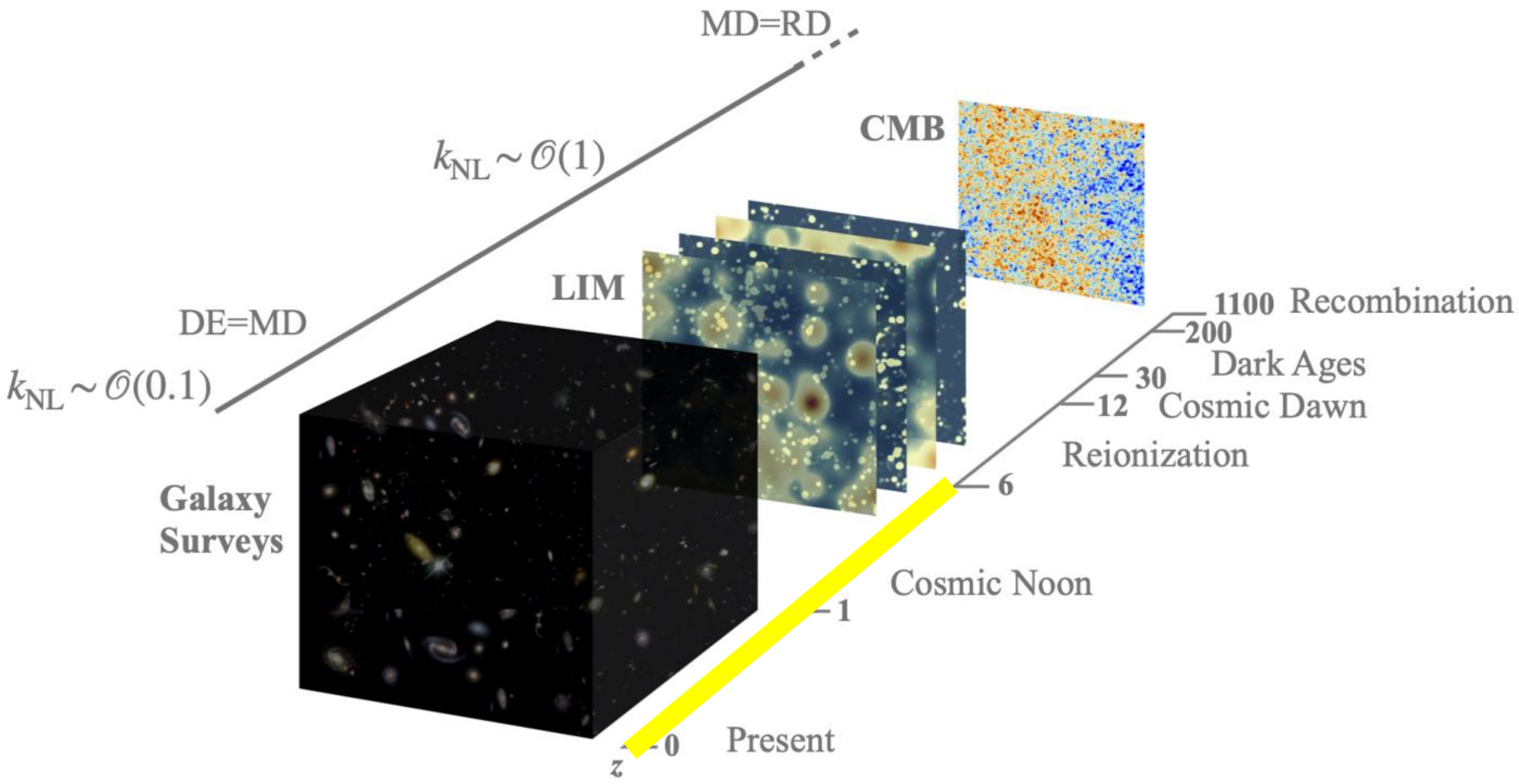
Cosmology in the post-reionization Universe with LIM

Matteo Viel - SISSA (Trieste, Italy)

5/10/25 - LIM 25 (Annecy, France)

Promises of the post-reionization Universe

- Ideal place to test structure formation
- … and cosmological models in and beyond **ΛCDM** (Universe being more linear)
- Large volume to be probed
- … but LIM is sensitive to small scale (astro) physics (intrinsically no threshold)



Clustering of LSS tracers (>Mpc) is coupled to the astrophysics of line intensity (~O(pc))

Bernal & Kovetz 2022

Promises of the post-reionization Universe

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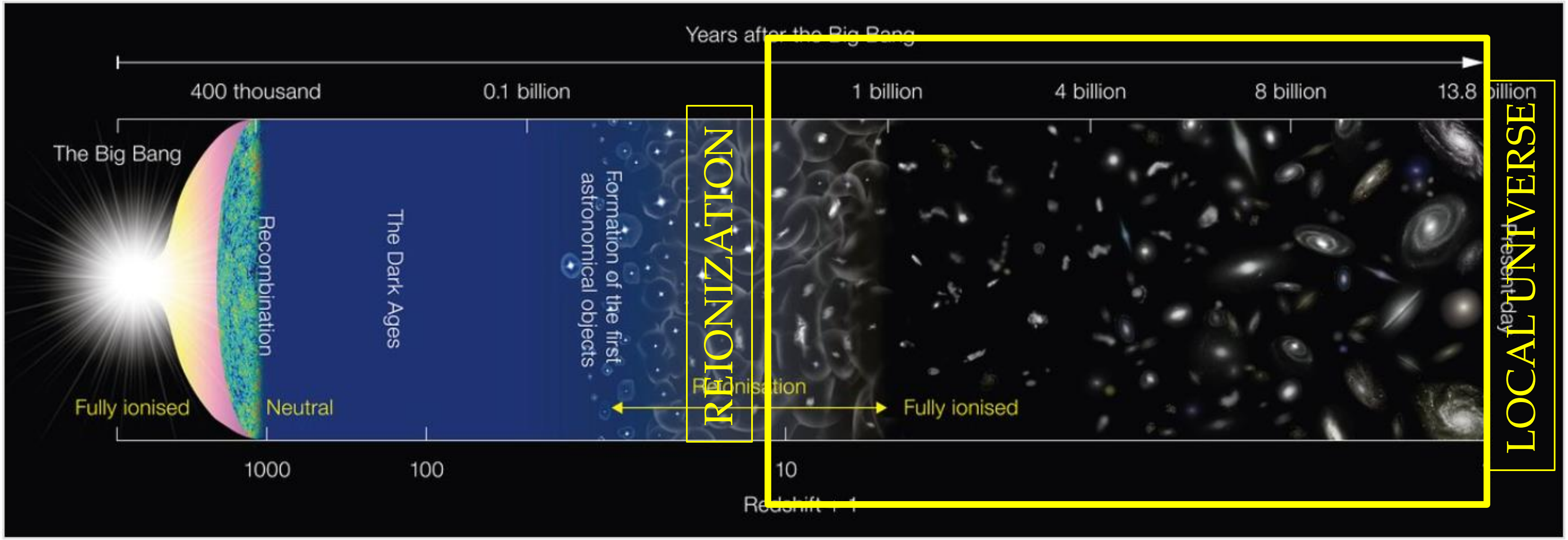

Long lever arm in terms of scales/redshifts will in turn allow to break degeneracies between astro and cosmo parameters with:

- cross-correlations of different tracers
- new estimators (e.g. VID, bispectrum, Machine Learning)

It is an "active phase" of structure formation processes (see Rachel's talk)

Promises of the post-reionization Universe

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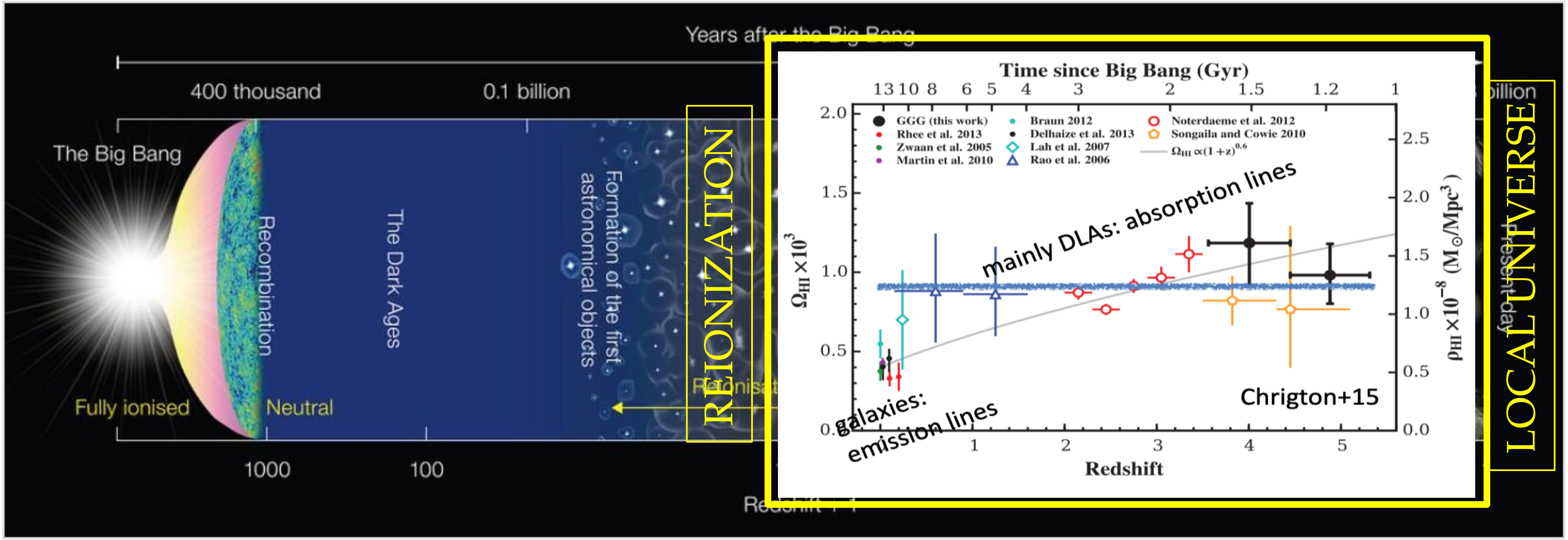

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What are the big questions?

- What is Dark Matter?
- Is evolving Dark Energy real?
- Can we measure neutrino masses?
- Can we probe the matter power spectrum down to the smallest scales?
- Can we test inflation?
- Is there new physics like Primordial Magnetic Fields?

- Can we constrain galaxy formation? [highly complementary to JWST observations]

What are the big questions?

Matteo Viel

- What is Dark Matter? — *Signature in clustering, decay, annihilation*
- Is evolving Dark Energy real? — *BAOs*
- Can we measure neutrino masses? — *Neutrino free-streaming at large/medium scales*
- Can we probe the matter power spectrum down to the smallest scales? — *DM acoustic oscillations, suppression of power*
- Can we test inflation? — *Non Gaussianity*
- Is there new physics like Primordial Magnetic Fields? — *Increase of power at small scales*

- Can we constrain galaxy formation? [highly complementary to JWST observations] — *High redshift Universe is becoming a very interesting place to constrain galaxy formation models [tail of reionization]*

Modelling LIM power to linear order

Matteo Viel

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

Linear power (cosmology)

Brightness HI temperature or other lines

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

Amount of HI

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

HI bias

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

Shot-Noise power spectrum

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

New physics from P(k) or n(M)

Halo mass function (cosmology)

Amount of HI in each DM halo (astrophysics)

Modelling of the LIM power with the halo model

Matteo Viel

- Halo models important for reaching small scales
- Can be easily extended to any IM line
- Profile must be specified

- M_{HI} and Ω_{HI} from sims or from observed HI mass function or DLAs

$$P_{\rm HI}(k,z) = P_{\rm HI,1h}(k) + P_{\rm HI,2h}(k) \qquad P^{\rm SN}_{\rm HI}(z) = \lim_{k\to 0} P_{\rm 1h,HI}(k,z)$$

$$P_{\rm HI,1h}(k,z) = \frac{1}{(\rho_c^0 \Omega_{\rm HI}(z))^2} \int_0^\infty dM n(M,z) M^2_{\rm HI}(M,z)\,|u_{\rm HI}(k|M,z)|^2$$

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

COSMOLOGY

Padmanabhan+16,+17; Bernal, Breyesse, Gil-Marin, Kovetz 19; Villaescusa—Navarro et al. 2018, Padmanabhan 2024 (review)

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COSMOLOGY

ASTROPHYSICS OF THE HALOES

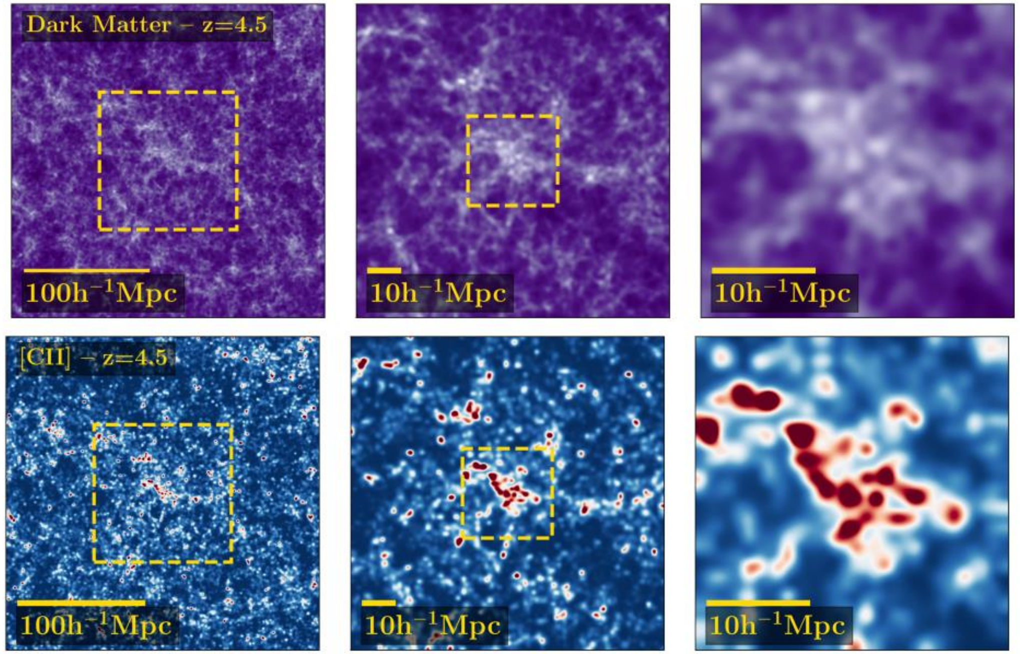
$$M_{\rm HI}(M,z) = \alpha f_{\rm H,c} M \left(\frac{M}{10^{11} h^{-1} M_\odot}\right)^\beta \exp\left[-\left(\frac{v_{c0}}{v_c(M,z)}\right)^3\right] \qquad \rho_{\rm HI}(r; M, z) = \rho_0 \exp(-r/r_{\rm s,HI})$$

Physically-rich modelling: involves a set of parameters that are calibrated on sims to fit observations

Padmanabhan+16,+17; Bernal, Breyesse, Gil-Marin, Kovetz 19; Villaescusa—Navarro et al. 2018, Padmanabhan 2024 (review)

New modelling of LIM power with the halo model

Matteo Viel



- Alcock-Paczynski parameters and BAO wiggles
- State-of-the-art treatment of (non) Poisson shot noise
- Bias of the different lines [CII] and CO
- EFT inspired perturbation theory at 1-loop
- Comparison with large scale/high res. (DM only) mocks

