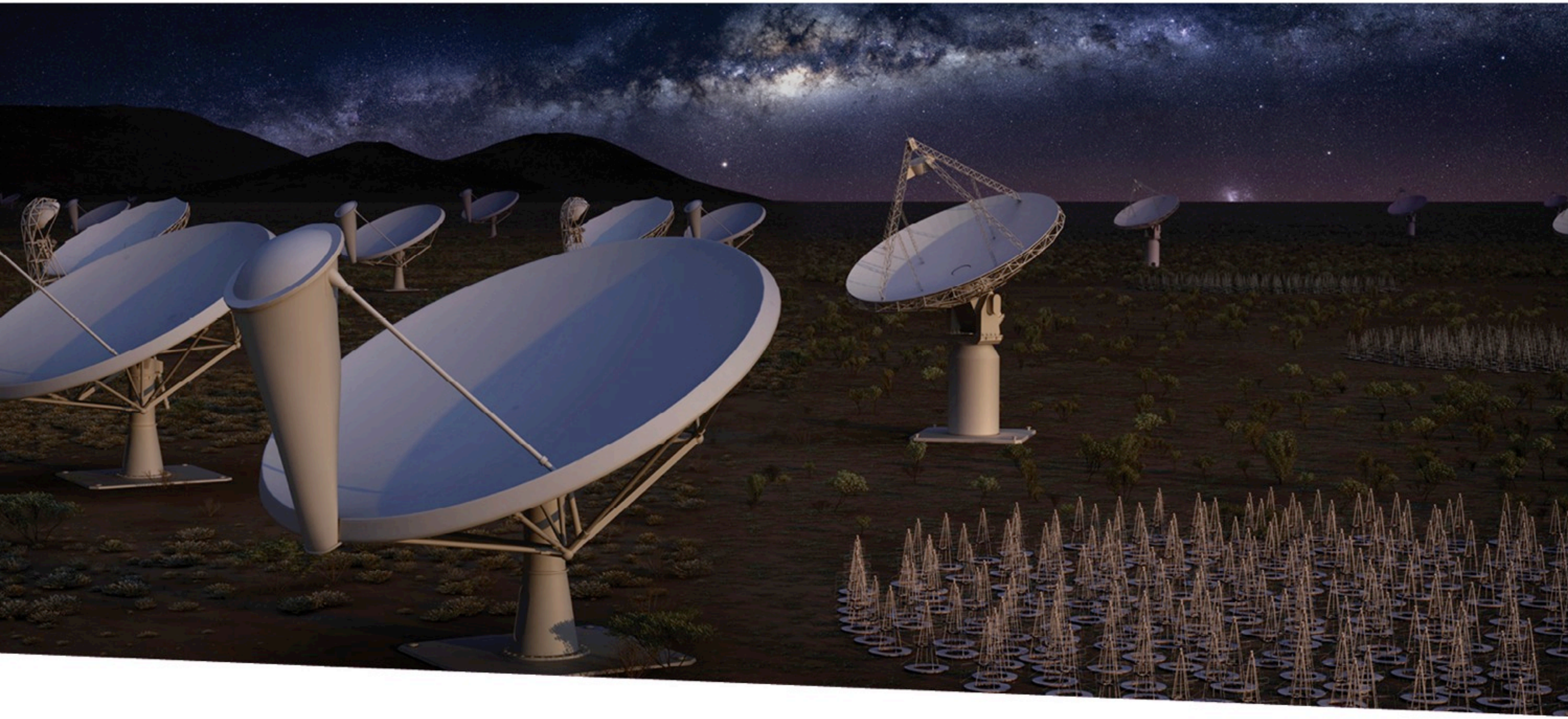
EoR imaging with the SKA: the challenge of foreground removal



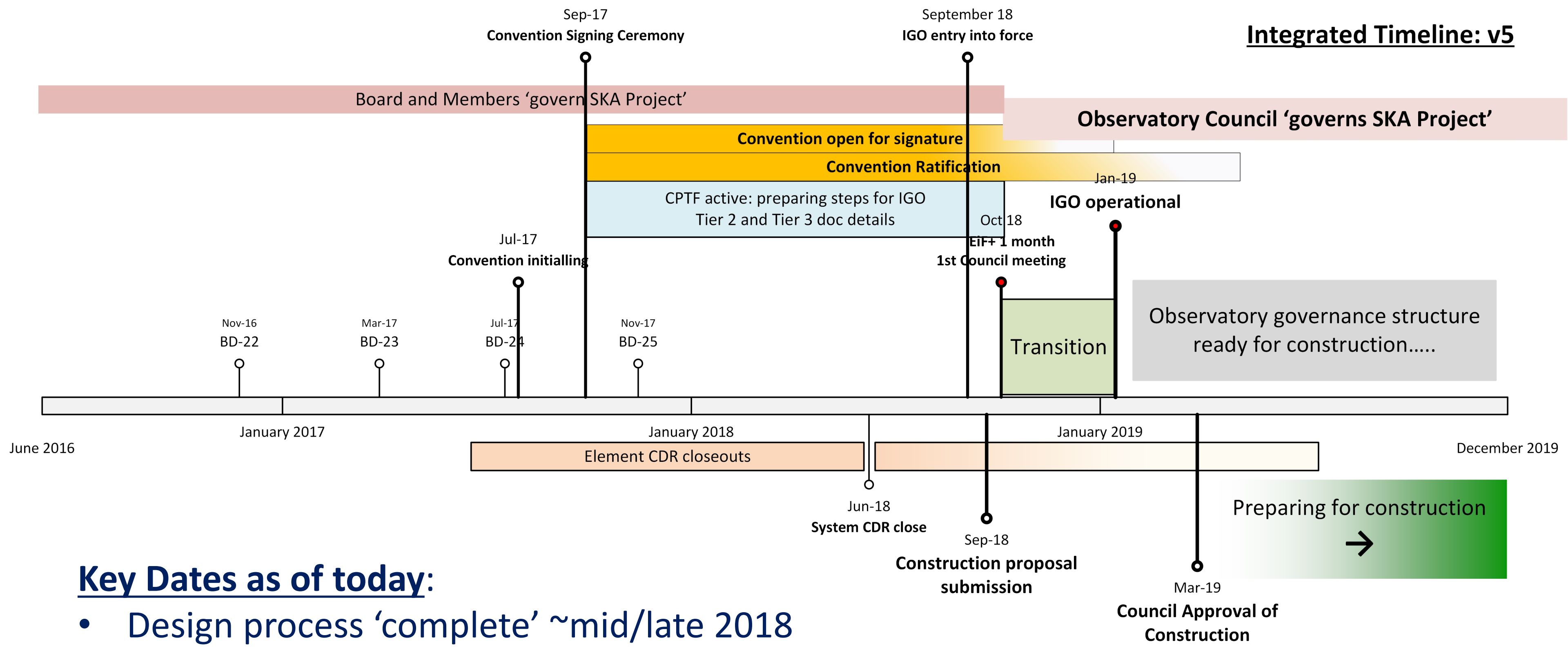
SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

Anna Bonaldi

SKA Project Scientist

The overall project schedule…..

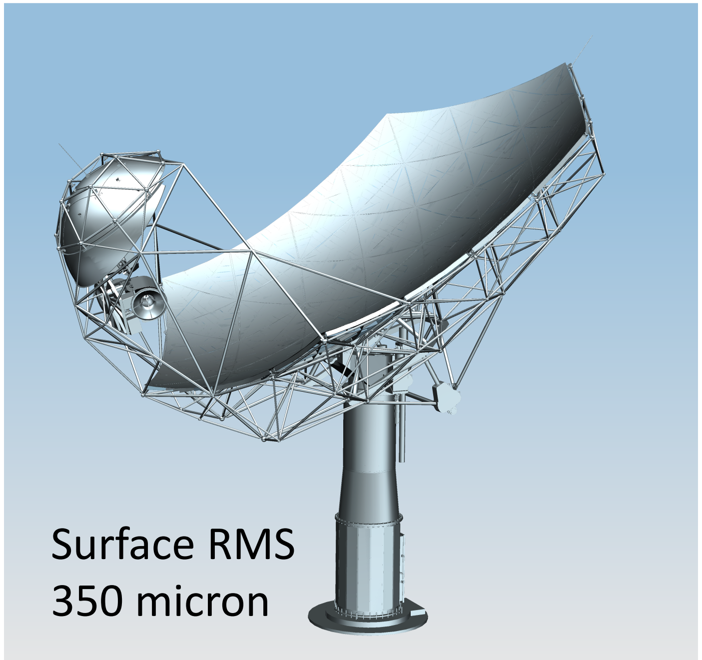


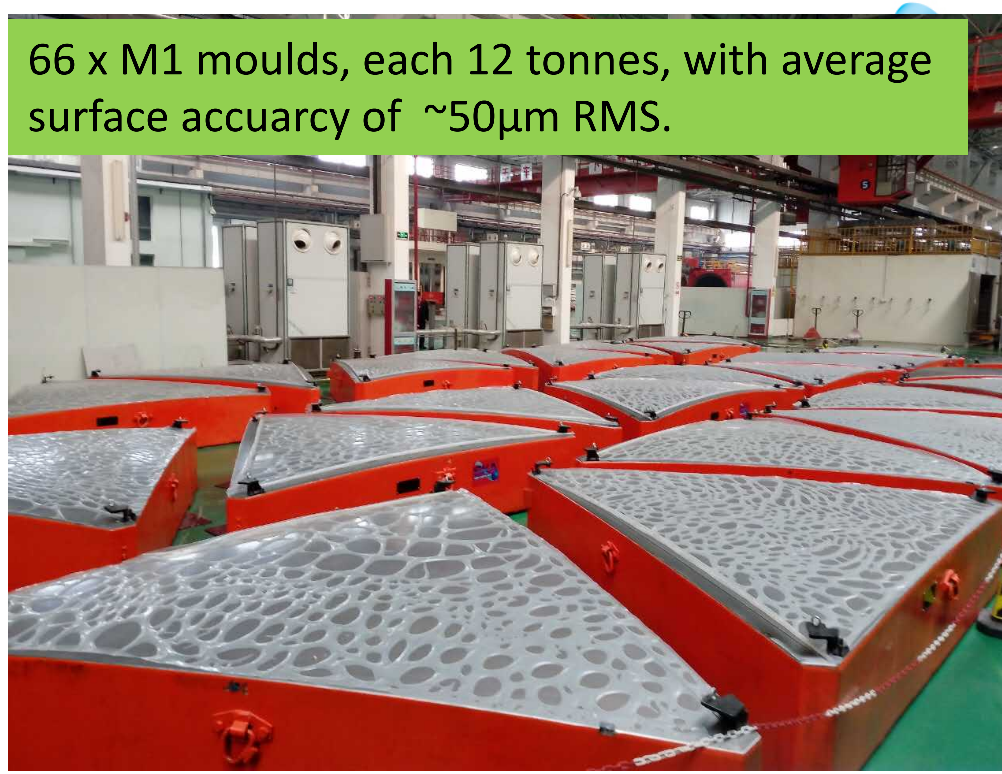
Key Dates as of today:

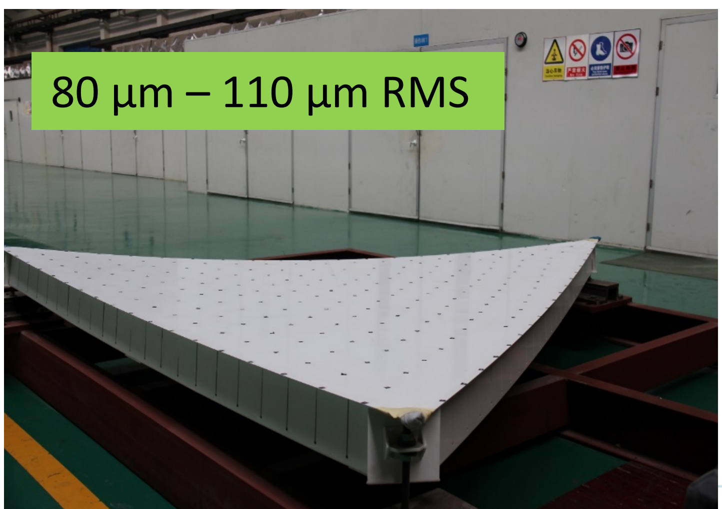
- Design process 'complete' ~mid/late 2018
- IGO in operation: early 2019
- IGO Council approves construction: early/mid 2019
- SKA1 construction procurement begins: ~late 2019

