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

The BINGO radio telescope:
an instrument to explore the Universe in the 21cm wavelength

Carlos Alexandre Wuensche and the BINGO Collaboration[1]

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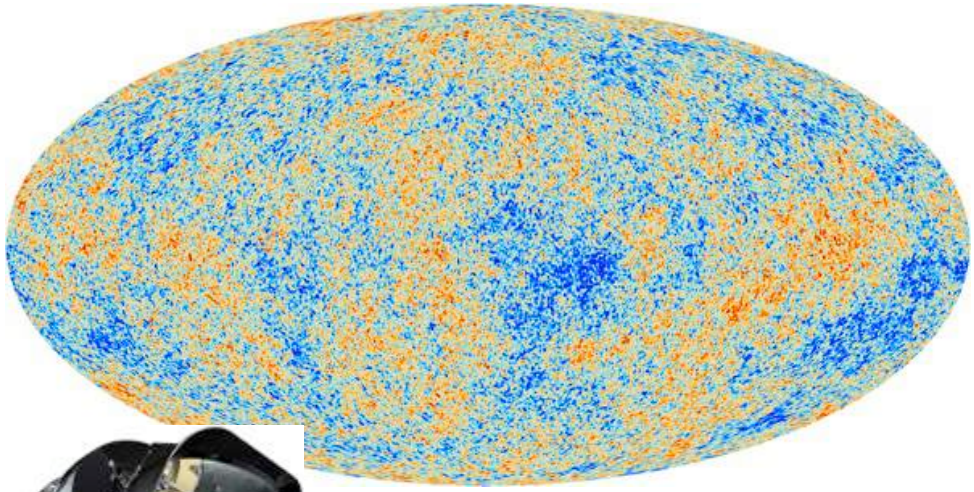
South American Workshop on Cosmology in the LSST Era

December 17-21, 2018

[1]www.bingotelescope.org

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?



CMB map from Planck collaboration et al. (2016)

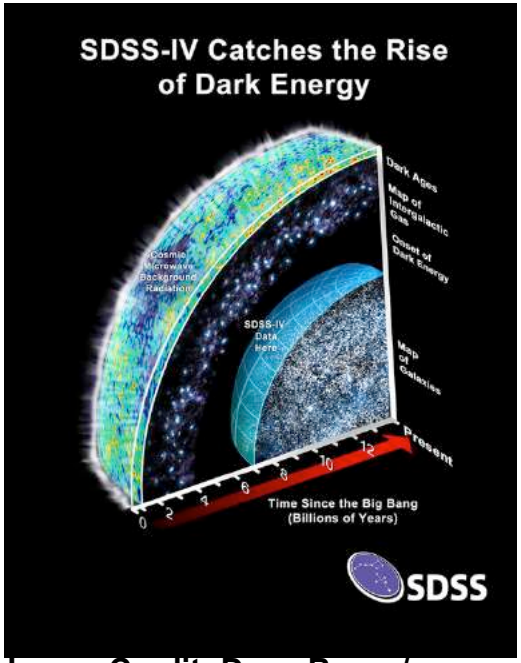


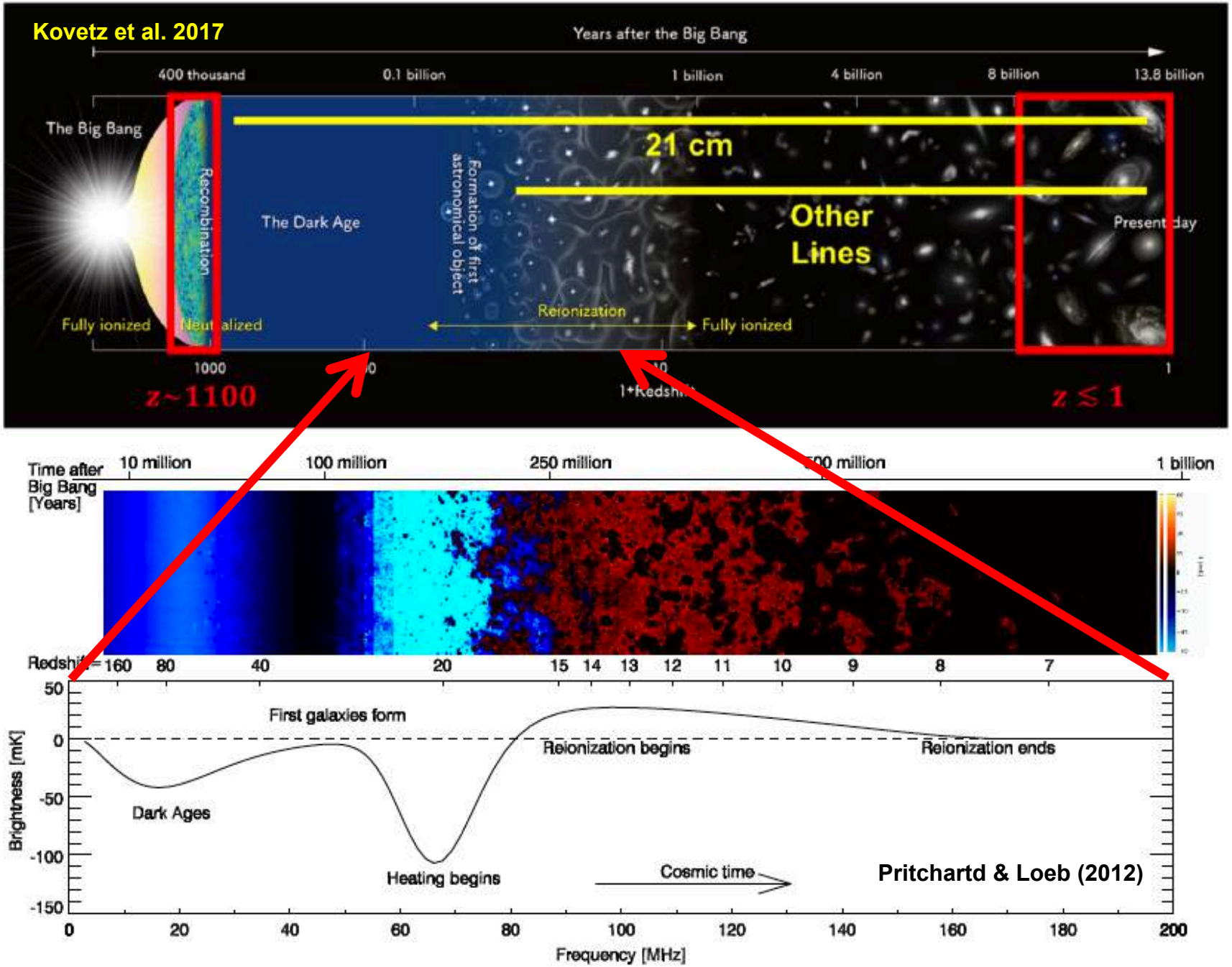
Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.

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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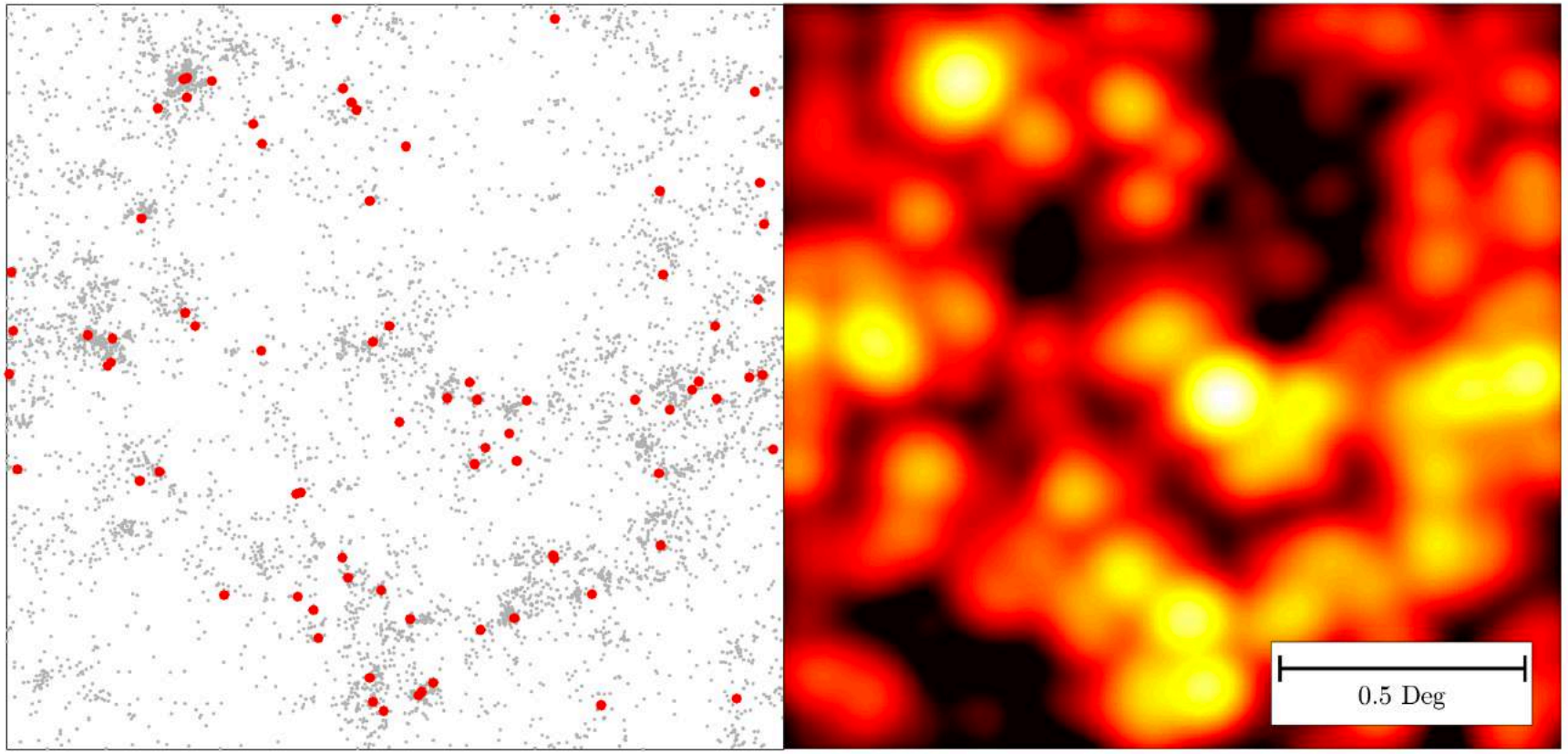
The intensity mapping concept

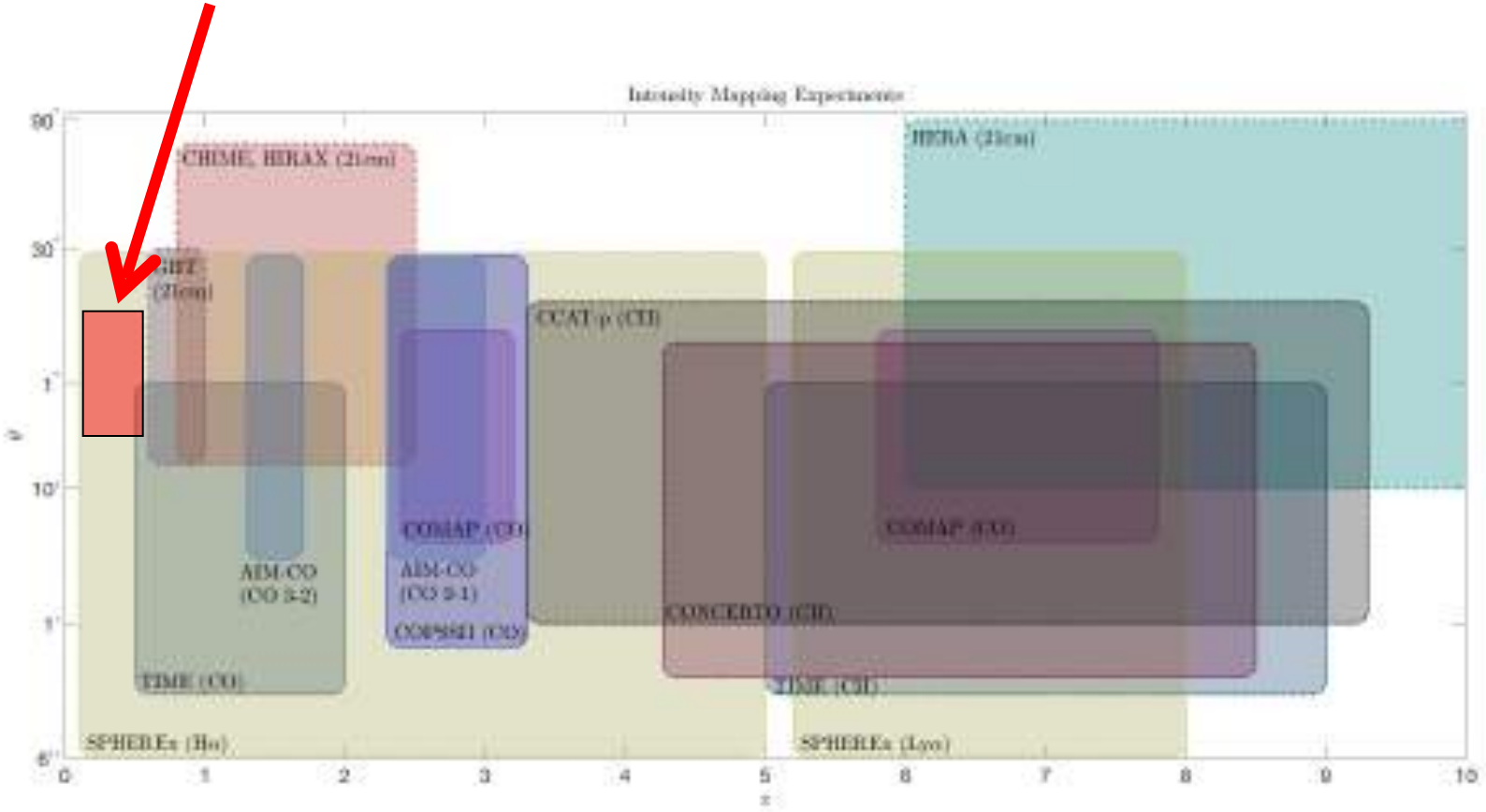
Measure the large scale features from the integrated emission of galaxies + IGM, from spectral line of different elements (H, C, O, …), not worrying about individual objects



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

Kovetz et al, (arXiv:1709.09066)

BINGO would fit here (and is now an update of pag. 44 of Kovetz et al (2017)



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Temperature x matter fluctuations

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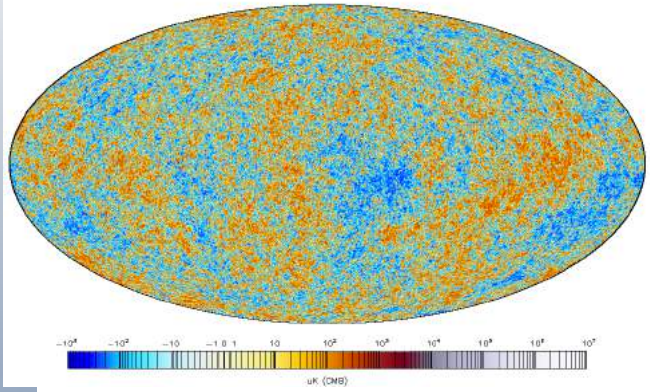

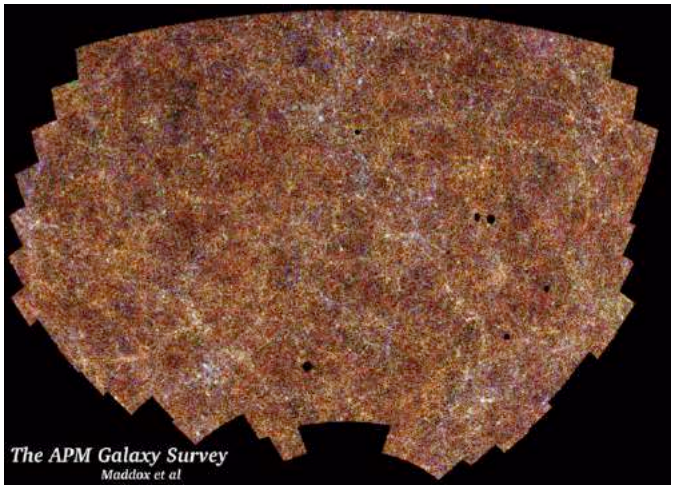

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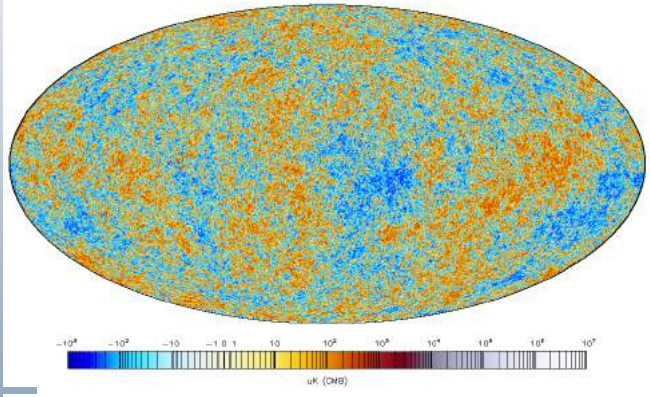

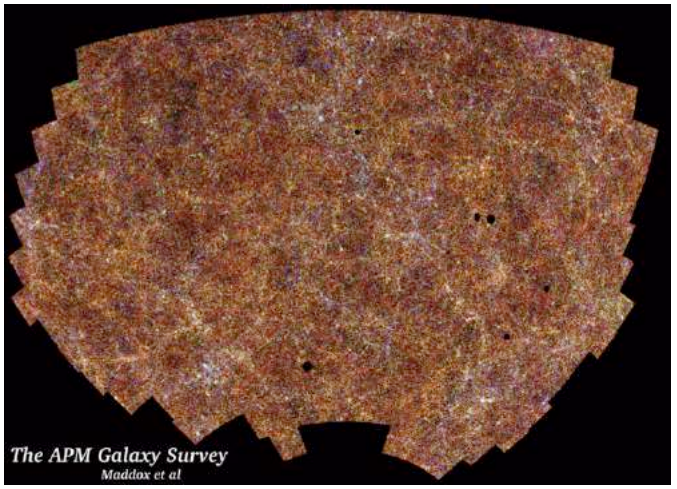

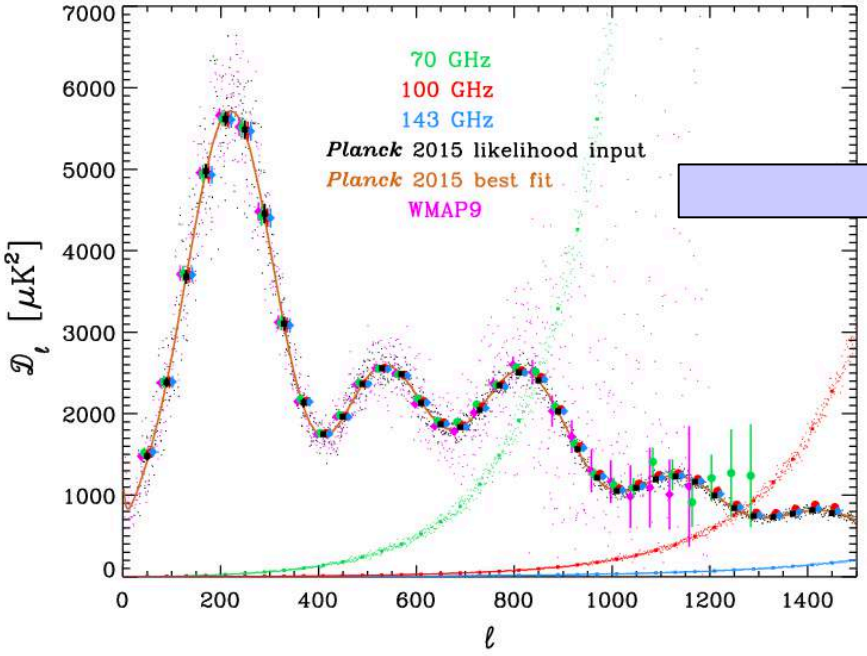

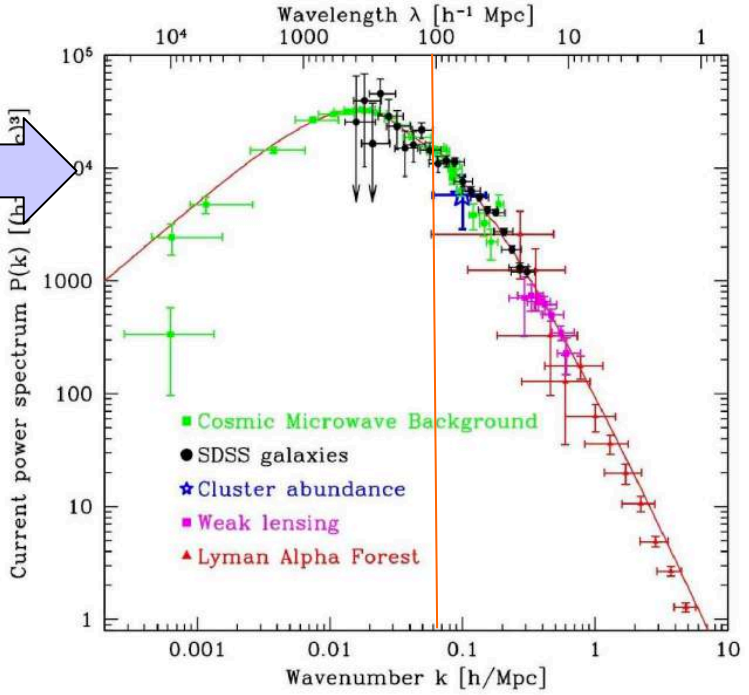

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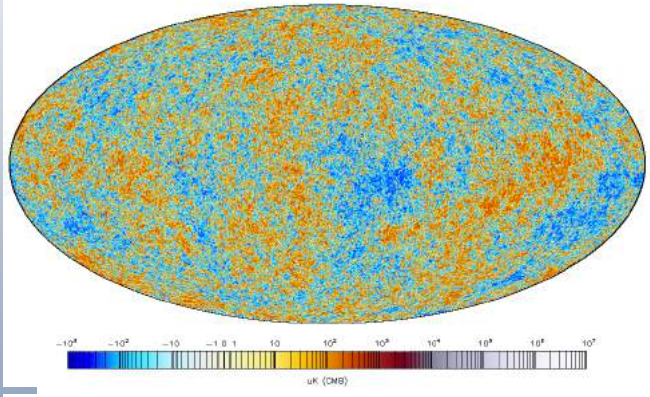

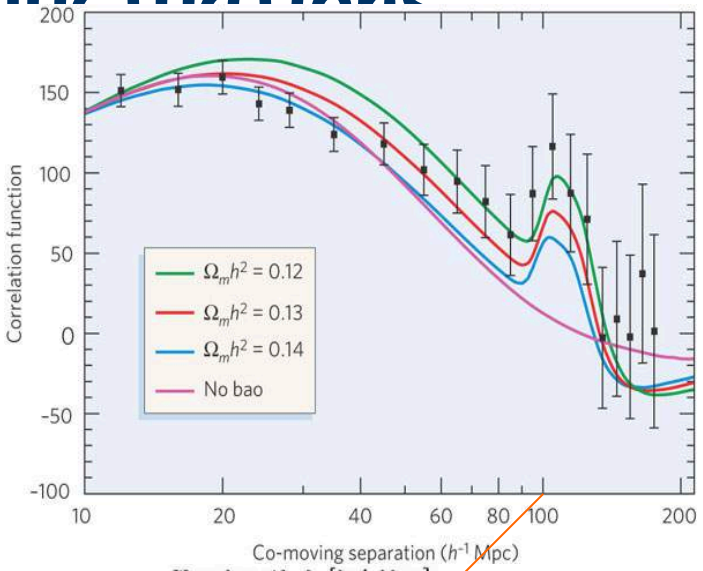

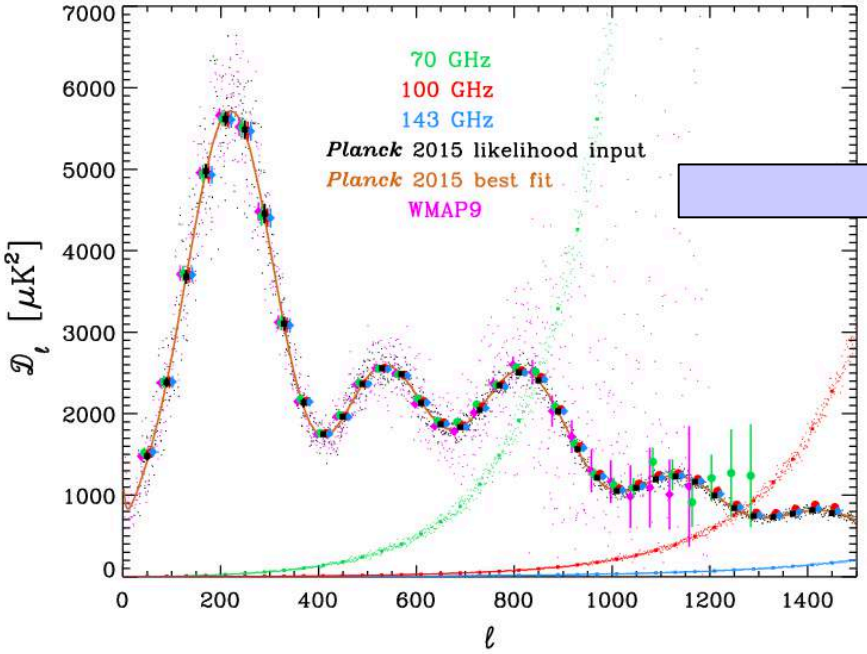

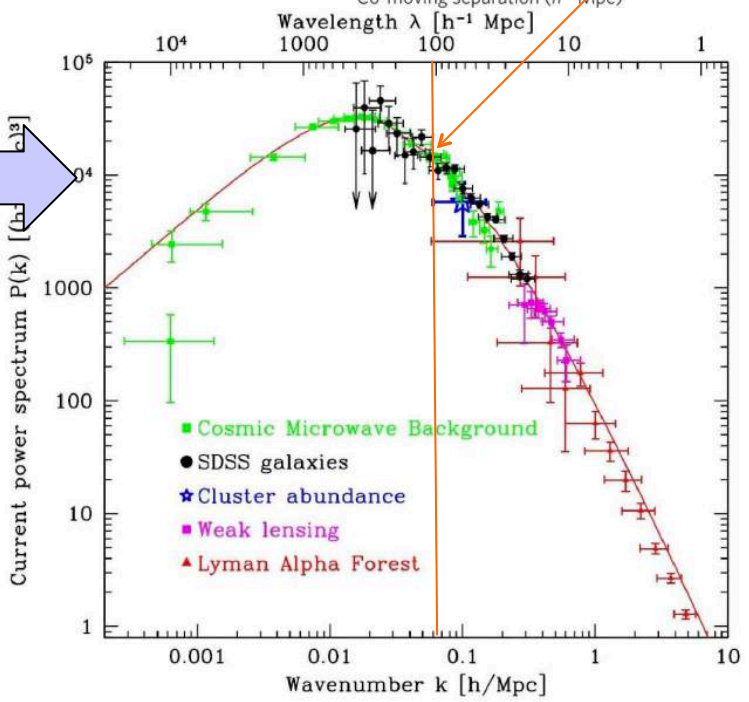

Baryon Acoustic Oscillations (BAOs)

