INTENSITY MAPPING IN THE POST REIONIZATION ERA

Matteo Viel

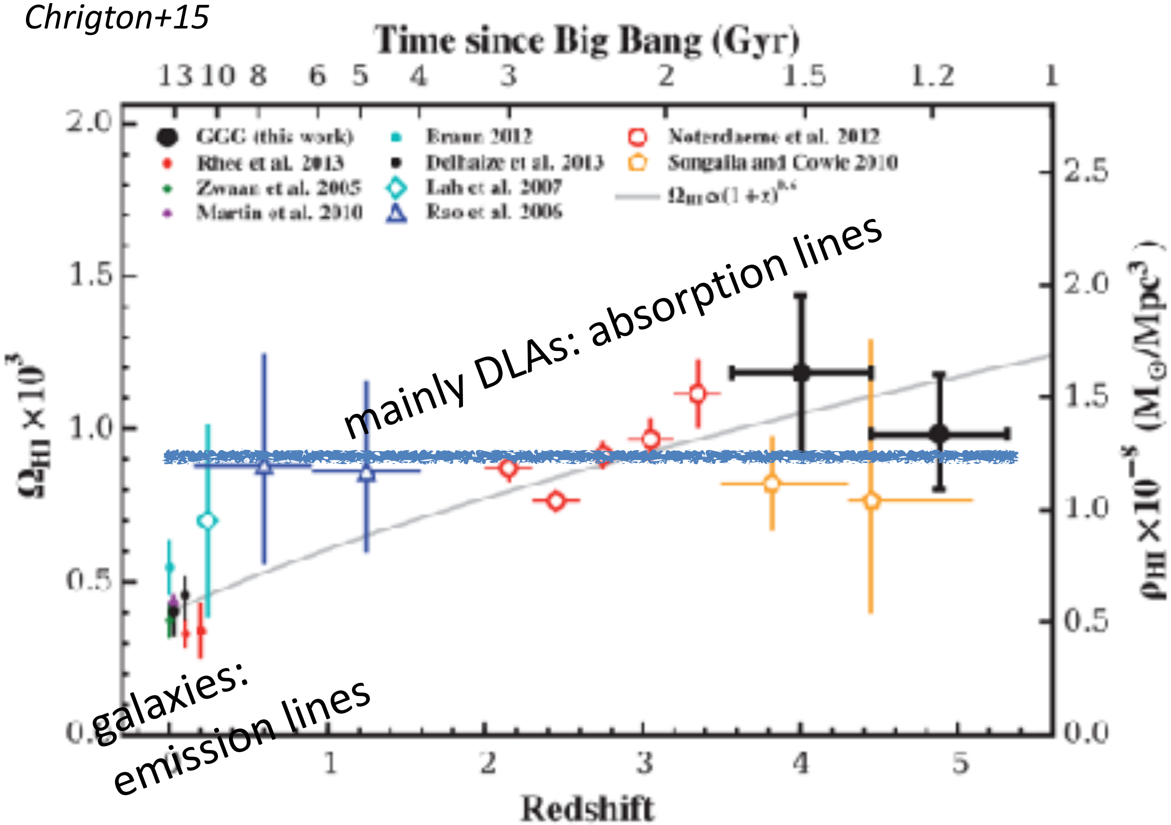
3rd national workshop on the SKA project

5-10-2021

Neutral Hydrogen (HI) as a cosmic tracer

$$\Omega_{\rm HI} \sim \Omega_{\nu} \sim \Omega_{\star}$$

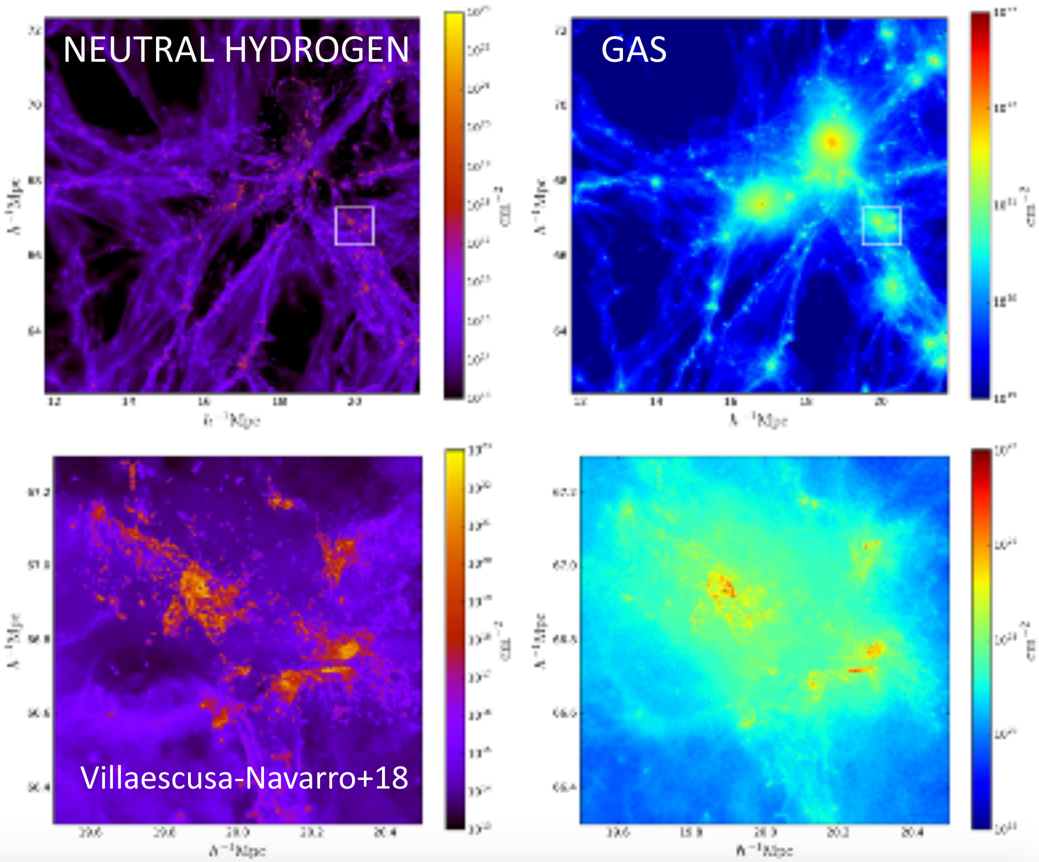
Chrigton+15



- **Mild or no evolution** over 12 Gyrs (in the same period UV, thermal state star formation change dramatically).
- Most of the HI (in **mass**) associated to Damped Lyman-Alpha systems, most of the HI (in **volume**) probed by the Lyman-alpha forest.