- **Commissioning/science verification from 2021**
- **Full operations from 2025**

Technical Progress



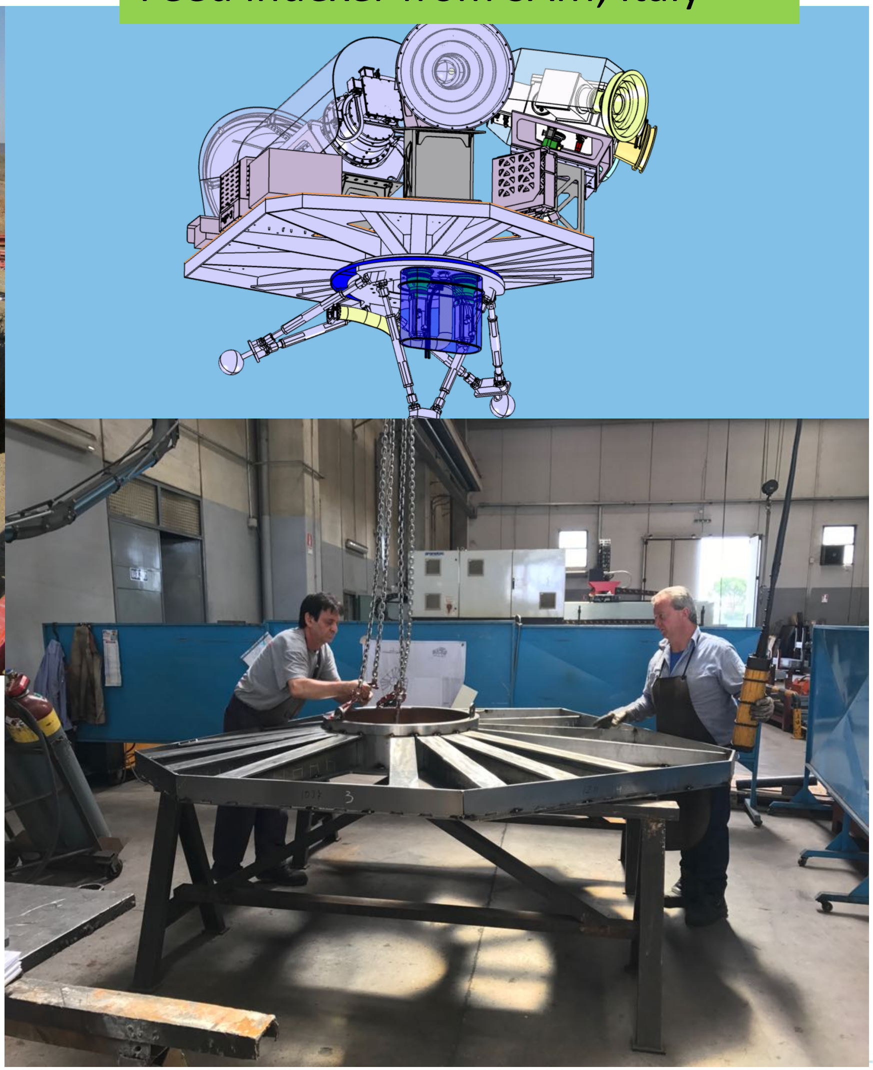




Technical progress

Dish foundation

Feed indexer from SAM, Italy



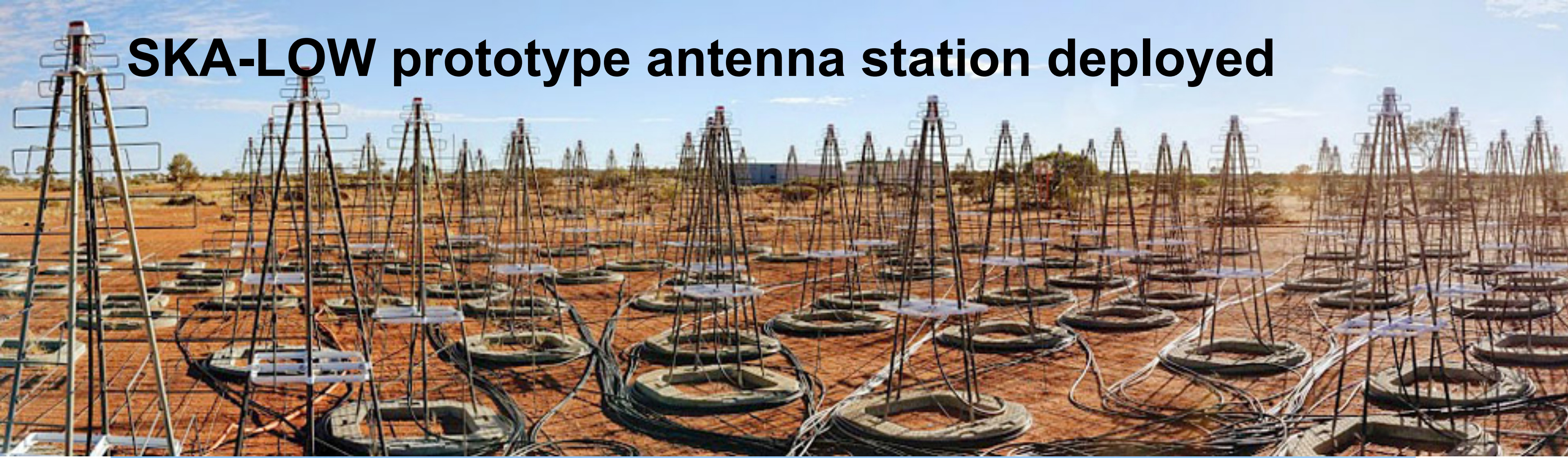
- SKA-P Prototype

  Assembly starts in China 09/2017

- SKA-MPI Prototype

  Assembly starts in South Africa end of 2017

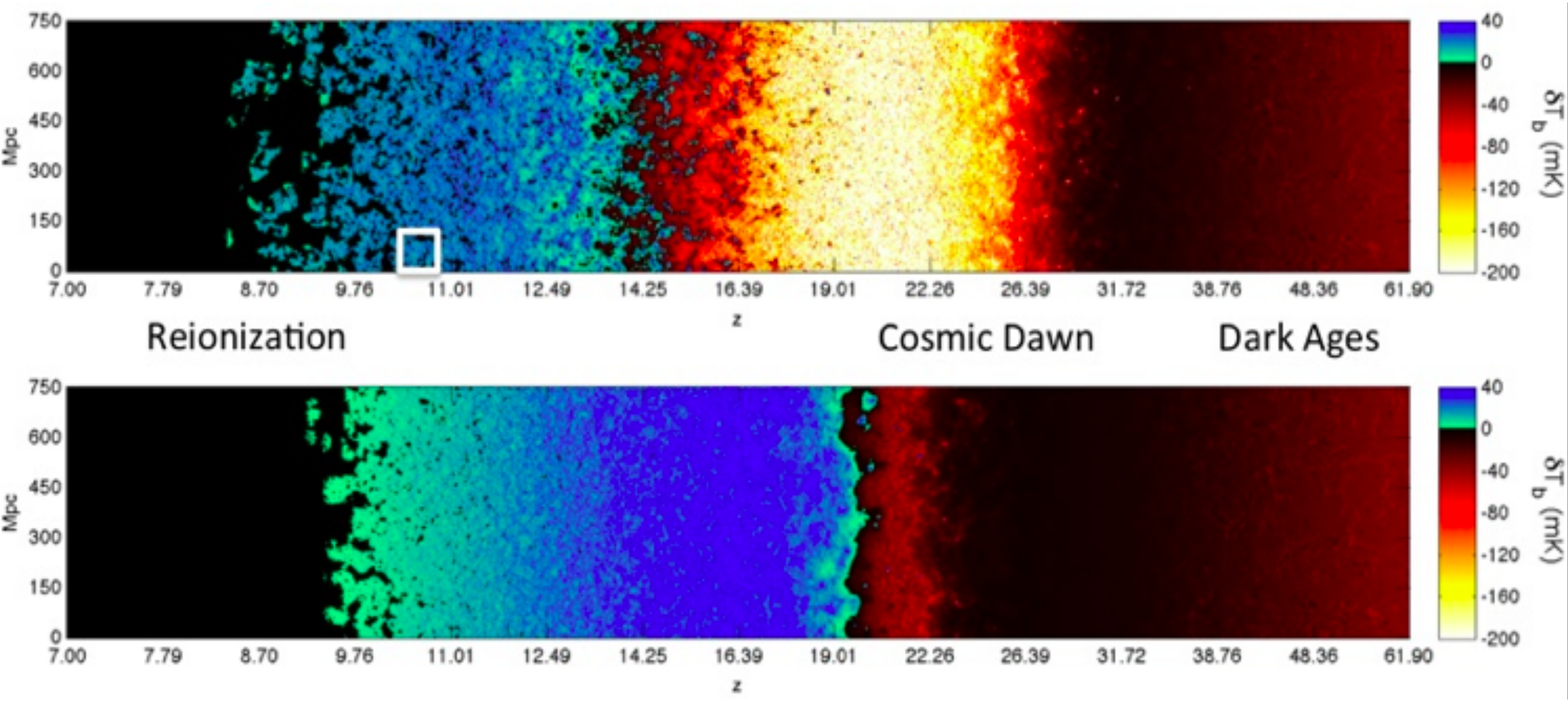
SKA-LOW prototype antenna station deployed



