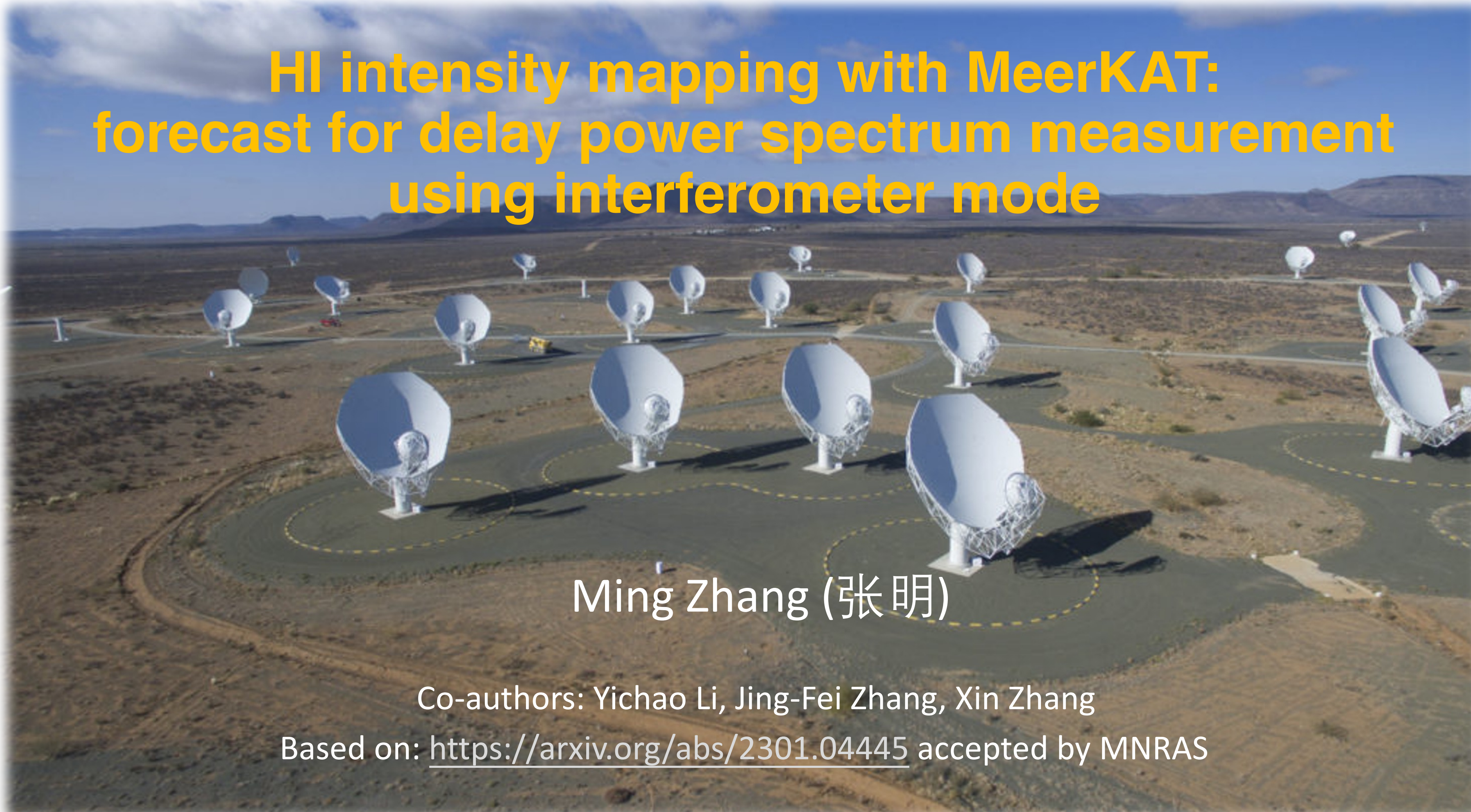

HI intensity mapping with MeerKAT: forecast for delay power spectrum measurement using interferometer mode

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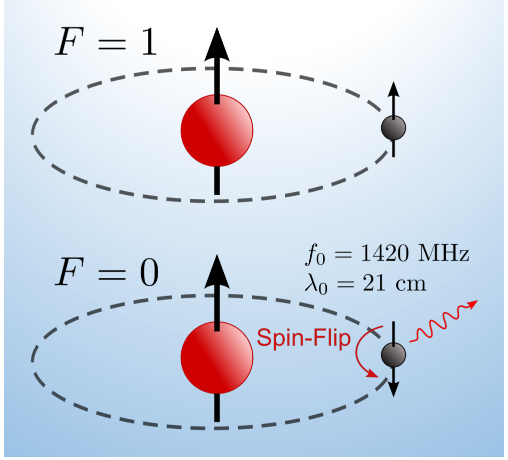
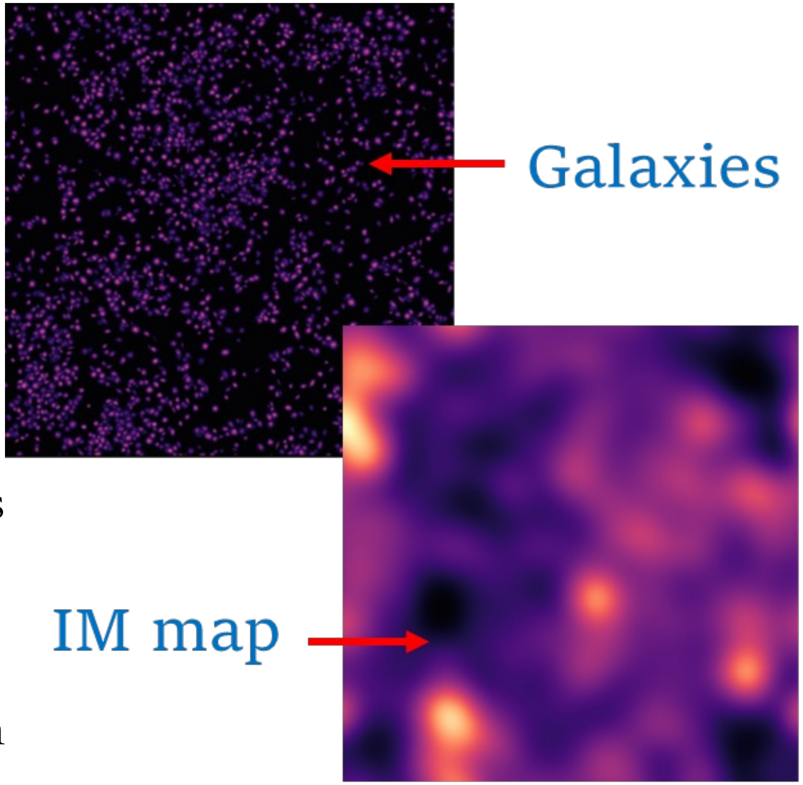
HI intensity mapping





