UNIVERSITY OF CAMBRIDGE

CAVENDISH ASTROPHYSICS
RADIO COSMOLOGY
Science Technology Engineering Mathematics

Joint analysis constraints on the physics of the first galaxies

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With
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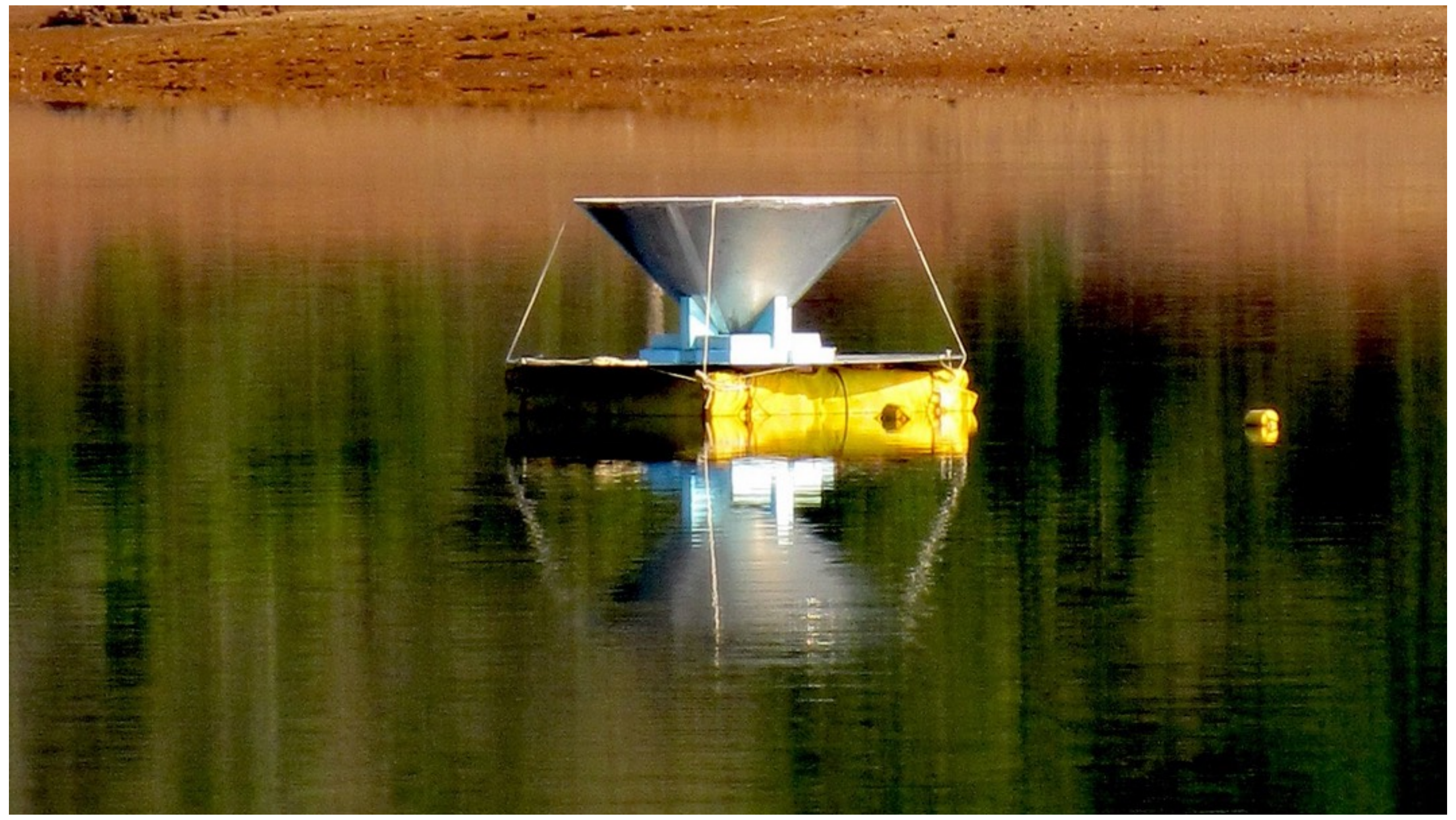
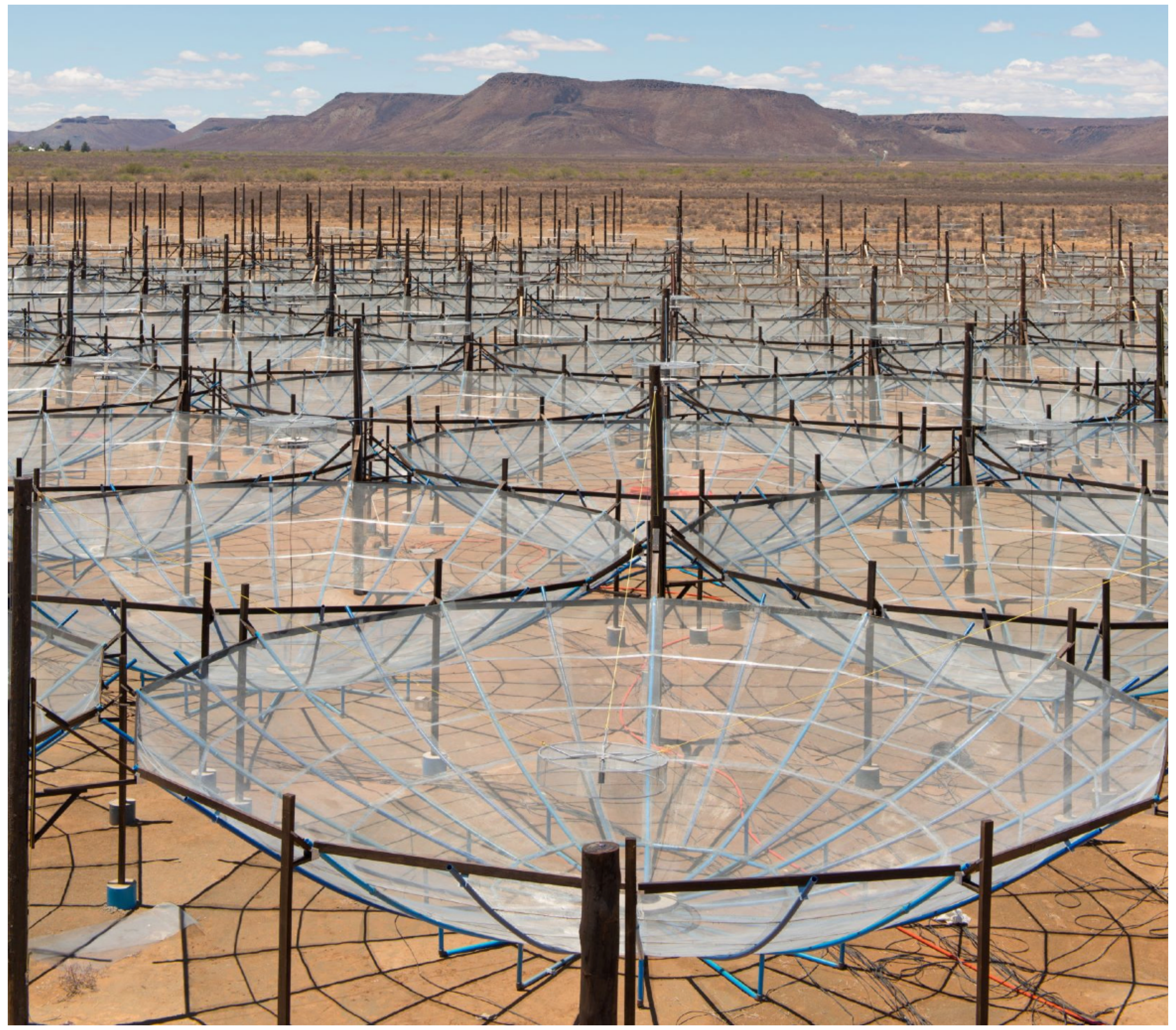
The Plan

