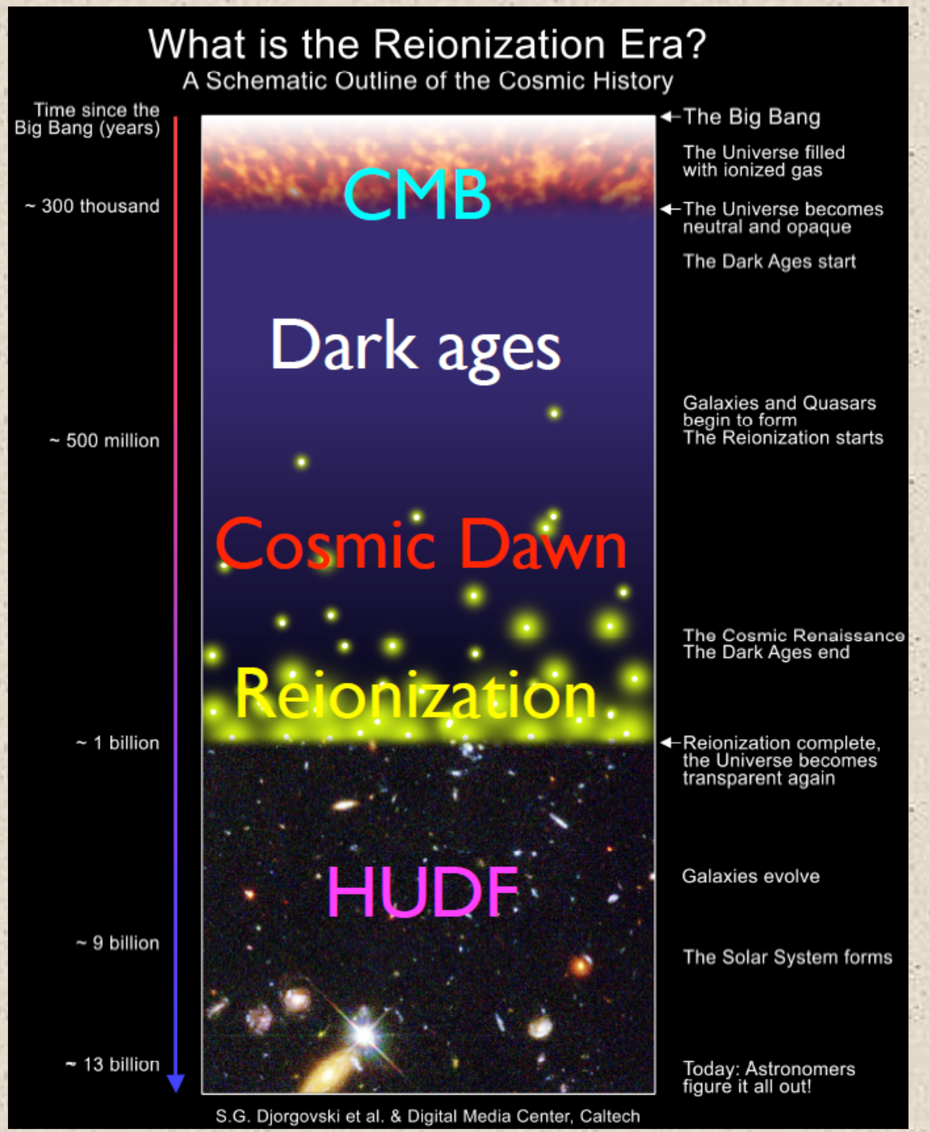
Constraining Cosmic Dawn with Global 21-cm Signal Observations from the Lunar Farside

David Rapetti
University of Colorado Boulder / NASA Ames

The work presented here is in collaboration with:
Keith Tauscher (CU Boulder), Jack Burns (CU Boulder), Jordan Mirocha (UCLA), Rich Bradley (NRAO), Steven Furlanetto (UCLA), Bang Nhan (CU Boulder/NRAO), Eric Switzer (NASA Goddard)

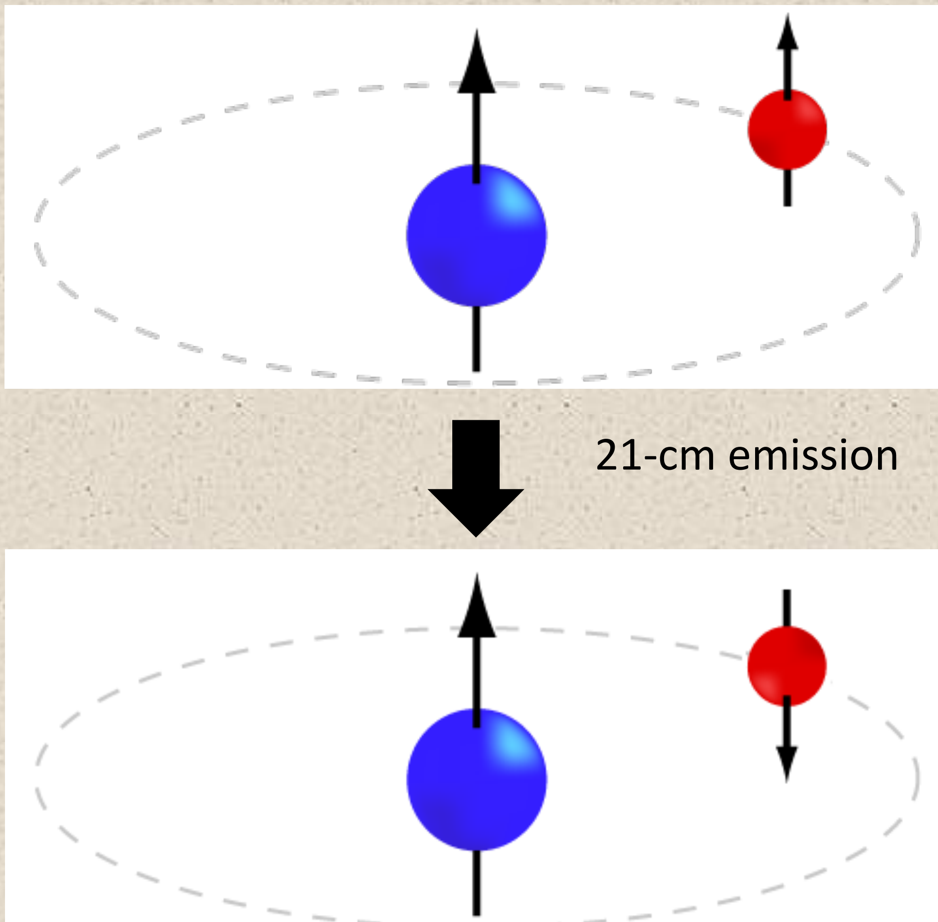
August 29, 2017 COSMO-17, Paris

Motivation: current cosmic knowledge



- We have measurements of
  - The early Universe from e.g. the CMB.
  - The Universe since about 1 billion years ago from distant galaxies by e.g. the Hubble telescope.
- But, we have essentially no constraints on:
  - Dark Ages
  - Cosmic Dawn
  - Onset of reionization
- During Dark Ages, the Universe consisted almost entirely of neutral hydrogen.

