BINGO Pipeline overview

(BINGO forecasting for non-gaussian features in 21cm intensity mapping)

Karin Fornazier - INPE

BINGO Pipeline

Leader: Filipe B. Abdalla (UCL)

TEAM: **Jordany Vieira (PhD Student- IFUSP)**, Lucas Olivari (Pos-Doc-IFUSP), André Alencar da Costa (Pos-Doc IFUSP), Henrique Xavier (Pos-Doc UCL), Isabela Carruci (Pos-Doc UCL), Alessandro Marins (PhD Student- IFUSP), Priscilla Gutierres (Msc Student IFUSP-IME), Andrei Cuceu (PhD Student UCL)

BINGO

TOPICS

- Motivation
- Intensity Mapping
- BINGO
- BINGO Pipeline
- Bispectrum Module

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

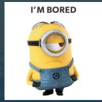
Motivation

The distribution of perturbations in the matter density supplies a wealth of information on the late-time evolution of the Universe on cosmological scales.

Optical redshift surveys → redshift $z<1.5$ → BAO or RSDs

large integration times → limits the number density of sources with observed redshifts and restricts the maximum radial distance

Photometric redshift surveys → higher number density of sources and reach larger redshifts



cost of losing almost all the relevant information in the radial direction

Intensity Mapping → is based on measuring the radio emission from different patches of the sky and different frequencies.

INTENSITY MAPPING

Any pocket of neutral hydrogen will emit in the isolated 21cm line → $\nu_{obs} = \nu_{21}/(1+z)$, where $\nu_{21} = 1420.4$ MHz → rest-frame frequency of the 21cm line → hyperfine spin-flip transition of the 1s ground state.

Probing dark energy with baryonic oscillations and future radio surveys of neutral hydrogen F. B. Abdalla S. Rawlings

Measuring the intensity of radio emission from different directions in the sky, it is in principle possible to trace 3D distribution of neutral hydrogen in the Universe

Intensity Mapping → not to focus on measuring the flux of individual galaxies, but rather the combined emission arriving from relatively wide patches of the sky

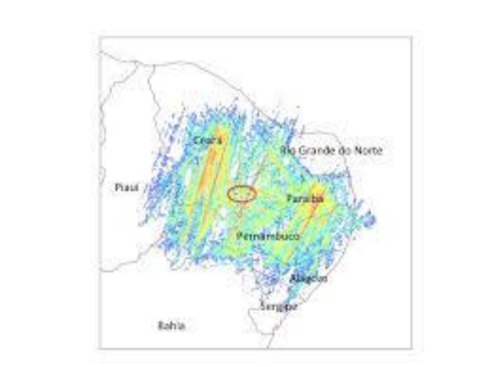
Jeff Peterson et al (https://arxiv.org/abs/0902.3091)

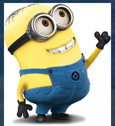
Battye R. A., Davies R. D., Weller J., 2004, Mon. Not. Roy. Astron. Soc., 355, 1339

BINGO

BINGO (<u>Baryon Neutral Gas Acoustic Oscillation Observations)</u>
radio telescope designed to make detections of Radio Acoustic Oscillations by means of radiofrequency.

Investigate BAO using HI emission at redshifted frequencies between 960 and 1260 MHz (0,48 > z > 0,13).





We need a pipeline to simulate and analyse data

C. A. Wuensche et al. https://arxiv.org/pdf/1803.01644.pdf

BINGO Pipeline HIDE & SEEK

HIDE (HI Data Emulator) & SEEK (Signal Extraction and Emission Kartographer) is a set of two independent software packages that simulate and analyze single-dish radio survey data.

HIDE forward models the entire radio survey system chain:

https://github.com/cosmo-ethz/hide

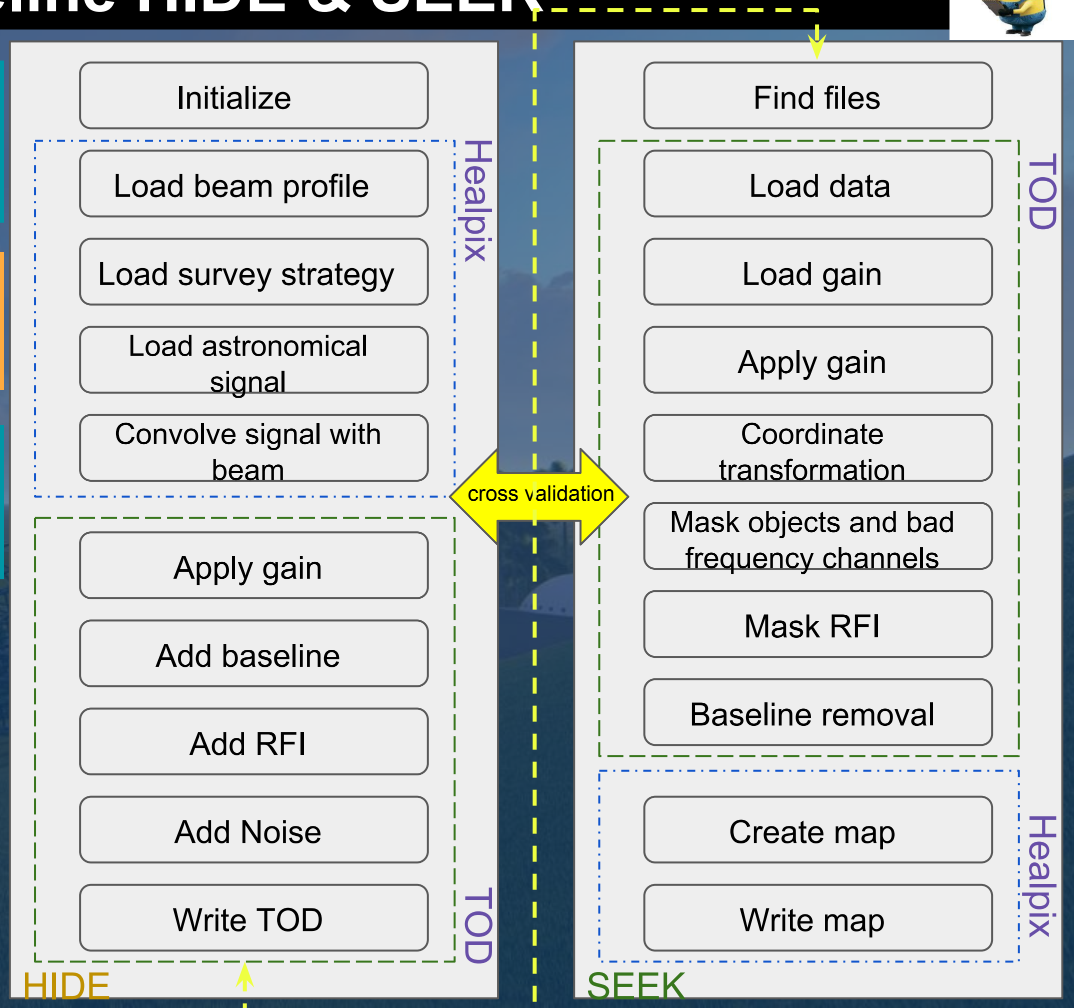
SEEK processes simulated (or observed) survey data

https://github.com/cosmo-ethz/seek

single-dish → 1 horn

(Blaine Radiotelescopy)

HIDE & SEEK: End-to-End Packages to Simulate and Process Radio Survey Data Joel Akeret et al, 2016



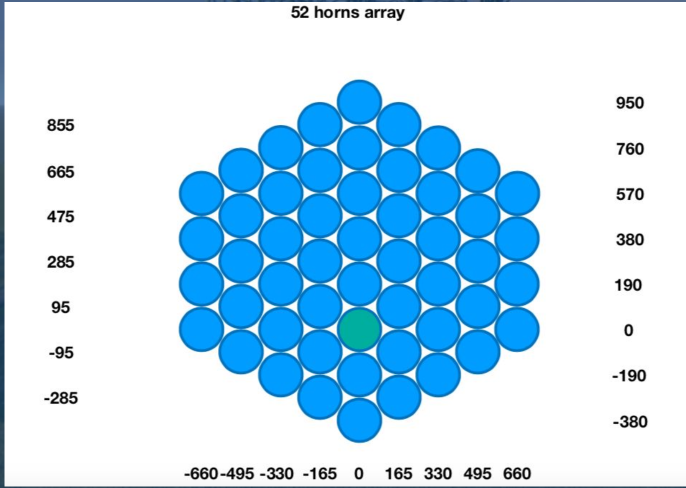
Pipeline HIDE & SEEK-4 BINGO

HIDE 4 BINGO:

https://bitbucket.org/lolivari/hide4bingo

SEEK 4 BINGO

https://bitbucket.org/lolivari/seek4bingo




```
Created on August, 2018
author: Lucas Olivari
'''
from __future__ import print_function, division, absolute_import, unicode_literals

from ivy.plugin.parallel_plugin_collection import ParallelPluginCollection

####################################################################
#### THIS IS THE CONFIGURATION FILE THAT WILL SIMULATE BINGO
####################################################################
# ==================================================================
# TELESCOPE
# ==================================================================
# BINGO
#-----------------
telescope_latitude = -7.0
telescope_longitude = -35.
telescope_elevation = 0.          # altitude
```