2.6 MWhr lithium ion battery

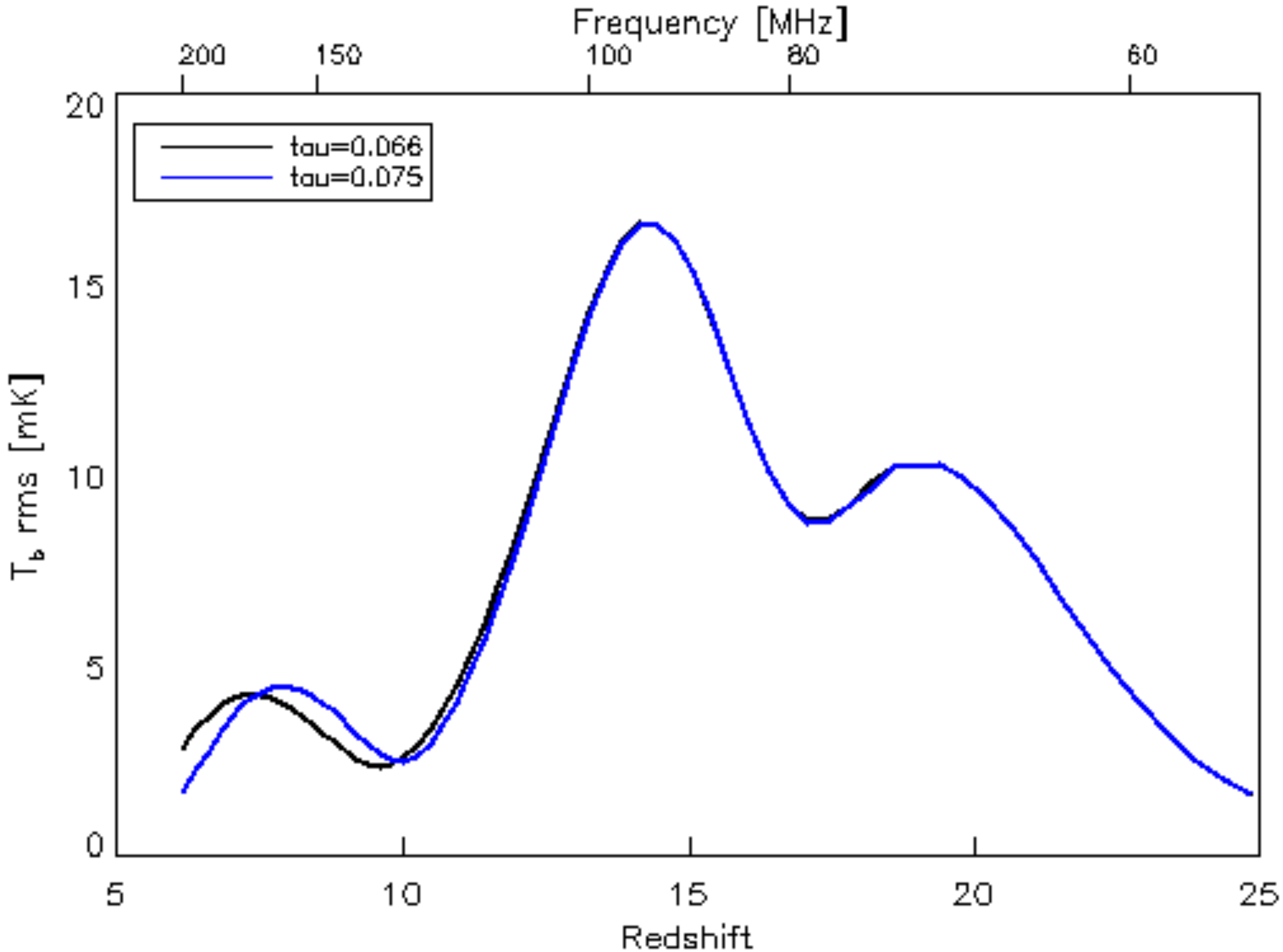

IAU
Peering towards Cosmic Dawn
IAU Symposium 333, 2nd-6th October 2017, Dubrovnik, Croatia

CD/EoR signal



Redshift (frequency) dependence

On k = 0.2/Mpc



Models: Courtesy of J. Pritchard

Data model

$$x = \mathbf{H}s + n$$

data maps → x

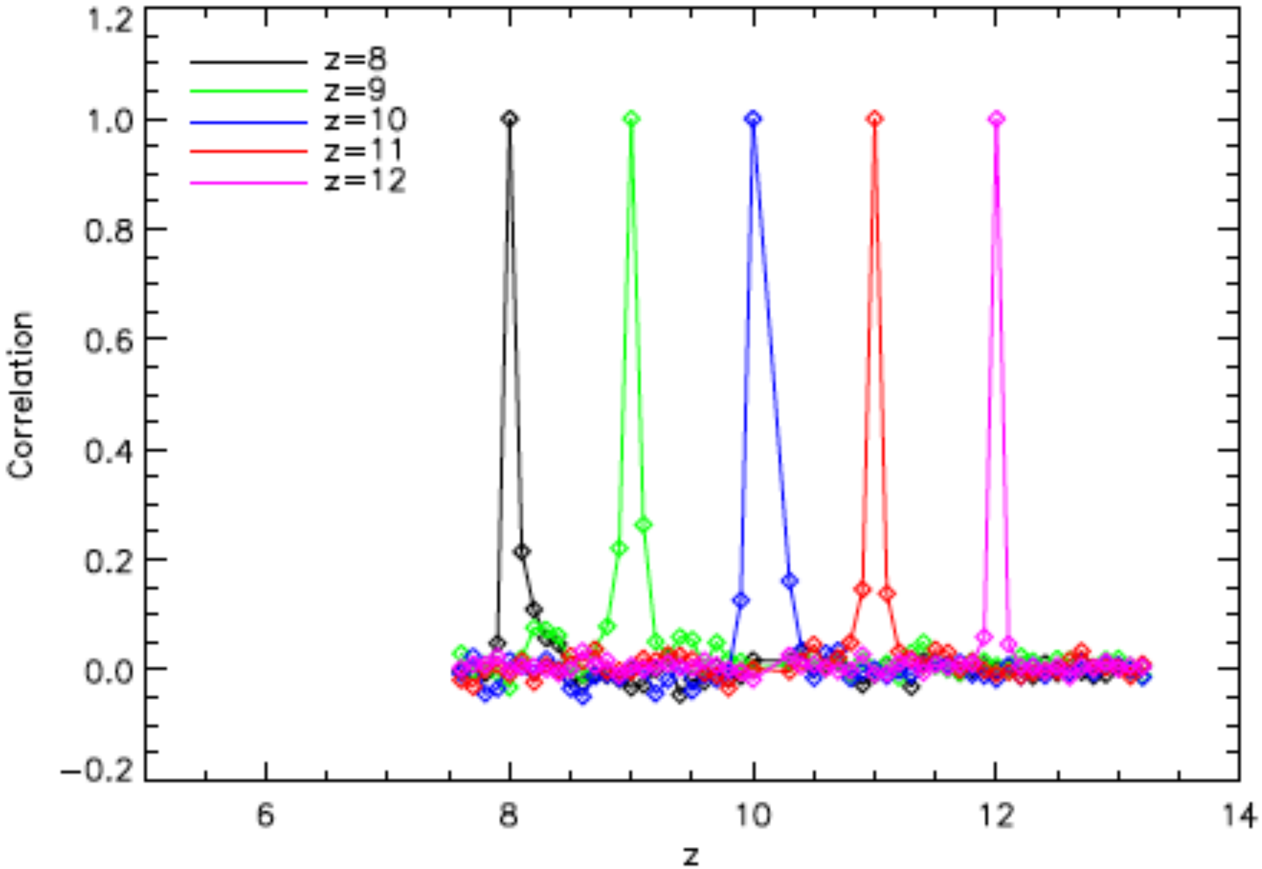
noise + HI signal → n

Mixing Matrix: contains the frequency scalings → $\mathbf{H}$

Foreground components (syn, ff) → s

- Data are a linear mixture of a set of components S
- Components have the same morphology at different frequency and vary in intensity
- Intensity ratios are in the mixing matrix H

HI frequency-frequency correlation



Behaves more like a noise contribution

HI signal extraction:

data maps

Cosmological signal

$$\vec{n}_{\mathrm{HI}} + \vec{n}_{\mathrm{inst}} = \vec{x} - \mathbf{H}\vec{\hat{s}},$$

noise maps

Reconstructed foreground components

Foreground reconstruction

- We assume to rely on a LINEAR component separation operator, i.e. to get an estimate of the foreground components through a suitable linear mixture of channels:

$$\hat{s} = \mathbf{W}x$$

- Reconstruction matrix W should minimize contamination between components and noise:

$$\mathbf{W} = (\hat{\mathbf{H}}^{\mathrm{T}}\mathbf{N}^{-1}\hat{\mathbf{H}})^{-1}\hat{\mathbf{H}}^{\mathrm{T}}\mathbf{N}^{-1}$$

- $\hat{\mathbf{H}}$ is an estimate of the mixing matrix which can be performed by several different methods
- Estimated componets are then subtracted to the data

Steps to foreground cleaning:

1. Estimate the frequency spectra of foreground components (mixing matrix)
2. Use this information to reconstruct amplitudes of foreground components from the data
3. Subtract foreground components at each channels

How can we predict foreground removal performance?

1) Full simulation of data and apply component separation pipelines
   - ❑ Accurate modelling of all effects
   - ❑ Time consuming, feasible for a single or a few scenarios
2) Quick forecast
   - ❑ More approximate
   - ❑ Fast to run, can explore a range of scenarios

Bonaldi et al. 2011, 2014 applied to the CMB

Component separation forecast

$$x = \mathbf{H}s + n$$

- Component residuals at each frequency are:

$$(\mathbf{WH} - \mathbf{I})s$$

Identity matrix

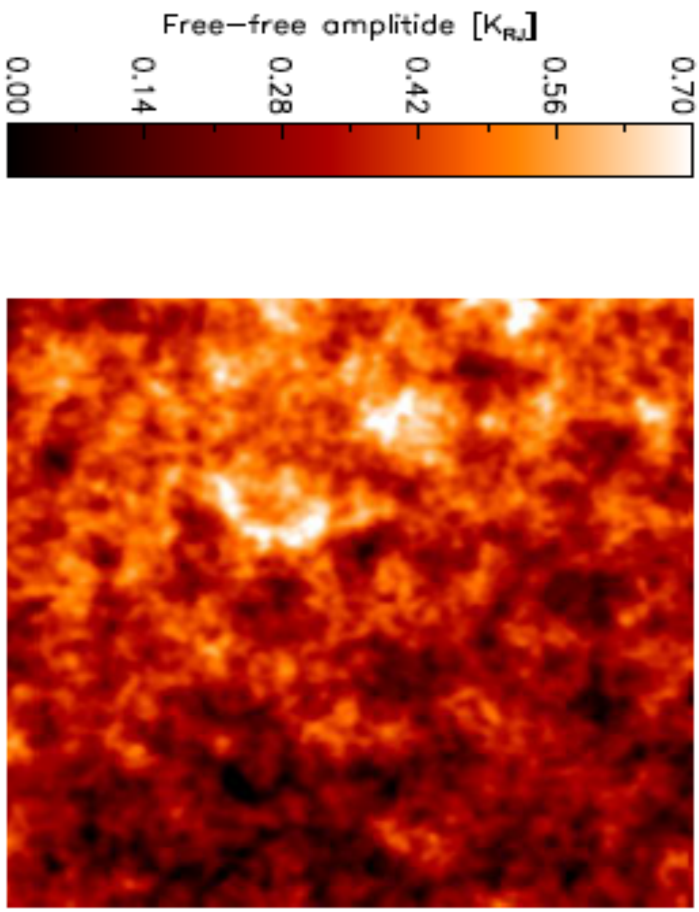
Depends on the estimated mix matrix $\hat{\mathbf{H}}$

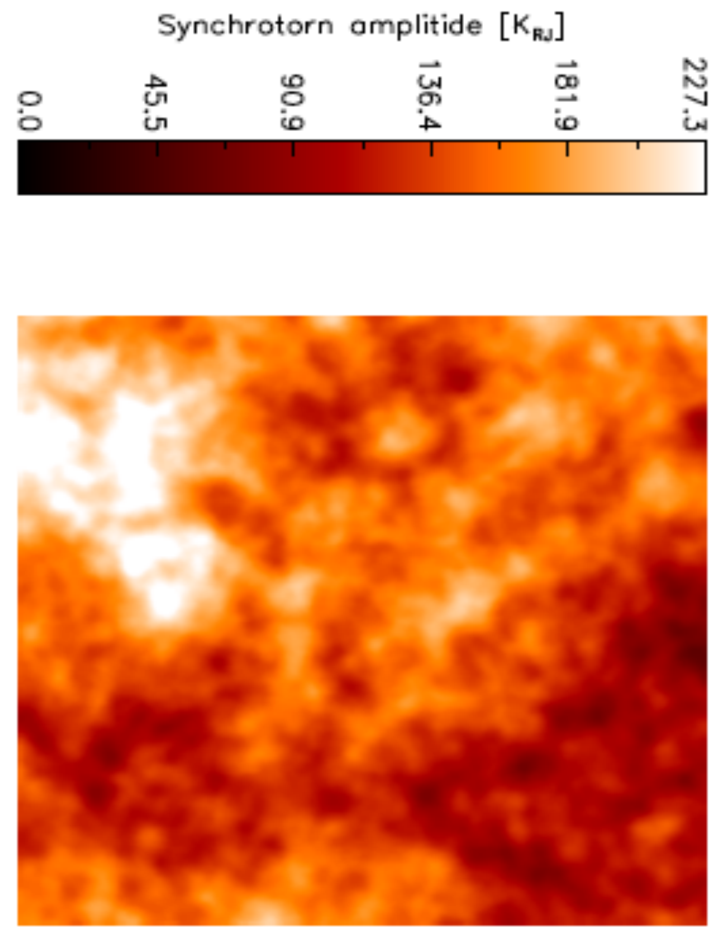
True mixing matrix

Set of simulated components

- Residuals increase with the mismatch between $\mathbf{H}$ and $\hat{\mathbf{H}}$
- Residuals on foreg components added at each frequency to get residuals on 21 cm signal

