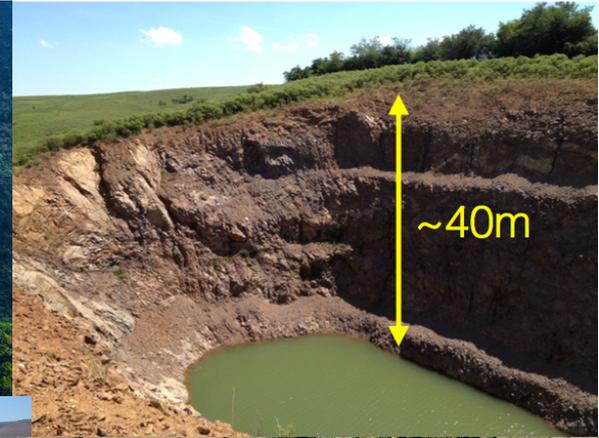


# 21-cm intensity mapping: observational prospects



Yin-Zhe Ma

University of KwaZulu-Natal

- **General forecasts for BINGO, FAST and SKA:**
- Xiaodong Xu, Yin-Zhe Ma, Amanda Weltman, 2018, Physical Review D (Impact factor: 4.506), 97, 083504, Constraining the interaction between dark sectors with future HI intensity mapping observations
- M.-A. Bigot-Sazy, Y.-Z. Ma, R. A. Battye, I. W. A. Browne, T. Chen, C. Dickinson, S. Harper, B. Maffei, L. C. Olivari, P. N. Wilkinson, 2016, Astronomical Society of the Pacific Conference Series, 502, 41–48 (8 pages), HI Intensity Mapping with FAST
- L. C. Olivari, C. Dickinson, R. A. Battye, Y.-Z. Ma, A. A. Costa, M. Remazeilles and S. Harper, 2018, Monthly Notices of the Royal Astronomical Society (Impact factor: 4.952), 473, 4242–4256, Cosmological parameter forecasts for H I intensity mapping experiments using the angular power spectrum
- Yi-Chao Li, Yin-Zhe Ma, 2017, Physical Review D (Impact factor: 4.506) 96, 063525 Constraints on Primordial non-Gaussianity from Future HI Intensity Mapping Experiments
- **Specific forecasts for SKA:**
- Stuart Harper, Clive Dickinson, Richard Battye, Sambit Roychowdhury, Ian Browne, Yin-Zhe Ma, Lucas Olivari, Tianyue Chen, 2018, MNRAS, 478, 2416, “Impact of Simulated 1/f Noise for HI Intensity Mapping Experiments”
- Santos et al., 1709.06099
- **Specific forecasts for BINGO:**
- Marie-anne Bigot-Sazy, Clive Dickinson, Richard A. Battye, Ian Browne, Yin-Zhe Ma, Bruno Maffei, Fabio Noviello, Mathieu Remazeilles, Peter Wilkinson, 2015, Monthly Notice of Royal Astronomical Society (Impact factor: 4.952), 454, 3240 (14 pages) Simulations for single-dish intensity mapping experiments
- Battye et al., 1610.06826

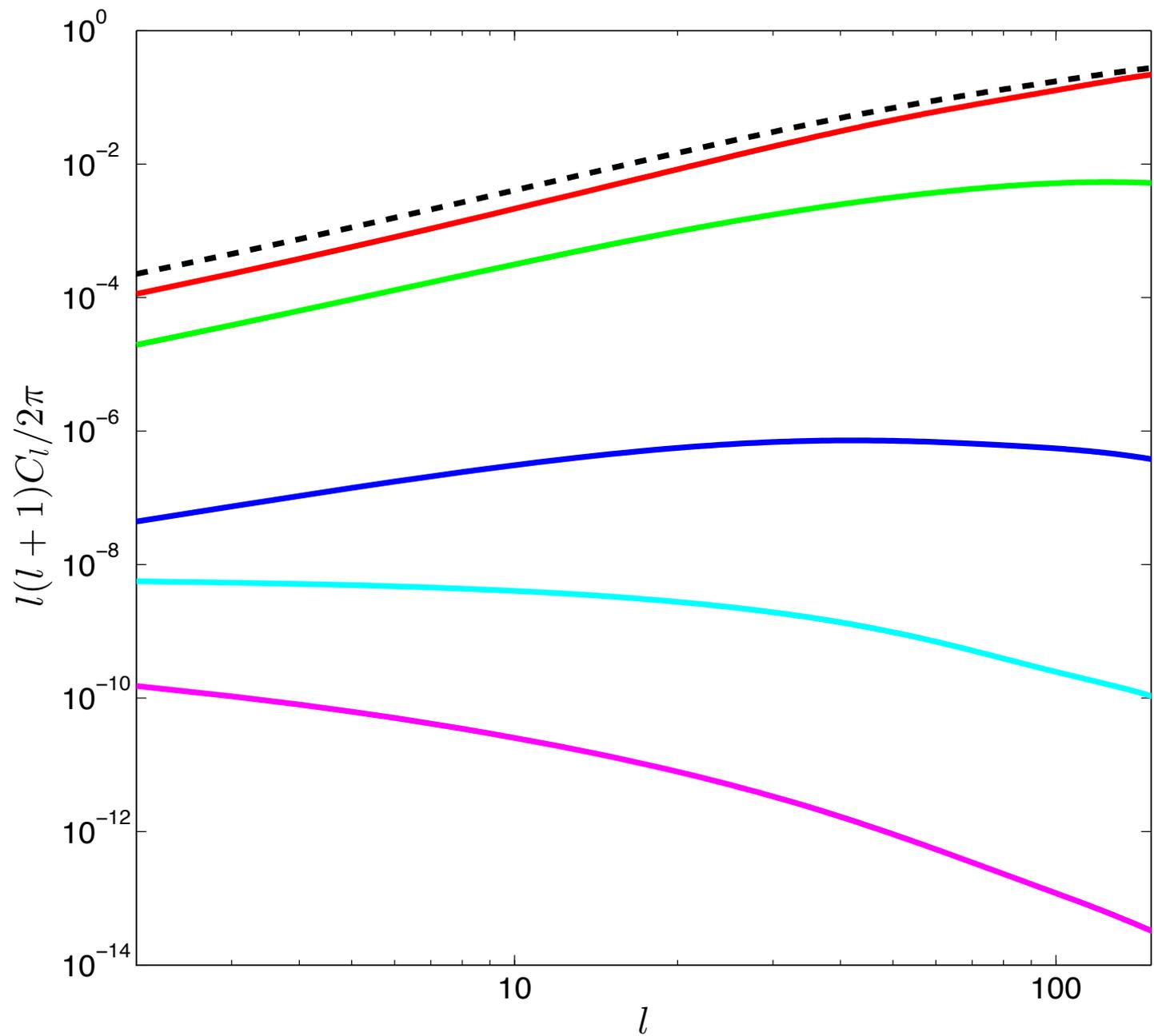
- BAO measurement
- Cosmological Forecasts
- Foreground cleaning
- $1/f$  noise

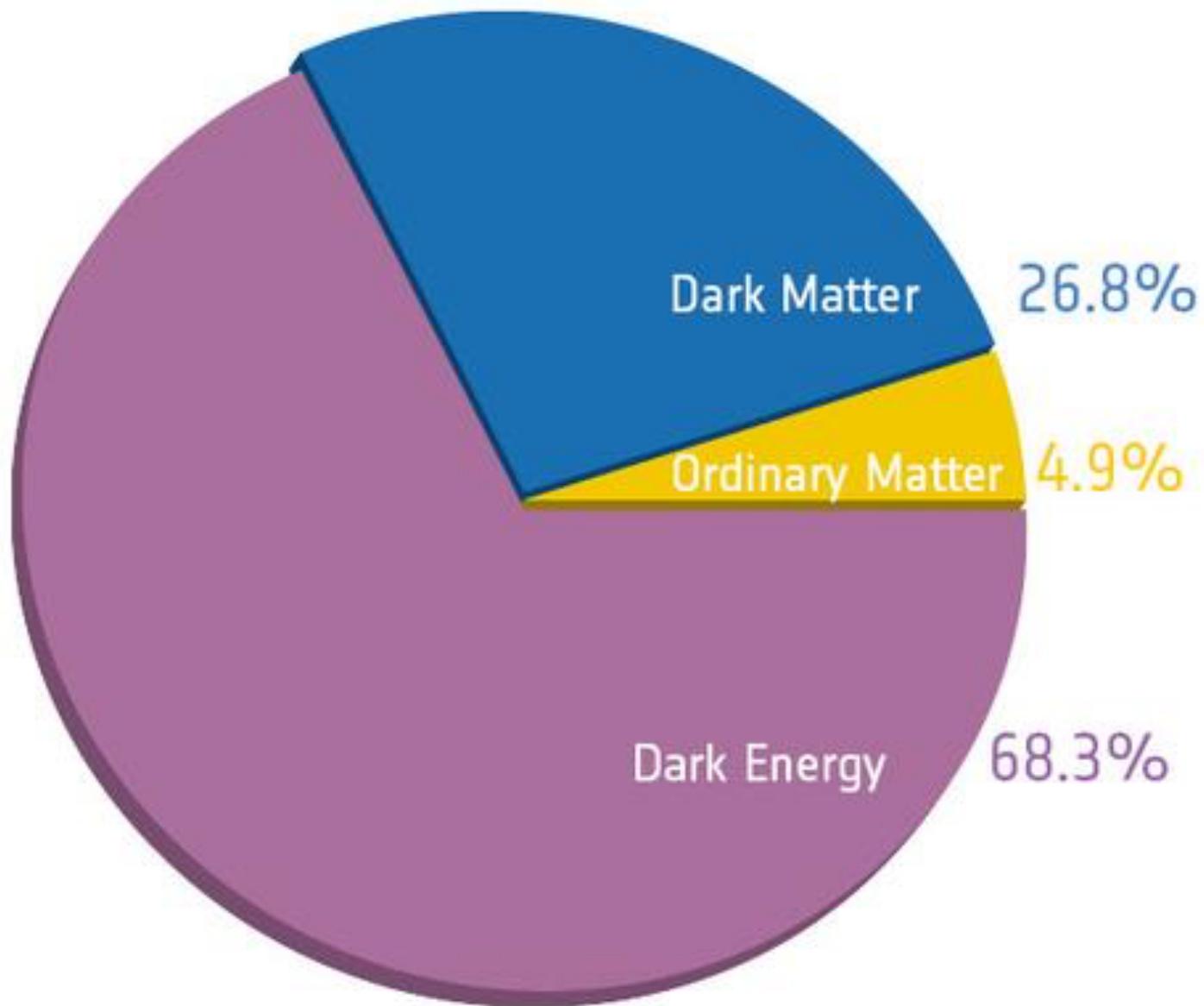
- **BAO measurement**
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- $1/f$  noise

$$\Delta_{T_b,l}^W(\mathbf{k}) = \int_0^\infty dz W(z) \Delta_{T_b,l}(\mathbf{k}, z)$$

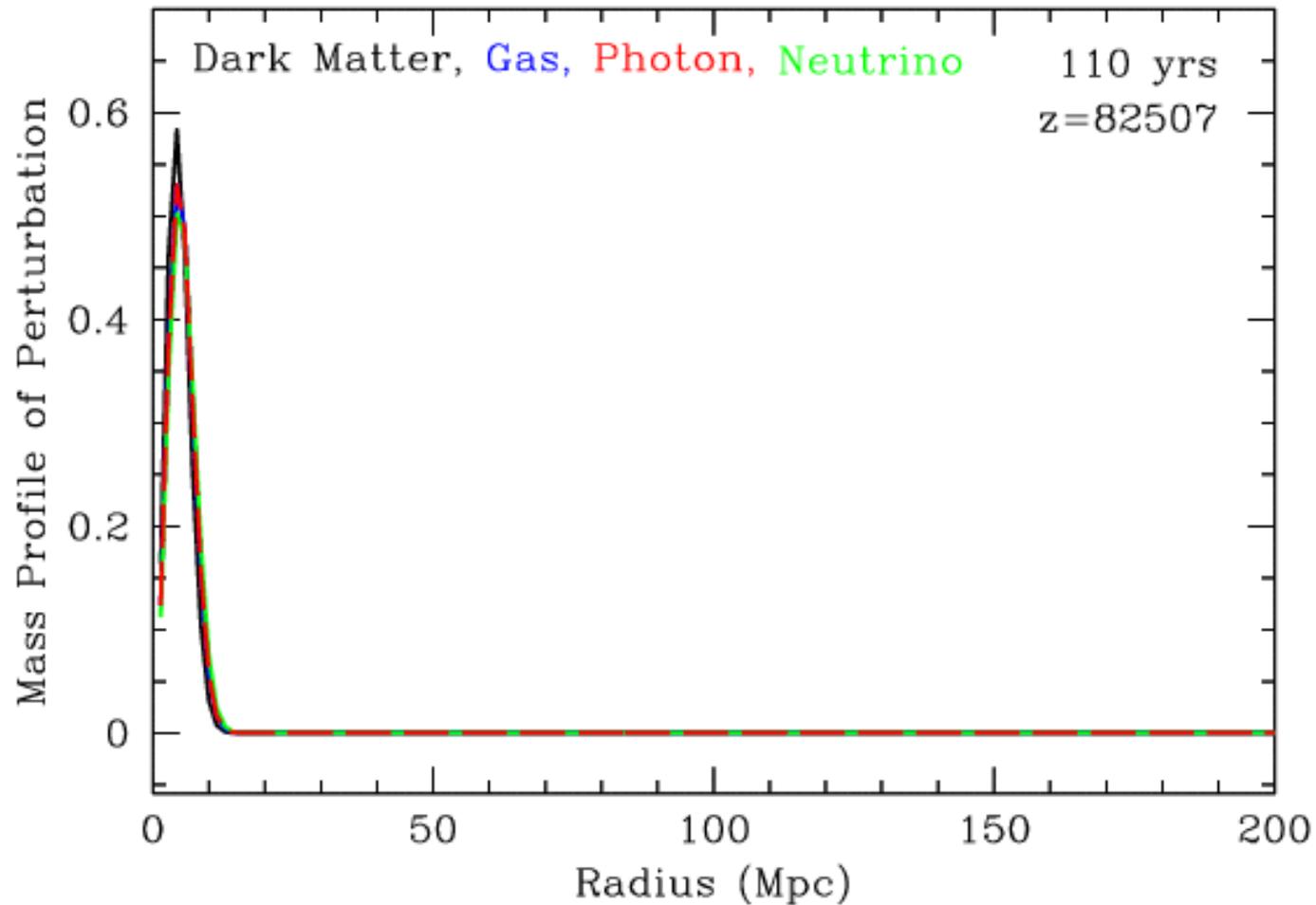
$$\Delta_{T_b,l}^{\dot{W}}(k) \equiv \Delta_{T_b,l}^W(\mathbf{k}) / \mathcal{R}(\mathbf{k})$$

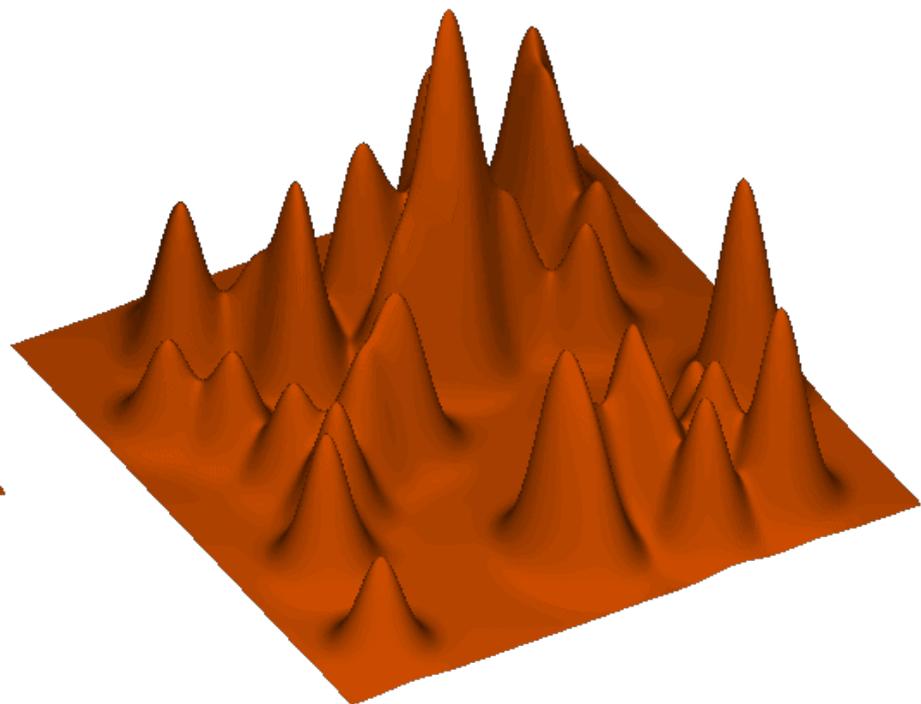
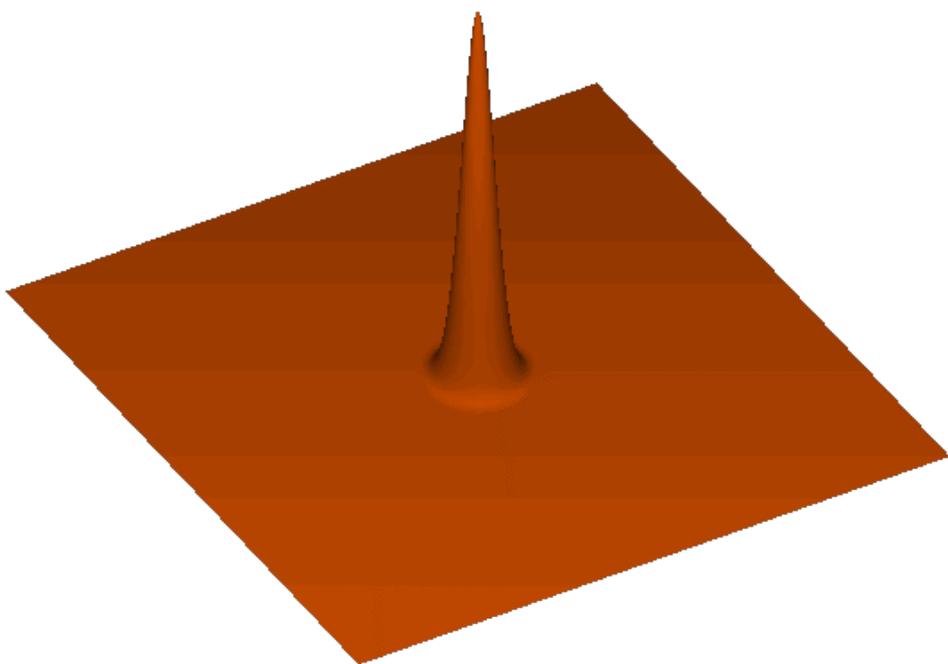
$$C_l^{WW'} = 4\pi \int d \ln k \mathcal{P}_{\mathcal{R}}(k) \Delta_{T_b,l}^W(k) \Delta_{T_b,l}^{W'}(k)$$

