Foreground Subraction in redShifted 21cm Global Signal experiments

– using artificial Neural networks.

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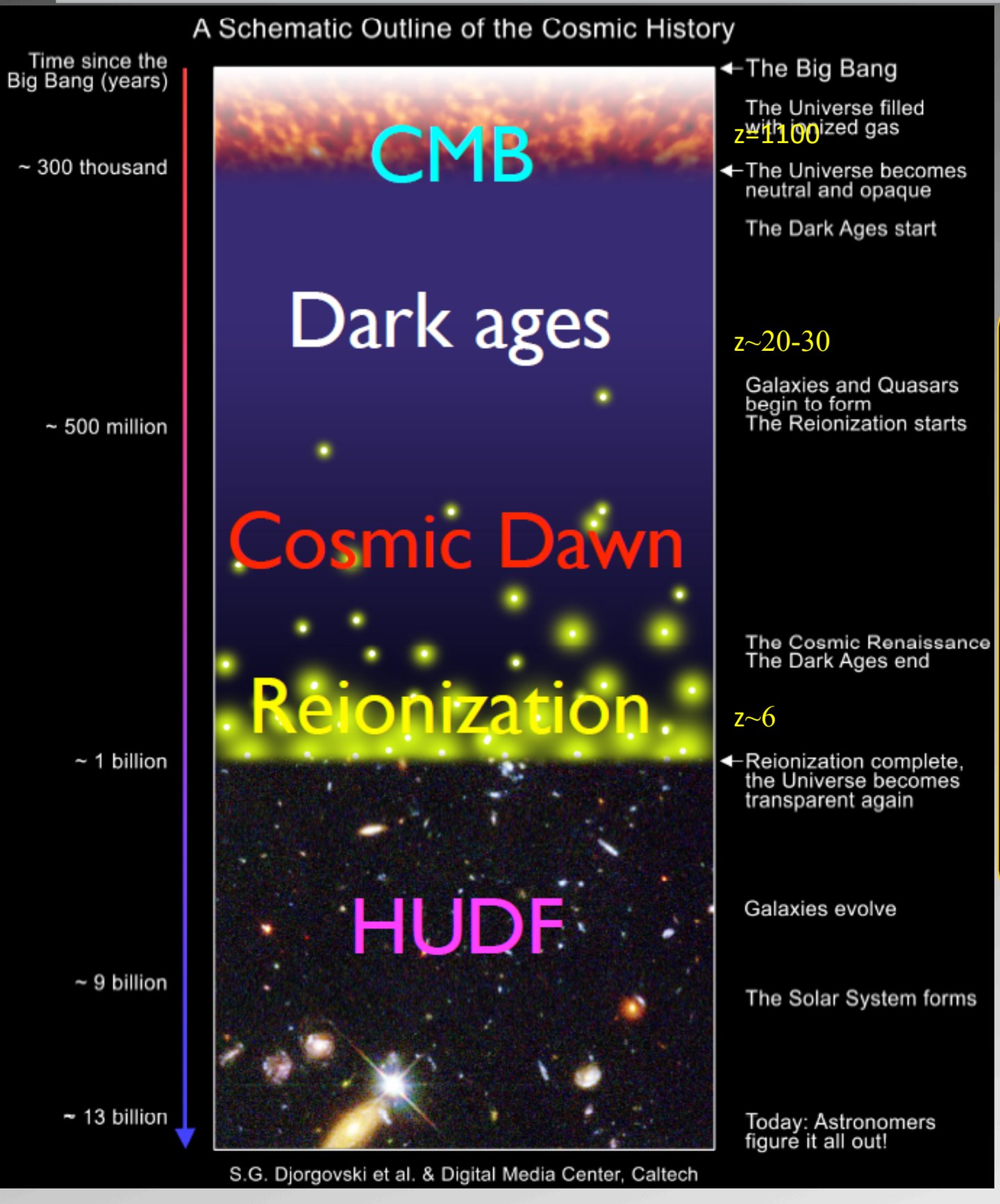
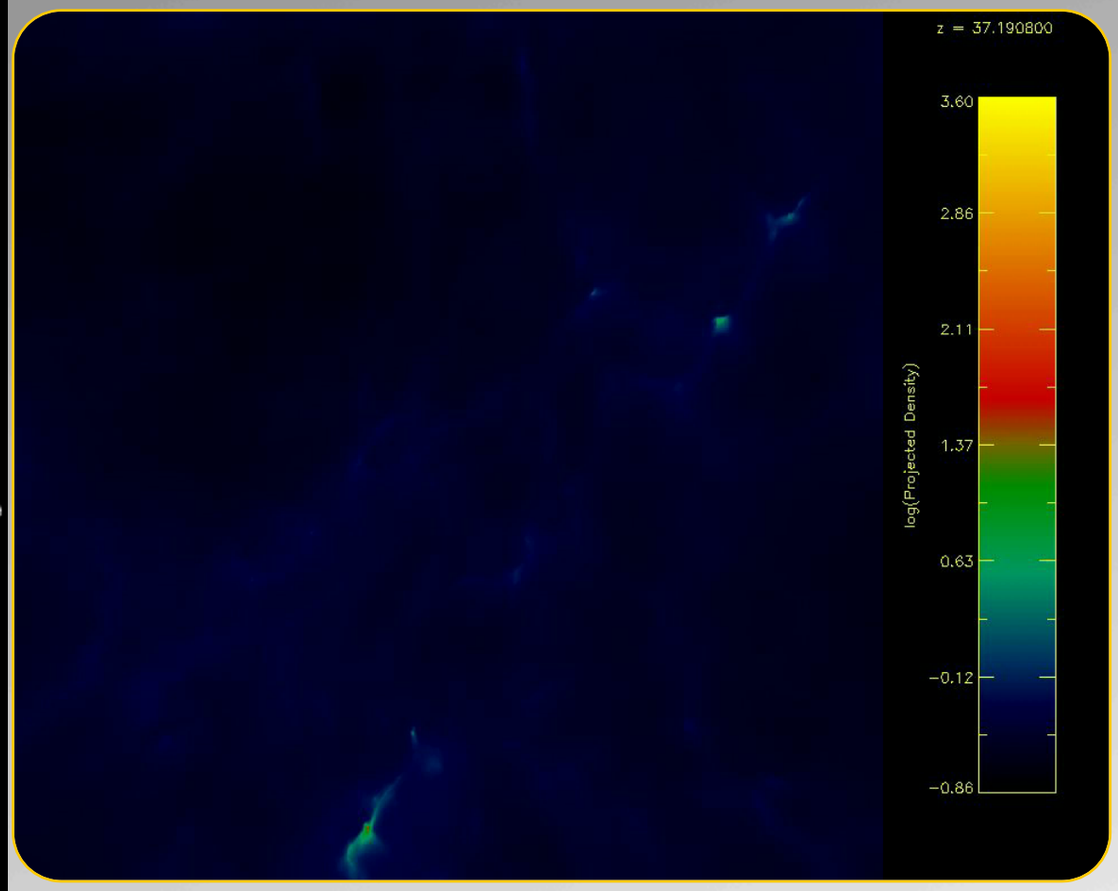
The First 0.5 Billion Years