Intensity mapping

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



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

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

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

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

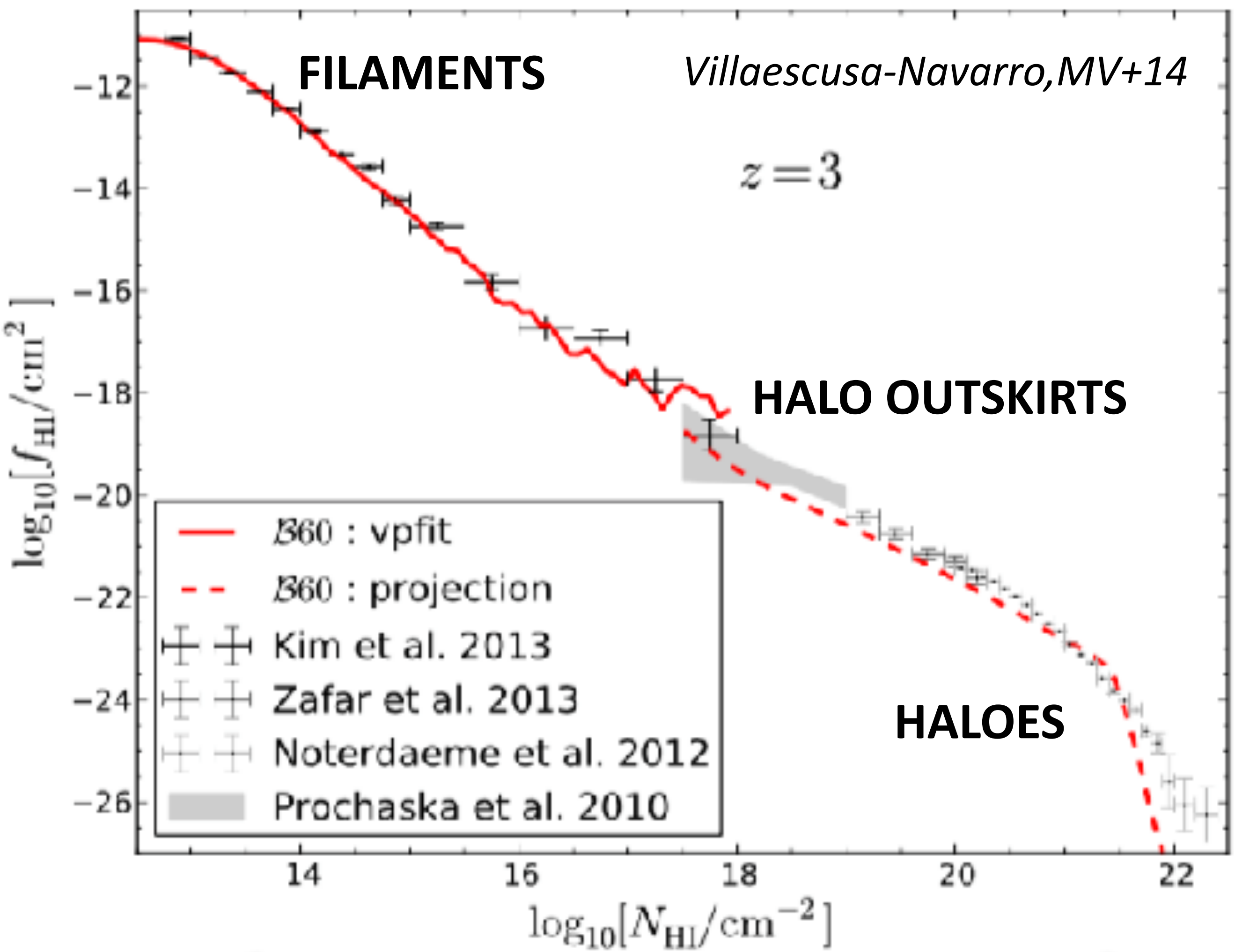
$$M_{\mathrm{H\,I}}(M, z) = M_0\left(\frac{M}{M_{\mathrm{min}}}\right)^\alpha \exp(-(M_{\mathrm{min}}/M)^{0.35}).$$

M_{min} decreases with redshift
alpha increases with redshift

- degeneracy between b_{HI} and Ω_{HI} broken by using other probes (cross-corr.)
- low-z HI bias (~0.8) from observations (Obuljen+18) – Pen+09, Switzer+13 (auto and cross to constrain Ω_{HI} x b_{HI}), Anderson+18 (cross. with galaxies).
- **IM signal:** main ingredient is the function $M_{HI}(M_{halo})$ with its scatter.

