# LOFAR Calibration and Energy Scale

K. Mulrey, A. Bonardi, S. Buitink, A. Corstanje, H. Falcke, B. M. Hare, J. R. Hörandel, P. Mitra, A. Nelles, I. Plaisier, J. P. Rachen, L. Rossetto, P. Schellart, O. Scholten, S. ter Veen, S. Thoudam, T.N.G. Trinh, T. Winchen

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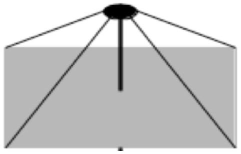
# LOFAR LBA Calibration

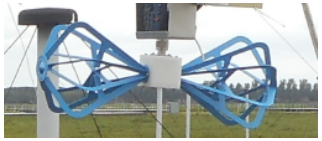
measured signal recorded in ADC counts ($P_m$) → voltage received at the antenna ($P_e$)



## 2 independent methods

*Nelles, A. et al. 2015,Journal of Instrumentation, 10, P11005*

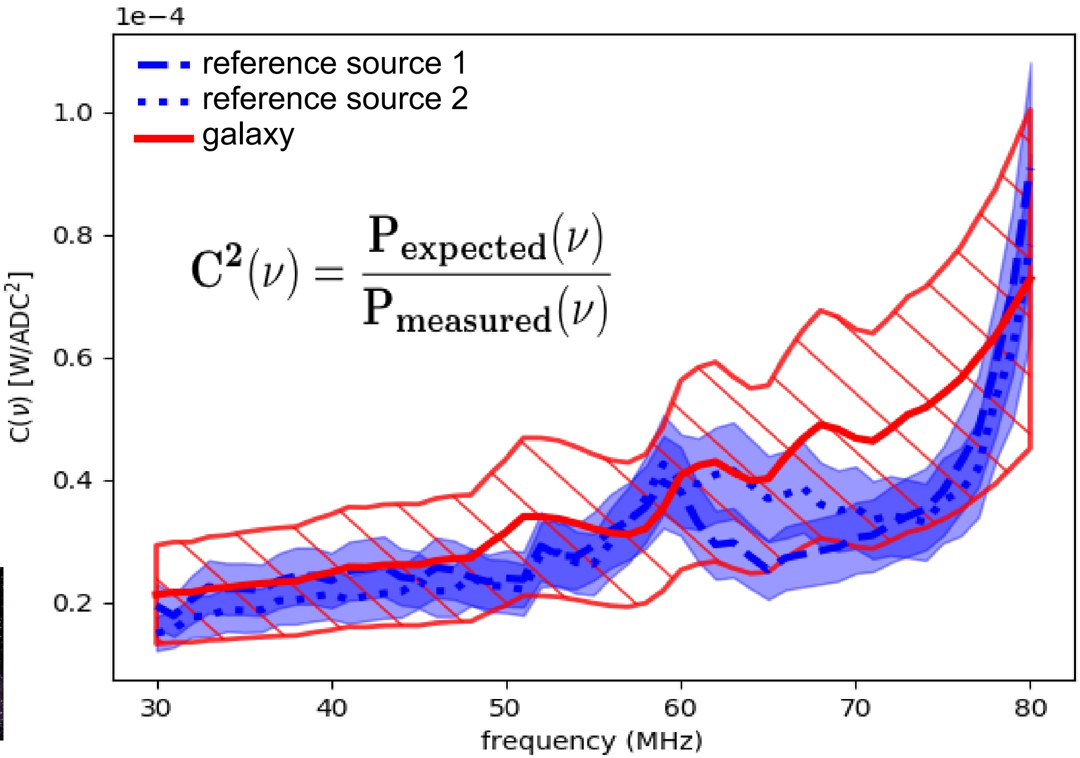
### 1. Reference Source



+ Angular response
- Relies on conflicting manufacturer data sheets
- Not easily repeatable

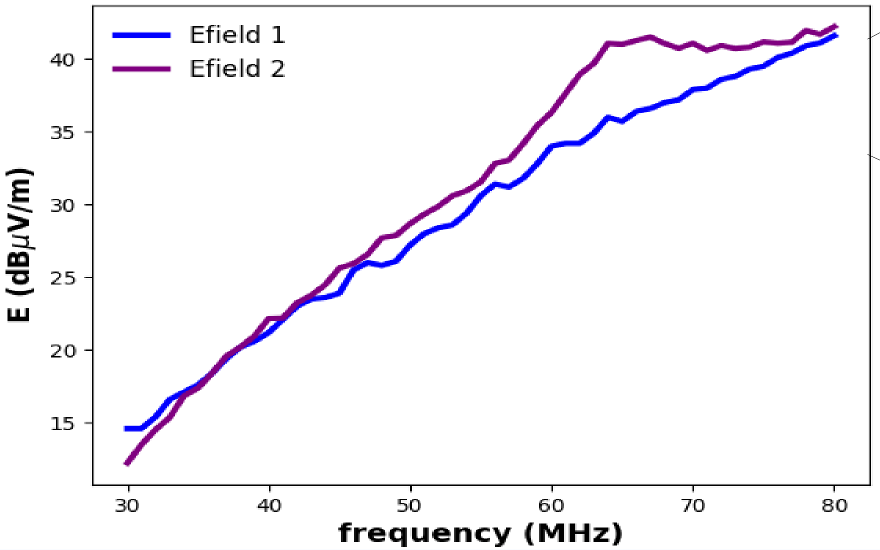
### 2. Galactic Emission

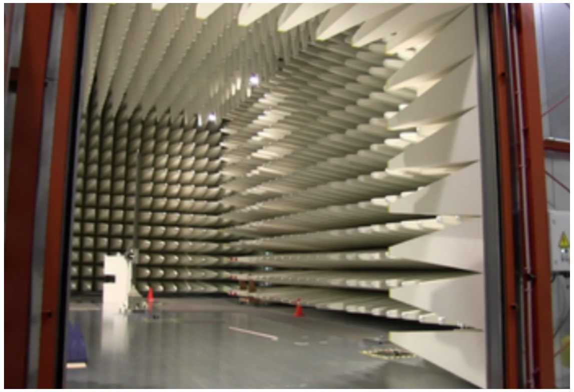
- Average over whole sky
+ Can be done anytime
- Large error bars due to electronic noise



# Revisiting the LOFAR Calibration

- Absolute energy scale uncertainty ~50%
- Large uncertainty between methods, conflicting data sheets for reference source
- Galaxy method is repeatable, but limited by uncertainty electronic noise
- New frequency spectrum analyses require detailed knowledge of spectral shape



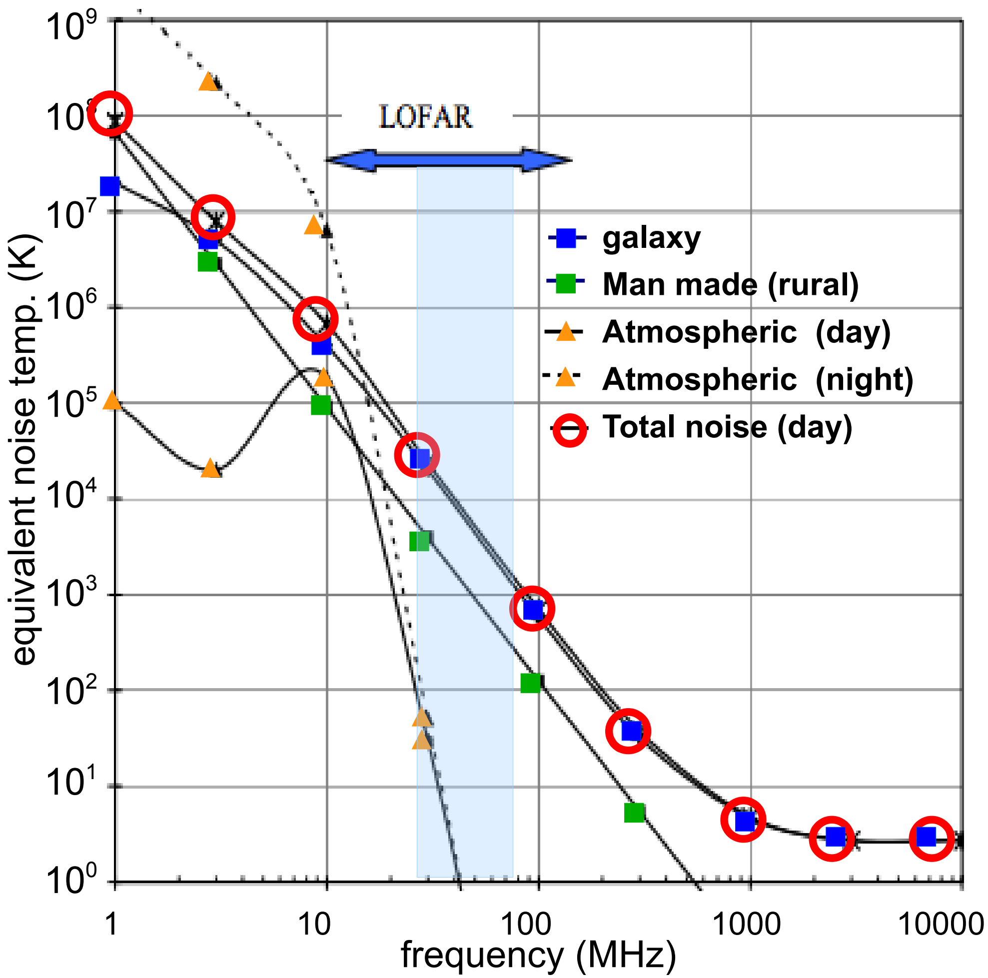



Method 1: Anechoic chamber + reflective ground

Method 2: GTEM cell

★ Redo the **galactic calibration** with the goal of characterizing electronic noise and lowering systematic uncertainties

# Galactic Calibration



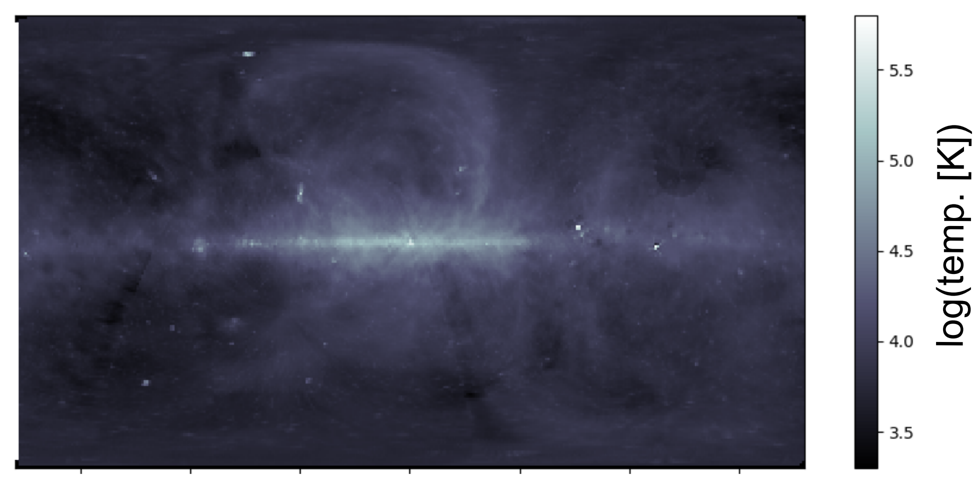

$$C^2(\nu) = \frac{P_{sky+elec.noise}(\nu)}{P_{measured}(\nu)}$$

- Galaxy noise is primary external source of noise in LBA frequency range

  **Galaxy noise + electronic noise = recorded signal**

- **Lfmap** software provides frequency dependent galactic noise temperature

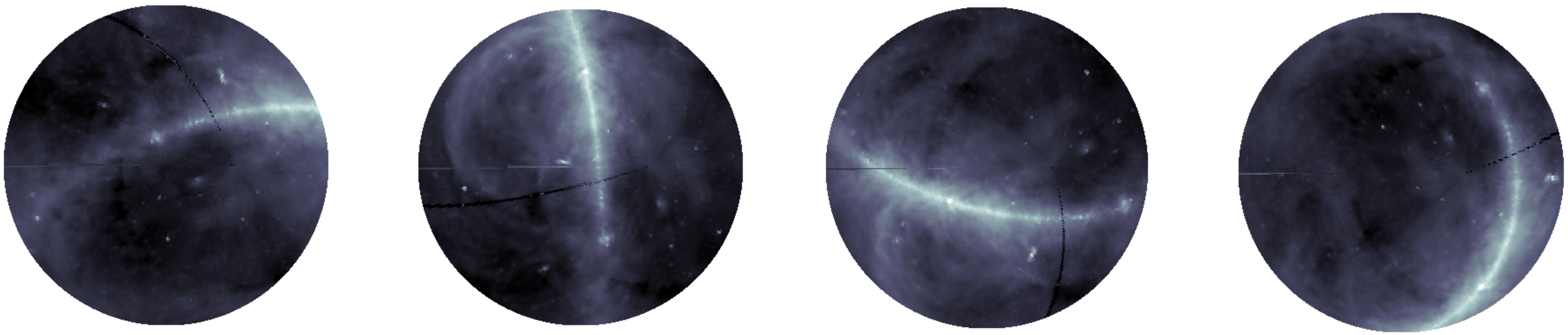
$$T_{sky}(\nu, \alpha, \delta) = T_{CMB} + T_{Iso}(\nu) + T_{gal}(\nu, \alpha, \delta)$$

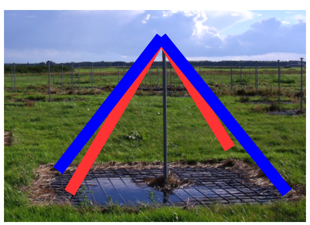



*E. Polisensky, LFmap: A Low Frequency Sky Map Generating Program. , Long Wavelength Array (LWA) Memo Series 111 (2007).*

