Cosmological constraints using 2- and 3-point corRoylations with MeerKAT, the SKA, and HIRAX

UNIVERSITY of the WESTERN CAPE

RESPICE PROSPICE

UNIVERSITY OF KWAZULU-NATAL

COSMIC ROY 70

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In Collaborations with: Prof Roy Maartens & Dr Dionysis Karagiannis

10 March 2025

Papers with Roy …

1. **Liantsoa F. Randrianjanahary**, Dionysios Karagiannis, Roy Maartens,
   "Cosmological constraints from the EFTofLSS power spectrum and tree level bispectrum of 21cm intensity maps,"
   Physics of the Dark Universe (under review),
   https://arxiv.org/abs/2312.02511

2. Dionysios Karagiannis, Roy Maartens, **Liantsoa F. Randrianjanahary**,
   "Cosmological constraints from the power spectrum and bispectrum of 21cm intensity maps,"
   Journal of Cosmology & Astroparticle Physics 11 (2022) 003,
   https://arxiv.org/abs/2206.07747v3

OUTLINE

- Concept & Methodology
- Surveys
- Cosmological constraints from the power spectrum and bispectrum of 21cm intensity maps
- Cosmological constraints from EFT power spectrum and tree-level bispectrum of 21cm intensity maps
- Conclusion and … Gratitude

Aim and Scope

- We explore the information from HI power spectra (tree-level and one-loop) in redshift space and bispectrum tree-level models.

- We use Fisher predictions to examine how useful some surveys might be for constraining cosmological parameters, growth function, and what they mean for dynamical dark energy and modified gravity.

PART 2: CONCEPT & METHODOLOGY

Linear HI power spectrum model

$$P_{\rm HI}(\boldsymbol{k},z) = \bar{T}(z)^2\Big[D^P_{\rm FoG}(\boldsymbol{k},z)Z_1(\boldsymbol{k},z)^2P_{\rm m}(k,z) + P_\varepsilon(z)\Big] + P_{\rm N}(\boldsymbol{k},z),$$

$$D^P_{\rm FoG}(\boldsymbol{k},z) = \exp\left[-k^2\mu^2\,\sigma_P(z)^2\right]$$

$$q(k,\mu) = k\alpha(\mu)\ ,\quad \nu(k,\mu) = \frac{\mu}{\alpha(\mu)}\frac{H_{\rm true}}{H_{\rm fid}}\ ,$$

$$\alpha(\mu) = \left[\left(\frac{H_{\rm true}}{H_{\rm fid}}\right)^2\mu^2 + \left(\frac{D_{A,{\rm fid}}}{D_{A,{\rm true}}}\right)^2(1-\mu^2)\right]^{1/2}$$

$$P^{\rm obs}_{\rm HI}(k,\mu,z) = \left(\frac{H_{\rm true}}{H_{\rm fid}}\right)\left(\frac{D_{A,{\rm fid}}}{D_{A,{\rm true}}}\right)^2 P_{\rm HI}(q,\nu,z)$$

HI bispectrum model

$$B_{\mathrm{HI}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3,z) = \bar{T}(z)^3\Big\{ D^B_{\mathrm{FoG}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3,z)$$
$$\times\Big[2Z_1(\boldsymbol{k}_1,z)Z_1(\boldsymbol{k}_2,z)Z_2(\boldsymbol{k}_1,\boldsymbol{k}_2,z)P^{\mathrm{L}}_{\mathrm{m}}(k_1,z)P^{\mathrm{L}}_{\mathrm{m}}(k_2,z) + 2\ \mathrm{perm}\Big]$$
$$+ 2P_{\varepsilon\varepsilon_\delta}(z)\Big[Z_1(\boldsymbol{k}_1,z)P^{\mathrm{L}}_{\mathrm{m}}(k_1,z) + 2\ \mathrm{perm}\Big] + B_\varepsilon(z)\Big\}.$$

$$D^B_{\mathrm{FoG}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3,z) = \exp\left[-\left(k_1^2\mu_1^2 + k_2^2\mu_2^2 + k_3^2\mu_3^2\right)\sigma_B(z)^2\right]$$

$$Z_1(\boldsymbol{k}_i) = b_1 + f\mu_i^2,$$
$$Z_2(\boldsymbol{k}_i,\boldsymbol{k}_j) = b_1F_2(\boldsymbol{k}_i,\boldsymbol{k}_j) + f\mu_{ij}^2G_2(\boldsymbol{k}_i,\boldsymbol{k}_j) + \frac{b_2}{2} + \frac{b_{s^2}}{2}S_2(\boldsymbol{k}_i,\boldsymbol{k}_j)$$
$$+ \frac{1}{2}f\mu_{ij}k_{ij}\left[\frac{\mu_i}{k_i}Z_1(\boldsymbol{k}_j) + \frac{\mu_j}{k_j}Z_1(\boldsymbol{k}_i)\right],$$

$$B^{\mathrm{HI}}_{\mathrm{obs}} = \left(\frac{H}{H_{\mathrm{fid}}}\right)^2\left(\frac{D_{A,\mathrm{fid}}}{D_A}\right)^4 B^{\mathrm{HI}}$$

Noise:

(Thermal noise, we neglect shot noise in the case of HI Intensity Mapping)

