

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

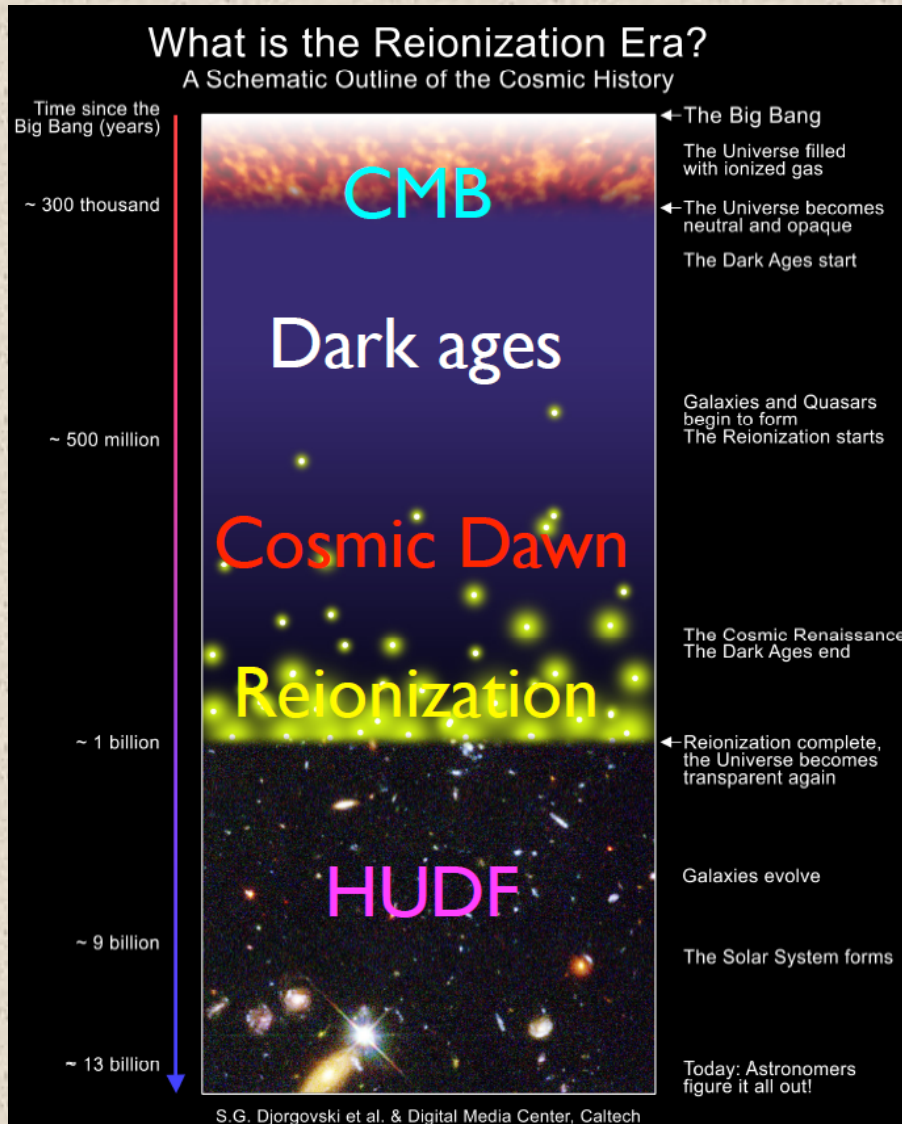
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University of Colorado Boulder / NASA Ames

The work presented here is in collaboration with:

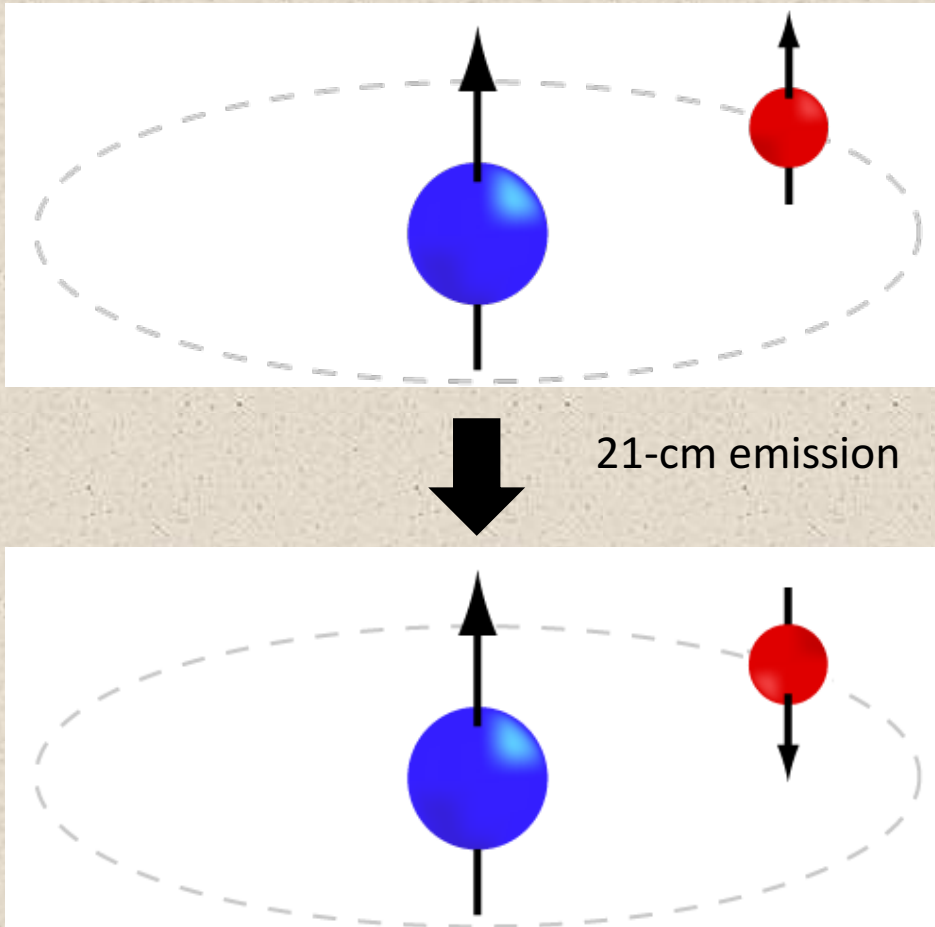
Keith Tauscher (CU Boulder), Jack Burns (CU Boulder), Jordan Mirocha (UCLA), Rich Bradley (NRAO), Steven Furlanetto (UCLA), Bang Nhan (CU Boulder/NRAO), Eric Switzer (NASA Goddard)