Moradinezhad Dizgah, Nikakthar, Keating, Castorina 22

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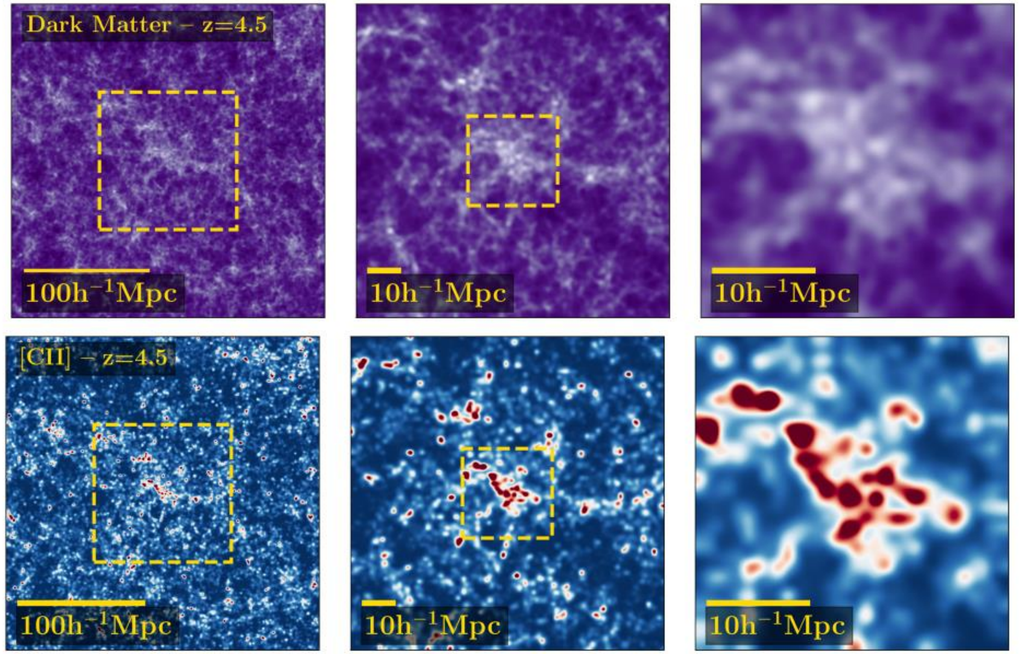
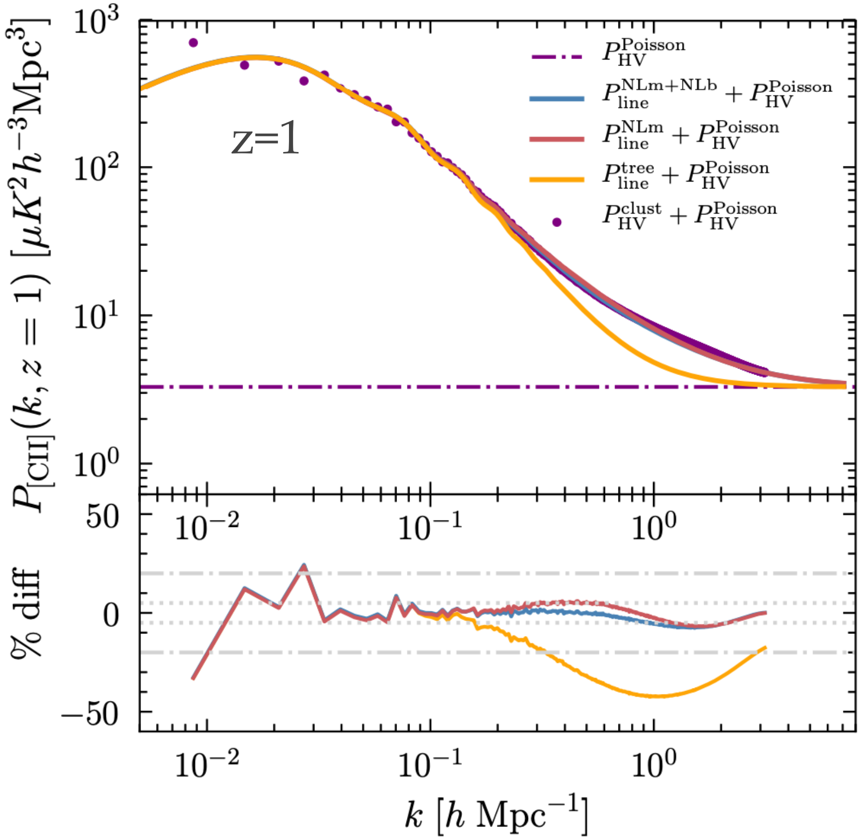


Different treatment of non linearities in matter and bias

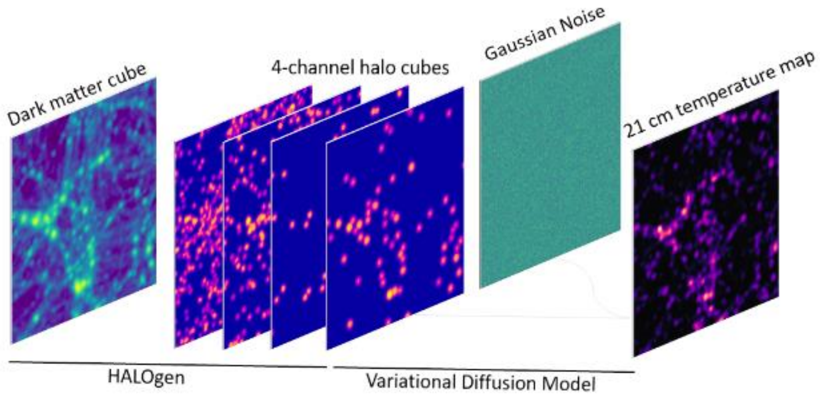


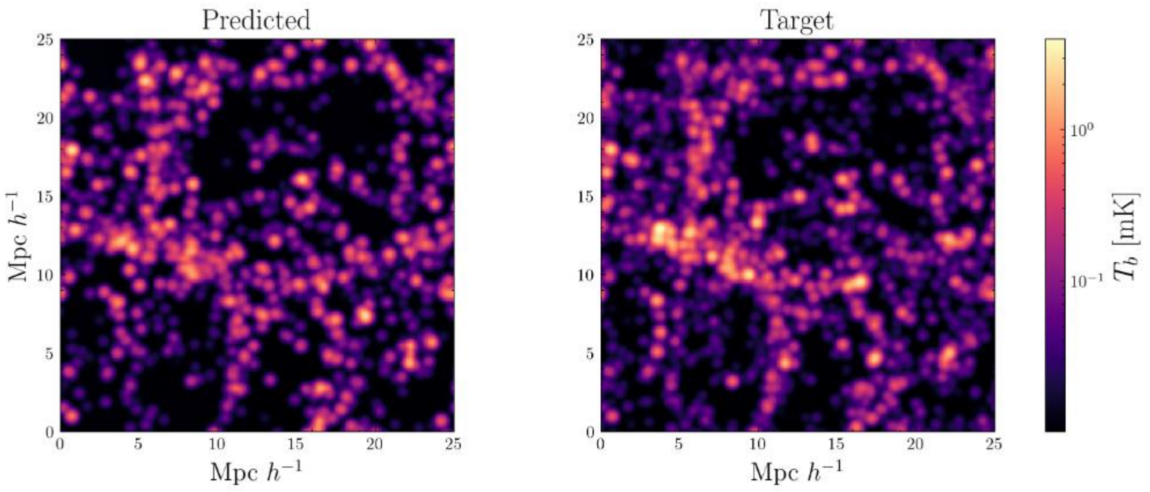
- Alcock-Paczynski parameters and BAO wiggles
- State-of-the-art treatment of (non) Poisson shot noise
- Bias of the different lines [CII] and CO
- EFT inspired perturbation theory at 1-loop
- Comparison with large scale/high res. (DM only) mocks
- Range of validity k~1 *h*/Mpc at z=1 (5% agreement)

Moradinezhad Dizgah, Nikakthar, Keating, Castorina 22

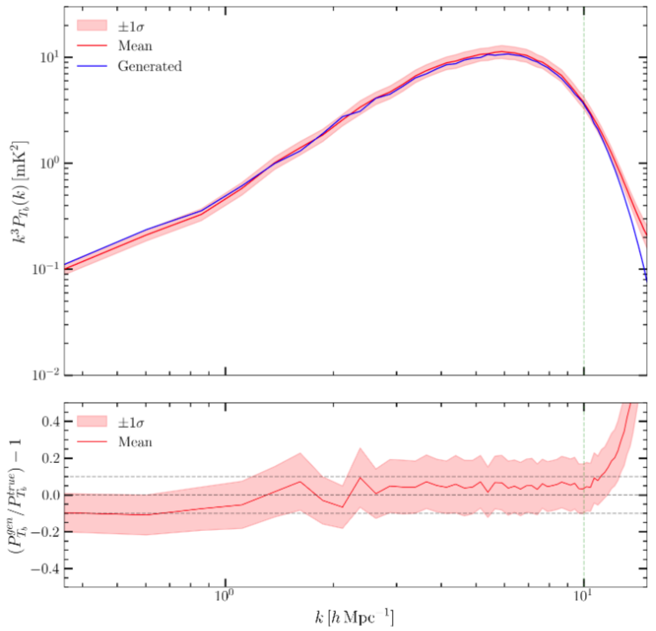
Learning LIM with diffusion models

LODI: Latent **O**verlap **D**iffusion for **I**ntensity Mapping





1st step: DM → haloes (via CNN)
2nd step: Haloes → Intensity voxel map (via Diffusion model)



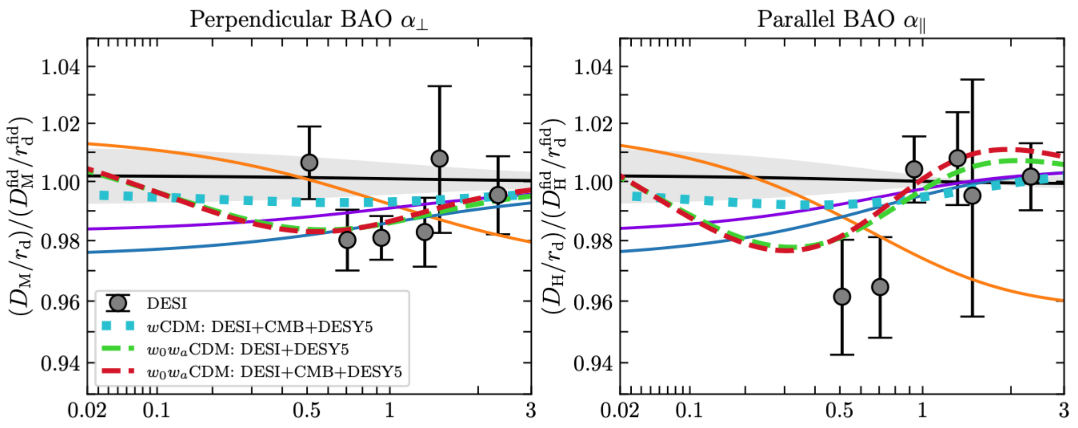
Trained on CAMELS simulations
Agreement up to k = 10 h/Mpc
Extendable to other LIM lines

Mishra, Trotta, Viel, 2025 (to appear soon)

Evolving Dark Energy - I

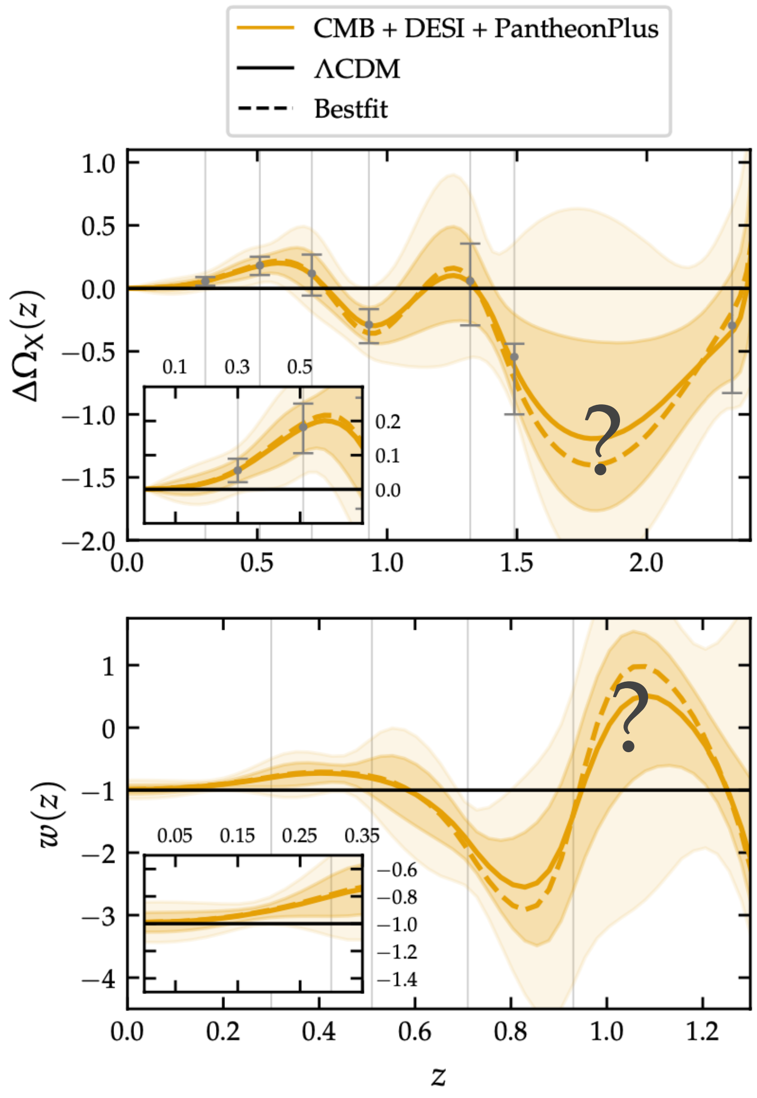
Matteo Viel

- Evolution of dark energy at high-redshift



DESI 2025

RECONSTRUCTING DYNAMICAL DARK ENERGY



$$\Omega_X(z) = \Omega_\Lambda(z)\,[1 + \Delta\Omega_X(z)]$$

$$w(z) = \frac{1+z}{3(1+\Delta\Omega_X(z))}\frac{d\Delta\Omega_X(z)}{dz} - 1$$

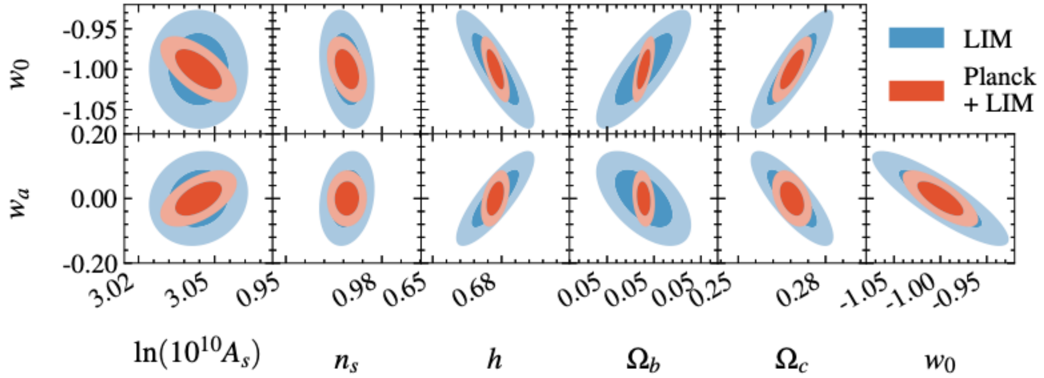
Berti, Bellini, Bonvin, Kuntz, Viel, Zumalacarregui arxiv:2503.13198

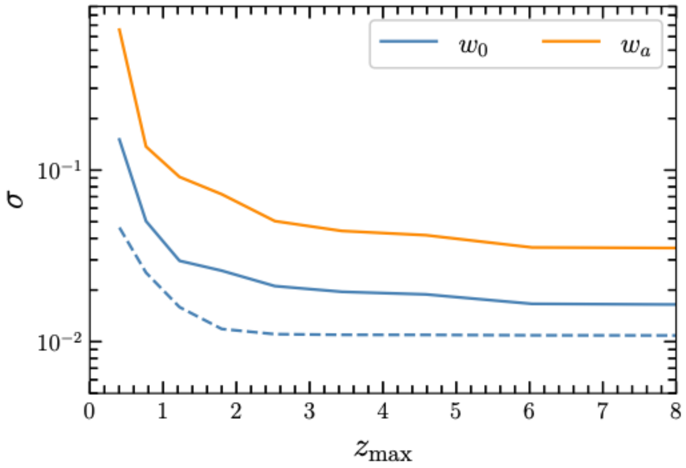
Evolving Dark Energy - II

Matteo Viel

- Testing GR and DE with LIM (Horndeski, Bransk-Dicke, early dark energy models)
- Fisher matrix analysis for CO and [CII] on P(k) including modelling of the interlopers; scatter in L(M); shot noise; instrumental noise
- Effectively a linear model, which is sensitive to geometry and dynamics

CPL parameterization





Moradinezhad Dizgah, Bellini, & Keating 2024
(also Berti, MV+21 for 21cm)

Beyond P(k): Voxel Intensity Distribution

Matteo Viel

cosmology

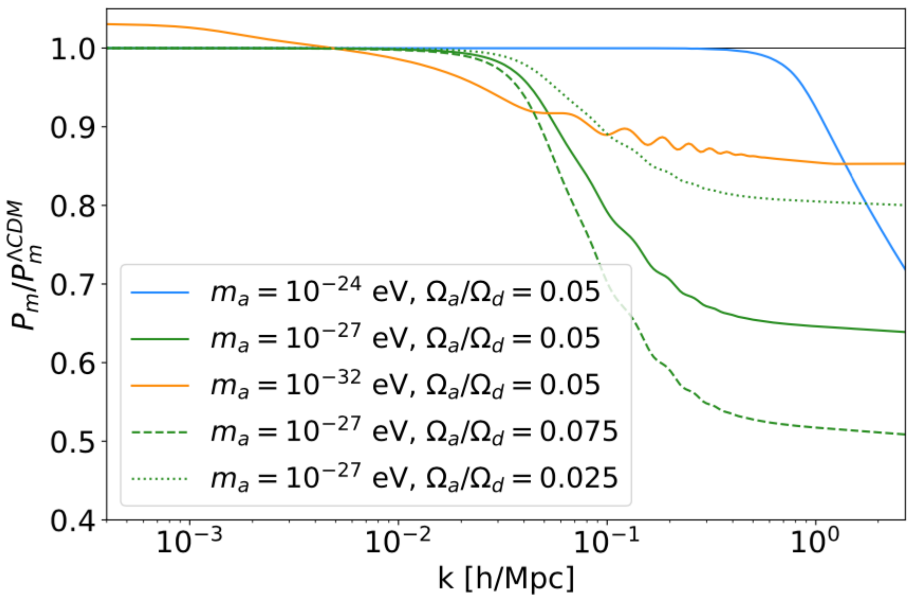
$$\mathcal{T}^2(k) \equiv \frac{P_{\rm nCDM}(k)}{P_{\rm CDM}(k)} = \begin{cases} 1 & \text{if } k \leq k_{\rm cut} \\ \left(\frac{k}{k_{\rm cut}}\right)^{-n} & \text{if } k > k_{\rm cut} \end{cases}$$

astrophysics

$$\frac{L_{\rm CO}}{L_\odot}(M) = 4.9 \times 10^{-5} \frac{C}{(M/M_*)^A + (M/M_*)^B}$$

