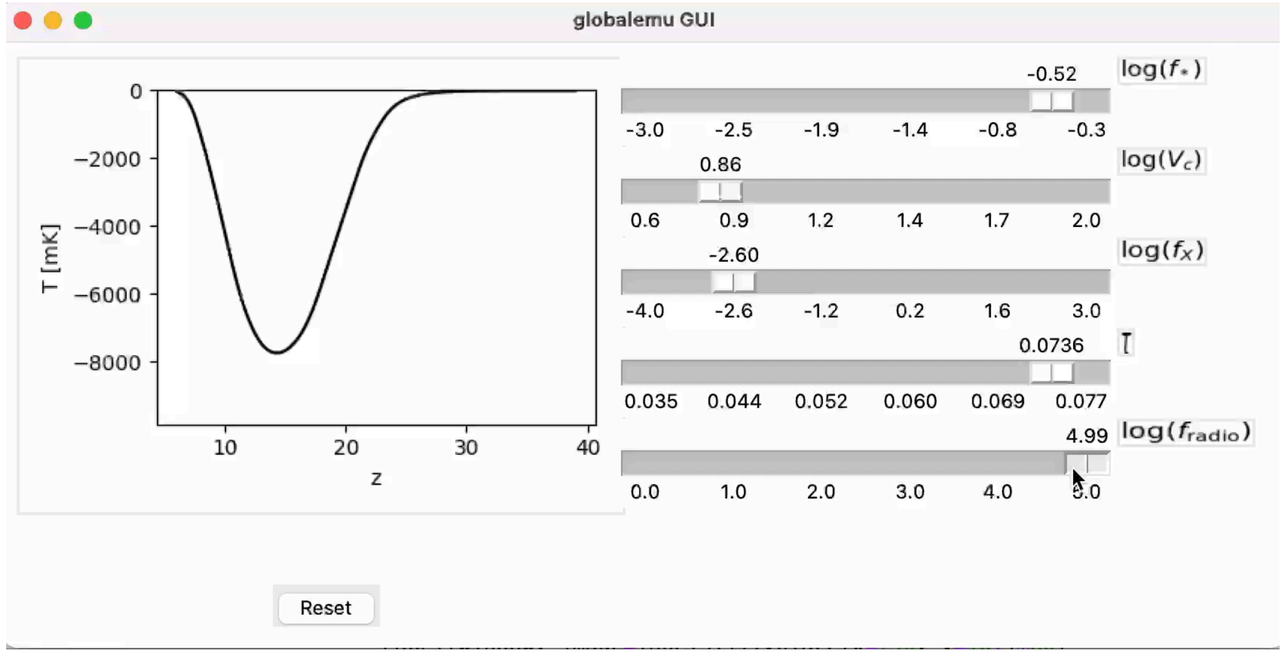




High $f_{\rm radio}$ or high A_r → large radio backgrounds → deep 21-cm signals

The signal models

- We use the neural network signal emulator *globalemu* [Bevins et al. 2021 arXiv:2104.04336]
- 95th percentile RMSE is 20.53 and 23.06 mK for Radio Galaxies and Synchrotron radio background models
- Equivalent to $< 10\,\%$ of the RMS from the foreground modelling



Background	Radio Galaxies	Synchrotron
Training Models	4311	9304
Testing Models	479	1034
Mean RMSE	5.11	7.98
95 Percentile RMSE	20.53	23.06
Worst RMSE	81.70	85.65

Bayesian Inference

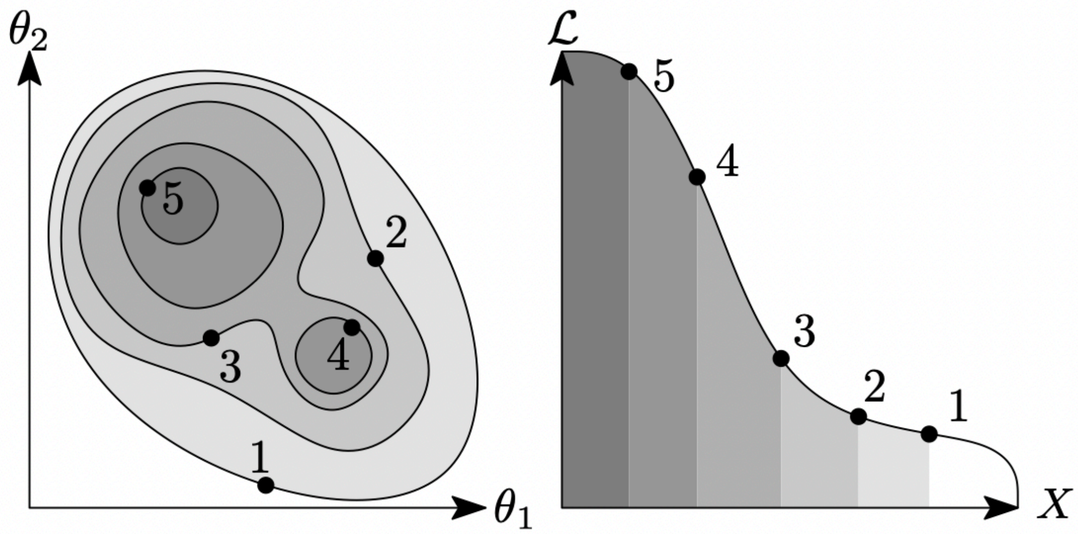
- Gaussian likelihood

$$\log \mathscr{L} = \sum_i \left(-\frac{1}{2}\log(2\pi\sigma^2) - \frac{1}{2}\left(\frac{T_{\rm D}(\nu_i) - T_{\rm fg}(\nu_i) - T_{21}(\nu_i)}{\sigma} \right)^2 \right)$$

- Uniform and log-uniform wide priors on astrophysical parameters and a prior of -10 and 10 on the foreground parameters

- Using Bayes theorem and nested sampling

$$P(\theta \,|\, D, M) = \frac{\mathscr{L}(\theta)\pi(\theta)}{\mathscr{Z}}$$

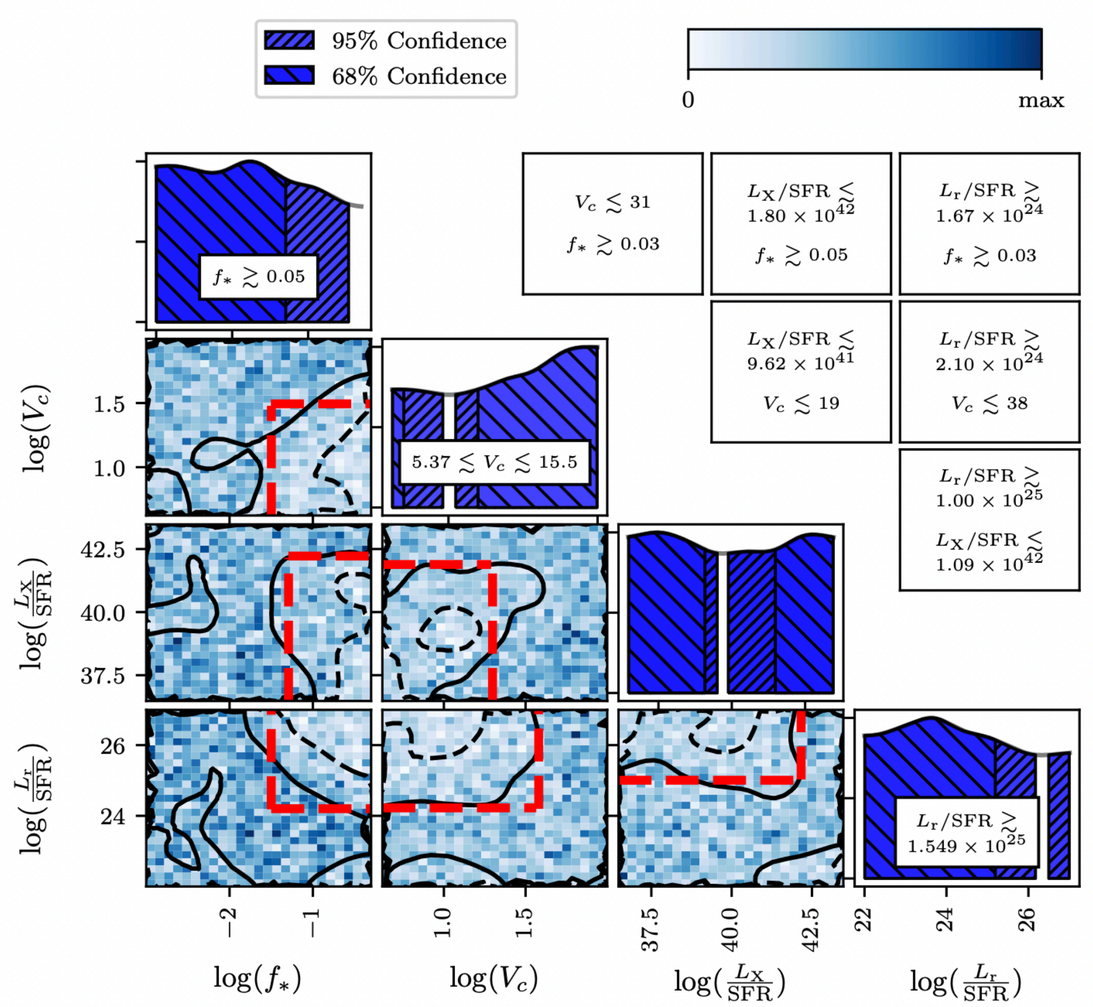


Polychord [Handley et al. 2015, arXiv:1502.01856, arXiv:1502.01856]

