FUNDAMENTAL PHYSICS WITH LARGE/MEDIUM/SMALL SCALE STRUCTURES

LECTURE 1

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2022 Winter School
Tenerife (Spain)

Euclid Flagship Simulation

SISSA

PLAN

INTRO

FUNDAMENTAL PHYSICAL TESTS "BEFORE" GALAXIES ARE FORMED IN THE POST-REIONIZATION UNIVERSE

INTENSITY MAPPING
IGM

GALAXY CLUSTERING: DYNAMICAL AND GEOMETRICAL PROBE

GALAXY CLUSTERS

WEAK LENSING

CONNECTIONS

FABIO FINELLI: CMB x LSS

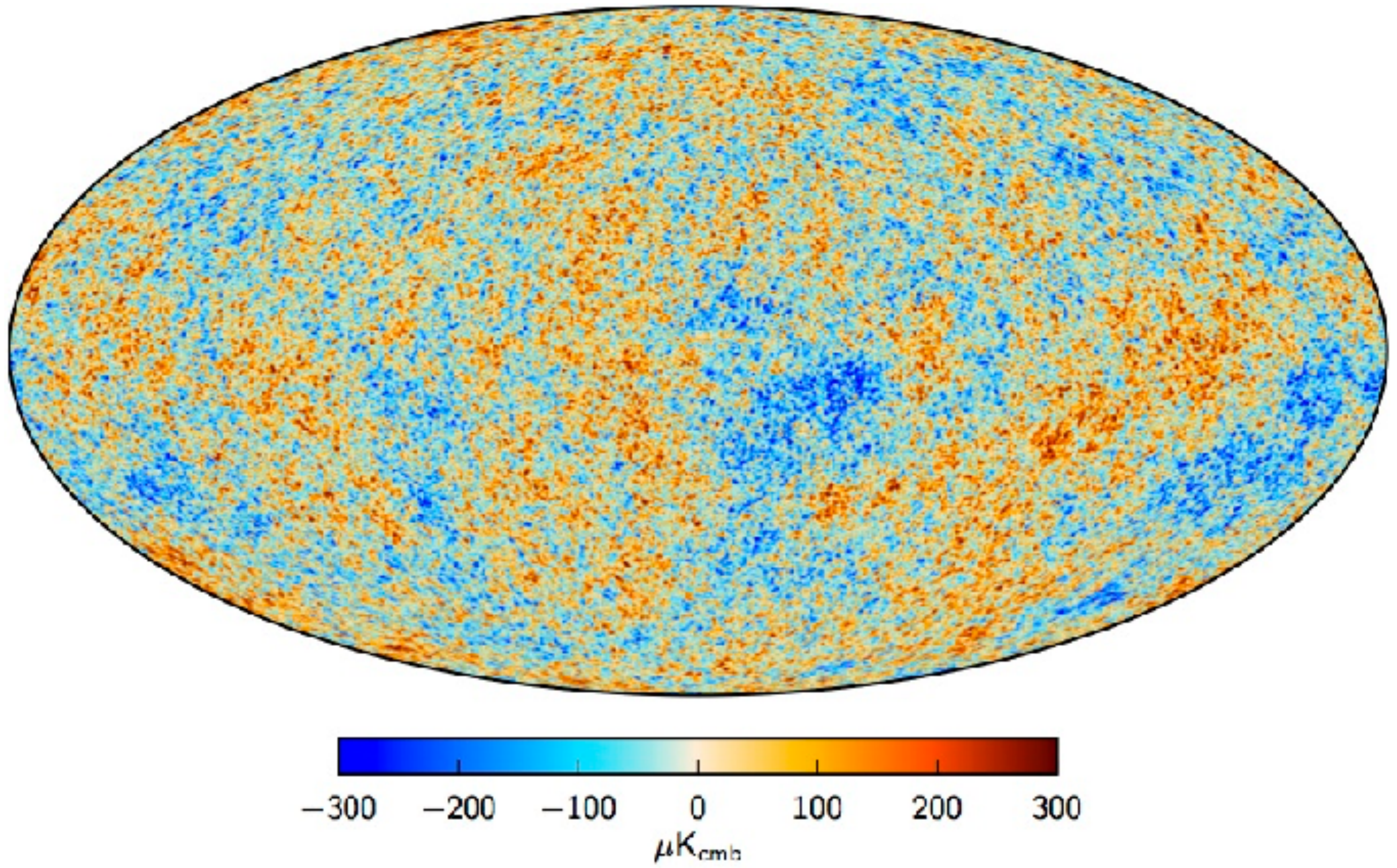
KFIR BLUM: SMALLER SCALES PROPERTIES OF GALAXIES

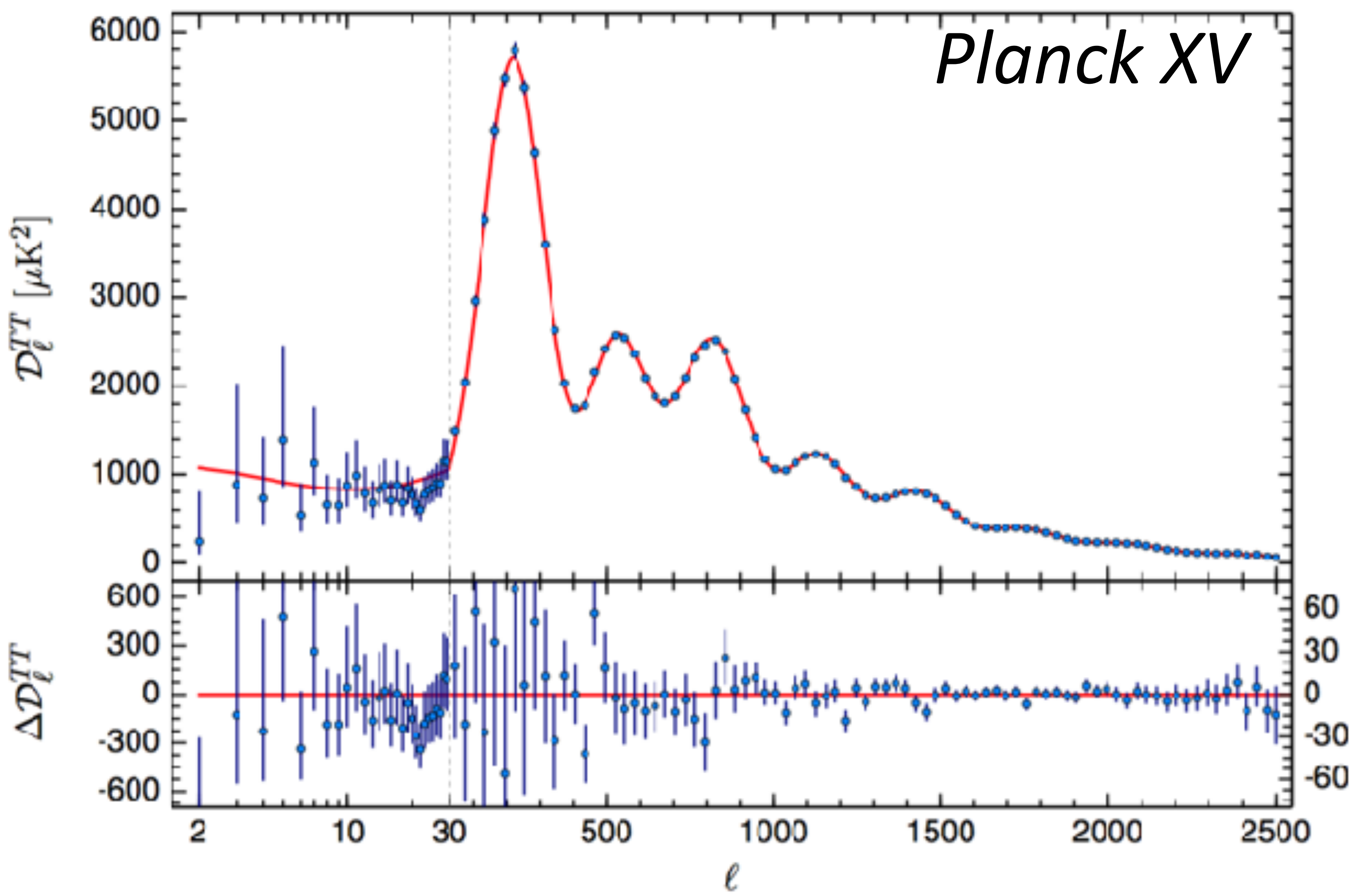
LUCA AMENDOLA: MODIFICATION OF GRAVITY/DARK ENERGY

OLGA MENA: NEUTRINOS

TRACY SLATYER: DARK MATTER

The standard ΛCDM model – I: CMB





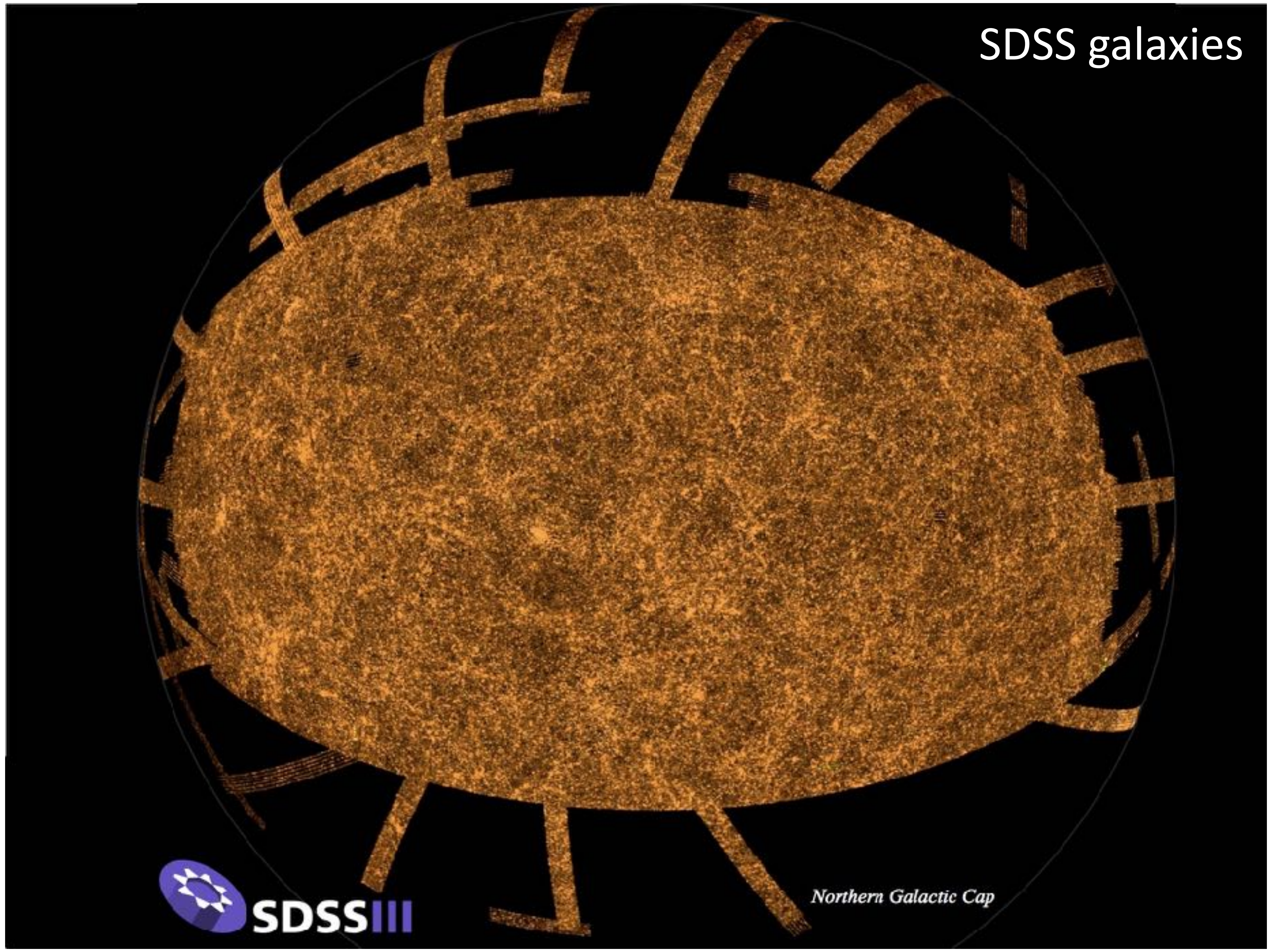
Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012

primary params.

derived params.

- Planck spectacular confirmation of a **6 parameter model.** FRWL metric + linear perturbations of hot plasma (Thomson scattering).
- Non baryonic and baryonic matter fluids required at 80 and 140σ.
- Rich structure full of information on (but not only!) our Universe at z~1100.
- Frontier is now **lensing** and (more importantly) **polarization.**

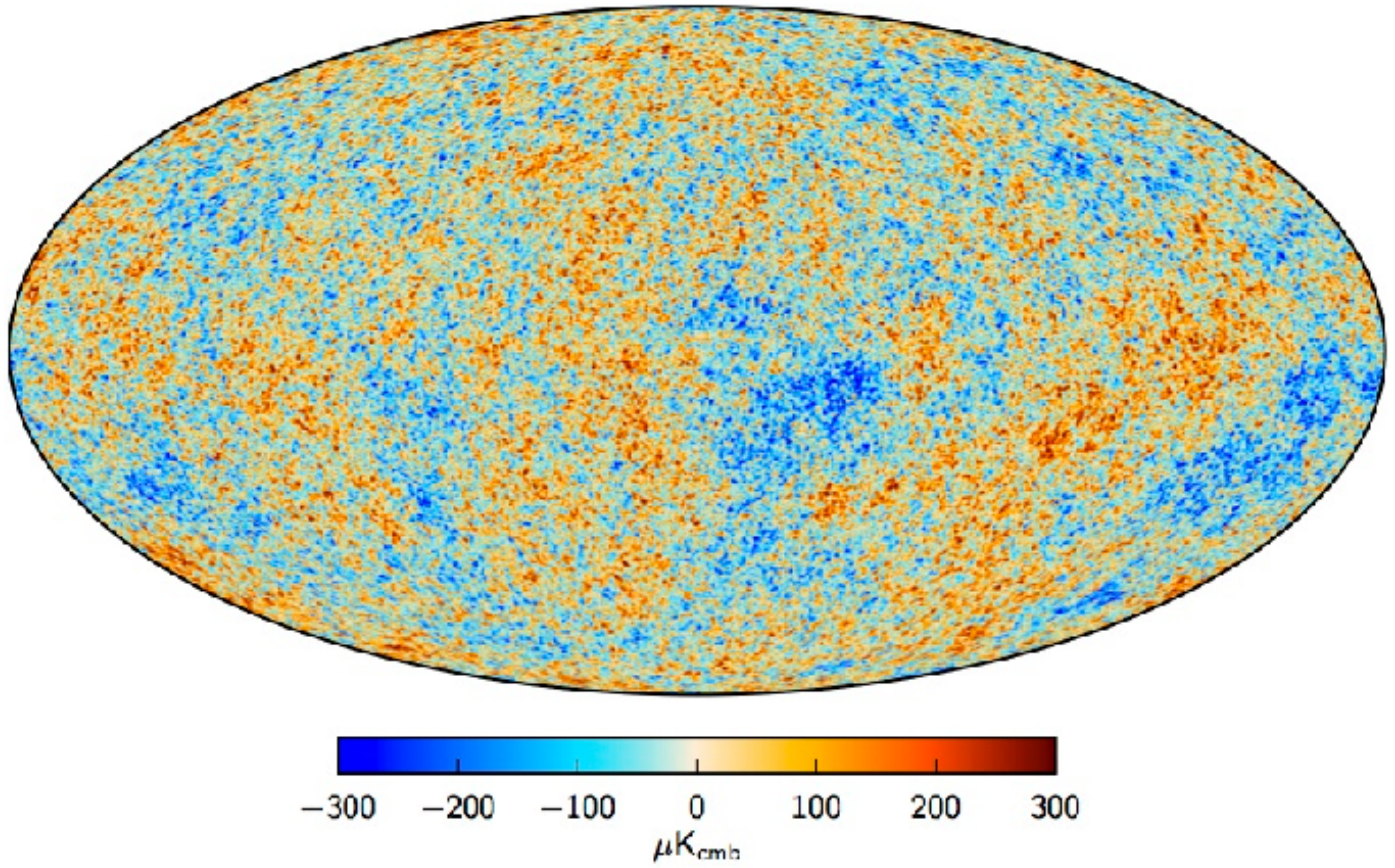
The standard ΛCDM model – II: LSS



- Large Scale Structure (LSS) is a **tracer of the underlying matter** (cold? total?) density field.
- Different redshifts, scales, systematics compared to CMB.
- Most used: **galaxies** red. space distortions, weak lensing.
- Difficulties: **physics not linear** any more. Galaxies are a biased tracer.
- Note: *modelling galaxies as points is pointless.*

$$\boxed{\delta_{\mathrm{tracer}} = F(\mathbf{x}, z, \textit{environment?}\,, \textit{physics?}\,, \textit{luminosity?}\ \textit{etc.}) \times \delta_{CDM}}$$

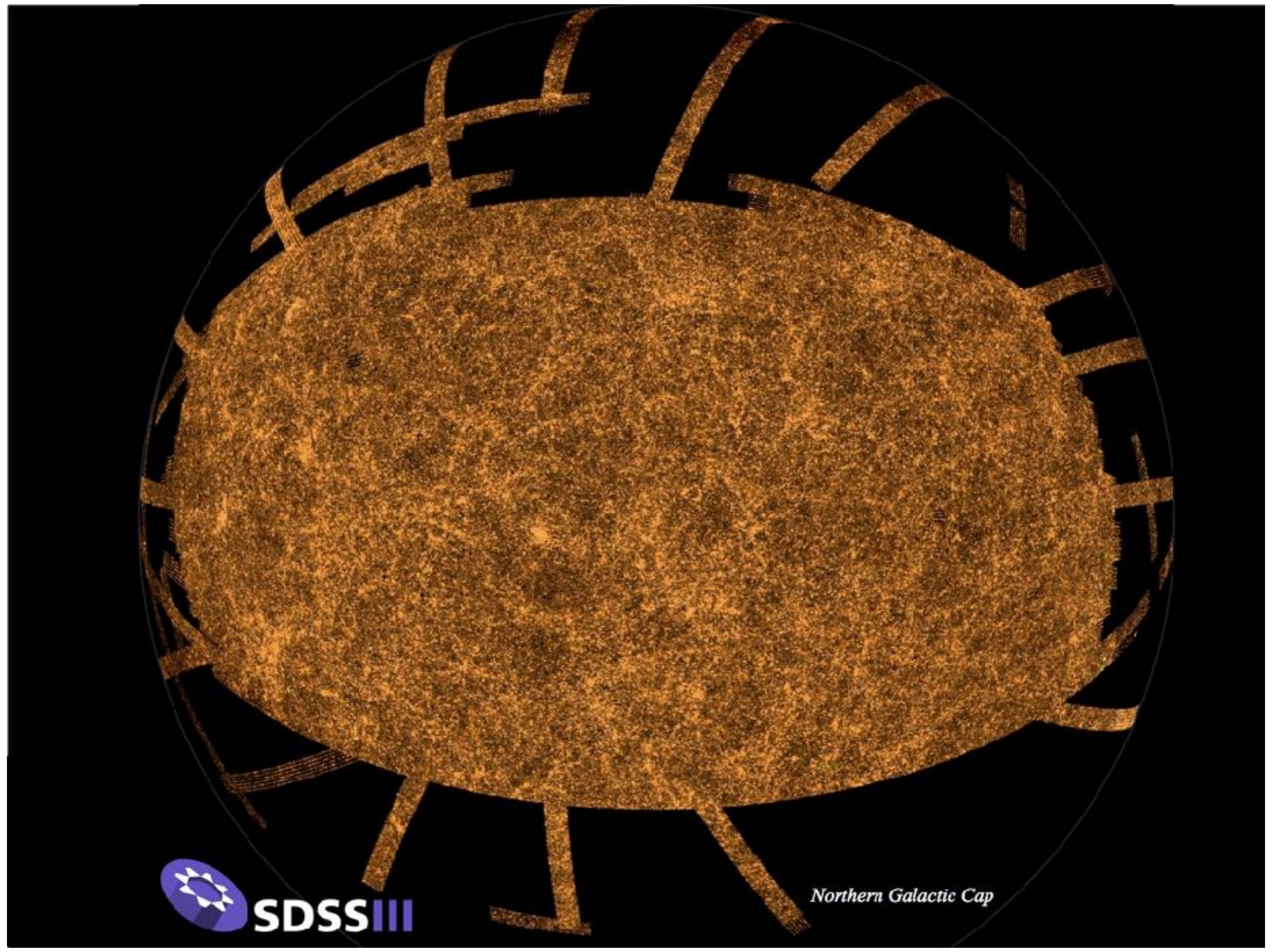
Initial Conditions



13 Gyrs later

Under the influence of gravity
and astrophysical processes....

Non-linear Universe



SUMMER 1982

SUMMER 1982

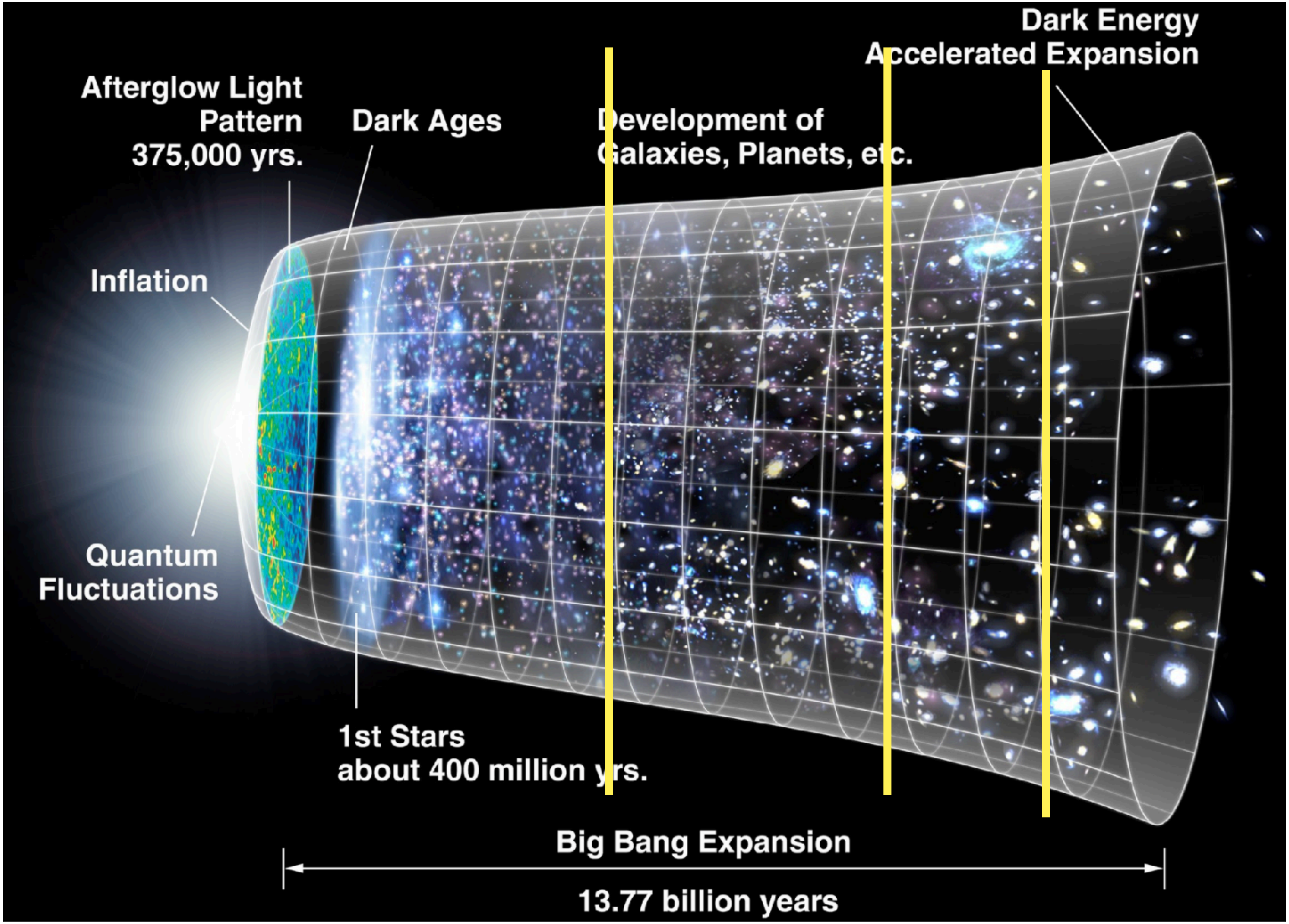
DARK MATTER IS NEEDED ....

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. Peebles
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.
Subject headings: cosmic background radiation — cosmology — galaxies: formation


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

RATIONALE BEHIND A "TOMOGRAPHIC MULTI PROBE APPROACH"

1) **NEW FUNDAMENTAL PHYSICS IS USUALLY WELL HIDDEN**: TO MAKE A CONVINCING CASE --> MORE OBSERVABLES
STRONG CLAIMS NEED STRONG PROOFS!

