MINISTÉRIO DA CIÊNCIA, TECNOLOGIA, INOVAÇÕES E COMUNICAÇÕES
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

JSPS-FAPESP Workshop on Dark Energy, Dark Matter, and Galaxies

# The BINGO radio telescope: construction status update


**Carlos Alexandre Wuensche and the BINGO Collaboration**

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https://portal.if.usp.br/bingotelescope/

# Era of precision cosmology

- Cosmology is now in a golden area (Planck, SDSS, DES and other large surveys) but there are still a few key questions to be answered!
  - Inflation ($t<10^{-32}$ s) – maybe CMB with B-mode polarization results
  - Dark energy – DES, e-BOSS, EUCLID, HETDEX and others?

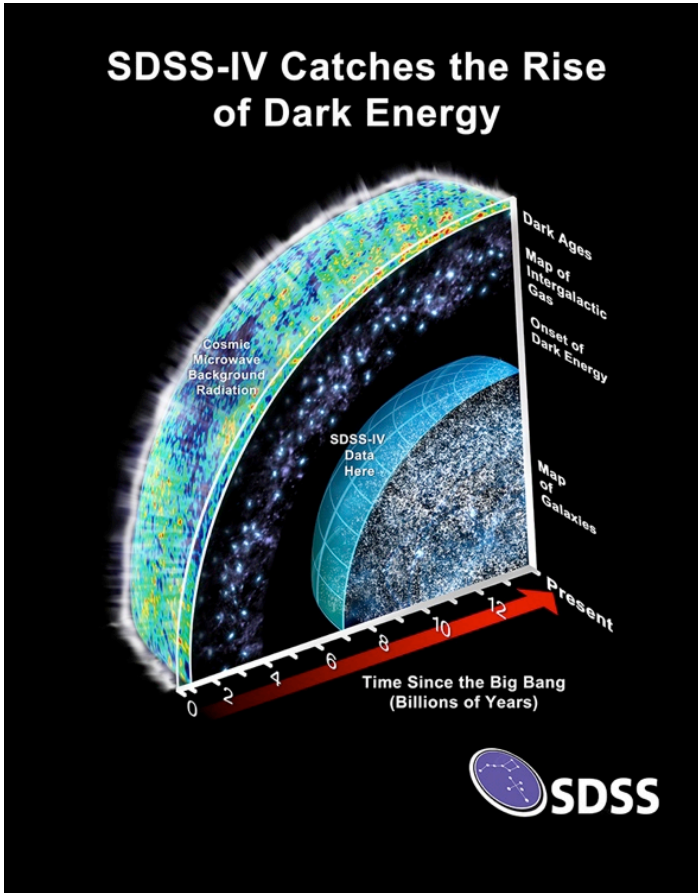
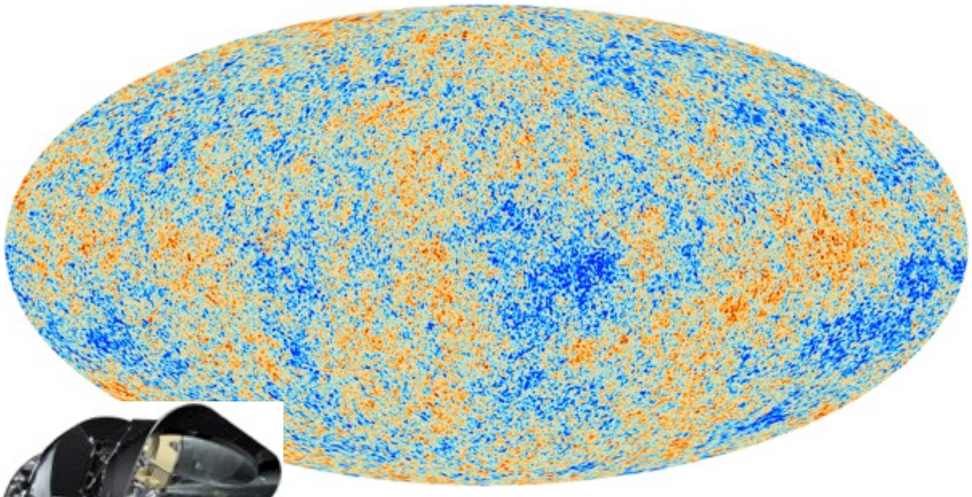


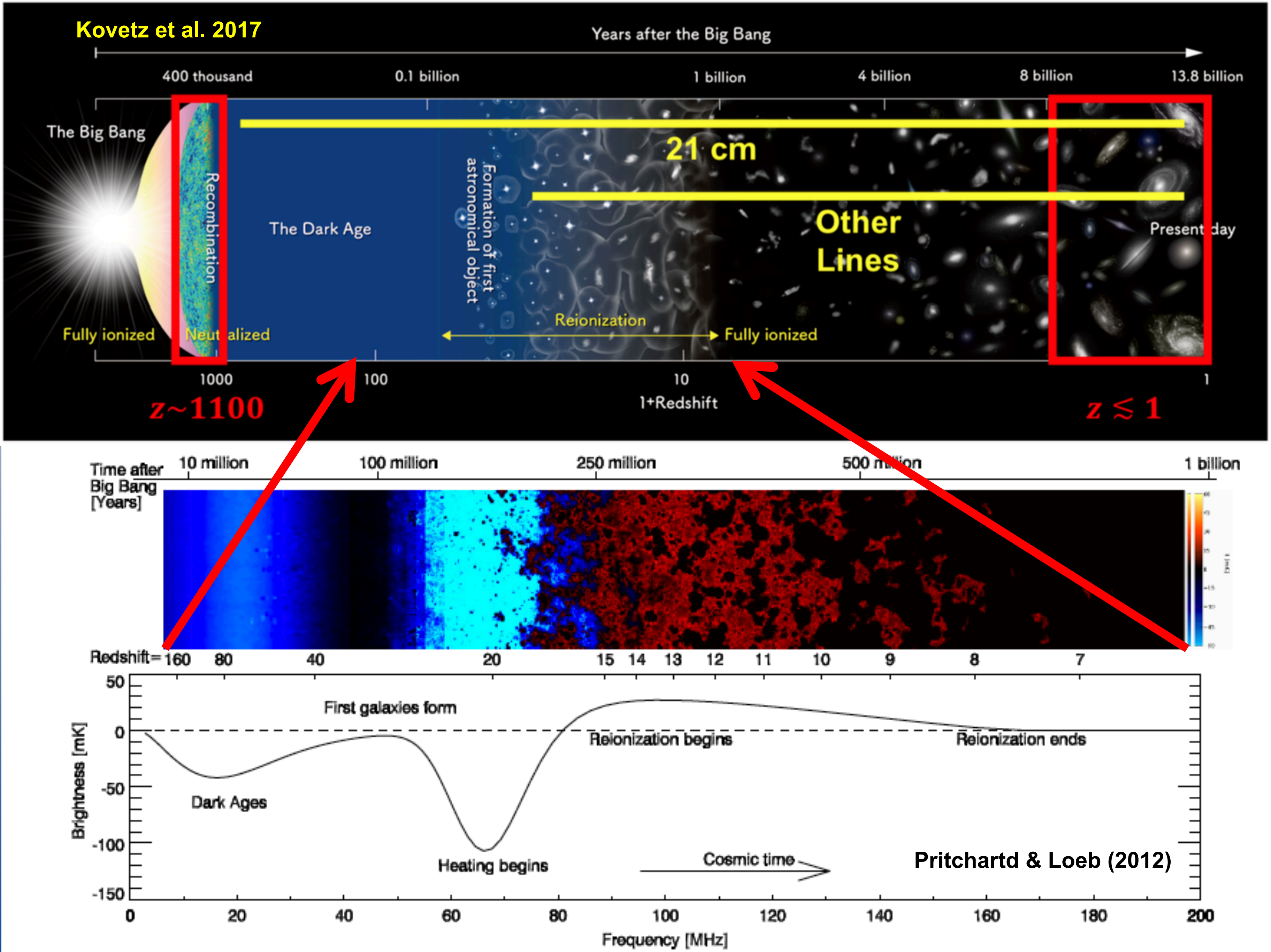

Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.



CMB map from Planck collaboration et al. (2018)

# 21 cm cosmology

- Universe is reasonably well understood from t ~ $10^{-6}$s to t ~ 380.000 years and then after Cosmic Dawn (t ~ 180 Myears)
- History of matter evolution can be traced via HI (and its disappearance) from z=20 to z=0
  - 0 < z < 2 – Dark energy
  - 2 < z < 6 – Curvature
  - 0 < z < 6 – Primordial NG
  - What's next???
- For reference
  - Z = 0.5 => t = 8,63 Gy
  - Z = 2 => t = 3,32 Gy
  - Z = 6 => t = 0.94 Gy
  - Z = 20 => t = 0,18 Gy
- HI bias related to the size of the hot dark matter halos. Too small => low density => low shield => H ionization

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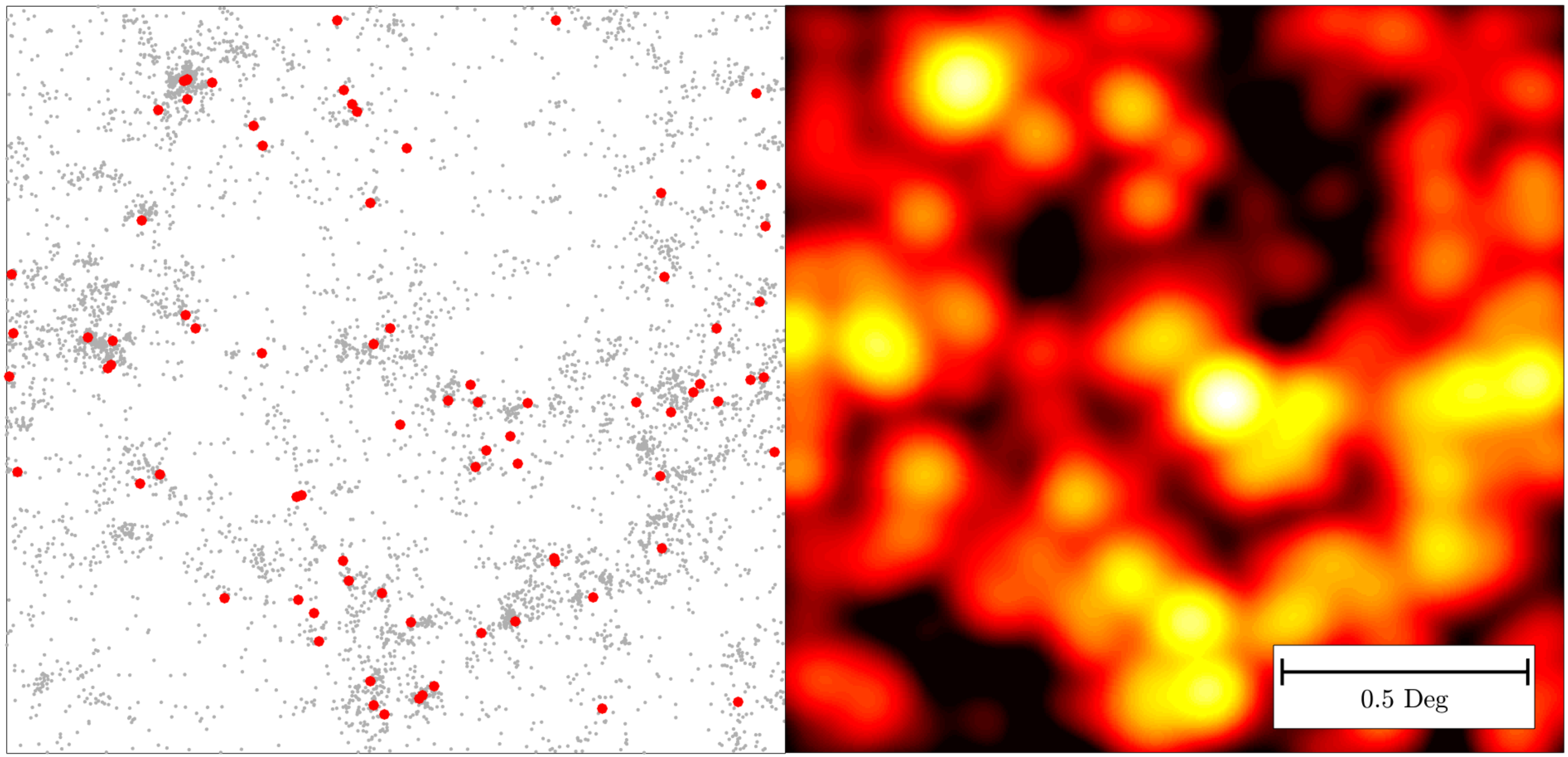
# The intensity mapping concept

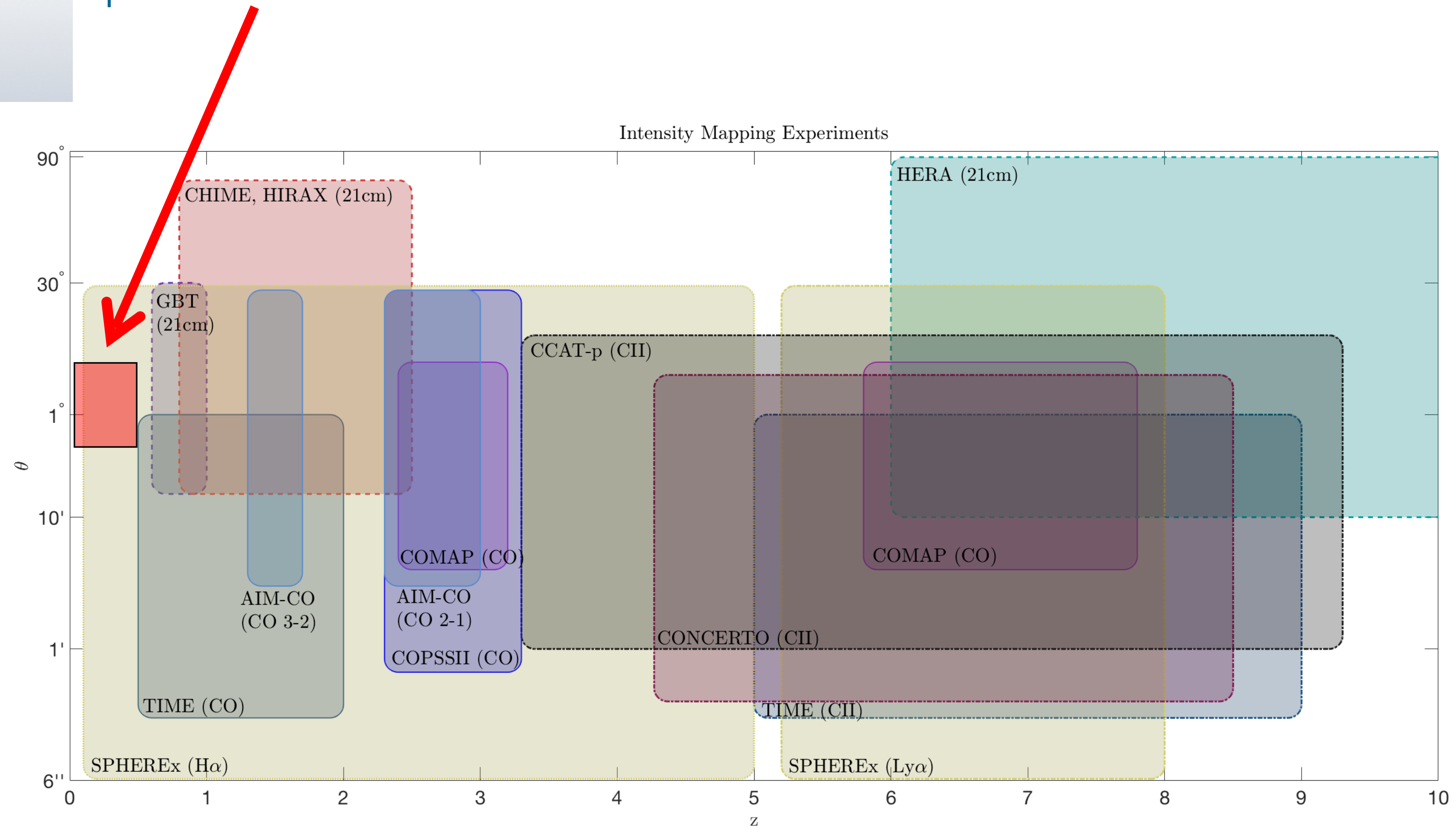
Measure the large scale features from the integrated emission of galaxies + IGM, from spectral line of different elements (H, C, O, … ), not worrying about individual objects




Simulated 2.5 deg field with galaxy positions (left) and CO IM (right).