BINGO case
double-dish → many horns

Pipeline HIDE & SEEK-4 BINGO - SKY MODULE

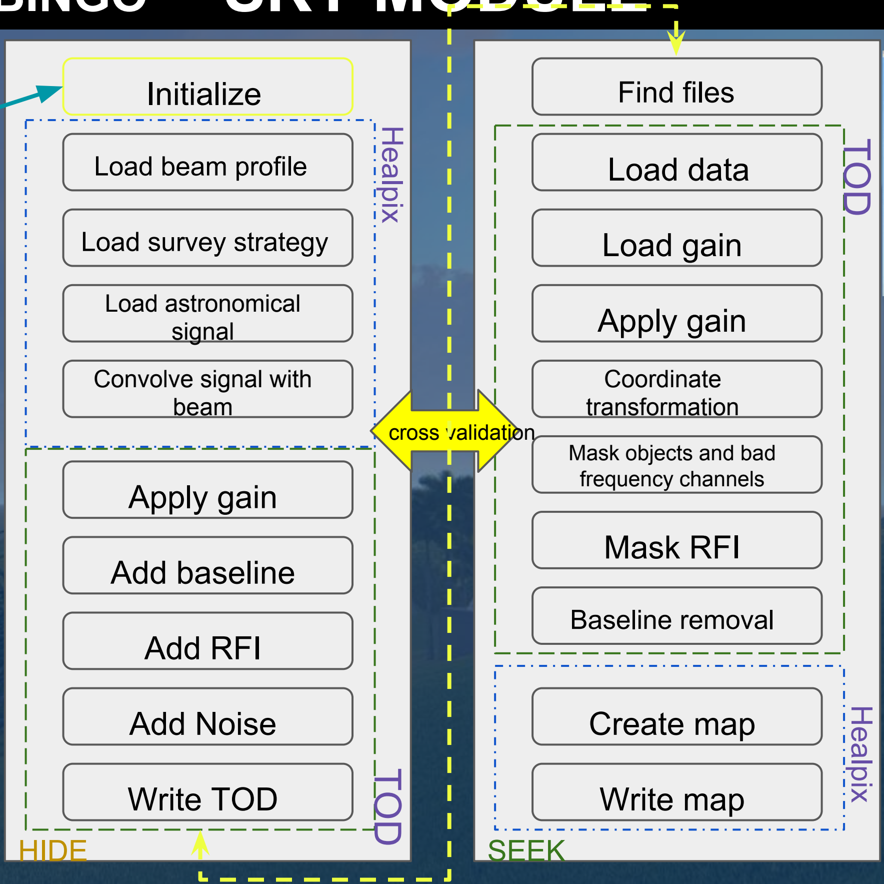
INPUT
- UCL-CL's → HI 21 cm
- Modified CAMB→ HI 21 cm
- FLASK
- Foregrounds
- Noise (Thermal Noise)

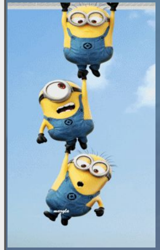
Modified CAMB→ HI 21 cm → Published in Eur.Phys.J. C78 (2018) no.9, 746 SLAC-PUB-17304