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$

- Pheno model that captures axion + cold DM
- COMAP-Y5 experiment (z=2.9)
- Monopole of the power spectrum + Voxel intensity distribution (VID) – this is important to capture non gaussian nature of signal



Breysse, Kovetz+17, Sato-Polito & Bernal 22, Sabla, Bernal, Sato-Polito, Kamionkowski 24

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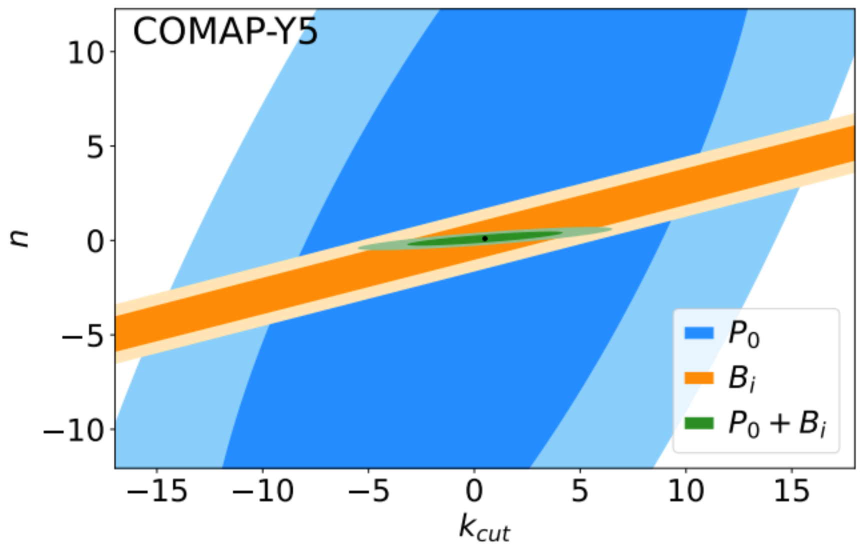
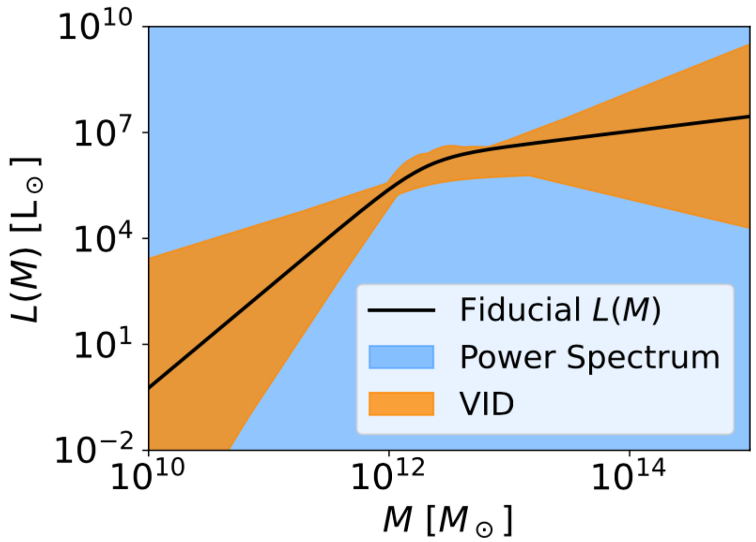
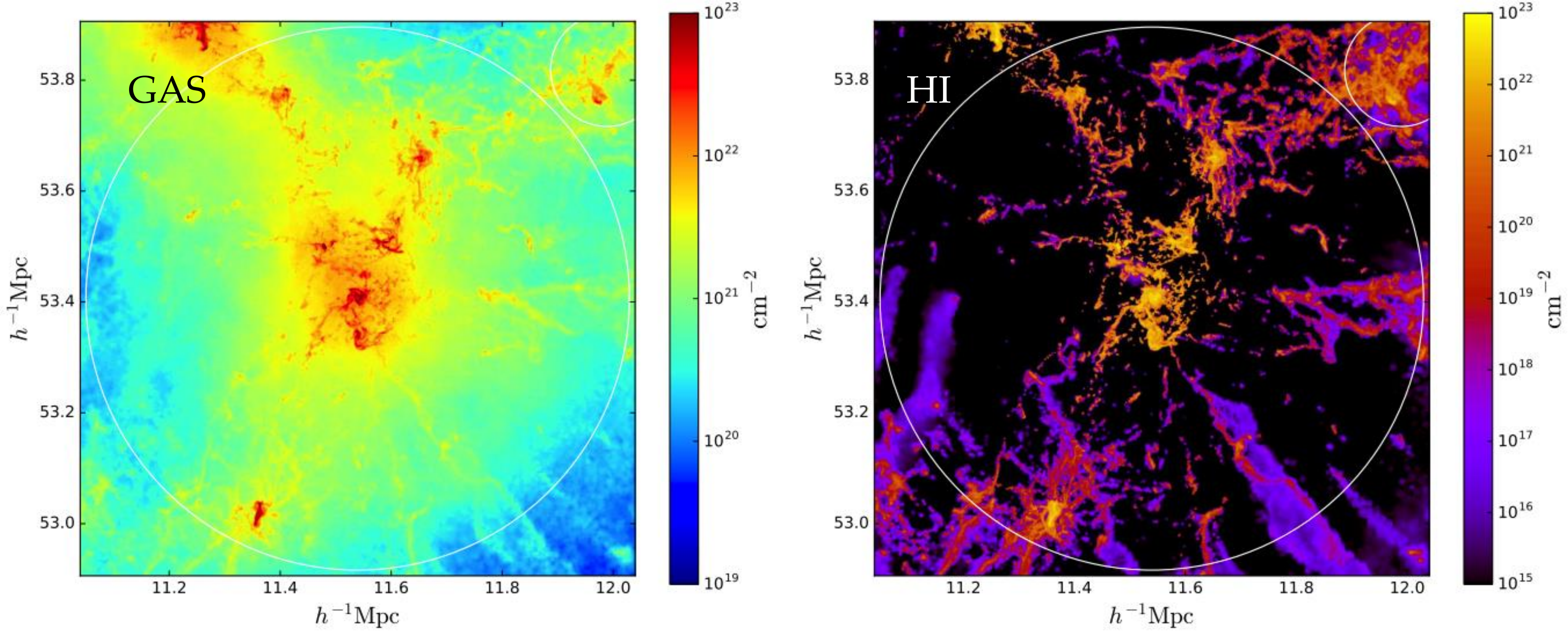




Breysse, Kovetz+17, Sato-Polito & Bernal 22, Sabla, Bernal, Sato-Polito, Kamionkowski 24

How is HI distributed in cold DM haloes?

$10^{13}\,M_{\odot}$ halo at z=3



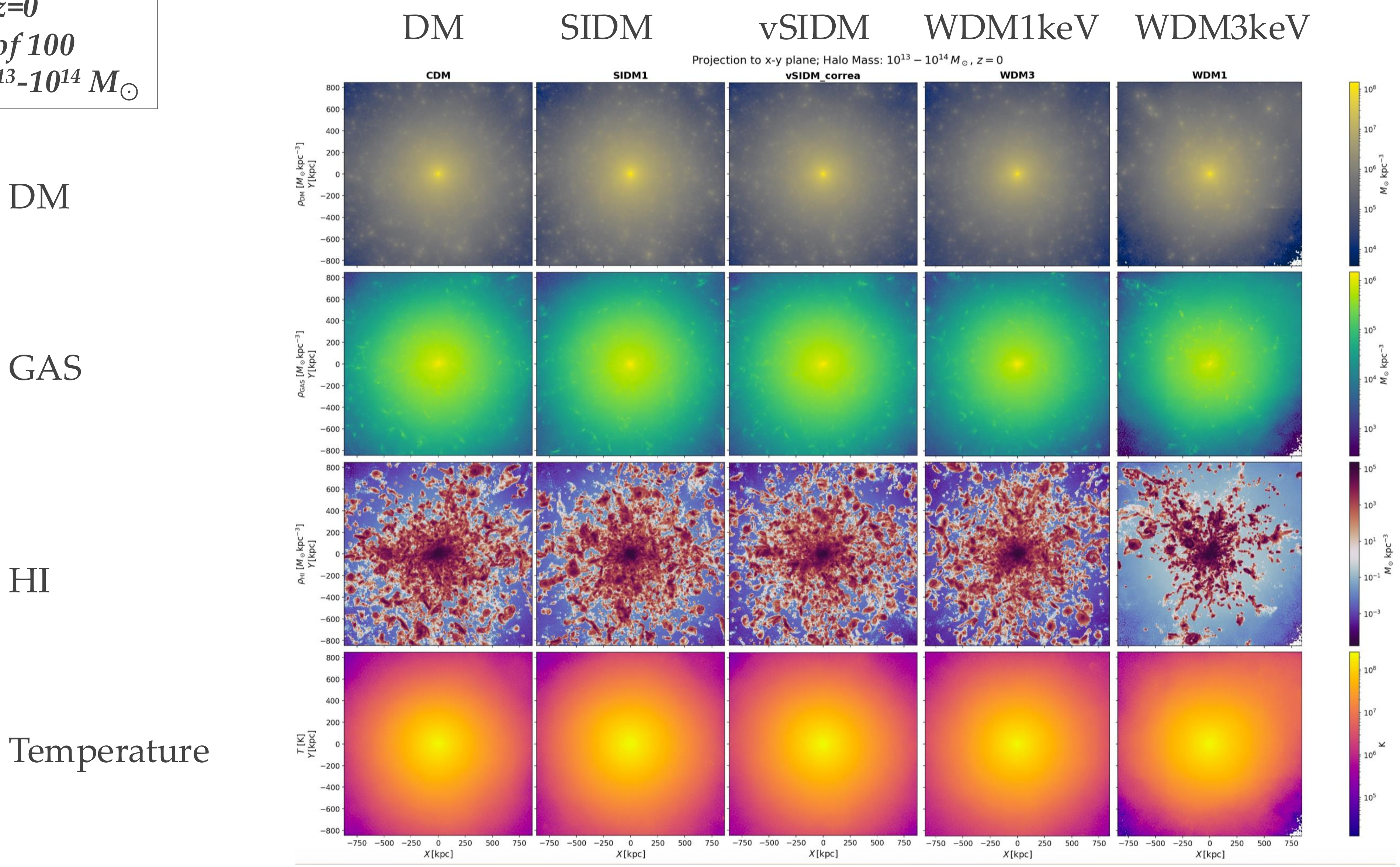
Feedback/star formation is shaping the properties of HI…
…unfortunately this above cannot be directly observed

Villaescusa-Navarro+ 2018

How is HI distributed in non-cold DM haloes at z=0?

Matteo Viel

Redshift z=0
stacking of 100
haloes 10^{13}-10^{14} $M_\odot$



Zhang, Garaldi, Despali, Viel 2025 in prep.

How is HI distributed in non-cold DM haloes at z=3?

