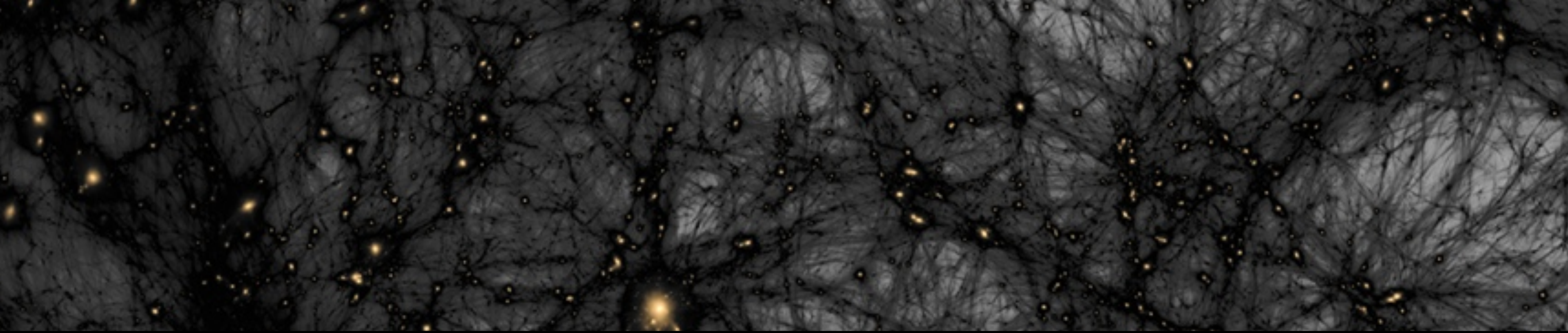
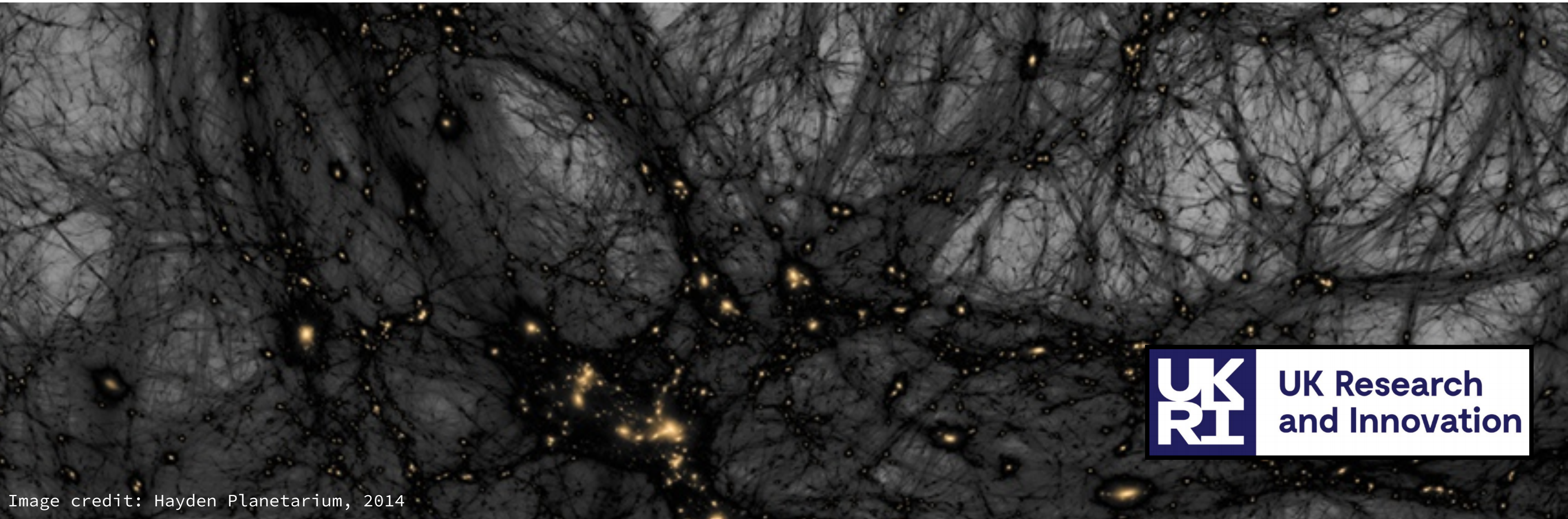


# Neutral hydrogen intensity mapping

*Alkistis Pourtsidou*
*Higgs Centre & Institute for Astronomy*
THE UNIVERSITY OF EDINBURGH



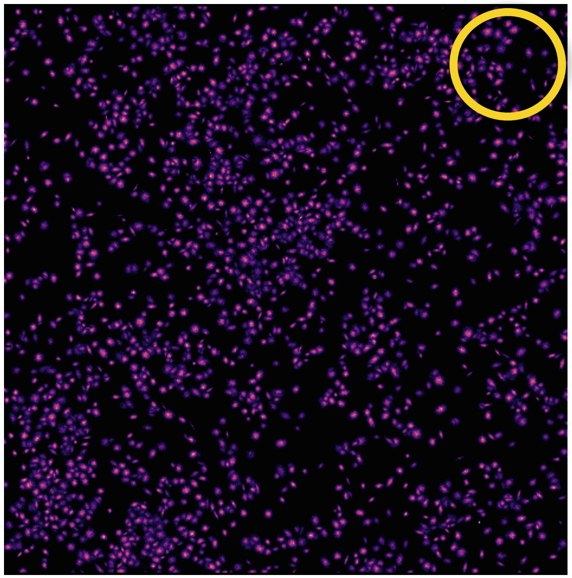
UK Research and Innovation

Image credit: Hayden Planetarium, 2014

# RADIO PRECISION COSMOLOGY: THE INTENSITY MAPPING METHOD

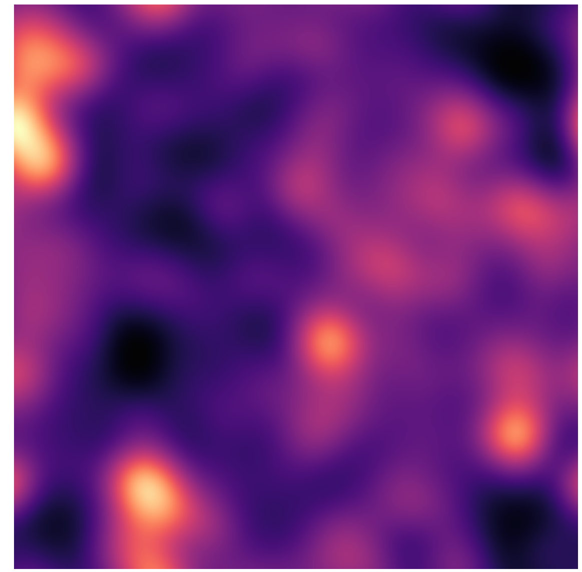
*[Chang et al 2008, Peterson et al 2009, Seo et al 2010, …]*