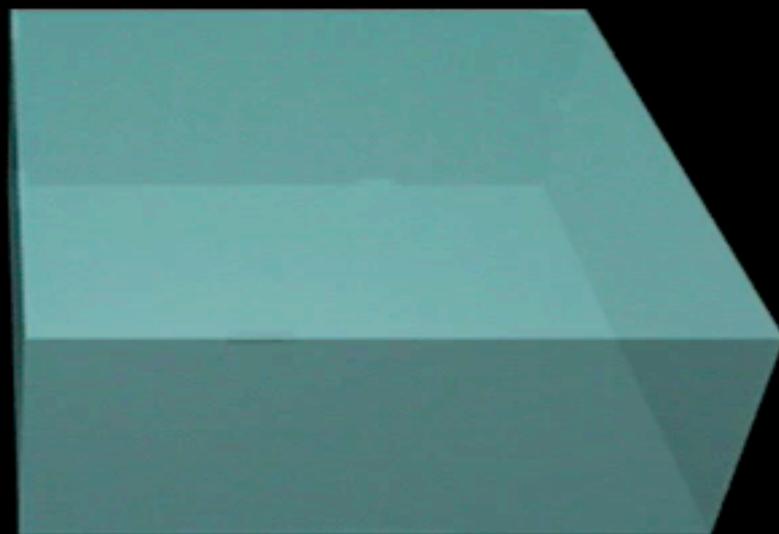




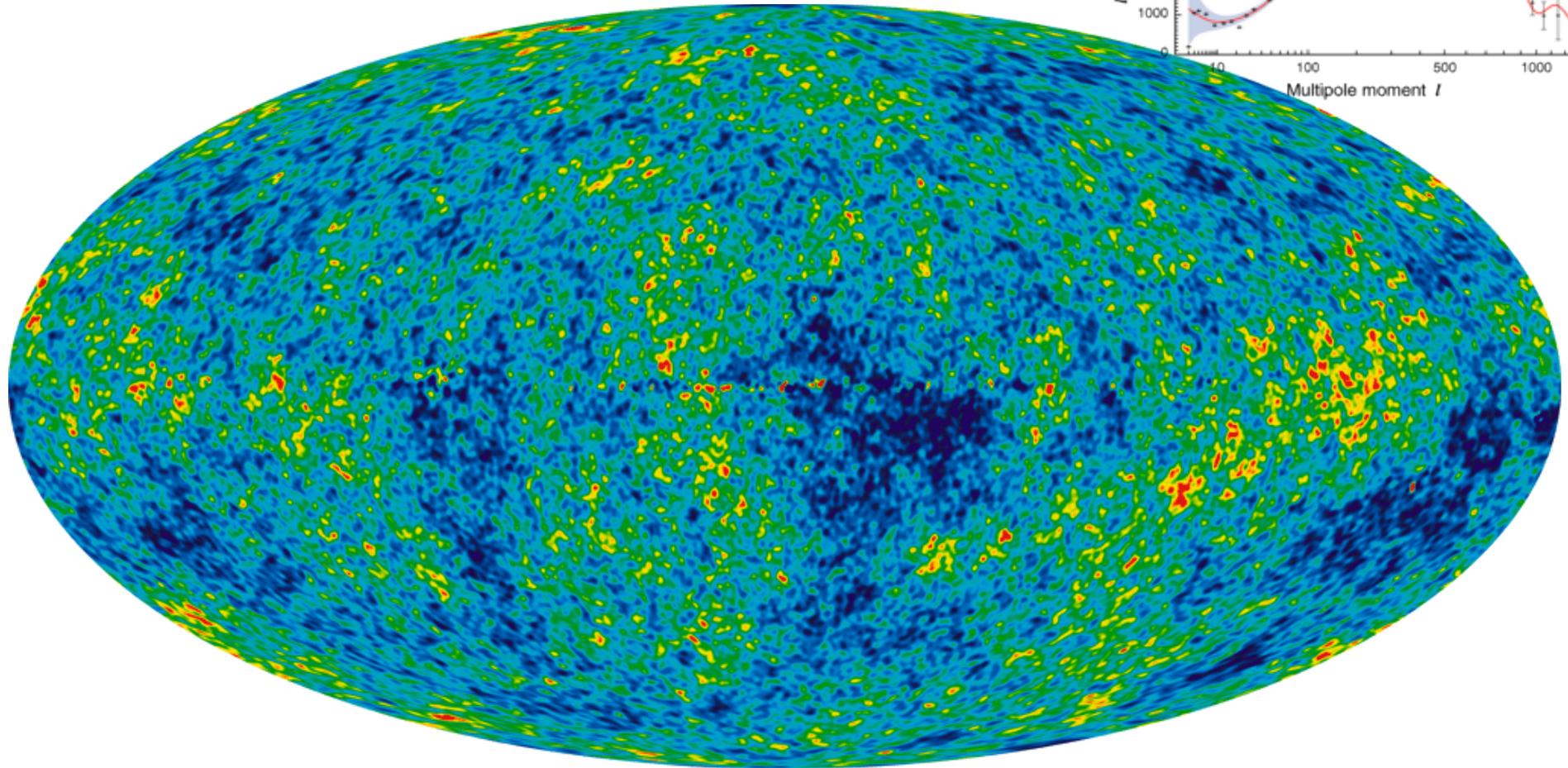
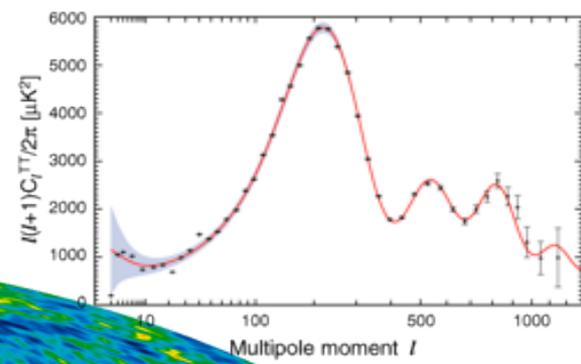
# Baryon Acoustic Oscillations





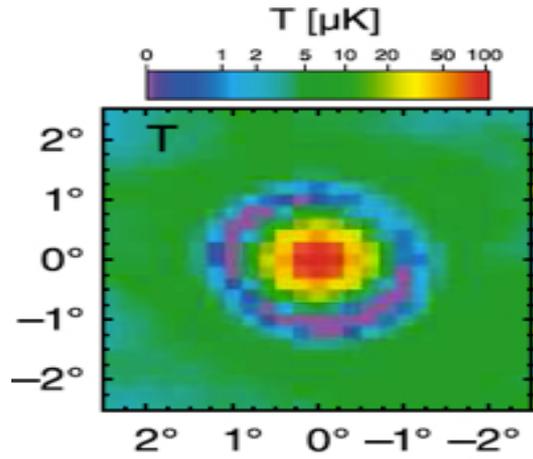


# BAO in the CMB

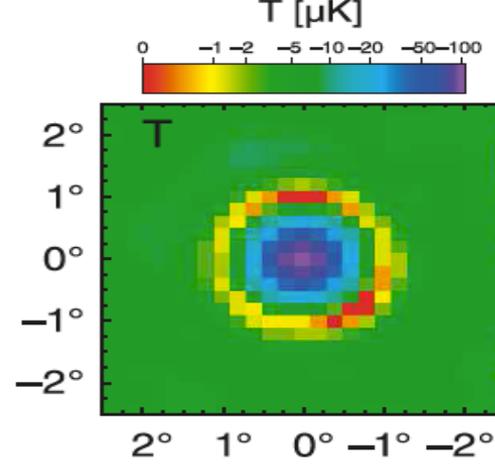


BAO have been observed in the CMB, and set the acoustic scale:  $l_A = 302.69 \pm 0.69$  @  $z=1091$ .

• Average hot spot

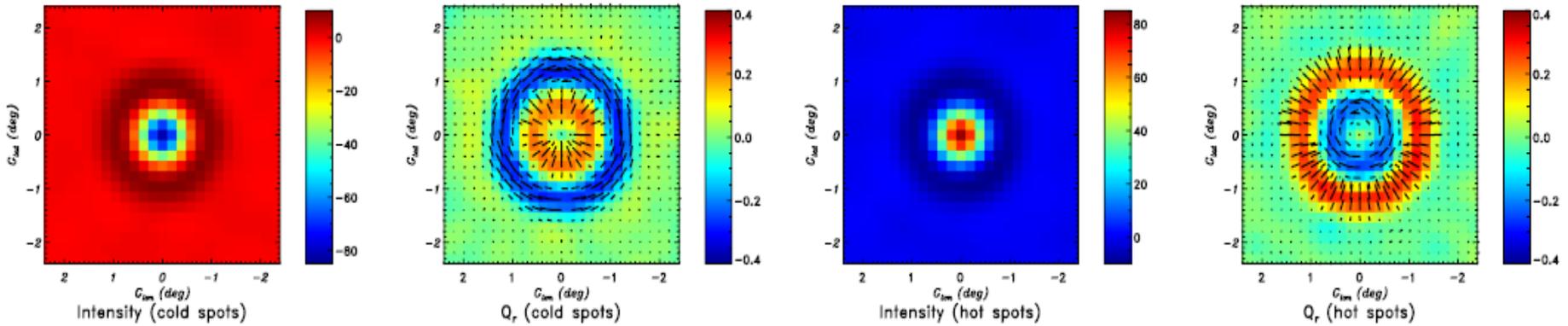


• Average cold spot

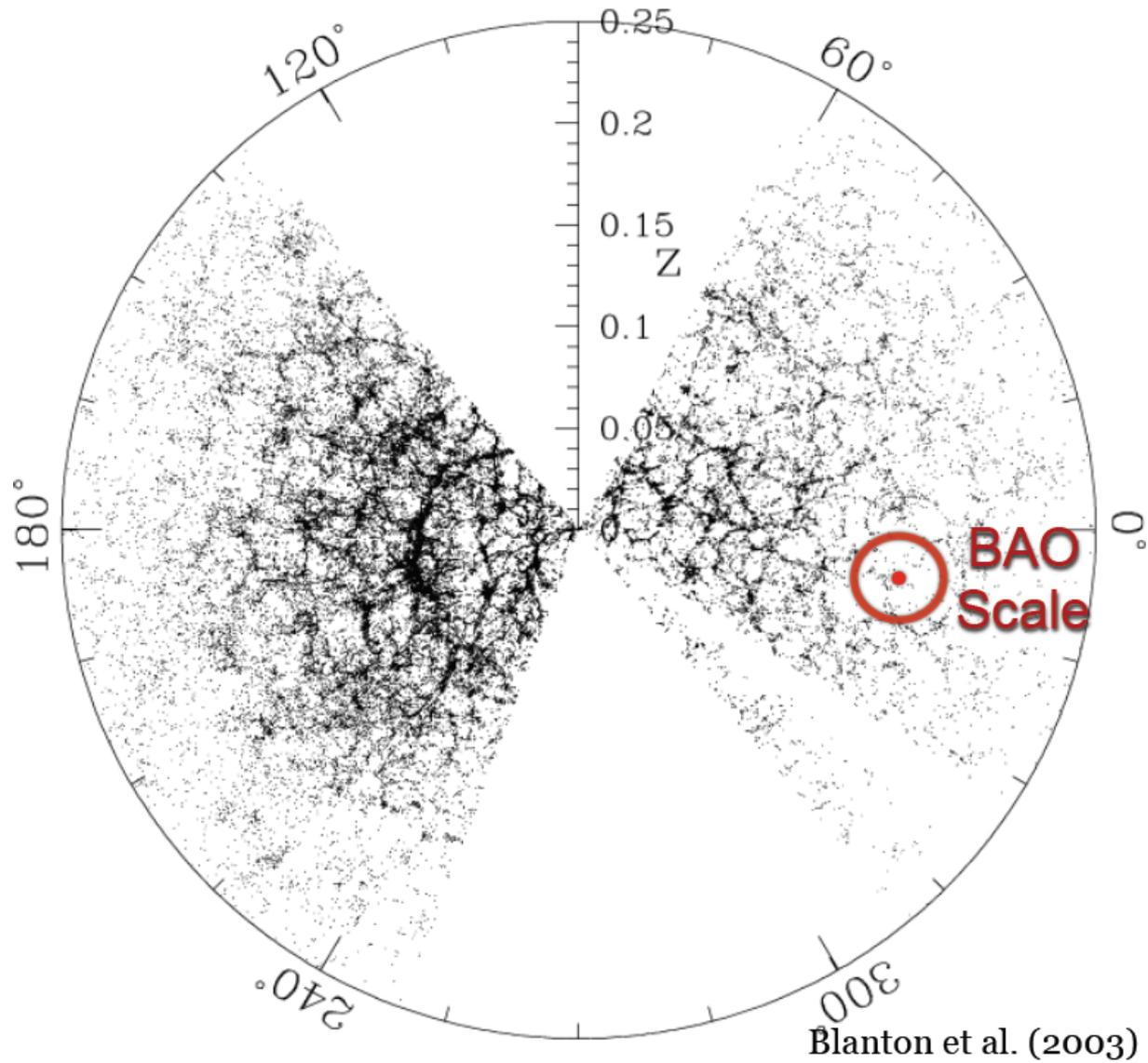


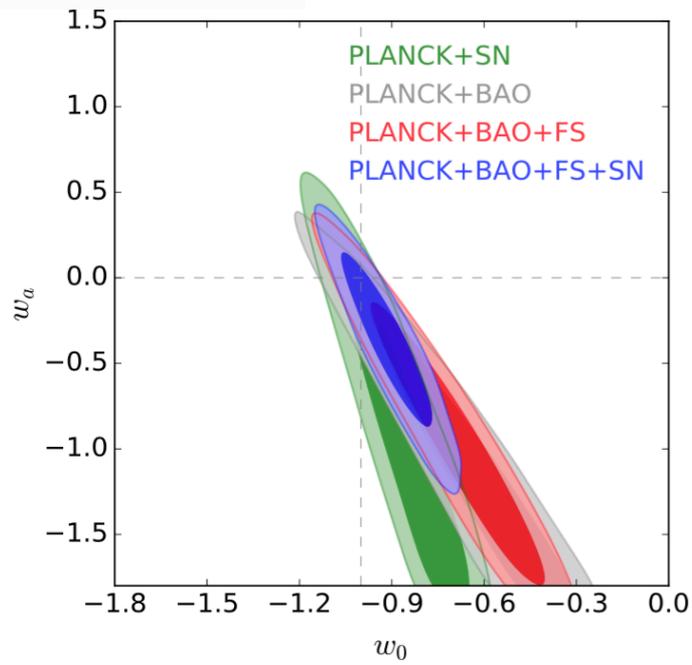
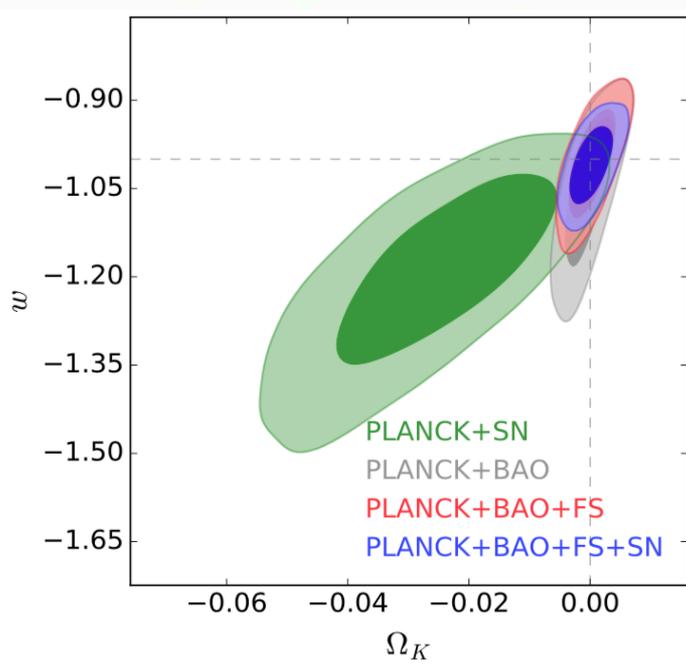
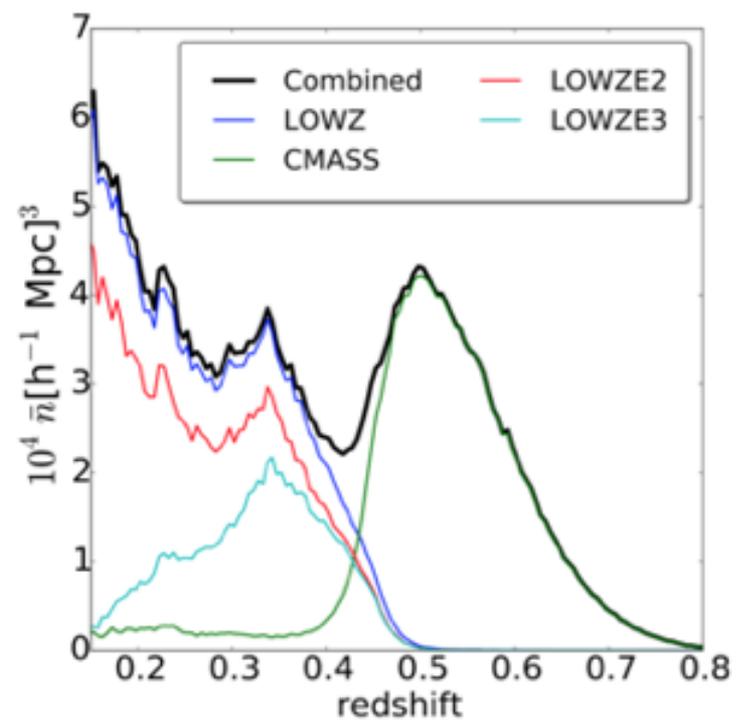
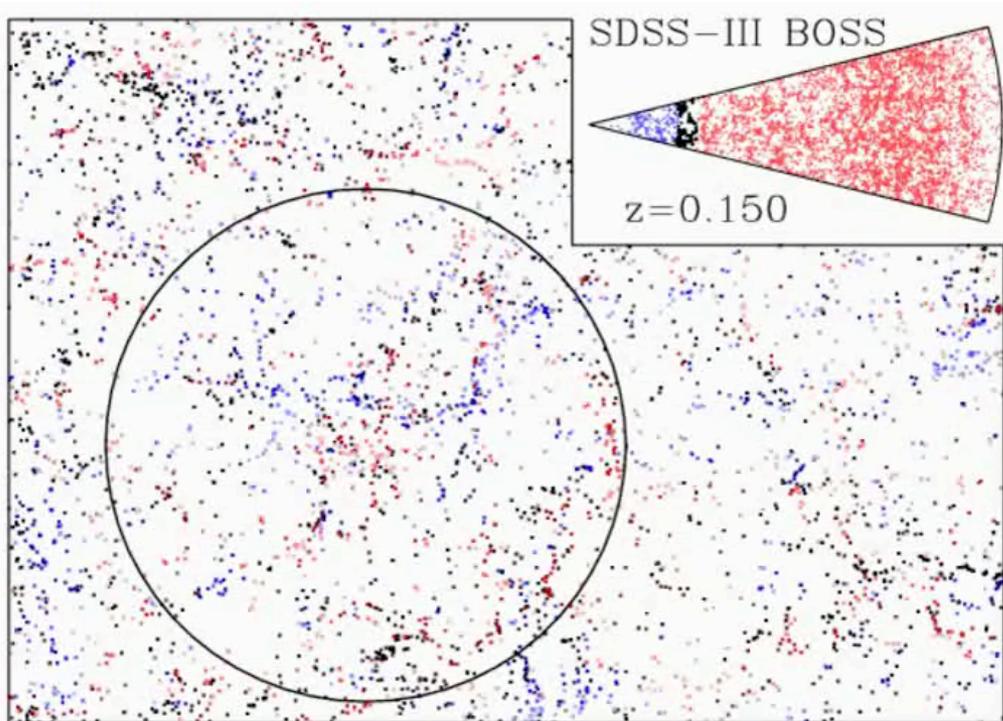
• WMAP:

• Planck:

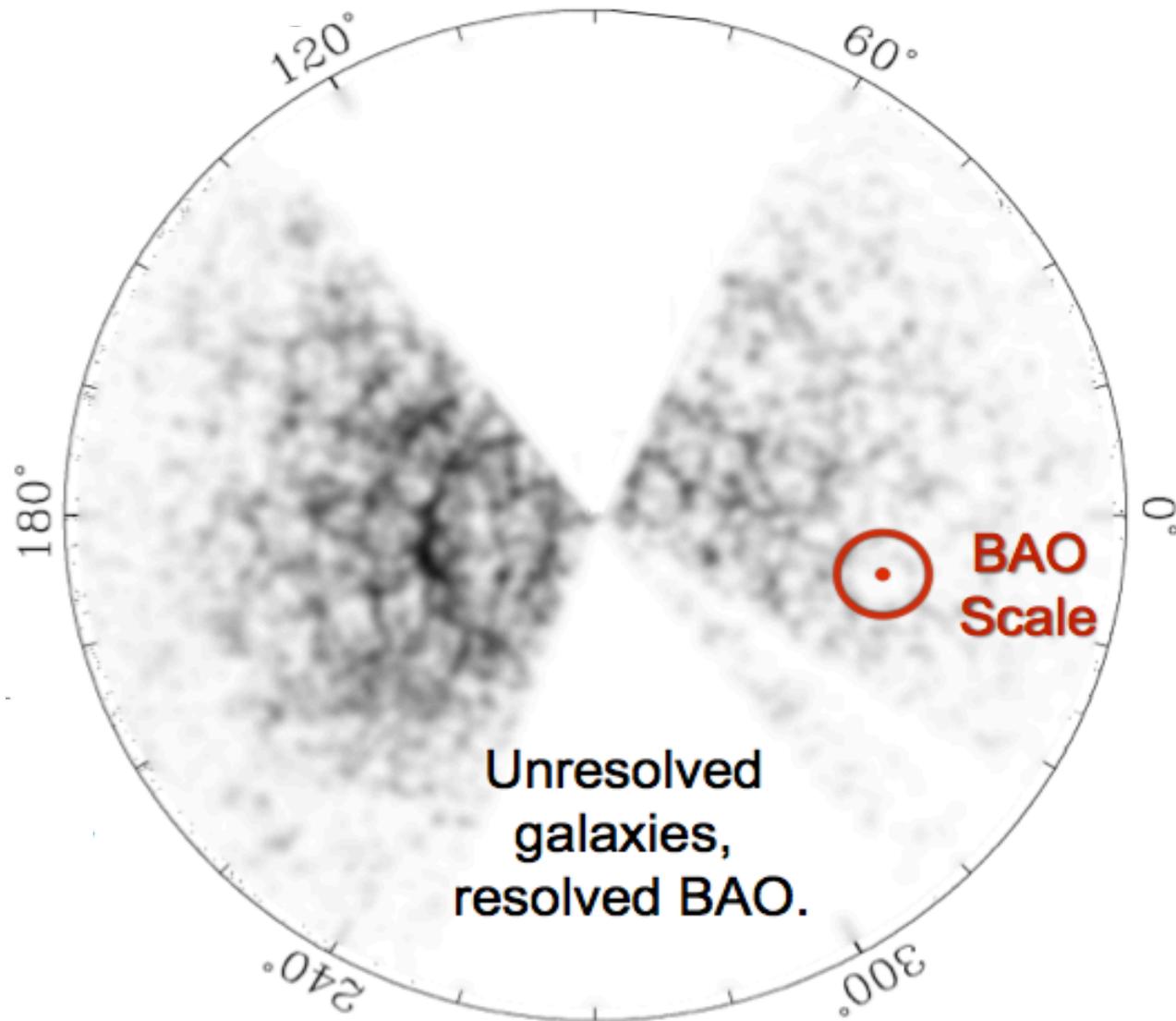


# Optical Galaxy Surveys

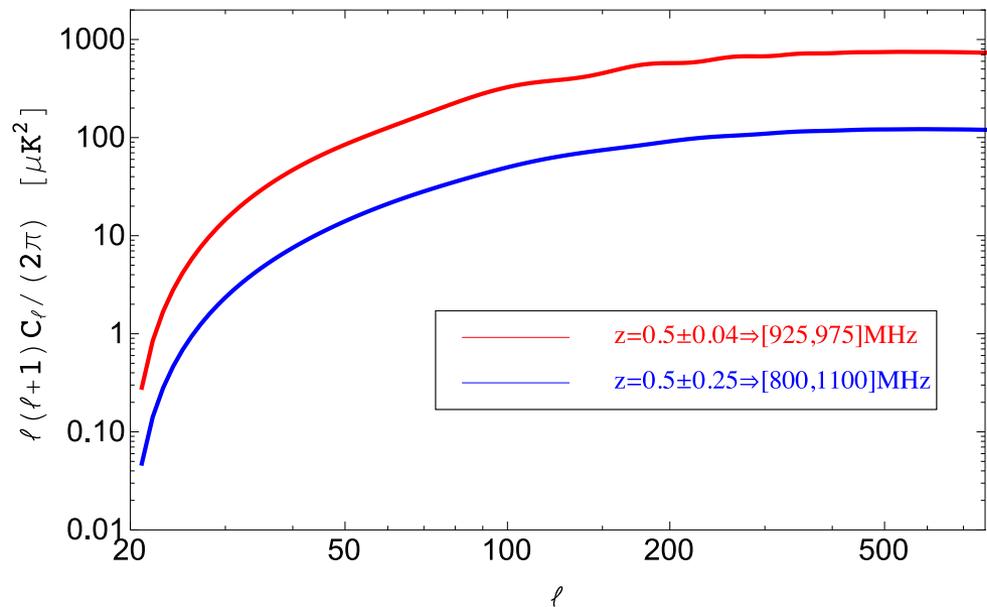




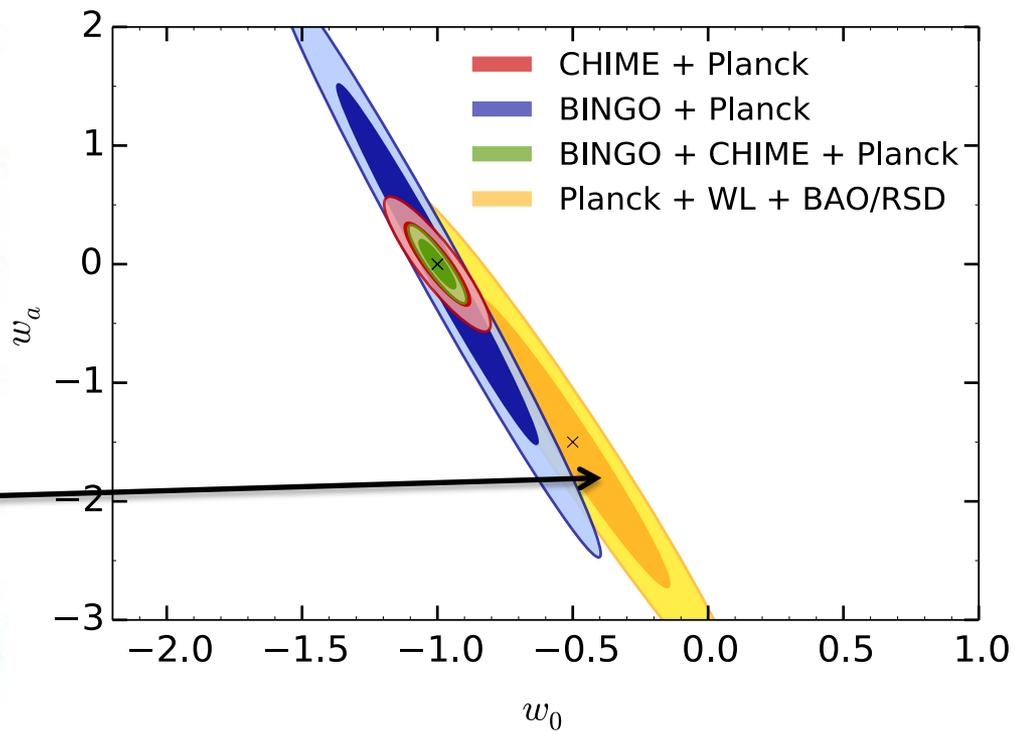
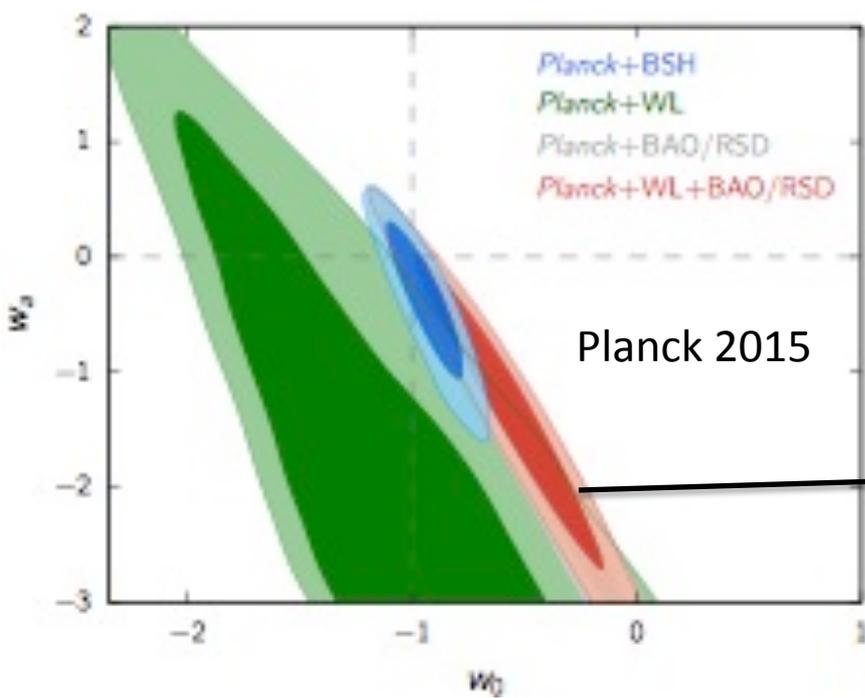
# Hydrogen Intensity Mapping



- BAO measurement
- Cosmological Forecasts
  - (1) Cosmological parameters
  - (2) Primordial non-Gaussianity
- Foreground cleaning
- $1/f$  noise



$$w(a) = w_0 + w_a(1-a)$$



# Primordial non-Gaussianity

## The Primordial Bispectrum

$$\phi = \phi_G + f_{\text{NL}}(\phi_G^2 - \langle \phi_G^2 \rangle)$$

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

## Bispectrum Shapes

Local Shape

$$k_3 \ll k_2 \simeq k_1$$

Equilateral Shape

$$k_3 \simeq k_2 \simeq k_1$$

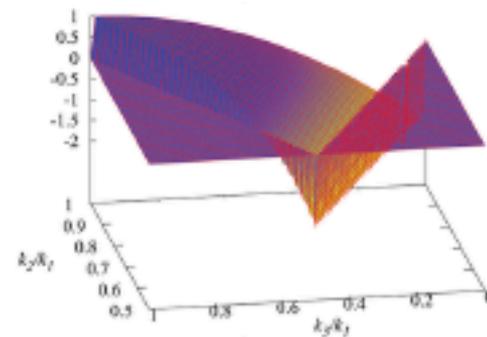
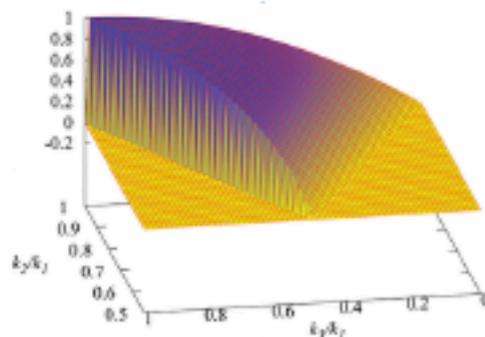
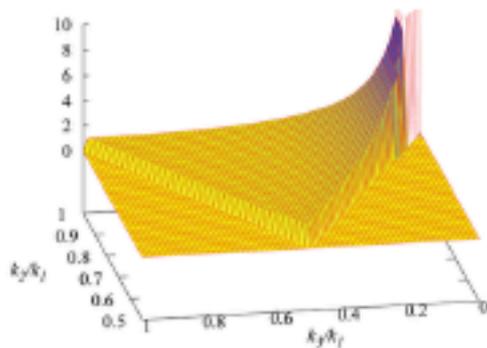
Orthogonal Shape

$$k_3 \simeq k_2 \simeq k_1 \text{ (positive)}$$

Enfolded Shape

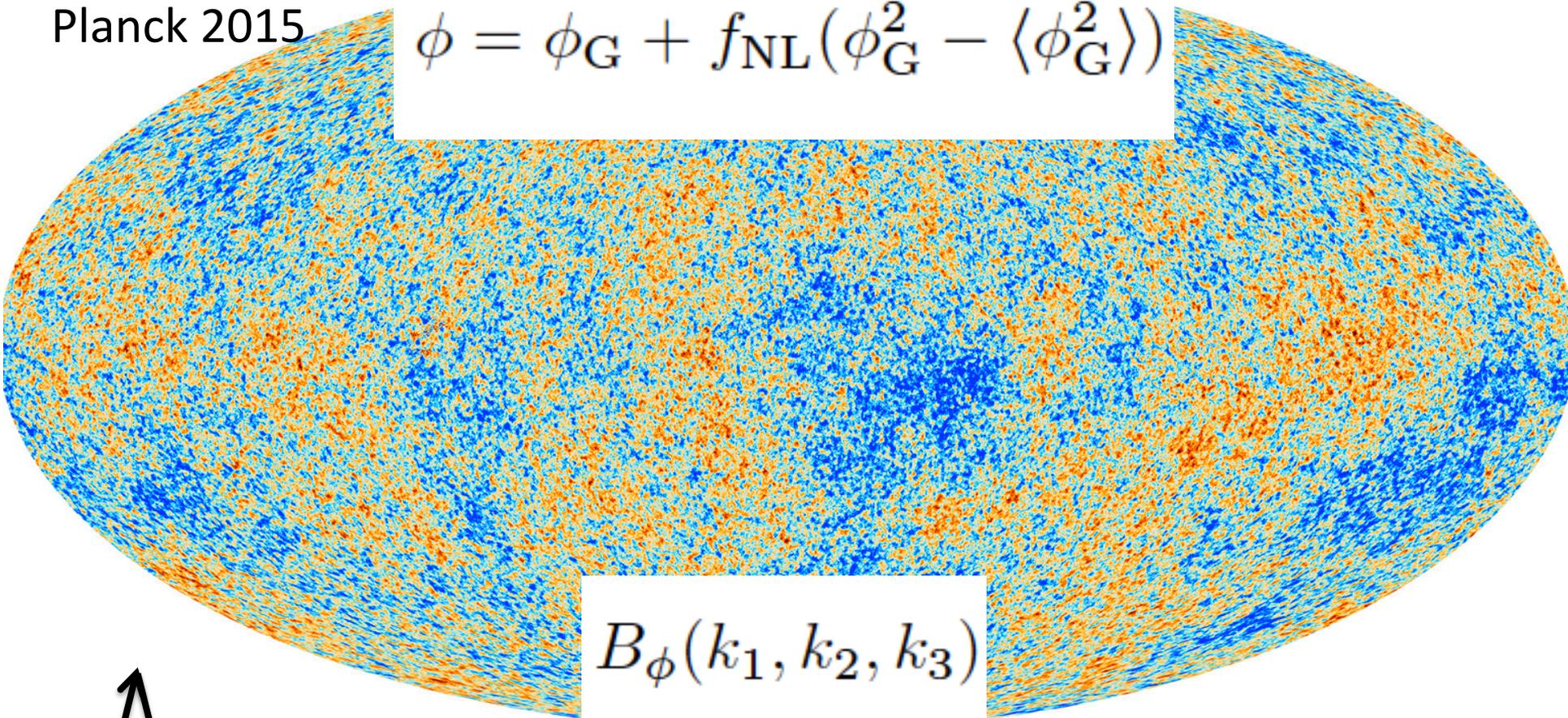
$$2k_3 \simeq 2k_2 \simeq k_1$$

$$2k_3 \simeq 2k_2 \simeq k_1 \text{ (negative)}$$

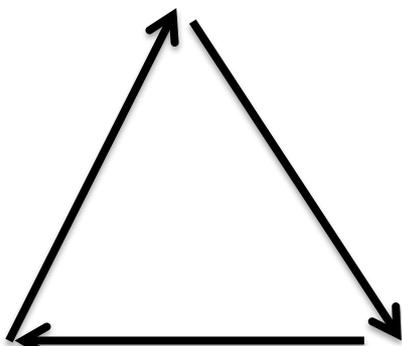
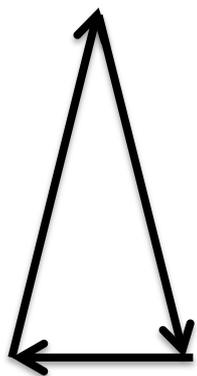


Planck 2015

$$\phi = \phi_G + f_{\text{NL}}(\phi_G^2 - \langle \phi_G^2 \rangle)$$

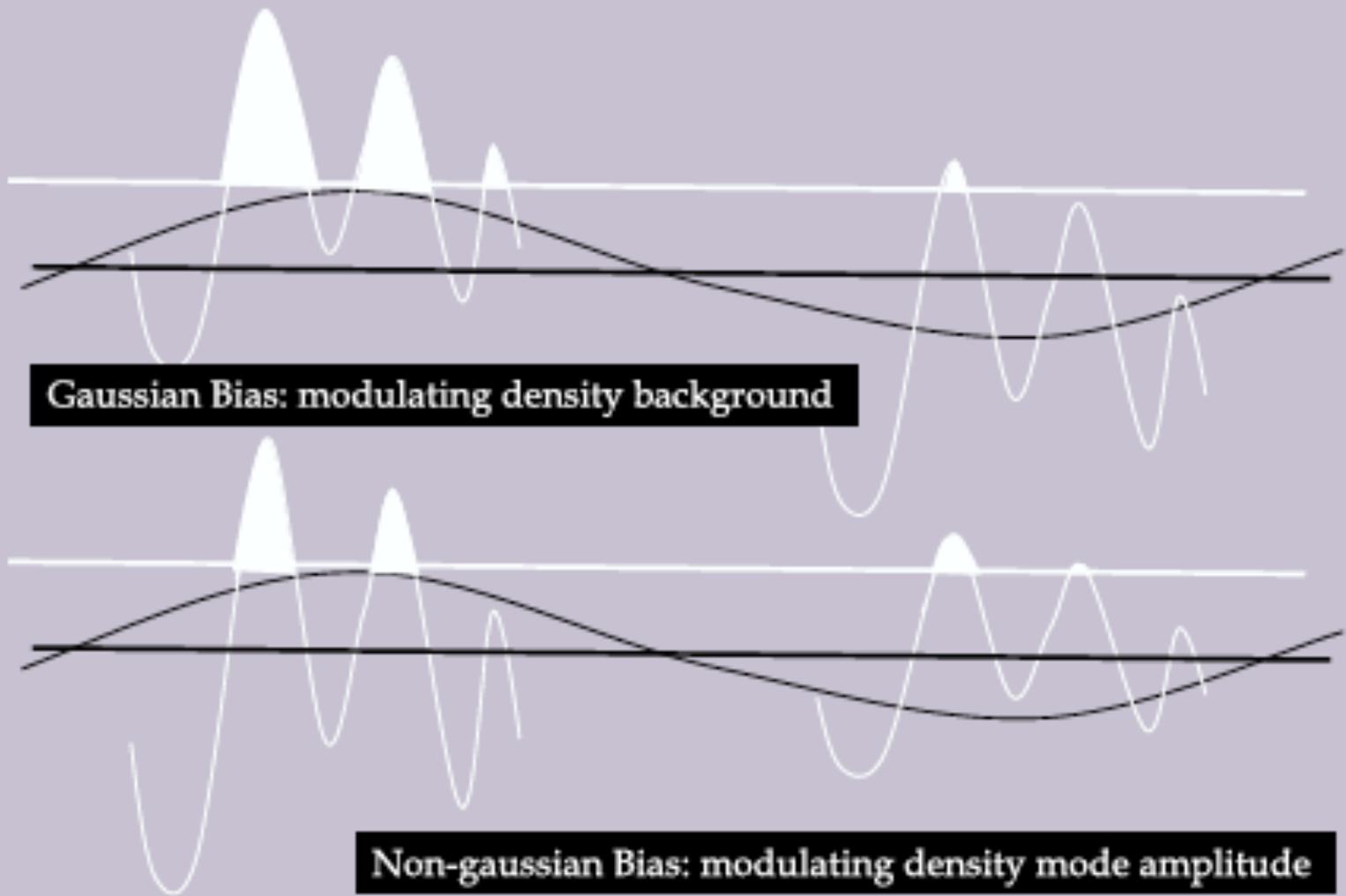


$$B_\phi(k_1, k_2, k_3)$$



Independent shape

$$f_{\text{NL}}^{\text{local}} = 0.8 \pm 5.0, f_{\text{NL}}^{\text{equil}} = -4 \pm 43 \text{ and } f_{\text{NL}}^{\text{ortho}} = -26 \pm 21$$



# f\_NL Constraint:

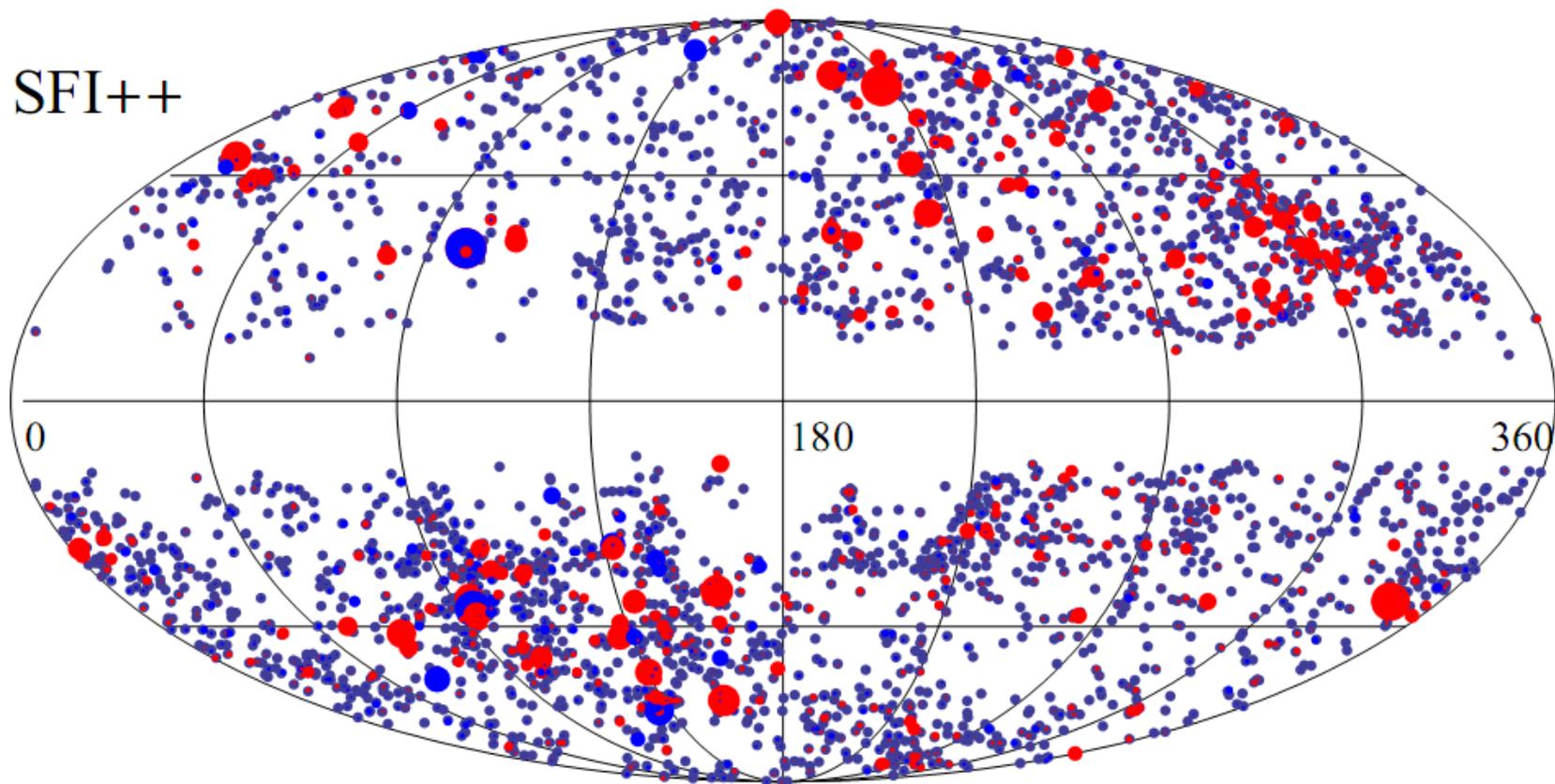
- Peculiar velocity field data
- (Future) 21-cm intensity mapping
- (Future) Multi-tracer technique

YZM, Douglas Scott, James E. Taylor, 2013, MNRAS

Yi-Chao Li and YZM, 2017, ArXiv: 1701.00221

# $f_{\text{NL}}$ Constraint:

- Peculiar velocity field data
- (Future) 21-cm intensity mapping
- (Future) Multi-tracer technique