1. The Goal of the Work

2. The Methodology

3. The Results





The Goal of the work

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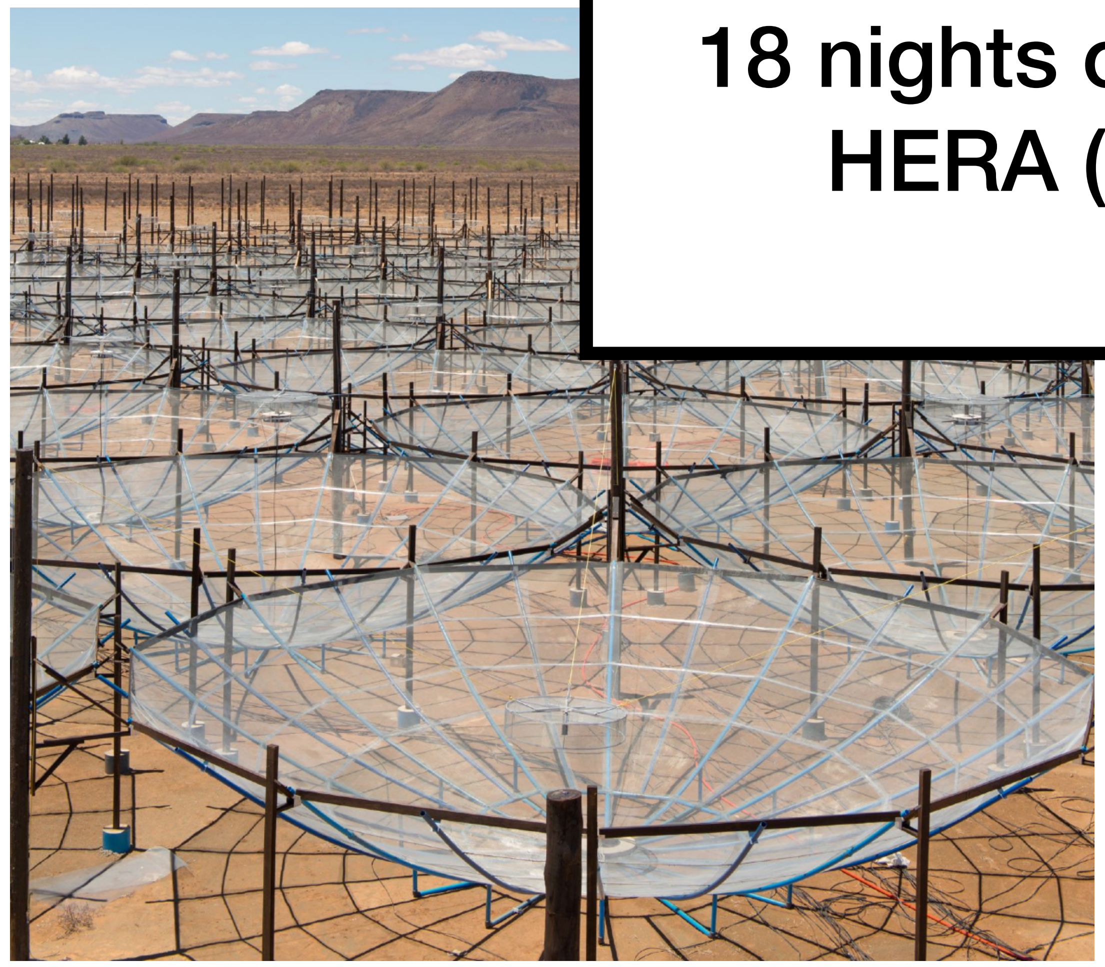
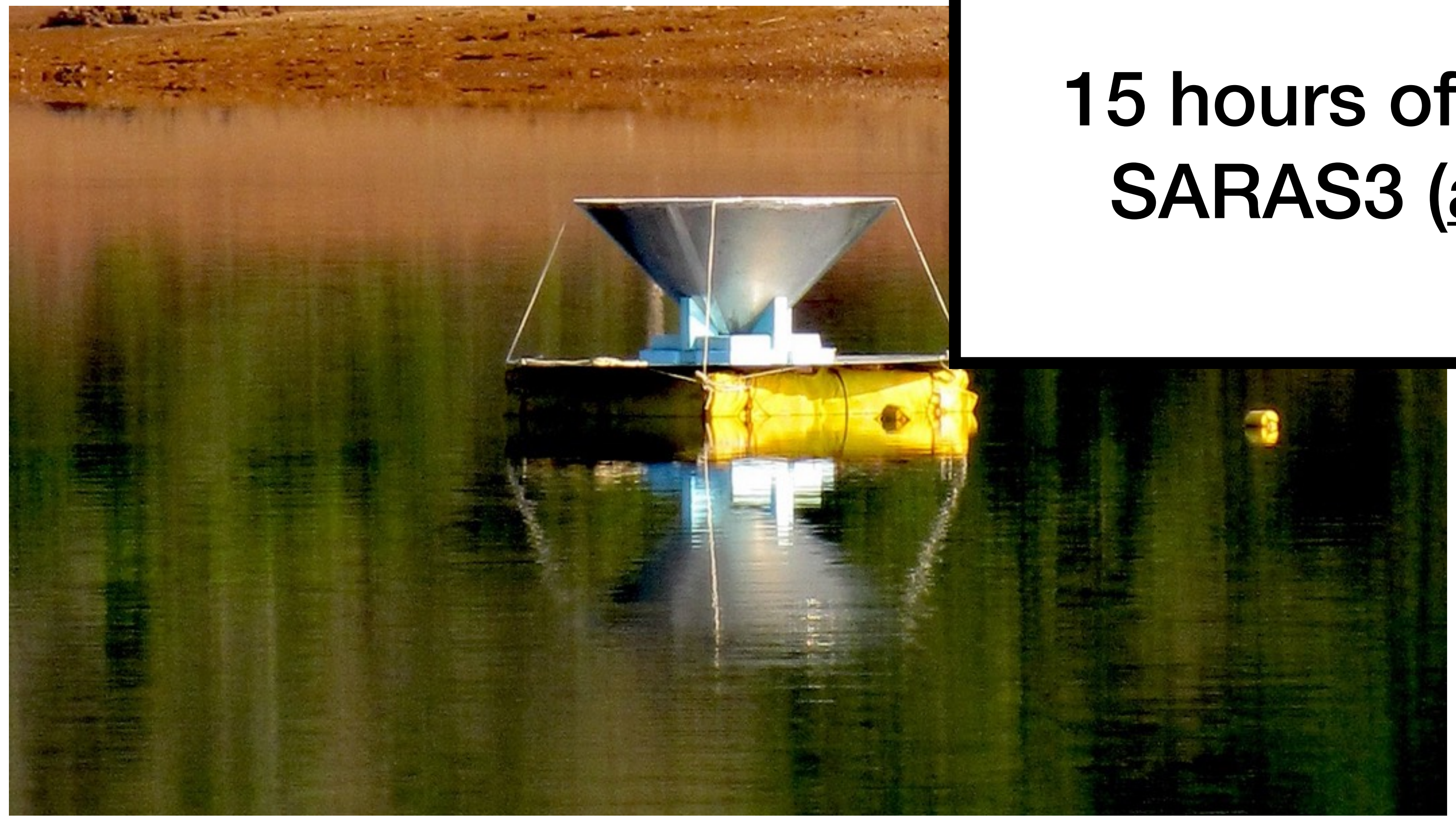


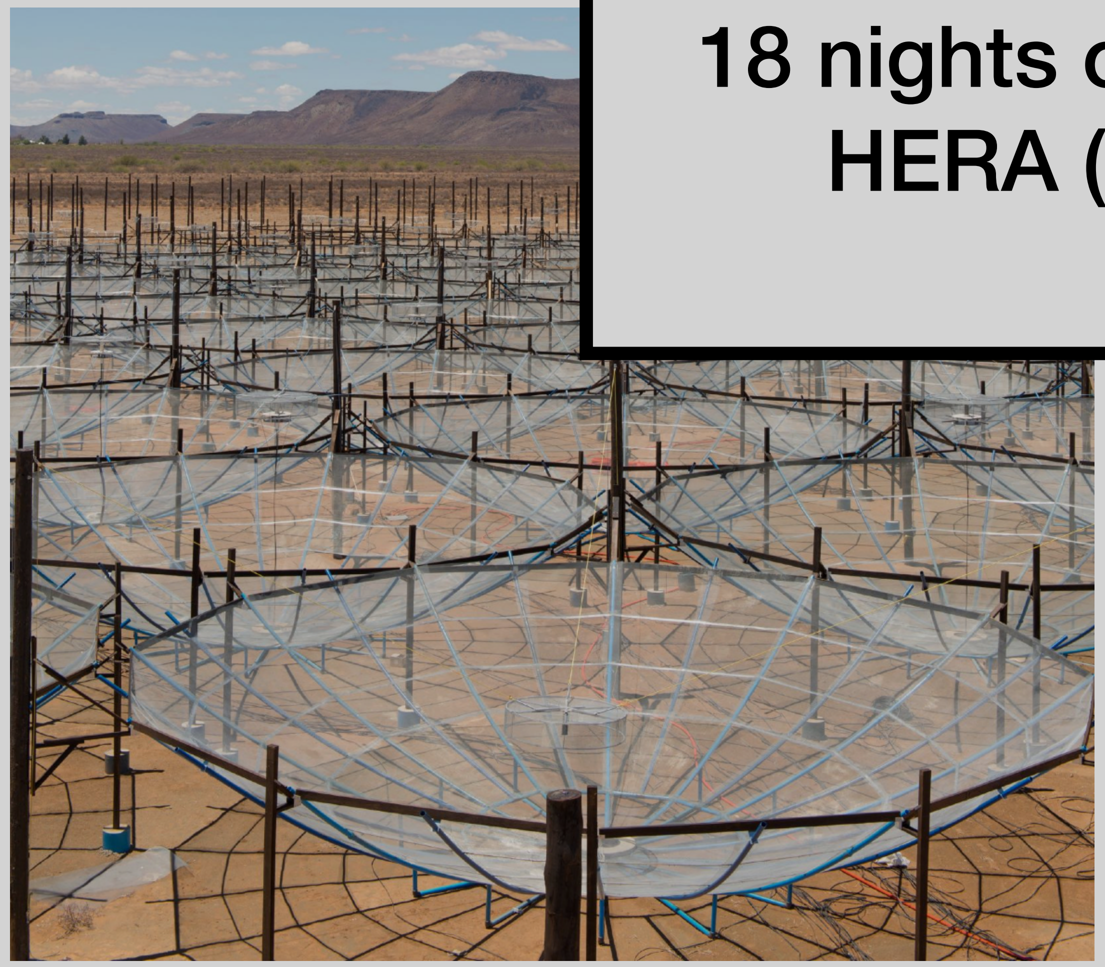
18 nights of observations from HERA (arxiv2108.07282)



15 hours of observations from SARAS3 (arXiv:2112.06778)

