PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

INSTITUTO DE FÍSICA
Universidade Federal Fluminense

Update of long-term calibration of AERA stations using the Galactic radio emission

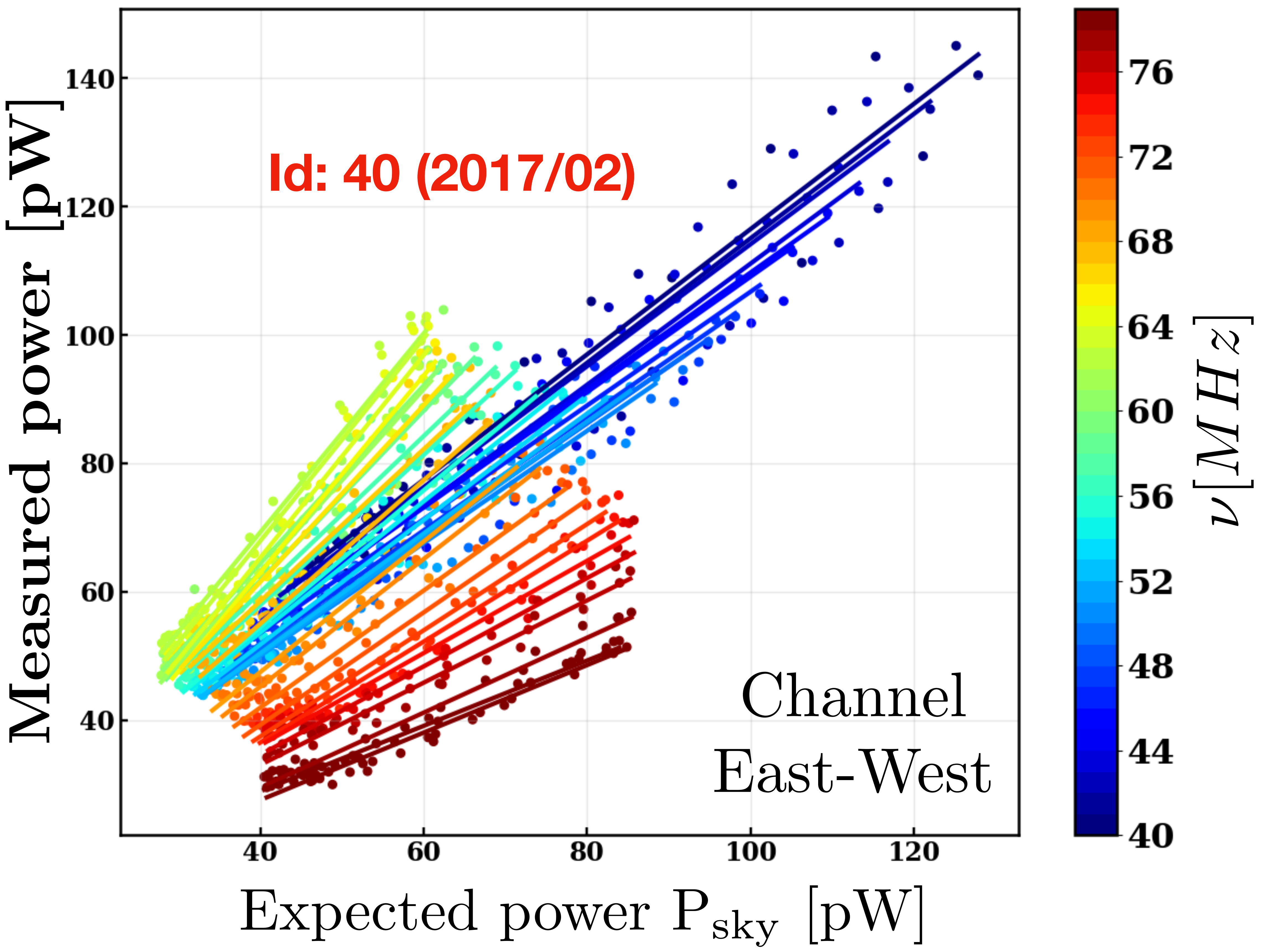
Diego Correia dos Santos, Rogério Menezes de Almeida

LTP meeting
October 2023

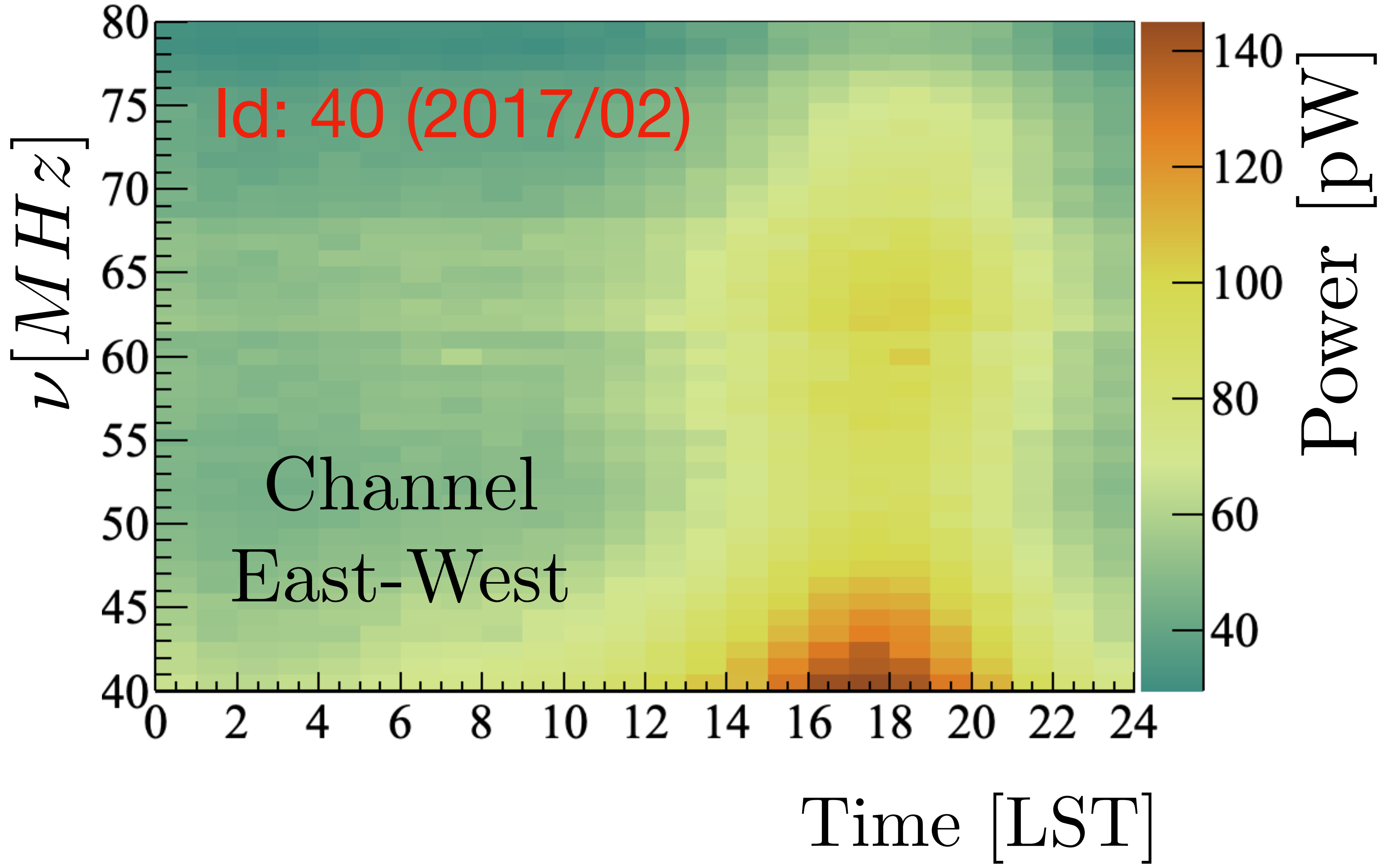
Calibration method overview

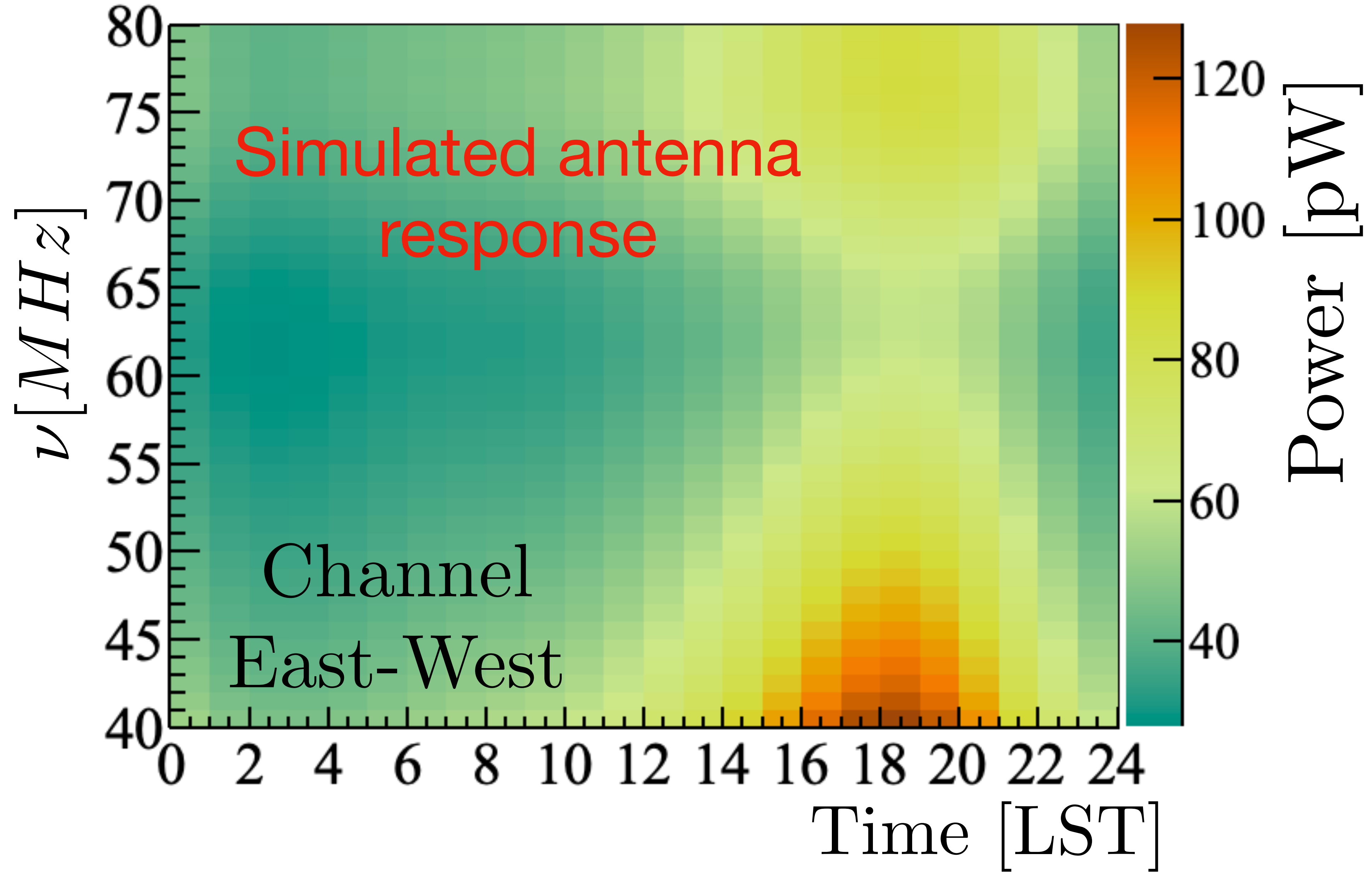
$$P_{model}(t,\nu) = P_{sky}(t,\nu)G_{ant}(\nu)G_{RCU}(\nu)\,C_0^2(\nu) + N_{tot}(\nu)$$

- Independent linear fit for each frequency band



After removing RFI





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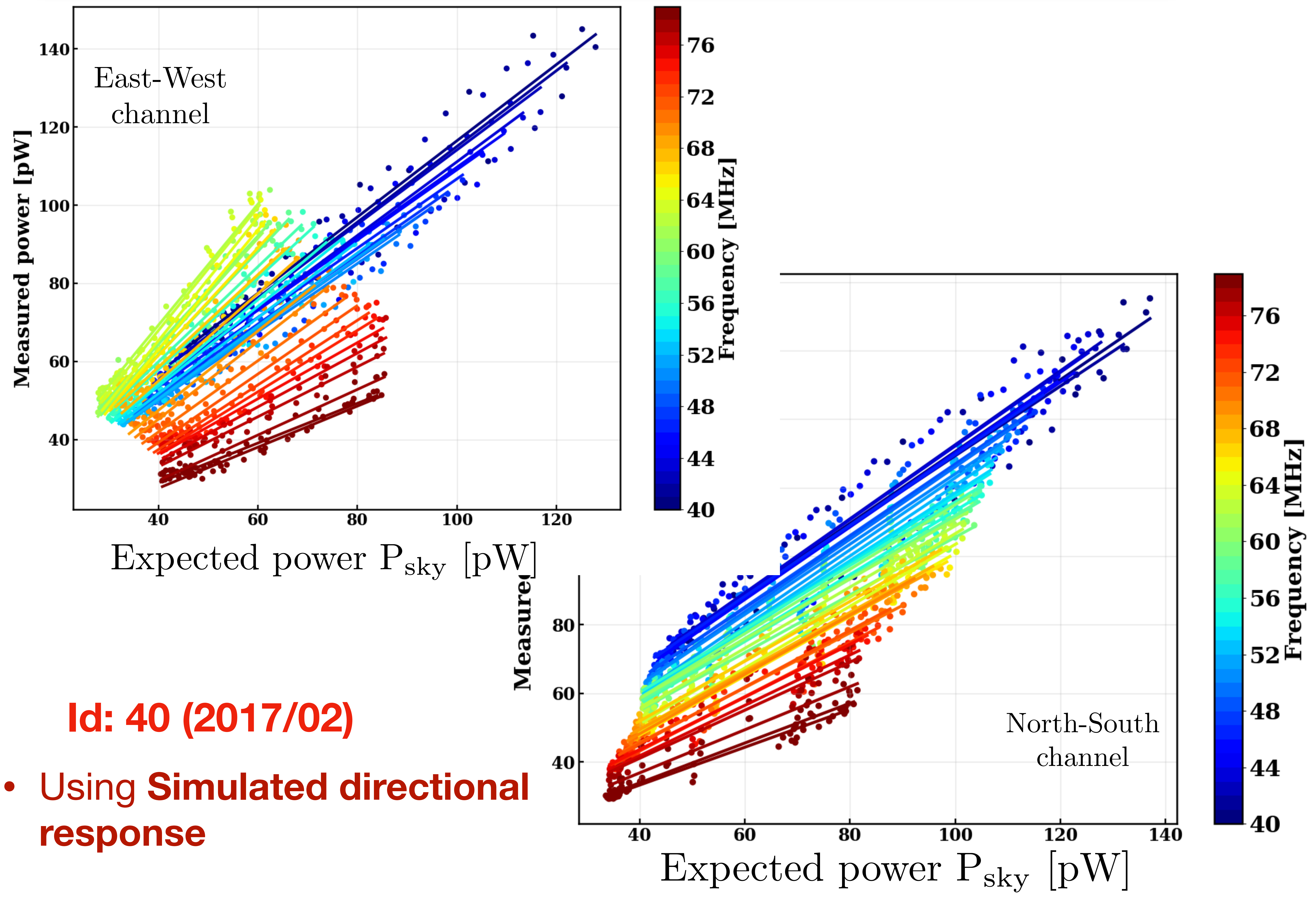
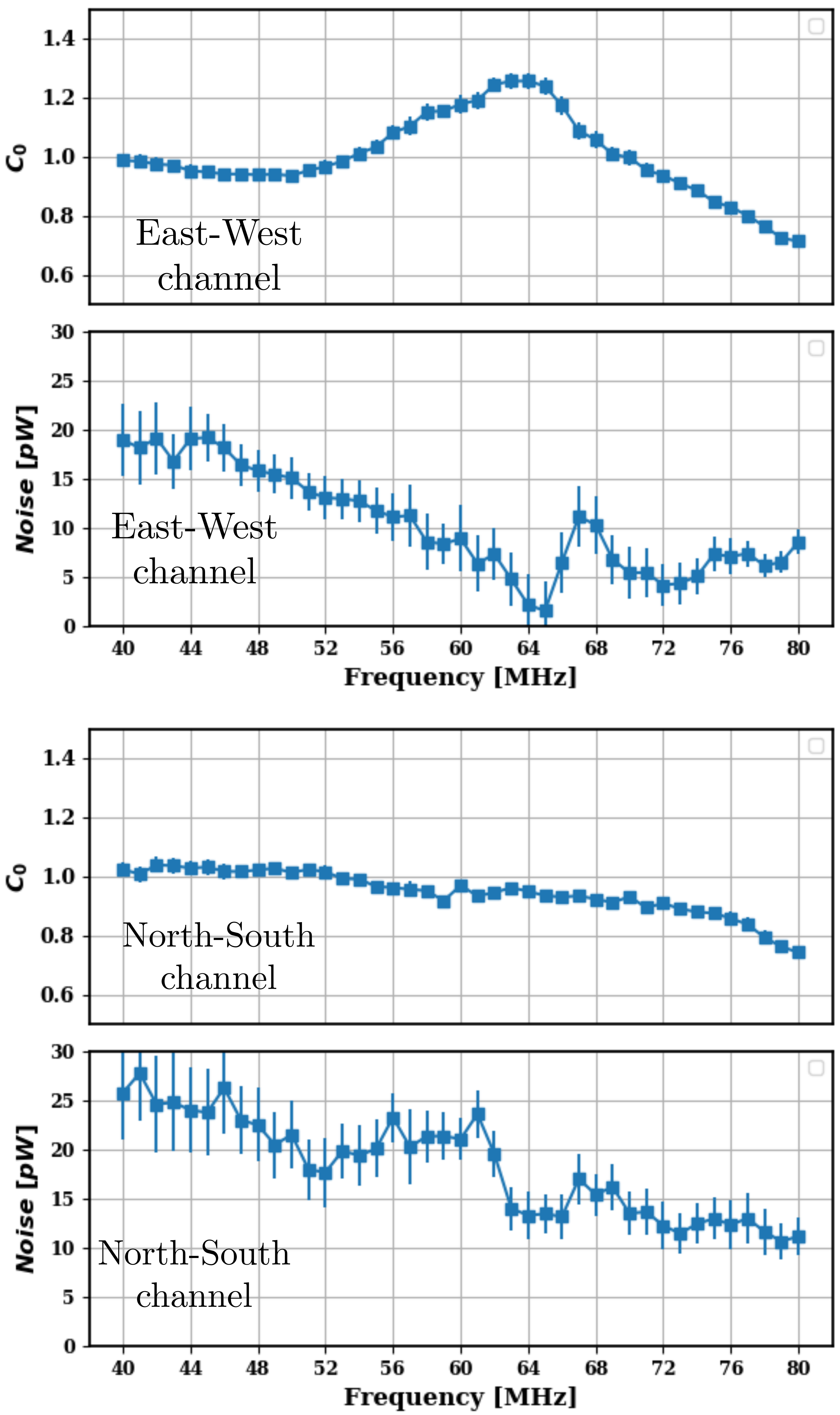


