12th July 2024

Impact of extragalactic point sources on the foregrounds and 21-cm observations

Shikhar Mittal

with Girish Kulkarni (TIFR), Dominic Anstey (Cambridge), Eloy de Lera Acedo (Cambridge)

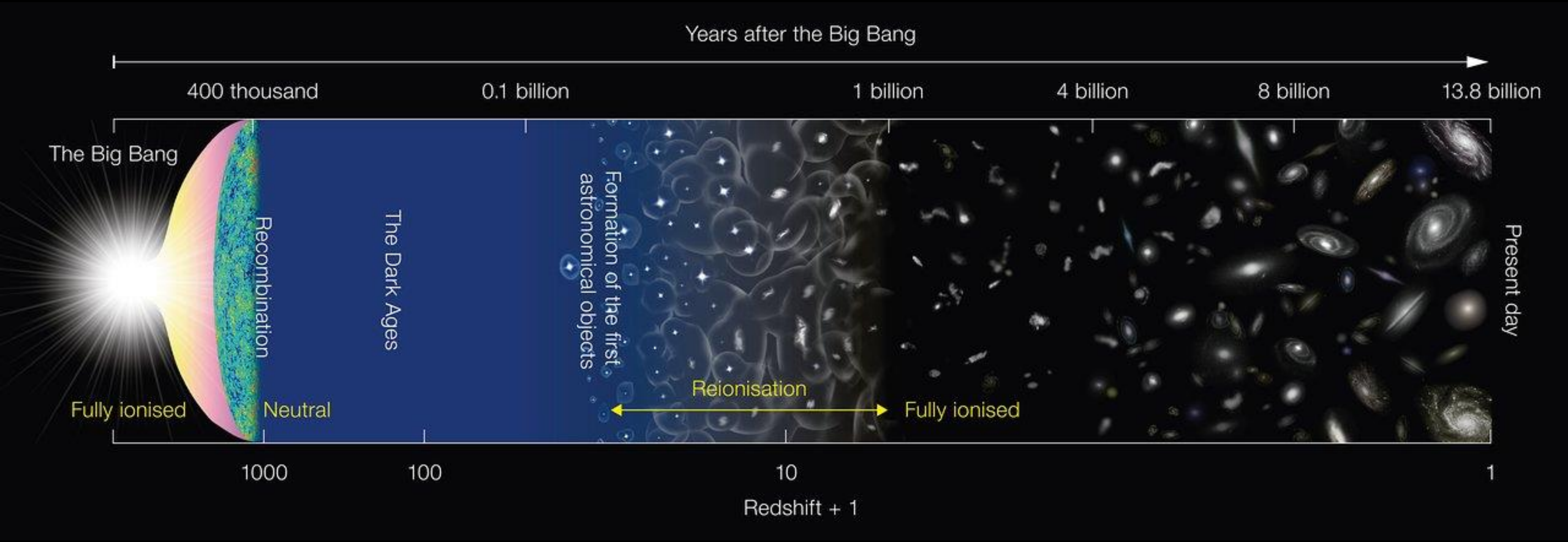
State of the Universe Seminar

arXiv: 2406.17031

Outline

- Context
- Part 1 – A model for extragalactic point sources and foregrounds
- Part 2 – Bias in the signal reconstruction due to point sources
- Conclusion

Cosmic timeline

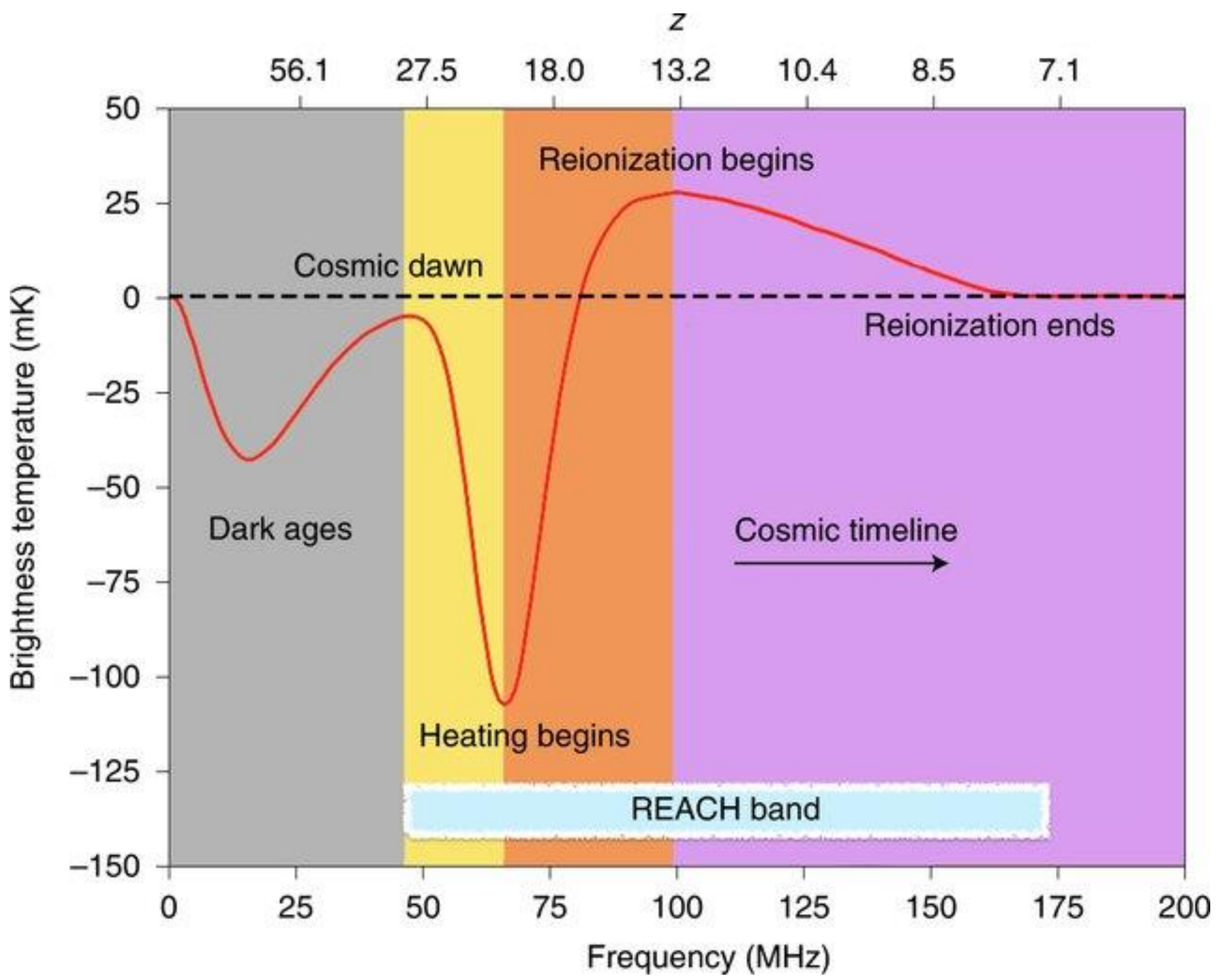


21-cm experiments are targeting cosmic dawn

- EDGES (PI: Judd Bowman, ASU): They made the first detection in 2018
- SARAS (PI: Saurabh Singh, RRI): Reject EDGES measurement
- **REACH** (PI: Eloy de Lera Acedo, University of Cambridge)
  1. **R**adio **E**xperiment for the **A**nalysis of **C**osmic **H**ydrogen
  2. Will cover $28 > z > 7.5$
  3. Karoo radio reserve in South Africa
  4. Funded by Kavli Foundation and Stellenbosch University
  5. Data expected by the end of 2024

