UNIVERSITY OF CAMBRIDGE

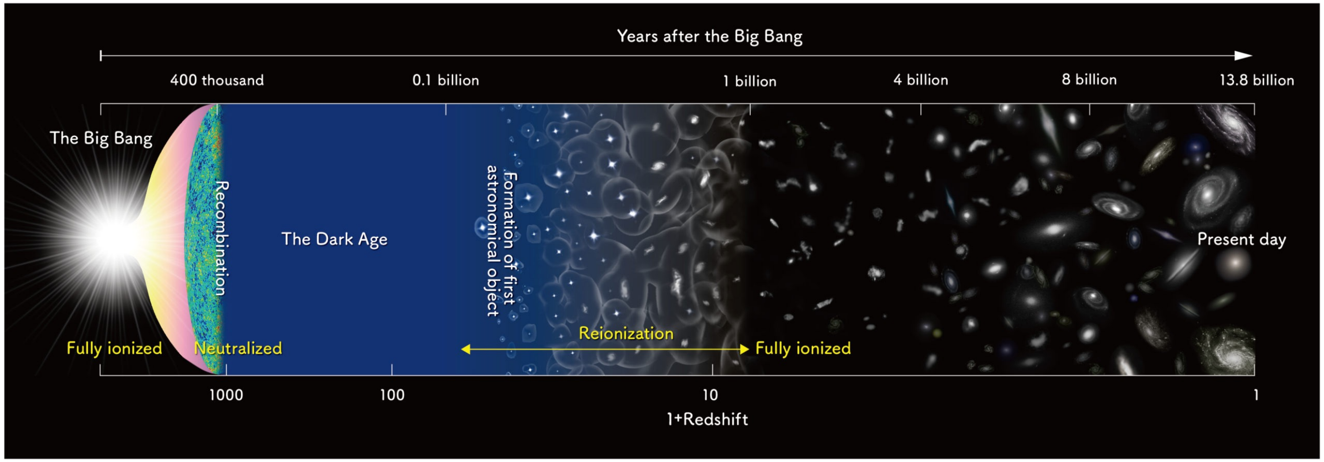
Joint astrophysical constraints on 21-cm models with multiwavelength observations

Simon Pochinda (sp2053@cam.ac.uk)

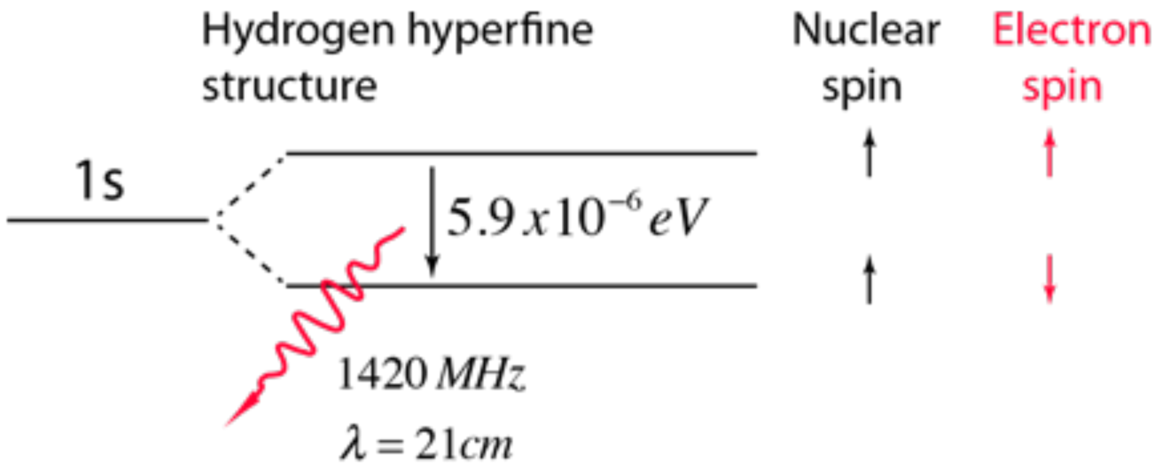
Cavendish Radio Cosmology

Motivation

- Uncharted Dark Ages, Cosmic Dawn, and Epoch of Reionization
- 21-cm line of neutral hydrogen
- Wealth of 21-cm data from upcoming experiments.
- Jointly inferring astrophysical parameters using probes across the entire electromagnetic spectrum.



