Impact of Simulated 1/f Noise for HI Intensity Mapping Experiments

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Topics

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Introduction

- Most cosmological parameters are known to 1% accuracy

- Potential probe: hyperfine 21 cm spin-flip transition of neutral hydrogen (HI)
  - ↪ Expected to have far more information content than CMB

- Contemporary instrumentation lacks the sensitivity to conduct a HI galaxy survey
  - ↪ Alternative: HI intensity mapping (IM) method

- SKA-MID array proposed for HI IM survey
  - ↪ collection of single-dish radio telescopes

- Investigate the impact on the recovery of the HI angular power spectrum in the presence of a single instrumental systematic: *1/f* noise

Single-Dish Intensity Mapping and 1/f noise

SKA as an array of single-dish instruments

Pros	Cons
• increased surface brightness • increased sensitivity on large angular scales	• poor resolution of observations • separating contaminants from the signal

1/*f* noise:

- Form of correlated noise present in radio receiver systems

- Manifests as small gain fluctuations
  ↪ how it manifests in sky maps depends on the noise properties and the details of the observing strategy

- Phenomenon separate to thermal noise
  ↪ can be accurately modelled as a Gaussian white noise distribution

- Can be modelled and phenomenologically described by a few statistical properties
  ↪ α: spectral index of the noise
  ↪ $\begin{cases} \beta = 0\text{: identical 1/f in every channel} \\ \beta = 1\text{: independent } 1/f \text{ in every channel} \end{cases}$

Pipeline and Simulations

Instrument Design

- Modelling the telescope array and scanning strategy:

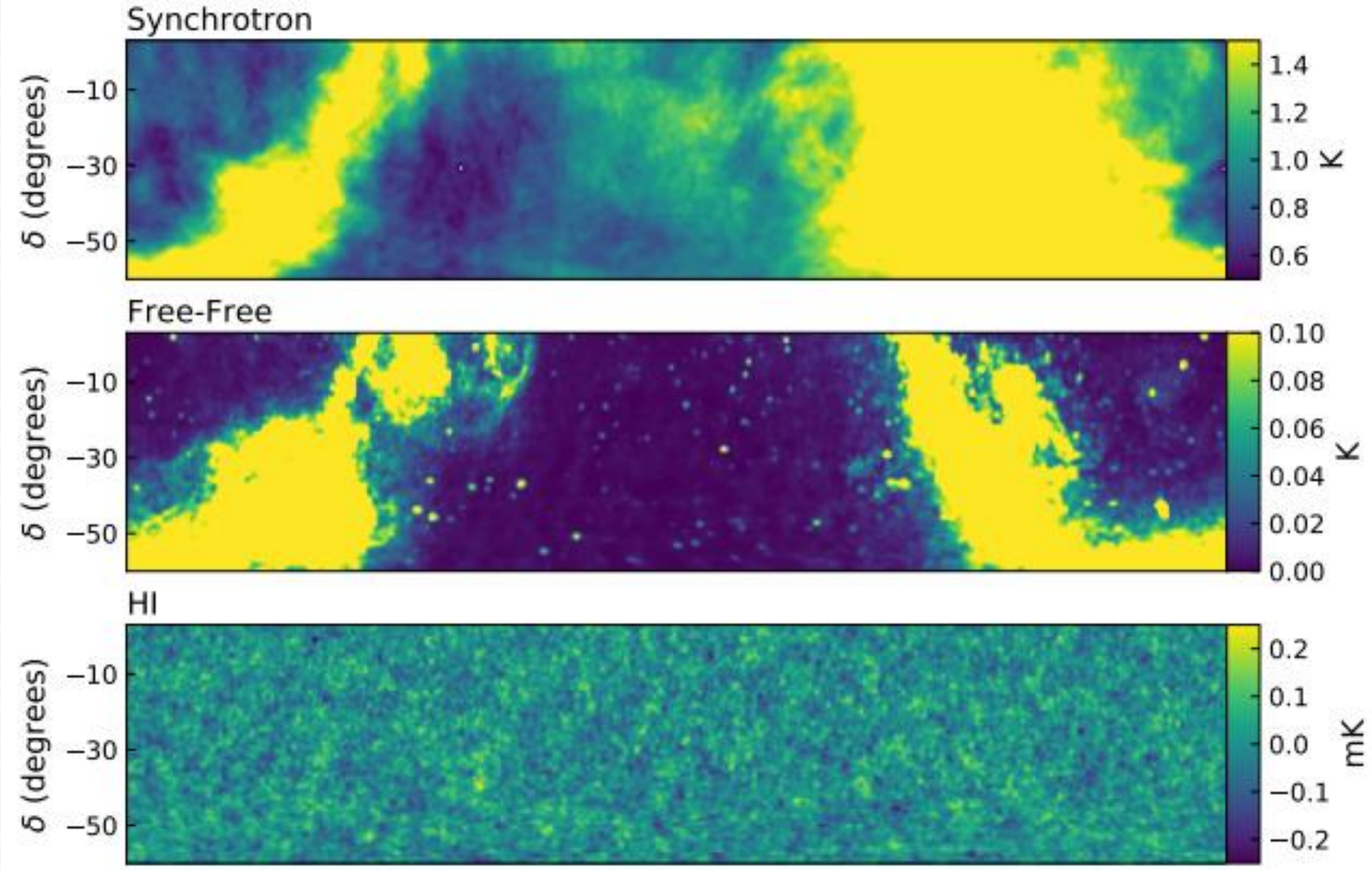
Description	Parameter	Value
Dish Diameter	D_{dish}	$15\ m^a$
N° Dishes	N_{dish}	200
Receiver + CMB	$T_{CMB} + T_{rx}$	$20K^b$
N° Polarimeters	N_{pol}	2
N° Channels	N_ν	23
Bandwidth	$\Delta\nu$	$950 < \nu < 1410\ MHz$
Channel width	$\delta\nu$	$20\ MHz$
Sample Rate	f_{sr}	$4\ Hz$
Integration Time	T_{obs}	$30\ days$
Elevation	E	$55\ deg$
Slew Speed	v_t	$0.5 < v_t < 2.0\ deg\ s^{-1}$

