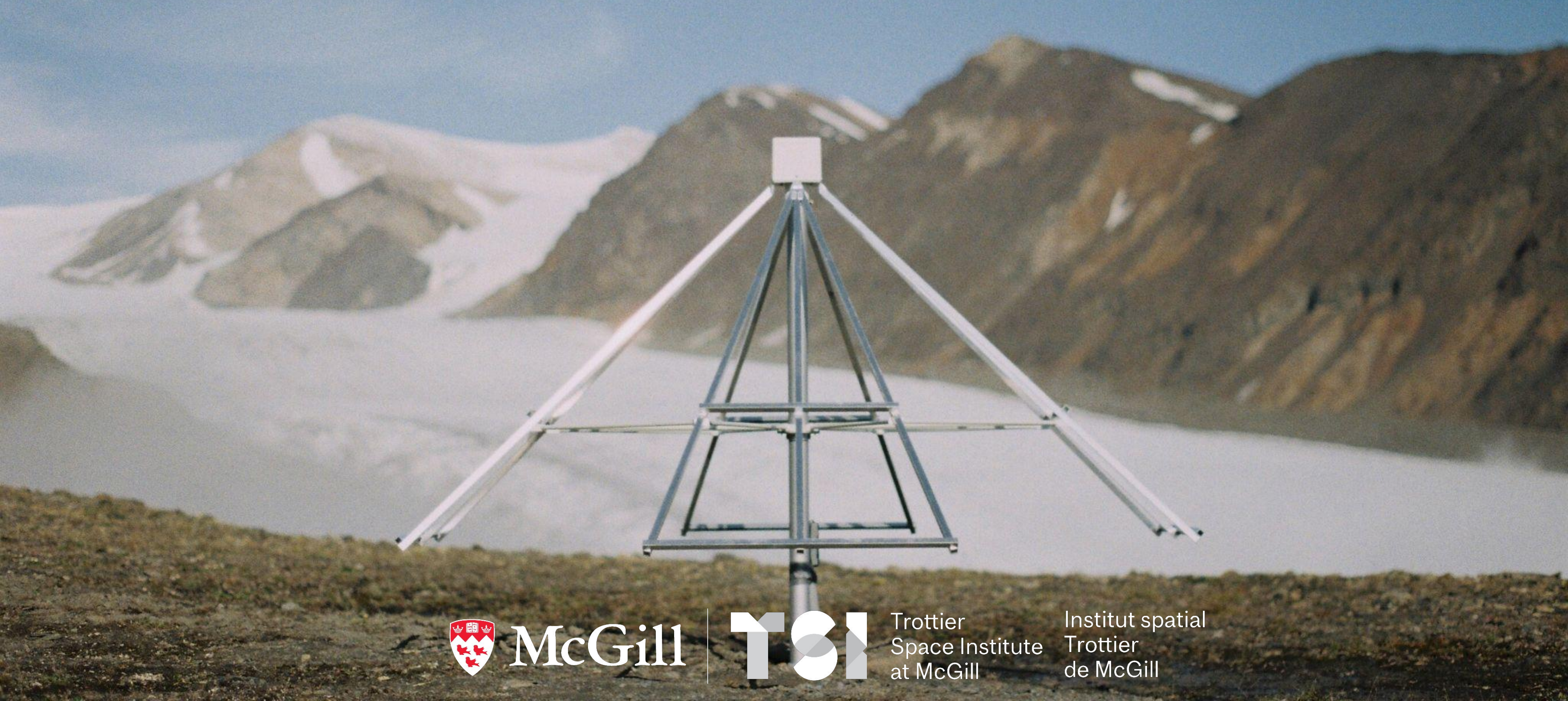
# Ultra-low frequency science with ALBATROS

Mohan Agrawal (mohan.agrawal@mail.mcgill.ca)
ALBATROS Collaboration



McGill
Trottier Space Institute at McGill
Institut spatial Trottier de McGill

# What is ALBATROS?

**A**rray of

8 antennas

**L**ong **B**aseline **A**ntennas

Pairs of antennas spread 100 m to 10 km apart

for **T**aking **R**adio **O**bservations

Want to image the sky at radio frequencies of < 20 MHz.

from **S**eventy-ninth parallel


## Axel Heiberg Island (79.8° N, 91.3° W)

# Why <20 MHz?

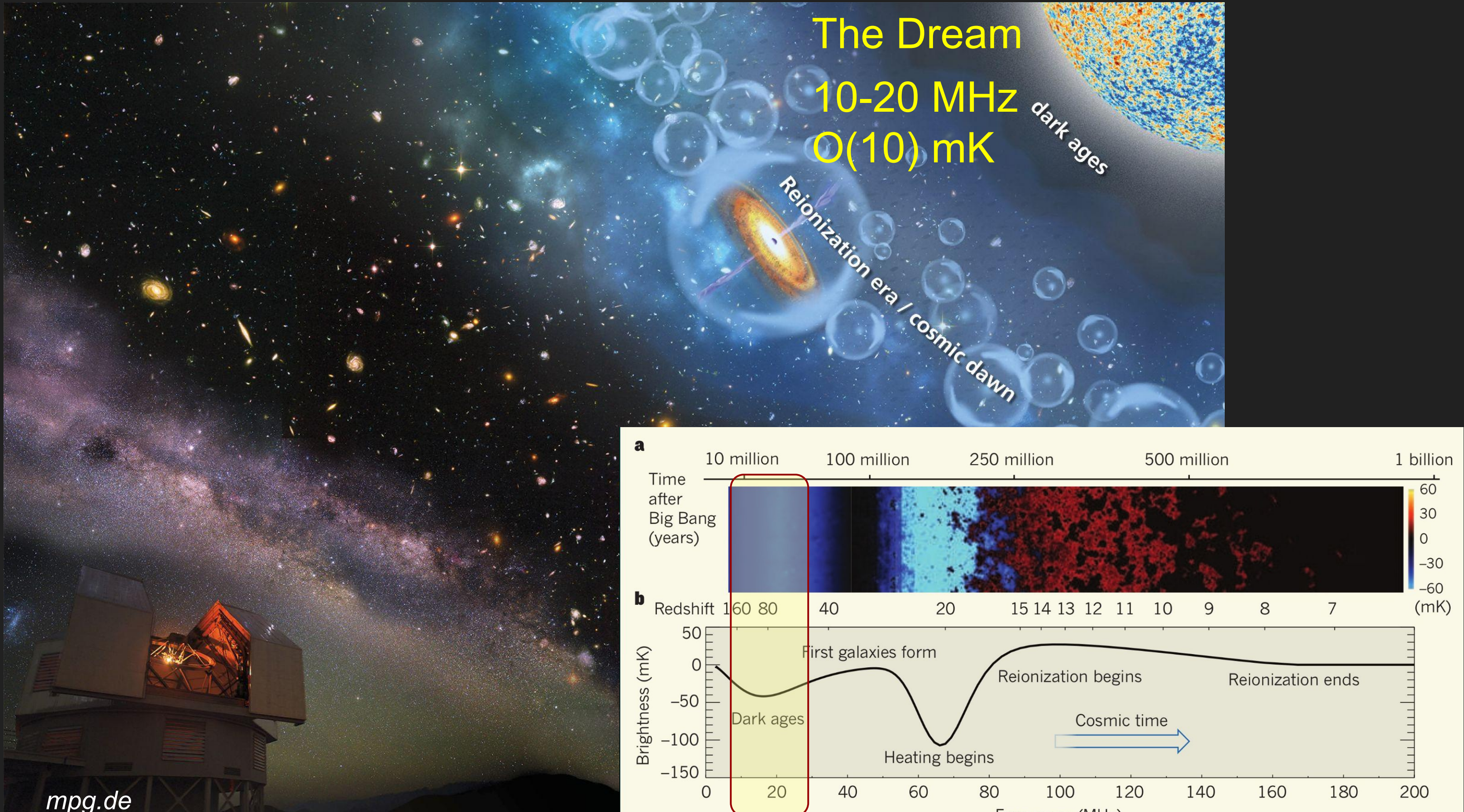



Image: Pritchard and Loeb, Nature, 2010

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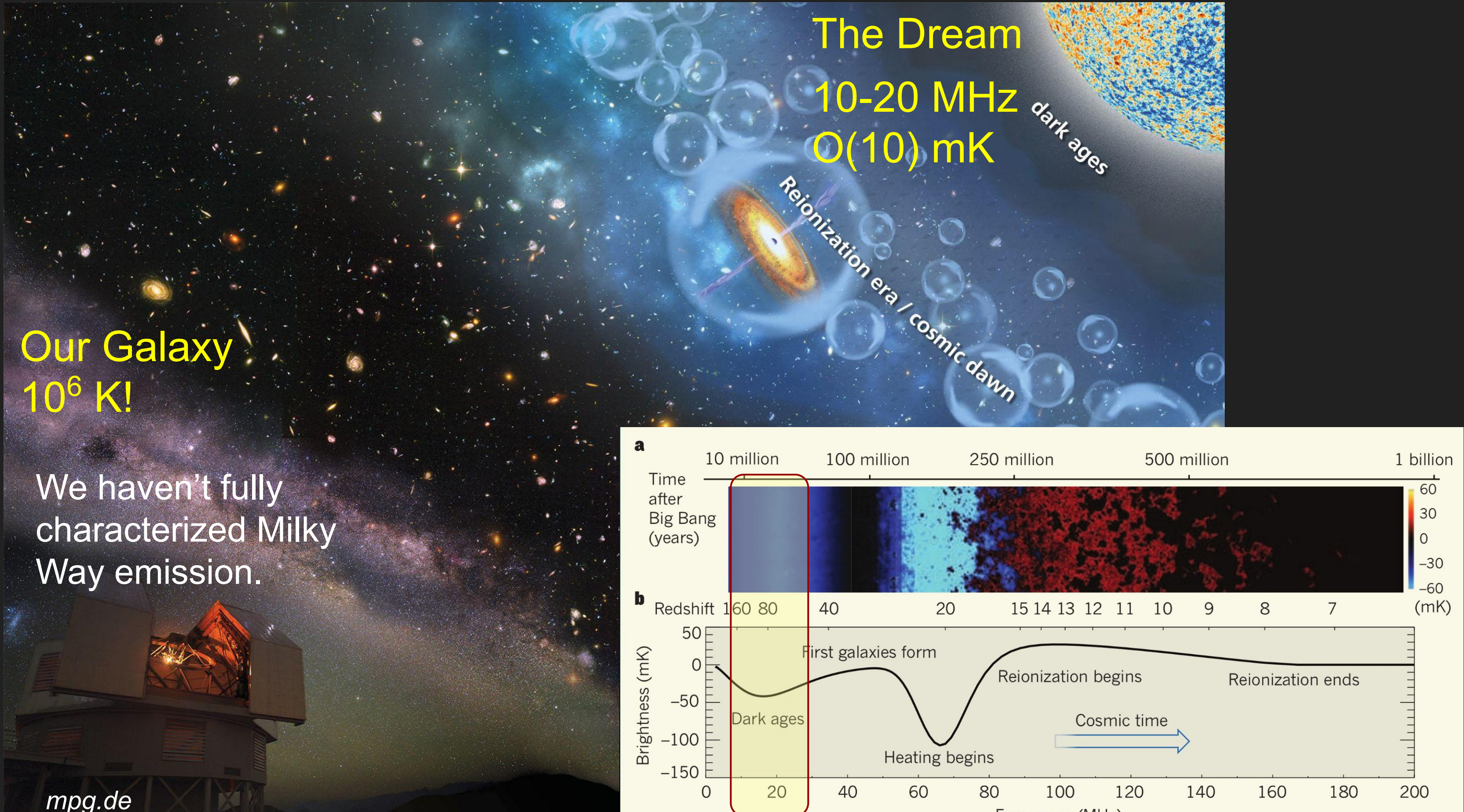


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# Current state of Galactic emission understanding

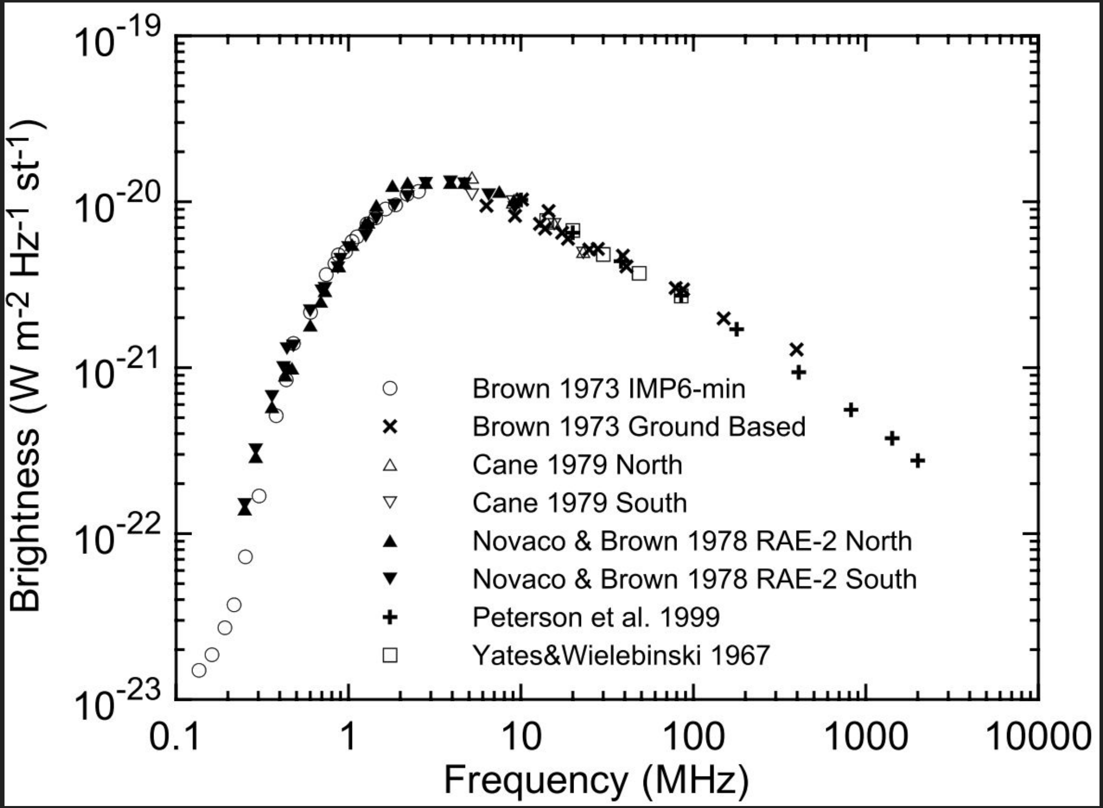


Fig. from Peterson & Webber (2002)

Maps and references to all the authors at
https://lambda.gsfc.nasa.gov/product/foreground/fg_diffuse.html

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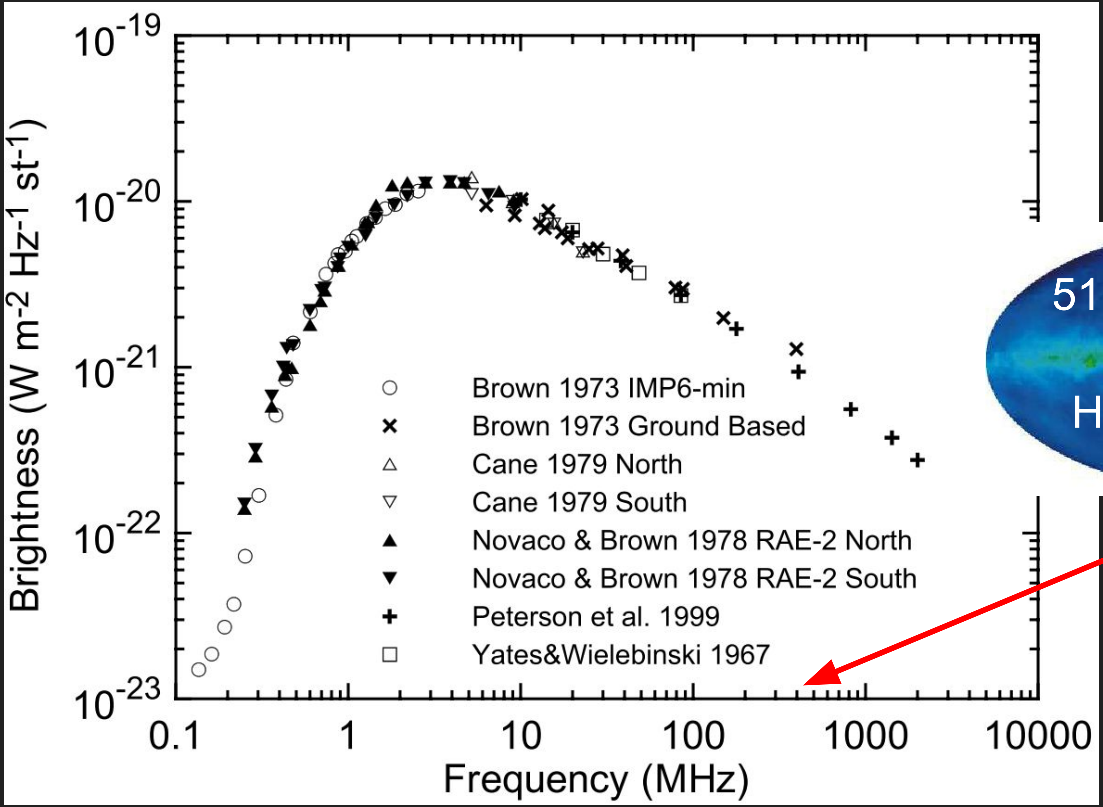


