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 on behalf of the

BINGO Collaboration

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Plan of the talk

- Cosmological motivation
- The BINGO concept
- Current status

BAO Integrated Neutral Gas Observations

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 – EUCLID, HETDEX
  - Dark energy – DESI and LSST (DoE flagship projects)

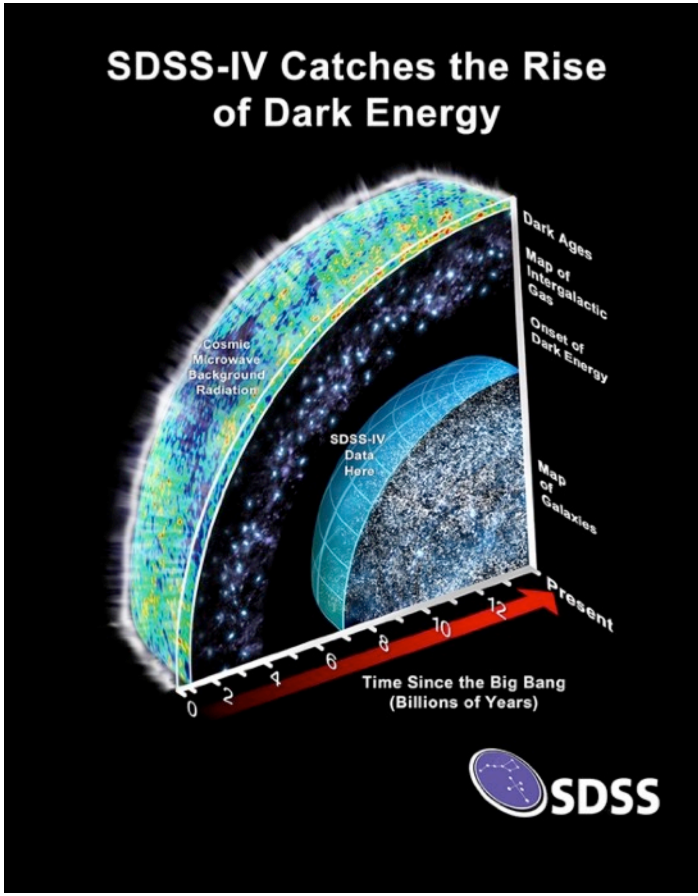
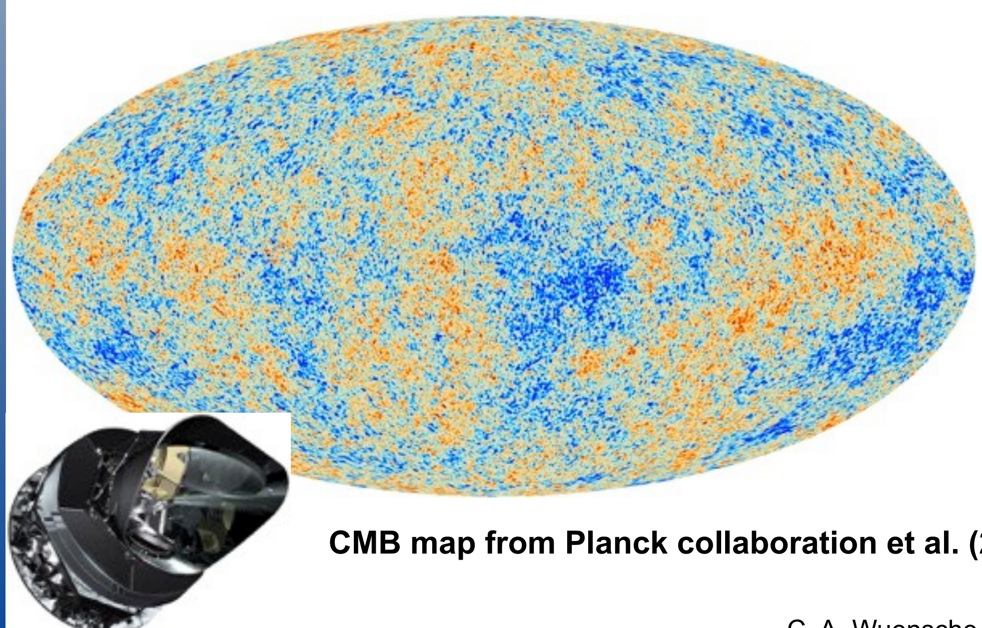
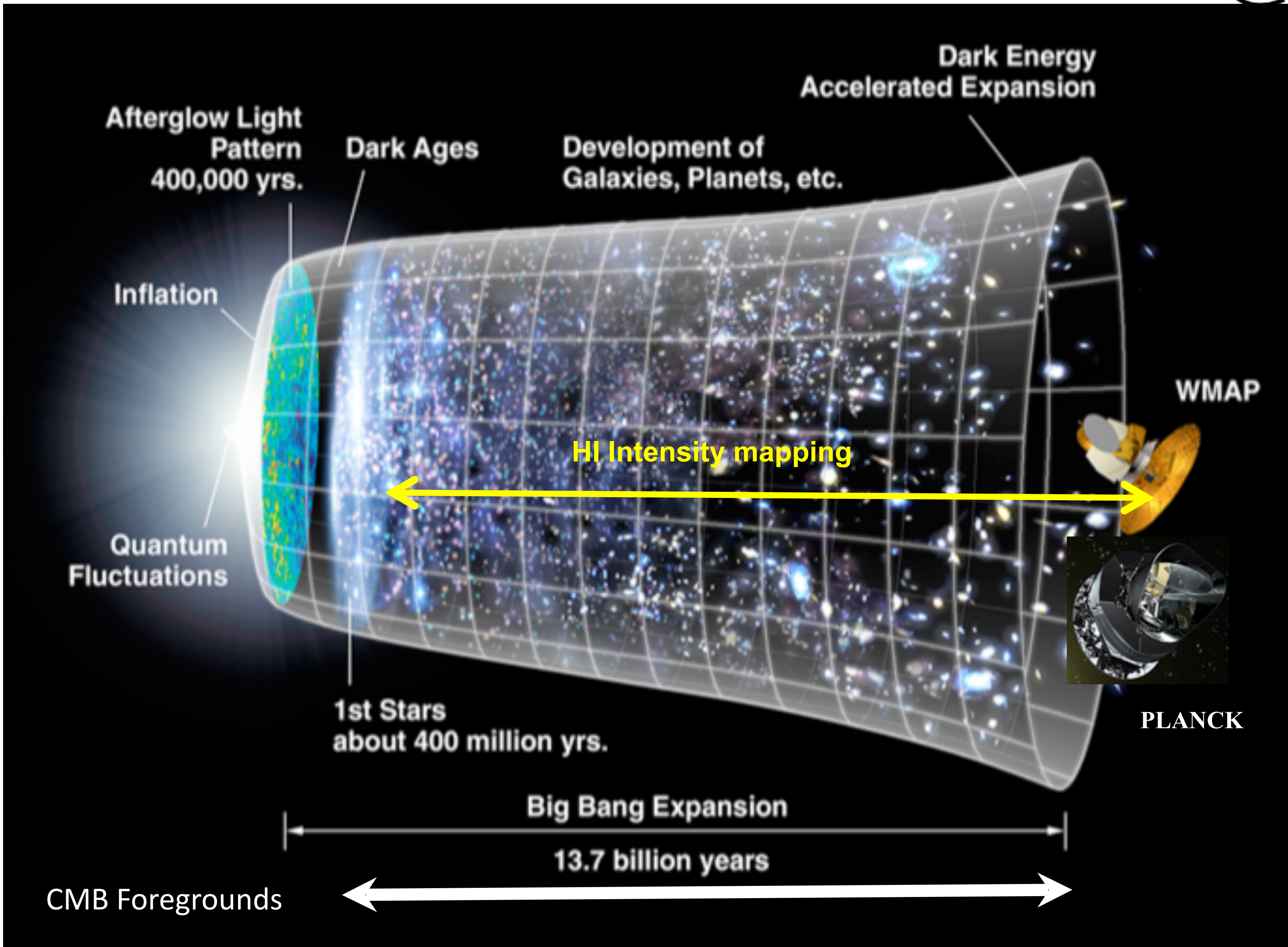


Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.



CMB map from Planck collaboration et al. (2018)



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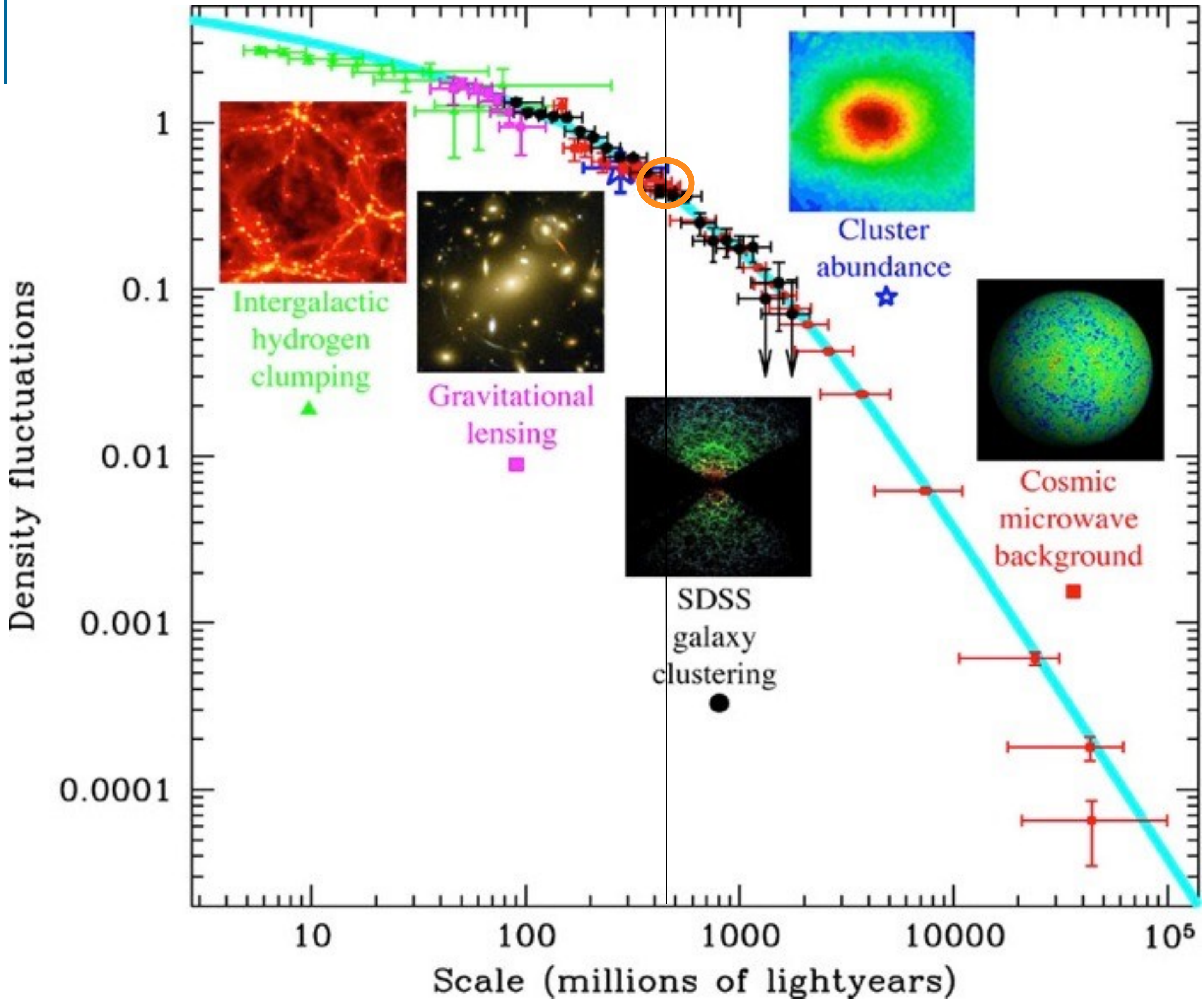

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Dark Energy Observation program

- Instruments: JWST, SKA, LSST, Euclid, DESI
- 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), Ansari et al. arXiv:1810.09572

Standard Cosmological Model

Observational tests

Geometry of the Universe (k=0)

SN Ia

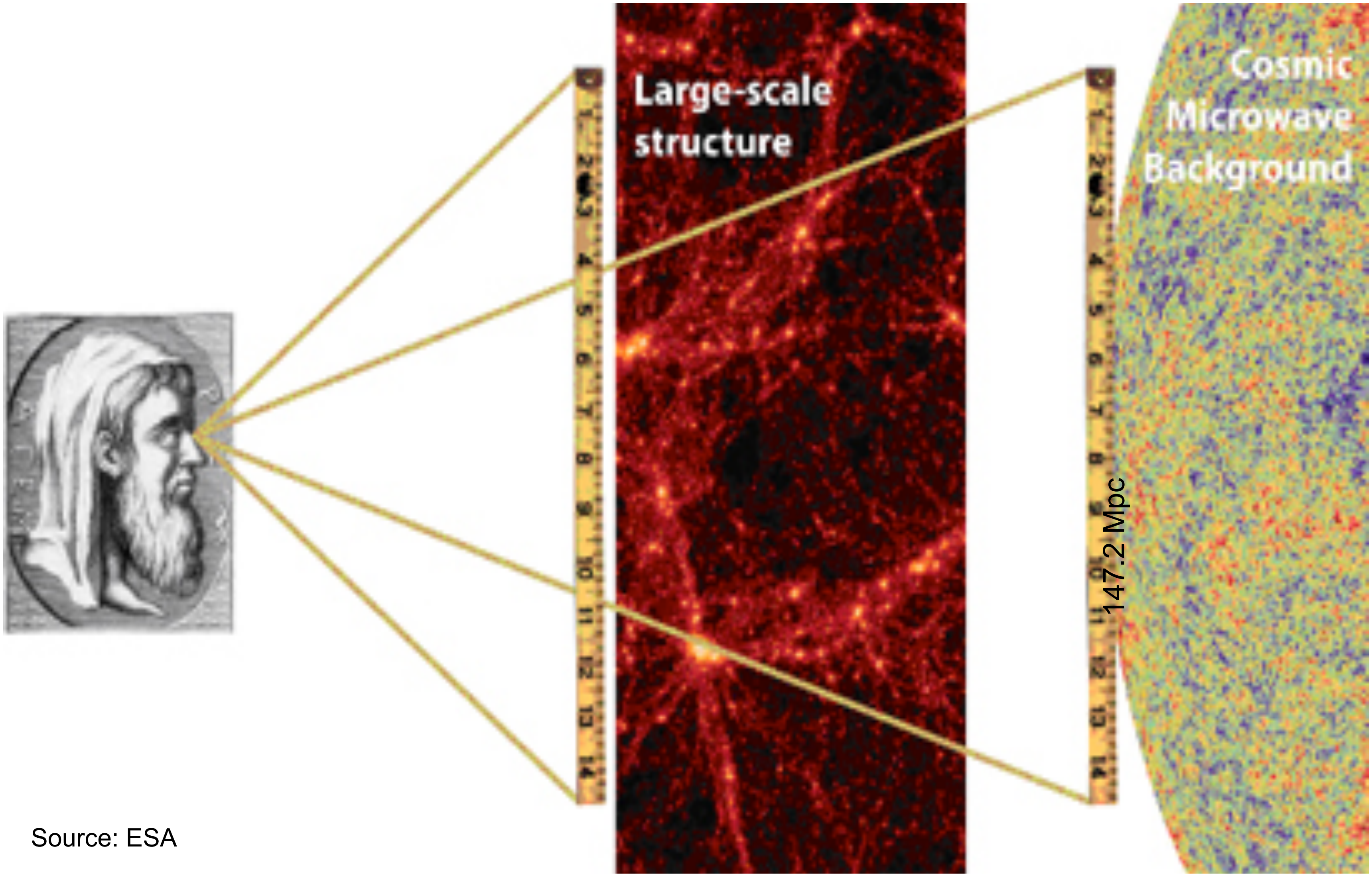
Weak Lensing

CMB

Baryon Acoustic Oscillations

Cluster Counting

Baryon Acoustic Oscillations (BAOs)



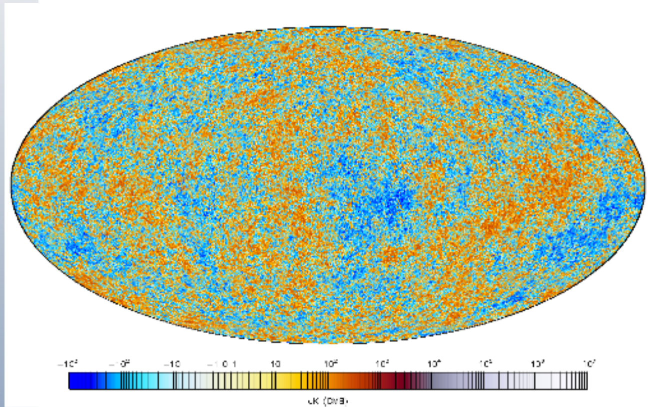
Source: ESA

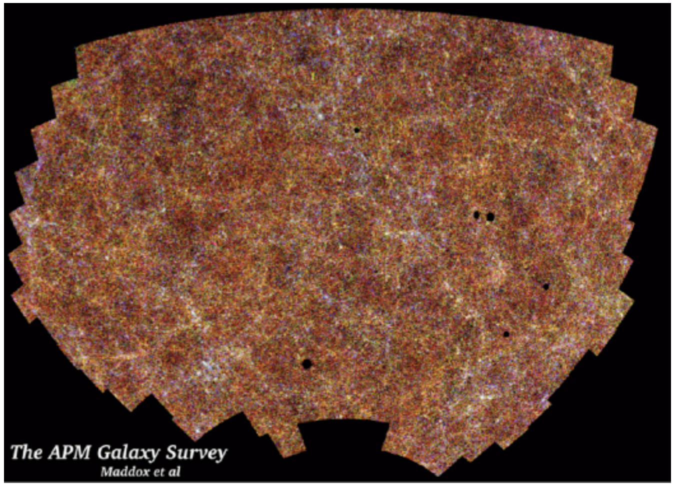
Baryon Acoustic Oscillations (BAOs)

- 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

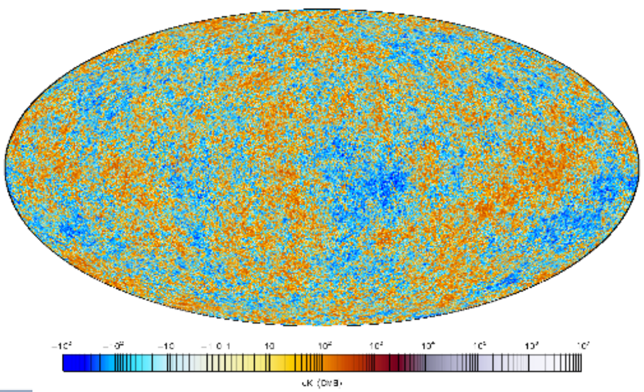
Temperature x matter fluctuations

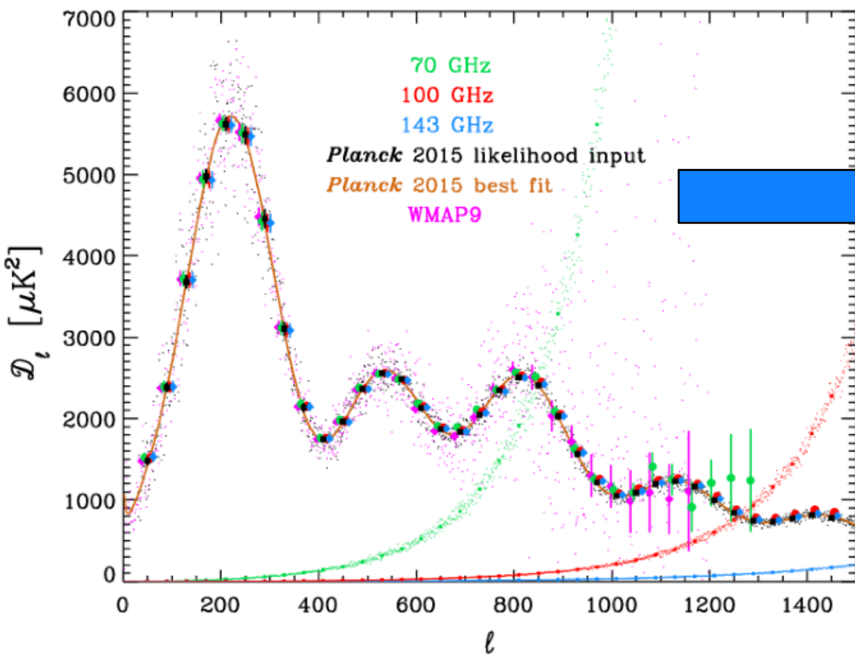
Temperature x matter fluctuations

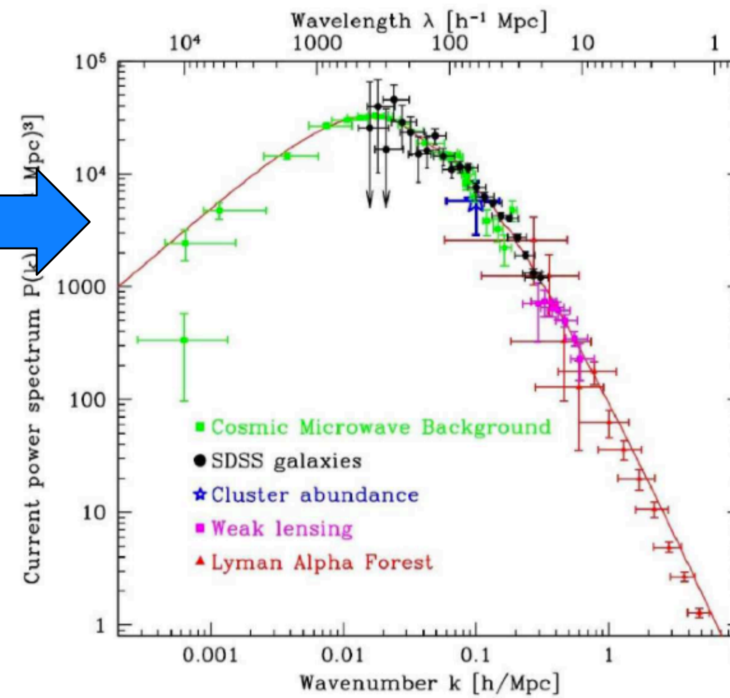




Temperature x matter fluctuations







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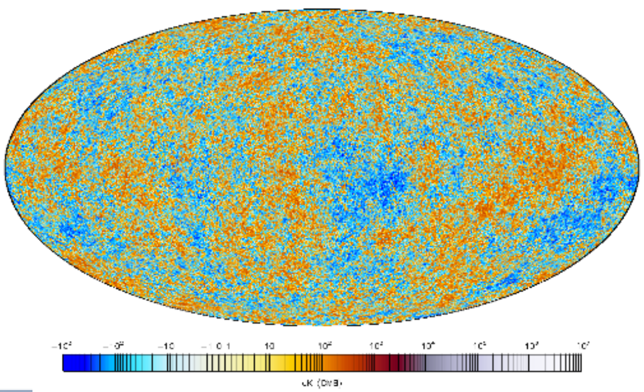
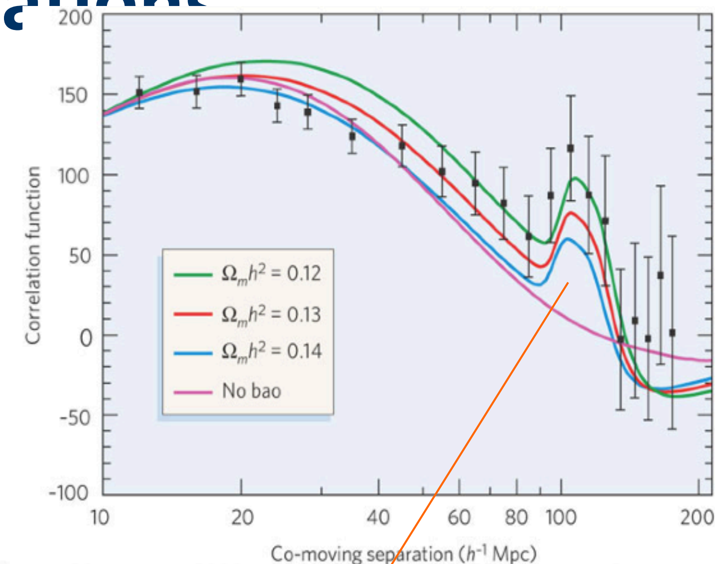
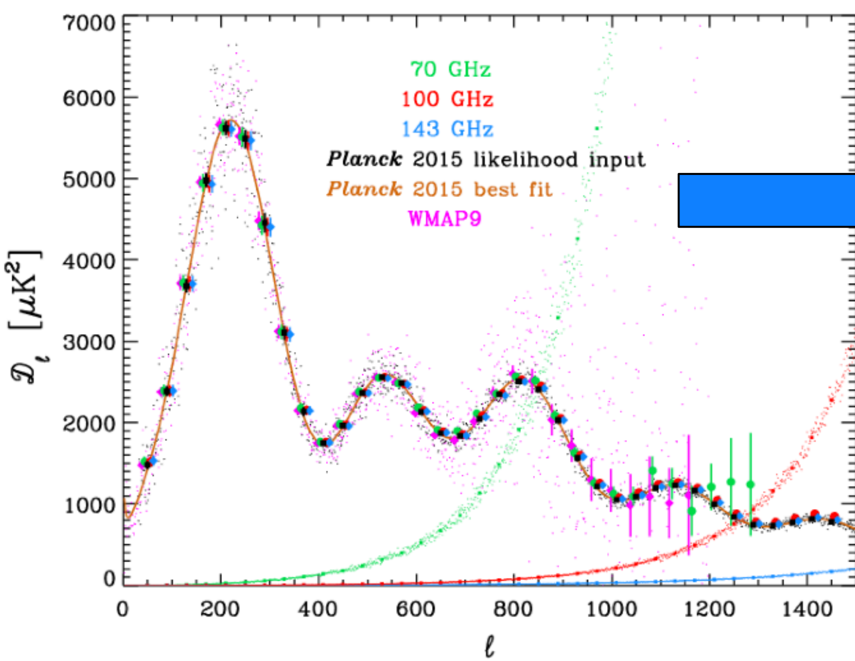
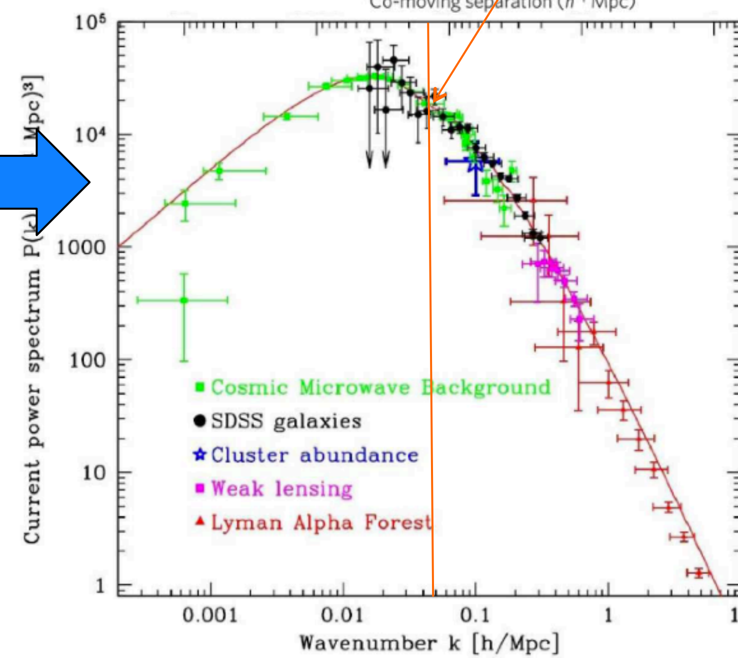
Temperature x matter fluctuations









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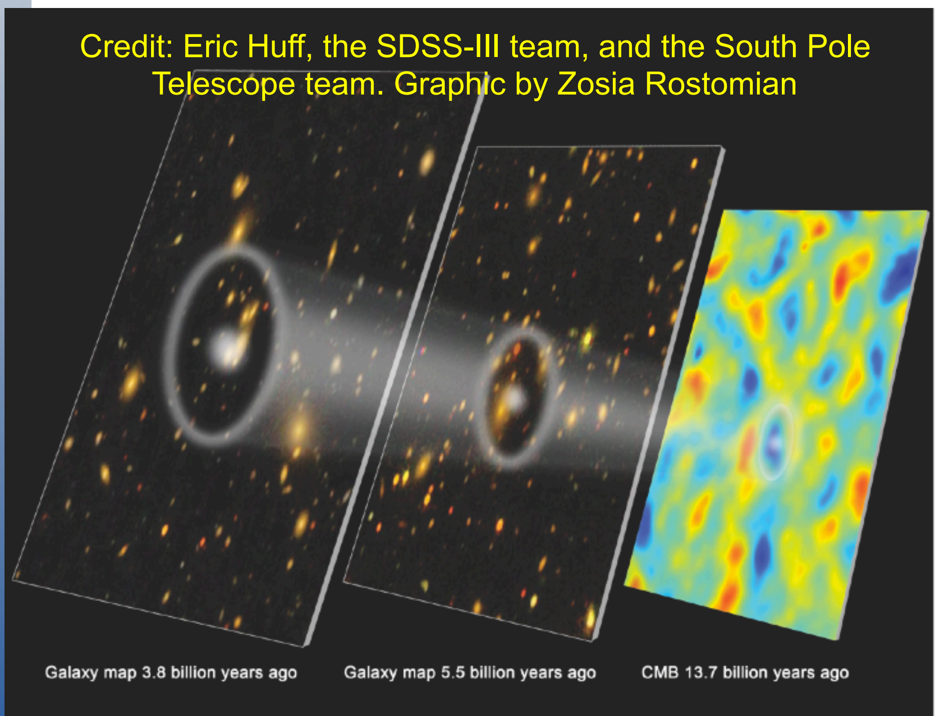
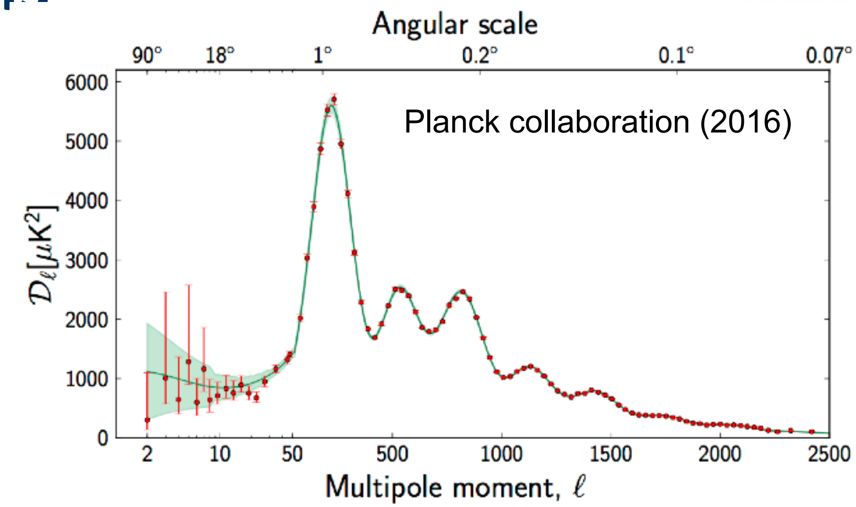
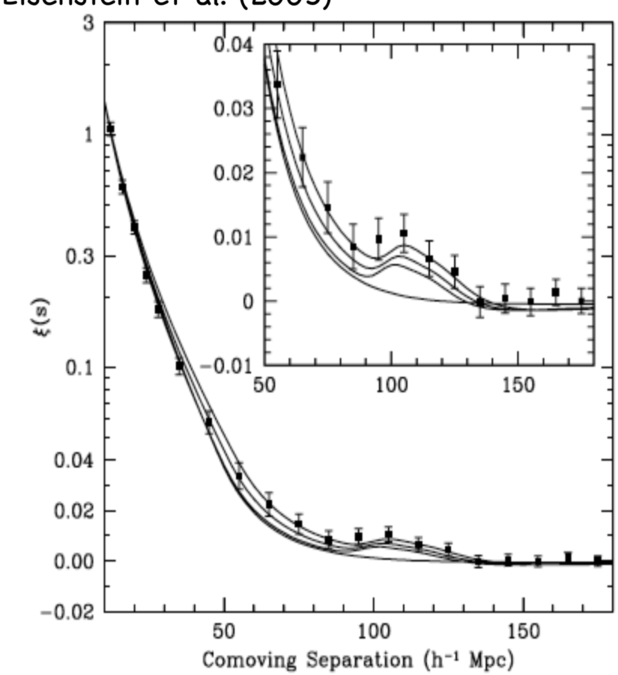
Baryon Acoustic Oscillations (BAOs)





Eisenstein et al. (2005)



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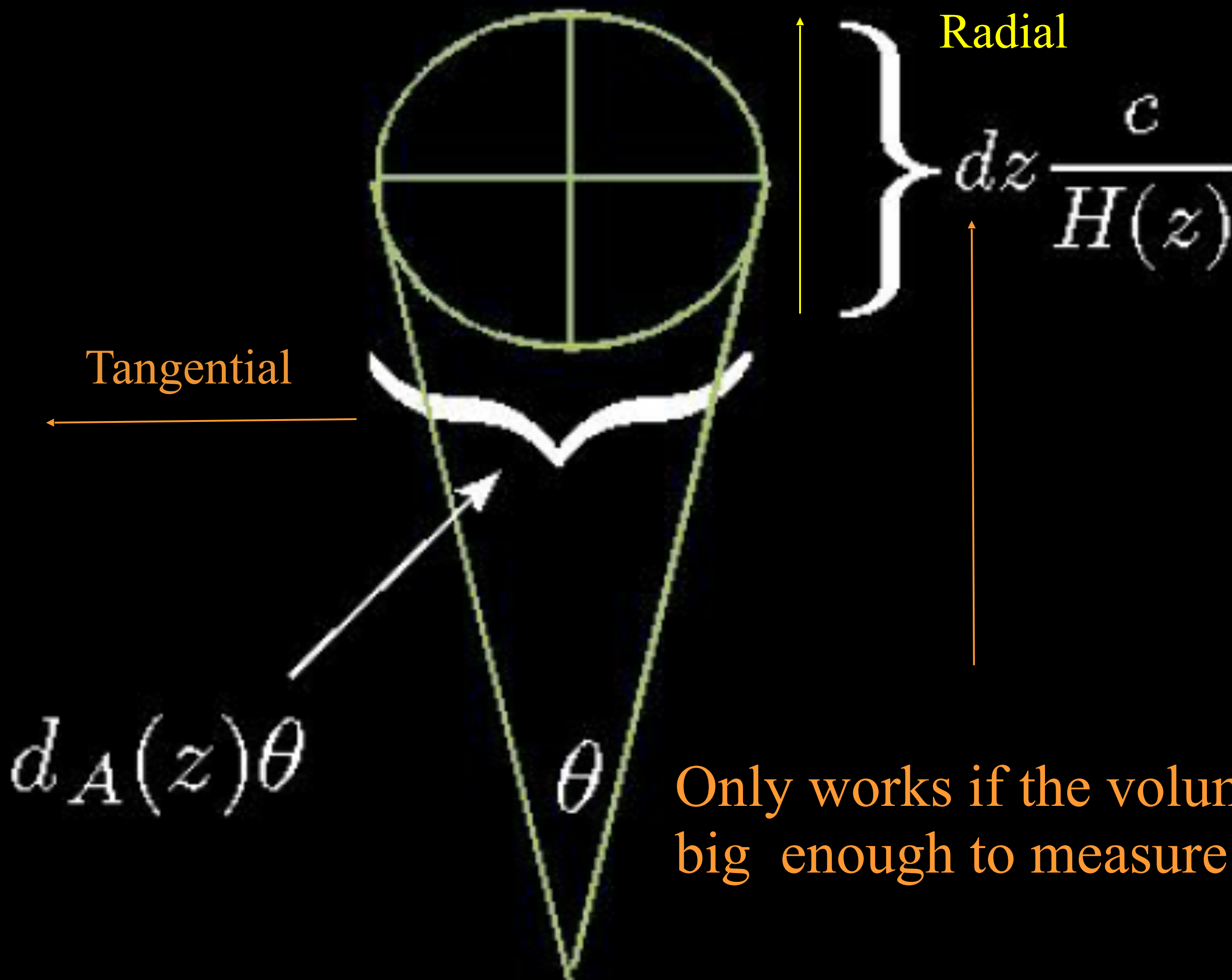
The Beauty of Standard Volumes