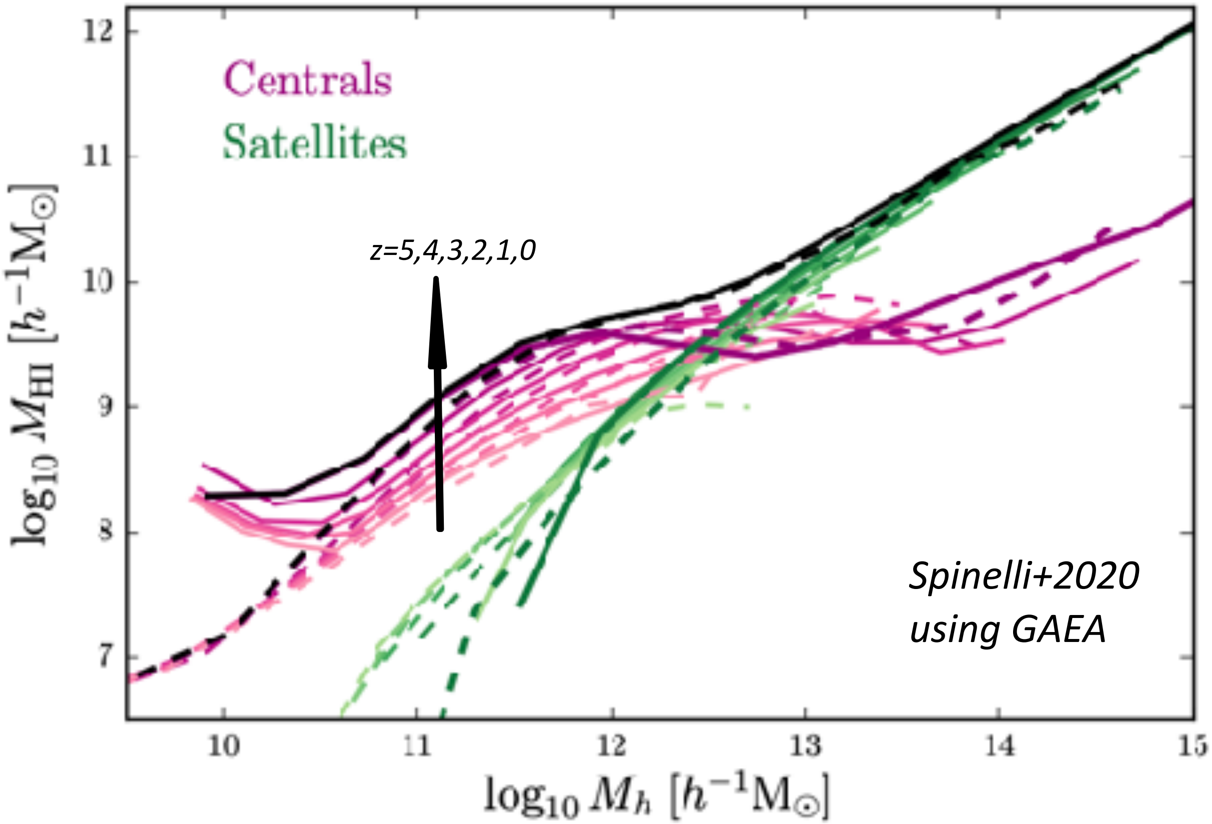
Towards a consistent model

$$\delta = -1 \rightarrow \delta \sim 30 \rightarrow \delta \sim 100$$



Wide range in column density - 10 orders of magnitude

…obtained from an interplay between hydrosims and galaxy formation models

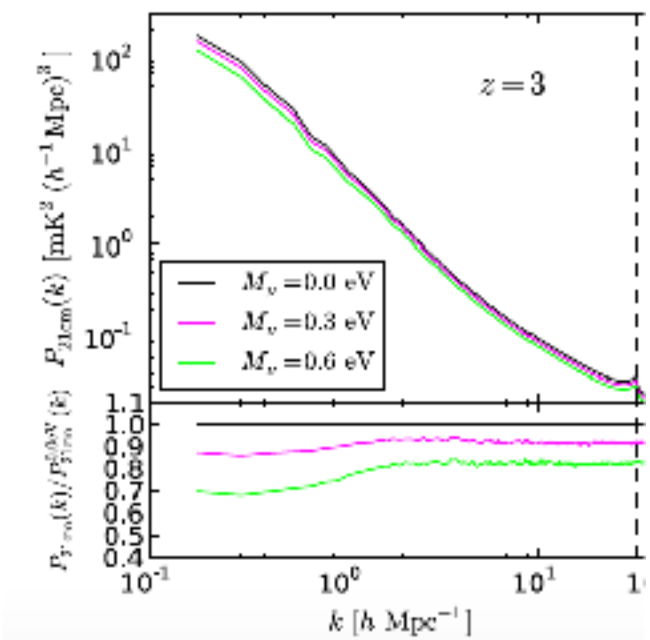


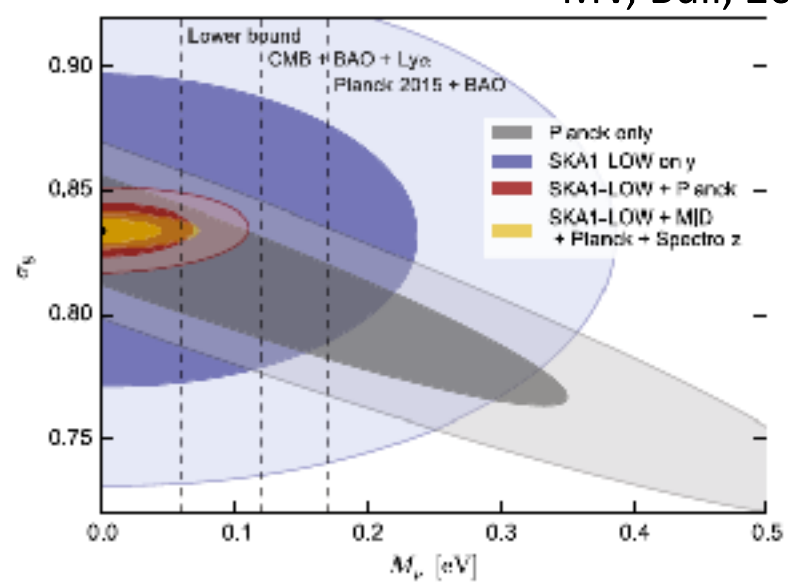
…further progress: interfacing this “small-scale” accurate and physical information with large scale methods for extensive mock productions e.g. PINOCCHIO LPT light-cone halos (Spinelli, Carucci+2021)

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 Ω_{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.