What is the 21-cm line?



- Relative population of hyperfine states defined by

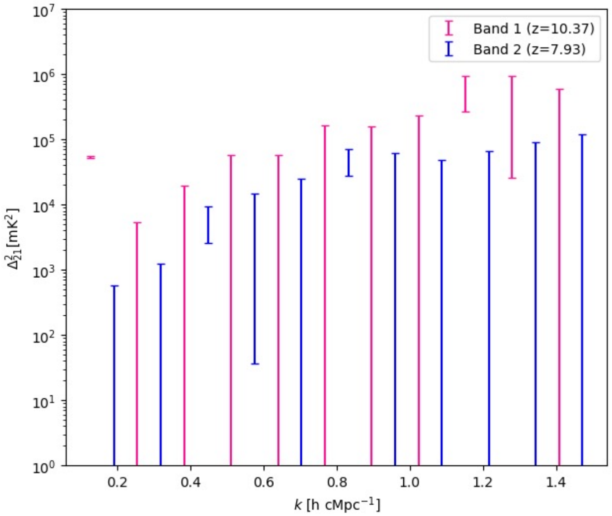
$$\frac{n_1}{n_0} = 3\exp\left(\frac{T_*}{T_S}\right).$$

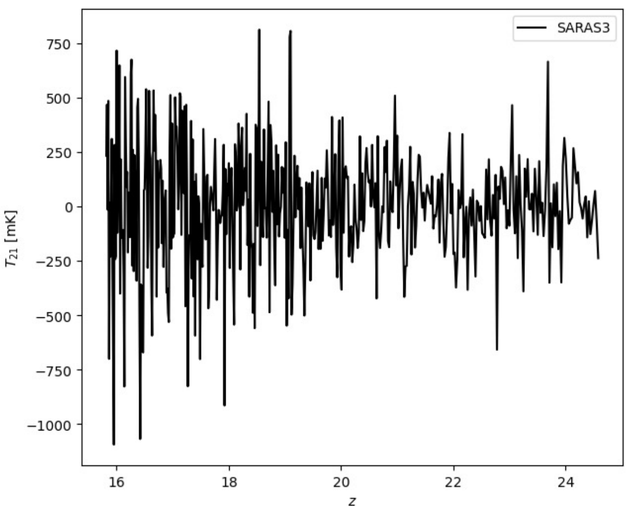
- Interested in the brightness temperature contrast to the CMB

$$T_{21} = \delta T_b = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau_{21}}\right).$$

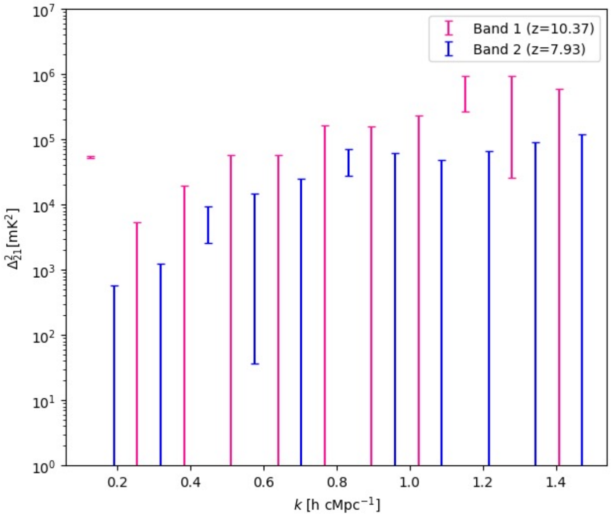
- Spin temperature – collisional coupling, radiative coupling, WF effect (Furlanetto+2006)