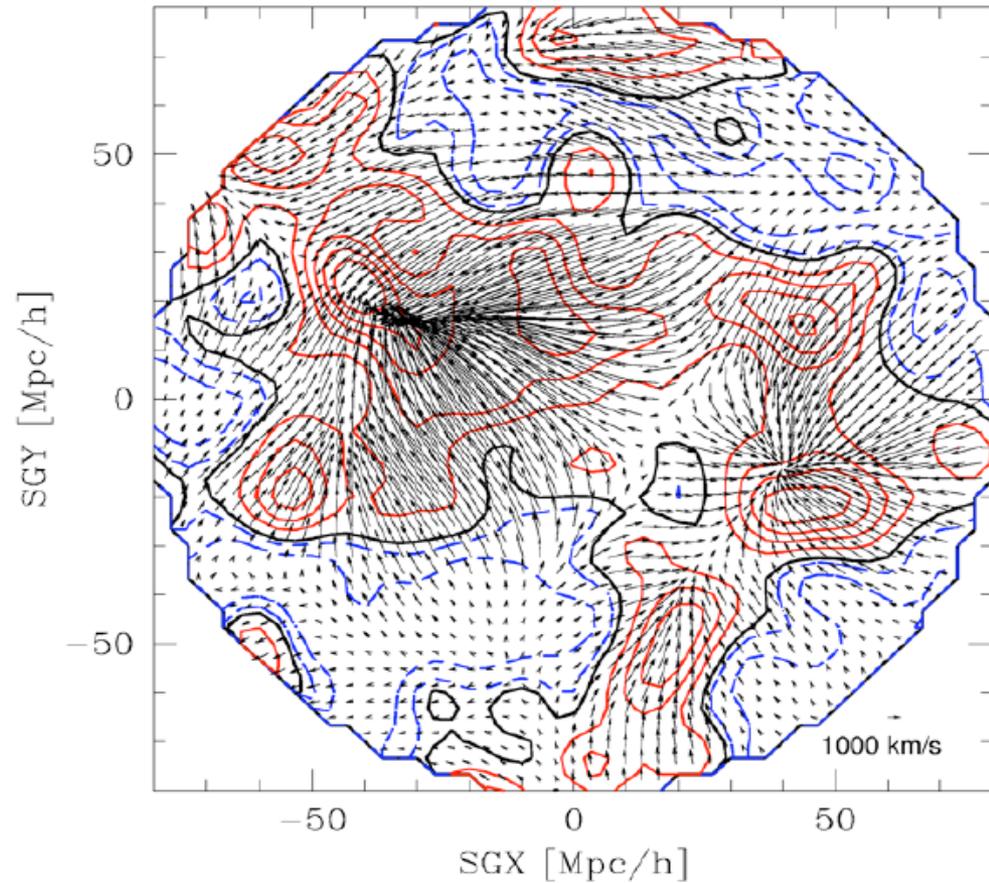
$$cz = H_0 r + v$$

# Linear perturbation theory: (Peebles 1971)

$$\vec{v}_g(\vec{x}) = \frac{H_0 f_0}{4\pi} \int d^3 \vec{x}' \delta_m(\vec{x}', t) \frac{(\vec{x}' - \vec{x})}{|\vec{x}' - \vec{x}|^3}$$

$$\delta_g = b\delta_m \quad f \equiv \frac{a}{D_1} \frac{dD_1}{da}$$

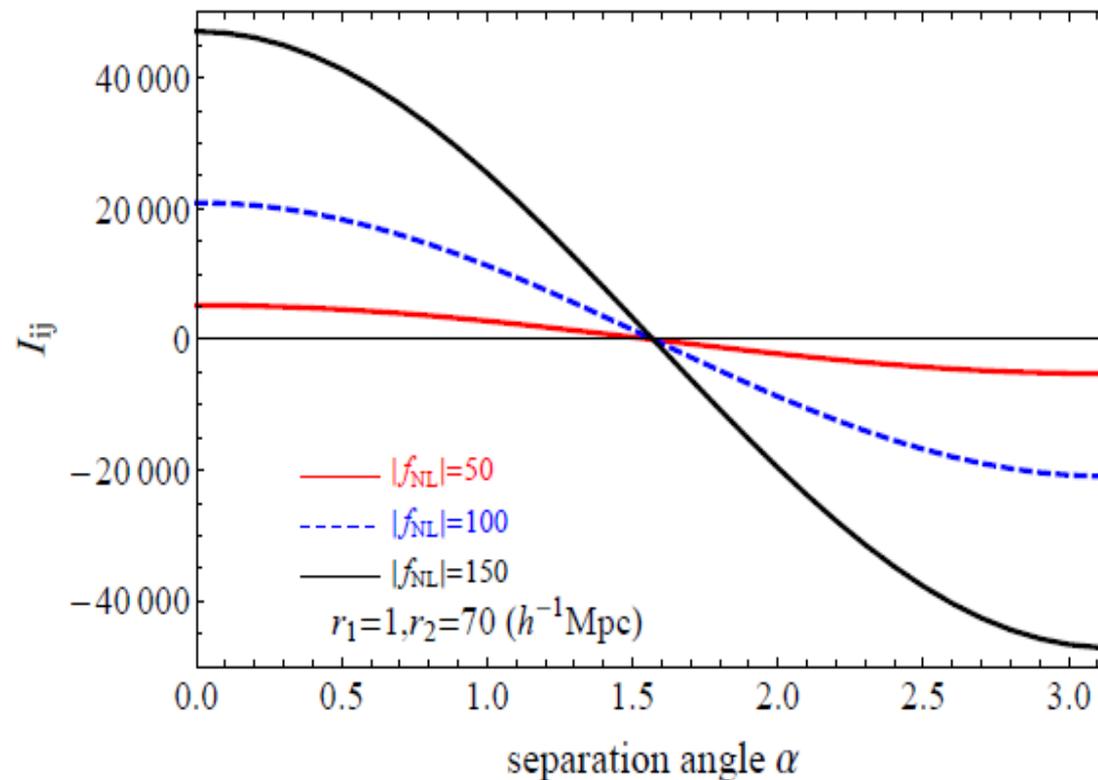
$$\vec{v}_g(\vec{x}) = \frac{H_0 \beta}{4\pi} \int d^3 \vec{x}' \delta_g(\vec{x}', t) \frac{(\vec{x}' - \vec{x})}{|\vec{x}' - \vec{x}|^3}$$

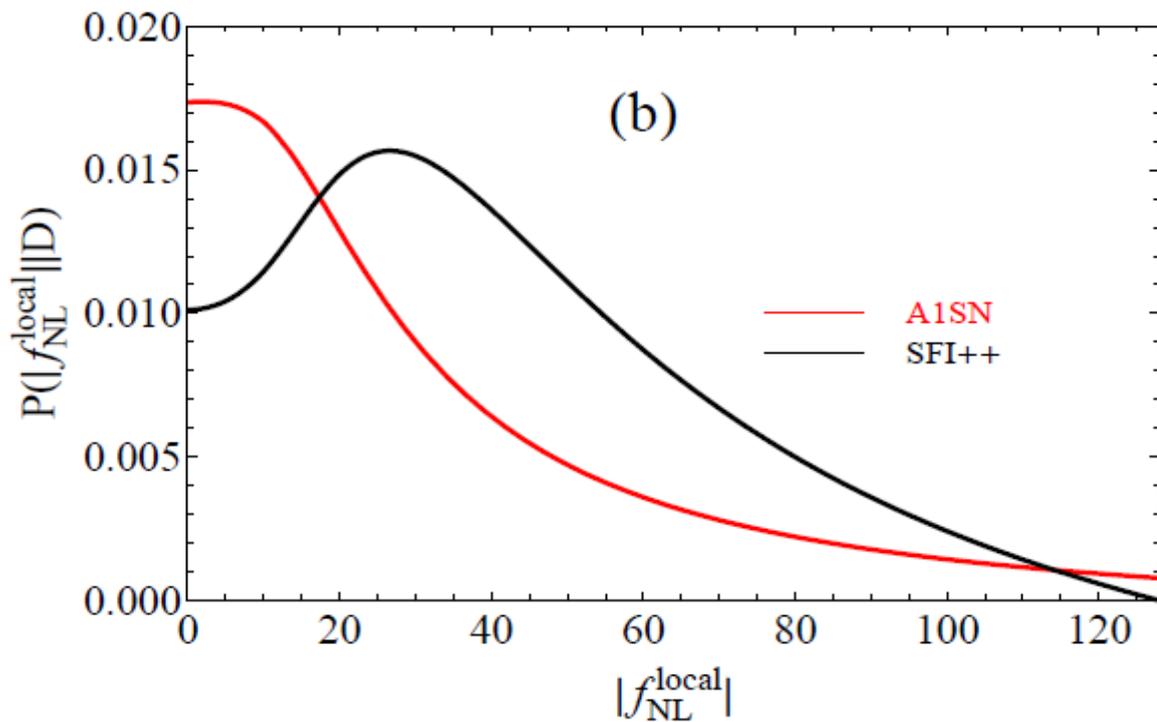


$$\mathbf{v}(\mathbf{r}) = \frac{H_0\beta}{4\pi} \int d^3\mathbf{r}' \delta_g(\mathbf{r}') \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} - \frac{iH_0(f/b)}{(2\pi)^3} \int d^3\mathbf{k} (\Delta b(k)) \delta_m(\mathbf{k}) \frac{\mathbf{k}}{k^2} \exp(i\mathbf{k} \cdot \mathbf{r})$$

Dalal et al. 2008:

$$\Delta b(k) = (b-1) f_{\text{NL}}^{\text{local}} A(k) \quad A(k) = \frac{3\delta_c(z)\Omega_m h^2}{k^2 T(k)} \left(\frac{H_0}{c}\right)^2$$





Data set	Model	$\beta$ value	$ f_{\text{NL}}^{\text{local}} $ value	$-\log L_{\min}$
A1SN	$\beta$ - $f_{\text{NL}}^{\text{local}}$	$0.53^{+0.15}_{-0.04}$	$0.0 \pm 25.7$	681.7
	$\beta$ -only	$0.65^{+0.07}_{-0.06}$		681.7
SFI++	$\beta$ - $f_{\text{NL}}^{\text{local}}$	$0.49^{+0.03}_{-0.05}$	$26.6 \pm 33.0$	14159.1
	$\beta$ -only	$0.49^{+0.04}_{-0.03}$		14159.1

(i) Radio sources from the NRAO VLA Sky Survey (NVSS), the quasar and MegaZ-LRG (DR7) catalogues of the SDSS, and the SDSS LRG redshift survey (Xia et al.(2011) found):

$$f_{\text{NL}}^{\text{local}} = 48 \pm 20 (1\sigma\text{CL}). \quad (8)$$

(ii) Photometric SDSS data (Nikoloudakis et al. (2013)):

$$f_{\text{NL}}^{\text{local}} < 120 (84\%). \quad (9)$$

(iii) SDSS-III (BOSS) DR9 (Ross et al. (2013)):

$$-45 < f_{\text{NL}}^{\text{local}} < 195 (2\sigma\text{CL}). \quad (10)$$

(iv) *Planck* CMB (2013):

$$-45 < f_{\text{NL}}^{\text{local}} = 2.7 \pm 5.8 (1\sigma\text{CL}). \quad (11)$$

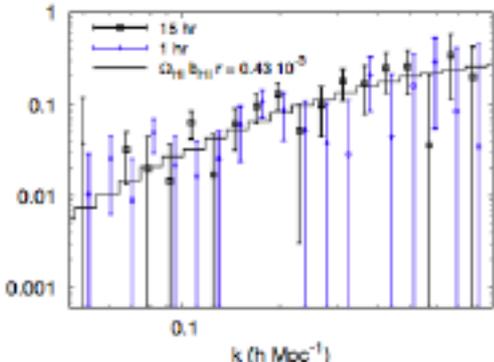
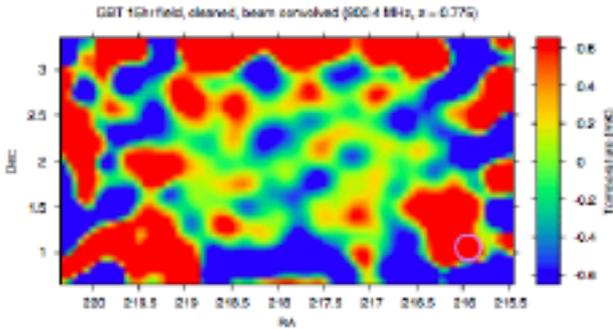
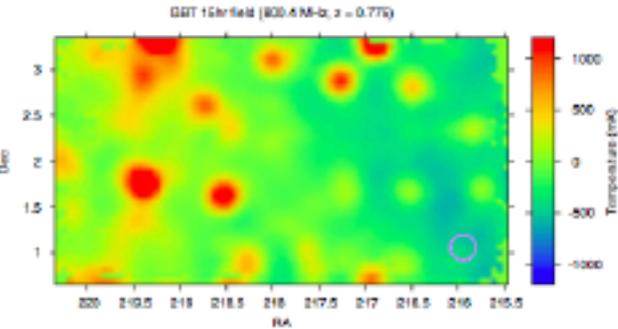
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# f\_NL Constraint:

- Peculiar velocity field data
- (Future) 21-cm intensity mapping
- (Future) Multi-tracer technique

No time to mention foreground analysis, see other people's talk.

# HI Intensity Mapping



Masui et. al. ApJL 763:L20 (2013)



# Bias

$$b_{\text{HI}}^{\text{NG}}(z, k) = b_{\text{HI}}(z) + \Delta b_{\text{HI}}(z, k)$$

$$\begin{array}{c} \uparrow \\ b_{\text{L}} + 1 \end{array}$$

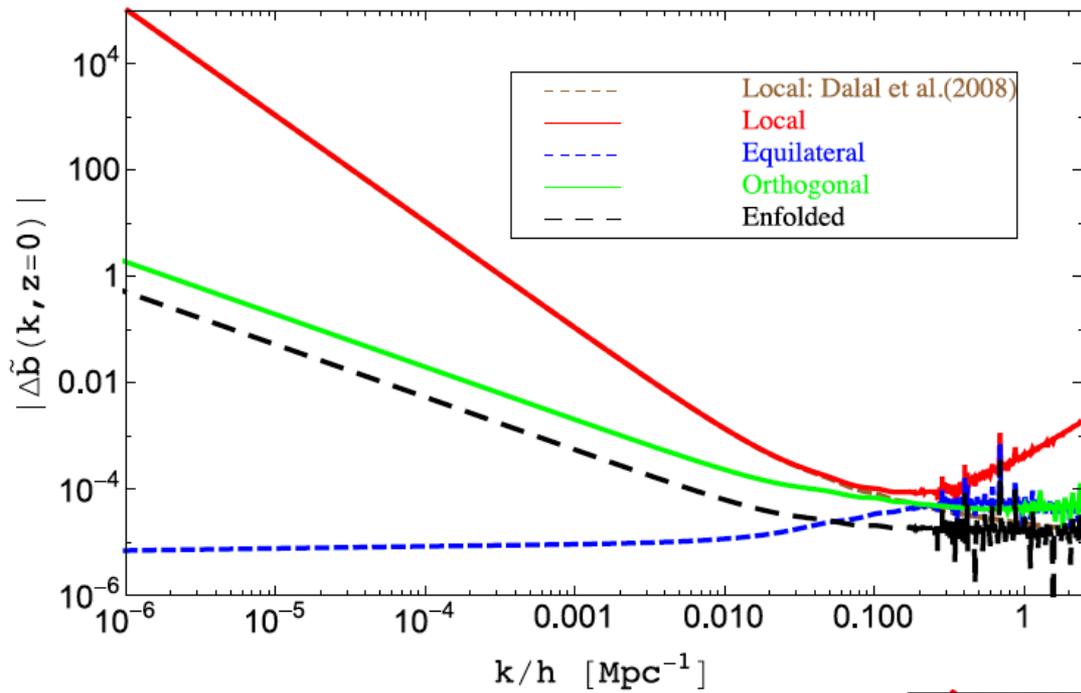
$$\begin{array}{c} \uparrow \\ \sim f_{\text{NL}} b_{\text{L}} \end{array}$$

S. Matarrese and L. Verde, 2008

N. Dalal, et al., 2008

Y.-C. Li and YZM, 2017, ArXiv: 1701.00221

Yi-Chao Li and YZM, 2017,  
 ArXiv: 1701.00221  
 C. Fedeli et al., 2011,  
 MNRAS

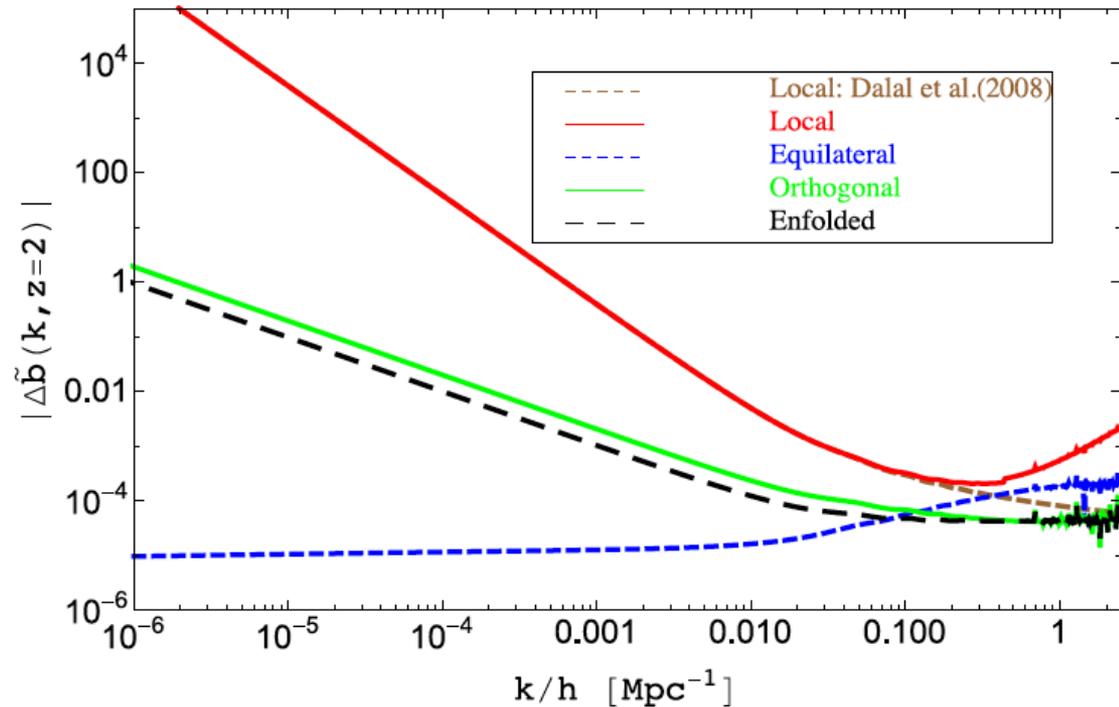


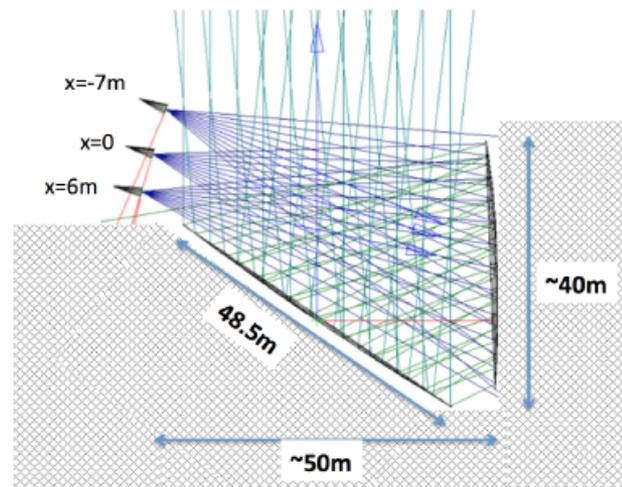
$$\Delta b(\text{Local}) \sim k^{-2}$$

$$\Delta b(\text{Equilateral}) \sim \text{const}$$

$$\Delta b(\text{Enfolded}) \sim k^{-1}$$

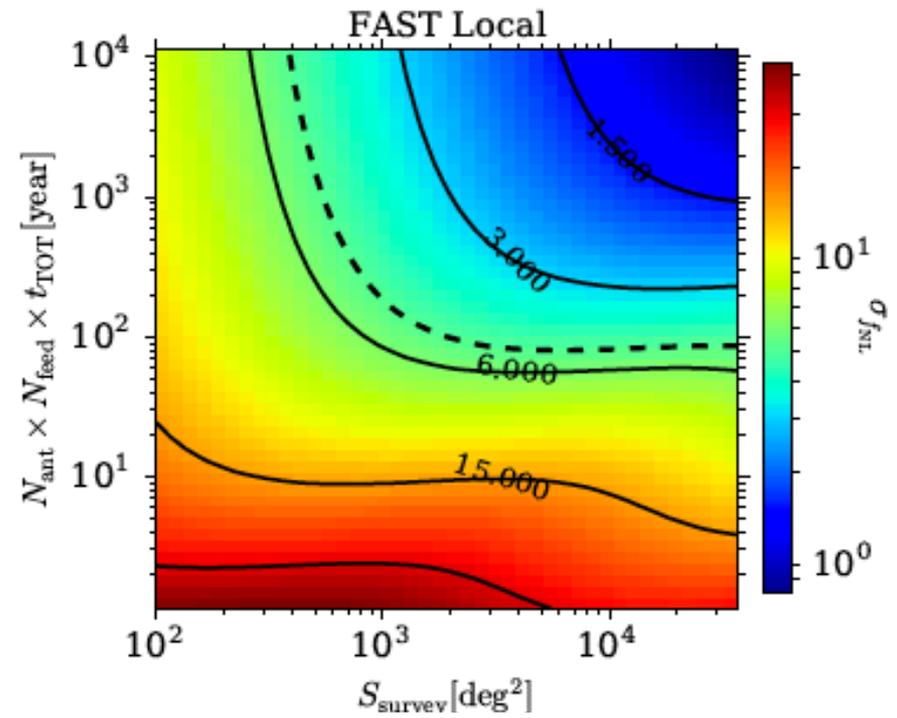
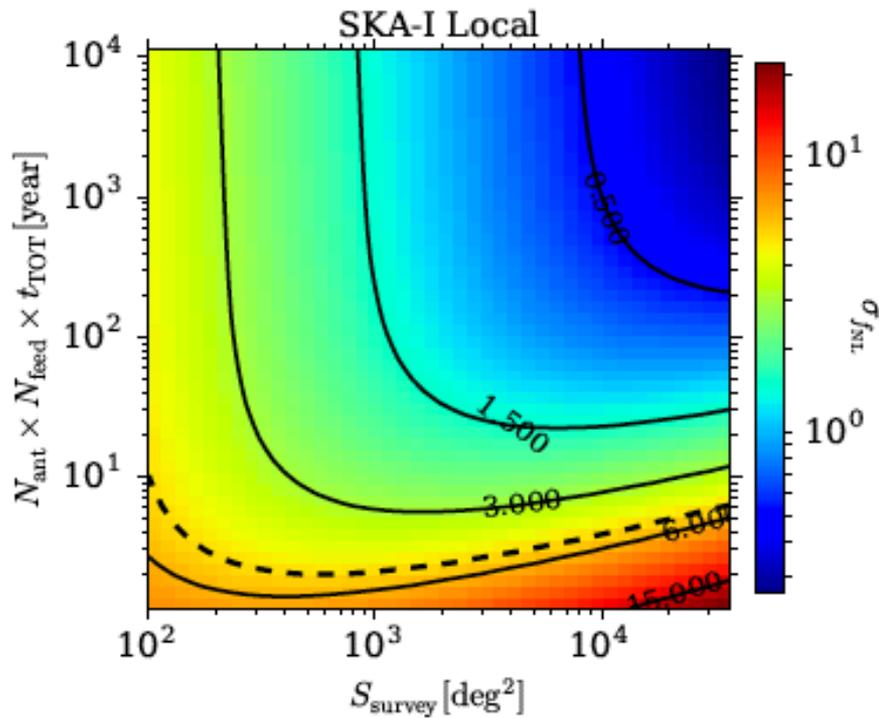
$$\Delta b(\text{Orthogonal}) \sim k^{-1}.$$



