# Cosmological forecast from bispectrum of 21cm intensity mapping

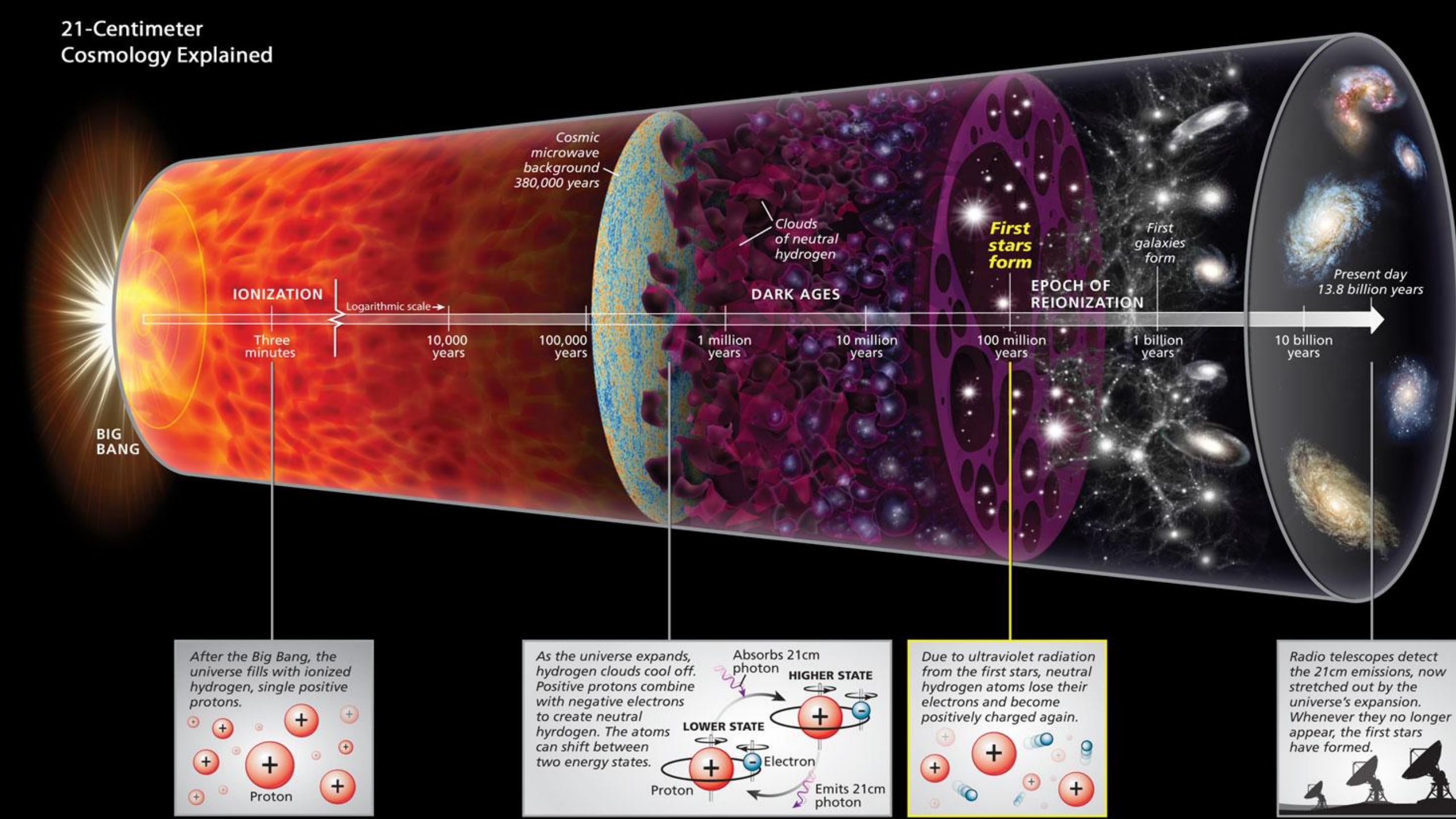
in collaboration with André Costa, Rodrigo Pinheiro, Chang Feng, Yanling Song, Bin Wang

**Yu Sang 桑 语**

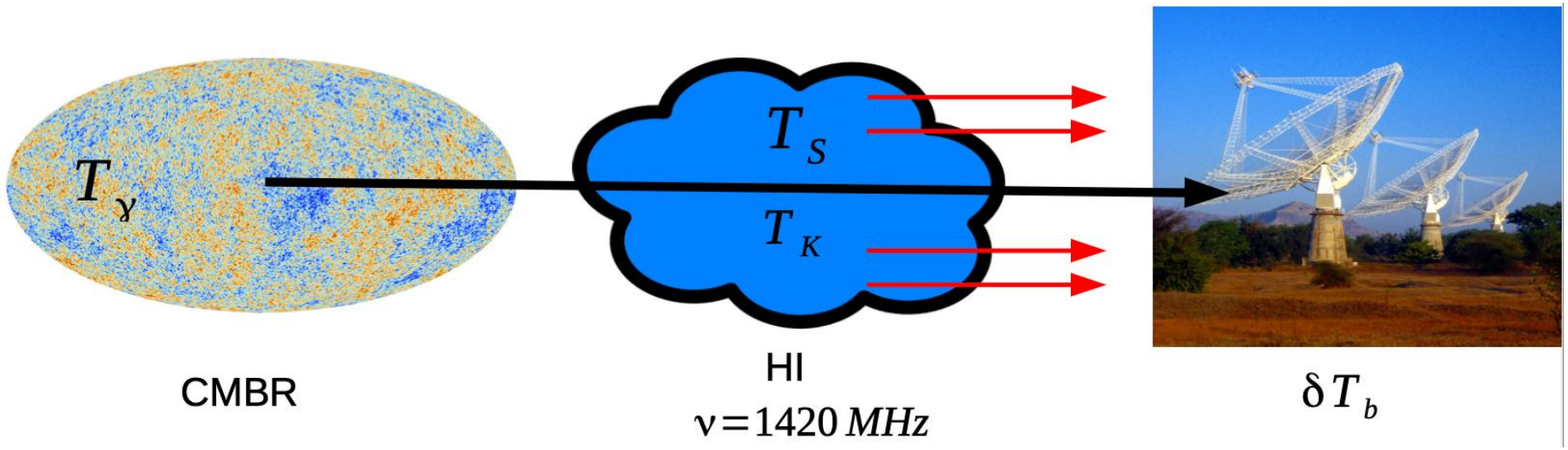
**CGC @ Yangzhou University**

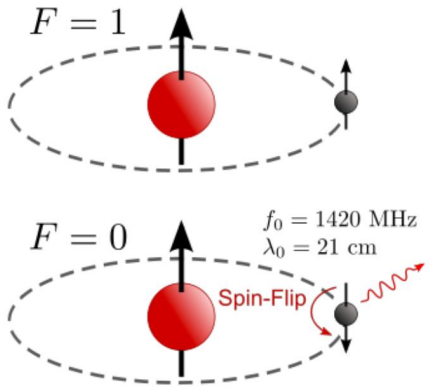
BRICS-AGAC Symposium 2026
2026/11/08, Hangzhou

# 21-Centimeter Cosmology Explained



# 21 cm line from neutral hydrogen



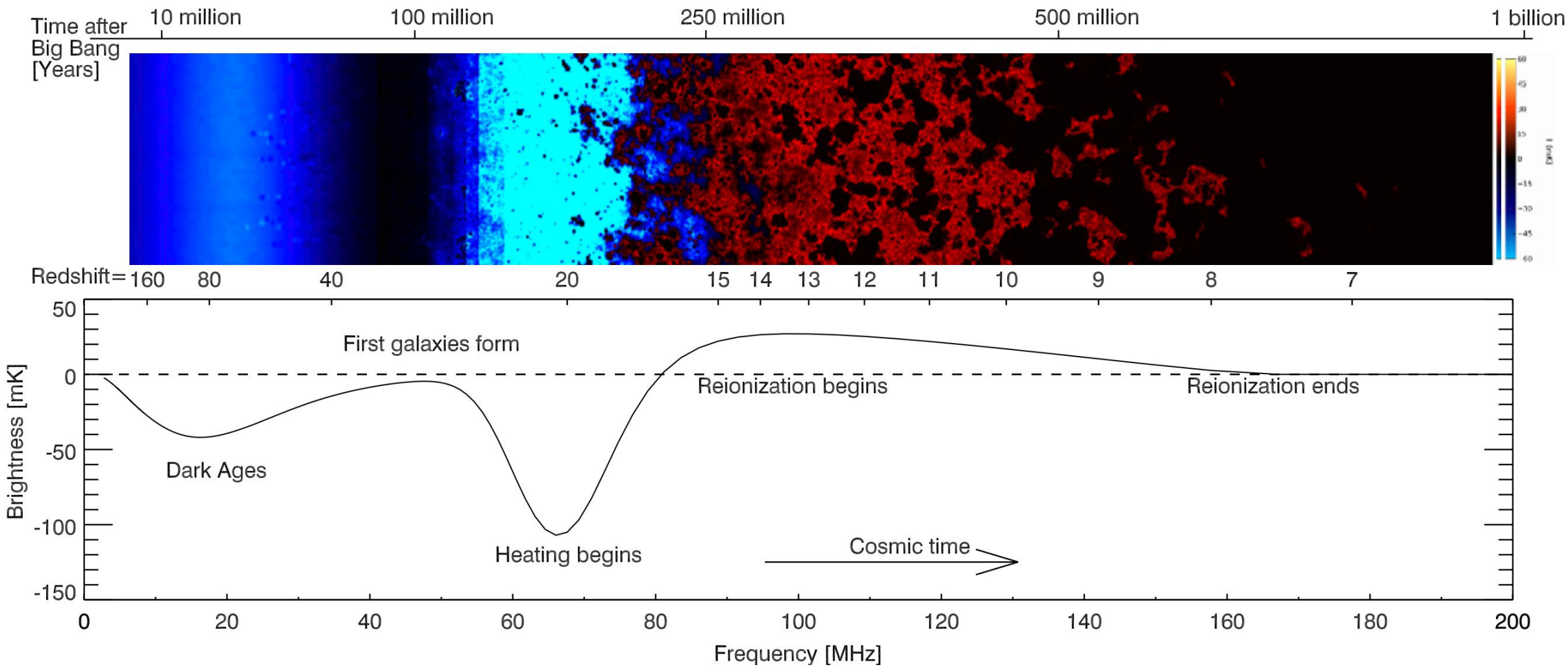




$$\lambda_{obs} = (1+z)\lambda_{21cm}$$

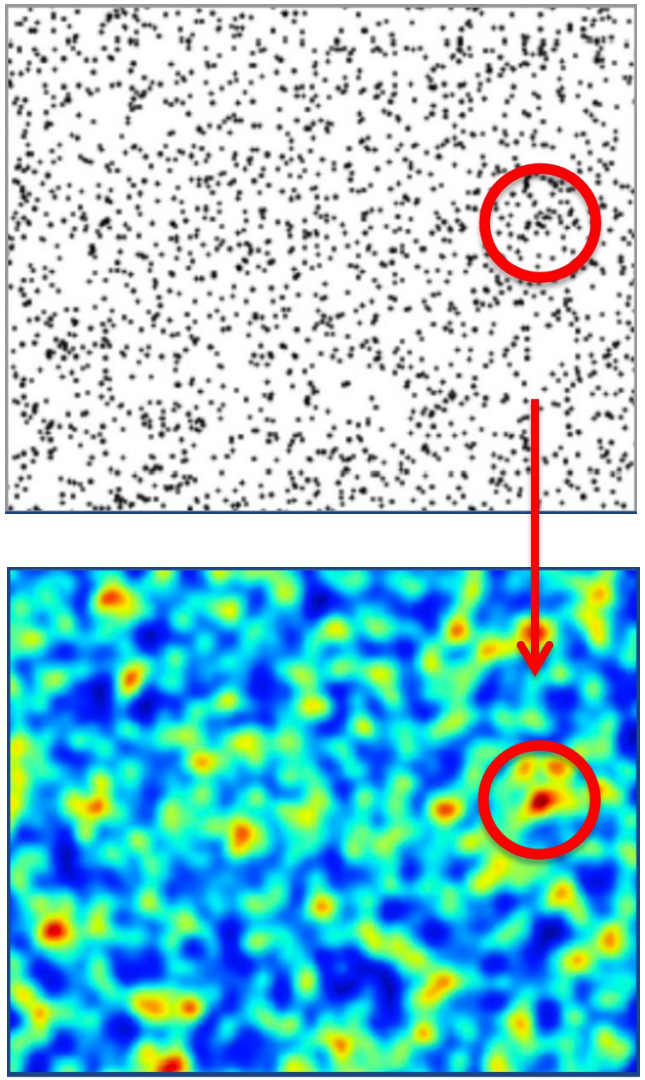
$$\delta T_b \approx 28\text{mK}\,(1+\delta)\,x_{HI}\,\frac{T_s - T_{CMB}}{T_s}\,\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Astrophysics

Cosmology


Time after Big Bang [Years]
10 million
100 million
250 million
500 million
1 billion
Redshift=
160
80
40
20
15
14
13
12
11
10
9
8
7
First galaxies form
Reionization begins
Reionization ends
Dark Ages
Heating begins
Cosmic time
Brightness [mK]
50
0
-50
-100
-150
0
20
40
60
80
100
120
140
160
180
200
Frequency [MHz]

# 21 cm Intensity Mapping



- Use large beam
- Measure HI fluctuations
- Similar to CMB, using

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

- HI intensity mapping can be used as mass tracer, probing distortions in redshift space
- No competition in the radio
- Complementary to large optical surveys
- Single dish: GBT, FAST, BINGO
- Radio interferometers: CHIME, Tianlai, SKA