Id: 40 (2017/02)

- Using **Simulated directional response**

(Butterfly KIT/BUW AERA II)



AERA Galactic Calibration implementation within Offline

- We implemented two modules in Offline:

  ➔ **RdChannelGalacticCalibrationGenerator**

  Computes the calibration constants (**any sky temperature model**) for each antenna type (LPDA or Butterfly).

  ➔ **RdChannelGalacticCalibrator**

  Used to correct the trace using the calibration constants

- We describe all details about the implementation of the modules within Offline in **GAP2023_036.**

Pierre Auger Observatory GAP2023_036

AERA Galactic Calibration implementation within Offline

D. Correia dos Santos[1], R. M. de Almeida[1],

Universidade Federal Fluminense, RJ, Brazil[1]

Abstract

A comprehensive understanding of the antenna response is crucial to achieve accurate interpretation of the AERA data. Thus, careful calibration of the antennas is essential. This note provides a detailed explanation of how to perform an absolute calibration using the radio emission from the Galaxy. The approach involves propagating a model of the entire radio sky through the system response, which encompasses the antenna, filters, and amplifiers. The resulting output is then compared with the averaged spectra recorded by stations. We provide a comprehensive description of the modules designed to obtain calibration constants and correct traces within the Offline framework.

1 Introduction

The Auger Engineering Radio Array (AERA)[1] is currently the largest system designed to measure radio emissions from ultra-high energy extensive air showers in the frequency range between 30 MHz and 80 MHz in two polarization directions (East-West and North-South directions relative to magnetic north). An accurate description of the detector response is necessary to interpret the data collected by the stations correctly. Previously, this was achieved by measuring the analog chain in the laboratory and simulating and measuring the directional response of the antenna. In this work, we describe the implementation of the absolute Galactic calibration within the Offline framework. To achieve this, we developed two essential modules: one for determining the calibration constants for each antenna and another for applying these obtained constants to correct the traces. This document is intended to serve as a comprehensive reference guide for users of these modules, providing a detailed description of the applied methodology, including the computed quantities and their implementation within the Offline system.

Detailed study of antennas behavior over the years

- The calculation of the calibration constants on a monthly basis, covering a time span of approximately 10 years and involving a total of 152 antennas requires the analysis of a substantial volume of data, and caution is necessary to ensure that sporadic variations in local noise or antenna behavior do not compromise the accuracy of the Galactic calibration

- Goal: Study the behavior of each antenna over time. For this, we chose to analyze average spectral density patterns exhibited by each antenna over time, classifying them into four distinct categories. We describe the frequency of occurrence of each class and the extent of their impact on the absolute calibration.

- The average spectral density is defined as: $I = \frac{1}{N}\sqrt{\sum_{i=1}^{N} A^2(\nu_i)}$

  where *A* is the signal amplitude in frequency bin *i* and *N* is the total number of bins

Pierre Auger Observatory GAP2023-044

Analysis and classification of average spectral densities measured by AERA antennas from 2013 up to 2020

D. Correia dos Santos[1], R. M. de Almeida[1]

Universidade Federal Fluminense, RJ, Brazil[1]

Abstract

The Galactic calibration of AERA antennas is a crucial process, essential for ensuring the accuracy of their measurements. This calibration involves comparing the expected modulation of radio signal intensity as a function of Local Sidereal Time (LST), resulting from the passage of the Galaxy across the Auger site, to the actual measurements recorded at each detector station. To achieve this, we utilize periodically triggered data, which not only offer a reliable measure of the Galactic background but also contain cosmic ray signals and unwanted radio frequency interference (RFI) from both external sources and internal electronic noise. It is important to minimize the impact of these RFI on the calibration constant, as they can bias the results. We calculate the calibration constants on a monthly basis, covering a time span of approximately 10 years and involving a total of 152 antennas. This requires the analysis of a substantial volume of data, and caution is necessary to ensure that sporadic variations in local noise or antenna behavior do not compromise the accuracy of the Galactic calibration. In this work, we study the average spectral density patterns exhibited by each antenna over time, classifying them into four distinct categories. We describe the frequency of occurrence of each class and the extent of their impact on the absolute calibration. Tables reporting on the behavior of all KIT/BUW AERA antennas from 2013 to 2020, separated by channel, on a monthly basis are presented at the end.

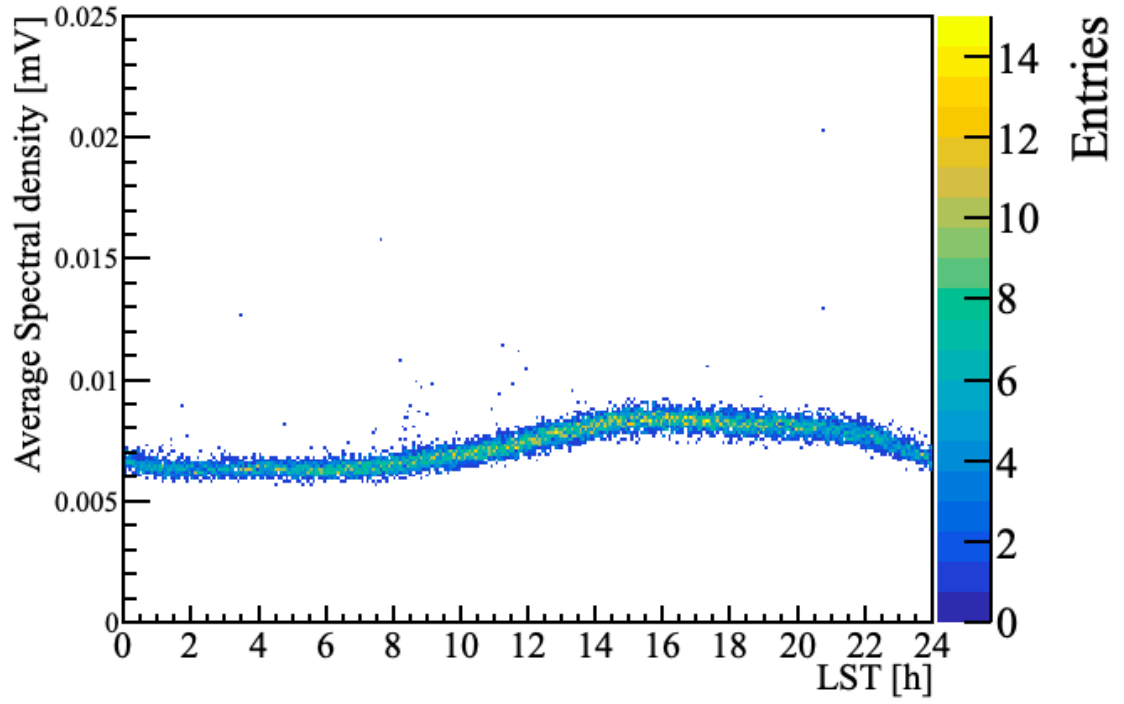
1 Introduction

A comprehensive understanding of the antenna response is crucial to achieve accurate interpretation of the AERA data. Thus, careful calibration of the antennas is essential. This is done by comparing the expected signal coming from the sky with the one measured by the detector station. A description of the Galactic calibration as well as its

Detailed study of antennas behavior over the years

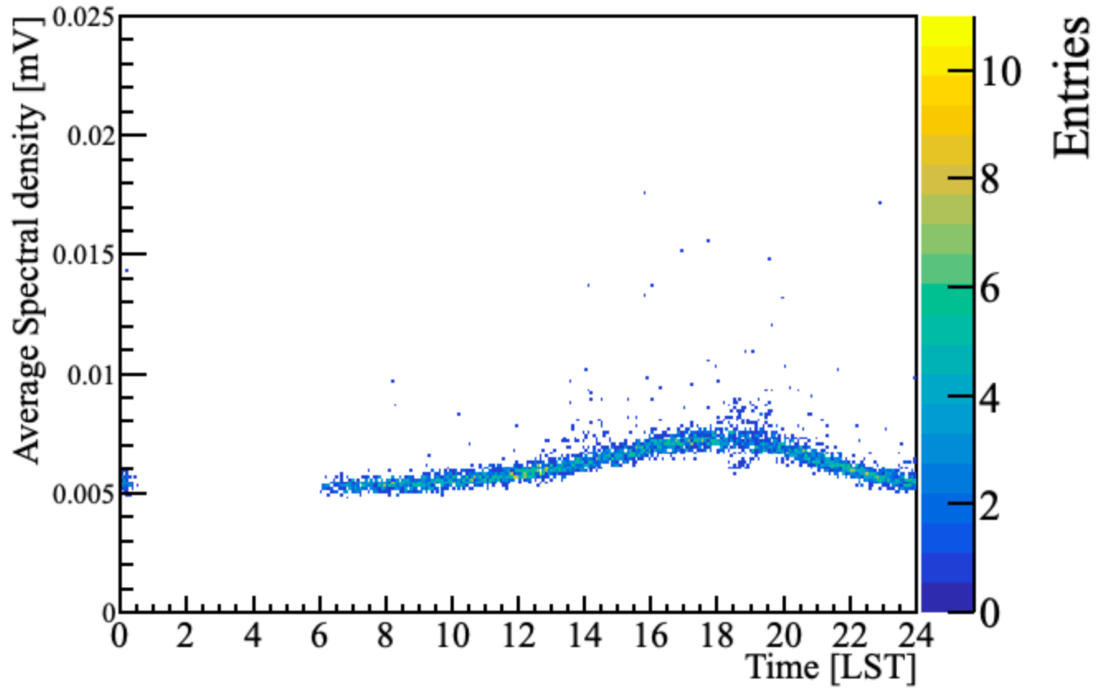
Spectral density with expected behavior

- This classification demonstrates a spectral density distribution along the LST consistent with the expected galactic modulation. These signals are stable throughout the entire LST and have noise that is easy to identify and remove using the standard threshold method.
- This classification corresponds to approximately 87% of all data from 2013 to 2020 for Butterfly antennas (**~90.5% in previous works**) and 74.8% for LPDA antennas (**~92.2% in previous works**).



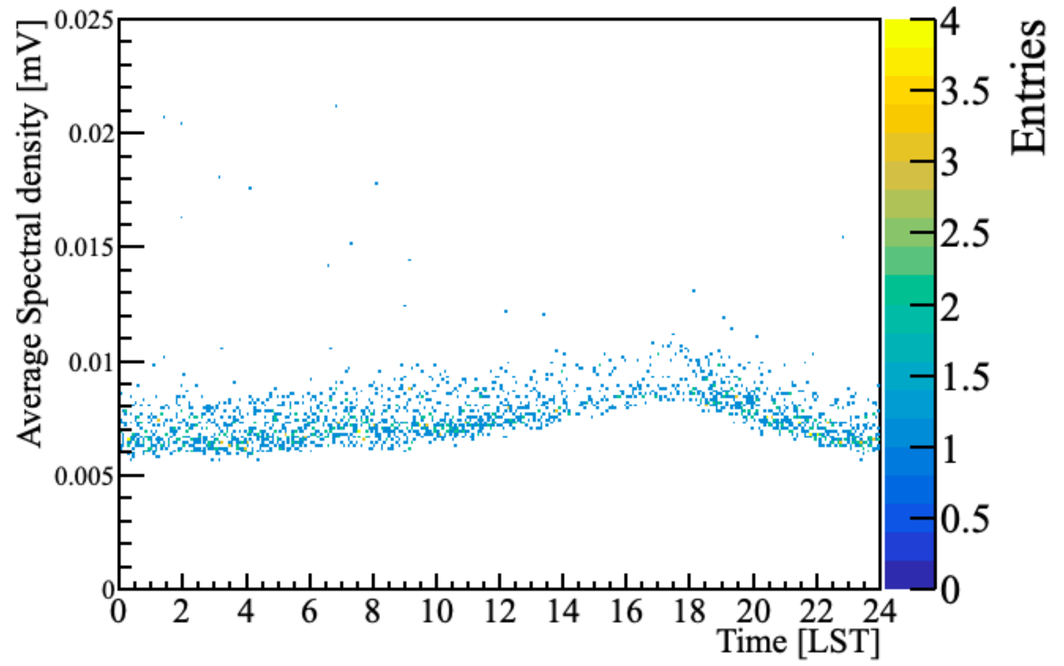
Spectral density with lack of data in ranges of LST

- This classification is characterized by an incomplete distribution regarding time in LST and, therefore, this data cannot be used in the present offline Galactic calibration approach.
- This classification corresponds to approximately 4% of all data from 2013 to 2020 for Butterfly antennas (**~1.9% in previous works**) and 10.7% for LPDA antennas (**~1.1% in previous works**).