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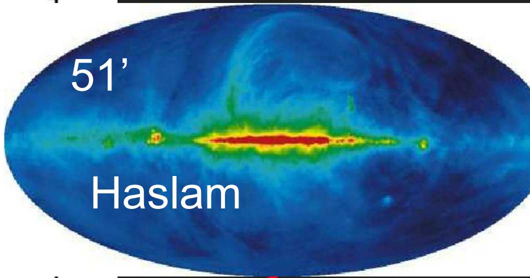


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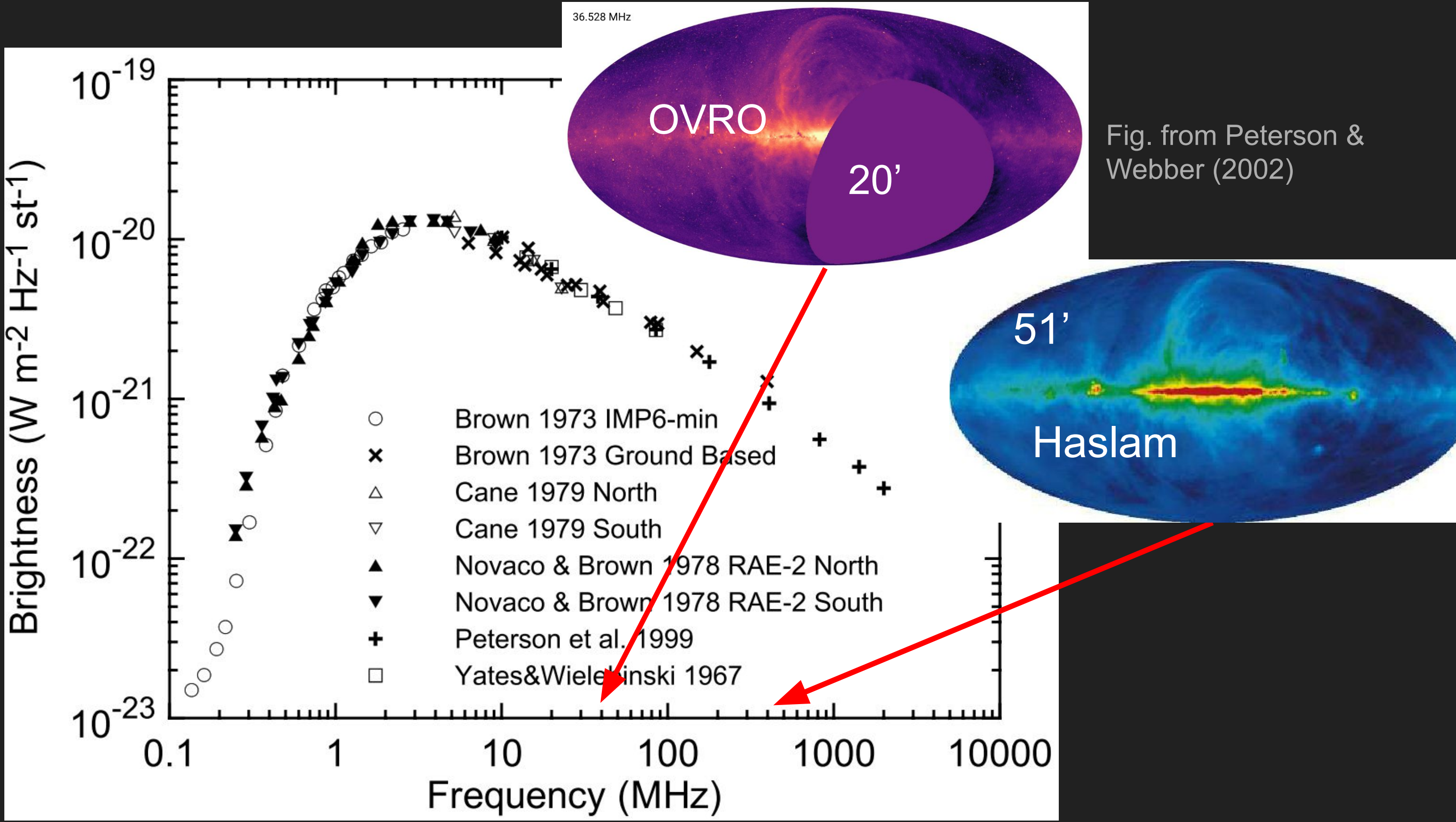


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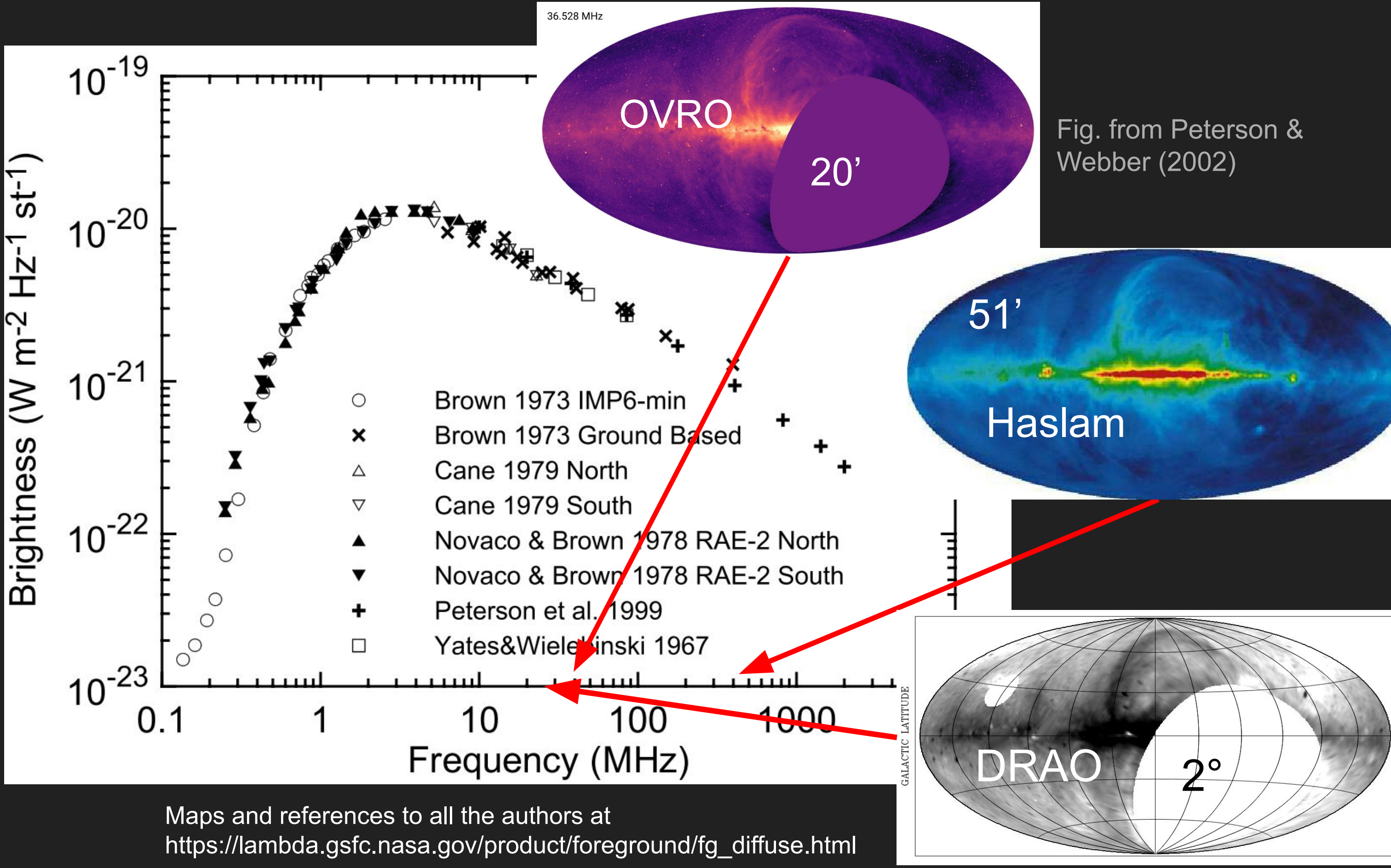


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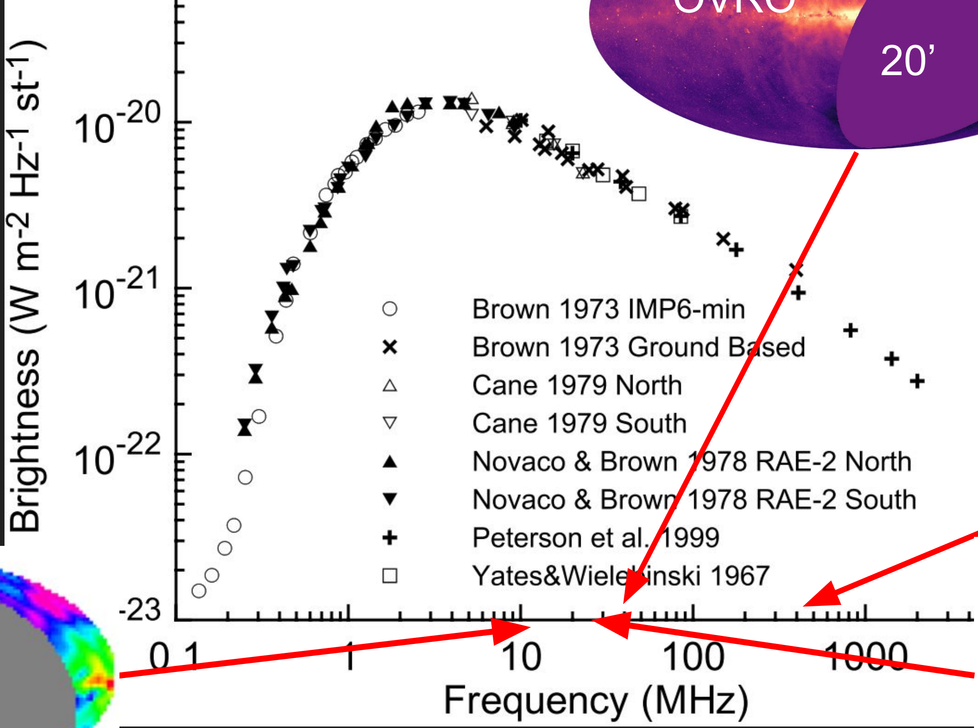


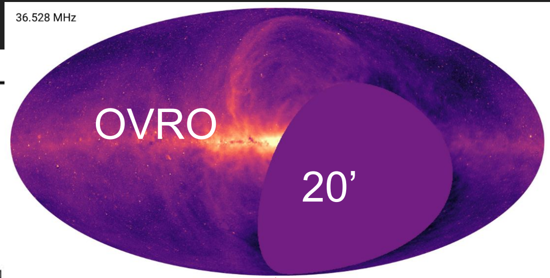


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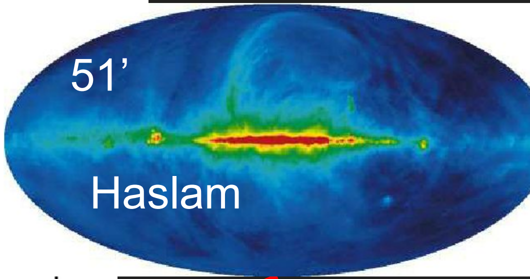


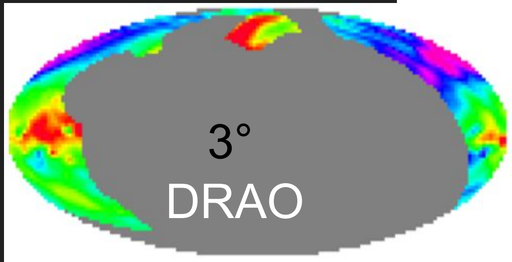


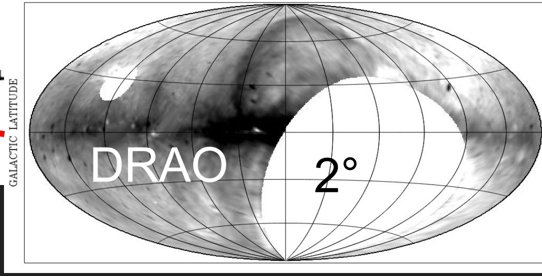


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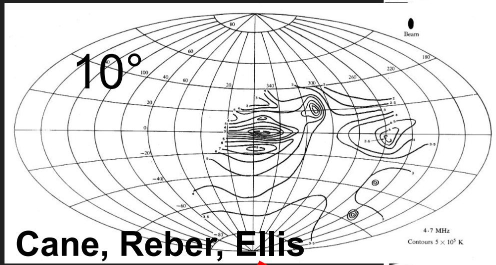


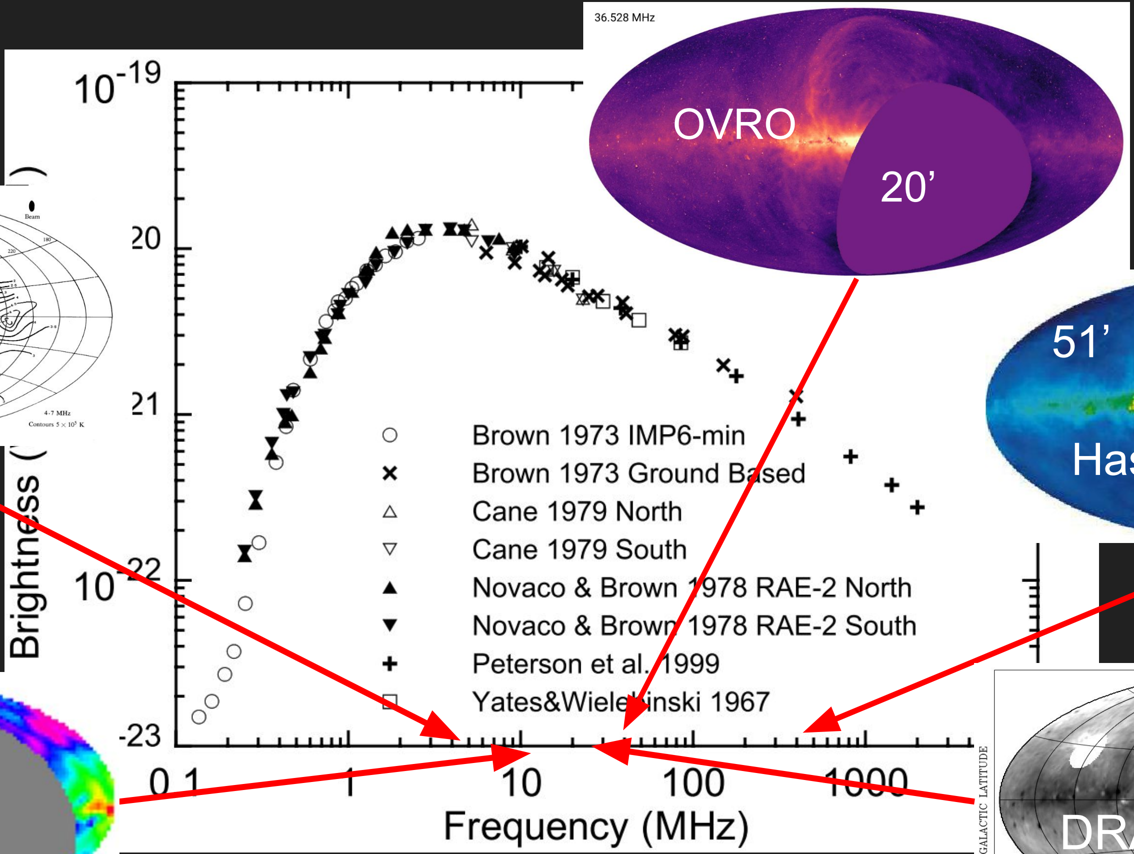


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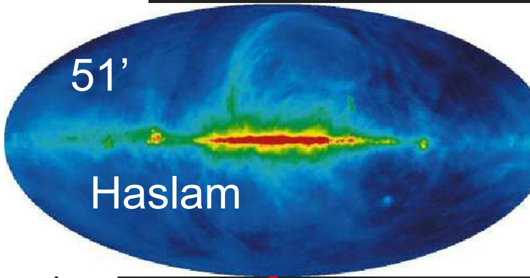