2) **WIDE REDSHIFT RANGE**: USEFUL TO BREAK DEGENERACIES BETWEEN ASTRO AND COSMO PARAMS

3) **MITIGATION OF SYSTEMATICS** DUE TO INSTRUMENTATION, OBSERVATIONAL BIAS, ETC. (different experiments, different people)

4) PARAMETER SPACE OF THEORETICAL MODELS BECOMES WIDER AND MORE TESTS CAN BE ENVISAGED
... A **RICHER LANDSCAPE,** WITH HUGE DISCOVERY POTENTIAL

INTENSITY MAPPING

Bibliography

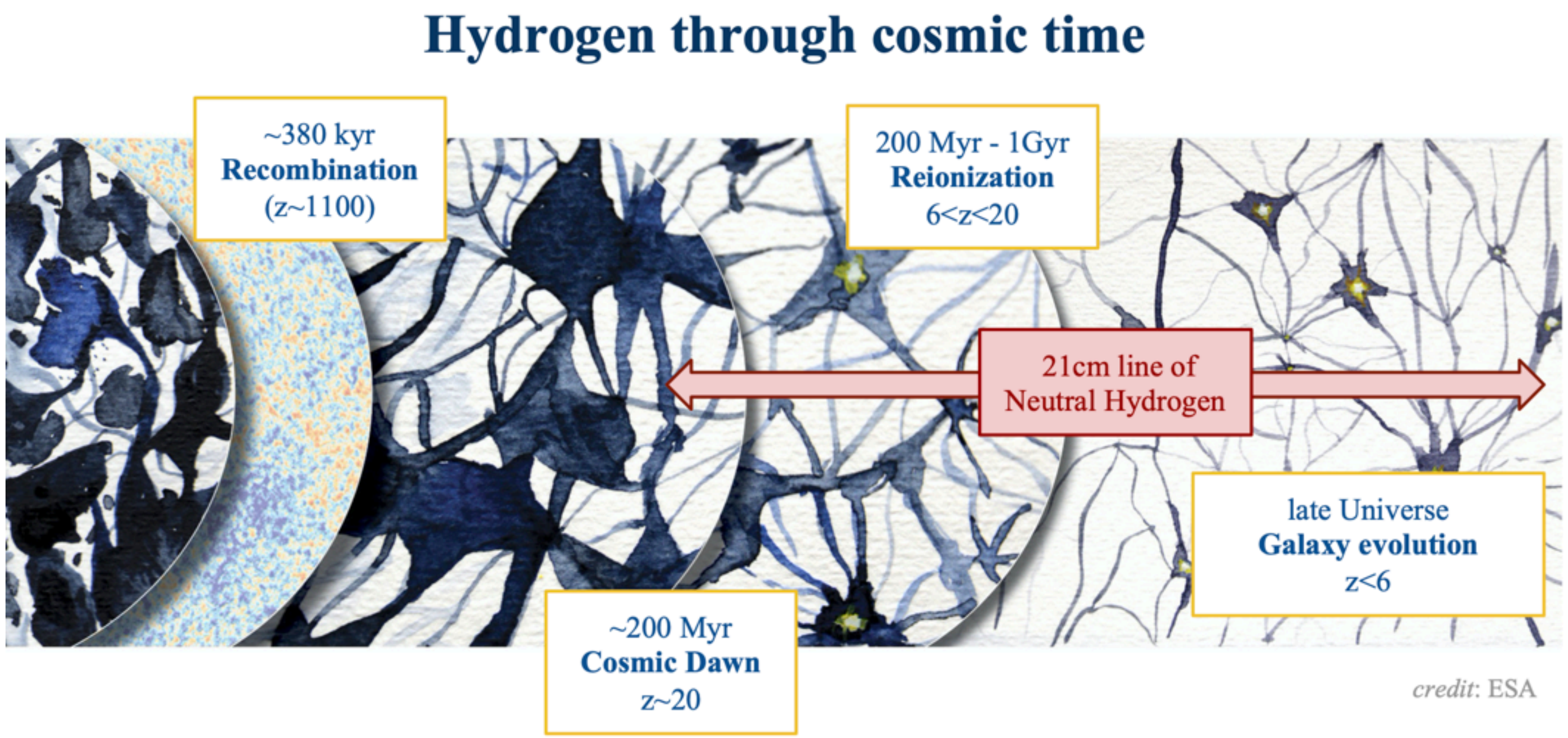
Kovetz+17 arXiv: 1709.09066 - Review

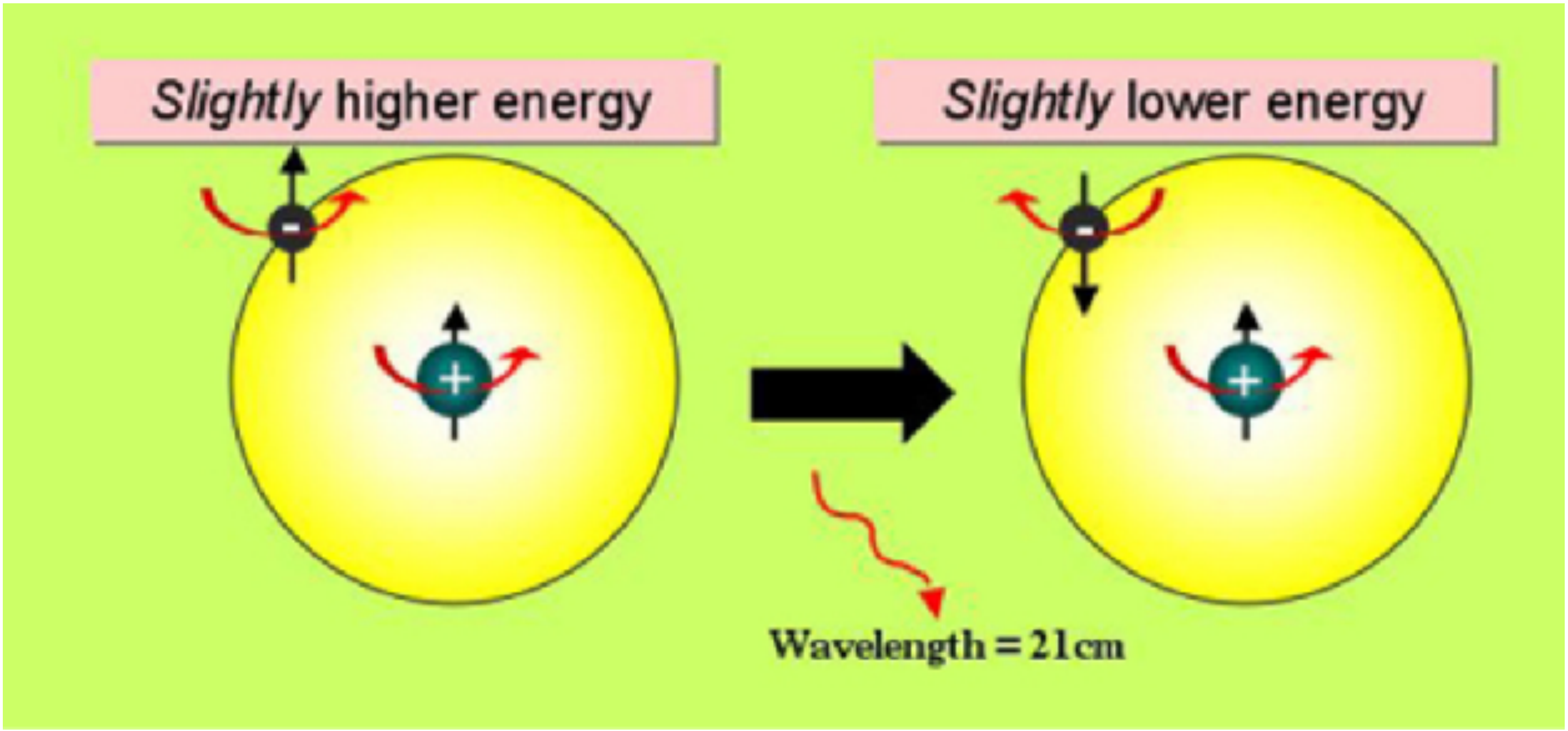
Villaescusa-Navarro+18 - Ingredients for IM
Berti, Spinelli, MV 22 - Realistic Likelihood
Berti, Spinelli, Haridasu, MV, Silvestri 22 - EFT of DE
Villaescusa-Navarro, Alonso, Viel 15 - BAO in IM
Carucci+14 - Warm Dark Matter
Wolz+22 - Cross-correlation measurements
Cunnington+22 - Cross-correlation measurements
Hall Bonvin Challinor 13 - Jolicoueor, Maartens+21 - Relativistic effects and MG
Moradinezhad Dizgah & Keating 19 - Non-Gaussianities (Inflation)
Spinelli (w MV) +20 - galaxy formation and IM
Carucci+20 - Foreground removal

PLAN

1) basics of HI intensity mapping
2) theoretical modelling
3) big questions to be addressed
4) experiments

HI in the Universe

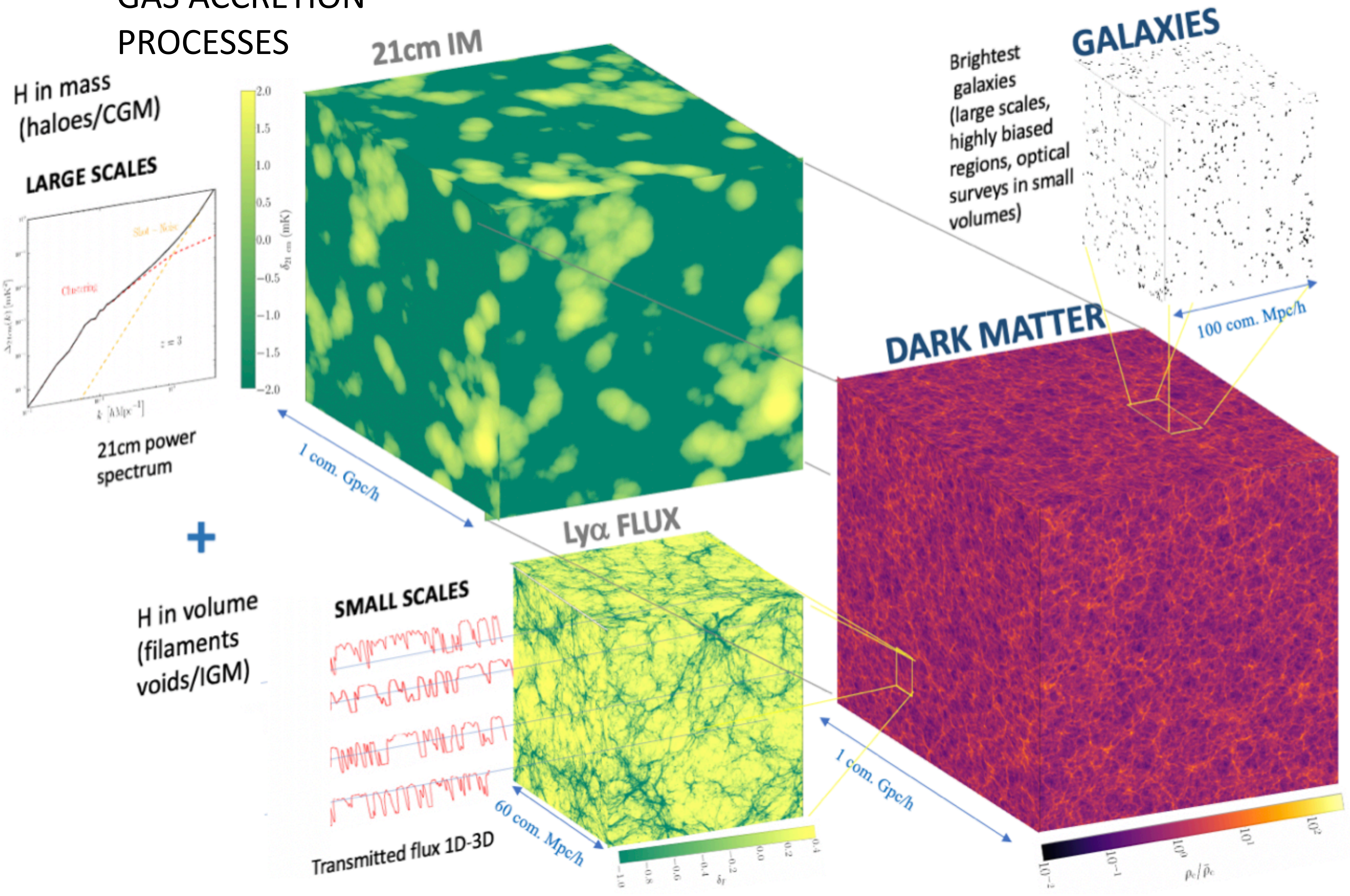




...note: different IM lines: 21cm, [CII], CO, Halpha, Lyalpha --> each of them tracing different environments

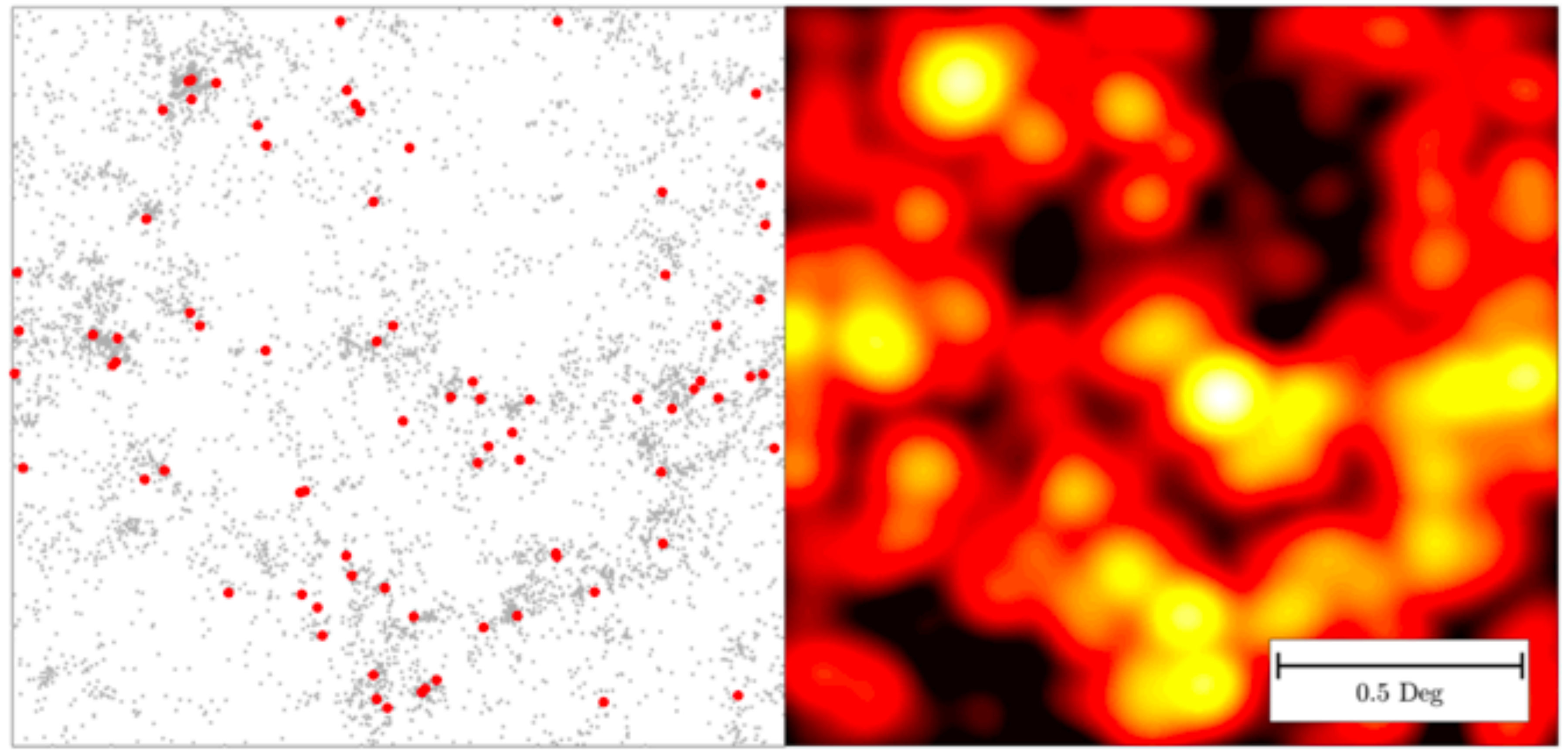
A very comprehensive view of high-z Universe

GAS ACCRETION PROCESSES



IM basics

Simulation of CO intensity mapping (right) and galaxies (left)



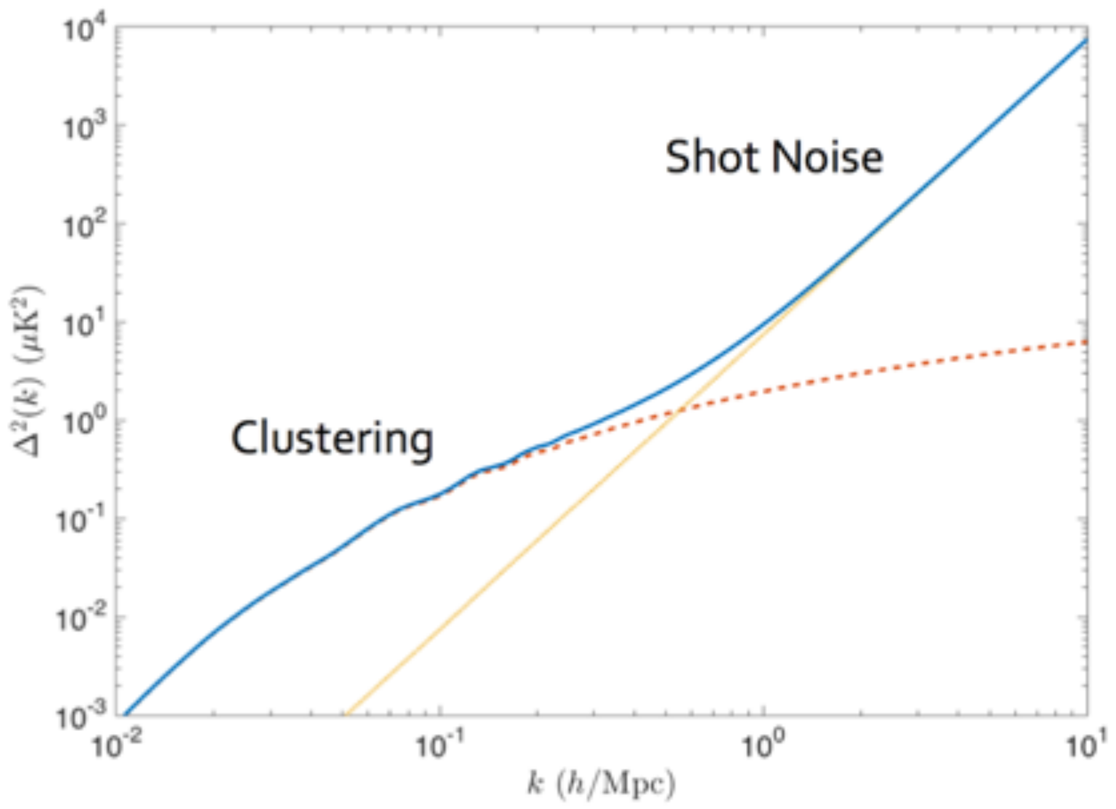
Large volumes!
Small scales integrated out

Large scale modelling [take P_m=P_lin]

$$P_k(z) = \langle I(z) \rangle^2 b^2(z) P_m(k, z) + P_{\rm shot}(z)$$

$$\langle I(z) \rangle \propto \int_0^\infty L\Phi(L, z) dL, \qquad P_{\rm shot}(z) \propto \int_0^\infty L^2 \Phi(L, z) dL.$$

$$\Phi(L, z) \equiv dn(z)/dL$$



Theoretical Modelling:

1) embed empirical galactic relations into halo models

2) semi-analytical galaxy formation models down to ISM properties

3) full hydro-sims down to ISM properties

... but one can also take P_m=P_nonlin or use halo model...

Halo models for 21cm

$$P_{\rm HI}(k,z) = P_{\rm HI,1h}(k) + P_{\rm HI,2h}(k)$$
$$P_{\rm HI,1h}(k,z) = \frac{1}{(\rho_c^0 \Omega_{\rm HI}(z))^2} \int_0^\infty dM n(M,z) M_{\rm HI}^2(M,z) \left| u_{\rm HI}(k|M,z) \right|^2$$
$$P_{\rm HI,2h}(k,z) = \frac{P_{\rm lin}(k,z)}{(\rho_c^0 \Omega_{\rm HI}(z))^2} \left[\int_0^\infty dM n(M,z) b(M,z) M_{\rm HI}(M,z) |u_{\rm HI}(k|M,z)| \right]^2$$

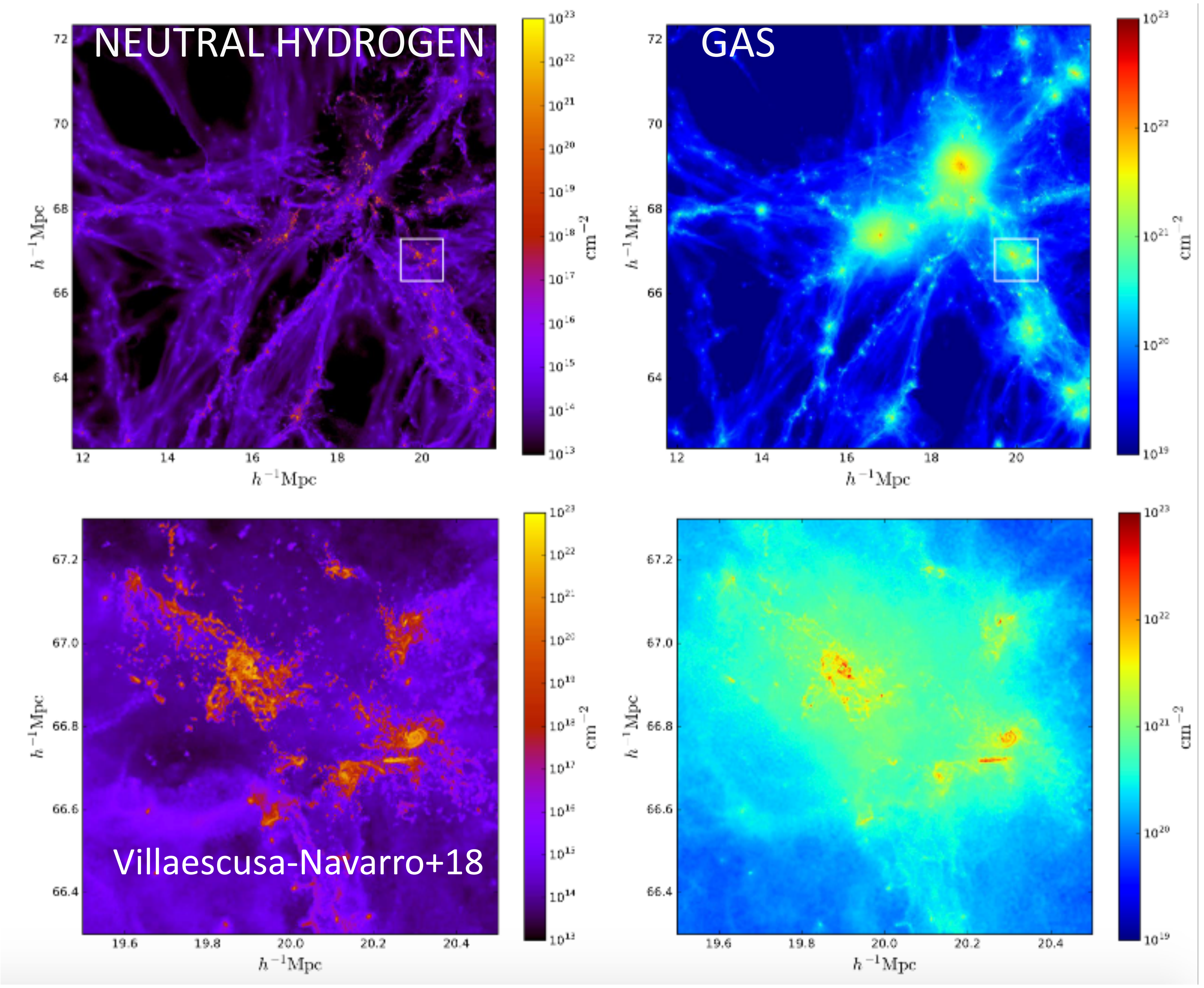
u is the normalized Fourier transform of the HI halo profile

$$\rho_{\rm HI}(r) = \frac{\rho_0}{r^{\alpha_\star}} \exp(-r_0/r)$$

in this model the Shot noise term is the large scale limit of P_1halo

Intensity mapping @ 21cm

Linear theory model: $$P_{21\,\mathrm{cm}}(k,\mu,z) = \bar{T}_b(z)^2[(b_{\mathrm{H\,I}}(z) + f(z)\mu^2)^2 P_{\mathrm{m}}(k,z) + P_{\mathrm{SN}}(z)],$$



$$M_{\mathrm{H\,I}}(M,z) = M_0\left(\frac{M}{M_{\min}}\right)^{\alpha}\exp(-(M_{\min}/M)^{0.35}).$$

M_{min} decreases with redshift
alpha increases with redshift

$$\bar{T}_b(z) = 189h\left(\frac{H_0(1+z)^2}{H(z)}\right)\Omega_{\mathrm{H\,I}}(z)\ \mathrm{mK},$$

$$\Omega_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

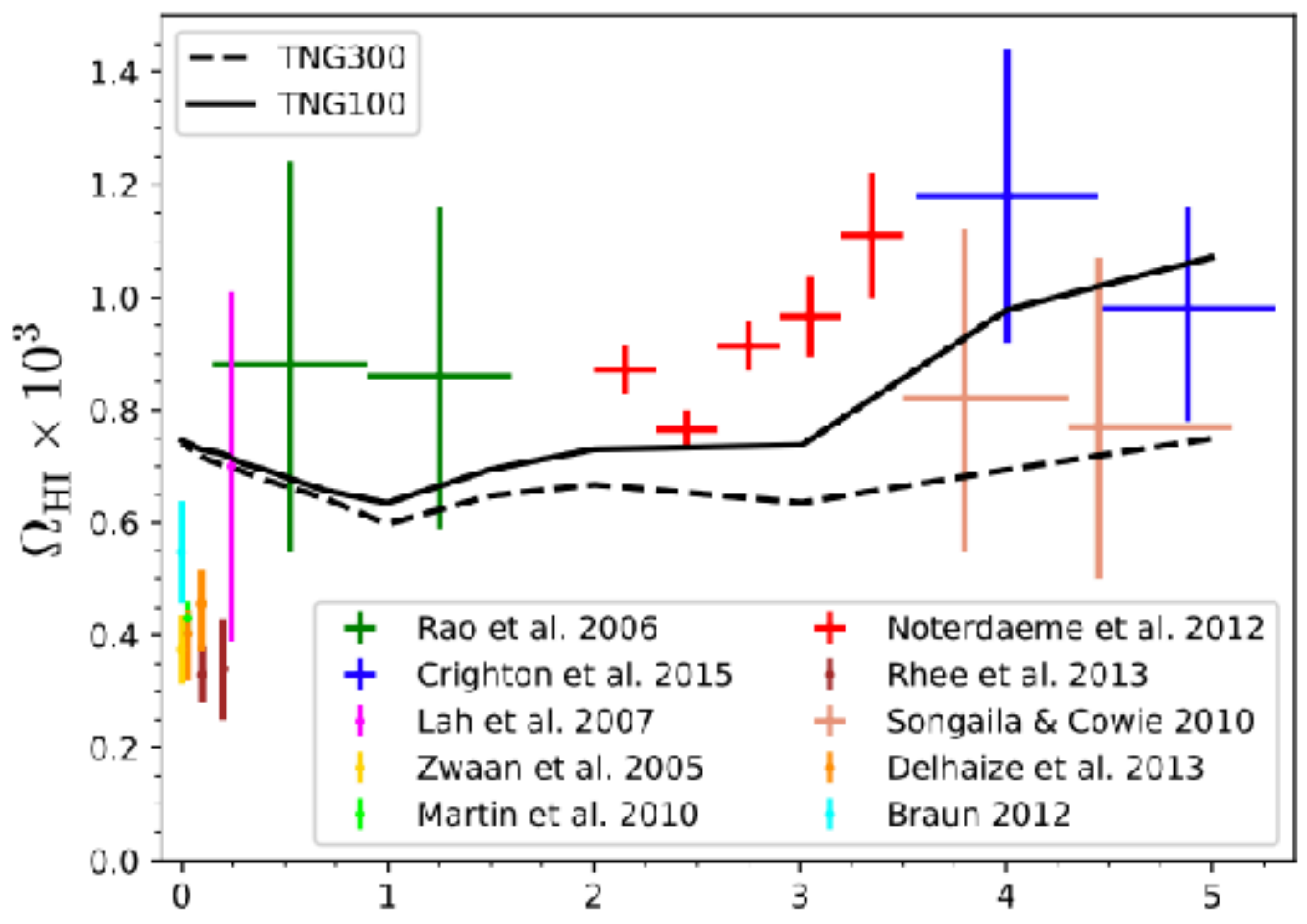
$$b_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0\Omega_{\mathrm{H\,I}}(z)}\int_0^\infty n(M,z)b(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

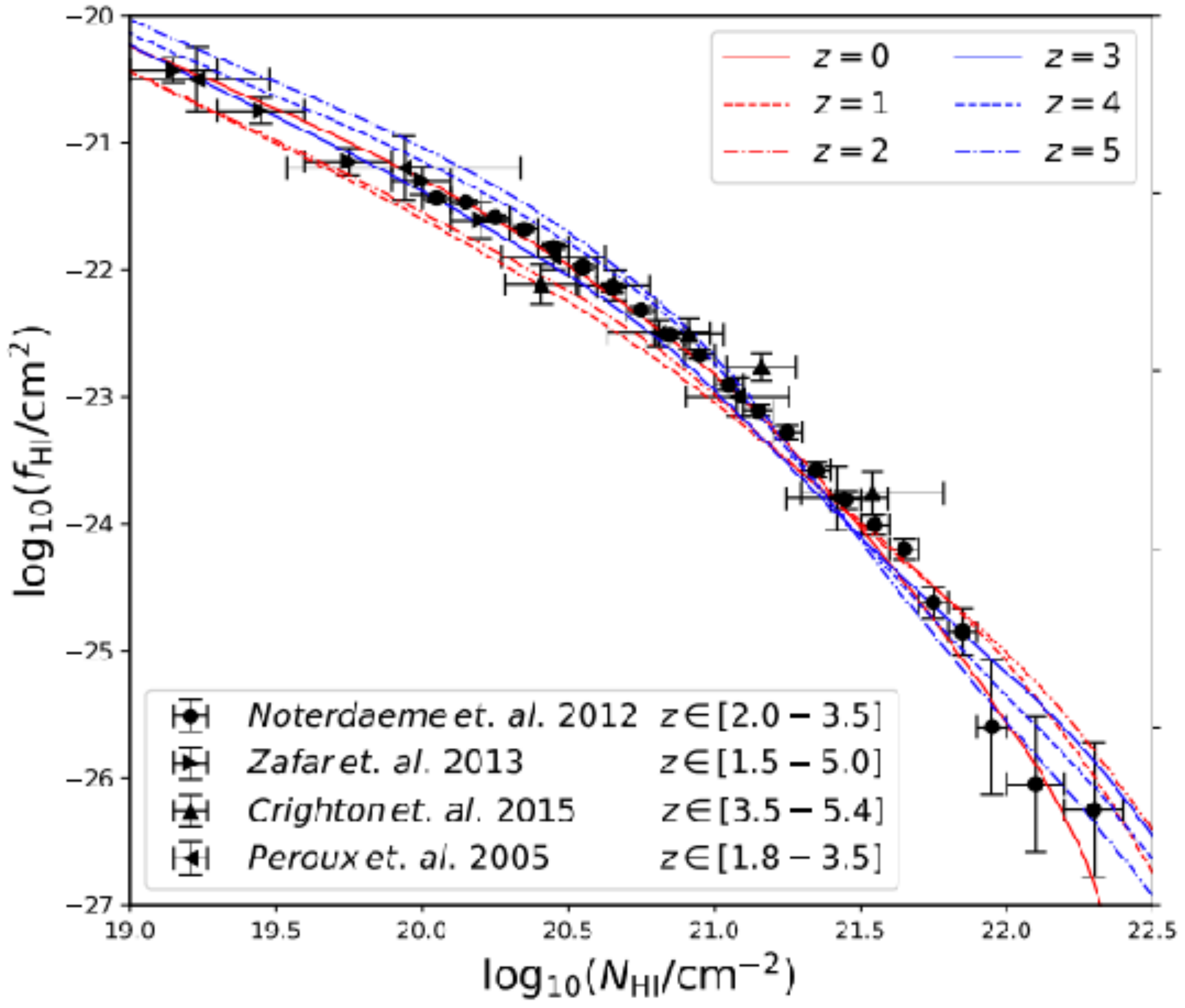
$$P_{\mathrm{SN}}(z) = \frac{1}{(\rho_c^0\Omega_{\mathrm{H\,I}}(z))^2}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}^2(M,z)dM,$$

- degeneracy between b_{HI} and $Omega_{HI}$, which can be broken by using other probes (cross-corr.)
- Progress made mainly in the modelling and in determining the low-z HI bias (~0.8) from observations (Obuljen+18) - Pen+09, Switzer+13 (auto and cross to constrain Omega_HI x bias_HI), Anderson+18, Cunnington+22 (cross. with galaxies).
- **IM signal:** main ingredient is the function $M_{HI}(M_{halo})$ with its scatter.