21-cm hyperfine transition

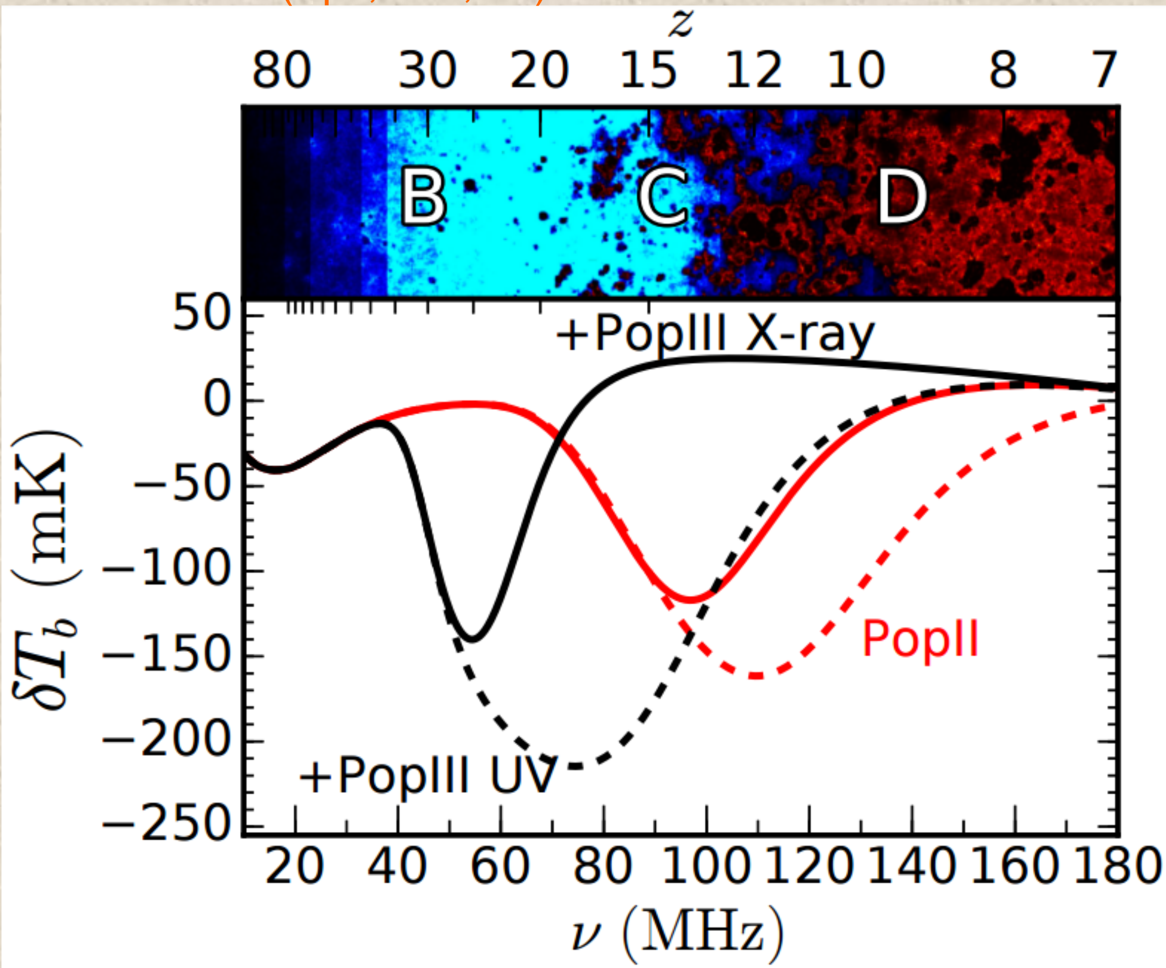


Images from Wikipedia

- Occurs in neutral hydrogen.
- Proton and electron have magnetic moments due to their spin.
- Energy difference between moments being aligned and anti-aligned is equal to the energy of a photon with rest wavelength (frequency) 21 cm (1420 MHz).

Global 21-cm signal from the first luminous objects

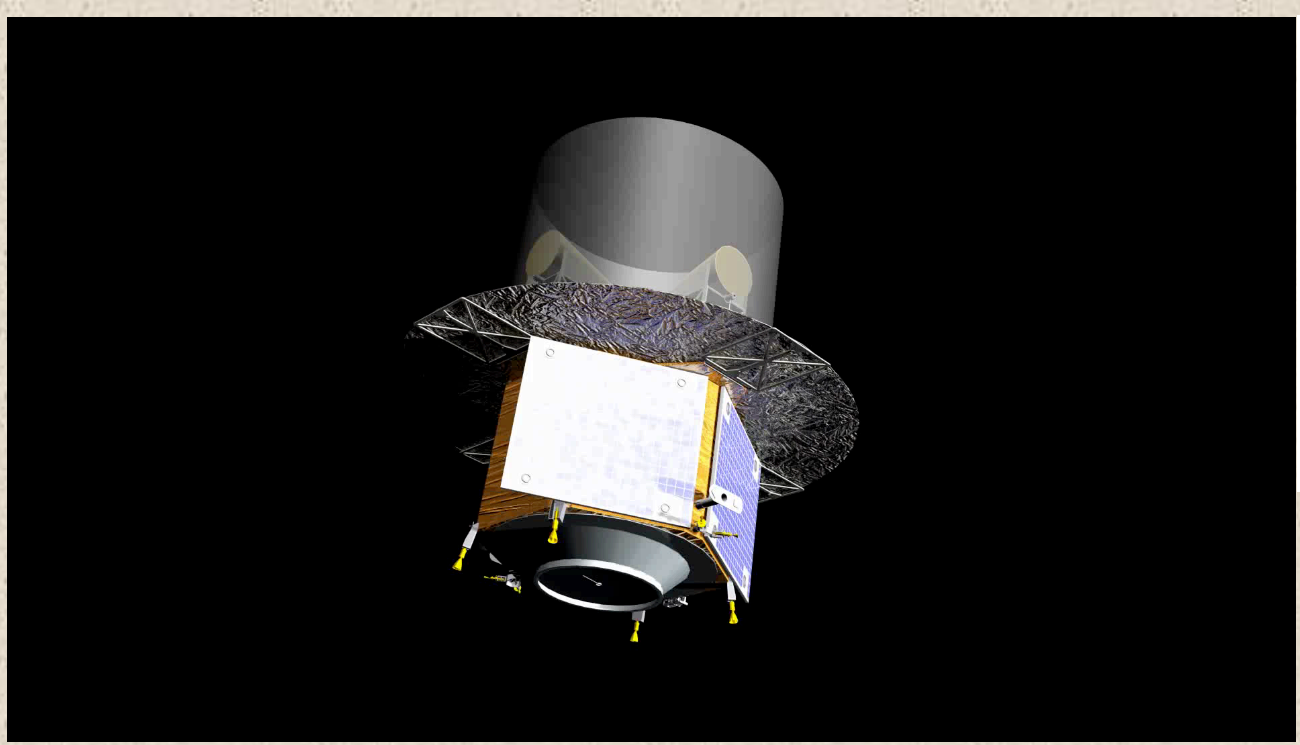
Burns et al 17 (ApJ, 844, 33)



$$\delta T_b(z) = 27 x_{\rm HI}(z) \left(1 - \frac{T_{\rm CMB}(z)}{T_{\rm s}(z)}\right) \left(\frac{1+z}{10}\right)^{1/2}$$

- **Region B**: First stars ignite. Their radiation decouples neutral hydrogen from the CMB and drives signal into absorption.
- **Region C**: First black holes accrete. The X-rays they emit drive signal from absorption towards emission.
- **Region D**: The Universe's hydrogen ionizes (epoch of reionization).

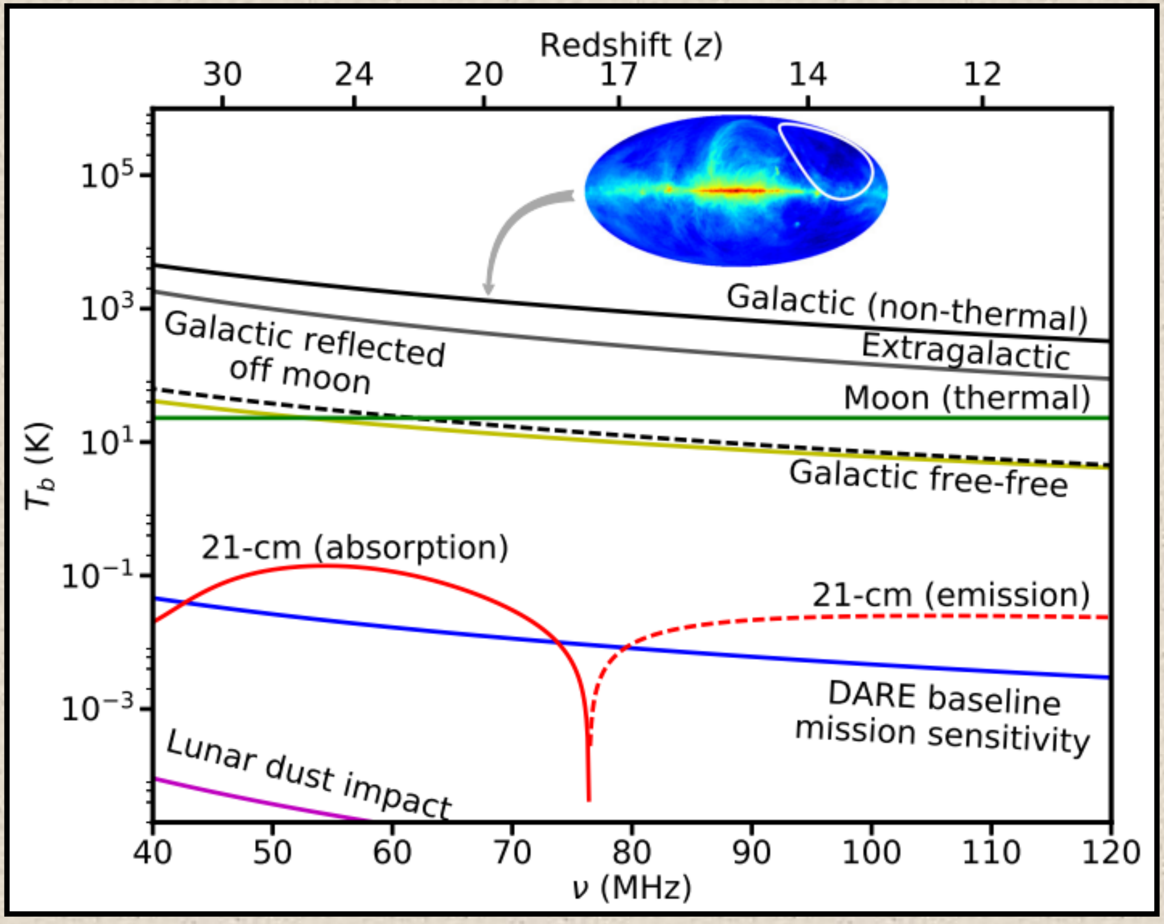
Dark Ages Radio Explorer (DARE)



- Space mission concept that uses dual polarization bicone antennas to measure the global 21-cm signal from the lunar farside.
- In this way, it avoids Earth-based challenges like ionospheric effects and RFI as well as radio solar emissions.