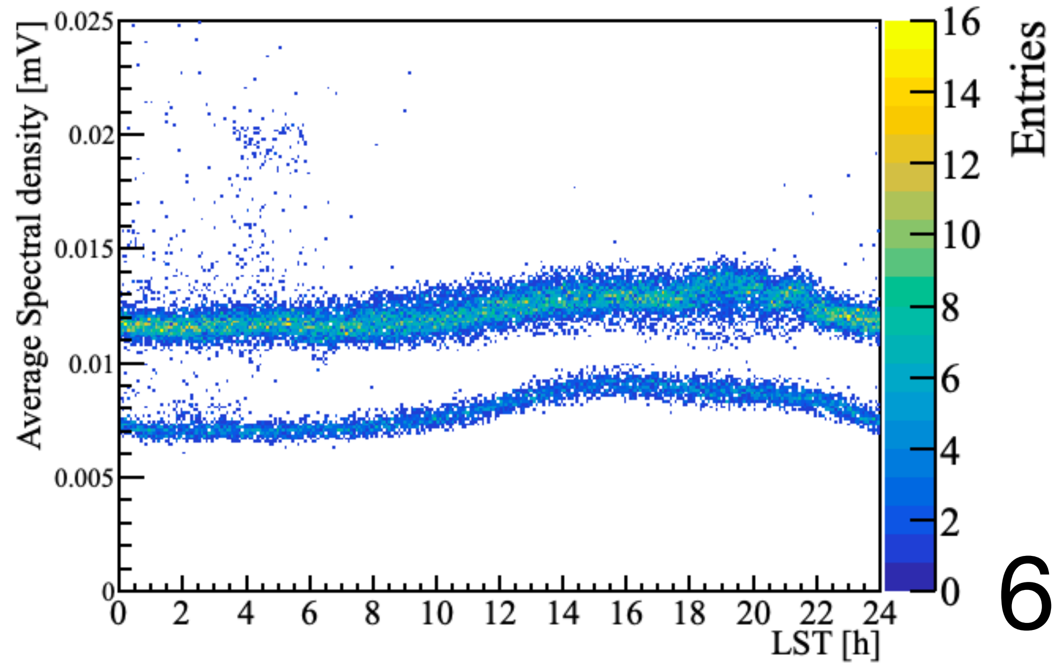
Spectral density with low statistics

- This classification is characterized by a low number of traces collected during a certain period of time (1 month).
- This classification corresponds to approximately 2% of all data from 2013 to 2020 for Butterfly antennas (**~1.9% in previous works**) and 6.4% for LPDA antennas (~**2.2% in previous works**).



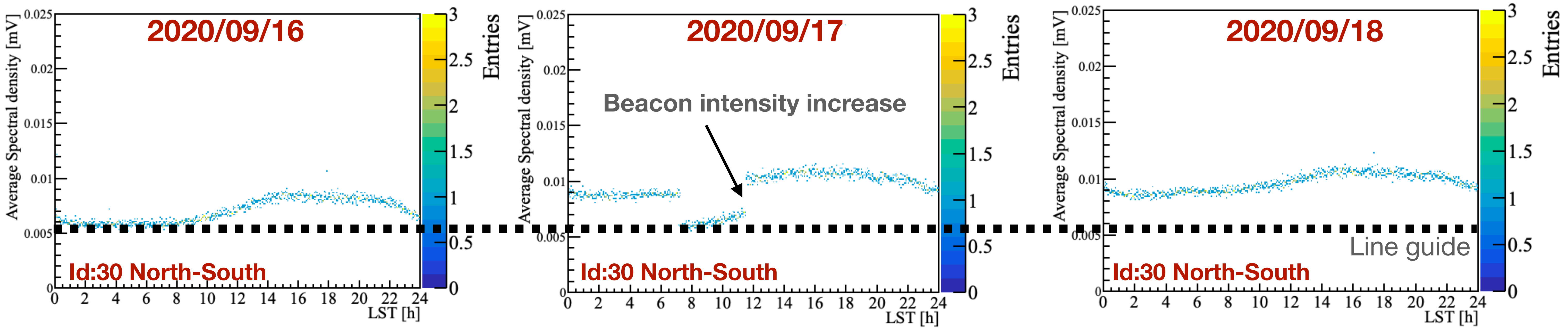
Spectral density with bimodal distribution

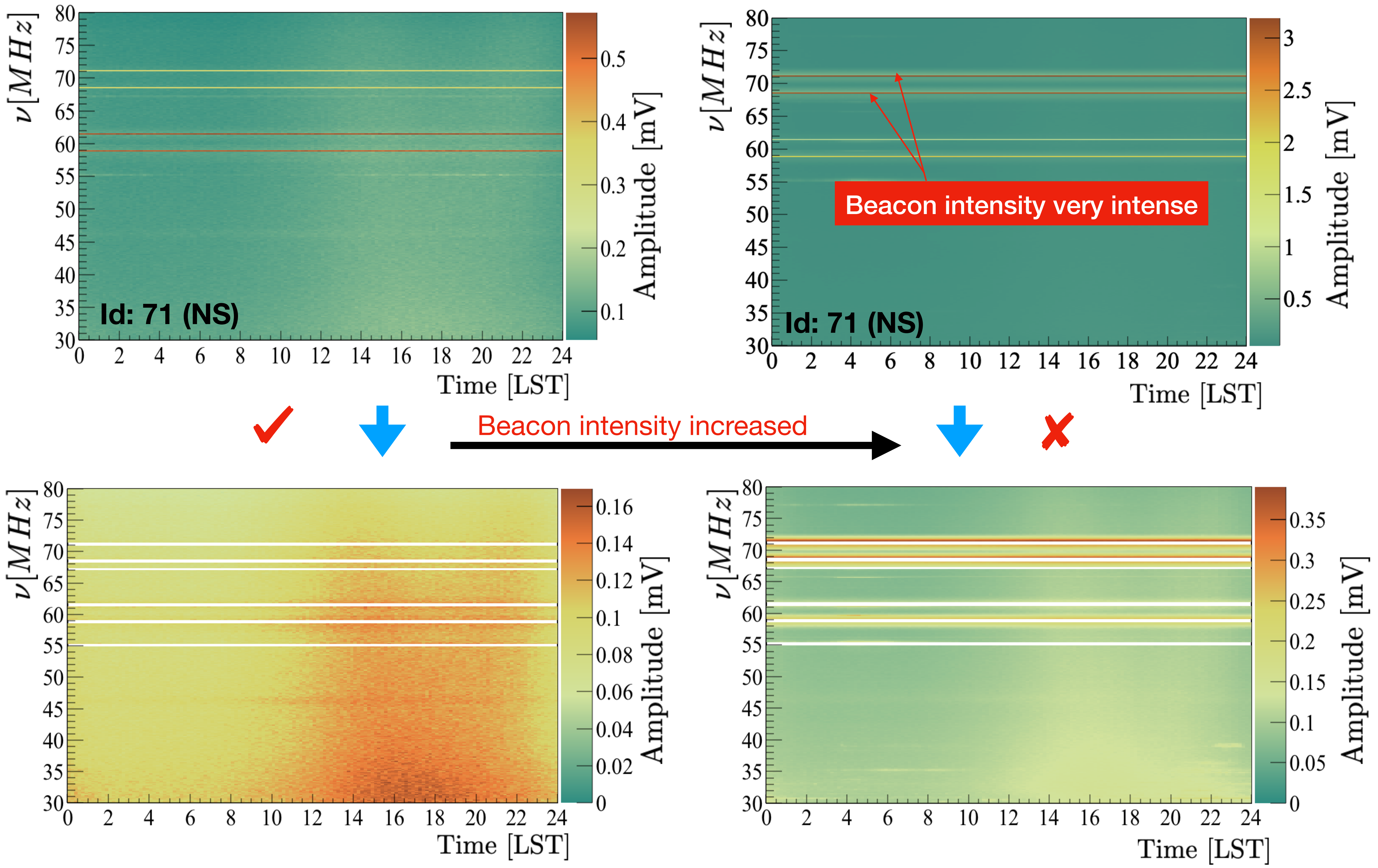
- This classification is characterized by the appearance of two or more distinct distributions in the average spectral density distribution within the same month and generates unreliable thresholds for rejecting broadband noise.
- This classification corresponds to approximately 6.8% of all data from 2013 to 2020 for Butterfly antennas (**~5.7% for previous works**) and approximately 8.1% for LPDA antennas (**~4.5% for previous works**).



Spectral density with bimodal distribution

- 2 factors contribute to the emergence of the dual distribution:
  - ➔ Sporadic appearance of noises in the antenna (very intense)
  - ➔ Beacon intensities change suddenly.
- Beacon intensity changed few times during the years 2014 - 2020
- These intensity changes affect all antennas, resulting in all of them exhibiting a dual spectral distribution.
- Removing only beacons frequencies leaves residual signals
- **We solve this problem by rejecting an additional frequency bin adjacent to the beacon frequency**
- The new results to be presented in this talk have already been corrected.
- We provide tables reporting the behavior of all KIT/BUW AERA antennas from 2013 to 2020, separated by channel, on a monthly basis.





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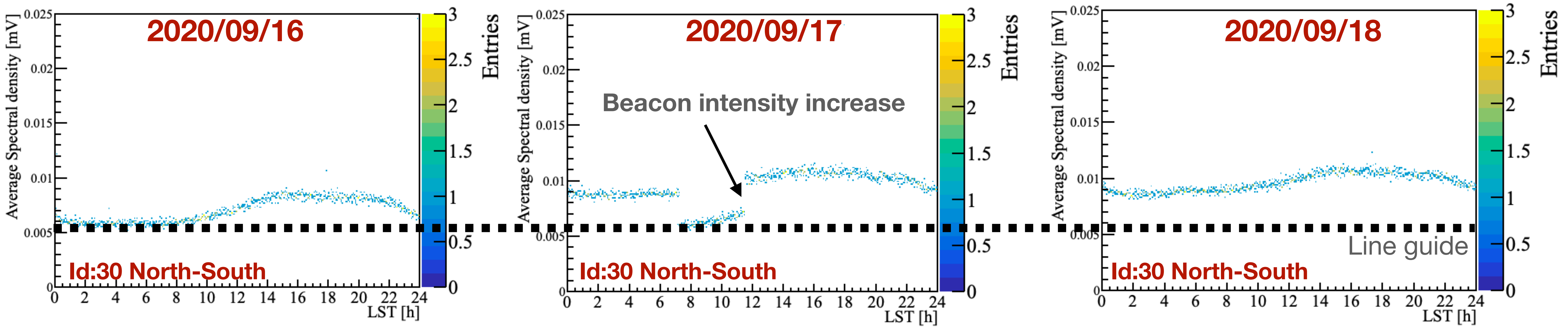

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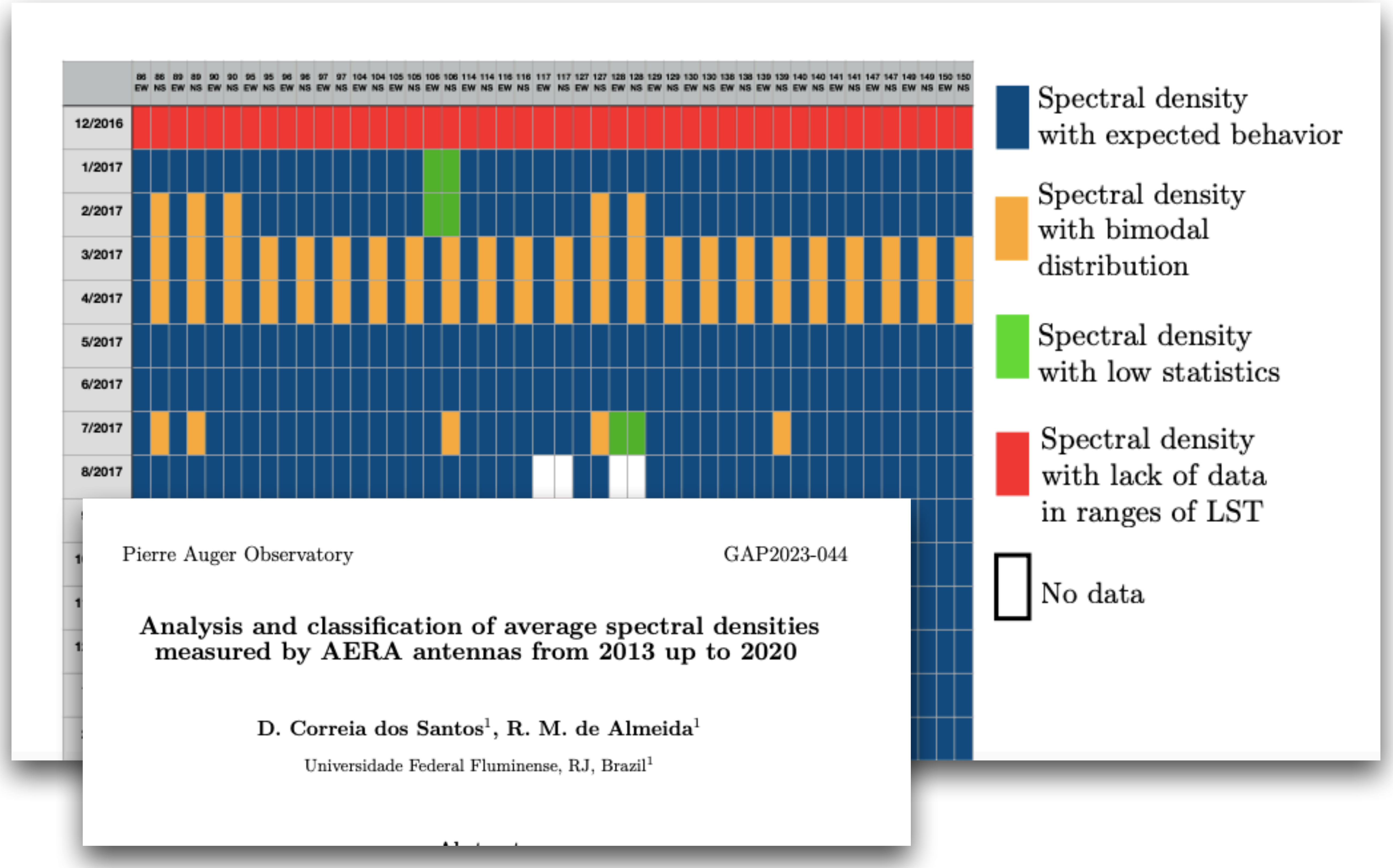

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Average spectral density over the years

```
/pauger/Radio/RD/2013:
  C- /pauger/Radio/RD/2013/04
  C- /pauger/Radio/RD/2013/05
  C- /pauger/Radio/RD/2013/06
  C- /pauger/Radio/RD/2013/07
  C- /pauger/Radio/RD/2013/08
  C- /pauger/Radio/RD/2013/09
  C- /pauger/Radio/RD/2013/10
  C- /pauger/Radio/RD/2013/11
  C- /pauger/Radio/RD/2013/12
```

* **Note:** No radio data for months 2013/01, 2013/02, 2013/03

- For the study of aging, the following quality cuts were made to the data:

➔ For **LPDA antennas**, 2016 has only 3 months of useful data, as either no data is available or they have incomplete spectral density. This motivated us to exclude all data before 2016 in the **LPDA antenna** aging study, as there is a large gap in time, and there are many cases of double spectral density.

➔ For **Butterfly AERA 2**, the year 2013 has only 7 months of the useful data, and in May and April, all antennas have incomplete spectral densities. This fact motivated us to exclude the year 2013 in the aging study for the Butterfly AERA 2 antennas.

➔ For the **Butterfly AERA 3**, there is no data available before 2015/02 and in the months 03, 04 and 05, the antennas have spectral density with lack of data in ranges of LST, so there are only 7 months of useful data in 2015, this motivated us to exclude 2015 in the aging study for the **Butterfly AERA 3** antennas.

