



# EDGES Calibration Pipeline

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Cambridge, 2020



# Outline



1. Intro to EDGES calibration
2. A more informative calibration
3. Effects on Nature Paper results
4. Plans for the future

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1.

Introduction to EDGES calibration



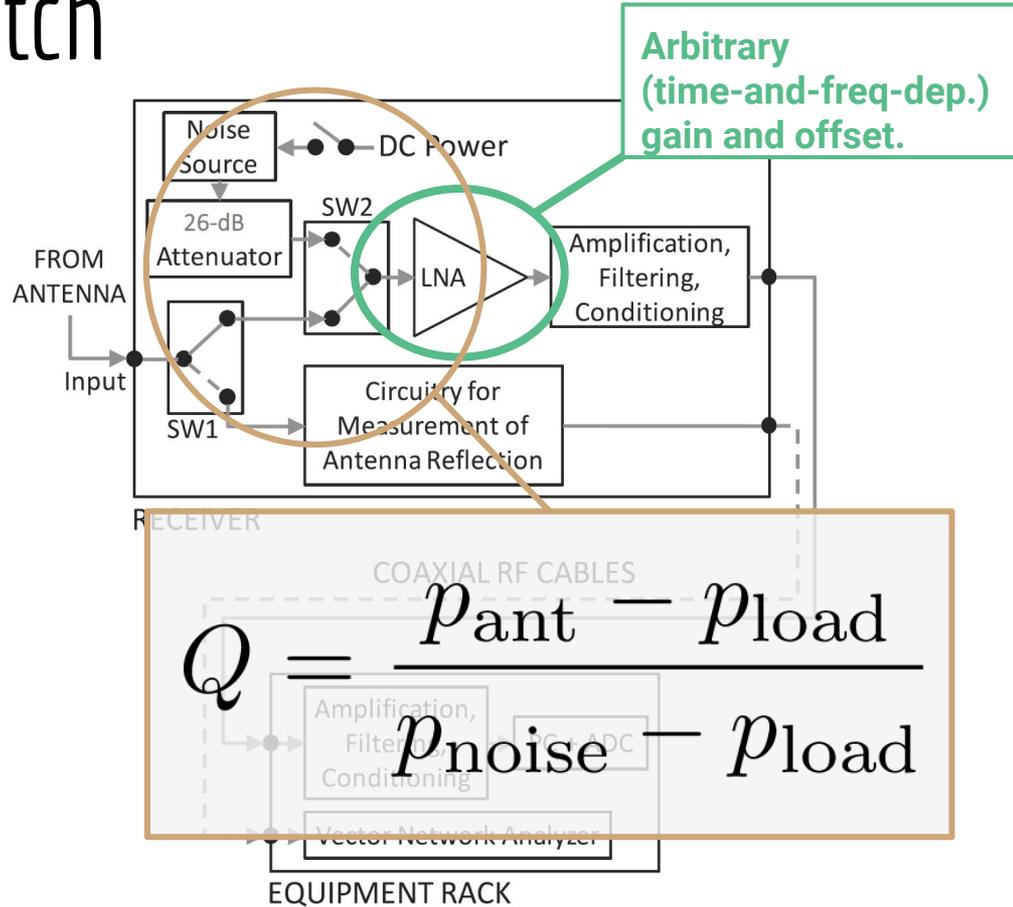
# The Three-Position Switch

“Q” removes gain.

Residual structure due to differing paths.

Get switch spectral structure *in the lab*. Assumed *time-independent*.

$$\hat{T} = A_{\nu}Q + B_{\nu}$$



# Lab Calibration

- **Monsalve (2017)** gives details for modelling A and B, dependent on  $S_{11}$  of sources.

$$K_0 A_\nu = 400 C_1$$

$$K_0 B_\nu = (300 - C_2) + K_1 T_{\text{unc}} + K_2 T_{\text{cos}} + K_3 T_{\text{sin}}$$

- **Measured** | **Fit (Polynomial)**
- Use four **known** input sources in place of antenna.
- **Iteratively** solve for the unknowns.



2.