Galaxies



the telescope beam

Intensity map



Credit: S. Cunnington

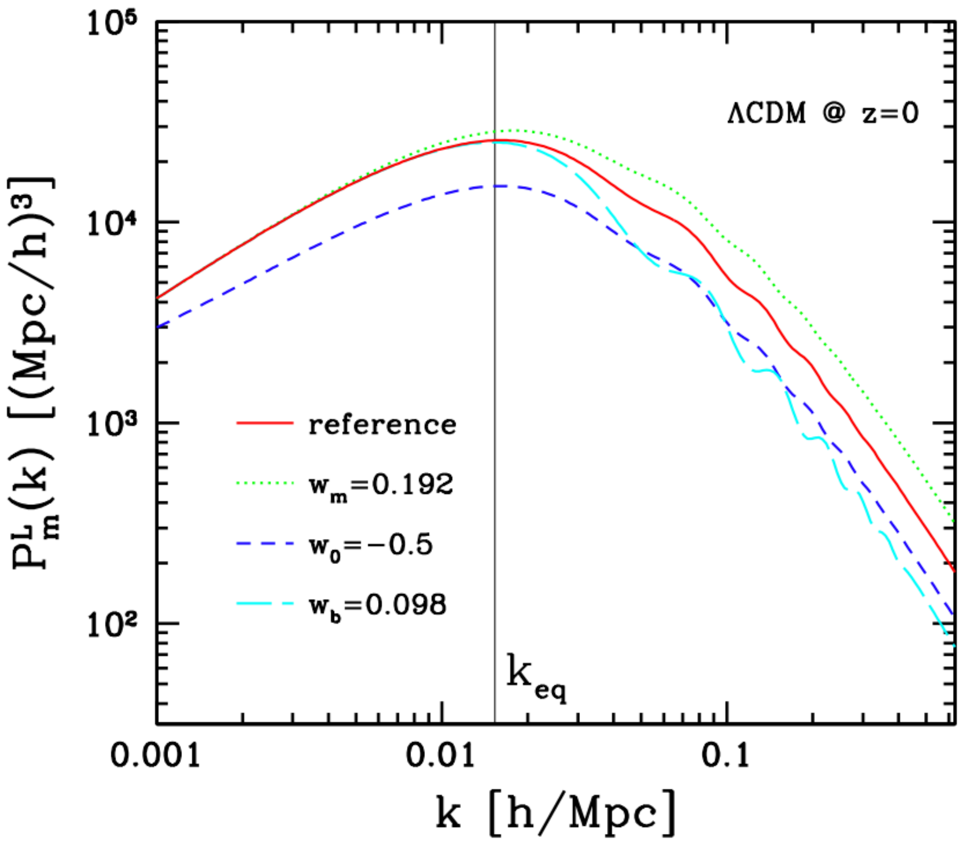
- Need redshifts: expensive
- 21cm line – sparse arrays not sensitive enough to be competitive, unless used in “single-dish” mode (MeerKAT, SKA)

- Intensity mapping is fast and gets all the photons
- High redshift resolution

21cm IM surveys: GBT, CHIME, HIRAX, MeerKAT, SKA, and more!

# FROM MAPS TO SUMMARY STATISTICS: THE POWER SPECTRUM

The better we measure the power spectrum, the better constraints on alternative theories (e.g. exotic dark energy, modified gravity) we will get!



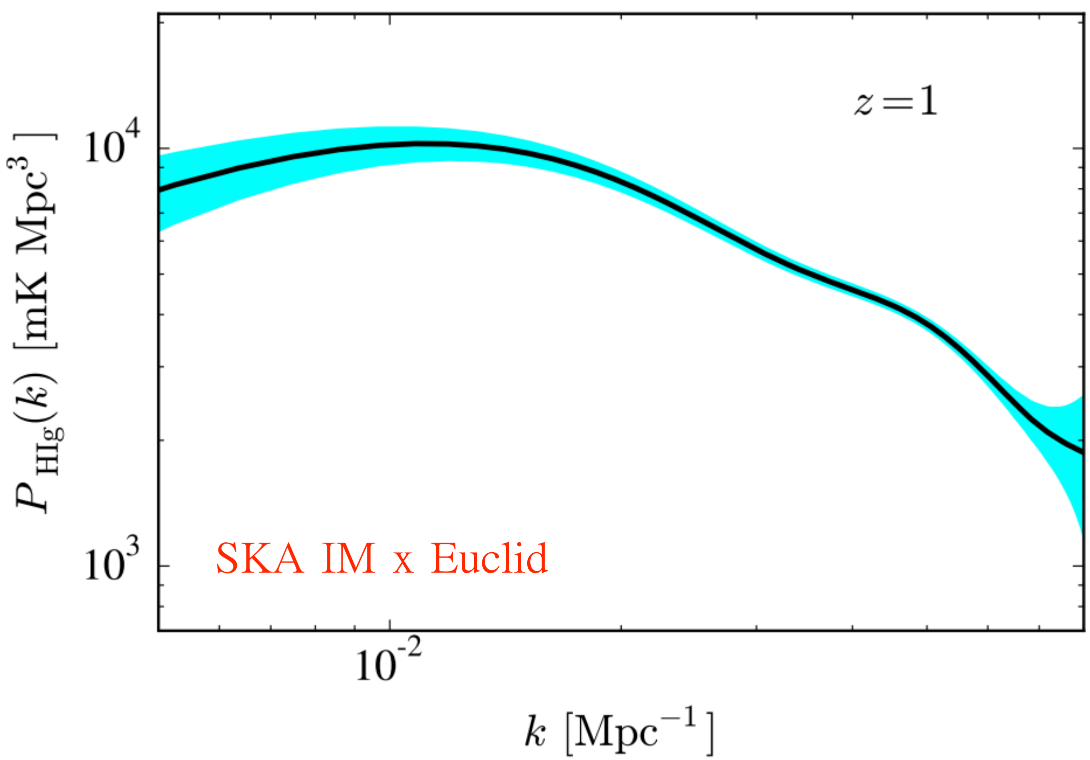

[Plot credit: Shun Saito]

# NEUTRAL HYDROGEN INTENSITY MAPPING POWER SPECTRUM

- With intensity mapping we can constrain HI and cosmological parameters

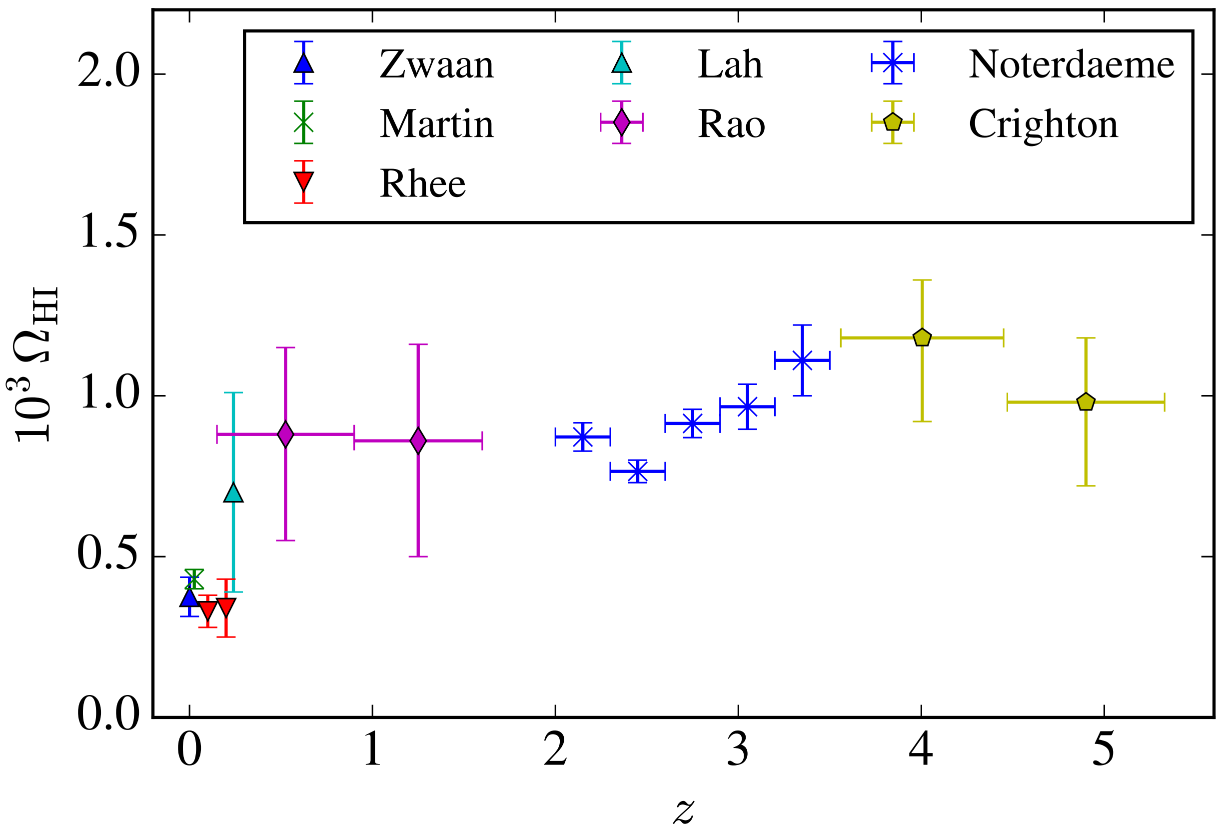
$$P_{\rm HI} \propto \Omega_{\rm HI}^2 b_{\rm HI}^2 P_{\rm m} \qquad P_{\rm HI,g} \propto \Omega_{\rm HI} b_{\rm HI} b_g r P_{\rm m}$$

- The r coefficient tells us about the HI content of different galaxy samples



# INTENSITY MAPPING AND GALAXY EVOLUTION

- HI abundance is currently quite poorly constrained…
- Important for astrophysics and cosmology alike!