Independent constraints on Omega_HI and bias_HI from QSO spectra

Villaescusa-Navarro+18





More than simple Omega_HI(z):

it is reasonable to expect that at least at large scales
b_HI = b_DLAs [strong absorbers carrying most of the HI]

$$f_{\rm HI}(N_{\rm HI}) = \frac{d^2 n(N_{\rm HI})}{dN_{\rm HI}dX}$$

$$\Omega_{\rm HI}(z) = \frac{m_{\rm H} H_0}{c\rho_c^0}\int_0^\infty f_{\rm HI}(N_{\rm HI},z) N_{\rm HI} dN_{\rm HI}$$

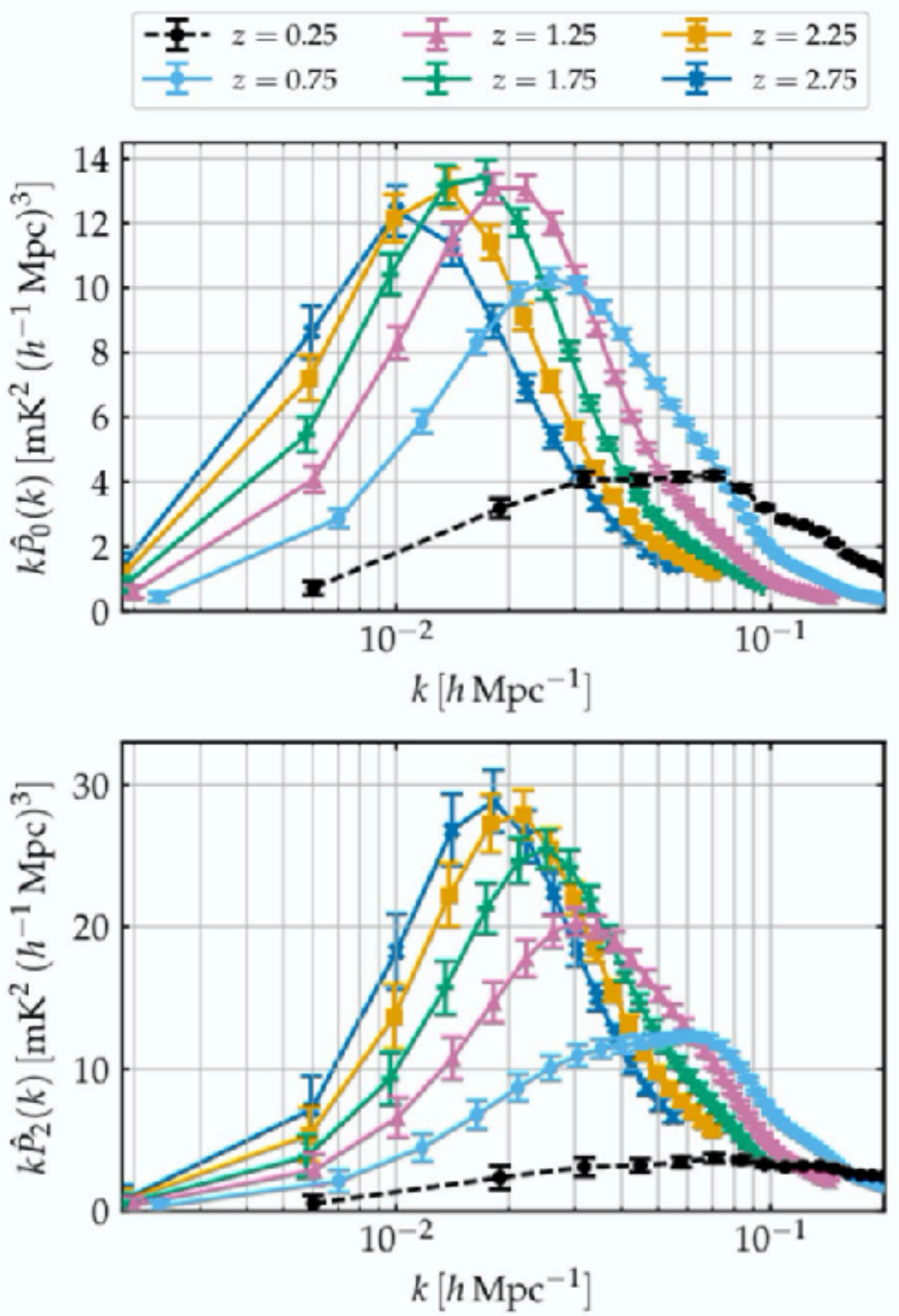
$$\sigma(M|N_{\rm HI},z) = A\left(\frac{M}{h^{-1}M_\odot}\right)^\alpha \left(1-e^{-(M/M_0)^\beta}\right)$$

$$b_{N_{\rm HI}}(z) = \frac{\int_0^\infty b(M,z)n(M,z)\sigma(M|N_{\rm HI},z)dM}{\int_0^\infty n(M,z)\sigma(M|N_{\rm HI},z)dM}$$

SKAO forecasts

$$P_{21}(z,k,\mu) = \bar{T}_b^2(z)\left[\, b_{\rm HI}(z) + f(z)\,\mu^2 \,\right]^2 P_{\rm m}(z,k)$$

$$P_\ell(z,k) = \frac{(2\ell+1)}{2}\,\bar{T}_b^2(z)\,P_{\rm m}(z,k)\int_{-1}^{1} {\rm d}\mu\,\mathscr{L}_\ell(\mu)\,\left[b_{\rm HI}(z) + f(z)\,\mu^2\right]^2$$

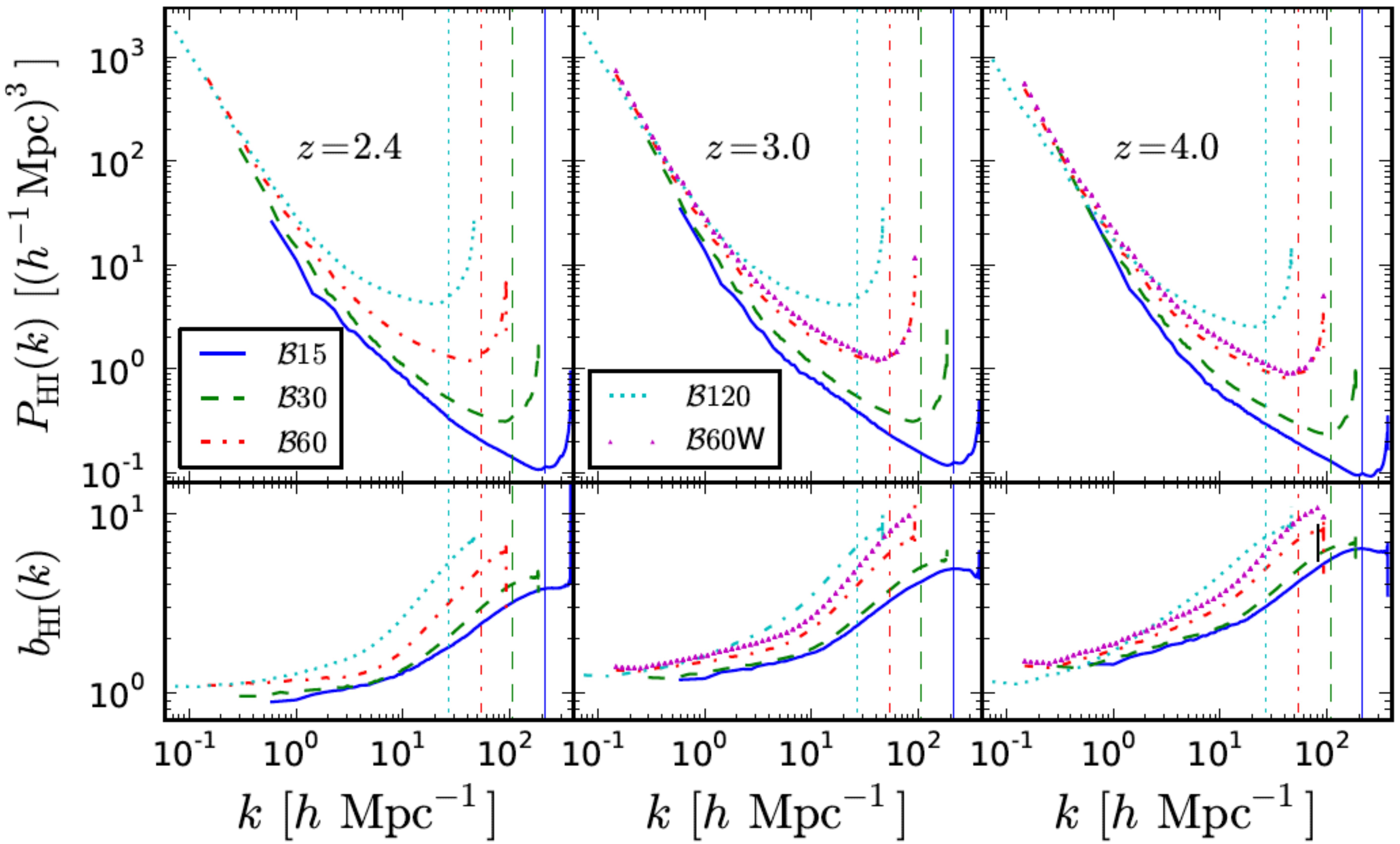


We consider only monopole and quadrupole l=0,2
SKA-Mid like observations

- **tomographic** (6 redshift between 0 and 3)
- **Single-dish**: beam effect
- expected noise and sky area

Berti, Spinelli & MV 2022

Simulating intensity mapping signal: the HI bias

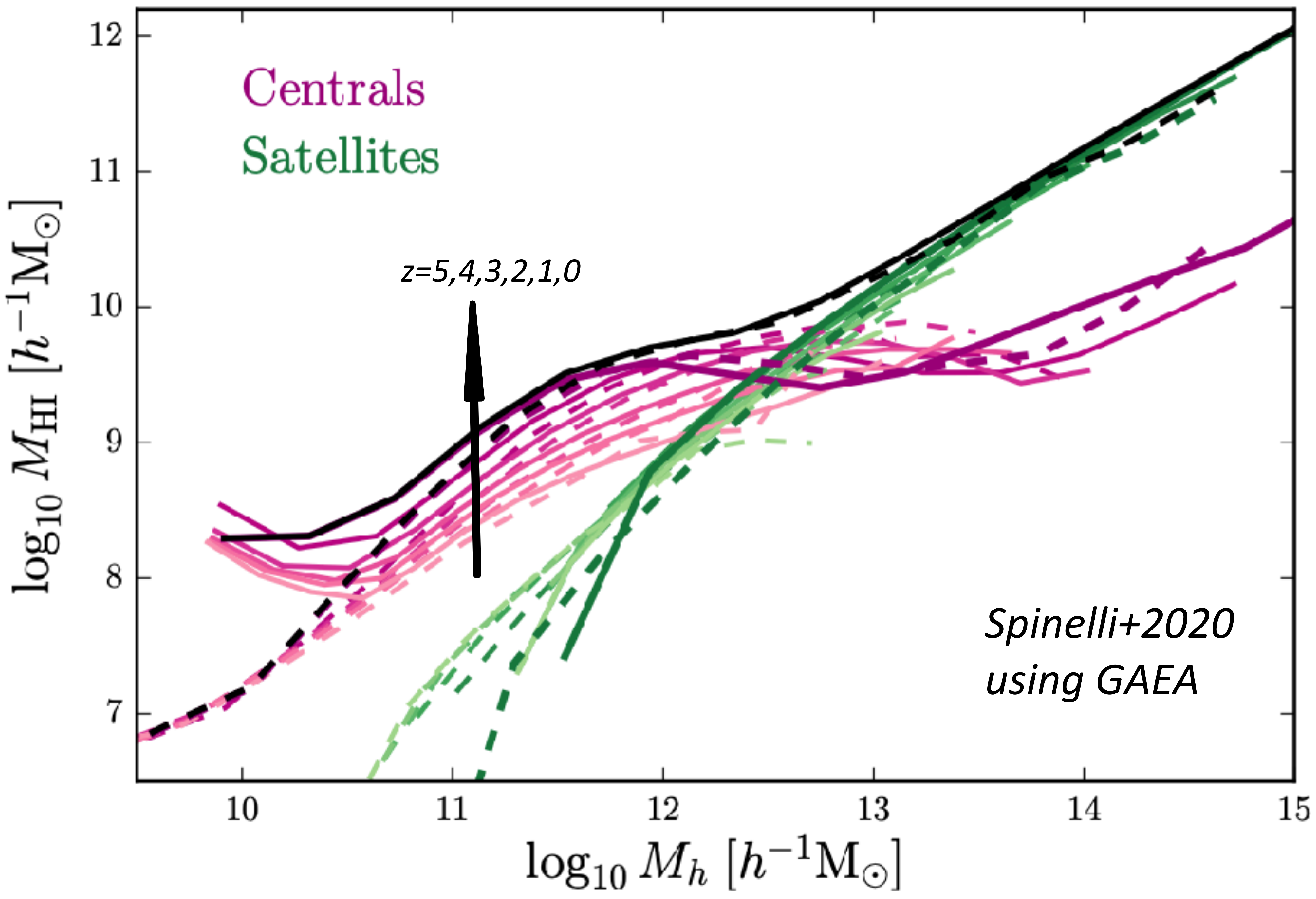


HI bias scale,z dependent
non-linear scales
carry information about
non-linear clustering of haloes
and their HI content

Villaescusa-Navarro,
MV + 2014

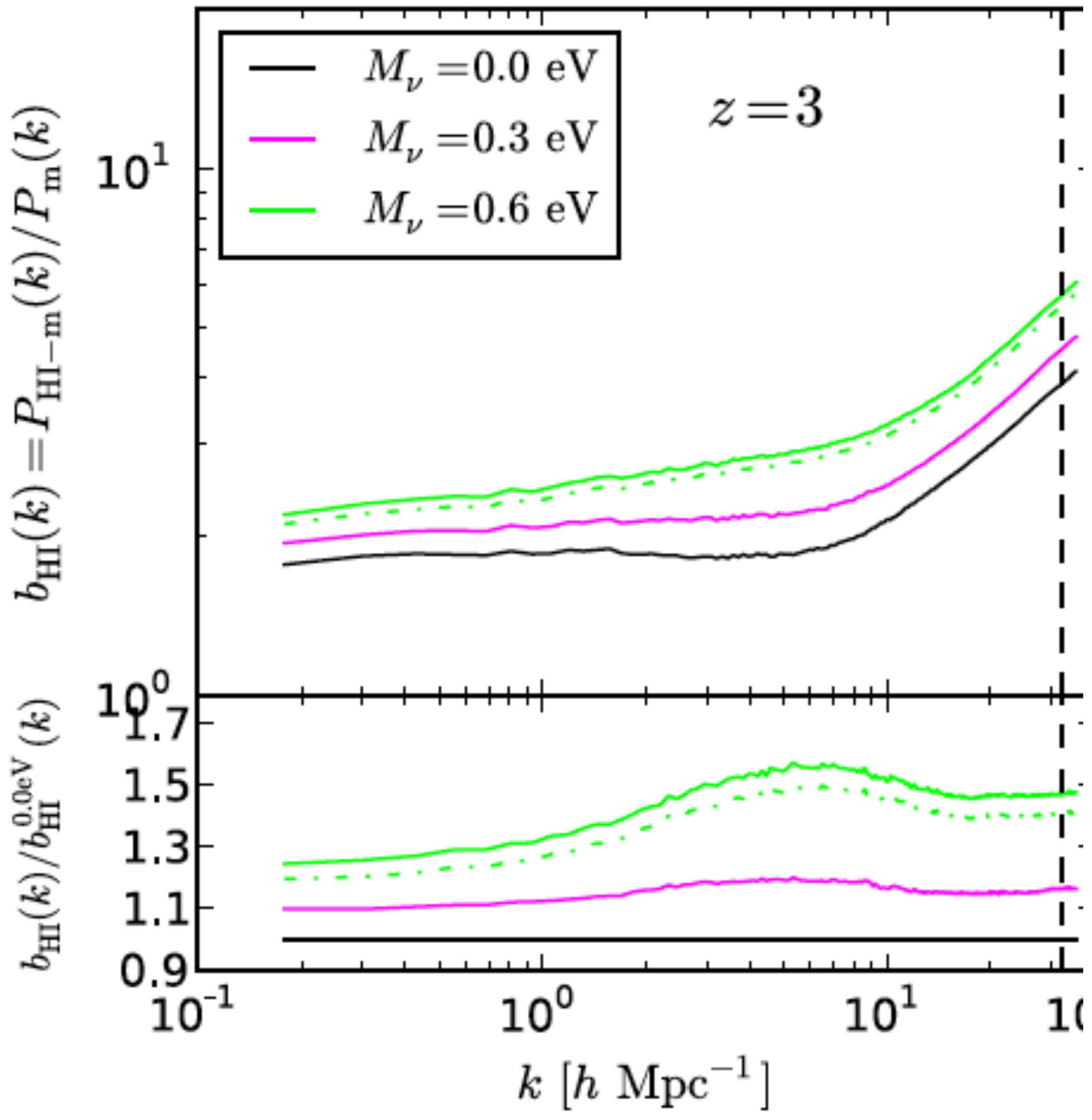
- Modelling of HI distribution based on particles and hydrosims of different box sizes of 15,30,60,120 Mpc/h linear size and different feedback implementation with and without galactic feedback (B60W with galatic winds, B60 without).

hydrosims and galaxy formation models

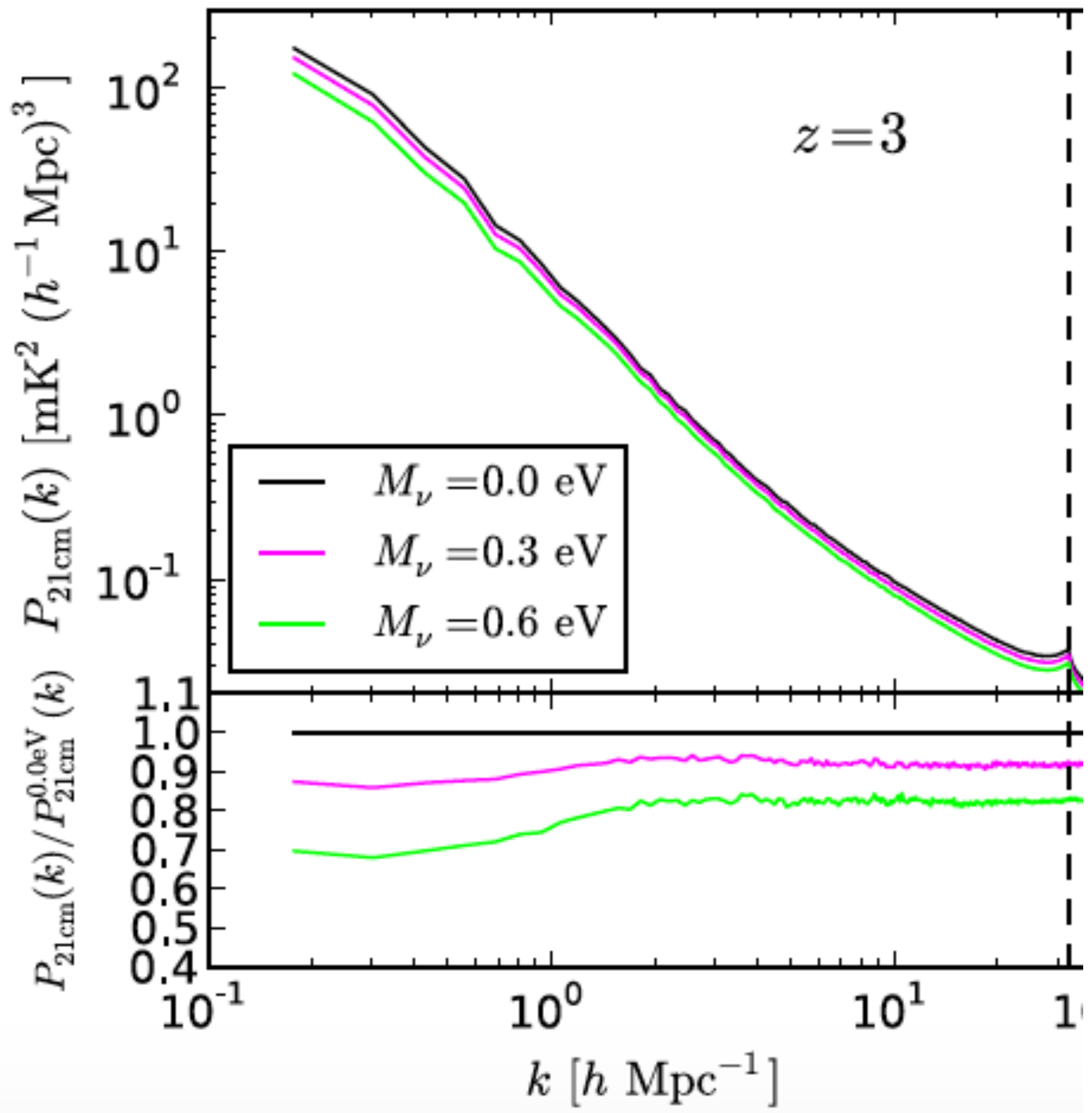


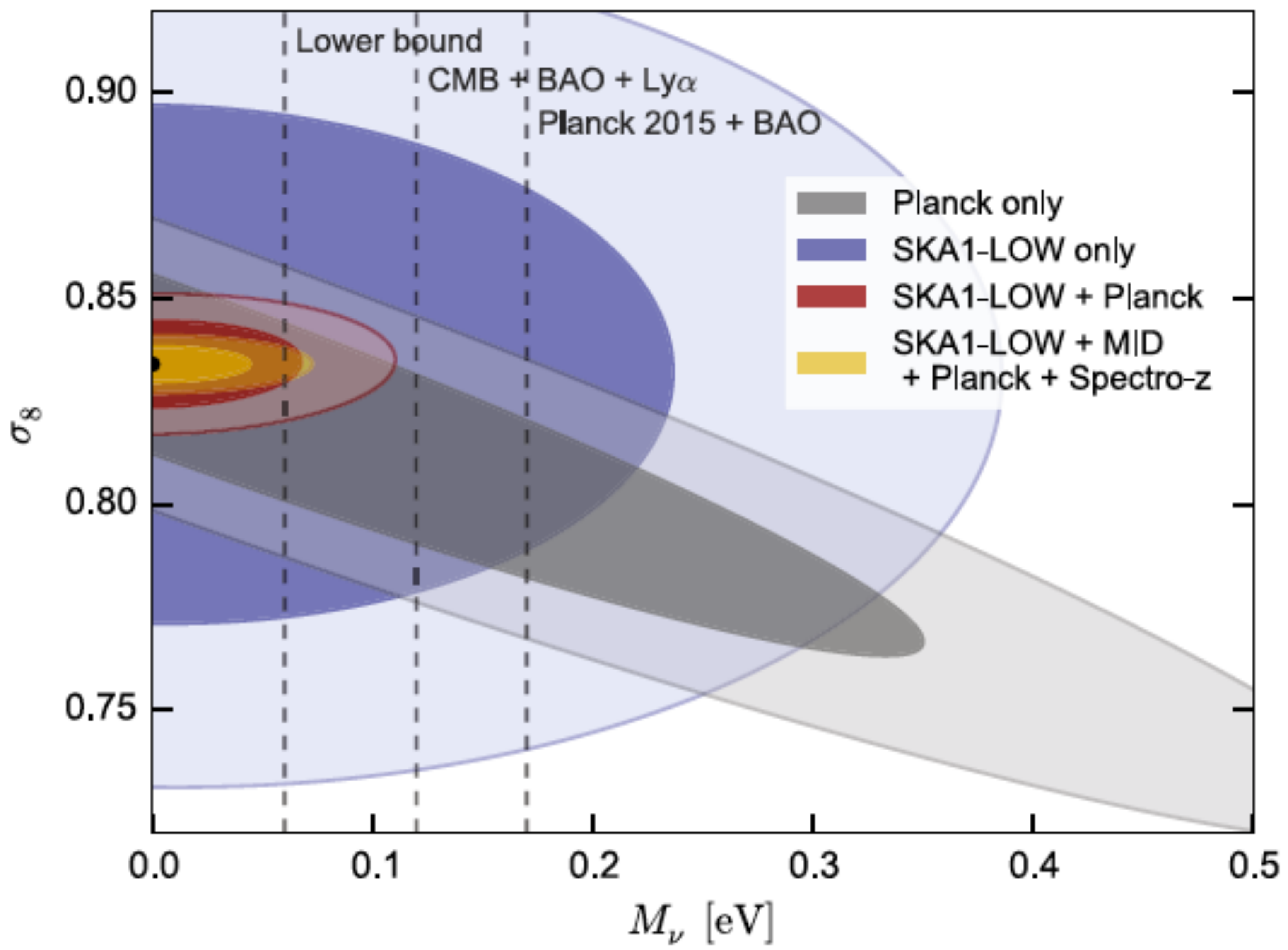
…further progress: interfacing this "small-scale" accurate and physical information with large scale methods for extensive mock productions e.g. PINOCCHIO LPT light-cone halos (Spinelli, Carucci+2021)