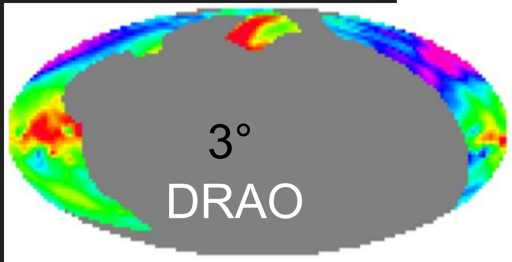


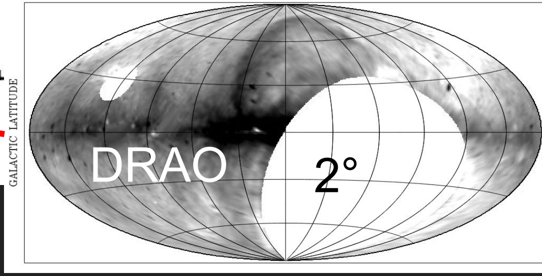


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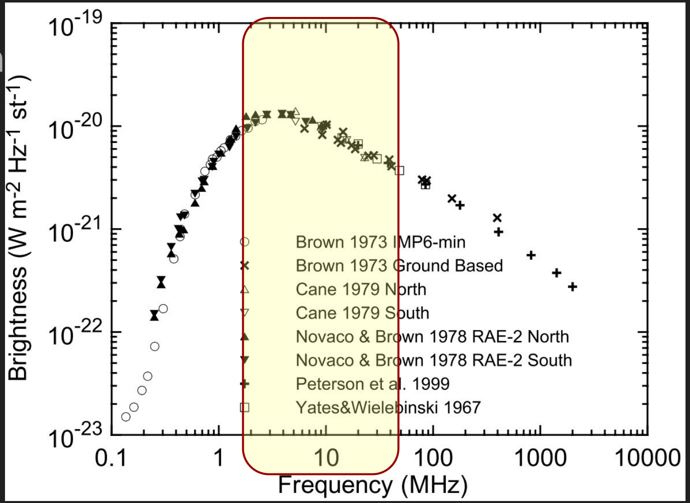
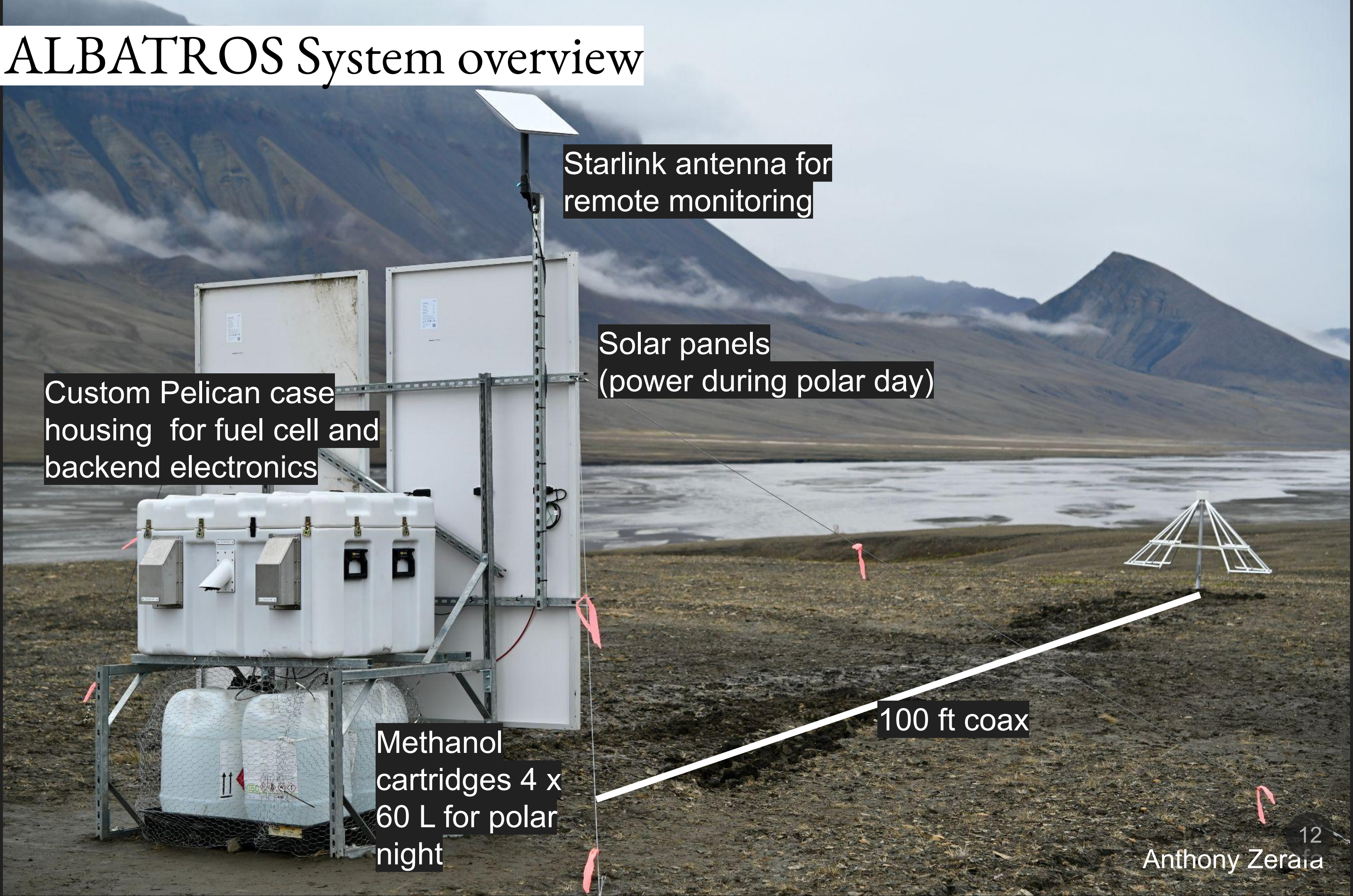
# Lots of interesting science at low-frequencies

- HII regions: measure 3D synchrotron emissivity, detection of new HII regions in absorption.
- Galactic magnetic field and cosmic ray transport studies with 3D emissivity measurements.
- Radio recombination lines for probing cold interstellar medium.
- Multifrequency maps at <10 MHz can probe line-of-sight electron density profile by exploiting diffuse free-free absorption.
- Ionosphere and space weather studies. Polar ionosphere is poorly understood and highly correlated with solar activity
- Searches for axion-like particles: conversion to photons in magnetized plasma creates low-frequency, narrow resonance peak (~few Hz width).



# ALBATROS System overview



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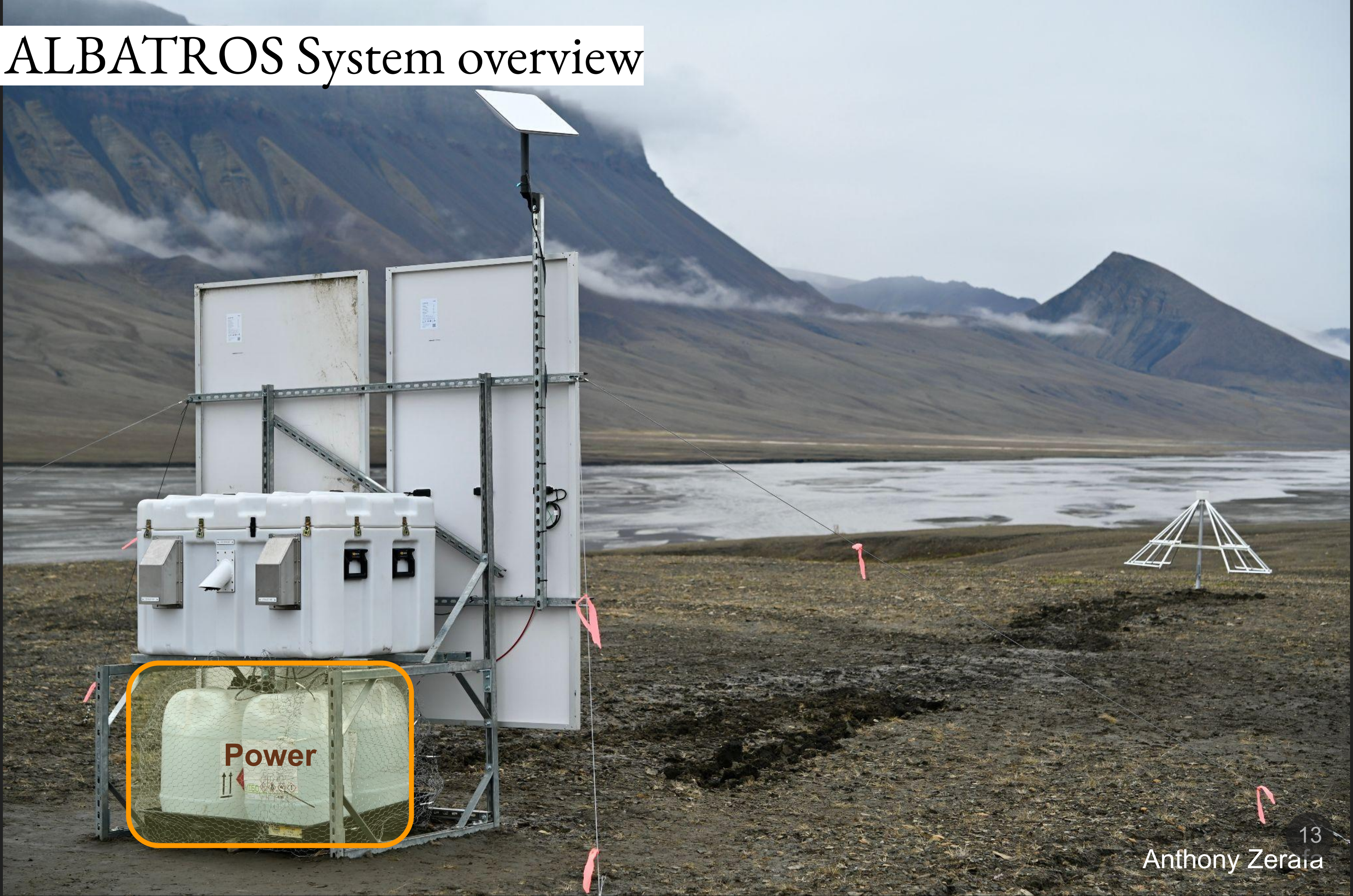

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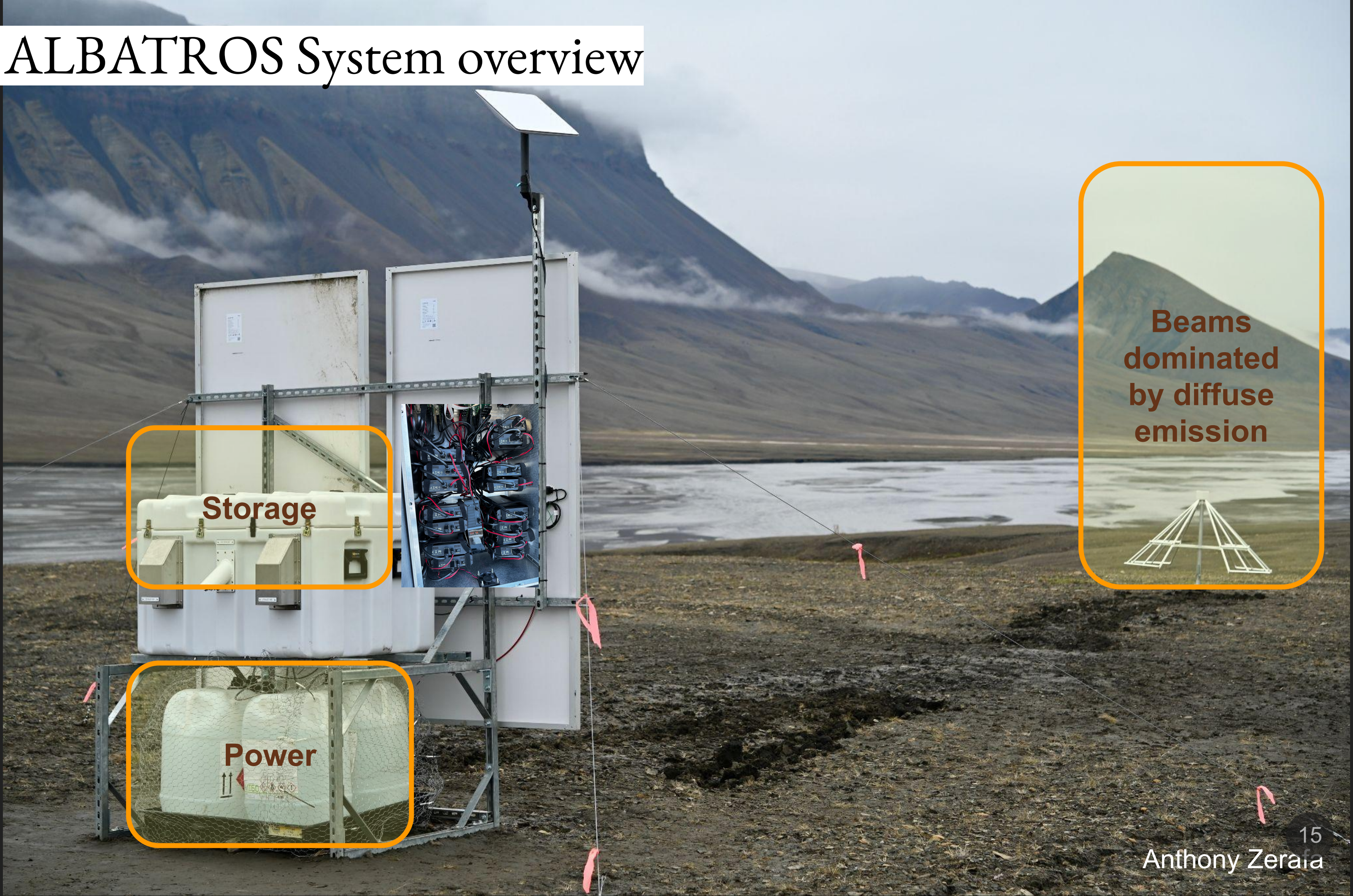




Anthony Zeraia

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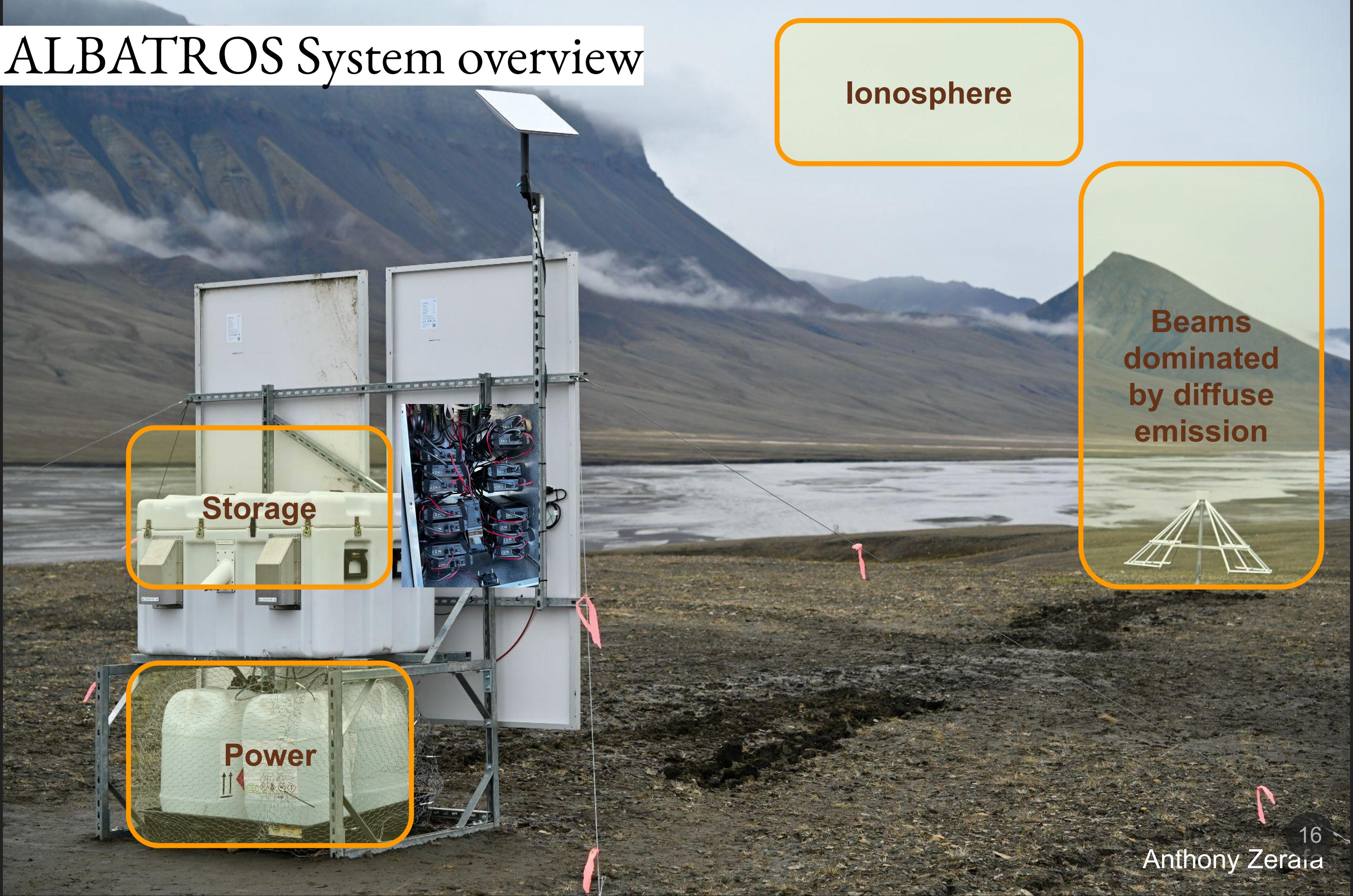

