

UNIVERSITY OF SÃO PAULO

Whispers of the Universe: theoretical and observational developments in the BINGO project.

I present the theoretical developments expected in the construction of the BINGO (BAO from Integrated Gas Observations) observatory, which is being supported by a consortium led by Brazil including China, UK, South Africa, France and Italy.

Elcio Abdalla
2023

TEAM

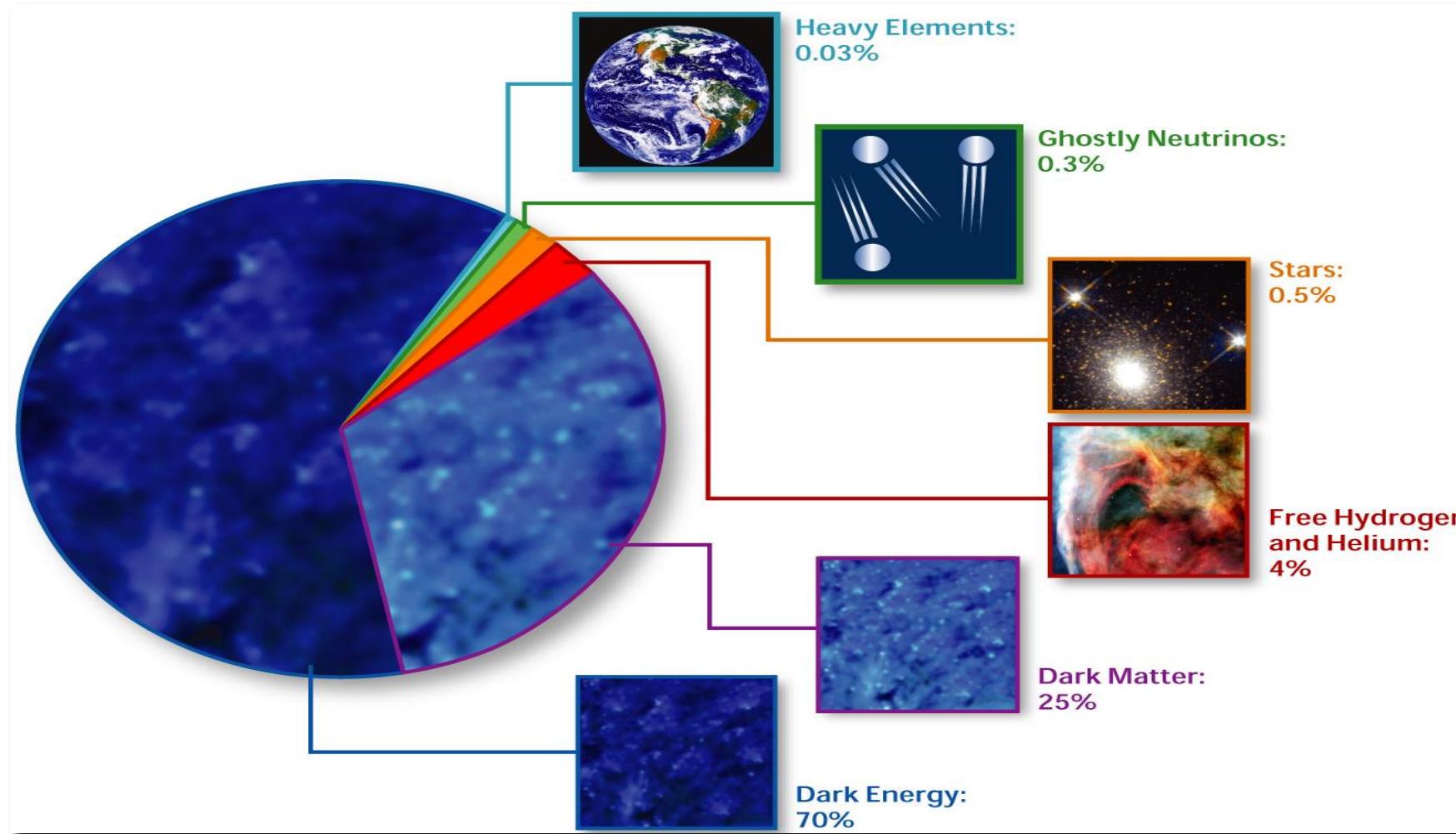
- Management: Elcio Abdalla, C. A. Wuensche, F. Abdalla, L. Barosi, A. Queiroz, T. Villela, Bin Wang
- Builders: JiaJun Zhang, Chang Feng, Ricardo Landim, Camila Novaes, Marcelo Santos, Larissa Santos, Alessandro Marins
- Members (USP): Jordany Vieira de Melo, Pablo Motta, João Alberto Barreto, Amanda Santos, Gabriel Hoerning, Lucas Formigari, Eveling Costa, Carlos Ottobone, Luiz Henrique Freitas.

OPEN PROBLEMS

- What is Dark Energy
- What is Dark Matter
- Gravity in Cosmology
- Fast Radio Bursts
- Pulsars

Standard Cosmological Model

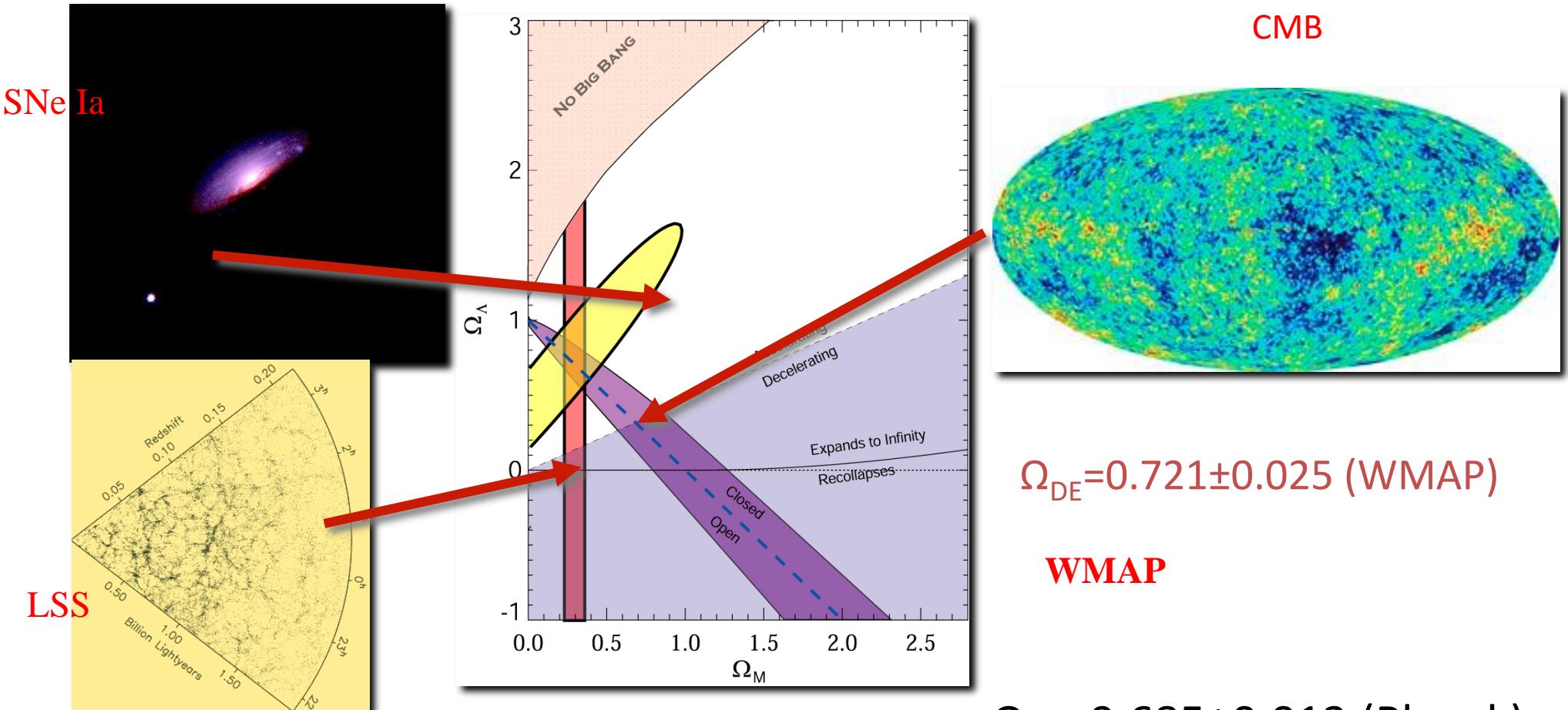
Composition of the Universe



What is Dark Energy?

The Evidence:

98's: The universe is expanding in an accelerated way.



What is causing the acceleration?



$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$



$$p < -\frac{\rho}{3} \rightarrow \omega < -\frac{1}{3}$$

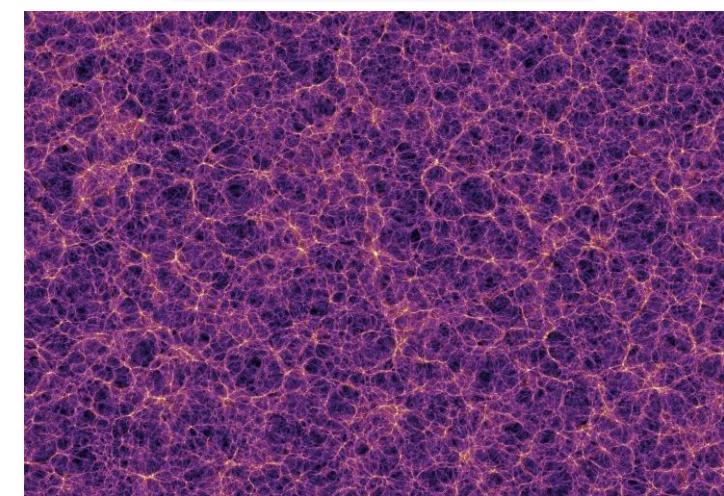
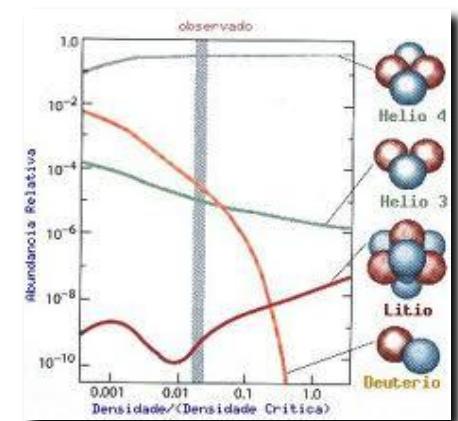
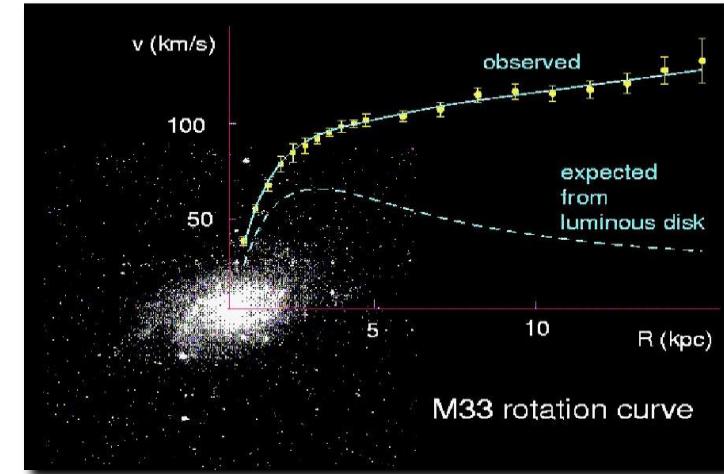
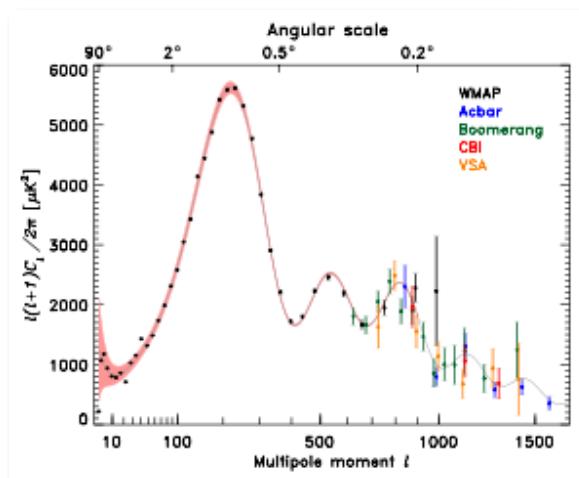
What is Dark Matter?

Evidences for Dark Matter

Huge amount of evidences indicating that dark matter exists. One of the biggest unsolved, but very well measured, problems in physics.

Observations indicate that DM interacts mainly gravitationally.

So far, we have no (non-contradictory) observations that DM was detected by any non-gravitational mechanism.



Candidates

Neutralinos (higgsino, bins, winos, singlinos)

Axinos

Gravitinos

Sneutrinos

Axions

Sterile neutrinos

4th generation neutrinos

Kaluza-Klein photons

Kaluza-Klein gravitons

Brane world dark matter/D-matter

Little higgs dark matter

Light scalars

Superheavy states (ie. “WIMPzillas”)

Self-interacting dark matter

Super-WIMPs

Asymmetric dark matter

Q-balls (and other topological states)

CHAMPs (charged massive particles)

Cryptons, ...



Supersymmetric

DE/DM Interaction

Each component is not conserved alone anymore.

Cosmological equations:

$$\dot{\rho}_m + 3H\rho_m = -Q,$$

$$\dot{\rho}_\phi + 3H(1+w_\phi)\rho_\phi = Q,$$

Many many models in the literature:

Phenomenological (For a classification see Koyama, Maartens, Song, 0907.2126; see also Wang, Abdalla, Atrio Barandela, Pavon Rep. Prog. Phys. 2016)
- Interaction depending on DM or DE

Constant coupling

or

Time varying coupling

Coupling must be small : constraints from observations!

In general no analytic solution!

Evidence Against Λ CDM?

