# The Canadian Galactic Emission Mapper (CGEM): An 8-10 GHz Polarization Survey to Aid in the Search for Primordial Gravitational Waves


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# Who am I?

**Pedro Villalba-González (he/him)**

**Where to find me:**
**Observational Cosmology Lab, UBC, Vancouver, Canada**

- 3rd year graduate student (1st year PhD) working on the Canadian Galactic Emission Mapper (CGEM)
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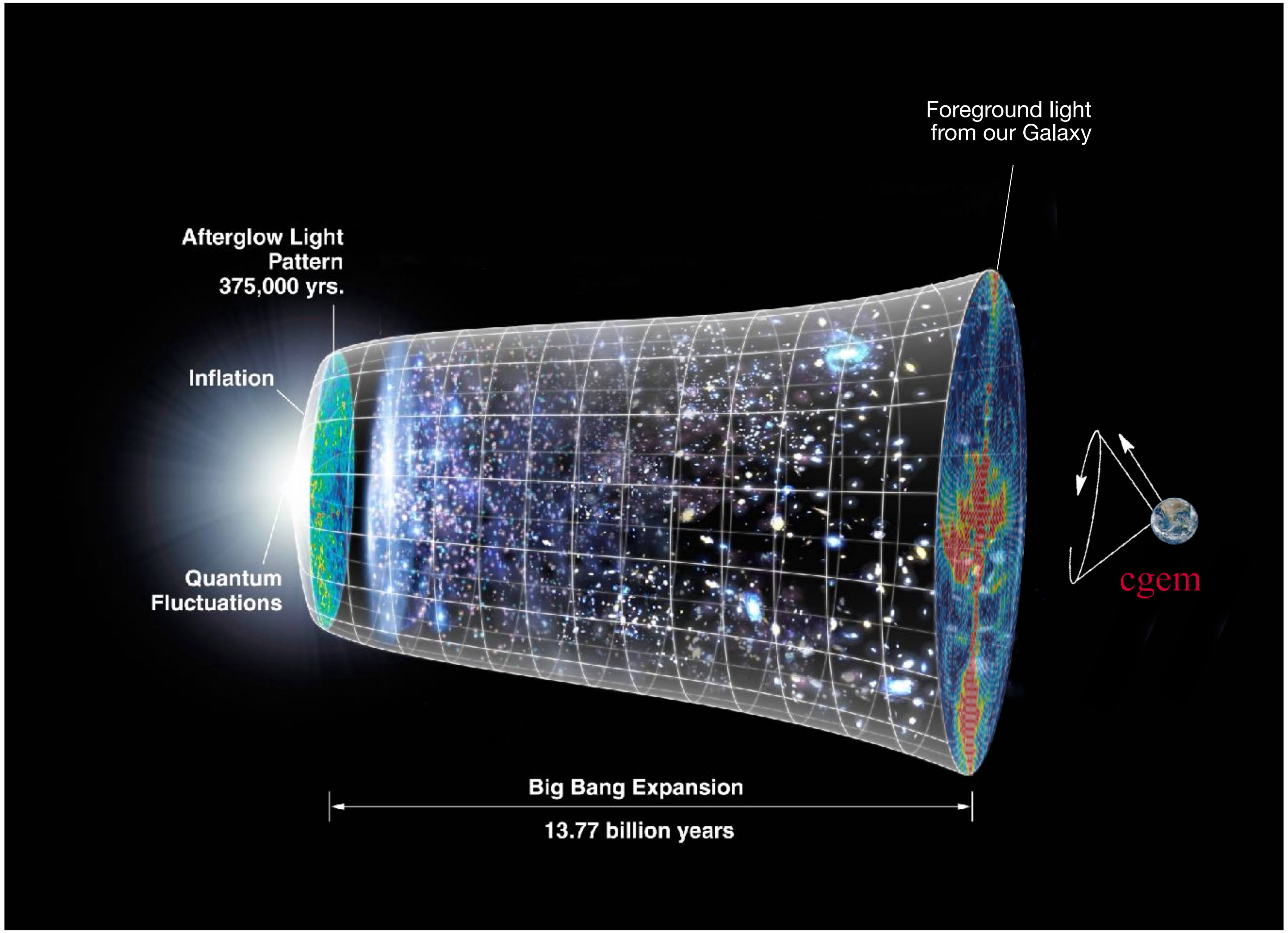
(Photo credit: Josh MacEachern)

# Inflation I - Introduction

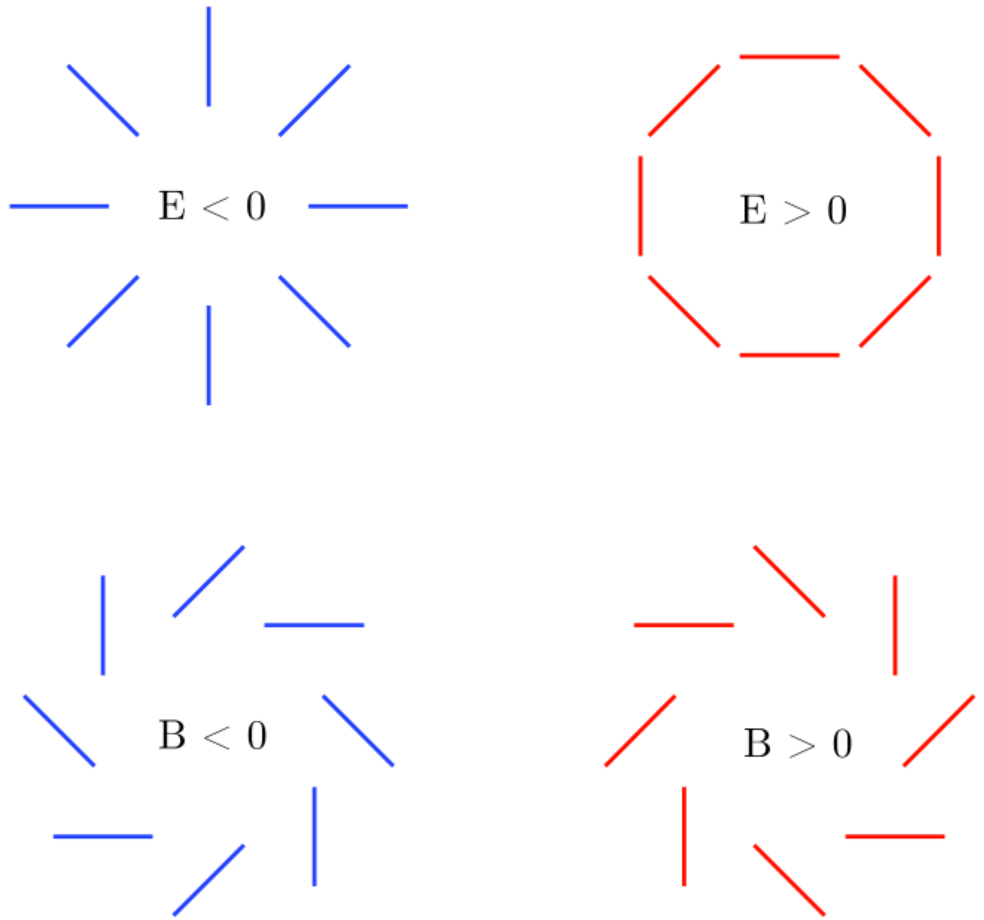



(Original figure idea: WMAP Science Team)

- ΛCDM describes the evolution of our universe from an initial high energy state.
- If points far away in the CMB were not in thermal contact at recombination, how is it so uniform?
- **Inflation** solves this: periods in the very early universe in which the universe expanded exponentially.
- If it happened, it could have left an imprint in the CMB polarization field.
- Inflation naturally predicts the coherence of the acoustic peaks in the CMB.

# Inflation II - E & B Modes Concept

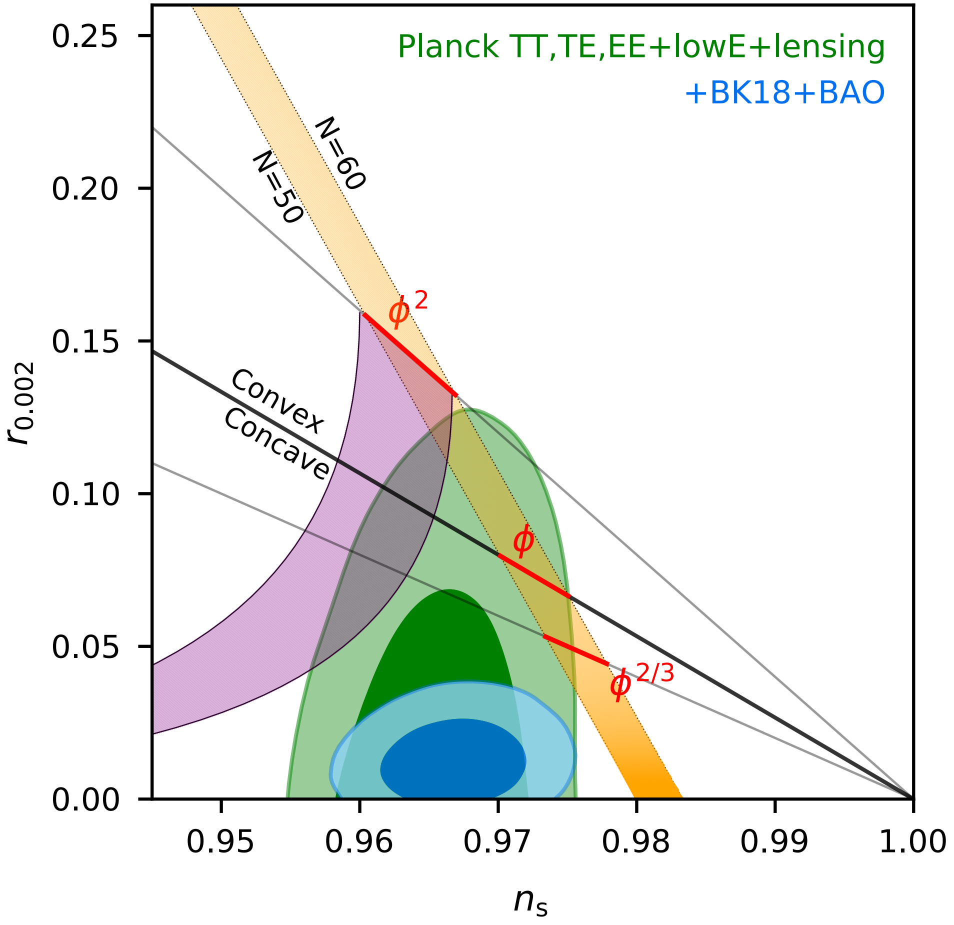
- Any polarization field is decomposed into E- (parity even) and B- (parity odd) mode.
- Scalar perturbations in the metric only induce E-modes.
- Tensor perturbations (**primordial gravity waves**) source E- and B- modes.
- B- modes would provide **‘smoking-gun’** evidence of inflation and information on the energy scale.
- Inflationary theories can be distinguished for their predicted tensor-to-scalar ratio, *r.*



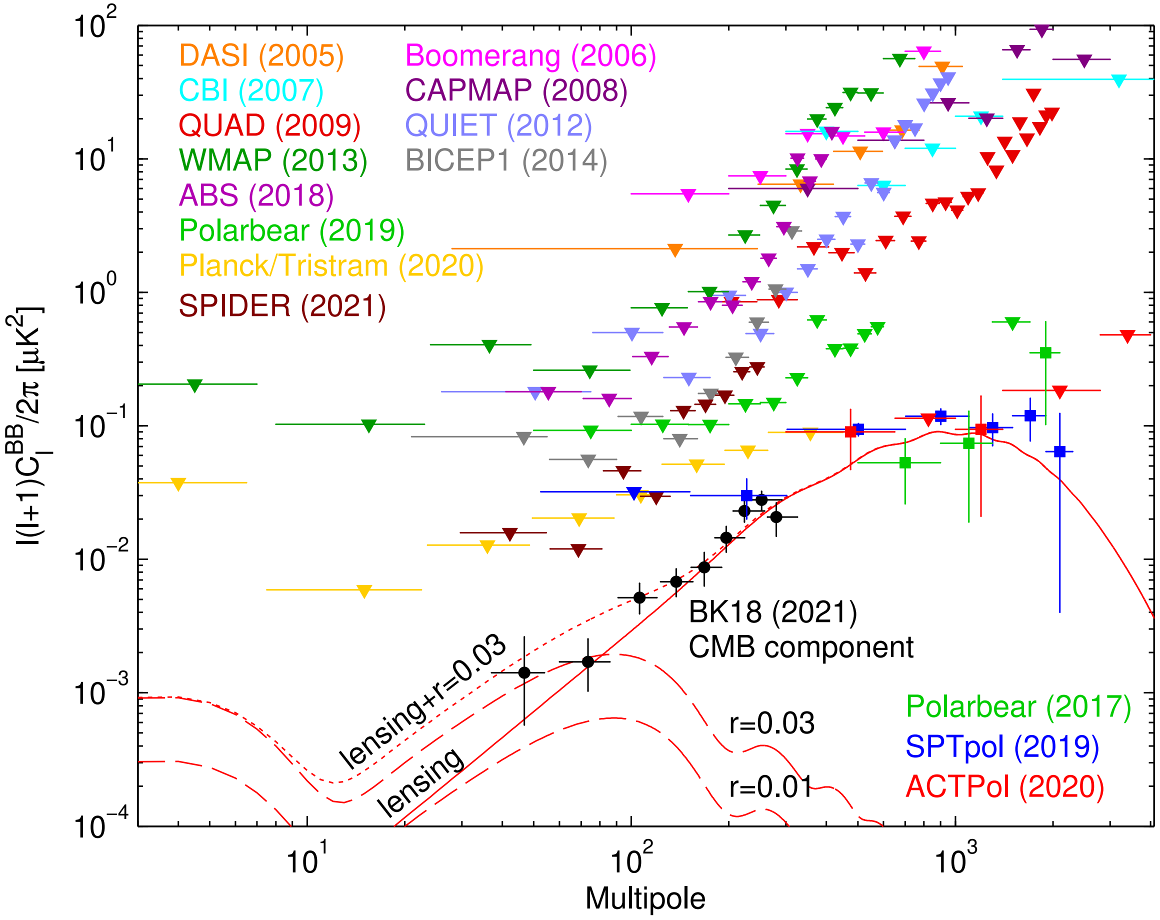

(Credit: Scott Dodelson)