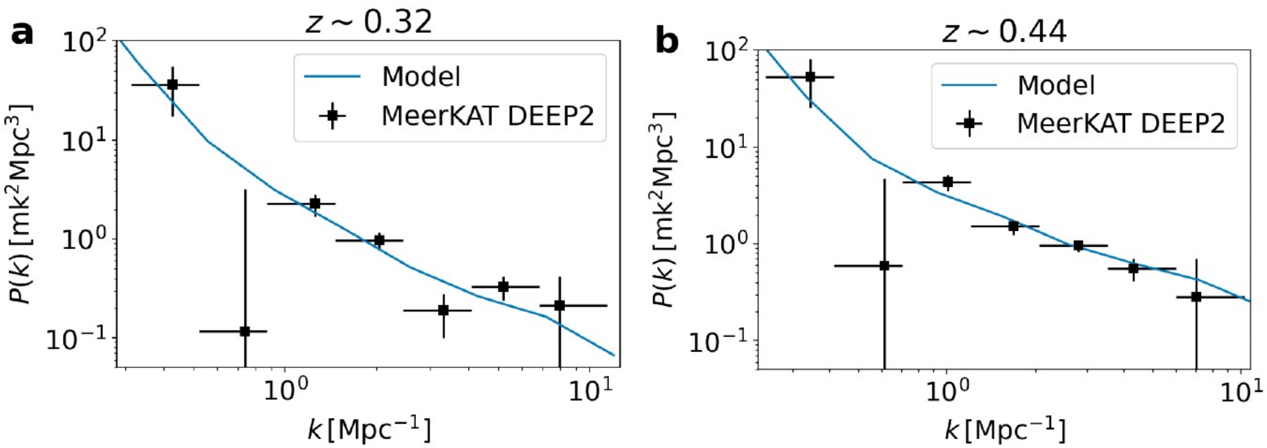
[Simulations by S. Cunnington]

- Cosmological information is on large scales
- Adopt low resolution without resolving individual galaxies
- Get intensity map of the HI 21 cm emission line like CMB but 3D!
- Excellent redshift resolution

$$f_{\rm obs} = \frac{1420}{1+z}\,{\rm MHz}$$

HI delay spectrum

$$P_{\mathrm{D}}(k_{\perp}, k_{\parallel}) \equiv \frac{A_e}{\lambda^2 B} \frac{r^2 r_\nu}{B} \left|\tilde{V}(\boldsymbol{u}, \tau)\right|^2 \left(\frac{\lambda^2}{2 k_{\mathrm{B}}}\right)^2$$



[Sourabh et al. 2023]

Advantages:

① *The different spectral behaviors between HI signal and foreground make it possible to isolate the latter in the Fourier space.*

② *In addition, the Fourier conjugate variable is associated with the Line of sight cosmological distance, therefore the 'delay spectrum' constructed in this method can recover the cosmological 3D HI power spectrum.*

MeerKAT

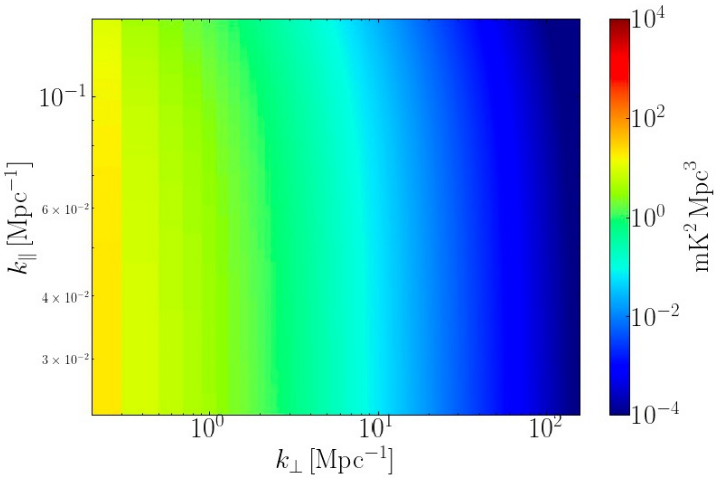
- 64*13.5m
- L band: 900–1200 MHz ($0.18 < z < 0.58$)
- UHF band: 580–1000 MHz ($0.42 < z < 1.45$)