Baryon Acoustic Oscillations in the Ly α forest of BOSS DR11 quasars.
T. Delubac et al. [BOSS Collaboration] – A&A 574, A59 (2015), arXiv: 1404.1801

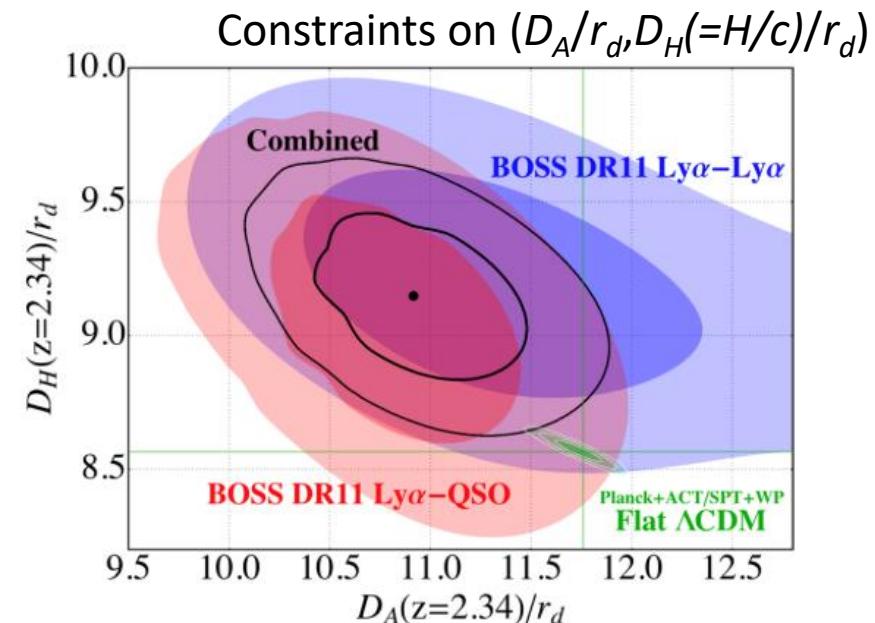
- From adjusting the BAO peaks and combining with the Λ CDM fiducial values from Planck+ WMAP:

$$H(z = 2.34) = (222 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}) \times \frac{147.4 \text{ Mpc}}{r_d}$$
$$D_A(z = 2.34) = (1662 \pm 96 \text{ Mpc}) \times \frac{r_d}{147.4 \text{ Mpc}}, \quad r_d = 147.4 \text{ Mpc}$$

- Values differ:
 1.8σ from Planck+WP;
 1.6σ from WMAP9+ACT+SPT

Conclusion: Approximately 2σ below the value of D_H

And 2σ above the value of D_A
compared to the Λ CDM prediction.



Evidence Against Λ CDM?

Baryon Acoustic Oscillations in the Ly α forest of BOSS DR11 quasars.

T. Delubac et al. [BOSS Collaboration] – A&A 574, A59 (2015), arXiv: 1404.1801

$$\frac{8\pi G}{3}\rho_{de}(z) = H^2(z) - H_0^2\Omega_M(1+z)^3 .$$



$$\frac{\rho_{de}(z=2.34)}{\rho_{de}(z=0)} = -1.2 \pm 0.8 .$$

~ 2.5σ difference from the expected from Λ CDM!

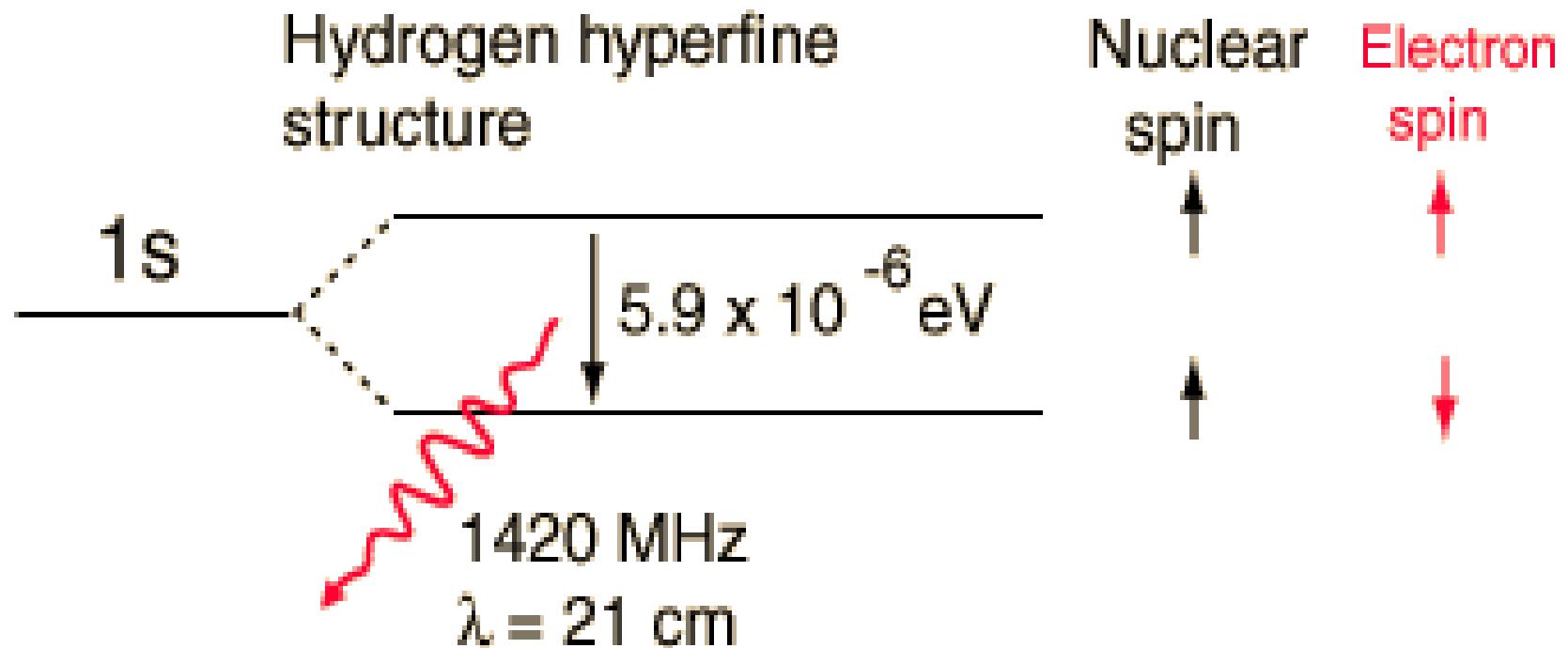
Parameters from
Planck+WMAP for
 Λ CDM

Parameter	Bestfit	σ
h	0.706	0.032
$\Omega_{DM}^0 h^2$	0.143	0.003
Ω_{DE}^0	0.714	0.020
$\Omega_b^0 h^2$	0.02207	0.00033

Interacting dark energy

Review Rep. Progr. Phys.: Wang, E.A., Atrio-Barandela, Pavon

21 cm Physics – The Hyperfine Structure



BINGO TELESCOPE

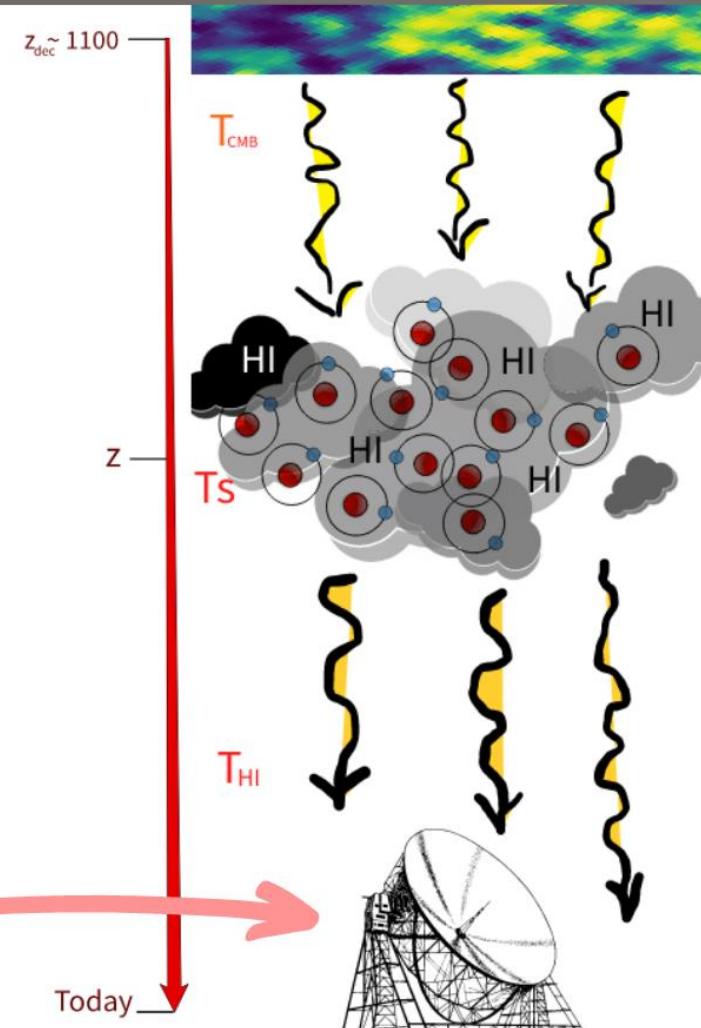
21cm Cosmology

- Used to trace the distribution of matter at radiofrequency
- Gives information between CMB and the Local Universe
- Informs about several astrophysical process at high-z
- Sensitive to the dynamics of the Universe
- Informs about the ionization state of hydrogen

Brightness Temperature HI

$$T_{\text{HI}}(z) = \left(\frac{9hc^3 A_{10}}{256\pi^2 Gk_B \nu_{10}^2 m_{\text{HI}}} \right) \frac{\Omega_{\text{HI}}(z)}{(1+z)^2} \frac{H_0^2}{\|dv_{\parallel}/d\chi\|}$$

$$\begin{aligned} \delta T_{\text{HI}}(z, \hat{n}) &= \delta_n - \frac{1}{\mathcal{H}} \hat{n} \cdot (\hat{n} \cdot \nabla \hat{v}) \\ &+ \left(\frac{d}{d\eta} \ln(a^3 \bar{n}_{\text{HI}}) - \frac{\dot{\mathcal{H}}}{\mathcal{H}} - 2\mathcal{H} \right) \delta\eta + \frac{1}{\mathcal{H}} \dot{\Phi} + \Psi \end{aligned}$$



INTENSITY MAPPING

- No Search for particular emission
- Search instead for general Hydrogen emission
- Large clouds

BINGO TELESCOPE

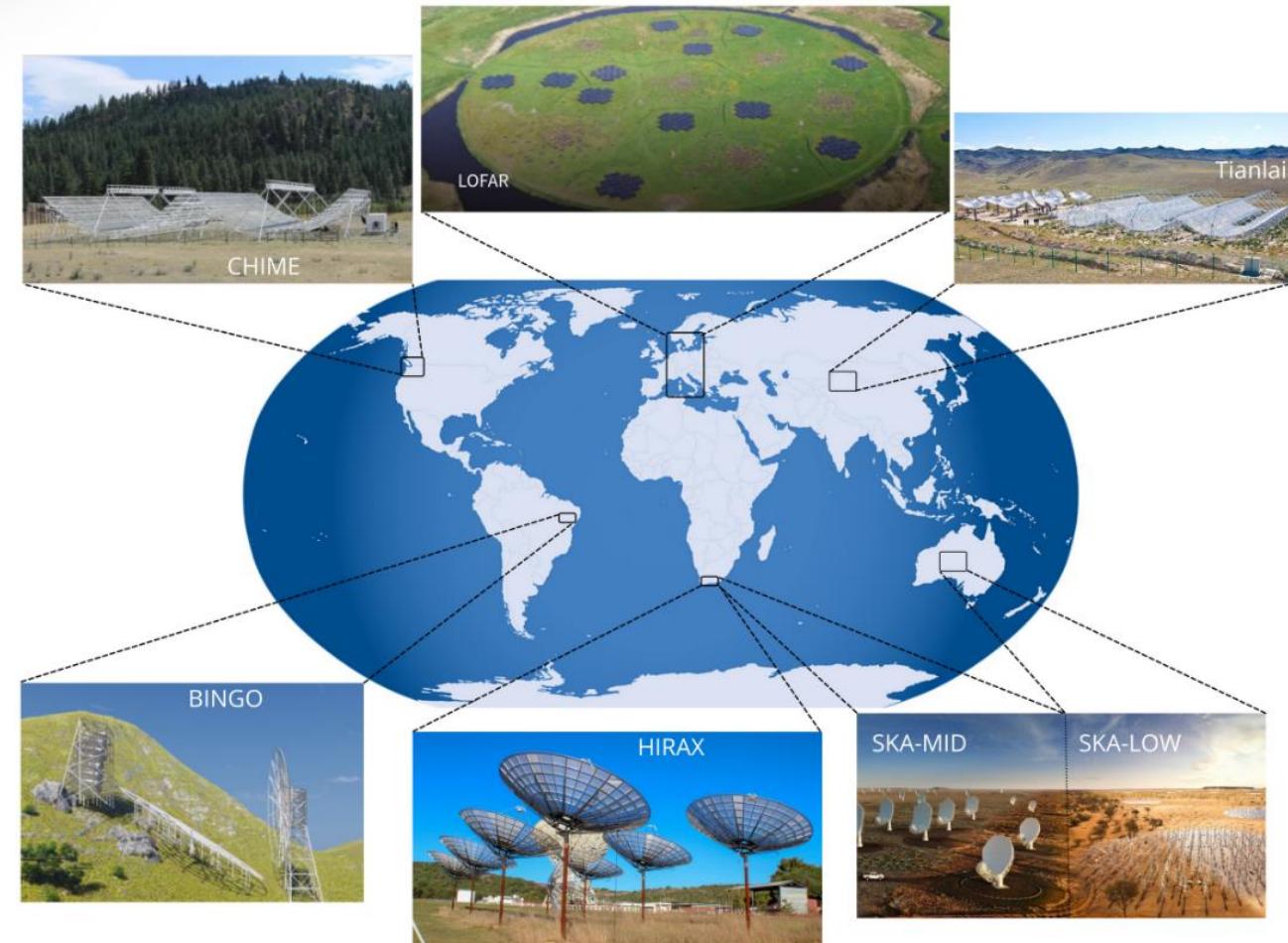
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21cm intensity mapping projects

Some IM projects

- BINGO
- CHIME
- FAST
- MeerKAT
- Tianlai
- NenuFAR
- HIRAX
- MWA
- SKA
- HERA
- EDGE
- LOFAR

 Projects in the image on the right





The BINGO radio telescope and 21 cm Cosmology

Bingo's aims

- *BAO for Integrated Neutral Gas Observations*
- *Large scale structure and constraints on Cosmological parameters (particularly DE)*
- *H I intensity map at $0.127 < z < 0.448$*
- *Astrophysical phenomena: Fast Radio Bursts and Pulsars*

What is *Bingo*?