Biggest challenges of measuring the global signal

Burns et al 17 (ApJ, 844, 33)



- Unavoidable (beam-averaged) foregrounds which are $> \sim 10^4$ times larger than the signal.
- Beam chromaticity mixes spatial and spectral structure of the foregrounds with that of instrument.

As part of the solution, however: The pipeline will utilize the differences in spatial and spectral variations as well as polarization between the signal and foregrounds.

Singular Value Decomposition (SVD)

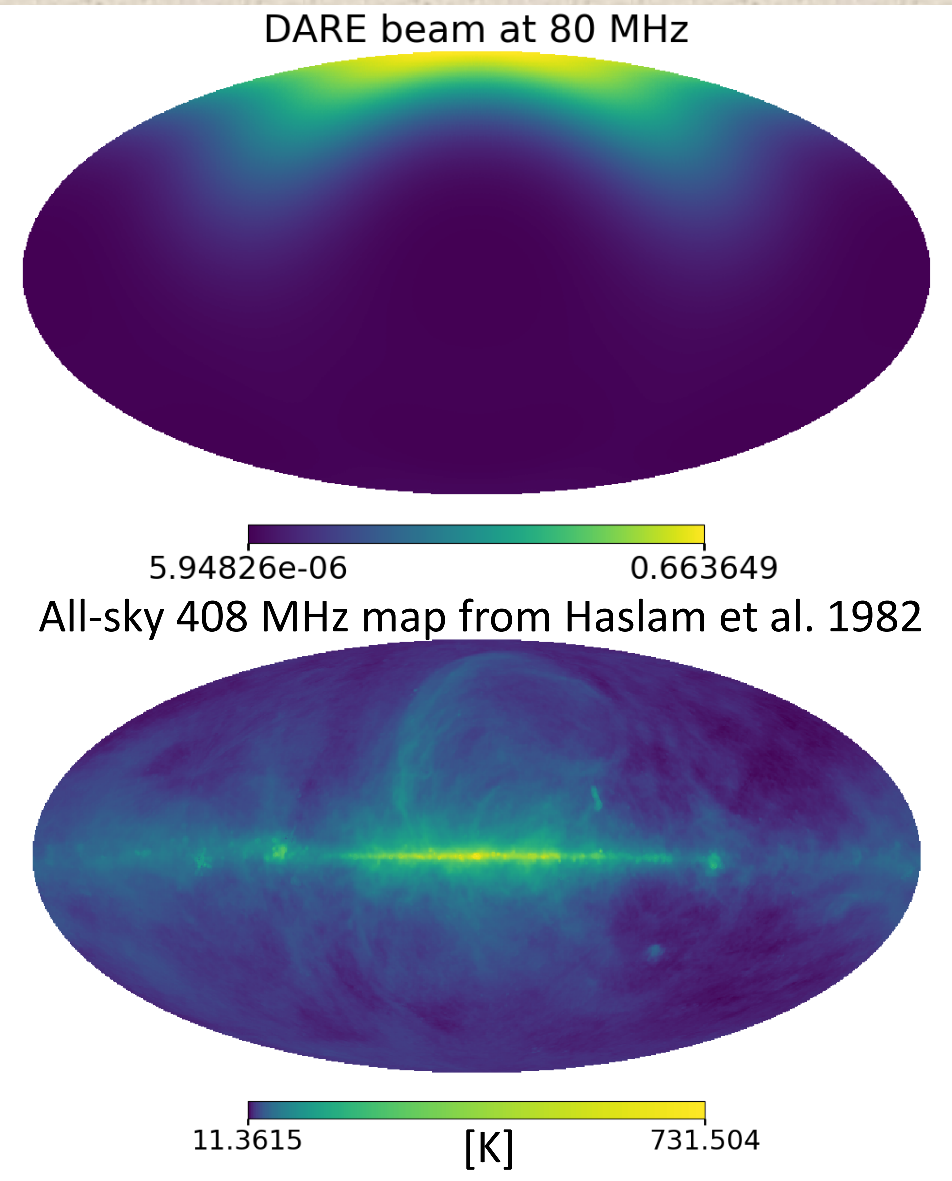
$$\underbrace{\boldsymbol{M}} = \underbrace{\boldsymbol{U}}\boldsymbol{\Sigma}\boldsymbol{V}^T$$

Training Set: $(N_{channel} \times N_{curves})$

Ordered basis functions: $(N_{channel} \times N_{channel})$

- SVD computes and orders by importance the orthogonal modes of the N_{curves} curves of the training set, $\boldsymbol{M}$, by importance.
- $\boldsymbol{\Sigma}$ is a diagonal matrix containing the importance of the modes (square root of eigenvalues of $\boldsymbol{M}\boldsymbol{M}^T$).

Foreground training set



- Antenna temperature simulated from beam, $B(\nu, \Omega)$, and sky, $T_{sky}(\nu, \Omega)$, through

$$T_A(\nu) = \frac{\int B(\nu, \Omega)\, T_{sky}(\nu, \Omega)\, d\Omega}{\int B(\nu, \Omega)\, d\Omega}$$

- CST code used to model beam

- Sky maps from Guzman et al. (2010) and Haslam et al. (1982)

Instrument simulation

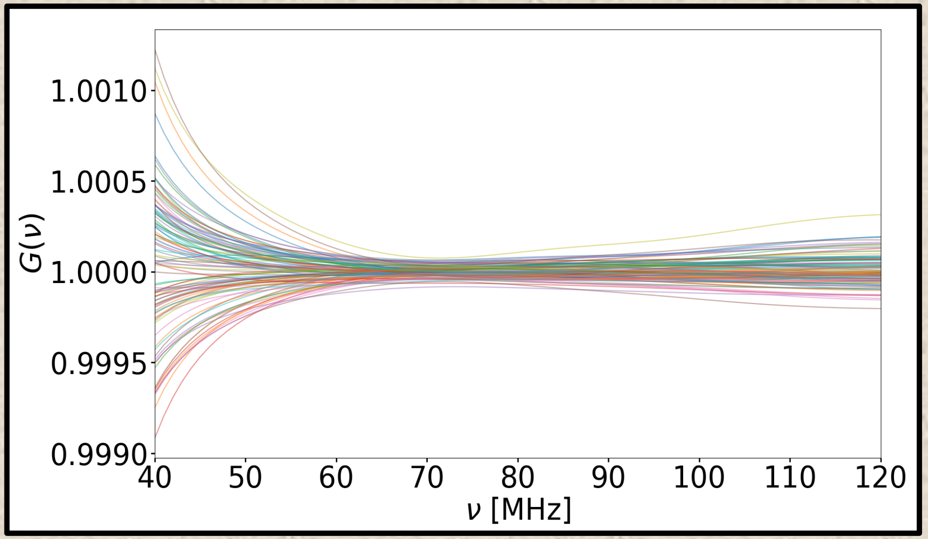
- Instrument systematics are simulated through the following calibration equation:

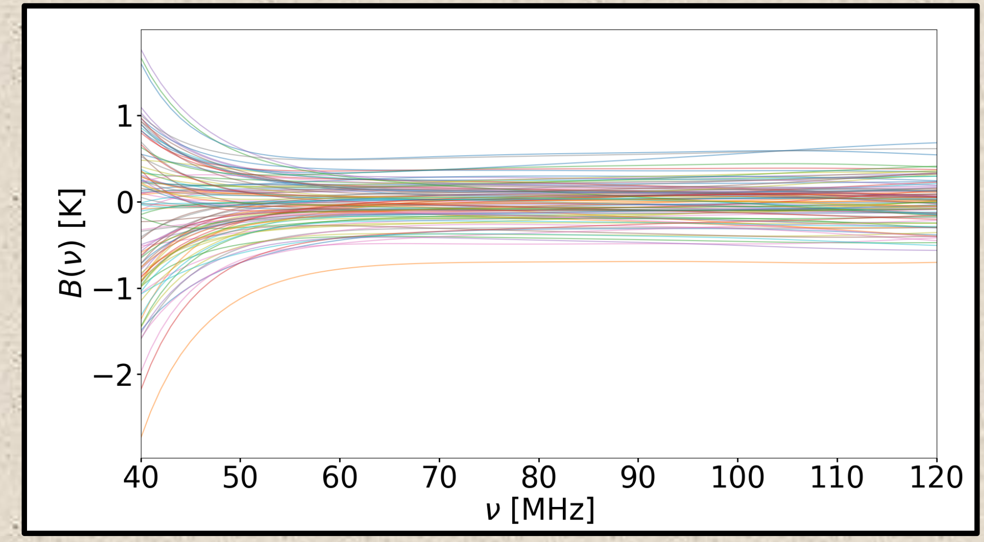
$$P = g\left[|F|^2(1-|\Gamma_A|^2)T_A + T_{off}\right]$$

- Applying this equation and then its inverse with slightly different parameters on an antenna temperature yields a calibrated antenna temperature that differs by a multiplicative factor, G, and an additive offset, B, which are functions of frequency:

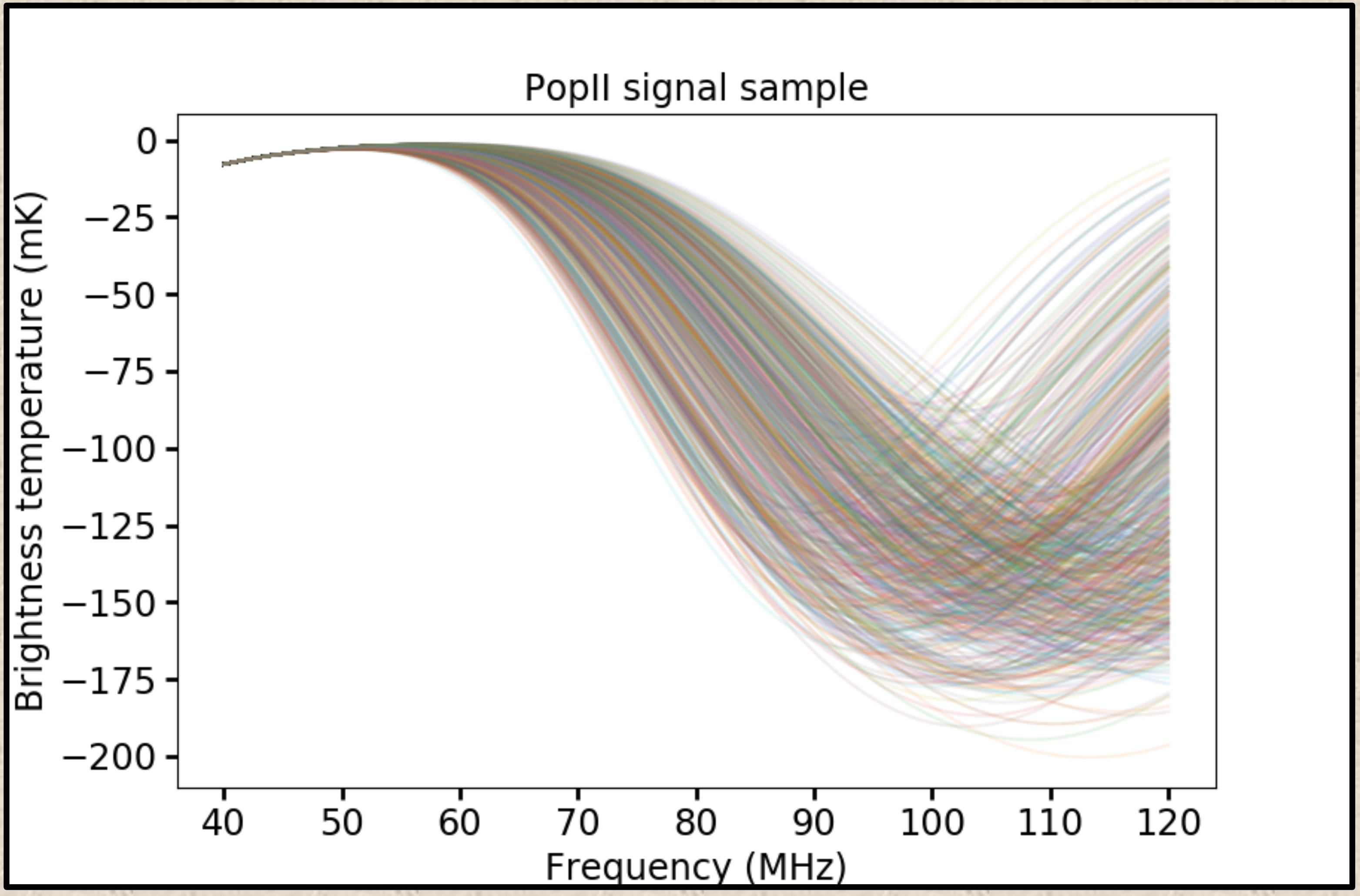
$$(T_A)_{cal} = G * (T_A)_{ideal} + B$$

Instrument training sets





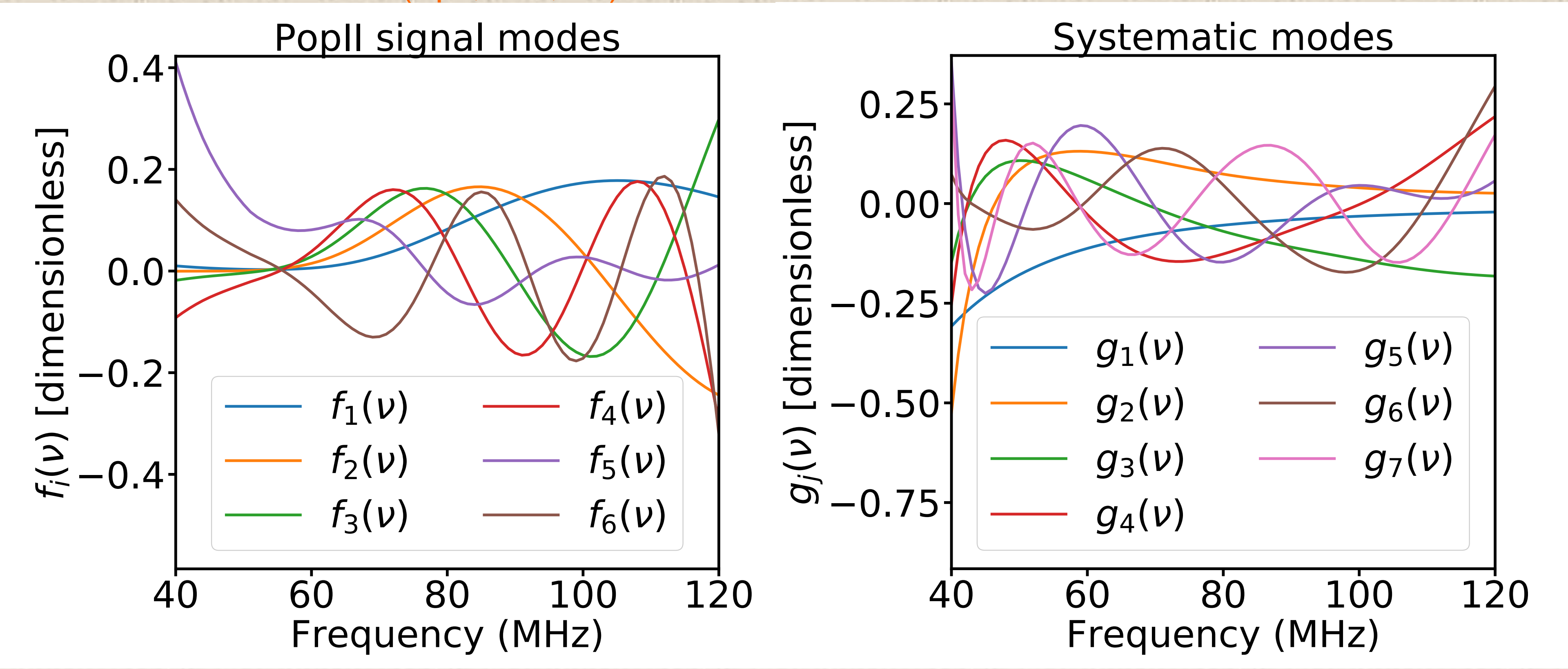
Signal training set



- Signals created by exploring the parameter space of the *ares* code: https://bitbucket.org/mirochaj/ares