- 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)

- 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

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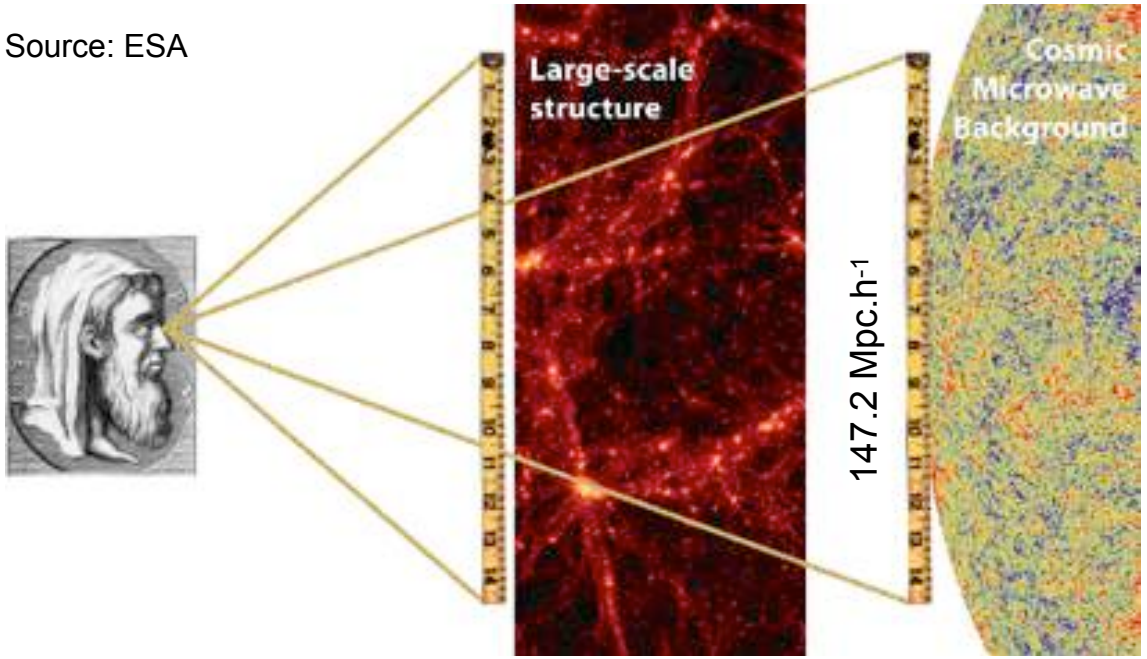
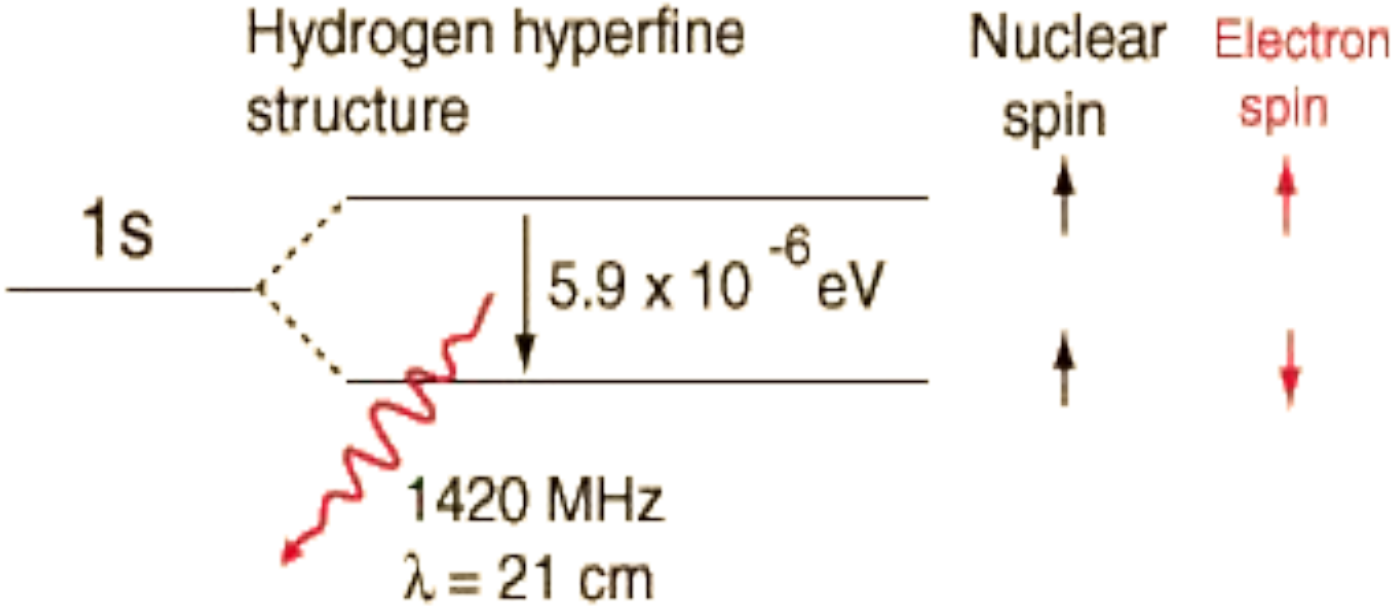
Source: ESA



Why BAO in radio?



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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

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 => $z \approx 0.93$

Adapted from Bull et al. 2015

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  - 100 MHz => $z \approx 0.93$ Lots of RFI in this frequency range

Adapted from Bull et al. 2015

The BINGO Telescope

BINGO concept (as of June 2018)

Instrument characteristics

- Dish diameter : 45m and 38m
- Resolution (°): ~ 0.67
- Horn opening (°): ~ 25
- Frequency range (MHz): 960 – 1260
- Channel resolution ~ 1 MHz
- Z interval: 0.13 - 0.48

Instrument characteristics

- Number of feeds : 50 (dual pol.)
- Horn largest diameter: 1.9m
- Horn length: 4.3m
- Focal plane size: 19m x 9,5m
- Estimated scan area: ~ 5000□
- No cryogenics : $T_{sys} \approx 50K$

Fixed wire-mesh parabolas

No moving parts

Transit telescope

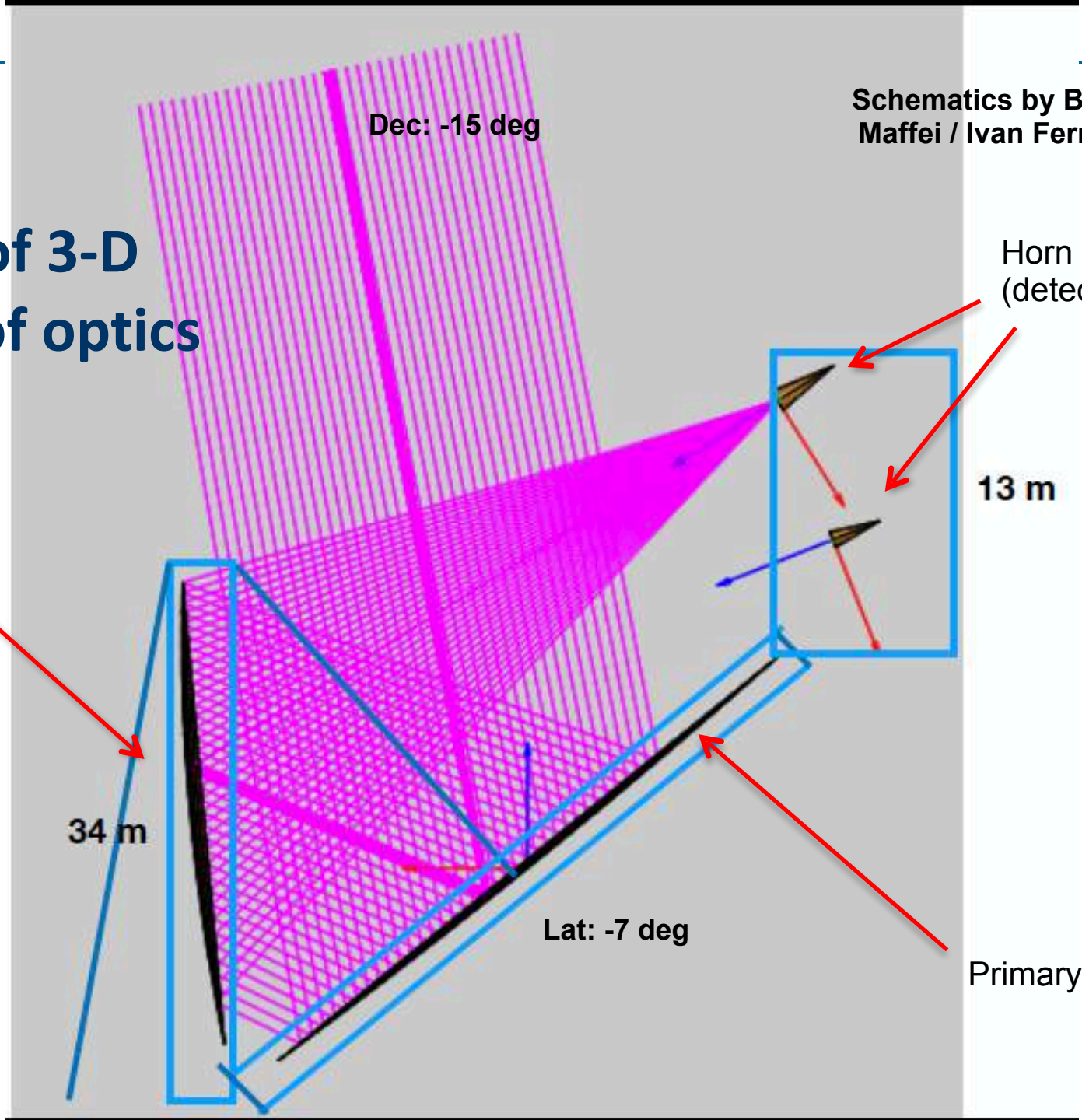
Most components "off-the-shelf"

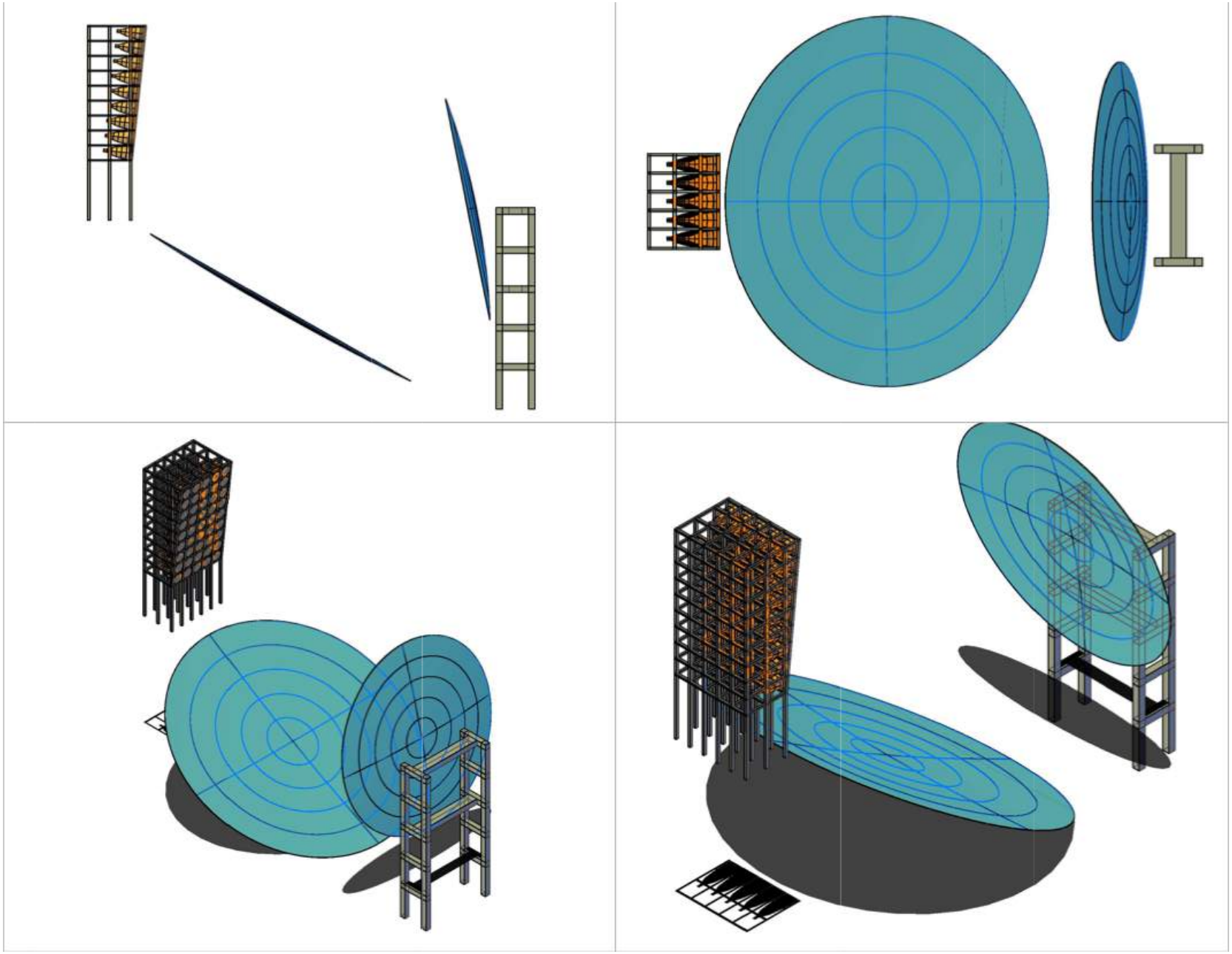
Guiding principle : simplicity !