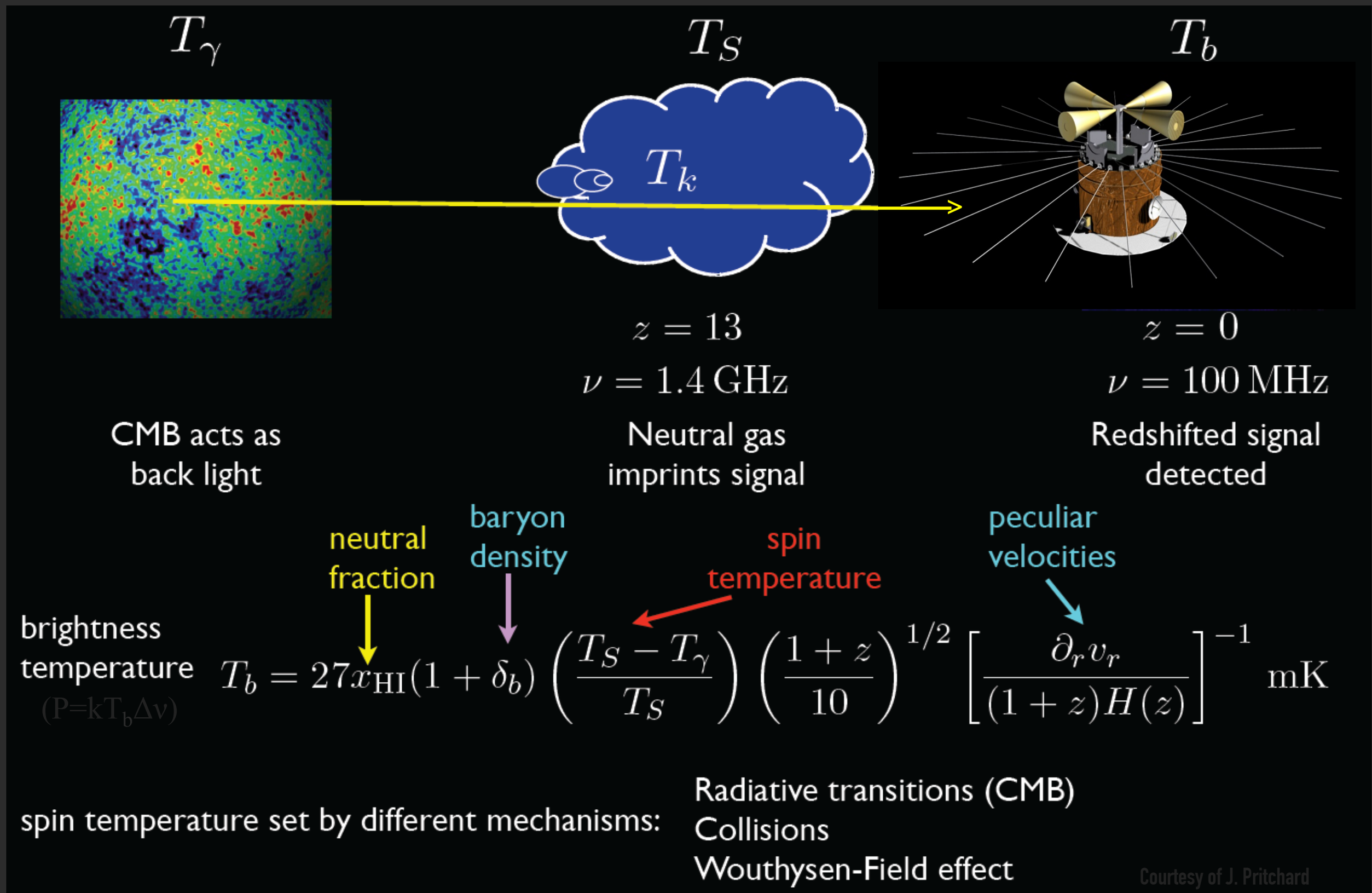




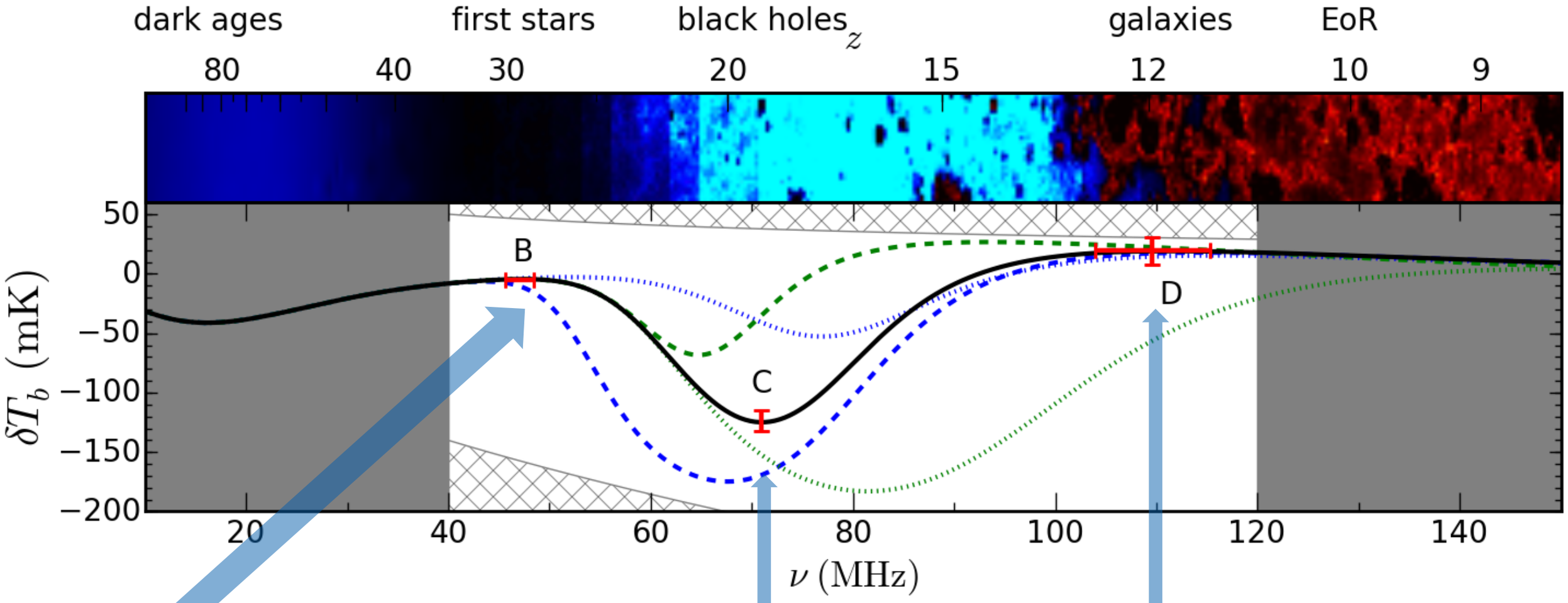
The First Stars

John Wise, Georgia Tech

The 21-cm Line in Cosmology



The 21-cm Global Signal



- B: ignition of first stars
  - When did the First Stars ignite? What were these First Stars?
  - What surprises emerged from the Dark Ages?