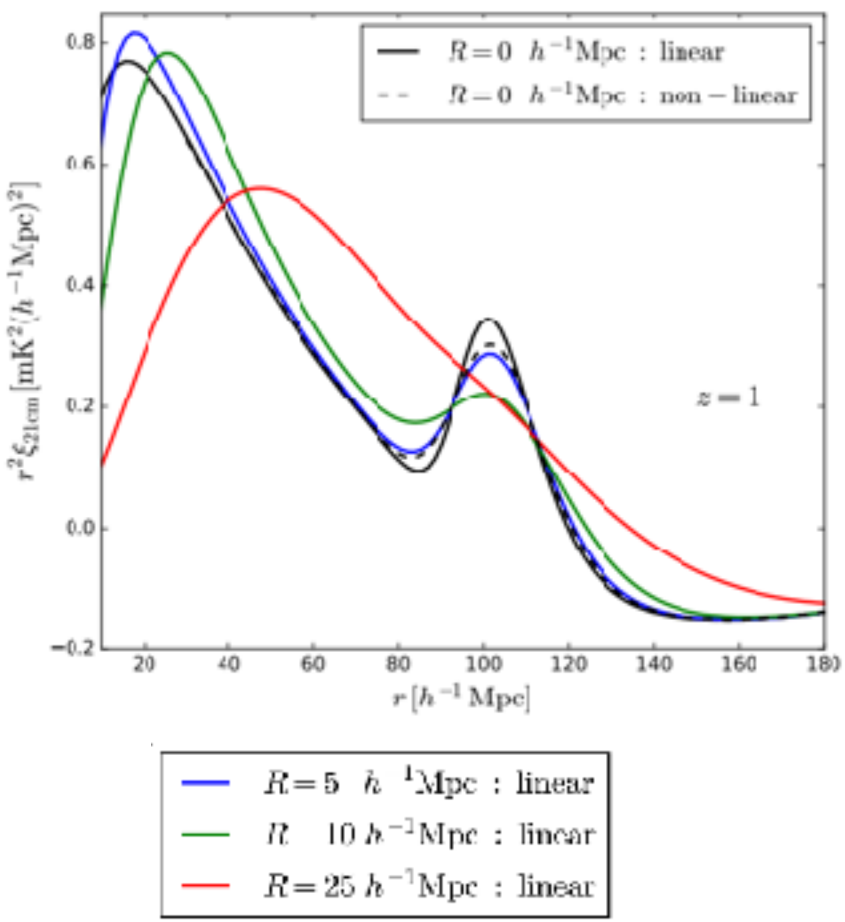
Villaescusa-Navarro, MV, Bull, 2015



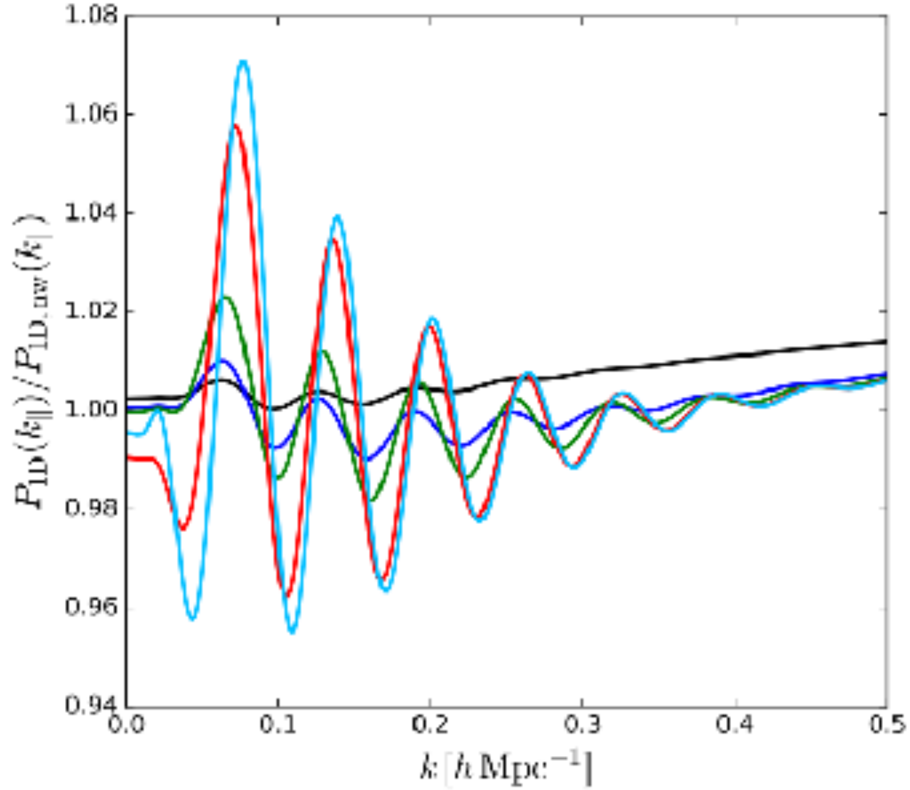


BAOs with SKA1-MID - I

3D correlation Function



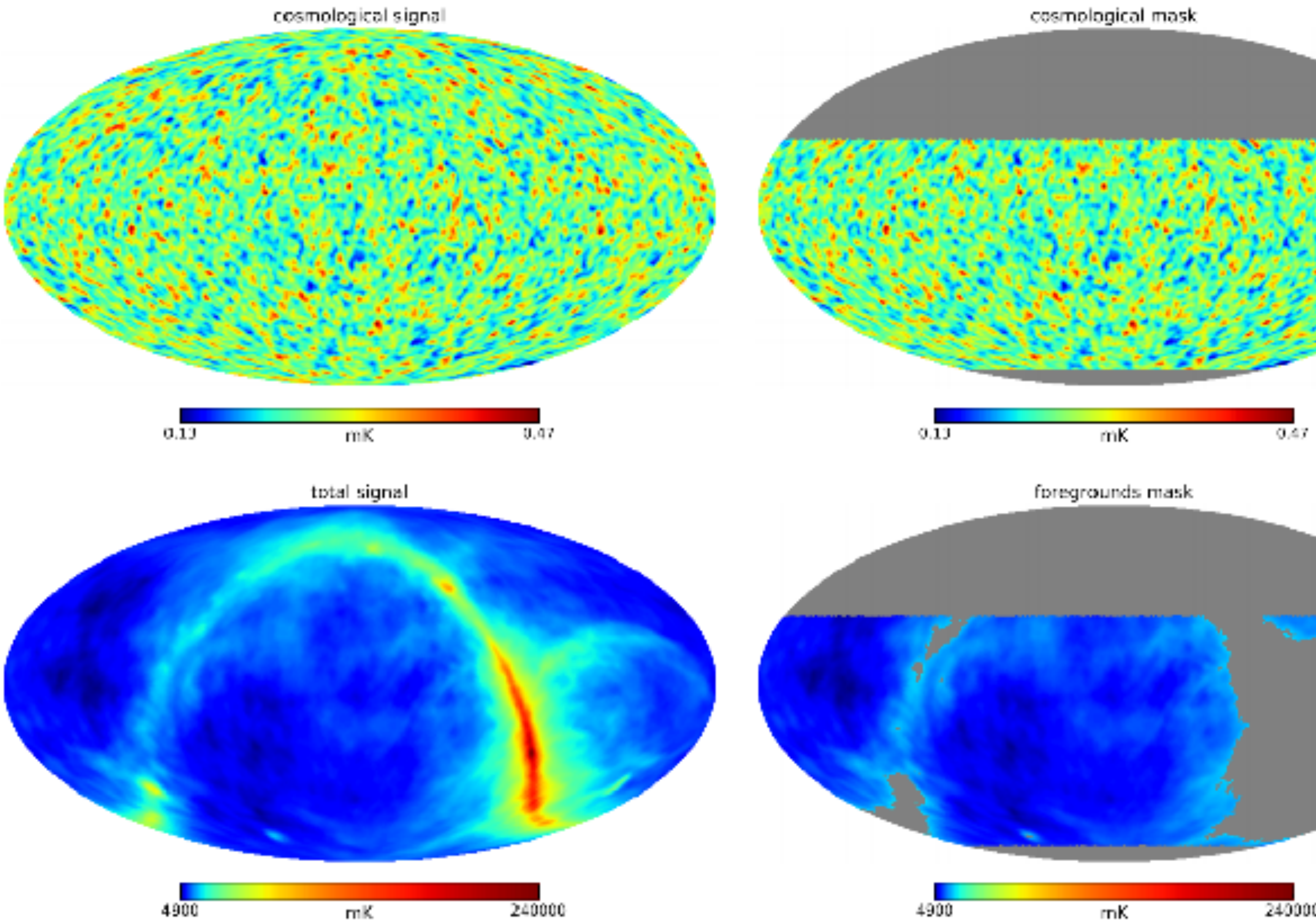
1D power



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

