21-cm intensity mapping: observational prospects

Yin-Zhe Ma
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- 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

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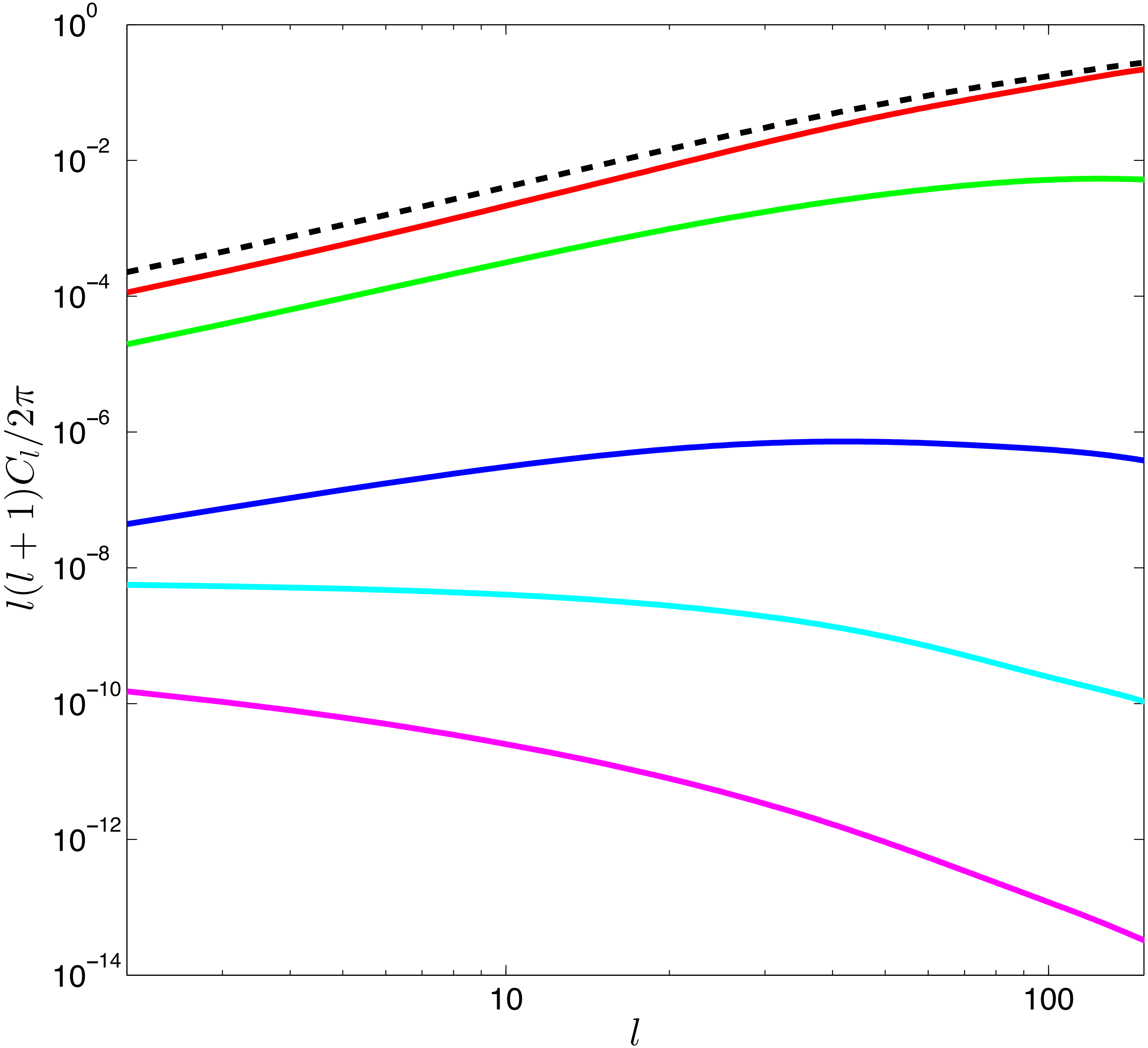
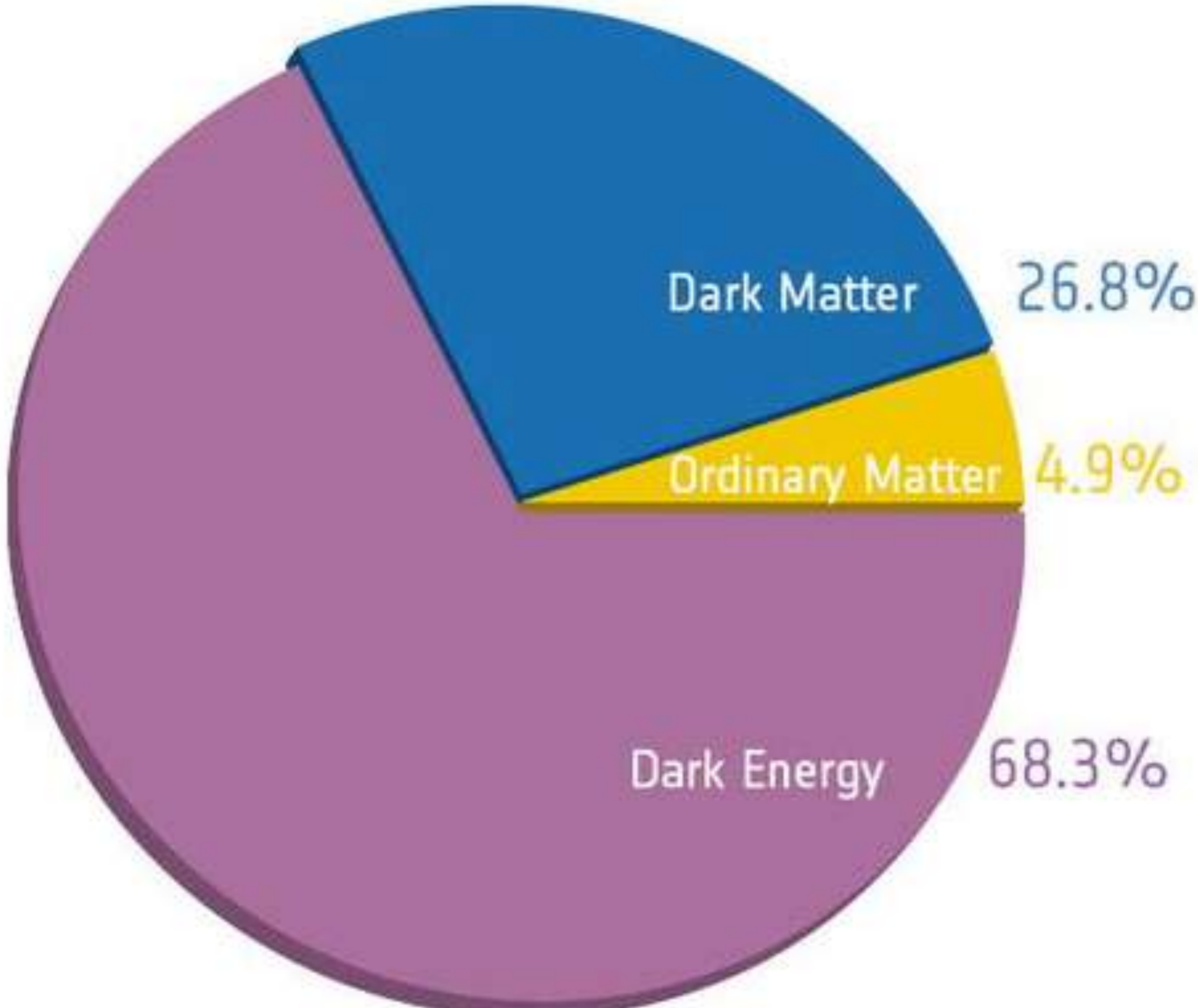
$$\Delta^{W}_{T_b,l}(\mathbf{k}) = \int_0^\infty \mathrm{d}z W(z) \Delta_{T_b,l}(\mathbf{k}, z)$$

$$\widehat{\Delta}^{W}_{T_b,l}(k) \equiv \Delta^{W}_{T_b,l}(\mathbf{k}) / \mathcal{R}(\mathbf{k})$$

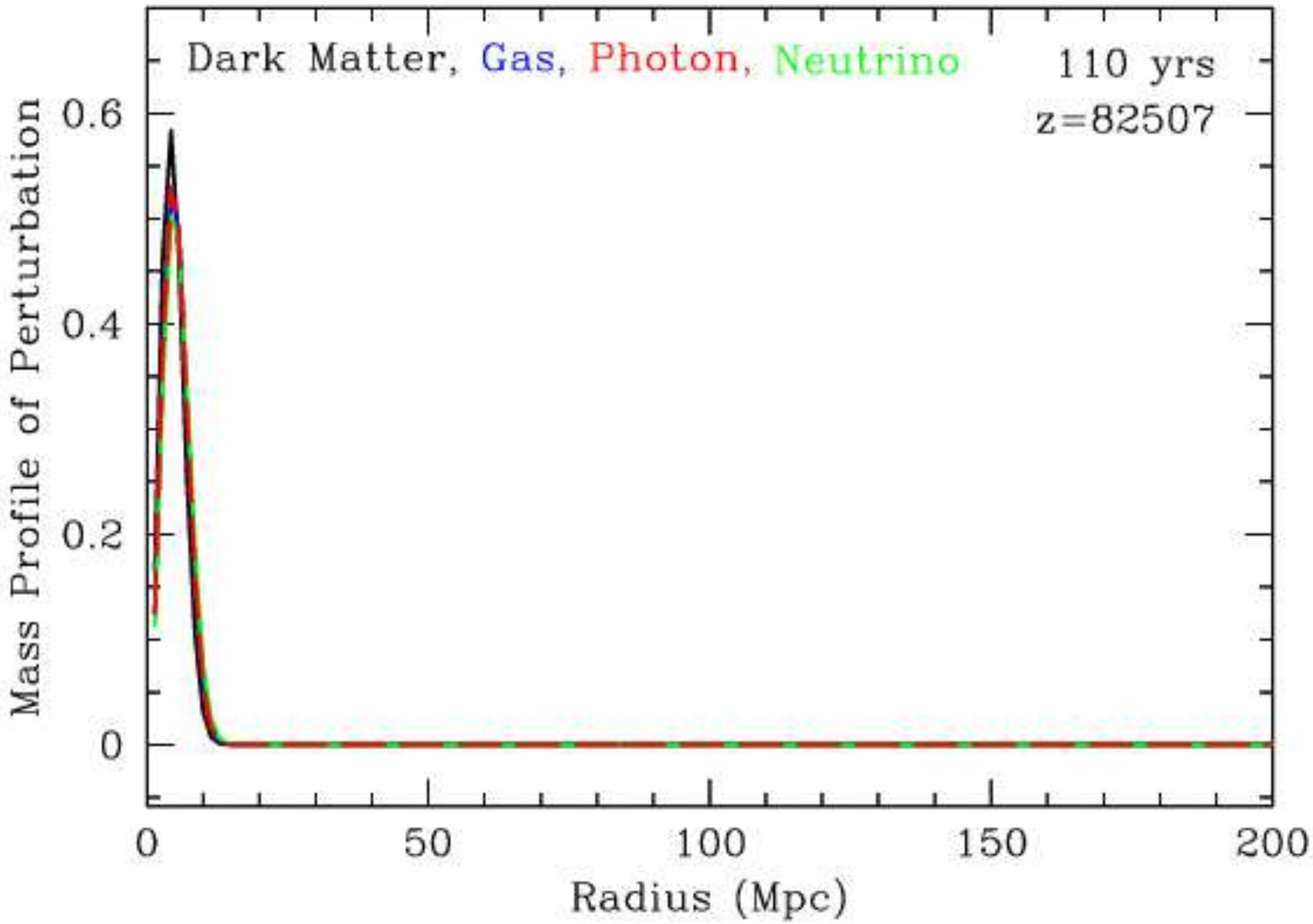
$$C_l^{WW'} = 4\pi \int \mathrm{d}\ln k \, \mathcal{P}_{\mathcal{R}}(k) \Delta^{W}_{T_b,l}(k) \Delta^{W'}_{T_b,l}(k)$$



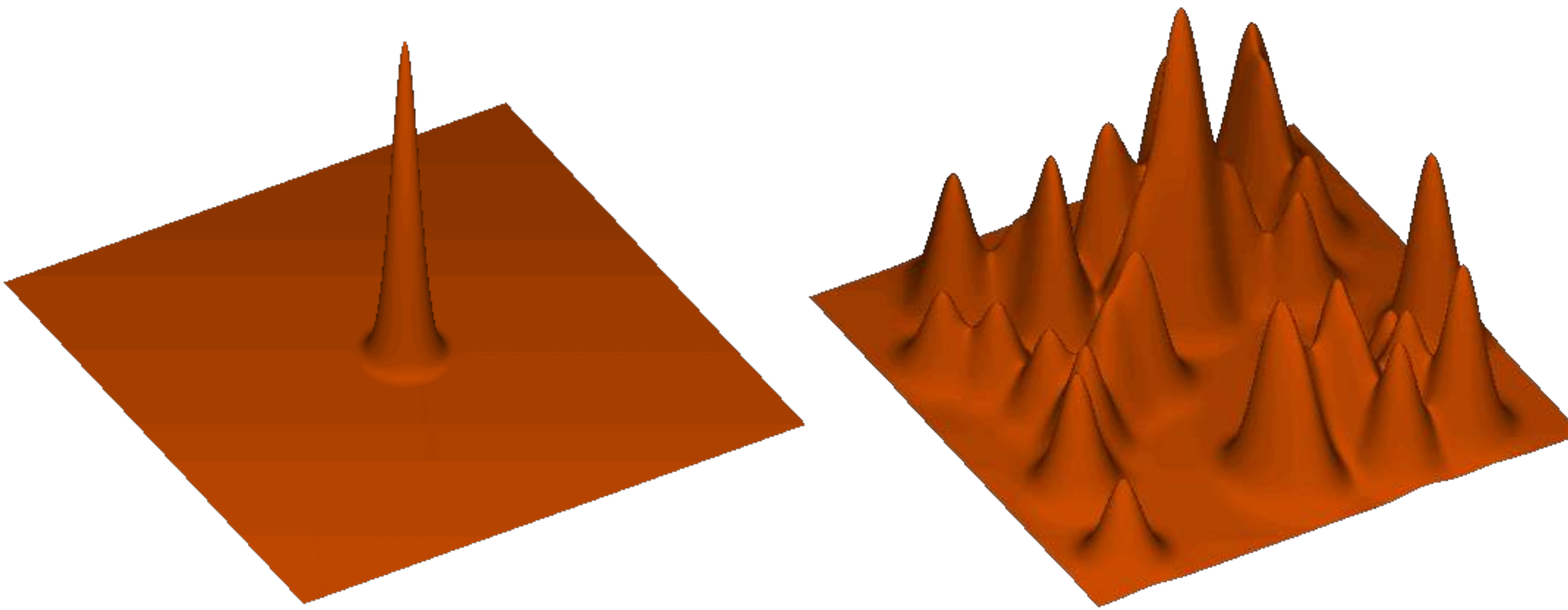
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10
100
l
$l(l+1)C_l/2\pi$

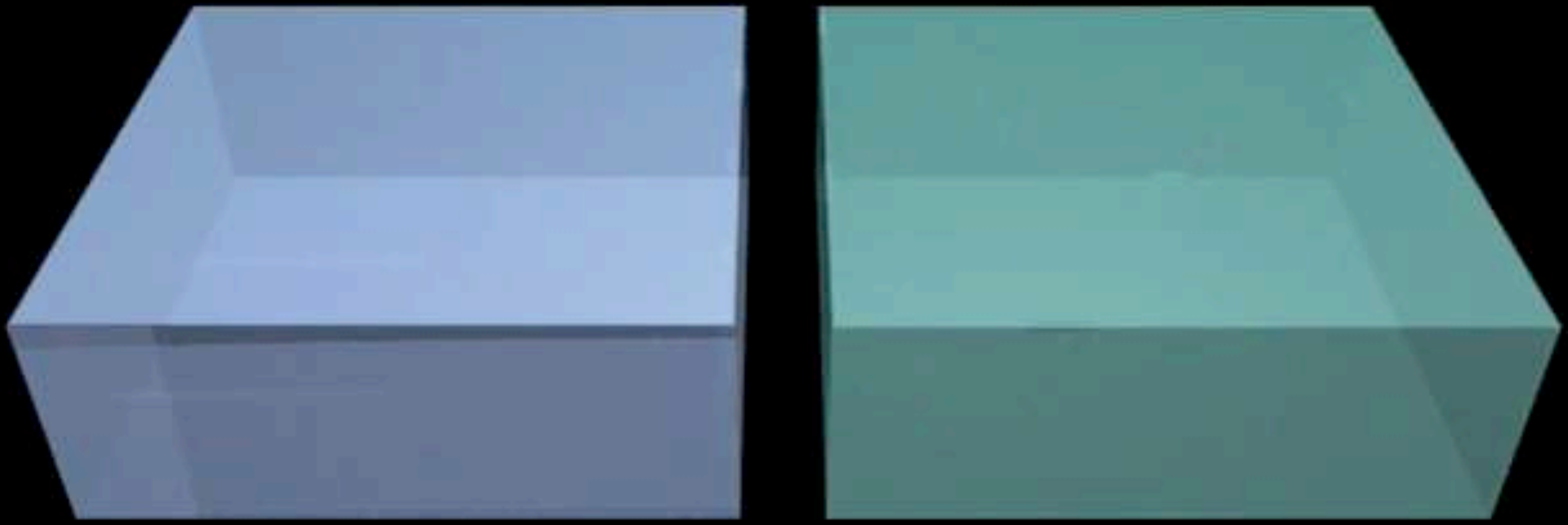

Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

Baryon Acoustic Oscillations

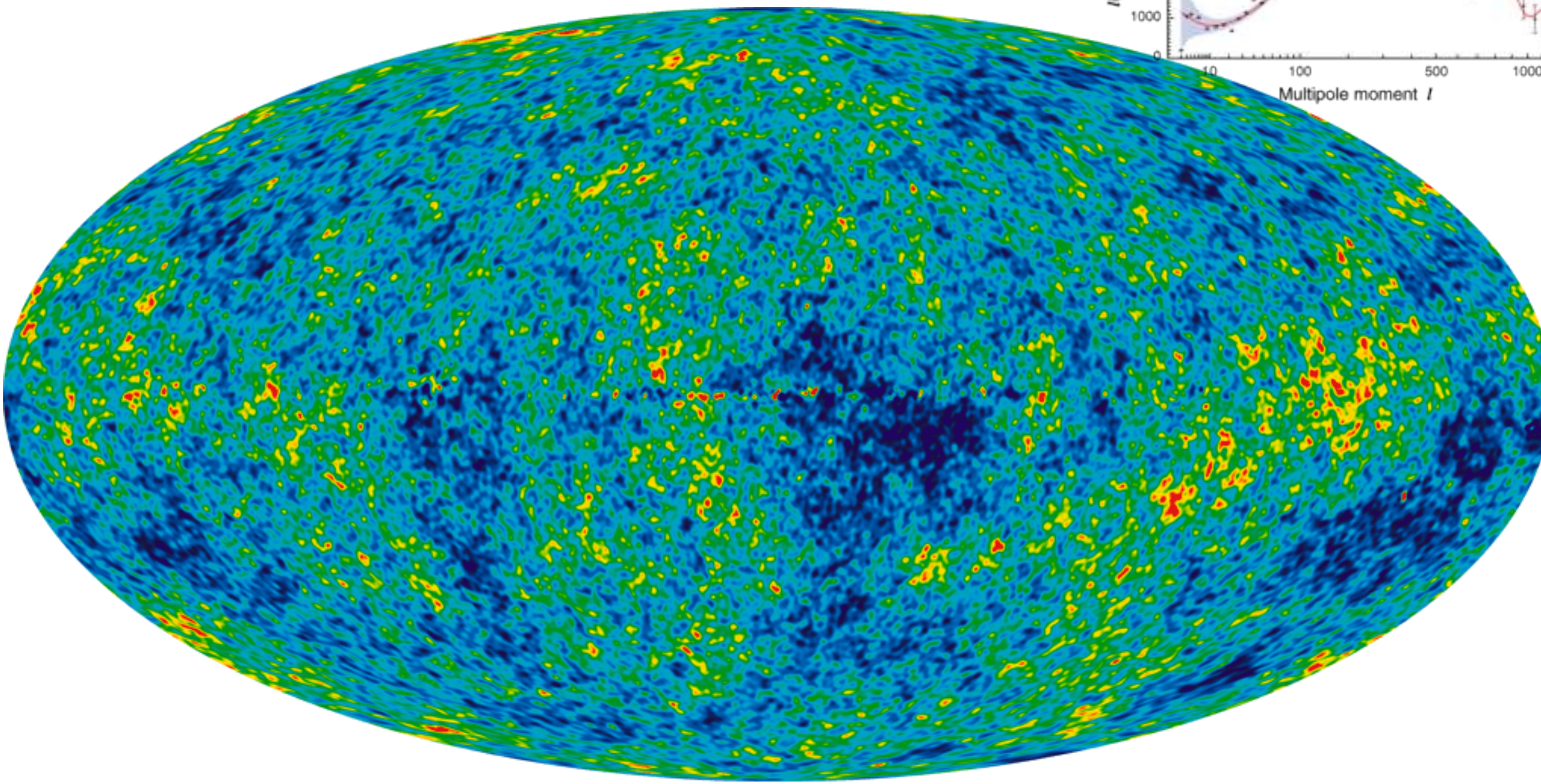


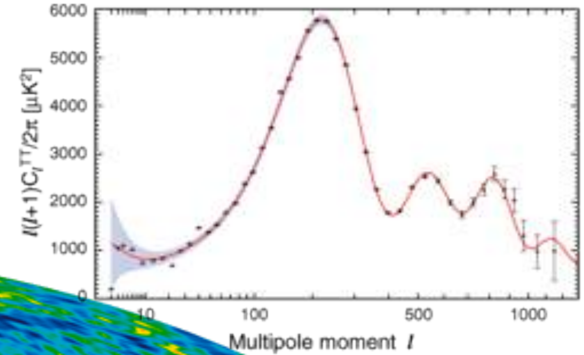
Eisenstein





BAO in the CMB

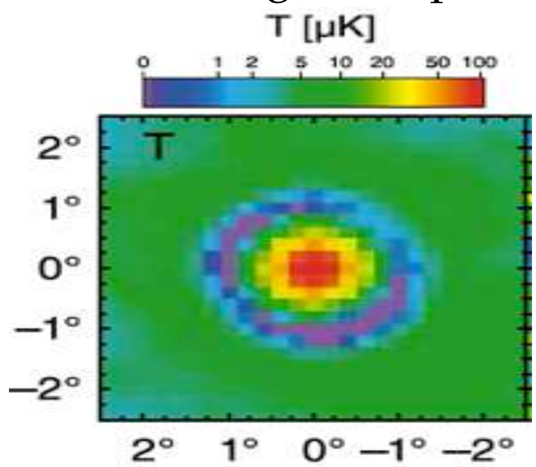


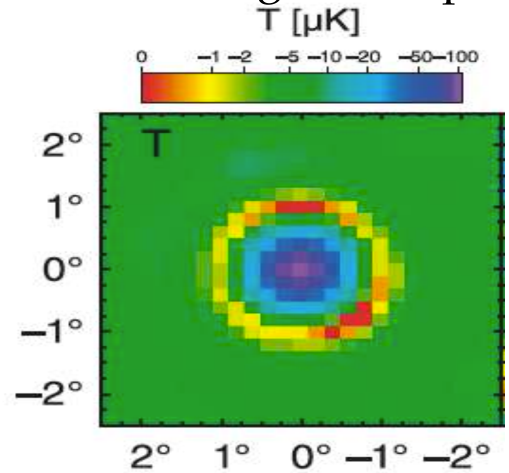


BAO have been observed in the CMB, and set the acoustic scale: $l\_A = 302.69 \pm 0.69$ @ z=1091.