# 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

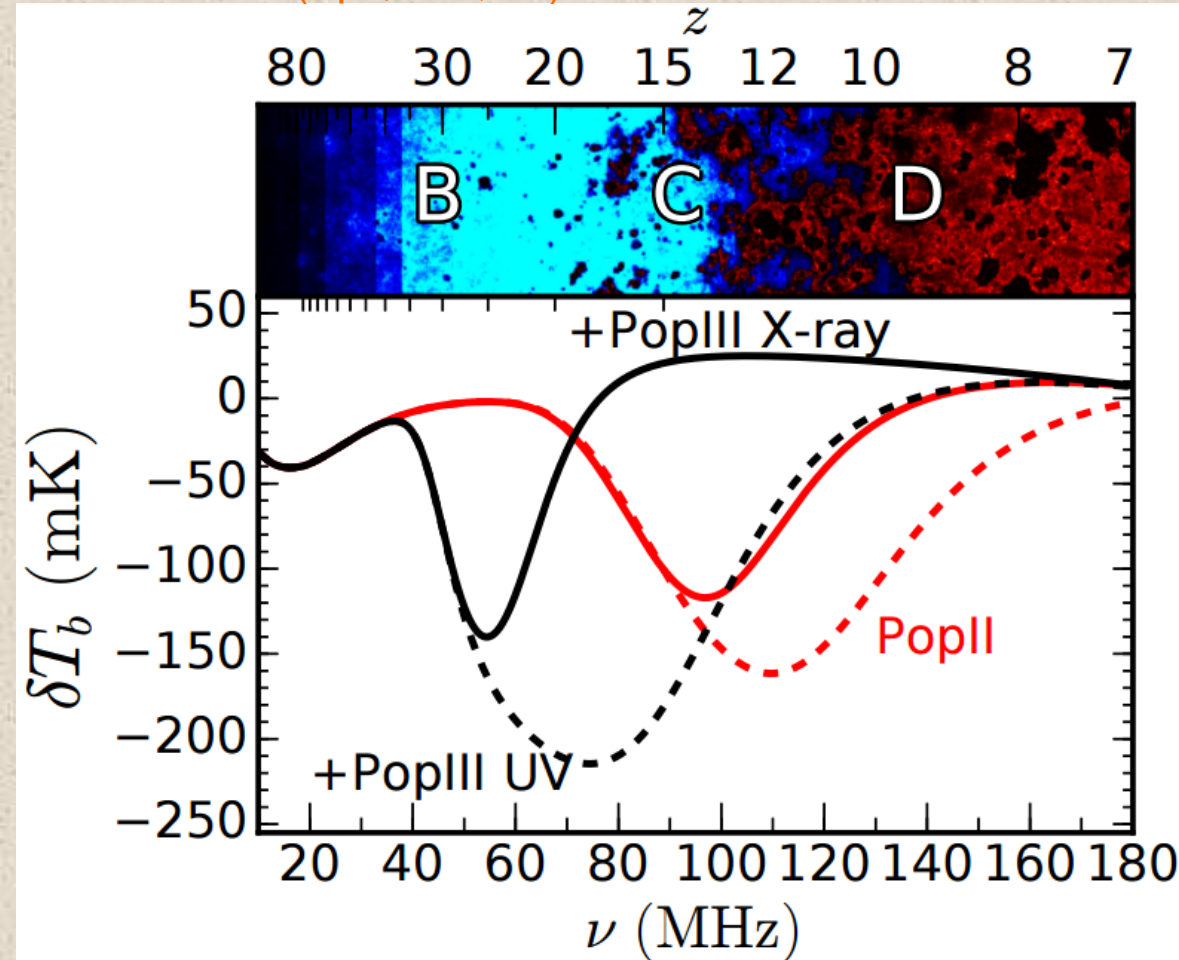


- Occurs in neutral hydrogen.
- Proton and electron have magnetic moments due to their spin.
- Energy difference between moments being aligned and anti-aligned is equal to the energy of a photon with rest wavelength (frequency) 21 cm (1420 MHz).

Images from Wikipedia

# Global 21-cm signal from the first luminous objects

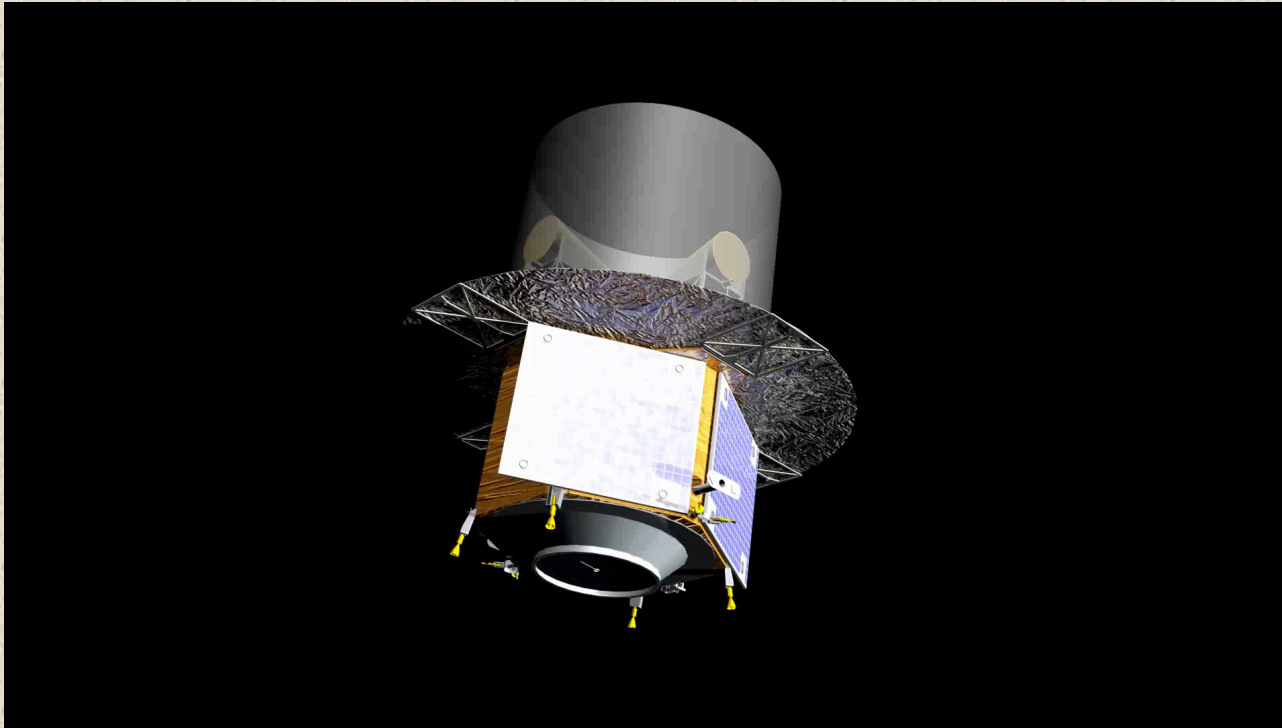
Burns et al 17 (*ApJ*, 844, 33)



- **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).

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

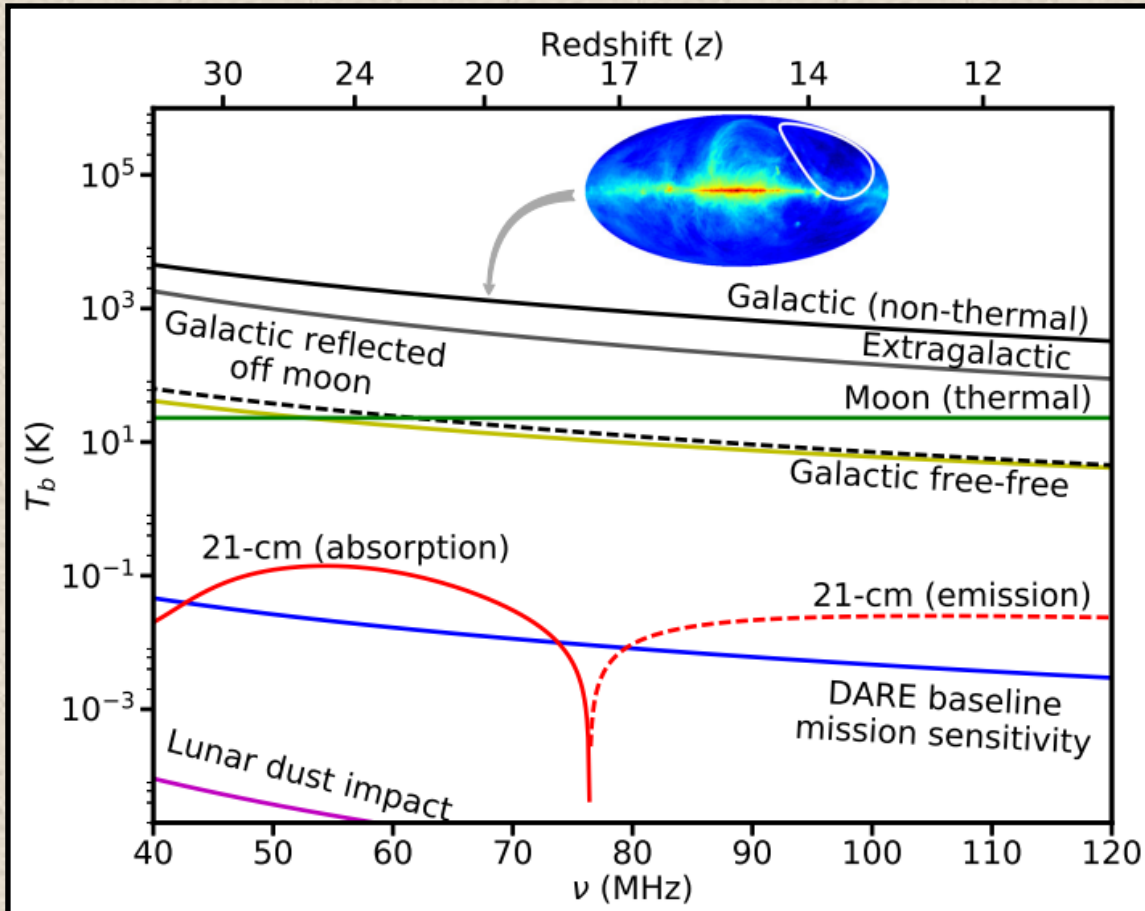
# Dark Ages Radio Explorer (DARE)