Foregrounds

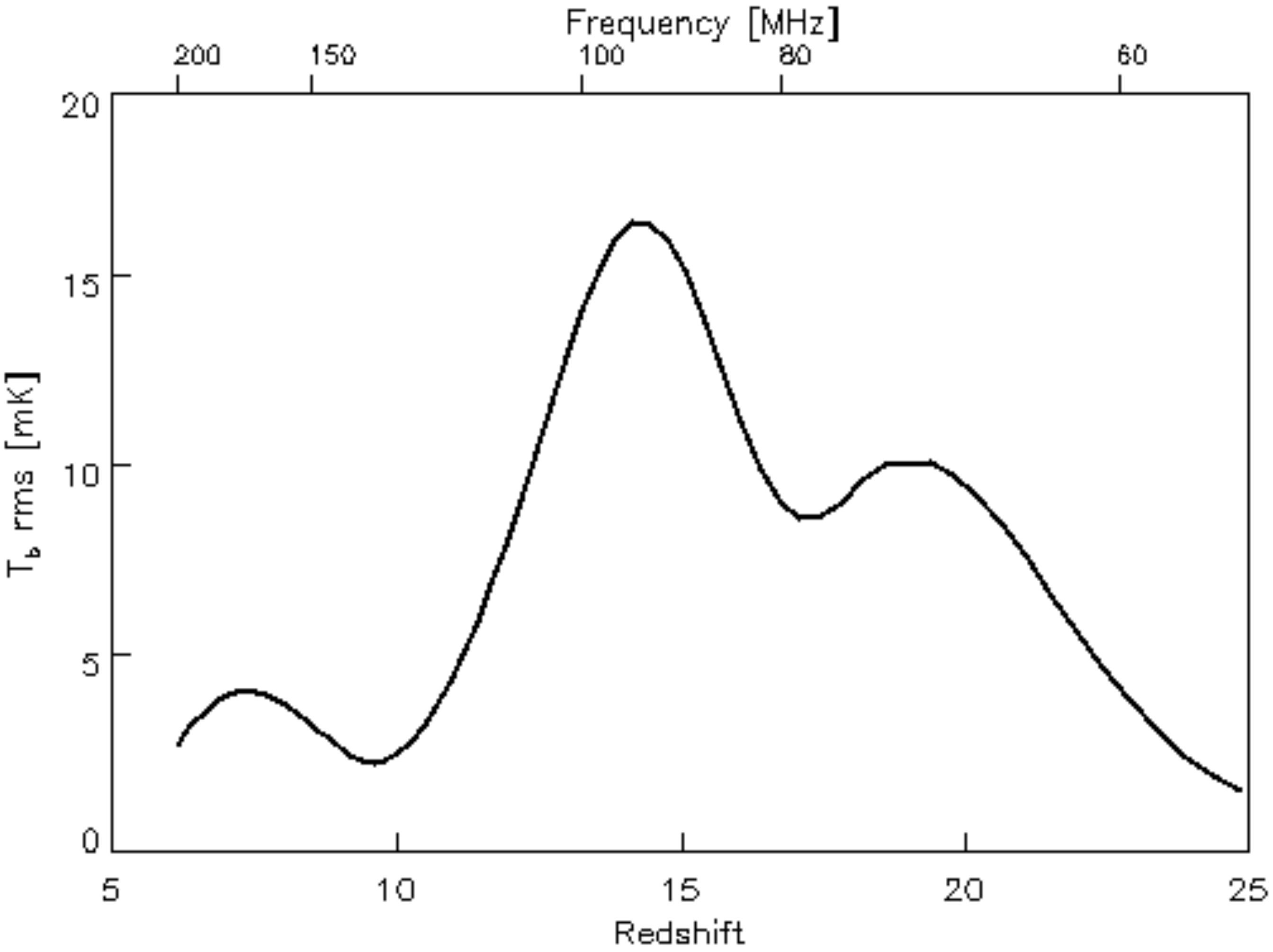




Forecast parameters

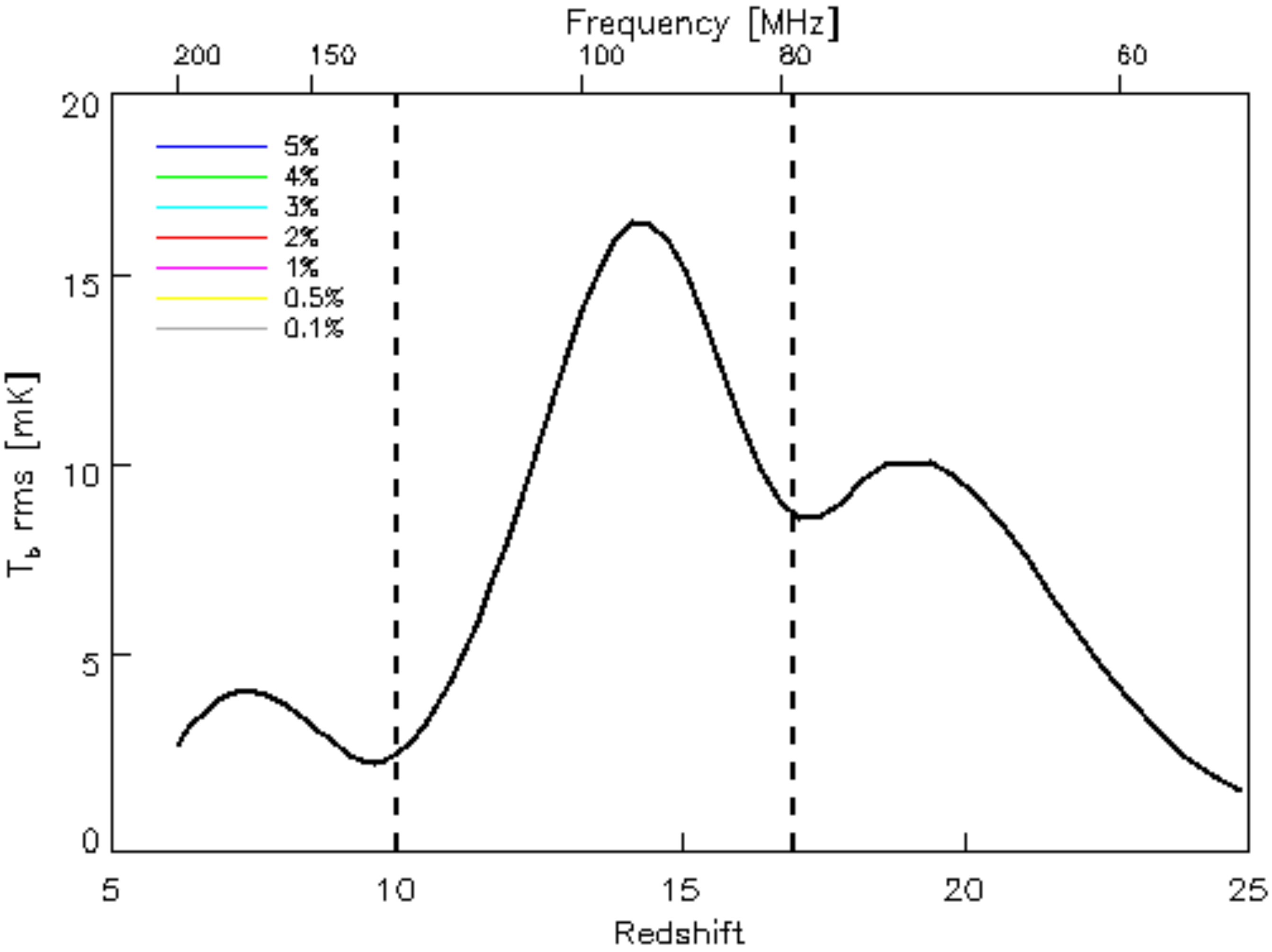
- Synchrotron scaled in frequency with a power law
- Assume an error in the synchrotron spectral index
- No error on free-free spectral law
- Propagate this error on foreground residual per frequency
- 21 cm Residual RMS to be compared with CD/EoR models
- A simple description of SKA noise levels and beam