Joint analysis of this data?
Never been attempted before

The Goal of the Work



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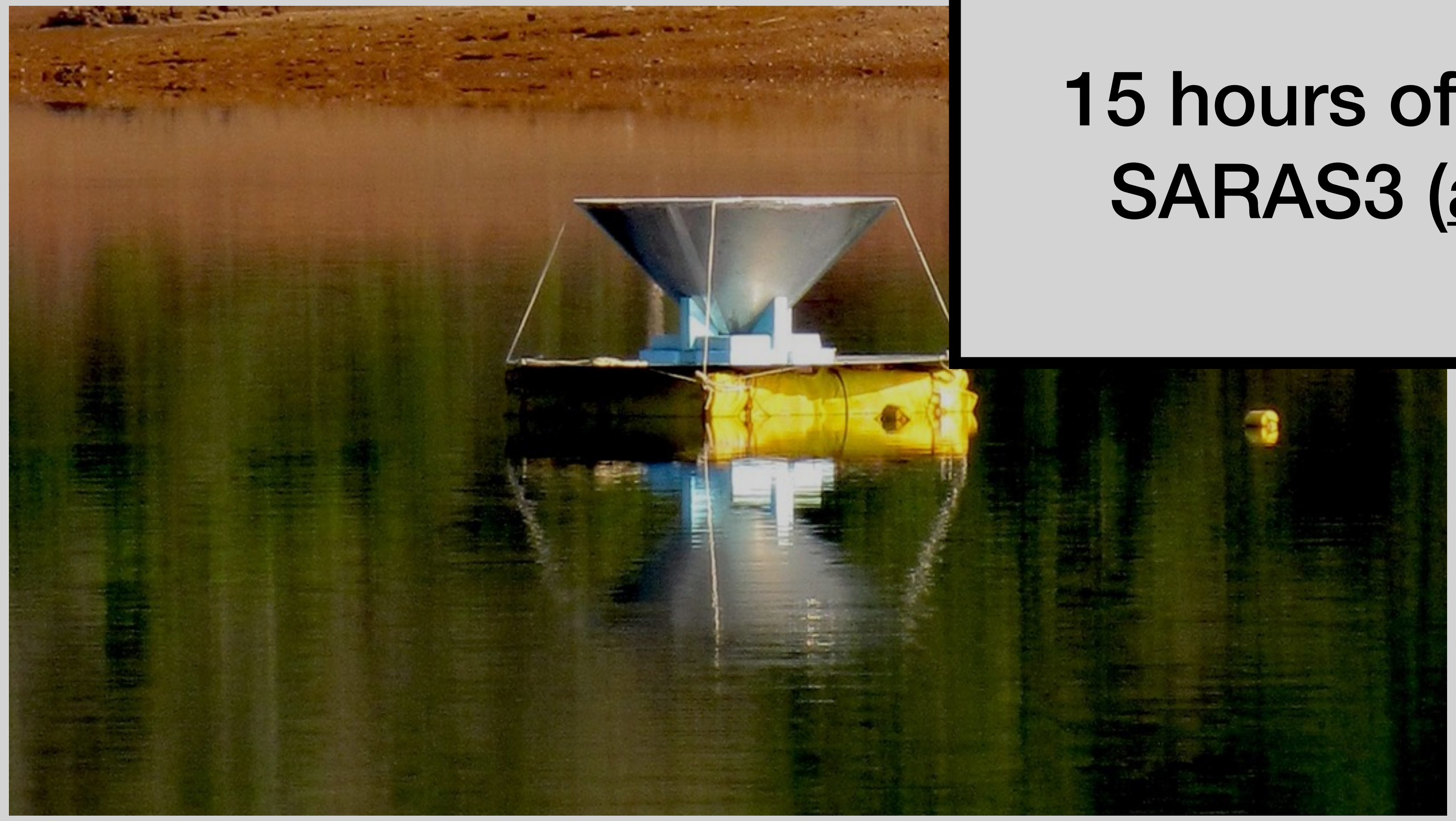

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Joint analysis of this data? Never been attempted before

How about adding in LOFAR (arXiv:1702.08679), MWA (arXiv:2002.02575) and SARAS2 (arXiv:2201.11531)?

The Methodology

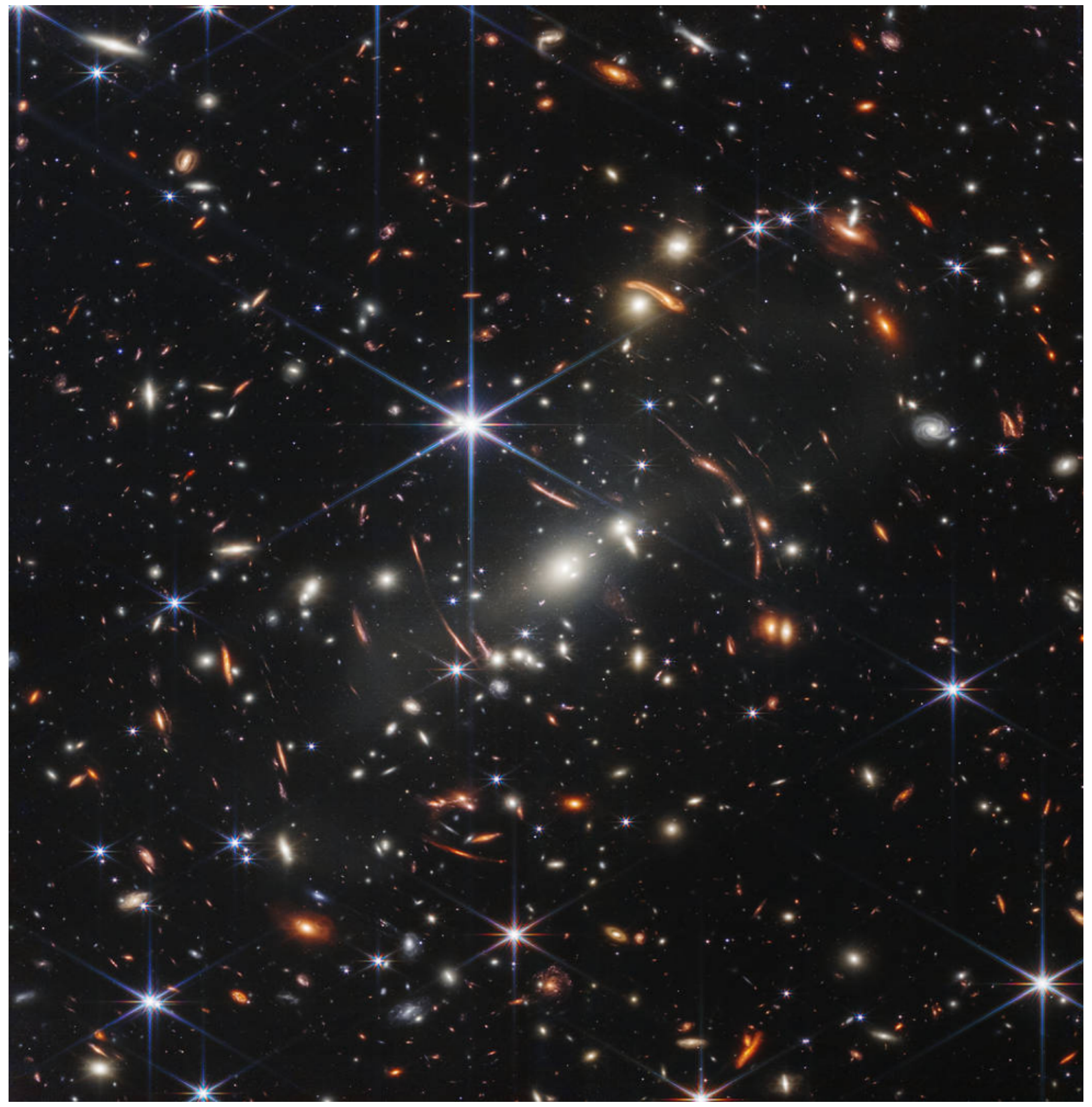
The Methodology: Signal Modelling

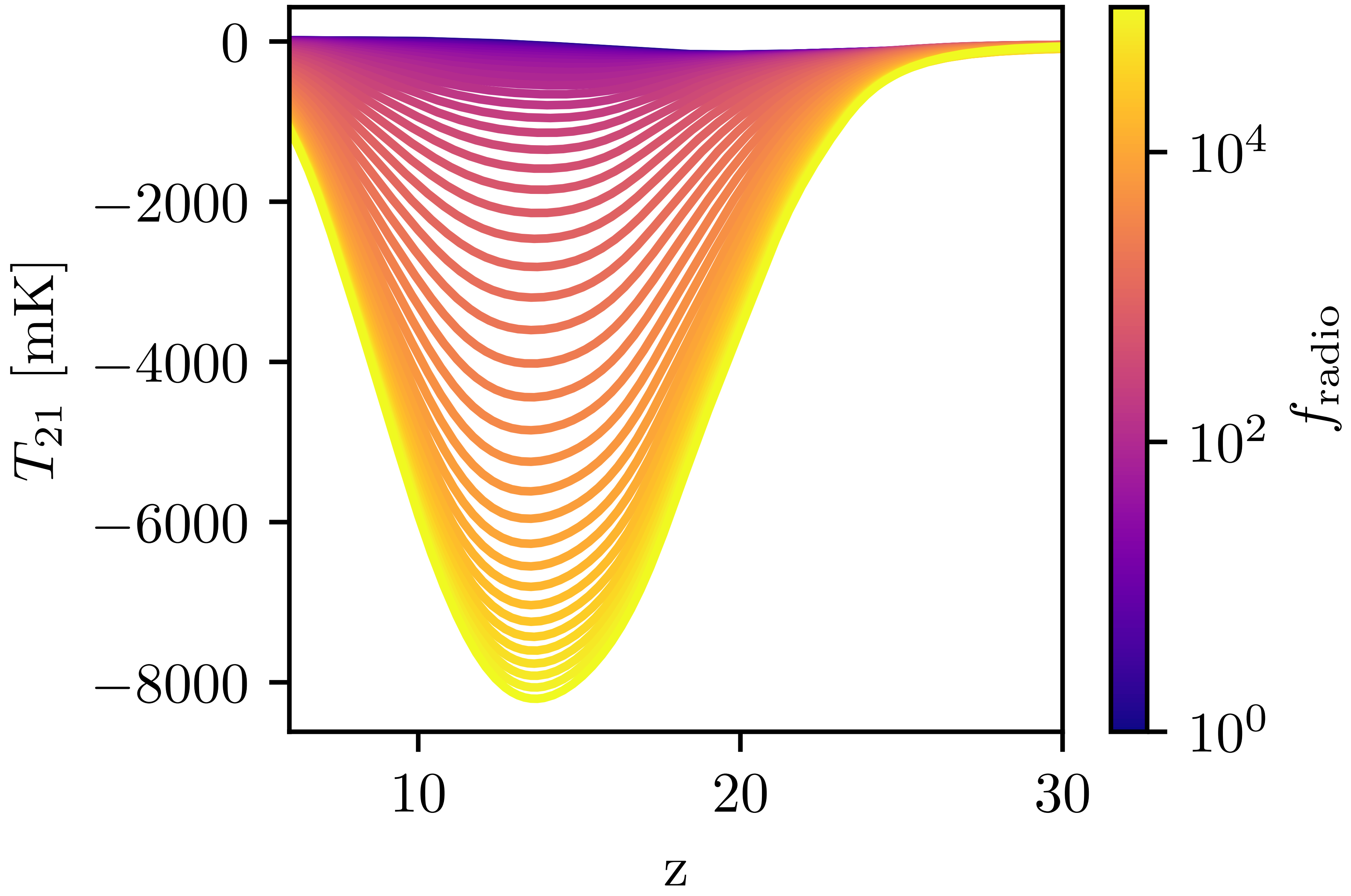
Any joint analysis requires consistent modelling of the signal.