Matteo Viel

Redshift z=3
stacking of 100
haloes 10^{12}-10^{13} $M_\odot$

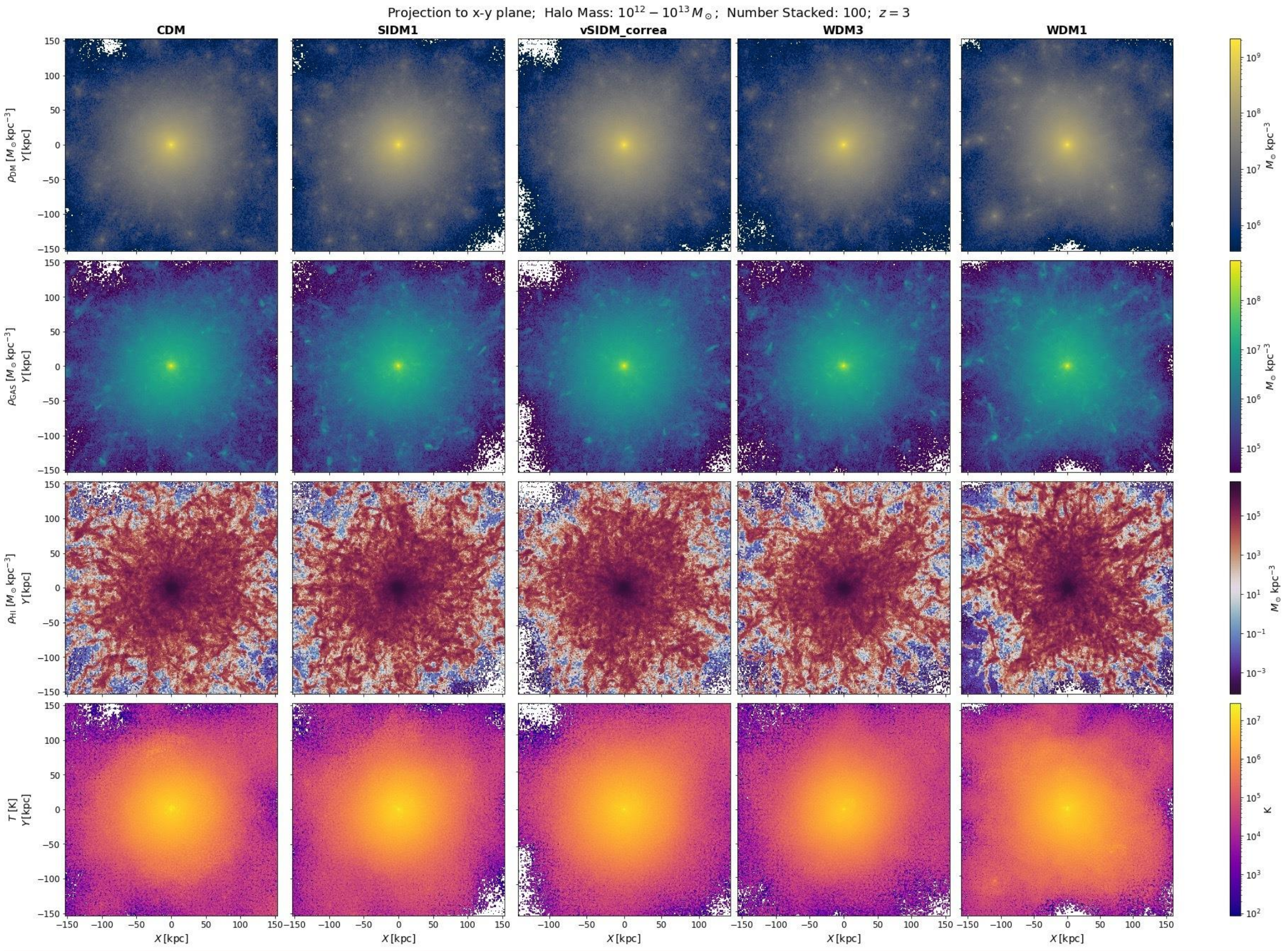
DM SIDM vSIDM WDM1keV WDM3keV

DM

GAS

HI

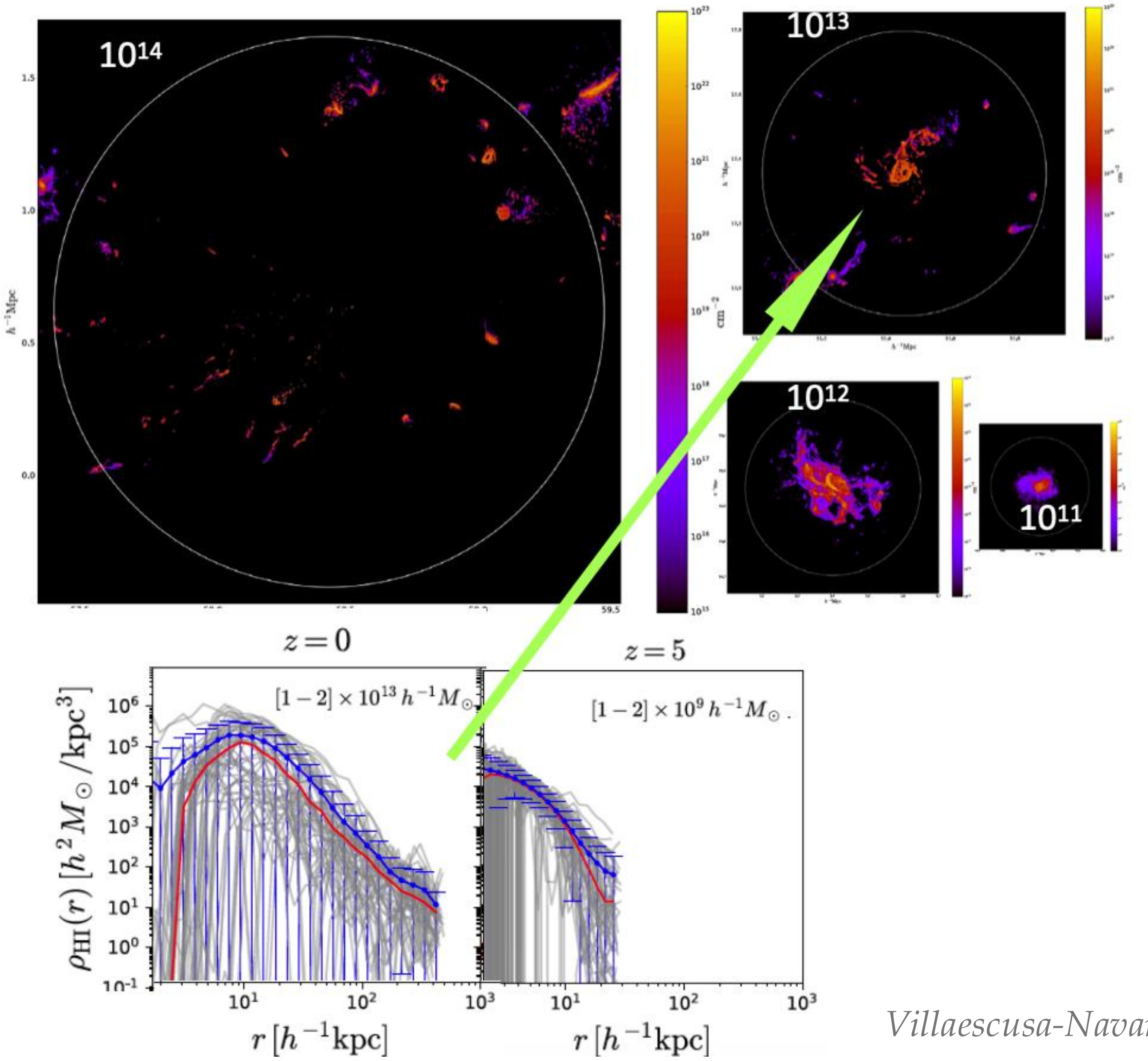
Temperature



Zhang, Garaldi, Despali, Viel 2025 in prep.

How does HI is distributed in DM haloes?

Matteo Viel



Villaescusa-Navarro+ 2018

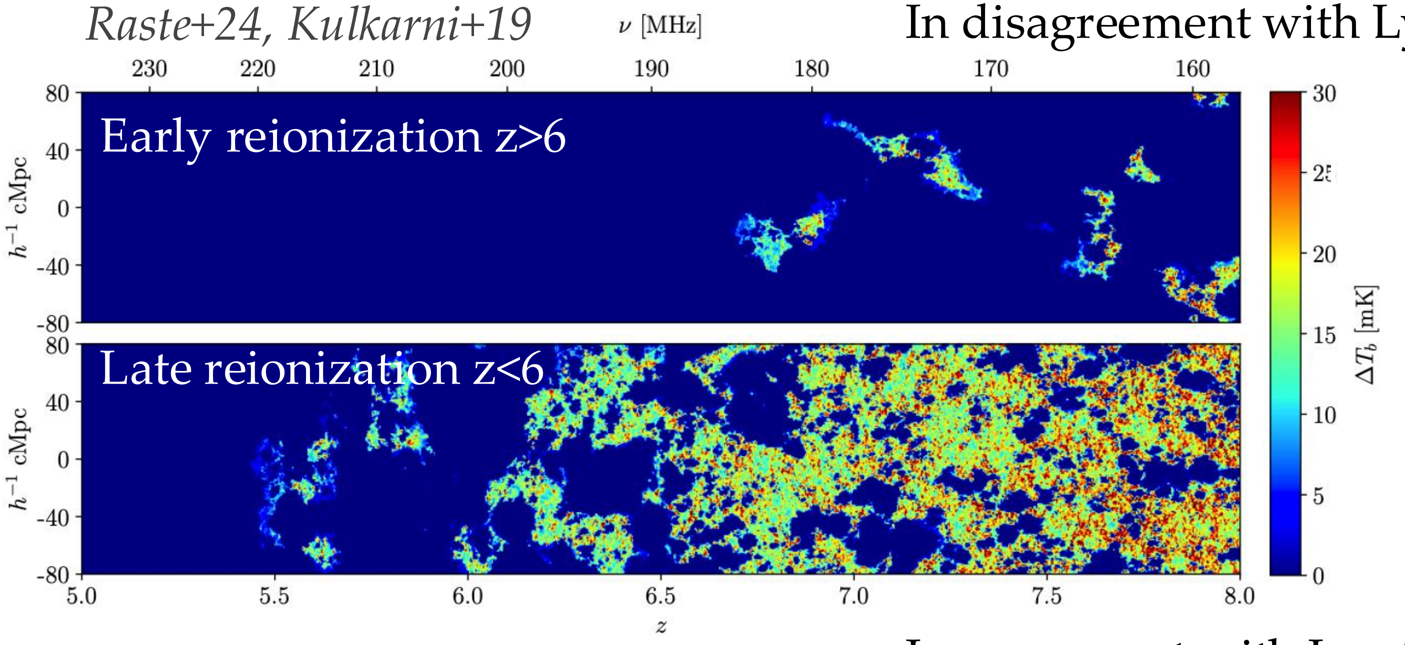
- Modeling of HI halo important also for halo models - Surely affected by feedback but maybe also sensitive to DM nature?
- Large scatter in the HI density profile (correlates with environmental properties)
- Rationale behind: we are tracing the **cold gas** at high-z, i.e. building blocks of star formation

The relics of reionization

Matteo Viel

Raste+24, Kulkarni+19

In disagreement with Lya forest



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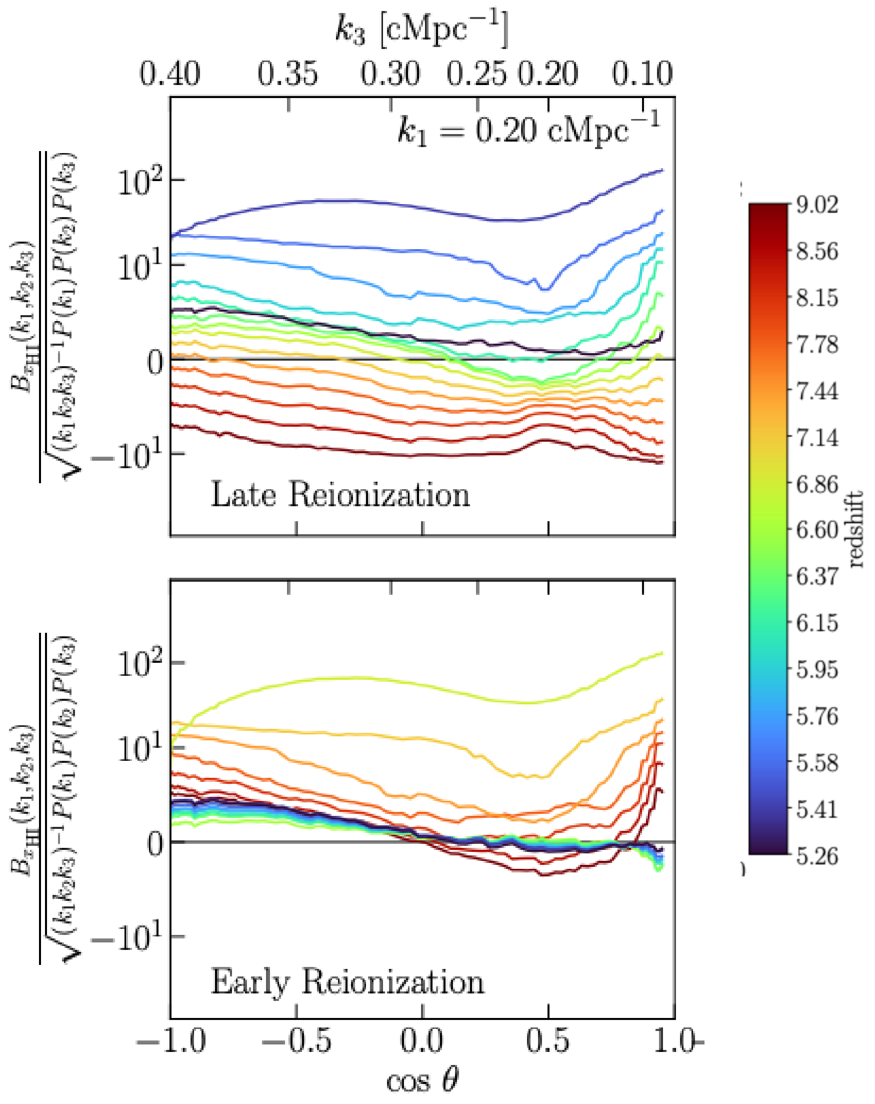

- ➢ 21cm power spectrum typically boosted
- ➢ And bispectrum (which follows x_{HI}) shows distinctive features
- ➢ New window of opportunity for the bispectrum after EoR (Leon Noble's talk later)

The relics of reionization

Raste+24, Kulkarni+19

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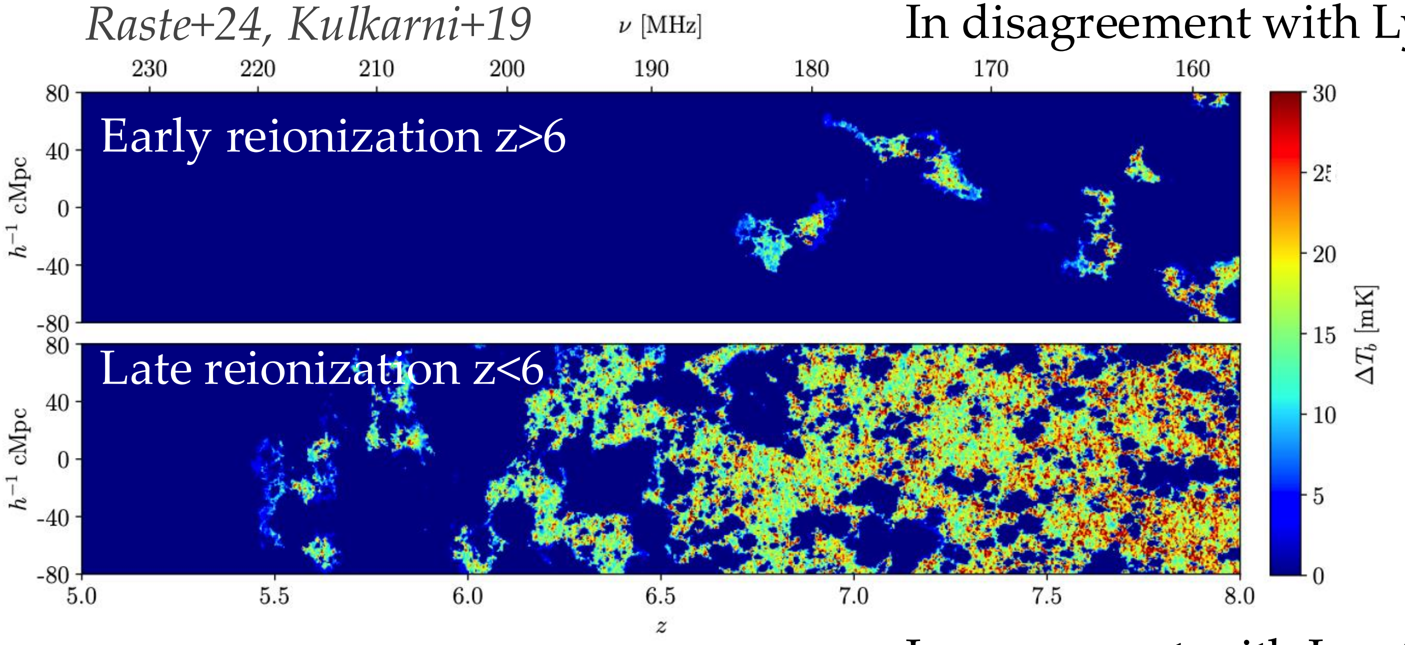

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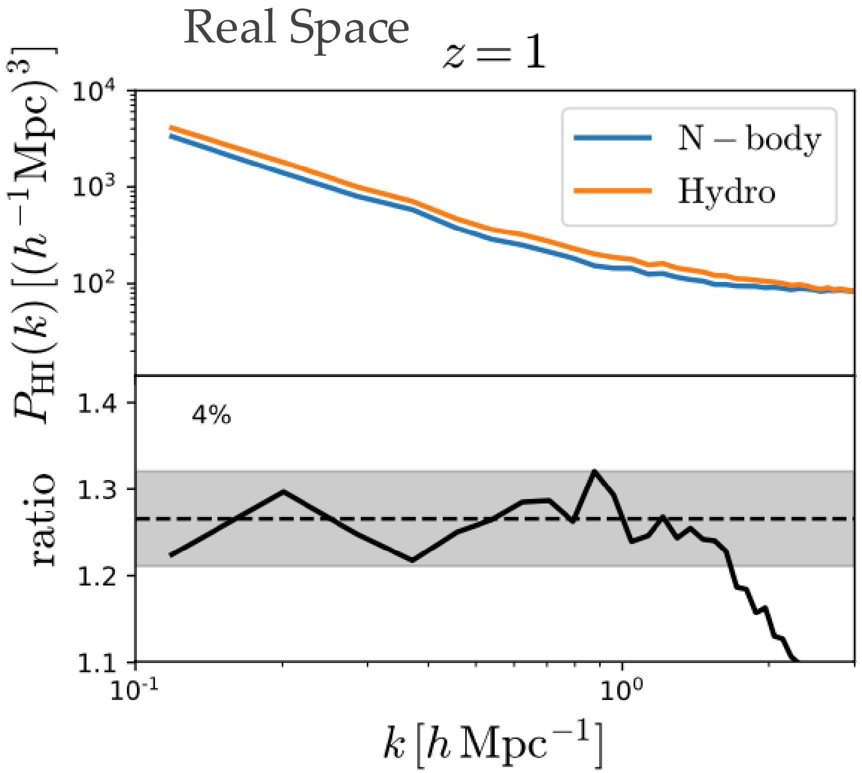
Is the small scale HI distribution important?



Villaescusa-Navarro+ 2018

Is the small scale HI distribution important?