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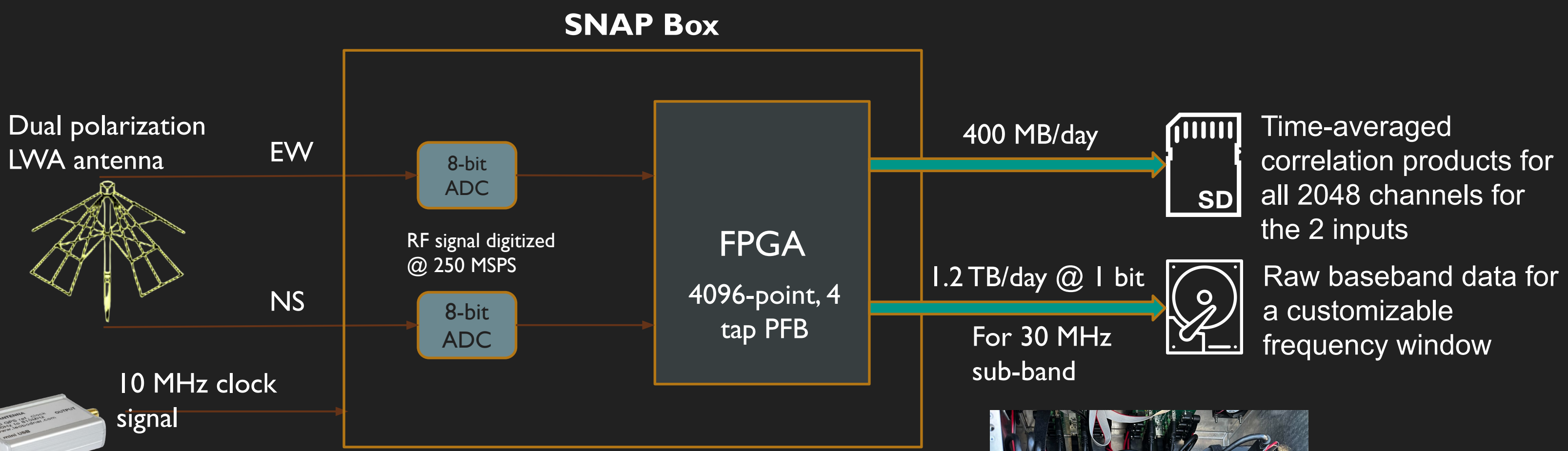
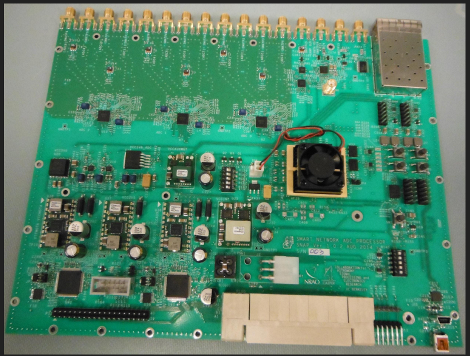



Leo Bodnar
GPS-locked clock

250 mW

Phase jitter @ 20 MHz approaches 1 rad on 1 hour timescale.



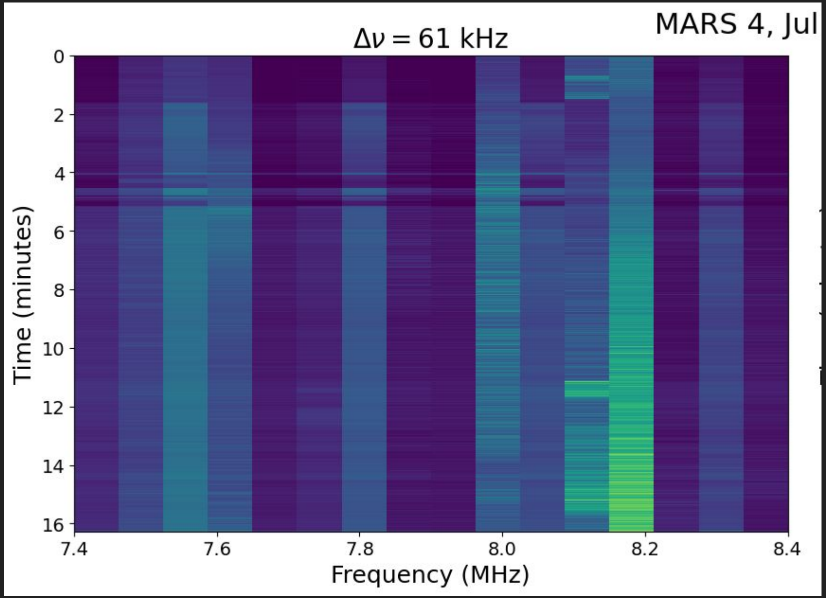
256 TB/station.
2 PB total!

1 bit with 61 kHz channels

# Imaging challenge #1 - upchannelization

Coarse channelization to make the most of limited storage. Default channel width 61 kHz. For all-sky imaging with long-baselines need at least ~10 kHz.

Retrieve timestream using a new fast and stable polyphase filter bank (PFB) inversion scheme. Then re-channelize for finer resolution.



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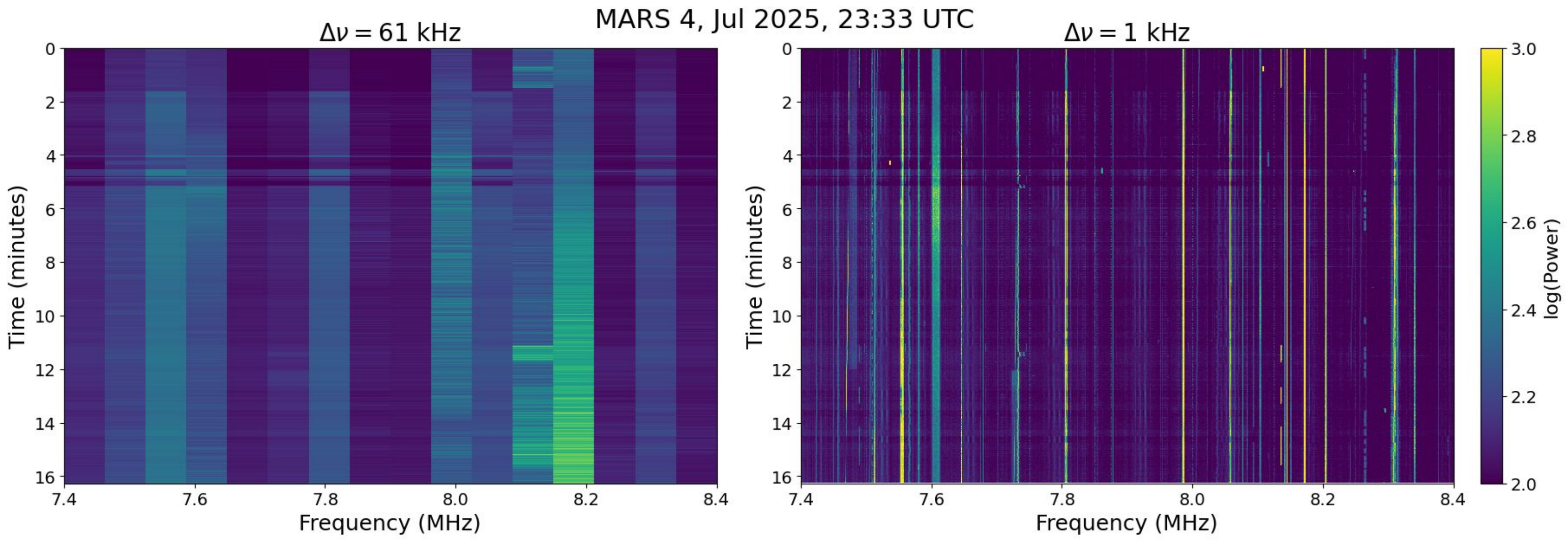

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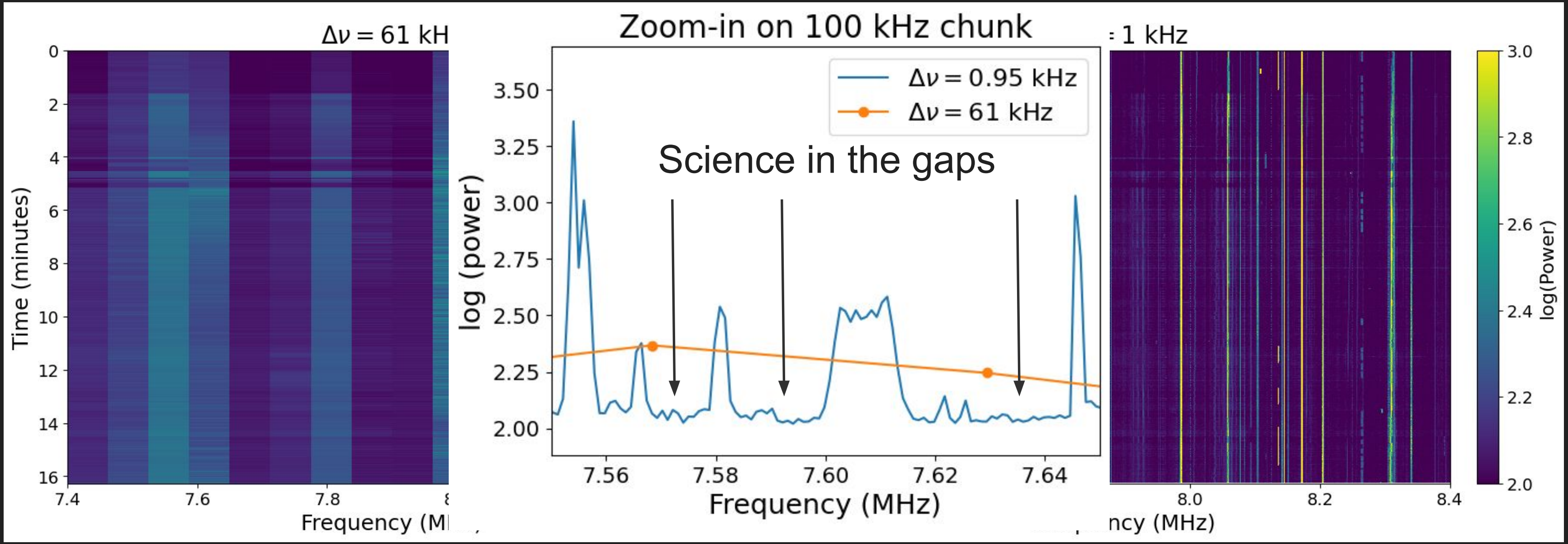

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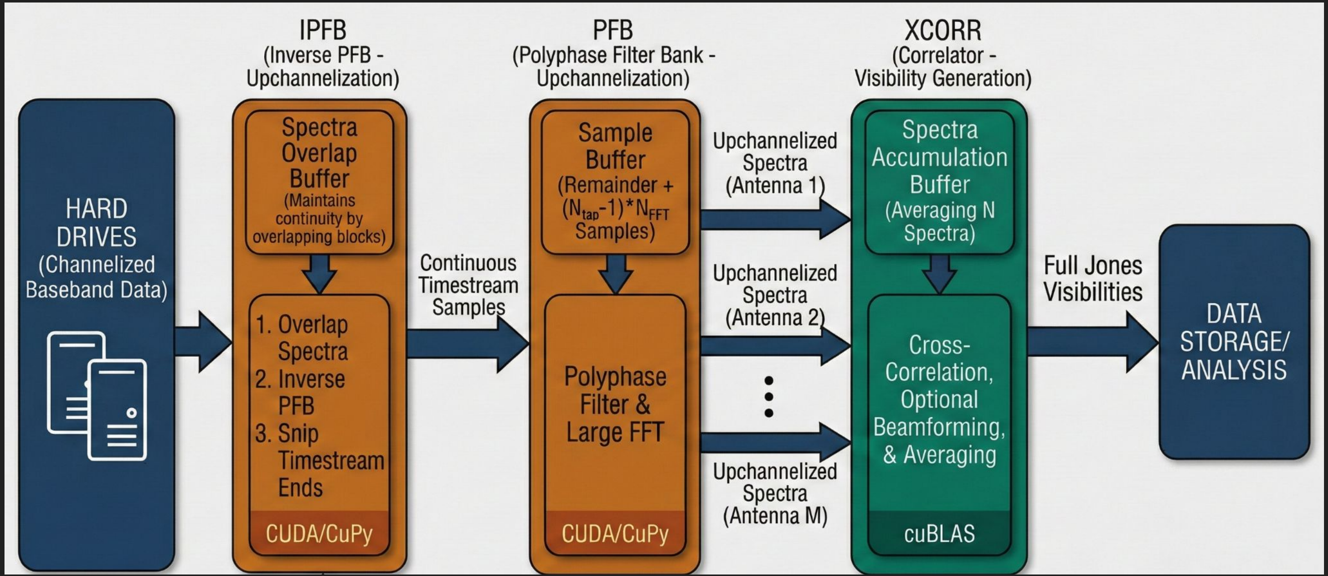
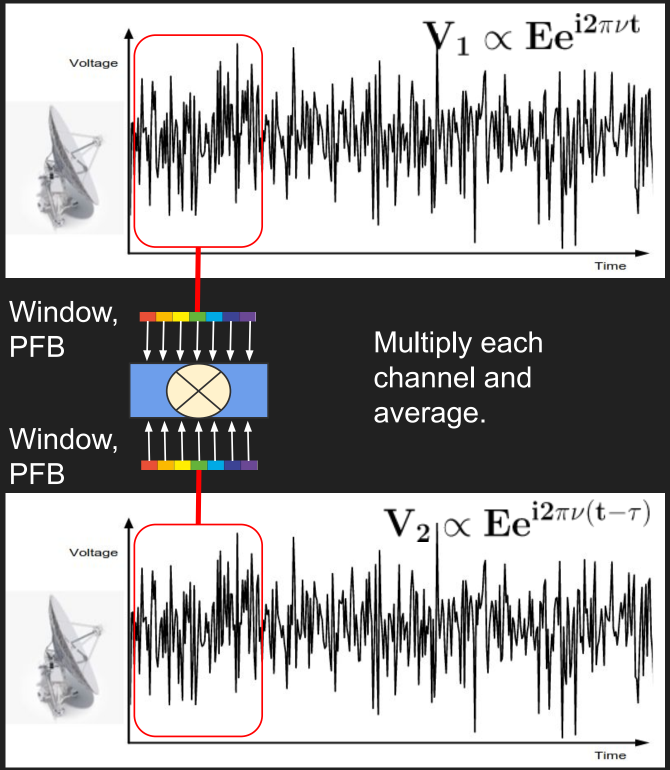



Very fast! IPFB bandwidth of **55 Gsamp/s** on Nvidia H100.

Up-channelized, Jones visibilities for 1 day of data from the **entire array** (8 antennas x 2 pols) **in ~2 hours.**

Can push extreme upchannelization factors. E.g. **PFB with $2^{28}$-long FFTs (sub-Hz resolution)** doesn't hog 10s of GBs of GPU memory. *Implementation and benchmark paper in prep (Mohan Agrawal, Philippe Joly)*

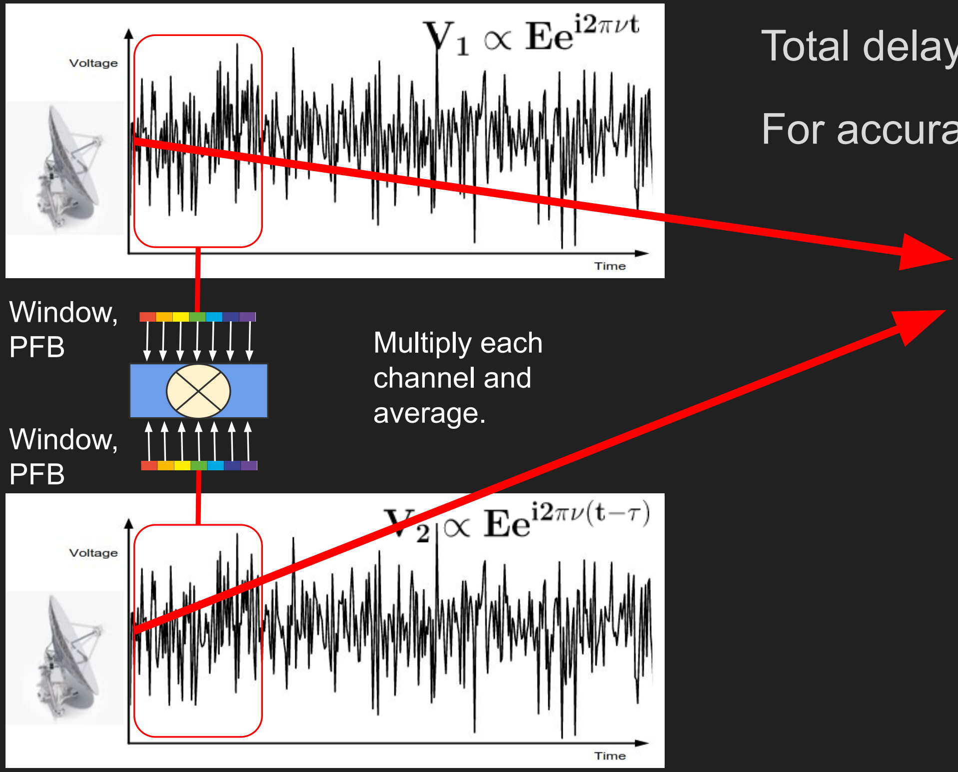
# Imaging challenge #2 - accurate timing




Total delay measured ≈ $\tau_g + \tau_{clk} + \tau_{iono}$.