HI signal power spectrum

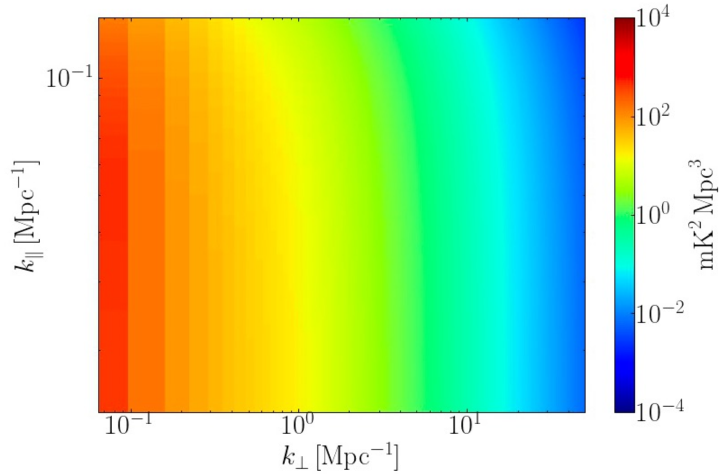
$$P_{\mathrm{HI}}(k,\mu,z) = \bar{T}_{\mathrm{b}}^{2}(z) F_{\mathrm{RSD}}(k,\mu) P(k,z)$$

$$F_{\mathrm{RSD}}(k,\mu) = \left(b_{\mathrm{HI}}^{2}(z) + f\mu^{2}\right)^{2} \exp\left(-k^{2}\mu^{2}\sigma_{\mathrm{NL}}^{2}\right)$$

z=0.3 (L band)



z=1.2 (UHF band)



- The scales available for HI IM in interferometer mode observation are limited by the detailed configuration

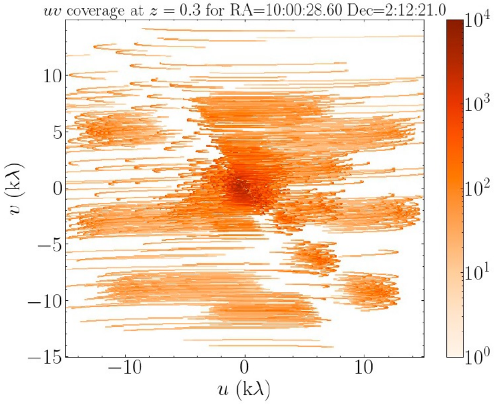
$$k_{\parallel}^{\min} = 2\pi/(r_{\nu}\Delta\nu/\nu_{21}), \qquad k_{\perp}^{\min} = 2\pi|\boldsymbol{u}|_{\min}/r,$$

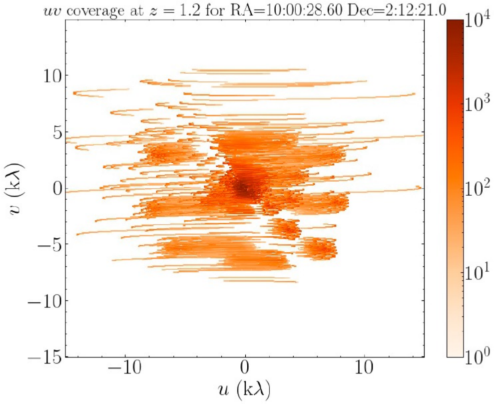
$$k_{\parallel}^{\max} = 1/\sigma_{\mathrm{NL}}, \qquad k_{\perp}^{\max} = 2\pi|\boldsymbol{u}|_{\max}/r.$$

MeerKAT noise power spectrum

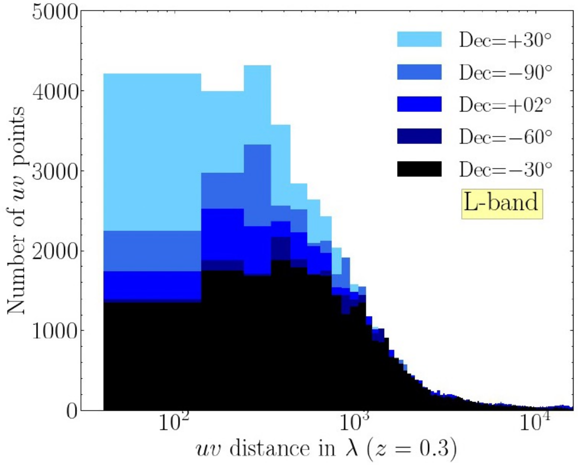
$$P_{\mathrm{N}}(k,\mu,z) = r^2(z) r_\nu(z) \frac{T_{\mathrm{sys}}^2 \lambda^4}{n_{\mathrm{pol}} \nu_{21} t_{\mathrm{int}} A_e^2 n(\boldsymbol{u})}$$