Villaescusa-Navarro, Alonso, MV, 2017

BAOs with SKA1-MID - III



Villaescusa-Navarro, Alonso, MV, 2017

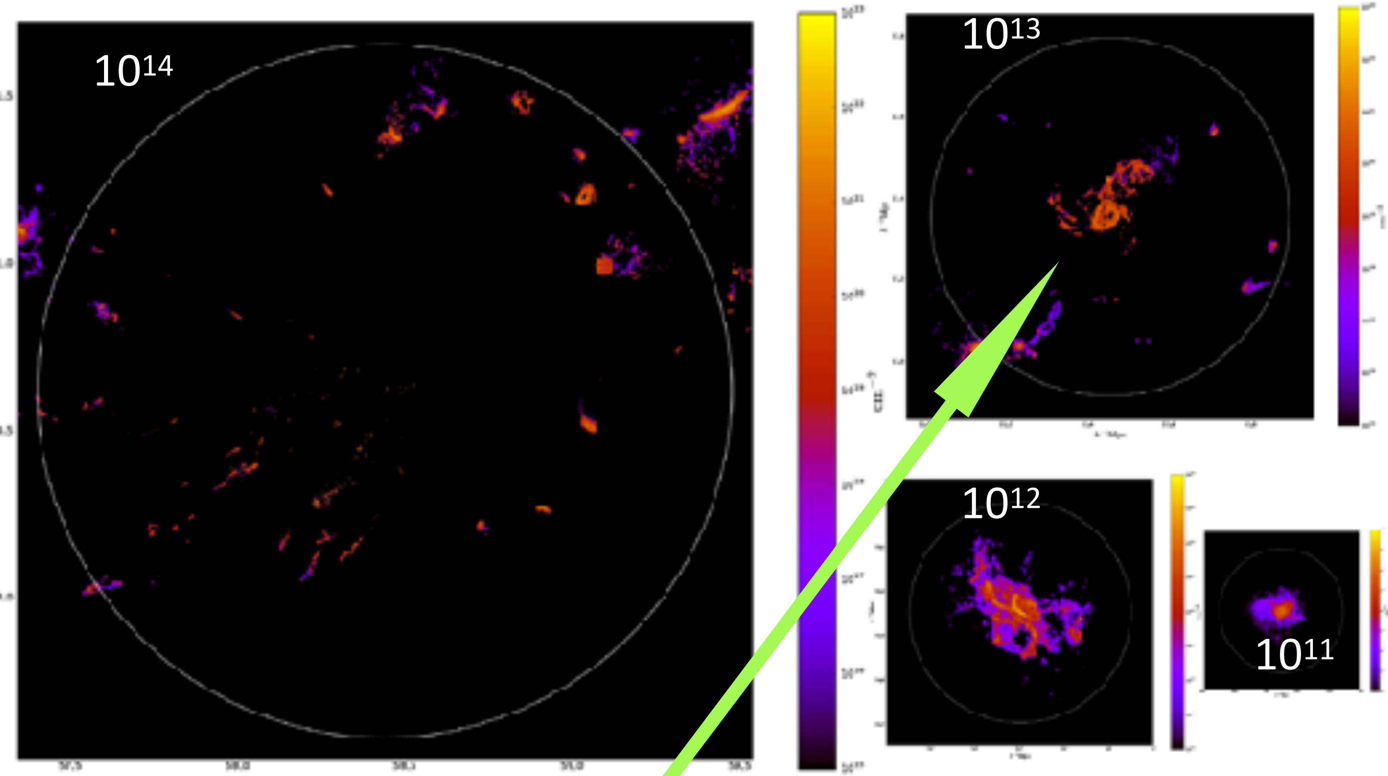
BAOs with SKA1-MID - IV

Villaescusa-Navarro, Alonso, MV, 2017

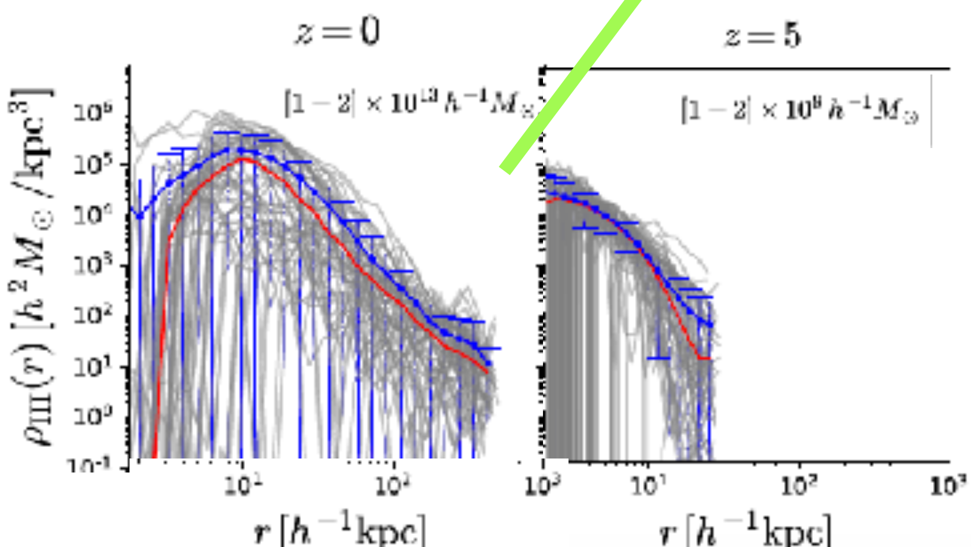
z range	$\langle z \rangle$	mask	σ_α (C)	(C+N)	(C+N+FG)
[0.36-0.75]	0.6	no	1.008 ± 0.016	1.008 ± 0.016	1.007 ± 0.016
		yes	1.006 ± 0.020	1.006 ± 0.021	1.006 ± 0.024
[0.75-1.26]	1.0	no	0.996 ± 0.010	0.997 ± 0.011	0.996 ± 0.011
		yes	0.997 ± 0.012	0.997 ± 0.013	0.998 ± 0.015
[1.26-1.98]	1.6	no	1.001 ±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