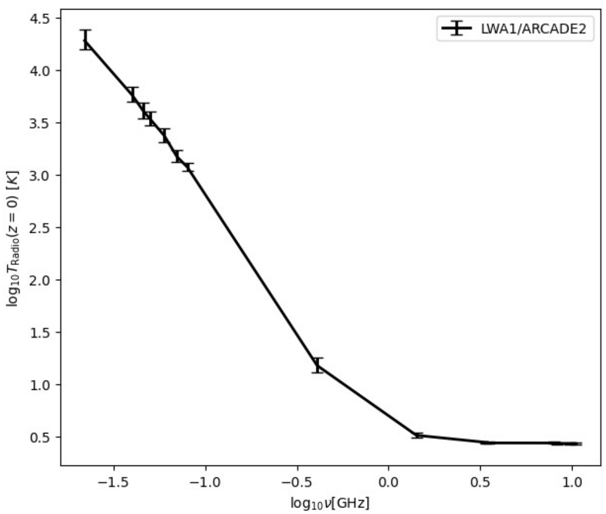
21 cm experiments

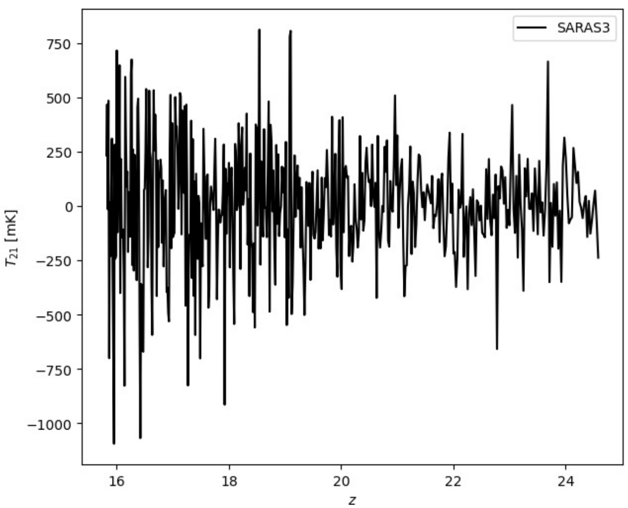




Multiwavelength data







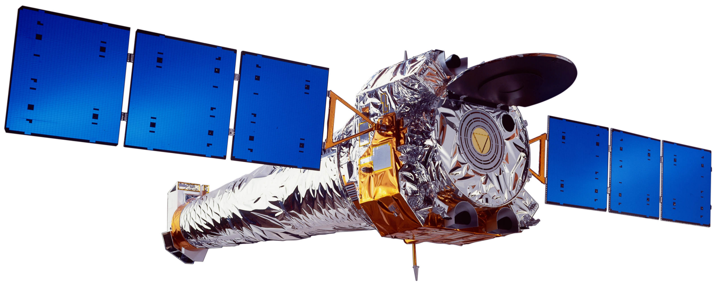
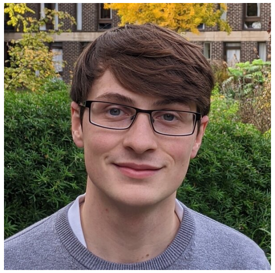


Table 1. Cosmic X-ray Background

Data set	S [erg cm^{-2} s^{-1} deg^{-2}]
(1)	(2)
Hickox & Markevitch (2006), 1 − 2 keV	$(1.04 \pm 0.14) \times 10^{-12}$
Hickox & Markevitch (2006), 2 − 8 keV	$(3.4 \pm 1.7) \times 10^{-12}$
Harrison et al. (2016), 8 − 24 keV	$(1.832 \pm 0.042) \times 10^{-11}$
Harrison et al. (2016), 20 − 50 keV	$(2.0 \pm 0.083) \times 10^{-11}$

Semi-numerical 21-cm models

- Goal: Simulate the 21-cm brightness temperature (Fialkov et al., Gessey-Jones+2023 for a review)
- Initial conditions
  - Evolve density and velocity field from CAMB
  - Gas temperature and ionization fraction from RECFAST
- Parameterized star formation and emission
  - Free parameters: $f_{\mathrm{star,II}}$, $f_{\mathrm{star,III}}$, V_c, f_X, α_X, $\nu_{X,\mathrm{min}}$, τ, f_{Radio}, pop
- Advantage: Faster than full N-body simulations. But still too slow…