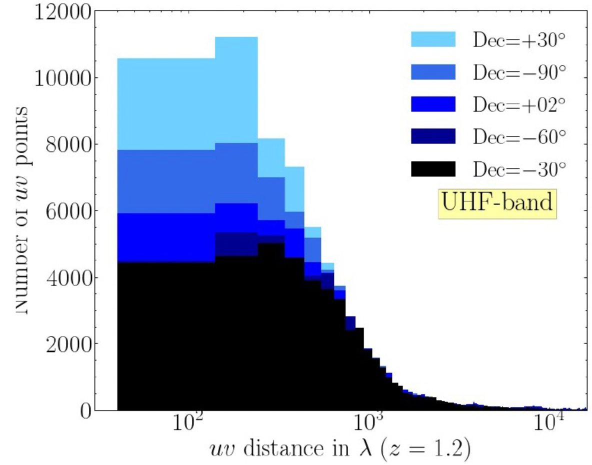
- 10 hours tracing of the COSMOS field





- The average number of MeerKAT baselines as a function of uv distance

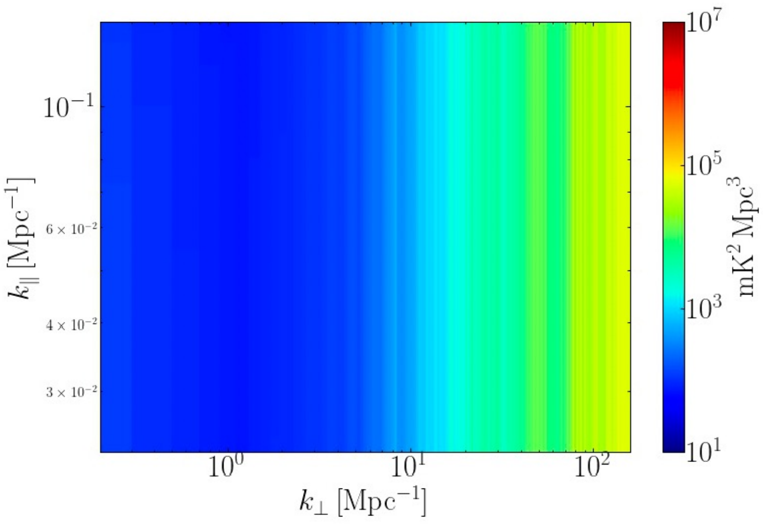




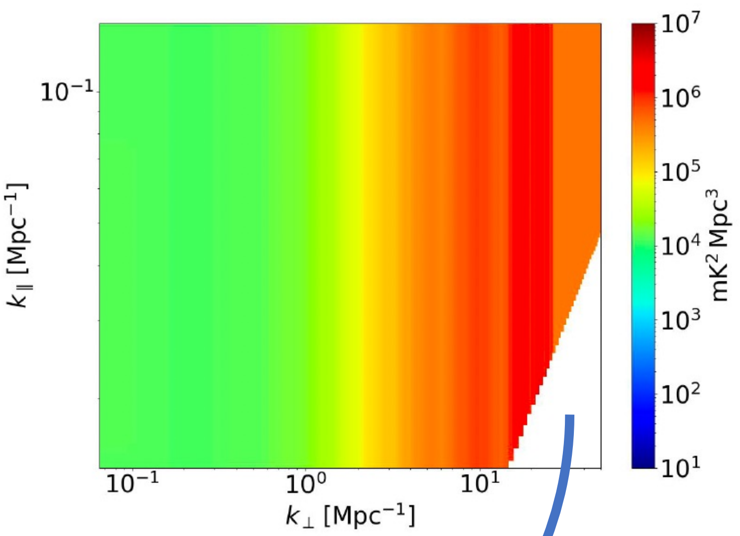
Total power spectrum

- Total = signal + noise + shot noise + foregrounds
  - Poisson fluctuations in halo number: $P_{\rm HI}^{\rm shot}(z) = \left(\frac{\bar{T}_b(z)}{\rho_{\rm HI}(z)}\right)^2 \int_{M_{\rm min}}^{M_{\rm max}} {\rm d}M \frac{{\rm d}n}{{\rm d}M} M_{\rm HI}^2(M)\ .$

z=0.3 (L band)



z=1.2 (UHF band)