FLASK

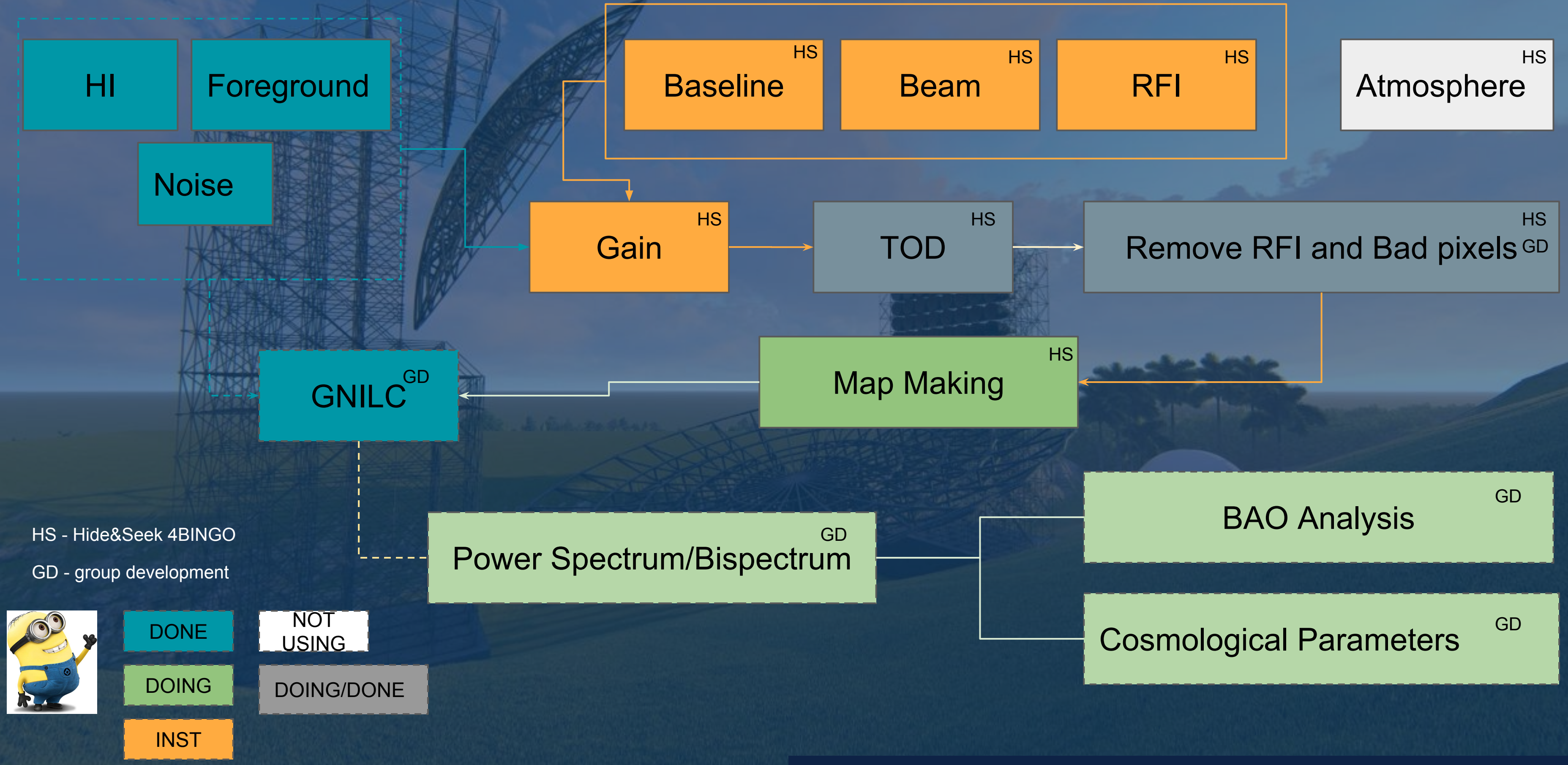
http://www.astro.iag.usp.br/~flask/

T_sky = T_21cm + T_CMB + T_sync + T_freefree + T_noise





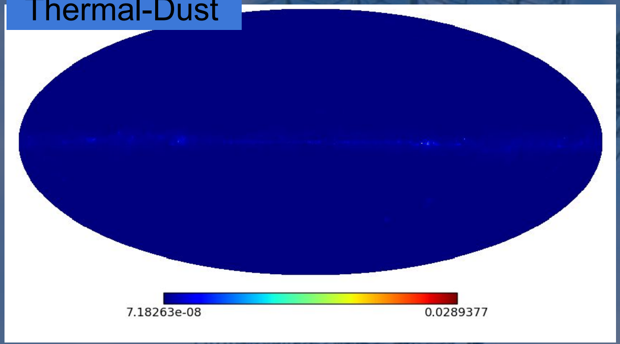
Pipeline HIDE & SEEK-4 BINGO - Data Flow



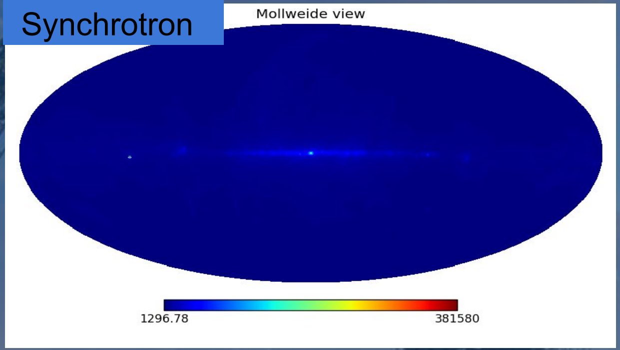
FAPESP-JPS Workshop on dark energy, dark matter and galaxies - Feb 2019