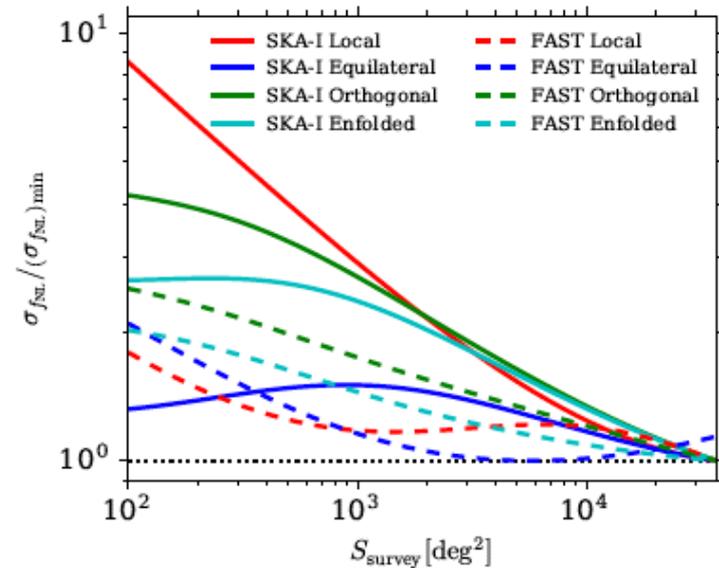


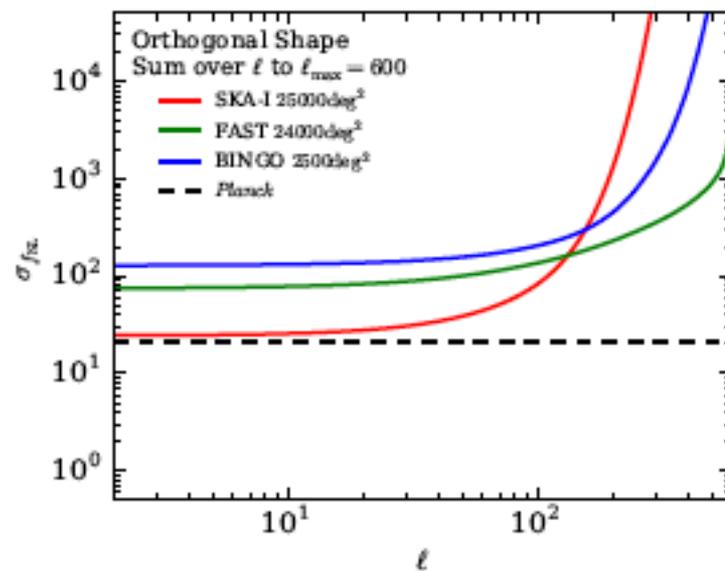
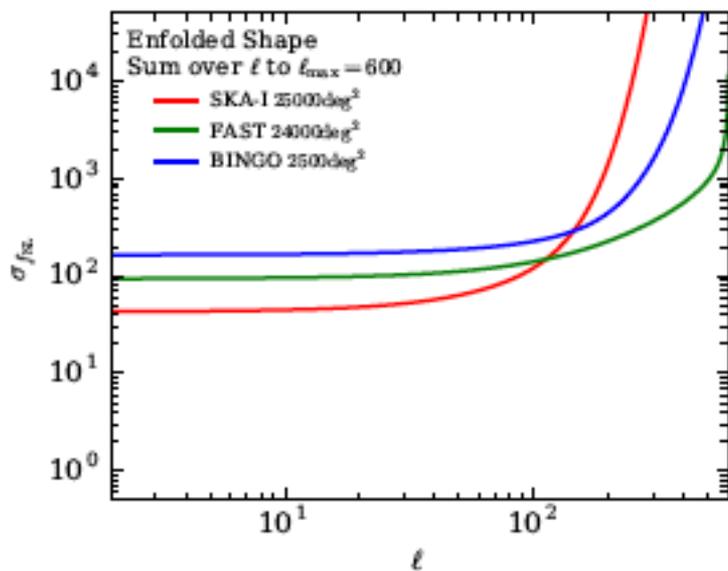
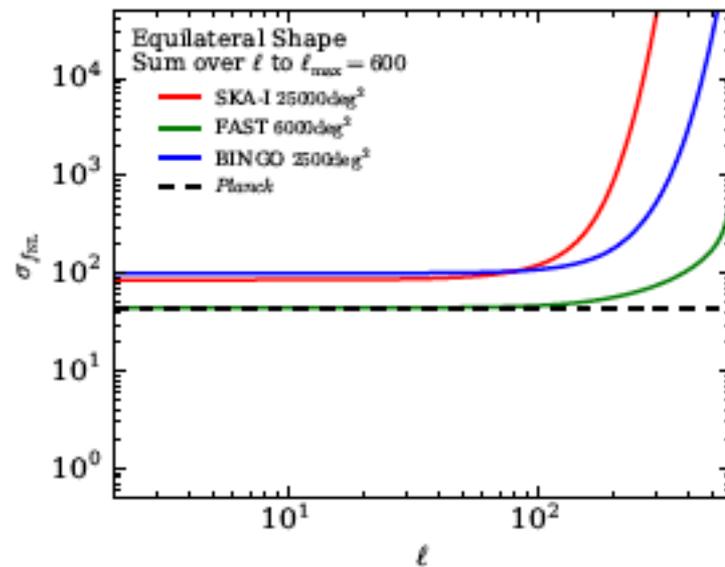
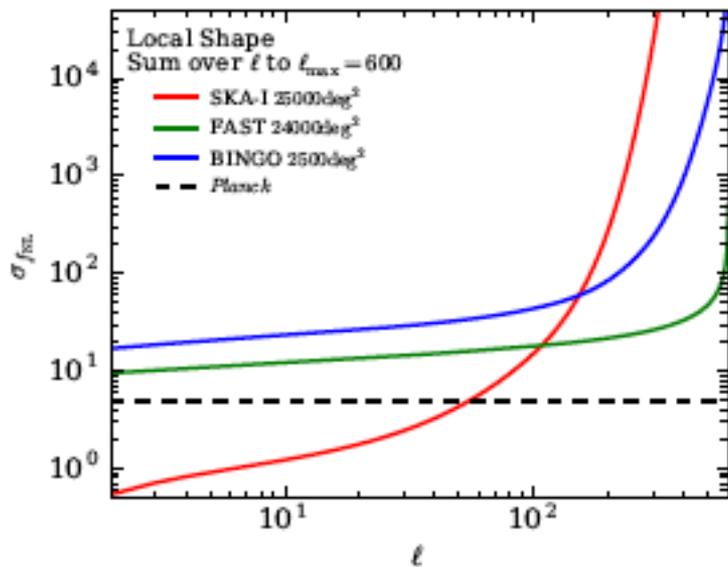
	FAST	SKA-I	BINGO
$\nu_{\min}$ [MHz]	1050	350	960
$\nu_{\max}$ [MHz]	1350	1050	1260
$\Delta\nu$ [MHz]	10	10	10
$n_\nu (n_z)$	30	70	30
$D_{\text{dish}}$ [m]	300	15	25
$N_{\text{ant}} \times N_{\text{feed}}$	$1 \times 19$	$190 \times 1$	$1 \times 60$
$t_{\text{TOT}}$ [yr]	1	1	1
$T_{\text{rec}}$ [K]	25	28	50
$S_{\text{survey}}$ [deg <sup>2</sup> ]	< 24000	< 25000	2500





Yi-Chao Li and YZM, 2017,  
 PRD, ArXiv: 1701.00221  
 S. Camera, M. G. Santos, P.  
 G. Ferreira, and L.  
 Ferramacho, 2013, PRL





Yi-Chao Li and YZM, 2017,  
PRD, ArXiv: 1701.00221

	<i>Planck</i> 2015	Current Configuration			Extentions		
		FAST	SKA-I	BINGO	SKA-I 2yr <sup>†</sup>	FAST 2yr <sup>††</sup>	FAST low <sup>‡</sup>
Local	5	9.5	<b>0.54</b>	17	<b>0.43</b>	7.4	<b>1.6</b>
Equilateral	43	44	86	100	66	<b>32</b>	53
Orthogonal	21	75	25	128	<b>20</b>	59	39
Enfolded	–	94	43	164	36	70	64

<sup>†</sup> SKA-I with two-year observation; <sup>††</sup> FAST with two-year observation; <sup>‡</sup> FAST with low frequencies range from 350MHz to 1050MHz

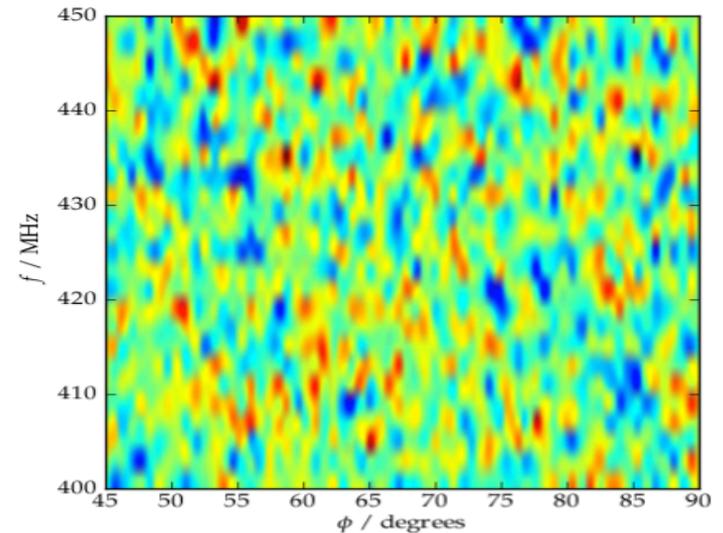
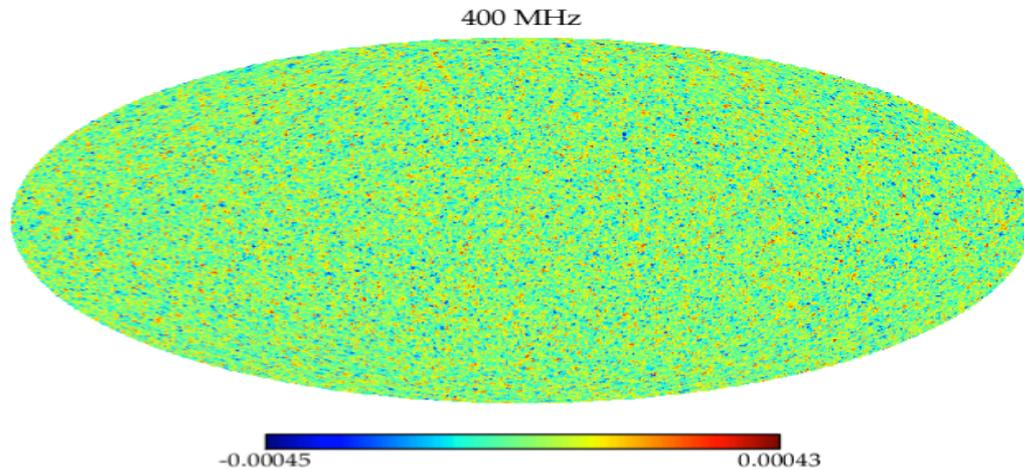
Extended to 2-years, extended to 250 MHz receivers

Y.-C. Li and YZM, 2017, PRD,  
1701.00221

- BAO measurement
- Cosmological Forecasts
  - (1) Cosmological parameters
  - (2) Primordial non-Gaussianity
- **Foreground cleaning**
- $1/f$  noise

# Hydrogen intensity signal

Amplitude 1 mK, lots of spectral structure



Simulated 21 cm signal, tracer of  $\rho_{HI}(\theta, ; z)$ :  $\Delta T \sim 1$  mK

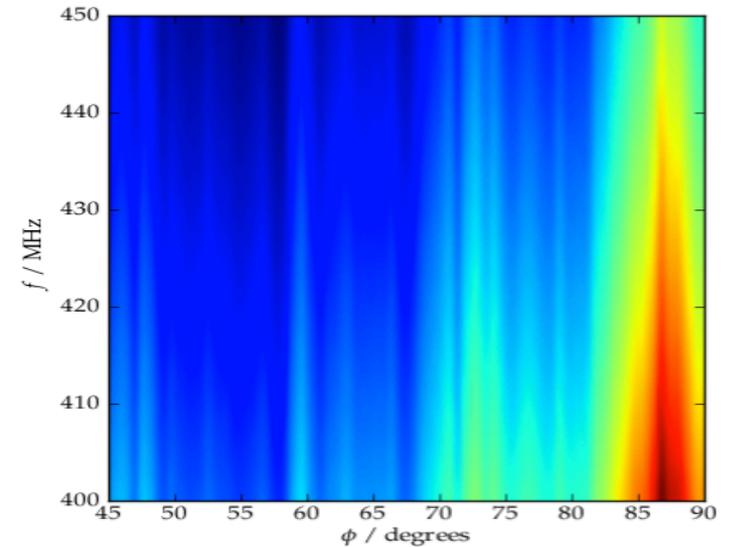
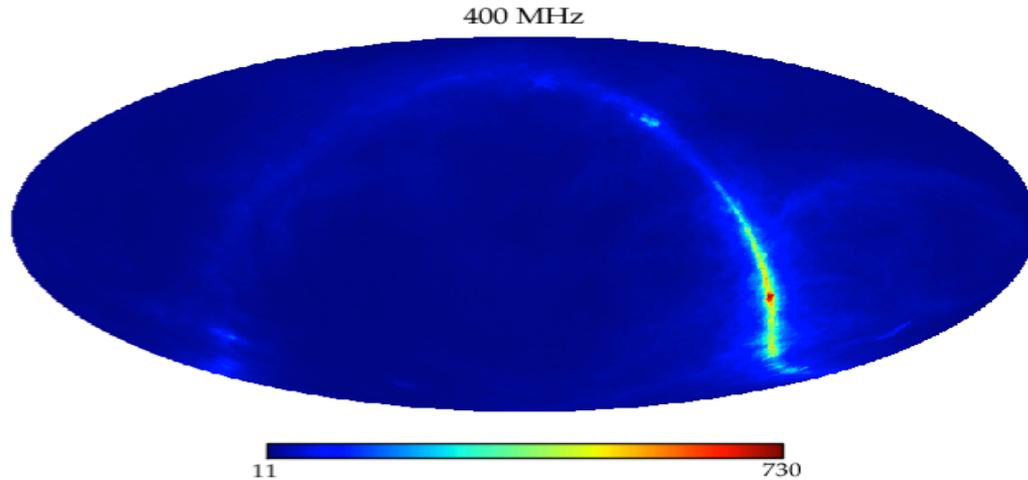
*left* - over full sky at 400 MHz,

*right* - over 50 MHz at 1 declination

Main goal is to measure BAO structure in  $P_{HI}(k)$ ,  
less concerned about amplitude of  $P_{HI}(k)$ .

# The “other” signal: synchrotron (primarily)

Amplitude 700 K, spectrally smooth



Modeled Galaxy signal,  $\Delta T \sim 700 \text{ K}$ !

*left* - over full sky at 400 MHz,

*right* - over 50 MHz at 1 declination - spectrally smooth

## **Noise:**

1. uncorrelated noise white noise
2. correlated noise in time and frequency  $1/f$  noise
3. Atmospheric noise

## **Systematic effect:**

1. sidelobes: near, intermediate, far (mode mixing)
2. band-pass calibration
3. Ground spilled over
4. Cross polarization
5. beam ellipticity ....

Without those details, radio cosmology is an unrealistic dream.

# Pipeline Logistics

Input experimental parameters and data file

TOD Simulation

**Sky Model (s):**

- Cosmological 21cm signal
- CO emission
- CMB
- foreground signal including
  - (a) free-free emission
  - (b) spinning dust
  - (c) synchrotron
  - (d) point sources, and clusters
  - (e) line emission
  - (f) de-polarization (Q,U into I)
- atmospheric signal
- ground spill-over (emission from the ground)
- straight light (moon/sub/galaxy)

**Pointing Matrix(A):**  
Pointing and scanning strategy (each frequency channel, with bandpass)

**Noise Sim (n):**

- white noise
- 1/f noise
- atmosphere noise

**Map-Making:**  
 $\hat{\mathbf{s}} = (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{N}^{-1} \mathbf{d}, \mathbf{d} = \mathbf{A} \mathbf{s} + \mathbf{n}$

Data Analysis

**Component Separation:**

- Principle Component Analysis
- Generalized Needlet Internal Linear Combination

**Cosmological data analysis:**  
Power spectrum  $C_\ell$ ,  
Cosmological Parameters:  $(\Omega_c, \Omega_b, n_s, w, \sum m_\nu)$

# Principal Component Analysis

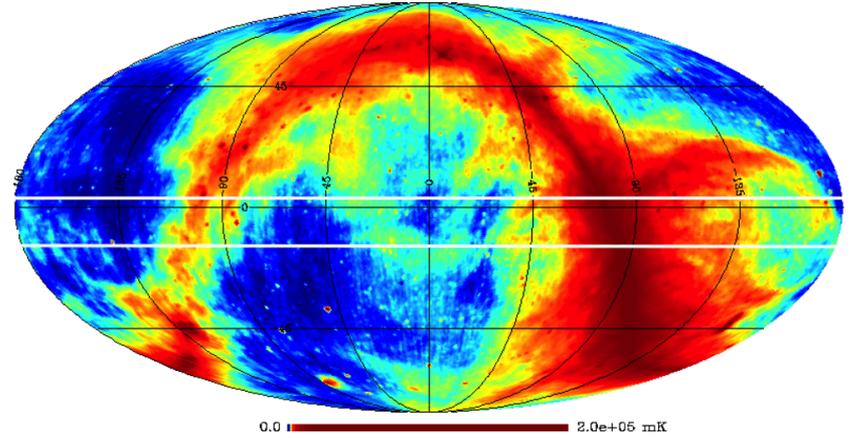
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## Survey parameters

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Redshift range $[z_{\min}, z_{\max}]$	[0.13, 0.48]
Frequency range $[\nu_{\min}, \nu_{\max}]$ (MHz)	[960, 1260]
Channel width $\Delta\nu$ (MHz)	15
FWHM (arcmin) at 1 GHz	40
Number of feed horns $n_f$	56
Sky coverage $\Omega_{\text{sur}}$ (deg <sup>2</sup> )	3000
Observation time $t_{\text{obs}}$ (yr)	1
System temperature $T_{\text{sys}}$ (K)	50
Sampling rate (Hz)	0.1

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Synchrotron	Characteristics	Mean $\beta$	rms $\beta$
Model 1	$\beta$ constant on the sky	-2.8	$\beta$ constant
Model 2	A Gaussian spatial distribution of $\beta$	-2.8	0.17
Model 3	de Oliveira-Costa et al. (2008) model	-2.5	0.03

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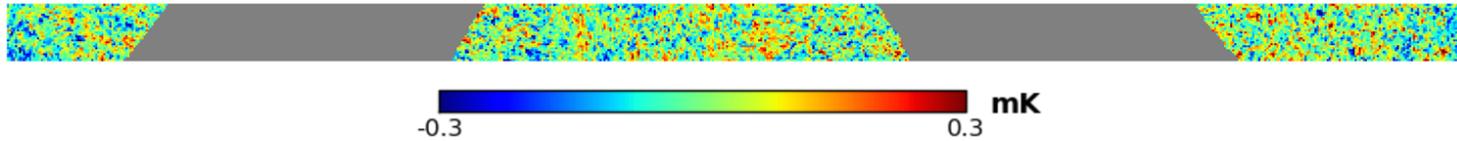
$$\hat{\mathbf{s}} = (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{N}^{-1} \mathbf{d}$$