SD case

$$P_{\rm N}^{\rm SD}(k_\perp, z) = T_{\rm sys}(z)^2 \chi(z)^2 \lambda(z) \frac{(1+z)}{H(z)} \frac{S_{\rm area}}{\eta\, N_{\rm pol}\, N_{\rm dish}\, t_{\rm survey}\, \beta_\perp(k_\perp, z)^2} ,$$

$$\beta_\perp(k, \mu, z) = \exp\left[-\frac{k_\perp^2 \chi(z)^2 \theta_{\rm b}(z)^2}{16 \ln 2}\right] .$$

IF case

$$P_{\rm N}^{\rm IF}(k_\perp, z) = T_{\rm sys}(z)^2 \chi(z)^2 \lambda(z) \frac{(1+z)}{H(z)} \left[\frac{\lambda(z)^2}{A_{\rm e}}\right]^2 \frac{1}{2\, n_{\rm b}(u, z)\, t_{\rm survey}} \frac{S_{\rm area}}{\theta_{\rm b}(z)^2} ,$$

$$\theta_{\rm b}(z) = 1.22\, \lambda(z)/D_{\rm dish}$$

$$A_{\rm e} = \eta\pi(D_{\rm dish}/2)^2$$

Non-linear HI power spectrum model for EFT

- We need to access non-linear scales to improve the signal,
- We use the 1-loop EFT to do this. [**Arxiv 2106.09713**]

The expression for the EFT (effective field theory) one-loop redshift space power spectrum is given as follows,

$$P^{\mathrm{HI}}_{\mathrm{EFT}} = P^{\mathrm{HI}}_{1-\mathrm{loop}} + (\alpha_0 + \alpha_2\mu^2 + \alpha_4\mu^4)(k/k_*)^2 P^{\mathrm{Zel}}_{\mathrm{cb}} + N_0 + N_2(\mu k)^2 + N_4(\mu k)^4$$

Where, $P^{\mathrm{HI}}_{1-\mathrm{loop}} = P^{\mathrm{HI}}_{11} + P^{\mathrm{HI}}_{22} + P^{\mathrm{HI}}_{13}$

N_n : stochastic contributions and small-scale velocities (FoG effects)
α_n : handful of counterterms

$$P^{\mathrm{HI}}_{\mathrm{EFT,obs}} = \frac{H}{H^{\mathrm{fid}}} \frac{D^{\mathrm{fid}\ 2}_{\mathrm{A}}}{D^2_{\mathrm{A}}} P^{\mathrm{HI}}_{\mathrm{EFT}}$$

- Foreground radial avoidance

Foreground affects the long-wavelength line of sight modes. We exclude these modes using a cut off,

$$k_{||,\,\mathrm{fg}} = 0.01h\,\mathrm{Mpc}^{-1}$$

- Foreground wedge avoidance

We exclude all modes lying in the foreground wedge by applying the following condition,

$$k_{||} \geq A_{\mathrm{wedge}}\, k_{\perp} \quad \text{such that} \quad A_{\mathrm{wedge}} = \frac{\chi(z)\, H(z)}{c(1+z)} \sin[0.61 N_{\mathrm{w}} \theta_{\mathrm{b}}]$$

Methodology of Forecast : FISHER FORMALISM

$$F_{ij}^{P} = \sum_{k_f \leq k} \int_{-1}^{1} \frac{d\mu}{2} \frac{\partial P_{\rm obs}^{\rm HI}}{\partial \theta_i} \frac{\partial P_{\rm obs}^{\rm HI}}{\partial \theta_j} \frac{1}{\Delta P^2}$$

$$\Delta P^2 = \frac{4\pi^2}{V k^2 \Delta k} \tilde{P}_{\rm obs}^{\rm HI\ 2}$$

$$F_{ij}^{B} = \frac{1}{4\pi} \sum_{k_1, k_2, k_3} \int_{-1}^{1} \mathrm{d}\mu_1 \int_{0}^{2\pi} \mathrm{d}\phi \frac{\partial B_{\rm obs}^{\rm HI}}{\partial \theta_i} \frac{\partial B_{\rm obs}^{\rm HI}}{\partial \theta_j} \frac{1}{\Delta B^2}$$

$$\Delta B^2 = s_{123} \pi k_{\rm f}^3 \frac{\tilde{P}_{\rm obs}^{\rm HI} \tilde{P}_{\rm obs}^{\rm HI} \tilde{P}_{\rm obs}^{\rm HI}}{k_1 k_2 k_3 [\Delta k]^3}$$