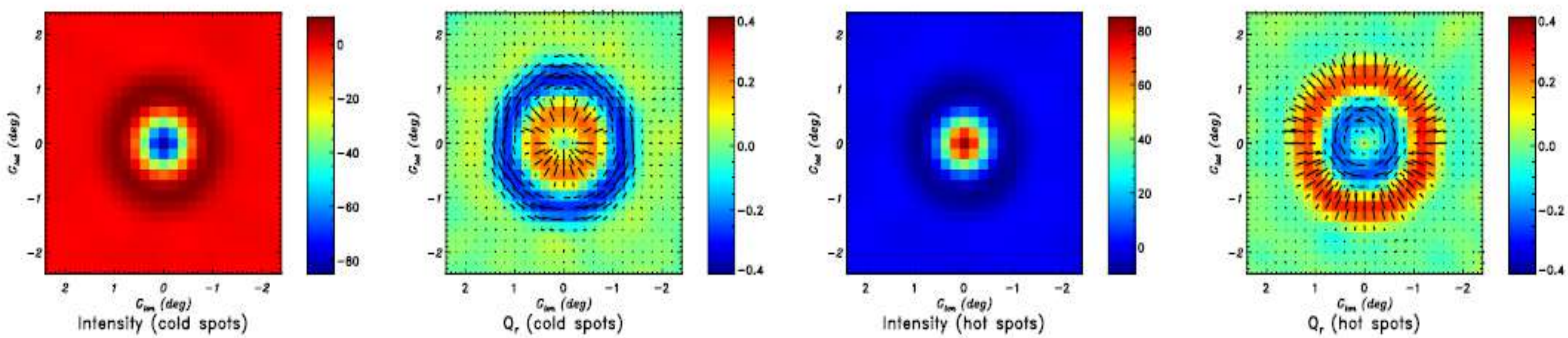
- Average hot spot
- Average cold spot

- WMAP:

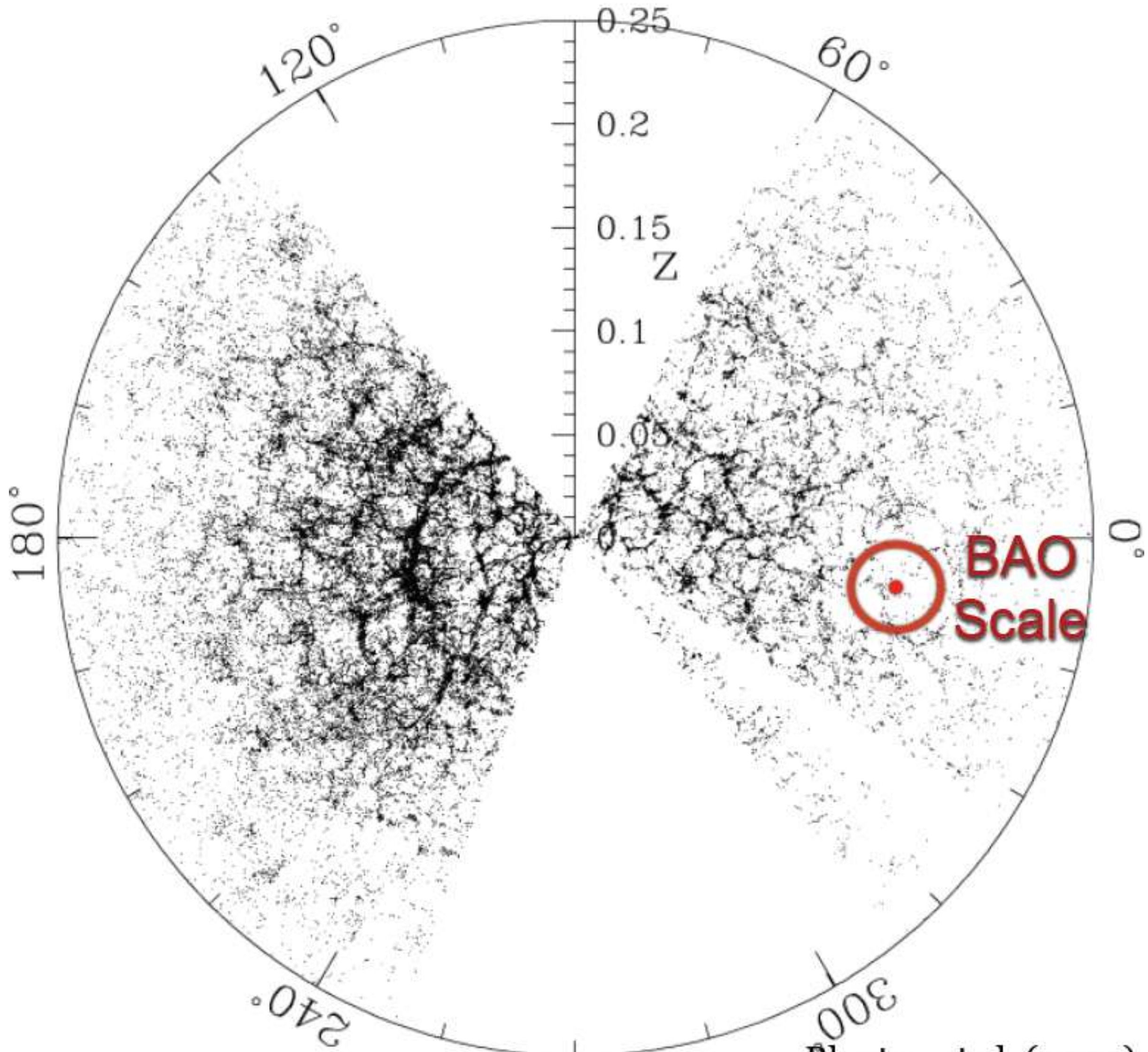




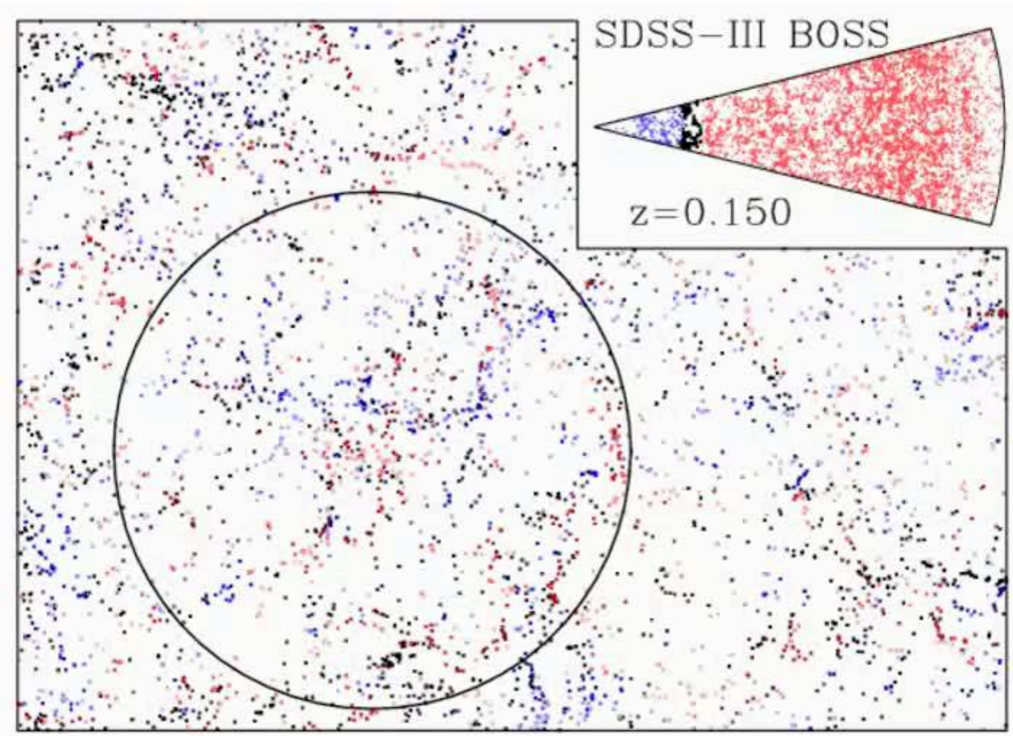
- Planck:

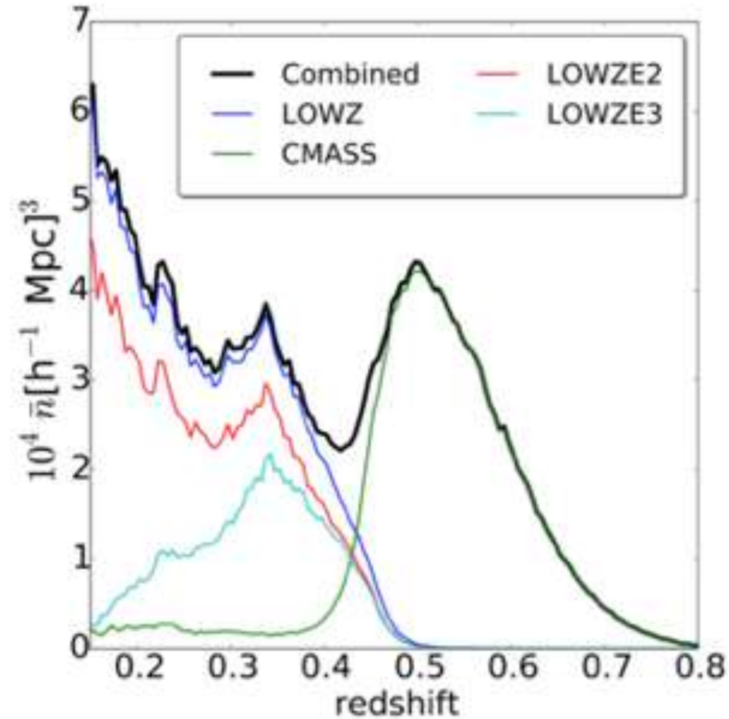


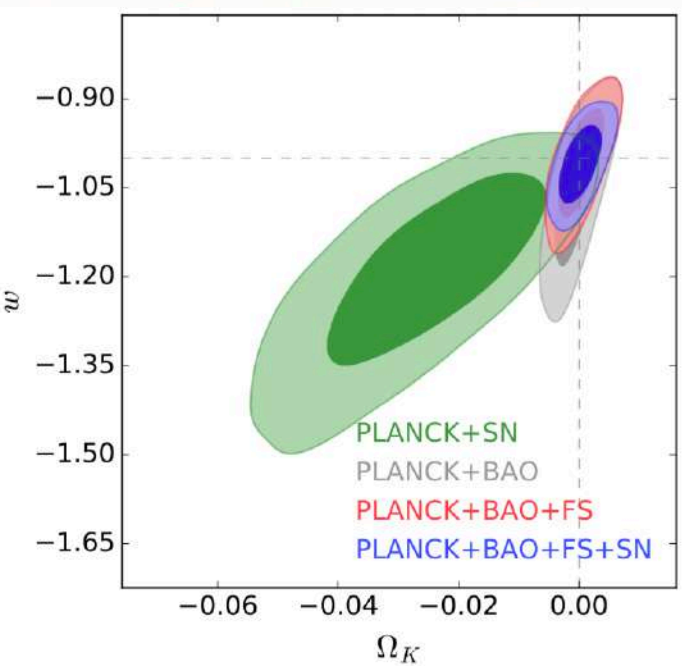
Optical Galaxy Surveys

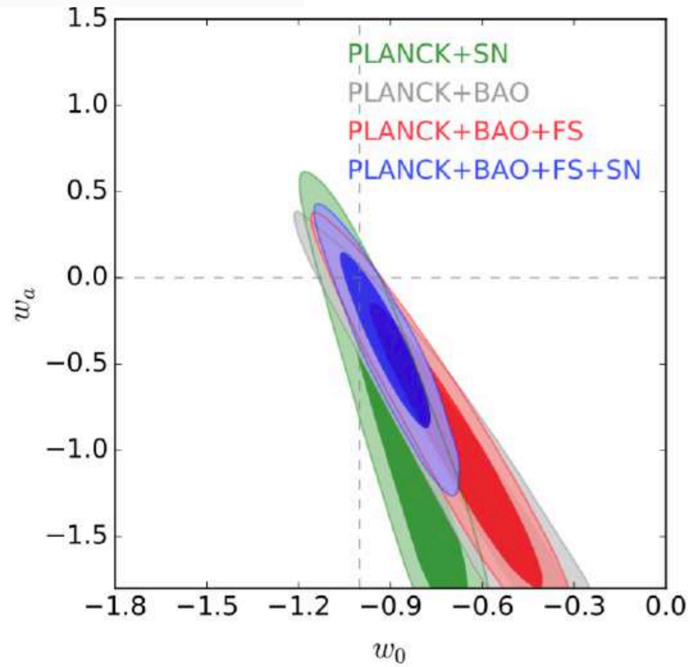


Blanton et al. (2003)