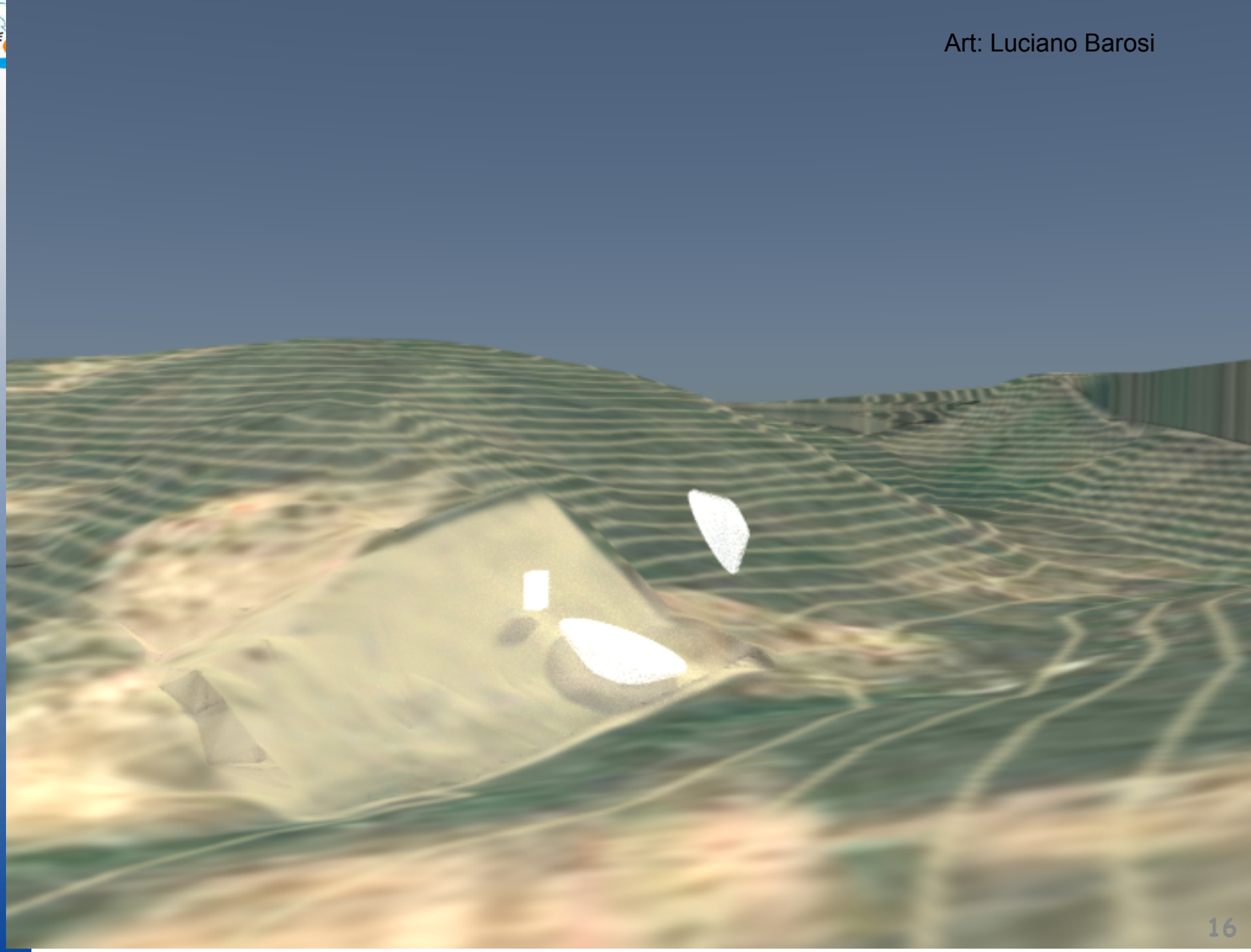
Project status

- 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

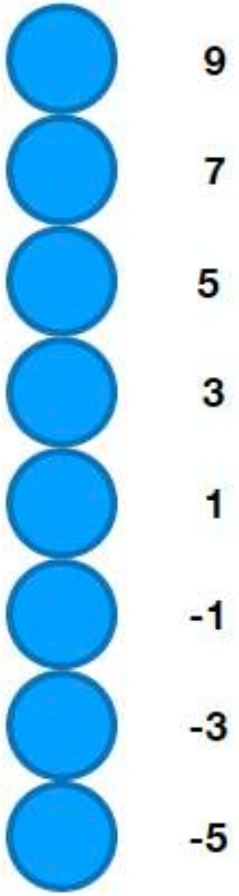


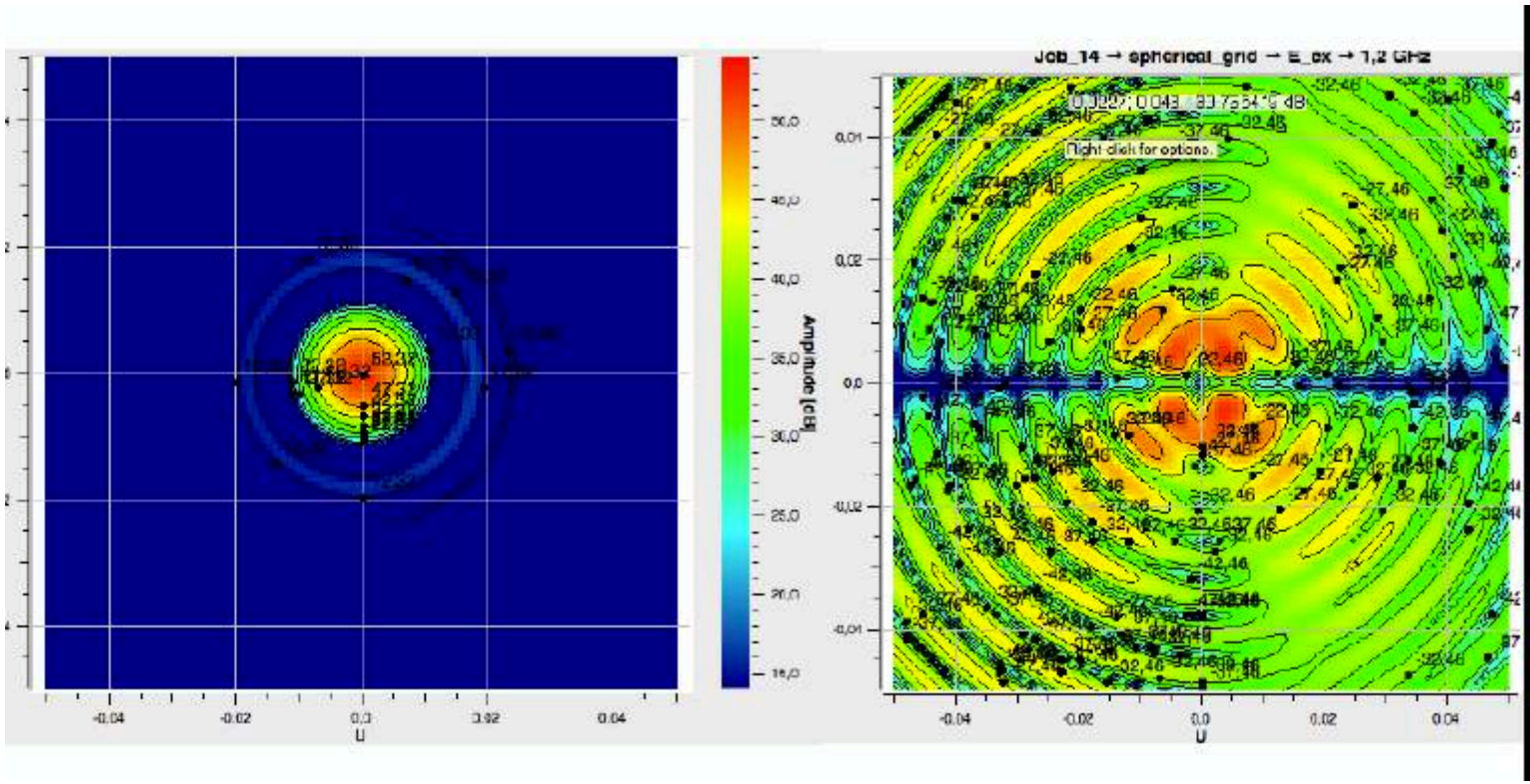



Art: Luciano Barosi

Central Pixel

Schematics by Bruno Maffei / Ivan Ferreira





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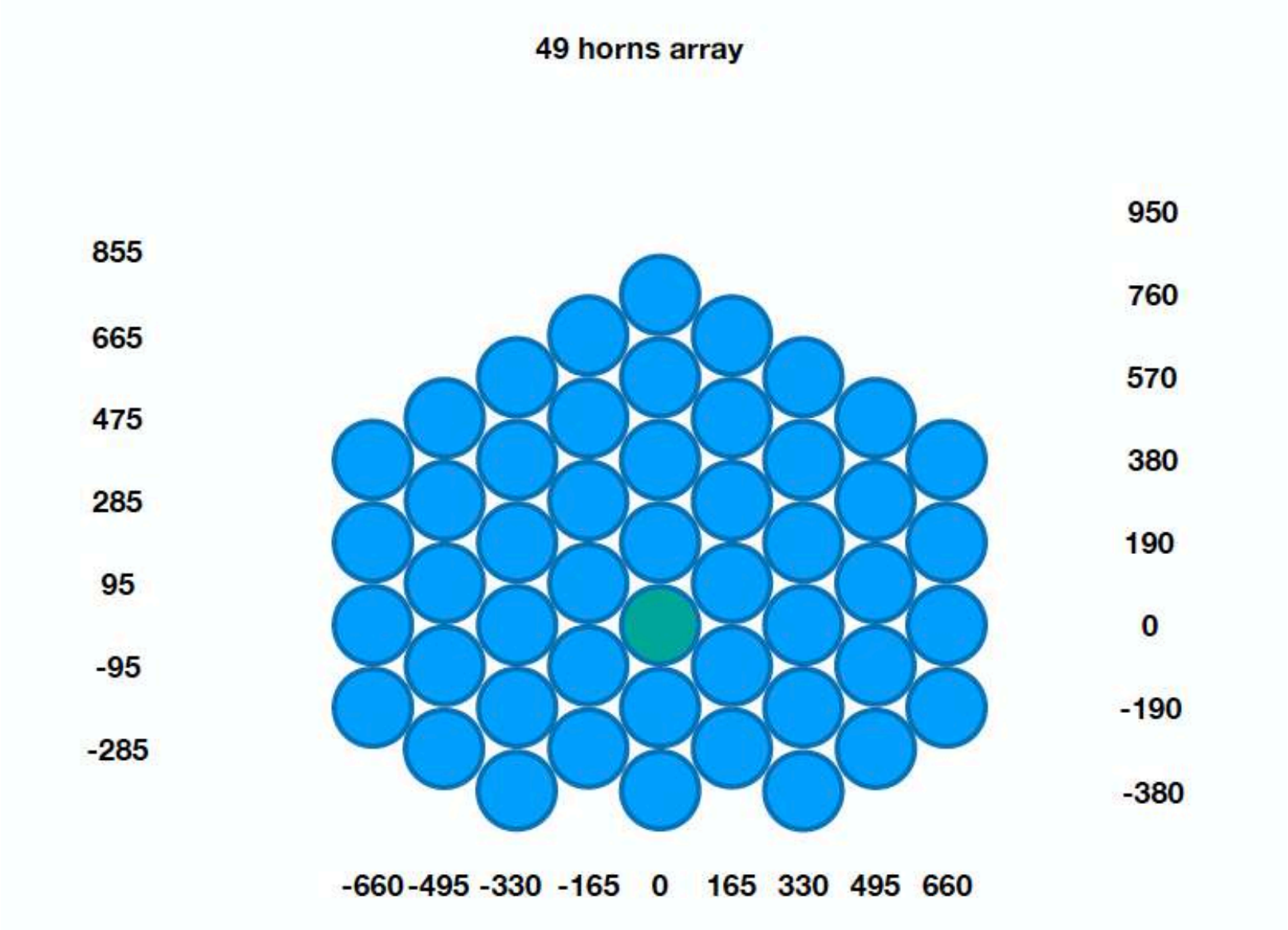
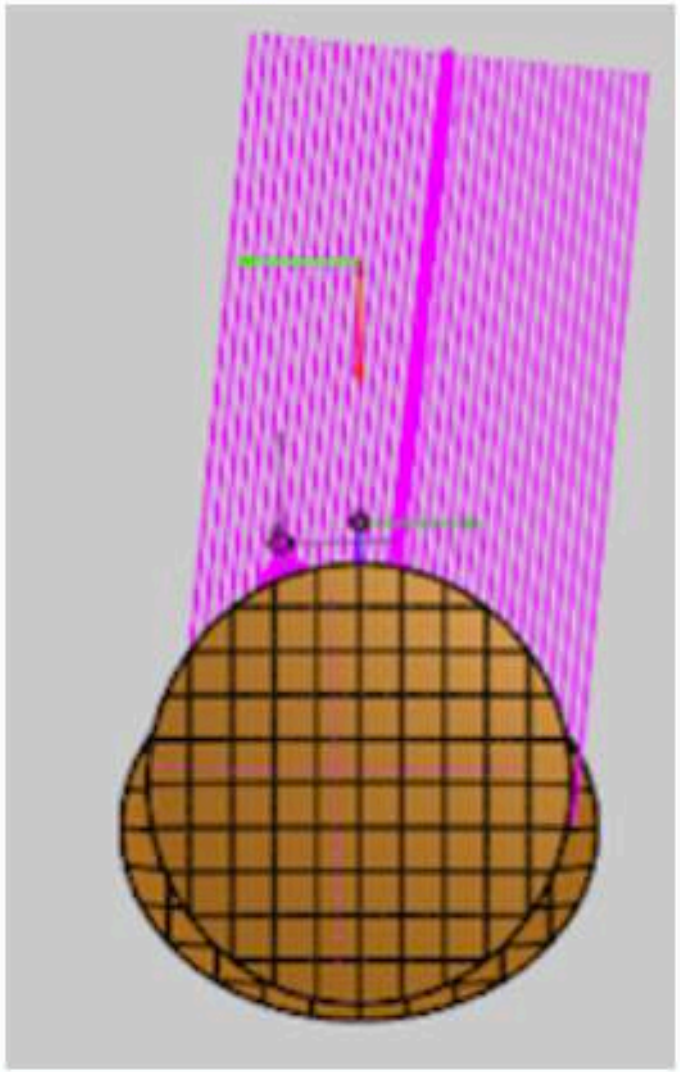
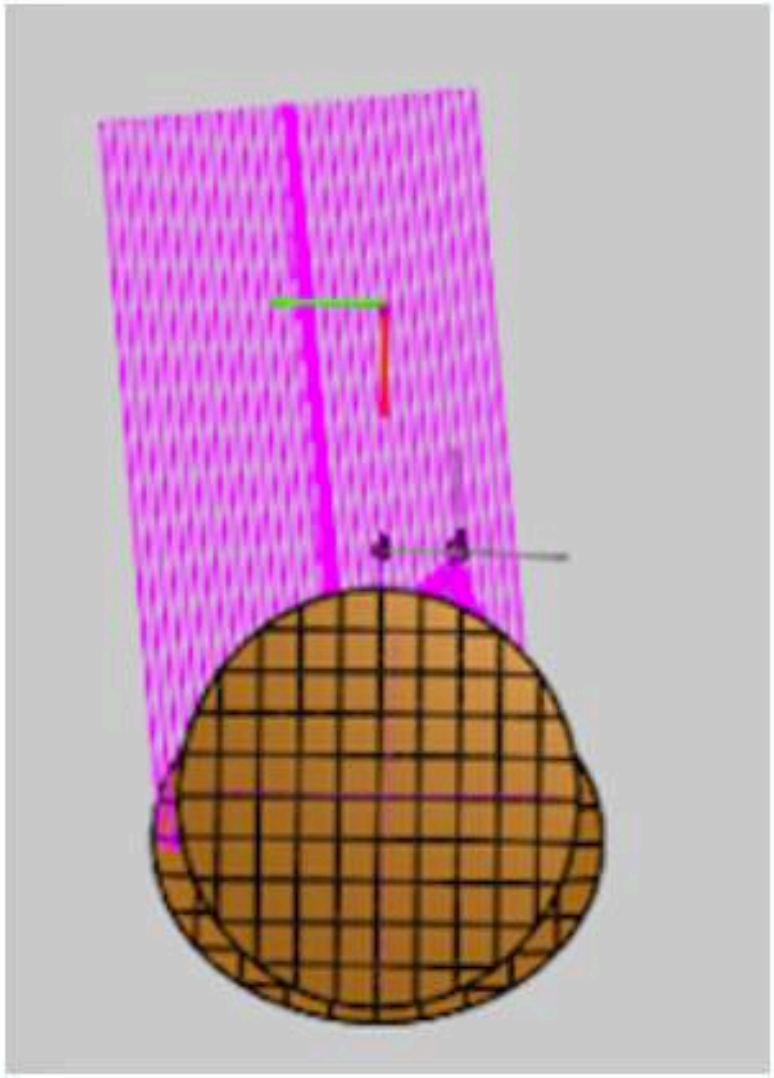


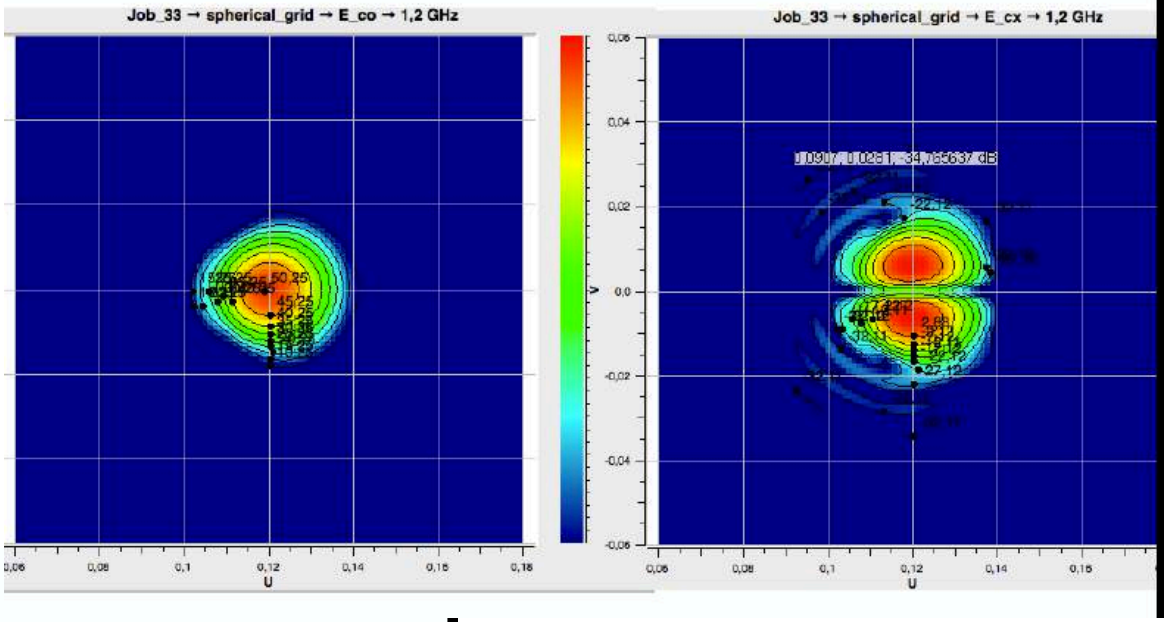
Beam -660 and 660

Schematics by Bruno Maffei / Ivan Ferreira

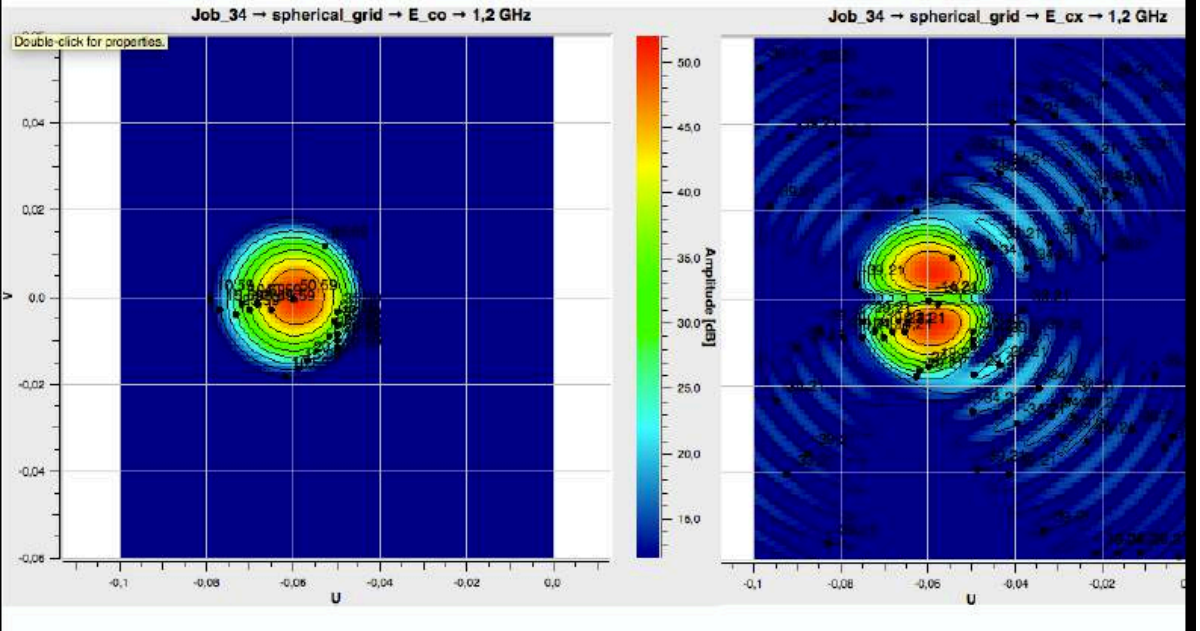




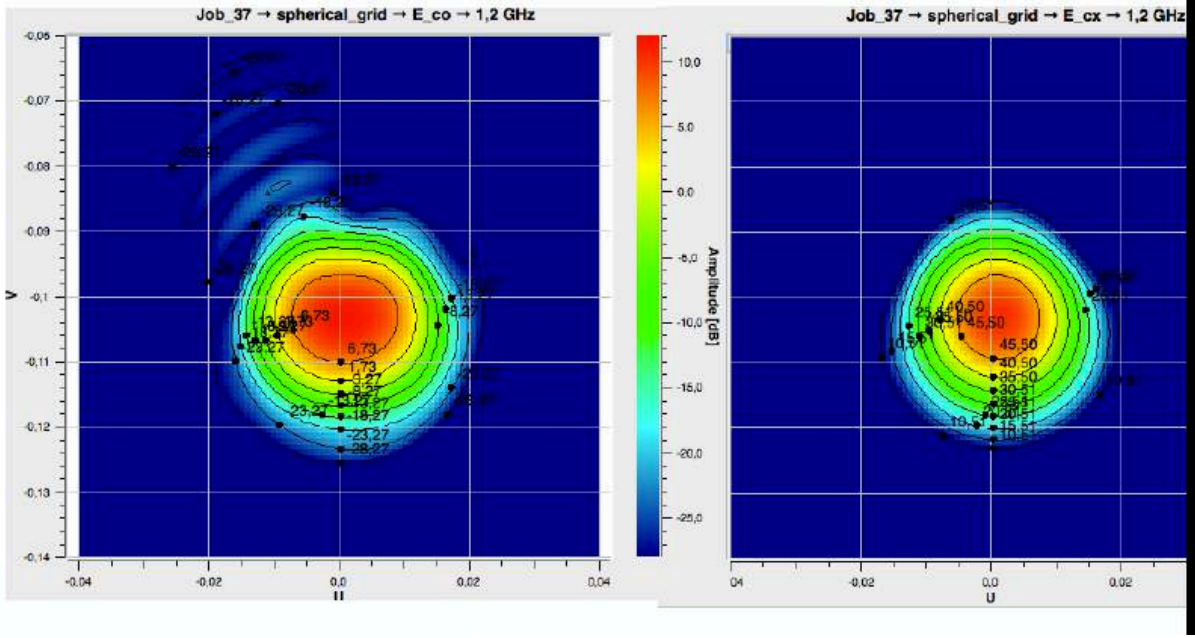
Pixel 0,760



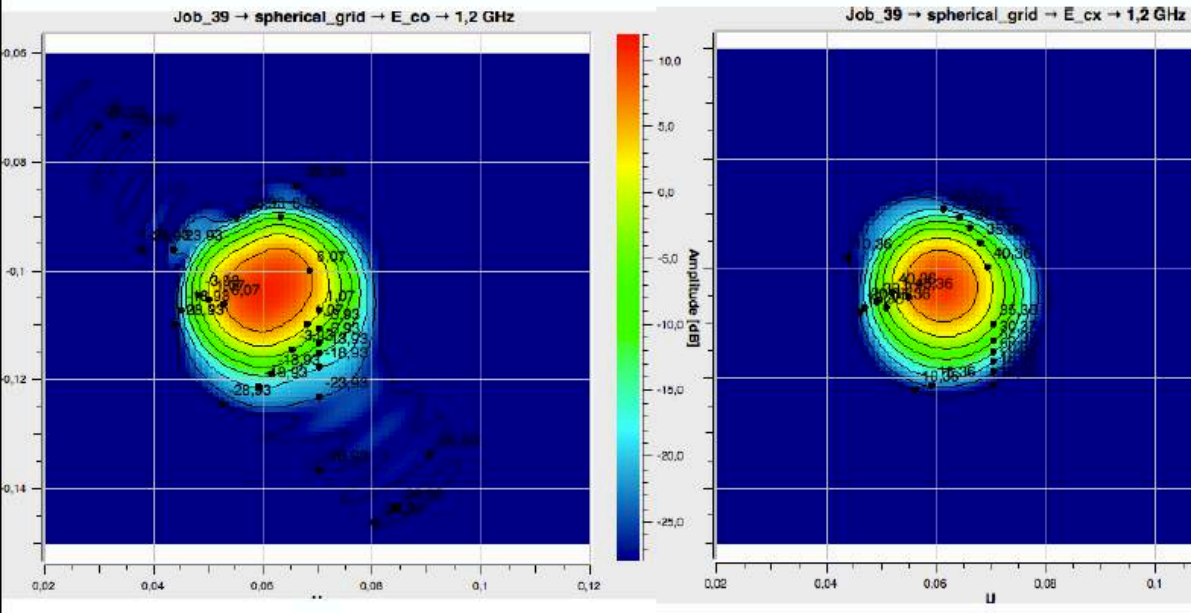
Pixel 0,-380



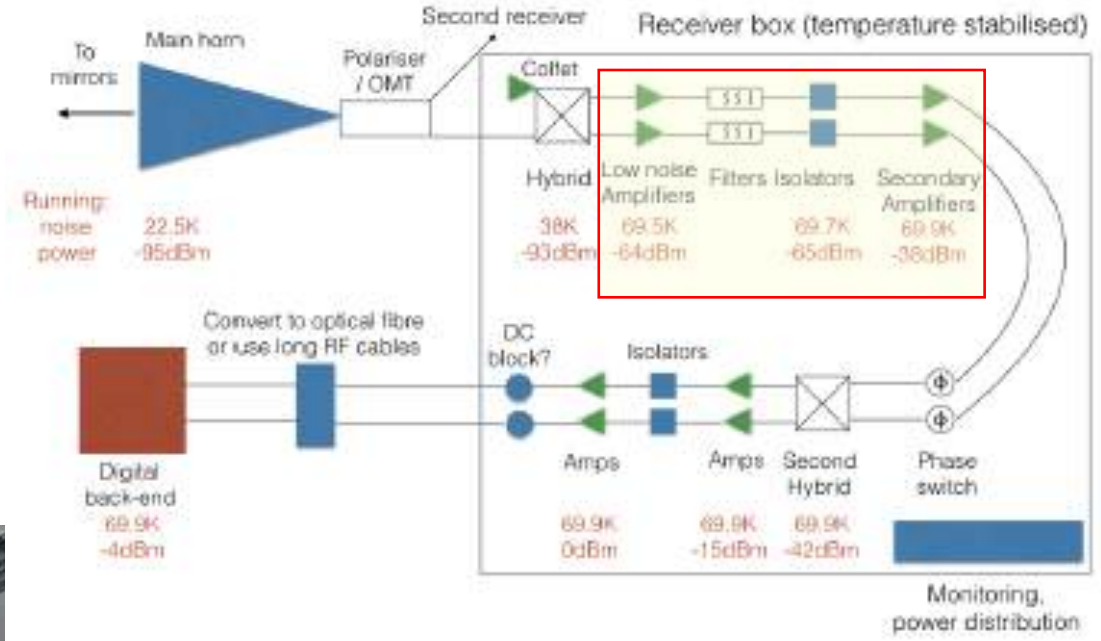
Pixel -660,0



Pixel -660,380



Receiver status



8)

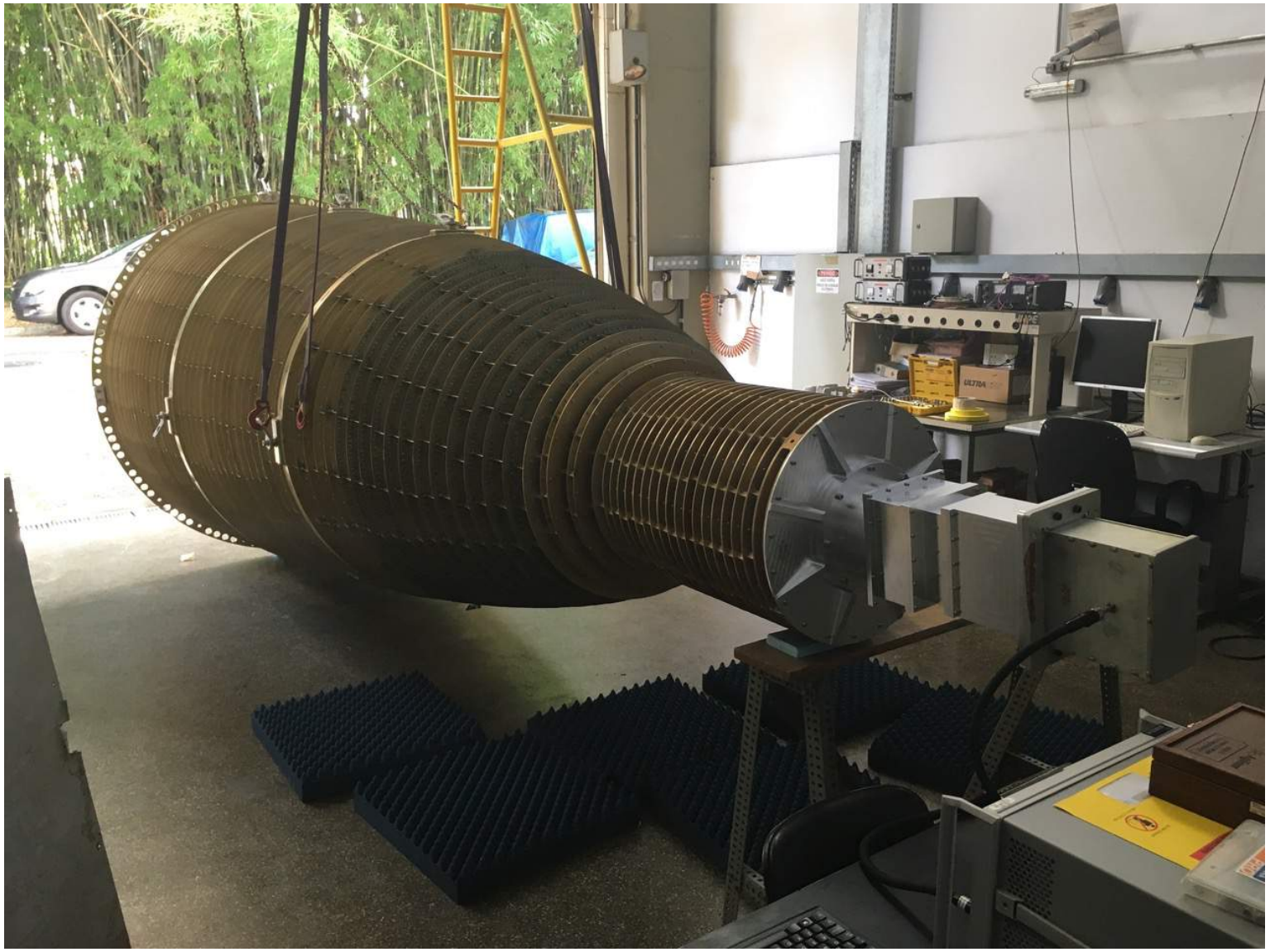
Horn & polarimeter status

- Aluminum horns
  - 6060 T4 alloy
  - Mass: 347 kg, not including screws and bolts, which may add ~ 30 kg to the unit
  - Number of rings (sectors): 127
  - Length: 4318 mm
  - Mouth: 1900 mm
  - Throat: 250 mm
- Construction
  - Calfer (Brazil)

- Polarimeters (aluminum)
  - Mass: 90kg,
- Construction
  - Metalcard (Brazil)

- EM project: Bruno Maffei (IAP, France)
- Mechanical project : Luiz Reitano (INPE, Brazil)

Horns



"BINGO: Horn design, fabrication and testing" (Wuensche et al. 2018, in preparation)