# Primordial Non-Gaussianity

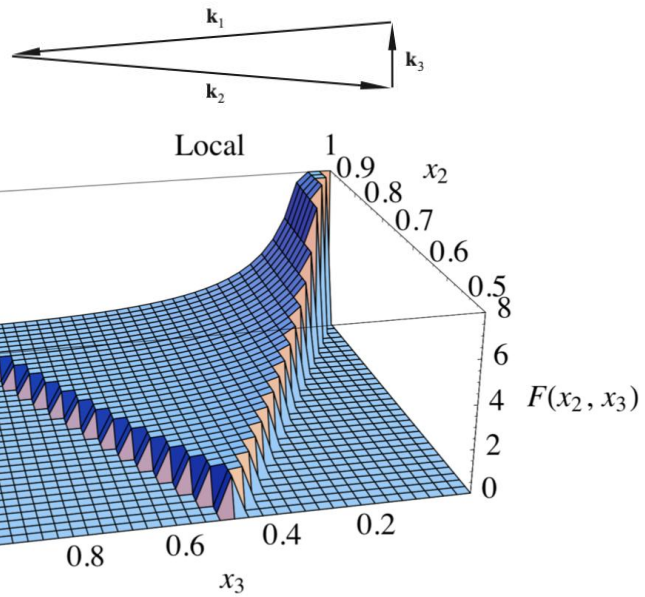
$$\begin{aligned}\Phi(\mathbf{x}) &= \Phi_{\rm L}(\mathbf{x}) + \Phi_{\rm NL}(\mathbf{x}) \\ &= \Phi_{\rm L}(\mathbf{x}) + f_{\rm NL}[\Phi_{\rm L}^2(\mathbf{x}) - \langle\Phi_{\rm L}^2(\mathbf{x})\rangle]\end{aligned}$$

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

# Bispectrum Shape

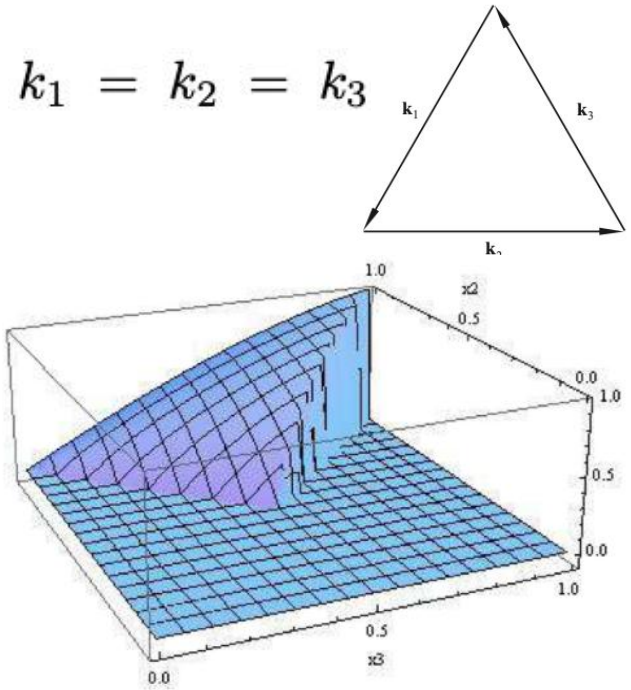
- Local Shape

$$k_3 \ll k_1 \sim k_2$$



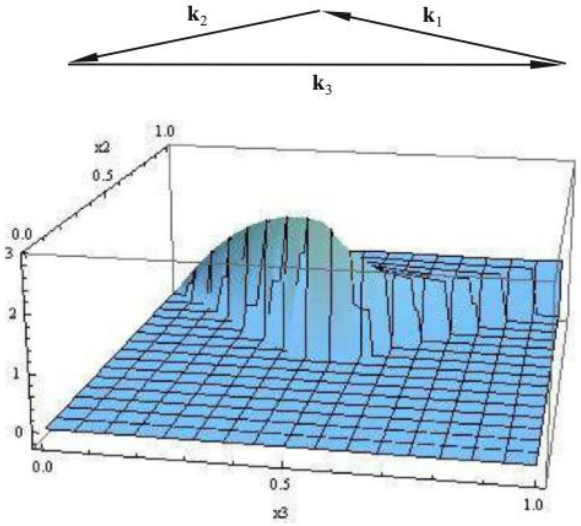

- Equilateral Shape

$$k_1 = k_2 = k_3$$




- Folded Shape

$$k_1 = k_2 + k_3$$



# Primordial Universe

## Gaussian

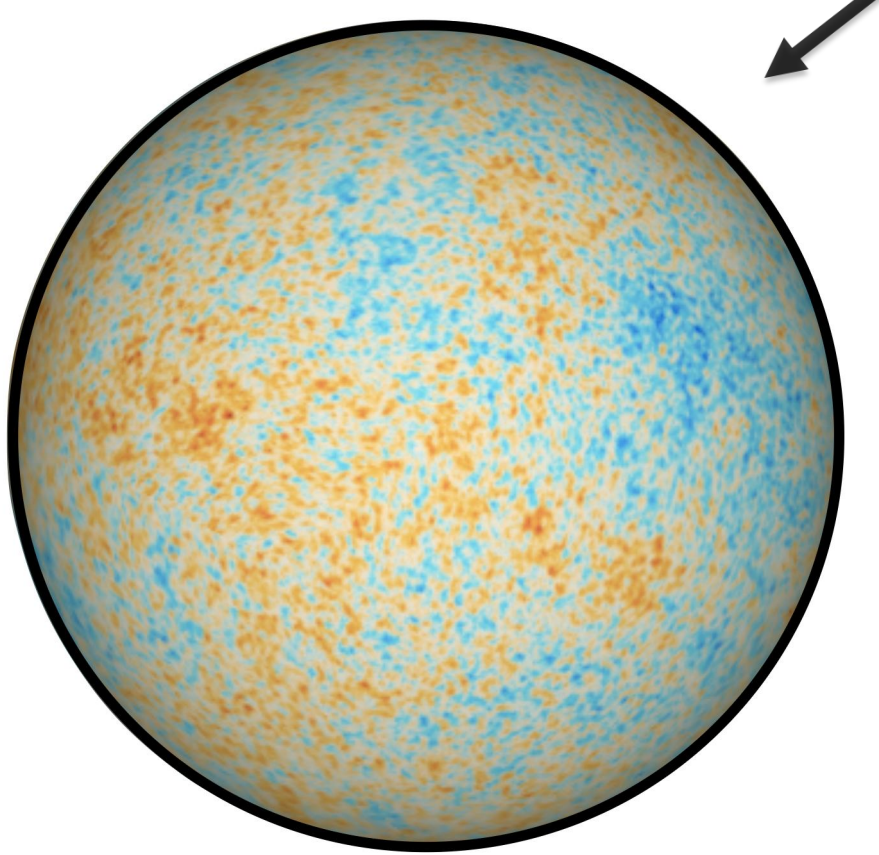
- Single field inflation
- Canonical kinetic term
- Sufficiently smooth potential (slow-roll)

Chaotic inflation, Hybrid inflation, SUGRA inflation, Brane inflation, natural inflation, Hilltop inflation etc.

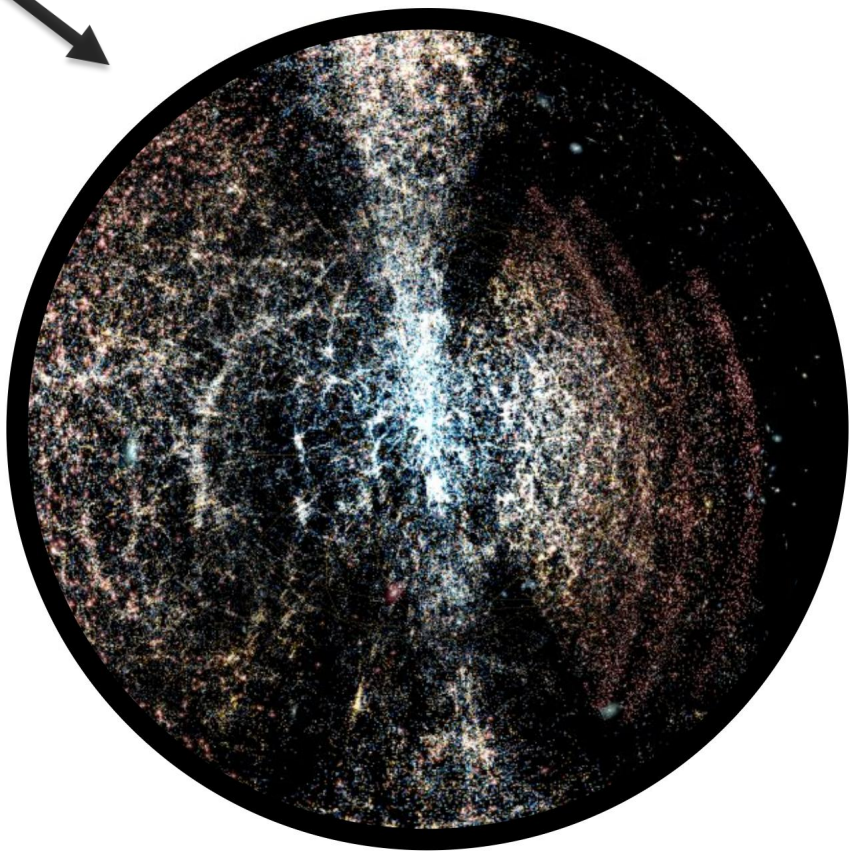
## Non-Gaussian

- Multi-field inflation
- K-essence/ DBI
- Curvaton scenario
- Exotic Mechanism: preheating

# Primordial Universe



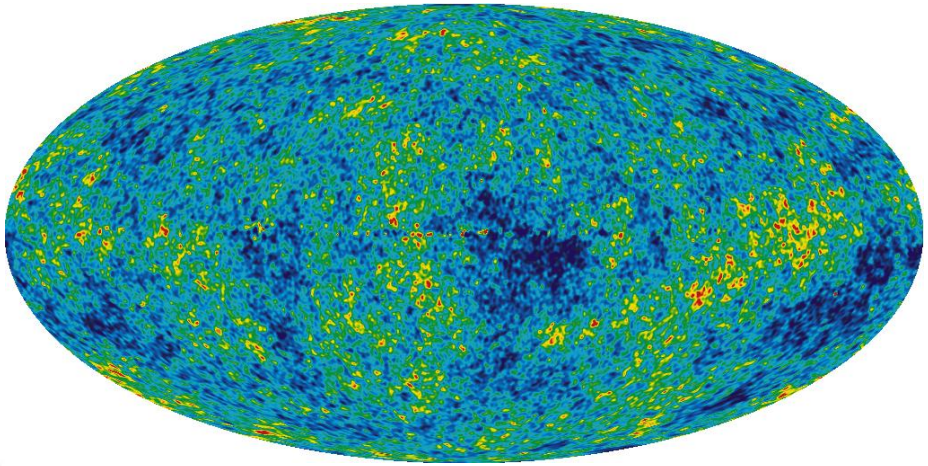
*Cosmic Microwave Background*
*image: Planck*



*Large Scale Structure*
*image: SDSS*

# PNG Constraints from Planck CMB

$$B_\Phi(k_1, k_2, k_3)$$



$$B^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3} = \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$$

| Shape | Independent | Lensing subtracted |
|---|---|---|
| | SMICA $T$ | |
| Local . . . . . | 6.7 ± 5.6 | −0.5 ± 5.6 |
| Equilateral . . . . . | 4 ± 67 | 5 ± 67 |
| Orthogonal . . . . . | −38 ± 37 | −15 ± 37 |
| | SMICA $T$+$E$ | |
| Local . . . . . | 4.1 ± 5.1 | −0.9 ± 5.1 |
| Equilateral . . . . . | −25 ± 47 | −26 ± 47 |
| Orthogonal . . . . . | −47 ± 24 | −38 ± 24 |

**Planck 2018 results.**
**IX, arXiv:1905.05697**

**Planck 2013**

**2.7 ± 5.8**
**−42 ± 75**
**−25 ± 39**

# Effect of PNG on 21 cm Intensity Mapping

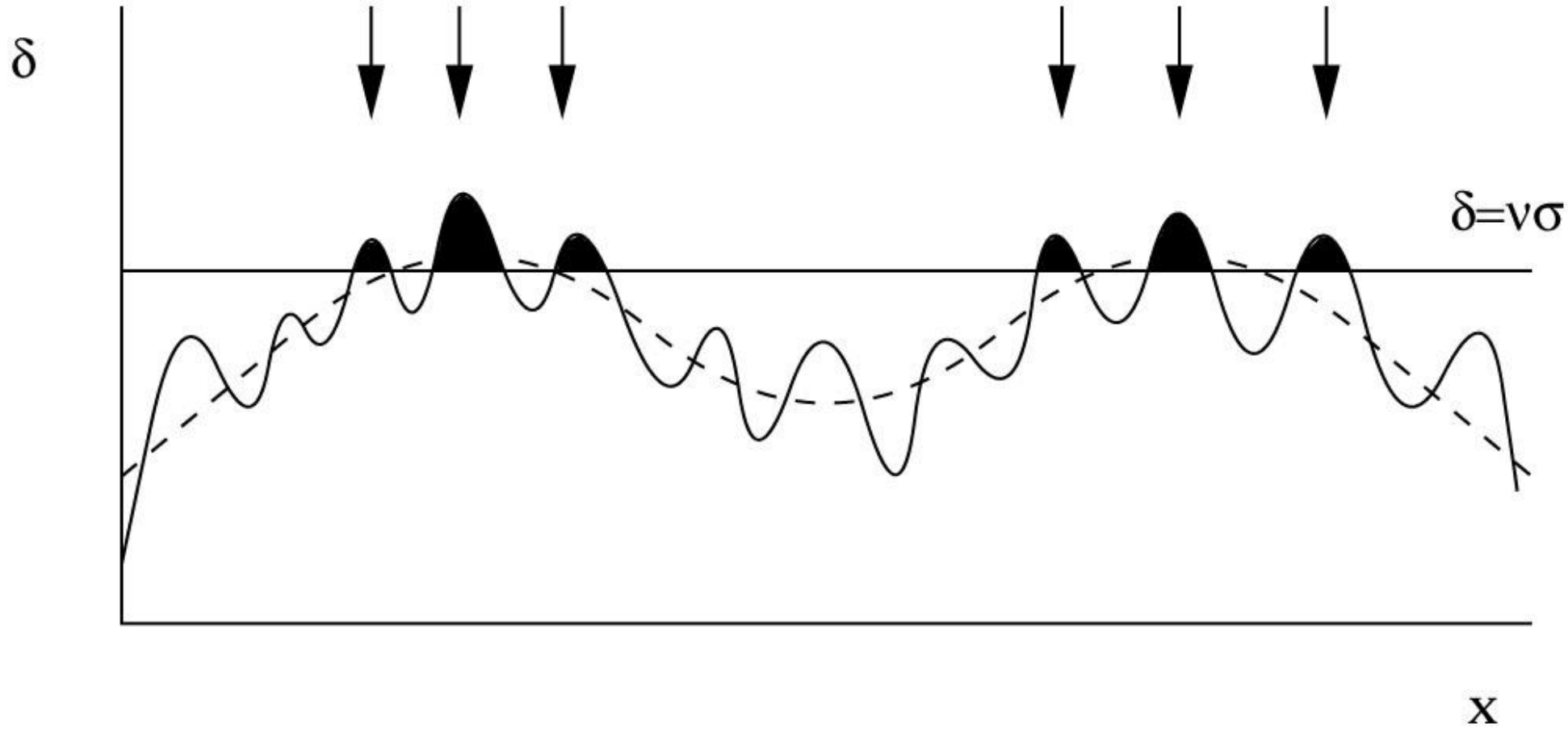
$$\left\langle a_{\ell m}(z_i) a^*_{\ell' m'}(z_j) \right\rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell(z_i, z_j)$$