C: heating by first black holes

- **When did the first accreting black holes turn on? What was the characteristic mass?**

D: the onset of reionization

- **When did Reionization begin?**

--- ••• uncertainties in 1st star models

--- ••• uncertainties in 1st black hole models

Adapted from : Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006 and Mirocha et al. (2015)

Observational Approaches for Detection of Global 21-cm Monopole

Single Antenna Radiometers	Small, Compact Interferometric Arrays
•EDGES (Bowman & Rogers)	•Vedantham et al.
•SARAS (Patra et al.)	•Mahesh et al.
•LEDA (Greenhill, Bernardi et al.)	•Presley, Parsons & Liu
•SCI-HI (Peterson, Voytek et al.)	•Subrahmanyan, Singh et al.
•BIGHORNS (Sokolowski et al.)	
•DARE (Burns et al.)	
Challenges include systematics arising from stability issues, accurate calibration, polarization leakage, foregrounds.	Challenges include cross-talk among antenna elements, mode-coupling of foreground continuum sources into spectral confusion, sensitivity.

FOREGROUNDS: MAJOR CHALLENGE

- **Earth's Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2016; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - Effects scale as ν^{-2} so they get much worse quickly below ~100 MHz.
- **Radio Frequency Interference (RFI)**
  - RFI particularly problematic for FM band (88-110 MHz).
  - Reflection off the Moon, space debris, aircraft, & ionized meteor trails are an issue everywhere on Earth (e.g., Tingay et al. 2013; Vedantham et al. 2013).
  - Even in LEO (10^8 K) or lunar nearside (10^6 K), RFI brightness T_B is high.
- **Galactic/Extragalactic**
  - Mainly synchrotron with expected smooth spectrum (~3rd order log polynomial,

$$\log T_{\rm fg} = \sum_{i=0}^{N_{\rm poly}} a_i \log\left(\frac{\nu}{\nu_0}\right)^i$$

, although it is corrupted by antenna beam; e.g., Bernardi et al. 2015).

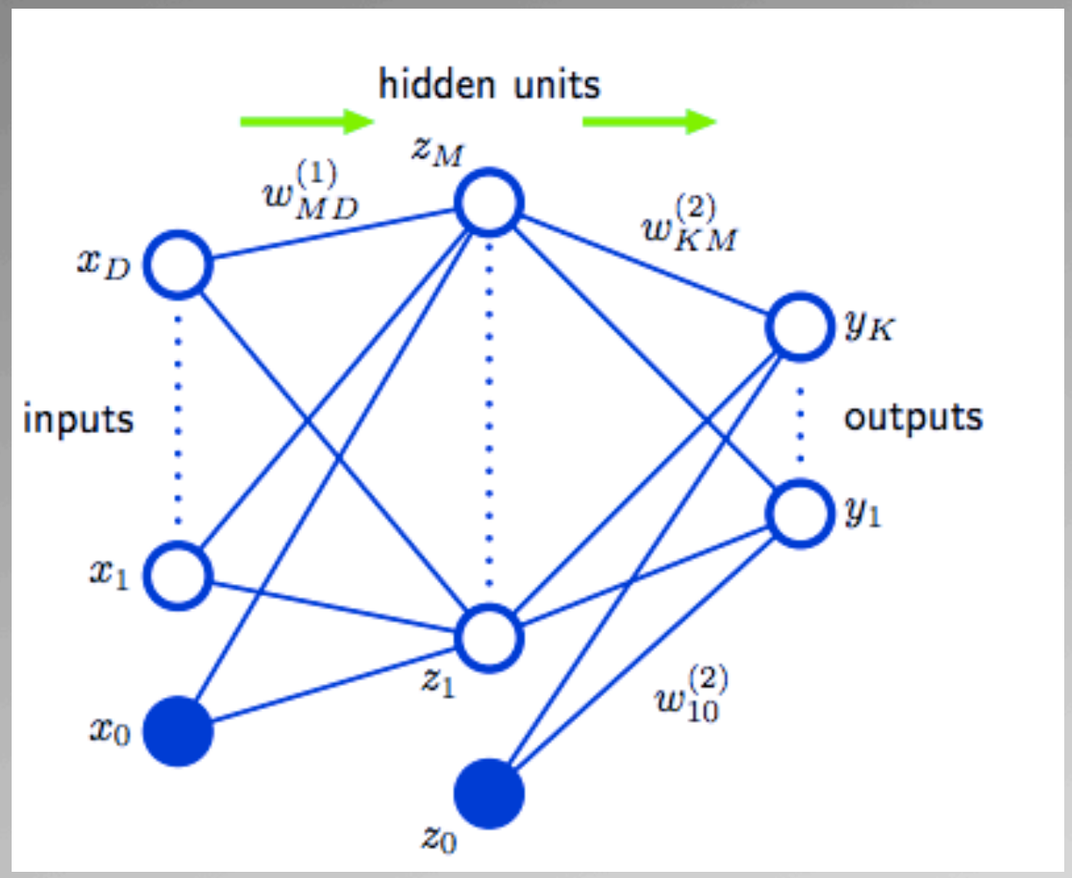
EDGES finds spectral structure at levels < 12 mK in foreground at 100-200 MHz.

ARTIFICIAL NEURAL NETWORK

- These are machine learning algorithms which mimics the functioning of our brains.
- By feeding the network, enough amount of training data, the network can be trained to perform a certain task.
- You must have noticed how efficiently Google predicts your search queries as you begin typing your query in the search box. This is a very common application of pattern recognition techniques being used today.
- Further applications are seen in biometrics, gene-replication research, efficient compression of sequential files, etc.
- More recent works in HI Cosmology, Gravitational Lens, etc

Structure of the Network

- Input layer : We provide the training dataset to the input neurons.
- Hidden layer: The inputs are assigned weights and then activated using an activation function.
- Output layer: The information from the hidden layer is passed on to the output layer again by assigning weights.
- Training: The weights are adjusted so as to minimise the cost function, using the back-propagation algorithm.
- This is an iterative process, which assigns a different weight to each input till the cost function converges.



