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

21 cm cosmology and the BINGO Telescope

Reuven Opher Workshop on Challenges of New Physics in Space

Carlos Alexandre Wuensche

Divisão de Astrofísica - INPE

December 2021

ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

IFT - UNESP INSTITUTO DE FÍSICA TEÓRICA


IX WORKSHOP
Nova Física no Espaço

Plan of the talk

- **21 cm cosmology**
- the BINGO project

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
  - What is the nature of Dark Matter?
  - What is the nature of Dark Energy?
  - Dark energy (EUCLID, HETDEX, DESI, LSST - DoE flagship projects)

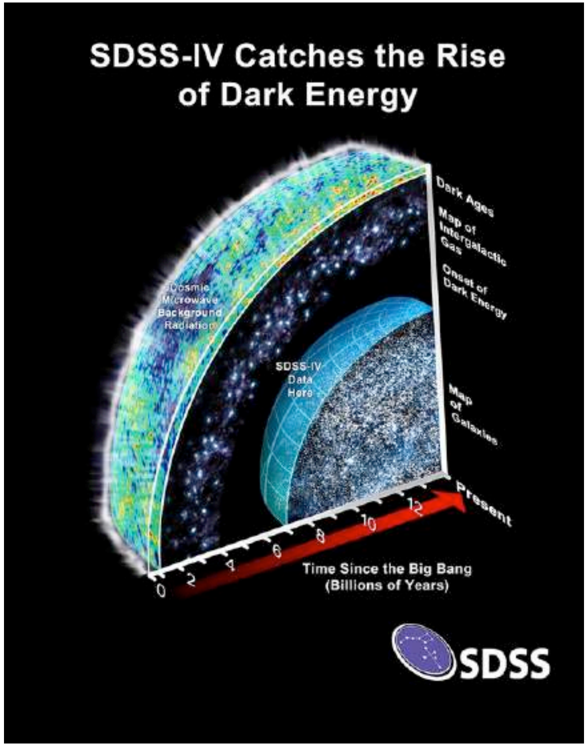
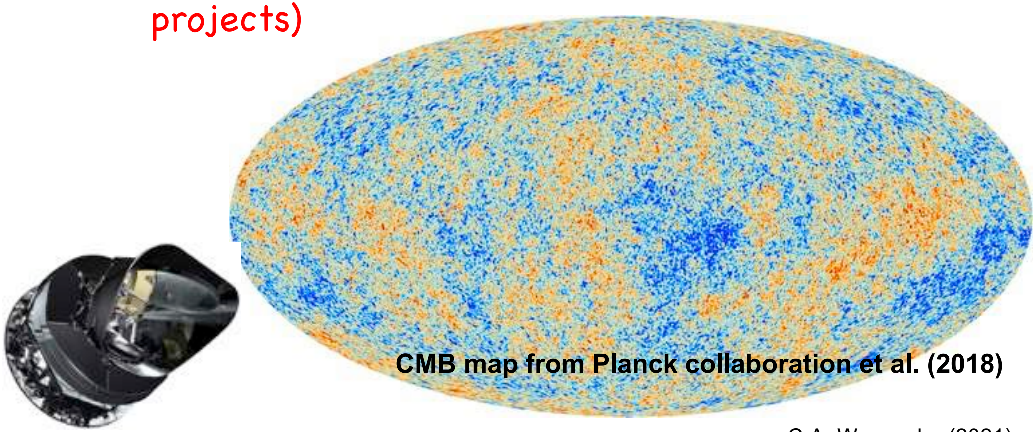


Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.



CMB map from Planck collaboration et al. (2018)

C.A. Wuensche (2021)

Dark Energy Observation program

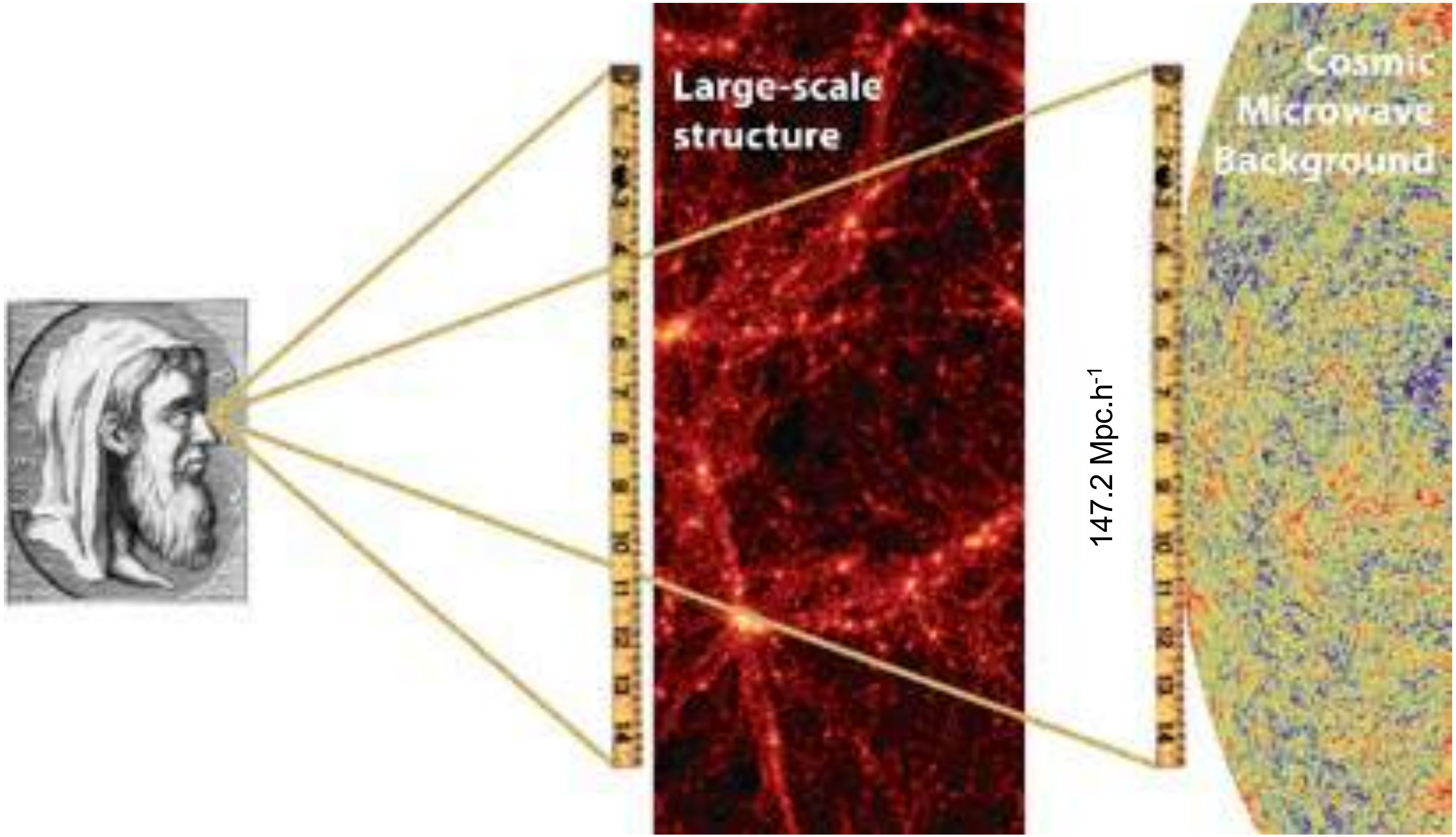
- Instruments: JWST, SKA, LSST, Euclid, DESI
- Observational targets
  - Galaxy Cluster Counting
    - Targets: SZ and X-ray cluster surveys
  - SN Ia
    - Targets: Large, low-z, SN survey
  - Weak Gravitational Lensing
    - Targets: optical surveys and 21 cm interferometric measurements
  - **Baryon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

↔ Can also be studied in different (higher z) with radio observations (mostly 21 cm data)!!!!

Weinberg et al., Phys Rep. (2013), Ansari et al. arXiv:1810.09572

21 cm cosmology and BAO

Source: ESA



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

BAO highlights

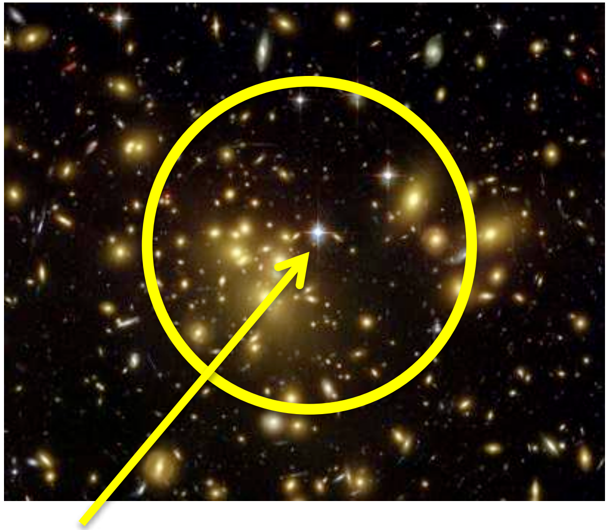
- Acoustic waves imprinted on CMB 380,000 years after Big Bang
- Acoustic scale **D** set by distance light travelled at that time
  - Known precisely from CMB power spectrum => **D=147.18±0.29 Mpc (from Planck)**
- Universe is reasonably well understood from t ~ 10^{-6}s to t ~ 380 kyears and then after Cosmic Dawn (t ~ 180 Myears)
- History of matter evolution can be traced via HI (and its "disappearance") from z=20 to z=0

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:

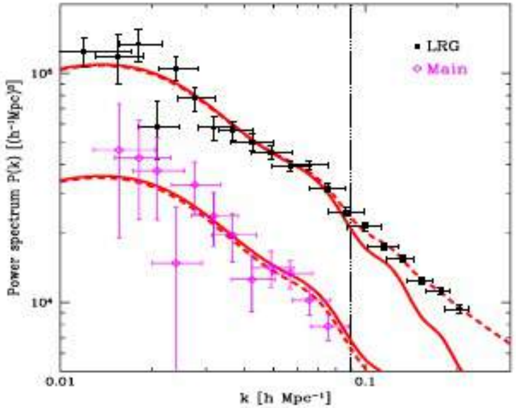
$$\Delta T_{CMB} = \Delta T_{CMB}(\theta, \phi, z = 1100)$$

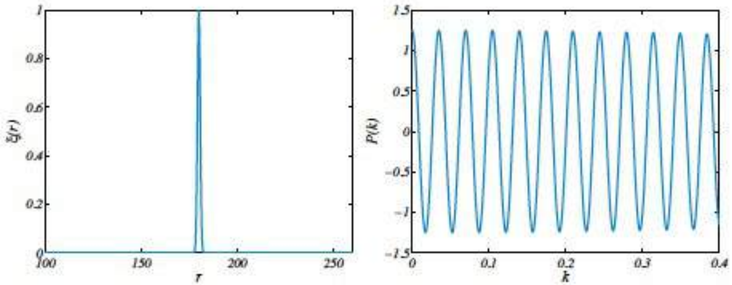
$$\Delta T_{HI} = \Delta T_{HI}(\theta, \phi, z)$$



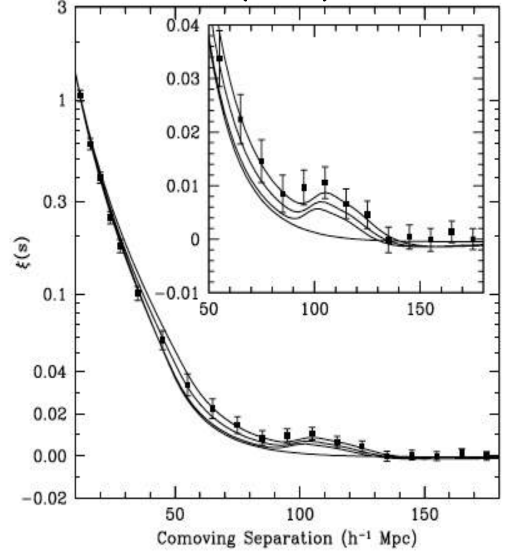
- Large beam on the sky (≈1 deg) contains many galaxies.
- HI signal is measured through its overall intensity

Tegmark et al. (2006).