Simulating intensity mapping signal: large scales



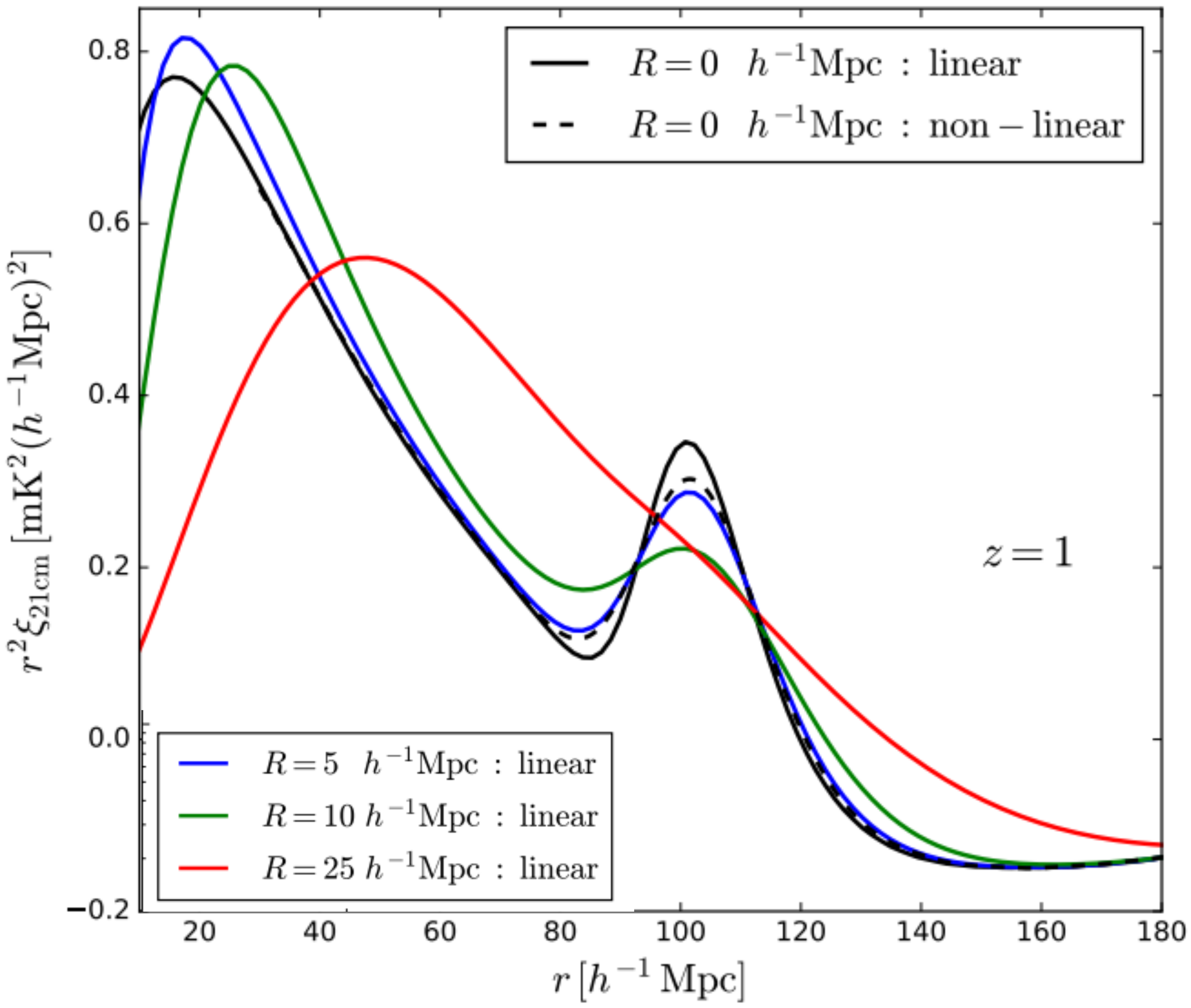
- Scale dependence bias also present in massive neutrino cosmologies.
- $M_{HI}(M)$ not affected by the presence of neutrinos.
- HI is more clustered in massive neutrino sims. (but Omega$_{HI}$ lower) - because small mass haloes are suppressed i.e. impact on $n_{HALO}(M)$.
- IM alone would provide constraint of about sigma(M_nu) = 30 meV (not very constraining compared to other probes).
- Radiative transfer postprocessing important but does not impact much the limit above





Villaescusa-Navarro, MV, Bull, 2015

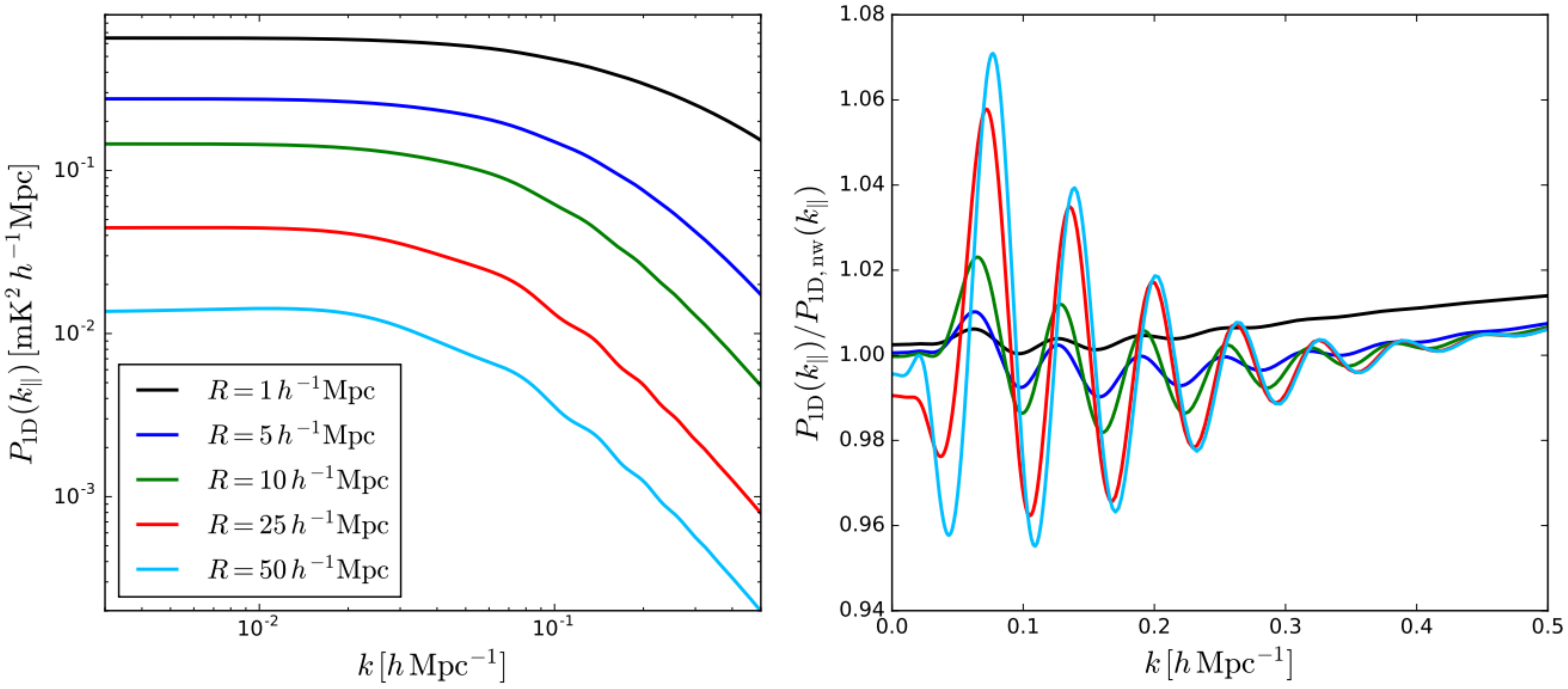
BAOs with SKA1-MID - I



Villaescusa-Navarro, Alonso, MV, 2017

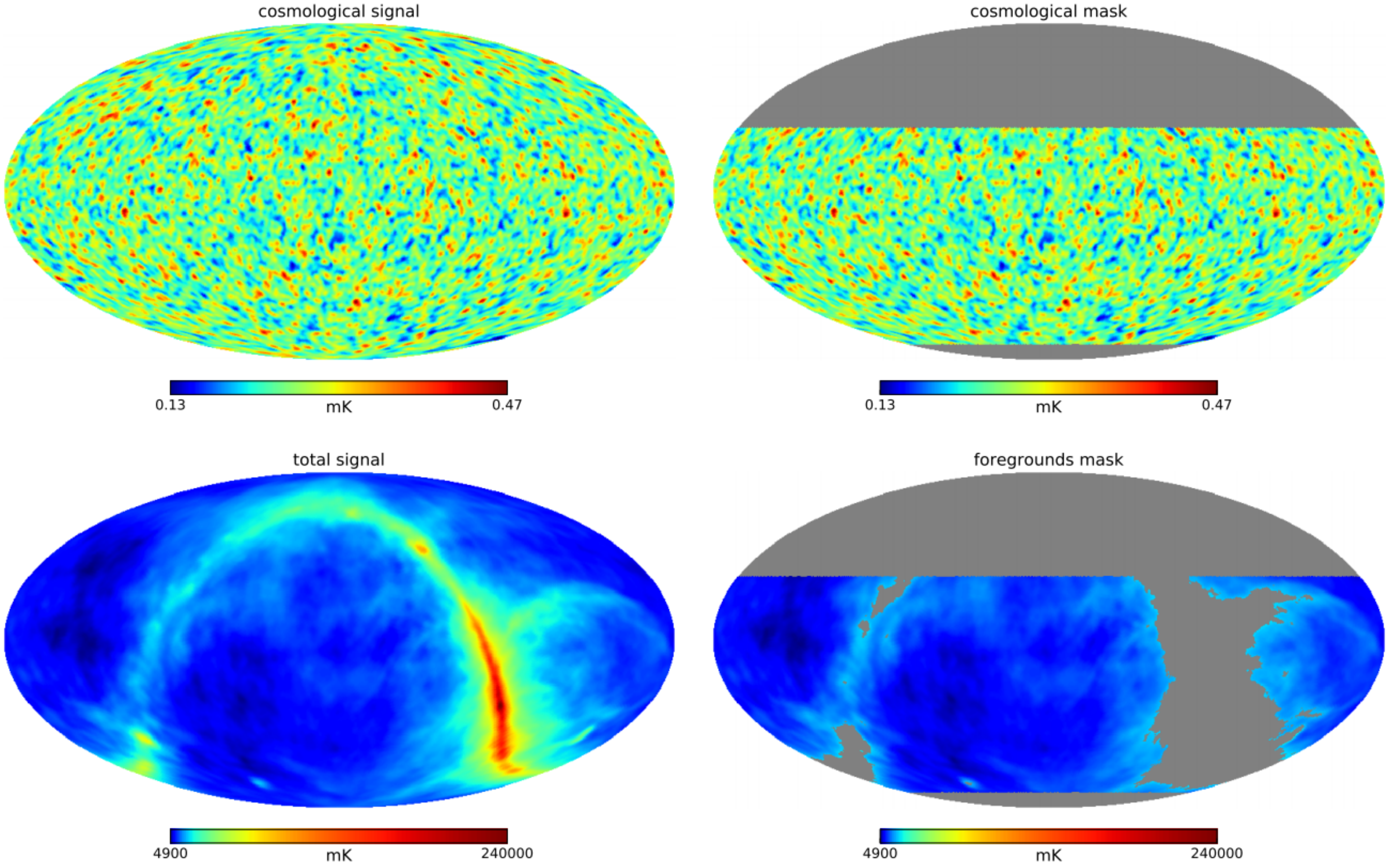
BAOs with SKA1-MID - II

$$\lim_{R\to\infty} P_{21\mathrm{cm,obs,1D}}(k_\parallel, z) = \frac{1}{4\pi R^2} P_{21\mathrm{cm}}(k_\parallel, z)$$



Villaescusa-Navarro, Alonso, MV, 2017

BAOs with SKA1-MID - III



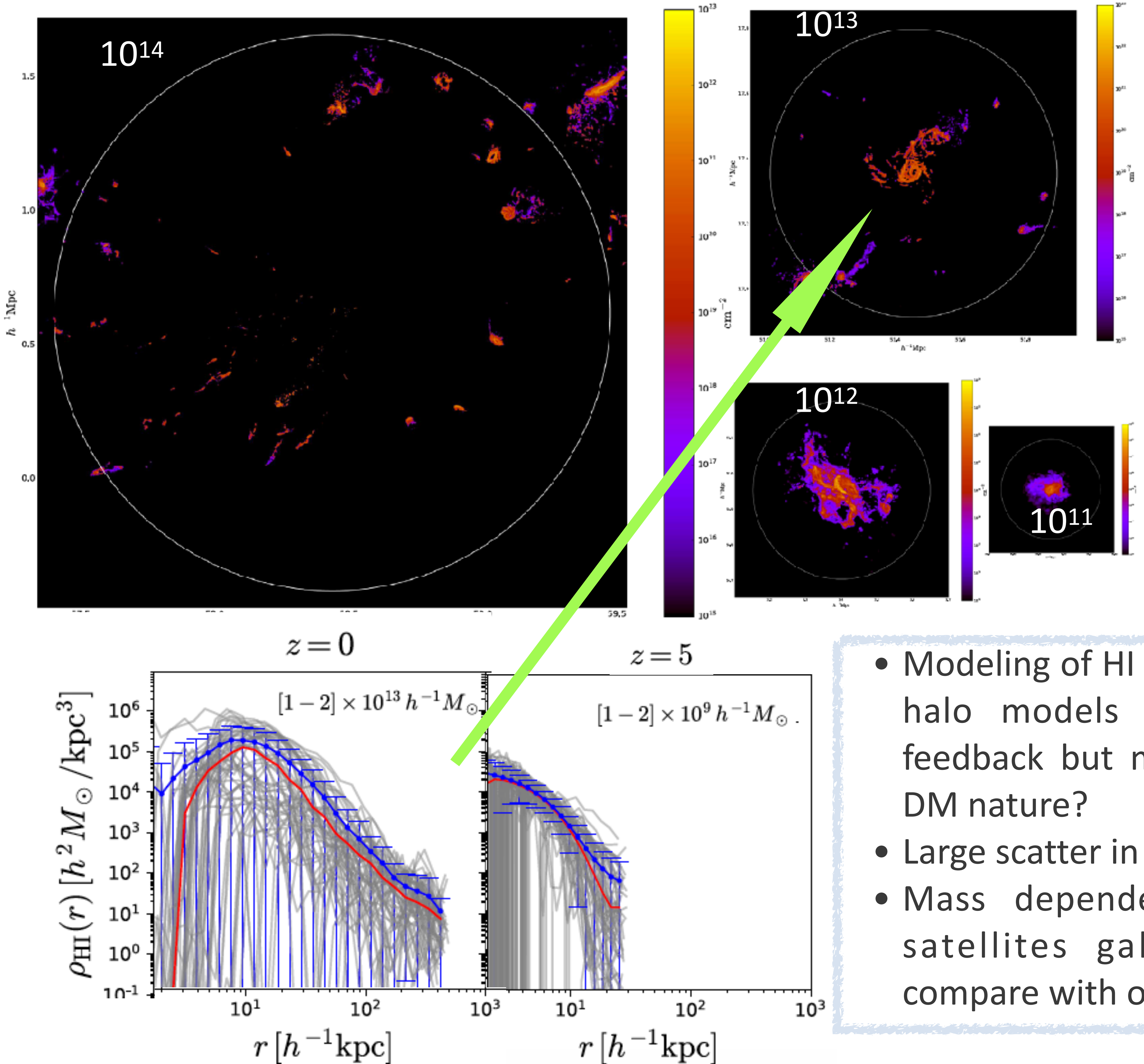
Villaescusa-Navarro, Alonso, MV, 2017

BAOs with SKA1-MID - IV

z range	$\langle z \rangle$	mask	σ_α (C)	(C+N)	(C+N+FG)
[0.36-0.75]	0.6	no	1.008 ± 0.016	1.008 ± 0.016	1.007 ± 0.016
		yes	1.006 ± 0.020	1.006 ± 0.021	1.006 ± 0.024
[0.75-1.26]	1.0	no	0.996 ± 0.010	0.997 ± 0.011	0.996 ± 0.011
		yes	0.997 ± 0.012	0.997 ± 0.013	0.998 ± 0.015
[1.26-1.98]	1.6	no	1.001 ± 0.011	1.004 ± 0.014	1.003 ± 0.014
		yes	1.000 ± 0.013	1.003 ± 0.016	1.004 ± 0.019
[1.98-3.05]	2.5	no	1.004 ± 0.013	1.003 ± 0.021	1.000 ± 0.021
		yes	1.004 ± 0.016	1.002 ± 0.026	1.002 ± 0.031

Villaescusa-Navarro, Alonso, MV, 2017

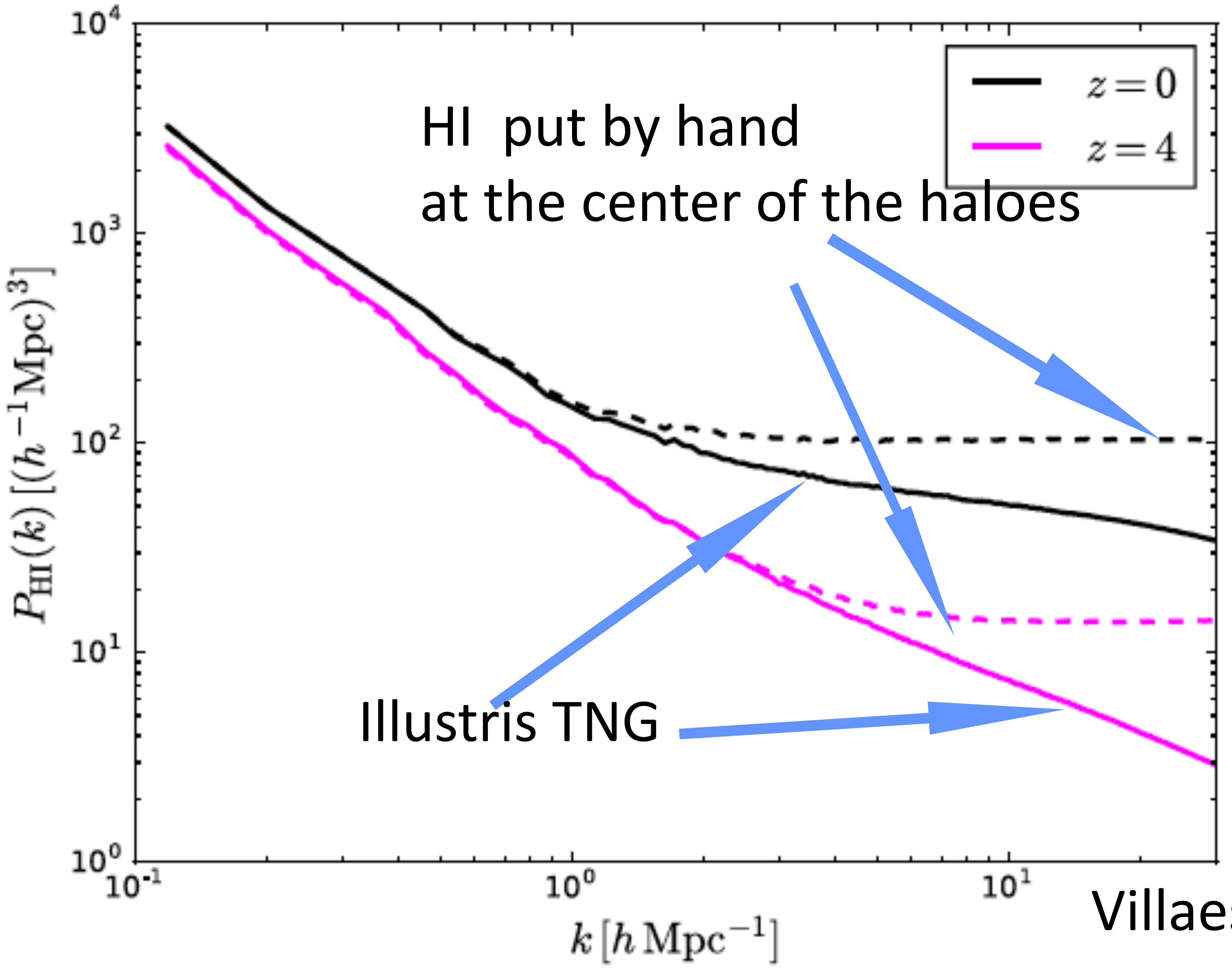
Simulating intensity mapping signal: small scales



Villaescusa-Navarro+18 based on Illustris TNG

- Modeling of HI halo important also for halo models - Surely affected by feedback but maybe also sensitive to DM nature?
- Large scatter in the HI density profile.
- Mass dependence and central vs. satellites galaxies important to compare with observations.

Simulating intensity mapping signal: small scales



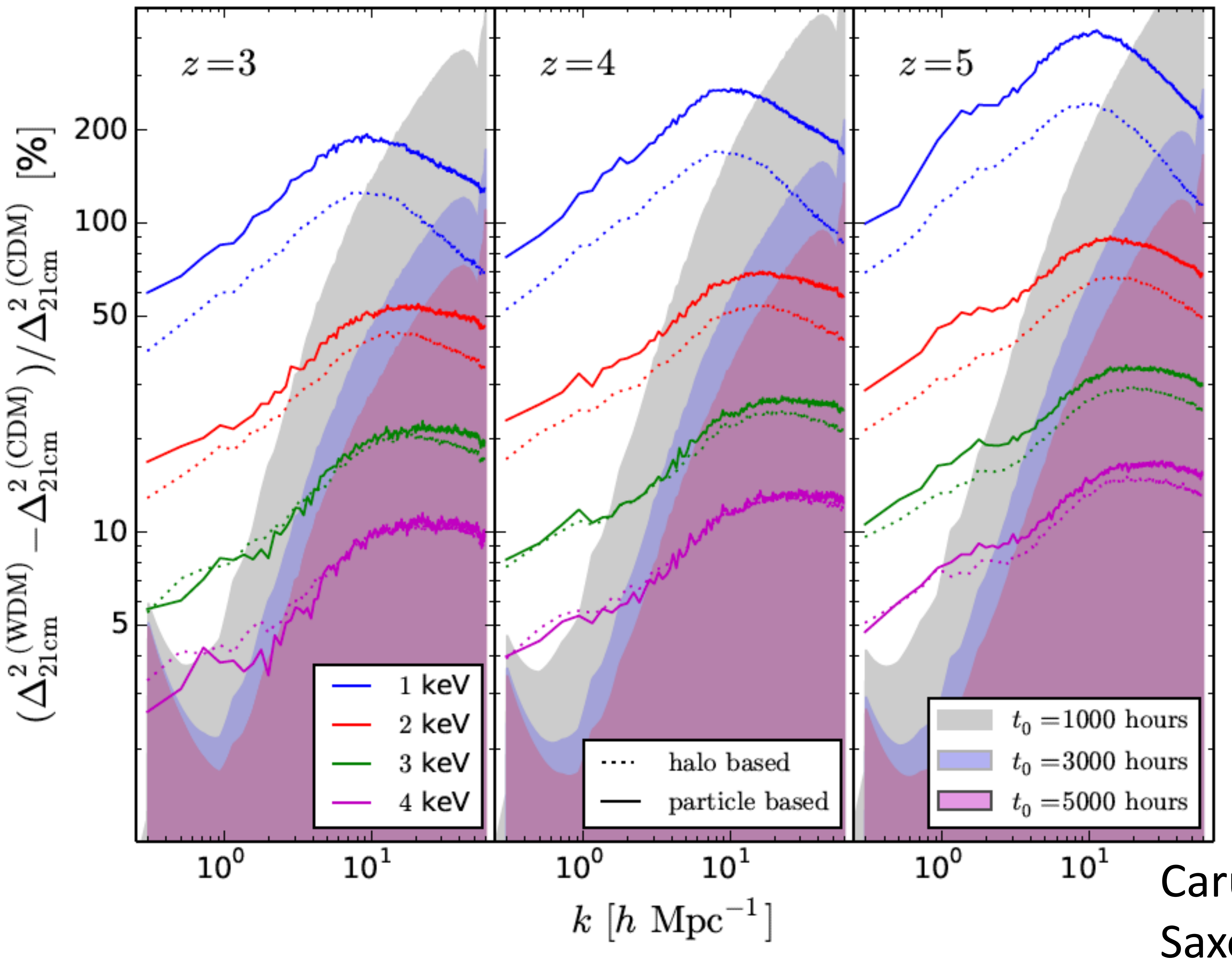
Villaescusa-Navarro+18

$$
\begin{aligned}
P_{\rm H\,I}^{\rm SN}(z) = \lim_{k\to 0} P_{\rm 1h,H\,I}(k,z) &= \frac{1}{[\rho_c^0 \Omega_{\rm H\,I}(z)]^2} \\
&\times \int_0^\infty n(M,z) M_{\rm H\,I}^2(M,z)\, dM \\
&= \frac{\int_0^\infty n(M,z) M_{\rm H\,I}^2(M,z)\, dM}{\left[\int_0^\infty n(M,z) M_{\rm H\,I}(M,z)\, dM\right]^2}.
\end{aligned}
$$

- Shot noise level in HI quite different from the standard case of galaxies and haloes good amount of HI substructure within each DM halo

- Note further that *numerical convergence of all quantities not fully achieved*.

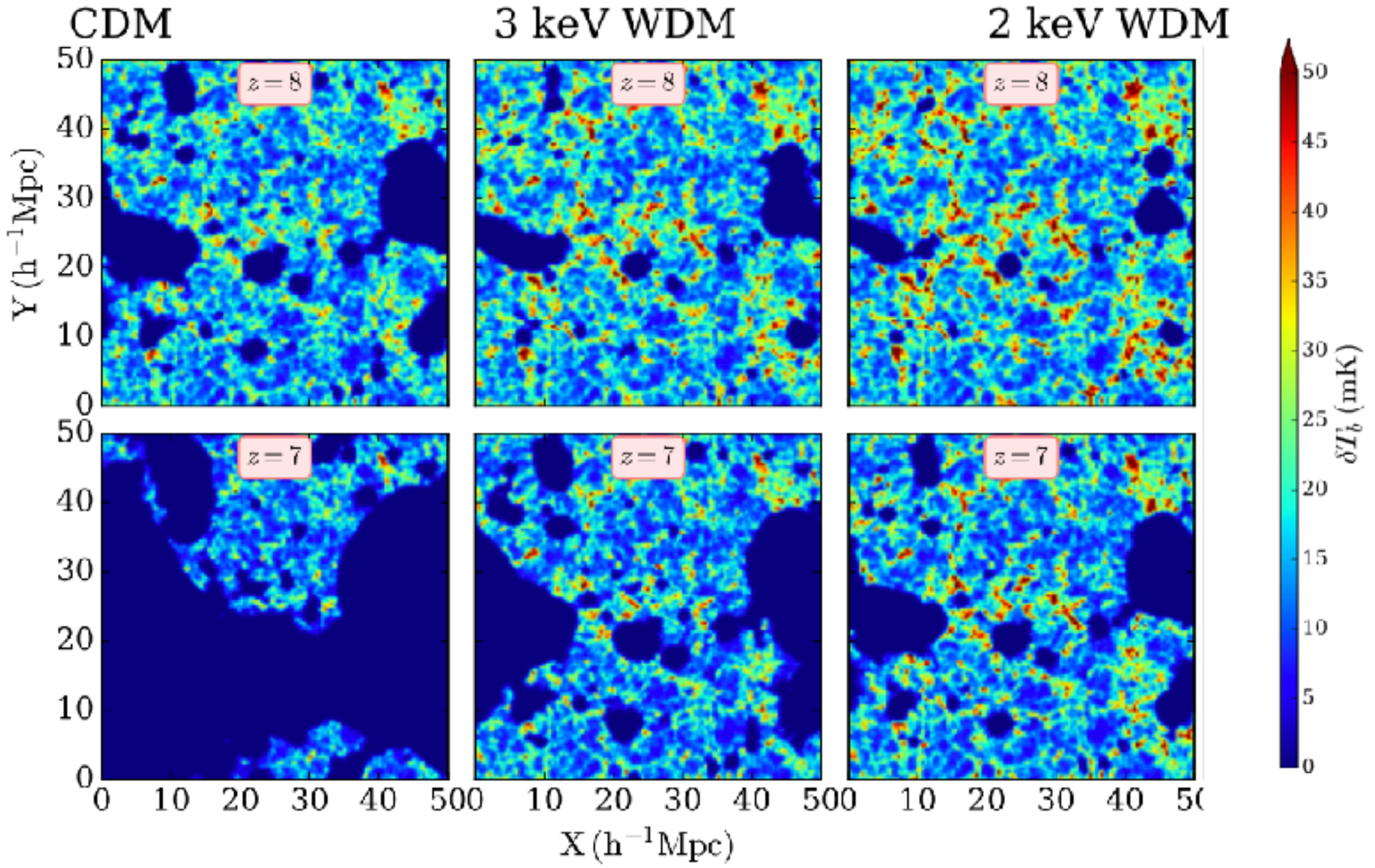
Simulating intensity mapping signal: WDM