$$\tilde{P}^{\rm HI} = P^{\rm HI} + P_{\rm N}$$

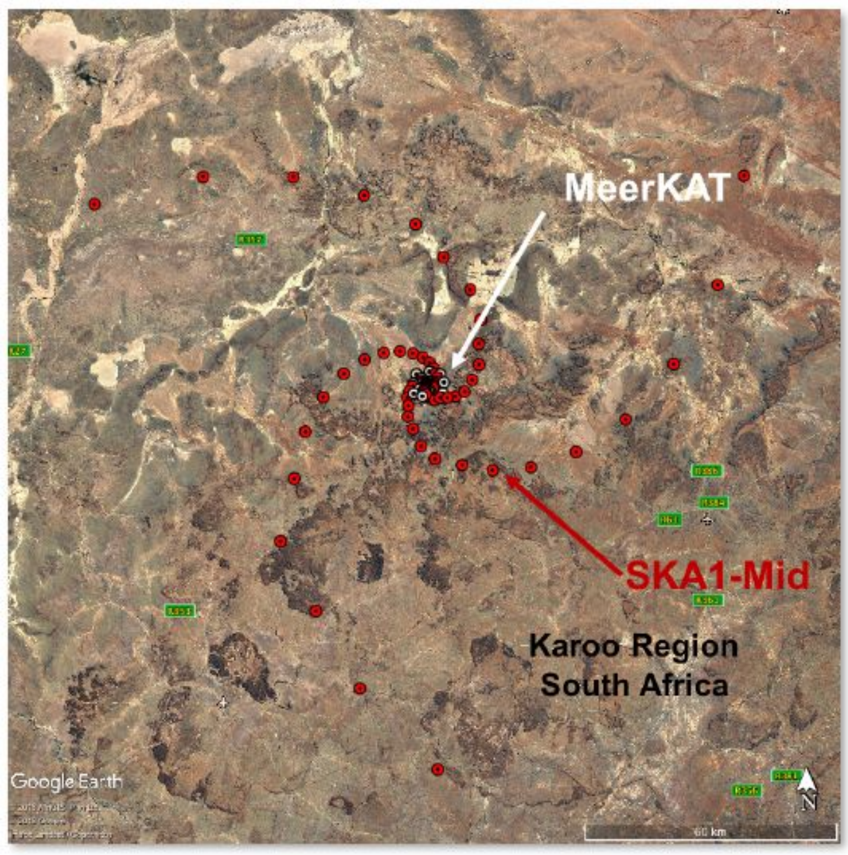
Part 2: Surveys: MEERKAT, SKA, HIRAX

MEERKAT Survey

SD Survey	MeerKAT	
	L Band	UHF Band
redshift	0.1^b–0.58	0.4^c–1.45
$N_{\rm dish}$	64	64
$D_{\rm dish}$ [m]	13.5	13.5
$S_{\rm area}$ [deg^2]	4,000	4,000
$t_{\rm survey}$ [hrs]	4,000	4,000

Meerkat radio interferometer is a Karoo Array Telescope that operates within the UHF frequency range of [580-1015]MHz and the L frequency range of [1.75-3.5]GHz.

SKAO Survey



The SKAO, which is currently in its construction phase, will be the world's largest radio telescope observatory. Our survey consists of Band 1 and Band 2 as follows,

SD Survey	SKAO[a]	
	Band 1	Band 2
redshift	0.35^{d}–3.05	0.1^{b}–0.49
$N_{\rm dish}$	197	197
$D_{\rm dish}$ [m]	15	15
$S_{\rm area}$ [deg^2]	20,000	20,000
$t_{\rm survey}$ [hrs]	10,000	10,000

HIRAX (The Hydrogen Intensity Real-time Analysis eXperiment)

HIRAX is **radio telescope** array that will map nearly all of the **southern sky** in **radio continuum** and neutral **hydrogen line emission** over a frequency range of **400 - 800MHz**

IF Survey	HIRAX-256	HIRAX-1024
redshift	$0.775 - 2.55$	$0.775 - 2.55$
N_{dish}	256	$1,024$
D_{dish} [m]	6	6
D_{max} [km]	0.25	0.25
S_{area} [deg^2]	$15,000$	$15,000$
t_{survey} [hrs]	$17,500$	$17,500$

Part 3: Cosmological constraints from the power spectrum and bispectrum of 21cm intensity maps

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Cosmological constraints from the power spectrum and bispectrum of 21cm intensity maps