Pipeline HIDE & SEEK-4 BINGO - Module Foregrounds

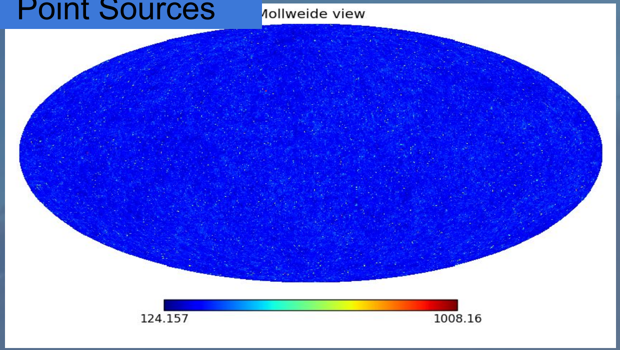
Thermal-Dust



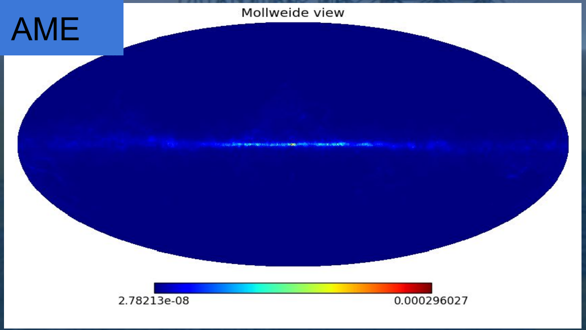
Synchrotron



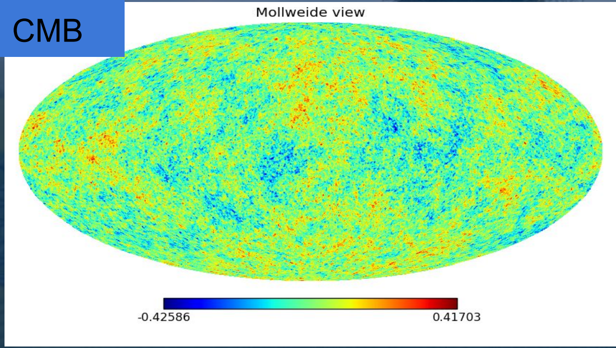
Point Sources



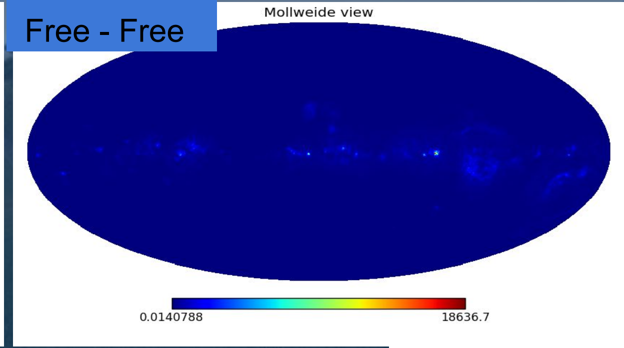
AME



CMB



Free - Free



https://arxiv.org/abs/1707.07647

Pipeline HIDE & SEEK-4 BINGO - GNILC

GNILC → Generalized Needlet Internal Linear Combination

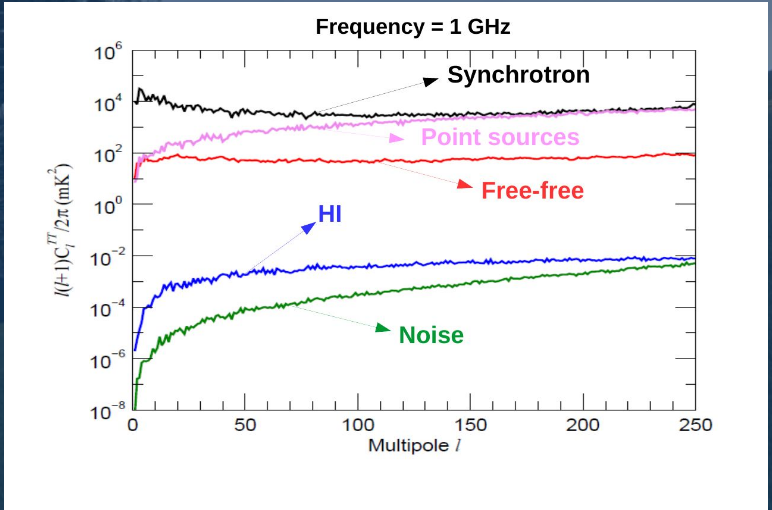
https://arxiv.org/abs/1707.07647

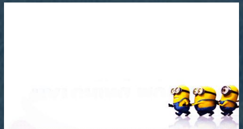
To perform any HI IM experiment we need to subtract the astrophysical contamination that will be present in the observed signal.

It is therefore important to quantify the potential contaminating effects of foreground residuals.

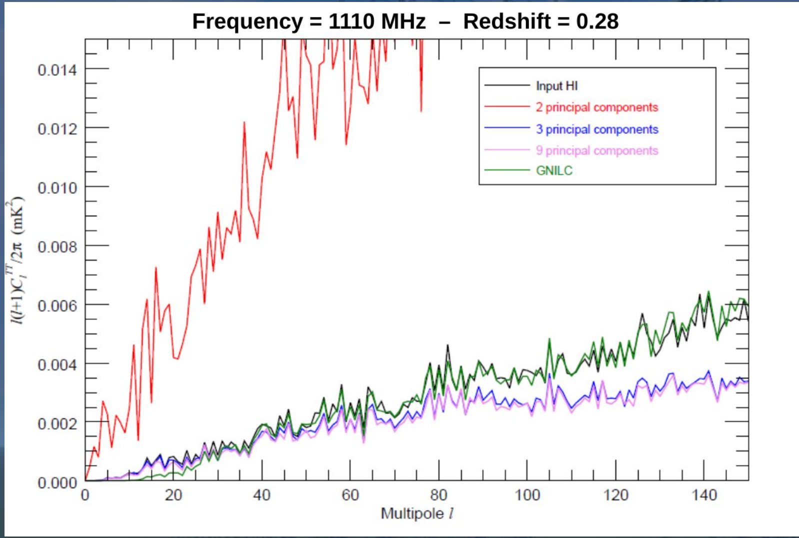
Uses both frequency and spatial information