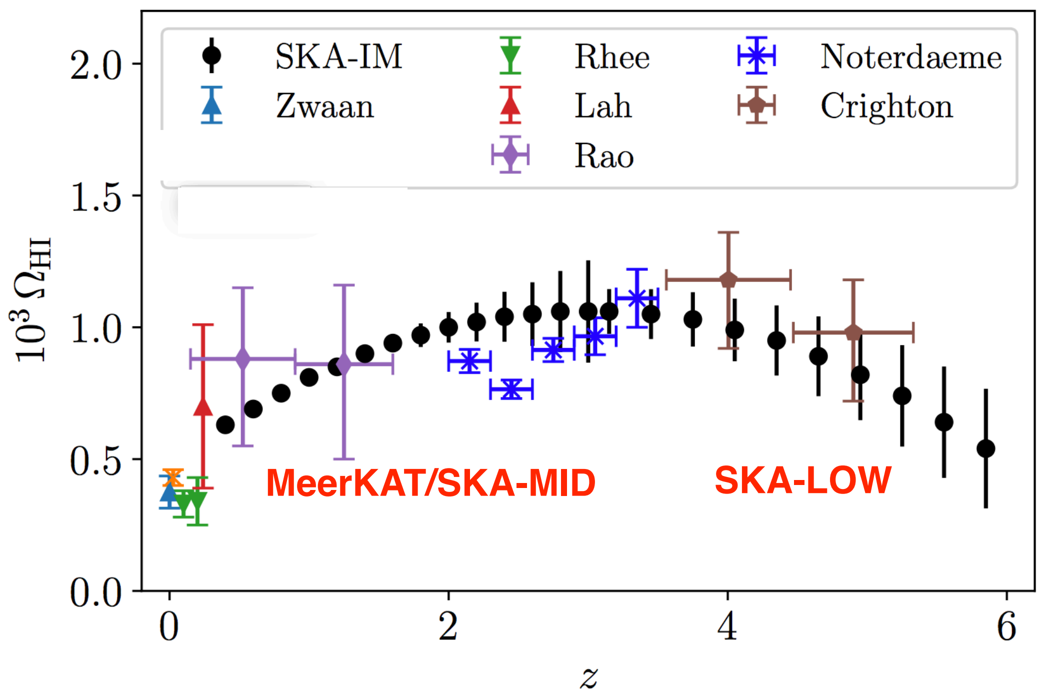

[c.f. Crighton et al 2015]

# GALAXY EVOLUTION

- Can greatly improve HI constraints with intensity mapping
- Cross-correlation with optical surveys helps with systematics and allows for studying the HI content of different galaxy samples

$$P_{\mathrm{HI}} \propto \Omega_{\mathrm{HI}}^2 b_{\mathrm{HI}}^2 P_{\mathrm{m}}$$

$$P_{\mathrm{HI,g}} \propto \Omega_{\mathrm{HI}} b_{\mathrm{HI}} b_g r P_{\mathrm{m}}$$




[Pourtsidou et al. 2017, SKA cosmology Red Book 2018]

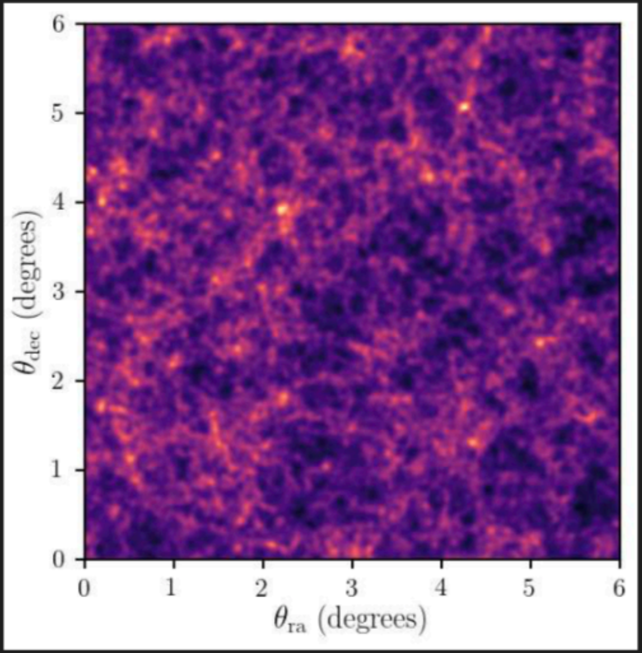
# SIMULATING 21CM OBSERVATIONS

work with S. Cunnington, P. Soares, C. Watkinson

## SIMULATIONS

*N*-body Sim → Halo Model → Galaxy Catalogue → HI galaxy properties → 21cm Intensity Map

$$\delta T_{\rm obs}(z) = \delta T_{\rm HI}(z) + \delta T_{\rm noise}(z) + \sum_i \delta T_i^{\rm FG}(z)$$




Intensity map using S$^3$SAX-Sky

# THE FOREGROUND CONTAMINATION PROBLEM

## Difficulties

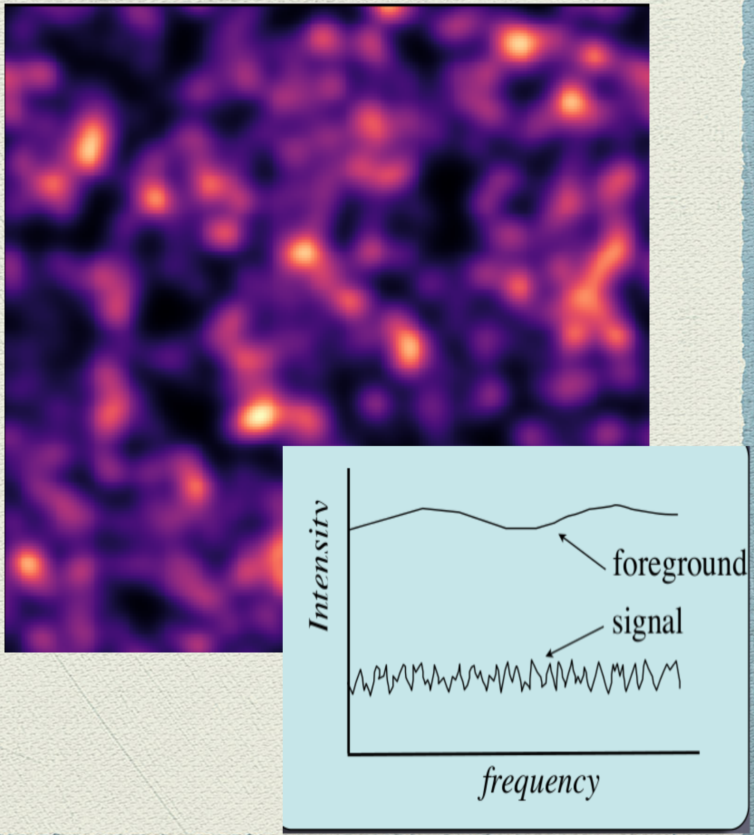
- 21cm signal is very weak
- Foregrounds are a big problem!