Horns

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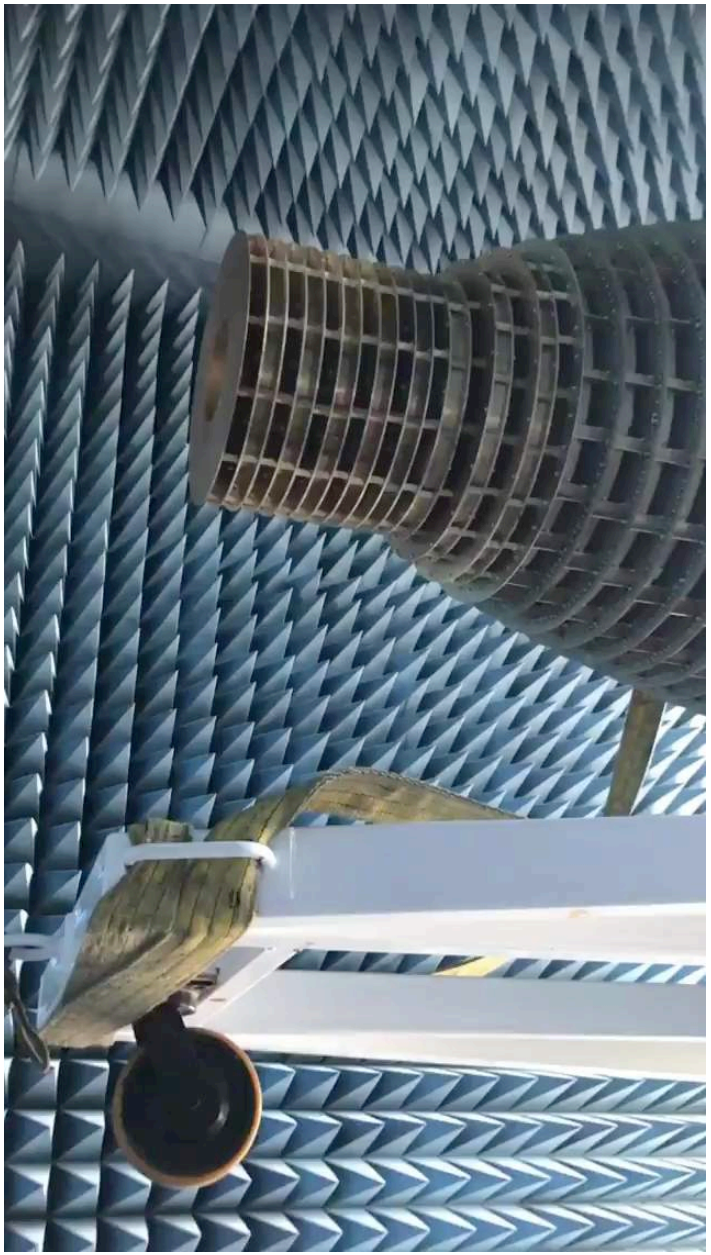
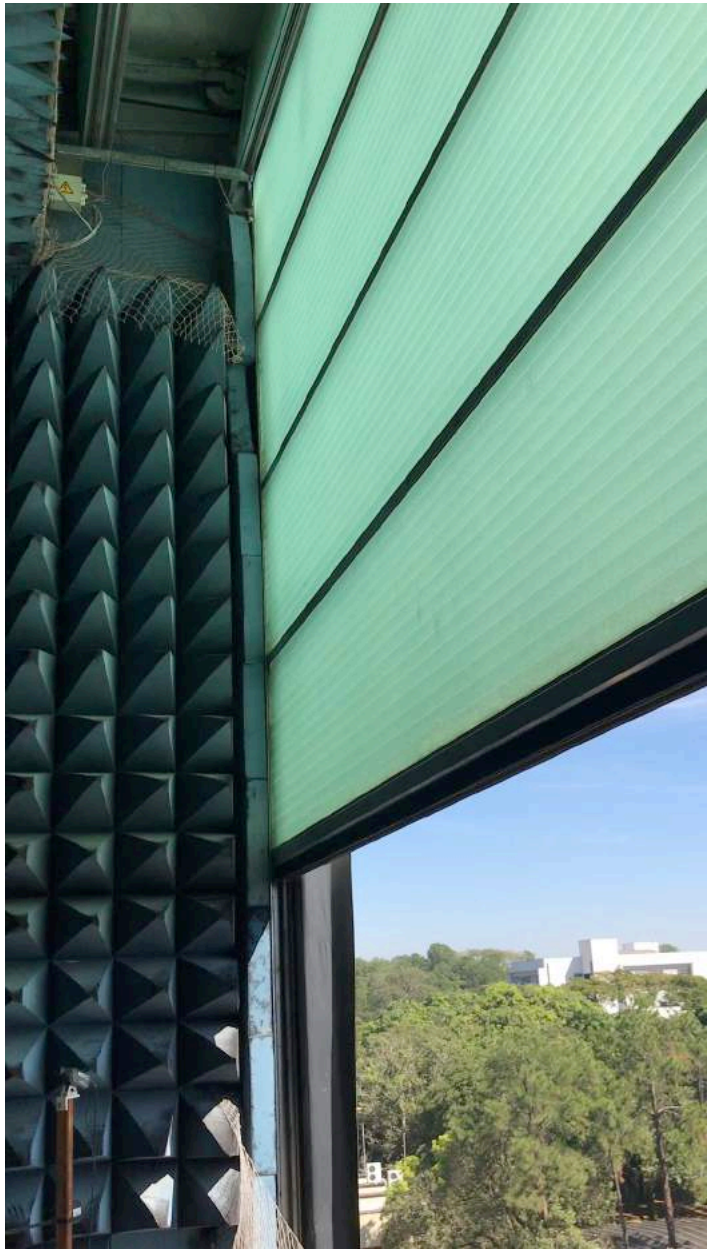
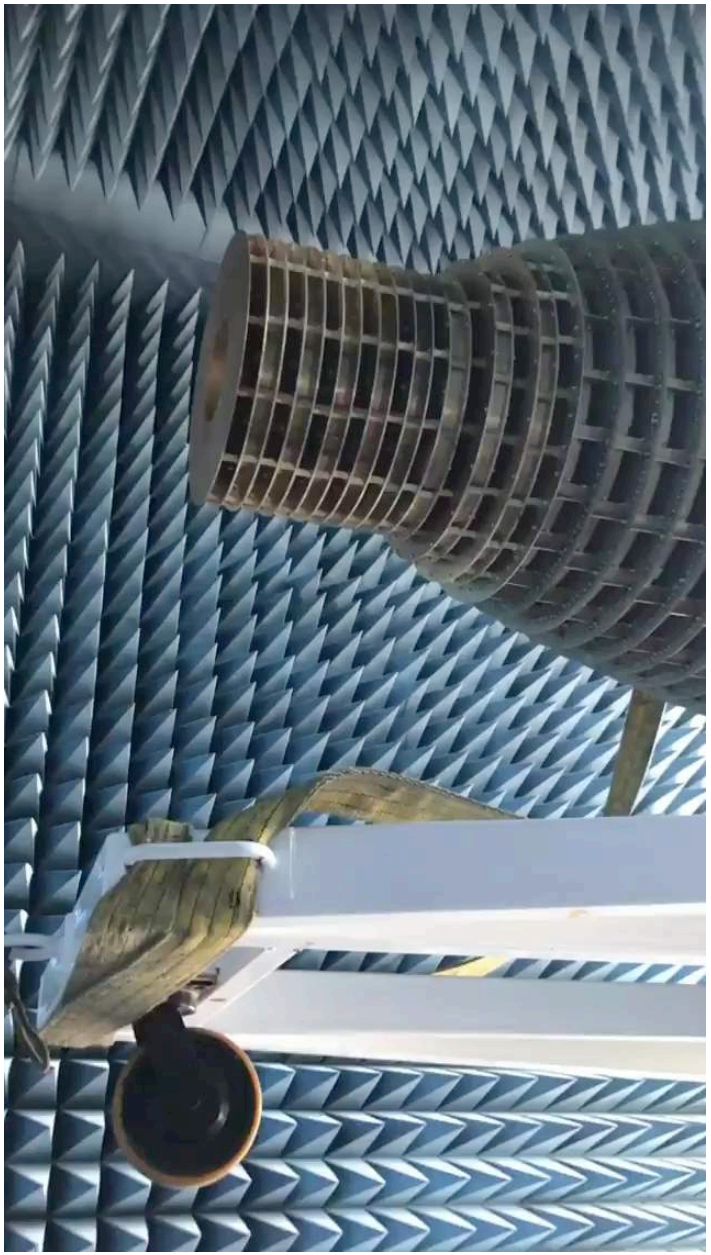
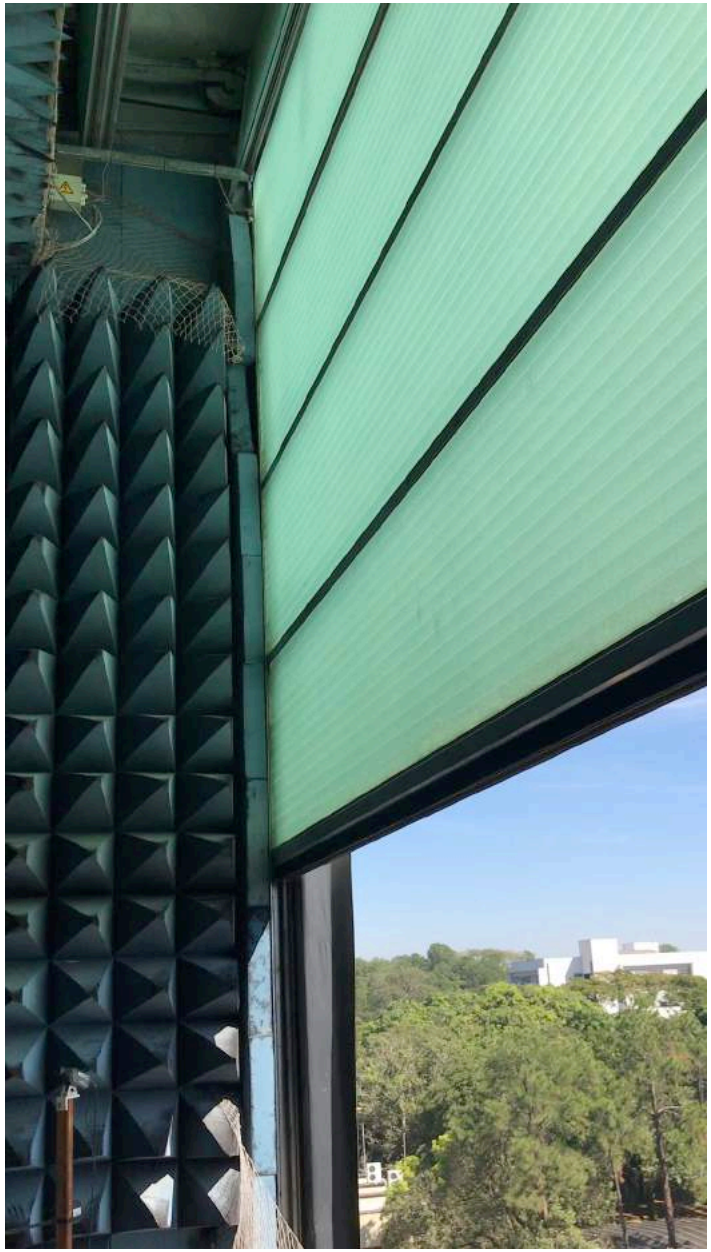
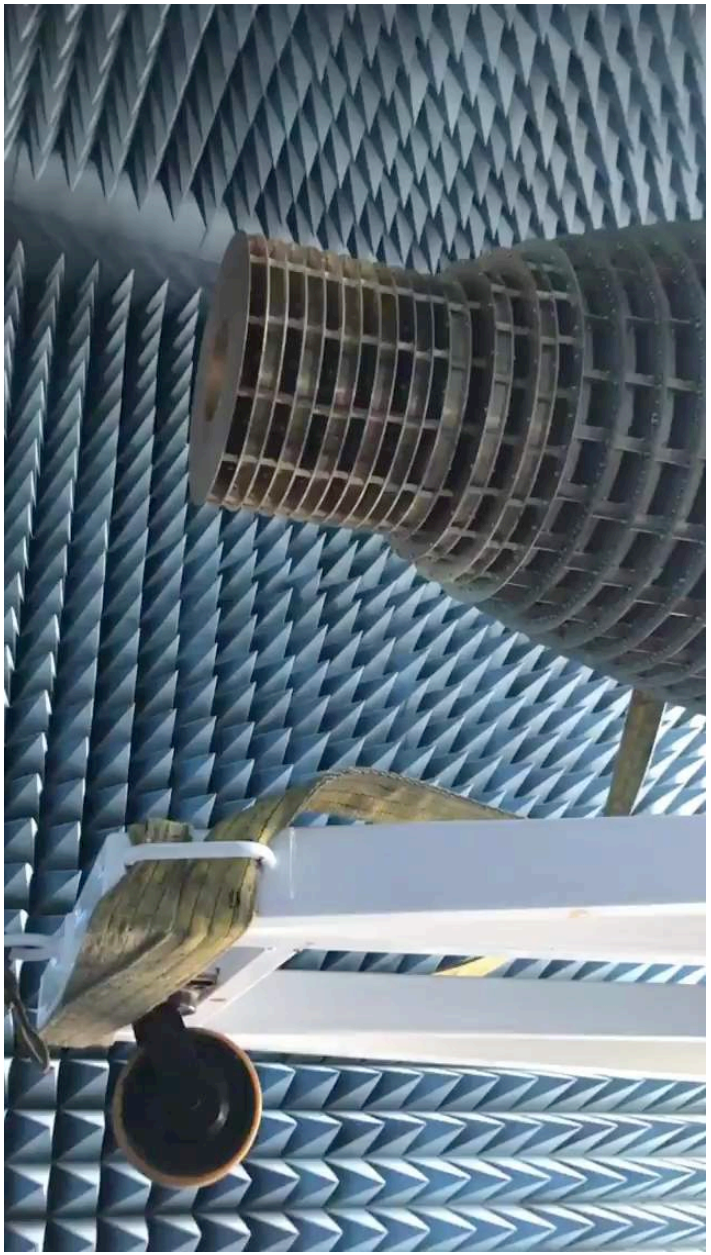
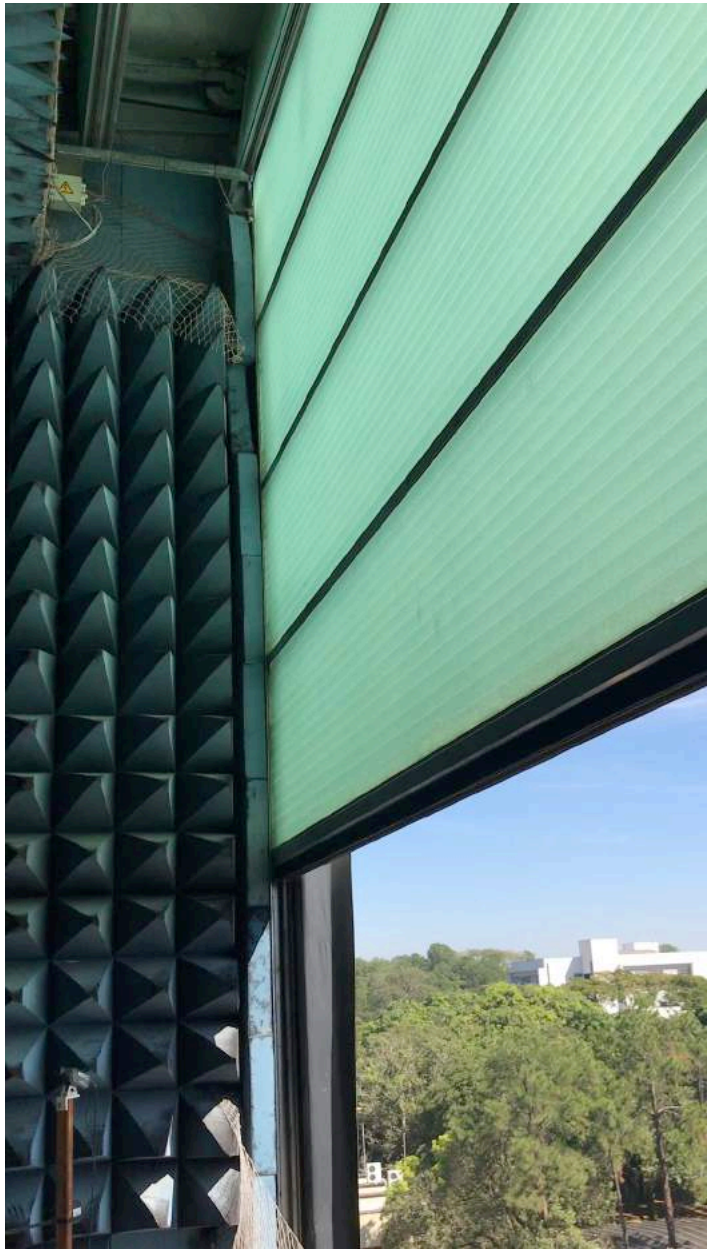


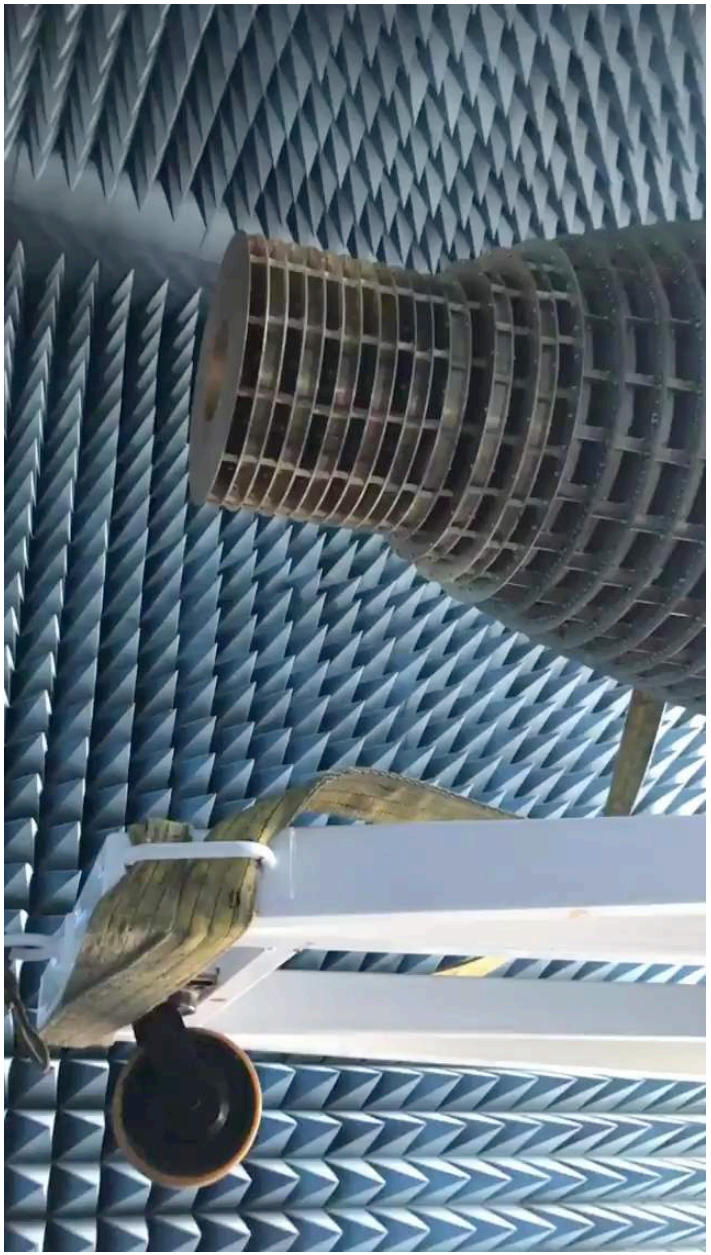


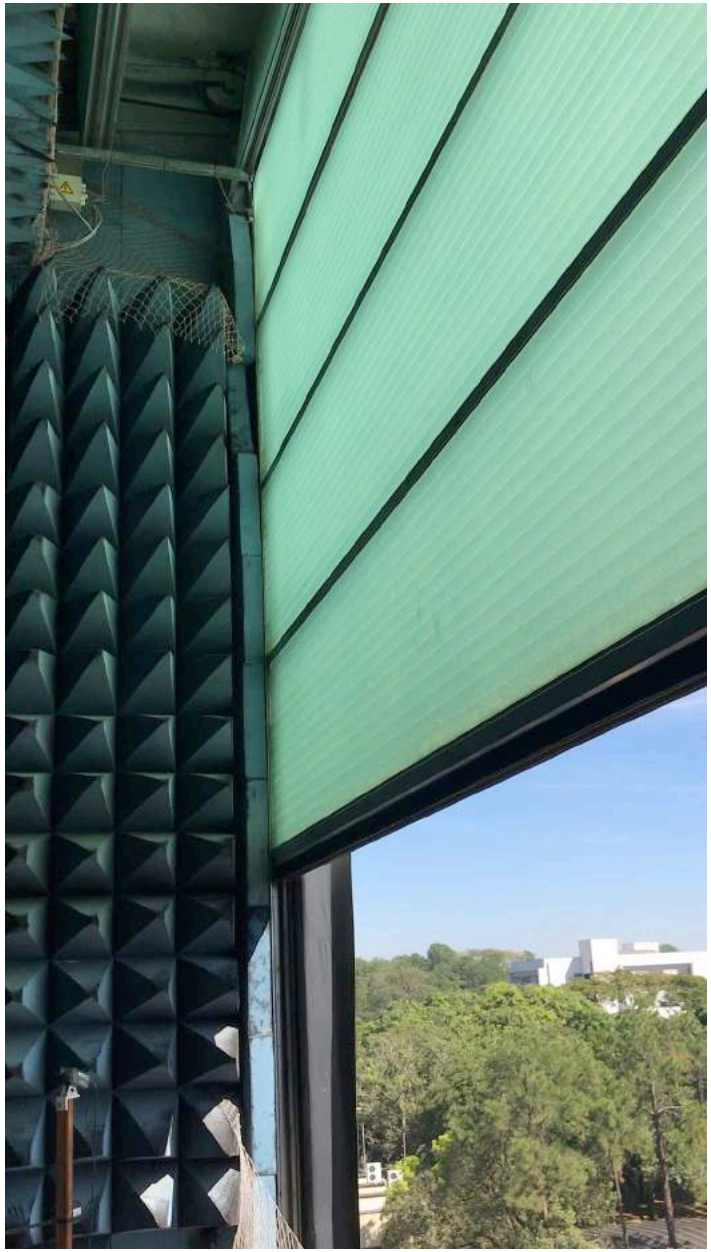




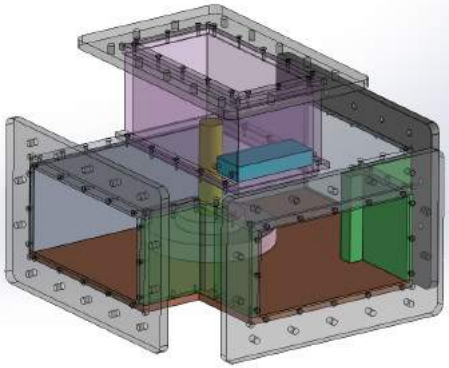


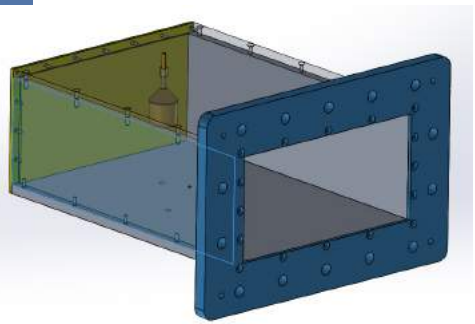


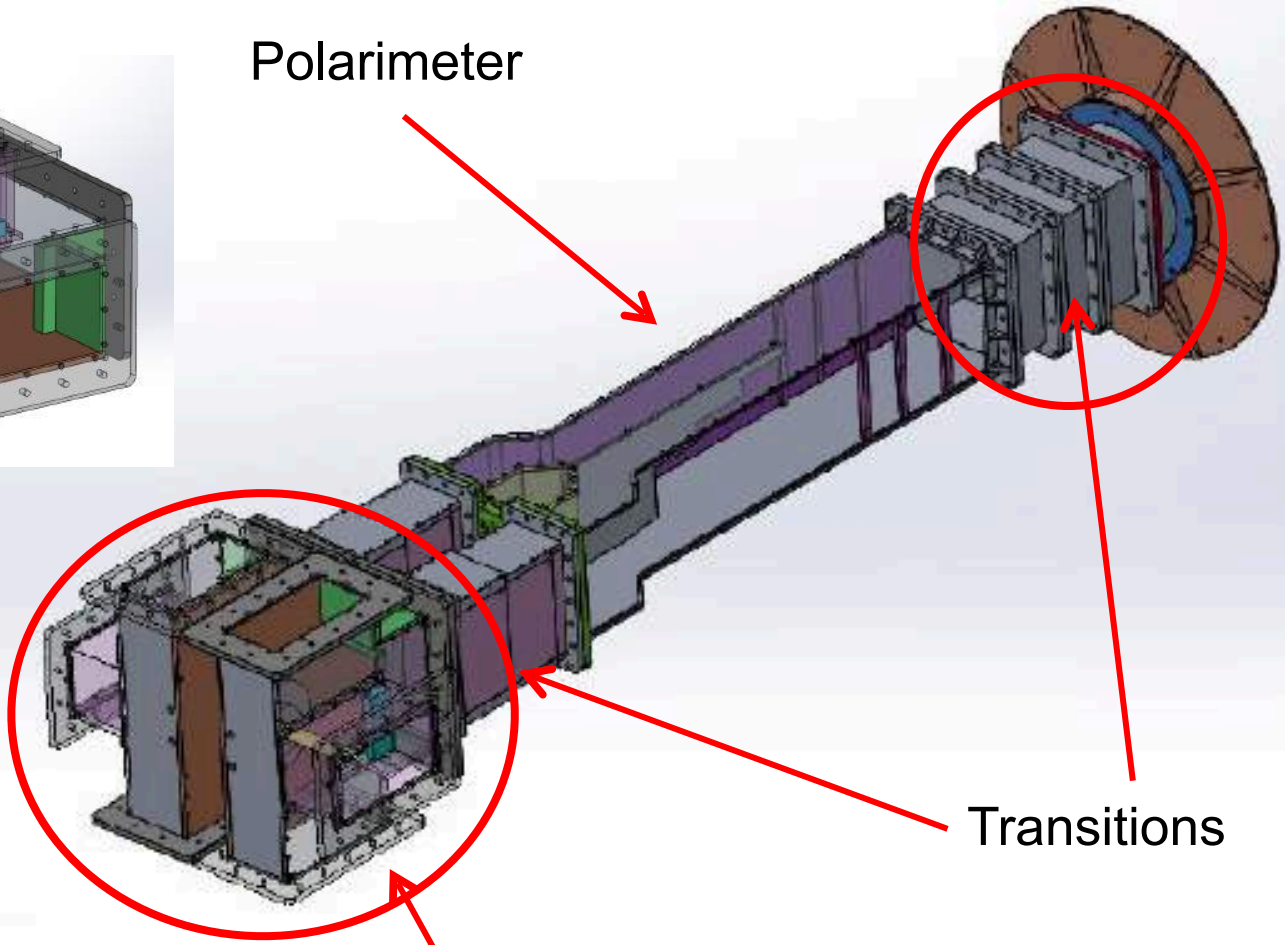




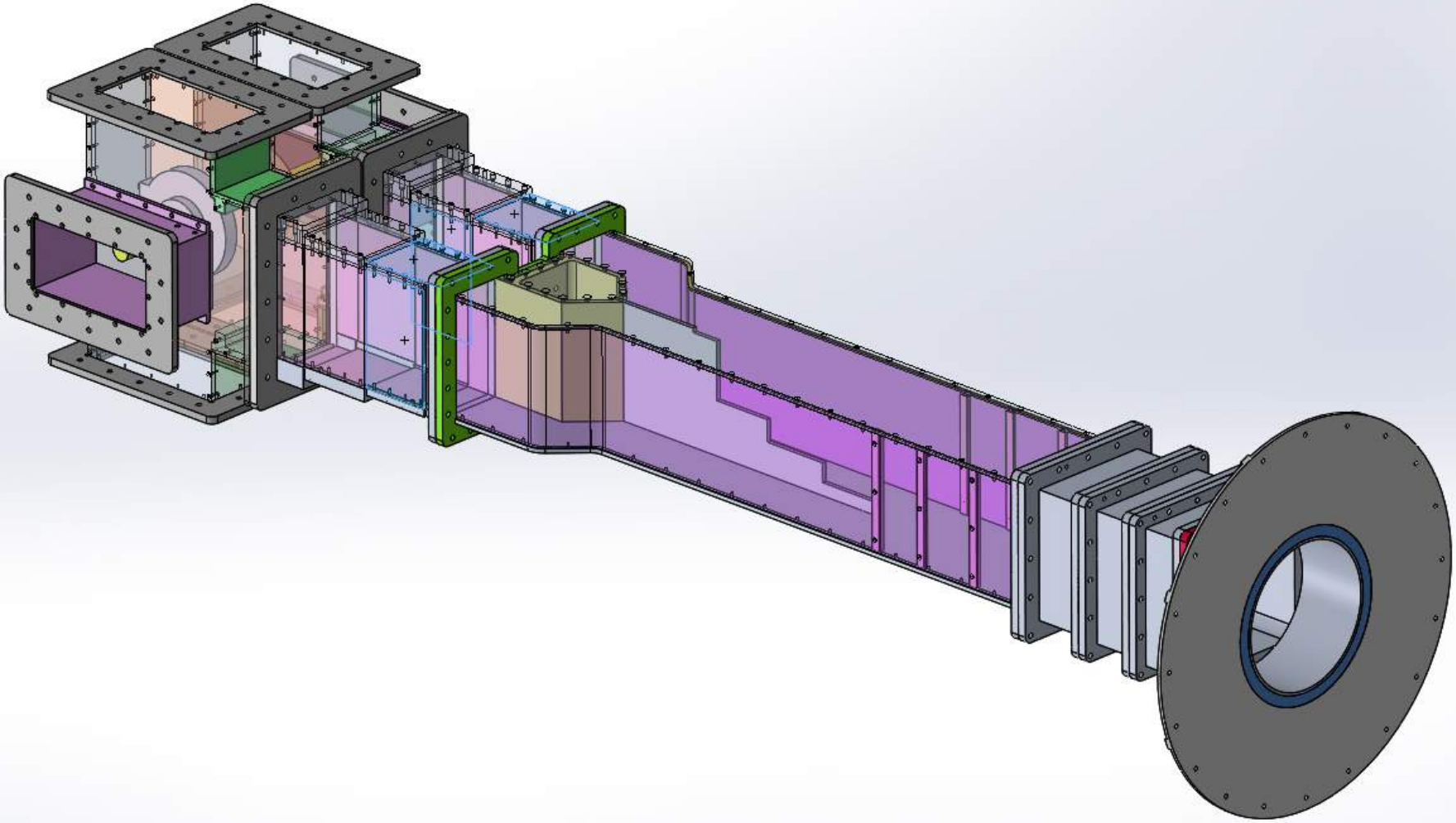
Polarimeters, transitions and magic tees