# Inflation III - E & B Modes Status

**Tensor to scalar ratio**

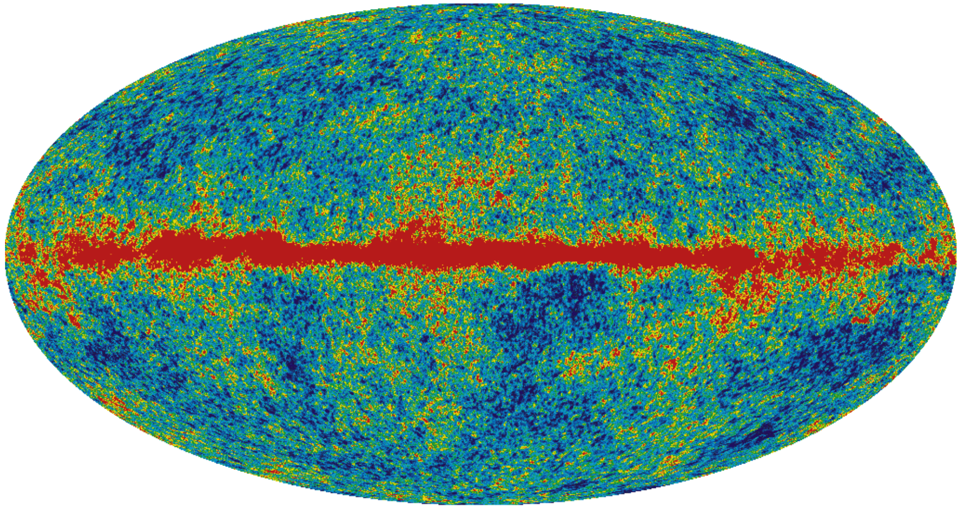


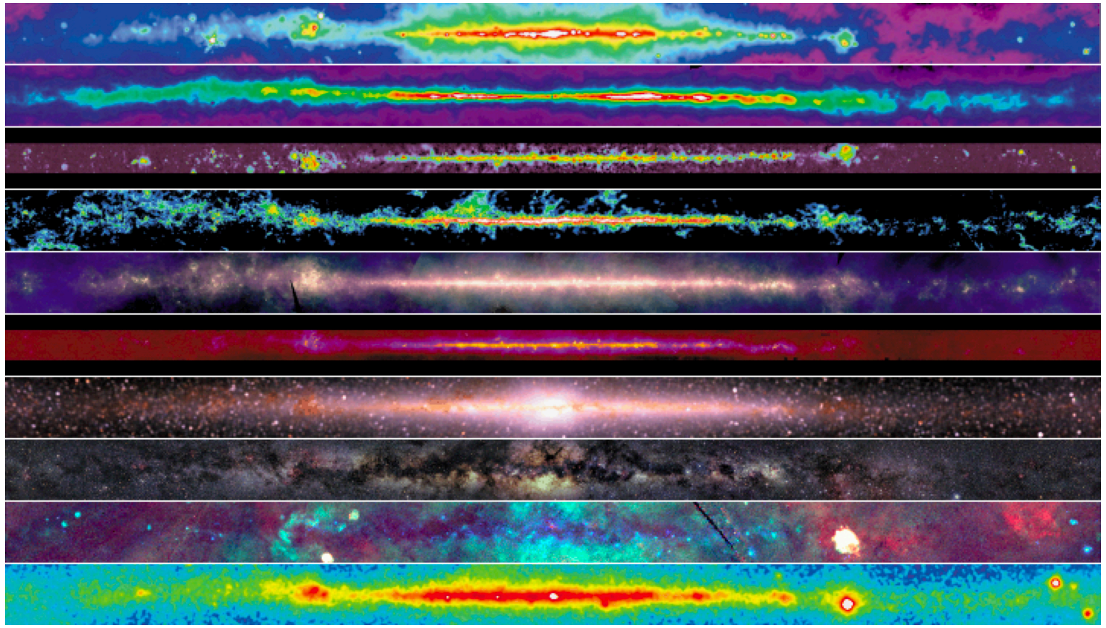

**BB Power Spectrum**

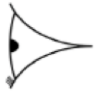


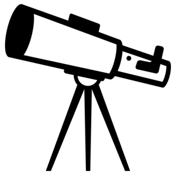

(Credit: BICEP Team)

# CMB Galactic Foregrounds I - Introduction









## Cosmic Microwave Background

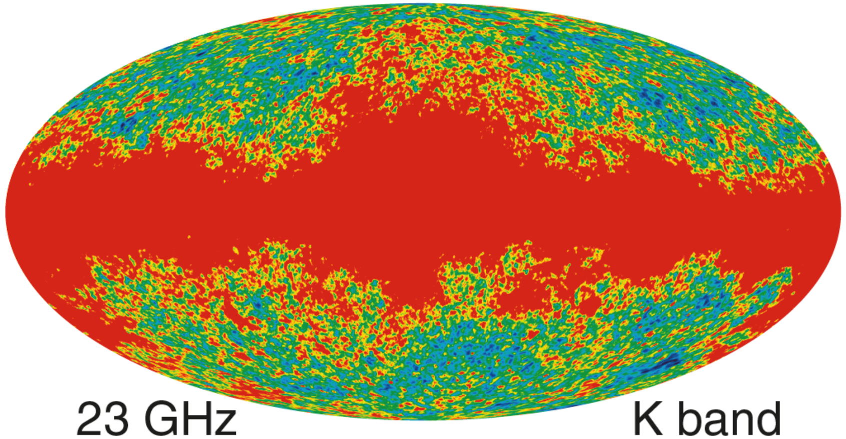
- Cosmological target
- Faint polarization
- E- modes characterized, now looking for B-modes

## Foregrounds

- Not so important in cosmology
- Strongly polarized
- Not all of them well characterized, some are frequency dependent

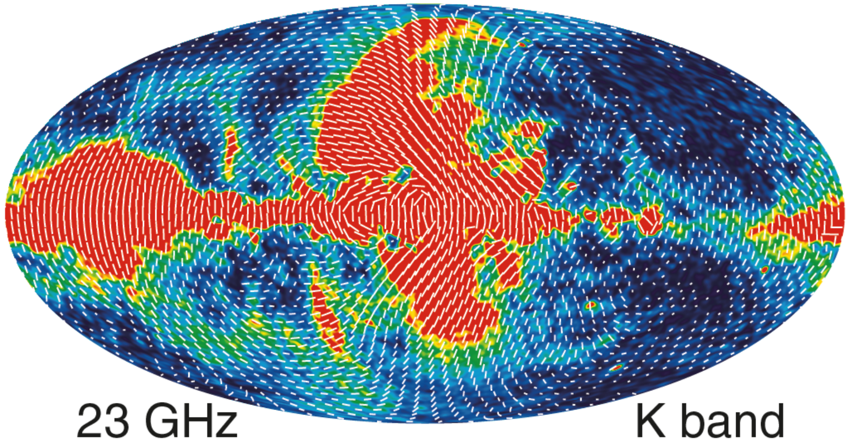
(Credit: WMAP team (left) and NASA Lambda Archive (right))

# CMB Galactic Foregrounds II - Observational Status



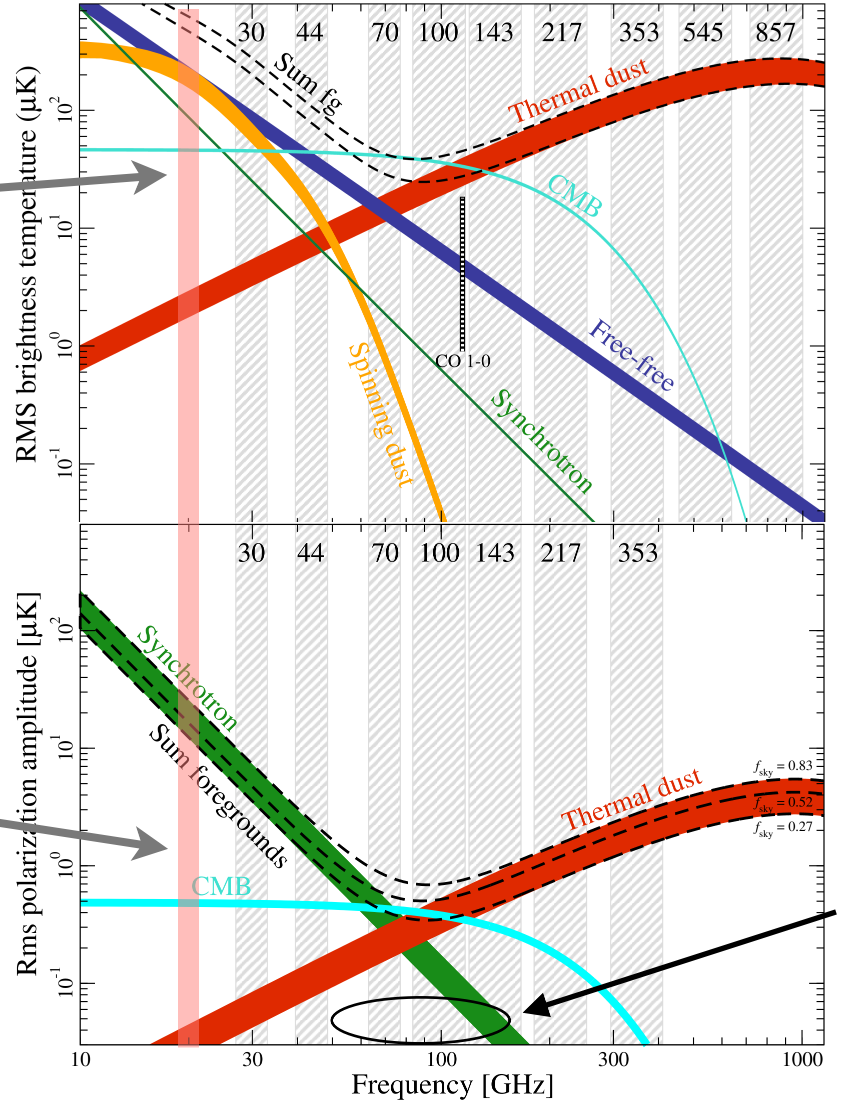
23 GHz K band

Temperature



23 GHz K band

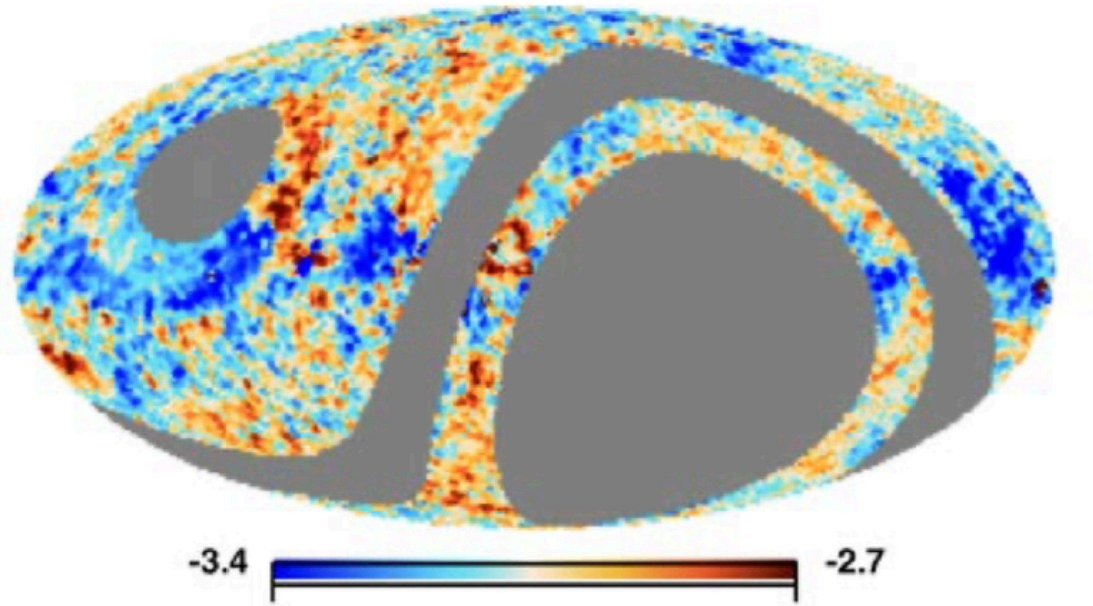
Polarization

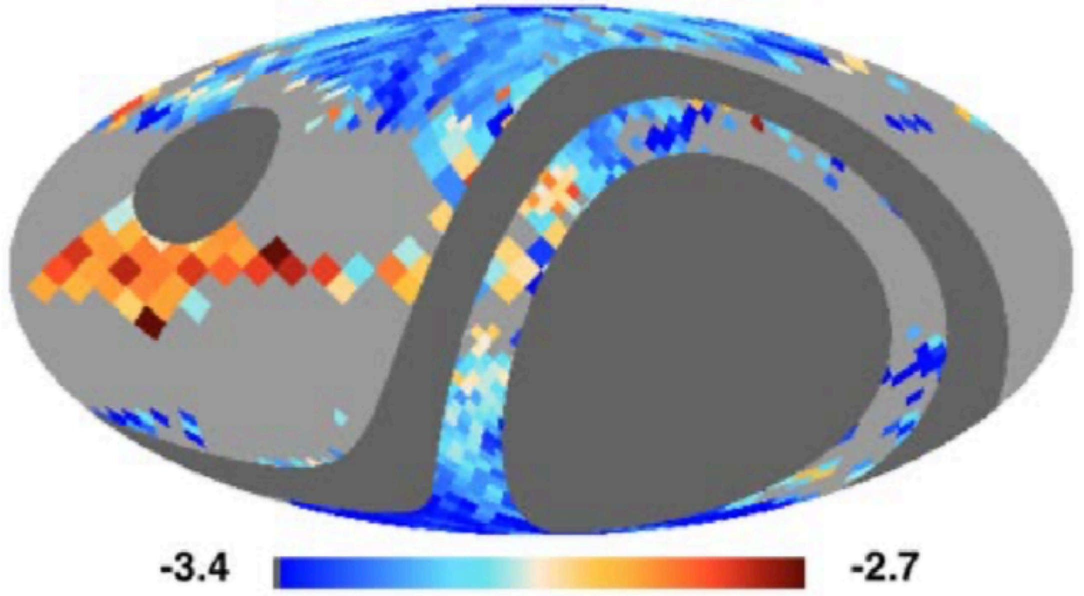



**B-mode detections are likely to come in this region.**

(Credit: WMAP team (left), Planck team (right))

# CMB Galactic Foregrounds III - Polarized Synchrotron Index




$\beta_{pol}$ in Galactic coordinates as determined from QUIJOTE 11 and 13 GHz data in combination with WMAP and Planck data [de la Hoz, 2022].