For accurate source localization, delay = $\tau_g$

# Imaging challenge #2 - accurate timing

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Don't know the start time very well.
(~ 0.1 s accuracy timestamping.)

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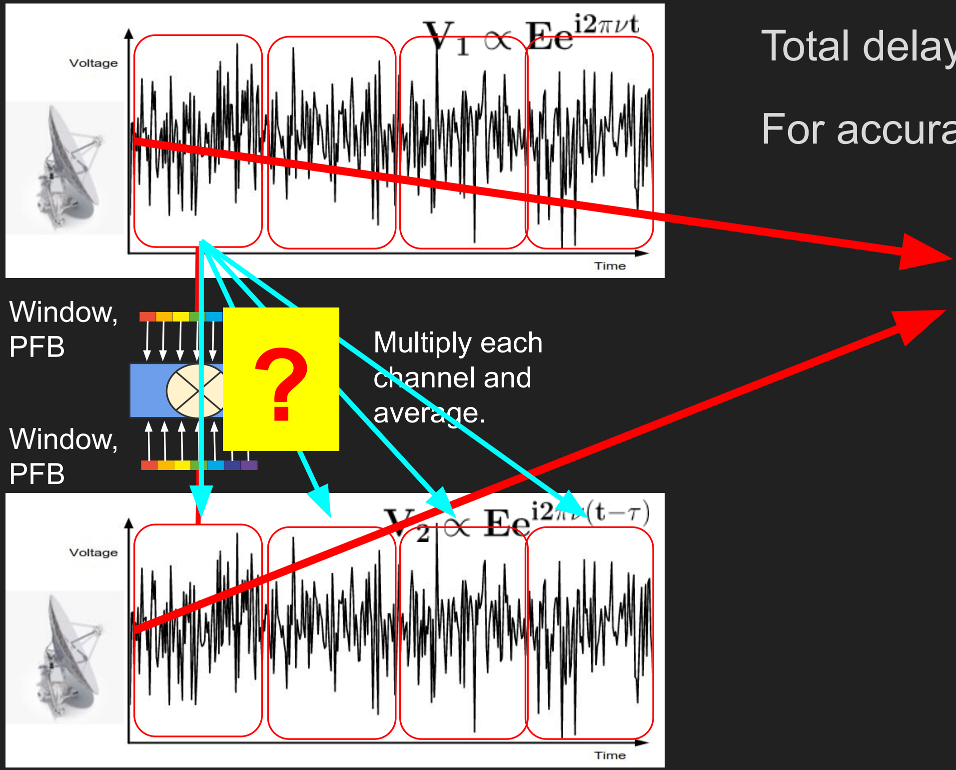


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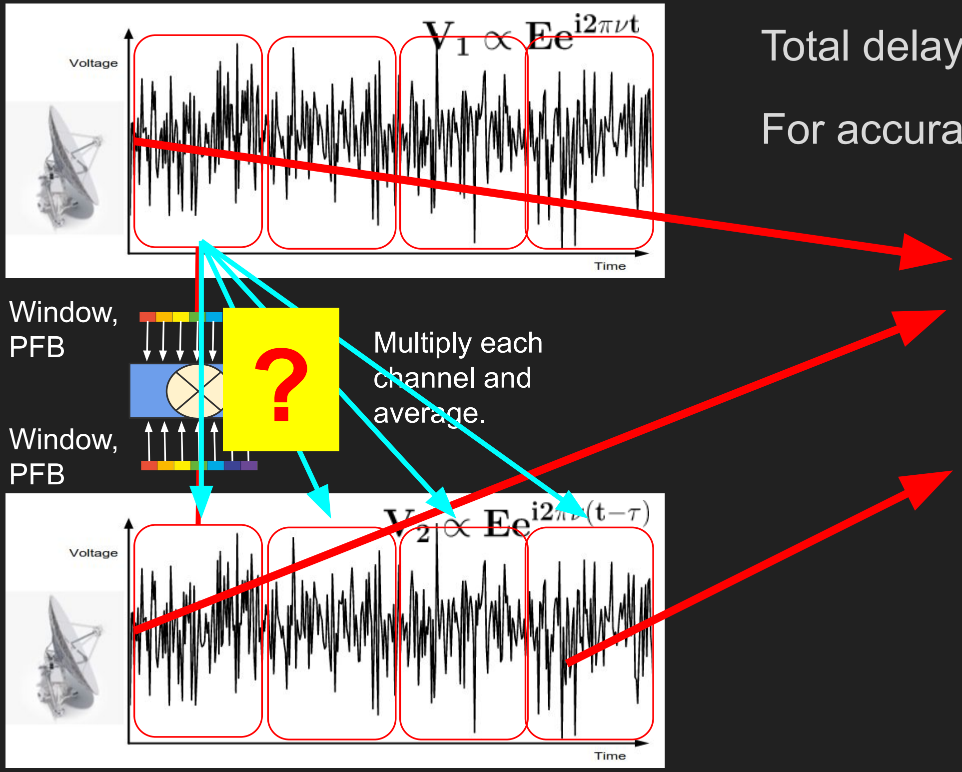


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Gain or lose one sample every hour.

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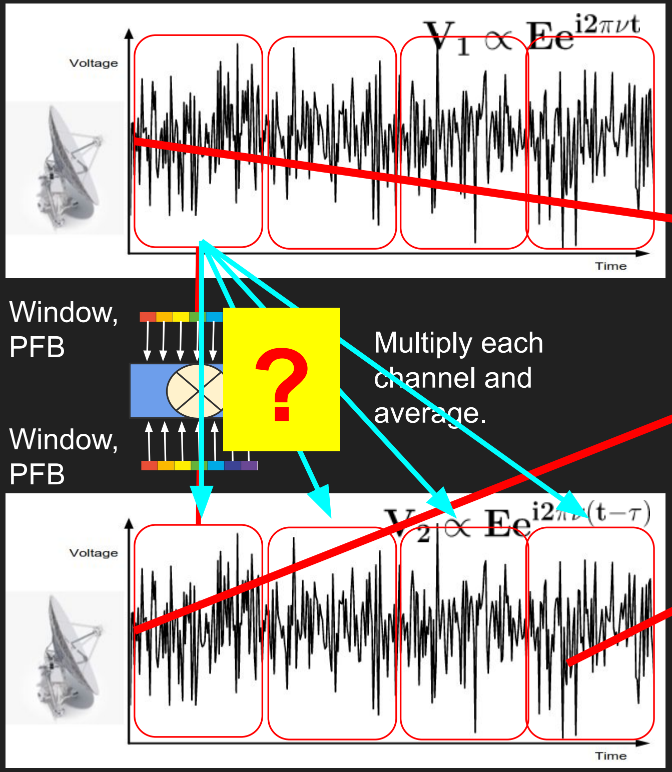


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For accurate source localization, delay = $\tau_g$

Don't know the start time very well.
(~ 0.1 s accuracy timestamping.)

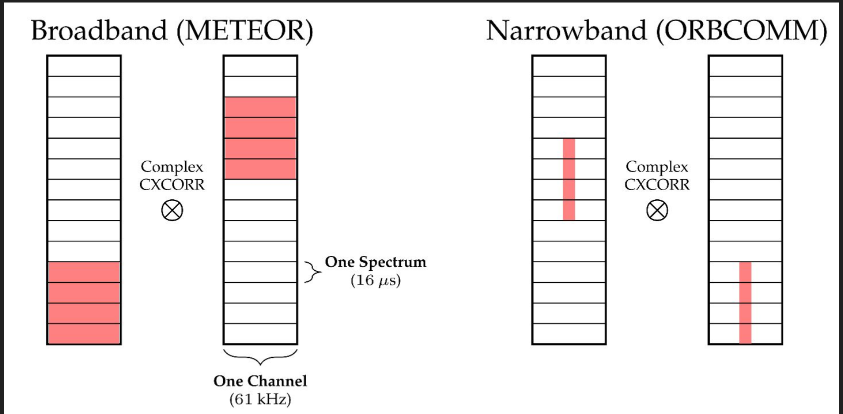
Oscillator frequency has jitter.
Gain or lose one sample every hour.

Clock delay = offset + slow drift

We start from 0.1 s relative alignment.

We require ~1 ns relative alignment at 30 MHz.

# Coarse alignment down to 1 spectrum



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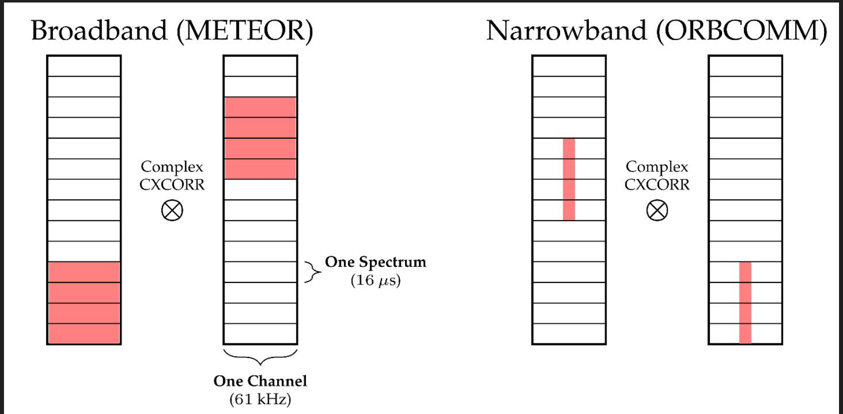
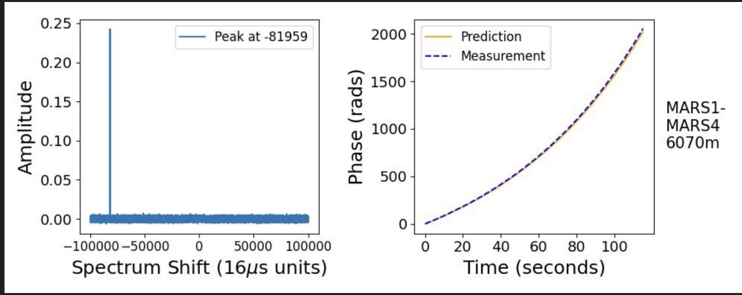
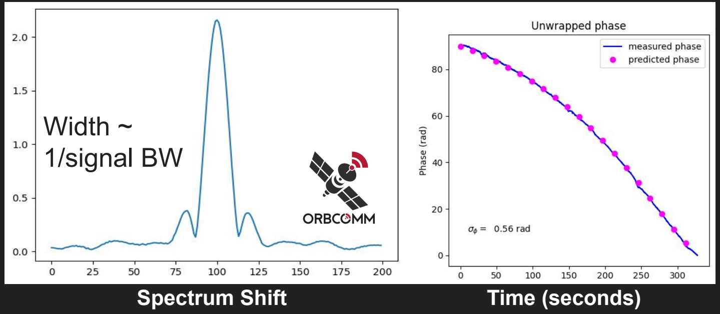



Plots from fully-automated satellite detection in baseband data.

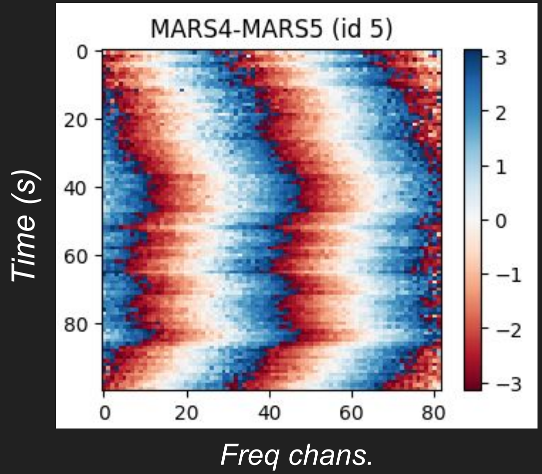


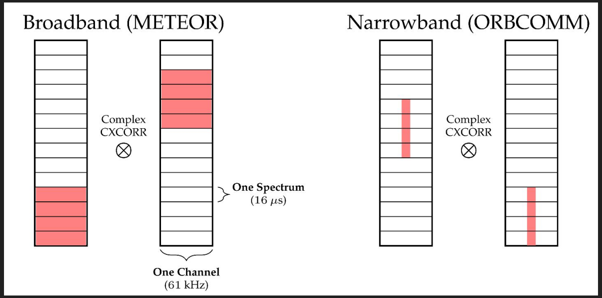




Mohan Agrawal, Thomas Bolder

# Coarse alignment down to 1 spectrum

After coarse alignment



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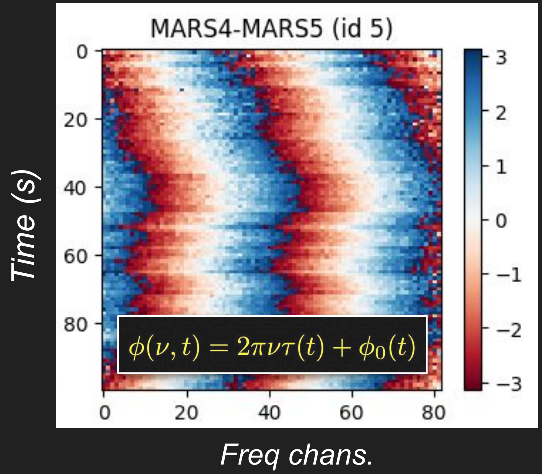
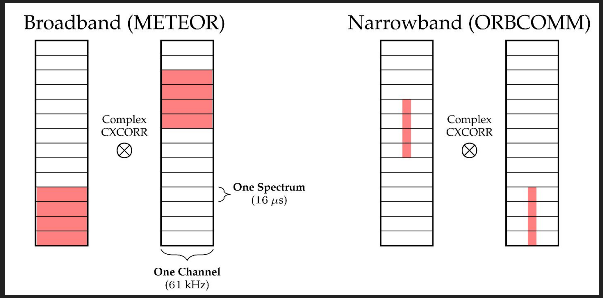


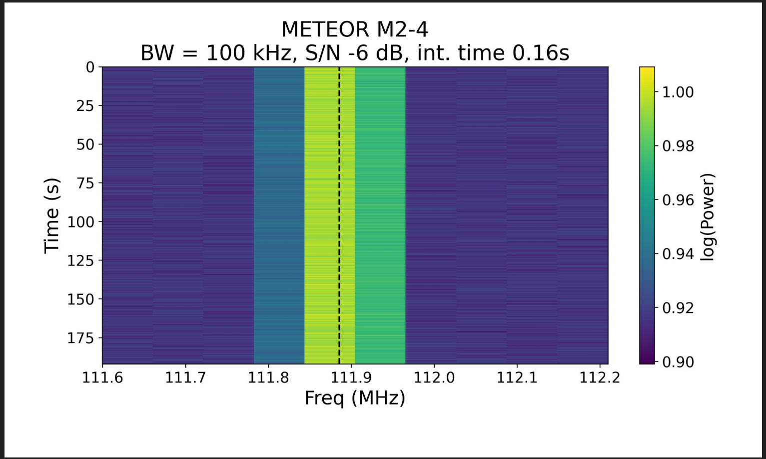

Traditionally, one would observe a bright calibration source and fit a line to each time sample.

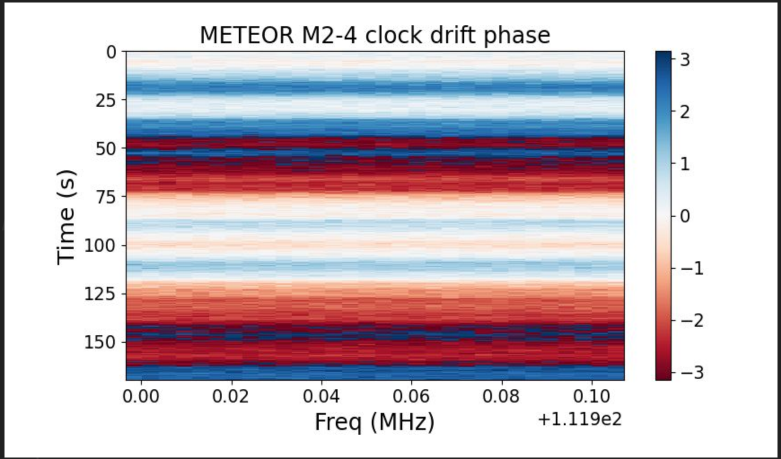
Bandwidth not enough large enough for good SNR on delay. We would like to average over the entire pass but clock is drifting…

Solution: Solve only for temporal structure, ignore overall offset. Use a prior on power spectrum of delays, if necessary (ADEV prior works.)