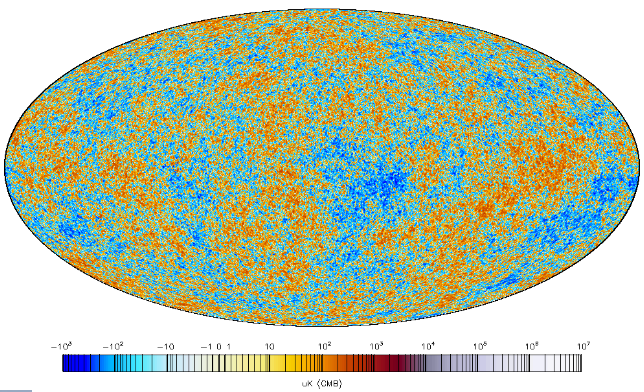
Kovetz et al, (arXiv:1709.09066)

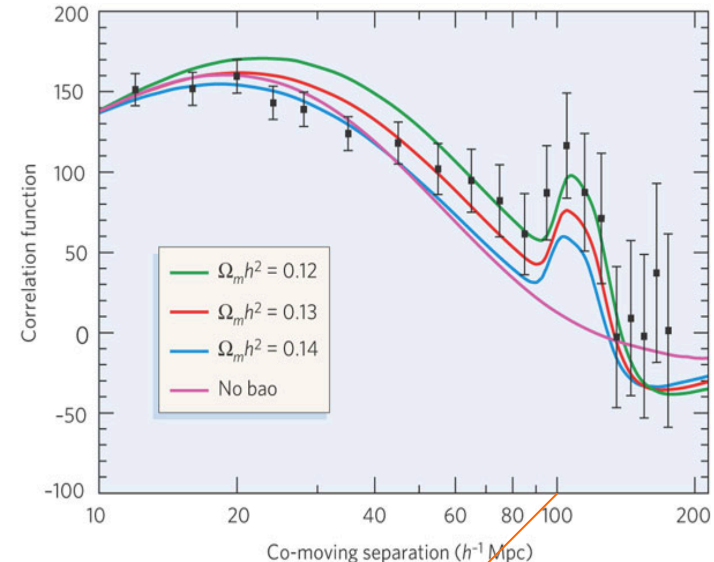
# BINGO would fit here – Our update of pag. 44 of Kovetz et al (2017)

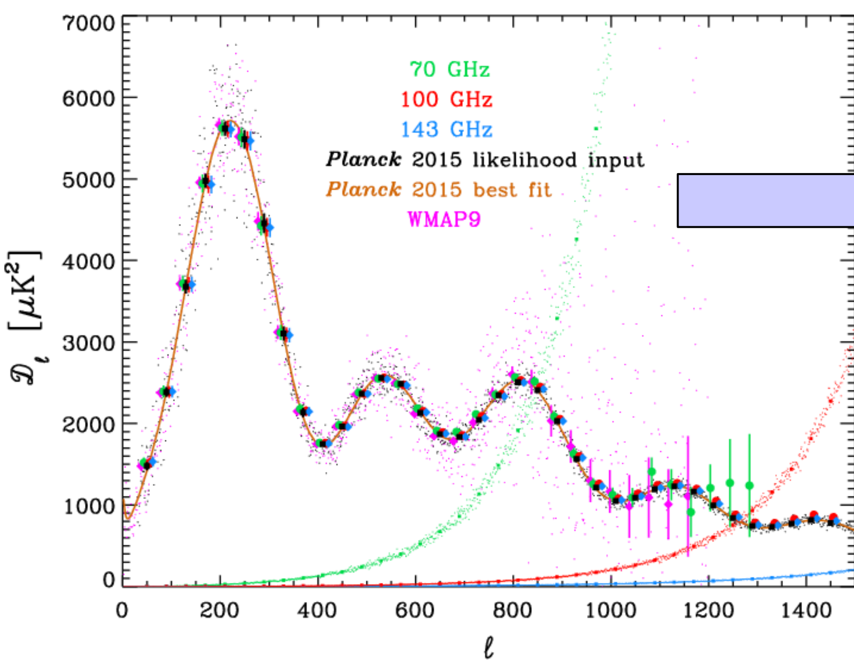


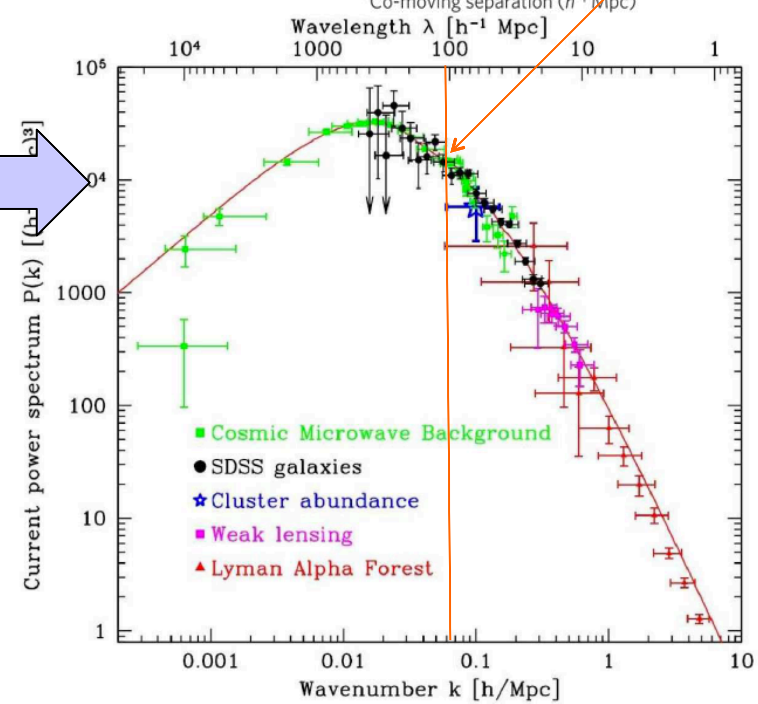

Kovetz et al, (arXiv:1709.09066)

# Temperature x matter fluctuations





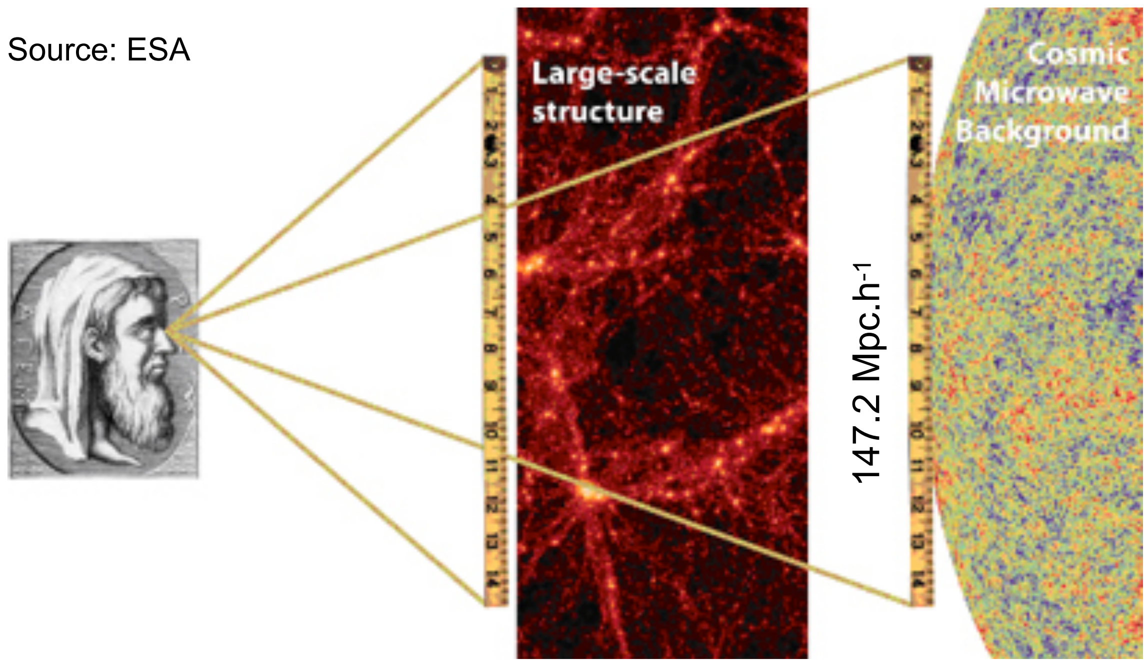



# Baryon Acoustic Oscillations (BAOs)

- Acoustic waves imprinted on CMB 380,000 years after Big Bang
- Acoustic scale **D** set by distance light travelled at that time
  - Known precisely from CMB power spectrum
  - D=147.18±0.29 Mpc (Planck Collaboration 2018 - VI)

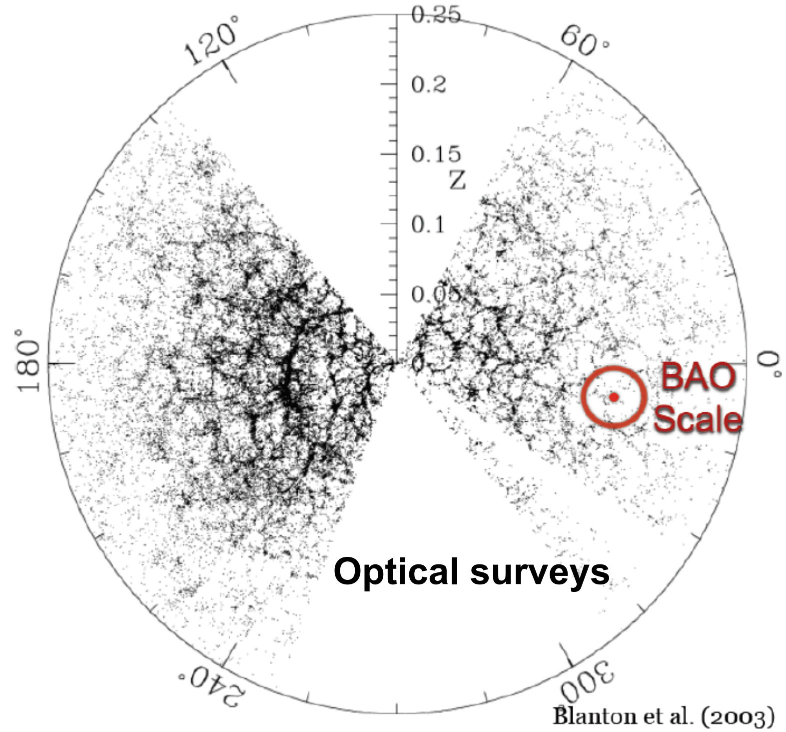
Source: ESA

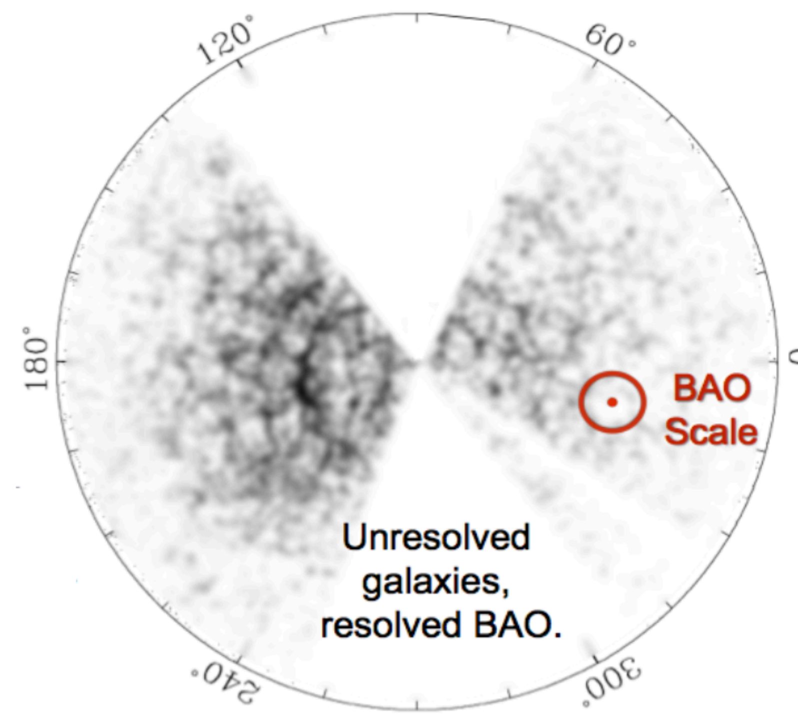
- BAO scale imprinted on all matter in the Universe
- Use as a "standard ruler"
- Baryon oscillations seen in the CMB distribution can be observed in the spatial distribution of galaxies



# Why BAO in radio?

- Complementary to optics, different systematics
- Decay time of HI hyperfine transition is ~ $10^{15}$ seconds, but 75% of visible matter in the Universe is made of H...
- Efficient alternative for measuring a large number of galaxies individually (plus integrating the signal “alla” CMB allows for the reutilization of a large background experinece in instrumentation and data analysis)
- Interferometers are excellent instruments for these measurements, but are expensive and hard to operate and maintain
- Approach: single-dish, many horns X single horn per dish

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# Desirable items for a single dish HI surveyor

- Large collecting area (> 500 $m^2$)
- Large covered area on the sky (care should be taken with leaving out very small scales, < 0.1 $Mpc.h^{-1}$)
- Low sidelobes and good (precise shape) beam
- Long observing time (> 1 year)
- Sensitivity to intermediate scales, where BAO is important ($0 < z < 2$)
- Redshift range: $0.1 < z < 1$ (bias larger than 0.7 after that)
- Frequency range:
  - 1300 MHz => $z \approx 0.08$
  - 100 MHz => $z \approx 0.93$ Lots of RFI in this frequency range

Adapted from Bull et al. 2015

# The BINGO Telescope

# BINGO concept (Dec 2018)

Instrument characteristics

- Dish diameter : 40m and 34m
- Resolution (°): ~ 0.67
- Focal length (m): 63.2m
- Frequency range (MHz): 960 – 1260
- Channel resolution (TBD, but can be down to 10s' of kHz)
- Z interval: 0.13 - 0.48

**Fixed wire-mesh parabolas**
**No moving parts**
**Transit telescope**
**Most components "off-the-shelf"**
**Guiding principle : simplicity !**

Instrument characteristics

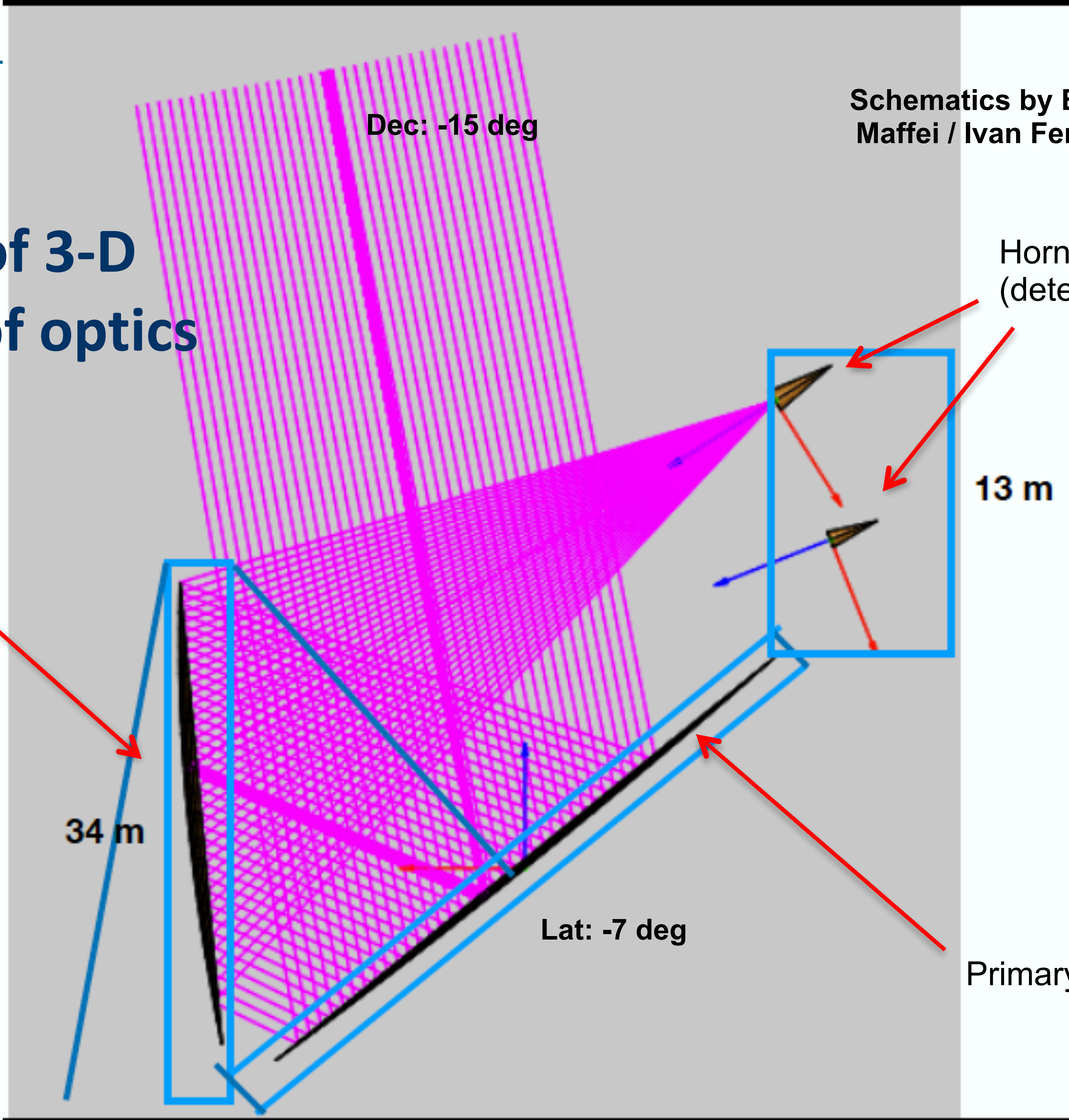
- Number of feeds : 49 (dual pol.)
- Horn largest diameter: 1.9m
- Horn length: 4.3m
- Focal plane: 13,3 m (H) x 13,2 m (W)
- Estimated scan area: ~ 5000□
- No cryogenics : $T_{sys} \approx 70K$

# Project status

- BINGO is under construction
  - horn prototype completed
  - transitions, polarimeter, transitions and magic tee prototypes going to fabrication
  - receiver waiting for components to arrive
  - RFI initial measurements on site completed => permanent monitor received from Swiss to be installed on site
  - Topography sorted out => optical design in preparation
  - Legal issues regarding property, electrical power, roads and silence protection zone being handled by collaborators in Paraiba
- About 80% completely funded
  - (total ~ R$ 17.5 M => ~ US$ 4,25 M)