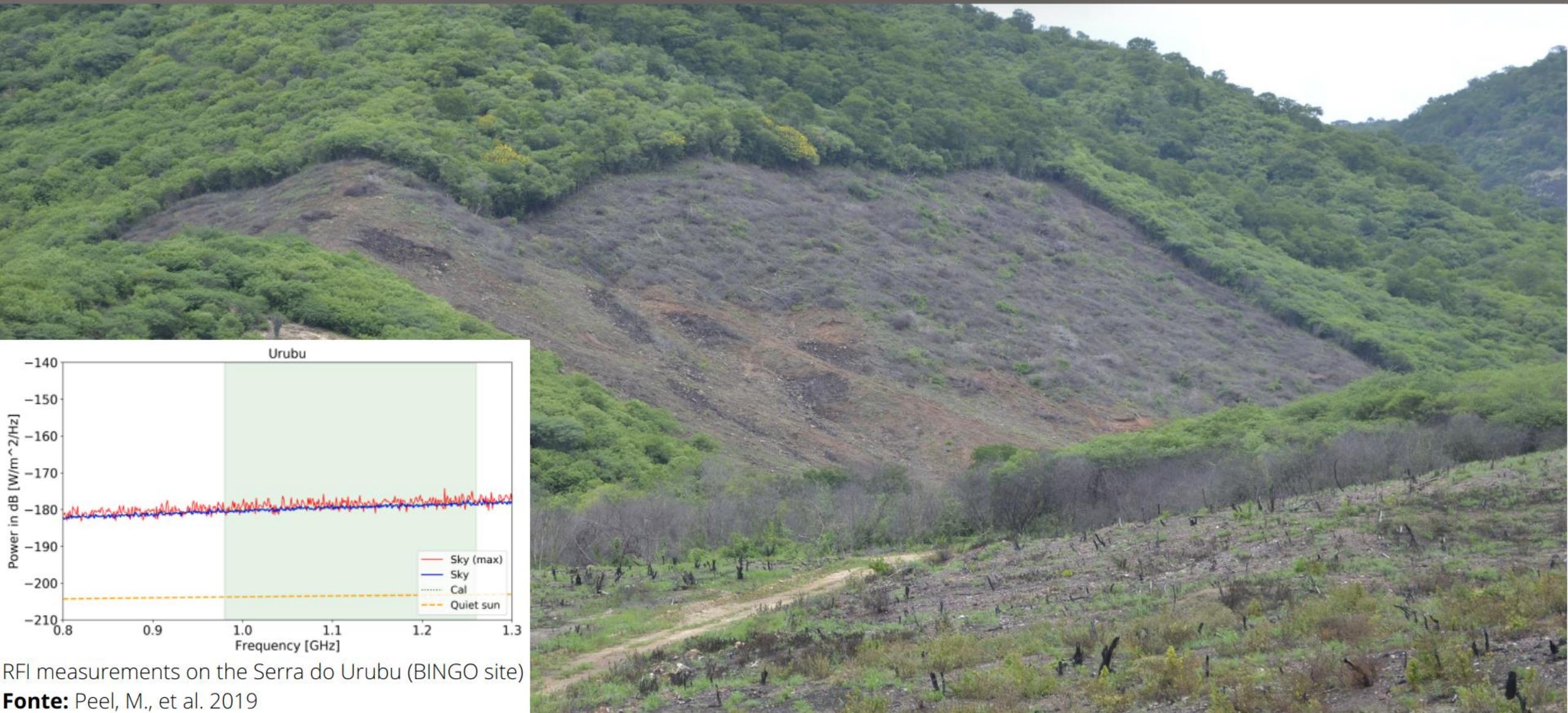
- *BAO for Integrated Neutral Gas Observations*
- *A single/double dish multiple Horns Radio Telescope, mainly to measure BAO*
- *Short scale phenomena (we can pinpoint short lumps)*

The Jnstrument

- Two dishes (40 and 39 meters)
- 28 Horns (1.8 m wide, 4.8 m long)
- System Temperature 50 K (up to now, we have 70K)
- Simple off the shelf electronics in phase 1
- Phased arrays in bingo 2
- Site at “Serra do Urubu” (Vulture heights) in Paraíba, Brazil

THE SITE

BINGO TELESCOPE



RFI measurements on the Serra do Urubu (BINGO site)