(i) Galactic synchrotron - relativistic cosmic ray electrons accelerated by the galactic magnetic field

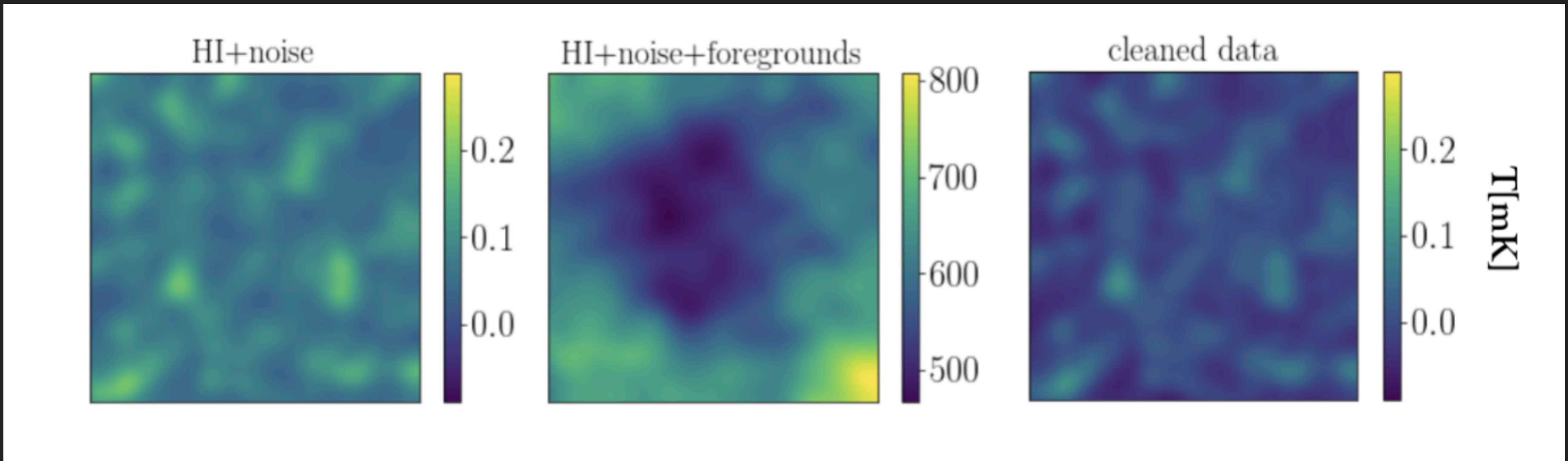
(ii) Extra-galactic point sources - objects beyond our own galaxy emitting signals close to 21cm signal

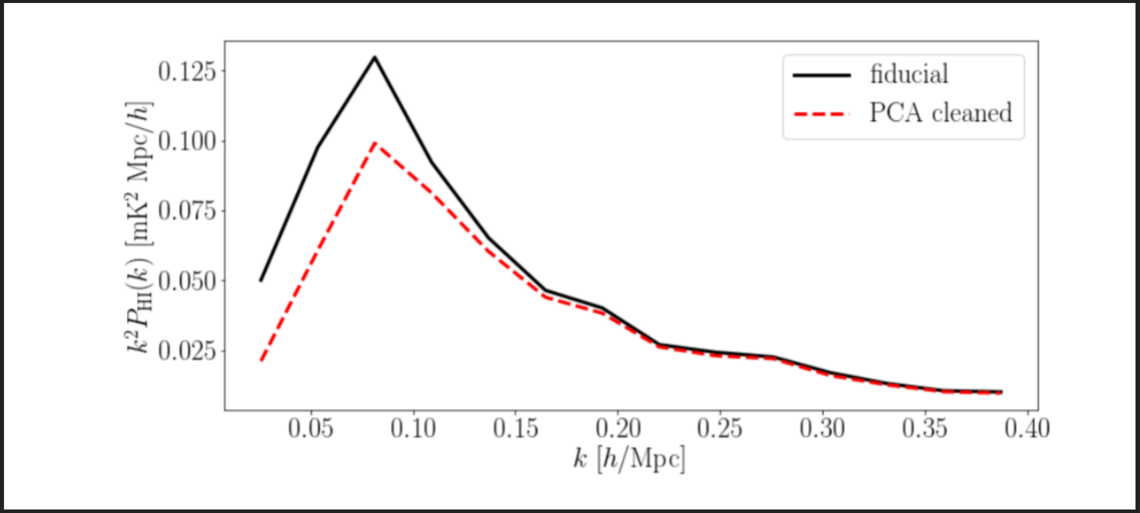
(iii) Extra-galactic free-free emission - free electrons scattering off ions without being captured and remaining free after the interaction

(iv) Galactic free-free emission - as above but within our own galaxy



# 21CM FOREGROUNDS CLEANING: SIGNAL LOSS EFFECT




Soares, Cunnington, AP, Blake 2020

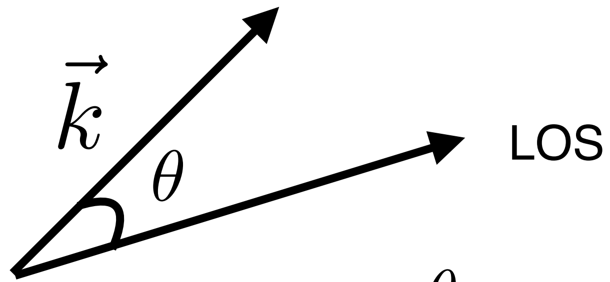
**Also see work by e.g. Alonso et al., Chapman et al., Shaw et al., Wolz et al.**

- Following optical galaxy surveys, we express the anisotropic power spectrum with the help of Legendre multipoles

$$P^{\rm obs}(k,\mu) = \sum_{\ell} P_\ell(k)\mathcal{L}_\ell(\mu)$$

The multipoles can be expressed as

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu P^{\rm obs}(k,\mu)\mathcal{L}_\ell(\mu)$$




$$\mu \equiv cos\theta$$

- Monopole: ell = 0, our well known spherically averaged power spectrum
- Dipole ell = 1, quadrupole ell = 2, hexadecapole ell = 4, etc.

# Power spectrum multipoles

- What happens in linear theory?

$$P^{\rm sig}(k,\mu) = b^2(1+\beta\mu^2)^2 P_m^{\rm lin}(k)\,,$$

where $\beta = f/b$. Since the Kaiser formula contains terms only up to $\mu^4$, only the monopole, quadrupole, and hexadecapole are non-vanishing and we find:

$$P_0(k) = \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right) b^2 P_m^{\rm lin}(k)$$

$$P_2(k) = \left(\frac{4}{3}\beta + \frac{4}{7}\beta^2\right) b^2 P_m^{\rm lin}(k)$$

