Multiwavelength Cosmology with SKAO

Third National Workshop on the SKA Project

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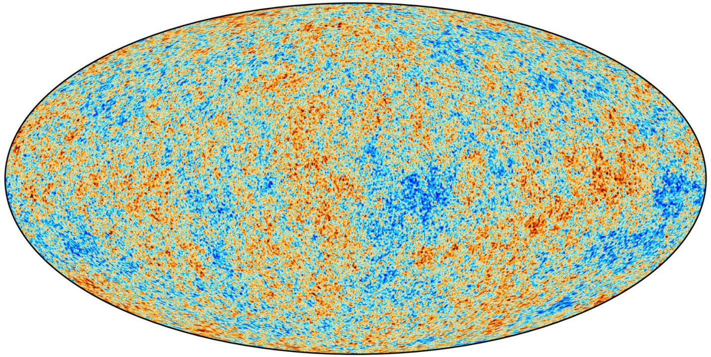
OAS

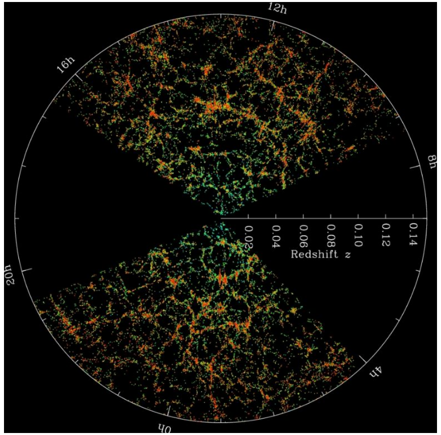
Current Situation

Precision cosmology data from **CMB** and large-scale structure (**LSS**):



https://www.cosmos.esa.int/web/planck

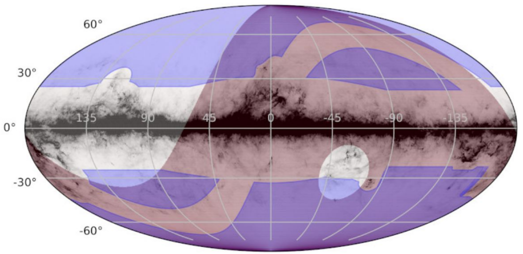
- Probes linear/quasilinear scales
- Cannot do tomography
- Systematics: astrophysical and instrumental

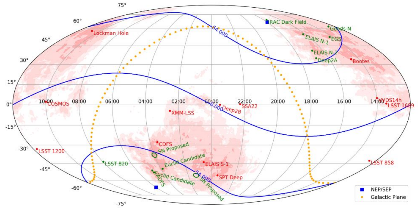


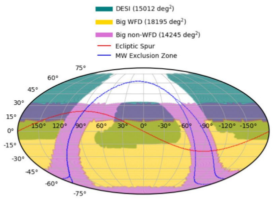
https://www.sdss.org

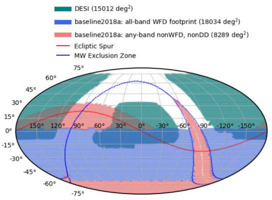
- Probes out to very small scales
- Can do tomography
- Systematics: photo-z, baryonic effects, intrinsic alignment…

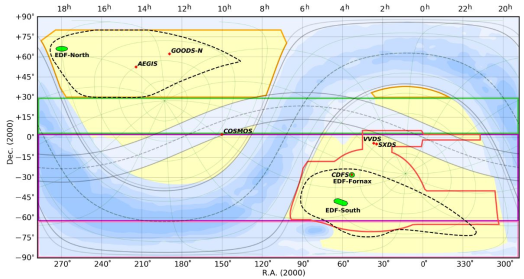
Future Situation

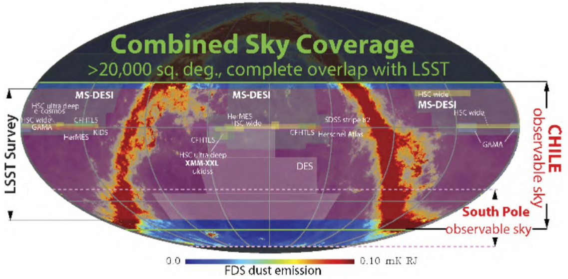












LSS:

- DESI (2021 -)
- Euclid (2022 - 2030)
- Rubin Observatory (2023 - 2033)
- SPHEREx (2024 - 2026)
- Roman Space Telescope (2025 - 2031)
- SKAO (2027 -)

CMB:

- Simons Observatory (2024 - 2027)
- CMB Stage-4 (2027 -)
- LiteBIRD (2028 - 2031)
- ...

