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INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

S.A.B.
Sociedade Astronômica Brasileira

The BINGO radio telescope project update

São Paulo, September 09, 2019

Carlos Alexandre Wuensche and the BINGO Collaboration

ca.wuensche@inpe.br

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

Era of precision cosmology

- Cosmology is now in a golden area with plenty of data (Planck, SDSS, DES and other large surveys)
- 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?

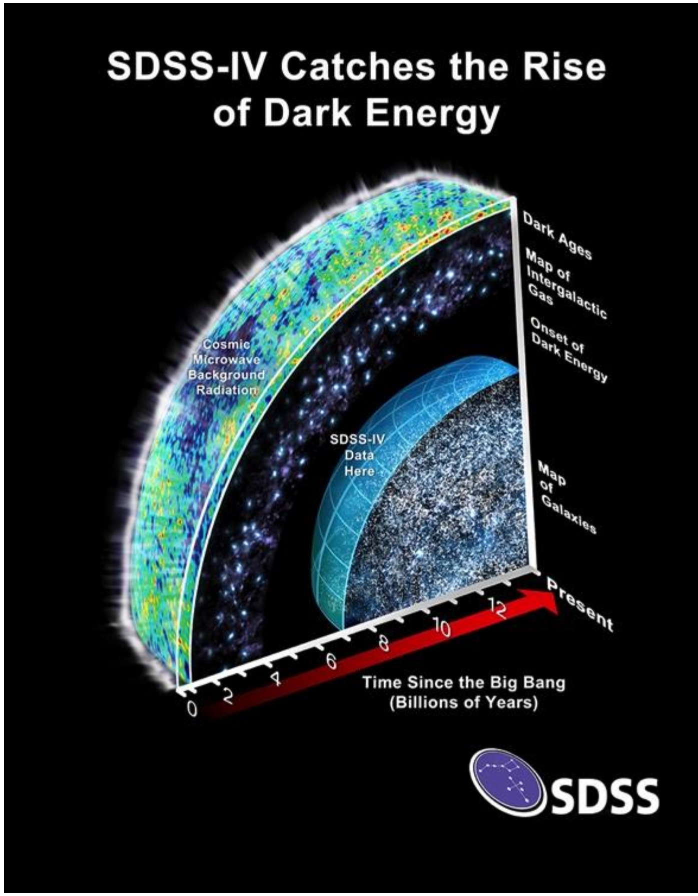
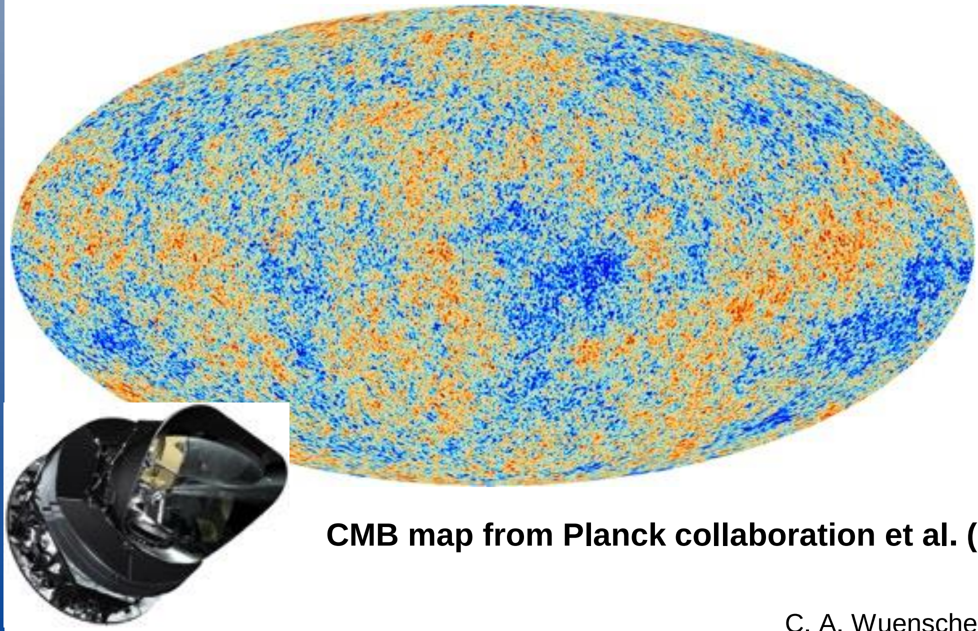
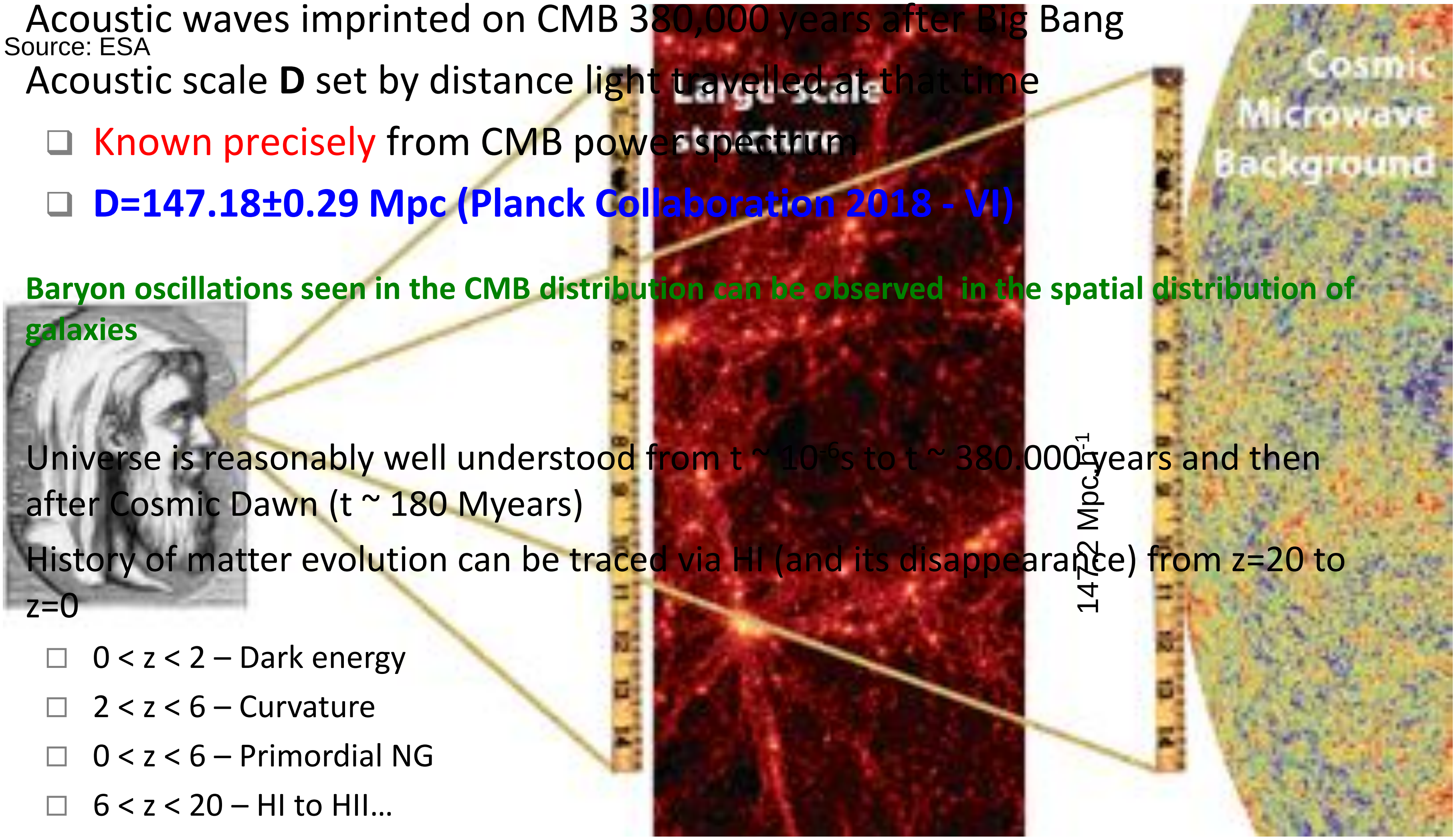


Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.



CMB map from Planck collaboration et al. (2018)

21 cm cosmology and Baryon Acoustic Oscillations (BAOs)



Source: ESA

- 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)**

- **Baryon oscillations seen in the CMB distribution can be observed in the spatial distribution of galaxies**

- 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
  - $6 < z < 20$ – HI to HII…

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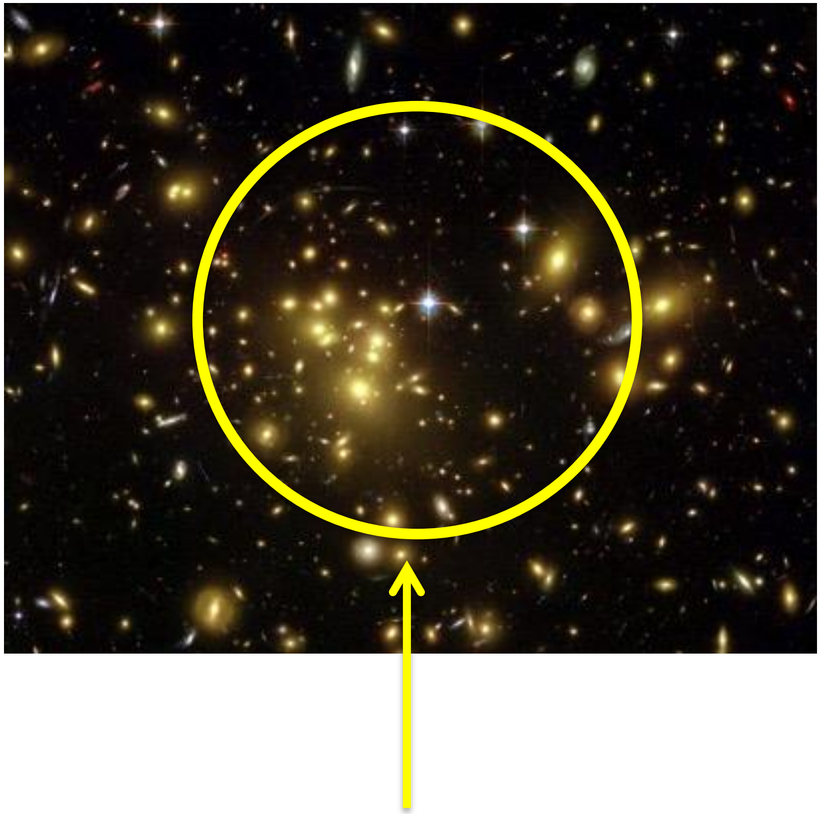
Alternative to optical BAO: HI Intensity mapping

- Use relatively large beam on the sky
  - ☐ Measure HI *fluctuations*
- HI intensity mapping can be used as mass tracer, probing distortions in redshift space
- No competition in the radio
- Complementary to large optical surveys
- Similar to CMB, using:

$$\Delta T_{CMB} = \Delta T_{CMB}(\theta, \phi, z = 1100)$$

$$\Delta T_{HI} = \Delta T_{HI}(\theta, \phi, z)$$



- Large beam on the sky (≈1 deg) contains many galaxies.
- HI signal is measured through its overall intensity

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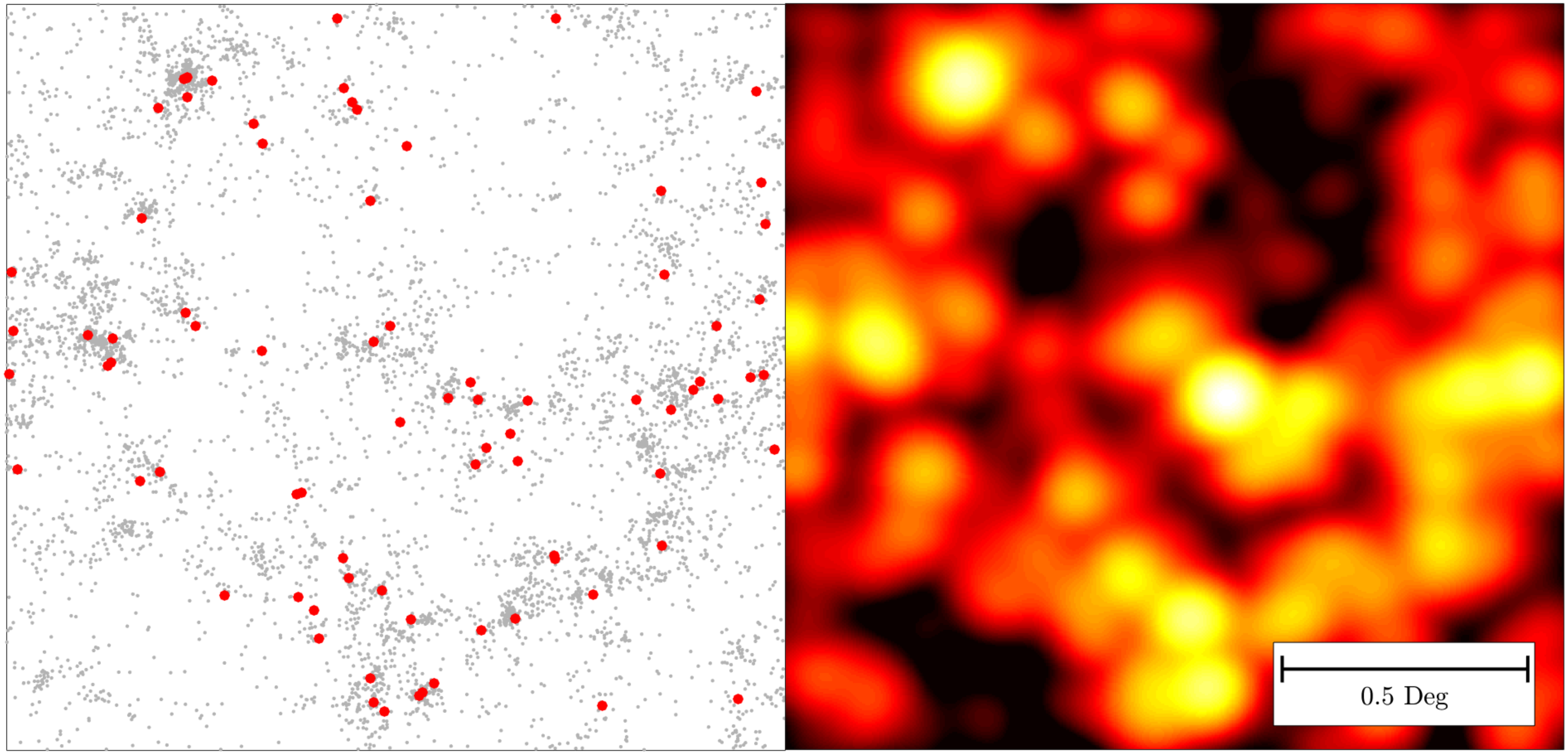
The intensity mapping concept

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)

The BINGO Telescope

BAOs from Integrated Neutral Gas Observations

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BINGO concept (August 2019)

Instrument characteristics

- Dish diameter : 40m and 34m
- Focal length (m): 63.2m
- Resolution (°): ~ 0.67
- Number of feed horns : 49 (dual pol.)
- Horn opening: 1.9m
- Horn length: 4.3m
- Focal plane: 13,3 m (H) x 13,2 m (W)

- Estimated scan area: ~ 5300□
- No cryogenics : $T_{sys} \approx 70K$
- Frequency range (MHz): 980 – 1260
- Z interval: 0.13 - 0.48
- Channel resolution: ≤ 1 MHz

Fixed wire-mesh parabolas

No moving parts

Transit telescope

Most components "off-the-shelf"

Guiding principle : simplicity !

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Project status

- BINGO is under construction
  - horn prototype completed and successfully tested
  - transitions, polarizer, transitions and magic tee prototypes completed and successfully tested
  - receiver main components (first stage LNAs and filters, secondary LNAs and filters) successfully tested
  - RFI initial measurements on site completed => permanent monitor received from Swiss periodically carried to site for inspection
  - optical design completed
  - Legal issues regarding property, electrical power and silence protection zone handled by Paraíba collaborators and local authorities
  - Major Project Review → **July 8 to 10, 2019. Green light to proceed to Phase 2.**
- About 80% completely funded
  - (total ~ R$ 17.5 M => ~ US$ 4,25 M)

Challenges as of October 2019

- Large telescope → **need to find a company to fabricate the dishes**
- Large horns → **fabrication process understood, need to reduce costs for 50. Donation of aluminum from private companies is being sought.**
- Calibration and stability → **use colfets and a CW source as internal calibration (full correlation receiver desired), sky radio sources for external calibration**
- Receiver 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 for the current horn array. TBC during commissioning**
- Radio Frequency Interference → **Mobile quiet zone has been already requested to the state authorities (both to State agencies and to ANATEL)**
- Support from Army Engineering Services → **road preparation and site cleaning and terrain planification (to implemented)**

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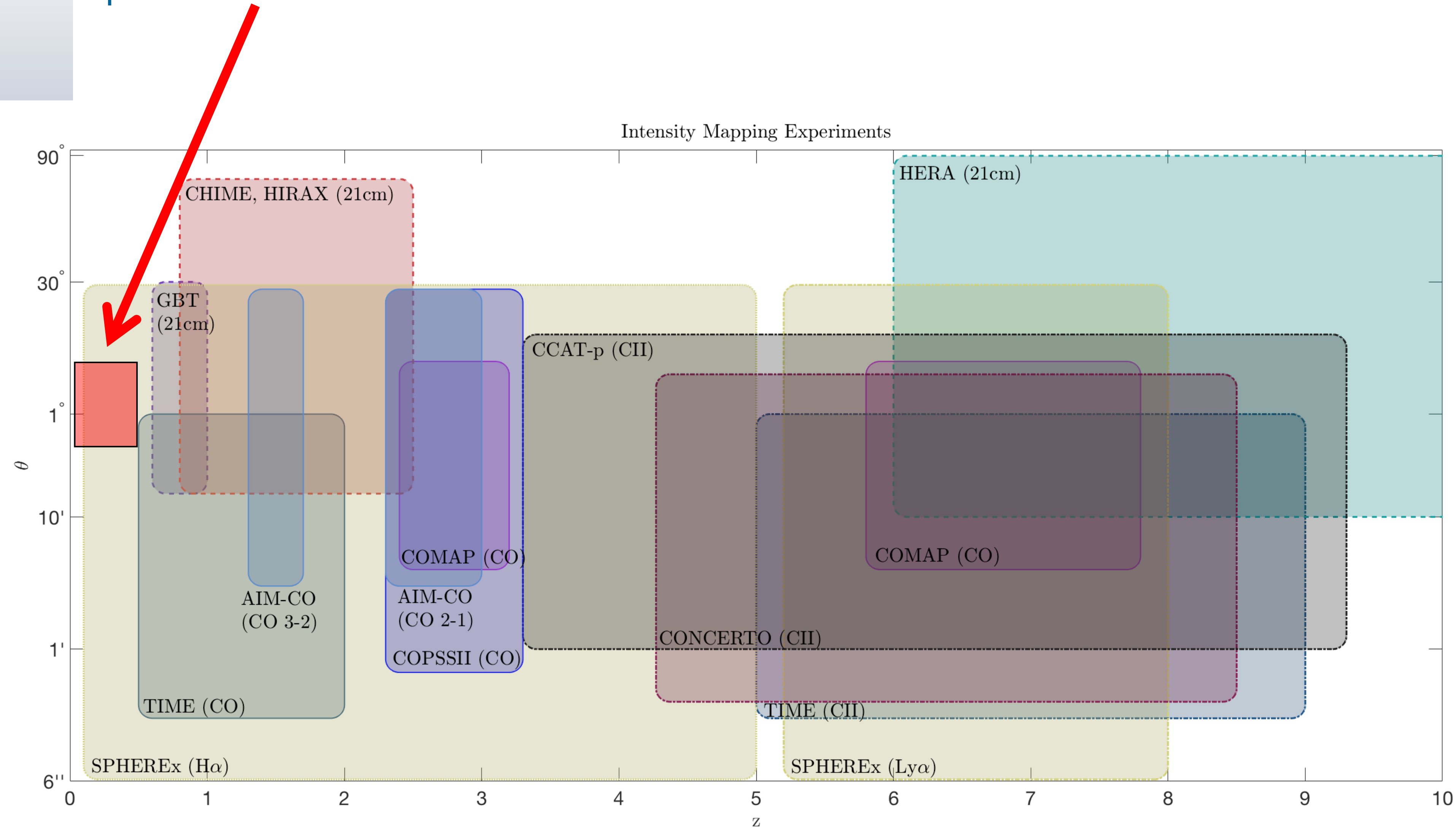
BINGO would fit here – Our update of pag. 44 of Kovetz et al (2017)



Kovetz et al, (arXiv:1709.09066)

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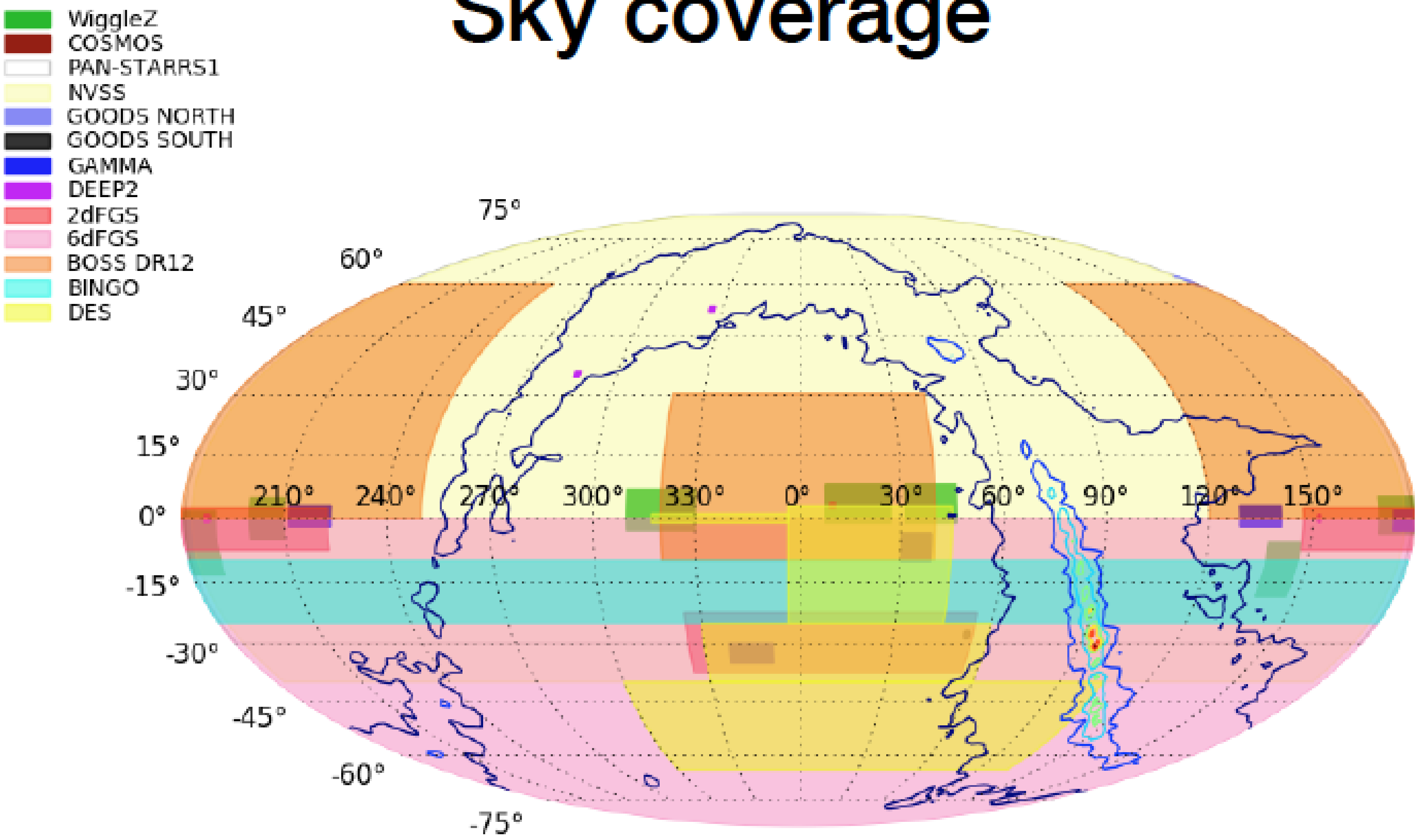
From Tianyue Chen

Sky coverage



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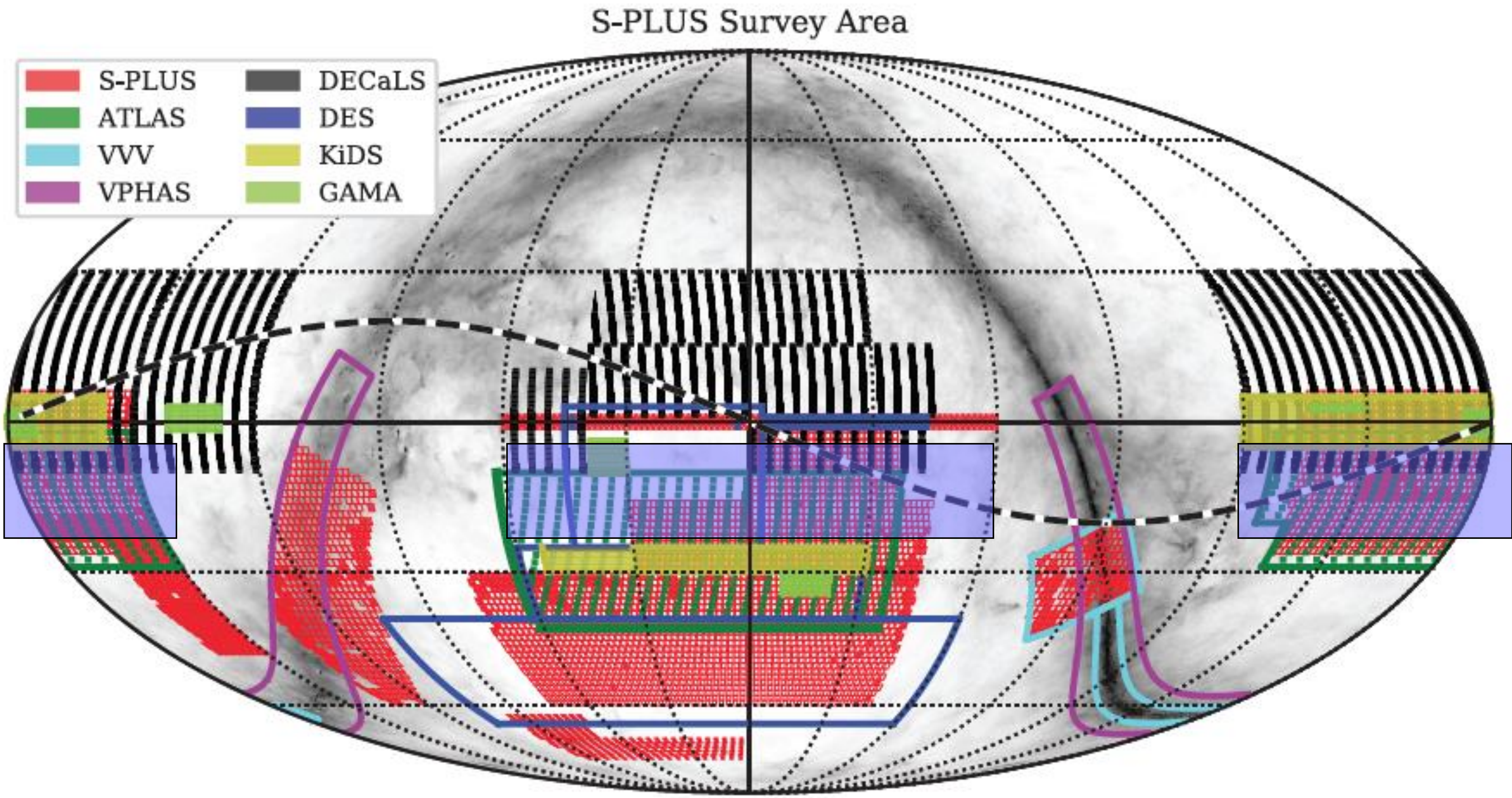

BINGO SUPERPOSITION

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Sketch of 3-D model of optics

Overal dimensions

Main Reflector

Paraboloid

R = 20 m

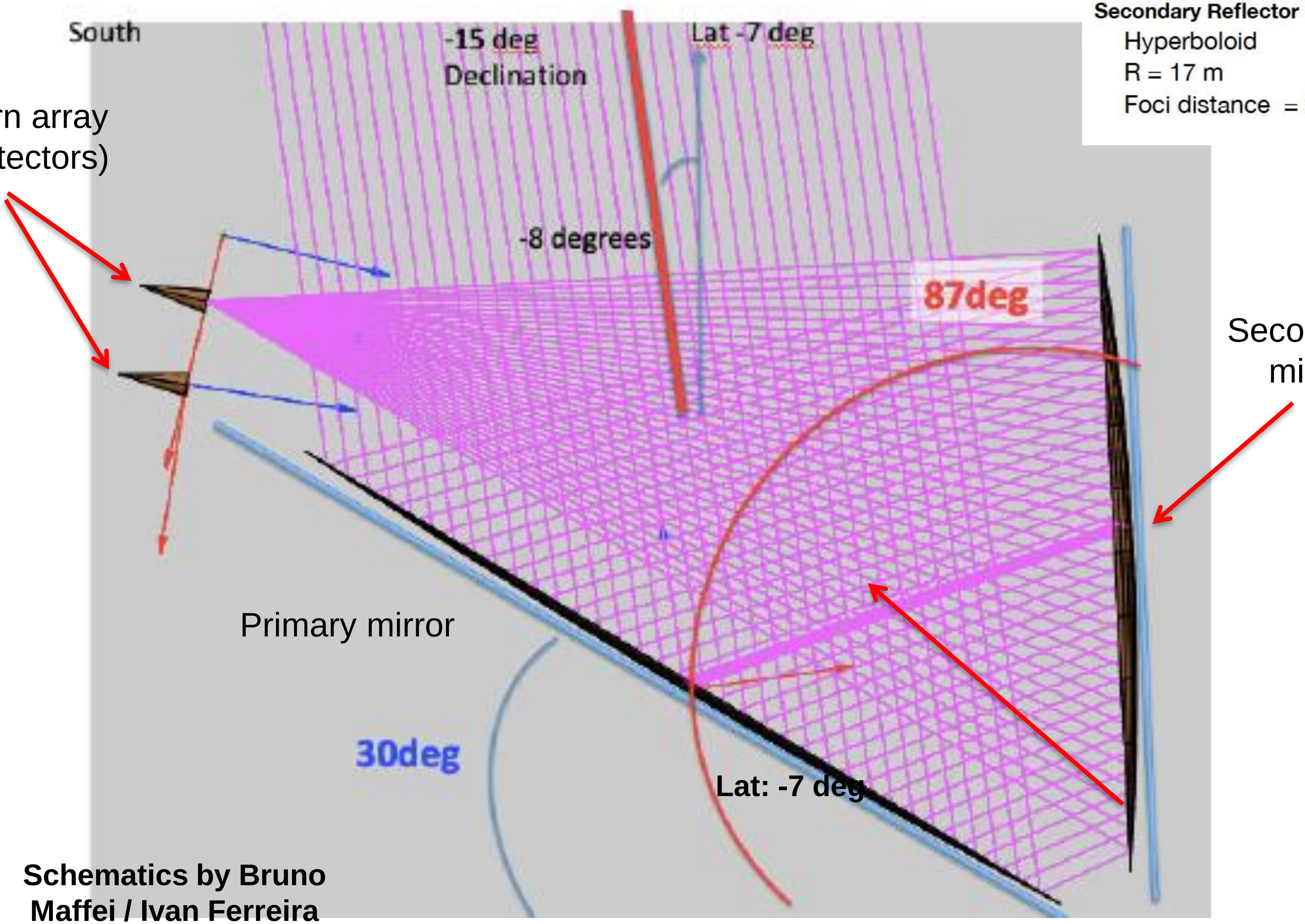
Focal Lengh = 140 m

Secondary Reflector

Hyperboloid

R = 17 m

Foci distance = 252 m



Horn array (detectors)