- 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)

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

Training Set:

$(N_{channel} \times N_{curves})$

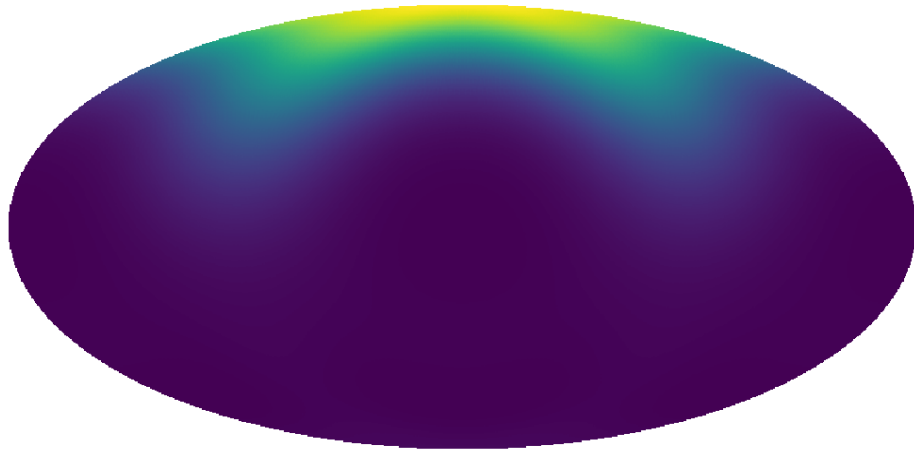
Ordered basis functions:

$(N_{channel} \times N_{channel})$

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

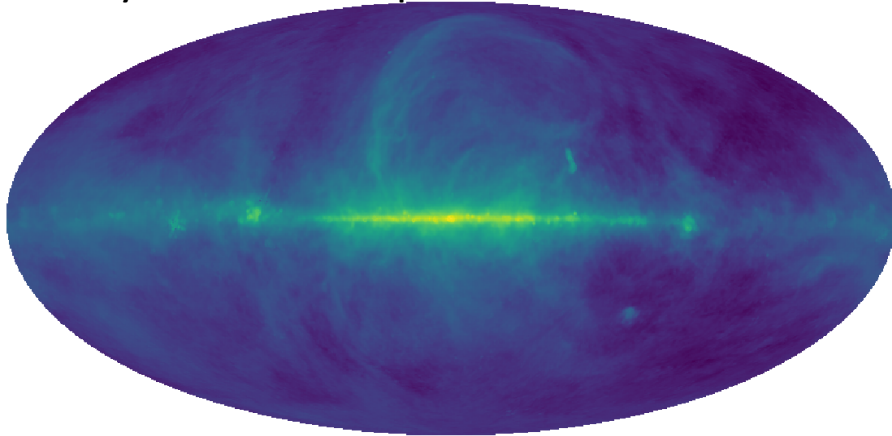
# Foreground training set

DARE beam at 80 MHz



5.94826e-06 0.663649

All-sky 408 MHz map from Haslam et al. 1982



11.3615 [K] 731.504

- 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

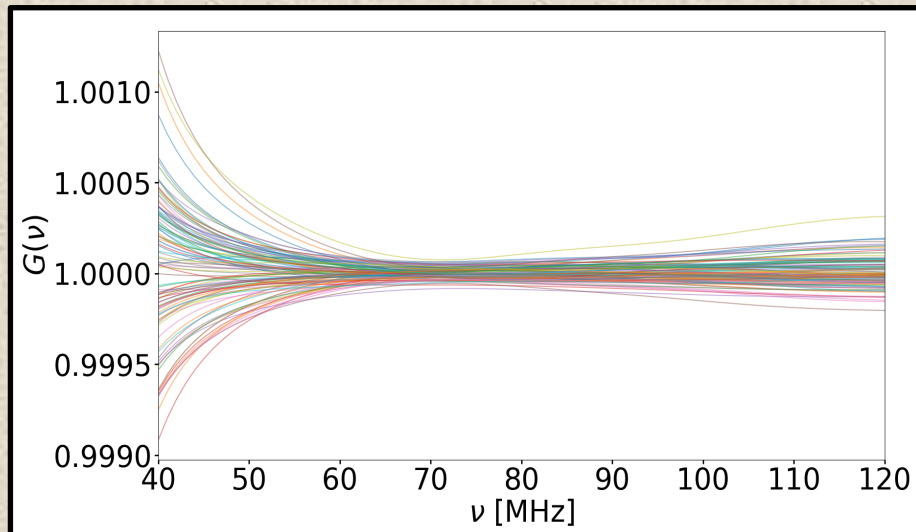
- Instrument systematics are simulated through the following calibration equation:

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

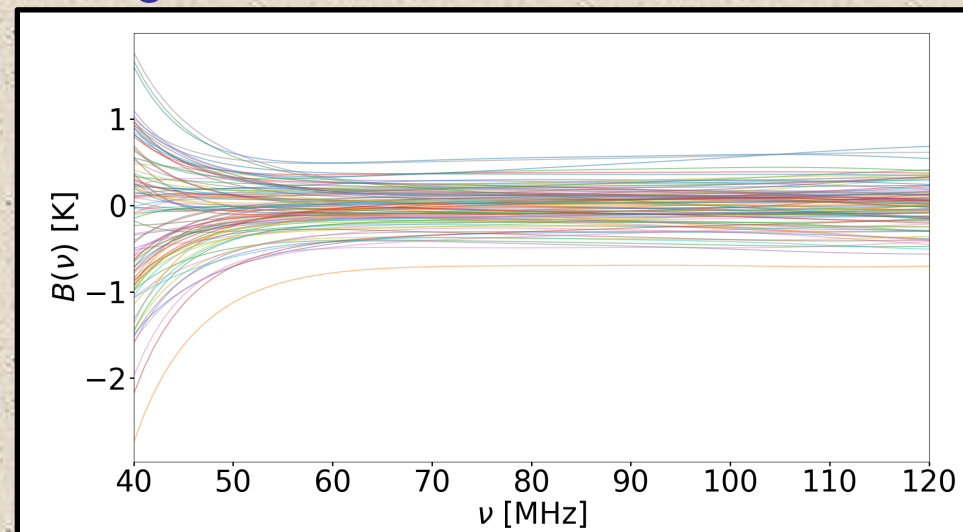
- Applying this equation and then its inverse with slightly different parameters on an antenna temperature yields a calibrated antenna temperature that differs by a **multiplicative factor,  $G$** , and an **additive offset,  $B$** , which are functions of frequency:

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

## Instrument training sets

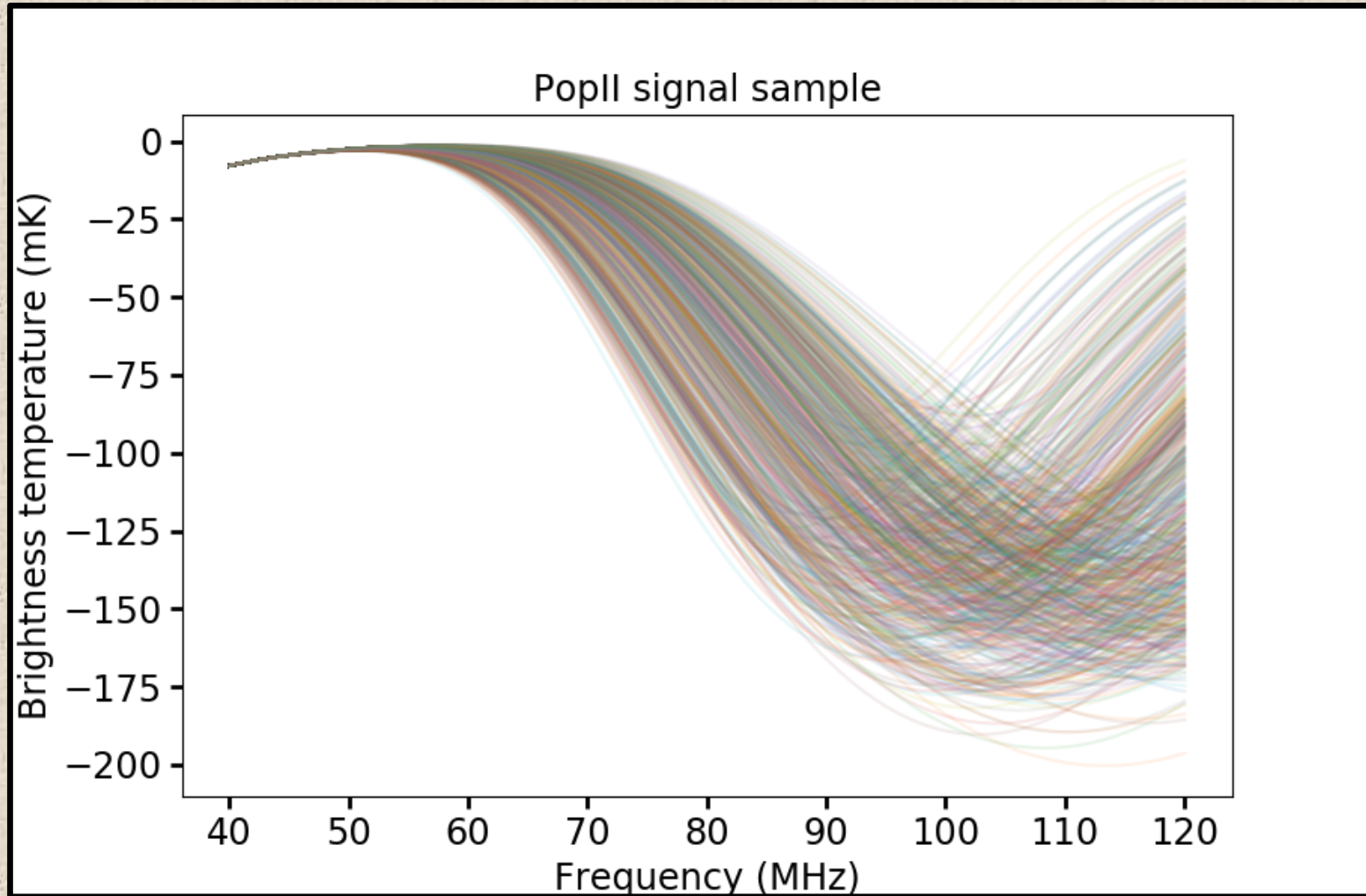


August 29, 2017



COSMO-17, Paris

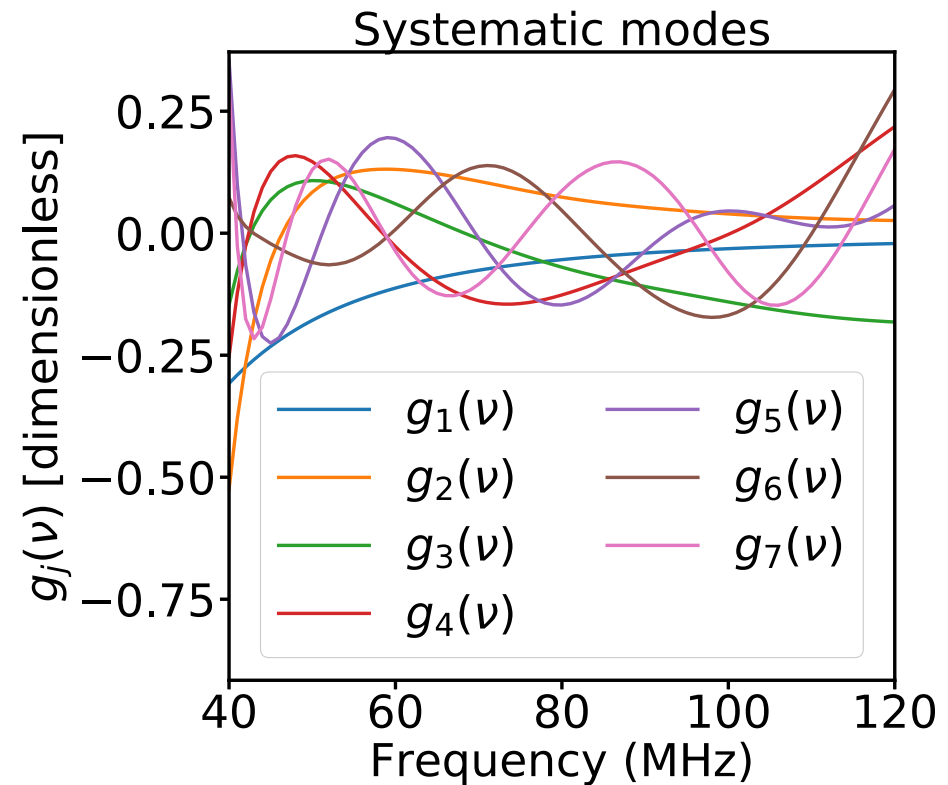
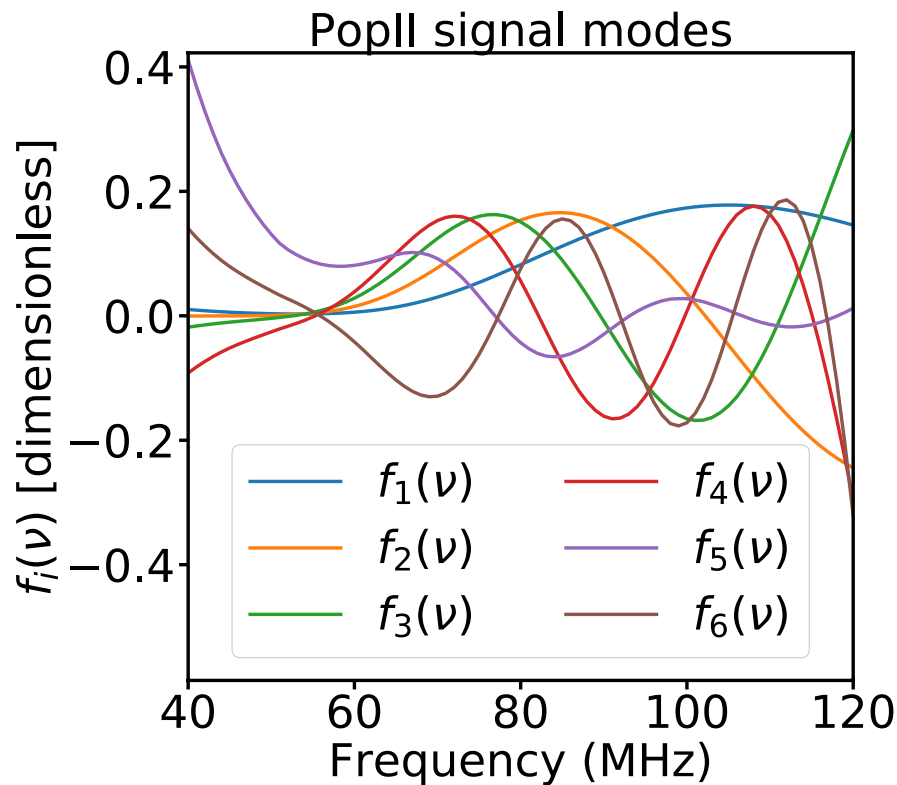
# Signal training set