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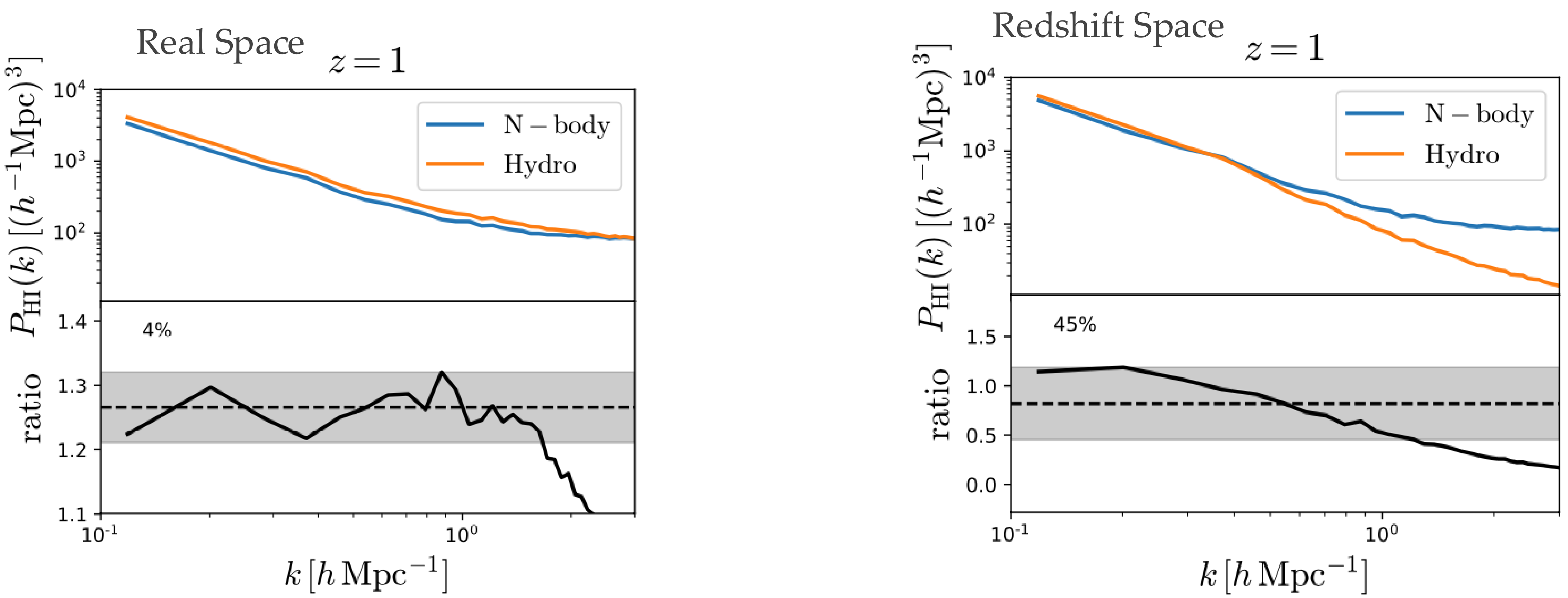
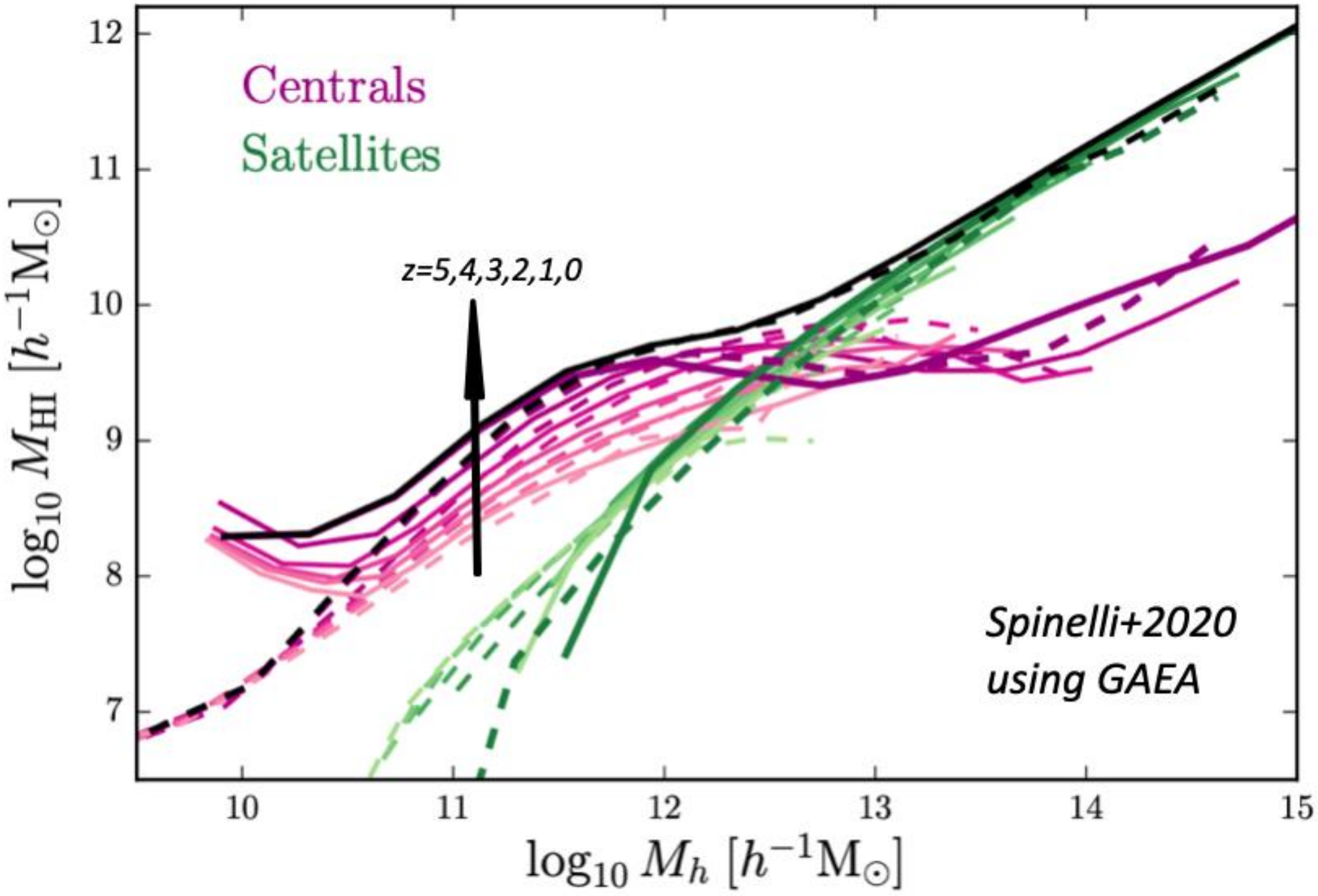


- N-body (all HI is in the center of the halo) vs. full hydro HI power spectrum (effectively there is a 1-halo term). Normalization is quite different but shape is reasonable.
- Kaiser effect (boosts power at large scales) vs. Finger of Gods (suppresses power at small scales <u>but not so small</u>). Behaviour in matter field and HI field is different…..!

Villaescusa-Navarro+ 2018

Cross correlating HI and galaxies



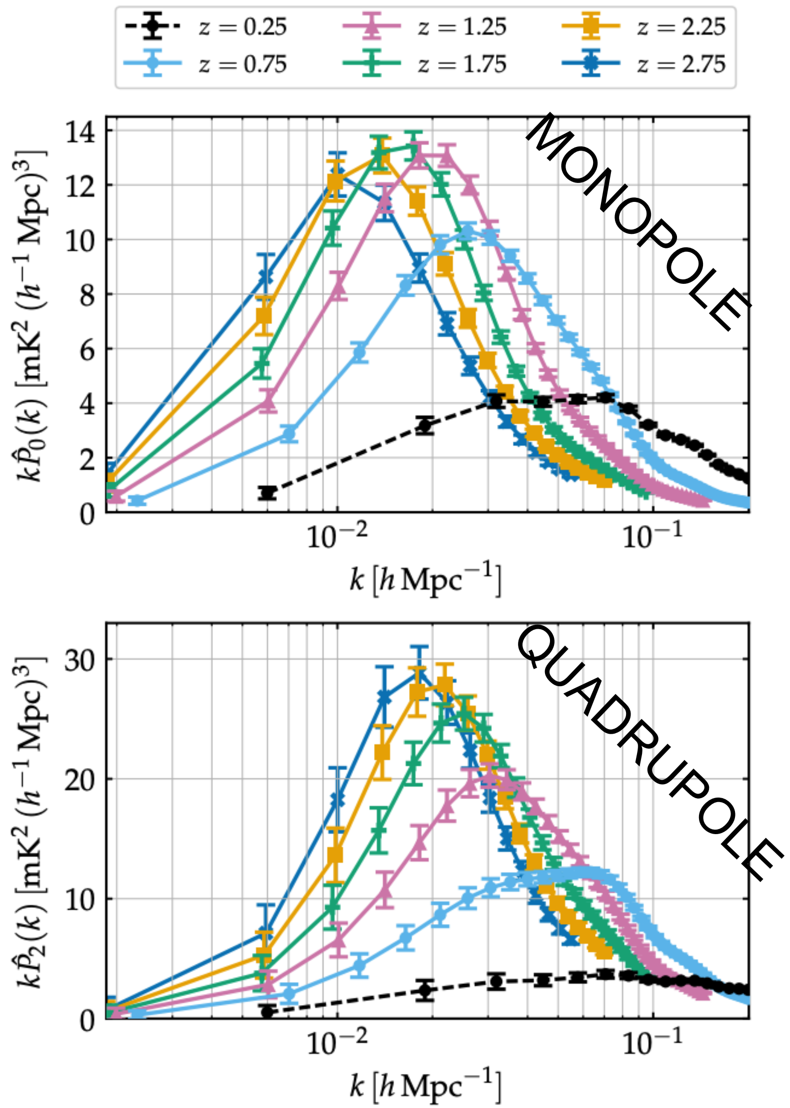
…further progress: interfacing this "small-scale" accurate and physical information with large scale methods for extensive mock productions

And machine learning techniques…

And higher order statistics…

Spinelli+2020 - Noble, Majumdar, MV+ 25 in prep.

Modelling the 21cm power: SKA-mid



- Beam is killing small/medium scales modes
- Modelling non-linearities is thus not so crucial (due to beam)
- But non-linear scales are indeed informative

Berti, Spinelli, MV (2023)

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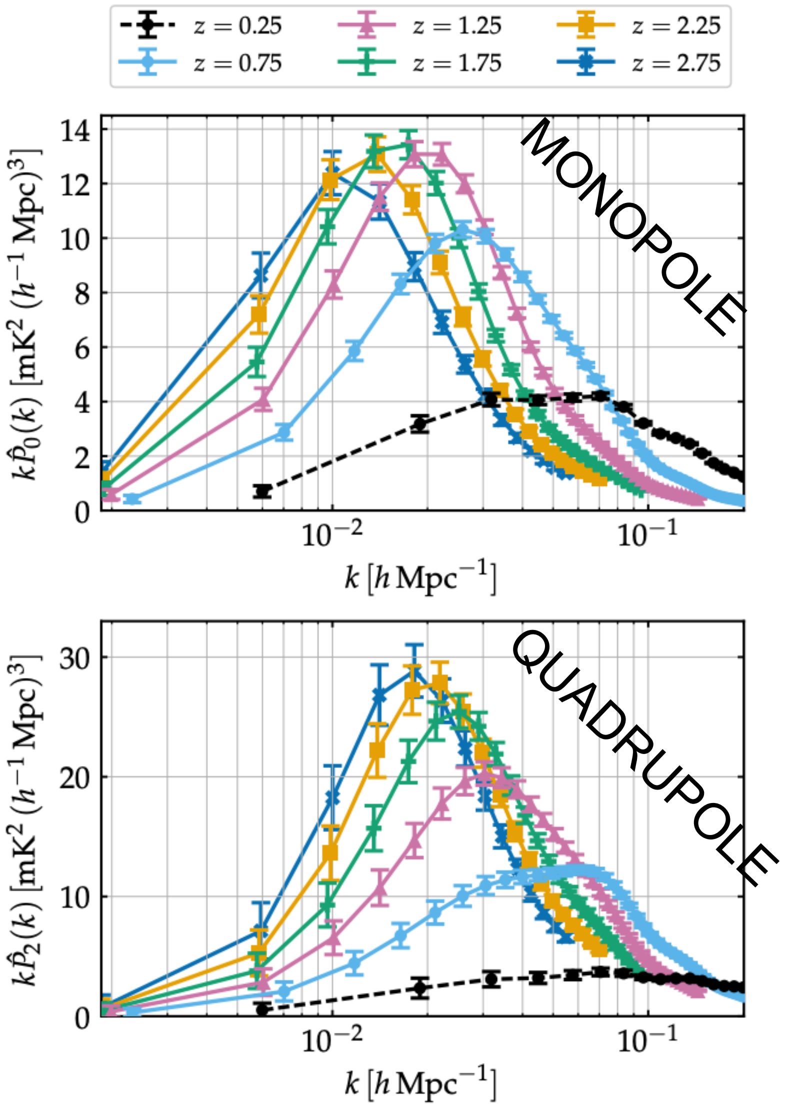
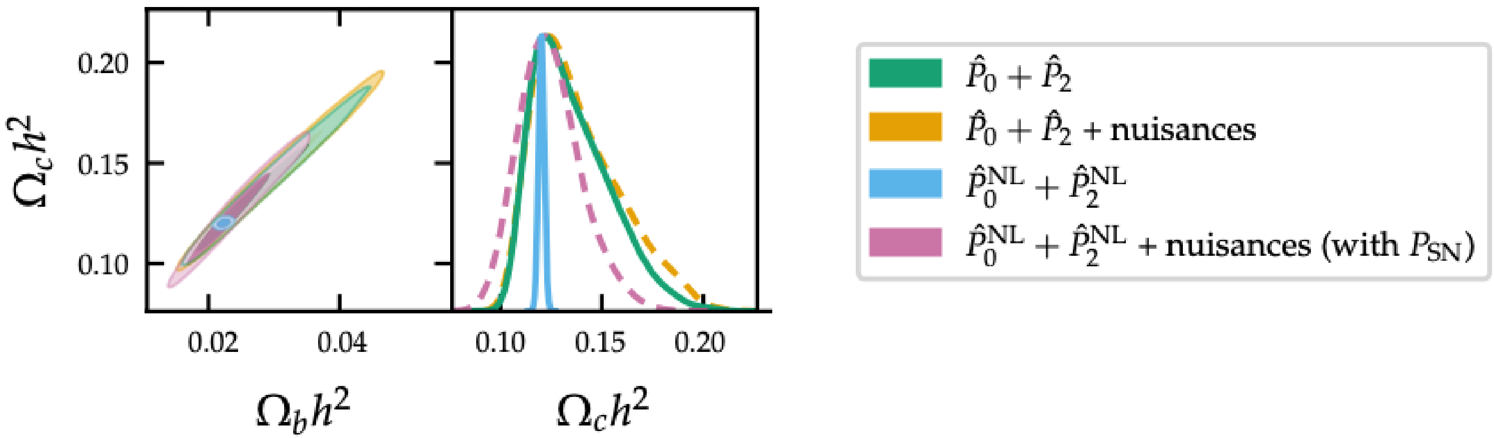


- Beam is killing small/medium scales modes
- Modelling non-linearities is thus not so crucial (due to beam)
- But non-linear scales are informative (to some extent)
- Compared to Planck only improvement of a factor 4 on the error on H_0, Ω_c



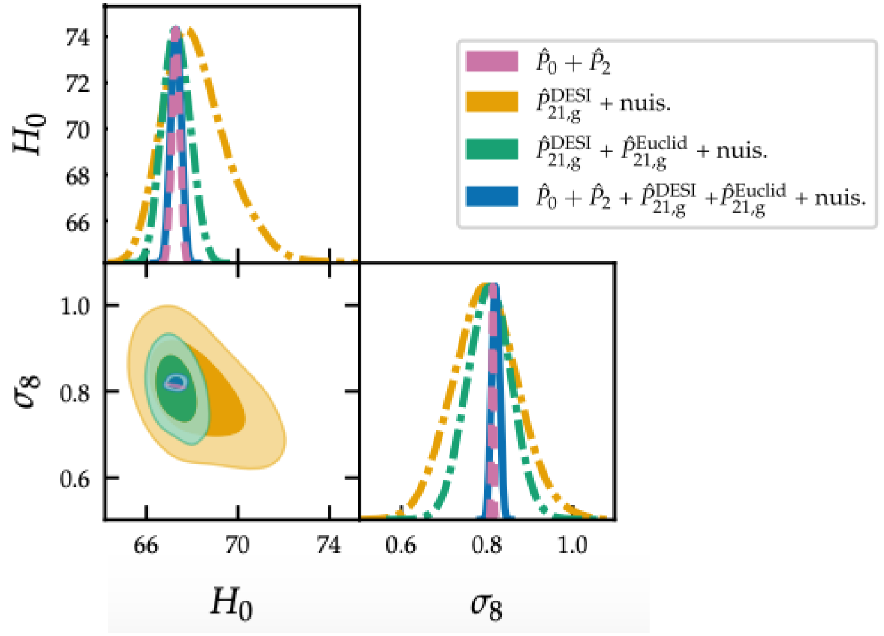
Berti, Spinelli, MV (2023)

Modelling the 21cm cross-power: SKA-mid X DESI/Euclid

Matteo Viel

$$P_g(z,k,\mu) = \left(b_g(z) + f(z)\,\mu^2\right)^2 P_m(z,k) + \frac{1}{\bar{n}_g(z)}$$

- Cross-correlation with spectroscopic samples
- Nuisance parameters to bracket instrumental and astrophysical uncertainties
- Very constraining (similar to auto-correlation)