# Simulating Galaxy Noise

**Visible galaxy at 00.00,6:00,12:00,18:00 Local Sidereal Time**

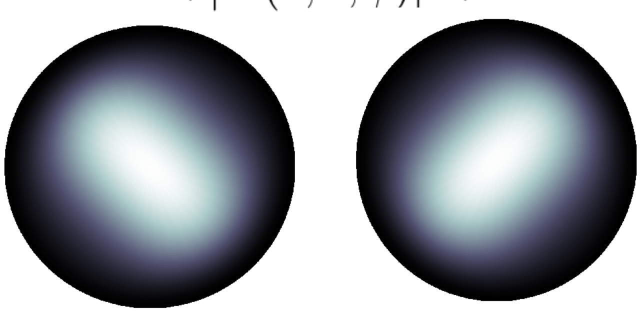




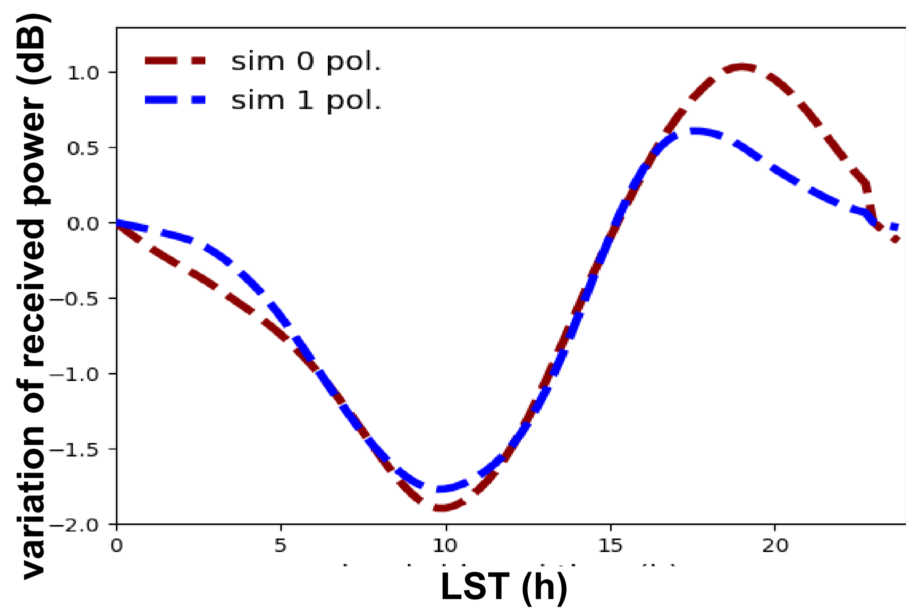
$$\mathbf{P}(\nu) = \frac{2\mathbf{k_B}}{\mathbf{c^2}}\nu^2 \int \mathbf{T_{sky}}(\nu,\theta,\phi)\frac{|\vec{\mathbf{H}}(\nu,\theta,\phi)|^2 \mathbf{Z_0}}{2\mathbf{Z_a}}\mathbf{d}\Omega \quad \mathbf{WHz^{-1}}$$

**Average antenna response at 55 MHz**

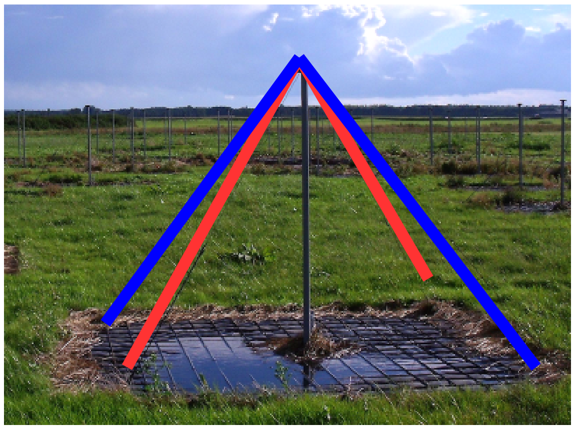
$$<|\vec{\mathbf{H}}(\nu,\theta,\phi)|^2>$$



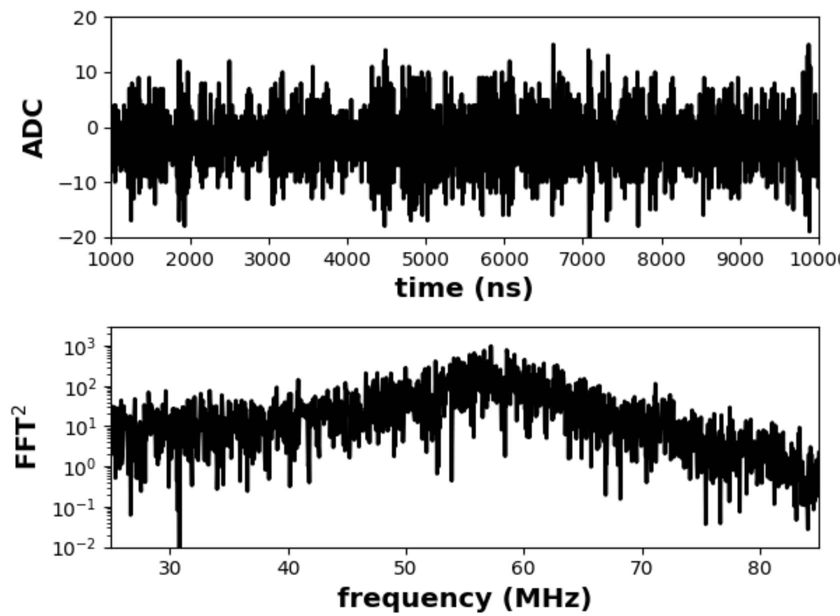
**pol 0** **pol 1**



# LOFAR Data



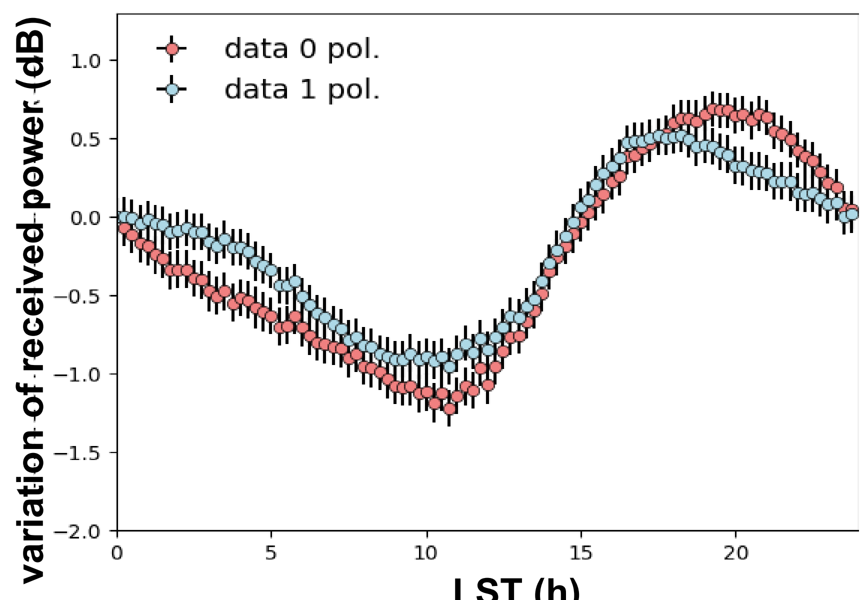
**Transient Buffer Boards** (TBBs) store 5 seconds of raw data when triggered



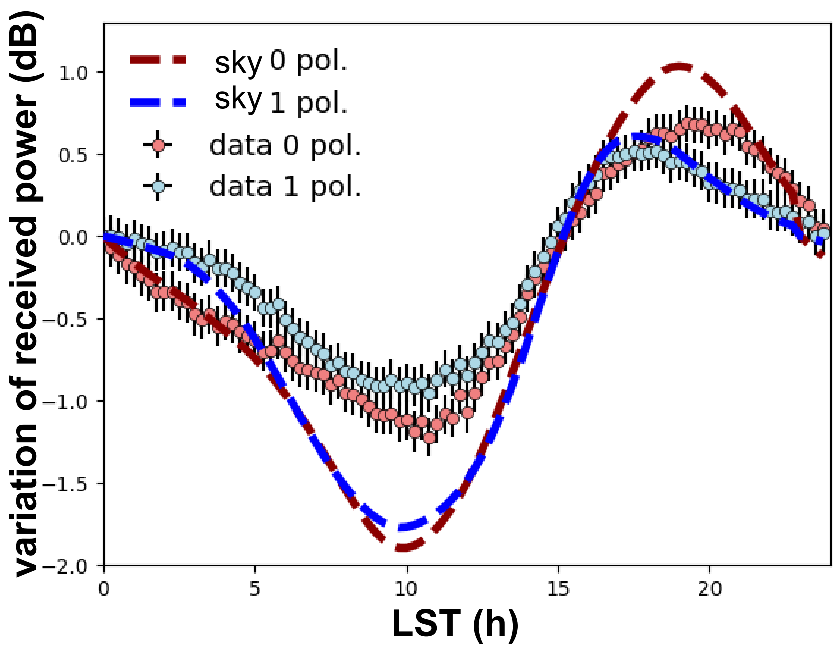

<u>For each LOFAR event</u>:

1. window out expected CR signal
2. remove RFI
3. calculate average power in 1 MHz bins
4. Bin events in 15 min LST intervals
   (~ 40 events x 48 antennas x 6 stations per bin)

*Using 'LBA OUTER' data

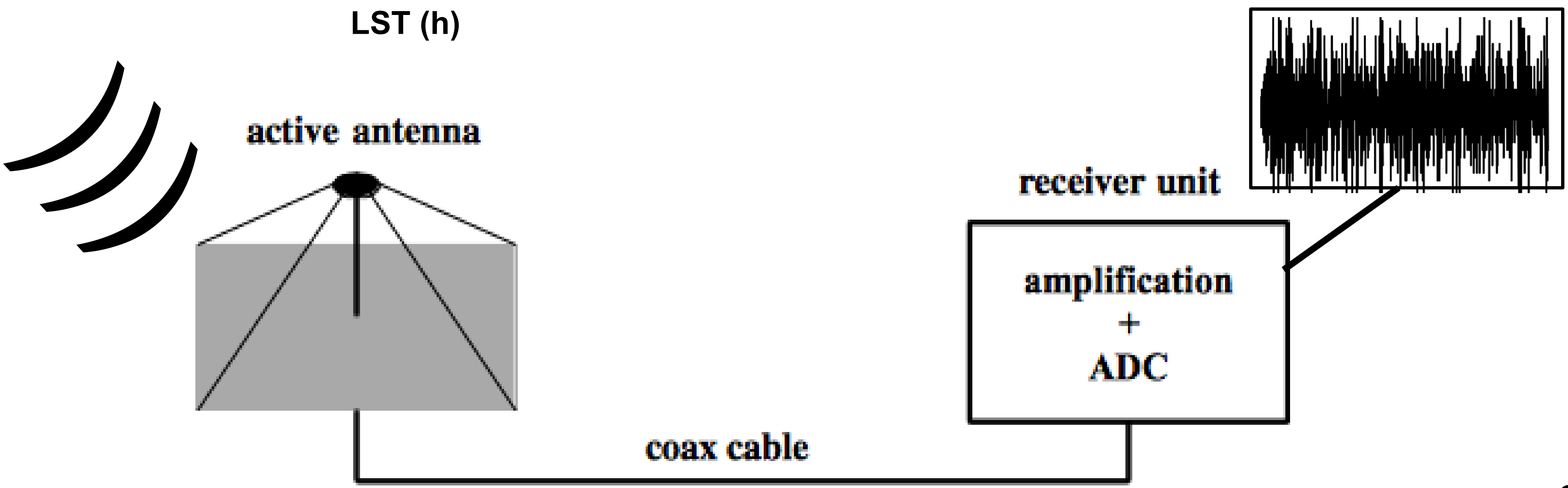


# Compare galactic noise and LOFAR Data

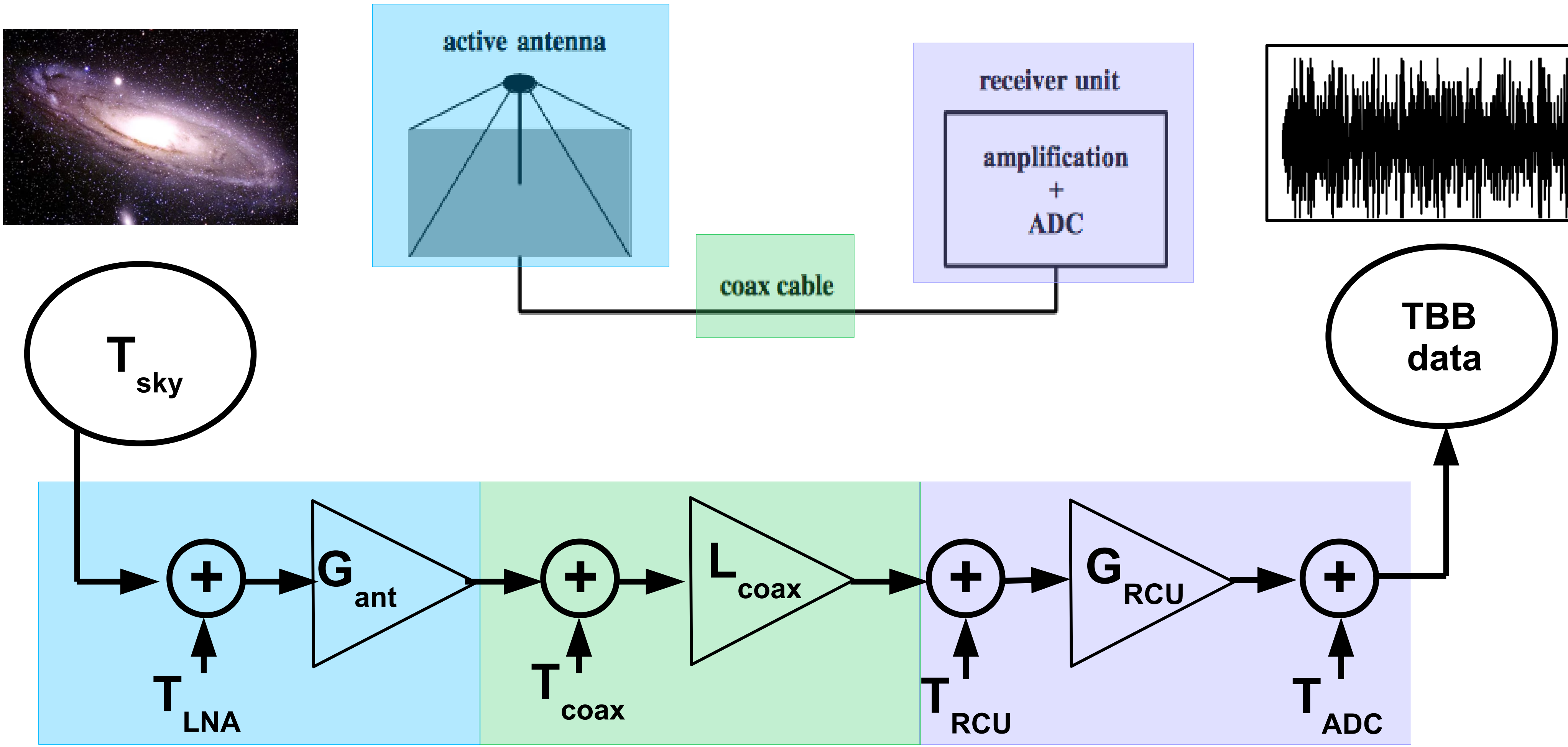



**Galaxy simulations show more variation over LST**

- Need to add electronic noise
- Electronic noise is expected to be flat to 1st order; we model the frequency dependance of the signal chain and fit for constant noise values