Forecast results

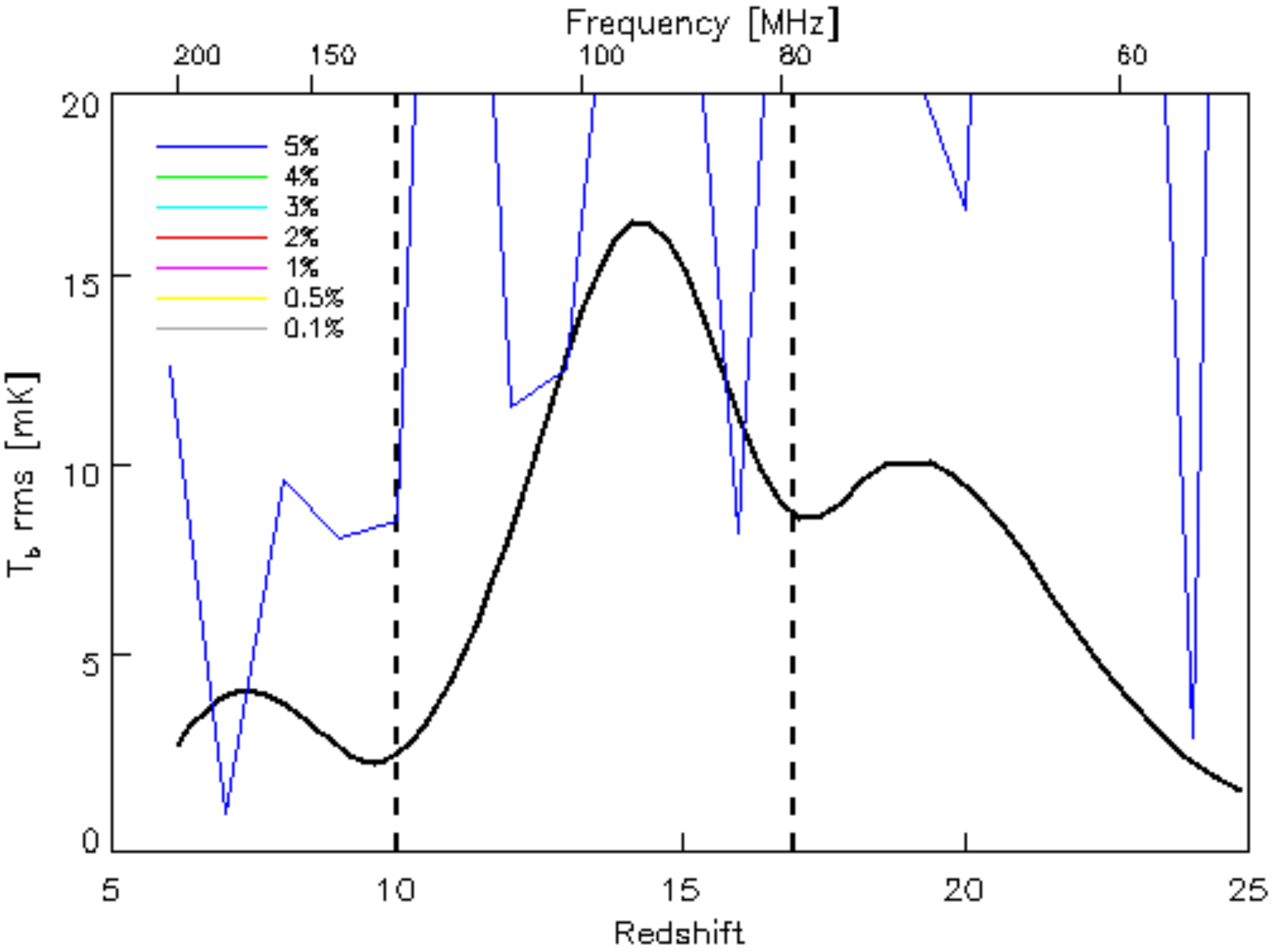


Models: Courtesy of J. Pritchard

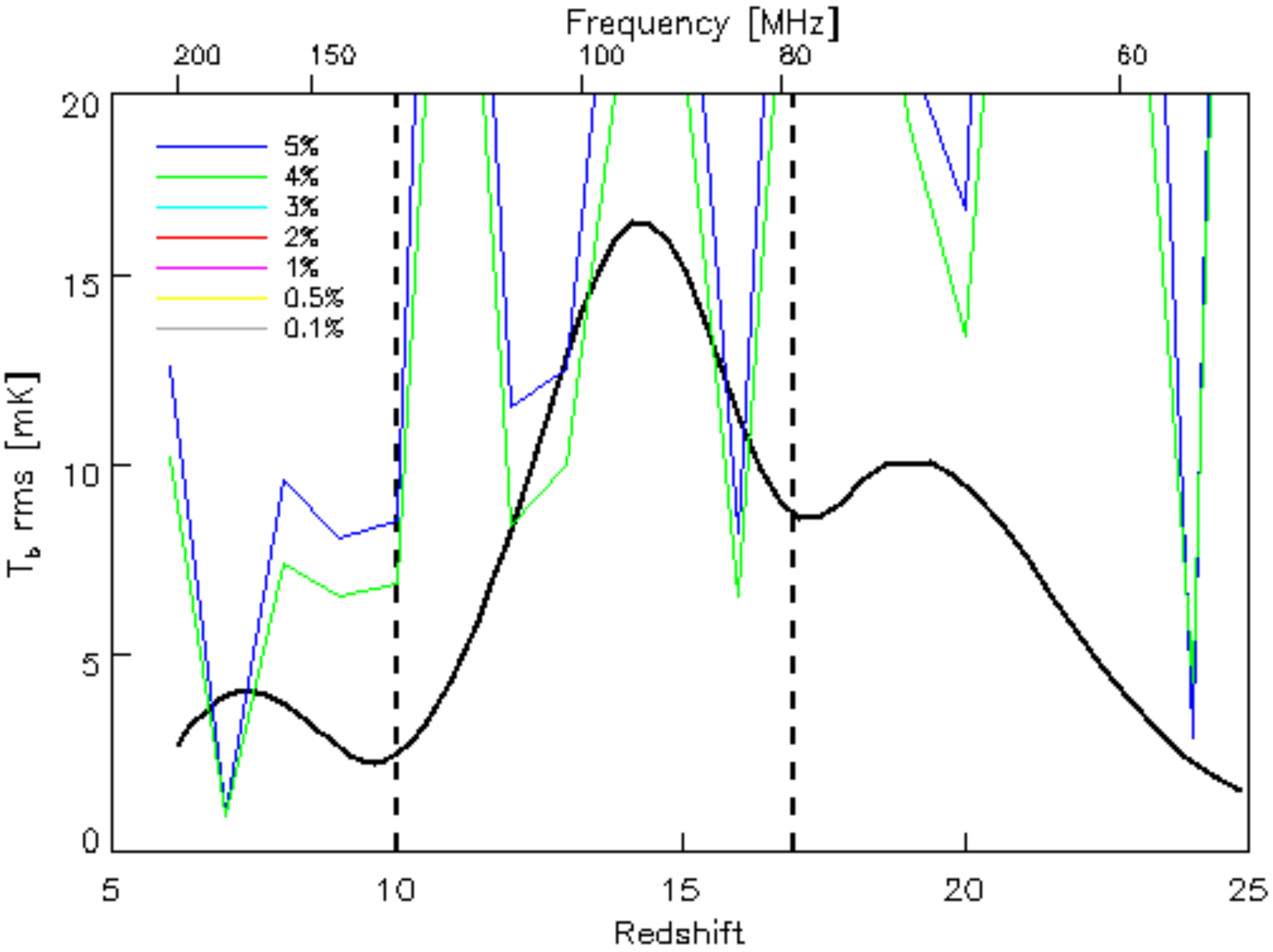
Forecast results



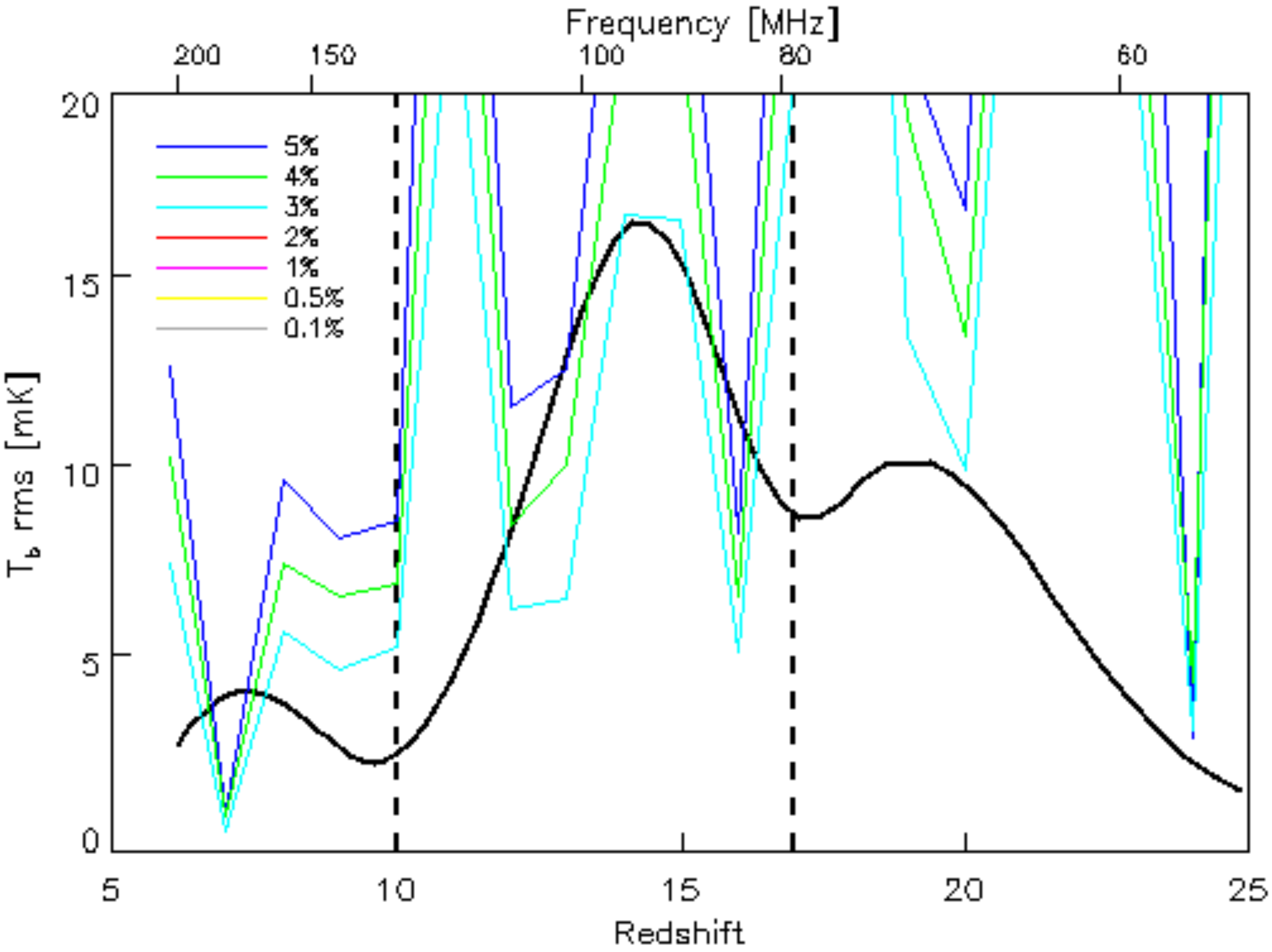
Forecast results



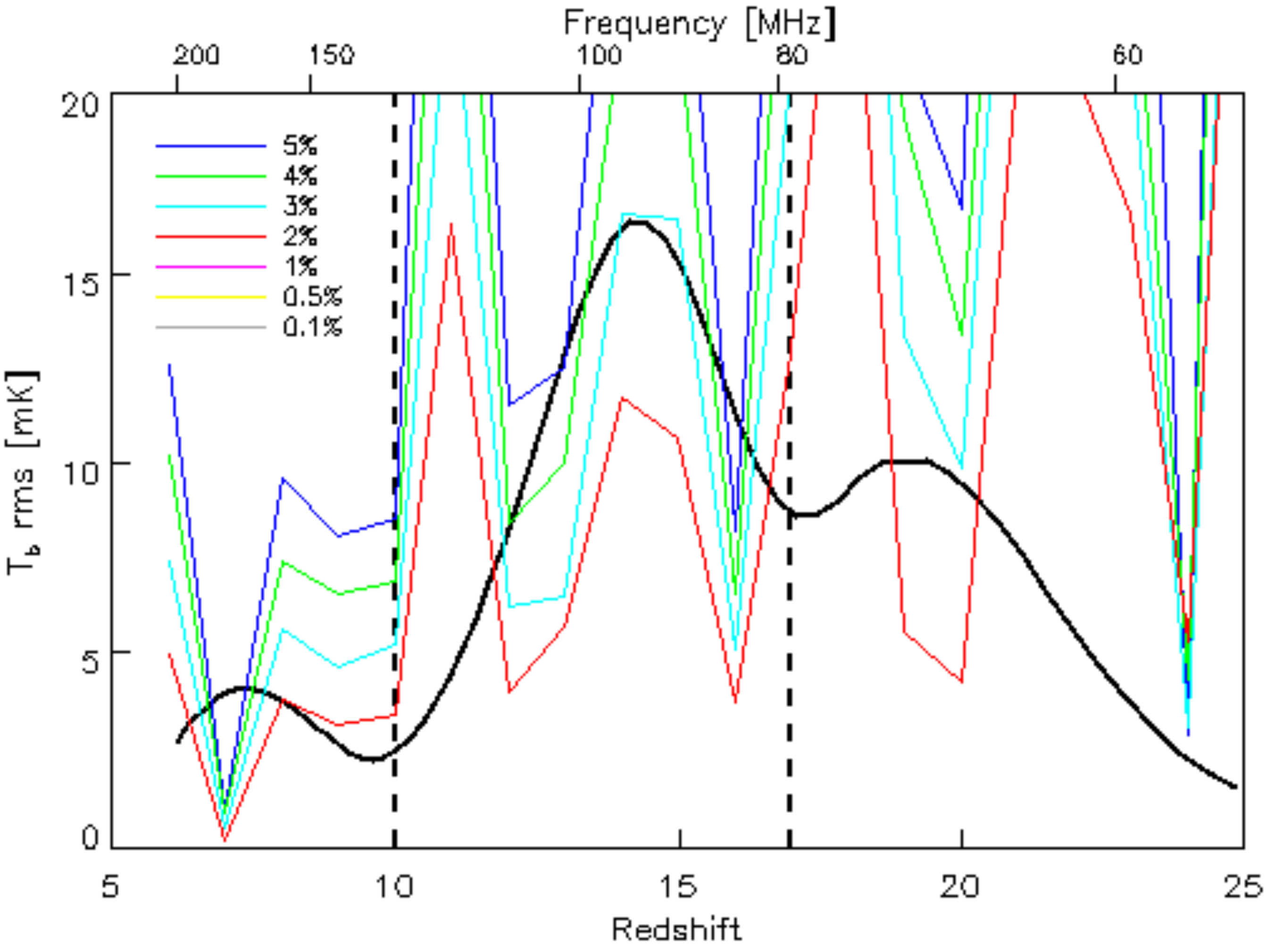
Forecast results