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

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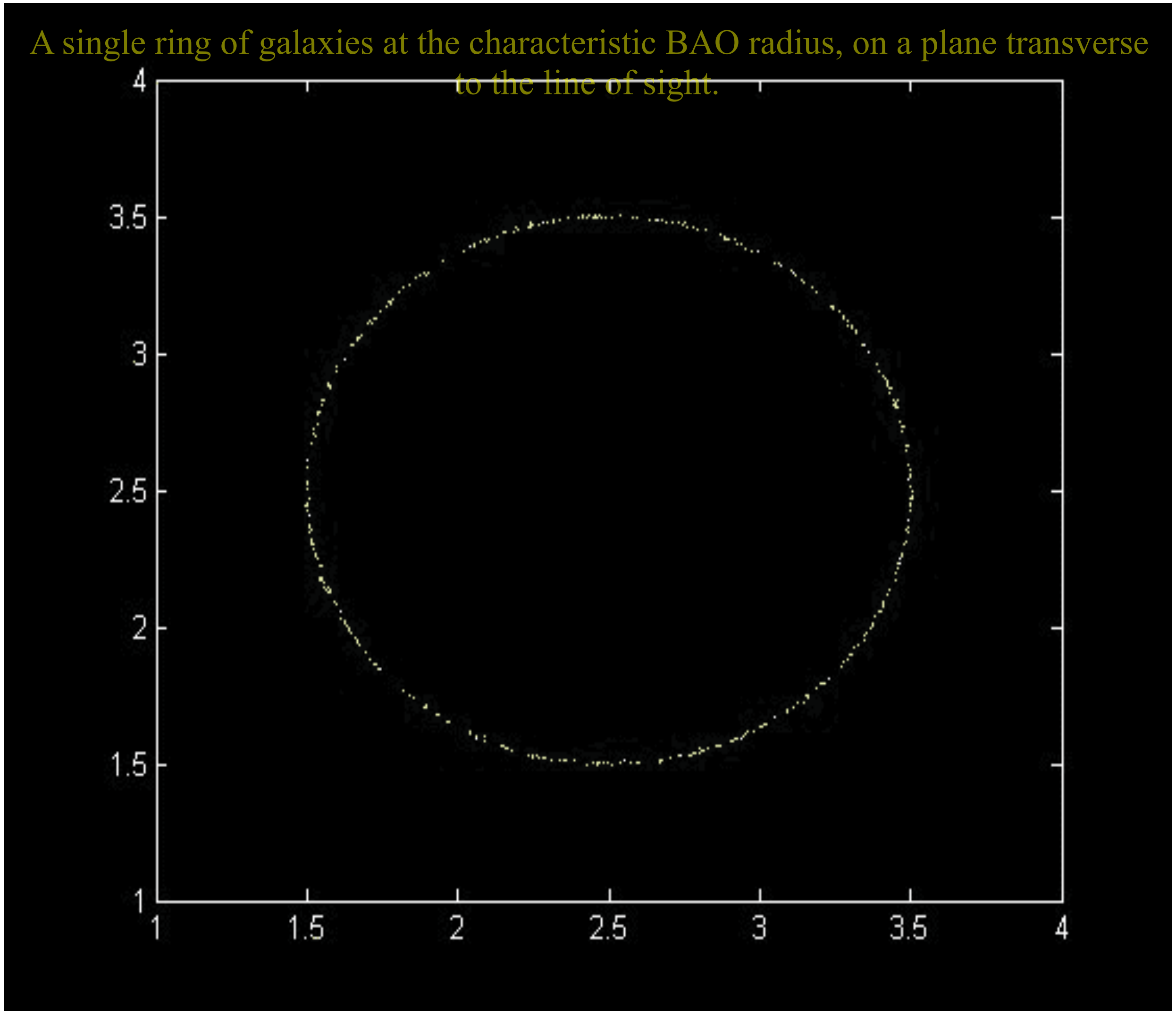
Rings of Power Superposed



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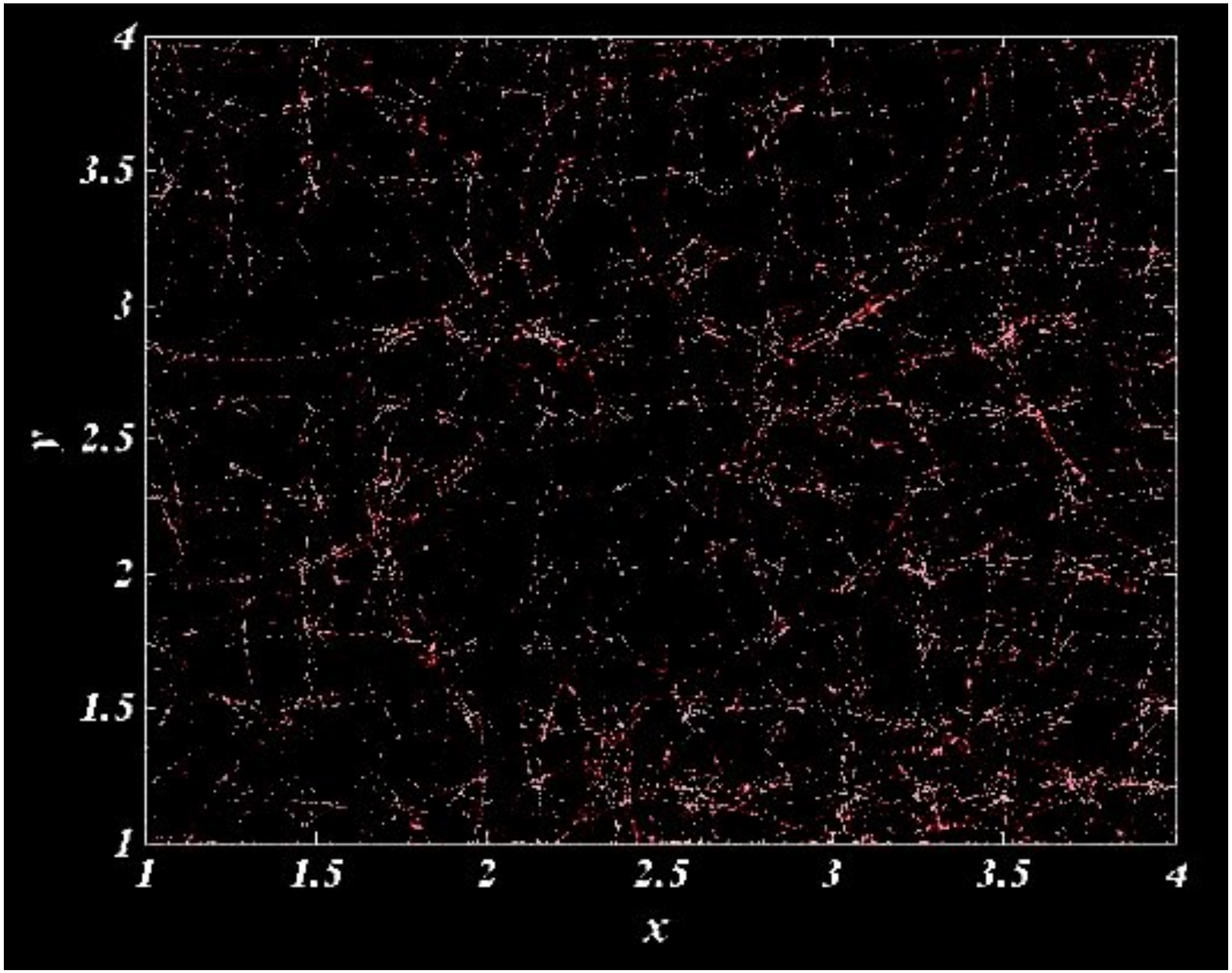
Statistical Standard Rulers



Bassett & Hlozek (2009)

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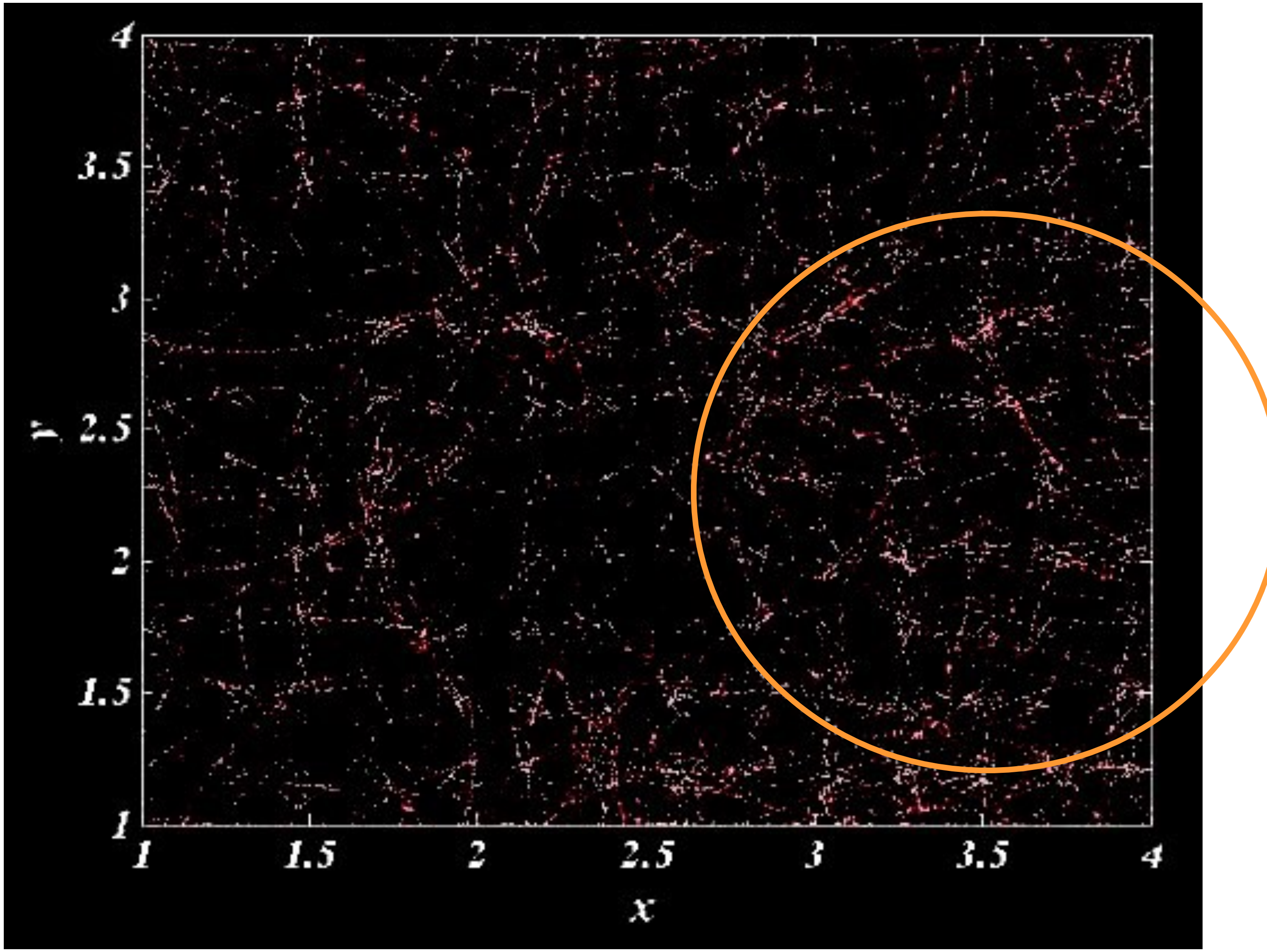

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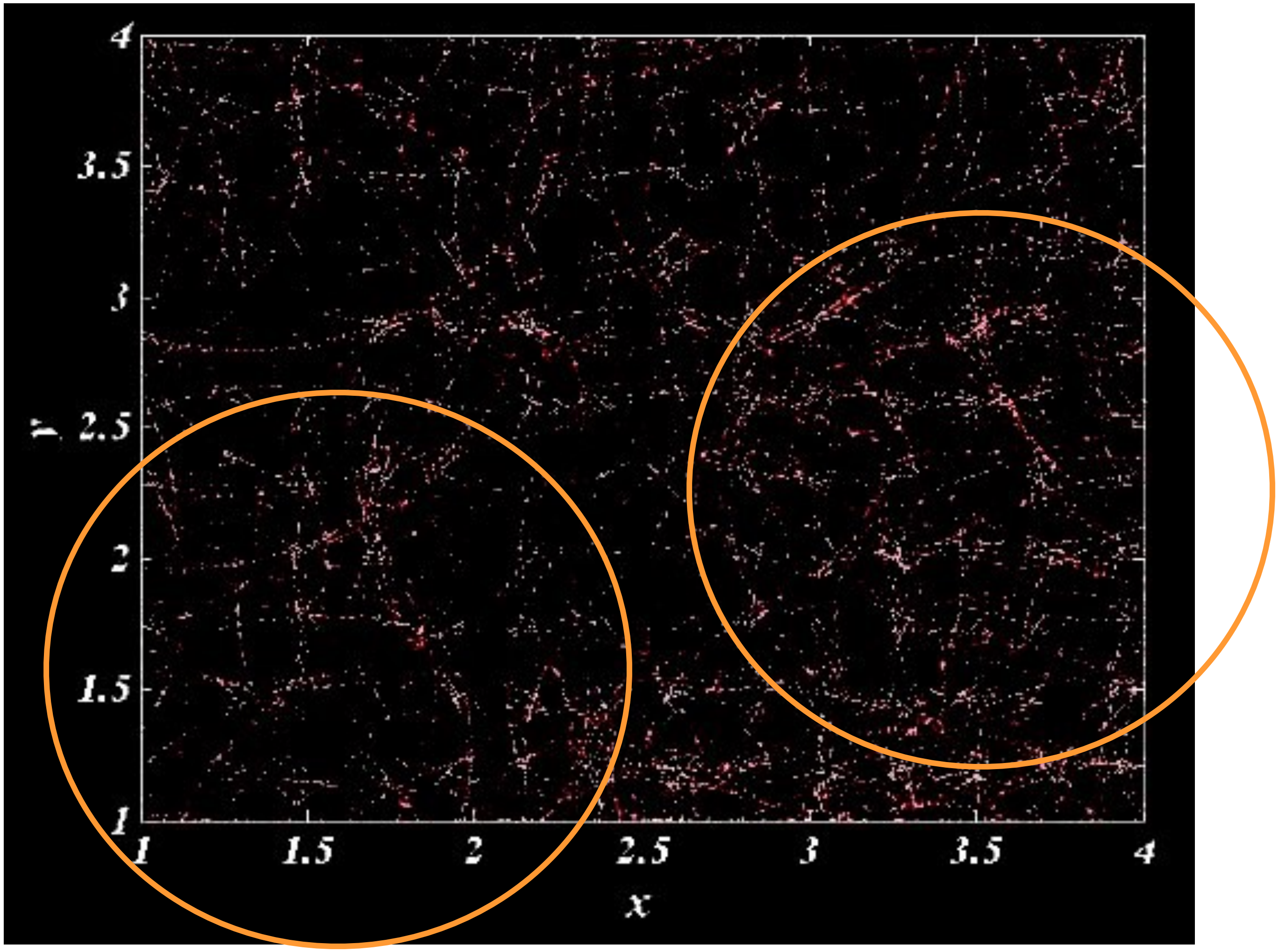


Bassett & Hlozek (2009)

Power Spectrum Errors

$$\frac{\delta P}{P} = \frac{1}{\sqrt{m}}\left(1 + \frac{1}{nP}\right)$$

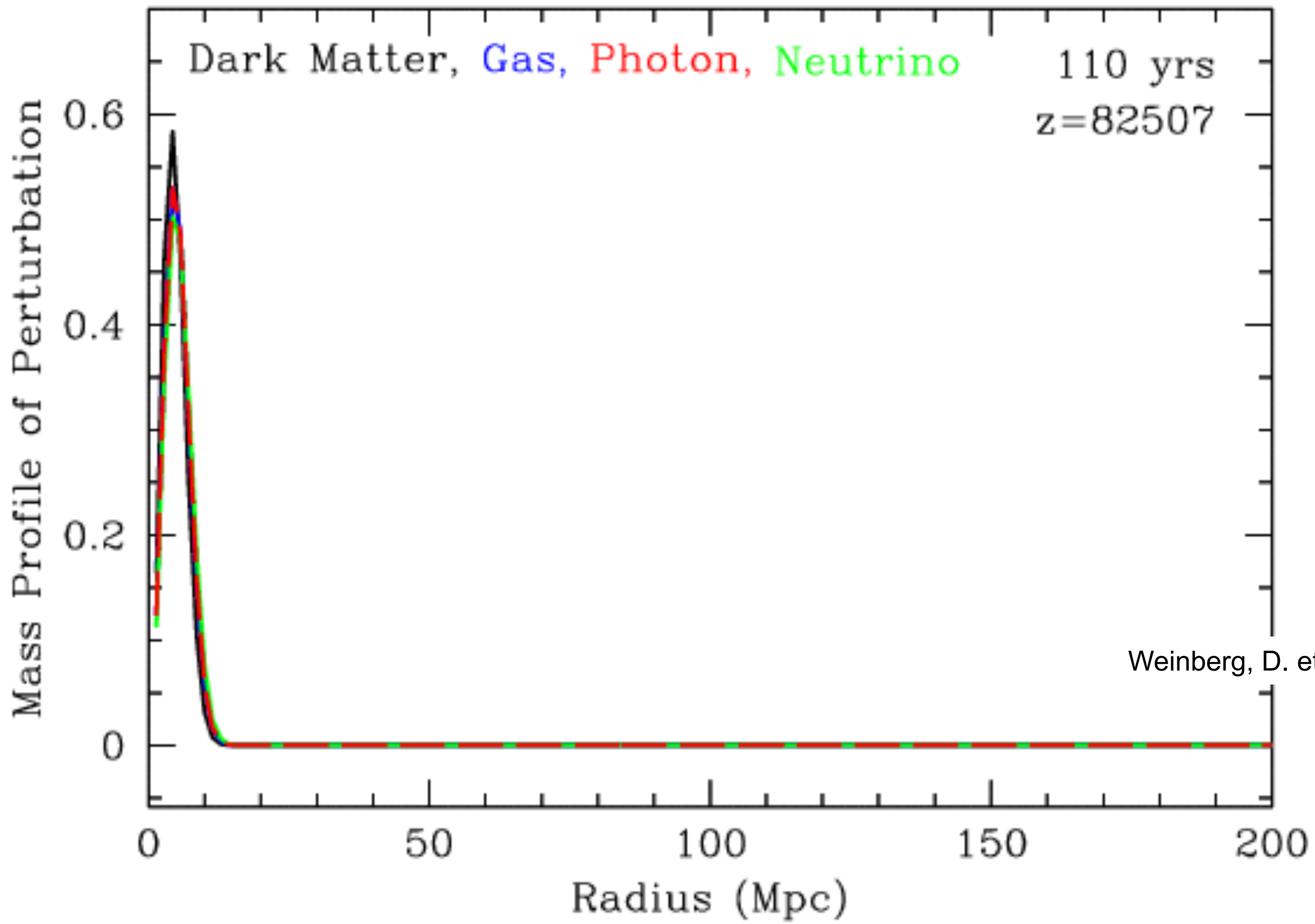
Cosmic Variance

Shot Noise

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

Bassett & Hlozek (2009)

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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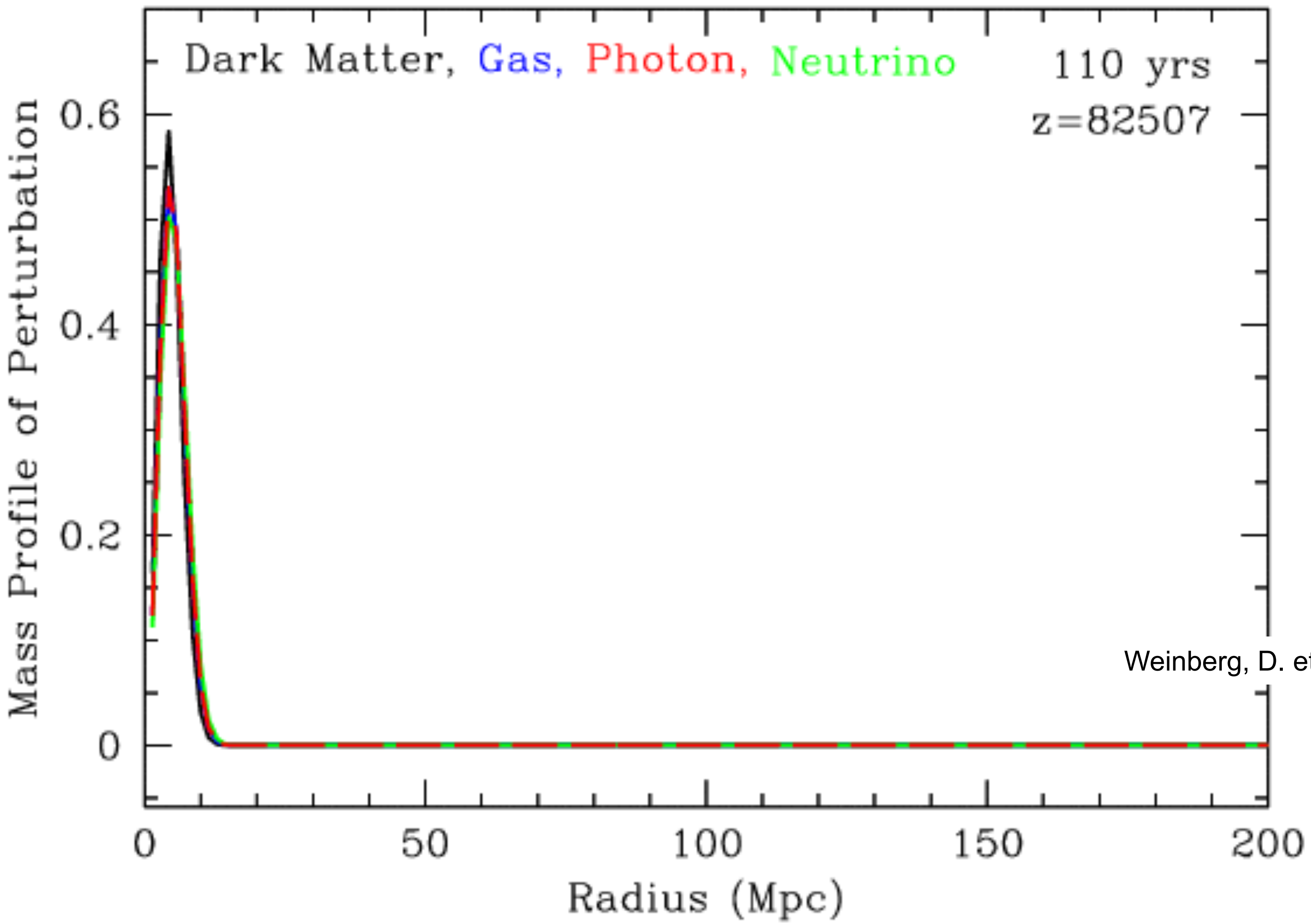

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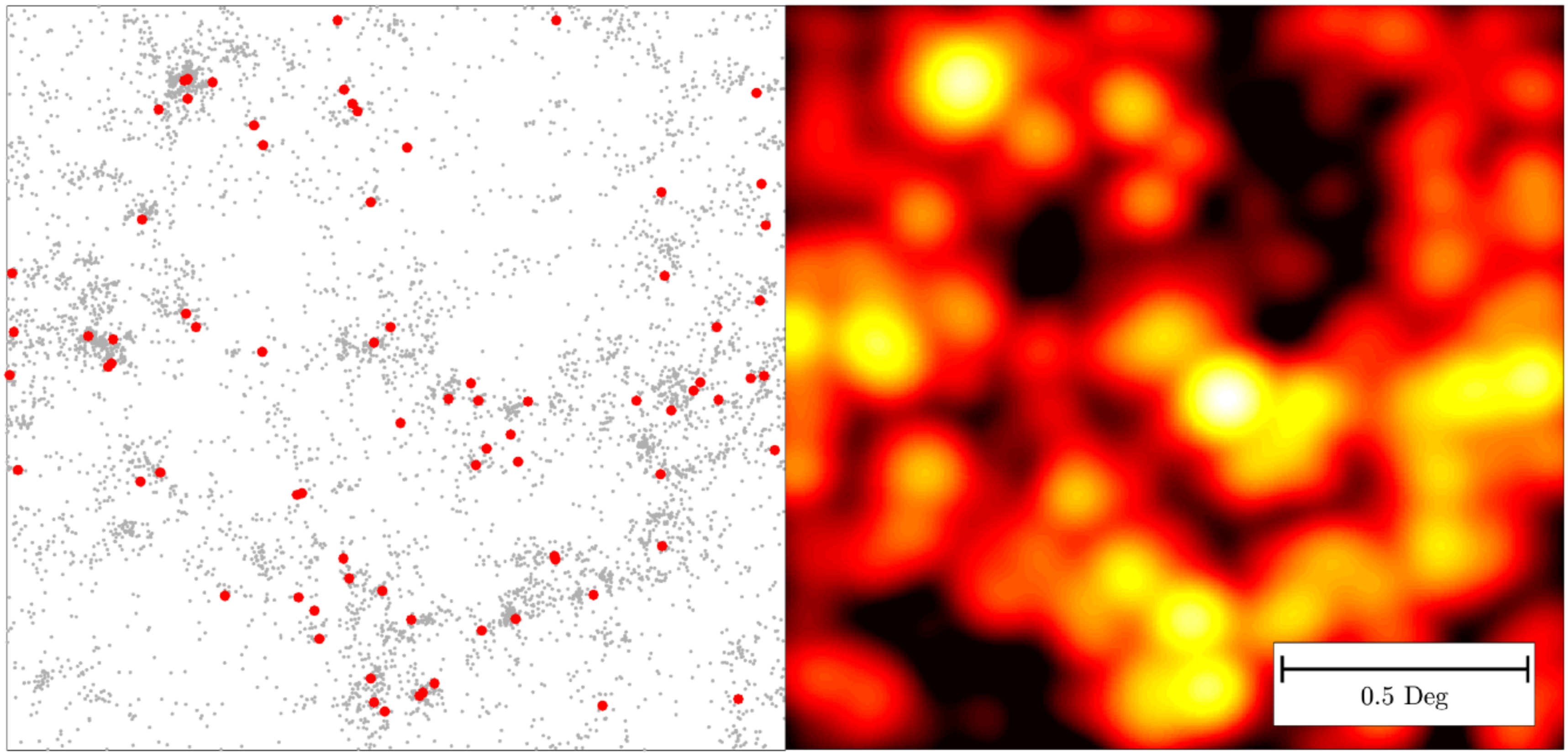
Animation: http://burro.case.edu/Academics/Astr328/Notes/StructForm/BAO.html

The Intensity Mapping (IM) 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

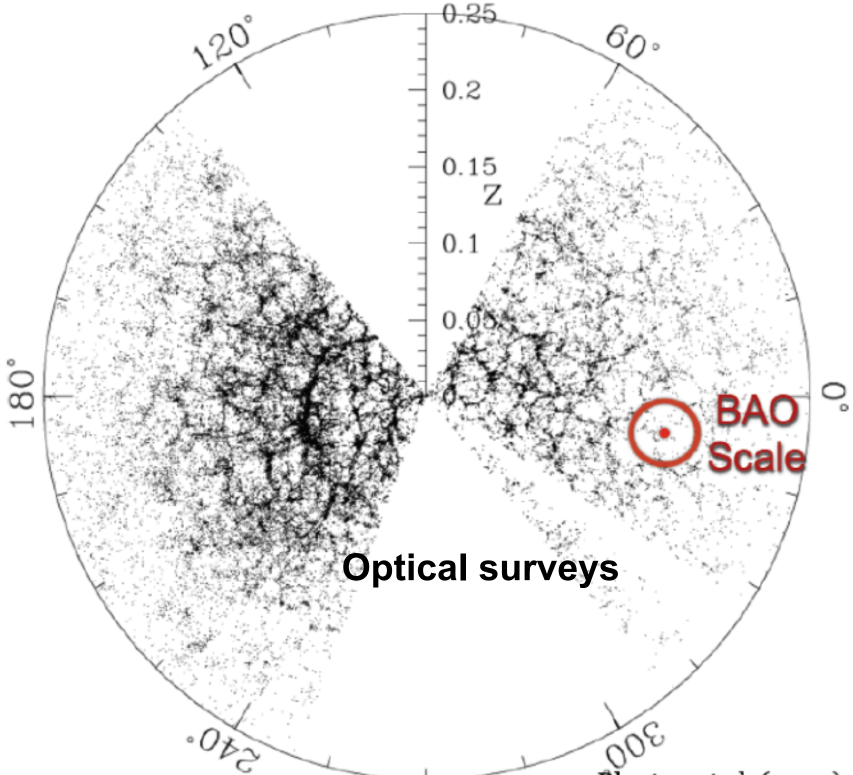
CO emission



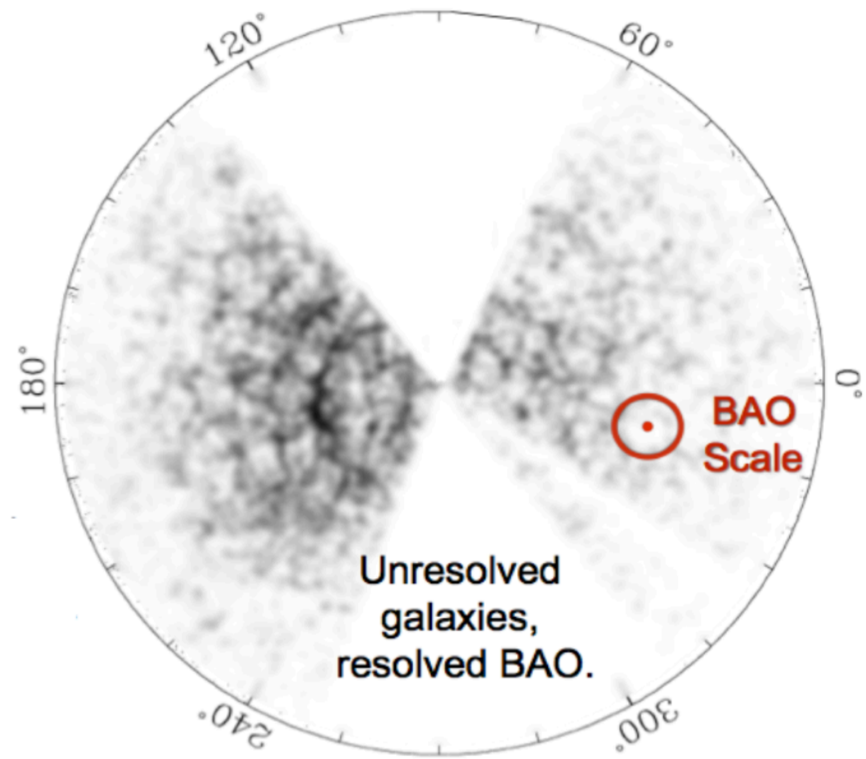
VLA (simulated, 4500h, detects 1% of all emitting sources in the FoV)

COMAP (simulated, 1500h, sensitive to all sources emitting in the FoV)

Kovetz et al, (arXiv:1709.09066)