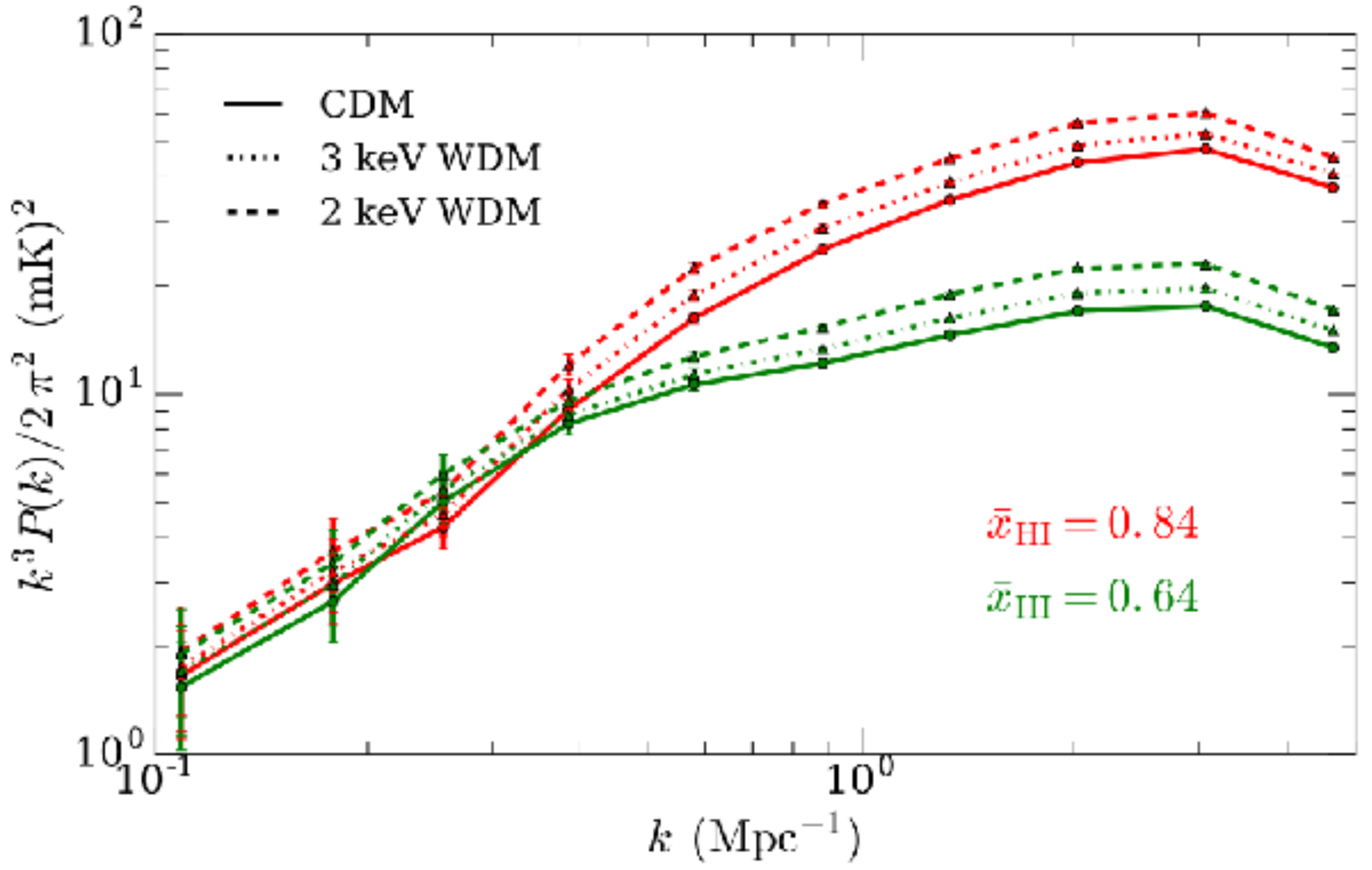
Carucci+15
Saxena,Majumdar,Kamran,MV+20

Probably able **to rule out a 4 keV WDM model** with 5000 hours of observations at z > 3, while a smaller mass of 3 keV, comparable to present day constraints, can be ruled out at more than 2 confidence level with 1000 hours of observations at z > 5 - Note that *density inside haloes poorly modelled.*

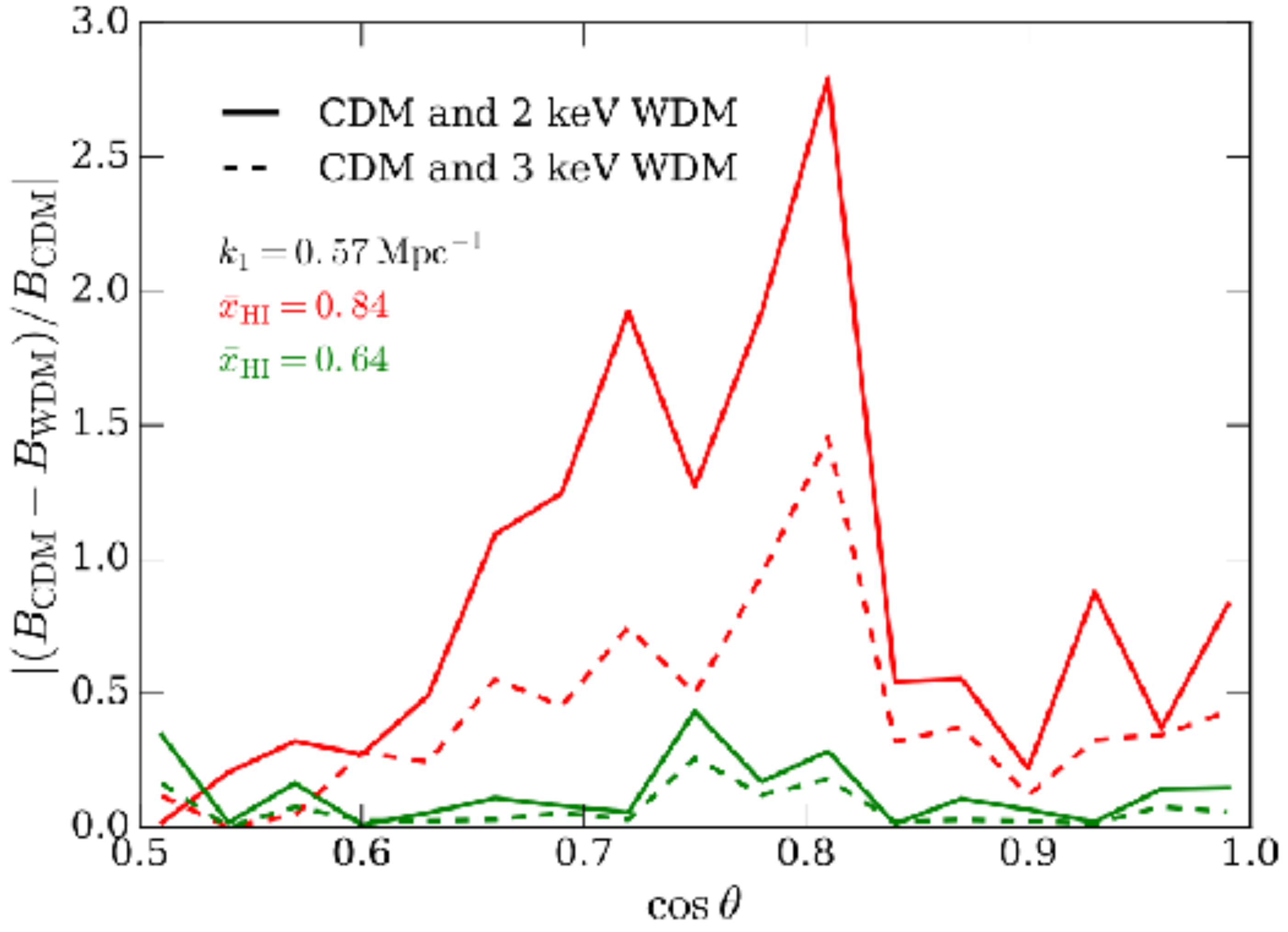
Simulating intensity mapping signal: WDM and bispectrum



Power spectrum

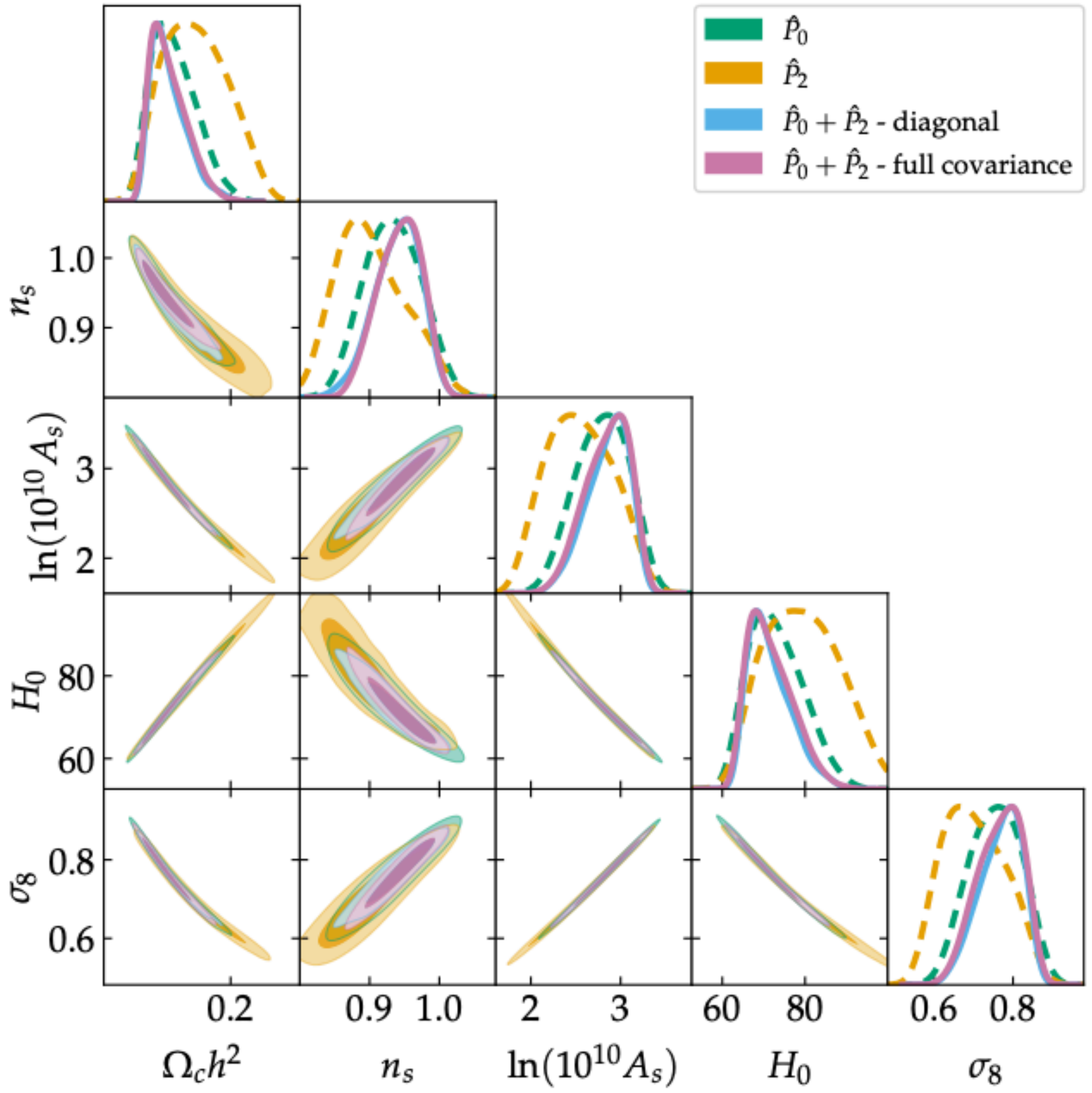


Bispectrum



Saxena,Majumdar,Kamran,MV 2020

SKAO Mid - Power spectrum from HI only



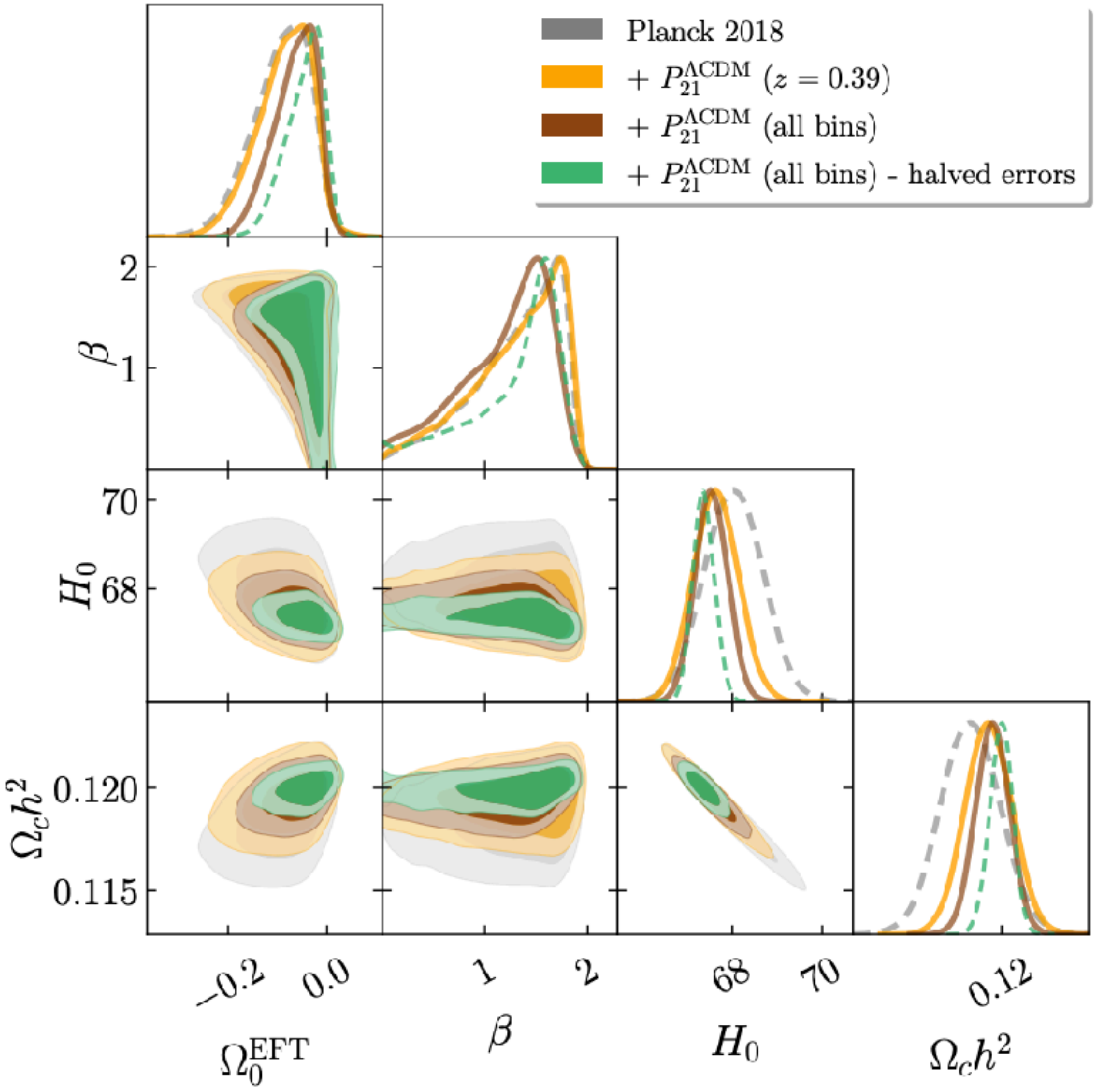
Berti, Spinelli, MV 2022

Table 1. Assumed specifications for SKA-Mid survey (SKA Cosmology SWG 2020).

Parameter		Value
D_{dish} [m]	SKAO dish diameter	15
N_{dish}	SKAO dishes	133
t_{obs} [h]	observing time	10000
T_{sys} [K]	system temperature	25
$\delta\nu$ [MHz]	frequency range	1
A_2 [deg^2]	survey area (Band 2)	5000
$\Omega_{sur,1}$ [sr]	survey area (Band 2)	1.5
A_1 [deg^2]	survey area (Band 1)	20000
$\Omega_{sur,2}$ [sr]	survey area (Band 2)	6.1
$f_{sky,2}$	covered sky area (Band 2)	0.12
$f_{sky,1}$	covered sky area (Band 1)	0.48
Δz	width of the redshift bins	0.5

Realistic mock data set
Constraining power ~10% for many cosmo params
If added to Planck data the improvement
compared to Planck only could be up to a factor 2
for H0, sigma8

SKAO Mid - Conservative EFT constraints



Berti, Spinelli, Haridasu, MV, Silvestri 2022

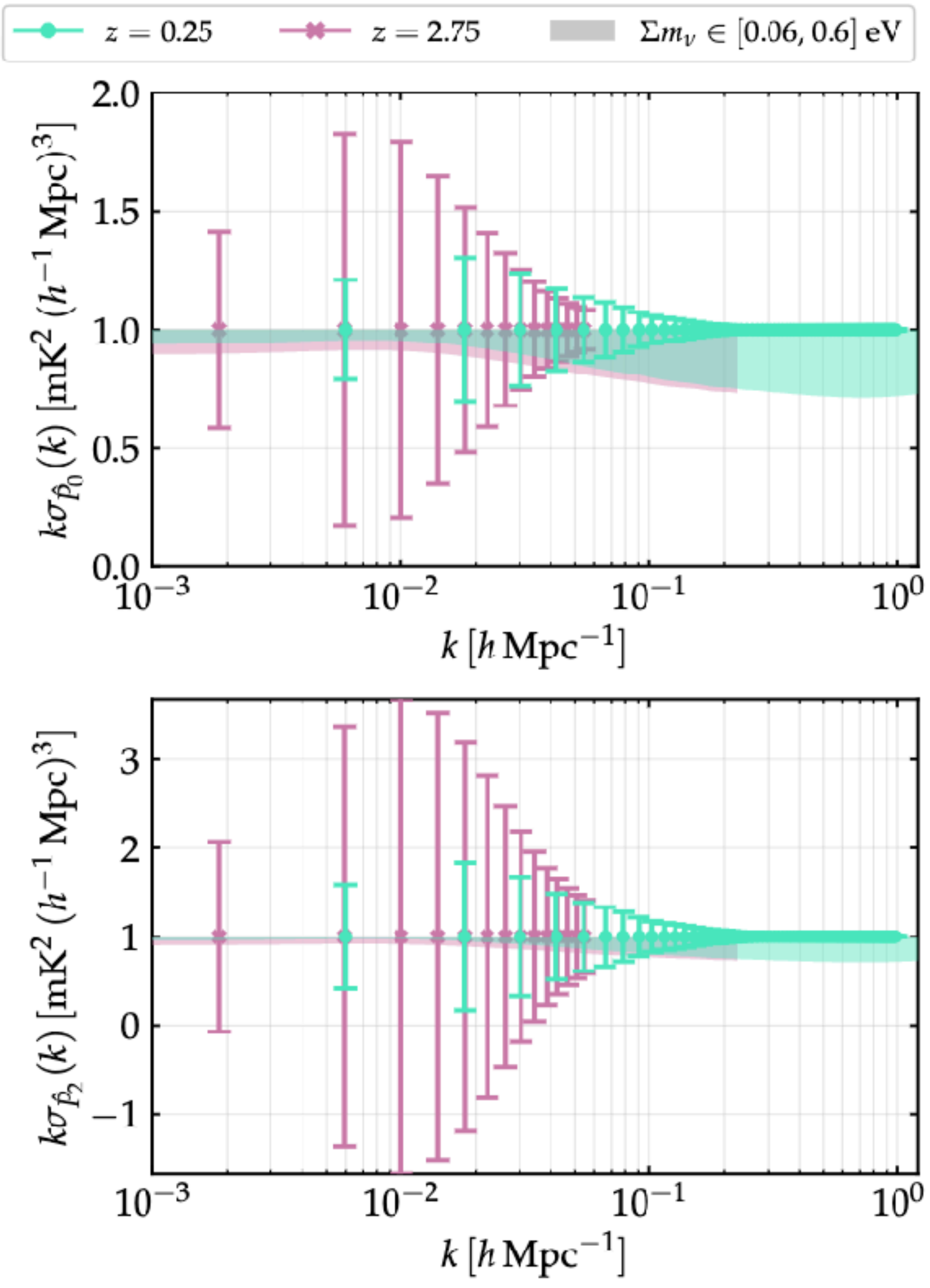
$$\Omega^{\mathrm{EFT}}(a) = \exp(\Omega_0^{\mathrm{EFT}} a^\beta) - 1$$

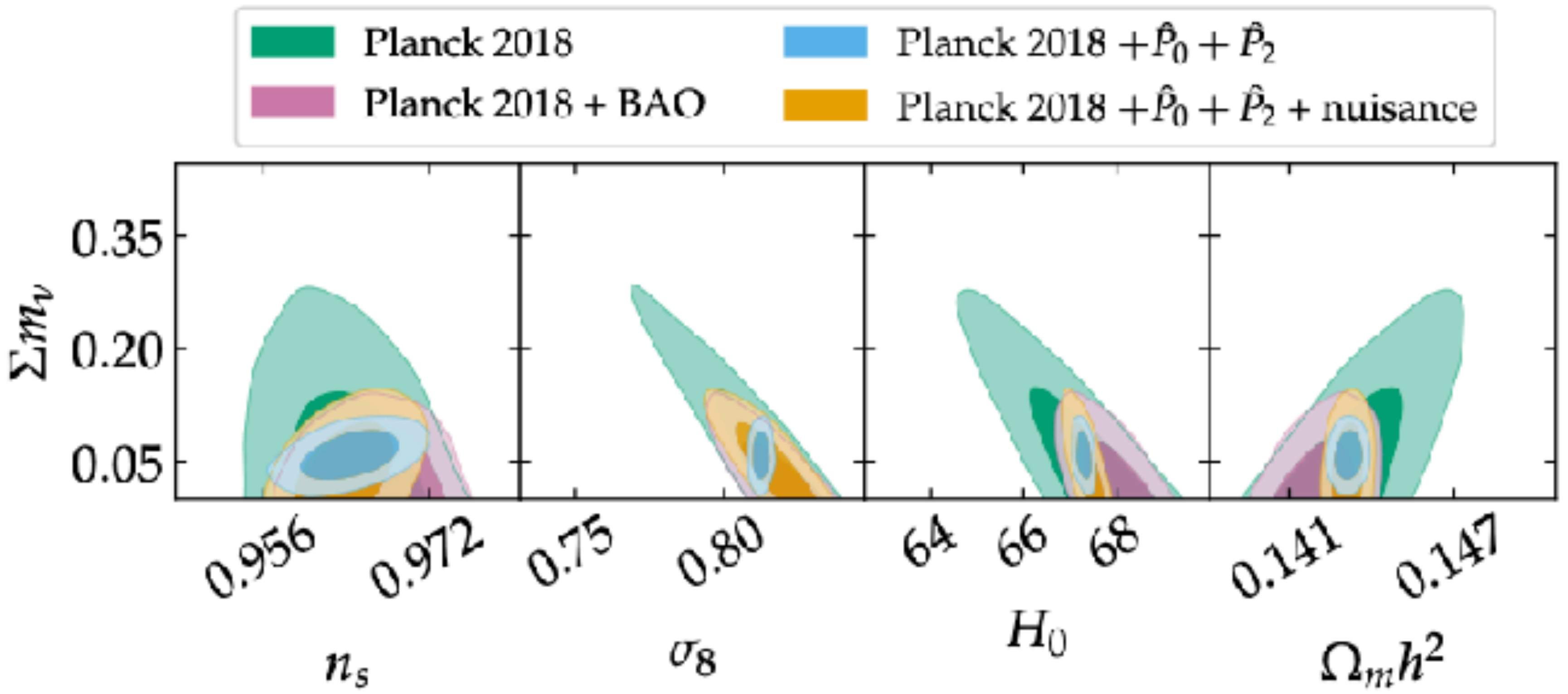
PARAMETER	Planck 2018 $+ P_{21}^{\mathrm{EFT}}(z = 0.39)$	Planck 2018 $+ P_{21}^{\mathrm{EFT}}$(bins)
$\Omega_c h^2$	0.1194 ± 0.0011 (-22%)	0.12042 ± 0.00080 (-43%)
Ω_0^{EFT}	$-0.086^{+0.064}_{-0.038}$ (-10%)	$-0.079^{+0.047}_{-0.036}$ $(-\mathbf{26}\%)$
β	$1.28^{+0.58}_{-0.22}$ $(+4\%)$	$1.08^{+0.42}_{-0.25}$ $(-\mathbf{13}\%)$
H_0	$67.63 \pm 0.50(-24\%)$	67.15 ± 0.36 (-46%)

PARAMETER	Planck 2018 $+ P_{21}^{\Lambda\mathrm{CDM}}$ $(z = 0.39)$	Planck 2018 $+ P_{21}^{\Lambda\mathrm{CDM}}$(bins)
$\Omega_c h^2$	0.1194 ± 0.0011 (-22%)	0.11957 ± 0.00082 (-41%)
Ω_0^{EFT}	$-0.086^{+0.068}_{-0.039}$ (-10%)	$-0.066^{+0.055}_{-0.031}$ $(-\mathbf{24}\%)$
β	$1.28^{+0.58}_{-0.22}$ $(+4\%)$	$1.18^{+0.57}_{-0.26}(-\mathbf{8}\%)$
H_0	67.63 ± 0.51 (-23%)	67.54 ± 0.37 (-44%)

PARAMETER	$P_{21}^{\Lambda\mathrm{CDM}}$(bins)	P_{21}^{EFT}(bins)
Ω_0^{EFT}	$0.053^{+0.075}_{-0.17}$	$-0.14^{+0.13}_{-0.10}$
β	$1.26^{+0.55}_{-0.30}$	$1.10^{+0.49}_{-0.29}$
H_0	$74.1^{+8.1}_{-11}$	70 ± 9