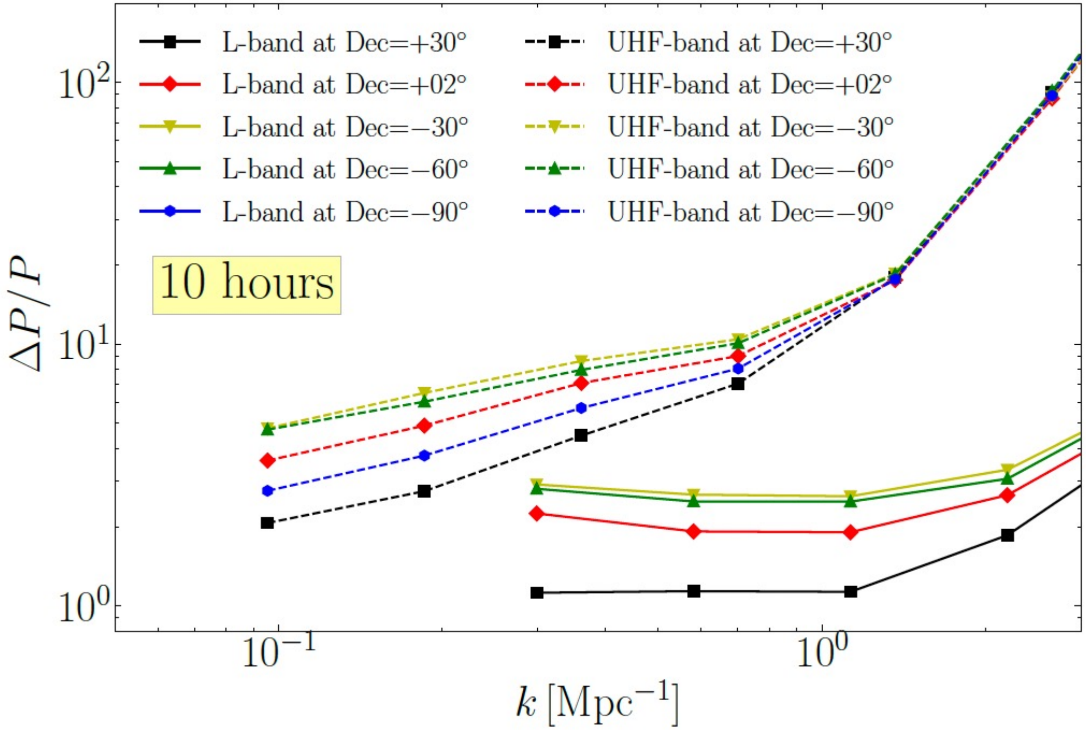


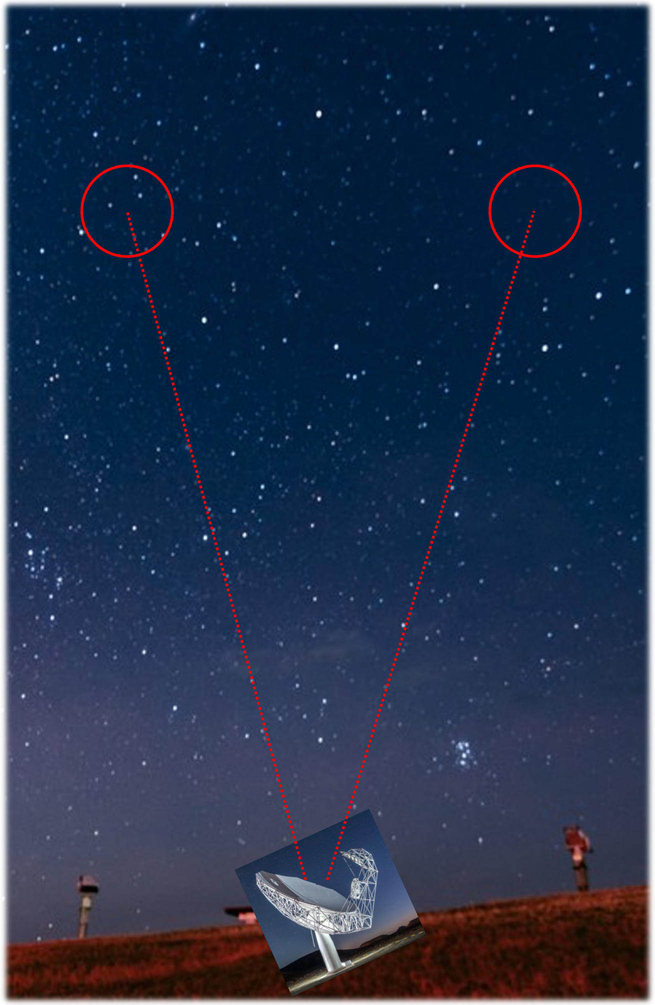
- The foreground wedge: $k_{\parallel} < \frac{r(z)H(z)\sin(\theta)}{c(1+z)} k_{\perp}$

Power spectrum estimation

10 h observations at the different declinations

$$\left(\frac{\Delta P}{P}\right)^2 = \left[\frac{1}{8\pi^2} V_{\rm bin} \int k^2 {\rm d}k {\rm d}\mu \left(\frac{P_{\rm HI}(k,\mu)}{P_{\rm tot}(k,\mu)}\right)^2\right]^{-1}$$