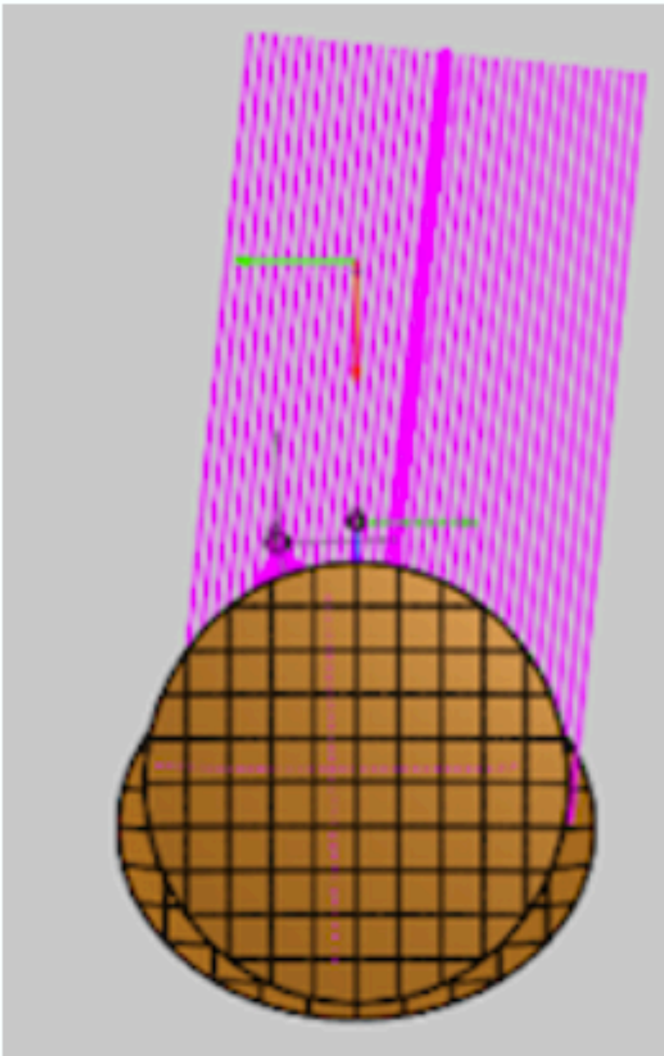
# Sketch of 3-D model of optics

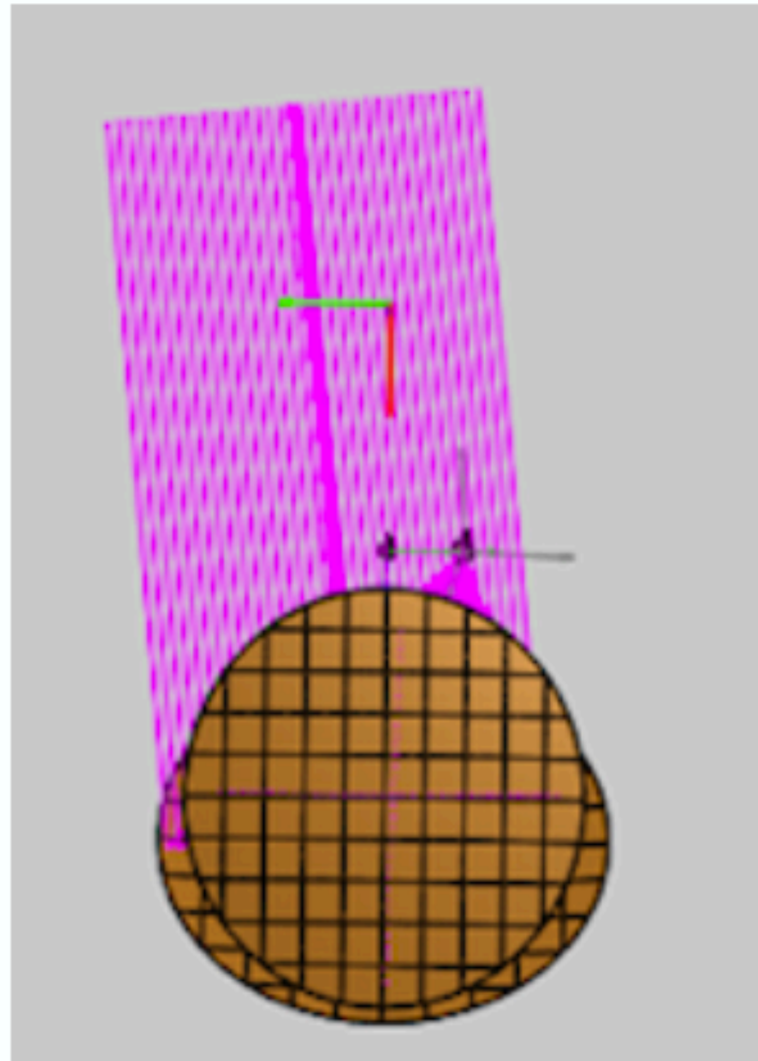
Schematics by Bruno Maffei / Ivan Ferreira



# Beam -660 and 660

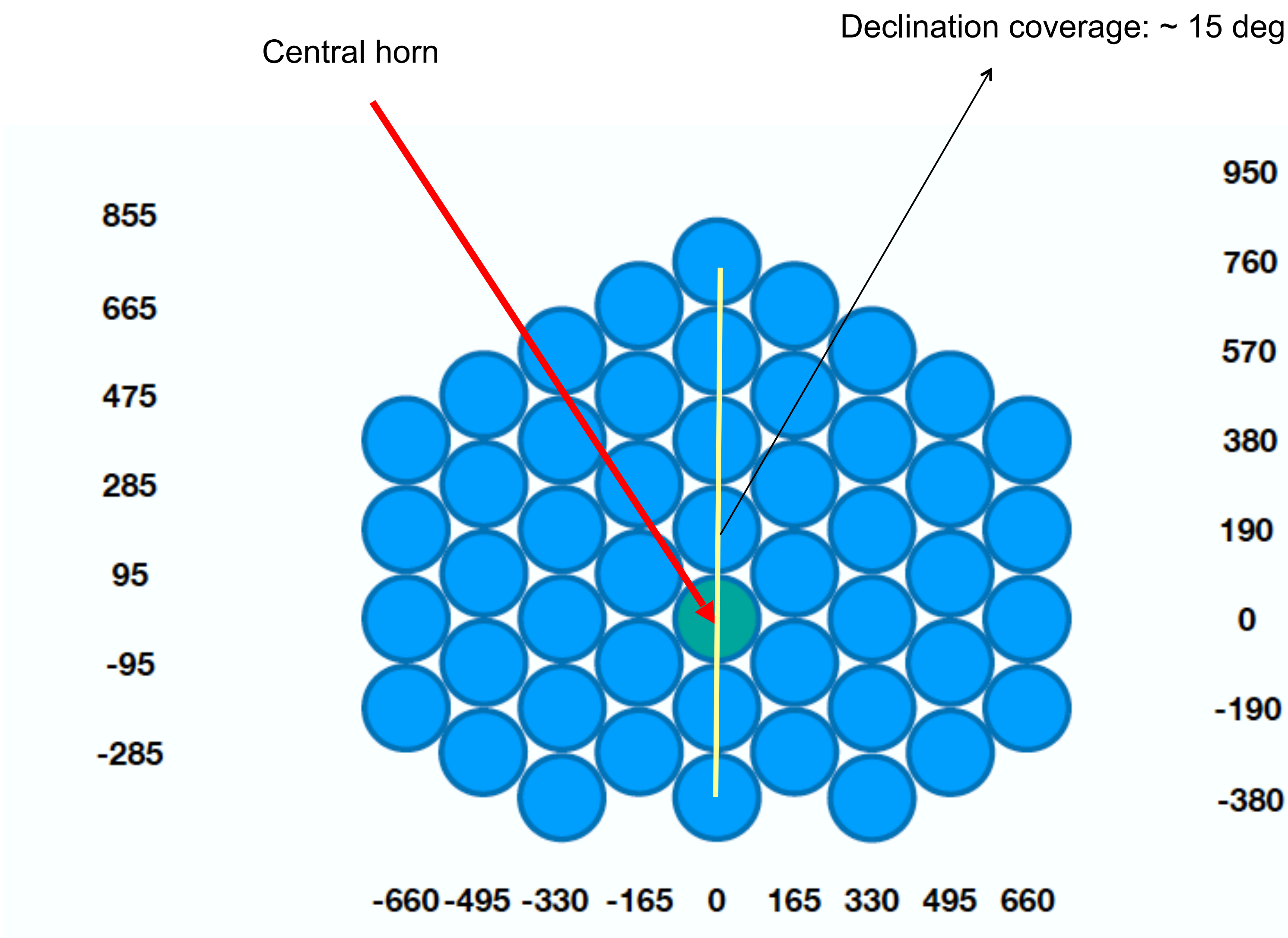
**Schematics by Bruno Maffei / Ivan Ferreira**





# Focal plane – 49 horns

**Schematics by Bruno Maffei / Ivan Ferreira**

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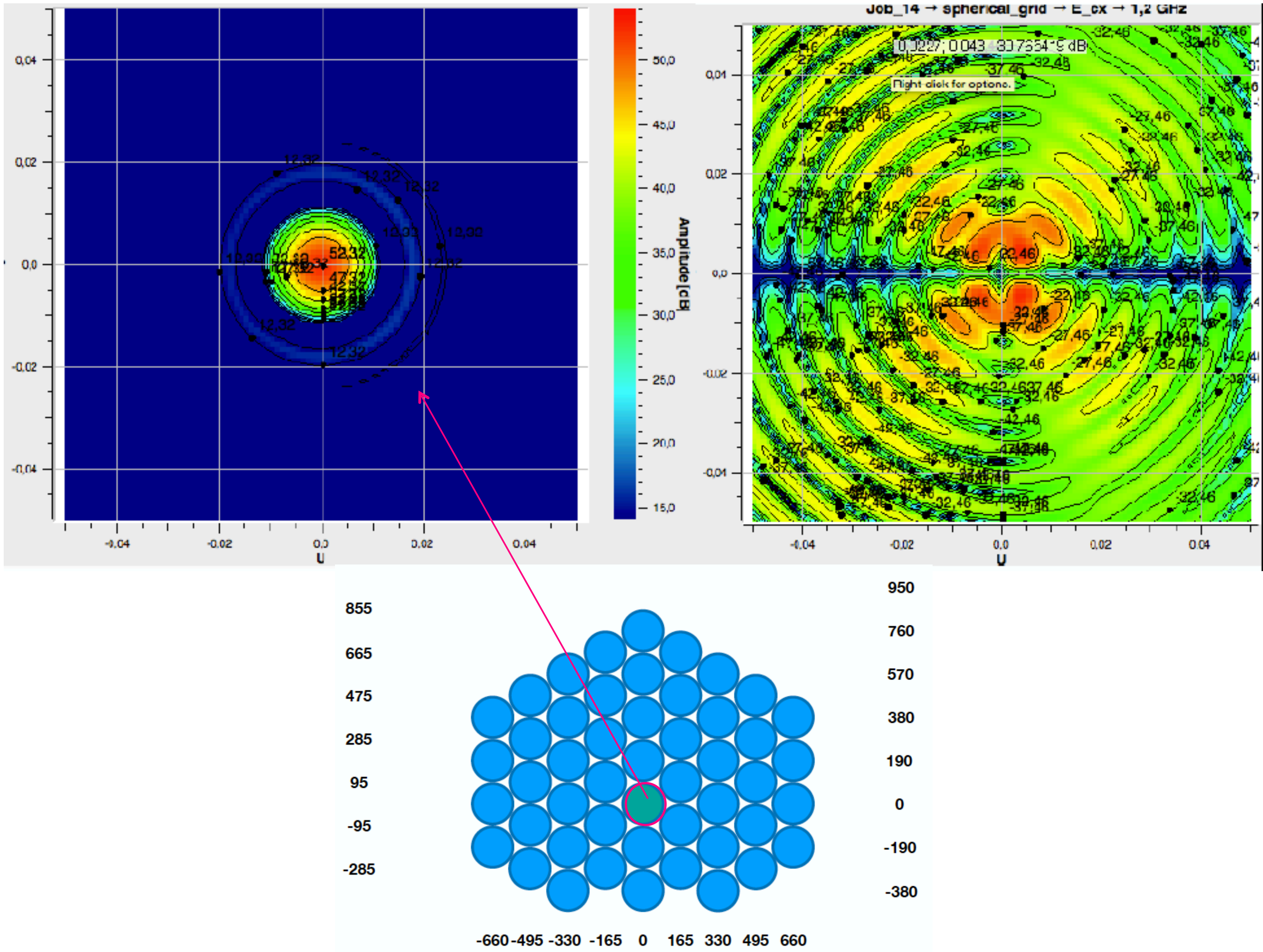
# Central Pixel

**Schematics by Bruno Maffei / Ivan Ferreira**

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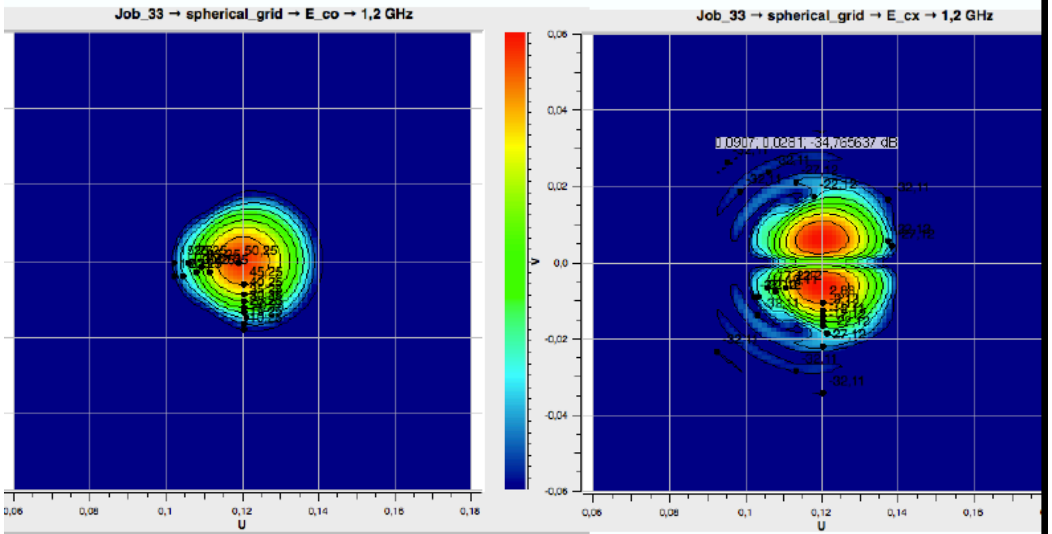
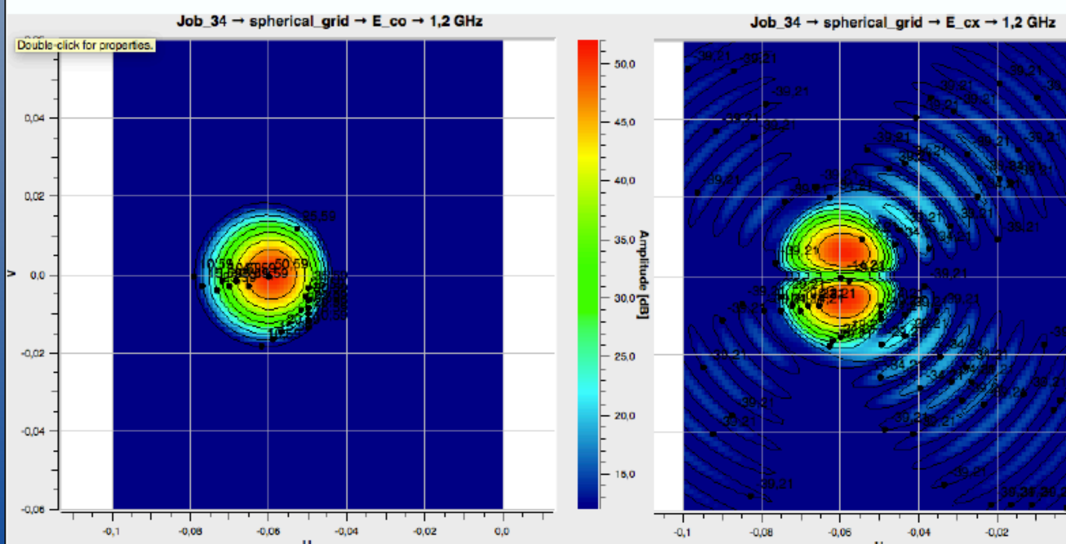
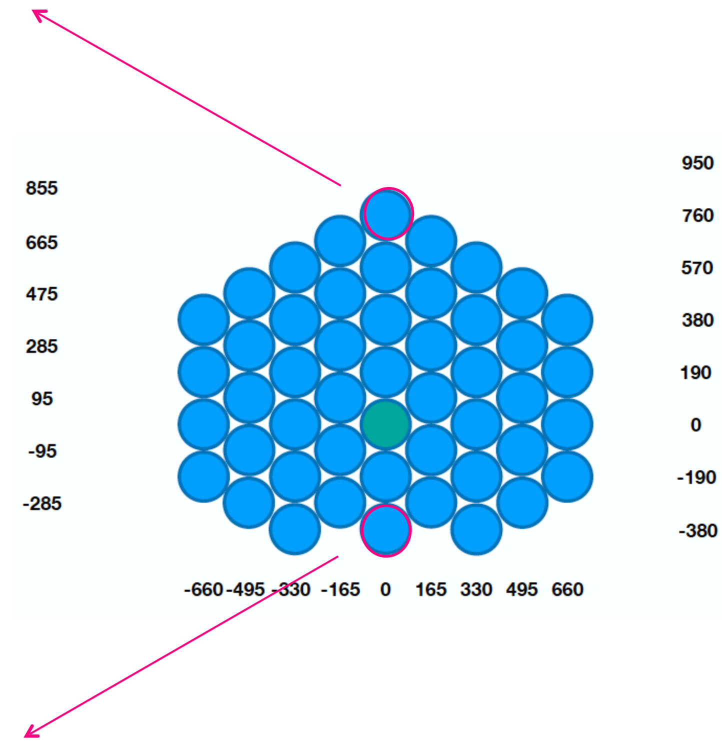
## Pixel 0,760