# Component separation: PCA

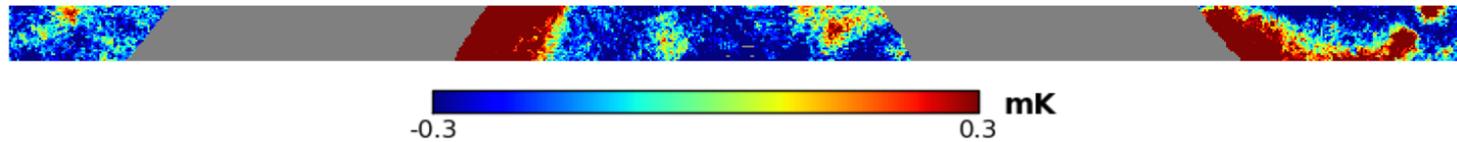
$$C_{ij} = \frac{1}{N_p} S S^T = \frac{1}{N_p} \sum_{p=1}^{N_p} T(\mathbf{v}_i, \hat{n}_p) T(\mathbf{v}_j, \hat{n}_p)$$

$$R_{jk} = \frac{C_{jk}}{C_{jj}^{1/2} C_{kk}^{1/2}}$$

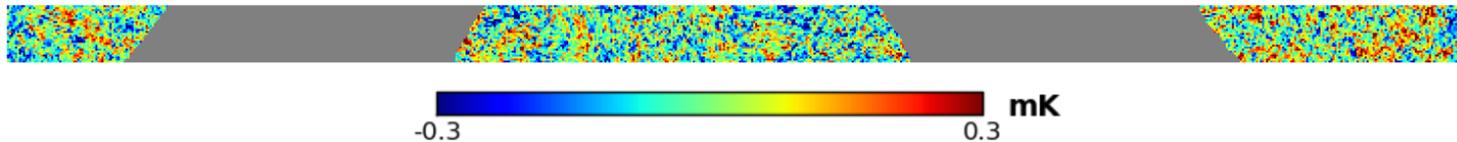
$$P^T R P = \Lambda \equiv \text{diag} \{ \lambda_1, \dots, \lambda_{N_f} \} \quad \phi = P_C^T S \quad S_C = P_C \phi \quad S_{\text{HI}} = S - S_C$$



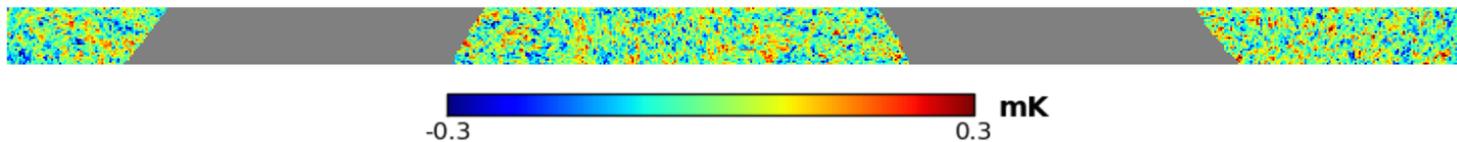
(a) Input HI signal



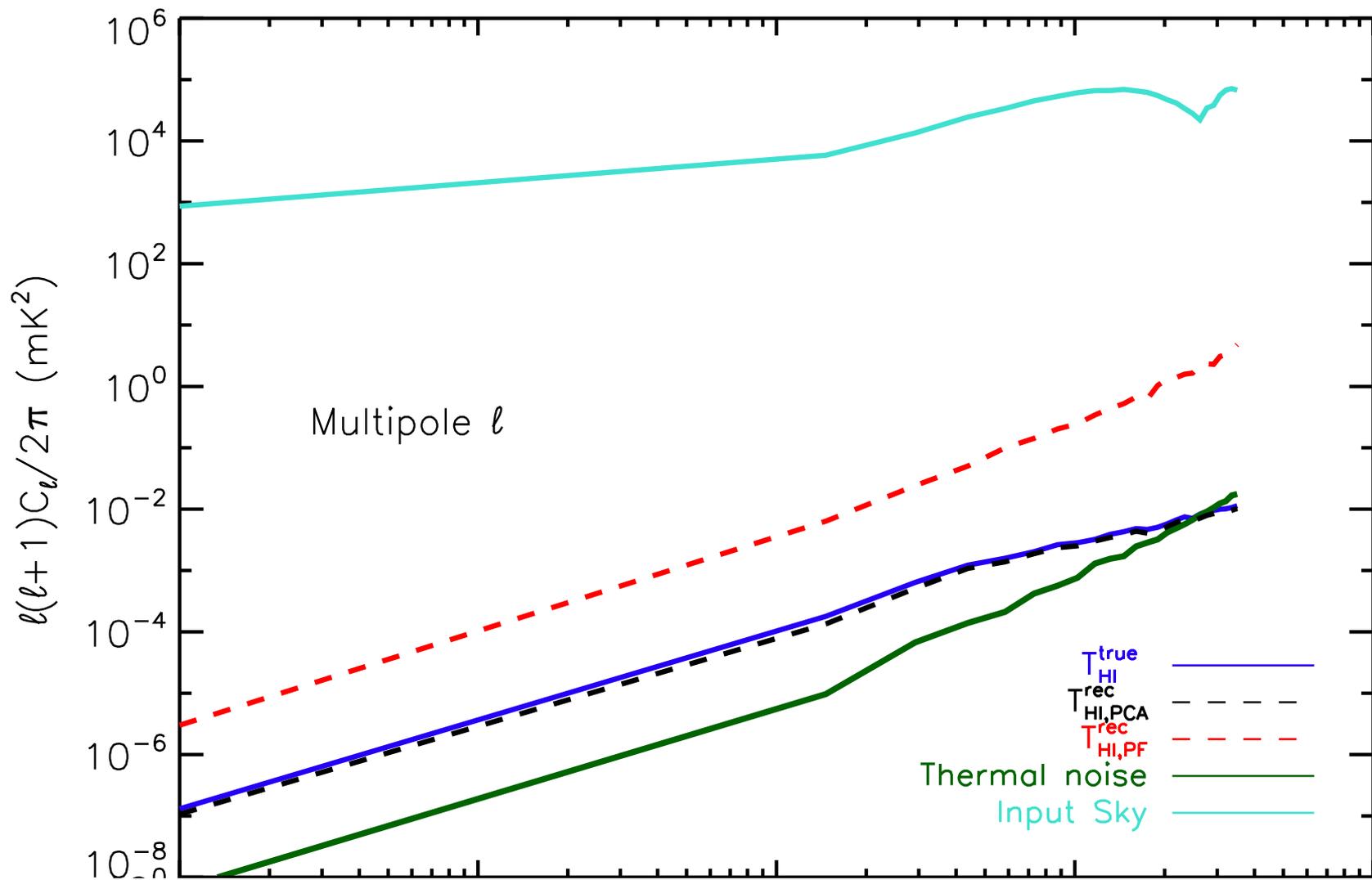
(b) PCA 1 mode removed

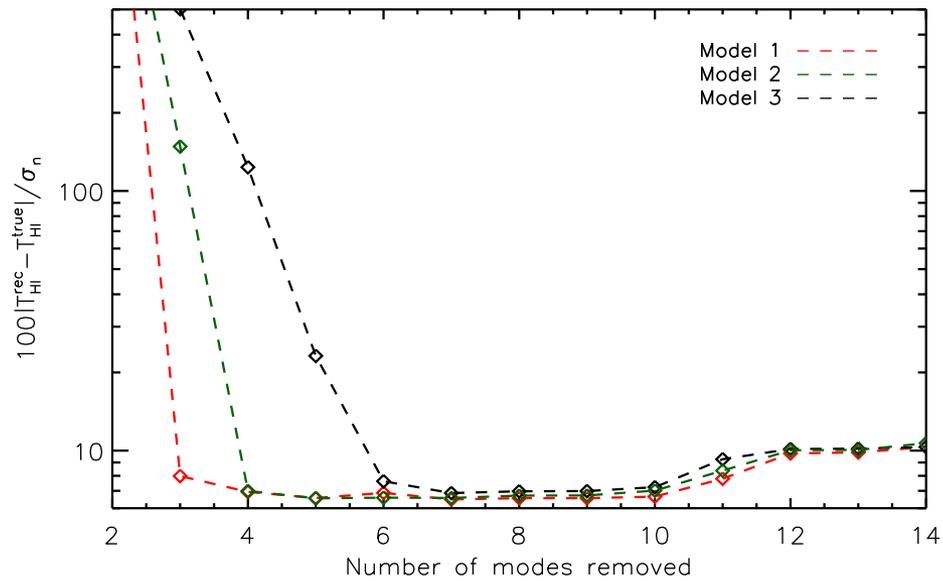
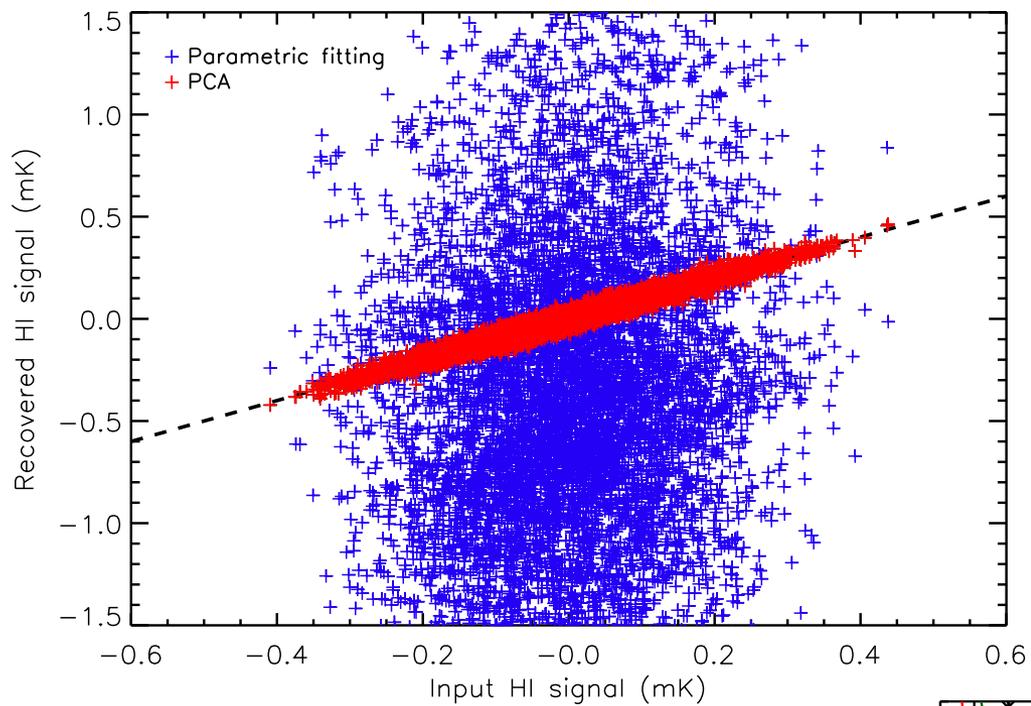


(c) PCA 3 modes removed



(d) PCA 7 modes removed





- BAO measurement
- Cosmological Forecasts
  - (1) Cosmological parameters
  - (2) Primordial non-Gaussianity
- Foreground cleaning
- **1/f noise**

# 1/f noise:

Correlated fluctuation in time

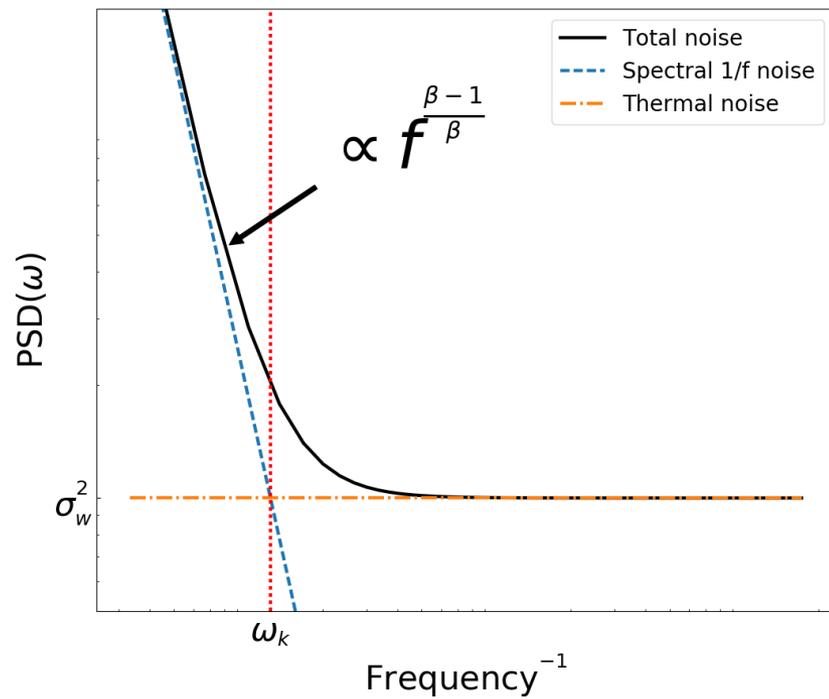
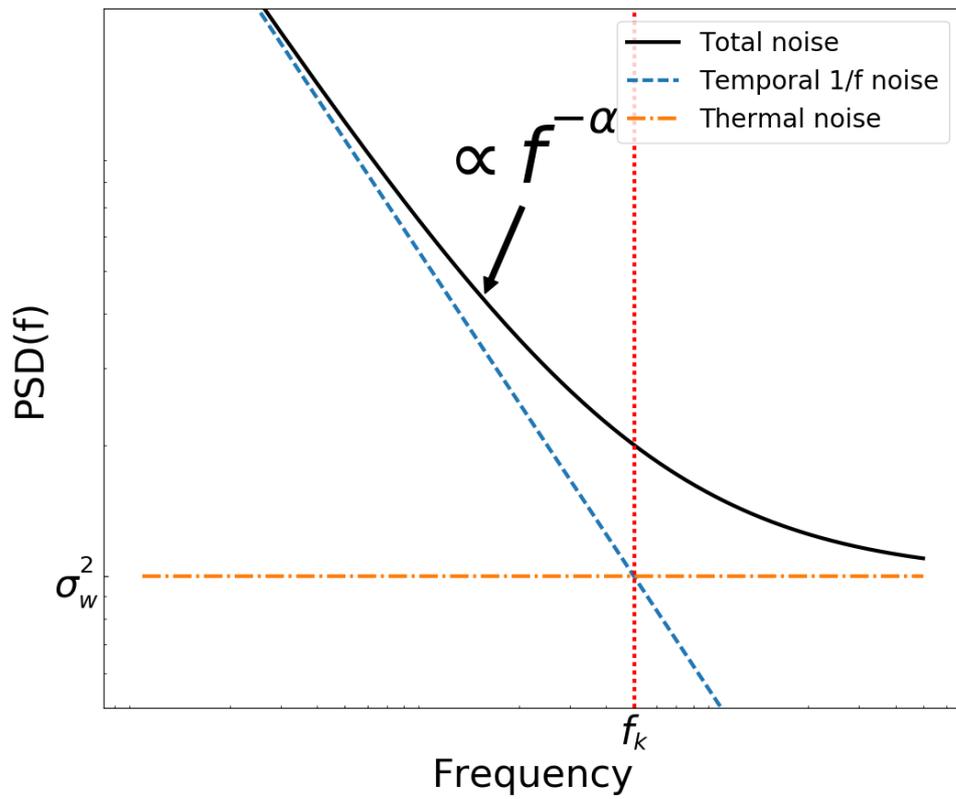
Fluctuations across spectrum,  
i.e. spectroscopic noise

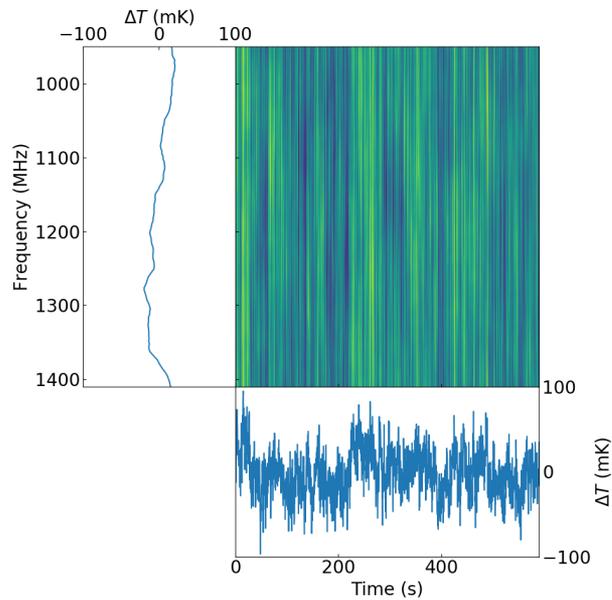
$$\text{PSD}(f, \omega) = \frac{T_{\text{sys}}^2}{\delta\nu} \left[ 1 + C(\beta, N_{\nu}) \left( \frac{f_k}{f} \right)^{\alpha} \left( \frac{1}{\omega \Delta\nu} \right)^{\frac{1-\beta}{\beta}} \right]$$

$\omega$  is the inverse spectroscopic frequency wavenumber

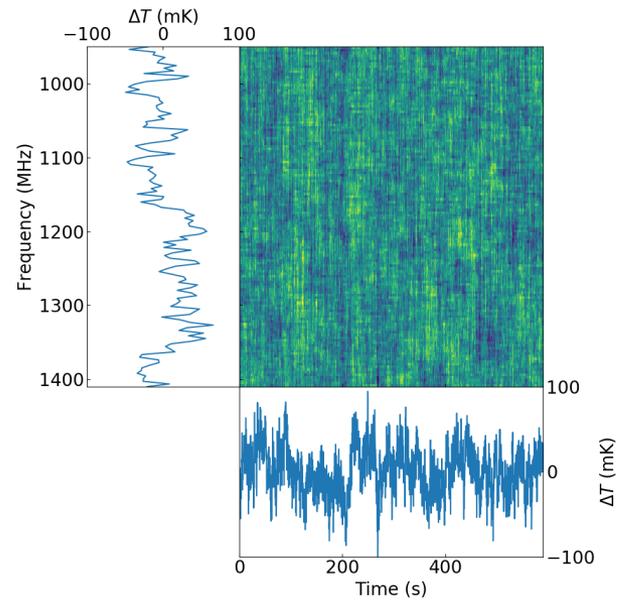
## SKA forecast:

Description	Parameter	Value
Dish Diameter	$D_{\text{dish}}$	15 m <sup>a</sup>
No. Dishes	$N_{\text{dish}}$	200
Receiver + CMB	$T_{\text{CMB}} + T_{\text{rx}}$	20 K <sup>b</sup>
No. Polarimeters	$N_{\text{pol}}$	2
No. Channels	$N_{\nu}$	23
Bandwidth	$\Delta\nu$	950 < $\nu$ < 1410 MHz
Channel width	$\delta\nu$	20 MHz
Sample Rate	$f_{\text{sr}}$	4 Hz
Integration Time	$T_{\text{obs}}$	30 days
Elevation	E	55 deg
Slew Speed	$\nu_t$	0.5 < $\nu_t$ < 2.0 deg s <sup>-1</sup>

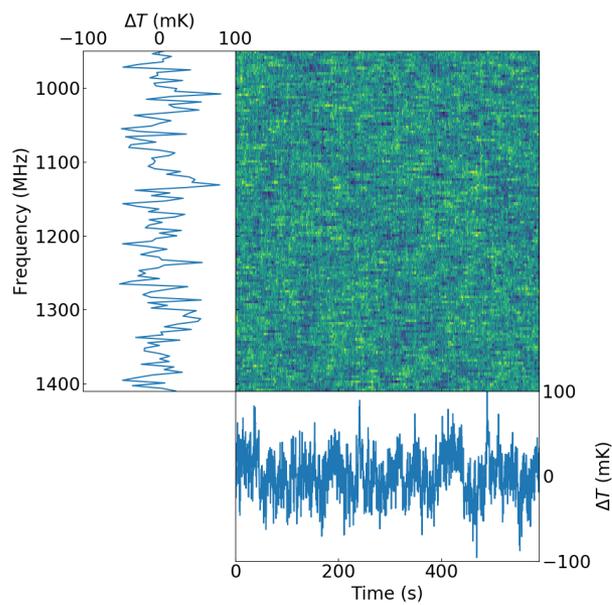




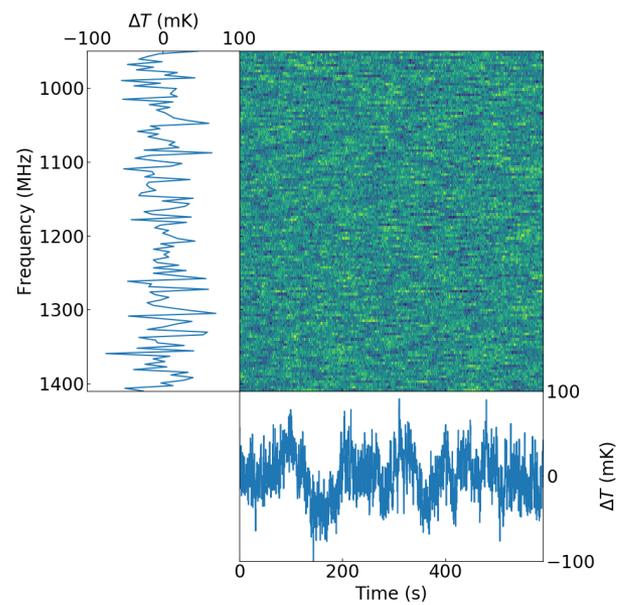
(a)  $\beta = 0.25$ ,  $\alpha = 1$ ,  $f_k = 1$  Hz