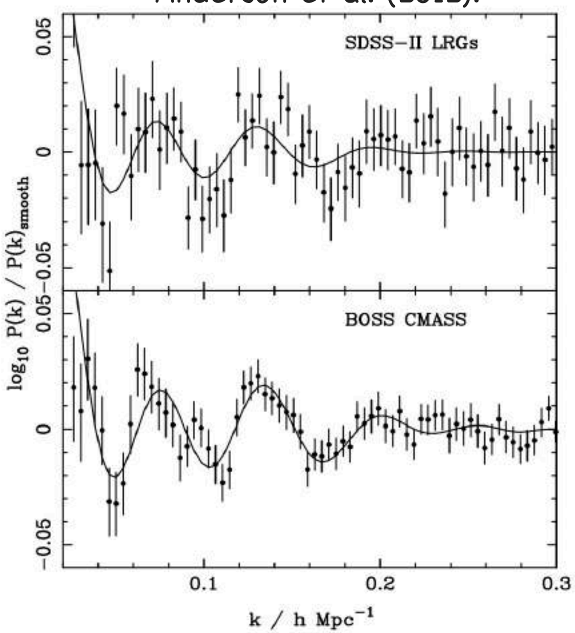




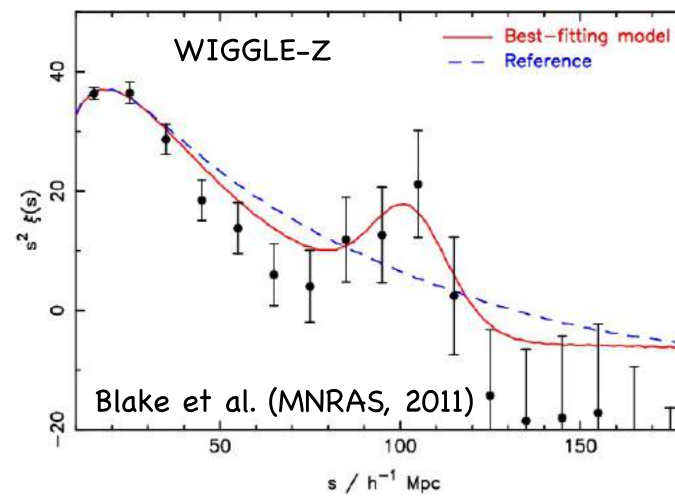
Eisenstein et al. (2005)



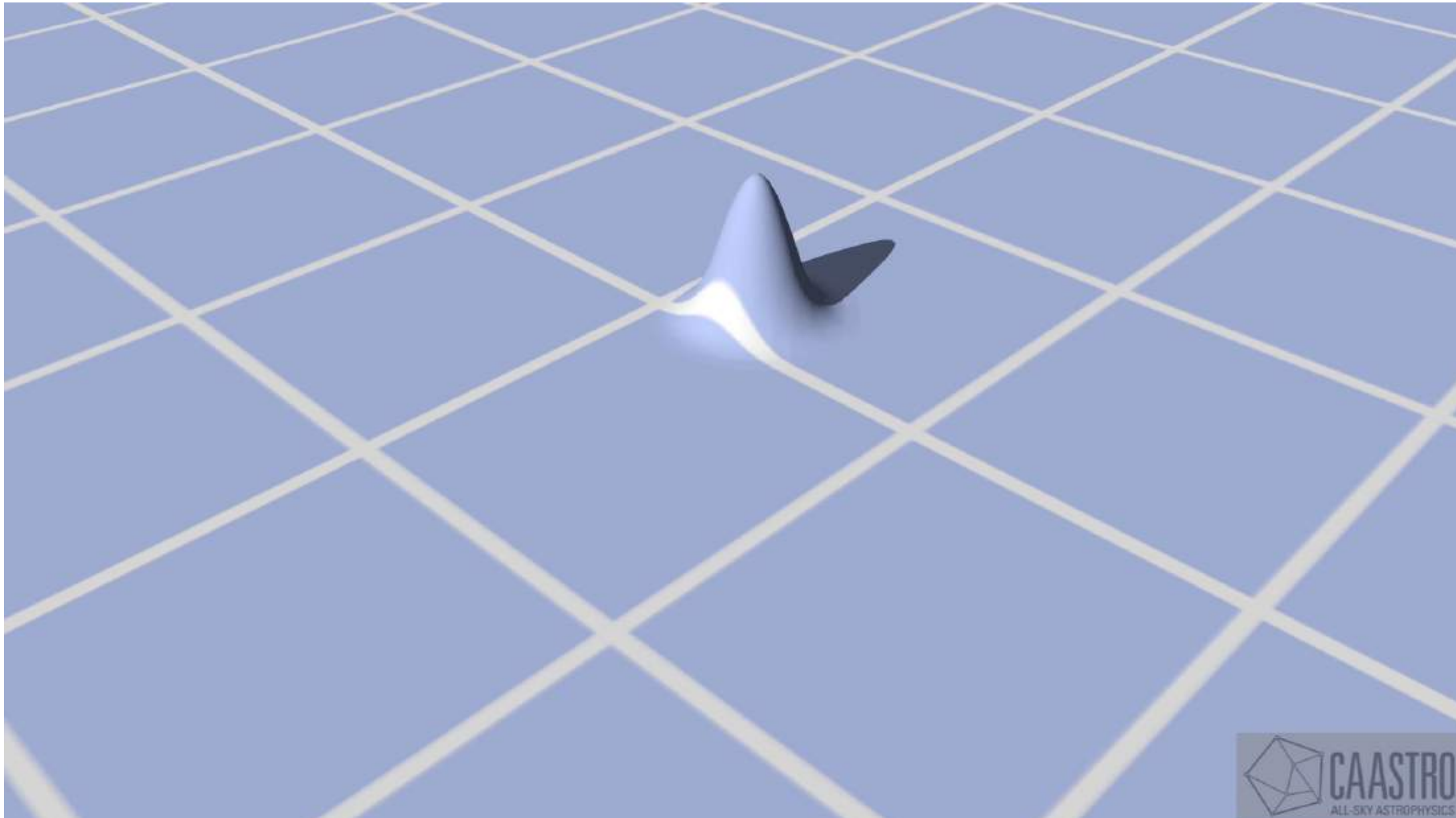
Anderson et al. (2012).



P(k) and ξ(r) are Fourier pairs!!!! A peak in the correlation function (r) space corresponds to oscillations in the power spectrum (k) space



Blake et al. (MNRAS, 2011)

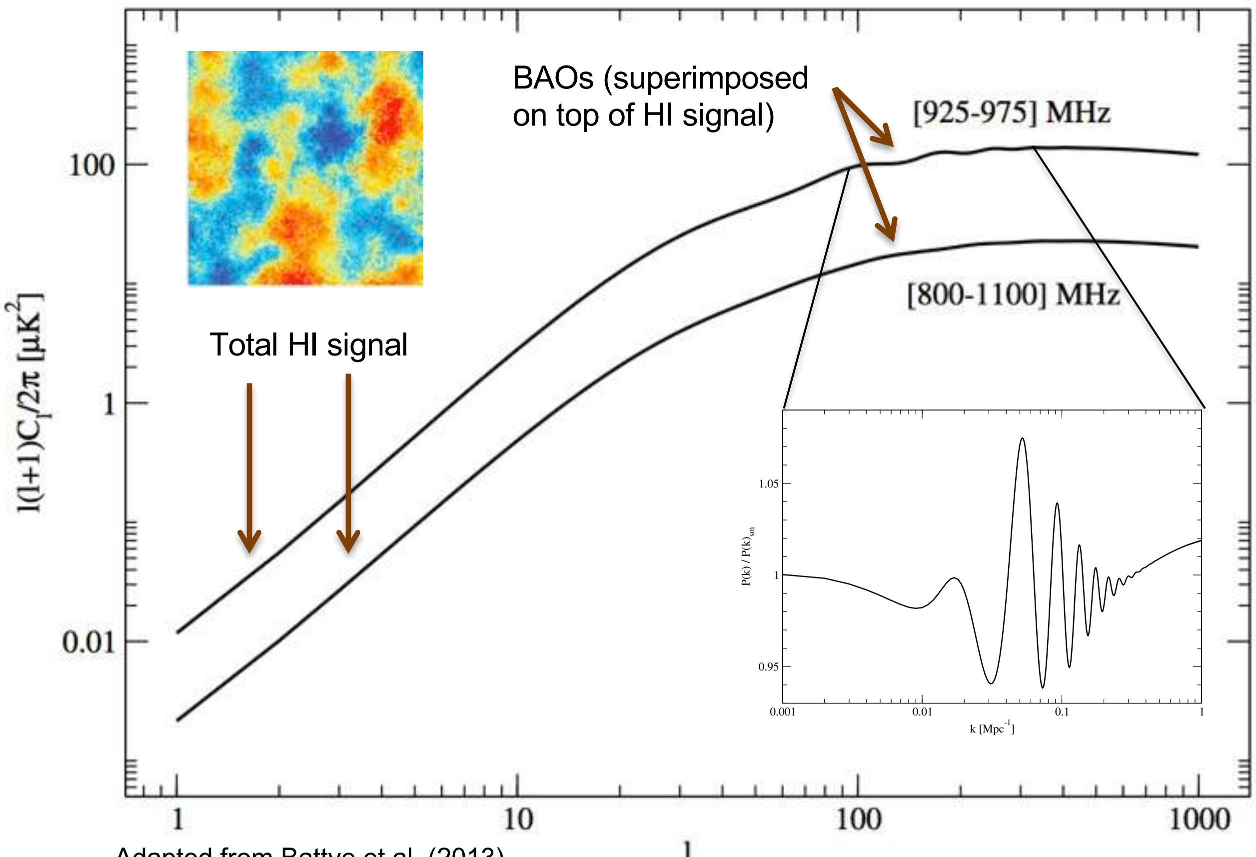


Source: CAASTRO (Centre of Excellence for All-sky Astrophysics), https://www.youtube.com/watch?v=jpXuYc-wzk4

The HI signal power spectrum

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

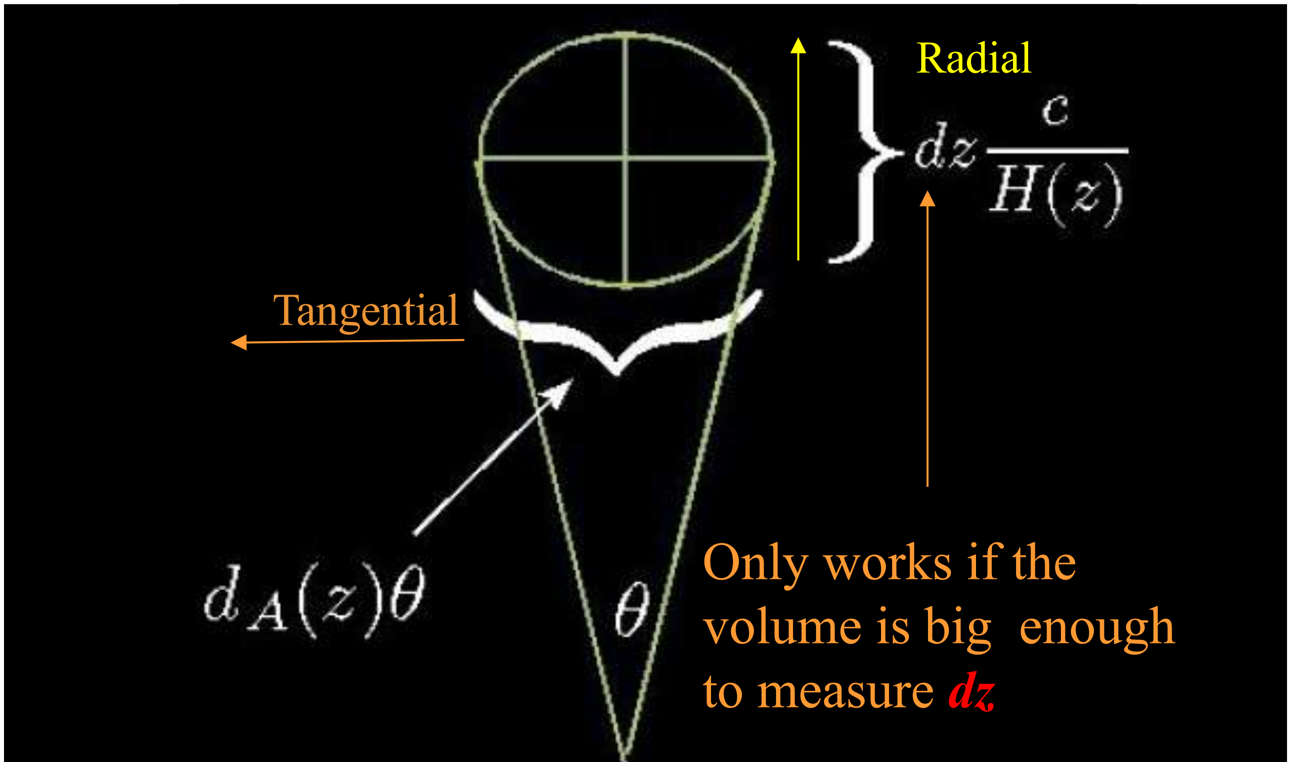
$$\bar{T}_{\rm obs}(z) = 44\,\mu{\rm K}\left(\frac{\Omega_{\rm HI}(z)h}{2.45\times10^{-4}}\right)\frac{(1+z)^2}{E(z)}$$



Adapted from Battye et al. (2013)

More on this later…

The Beauty of Standard Volumes

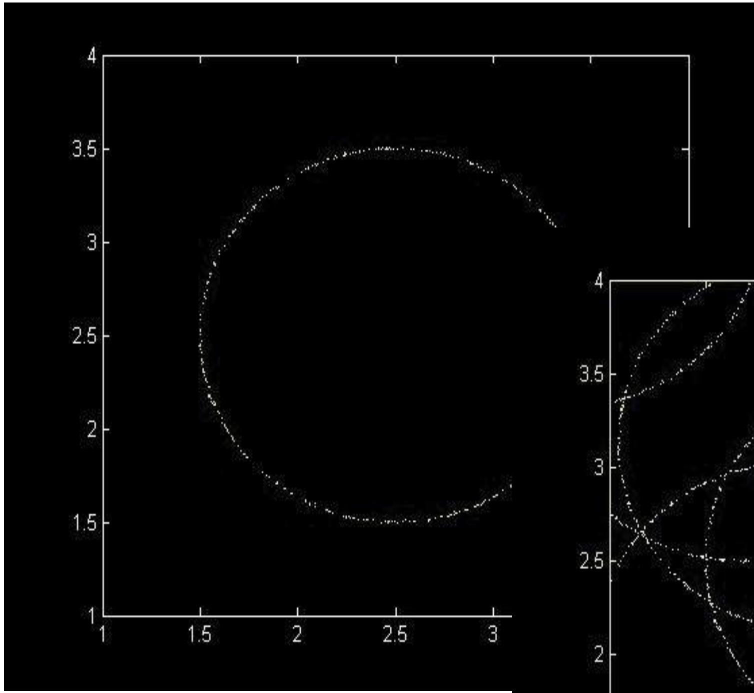


$$H(z) = \frac{c\Delta(z)}{s_{\|}(z)}$$

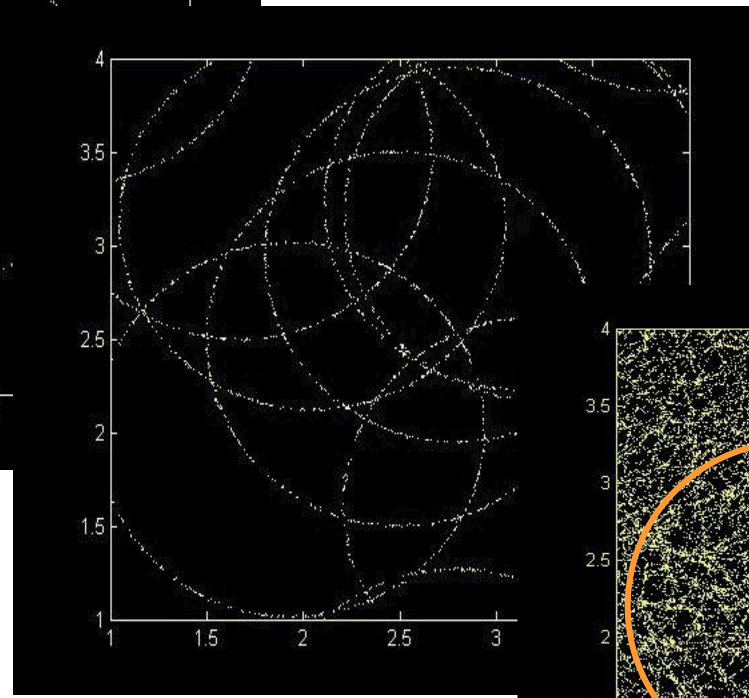
$$d_A(z) = \frac{s_{\perp}(z)}{\Delta\theta(1+z)}$$