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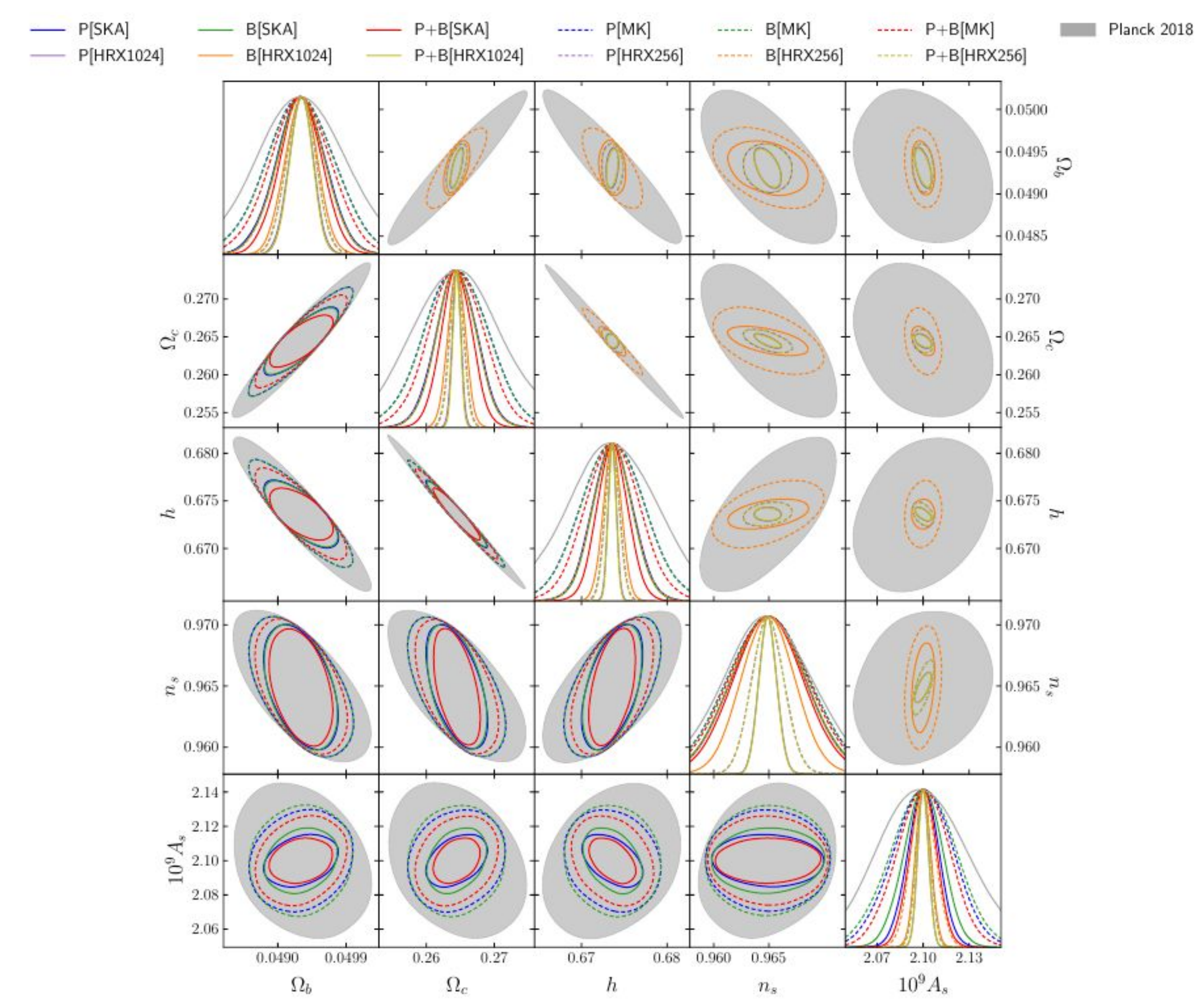
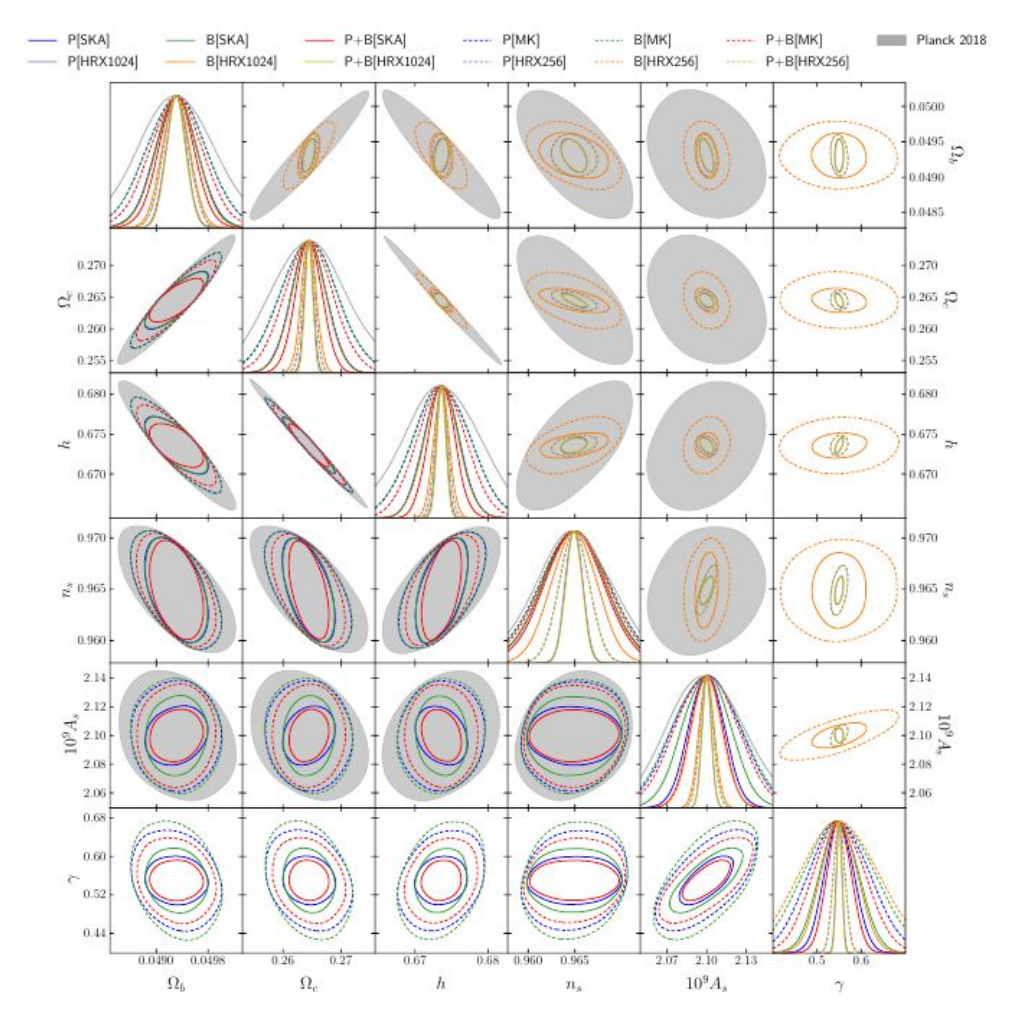