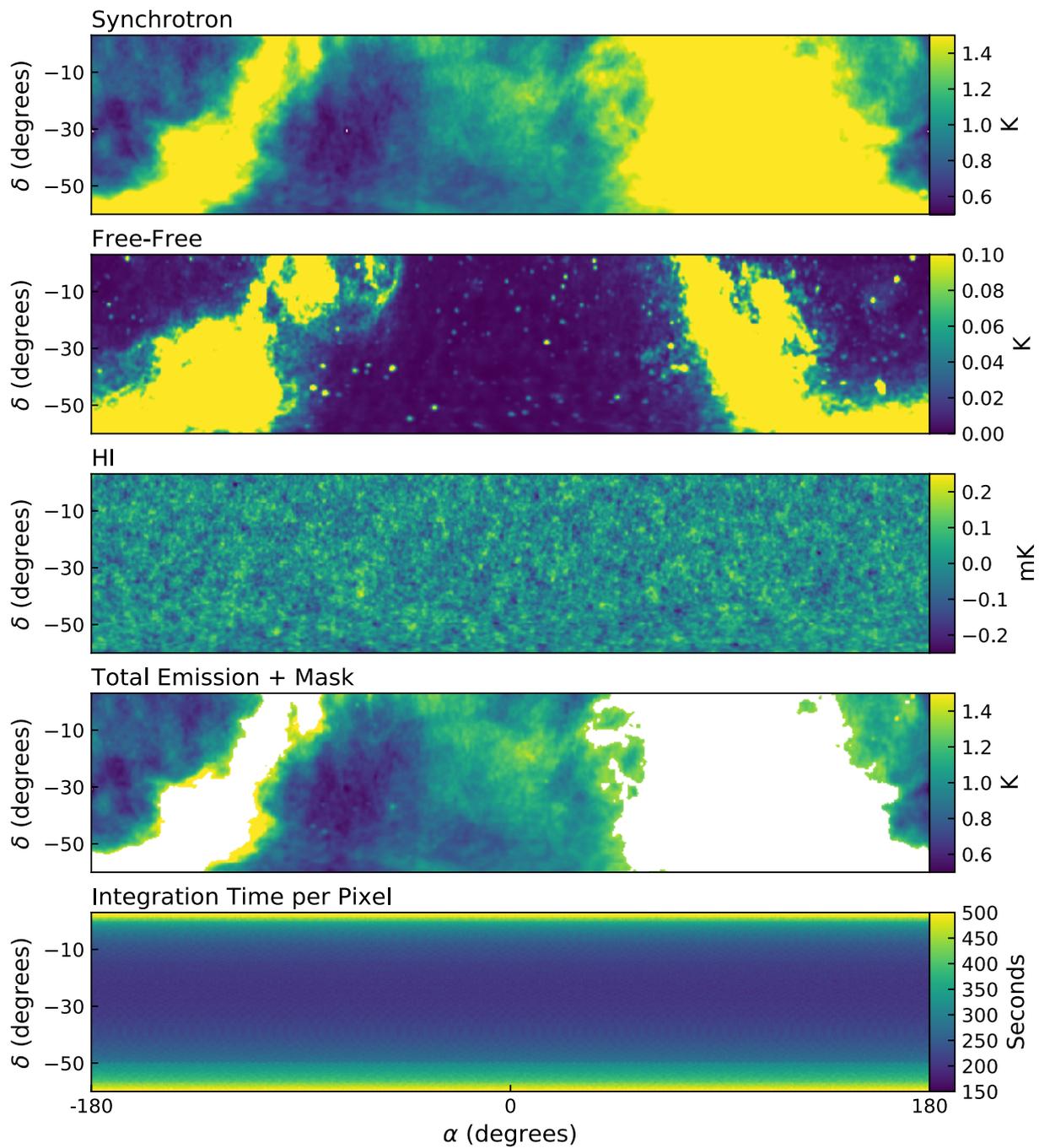
(b)  $\beta = 0.5$ ,  $\alpha = 1$ ,  $f_k = 1$  Hz

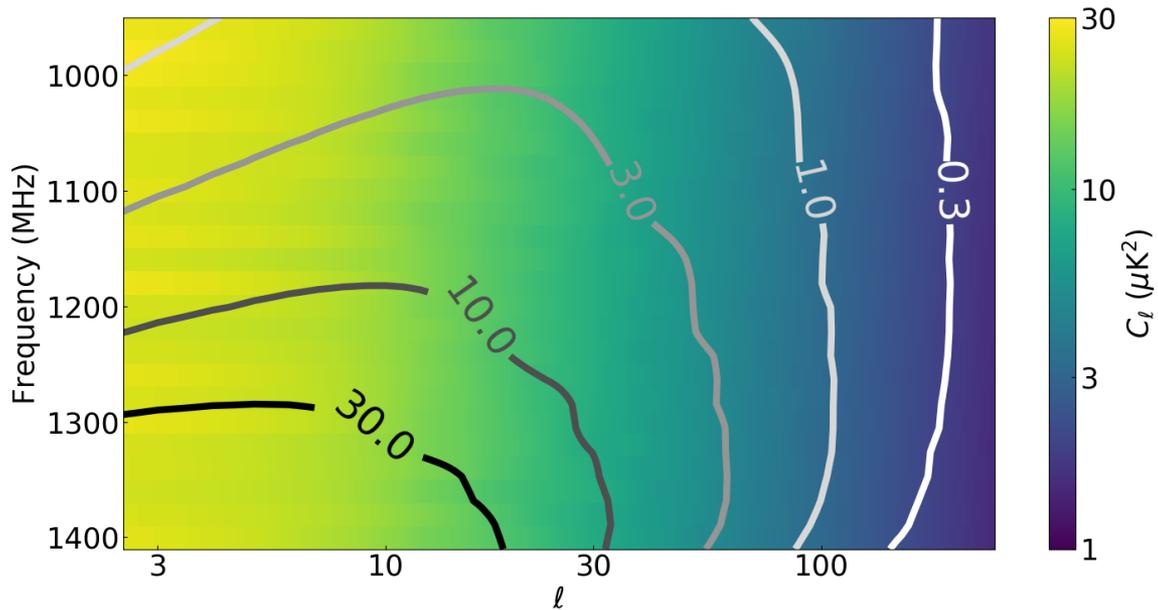
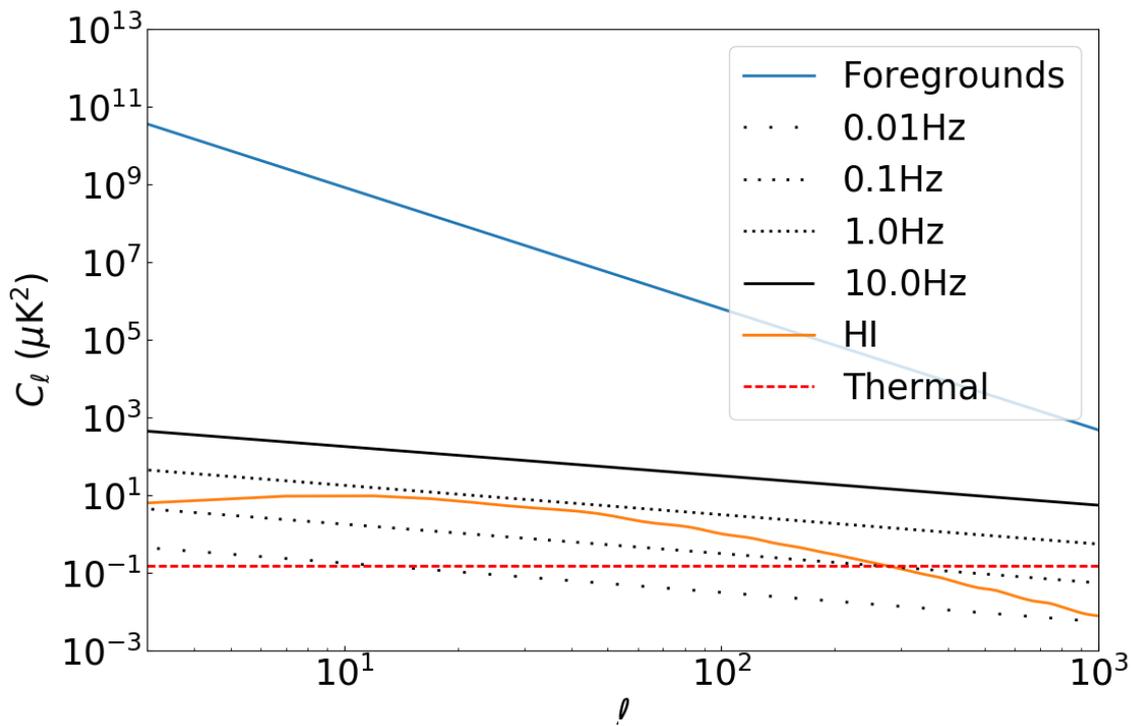


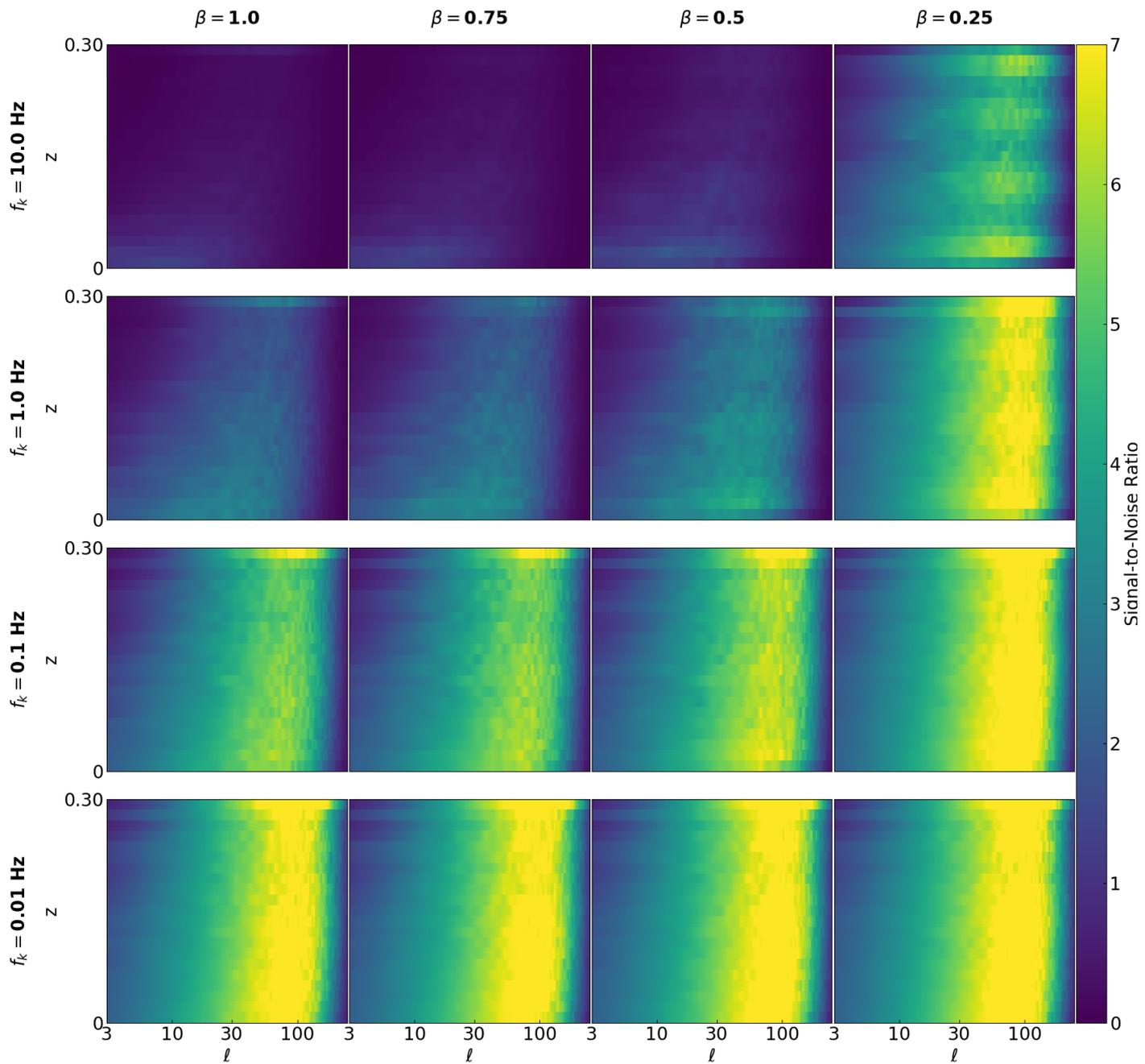
(c)  $\beta = 0.75$ ,  $\alpha = 1$ ,  $f_k = 1$  Hz



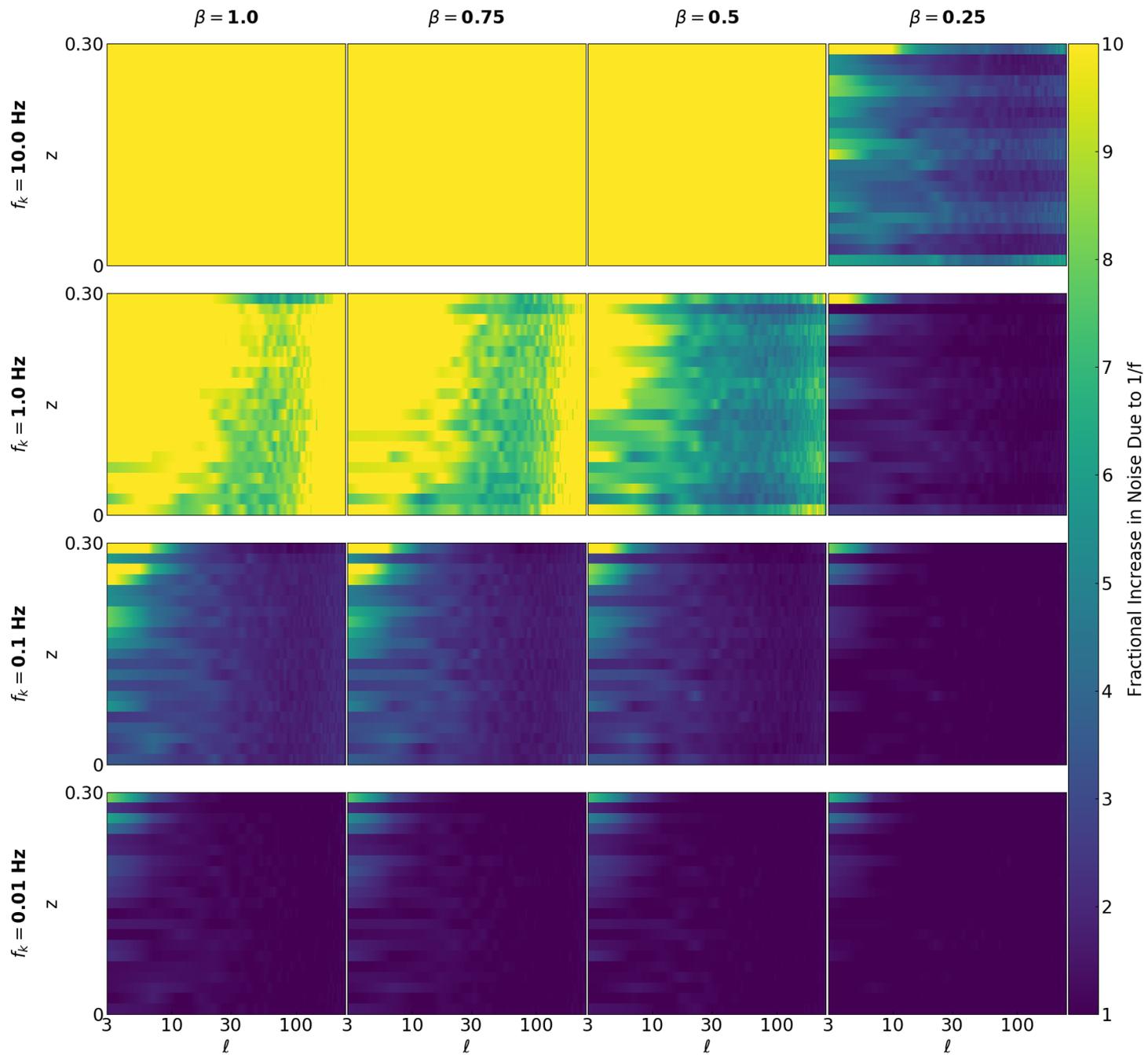
(d)  $\beta = 1.0$ ,  $\alpha = 1$ ,  $f_k = 1$  Hz

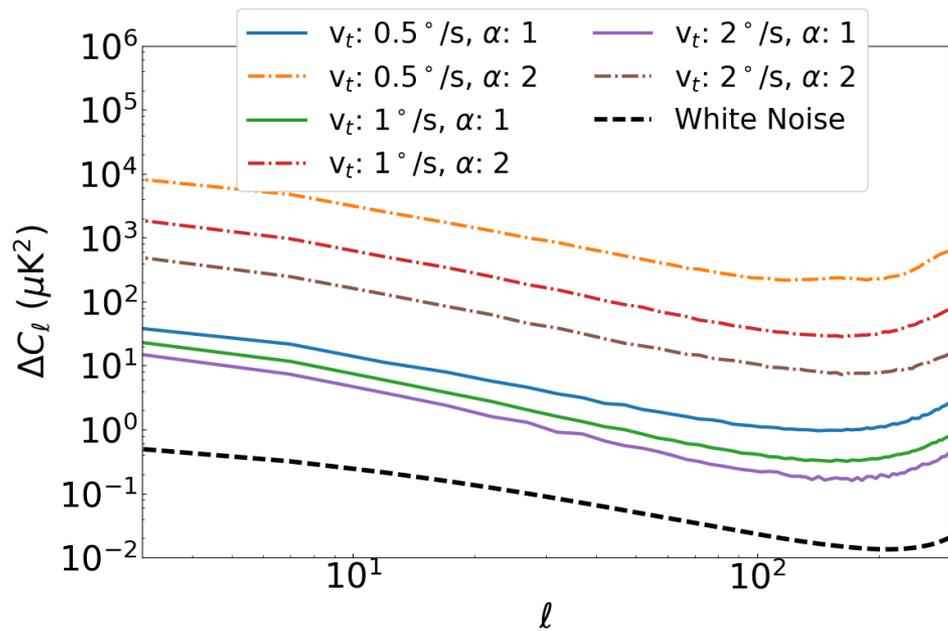
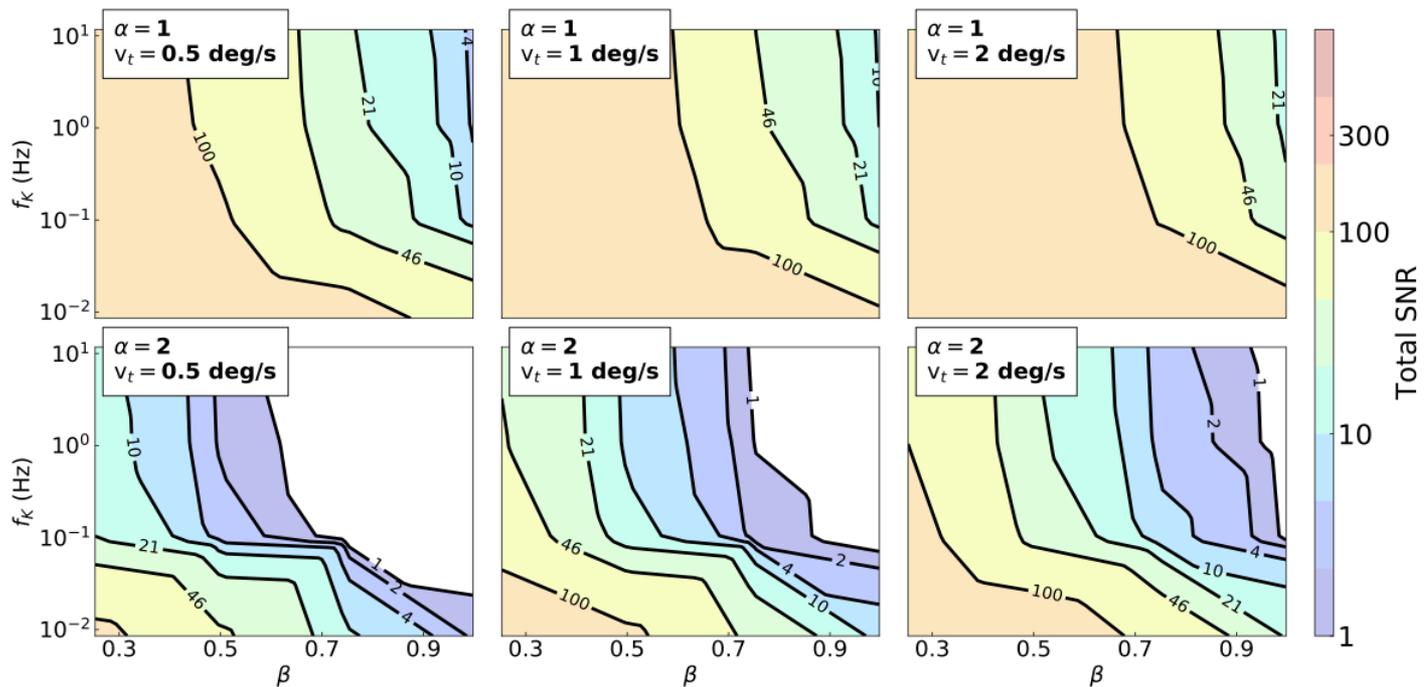