Scale dependent bias

$$\Phi = \varphi - f_{\rm NL}\left(\varphi^2 - \langle\varphi^2\rangle\right)$$

$$B^{\ell_1\ell_2\ell_3}_{m_1 m_2 m_3}(z_1, z_2, z_3) \;=\; \langle a_{\ell_1 m_1}(z_1) a_{\ell_2 m_2}(z_2) a_{\ell_3 m_3}(z_3)\rangle$$

# Galaxies & Neutral hydrogen: biased tracers of dark matter

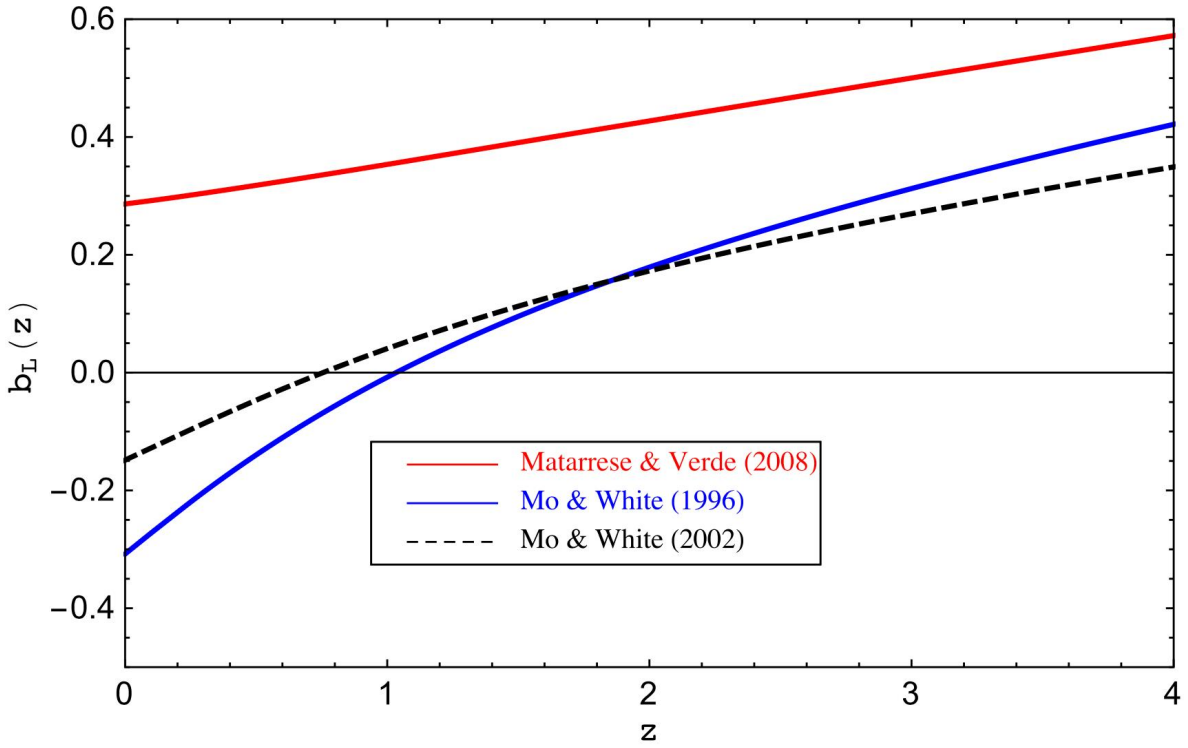


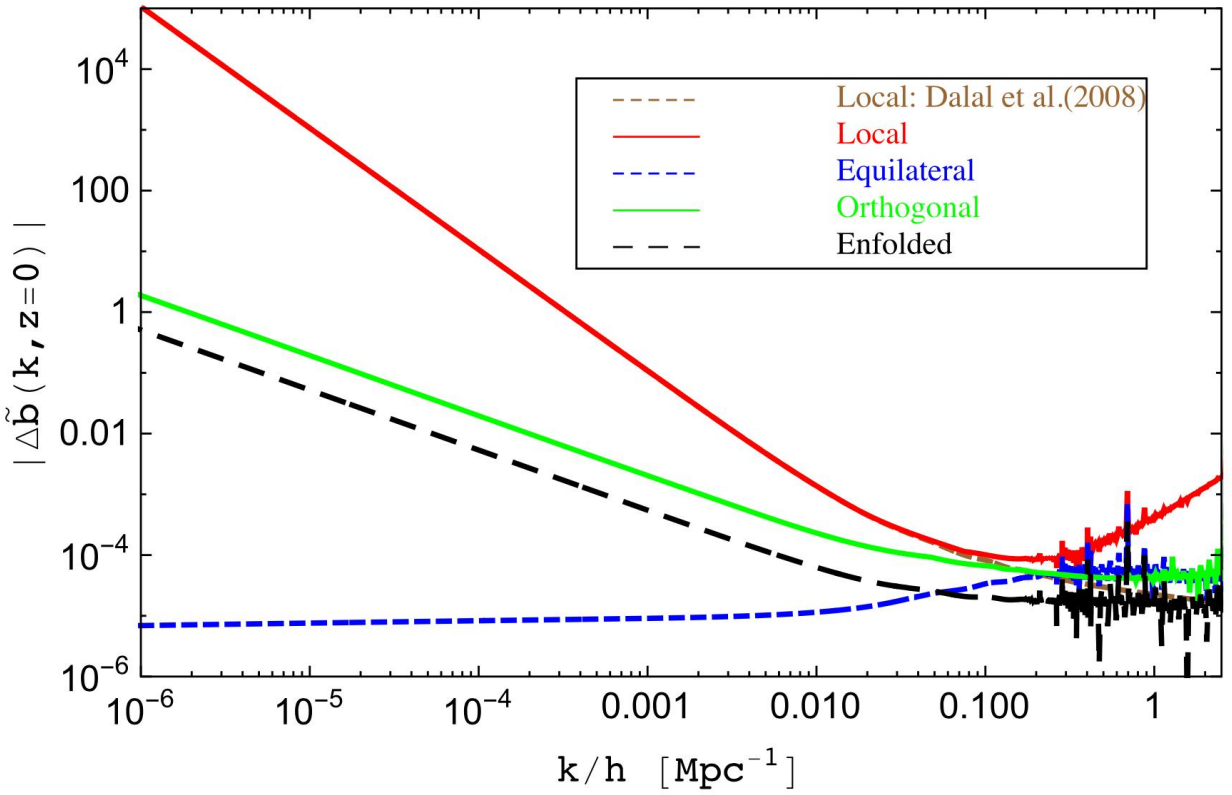

Peacock, arXiv:astro-ph/0309240

# Scale dependent bias

$$b(z) \to b(z) + \Delta b(z,k),$$

$$\Delta b(z,k) = [b(z) - 1] \frac{3\Omega_m H_0^2 q \delta_{\rm cr}}{k^2 T(k) D(z)} f_{\rm NL},$$




Yi-Chao Li, Yin-Zhe Ma, Phys. Rev. D 96, 063525 (2017)

# Scale dependent bias

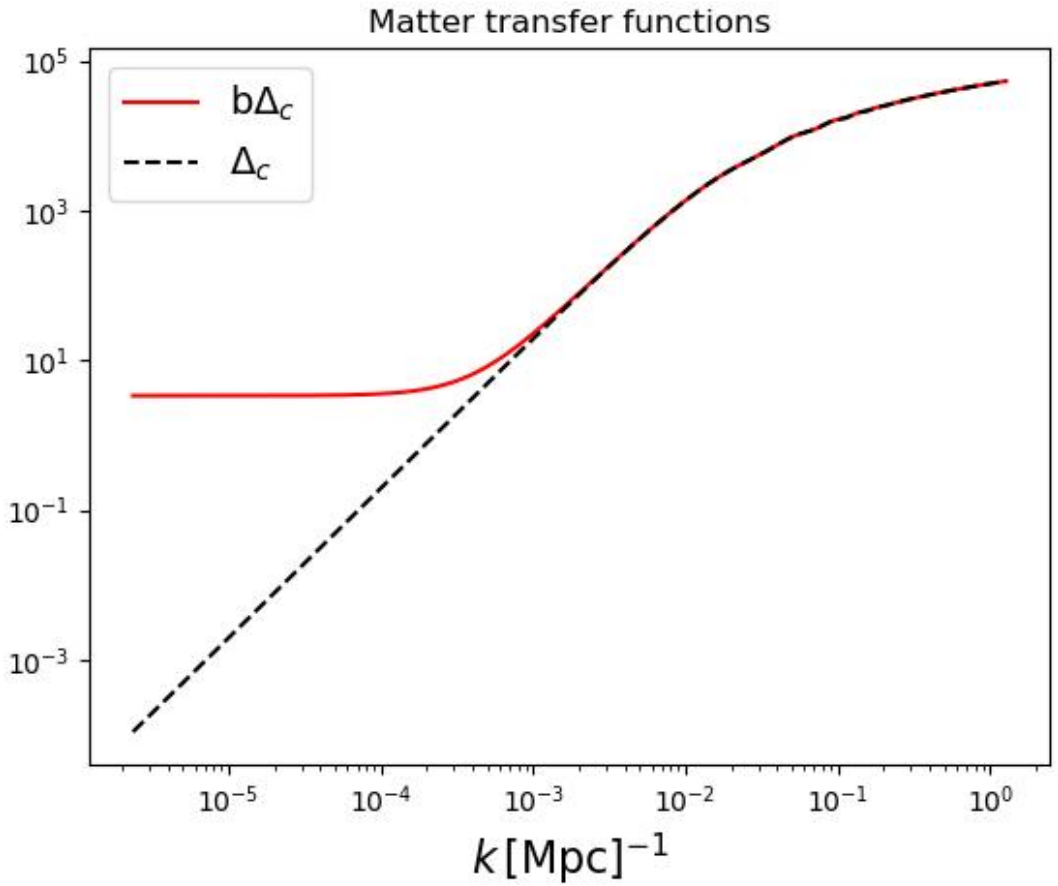
$$\Phi = \varphi - f_{\rm NL}\left(\varphi^2 - \langle\varphi^2\rangle\right)$$

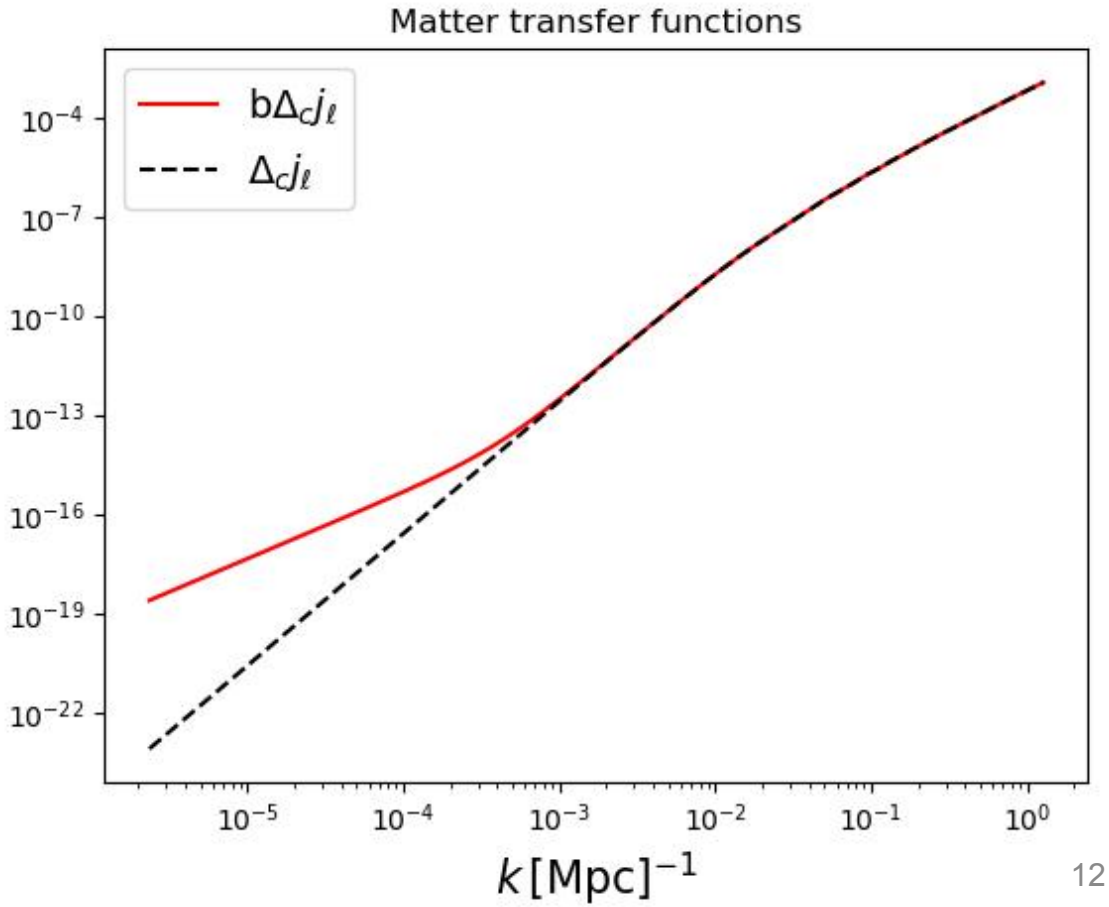
$$\Delta_{T_{b,\ell}}(\mathbf{k}, z) = \delta_{\rm HI} j_\ell(k\chi)$$

$$\delta_{\rm HI} = b_{\rm HI}\,\delta_m$$

$$b(z) \to b(z) + \Delta b(z,k),$$

$$\Delta b(z,k) = [b(z)-1]\frac{3\Omega_m H_0^2 q \delta_{\rm cr}}{k^2 T(k) D(z)} f_{\rm NL},$$