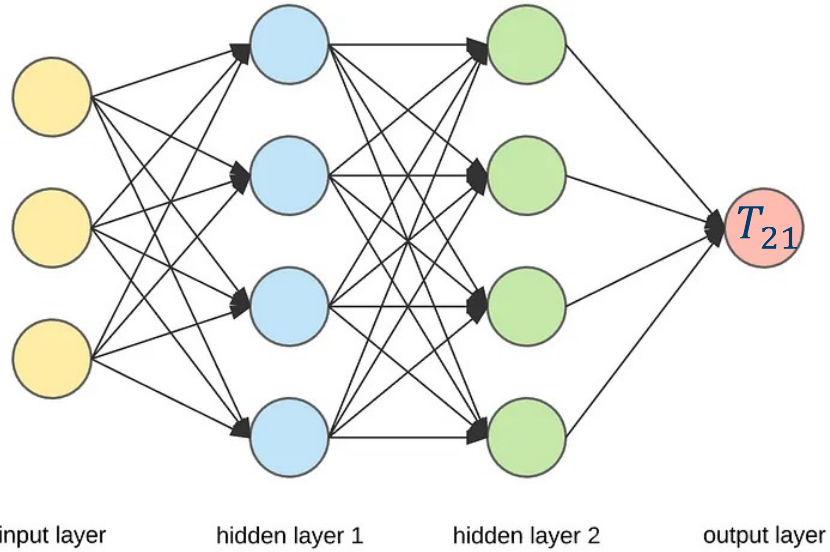


Thomas Gessey-Jones

Training emulators

- Train emulator to learn simulation quantities (Δ_{21}^2, SFR, X-ray background, and T_{21})
- Emulations in $\mathcal{O}(1\ \mathrm{ms})$
- Global signal emulator: globalemu

$f_{\mathrm{star,II}}$
$f_{\mathrm{star,III}}$
V_c
f_X
α_X
$\nu_{X,\mathrm{min}}$
τ
f_{Radio}
pop
z




Harry Bevins


Stefan Heimersheim

Explicit parameter inference

- Nested sampling with Polychord

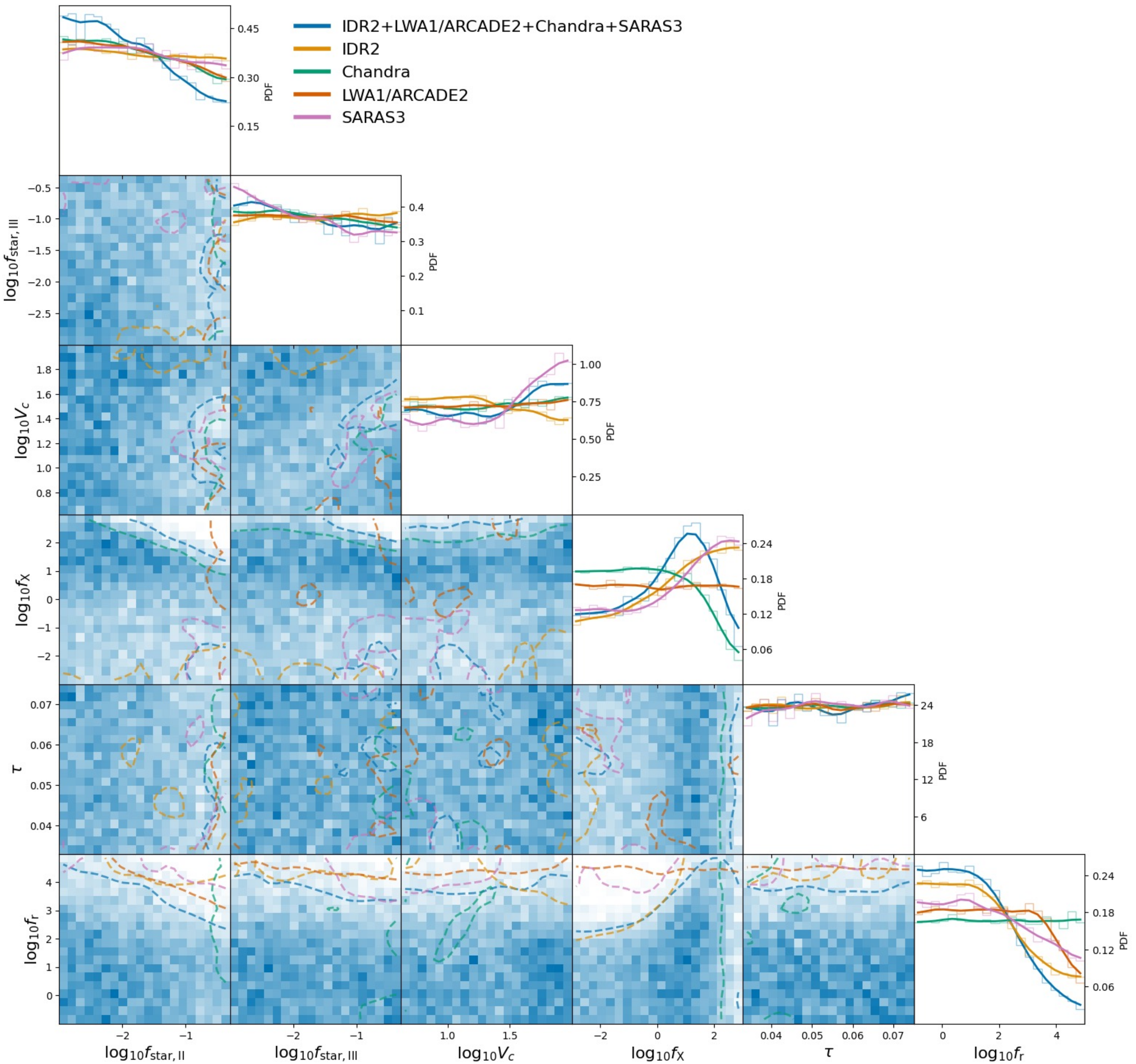
- Upper limit likelihood on for Δ^2_{21}, T_{Radio} and the CXB