Our models (Fialkov et al.) include:

- A contribution to the radio background from high-z galaxies
- Lyman-α heating, CMB heating and X-ray heating
- Multiple scattering of Lyman-α photons

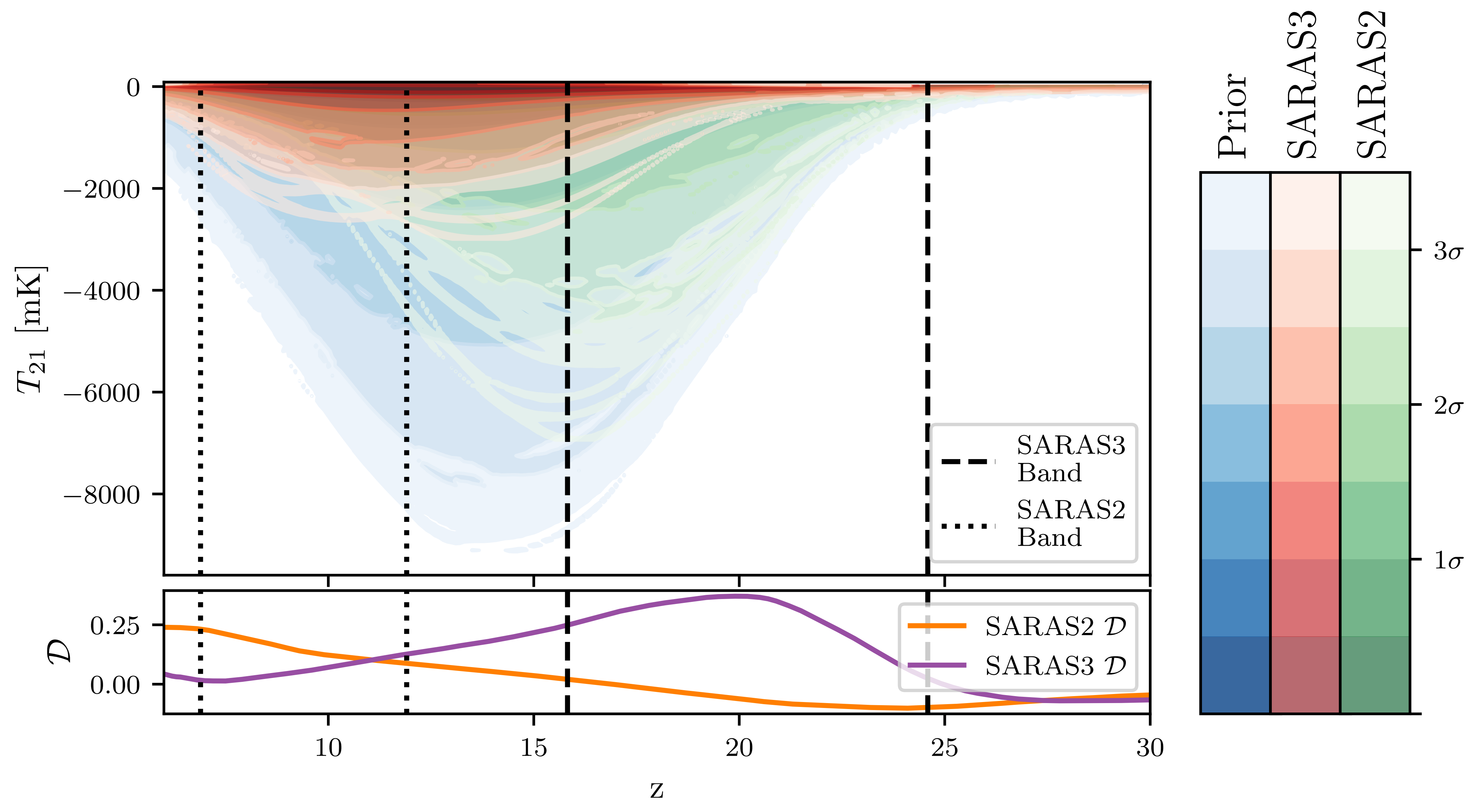
Parameterised by star formation, X-ray and radio production efficiencies ($f_*, f_X, f_{\mathrm{radio}}$), the CMB optical depth (τ) and minimum halo mass for star formation ($M_c \rightarrow V_c$).



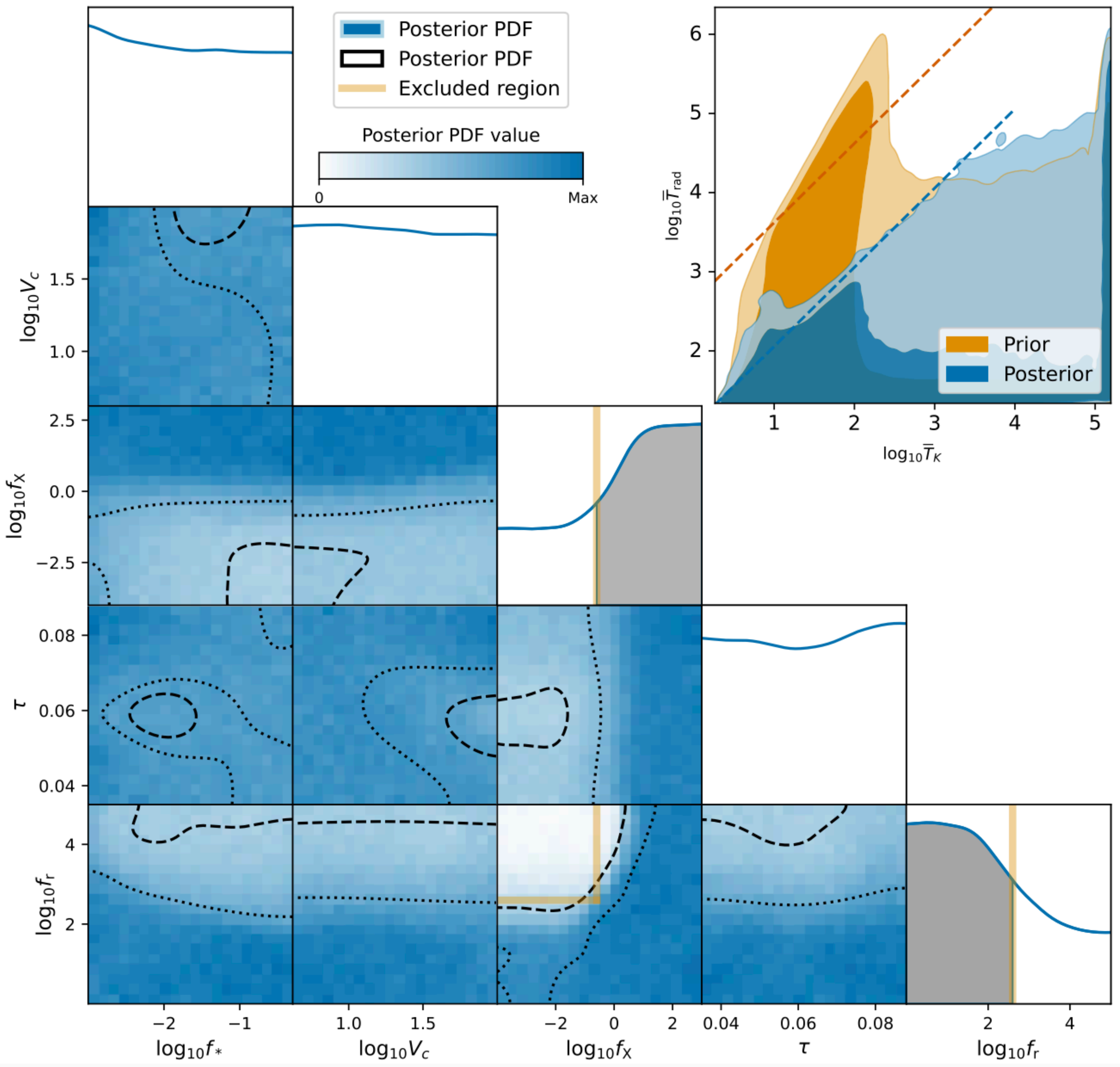


The Methodology: But we have existing constraints?

- We already have constraints from HERA and SARAS3 on this class of models.
- Can we take advantage of this existing body of work?



Bevins et al. 2022 (arXiv:2112.06778)



The HERA Collaboration, 2022 (2108.07282)

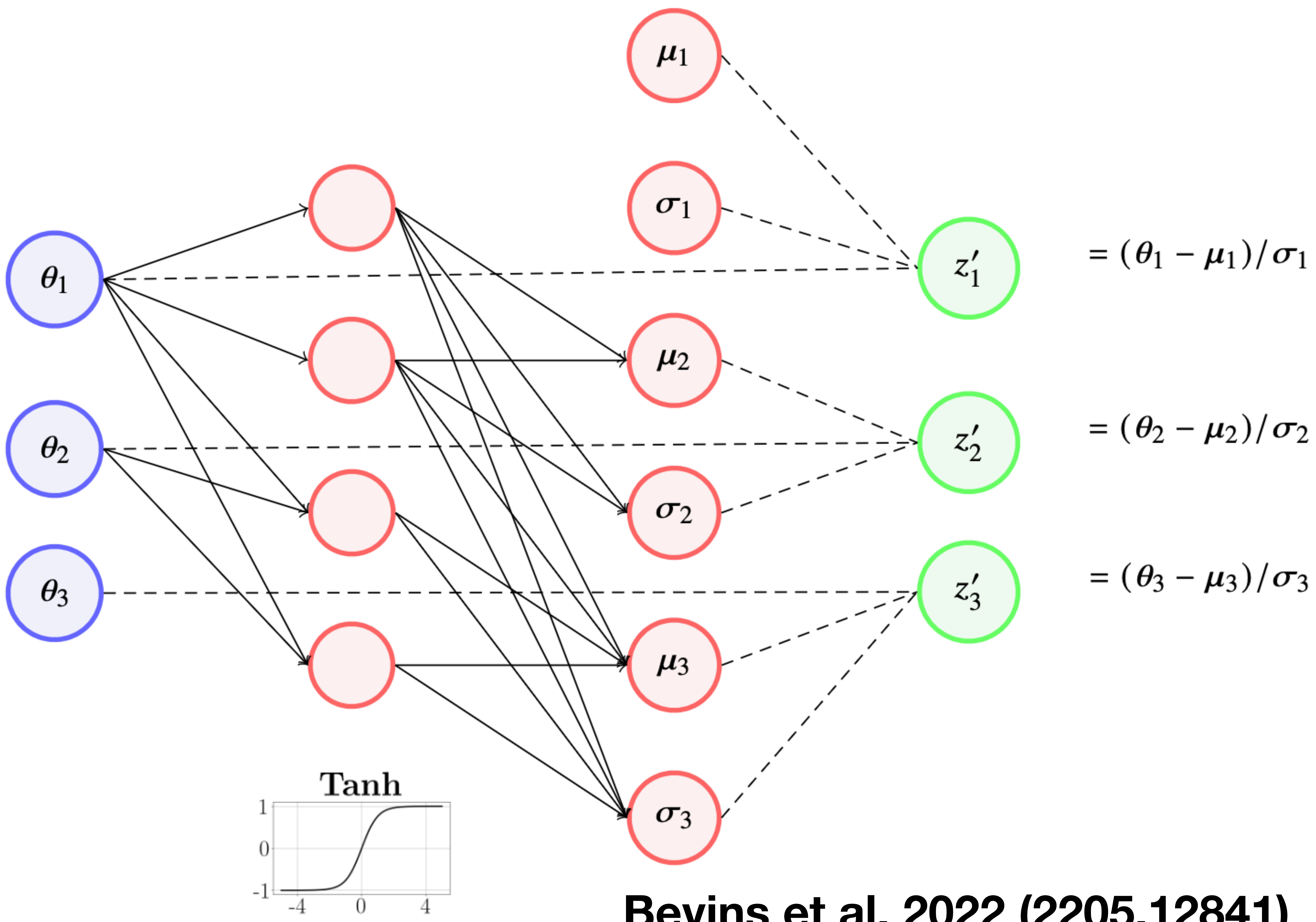
The Methodology: Utilising Normalizing Flows?