# Fine alignment - TOD simulations

Generate two copies of a narrow band signal, one delayed with simulated clock drift



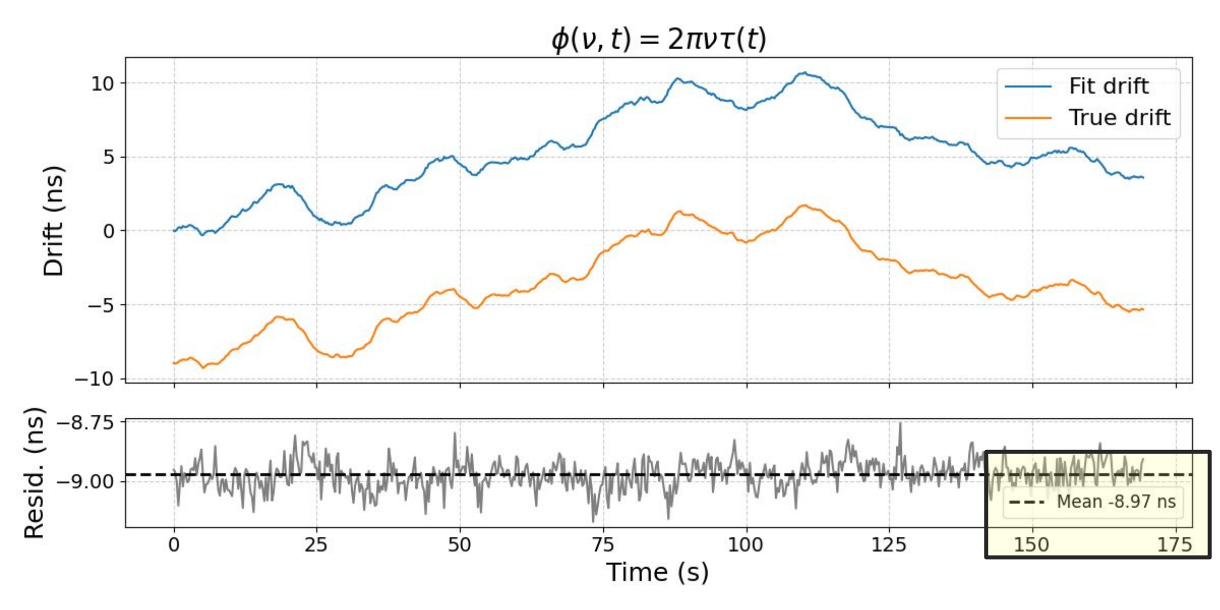




- Signals simulated and delayed at the ADC voltage level @ 250 Msamp/s.
- 3 minutes (50 billion samples), Noise spectra spans 25 μHz to 250 MHz.

***How to generate 13 decades of 1/f-type noise without requiring 100 TB of RAM?***
*(M. Agrawal, J. L. Sievers, in prep)*

# 3 minutes of Meteor pass, 137 MHz carrier

## Upchannelize, coarsely align, cross-correlate, integrate

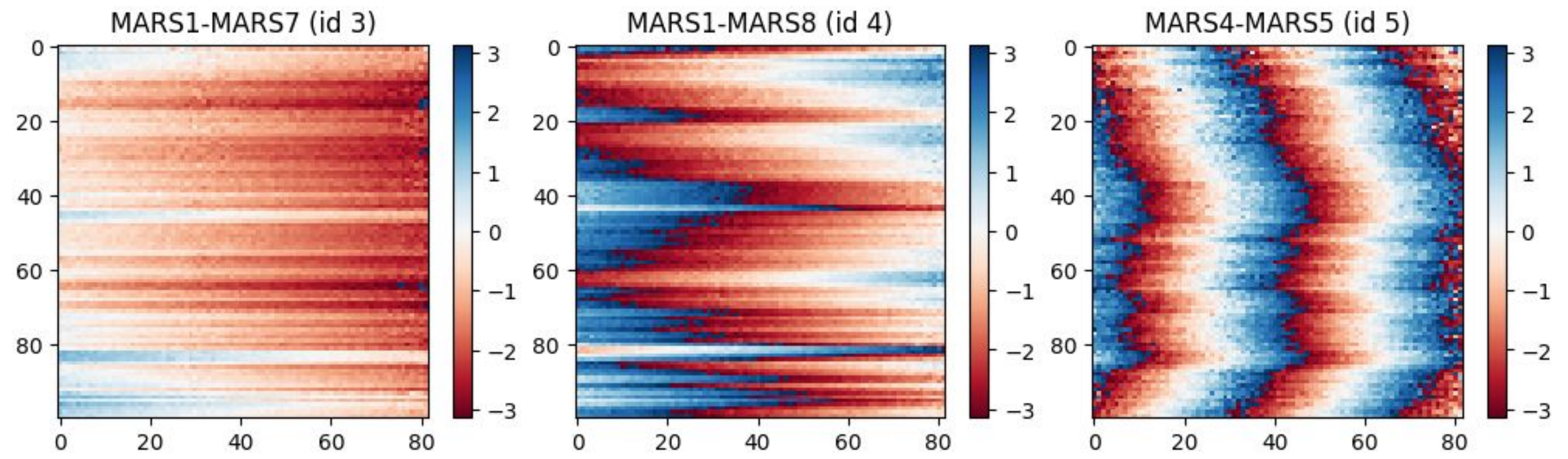



We can go back and apply this delay, and then average over the whole pass.

# Fine alignment - 1-bit upchannelized data

Timing algorithm in practice: 2 minutes of data, 80 kHz, 6 antennas (15 baselines).

*2 minutes of Meteor pass at 137 MHz - before correction*



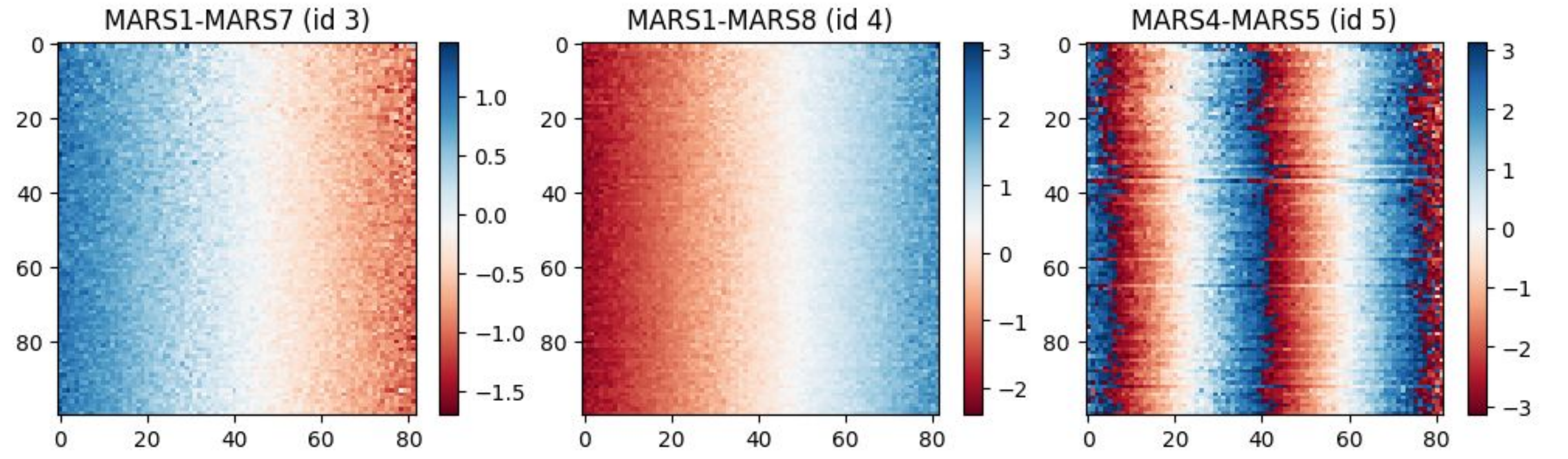
# Fine alignment - 1-bit upchannelized data

Timing algorithm in practice: 2 minutes of data, 80 kHz, 6 antennas (15 baselines).

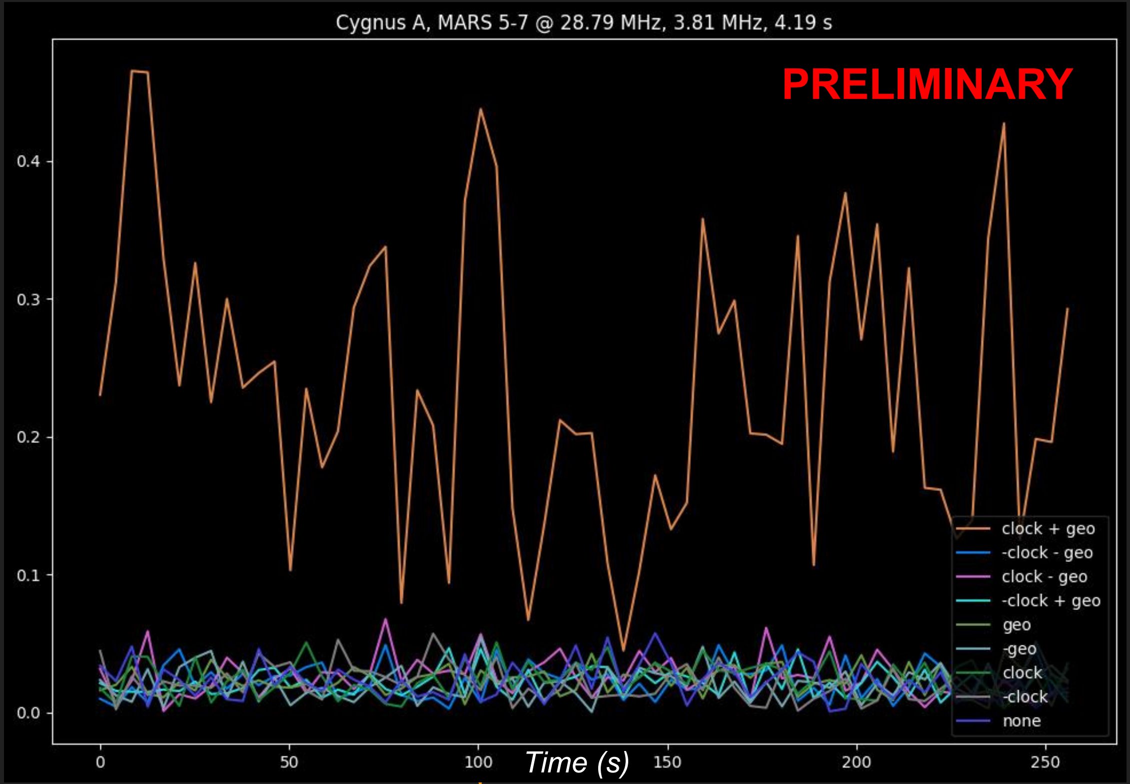
We can average over the whole pass now! Achieving 5 ns RMS timing accuracy.

Upchannelization, timing, and correlation paper in prep *(Mohan Agrawal, Thomas Bolder et al.)*

*2 minutes of Meteor pass at 137 MHz - after correction*

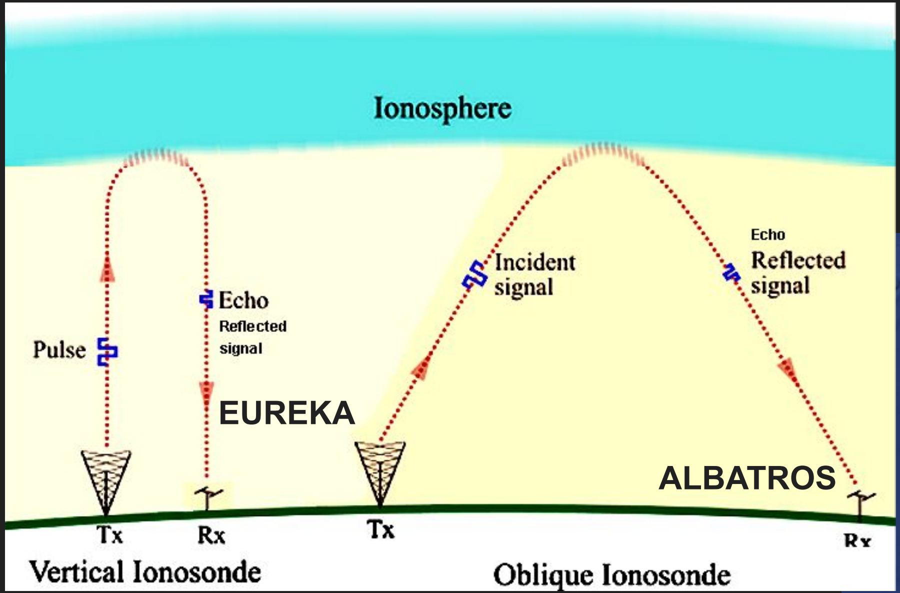


# Preparation for ongoing mapmaking work




**Sanity checks:** Only a unique sign combination of clock and geometrical delay during phasing should work. And BOTH should be needed.

# Imaging challenge #3 - Ionosphere




Ionosphere near the magnetic pole is poorly understood. It refracts, reflects, and scatters.

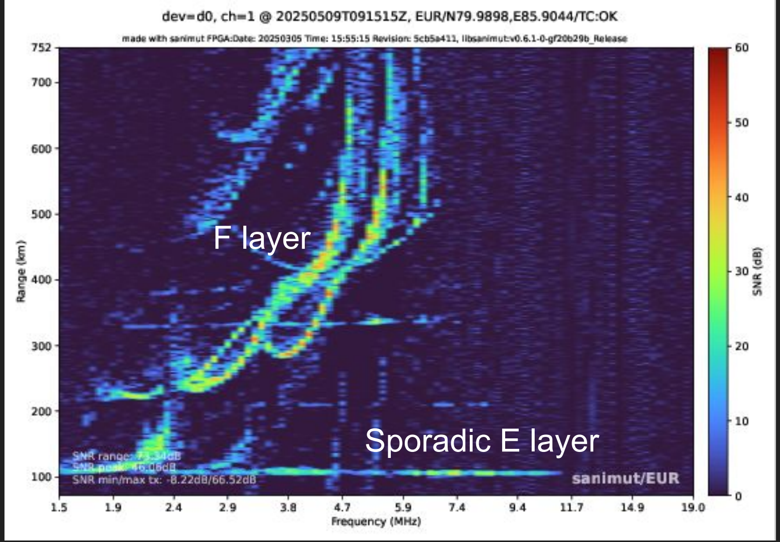
We need to monitor plasma's critical frequency to correct for refraction effects.


Canadian High-Arctic Ionosonde Network (CHAIN) in the Arctic.

We know the pseudo-random codes being broadcast, and we can detect the reflections in baseband!

# Vertical sounding at Eureka.

(Credits Dr. Torsten Reuschel and CHAIN, University of New Brunswick)




**Sporadic-E is unpredictable and not fully understood.**

**We're going through maximum of the solar activity cycle.**

**Lots of interesting phenomena at the geomagnetic poles!**

Vertical sounding at **Eureka.**

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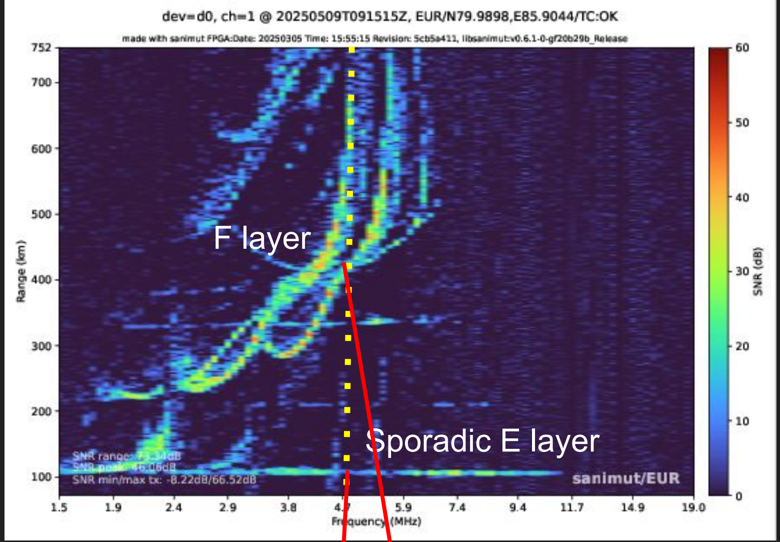
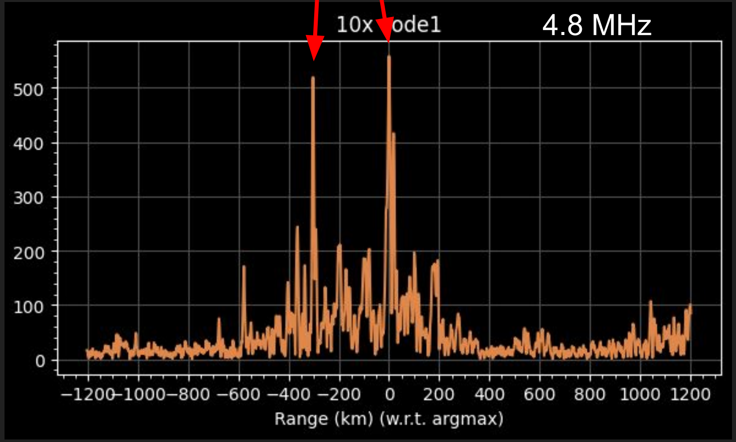