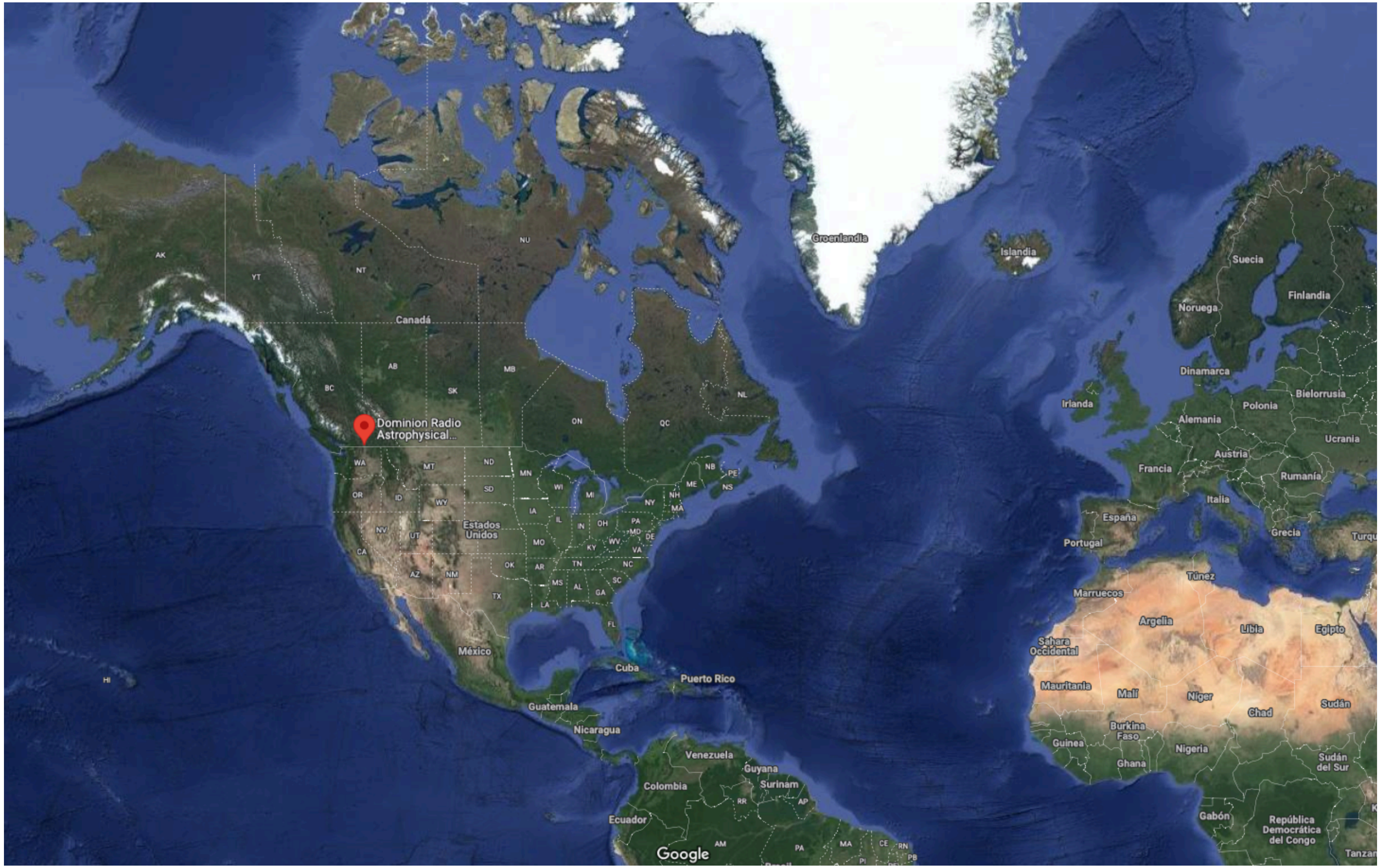
$\beta_{pol}$ as determined from 1.4 and 2.3 GHz data in combination with WMAP data (only WMAP data are used in the plane to avoid Faraday rotation effects). [Weiland et al. 2022].

# The Canadian Galactic Emission Mapper (CGEM)

- CGEM will be a 4 m on-axis telescope located at DRAO.
- The telescope will lie inside a ground screen that prevents contamination from the ground.
- It will map the northern sky in the 8-10 GHz range with ~0.5 degree angular resolution.
- The goal is to obtain a high signal-to-noise map of polarized Galactic synchrotron and spinning dust emission (if it is polarized).
- These maps will provide a foreground template that will be used by B-mode search experiments.

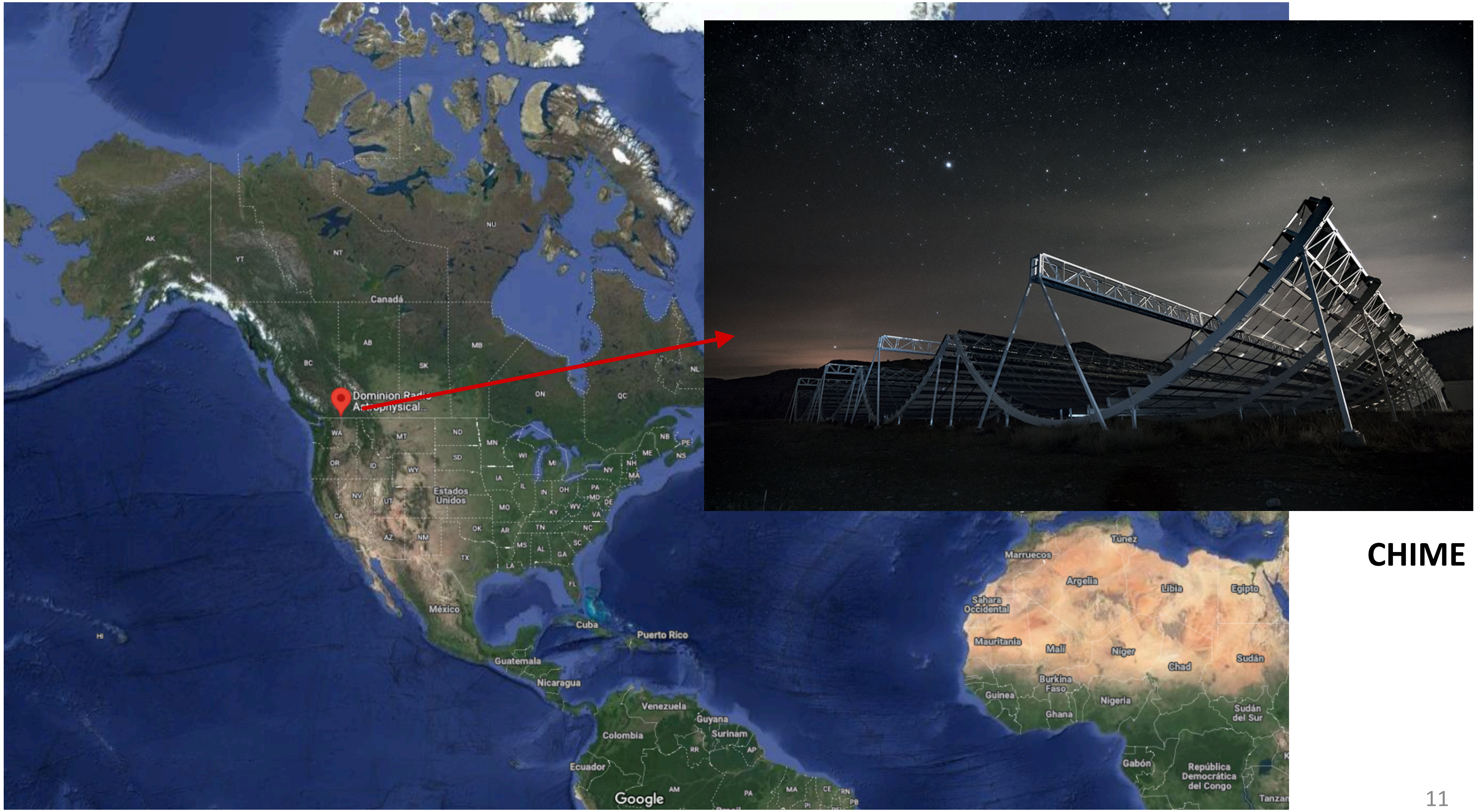
Target sensitivity @ 150 GHz: $\sigma_P \sim 30$ nK (1 deg$^2$)
Required sensitivity @ 10 GHz: $\sigma_P \sim 25 - 100$ μK (1 deg$^2$, depending on $\beta_S$)

# CGEM II - Site



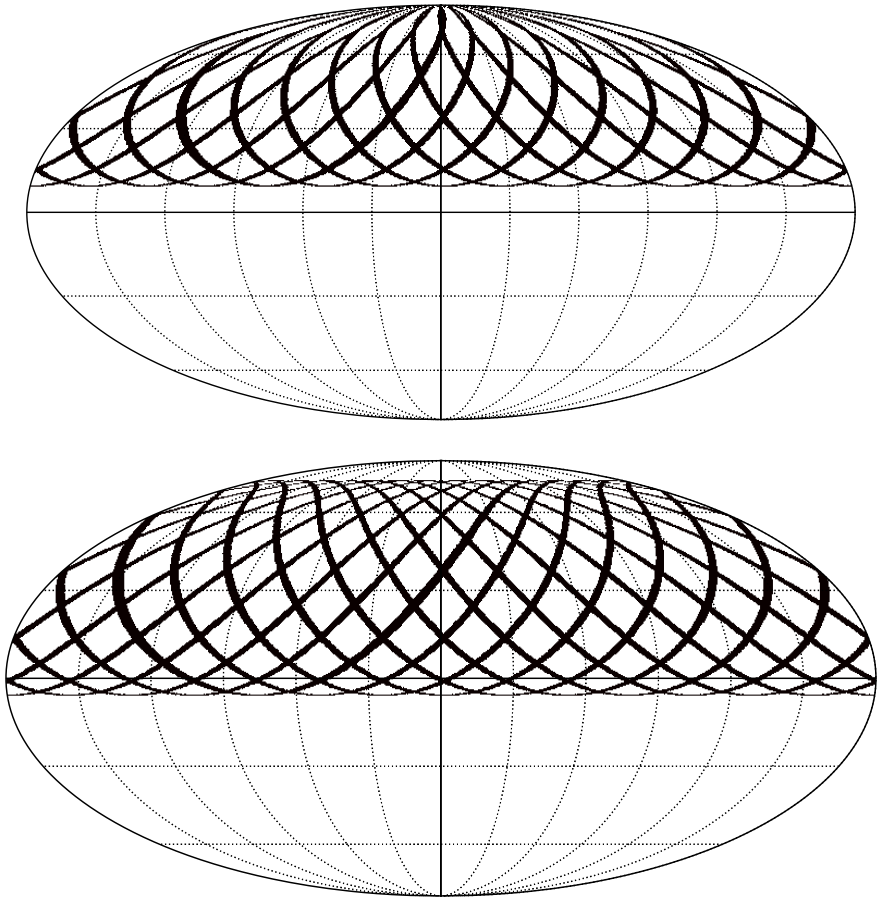
Dominion Radio
Astrophysical...
Canadá
Estados Unidos
México
Cuba
Puerto Rico
Guatemala
Nicaragua
Venezuela
Guyana
Surinam
Colombia
Ecuador
Groenlandia
Islandia
Suecia
Finlandia
Noruega
Dinamarca
Irlanda
Polonia
Bielorrusia
Alemania
Ucrania
Austria
Francia
Rumania
Italia
España
Portugal
Grecia
Túnez
Marruecos
Argelia
Libia
Egipto
Sahara Occidental
Mauritania
Malí
Níger
Chad
Sudán
Burkina Faso
Guinea
Nigeria
Ghana
Sudán del Sur
Gabón
República Democrática del Congo
Google