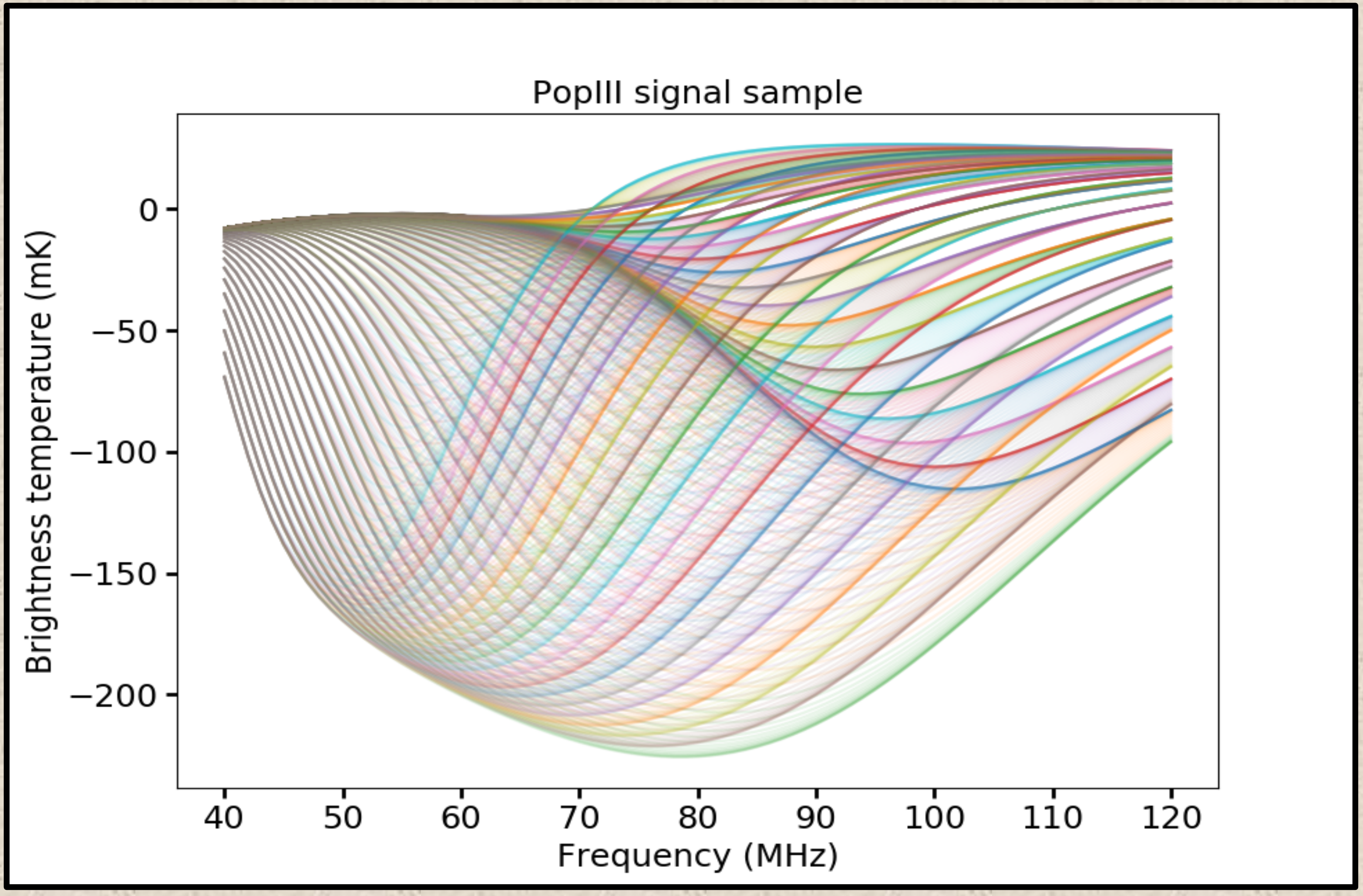
SVD modeling of the signal and systematics

Burns et al 17 (ApJ, 844, 33)



- SVD orthonormal modes. The ability to separate the 21-cm signal from DARE's systematics hinges on the ability to distinguish between the signal (f) and systematic (g) modes. Therefore, we want minimal overlap between them.

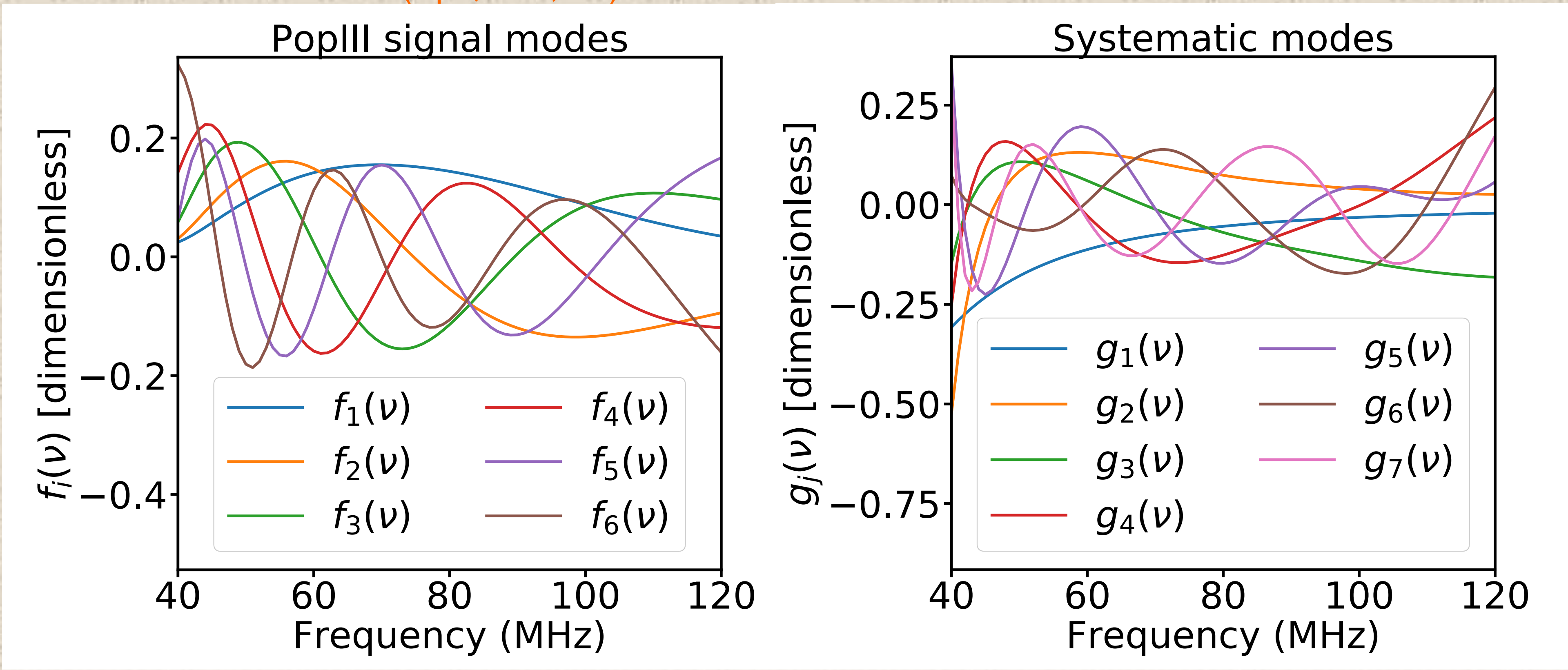
Signal training set



- Derived by randomly sampling the parameter space surveyed in Mirocha et al 17 with the addition of two parameters describing UV and X-ray photon production efficiency in minihalos.