What can Cross-Correlation add?

We want a **new product** from CMB and LSS data which can:

- Beat systematics (different/uncorrelated systematics)
- Construct new estimators → additional constraining power
- Enhance low amplitude signals → optimise use of data
- Probe interesting physics

The combination can be more than the sum of its parts!

What can we do with Cross-Correlation?

- Calibration of systematics, e.g. photo-z
- Primordial non-Gaussianity: initial conditions of the Universe
- Neutrinos mass and hierarchy
- Models of gravity on ultra-large scales, models of dark energy, ...

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Calibration

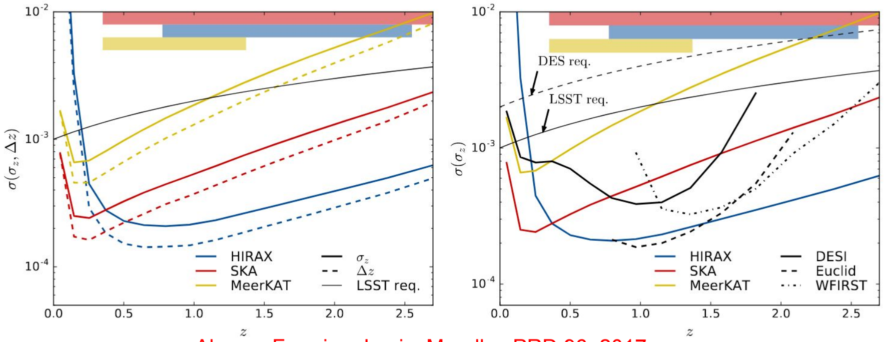
Intensity maps of the HI emission (or a spectroscopic galaxy survey) can be used to improve the scientific output of photometric redshift surveys.

- Gaussian photo-z

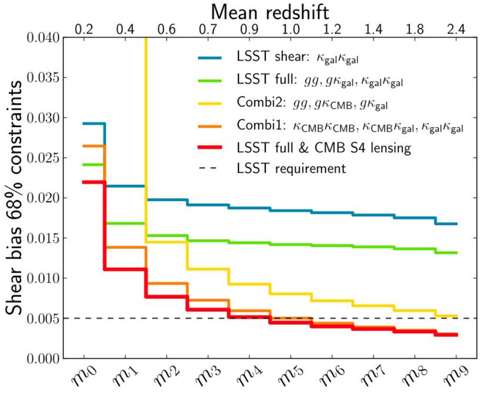
$$p\left(z_{\rm ph}|z\right) = \frac{1}{\sqrt{2\pi\sigma_z^2}} \exp\left[-\frac{\left(z_{\rm ph} - z - \Delta_z\right)^2}{2\sigma_z^2}\right]$$

- Multiplicative shear bias

$$\kappa_{{\rm gal},i} \longrightarrow \left(1 + m_i\right)\ \kappa_{{\rm gal},i}$$