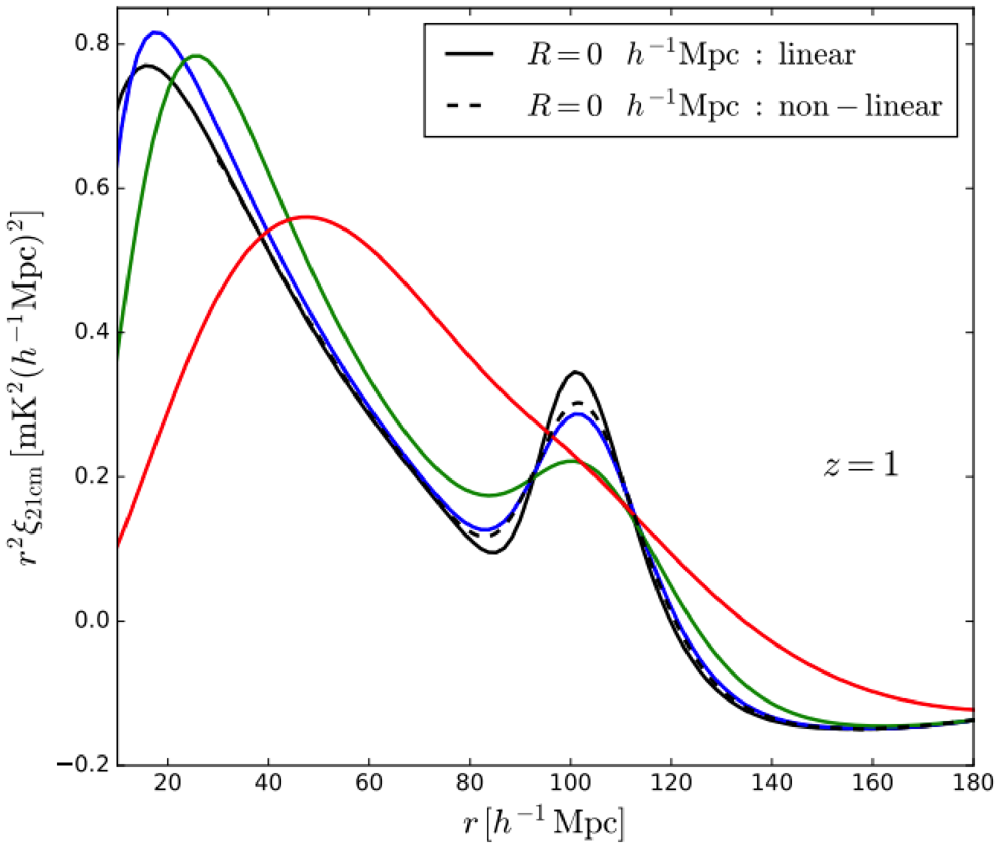
Parameter	$\hat{P}_0 + \hat{P}_2$	$\hat{P}^{\rm DESI}_{21,g}$	$\hat{P}^{\rm DESI}_{21,g}$ + nuis.	$\hat{P}^{\rm Euclid}_{21,g}$	$\hat{P}^{\rm Euclid}_{21,g}$ + nuis.	$\hat{P}^{\rm DESI}_{21,g} + \hat{P}^{\rm Euclid}_{21,g}$ + nuis.	$\hat{P}_0 + \hat{P}_2 + \hat{P}^{\rm DESI}_{21,g} + \hat{P}^{\rm Euclid}_{21,g}$ + nuis.
H_0	0.25%	0.69%	1.96%	0.49%	1.07%	0.87%	0.33%

Berti, Spinelli, MV (2024)

Baryonic Acoustic Oscillations in 21cm IM

Matteo Viel

- Poor angular resolution, will smooth BAO feature
- But in the k parallel direction, frequency resolution is very high → radial BAO
- 1D power is reduced in amplitude compared to 3D but wiggles are prominent



Villaescusa-Navarro, Alonso, MV 2017

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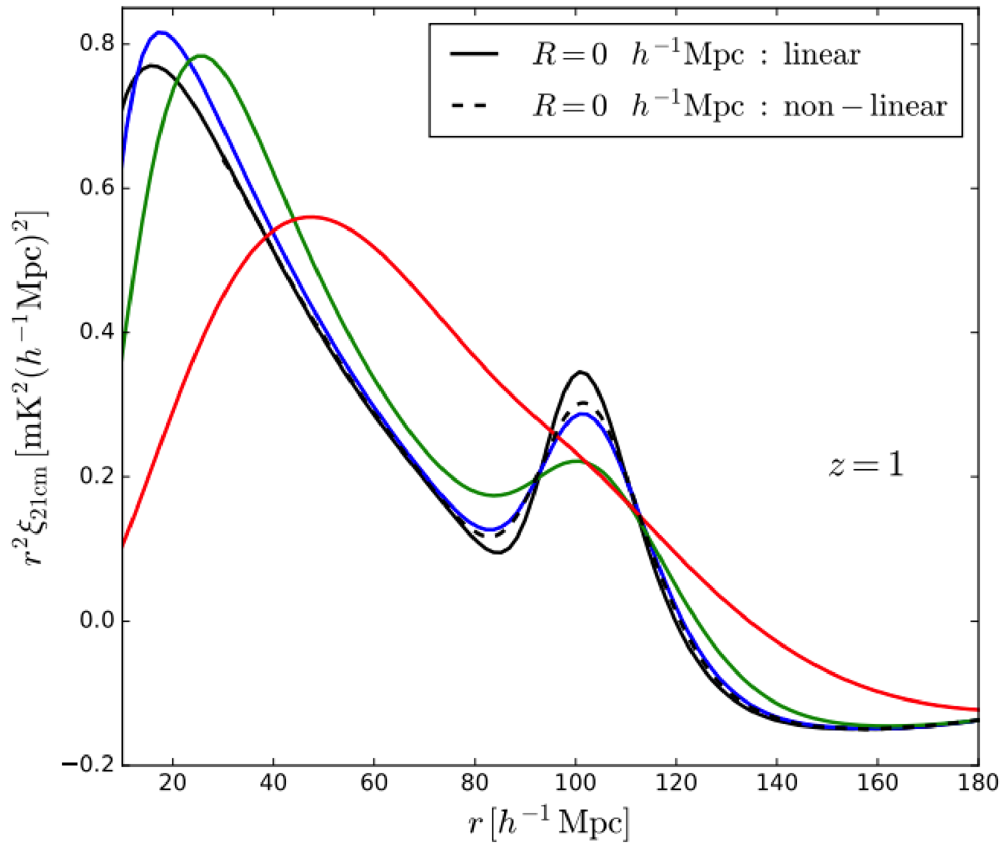
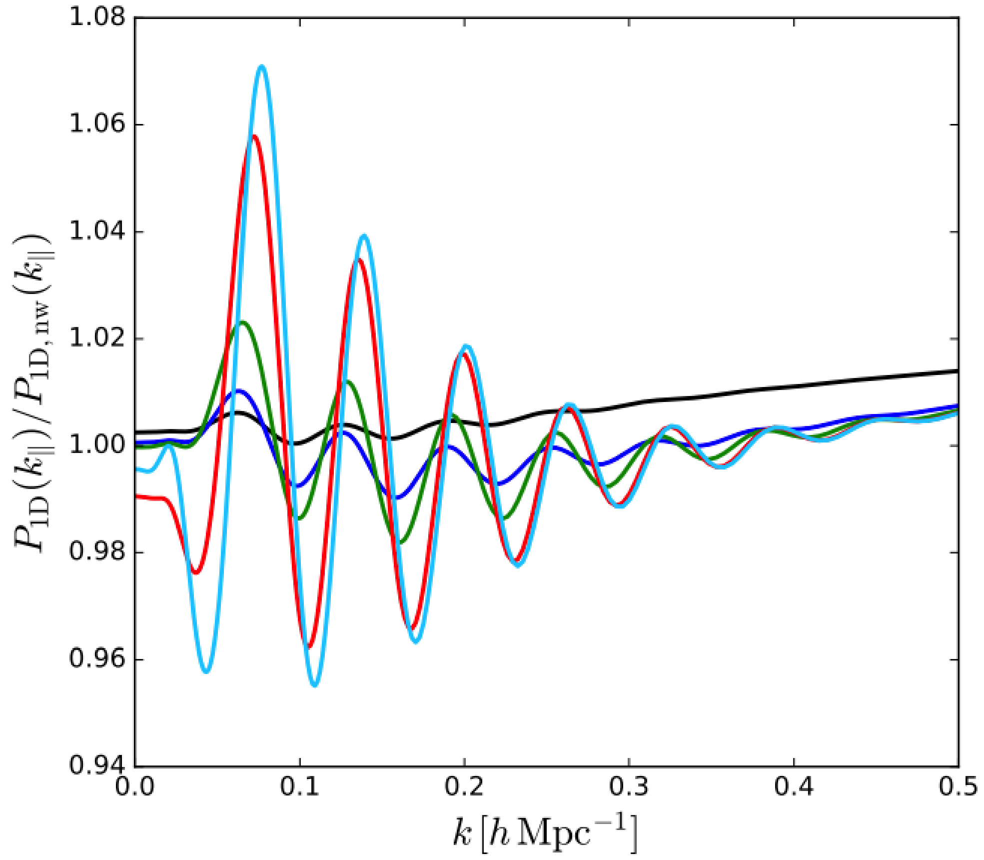


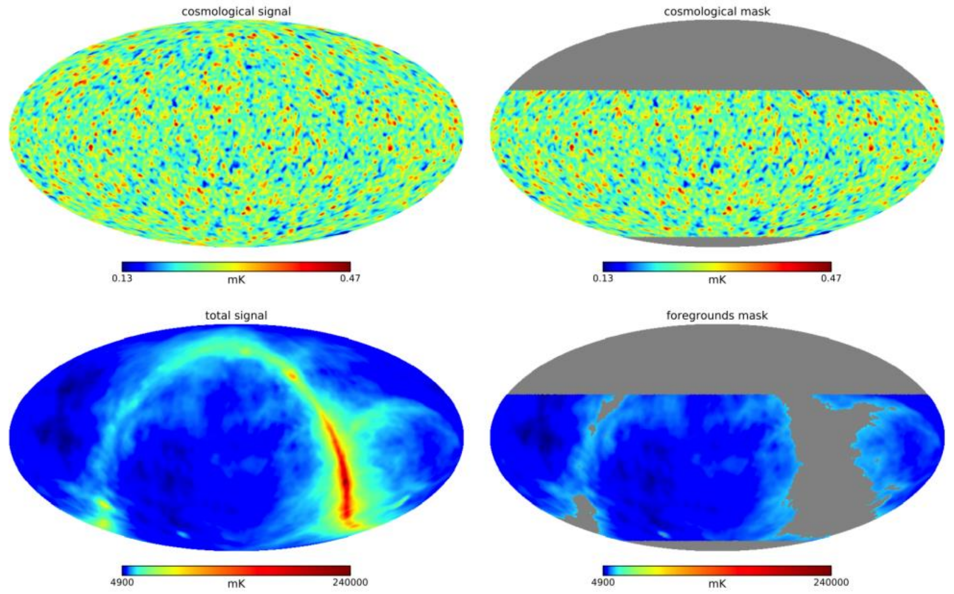
$$\lim_{R\to\infty} P_{21\mathrm{cm,obs,1D}}(k_\parallel, z) = \frac{1}{4\pi R^2} P_{21\mathrm{cm}}(k_\parallel, z)$$



Villaescusa-Navarro, Alonso, MV 2017

Baryonic Acoustic Oscillations in 21cm IM

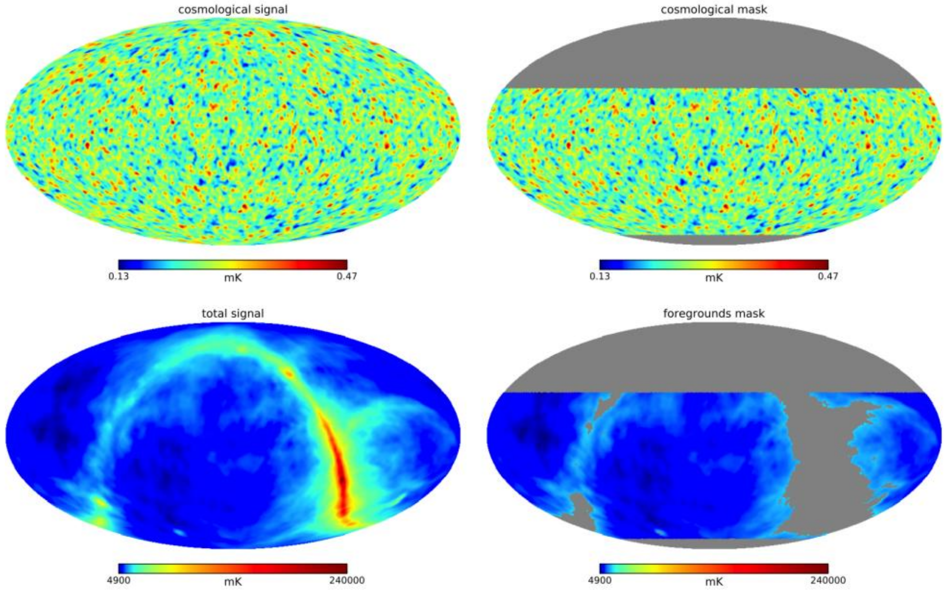
- SKA estimate: H(z) measured at sub-percent level up to z=2.5
- Made with mask, and foregrounds removal
- And realistic treatment of instrument noise

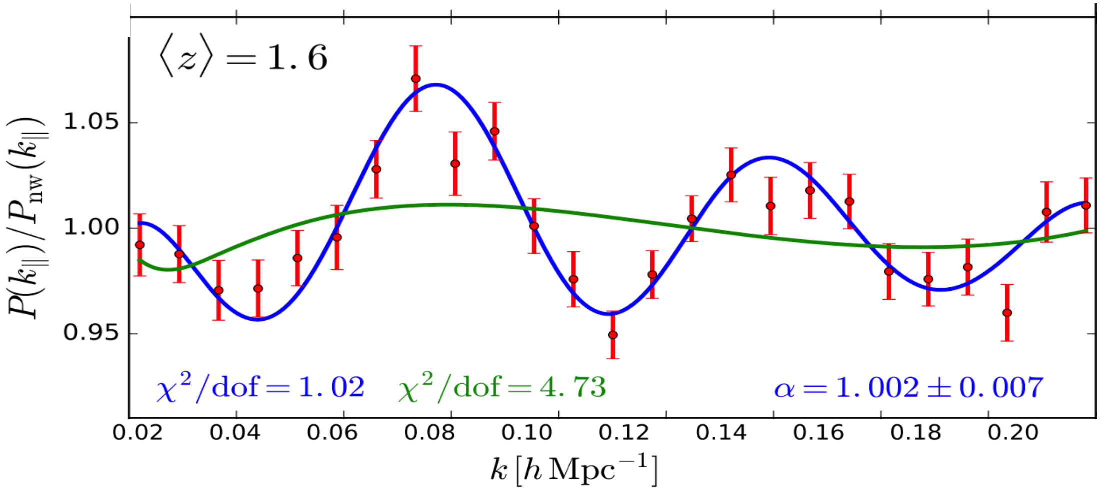


Villaescusa-Navarro, Alonso, MV 2017

Baryonic Acoustic Oscillations in 21cm IM

- SKA estimate: H(z) measured at sub-percent level up to z=2.5
- Made with mask, and foregrounds removal
- And realistic treatment of instrument noise

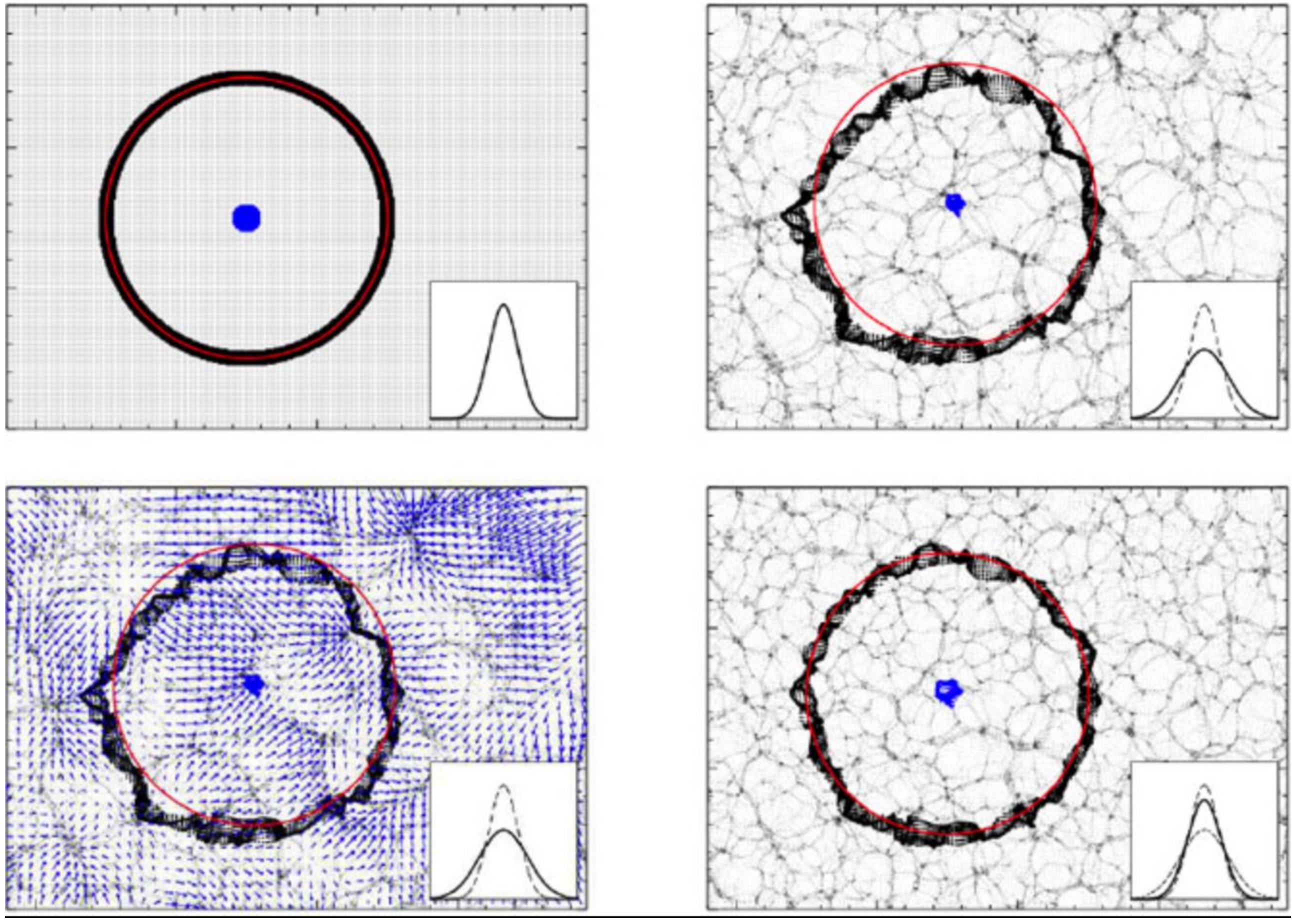




z range	$\langle z \rangle$	mask	σ_α (C)	(C+N)	(C+N+FG)
[0.36-0.75]	0.6	no	1.008 ± 0.016	1.008 ± 0.016	1.007 ± 0.016
		yes	1.006 ± 0.020	1.006 ± 0.021	1.006 ± 0.024
[0.75-1.26]	1.0	no	0.996 ± 0.010	0.997 ± 0.011	0.996 ± 0.011
		yes	0.997 ± 0.012	0.997 ± 0.013	0.998 ± 0.015
[1.26-1.98]	1.6	no	1.001 ±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