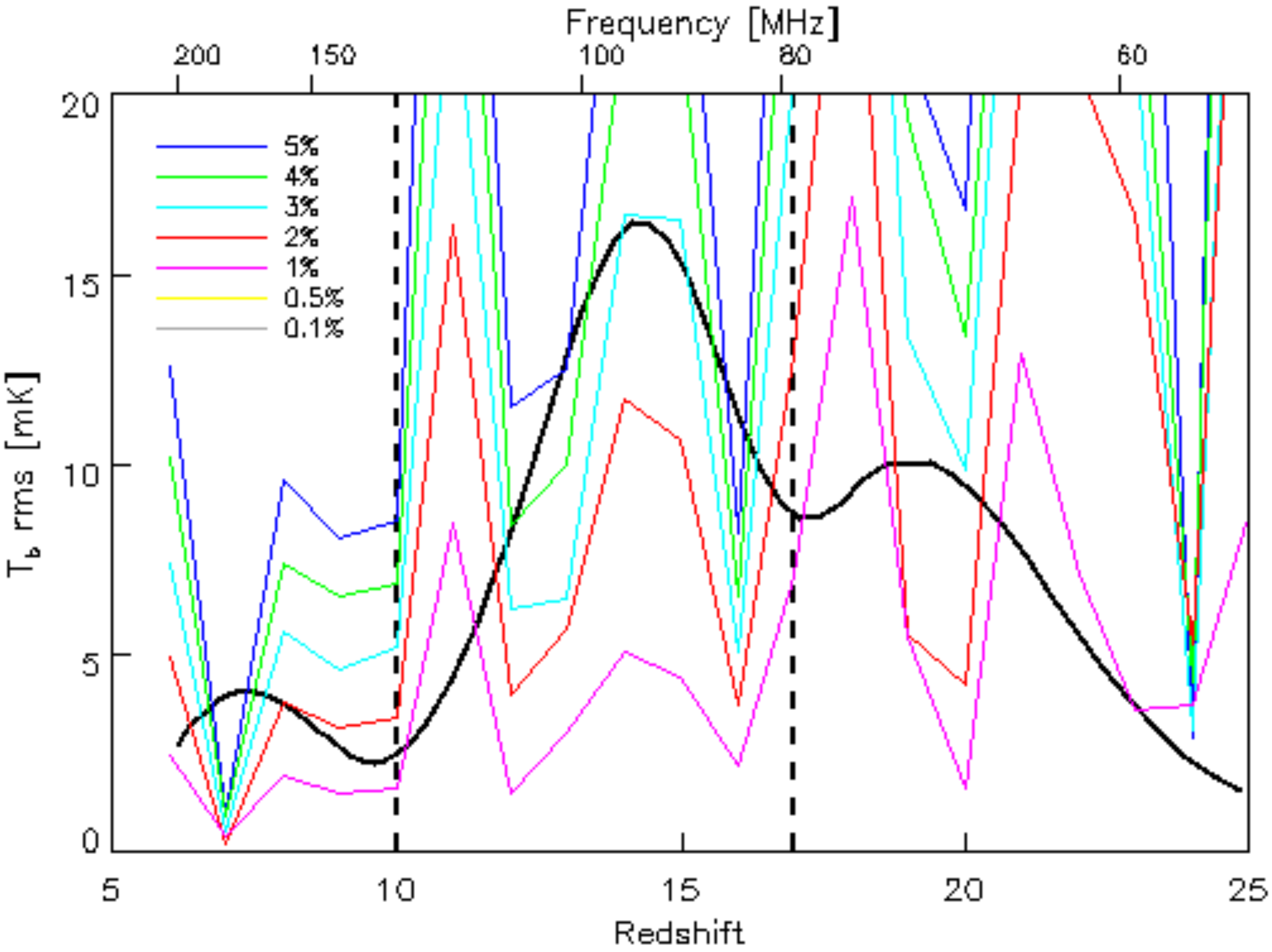
Forecast results



Forecast results



Forecast results



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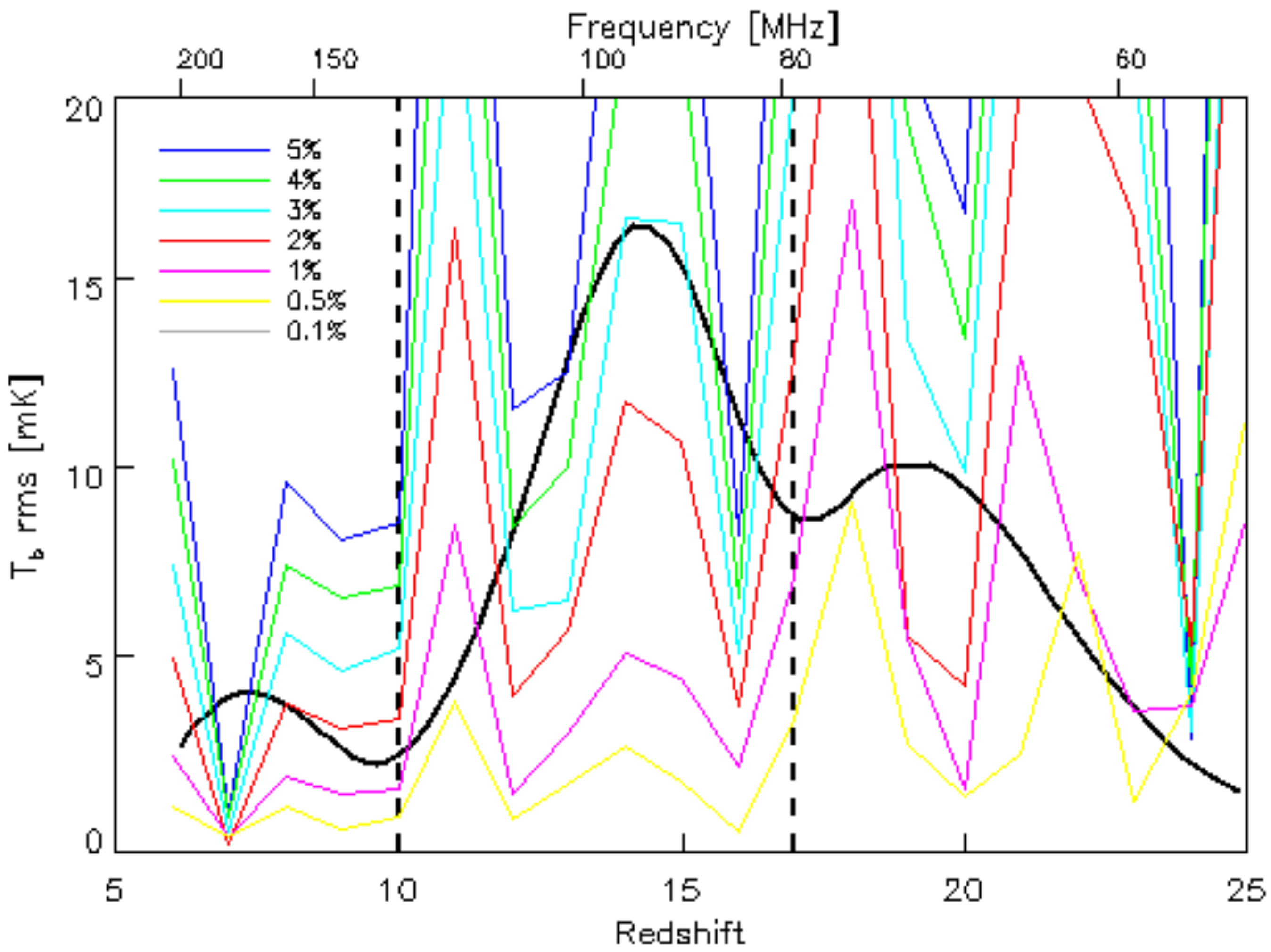

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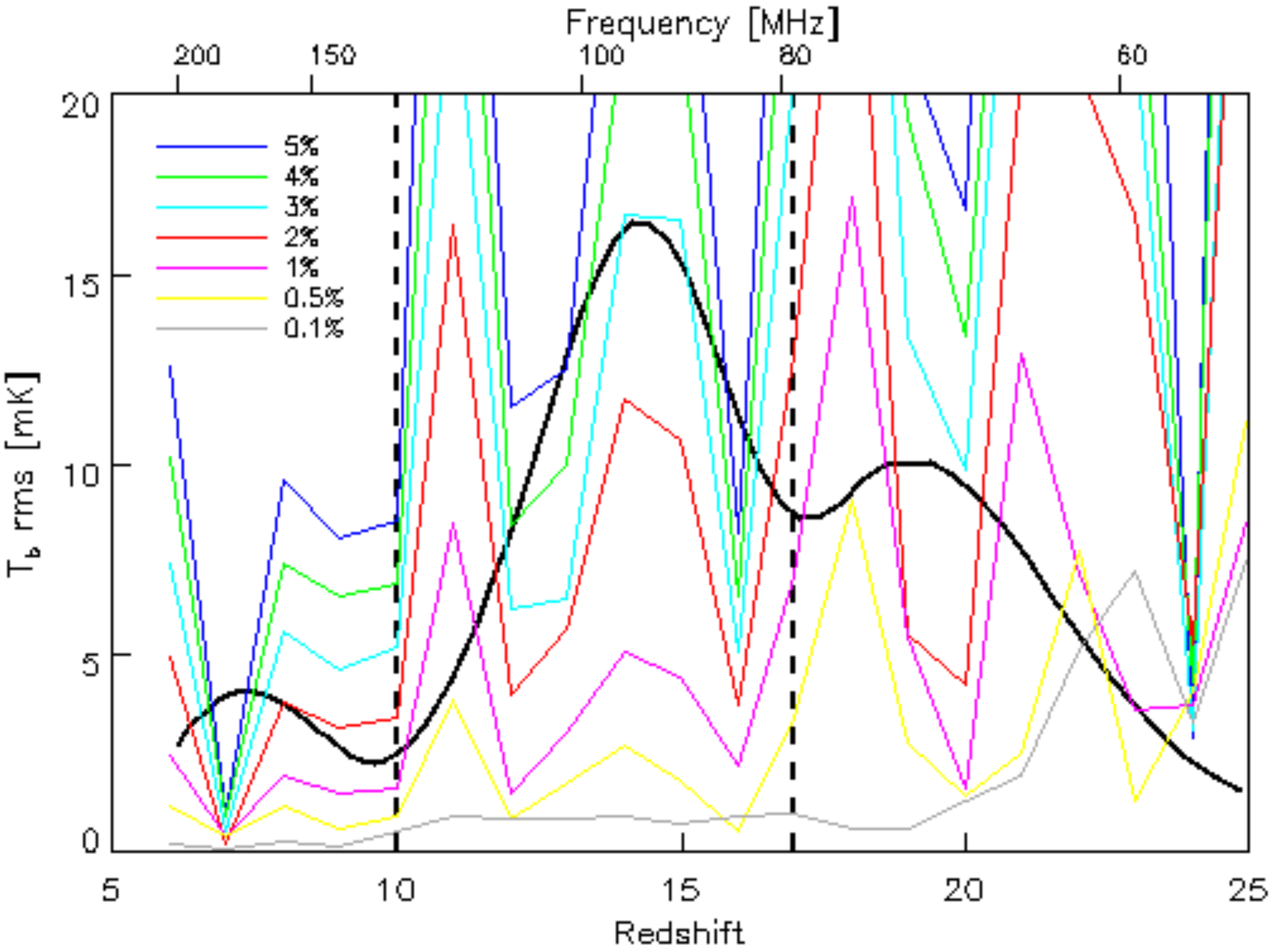