MIST, PRIzM, ALBATROS, PRATUSH, DARE and more in development

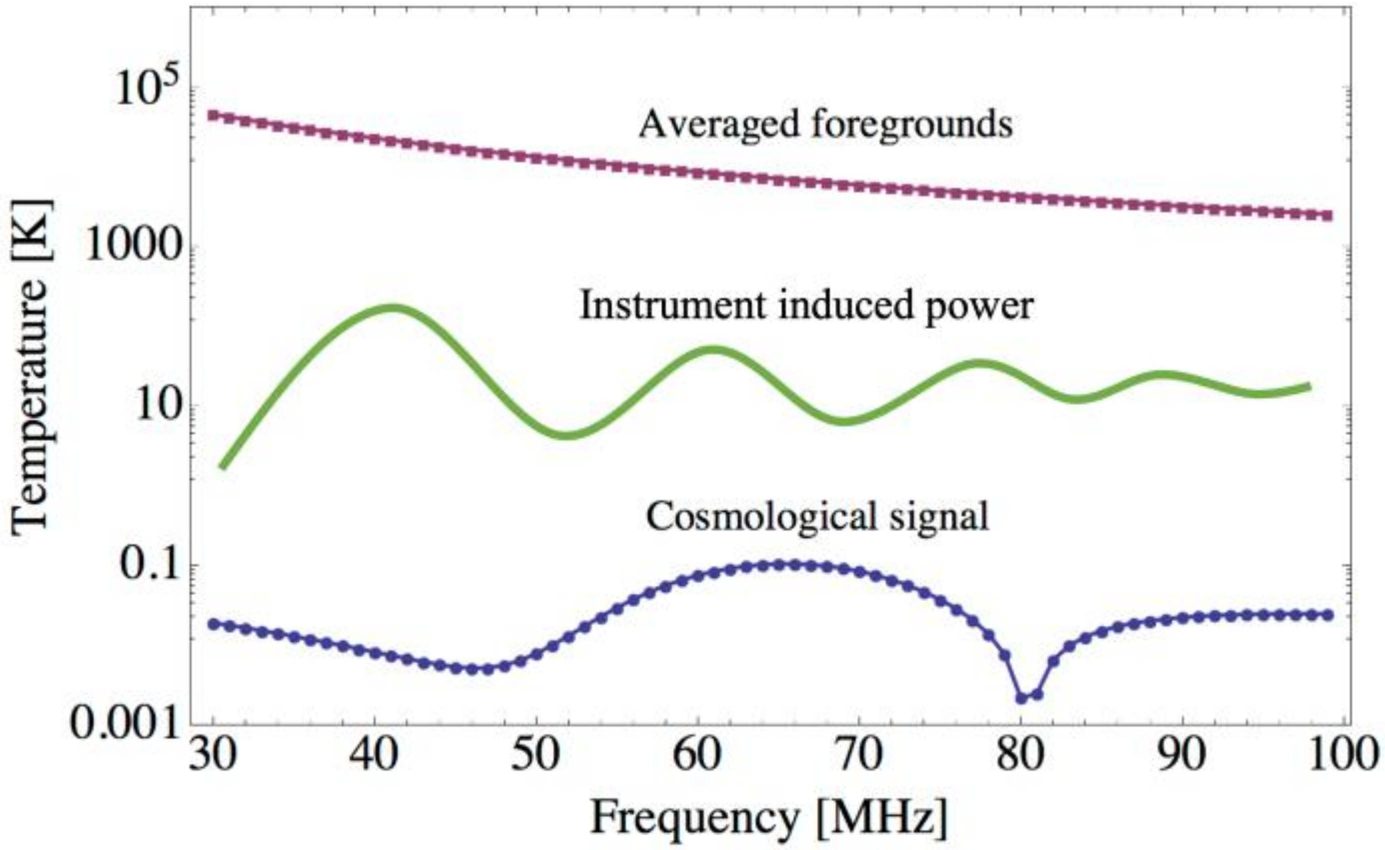
Global 21-cm signal is of the order of mK but …



REACH webpage

Foregrounds are 4-5 orders of magnitude stronger than the 21-cm signal

1. Foregrounds
    - Galactic
    - Extragalactic
2. Ionosphere
3. Instrument
4. Soil
5. 21-cm signal



E. de Lera Acedo, 5th Global 21-cm workshop

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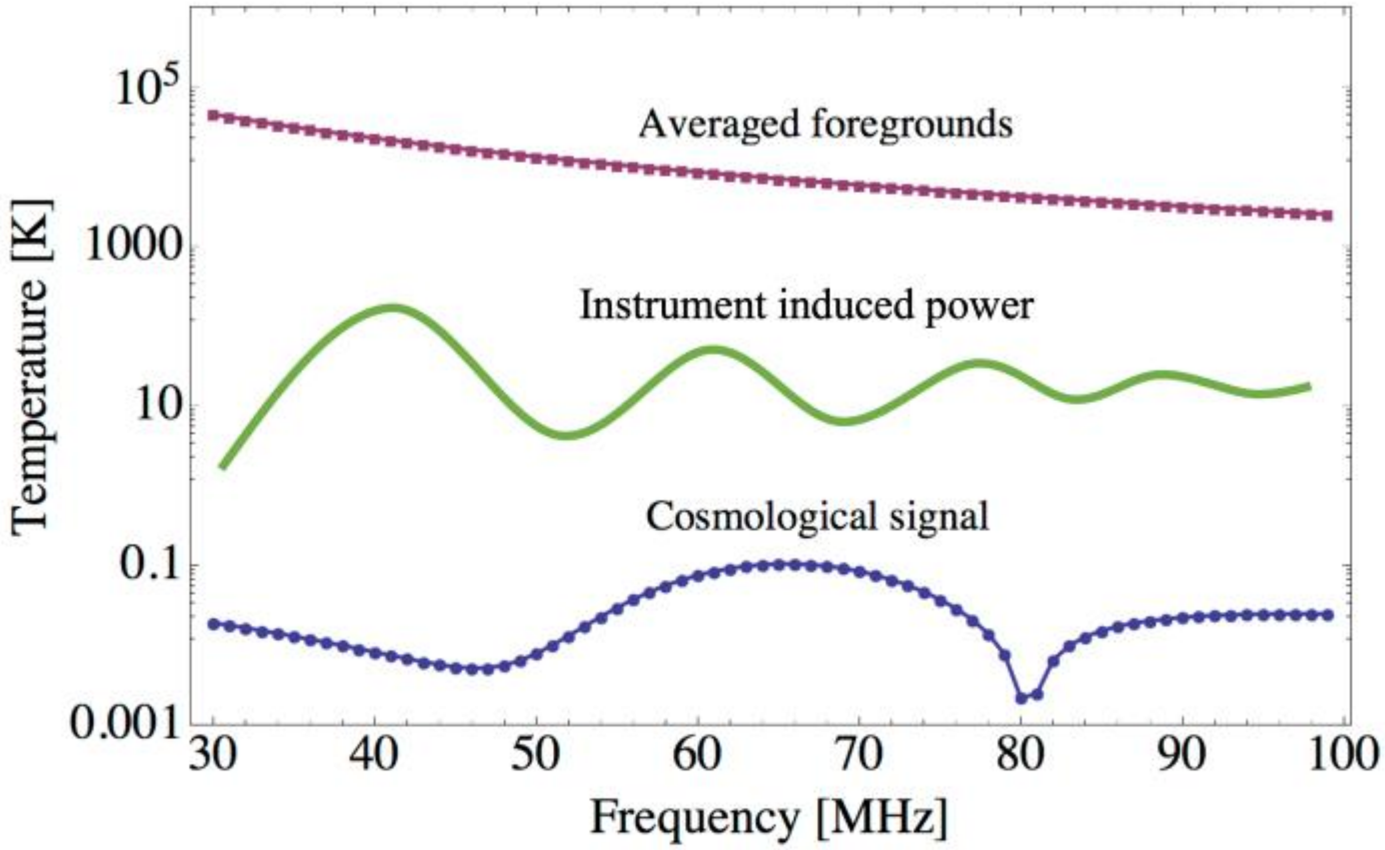