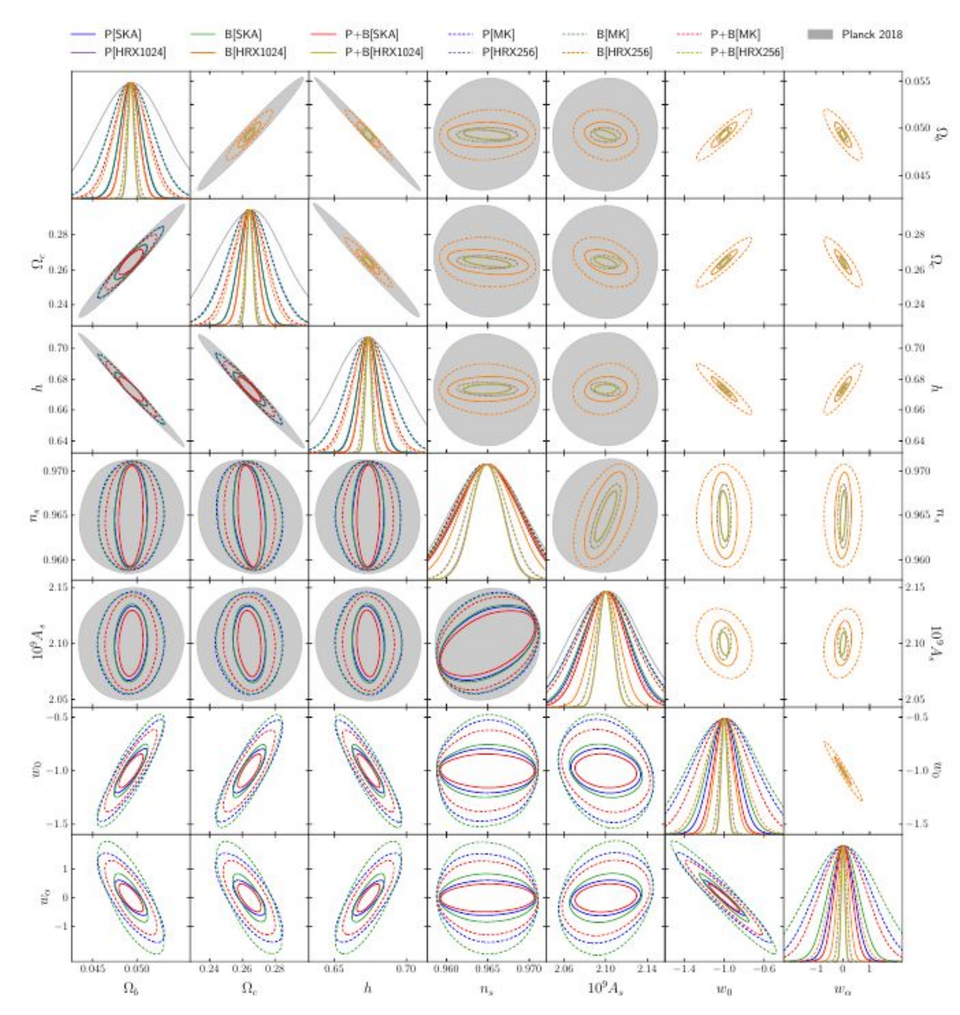
LambdaCDM parameters

Panels below the diagonal gives SD survey, Panels above give IF survey



gammaCDM parameters

Panels below the diagonal gives SD survey, Panels above give IF survey



w0waCDM parameters

Panels below the diagonal gives SD survey, Panels above give IF survey

Part 4: Cosmological constraints from EFT power spectrum and tree-level bispectrum of 21cm intensity maps

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Full length article

Cosmological constraints from the EFT power spectrum and tree-level bispectrum of 21 cm intensity maps