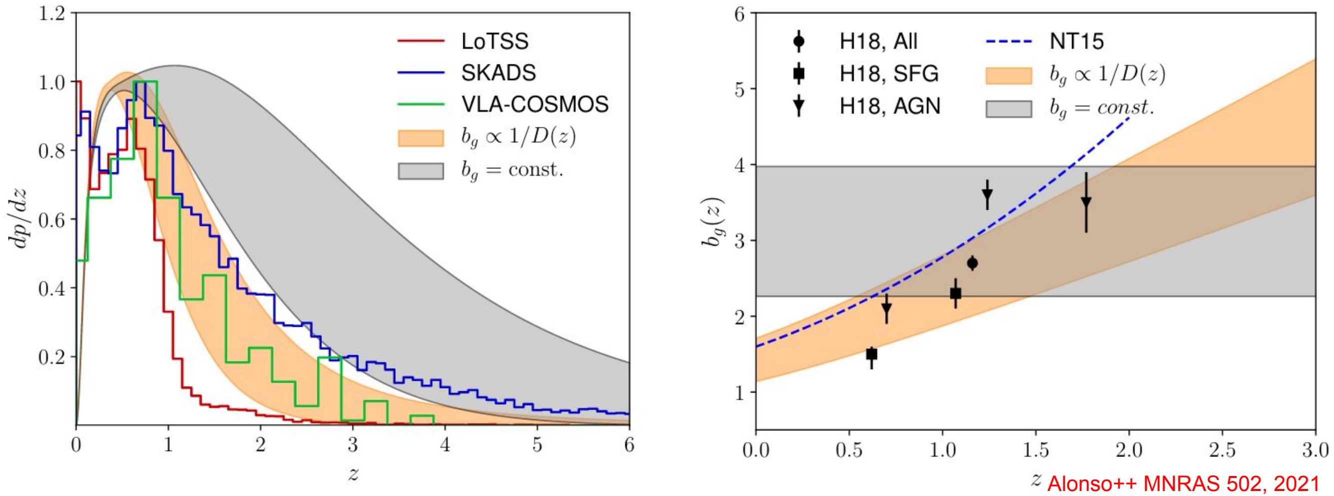
Alonso, Ferreira, Jarvis, Moodley PRD 96, 2017



Shaan++ PRD 95, 2017

Calibration

LoTSS DR1 cross-correlation CMB lensing allows to place constraints on the high-redshift tail of the redshift distribution, one of the largest sources of uncertainty in the use of continuum surveys for cosmology.



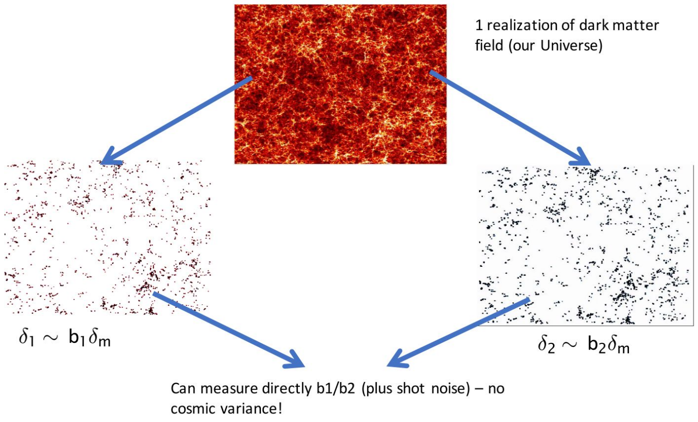
Alonso++ MNRAS 502, 2021

This could provide a robust way to extract cosmological information from samples with poor spectroscopic coverage in future surveys.

What can we do with Cross-Correlation?

- Calibration of systematics, e.g. photo-z
- **Primordial non-Gaussianity: initial conditions of the Universe**
- **Neutrinos mass and hierarchy**
- Models of gravity on ultra-large scales, models of dark energy, ...

Sampling Variance Cancellation



The ratio of the observed galaxy and lensing power spectrum (or another DM tracer) realizations has **no cosmic variance**, so that galaxy bias parameters on large scales can be measured with infinite precision from a single Fourier mode (Seljak PRL 102, 2009; McDonald, Seljak JCAP 10, 2009).

While being well studied for combination of biased tracers, e.g. IM x galaxies (Fonseca, Camera, Santos, Maartens ApJ 812, 2015), there is an expected further x2-3 factor improvement using combined LSS sample and CMB lensing (Schmittfull, Seljak PRD 97, 2018; **MB**, Matthewson, Maartens MNRAS 489, 2019; Bermejo-Climent, **MB**, Finelli++ PRD 103,2021; **MB**, Maartens 2109.03763).