- Observing strategy: continuously slew the SKA dishes 360° at a constant elevation of 55° to control systematics (local horizon or ground pick-up)

Sky Model

- *Synchrotron*:
  - ↪ Relativistic cosmic ray electrons interacting within the galactic magnetic field
  - ↪ Tracer for relatively recent star formation
  - ↪ Vastly brighter than any other emission from the sky at low radio frequencies
- *Free-Free*:
  - ↪ Unbound interactions within ionized interstellar regions
  - ↪ It will flatten the foreground spectrum at higher frequencies
  - ↪ Adds spectral curvature to the foreground components, making it more challenging to characterize and remove
- *HI*:

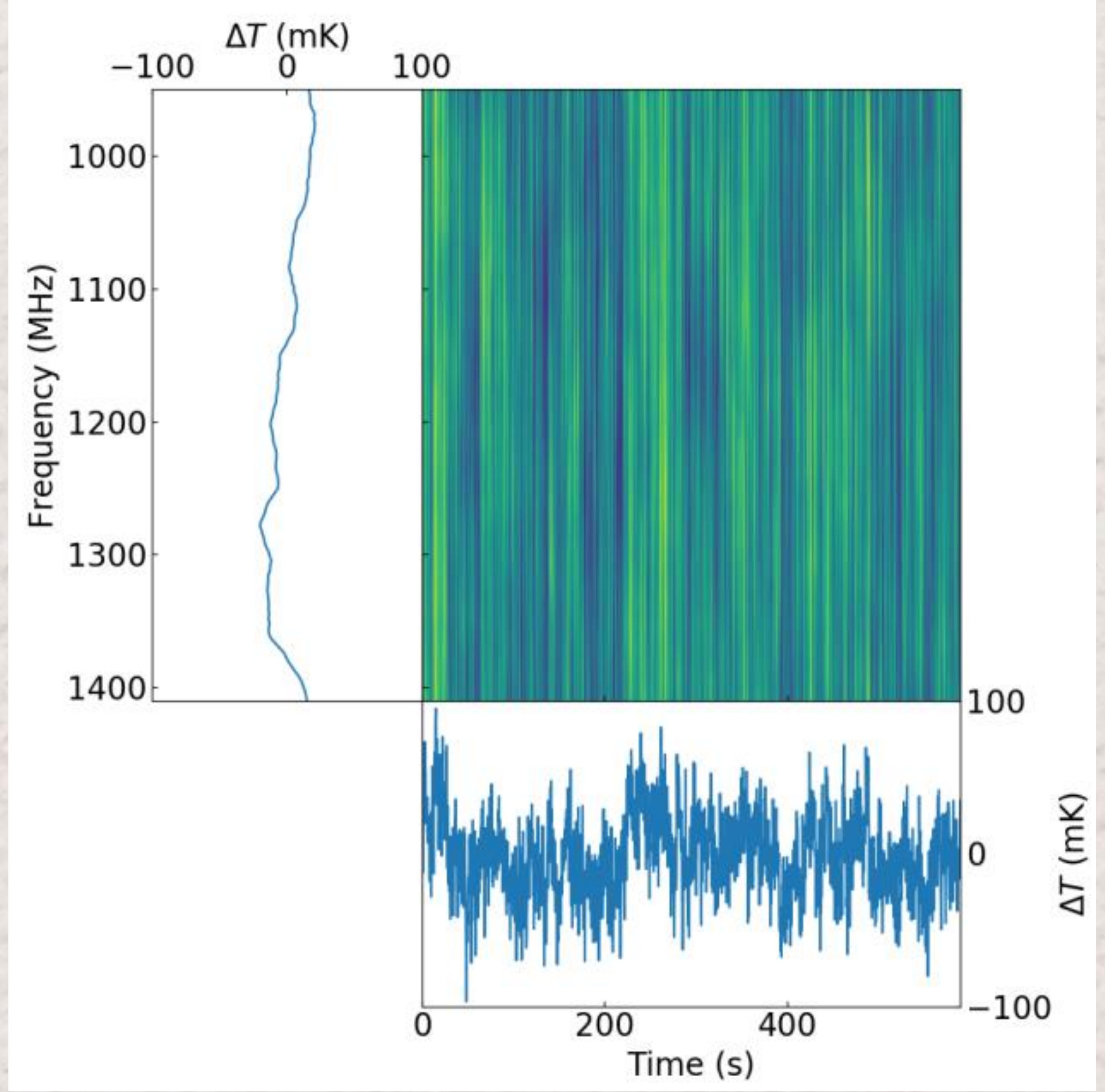
$$T_{obs} = 44\mu K \left(\frac{\Omega_{HI}(z) h}{2.45 \cdot 10^{-4}} \right) \frac{(1+z)^2}{E\,(z)} \longrightarrow C_l = \frac{H_0 b^2}{c} \int dz\, E(z) \left[\frac{T_{obs}(z)\, D(z)}{r(z)} \right]^2 P_{cdm} \left(\frac{l + \frac{1}{2}}{r} \right)$$



Cartesian projections in celestial coordinates of the simulated SKA HI IM survey strip