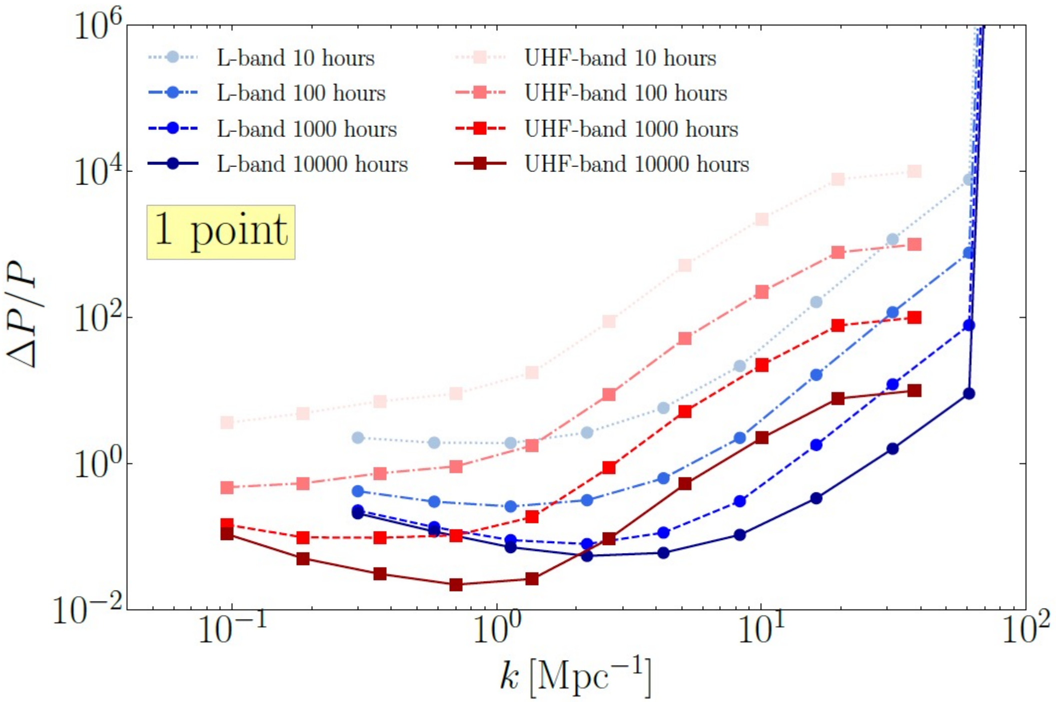


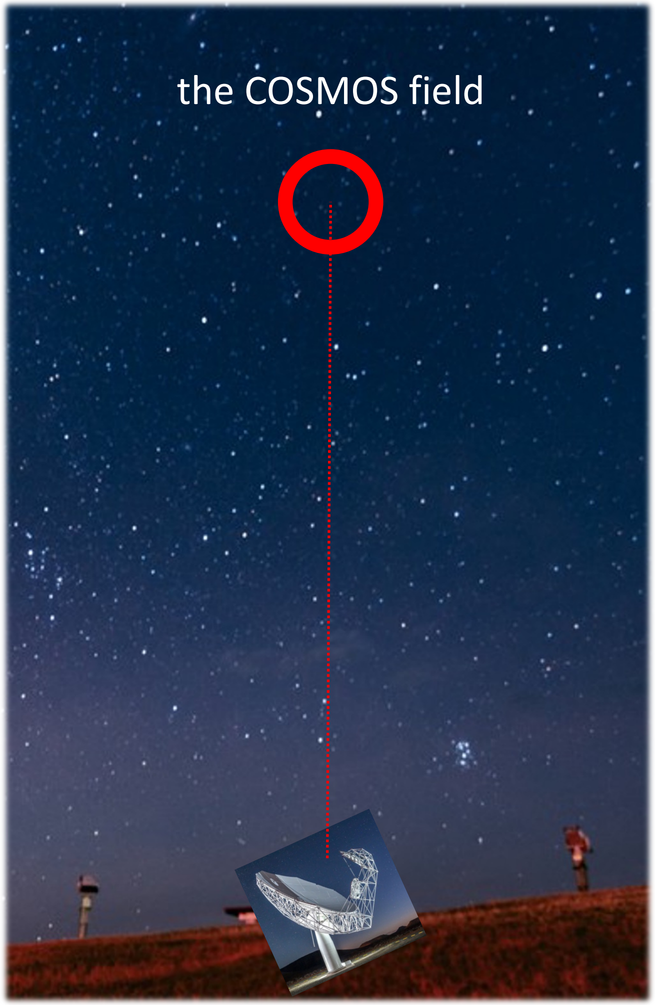


Power spectrum estimation

Different observation time of tracking the COSMOS field

$$\left(\frac{\Delta P}{P}\right)^2 = \left[\frac{1}{8\pi^2} V_{\rm bin} \int k^2 {\rm d}k {\rm d}\mu \left(\frac{P_{\rm HI}(k,\mu)}{P_{\rm tot}(k,\mu)}\right)^2\right]^{-1}$$