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Extragalactic foregrounds

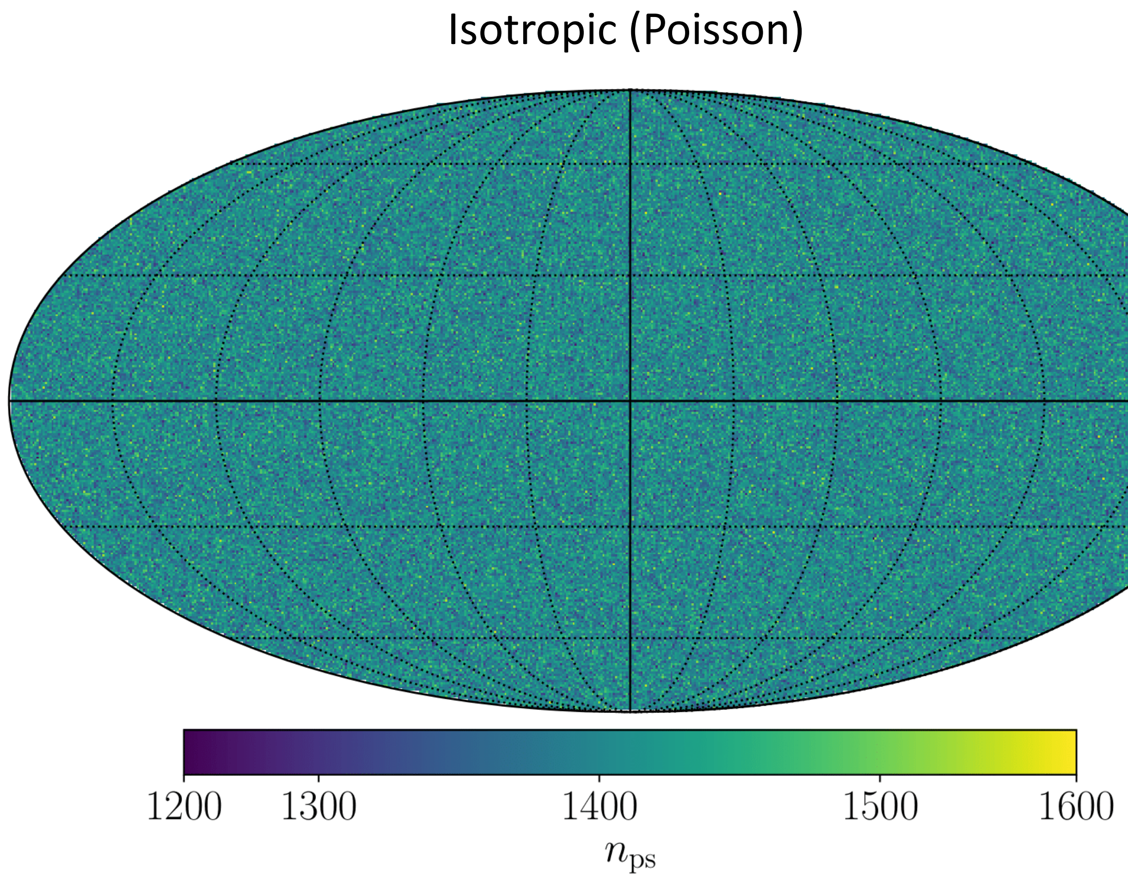
Extragalactic foregrounds

- Active galactic nuclei
- Radio galaxies
- Radio emission from star forming galaxies
- Free-free emission from haloes and IGM

We need 3 inputs to simulate foregrounds due to point sources

1. How are the sources positioned on the sky?
2. What are their fluxes at some reference frequency?
3. What is their spectral energy distribution (SED)?

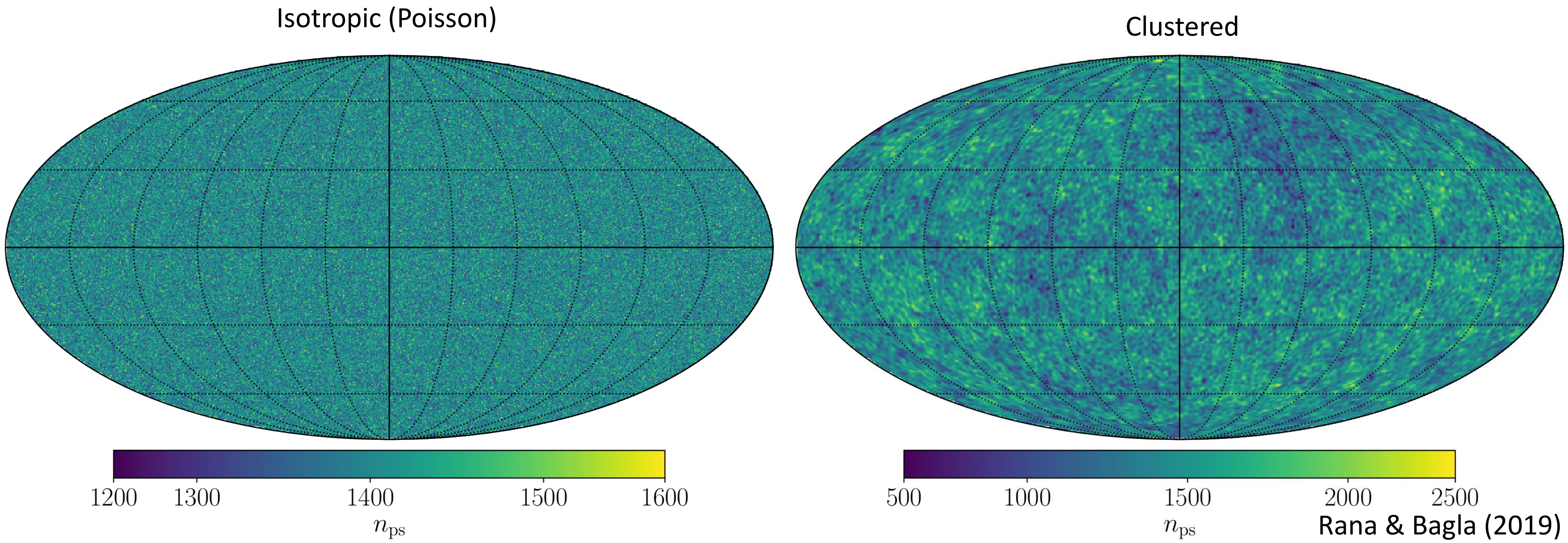
1. We use a power law form of correlation function



1. We use a power law form of correlation function

$C(\chi) = A\chi^{-\gamma}; A = 7.8 \times 10^{-3}, \gamma = 0.821$

Based on *TGSS-ADR1* survey by GMRT



Rana & Bagla (2019)

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Di Matteo et al (2004); Gervasi et al. (2008)