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

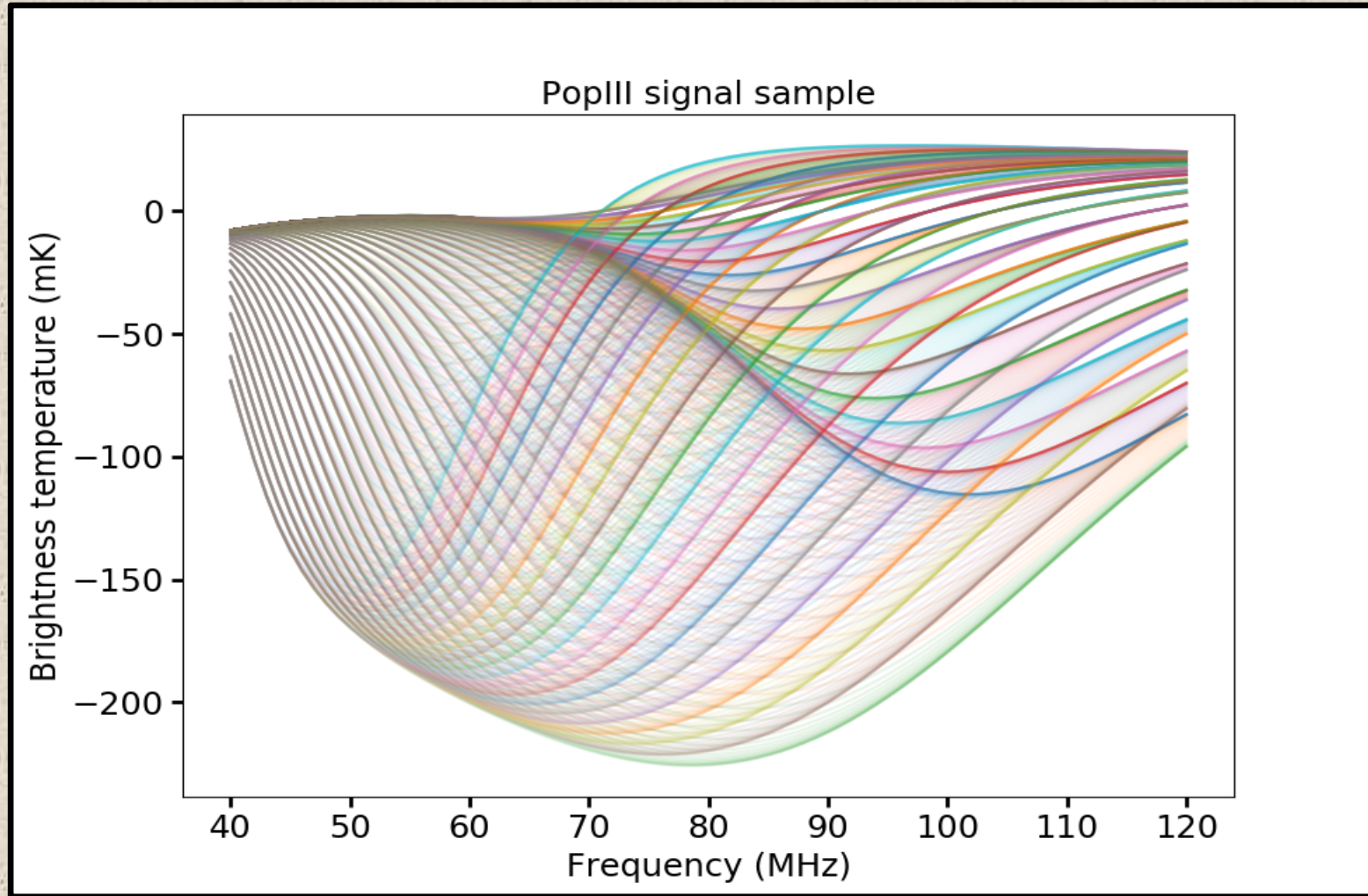
# SVD modeling of the signal and systematics

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

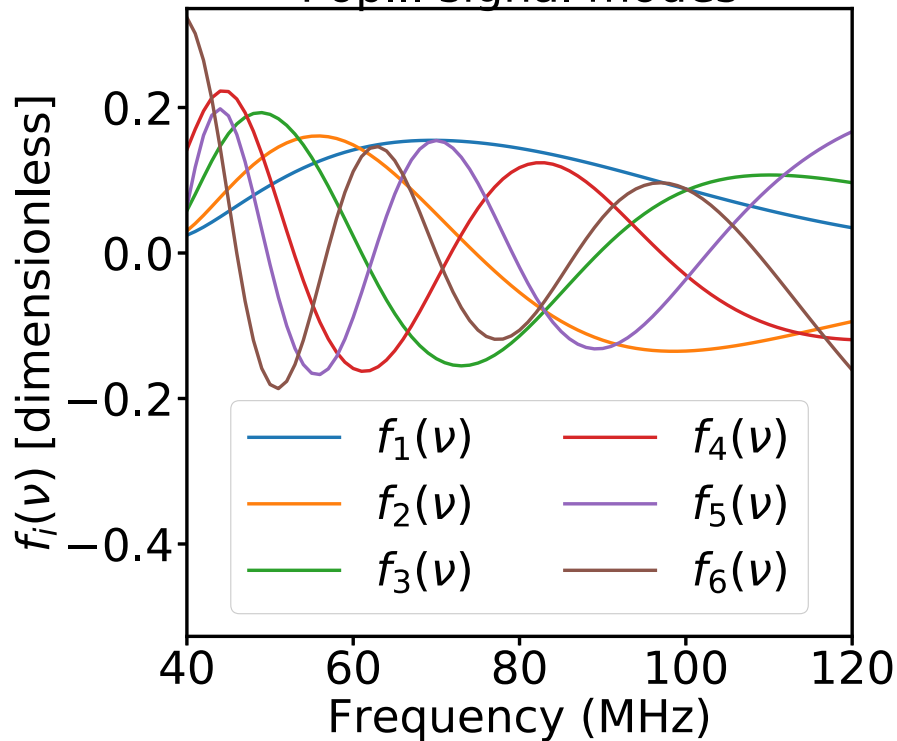


- Derived by randomly sampling the parameter space surveyed in [Mirocha et al 17](#) with the addition of two parameters describing UV and X-ray photon production efficiency in minihalos.

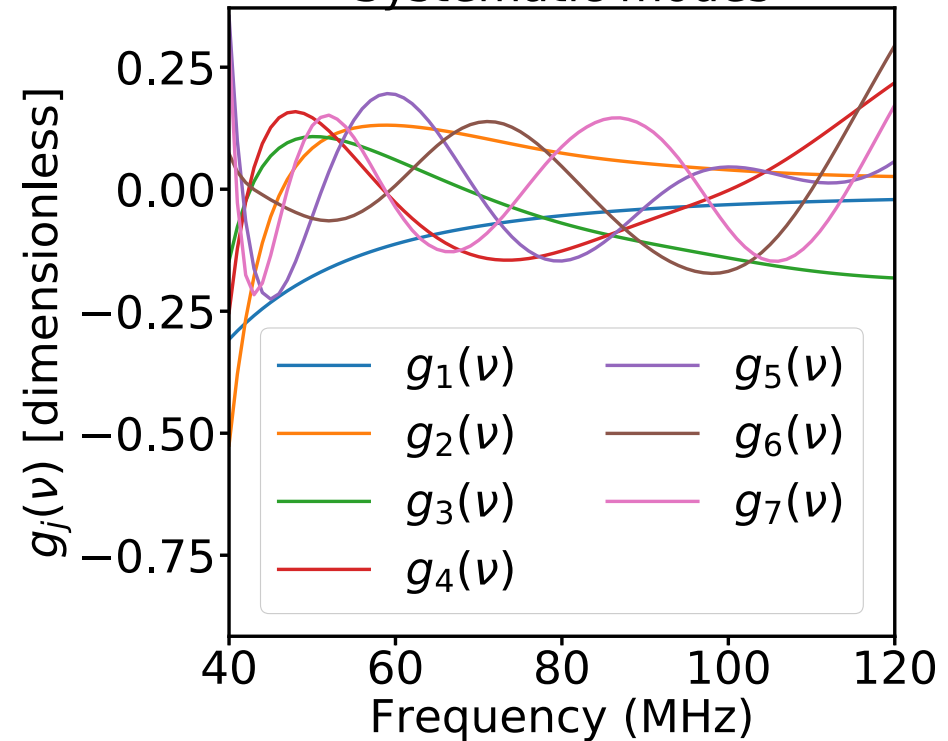
# SVD modeling of the signal and systematics

