Cosmological Constraints with HI intensity Mapping using Interferometer Mode

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HIRAX

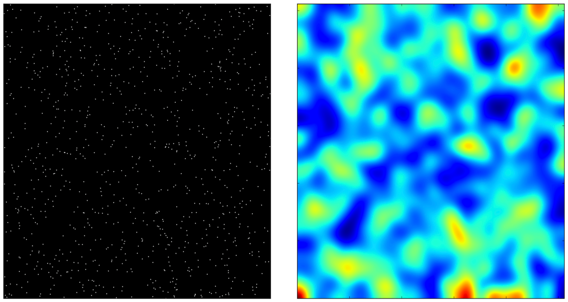
Preface

- We probe the cosmological constraints possible from upcoming radio-telescopes.
- 21cm intensity maps large-scale fluctuations in less time and still obtaining cosmological information.
- The surveys help to measure growth rate of structure using redshift space distortion (RSD).

$$f(z) = -\frac{d \ln \delta_m}{d \ln(1+z)} \approx \Omega_m(z)^{\gamma}, \ \gamma = 0.55$$

- RSD is the distortion of the real-space distribution in red-shift space and the distortions on large scales squashed in the line of sight direction: kaiser effect
- For RSD on smaller scales we add effective term called Finger of God effect.

21cm Intensity mapping

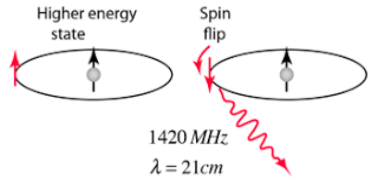


Villaescusa-Navarro et al.

- HI intensity experiments are low resolution maps of the Universe.
- No need to resolve individual galaxies to create a map.
- Instead, we map the fluctuations in the HI brightness temperature, like CMB using

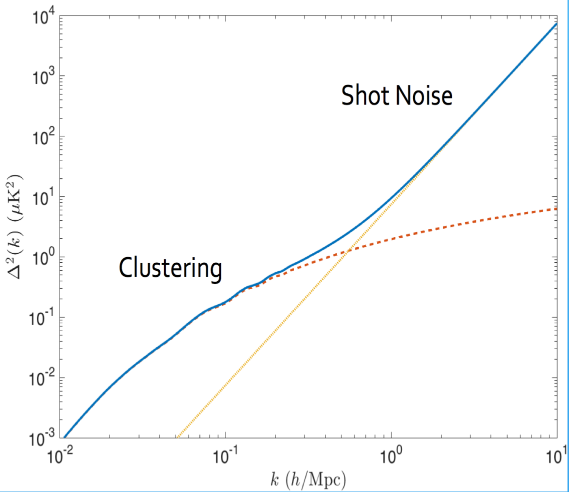
$$\Delta T_{\rm CMB} = \Delta T_{\rm CMB}(\theta, \phi, z = 1100)$$
$$\Delta T_{\rm HI} = \Delta T_{\rm HI}(\theta, \phi, z)$$

- HI in galaxies emits a spectral line with the rest frame $\nu_{21} = 1420MHz$. Then $\lambda_{21\rm cm} = 21\rm cm(1 + z)$



R Nave.

Information from HI power spectra

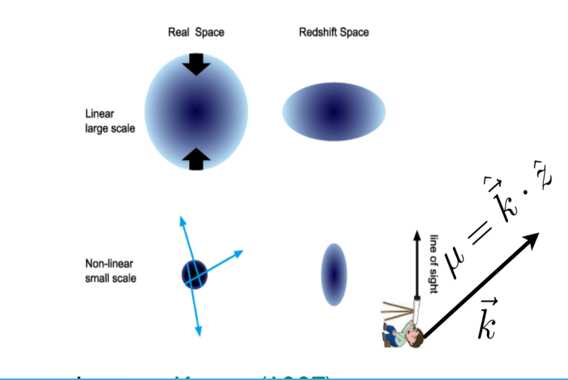


Kovetz et al. 2017.