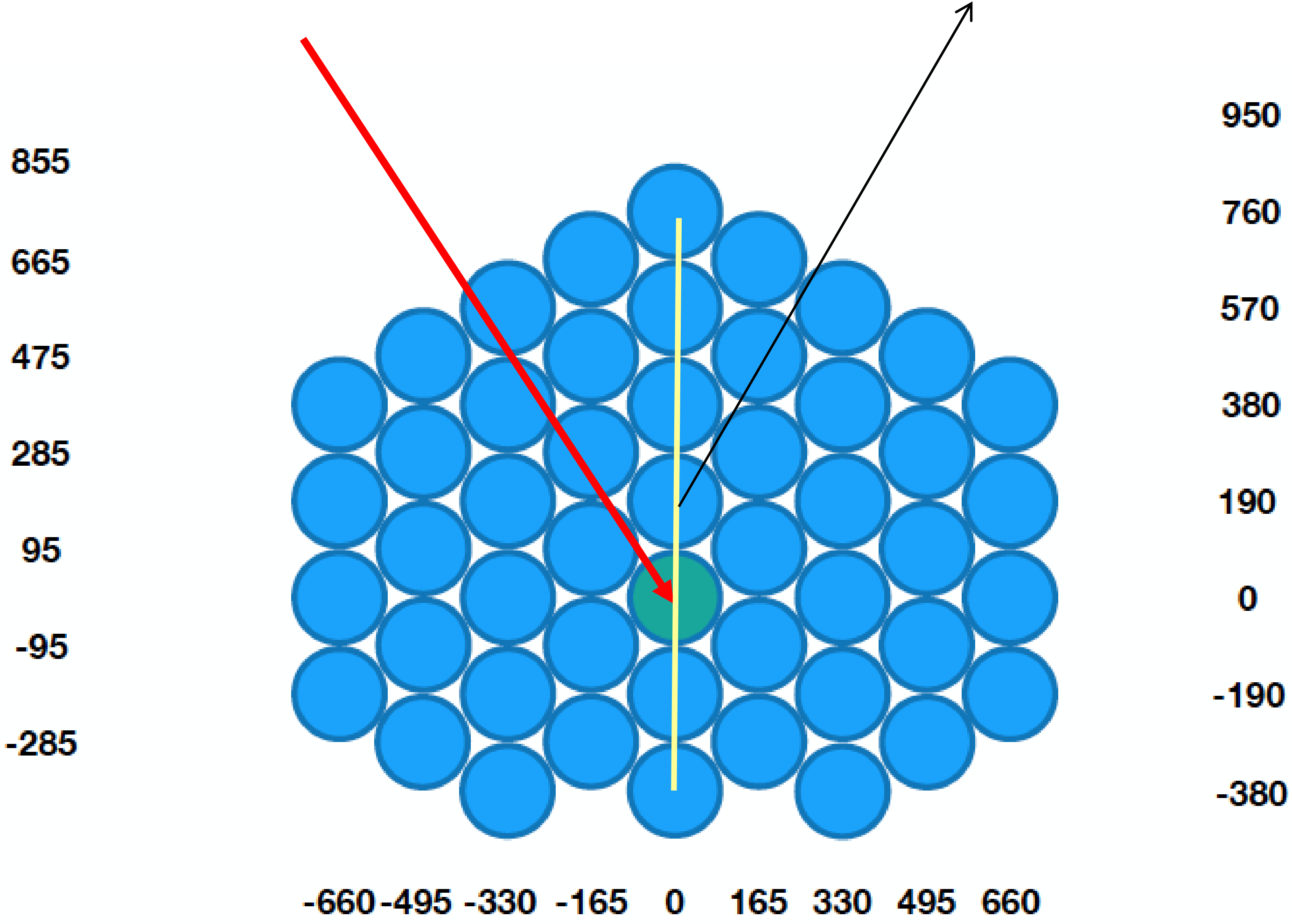
Secondary mirror

Primary mirror

Schematics by Bruno Maffei / Ivan Ferreira

Focal plane – 49 horns

Schematics by Bruno Maffei / Ivan Ferreira

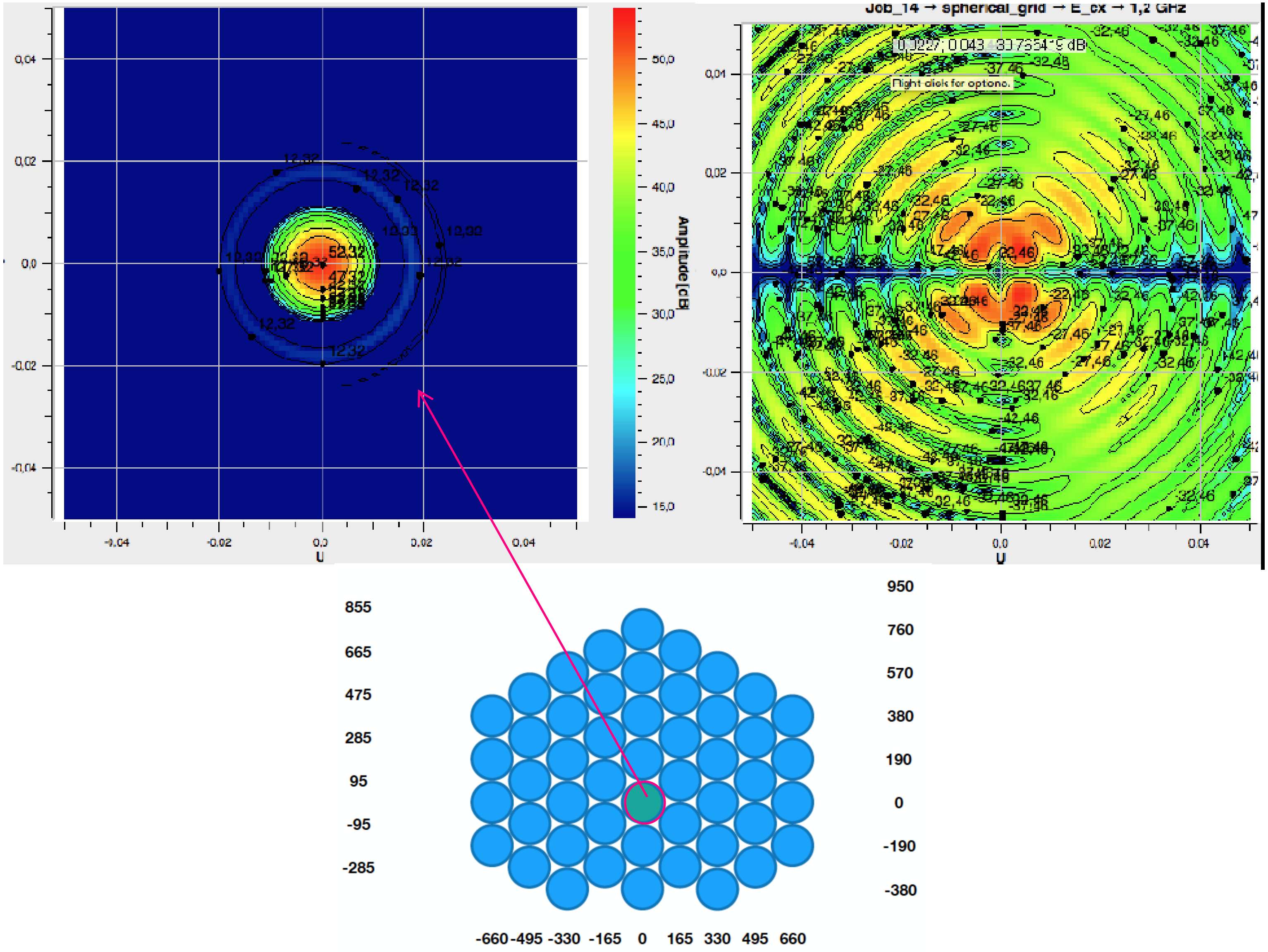


Central horn

Declination coverage: ~ 15 deg

Central Pixel

Schematics by Bruno Maffei / Ivan Ferreira



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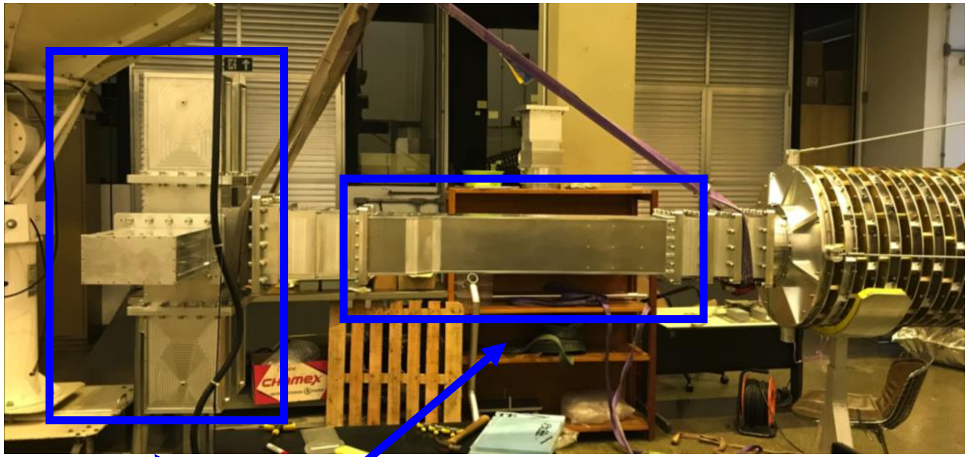

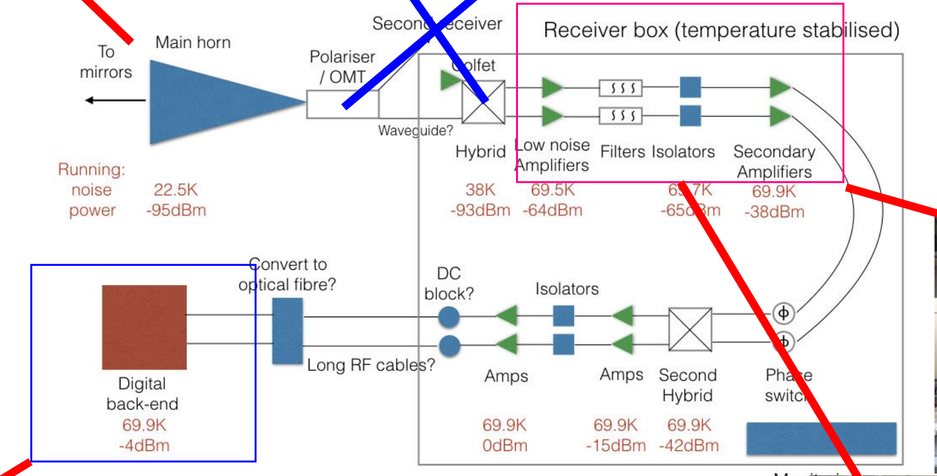

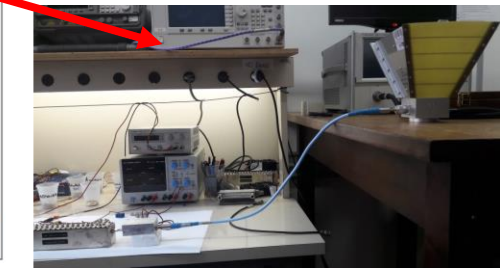

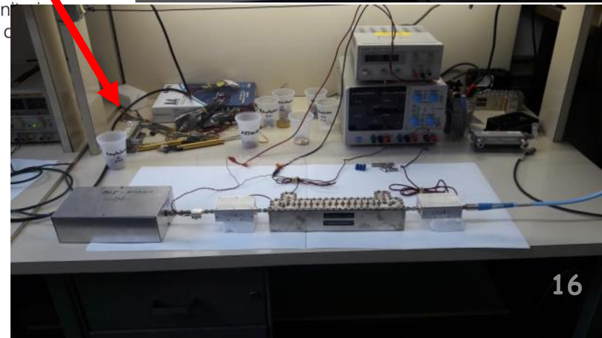

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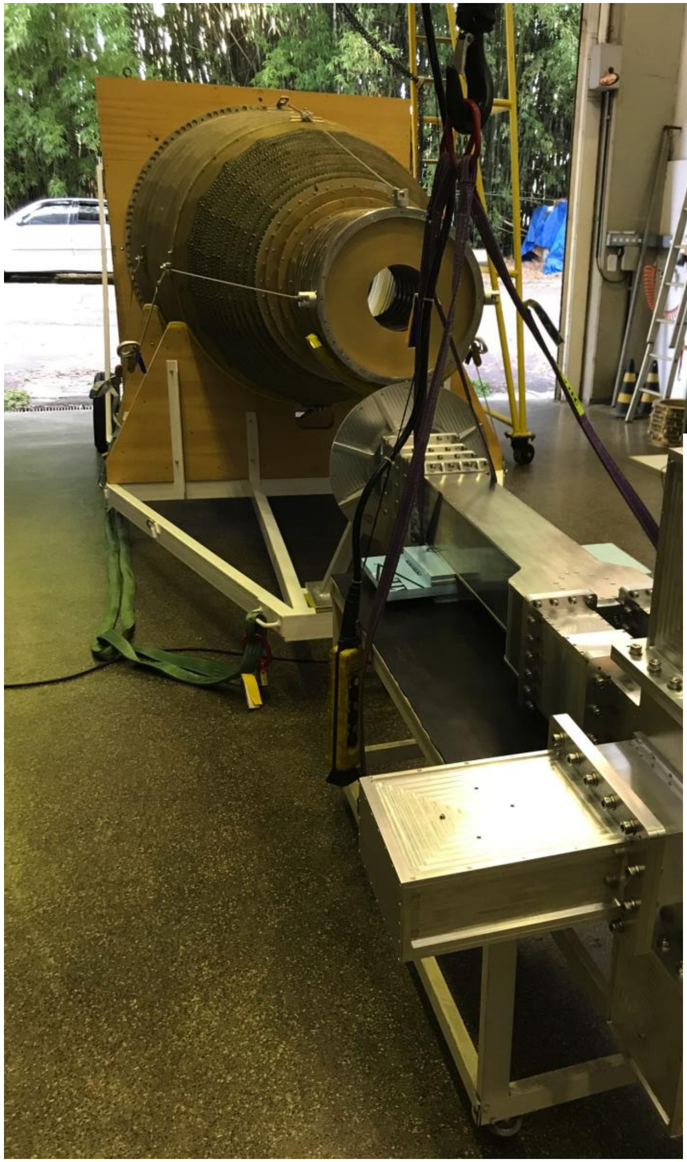

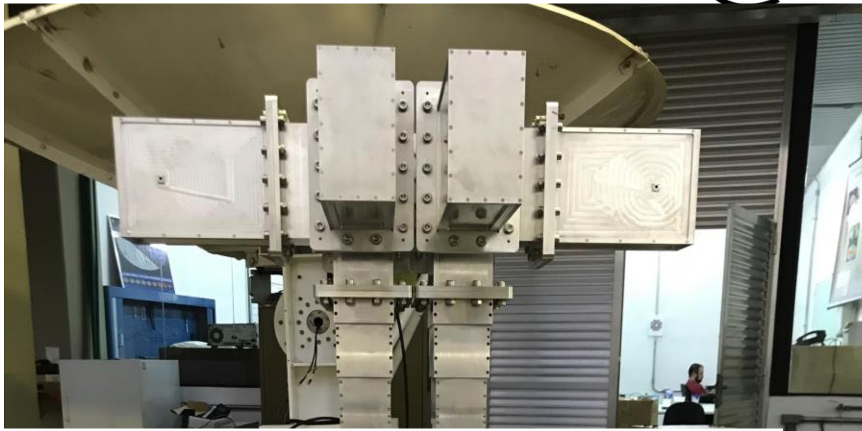

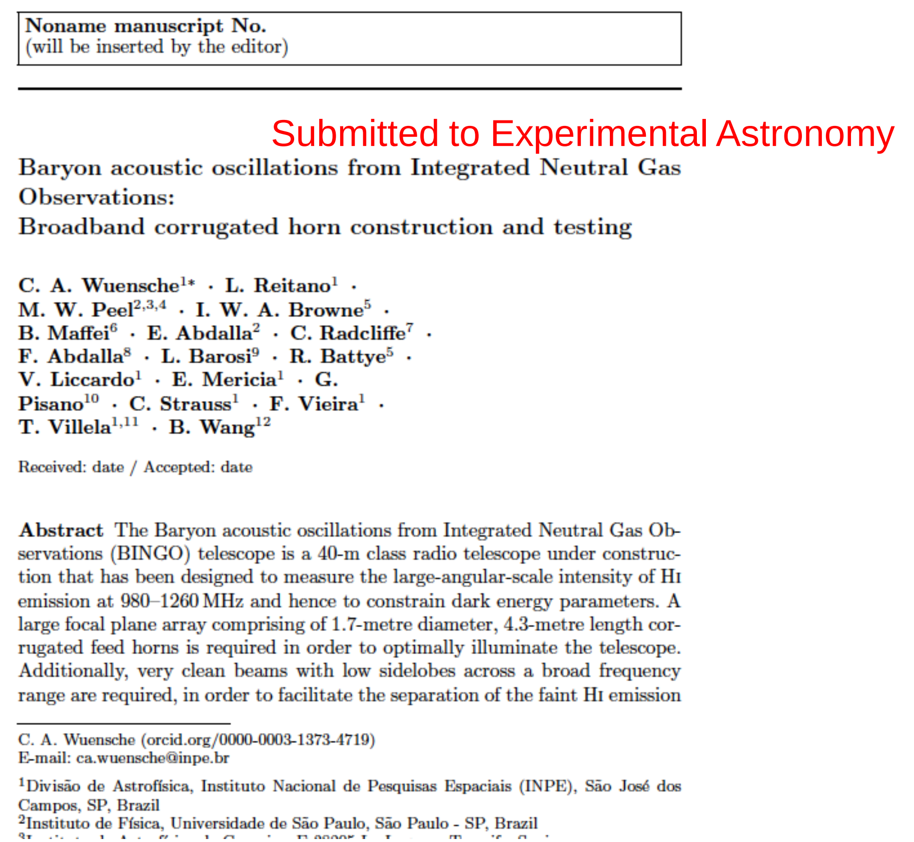

Noname manuscript No.
(will be inserted by the editor)

Submitted to Experimental Astronomy

Baryon acoustic oscillations from Integrated Neutral Gas Observations:
Broadband corrugated horn construction and testing

C. A. Wuensche[1*] · L. Reitano[1] ·
M. W. Peel[2,3,4] · I. W. A. Browne[5] ·
B. Maffei[6] · E. Abdalla[2] · C. Radcliffe[7] ·
F. Abdalla[8] · L. Barosi[9] · R. Battye[5] ·
V. Liccardo[1] · E. Mericia[1] · G.
Pisano[10] · C. Strauss[1] · F. Vieira[1] ·
T. Villela[1,11] · B. Wang[12]

Received: date / Accepted: date

Abstract The Baryon acoustic oscillations from Integrated Neutral Gas Observations (BINGO) telescope is a 40-m class radio telescope under construction that has been designed to measure the large-angular-scale intensity of HI emission at 980–1260 MHz and hence to constrain dark energy parameters. A large focal plane array comprising of 1.7-metre diameter, 4.3-metre length corrugated feed horns is required in order to optimally illuminate the telescope. Additionally, very clean beams with low sidelobes across a broad frequency range are required, in order to facilitate the separation of the faint HI emission

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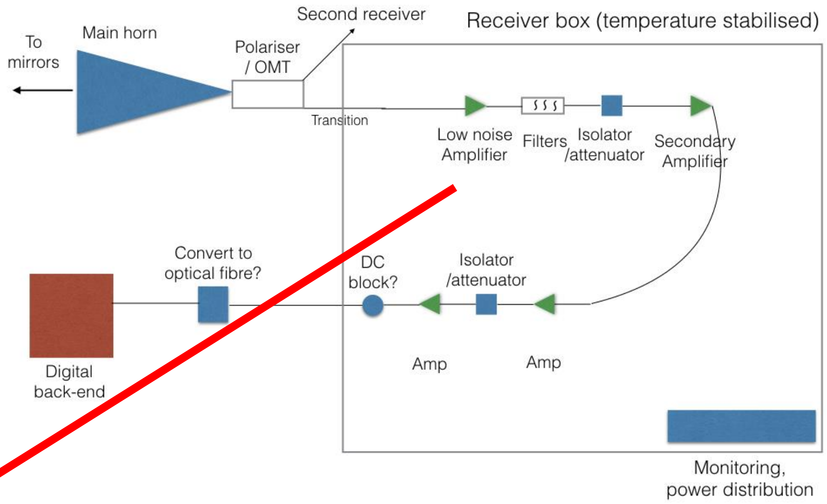
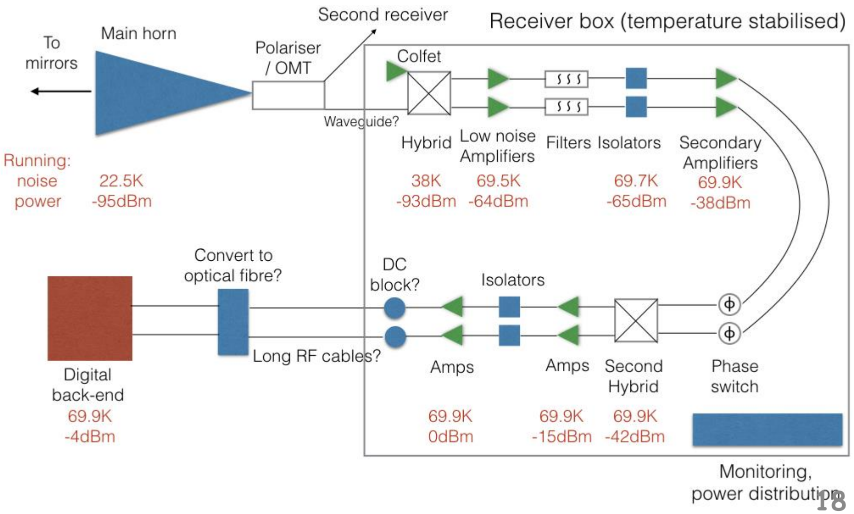
Receiver status