Next related slides from Bassett & Hlozek (2009)

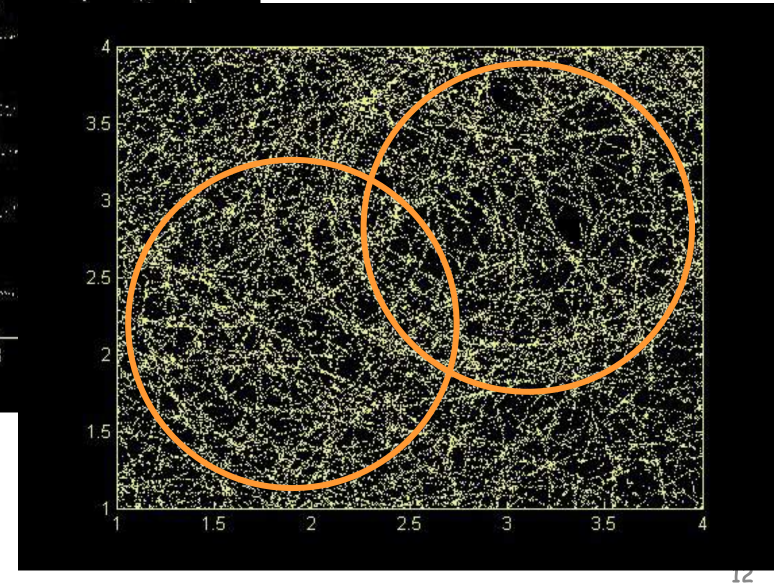
Rings of Power Superimposed



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



Detecting the characteristic radius is now a statistical problem



C. A. Wuensche (2021)

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
P = P(k)

Bassett & Hlozek (2009)

BAO scale

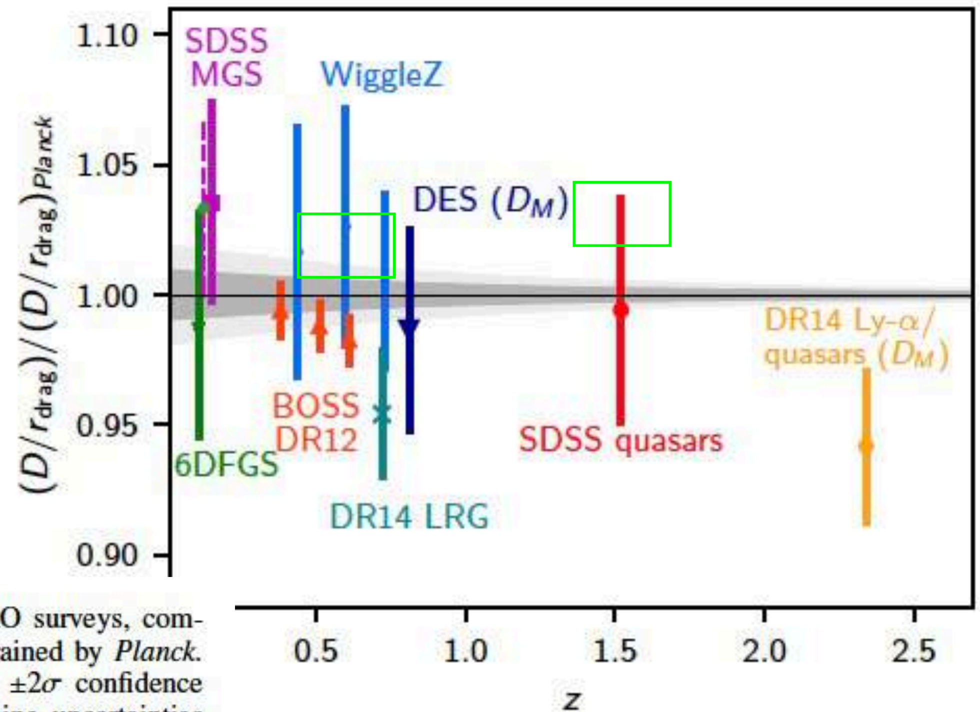


Fig. 27. Redshift-distance relation measured by BAO surveys, compared to the predictions of the ΛCDM model constrained by *Planck*. The grey band centred at unity shows the ±1 and ±2σ confidence regions for the *Planck* prediction, given the remaining uncertainties in the parameters. This is a percent-level prediction of the distance scale. The BAO points are: 6dFGS, green star (Beutler et al. 2011); SDSS MGS, purple square (Ross et al. 2015); BOSS DR12, red triangles (Alam et al. 2017); WiggleZ, blue circles (Kazin et al. 2014); SDSS quasars, red circle (Ata et al. 2018); and BOSS Ly α, yellow cross (Bautista et al. 2017).

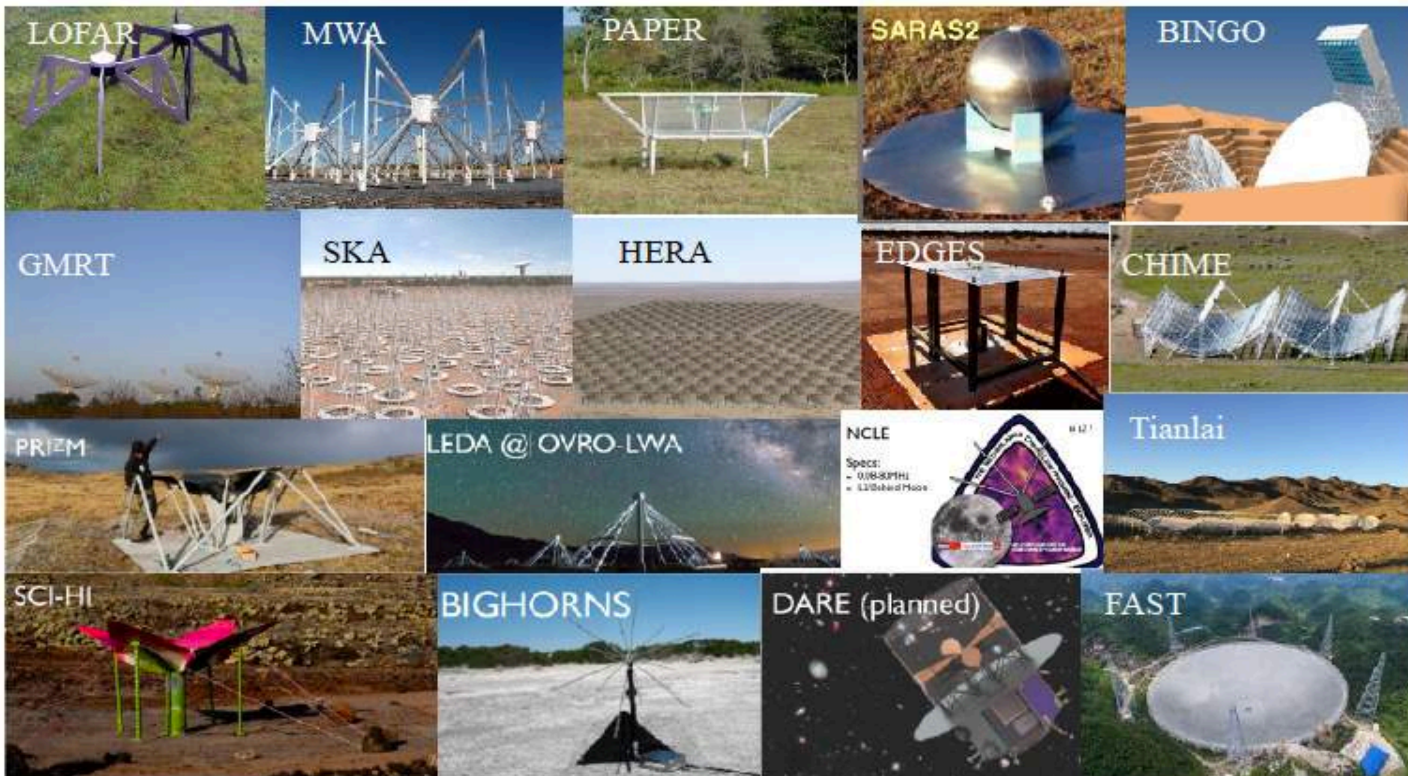
Planck 2018 results (Overview)

Why BAO in radio?

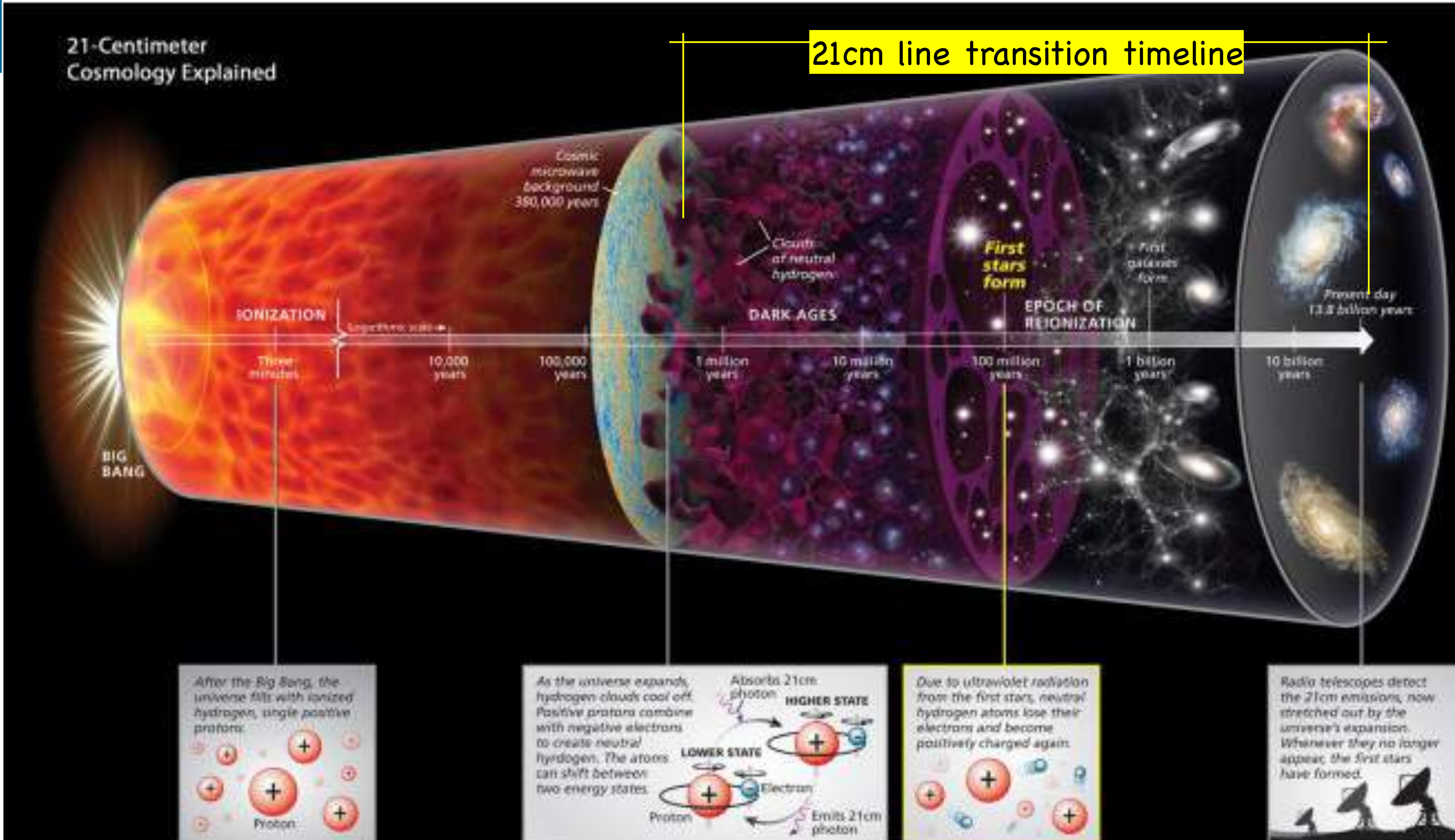
- Complementary to optics, different systematics
- Decay time of HI hyperfine transition is ~ 10^{15} seconds, but 75% of visible matter in the Universe is made of H…
- Efficient alternative for measuring a large number of galaxies individually (plus integrating the signal “alla” CMB allows for the reutilization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