A More Informative Calibration



# Motivation

**Systematics** may reduce necessity of absorption feature in data (Singh 2019, Sims 2020).

*What are the physical priors on such effects?*

Model number	Global signal model, $\delta T_b$	Log-polynomial order, $\bar{T}_{\text{Fg}}$	Damped sinusoid, $T_{\text{cal}}$	Noise model, N	log(evidence)	Residual RMS [mK]
1	-	3	-	white	$-4289.96 \pm 0.36$	255.7
2	-	4	-	white	$-4121.56 \pm 0.35$	237.9
3	ARES	3	-	white	$-3429.35 \pm 0.25$	224.4
4	ARES	4	-	white	$-3402.66 \pm 0.25$	217.2
5	-	3	Equation 19	white	$-2876.04 \pm 0.29$	223.4
6	-	4	Equation 19	white	$-2185.80 \pm 0.29$	179.2
7	ARES	3	Equation 19	white	$-2074.01 \pm 0.24$	189.0

# The Problem With Iterative Fits

You don't know the **uncertainties**.

Each fitted parameter (there are ~50) has uncertainties that **should** propagate to the final spectrum as a **covariance**.

This information is **lost**.

# A Bayesian Model

Set up a simple  $\chi^2$  likelihood:

$$\ln \mathcal{L}(\mathbf{Q}_\nu | \vec{\theta}) = - \sum_{\text{src}} \sum_{\nu} \ln \sigma_Q(\nu | \vec{\theta}, \text{src}) + \frac{[\mathbf{Q}_\nu^{\text{src}} - Q(\nu | \vec{\theta}, \text{src})]^2}{2\sigma_Q^2(\nu | \vec{\theta}, \text{src})},$$

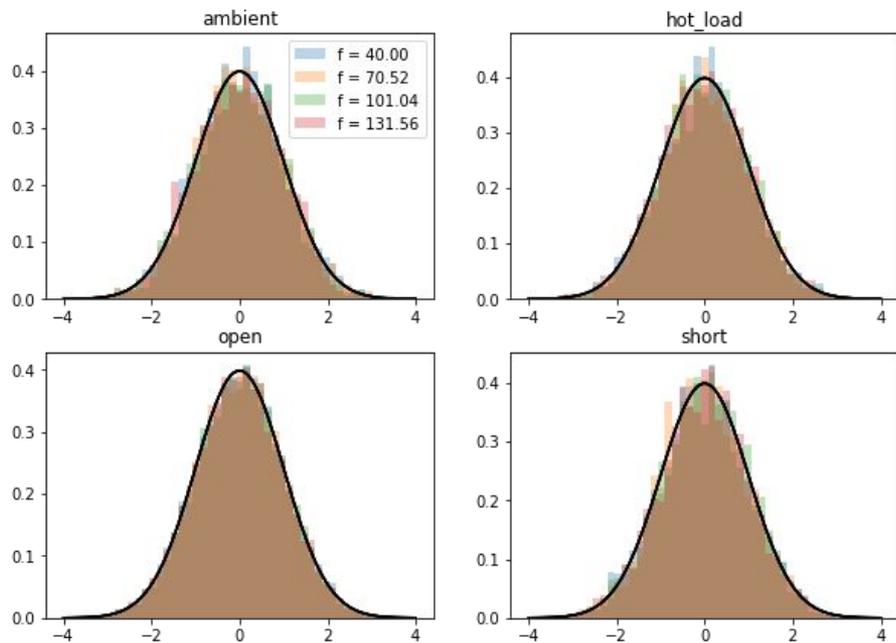
Recall:

$$Q_{\text{src}} = \frac{T_{\text{src}}^{\text{meas}} - B_{\text{src}}}{A_{\text{src}}}$$

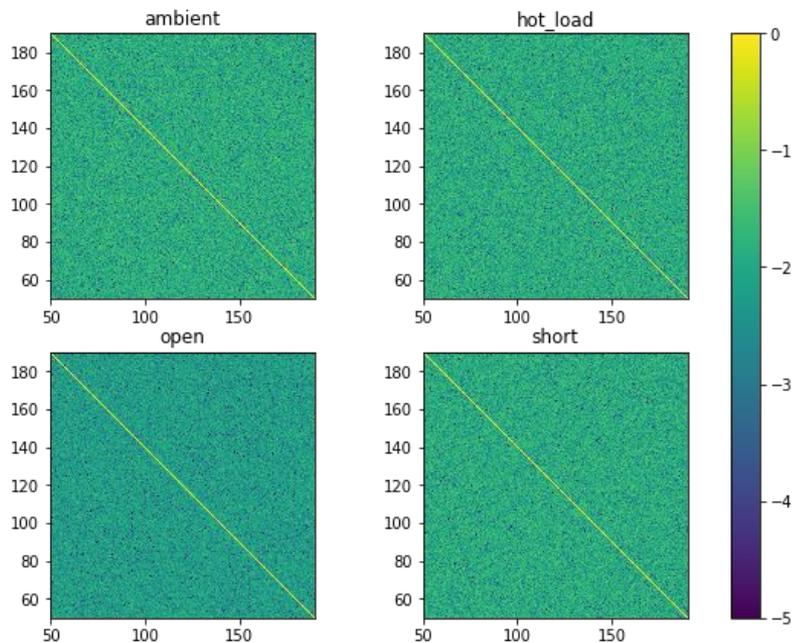
Use **MCMC/Nested-Sampling** to fit.