Using the framework in

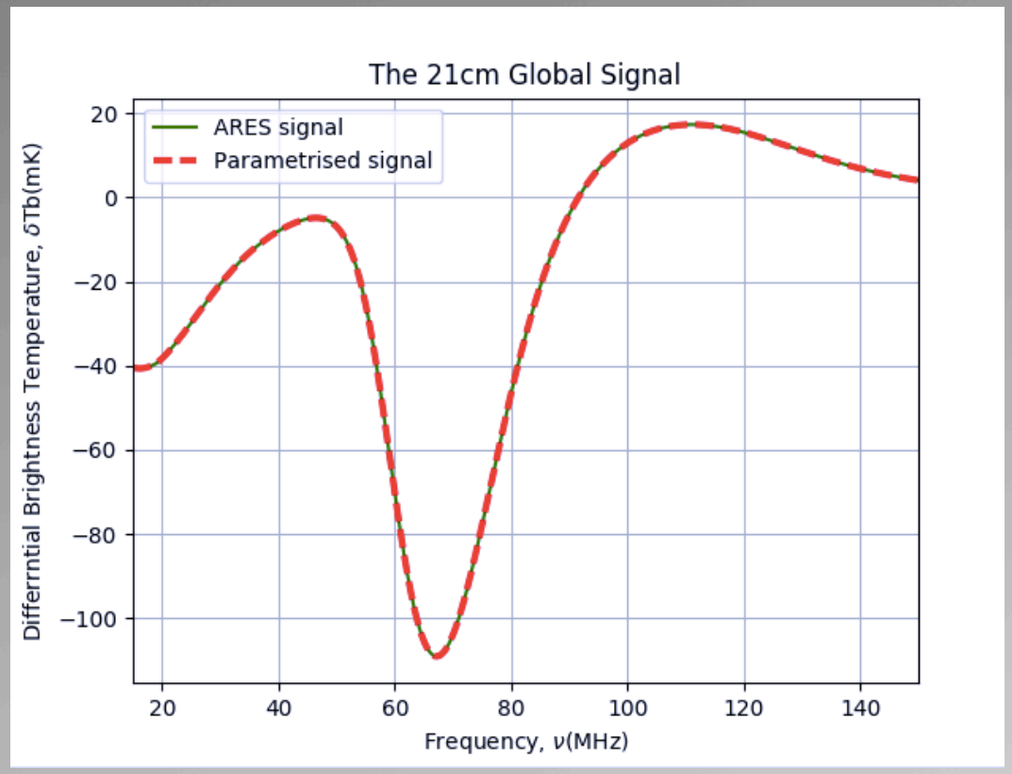
KERAS package : https://keras.io/

MODEL GLOBAL 21CM SIGNAL

- We use the Accelerated Reionization Era Simulations (ares) code was designed to rapidly generate models for the global 21-cm signal (Mirocha et al, 2012, 2015).
- We have used the tanh model for parametrising the global signal, where the parameters , A(z) are the parameters for the global signal.

$$A(z) = \frac{A_{\rm ref}}{2}\{1 + \tanh[(z_0 - z)/\Delta z]\}$$

- The following plot shows the simulated signal from ARES and the calculated result for the signal.



PARAMETERS evolve according to a tanh model

- J(z)––Lyman-alpha background(which determines the strength of W-F coupling)
- Xi(z)–– Ionized fraction of hydrogen
- T(z)––temperature of the IGM

FOREGROUND MODEL

- The foreground model used is of the form:

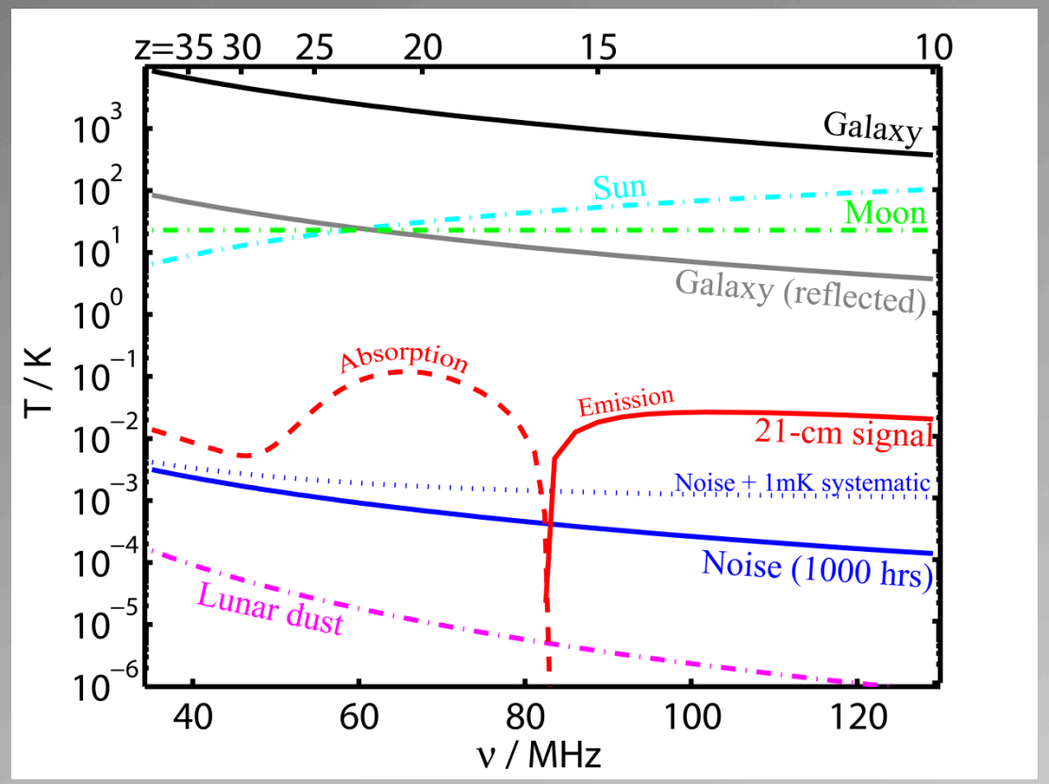
$$\log T_{\rm FG}^i = \log T_0^i + a_1^i \log(\nu/\nu_0) + a_2^i [\log(\nu/\nu_0)]^2 + a_3^i [\log(\nu/\nu_0)]^3 ,$$