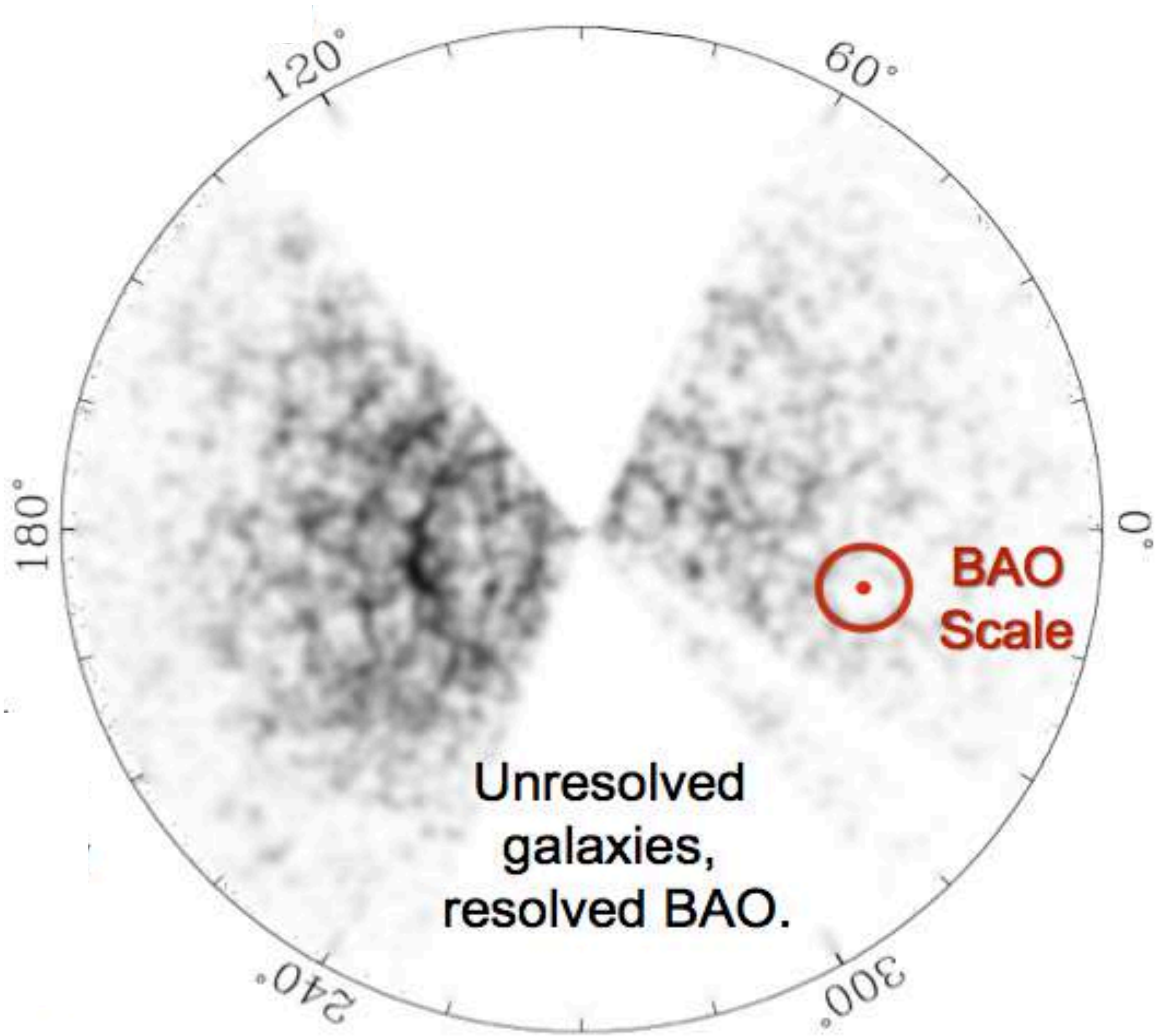






Alam et al. 2017

Hydrogen Intensity Mapping

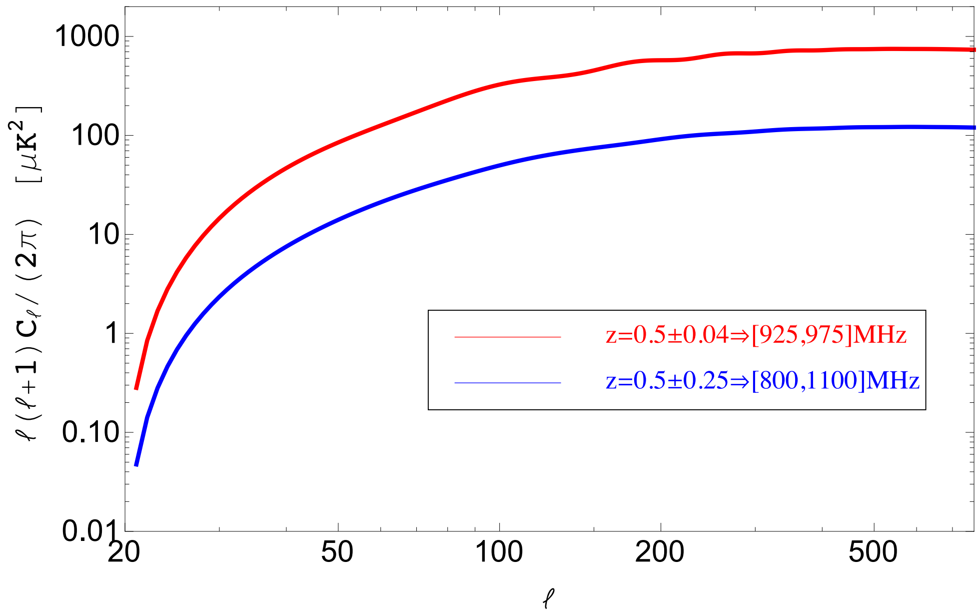


- BAO measurement
- Cosmological Forecasts

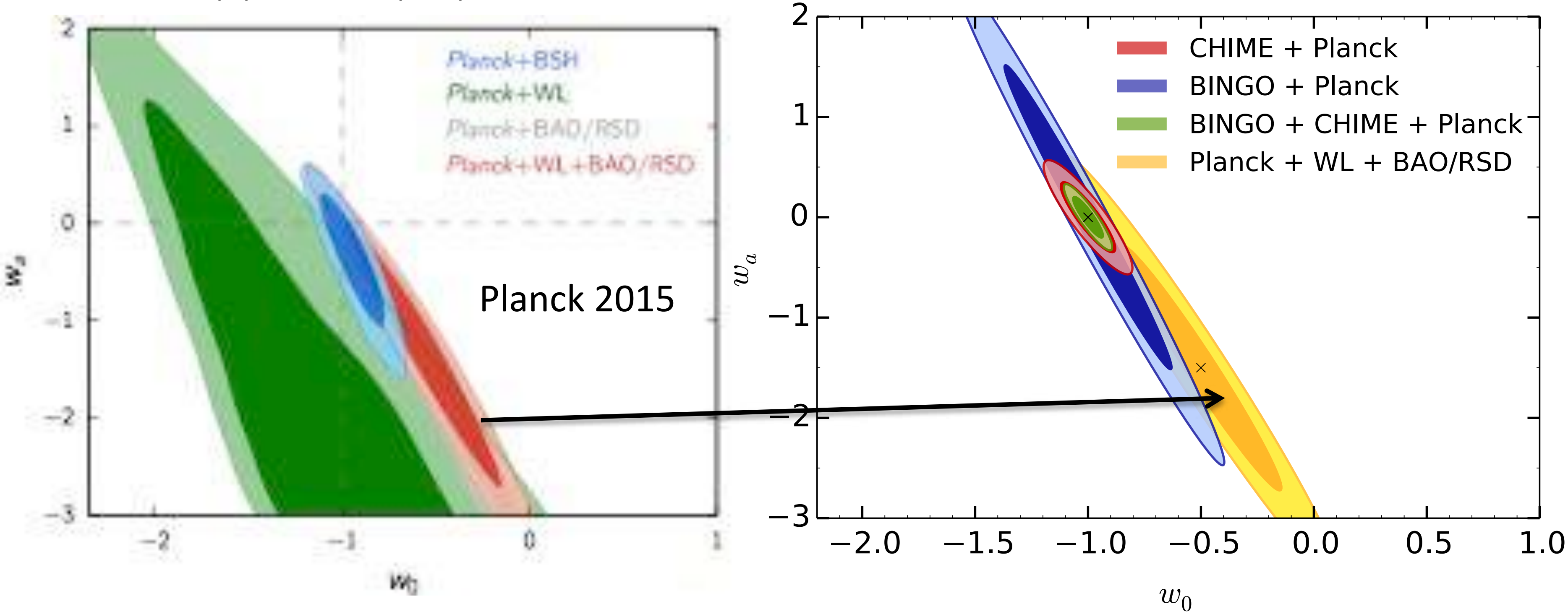
(1) Cosmological parameters

(2) Primordial non-Gaussianity

- Foreground cleaning
- 1/f noise


1000
100
10
1
0.10
0.01
20
50
100
200
500
ℓ
ℓ(ℓ+1)C_ℓ/(2π) [μK²]
z=0.5±0.04⇒[925,975]MHz
z=0.5±0.25⇒[800,1100]MHz

w(a)=w0+wa(1-a)


Planck+BSH
Planck+WL
Planck+BAO/RSD
Planck+WL+BAO/RSD
Planck 2015
CHIME + Planck
BINGO + Planck
BINGO + CHIME + Planck
Planck + WL + BAO/RSD
w_a
w_0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
2
1
0
−1
−2
−3

Primordial non-Gaussianity

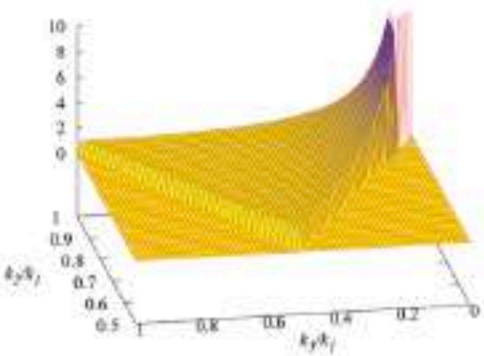
The Primordial Bispectrum

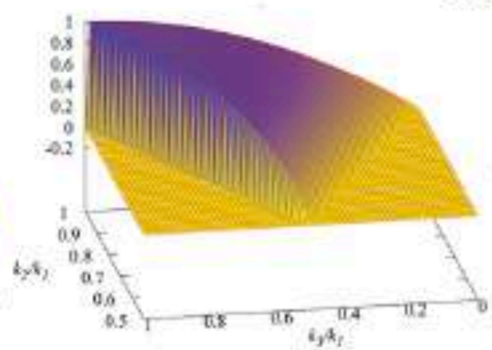
$$\phi = \phi_G + f_{\rm NL}(\phi_G^2 - \langle \phi_G^2 \rangle)$$

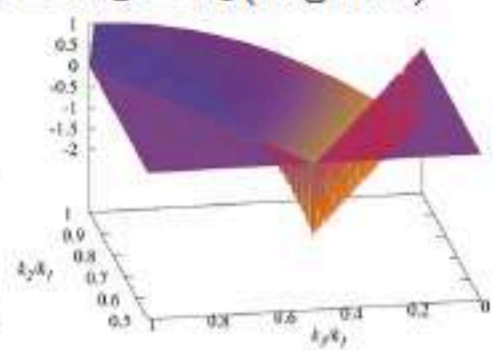
$$\langle \phi_{\mathbf{k}_1} \phi_{\mathbf{k}_2} \phi_{\mathbf{k}_3} \rangle \equiv (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B_\phi(k_1, k_2, k_3)$$

Bispectrum Shapes

Local Shape	Equilateral Shape	Orthogonal Shape	Enfolded Shape
$k_3 \ll k_2 \simeq k_1$	$k_3 \simeq k_2 \simeq k_1$	$k_3 \simeq k_2 \simeq k_1 (\text{positive})$ $2k_3 \simeq 2k_2 \simeq k_1 (\text{nagitive})$	$2k_3 \simeq 2k_2 \simeq k_1$

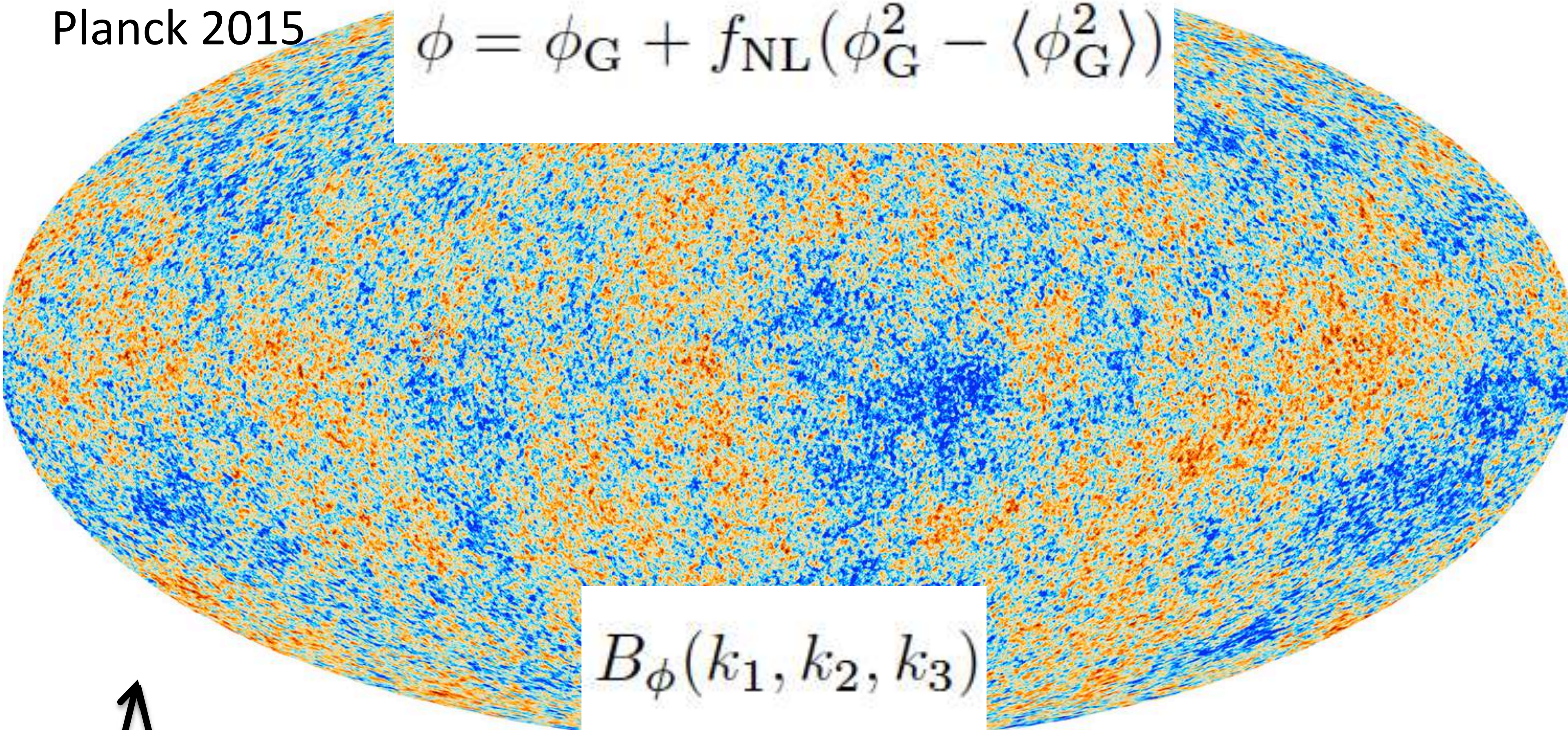






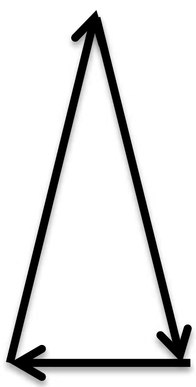
Tomo Takahashi; Prog Theor Exp Phys 2014; 2014 (6): 06B105.

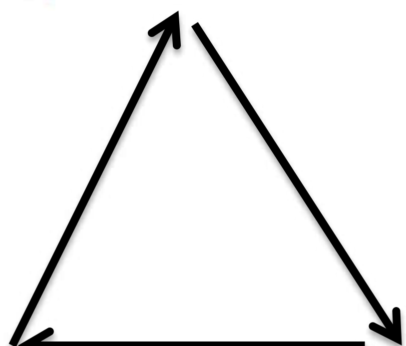
Planck 2015



$$\phi = \phi_{\rm G} + f_{\rm NL}(\phi_{\rm G}^2 - \langle \phi_{\rm G}^2 \rangle)$$

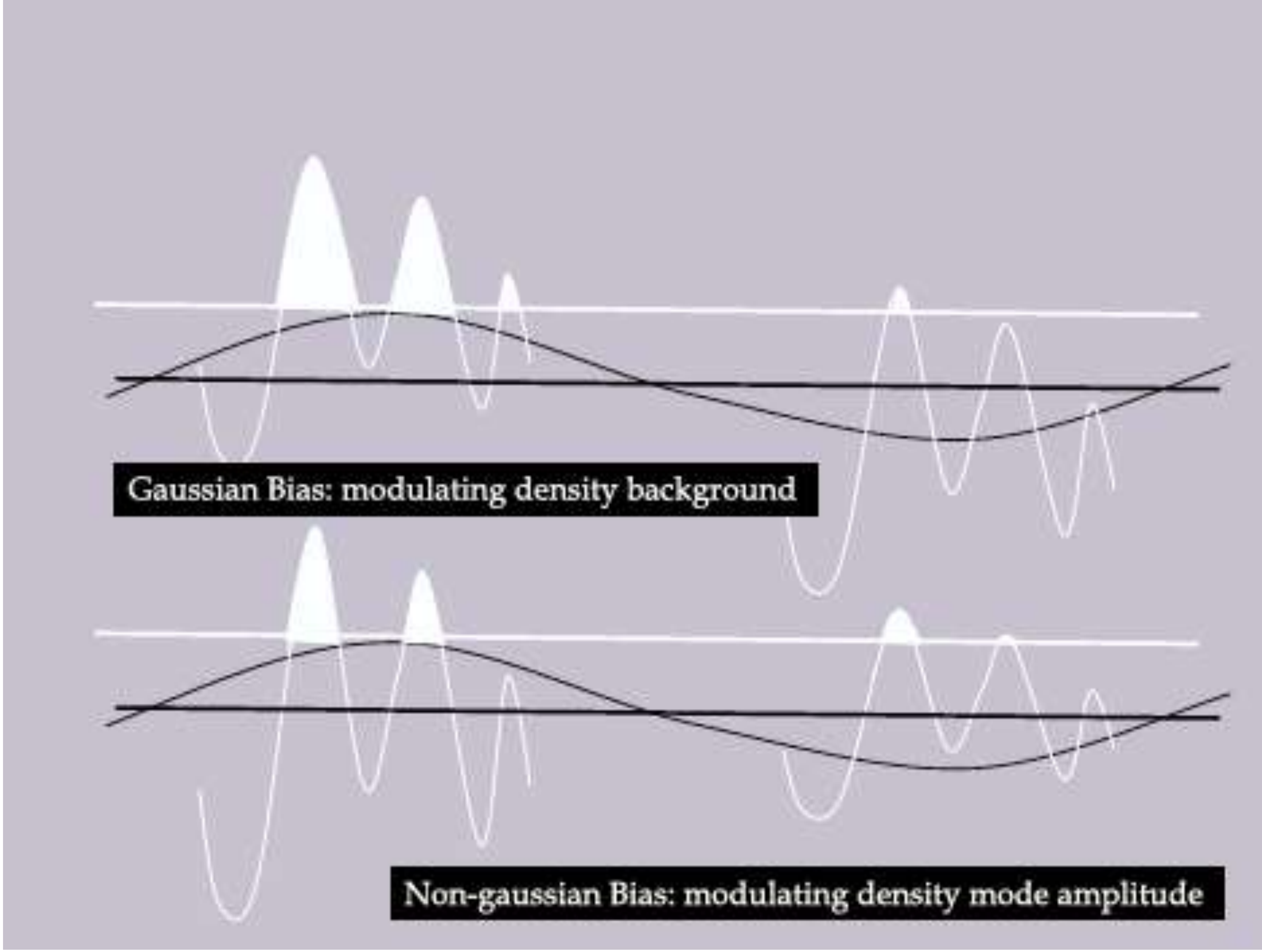
$$B_\phi(k_1, k_2, k_3)$$





Independent shape

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



Afshordi, Tolley, 2008.

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

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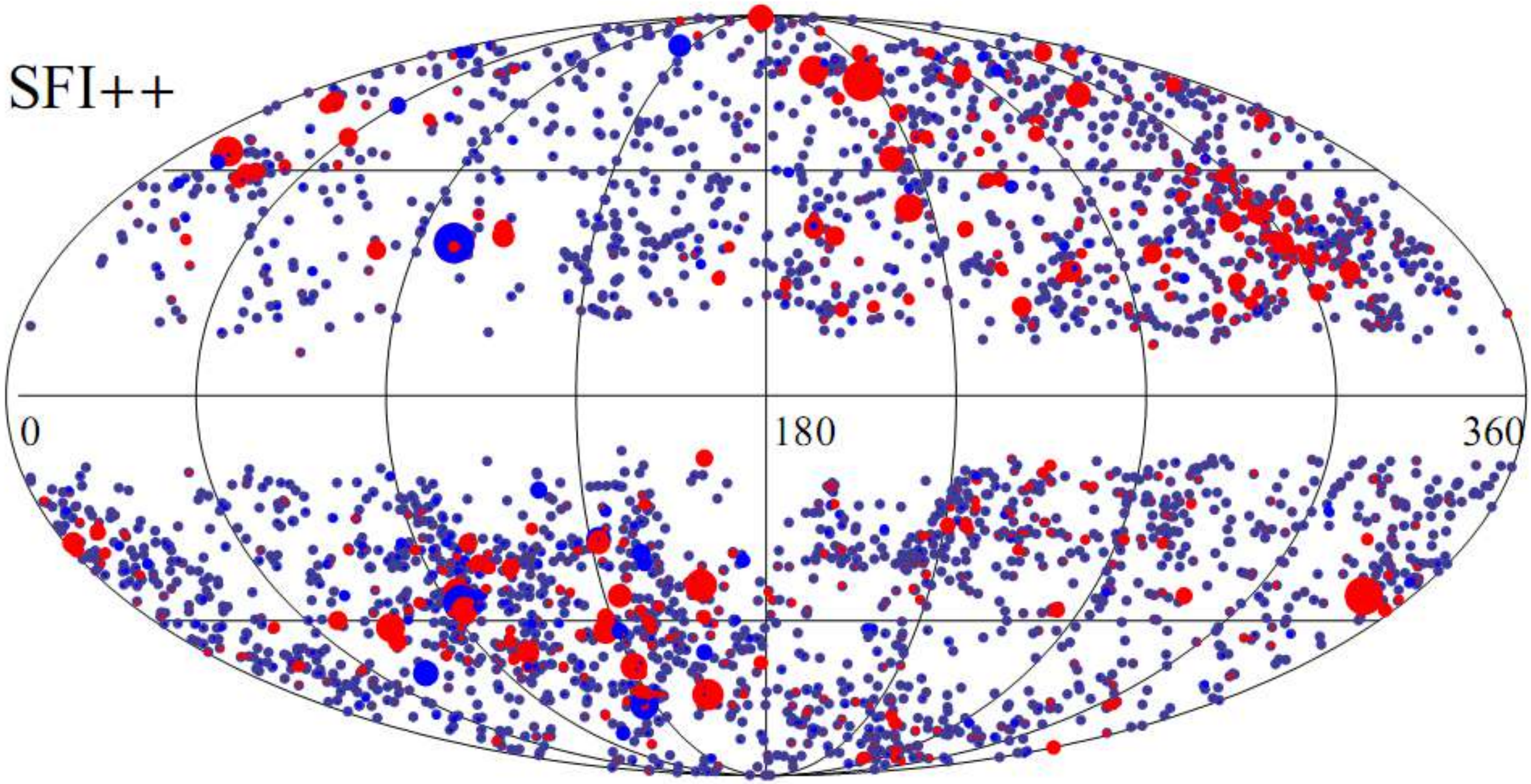