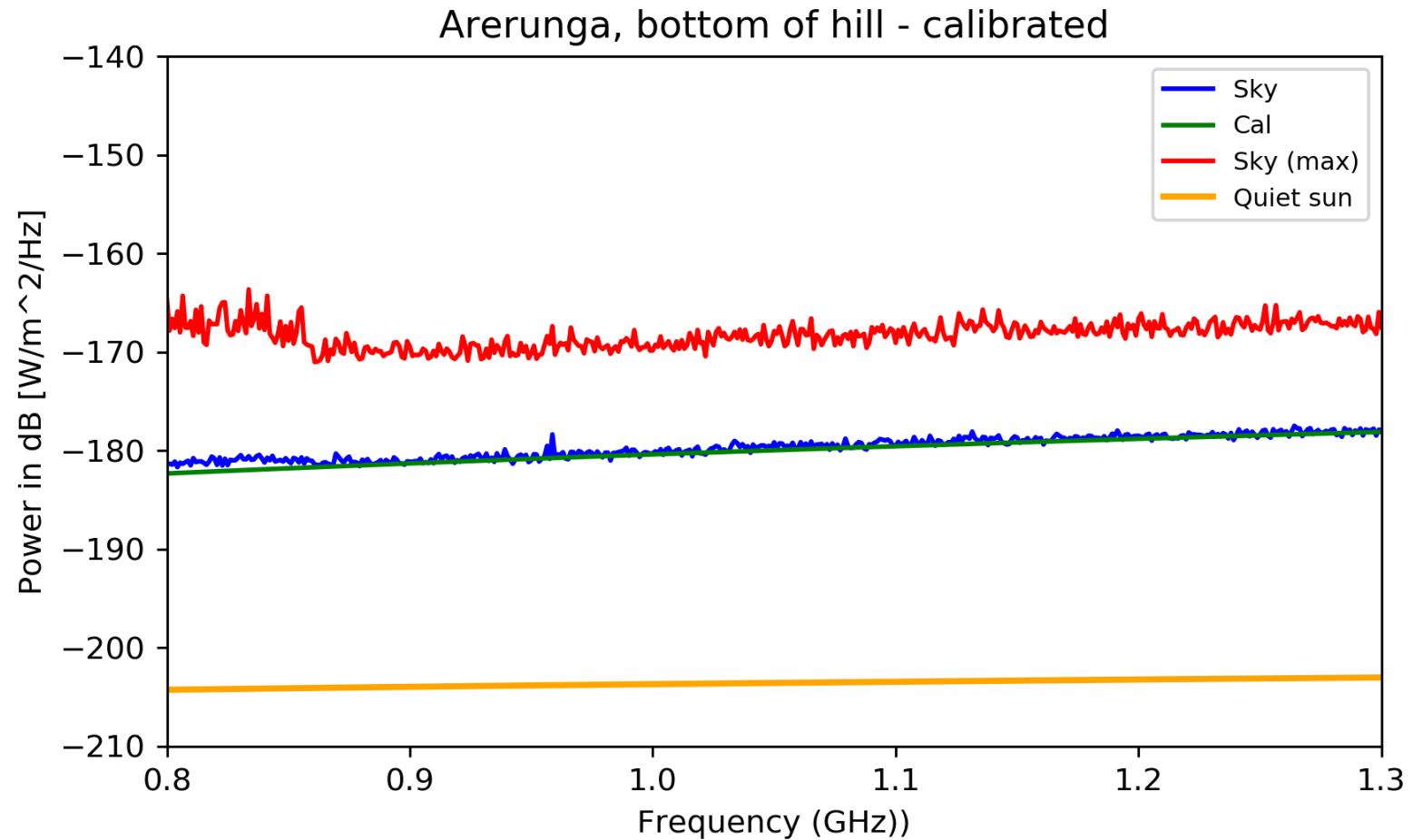
Fonte: Peel, M., et al. 2019

BINGO TELESCOPE

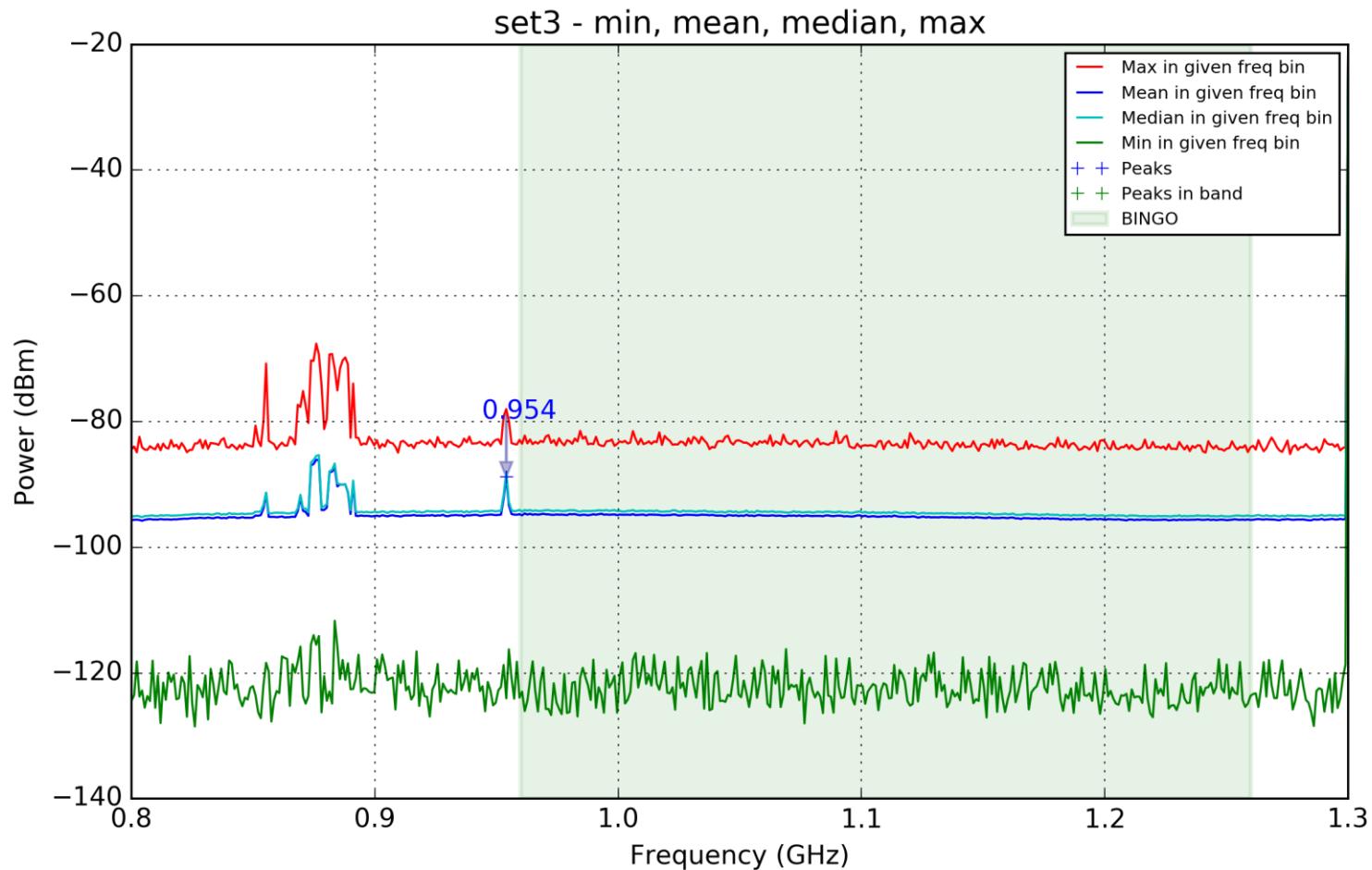


Artist's View

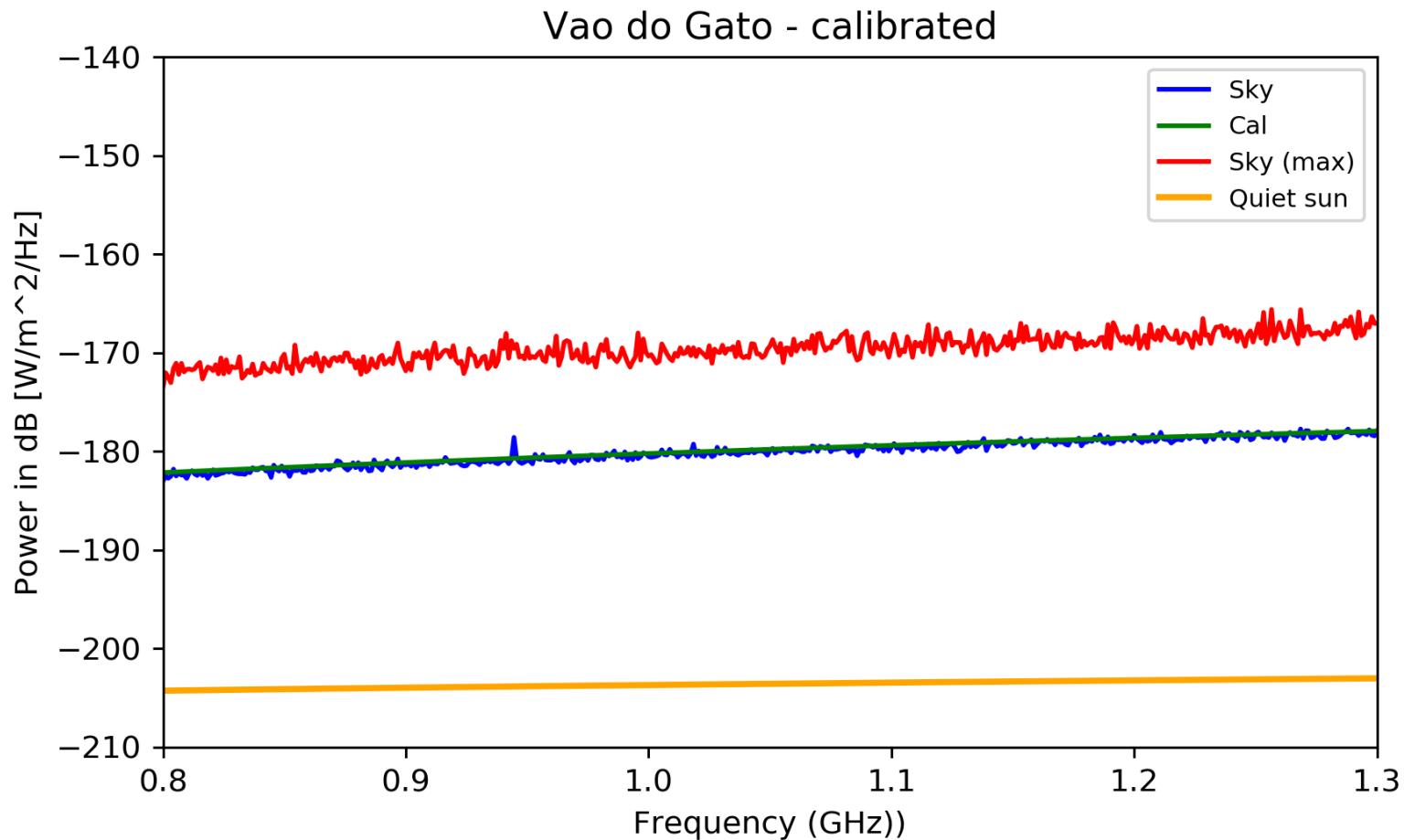
Uruguay



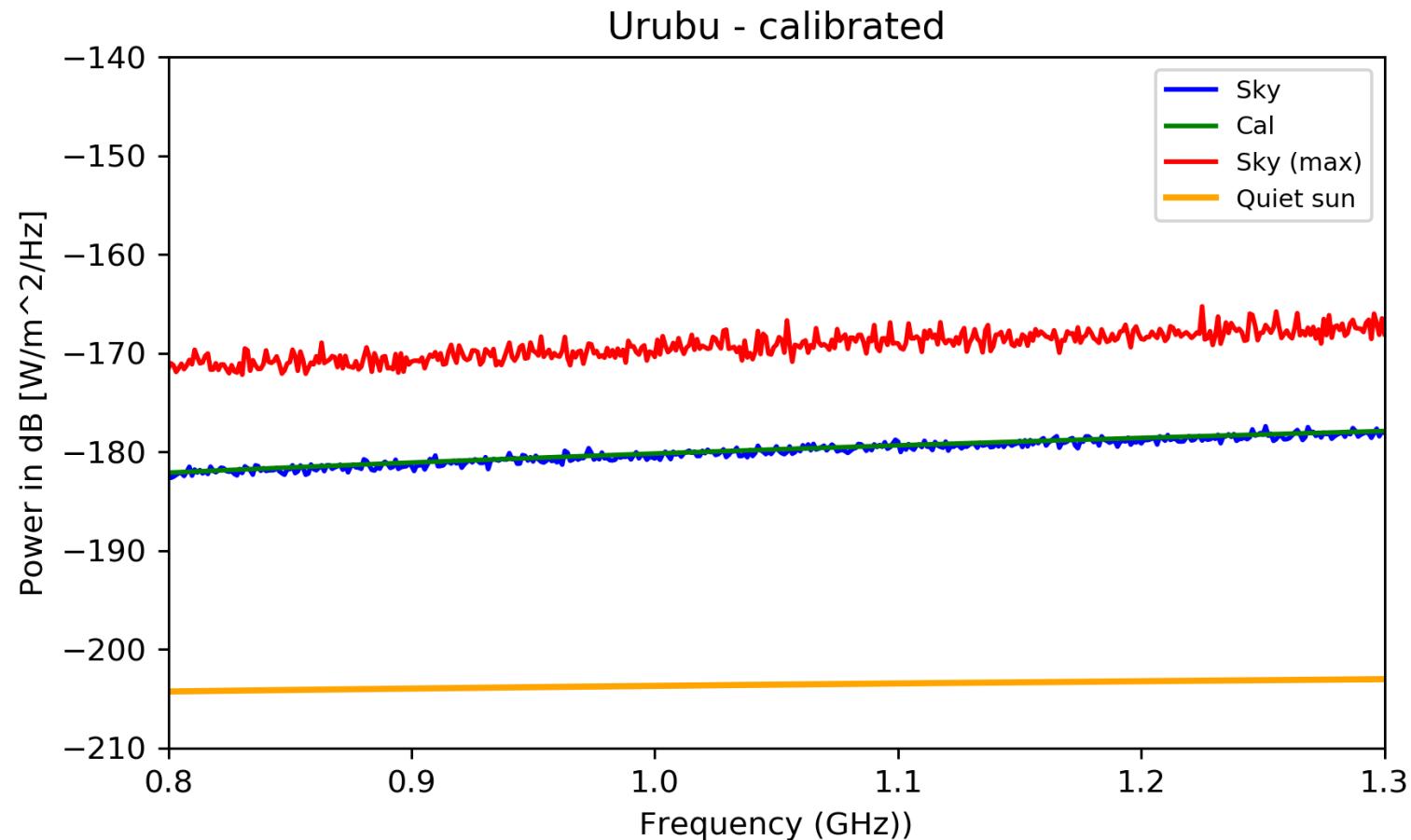
Cachoeira Paulista (SP)



Vão do Gato (Cat's den) Paraíba



Urubu (Vulture), Paraíba

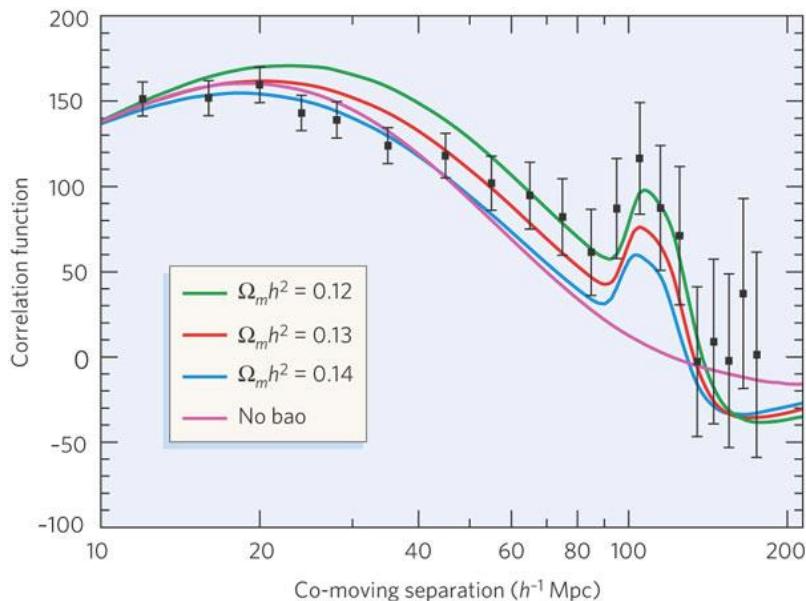


Motivations for BINGO

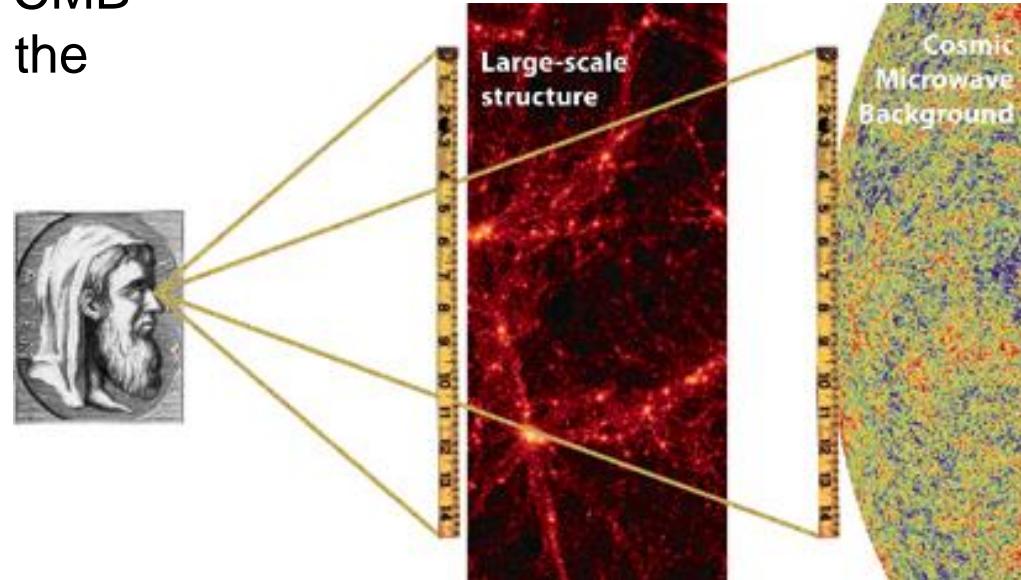
- HI intensity mapping to measure BAO
- Structure formation
- Dark Sector properties (last half history of the Universe)
- Static telescope, excellent for looking after transient phenomena
- Fast astrophysical phenomena:
- Pulsar properties
- Fast Radio Bursts

Baryon Acoustic Oscillations (BAOs)

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



Credit: Bennett, *Nature* (2006)

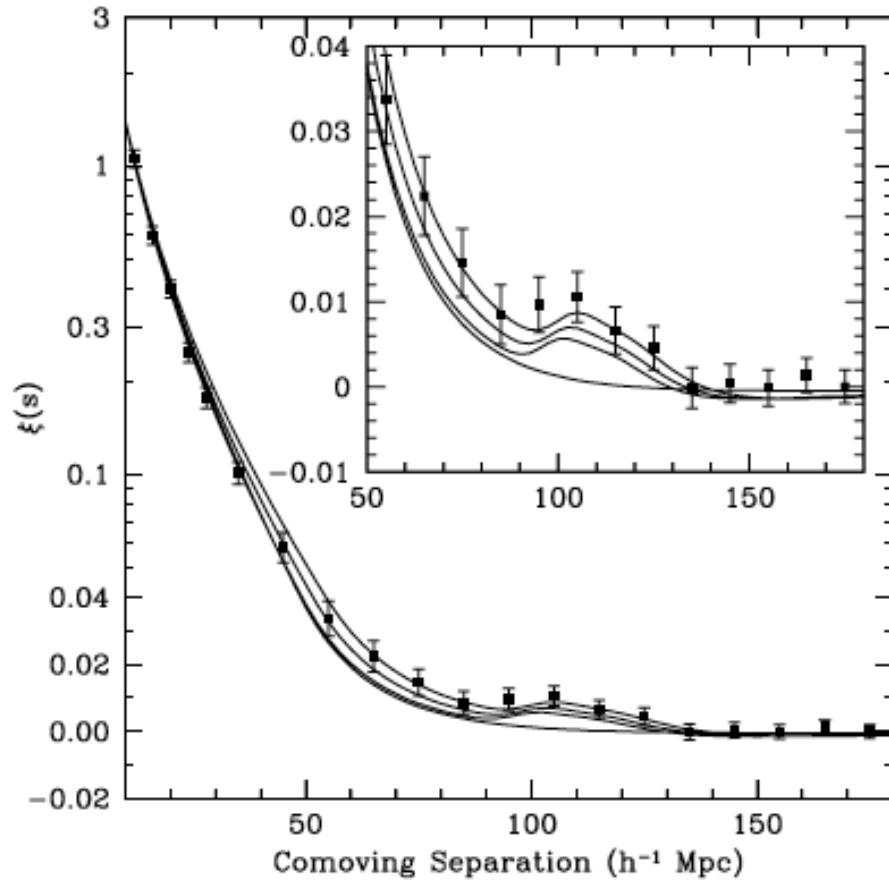


Credit: EUCLID website (ESA)

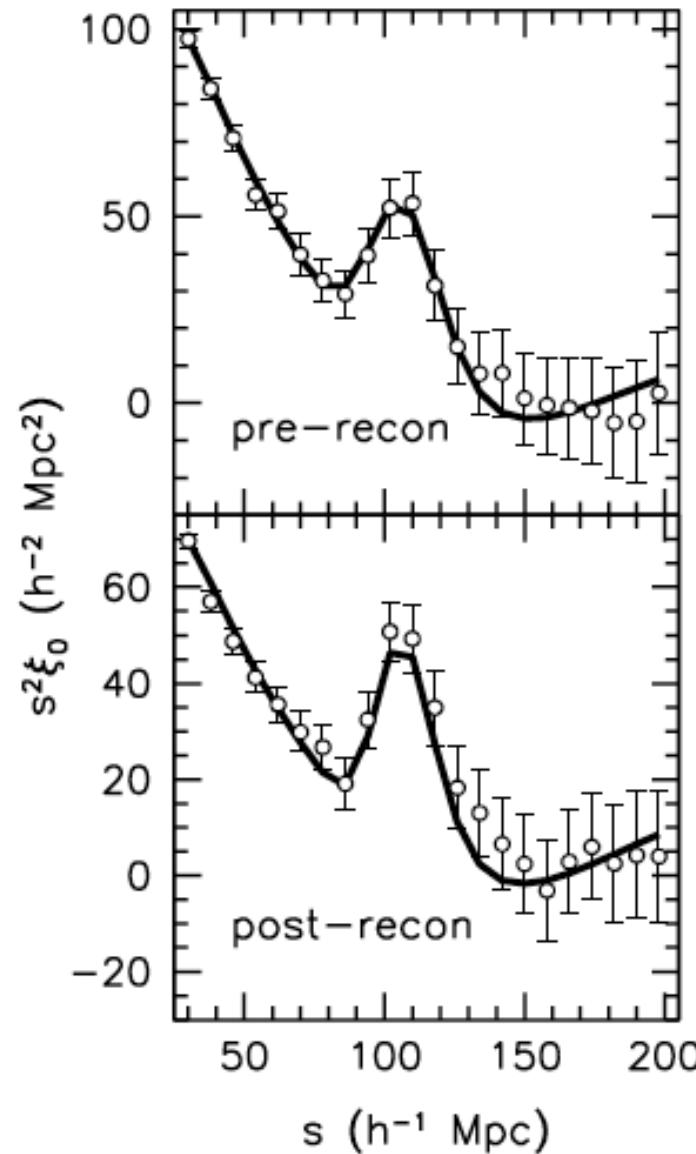
- The acoustic peak gives the ratio of the distances to $z=0.35$ and $z=1,100$ to 4% fractional accuracy.
- absolute distance to $z=0.35$ is determined to 5% accuracy.
- co-moving sound horizon scale $150 h^{-1}$ Mpc.