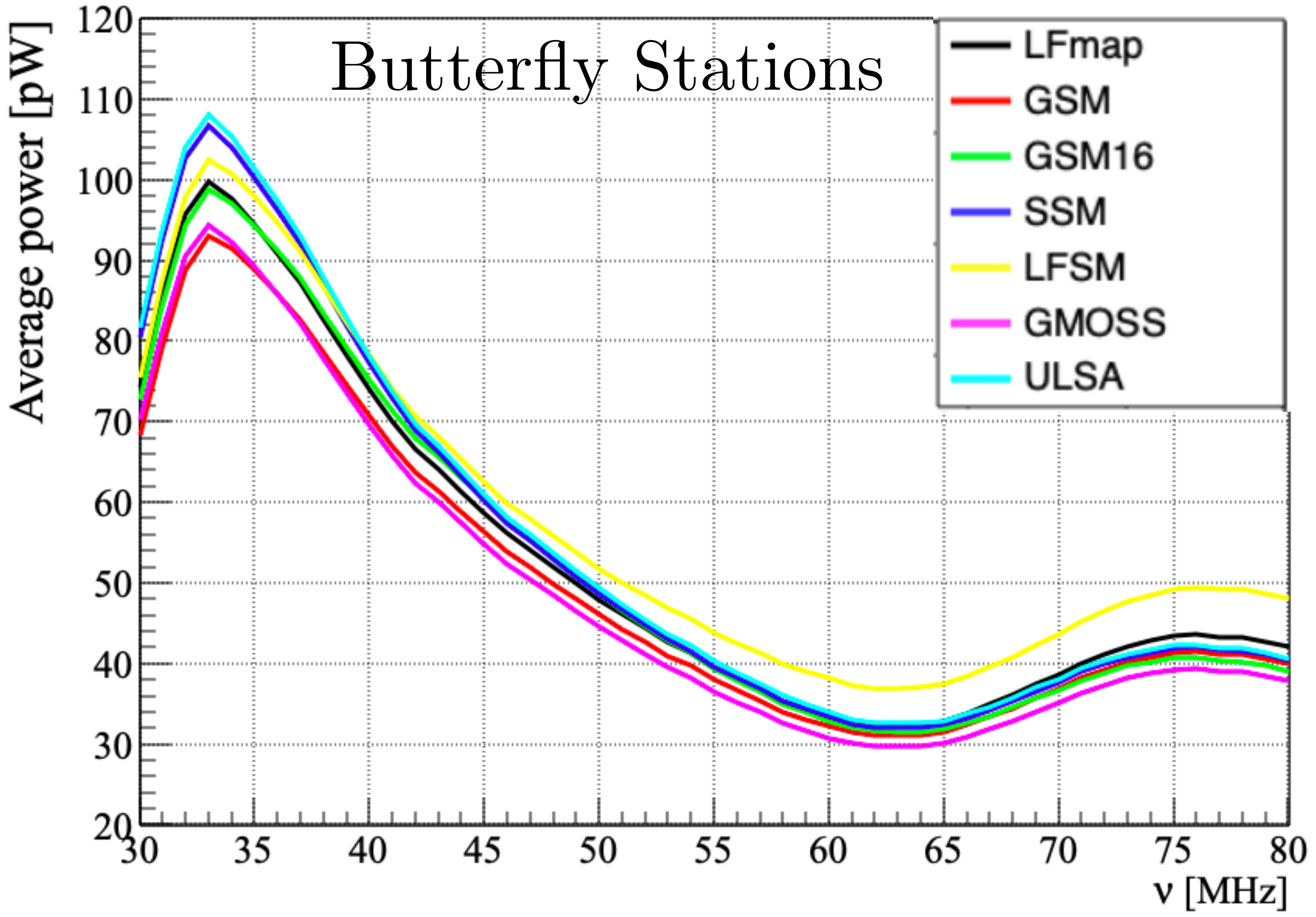
- The same quality cutoffs were made in previous studies (ICRC23).

- For more details, see the gap note GAP2023_044

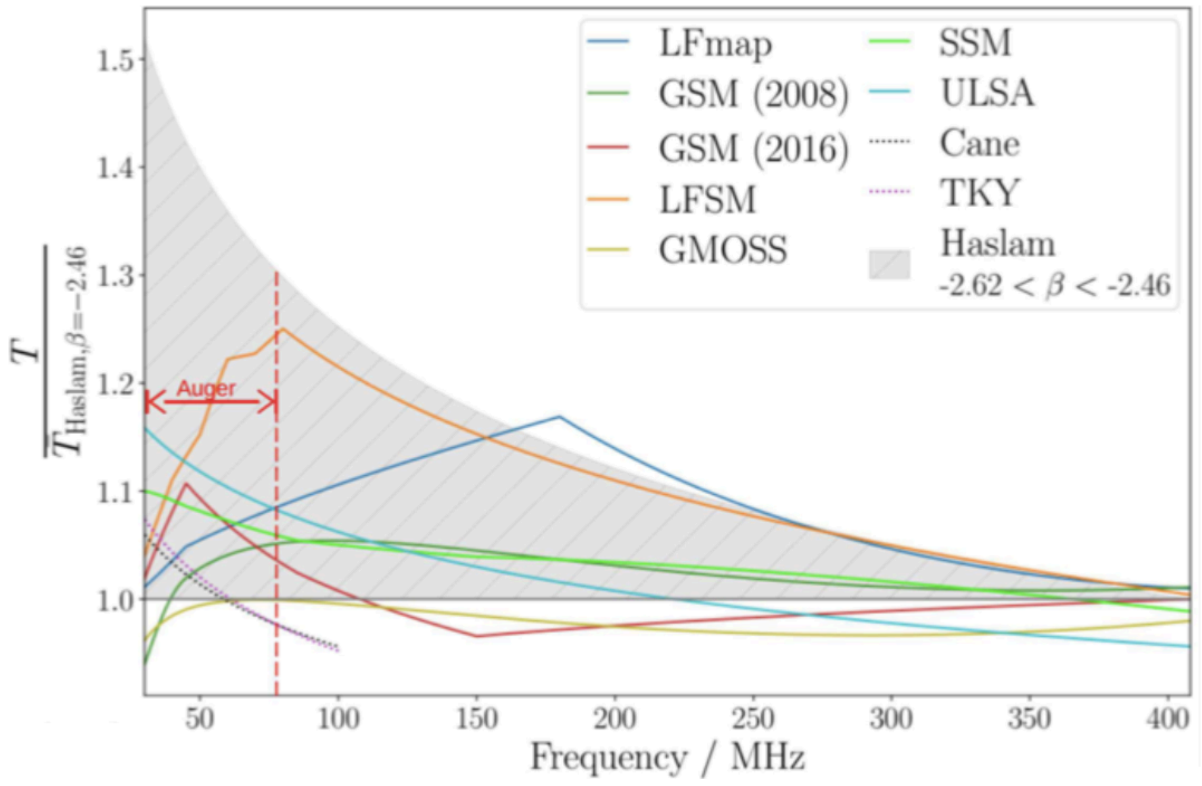
Galactic calibration using different sky temperature models

- The expected power **as a function of frequency (integrated in LST)** taking into account the antenna directional response follows is in accordance with Max Büsken study.

- Since the LFMap is a king of “average model”, a first analysis of this plot could induce us to conclude that the calibration constantes obtained for the LFMap model should also be a kind of “averaged calibration over the models”



Max Büsken



- This is not the case because the Galactic calibration is performed **as function of LST.** As we can see, the hierarchy of the models as a function of LST is different from the hierarchy as a function of frequency. In particular, the LFMap model predicts a hotter GC than other models and the hierarchy of the models also change as a function of LST

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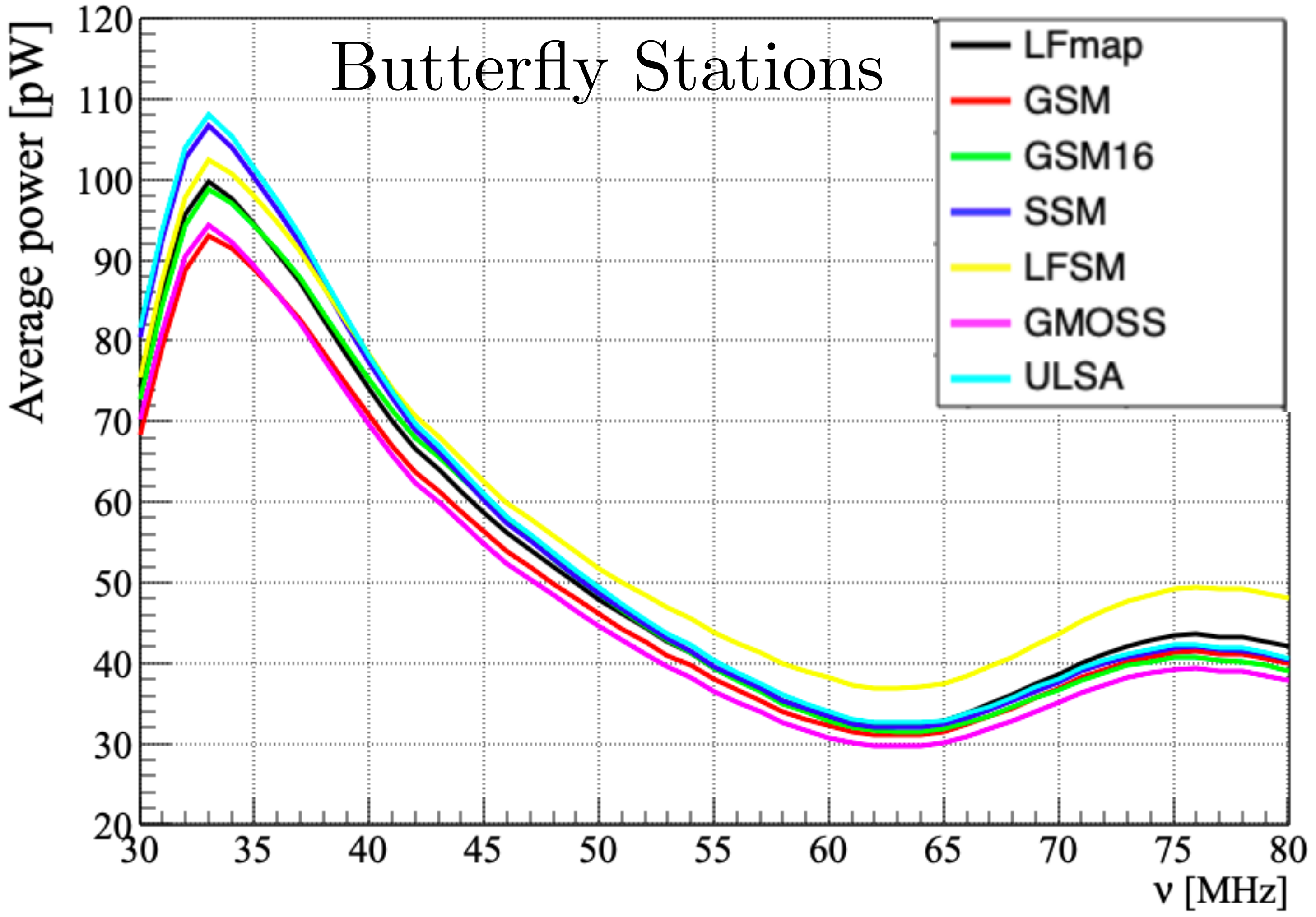

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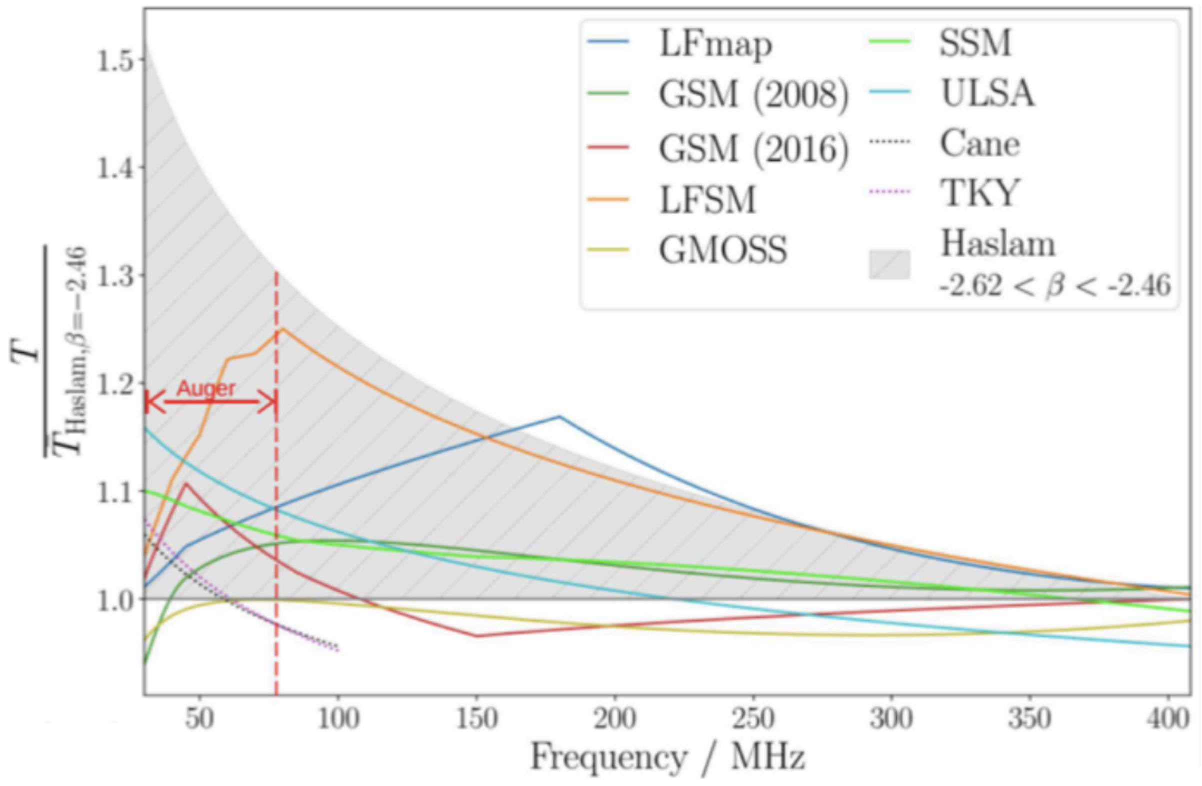

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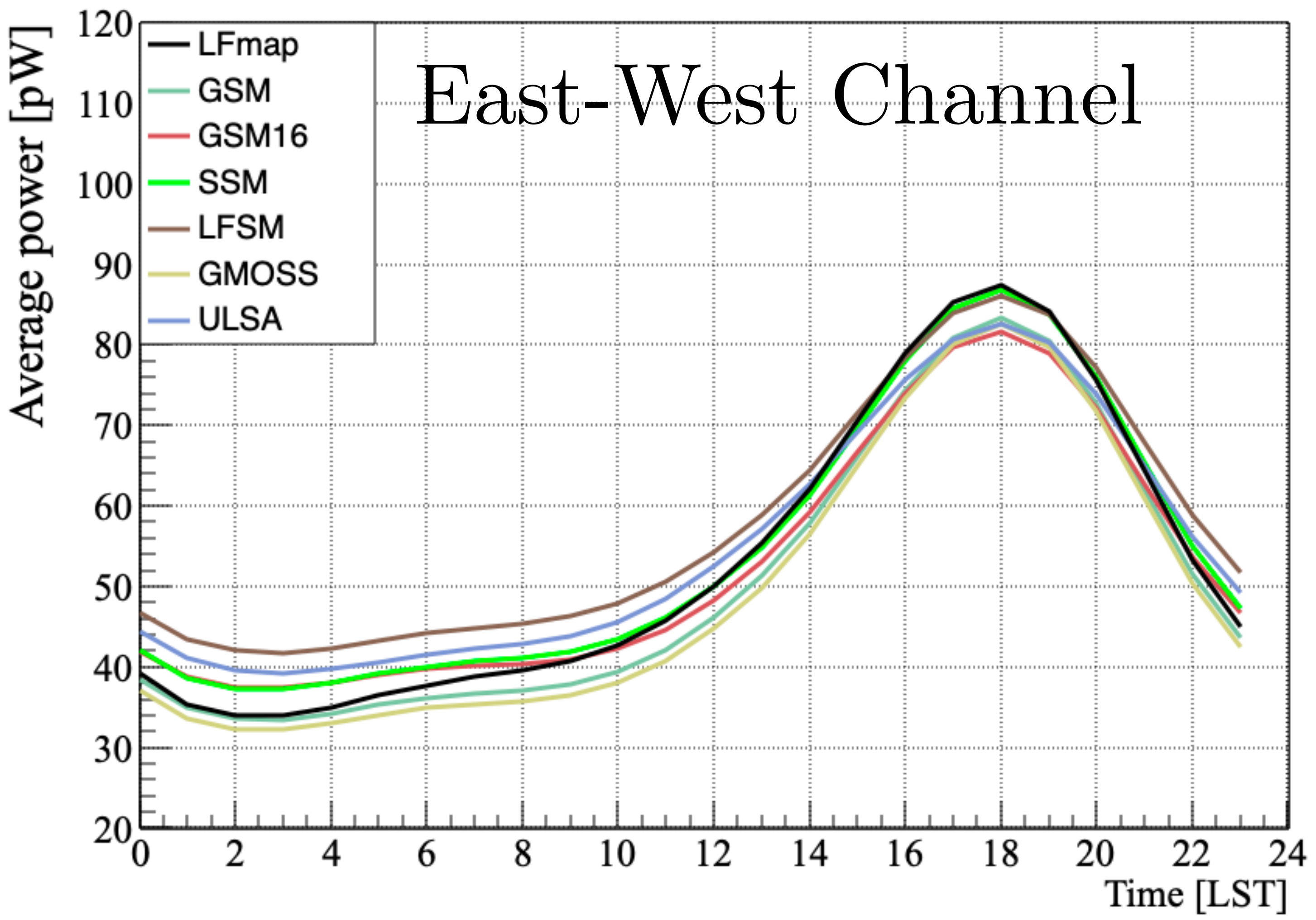