The Results

Radio Galaxies Results: Parameters

- We disfavour galaxies at 68% confidence that;
  - Have minimum star forming halos of mass $4.4 \times 10^5\ M_\odot \lesssim M \lesssim 1.1 \times 10^7\ M_\odot$



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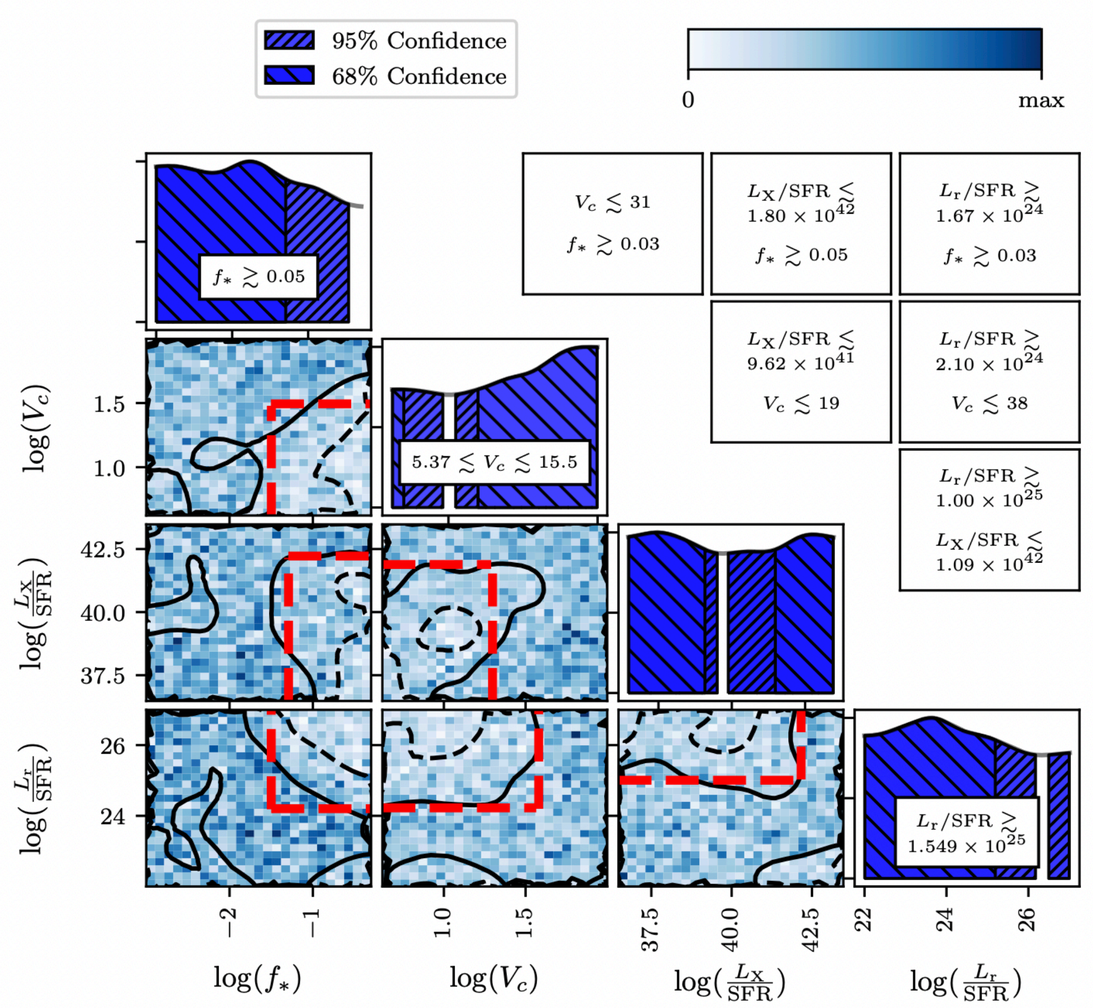

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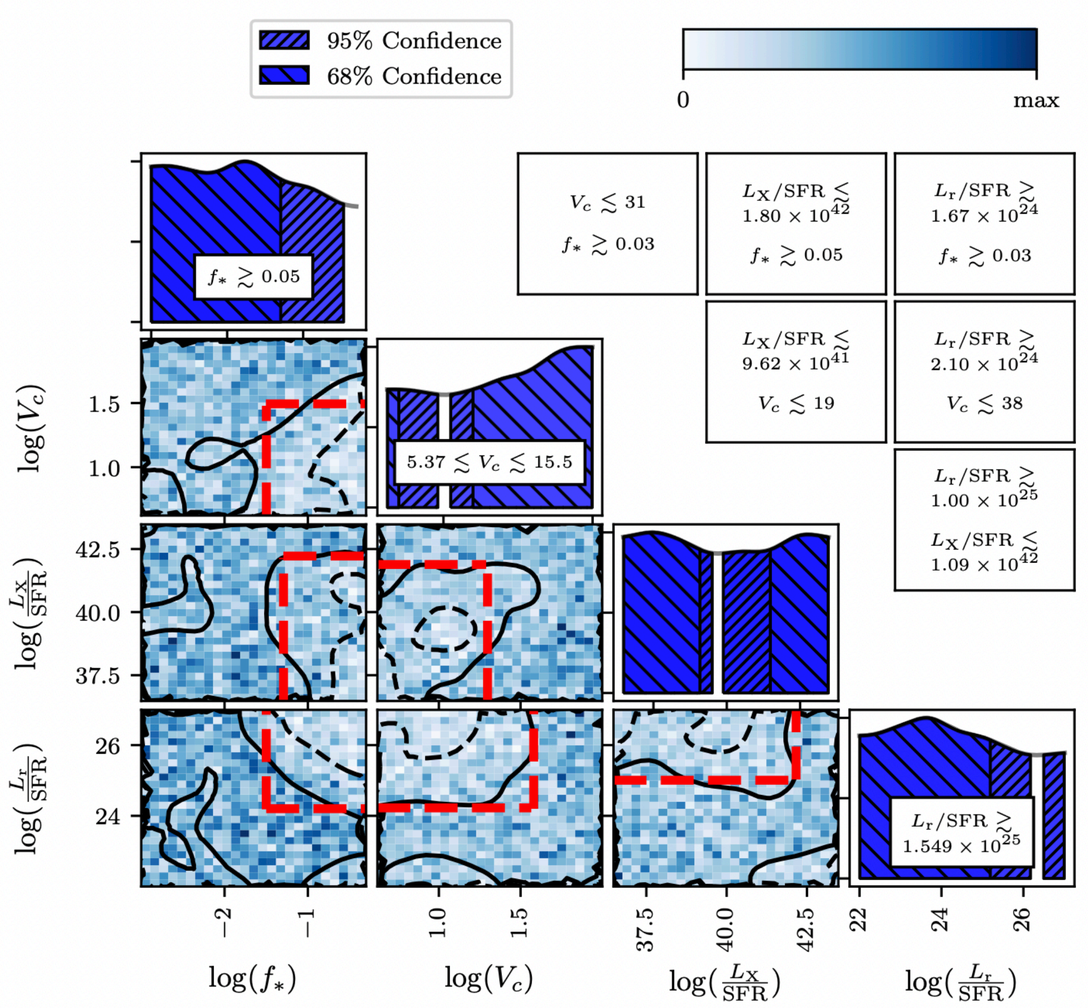
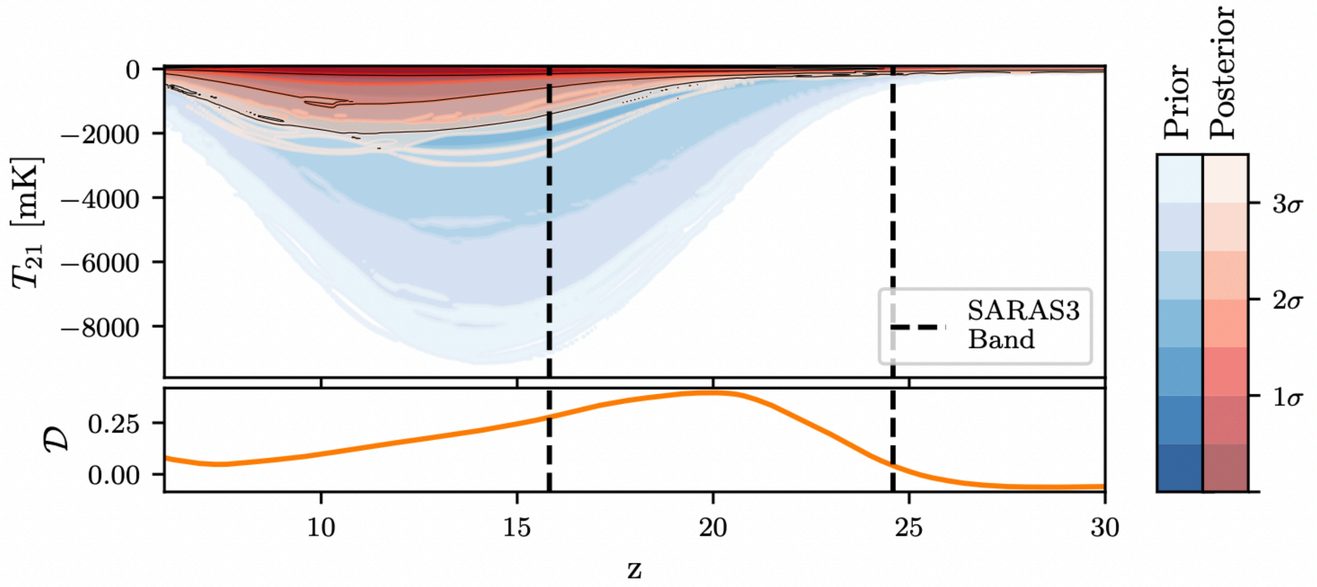
  - Convert more than $5\ \%$ of their mass to stars
  - Have X-ray luminosity of $L_{\rm X}/{\rm SFR} \lesssim 6.3 \times 10^{39} {\rm erg\ s^{-1} } M_\odot^{-1} yr$ in combination with $L_{\rm r}/{\rm SFR} \gtrsim 4.07 \times 10^{24}\ WHz^{-1} M_\odot^{-1} yr$