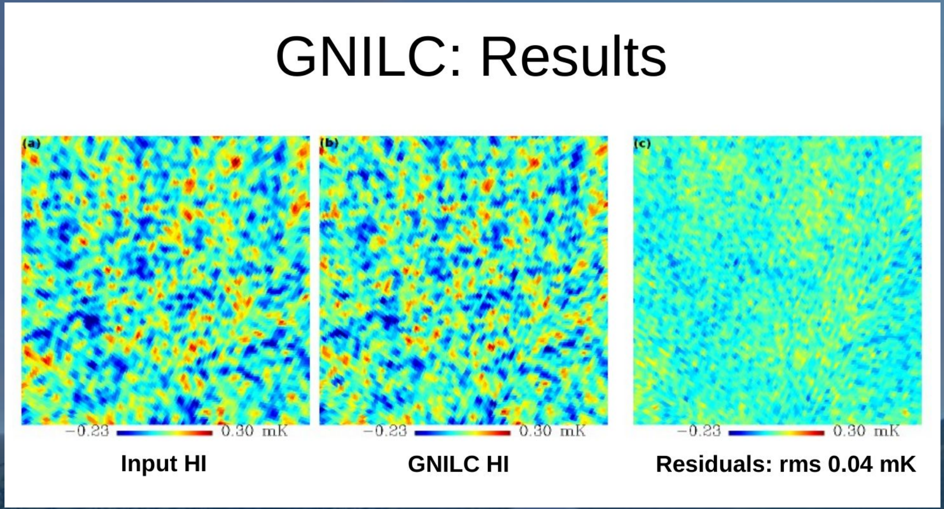
ILC: weight matrix that offers unit response to the desired component (HI) while it minimizes the total variance of the other components





Pipeline HIDE & SEEK-4 BINGO - GNILC





Non-Gaussianity - Bispectrum

1) Decompose the temperature anisotropy into multipoles

$$a_{lm} = \int d\hat{\mathbf{n}} \frac{\Delta T}{T}(\hat{\mathbf{n}}) Y^*_{lm}(\hat{\mathbf{n}})$$

2) The temperature can also be represented in terms of the primordial gravitational potential perturbation and the radiation transfer function

$$\frac{\Delta T}{T}(\hat{\mathbf{n}}) = \int \frac{d^3k}{(2\pi)^3} \sum_{l=0}^{\infty} (-i)^l (2l+1) \Psi(\mathbf{k}) \Delta_l(k) P_l(\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})$$

3) We replace the Legendre polynomial with it's spherical harmonic expansion

$$P_l(\hat{\mathbf{k}} \cdot \hat{\mathbf{n}}) = \frac{4\pi}{2l+1} \sum_{m=-l}^{l} Y_{lm}(\hat{\mathbf{k}}) Y^*_{lm}(\hat{\mathbf{n}})$$

4) Substituting gives an expression for the multipoles in terms of the primordial gravitational potential perturbation and the radiation transfer function

$$a_{lm} = 4\pi(-i)^l \int \frac{d^3k}{(2\pi)^3} \Psi(k) \Delta_l(k) Y^*_{lm}(\hat{\mathbf{k}})$$

Non-Gaussianity - Bispectrum

5) The bispectrum is the three point correlator of the alm 's

$$B^{m_1 m_2 m_3}_{l_1 l_2 l_3} = \langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle$$
$$= (4\pi)^3 (-i)^{l_1+l_2+l_3} \int \frac{d^3\mathbf{k}_1}{(2\pi)^3} \frac{d^3\mathbf{k}_2}{(2\pi)^3} \frac{d^3\mathbf{k}_3}{(2\pi)^3} \langle \Psi(\mathbf{k}_1)\Psi(\mathbf{k}_2)\Psi(\mathbf{k}_3) \rangle$$
$$\Delta_{l_1}(k_1)\Delta_{l_2}(k_2)\Delta_{l_3}(k_3) Y^*_{l_1 m_1}(\hat{\mathbf{k}}_1) Y^*_{l_2 m_2}(\hat{\mathbf{k}}_2) Y^*_{l_3 m_3}(\hat{\mathbf{k}}_3).$$

6)The three point correlator of the primordial gravitational potential perturbation consists of a delta function and a shape function F which only depends on the magnitudes of the k's

$$\langle \Psi(\mathbf{k}_1)\Psi(\mathbf{k}_2)\Psi(\mathbf{k}_3) \rangle = (2\pi)^3 F(k_1, k_2, k_3) \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

7) We substitute and replace the delta function with its integral representation expanded in Bessel functions and spherical harmonics

$$\delta(\mathbf{k}) = \frac{1}{(2\pi)^3} \int e^{i\mathbf{k}\cdot\mathbf{x}} d^3x$$

$$e^{i\mathbf{k}_1\cdot\mathbf{x}} = 4\pi \sum_l i^l j_l(k_1 x) \sum_m Y_{lm}(\hat{\mathbf{k}}_1) Y^*_{lm}(\hat{\mathbf{x}})$$

8) The bispectrum then splits into a geometric factor given by the Gaunt integral times the reduced bispectrum

$$B^{m_1 m_2 m_3}_{l_1 l_2 l_3} = \mathcal{G}^{l_1 l_2 l_3}_{m_1 m_2 m_3} b_{l_1 l_2 l_3}$$