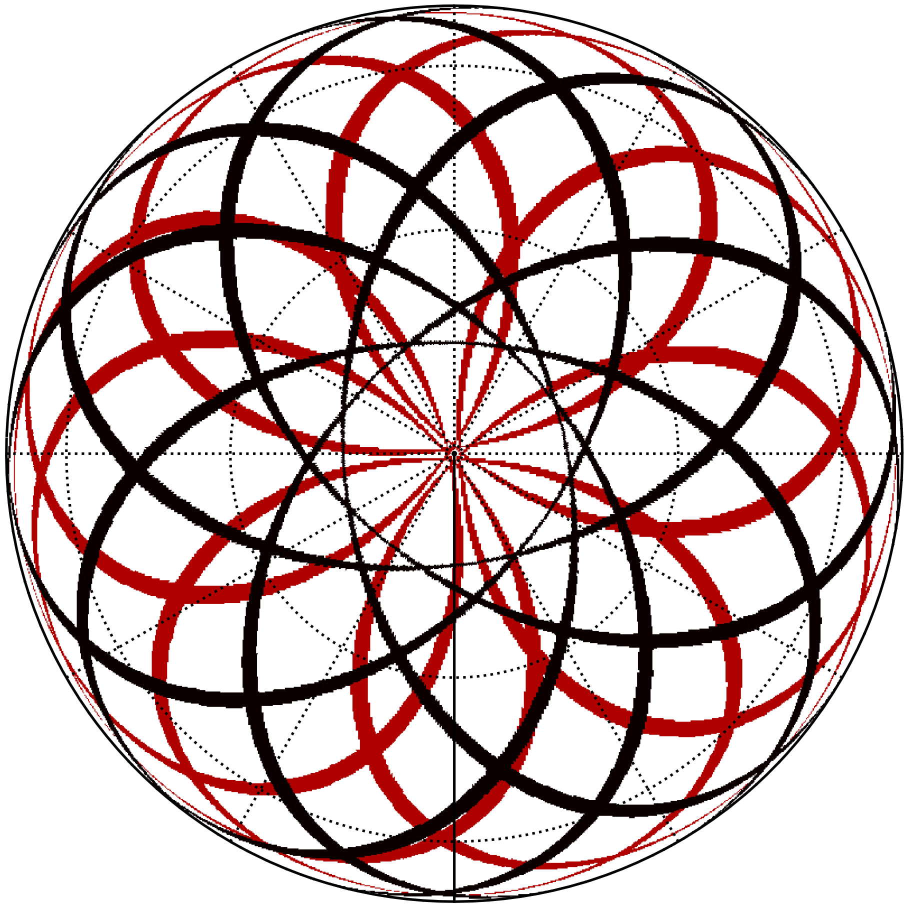
# CGEM II - Site




CHIME

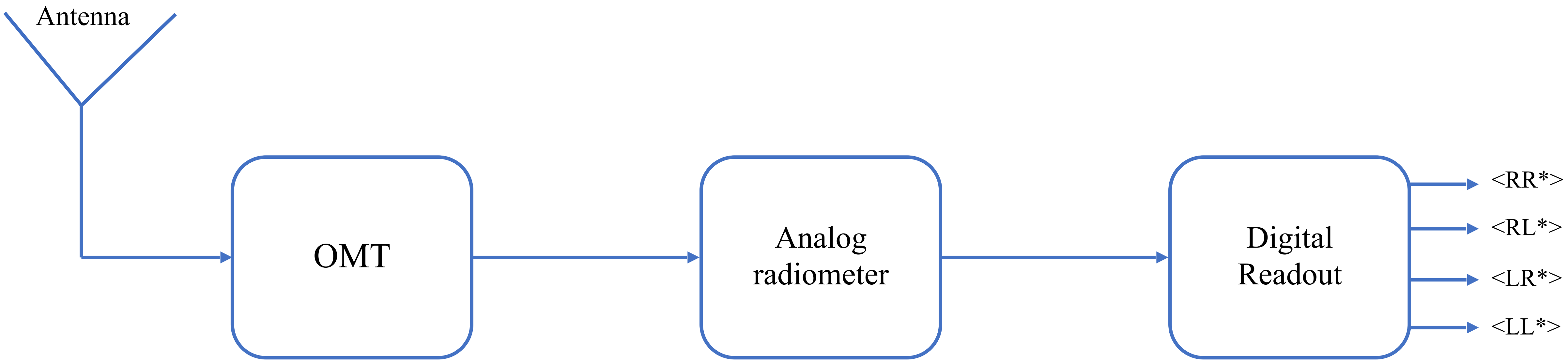
# CGEM III - Scan Strategy





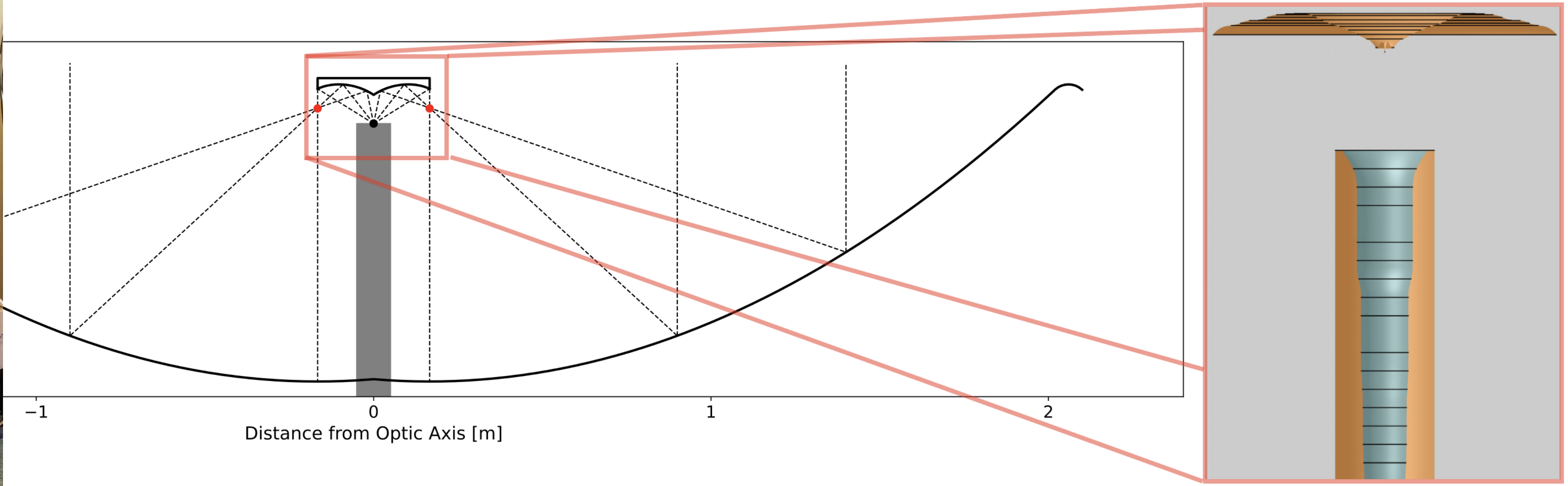
At 40 degrees off zenith (*top left*) the telescope passes the north celestial pole on every spin.
At 55 degrees off zenith (*bottom left*) it reaches dec. = −5 degrees and has a different set of polarization attack angles.
The mapping strategy will employ a range of elevation angles with a semi-equal area coverage strategy

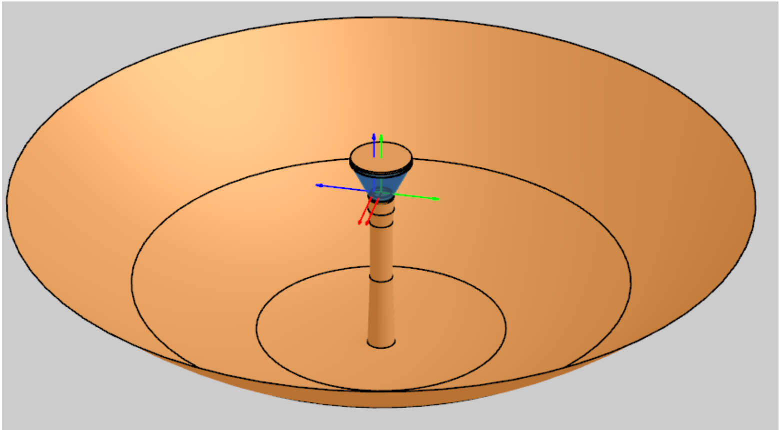
# CGEM Signal Chain I - Concept




$$\begin{bmatrix} <RR^*> \\ <LL^*> \\ <RL^*> \\ <LR^*> \end{bmatrix} = \begin{bmatrix} T+V+\text{Cross ploar term+noise bias} \\ T-V+\text{Cross polar term+noise bias} \\ Q+iU+\text{Cross polar term} \\ Q-iU+\text{Cross polar term} \end{bmatrix}$$

# CGEM Signal Chain II - Optical Design



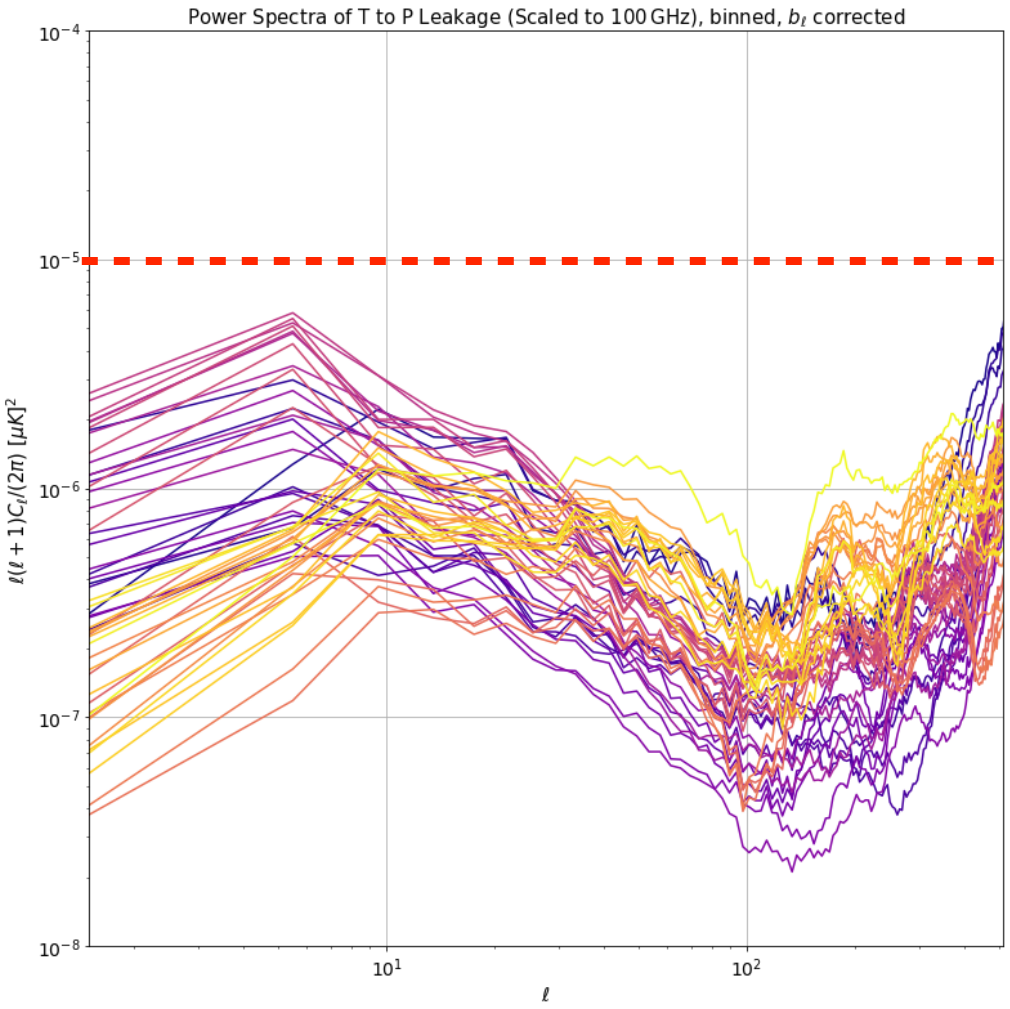
The optical design consists of a small “hat feed” mounted on a circular waveguide (supported by a dielectric) that illuminates a 4 m primary mirror.

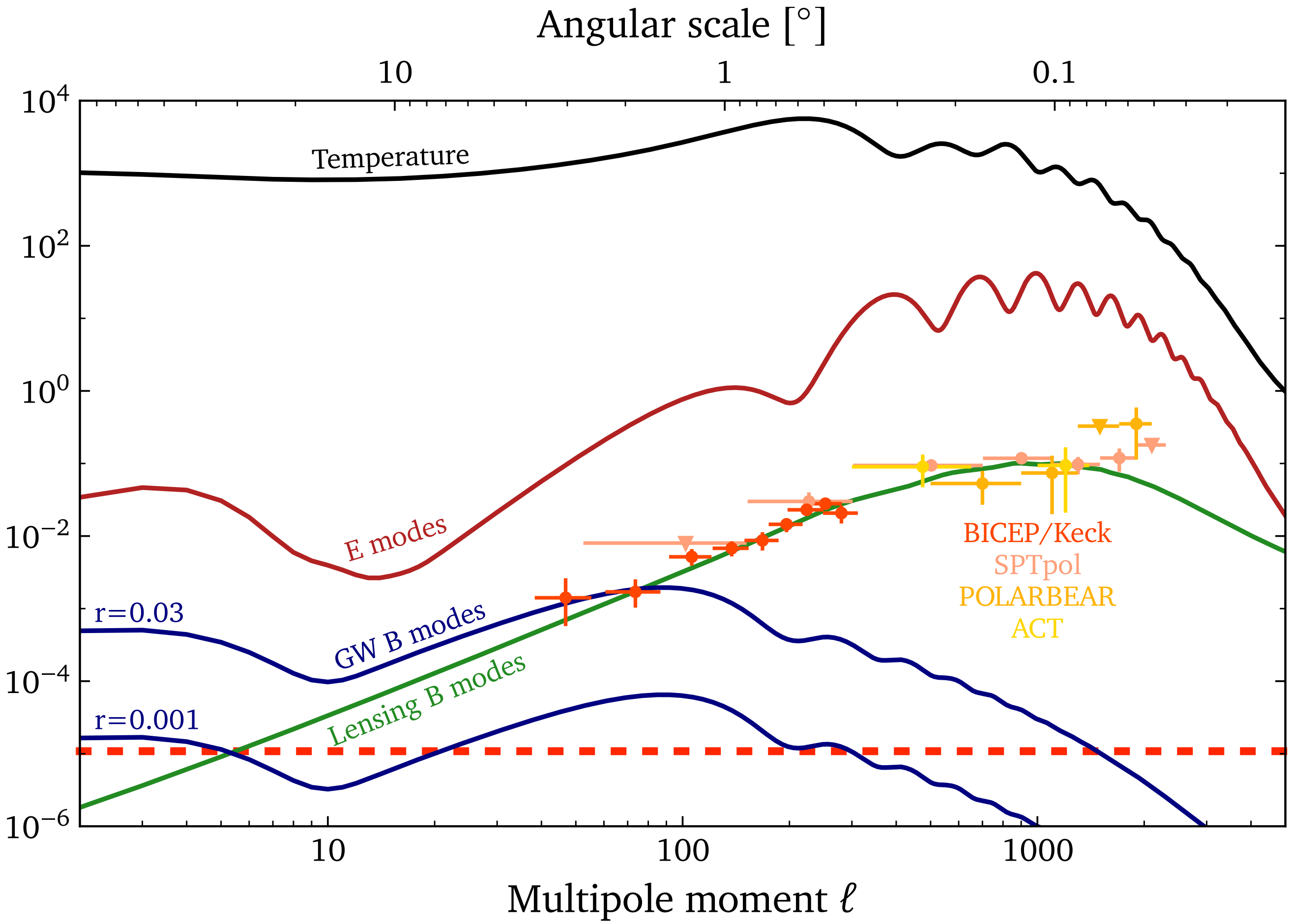
*Above* - cross section of optical elements with an $f/0.25$ mirror.

*Left* - the design has intrinsic azimuthal symmetry.

(Credit: Joshua MacEachern)

# CGEM Signal Chain III - Optical Design Simulated Performance



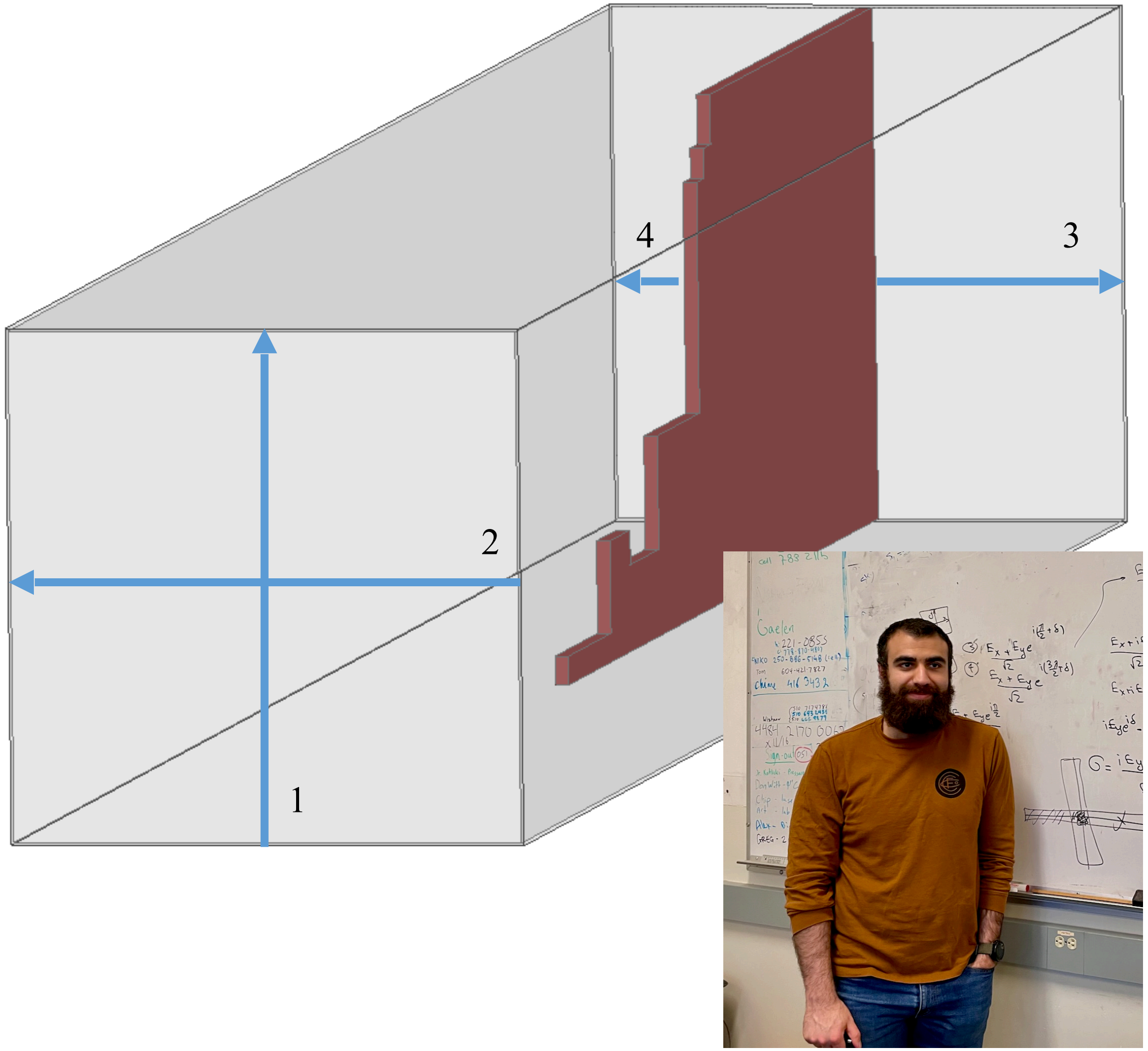

(Credit: Joshua MacEachern (left), Achúcarro et al. (2022) (right)