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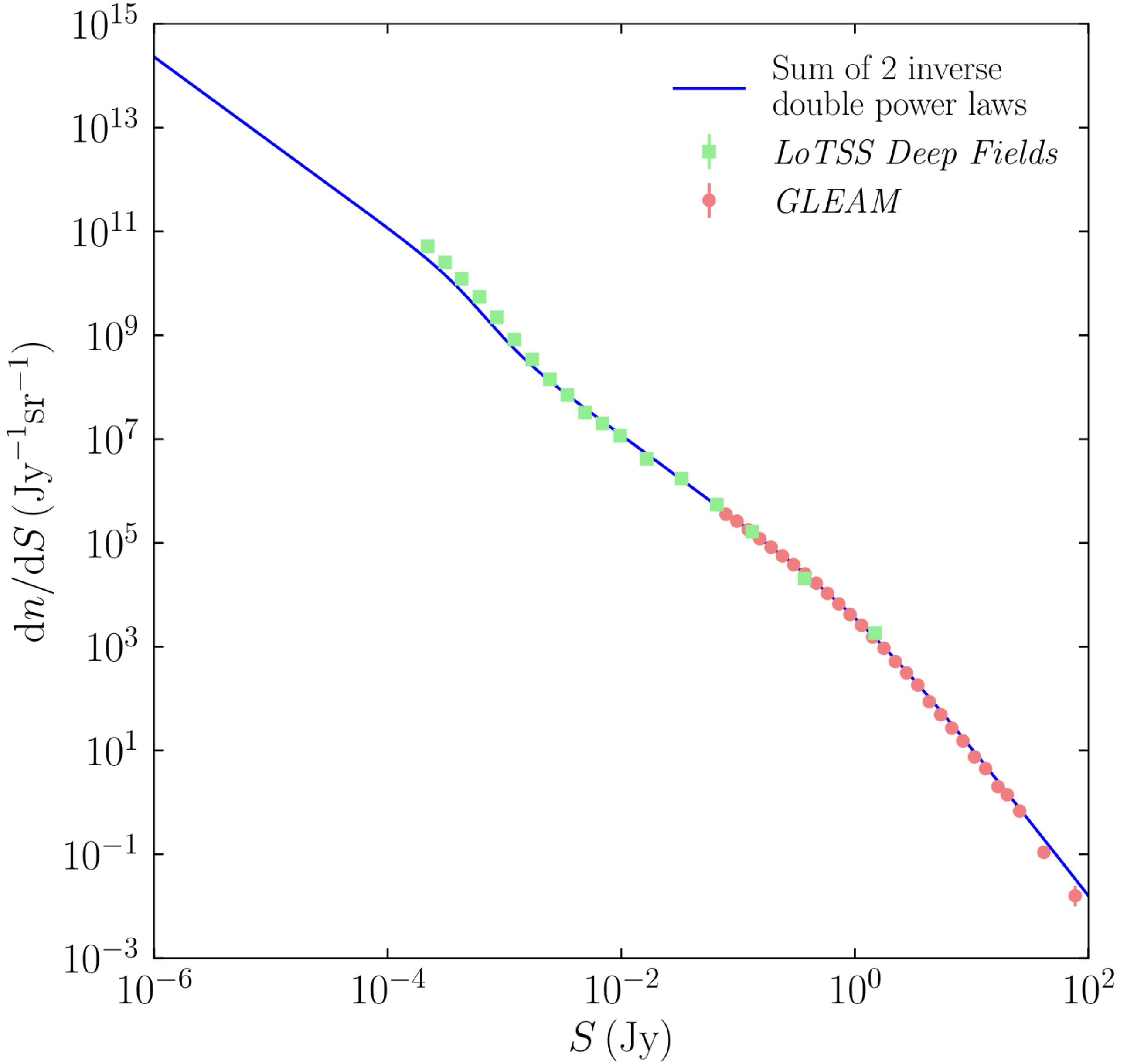
- For our chosen distribution $S_{\max} = 100$ Jy and $S_{\min} = 10^{-6}$ Jy is sufficient

$$N_{\mathrm{ps}} \sim 4.4 \times 10^{9}$$



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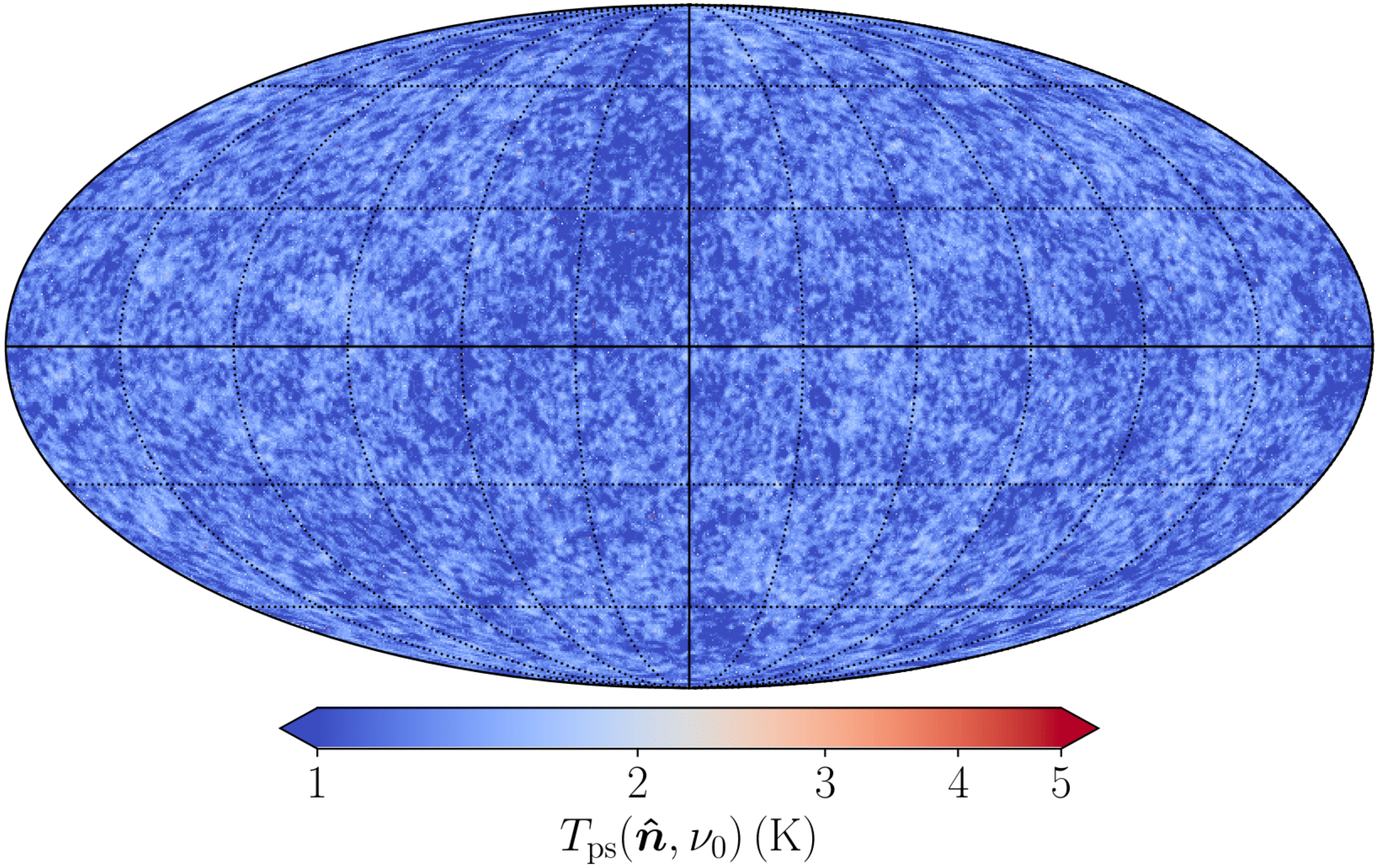
β has a Gaussian distribution:

$$\mathcal{P}(\beta) = \frac{1}{\sqrt{2\pi}\sigma_\beta} \exp\left[-\frac{(\beta - \beta_0)^2}{2\sigma_\beta^2}\right]$$

where $\beta_0 = 2.68$ and $\sigma_\beta = 0.5$ (Fiducial model)

Tegmark et al (2000); Gervasi et al (2008), Liu et al (2008, 2011)

Sky map of the brightness temperature due to point sources at $\nu = 150$ MHz, ($z \approx 8.5$)



Couple this with the REACH beam …

Mittal et al (2024)