21 cm cosmology/astrophysics

A hot topic in today's astronomy

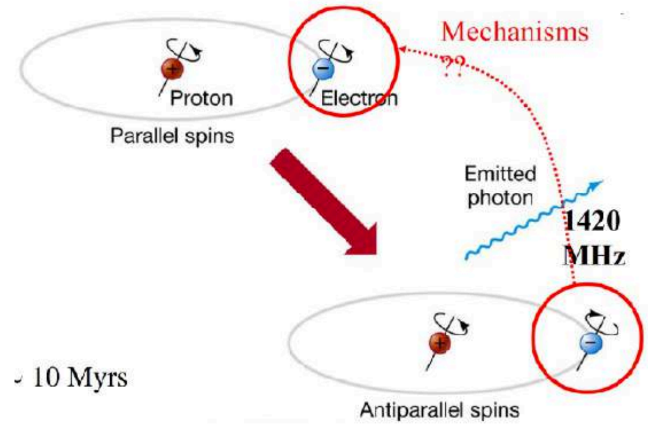


Credit: Marta Bruno Silva (Univ of Oslo)

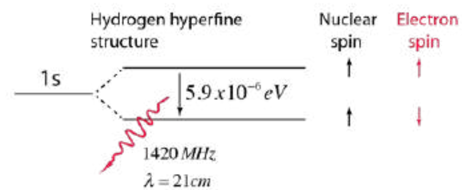


Credit: https://www.discovermagazine.com/the-sciences/chasing-the-universes-first-generation-of-stars

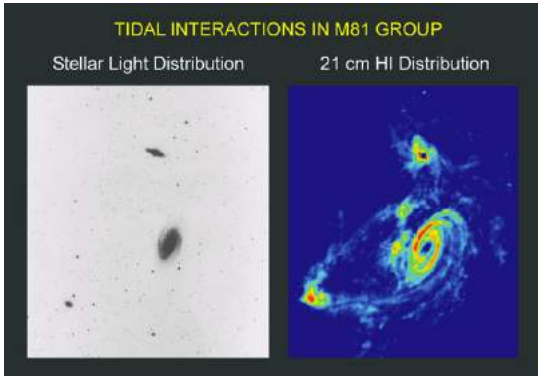
21 cm hyperfine transition line…



- H is the most abundant element in the Universe
- Neutral H (HI) is most important, BUT:
  - Very difficult to detect in cosmological distances
- 21 cm "forbidden" transition line
  - 1 atom emits a photon every 10^{15} s (~ 30 Myr), so it shou very weak signal
  - But…. There are zillions of H atoms in the Universe!
  - Frequency: 1420.406 MHz (⟹ wavelength ≈ 21.106 cm – radio)
- Observed since 1950s' but only restricted to the Galaxy and neighbour galaxies (z < 0.1)

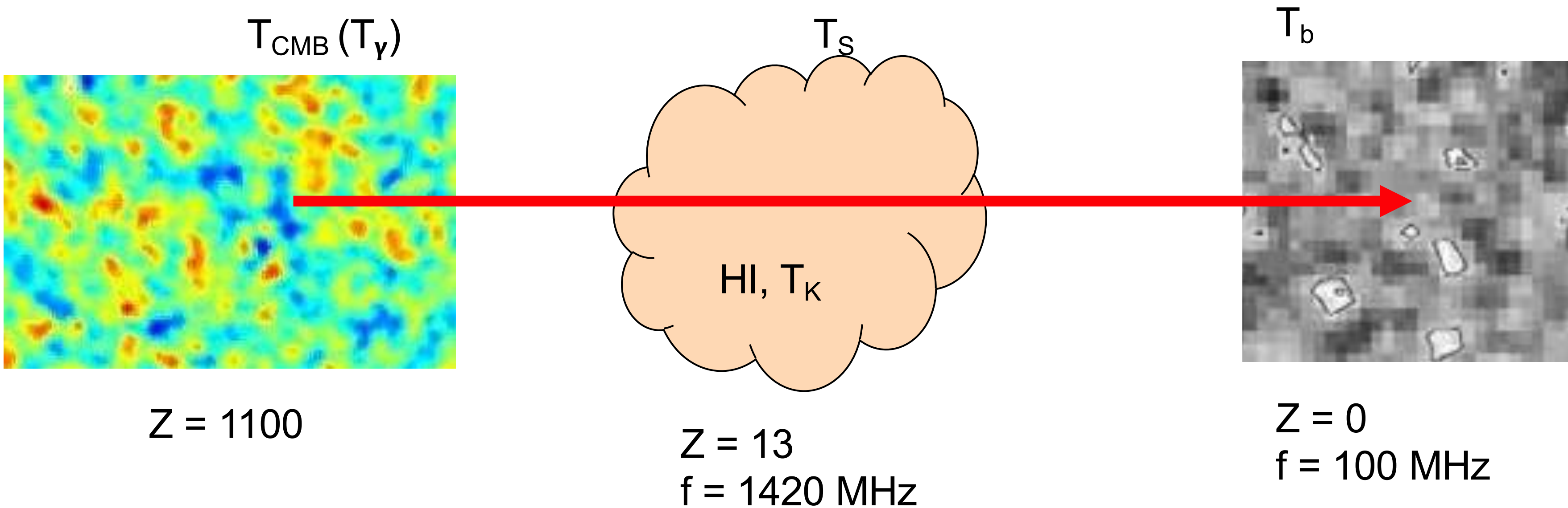


- Doppler shift of HI line gives direct information of velocity and distance
- Redshift of interest starts at frequencies < 1 GHz



The basic idea...

$$T_b = T_b(0)\, e^{-\tau_\nu} + T_S(1 - e^{-\tau_\nu}),$$



$$T_b'(z) = T_b(z)(1+z) = T_S\, e^{-\tau_\nu} + T_\gamma(z)(1 - e^{-\tau_\nu}).$$

The temperature of the 21 cm line transition

Fraction of HI

Radiation field temperature

Astrophysics

Cosmology

$$\delta T_b(\nu) \approx 9 X_{HI}(1+\delta_b)\left[1 - \frac{T_{\gamma(z)}}{T_S}\right] (1+z)^{1/2}\left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}}\right] \text{ mK}$$

Baryon fractional overdensity

Spin temperature

LoS velocity gradient

- T_S is dominated by different sources along the history of the Universe:
  - CMB interaction (mostly absorption, but also stimulated emission)
  - Collisional coupling with e^-, p and other H atoms
  - Ly-α scattering (the Wouthuysen-Field effect)
- The coupling constants define which process dominates in a given epoch

$$T_S \sim T_\alpha \sim T_K$$

W-F

recoils

Remember that $E_{21} = kT_{21}$
E_{21}=5.9 x 10^{-6} eV, T_{21}= 0.068

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

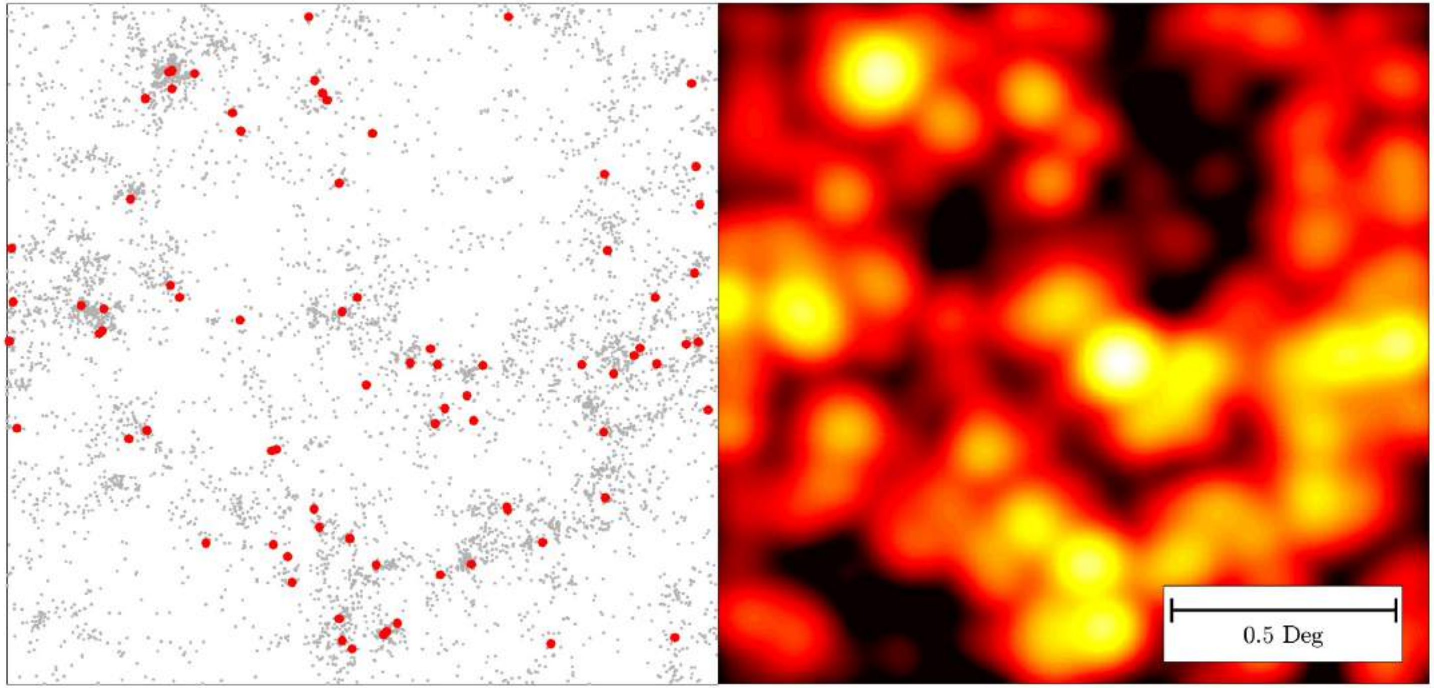
T_γ => CMB
T_α => Wouthuysen-Field coupling
T_K => gas kinetic temp (scattering)
x_i => coupling constants

A detailed derivation can be found in Furlanetto, Oh & Briggs (Phys. Rep. 2006)

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

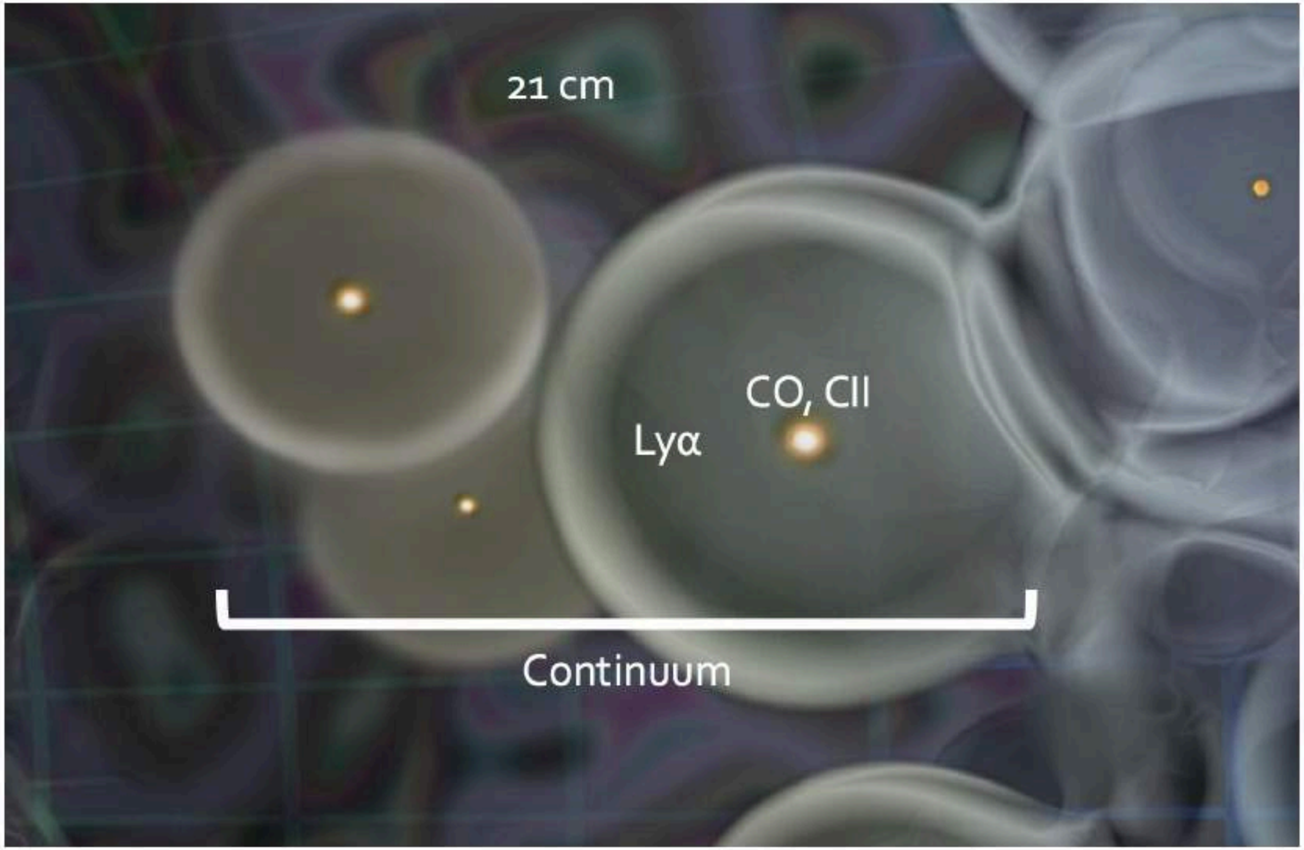
CO emission



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)