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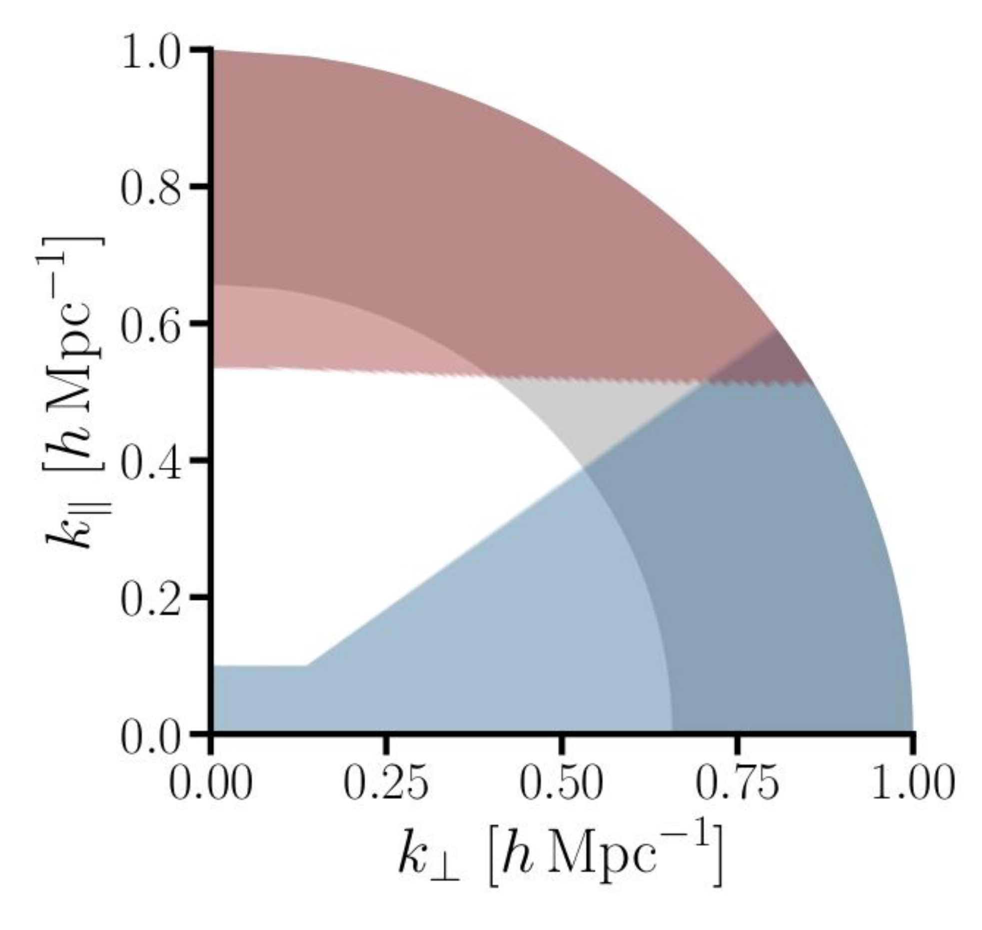
Available modes [Non shaded region of the plot]

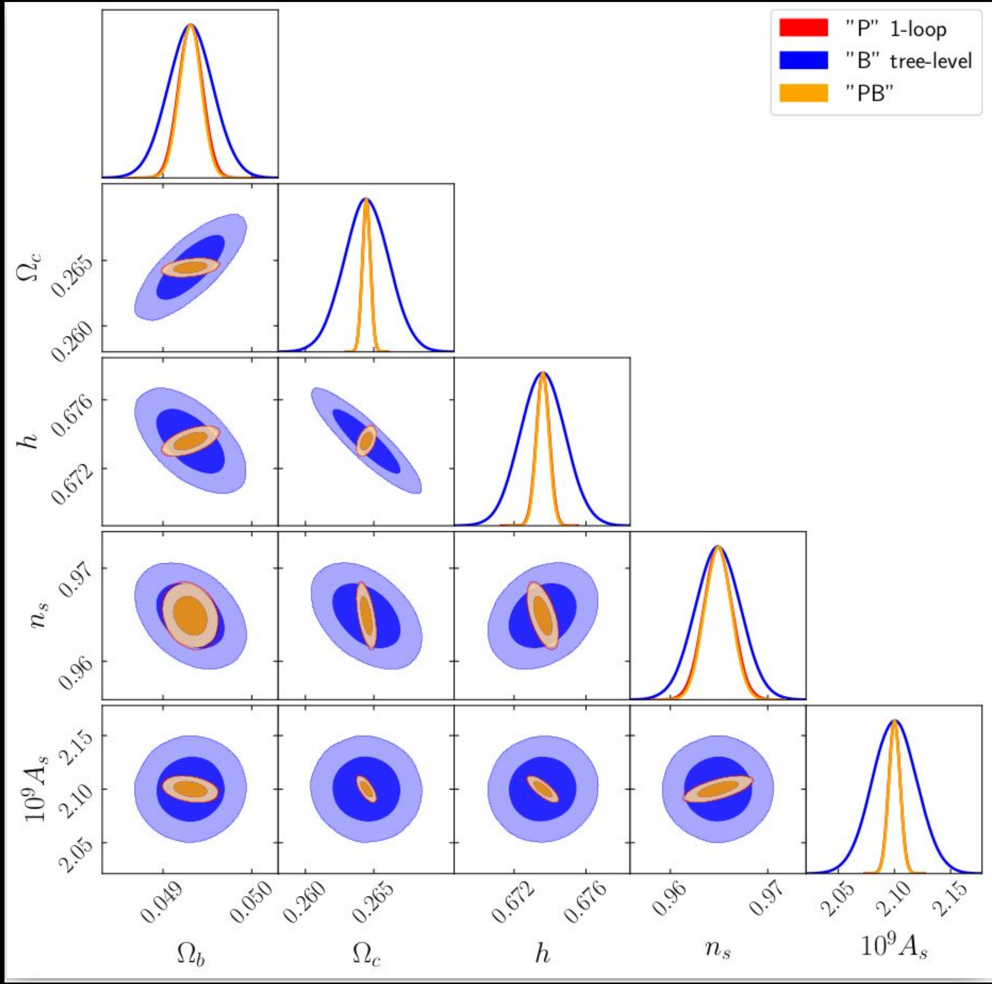


Courtesy: N. Sailer et al.