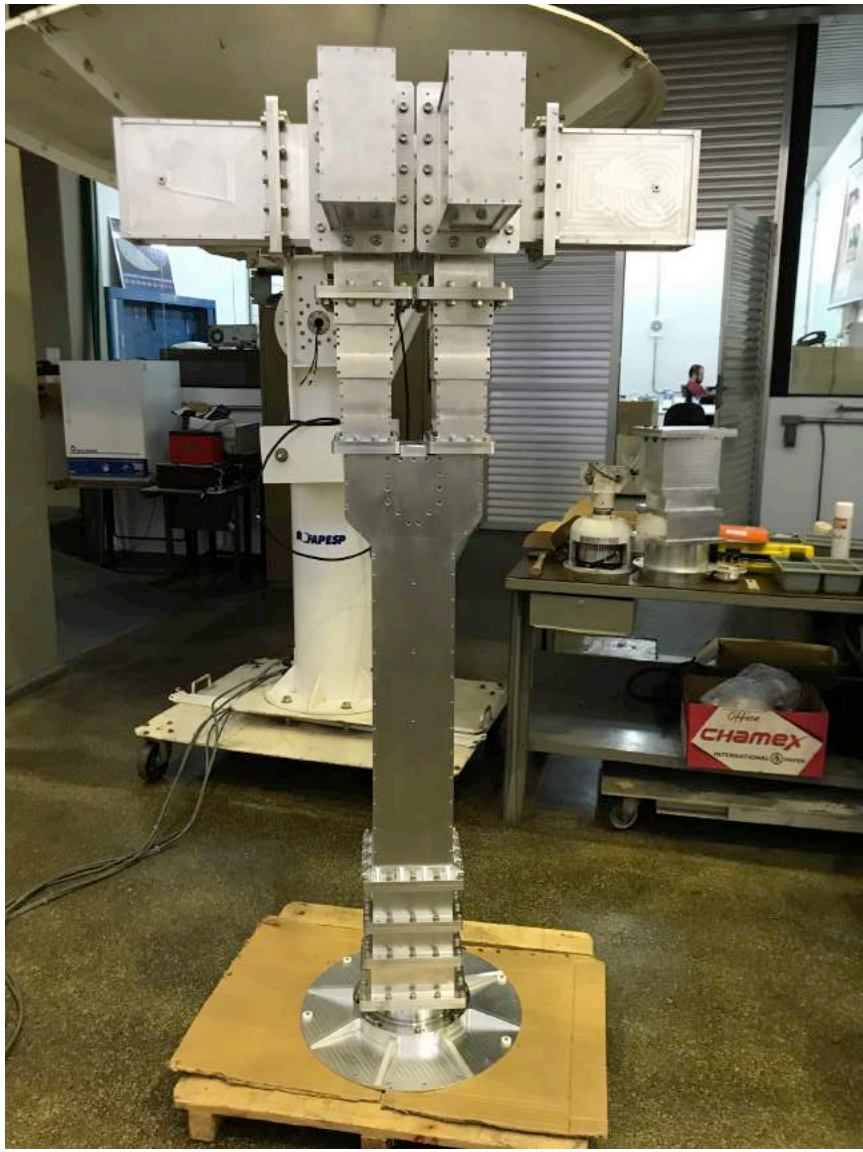


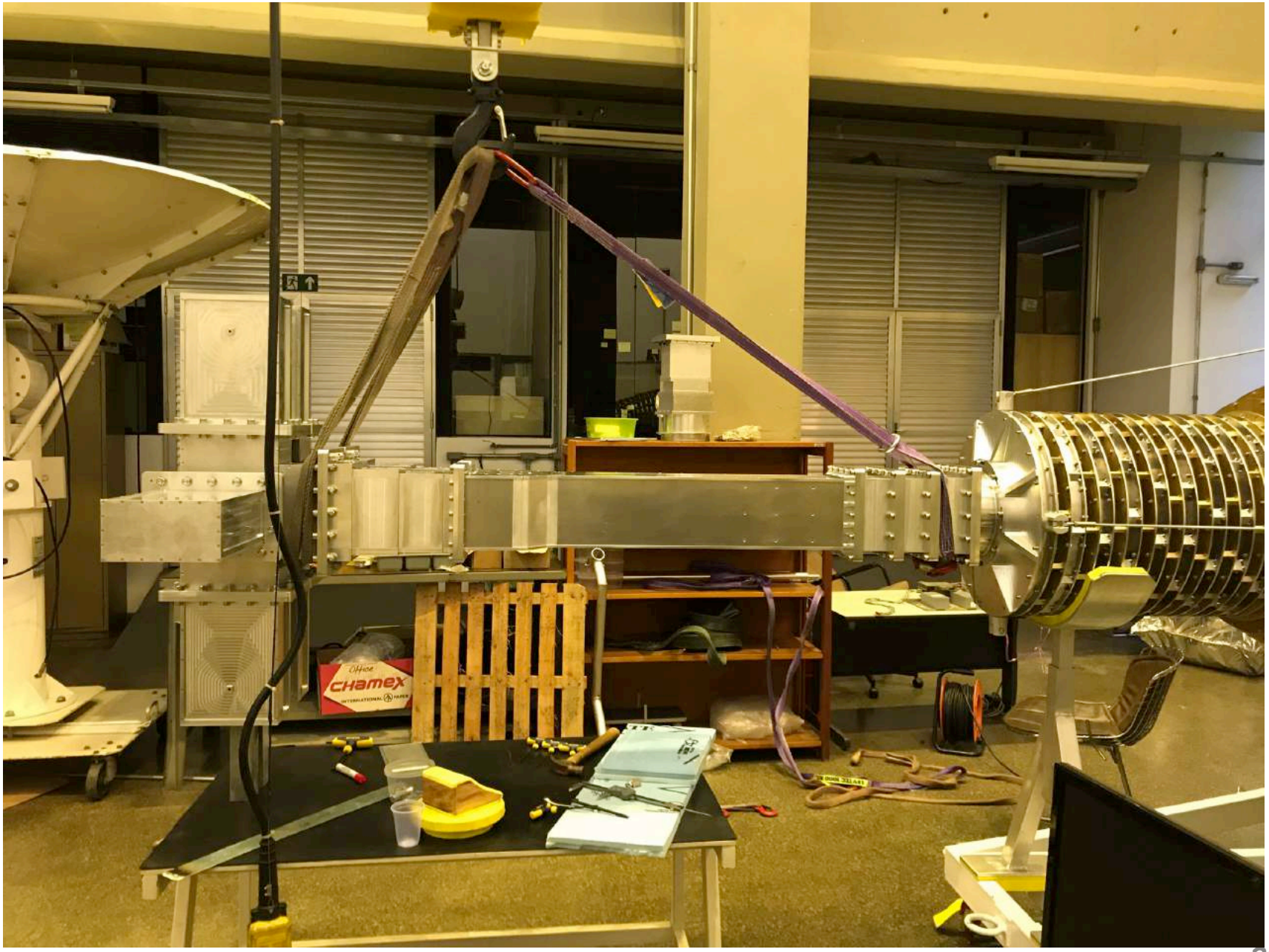




Crédito: L. A. Reitano




FAPESP
Chamex



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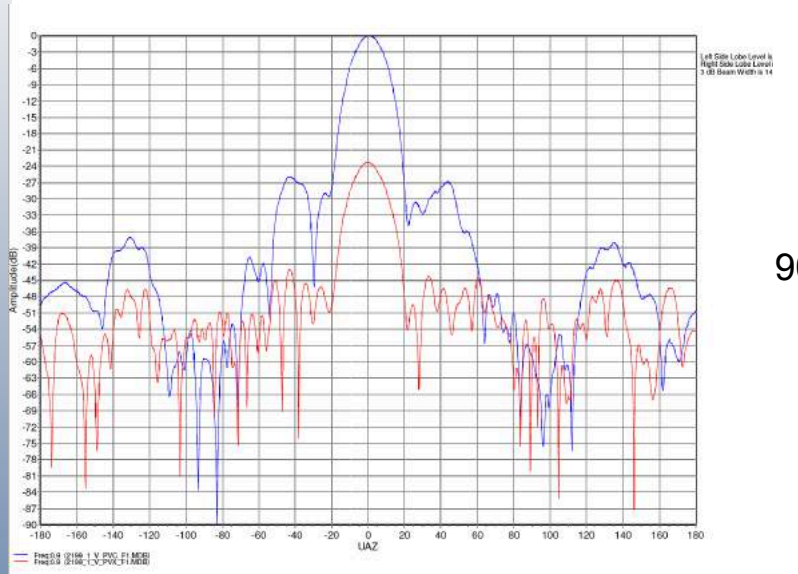
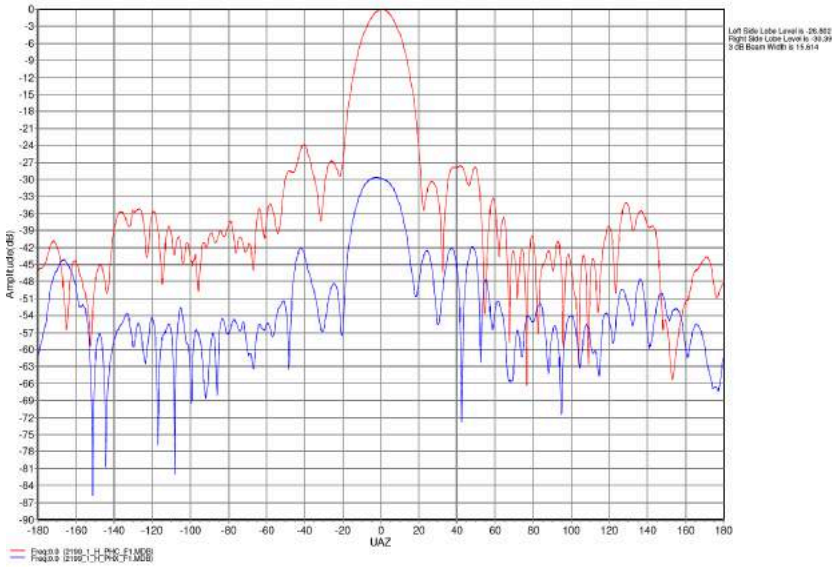
Horn testing results –polarization

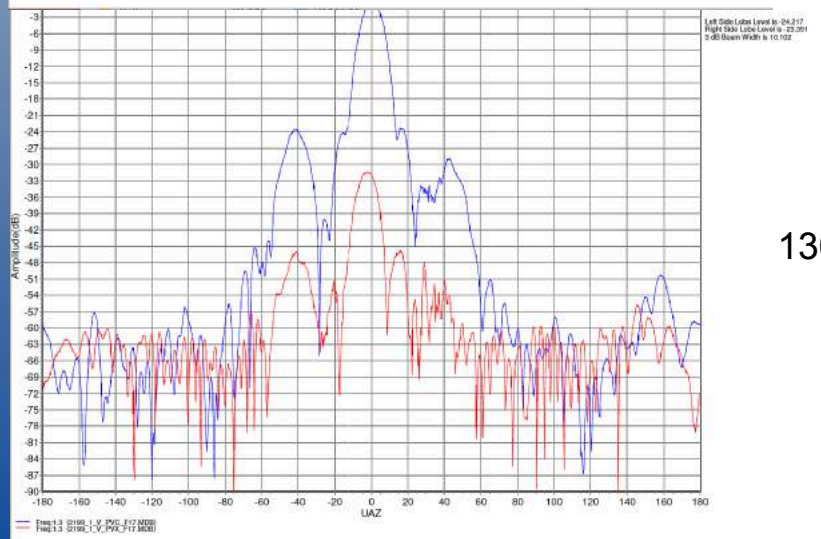
VERTICAL



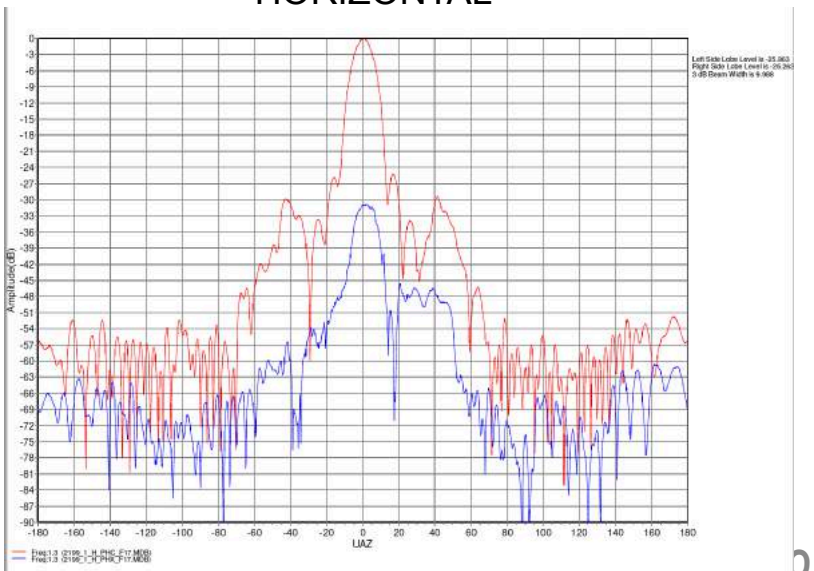
900 MHz



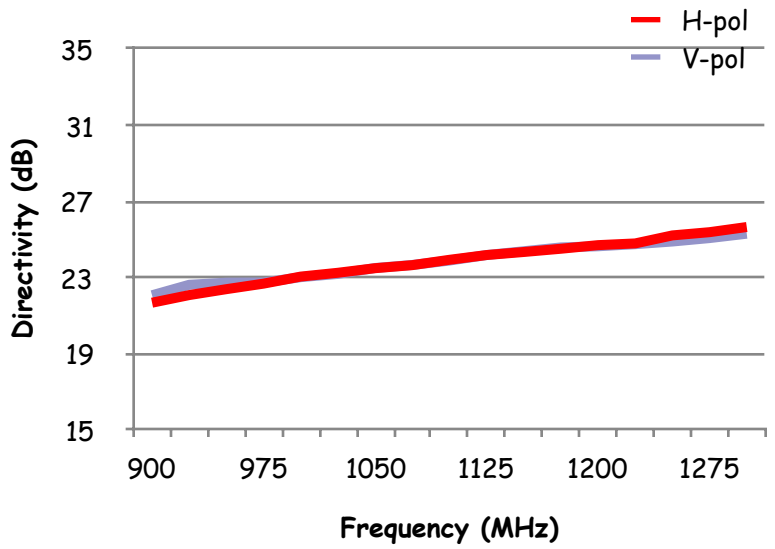
HORIZONTAL

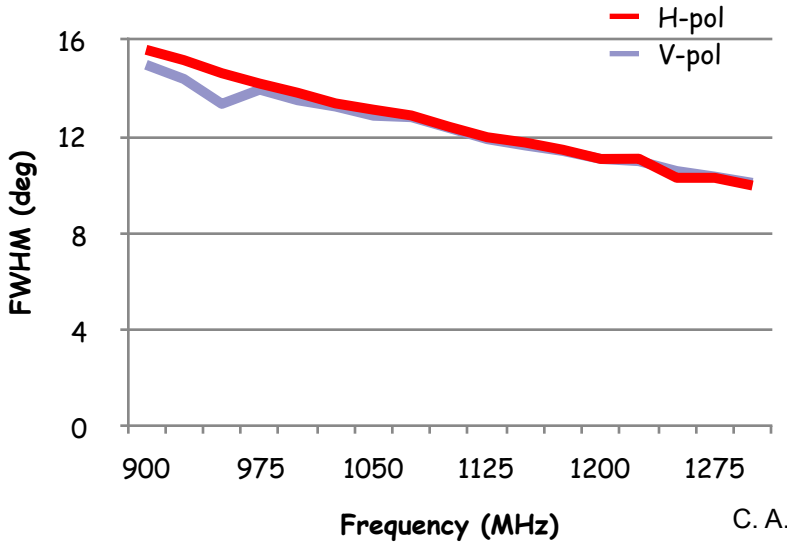


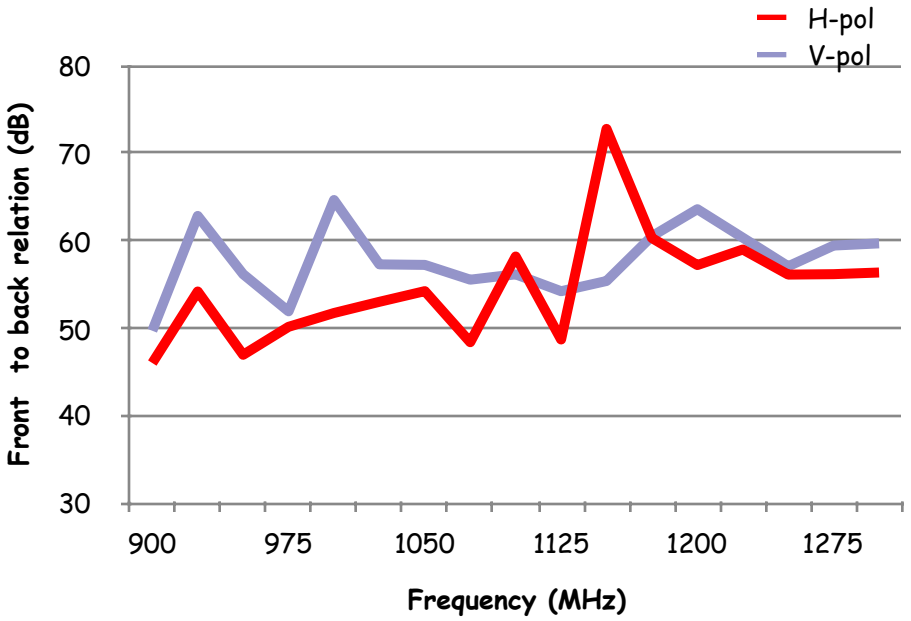
1300 MHz



Horn testing results







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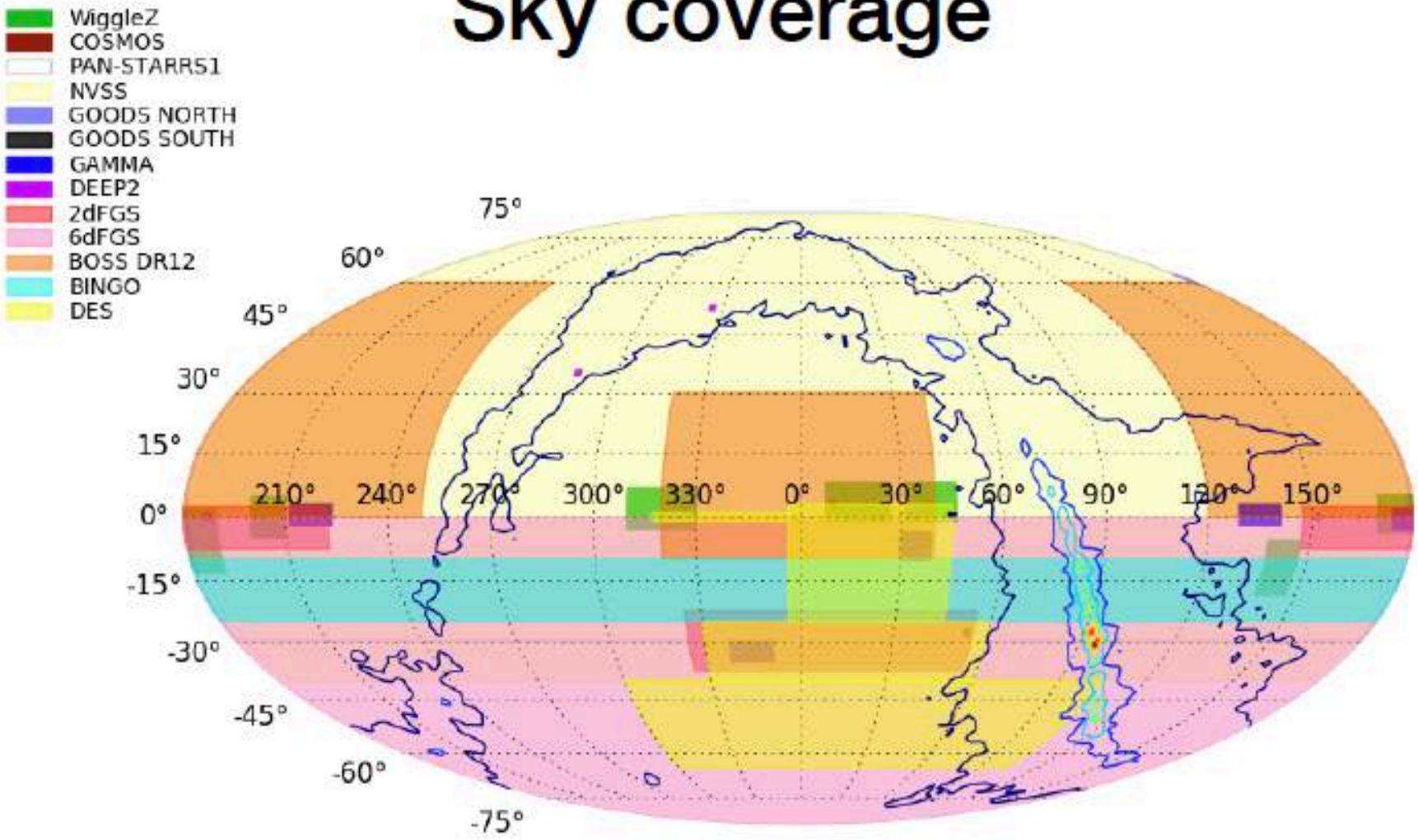
Sky coverage

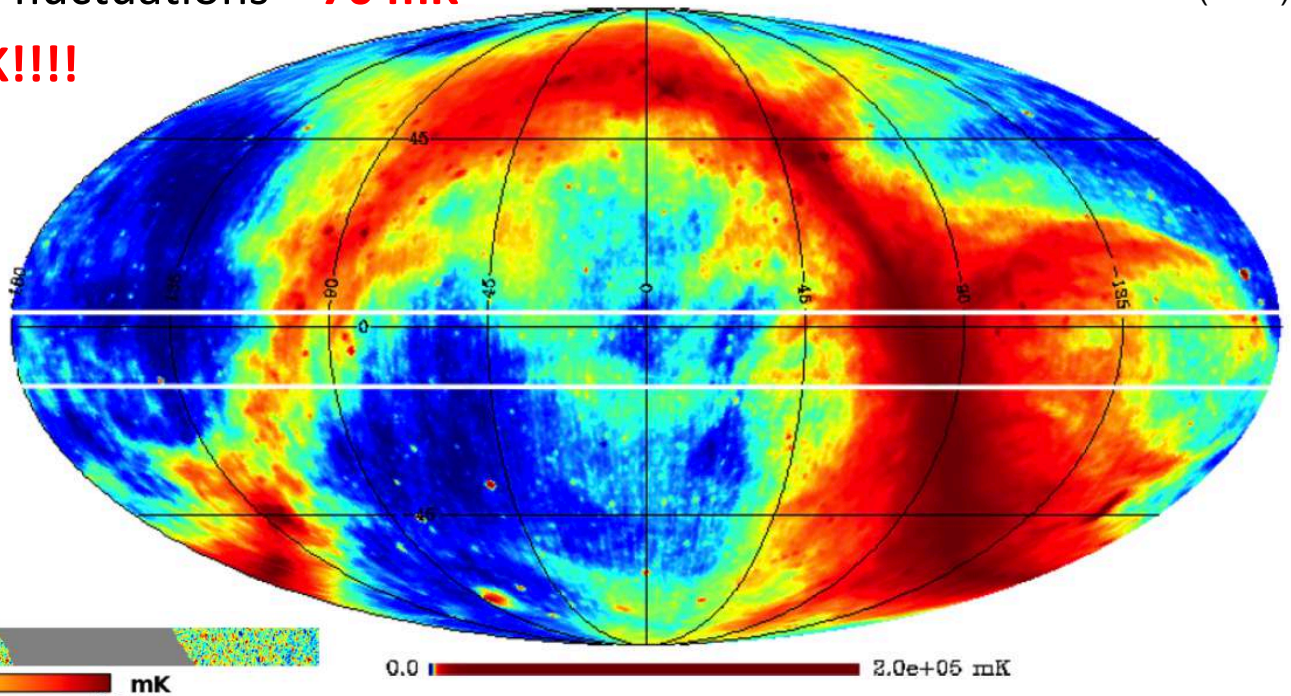


FORECASTS: Foregrounds

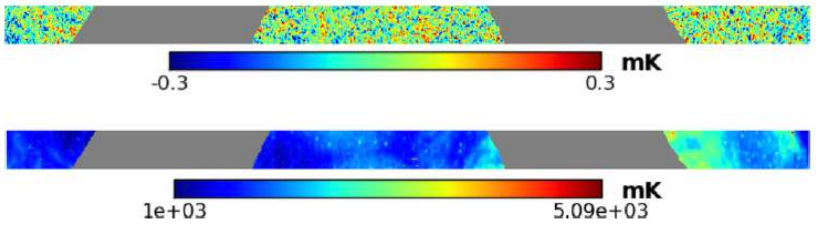
From Bigot-Sazy et al. (2015)

- 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

C. A. Wuensche (2018)

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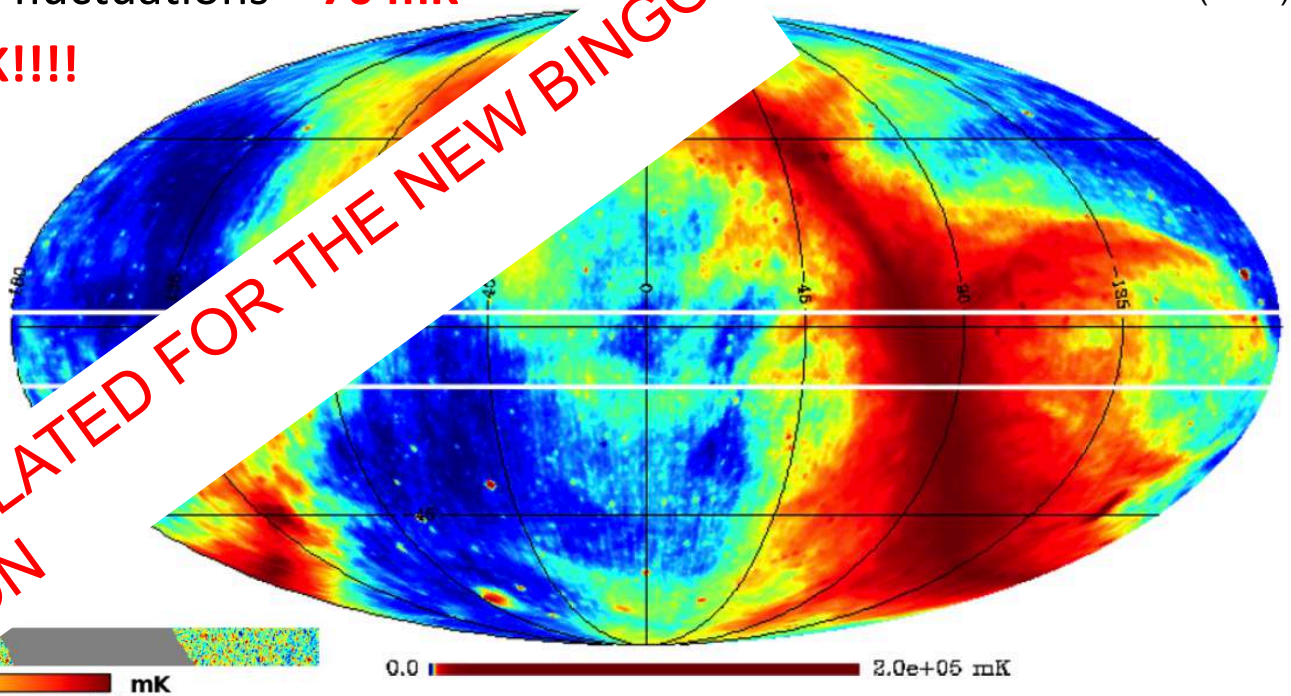
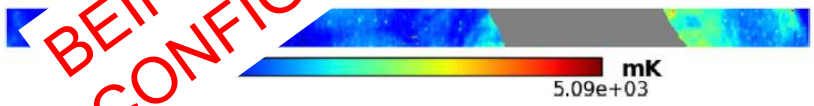