Radio Galaxies Results: The global signal

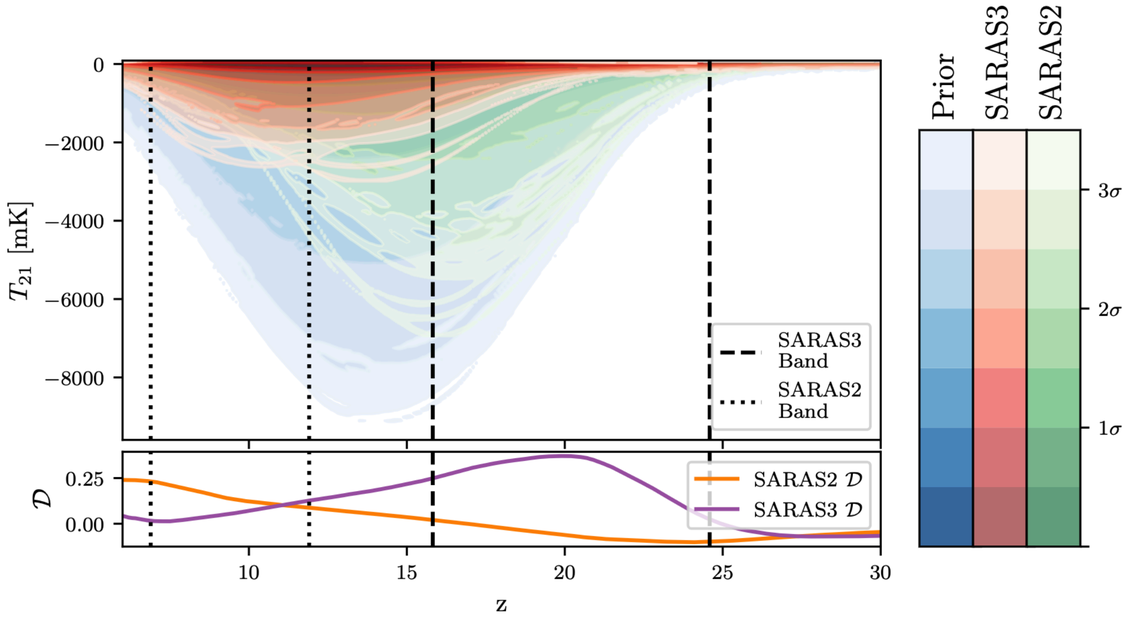
- This translates to constraints on the magnitude of the global 21-cm signal
- Comparing the functional prior with the functional posterior shows that the largest information gain is inside the SARAS3 band

$$\mathscr{D}(\mathscr{P}||\pi) = \int \mathscr{P}(\theta)\log_e\left(\frac{\mathscr{P}(\theta)}{\pi(\theta)}\right)d\theta = \left\langle \log_e\left(\frac{\mathscr{P}(\theta)}{\pi(\theta)}\right)\right\rangle_{\mathscr{P}}$$



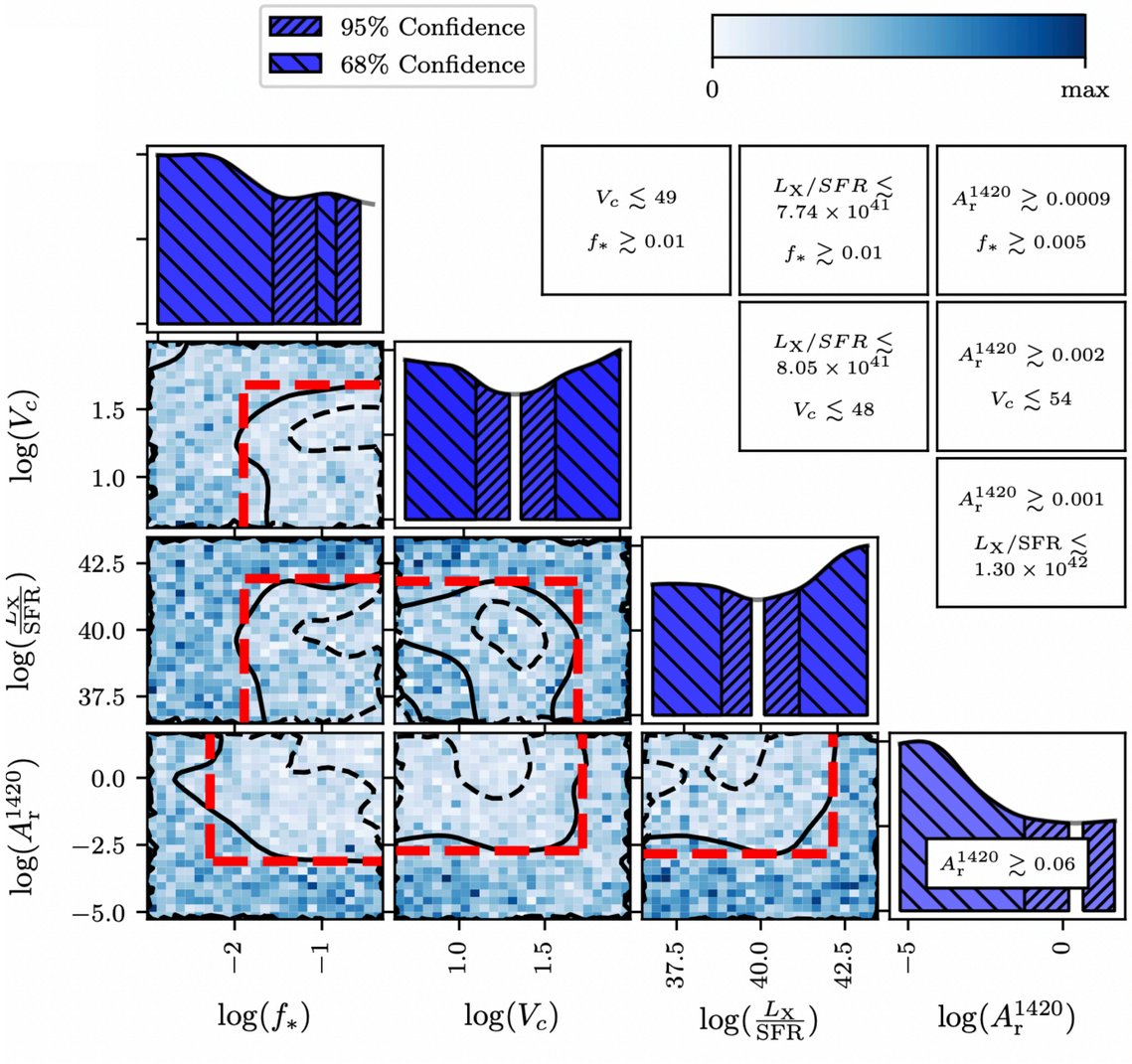
Radio Galaxies Results: A comparison to SARAS2