$$k^P_{\mathrm{max}}(z) = k_{\mathrm{max},0}\, D(z)^{-4/3.3}$$

$$k^B_{\mathrm{max}}(z) = 0.75\, k_{\mathrm{NL}}(z)$$

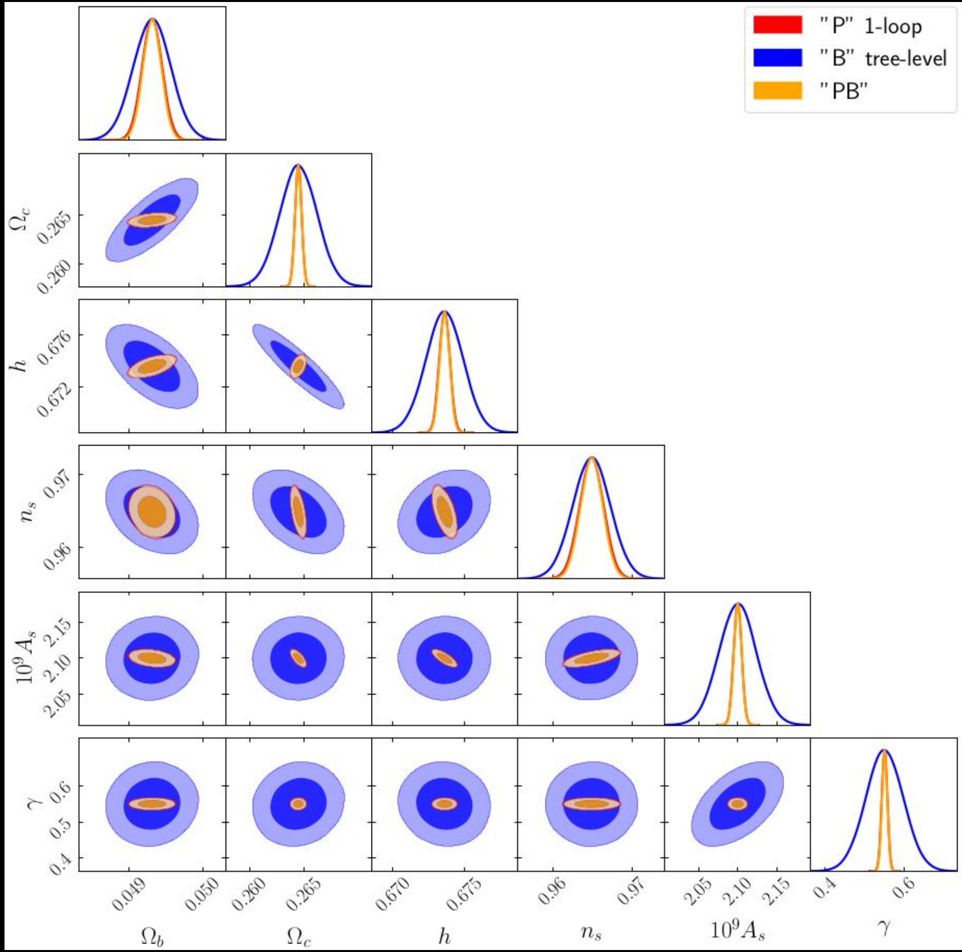
Result for ΛCDM



Cosmological parameters:
A_s : Scalar amplitude
n_s : Scalar spectral index (slope)
Ω_b : Baryon density parameter
Ω_c : Dark matter density parameter
h : Hubble parameter

- Marginalisation over bias and nuisance parameters
- Hirax breaks degeneracies between some parameter not all.
- Constraints can be improved if combine EFT 1-loop power spectrum with tree-level bispectrum

Extensions of ΛCDM (Modified gravity and Dark energy models) - γCDM



Cosmological parameters:

A_s : Scalar amplitude

n_s : Scalar spectral index (slope)