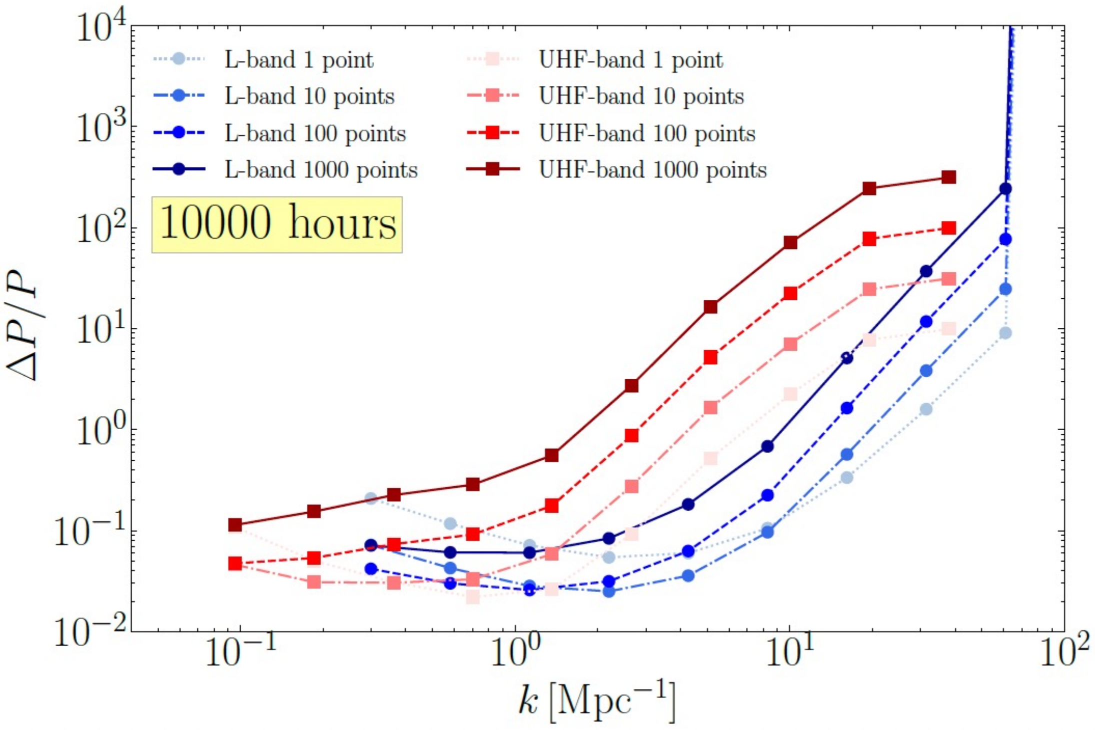


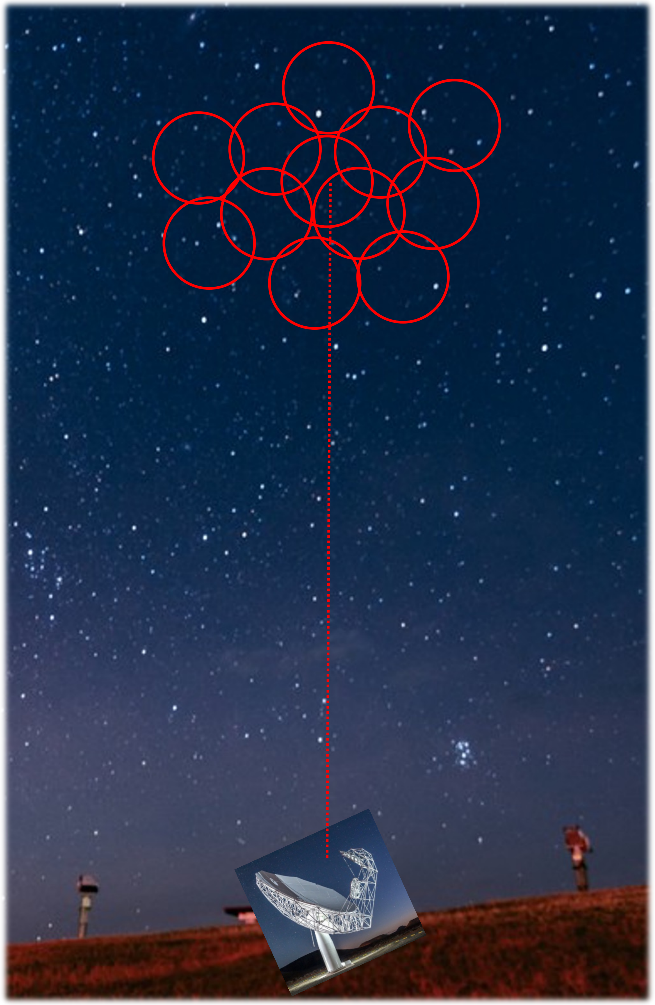


Power spectrum estimation

Tracking different numbers of points in a 10000 h observation

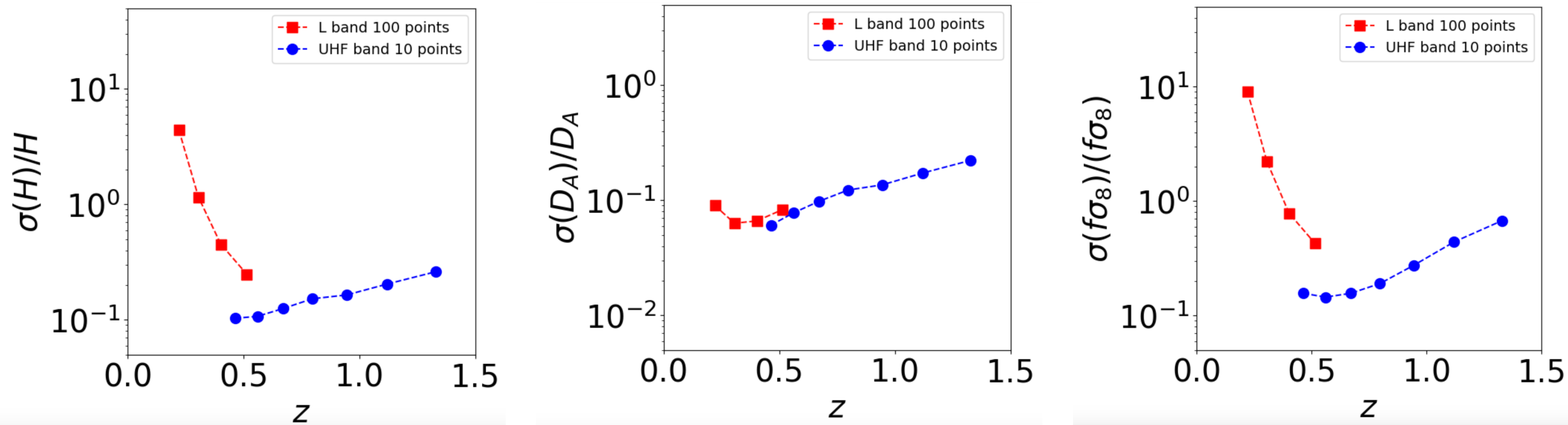
$$\left(\frac{\Delta P}{P}\right)^2 = \left[\frac{1}{8\pi^2}V_{\rm bin}\int k^2 {\rm d}k{\rm d}\mu\left(\frac{P_{\rm HI}(k,\mu)}{P_{\rm tot}(k,\mu)}\right)^2\right]^{-1}$$





Cosmological parameters estimation

$$F_{ij} = \frac{1}{8\pi^2} V_{\rm bin} \int_{-1}^{1} {\rm d}\mu \int_{k_{\rm min}}^{k_{\rm max}} k^2 {\rm d}k \frac{\partial P_{\rm tot}}{\partial p_i} \frac{\partial P_{\rm tot}}{\partial p_j}$$



- H(z): the hubble parameter
- D_A(z): the angle diameter distance
- $f\sigma_8$(z): the growth rate
- bσ_8(z): the HI bias
- σ_{NL}: the non-linear dispersion scale

Dark energy parameters estimation

ΛCDM

Planck	L band	UHF band
$\sigma(H_0) = 0.59$	$\sigma(H_0) = 2.8$	$\sigma(H_0) = 2.0$
$\sigma(\Omega_m) = 0.008$	$\sigma(\Omega_m) = 0.044$	$\sigma(\Omega_m) = 0.028$

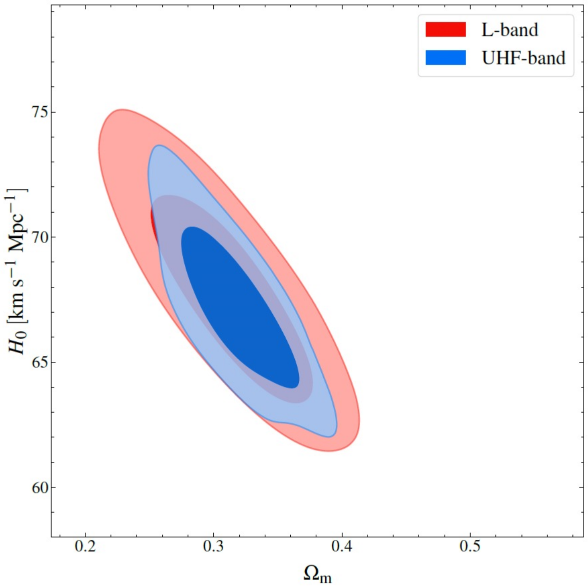


Figure 8. Constraints on Ω_m and H_0 with MeerKAT L-band and UHF-band in the ΛCDM model.