# CGEM Signal Chain IV - Optical Design Reality

(Credit: Joshua MacEachern)

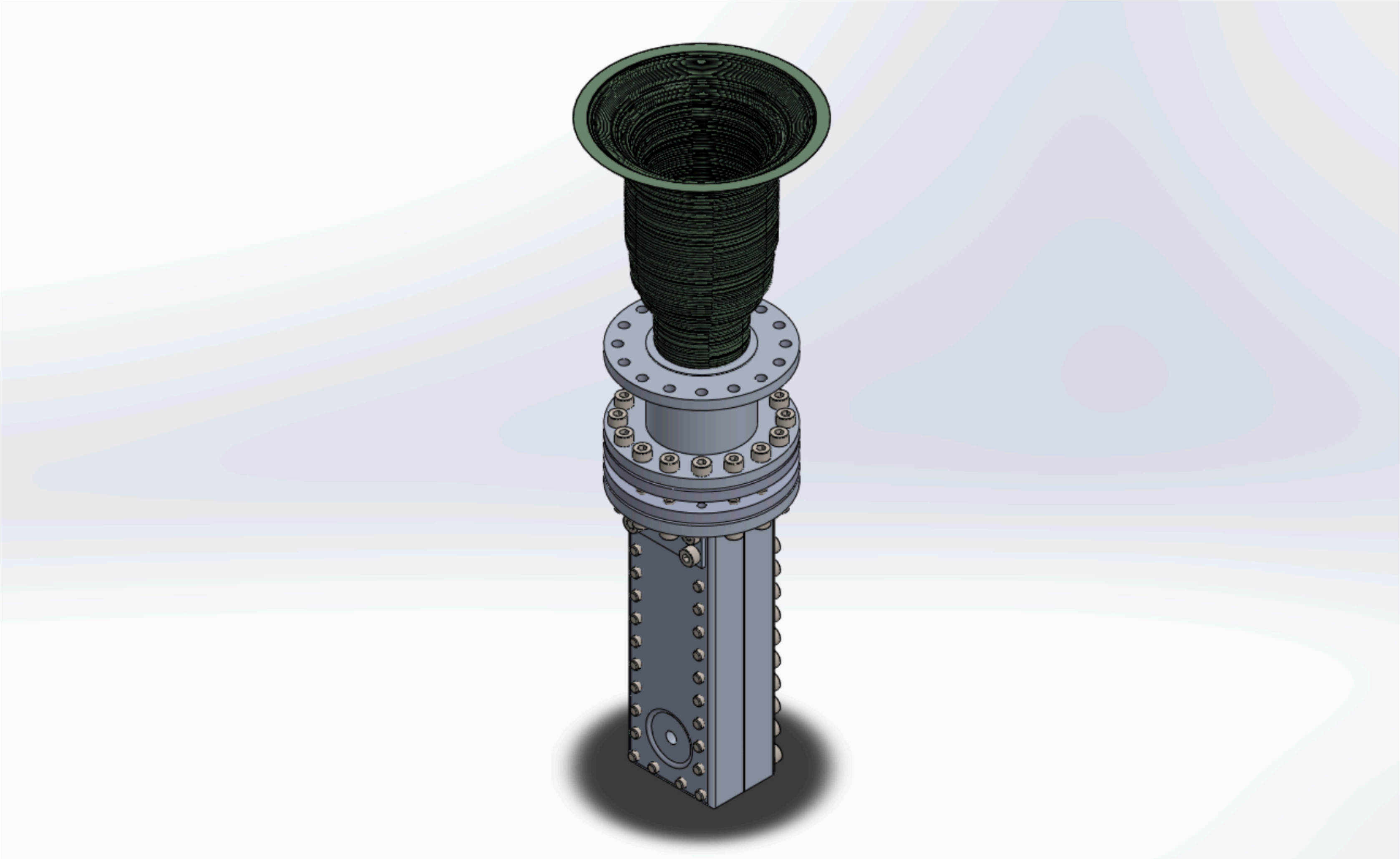
# CGEM Signal Chain V - Orthomode Transducer

- OMT is a device which:
  1. Creates two independent fundamental modes from the pair of degenerate orthogonal modes at the common port.
  2. Creates a pair of degenerate orthogonal modes at the common port from any one of the other physical ports
- An ordinary OMT is a passive device that has:
  1. Three physical ports
  2. Four electrical ports
  3. One physical port (common port) has two orthogonal electric ports.
  4. The other two physical port contain one electrical port operating at the fundamental mode.




(Credit: Parham Zarei)

# CGEM Signal Chain V - Optical Tube Design (OMT + Horn)



(Credit: Parham Zarei & Josh MachEachern)

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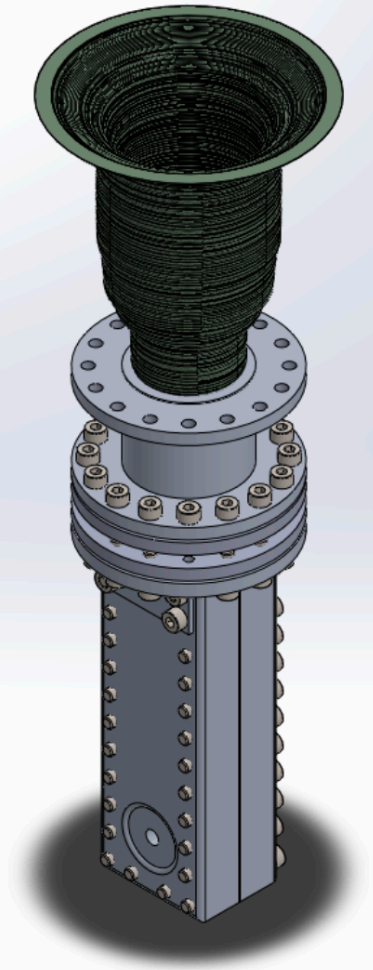
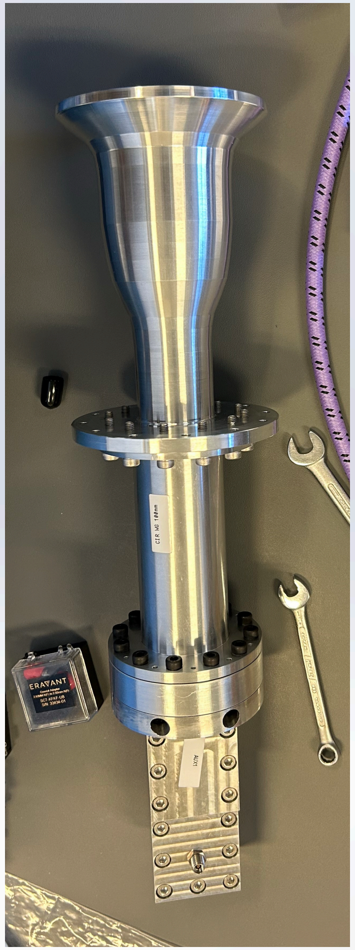
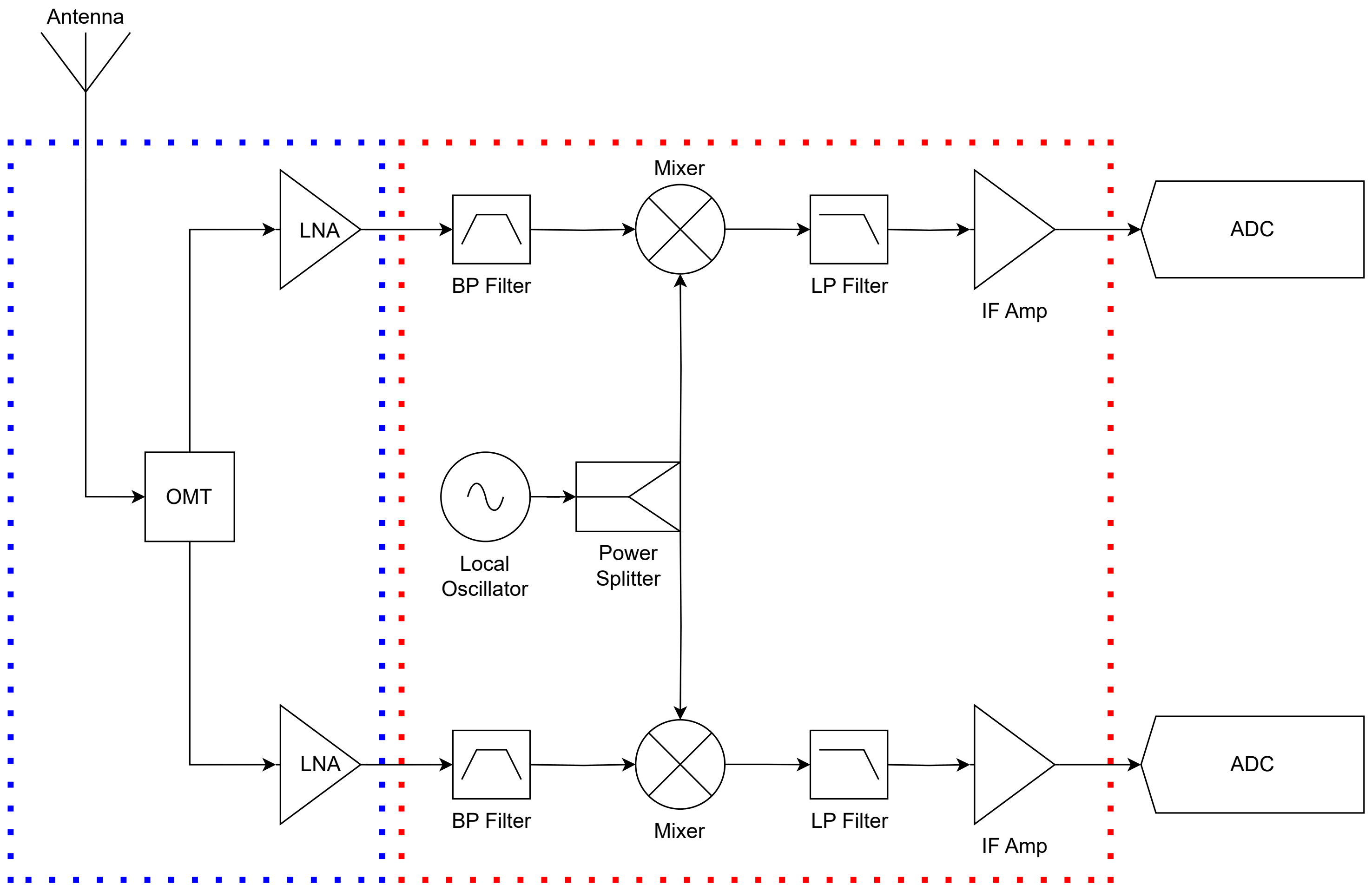




(Credit: Parham Zarei & Josh MachEachern)

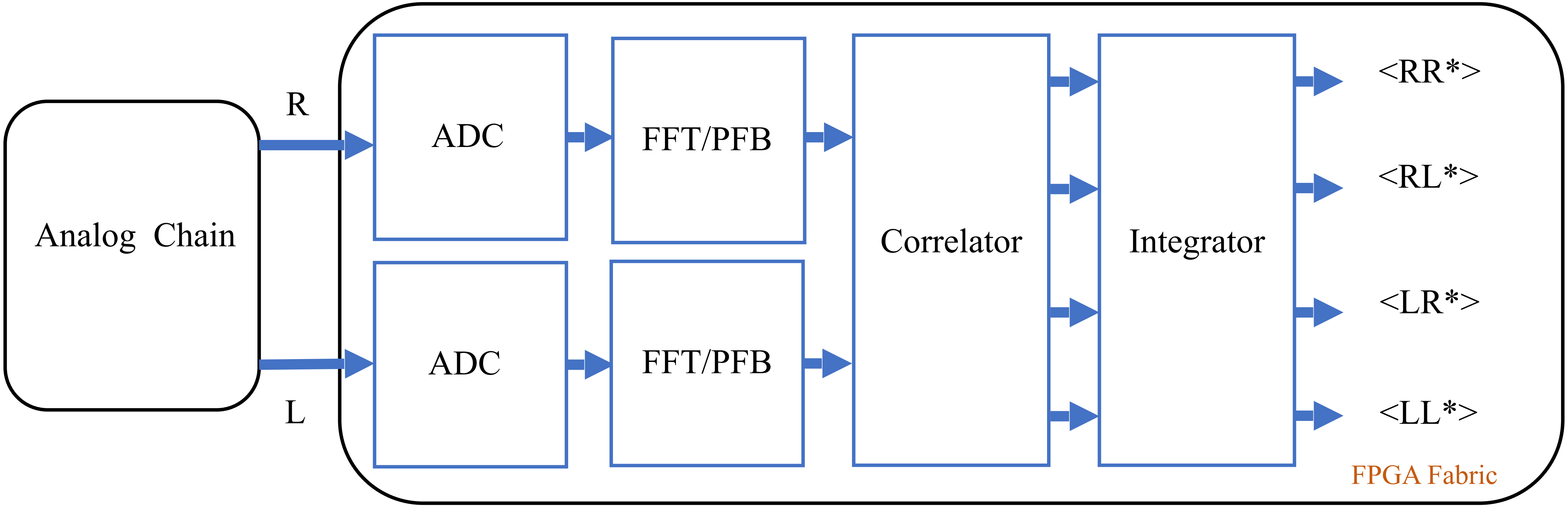
# CGEM Signal Chain VI - Analog Radiometer Concept




- A cryostat placed after the antenna holds an OMT, and low noise amplifiers.
- Frequency of operation ~ 8-10 GHz
- Warm electronics down-converts signals to lower frequencies to be digitized by ADC.
- Down-conversion is done by local oscillator, power splitter and two mixers.
- The filters ahead of the mixer block unwanted signals while the filter following the mixers prevent aliasing in the digitization stage.

- LNA = Low Noise Amplifier
- RF = Radio Frequency
- IF = Intermediate Frequency

# CGEM Signal Chain VIII - Readout system




- 2 Channels
- Superheterodyne RX
- Downconverter

- 4096 MSPS
- 16GB/s
- 1st Nyquist zone

- Finite Impulse Response filter
- Filter is designed to de-correlate the frequency bins.
- Real FFT | 4096 frequency bins
- Resolution of 1 MHz per bin
- Correlate RCP and LCP and creates 4 cross and auto correlation products
- Average for certain length to reduce noise and throughput

(Credit: Parham Zarei)

# Conclusions

- We are working on a 8-10 GHz Northern Sky Polarization survey to aid in the search for Primordial Gravitational Waves.
- We have almost finalized the design and started characterizing the signal chain of CGEM. The first version of it, which I presented, will be installed in our warm radiometer, ~100 K.