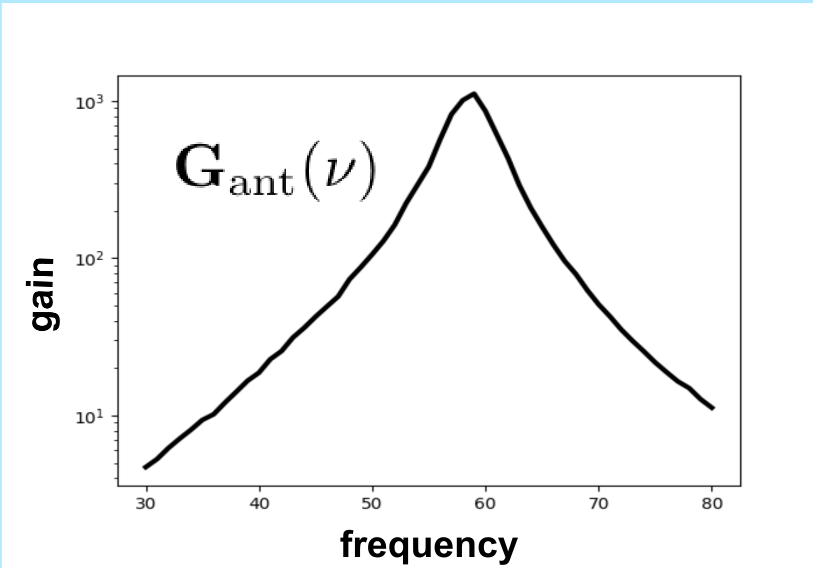
# LOFAR Signal Chain




$G_{ant}$ , $L_{coax}$ , $G_{RCU}$ → **Freq. Dependent losses and gains**

$T_{LNA}$ , $T_{coax}$ , $T_{RCU}$ , $T_{ADC}$ → **Constant noise values**

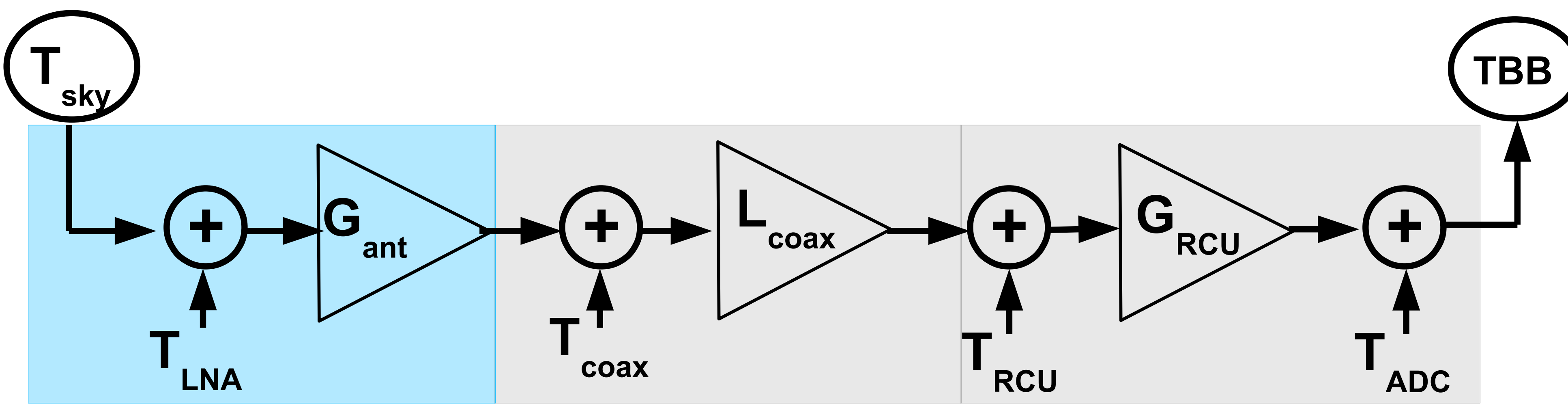
# LOFAR Signal Chain



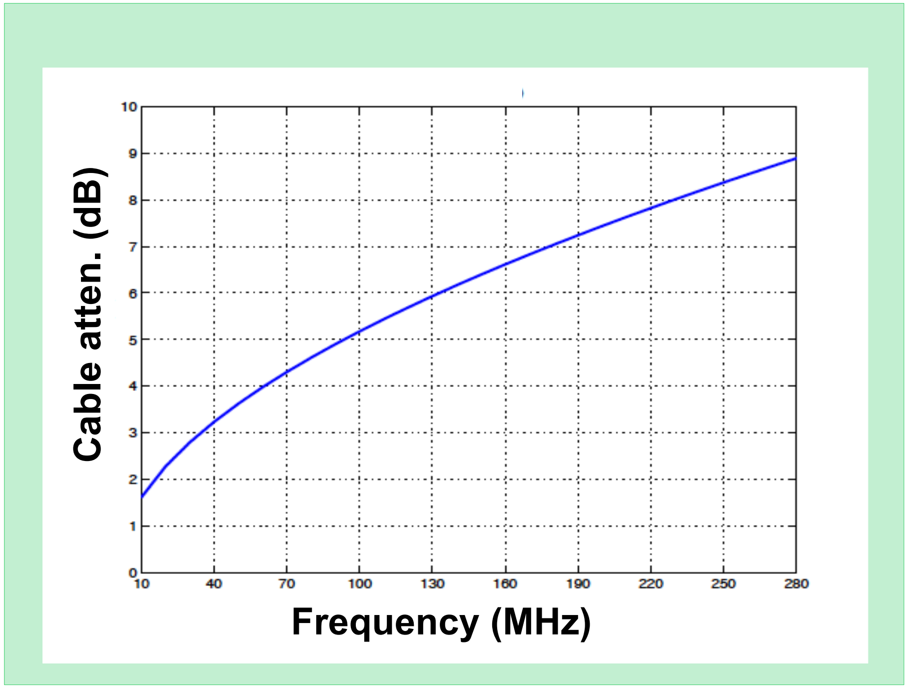

$$\left(\mathbf{P}_{\mathrm{sky}}(\nu,\mathbf{t}) + \mathbf{T}_{\mathrm{LNA}}\right)\mathbf{G}_{\mathrm{ant}}(\nu)\mathbf{A}(\nu)$$

$\mathbf{G}_{\mathrm{ant}}(\nu)$ Antenna gain, simulated with WIPL-D software, with known misaligned resonance frequency

$\mathbf{A}(\nu)$ correction to antenna model



# LOFAR Signal Chain

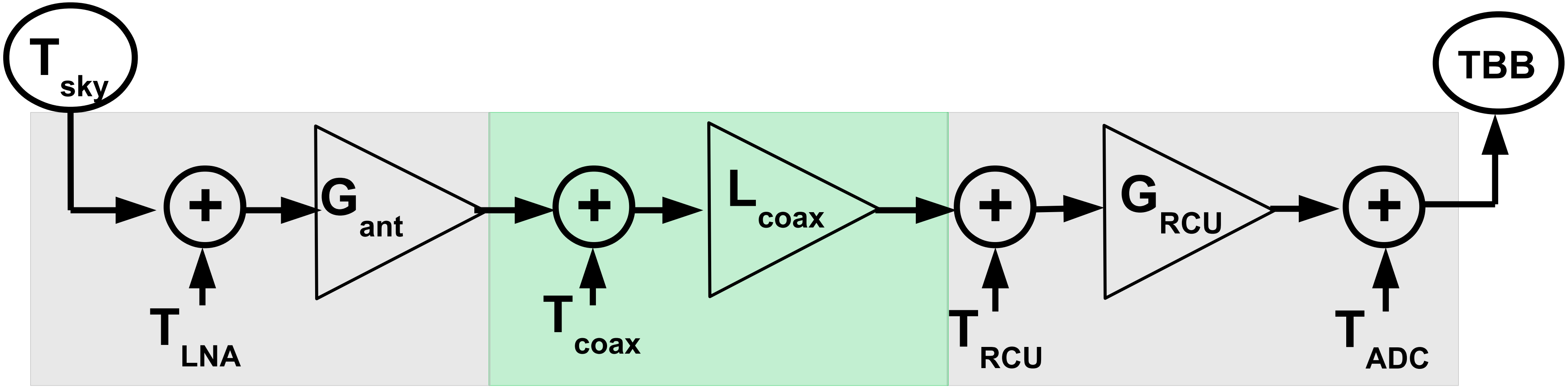



$$\left(\mathbf{P}_{\text{sky}}(\nu,\mathbf{t})+\mathbf{T}_{\text{LNA}}\right)\mathbf{G}_{\text{ant}}(\nu)\mathbf{A}(\nu)\mathbf{L}_{\text{coax}}(\nu)$$

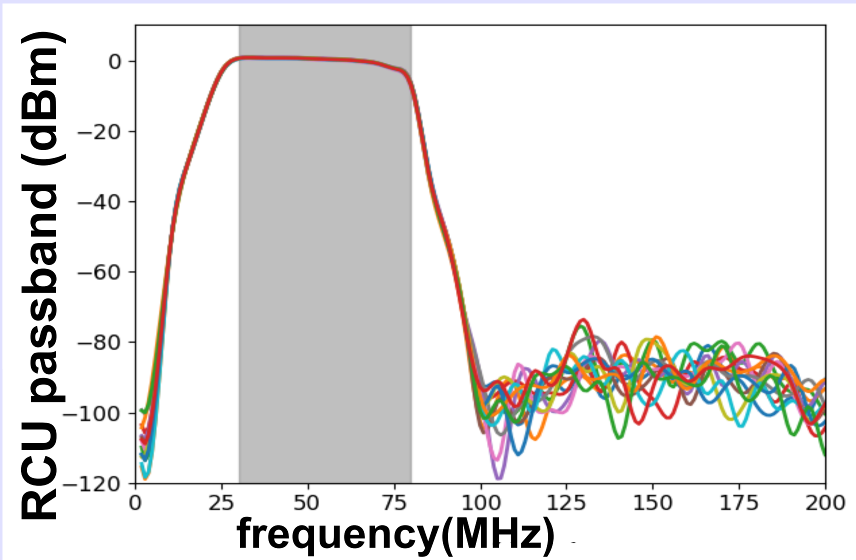
$\mathbf{L}_{\text{coax}}(\nu)$ Cable attenuation (50m, 80m ,115m)

$$\mathbf{T}_{\text{coax}} << \mathbf{T}_{\text{LNA}}, \mathbf{T}_{\text{RCU}}, \mathbf{T}_{\text{ADC}}$$

(not included in model)