BEING RECALCULATED FOR THE NEW BINGO CONFIGURATION

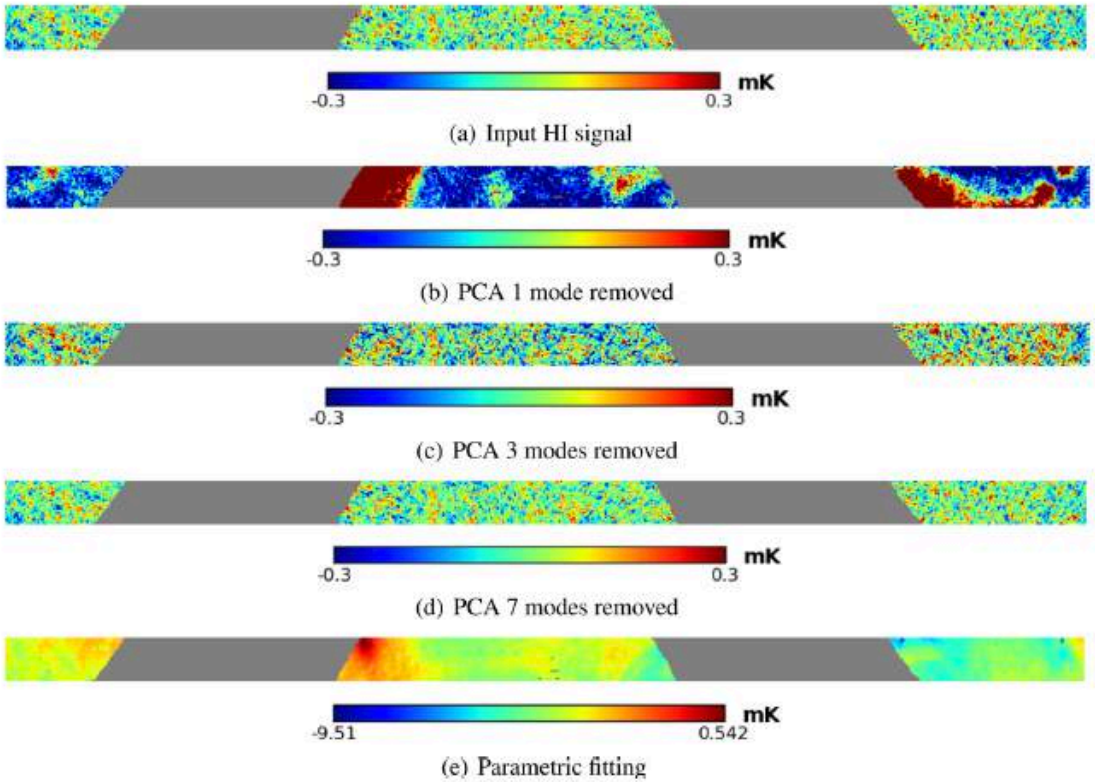
HI only



HI + Galaxy + unresolved point sources

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 found in Olivari et al. (2015)



Bigot-Sazy et al. 2015

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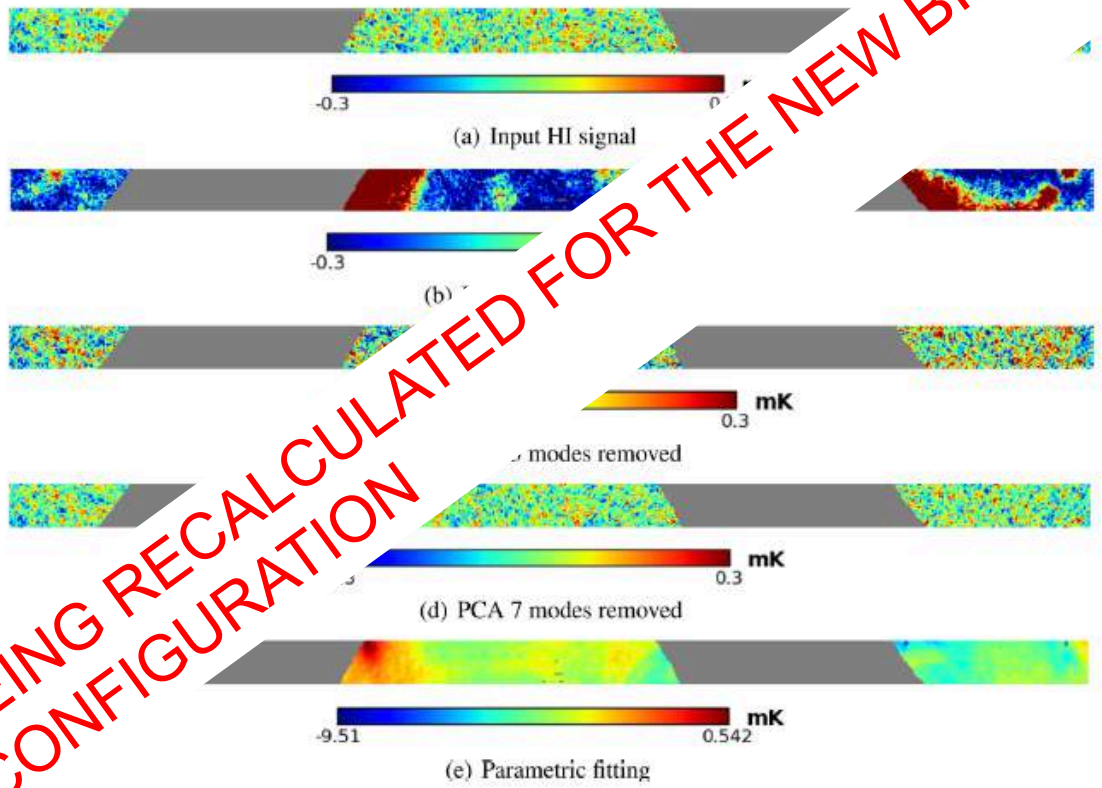
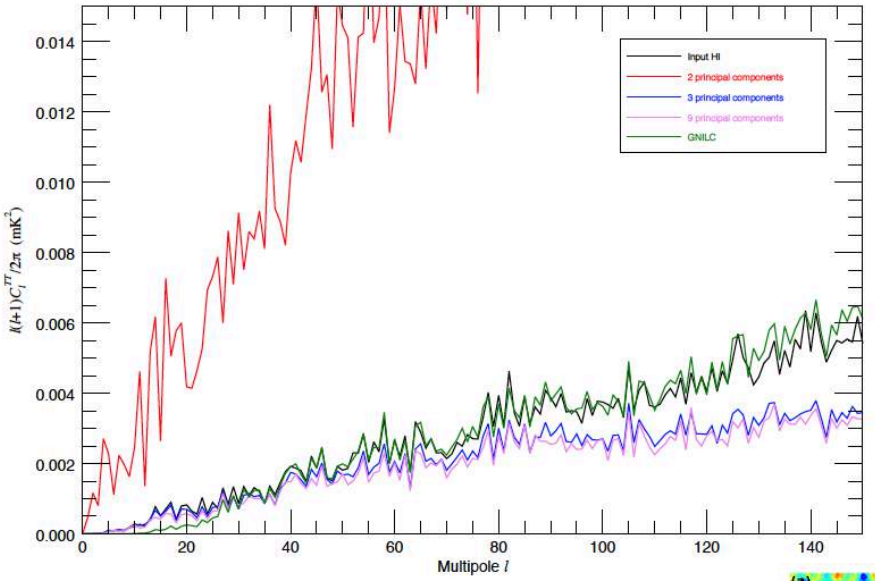


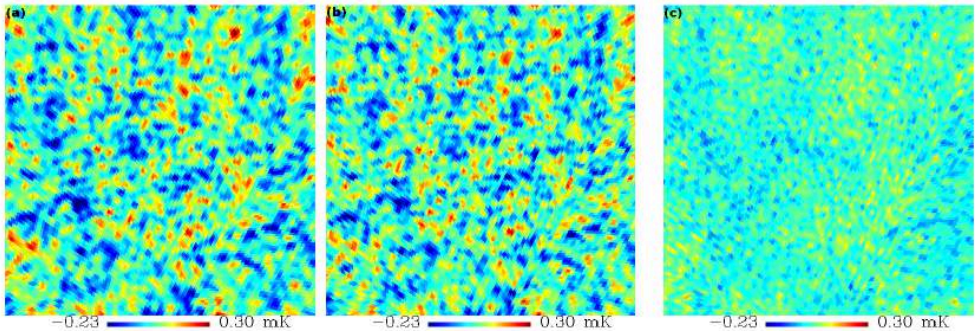
Bigot-Sazy et al. 2015

Data analysis efforts

- HI power spectrum reconstruction (Olivari et al., 2015)
- Cosmological parameters forecast (Olivari et al. 2017)



Parameters	
Redshift range $[z_{\min}, z_{\max}]$	[0.13, 0.48]
Bandwidth $[\nu_{\min}, \nu_{\max}]$ (MHz)	[960, 1260]
Number of feed horns n_f	80
Sky coverage Ω_{sur} (deg^2)	21000
Observation time t_{obs} (yrs)	1
System temperature T_{sys} (K)	50
Beamwidth at the first channel (arcmin)	40



HI input HI reconstructed Noise

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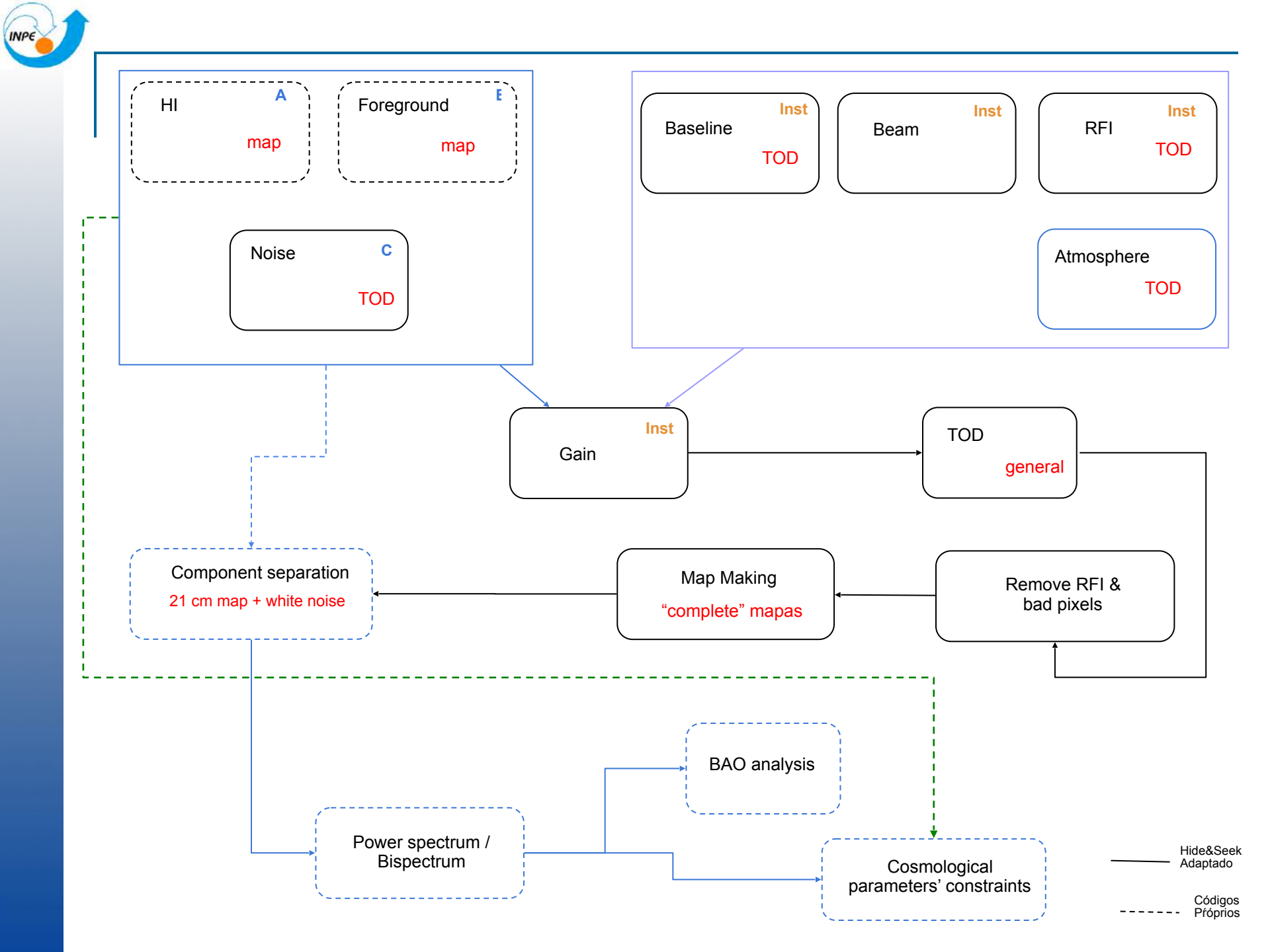
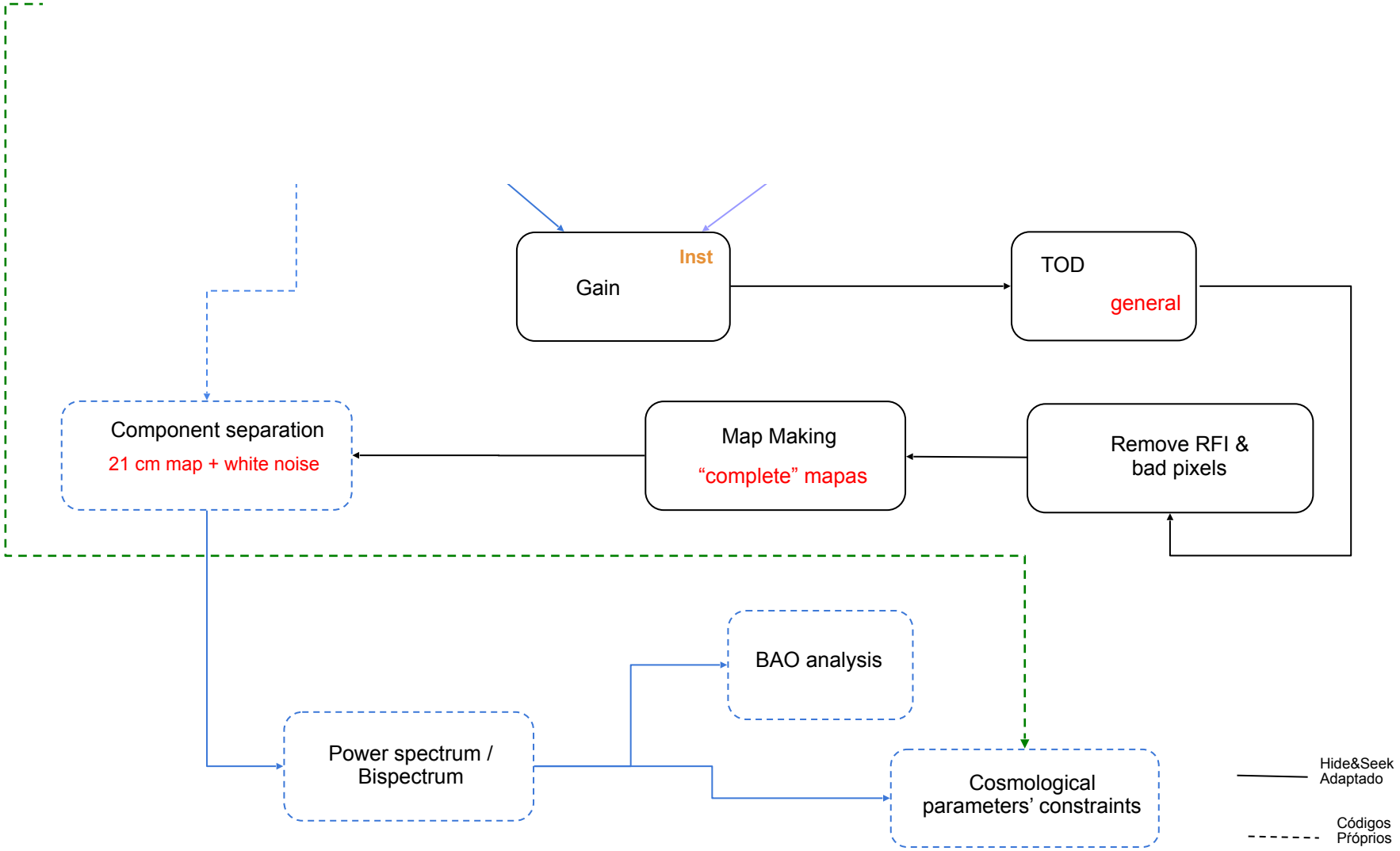

HI
A
map
Foreground
B
map
Noise
C
TOD
Baseline
Inst
TOD
Beam
Inst
RFI
Inst
TOD
Atmosphere
TOD
Gain
Inst
TOD
general
Component separation
21 cm map + white noise
Map Making
“complete” mapas
Remove RFI &
bad pixels
BAO analysis
Power spectrum /
Bispectrum
Cosmological
parameters’ constraints
Hide&Seek
Adaptado
Códigos
Próprios

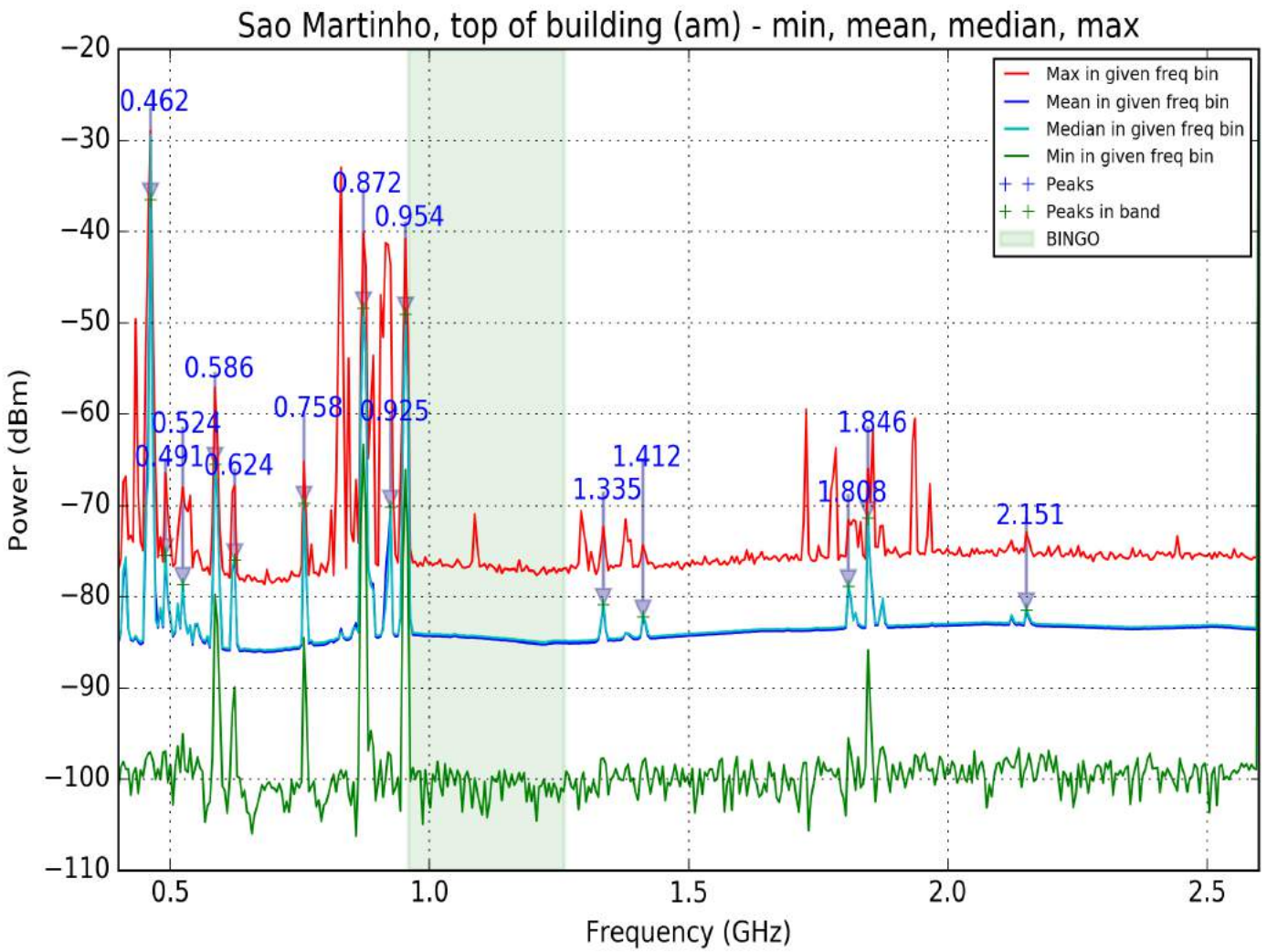
Currently 2 pipelines under development

- Manchester (mostly developed by Dickinson and Harper)
- USP/INPE (based upon Hide&Seek – arxiv:1607.07443 - and adapted by Abdalla, Olivari, Fornazier et al.)

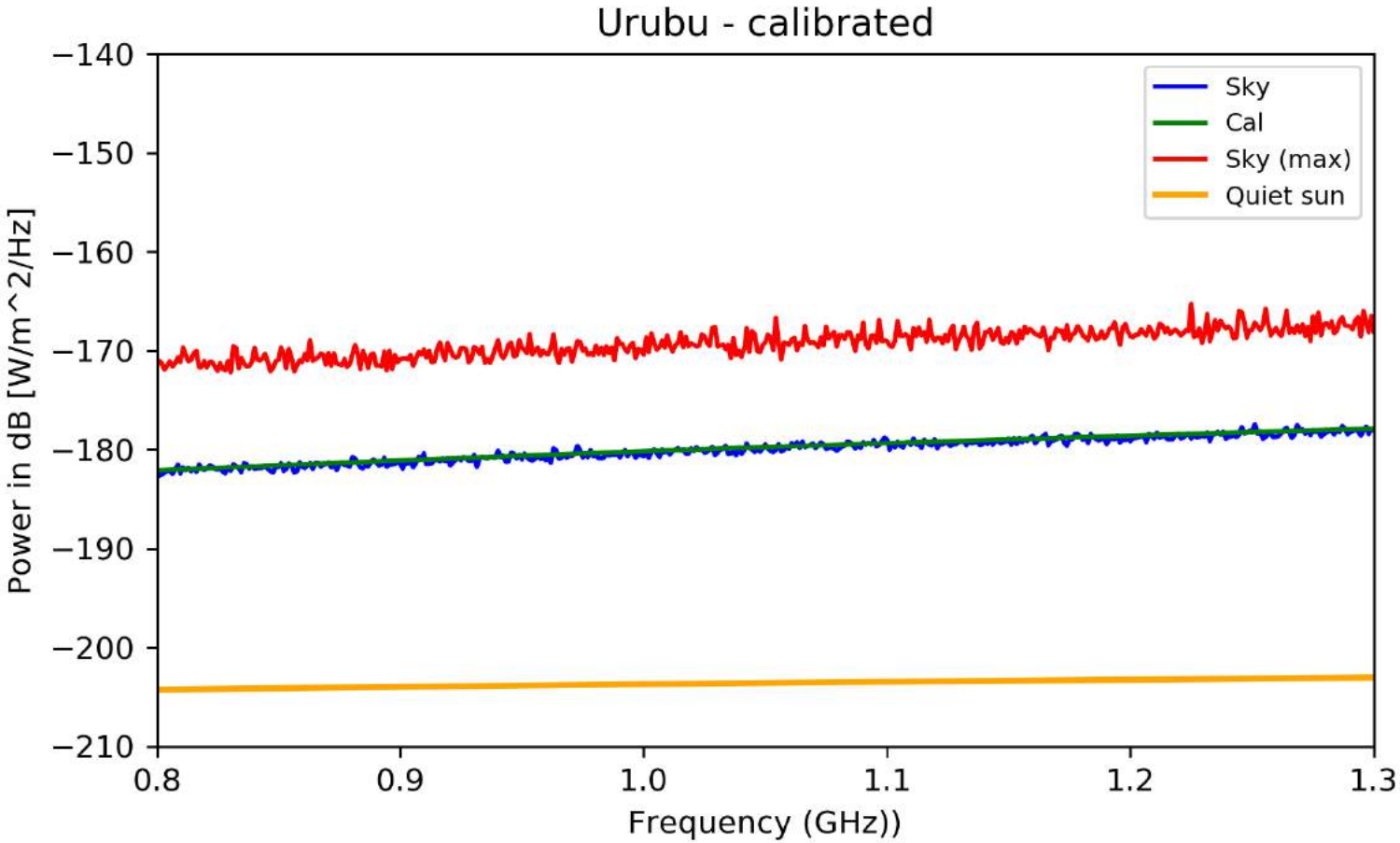


Site selection

S. Martinho, INPE's center, South of Brazil



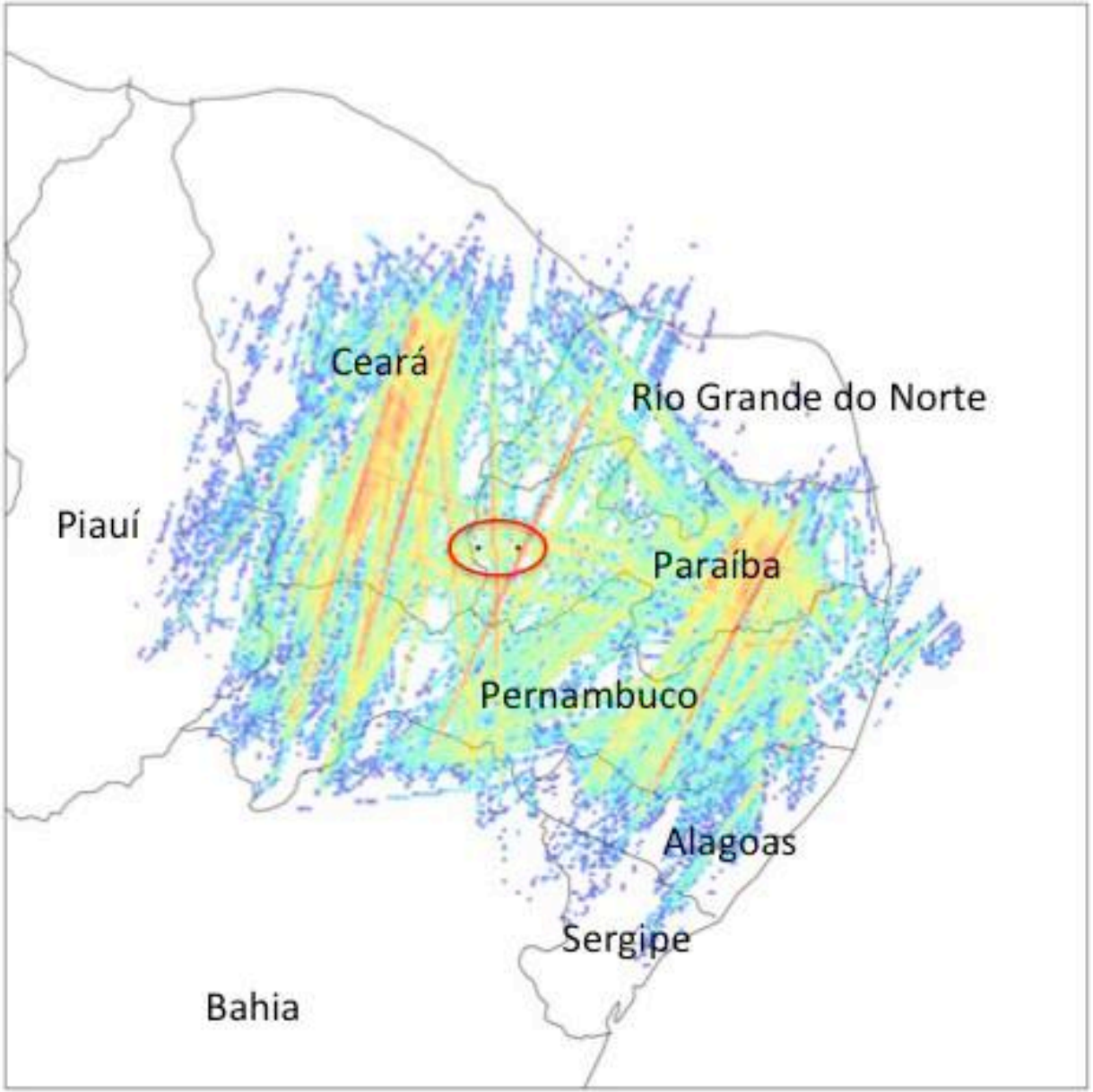
Paraíba sites



C. A. Wuensche (2018)

Still concern about airplan coverage…

Peel, Wuensche et al. (Journ. of Astron. Instr., accepted)



And satellites….