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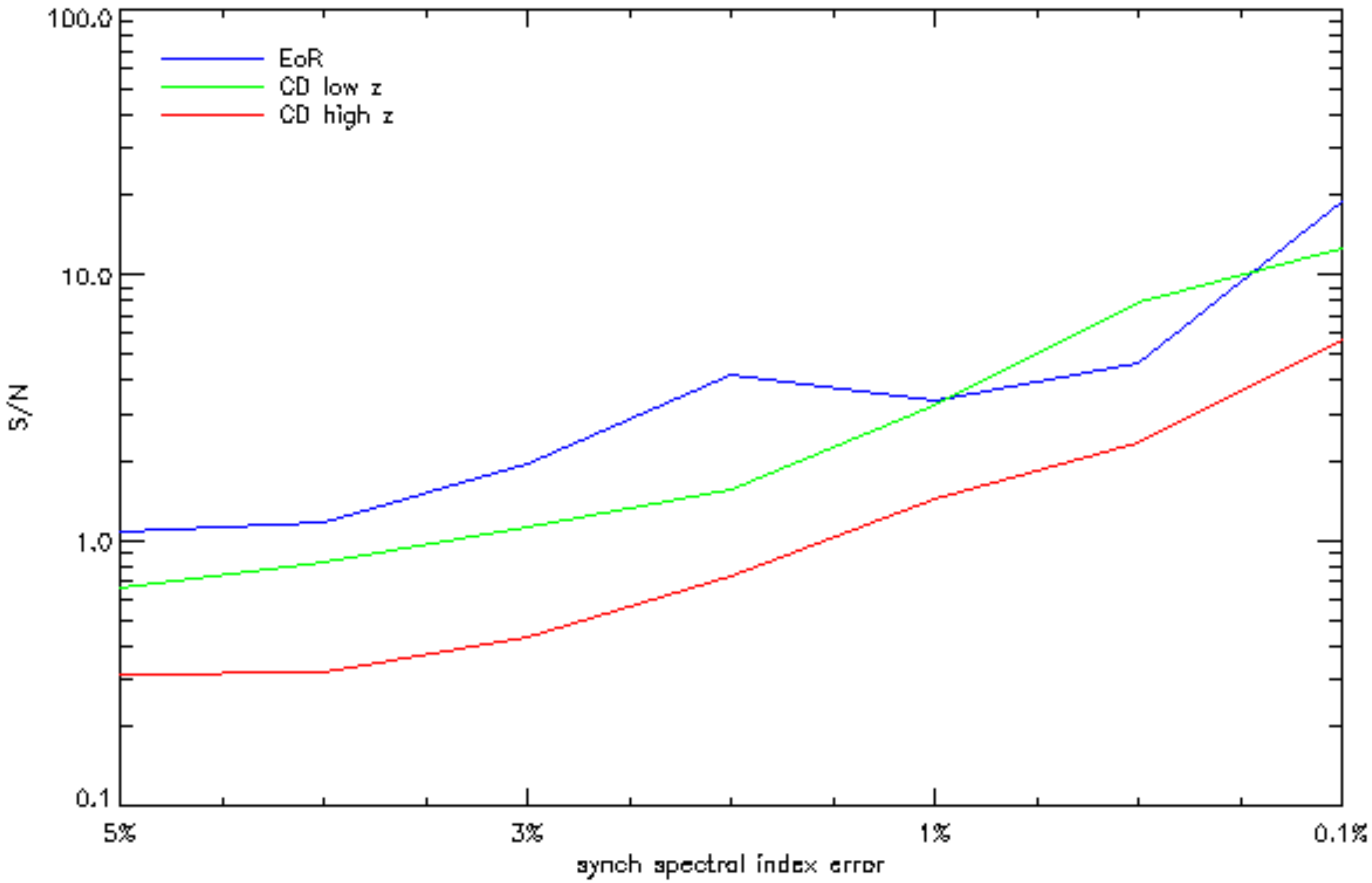

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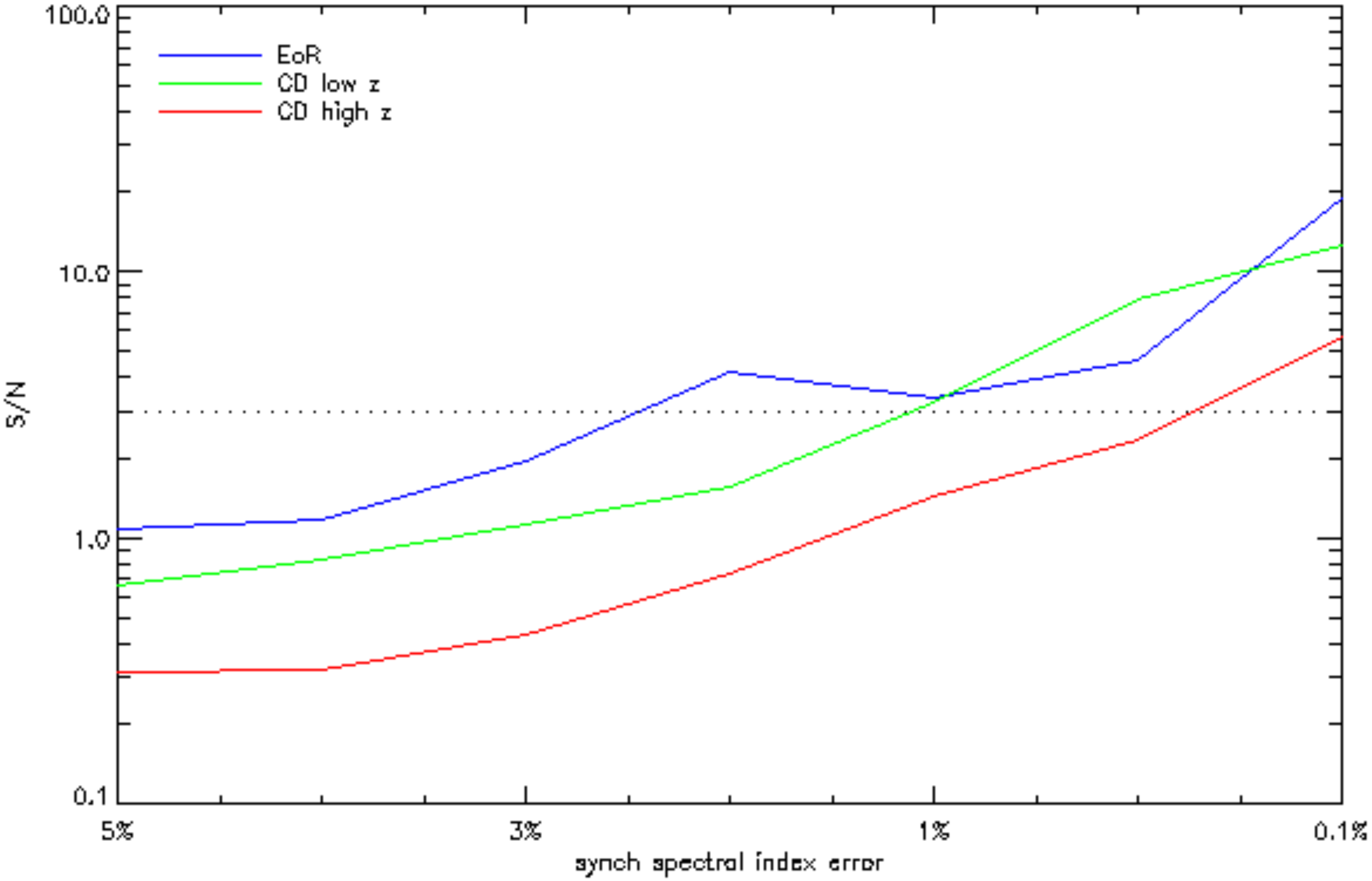

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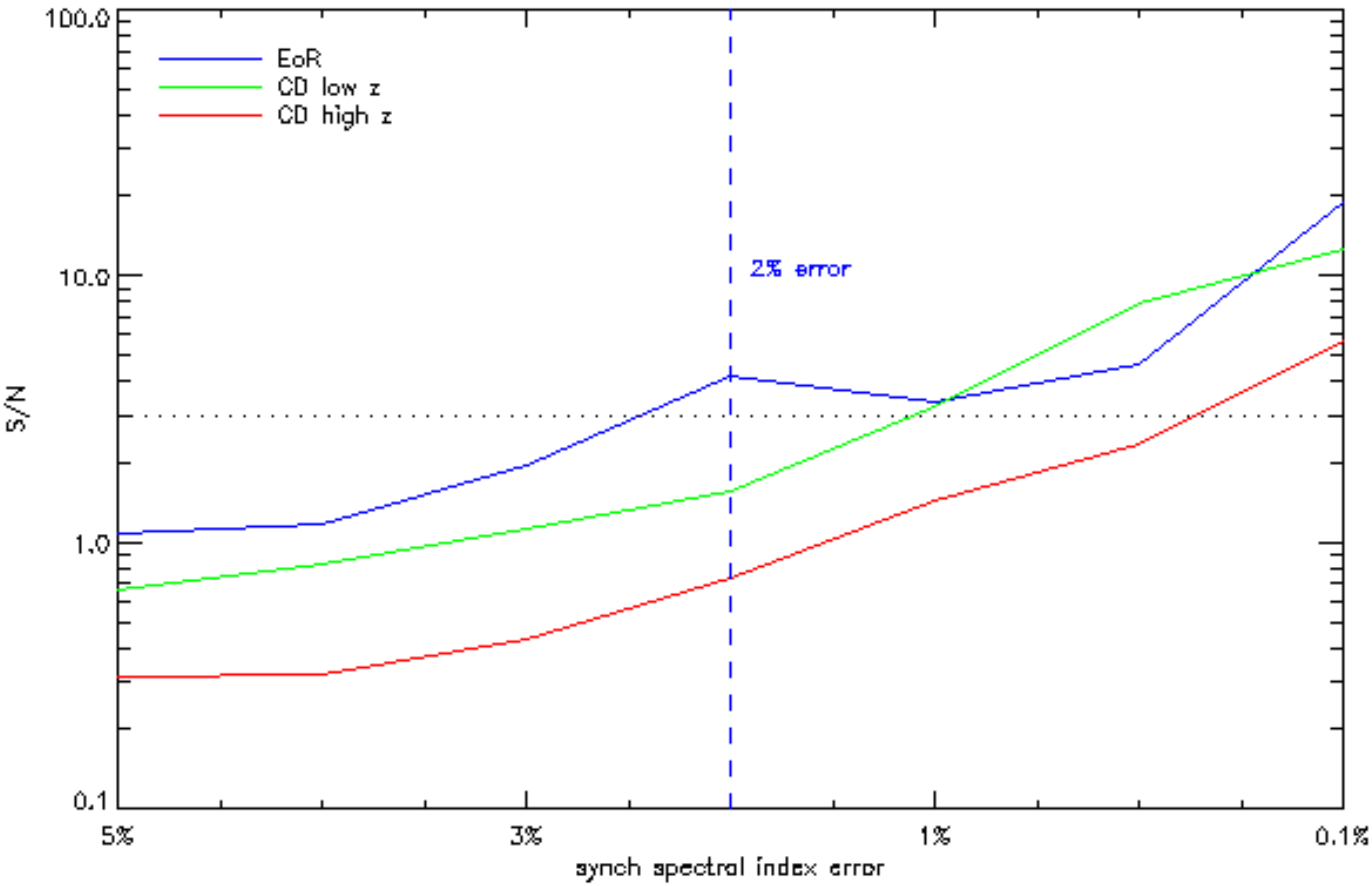