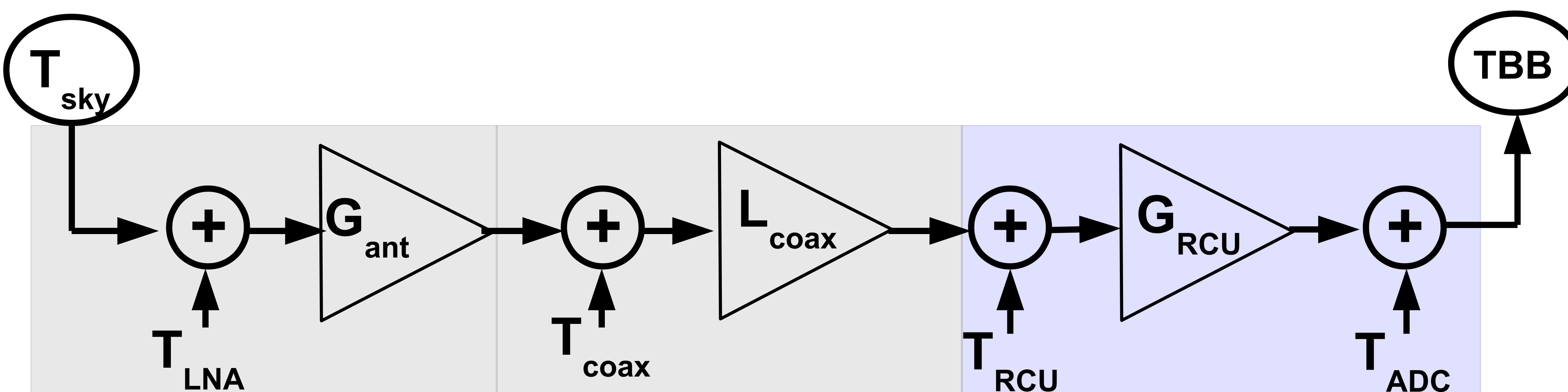


# LOFAR Signal Chain

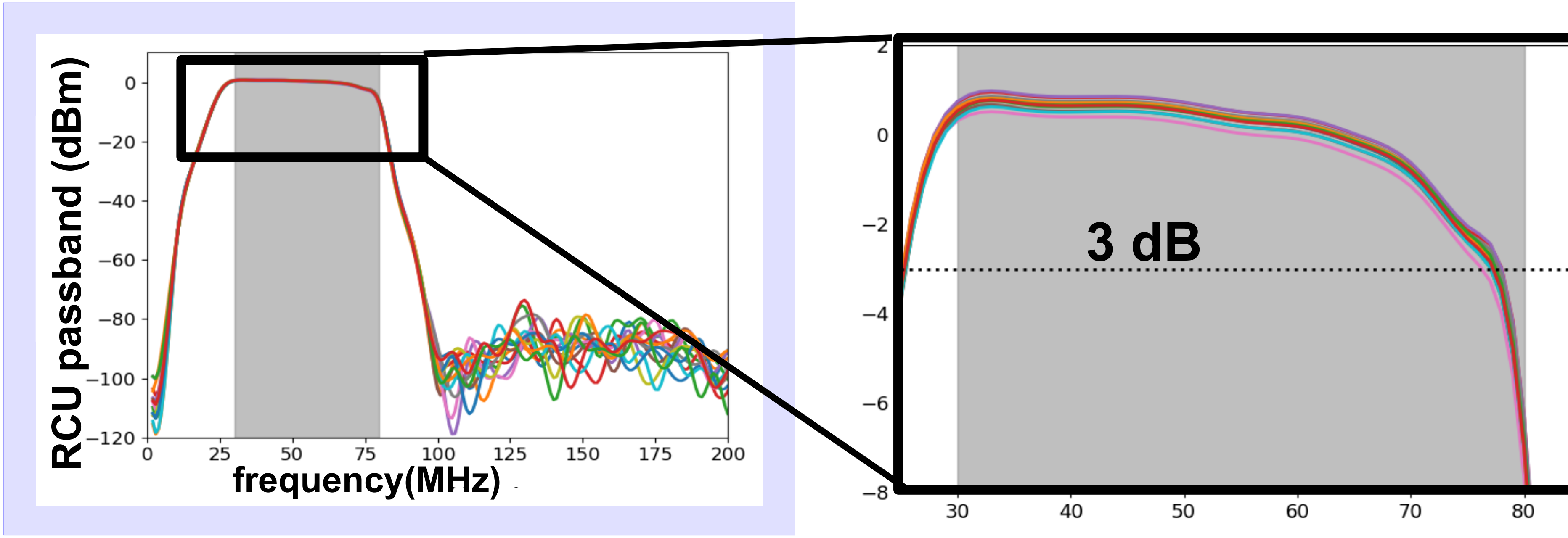



| | |
|---|---|
| $\mathbf{T}_{\mathbf{RCU}}$ | Noise from amplification in RCU |
| $\mathbf{G}_{\mathrm{RCU}}(\nu)$ | RCU passband filter |
| $\mathbf{S}$ | scale factor between voltage and ADC units |
| $\mathbf{T}_{\mathrm{ADC}}$ | time jitter noise from digitization |

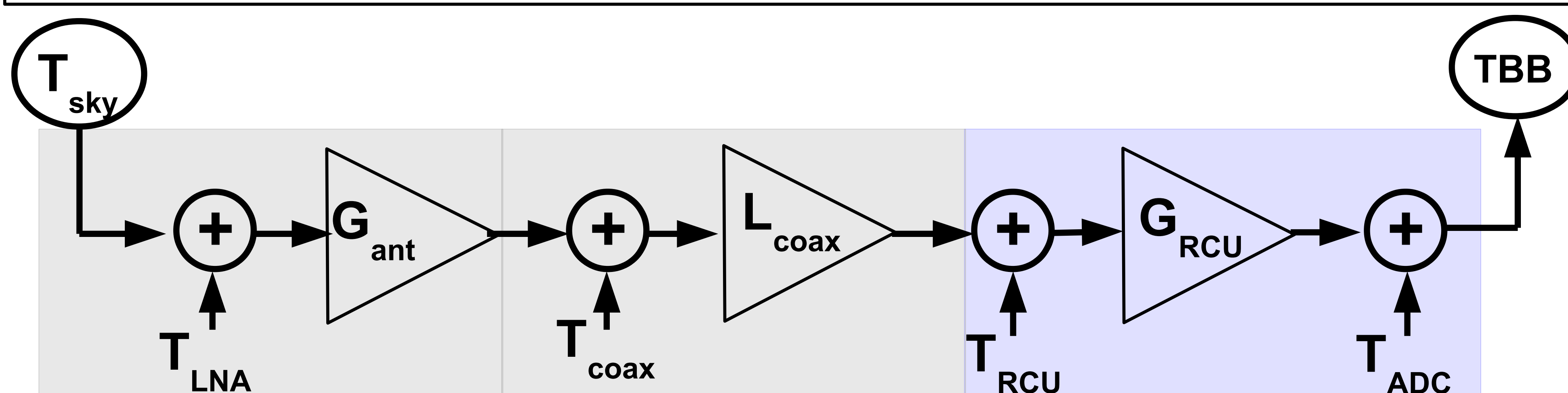
$$\left(\left(\mathbf{P}_{\mathrm{sky}}(\nu, \mathbf{t}) + \mathbf{T}_{\mathrm{LNA}}\right)\mathbf{G}_{\mathrm{ant}}(\nu)\mathbf{A}(\nu)\mathbf{L}_{\mathrm{coax}}(\nu) + \mathbf{T}_{\mathbf{RCU}}\right)\mathbf{G}_{\mathrm{RCU}}(\nu)\mathbf{S} + \mathbf{T}_{\mathrm{ADC}} = \mathbf{P}_{\mathrm{sim}}(\nu, \mathbf{t})$$



# LOFAR Signal Chain

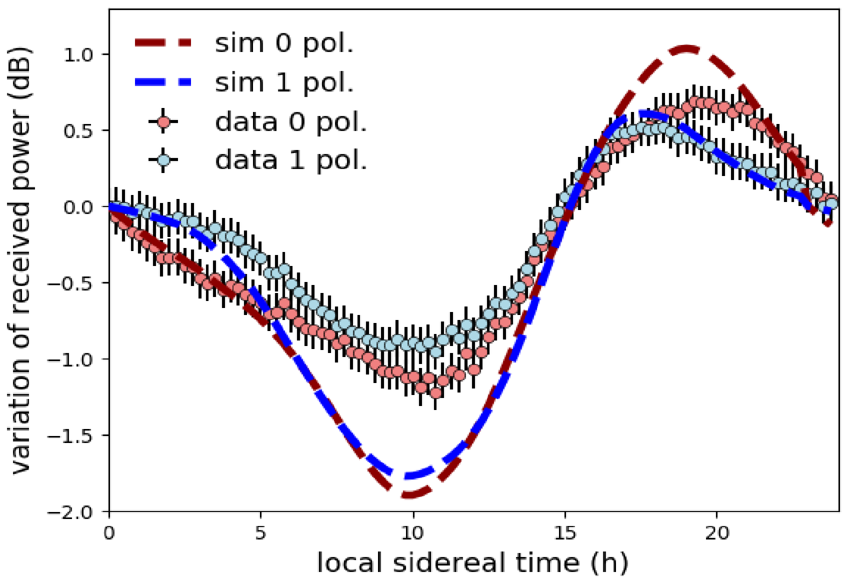



$$\left(\left(\mathbf{P}_{\mathrm{sky}}(\nu,\mathbf{t}) + \mathbf{T}_{\mathrm{LNA}}\right)\mathbf{G}_{\mathrm{ant}}(\nu)\mathbf{A}(\nu)\mathbf{L}_{\mathrm{coax}}(\nu) + \mathbf{T}_{\mathbf{RCU}}\right)\mathbf{G}_{\mathrm{RCU}}(\nu)\mathbf{S} + \mathbf{T}_{\mathrm{ADC}} = \mathbf{P}_{\mathrm{sim}}(\nu,\mathbf{t})$$



# Fitting for Electronic Noise

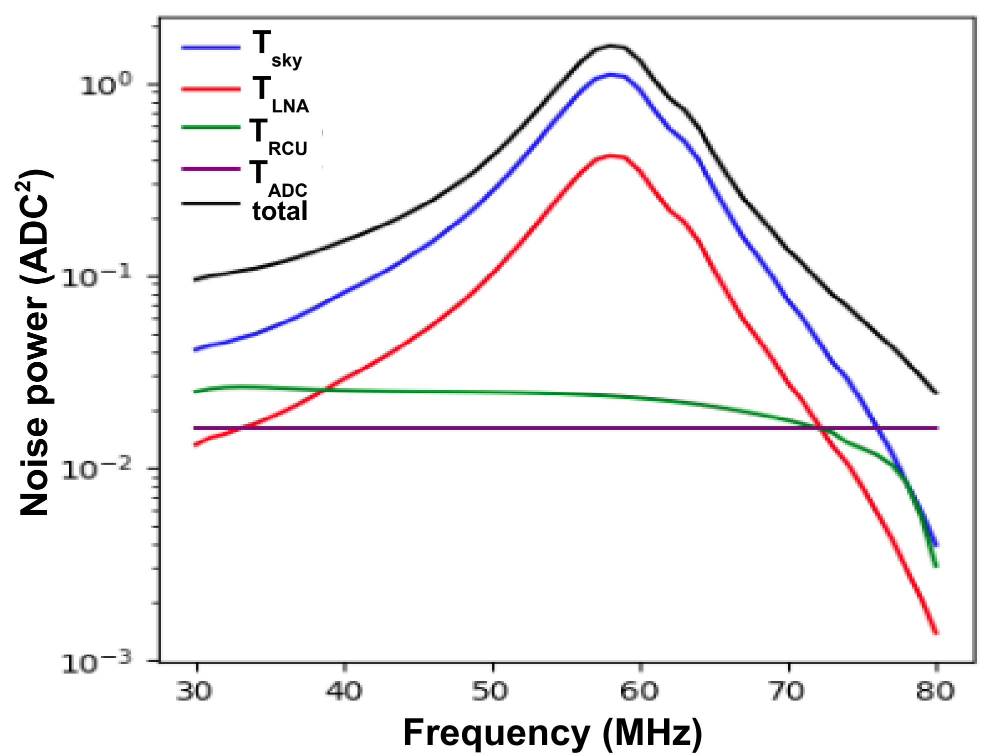
$$\left(\left(\mathbf{P}_{\rm sky}(\nu,\mathbf{t}) + \mathbf{T}_{\rm LNA}\right)\mathbf{G}_{\rm ant}(\nu)\mathbf{A}(\nu)\mathbf{L}_{\rm coax}(\nu) + \mathbf{T}_{\rm RCU}\right)\mathbf{G}_{\rm RCU}(\nu)\mathbf{S} + \mathbf{T}_{\rm ADC} = \mathbf{P}_{\rm sim}(\nu,\mathbf{t})$$




known, frequency dependent quantity

unknown, constant quantity

## Fitted noise values at ADC

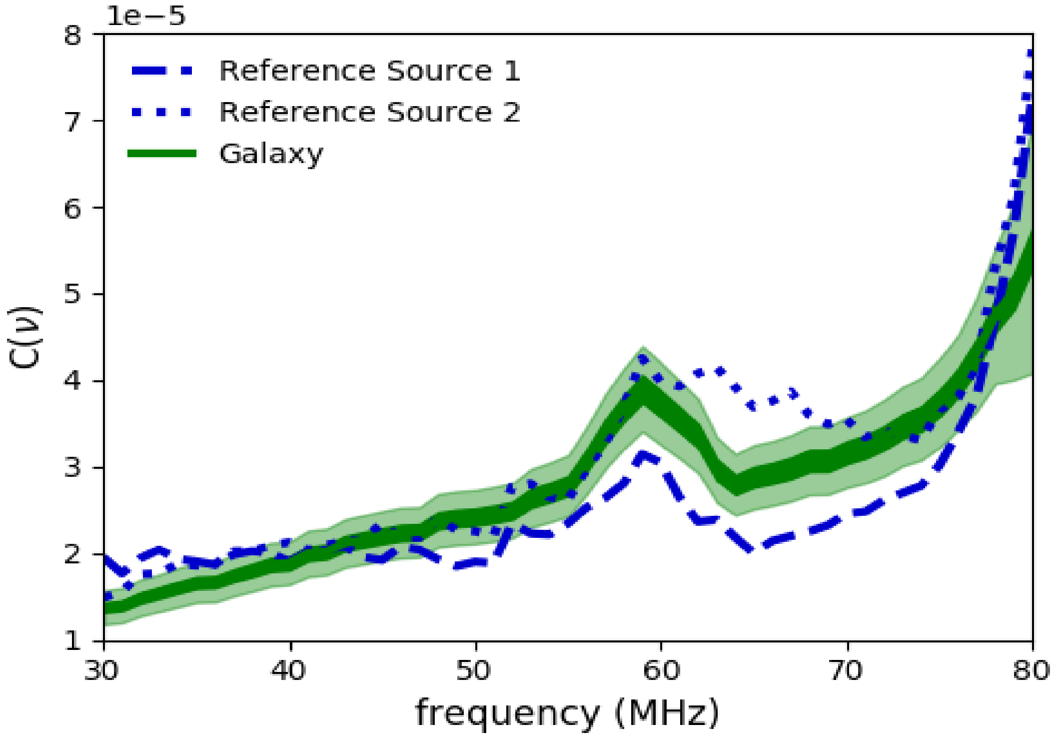



$$X^2 = \sum \frac{(\mathrm{P}(\nu,\mathrm{t})_{\rm data} - \mathrm{P}(\nu,\mathrm{t})_{\rm sim})^2}{\sigma(\nu,\mathrm{t})_{\rm data}}$$

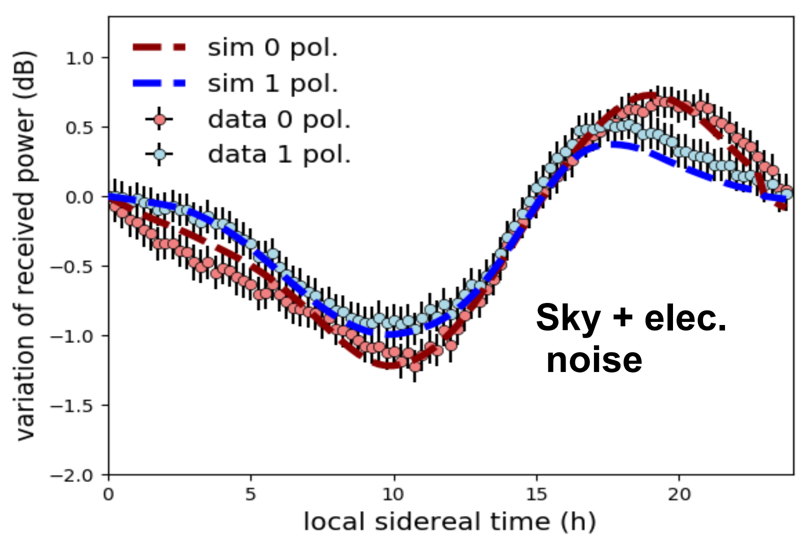
★ All noise contributions are required to fit simulation to data at all frequencies