Ω_b : Baryon density parameter

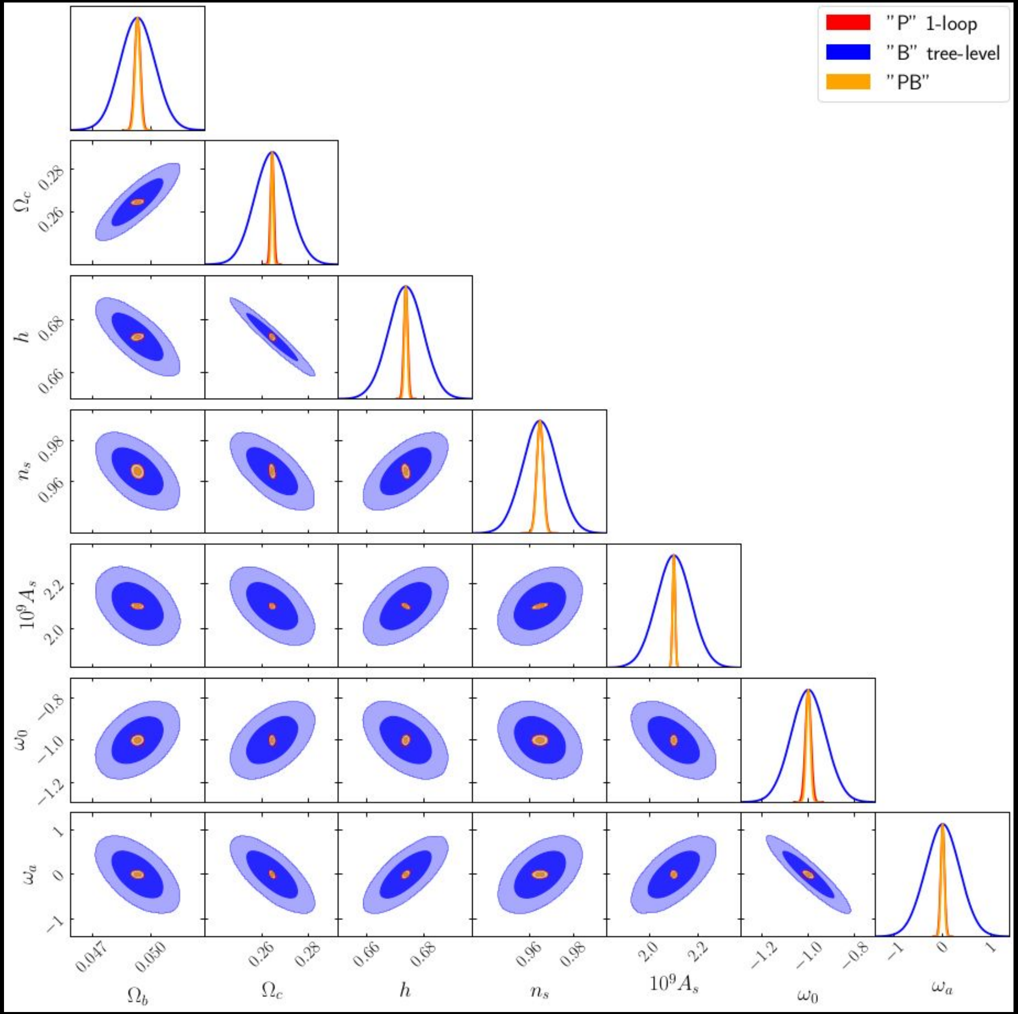
Ω_c : Dark matter density parameter

h : Hubble parameter

γ : Growth index (modified gravity parameter)

- The 1-loop power spectrum outperforms the tree-level bispectrum
- Degeneracies are broken between some parameters
- Constraints can be improved if the EFT 1-loop power spectrum is combined with a tree-level bispectrum.

- w0waCDM



Cosmological parameters:
A_s : Scalar amplitude
n_s : Scalar spectral index (slope)
Ω_b : Baryon density parameter
Ω_c : Dark matter density parameter
h : Hubble parameter
w0: Dark Energy E.o.S parameter
w : Dark Energy E.o.S parameter

- The more we add parameters, the more precision decreases due to the extra correlation
- Degeneracies are broken between some parameters
- The 1-loop power spectrum outperforms the tree-level bispectrum

Conclusion:

1. Cosmological constraints from the power spectrum and bispectrum of 21cm intensity maps

We find that, together with Planck priors, and marginalising over clustering bias and nuisance parameters:

.HIRAX achieves sub-percent precision on the ΛCDM parameters, with SKAO delivering slightly lower precision.

. The modified gravity parameter γ is constrained at 1% (HIRAX) and 5% (SKAO)

. For the dark energy parameters w0, wa, HIRAX delivers percent-level precision while SKAO constraints are weaker.

. HIRAX achieves sub-percent precision on the BAO distance functions DA, H, while SKAO reaches 1 - 2% for $0.6 \leq z \leq 1$.

. The growth rate f is constrained at a few-percent level for the whole redshift range of HIRAX and for $0.6 \leq z \leq 1$ by SKAO.

2. Cosmological constraints from the EFT power spectrum and tree-level bispectrum of 21cm intensity maps

Our finding with HIRAX consists of:

- The improvement of the constraints for the ΛCDM model when considering the NLO orders of the perturbative terms of the power spectrum in the EFT framework and also combing the power spectrum with the bispectrum provides better precision

- For the extensions of ΛCDM model, we got stringent constraints, which are at the level of 1.27% for the modified gravity parameter γ, and respectively 1.02% for w0, 3.80% for wa which are dynamical dark energy parameters.

- Compared to the tree-level power spectrum from our previous work, we find that EFT improves on Ωb, Ωc, and h precision.

- The EFT power spectrum demonstrates the potential to break parameter degeneracies.

Thank you !!!

- I am immensely grateful and feel incredibly lucky to have you as a role model, **Roy**.
- Your guidance and support throughout my PhD journey have been invaluable, and I am deeply appreciative.
- I am truly proud to be your student and to have learned under your mentorship.
- **I will forever cherish the legacy you have shared, especially your strong ethics and profound sense of humanity!**

MISAOTRA E!