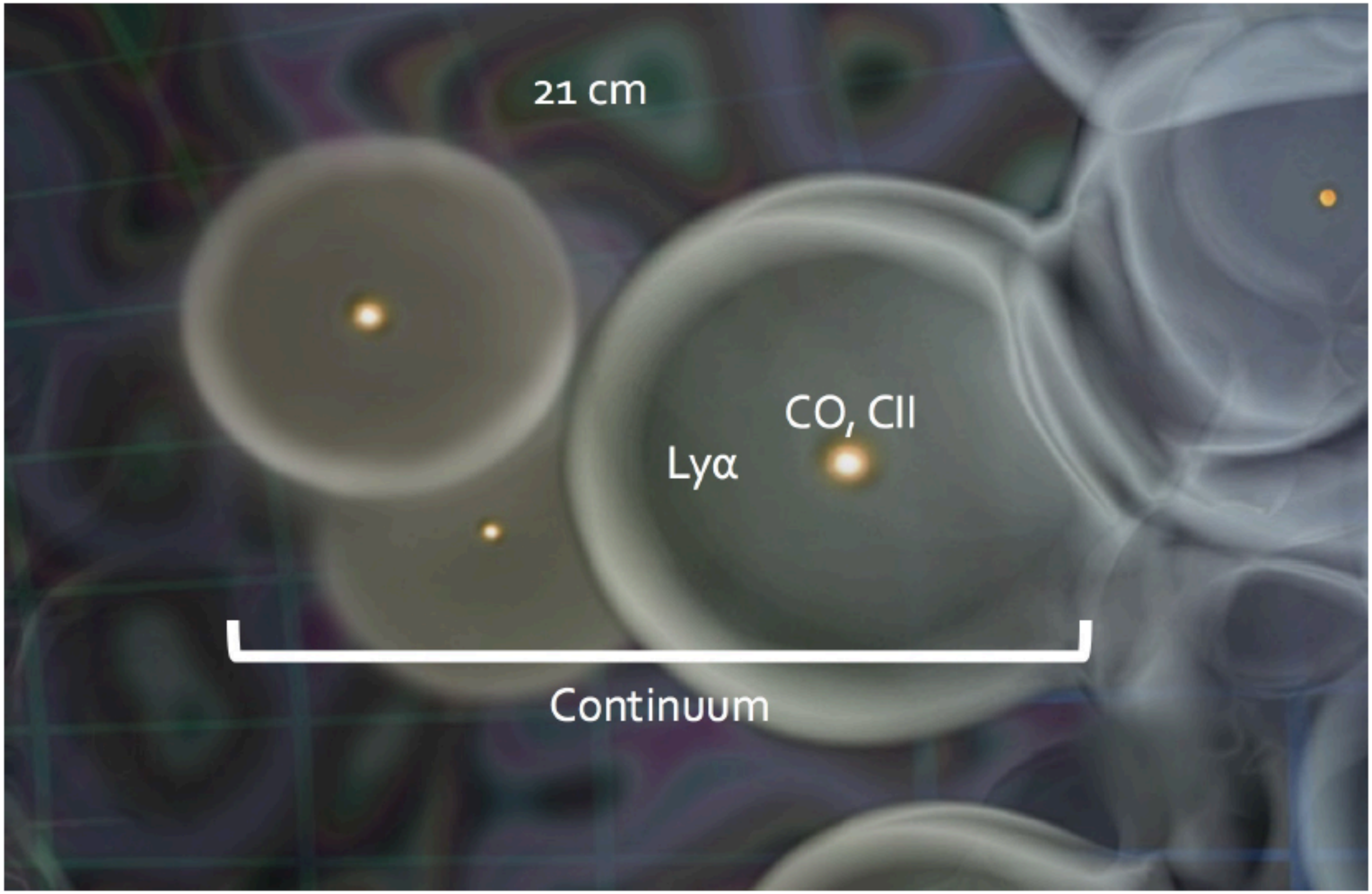


Blanton et al. (2003)



Line IM highlights

- Uses the integrated emission from spectral lines in galaxies and/ or diffuse IGM to track growth and evolution of cosmic structure
- Covers very large volumes in a smaller amount of time, compared to optical surveys
- Reduced angular resolutions also allows for a wider instantaneous FOV
- Measure spatial fluctuations of the integrated flux of many unresolved objects instead of tracking one by one
- Sensitive to all objects emitting in that line, instead of being flux-limited
- Frequency of line emission directly relates to the z
- Besides HI, we can also investigate Hα, CO, C[II], Ly-α and OII



CO, CII – star formation regions
Ly-alpha – galaxy halos
HI – neutral gas from outside bubbles
Continuum - CIB

→ **Different environments, different physics, deeper understanding of the star formation process at high-z**

Kovetz et al, (arXiv:1709.09066)

Line IM challenges

- Disentanglement of galactic and radio source emission, much stronger than the IM signal
- Confusion from interloping emission lines
- Non-gaussian nature of the signal
- Calibration uncertainties can significantly hamper the signal of interest
    - RFI interference
    - Beam calibration
        - many individual dishes and one beam for each dish
        - many beams illuminating a single dish
    - Receiver stability & gain fluctuations

IM Formalism

Matter power spectrum

Shot noise power spectrum

$$P_k(z) = < I(z) >^2 \;\; b^2(z) \;\; P_m(k,z) + P_{shot}(z)$$

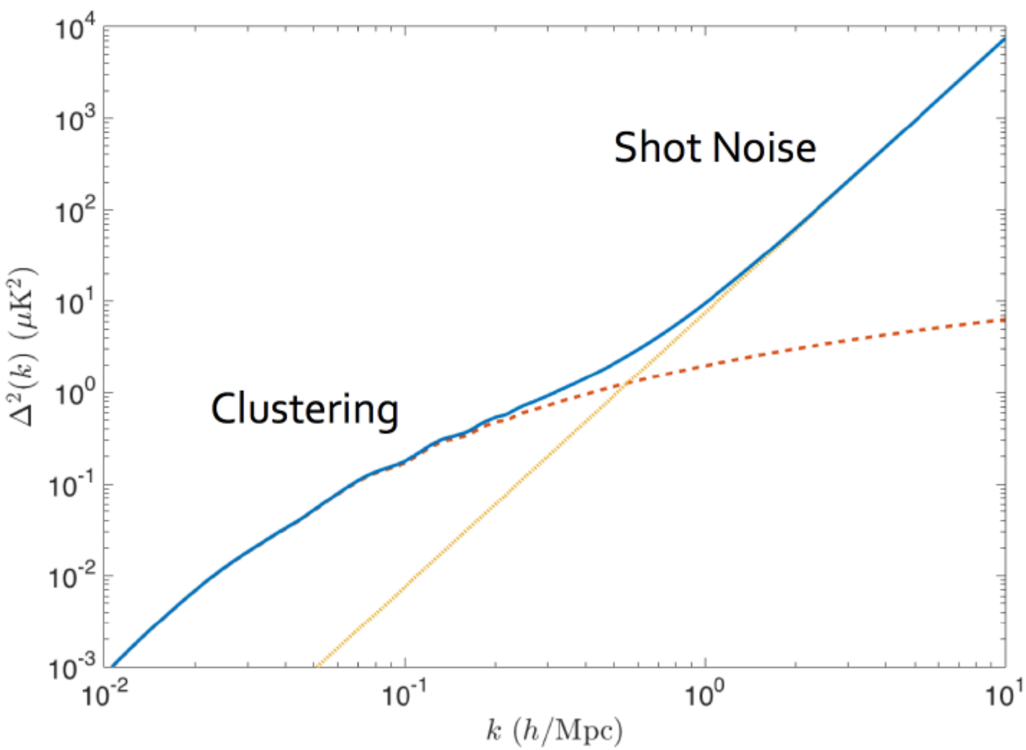
bias

$$< I(z) > \;\; \propto \int_0^\infty L\Phi(L,z)dL$$

$$P_{shot}(z) \;\; \propto \int_0^\infty L^2\Phi(L,z)dL$$

$$\Phi(L,z) \equiv dn(z)/dL$$

Line luminosity function



$P_k(z)$ of the target emission line is determined by the astrophysical processes that take place in galaxies at different z

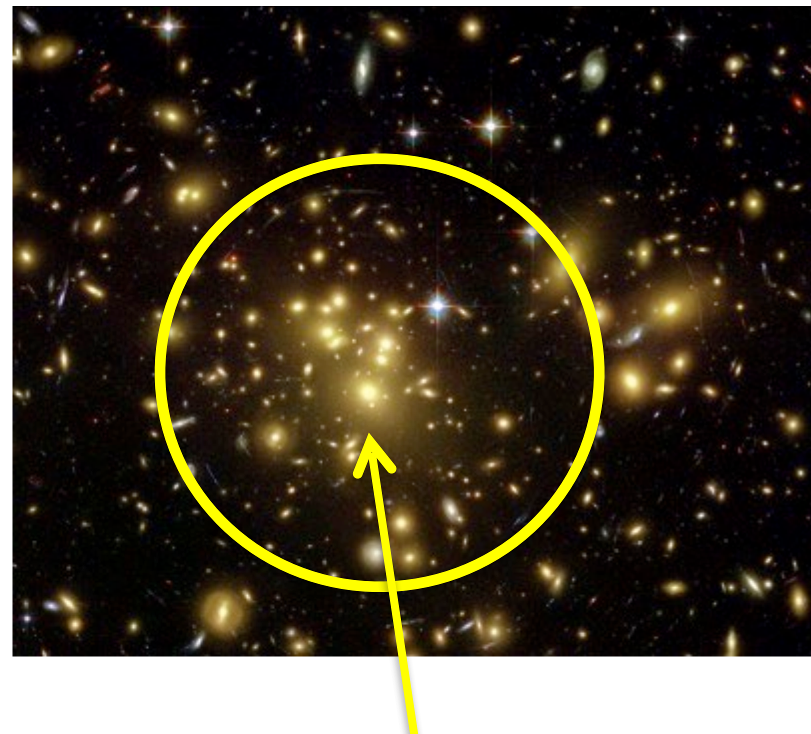
Kovetz et al, (arXiv:1709.09066)

Alternative to optical BAO

- 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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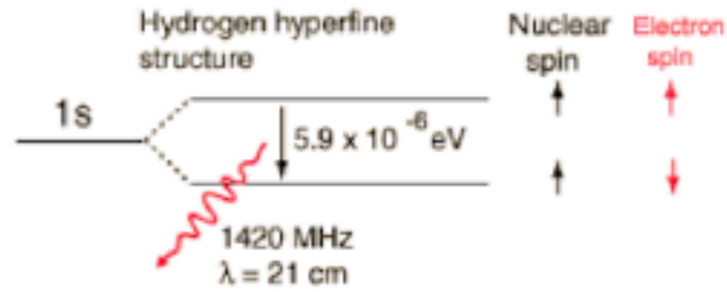
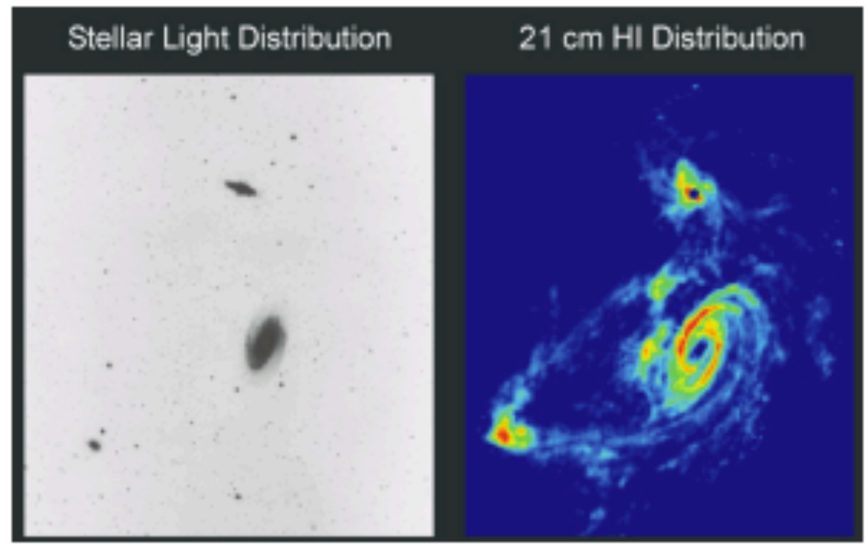
21 cm cosmology (HI)

- Physics of the early Universe is reasonably well understood from 10^{-6} s < t < 3.8×10^5 yrs (Decoupling)
- Physics after Cosmic Dawn (t ~ 180×10^6 yrs) is again reasonably well understood
- HI "is formed" at decoupling and starts to disappear after Cosmic Dawn
- 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
  - 6 < z < 20 – HII to HI…
- 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.

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

Summary of the 21 cm cosmology

Astrophysics **Cosmology** **Astrophysics**

LoS velocity gradient

$$\delta T_b(\nu) \approx 27 X_{HI}(1+\delta_b)\boxed{\left(\frac{0.15}{\Omega_M h^2}\frac{1+z}{10}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)}\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{\partial_r v_r}{(1+z)H(z)}\right)\ \mathrm{mK}$$

Fraction of HI

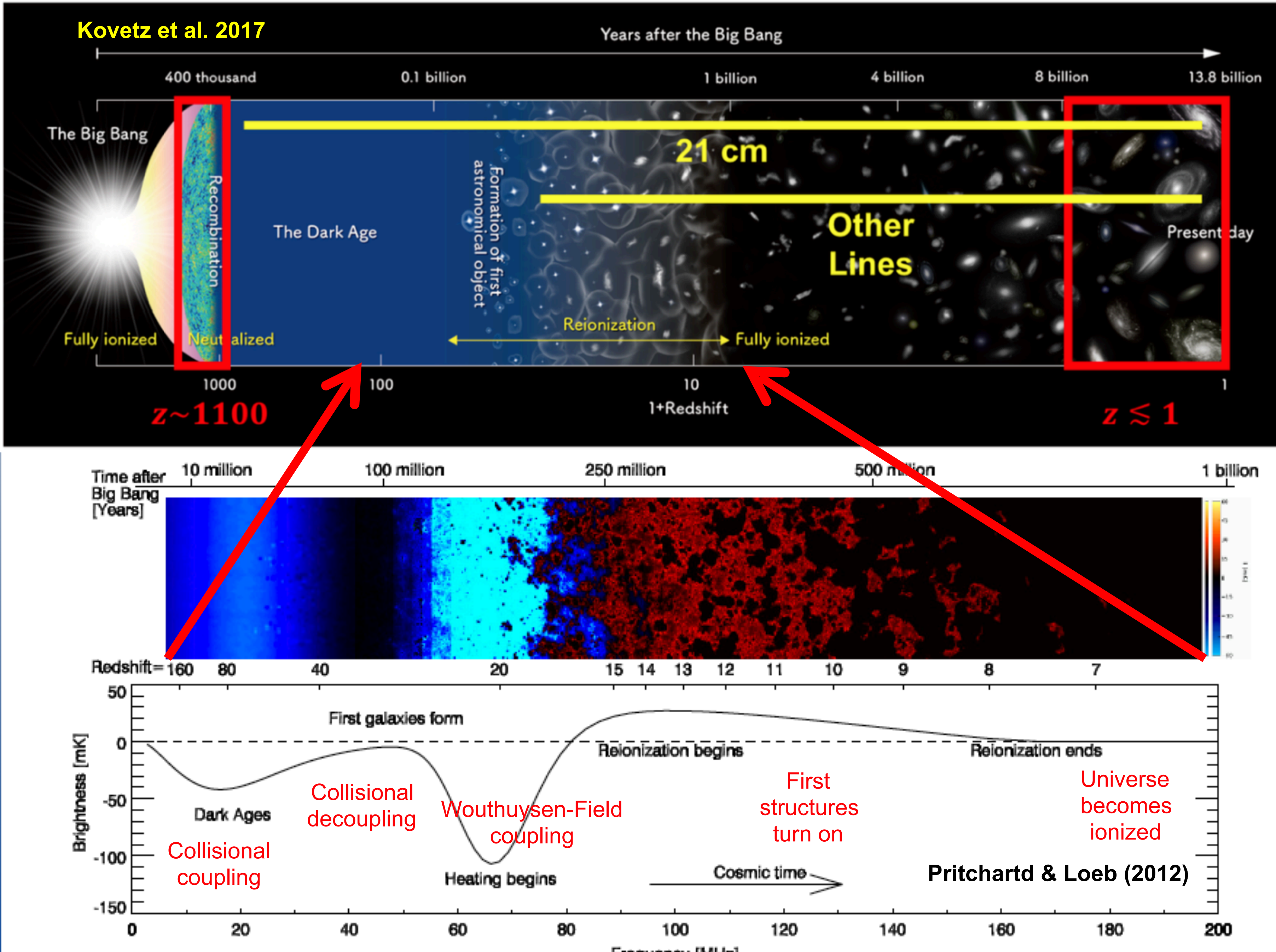
Baryon fractional overdensity

Spin temperature

$$\boxed{T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}}$$

α => coupling constants
T_γ => CMB
T_α => WF coupling
T_K => scattering
x_i => coupling constants

Derivation from Pritchard & Loeb (Rep. Prog. Phys., 2012)



Adapted from Pritchard & Loeb (Rep. Prog. Phys., 2012)

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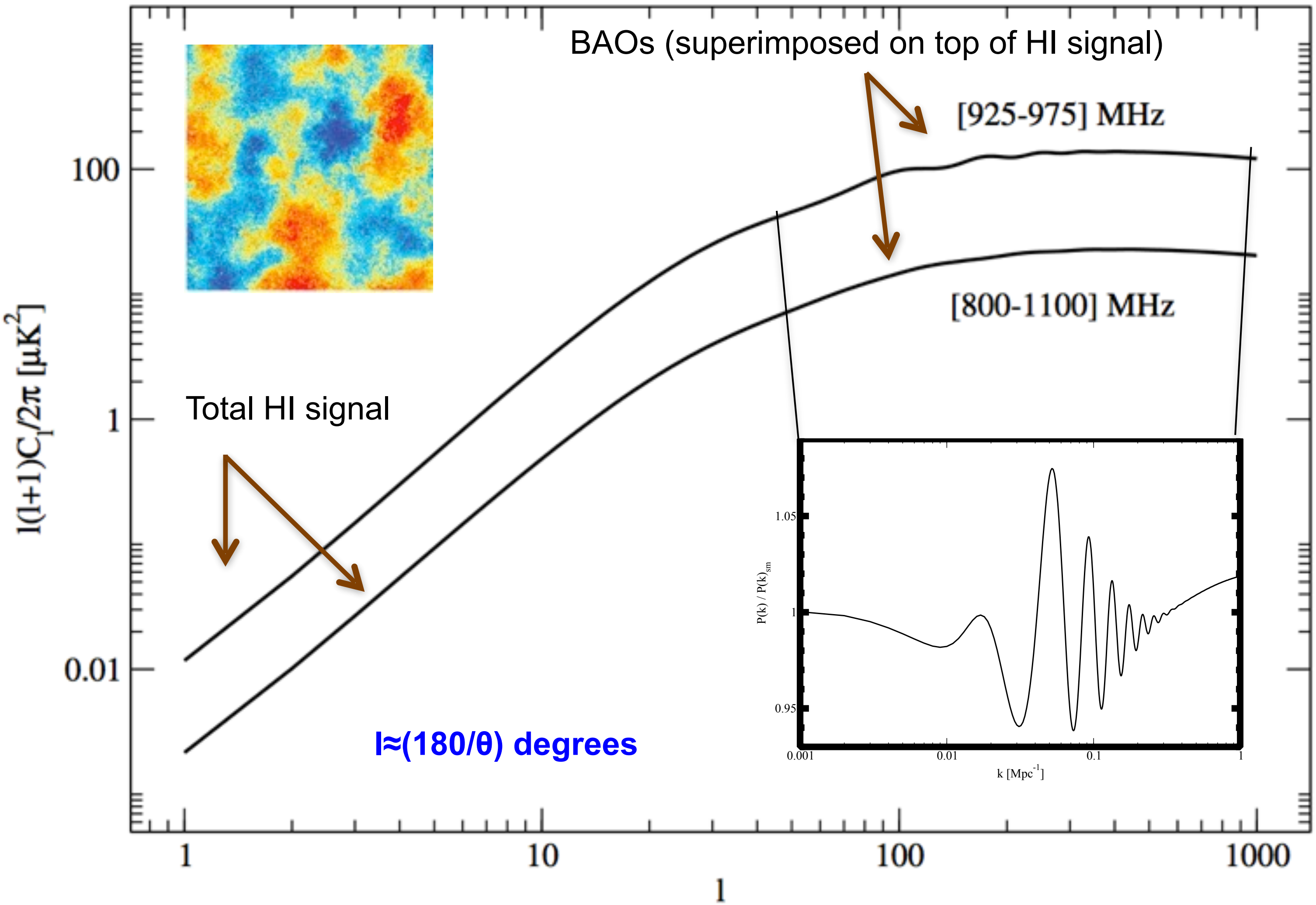
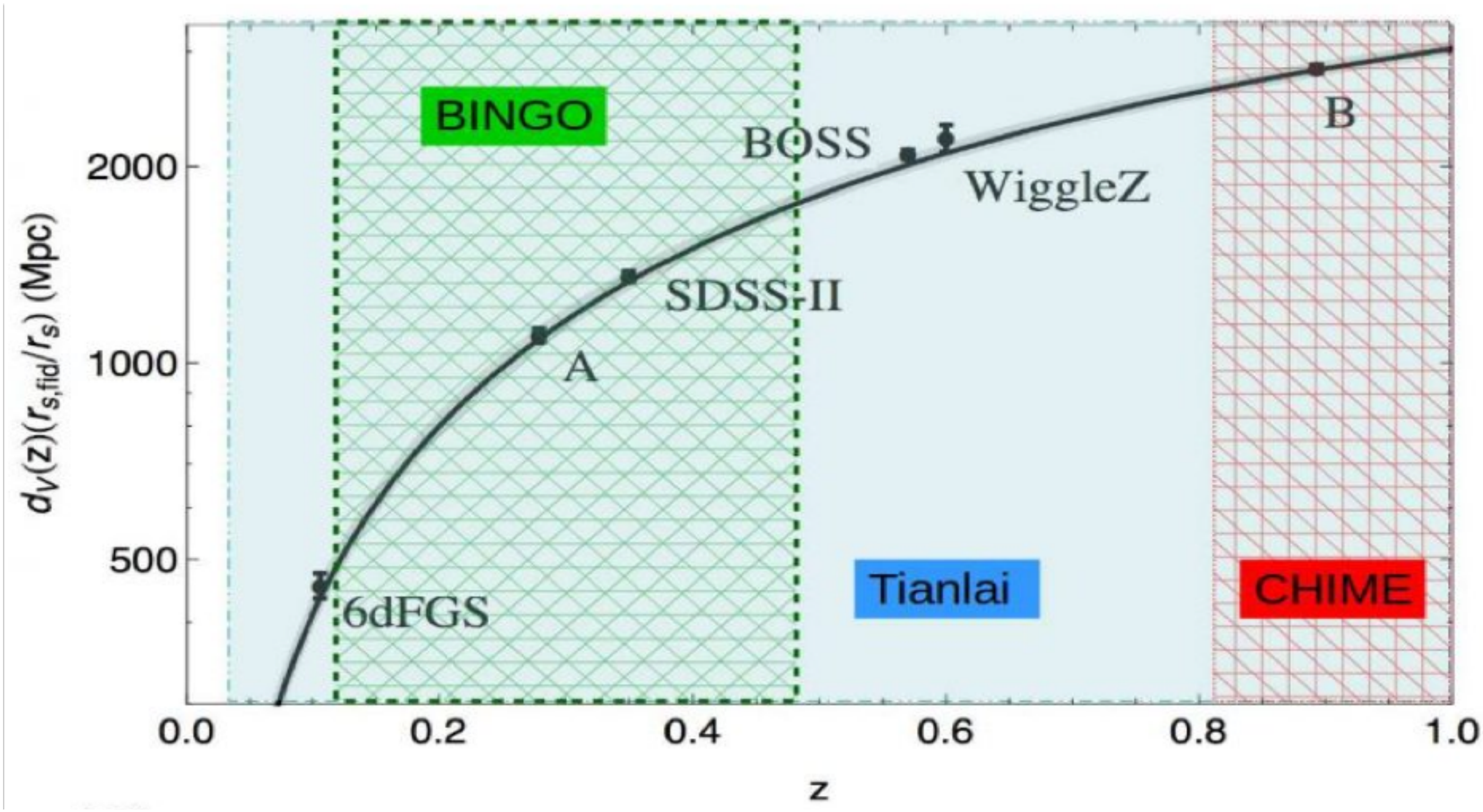
The HI signal power spectrum

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

$$\bar{T}_{\rm obs}(z) = 44\,\mu{\rm K}\left(\frac{\Omega_{\rm HI}(z)h}{2.45\times10^{-4}}\right)\frac{(1+z)^2}{E(z)}$$



Battye et al. 2013)



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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 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

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

Adapted from Bull et al. 2015

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  - 1... ...z≈0.08
  - 10... ...z => z≈0.93

BINGO meets all of them

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

Adapted from Bull et al. 2015

The BINGO Telescope

BAOs from **I**ntegrated **N**eutral **G**as **O**bservations

BINGO

BAOs from Integrated Neutral Gas Observations

FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

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IAS Orsay

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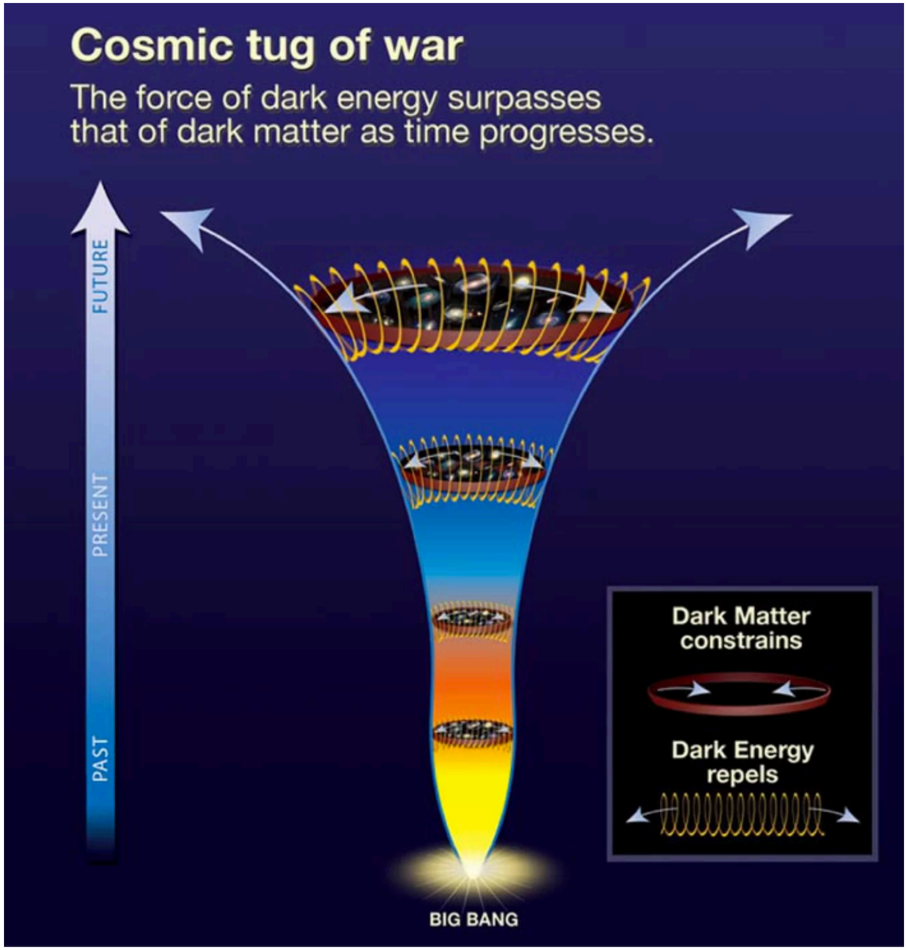
The science – main case

- 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



Project management status

- Most of the funding (> 80%) is already granted
  - FAPESP: main funding agency.
  - General coordination: Elcio Abdalla (IF/USP)

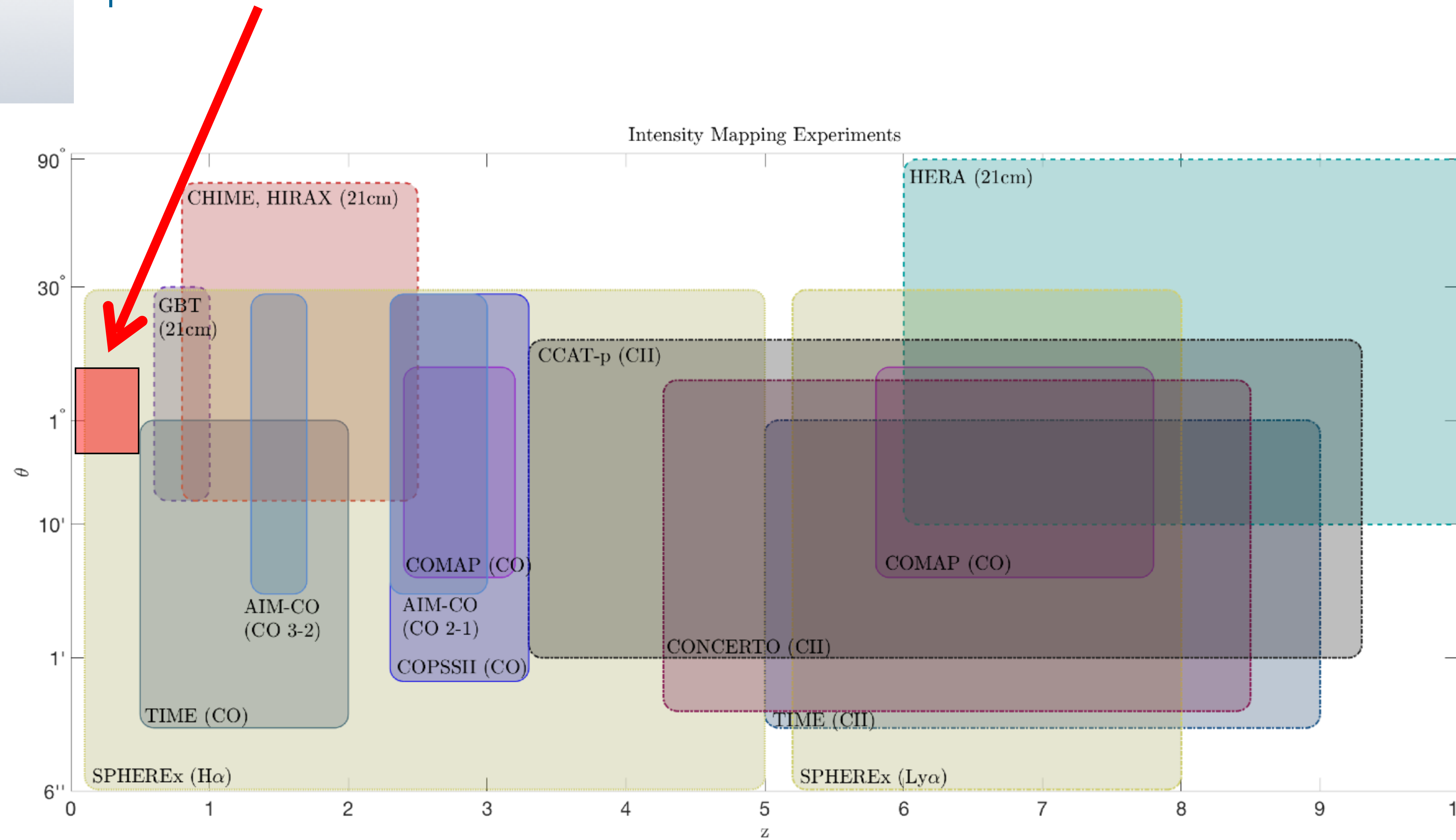
- BINGO construction proceeds…
  - Site defined => RFI initial measurements on site completed
  - Site waiting for return to normal conditions to start road work and cleaning
  - Horn, transitions, polarizer, and magic tee prototypes completed and successfully tested
  - main receiver components (first stage LNAs and filters, secondary LNAs and filters) successfully tested
  - Major Project Review 2019 → **green light to proceed to Phase 2.**
  - “Antenna” to be integrated and tested at INPE (no sky measurements)
  - “Antenna” to be integrated and tested in Paraíba (sky measurements)
  - Optical design almost completed
  - Engineering projects in discussion
  - Dish fabrication in discussion

Additional science with BINGO

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

- BAOs contain additional information about
  - Matter density
  - Redshift distortions
  - Anisotropic BAOs…
- Life history of hydrogen
- Radio recombination lines
- Galactic continuum
- And, of course, **FRBs**, which will be delivered for free due to the nature of BINGO observational strategy

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



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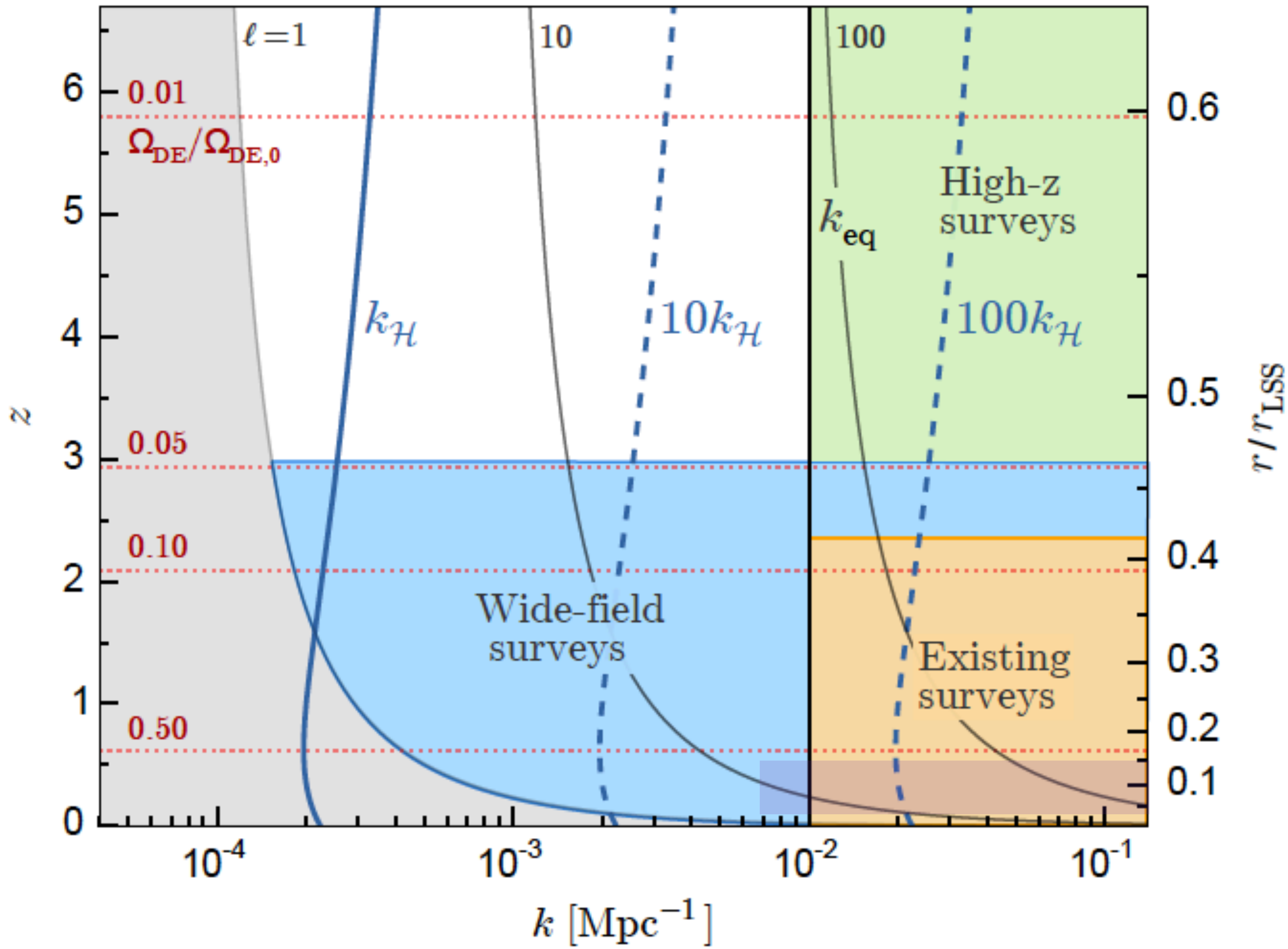