Photo: M. Peel @ INPE's lab

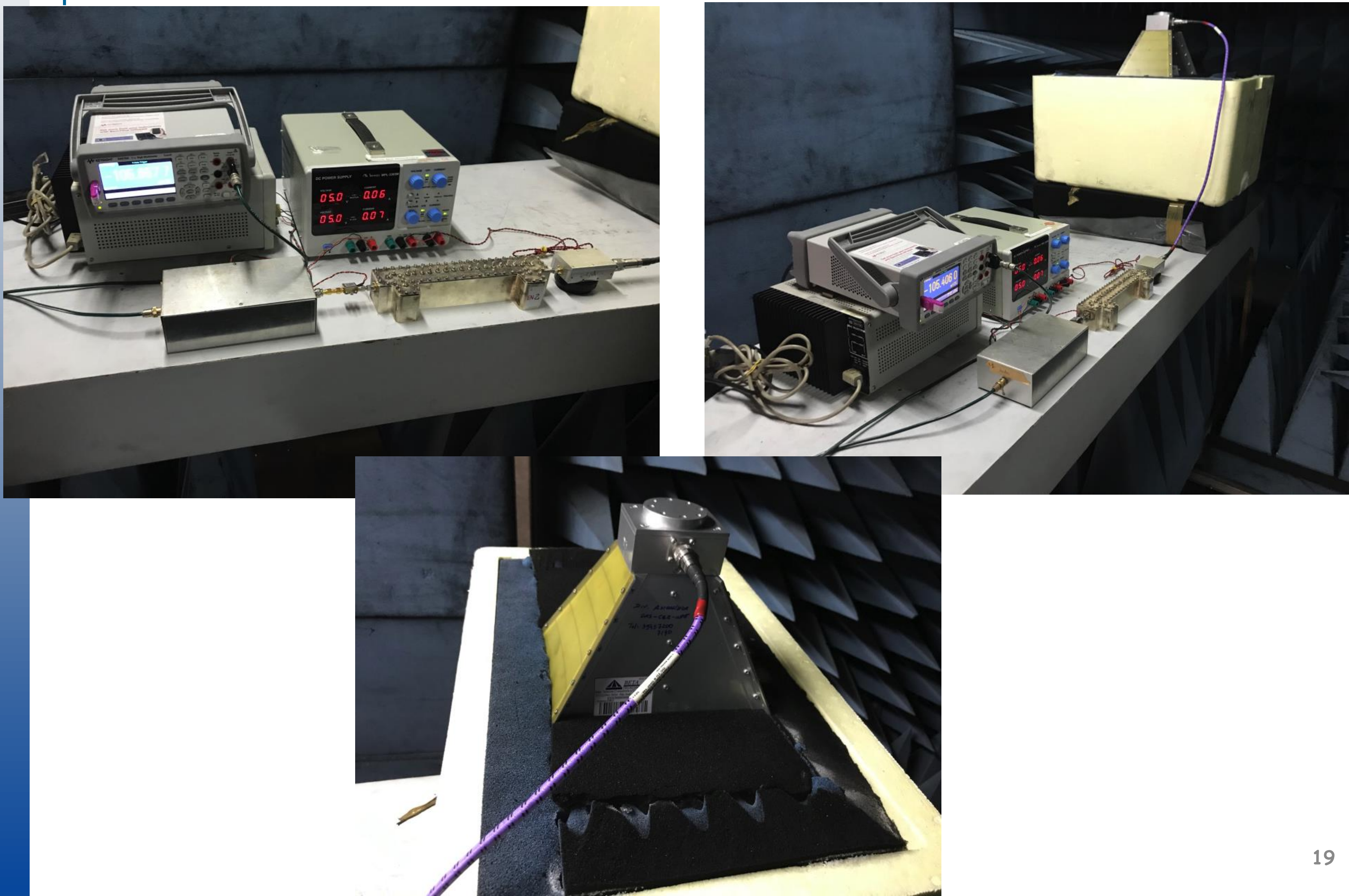
Simple radiometer

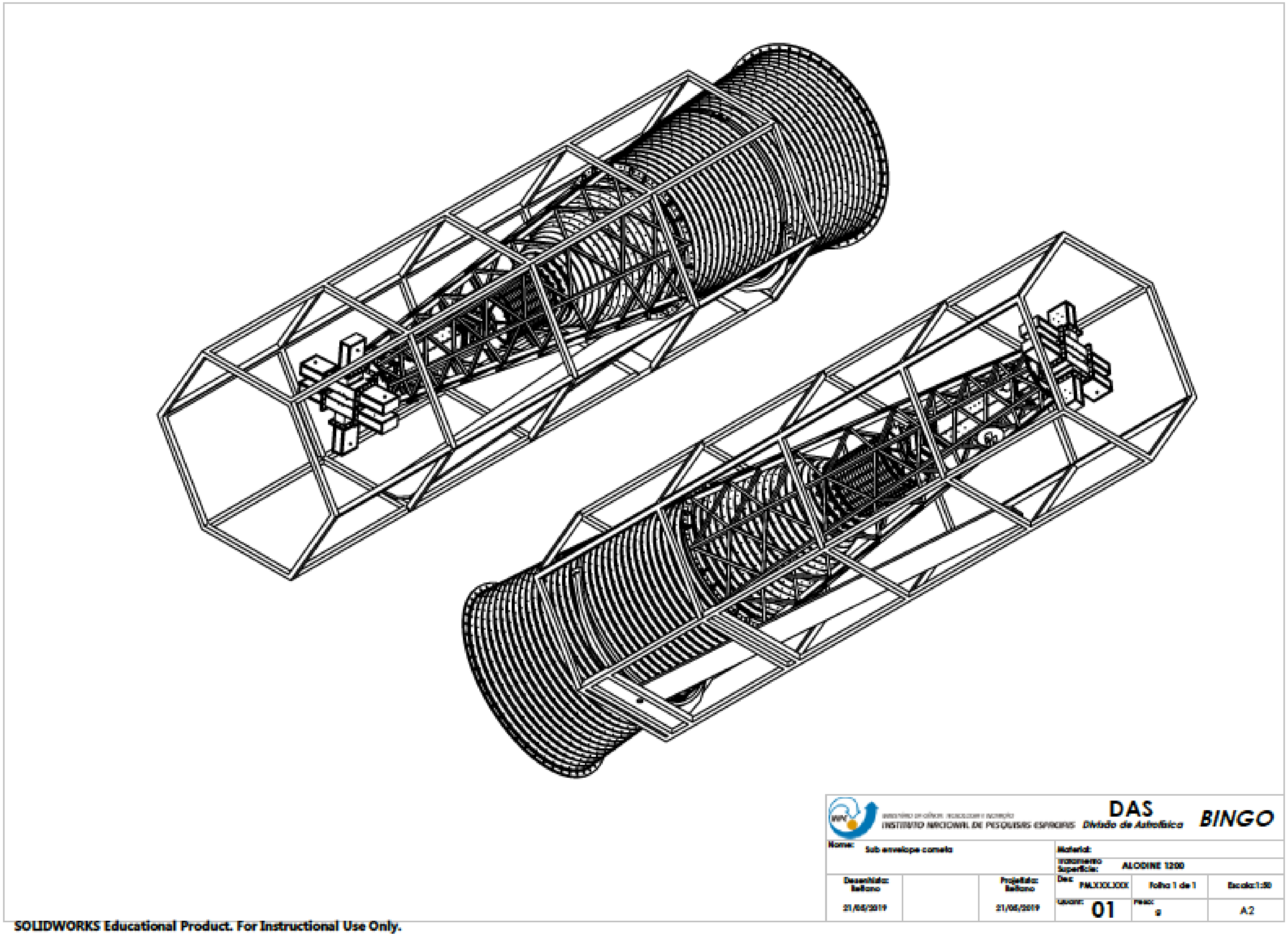


Desired: full orrelation receiver



Receiver status





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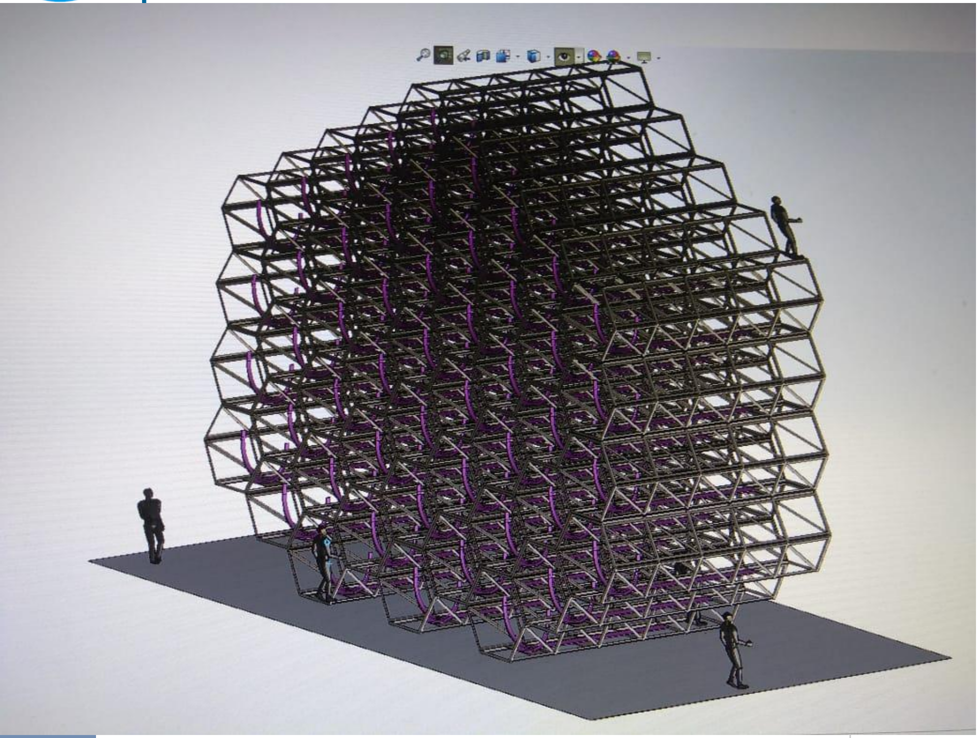
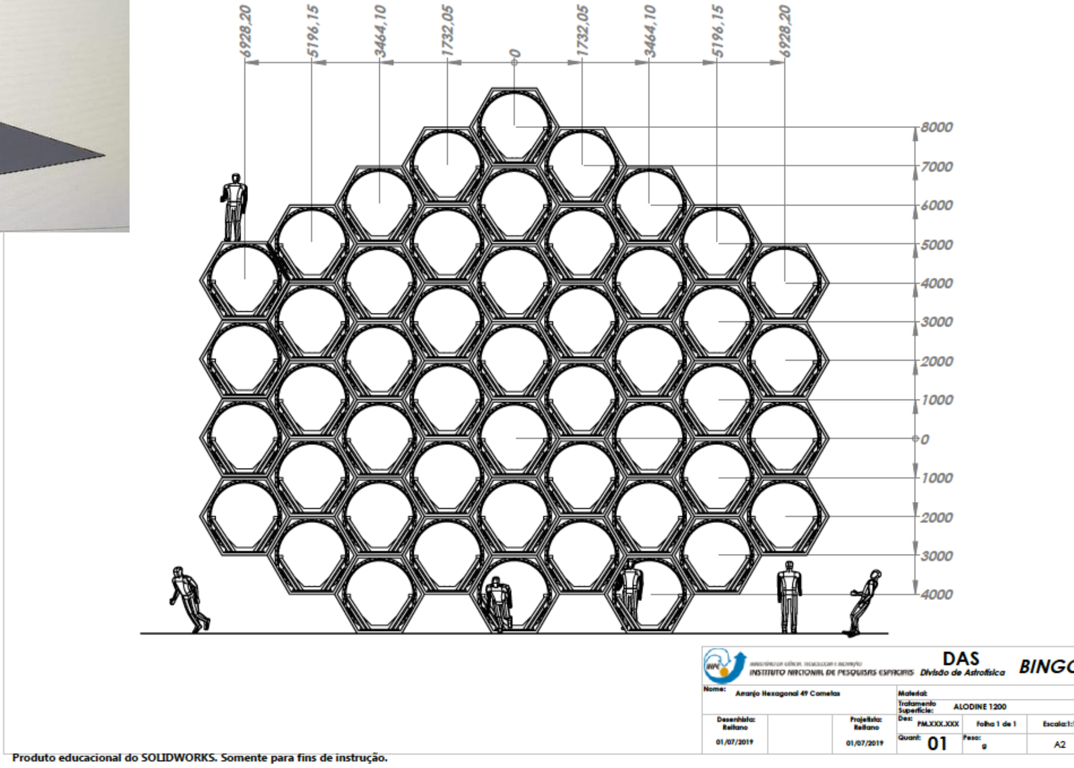
DAS
Divisão de Astrofísica

BINGO

Nome: Sub envelope corneta
Material:
Tratamento Superfície: ALODINE 1200
Desenhista: Bellono 21/08/2019
Projetista: Bellono 21/08/2019
Des: PMLXXXLXXX
Folha 1 de 1
Escala:1:50
Quant: 01
Peso: g
A2





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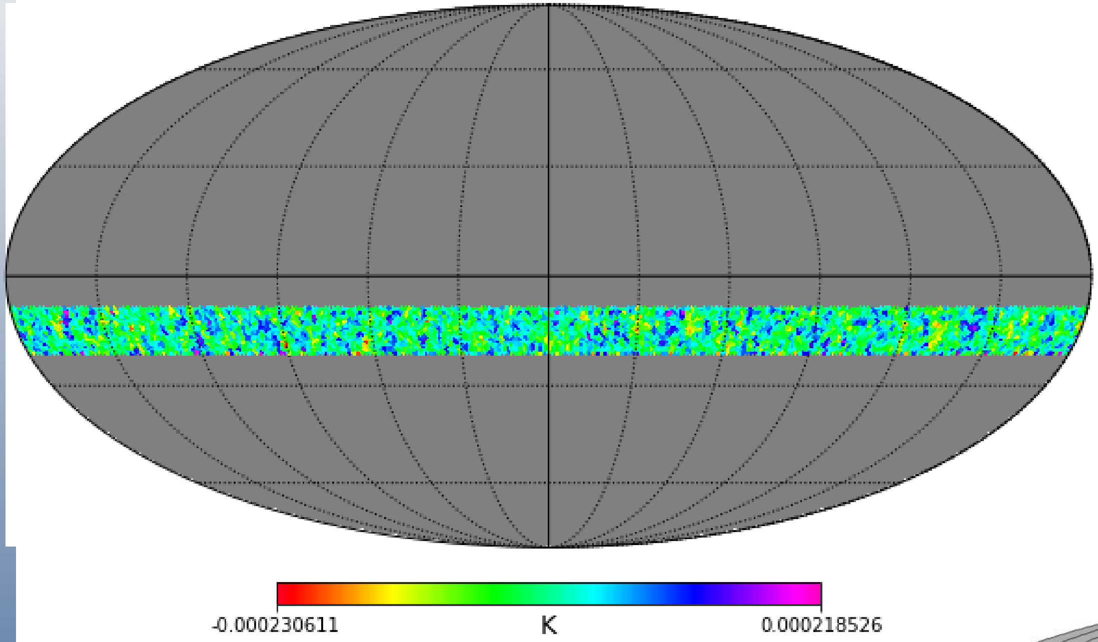
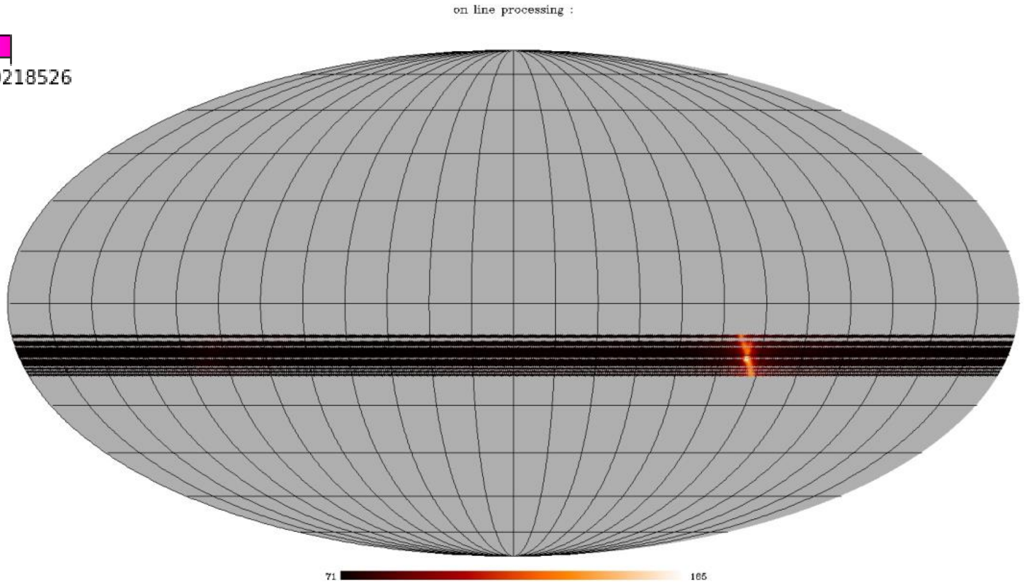
For 2019 configuration – 31 horns, 1 year observation



Input:

- CMB
- 21cm
- Synchrotron
- bremsstrahlung radiation

- Resolution: 27’
- **Estimated survey sensitivity: 41μK**



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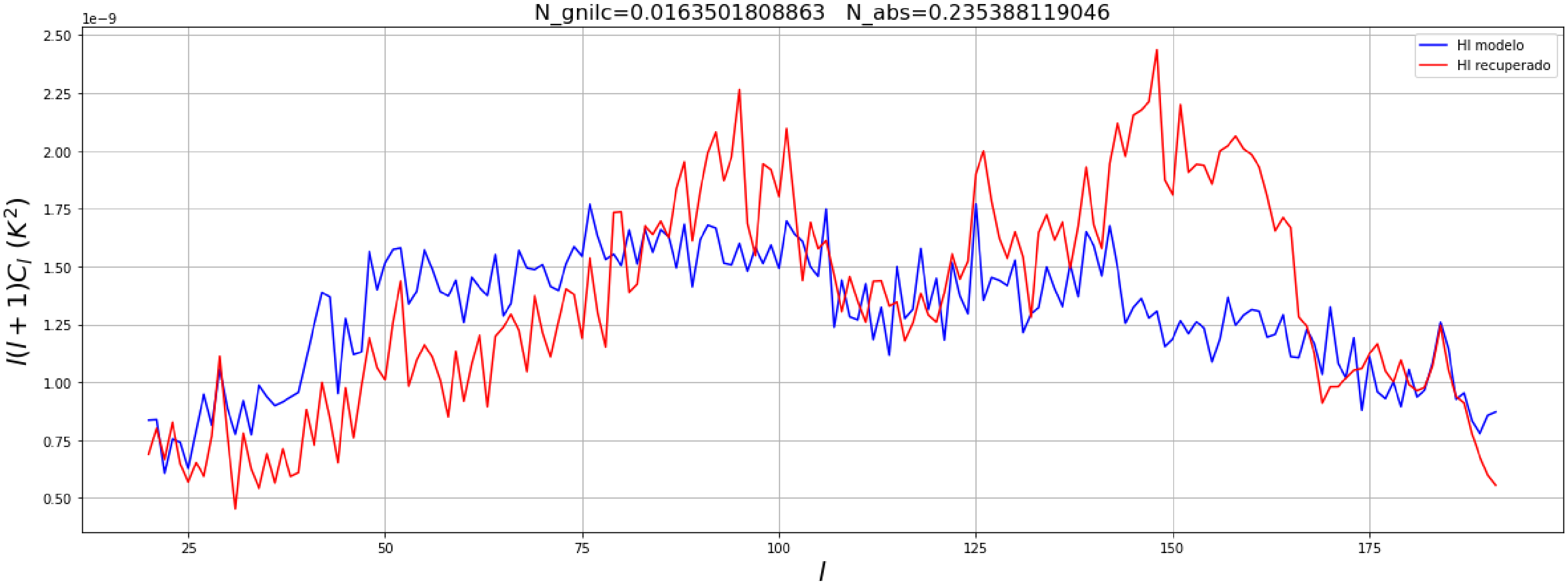
For 2019 configuration



Attempt to recover the HI power spectrum after component separation… still needs improvement.

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Foreground budget

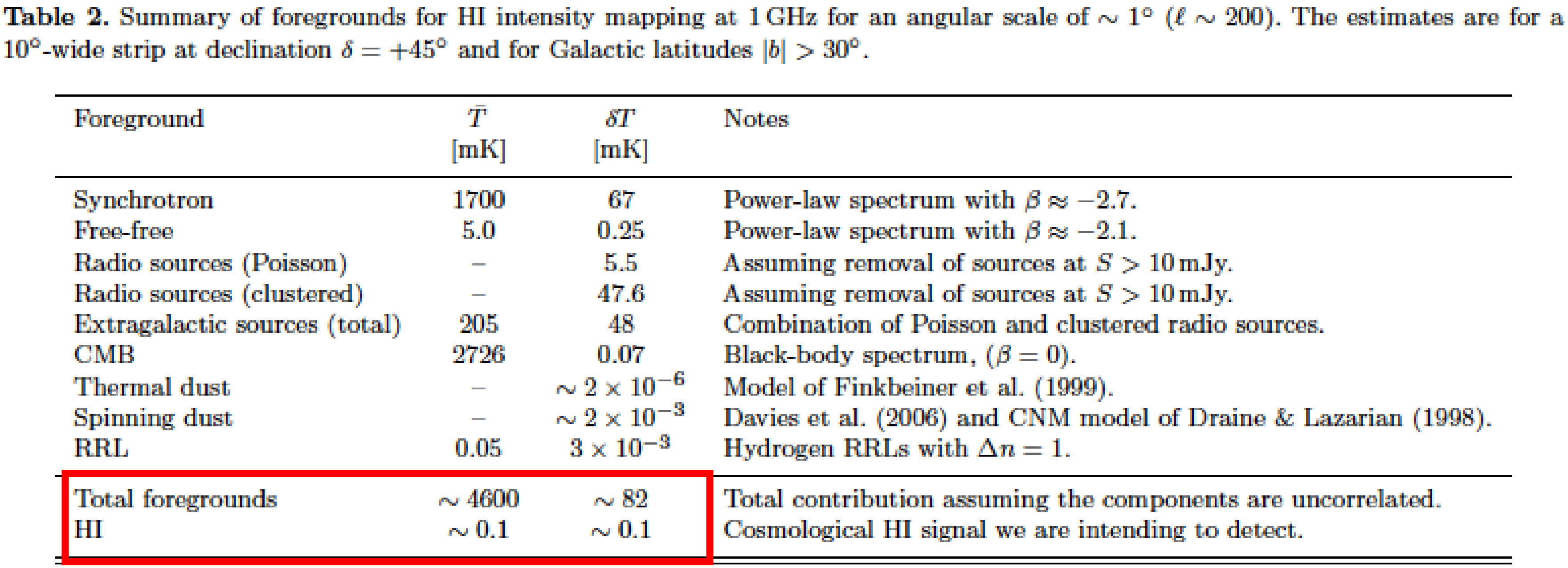
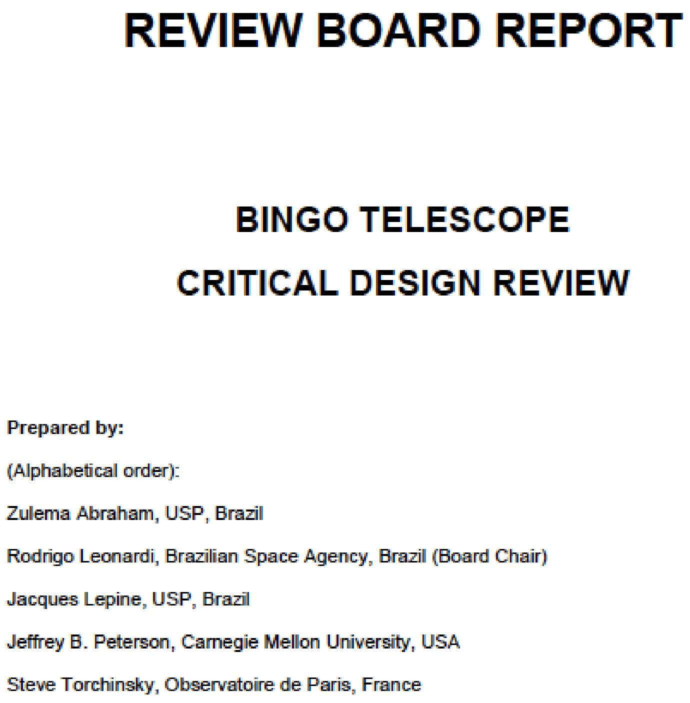


Table 2. Summary of foregrounds for HI intensity mapping at 1 GHz for an angular scale of $\sim 1^\circ$ ($\ell \sim 200$). The estimates are for a 10°-wide strip at declination $\delta = +45^\circ$ and for Galactic latitudes $|b| > 30^\circ$.

Foreground	$\bar{T}$ [mK]	δT [mK]	Notes
Synchrotron	1700	67	Power-law spectrum with $\beta \approx -2.7$.
Free-free	5.0	0.25	Power-law spectrum with $\beta \approx -2.1$.
Radio sources (Poisson)	–	5.5	Assuming removal of sources at $S > 10\,$mJy.
Radio sources (clustered)	–	47.6	Assuming removal of sources at $S > 10\,$mJy.
Extragalactic sources (total)	205	48	Combination of Poisson and clustered radio sources.
CMB	2726	0.07	Black-body spectrum, ($\beta = 0$).
Thermal dust	–	$\sim 2 \times 10^{-6}$	Model of Finkbeiner et al. (1999).
Spinning dust	–	$\sim 2 \times 10^{-3}$	Davies et al. (2006) and CNM model of Draine & Lazarian (1998).
RRL	0.05	3×10^{-3}	Hydrogen RRLs with $\Delta n = 1$.
Total foregrounds	~ 4600	~ 82	Total contribution assuming the components are uncorrelated.
HI	~ 0.1	~ 0.1	Cosmological HI signal we are intending to detect.

- From Battye et al. (2013)
- Need to recalculate this budget for current BINGO concept

Major Project Review



REVIEW BOARD REPORT

BINGO TELESCOPE

CRITICAL DESIGN REVIEW

Prepared by:

(Alphabetical order):

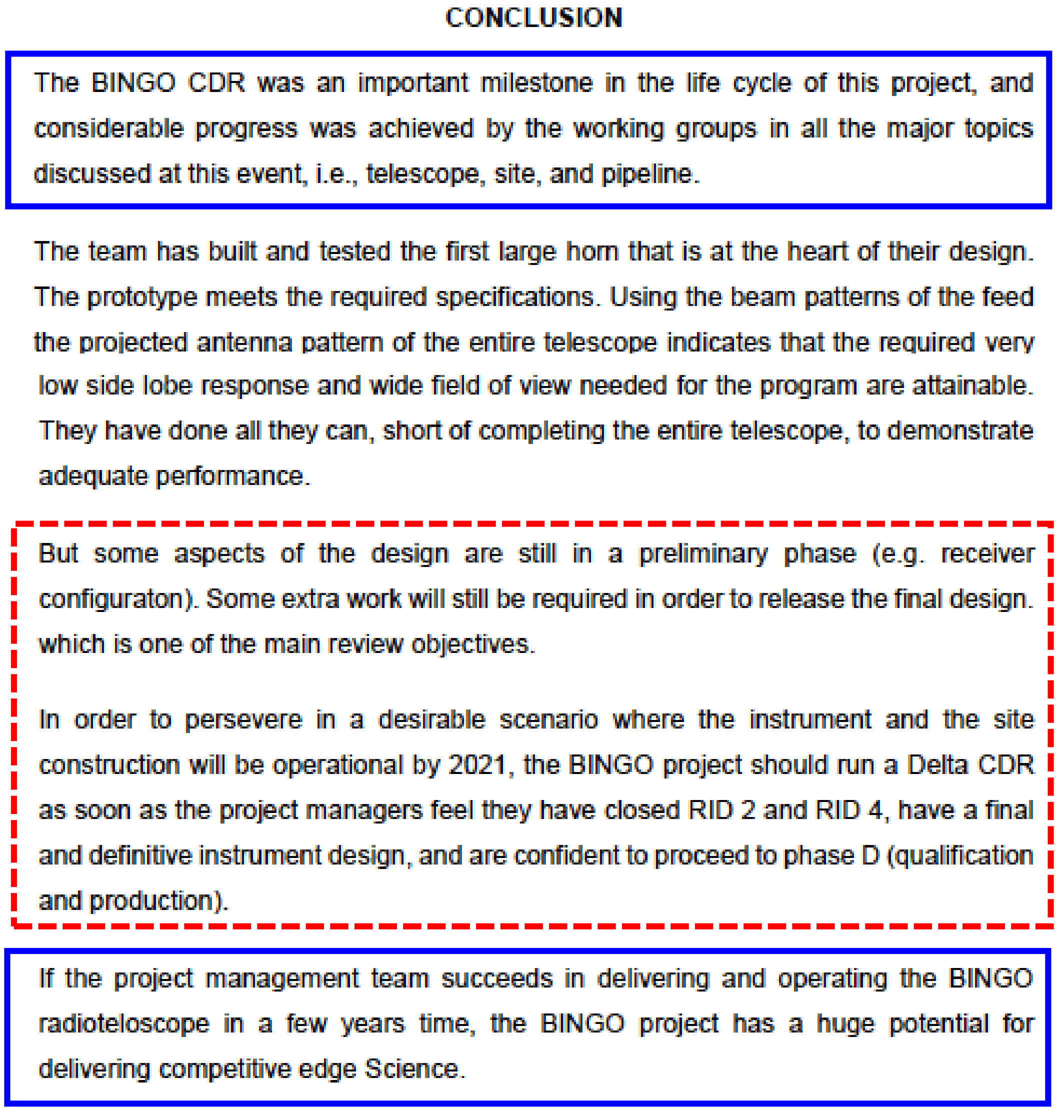
Zulema Abraham, USP, Brazil

Rodrigo Leonardi, Brazilian Space Agency, Brazil (Board Chair)

Jacques Lepine, USP, Brazil

Jeffrey B. Peterson, Carnegie Mellon University, USA

Steve Torchinsky, Observatoire de Paris, France



CONCLUSION

The BINGO CDR was an important milestone in the life cycle of this project, and considerable progress was achieved by the working groups in all the major topics discussed at this event, i.e., telescope, site, and pipeline.

The team has built and tested the first large horn that is at the heart of their design. The prototype meets the required specifications. Using the beam patterns of the feed the projected antenna pattern of the entire telescope indicates that the required very low side lobe response and wide field of view needed for the program are attainable. They have done all they can, short of completing the entire telescope, to demonstrate adequate performance.

But some aspects of the design are still in a preliminary phase (e.g. receiver configuraton). Some extra work will still be required in order to release the final design. which is one of the main review objectives.

In order to persevere in a desirable scenario where the instrument and the site construction will be operational by 2021, the BINGO project should run a Delta CDR as soon as the project managers feel they have closed RID 2 and RID 4, have a final and definitive instrument design, and are confident to proceed to phase D (qualification and production).

If the project management team succeeds in delivering and operating the BINGO radiotelescope in a few years time, the BINGO project has a huge potential for delivering competitive edge Science.

INPE

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DO ESTADO DE SÃO PAULO

BINGO

BAOs from Integrated Neutral Gas Observations

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Thank you!

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

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Foreground removal

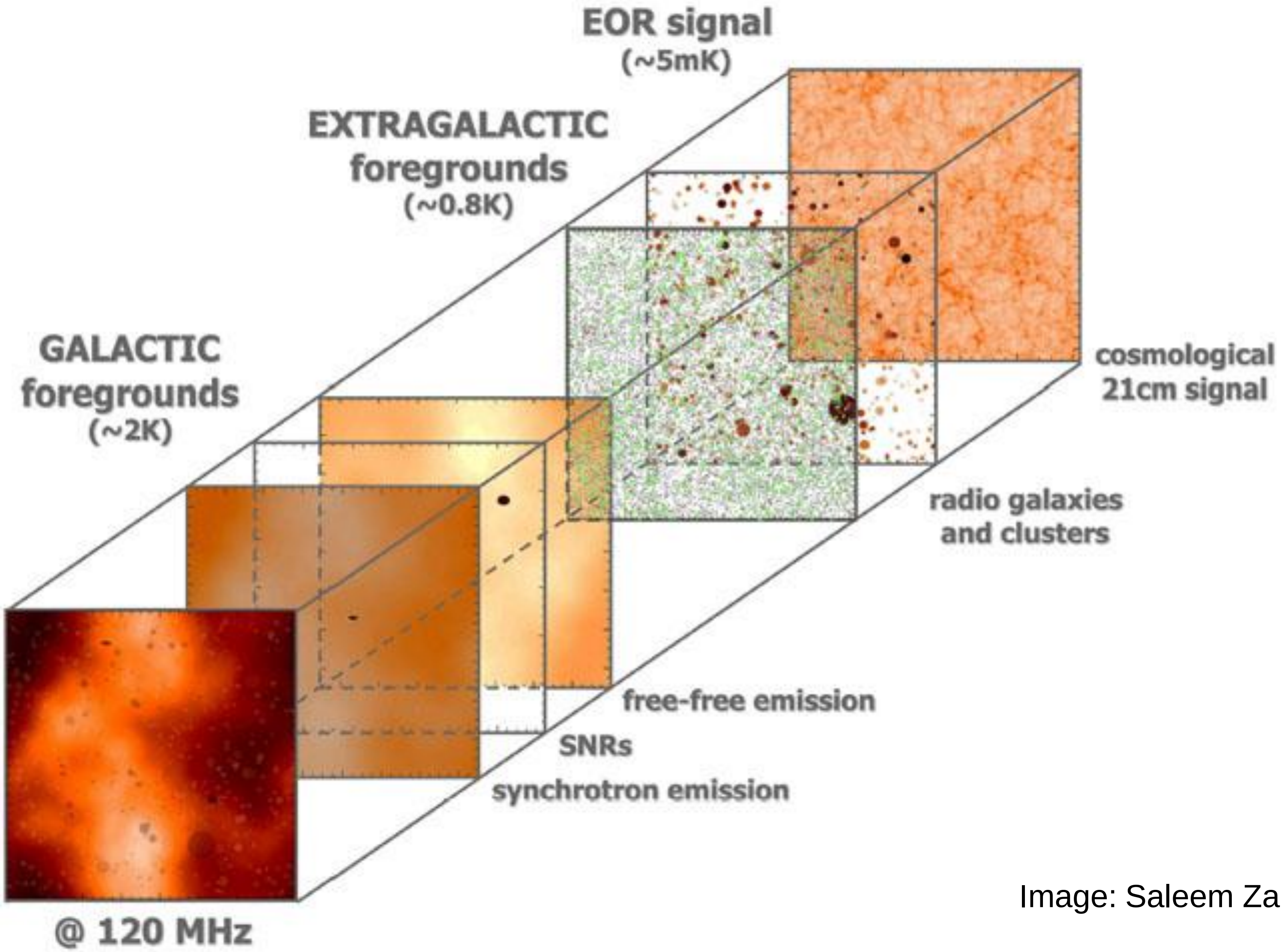


Image: Saleem Zaroubi

Additional science with BINGO

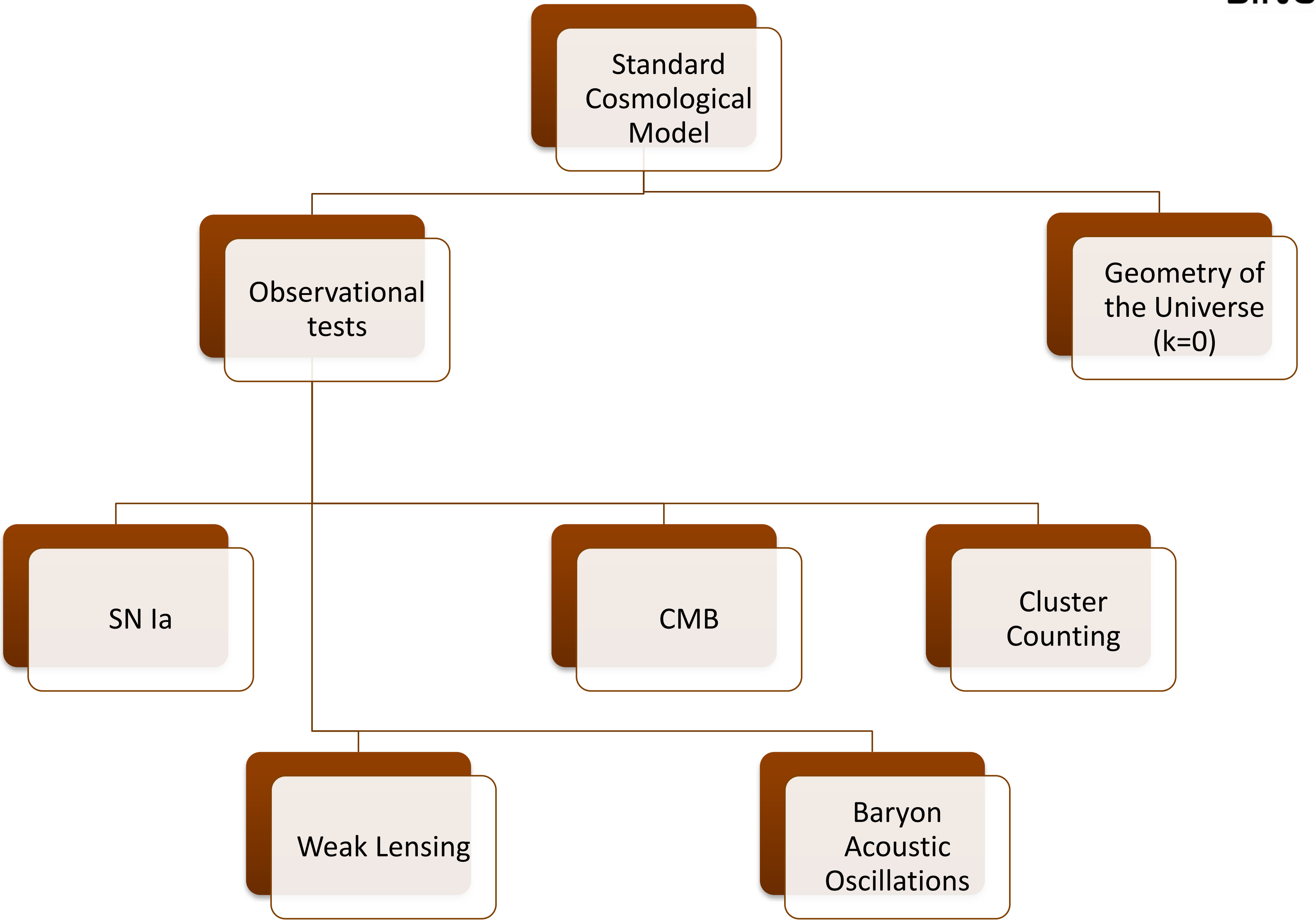
(We are building an ultra-deep large-area spectral survey at 980-1260 MHz)

- 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.