Simulated observed antenna temperature

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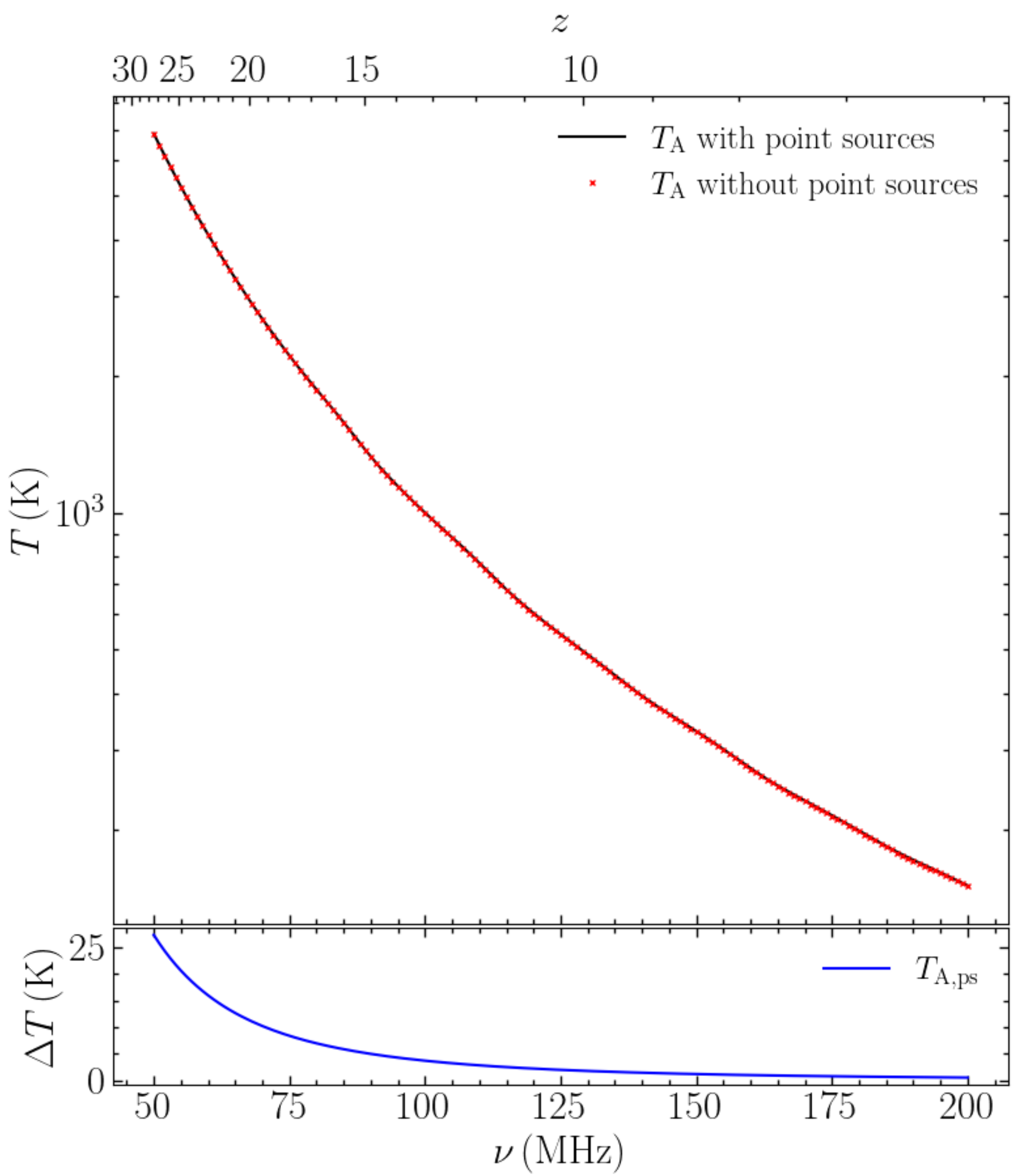

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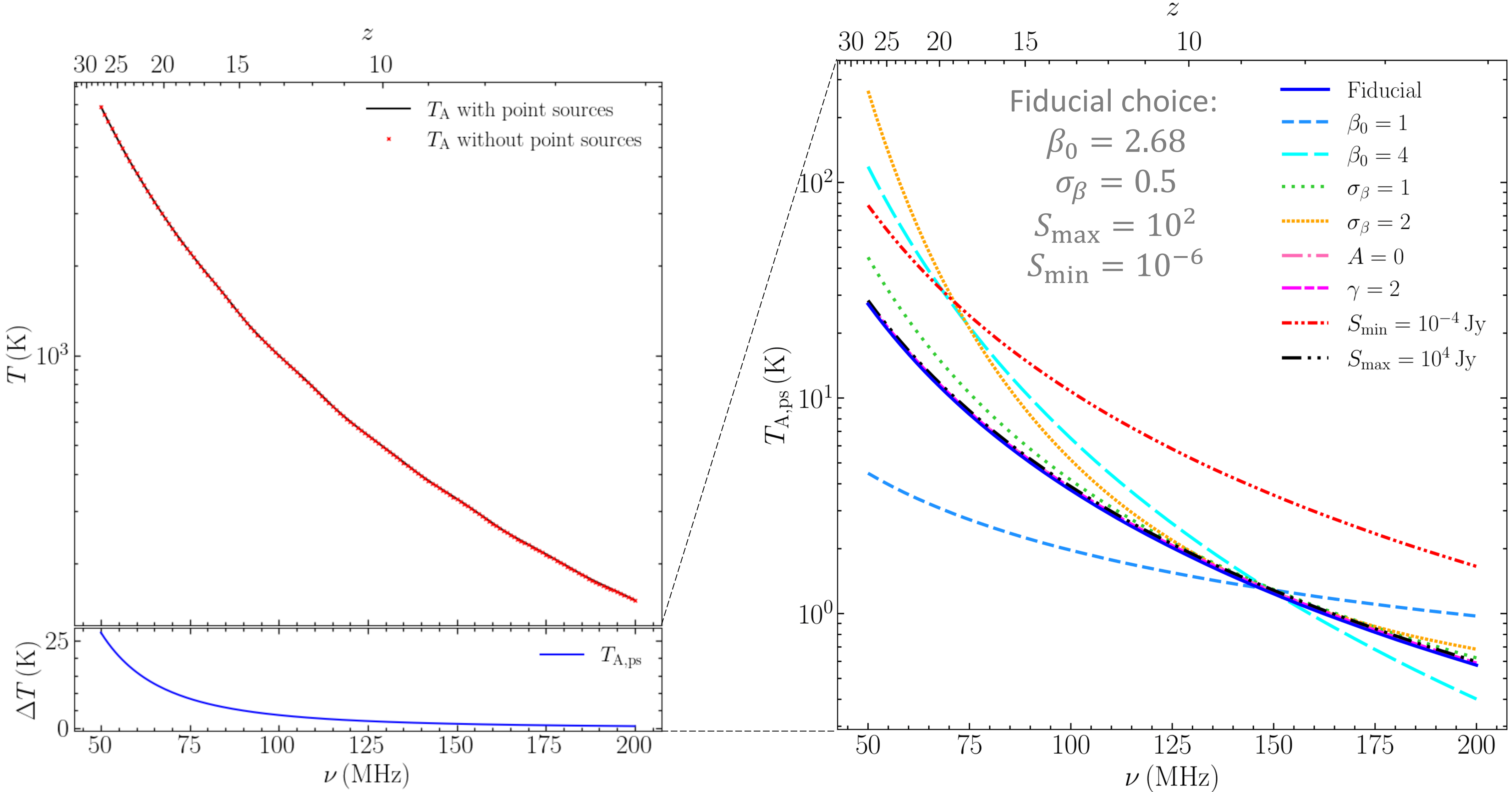


Given the antenna temperature data can we reliably extract the 21-cm signal?