- We can compare our results with previous constraints from SARAS2 [Bevins et al. 2022 arXiv:2201.11531]
- Looking at the functional posteriors it appears that SARAS3 constraints the magnitude of the global signal to a higher degree
- However, the KL divergence tells us that each experiment provides the strongest constraints in their respective bands



Synchrotron Background Results: Parameters

- We disfavour key combinations of parameters at $68\,\%$ confidence corresponding to ;
  - A radio background in excess of the CMB by $\gtrsim 0.2\,\%$ at 1.4 GHz and $L_{\mathrm{X,0.2-95keV}} \lesssim 1.30 \times 10^{42}\ \mathrm{erg\ s^{-1} M_{\odot}^{-1} yr}$



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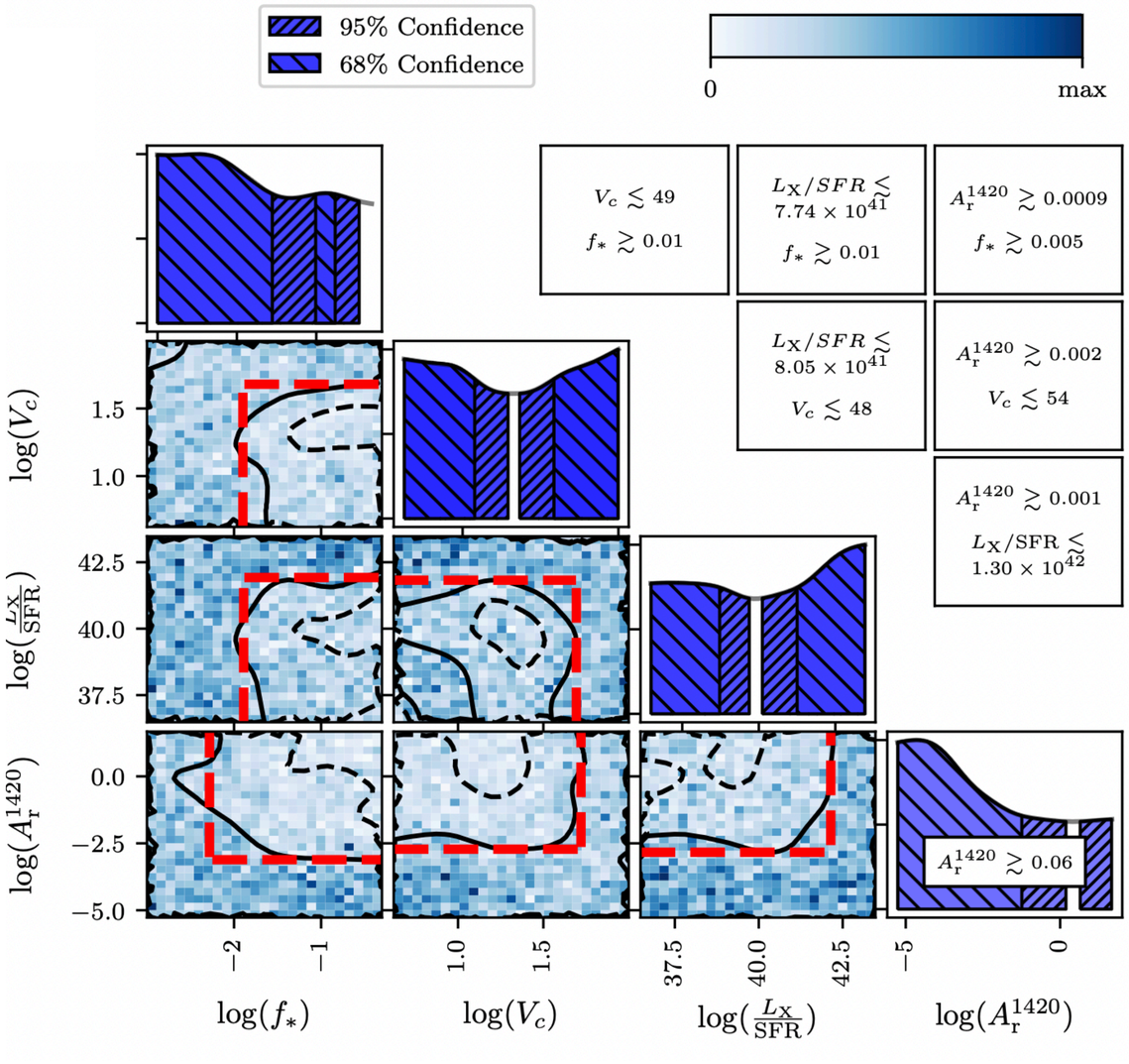
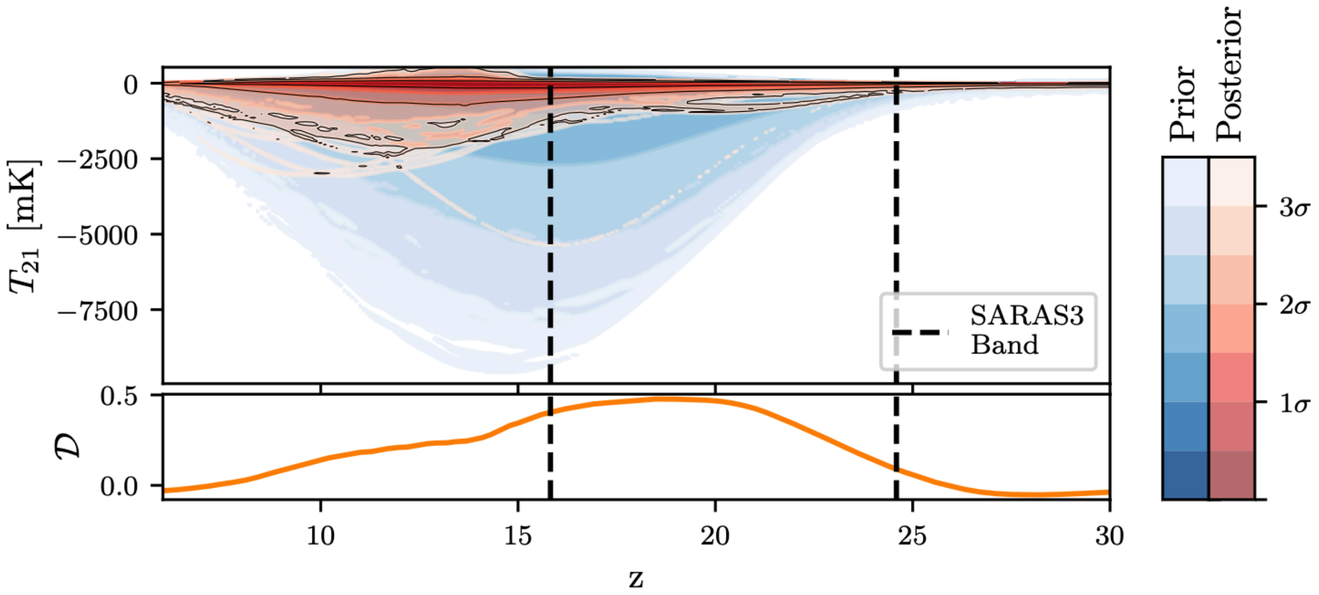
  - Galaxies in which $\gtrsim 1\,\%$ of gas is converted to stars with dark matter halo masses $M \lesssim 3.37 \times 10^{8}\ M_{\odot}$ at $z = 20$.