SVD modeling of the signal and systematics

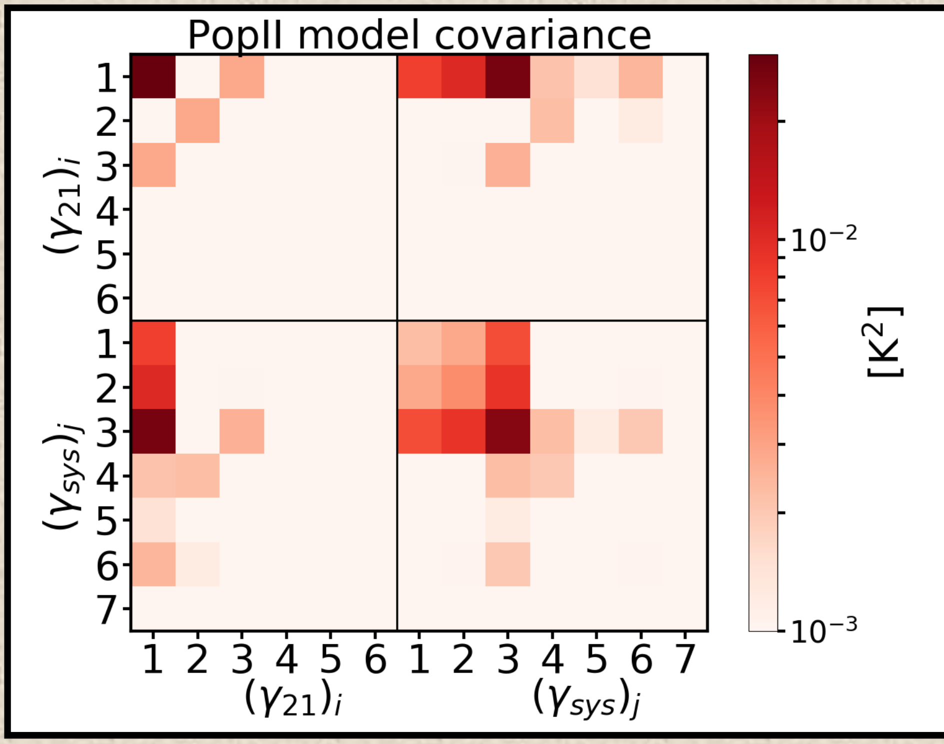
Burns et al 17 (ApJ, 844, 33)

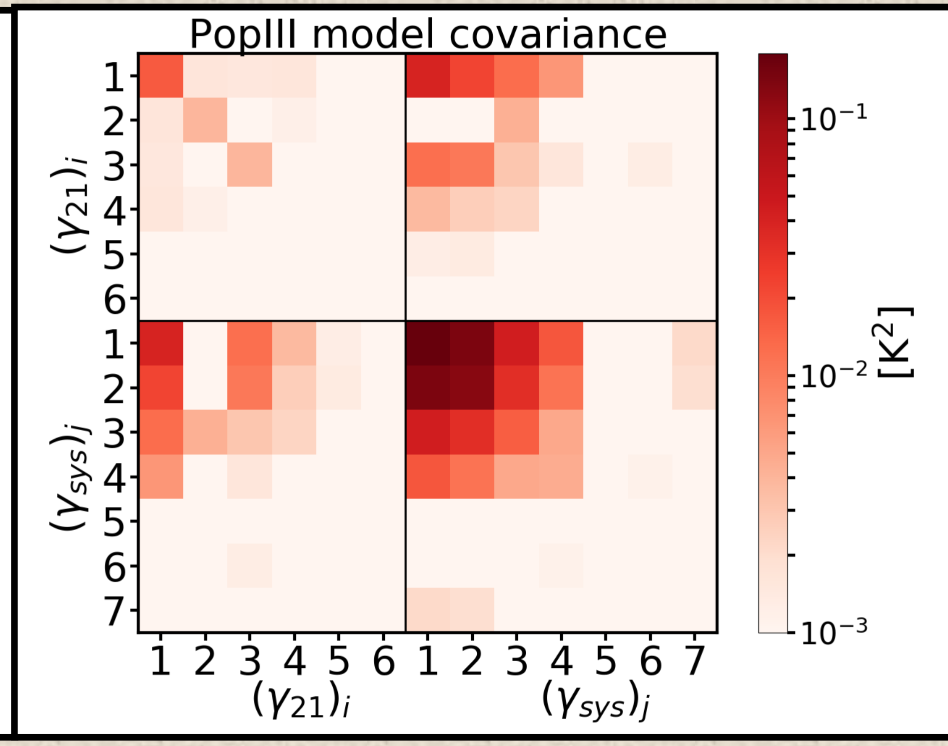


- SVD orthonormal modes. The ability to separate the 21-cm signal from DARE's systematics hinges on the ability to distinguish between the signal (f) and systematic (g) modes. Therefore, we want minimal overlap between them.

Covariances between the signal and systematics modes

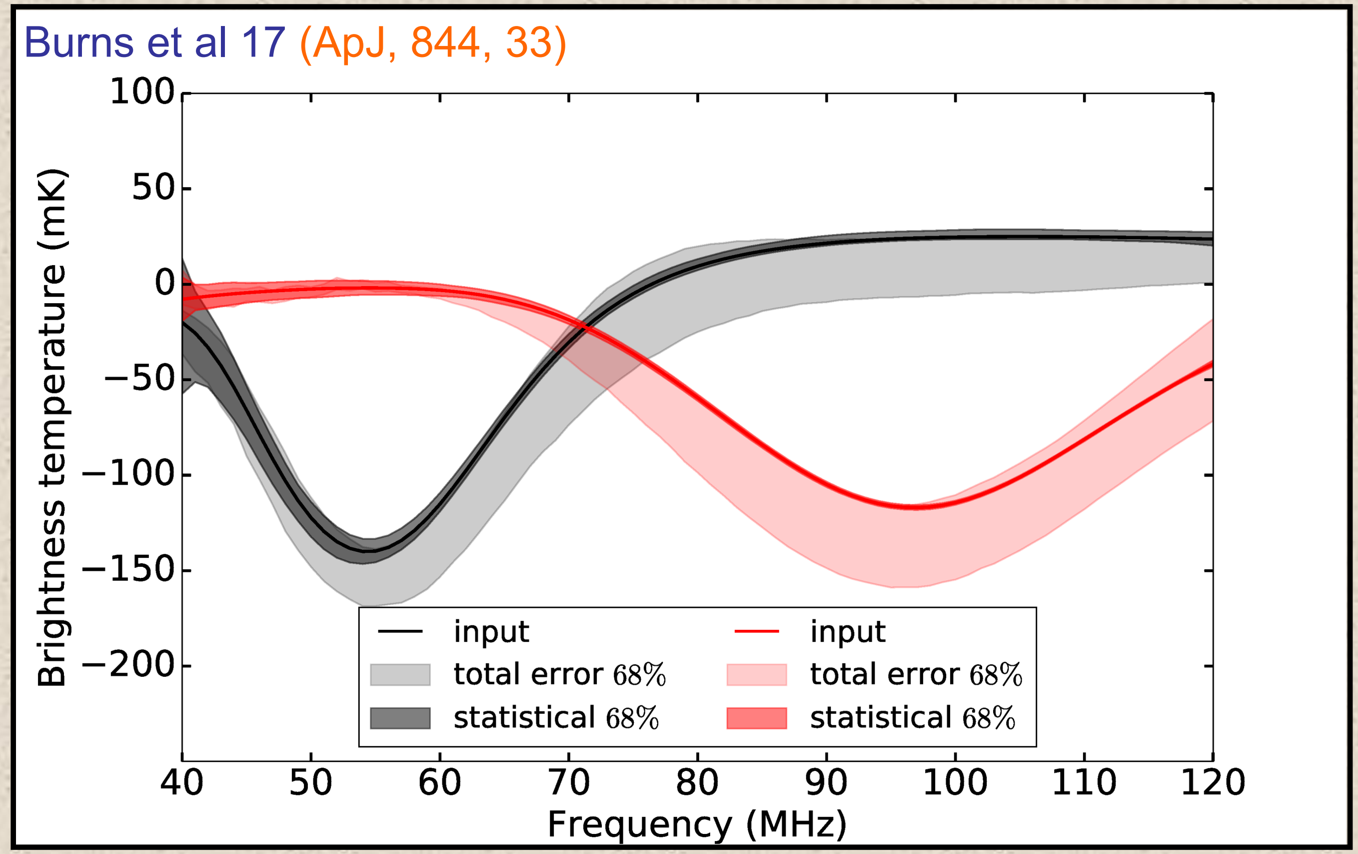
Burns et al 17 (ApJ, 844, 33)