Optical BAOs

Eisenstein et al. (2005)



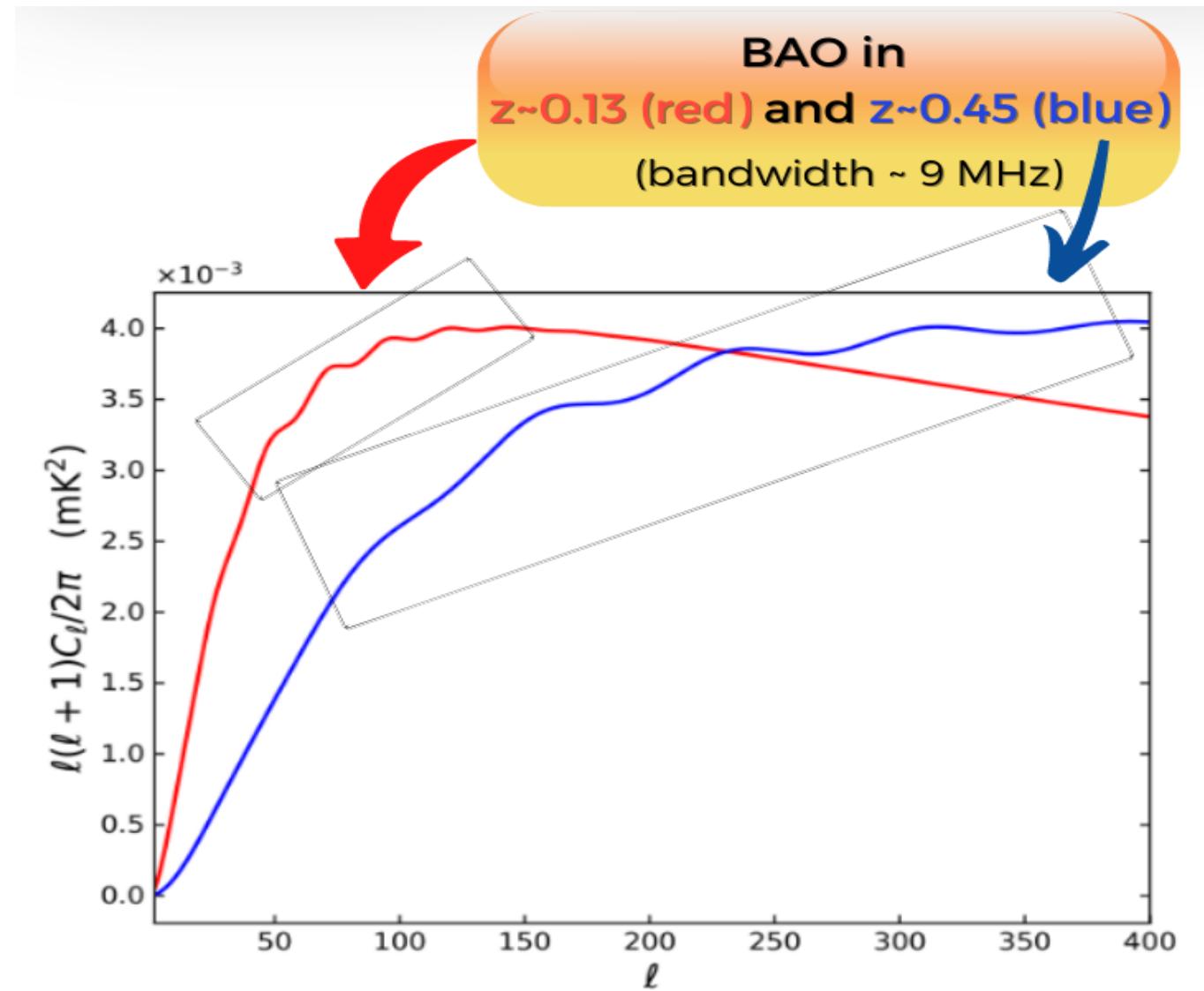
Anderson et al. (2014)



C.A. Wuensche (2016)

Baryon Acoustic Oscillations (BAOs)

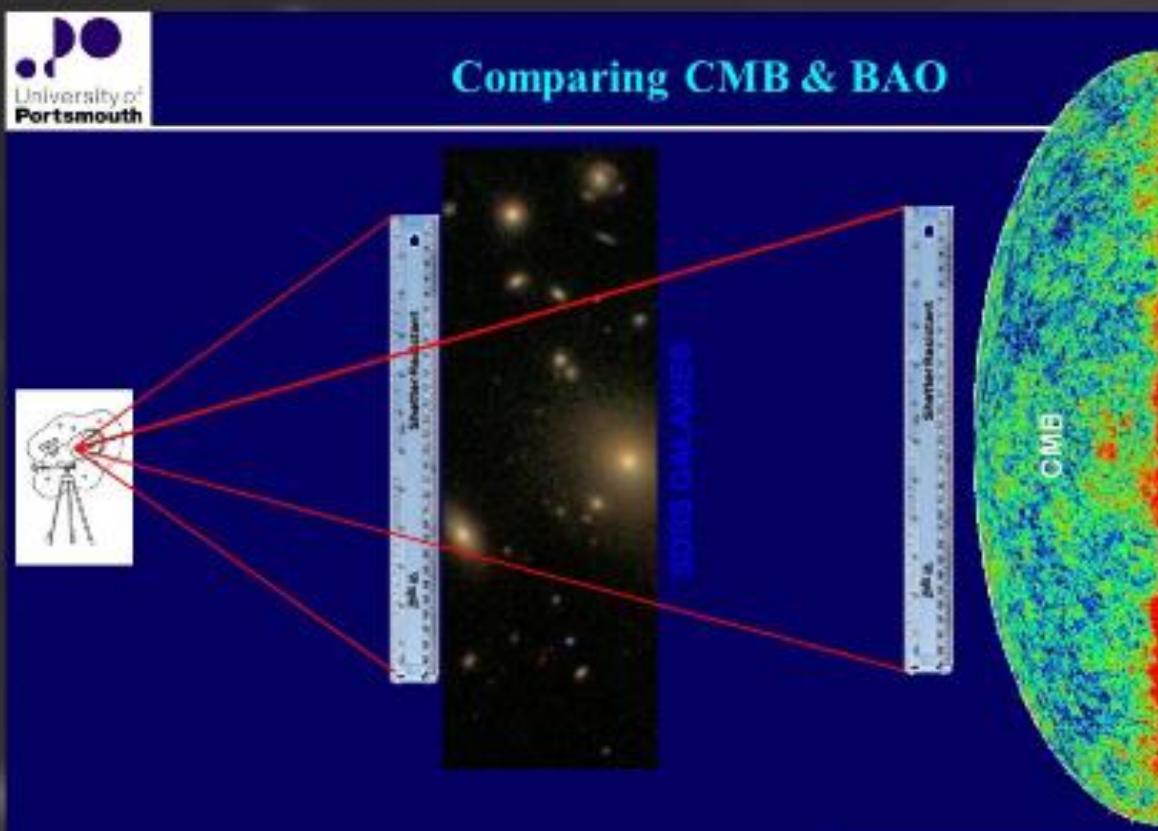
- Acoustic waves imprinted on CMB 380,000 years after Big Bang
- Acoustic scale set by distance light travelled at that time
 - Known **precisely** from CMB power spectrum
 - $D=149 \pm 0.6$ Mpc
- BAO scale imprinted on all matter in the Universe
 - Use as a “standard ruler”



Fonte: Abdalla, E. et al 2021

The Science

- Acoustic waves imprinted on CMB 380,000 years after Big Bang
- The acoustic scale is set by distance light travelled at that time
- Known precisely from CMB power spectrum: $D=149 \pm 0.6$ Mpc (Planck 2015)
- BAO scale imprinted on all matter in the Universe, use as a “standard ruler”
- HI intensity mapping, measure HI FLUCTUATIONS, using a ~ 0.7 deg beam on the sky



Some scientific challenges

Foregrounds ~ 10000 stronger than BAO signal!!!!

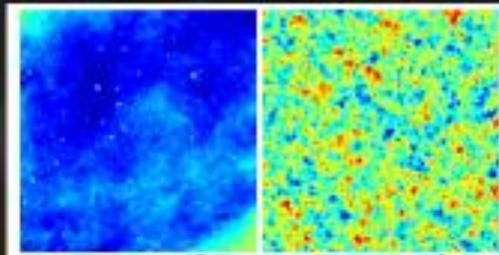
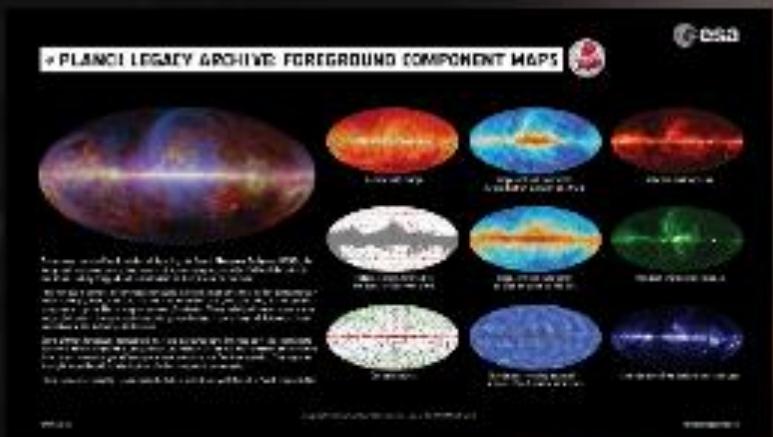
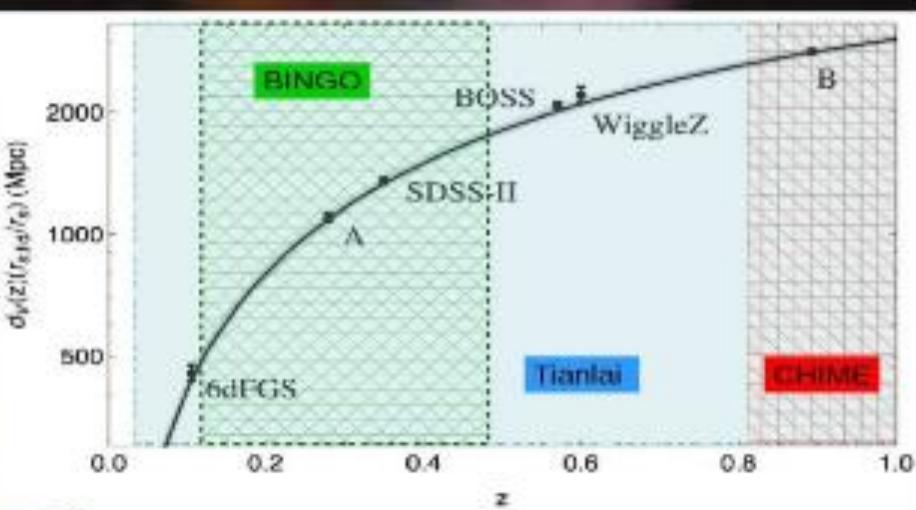
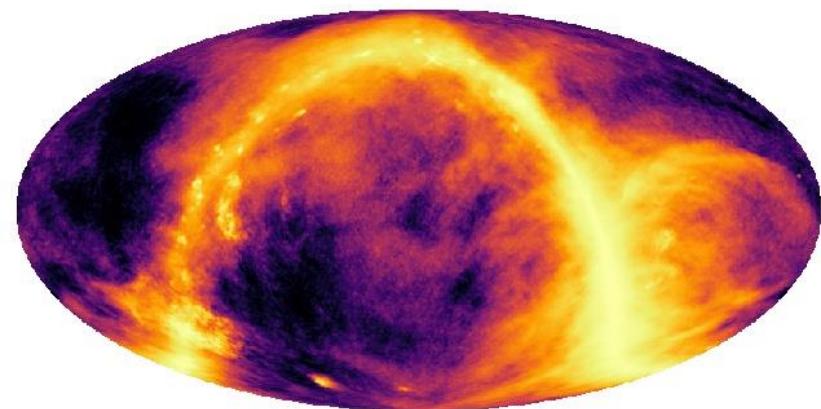


Figure 6: Astrophysical emission (Galactic synchrotron, Galactic free-free, and extragalactic point sources) (left) and HI emission (right) at 1 GHz. The maps are centered at Galactic coordinates (30; 120). The map resolution is 40 arcmin. Astrophysical emissions are $\sim 10^4$ stronger than HI emission.