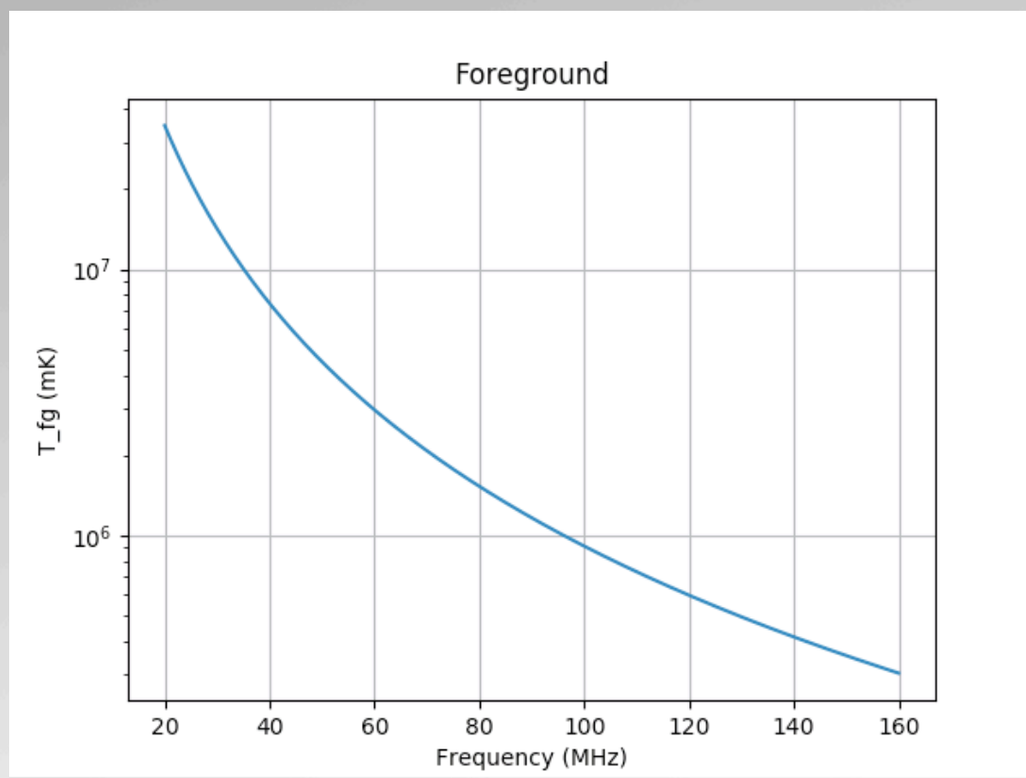
$$\nu_0 = 80$$

Foreground parameters

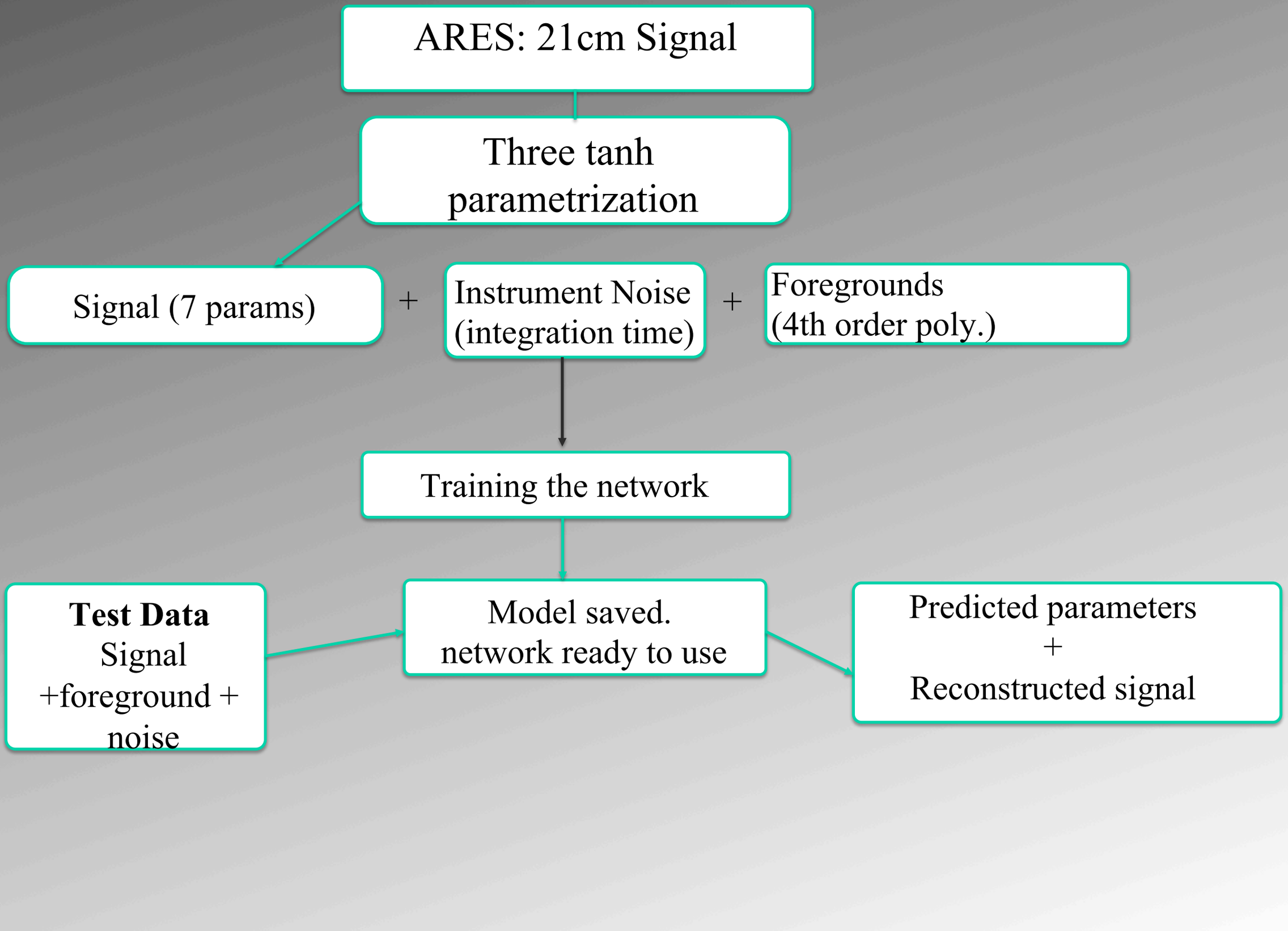
- a0=(log T0), a1,a2,a3

- Where, all temperatures are in K, and Hz, is an arbitrary reference frequency, which is chosen to lie in the middle of our band.