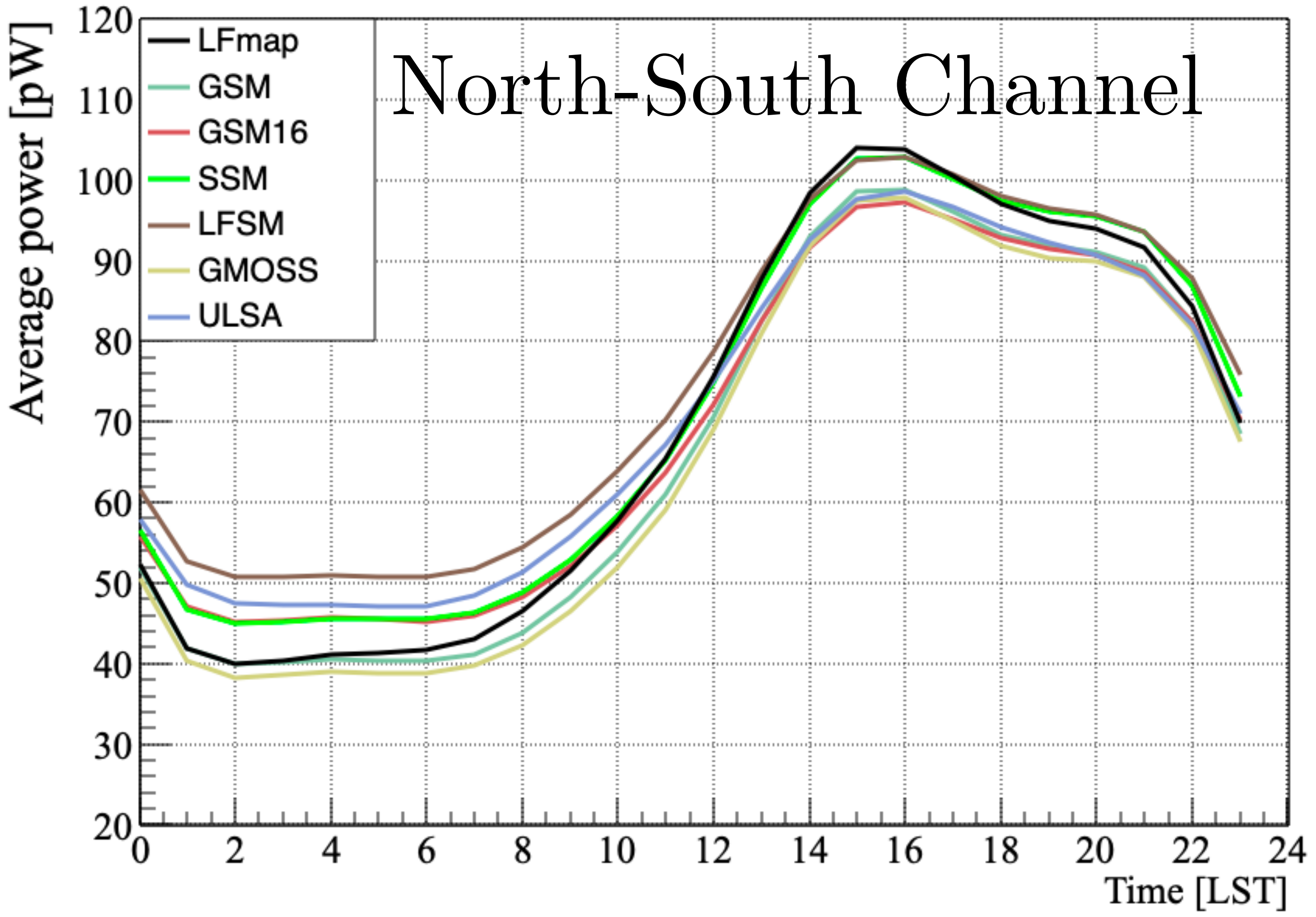

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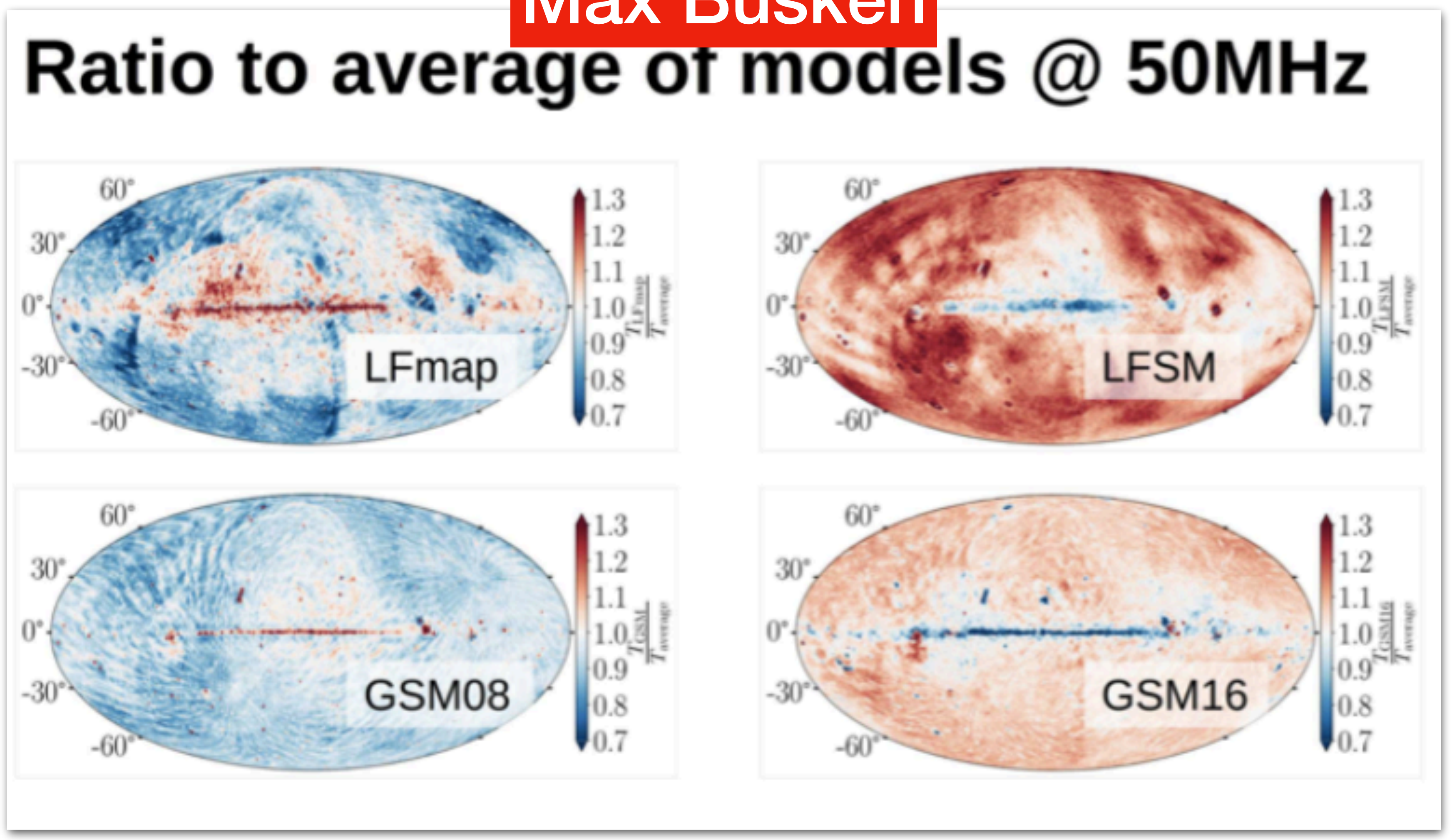


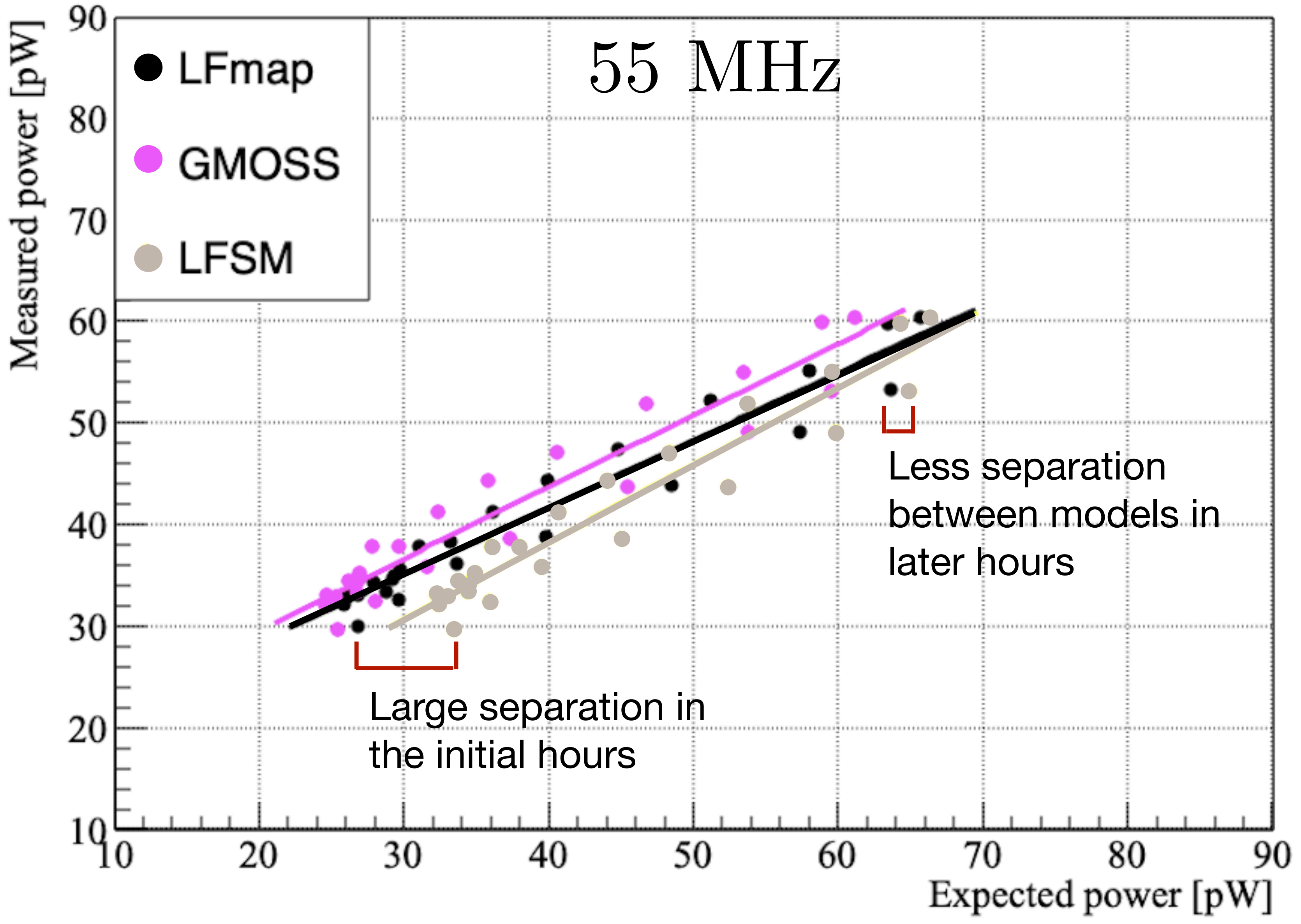
- LFmap has a "hotter" galactic center than the other models.

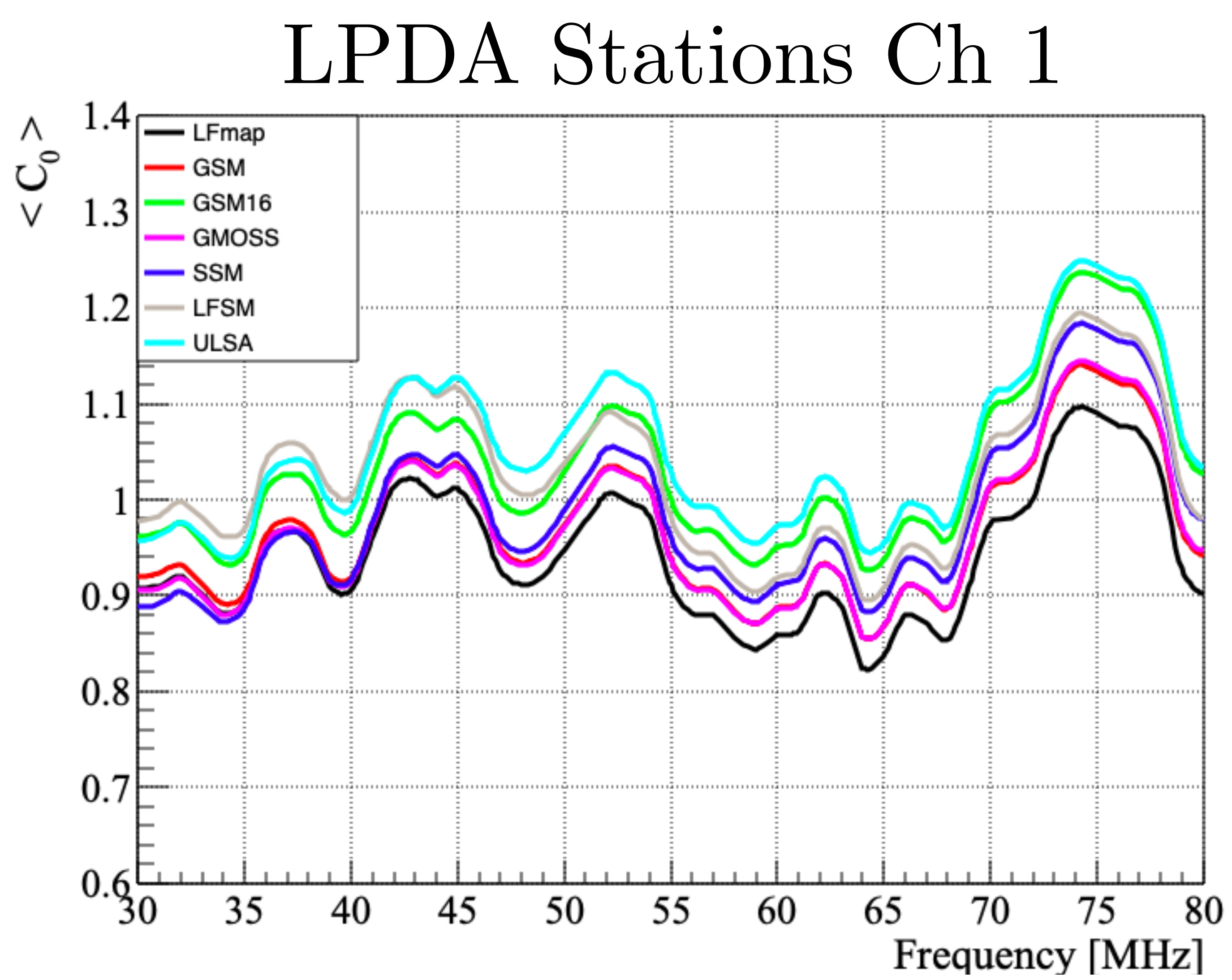
Galactic calibration using different sky temperature models