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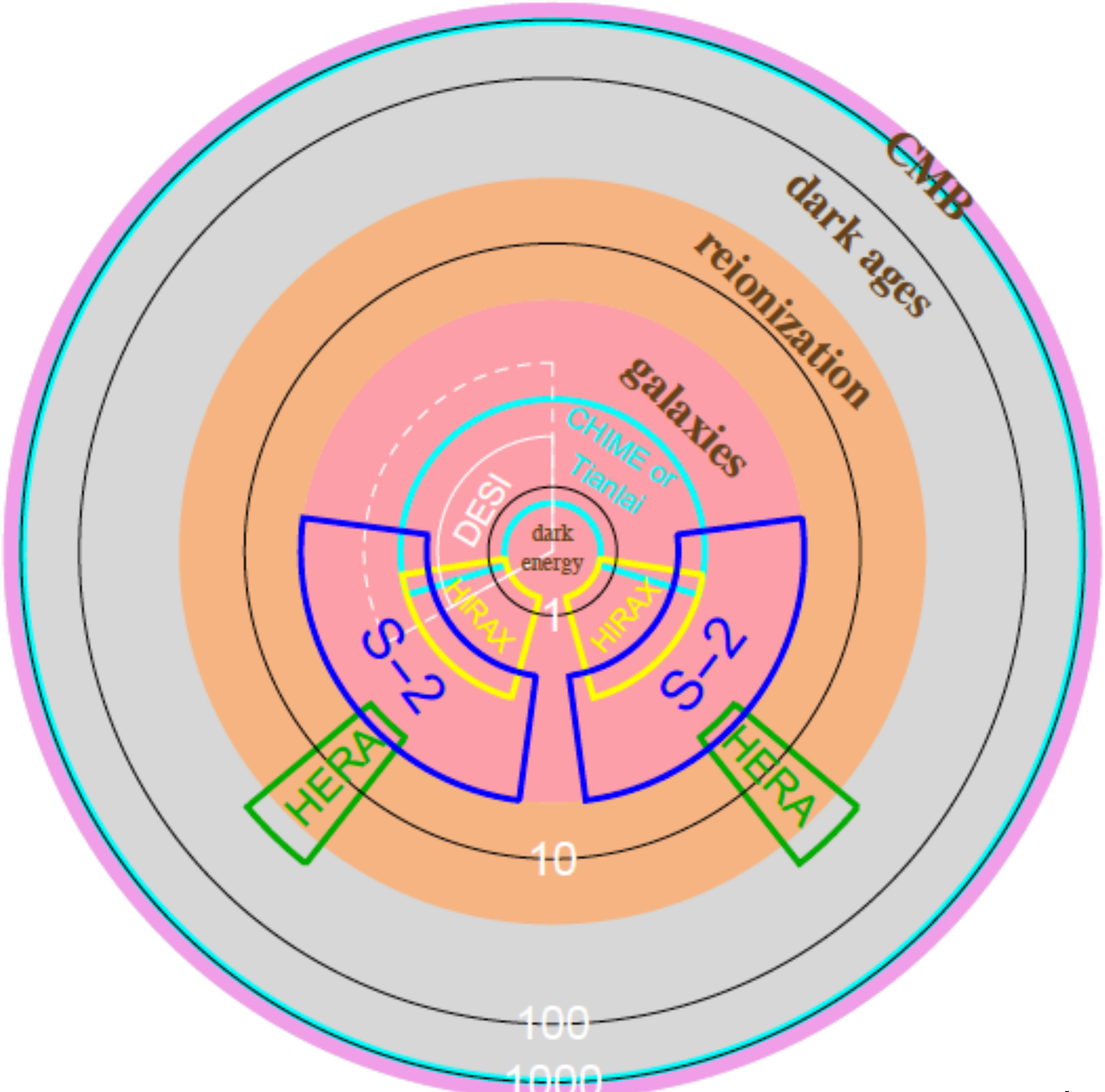
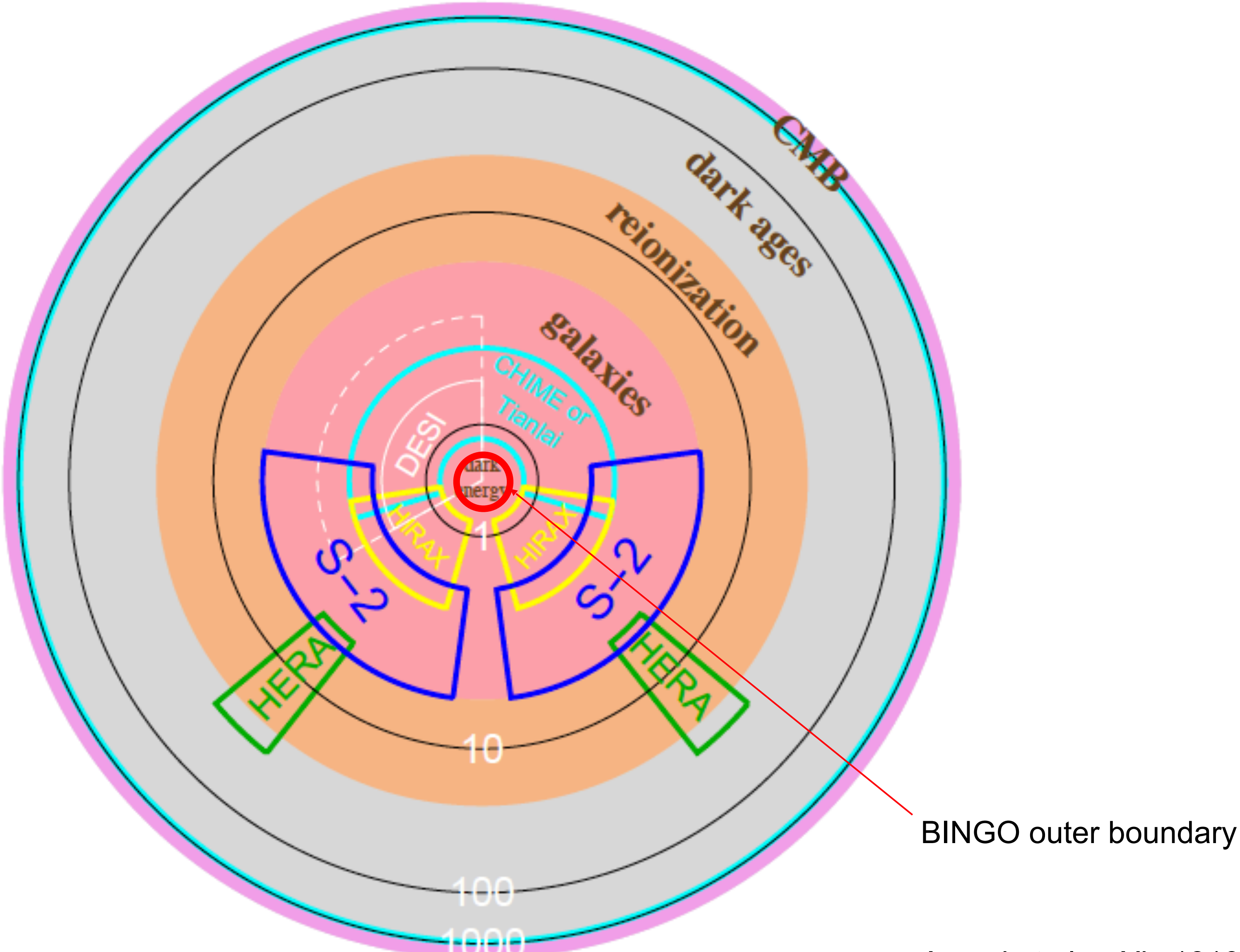


Ansari et al. arXiv:1810.09572

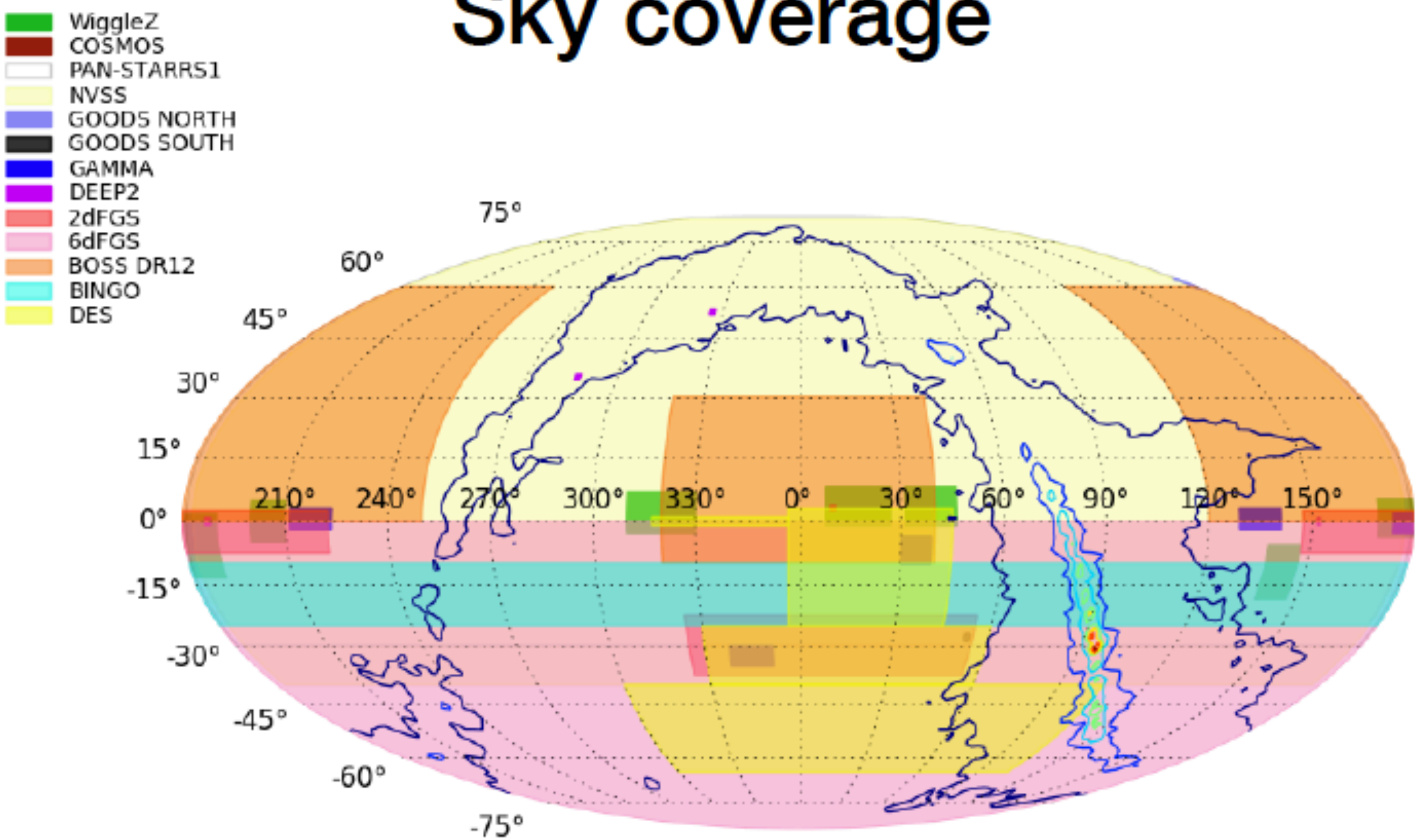


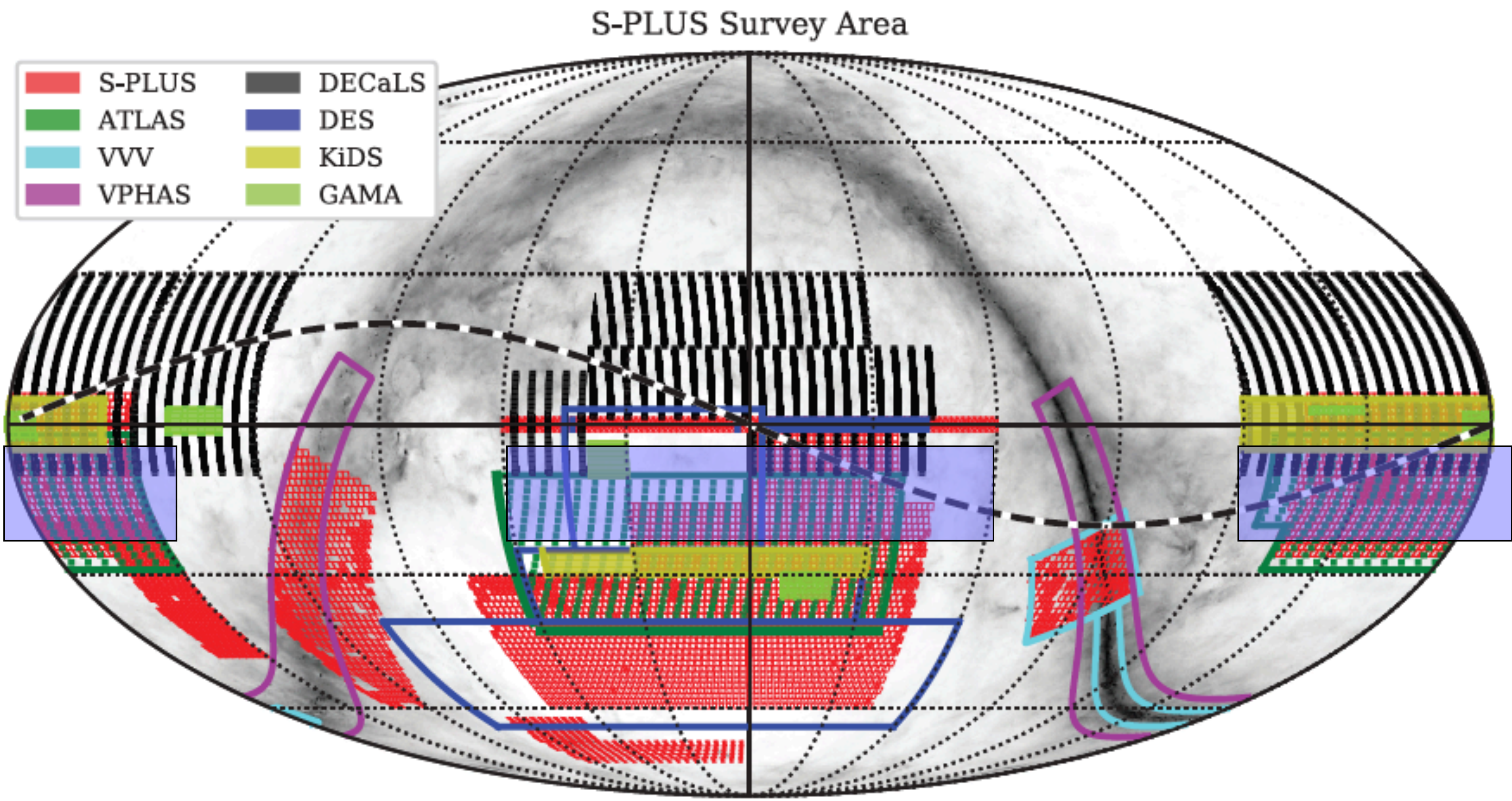
Ansari et al. arXiv:1810.09572

C. A. Wuensche (2020)

From Tianyue Chen

Sky coverage

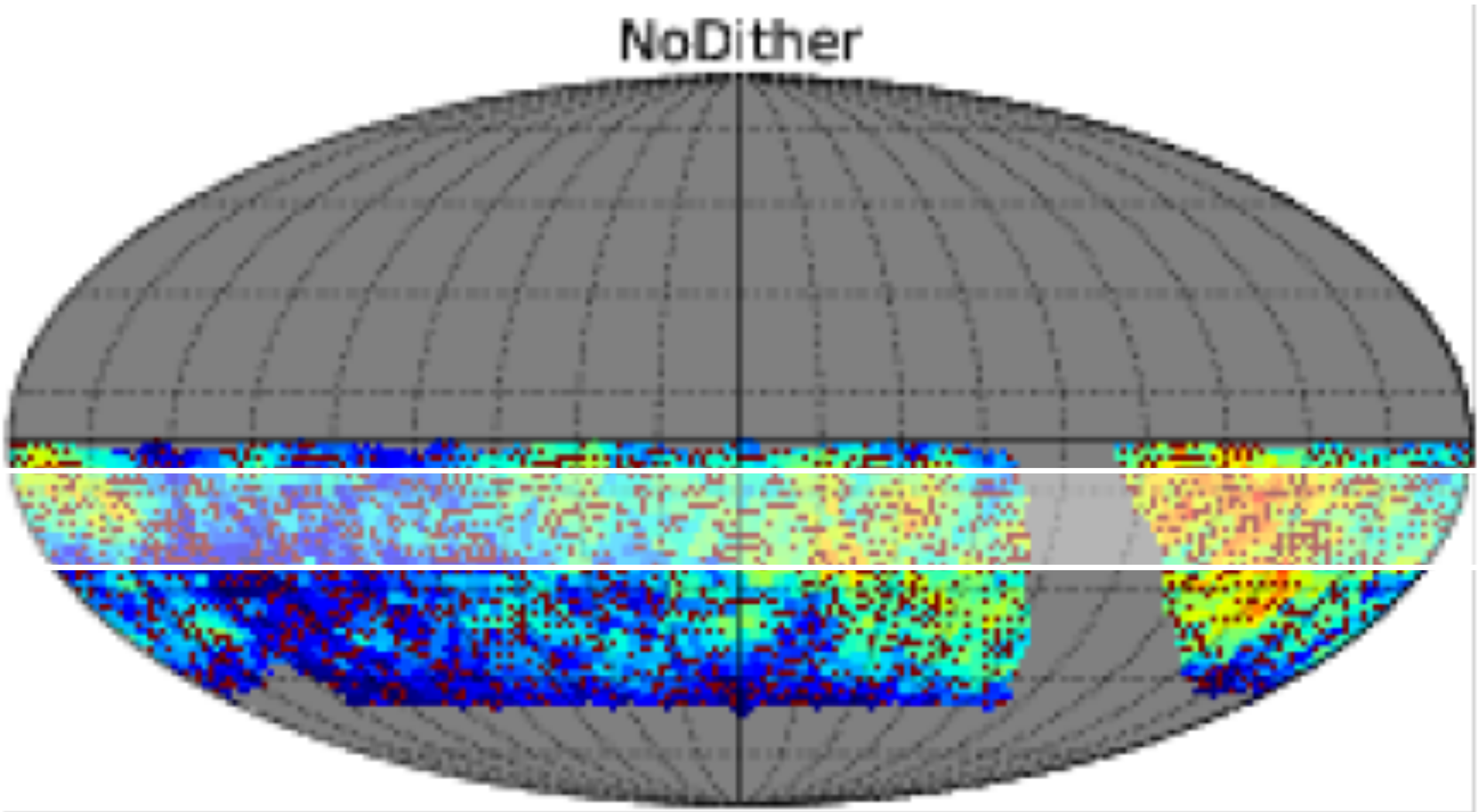




BINGO SUPERPOSITION

C. A. Wuensche (2020)

LSST Cosmology map



LSST Cosmology map (simulated). arXiv:1708.04058, chap. 9, fig. 9.3.
BINGO coverage area in white

The “FIDUCIAL” BINGO (May 2020)

FIDUCIAL BINGO	
T_sys (K)	70
Frequency band (MHz)	280,00
#channels	40
Sampling time (Hz)	10,00
Minimum frequency (MHz)	980,00
Maximum frequency (MHz)	1260,00
Frequency band (for 40 channels, MHz)	7,5
Maximum redshift	0,45
Minimum redshift	0,13
Redshift band (for 40 channels)	0,008
Instrument noise (mK, 1 second)	26,5

FIDUCIAL BINGO	
Site coordinates (vertex of the area)	
7° 2' 27,6" S	38° 16' 4.8" W
Site denomination: Serra da Catarina, Aguiar (PB)	
Focal length (m)	63,2
Primary major semi-axis (m)	25,7
Primary minor semi-axis (m)	20,0
Secondary major semi-axis (m)	18,3
Secondary minor semi-axis (m)	18,0
Pixel solid angle (sr)	0,35
Optics FWHM (deg)	0,67
Survey area (square deg)	5359,75
Horns	40

The “FIDUCIAL” BINGO (May 2020)

FIDUCIAL BINGO	
T_sys (K)	70
Frequency band (MHz)	280,00
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Minimum redshift	[illegible]
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Optics FWHM (deg)	0,67
[illegible])	5359,75
[illegible]	40

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

C. A. Wuensche (2020)

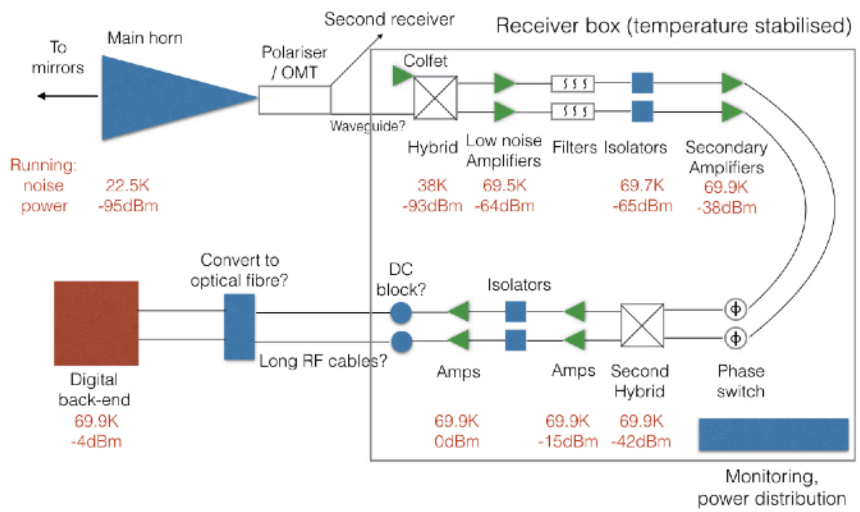
Challenges as of May 2020

- Large telescope: **discussions ongoing with the company to produce the dishes**
- Large horns: **fabrication process understood, discussions ongoing with the company to produce the horns**
- Calibration and stability: **use colfets and a CW source as internal calibration. Noise and stability for both are under investigation**
- Receiver stability: **has to be tested with internal cooling and later, under the hot environment temperature in Paraíba**
- Digital backend: **SKARAB boards are the choice. Learning curve for their programming is not known yet, need to be integrated to the system in the lab**
- Optical design: **optics simulations indicate very small distortions of the beams for the current horn array. Final horn positioning still to be determined. TBC during commissioning**
- Radio Frequency Interference → **Mobile quiet zone has been already requested to the state authorities (both to State agencies and to ANATEL)**

The BINGO subsystems

Receiver prototype

Led by CAW



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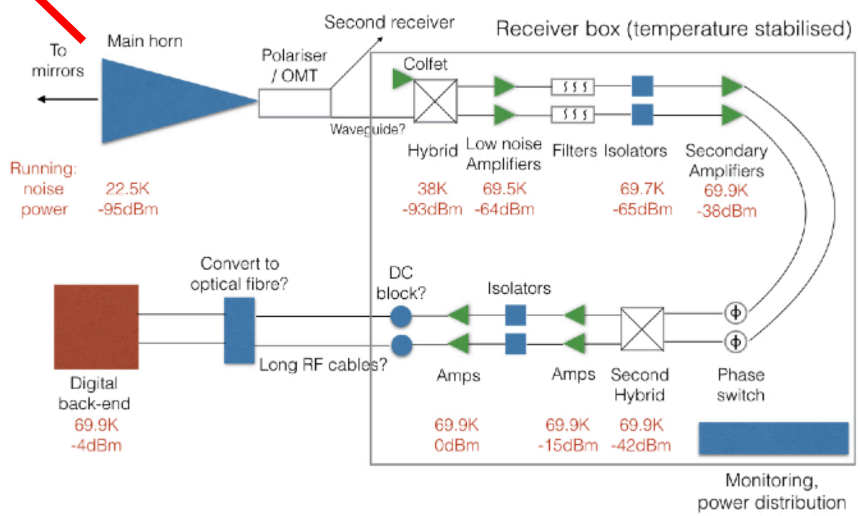
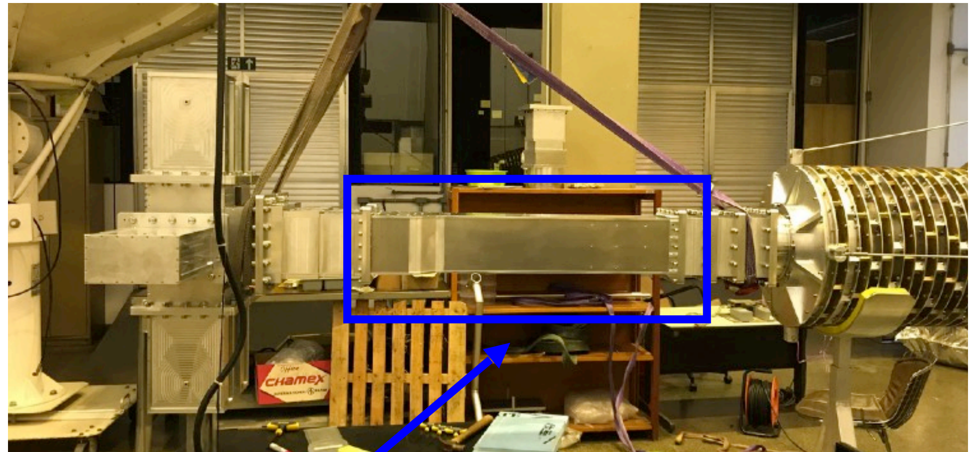
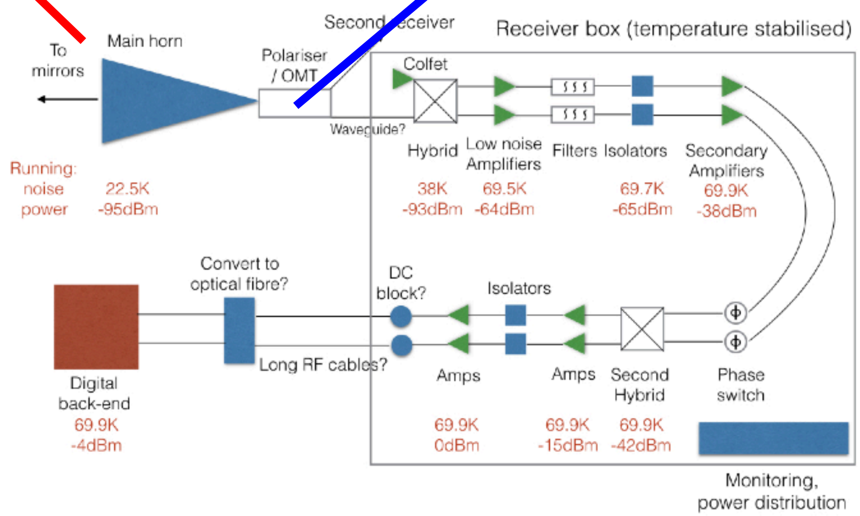
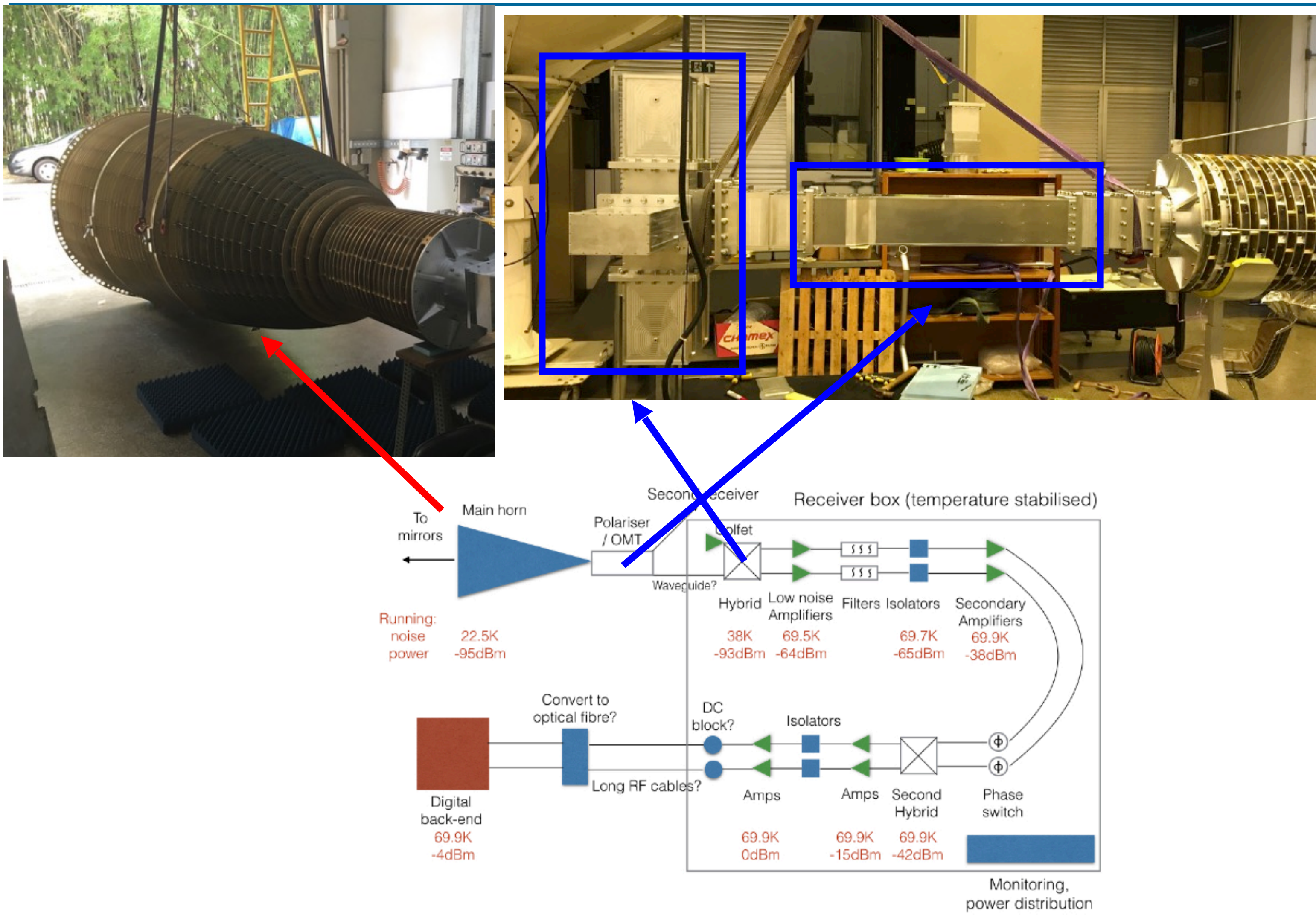


C. A. Wuensche (2020)





To mirrors
Main horn
Polariser / OMT
Second receiver
Receiver box (temperature stabilised)
Colfet
Waveguide?
Hybrid
Low noise Amplifiers
Filters
Isolators
Secondary Amplifiers
Running: noise power
22.5K -95dBm
38K -93dBm
69.5K -64dBm
69.7K -65dBm
69.9K -38dBm
Convert to optical fibre?
DC block?
Isolators
Long RF cables?
Amps
Amps
Second Hybrid
Phase switch
Digital back-end
69.9K -4dBm
69.9K 0dBm
69.9K -15dBm
69.9K -42dBm
Monitoring, power distribution



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Main horn
Polariser / OMT
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Receiver box (temperature stabilised)
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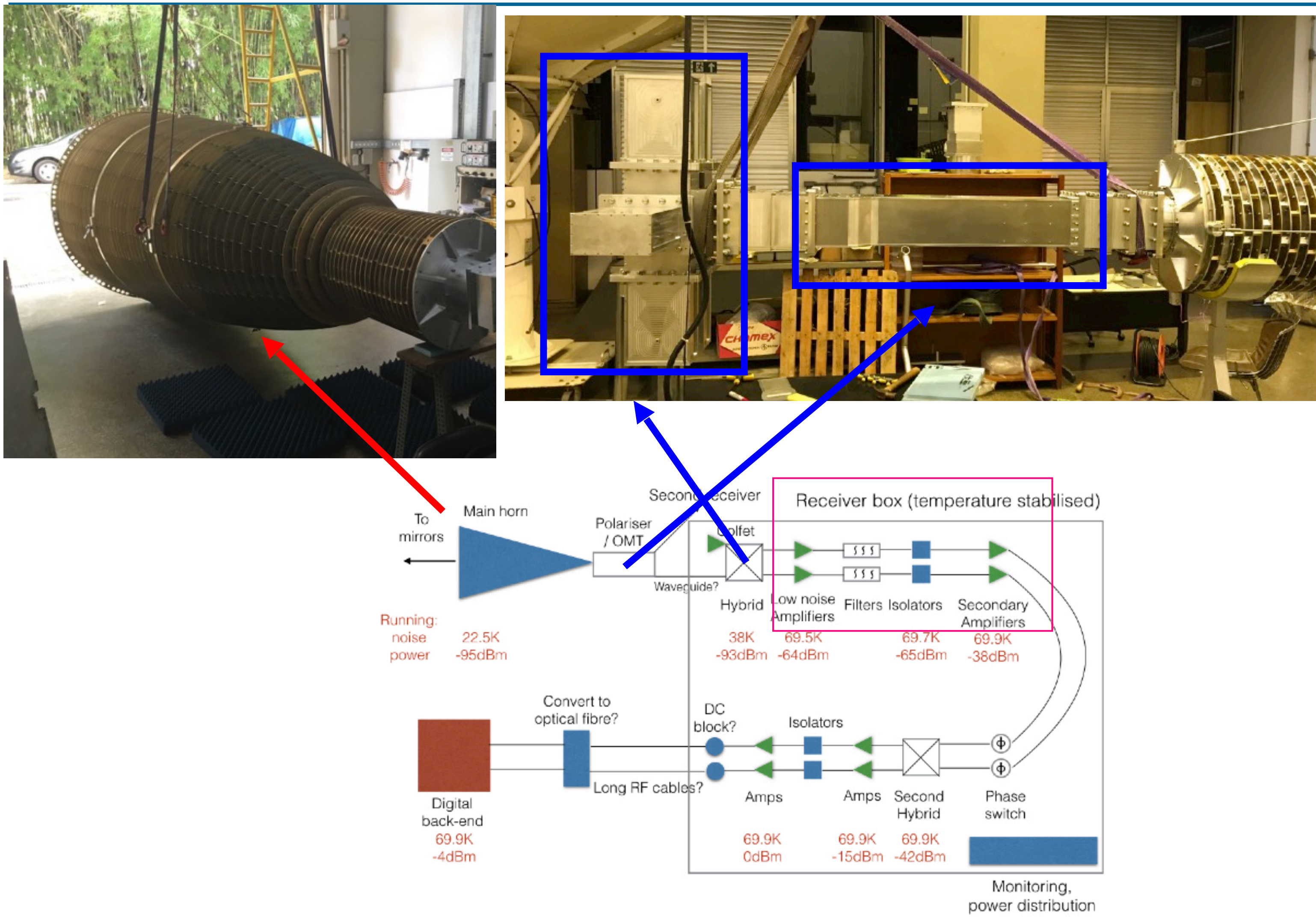