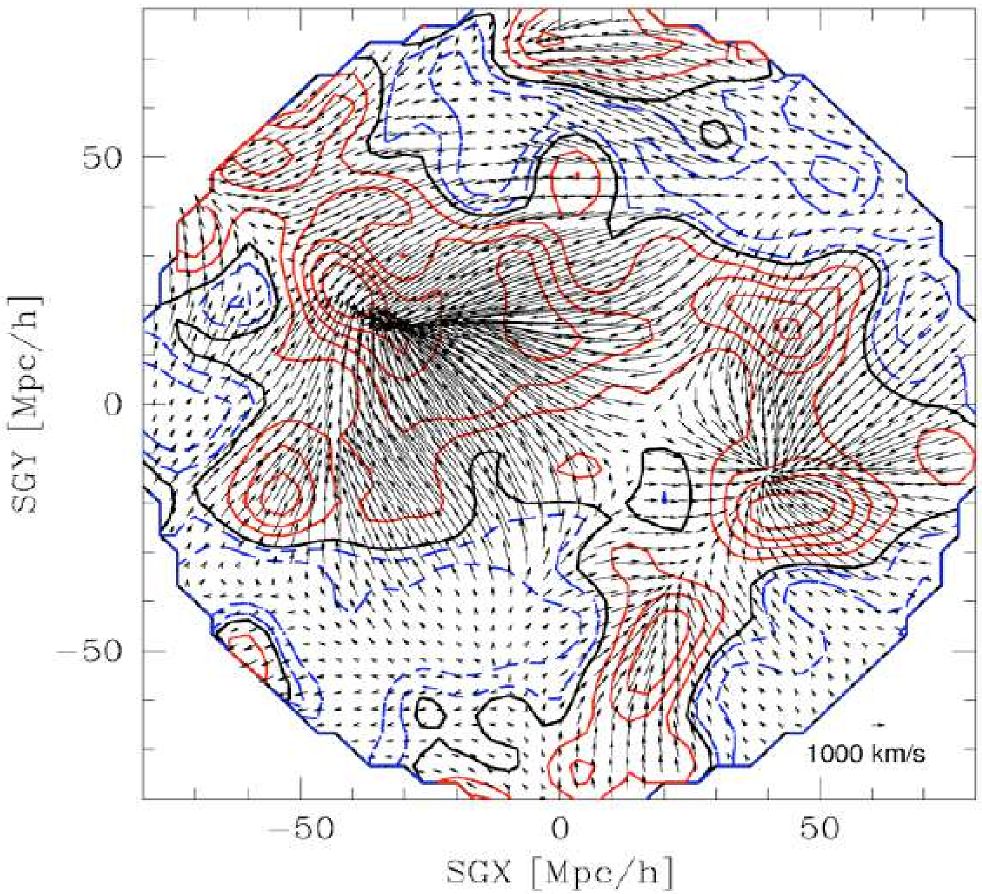
$$cz = H_0 r + v$$

Linear perturbation theory: (Peebles 1971)

$$\vec{v}_{\rm g}(\vec{x}) = \frac{H_0 f_0}{4\pi} \int d^3\vec{x}'\,\delta_{\rm m}(\vec{x}', t)\frac{(\vec{x}' - \vec{x})}{|\vec{x}' - \vec{x}|^3}$$

$$\delta_{\rm g} = b\delta_{\rm m} \qquad f \equiv \frac{a}{D_1}\frac{dD_1}{da}$$

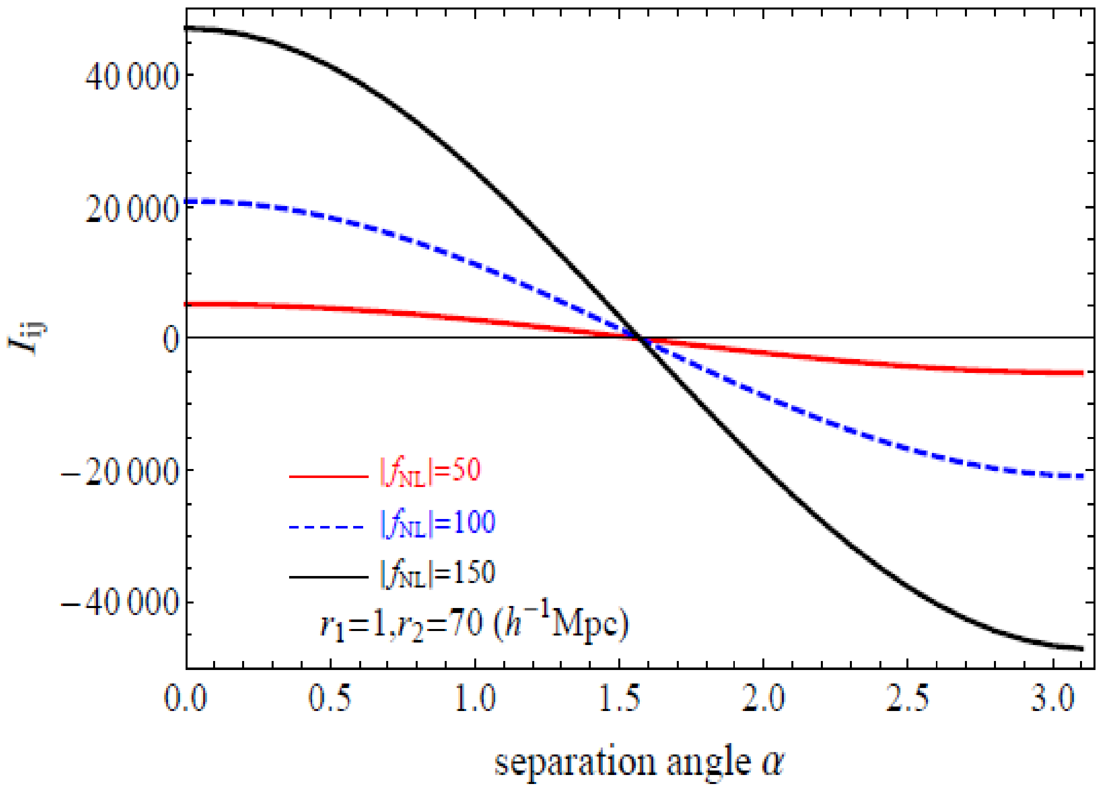
$$\vec{v}_{\rm g}(\vec{x}) = \frac{H_0 \beta}{4\pi} \int d^3\vec{x}'\,\delta_{\rm g}(\vec{x}', t)\frac{(\vec{x}' - \vec{x})}{|\vec{x}' - \vec{x}|^3}$$

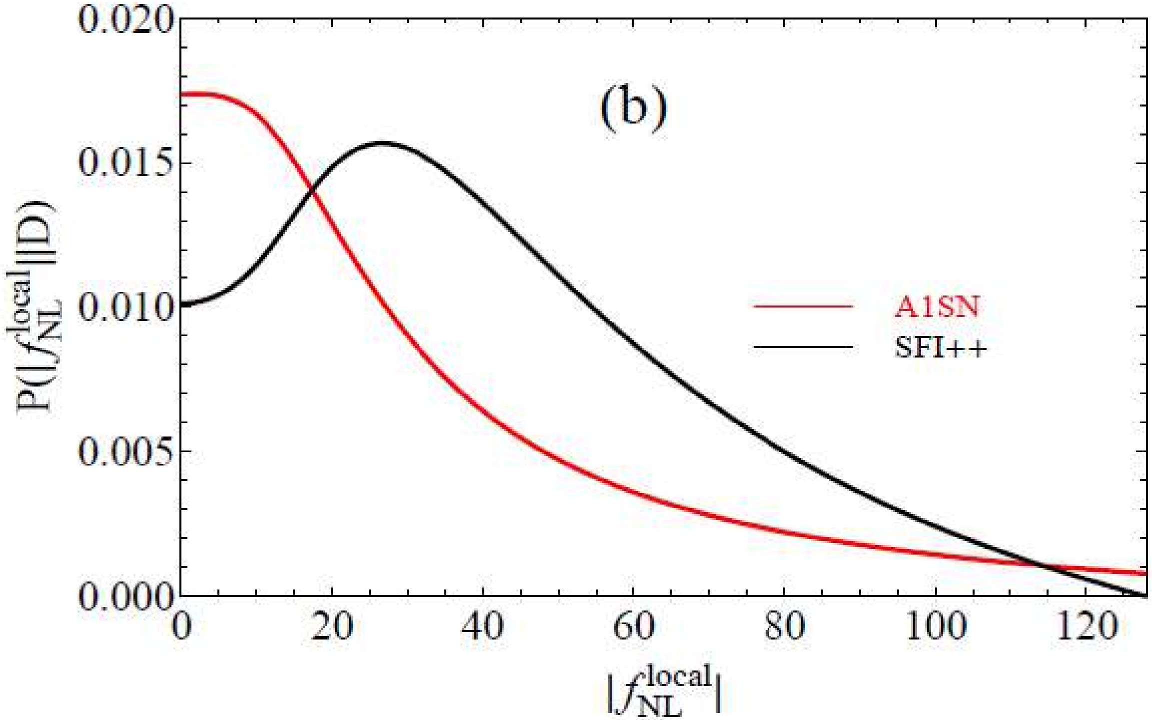


$$
\begin{aligned}
\mathbf{v}(\mathbf{r}) &= \frac{H_0\beta}{4\pi}\int d^3\mathbf{r}'\delta_g(\mathbf{r}')\frac{\mathbf{r}'-\mathbf{r}}{|\mathbf{r}'-\mathbf{r}|^3} \\
&- \frac{iH_0(f/b)}{(2\pi)^3}\int d^3\mathbf{k}(\Delta b(k))\delta_m(\mathbf{k})\frac{\mathbf{k}}{k^2}\exp(i\mathbf{k}\cdot\mathbf{r})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

Dalal et al. 2008:

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





Data set	Model	β value	$\left|f_{NL}^{local}\right|$ value	$-\log L_{min}$
A1SN	β- f_{NL}^{local}	$0.53^{+0.15}_{-0.04}$	0.0 ± 25.7	681.7
	β-only	$0.65^{+0.07}_{-0.06}$		681.7
SFI++	β- f_{NL}^{local}	$0.49^{+0.03}_{-0.05}$	26.6 ± 33.0	14159.1
	β-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):

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

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

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

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

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

(iv) *Planck* CMB (2013):

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

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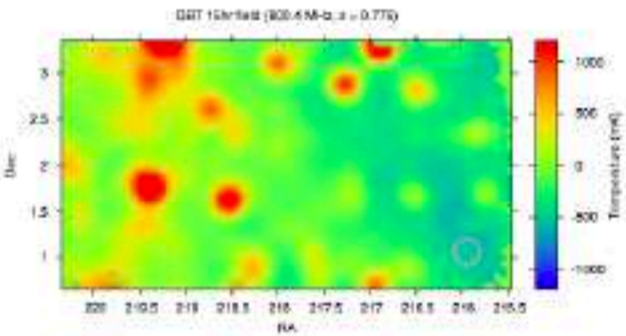
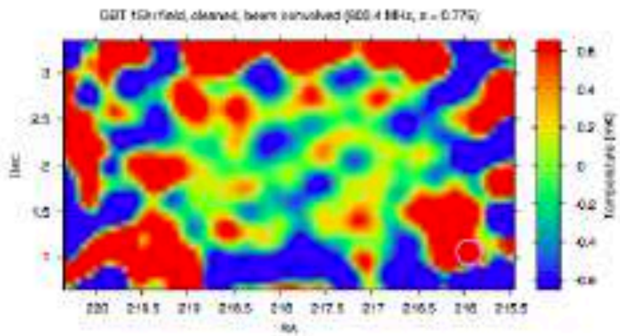
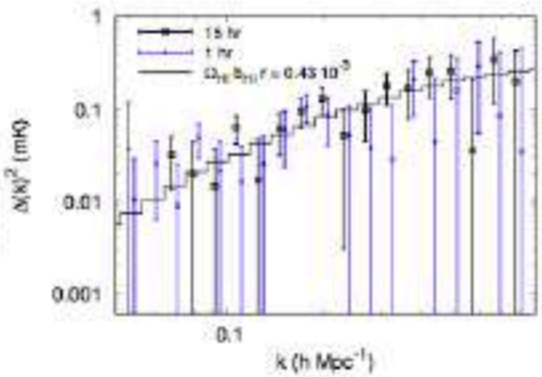
No time to mention foreground analysis, see other people's talk.

HI Intensity Mapping







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

Bias

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

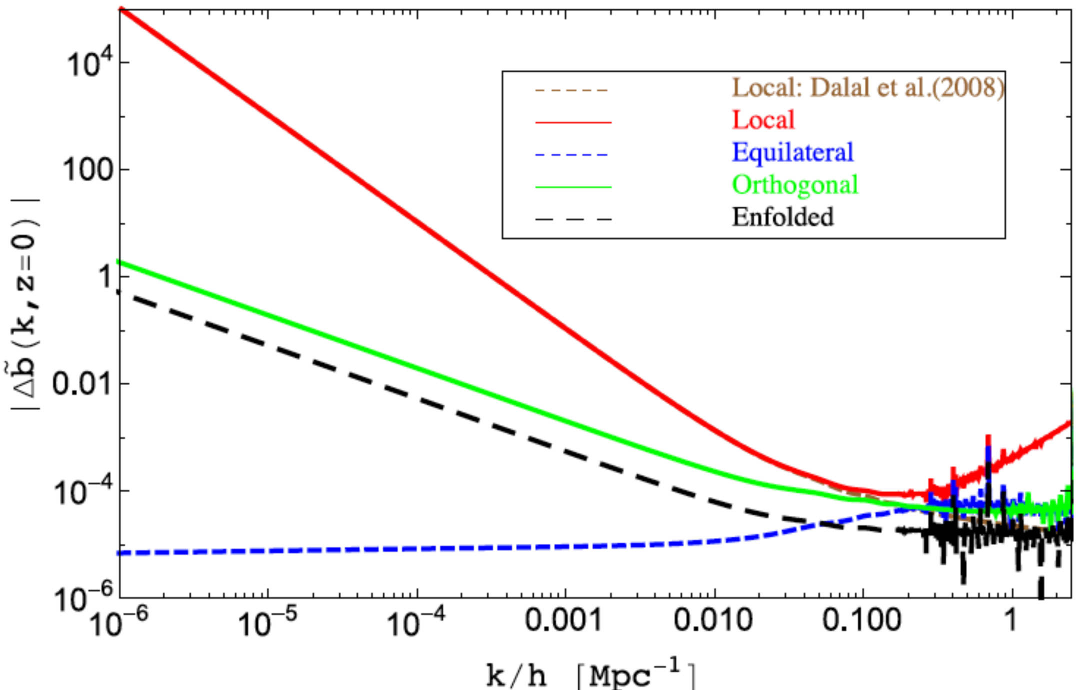
$b_{\mathrm{L}} + 1$

$$b_{\mathrm{L}} + 1 \qquad \sim f_{\mathrm{NL}}\, b_{\mathrm{L}}$$

S. Matarrese and L. Verde, 2008

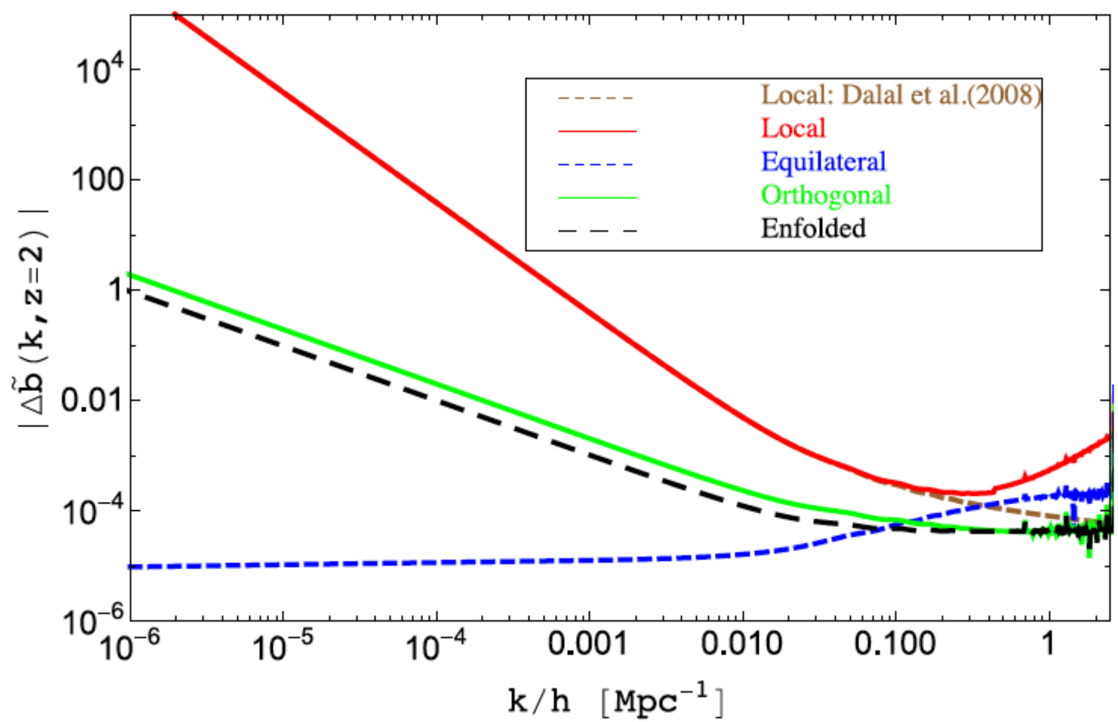
N. Dalal, et al., 2008

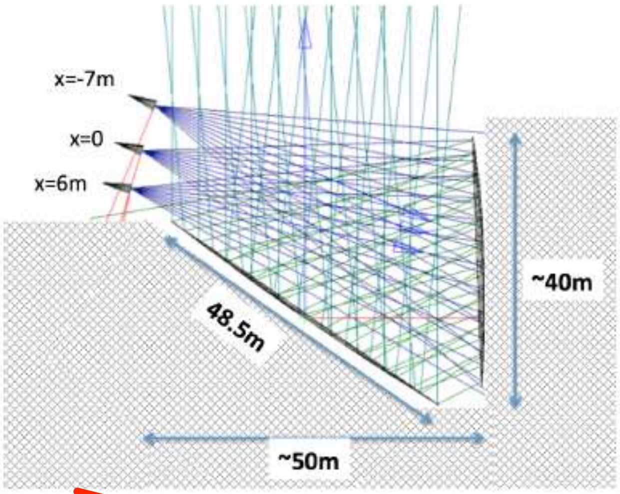
Y.-C. Li and YZM, 2017, ArXiv: 1701.00221



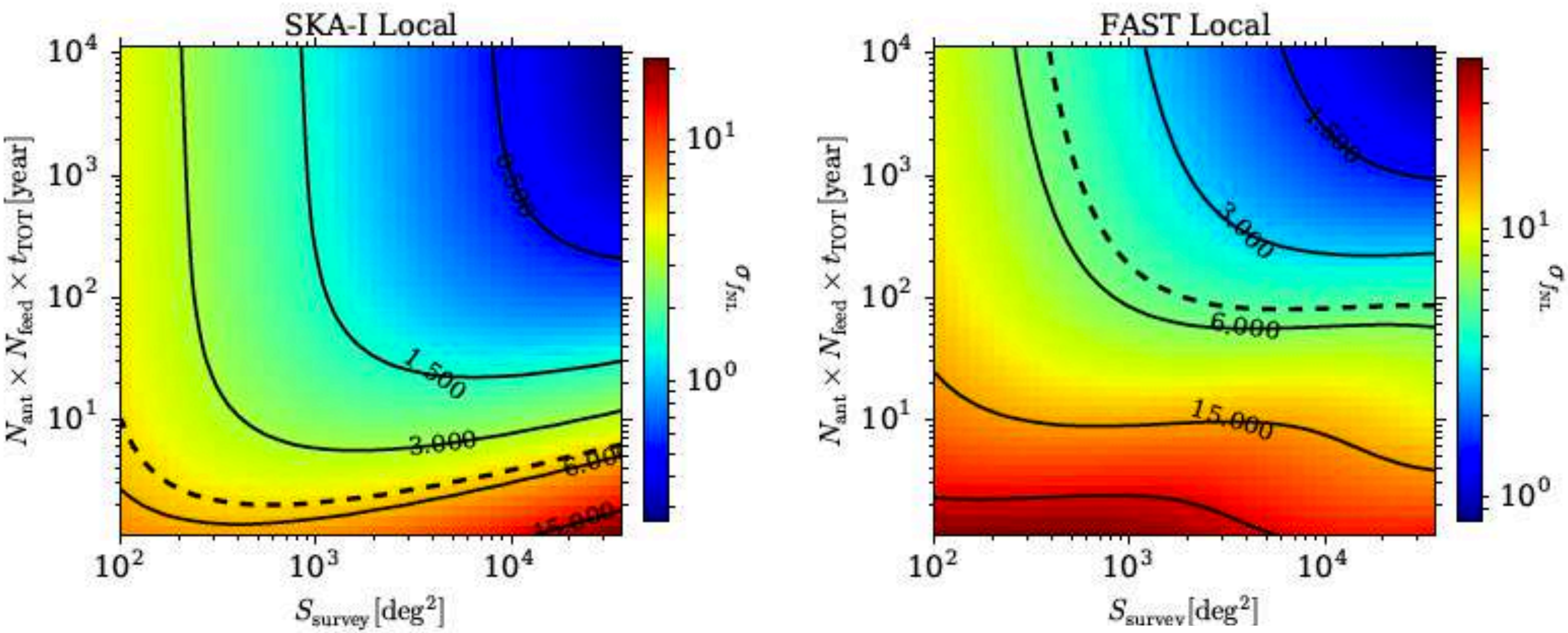
Yi-Chao Li and YZM, 2017, ArXiv: 1701.00221
C. Fedeli et al., 2011, MNRAS

$$\Delta b(\text{Local}) \sim k^{-2}$$
$$\Delta b(\text{Equilateral}) \sim \text{const}$$
$$\Delta b(\text{Enfolded}) \sim k^{-1}$$
$$\Delta b(\text{Orthogonal}) \sim k^{-1}.$$