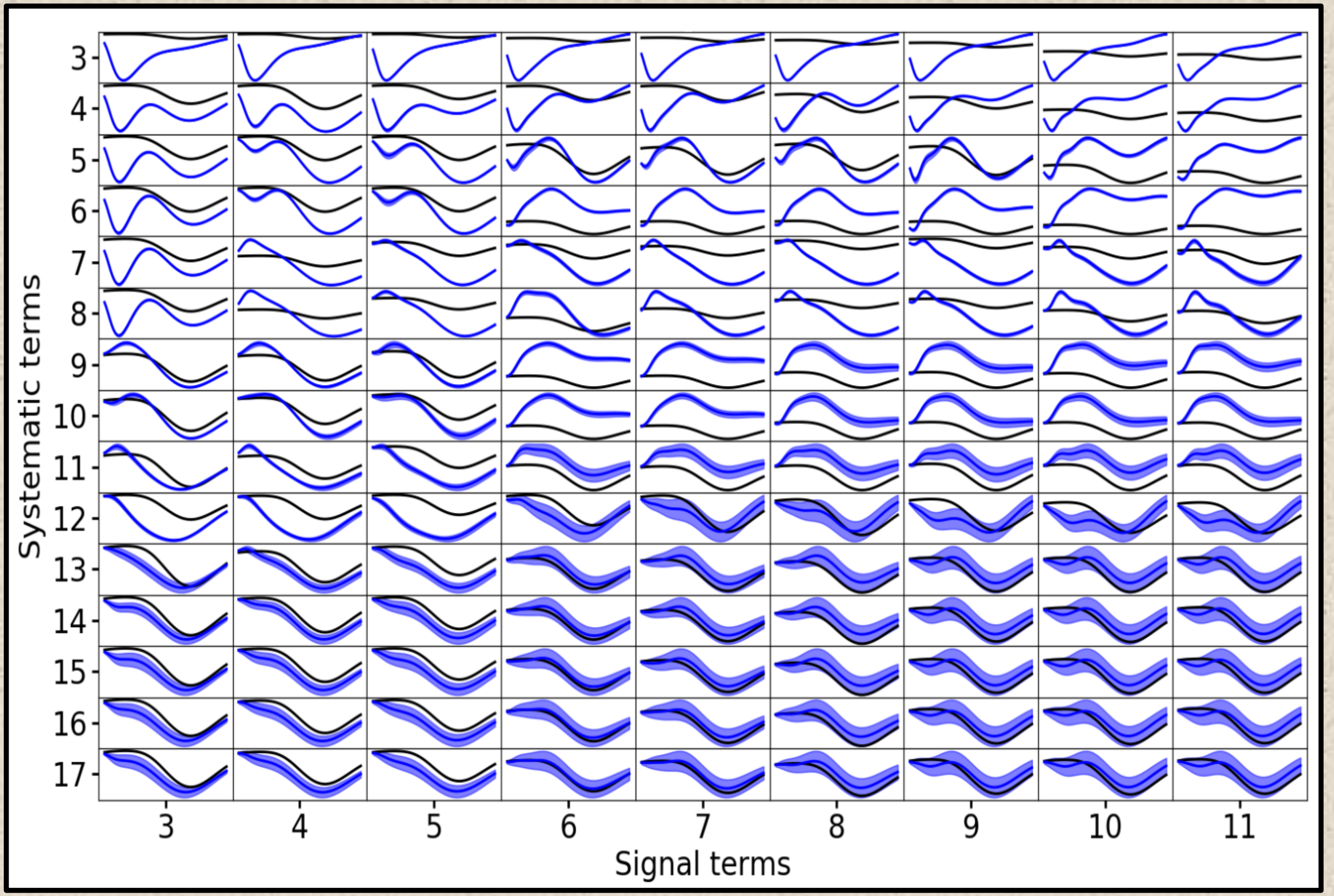
-The vertical and horizontal black lines separate the regions with covariances between signal parameters (top left) and systematic parameters (bottom right). The other two regions are symmetric and show the covariances between signal and systematic parameters.

Extracting the signal from the systematics



- The extracted 21-cm spectra for models with primordial Pop II (red) and Pop III (black) stars for 800 hours of observation with DARE.
- Dark bands: thermal (statistical) noise from the sky. Lighter bands: total uncertainty, statistical plus systematic effects (instrument and foreground).
- The covariance between SVD signal and systematic modes dominates the total error.

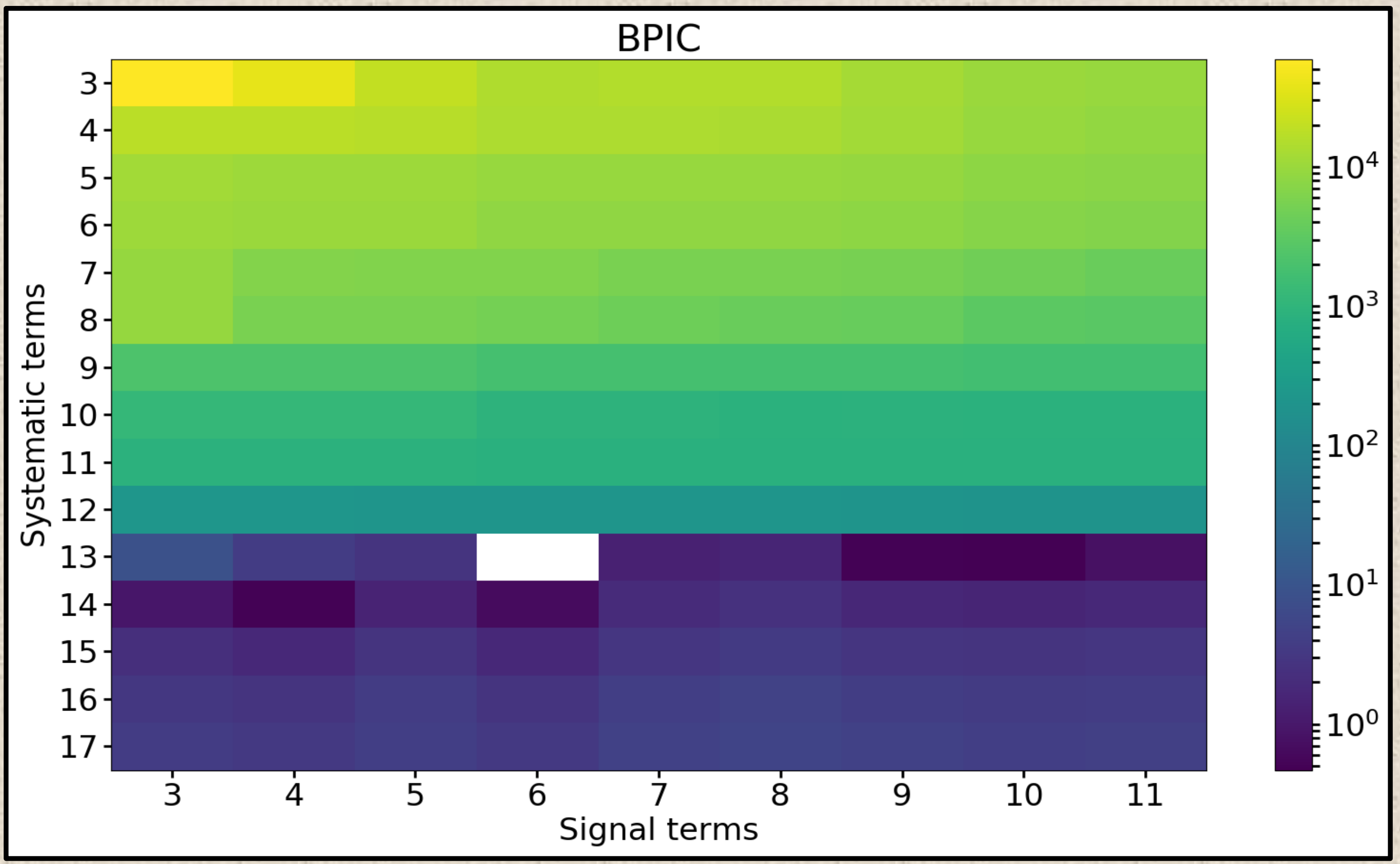
Model selection using BPIC: number of SVD modes (preliminary)



Optimizing Signal Extraction: The black line for all panels is the input 21-cm signal. The blue bands are the pipeline reconstructions of the signal for a given number of SVD signal and systematic parameters/modes.

(See Tauscher et al. 2017 in prep.)

Model selection using BPIC: number of SVD modes (preliminary)

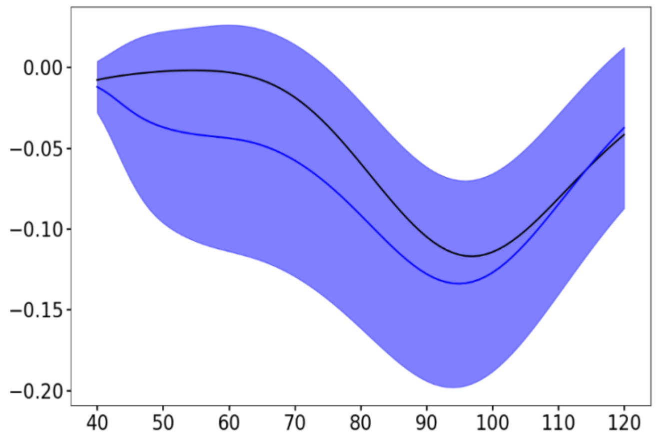


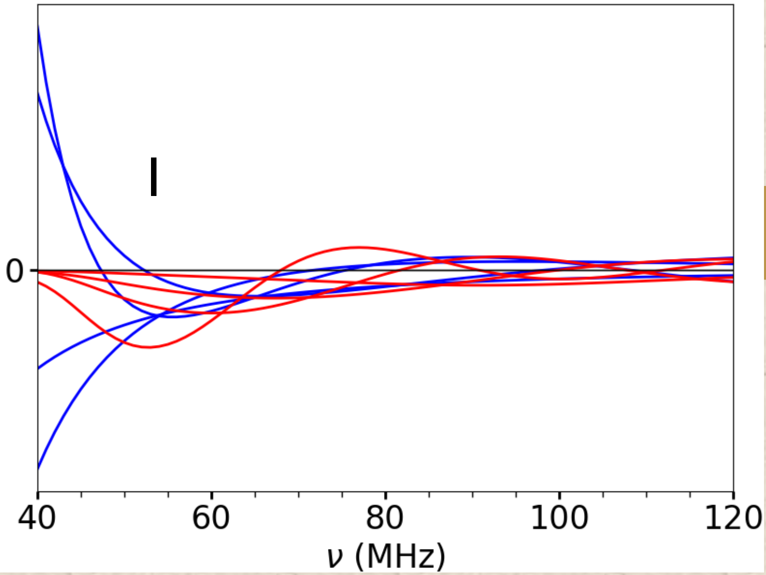
Optimizing Signal Extraction: We propose to employ the BPIC (Bayesian Predictive Information Criterion) statistic to blindly select a model that fits well all the data and reconstructs the input signal. The chosen model (white rectangle) has the minimum BPIC.