Reconstruction of the BAO peak with pixels



- For galaxies, undoing non-linearities with Zeldovich to sharpen the BAO peak
- How would this work for pixels?
- Even less computationally demanding, pixels are moved… and local density estimates (grid based) are for free

Obuljen, Villaescusa-Navarro, Castorina, MV 2017

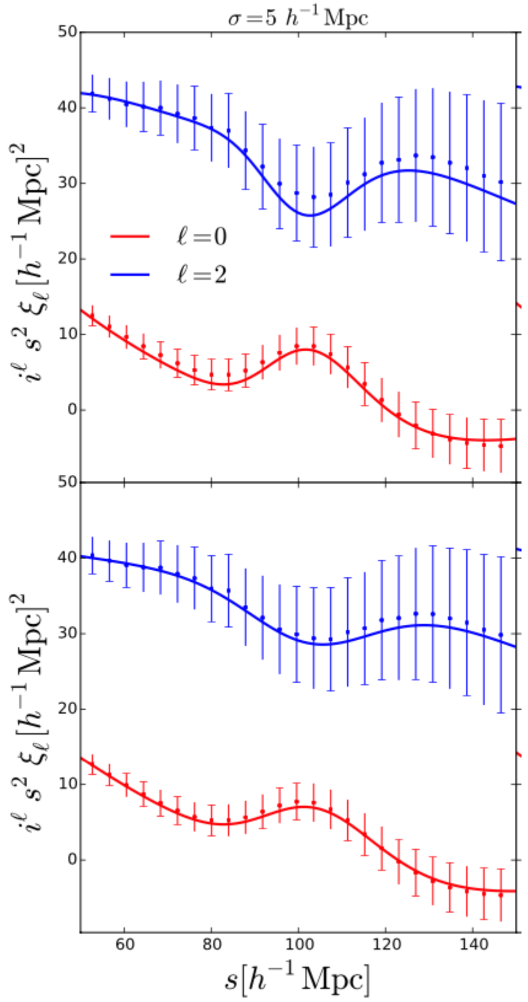
Reconstruction of the BAO peak with pixels

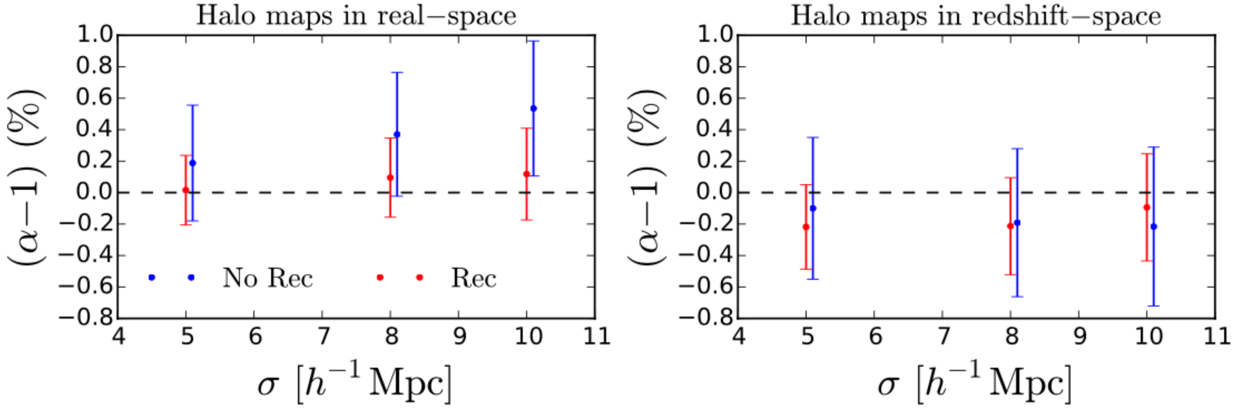
Matteo Viel

$$\alpha_{||} \equiv \frac{H_f r_{d,f}}{H r_d} \quad \text{and} \quad \alpha_{\perp} \equiv \frac{D_A r_{d,f}}{D_{A,f} r_d}$$

- Errors on α decreases by 40% after reconstructon, and this depends on the angular resolution

$$\alpha = \alpha_{||}^{1/3} \alpha_{\perp}^{2/3}$$

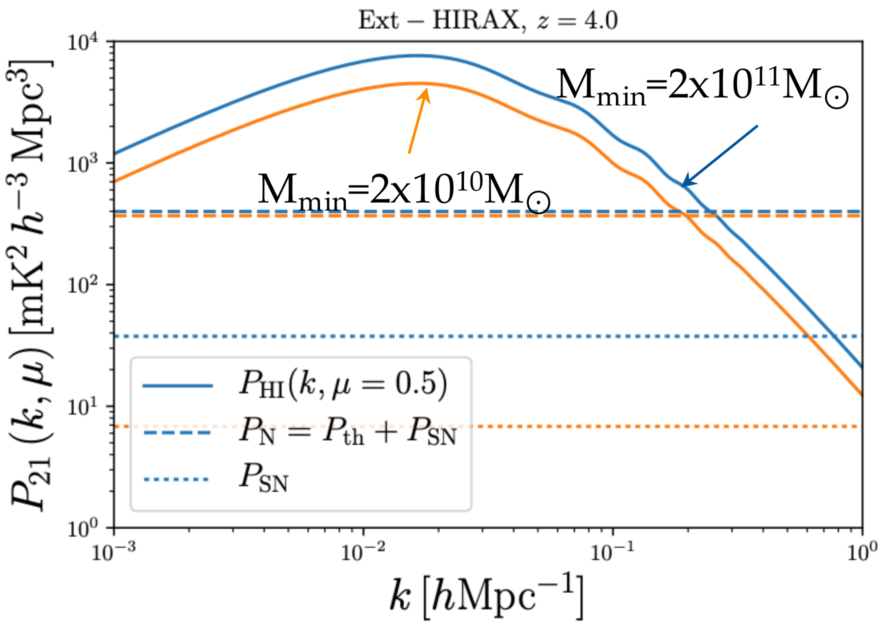


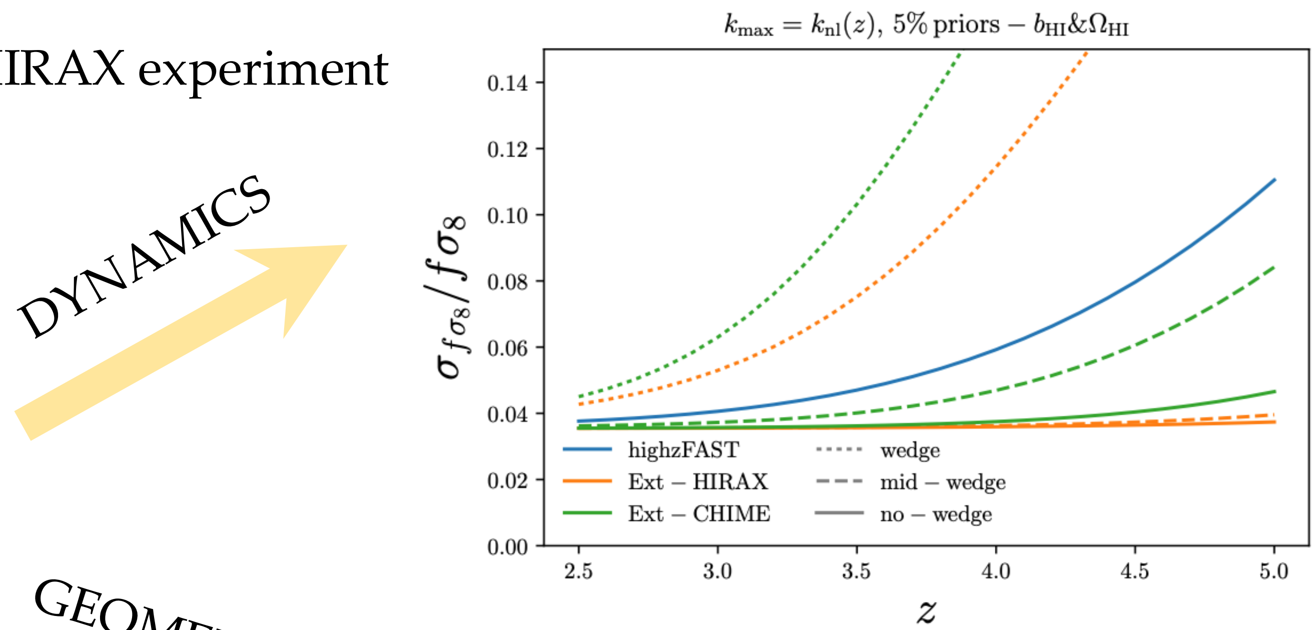


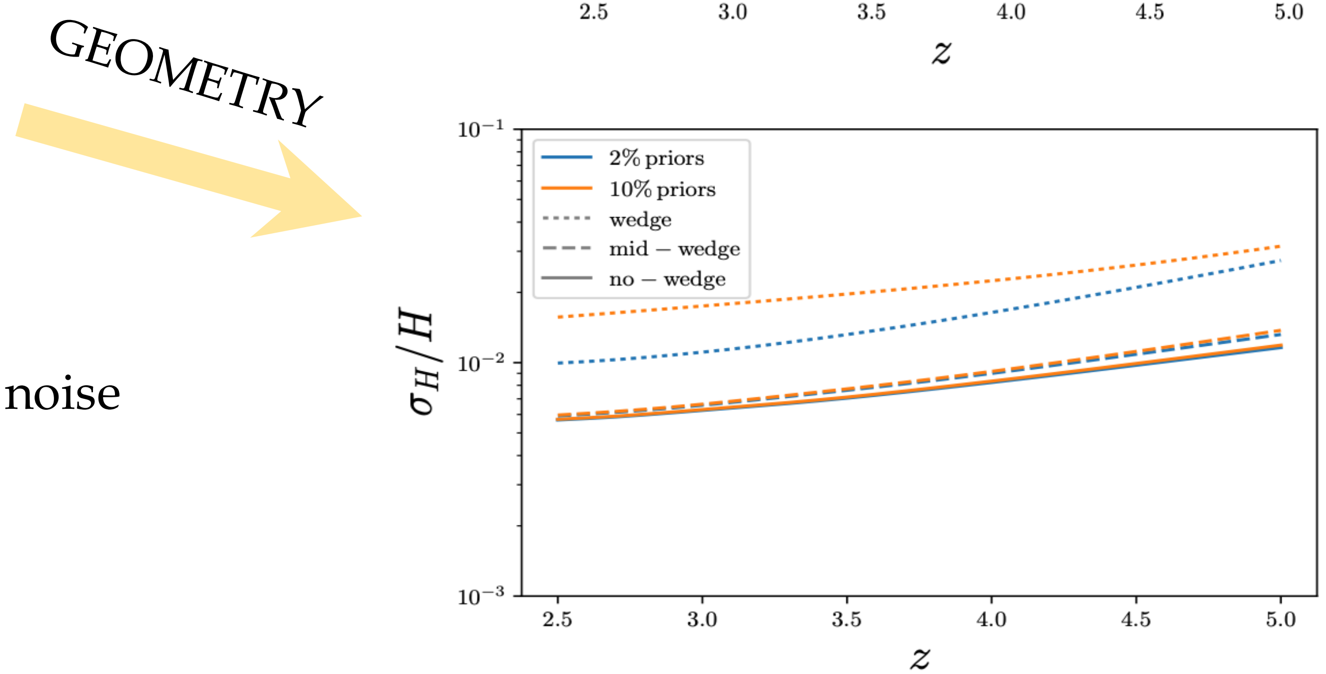
Obuljen, Villaescusa-Navarro, Castorina, MV 2017

Post-reionization cosmology with IM experiments

Fisher matrix analysis of future "extended" HIRAX experiment



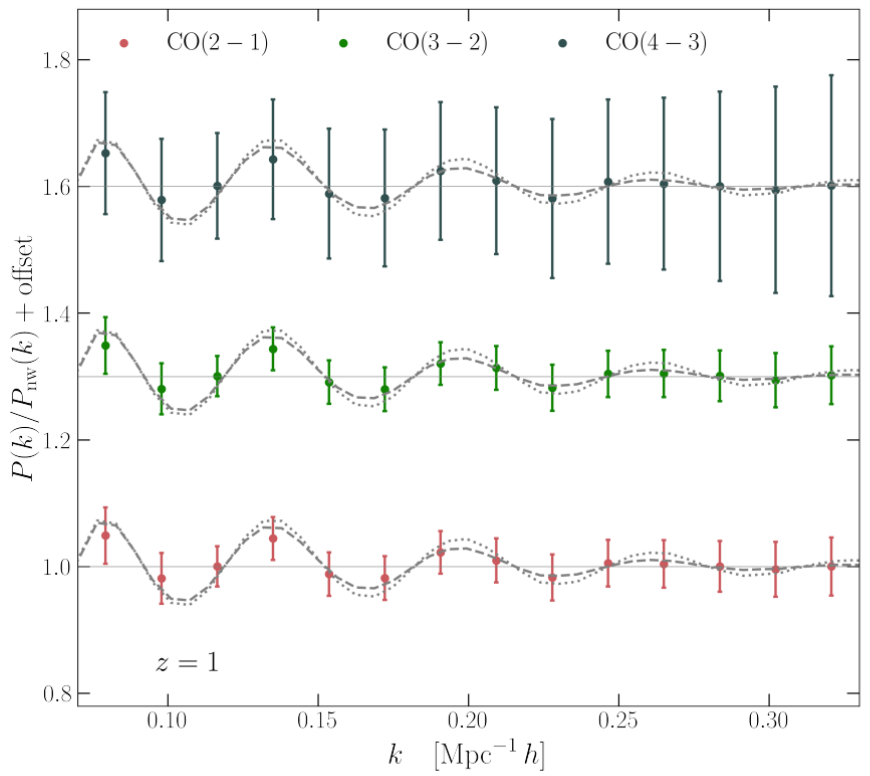




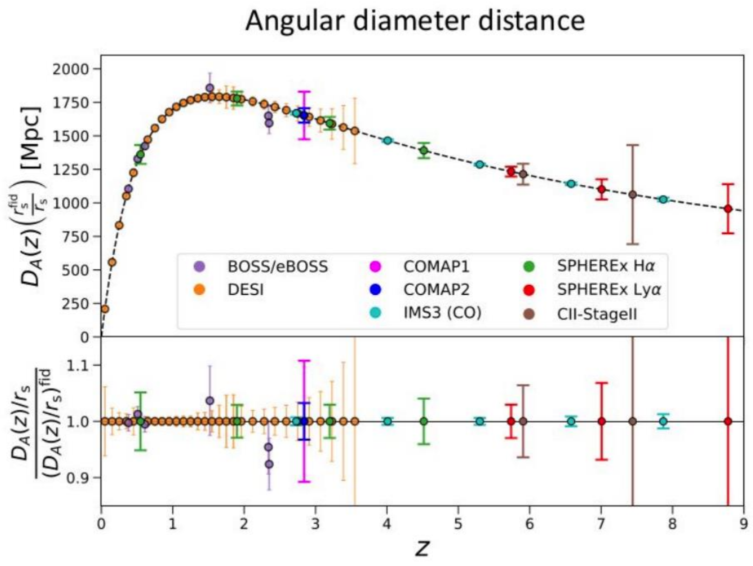
Considering also the wedge, beam, noise
Shot noise of the tracer