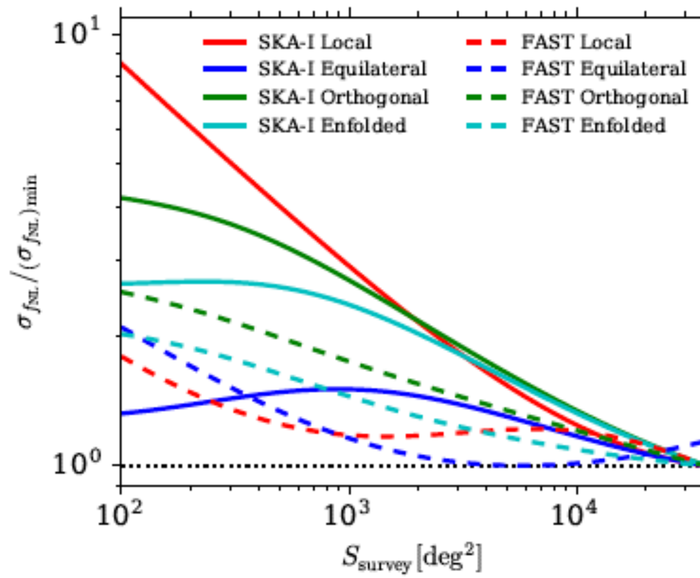


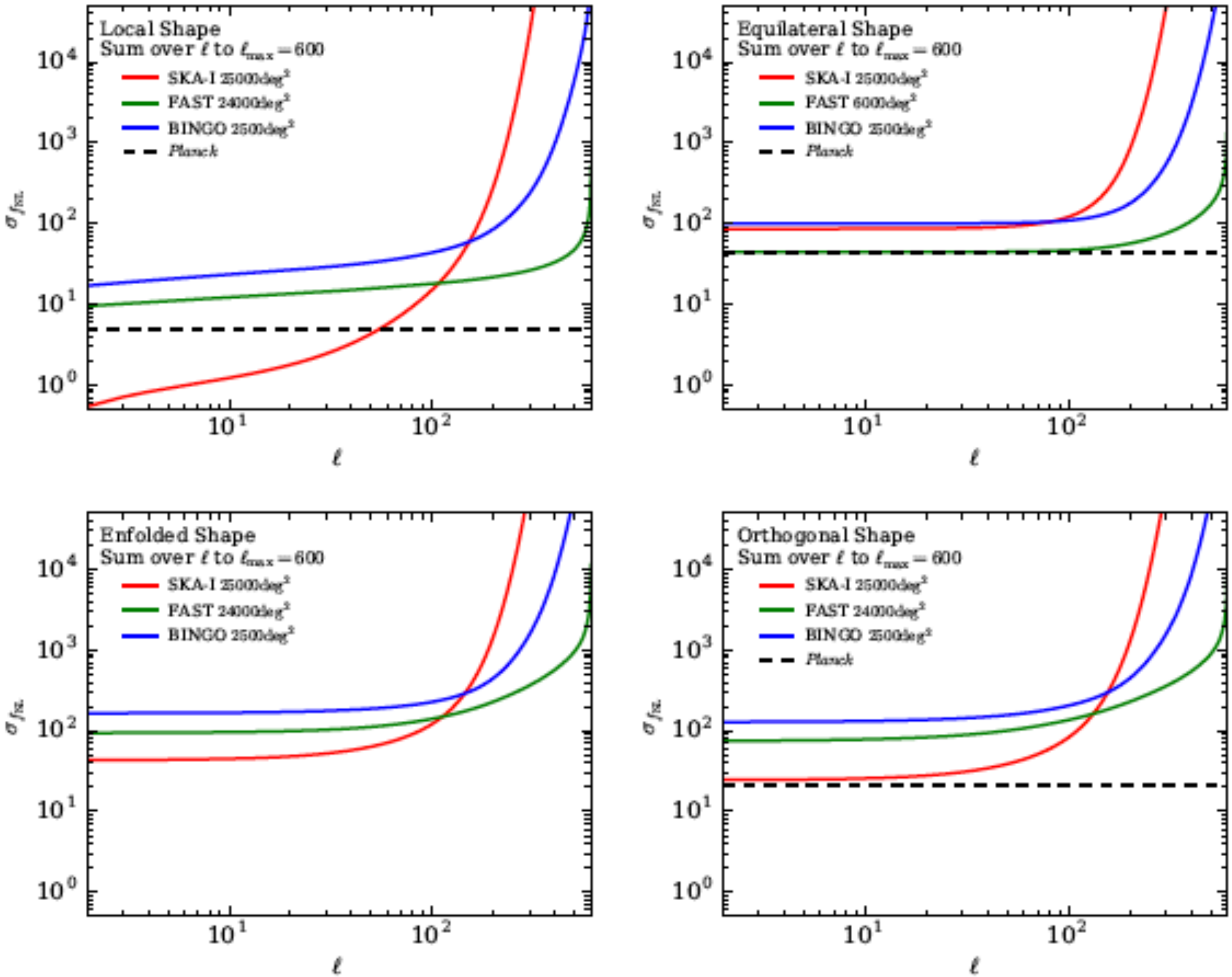
	FAST	SKA-I	BINGO
$\nu_{\rm min}$[MHz]	1050	350	960
$\nu_{\rm max}$[MHz]	1350	1050	1260
$\Delta\nu$[MHz]	10	10	10
$n_\nu(n_z)$	30	70	30
$D_{\rm dish}$[m]	300	15	25
$N_{\rm ant} \times N_{\rm feed}$	1×19	190×1	1×60
$t_{\rm TOT}$[yr]	1	1	1
$T_{\rm rec}$[K]	25	28	50
$S_{\rm survey}$[deg^2]	< 24000	< 25000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

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

† SKA-I with two-year observation; †† FAST with two-year observation; ‡ 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

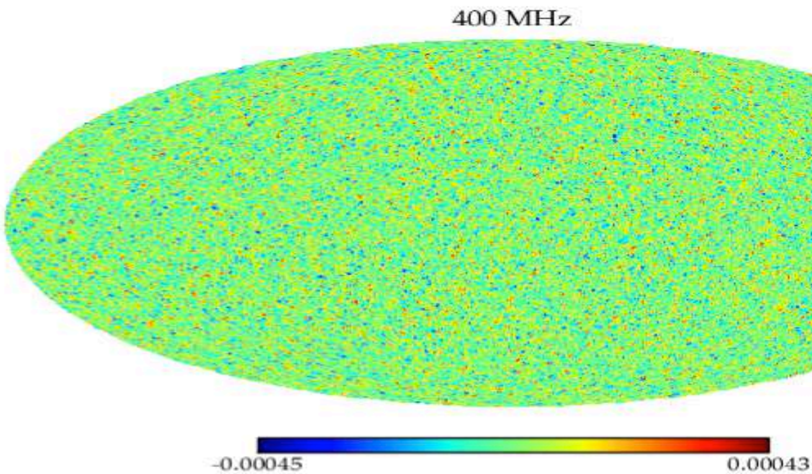
(1) Cosmological parameters

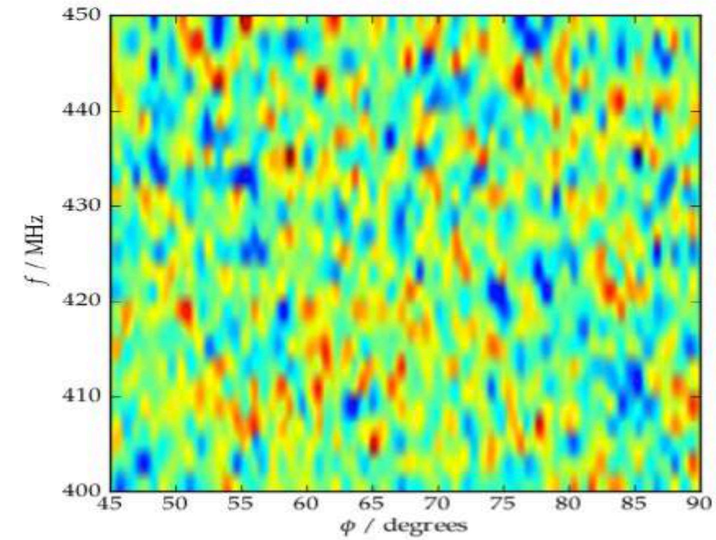
(2) Primordial non-Gaussianity

- Foreground cleaning
- 1/f noise

Hydrogen intensity signal

Amplitude 1 mK, lots of spectral structure





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

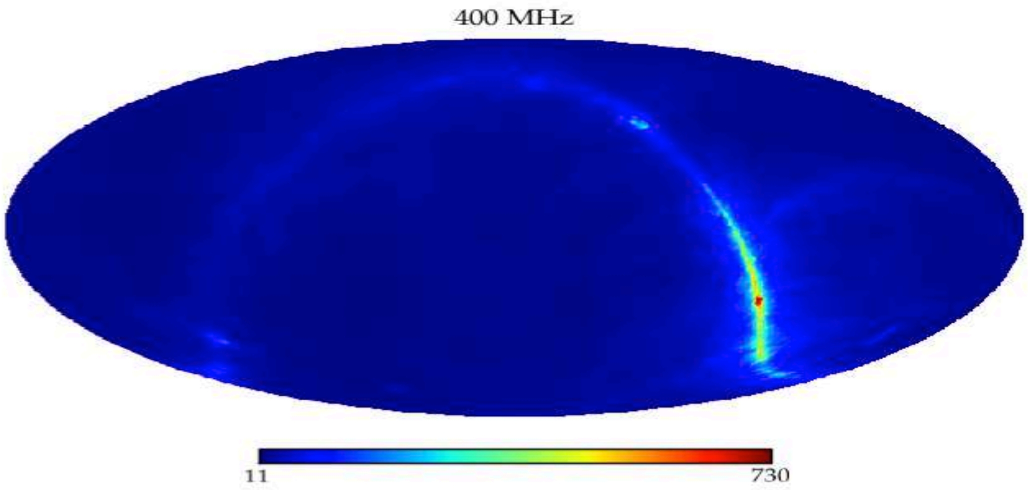
left - over full sky at 400 MHz,

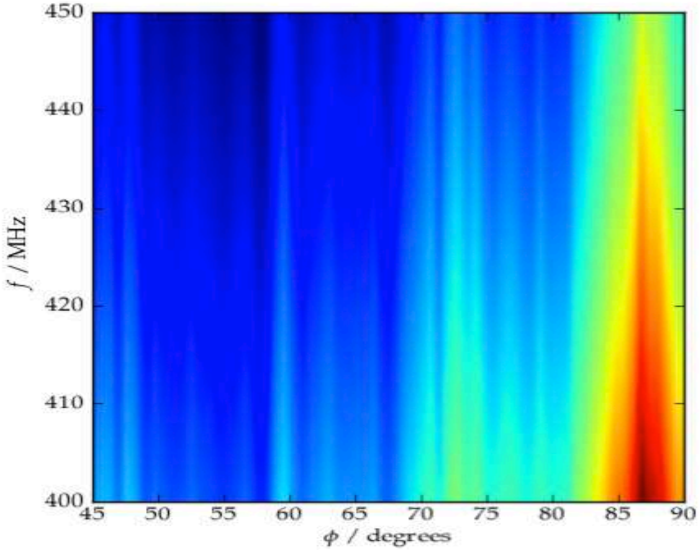
right - over 50 MHz at 1 declination

Main goal is to measure BAO structure in *PHI(k)*, less concerned about amplitude of *PHI(k)*.

The “other” signal: synchrotron (primarily)

Amplitude 700 K, spectrally smooth





Modeled Galaxy signal, ΔT ~ 700 K!
left - over full sky at 400 MHz,
right - over 50 MHz at 1 declination - spectrally smooth

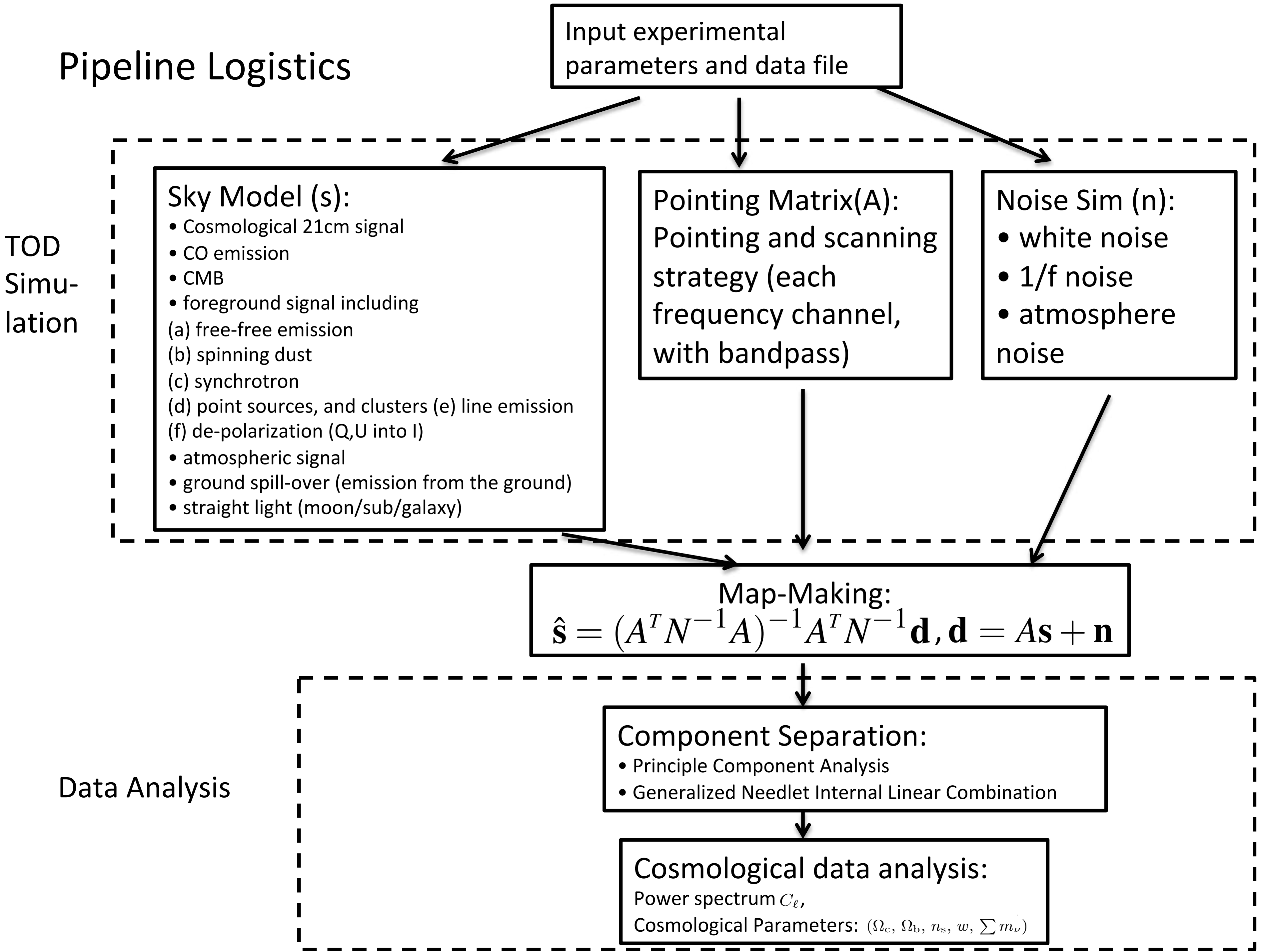
Noise:

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 ....

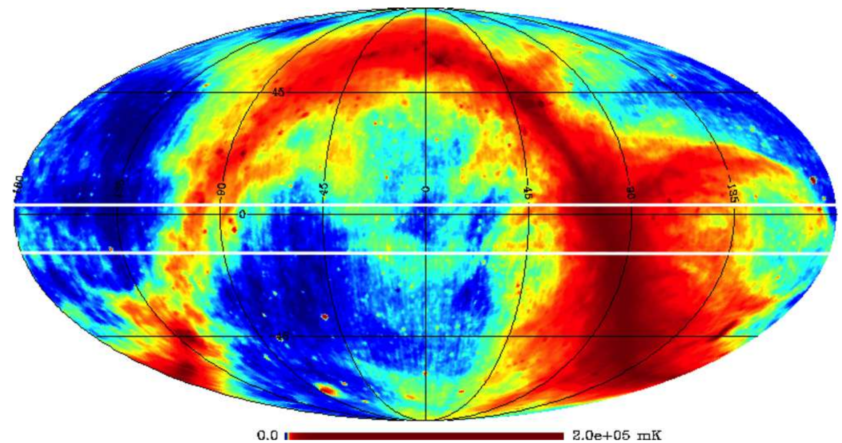
Without those details, radio cosmology is an unrealistic dream.



Pipeline Logistics
Input experimental parameters and data file
TOD Simu-lation
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:
$\hat{\mathbf{s}} = (A^T N^{-1} A)^{-1} A^T N^{-1} \mathbf{d}, \mathbf{d} = A\mathbf{s} + \mathbf{n}$
Data Analysis
Component Separation:
• Principle Component Analysis
• Generalized Needlet Internal Linear Combination
Cosmological data analysis:
Power spectrum C_ℓ,
Cosmological Parameters: $(\Omega_c, \Omega_b, n_s, w, \sum m_\nu)$

Principal Component Analysis

Survey parameters	
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 Ω_{sur} (deg^2)	3000
Observation time t_{obs} (yr)	1
System temperature T_{sys} (K)	50
Sampling rate (Hz)	0.1



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

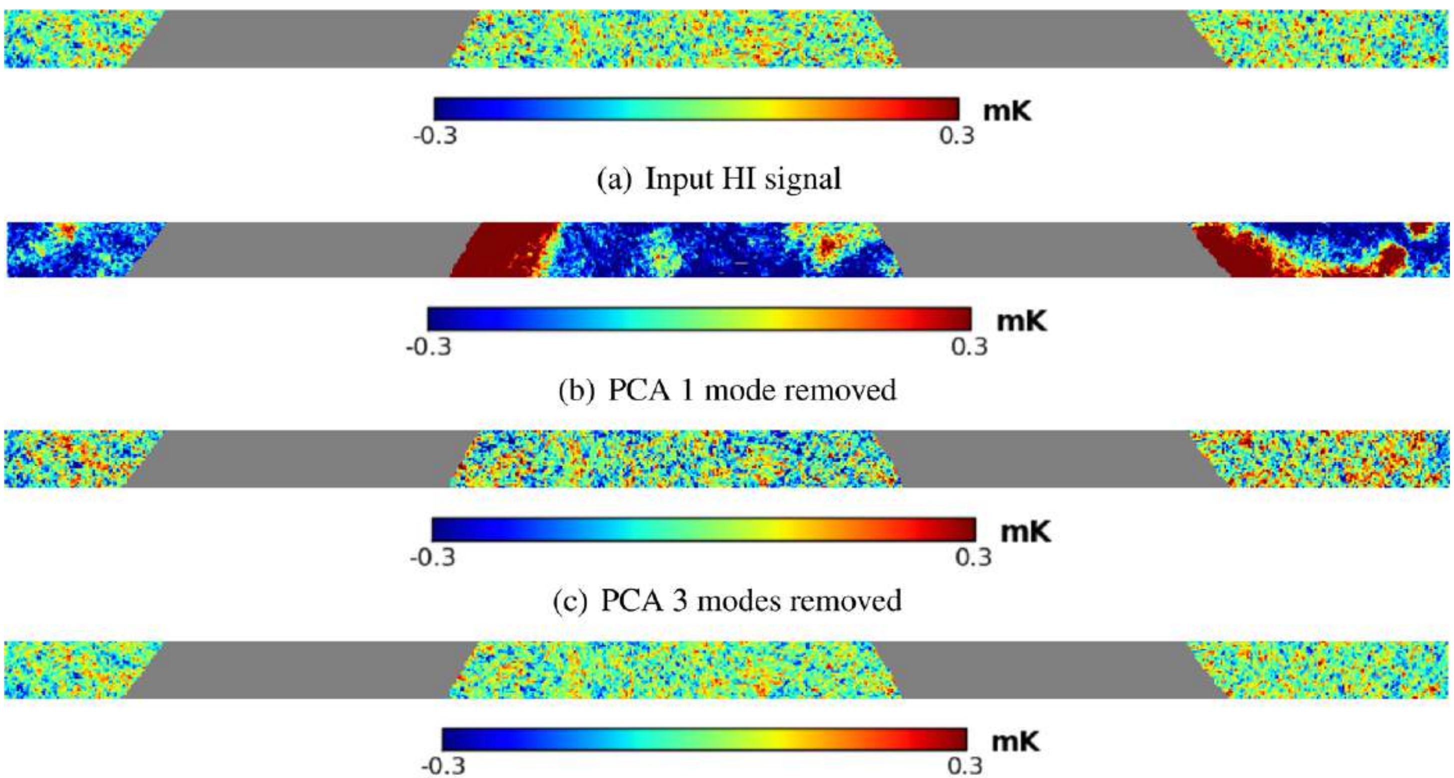
$$\hat{\boldsymbol{s}} = (A^{\mathrm{T}} N^{-1} A)^{-1} A^{\mathrm{T}} N^{-1} \boldsymbol{d}$$