Neutrino free streaming

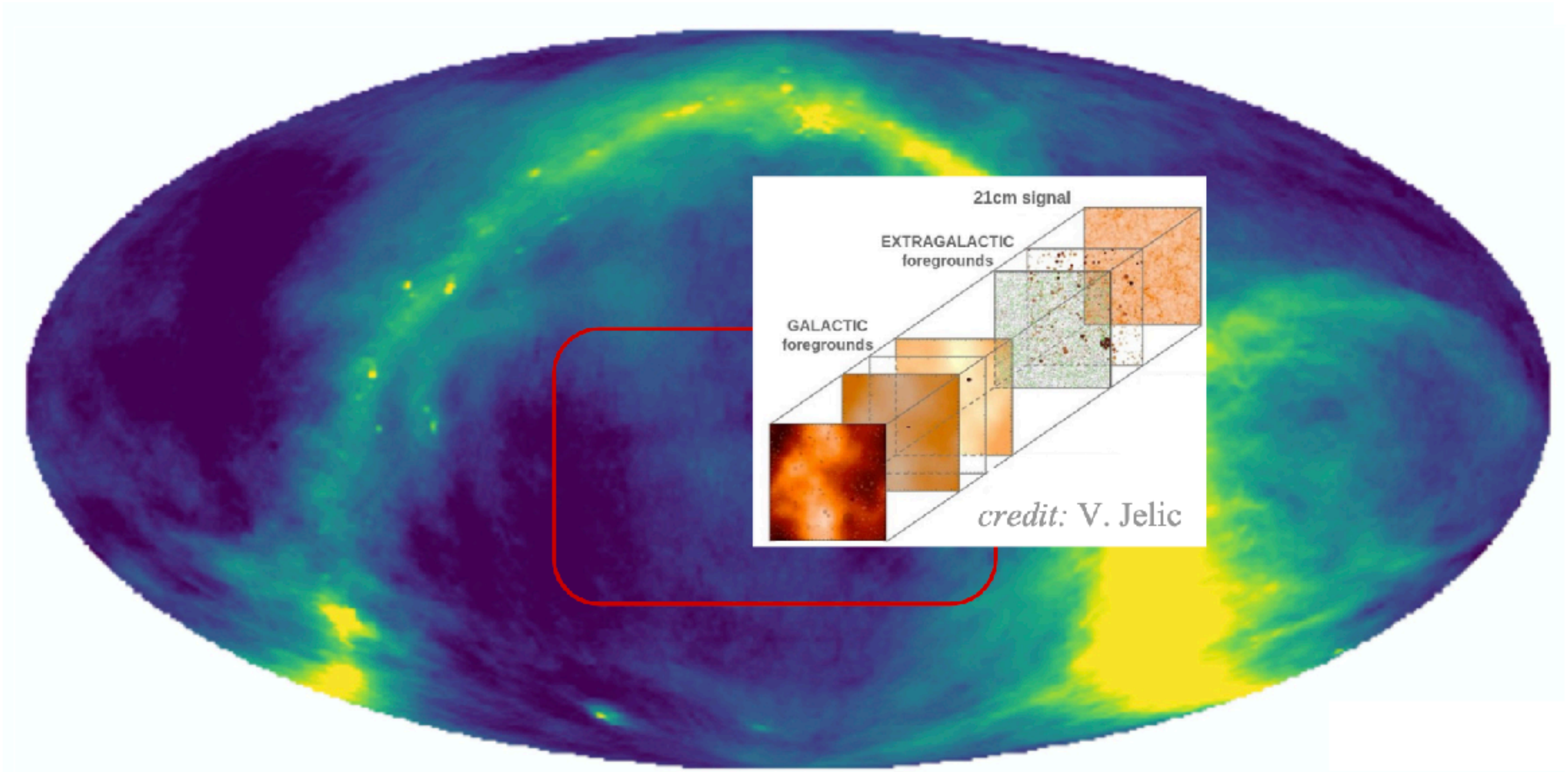




22 meV 1sigma error bar from Planck18+BAO+conservative IM

Berti, MV, Spinelli 22 in prep

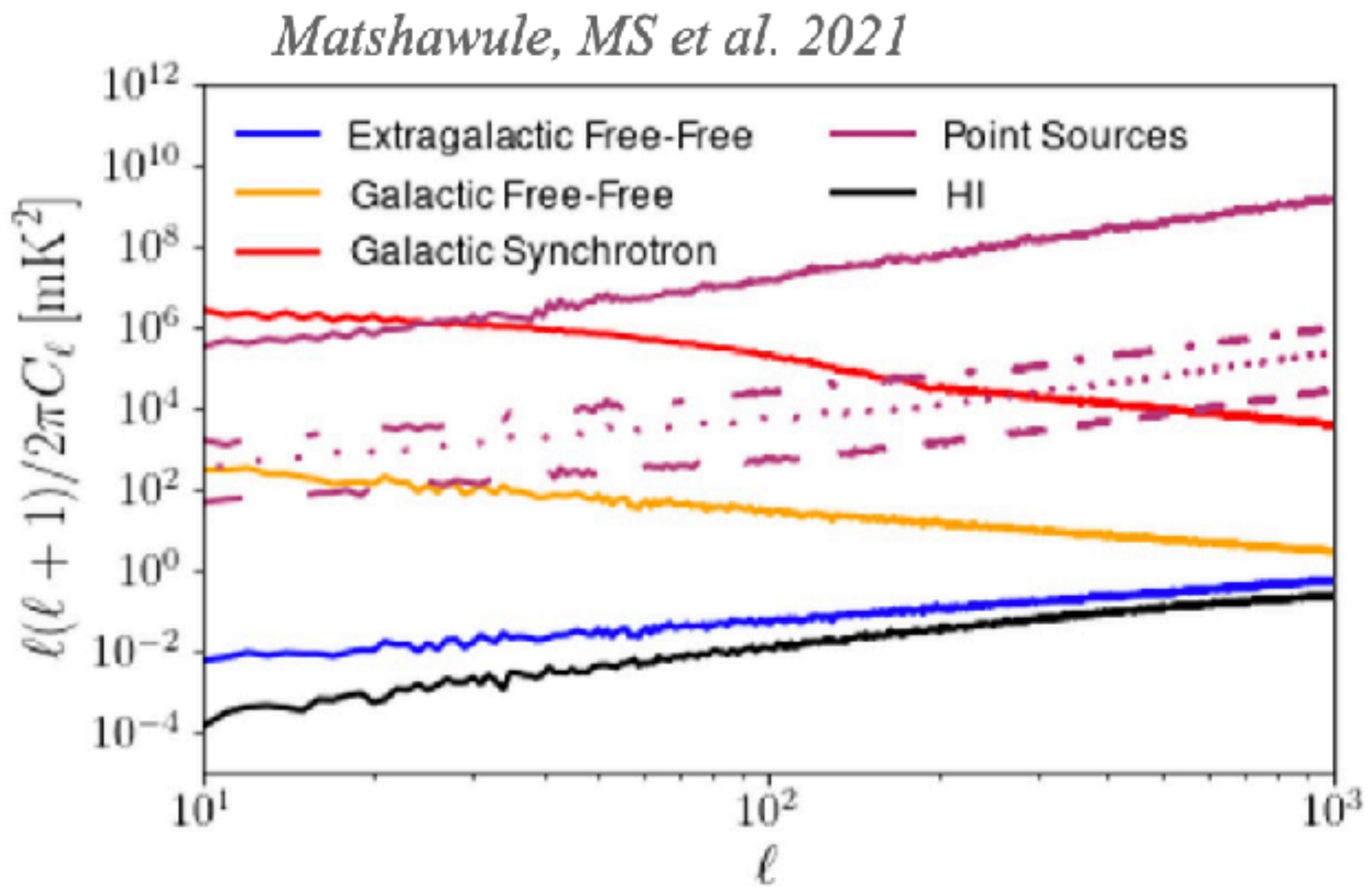
Foregrounds

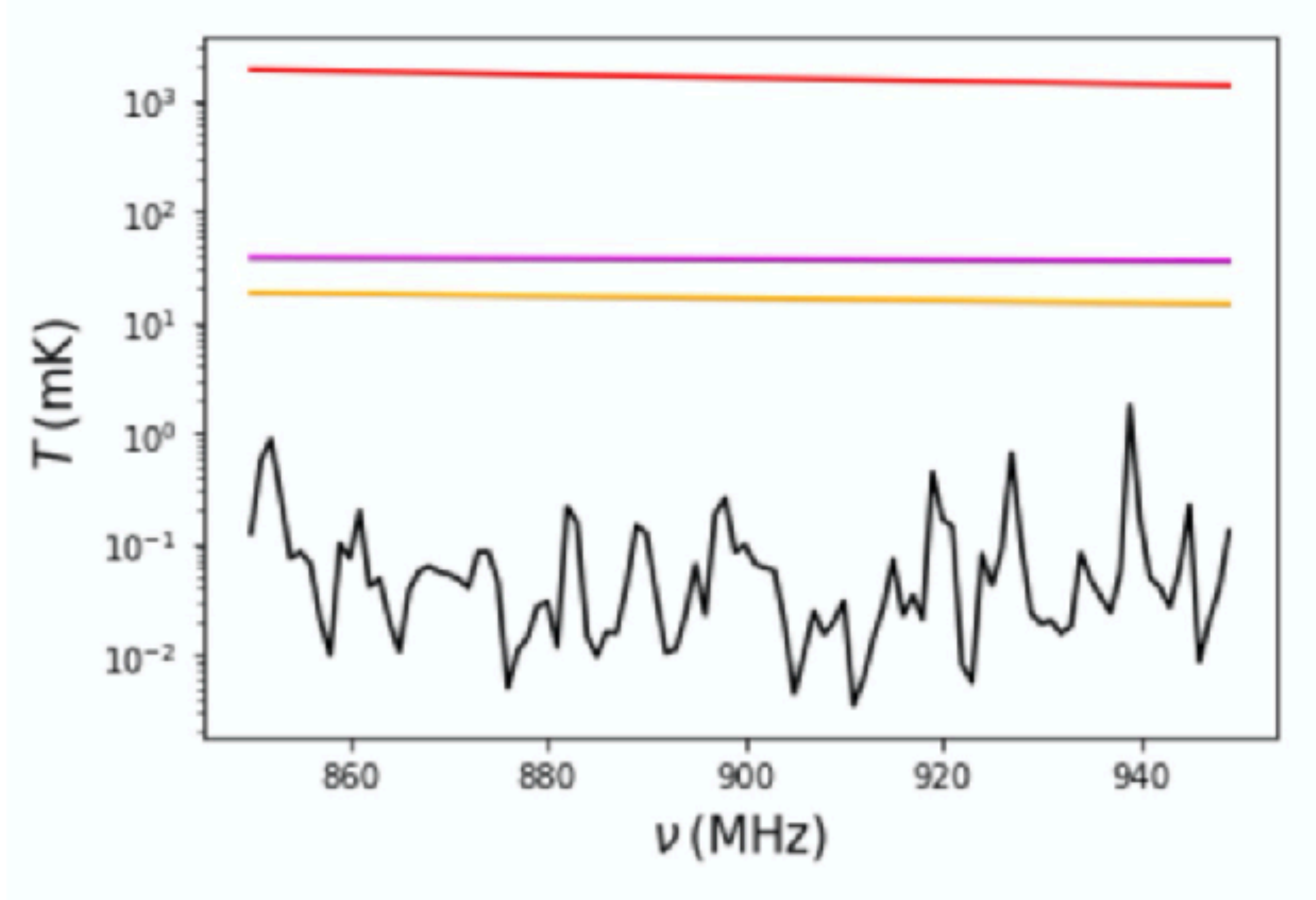


adapted from Haslam et al. (1982)

+ Radio frequency interference and instrumental noise

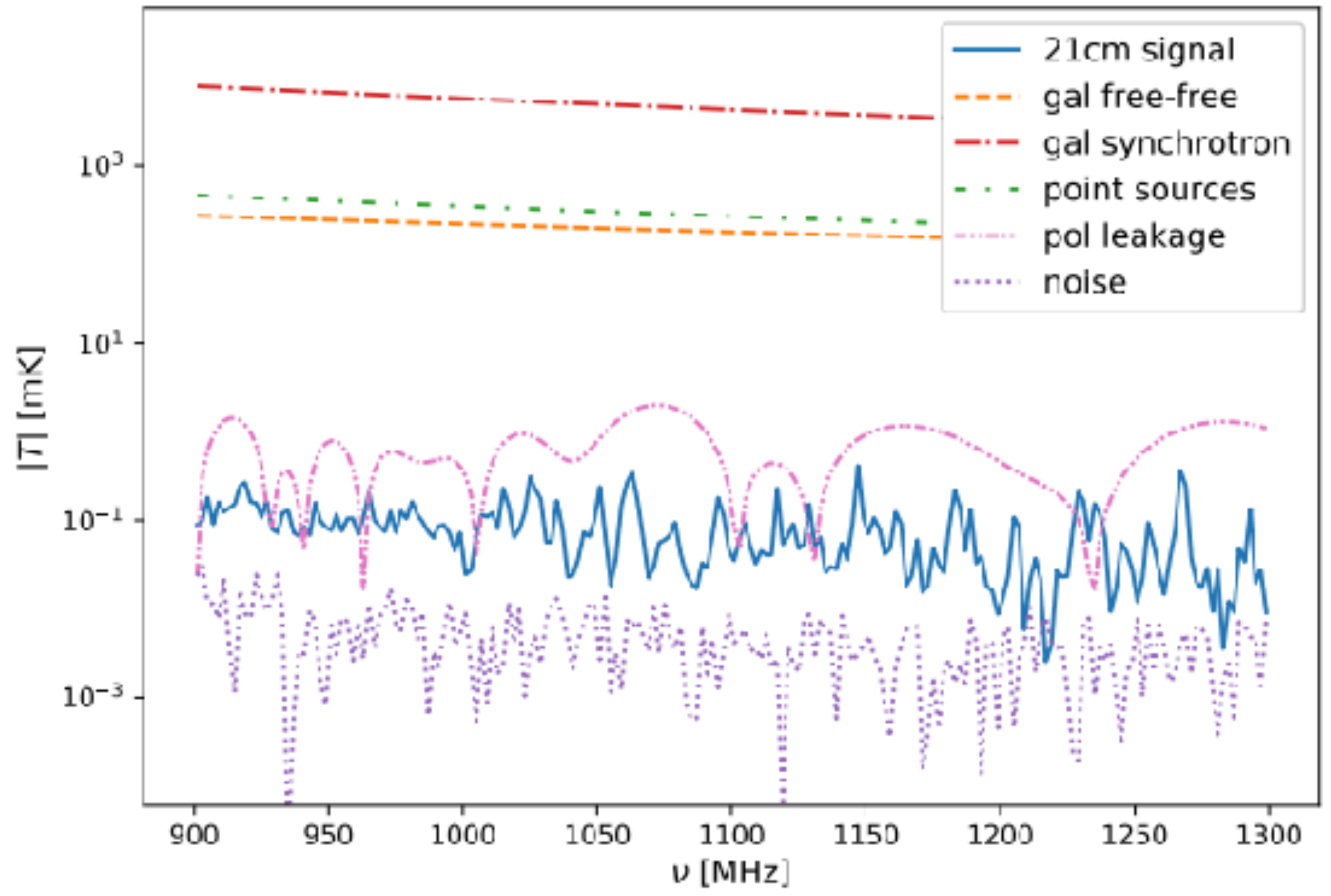
Foregrounds - II





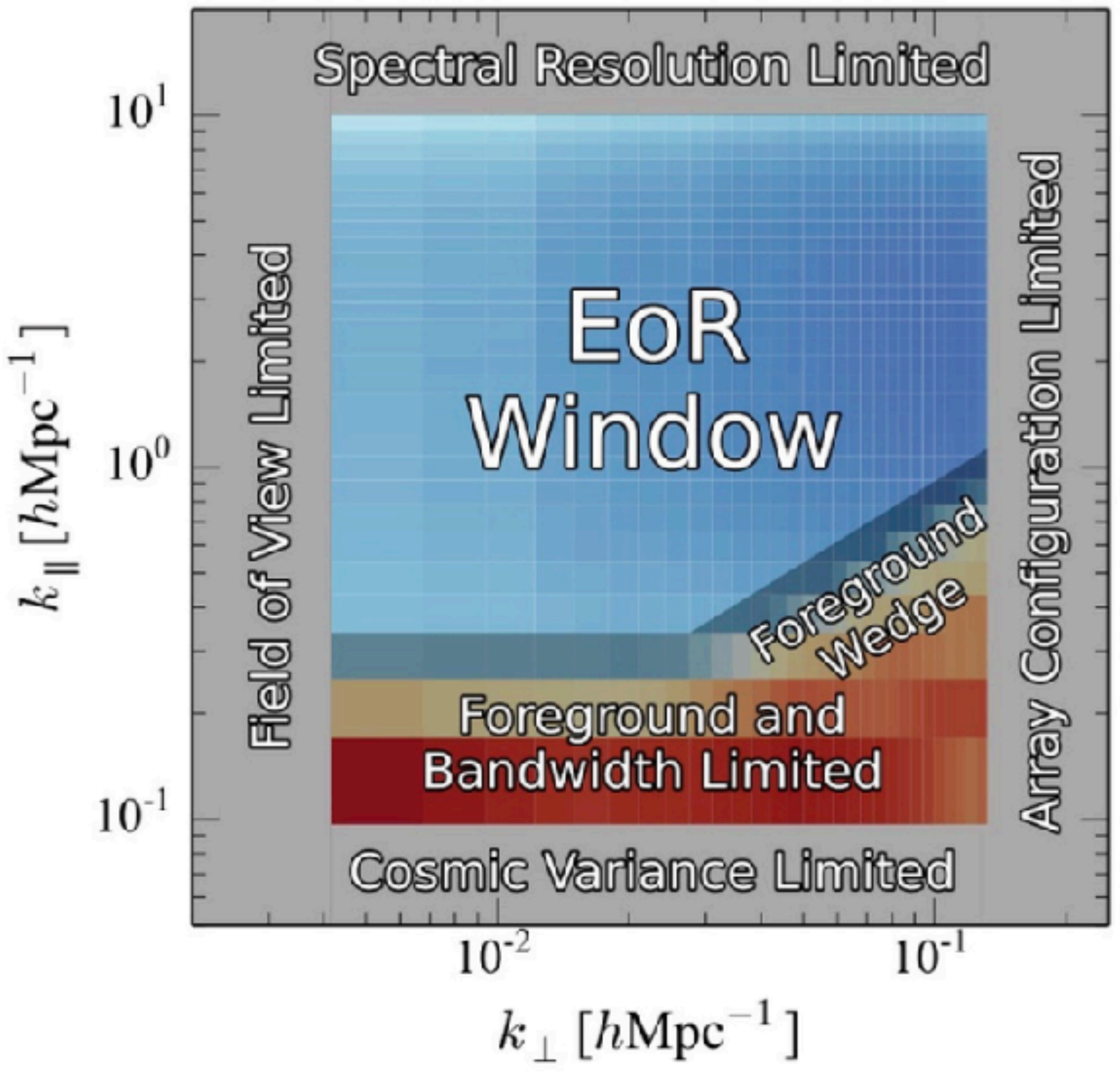
Foregrounds are usually smooth (highly correlated in frequency)
Can we separate them from the signal?

...but....... polarization leakage has structure



Carucci+20

Foregrounds - III

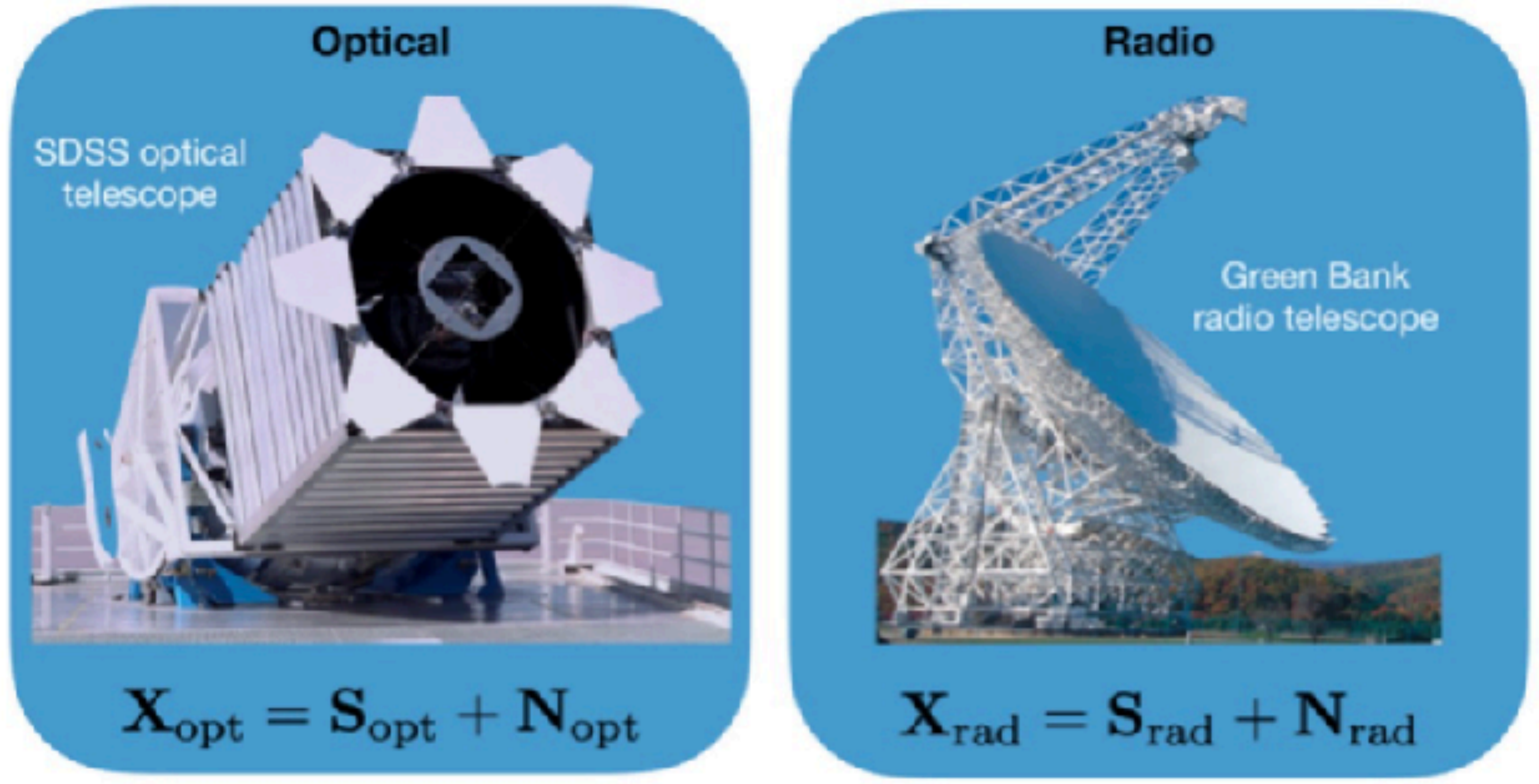


Liu et al. (2014)

Strategies for FGs:
1) avoid them
2) model them
3) subtract (clean/separate) them

Techniques:
Principal Component Analysis
Independent Component Analysis
Generalised Morphological Component Analysis
Machine Learning
Deep Learning
CNN
etc.

Cross-correlations



Auto Correlation:

uncorrelated

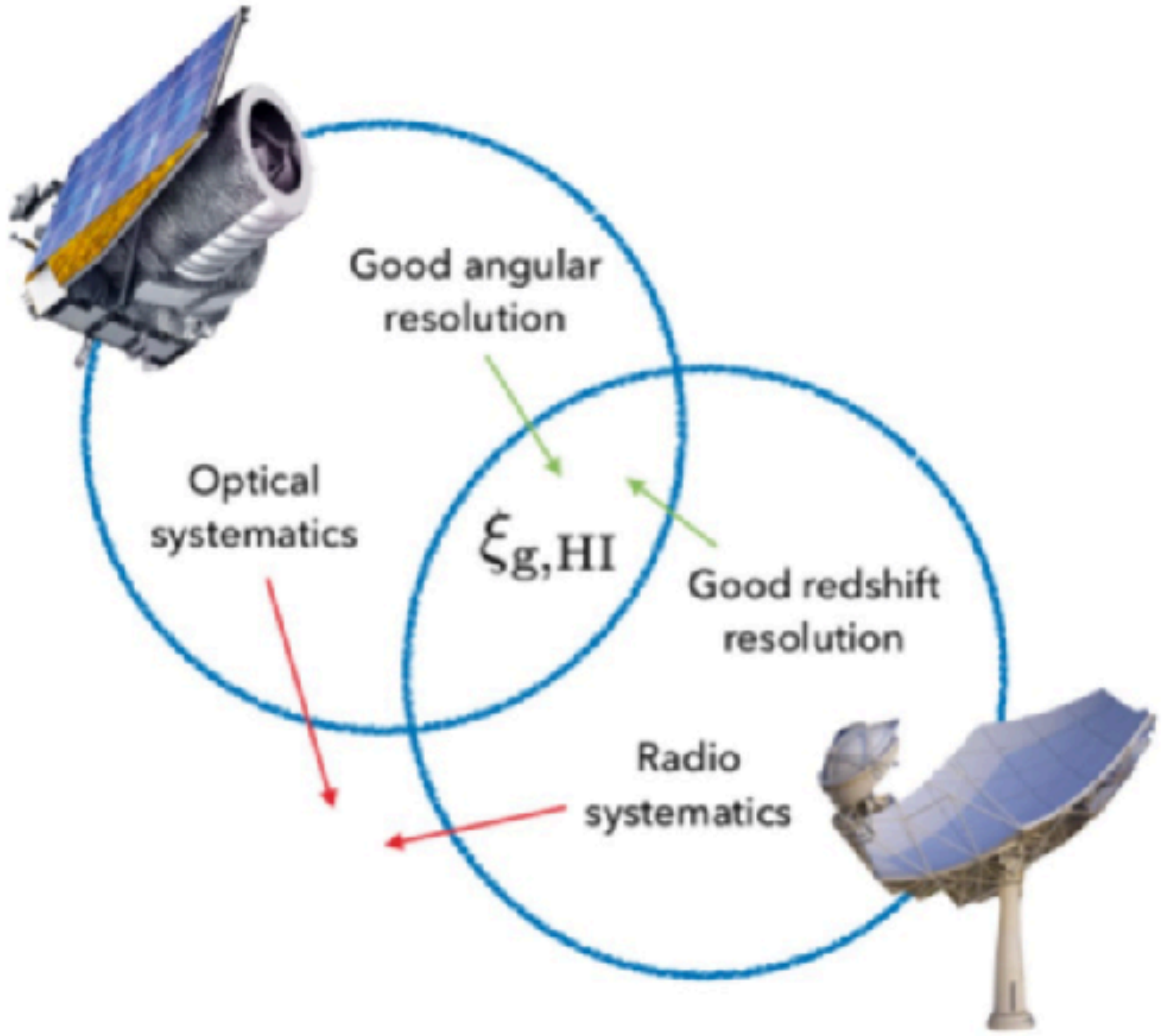
$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm opt}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm opt}\rangle + 2\cancel{\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm opt}\rangle} + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm opt}\rangle$$

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm opt}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm opt}\rangle + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm opt}\rangle$$

signal you want *noise you don't want*

Cross Correlation:

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm rad}\rangle + \cancel{\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm rad}\rangle} + \cancel{\langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm opt}\rangle} + \cancel{\langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm rad}\rangle}$$



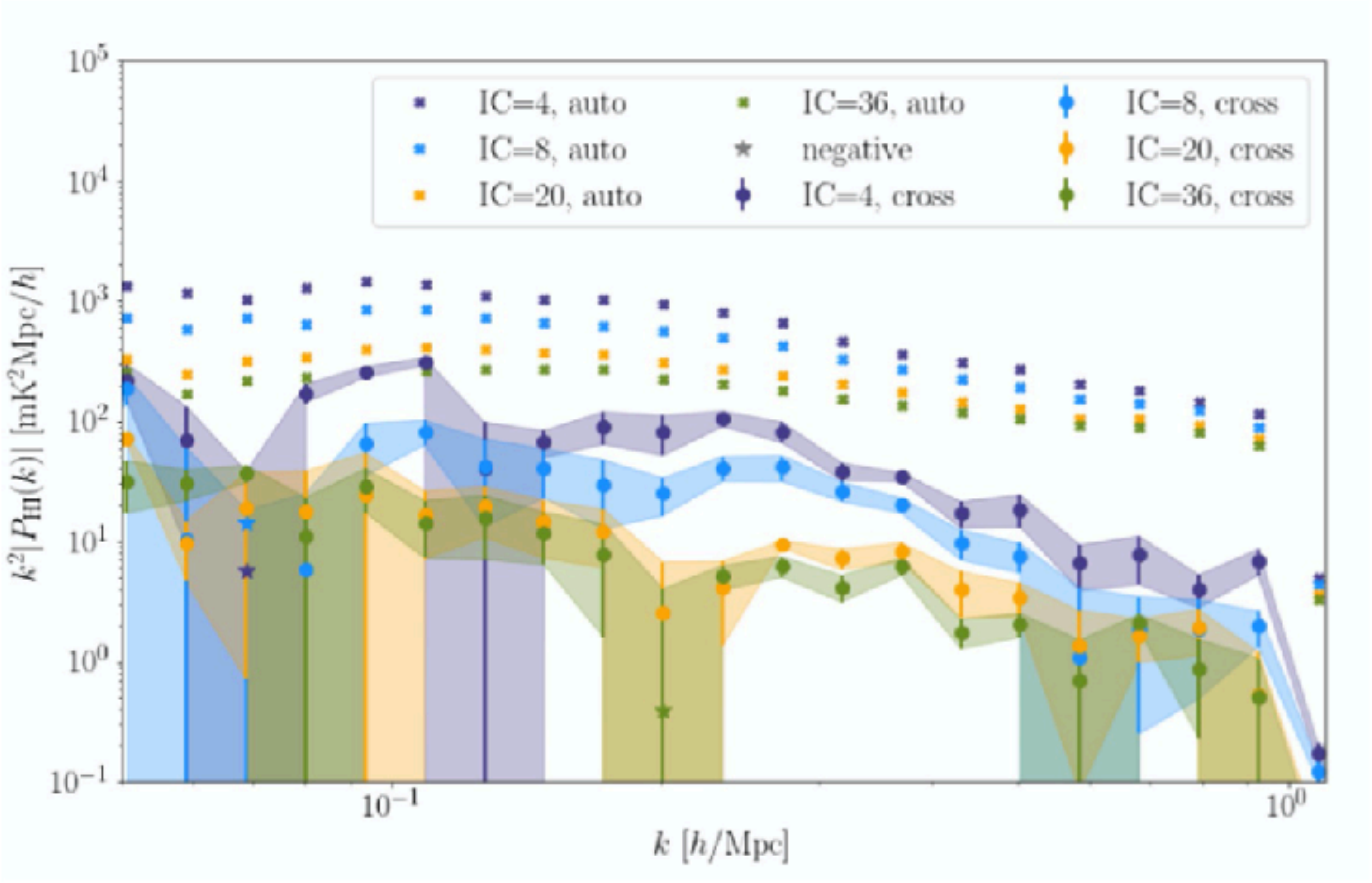
courtesy of Steve Cunnington

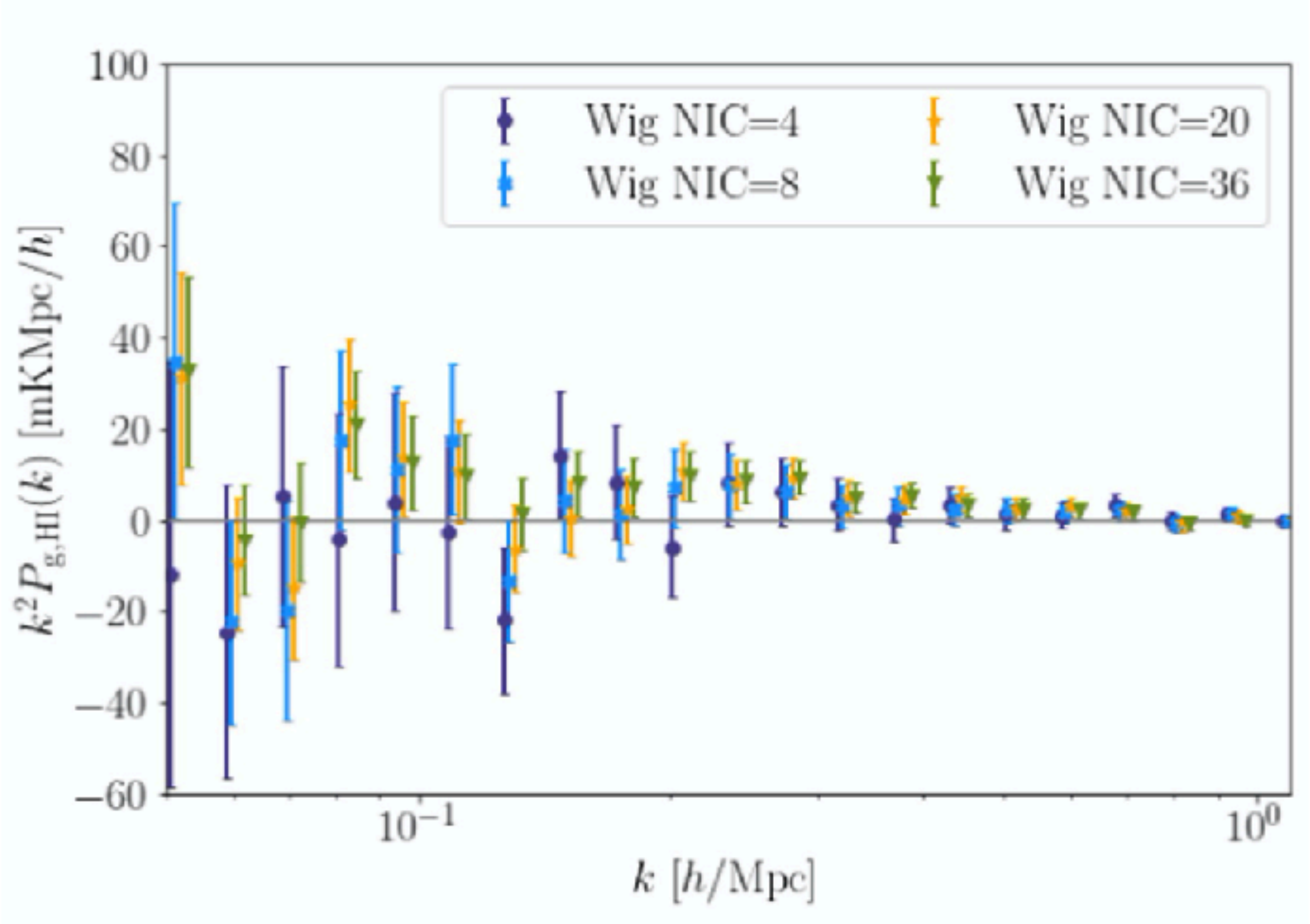
Cross-correlation

AUTO POWER SPECTRUM and CROSS POWER BETWEEN DIFFERENT SEASONS

Wolz et al. 2022

CROSS-CORRELATION WITH GALAXIES





Cross-correlation of GBT data (HI) with WiggleZ (active star forming galaxies), BOSS ELG (emission line galaxies) and BOSS LRG (Luminous Red Galaxies)
IMPORTANT: the galaxies have different dN/dz so this study allows to "filter" the signal