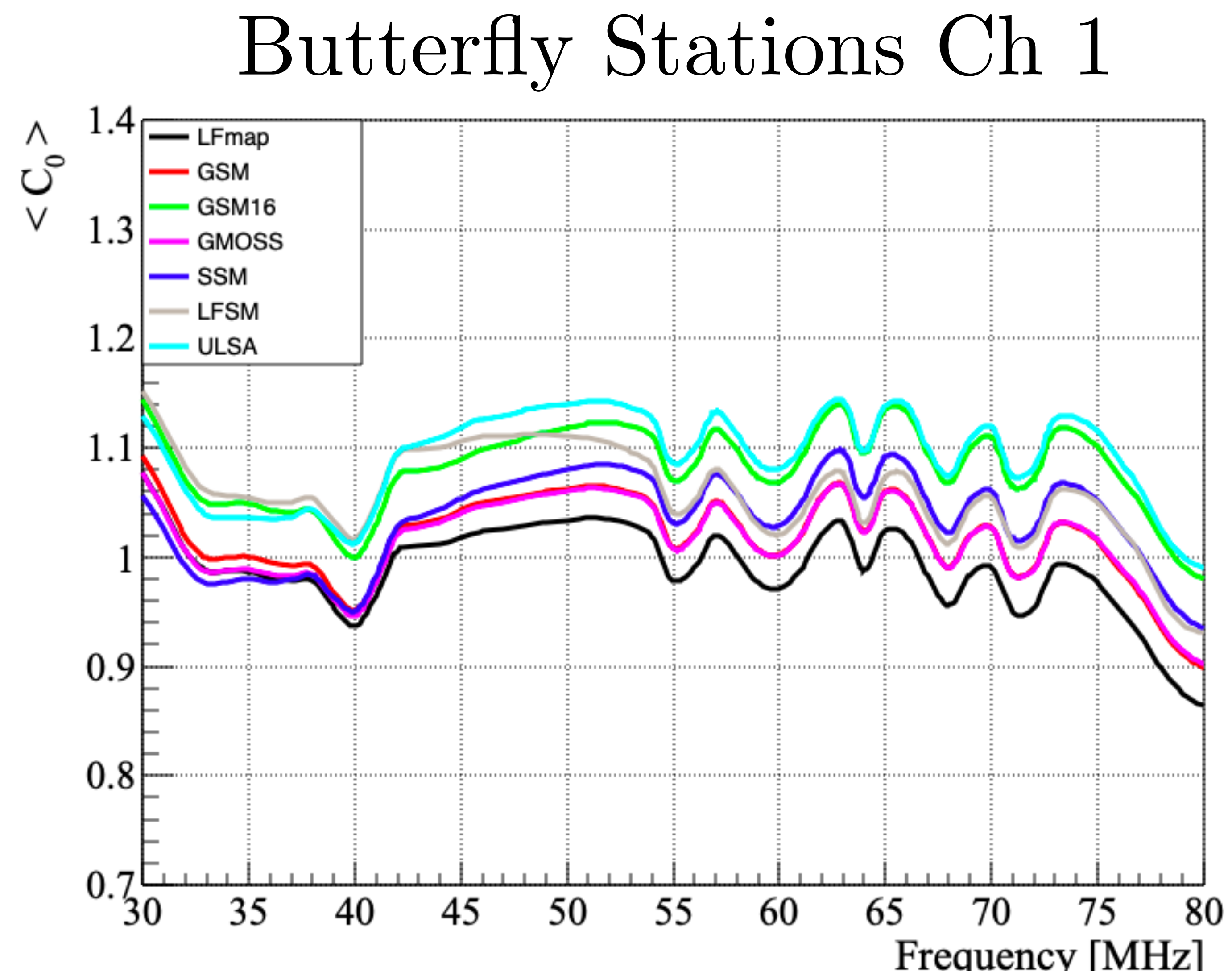
$$< C_0 > = \sum_{i=1}^{N_f} C_0(f_i) \frac{1}{N_f}$$

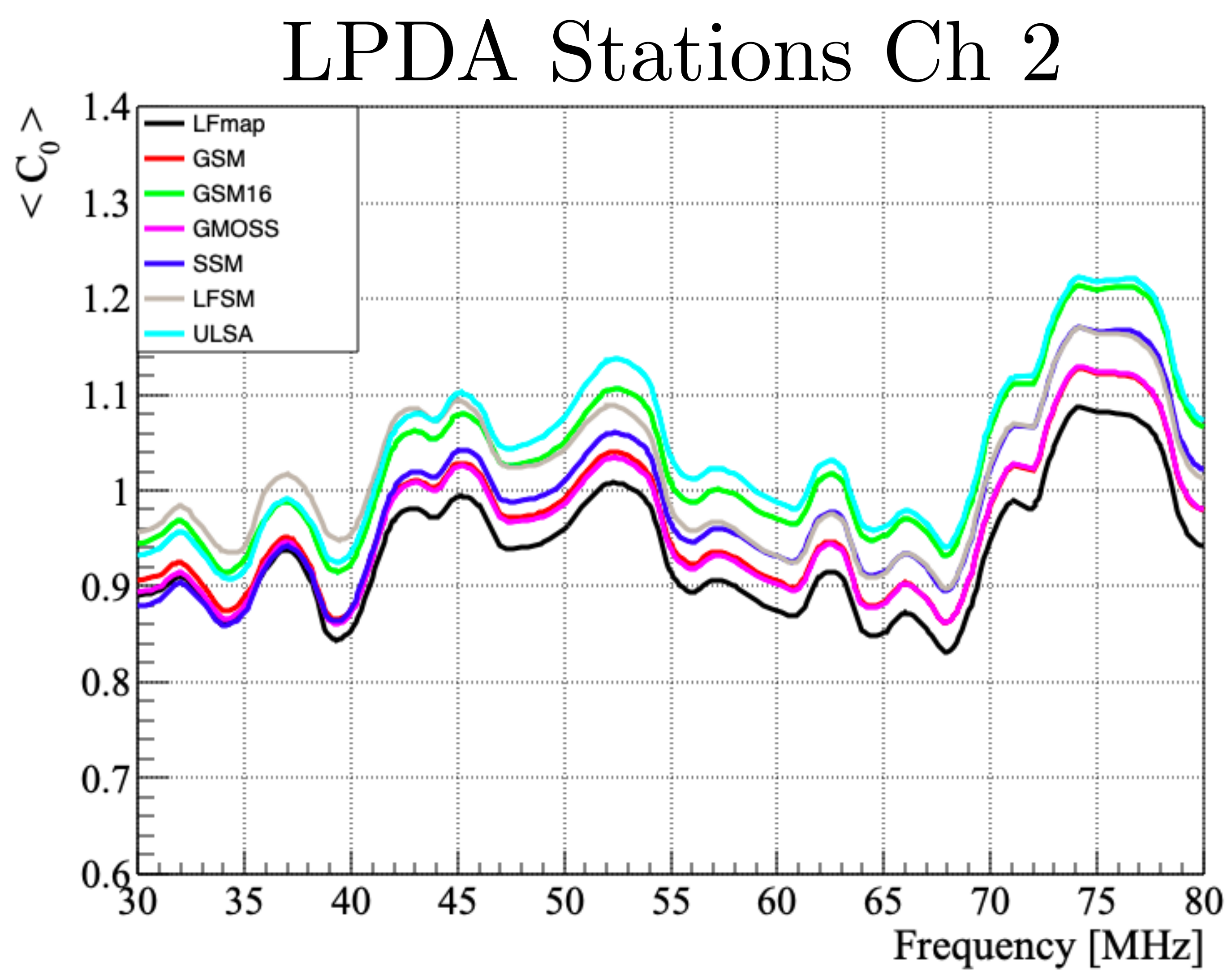
- The hierarchy of calibration constants doesn't exhibit the same behavior as the analysis of average power versus frequency (integrated over LST). This is because the Galactic calibration is carried out by taking into account the relationship between average power and LST. If there is an inversion in the hierarchy of models at certain hours of LST, it is reflected in the fitting process, leading to higher or lower C0 values.

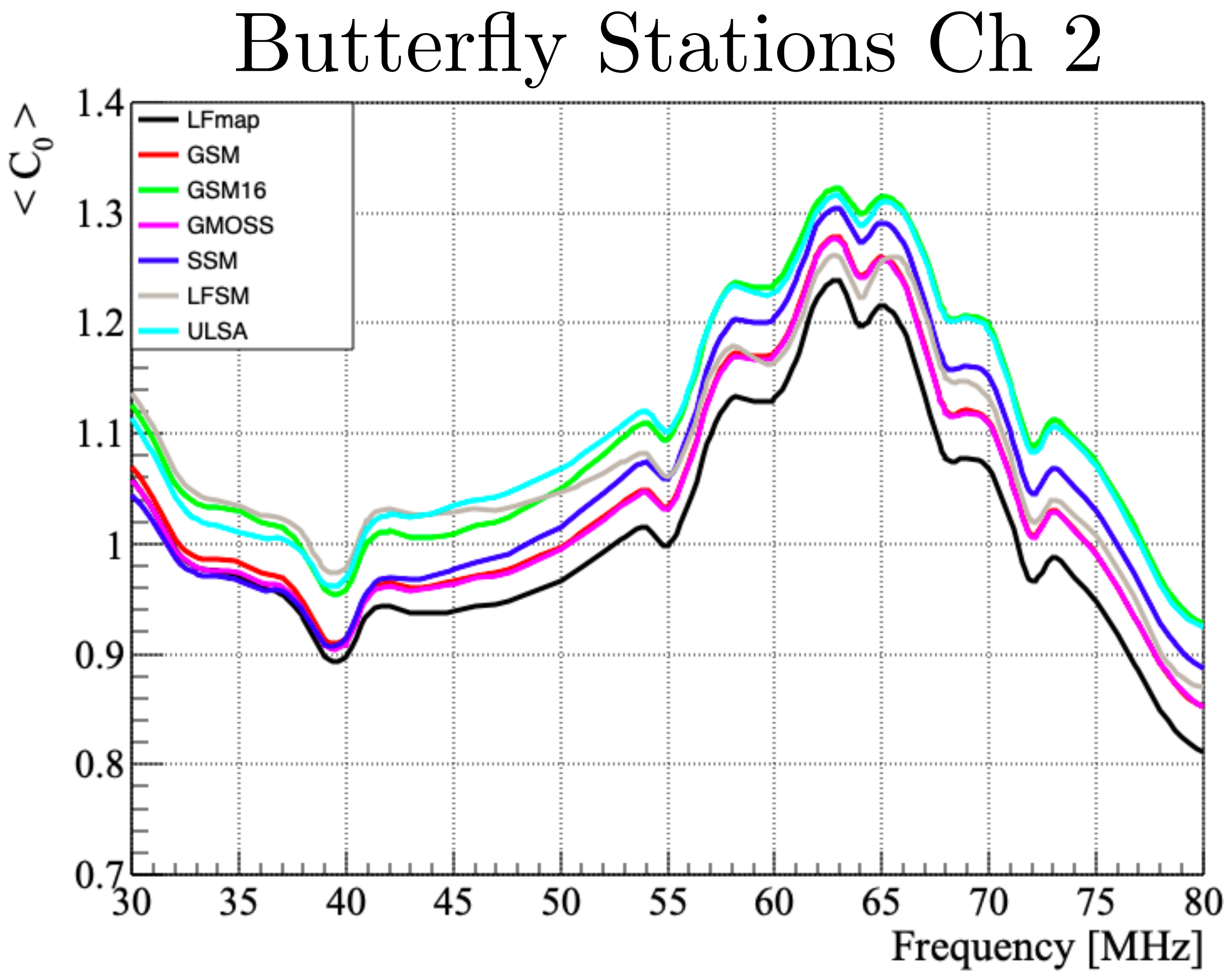
- The calibration constants obtained for each model present a hierarchy distinct from that seen in the average expected power as a function of frequency of each model.











C_0 as a function of the time (compute Aging)

- Error bar: RMS/$\sqrt{N}$ each month

$$< C_0 >= \sum_{i=1}^{N_f} C_0(f_i)\frac{1}{N_f}$$

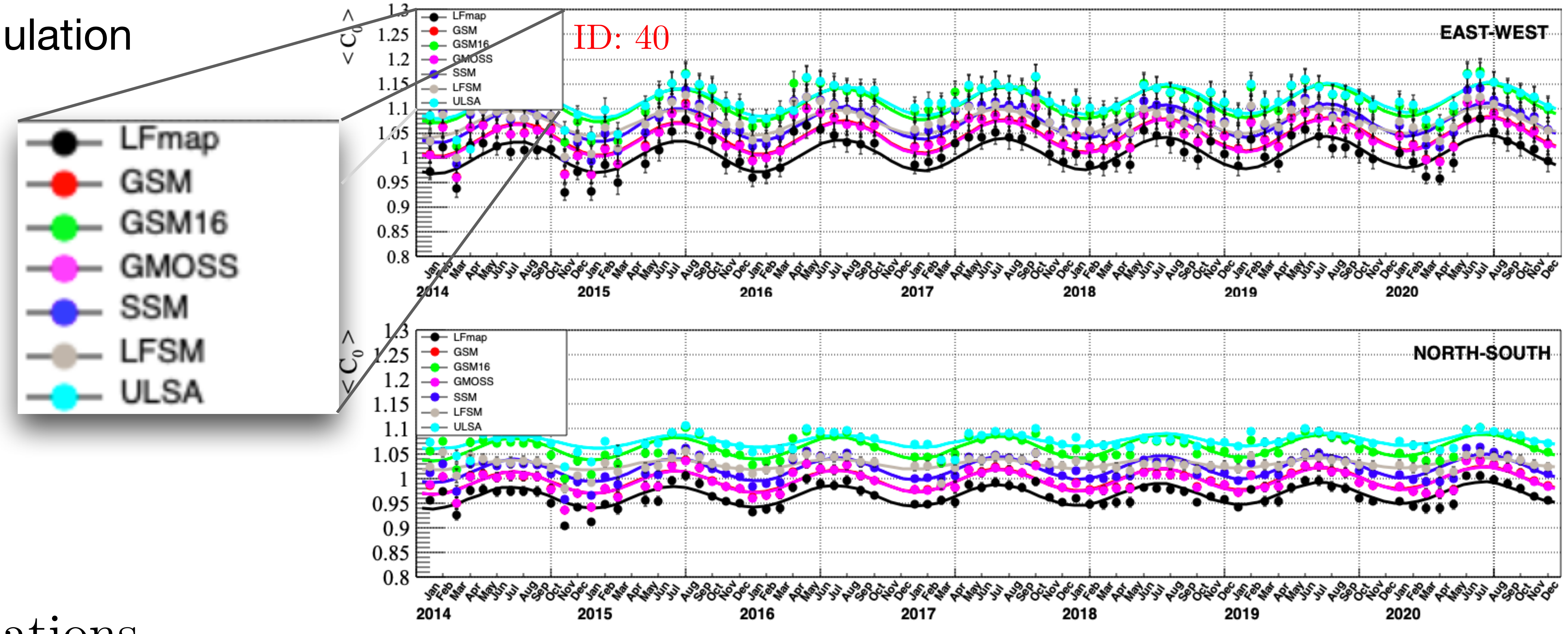
- Use a cosine + linear function to account for seasonal modulation

$$< C_0 >= A\cos\left(\frac{\pi}{6}t+\phi\right)+at+b$$

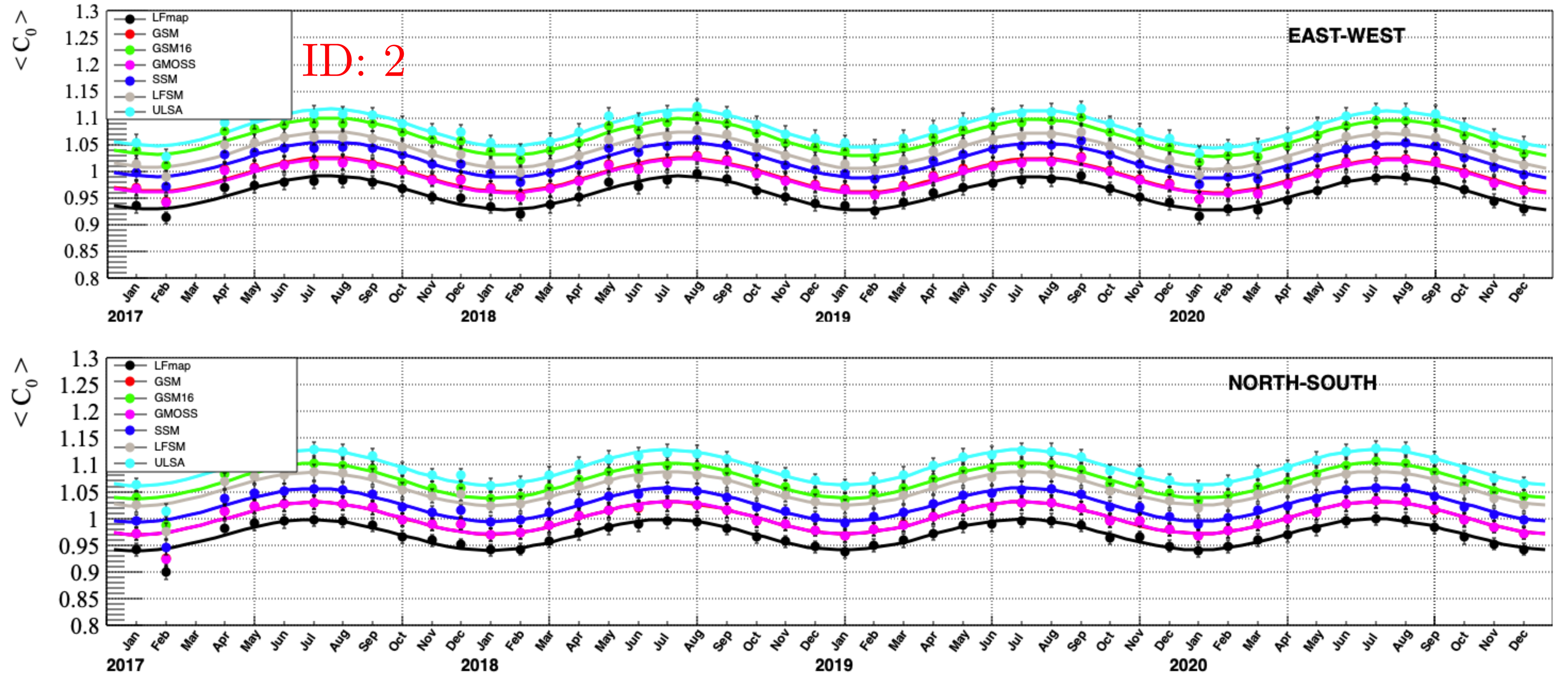
(t: Months; at: Aging)