Dark Energy Observation program

- Instruments: JWST, SKA, LSST, Euclid
- Observational targets
  - ☐ Galaxy Cluster Counting
    - Targets: SZ and X-ray cluster surveys
  - ☐ SN Ia
    - Targets: Large, low-z, SN survey
  - ☐ Weak Gravitational Lensing
    - Targets: optical surveys and 21 cm interferometric measurements
  - ☐ **Baryon Acoustic Oscillations**
    - **Targets: D(z), H(z)**

Weinberg et al., Phys Rep. (2013)



Standard Cosmological Model

Observational tests

Geometry of the Universe (k=0)

SN Ia

CMB

Cluster Counting

Weak Lensing

Baryon Acoustic Oscillations

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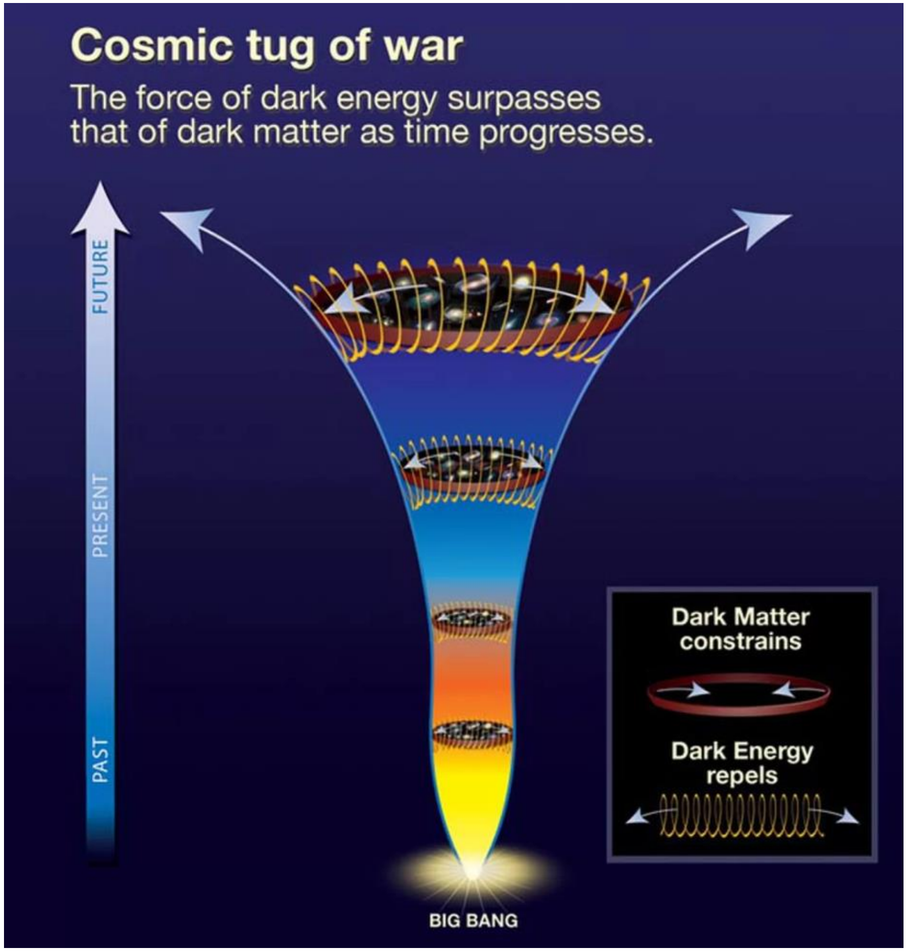
The science – main case

- Measure BAOs on top of the 21 cm Hydrogen spectrum => intensity mapping in radio
- Redshift interval BINGO will reach starts right after DE starts dominating the Universe => possible to set constraints on its properties
- HI intensity mapping can be used as mass tracer, probing distortions in redshift space
- Complementary to large optical surveys



- Similar to CMB:

$$\Delta T_{CMB} = \Delta T_{CMB}(\theta, \phi, z = 1100)$$

$$\Delta T_{HI} = \Delta T_{HI}(\theta, \phi, z)$$

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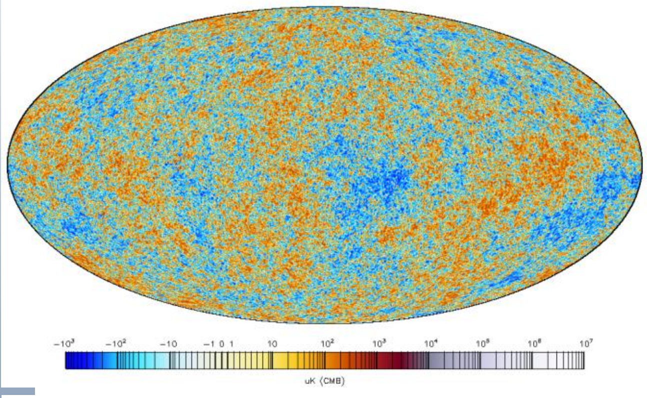
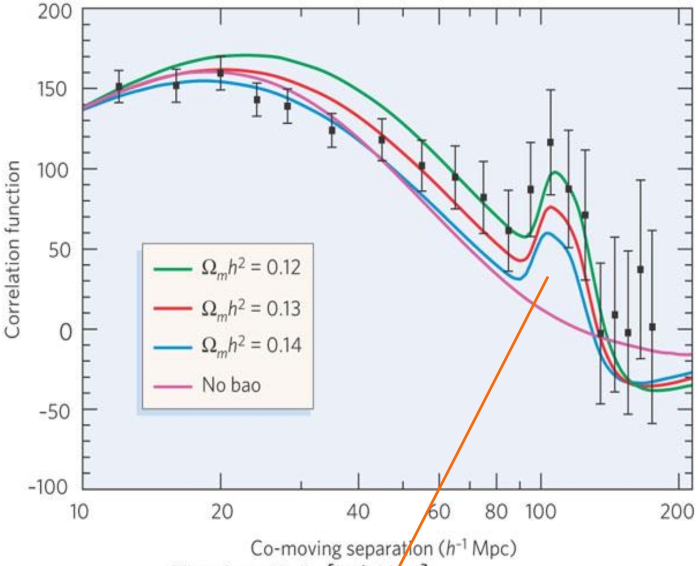
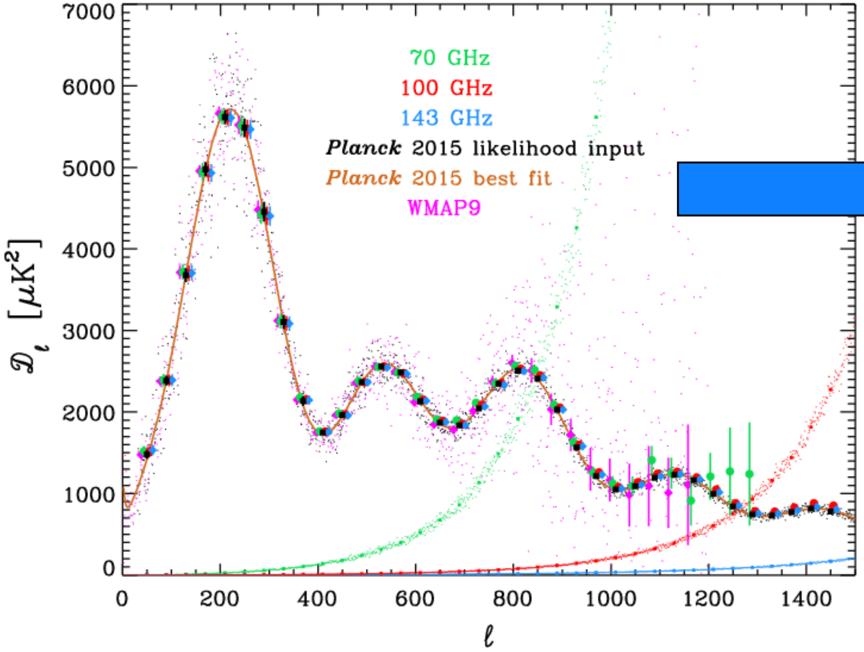
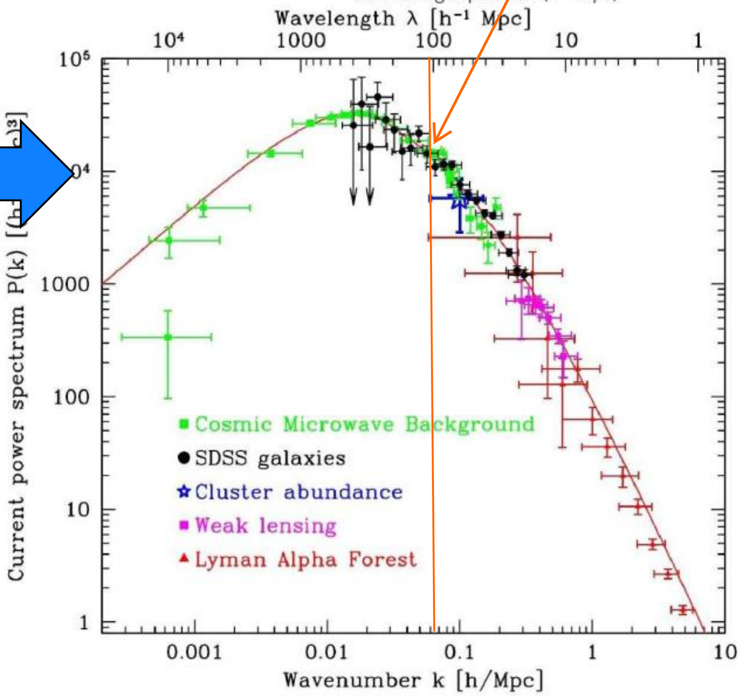
Temperature x matter fluctuations



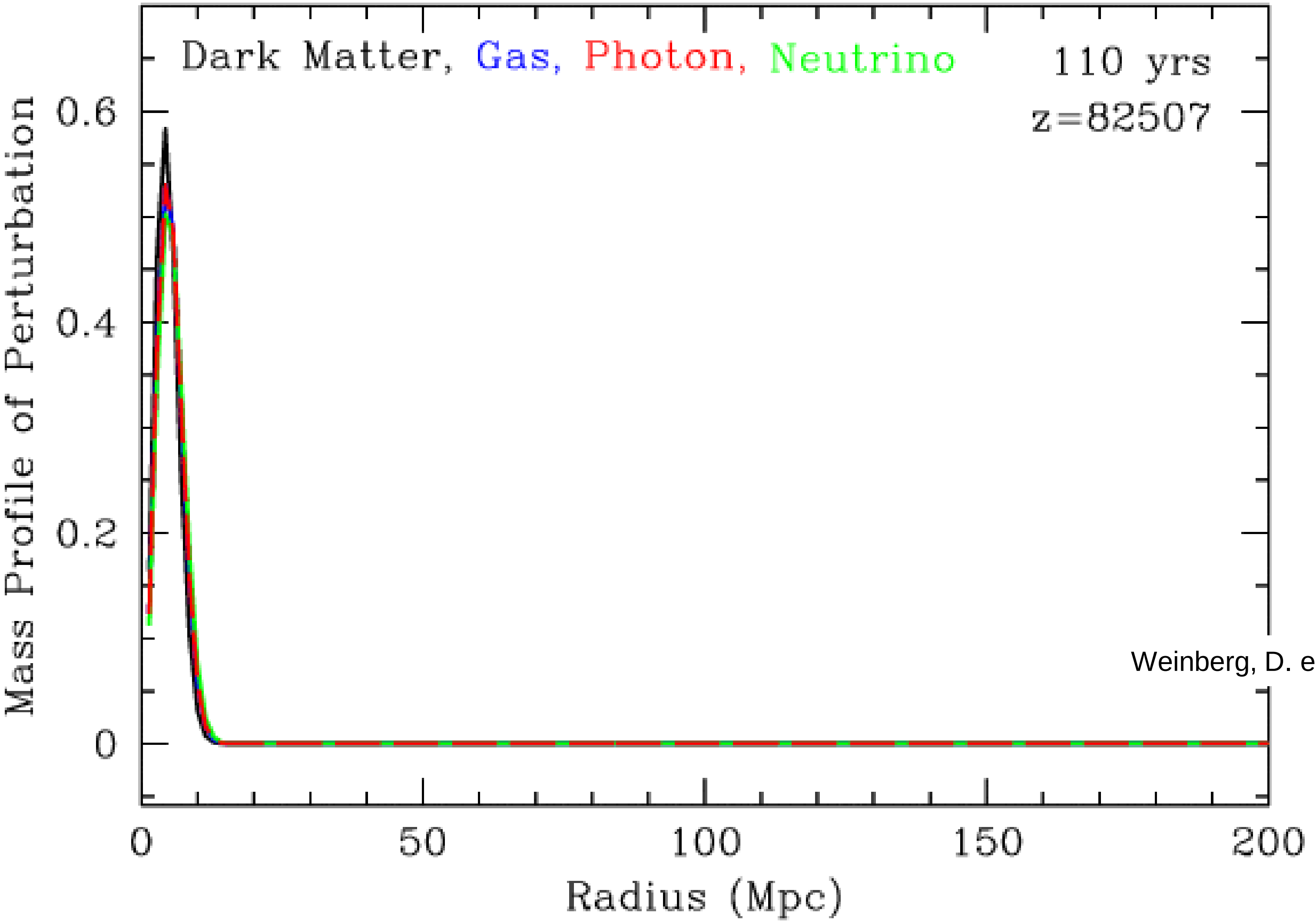






C. A. Wuen

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



Weinberg, D. et al (2013)

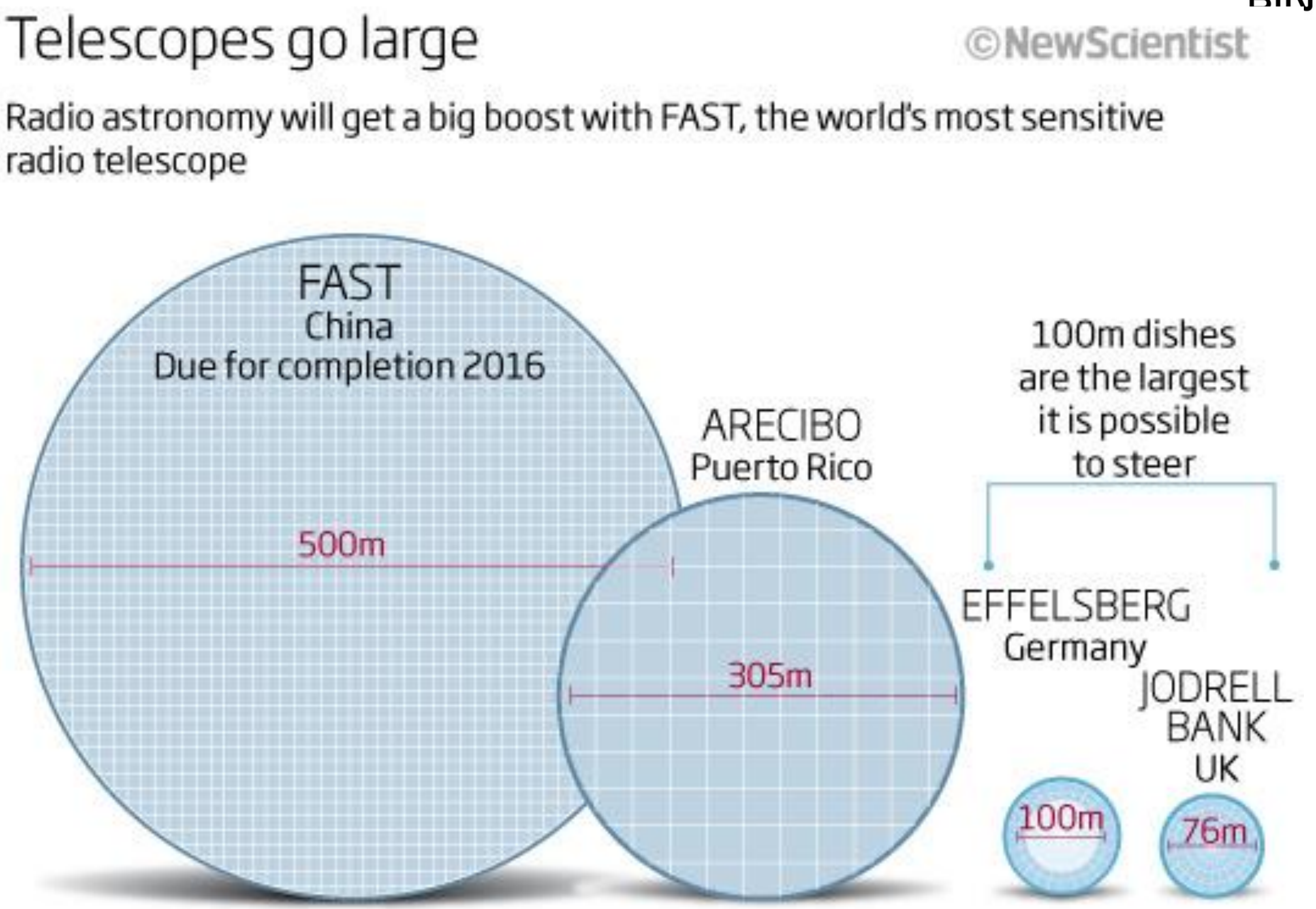
After decoupling there is a wave of matter and dark matter, which will gravitationally converge to a common radius.

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

C. A. Wuensche (2019)

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 experience in instrumentation and data analysis)
- Interferometers are excellent instruments for these measurements, but: more expensive, hard to operate, hard to maintain
- Approach: single-dish, many horns X single horn per dish



Telescopes go large

©NewScientist

Radio astronomy will get a big boost with FAST, the world's most sensitive radio telescope

C. A. Wuensche (2019)

Desirable items for a single dish HI surveyor

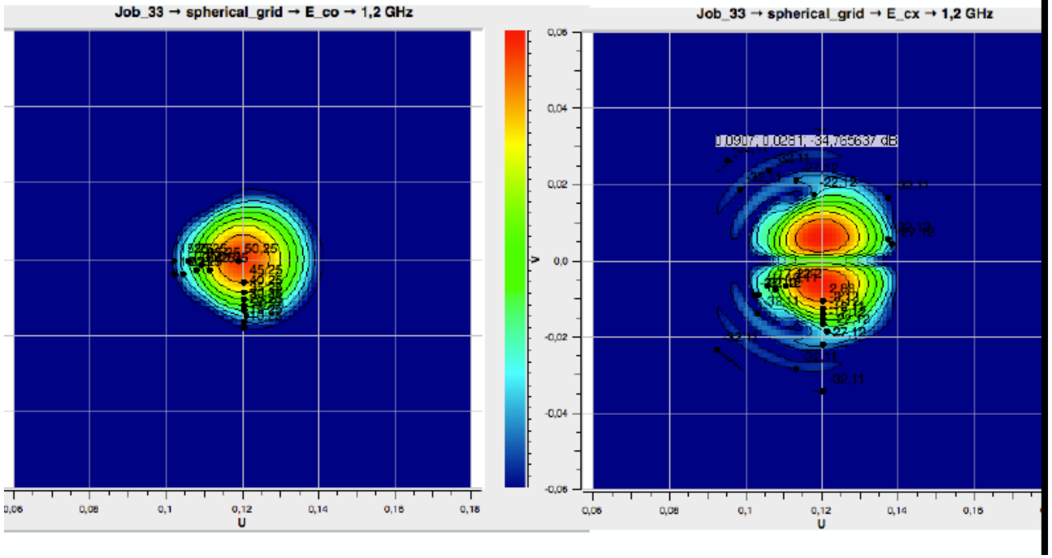
- Large collecting area (> 500 m^2)
- Large covered area on the sky (care should be taken with leaving out very small scales, < 0.1 $Mpc.h^{-1}$)
- Low sidelobes and good (precise shape) beam
- Long observing time (> 1 year)
- Sensitivity to intermediate scales, where BAO is important ($0 < z < 2$)
- 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 Radio Frequency Interference (RFI) in this frequency range

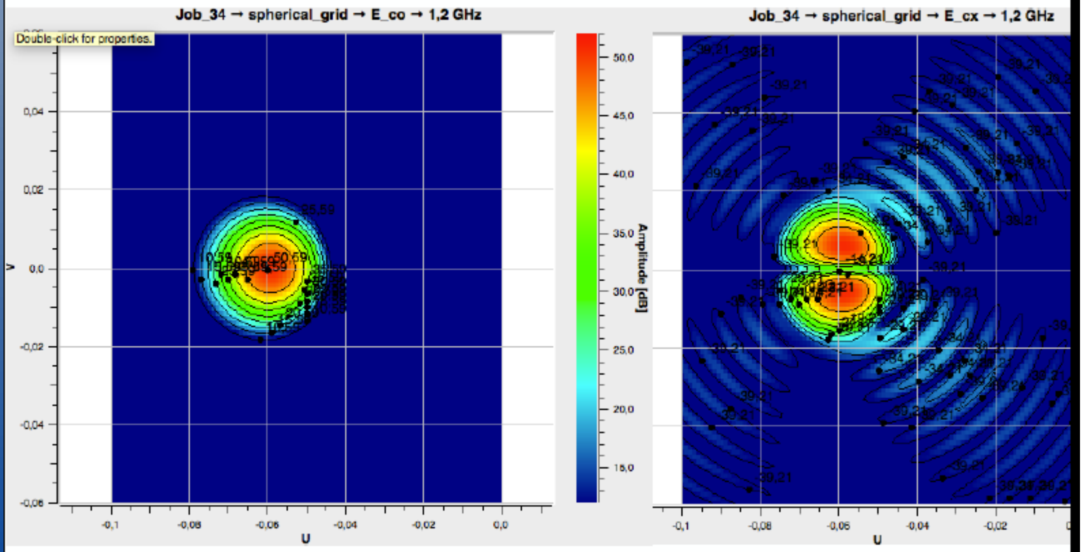
Adapted from Bull et al. 2015

C. A. Wuensche (2019)

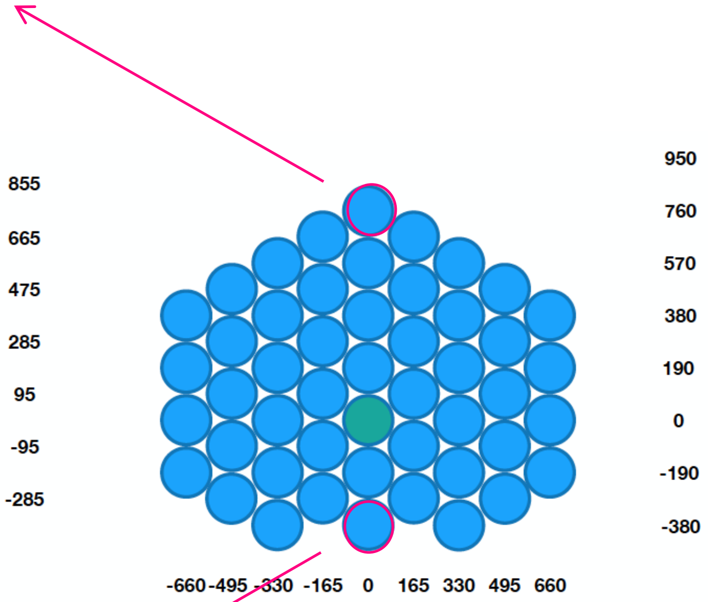
Pixel 0,760



Pixel 0,-380



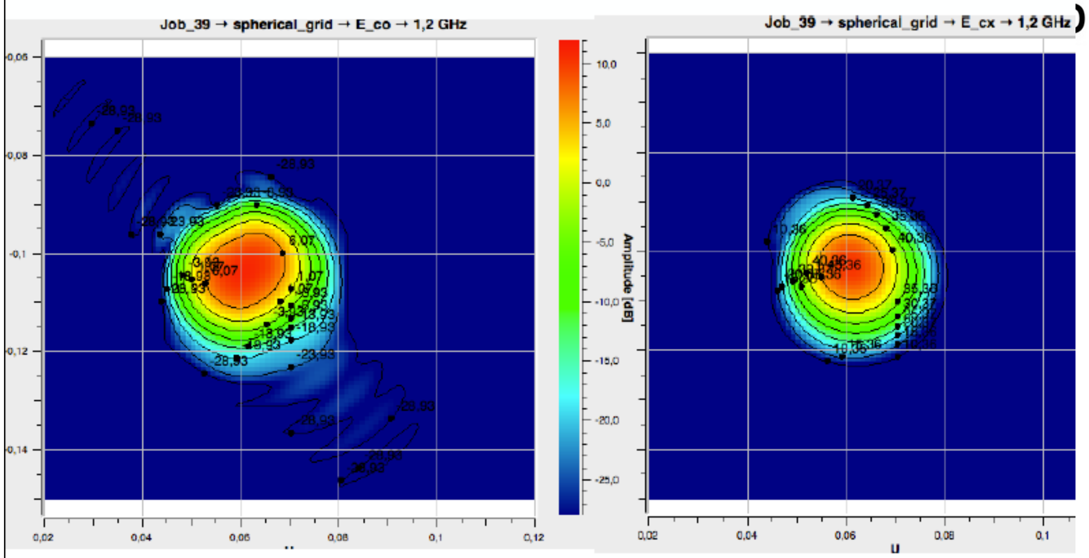
Schematics by Bruno Maffei / Ivan Ferreira



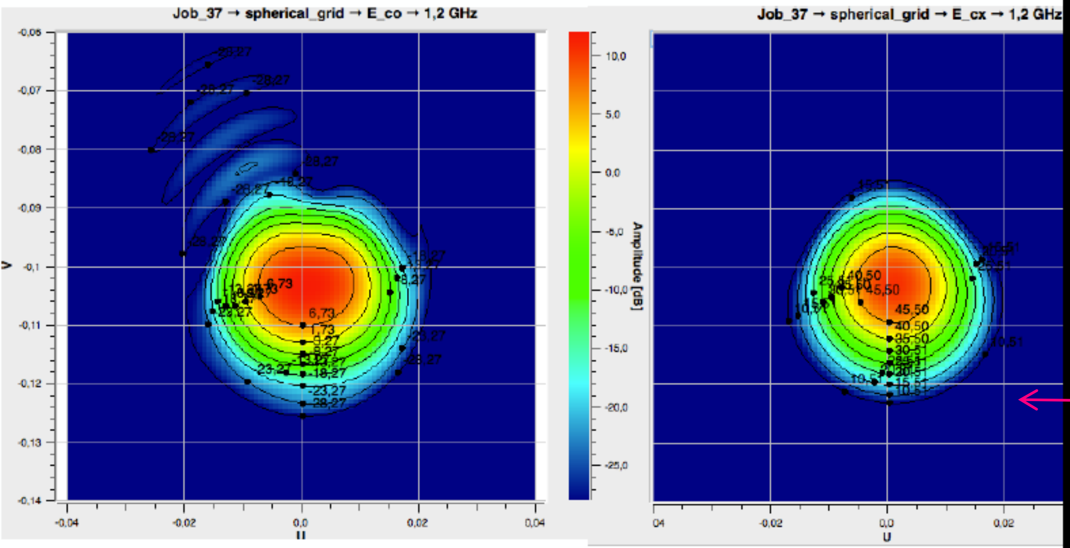
C. A. Wuensche (2019)

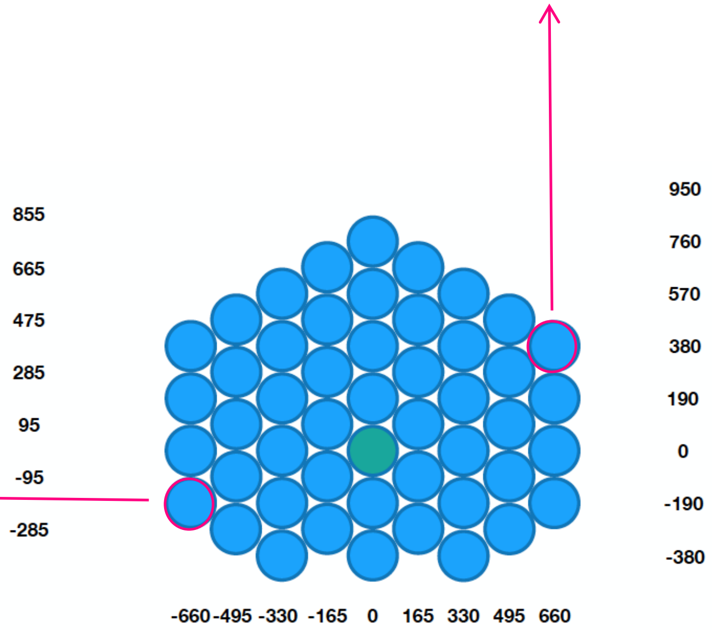
Schematics by Bruno Maffei / Ivan Ferreira