# Forecastn on PNG using power spectrum

| Project | Type[a] | $\theta_{\rm FWHM}$ | Freq. [MHz] | Channels[b] | Beams | $f_{\rm sky}$ | Dec.[c] [deg] | $T_{\rm sys}$ [K] | $\sigma_{\rm pix}$ (1yr) [$\mu$K][d] | $\sigma_{\rm pix}$ (5yr) [$\mu$K] |
|---|---|---|---|---|---|---|---|---|---|---|
| BINGO | SD | 40' | 980-1260 | 30 | 28 | 0.128 | (-25,-10) | 50-70 | 247-345 | 110-154 |
| ABDUS-1 | PA | 40' | 450-1420 | 100 | 44 | 0.128 | (-25,-10) | 40-60 | 155-232 | 69-104 |
| ABDUS-2 | PA | 27' | 450-1420 | 100 | 200 | 0.785 | (-52, 38) | 40-60 | 359-539 | 161-241 |

$$F_{ij} \equiv \left\langle -\frac{\partial \ln \mathcal{L}}{\partial\theta_i\,\partial\theta_j} \right\rangle = \frac{1}{2}\mathrm{Tr}\left[\mathbf{C}^{-1}\frac{\partial \mathbf{C}}{\partial\theta_i}\mathbf{C}^{-1}\frac{\partial \mathbf{C}}{\partial\theta_j}\right]$$

$$C_\ell(z_i, z_j) = 4\pi \int d\ln k \mathcal{P}_{\mathcal{R}}(k)\Delta^W_{T_{b,\ell}}(\mathbf{k}, z_i)\Delta^{W'}_{T_{b,\ell}}(\mathbf{k}, z_j)$$

$$\Delta_{T_{b,\ell}}(\mathbf{k}, z) \;=\; \delta_{\rm HI} j_\ell(k\chi) \qquad \delta_{\rm HI} = b_{\rm HI}\,\delta_m$$

$$\Phi = \varphi - f_{\rm NL}\left(\varphi^2 - \langle\varphi^2\rangle\right)$$

$$b(z) \to b(z) + \Delta b(z, k),$$

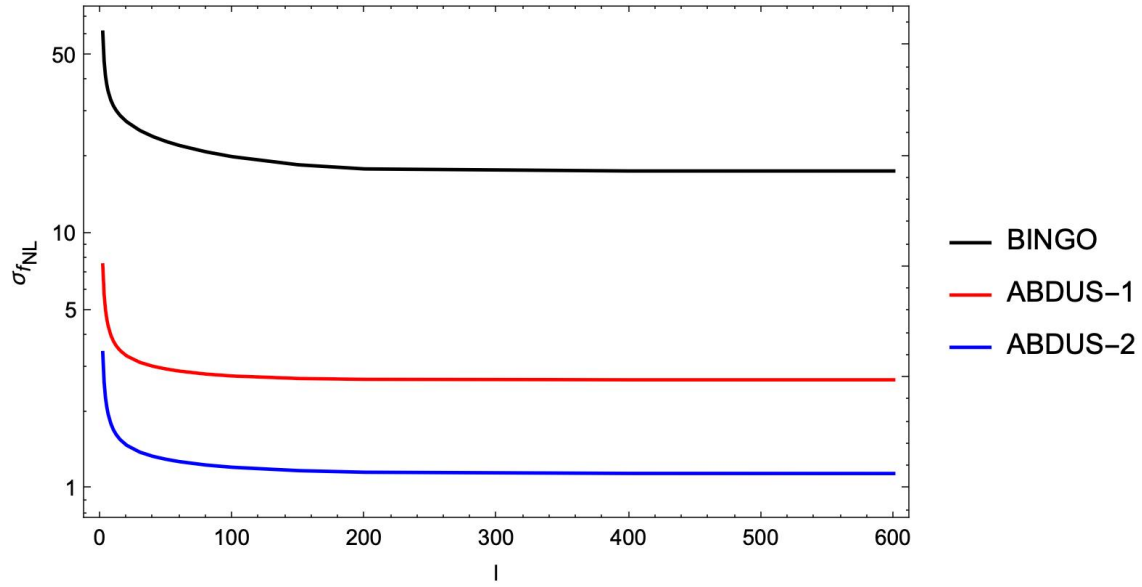
$$\Delta b(z, k) = [b(z) - 1]\frac{3\Omega_m H_0^2 q \delta_{\rm cr}}{k^2 T(k) D(z)} f_{\rm NL},$$

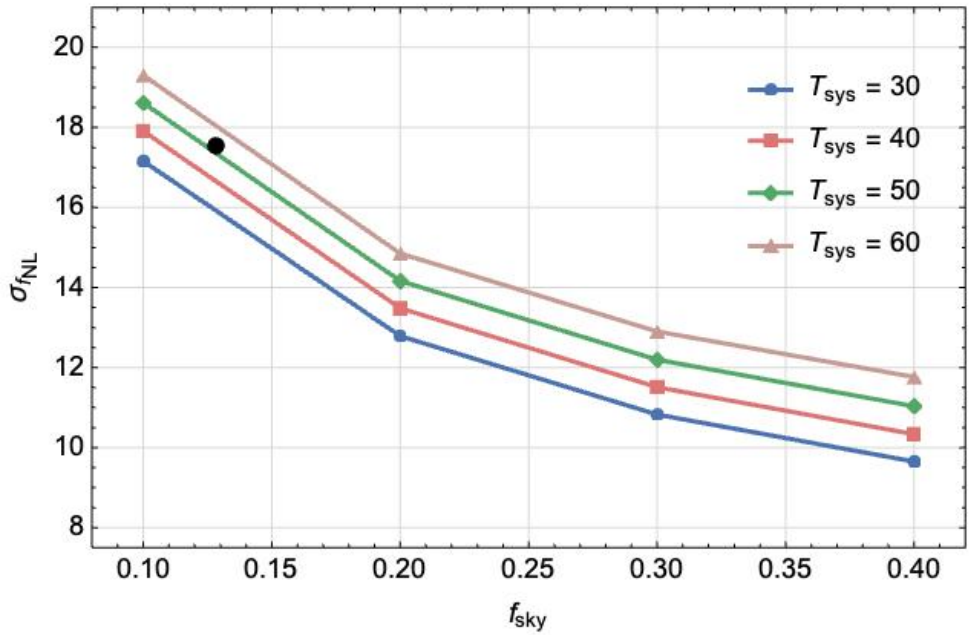
l_max = 400

BINGO $\sigma_{f_{NL}^{\rm loc}} = 17.5$

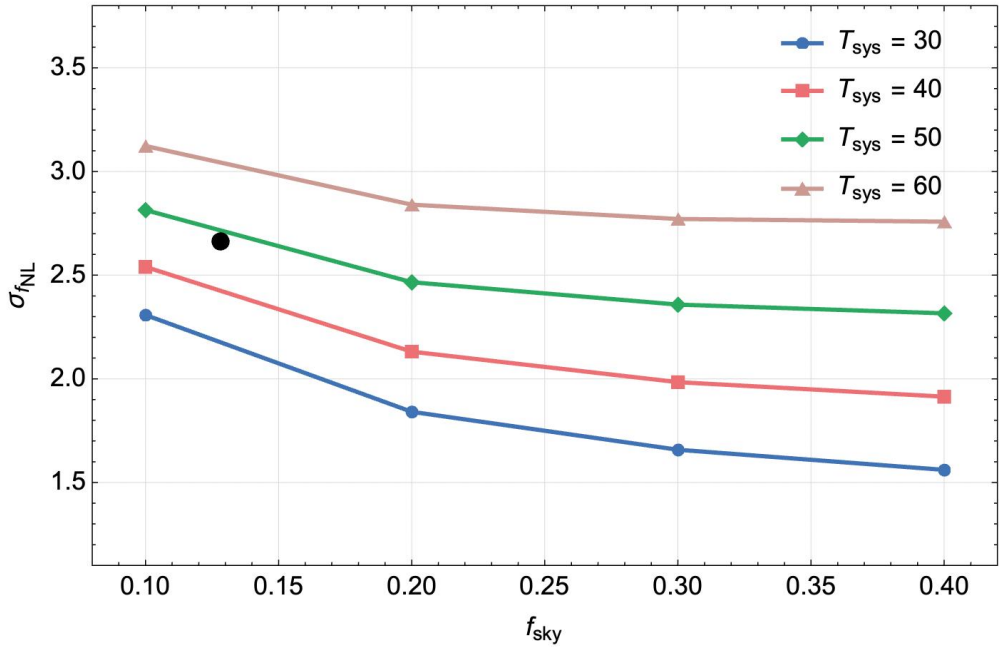
ABDUS-1 $\sigma_{f_{NL}^{\rm loc}} = 2.7$

ABDUS-2 $\sigma_{f_{NL}^{\rm loc}} = 1.1$




BINGO




ABDUS-1

# Bispectrum of 21 cm Intensity Mapping

$$\Delta = \Delta^{(1)} + \Delta^{(2)}$$

$$\Delta^{(1)} = b_1 \delta^{(1)} + \mathcal{H}^{-1} \partial_r^2 v^{(1)}$$

$$\begin{aligned}\Delta^{(2)}(\mathbf{n}, z) =& b_1 \delta^{(2)} + \frac{1}{2} b_2 (\delta^{(1)})^2 + b_s s^2 + \mathcal{H}^{-1} \partial_r^2 v^{(2)} \\ &+ \mathcal{H}^{-2} [(\partial_r^2 v^{(1)})^2 + \partial_r v^{(1)} \partial_r^3 v^{(1)}] \\ &+ \mathcal{H}^{-1} [\partial_r v^{(1)} \partial_r \delta^{(1)} + \partial_r^2 v^{(1)} \delta^{(1)}]\end{aligned}$$

$$\langle \Delta^{(1)} \Delta^{(1)} \Delta^{(1)} \rangle \propto f_{\rm NL}$$

**Primordial**

$$\langle \Delta^{(2)} \Delta^{(1)} \Delta^{(1)} \rangle + \circlearrowleft$$

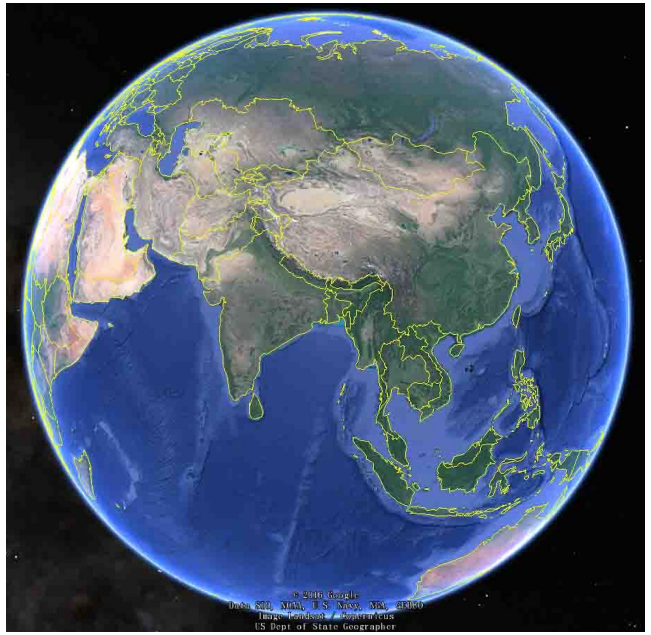
**Non-linear Gravitational**

## Flat-sky approximation
## 平坦天空近似
## 小天区近似




$$B_{\rm HI}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3, z)$$

## Full-sky Analysis
## 全天空分析



$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$$

# Primordial Bispectrum

$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} \propto f_{\rm NL}$$

$$\frac{\Delta T}{T}(\hat{\mathbf{n}}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\hat{\mathbf{n}}) \rightarrow B^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3}(z_1, z_2, z_3) = \langle a_{\ell_1 m_1}(z_1) a_{\ell_2 m_2}(z_2) a_{\ell_3 m_3}(z_3) \rangle$$

$$= b_{\ell_1 \ell_2 \ell_3}(z_1, z_2, z_3) \mathcal{G}^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3}$$

$$b_{\ell_1 \ell_2 \ell_3}(z_1, z_2, z_3) = \left(\frac{2}{\pi}\right)^3 \int x^2 dx \int dk_1 dk_2 dk_3 \; (k_1 k_2 k_3)^2 \; B_\Phi(k_1, k_2, k_3)$$

$$\times \Delta_{\ell_1}(k_1, z_1) \Delta_{\ell_2}(k_2, z_2) \Delta_{\ell_3}(k_3, z_3) \, j_{\ell_1}(k_1 x) \, j_{\ell_2}(k_2 x) \, j_{\ell_3}(k_3 x)$$