Synchrotron Background Results: The global signal

- Again these constraints correspond to strong constraints on the depth of the signal
- With the strongest constraint in the SARAS3 band

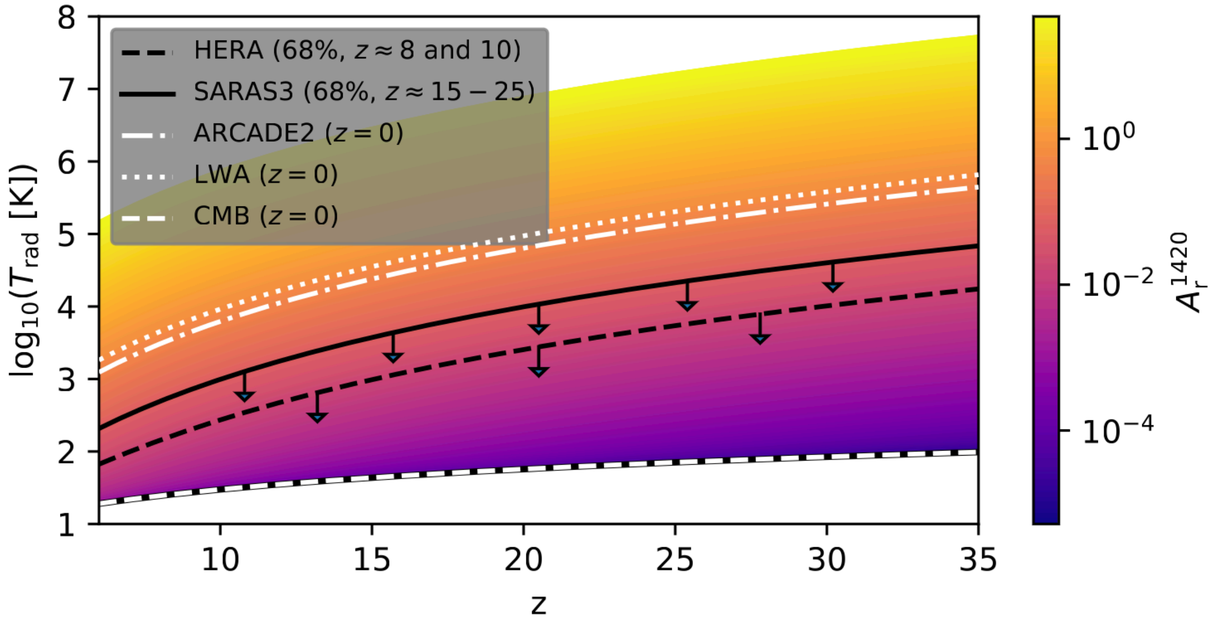


Synchrotron Background Results: The radio background

- We can compare constraints from HERA and SARAS3 with the measurements of the background from LWA and ARCADE2

$$T_{\rm rad} = T_{\rm CMB}\left[1 + A_{\rm r}^{78}\left(\frac{\nu}{78{\rm MHz}}\right)^{\beta}\right]$$

$$A_{\rm r}^{78} = A_{\rm r}^{1420}\left(\frac{0.078}{1.420}\right)^{\beta}$$

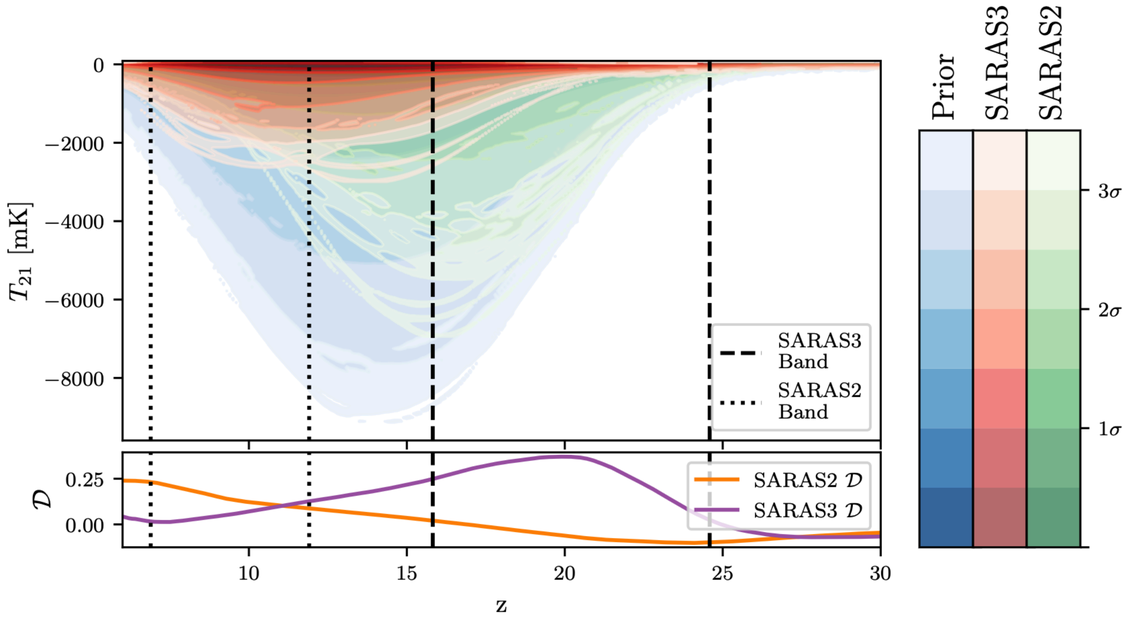


Future Work

Combining Datasets: the idea

with Stefan Heimersheim, Irene Abril-Cabezas, Anastasia Fialkov, Eloy de Lera Acedo,
Will Handley, Saurabh Singh and Rennan Barkana

- We want to take advantage of the constraining power of different available data sets including power spectrum data
- Further, we want to improve our knowledge of the signal across a wide range of frequencies
- We use the marginal Bayesian statistics code *margarine [Bevins et al. 2022 arXiv:2205.12841 and arXiv:2207.11457]* to explore this concept



Stefan Heimersheim, 4th Year PhD, IoA Cambridge, UK

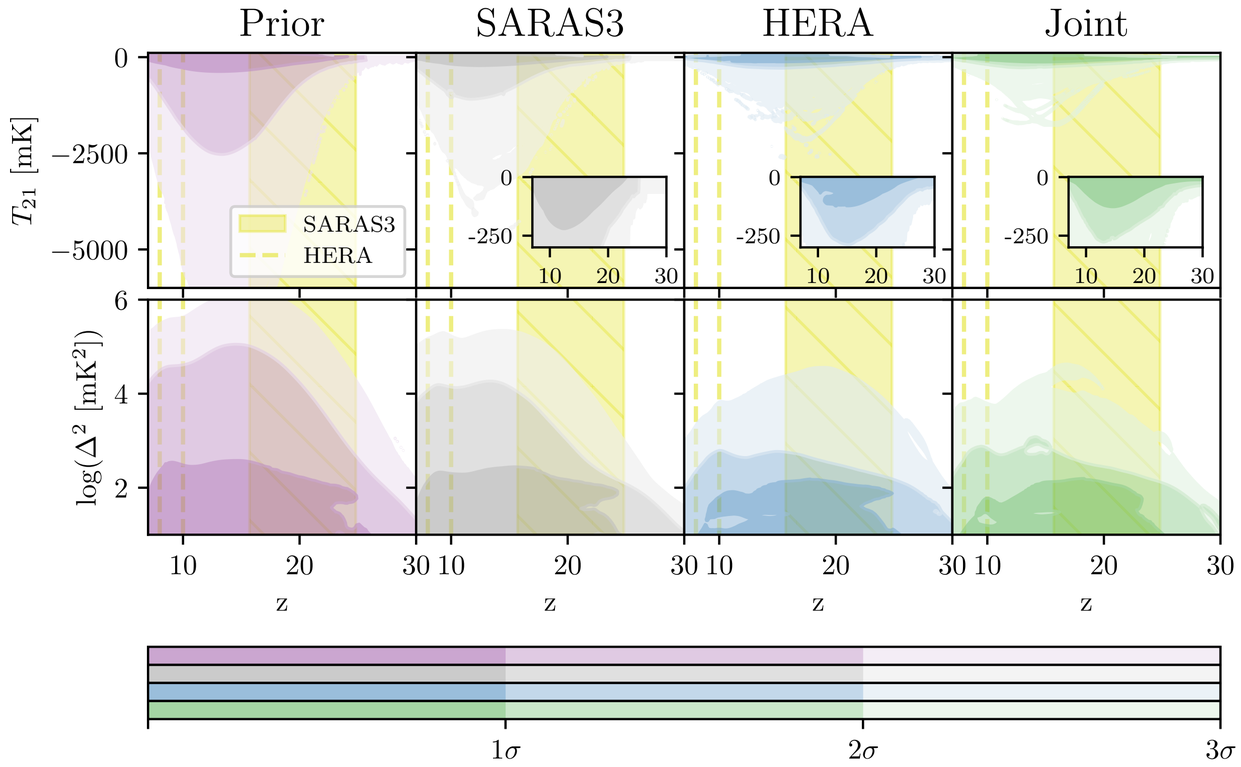
Irene Abril-Cabezas, 1st Year PhD, DAMTP Cambridge, UK