# Calibration Results

$$\mathbf{C^2(\nu) = [A(\nu)L_{coax}(\nu)G_{RCU}(\nu)S]^{-1}}$$

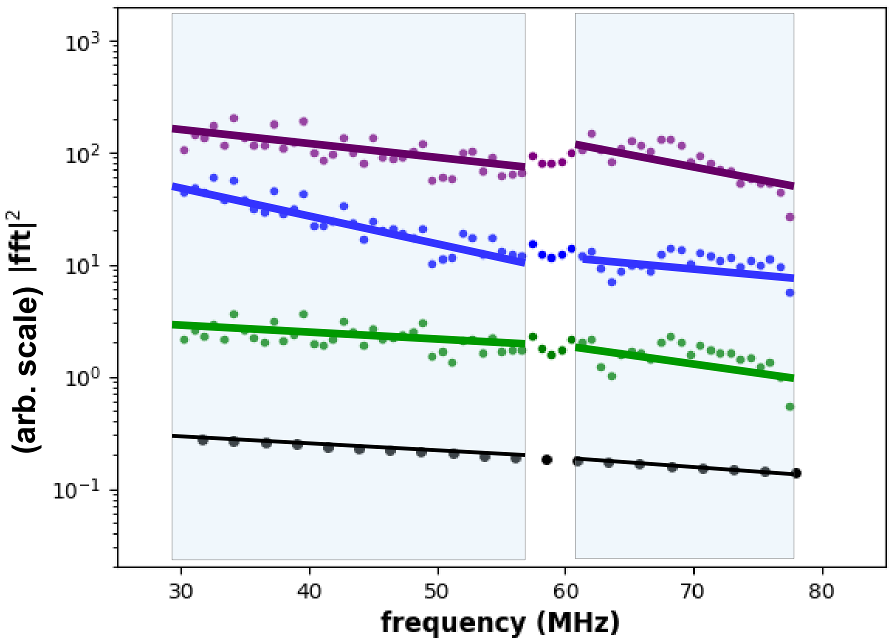



| Uncertainty | Percentage |
|---|---|
| event-to-event fluctuation | 4 |
| galaxy model | 12 |
| electronic noise < 77 MHz | 5-6 |
| electronic noise > 77 MHz | 10-20 |
| **total < 77 MHz** | **14** |

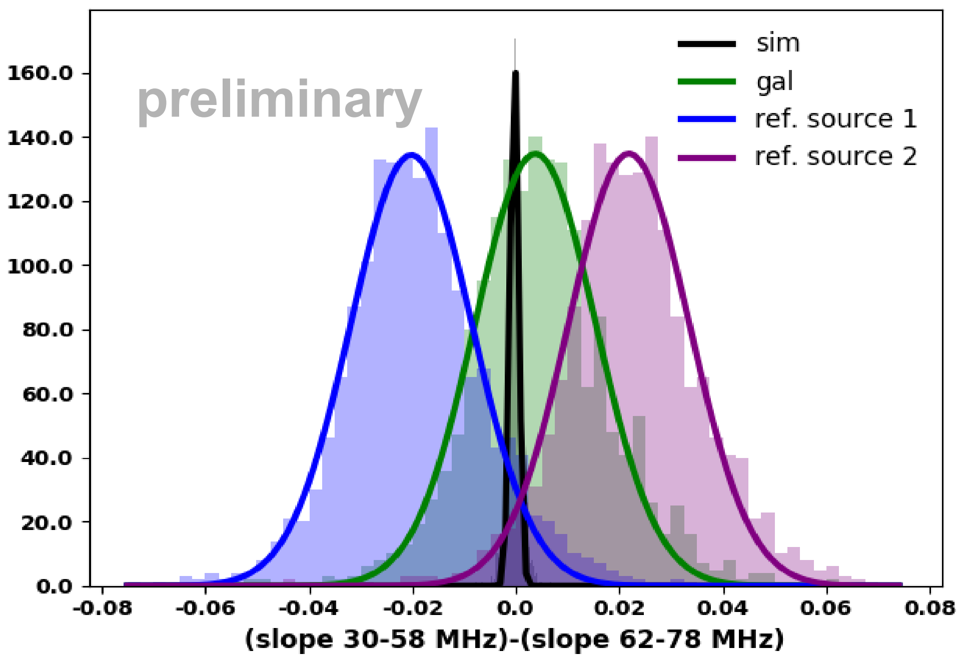


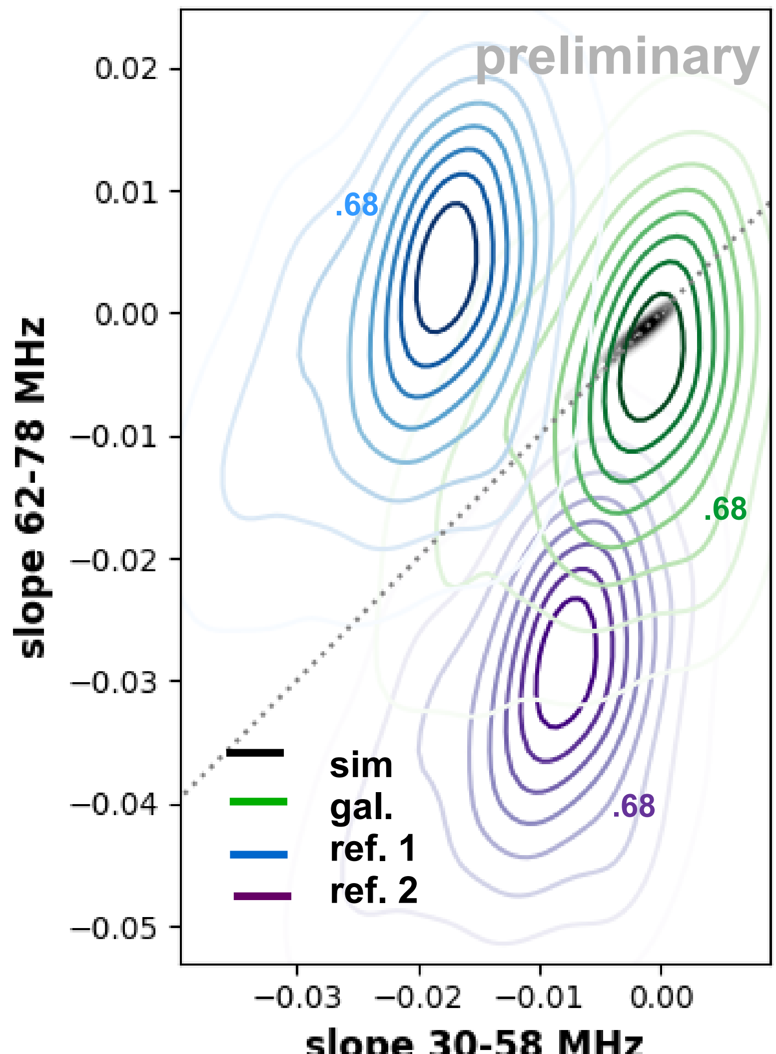

- Galaxy model now limits systematic uncertainties
- Uncertainties from electronic noise are found by comparing resulting calibration constants for different antennas

# Comparison to CoREAS

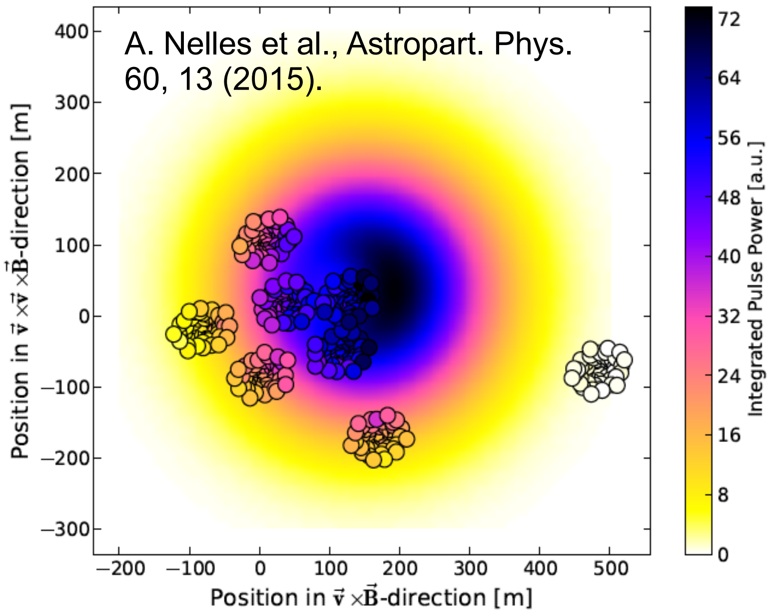



For ~20 strong events (x 3 stations x 48 antennas), compare slope on either side of resonance frequency



# Absolute Energy Scale




## LOFAR 2D radio LDF

CR time-integrated power, new calibration

$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_c)^2 + (y' - Y_c)^2]}{\sigma_+^2}\right)$$
$$- C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x' - (X_c + x_-))^2 + (y' - Y_c)^2]}{(C_3 \cdot e^{C_1 + C_2 \cdot \sigma_+})^2}\right)$$

**Radiation Energy**

$$S_{\text{radio}} = \frac{1}{\sin^2 \alpha} \int_{\mathbb{R}^2} f(\vec{r}) d^2 \vec{r}$$
$$= \frac{A_+ \pi}{\sin^2 \alpha} (\sigma^2 - C_0 C_3^2 \, e^{2\sigma * C_2 + 2C_1})$$

**CR Energy**

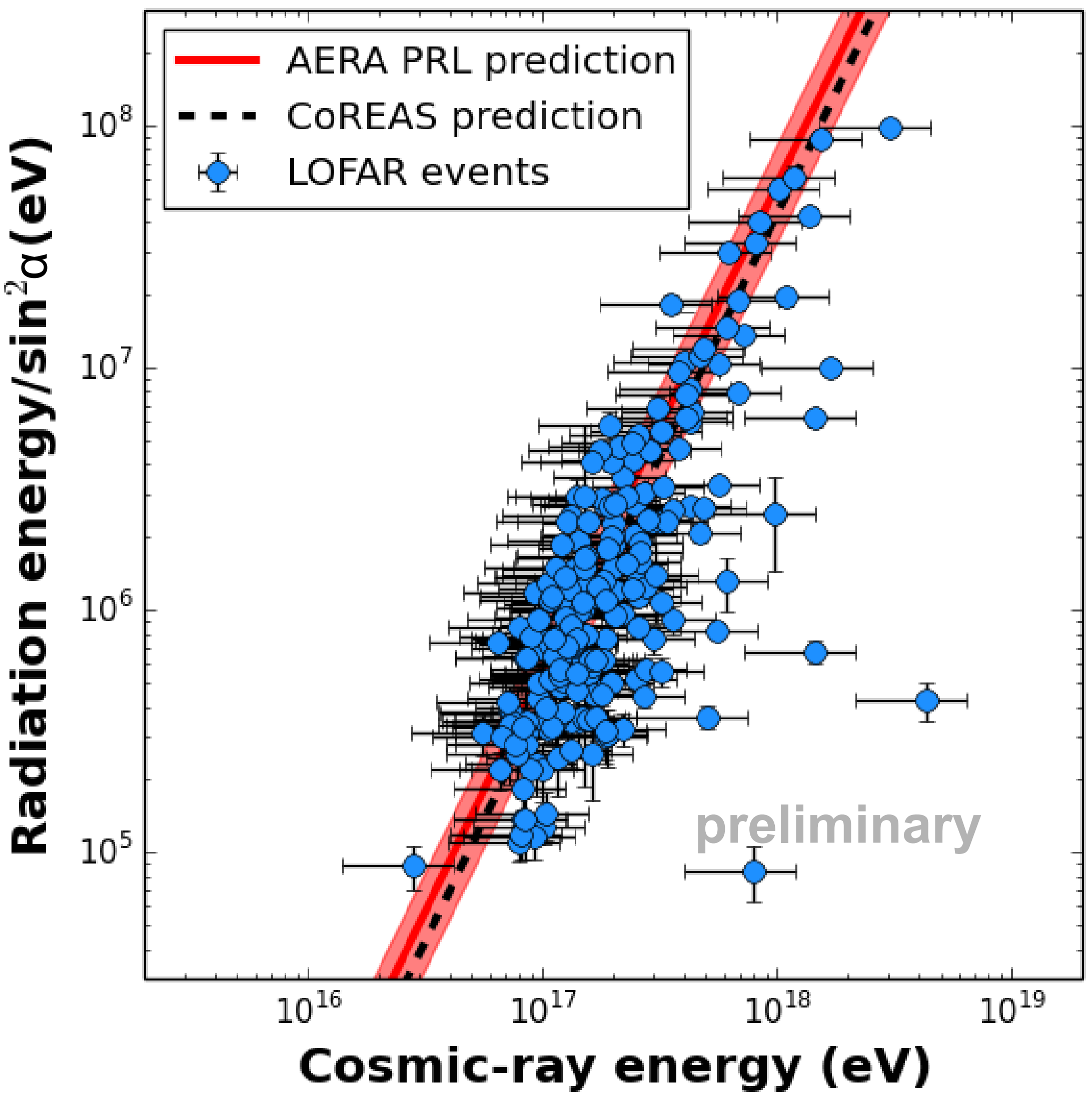
$$S_{\text{radio}} = A \times 10^7 \, \text{eV} \, (E_{\text{CR}} / 10^{18} \, \text{eV})^B$$

$$E_{30-80\,\text{MHz}} = (15.8 \pm 0.7(\text{stat}) \pm 6.7(\text{sys}))\,\text{MeV} \times \left(\sin \alpha \, \frac{E_{\text{CR}}}{10^{18}\,\text{eV}} \, \frac{B_{\text{Earth}}}{0.24\,\text{G}}\right)^2$$