# CGEM Status

- Primary mirror attached to mount, both inside the ground shield
- Feed horns manufactured and ready for testing
- Waveguide network currently being tested
- Designs underway for cryostat
- Secondary mirror and hat support in fabrication
- Deployment of a warm receiver this summer
- Cold radiometer deployment to follow in early 2024

**CHIME**

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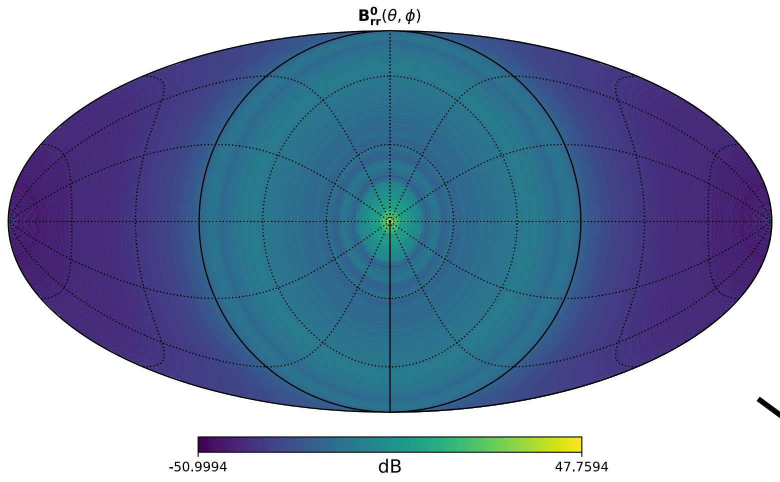
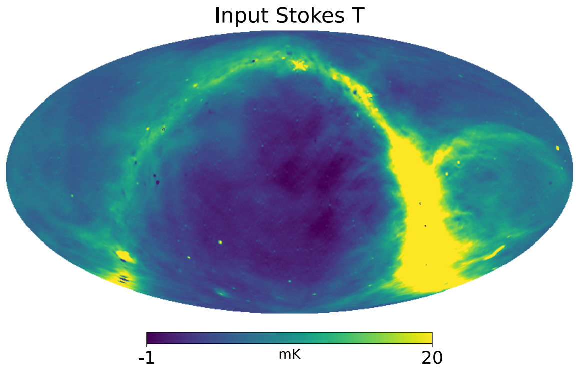
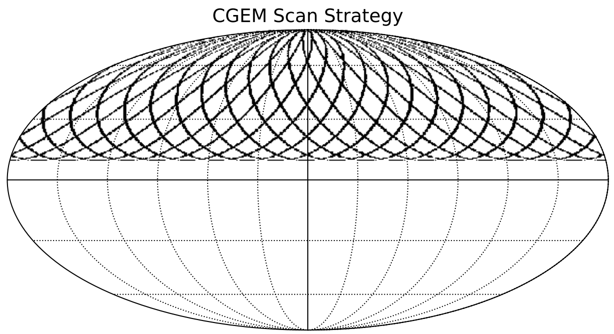
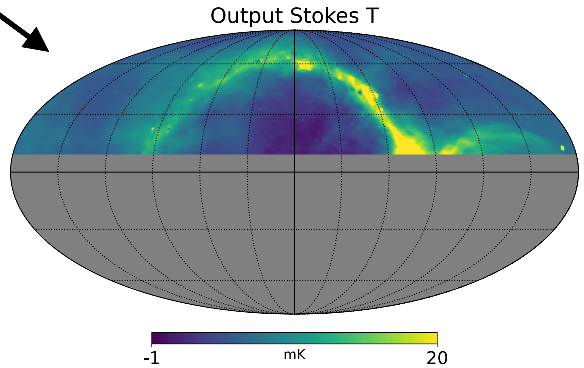
# Extra Slides

# CGEM IV - Simulation Pipeline Concept



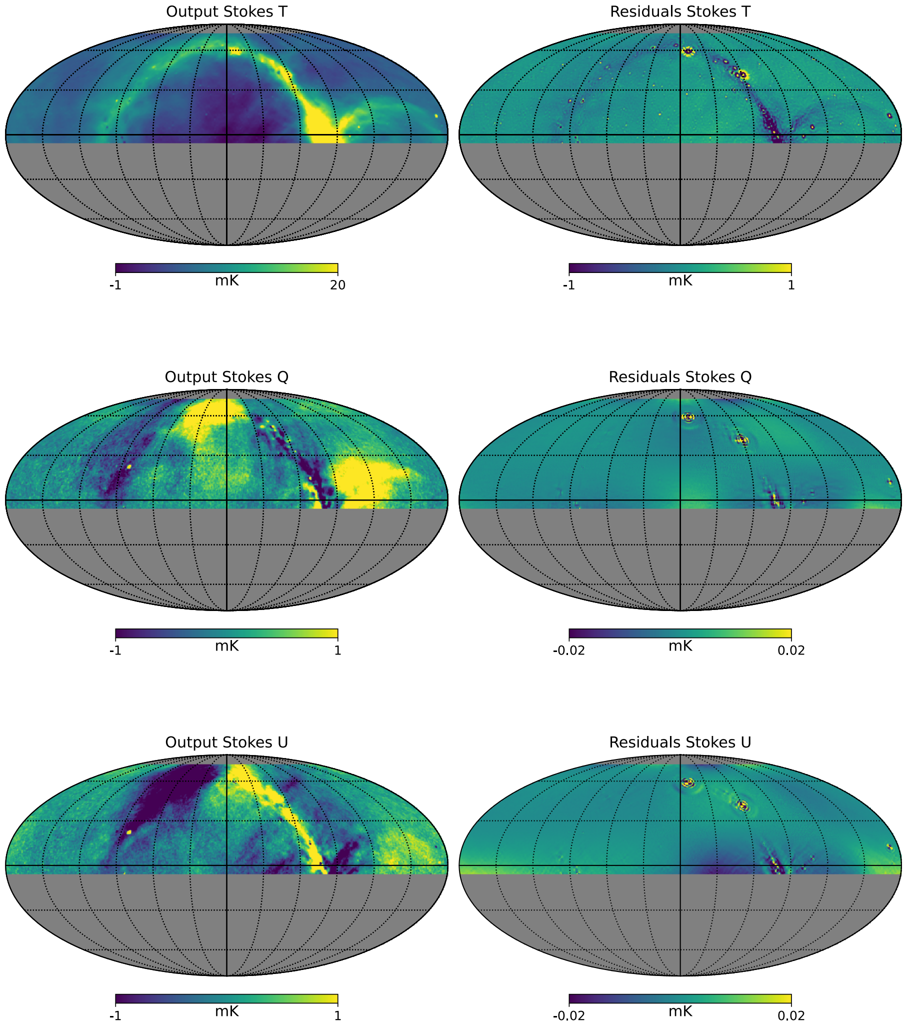




End to end simulations are being developed to assess the performance of many aspects of the CGEM design: co- and cross-polar beam response, contamination of *Q* and *U* by cross-polar terms, etc.

# CGEM V - Simulation Pipeline Results




- Residuals in a 50x finer scale than the maps.
- Artifacts around Cas A and Cygnus A and from the wake of the ground shield.
- Improvement in the residuals when corrected for the cross polar terms.
- Working on combining scan strategies at different elevations to minimize systematics.
- Simulations displayed at 8 GHz
- The pipeline has influenced our decisions on the optical design

# CGEM VII - RFI Challenge Satellites

Presumed **Starlink** satellites

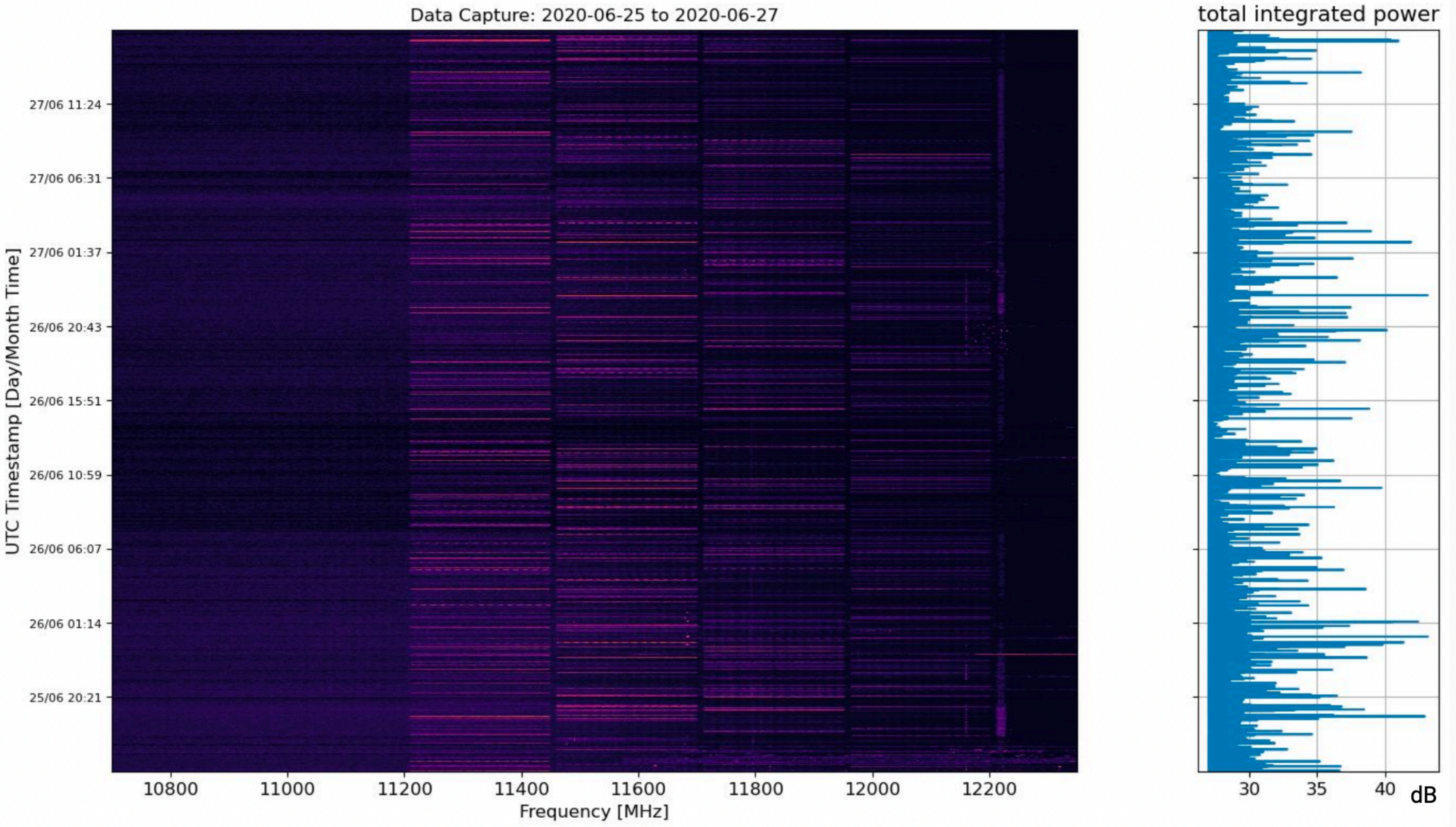
Single pointing direction

11.2-12.2GHz **data badly contaminated** (1GHz band!)

**Variable** (due to satellite movement)

This is over 1.5 days

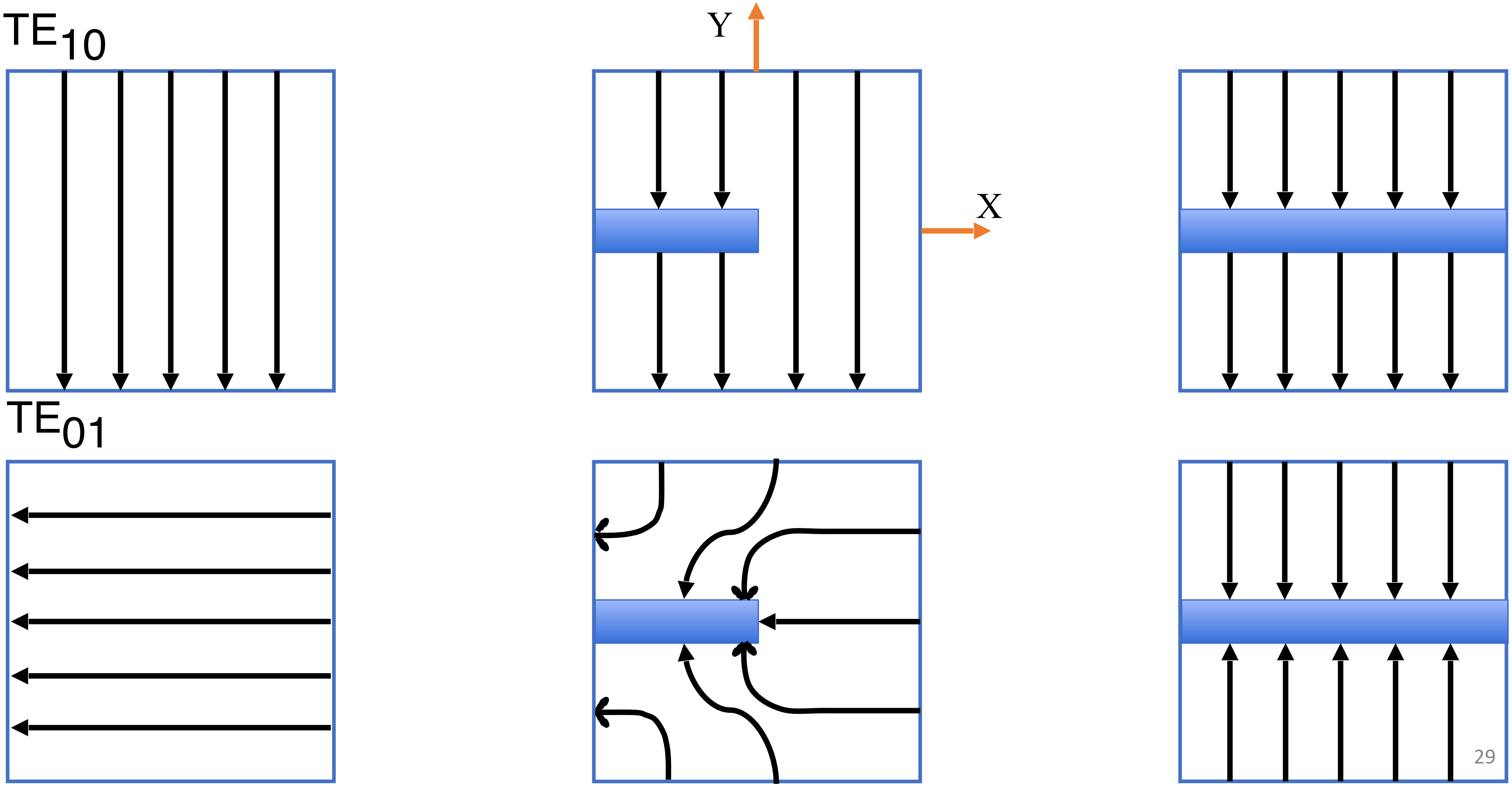
Thanks to Federico Di Vruno (SKAO)




(Slide from a May 2022 QUIJOTE talk by Mike Peel.) Observations of satellite RFI from 10.8 - 12.2 GHz - mainly the Starlink constellation. Their comm. bands are documented to cut off below 10.7 GHz. We hope that is accurate…

(Credit: Parham Zarei)

# Mode Conversion Principles



# Orthomode Transducer

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- An ordinary OMT is a passive device that has:
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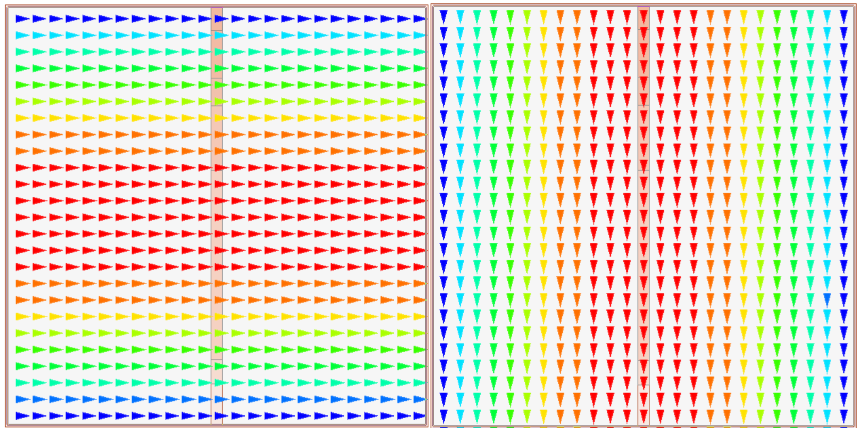
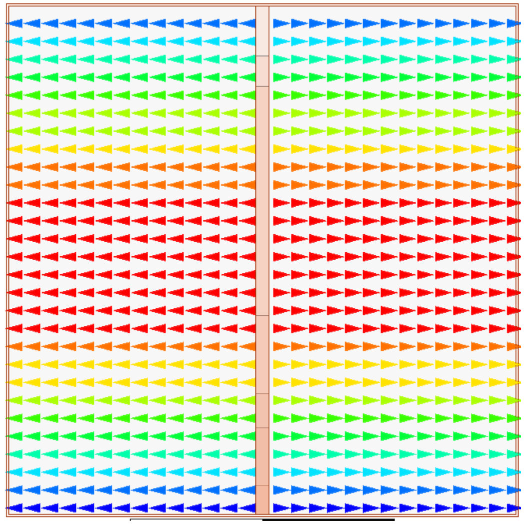
  2. Four electrical ports
  3. One physical port (common port) has two orthogonal electric ports.
  4. The other two physical port contain one electrical port operating at the fundamental mode.