Pixel -660,380



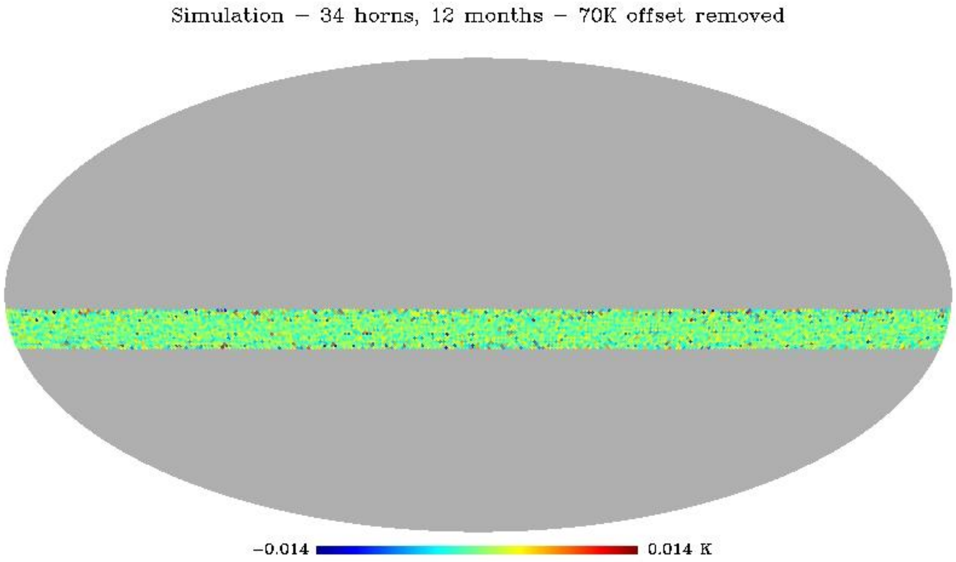
Pixel -660,0

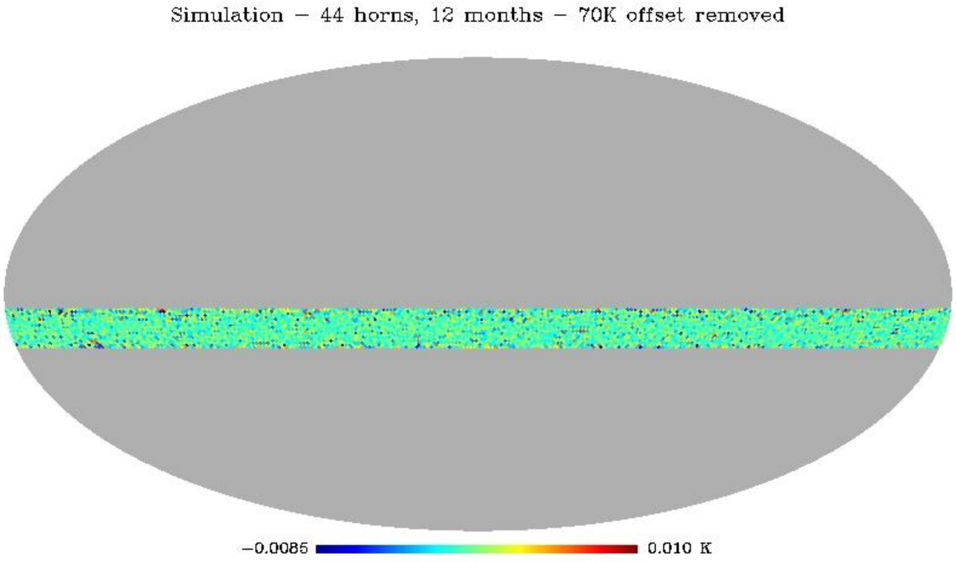


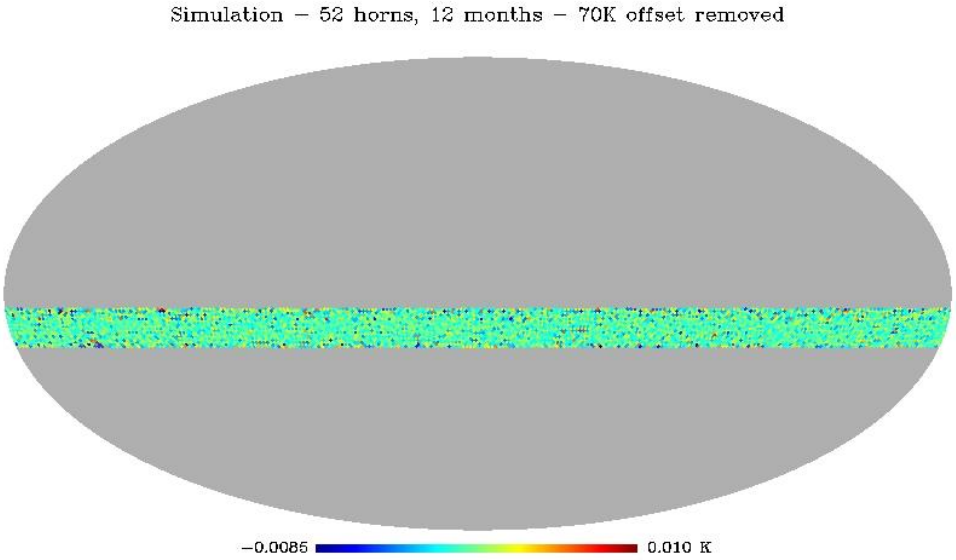


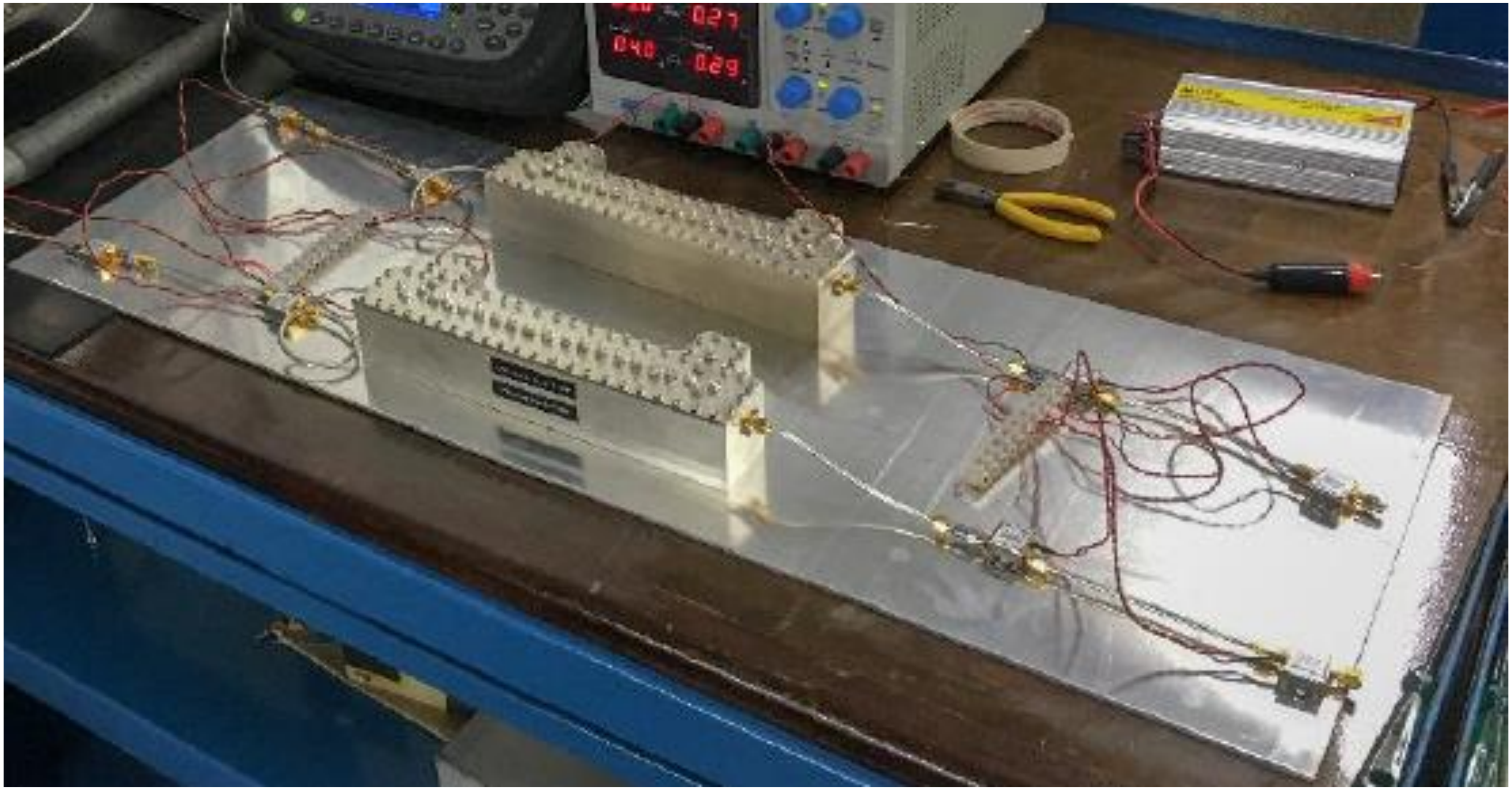
C. A. Wuensche (2019)

Remodeling BINGO (2019)









C. A. Wuensche (2019)

SIMULATION PARAMETERS (small subset of them… ☺)

```
# 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
```

C. A. Wuensche (2019)

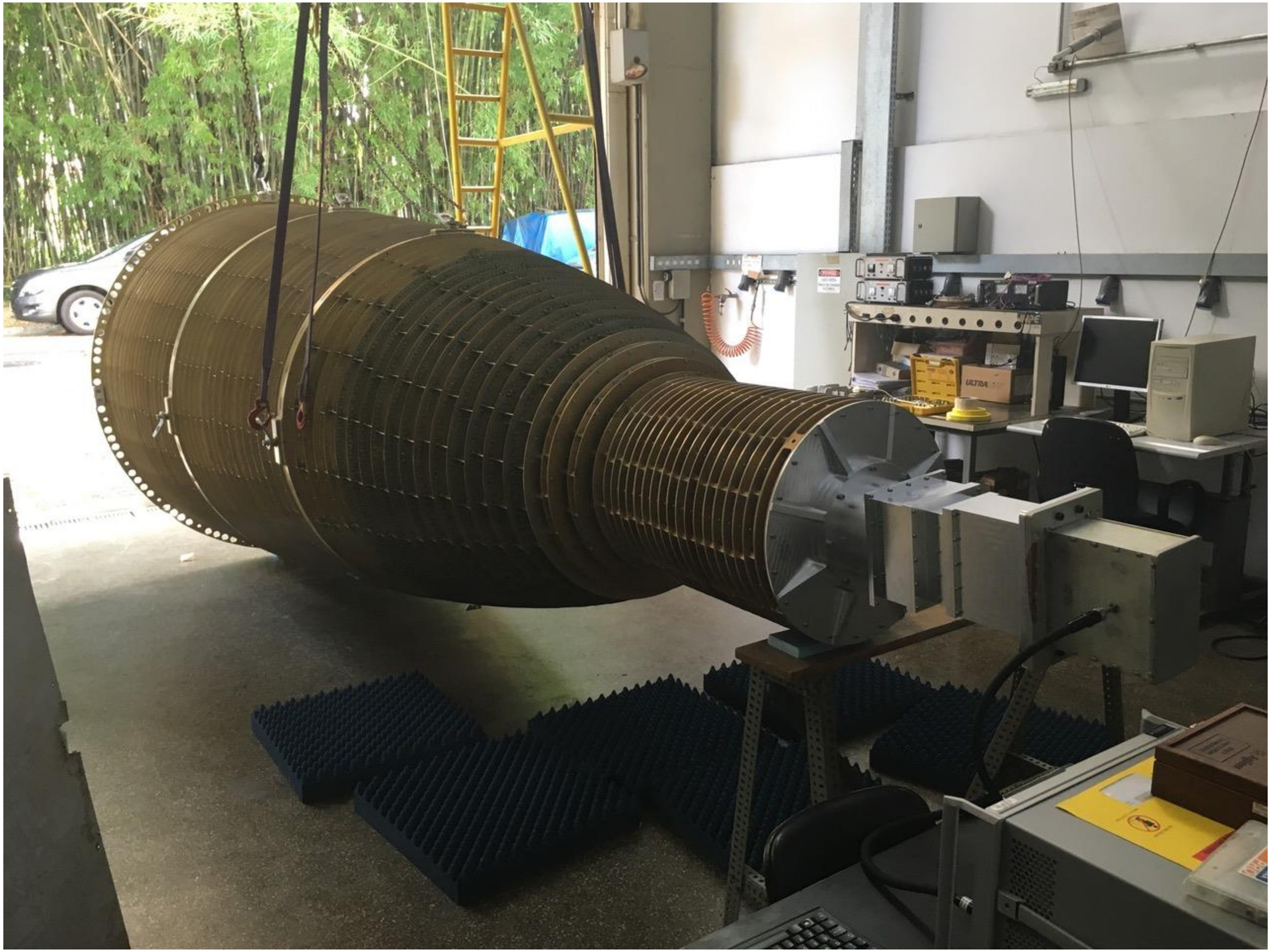
Horn & polarimeter status

- 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)

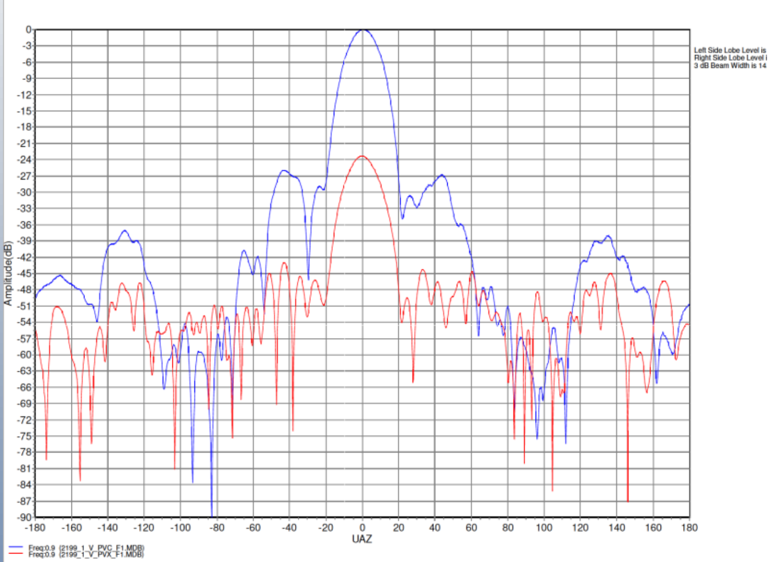
Horns



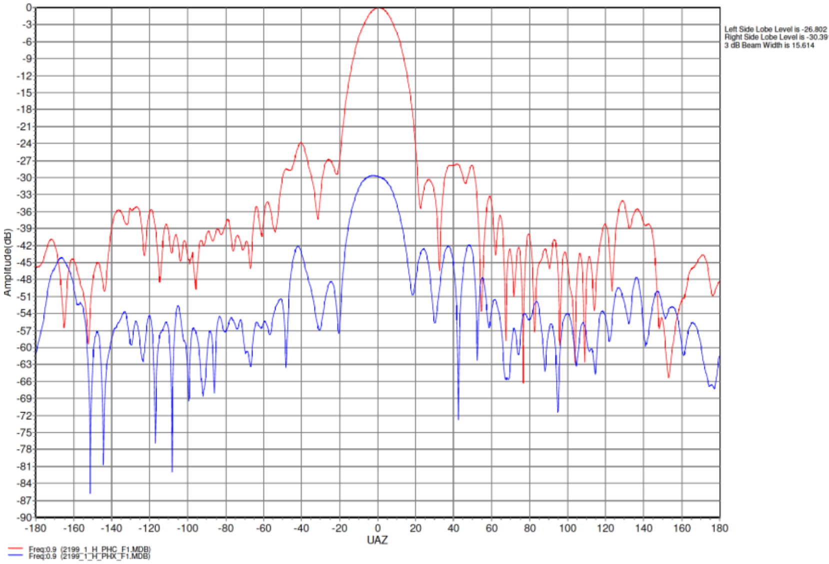
"BINGO: Horn design, fabrication and testing" (Wuensche et al. 2019, submitted)