Burns et al 17 (ApJ, 844, 33)

PopIII signal modes



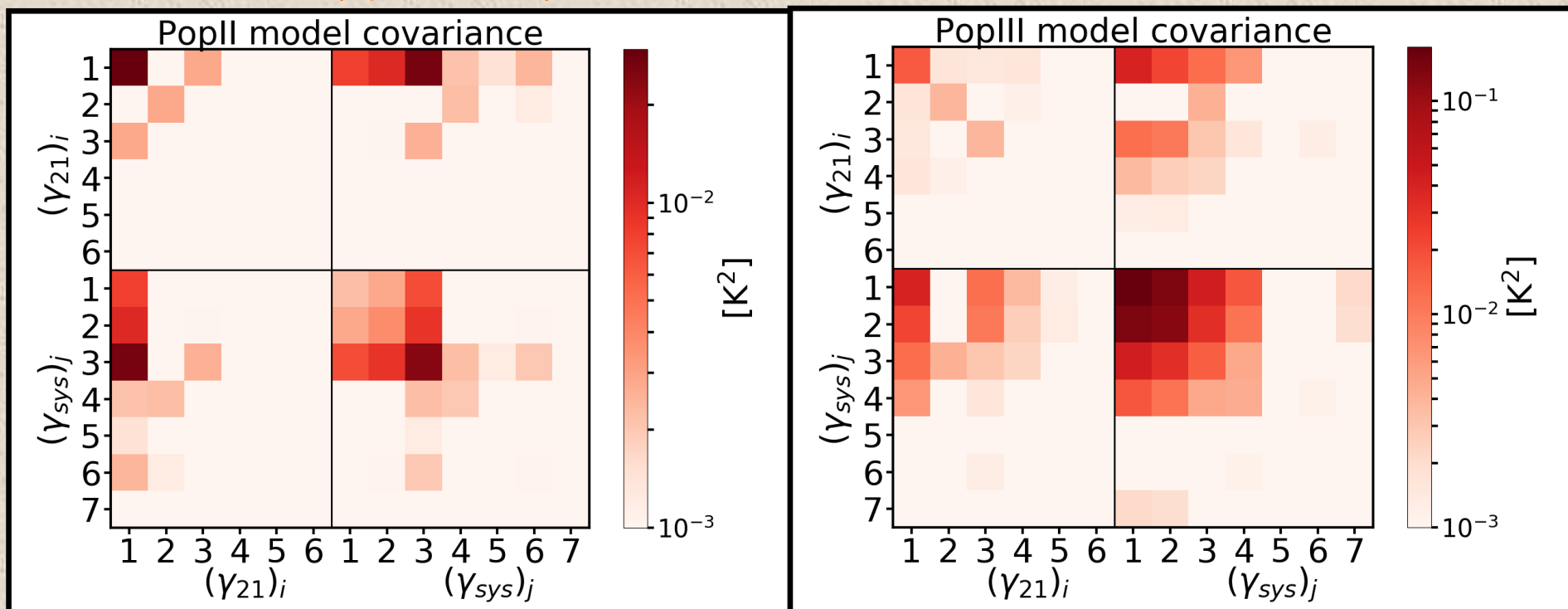
Systematic modes



- **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.

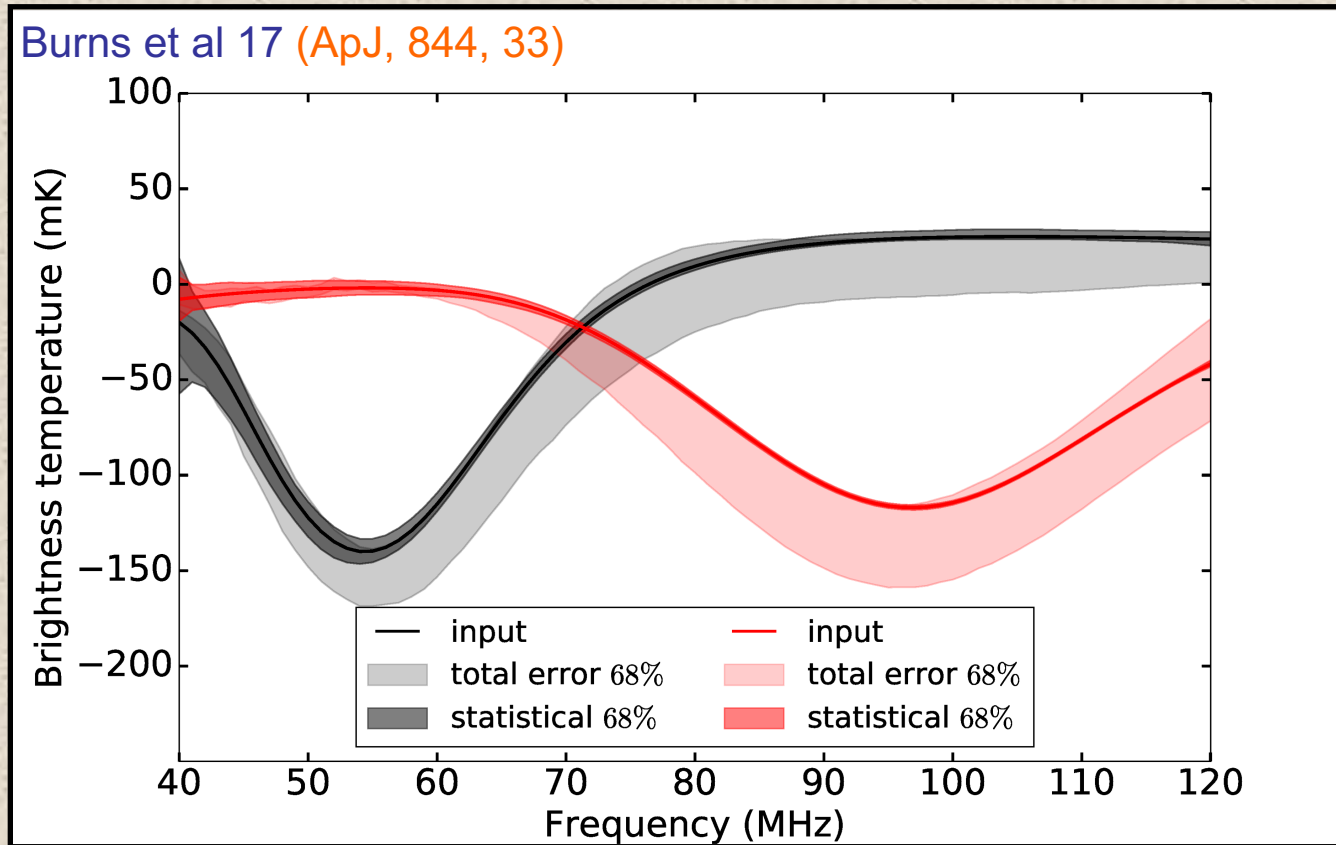
# Covariances between the signal and systematics modes

Burns et al 17 (ApJ, 844, 33)