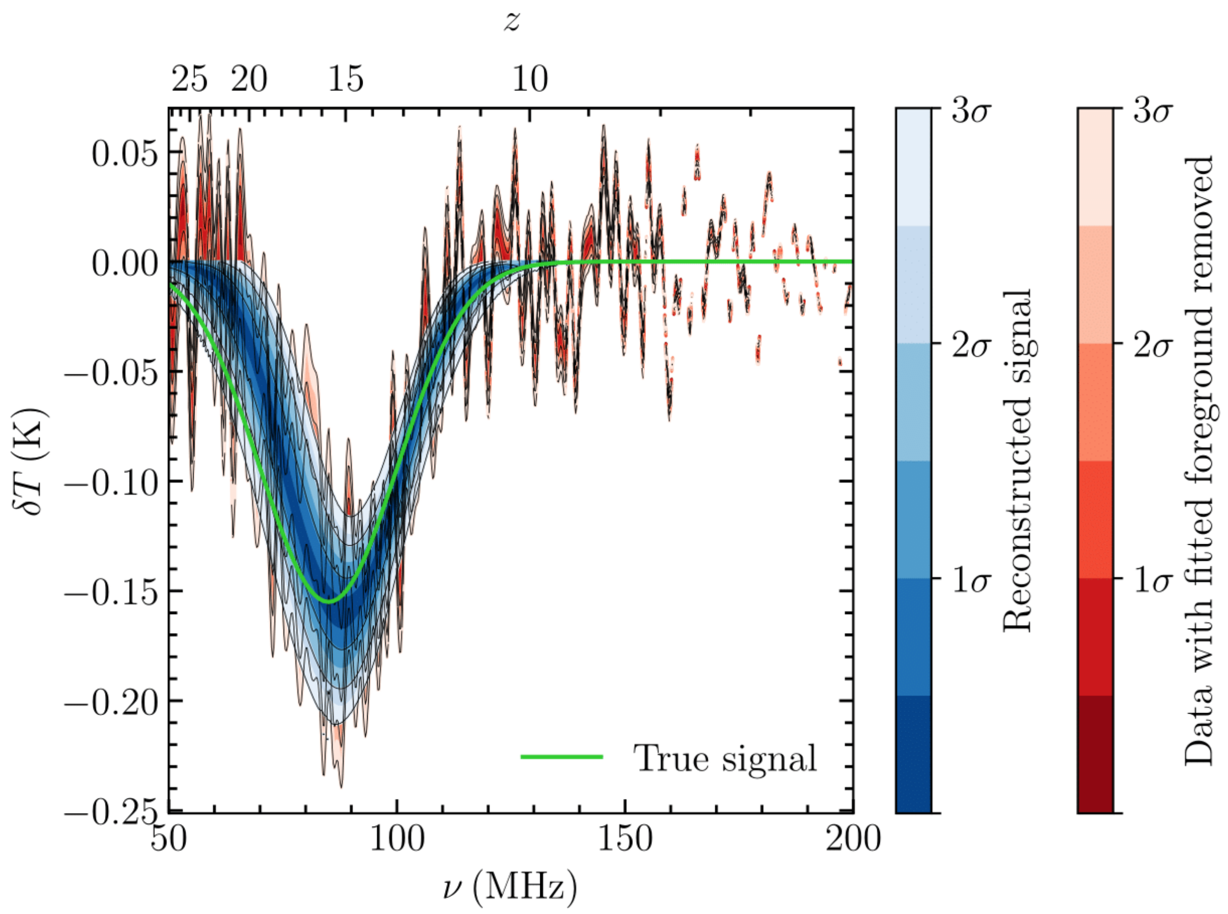
We use a Bayesian framework for inference

- $P(\theta|\mathcal{D}) \propto P(\mathcal{D}|\theta)P(\theta)$
- A Gaussian likelihood, $P(\mathcal{D}|\theta)$
- Uniform priors, $P(\theta)$

Model for inference = Foregrounds + antenna noise + 21-cm signal

Without PS in the data, signal recovery is good

Default pipeline; no point sources



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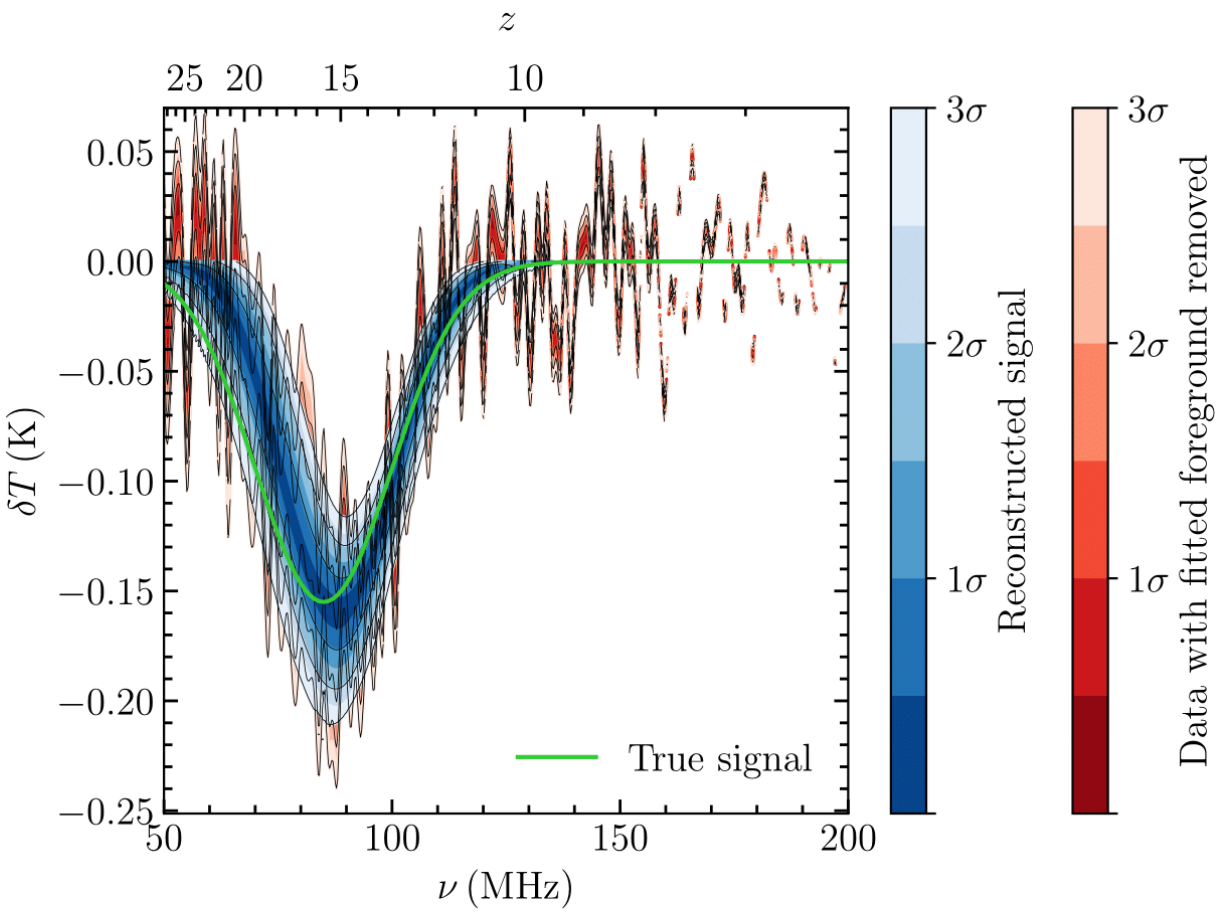
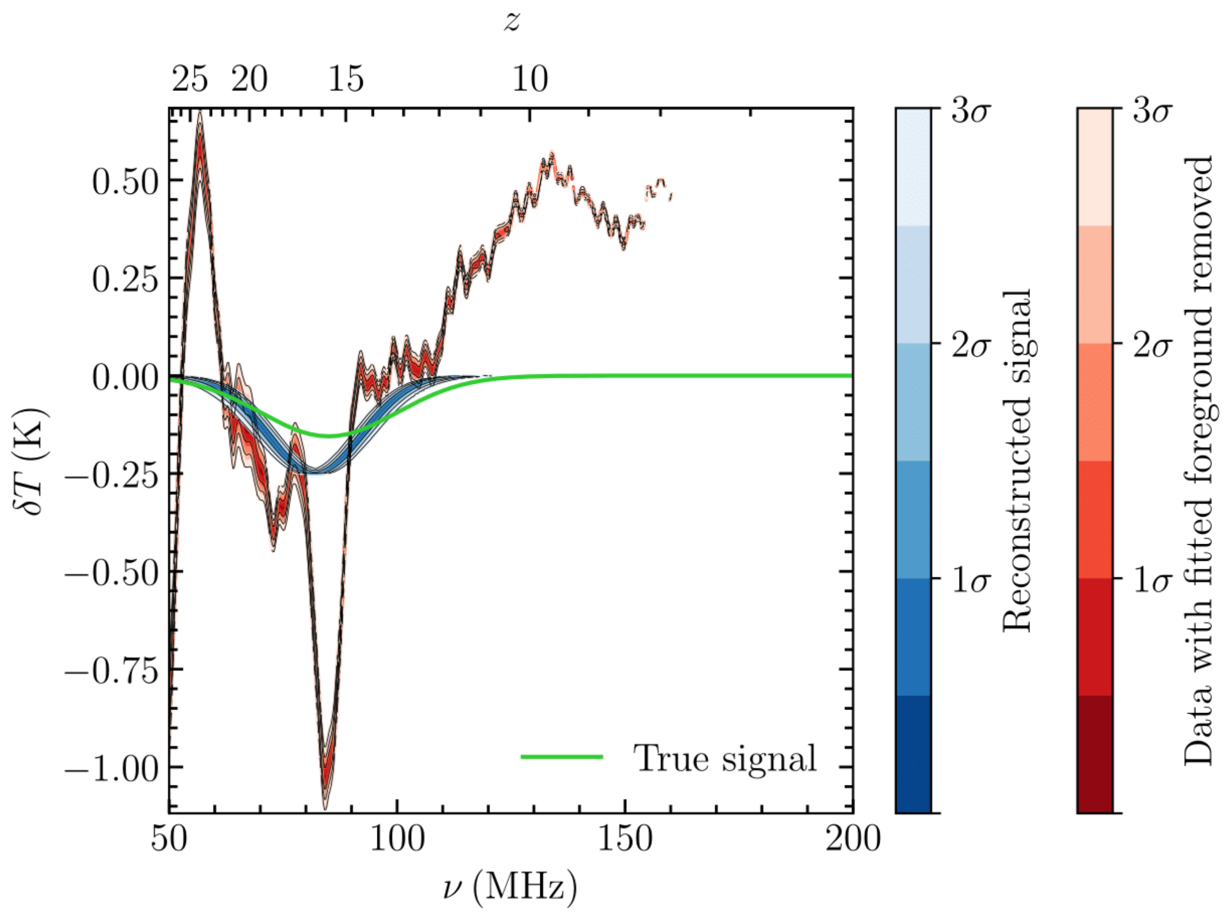