OUTLINE

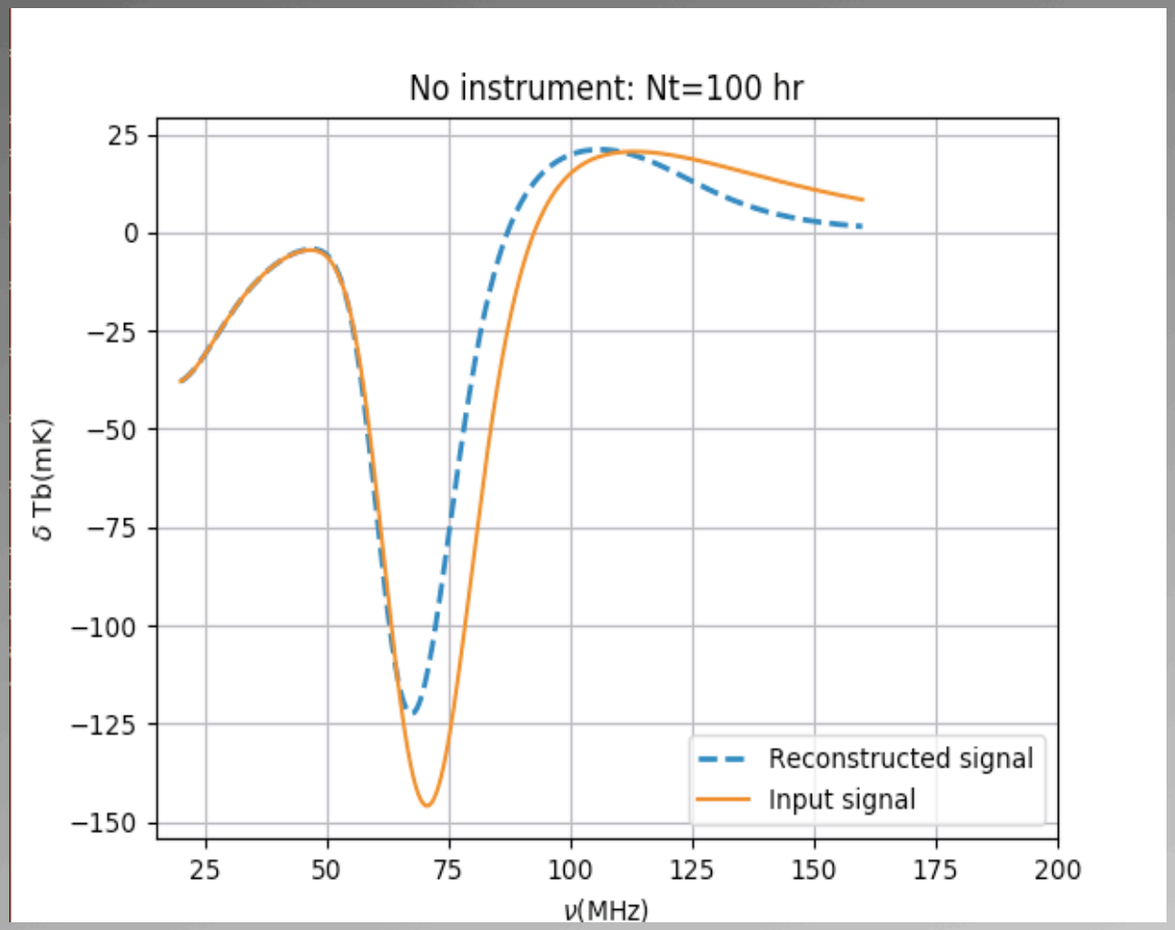

ARES: 21cm Signal
Three tanh parametrization
Signal (7 params)
+
Instrument Noise (integration time)
+
Foregrounds (4th order poly.)
Training the network
Test Data
Signal +foreground + noise
Model saved. network ready to use
Predicted parameters
+
Reconstructed signal

Training the Network

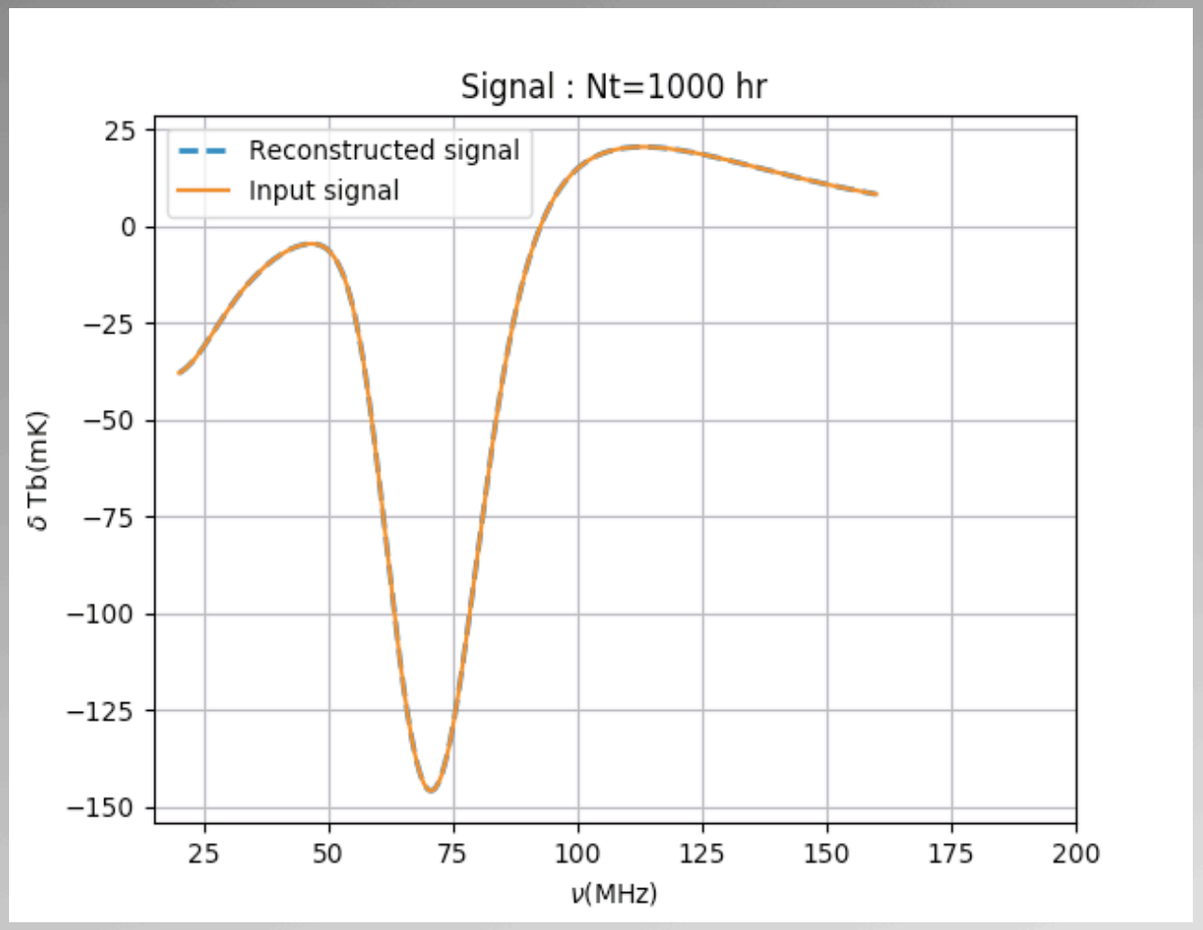
- We have generated 2500 datasets for input to the network, which was then split into training (70%) and the testing datasets(30%).
- Each dataset has 1024 frequency channels (20,160) MHz, i.e. Z~ (70, 8).
- The network is trained with thermal noise and with/without instrument response.
- We have used an ANN with a single hidden layer with 15-18 neurons, and there are 11-13 output neurons corresponding to the 11-13 parameters.