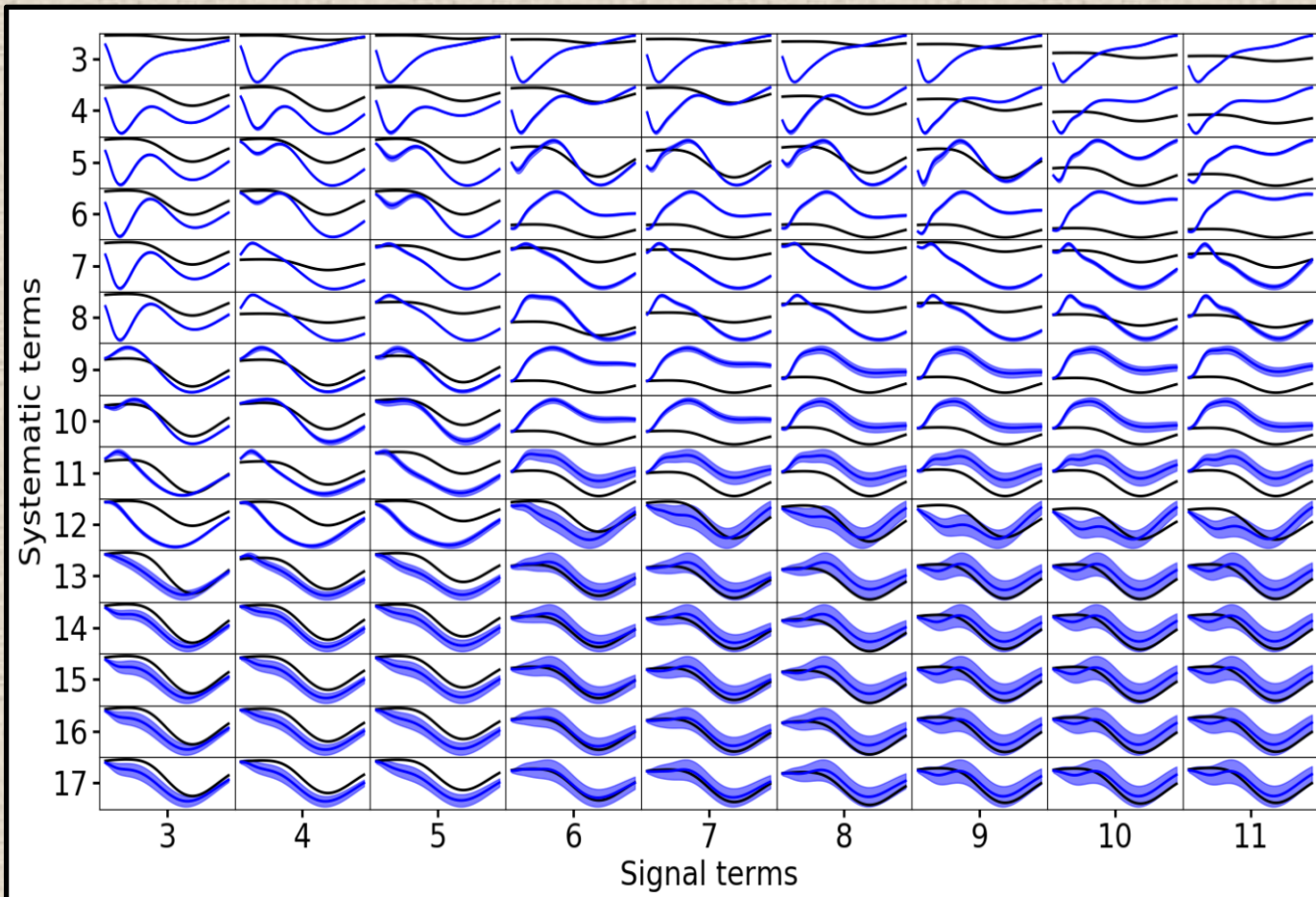
-The vertical and horizontal black lines separate the regions with covariances between **signal** parameters (**top left**) and **systematic** parameters (**bottom right**). The other two regions are symmetric and show the covariances between signal and systematic parameters.

# 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)

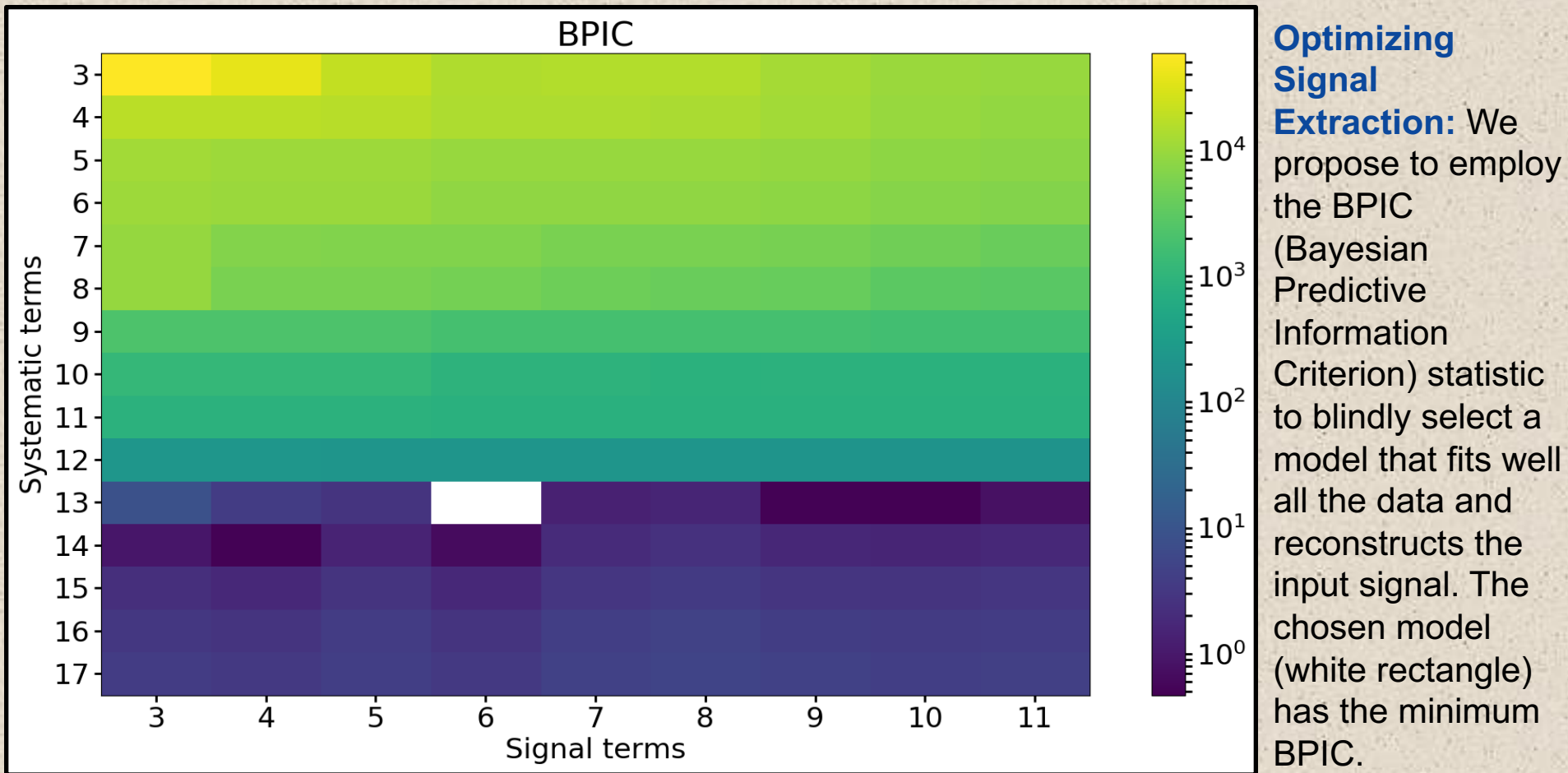


**Optimizing Signal Extraction:** The black line for all panels is the input 21-cm signal. The blue bands are the pipeline reconstructions of the signal for a given number of SVD signal and systematic parameters/modes.

(See Tauscher et al. 2017 in prep.)