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)

IM Formalism

Matter power spectrum — Shot noise power spectrum

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

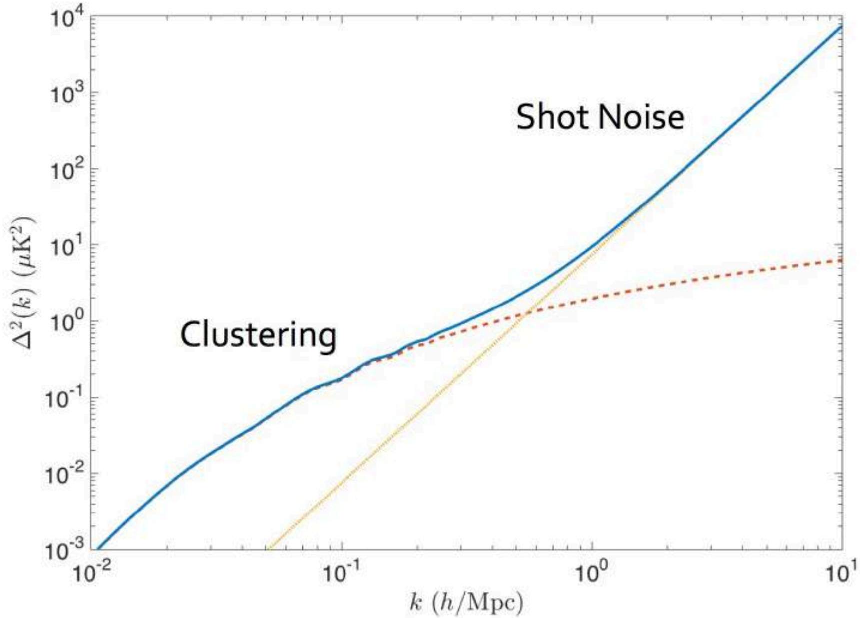
bias

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

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

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

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

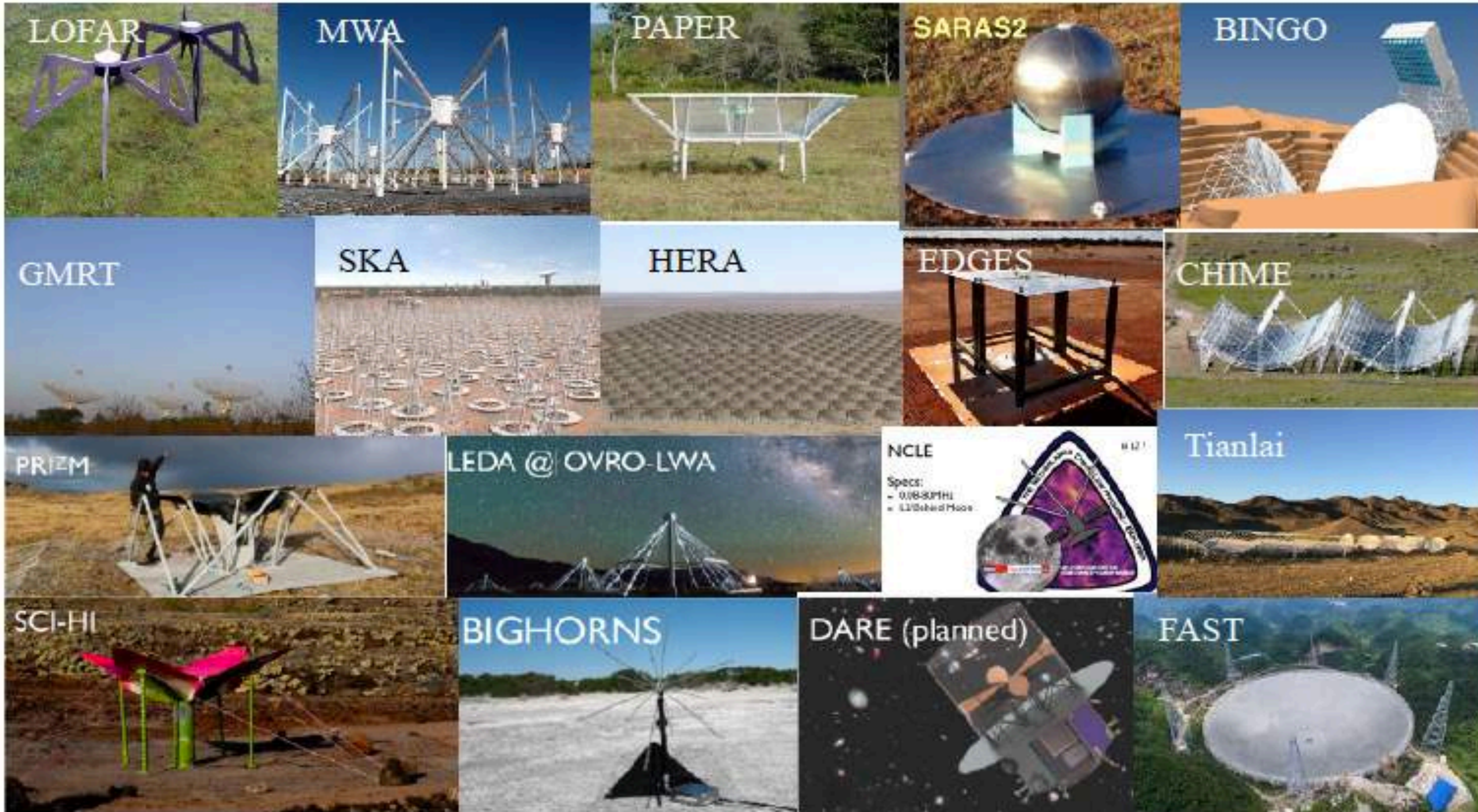
Kovetz et al. (arXiv:1709.09066)

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

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


LOFAR
MWA
PAPER
SARAS2
BINGO
GMRT
SKA
HERA
EDGES
CHIME
PRIZM
LEDA @ OVRO-LWA
NCLE
Specs:
Tianlai
SCI-HI
BIGHORNS
DARE (planned)
FAST

Intensity Mapping experiments status

Probe		Results Published	Currently Observing / Under Construction		Planned
HI	Low z	GBT Parkes	CHIME HIRAX → PRIZM TAINLAI →	SKA BINGO GBT-HIM	
	Med. z	PAPER	HERA →		
Lyalpha Hbeta Halpha					SPHEREX
CO		COPSS	mmIME	AIM-CO COMAP	
[CII]				TIME CONCERTO	CCAT-p PIXIE
[NII]				STARFIRE	
[OI]					

credit: Abigail Crites

Desirable items for a single dish HI surveyor

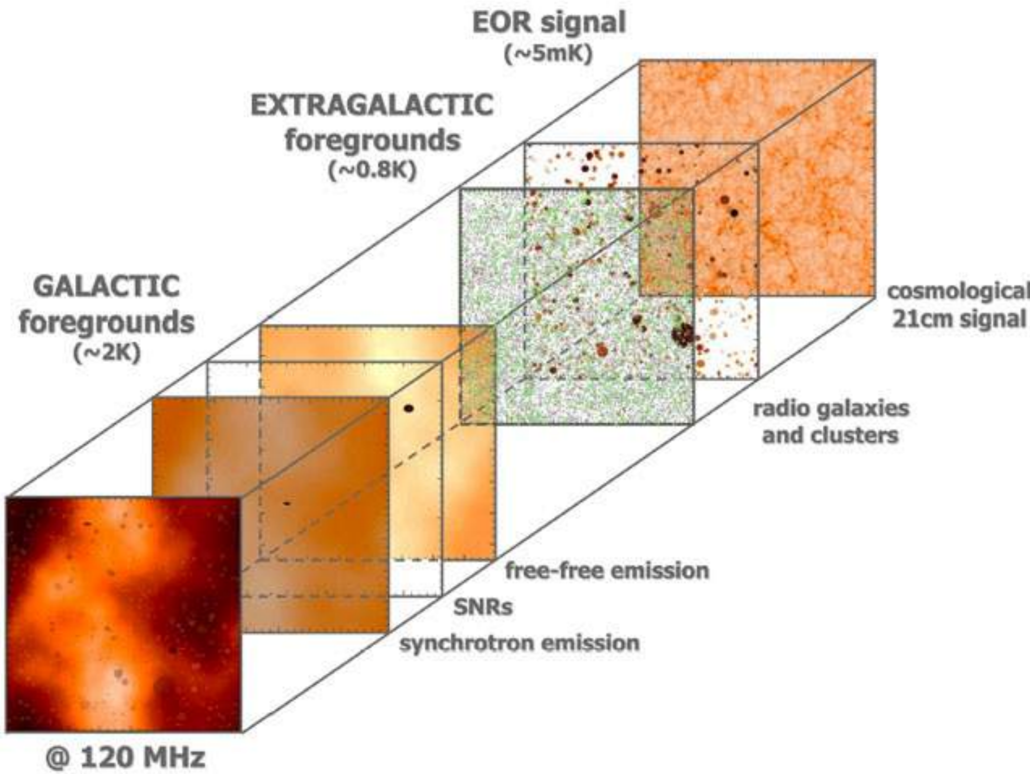
- Large collecting area (> 500 m^2)
- Large covered area on the sky (care should be take… …ving out very small scales, < 0.1 Mpc.h^{-1})
- Low sidelobes and good (precise shape) b…
- Long observing time (> 1 year)
- Sensitivity to intermediate scal… …AO is important (0 < z < 2)
- Redshift range: 0.1 < z < 1 … … than 0.7 after that)
- Frequency range:
  - 1300 MHz => z≈0…
  - 100 MHz =>

BINGO meets all of them!!!

BUT…. lots of Radio Frequency Interference (RFI) in this frequency range

Adapted from Bull et al. 2015

Foreground removal



1. Astrophysical Challenges
   1. Foregrounds: total intensity
   2. Foregrounds: polarized
   3. Ionosphere
   4. Etc.
2. Instrumental challenges
   1. Beam stability
   2. Calibration
   3. Resolution
   4. uv coverage
   5. Etc.
3. Computational challenges
   1. Multi petabyte data set
   2. Calibration
   3. inversion