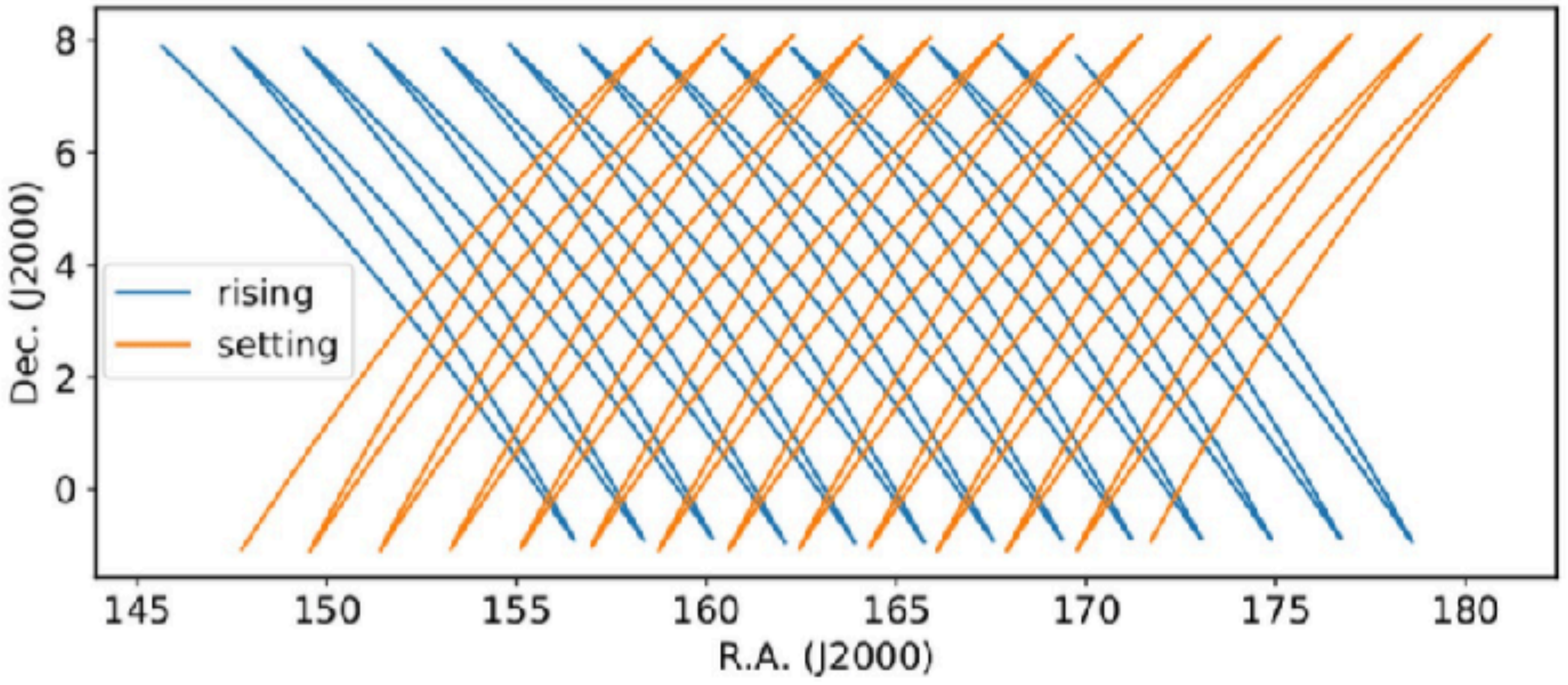
POWER SPECTRUM: convergent results for IC>20 in cross
Effectively a noise measurement (FastICA used)

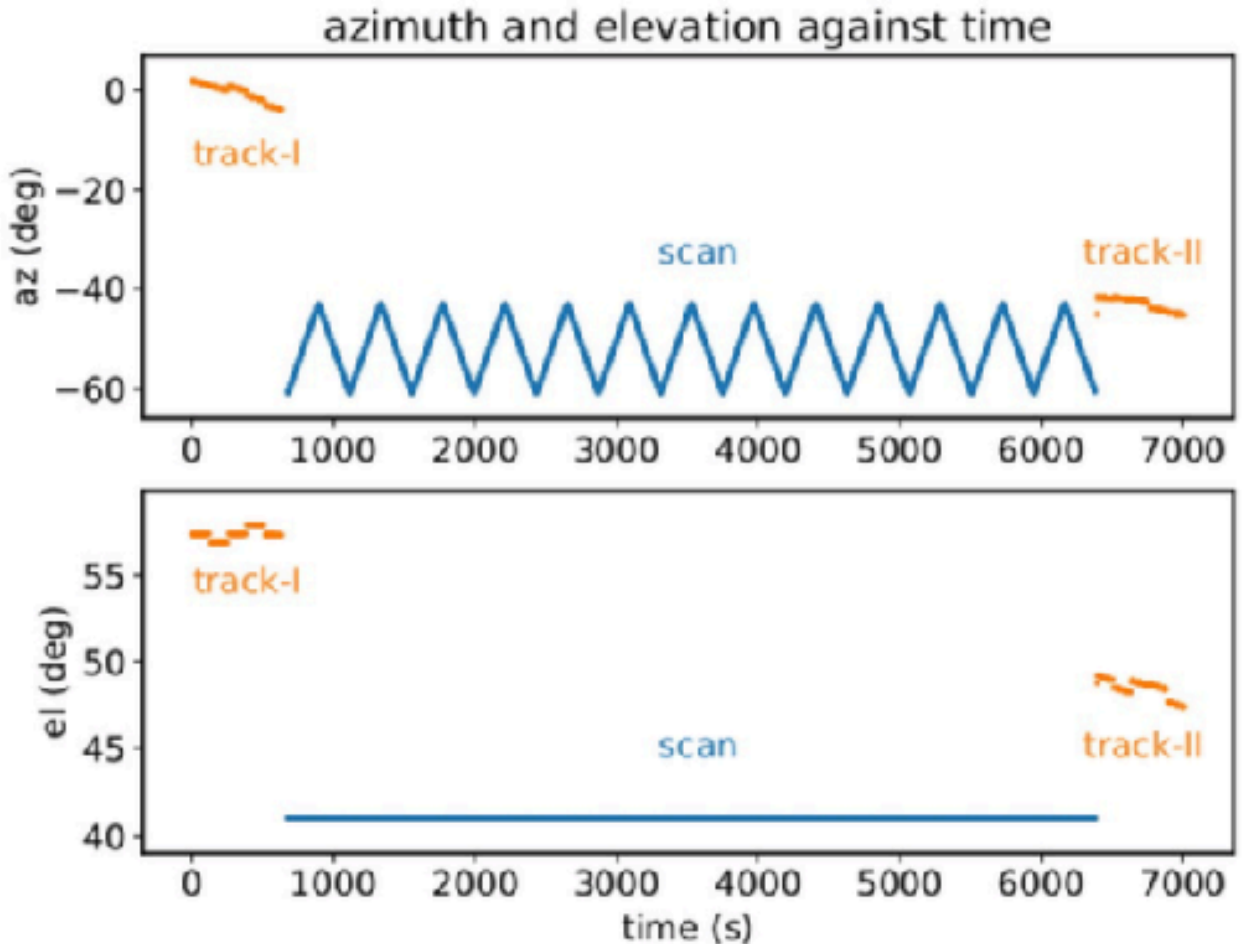
$$P_{\rm HI,g}(k) = T_{\rm HI} b_{\rm HI} b_{\rm g} r_{\rm HI,opt} P_{\delta\delta}(k)$$

$$r(k) = \frac{\Delta^2_{\rm X}(k)}{\sqrt{\Delta^2_{\rm HI}(k)\Delta^2_{\rm galaxy}(k)}}$$

MeerKAT

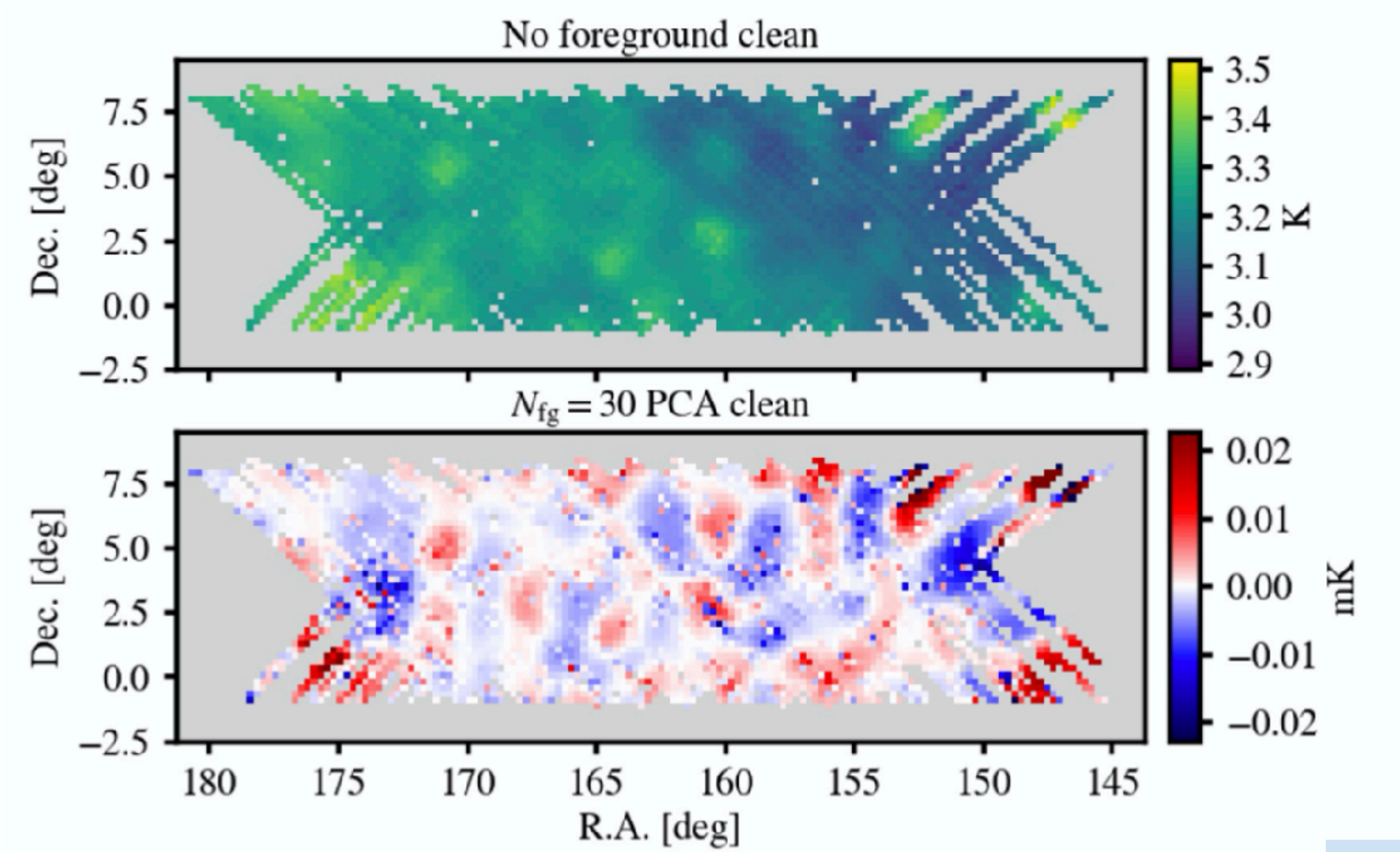
Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz
Frequency resolution	0.2 MHz
Time resolution	2s
Exposure time	1.5hr x 7 scans
Target field	WiggleZ 11hr field ($10^\circ \times 30^\circ$)

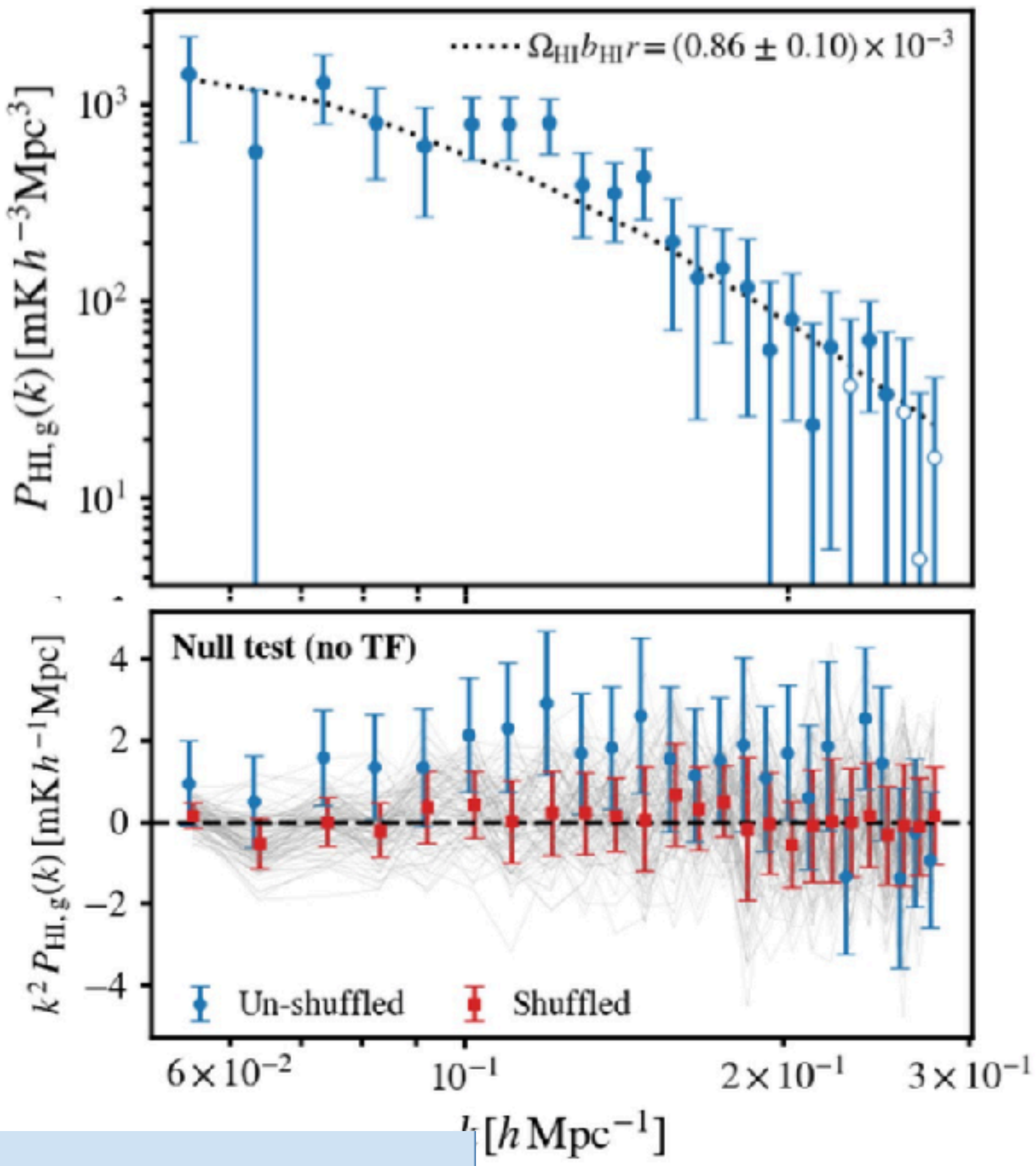




courtesy of Marta Spinelli

MeerKAT - II

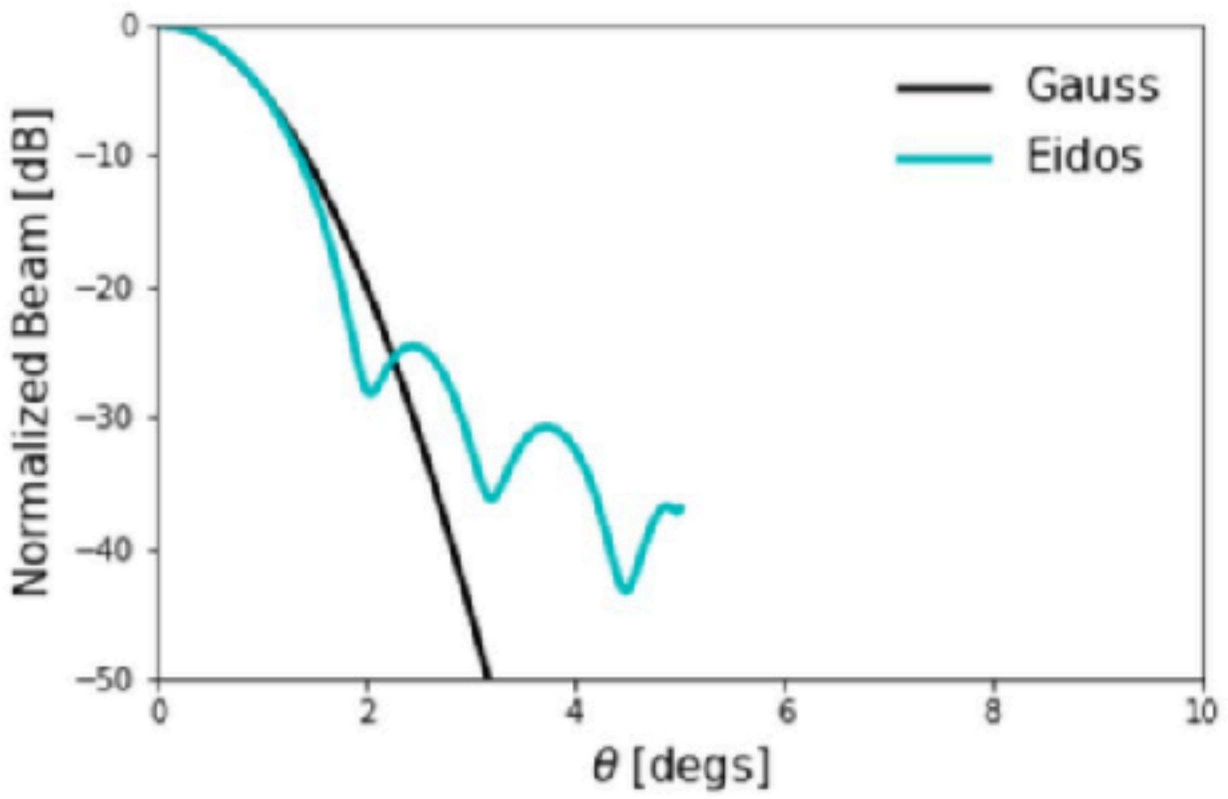


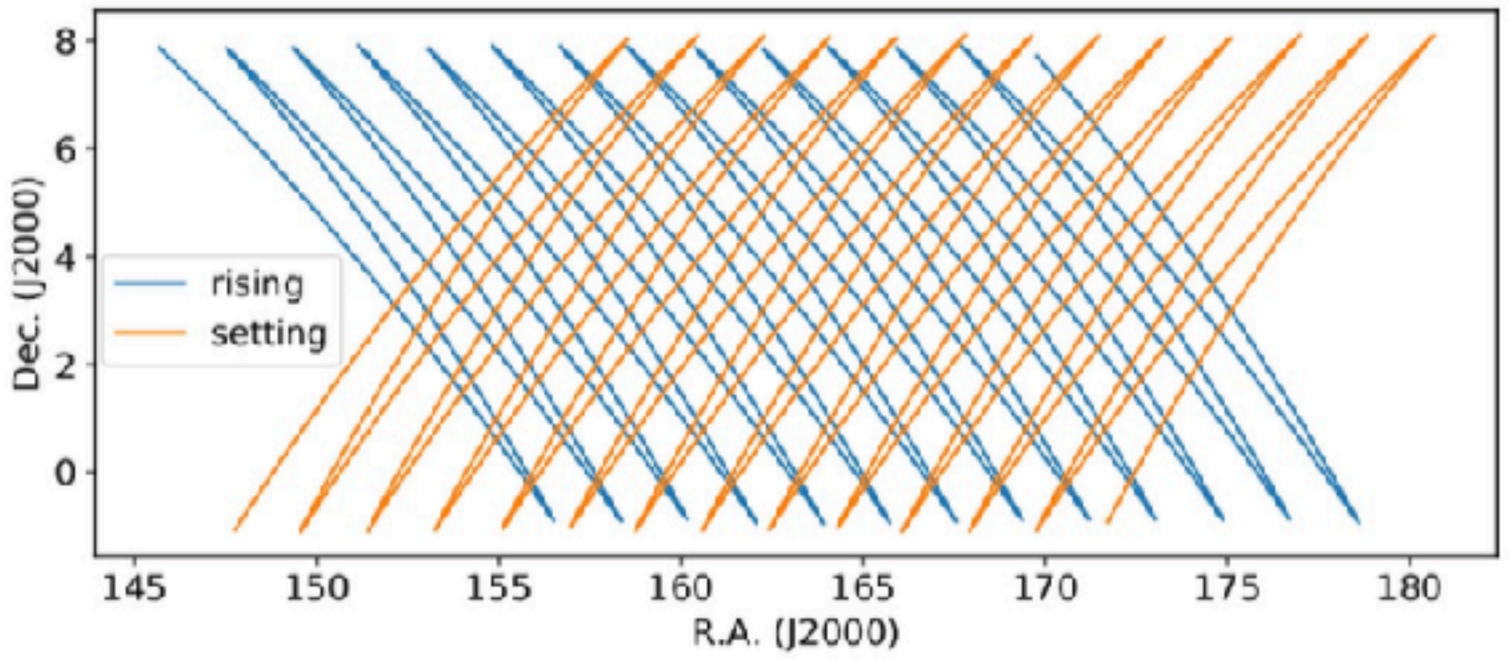


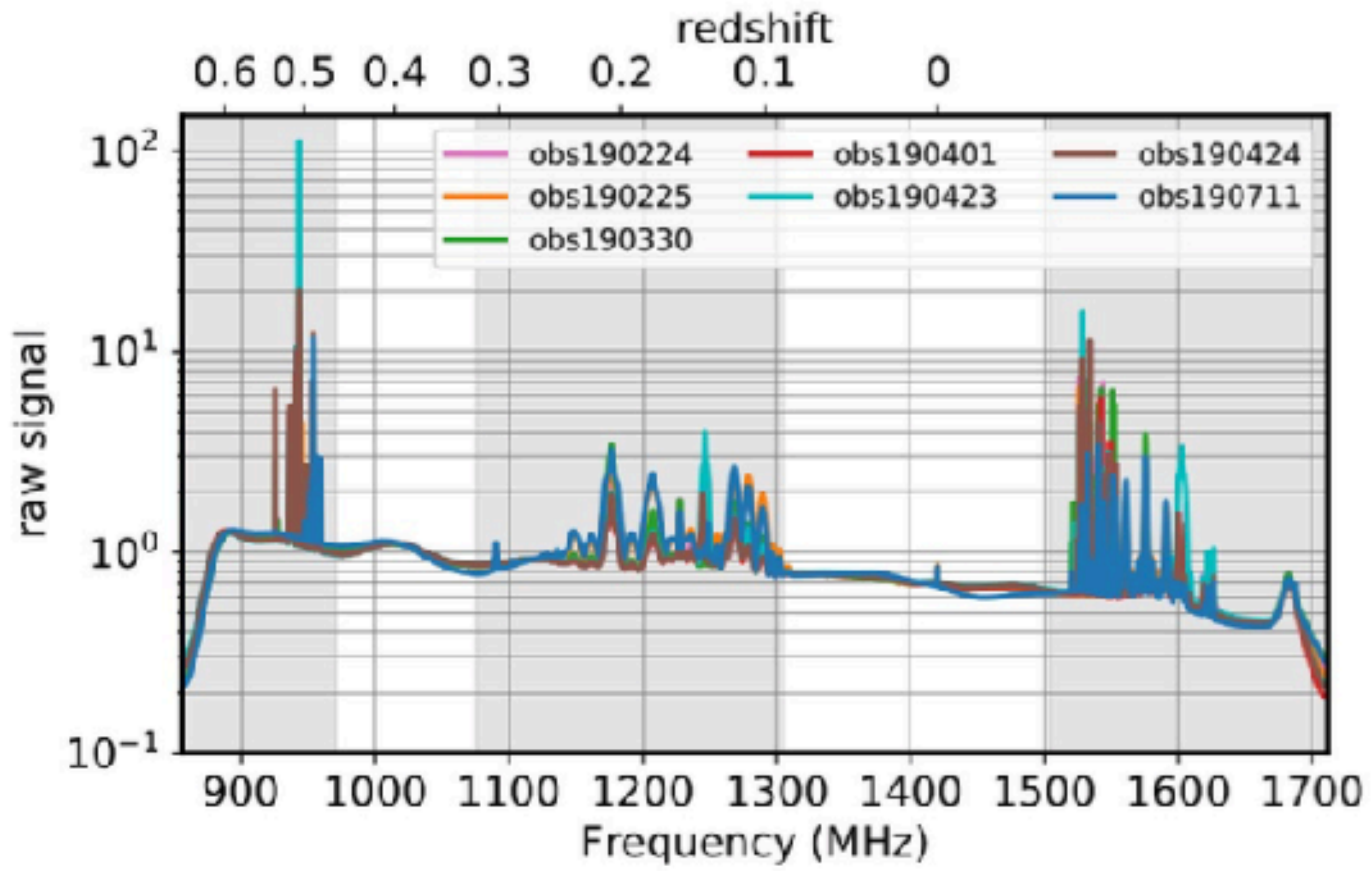
Cunnington+22

7.7 σ detection of cross-correlation

Systematics







Need a realistic beam modeling
side-lobes, frequency evolution,
more accurate deconvolution

Scanning strategy
non homogeneous noise, need
for real space convolution,
polarization leakage

Radio Frequency Interference (RFI)
impact on cleaning,
impact on signal interpretation