Combing Datasets: SARAS3 + HERA

- HERA Collaboration 2022 *ApJ* **924** 51 [arXiv:2108.07282]
- Previously shown SARAS3 results with radio background from high redshift radio galaxies

$$P(\theta \mid D, M) = \frac{\mathcal{L}(\theta)\pi(\theta)}{\mathcal{Z}}$$

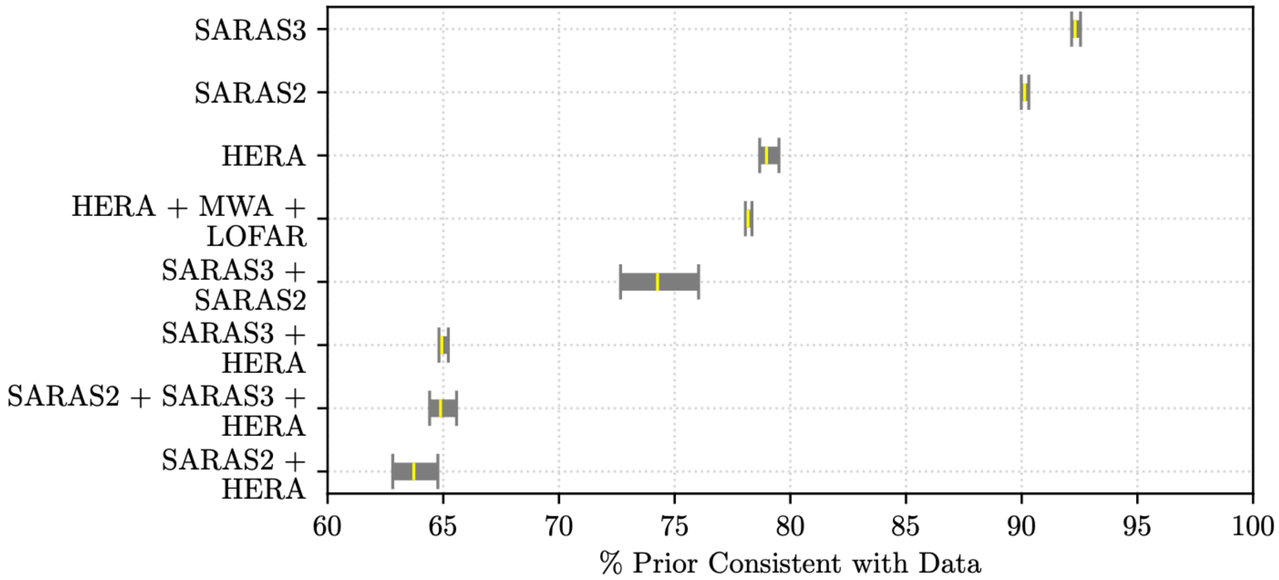
$$\log(\mathcal{L}_{\text{joint}}(\theta_{21})) = \log(\mathcal{L}_{\text{HERA}}(\theta_{21})) + \log(\mathcal{L}_{\text{SARAS3}}(\theta_{21}))$$



Combining Datasets: Other experiments

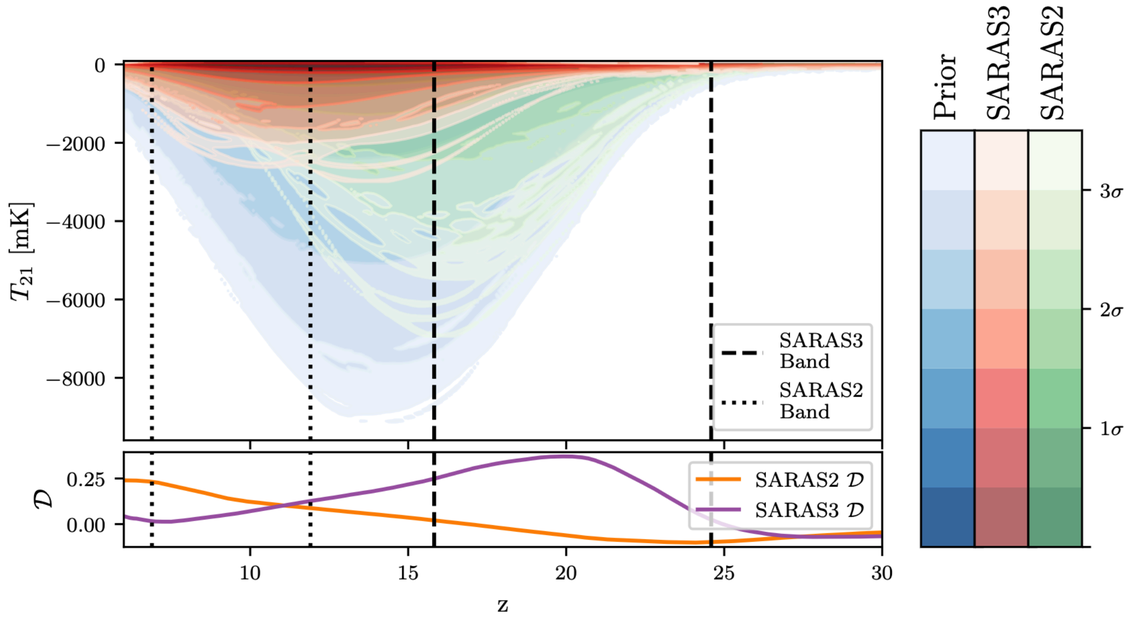
- How about other interferometers and global experiments?

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



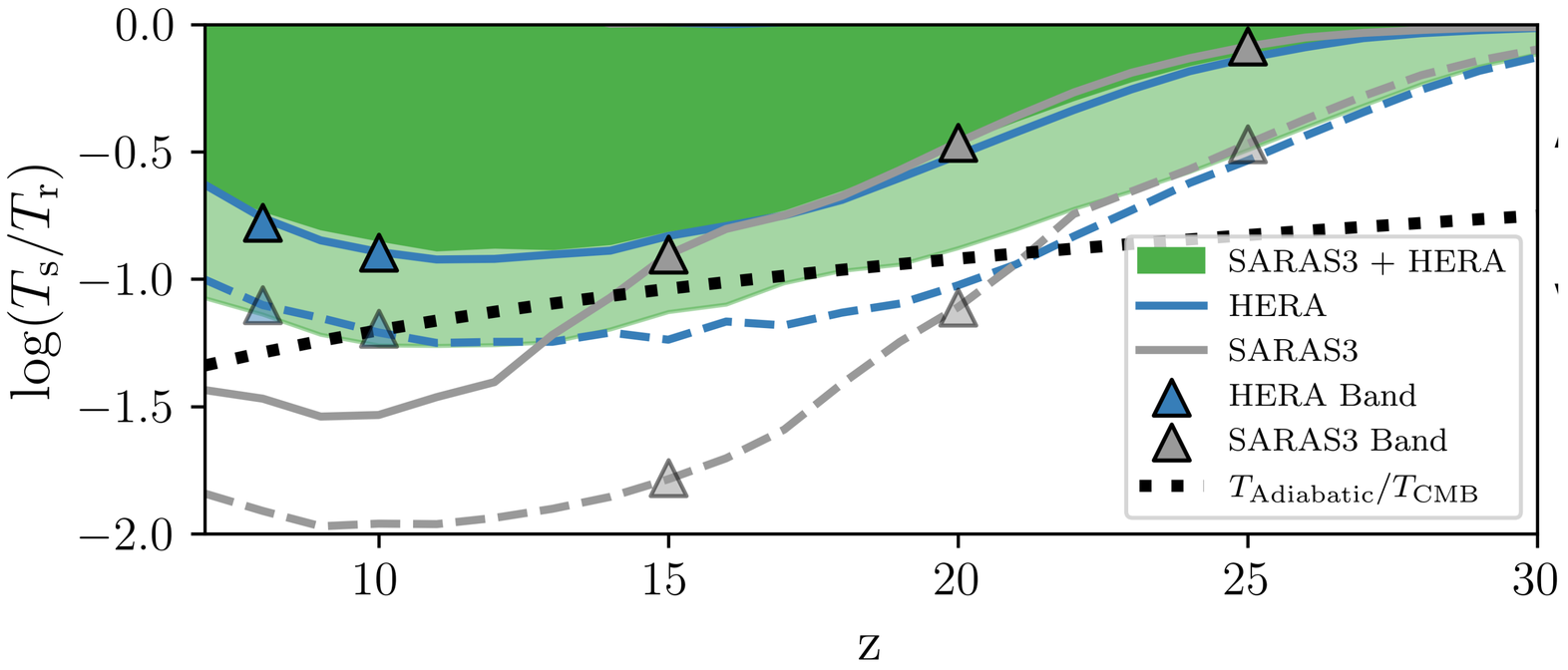
Conclusions

- Although weak the SARAS3 constraints are the first from a global 21-cm experiment at high redshifts $z = 15 - 25$
- We disfavour scenarios with large radio backgrounds and inefficient X-ray production
- We put constraints on the star formation properties of early galaxies
- We are beginning to explore the benefits of combining constraints from multiple different probes