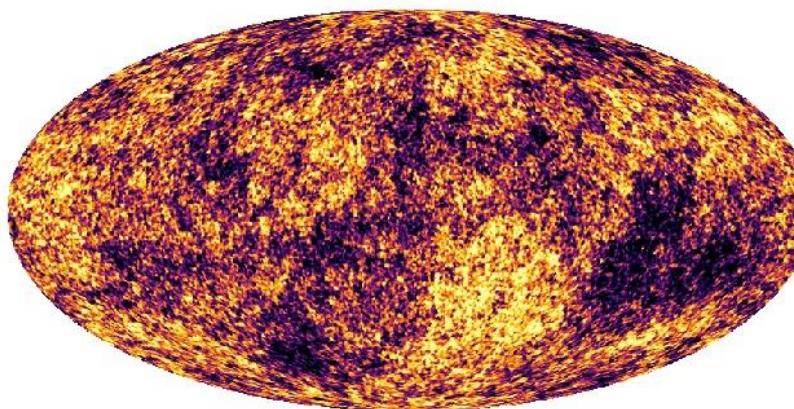


TOTAL



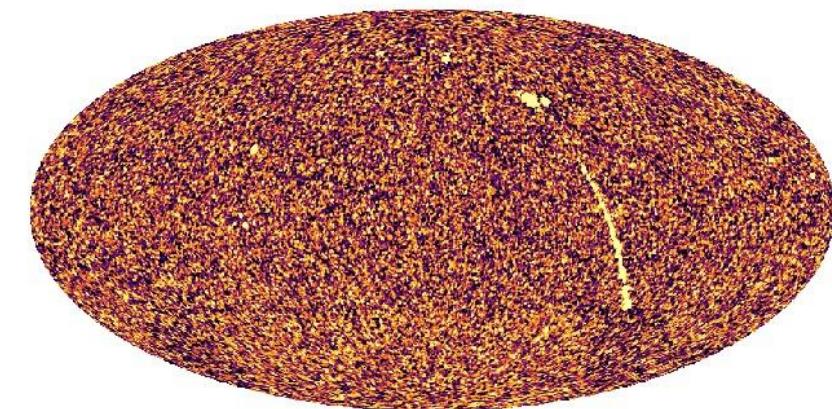
301.403 mK 165476

CMB



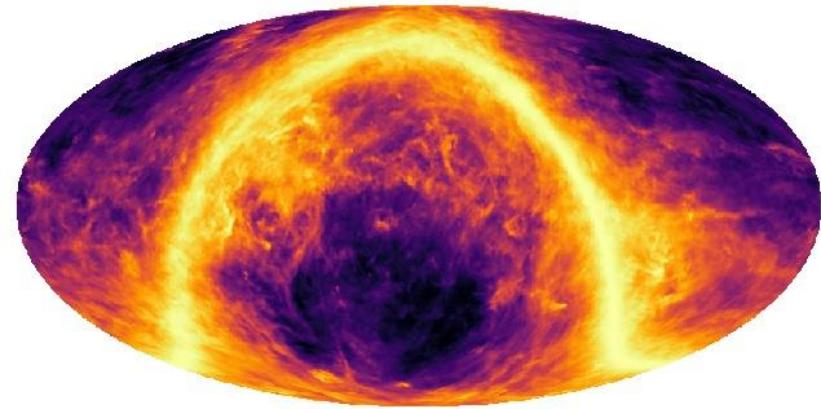
-0.348303 mK 0.383637

POINT SOURCES



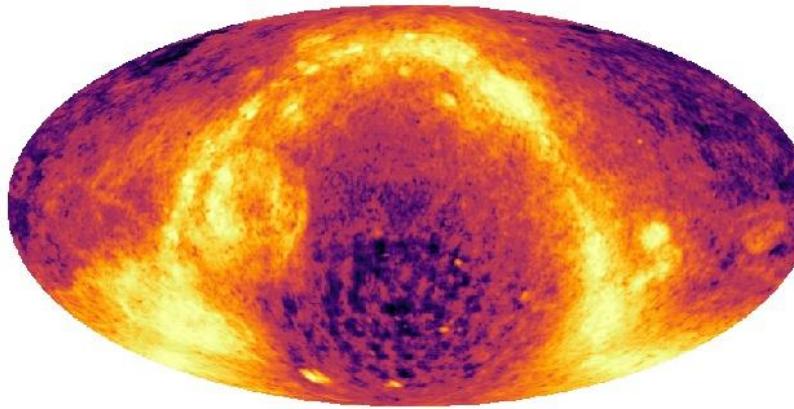
36.3582 mK 1269.76

AME



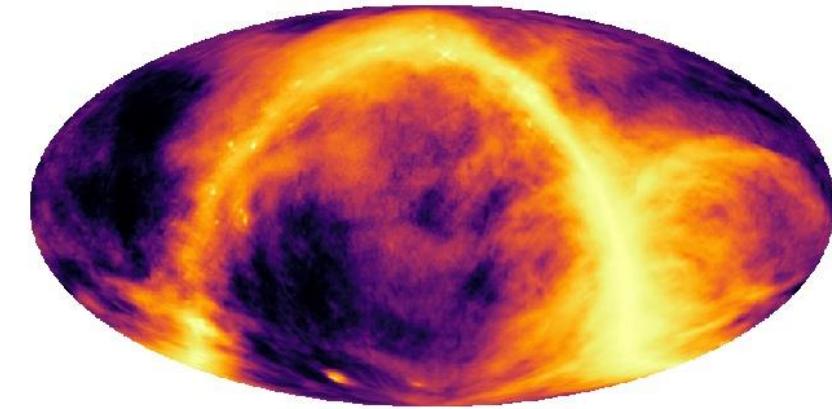
0.000909162 mK 1.75552

FREE-FREE



-0.13996 mK 51424.5

SYNCHROTRON



232.101 mK 164817

Technological challenges

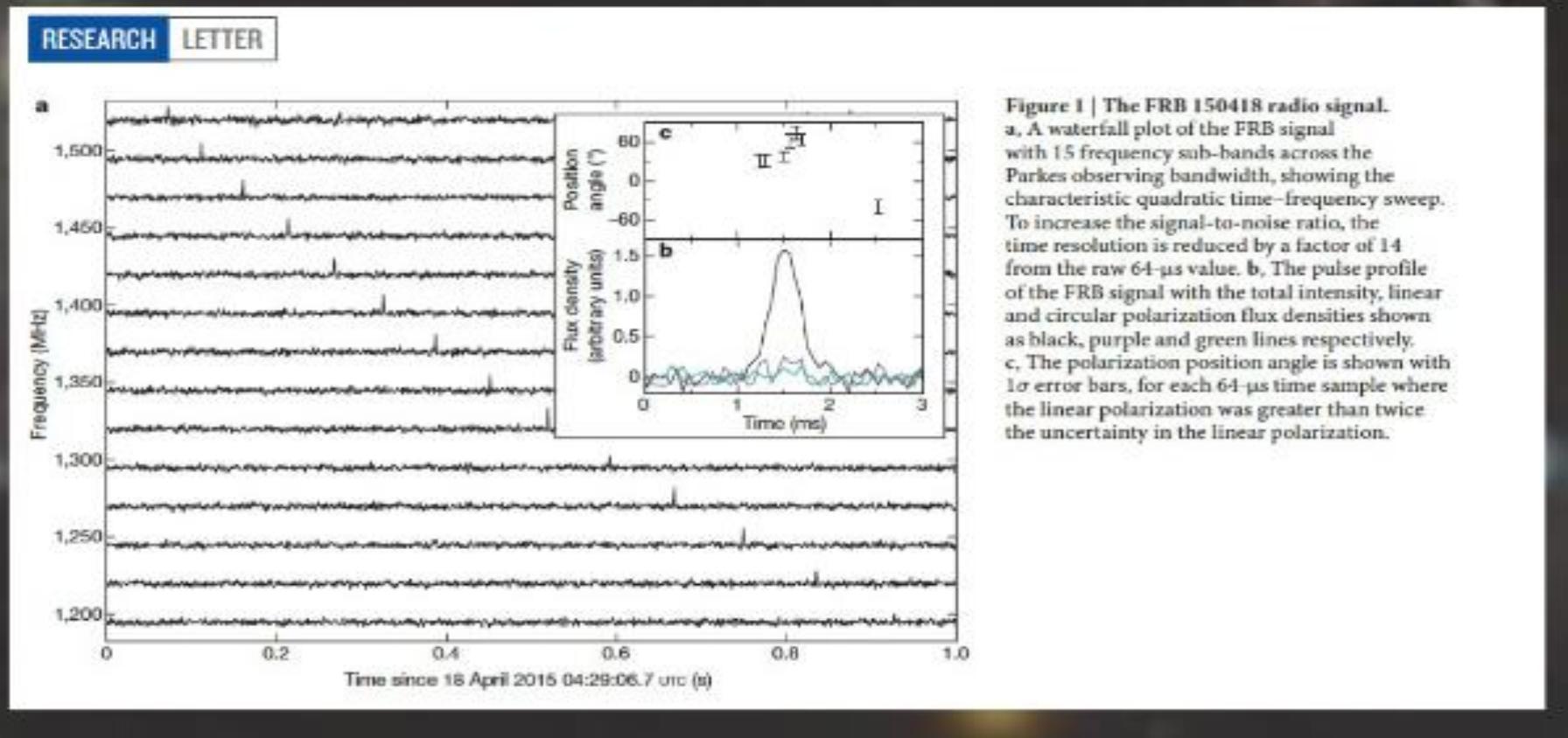
Some of the challenges BINGO will have to deal with:

- Build the 50, ~ 4.8 x 1.8 m, horns to a 0.5 mm precision
- Transport to and build the 2, ~ 40 m dishes in "Sertão da Paraíba"
- Same thing for the horns
- Data stewardship of the 50 horns
- RFI from mobile phones, airplane routes, radio links and microwave ovens are a permanent threat to the quality of BINGO data!!!!
- Continuously monitor the radio environment around BINGO

Additional Science

- Life history of HI
- Fast Radio Bursts
- Pulsar timing
- Recombination lines
- Galactic science

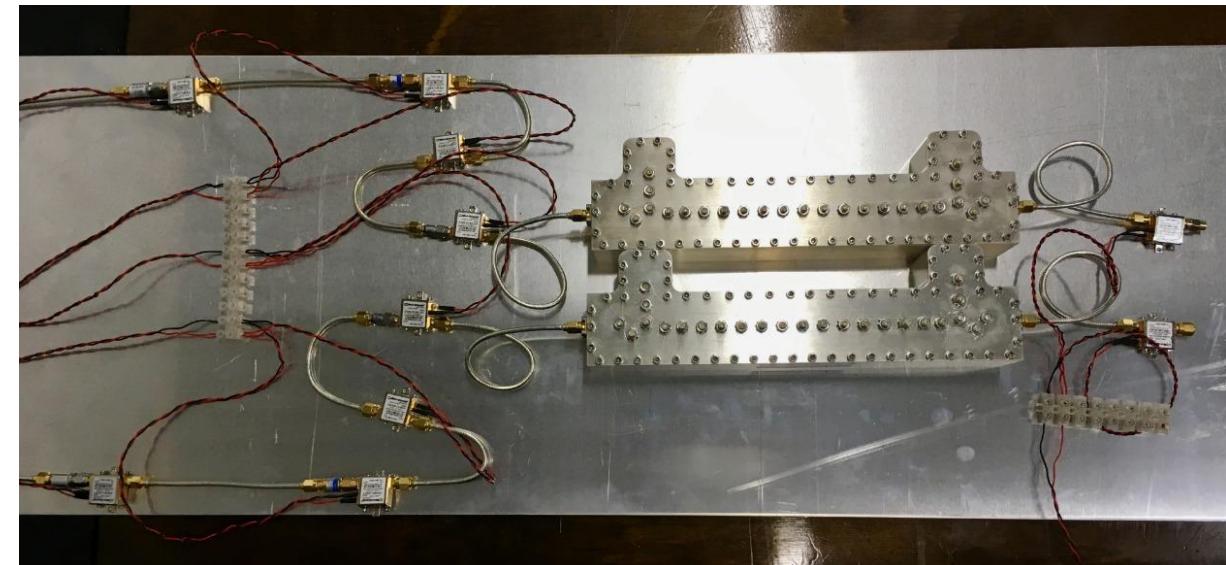
- First detected in 2007 (Lorimer et al., Science 2007)
- Duration: ~ millisecs to ~ 10s of millisecs
- Extragalactic origin, unknown causes (magnetar flares, short GRB bursts)



THE VARIOUS STAGES

Stage 0

- The Instrument:
- Horns (basically done)
- Receiver (already projected, now in series)