The BINGO Telescope

BAOs from Integrated Neutral Gas Observations

BINGO - BAOs in Integrated Neutral Gas Observations

Visit us at https://bingotelescope.org

C. A. Wuensche (2021)

Our sponsors

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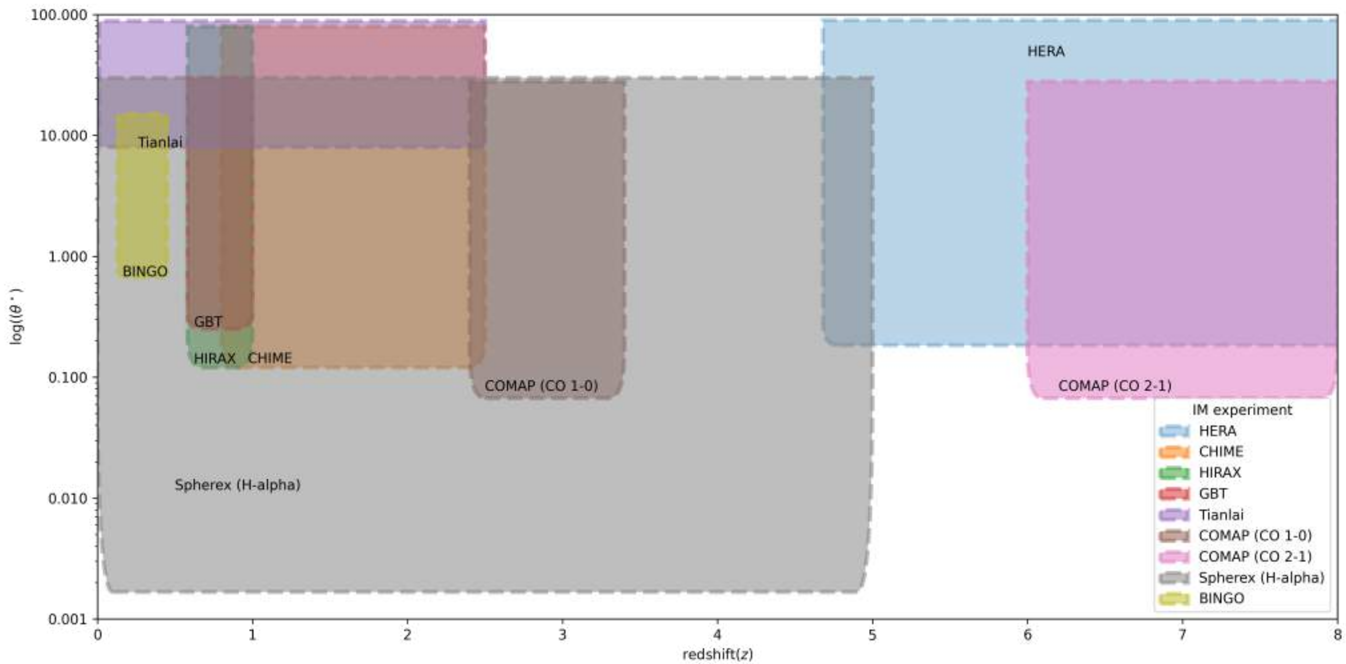
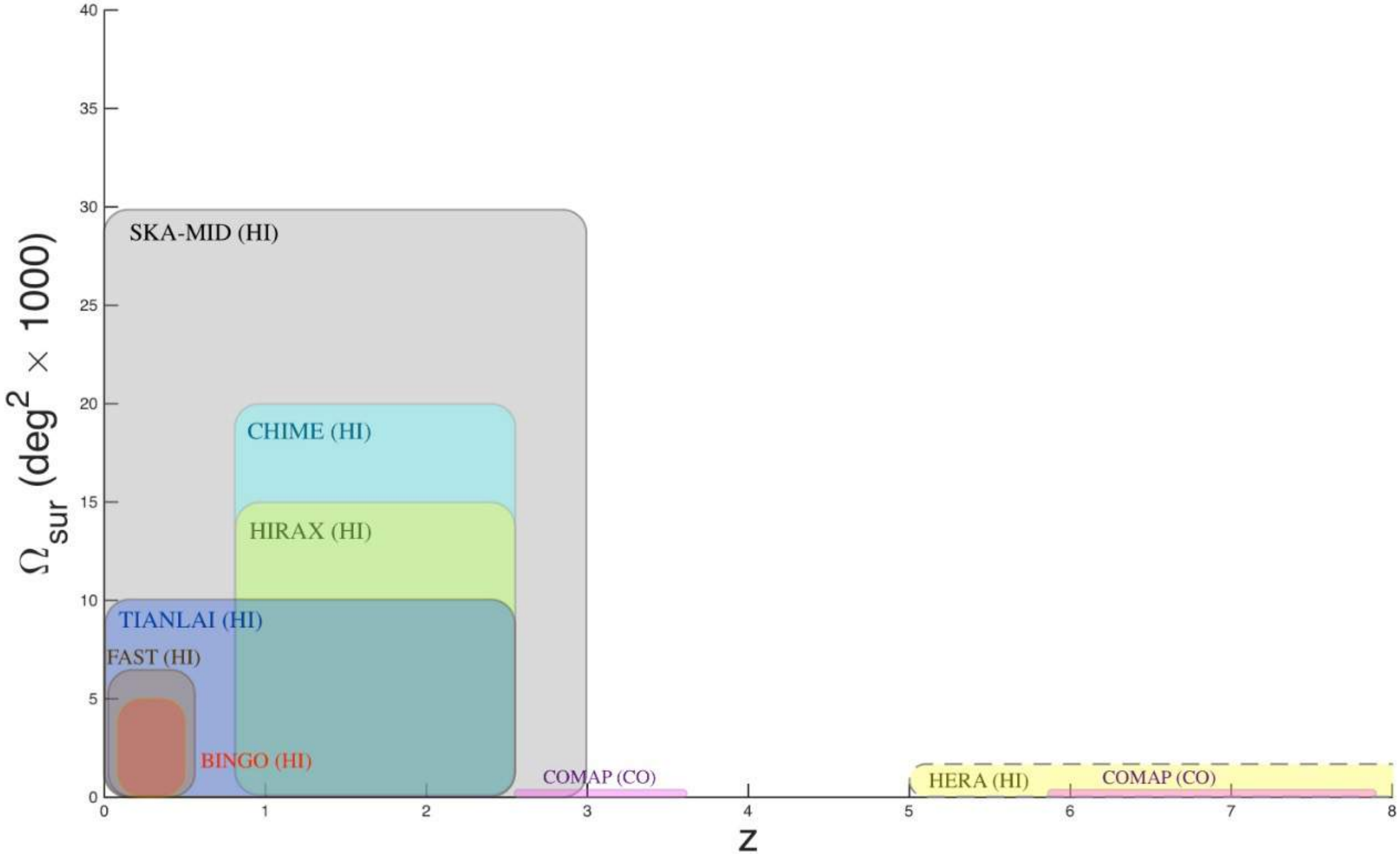
A survey of current and future experiments…



Source: The BINGO Collaboration



Abdalla et al. (arXiv:2107.01633, 2021

The BINGO main science case

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

- 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

Additional science with BINGO

- BAOs contain additional information about matter density, redshift distortions and anisotropic BAOs…
- Life history of hydrogen
- Radio recombination lines
- Galactic continuum
- **FRBs**, delivered "for free" due to the nature of BINGO observational strategy

Project management status (December 2021)

- Most of the funding (> 60%) is already granted
  - FAPESP: main funding agency
  - General coordination: Elcio Abdalla (IF/USP)
  - Management team: C. A. Wuensche (INPE), Luciano Barosi (UFCG), Filipe Abdalla (UCL), Bin Wang (YangZhou Univ.)

- BINGO construction proceeds…
  - Road work and site preparation started January 2021
  - Horn, transitions, polarizer, and magic tee prototypes successfully tested (2018 – 2021)
  - Main receiver components (first stage LNAs and filters, secondary LNAs and filters) qualified (2020 – 2021)
  - Simple radiometer successfully integrated to the digital backend at INPE
  - First horn prototype coupled to a simple radiometer currently looking at the sky in Paraíba
  - Optical design completed (2021)
  - Civil engineering project near completion
  - Data analysis pipeline in a very advanced stage – needs integration in an end-to-end format

Project management status (December 2021)

YESTERDAY THE PARAIBA STATE GOVERNMENT GRANTED
R$ 12M FOR DISH FABRICATION

- ☐ General coordination:
- ☐ Management team: C. Wang (YangZhou Univ.

- BINGO construction p
  - ☐ Road work and site pre
  - ☐ Horn, transitions, polar
  - ☐ Main receiver compon (2020 – 2021)
  - ☐ Simple radiometer suc
  - ☐ First horn prototype cc
  - ☐ Optical design complet
  - ☐ Civil engineering proje
  - ☐ Data analysis pipeline i

C. A. Wuensche (2021)

The “FIDUCIAL” BINGO – Phase 1 (June 2021)

TELESCOPE INFORMATION	
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
Primary area (m^2)	1620
Effective area (average, m^2)	
Number of horns	
Telescope orientation	
Central declination (deg.)	

RECEIVER INFORMATION	
T_sys (K)	70
Minimum frequency (MHz)	980
Maximum frequency (MHz)	1260
Frequency band (for 30 channels, MHz)	9.33
Instrument noise (mK, 1 second)	26.5
Digital backend FFT channels	2048
Sampling time (s)	0.1

…VEY INFORMATION	
…on (FWHM, deg.)	0.67
…d area (sqr deg)	5300

Fixed wire-mesh parabolas

No moving parts

Transit telescope

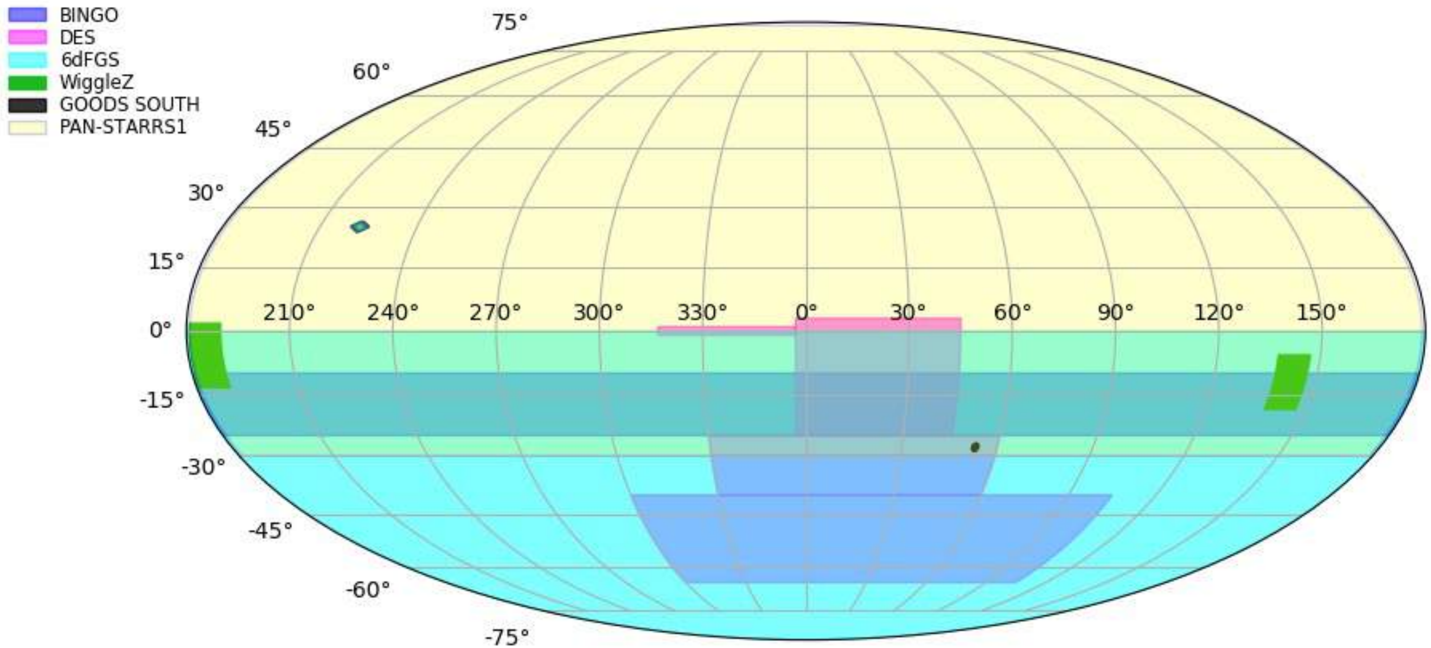
Most components “off-the-shelf”

Guiding principle : simplicity !

Challenges (December 2021)

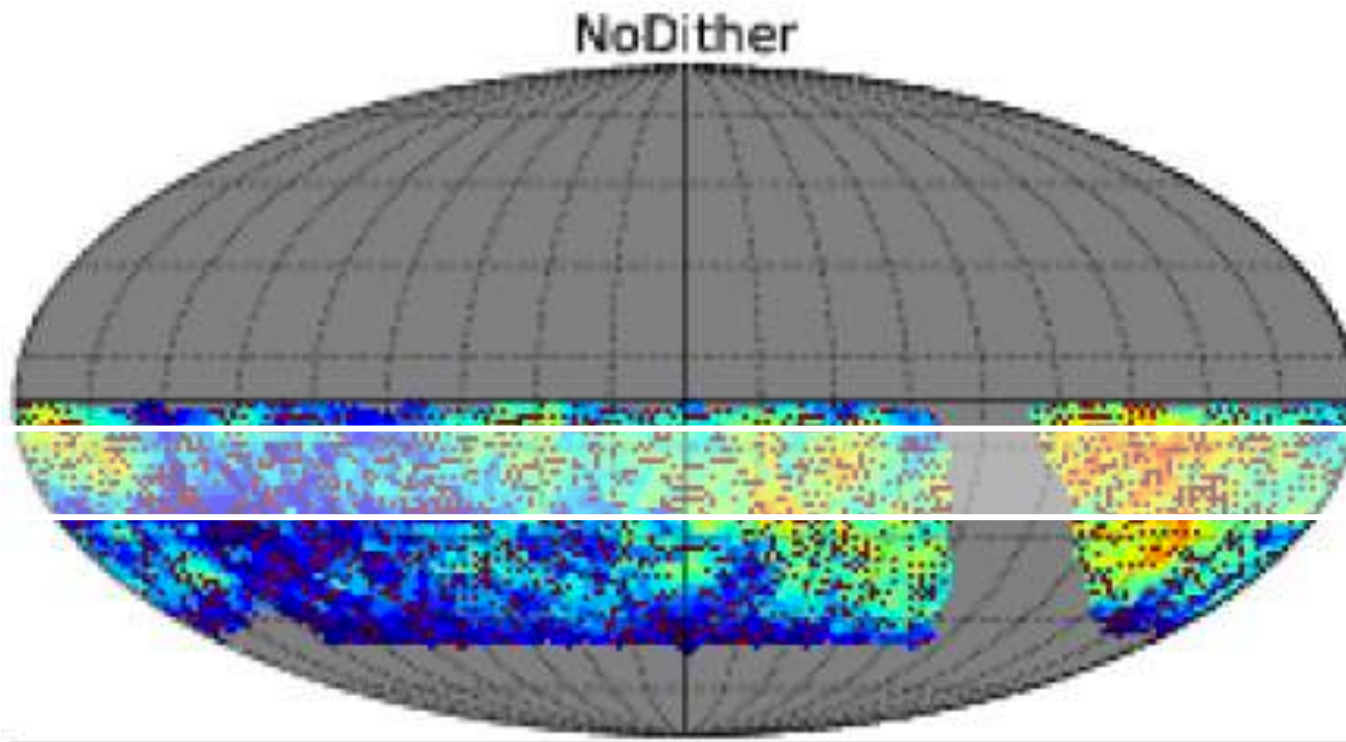
- Large telescope: **dishes will be made in China, should be mounted, aligned with the needed precision**
- Large horns: **fabrication process understood, working with the manufacturing company to improve horn fabrication process**
- Calibration and stability: **use colfets and a CW source as internal calibration. Noise and stability for both are the final steps for the full correlation**
- Receiver stability: **working on a Peltier cooling system to reduce system temperature and improve system stability**
- Digital backend**: SKARAB boards are in the lab. ROACH2 was integrated to the receiver and, as soon as the tests are completed we will migrate the software to the SKARABs**
- Optical design: **optics simulations indicate very small distortions of the beams for the current horn array. Final horn positioning in the structure are being calculated.**
- Radio Frequency Interference: **Mobile quiet zone implementation is negotiated with ANATEL**