Common port with two degenerate orthogonal electrical ports

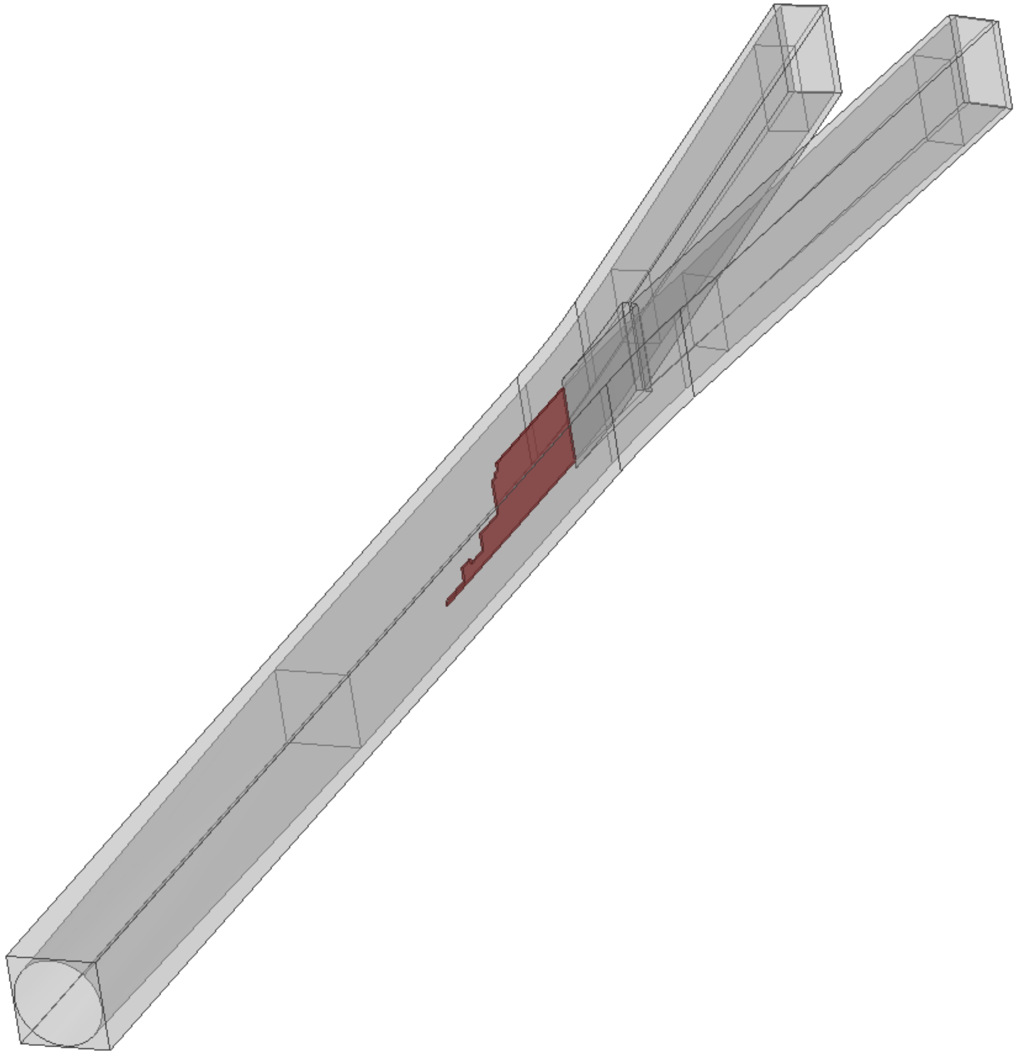


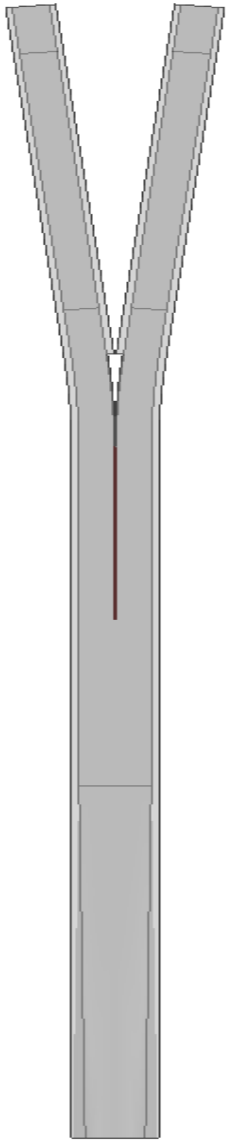
Two physical port each with one electrical port

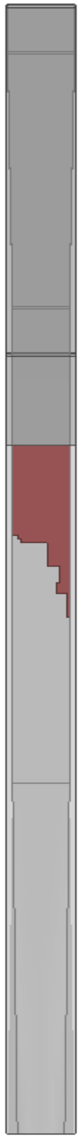


(Credit: Parham Zarei)

# Circular to Square + OMT + Bend + Transition to WR90

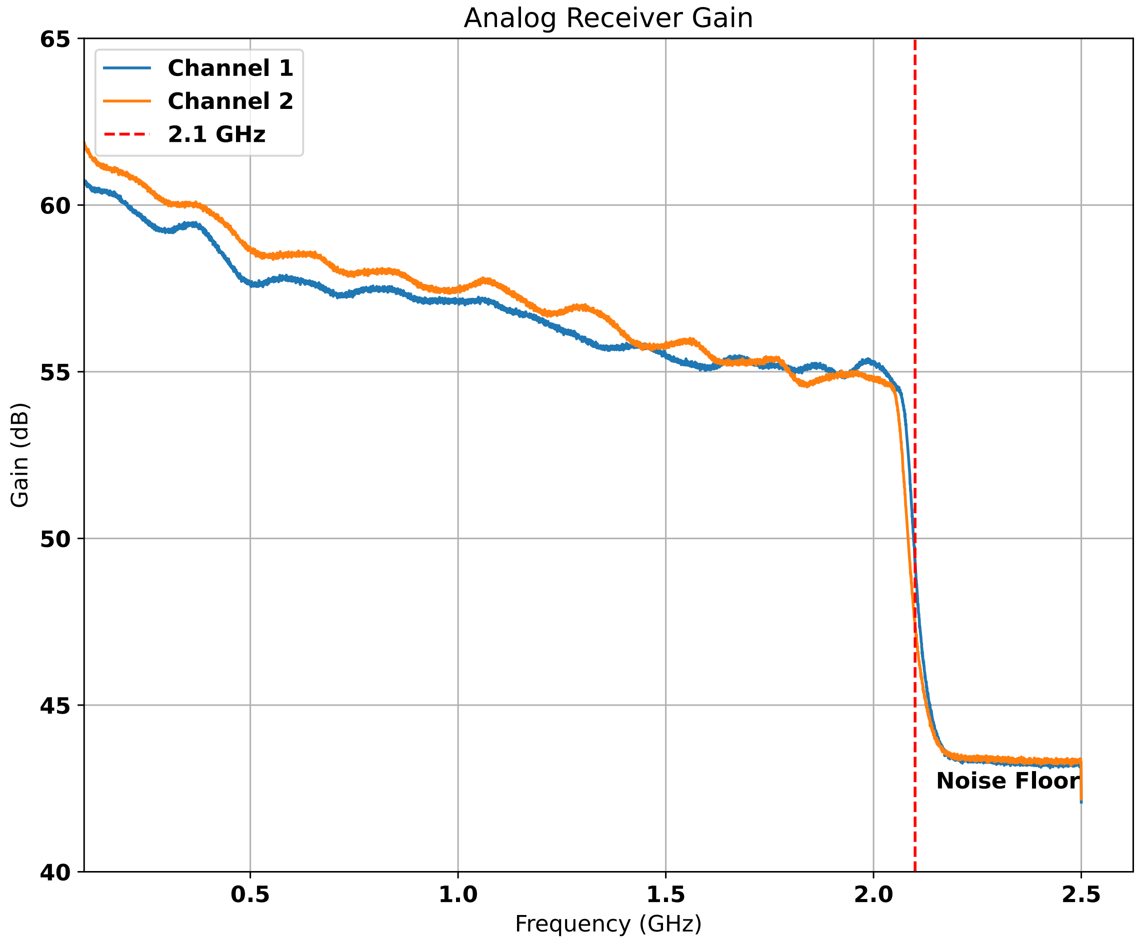






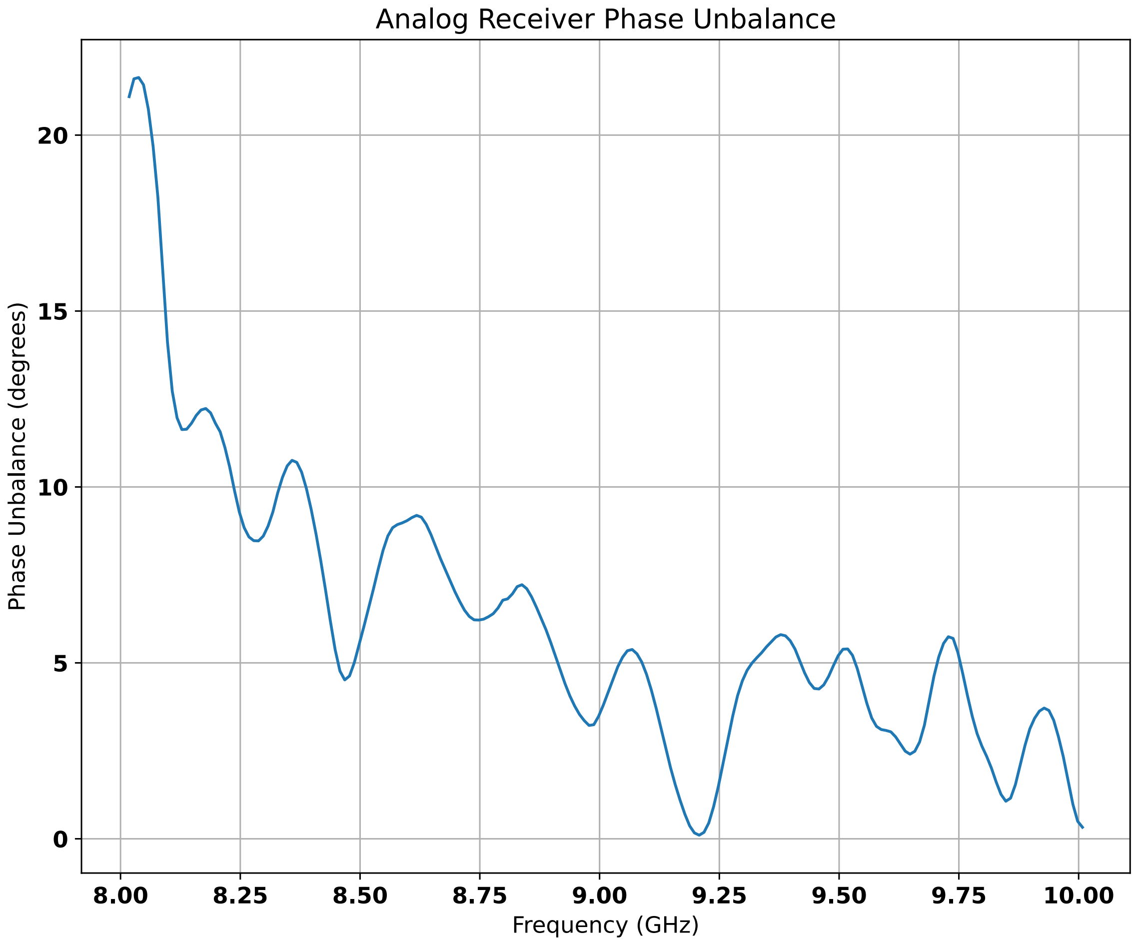
(Credit: Parham Zarei)

# Receiver Performance I - Gain



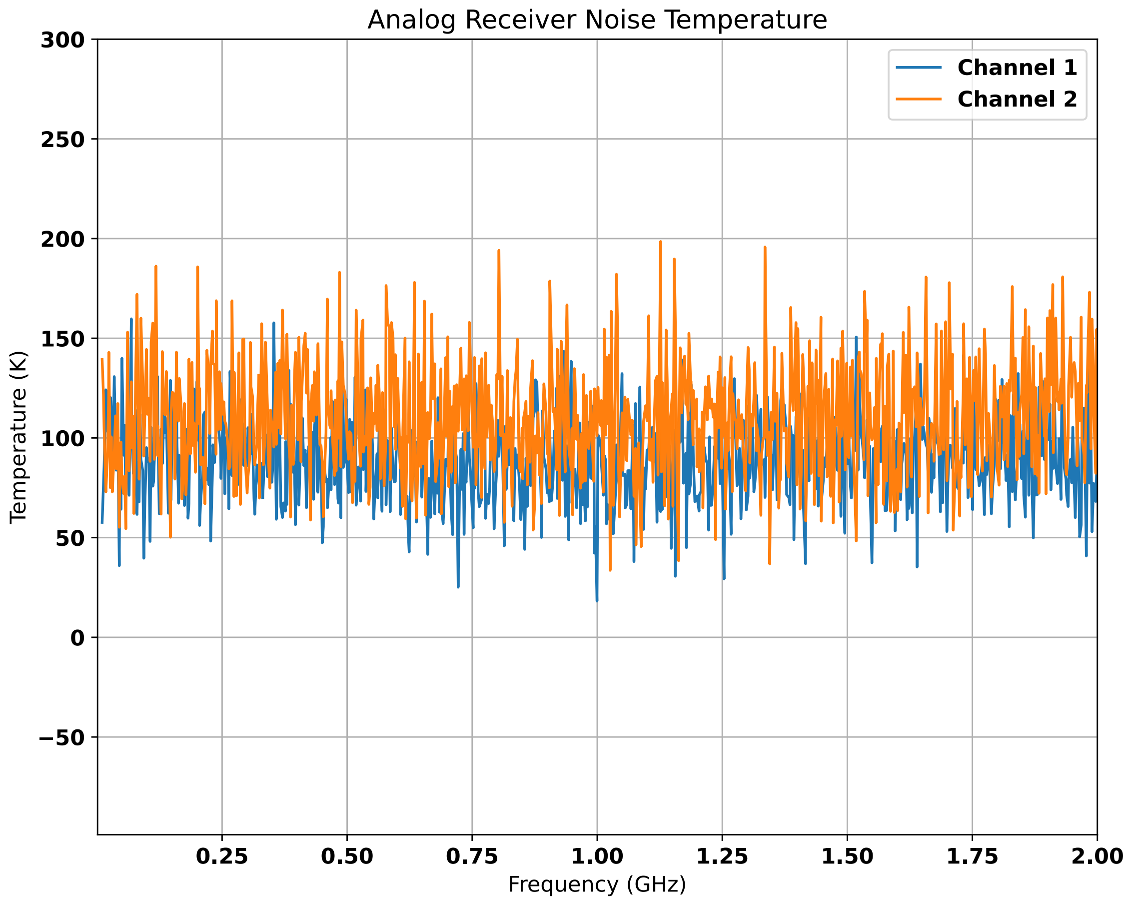

- Around 55 dB gain across band. Downconversion included.
- Difference coming mainly from the LNAs and Band Pass Filters.
- We will explore the possibility of adding another Low Pass Filter before the ADC to improve the stop band.
- Further development will focus on making the gain flatter across band.