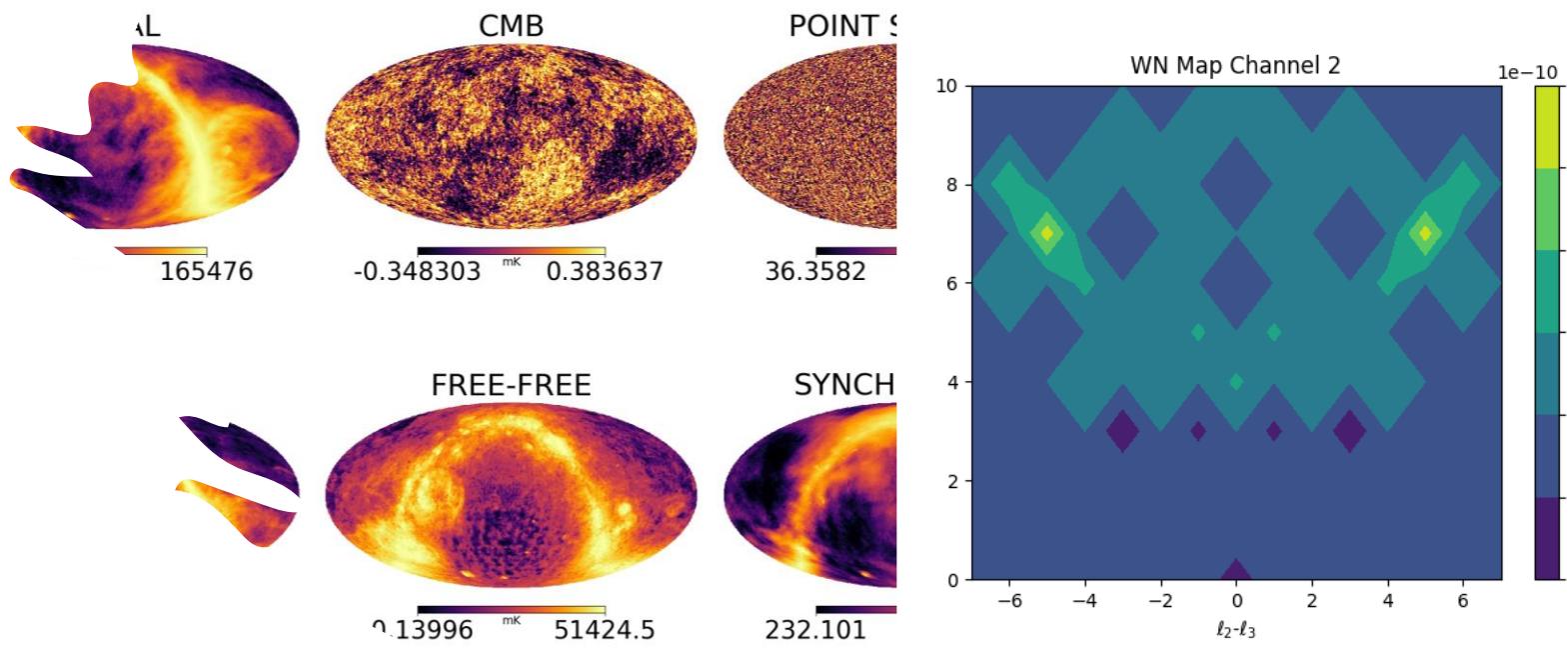
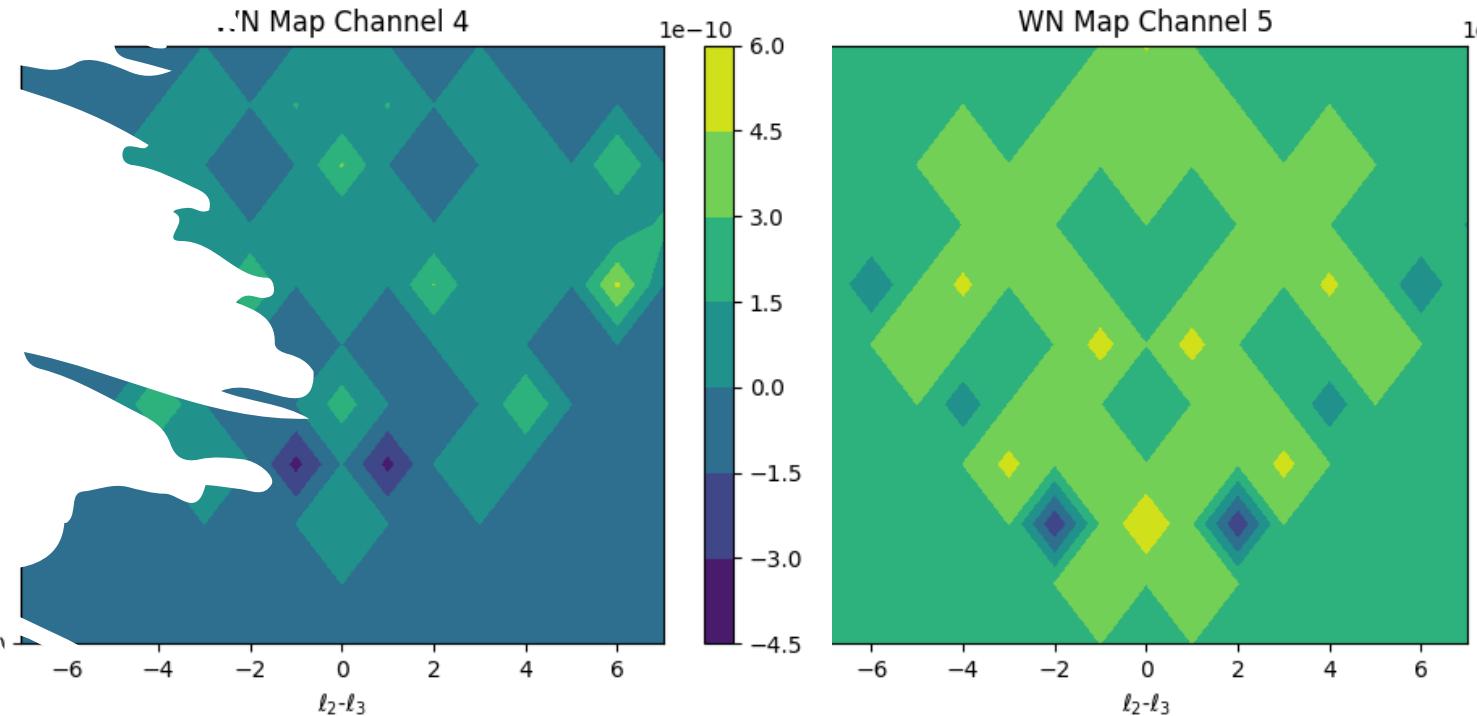
Stage 1

- Raw data
- FRB's
- Outriggers (Uiapuru in Campina Grande University campus, Paraiba)



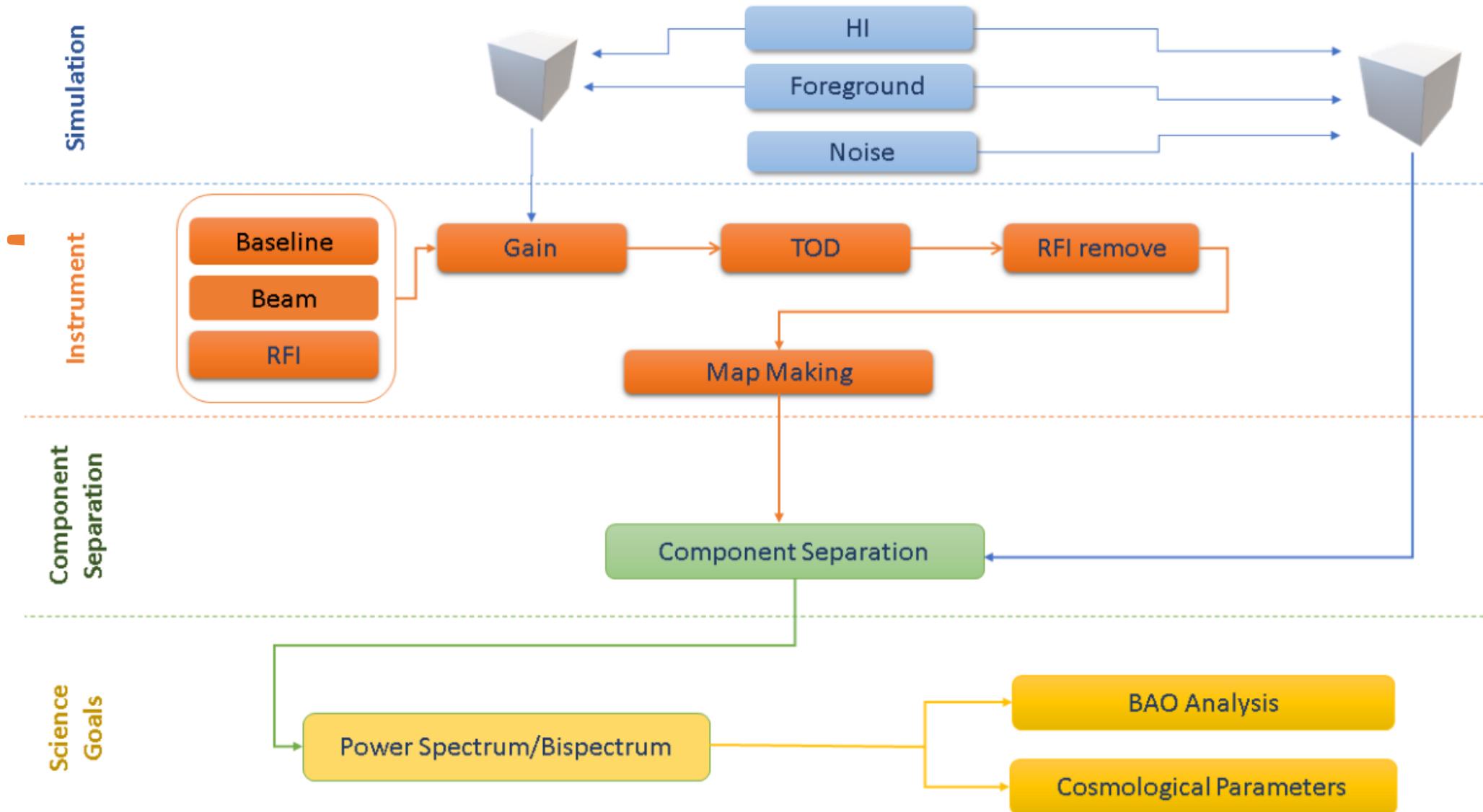
Stage 2

- Component Separation
- Bispectrum



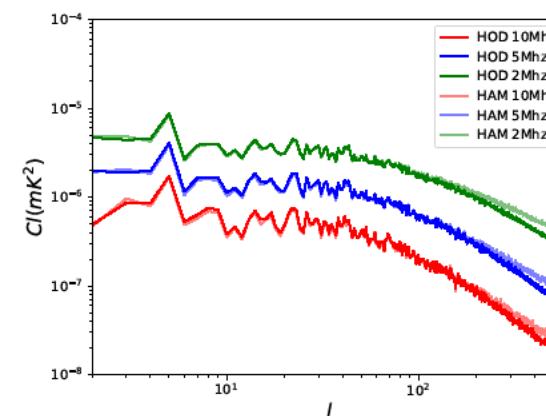
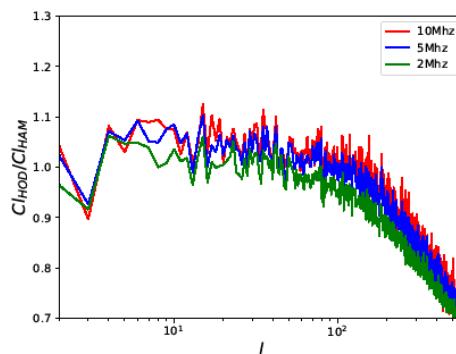
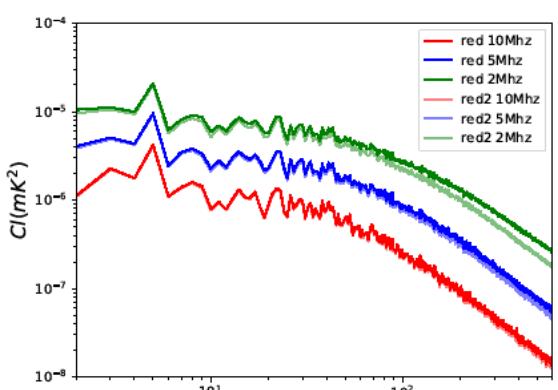
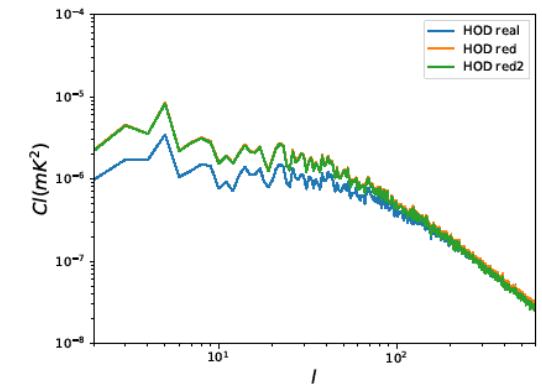
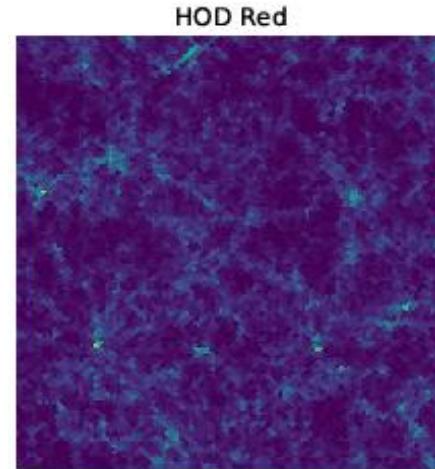
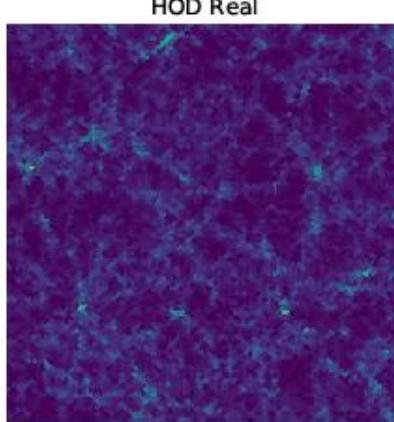
STAGE 2

- Component Separation: power spectrum, BAO, Cosmological Parameters



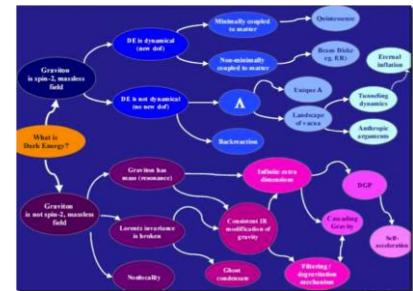
STAGE 3

- Mocks



• Theory

STAGE 4



Candidates

- Neutralinos (higgsino, bino, winos, singlino)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Super-WIMPs states (ie. "WIMPzillas")
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPS (charged massive particles)
- Cryptons, ...

Equações Cosmológicas

- Seja $\rho(t)$ a densidade média de matéria do Universo, e $p(t)$ a pressão correspondente.

Equações de Einstein:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$$

onde

$$T_{\mu\nu} = \begin{bmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{bmatrix}$$

THEORY

- Structure of Dark Sector
- cosmological parameters
- DE/DM interactions
- Models of DM/DE
- FRB's and cosmological parameters/consequences
- Mass distribution
- Pulsars
- Flaring stars
- Astrophysical signs and consequences
-

CONSTRUCTION

- Ongoing construction operations



OUTREACH AND EDUCATION



O universo é imenso e fascinante. Possui planetas, estrelas, galáxias, cometas, nebulosas ...

Muitos estudos são realizados para encontrar respostas ainda questionáveis pelo ser humano!!

Ainda sendo existem ferramentas de mapear o universo. Nesse projeto o



Este é apenas o primeiro livro da coleção sobre o projeto. Nós vamos introduzir conceitos fundamentais, como: a diferença entre um telescópio óptico e um radiotelescópio, os tipos de ondas e o espectro eletromagnético.

MAS O QUE É O BINGO???

O BINGO é um grande telescópio construído aqui no Brasil que irá operar na faixa de rádio, por isso, é um radiotelescópio.