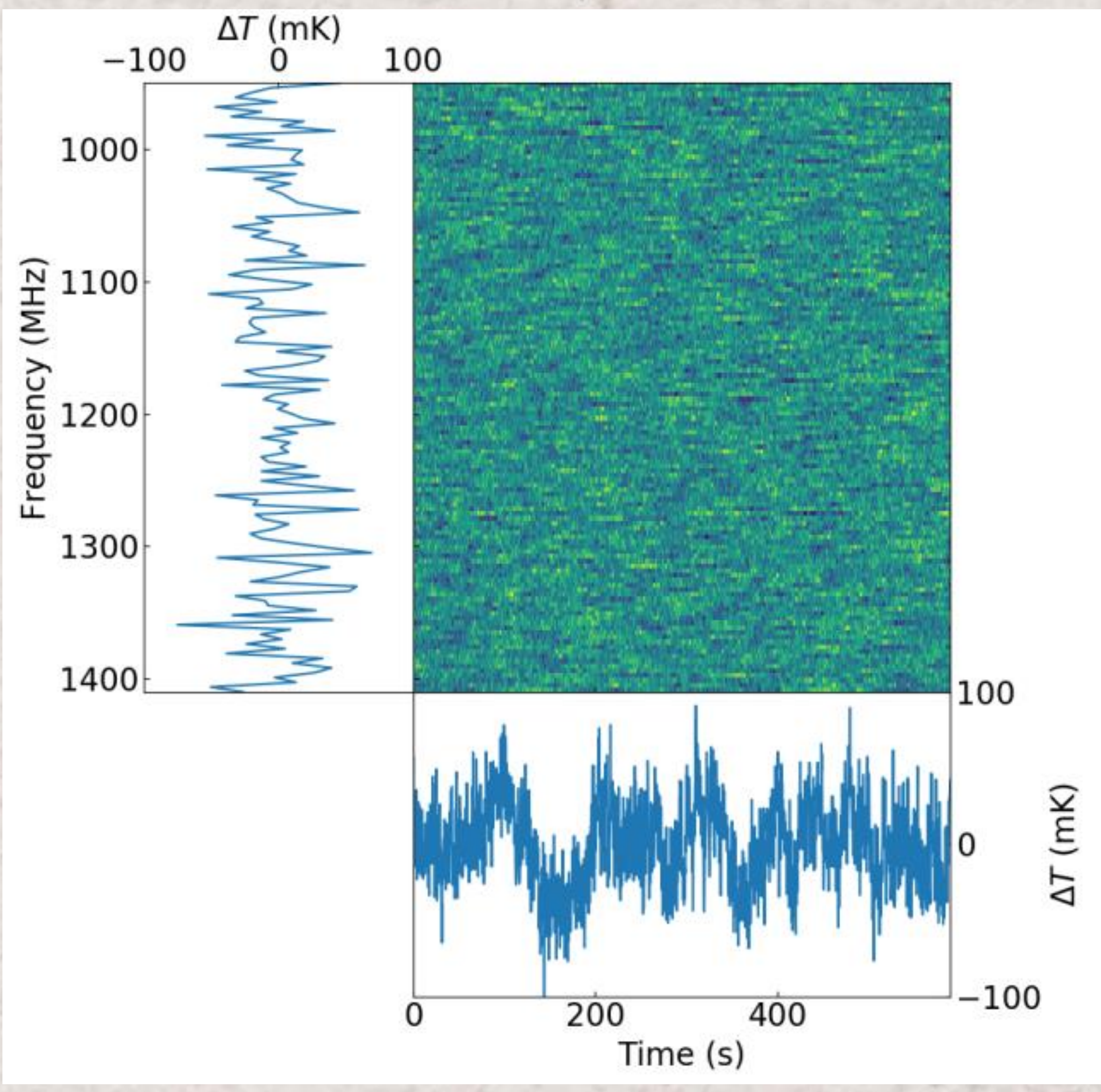
Modelling 1/f Noise

- 1/f in TOD originates as correlated fluctuations in the gain of the receiver amplifiers



Highly correlated

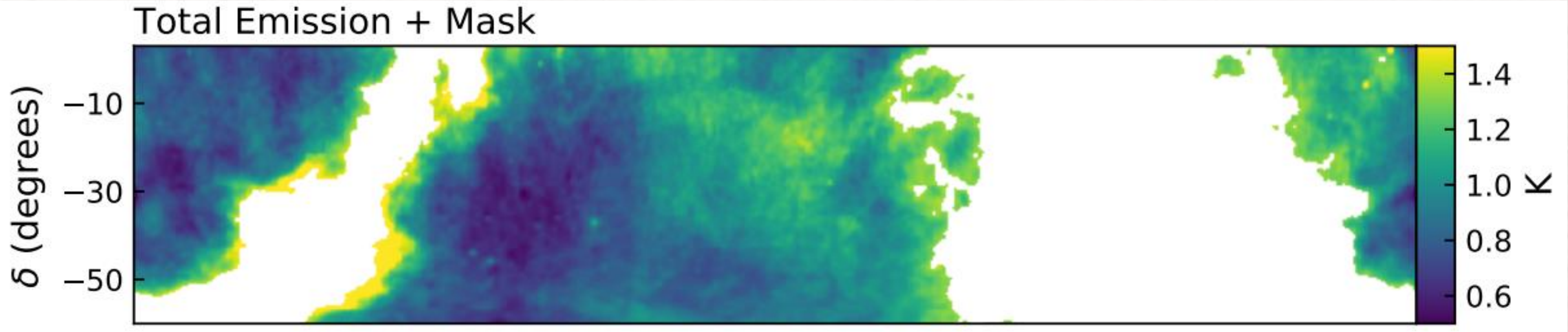
Time-frequency plots generated using the simulation pipeline