## Pixel 0,-380




## Schematics by Bruno Maffei / Ivan Ferreira

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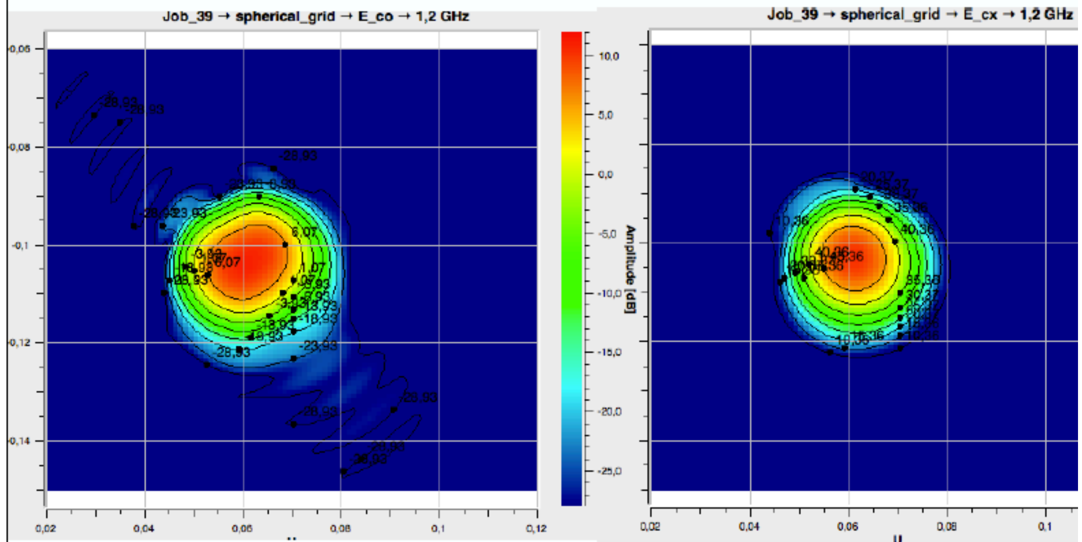
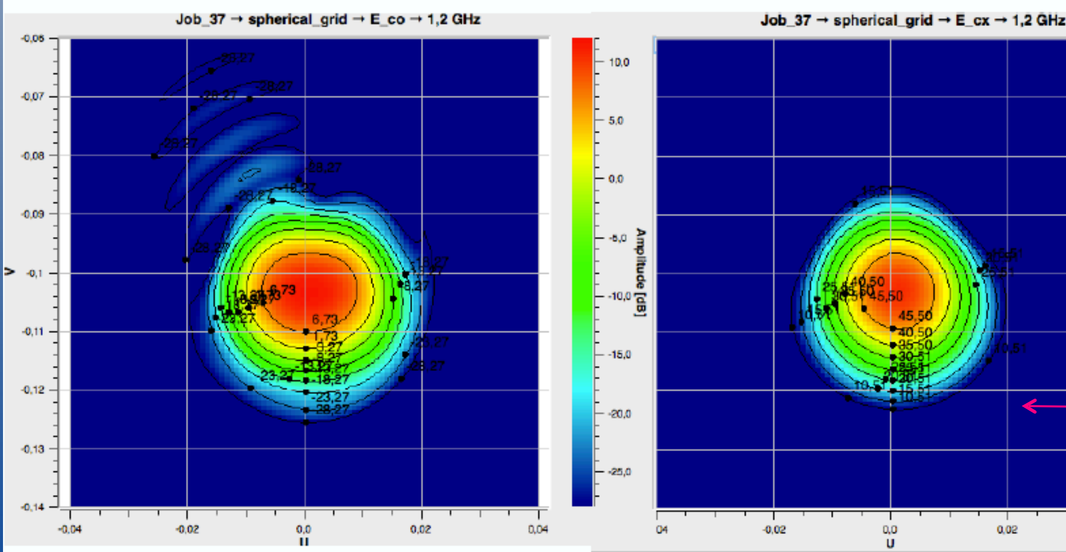
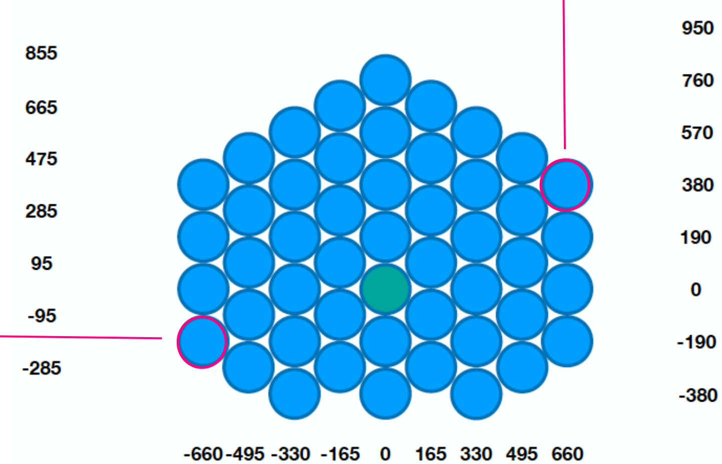
## Schematics by Bruno Maffei / Ivan Ferreira

**Pixel -660,380**




**Pixel -660,0**

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# Receiver status

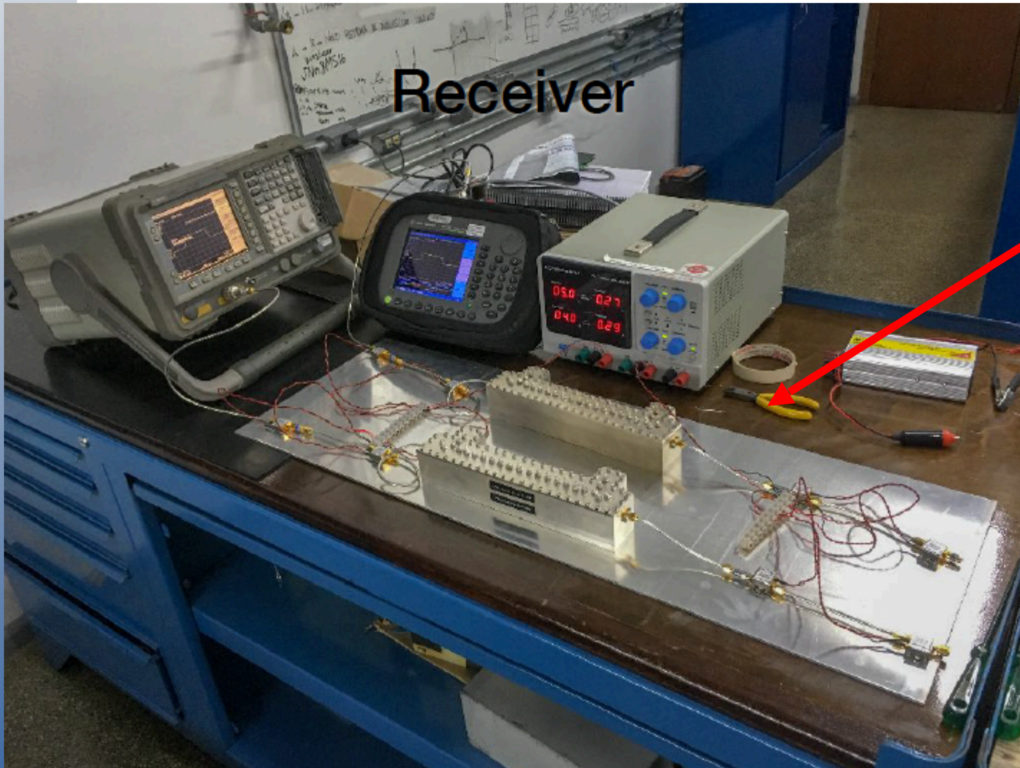
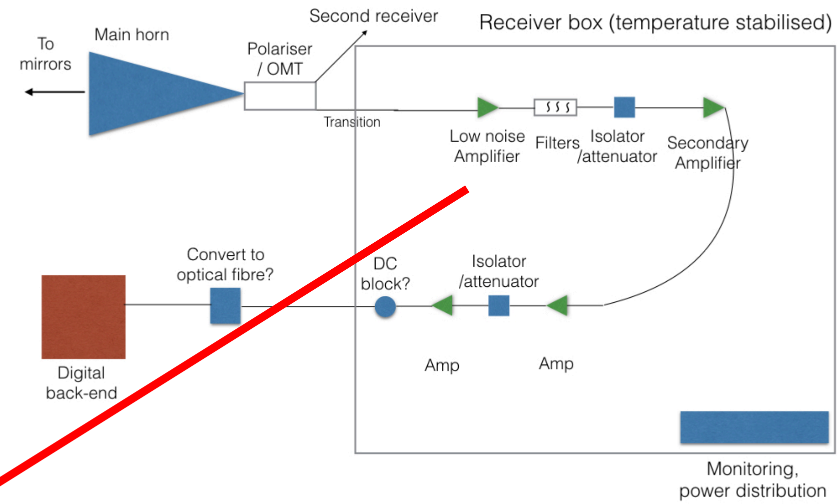
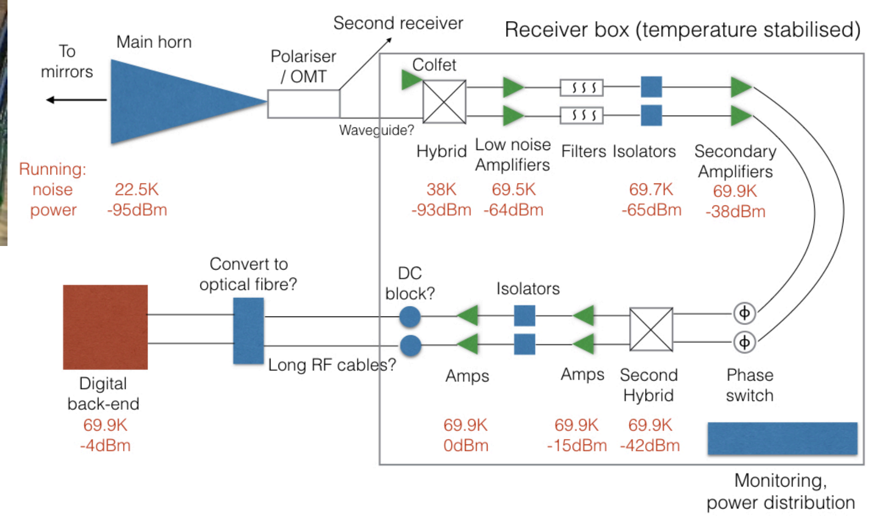



Photo: M. Peel @ INPE's lab

Simple radiometer




Desired: full orrelation receiver

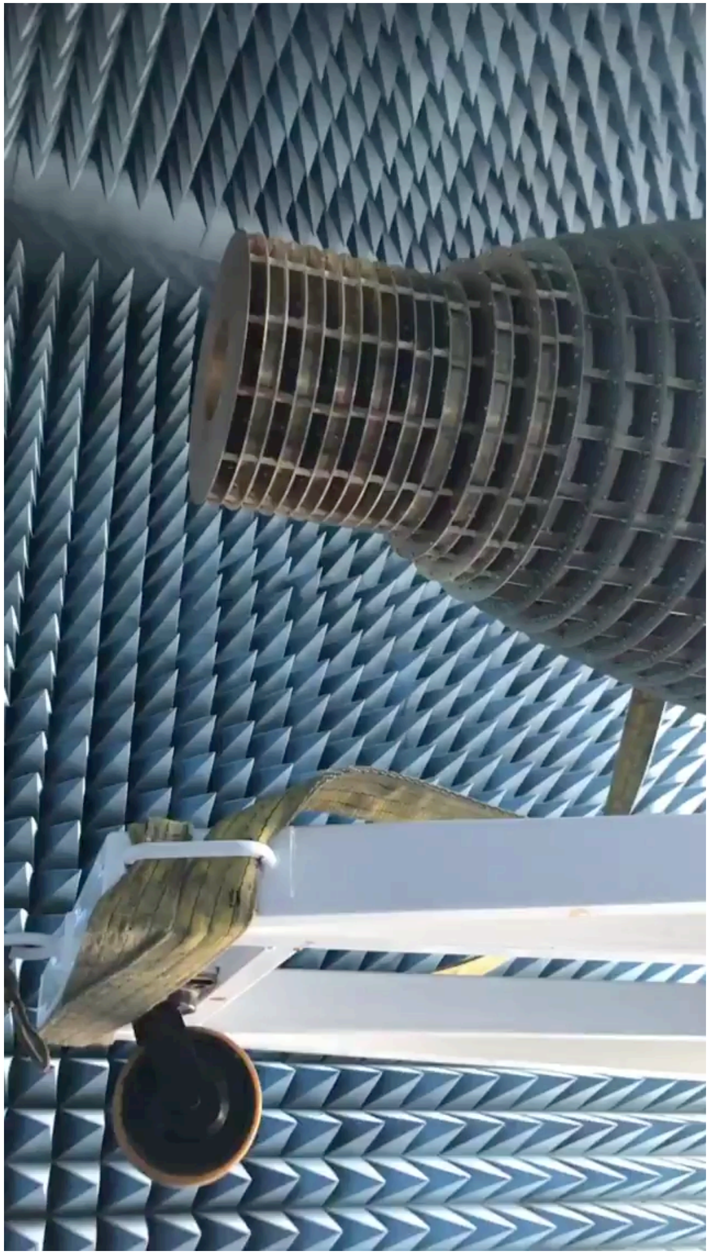


# Horn & polarimeter status

- Aluminum horns
  - 6060 T4 alloy
  - Mass: ~ 400 kg
  - Number of rings (sectors): 127
  - Length: 4318 mm
  - Mouth: 1900 mm
  - Throat: 250 mm
- Construction
  - Calfer (Brazil)

- Polarimeters transitions and magic tees (aluminum)
  - Mass: ~ 90kg,
- Construction
  - Metalcard (Brazil)

- EM project: Bruno Maffei (IAP, France)
  - Contributions from Chris Radcliffe (Phase 2 Microwave, UK)
- Mechanical project : Luiz Reitano (INPE, Brazil)



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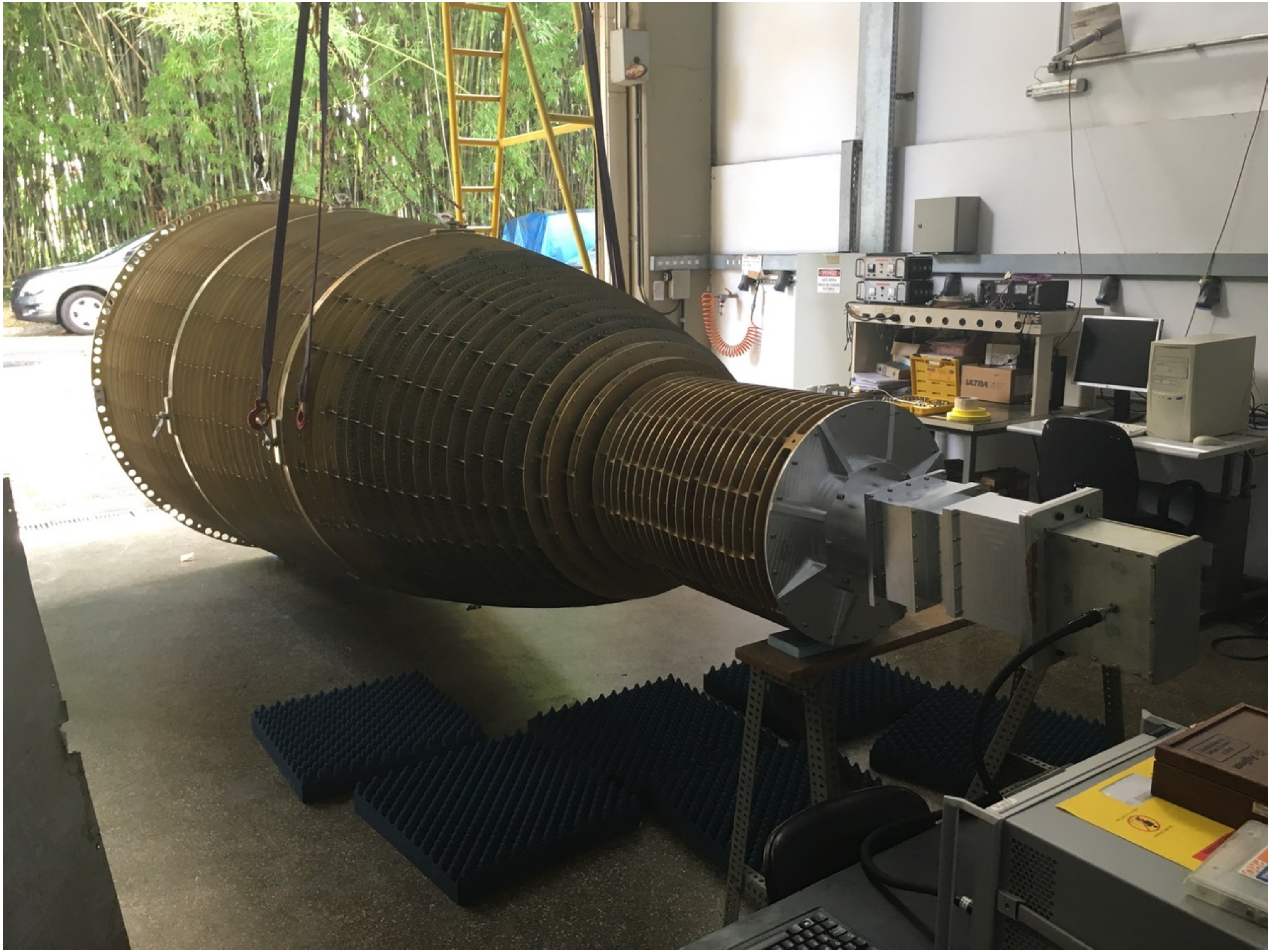
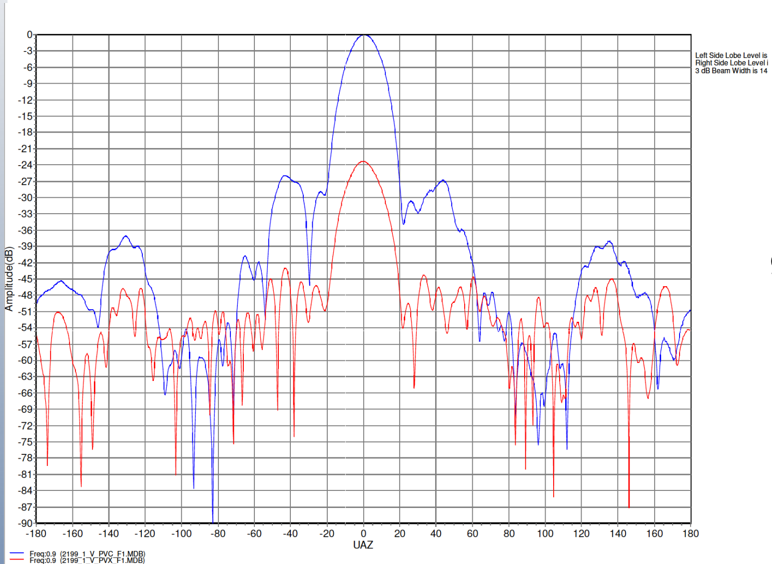
# Horns