$$B_\Phi(k_1, k_2, k_3) = 2 f_{\rm NL} \left[ P_\Phi(k_1) P_\Phi(k_2) + P_\Phi(k_2) P_\Phi(k_3) + P_\Phi(k_3) P_\Phi(k_1) \right]$$

$$\Phi = \varphi - f_{\rm NL}\left(\varphi^2 - \langle\varphi^2\rangle\right)$$

Initial condition

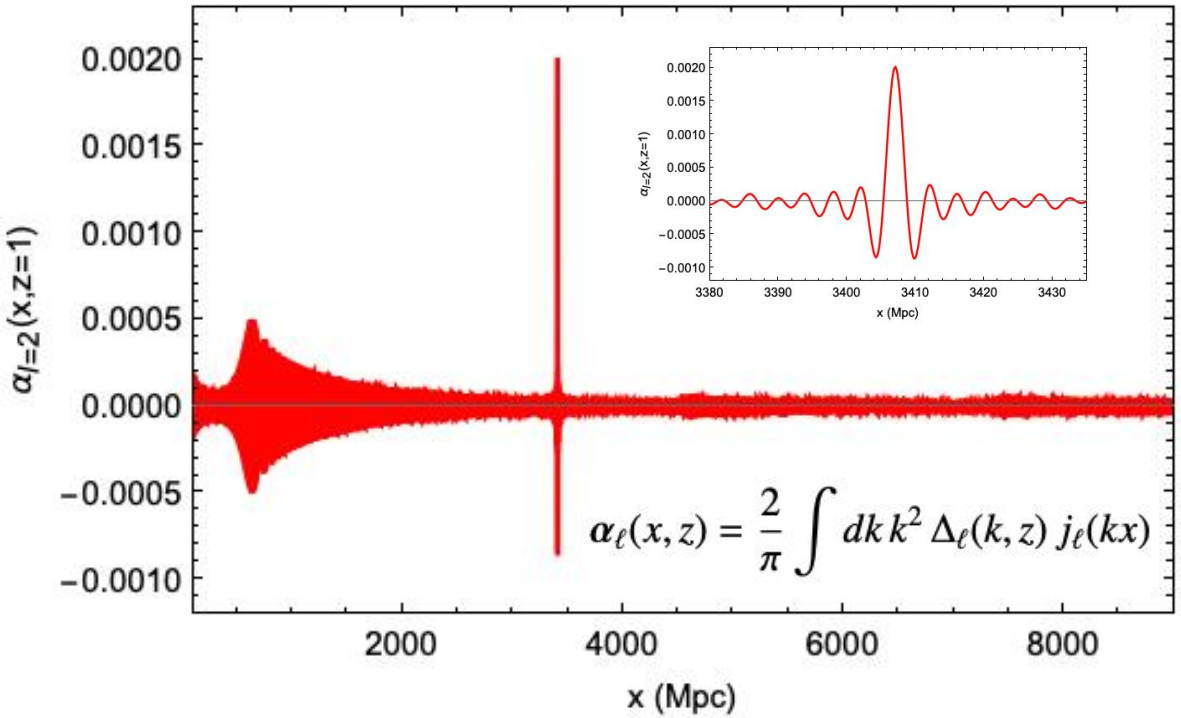
Cosmological evolution

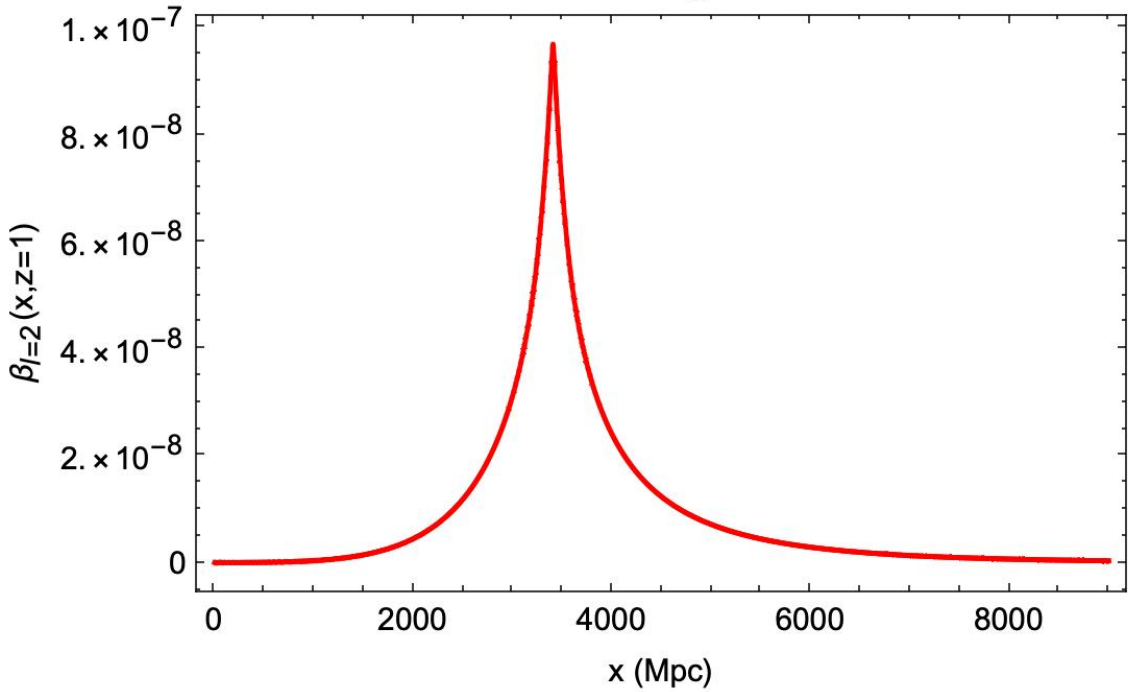
$$\Delta_{T_{b,\ell}}(\mathbf{k},z) = \delta_{\rm HI}\, j_\ell(k\chi) + \frac{kv}{\mathcal{H}} j_\ell''(k\chi) + \left(\frac{1}{\mathcal{H}}\dot{\Phi} + \Psi\right) j_\ell(k\chi)$$
$$- \left[\frac{1}{\mathcal{H}}\frac{d\ln(a^3\bar{n}_{\rm HI})}{d\eta} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - 2\right]\left[\Psi j_\ell(k\chi) + v j_\ell'(k\chi) + \int_0^\chi (\dot{\Psi}+\dot{\Phi}) j_\ell(k\chi')d\chi'\right]$$

$$b_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) = \left(\frac{2}{\pi}\right)^3 \int x^2dx \int dk_1dk_2dk_3\ (k_1k_2k_3)^2 B_\Phi(k_1,k_2,k_3)$$
$$\times \Delta_{\ell_1}(k_1,z_1)\,\Delta_{\ell_2}(k_2,z_2)\,\Delta_{\ell_3}(k_3,z_3)\, j_{\ell_1}(k_1x)\, j_{\ell_2}(k_2x)\, j_{\ell_3}(k_3x)$$

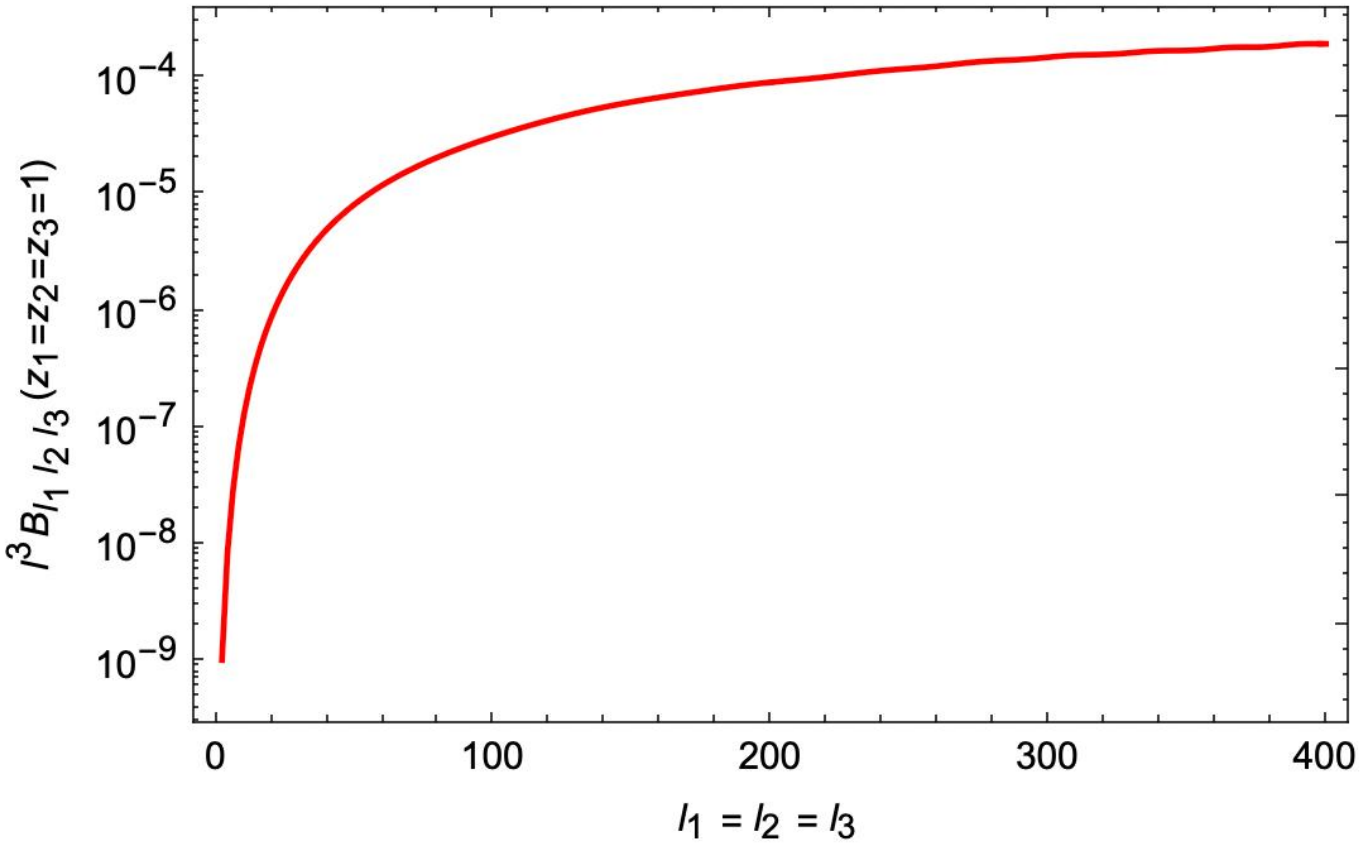
$$b^{\rm local}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) = \int x^2dx\left[\boldsymbol{\alpha}_{\ell_1}(x,z_1)\boldsymbol{\beta}_{\ell_2}(x,z_2)\boldsymbol{\beta}_{\ell_3}(x,z_3) + 2\ \text{perm.}\right]$$

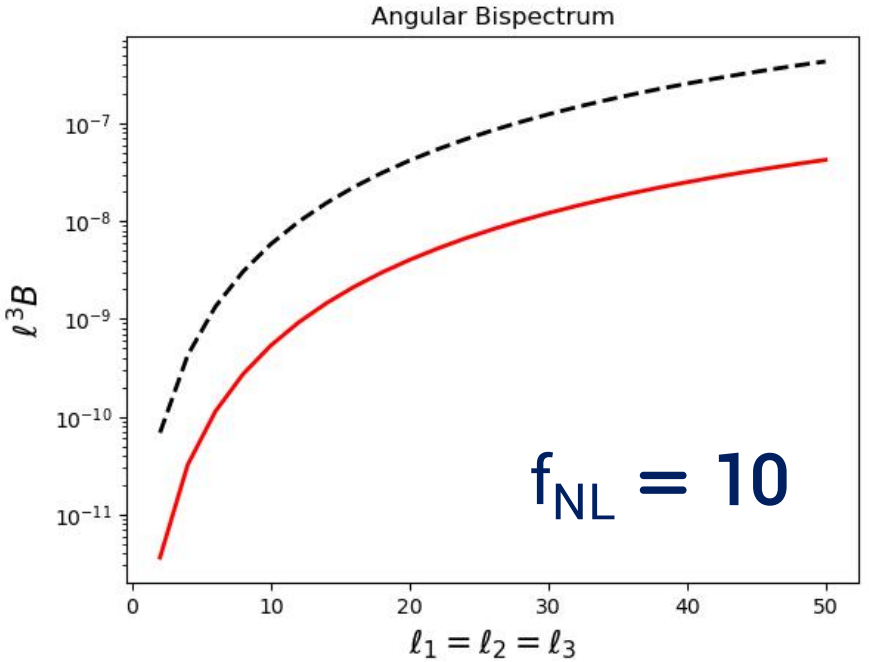
$$\boldsymbol{\beta}_\ell(x,z) = \frac{2}{\pi}\int dk\, k^2 P_\Phi(k)\,\Delta_\ell(k,z)\, j_\ell(kx)$$