Normalizing flows parameterise a transformation from a known base distribution to a target distribution

Trainable and bijective density estimators

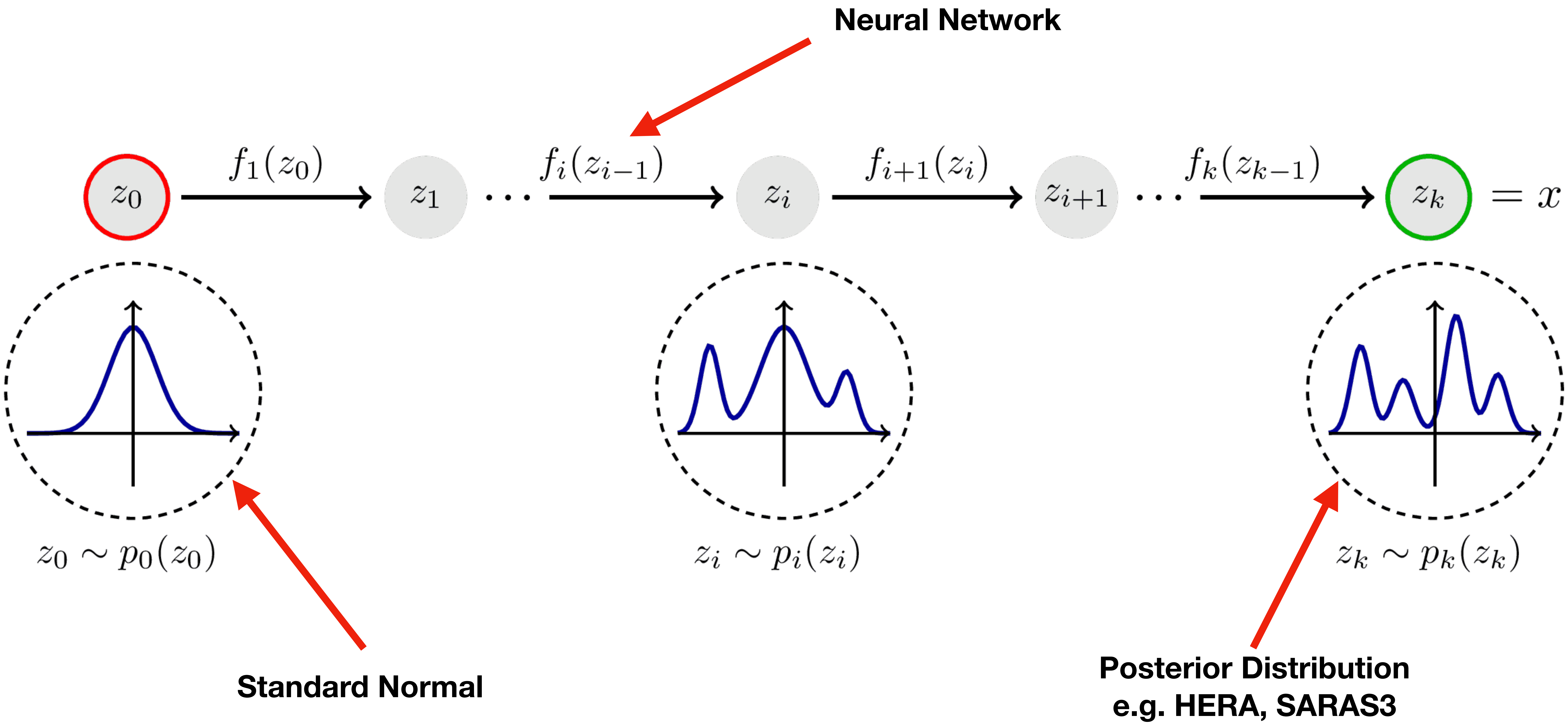
Bijective property allows us to do lots of cool things!

Using the package *margarine* (https://github.com/htjb/margarine)



Bevins et al. 2022 (2205.12841)

The Methodology: Utilising Normalizing Flows?

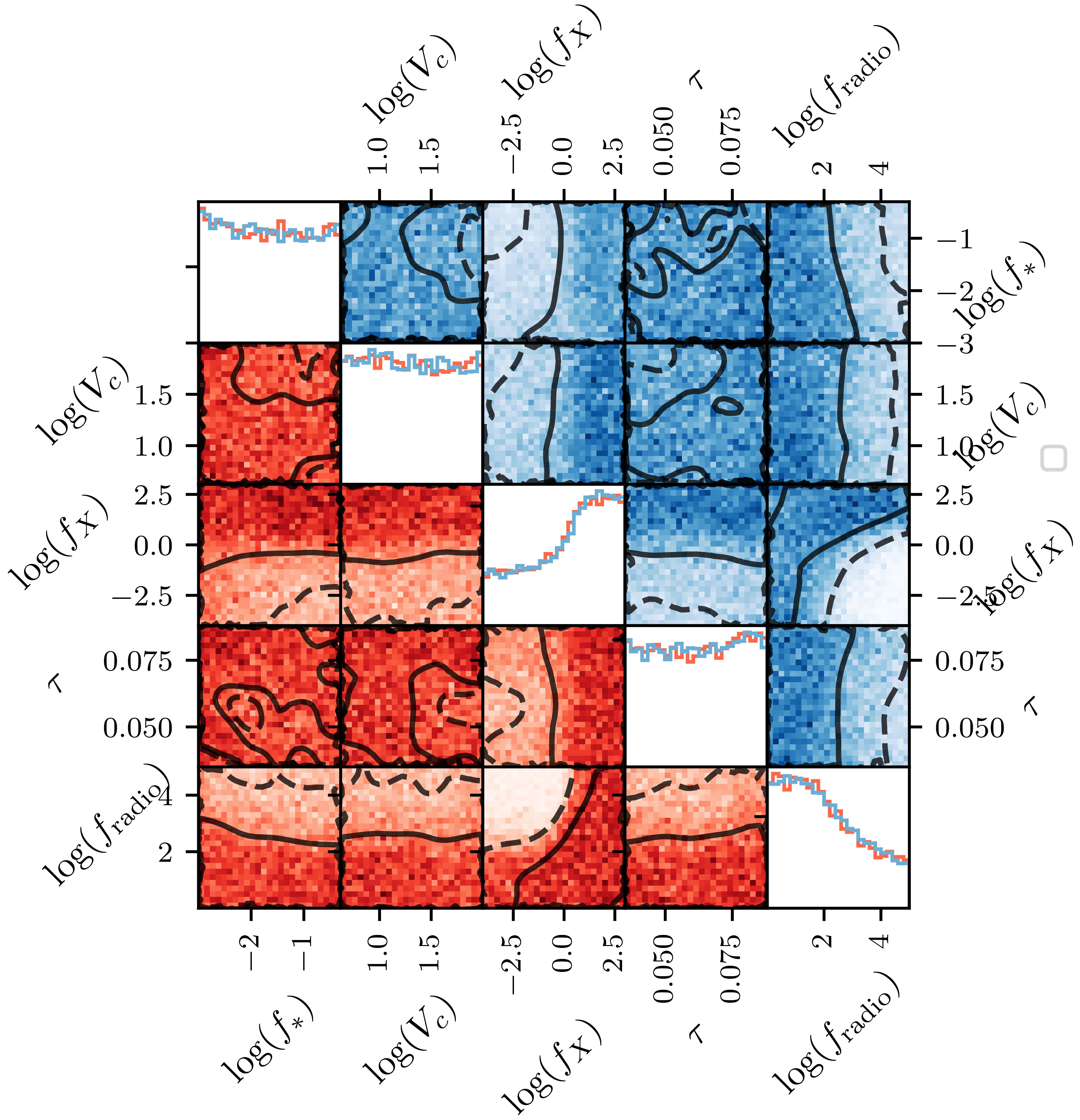


The Methodology: How are the flows useful?