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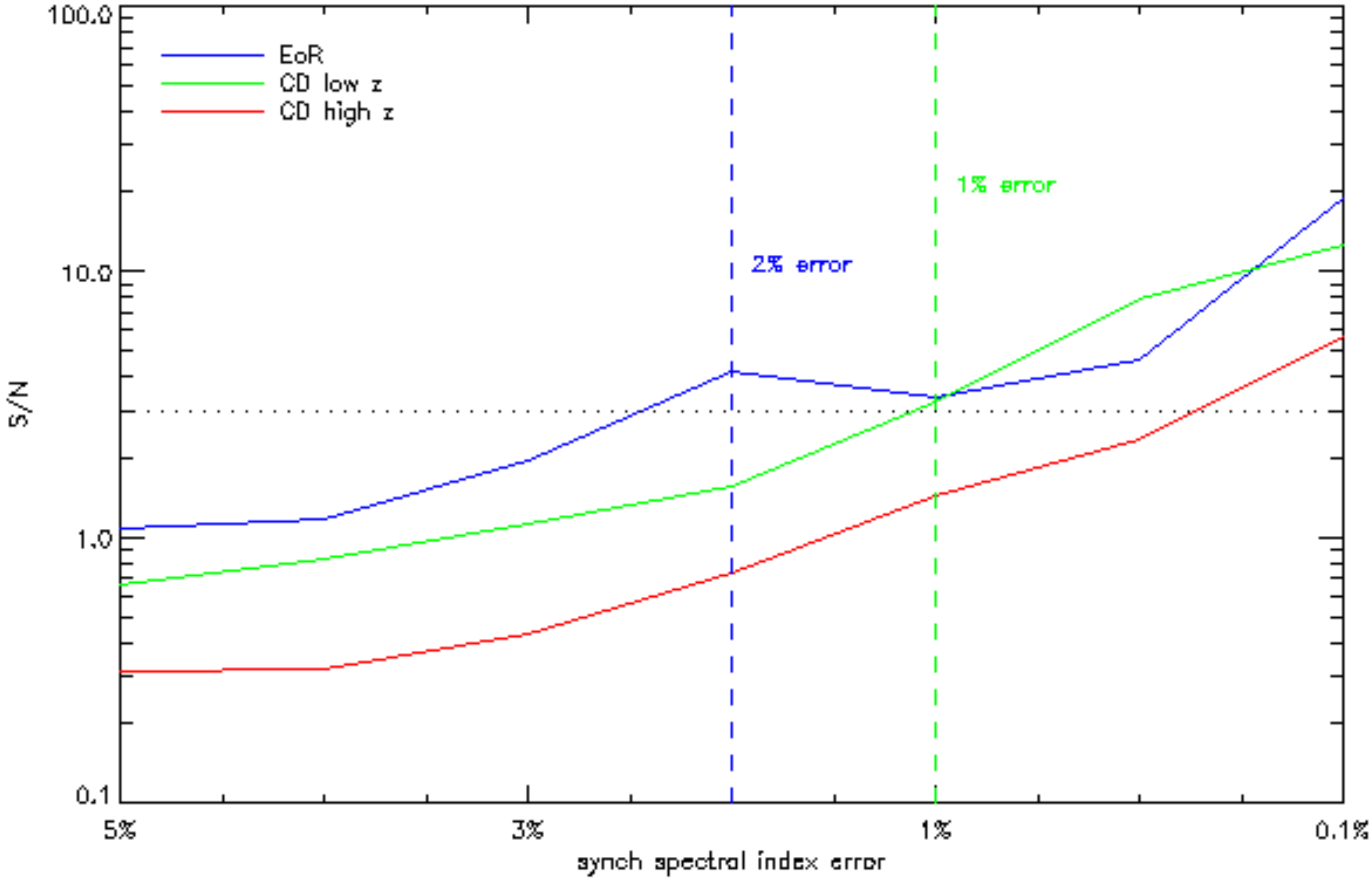

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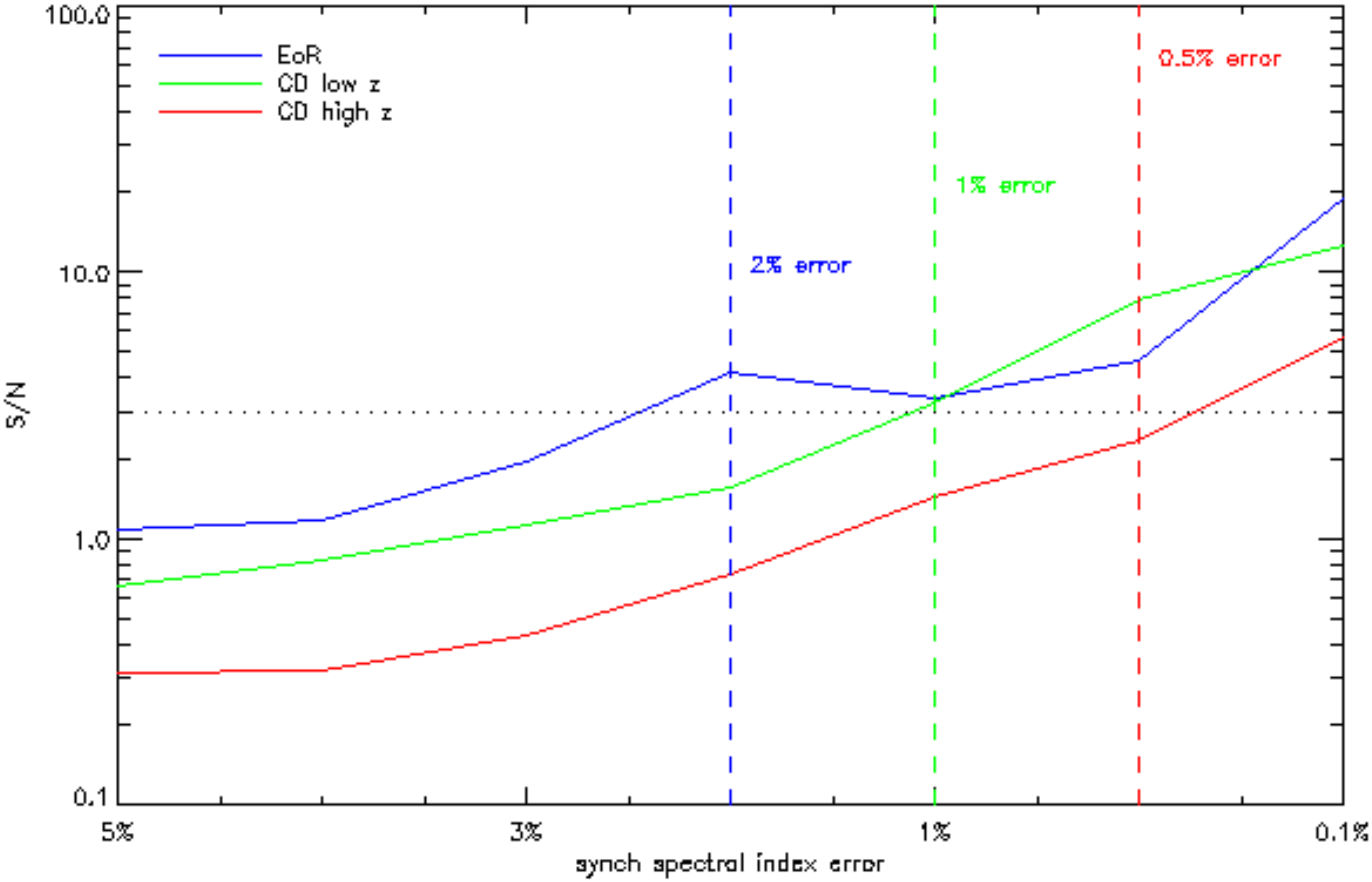

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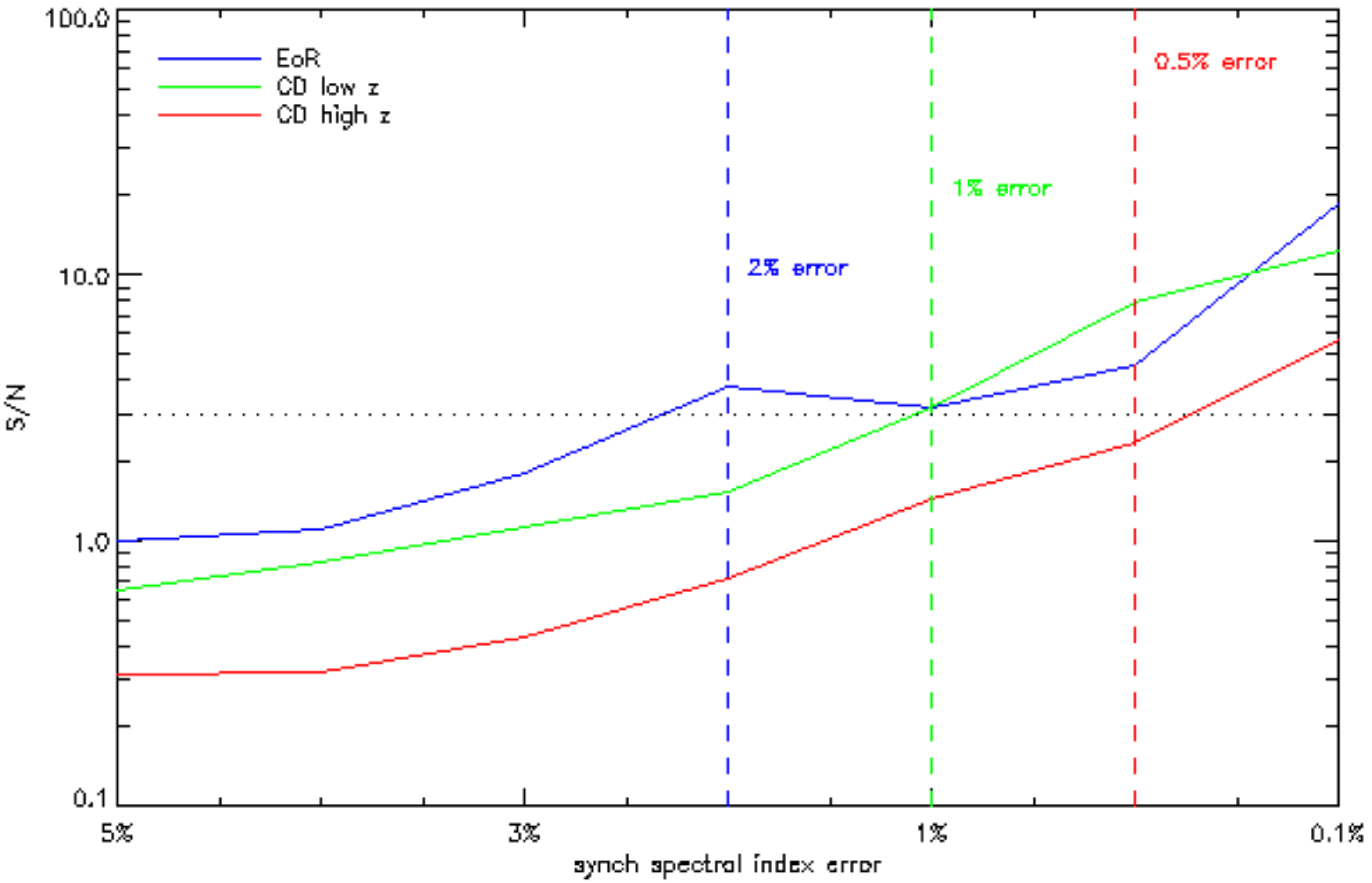

Possible improvements

- More realistic/complex foreground spectra
- More general treatment of errors on spectra
- A wider library of CD/EoR models
- A more general compsep framework to represent different foreground-removal methods
- Available as IDL and python script

Conclusions

- **SKA construction is on the horizon:**
  - Construction from mid 2019
  - Commissioning/Science verification from 2021
  - Full operations from 2025
- **Forecasting foreground-removal requirements for CD/EoR**
  - A quick way to look at the problem before running a full simulation and as diagnostic tool
  - Runs in a few minutes for a set of models
  - EoR measurement is hard:
    - 2% error on synch spectral index
    - Depends on tau
  - CD measurement is harder:
    - 1% error on synch spectral index for the feature at z=13
    - 0.5% error on synch spectral index for the features at higher redshift
    - Depends on radiation efficiencies etc.