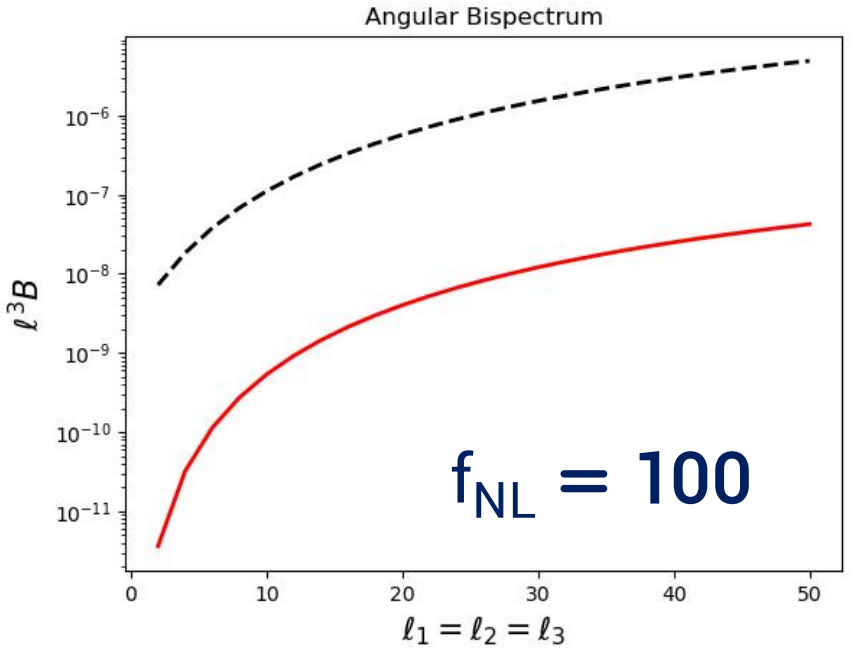


# Primordial Bispectrum



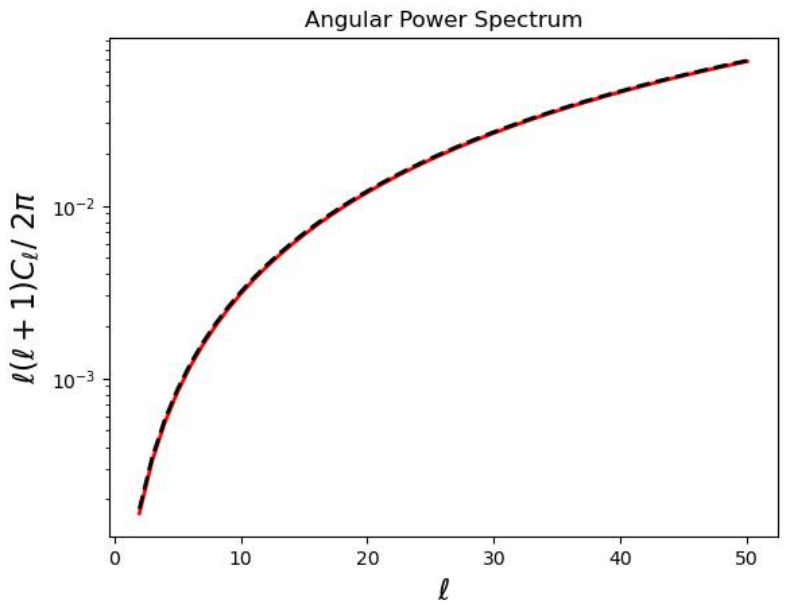



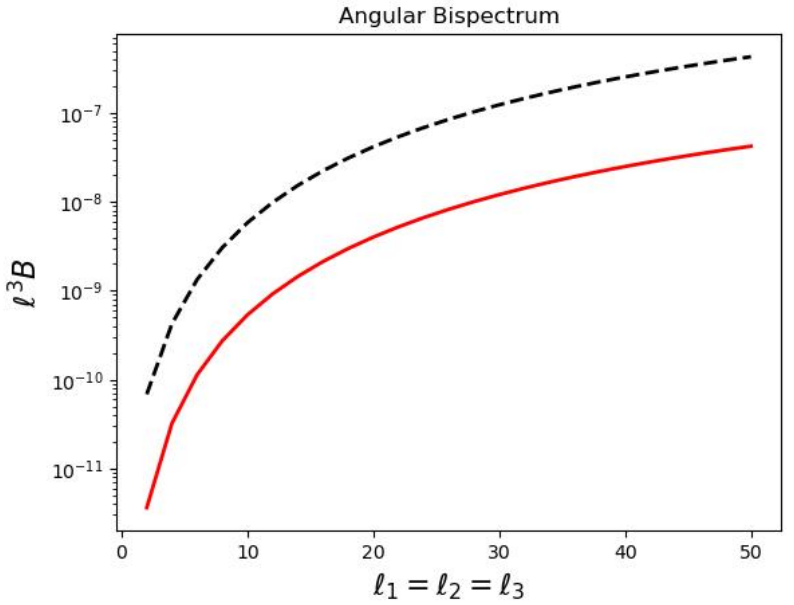



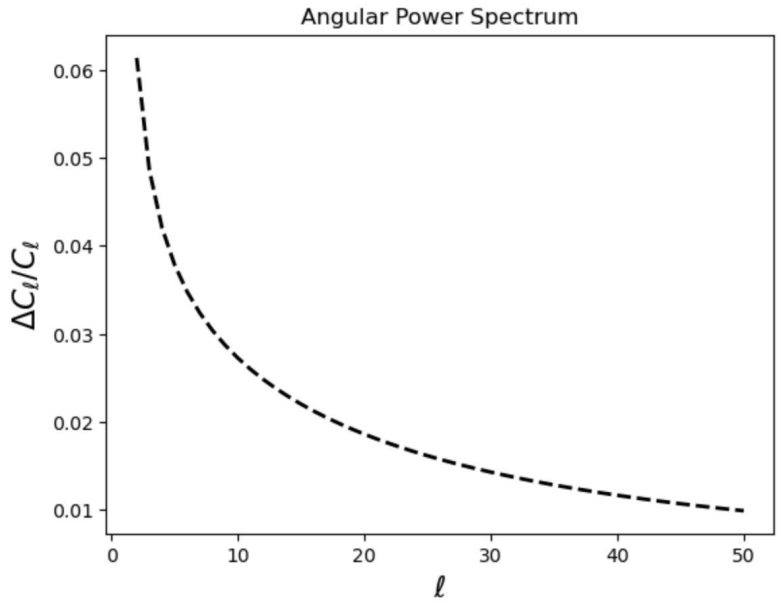
# Power Spectrum and Bispectrum

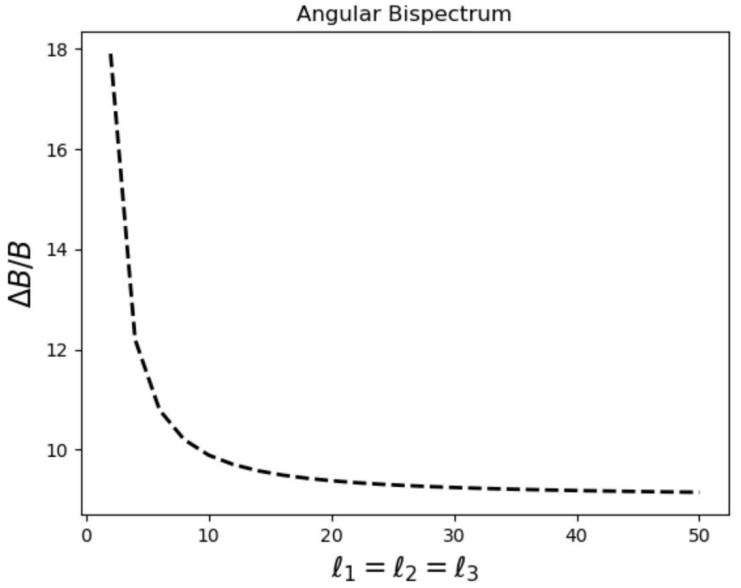
$$\Phi = \varphi - f_{\rm NL}\left(\varphi^2 - \langle\varphi^2\rangle\right) \quad f_{\rm NL} = 10$$

$$b(z) \to b(z) + \Delta b(z,k)$$



# Forecast on PNG using Bispectrum

$$\boldsymbol{F}_{ij} = \sum_{\nu} \sum_{\ell_1 \ell_2 \ell_3} \frac{\mu^{\nu,\ell_1\ell_2\ell_3}_{,i}\, \mu^{\nu,\ell_1\ell_2\ell_3}_{,j}}{\Delta_{\ell_1\ell_2\ell_3} C^{\nu}_{\ell_1} C^{\nu}_{\ell_2} C^{\nu}_{\ell_3}}$$

$$\mu^{\nu,\ell_1\ell_2\ell_3}_{,i} = \frac{\partial B_{\ell_1\ell_2\ell_3}(\nu)}{\partial \theta_i}$$

| Survey | BINGO | SKA-MID Band 2 | SKA-MID Band 1 |
|---|---|---|---|
| Frequency (Mhz) | $980 - 1260$ | $950 - 1410$ | $350 - 1050$ |
| $\Delta\nu$ (Mhz) | 10 | 10 | 10 |
| $N_{\rm bins}$ | 28 | 46 | 70 |
| $N_{\rm horn}$ | 28 | 197 | 197 |
| $f_{\rm sky}$ | 0.07 | 0.12 | 0.48 |
| $t_{\rm obs}$ (yr) | 1 | 1 | 1 |
| $T_{\rm sys}$ | 70 | 15 | Eq |
| $\theta_{\rm FWHM}$ | 40’ | 63’ | 106’ |
| $\sigma_{f_{\rm NL}}$ | 10.70 | 5.20 | 3.63 |

# Bispectrum from non-linear gravity

$$\Delta = \Delta^{(1)} + \Delta^{(2)}$$

$$\Delta^{(1)} = b_1 \delta^{(1)} + \mathcal{H}^{-1} \partial_r^2 v^{(1)}$$

$$\begin{aligned}\Delta^{(2)}(\mathbf{n}, z) =& b_1 \delta^{(2)} + \frac{1}{2} b_2 (\delta^{(1)})^2 + b_s s^2 + \mathcal{H}^{-1} \partial_r^2 v^{(2)} \\ &+ \mathcal{H}^{-2} [(\partial_r^2 v^{(1)})^2 + \partial_r v^{(1)} \partial_r^3 v^{(1)}] \\ &+ \mathcal{H}^{-1} [\partial_r v^{(1)} \partial_r \delta^{(1)} + \partial_r^2 v^{(1)} \delta^{(1)}]\end{aligned}$$

$$\langle \Delta^{(1)} \Delta^{(1)} \Delta^{(1)} \rangle \propto f_{\rm NL}$$

**Primordial**

$$\langle \Delta^{(2)} \Delta^{(1)} \Delta^{(1)} \rangle + \circlearrowleft$$

**Non-linear Gravitational**

$$\Delta^{(2)}(\mathbf{n},z) = b_1\delta^{(2)} + \frac{1}{2}b_2(\delta^{(1)})^2 + b_s s^2 + \mathcal{H}^{-1}\partial_r^2 v^{(2)} + \mathcal{H}^{-2}[(\partial_r^2 v^{(1)})^2 + \partial_r v^{(1)}\partial_r^3 v^{(1)}] + \mathcal{H}^{-1}[\partial_r v^{(1)}\partial_r\delta^{(1)} + \partial_r^2 v^{(1)}\delta^{(1)}]$$

$$\Delta^{(1)} = b_1\delta^{(1)} + \mathcal{H}^{-1}\partial_r^2 v^{(1)}$$

$$\langle \Delta^{(2)}\Delta^{(1)}\Delta^{(1)}\rangle + \circlearrowleft$$

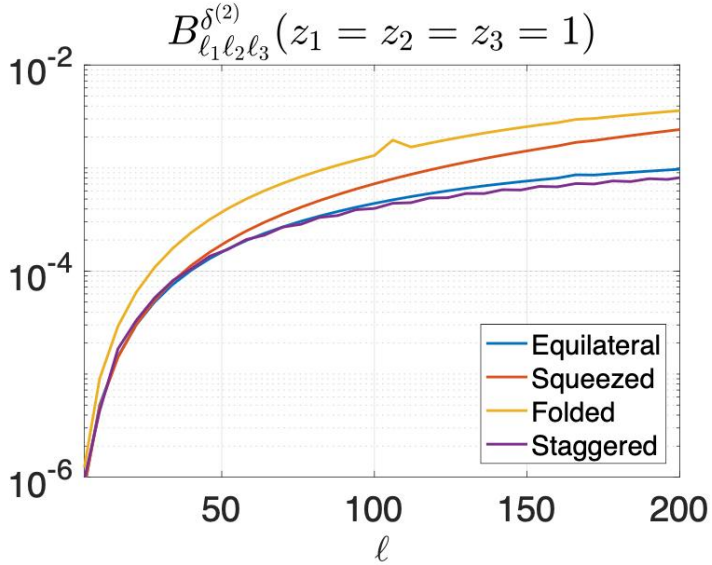
$$b_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) = b^{\delta^{(2)}}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{v^{(2)\prime}}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{\delta v'}_{\ell_2'\ell_2\ell_3}(z_1,z_2,z_3) + b^{v'^2}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{\delta' v}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{v''v}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3)$$

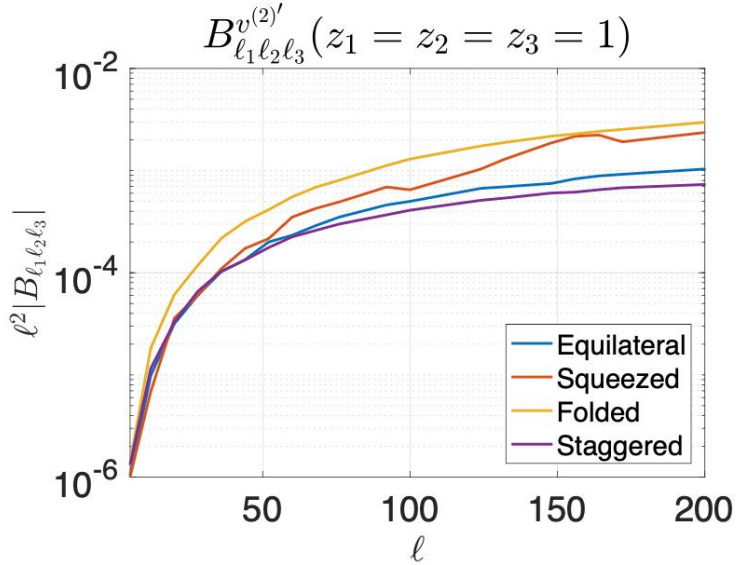
$$b^{\delta 0}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) = \frac{34}{21}c^{\delta\Delta}_{\ell_1}(z_1,z_3)c^{\delta\Delta}_{\ell_2}(z_2,z_3)$$