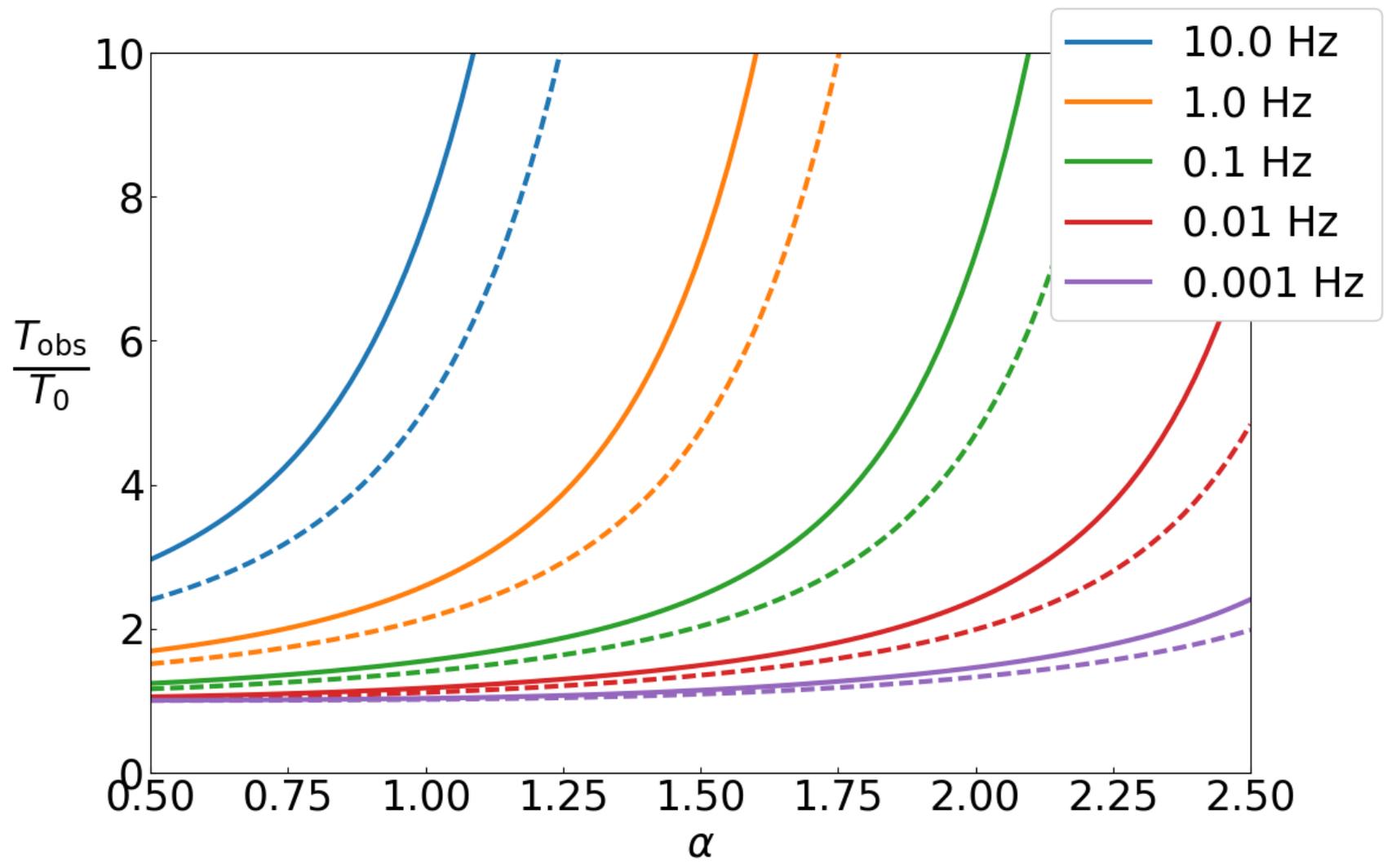


$$r = \frac{\Delta F_\ell}{\Delta N_\ell}$$

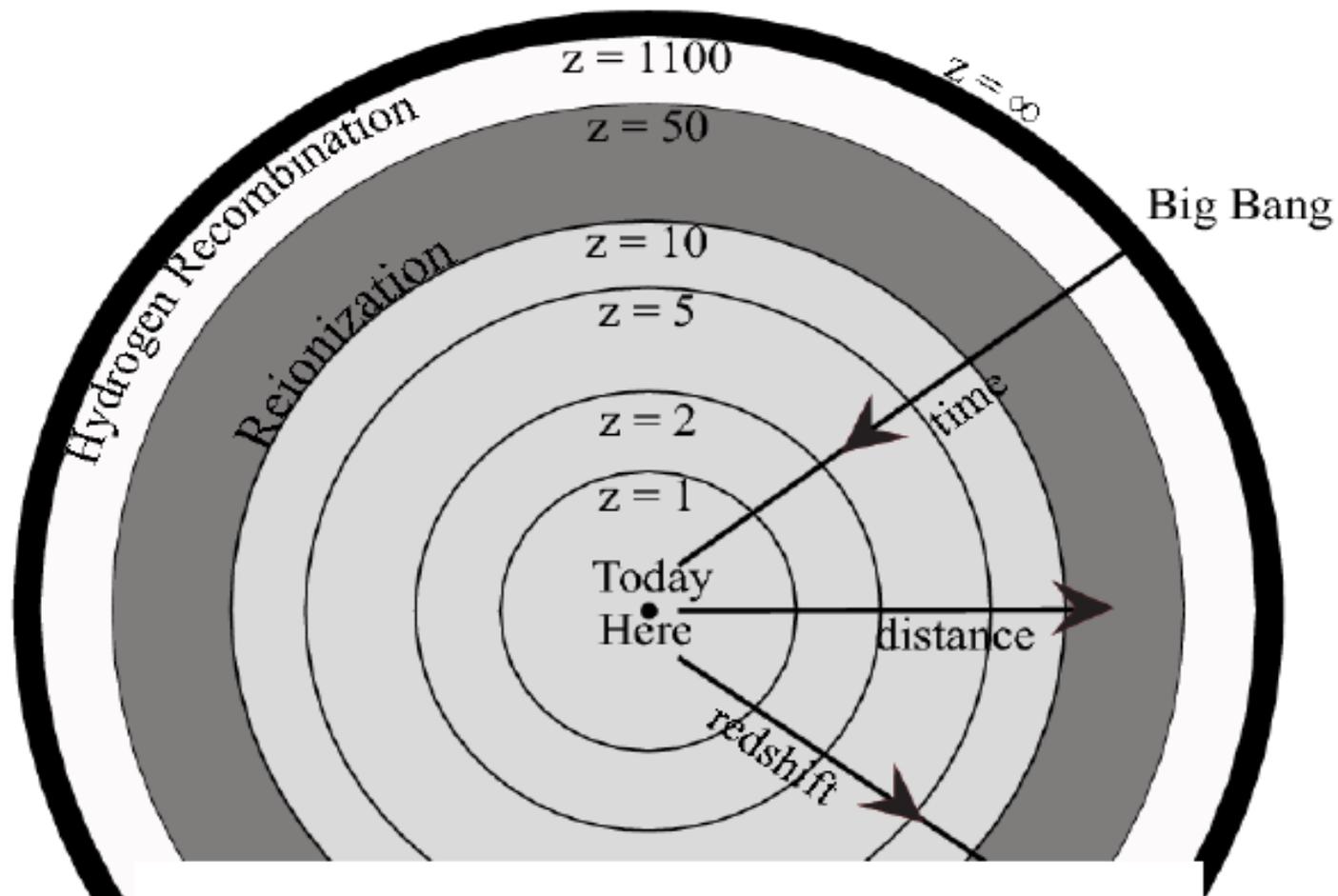




$$T_{\text{obs}} = T_0 \frac{\text{SNR}_w}{\text{SNR}}$$



# The Visible Universe



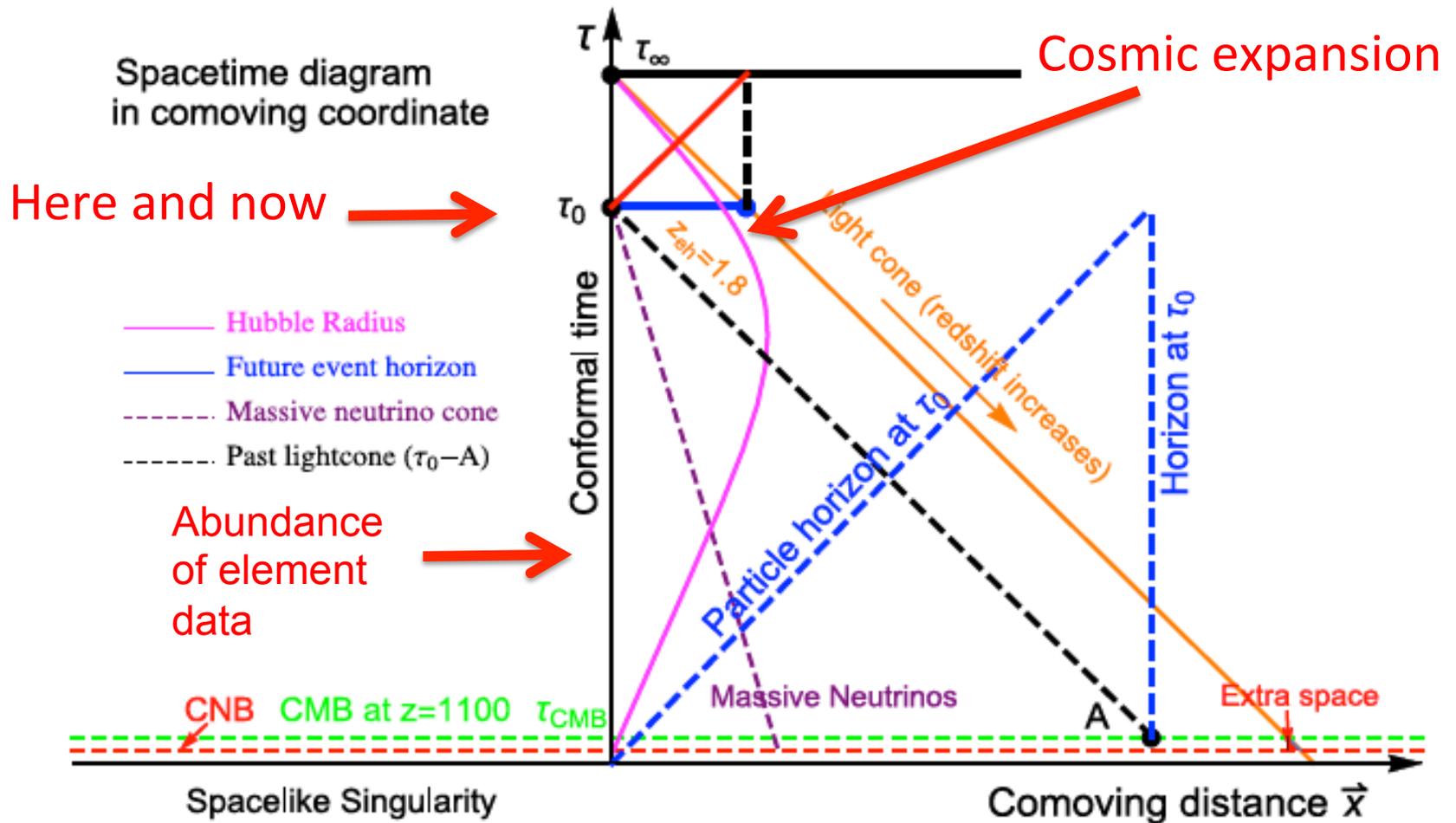
*$z > 5$ : most comoving volume (best statistical constraints on high  $k$ -modes)*

99 per cent of the Cosmology is to measure: (information ascending)

(1) Abundance of the light elements

(2) Cosmic Expansion

(3) Growth of perturbations



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## How much cosmological information can be measured?

Yin-Zhe Ma<sup>1,2,\*</sup> and Douglas Scott<sup>2,†</sup>

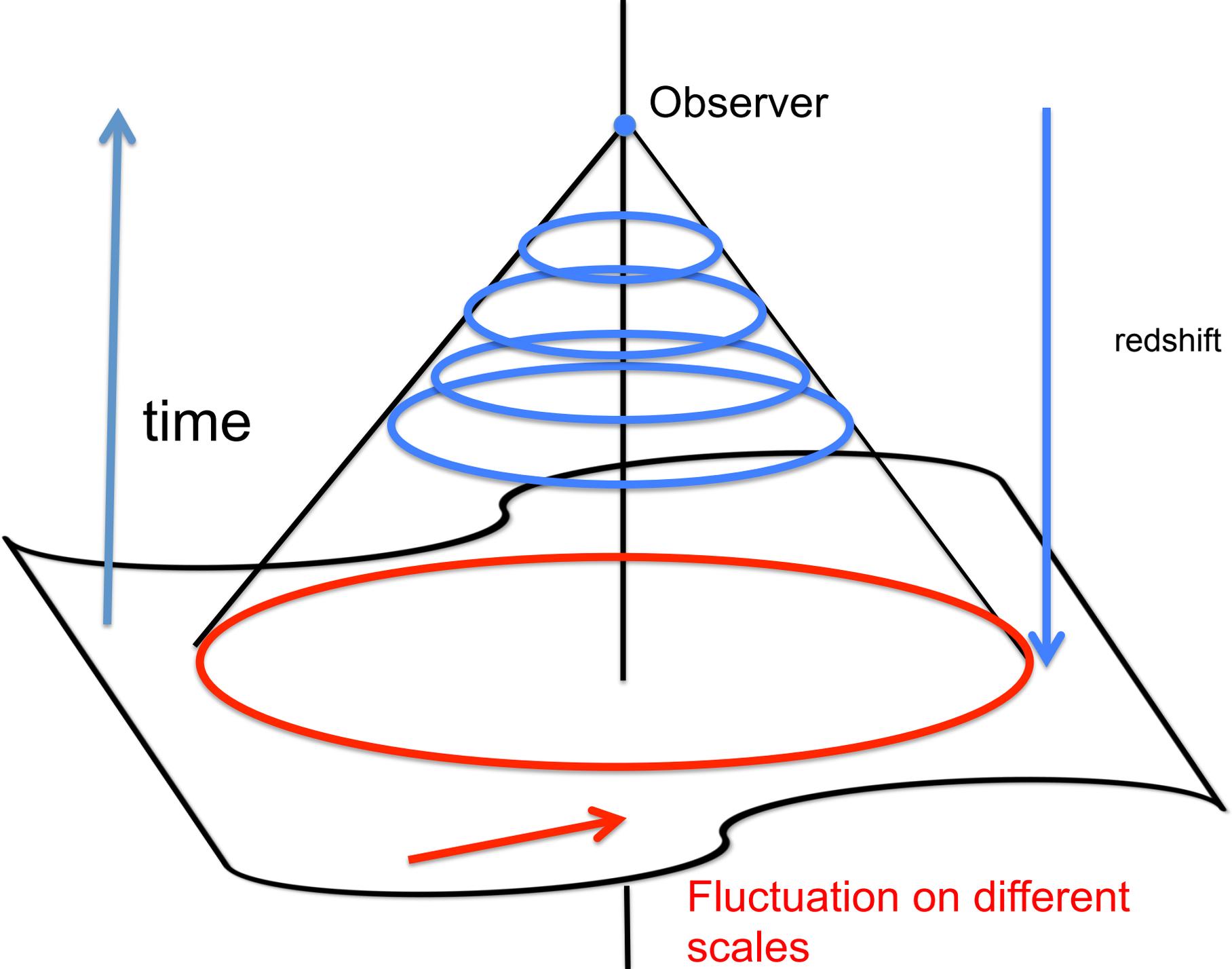
<sup>1</sup>*School of Chemistry and Physics, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*

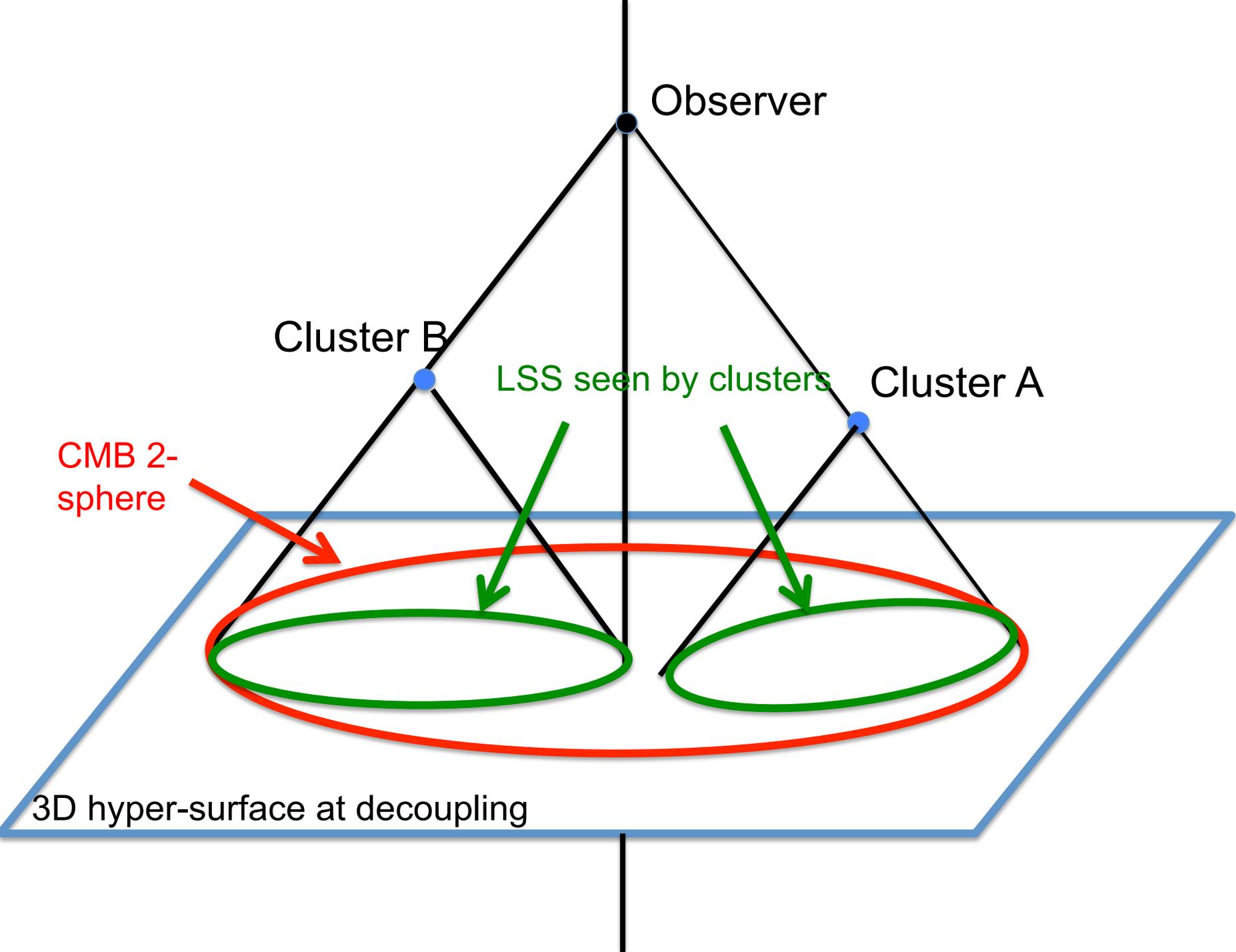
<sup>2</sup>*Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia, Canada V6T 1Z1*

(Received 28 October 2015; published 13 April 2016)

It has become common to call this the “era of precision cosmology,” and hence one rarely hears about the finiteness of the amount of information that is available for constraining cosmological parameters. Under the assumption that the perturbations are purely Gaussian, the amount of extractable information (in terms of total signal-to-noise ratio for power spectrum measurements) is the same (up to a small numerical factor) as an accounting of the number of observable modes. For studies of the microwave sky, we are probably within a factor of a few of the amount of accessible information. To dramatically reduce the uncertainties on parameters will require three-dimensional probes, such as ambitious future redshifted 21-cm surveys. However, even there the available information is still finite, with the total effective signal-to-noise ratio on parameters probably not exceeding  $10^7$ . The amount of observable information will increase with time (but very slowly) into the extremely distant future.

J. Silk’s talk:  $\sim 10^{12}$  number of modes





# Ultimate precision of cosmological parameters

$$I_{\alpha} \equiv - \left\langle \frac{\partial^2 \ln \mathcal{L}(\alpha | \text{data})}{\partial \alpha^2} \right\rangle$$

$$I_{A_s} = \frac{1}{4\pi^2} \int_0^{V(\tau_{\text{obs}})} dV \int_0^{k_{\text{max}}(\tau_e)} k^2 dk \left( \frac{\partial \ln P(k)}{\partial \ln A_s} \right)^2 = N_{\text{modes}}/2$$

$$\Delta A_s / A_s \simeq 10^{-7}$$

- We are developing the 21cm intensity mapping pipeline which can allow us to simulate the noise and reduce the foreground emission, therefore recover the true 21-cm signal.
- The PCA analysis with realistic simulation shows promising ability to reconstruct power spectra, better than polynomials fitting
- We also test  $1/f$  noise, which is crucial for recovery of 21-cm power spectra. Detail experiences are
  - (1) First, and most importantly, attempts to measure the  $\alpha$  and  $\beta$  of SD HI IM receivers should be made in order to inform the planning of any future survey.
  - (2) The frequency correlations as described by  $\beta$  (or any other functional form) are critical to determine. Instruments with highly uncorrelated  $1/f$  noise in frequency will find HI IM significantly challenging.
  - (3) Care should taken to preserve the statistical properties of the  $1/f$  noise frequency spectrum to avoid inadvertently increasing the effective  $\beta$  of the  $1/f$  noise.
  - (4) Scan speeds should be as fast as feasibly possible, at least achieving a speed that matches the period of slew speed to the knee frequency of  $1/f$  noise.
  - (5) The observing time of the experiment should be long enough such that the integrated angular power of the  $1/f$  noise in the map is less than the HI angular power spectrum at all scales of interest.