Dark energy parameters estimation

wCDM

$$f_{\rm de}(z) = (1+z)^{3(1+w)}$$

	Error
Planck+L band	$\sigma(w) = 0.120$
Planck+ UHF band	$\sigma(w) = 0.080$
BINGO	$\sigma(w) = 0.130$
FAST	$\sigma(w) = 0.075$
Planck+SKA1-MID (single-dish mode)	$\sigma(w) = 0.013$
Planck+Tianlai (full cylinders)	$\sigma(w) = 0.014$

[Wu PJ & Zhang X, JCAP 2021]

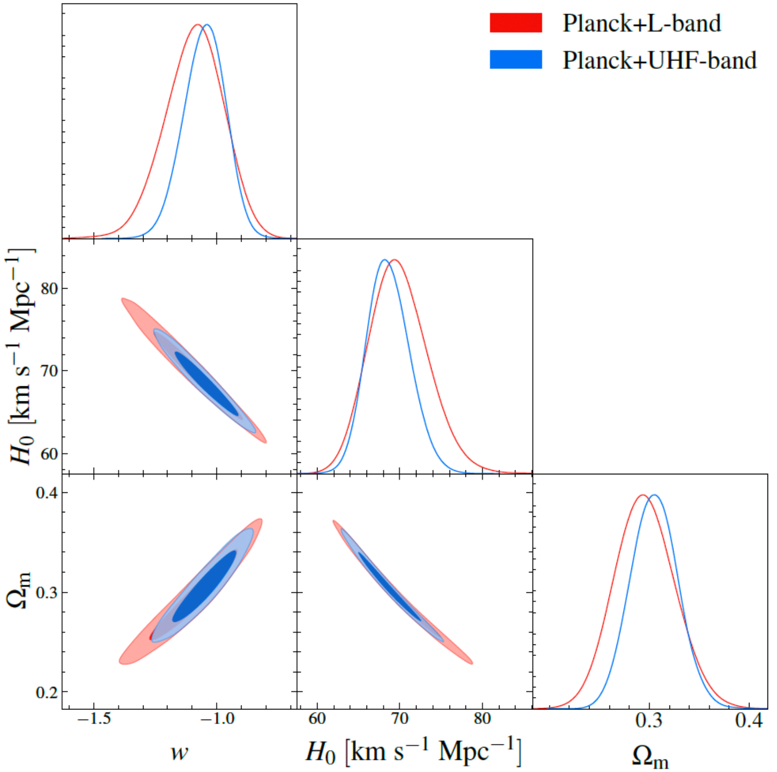


Figure 9. Constraints on Ω_m, H_0 and w with MeerKAT L-band and UHF-band in combination with *Planck* data in the wCDM model.

Dark energy parameters estimation

$w_0 w_a$CDM

$$f_{\rm de}(z) = (1+z)^{3(1+w_0+w_a)} \exp\left(-3w_a z/(1+z)\right)$$

	Error
Planck+L band	$\sigma(w_0) = 1.10$ $\sigma(w_a) = 4.30$
Planck+ UHF band	$\sigma(w_0) = 0.60$ $\sigma(w_a) = 2.00$
Planck+SKA1-MID (single-dish mode)	$\sigma(w_0) = 0.08$ $\sigma(w_a) = 0.25$
Planck+Tianlai (full cylinders)	$\sigma(w_0) = 0.11$ $\sigma(w_a) = 0.31$

[Wu PJ & Zhang X, JCAP 2021]

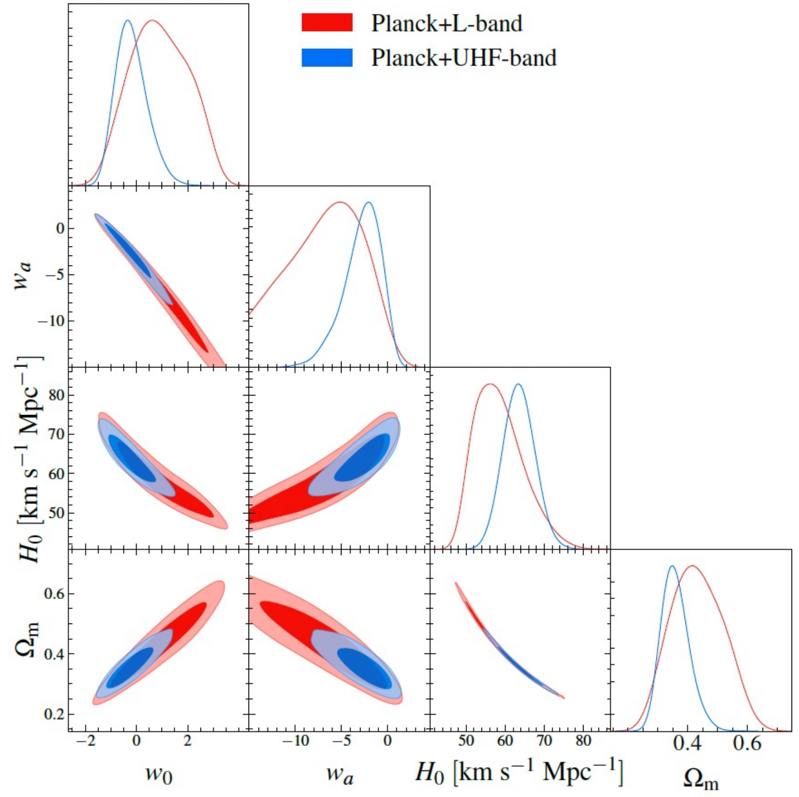


Figure 10. Constraints on Ω_m, H_0, w_0 and w_a with MeerKAT L-band and UHF-band in combination with *Planck* data in the $w_0 w_a$CDM model.

Summary

● Power spectrum

- *The choice of survey fields significantly impacts the fractional errors on the power spectrum ($\Delta P/P$) within limited observational time of 10 hours.*
- *As the integration time increases from 10 hours to 10,000 hours, $\Delta P/P$ progressively decreases until cosmic variance begins to dominate.*
- *For a total observation time of 10,000 hours, the lowest $\Delta P/P$ at low k can be achieved by tracking 100 points for MeerKAT L-band and 10 points for MeerKAT UHF-band.*

● Dark energy

- *MeerKAT HI IM survey in interferometer mode demonstrates limited capability in constraining the dark-energy equation of state, even when combined with Planck data.*

Thanks for your listening!