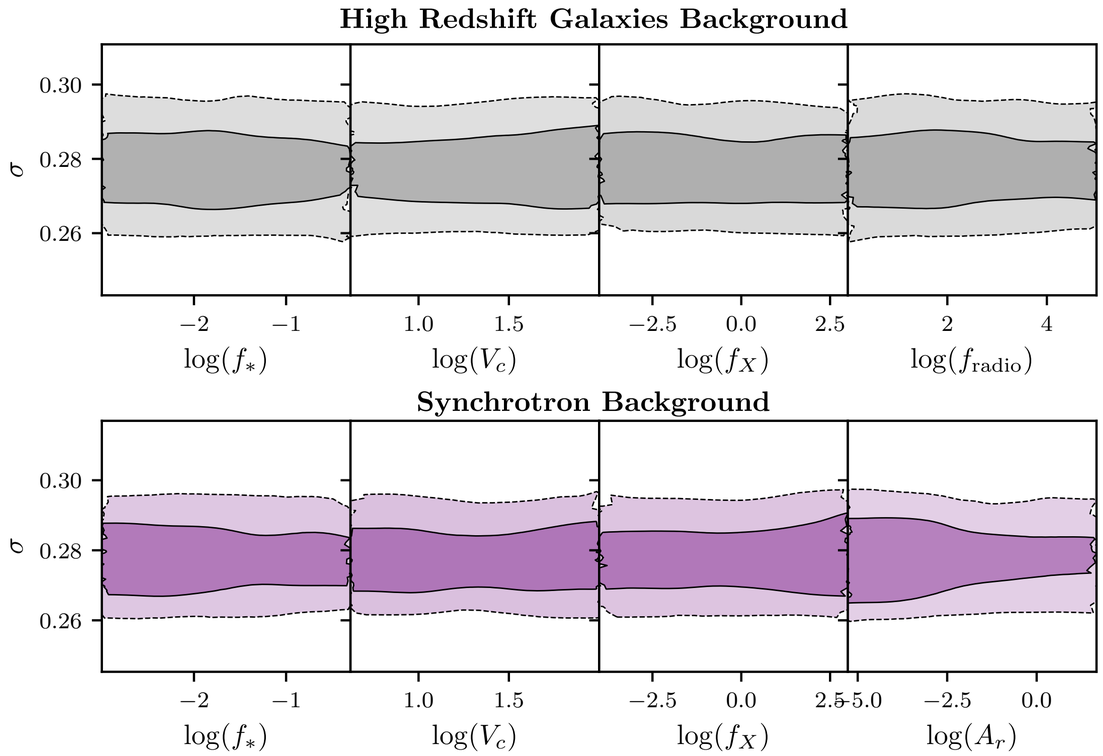


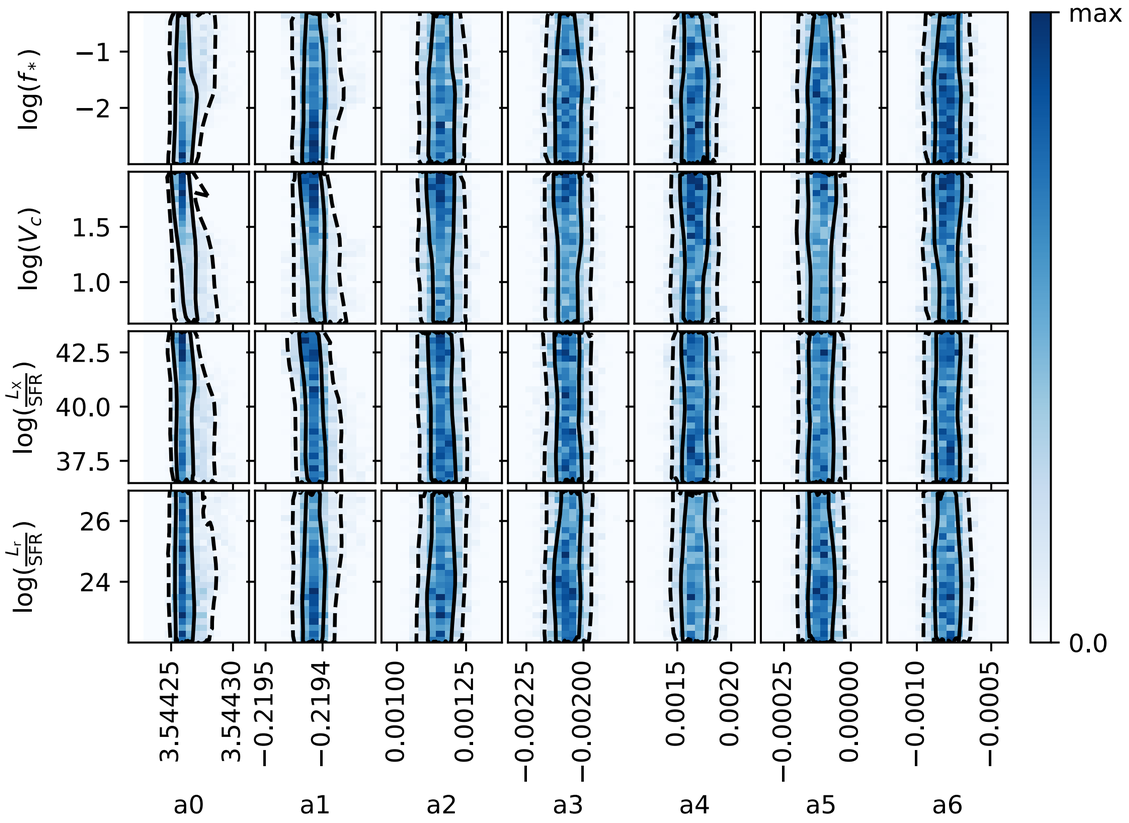
I'm looking for postdocs starting October 2023! Happy to chat about ways I can fit into your research groups…