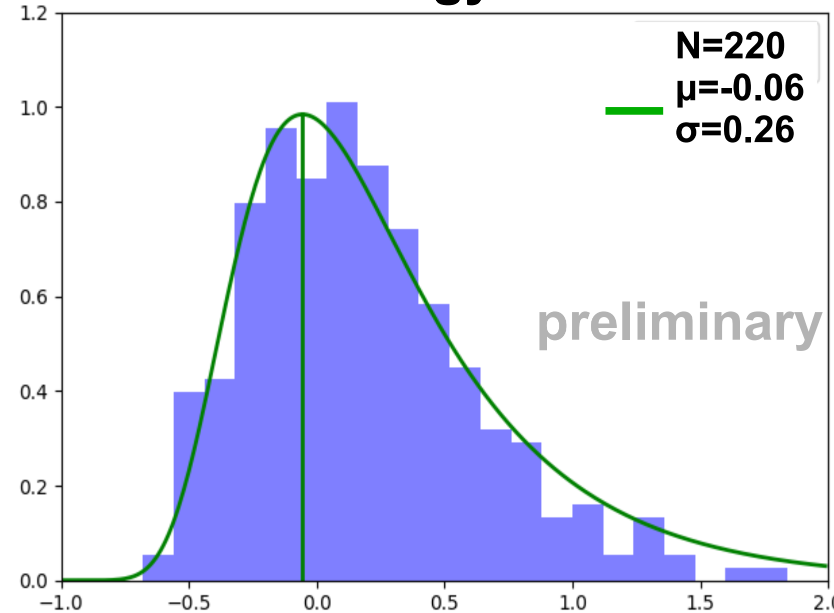
★ **Radiation Energy and CR Energy found using AERA method**

**Adapted for LOFAR from *C. Glaser, M. Erdmann, J. Horandel, et. al, J. Cosmol. Astropart. Phys. 09 (2016) 024* and *A. Aab, et al., Phys Rev. D (2015)***

# Absolute Energy Scale




## Relative Energy Resolution




$$\frac{2(E_{particle} - E_{radio})}{E_{particle} + E_{radio}}$$

- Cuts on core positions, LDF radio fit uncertainties, SNR

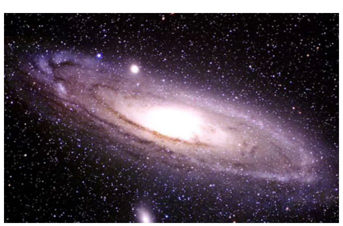
Cosmic-ray energy given by the LORA particle detector energy reconstruction (NKG fitting method)

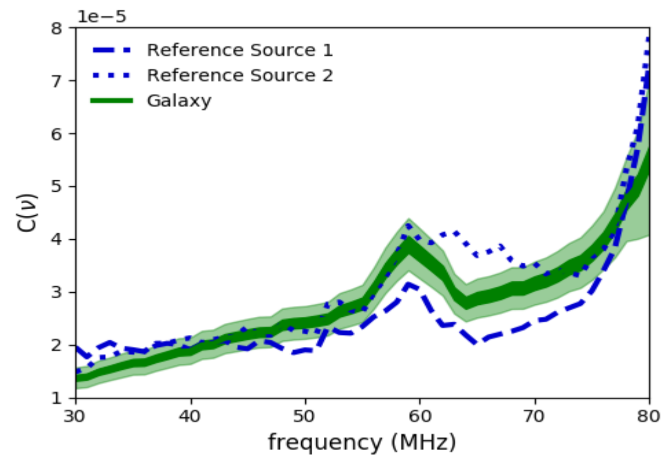
*T. Antoni et al., NIM A 513 (2003) 490.*

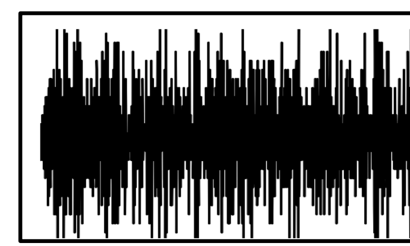
*S. Thoudam et al., Astroparticle Physics 73 (Jan., 2016) 34–43,*

# Conclusions

- Galactic calibration now possible with detailed modeling of the signal chain
- New calibration provides low uncertainties, decreasing uncertainty on LOFAR energy scale, and allows us to proceed with spectral analyses
- Energy scale set with LOFAR radio data and particle data consistent with CoREAS and AERA results



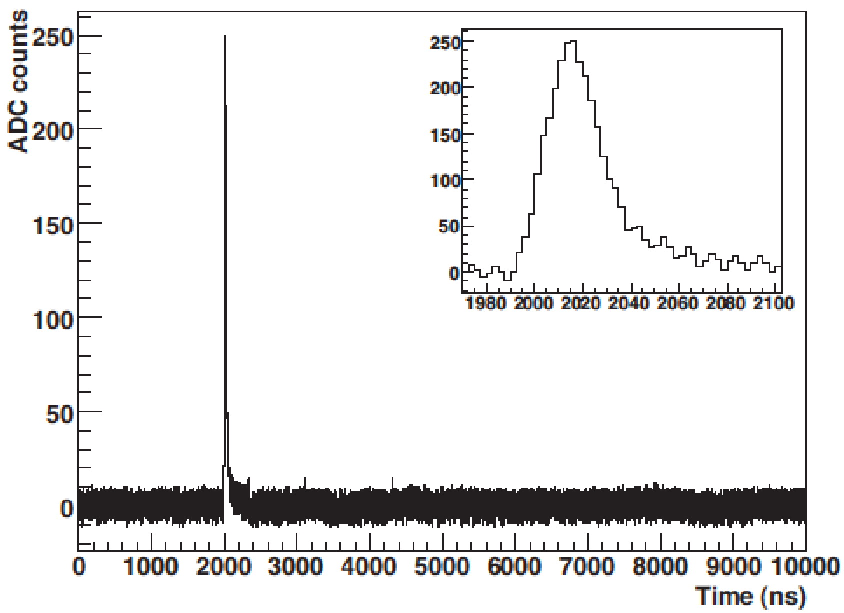


$$\left(\left(\mathbf{P}_{\rm sky}(\nu,\mathbf{t}) + \mathbf{T}_{\rm LNA}\right)\mathbf{G}_{\rm ant}(\nu)\mathbf{A}(\nu)\mathbf{L}_{\rm coax}(\nu) + \mathbf{T}_{\rm RCU}\right)\mathbf{G}_{\rm RCU}(\nu)\mathbf{S} + \mathbf{T}_{\rm ADC} = \mathbf{P}_{\rm sim}(\nu,\mathbf{t})$$

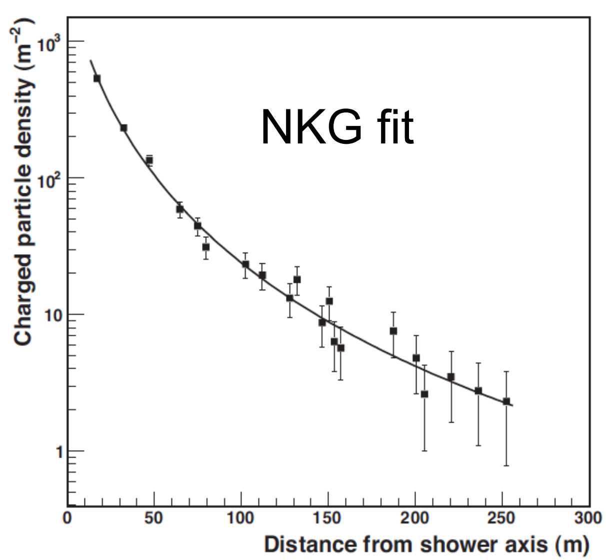
# Backup slides

# LORA Energy Calculation



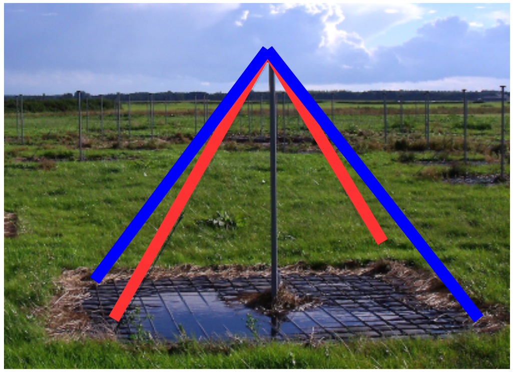

$$\rho(r) = N_{ch} C(s) \left(\frac{r}{r_M}\right)^{s-2} \left(1 + \frac{r}{r_M}\right)^{s-4.5}$$

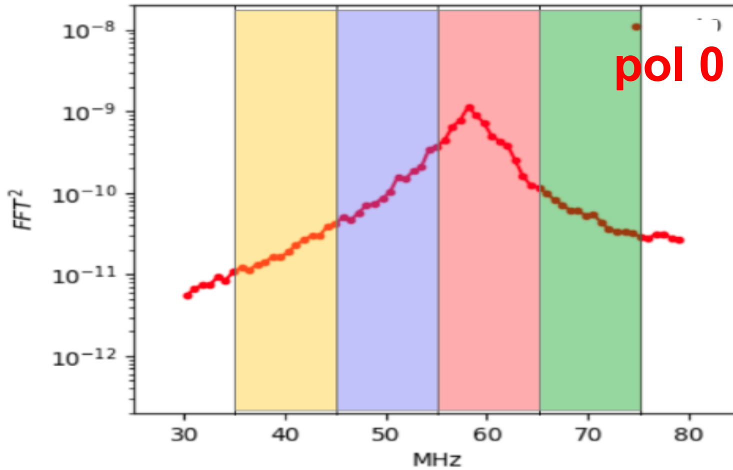
$$\log_{10} E_{\mathrm{p}} = \zeta + \xi \cdot \log_{10} N_{\mathrm{ch},21^\circ}$$

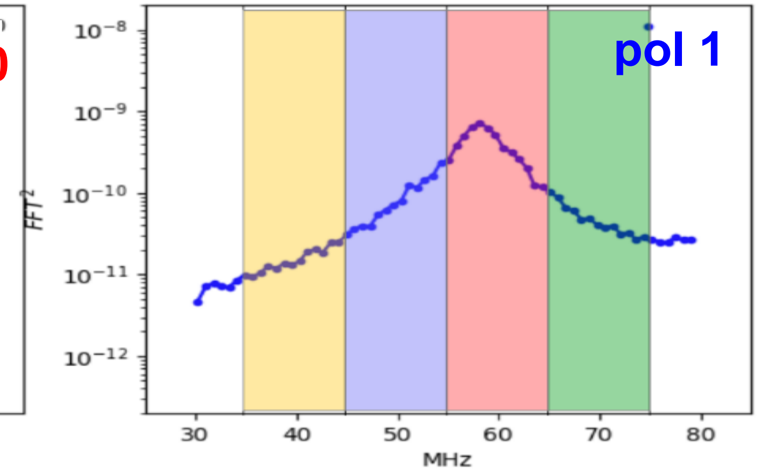



| Composition | $\zeta$ | $\xi$ | $\chi^2$/dof |
|---|---|---|---|
| mixed | $1.23 \pm 0.14$ | $0.95 \pm 0.02$ | 19.3/14 |
| hydrogen | $1.48 \pm 0.13$ | $0.93 \pm 0.02$ | 19.3/14 |
| iron | $1.12 \pm 0.14$ | $0.96 \pm 0.03$ | 19.3/14 |