- We used HI fluctuations to probe the power spectrum of matter fluctuations
- The Fourier transform:

$$P_{\mathrm{HI}}(k,z) = \bar{T}^2_{\mathrm{HI}}(z) b^2_{\mathrm{HI}}(z) P_m(k,z) + P_{shot}$$

Redshift Space Distortions



Shun Saito.

- The distortion of the real-space distribution in red-shift space

- Kaiser RSD adds an additional term $f\mu^2$
- On smaller scales the FoG damps power

$$\frac{P_{\mathrm{HI}}(z,k,\mu)}{P_m(z,k)} = \underbrace{D_{\mathrm{FOG}}(k,\mu)}_{\text{Small scale}} \overbrace{T^2_{\mathrm{HI}}(z)\left[b(z)+f(z)\mu^2\right]^2}^{\text{Large scale}}$$

- On small scales fluctuations are stretching along the line of sight

Survey specifications

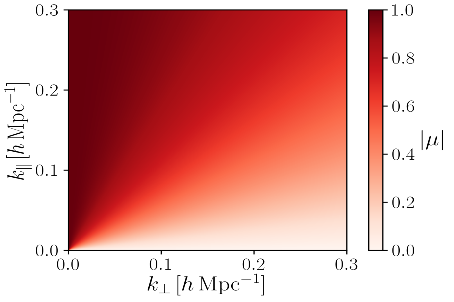
	HIRAX	PUMA
red-shift range	0.8 – 2.5	0.3 – 6.0
D_d[m]	6	6
t_{tot} [$10^3 hr$]	17.5	40
$N_{\rm d}$	256/1024	5000/32000
T_a[K]	50	95
f_{sky}	0.36	0.50
η_a	0.7	0.7

The HI surveys using interferometer mode (IF)

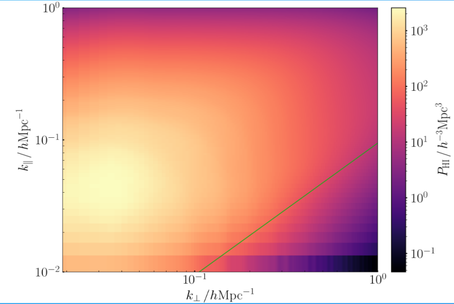
- Beam of telescope:

$$\theta_b = 1.22 \frac{\lambda_{21}(1+z)}{D_d}$$

Practical Challenges



Cunnington et al(2020).



- The complications and suggested mitigation for a successful IF survey
- Loss of small radial wave-number

$$k_\parallel < k_{\parallel,fg} \approx 0.01h\mathrm{Mpc}^{-1}$$

- Loss of foreground wedge

$$k_\parallel < A_{wedge} k_\perp$$

$$A_{wedge} = r\mathcal{H} \sin[0.61\theta_b]$$

Fisher matrix forecast

- Forecast the precision of measurement on cosmological paramaters
- Assumes Gaussian errors on each observable, characterized by variance

$$\mathrm{var}[P_{\mathrm{HI}}(z_i, k, \mu)] \propto \underbrace{\left[P_{\mathrm{HI}}(z_i, k, \mu) + P_{\mathrm{noise}}\right]^2}_{\text{Cosmological model + Instrumental noise}}$$

- The Fisher matrix in redshift bin centred at z_i:

$$F_{\alpha\beta}(z_i) = \sum_{\mu=-1}^{+1} \sum_{k_{\min}(z)}^{k_{\max}(z)} \frac{1}{\mathrm{var}[P_{\mathrm{HI}}(z_i, k, \mu)]} \frac{\partial P_{\mathrm{HI}}(z_i, k, \mu)}{\partial \theta_\alpha} \frac{\partial P_{\mathrm{HI}}(z_i, k, \mu)}{\partial \theta_\beta}, \quad \overbrace{F_{\alpha\beta}(\leq z_n) = \sum_{i=1}^{n} F_{\alpha\beta}(z_i)}^{\text{Total Fisher}}$$

- The step-size of each red-shift bin, $\Delta z = 0.1$
- k_{min} depends on the suvery where k_{max} is restricted to

$$k_{\max}(z) = 0.2(1+z)^{2/(2+n_s)}\, h\, \mathrm{Mpc}^{-1}$$

Marginalizing over parameters

- We invert the total Fisher to obtain the covariance matrix

$$C_{\alpha,\beta} = (F^{-1})_{\alpha,\beta}$$

- Marginalized errors are the diagonal elements of the matrix :