# Justification of uncorrelated Gaussian Likelihood

Distribution of power in single channel over time (single file)



Log|Corr| of spectra between frequencies



# What about the model variance?

- Assuming Gaussianity and hot noise-source (and perfect impedance matching...):

$$\sigma_{Q_t}^2 = \alpha \left( \frac{T_A - T_L}{T_{NS}} \right)^2 \left[ \frac{T_A^2 + 2T_{LNA}^2 + T_L^2}{(T_A - T_L)^2} - 2 \frac{T_L^2 + T_{LNA}^2}{(T_A - T_L)T_{NS}} + \frac{2T_L^2 + T_{NS}^2 + 2T_{LNA}^2}{T_{NS}^2} \right]$$

- Non-matched solution being worked on.
- $\alpha$  requires a model of the spectrometer efficiency.
- For now... just **measure** the variance from data.



3.

Effects on Nature Paper Results



# The Idea

Recalibrate & Refit B18

How much extra uncertainty is there on the Bowman et al. (2018) parameters, if calibration uncertainty is accounted for?

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# Re-Calibration of Bowman (2018) Data

## The initial process:

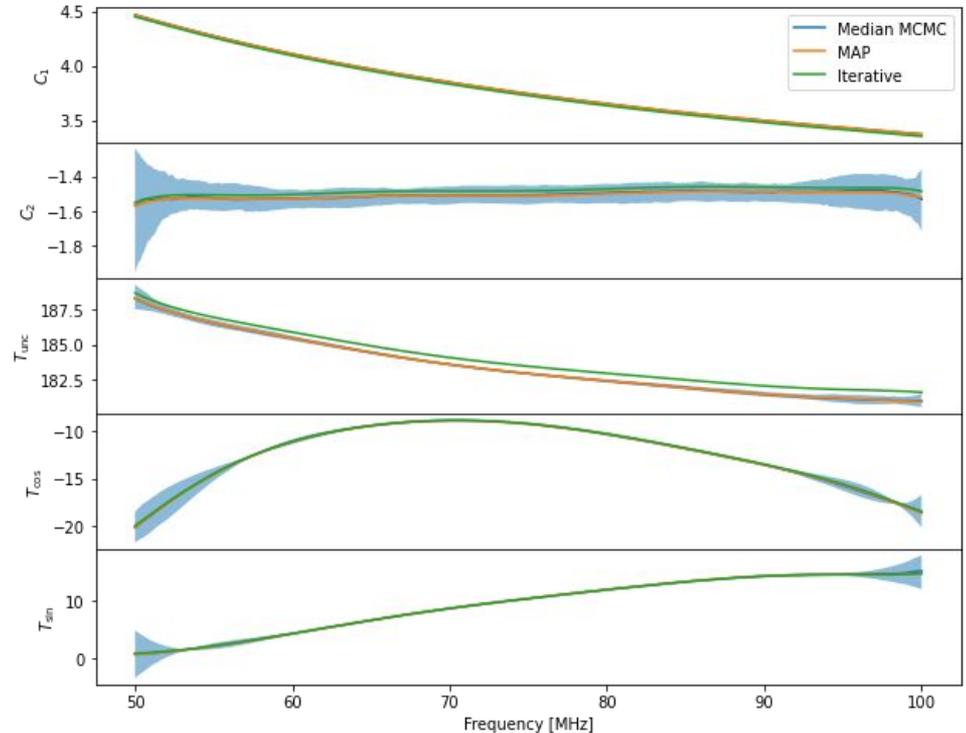
1. Generate full **posterior** on calibration parameters.
2. De-calibrate B18 data using best-fit.
3. Re-calibrate from posterior to generate **data covariance**.
4. Re-fit absorption+foregrounds with new covariance

# Uncertainties on Calibration Parameters

Bayesian fits mostly **comparable** to iterative fit (except  $T_{\text{unc}}$ ).