# Using TBBs to Monitor Antennas



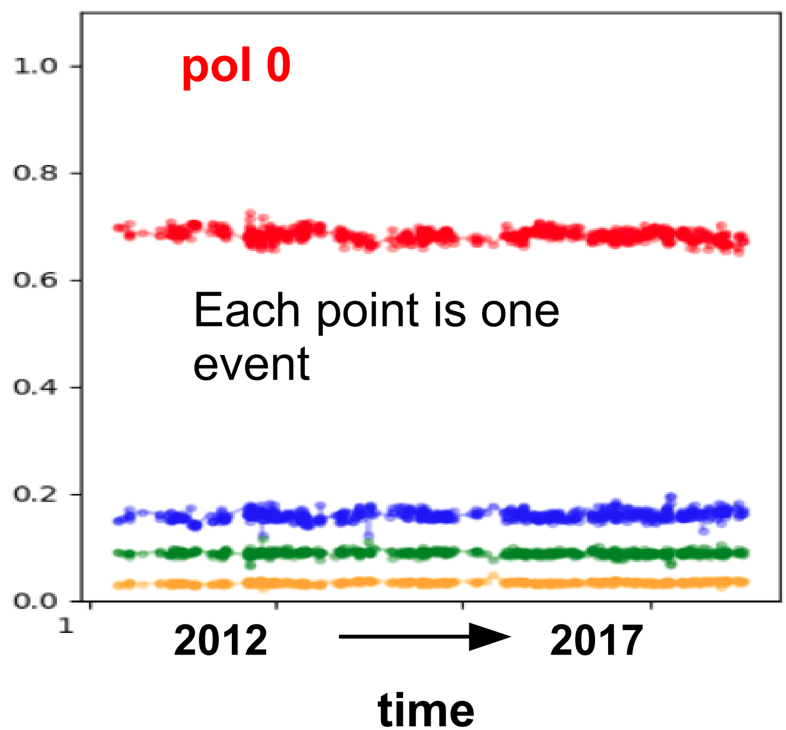


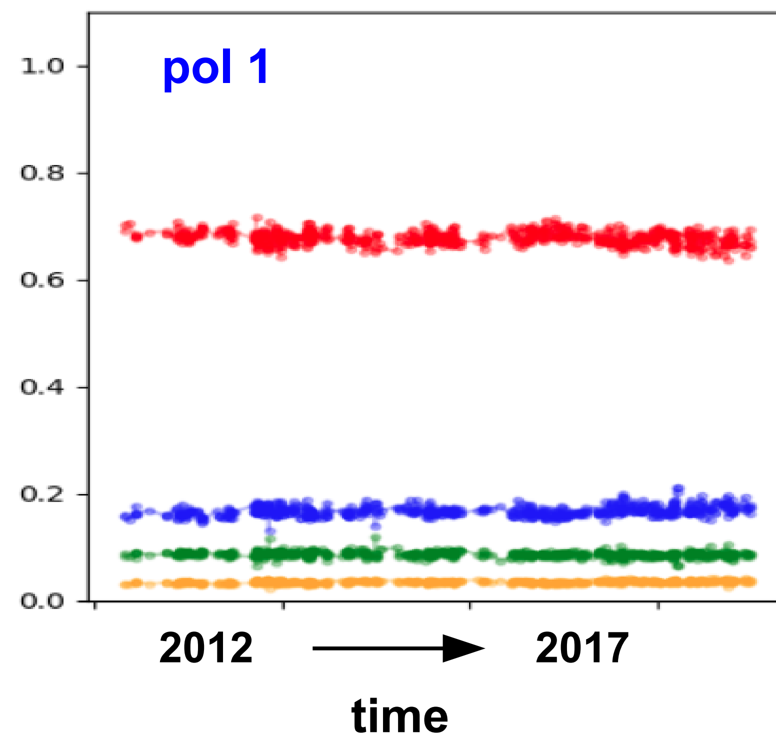




**Track power in each antenna, over lifetime of experiment**

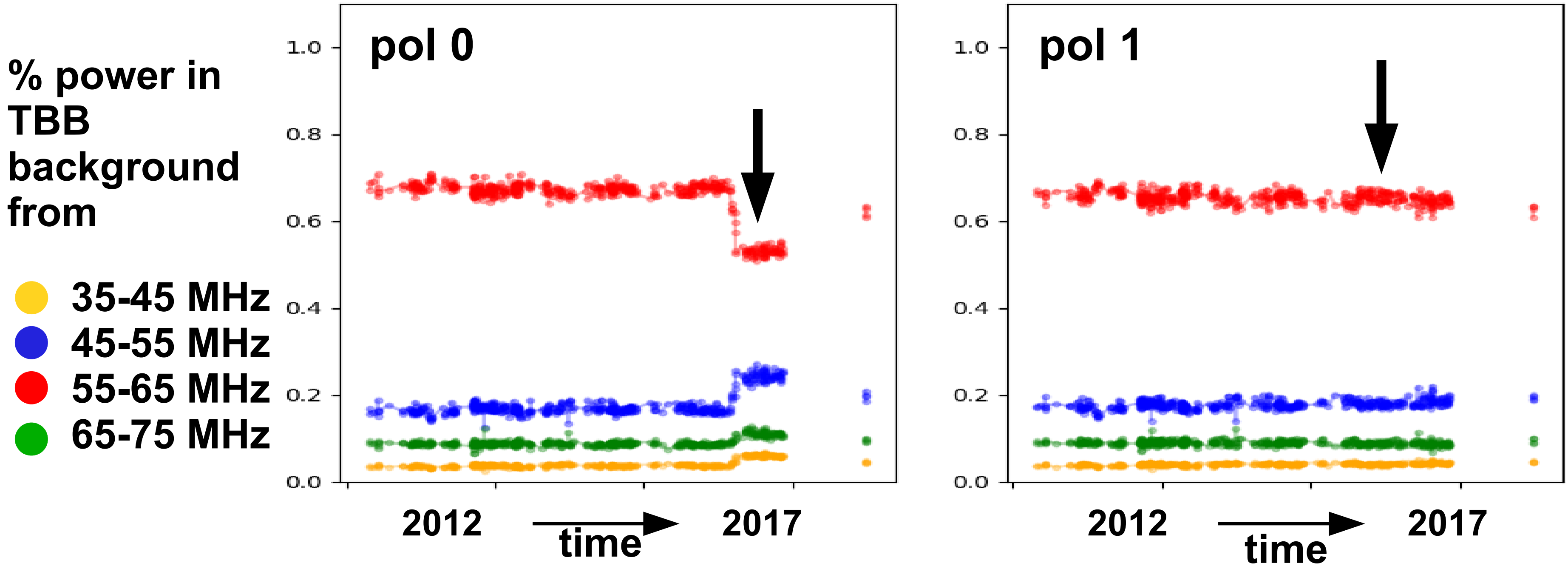
**% power in TBB background from**

- 35-45 MHz
- 45-55 MHz
- 55-65 MHz
- 65-75 MHz

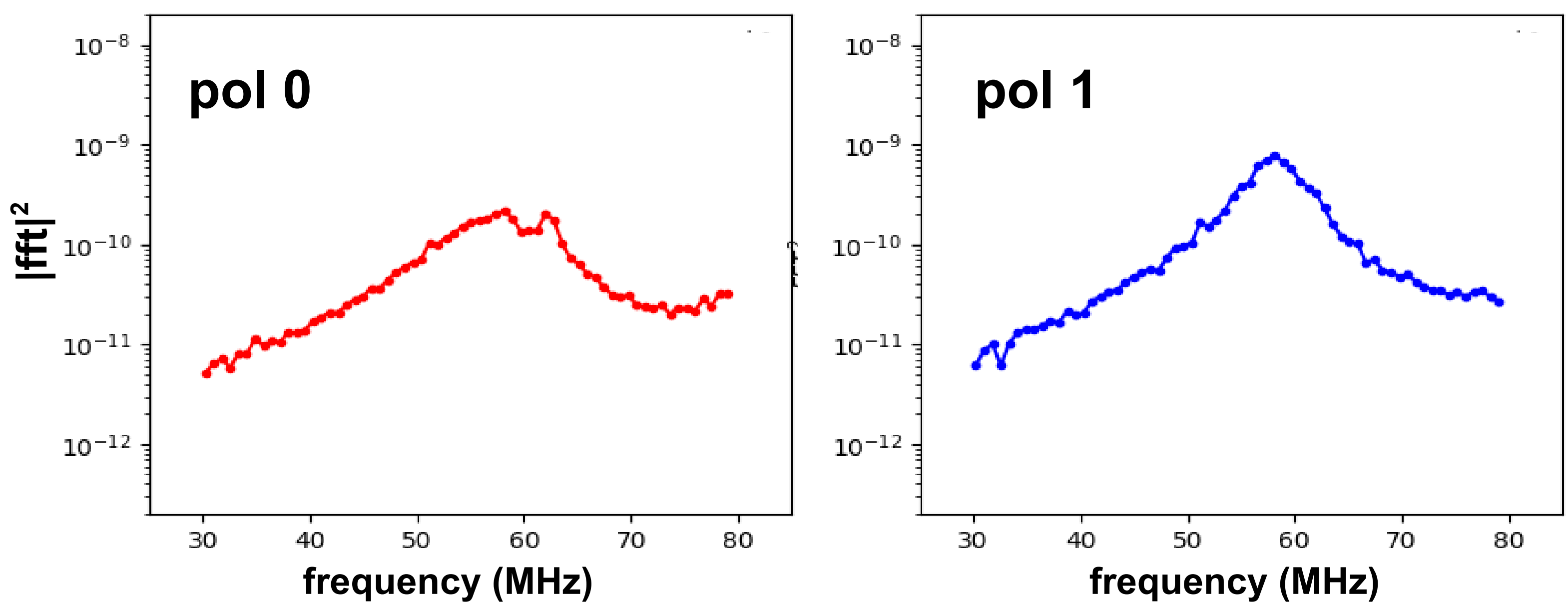


# TBB Monitoring



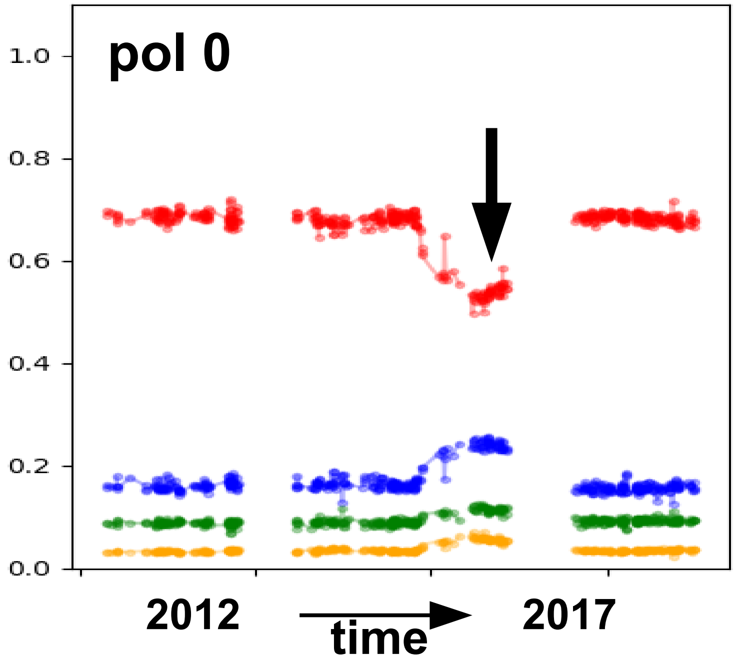

Antenna pol 0 is broken, resonance frequency changed

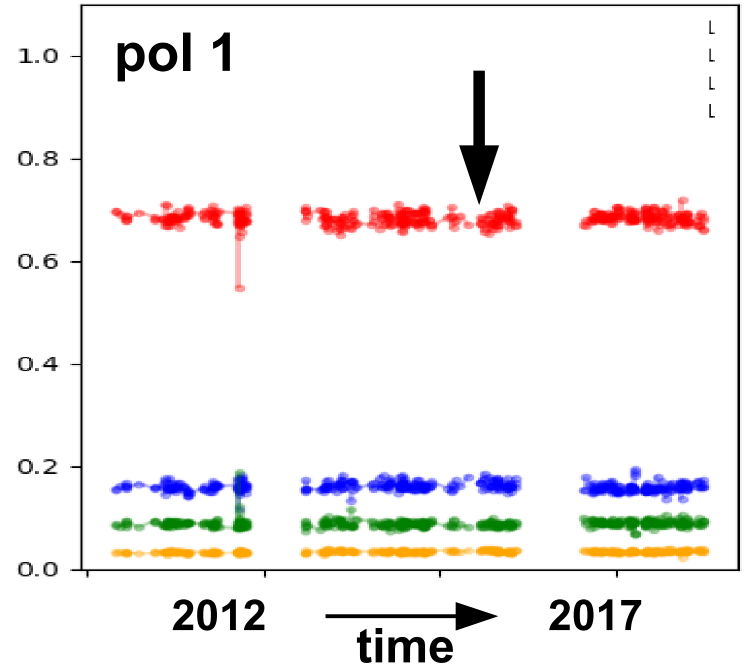


# TBB Monitoring

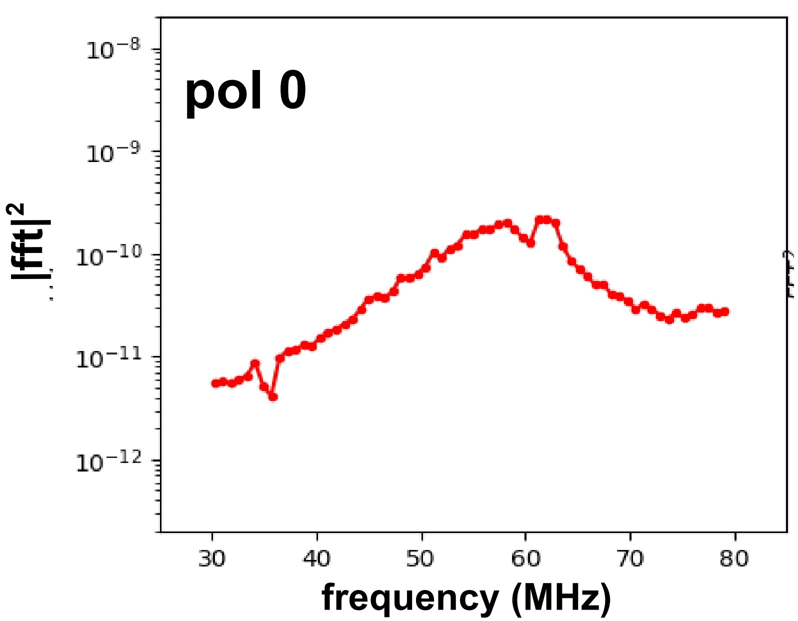
**% power in TBB background from**

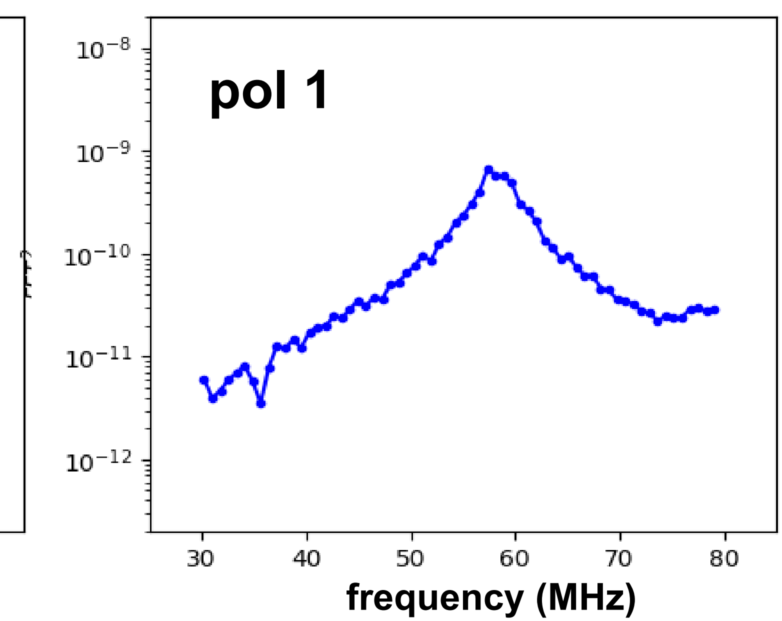
- 35-45 MHz
- 45-55 MHz
- 55-65 MHz
- 65-75 MHz