Sky coverage



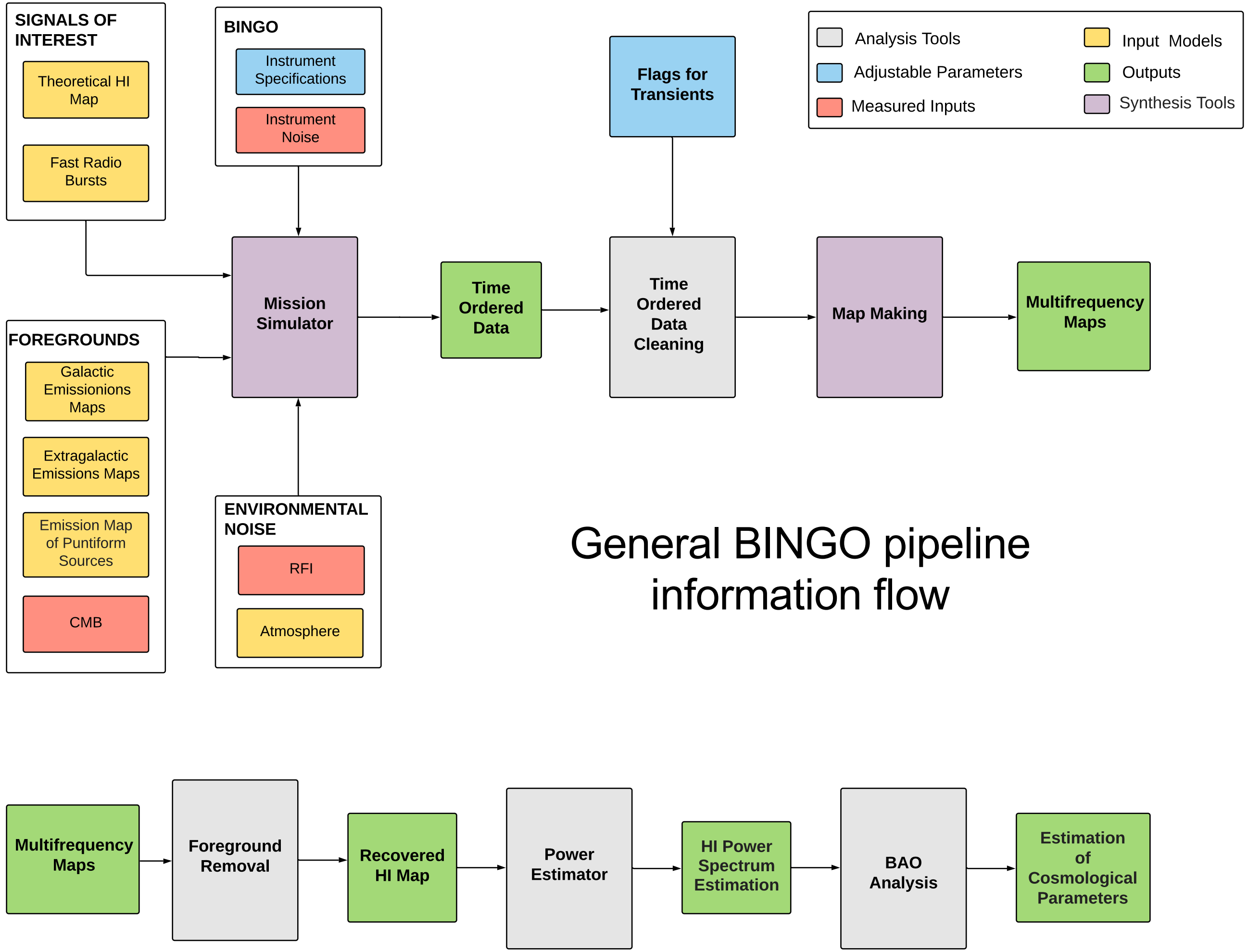
Source: The BINGO Collaboration

LSST Cosmology map



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

General BINGO pipeline information flow



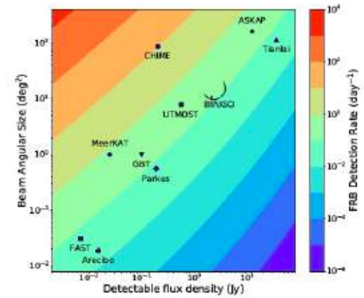
From E. Merícia

E. Abdalla et al. "The BINGO Project I: Baryon Acoustic Oscillations from Integrated Neutral Gas Observations".
arXiv:2107.01633

Contents

* eabdalla@usp.br

FRB detection estimates



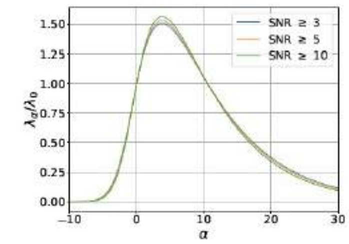
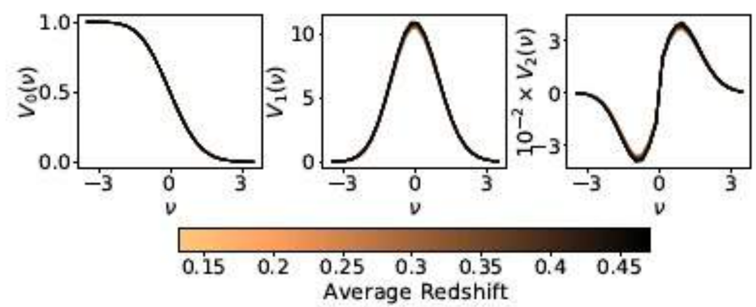
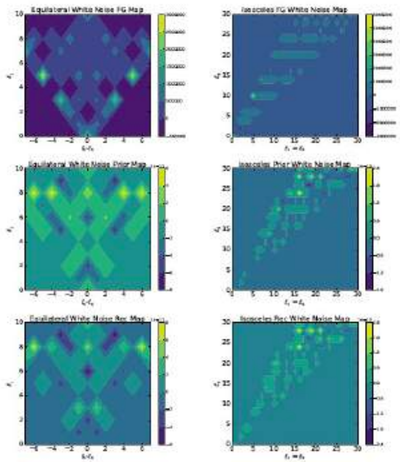


Fig. 9: Detection rate for the BINGO telescope for different spectral indices and SNRs, normalized to the corresponding values for $\alpha = 0$.

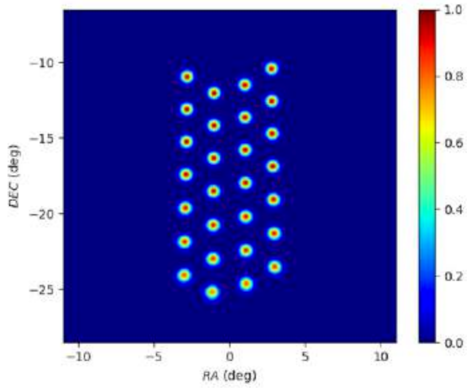
Minkowski functionals

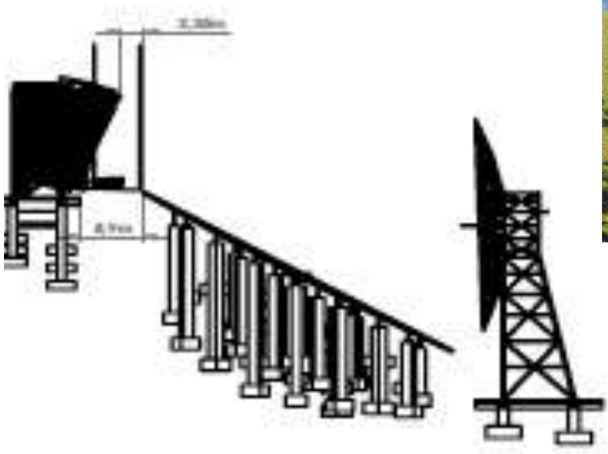




Bispectrum analysis

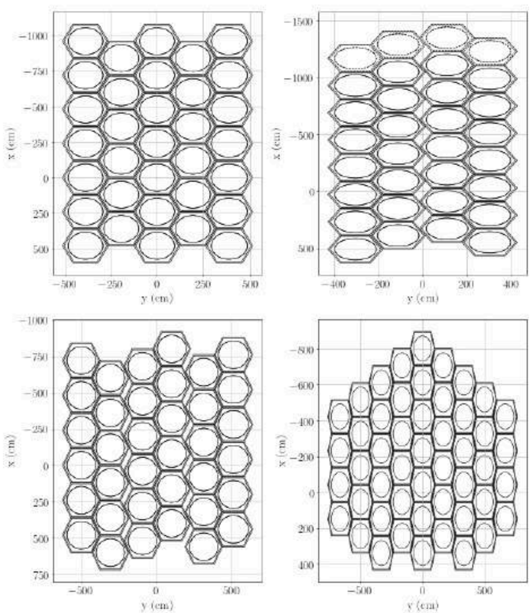
C. A. Wuensche et al. " The BINGO Project II: Instrument Description".
arXiv:2107.01634

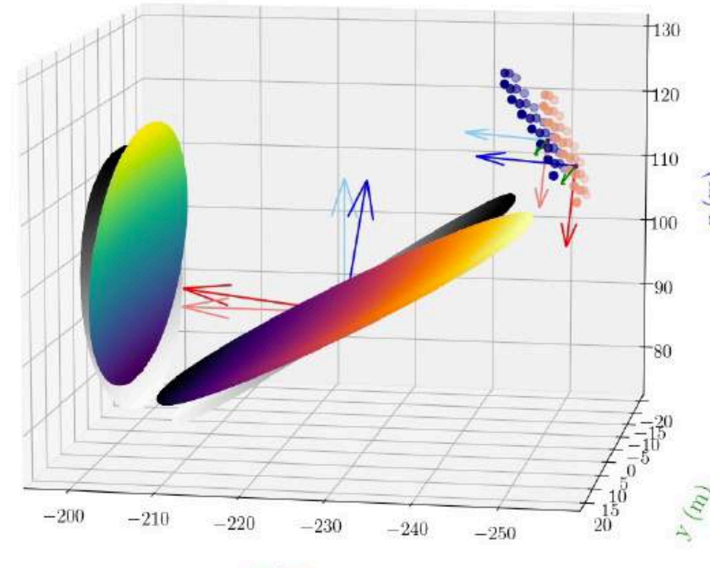


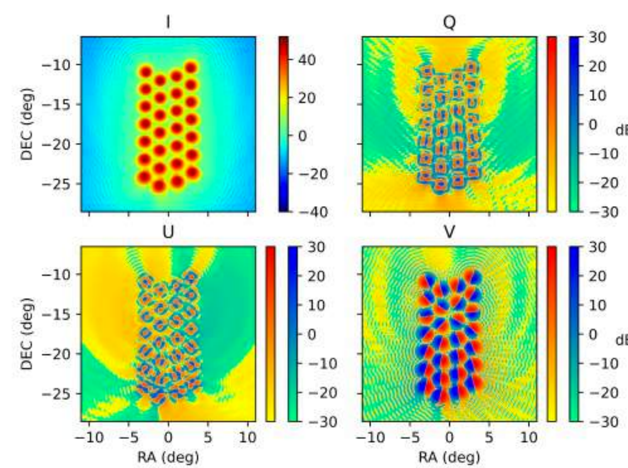


C. A. Wuensche (2021)

F. Abdalla et al. "The BINGO Project III: Optical design and optimisation of the focal plane
arXiv:2107.01635

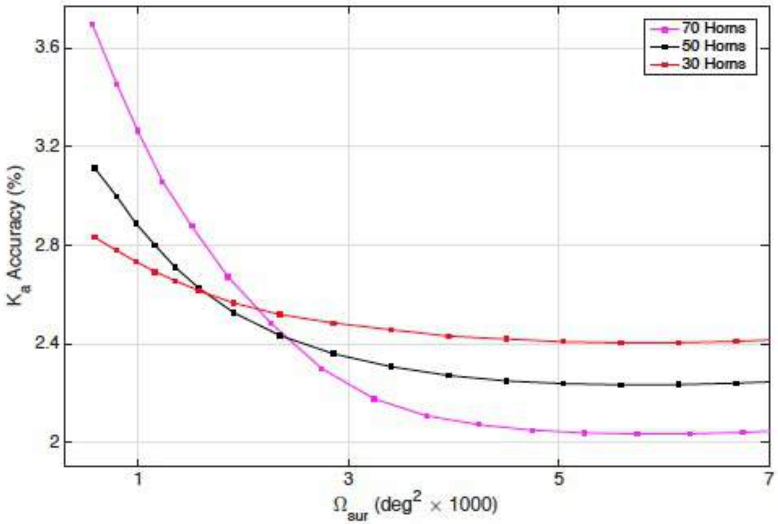


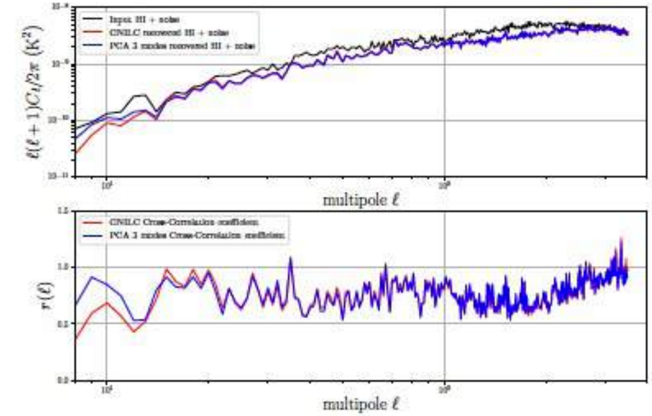


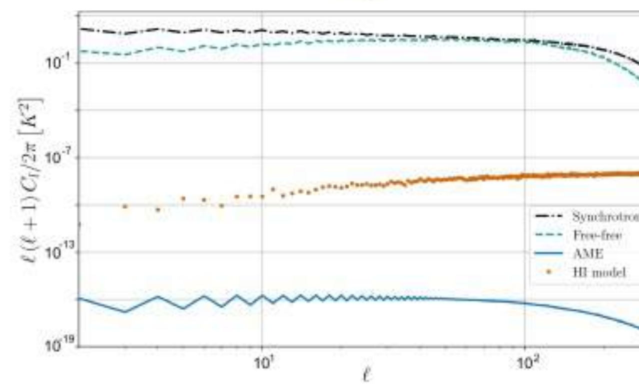


Design of an optimal configuration for the optical system, including the focal plane positioning and the beam behavior for BINGO. The chosen optical design meets the requirements for the project in terms of polarisation purity, area coverage as well as homogeneity of coverage so that BINGO can perform a successful BAO search.