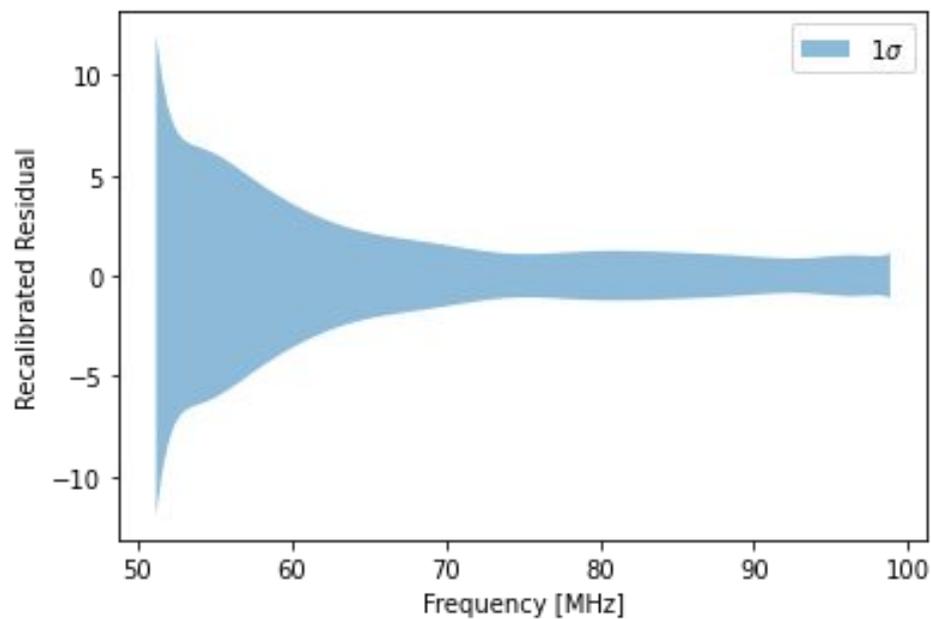
Higher **uncertainty** at band edges (expected).

100-150mK overall amplitude uncertainty.