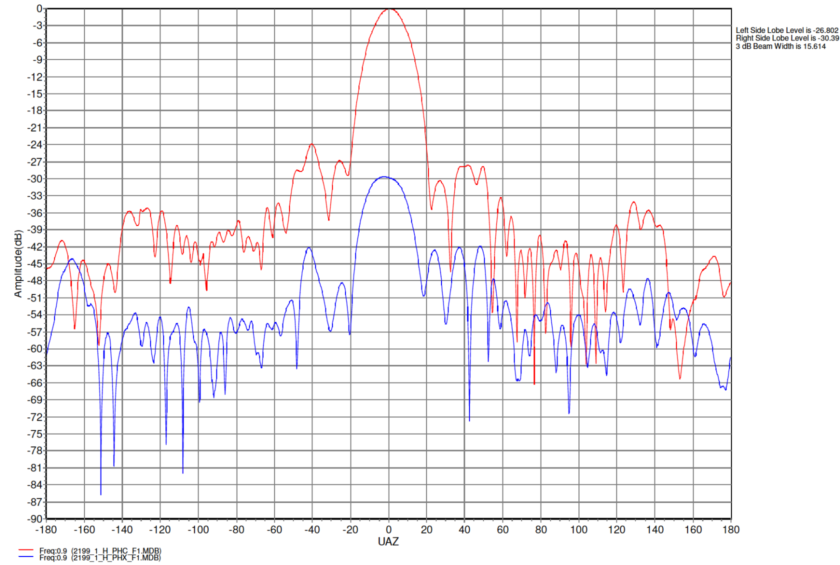
"BINGO: Horn design, fabrication and testing" (Wuensche et al. 2019, in preparation)

# Horn testing results –polarization

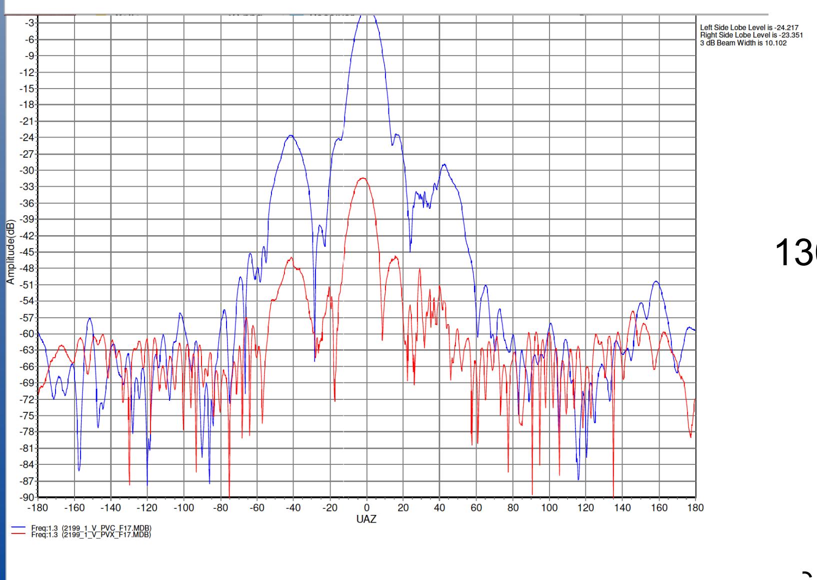
VERTICAL



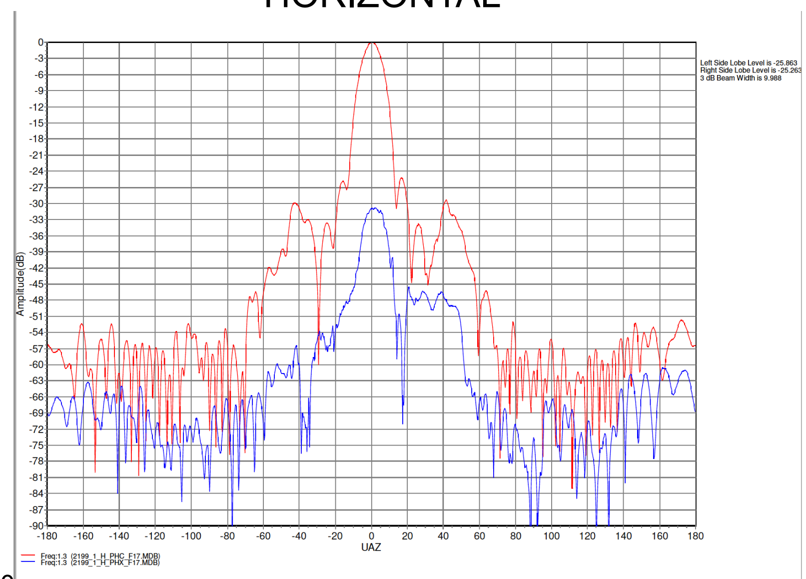

900 MHz



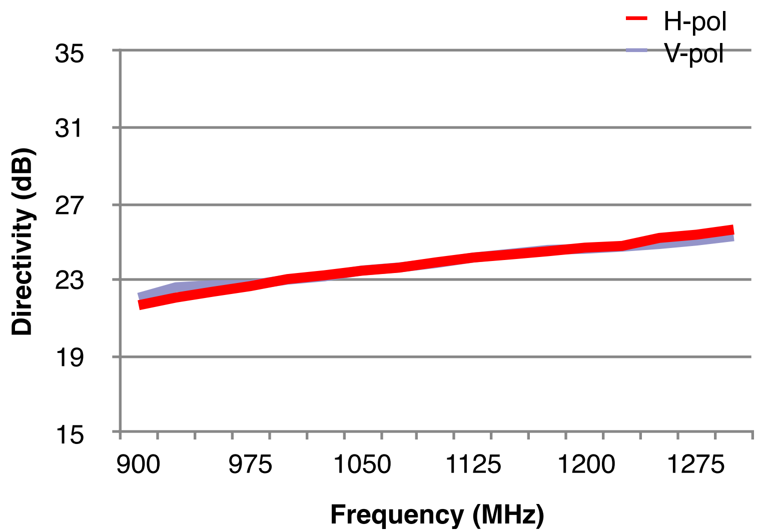

HORIZONTAL

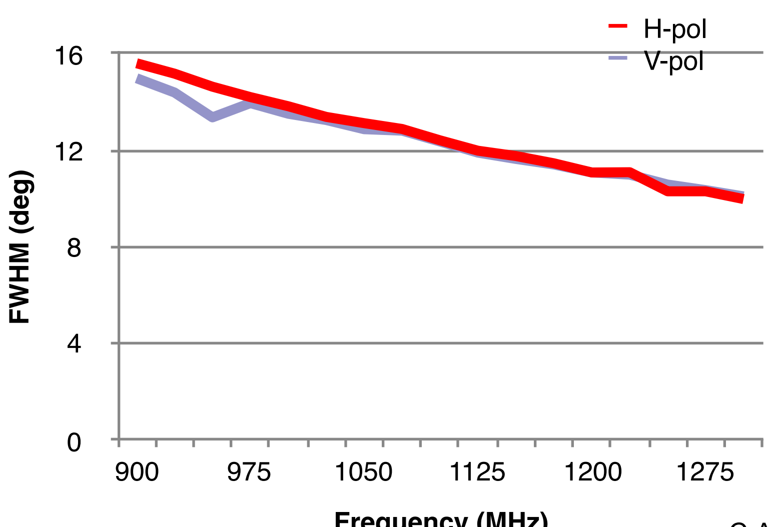


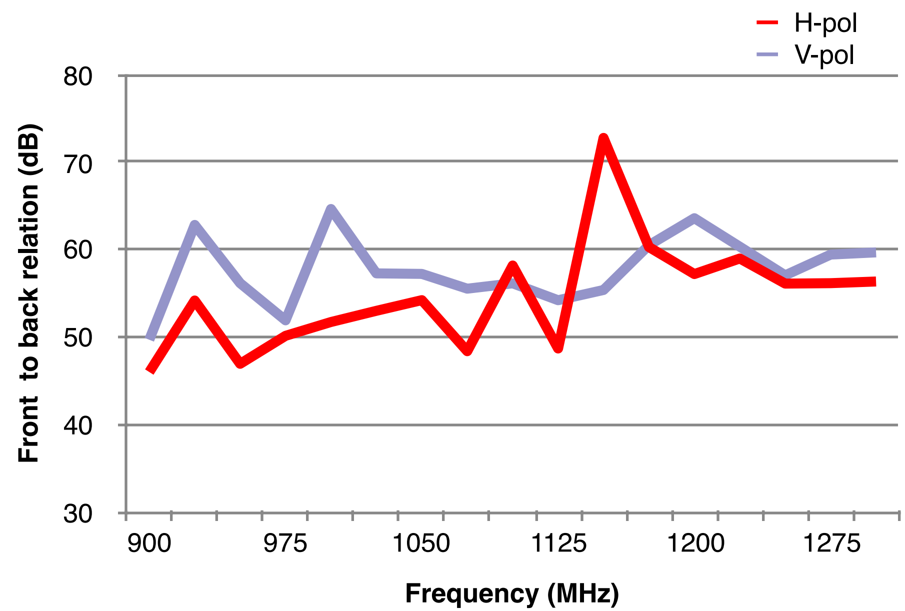

1300 MHz



# Horn testing results

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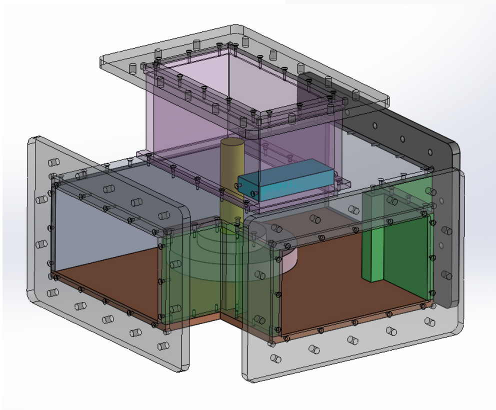
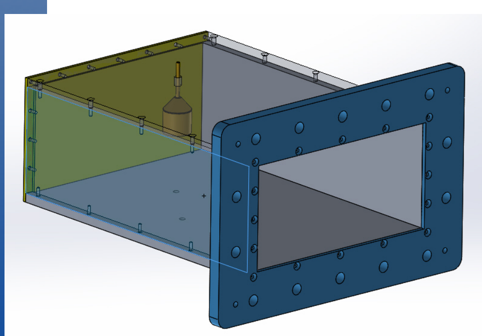
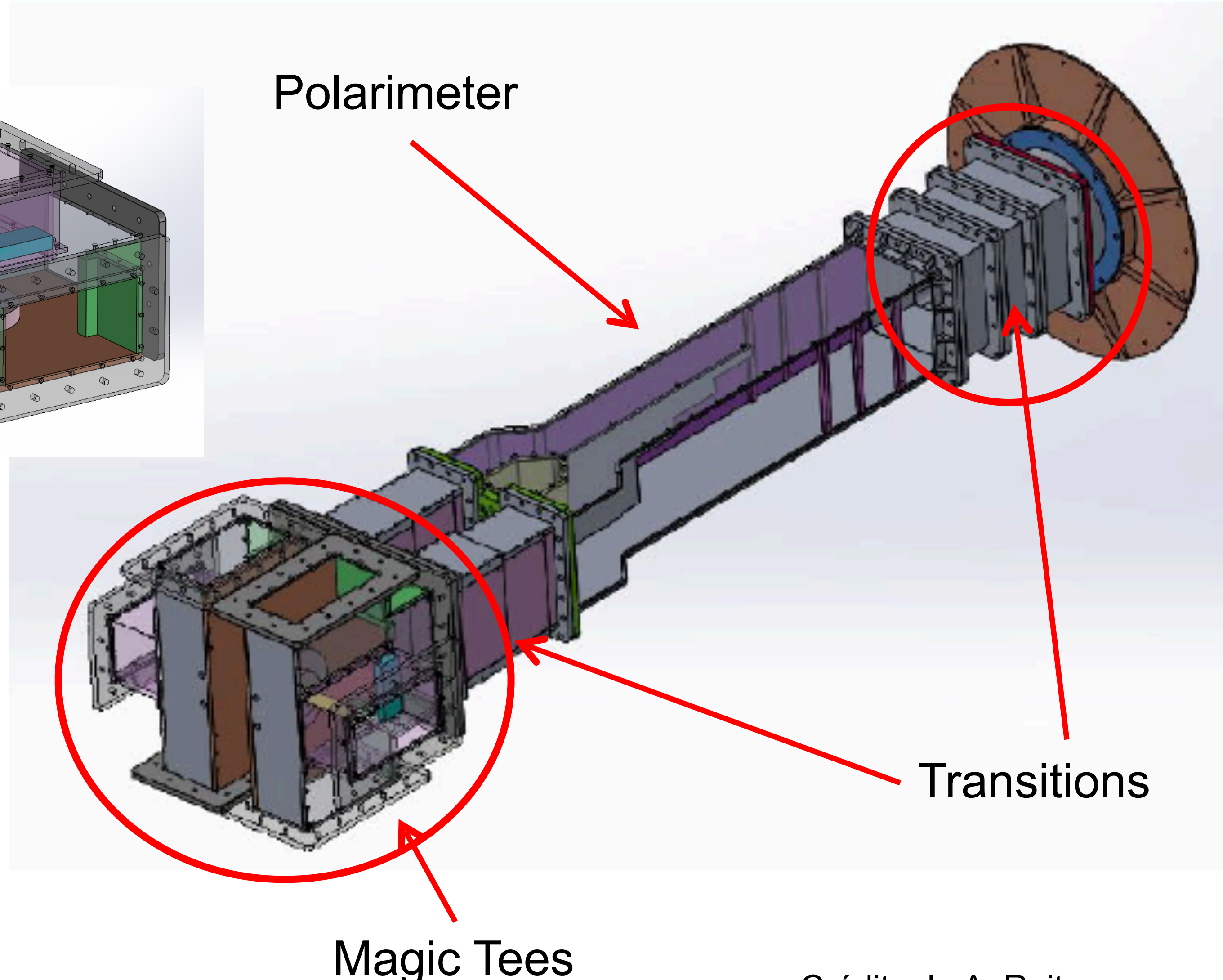
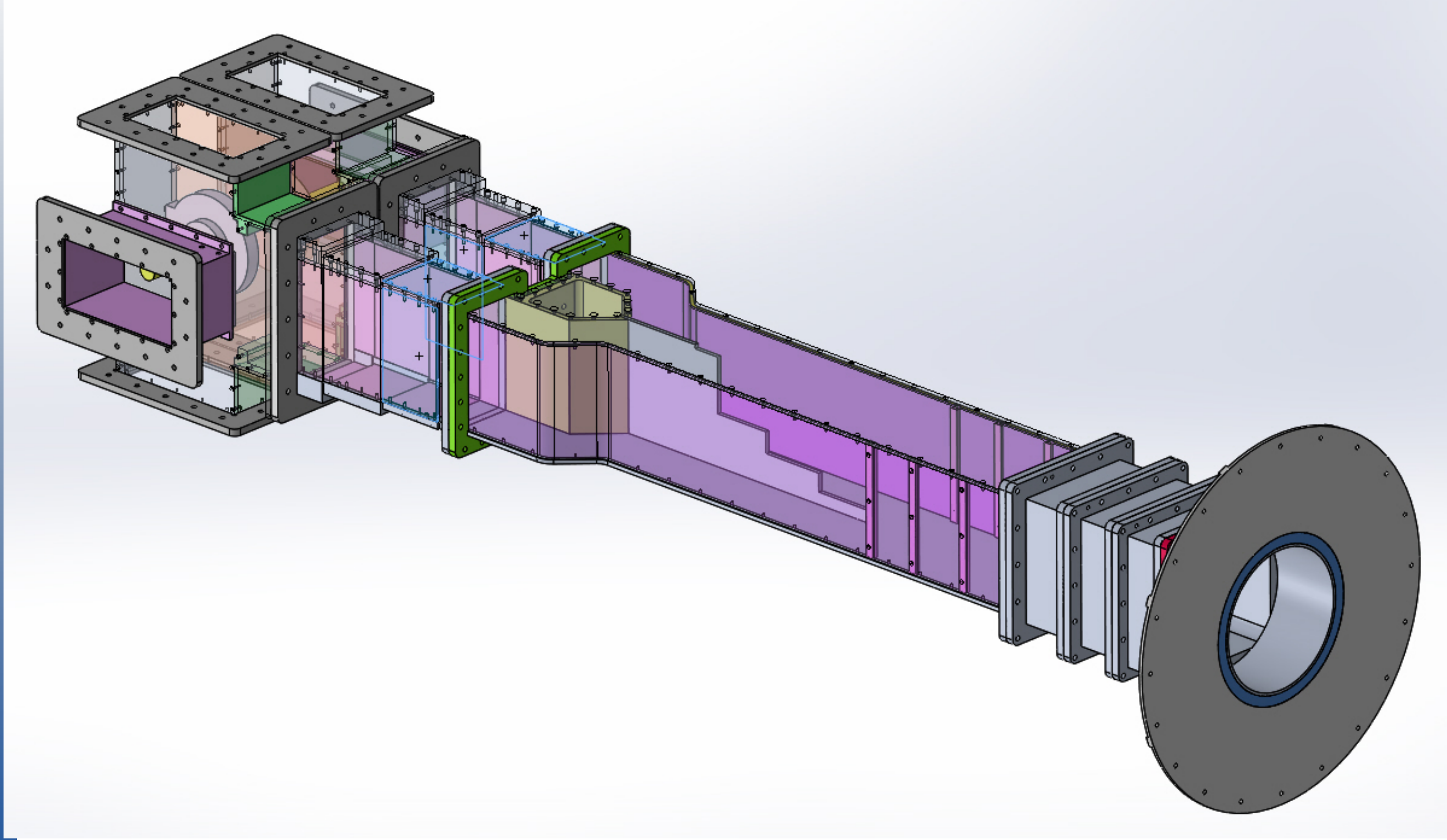
# Polarimeters, transitions and magic tees