Non-Gaussianity - Bispectrum

8) The bispectrum then splits into a geometric factor given by the Gaunt integral times the reduced bispectrum

$$B^{m_1 m_2 m_3}_{l_1 l_2 l_3} = \mathcal{G}^{l_1 l_2 l_3}_{m_1 m_2 m_3} b_{l_1 l_2 l_3}$$

$$\mathcal{G}^{l_1 l_2 l_3}_{m_1 m_2 m_3} = \int d\Omega \, Y_{l_1 m_1} Y_{l_2 m_2} Y_{l_3 m_3} = \sqrt{\frac{(2l_1+1)(2l_2+1)(2l_3+1)}{4\pi}} \begin{pmatrix} l_1 & l_2 & l_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$

$$b_{l_1 l_2 l_3} = \left(\frac{2}{\pi}\right)^3 \int dx dk_1 dk_2 dk_3 (x k_1 k_2 k_3)^2 F(k_1, k_2, k_3) \Delta_{l_1}(k_1) \Delta_{l_2}(k_2) \Delta_{l_3}(k_3) j_{l_1}(k_1 x) j_{l_2}(k_2 x) j_{l_3}(k_3 x).$$

Binned bispectrum estimator

Binned, or coarse-grained, pseudo-bispectrum → full-sky spherical harmonic transforms → masked sky → recovered alm coefficients are a convolution of the real CMB multipole coefficients with the multipole coefficients of the mask.

https://arxiv.org/abs/1509.08107

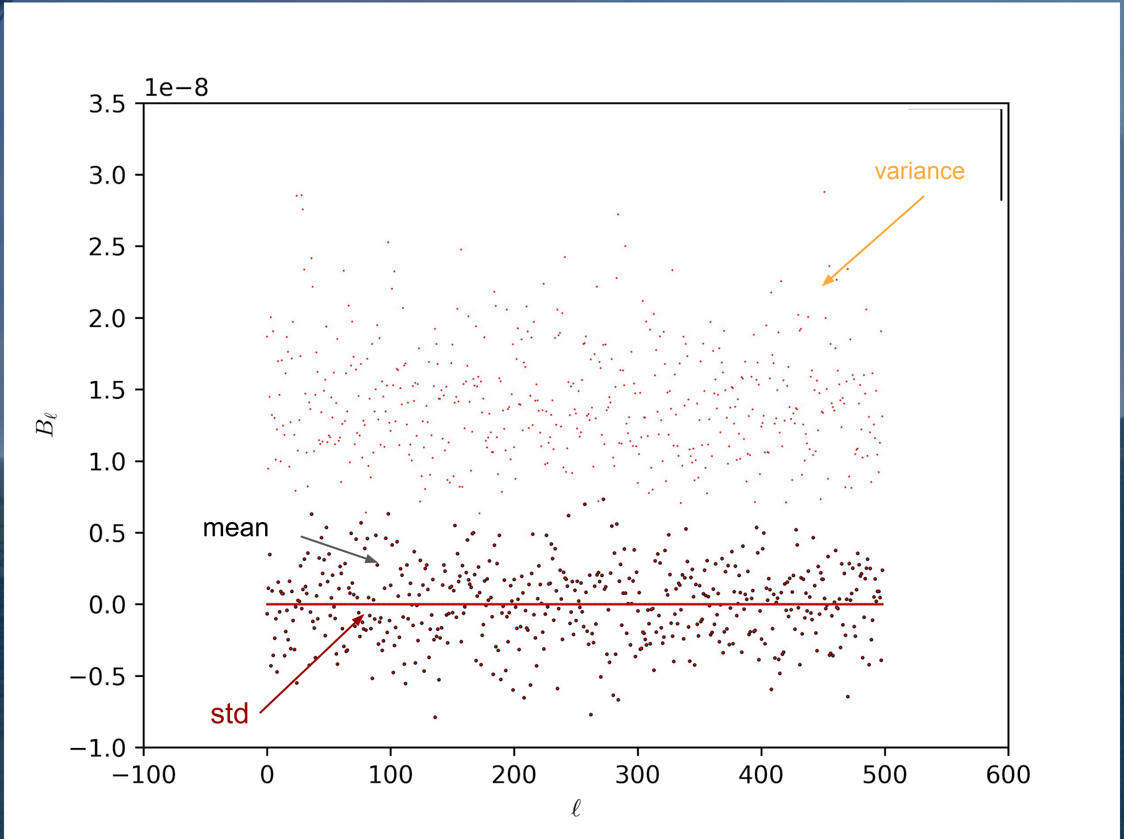
Non-Gaussianity - Bispectrum

Goals→ Not only non-Gaussianity in CMB (as independent module) but, for BINGO case - non-gaussianity of Galaxies (21 cm)