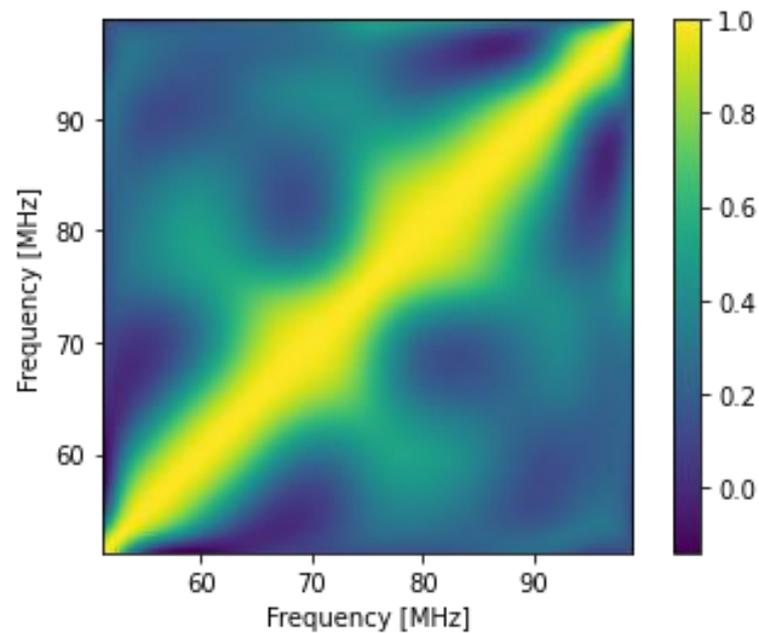


# Re-Calibration of Bowman (2018) Data

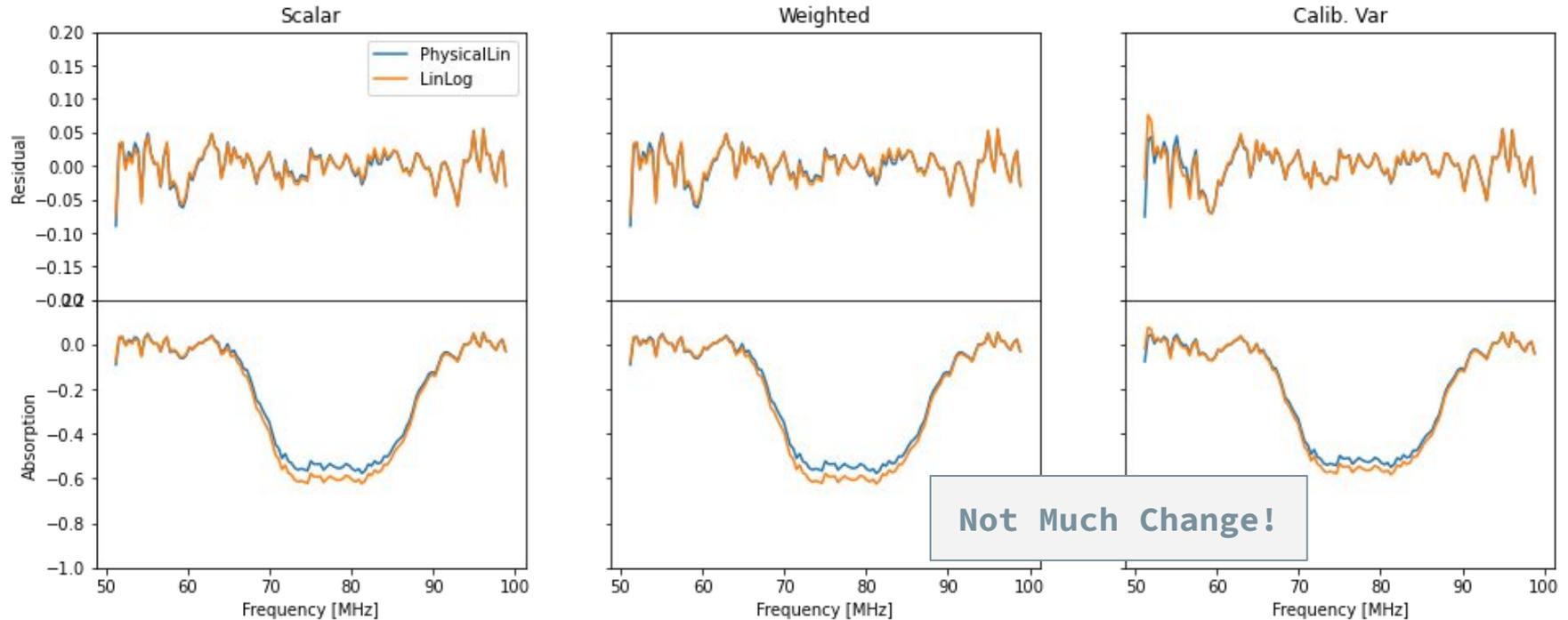
Spectrum Variance from calibration.