Horn testing results –polarization

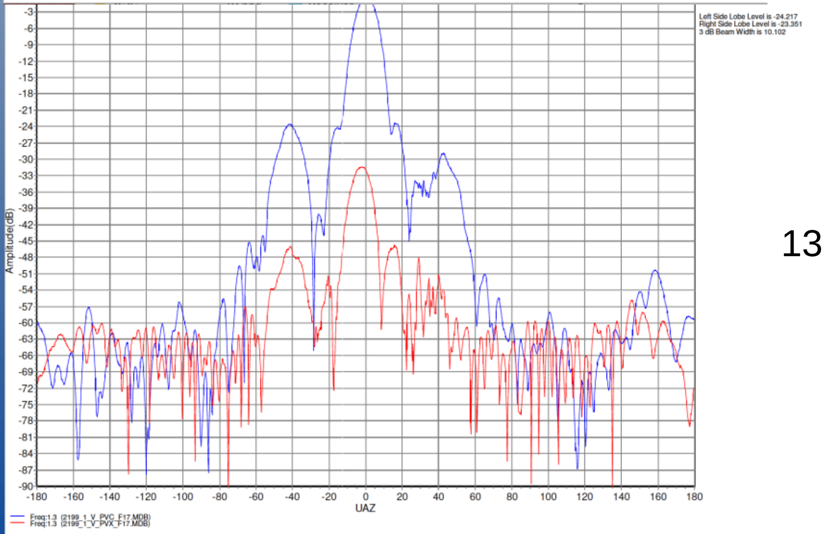
VERTICAL



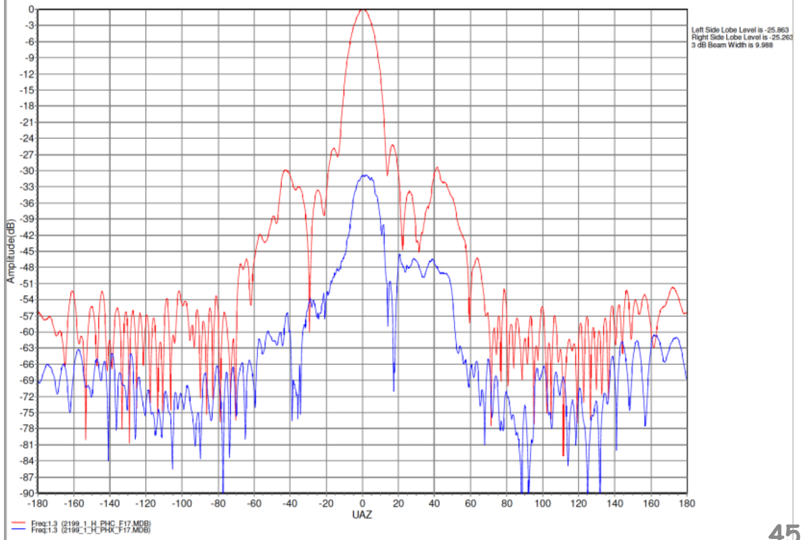
900 MHz



HORIZONTAL

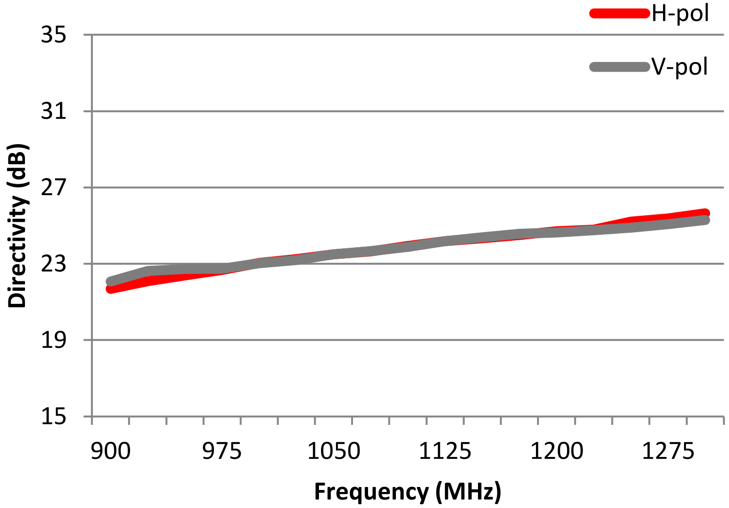


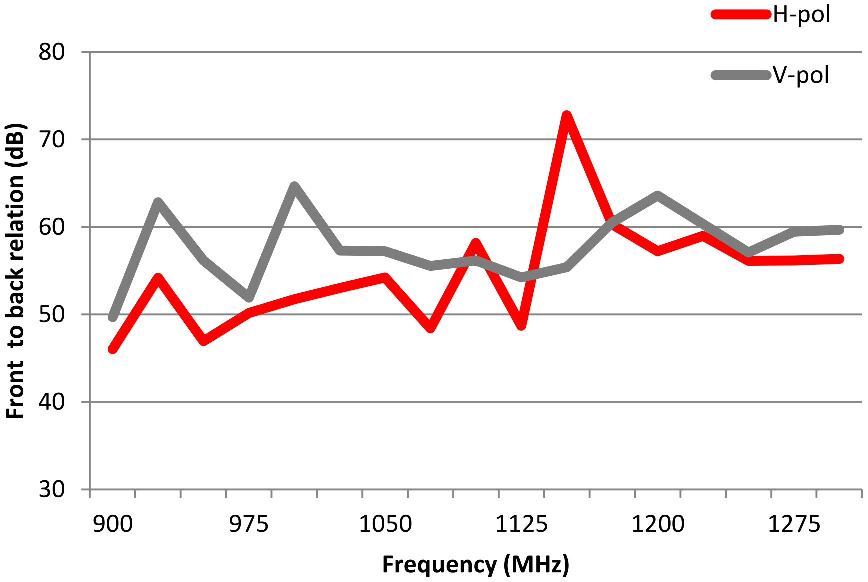
1300 MHz

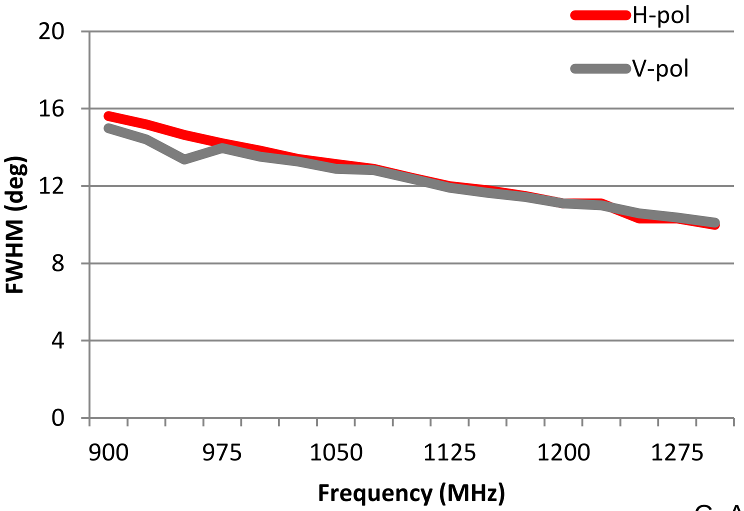


C. A. Wuensche (20)

Horn testing results

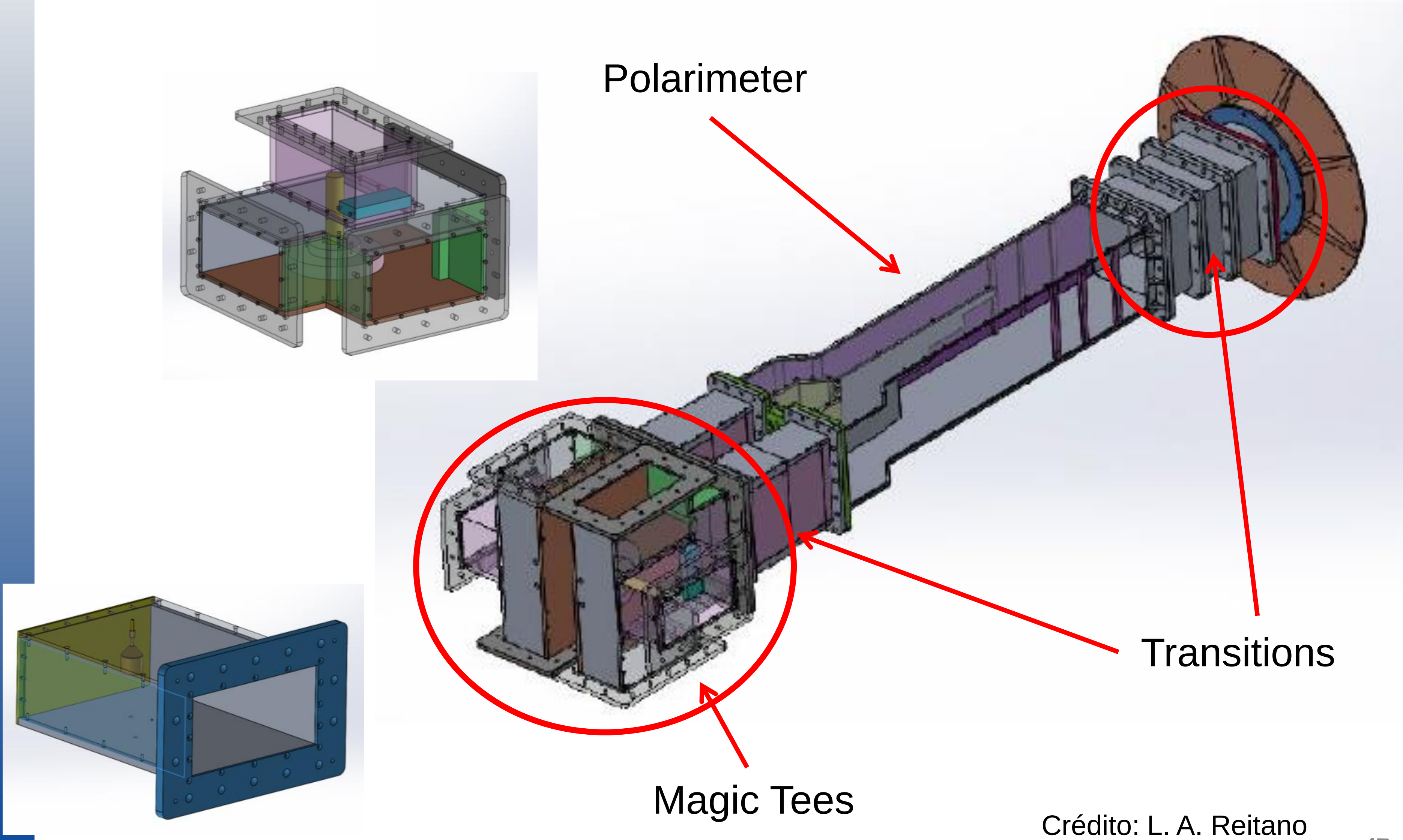






C. A. Wuensche (2019)

Polarimeters, transitions and magic tees

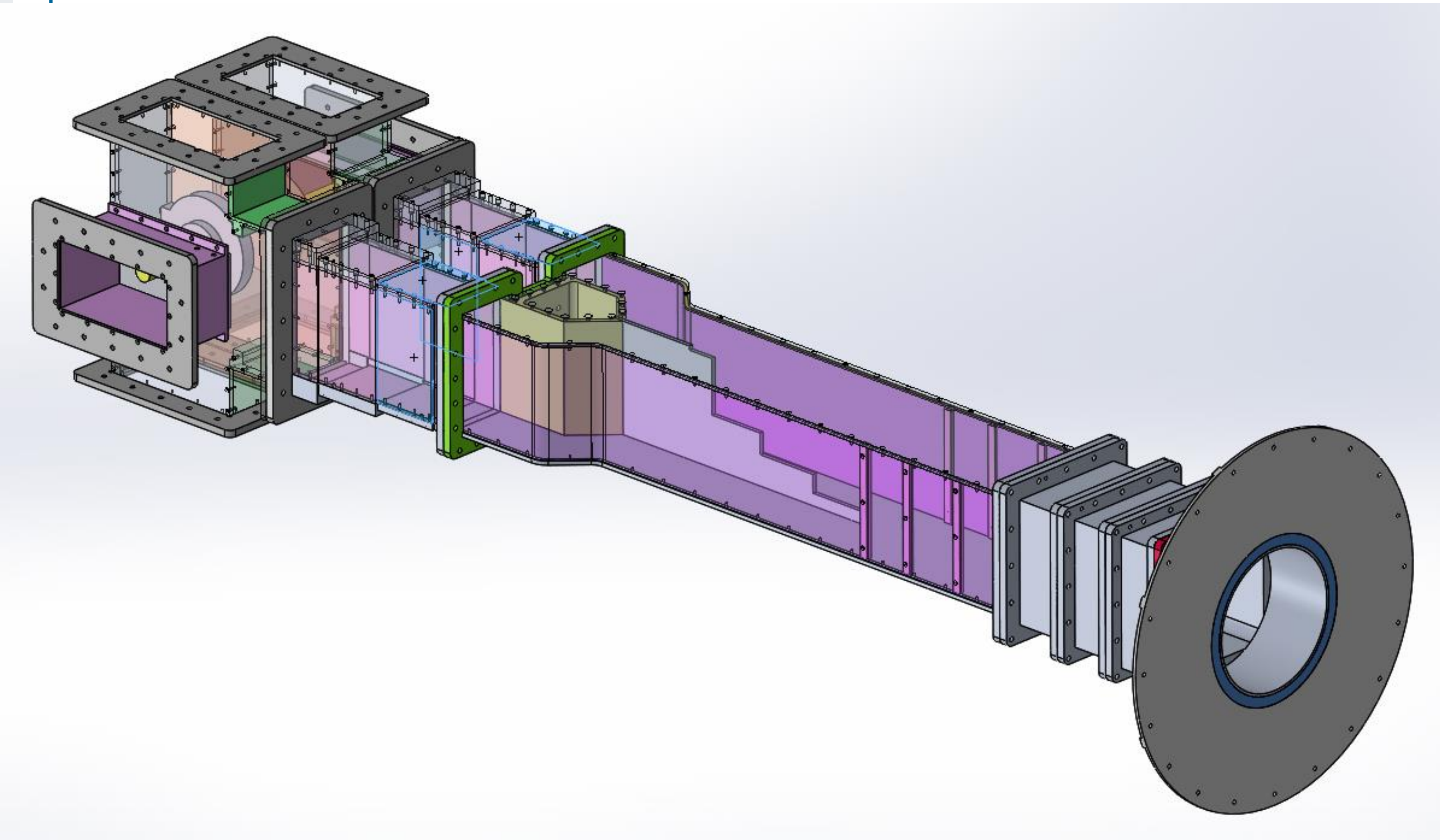


Polarimeter

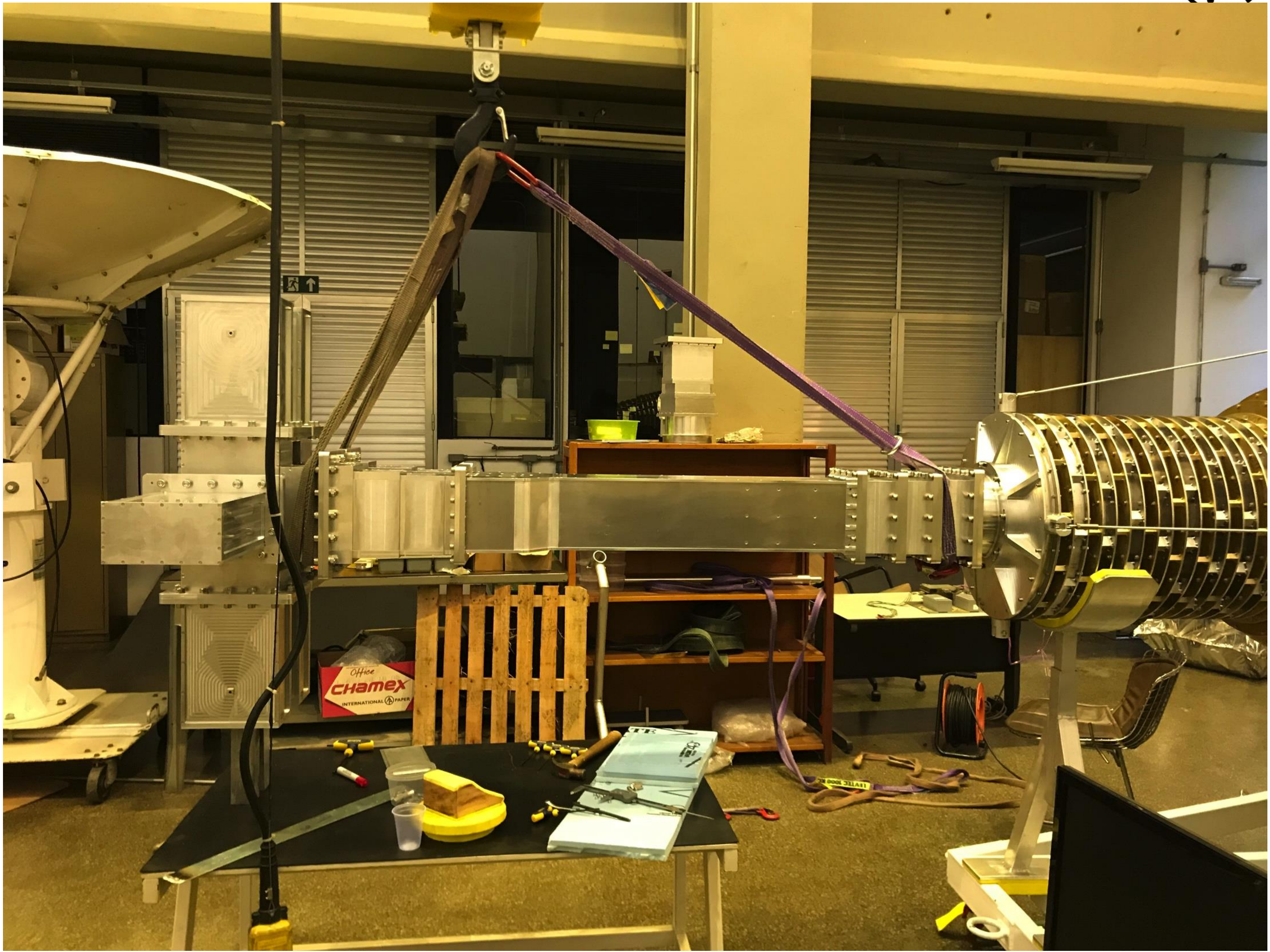
Transitions

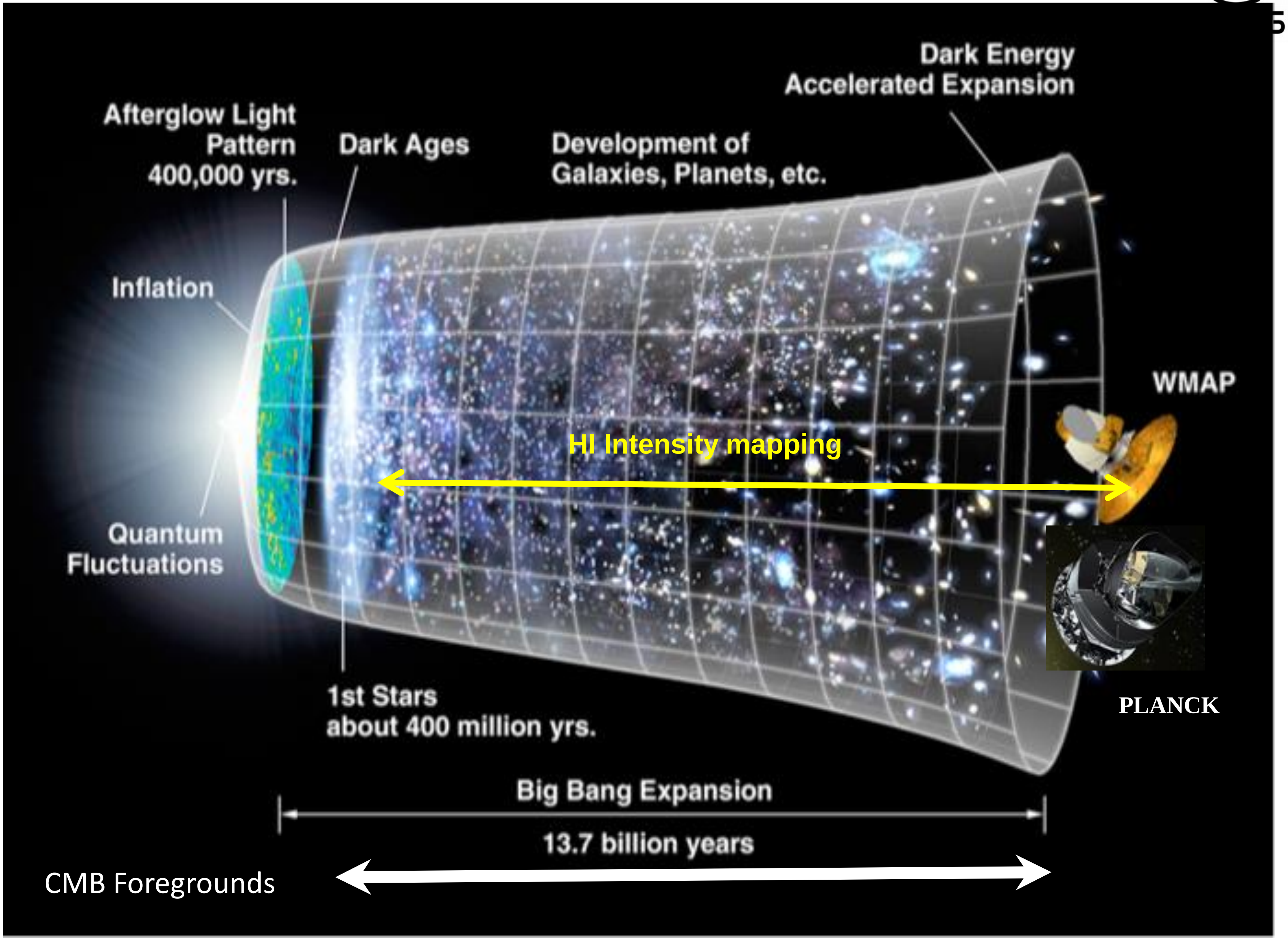
Magic Tees

Crédito: L. A. Reitano

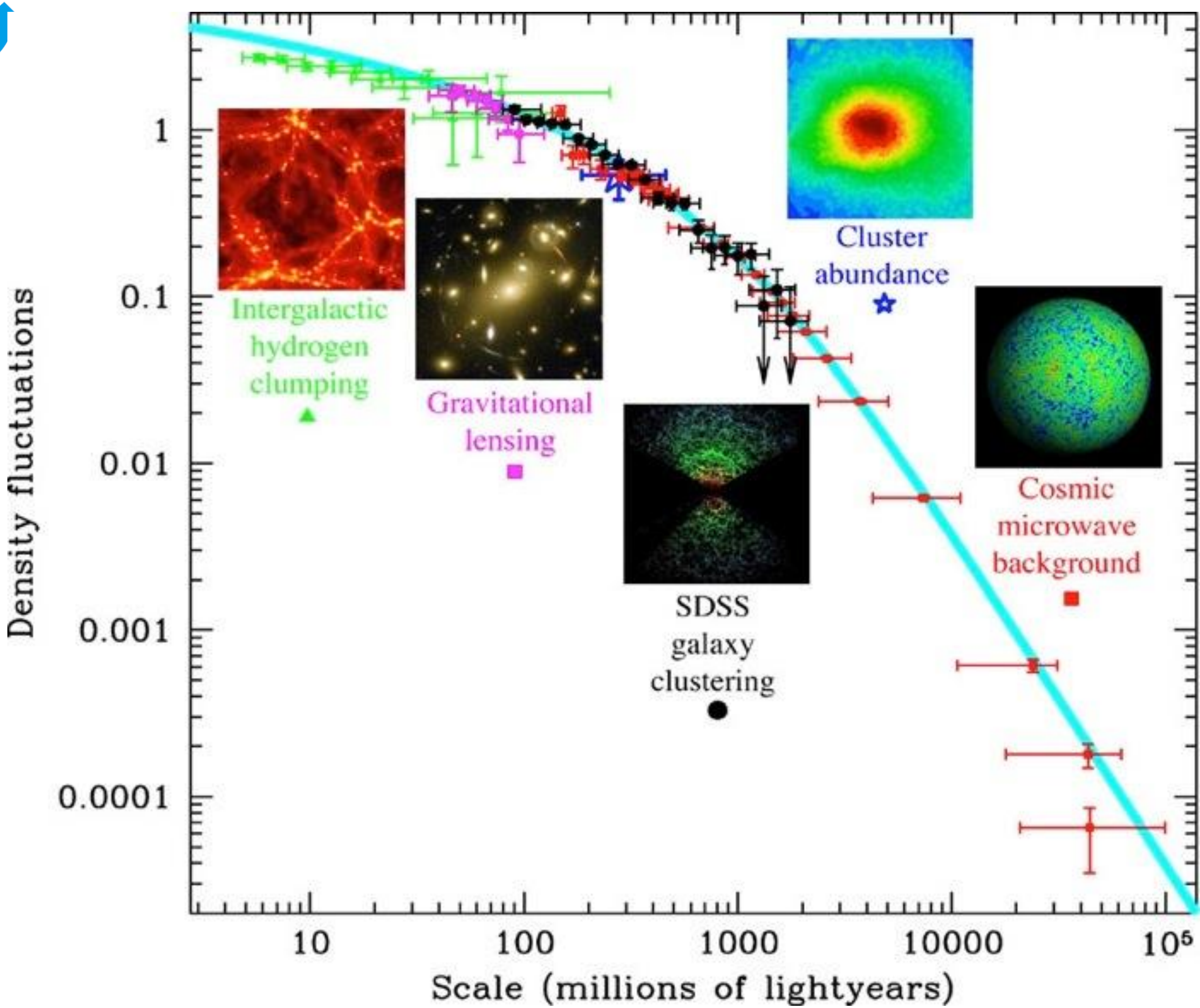


C. A. Wuensche (2019)

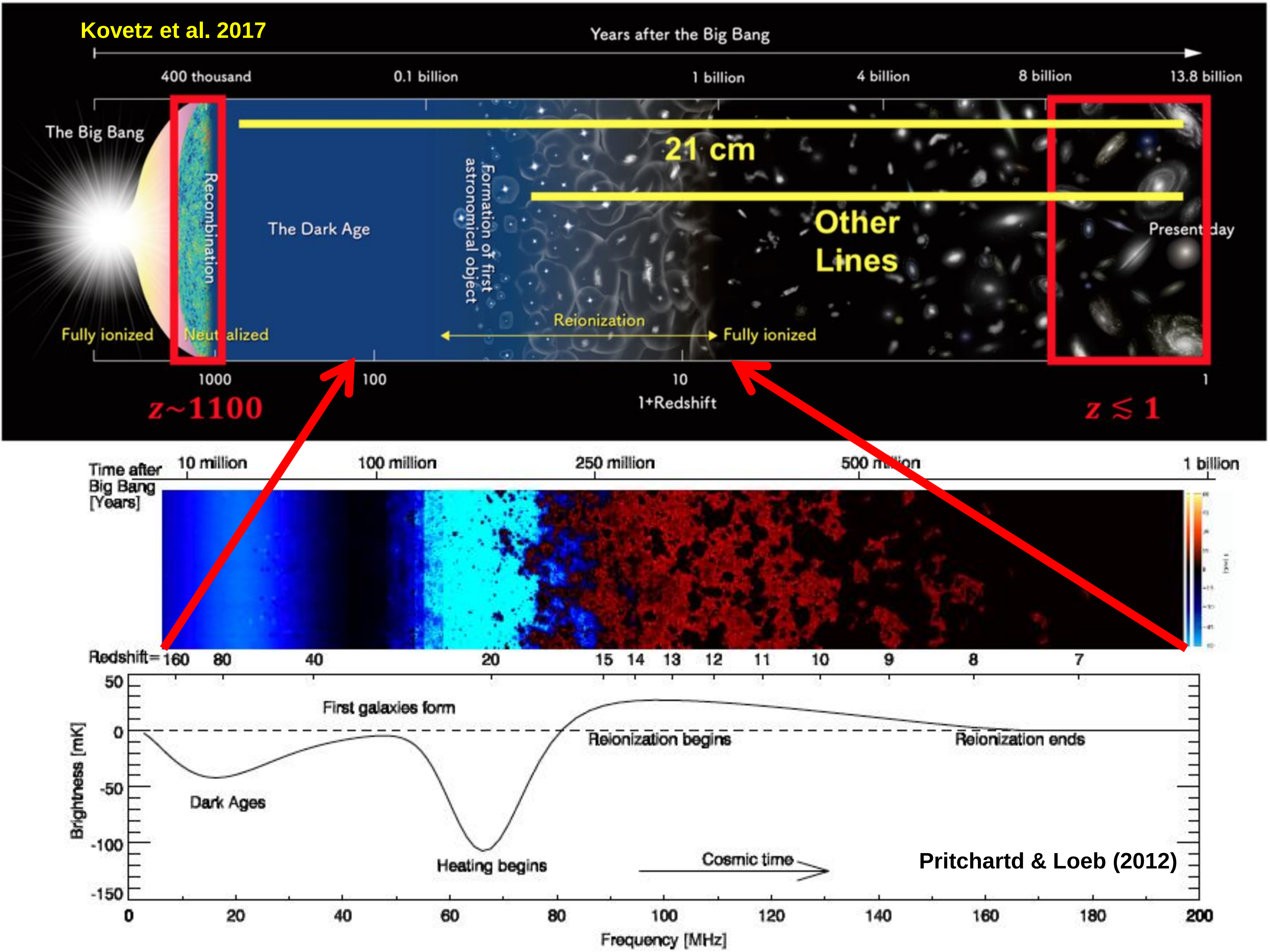

Office
CHAMEX
INTERNATIONAL PAPER



C. A. Wuensche (2019)

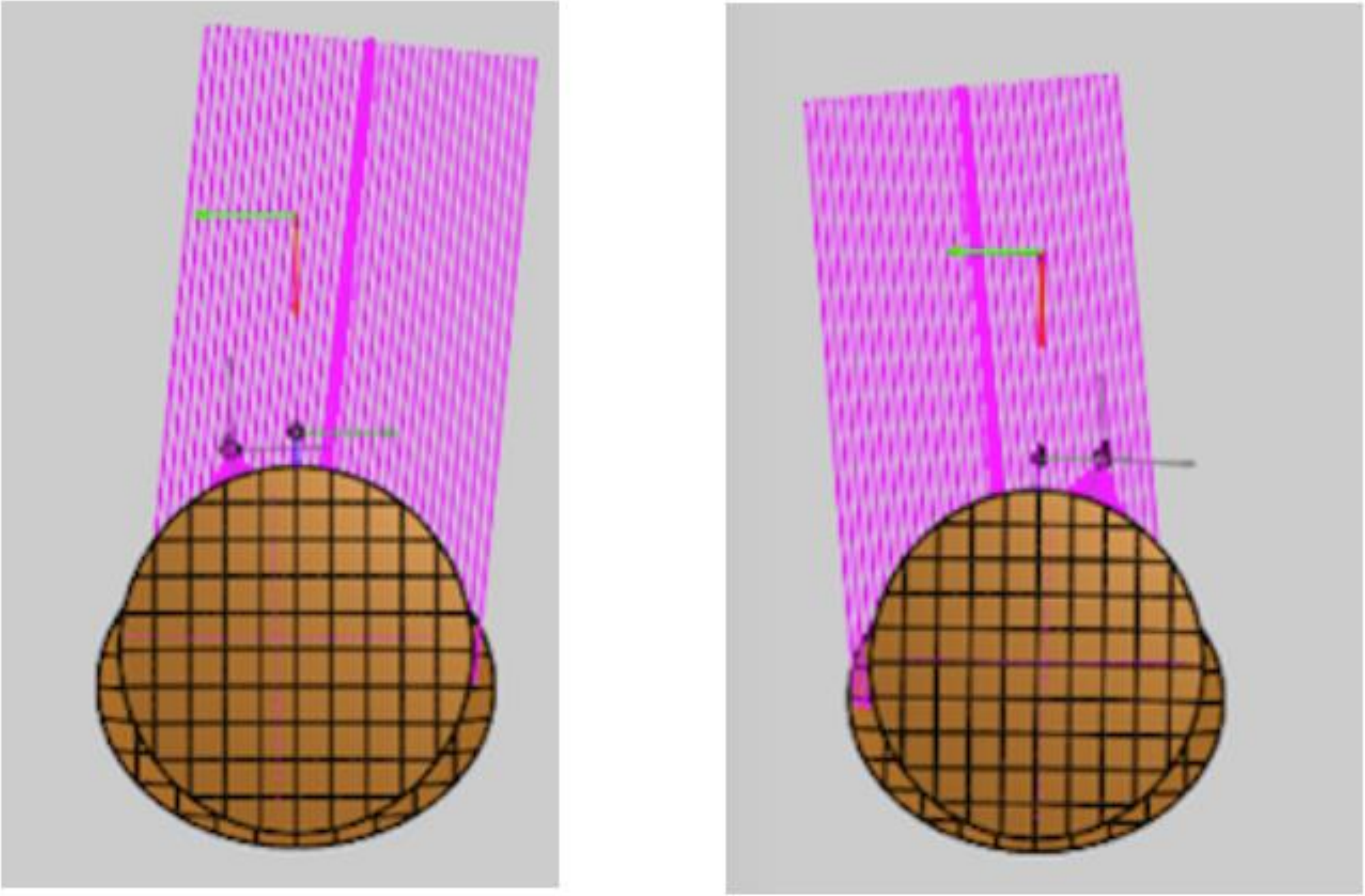


C. A. Wuensche (2019)


Kovetz et al. 2017
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
21 cm
Other Lines
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift
z~1100
z ≲ 1
Time after Big Bang [Years]
10 million
100 million
250 million
500 million
1 billion
Redshift= 160
80
40
20
15
14
13
12
11
10
9
8
7
Brightness [mK]
50
0
-50
-100
-150
First galaxies form
Reionization begins
Reionization ends
Dark Ages
Heating begins
Cosmic time
Pritchartd & Loeb (2012)
0
20
40
60
80
100
120
140
160
180
200
Frequency [MHz]

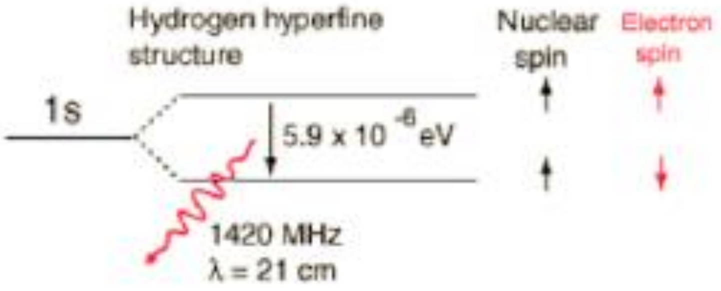
Beam -660 and 660

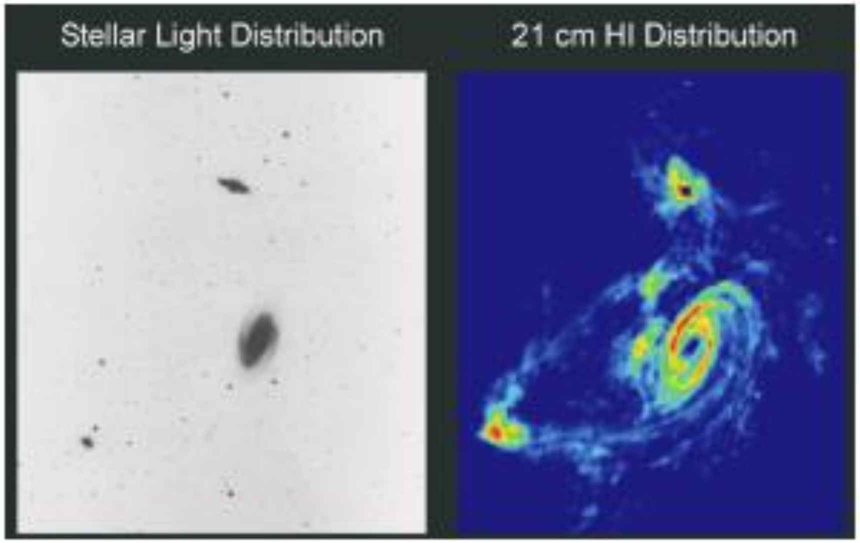
Schematics by Bruno Maffei / Ivan Ferreira



Atomic Hydrogen 21 cm line

- H is the most abundant element in the Universe
- Neutral H (HI) is most important, BUT:
  - Very hard to detect in cosmological distances
- 21 cm “forbidden” transition line
  - 1 atom emits a photon every 10^{15} s
  - Weak signal
  - Frequency: 1420.406 MHz (~ 21 cm waveleght – radio)
- Observed since 1950s’ but only restricted to the Galaxy and neighbor galaxies (z < 0.1)
- Doppler shift of HI line gives direct information of velocity and distance





HI line traces neutral hydrogen in galaxies

And satellites….

Harper & Dickinson (MNRAS 2018)

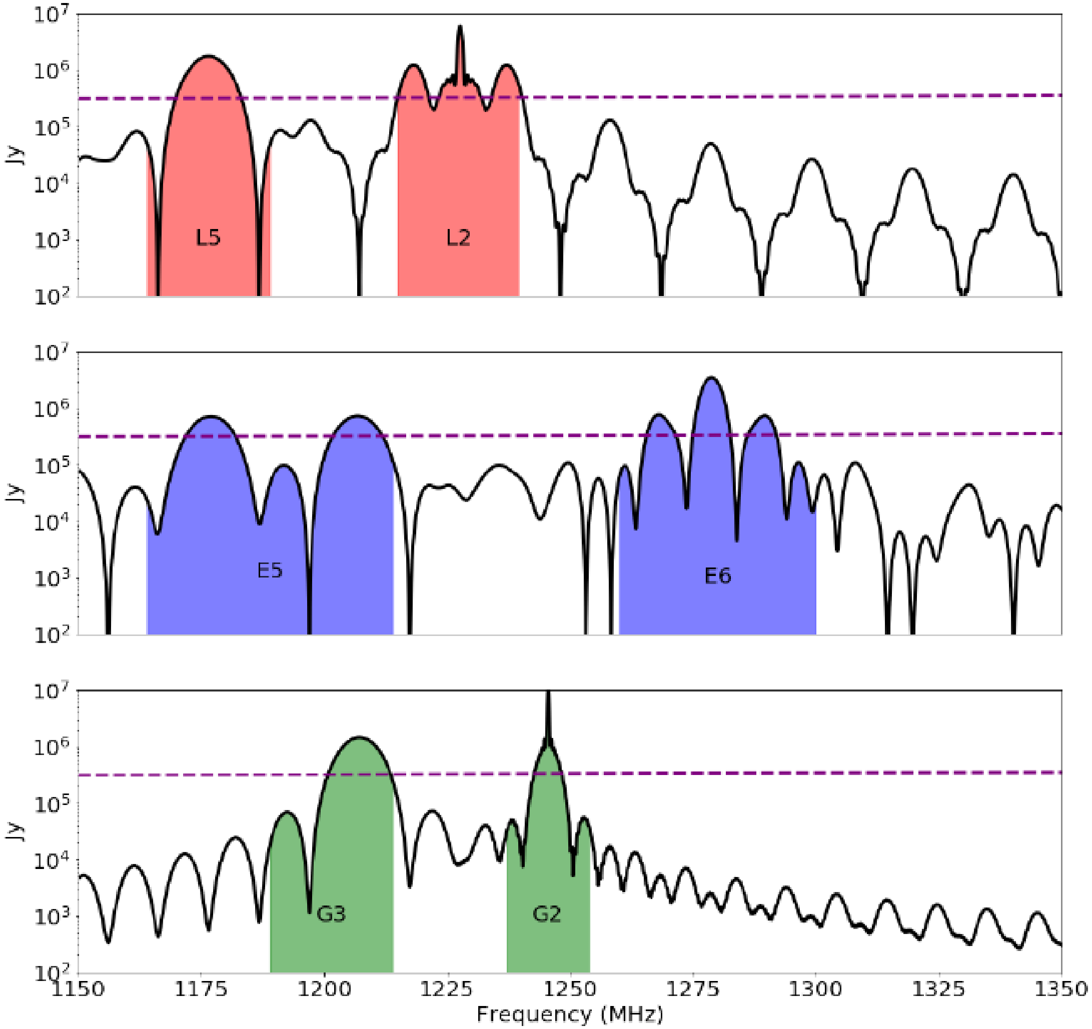
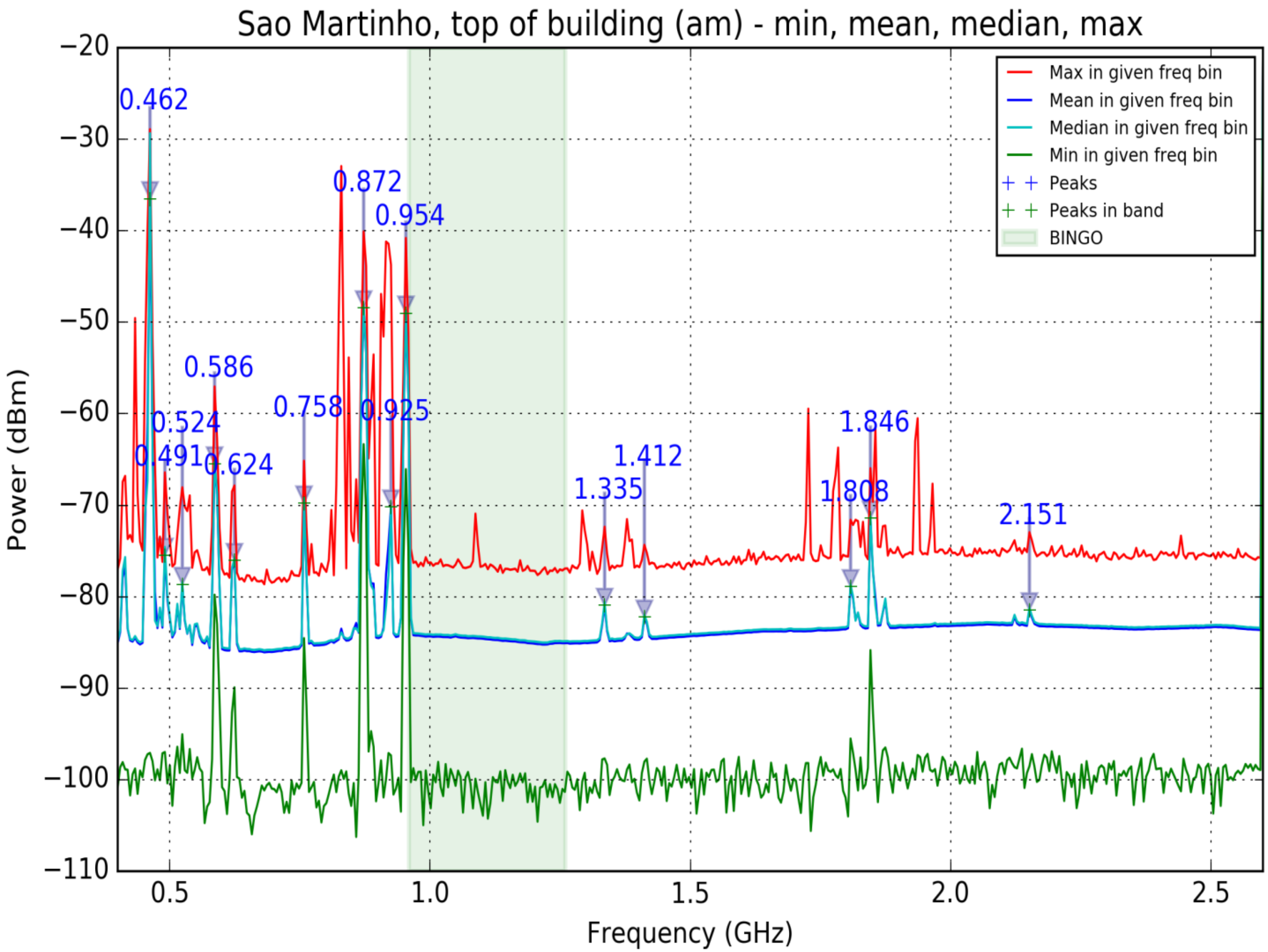


Figure 3. Typical spectral energy distribution as measured from the Earth of GNSS transmissions at frequencies less than 1410 MHz. The *top* plot shows the SED for GPS, the *middle* plot shows Galileo, and the *bottom* shows GLONASS. Highlighted regions in the SEDs represent the nominal frequency allocations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

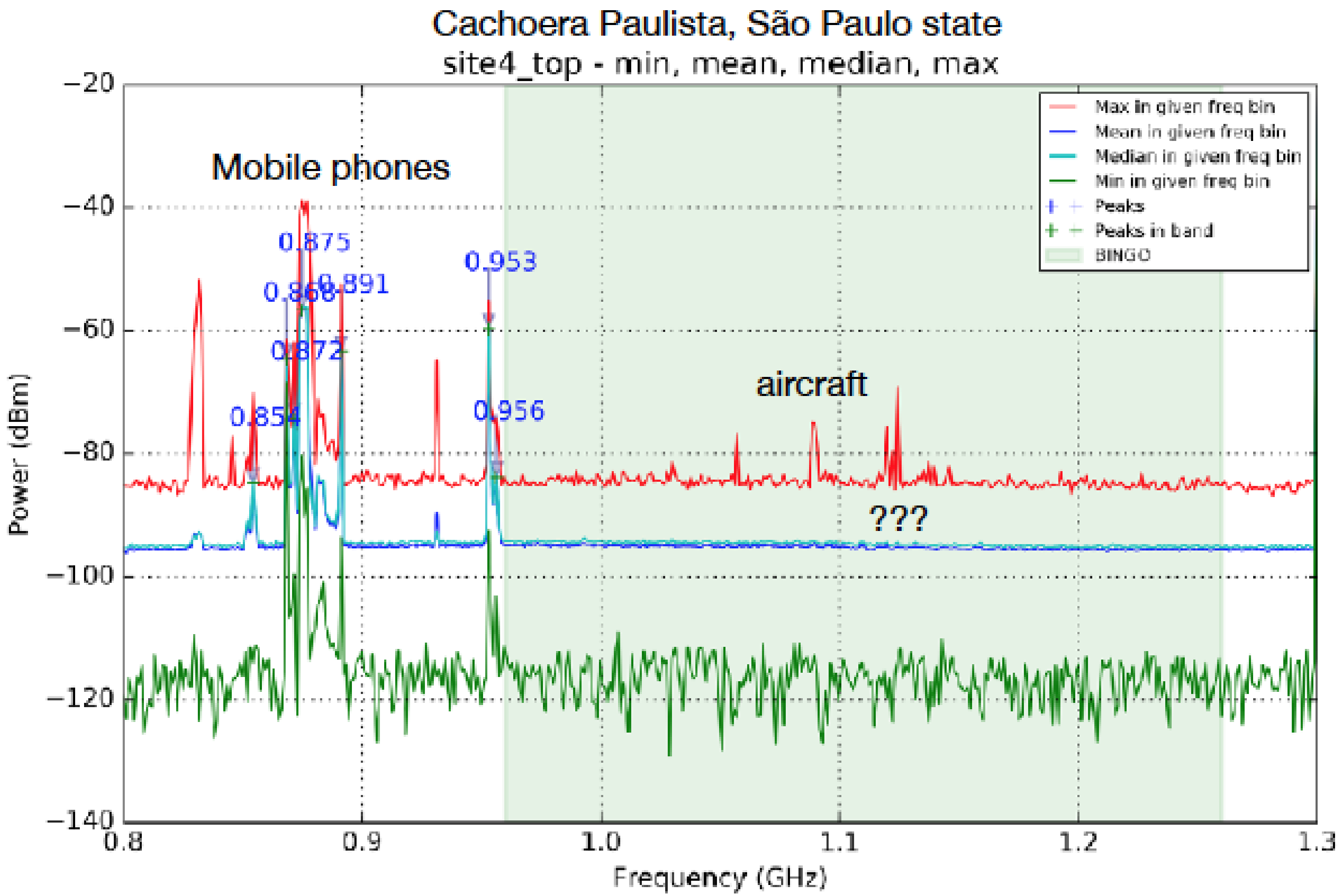
- Hard to get software solutions (no smooth spectrum)
- Hardware possible solutions:
  - cross-correlating data from auxiliary telescopes that are tracking GNSS satellites (Galt 1991)
  - hardware simulated GNSS signals (Ellingson et al. 2001) with data from the primary observing
  - phased array feeds (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).