Moreover, the use of cross-correlation measurements helps to **break parameter degeneracies**:

$$C_\ell^{gg} \propto b^2 \sigma_8^2$$
$$C_\ell^{\kappa g} \propto b \sigma_8^2$$

Formalism

Cross-correlating two projected 2D fields:

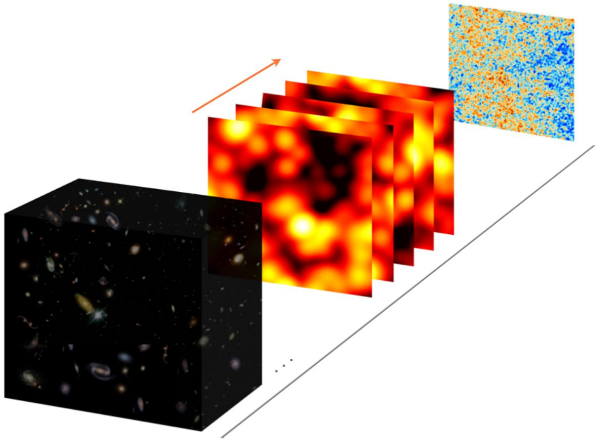
$$C_\ell^{\rm XY} = 4\pi \int \frac{{\rm d}k}{k} \mathcal{P}_{\mathcal{R}}(k) I_\ell^{\rm X}(k) I_\ell^{\rm Y}(k)$$

with kernels:

$$I_\ell^{\Delta}(k, z_{\rm i}) = \int {\rm d}z\, W(z, z_{\rm i})\, \Delta_\ell(k, z)$$

$$I_\ell^{\rm ISW}(k) = \int {\rm d}z\, e^{-\tau(z)} \mathcal{T}_{\dot\phi+\dot\psi}(k, z)\, j_\ell(k\chi(z))$$

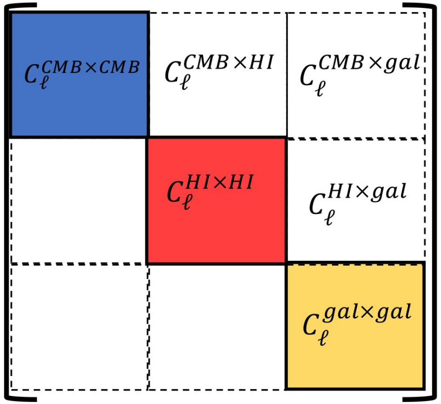
$$I_\ell^{\phi}(k) = \frac{3\Omega_{m,0} H_0^2}{k^2 c} \int_0^\infty \frac{{\rm d}z}{(2\pi)^{3/2}} \frac{1+z}{H(z)} \left(\frac{\chi(z_*) - \chi(z)}{\chi(z_*)\chi(z)} \right) \delta_k^{\rm c}(z) j_\ell(k\chi(z))$$



Silva++ 1908.07533, 2019

So cross-correlation expresses the “overlap” between two projected fields that at least in part probe the same underlying signal.

Forecasts Ingredients



Three-Tracers Analysis:

- CMB lensing reconstruction κ from **CMB-S4**
  (assume θ_{FWHM} = 3 arcmin, $\sigma_T = \sigma_P/2$ = 1 μK^2 arcmin^2).
- Various LSS samples: SKAO-MID, PUMA, Euclid, LSST.
- Split LSS samples into redshift bins: SKAO-MID (27), PUMA (57), Euclid (10), LSST (10).
- Marginalizing over cosmological parameters plus two bias parameter per redshift bin, i.e. clustering and magnification bias.
- Focusing on quasi-linear scales $k_{max} \leq 0.1$ h/Mpc.
- Assuming for each survey his own sky coverage (they do not perfectly overlap).

Forecasts Ingredients

Intensity maps of the 21cm emission of neutral hydrogen observed by SKAO (single-dish mode) and by PUMA (interferometer mode).

$$b_{\rm HI}(z) = 0.667 + 0.178\, z + 0.0502\, z^2 ,$$
$$\bar{T}_{\rm HI}(z) = 0.0559 + 0.232\, z - 0.0241\, z^2 \text{ mK}.$$

- **SKAO** (MeerKLASS Collaboration 1709.06099)

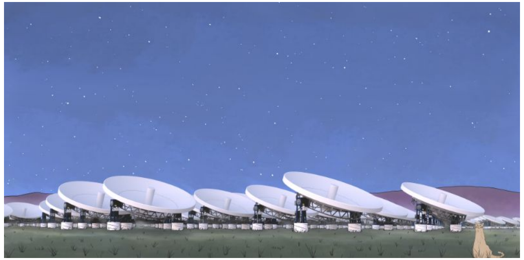
$$\sigma_{\rm HI}(\nu_i) = \frac{4\pi f_{\rm sky} T^2_{\rm sys}(\nu_i)}{2 N_{\rm dish}\, t_{\rm tot}\, \Delta\nu} ,$$
$$T_{\rm sys}(\nu_i) = 25 + 60 \left(\frac{300\,\text{MHz}}{\nu_i}\right)^{2.55} \text{K}$$
$$N_\ell^{\rm HI}(\nu_i) = \sigma_{\rm HI}(\nu_i)\, B_\ell^{-2}(\nu_i)$$
$$B_\ell = \exp\left[-\ell(\ell+1)\frac{\theta^2_{\rm FWHM}}{16 \ln 2}\right]$$