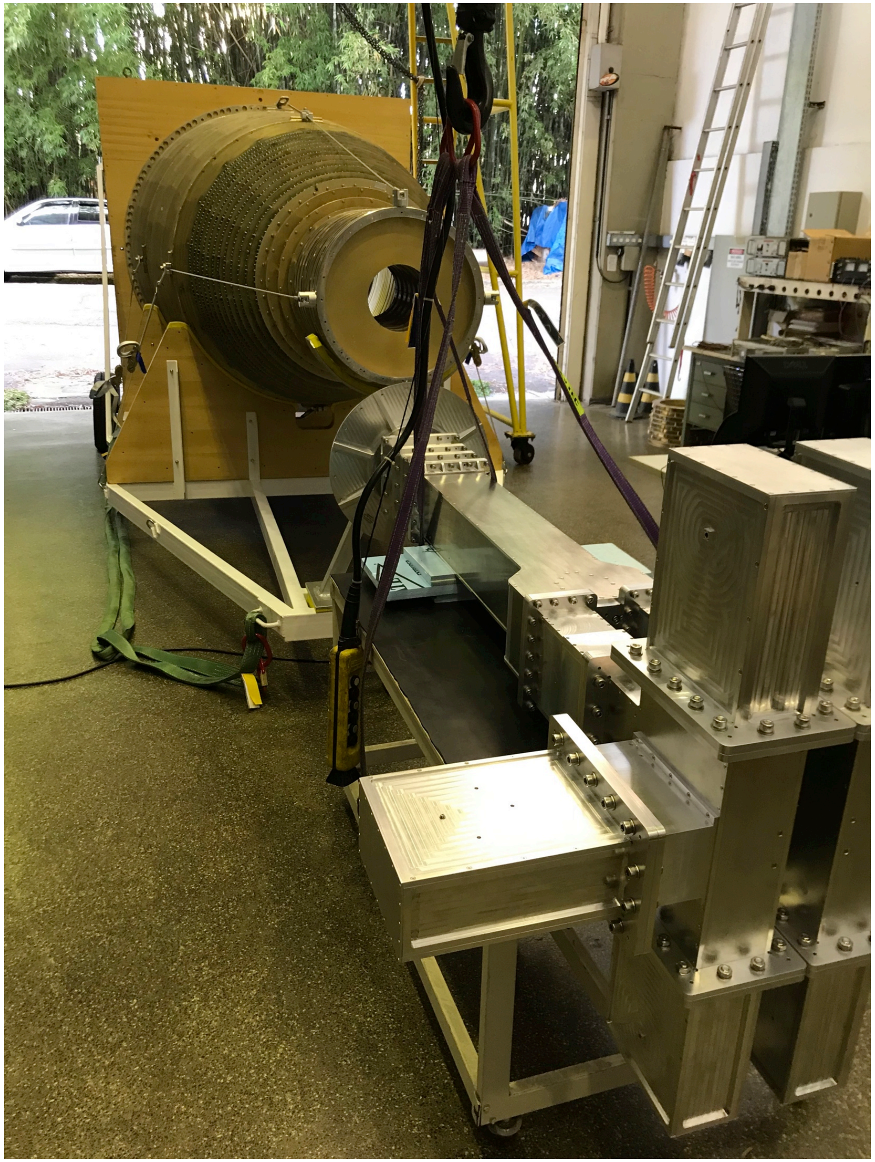


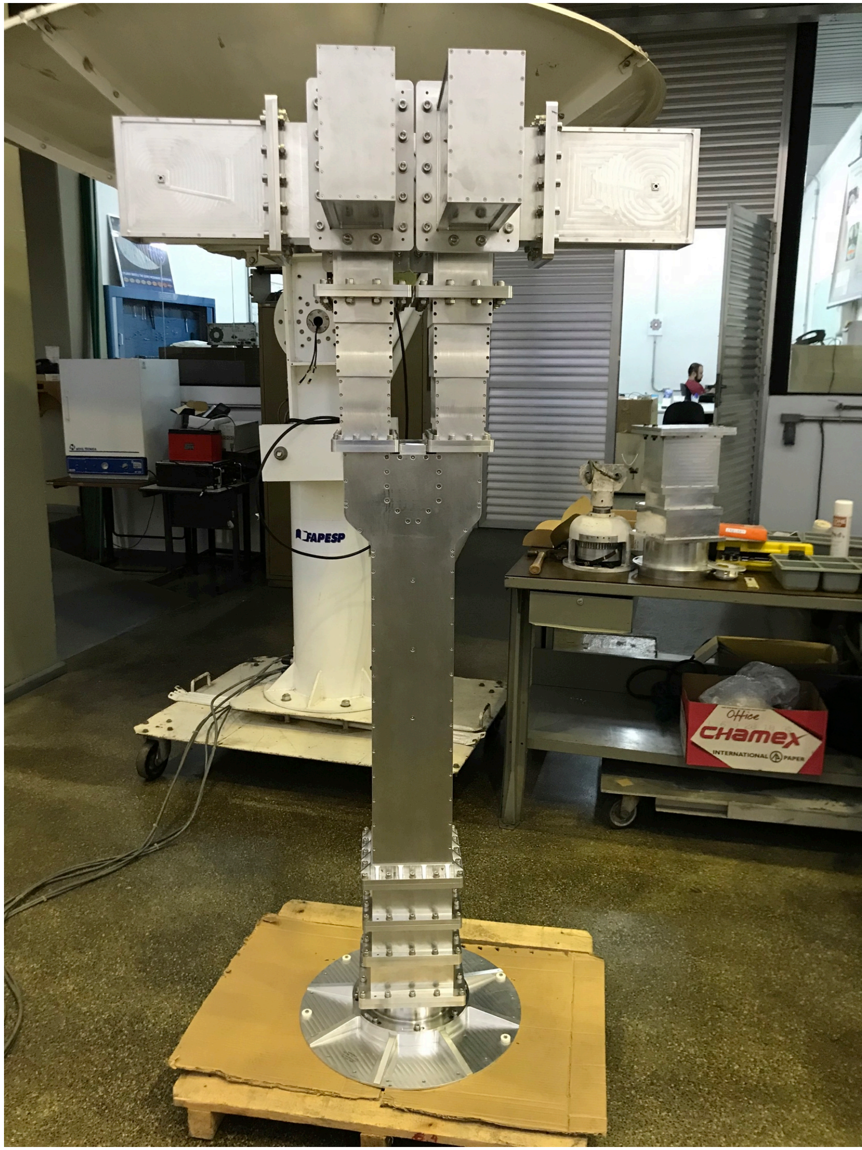


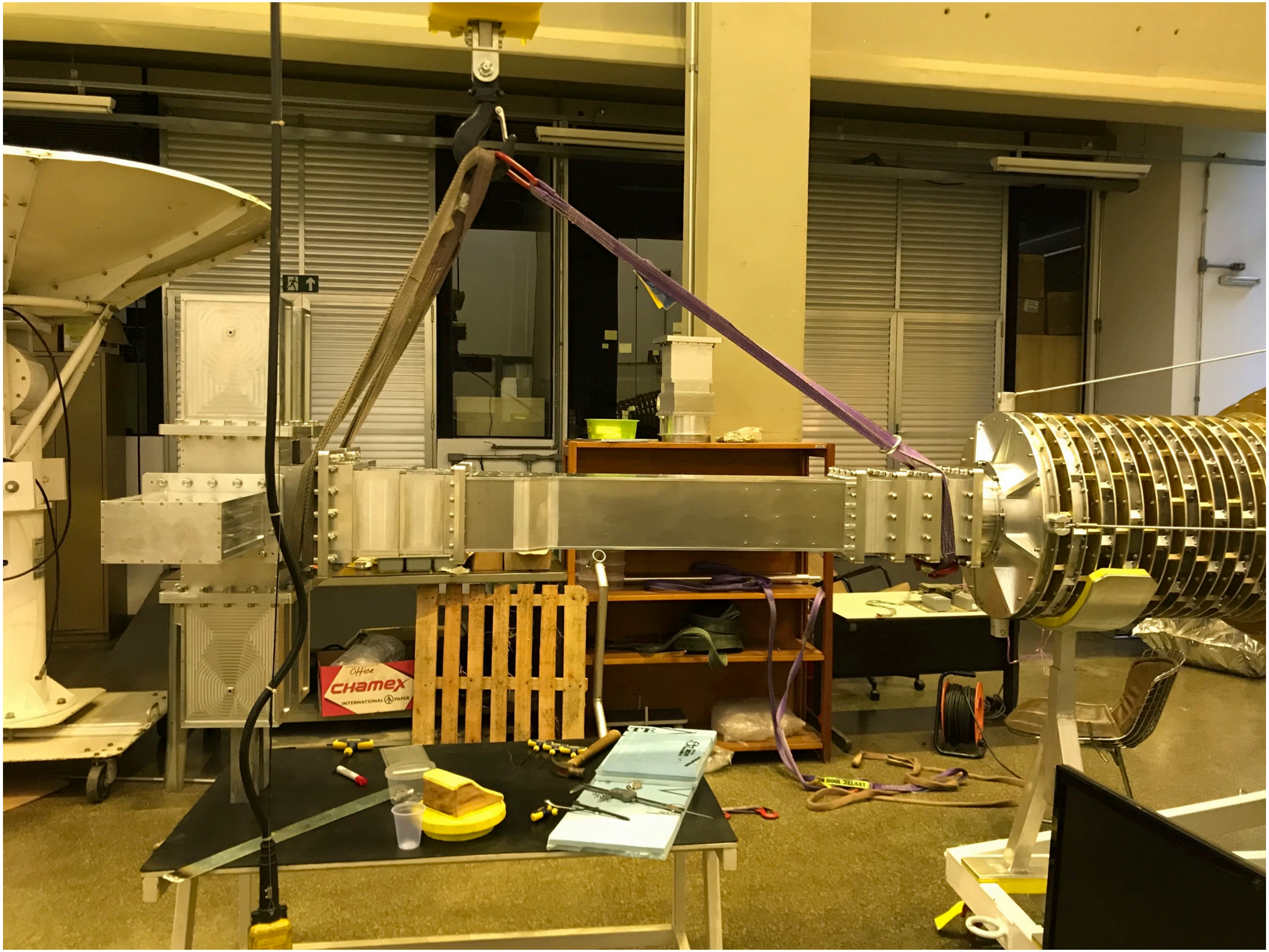



Crédito: L. A. Reitano






FAPESP
Chamex

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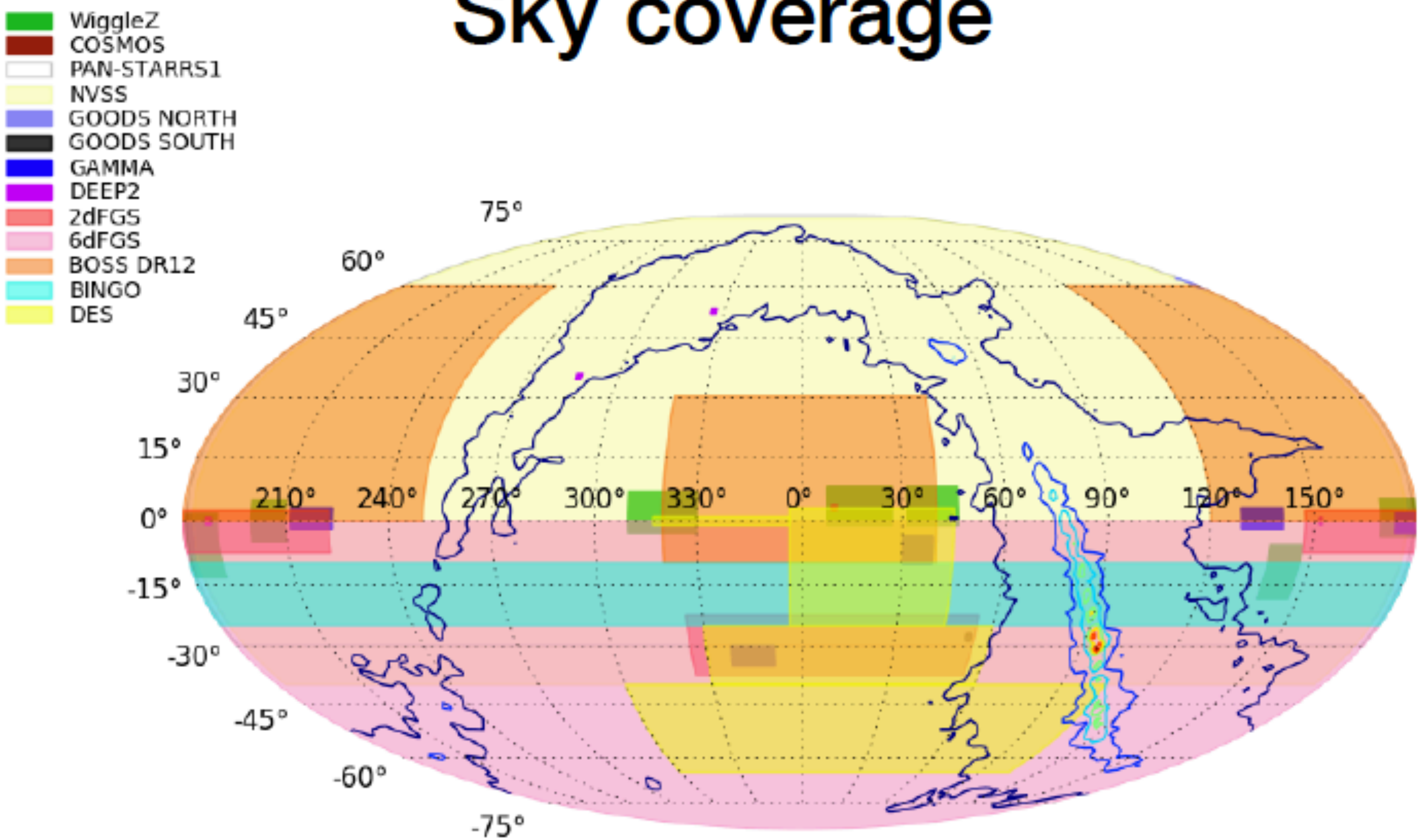
From Tianyue Chen

# Sky coverage

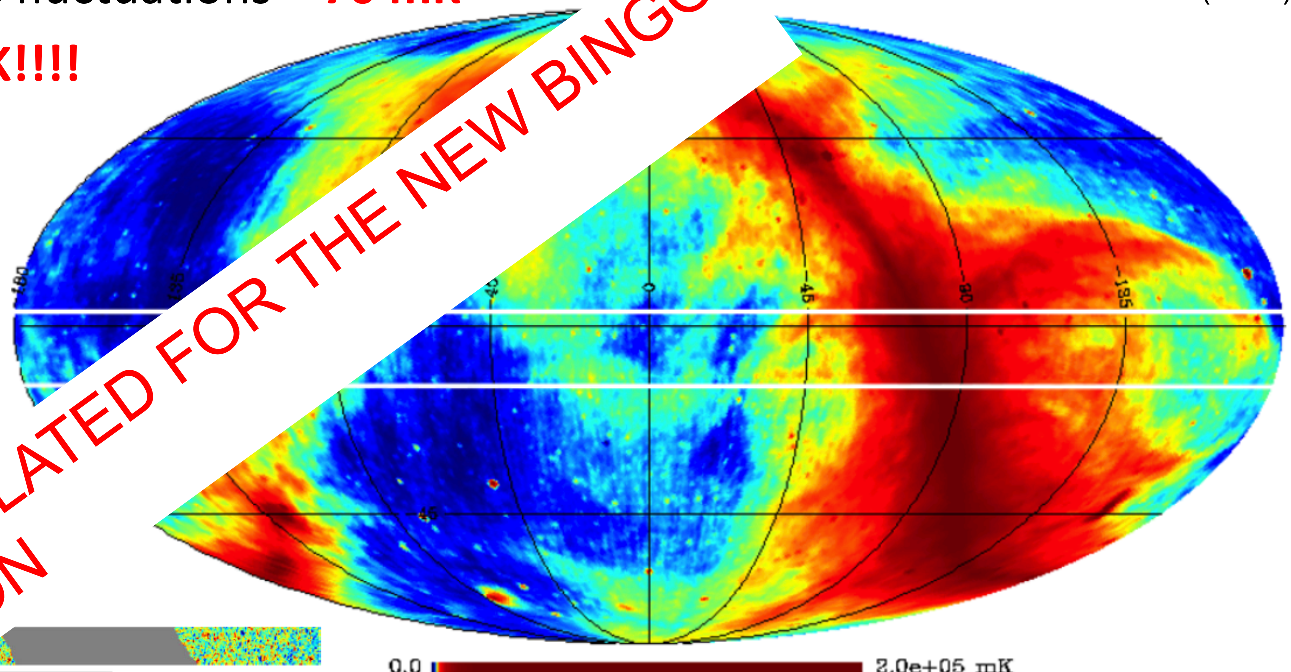


# FORECASTS: Foregrounds

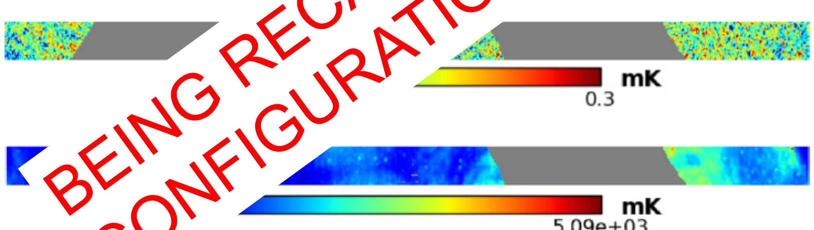
From Bigot-Sazy et al. (2015)

- Diffuse galactic continuum – mostly synchrotron and bremsstrahlung
- Expected smooth spectrum (should facilitate subtraction)
- Mean Galactic temperature @ 1 GHz ~ 5 K
- Expected Galactic fluctuations **~ 70 mK**
- **HI signal ~ 0.1 mK!!!!**

Improved 408 Mhz map (Haslam)
from Remazeilles et al. (2015)