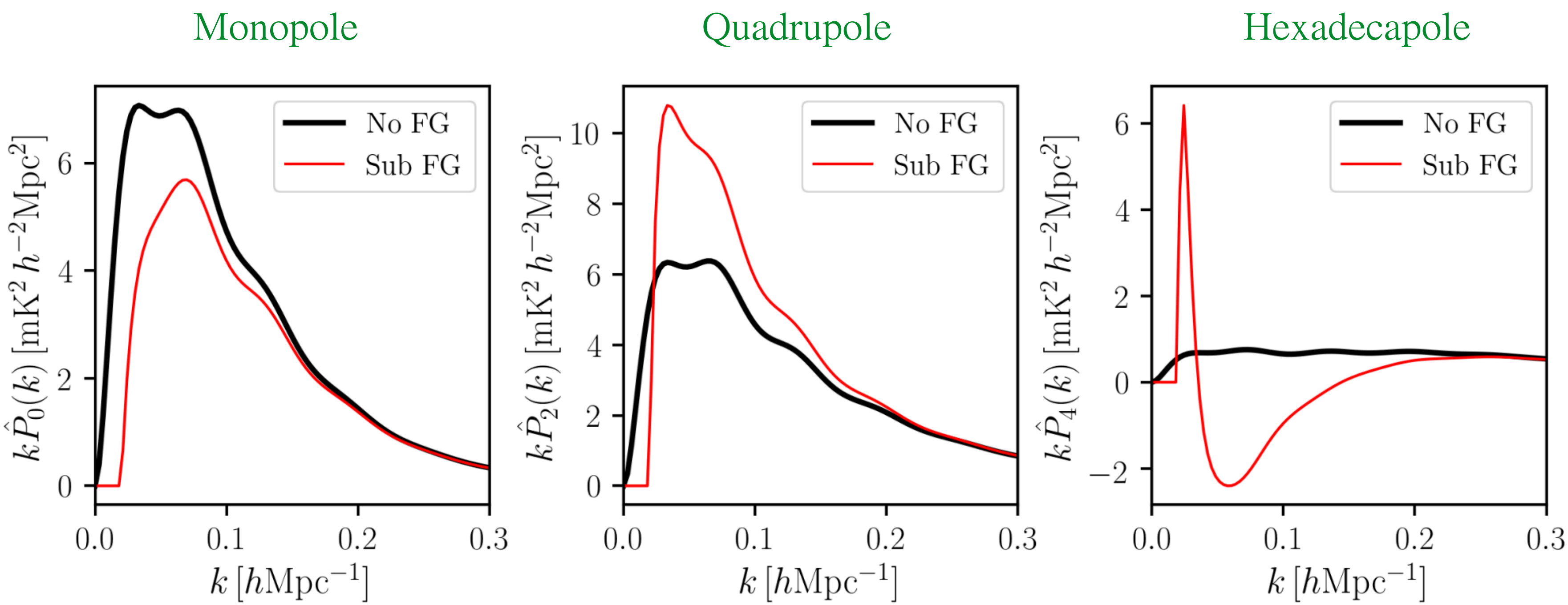
$$P_4(k) = \frac{8}{35}\beta^2 b^2 P_m^{\rm lin}(k)\,.$$

- Quadrupole and hexadecapole are smoking gun for RSDs
- Dipole should be zero
- Higher order multipoles should be zero (in linear theory)
- Even when nonlinearities and other effects are taken into account the above should approximately hold (any extra signatures should be "small")

# ANISOTROPIC SYSTEMATIC EFFECTS

- Anisotropic systematic effects like beam and foreground removal signal loss will make our observed multipoles disagree with our theoretical modelling

- This is a general statement for single-dish experiments, interferometers, and EoR experiments … they all have anisotropic systematics

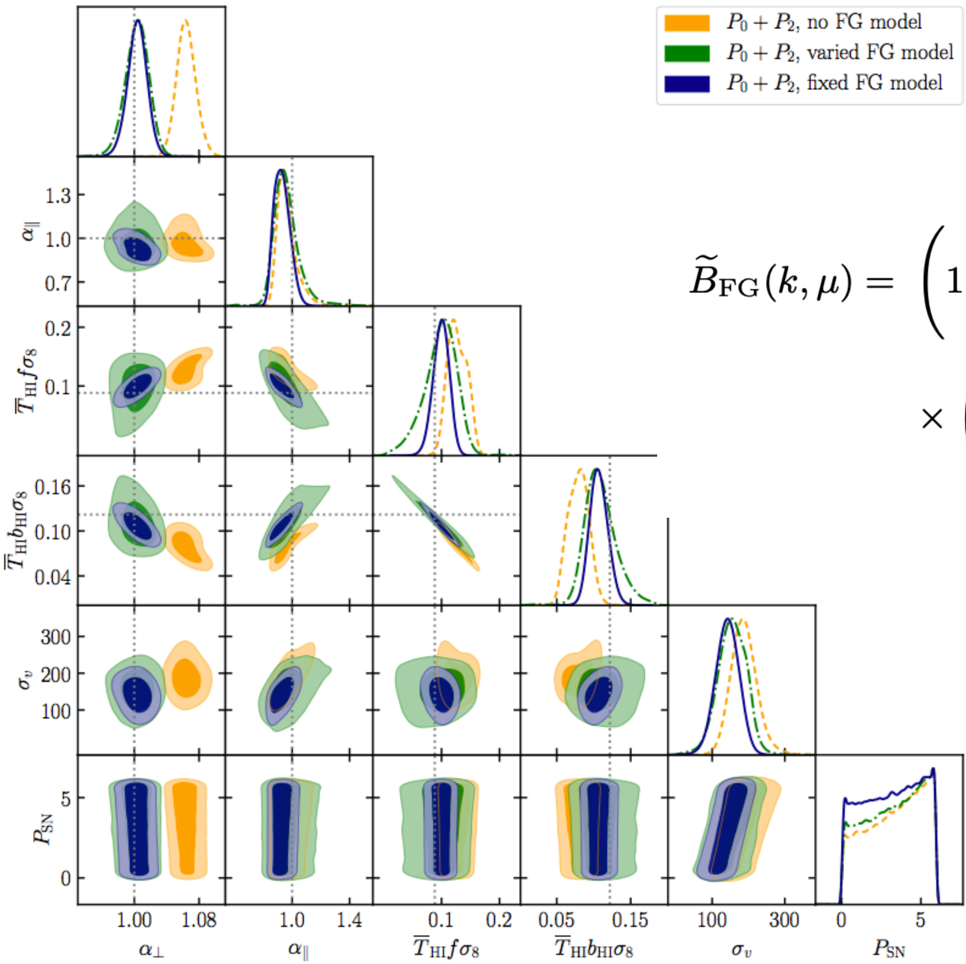



- Use multipoles for hunting for systematics
- Dipole and higher order multipoles can help …

Cunnington et al. 2019

# HOW TO TREAT FOREGROUNDS AT THE MODELLING LEVEL

- We proposed a model with 2 nuisance parameters to express the effect of foreground removal on the power spectrum.
- Without them, we get biased (wrong!) cosmological parameters in an MCMC analysis. With them, we recover the true values.
- Implication: Foreground transfer function is cosmology dependent



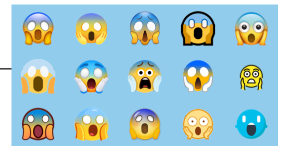

$$\widetilde{B}_{\rm FG}(k,\mu) = \left(1 - \exp\left\{-\left(\frac{k}{N_\perp k_\perp^{\rm min}}\right)^2 (1-\mu^2)\right\}\right) \times \left(1 - \exp\left\{-\left(\frac{k}{N_\parallel k_\parallel^{\rm min}}\right)^2 \mu^2\right\}\right) ,$$

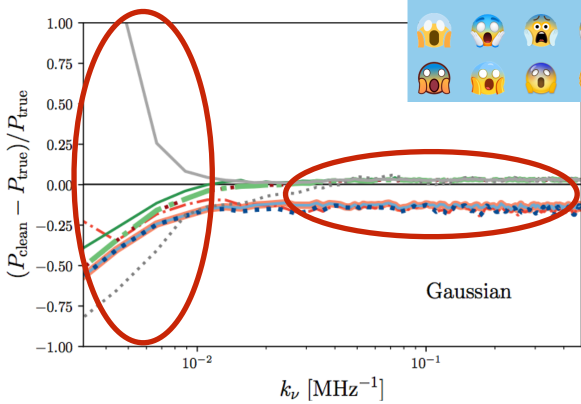
Soares et al. 2020

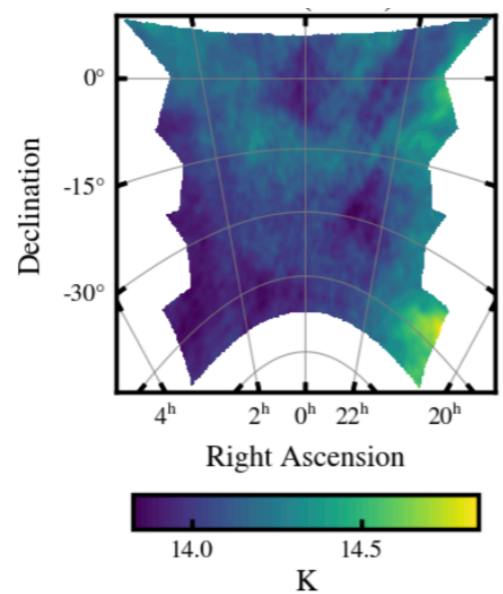
# What we really need: end-to-end simulations