M.-A.Bigot-Sazy, C. Dickinson, R. Battye, I. Browne, YZM et al., 2015, MNRAS

Component separation: PCA

$$C_{ij} = \frac{1}{N_p} SS^T = \frac{1}{N_p} \sum_{p=1}^{N_p} T(\nu_i, \hat{n}_p) T(\nu_j, \hat{n}_p) \qquad R_{jk} = \frac{C_{jk}}{C_{jj}^{1/2} C_{kk}^{1/2}}$$

$$P^T R P = \Lambda \equiv \mathrm{diag}\{\lambda_1, \ldots, \lambda_{N_f}\} \qquad \phi = P_c^T S \qquad S_c = P_c \phi \qquad S_{\mathrm{HI}} = S - S_c$$

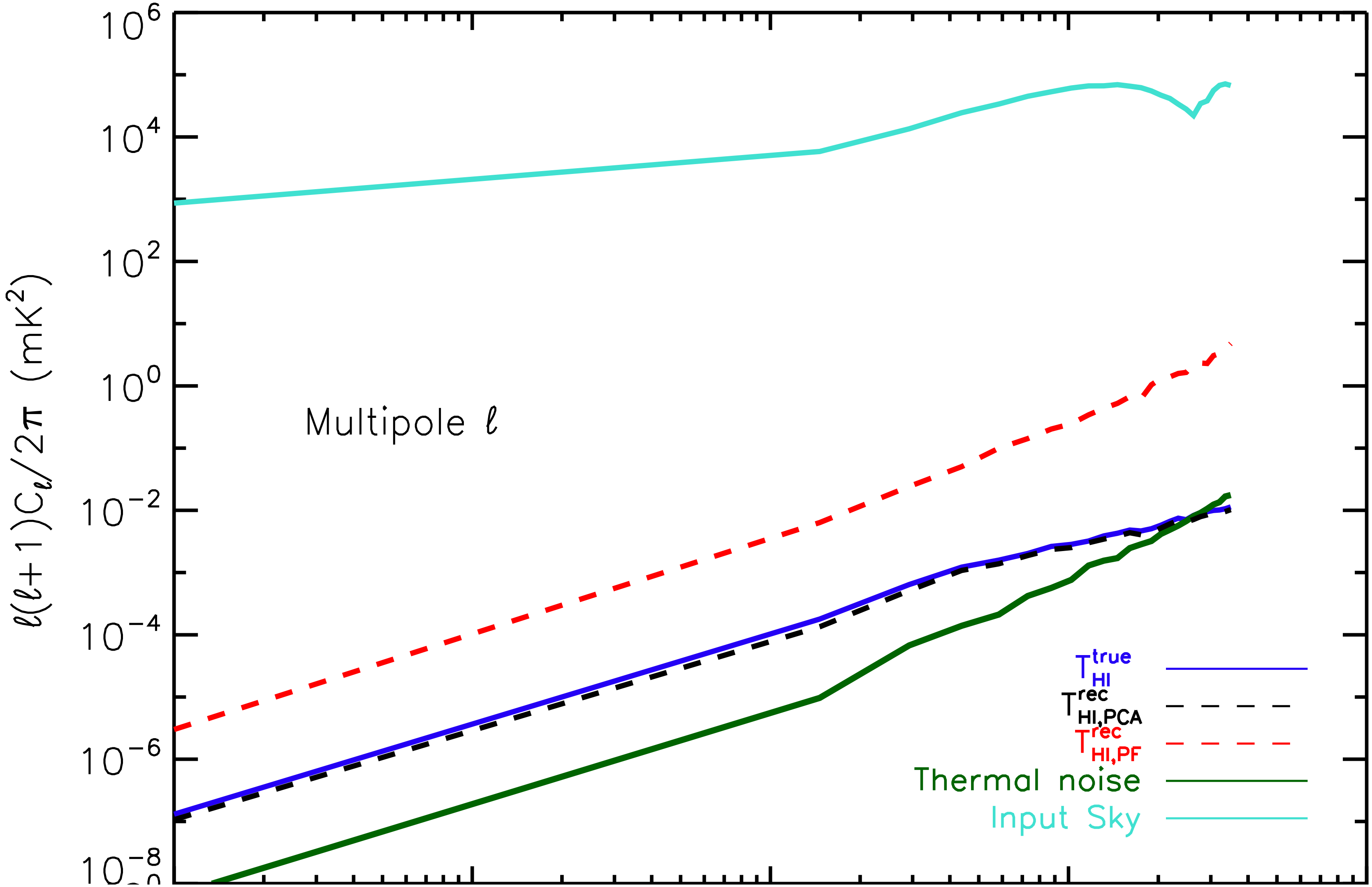


(a) Input HI signal

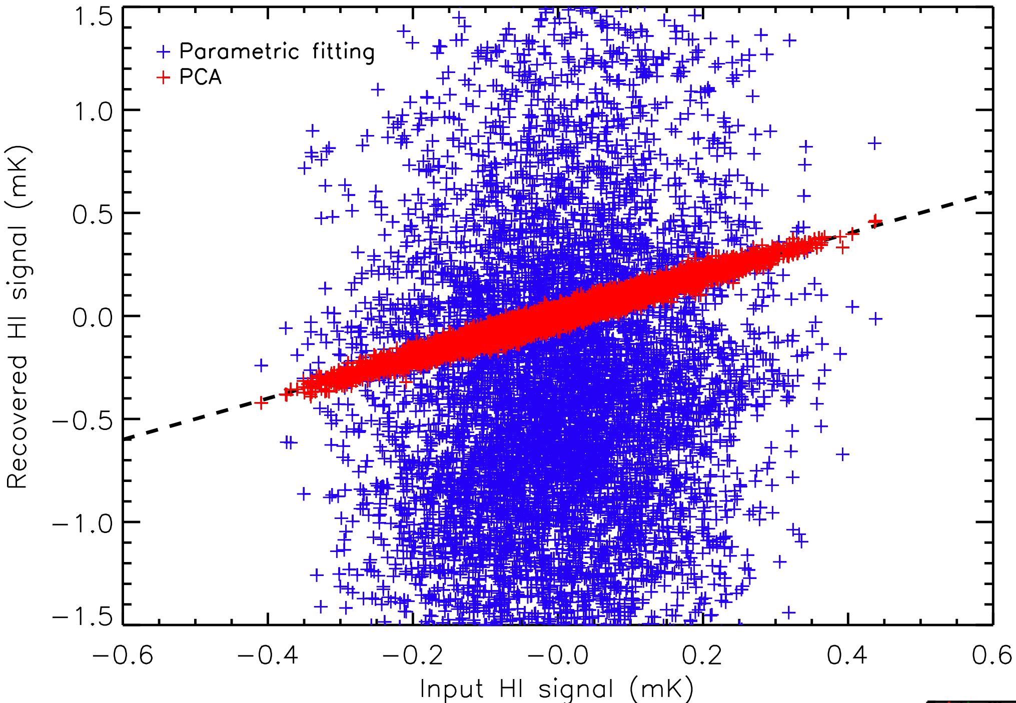
(b) PCA 1 mode removed

(c) PCA 3 modes removed

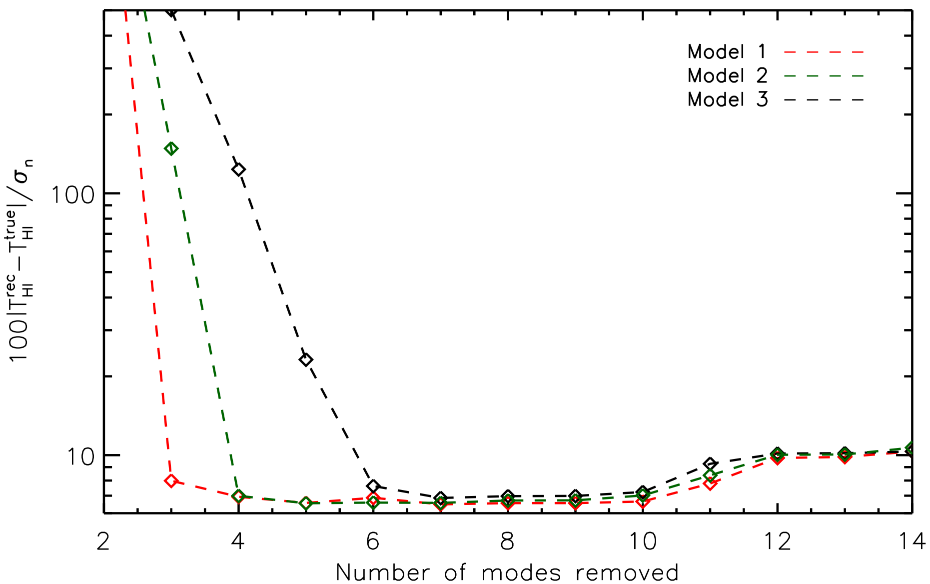
(d) PCA 7 modes removed



10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$\ell(\ell+1)C_\ell/2\pi$ (mK^2)
Multipole ℓ
T_{HI}^{true}
$T_{HI,PCA}^{rec}$
$T_{HI,PF}^{rec}$
Thermal noise
Input Sky



Parametric fitting
PCA
Recovered HI signal (mK)
Input HI signal (mK)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−0.6
−0.4
−0.2
−0.0
0.2
0.4
0.6



Model 1
Model 2
Model 3
$100|T_{HI}^{rec}-T_{HI}^{true}|/\sigma_n$
Number of modes removed
100
10
2
4
6
8
10
12
14

- 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

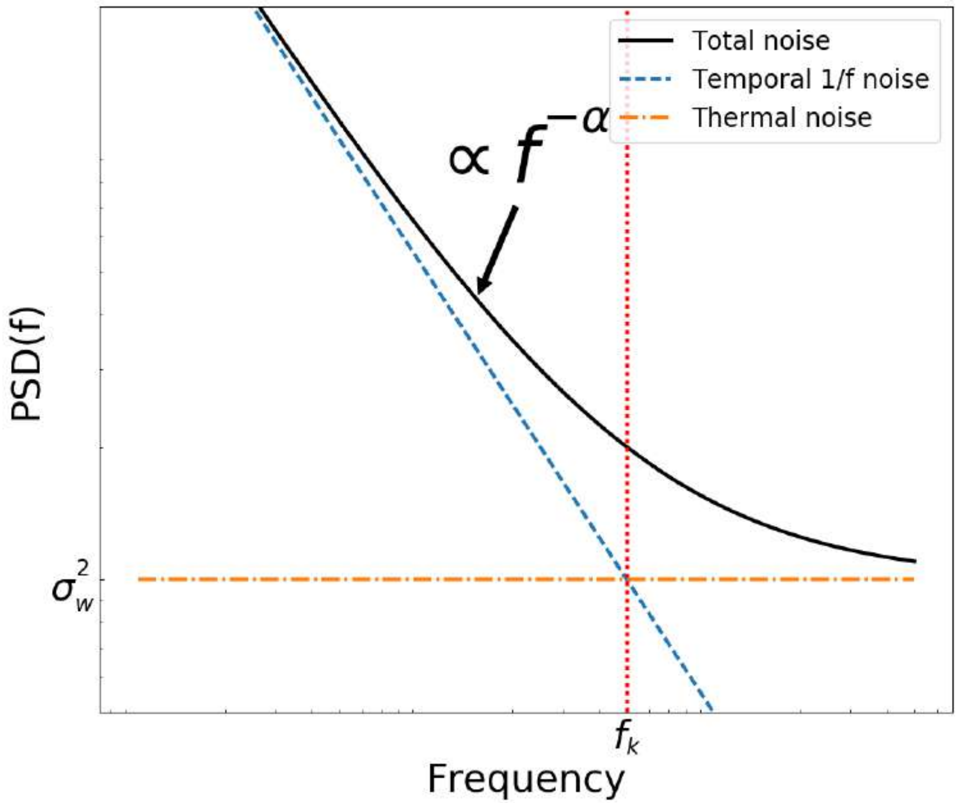
$$\mathrm{PSD}(f,\omega) = \frac{T_{\mathrm{sys}}^2}{\delta\nu}\left[1 + C(\beta, N_\nu)\left(\frac{f_k}{f}\right)^{\alpha}\left(\frac{1}{\omega\Delta\nu}\right)^{\frac{1-\beta}{\beta}}\right]$$

ω is the inverse spectroscopic frequency wavenumber

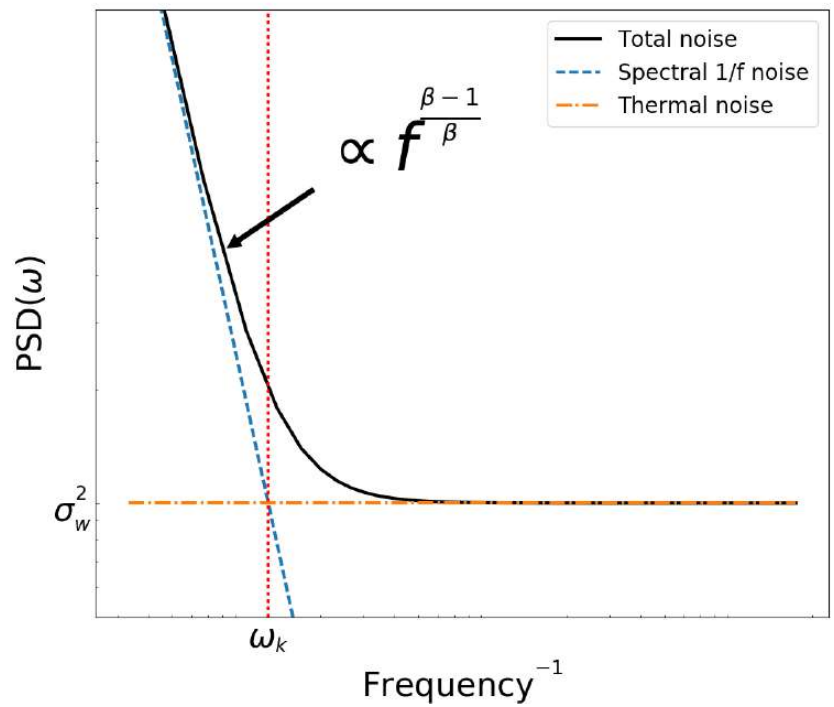
SKA forecast:

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

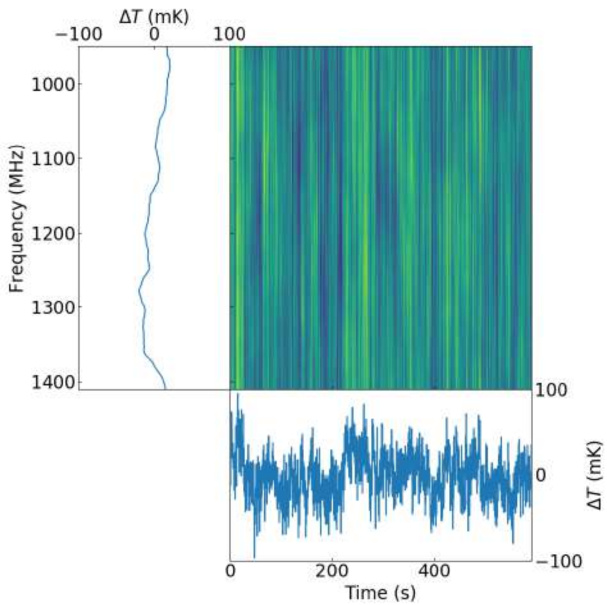
S. Harper, …, YZM, … 2018, MNRAS



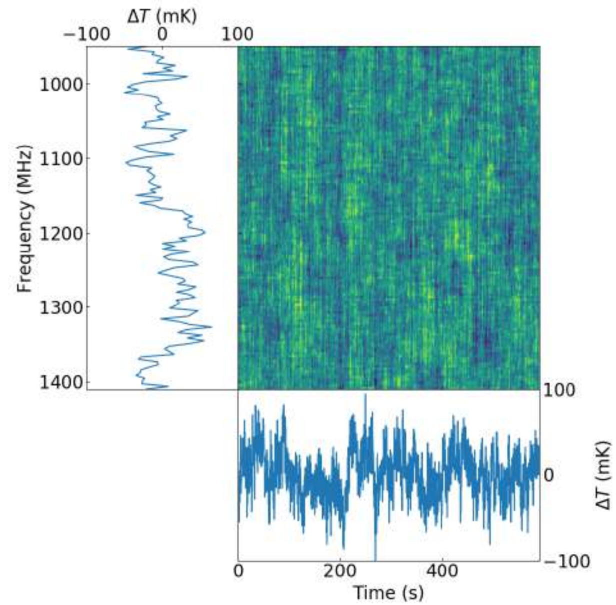
Total noise
Temporal 1/f noise
Thermal noise
$\propto f^{-\alpha}$
PSD(f)
σ_w^2
f_k
Frequency



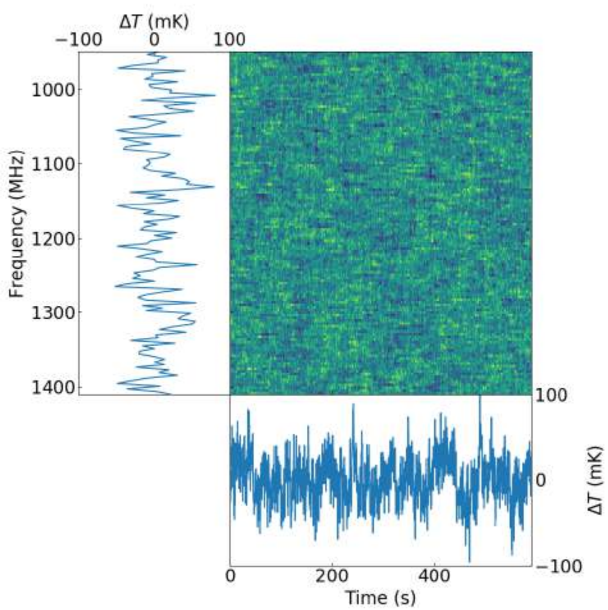
Total noise
Spectral 1/f noise
Thermal noise
$\propto f^{\frac{\beta-1}{\beta}}$
PSD(ω)
σ_w^2
ω_k
Frequency^{-1}



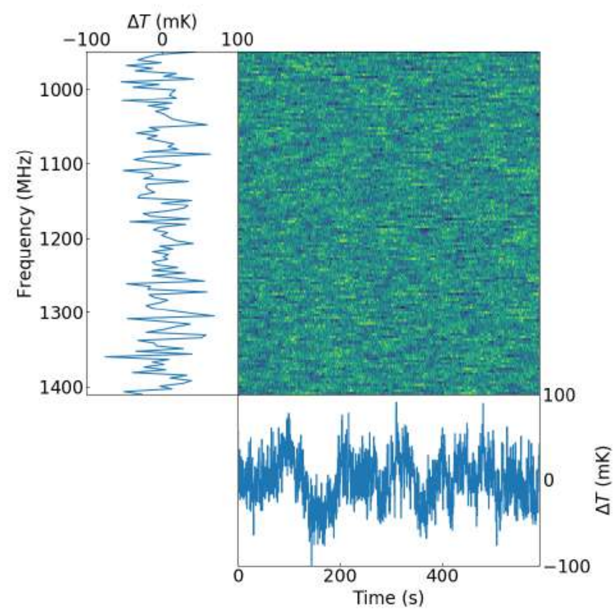
(a) $\beta = 0.25$, $\alpha = 1$, $f_\mathrm{k} = 1\,\mathrm{Hz}$