**HI only**




**HI + Galaxy + unresolved point sources**

BEING RECALCULATED FOR THE NEW BINGO CONFIGURATION

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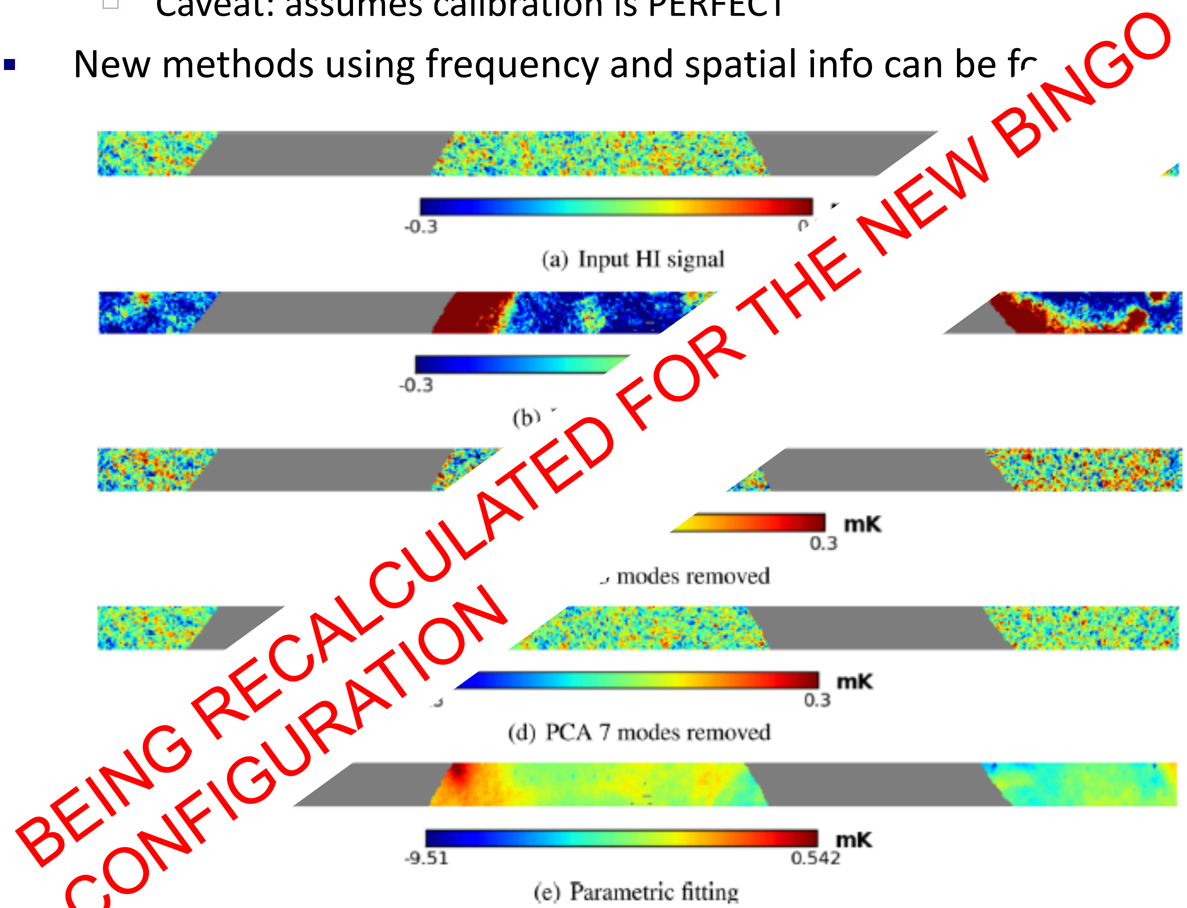
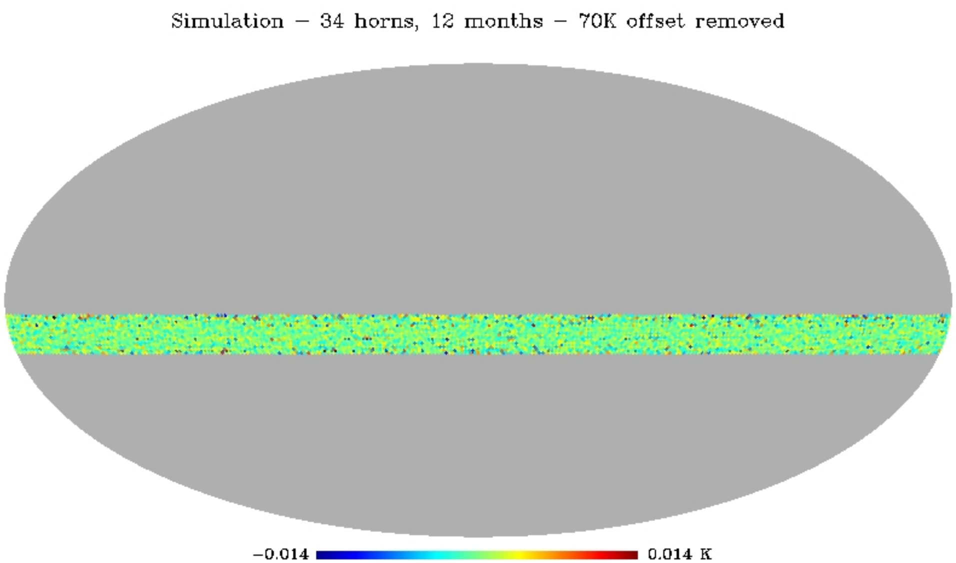
# FORECASTS: Component separation

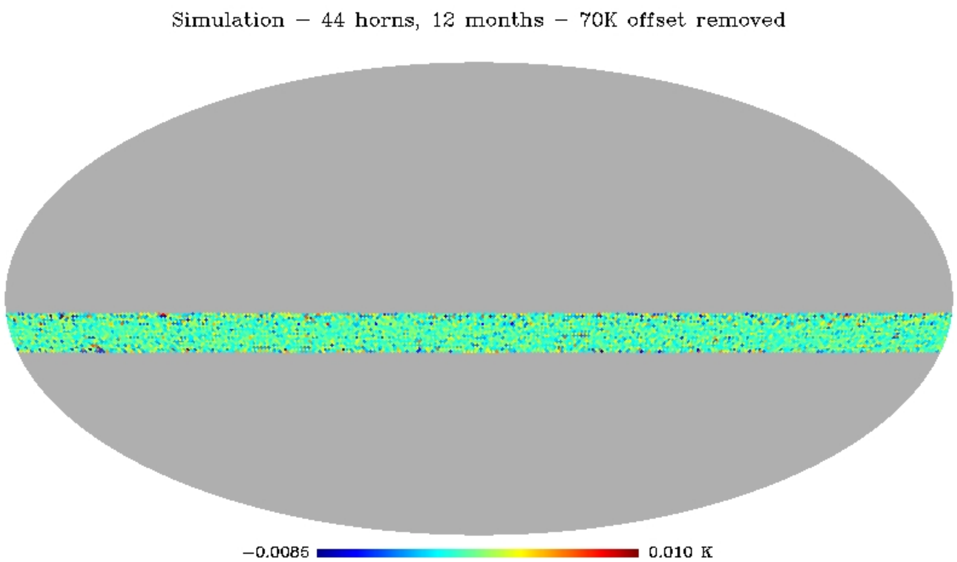
- Dominant foregrounds are expected to be spectrally smooth
- HI signal fluctuates in frequency, allowing for it to be extracted
- Simple PCA can do a remarkable job by removing the first few eigenmodes of the freq-freq covariance matrix
    - Caveat: assumes calibration is PERFECT
- New methods using frequency and spatial info can be fc ari et al. (2015)

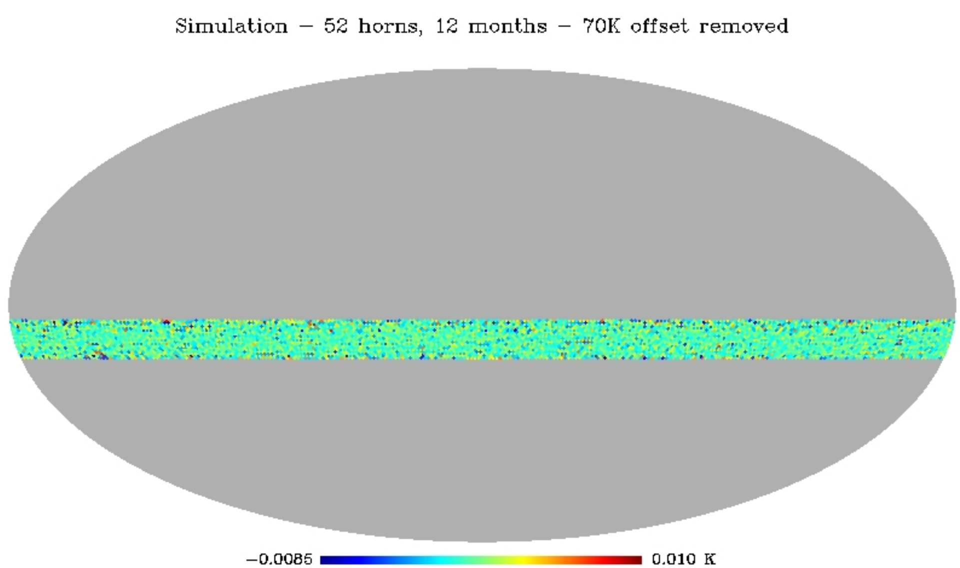



Bigot-Sazy et al. 2015

# Remodeling BINGO (2019)



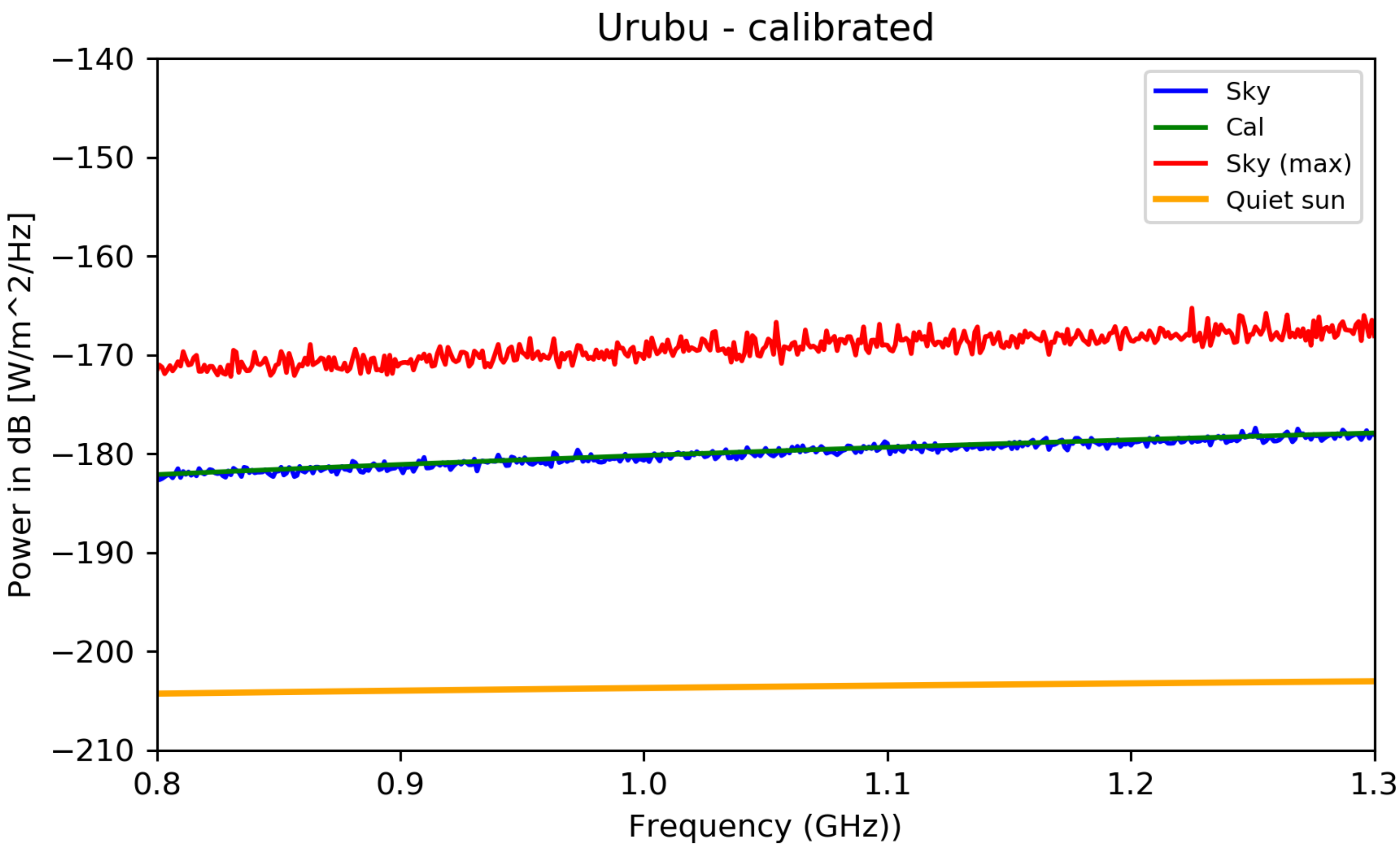
# More about BINGO related simulations on K. Fornazier's talk tomorrow

```
# Optics
focalLength : 63.2. # m
fwhm : 0.6677. # highest channel fwhm (degrees)
beamfile : gaussian
f0 : 1100 # MHz

[Telescope]
sampleRate                    : 10 # Hz
# Backend
nchannels : 30
maxFreq   : 12600e6 # Hz
minFreq   : 960e6 # Hz

[Observations]
mode : Continuous
ijd : 2458881.5 # init time
ejd : 2458891.5 # end time
elmax : 83.

[Fnoise]
noiseRatio : True
noisePower : 1 # power of noise at noiseFreq in Kelvin^2
noiseFreq  : 0.001 # Hz, at noiseFreq 1/f power = noisePower
dknee : None # Randomisations of 1/f noise
alpha : 1. # Temporal Correlations
cutoff : 1200000. # Time scale (seconds) for the longest frequency
1/f noise mode
beta : 1 # Frequency correlations (0 = Correlated, 1=Uncorrelated)
# Filtering of 1/f noise
filterScale : 360 # seconds
```

```
[Inputs]
# These let you choose if you want to generate TOD data
TOD          : True
Receiver     : True
Fnoise       : True
RFI          : False
SkyTOD       : False
Wnoise       : True

[Mapping]
# This Section need
Coords = 'Celestial'
Nside = 64    # HEALPix parameters
Order = 'Ring' # HEALPix parameters

[Synchrotron]
ancil_files      :
haslam408_dsds_Remazeilles2014_ns2048_Rotated.fits

[FreeFree]
ancil_files      : Te_COM_CompMap_freefree-
commander_0256_R2_Rotated.fits,
 electron_temp                : 7000 # K

[HI]
ancil_files      : HI_Powerspec.dat

[AME]
ancil_files      : Planck_map_t353_Rotated.fits
spdust_model                 : spdust2_cnm.dat
```

# Site selection

# Paraíba sites

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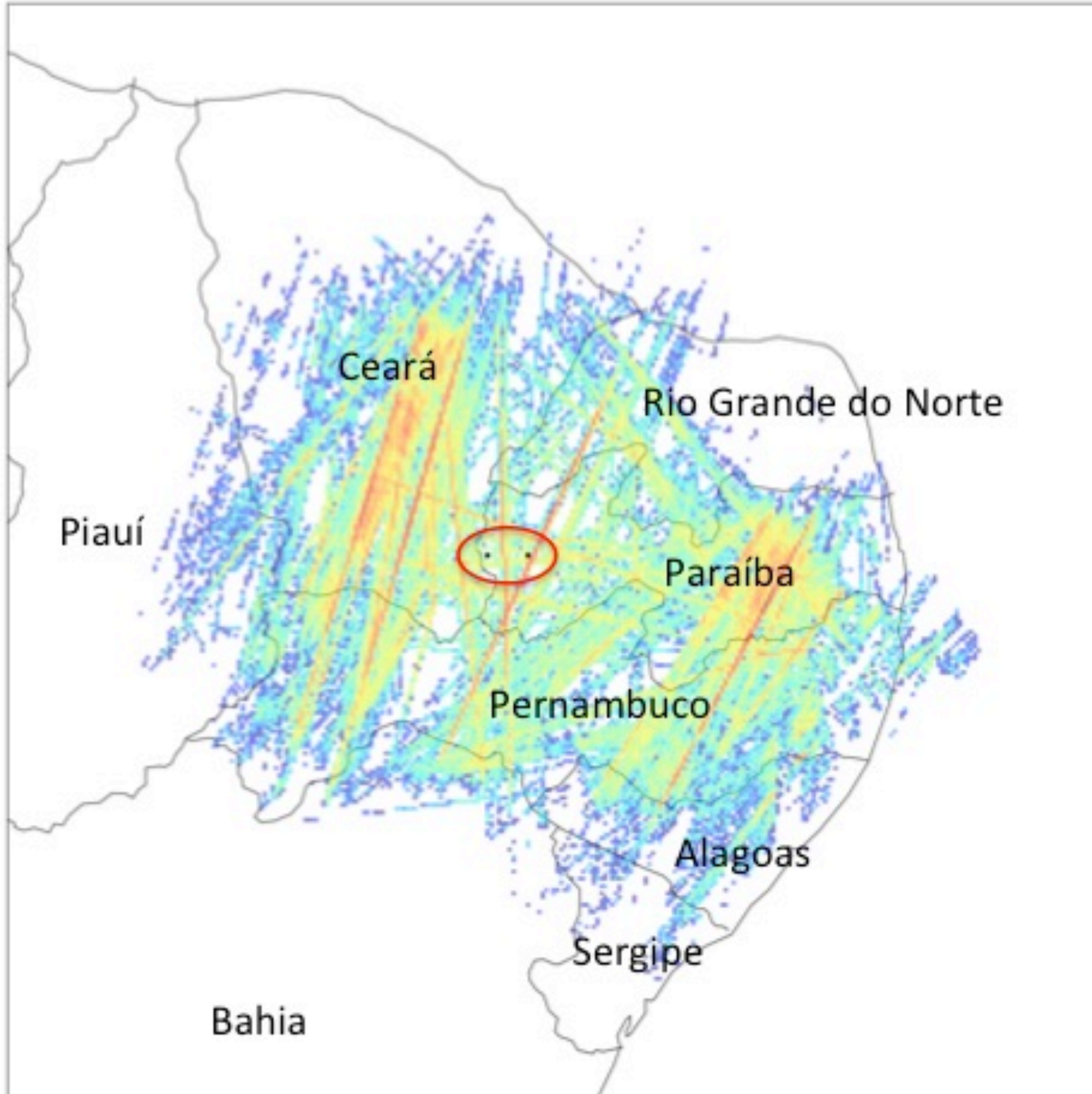
# Still concern about airplane coverage…




Peel et al (arXiv:1811.09464)