Spectrum Correlations



# Updated Fit to Bowman (2018) Data

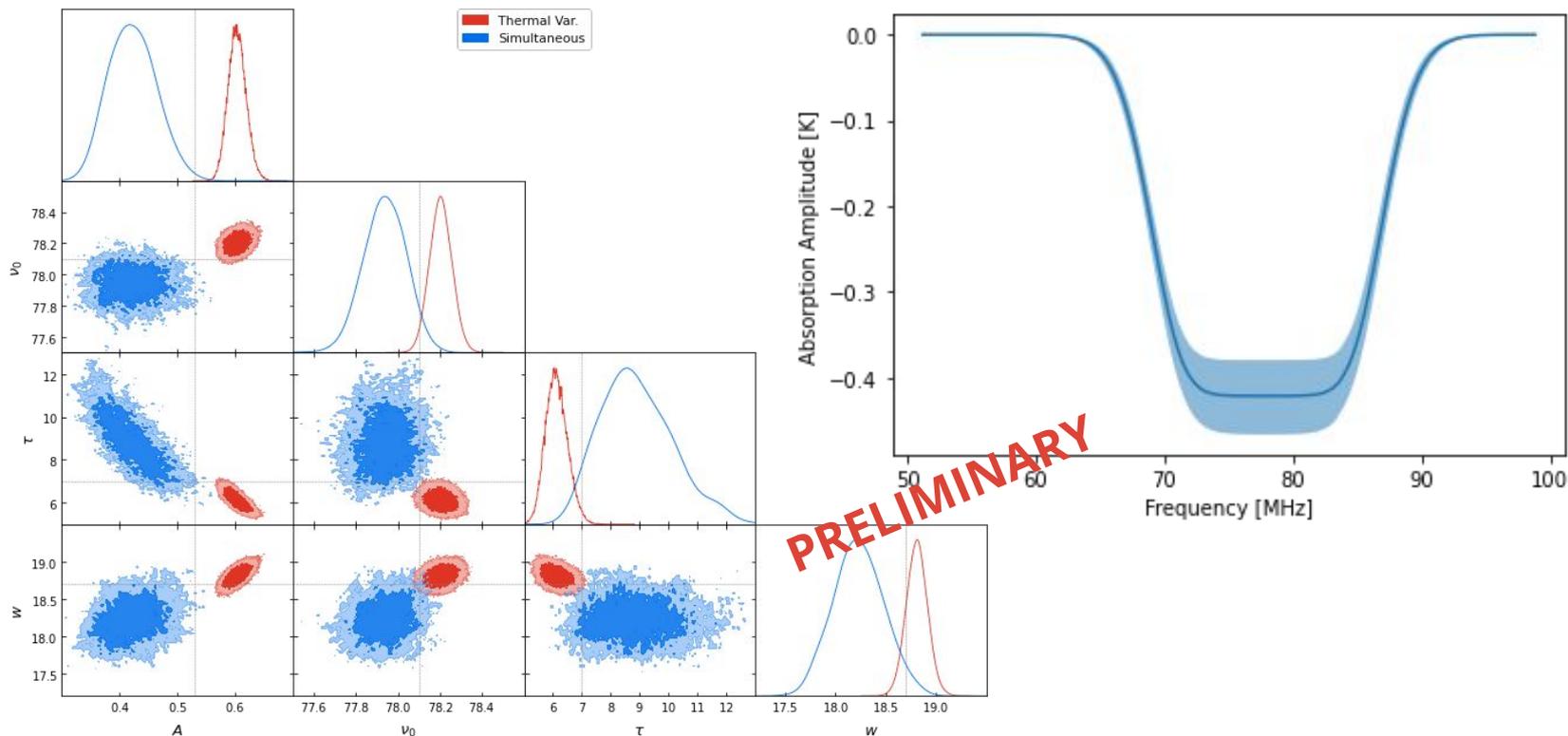


# More rigorous fit

Due to data covariance being highly structured:

- Single likelihood for *simultaneous* calibration and absorption/fg fitting.
- Re-calibrate data *within* MCMC.
- Absorption/fg likelihood has no *intrinsic covariance*.

# Updated Fit to Bowman (2018) Data



# Summary

Best-fit absorption feature is robust to **increased low-frequency variance**, and known **calibration uncertainties**.

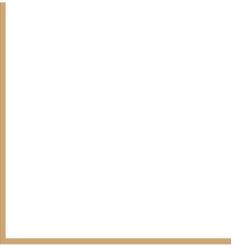
Low frequencies significantly more **sensitive** to calibration errors (as expected).

Uncertainties on absorption parameters **inflated by factor of ~3** after accounting for correlated calibration errors.



4.

Plans for the Future



# What Other Uncertainties Are There?

- Considered uncertainty of calibration model fitting.
- Other uncertainties:
  - $S_{11}$  measurements (and models!)
  - Beam model/correction
  - Ground-loss model
- It's the **covariance**, in the basis of the data, that is important.

# EDGES is Getting an Upgrade

- **EDGES-3** coming in (late) 2021.
- *Raw data* from B18 to be made public, along with a full pipeline spec for reproducing results (~late 2021).
- Data from EDGES-3 to be made public after reasonable period of analysis.
- To do this, need new software...

# New Software Pipeline

README.rst

## edges-io

build passing codecov 62%

Module for reading EDGES data and working with EDGES databases.

This package implements all necessary functionality for reading EDGES data. It's two main concerns are:

1. Reading the various file formats required for EDGES data: - VNA readings - fastspec output - thermistor readings - field weather recordings - field thermlog recordings

README.md

## fastspec

Multithreaded spectrometer code implemented in C++

### Overview

README.md

## edges\_cal

build passing codecov 81% code style black

Calculate calibration coefficients for EDGES Calibration Observations

### Installation

Download/clone the repo and do

## EDGES Collaboration

Collection of codes for working with EDGES data

<http://loco.lab.asu.edu/edges/>

Repositories 9 Packages People 6 Teams 1 Projects Settings

Find a repository... Type: All Language: All Customize pins

### edges-analysis

Python MIT 0 0 12 (1 issue needs help) 1 Updated 2 hours ago

### edges-io

Module for reading EDGES data and working with EDGES databases

Python MIT 0 0 2 1 Updated 2 hours ago

### edges-cal

Code to calibrate EDGES data

Jupyter Notebook MIT 0 0 10 2 Updated 21 hours ago

#### Top languages

Python Jupyter Notebook

#### People

Invite someone

# The Point:

We should (and will!) be accounting for complex modelling uncertainties.

Soon you can too.