$N_{\rm dish} = 197$
$D_{\rm dish} = 15$ m
$t_{\rm tot} = 10^4$ hr
$f_{\rm sky} = 20,000 \text{ deg}^2$
$0.35 < z < 3.05$ (Band1)

- **PUMA** (PUMA Collaboration 1907.12559)

$$N_\ell^{\rm HI}(\nu_i) = \frac{4\pi f_{\rm sky} T^2_{\rm sys}(\nu_i)}{2 N_{\rm dish}\, t_{\rm tot}\, \Delta\nu} \frac{\theta^2_{\rm FWHM}(\lambda_i)}{\eta^2\, N_{\rm b}\,(\ell\lambda_i/(2\pi))\, \lambda_i^2}$$
$$T_{\rm sys}(\nu_i) = \widetilde{T}_{\rm ampl} + \widetilde{T}_{\rm ground} + T_{\rm sky}$$
$$T_{\rm sky}(\nu_i) = 2.7 + 25 \left(\frac{400\,\text{MHz}}{\nu_i}\right)^{2.75} \text{K}$$

$N_{\rm dish} = 32,000$
$D_{\rm dish} = 6$ m
$t_{\rm tot} = 4 \times 10^4$ hr
$f_{\rm sky} = 50\%$
$0.3 < z < 6$



Forecasts Ingredients

Next-generation of deep and wide photometric galaxy survey

$$\bar{n}_g(z) \propto z^{\alpha} \exp\left[-\left(\frac{z}{z_0}\right)^{\beta}\right] \text{ gal/arcmin}^2$$

$$p(z_{\rm ph}|z) = \frac{1}{\sqrt{2\pi}\,\sigma_z} \exp\left[-\frac{(z-z_{\rm ph})^2}{2\sigma_z^2}\right]$$

$$\mathcal{N}_\ell^{gi} = \left(\int {\rm d}z\, n_g^i(z)\right)^{-1}$$

$$\Delta_\ell^{\rm GR} \equiv \Delta_\ell^{\rm L} + \Delta_\ell^{\rm V} + \Delta_\ell^{\rm ULS}\,,$$

$$\Delta_\ell^{\rm L} = \frac{\ell(\ell+1)}{2}(2-5s) \times \int_0^{\chi} {\rm d}\tilde\chi \frac{(\chi-\tilde\chi)}{\chi\tilde\chi}\left[\psi_{\boldsymbol k}(\tilde\chi)+\phi_{\boldsymbol k}(\tilde\chi)\right] j_\ell(k\tilde\chi)$$

$$\Delta_\ell^{\rm V} = \left[\frac{2-5s}{\mathcal{H}\chi} + 5s - b_e + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right] v_{\boldsymbol k}\, j'_\ell(k\chi)\,,$$

$$\Delta_\ell^{\rm ULS} = \left\{\left[\frac{2-5s}{\mathcal{H}\chi} + 5s - b_e + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + 1\right]\psi_{\boldsymbol k} + (5s-2)\phi_{\boldsymbol k} + \frac{\dot\phi_{\boldsymbol k}}{\mathcal{H}} + (b_e-3)\,\mathcal{H}\frac{v_{\boldsymbol k}}{k}\right\} j_\ell(k\chi) + \left[\frac{2-5s}{\mathcal{H}\chi} + 5s - b_e + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right]\int_0^{\chi} {\rm d}\tilde\chi \left[\dot\psi_{\boldsymbol k}(\tilde\chi) + \dot\phi_{\boldsymbol k}(\tilde\chi)\right] + \frac{(2-5s)}{\chi}\int_0^{\chi} {\rm d}\tilde\chi\left[\psi_{\boldsymbol k}(\tilde\chi)+\phi_{\boldsymbol k}(\tilde\chi)\right] j_\ell(k\tilde\chi)\,.$$