- Gaussian likelihood for the global signal, T_{21}.

- Joint likelihood:

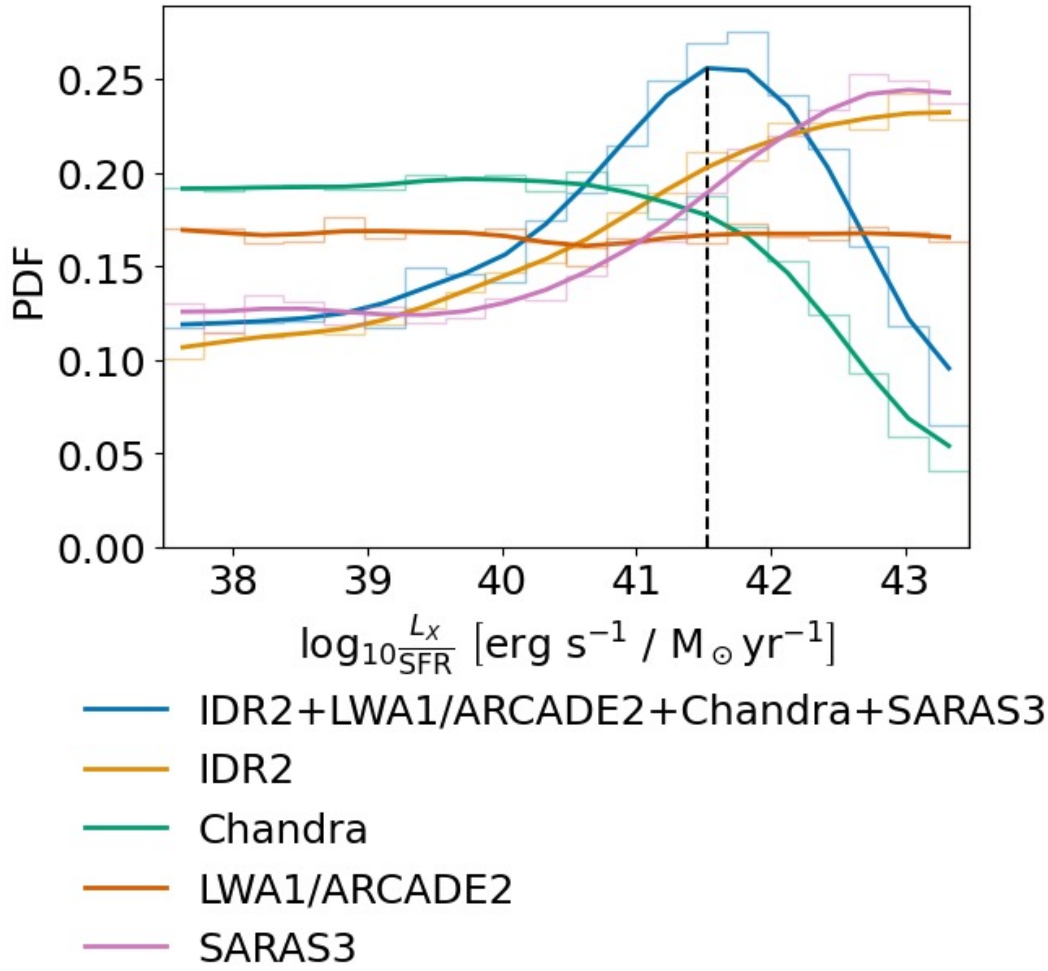
$$\mathcal{L}_{\mathrm{total}} = \mathcal{L}_{\Delta^2_{21},\mathrm{HERA}} \times \mathcal{L}_{\mathrm{CXB}} \times \mathcal{L}_{T_{\mathrm{Radio}}} \times \mathcal{L}_{\mathrm{SARAS3}}.$$