Antenna pol 0 is broken, resonance frequency missing

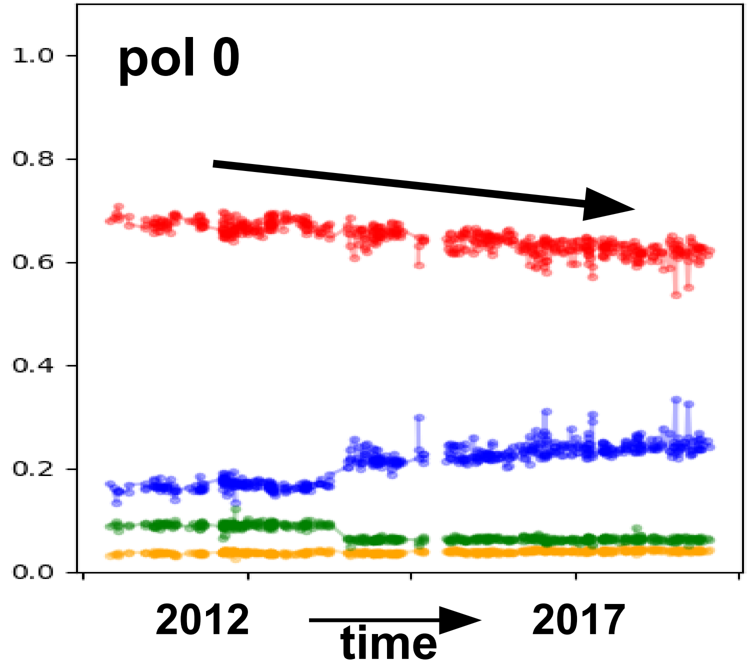


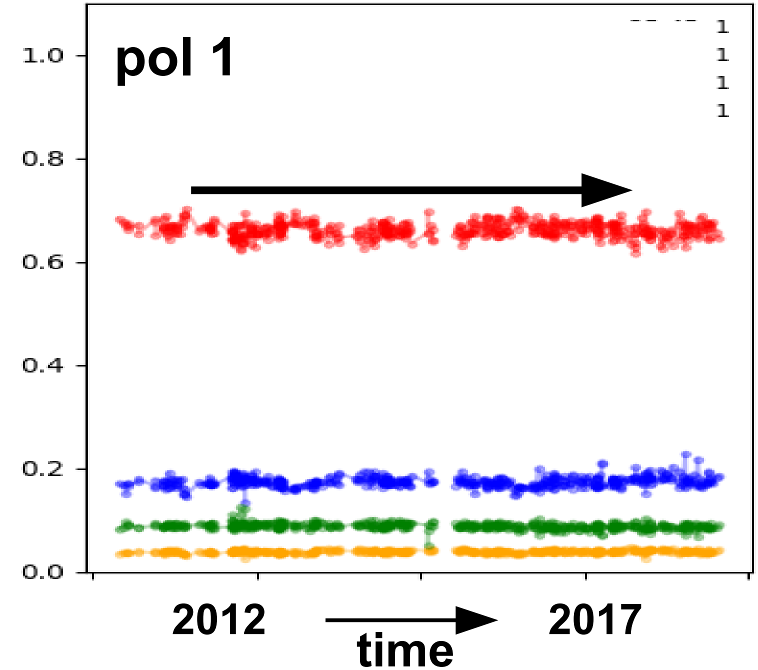



# TBB Monitoring

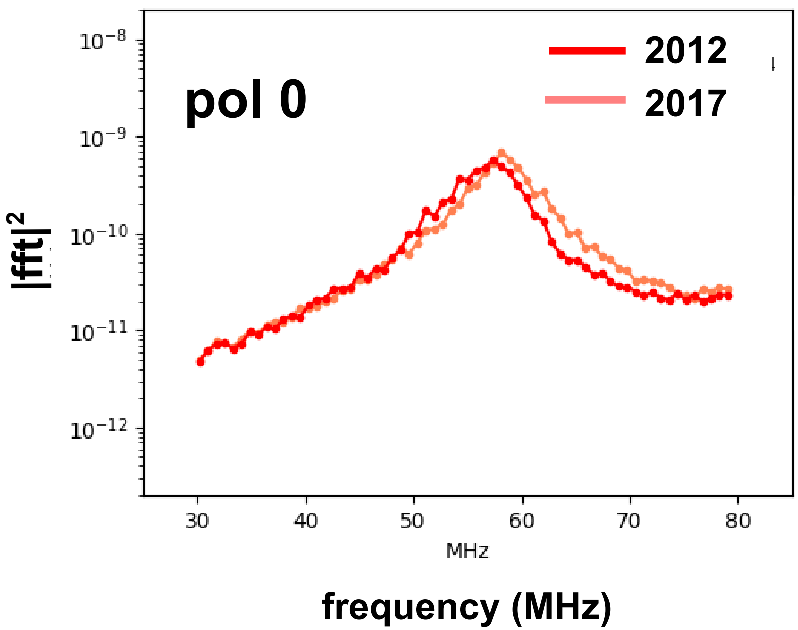
**% power in TBB background from**

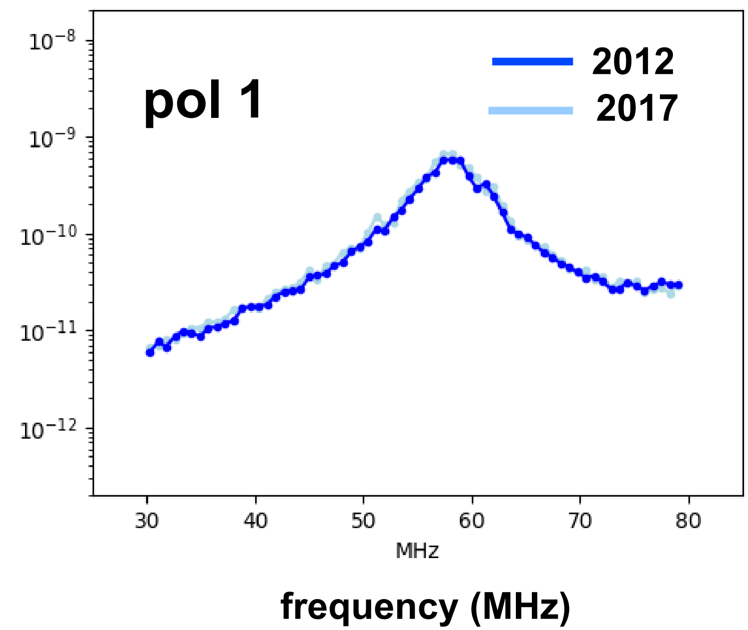
- 35-45 MHz
- 45-55 MHz
- 55-65 MHz
- 65-75 MHz



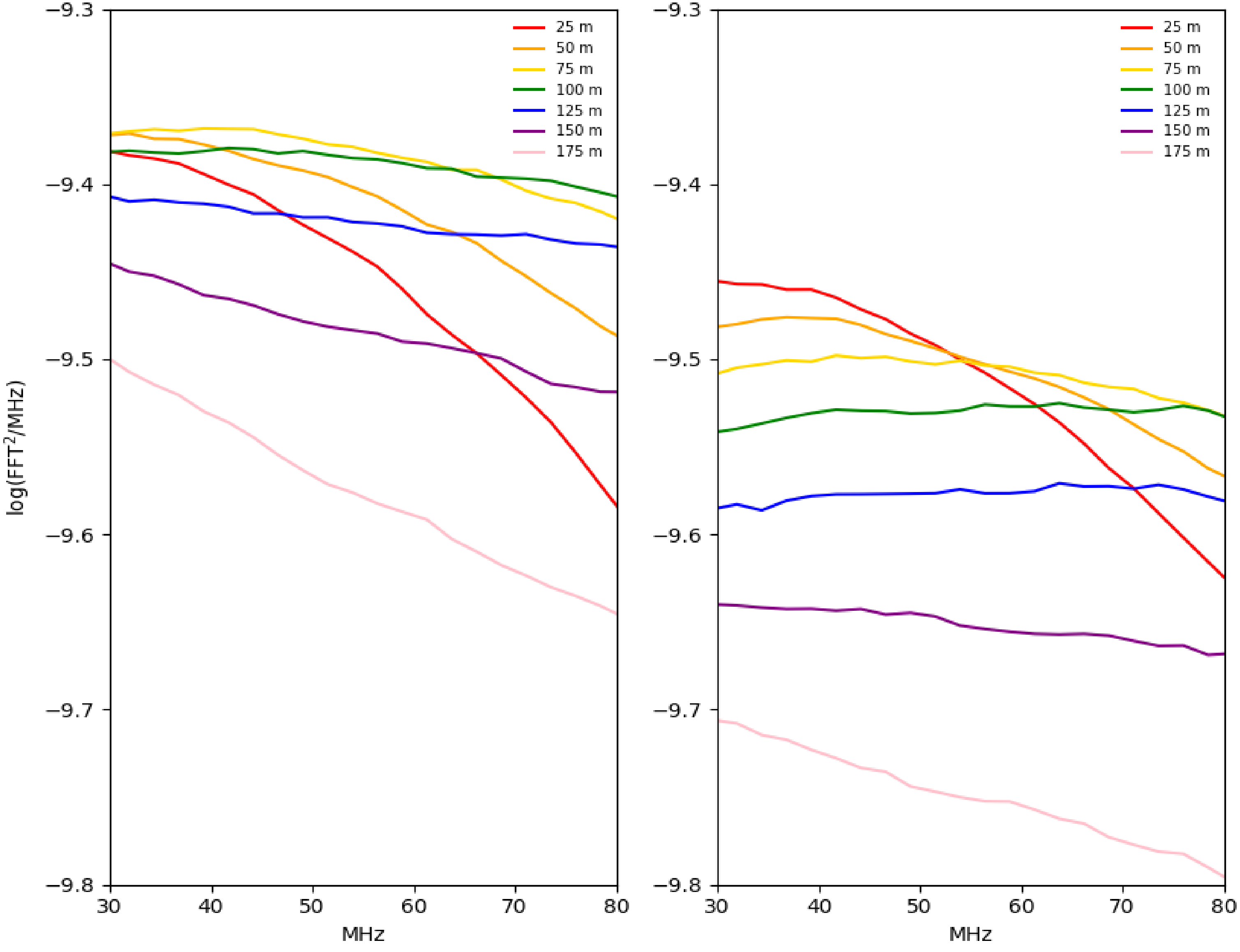




Gradual shift of resonance frequency in pol 0

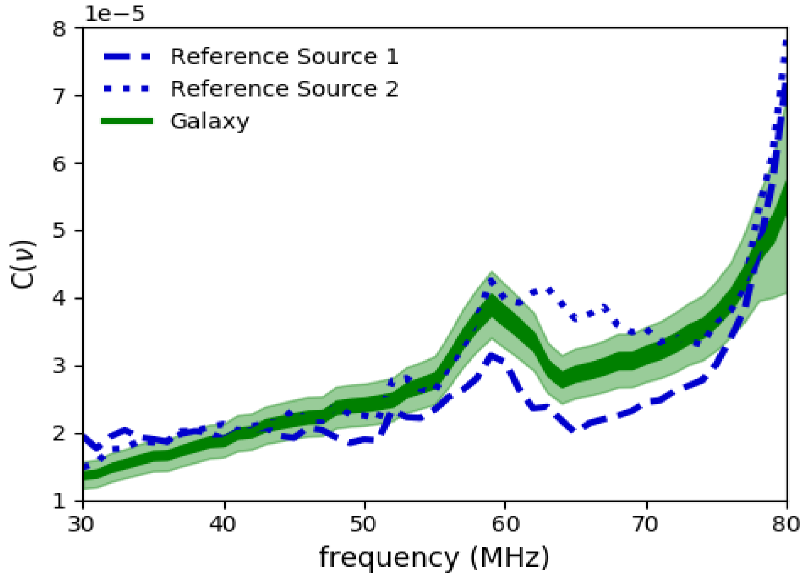


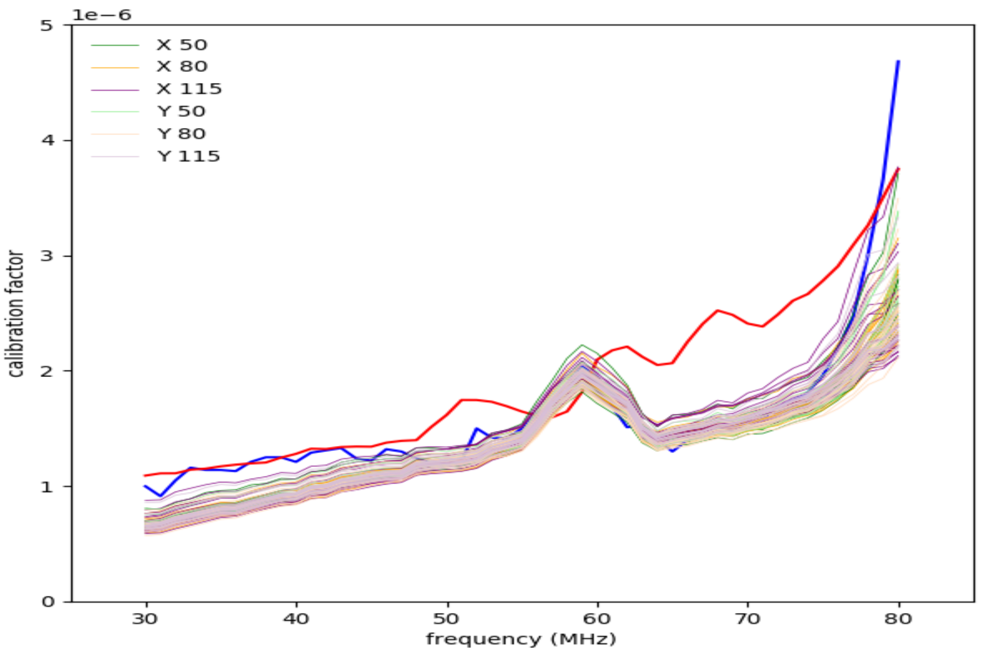
# Example Spectra



# Electronic Noise Uncertainty




| Uncertainty | Percentage |
|---|---|
| event-to-event fluctuation | 4 |
| galaxy model | 12 |
| electronic noise < 77 MHz | 5-6 |
| electronic noise > 77 MHz | 10-20 |
| **total < 77 MHz** | **14** |




## <u>Uncertainty in the electronic noise</u>

1. find noise constants from fit using all antennas
2. use constant T to find calibration factor for individual antennas
3. take frequency dependent standard deviation of individual antenna calibrations

# Fit by Frequency