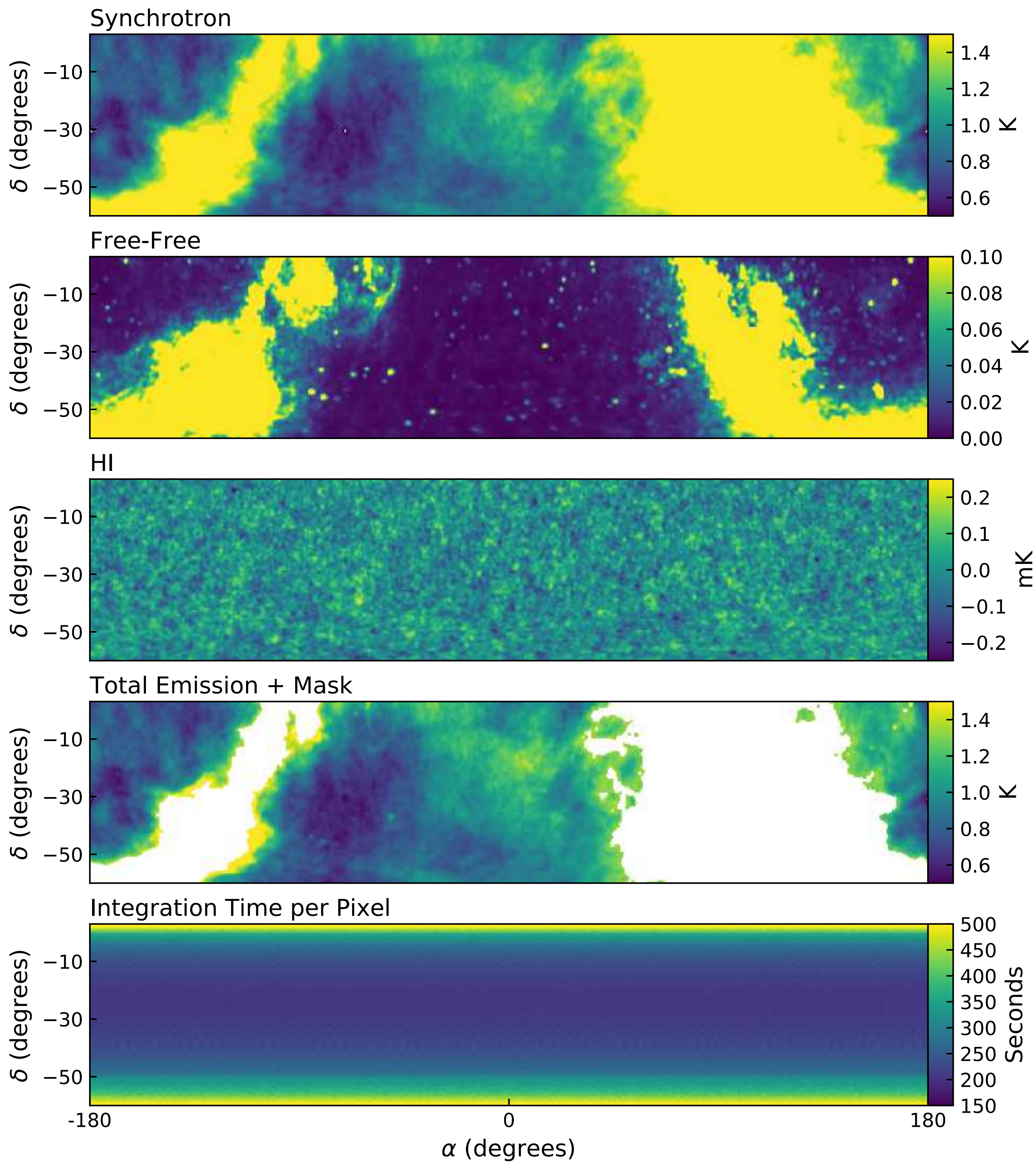
(b) $\beta = 0.5$, $\alpha = 1$, $f_\mathrm{k} = 1\,\mathrm{Hz}$



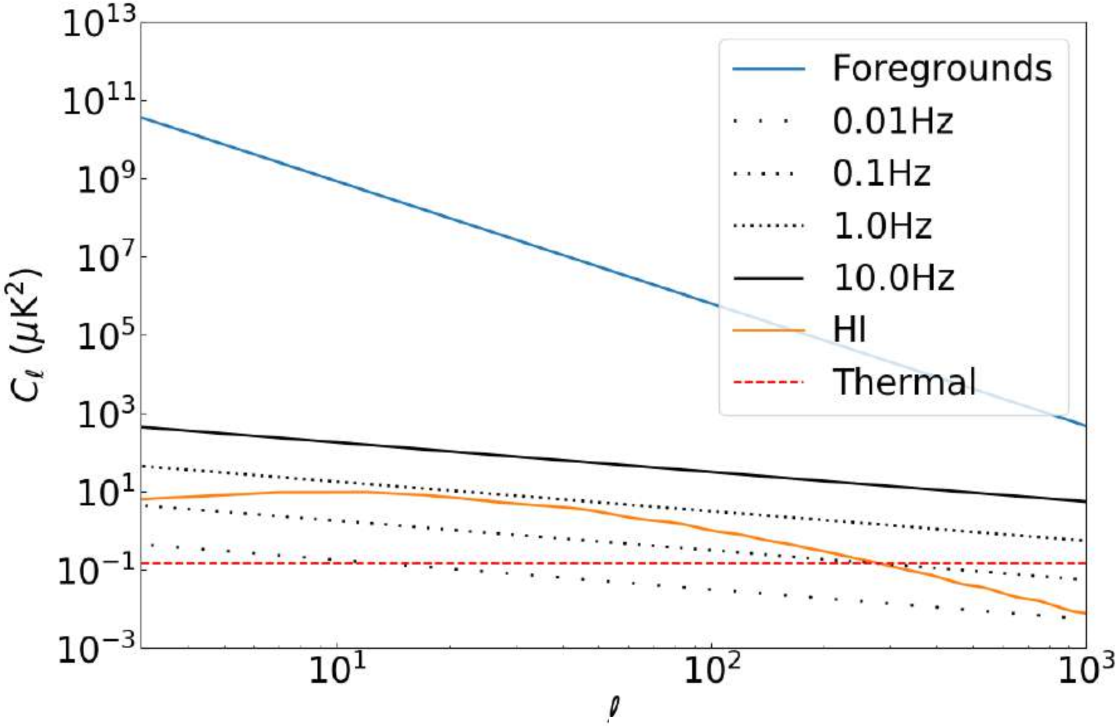
(c) $\beta = 0.75$, $\alpha = 1$, $f_\mathrm{k} = 1\,\mathrm{Hz}$



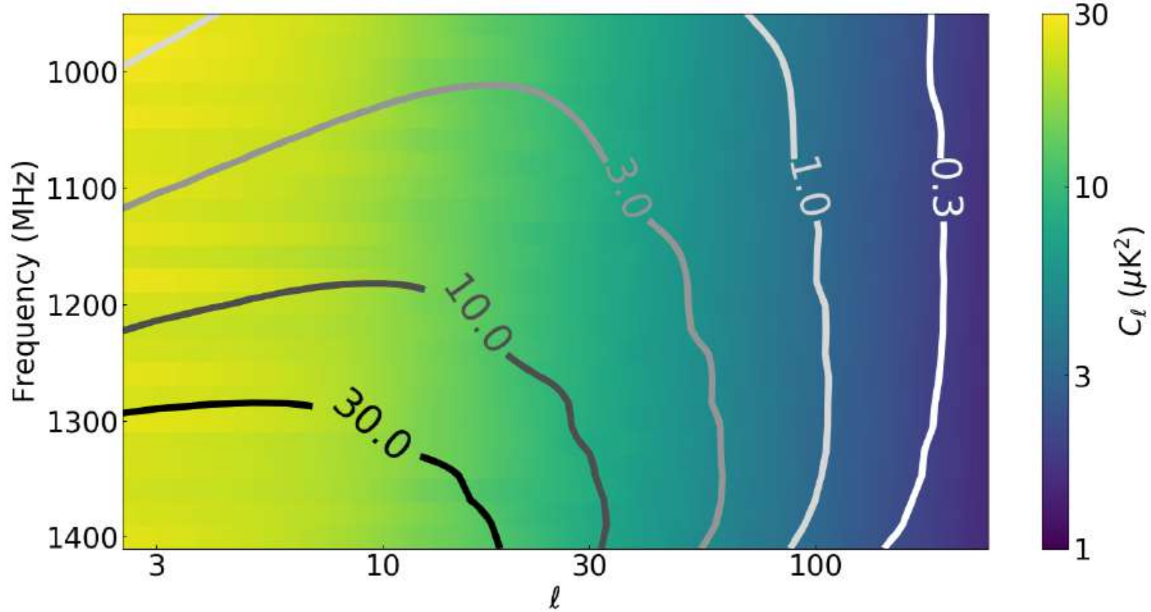
(d) $\beta = 1.0$, $\alpha = 1$, $f_\mathrm{k} = 1\,\mathrm{Hz}$



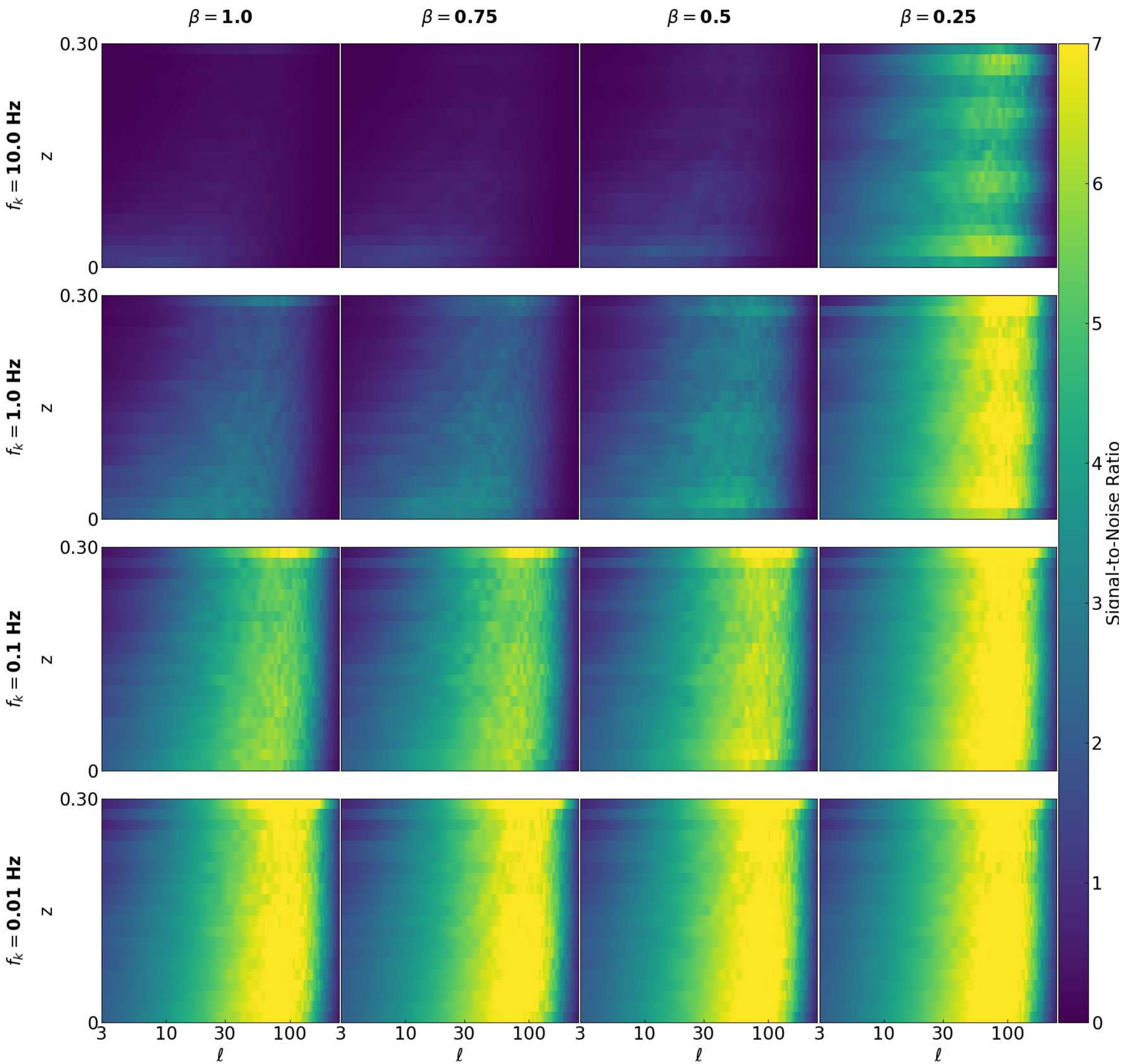
Synchrotron
Free-Free
HI
Total Emission + Mask
Integration Time per Pixel
δ (degrees)
−10
−30
−50
K
1.4
1.2
1.0
0.8
0.6
0.10
0.08
0.06
0.04
0.02
0.00
mK
0.2
0.1
0.0
−0.1
−0.2
Seconds
500
450
400
350
300
250
200
150
-180
0
180
α (degrees)



Foregrounds
0.01Hz
0.1Hz
1.0Hz
10.0Hz
HI
Thermal
C_ℓ (μK^2)
ℓ

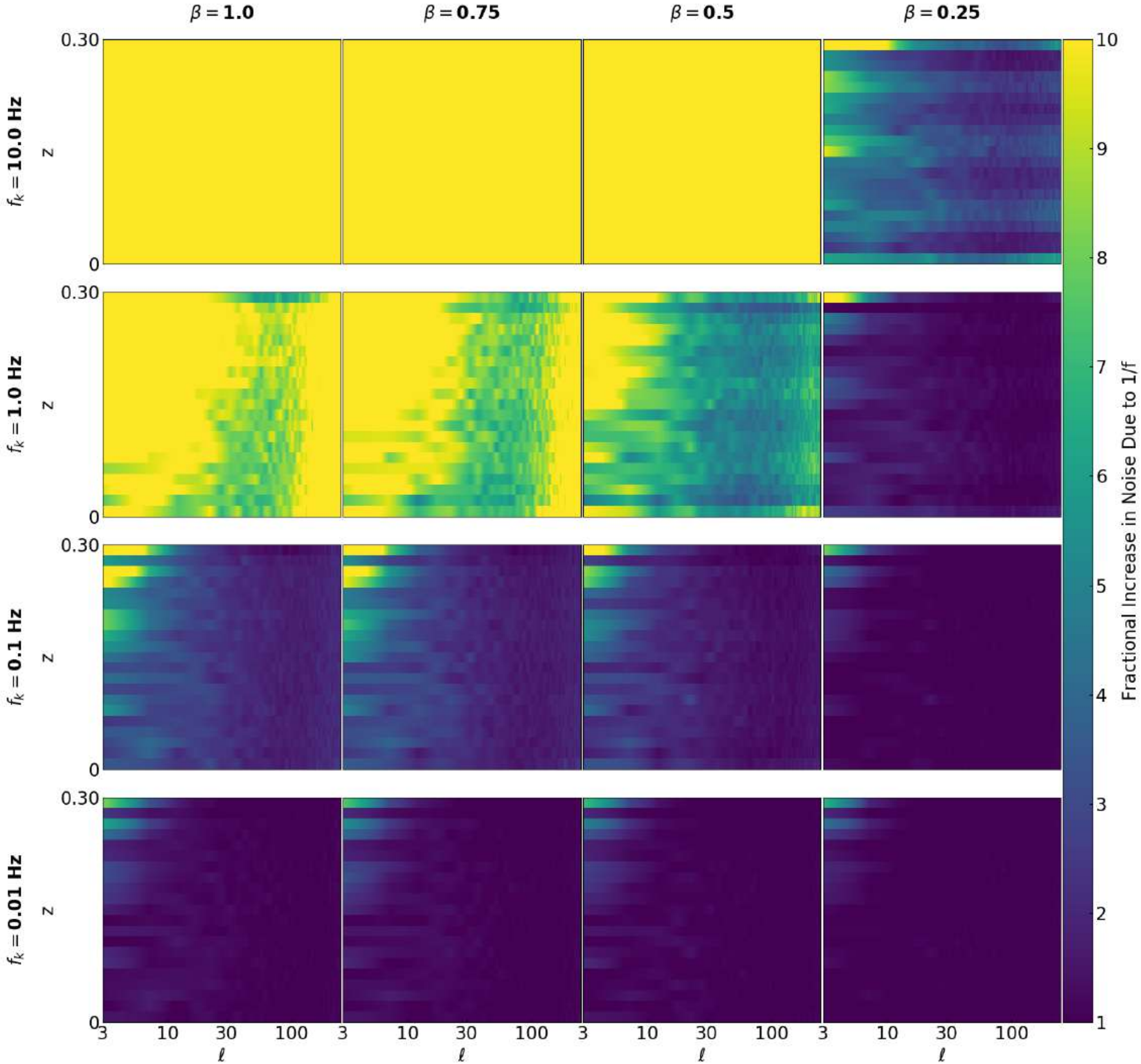


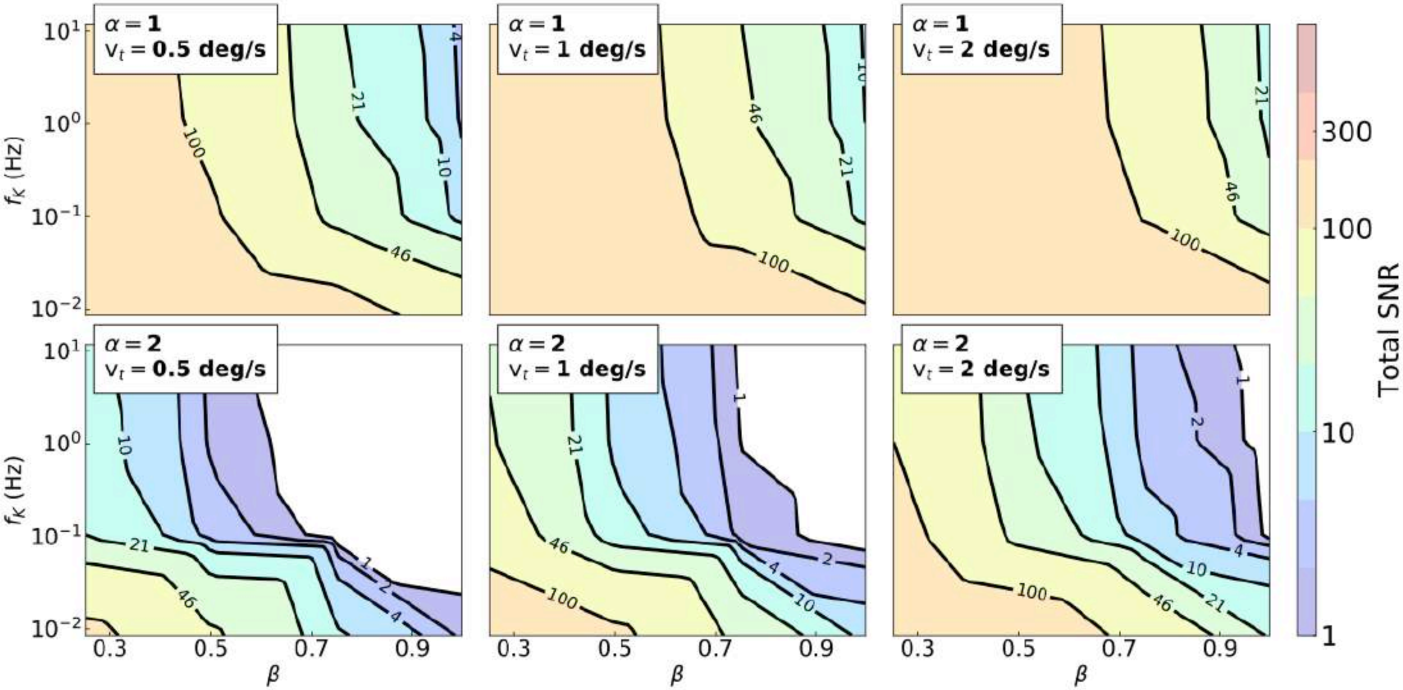
Frequency (MHz)
ℓ
C_ℓ (μK^2)
30.0
10.0
3.0
1.0
0.3



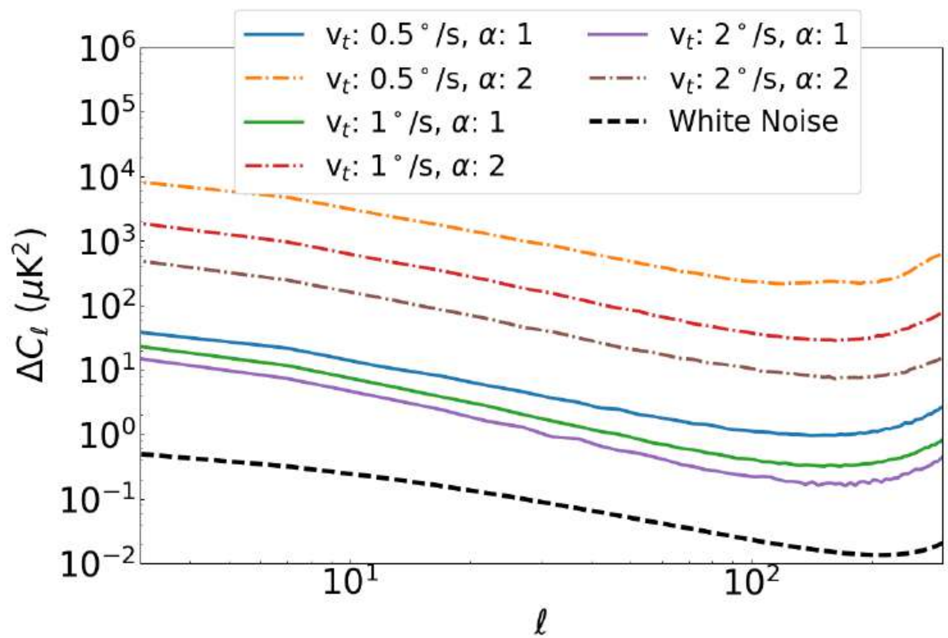
$\beta = \mathbf{1.0}$
$\beta = \mathbf{0.75}$
$\beta = \mathbf{0.5}$
$\beta = \mathbf{0.25}$
$f_k = \mathbf{10.0\ Hz}$
$f_k = \mathbf{1.0\ Hz}$
$f_k = \mathbf{0.1\ Hz}$
$f_k = \mathbf{0.01\ Hz}$
z
0.30
0
3
10
30
100
ℓ
Signal-to-Noise Ratio
0
1
2
3
4
5
6
7