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



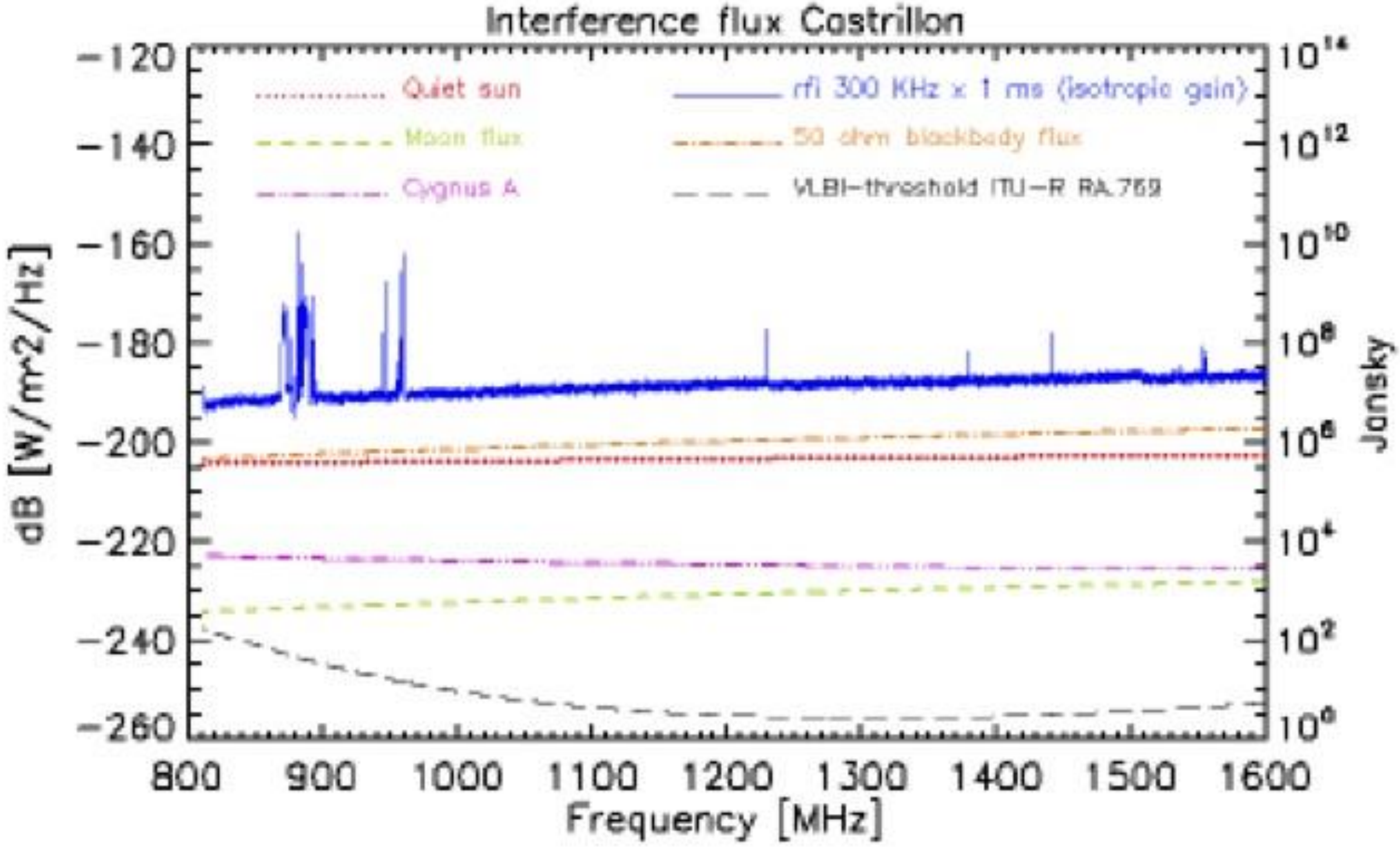
C. A. Wuensche (2019)

Cach. Paulista, INPE’s center, near S. Paulo



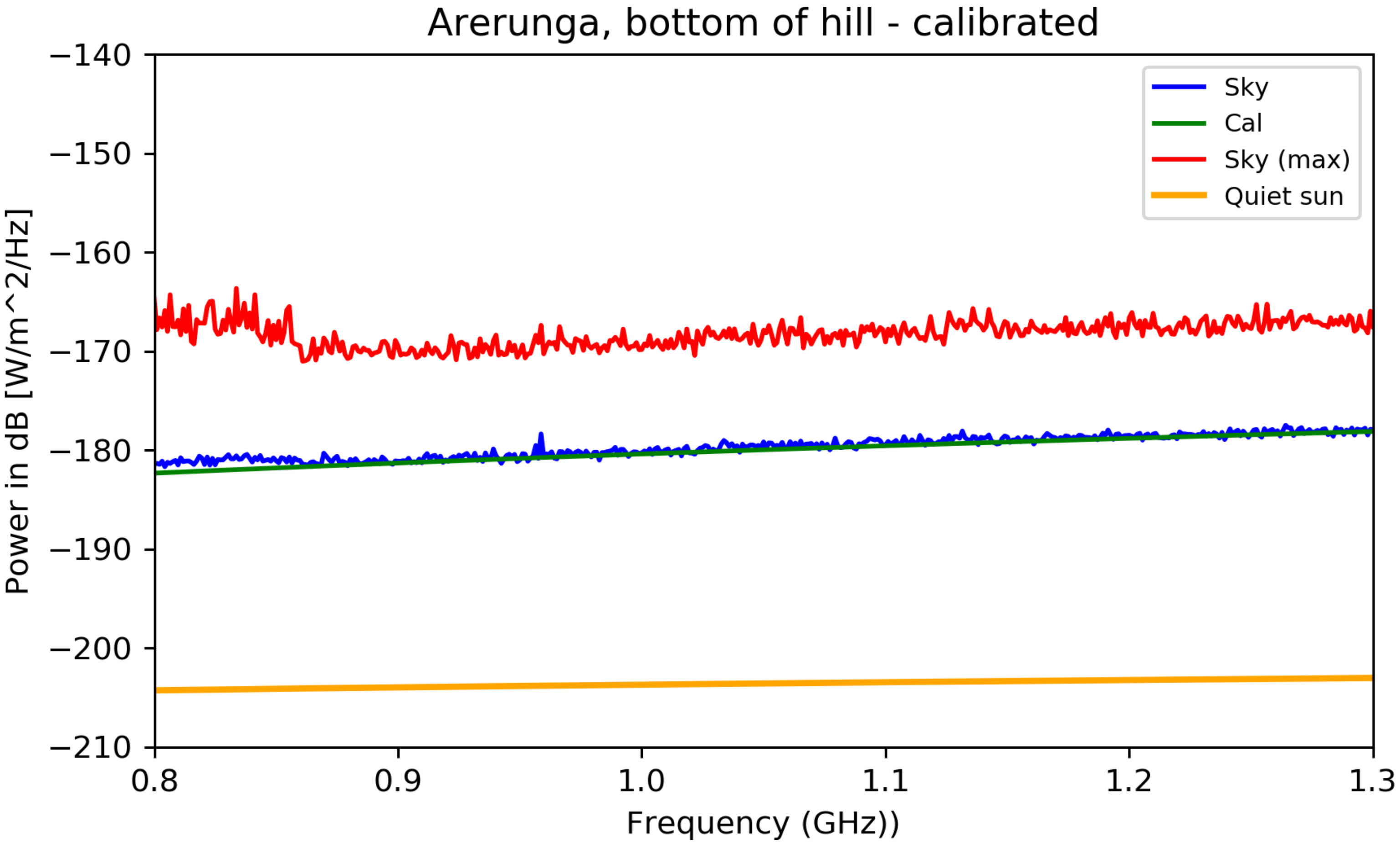
C. A. Wuensche (2019)

Uruguay sites



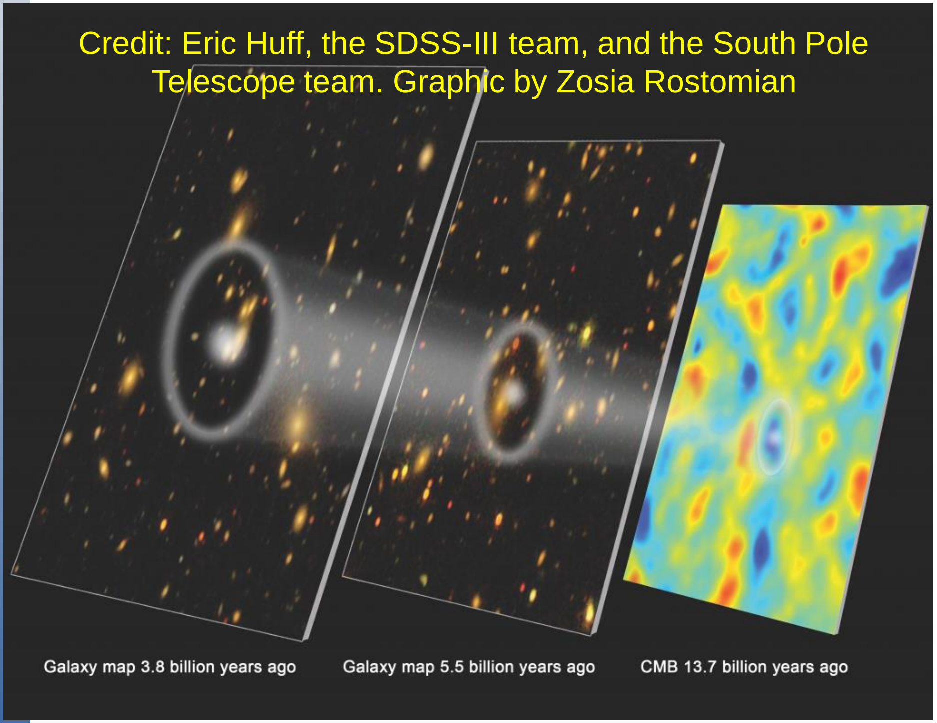
C. A. Wuensche (2019)

Uruguay sites

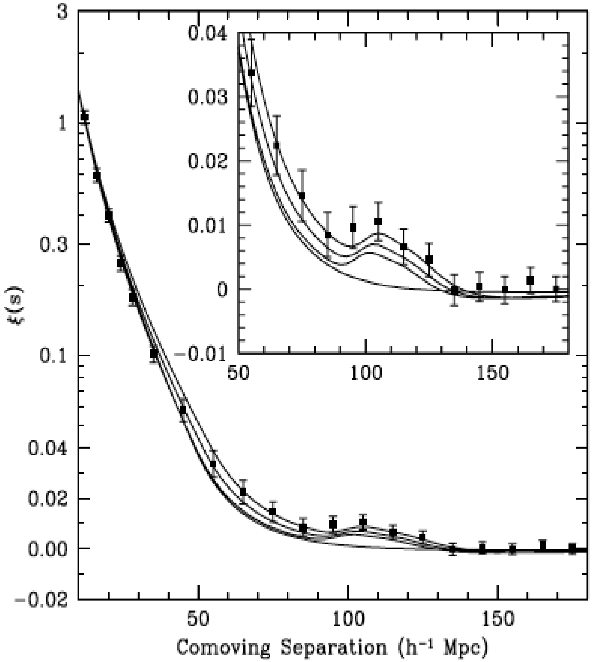


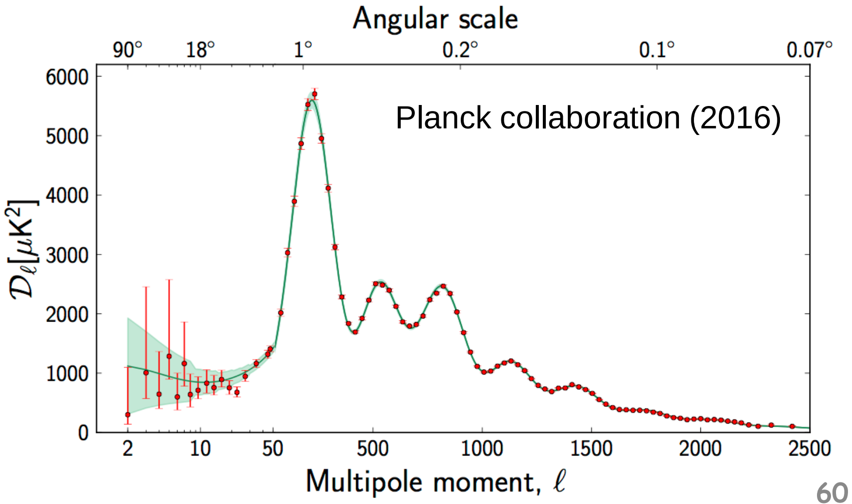
C. A. Wuensche (2019)

Baryon Acoustic Oscillations (BAOs)

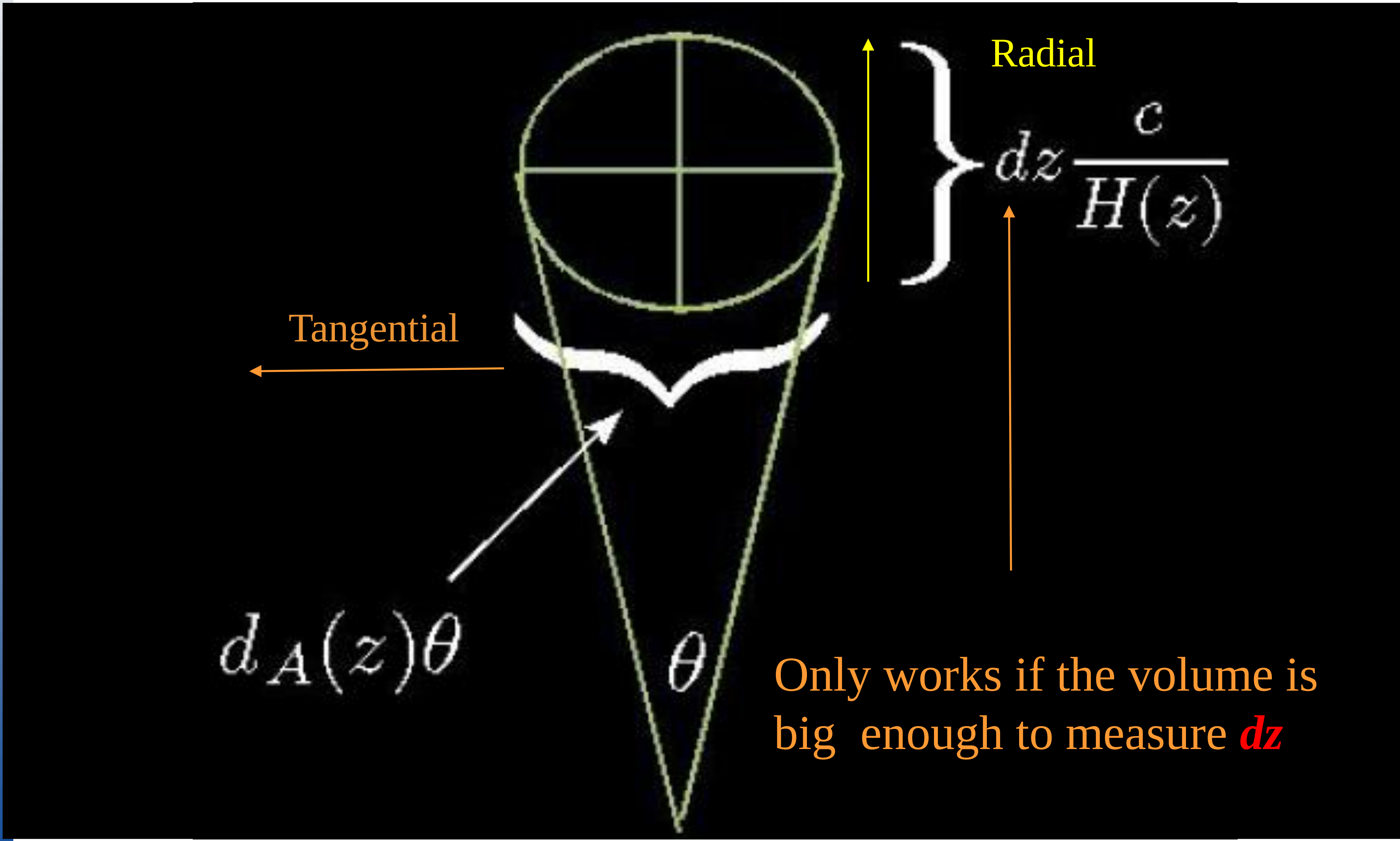

Credit: Eric Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian

Eisenstein et al. (2005)




Planck collaboration (2016)

The Beauty of Standard Volumes



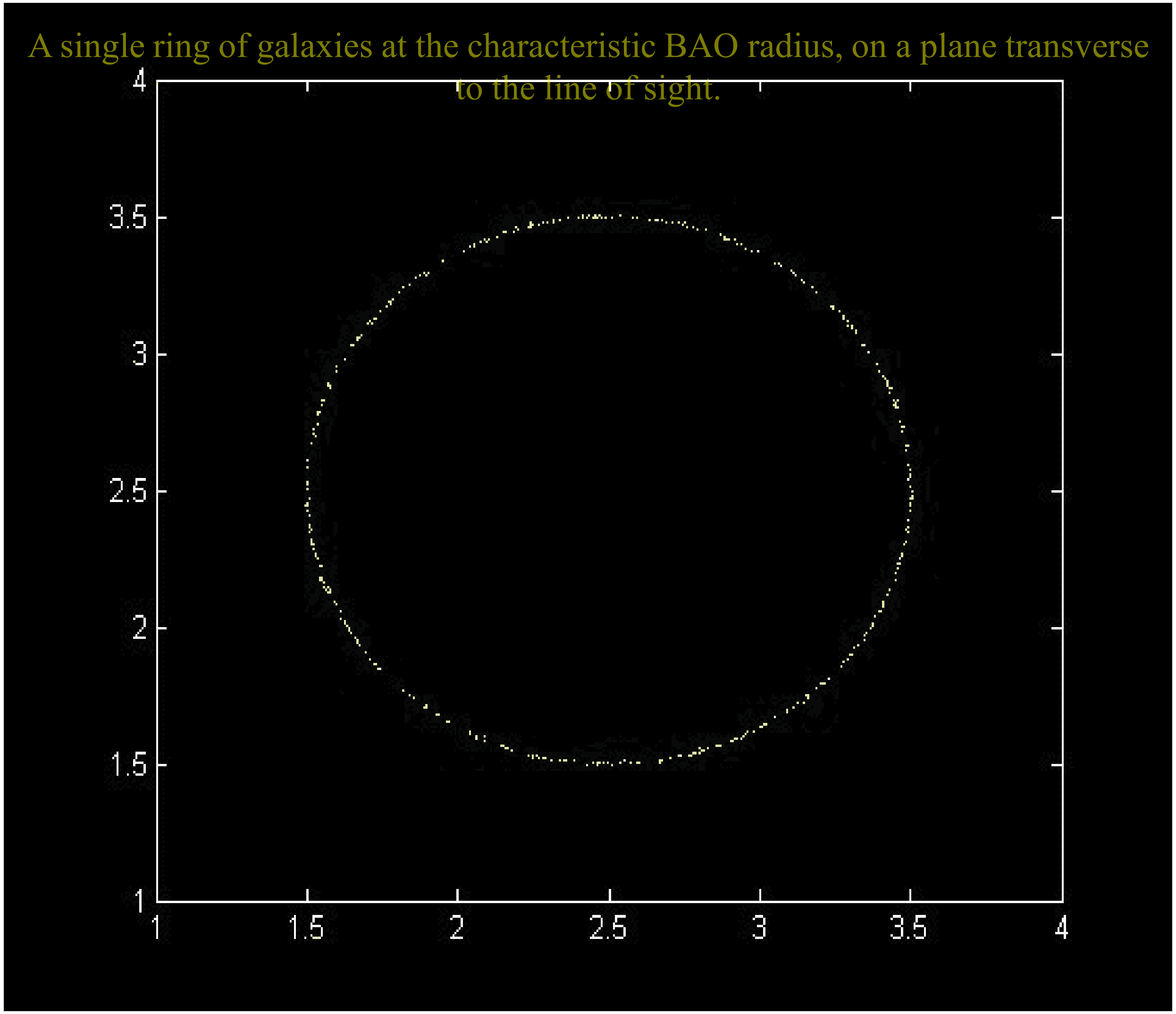
Radial

Tangential

Only works if the volume is big enough to measure ***dz***

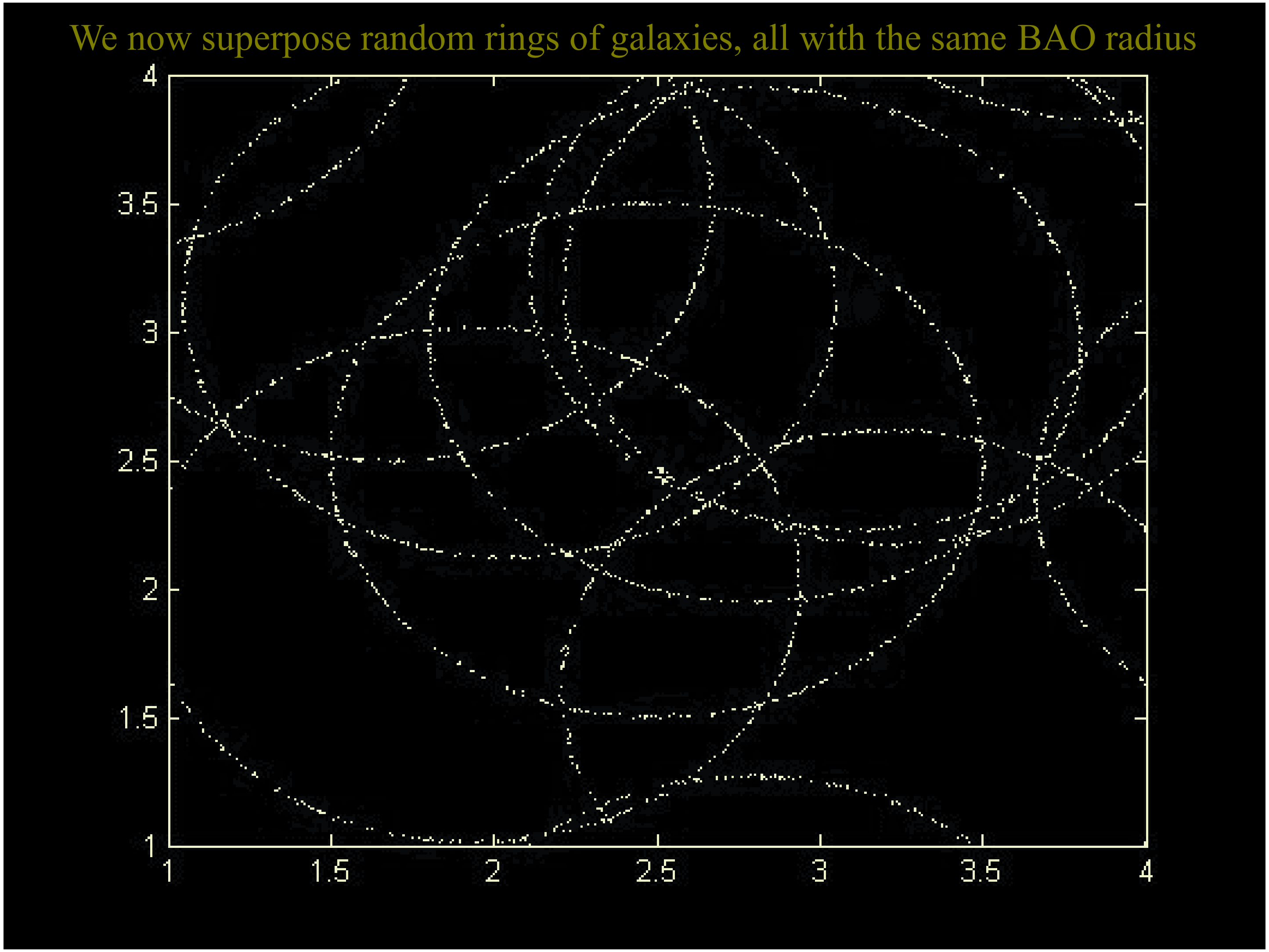
Bassett & Hlozek (2009)

Rings of Power Superposed


A single ring of galaxies at the characteristic BAO radius, on a plane transverse to the line of sight.

Bassett & Hlozek (2009)

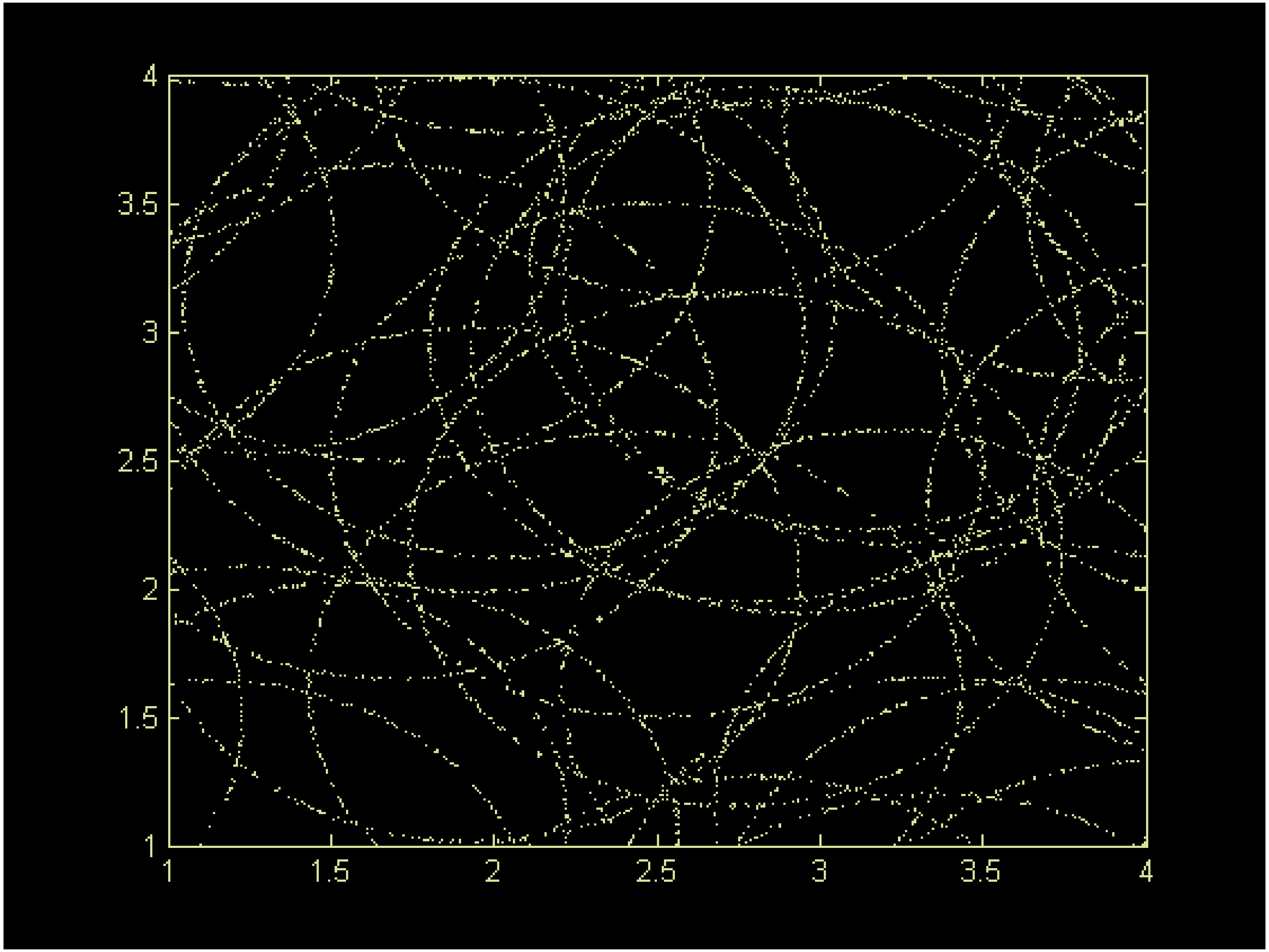
Rings of Power Superposed



We now superpose random rings of galaxies, all with the same BAO radius

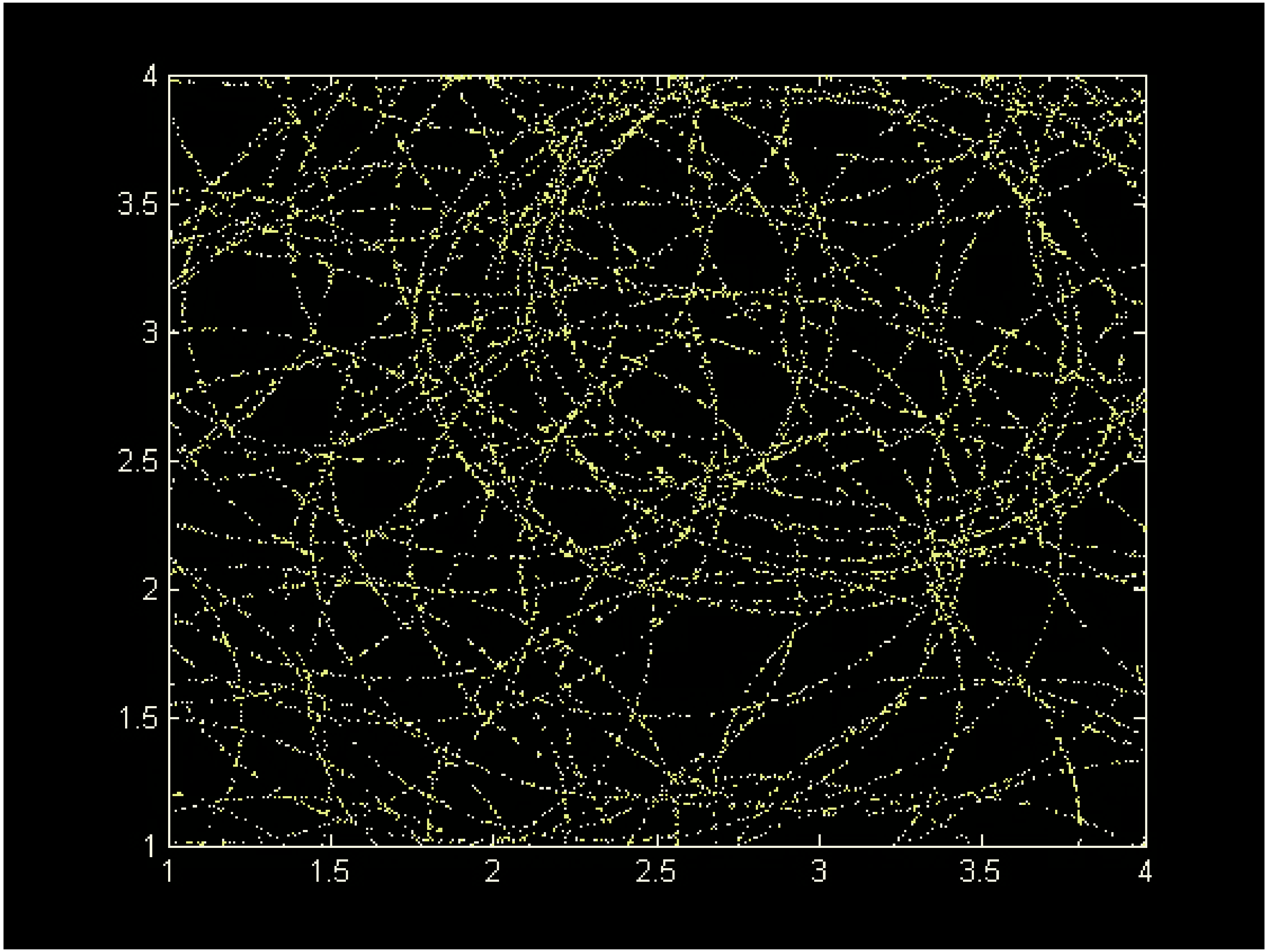
Bassett & Hlozek (2009)