Bispectrum module → by Test Driven Design → refactorate and modulate the code

500 thermal noise maps
l_{max} = 30

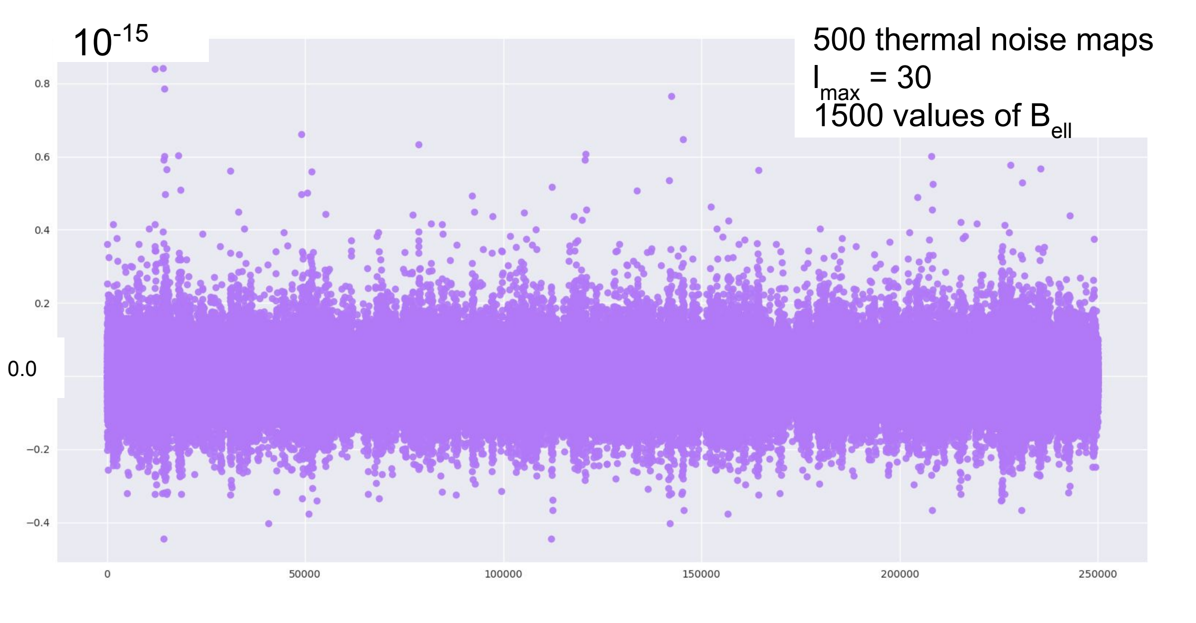
500 values →B_{ell} mean, std and variance



Non-Gaussianity - Bispectrum

Capacity of all the available cores in the machine → all the calculations simultaneously and we use text files to save the data of each iteration, then another module joined the pieces and can quickly calculate average and standard deviation in addition to plot the graphs

60 hours to approximately 8 hours



Next Steps

Pipeline

- Improvement → modules which depends on instrumental info BEAM, RFI, GAIN
- Inclusion on machine learning studies in RFI

Bispectrum Module

- Inclusion of ortho and local
- Estimation of f_{NL}
- Using FLASK - lognormal model
- Comparison with data (not BINGO data yet)

Thank you

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

Extras

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

Gaussianity

Statistical Properties (primordial fluctuations): Quantum fluctuations get stretched and enhanced by inflation can be described by harmonic oscillators in their ground state and the distribution of those fluctuations is Gaussian

If the Universe is Gaussian, homogeneous and statistically isotropic, then essentially all the information about inflation and linear evolution of the Universe is encoded in the variance, or two-point correlation function of **LSS/CMB**.

But it is not enough knowing the variance of the primordial fluctuations in order to single out which particular inflationary model was realized in our Universe→ we need the higher momenta of the distribution as well.

Model degeneracy → go beyond the framework of ΛCDM, Gaussian, spatially homogeneous and statistically isotropic Universe.

BINGO

Non-Gaussianity

While inflation predicts Gaussian CMB fluctuations to very good accuracy, strictly speaking, non-linearity in inflation produces weakly **non-Gaussian fluctuations**, which propagates through CMB

radiation transfer function

$$\frac{\Delta T}{T} \sim g_{\mathrm{T}} \Phi$$

curvature perturbations, Φ

CMB anisotropy, ΔT /T

$$\frac{\Delta T}{T} \sim g_{\mathrm{T}} \left[\Phi_{\mathrm{L}} + \left(f_{\Phi} + g_{\Phi}^{-1} f_{\delta\phi} + g_{\Phi}^{-1} g_{\delta\phi}^{-1} f_{\eta} \right) \Phi_{\mathrm{L}}^2 \right]$$

Even if Φ is Gaussian, ΔT /T can be non-Gaussian → general relativistic cosmological perturbation theory:

$$\frac{\Delta T}{T} \sim g_{\mathrm{T}} \left(\Phi + f_{\Phi} \Phi^2 \right)$$

higher-order correction (2nd perturbation theory)

$$\Phi(\mathbf{x}) = \Phi_{\mathrm{L}}(\mathbf{x}) + f_{\mathrm{NL}} \left[\Phi_{\mathrm{L}}^2(\mathbf{x}) - \left\langle \Phi_{\mathrm{L}}^2(\mathbf{x}) \right\rangle \right]$$