Flows allow us to:

- Draw samples from the target distribution
- Derive non-trivial priors
- Calculate log-probabilities on the target distribution for a set of parameters

See Bevins et al. 2022a,b and 2023 (2205.12841, 2207.11457, 2305.02930)



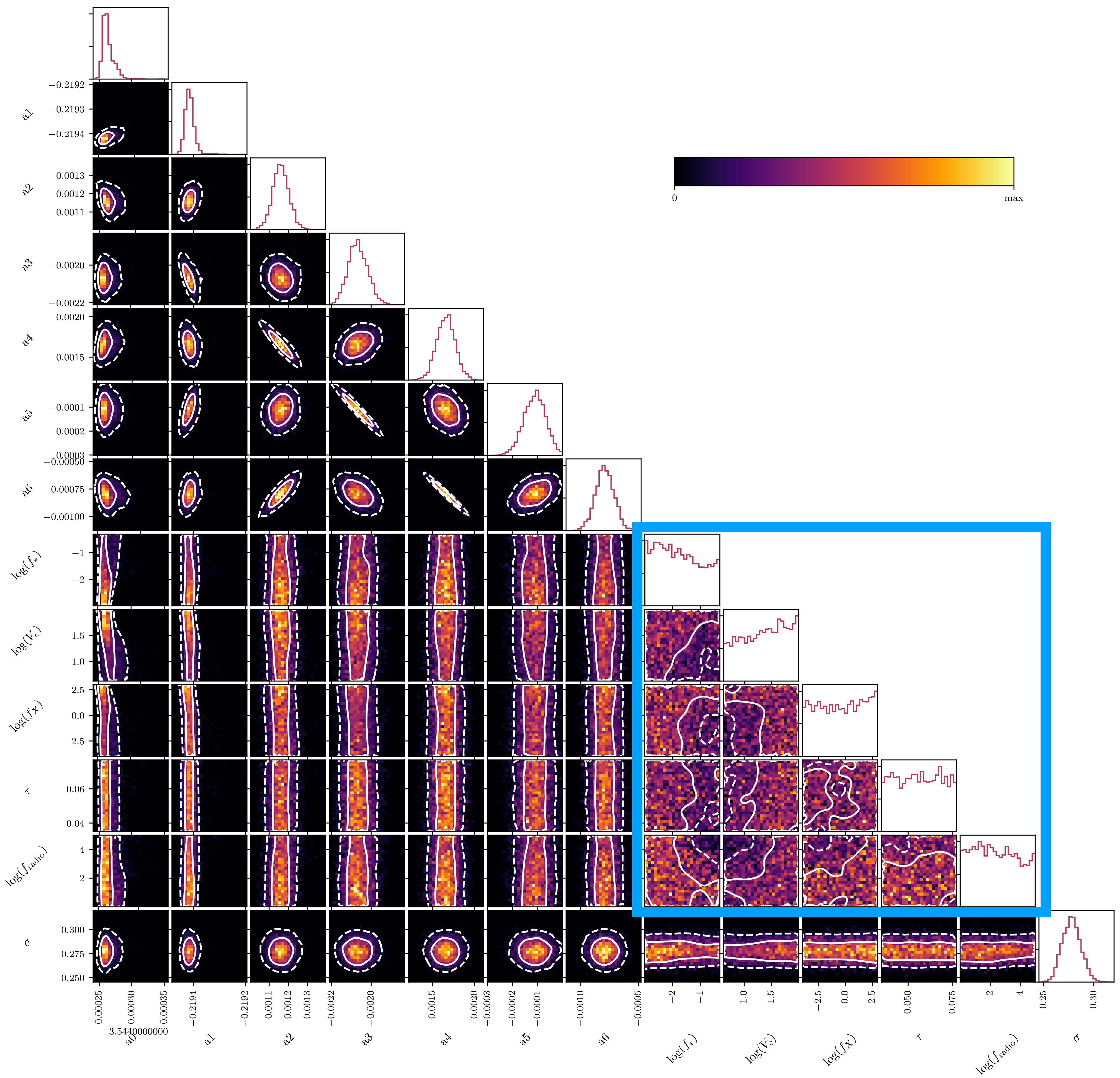
The Methodology: Why bother with normalizing flows?

Why not just run a joint likelihood over all of the parameters in an analytic likelihood?

The SARAS3 model has foreground parameters… but we are not really interested in these!

We refer to these as nuisance parameters!

Flows allow us to learn marginal parts of the parameter space



The Methodology: Joint likelihood?

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

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

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For an individual experiment we have…

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

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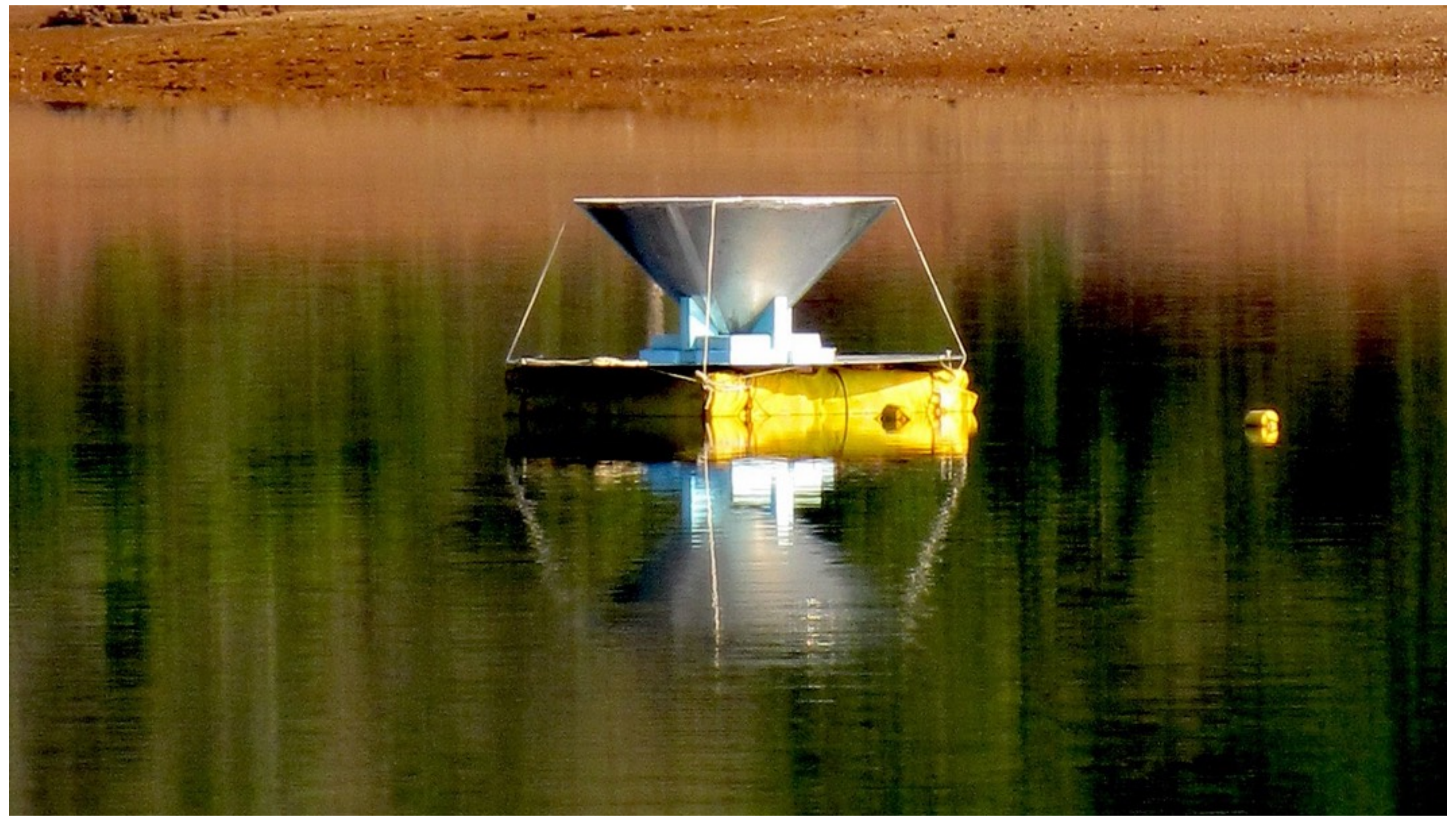
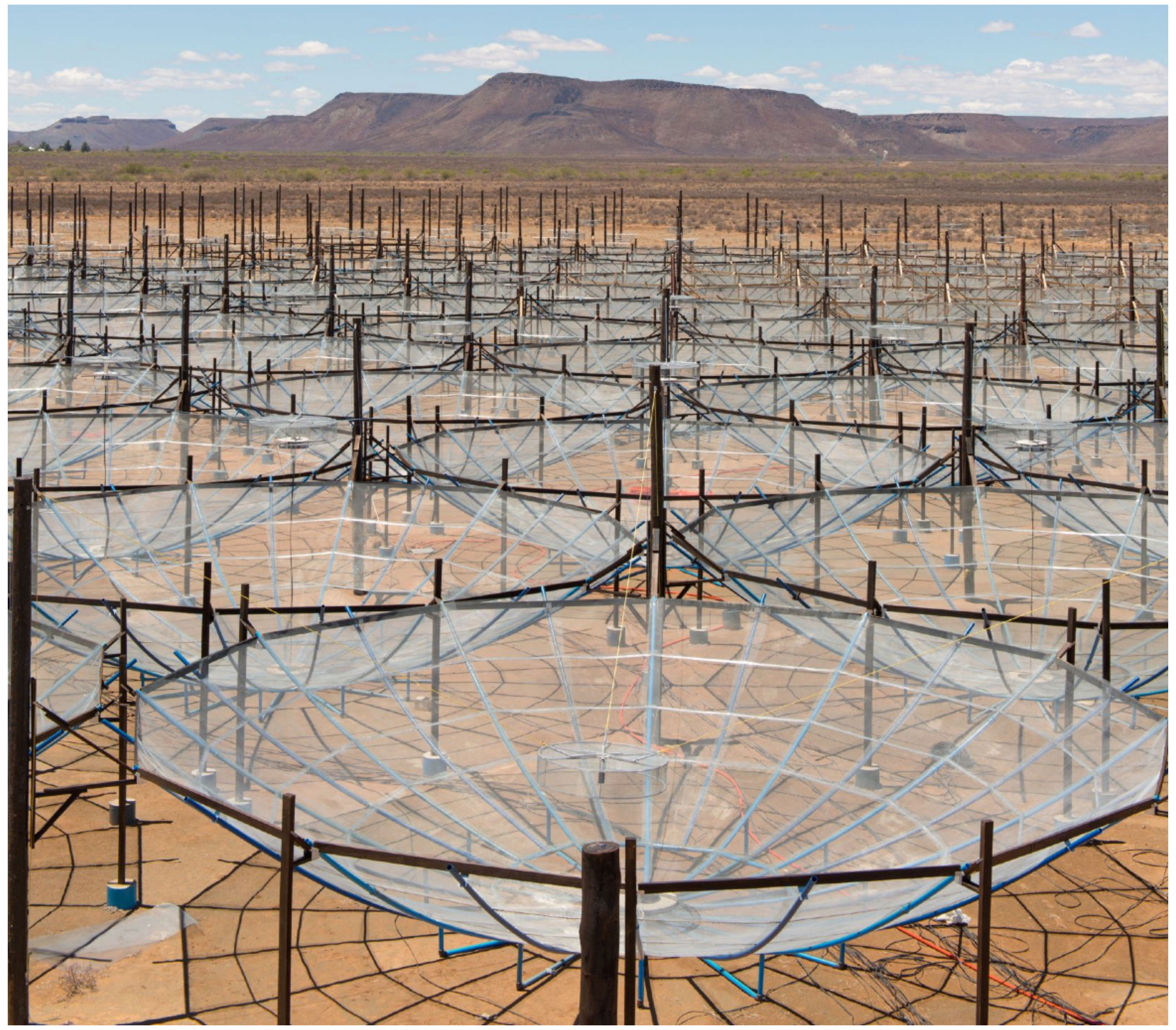