Receiver box (temperature stabilised)
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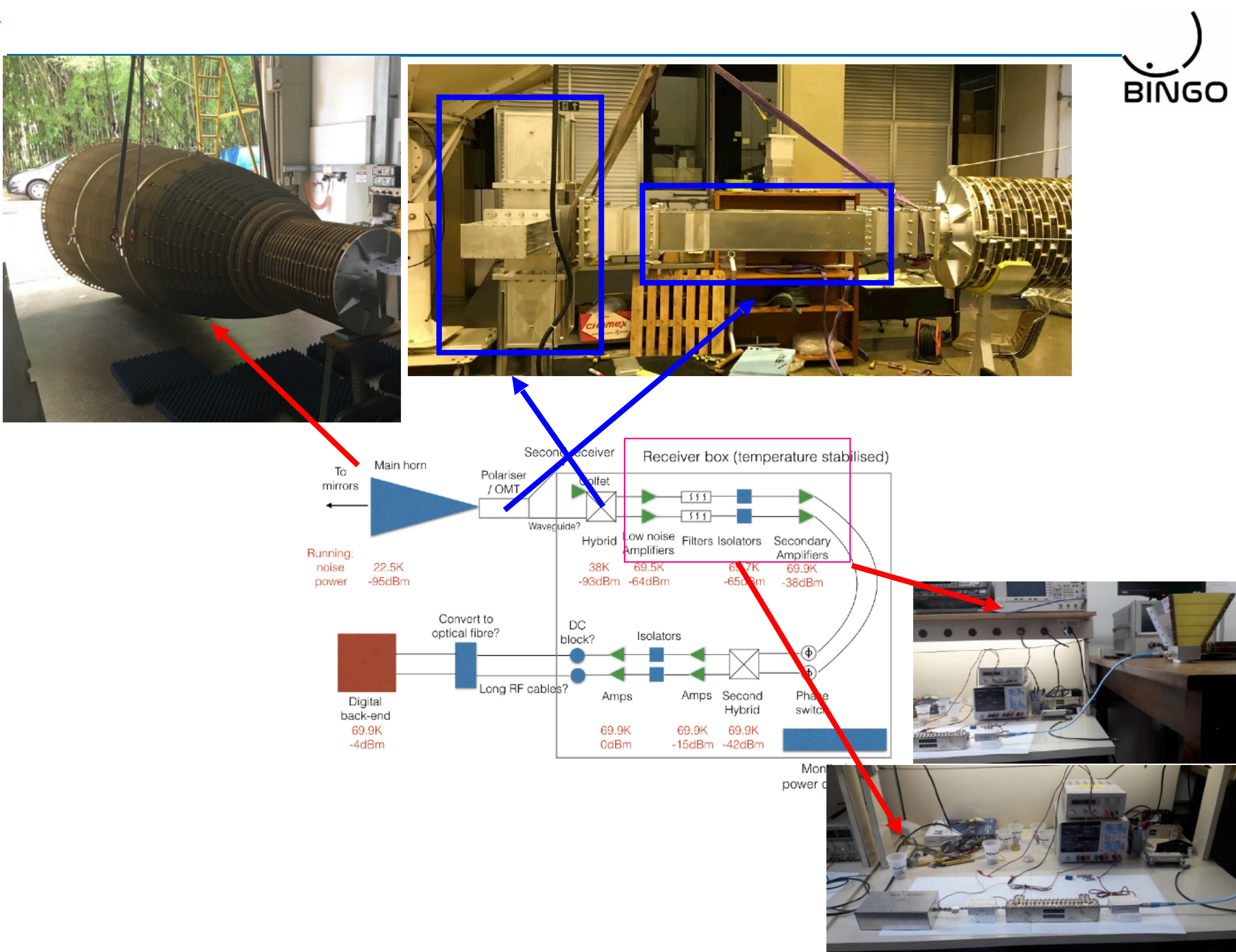
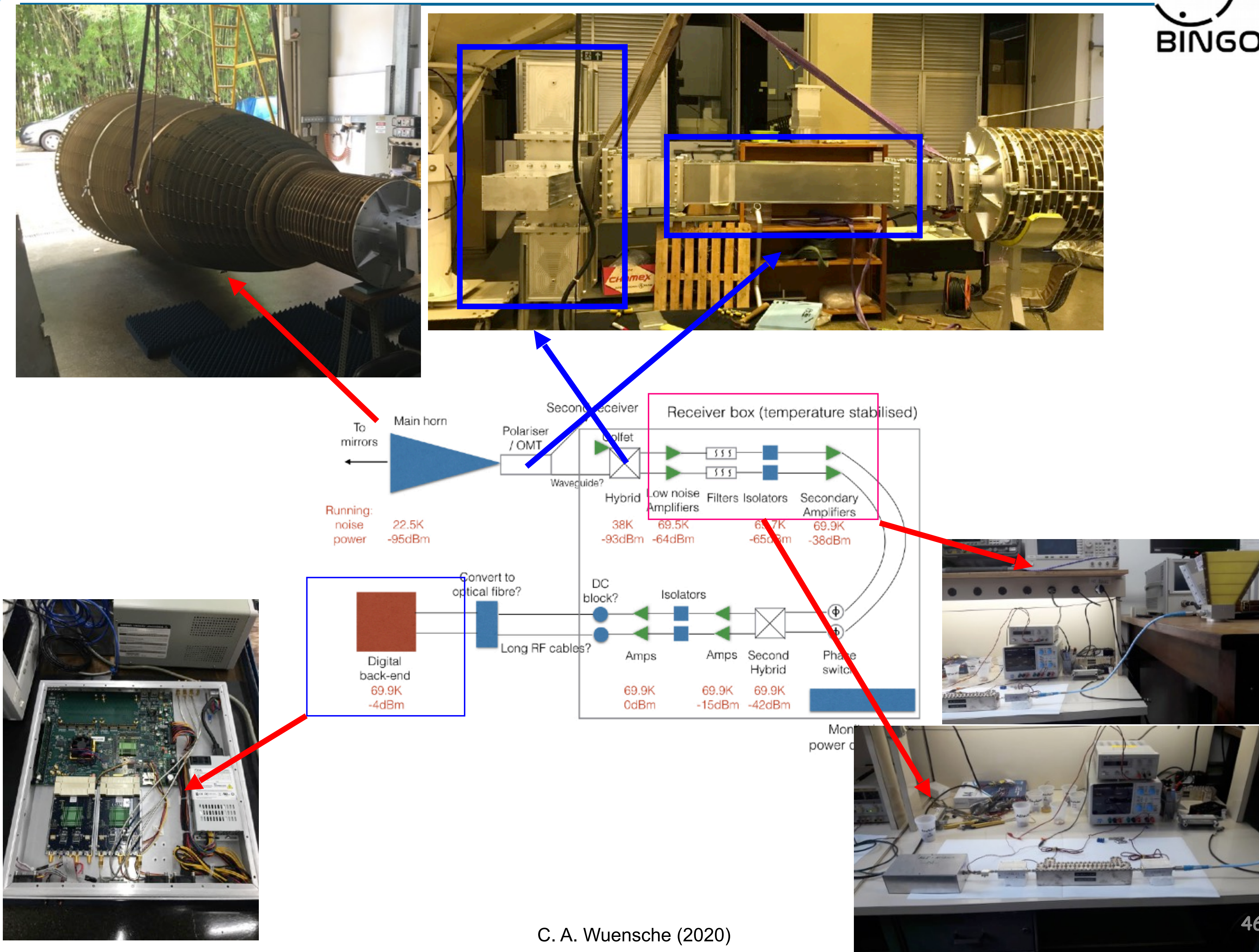


C. A. Wuensche (2020)



C. A. Wuensche (2020)

Receiver status

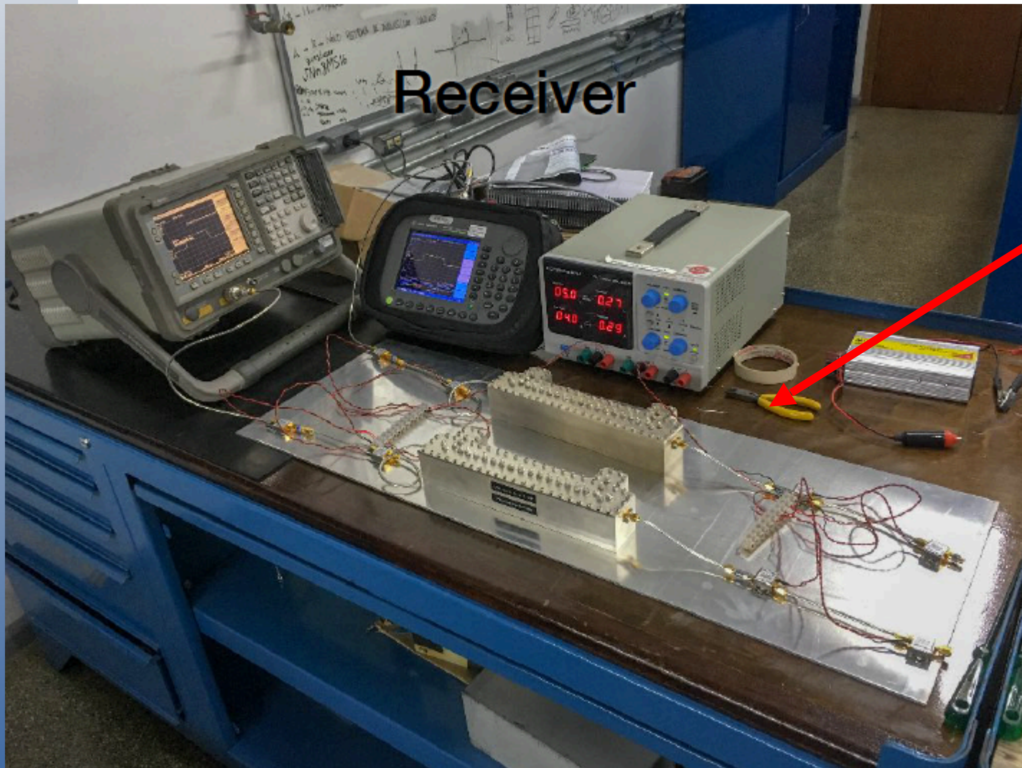
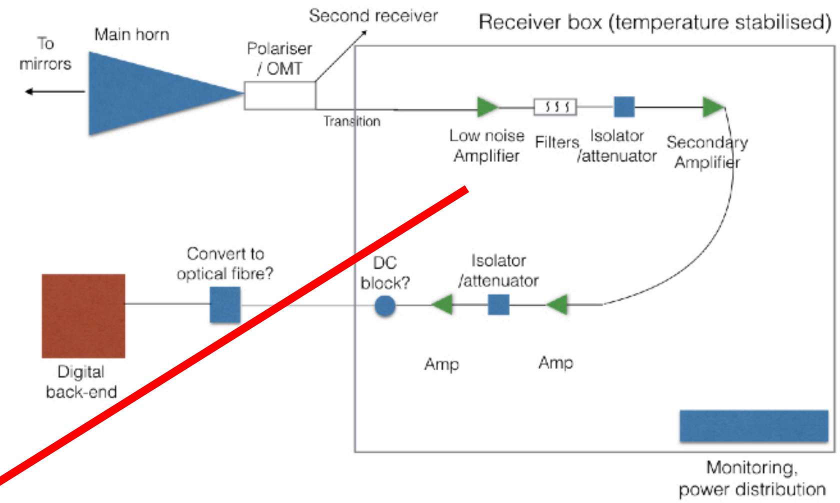
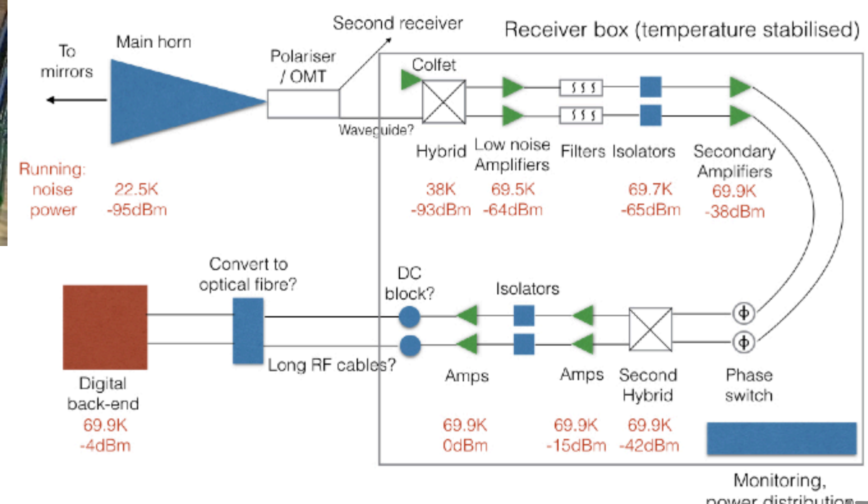


Photo: M. Peel @ INPE's lab

Simple radiometer



Desired: full orrelation receiver



Horn & polarimeter status

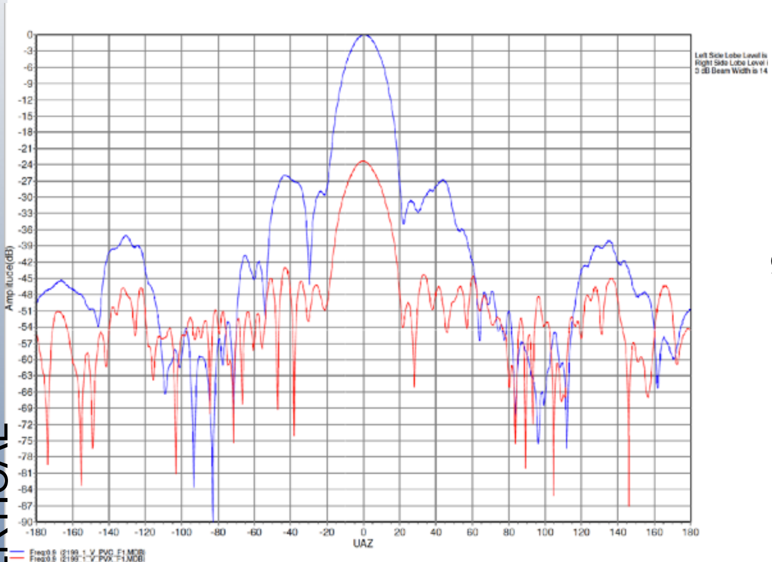
- Aluminum horns
  - 6060 T4 alloy
  - Mass: ~ 400 kg
  - Number of rings (sectors): 127
  - Length: 4318 mm
  - Mouth: 1900 mm
  - Throat: 250 mm
- Prototype construction
  - Calfer (Brazil)

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

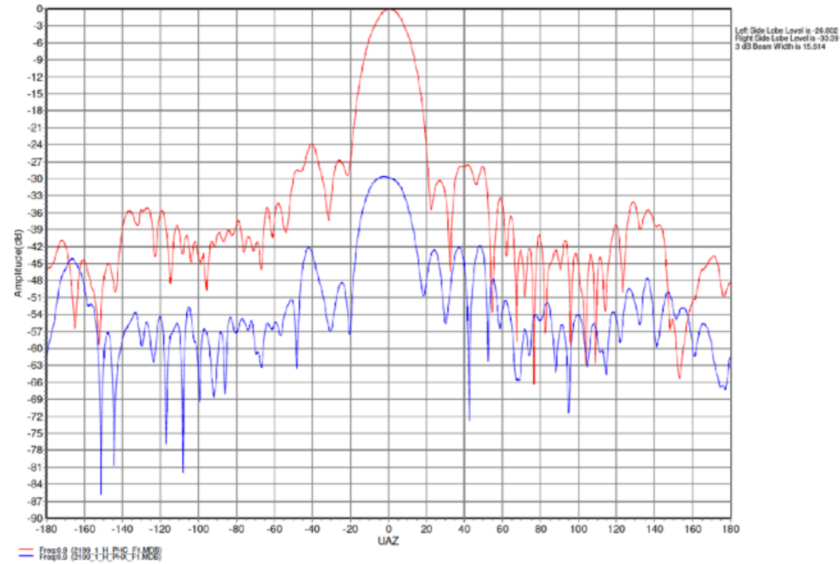
- EM project: Bruno Maffei (IAP, France)
  - Contributions from Chris Radcliffe (Phase 2 Microwave, UK)
- Mechanical project : Luiz Reitano (INPE, Brazil)

Horn testing results –polarization

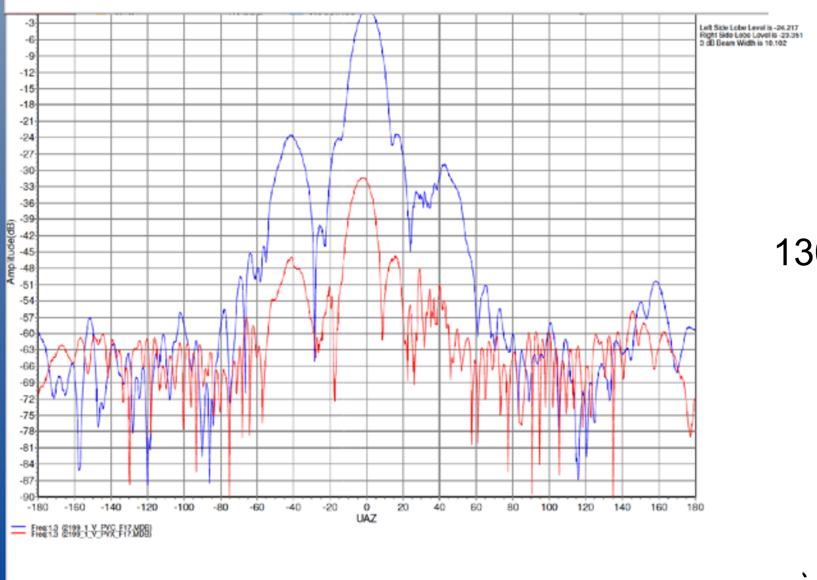
VERTICAL



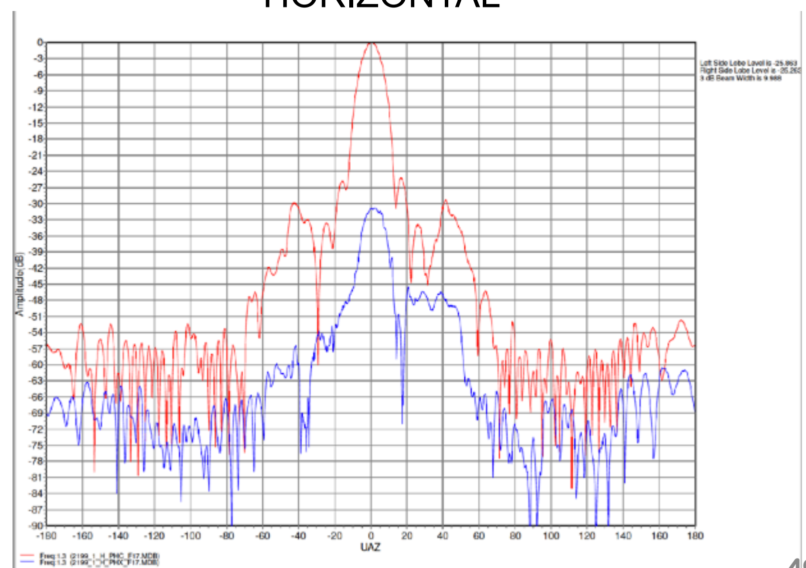
900 MHz



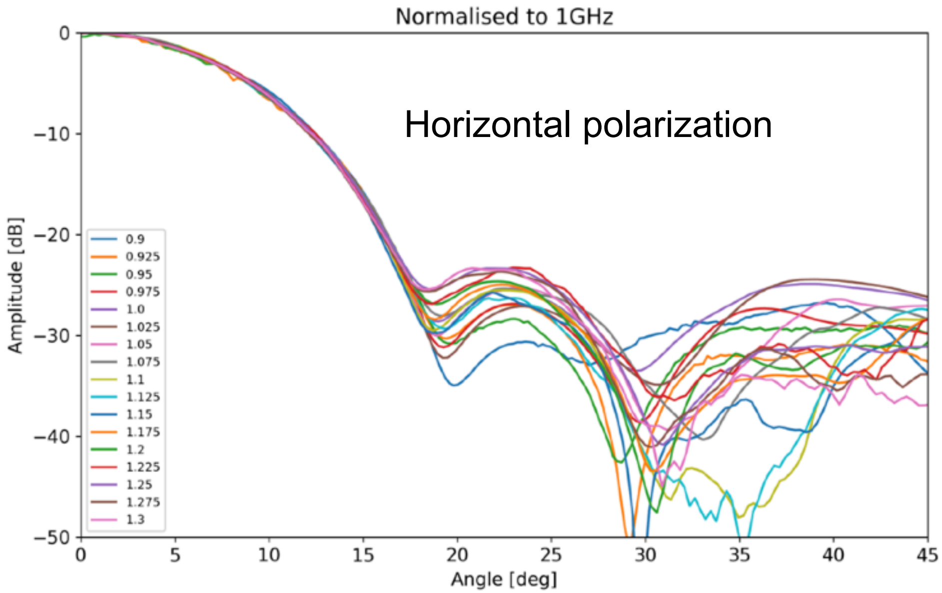
HORIZONTAL

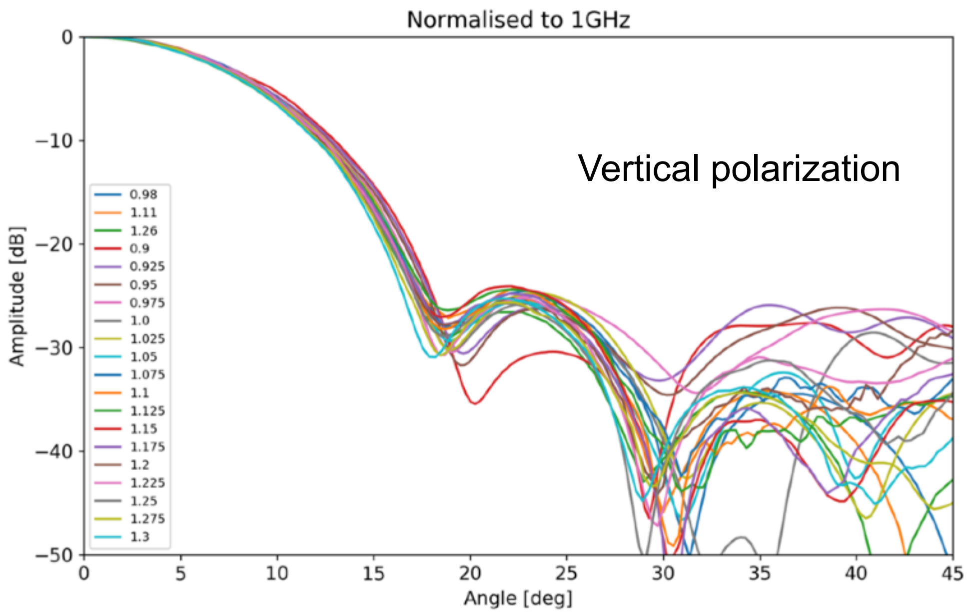


1300 MHz

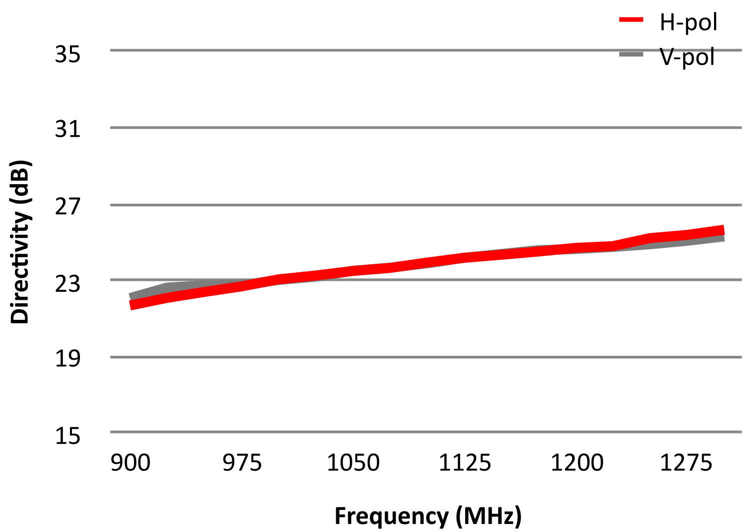


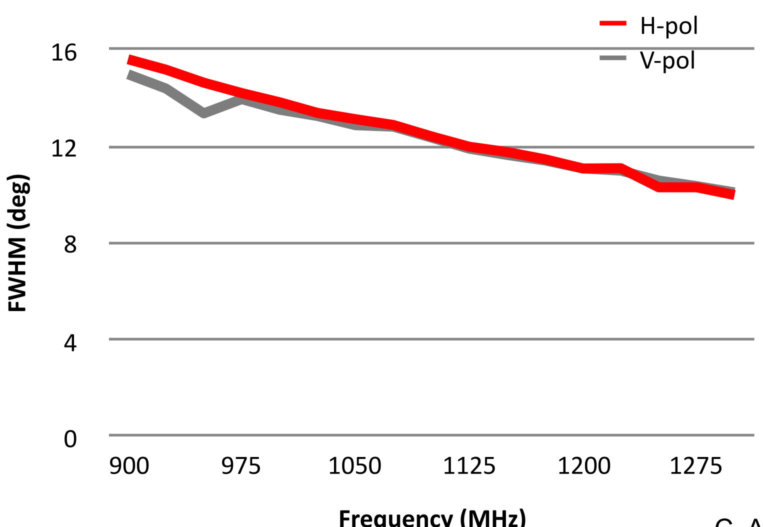
Horn testing results – Combination of all freqs.

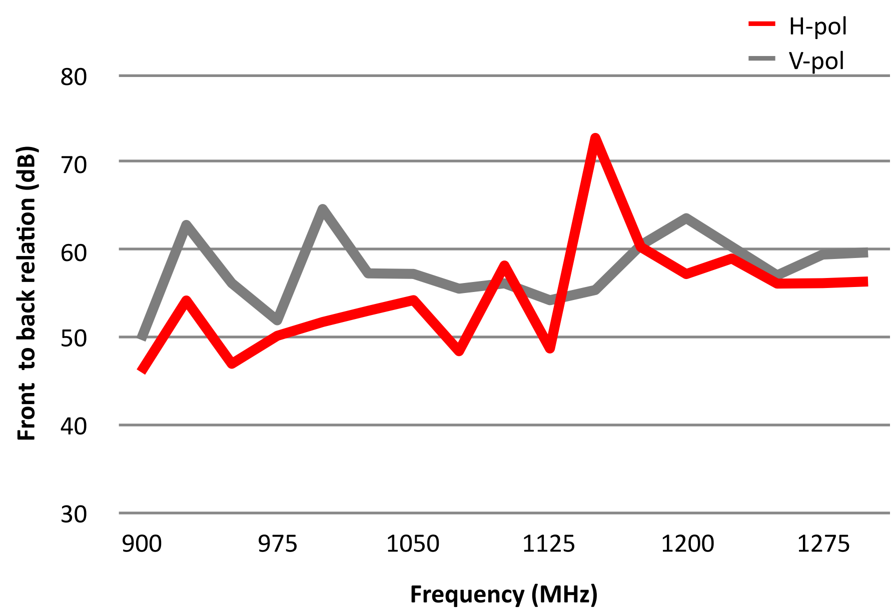




Horn testing results





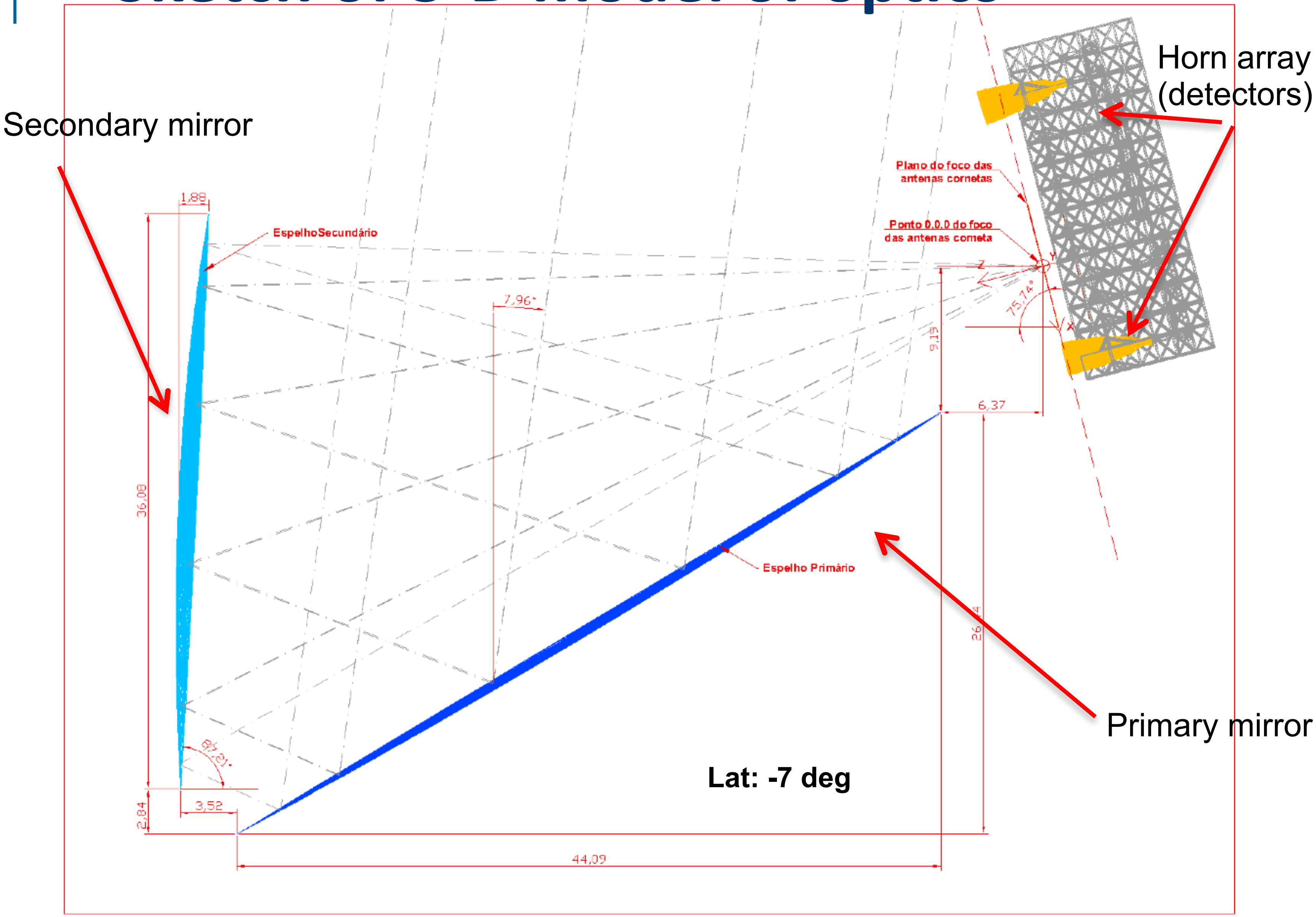


C. A. Wuensche (2020)

Optical design

Coordinated by F. Abdalla, with original work from B. Maffei and I. Ferreira

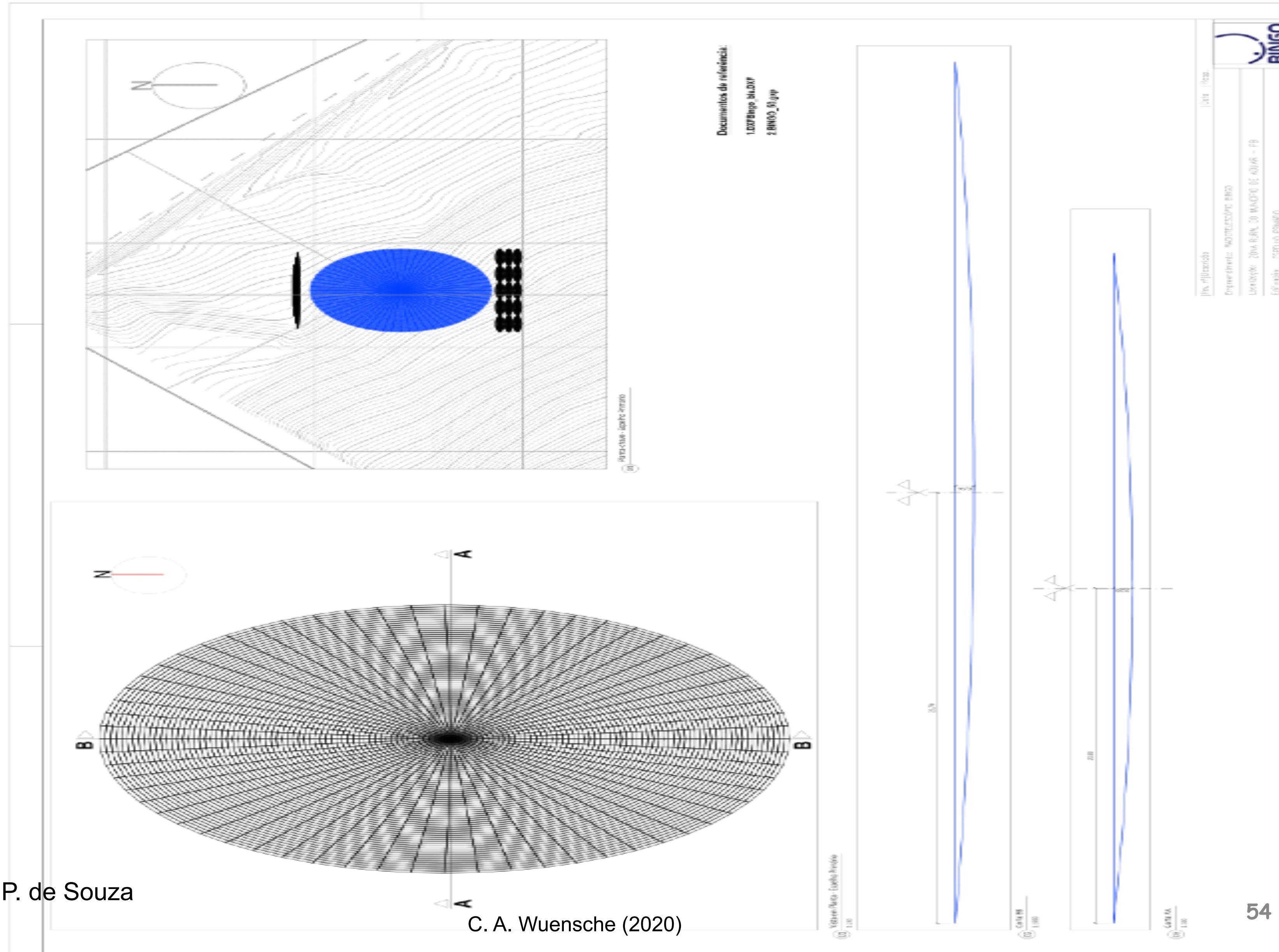
Sketch of 3-D model of optics



Maffei, Ferreira, Abdalla, Souza, in preparation

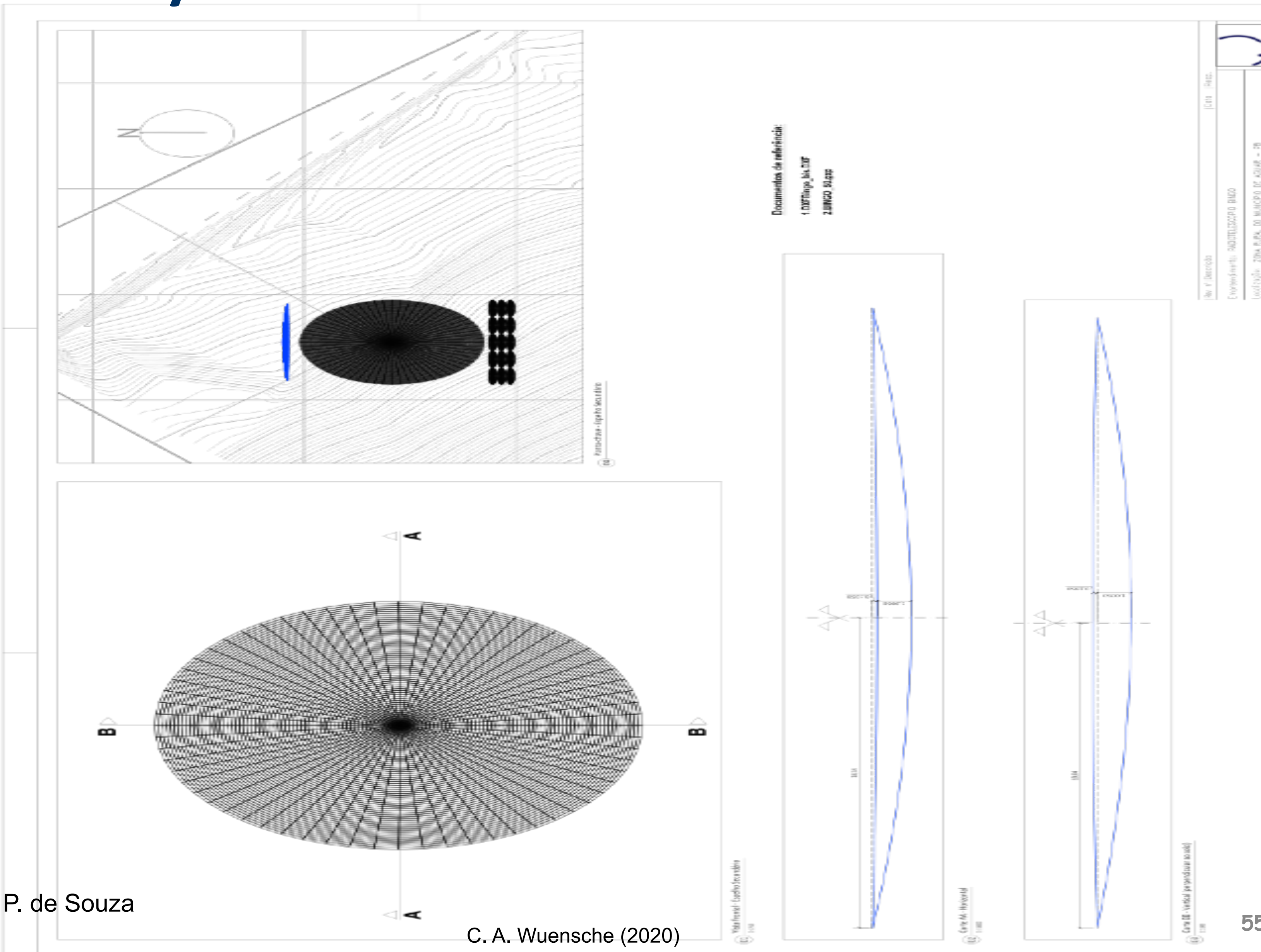
C. A. Wuensche (2020)