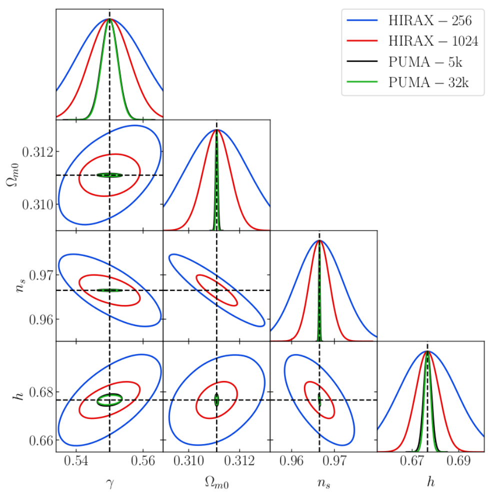
$$\sigma_\alpha \equiv (F^{-1})_\alpha$$

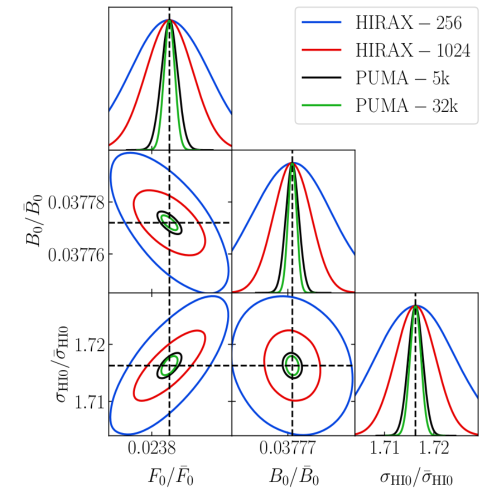
- Free Parameters

$$\theta_\alpha = \{B_0 = (\bar{T}_{\rm HI} b_{\rm HI} \sigma_8)_0,\ F_0 = (\bar{T}_{\rm HI} f \sigma_8)_0,\ \sigma_{\rm HI0},\ \gamma,\ h,\ n_s,\ \Omega_{m,0}\}$$

- We use simple 1-parameter models for $(\bar{T}_{\rm HI} b_{\rm HI} \sigma_8)_0$, $(\bar{T}_{\rm HI} f \sigma_8)_0$ and the FoG factor σ_{80}

Results


HIRAX – 256
HIRAX – 1024
PUMA – 5k
PUMA – 32k
Ω_{m0}
0.312
0.310
n_s
0.97
0.96
h
0.68
0.66
0.54
0.56
0.310
0.312
0.96
0.97
0.67
0.69
γ
Ω_{m0}
n_s
h


HIRAX – 256
HIRAX – 1024
PUMA – 5k
PUMA – 32k
$B_0/\bar{B}_0$
0.03778
0.03776
$\sigma_{\rm HI0}/\bar{\sigma}_{\rm HI0}$
1.72
1.71
0.0238
0.03777
1.71
1.72
$F_0/\bar{F}_0$
$B_0/\bar{B}_0$
$\sigma_{\rm HI0}/\bar{\sigma}_{\rm HI0}$

Results

- PUMA—32k delivers better precision than HIRAX

PUMA—32k	$(\sigma_{\theta_i}/\theta_i)\%$
γ	0.4%
n_s	0.008%
h	0.2%
Ω_{m0}	0.01%
B_0	0.005%
F_0	0.04%
σ_{HI0}	0.1%

- Followed by HIRAX-1024

- We did not include the information from the distance which involves Alcock-Paczynski effect Lopez-Corredoira(2013)

Future Work

- Extend the constraints to include other cosmological parameters
- To do the forecasts for cosmological measurements from cross-correlating 21cm intensity maps with galaxy number counts
  - HIRAX and Euclid (European Space Agency satellite)
  - PUMA and DESI (Dark Energy Survey), Euclid (in different redshift ranges)

Thank you!!