2-3% recovery
of the peak position
@ z=2.5 —> geometry constrained

Simulating intensity mapping signal: small scales

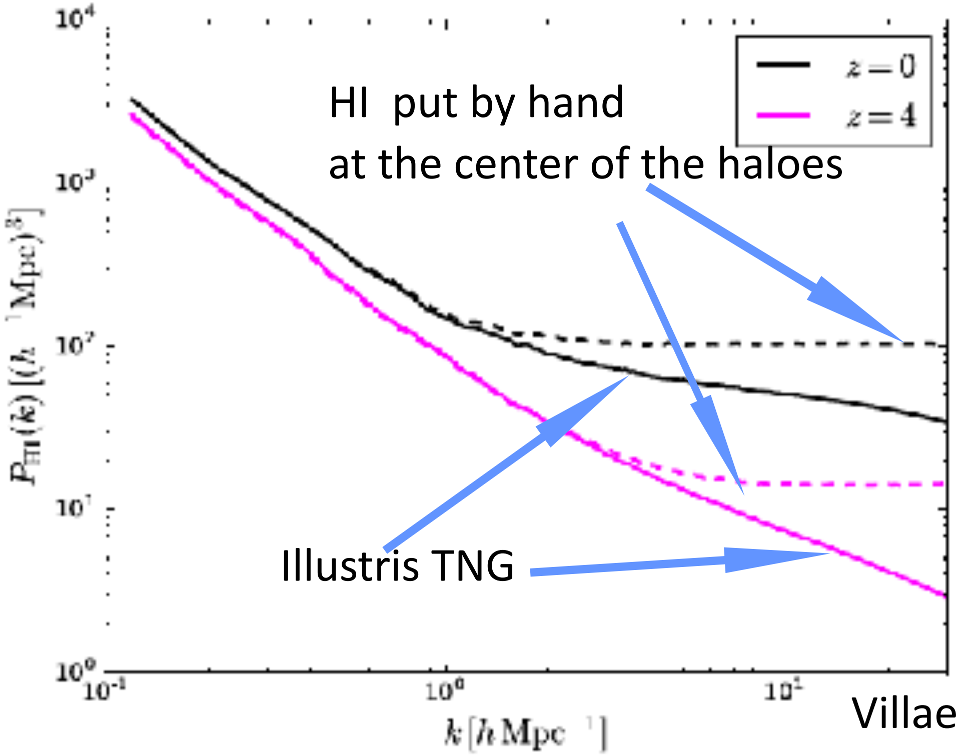


Villaescusa-Navarro+18 based on Illustris TNG



- 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



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

Villaescusa-Navarro+18, Spinelli+20

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

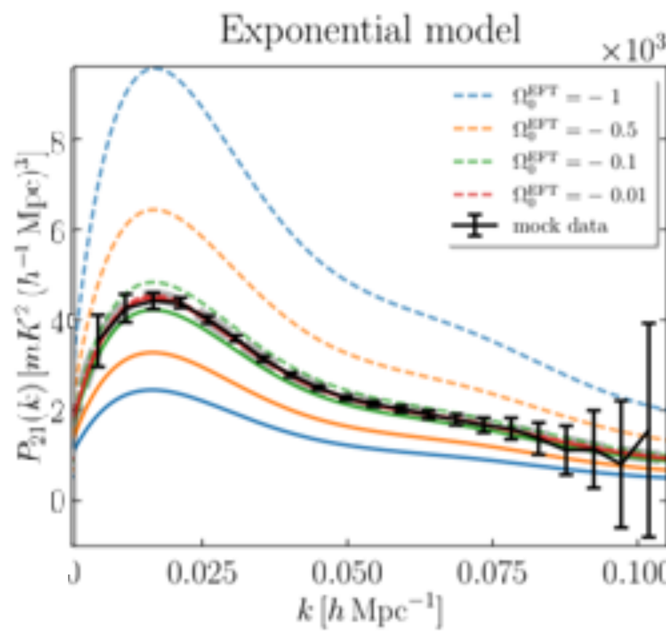
- Note further that *numerical convergence of all quantities not fully achieved*.

Beyond ΛCDM

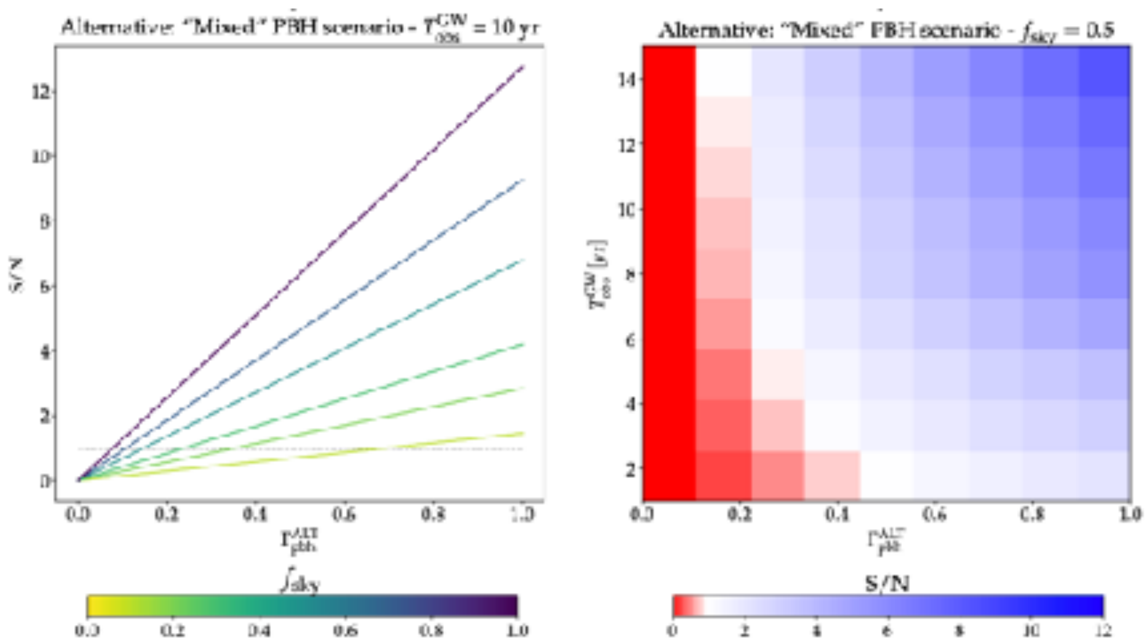
Maria Berti+2021
arXiv: 2109.03256

- Analysis made using present CMB data combined with realistic mock MeerKAT observations
- For ΛCDM adding P_{21} improves H_0 and Ω_c
- Beyond ΛCDM parameters improve at the 10% level with z=0.39 bin
- Adding tomography (z<1) improves at 35% level

$$
\begin{aligned}
S = \int d^4x\sqrt{-g}\Big\{ & \frac{m_0^2}{2}\left[1+\Omega^{\rm EFT}(\tau)\right]R + \Lambda(\tau) - c(\tau)a^2\delta g^{00} \\
& + \frac{M_2^4(\tau)}{2}\left(a^2\delta g^{00}\right)^2 - \frac{\bar{M}_1^3(\tau)}{2}a^2\delta g^{00}\delta K \\
& - \frac{\bar{M}_2^2(\tau)}{2}\left(\delta K\right)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K^\mu_\nu\delta K^\nu_\mu \\
& + m_2^2(\tau)(g^{\mu\nu}+n^\mu n^\nu)\partial_\mu\left(a^2 g^{00}\right)\partial_\nu\left(a^2 g^{00}\right) \\
& + \frac{\hat{M}^2(\tau)}{2}a^2\delta g^{00}\delta R^{(3)} + \dots \Big\} + S_m
\end{aligned}
$$