# And satellites….

Harper & Dickinson, arXiv:1803.06314

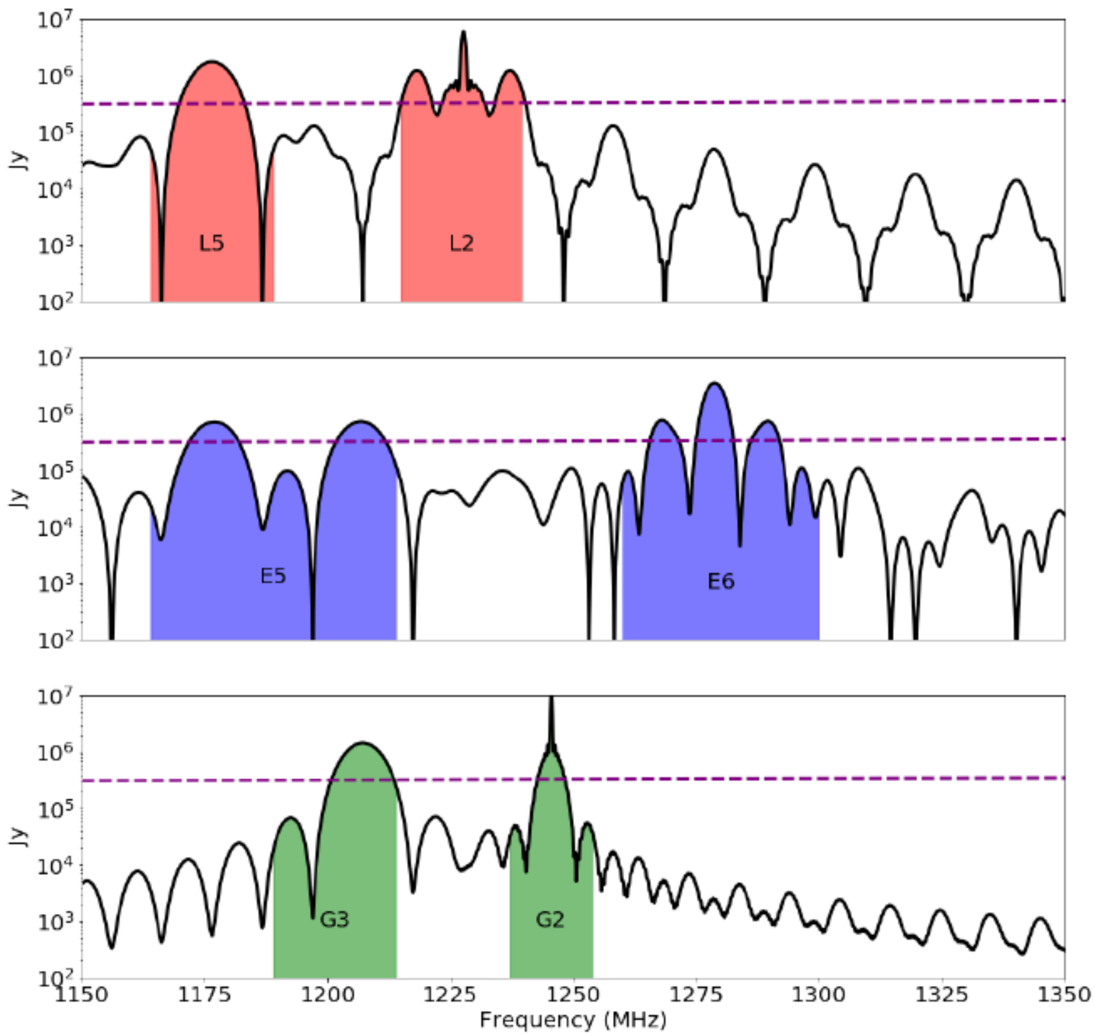
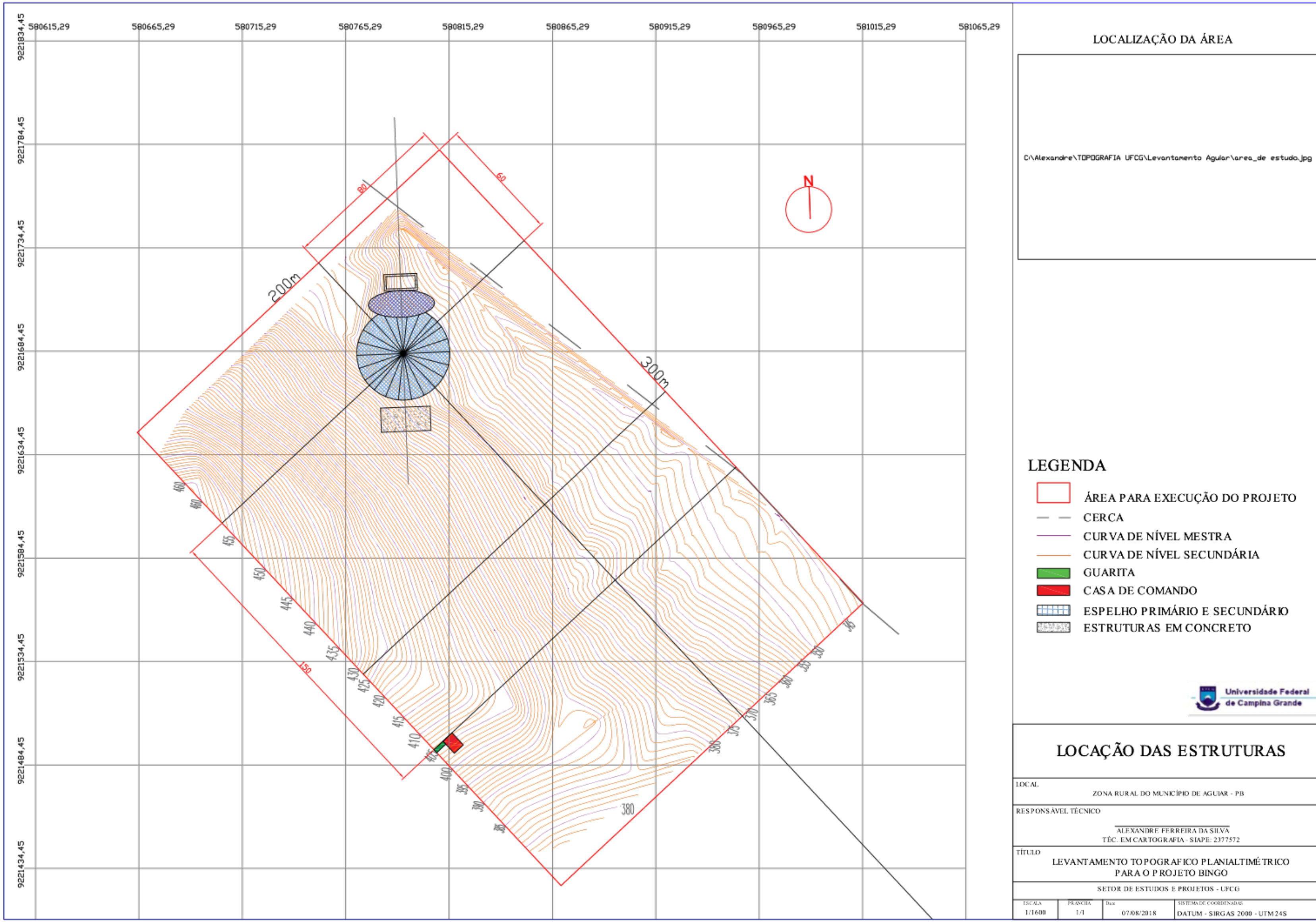



**Figure 3.** Typical spectral energy distribution as measured from the Earth of GNSS transmissions at frequencies less than 1410 MHz. The *top* plot shows the SED for GPS, the *middle* plot shows Galileo, and the *bottom* shows GLONASS. Highlighted regions in the SEDs represent the nominal frequency allocations for each service and service designation. GPS services are highlighted in *red*, Galileo in *blue* and GLONASS in *green*. Unhighlighted regions in the SED are the predicted out-of-band transmissions. The *dashed purple* line shows the expected integrated flux density of the quiet Sun for reference.

- Hard to get software solutions (no smooth spectrum)
- Hardware possible solutions:
  - cross-correlating data from auxiliary telescopes that are tracking GNSS satellites (Galt 1991)
  - hardware simulated GNSS signals (Ellingson et al. 2001) with data from the primary observing
  - phased array feeds (PAFs) can perform spatial filtering
  - to adaptively suppress transmissions from GNSS satellites (Hellbourg et al. 2012, 2014)
  - building a bespoke HI IM experiment and designing in strict requirements on beam sidelobe suppression such as with the BINGO telescope (Battye et al. 2013).

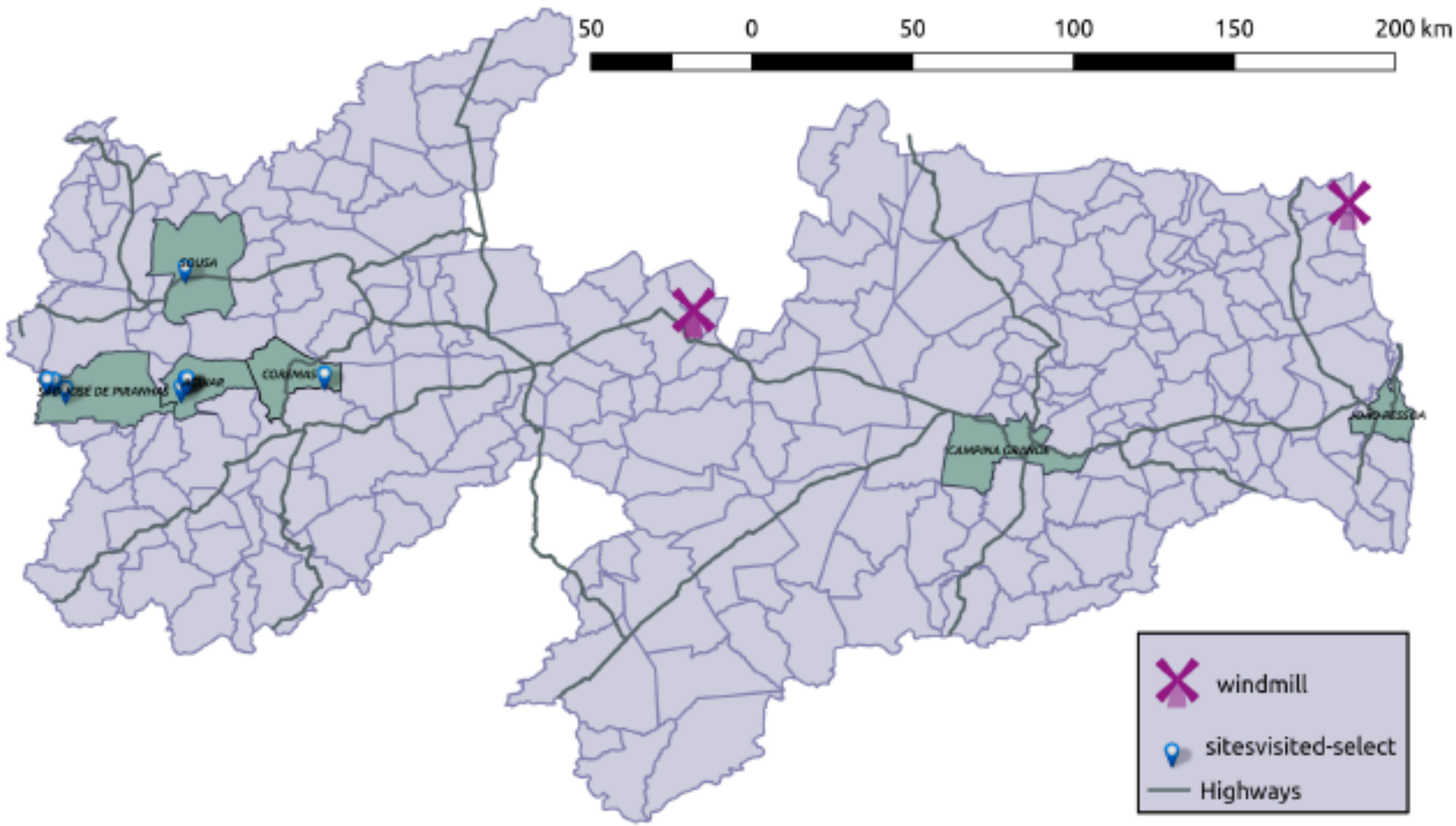









Credit: Andreia Souza

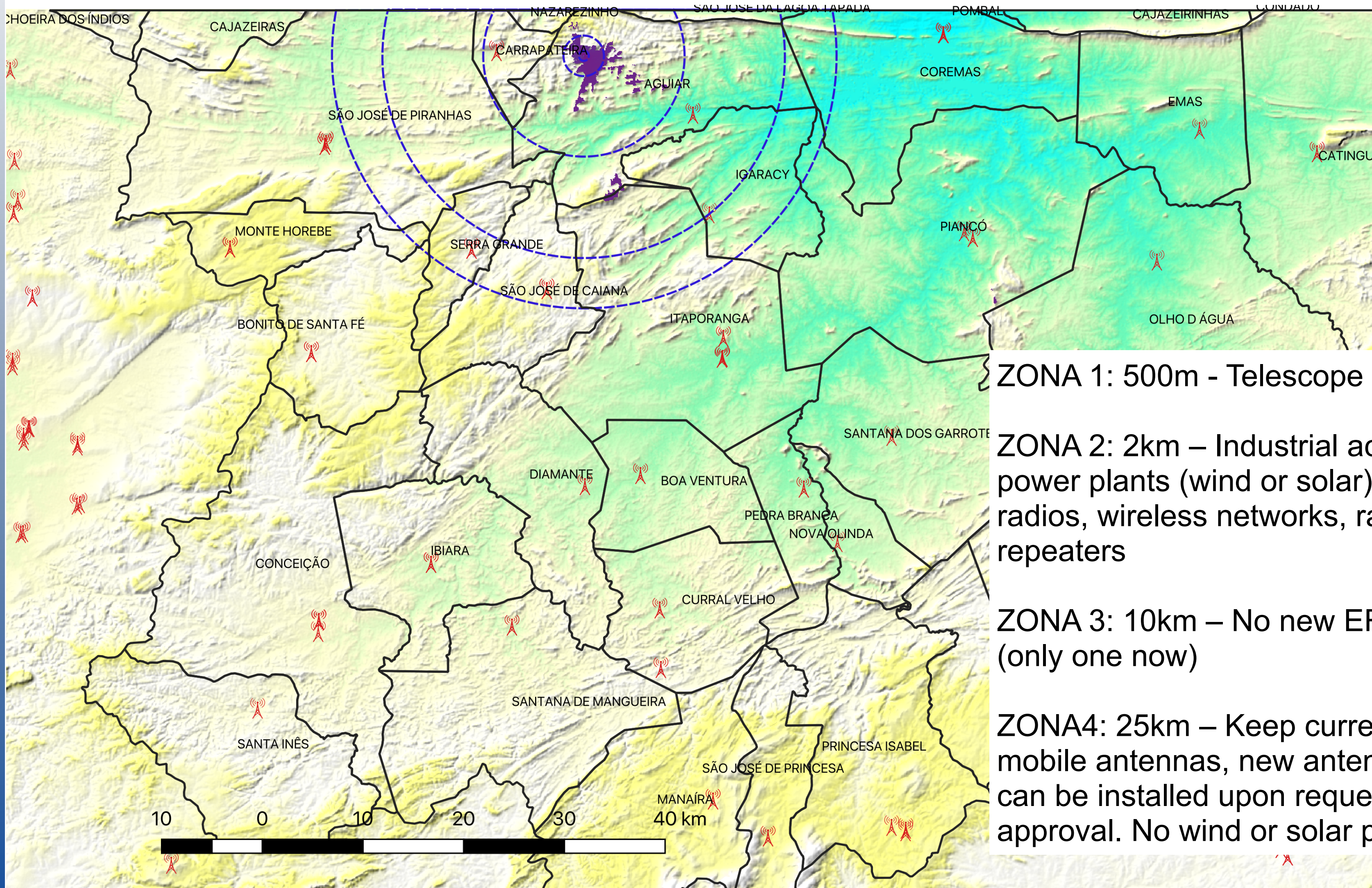



Peel et al (arXiv:1811.09464)

Serra da Catarina, Vale do Piancó (PB)
Lat: 07° 02’ 57.1” S
Long: 38°15’ 46"W

Photo: M. Peel

# Silence zone proposal (discussions with Anatel started October 2018)




ZONA 1: 500m - Telescope only

ZONA 2: 2km – Industrial activities, power plants (wind or solar), radios, wireless networks, radio repeaters

ZONA 3: 10km – No new ERB (only one now)

ZONA4: 25km – Keep current mobile antennas, new antennas can be installed upon request & approval. No wind or solar plants.

Credit: L. Barosi

# Additional science with BINGO

(We will have an ultra-deep large-area spectral survey at 960-1260 MHz)

- BAOs contain additional information
  - Matter density
  - Redshift distortions
  - Anisotropic BAOs…
- Life history of hydrogen
- Radio recombination lines
- Galactic continuum
- And, of course, **FRBs**, which will be a natural project for this kind of telescope.

# Main difficulties – as of January 2019

- Large telescope → **need to find a company to fabricate the dishes**
- Large horns → **fabrication process understood, need to reduce costs for 50**
- Calibration and stability → **use colfets and a CW source as internal calibration, sky radio sources for external calibration**
- Stability → **has to be tested with internal cooling and later, under the hot environment temperature in Paraíba**
- Sidelobe pick-up → **careful optical design (horn testing showed quite good rejection for 1st/2nd lobe and front/back lobe rejection; optics simulations show very small distortions of the beams in the current horn array)**
- Radio Frequency Interference → **Mobile quiet zone has been already requested to the state authorities**
- Bright foreground emission→ **Component separation techniques (alla Planck)**
    - **Diffuse Galactic radio emission**
    - **Extragalactic point sources**
    - **Different methods need to be tested (PCA, ICA, GNILC, SVD…?)**

# BINGO

## BAOs from Integrated Neutral Gas Observations

FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO (FAPESP)

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA, INOVAÇÕES E COMUNICAÇÕES
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS (INPE)

USP

Universidade Federal de Campina Grande (UFCG)

The University of Manchester

UCL

ETH Zürich

Yangzhou University

IAS Orsay

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UNIVERSIDAD DE LA REPÚBLICA URUGUAY

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# Thank you!