(See Tauscher et al. 2017 in prep.)

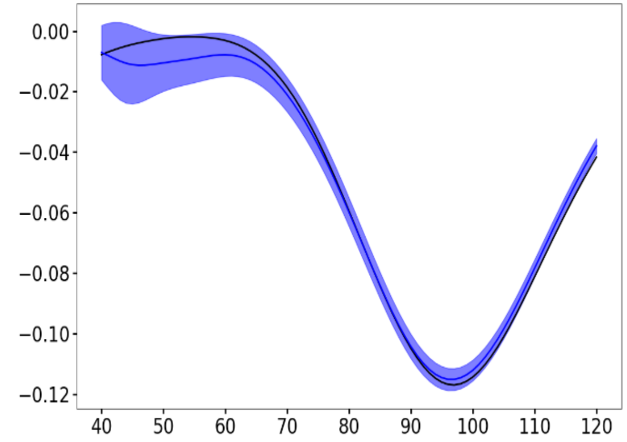
Separating systematics with induced polarization (preliminary)

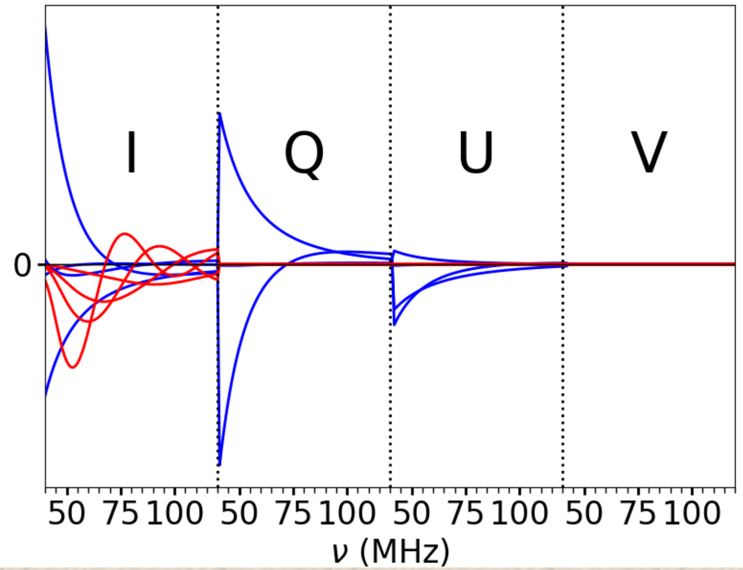
No polarization data used





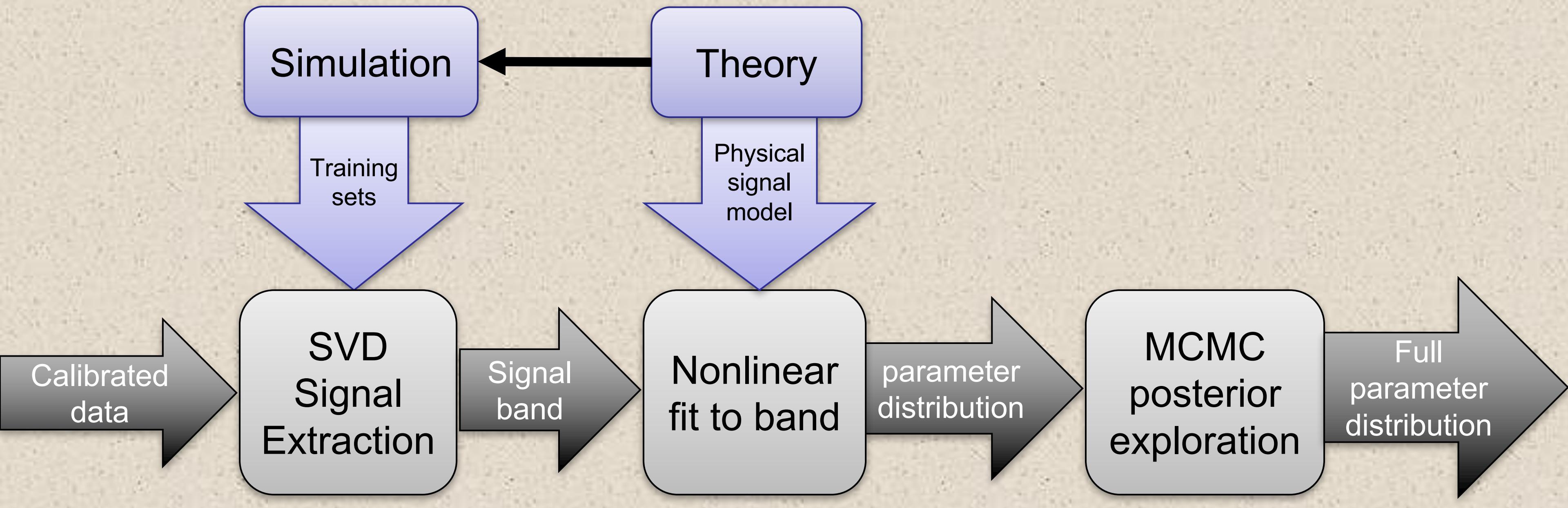
Polarization data used

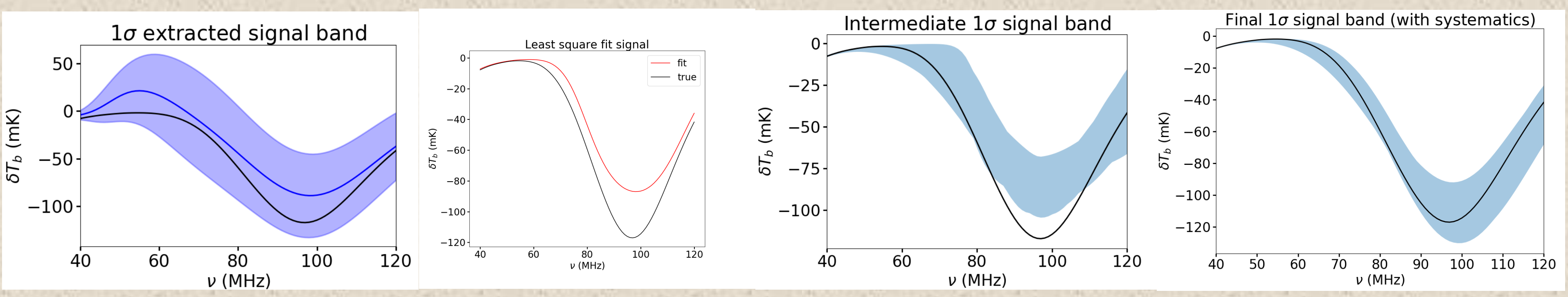




(See Tauscher et al. 2017b, in prep.)

SVD/MCMC data analysis pipeline to extract the signal and constrain physical parameters (preliminary)





(See Rapetti et al. 2017, in prep.)

Conclusions

- Take away: 21-cm signal realistically simulated constraints using end-to-end DARE simulations.
- A challenge of extracting the global 21-cm is the large foregrounds.
- However, unlike the foregrounds the signal is spatially uniform, has well-characterized spectral features, and is unpolarized.
- We benefit from these differences in our novel approach for signal extraction and physical parameter constraints, using an SVD/BPIC/MCMC pipeline.
- We obtain an order of magnitude improvement by using induced polarization data.
- We are also preparing to run our pipeline on ground based data from the Experiment to Detect Global Epoch of Reionization Signal (EDGES), which has been taking data for about a decade, and the Cosmic Twilight Polarimeter (CTP; currently being deployed), which will allow us to use non-simulated polarization data for the first time.