Primary dish



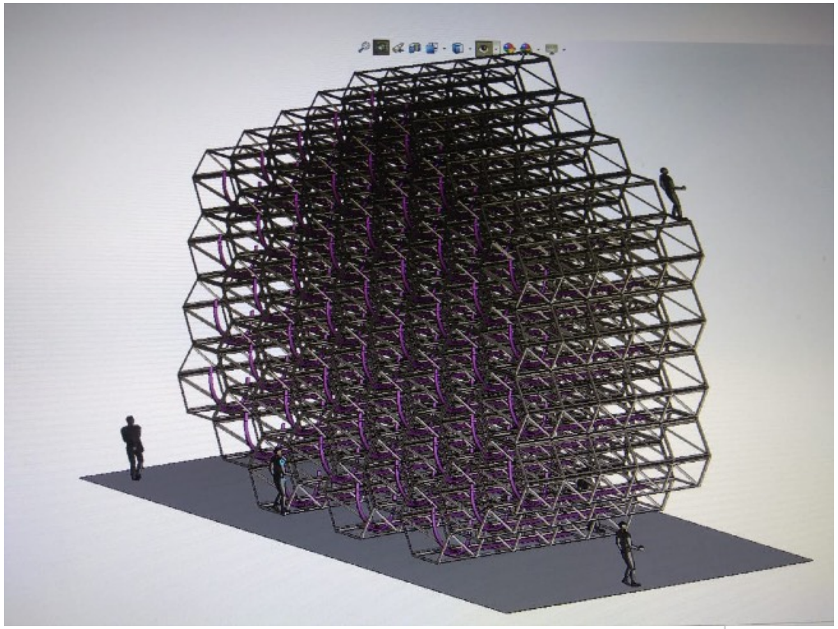
From A. P. de Souza

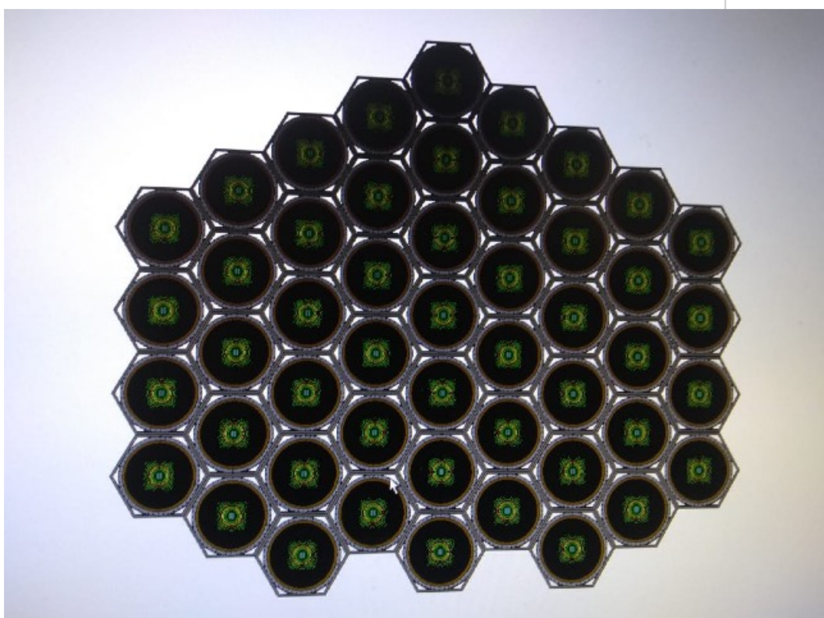
Secondary dish

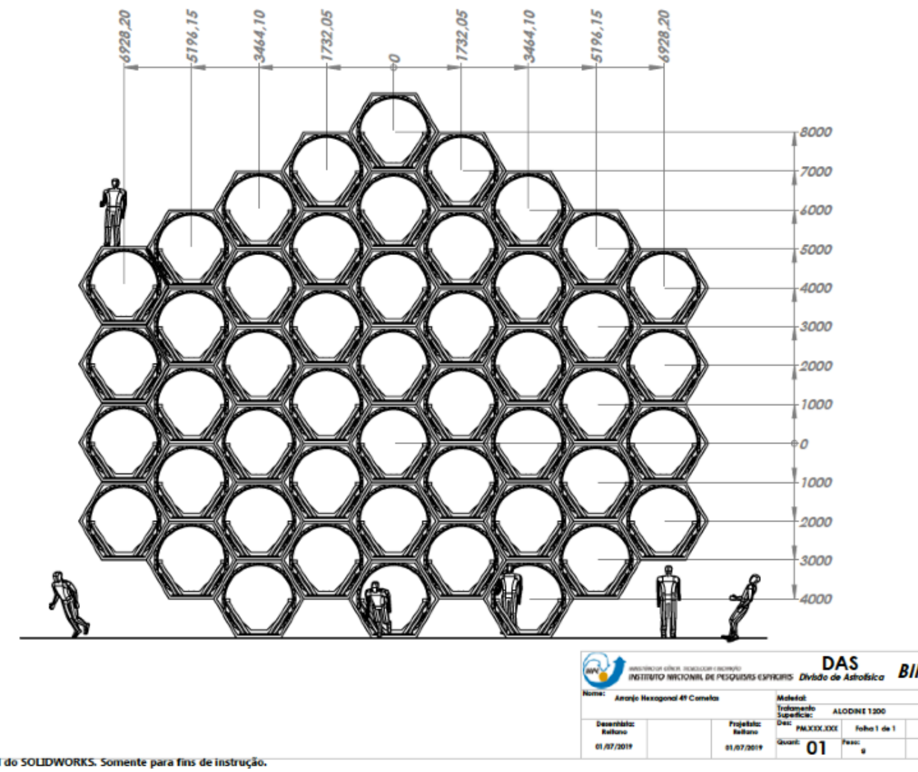


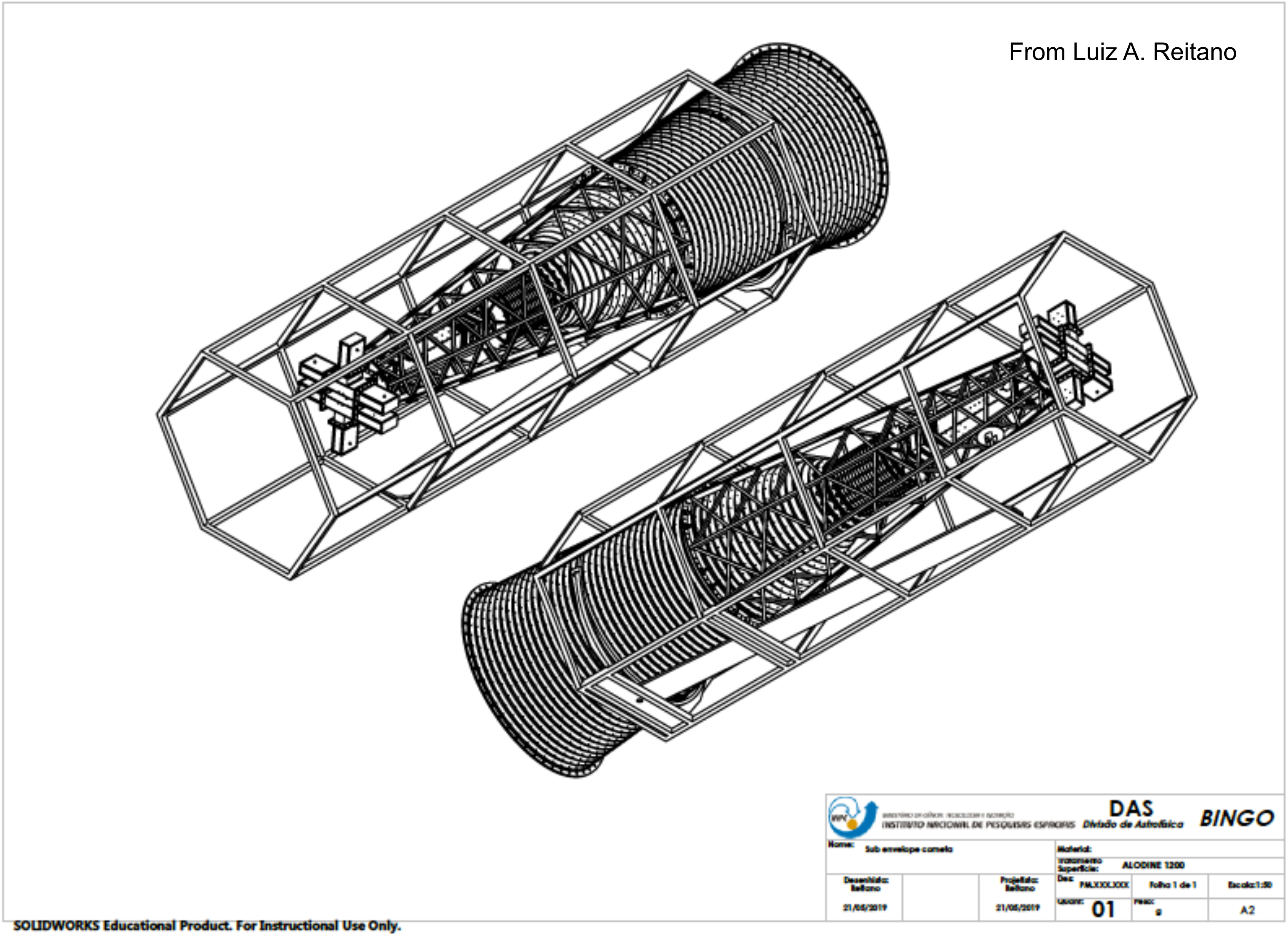
From A. P. de Souza

From Luiz A. Reitano



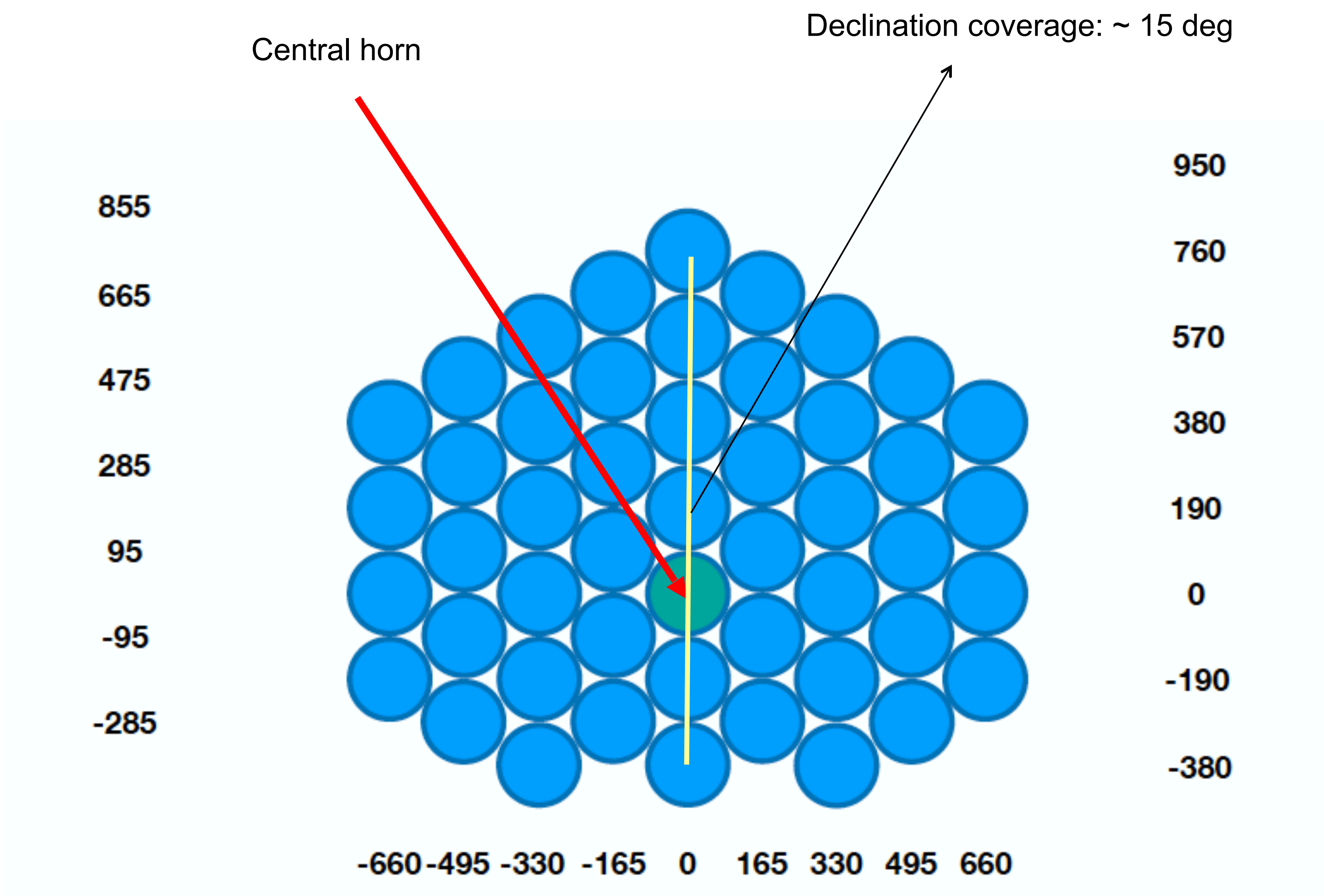




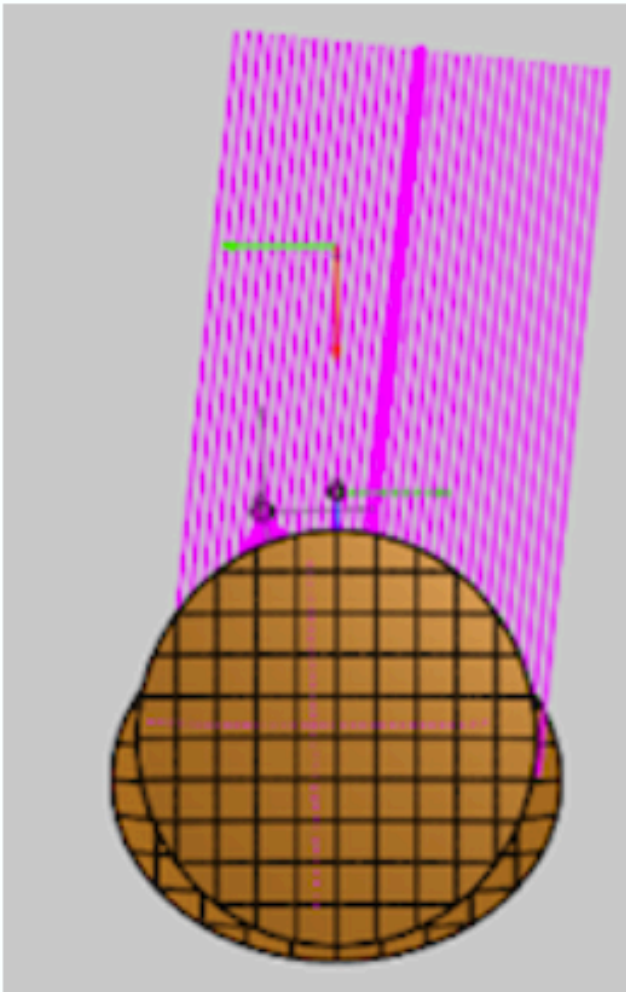

From Luiz A. Reitano
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS
DAS
Divisão de Astrofísica
BINGO
Nome: Sub envelope corneta
Material:
Tratamento Superfície: ALODINE 1200
Desenhista: Reitano
Projetista: Reitano
21/05/2019
21/05/2019
Folha 1 de 1
Escala:1:50
01
A2
SOLIDWORKS Educational Product. For Instructional Use Only.