Parameter constraints



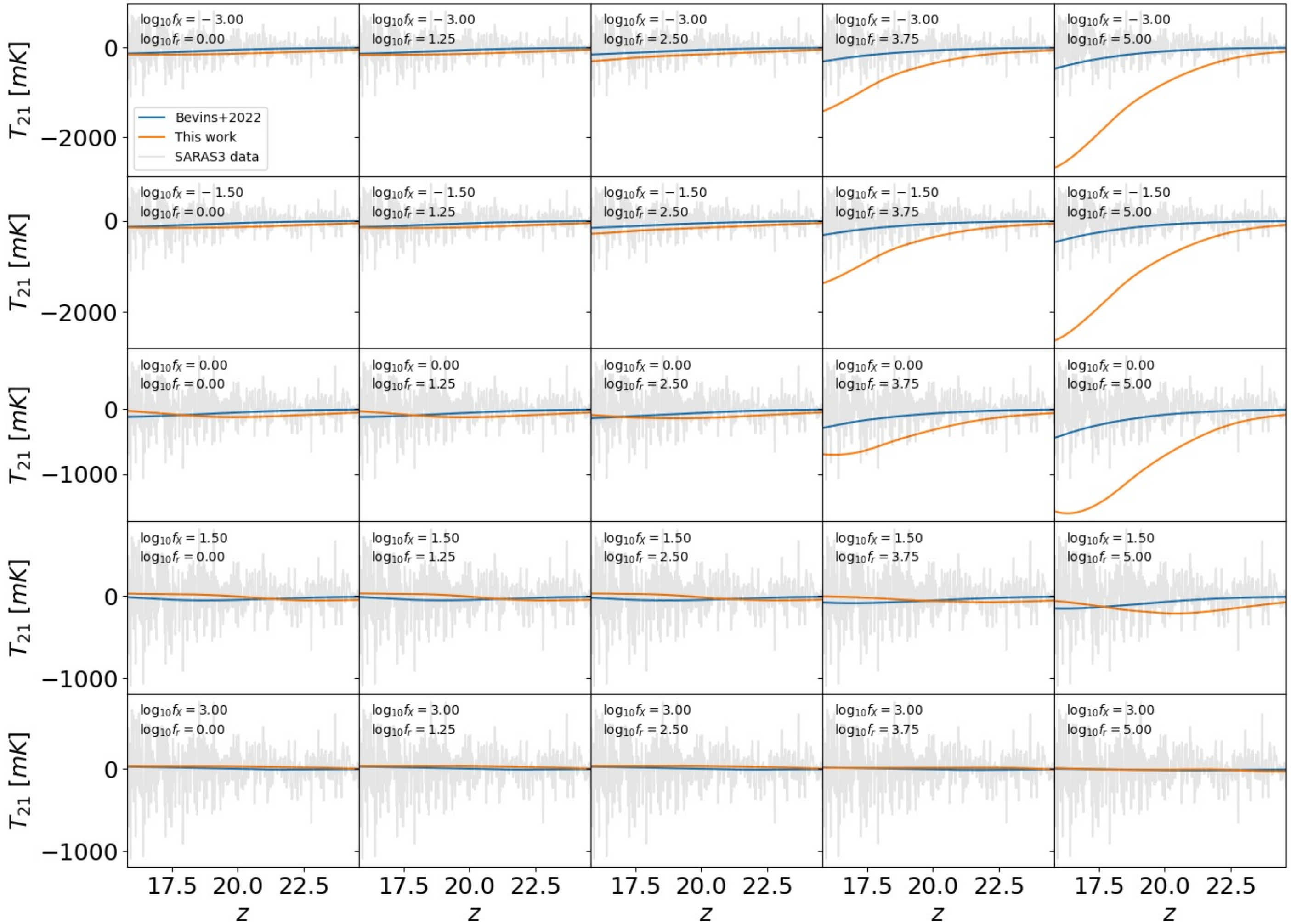
Constraints on the X-ray efficiency

- Chandra excludes high f_X models that exceed the X-ray background upper limits
- HERA IDR2 disfavours low f_X and high f_r, as these models produce high power spectra
- SARAS3 same as HERA. Low f_X and high f_r produce models deeper than the observations (new)