**Sporadic-E is unpredictable and not fully understood.**

**We're going through maximum of the solar activity cycle.**

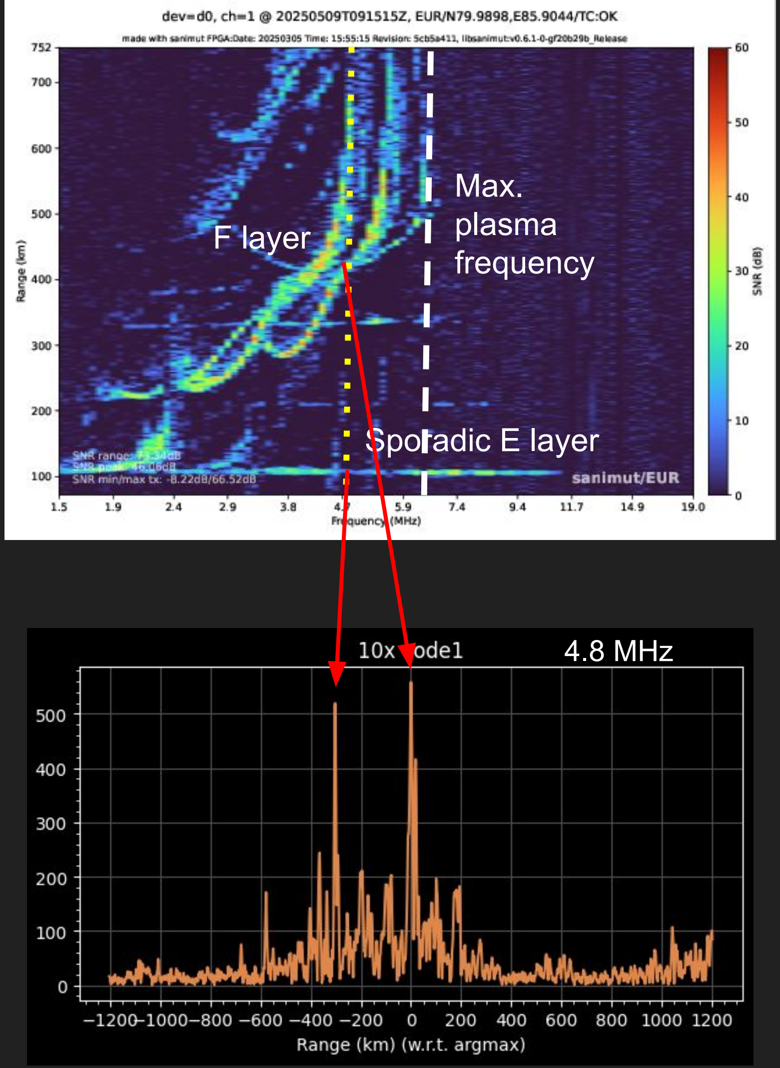
**Lots of interesting phenomena at the geomagnetic poles!**

Oblique detection by **ALBATROS.**

# Vertical sounding at Eureka.

(Credits Dr. Torsten Reuschel and CHAIN, University of New Brunswick)

Measurements of vertical electron density profile allows us to model the refraction and correct for ionospheric delays.




**Sporadic-E is unpredictable and not fully understood.**

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Oblique detection by ALBATROS.

# Summary

ALBATROS collecting its first 8-antenna overwinter data in 2025-26. 🤞

Ultra-low frequencies are under-explored and a goldmine of new, interesting science.

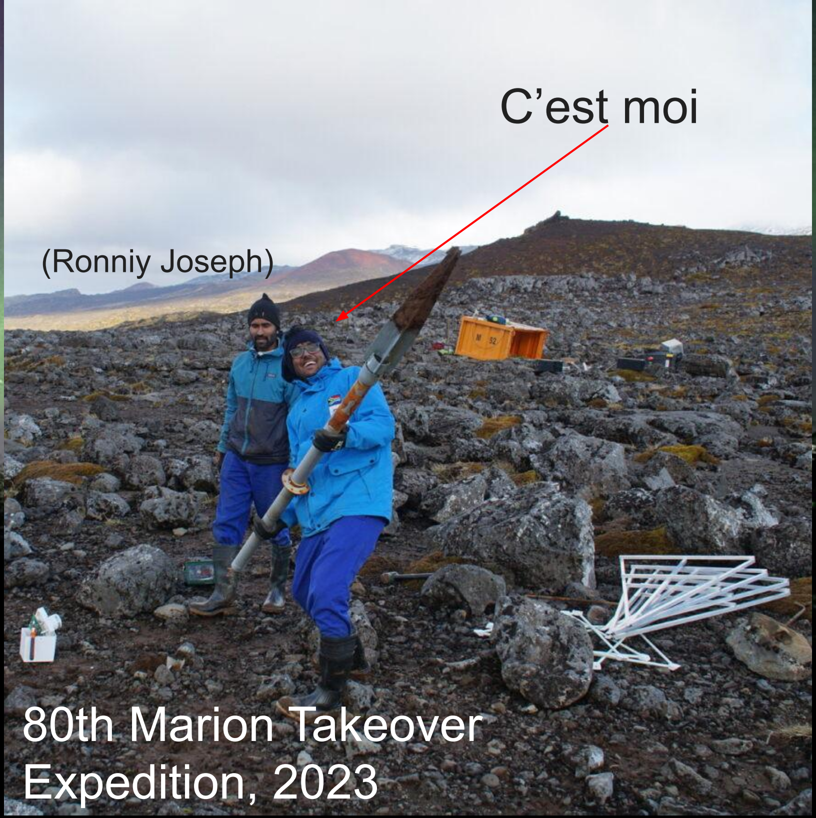
Streaming, backend agnostic (CPU/GPU) up-channelization + correlation pipeline ✅

Tracking clock offsets and drifts with satellites. ✅

RFI-flagging and map-making with 6-element 2024 overwinter data in progress. ⌛

Ionospheric science with ionosondes. ⌛

upchannelization, correlation, timing papers in prep…




I’ll be looking for postdoc positions later this year.

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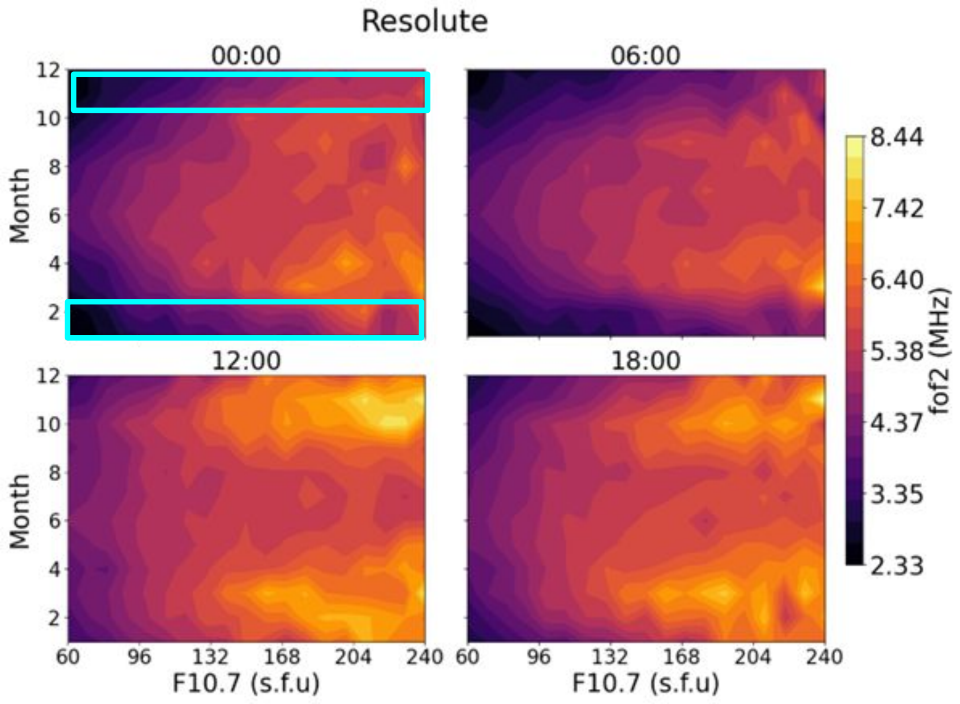
# Backups

# 75 years of Arctic ionosphere climatology

Can we get lucky for a few days in 4 months of polar night?




Polar night

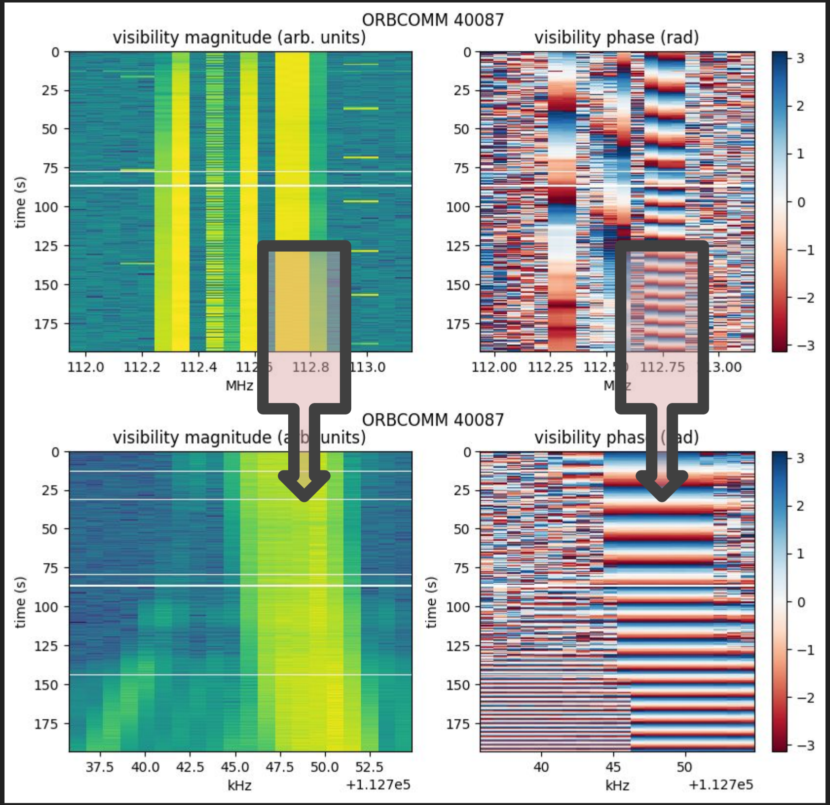
Plot courtesy of Dr. David Themens, U. Birmingham, UNB

# Imaging challenge #1 - upchannelization

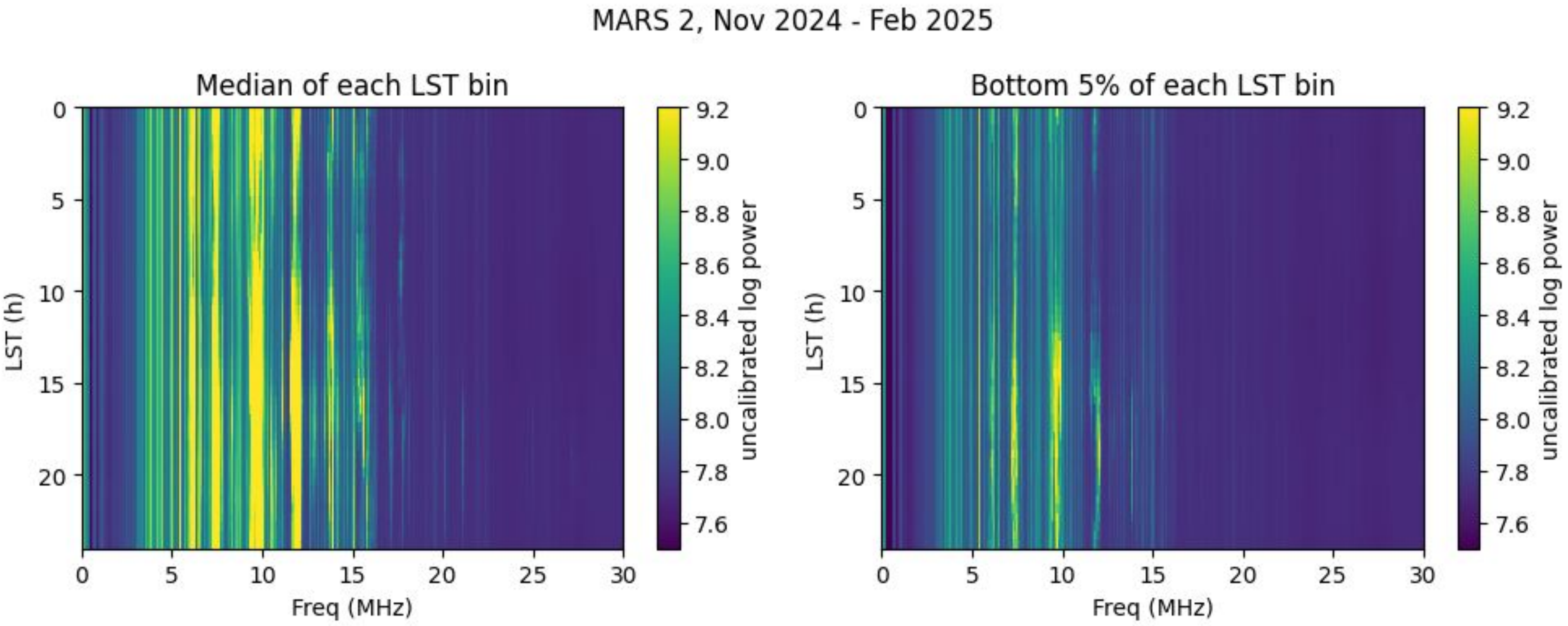
Inverse PFB algorithm deals with quantization noise.

Works well with 1 bit data..

**3 kHz doppler shift of ORBCOMM satellite (1-bit)**



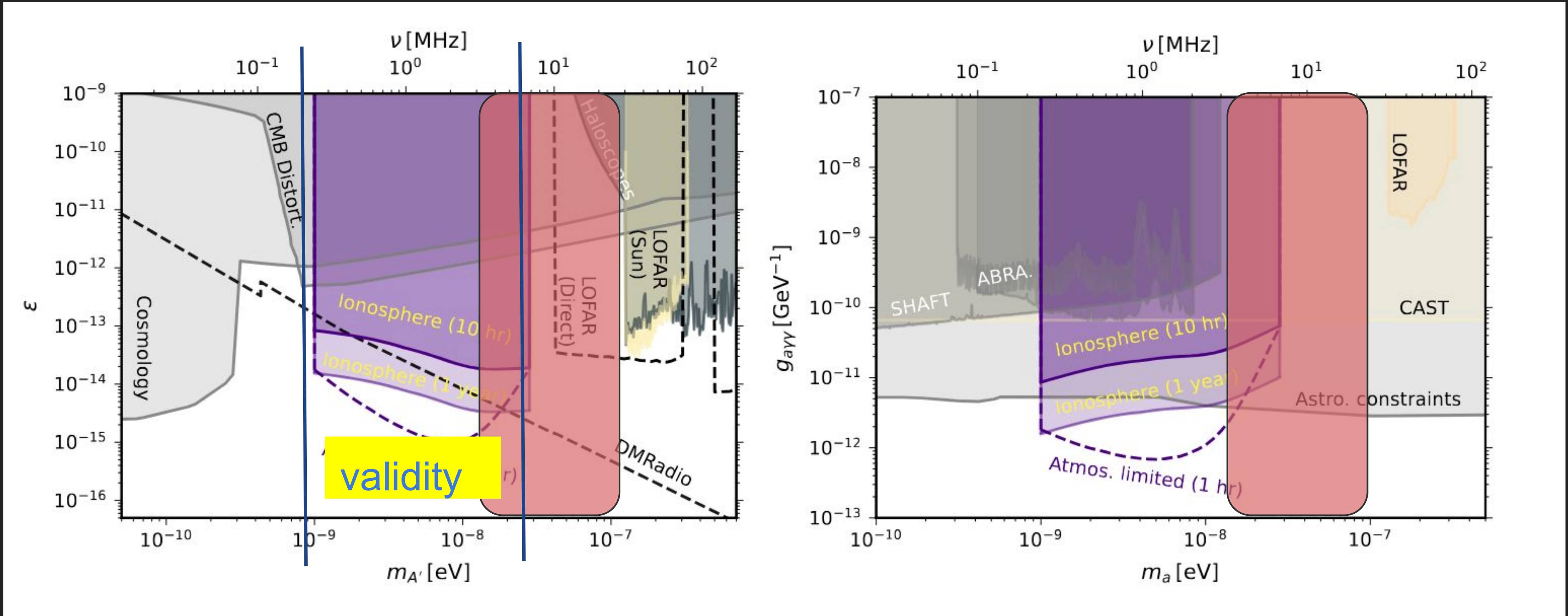
# LST binning



MARS 2, Nov 2024 - Feb 2025
Median of each LST bin
Bottom 5% of each LST bin
LST (h)
Freq (MHz)
uncalibrated log power
0
5
10
15
20
25
30
7.6
7.8
8.0
8.2
8.4
8.6
8.8
9.0
9.2