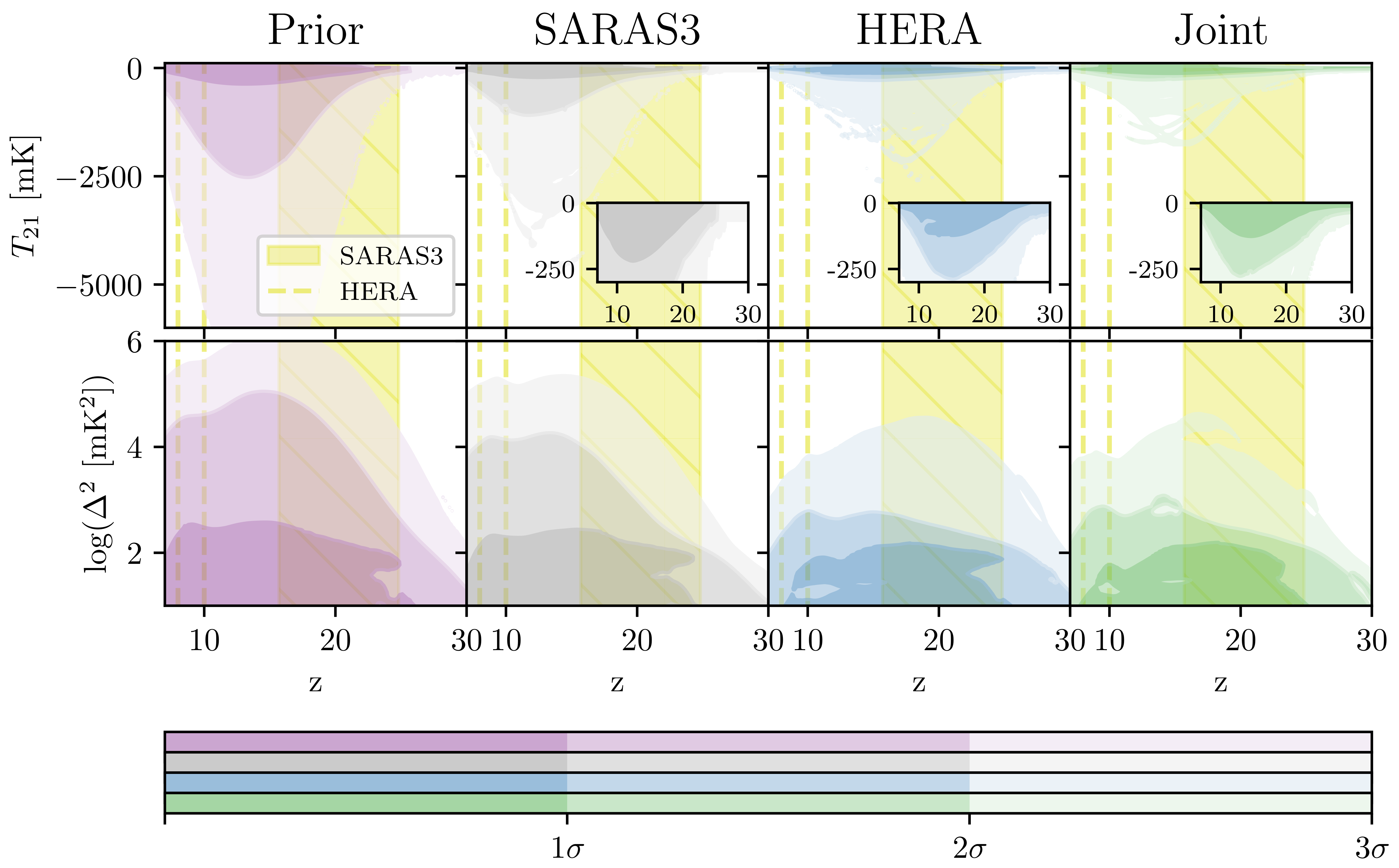


The Results

The Results: Constraints?

We get tighter constraints on the parameter space

Translates to tighter constraints on the 21-cm signal and the power spectrum

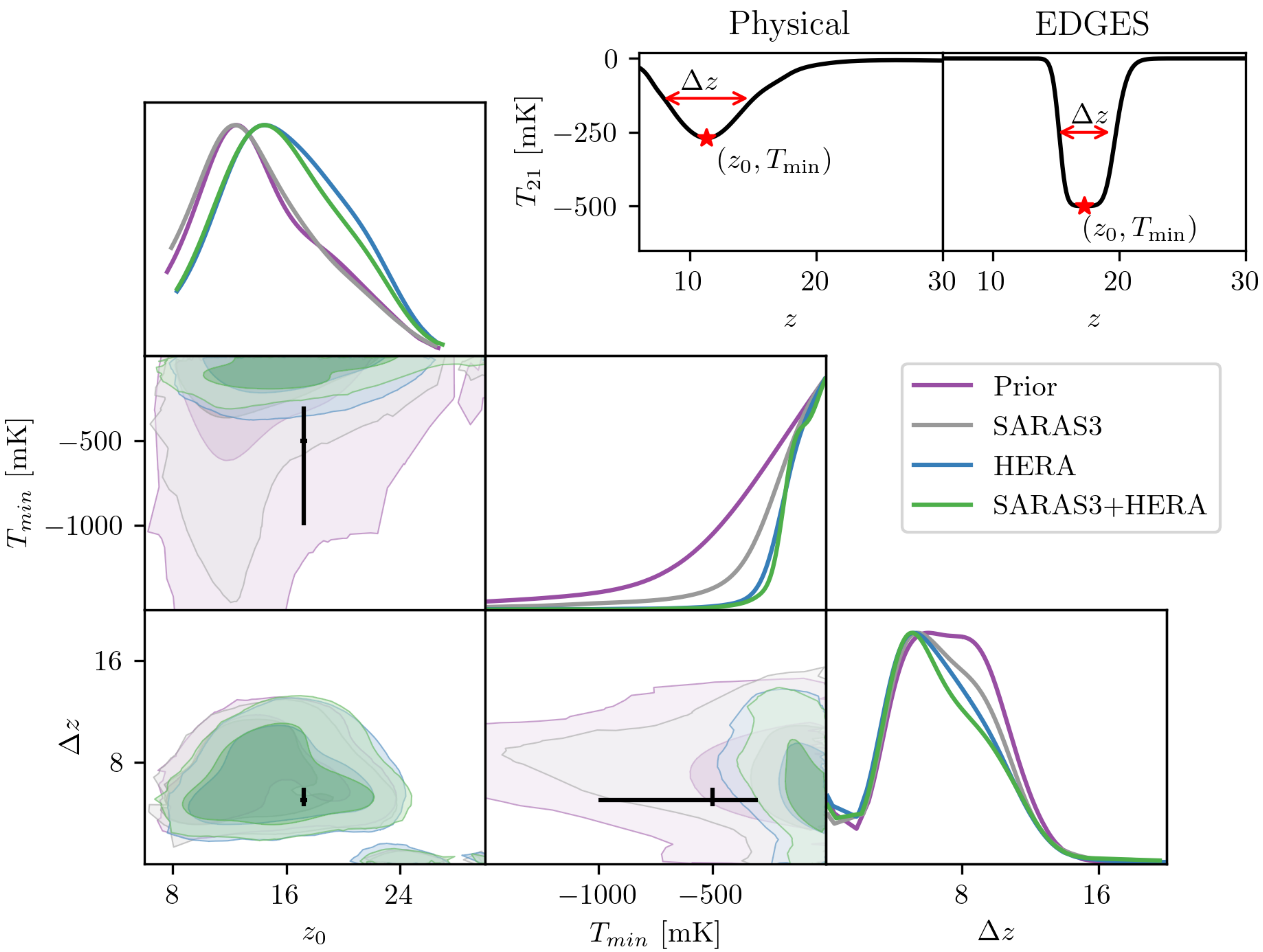


The Results: What can we say about EDGES?

We can take an approximate width, depth and central frequency

Both SARAS3 and HERA allow for physical signals with a depth consistent with EDGES…

… however together they disfavour this class of signals with two sigma confidence!



Conclusions

- Developed a novel method for performing joint analysis of different data sets
- Shown that by combining power spectrum and sky-averaged 21-cm signal data we can get improved constraints

Future Work

- Peter Sims - Looking at applications of the method to REACH
- Thomas Gessey-Jones - joint analysis constraints on Cosmic Strings
- Simon Pochinda - updated constraints with additional information from probes of the X-ray background
- Continued improvements to margarine