Completely uncorrelated

Sky Mask

- The sky maps from the simulation pipeline were multiplied with a mask that removes just the brightest regions of the Galactic plane



Regions that have been masked

- The resulting total observed sky fraction after masking is $f_{sky} = 0.3$

Component Separation and Power Spectrum Estimation

- Principle Component Analysis (PCA):
  ↪ not robust at removing foregrounds
  ↪ computationally fast: highly suited to Monte-Carlo simulations
  ↪ always remove components that are completely correlated in frequency

- For each realization and frequency, the angular power spectrum was calculated

- Each map was decomposed into spherical harmonic coefficients

- Before PSE, each map is smoothed to a full width at half maximum (FWHM)

Summary

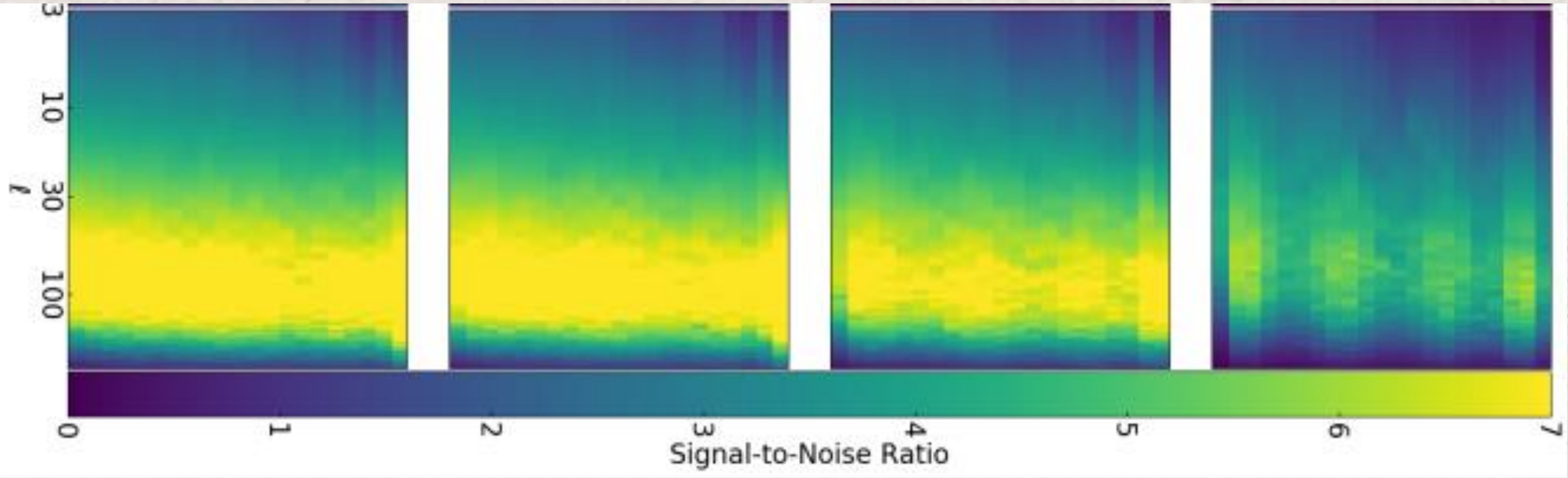
- Complete summary of each step taken in the process of the simulations:

1. Generate sky foreground and signal maps
2. Simulate TODs for the observing strategy
3. Produce a correlated 1/f noise signal for each block of TOD
4. Produce a noise-free data stream and add 1/ f noise and white noise.
   i. Combine the TOD into a realization map of the sky.
5. Separate each sky map realization into eigenmode components using PCA
6. Calculate the C_l of every map for each frequency and eigenmode.