# Receiver Performance II - Relative Phase




- Key quantity for polarization measurements
- Any phase unbalance corresponds to a rotation of Stokes Q and U by the same angle
- Structure across band coming mainly from Band Pass Filters
- A calibration block in the FPGA will be developed to correct for this
- Stability has been measured, see slide 9

# Receiver Performance III - Noise Characterization

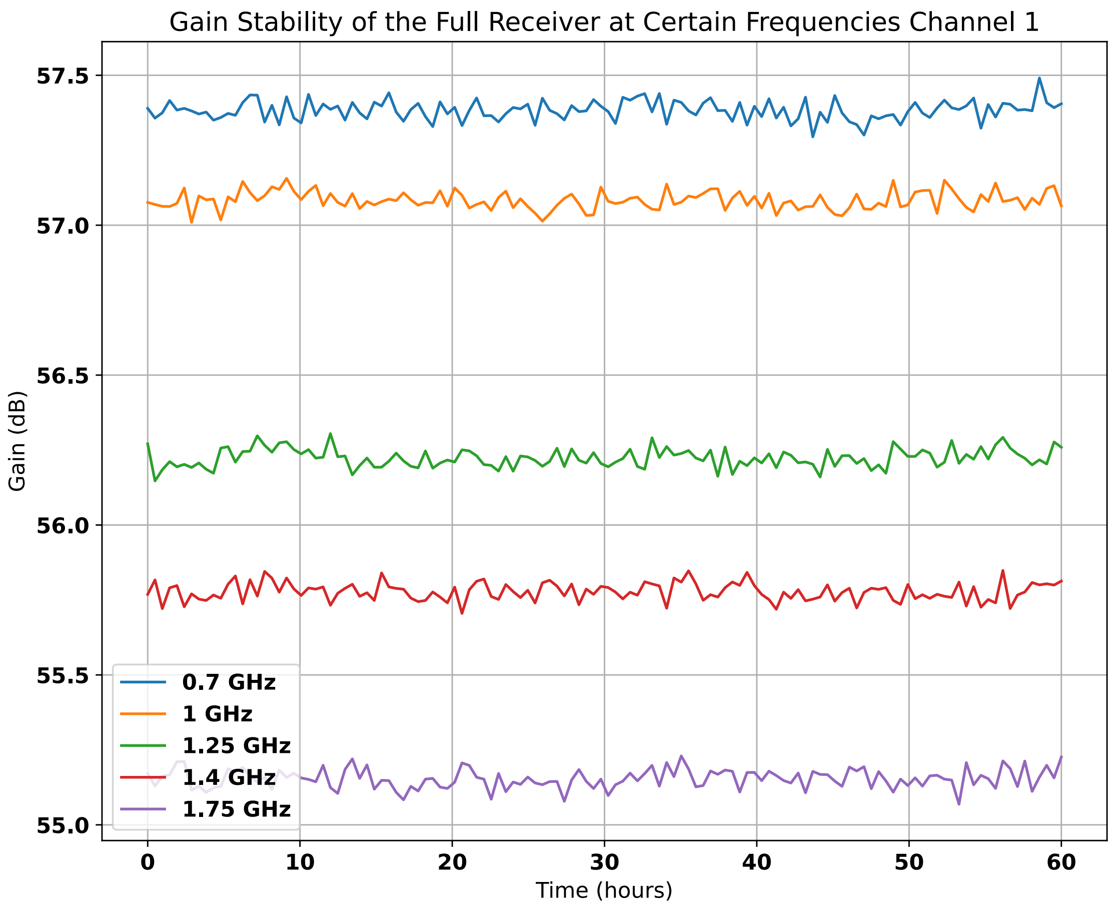



- Warm radiometer has an approximate noise temperature of ~ 100 K
- Noise temperature dominated by our first stage amplification, advertised noise temperature of 60 K
- Cold system will use cryogenic LNAs, which will significantly reduce the noise

Cascaded noise figure:

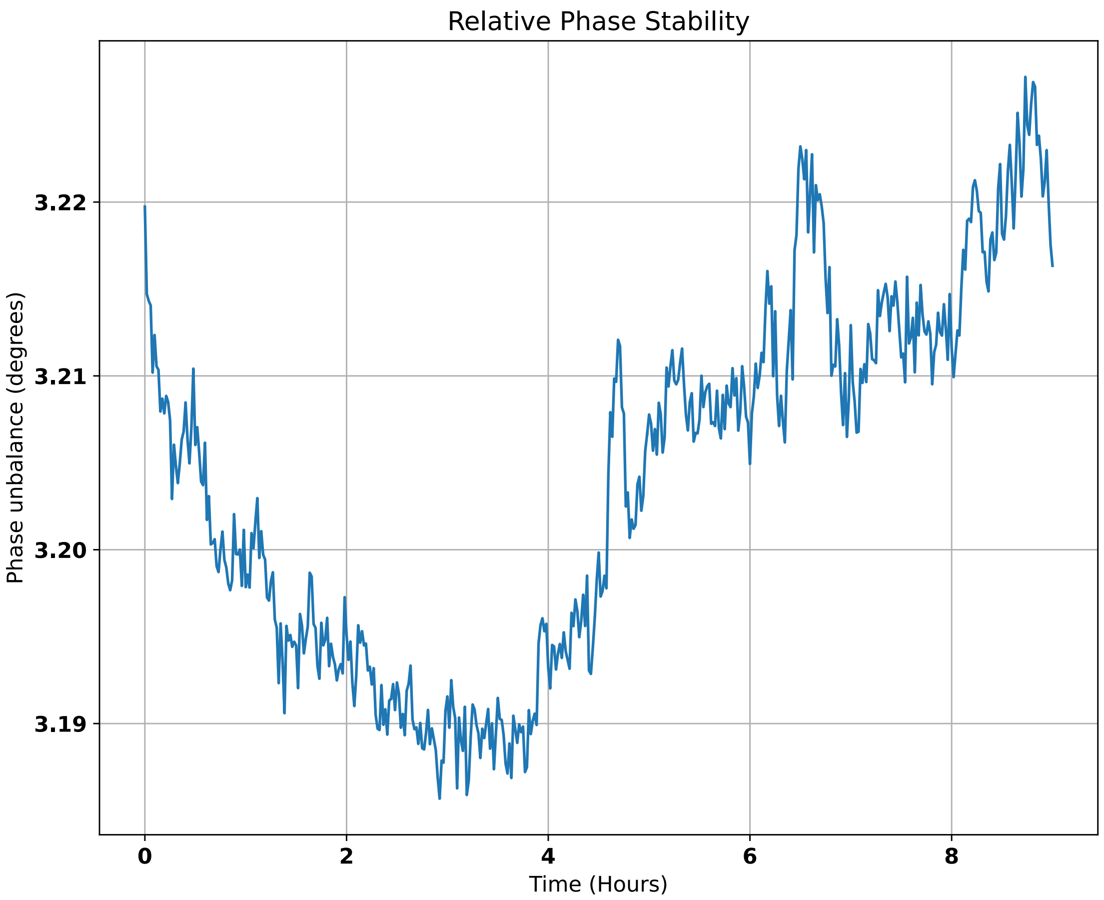
$$T_e = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \dots$$

# Receiver Performance IV - Gain Stability



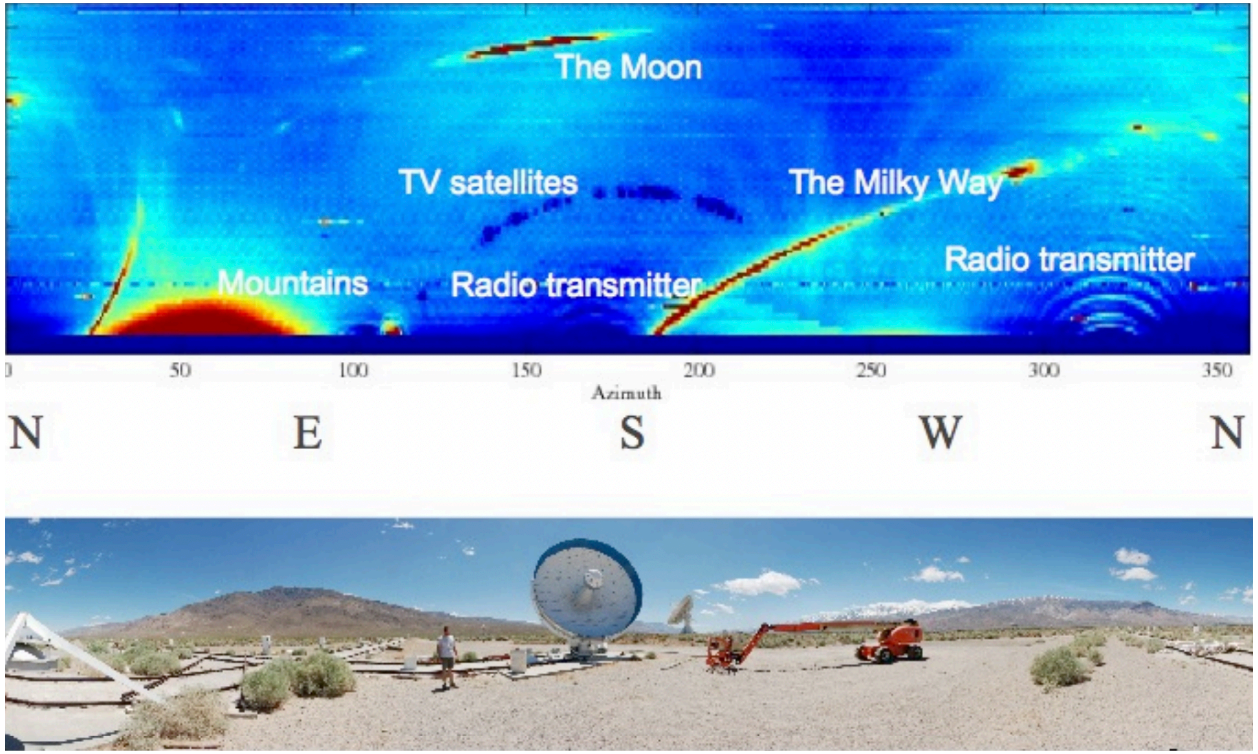

- There was a temperature drift of around 3 degrees through the 60 hours of this measurement
- No significant correlation with ambient temperature
- The gain of the receiver as a whole is relatively stable
- Same trend obtained when measuring channel 2.

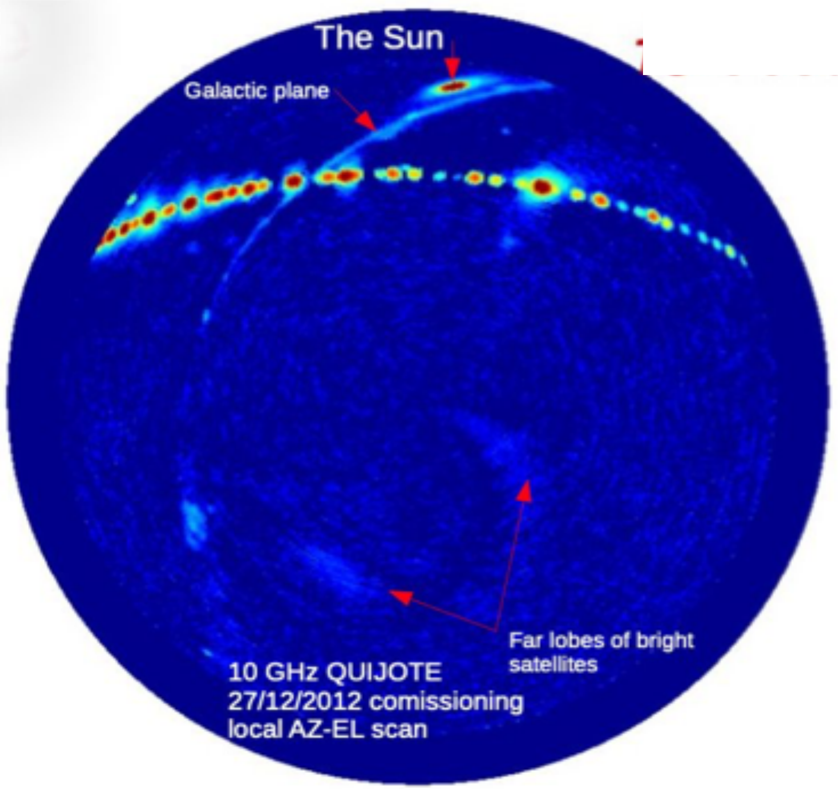
# Receiver Performance V - Relative Phase Stability




- There was a temperature drift of around 3 degrees through the 8 hours of this measurement
- Fixed frequency (9 GHz) measurement
- Strong correlation with temperature. We will install temperature sensors on board to correct for this.
- **Small drift (0.03 degrees) over the full 8 hours**

# CGEM VI - RFI Challenge




The C-BASS experiment has had to work hard to deal with RFI at 5 GHz in the Owens Valley. The map at top (scaled to the panorama photo) is an example of the early data prior to notching their band and adding baffles to the telescope.

(Slide from a May 2022 QUIJOTE talk by Mike Peel.) Observations of satellite RFI in the early QUIJOTE 11-13 GHz band. The line of geo-stationary satellites were as bright as the Sun…

# CGEM VII - RFI Challenge Satellites