Joint Analysis Paper

Methods paper

Bonus Slides

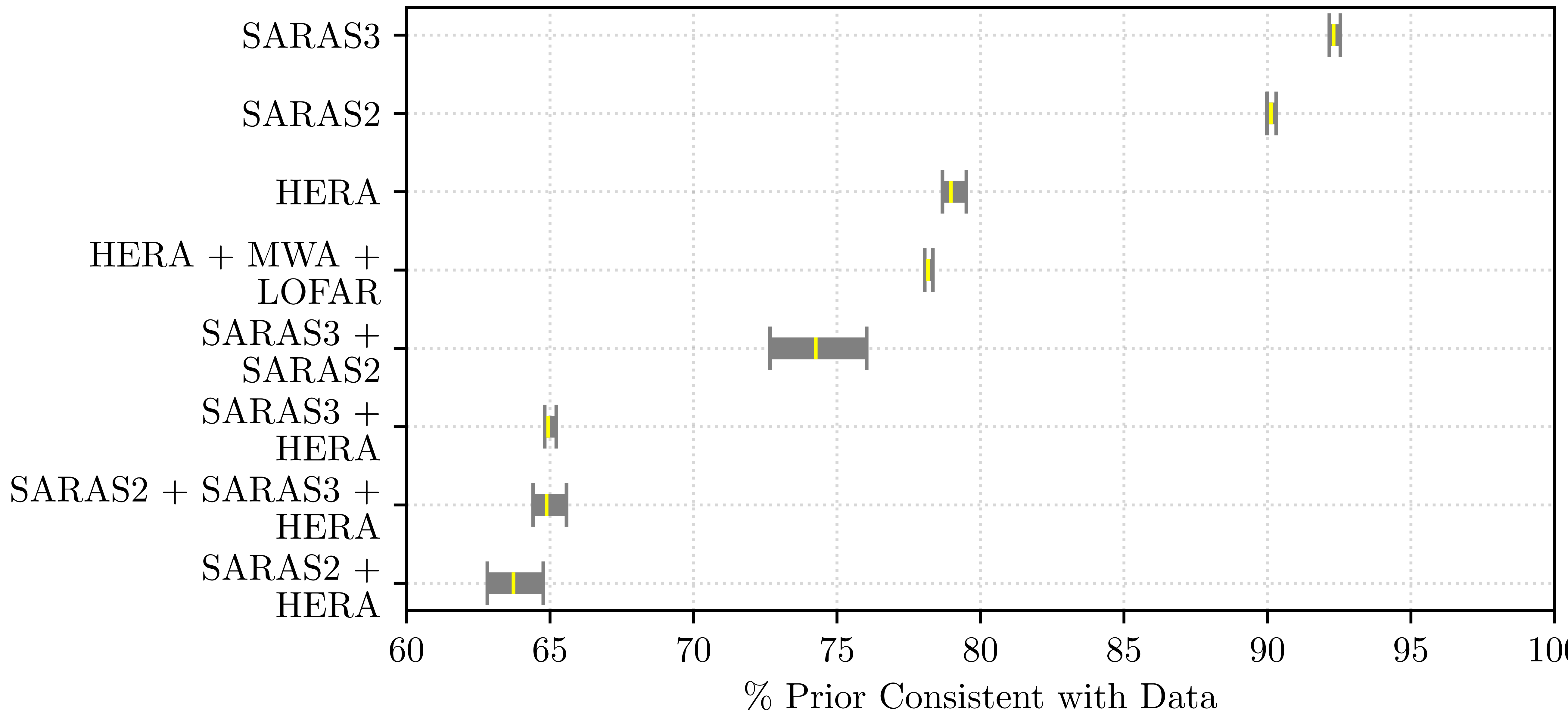
The Results: Constraining power?

Quantify constraining power with the *marginal* KL divergence via *margarine*

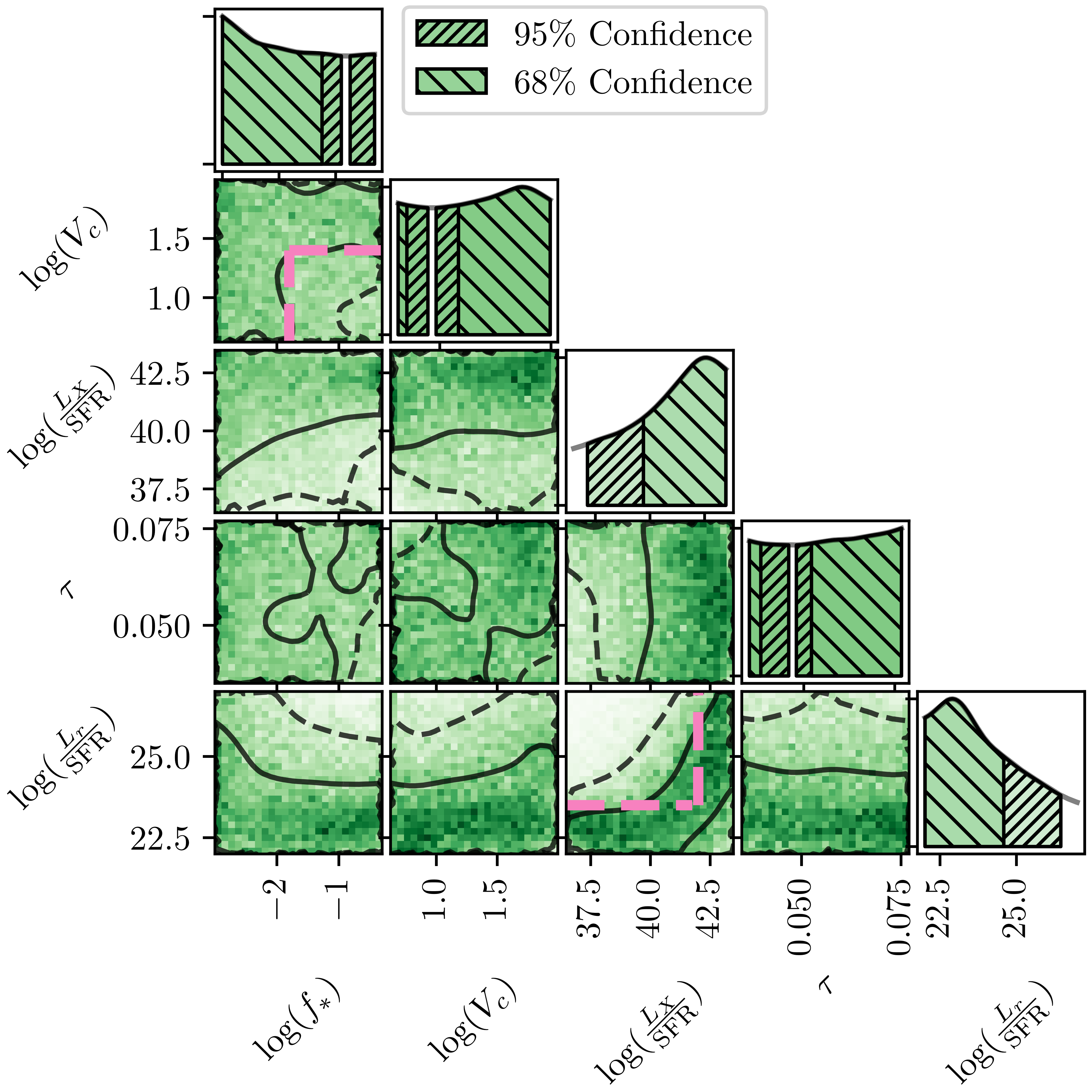
$$\mathcal{D}(P||\pi) = \left\langle \log \frac{P(\theta_{21})}{\pi(\theta_{21})} \right\rangle_{P(\theta_{21})} \approx -\log \frac{V_P}{V_\pi}$$

Contraction of prior on to posterior

SARAS3 $\approx 93\,\%$
HERA $\approx 78\,\%$
SARAS3 + HERA $\approx 65\,\%$



The Results: Parameters?



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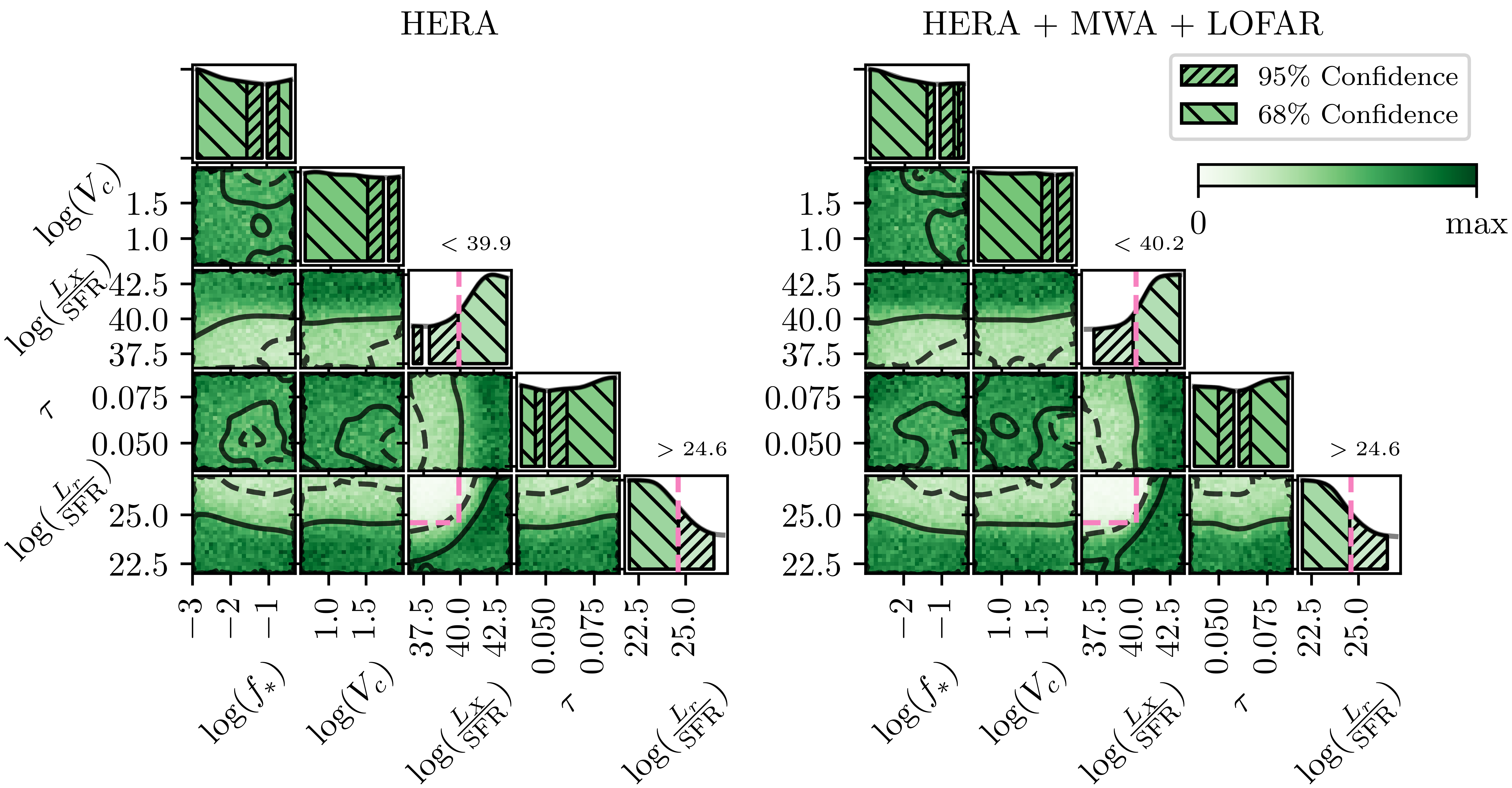

The Results: Other Global?