Harper & Dickinson, arXiv:1803.06314

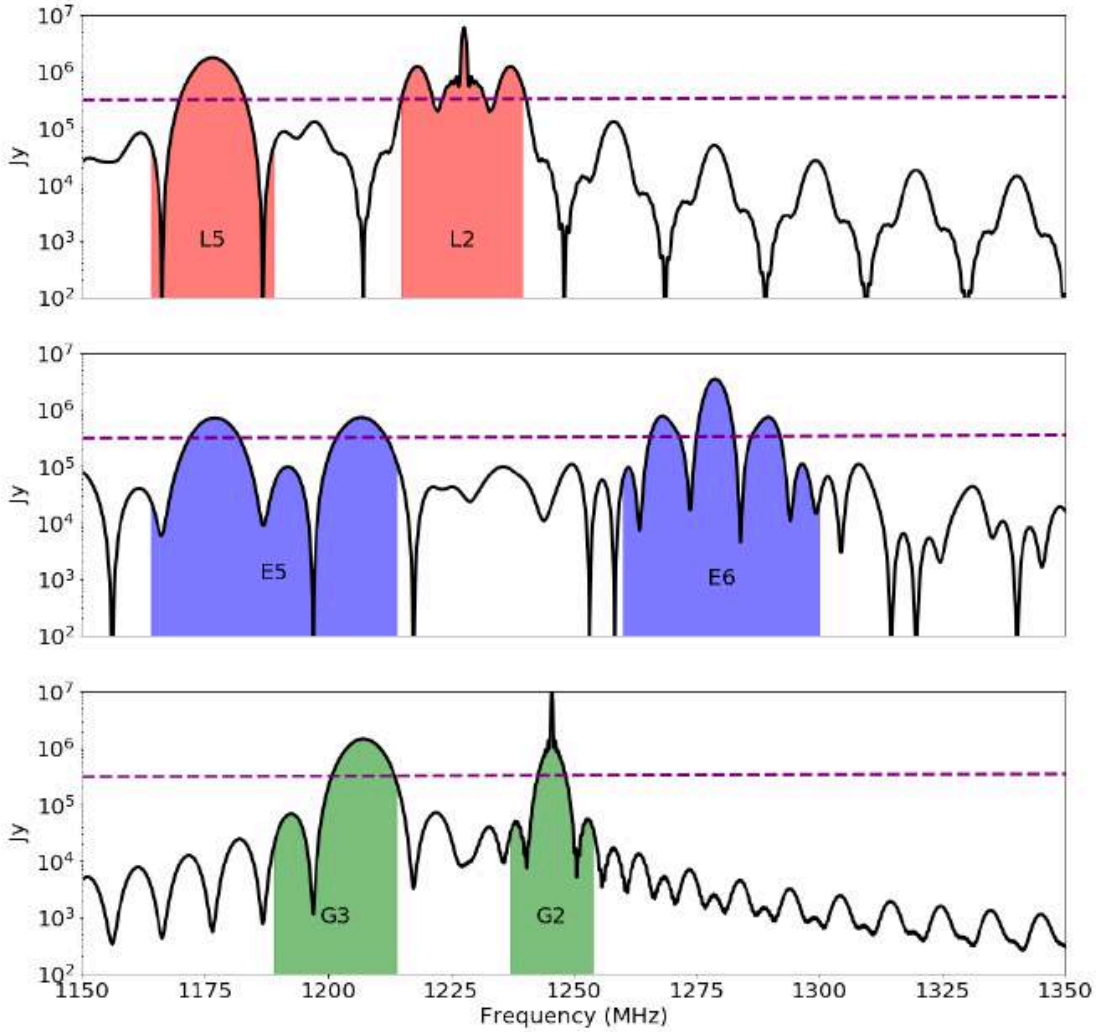


Figure 3. Typical spectral energy distribution as measured from the Earth of GNSS transmissions at frequencies less than 1410 MHz. The *top* plot shows the SED for GPS, the *middle* plot shows Galileo, and the *bottom* shows GLONASS. Highlighted regions in the SEDs represent the nominal frequency allocations 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).


Brazil
Caatinga
Brasília
Bolivia
La Paz
The Andes
Paraguay
Asuncion
Serra Geral Mountains
Ibera Wetlands
Mar Chiquita
© 2018 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
US Dept of State Geographer
Google Earth
Imagery Date: 12/13/2015 2°47'21.40" N 42°11'44.56" W elev -4359 m eye alt 4094.82 km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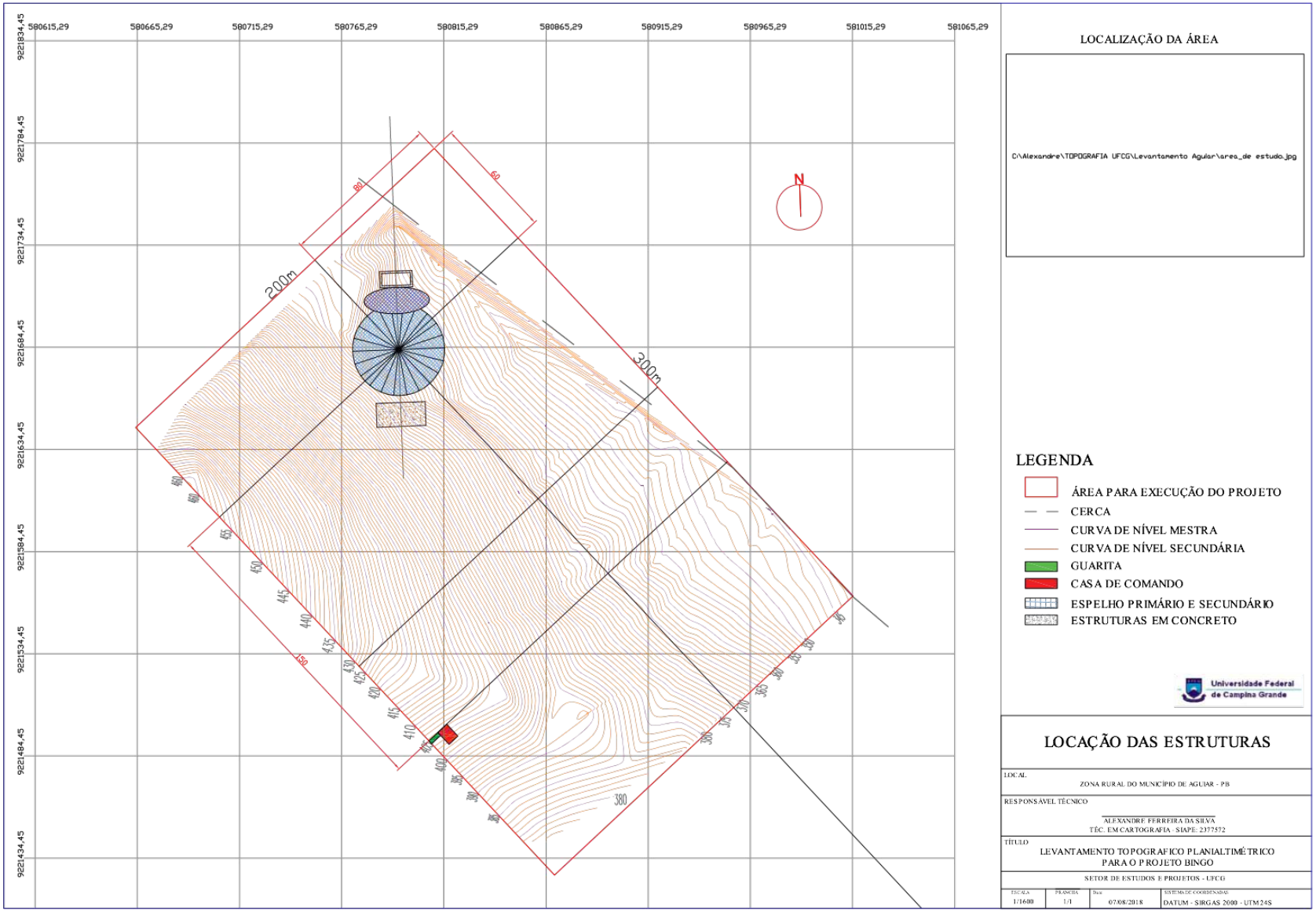
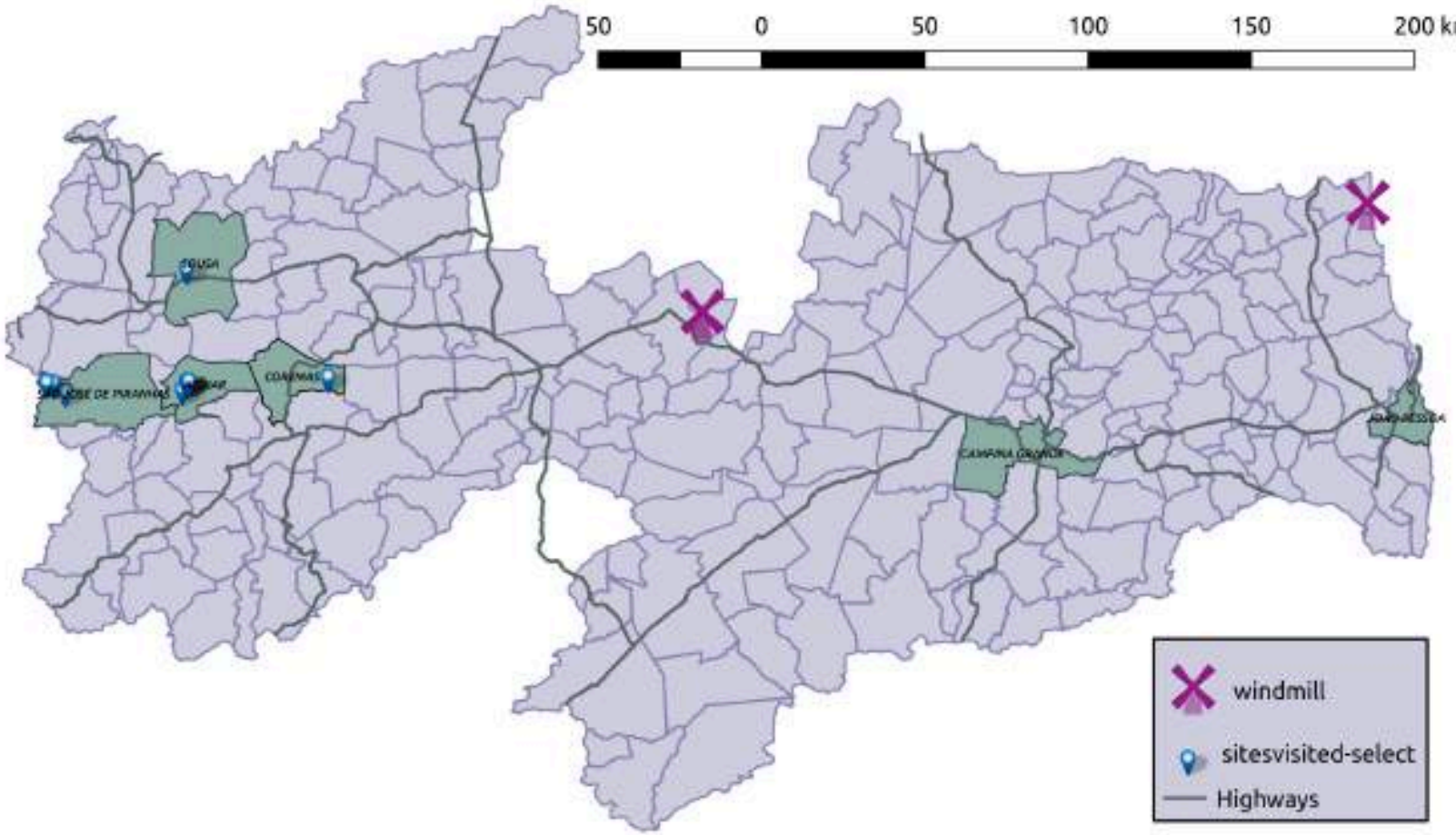


PRODUCED BY AN AUTODESK STUDENT VERSION

Produção: Andreia Souza

C. A. Wuensche (2018)



Peel et al (arXiv:1811.09464)

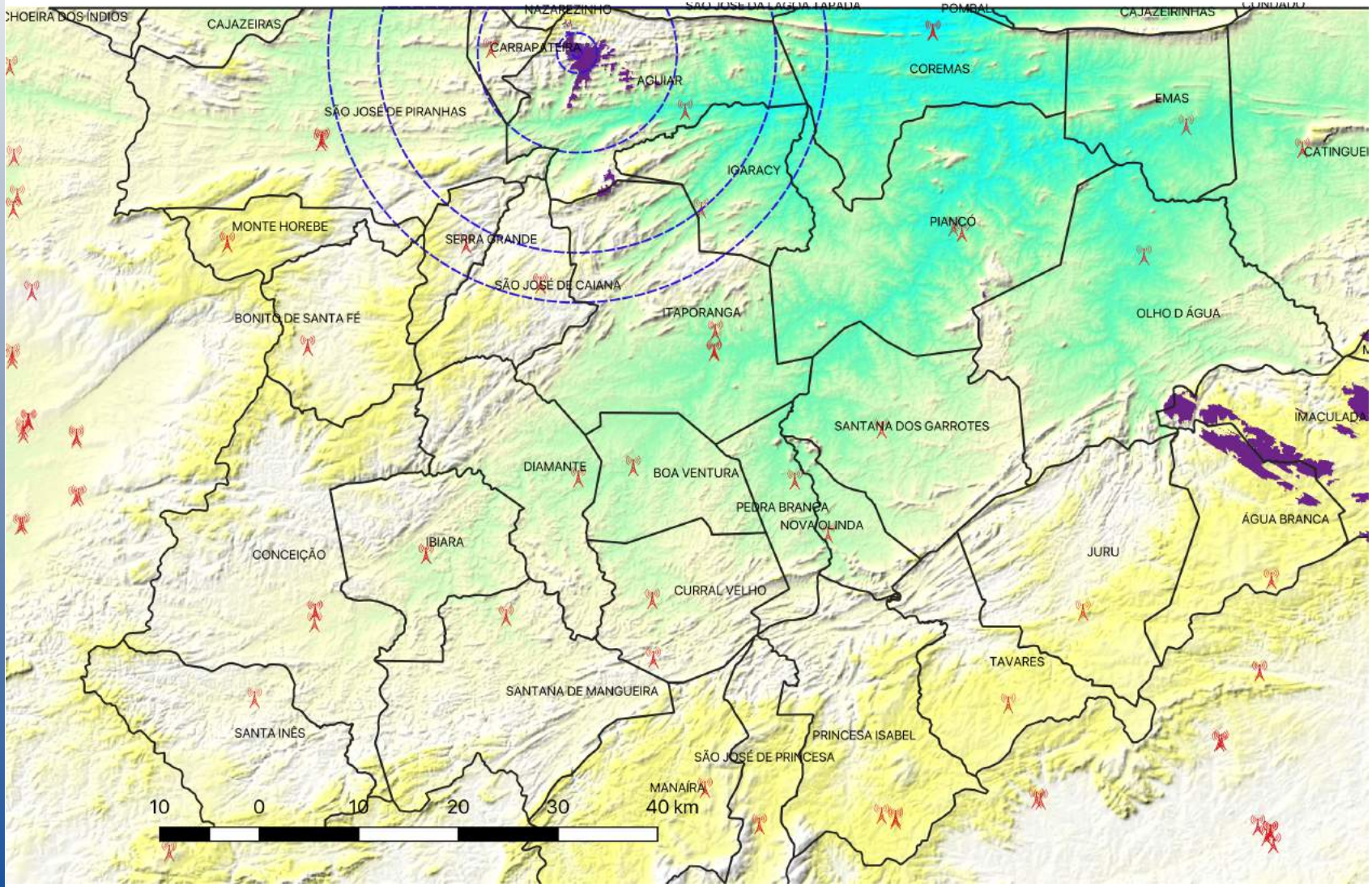
Serra da Catarina, Vale do Piancó (PB)
Lat: 07° 02’ 57.1” S
Long: 38°15’ 46"W

Crédito: M. Peel

Foto: M. Peel

Foto: M. Peel

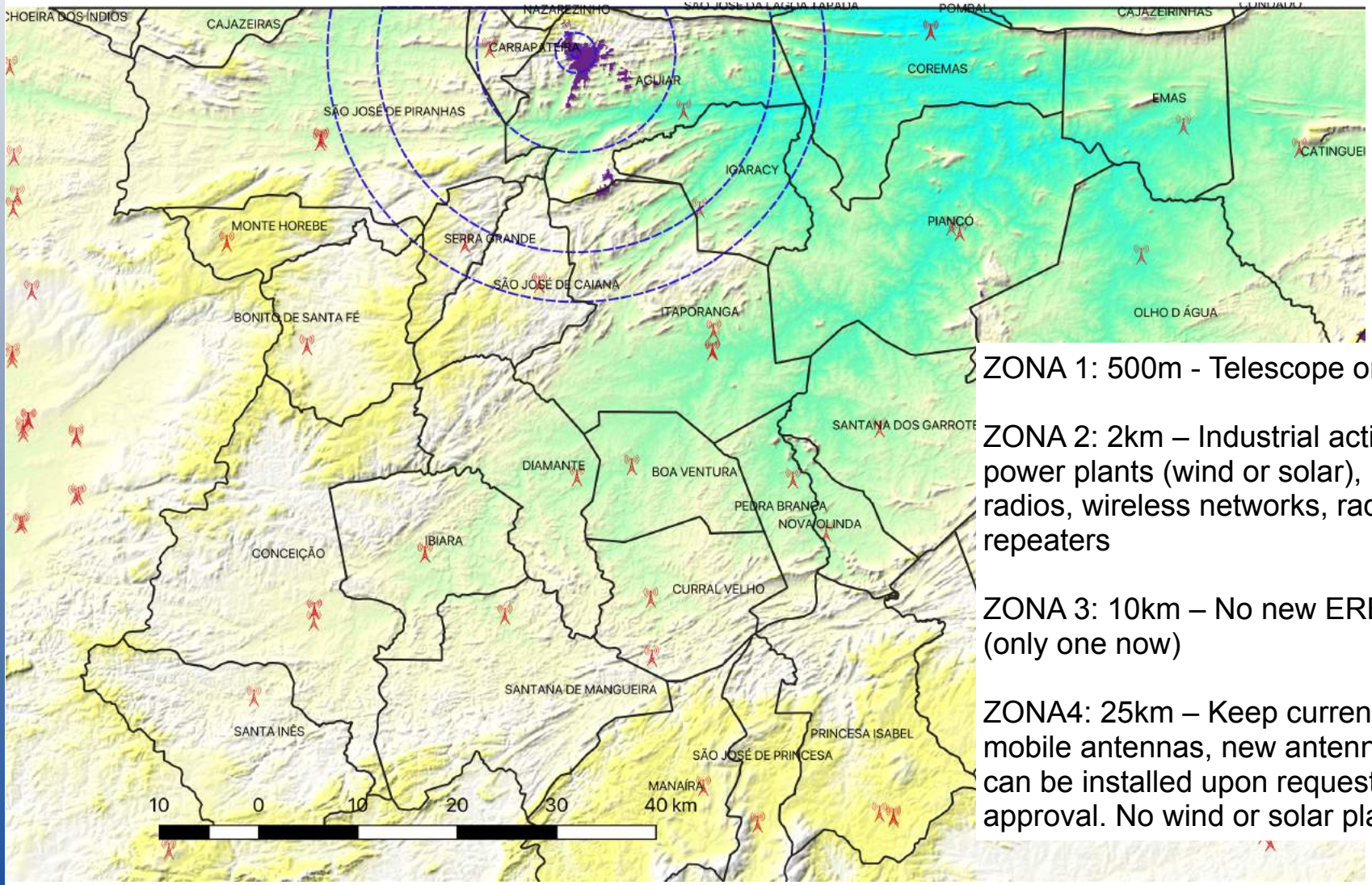
Silence zone proposal



Produção:L. Barosi

C. A. Wuensche (2018)

Silence zone proposal



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.

Produção: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 October 2018

- Large telescope → **need to find a company to fabricate the dishes**
- Large horns → **fabrication process understood, need to reduce costs for 50**
- 1/f noise → **Correlation receiver (needs to be reduced)**
- Calibration and stability → **use Moon and planets for additional calibration**
- Sidelobe pick-up → **careful optical design (horn testing showed quite good rejection for 1st/2nd lobe and front/back lobe rejection**
- Radio Frequency Intereference → **Mobile quiet zone has been already requested to the state authorities**
- Atmospheric fluctuations → **not a serious problem for BINGO frequencies**
- Bright foreground emission→ **Component separation techniques (alla Planck)**
  - **Diffuse Galactic radio emission**
  - **Extragalactic point sources**

BINGO

BAOs from Integrated Neutral Gas Observations

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INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

USP

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SUPRA OMNES LUX LUCIS
Universidade Federal de Campina Grande

MANCHESTER 1824
The University of Manchester

UCL

ETH zürich

Yangzhou University

IAS Orsay

UNIVERSIDAD DE LA REPÚBLICA URUGUAY

BINGO

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UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

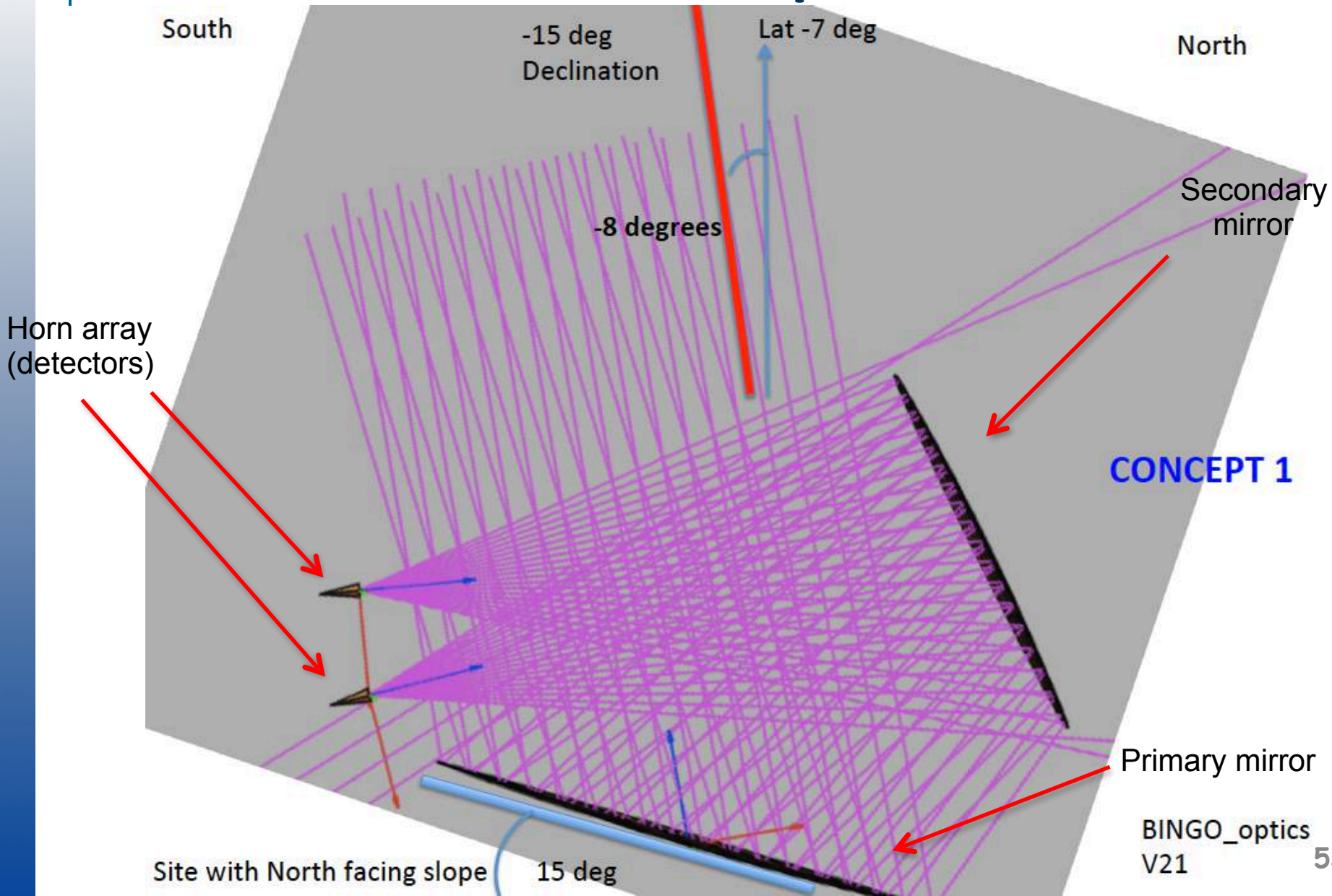
UNIVERSIDAD DE LA REPÚBLICA URUGUAY

Thank you!