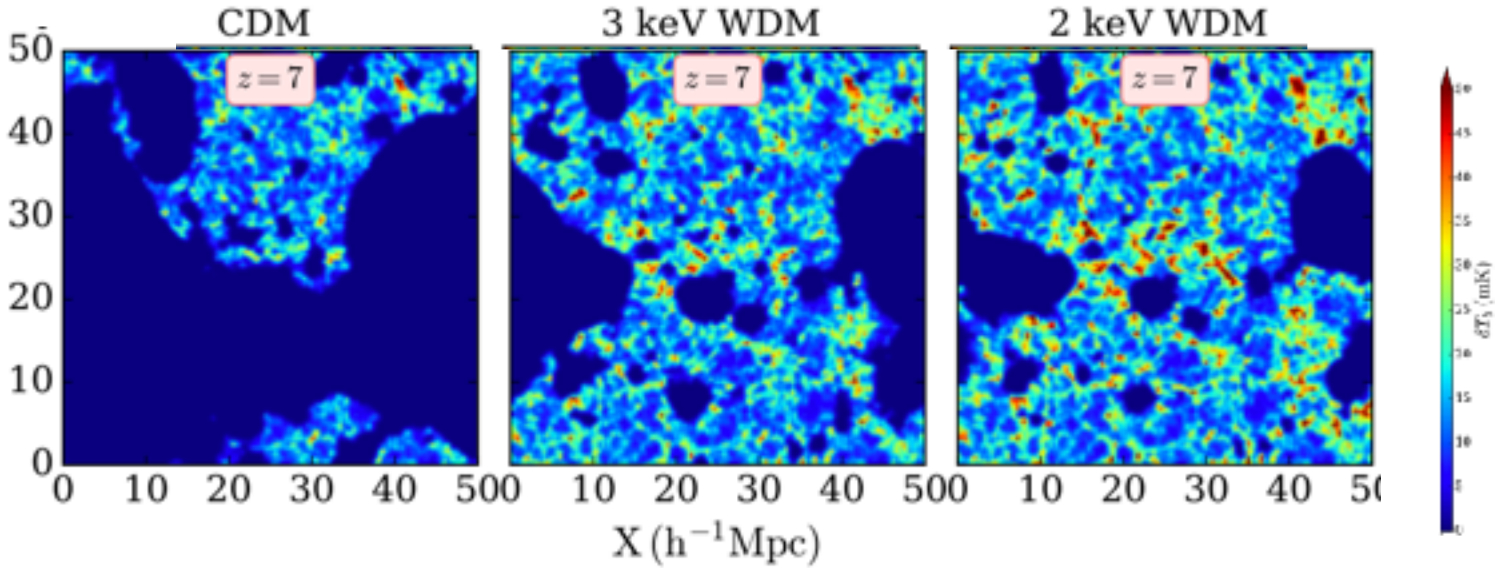
Cross-correlations of GWs with IM



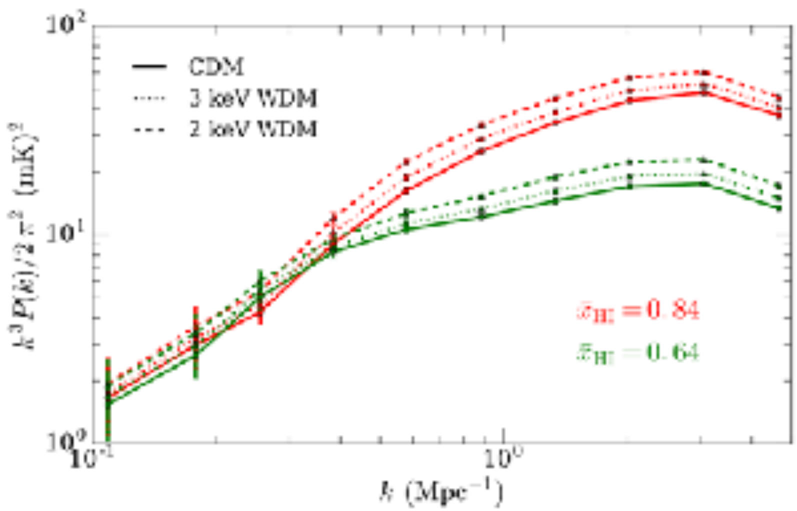
Giulio Scelfo+2021
arXiv: 2106.09786

- Statistical inference of GW distribution dN/dz due to exquisite frequency resolution of IM.
- Determination of the nature of progenitors (primordial vs. astrophysical BHs).
- Potentially detect non standard evolution of Dark Energy at high redshift.

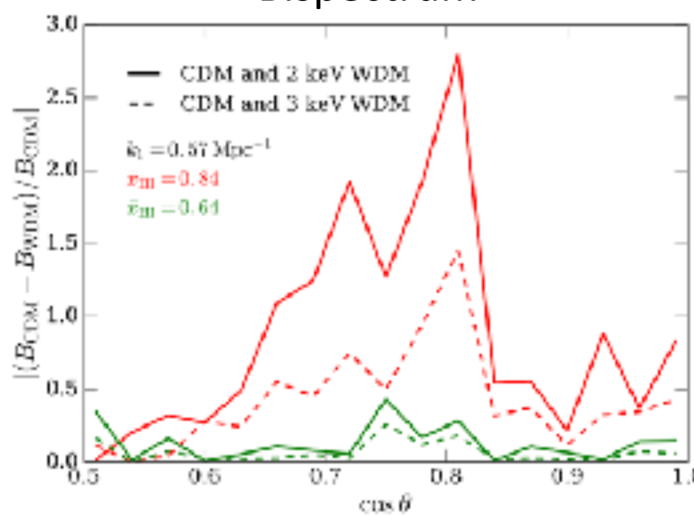
Simulating intensity mapping signal: WDM and bispectrum



Power spectrum



Bispectrum



Saxena, Majumdar, Kamran, MV 2020

SUMMARY

- HI important cosmic tracer to perform **quantitative cosmology** in the post-reionization era.

- Fundamental physics addressed with realistic forecasting methods:
  Neutrino masses
  Extending the Hubble diagram with BAO observations at high-z
  Modified gravity
  Nature of Dark Matter
  Cross-correlations

- **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 also needed).