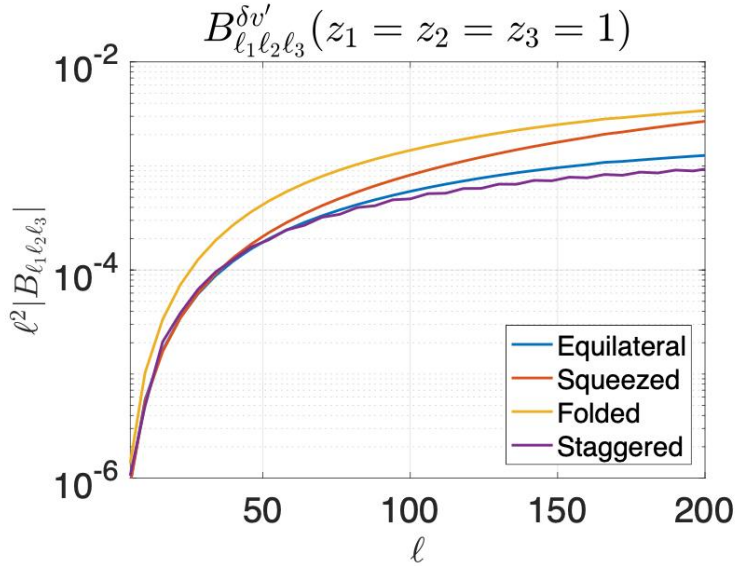
$$^{n}c^{AB}_{\ell\ell'}(z_1,z_2) = i^{\ell-\ell'}4\pi\int\frac{dk}{k}k^n\mathcal{P}_R(k)\Delta^A_\ell(k,r_1)\Delta^B_{\ell'}(k,r_2)$$

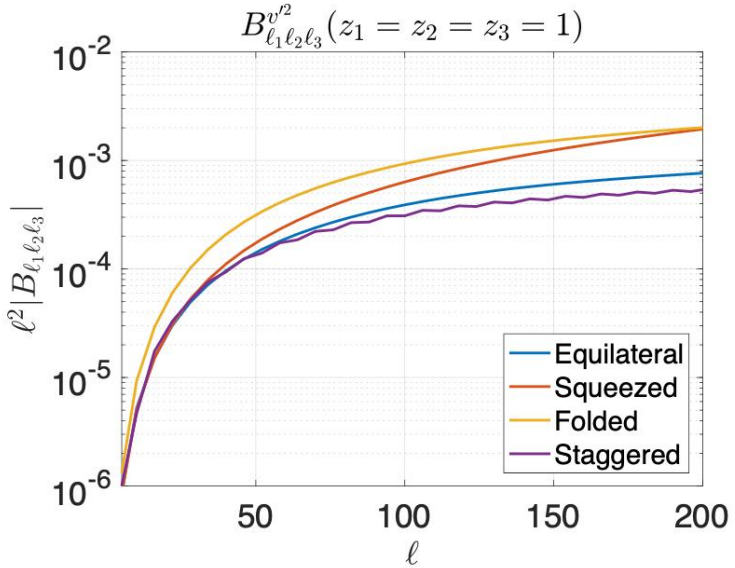
**Non-linear Gravitational**

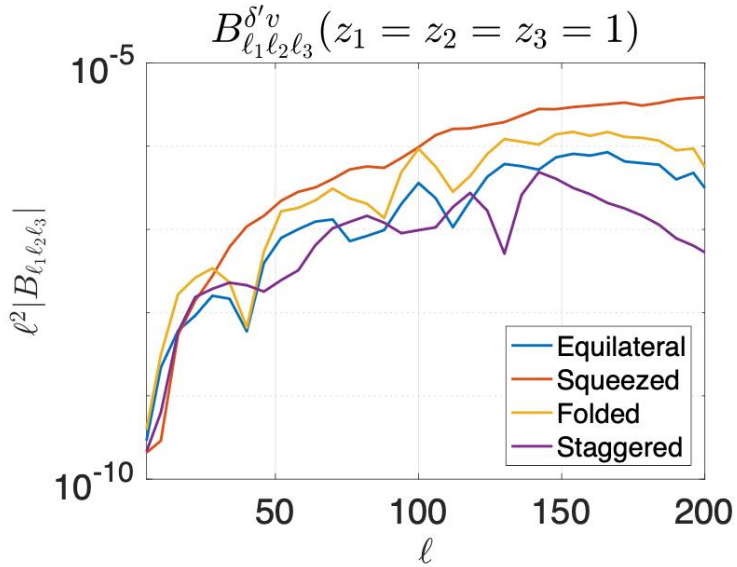
$$b_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) = b^{\delta^{(2)}}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{v^{(2)\prime}}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{\delta v'}_{\ell_2'\ell_2\ell_3}(z_1,z_2,z_3) + b^{v'^2}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{\delta' v}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3) + b^{v''v}_{\ell_1\ell_2\ell_3}(z_1,z_2,z_3)$$

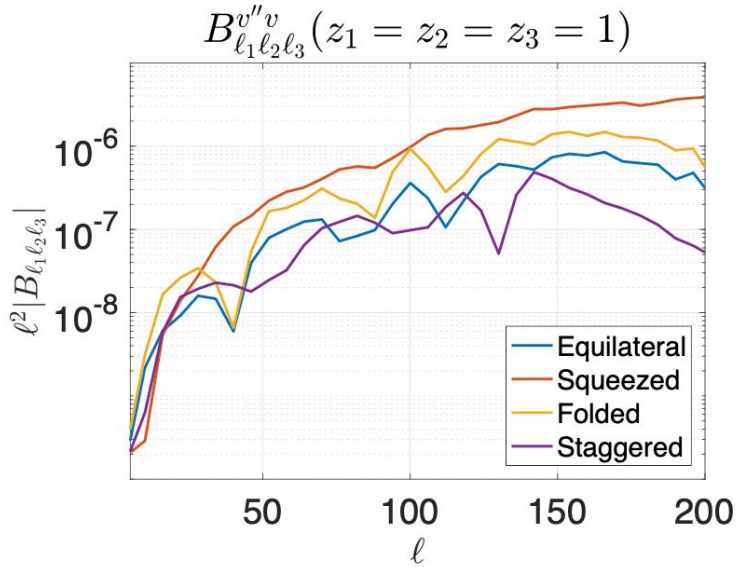


| Parameters | BINGO | SKA1-MID Band 2 |
|---|---|---|
| Frequency range | [980,1260] MHz | [950, 1405] MHz |
| Redshift range | [0.127,0.449] | [0.01, 0.49] |
| Number of frequency channels | 28 | 46 |
| Number of feed horns | 28 | 197 |
| Sky coverage with Galactic mask | 2900 $\mathrm{deg}^2$ | 5000 $\mathrm{deg}^2$ |
| Observational time ($t_{\mathrm{obs}}$ ) | 1 year | 1 year |
| System temperature ($T_{\mathrm{sys}}$ ) | 70 K | 15 K |
| Beam resolution ($\theta_{\mathrm{FWHM}}$) | 40 arcmin | 70 arcmin |

$$F_{ij} = \frac{1}{2}\mathbf{Tr}\left[\mathbf{C}^{-1}\frac{\partial \mathbf{C}}{\partial p_i}\mathbf{C}^{-1}\frac{\partial \mathbf{C}}{\partial p_j}\right]$$

$$\mathbf{C} = C_l(z_i, z_j) + \mathcal{N}_l(z_i, z_j)$$

$$\mathcal{N}_l(z) = \frac{T_{\mathrm{sys}^2}}{\Delta\nu t_{\mathrm{obs}}}\left(\frac{4\pi f_{\mathrm{sky}}}{2n_{\mathrm{f}}}\right)\frac{1}{b_\ell(z)^2}$$

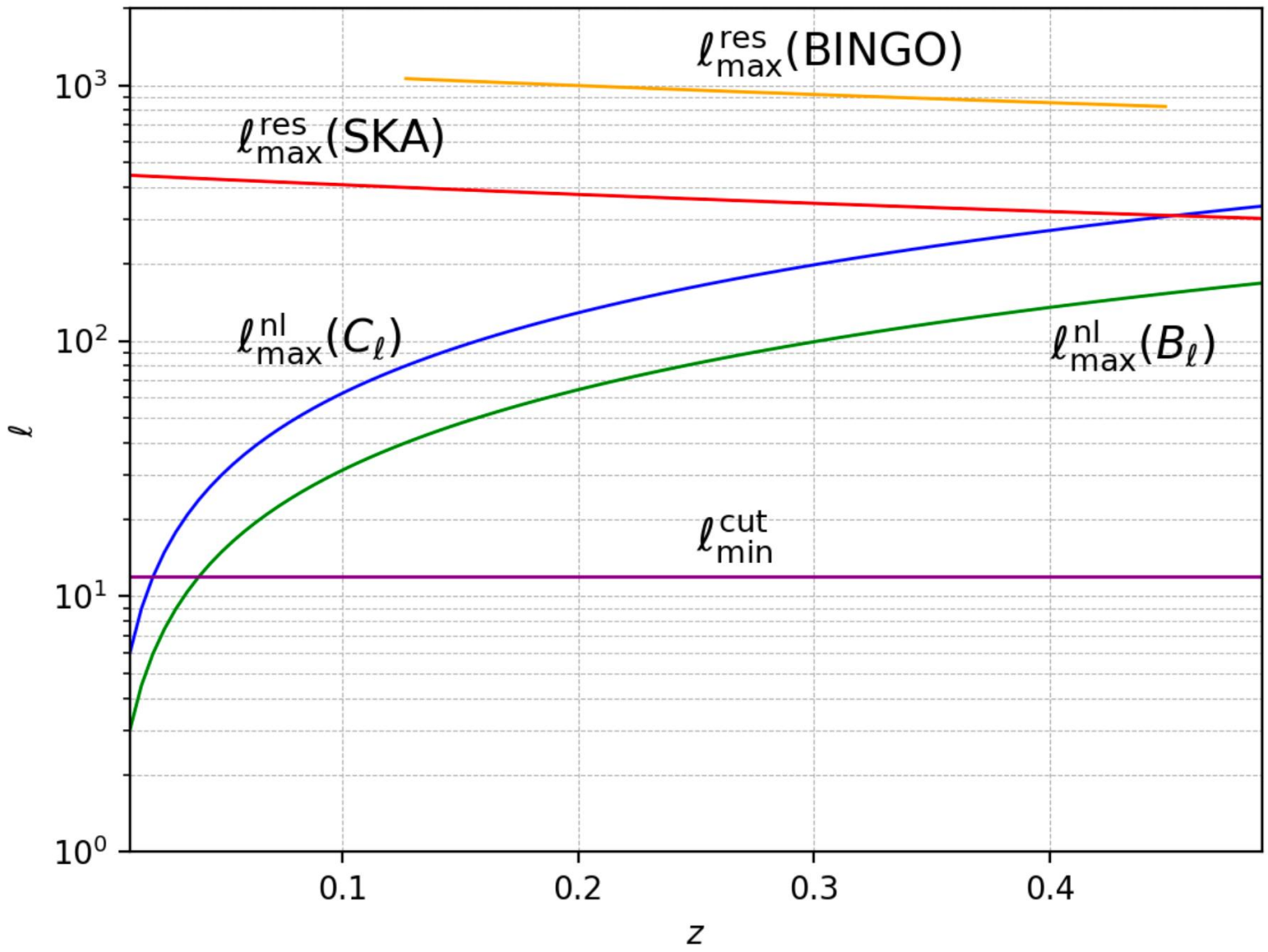
$$b_\ell(z_i) = \exp\left(-\frac{1}{2}\frac{\ell^2\theta^2_{\mathrm{FWHM}}(\nu_{\mathrm{center}})}{8\ln 2}\frac{\nu^2_{\mathrm{center}}}{\nu_i^2}\right)$$

$$F_{ij} = f_{sky}\sum_m \sum_{\ell_3\geq\ell_2\geq\ell_1} \frac{1}{\Delta_{\ell_1,\ell_2,\ell_3}}\sigma^{-2}_{\ell_1,\ell_2,\ell_3}(z_m, z_m, z_m)$$
$$\times \frac{\partial}{\partial p_i}B_{\ell_1,\ell_2,\ell_3}(z_m, z_m, z_m)\frac{\partial}{\partial p_j}B_{\ell_1,\ell_2,\ell_3}(z_m, z_m, z_m)$$

$$\sigma^2_{\ell_1,\ell_2,\ell_3}(z_m, z_m, z_m) = \tilde{C}^{mm}_{\ell_1}\tilde{C}^{mm}_{\ell_2}\tilde{C}^{mm}_{\ell_3}$$