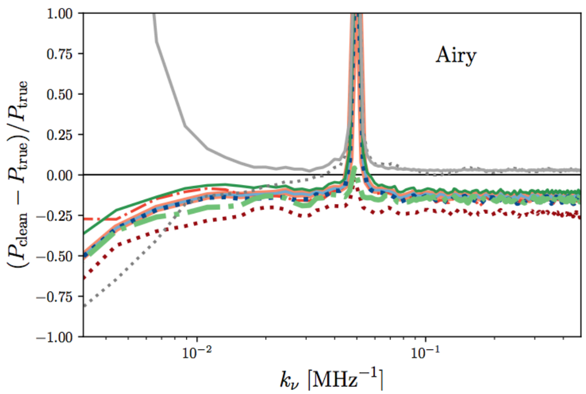
**SKAO HI Intensity Mapping: Blind Foreground Subtraction Challenge**

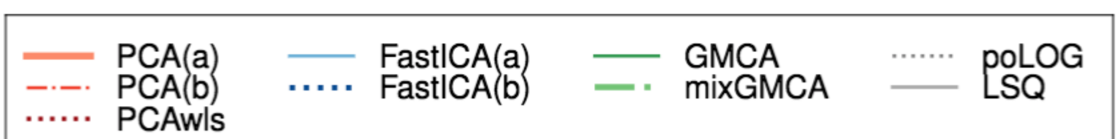
Marta Spinelli,[1,2,3★] Isabella P. Carucci,[4,5,6†] Steven Cunnington,[7] Stuart E. Harper,[8] Melis O. Irfan,[3,7]
José Fonseca,[7,3,9,10] Alkistis Pourtsidou,[7,3] Laura Wolz[8]





# INTENSITY MAPPING: CURRENTLY OPERATING TELESCOPES

First detection in x-cross with optical


North, whole sky, 0.8<z<2.5

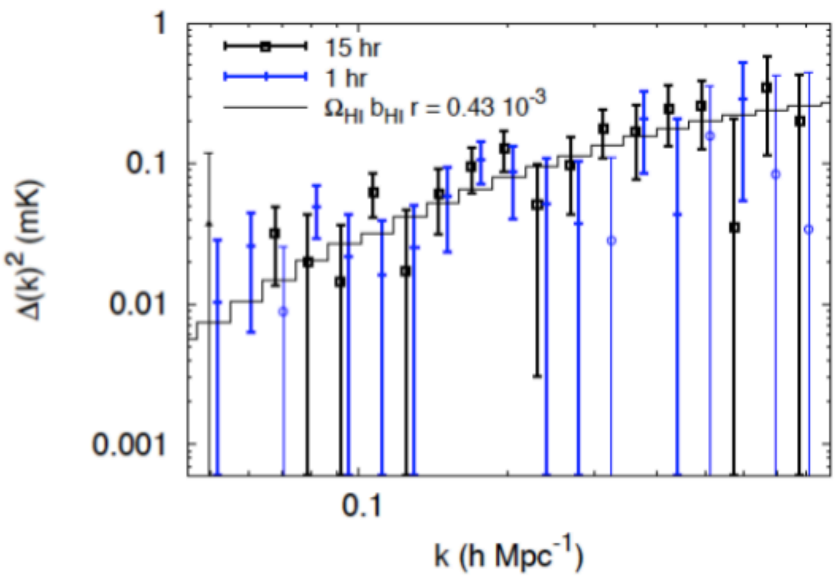


Survey at 0<z<0.5

# THE IMPORTANCE OF CROSS-CORRELATIONS

- Systematic effects are a big challenge for 21cm intensity mapping
- GBT x WiggleZ 2013 showed that cross-correlating with optical can mitigate this! Systematics drop out in cross-correlation.
- 2dF x Parkes 2018 detection, GBT x eBOSS detections last year!
- Constraints rely on transfer function correction for signal loss —> current methods inadequate for precise analyses …

$$\langle \delta T_{\rm HI} \delta_{\rm g} \rangle$$




Masui, et al., ApJ 2012,
Chang et al., Nature 2010

$$\Omega_{\rm HI} b_{\rm HI} r = [0.43 \pm 0.07(stat.) \pm 0.04(sys.)] \times 10^{-3}$$

# INTERFEROMETRIC INTENSITY MAPPING

- The best constraints on the growth of structure (via RSDs) should come from interferometric intensity mapping (high S/N across a wide range of scales)
- Assume CHORD and PUMA specs ( "Stage-IV" IM experiments)
- Take state of the art EFTofLSS perturbation theory model
- Vary 10 parameters in total (3 cosmological, 7 bias): interested in the cosmological + the linear HI bias

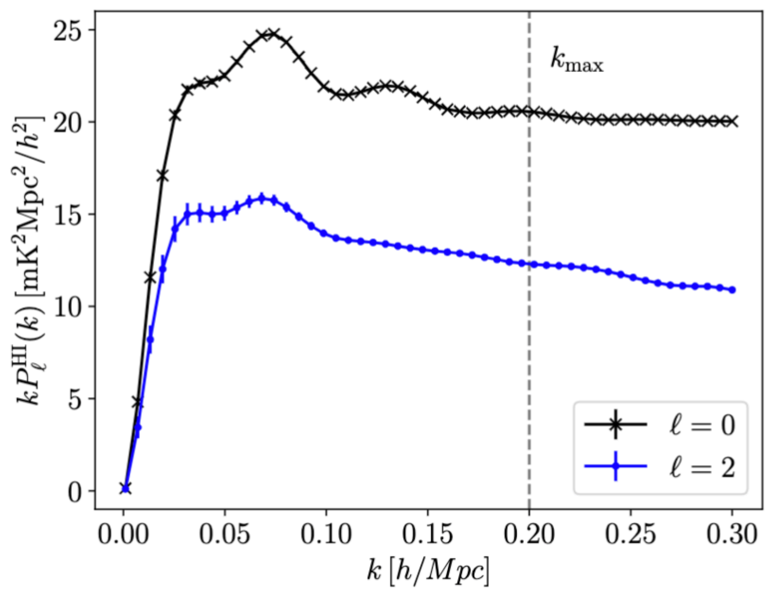
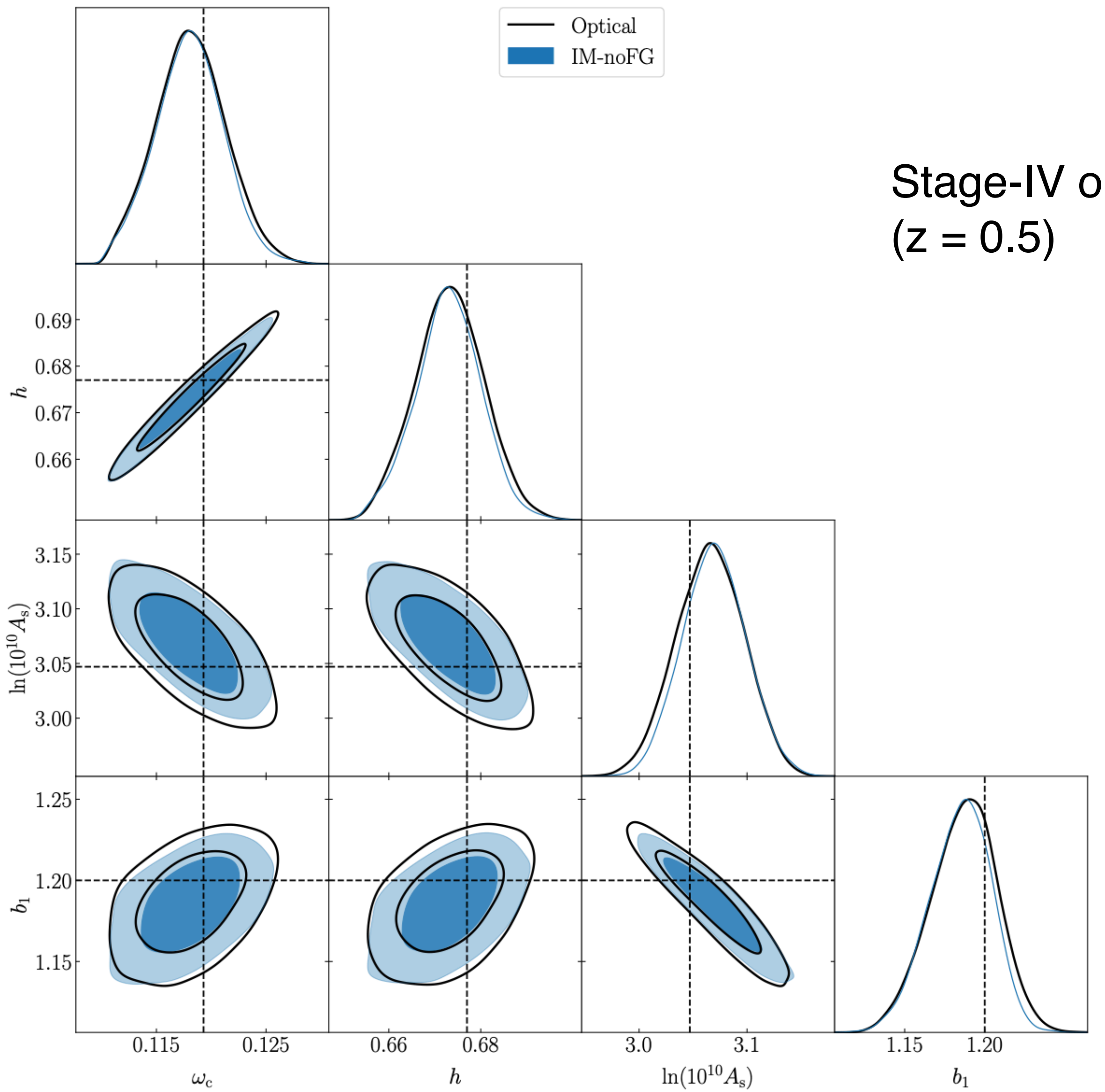