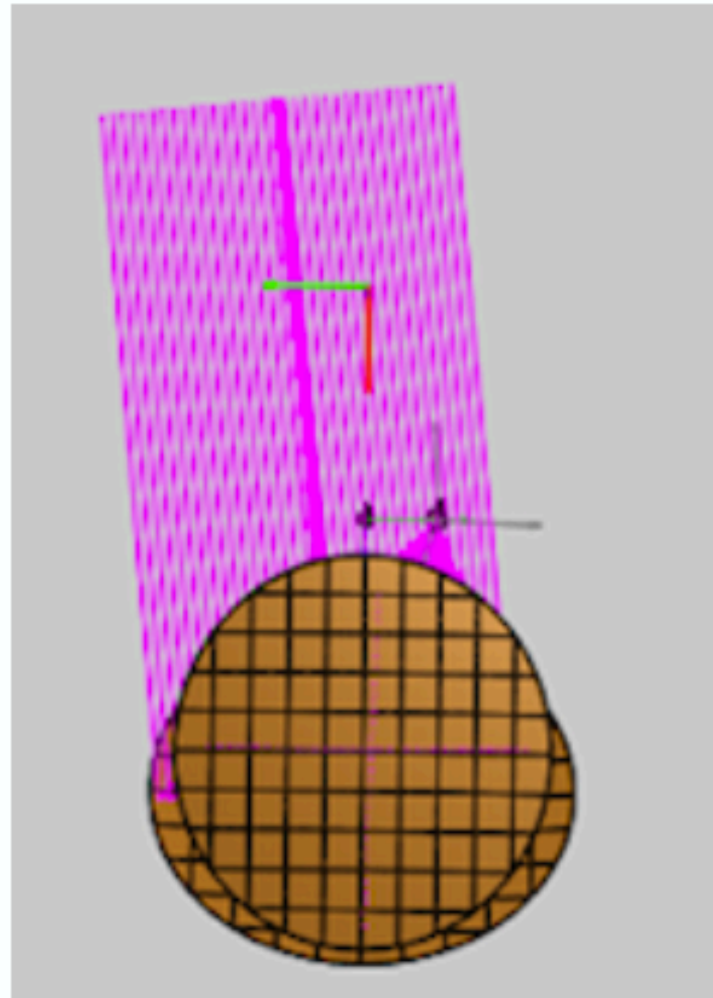
Focal plane – 49 horns

From: Bruno Maffei / Ivan Ferreira



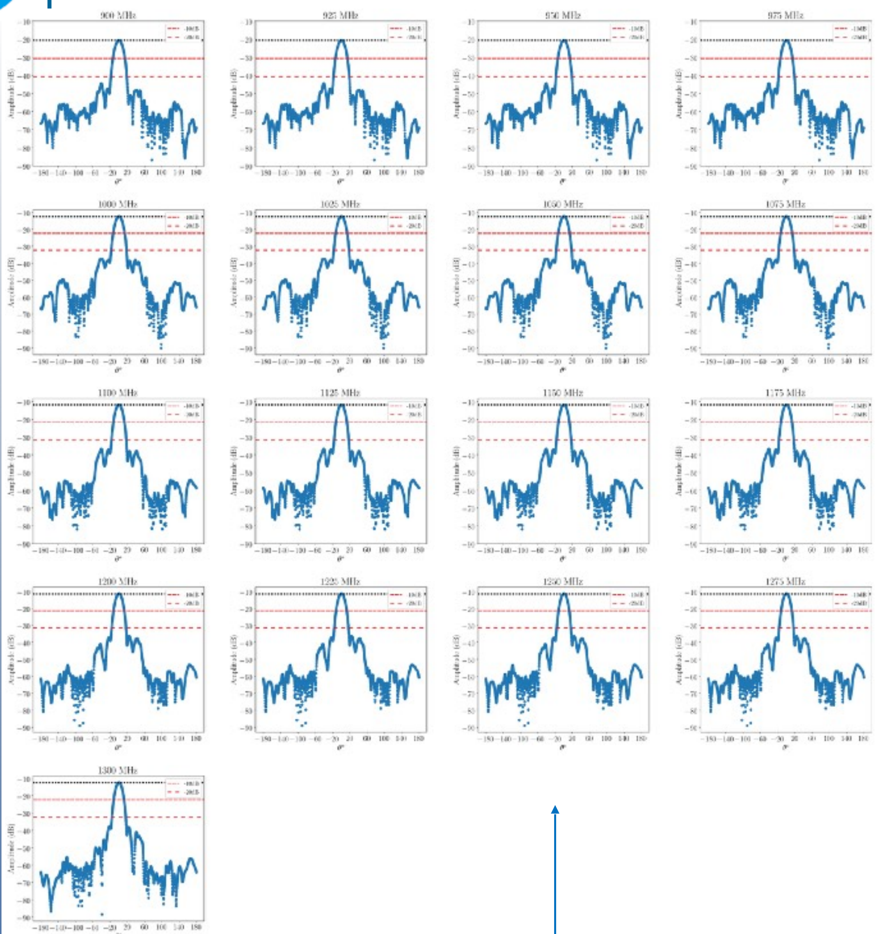
Beam -660 and 660





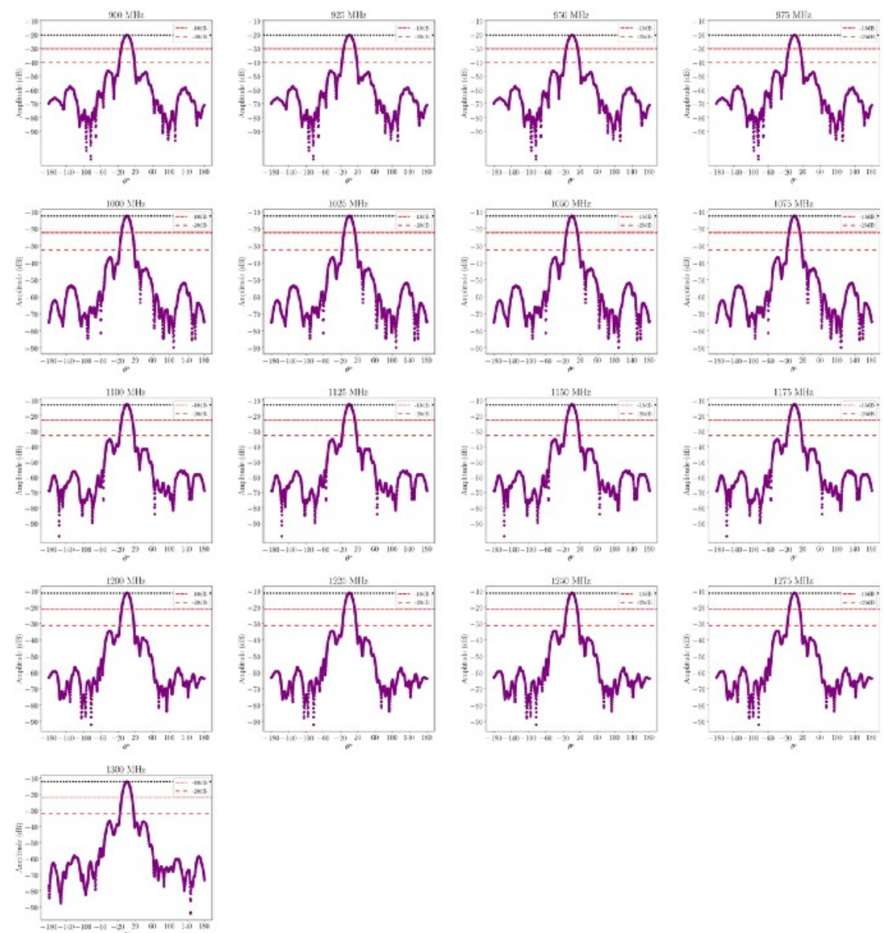
From Bruno Maffei / Ivan Ferreira

BINGO beams measured @ LIT

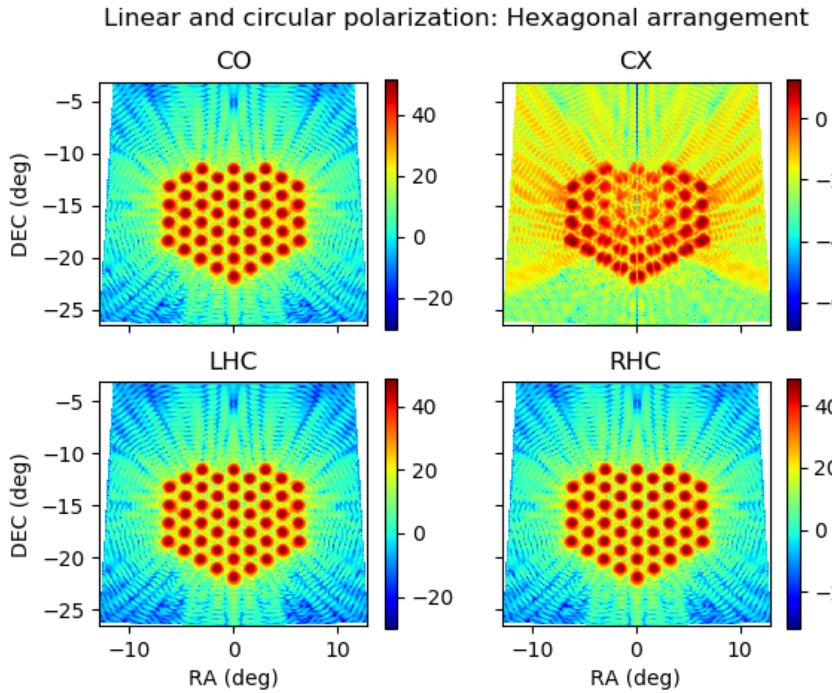


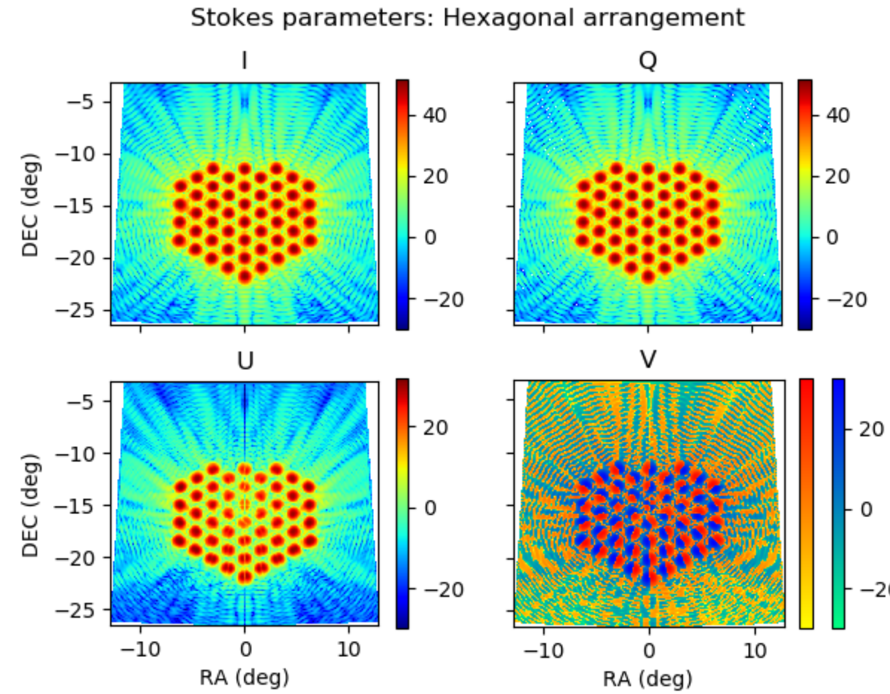
Horizontal polarization

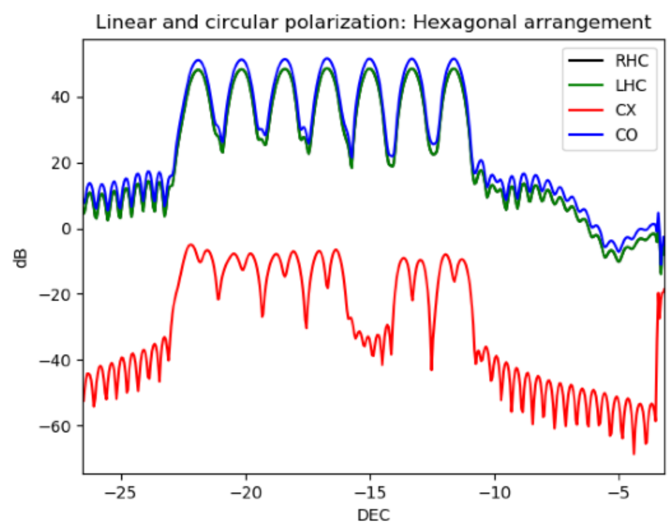
Vertical polarization



Abdalla, Marins, Mota et al., in preparation

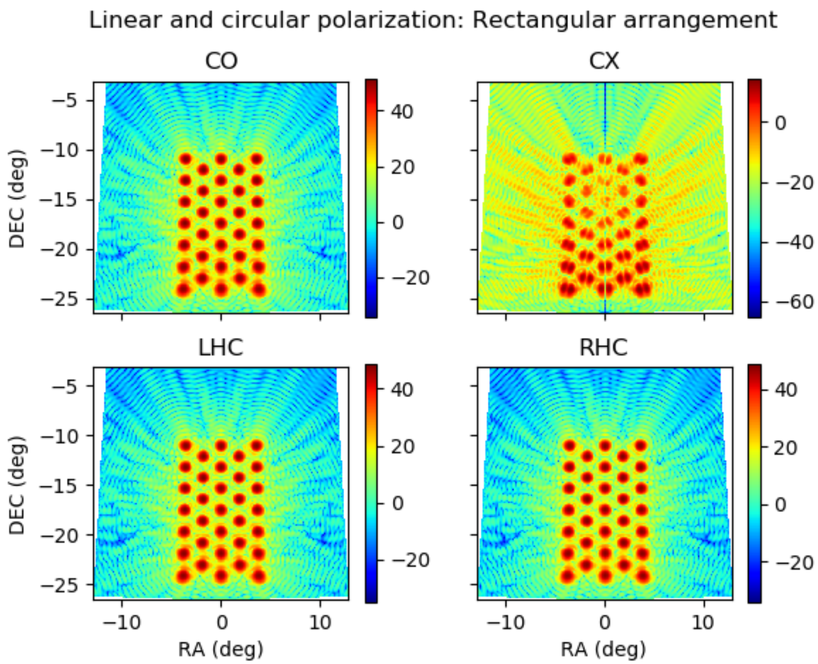


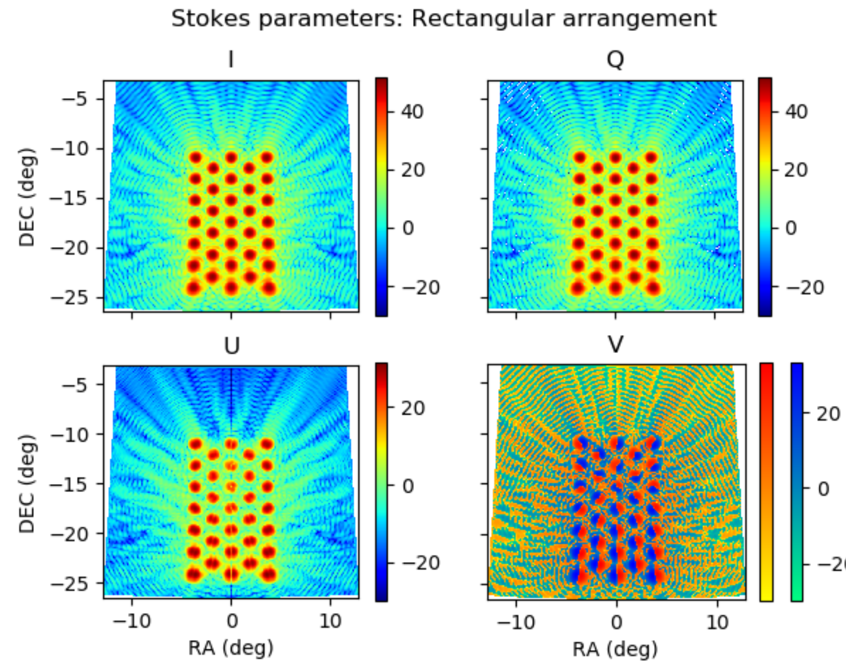


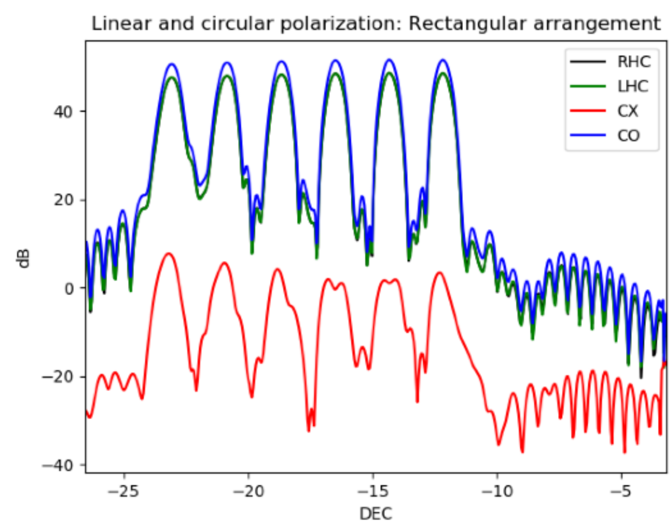


Abdalla, Marins, Mota et al., in preparation

C. A. Wuensche (2020)







Abdalla, Marins, Mota et al., in preparation

C. A. Wuensche (2020)

Data Analysis

Led by F. Abdalla

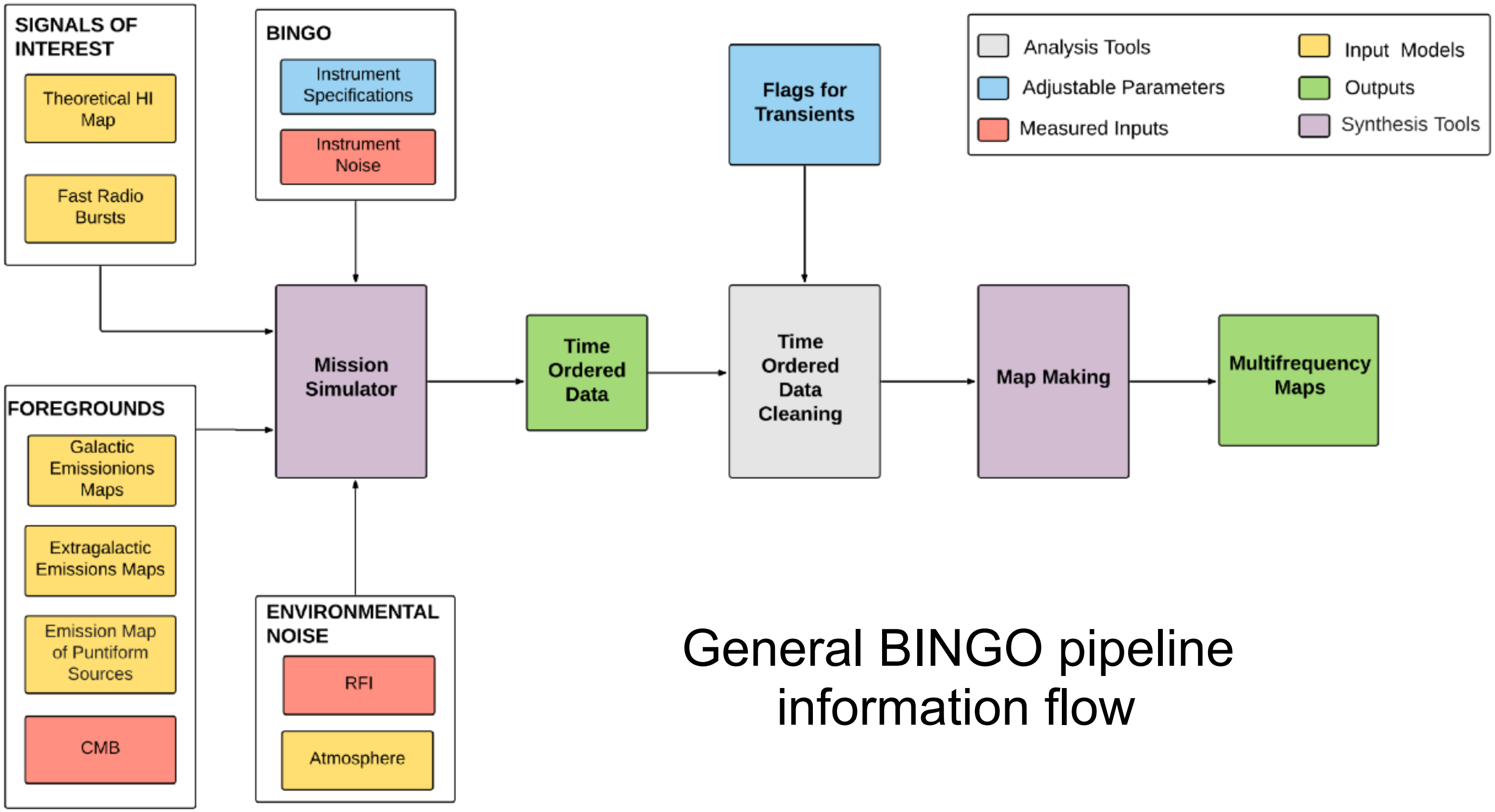
Foreground budget

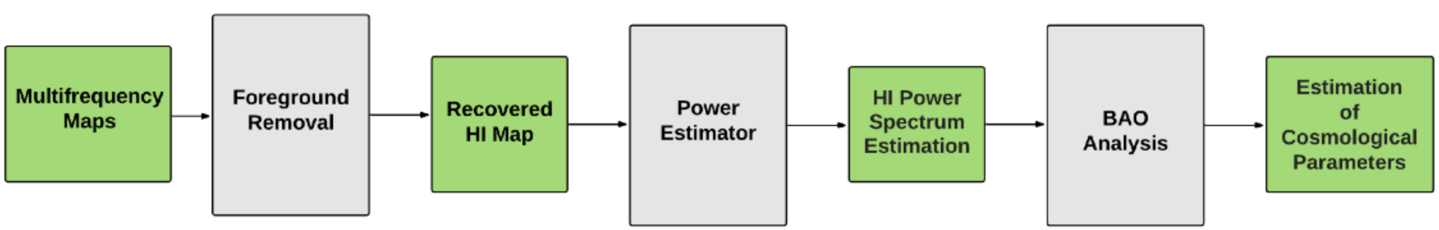
Table 2. Summary of foregrounds for HI intensity mapping at 1 GHz for an angular scale of $\sim 1^\circ$ ($\ell \sim 200$). The estimates are for a 10°-wide strip at declination $\delta = +45^\circ$ and for Galactic latitudes $|b| > 30^\circ$.

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.

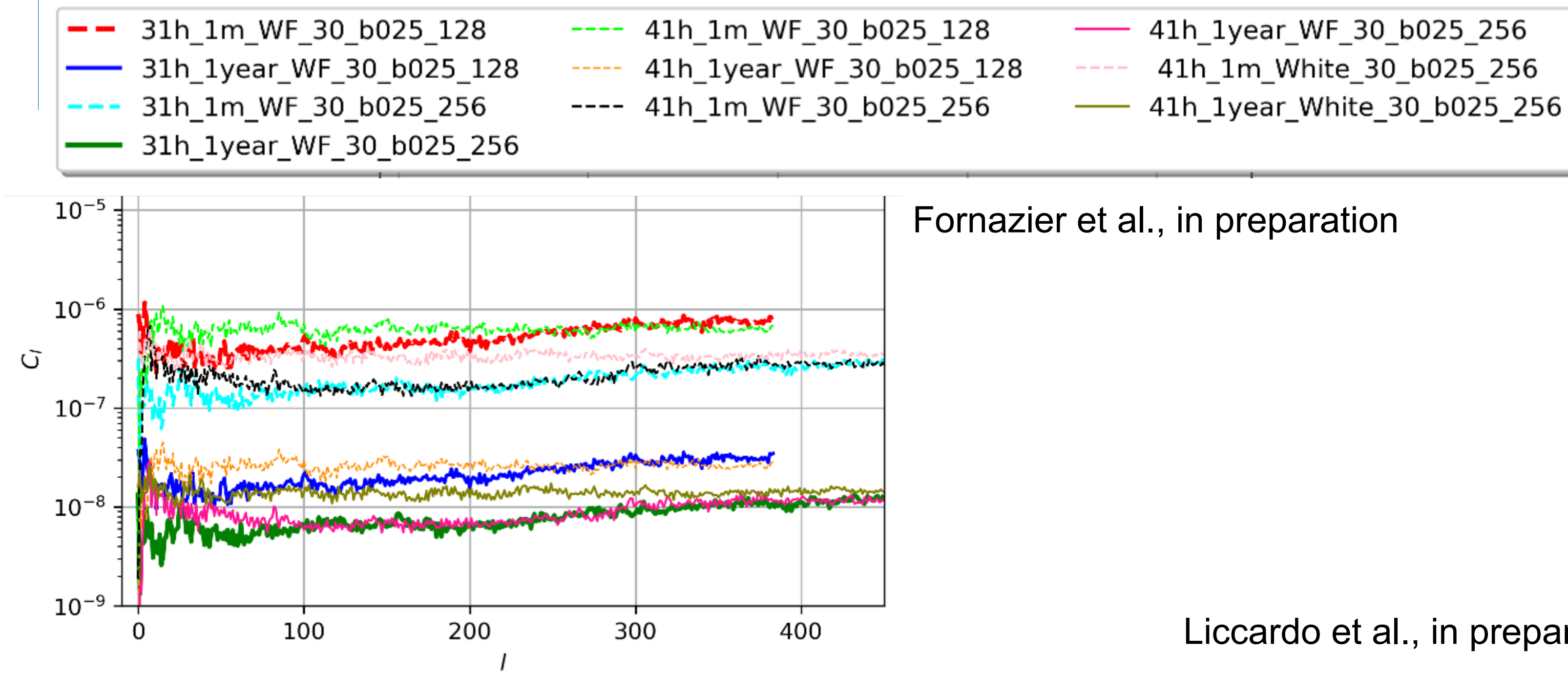
- From Battye et al. (2013), still valid for the current BINGO configuration

General BINGO pipeline information flow





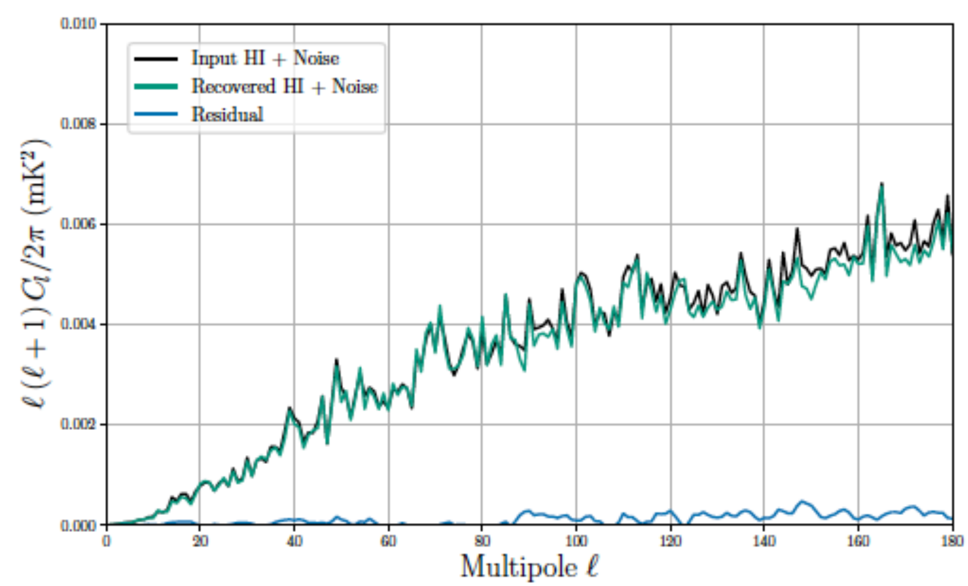
From E. Merícia



Fornazier et al., in preparation

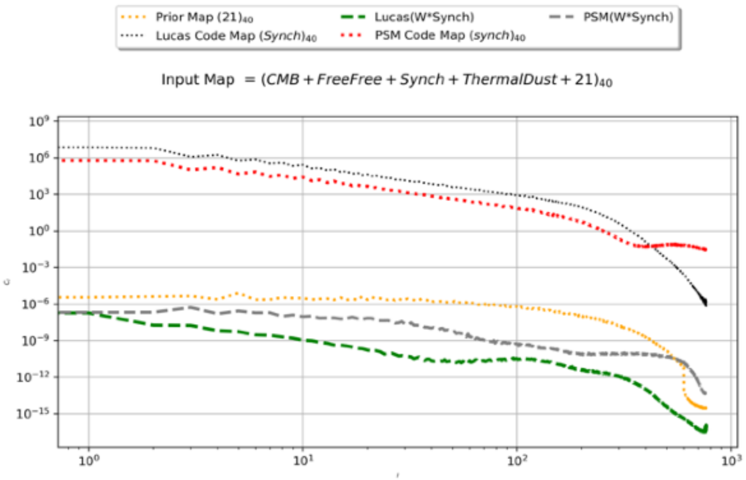
Liccardo et al., in preparation

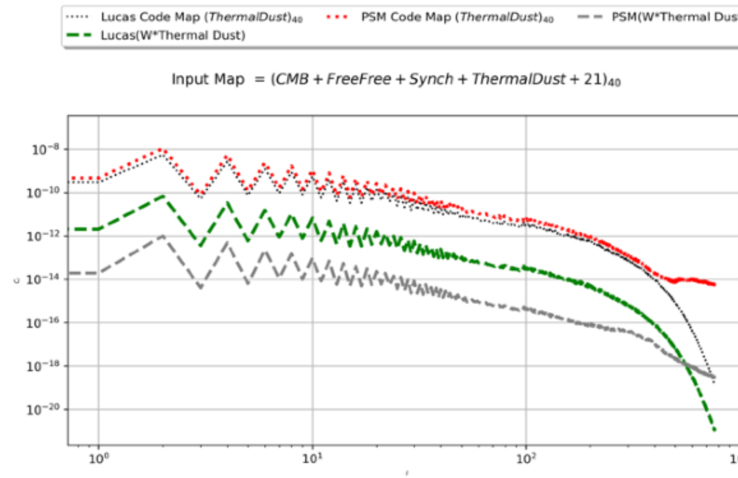
Range ℓ	N_{GNILC}
1 - 180	0.051
1 - 15	0.423
15 - 30	0.056
30 - 45	0.0412
45 - 60	0.0378
60 - 75	0.042
75 - 90	0.041
90 - 105	0.042
105 - 120	0.0437
120 - 135	0.046
135 - 150	0.05
150 - 165	0.05
165 - 180	0.042

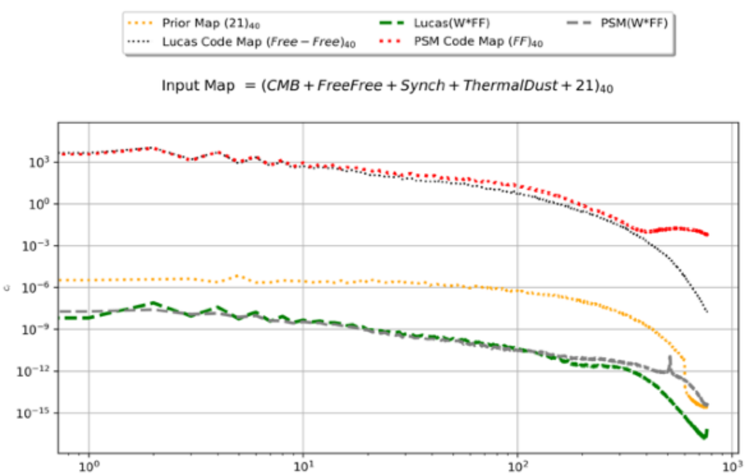


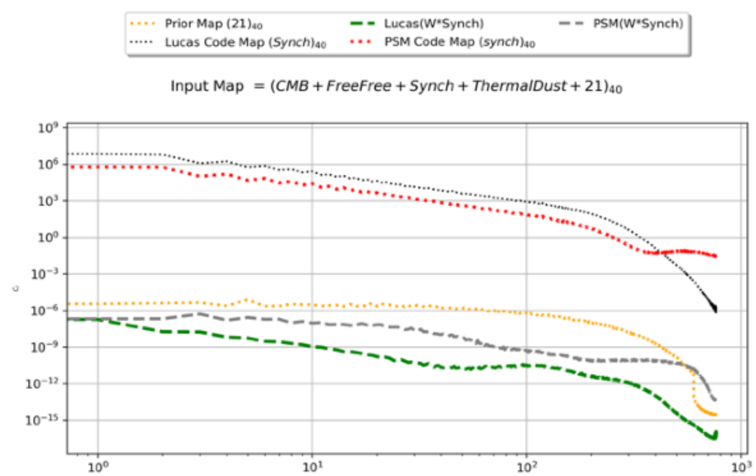
C. A. Wuensche (2020)

Component separation





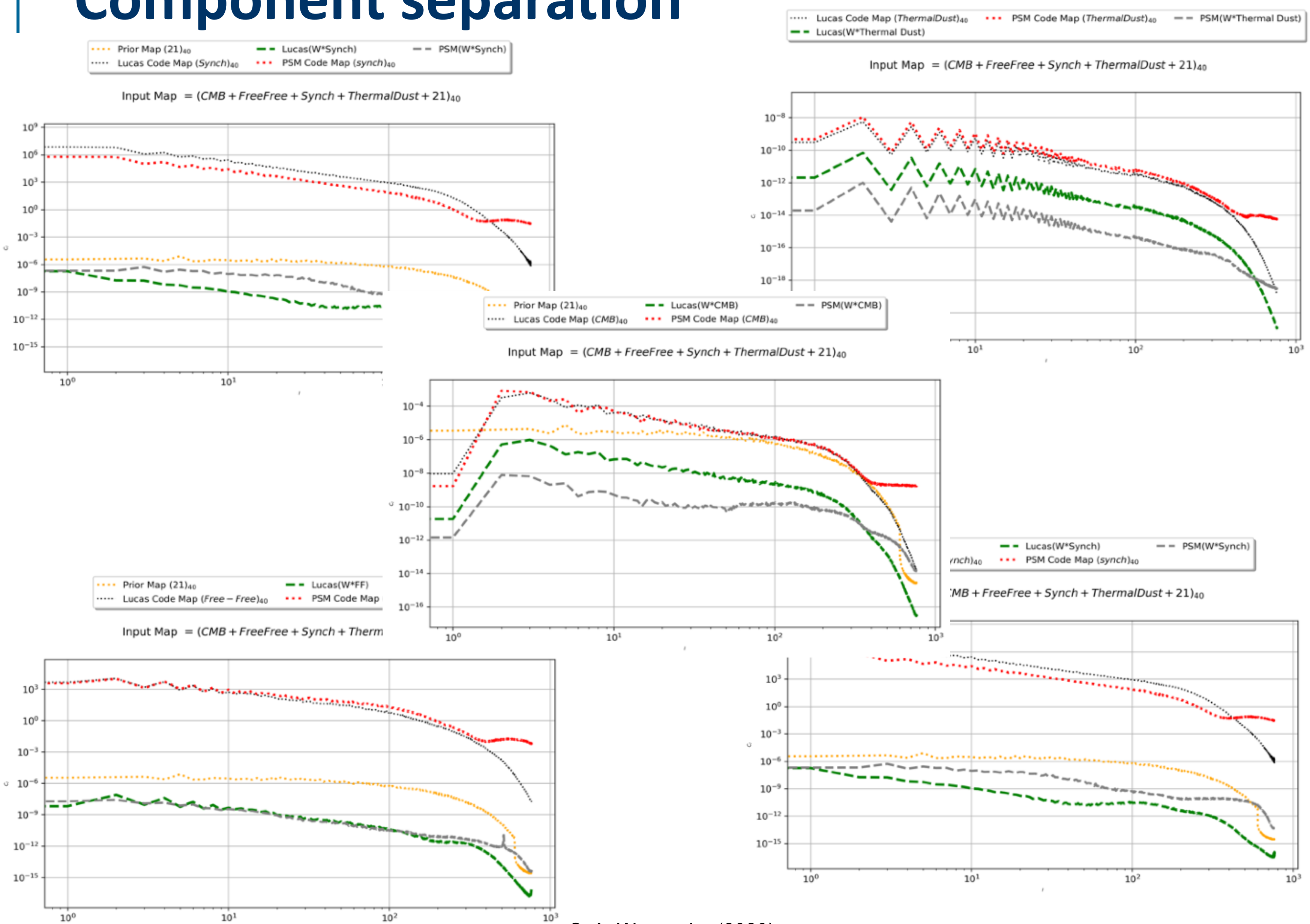




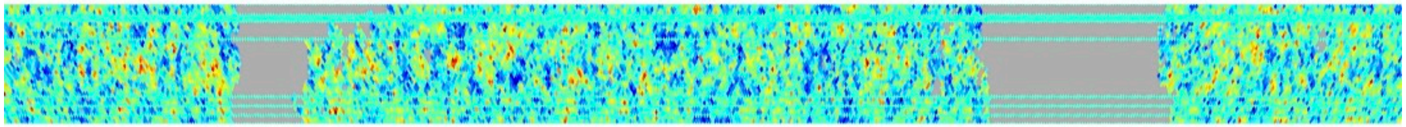
C. A. Wuensche (2020)

Component separation

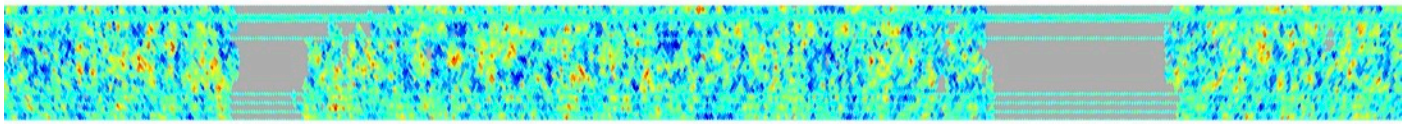
From K. Fornazier



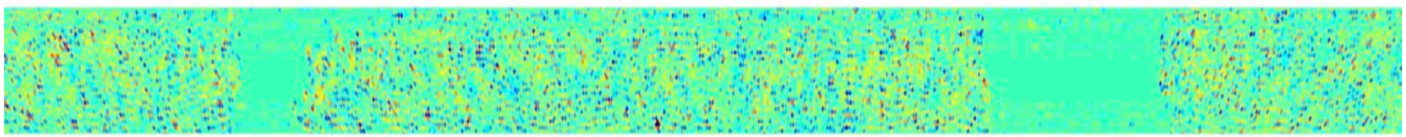
C. A. Wuensche (2020)



BINGO simulated input map @ 1100 MHz

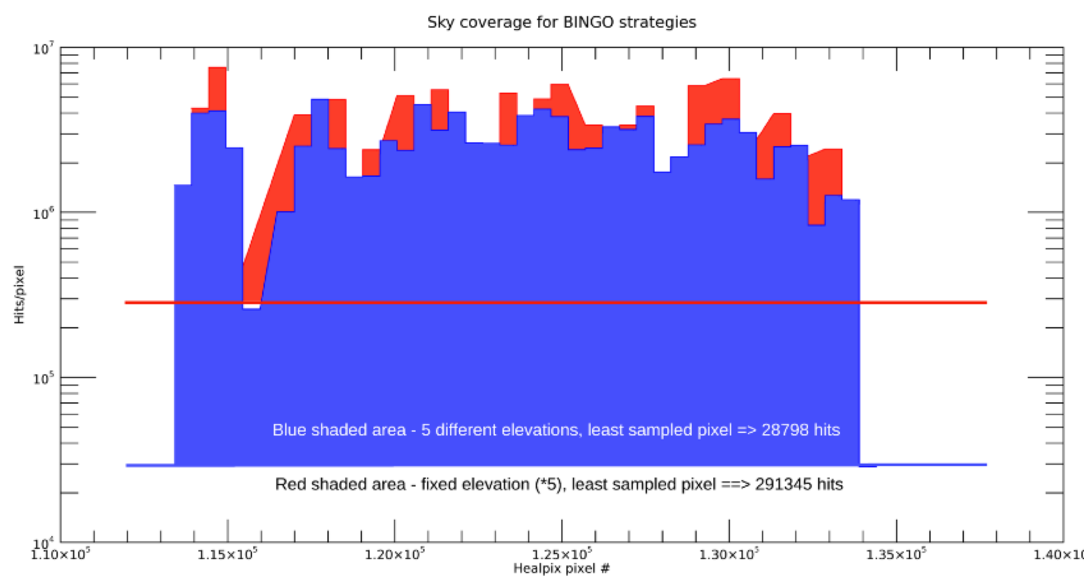


BINGO reconstructed map @ 1100 MHz



Residuals

From V. Liccardo



C. A. Wuensche (2020)

Fast Radio Bursts

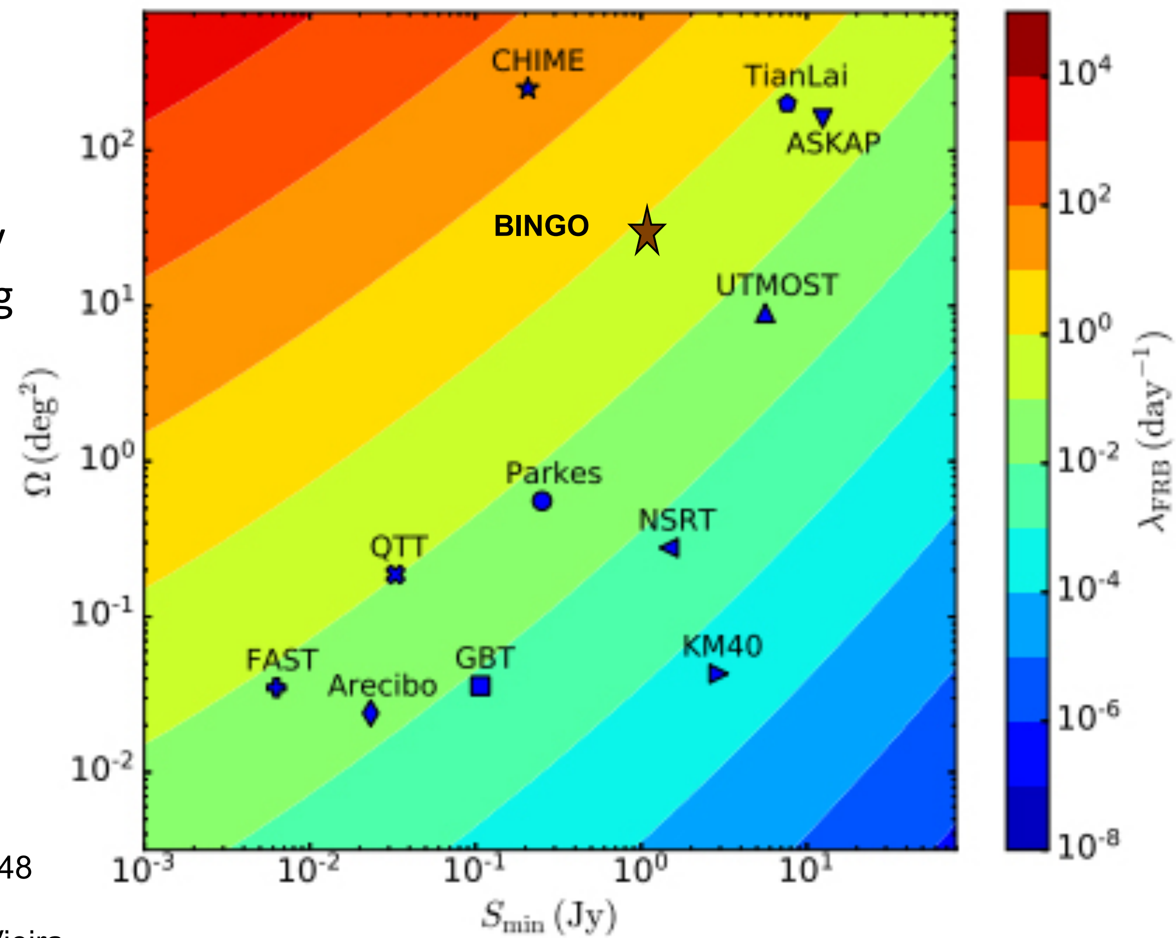
Led by R. Landim and F. Vieira

Fast Radio Bursts detection

- FRB is not BINGO main science, but serendipitous detections are expected
- Outriggers for interferometric pinpoint of the progenitor are being planned
- Need ADDITIONAL FUNDING!