- **Euclid**-like (Euclid preparation VII A&A 642, 2020)

$$b(z) = \sqrt{1+z}$$
$$\bar{n}_g = 30$$
$$f_{\rm sky} = 15,000 \text{ deg}^2$$
$$\sigma_z = 0.05(1+z)$$
$$0 < z < 2.5$$

- Rubin Observatory (**LSST**-like) (LSST DESC arXiv:1809.01669)

$$b(z) = 0.95/D(z)$$
$$\bar{n}_g = 48$$
$$f_{\rm sky} = 13,800 \text{ deg}^2$$
$$\sigma_z = 0.03(1+z)$$
$$0.2 < z < 1.2$$

Primordial non-Gaussianity

Primordial non-Gaussianity: probes the initial conditions of our Universe.
Current constraints f_{NL} = −0.9 ± 5.1 at 68% CL from the *Planck* 2018.

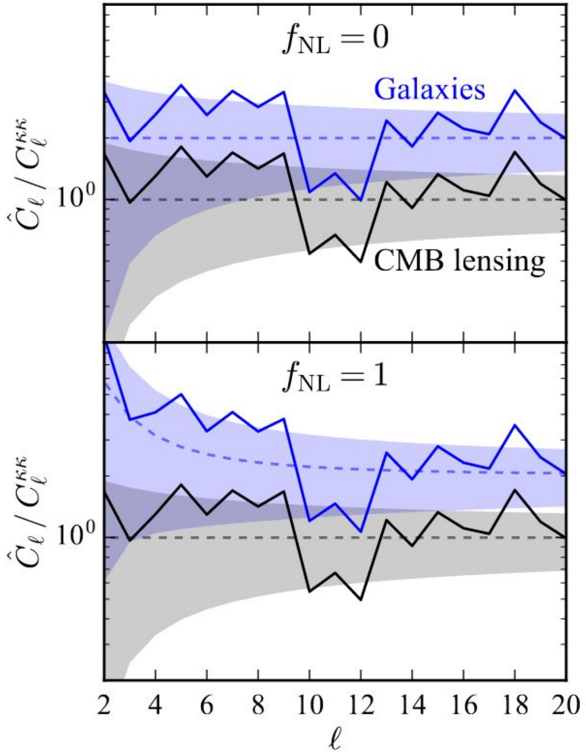
- Local primordial non-Gaussianity:

$$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}\left(\phi^2(\mathbf{x}) - \langle\phi^2\rangle\right) + \mathcal{O}\left(\phi^3\right)$$

- Mostly probes single-field vs multifield inflation (f_{NL} > 1).

- Leaves an imprint in the large-scale-dependence of the bias (Dalal, Doré, Huterer, Shirokov PRD 77, 2008; Matarrese, Verde ApJ 677, 2008):

$$\Delta b_1^E(k,z) = \frac{3\Omega_m H_0^2 f_{\rm NL}}{D(z)k^2T(k)}\delta_c(b_1^E(z) - p) \propto \frac{1}{k^2}$$



Schmittfull, Seljak PRD 97, 2018

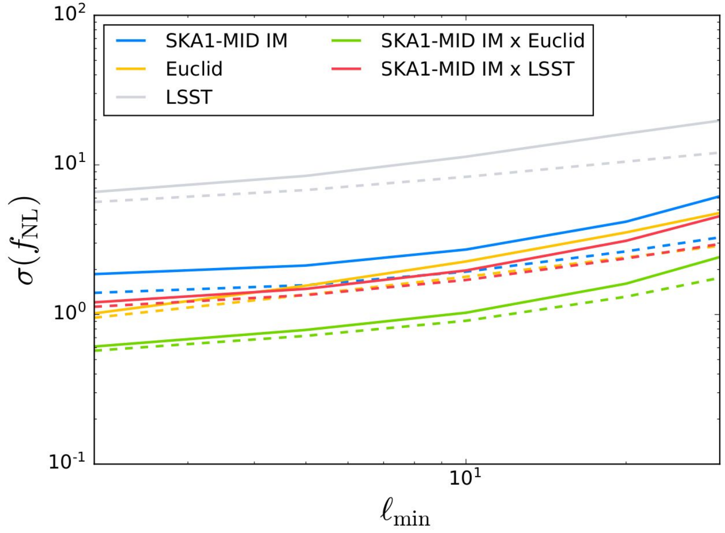
Primordial non-Gaussianity

MB, Matthewson, Maartens MNRAS 489, 2019

- Single tracer: $$\sigma(f_{\rm NL}) \simeq \begin{cases} 2.1 & \text{SKA1 } (\ell_{\rm min} = 5)\,, \\ 2.3 & \text{Euclid-like } (\ell_{\rm min} = 10)\,, \\ 16.2 & \text{LSST-like } (\ell_{\rm min} = 20)\,. \end{cases}$$