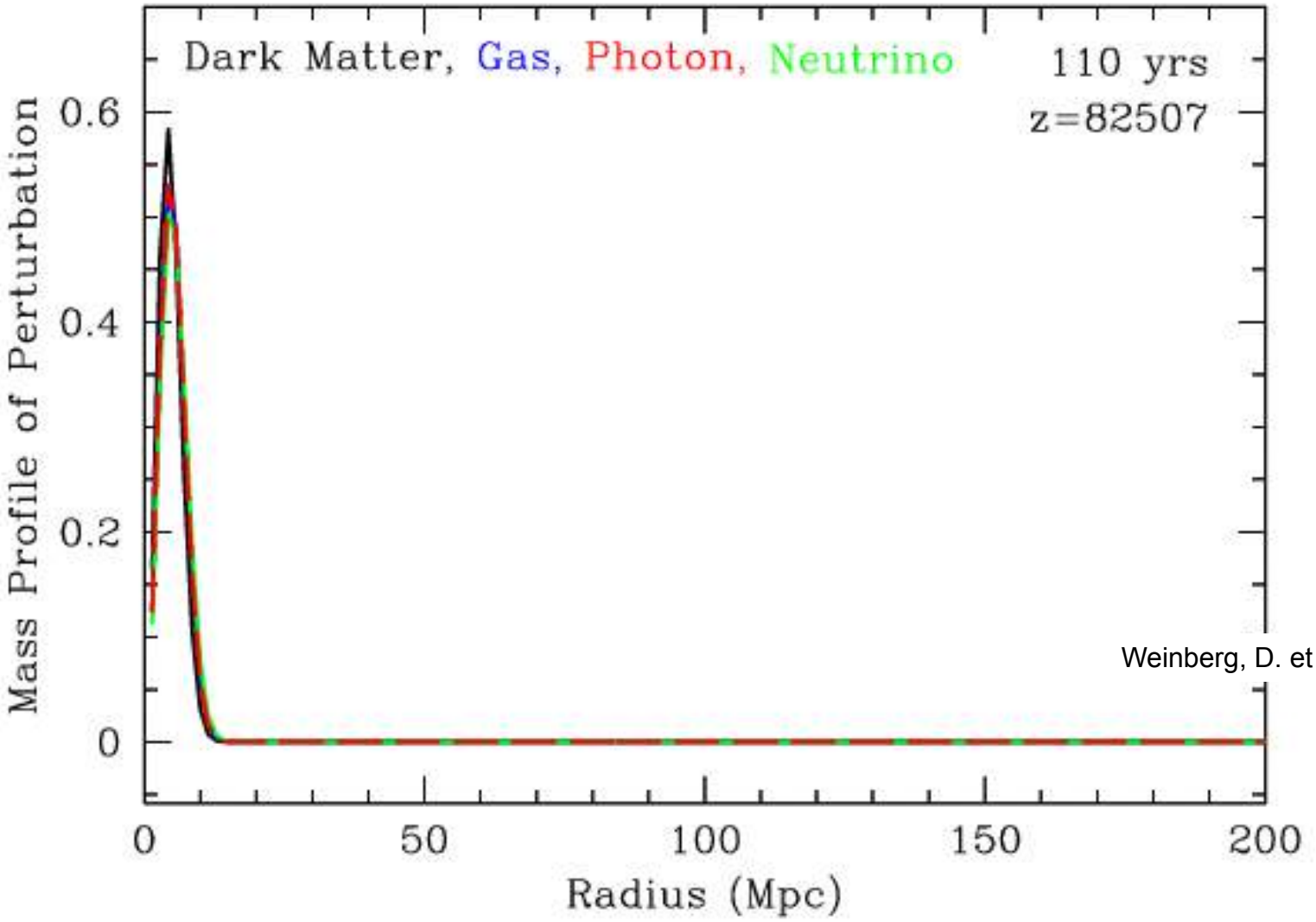
Please visit us at http://www.bingotelescope.org

Sketch of 3-D model of optics

Picture by Bruno Maffei



The evolution of perturbations for various cosmic components, in different cosmic times.



Weinberg, D. et al (2013)

After decoupling there is a wave of matter and dark matter, which will gravitationally converge to a common radius.

Animation: http://burro.case.edu/Academics/Astr328/Notes/StructForm/BAO.html

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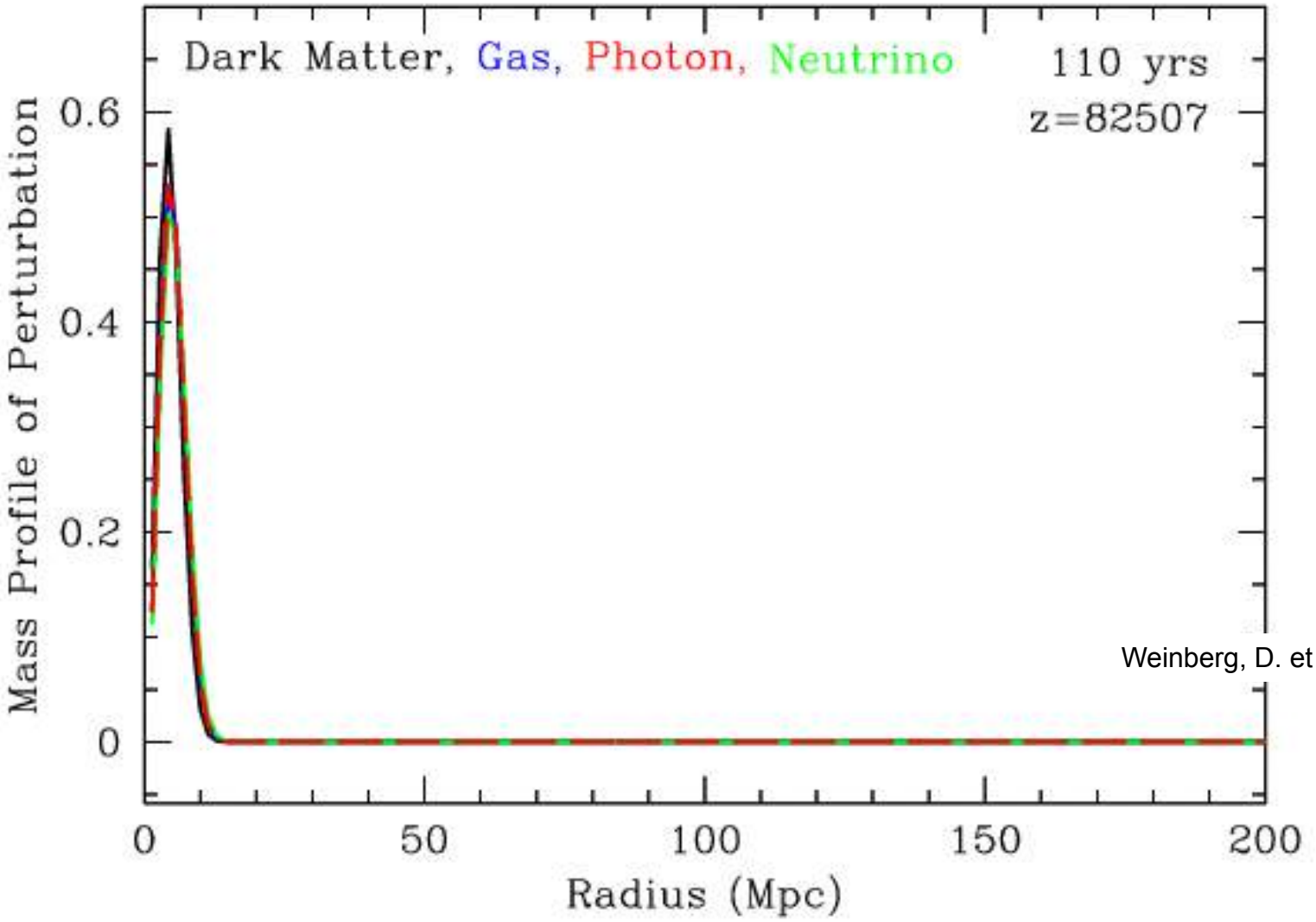

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RR
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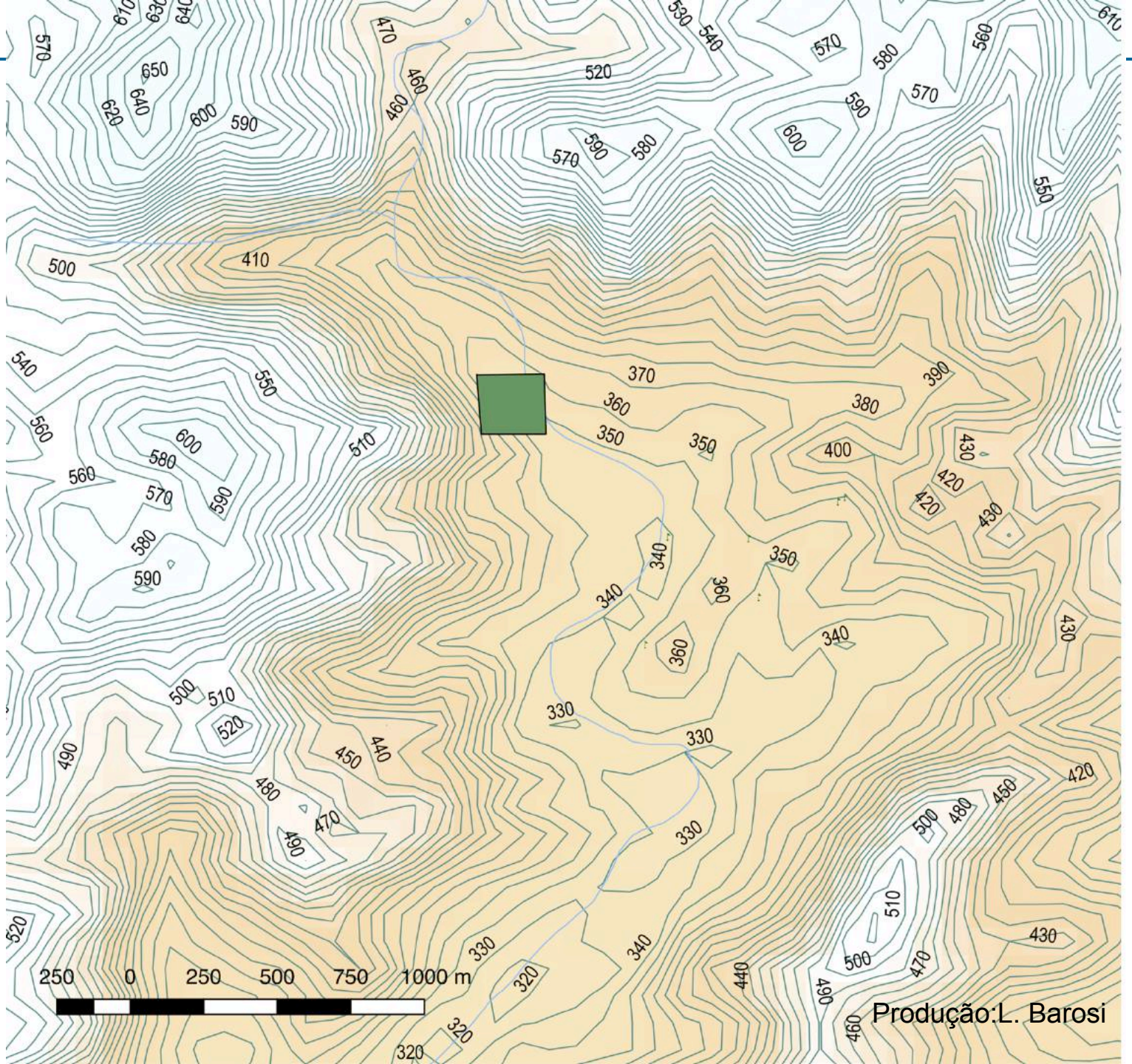
MA
RN
PB
PI
PE
AL
Brasil
AC
TO
SE
RO
Peru
MT
BA
GO
Bolívia
MG
ES
MS
2.000,00 km
SP
RJ
Paraguai
PR
Chile
SC
RS
3.325,70 km
Uruguai
Argentina
INPE Headquarters



Produção:L. Barosi

VÉRTICE	LONGITUDE	LATITUDE
V1	38° 15' 59,244" W	7° 2' 30,611" S
V2	38° 16' 3,998" W	7° 2' 35,068" S
V3	38° 16' 10,689" W	7° 2' 27,944" S
V4	38° 16' 5,935" W	7° 2' 23,488" S

Universidade Federal de Campina Grande

Legenda

- Poligonal
- Curvas secundárias
- Curvas mestras
- Vértices
- Cerca

Localização da Área

LEVANTAMENTO PLANIALTIMÉTRICO

Local: Zona Rural do Município de Aguiar UF: PB - Área: 6,00 ha	Prancha: 01/01	Data: 09/07/2018
Resp Técnico: Alexandre Ferreira da Silva, Técnico em Cartografia, SIAPE: 2377572	Escala: 1:1.500	

Sistema de Coordenadas Geográficas DATUM: WGS84

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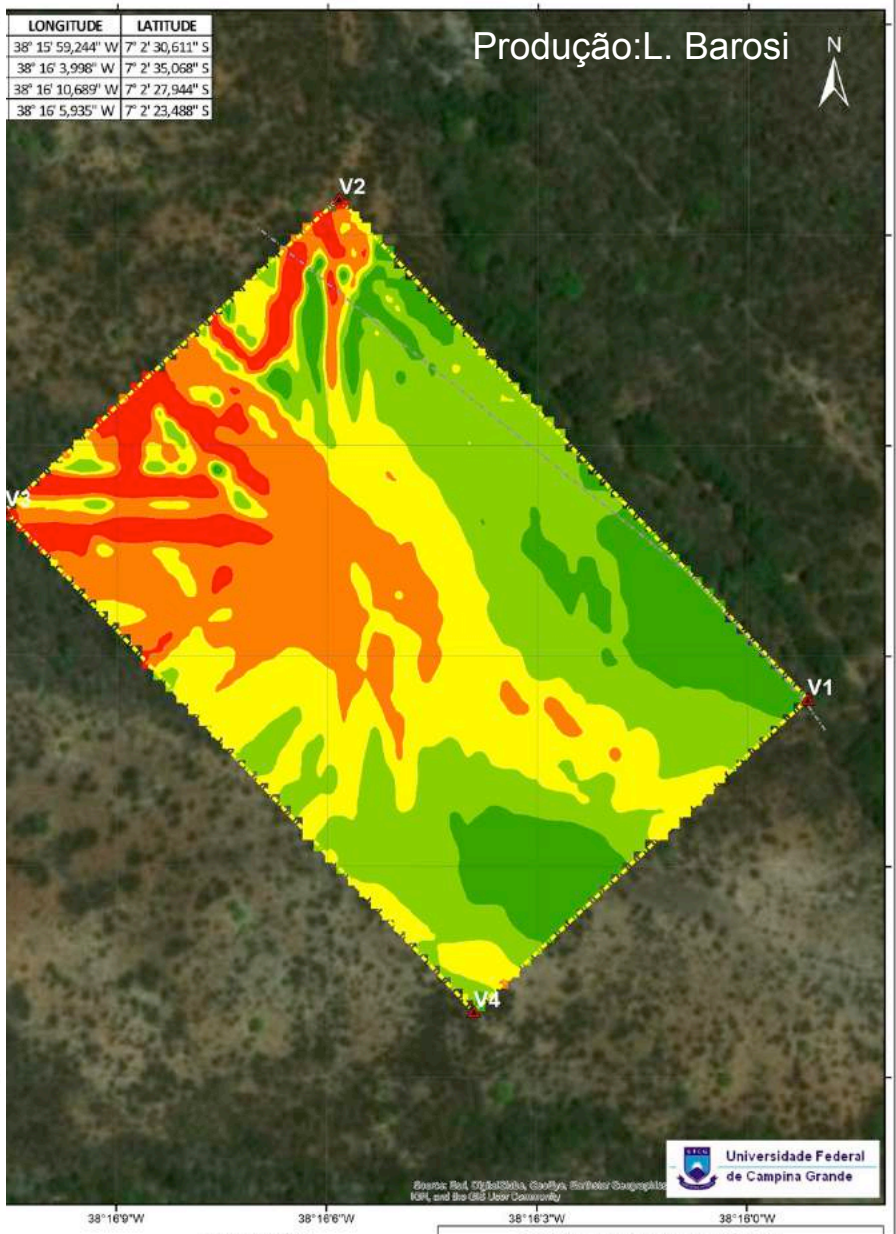

Universidade Federal de Campina Grande

Graus

Localização da Área

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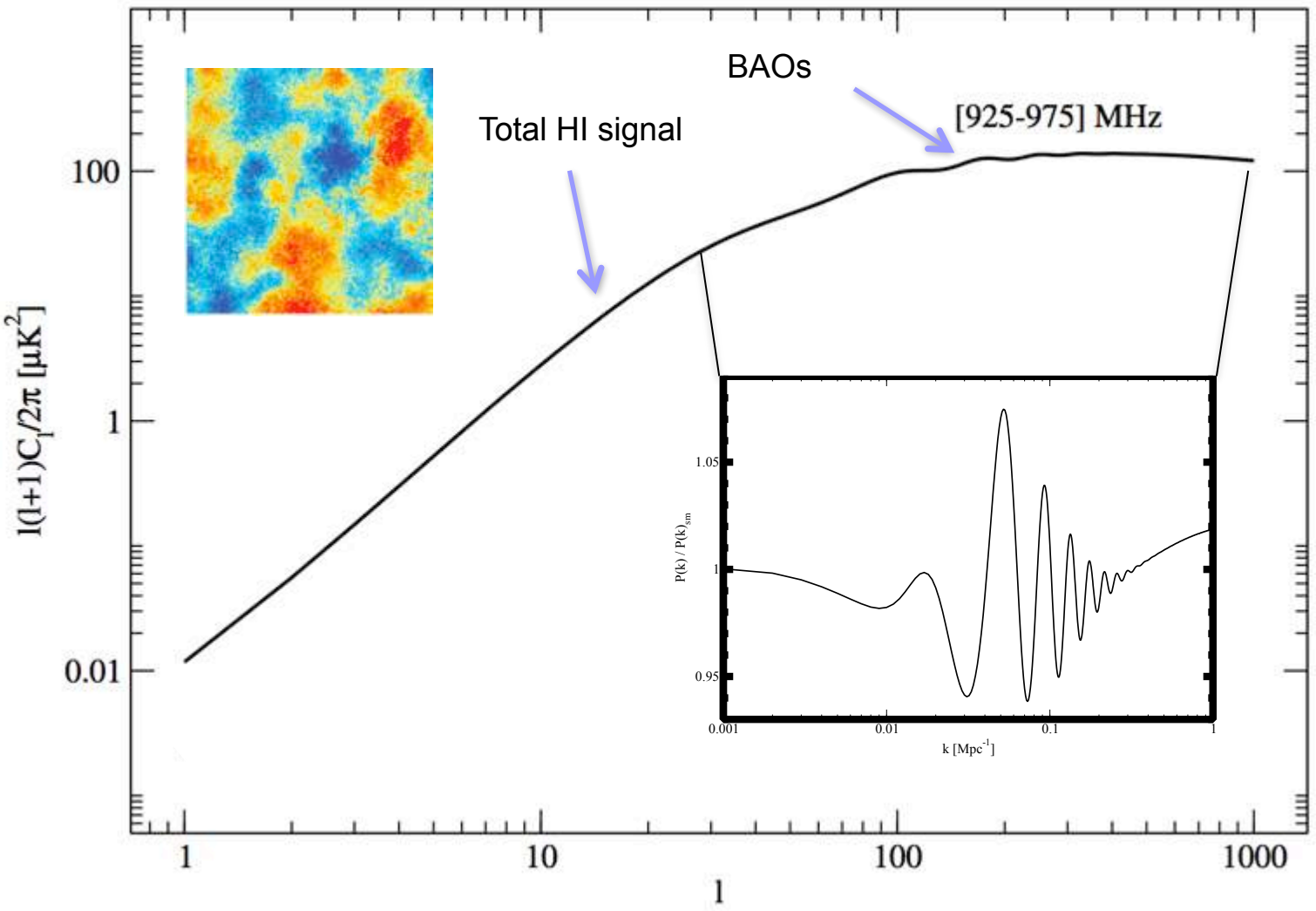
Sistema de Coordenadas Geográficas DATUM: WGS84

Talk outline

- Cosmological relevance
- The BINGO telescope
- Current status

The HI signal power spectrum

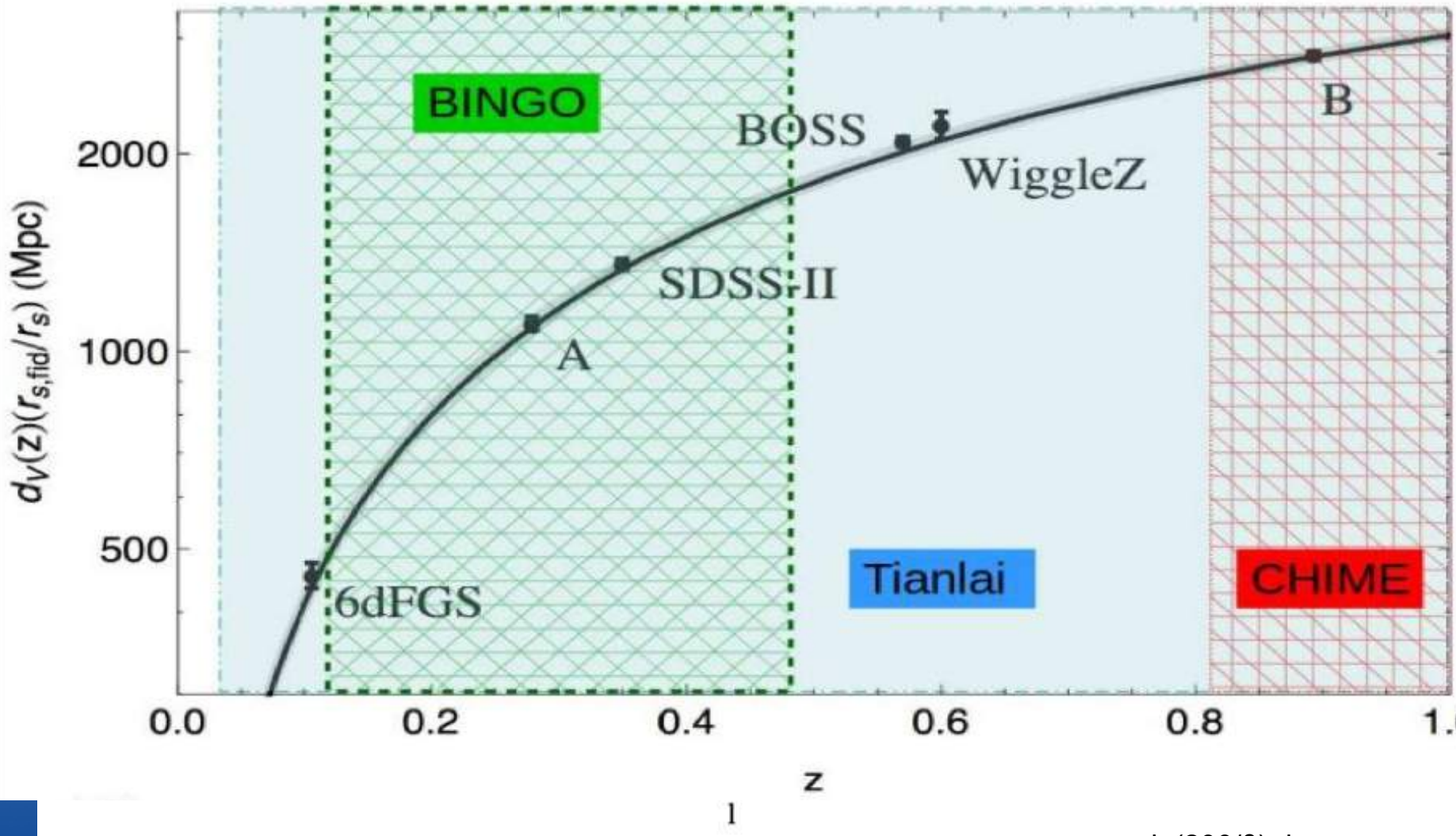
Cosmological HI signal is weak! (≈100 μK rms) and on degree scales



l≈(200/θ) degrees

The HI signal power spectrum

Cosmological HI signal is weak! (≈100 μK rms) and on degree scales



l≈(200/θ) degrees

C. A. Wuensche (2018)