M.Sc. thesis from F. Vieira (2020) presented a preliminary analysis performance regarding FRB detections

For ~ 3 Jy (max flux density) BINGO will likely see about 1 event every 2.84 days…



Luo et al., arXiv:2003.04848

Estimates for BINGO: F. Vieira

C. A. Wuensche (2020)

The Site


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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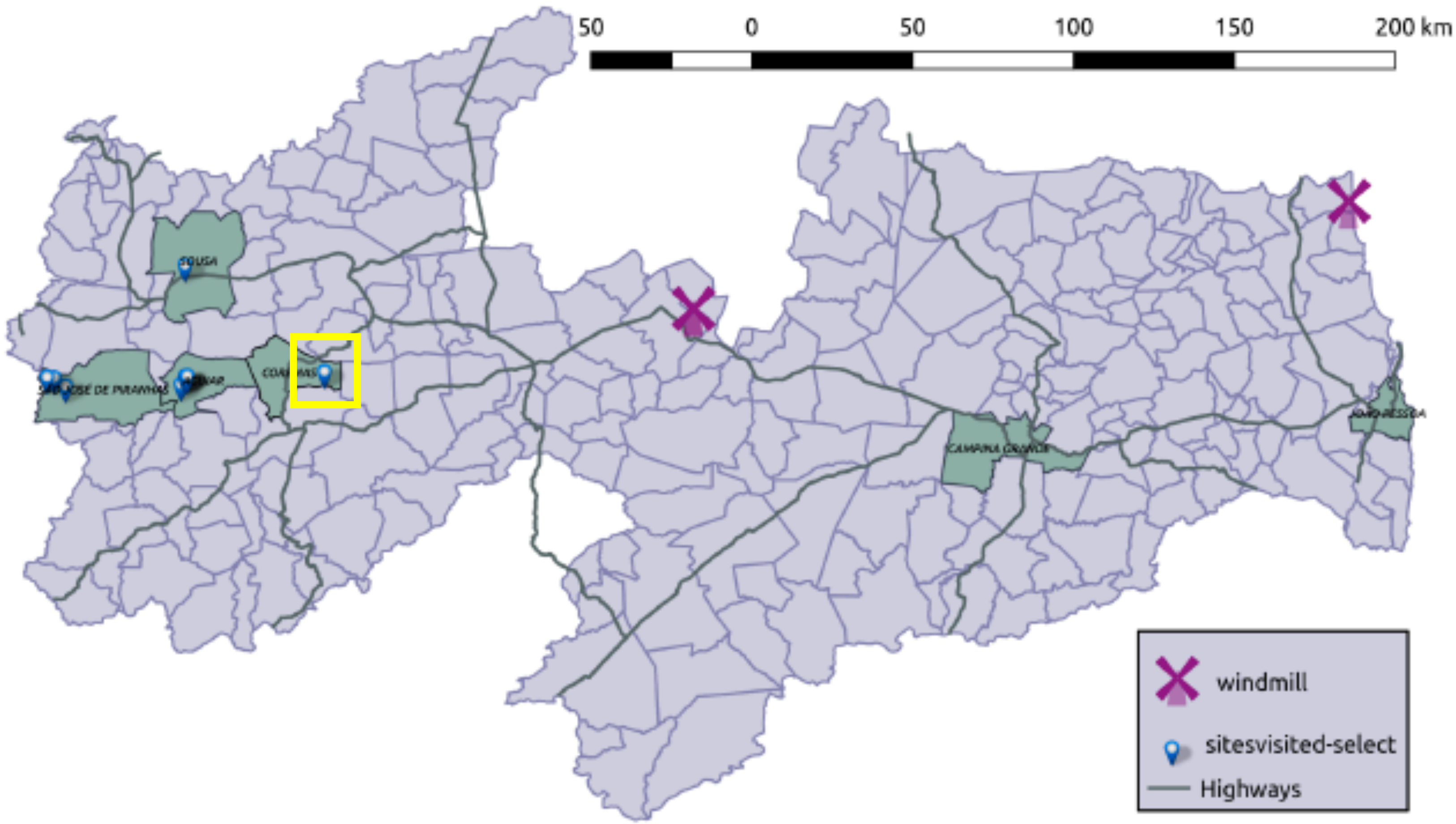
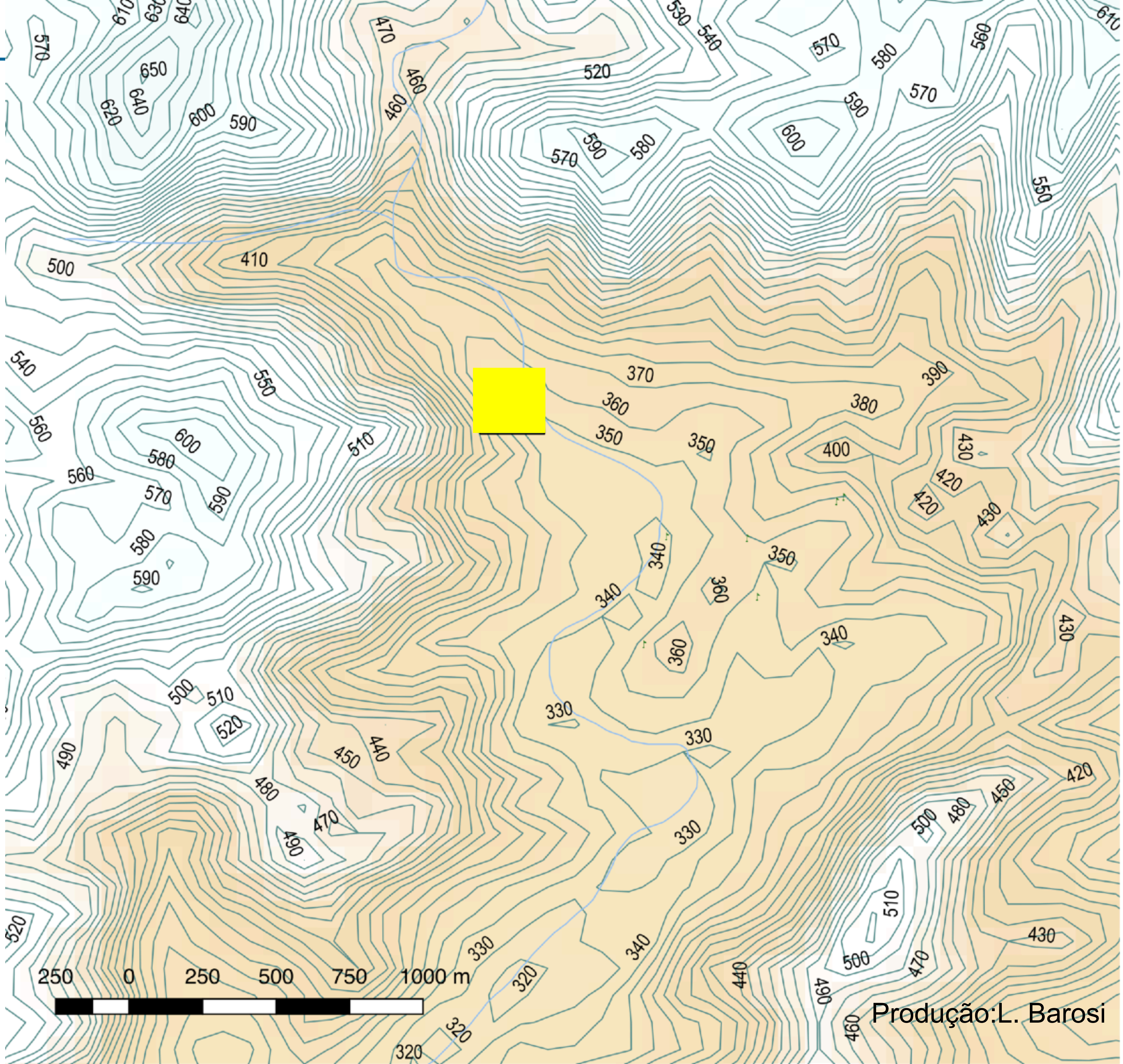
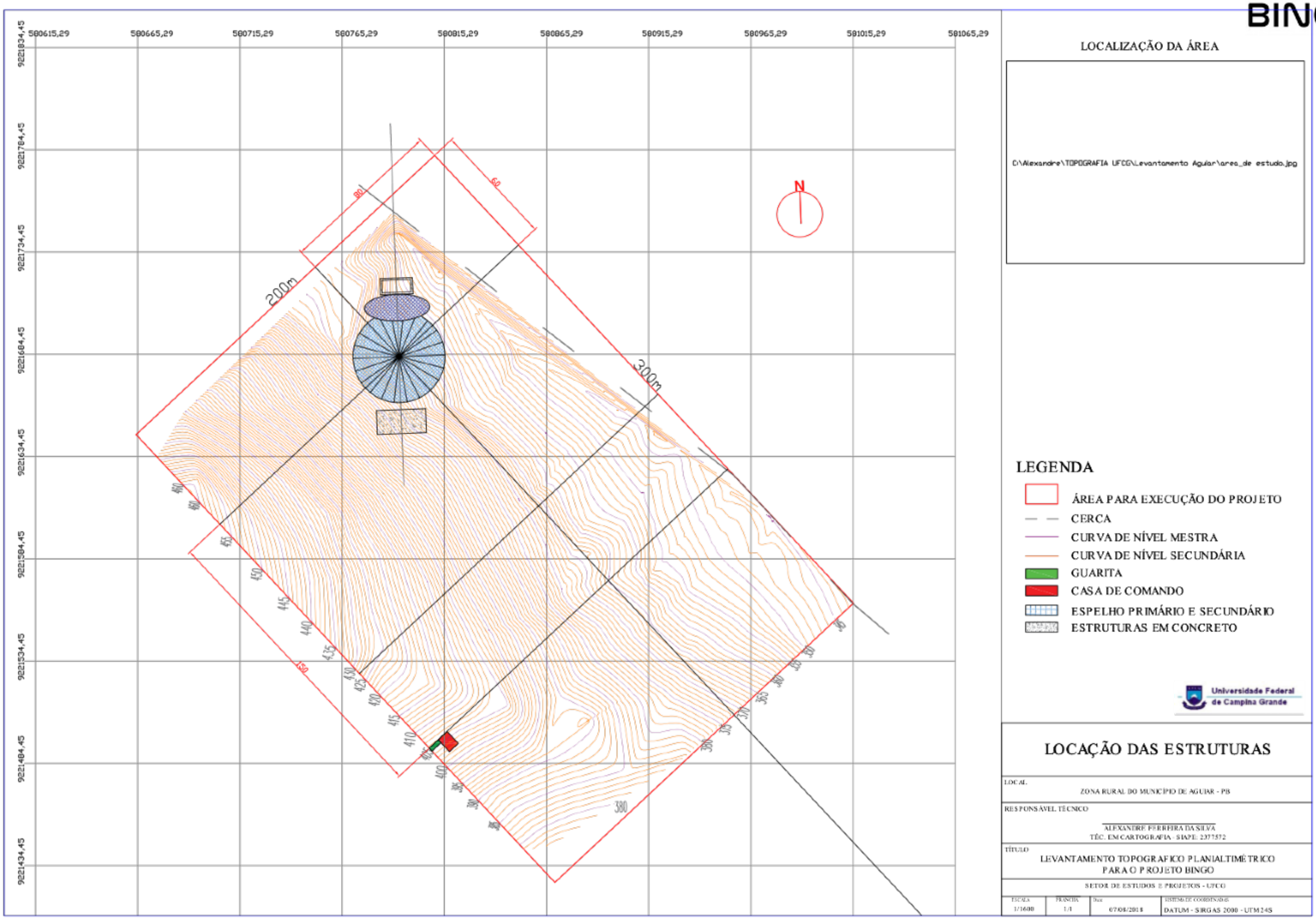


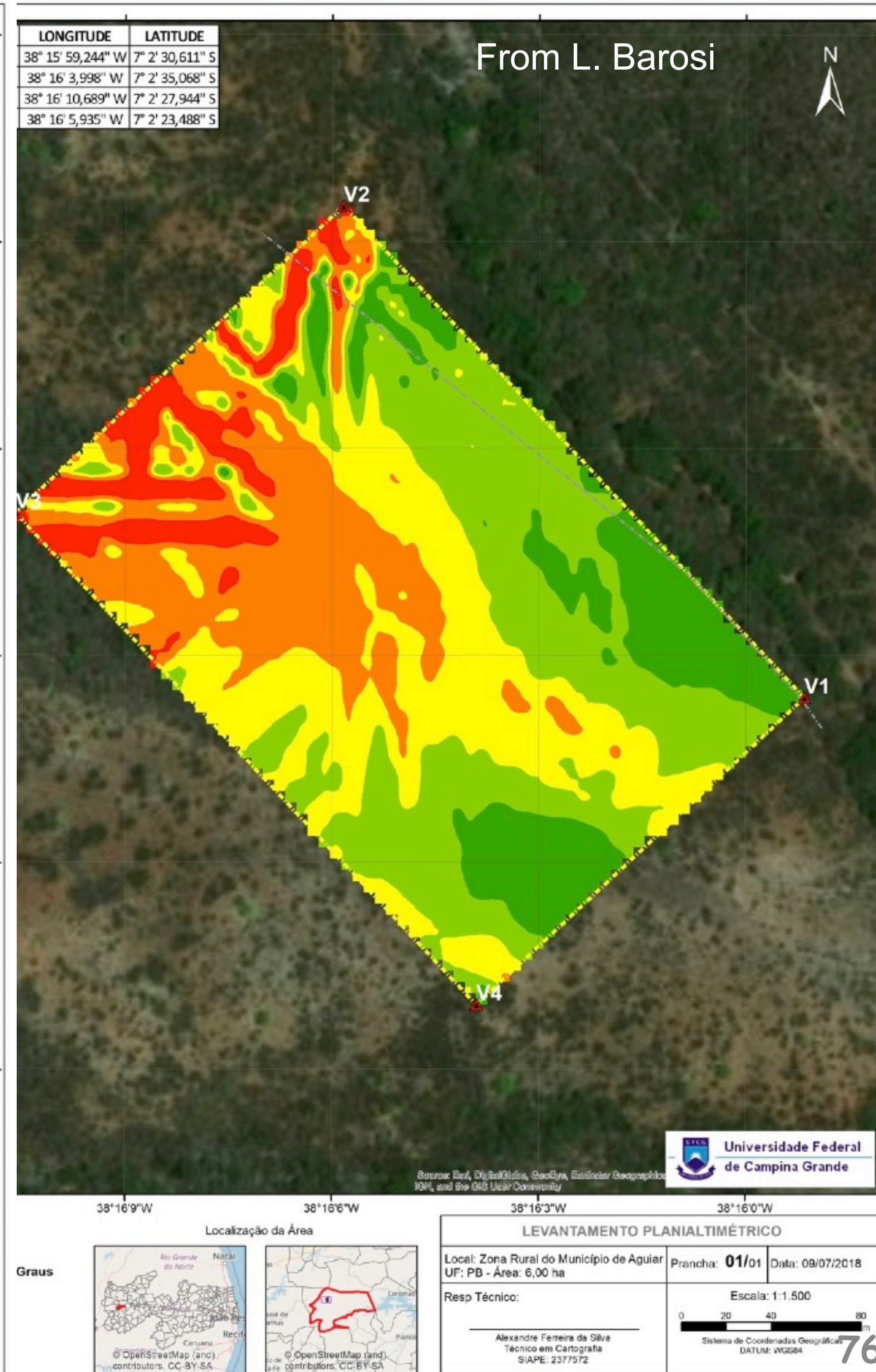
Peel et al, J. Astron. Instrum. (2019)


250 0 250 500 750 1000 m
Produção:L. Barosi



From A. P. Souza

From L. Barosi

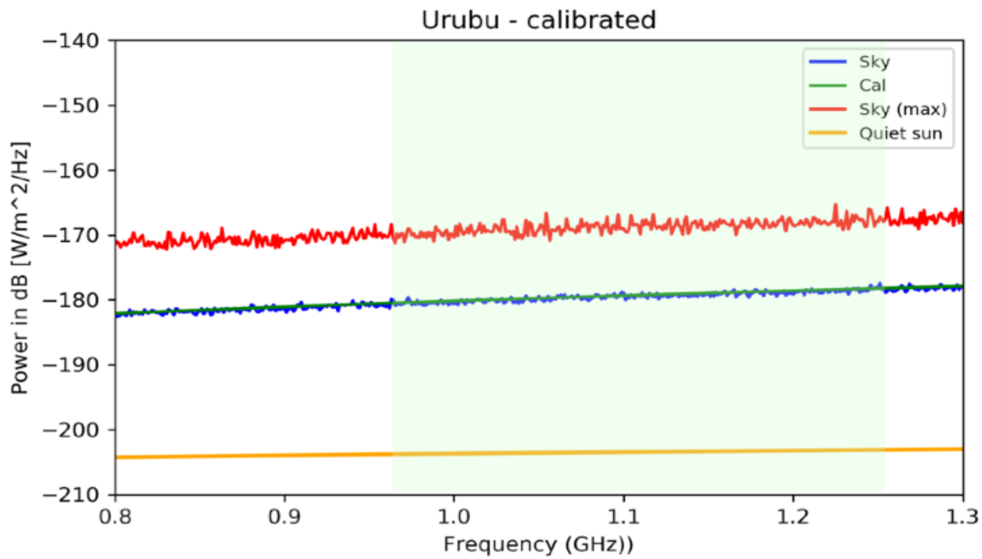


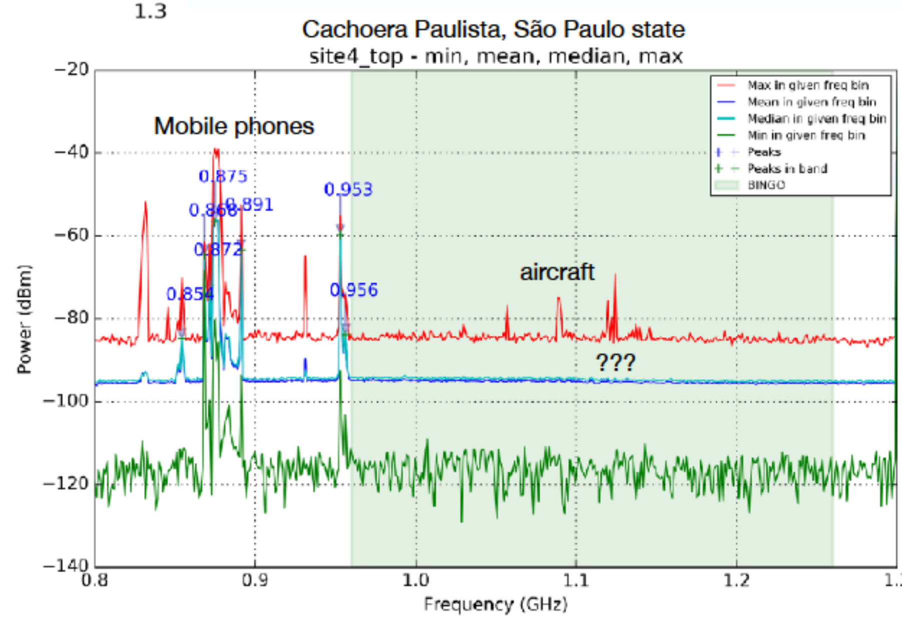
Serra da Catarina, Vale do Piancó (PB)

7° 2' 27,6" S; 38° 16' 4.8" W

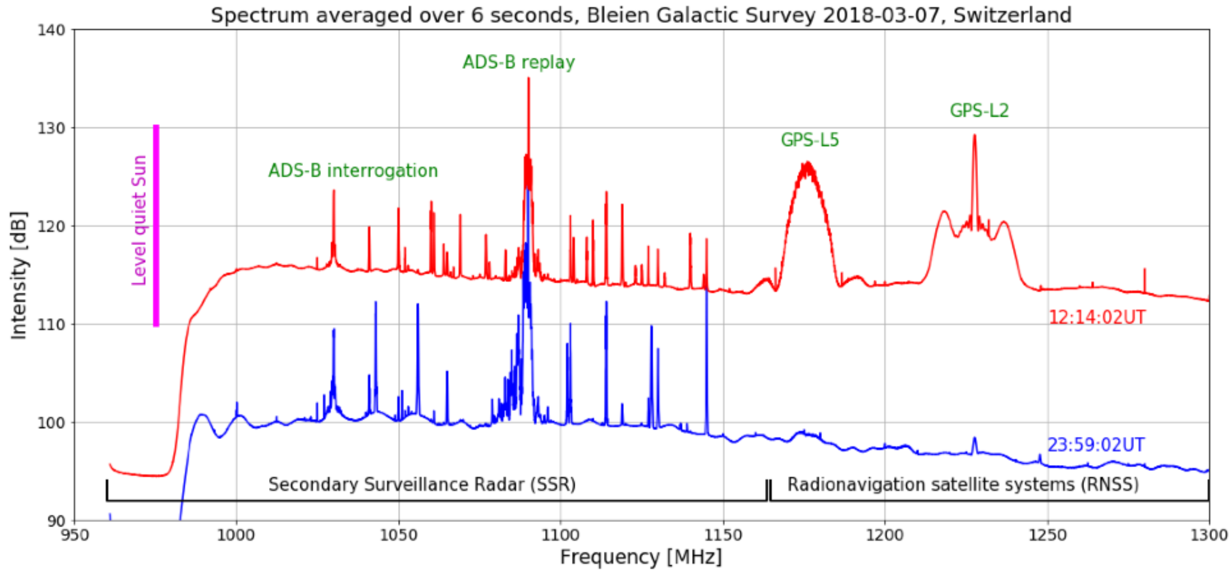
Photo: M. Peel

Paraíba site is VERY CLEAN in the radio band

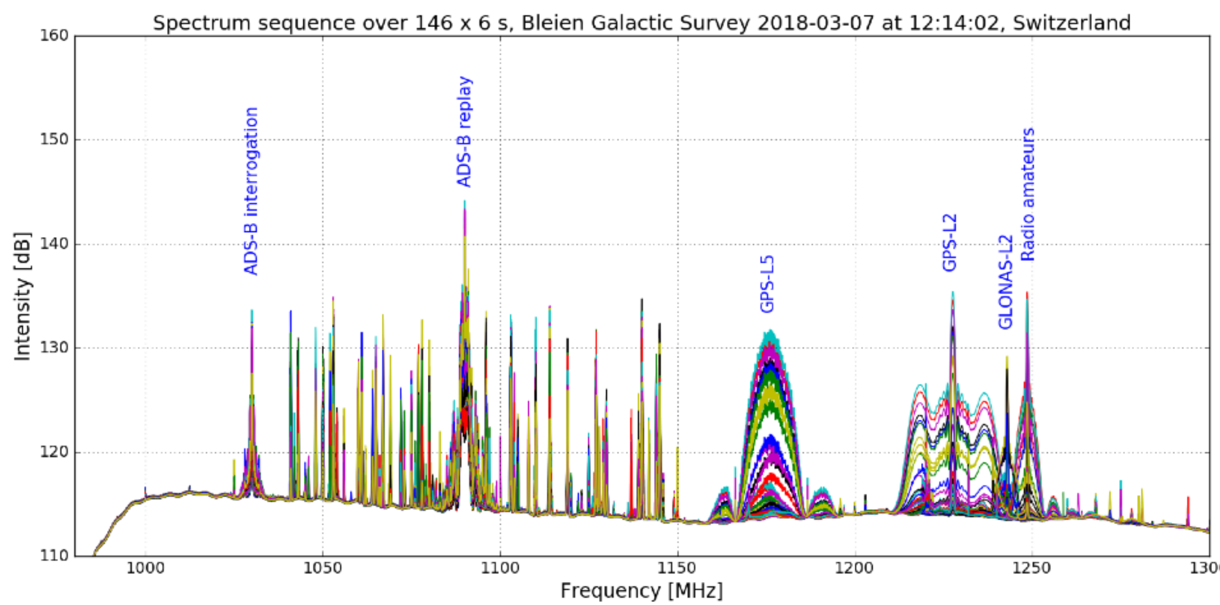




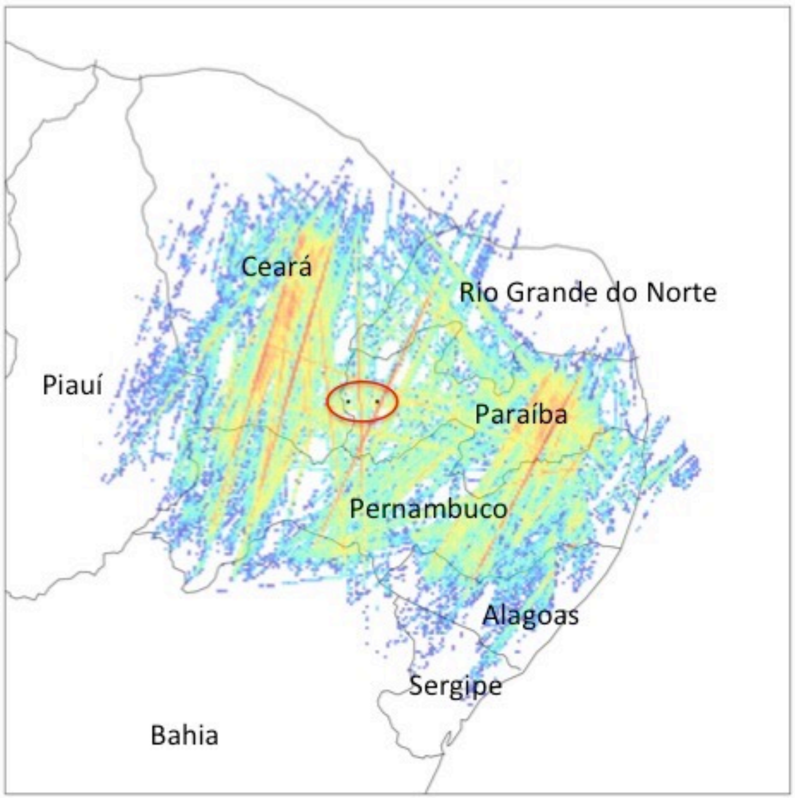
C. A. Wuensche (2020)



For comparison, in Bielen Observatory (Switzerland)…



Still,there are concerns about airplane coverage and geostationary satellites...



Peel, Wuensche et al (J. Astr. Instrumentation 2019)

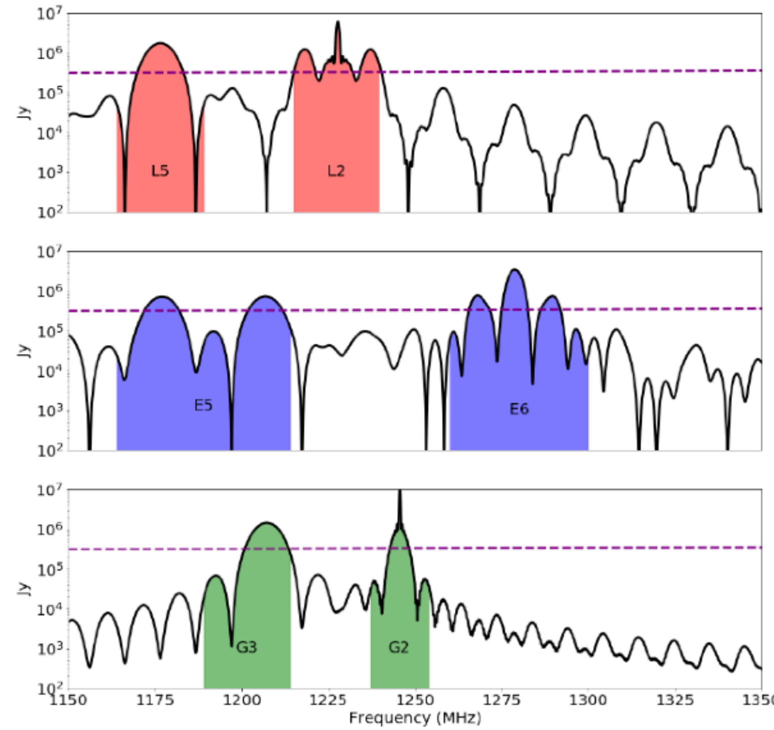


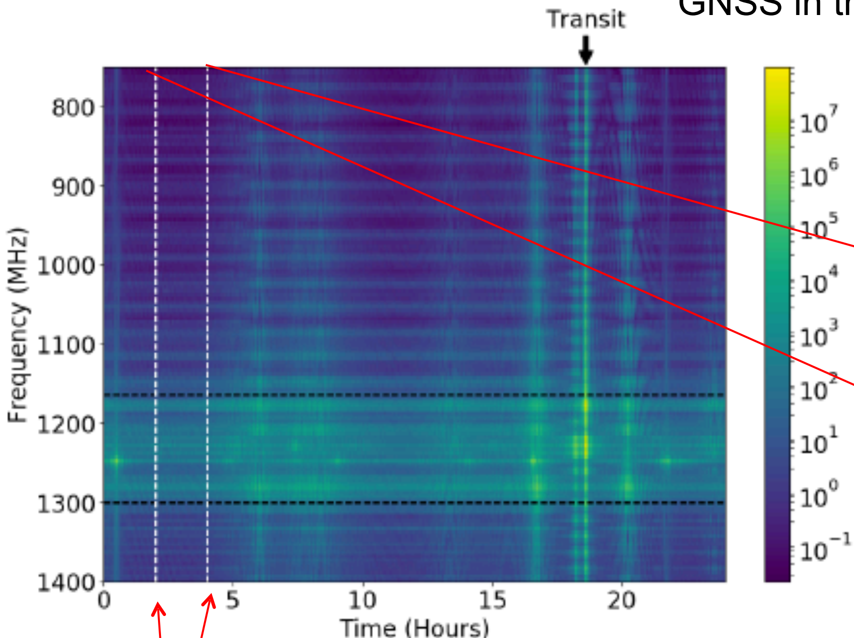
Figure 3. Typical spectral energy distribution as measured from the Earth of GNSS transmissions at frequencies less than 1410 MHz. The *top* plot shows the SED for GPS, the *middle* plot shows Galileo, and the *bottom* shows GLONASS. Highlighted regions in the SEDs represent the nominal frequency allocations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

Harper et al. (**arXiv**:1803.06314v2)

And GNSS…

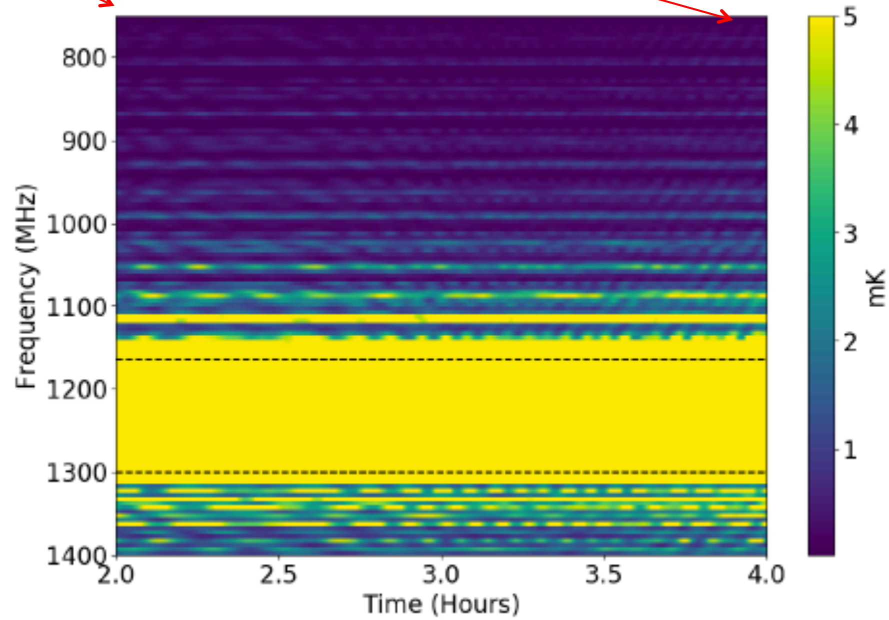
Harper & Dickinson, arXiv:1803.06314

GNSS in the beam of the telescope



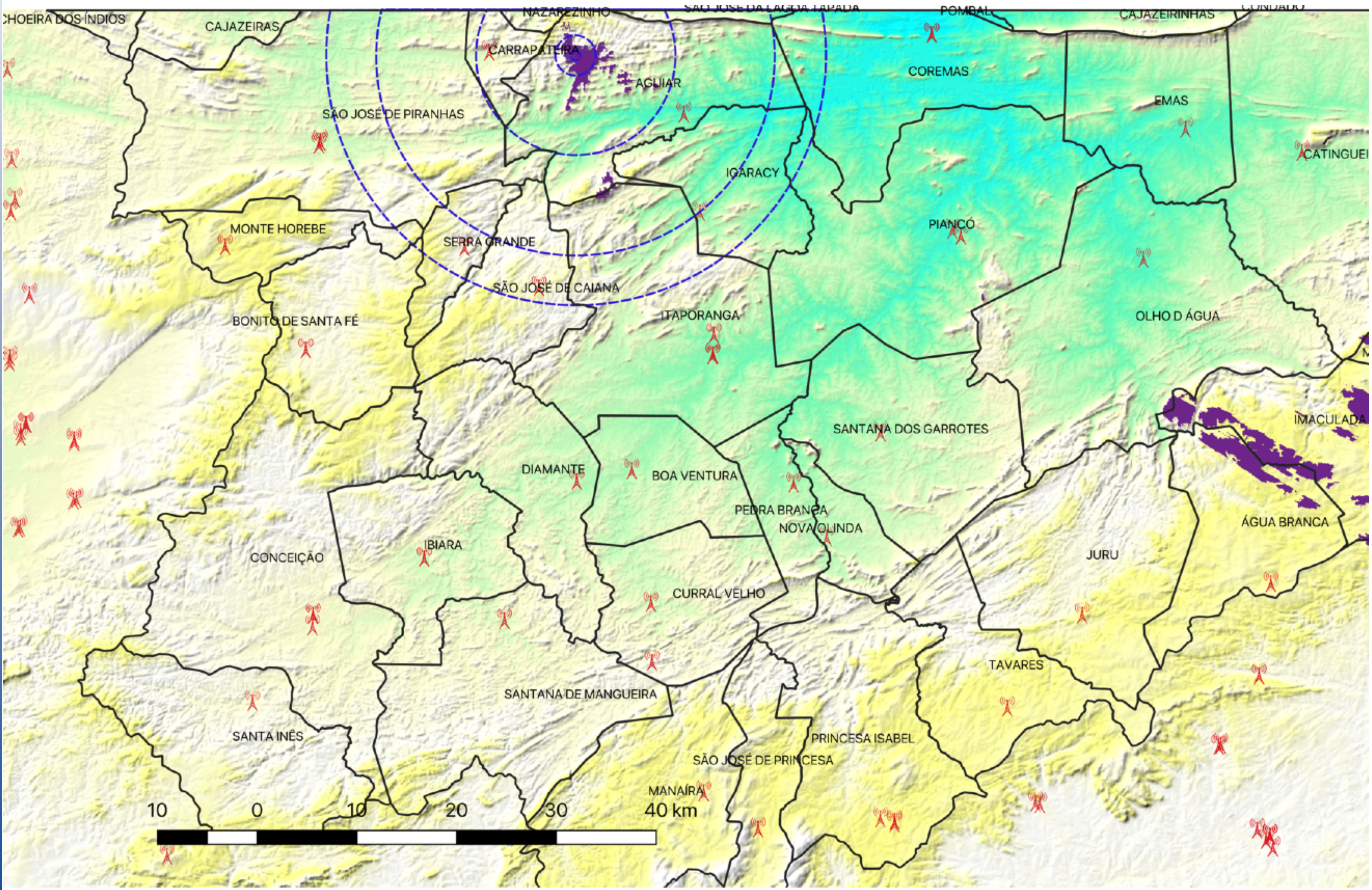
Black dashed lines: L5 (1164 MHz) and L2 bands (1260 MHz)

White lines: no GNSS closer than 29 deg. of the main be beam axias



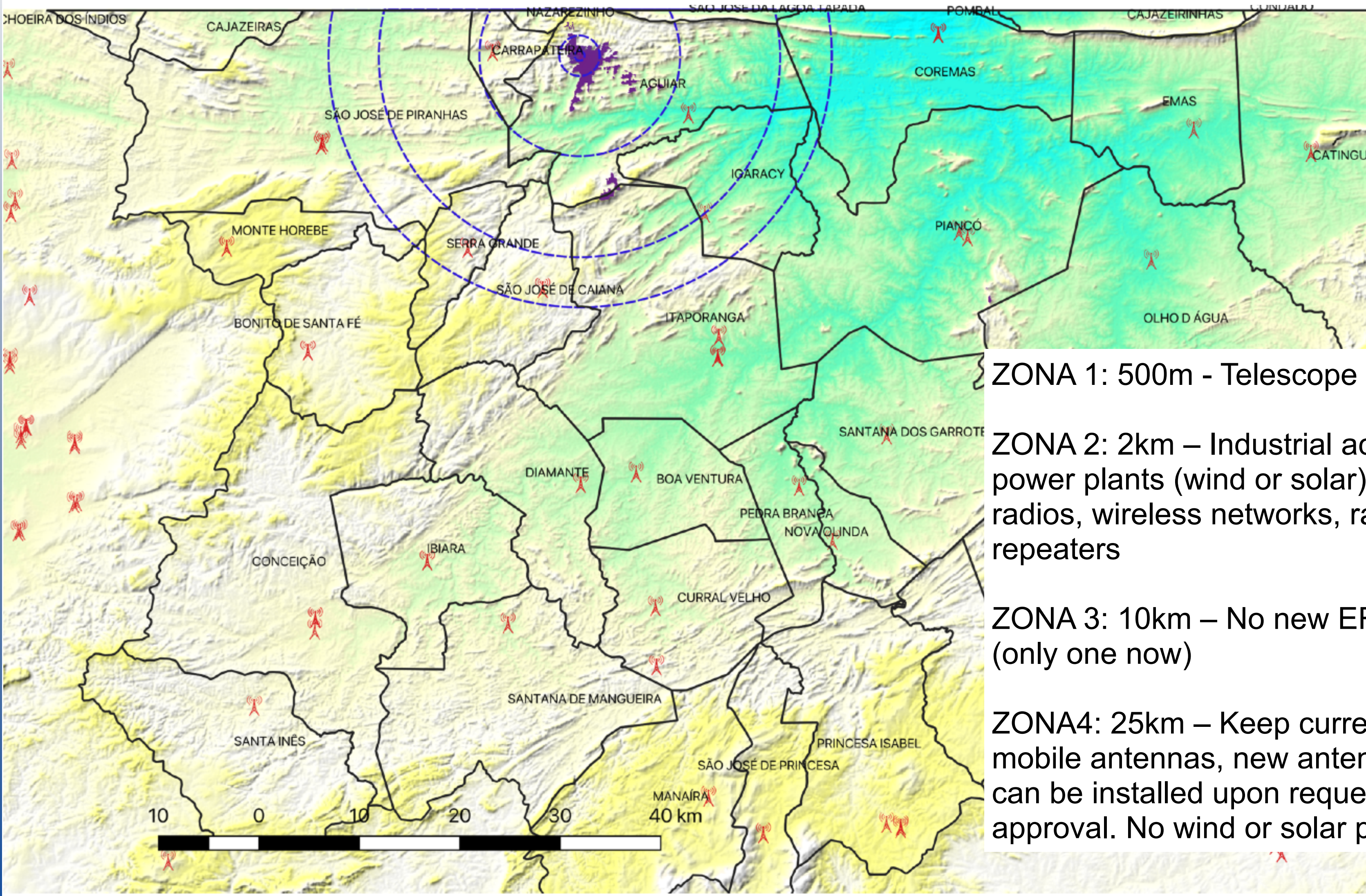
Yellow band (zoom and scale) to show the off-band leakage of GNNS into the band

Silence zone proposal (discussions with Anatel started October 2018)



Credit: L. Barosi

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

Thank you!

Visit us at http://portal.if.usp.br/bingotelescope/