- Two tracers: $$\sigma(f_{\rm NL}) \simeq \begin{cases} 1.6 & \text{SKA1} \times \text{CMB-S4}\,, \\ 1.8 & \text{Euclid-like} \times \text{CMB-S4}\,, \\ 10.5 & \text{LSST-like} \times \text{CMB-S4}\,. \end{cases}$$ $$\sigma(f_{\rm NL}) \simeq \begin{cases} 0.96 & \text{SKA1} \times \text{Euclid-like}\,, \\ 1.6 & \text{SKA1} \times \text{LSST-like}\,. \end{cases}$$

- Three tracers: $$\sigma(f_{\rm NL}) \simeq \begin{cases} 0.90 & \text{SKA1} \times \text{Euclid-like} \times \text{CMB-S4}\,, \\ 1.4 & \text{SKA1} \times \text{LSST-like} \times \text{CMB-S4}\,. \end{cases}$$



Extending the minimum multipole down to $\ell_{\rm min}$ = 2 we would reduce the uncertainties by a factor 1.5-2.

Primordial non-Gaussianity

MB, Matthewson, Maartens MNRAS 489, 2019

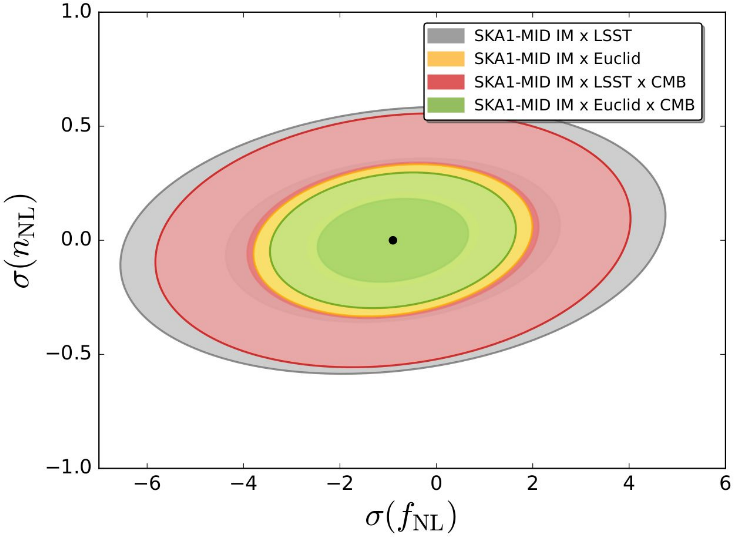
Extension to a running amplitude (Chen PRD 72, 2005):

$$f_{\rm NL}(k) = f_{\rm NL}\left(\frac{k}{k_{\rm piv}}\right)^{n_{\rm NL}}$$

Current constraints $-0.6 < n_{\rm NL} < 1.4$ at 68% CL for single-field curvaton scenario (Oppizzi++ JCAP 05, 2018).

$$\sigma\left(n_{\rm NL}\right) \simeq \begin{cases} 0.12 & \text{SKA1} \times \text{Euclid-like} \times \text{CMB-S4}\,, \\ 0.22 & \text{SKA1} \times \text{LSST-like} \times \text{CMB-S4}\,. \end{cases}$$

uncertainties on $f_{\rm NL}$ degradate by ~20%.