- Periodically triggered data
  - ➔ 52 Butterfly stations (AERA2) from 2014 until 2020
  - ➔ 24 Butterfly stations (AERA3) from 2016 until 2020
  - ➔ 14 LPDA stations from 2017 until 2020

Butterfly Stations



LPDA Stations



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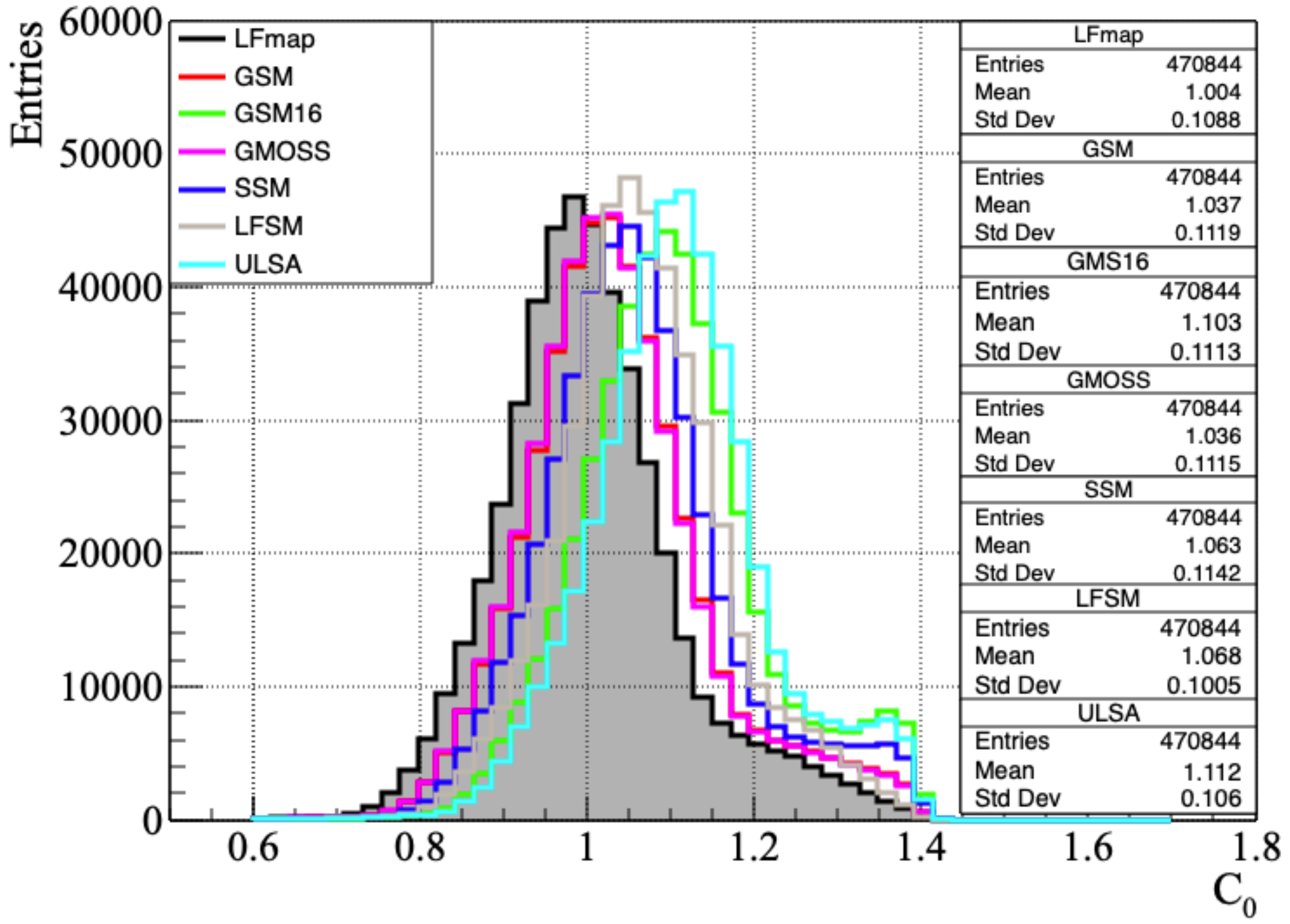

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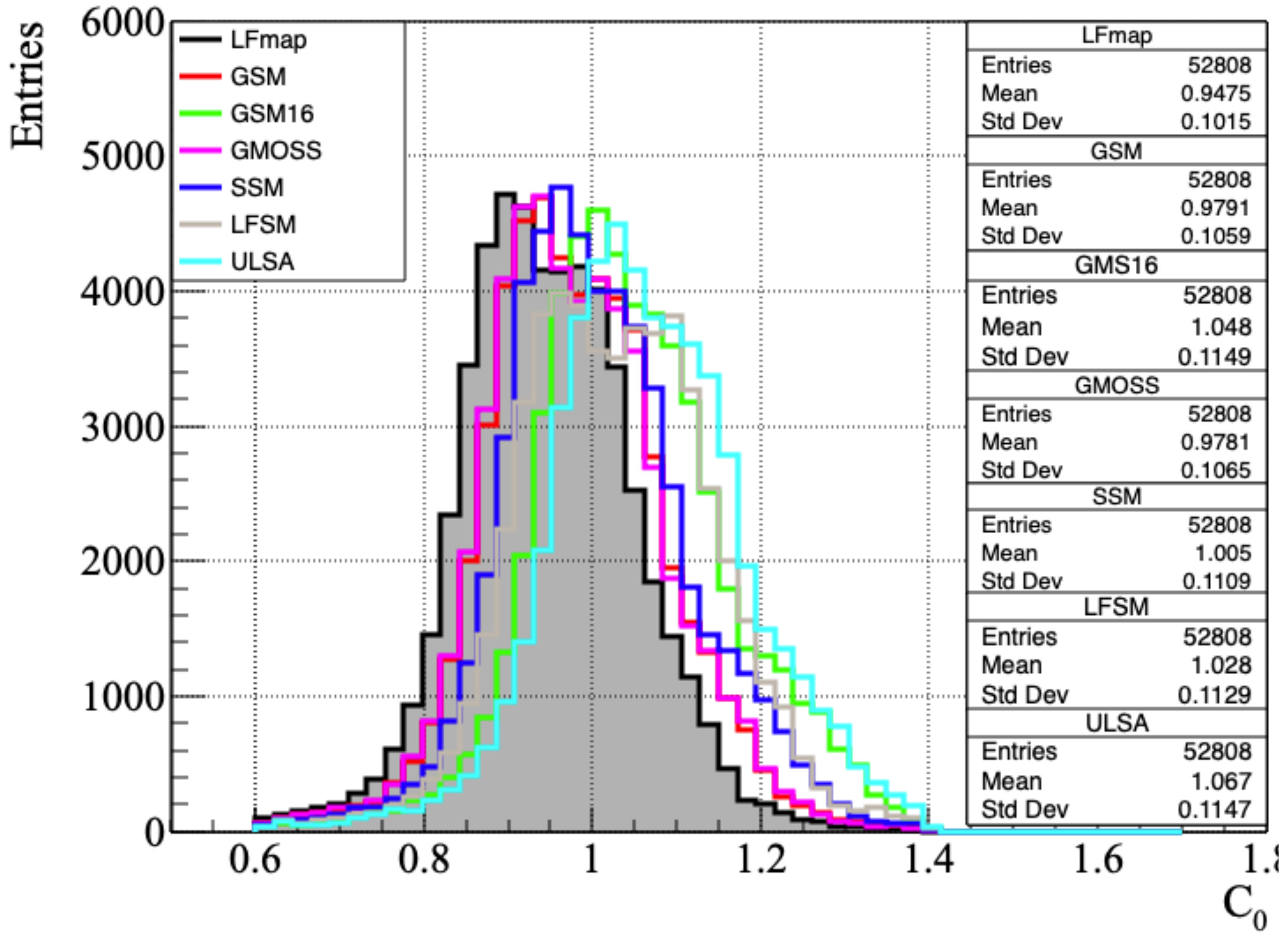
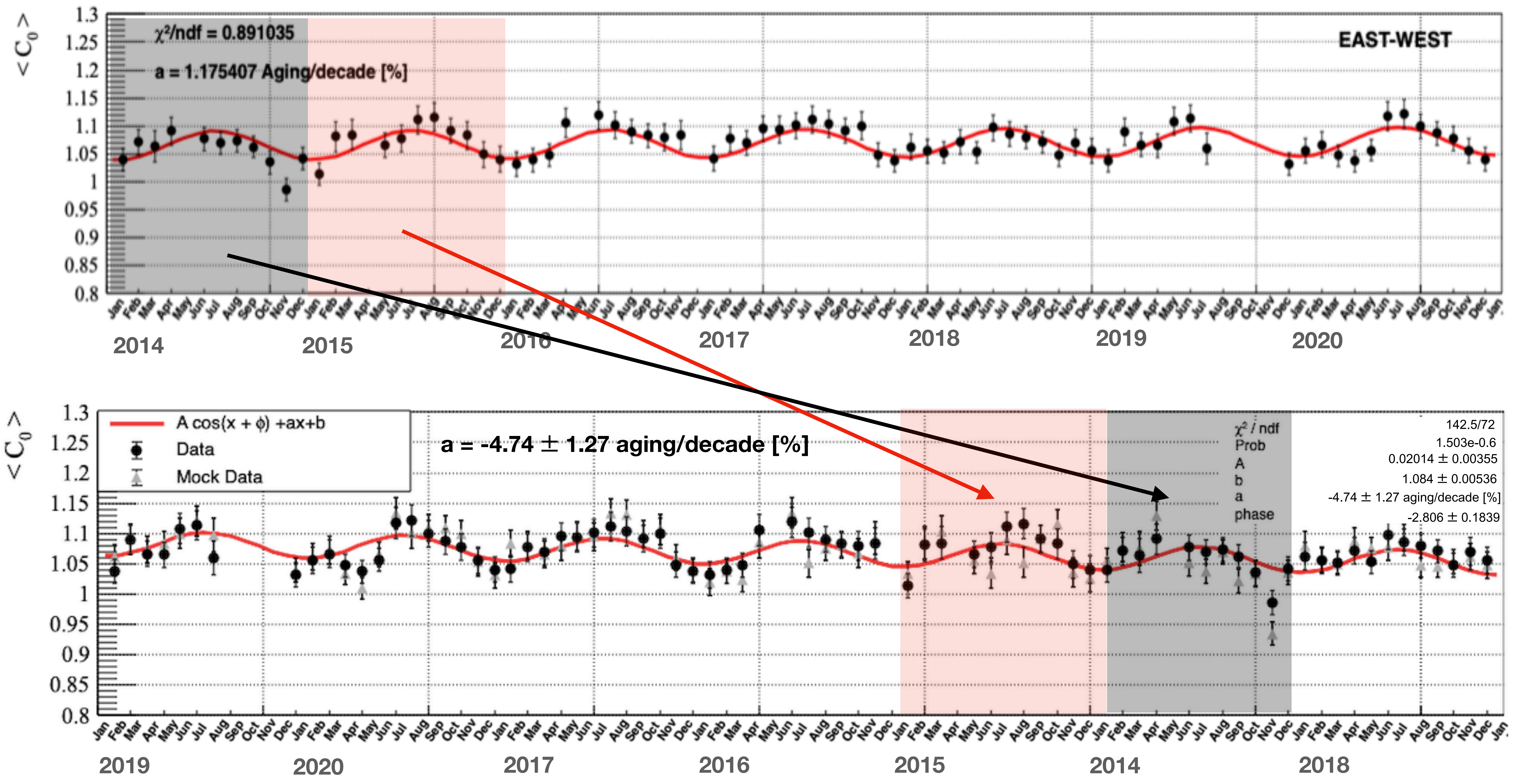
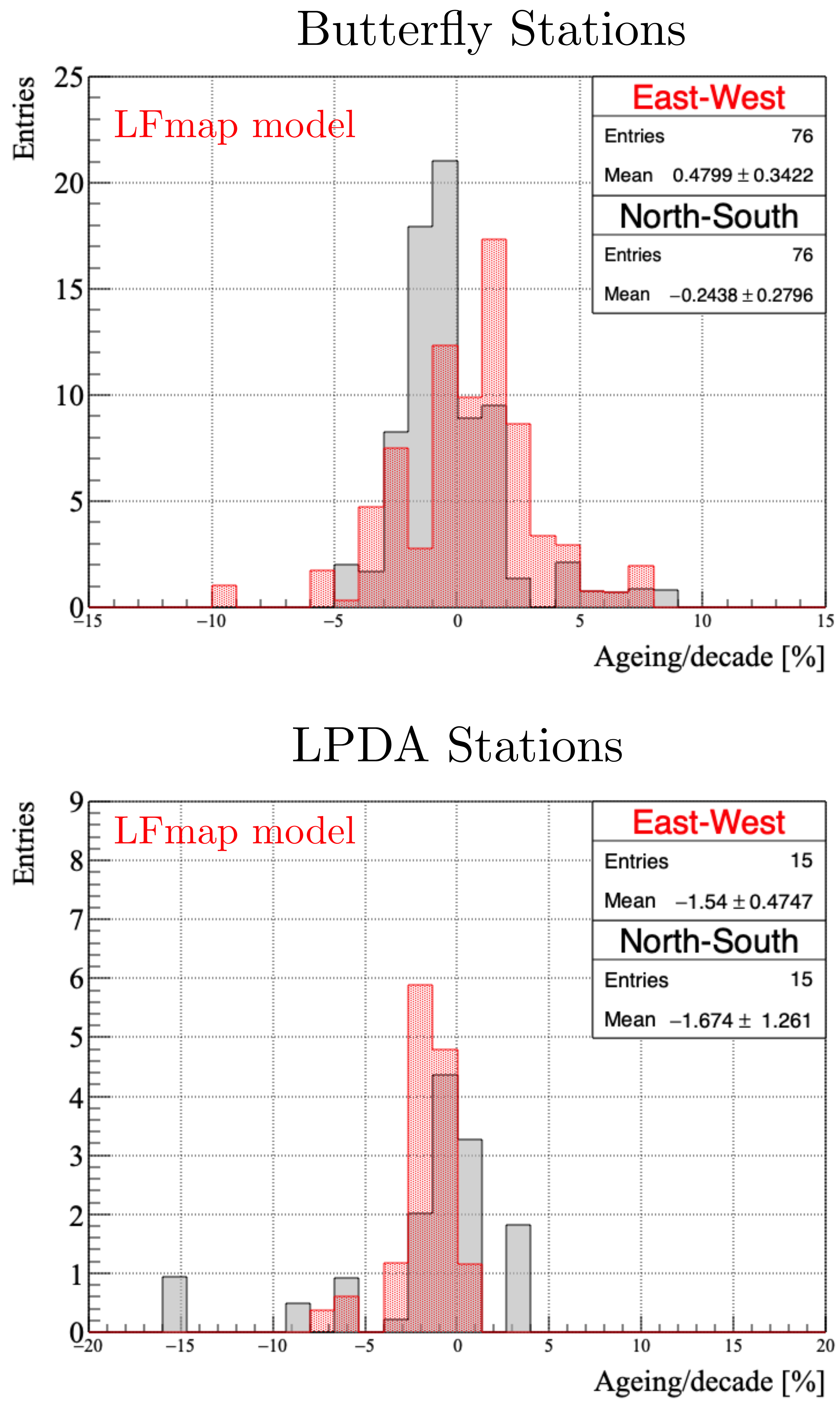


We highlight the LFmap model used in previous studies

Compute uncertainties

- Uncertainties are underestimated in the cosine + linear fit approach.
- **We have an unknown residual variation and we need to be careful to not confuse actual aging with some effect that just happened to be higher in later/earlier years.**
- How to account in the uncertainties for randomly strong fluctuations (not described by the fit) possibly observed for all antennas in some specific months?