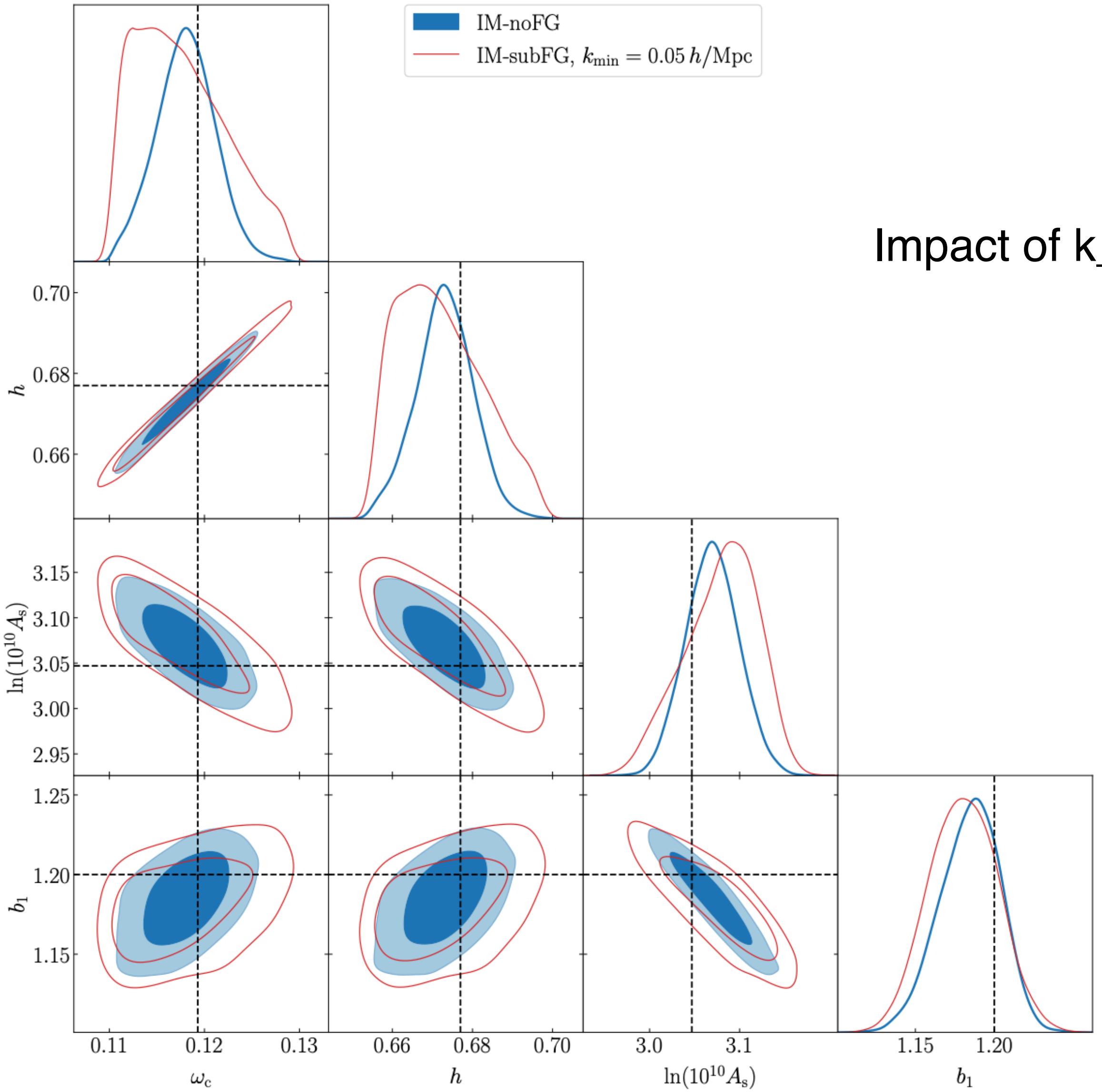

**Figure 1.** Fiducial monopole and quadrupole data, assuming a CHORD-like intensity mapping survey. The vertical dashed grey line denotes the maximum wavenumber (smaller scale) $k_{\rm max} = 0.2h/{\rm Mpc}$ at our chosen central redshift $z = 0.5$.