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



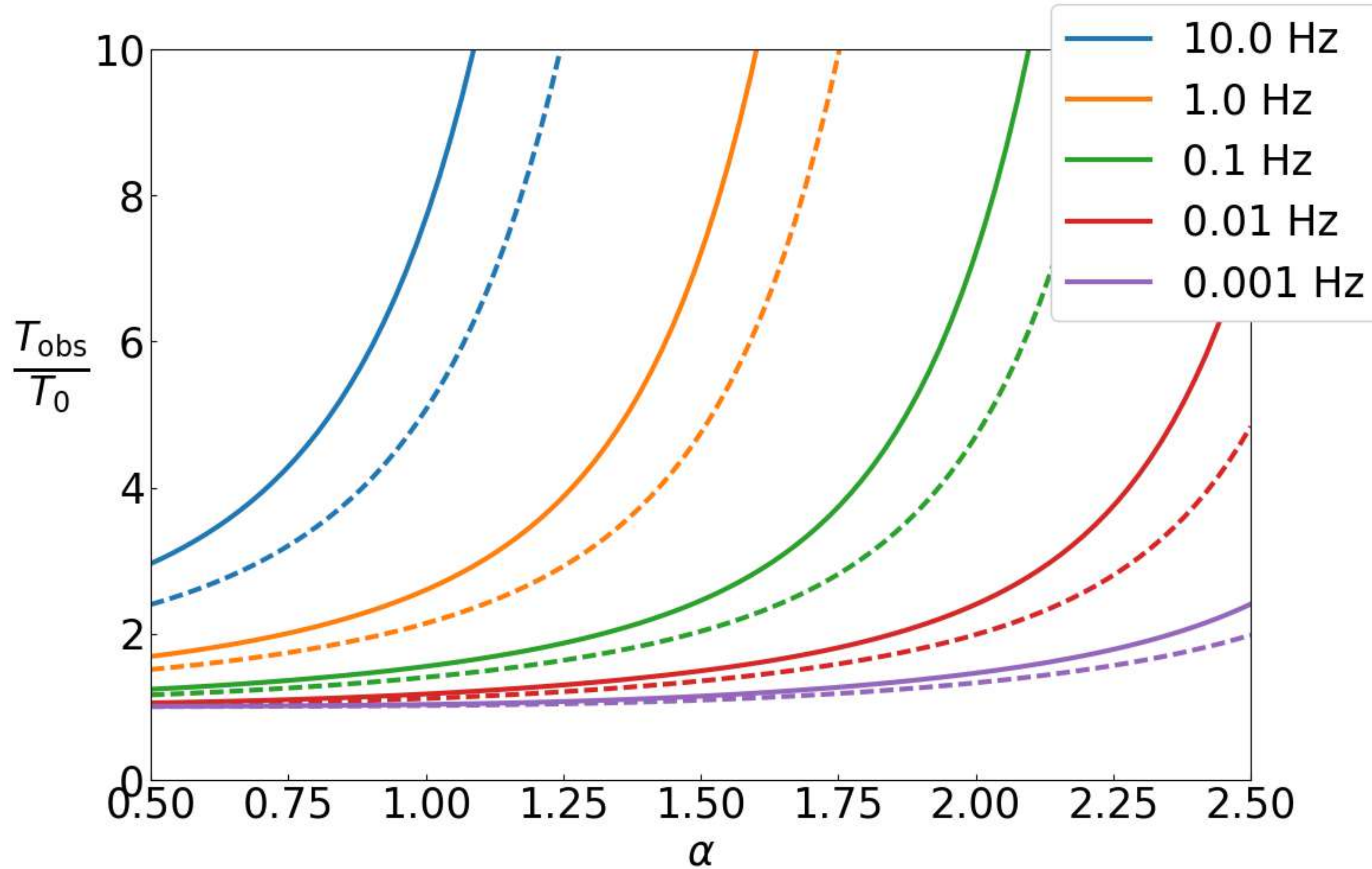


α = 1
v_t = 0.5 deg/s
α = 1
v_t = 1 deg/s
α = 1
v_t = 2 deg/s
α = 2
v_t = 0.5 deg/s
α = 2
v_t = 1 deg/s
α = 2
v_t = 2 deg/s
f_K (Hz)
β
Total SNR

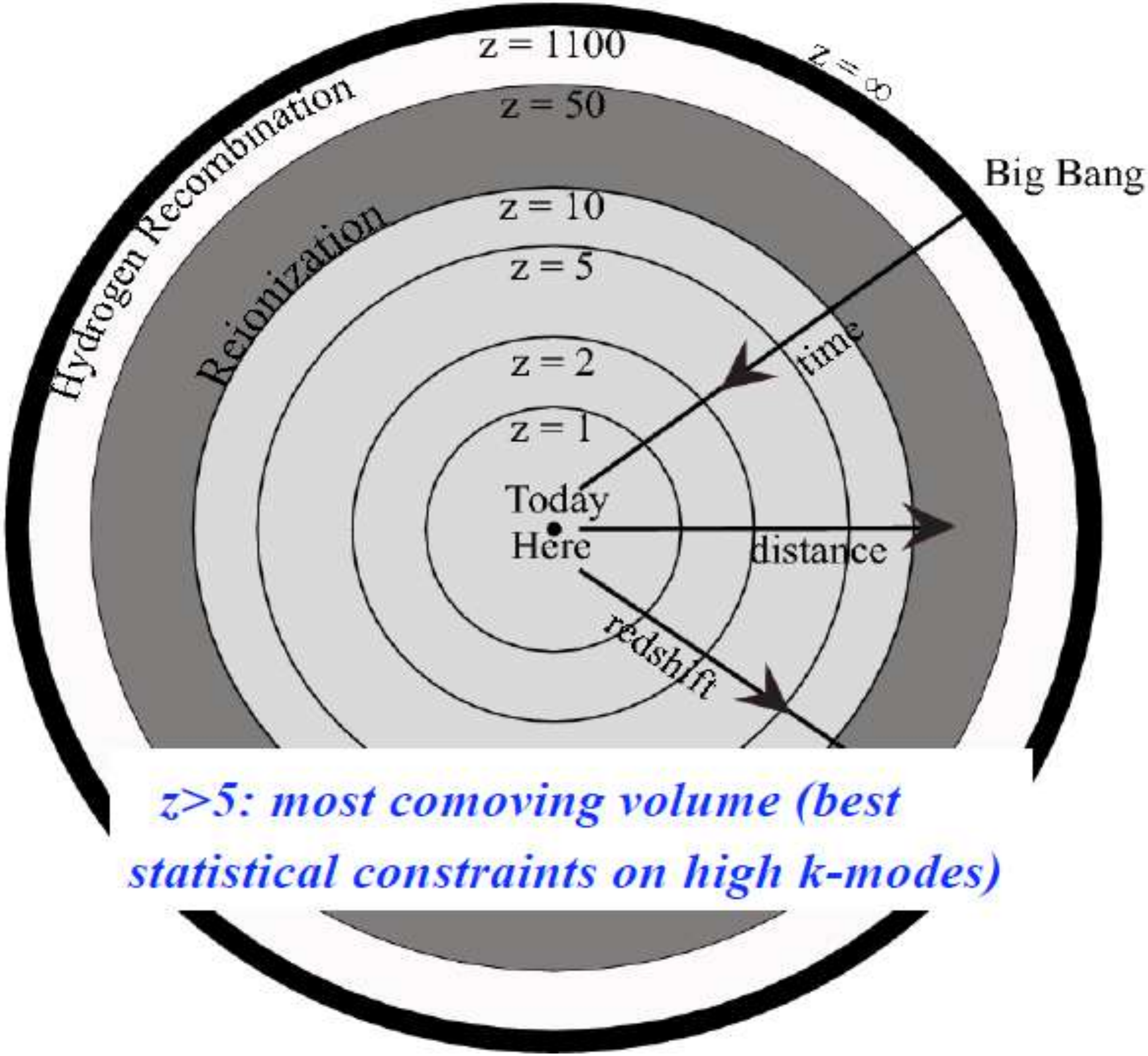


v_t: 0.5°/s, α: 1
v_t: 0.5°/s, α: 2
v_t: 1°/s, α: 1
v_t: 1°/s, α: 2
v_t: 2°/s, α: 1
v_t: 2°/s, α: 2
White Noise
ΔC_ℓ (μK²)
ℓ

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



The Visible Universe



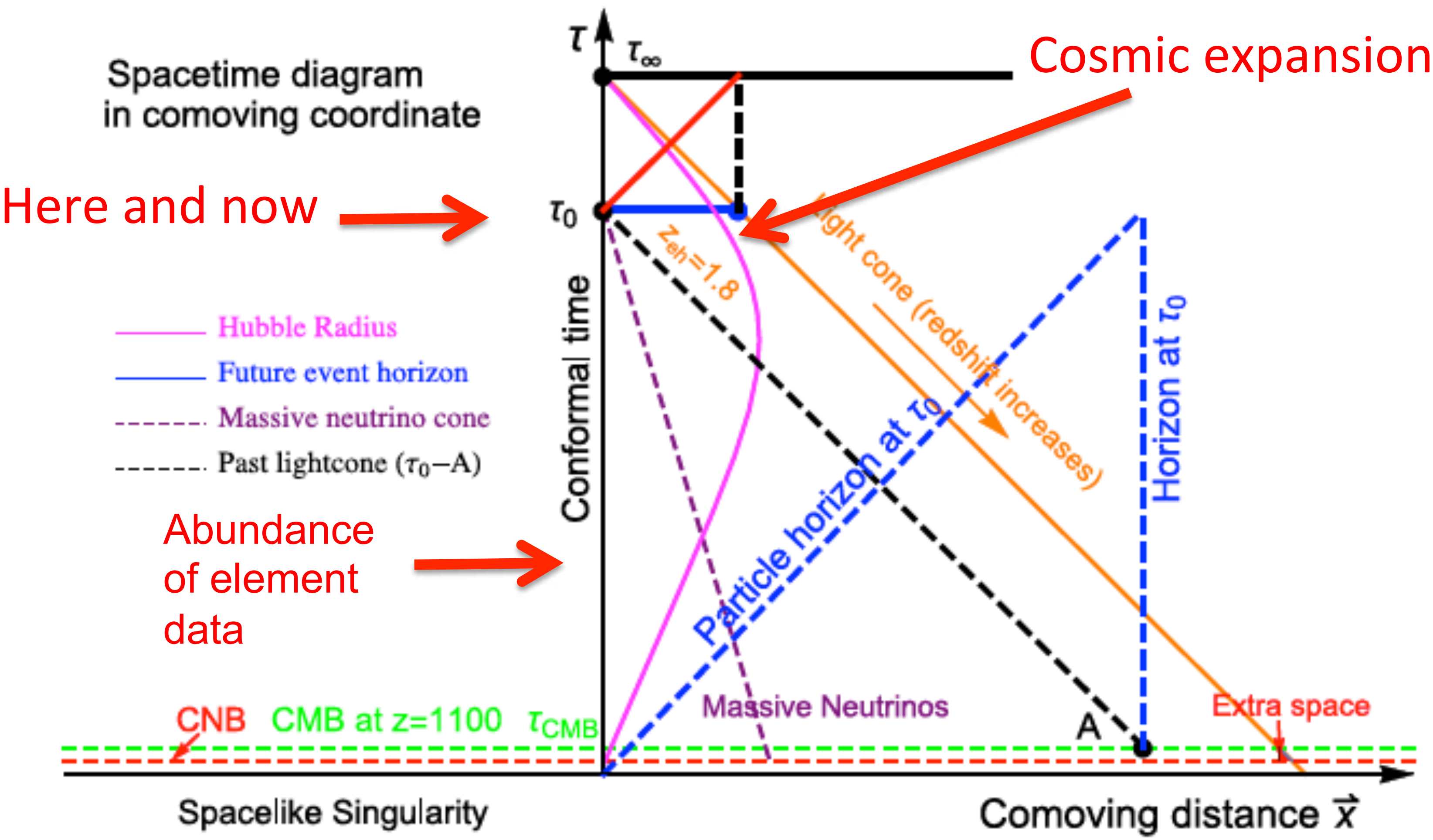
z>5: most comoving volume (best statistical constraints on high k-modes)

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

(1)Abundance of the light elements

(2)Cosmic Expansion

(3)Growth of perturbations



PHYSICAL REVIEW D **93**, 083510 (2016)

How much cosmological information can be measured?

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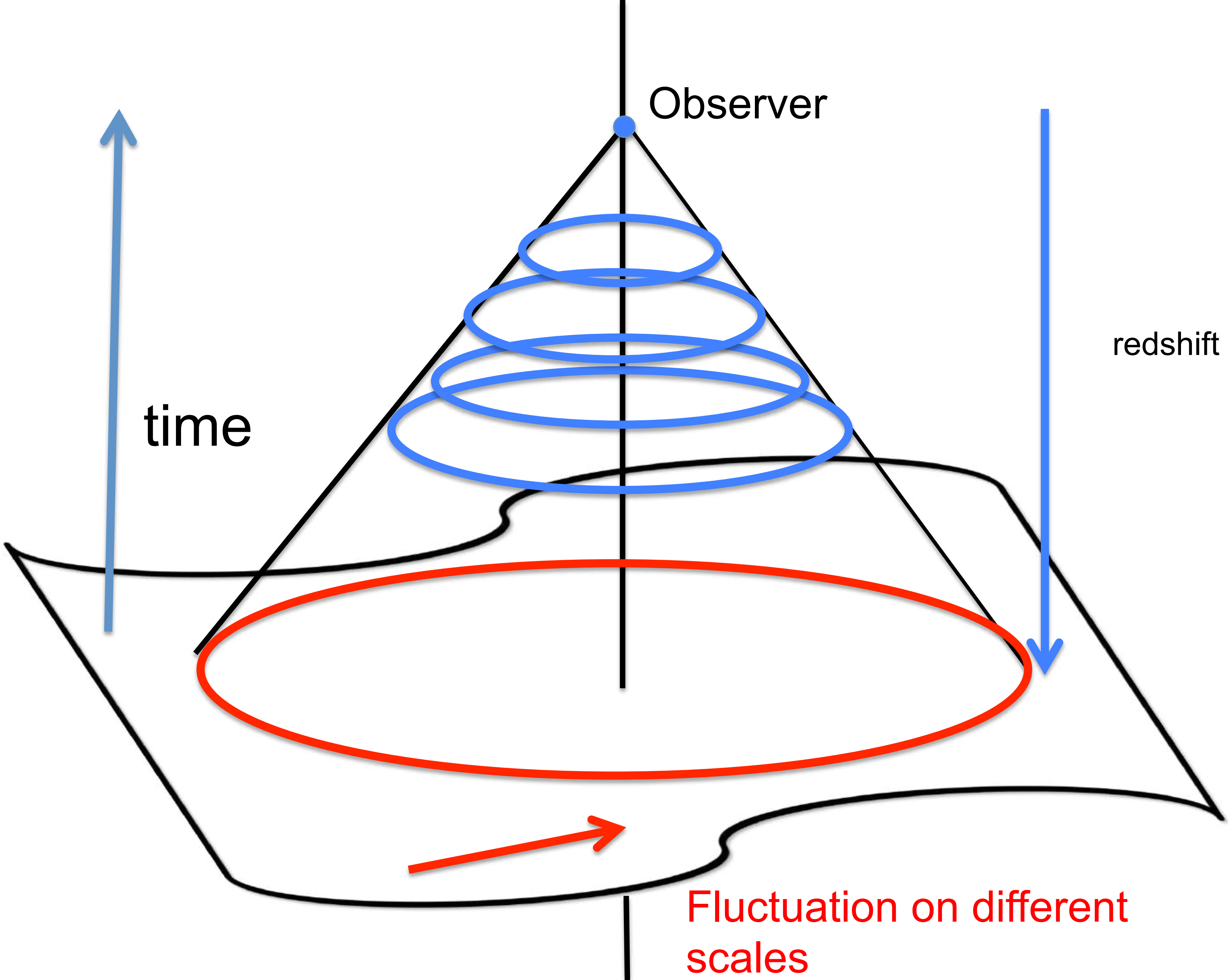
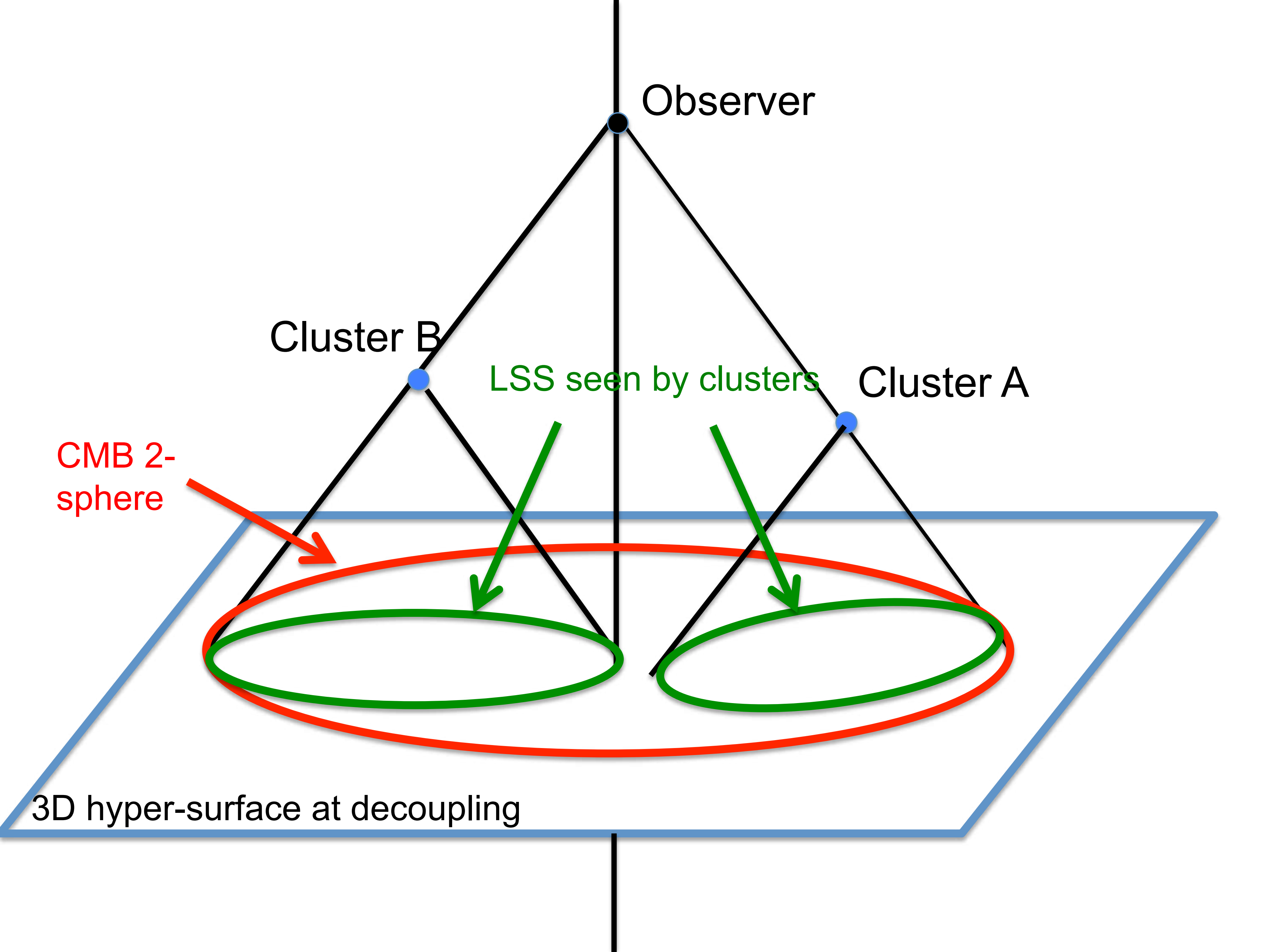
(Received 28 October 2015; published 13 April 2016)

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: ~10^12 number of modes


Observer
time
redshift
Fluctuation on different scales


Observer
Cluster B
LSS seen by clusters
Cluster A
CMB 2-
sphere
3D hyper-surface at decoupling

Ultimate precision of cosmological parameters

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

$$I_{A_\mathrm{s}} = \frac{1}{4\pi^2} \int_0^{V(\tau_\mathrm{obs})} dV \int_0^{k_\mathrm{max}(\tau_\mathrm{e})} k^2 dk \left(\frac{\partial \ln P(k)}{\partial \ln A_\mathrm{s}} \right)^2 = N_\mathrm{modes}/2,$$

$$\Delta A_\mathrm{s}/A_\mathrm{s} \simeq 10^{-7}$$

- 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 α and β 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 β (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 β 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.