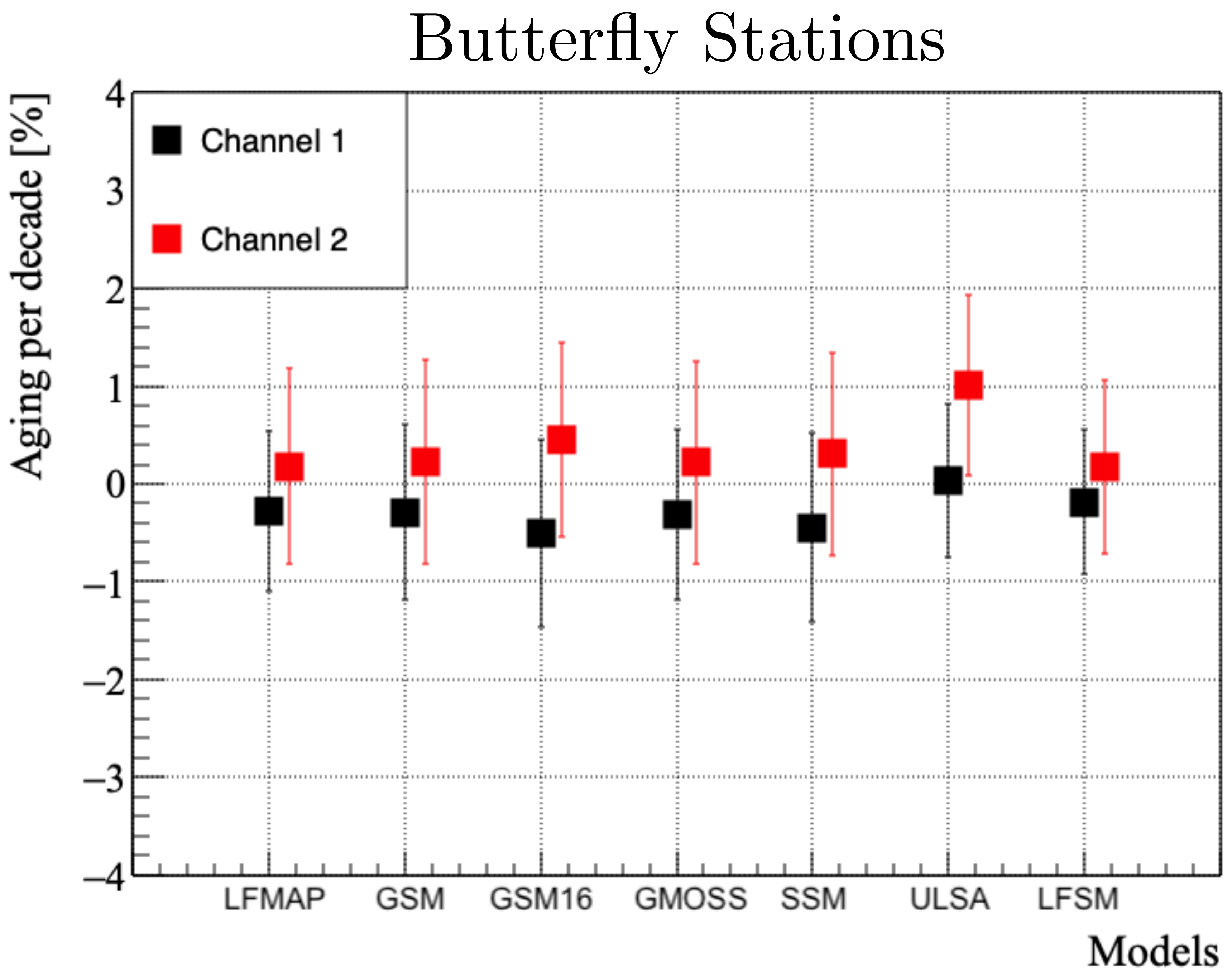


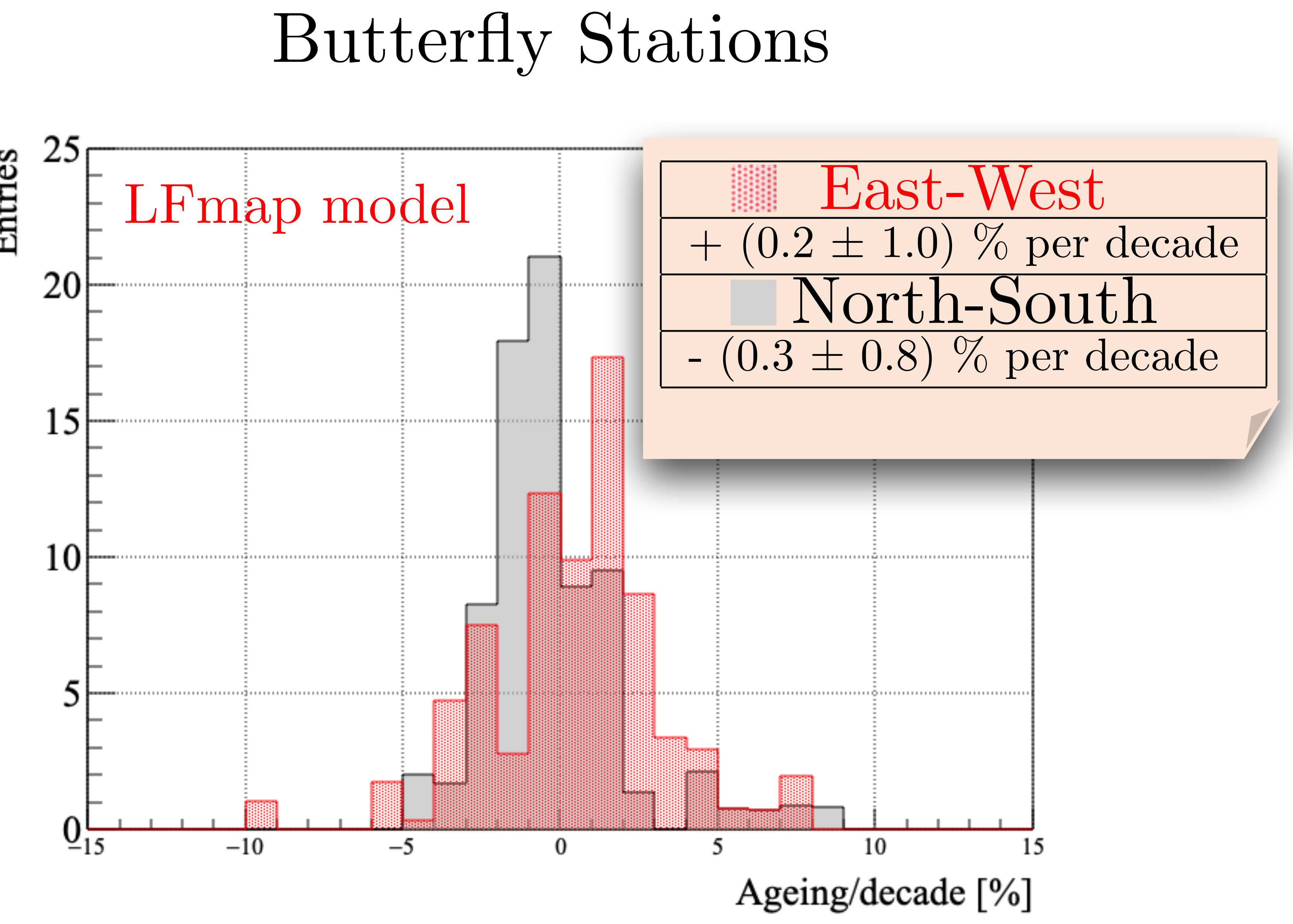


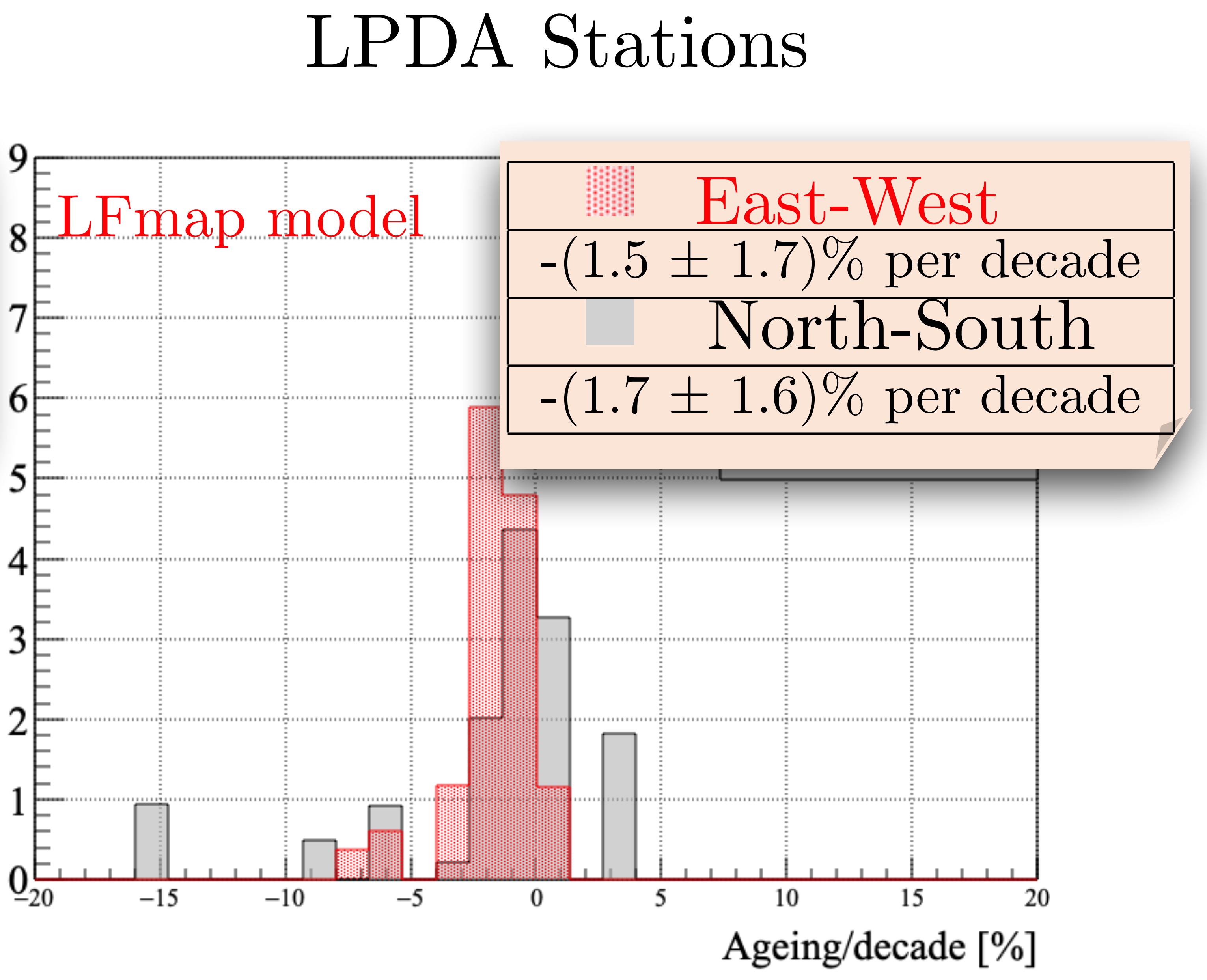
Study of C_0 as a function of the time

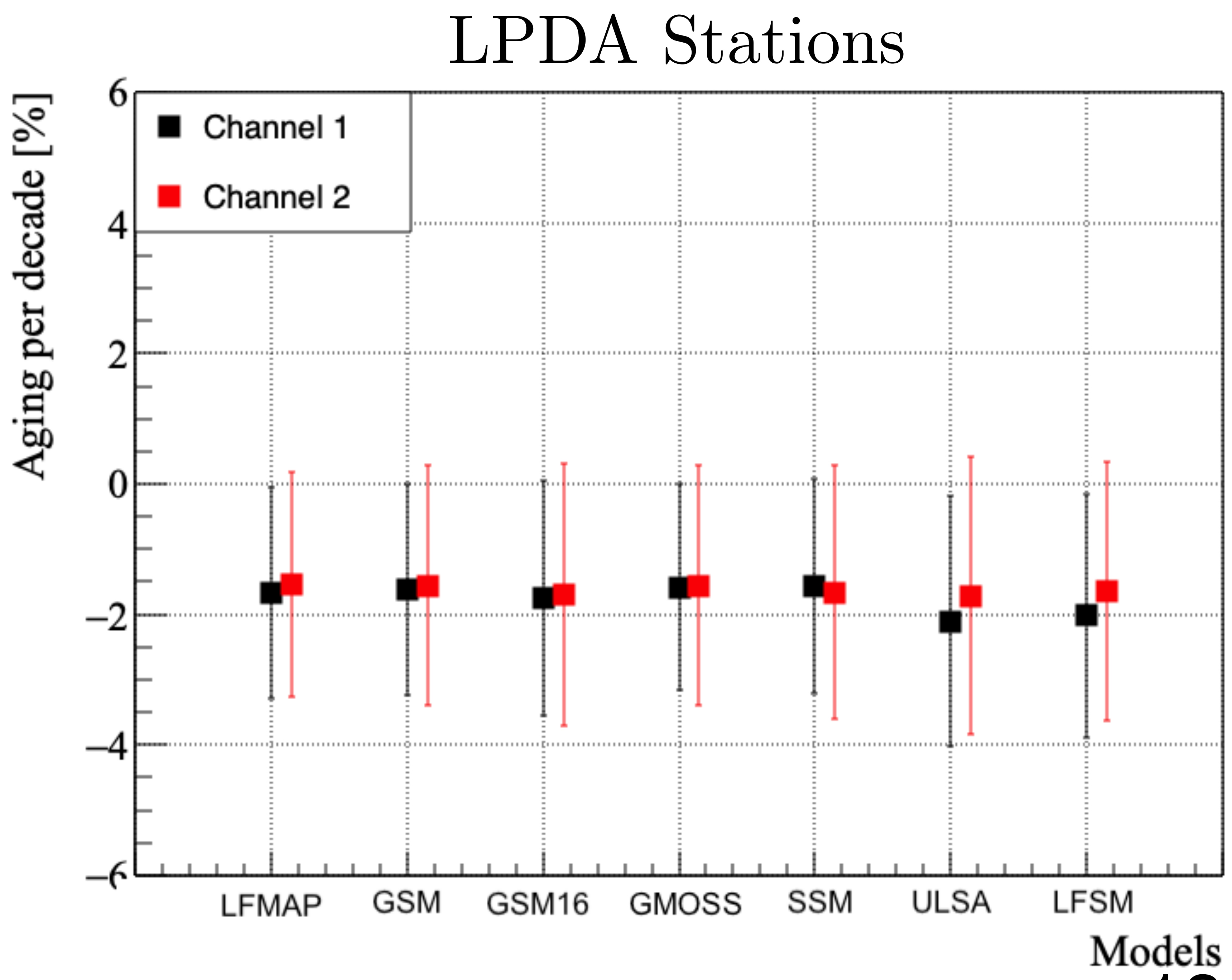
- The uncertainties are estimated by calculating the root mean square (RMS) of simulated mock data for calibration constants. This mock data is generated using Gaussian function with center value and error bar assigned for each month, and then the years are randomly shuffled.

- The final aging is given by the weighted average over the agings of all antennas









- Non relevant and non significant aging effect in AERA data

Conclusions

- Non relevant and non significant aging effect in AERA data
- All models are compatible with the same aging.
- Several studies performed to obtain Galactic calibration in a monthly basis for all AERA antennas
- Results particularly important for AERA energy scale paper and AERA antennas agings studies

Next Steps

- We need to decide on wh sky model should be used → We will use the average and RMS of all calibration constants obtained from all sky temperature models.