# INTERFEROMETRIC INTENSITY MAPPING



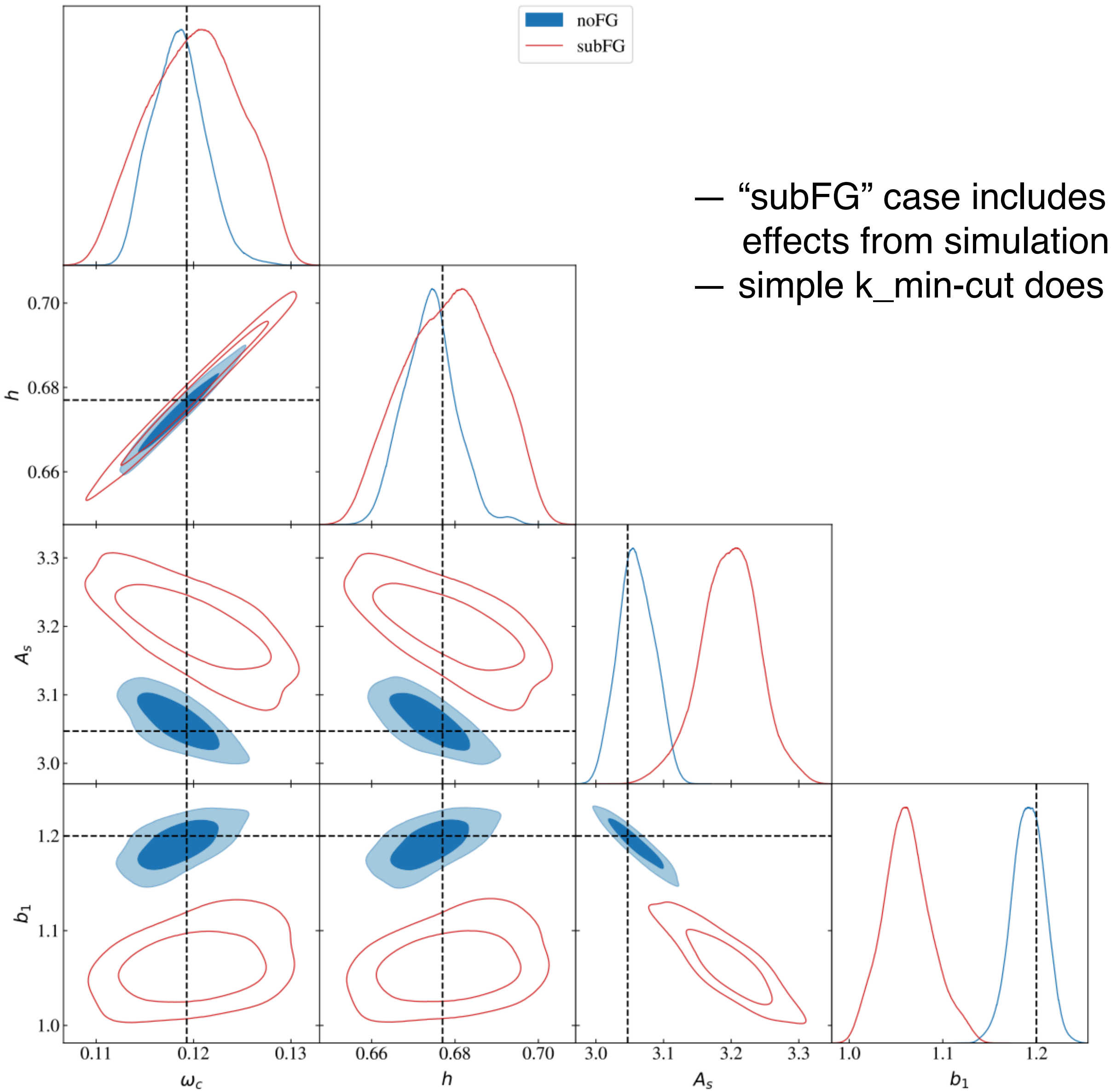

Stage-IV optical vs IM
(z = 0.5)

# INTERFEROMETRIC INTENSITY MAPPING




Impact of k_min cut

# INTERFEROMETRIC INTENSITY MAPPING




— “subFG” case includes FG removal effects from simulations

— simple k_min-cut does not work

# A NEW OBSERVABLE

- Back to the linear approximation:

$$P^{\rm sig}(k,\mu) = b^2(1+\beta\mu^2)^2 P_m^{\rm lin}(k)\,,$$

where $\beta = f/b$. Since the Kaiser formula contains terms only up to $\mu^4$, only the monopole, quadrupole, and hexadecapole are non-vanishing and we find:

$$P_0(k) = \left(1+\frac{2}{3}\beta+\frac{1}{5}\beta^2\right) b^2 P_m^{\rm lin}(k)$$

$$P_2(k) = \left(\frac{4}{3}\beta+\frac{4}{7}\beta^2\right) b^2 P_m^{\rm lin}(k)$$

$$P_4(k) = \frac{8}{35}\beta^2 b^2 P_m^{\rm lin}(k)\,.$$

- Take your measured multipoles and construct the following combination (described in papers by Tegmark, Scoccimarro):

$$\hat{Q}_0 = \hat{P}_0 - \frac{1}{2}\hat{P}_2 + \frac{3}{8}\hat{P}_4$$

# A NEW OBSERVABLE

- Q_0 is a proxy for the real space power spectrum (this is exact in linear theory)

$$Q_0 = b^2 P_m(k)$$

- Repurposing Q_0 for HI intensity mapping we get:

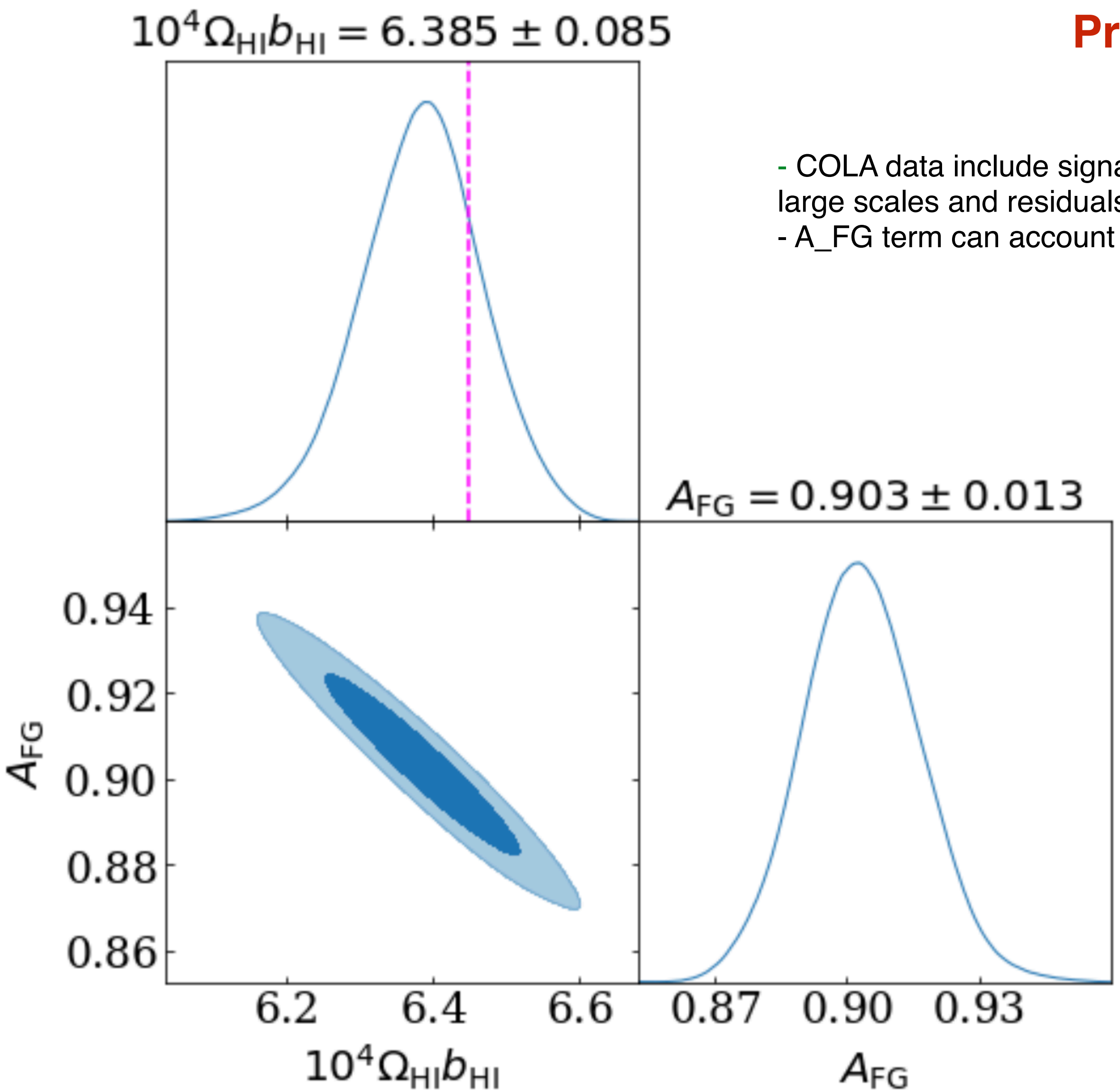
$$Q_0 = T_{\rm HI}^2 b_{\rm HI}^2 P_m(k)$$

- Advantages: we get rid of HI parameter degeneracies with growth rate f, modelling in real space is much easier than redshift space, FG removal effects also easier to account for …

# RESULTS

## Fits to COLA simulations including FG removal effects

**Preliminary results!**




- COLA data include signal loss on large scales and residuals on small scales
- A_FG term can account for both