Spin temperature vs radio background

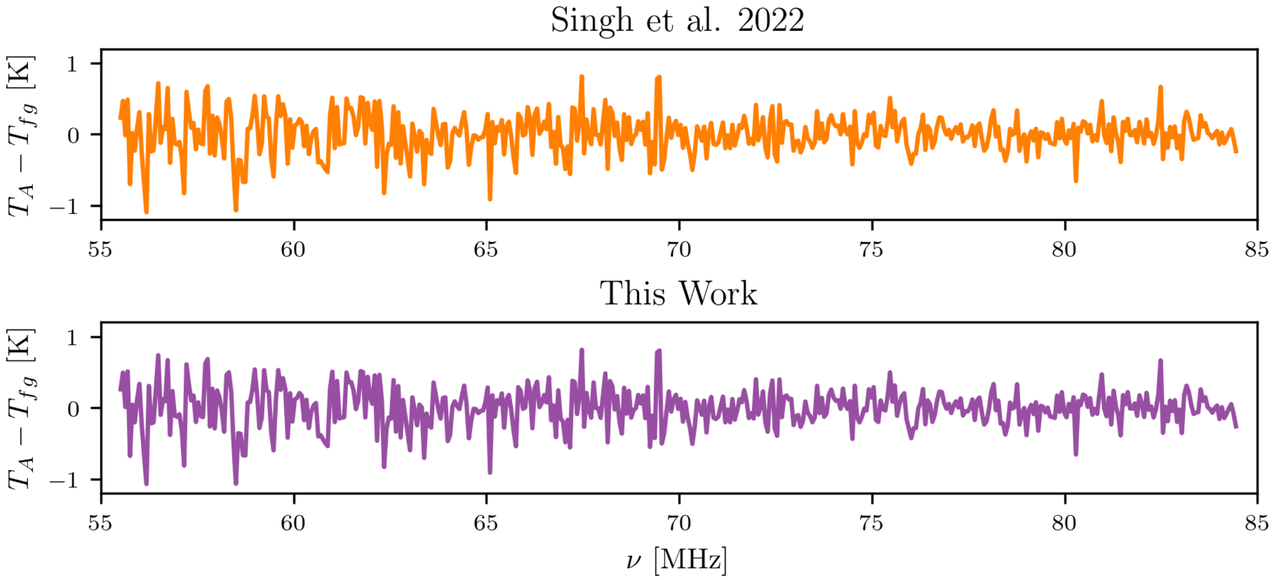


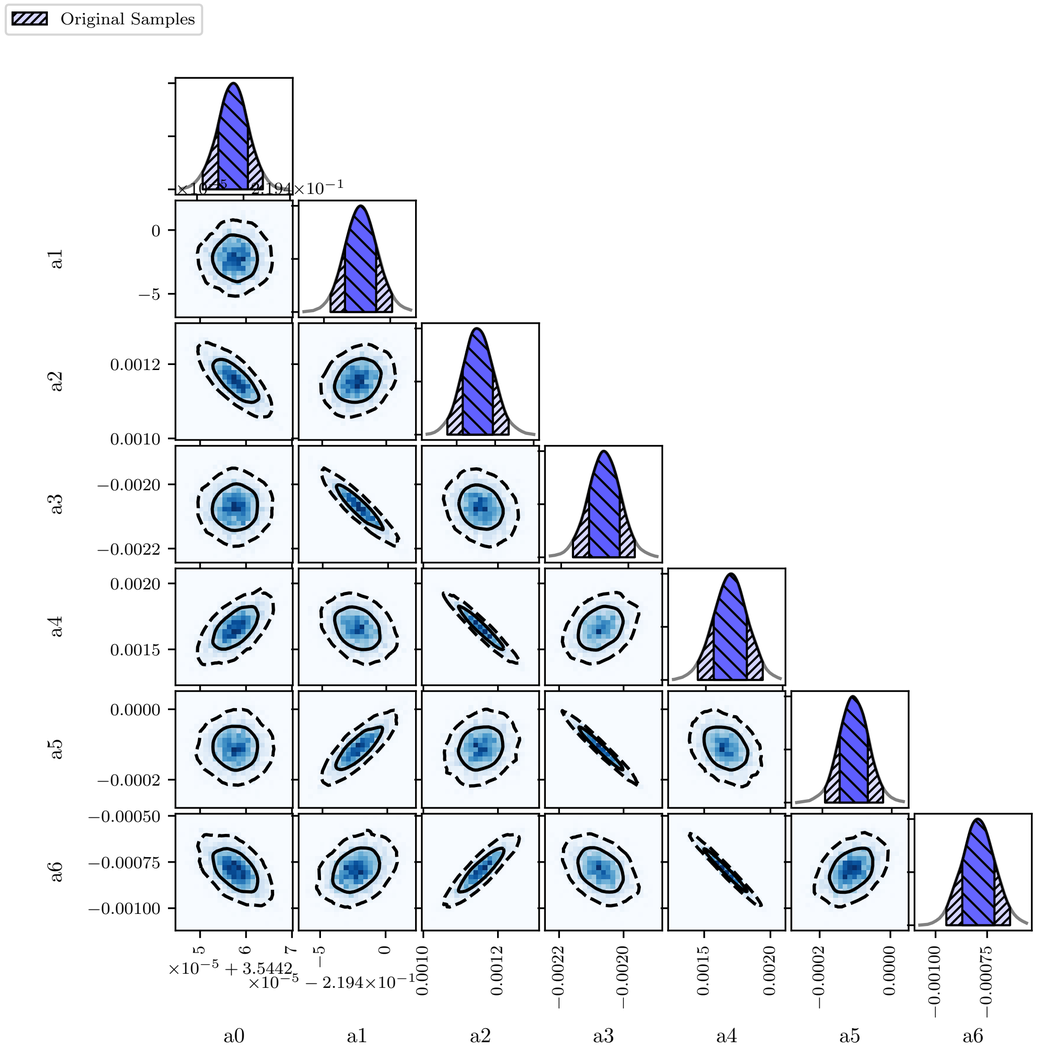
Independence of model components



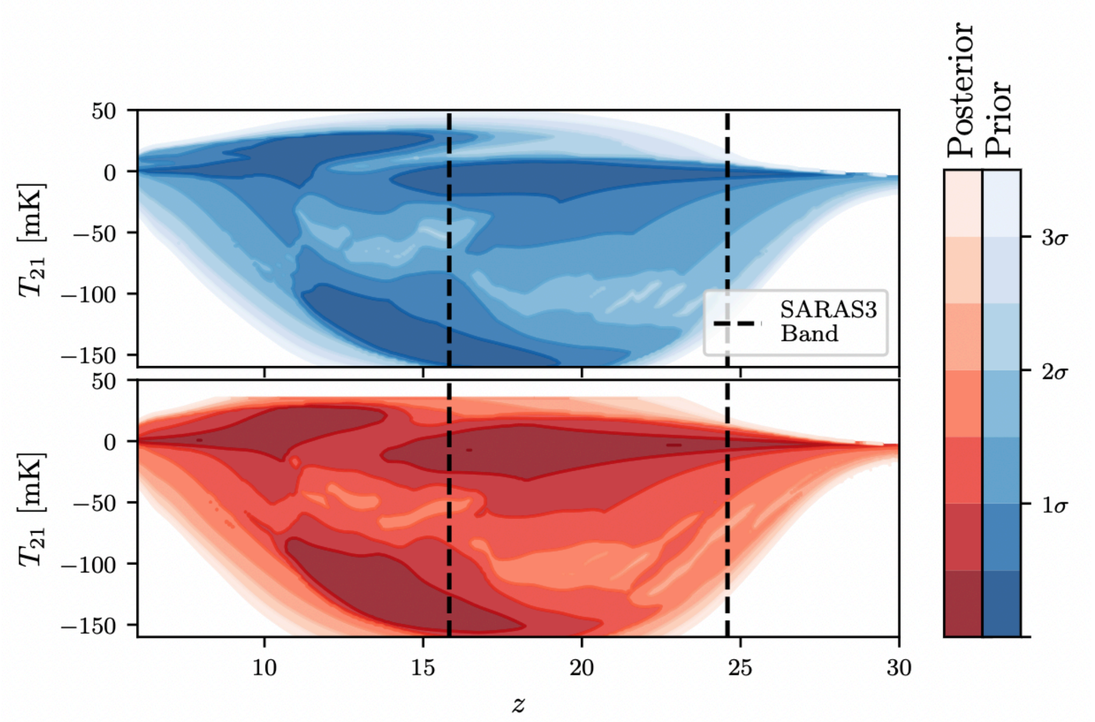


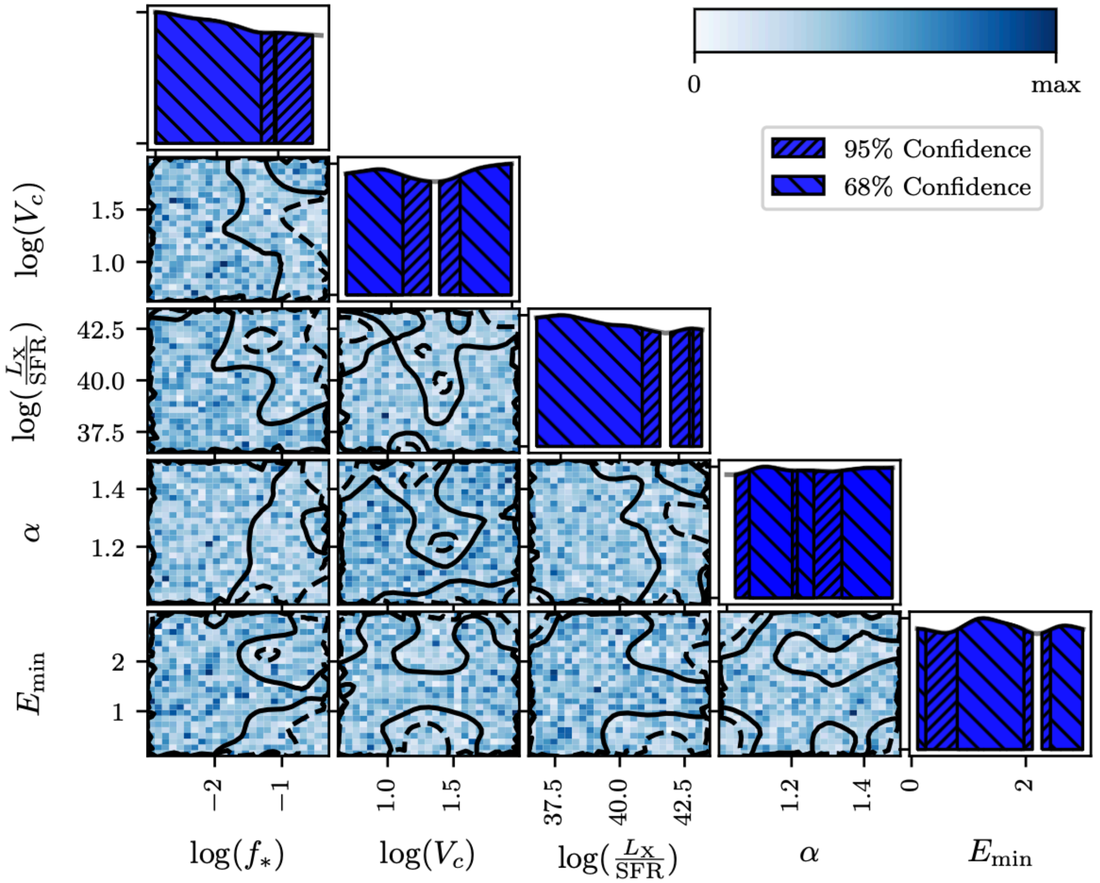
Foreground Modelling





CMB Background





Comparison to EDGES

- The prior is physical like EDGES signals → can't explain the implied rapid star formation and X-ray heating
- We find that $\approx 60\,\%$ of this parameter space is still consistent with the data
- *but* this is effectively under the assumption that the EDGES feature is indicative of a physical signal at $z \approx 17$