New constraints from SARAS3

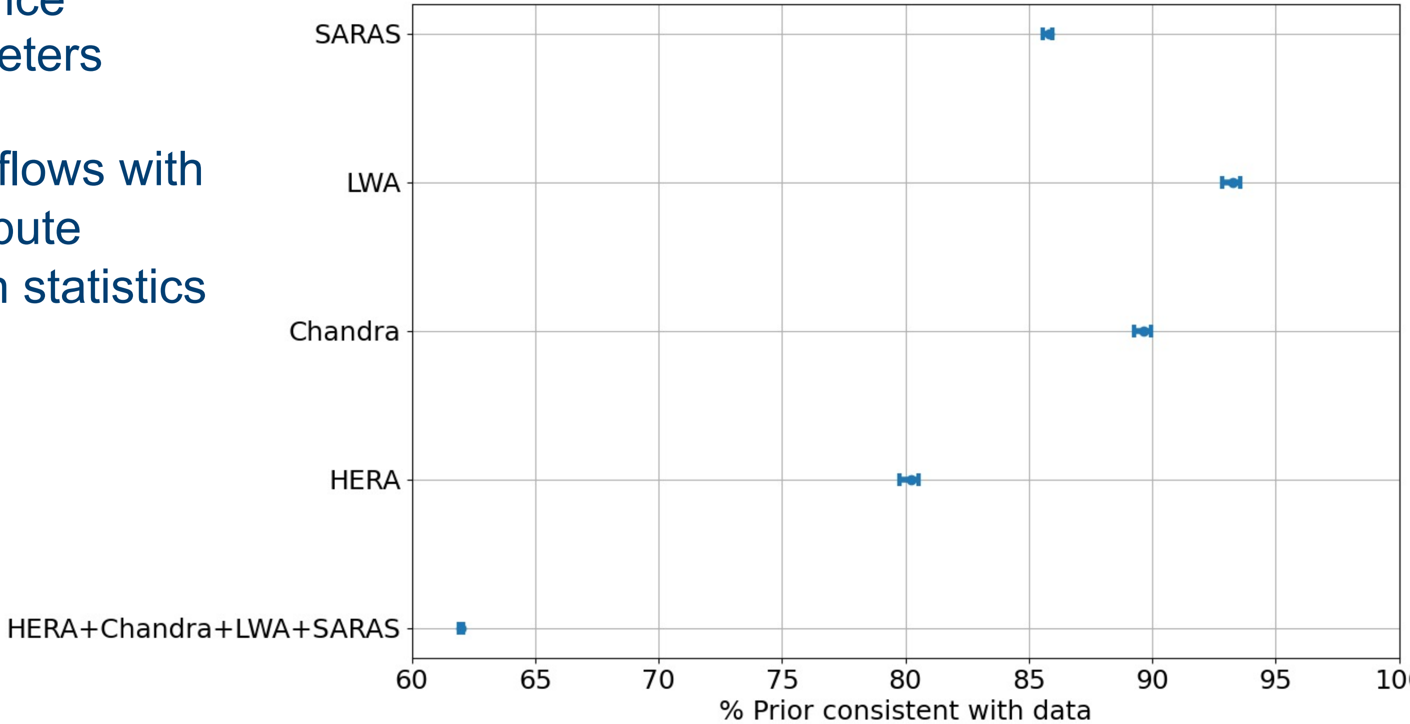
- New models produce deeper signals
- High f_X and low f_r constrained by new models.



Which observational data set provides the best constraints?

- Marginalize nuisance foreground parameters
- Train normalizing flows with margarine to compute marginal Bayesian statistics

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



Conclusions

- Combining measurements of the Cosmic X-ray Background with 21 cm data reveal a tighter constraint on the X-ray efficiency
- The new Pop III to Pop II star formation prescription provides new constraints on the X-ray efficiency with the SARAS3 data
- Joint constraints from multiwavelength observations provide a stronger upper limit on the radio efficiency of galaxies, and constrains star formation efficiencies.
- With better observations we will likely be able to provide constraints on Pop III properties with the new models.