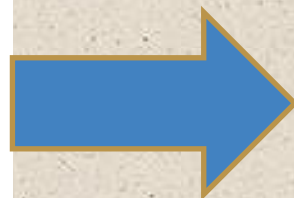
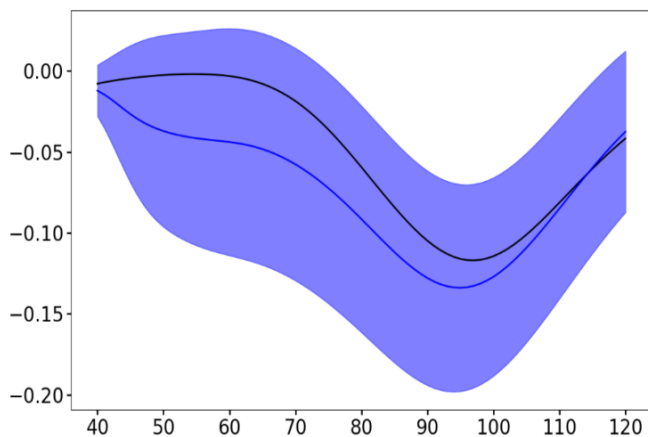
# Model selection using BPIC: number of SVD modes (preliminary)



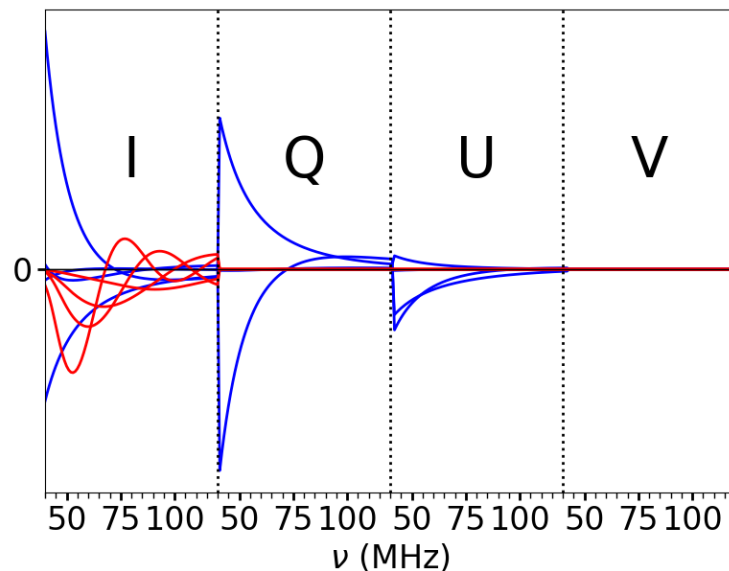
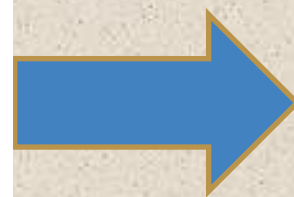
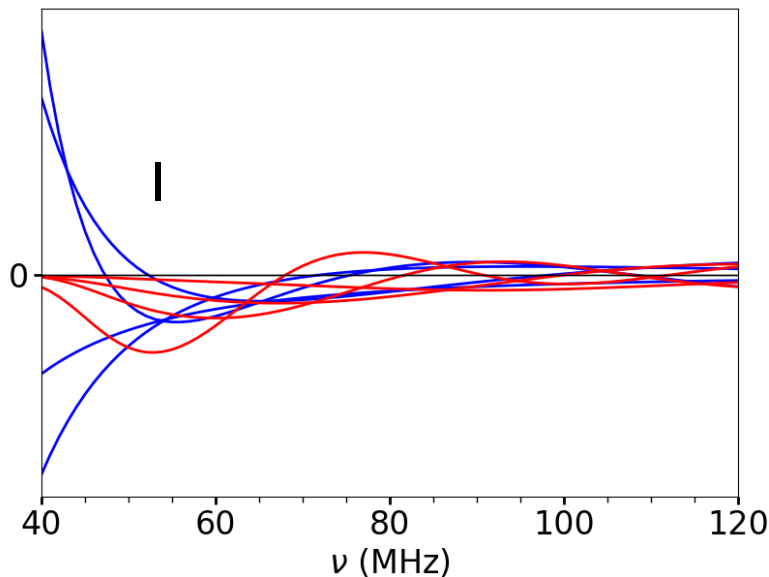
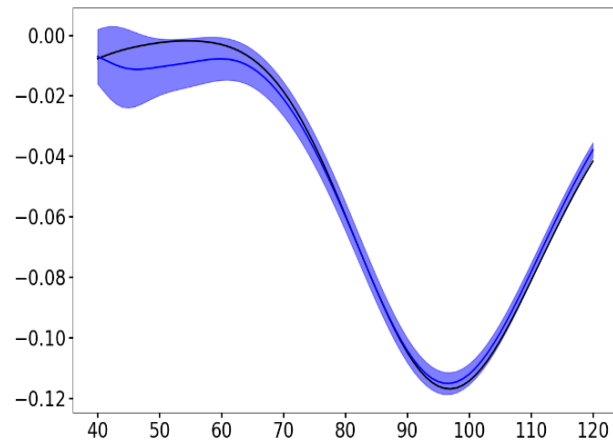
(See Tauscher et al. 2017 in prep.)

# Separating systematics with induced polarization (preliminary)

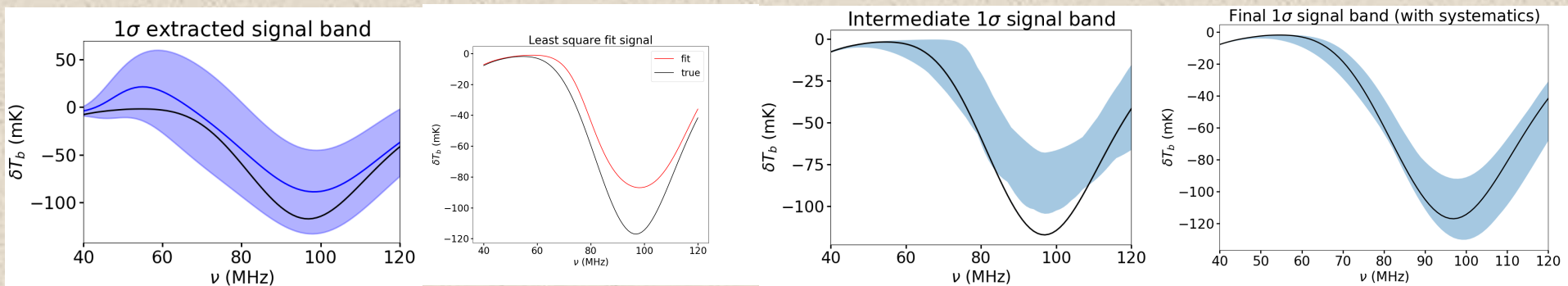
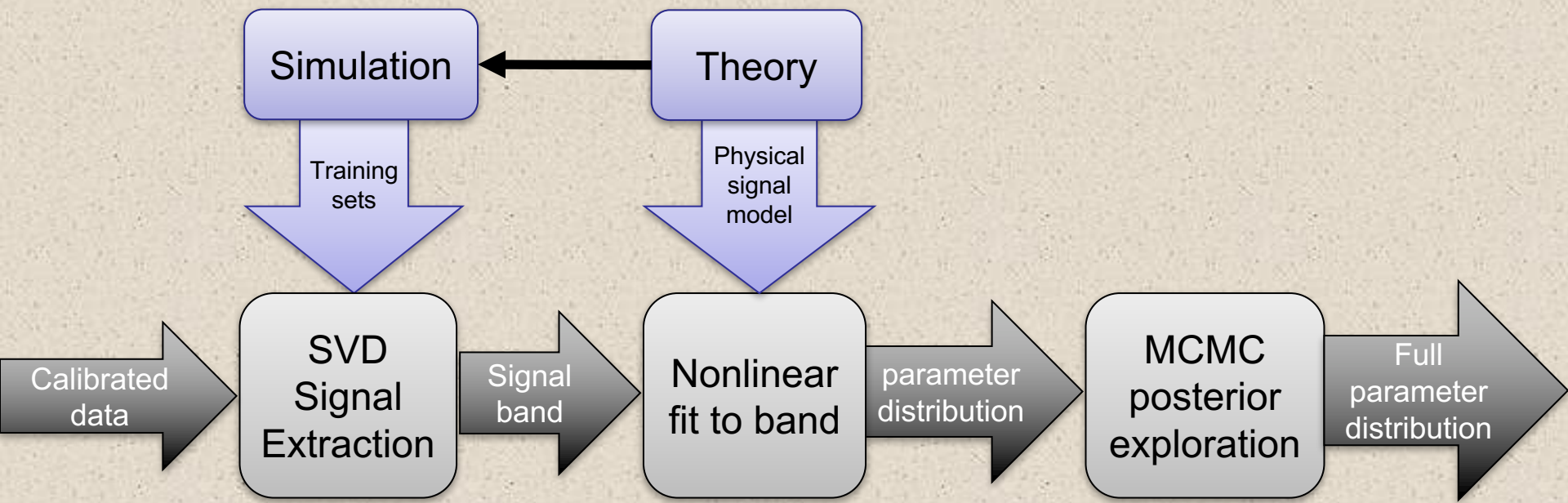
## No polarization data used



## Polarization data used



# 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.