Adding point sources to mock antenna data



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Total foregrounds model =

galactic +

$$\left[T_{\mathrm{f}} \left(\frac{\nu}{\nu_0} \right)^{-\beta_{\mathrm{f}} + \Delta\beta_{\mathrm{f}} \ln \nu/\nu_0} \right]$$

3 new parameters introduced

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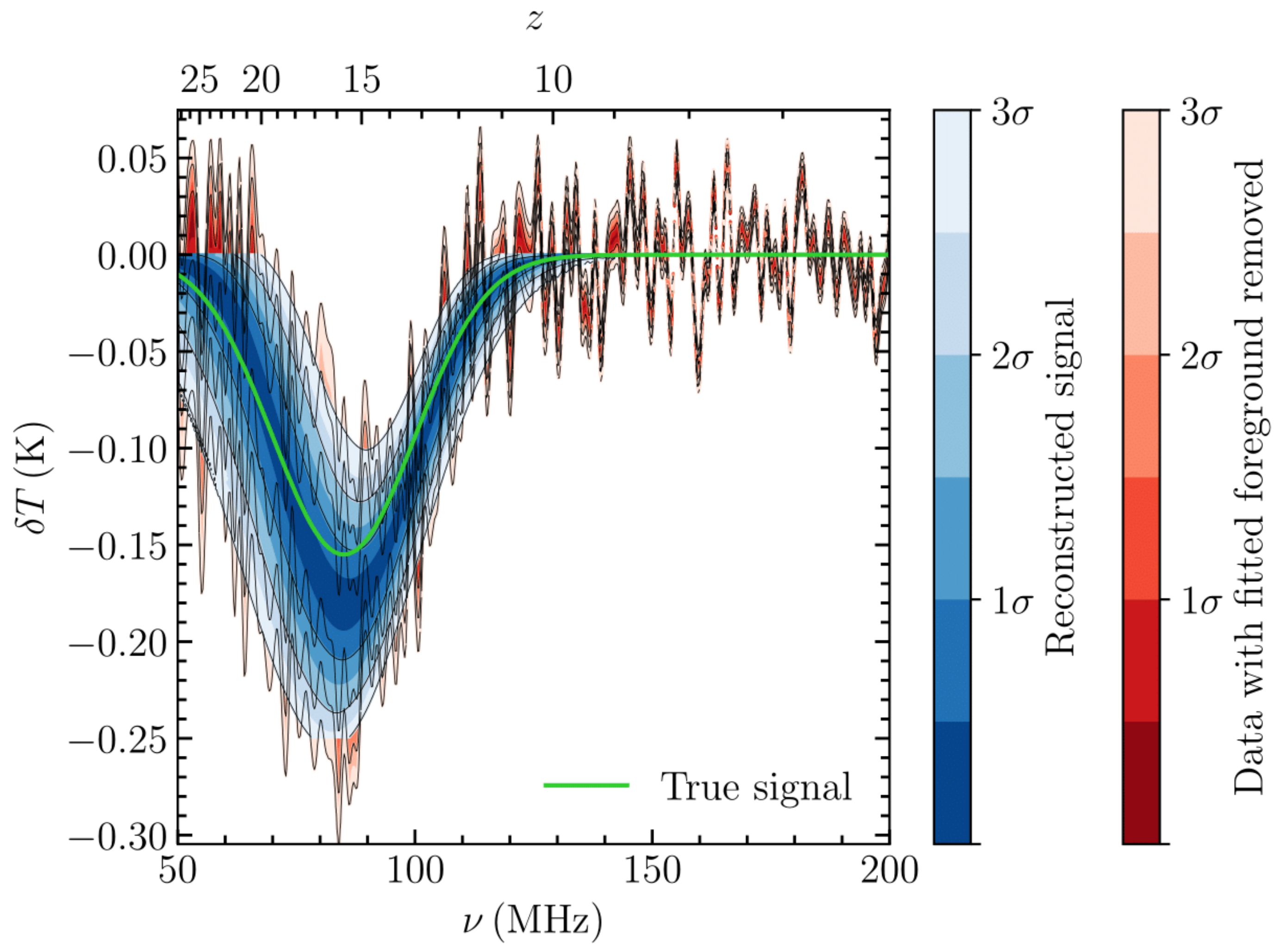
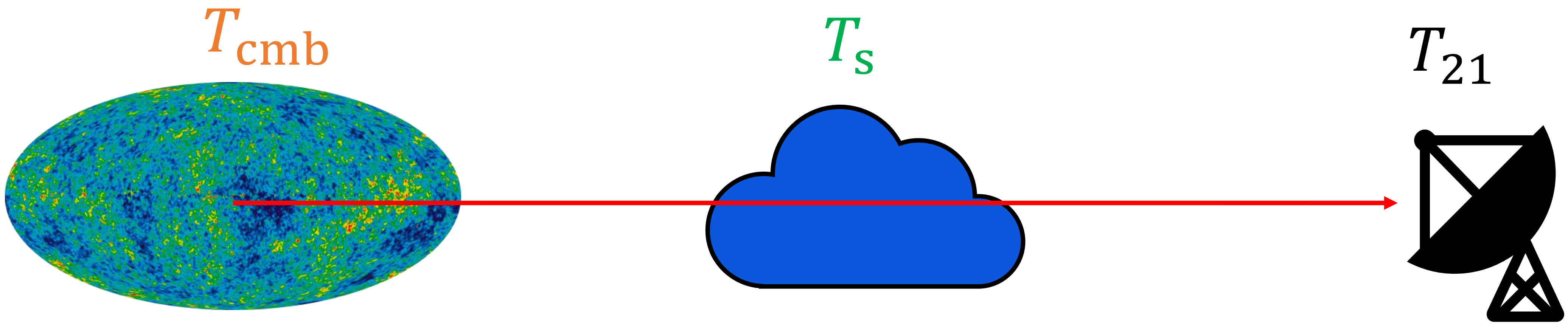