V. Liccardo et al. "The BINGO Project IV: Simulations for mission performance assessment and preliminary component separation steps"
arXiv:2107.01636

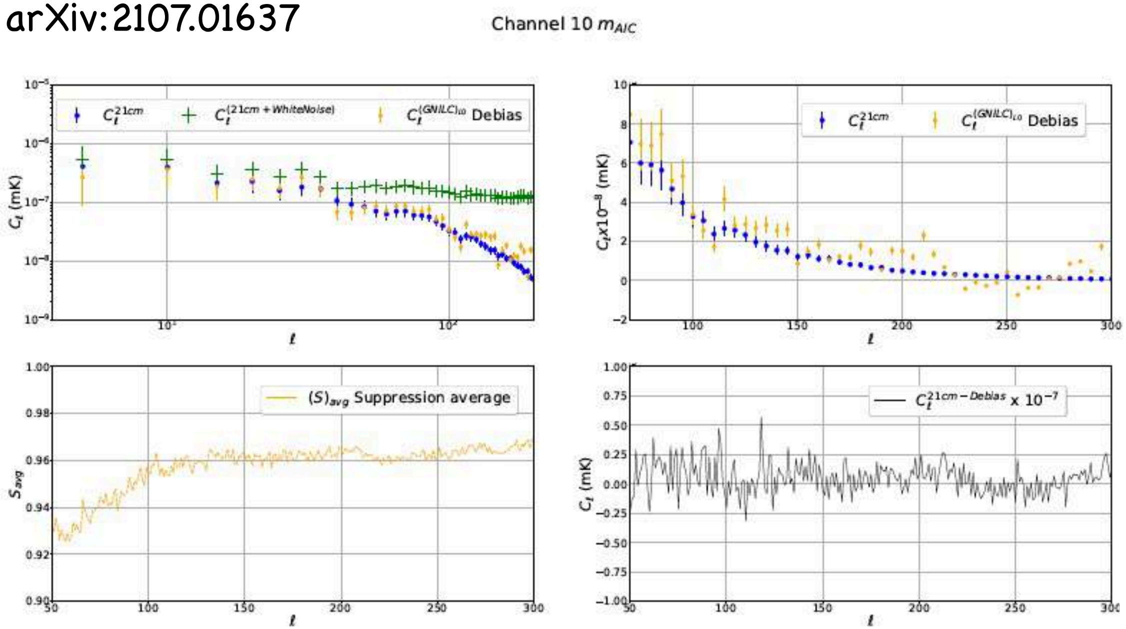






Simulations of a single-dish IM experiment with BINGO characteristics. According to the results obtained we have optimized the focal plane design of the telescope. We found it is feasible to extract the cosmological signal across a wide range of multipoles and redshifts.

K. Fornazier et al. "The BINGO Project V: Further steps in Component Separation and Bispectrum Analysis"
arXiv:2107.01637



- The component separation method allows the subtratiion of the foreground contamination in the BINGO channels down to levels below the cosmological signal and the noise, and to reconstruct the 21-cm power spectrum for different redshift bins without significant loss at multipoles 20< l < 500.
- The bispectrum analysis yields strong tests of the level of the residual foreground contamination in the recovered 21-cm signal, thereby allowing us to both optimize and validate our component separation analysis.

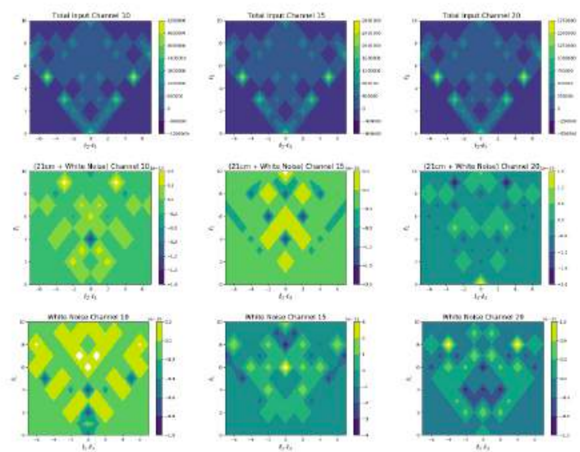
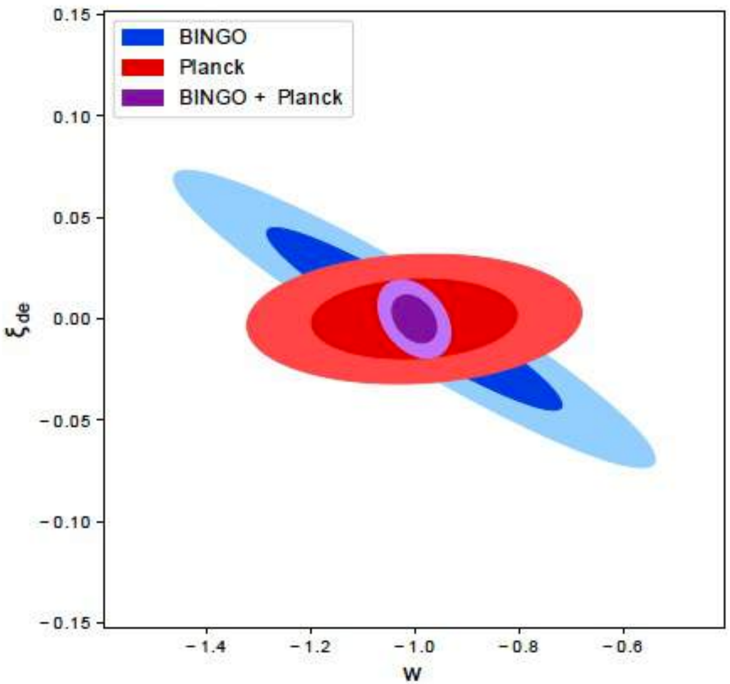
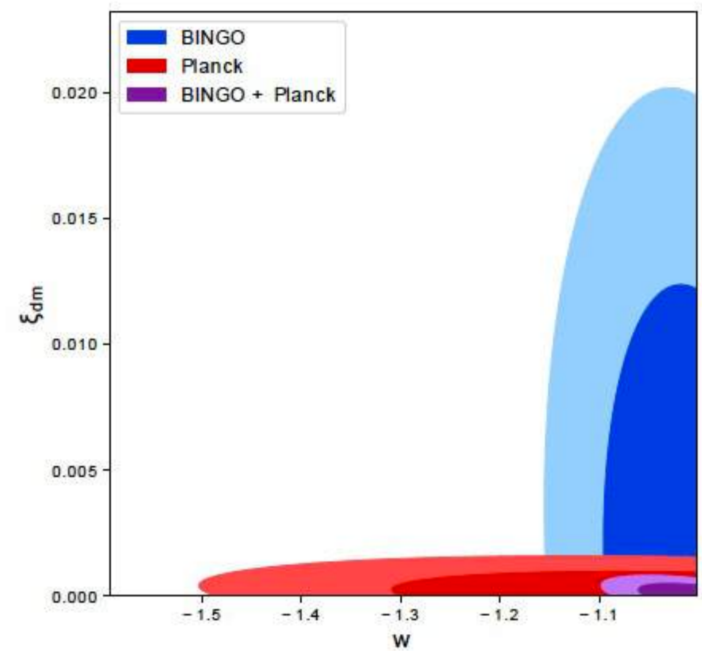


Fig. 13. Contour charts for the equisize configuration of the bispectrum in three different channels: 10 (first column), 15 (second column) and 20 (third column). Each line is related to each case analyzed: total foregrounds (first row), 21cm + white noise (second row) and white noise (third row).

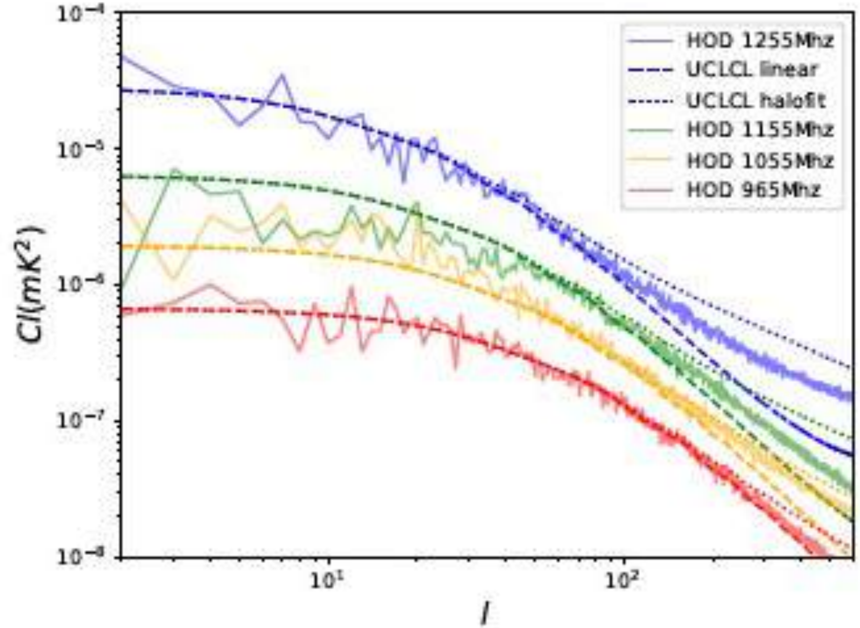
A. A. Costa et al. "The BINGO Project VI: Hi Halo Occupation Distribution and Mock Building" arXiv:2107.01639





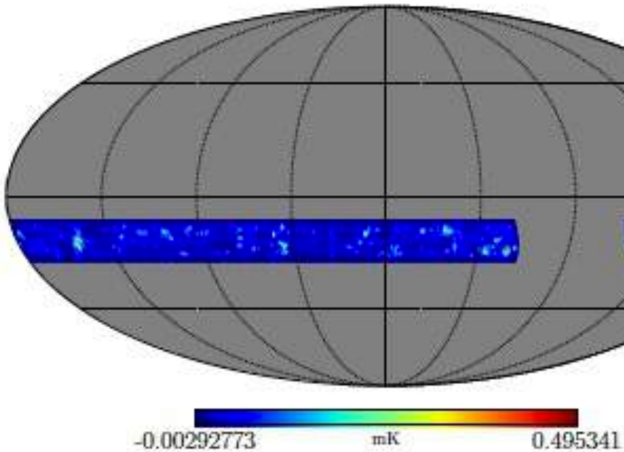
J. Zhang et al. "The BINGO Project VII: Cosmological Forecasts from 21-cm Intensity Mapping" arXiv:2107.01638

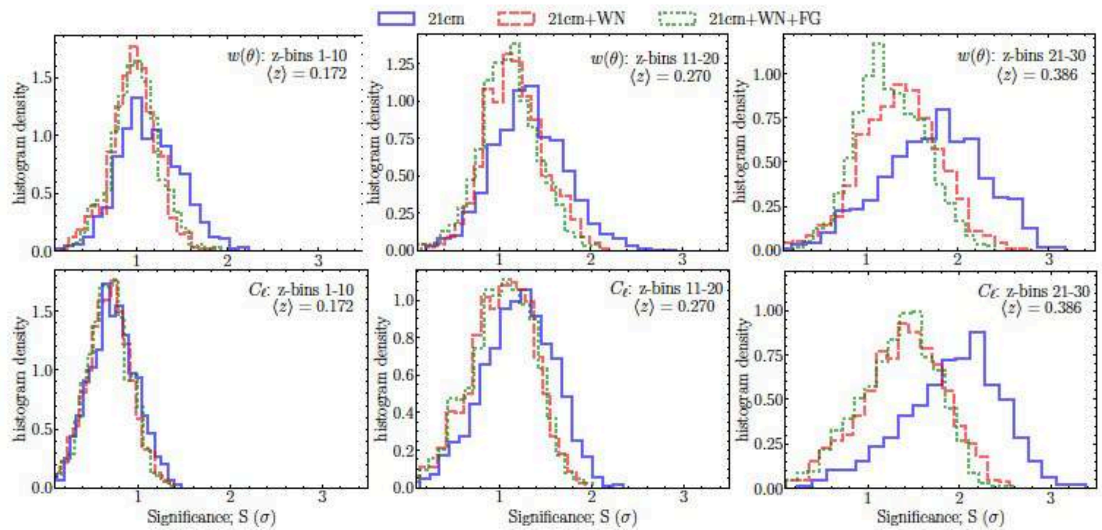
1 What is the effect of different ways of linking HI gas with galaxies (halos)?
2 What is the effect of RSD in angular power spectrum?
3 Can we identify the above difference with BINGO telescope?



- We have found that the bias is highly sensitive to the method of populating Hi in halos, which also means we can put constraints on the Hi distribution in halos by observing 21-cm intensity mapping.
- We have also illustrated that only with thin frequency bins (such as 2 MHz), we can discriminate the effect of Finger-of-God.
- All of our investigations using mocks provide useful guide for our expectation of BINGO experiments and other 21-cm intensity mapping experiments.

C. Novaes et al. "Forecasts on measuring the BAO signal with BINGO Hi intensity Mapping". Under final revision, to be submitted to arXiv in Jan. 2022





Forthcoming papers

- **FRB data analysis (led by Marcelo Novaes)**
- **Refining of foreground separation methods and map making (led by Eduardo Mericia)**
- **The BINGO receiver (led by Fred Vieira)**
- **Cross-correlations with optical surveys**
- **Other works in progress**

Our schedule, as of today, is to have the final system assembled and ready to start commissioning time no later than March 2023

Thank you!

Visit us at http://www.bingotelescope.org