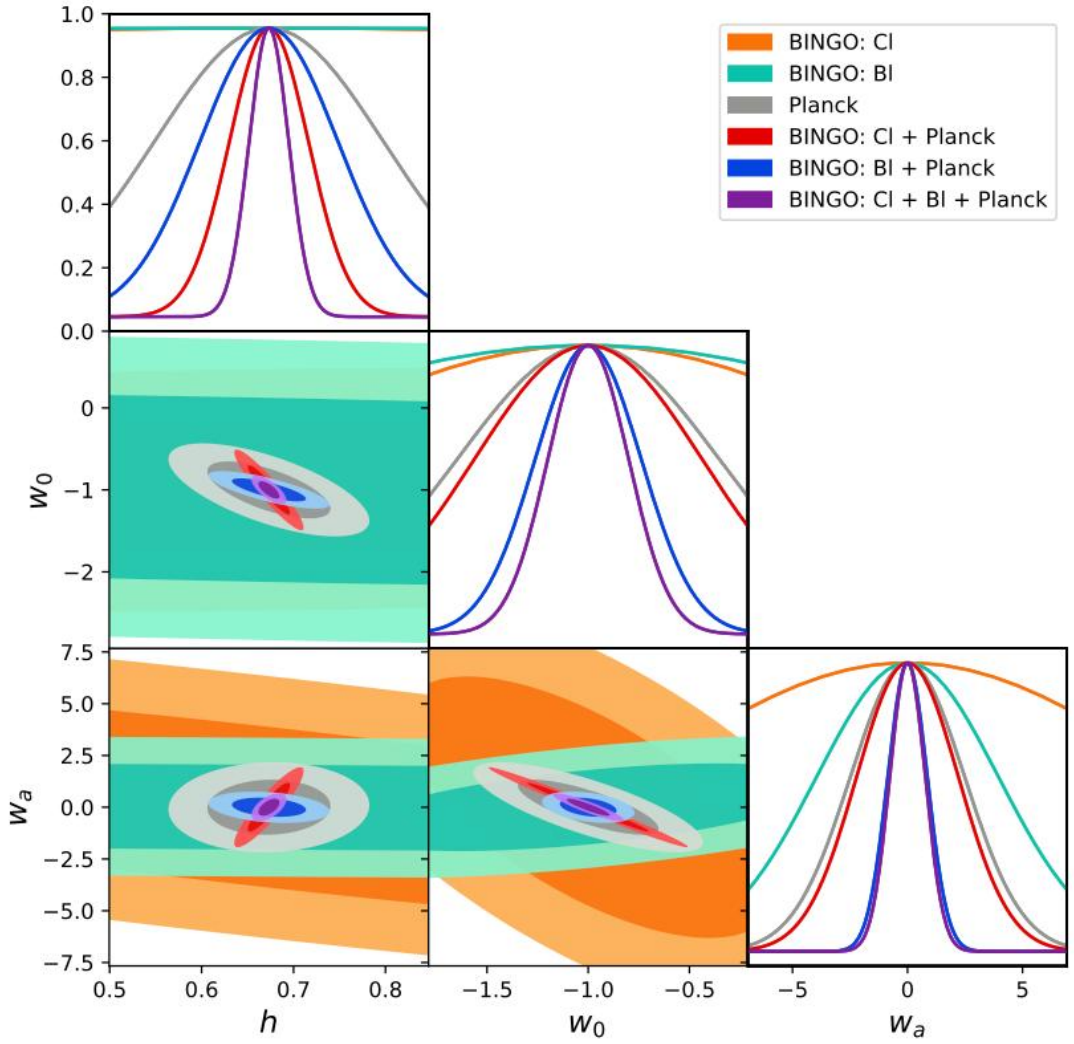
$$\ell^{\rm res}_{\rm max}(z) \approx \frac{2\pi D_d}{\lambda_{21}(1+z)}$$

$$\ell^{\rm nl}_{\rm max}(z) = r(z)k_{\rm nl}(z),$$
$$k_{\rm nl}(z) = k_{\rm nl}(0)(1+z)^{2/3}{\rm Mpc}^{-1}$$



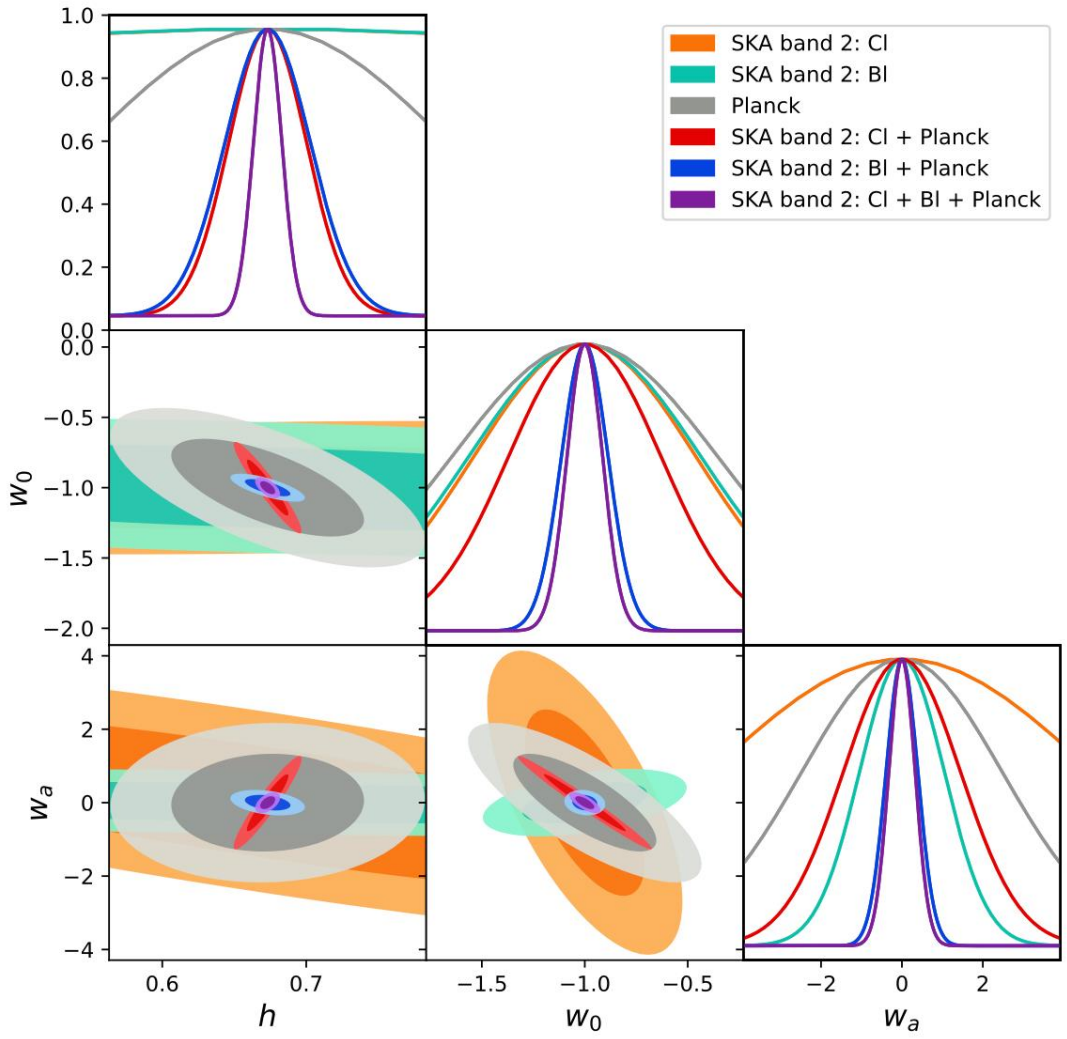
# BINGO Forecast

| Parameter | Planck | $C_\ell$ + Planck | $B_\ell$ + Planck | $C_\ell + B_\ell$ + Planck | Improvement |
|---|---|---|---|---|---|
| | | | ΛCDM | | |
| $\Omega_b h^2$ | 0.00015 (0.67%) | 0.00014 (0.63%) | 0.00015 (0.67%) | 0.00014 (0.63%) | 0% |
| $\Omega_c h^2$ | 0.0016 (1.3%) | 0.0014 (1.2%) | 0.0015 (1.2%) | 0.0013 (1.1%) | 7.1% |
| $\ln(10^{10} A_s)$ | 0.017 (0.56%) | 0.017 (0.56%) | 0.017 (0.56%) | 0.016 (0.53%) | 5.9% |
| $n_s$ | 0.0044 (0.46%) | 0.0042 (0.43%) | 0.0043 (0.45%) | 0.0041 (0.42%) | 2.4% |
| $h$ | 0.0067 (1%) | 0.0057 (0.85%) | 0.0064 (0.95%) | 0.0054 (0.8%) | 5.3% |
| $b_1$ | - | 0.012 (1.2%) | 0.026 (2.6%) | 0.012 (1.2%) | 0% |
| $b_2$ | - | - | 0.26 (26%) | 0.12 (12%) | - |
| $b_s$ | - | - | 0.32 (32%) | 0.30 (30%) | - |
| | | | wCDM | | |
| $\Omega_b h^2$ | 0.00015 (0.67%) | 0.00015 (0.67%) | 0.00015 (0.67%) | 0.00015 (0.67%) | 0 % |
| $\Omega_c h^2$ | 0.0014 (1.2%) | 0.0014 (1.2%) | 0.0014 (1.2%) | 0.0013 (1.1%) | 7.1% |
| w | 0.26 (26%) | 0.048 (4.8%) | 0.11 (11%) | 0.047 (4.7%) | 2.1% |
| $\ln(10^{10} A_s)$ | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0 % |
| $n_s$ | 0.0044 (0.46%) | 0.0043 (0.45%) | 0.0043 (0.45%) | 0.0042 (0.43%) | 2.3% |
| $h$ | 0.089 (13.22%) | 0.012 (1.8%) | 0.035 (5.2%) | 0.011 (1.6%) | 8.3 % |
| $b_1$ | - | 0.04 (4%) | 0.13 (13%) | 0.038 (3.8%) | 5% |
| $b_2$ | - | - | 0.26 (26%) | 0.13 (13%) | - |
| $b_s$ | - | - | 0.94 (94%) | 0.41 (41%) | - |
| | | | CPL | | |
| $\Omega_b h^2$ | 0.00016 (0.71%) | 0.00015 (0.67%) | 0.00015 (0.67%) | 0.00015 (0.67%) | 0% |
| $\Omega_c h^2$ | 0.0013 (1.1%) | 0.0013 (1.1%) | 0.0013 (1.1%) | 0.0013 (1.1%) | 0% |
| $w_0$ | 0.46 (46%) | 0.38 (38%) | 0.13 (13%) | 0.1 (10%) | 74% |
| $w_a$ | 1.7 | 1.5 | 0.46 | 0.4 | 73% |
| $\ln(10^{10} A_s)$ | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0% |
| $n_s$ | 0.0044 (0.46%) | 0.0044 (0.46%) | 0.0044 (0.46%) | 0.0043 (0.45%) | 2.3% |
| $h$ | 0.088 (13% ) | 0.028 (4.2%) | 0.037 (5.5%) | 0.012 (1.8%) | 57% |
| $b_1$ | - | 0.042 (4.2%) | 0.16 (16%) | 0.039 (3.9%) | 7.1% |
| $b_2$ | - | - | 0.4 (40%) | 0.27 (27%) | - |
| $b_s$ | - | - | 0.98 (98%) | 0.49 (49%) | - |



# SKA-MID Band 2 Forecast

| Parameter | Planck | $C_\ell$ + Planck | $B_\ell$ + Planck | $C_\ell + B_\ell$ + Planck | Improvement |
|---|---|---|---|---|---|
| | | | ΛCDM | | |
| $\Omega_b h^2$ | 0.00015 (0.67%) | 0.00013 (0.58%) | 0.00014 (0.63%) | 0.00012 (0.54%) | 7.7% |
| $\Omega_c h^2$ | 0.0016 (1.3%) | 0.0011 (0.92%) | 0.0013 (1.1%) | 0.00094 (0.78%) | 15% |
| $\ln(10^{10} A_s)$ | 0.017 (0.56%) | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0% |
| $n_s$ | 0.0044 (0.46%) | 0.0038 (0.39%) | 0.0041 (0.42%) | 0.0037 (0.38%) | 2.6% |
| $h$ | 0.0067 (1%) | 0.0044 (0.65%) | 0.0057 (0.85%) | 0.004 (0.59%) | 9.1% |
| $b_1$ | - | 0.01 (1%) | 0.019 (1.9%) | 0.01 (1%) | 0 % |
| $b_2$ | - | - | 0.15 (15%) | 0.074 (7.4%) | - |
| $b_s$ | - | - | 0.20 (20%) | 0.19 (19%) | - |
| | | | wCDM | | |
| $\Omega_b h^2$ | 0.00015 (0.67%) | 0.00015 (0.67%) | 0.00014 (0.63%) | 0.00014 (0.63%) | 6.7% |
| $\Omega_c h^2$ | 0.0014 (1.2%) | 0.0013 (1.1%) | 0.0013 (1.1%) | 0.0012 (1%) | 7.4% |
| w | 0.26 (26%) | 0.039 (3.9%) | 0.069 (6.9%) | 0.037 (3.7%) | 5.1% |
| $\ln(10^{10} A_s)$ | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0% |
| $n_s$ | 0.0044 (0.46%) | 0.0042 (0.43%) | 0.0042 (0.43%) | 0.004 (0.41%) | 4.8% |
| $h$ | 0.089 (13%) | 0.0065 (0.97%) | 0.02 (3%) | 0.0061 (0.91%) | 6.2% |
| $b_1$ | - | 0.026 (2.6%) | 0.077 (7.7%) | 0.025 (2.5%) | 3.8% |
| $b_2$ | - | - | 0.15 (15%) | 0.075 (7.5%) | - |
| $b_s$ | - | - | 0.53 (53%) | 0.24 (24%) | - |
| | | | CPL | | |
| $\Omega_b h^2$ | 0.00016 (0.71%) | 0.00015 (0.67%) | 0.00015 (0.67%) | 0.00015 (0.67%) | 0% |
| $\Omega_c h^2$ | 0.0013 (1.1%) | 0.0013 (1.1%) | 0.0013 (1.1%) | 0.0012 (1%) | 7.4% |
| $w_0$ | 0.46 (46%) | 0.26 (26%) | 0.08 (8%) | 0.061 (6.1%) | 77% |
| $w_a$ | 1.8 | 1 | 0.28 | 0.23 | 77% |
| $\ln(10^{10} A_s)$ | 0.016 (0.53%) | 0.016 (0.53%) | 0.016 (0.53%) | 0.015 (0.49%) | 6.3% |
| $n_s$ | 0.0044 (0.46%) | 0.0042 (0.43%) | 0.0043 (0.45%) | 0.004 (0.41%) | 4.8% |
| $h$ | 0.088 (13% ) | 0.019 (2.8%) | 0.021 (3.1%) | 0.007 (1.04%) | 63% |
| $b_1$ | - | 0.027 (2.7%) | 0.095 (9.5%) | 0.025 (2.5%) | 7.4% |
| $b_2$ | - | - | 0.23 (23%) | 0.15 (15%) | - |
| $b_s$ | - | - | 0.57 (57%) | 0.27 (27%) | - |



# Conclusions

| | |
|---|---|
| Primordial Non-Gaussianity | Important |
| Bispectrum | Useful |
| 21cm | Promising |

# Thank you