# Data in-hand

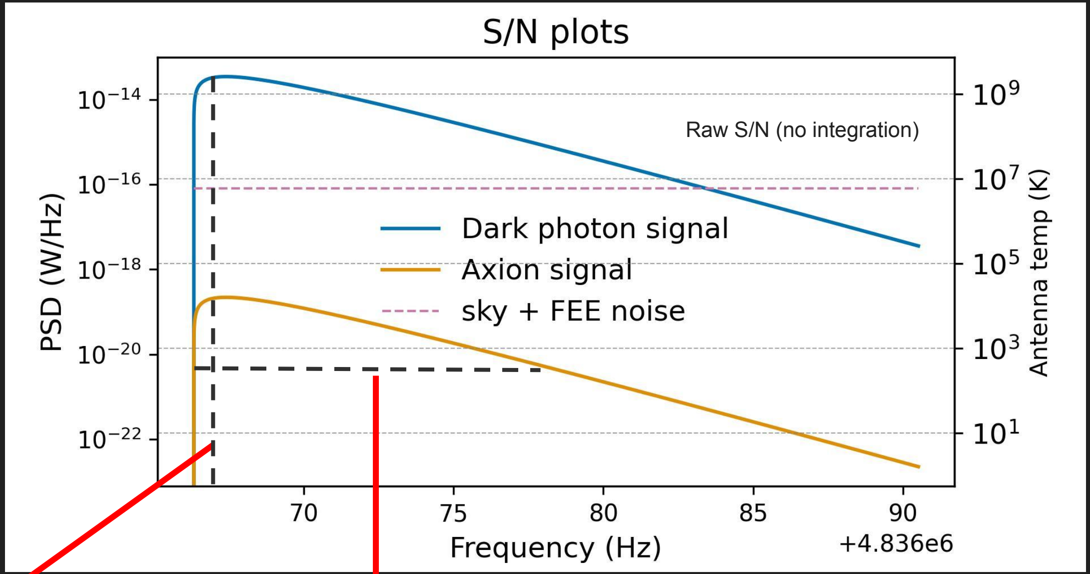
4-11 MHz **(RED)**, about 60 hours, 4-bits. Antenna location: 79d 24.925', -90d 46.385



# ALBATROS is in a unique position to search for Axions

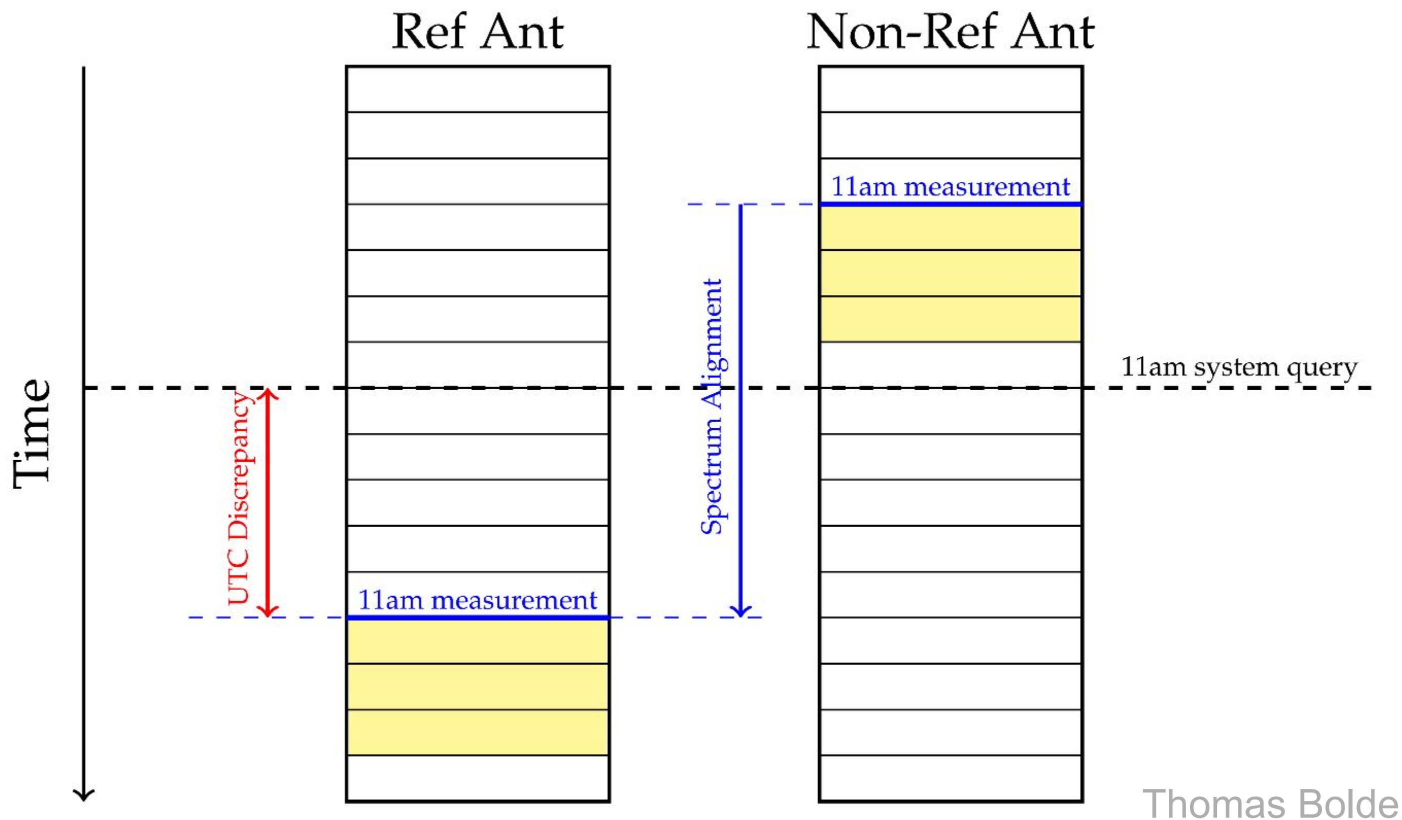
Axion-like particles (ALPs) can convert resonantly to photons in ionospheric plasma when ALP mass matches the plasma's critical frequency.

*(C. Beadle et al, 2024)*

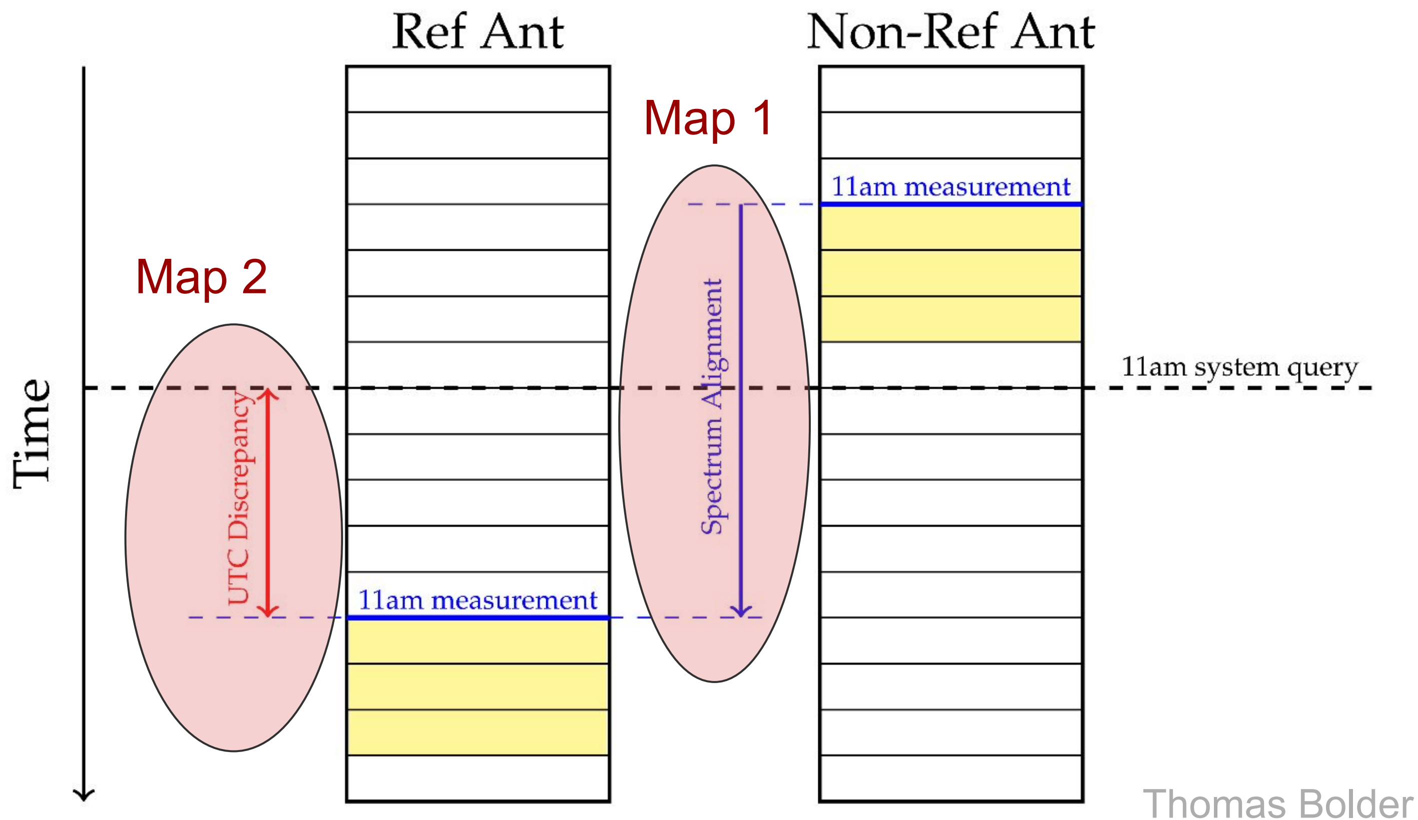



Peak location depends on ionospheric plasma frequency, which we can measure continuously!

Peak width is only a few-Hz, but we can upchannelize our data to sub-Hz resolution fast and efficiently!




Thomas Bolder

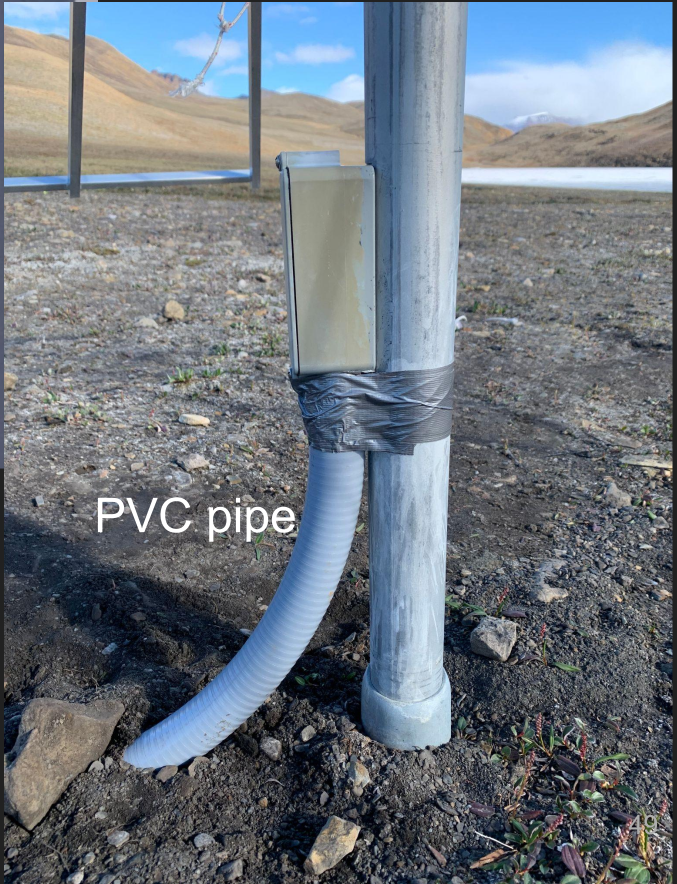


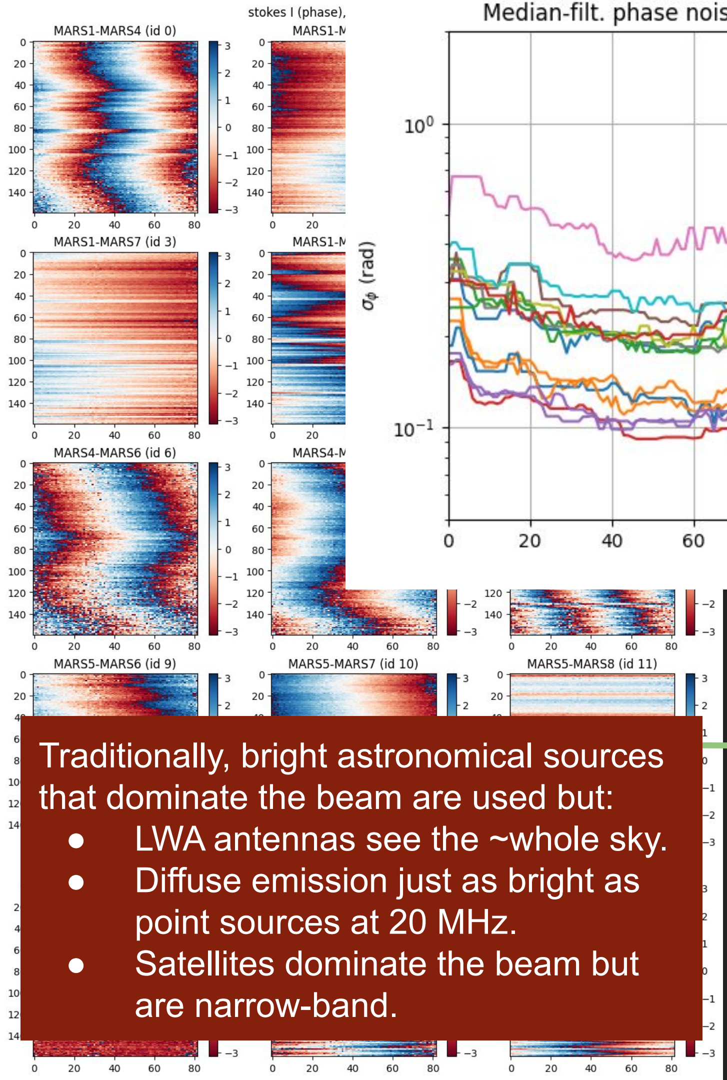

Thomas Bolder

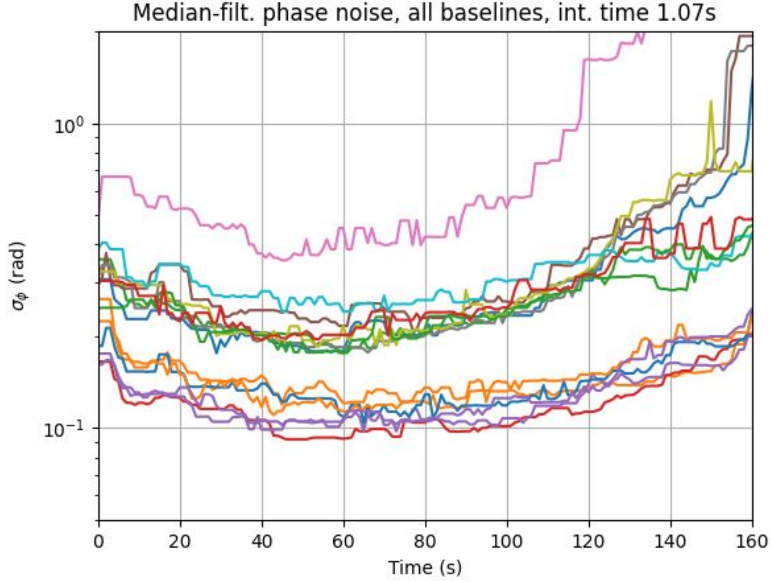

Chewed
kevlar
ropes

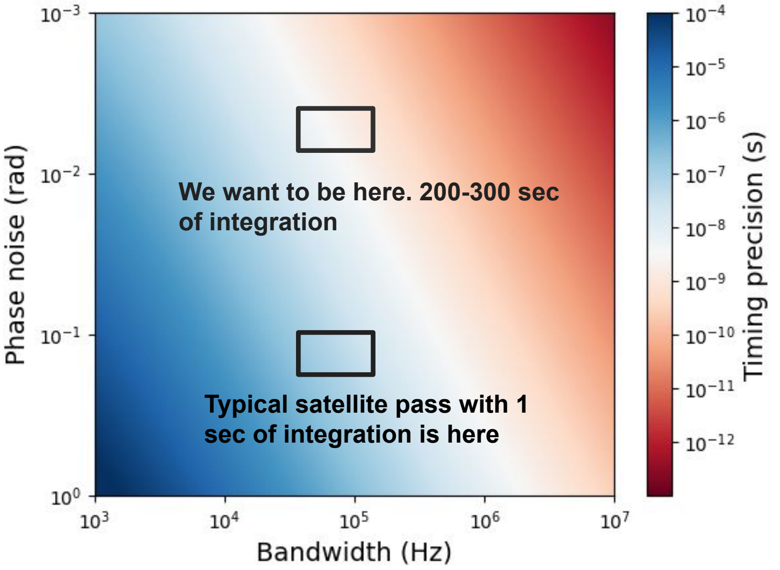

Chewed
coax


Drill divots


PVC pipe




Traditionally, bright astronomical sources that dominate the beam are used but:

- LWA antennas see the ~whole sky.
- Diffuse emission just as bright as point sources at 20 MHz.
- Satellites dominate the beam but are narrow-band.

Simple solution:
Fit a line per time sample.

$$\phi(\nu, t) = 2\pi\nu\tau(t) + \phi_0(t)$$

Error on the slope:

$$\sigma_\tau = \frac{\sqrt{12}.\,\sigma_\phi}{2\pi.\,\mathrm{BW}.\,\sqrt{SNR}}$$