OUTREACH AND EDUCATION

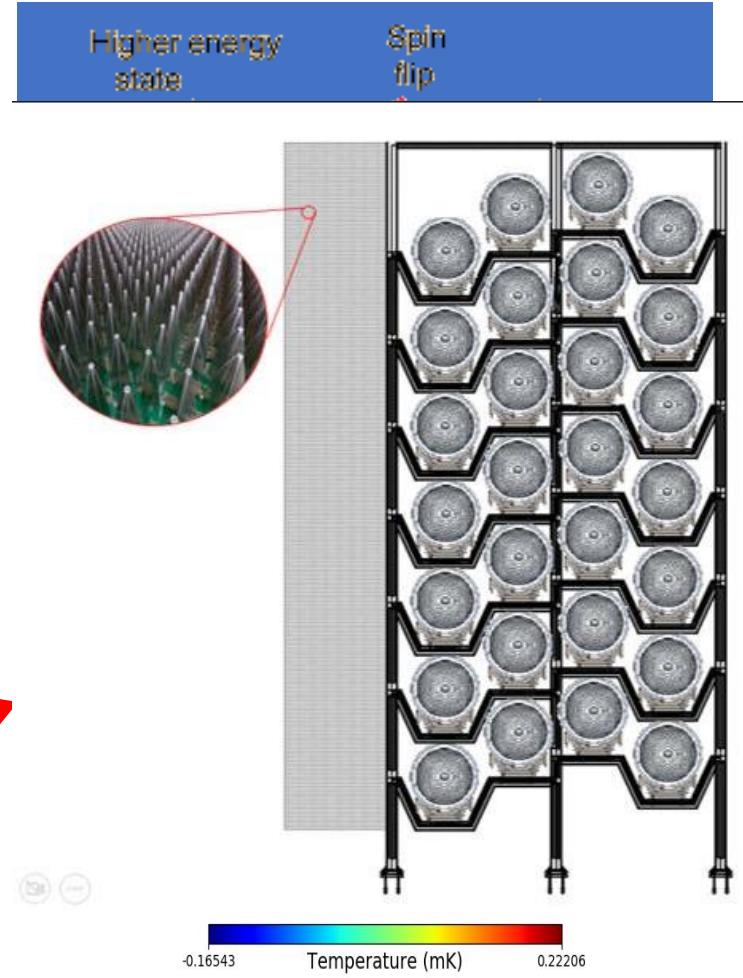
- Work with local population and support from local Secretary of education from the Paraiba State

BINGO HIGH RESOLUTION

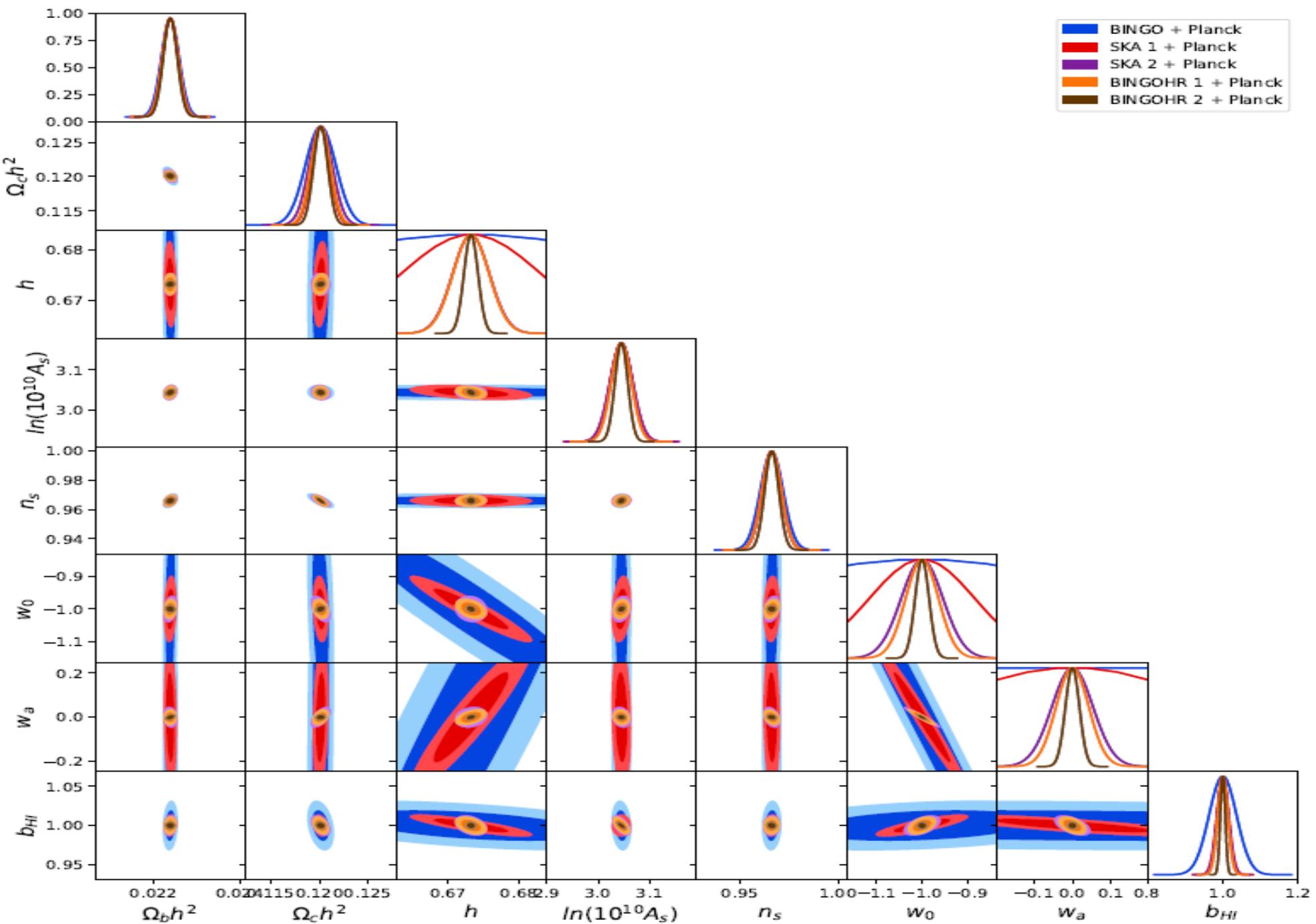
Filipe Abdalla

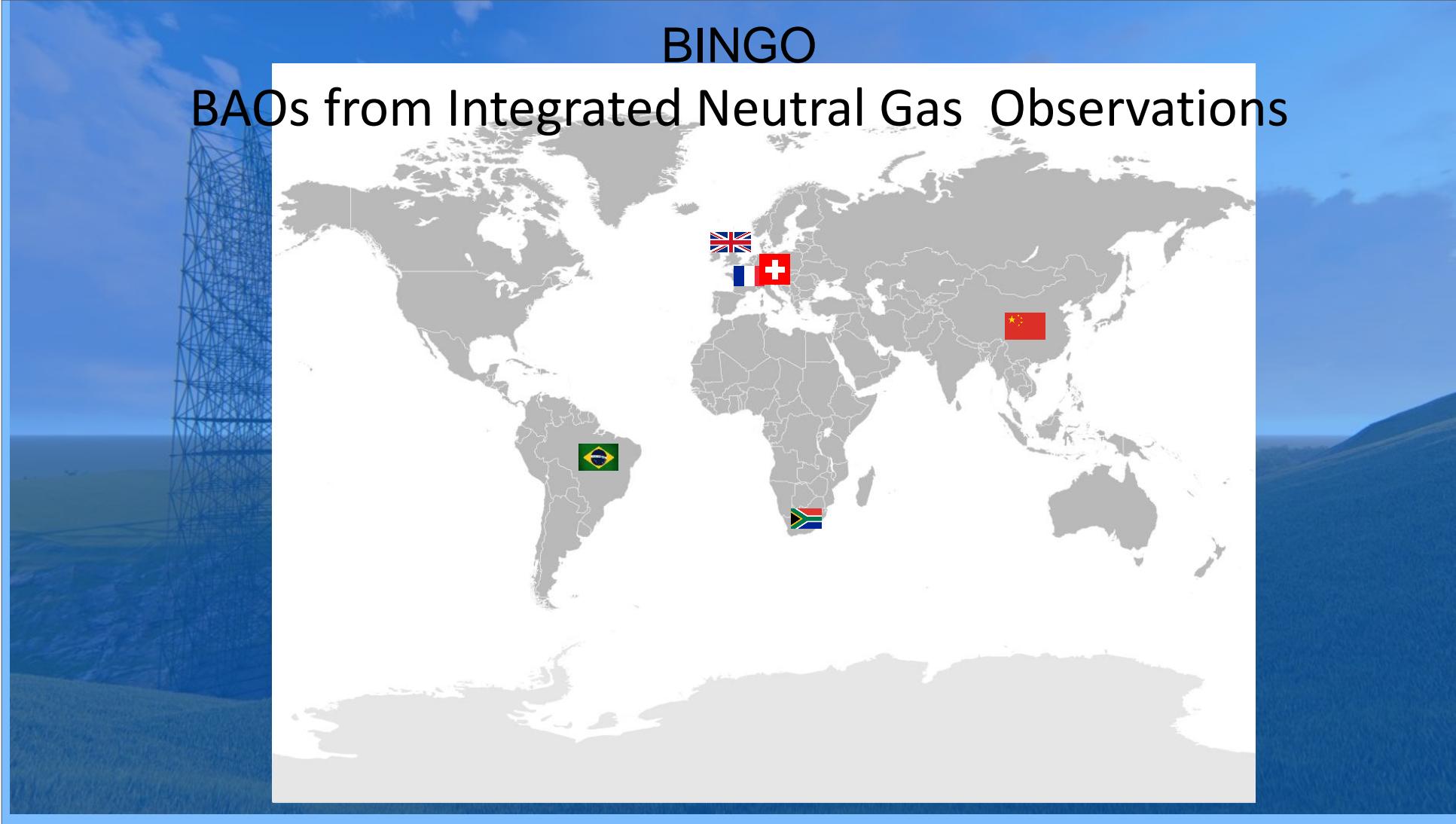


- 450 – 1450 MHz
- ($z \sim 0 - 2.1$)
- 1 MHz resolution
- 1.2 deg Resolution
- T system 40K
- Station 4500 m²



BINGO- HR FORECA STS





BINGO

BAOs from Integrated Neutral Gas Observations

BINGO TELESCOPE

BINGO Collaboration



上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

MANCHESTER
1824
The University of Manchester

UNIVERSITAS OSLOENSIS
MDCCCLX
UNIVERSITY
OF OSLO

UFES
UNIVERSIDADE FEDERAL
DO ESPÍRITO SANTO

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

TUM
Technische Universität München



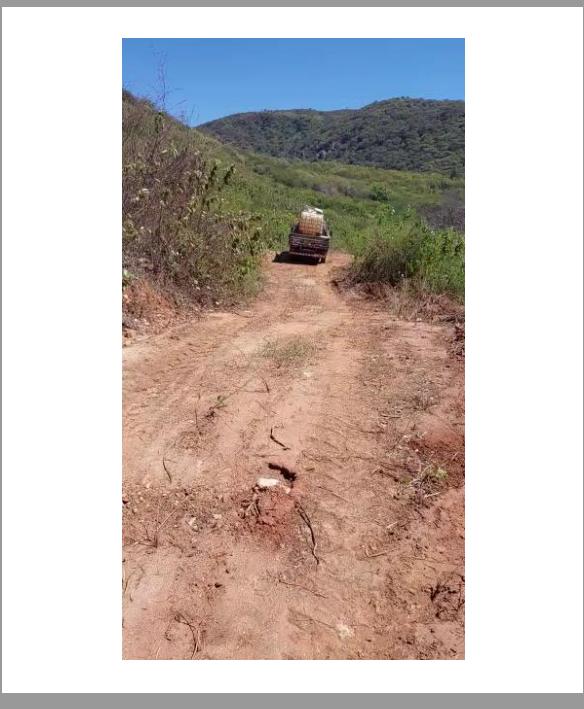
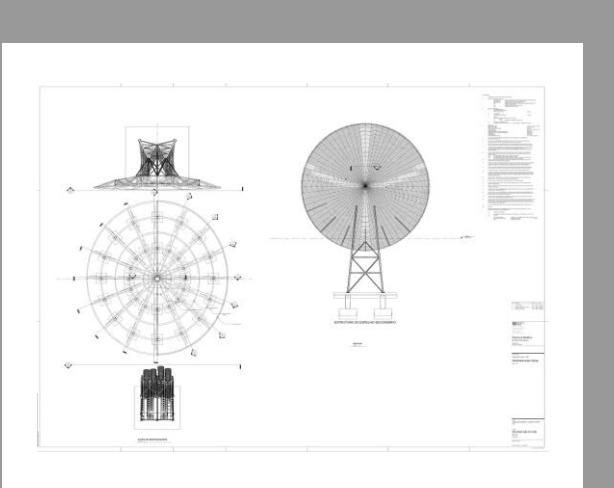
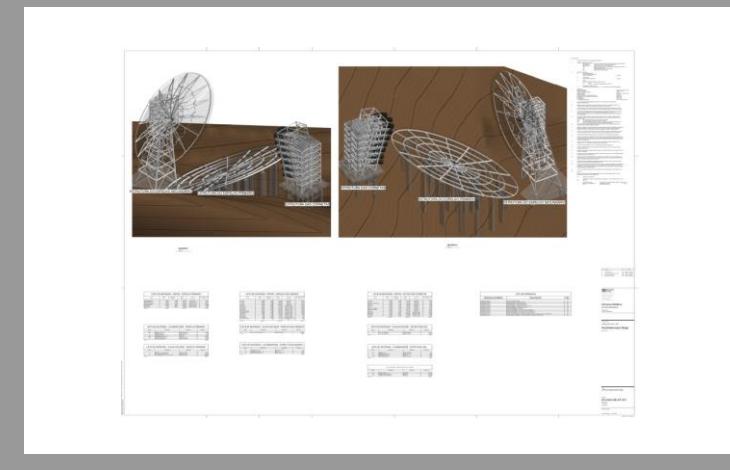
SUPPORT

- FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo)
- Paraiba government
- FINEP (Projects and Studies financing – Federal Government)
- Ministry of Science and Tecnology (Brazil)
- National Natural Science Foundation of China
- YangZhou University (China)
- INPE (National Institute of Space Research, Brazil)
- University of São Paulo
- Federal University of Campina Grande

MAIN COLLABORATING COMPANIES

- Alltec (São Paulo): metallurgy/horns
- CETC 54 (China): metal structure
- IBRTEL (Paraiba): construction
- Ponto de Apoio and GTP (projects)





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