Results

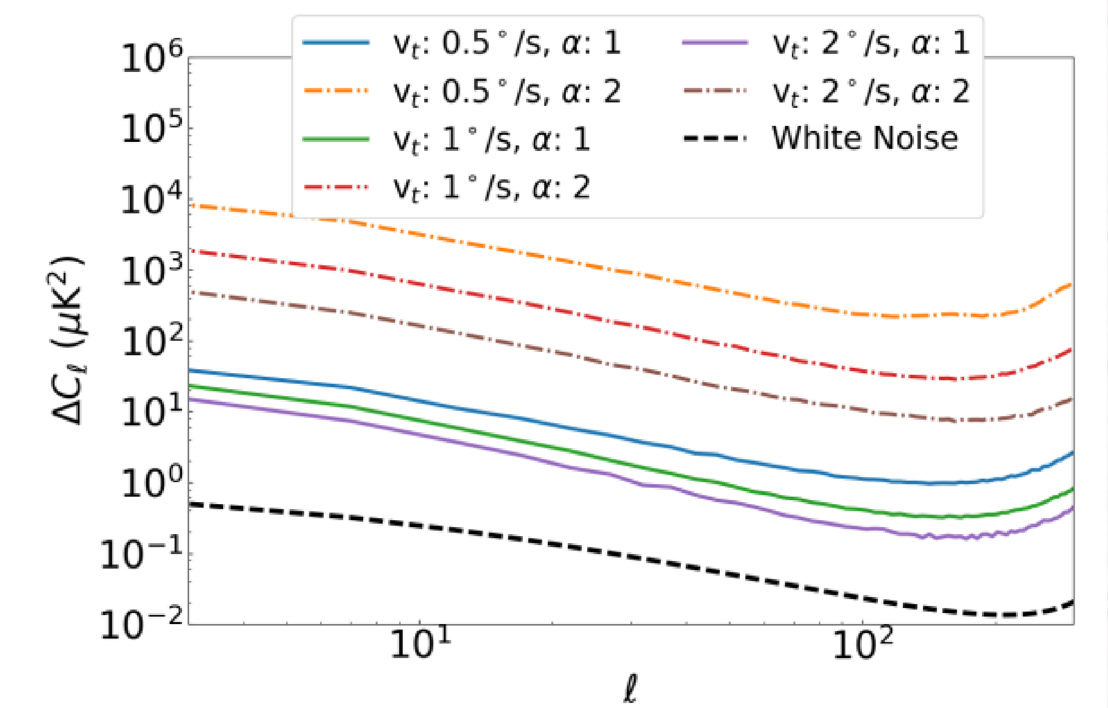
Power Spectra Uncertainty and Bias

- How much statistical uncertainty does 1/f contribute to the recovered HI C_l?



↪ Highly correlated 1/ f noise in frequency = very small contribution to the final HI statistical uncertainty

- Survey will be more sensitive to low redshift HI emission



- stable receivers are an order-of-magnitude more important than choice of scan speed
- scan speed is coupled with the spectral index of the 1/ f noise as is has greater impact for steep spectrum
- 1/ f noise can contribute additional uncertainty on all scales
- The bias is significant when the 1/f noise power exceeds the HI angular power
- Is it possible to model the 1/f noise bias and remove it?
  ↪ in these simulations that would be trivial as the input 1/f noise is known
  ↪ in real data where it might be non-Gaussian and coupled with other systematics, accurate modelling may be challenging

Discussion

Impact of Specific Data Analysis Methods and Systematics

- Could the impact of the 1/ f noise be reduced in a real HI IM survey?
  - ↪ use a more sophisticated component separation technique
  - ↪ use a more advanced mapmaking method
  - ↪ use a more carefully considered observing strategy
  - ↪ 1/f noise be suppressed during the calibration process

- Real observations suppression of 1/f noise will be more challenging due to the presence of other systematics in the data
  - ↪ intrinsic to the 1/f
  - ↪ intrinsic to the instrument or the observations
  - ↪ how the data is processed, calibrated and binned into maps

Conclusion

- Numerous assumptions have been made to simplify the 1/f noise signal:
  - ↪ intrinsic properties are assumed to have Gaussian distributed amplitudes
  - ↪ the interactions of the 1/ f noise with additional systematics is not explored

- Given those assumptions, this paper provides some guidelines:
  - ↪ a design for receivers to make the 1/f noise as correlated as possible
  - ↪ data analysis pipeline designed to not corrupt the receiver 1/ f noise properties

- 1/f noise could be significantly detrimental to future HI IM surveys

- Careful choices of observing strategy, data analysis and component separation method should be sufficient to recover the cosmological HI signal.

Thank you!