Conclusion

- We simulated the foregrounds due to extragalactic point sources
- With PS present in the data, the signal recovery is poor
- To improve, we propose a power law with a running index to capture the PS contribution

We release with this work a python package called `epspy`

21-cm signal as a thermometer



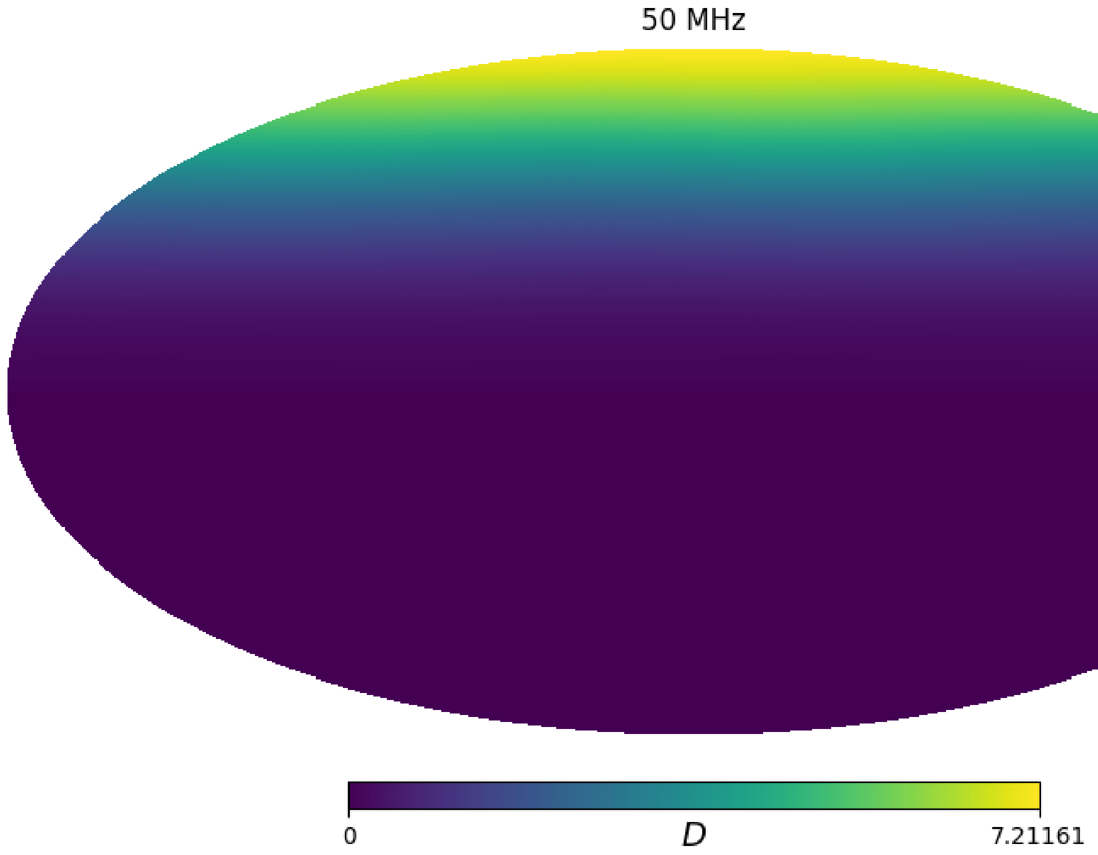
Our observable is the 21-cm brightness temperature relative to the background (CMB) temperature:

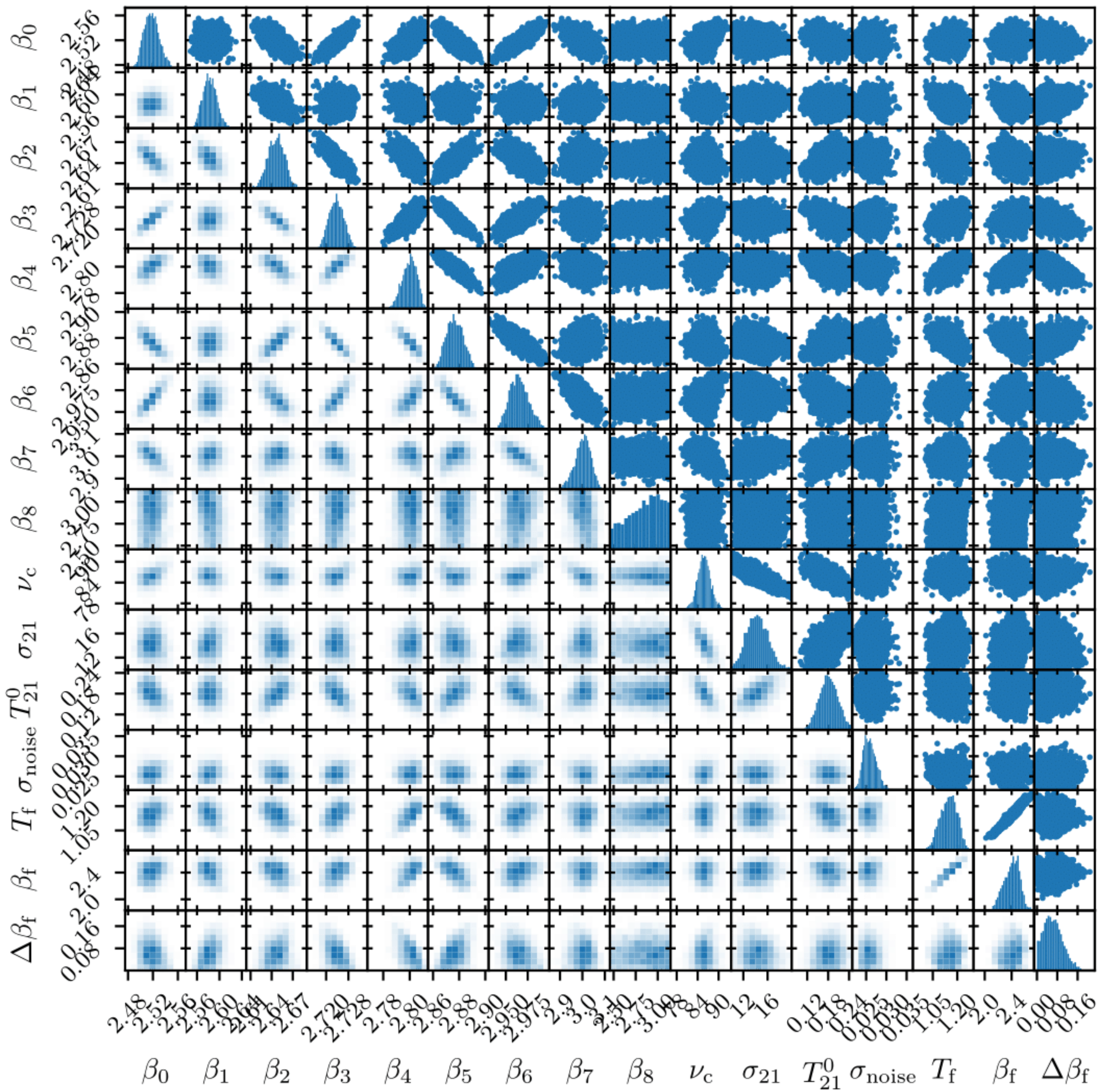
$$T_{21} = 27 x_{\rm HI} \left(\frac{1 - Y_{\rm p}}{0.76}\right)\left(\frac{\Omega_{\rm b} h^2}{0.023}\right)\sqrt{\frac{0.15}{\Omega_{\rm m} h^2}\frac{1+z}{10}}\left(1 - \frac{T_{\rm cmb}}{T_{\rm s}}\right)\ \text{mK}$$

Madau et al. (1997), Furlanetto (2006)

Beam directivity pattern at 50 MHz

A conical log-spiral antenna





β_0
β_1
β_2
β_3
β_4
β_5
β_6
β_7
β_8
ν_c
σ_{21}
T_{21}^0
σ_{noise}
T_f
β_f
$\Delta\beta_f$