Rings of Power Superposed



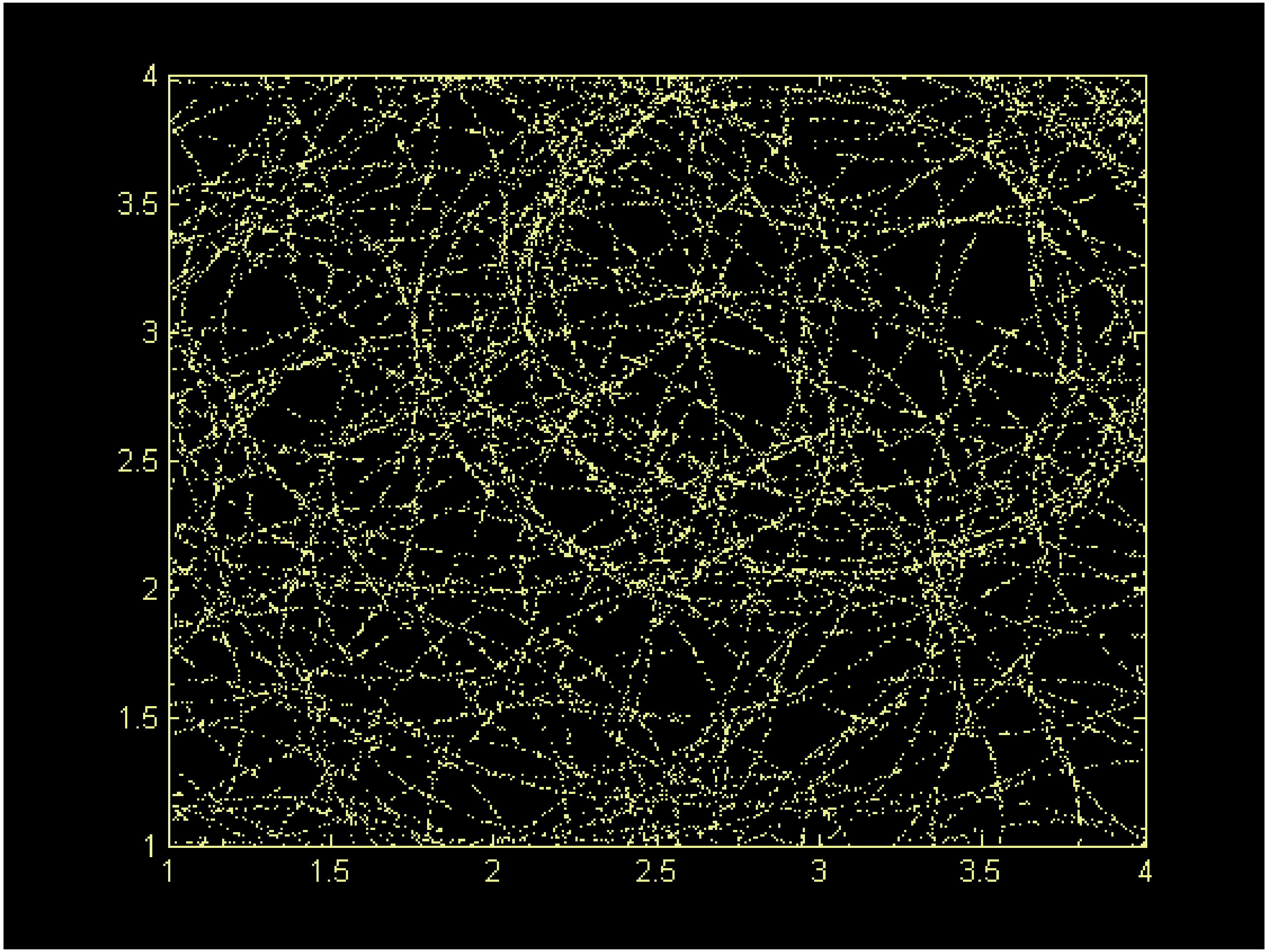
Bassett & Hlozek (2009)

Rings of Power Superposed



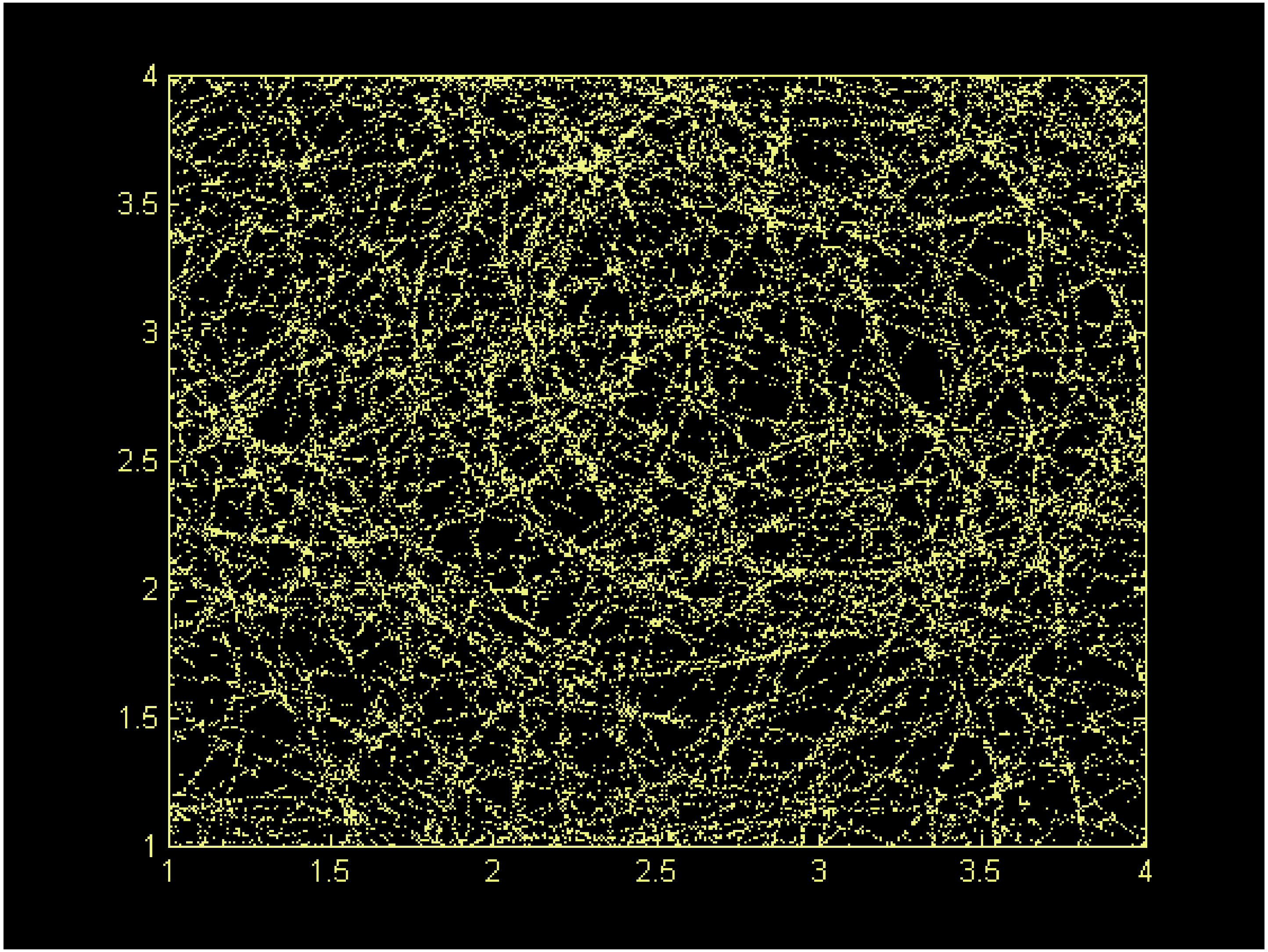
Bassett & Hlozek (2009)

Rings of Power Superposed



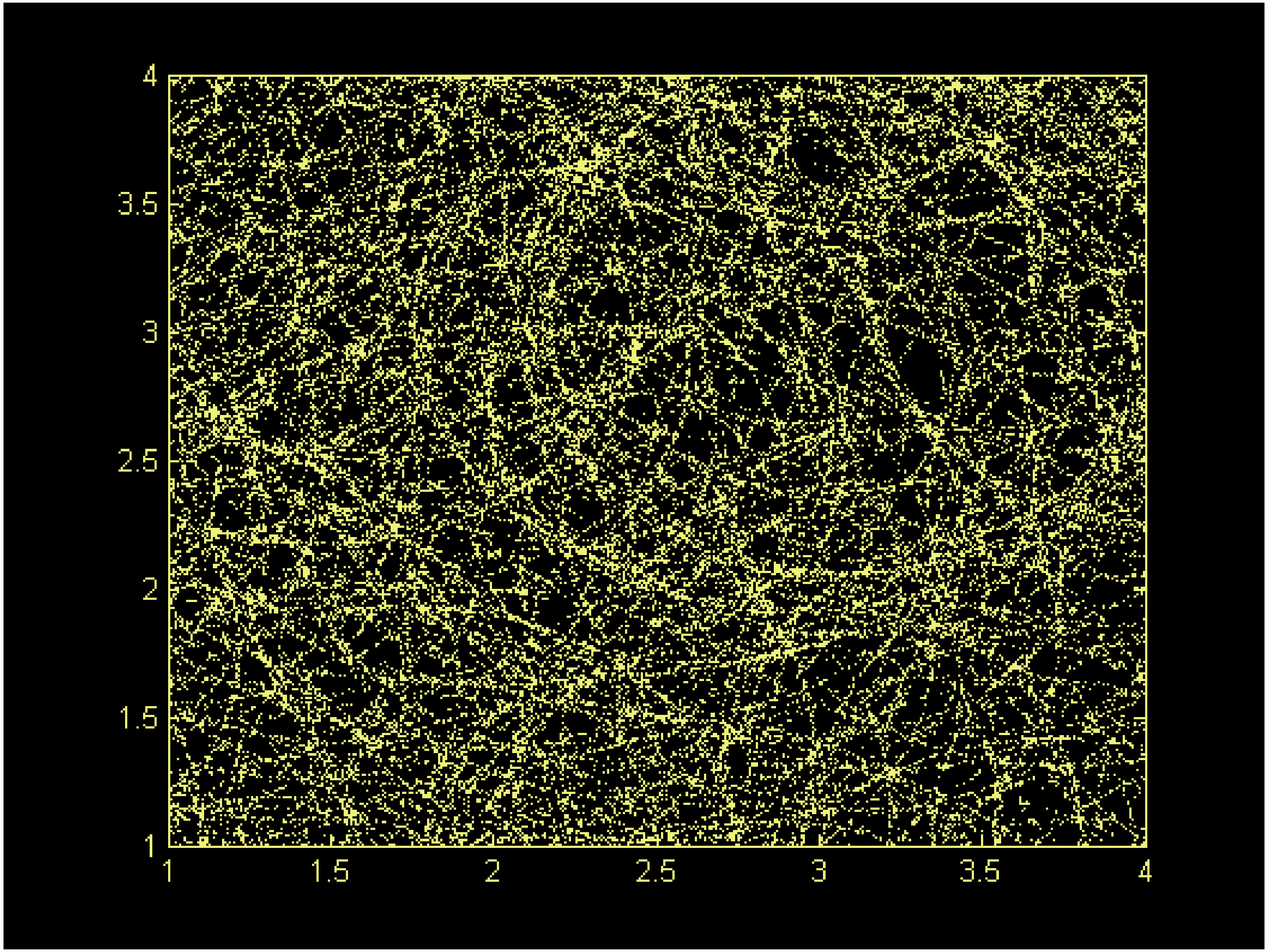
Bassett & Hlozek (2009)

Rings of Power Superposed



Bassett & Hlozek (2009)

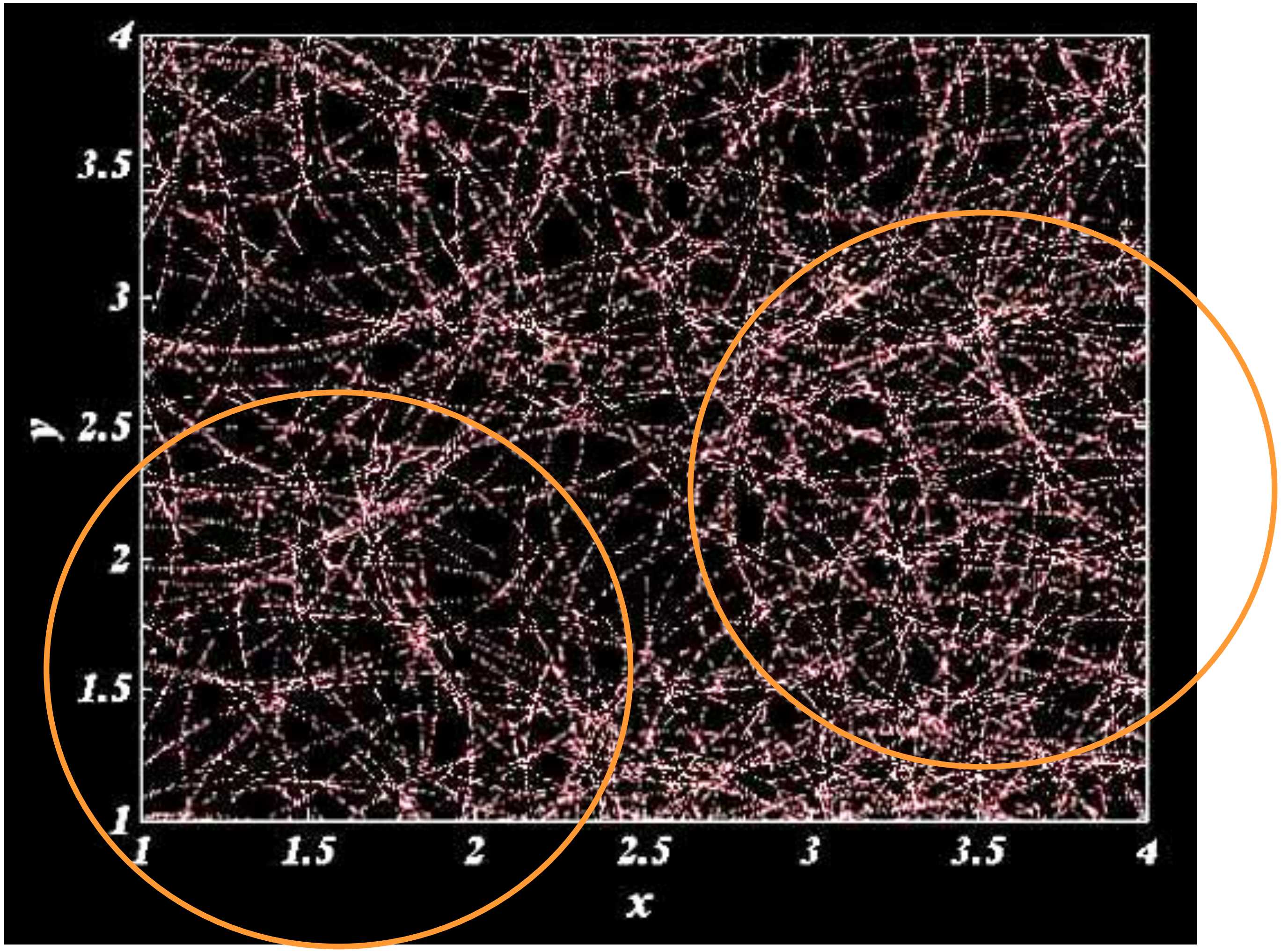
Rings of Power Superposed



Bassett & Hlozek (2009)

Detecting the characteristic radius is now a statistical problem

Statistical Standard Rulers



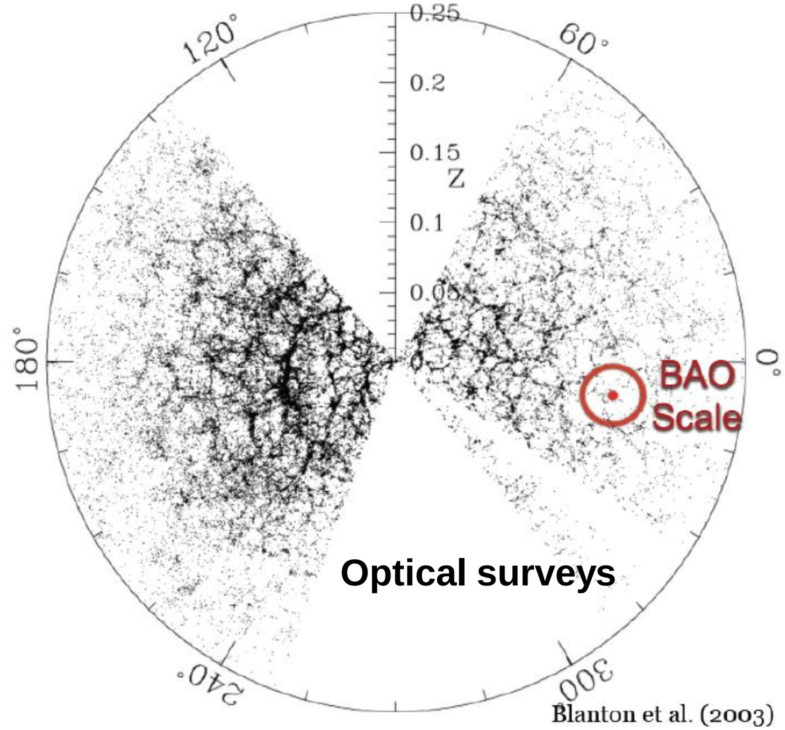
Bassett & Hlozek (2009)

Power Spectrum Errors

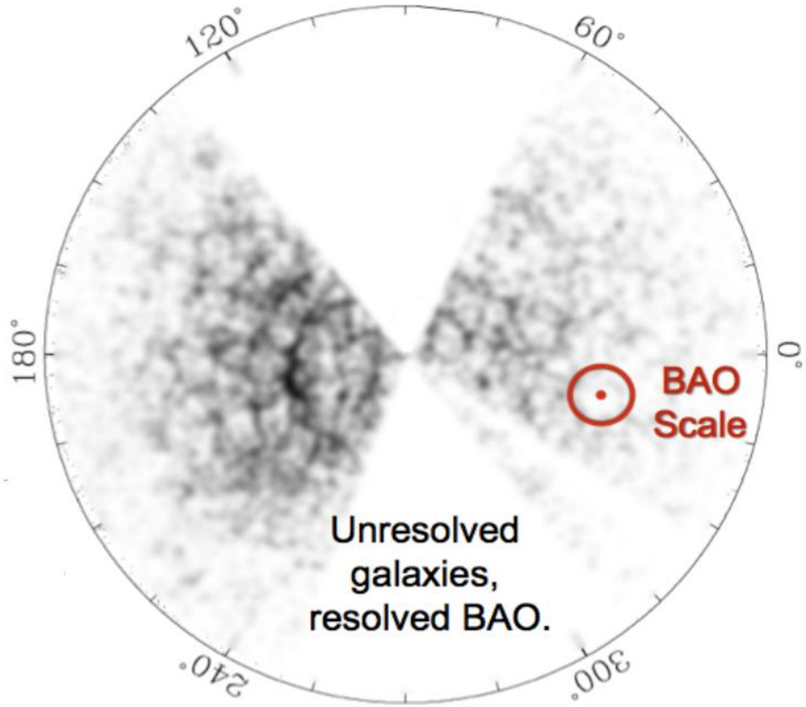
$$\frac{\delta P}{P} = \underbrace{\frac{1}{\sqrt{m}}}_{\text{Cosmic Variance}}\left(1 + \underbrace{\frac{1}{nP}}_{\text{Shot Noise}}\right)$$

m = number of Fourier modes measured in the survey
n = mean galaxy number density in the survey

Bassett & Hlozek (2009)



Blanton et al. (2003)

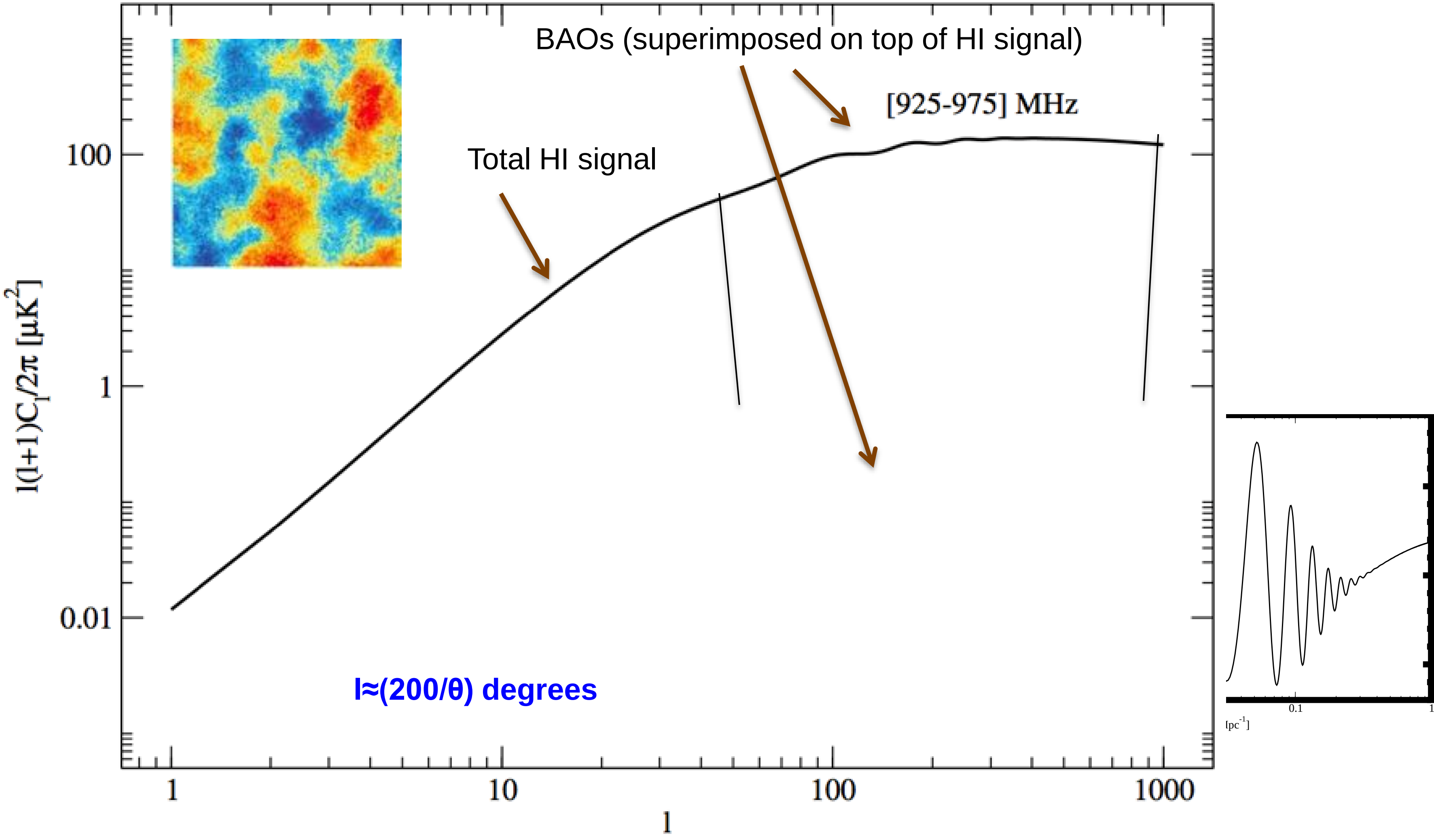


C. A. Wuensche (2019)

The HI signal power spectrum

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

$$\bar{T}_{\rm obs}(z) = 44\,\mu{\rm K}\left(\frac{\Omega_{\rm HI}(z)h}{2.45\times 10^{-4}}\right)\frac{(1+z)^2}{E(z)}$$



BAOs (superimposed on top of HI signal)

Total HI signal

l≈(200/θ) degrees

C. A. Wuensche (2019)

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
- Long observing time (> 1
- Sensitivity to i… 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≈0.08
  - ☐ 100 MHz => z≈0.93

BINGO meets all of them

Lots of Radio Frequency Interference (RFI) in this frequency range

Adapted from Bull et al. 2015

- 1000 - Telescope
  - 1100 - Antenna
    - 1110 - Horns
    - 1120 - Transitions
    - 1130 - Polarizer
    - 1140 - Magic Tee
  - 1200 - Receivers
  - 1300 - Digital BackEnd
  - 1400 - Dishes
    - 1410 - Parabola
    - 1420 - Hyperbole
  - 1500 - Control Cabin
    - 1510 - Houskeeping
    - 1520 - FRB Analysis
    - 1530 - Spectral Analysis
    - 1540 - Automated data reduction
    - 1550 - Storage
  - 1600 - Cabling
    - 1610 - Data Transfer
    - 1620 - Power
  - 1700 - Data Management
    - 1710 - Permanent Storage
    - 1720 - Data dissemination
    - 1730 - Virtual observatory
    - 1740 - Data transfer site - global
  - 1800 - Calibration
  - 1900 - Telescope comissioning

2000 - Construction Site

- 2100 - Power supply
  - 2110 - Substation
  - 2120 - Site cabling
- 2200 - Internet
- 2300 - Water
- 2400 - Security
- 2500 - Road Access
- 2600 - Terrain preparation
- 2700 - Foundations
- 2800 - Steel Structure
  - 2810 - Horns array steel structure
  - 2820 - Dishes steel structure
    - 2821 - Parabola steel structure
    - 2822 - Hyperbole steel structure
- 2900 - Silence Zone

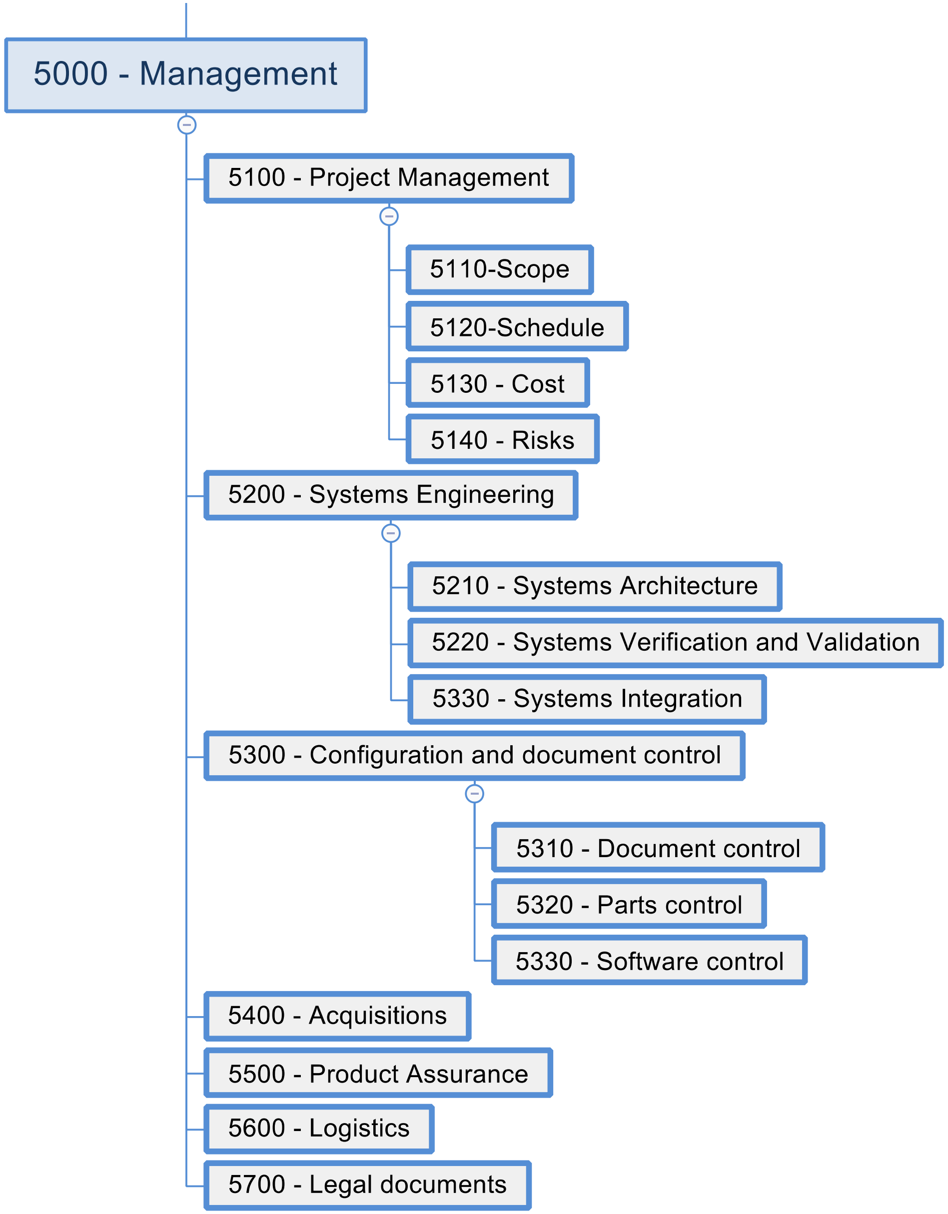
3000 - Pipeline and Science Forecast

- 3100 - Mission simulation
- 3200 - Component separation
- 3300 - Cosmological parameters forecast
- 3400 - Galactic science
- 3500 - Transient object science
- 3600 - Other science

4000 - Outreach

- 4100 - Audiovisual
- 4200 - Press material
- 4300 - Internet and social media
- 4400 - Papers and white papers

C.



- 5000 - Management
  - 5100 - Project Management
    - 5110-Scope
    - 5120-Schedule
    - 5130 - Cost
    - 5140 - Risks
  - 5200 - Systems Engineering
    - 5210 - Systems Architecture
    - 5220 - Systems Verification and Validation
    - 5330 - Systems Integration
  - 5300 - Configuration and document control
    - 5310 - Document control
    - 5320 - Parts control
    - 5330 - Software control
  - 5400 - Acquisitions
  - 5500 - Product Assurance
  - 5600 - Logistics
  - 5700 - Legal documents