Physics on ultra large scales

Perturbation to galaxy number counts:

$$\begin{aligned}\Delta_{\mathrm{N}}(\hat{\mathbf{n}},k,z) = & \boxed{bD_{\mathrm{M}}} + (f^{\mathrm{N}}_{\mathrm{evo}}-3)\frac{\mathcal{H}}{k}V_{\mathrm{M}} - \boxed{\frac{k}{\mathcal{H}}(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})^2 V_{\mathrm{M}}} \\ & + \Psi + (5s-2)\Phi + \mathcal{H}^{-1}\dot{\Phi} \\ & + \frac{2-5s}{2r_S}\boxed{\int_0^{r_S} dr\left[2-\frac{r_S-r}{r}\nabla_\Omega\right](\Phi+\Psi)} \\ & + \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+\frac{2-5s}{r_S\mathcal{H}}+5s-f^{\mathrm{N}}_{\mathrm{evo}}\right) \\ & \times\left(\Psi + i(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}})V_{\mathrm{M}} + \boxed{\int_0^{r_S} dr\,(\dot{\Phi}+\dot{\Psi})}\right).\end{aligned}$$

Density

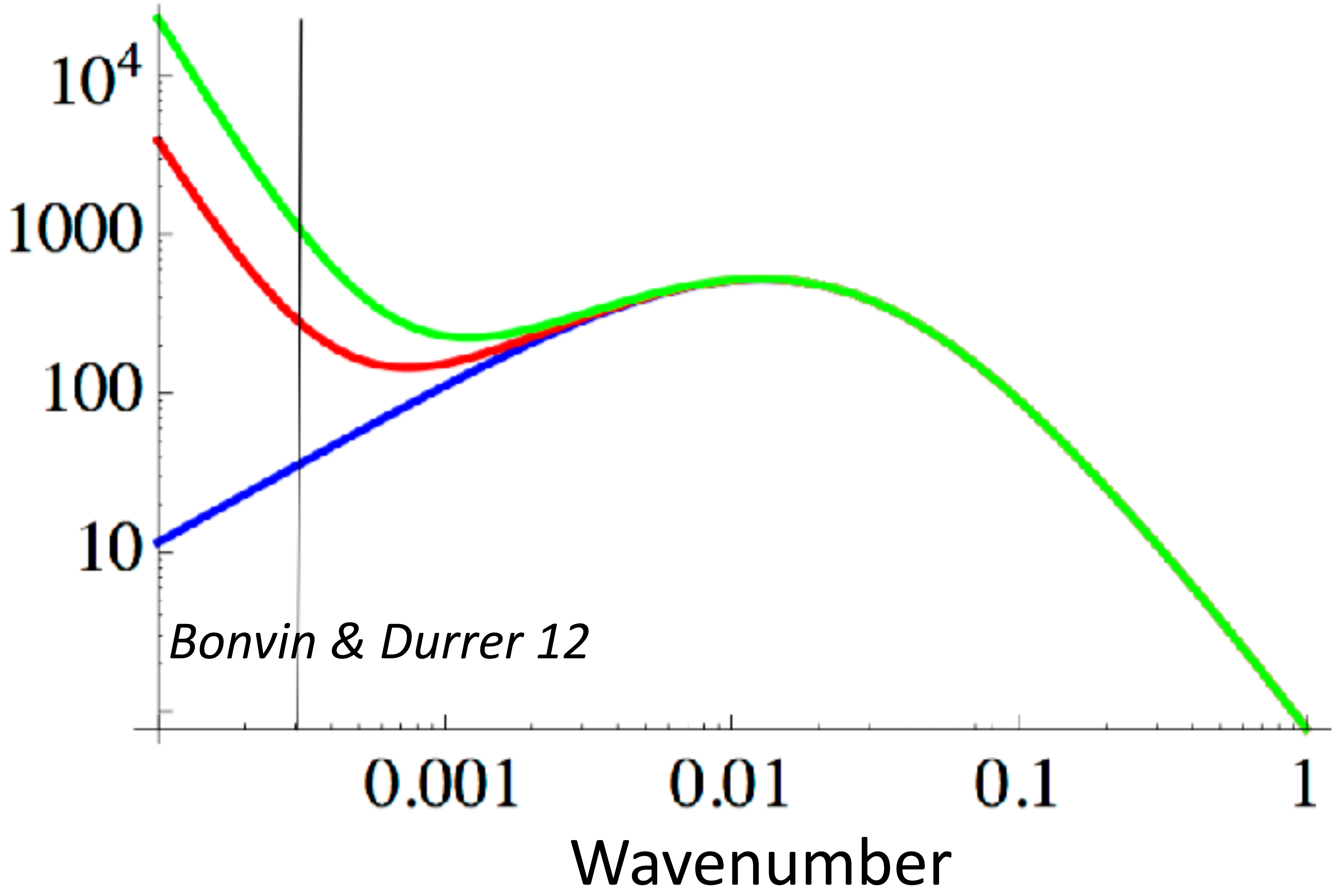
RSDs

Lensing

ISW

- Real observable is galaxy number counts (not matter!).
- At leading order reflects density but is richer than that.
- Could probe GR at the largest scales.

Power Spectrum

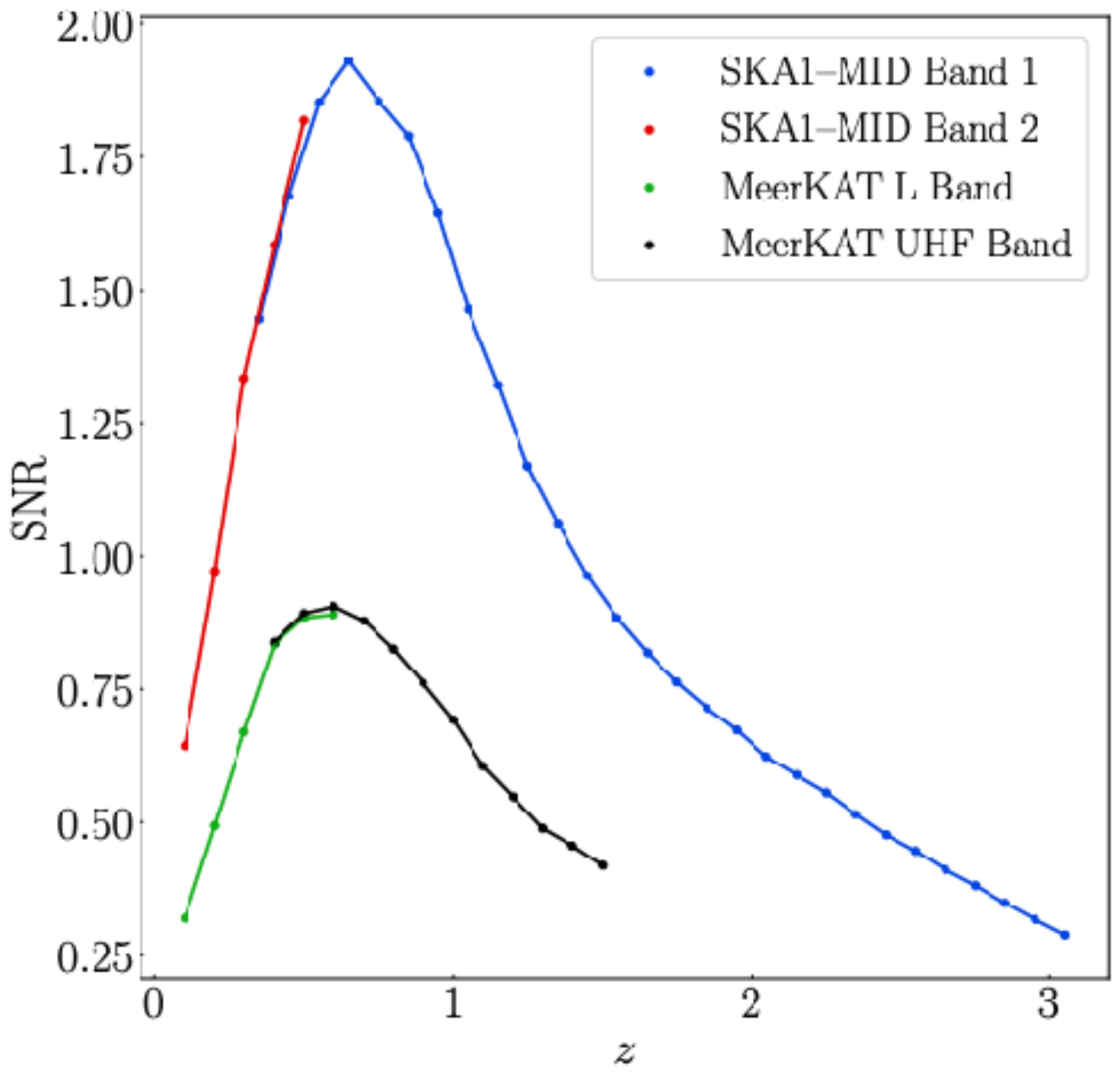


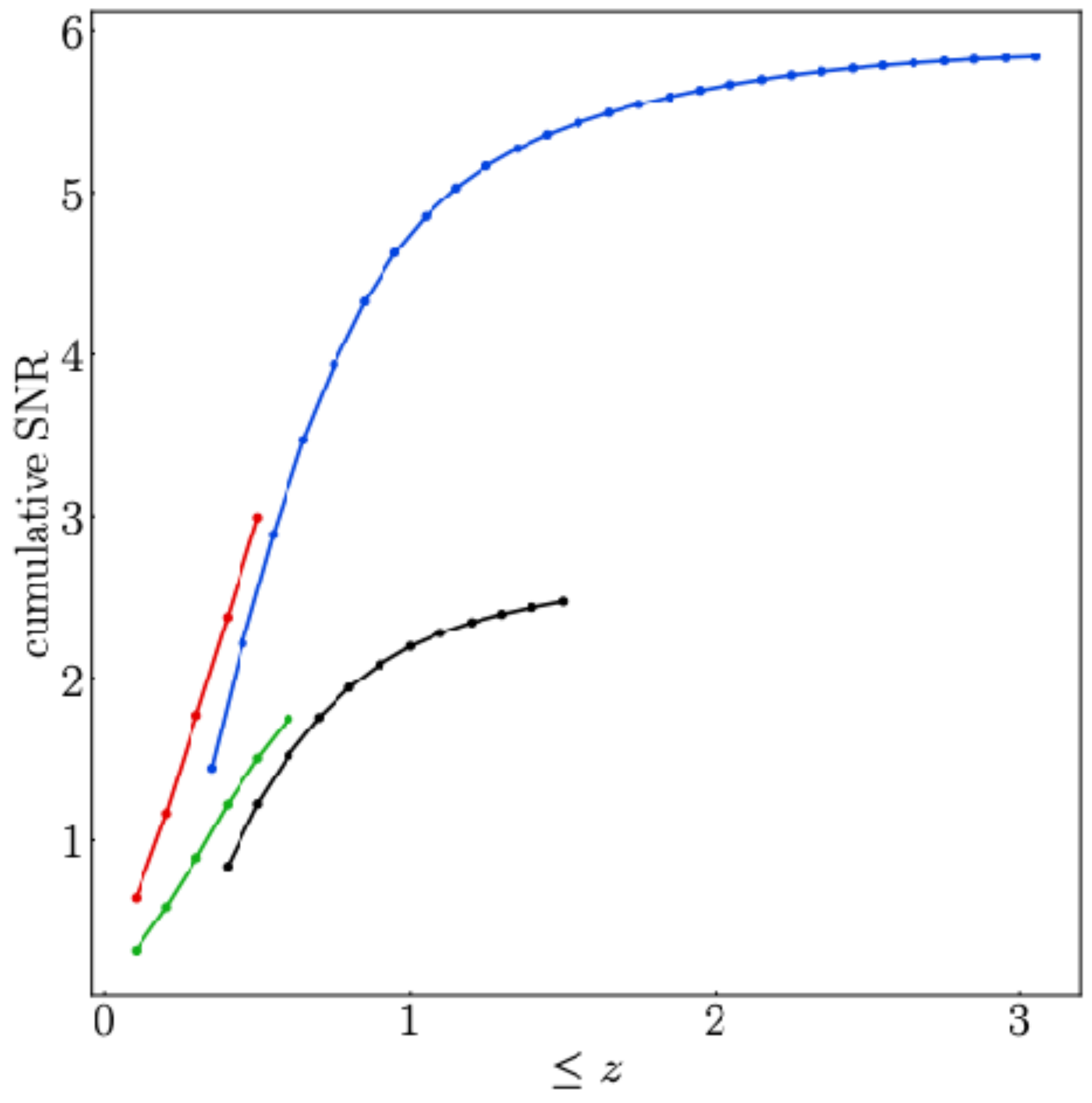
Comoving Gauge

Longitudinal Gauge

Uniform curvature hypersurface

Relativistic Effects





Imaginary part of the 21cm bispectrum is at leading order a purely relativistic effect

In Fourier space the leading order Doppler type signal will scale as i(H/k), then they cancel out in the power spectrum (suppressed) or they survive in cross-correlations

In the B(k) they survive since they couple with the Newtonian term

- **Standard (Newtonian) kernels:**

$$\mathcal{K}_{\rm N}^{(1)}(\boldsymbol{k}_a) = b_1 + f\mu_a^2\,, \tag{2.15}$$

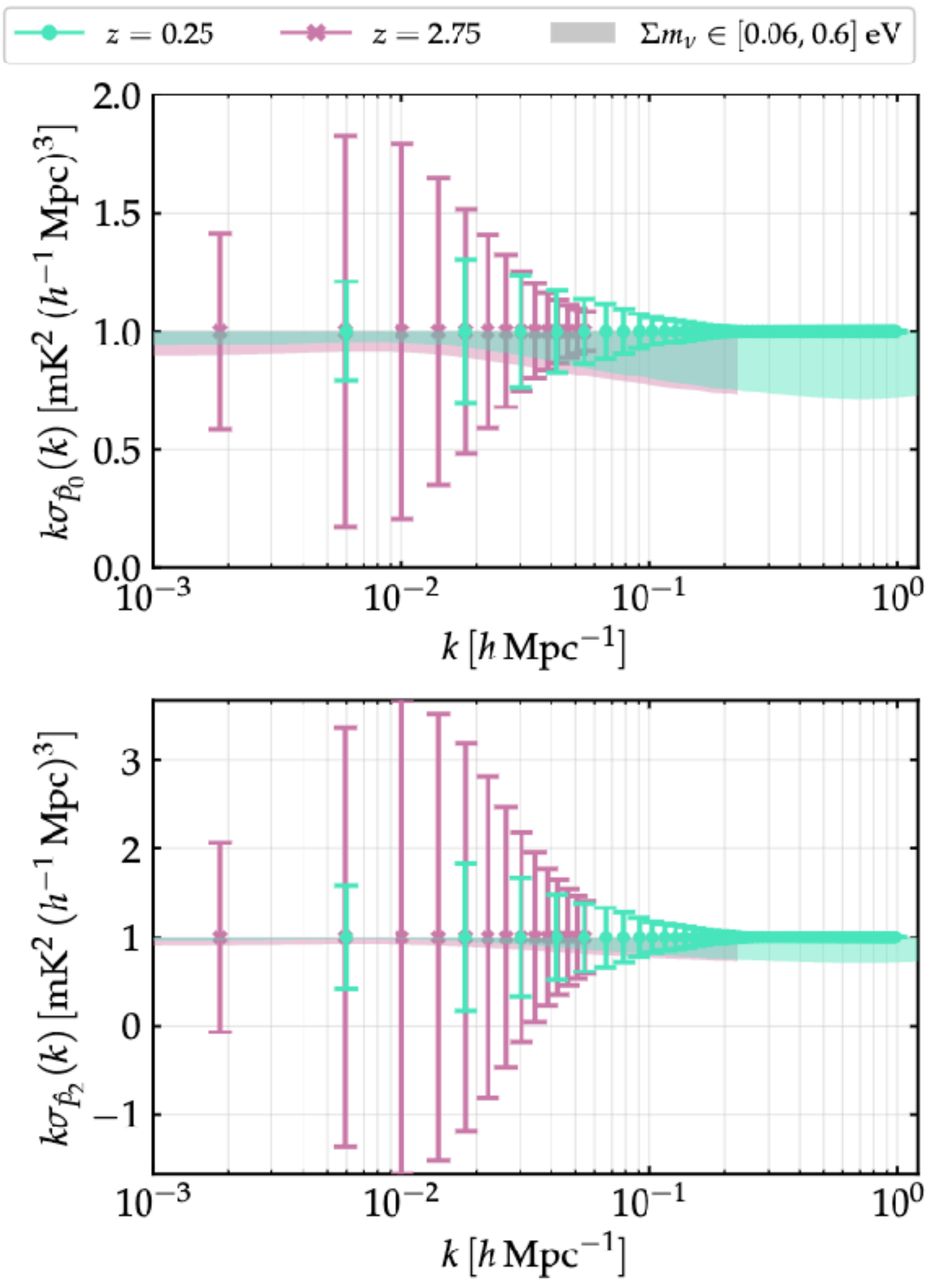
$$\mathcal{K}_{\rm N}^{(2)}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = b_1F_2(\boldsymbol{k}_1,\boldsymbol{k}_2) + b_2 + f\mu_3^2G_2(\boldsymbol{k}_1,\boldsymbol{k}_2) + fZ_2(\boldsymbol{k}_1,\boldsymbol{k}_2) + b_{s^2}S_2(\boldsymbol{k}_1,\boldsymbol{k}_2)\,, \tag{2.16}$$

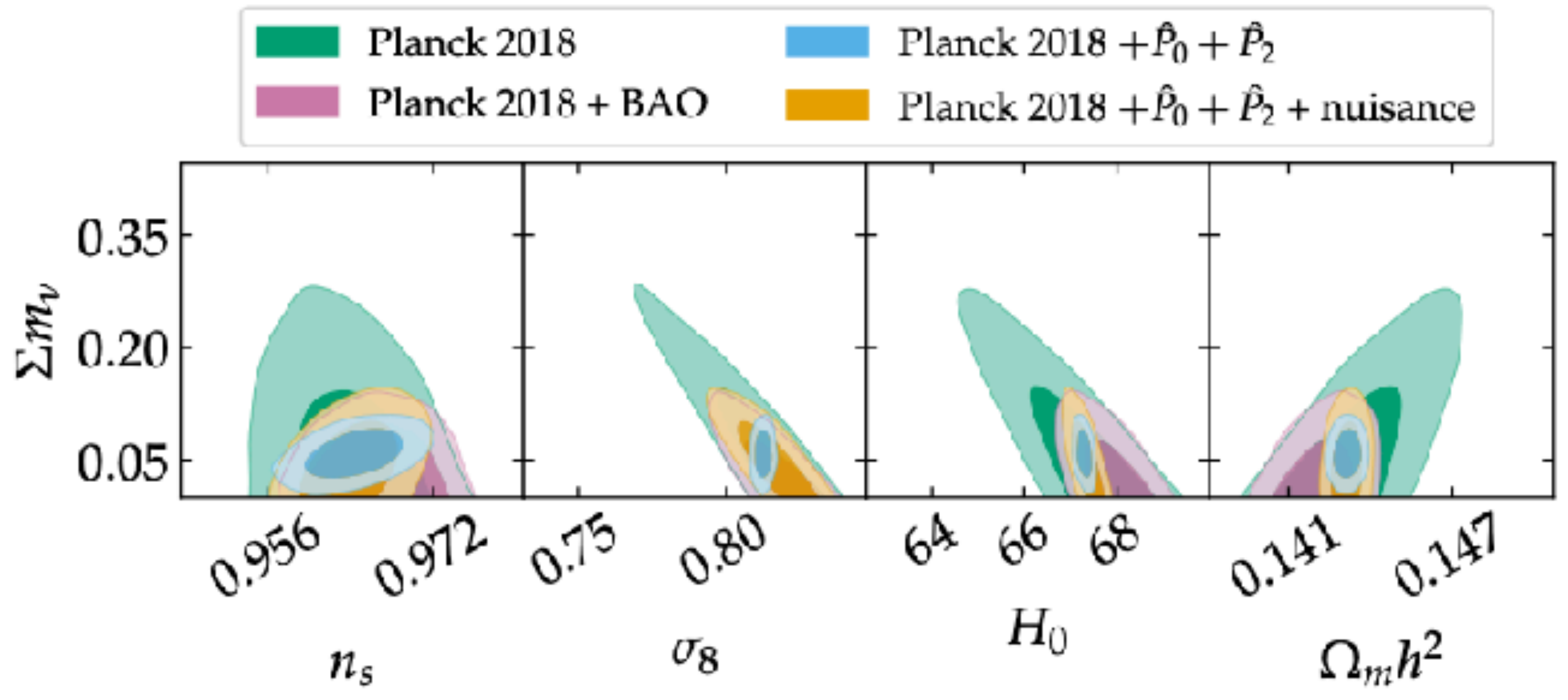
- **Leading-order relativistic kernels:**

$$\mathcal{K}_{\rm D}^{(1)}(\boldsymbol{k}_a) = \mathrm{i}\,\mathcal{H}fA\,\frac{\mu_a}{k_a}\,, \tag{2.17}$$

$$\begin{aligned}\mathcal{K}_{\rm D}^{(2)}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = \mathrm{i}\,\mathcal{H}f\bigg\{ & A\,\frac{\mu_3}{k_3}G_2(\boldsymbol{k}_1,\boldsymbol{k}_2) + \Big[b_1(A+f) + \frac{b_1'}{\mathcal{H}}\Big]\Big(\frac{\mu_1}{k_1}+\frac{\mu_2}{k_2}\Big) \\ & - \frac{3}{2}\Omega_{\rm m}\Big(\mu_1^3\frac{k_1}{k_2^2} + \mu_2^3\frac{k_2}{k_1^2}\Big) + \Big[\frac{3}{2}\Omega_{\rm m}(1+f) + 2f(A-2)\Big]\mu_1\mu_2\Big(\frac{\mu_1}{k_2}+\frac{\mu_2}{k_1}\Big) \\ & + 2f\,\hat{\boldsymbol{k}}_1\cdot\hat{\boldsymbol{k}}_2\Big(\frac{\mu_1}{k_1}+\frac{\mu_2}{k_2}\Big) - \frac{3\Omega_{\rm m}b_1}{2f}\Big(\mu_1\frac{k_1}{k_2^2}+\mu_2\frac{k_2}{k_1^2}\Big)\bigg\}\,,\end{aligned} \tag{2.18}$$

Neutrino free streaming



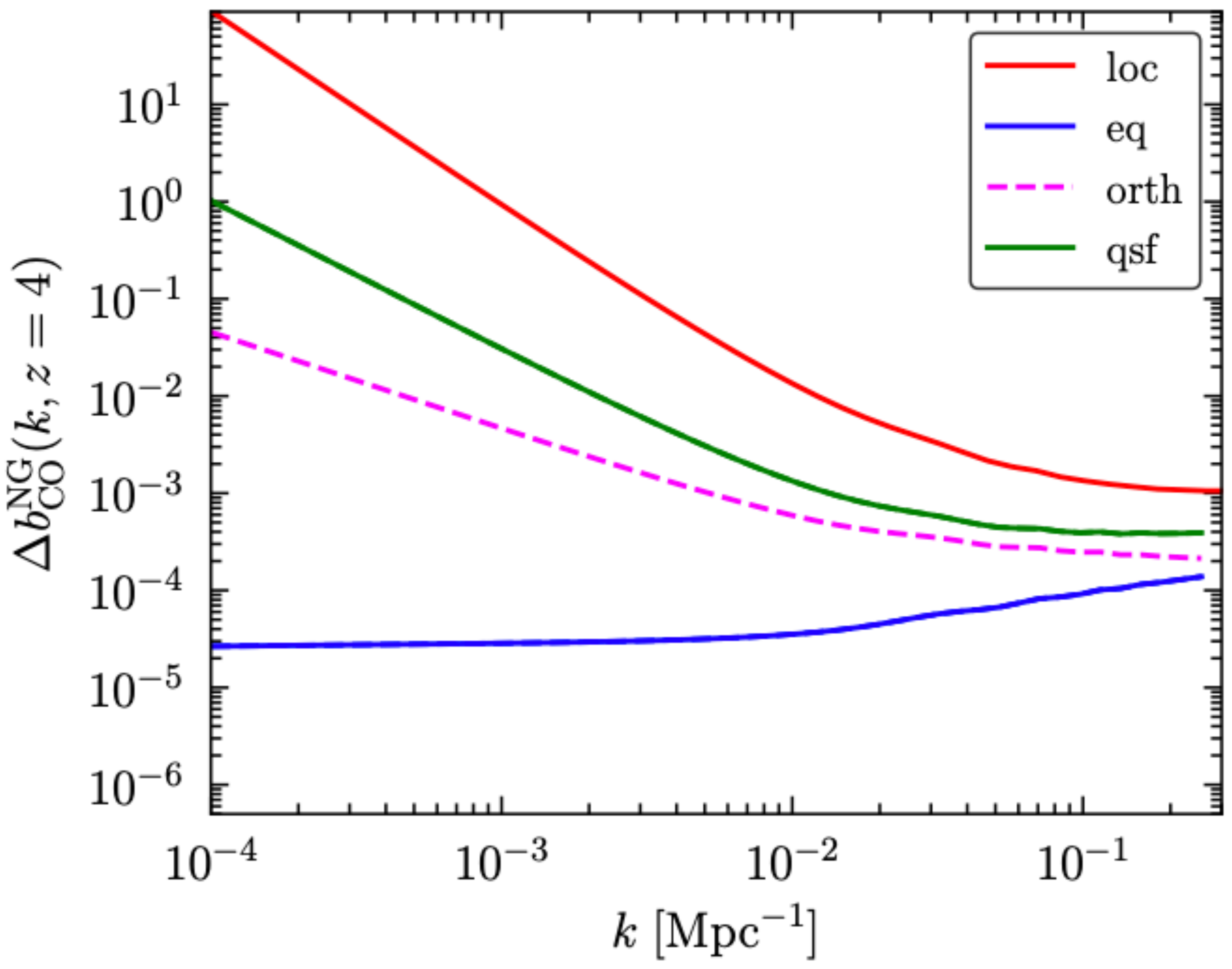


22 meV 1sigma error bar from Planck18+BAO+conservative IM

Berti, MV, Spinelli 22 in prep

Intensity Mapping and Primordial Non-Gaussianity

Correction to linear bias for CO line



Moradinezhad Dizgah & Keating 19

$$b_h(M,z) \to \tilde{b}_h(M,k,z) = b_h(M,z) + \Delta b_h^{\rm NG}(M,k,z)$$

$$\mathcal{M}(k,z) = -\frac{2}{5}\frac{k^2 T(k) D(z)}{\Omega_m H_0^2}$$

$$\mathcal{F}_R^{(3)}(k,z) = \frac{1}{4\sigma_R^2(z) P_\zeta(k)} \times \int \frac{d^3q}{(2\pi)^3} \left[\mathcal{M}_R(q,z)\mathcal{M}_R(|\mathbf{k}-\mathbf{q}|,z) \times B_\zeta(-\mathbf{k},\mathbf{q},\mathbf{k}-\mathbf{q})\right].$$

local

$$\Delta b_h^{\rm NG,loc}(M,k,z) = \frac{6}{5}\frac{f_{\rm NL}^{\rm loc}\delta_c\left[b_h(M,z)-1\right]}{\mathcal{M}(k,z)}$$

general shape

$$\Delta b_h^{\rm NG}(M,k,z) = \frac{2\mathcal{F}_R^{(3)}(k,z)}{\mathcal{M}_R(k,z)} \times \left[(b_h(M,z)-1)\delta_c + \frac{d\ln\mathcal{F}_R^{(3)}(k,z)}{d\ln\sigma_R}\right]$$

TABLE 7

1-σ MARGINALIZED CONSTRAINTS ON THE AMPLITUDE OF LOCAL, EQUILATERAL AND ORTHOGONAL SHAPES AND THE AMPLITUDE AND THE MASS PARAMETER OF QUASI-SINGLE-FILED NON-GAUSSIANITY WITH CO AND [CII] INTENSITY MAPPING.

line	$\sigma(f_{\rm NL}^{\rm loc})$	$\sigma(f_{\rm NL}^{\rm eq})$	$\sigma(f_{\rm NL}^{\rm orth})$	$\sigma(f_{\rm NL}^{\rm qsf})$	$\sigma(\nu)$
CO	1.00	125	44.9	62.1	14.8
[CII]	1.00	89.8	39.6	45.9	11.7

SUMMARY

- HI important cosmic tracer to perform **quantitative cosmology** especially at high redshift.

- Intensity Mapping: new technique, cheap, fast, no small scales

- Access to large volumes (high-z)

- **Mocking 21cm maps with N-body simulations with inputs calibrated with high-res hydro sims** and/or semi-analytical models of structure formation is promising (NOTE: small scales are not important but somewhat needed).

- Scientific questions:

  BAO, neutrinos, dark matter nature, cosmo params, inflation, relativistic effects, dark energy

- What's next: we try to be optimistic in the sense that foreground removal and instrumental effects are likely not to corrupt the signal much.

- Progress is being made: cross-correlations + machine learning techniques