Simulations

- Case 1: 21CM Signal + Foreground + Instrumental Noise



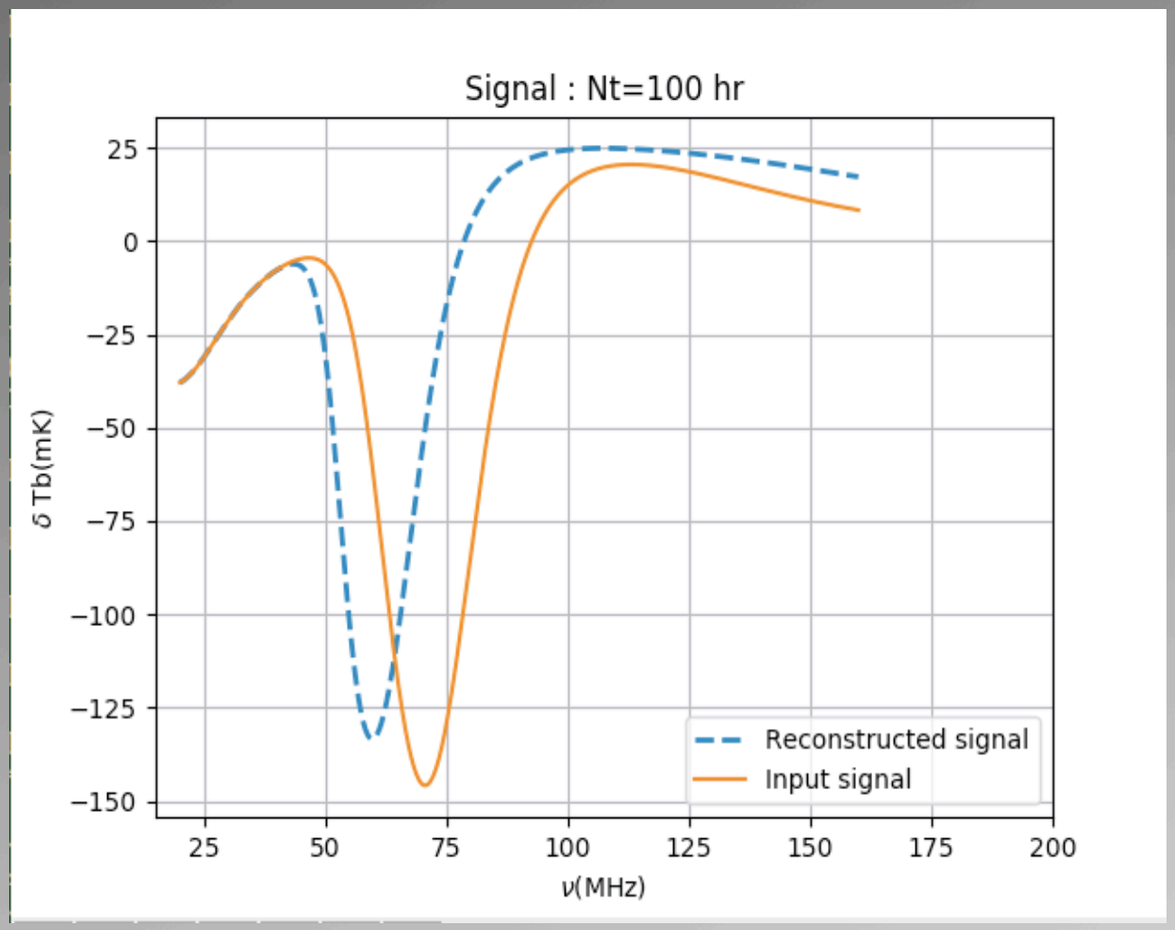
RMSE on Jref = 8 %

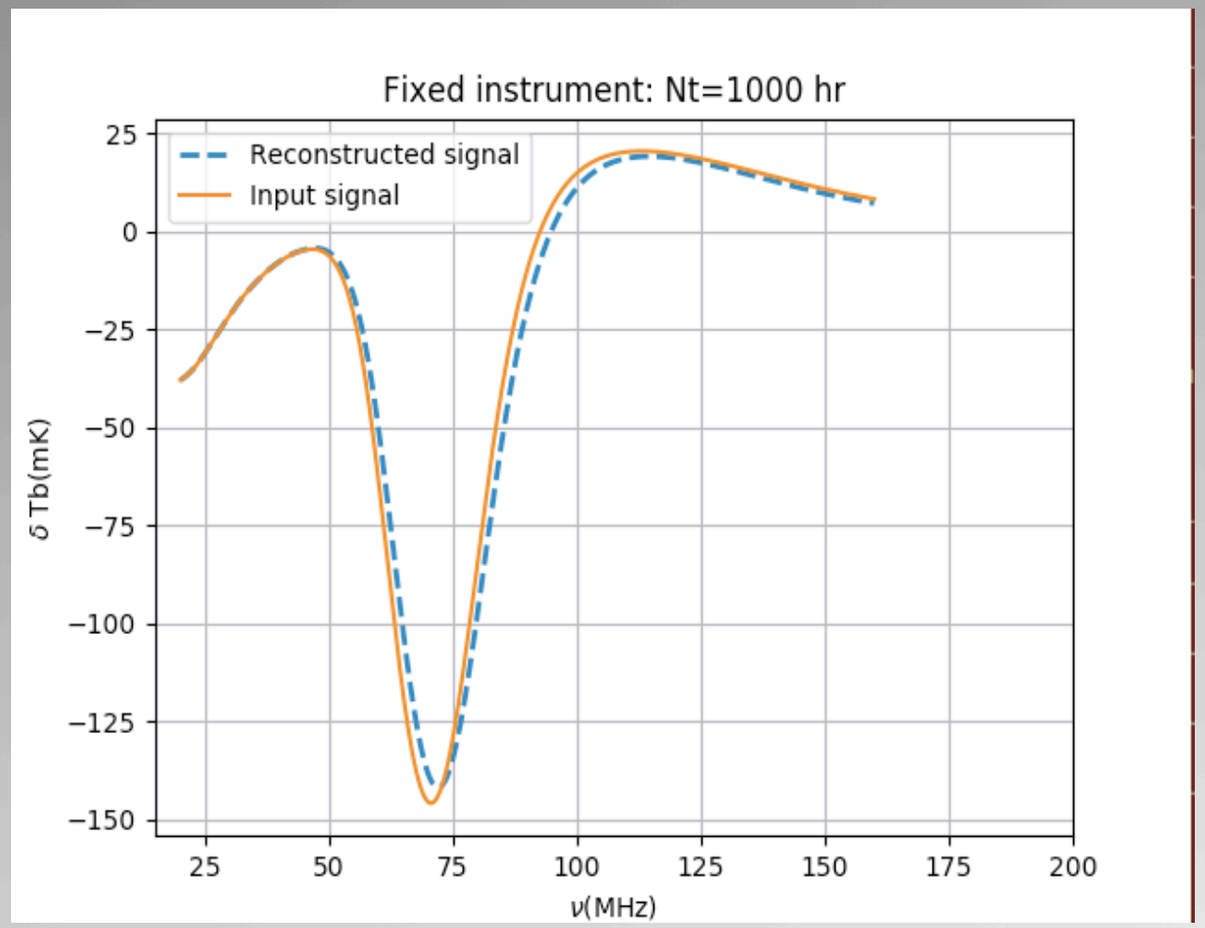


RMSE on Jref = 3 %

Simulations

- Case 2: 21CM Signal + Foreground + Instrumental Noise + Instrumental Gain (Bandpass) fixed over time