Primordial non-Gaussianity

$$\delta_g = \left(b_1 + \frac{\boxed{b_1 b_\phi f_{\rm NL}}}{\alpha}\right)\delta_m + \dots$$

The way to break this degeneracy is to assume a universal relation between b_ϕ and b_1. However:

- there is no guarantee that the universality relation is not necessary satisfied even for haloes in gravity only simulations
- simulations suggest that the exact relation is very likely tracer-dependent (Barreira++ JCAP 12, 2020; Barreira JCAP 12, 2020).

$$b_\phi = 2\delta_c(b_1 - 1)$$

$$\boxed{\begin{aligned} b_\phi &= 2\delta_c(b_1 - p) \\ b_\phi &= 2q\delta_c(b_1 - 1) \end{aligned}}$$

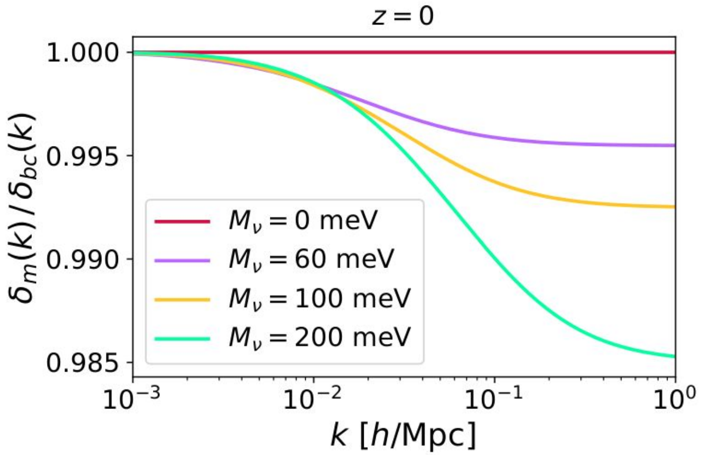
The addition of bispectrum information does not tighten the constraints for $f_{NL}b_\phi$ without making any assumption on the relation between b_ϕ and b_1.

Neutrino Mass

On scales larger than the neutrino free-streaming scale, and when neutrinos are non-relativistic, the bc and ν fluids are tightly coupled. On smaller scales, neutrino perturbations are damped and neutrinos do not cluster (Villaescusa-Navarro++ JCAP 03, 2014; LoVerde PRD 90, 2014).

$$\delta_m = \frac{\Omega_{bc}\delta_{bc} + \Omega_\nu \delta_\nu}{\Omega_m} = (1 - f_\nu)\delta_{bc} + f_\nu \delta_\nu$$

This adds to main signal from shape of total matter power spectrum (independent information).



Potential bias on cosmological parameters by neglecting this scale dependence (Raccanelli, Verde, Villaescusa-Navarro MNRAS 483, 2019).

Neutrino Mass

MB, Maartens 2109.03763, 2021

- Two tracers:

$$\sigma\left(M_\nu\right) \simeq \begin{cases} 45\ \mathrm{meV} & \text{SKAO-MID} \times \text{CMB-S4}\,, \\ 26\ \mathrm{meV} & \text{PUMA} \times \text{CMB-S4}\,, \\ 62\ \mathrm{meV} & \text{LSST} \times \text{CMB-S4}\,, \end{cases}$$

- Three tracers:

$$\sigma\left(M_\nu\right) \simeq \begin{cases} 12\ \mathrm{meV} & \text{SKAO-MID} \times \text{LSST} \times \text{CMB-S4}\,, \\ 11\ \mathrm{meV} & \text{PUMA} \times \text{LSST} \times \text{CMB-S4}\,, \end{cases}$$

Limiting on quasi-linear scales $k_{max} \leq 0.1$ h/Mpc and without a prior on the reionization optical depth.

Conclusions

Cross-correlation between SKAO and other observables which could:

- Beat systematics
- Create new estimators
- Handle redshift uncertainties
- Probe interesting physics as primordial non-Gaussianity and neutrino mass.
  This effect relies on sampling variance cancellation to measure scale-dependent bias (in general large-scale effects).

SKAO-MID IM x CMB x gal-photo:

- f_{NL} forecasts (< 1 at 68% CL) promising even if galaxy-galaxy auto-spectra are excluded. Results do not depend on small scales k_{max} > 0.1 h/Mpc but strongly depend on smallest multipole ℓ_{min} = 2 - 30.

- Neutrino mass constraints (~ 10 meV with $k_{max} \leq$ 0.1 h/Mpc and without a prior on the reionization optical depth) do not depend on small multipoles ℓ_{min} < 30 since neutrino free-streaming scale k ~ 0.05 h/Mpc.