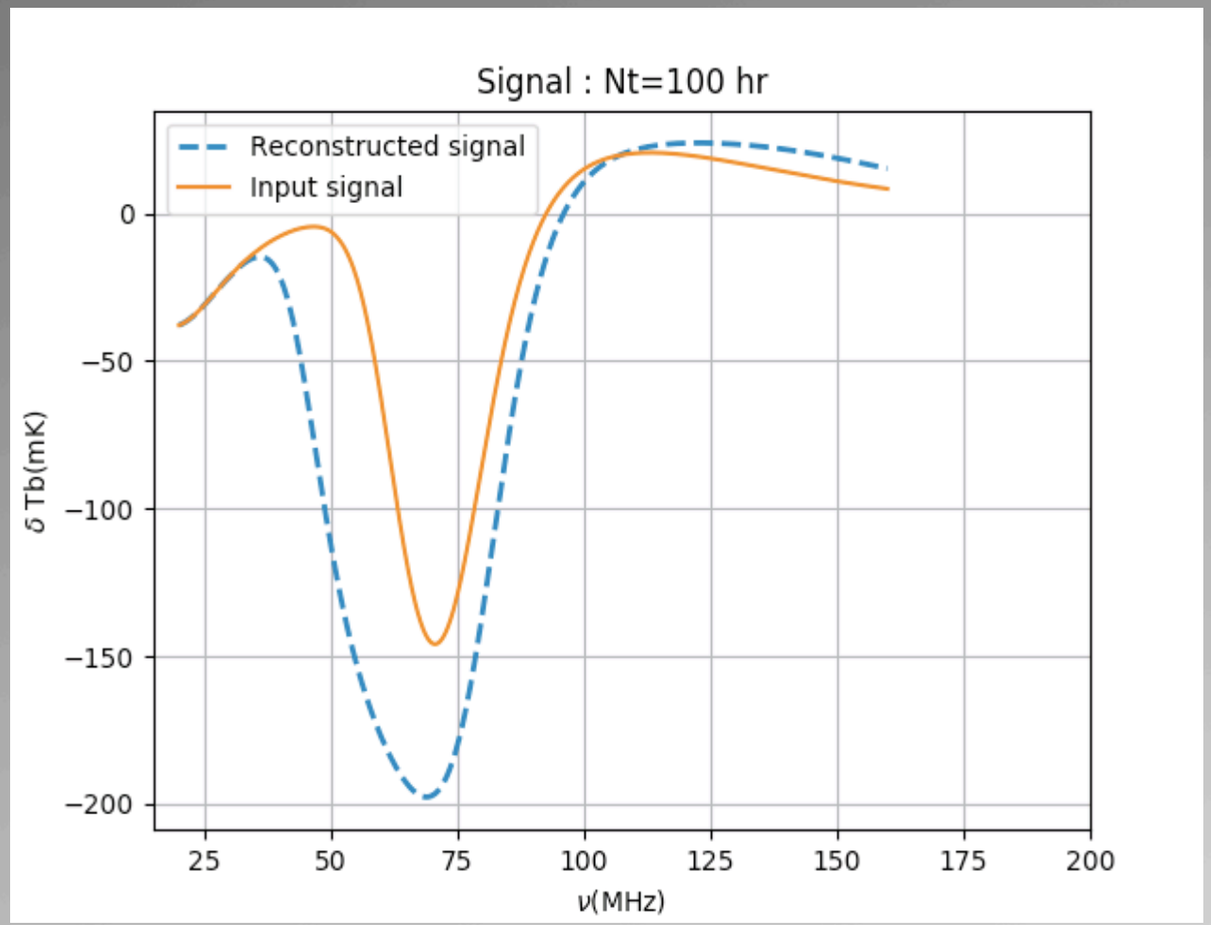


RMSE on Jref = 20 %

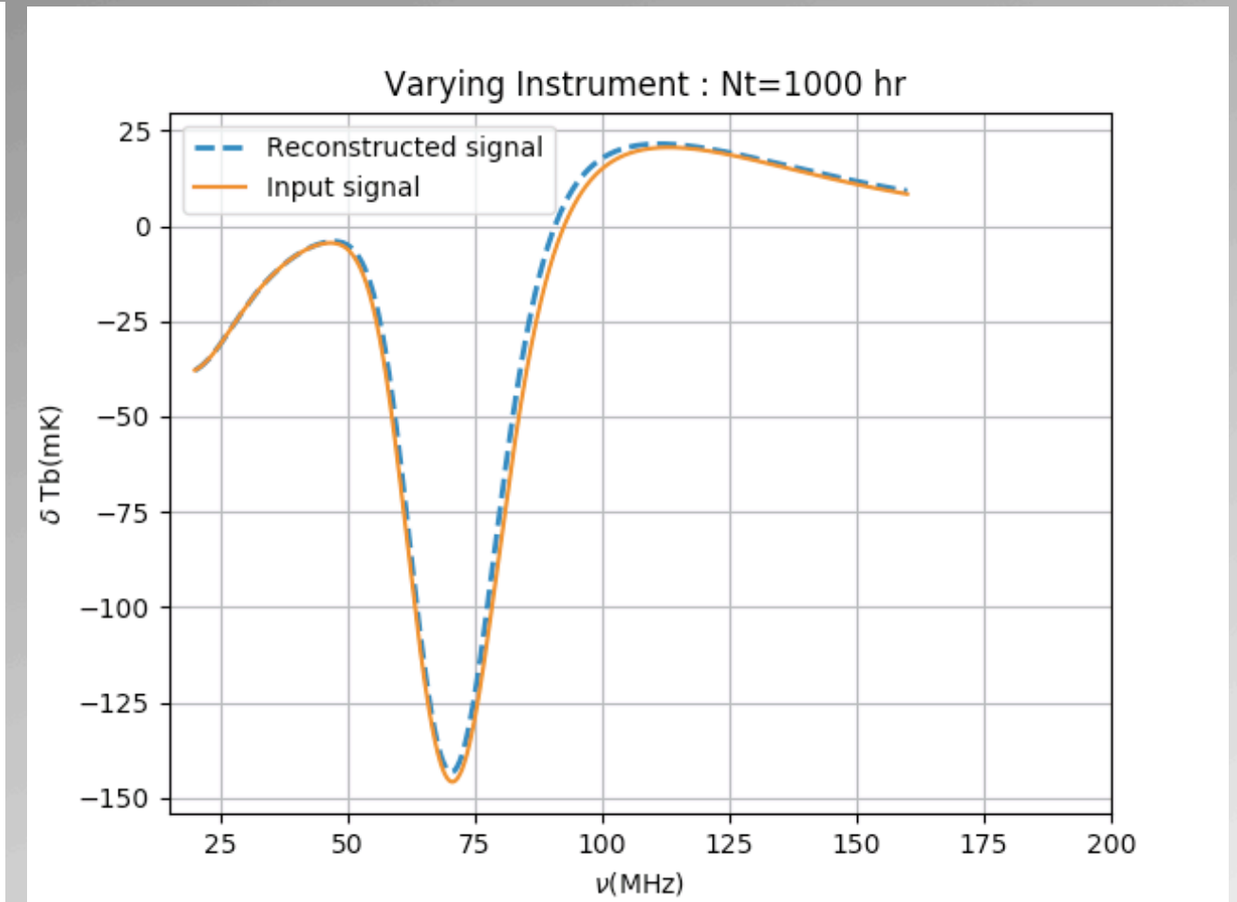
RMSE on Jref = 5 %

Simulations

- Case 3: 21CM Signal + Foreground + Instrumental Noise + Instrumenatal Gain (Bandpass) varying over time



RMSE on Jref = 38 %



RMSE on Jref = 13 %

Way Forward

- ANN seems to be a new flavor ..
- Alternate to MCMC – complimentarity ??
- Further simulations – Global and PS