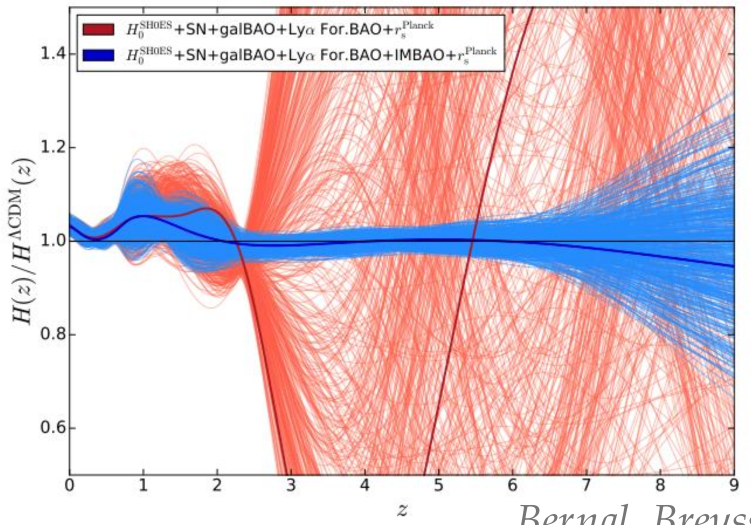
Obuljen, Castorina, Villaescusa-Navarro, MV 2018

BAO with LIM experiments



Moradinezhad Dizgah, Nikakthar, Keating, Castorina 22



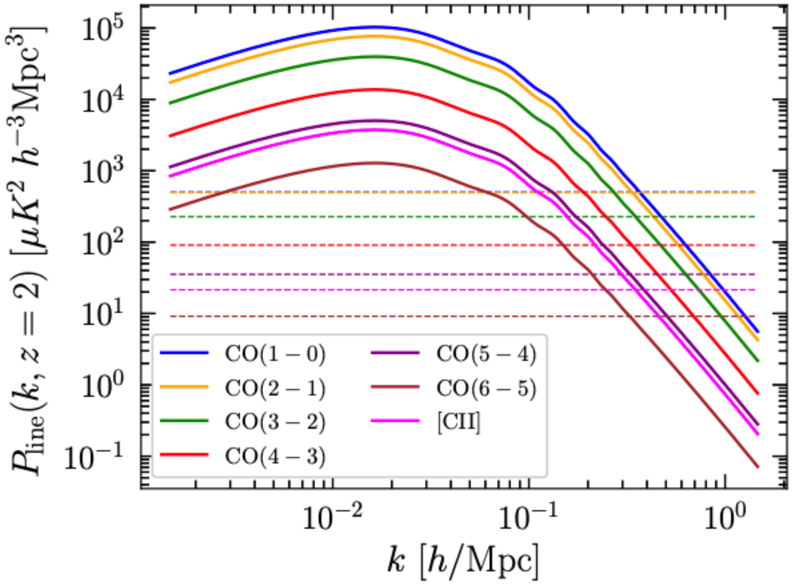


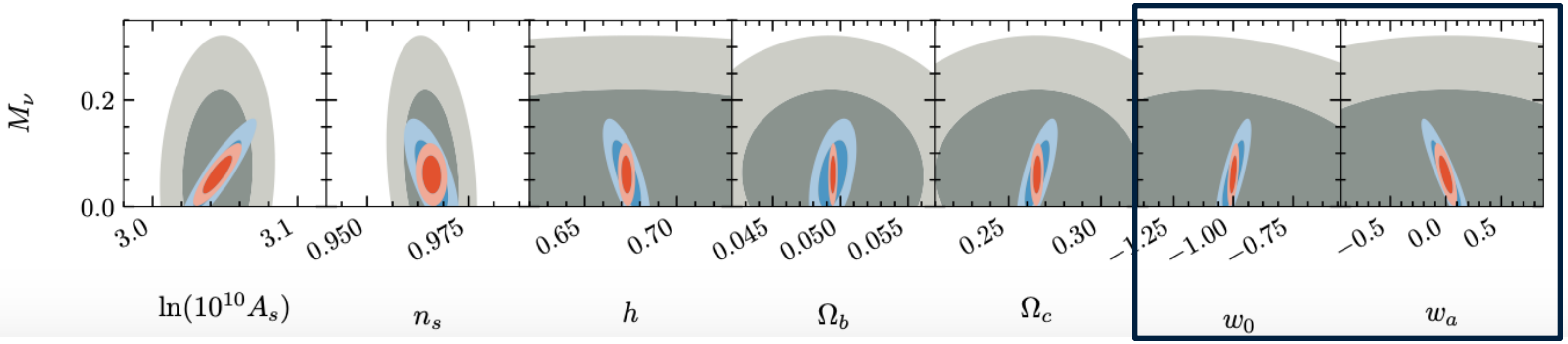
Bernal, Breysse, Kovetz 2019

Post-reionization cosmology: neutrino masses from CO

Matteo Viel

- Realistic Fisher-matrix based forecasts for CO and [CII] in a wide redshift range z=[0,12]
- Crucial different degeneracies pattern for LIM w.r.t. CMB data
- Especially true in the extended Mν – CPL model
- Very promising: 40% of the sky, with 10^8 spectrometer hours and no removal of interlopers could provide $\sigma(N_{eff})$~0.023 and $\sigma(M_\nu)$~13 meV



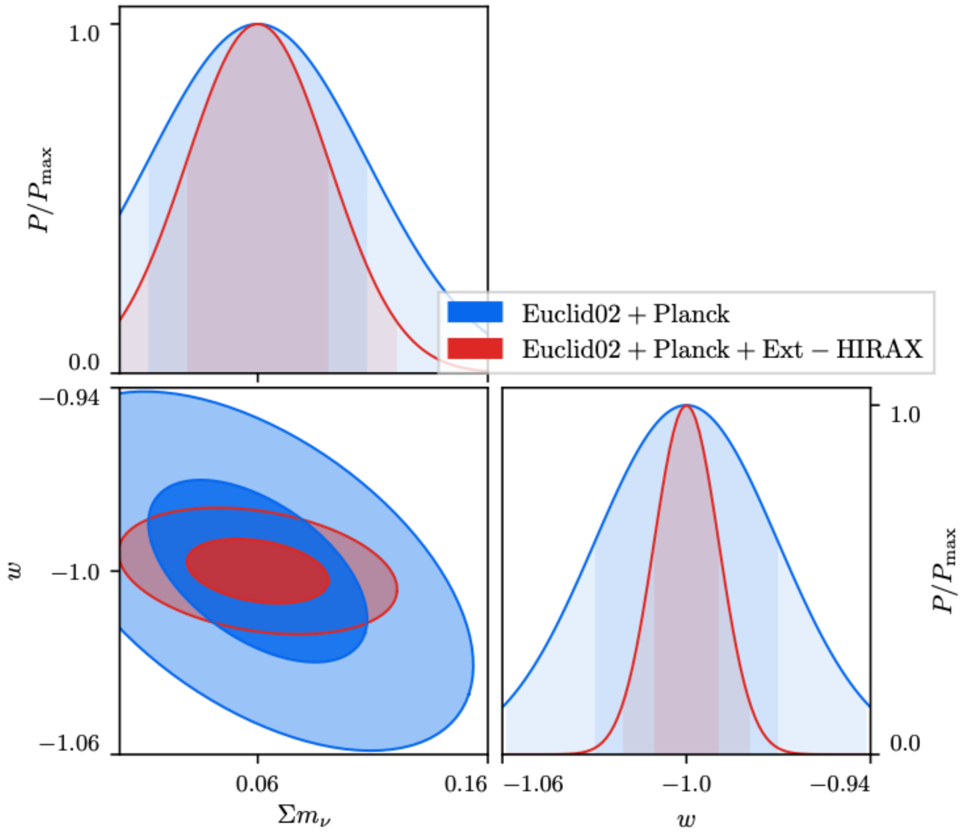


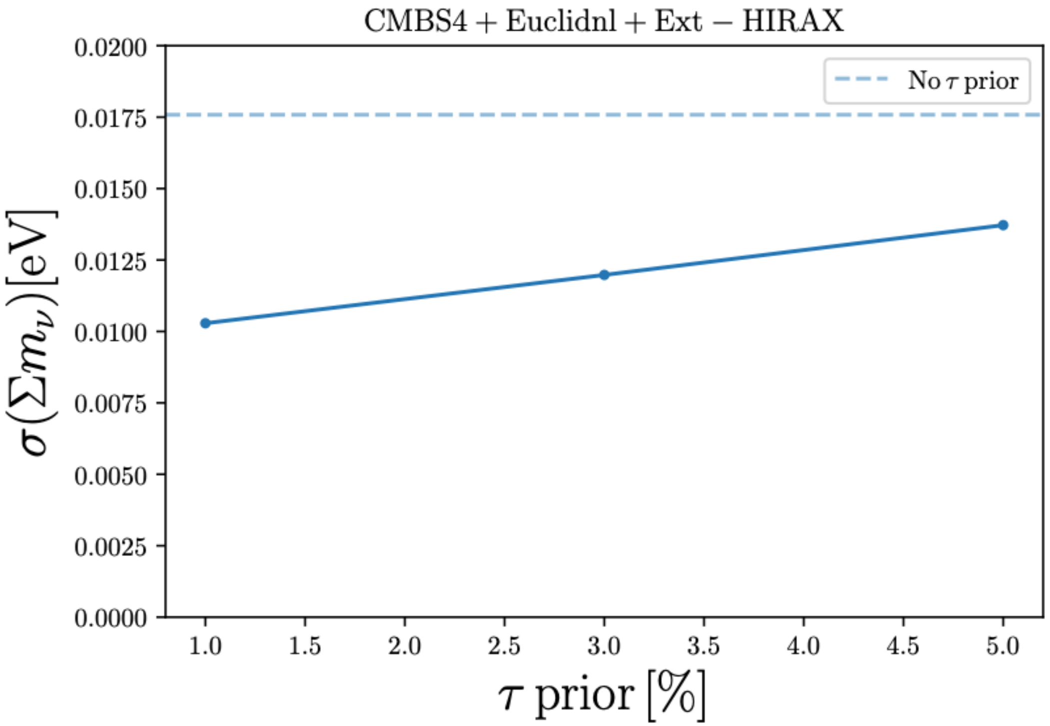
Moradinezahd Dizgah+2022

Post-reionization cosmology: neutrino masses

Matteo Viel

Obuljen, Castorina, Villaescusa-Navarro, MV 2018



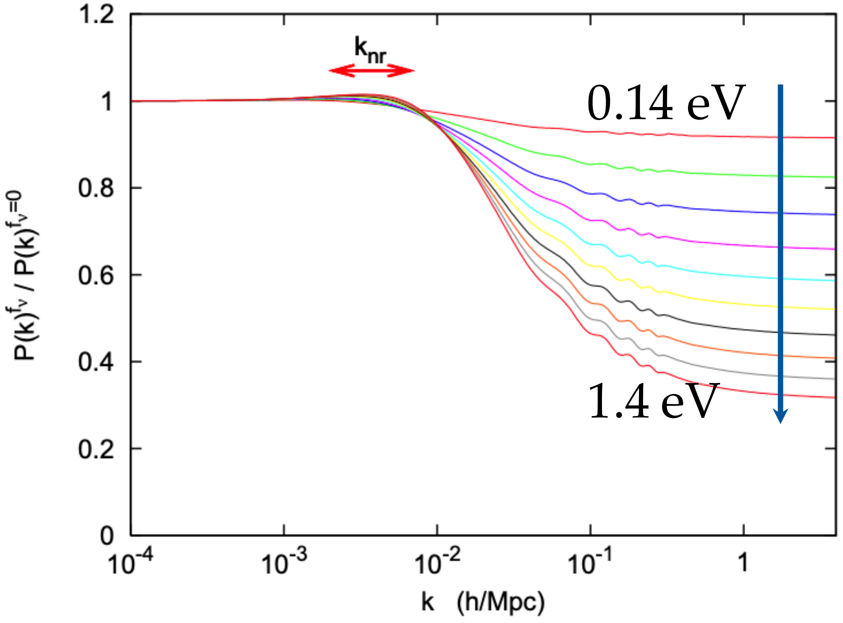


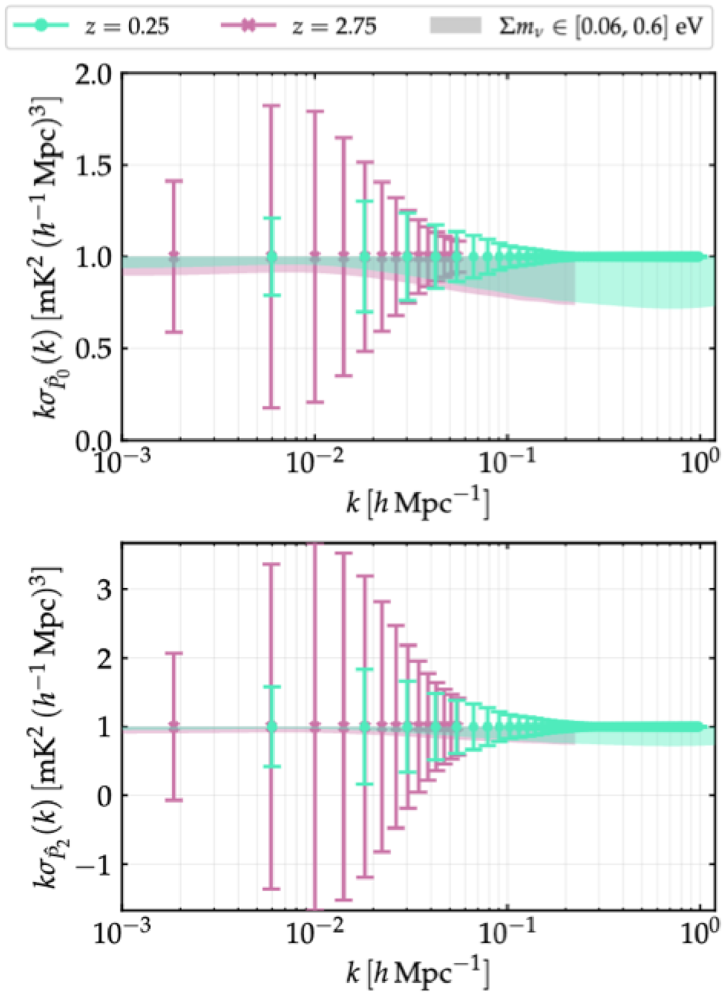
Prior on the CMB optical depth somehow fixes large scale amplitude inferred from the CMB… and helps measuring neutrino free streaming

Post-reionization cosmology: neutrino masses - II

Matteo Viel

Neutrino free streaming





21cm power
SKA mid
Monopole and quadruopole

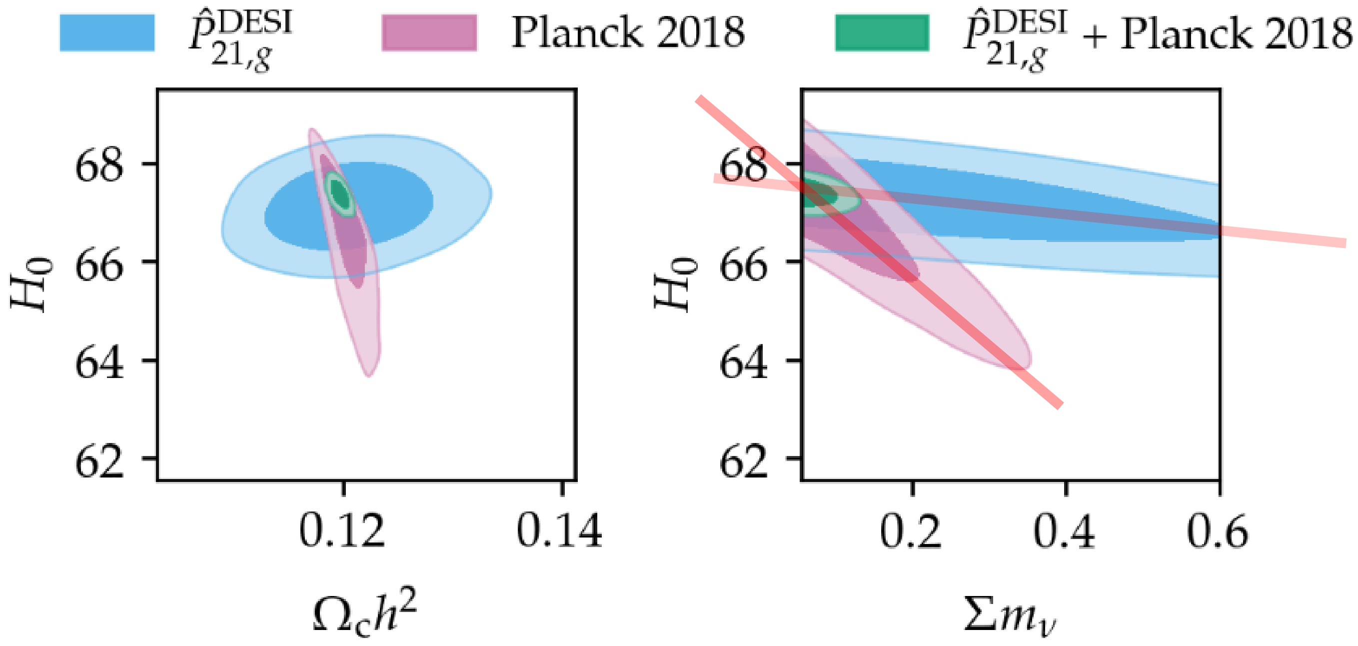
Autieri, Berti, Spinelli, Haridasu, MV (2025)

Post-reionization cosmology: neutrino masses - III

Matteo Viel

$$P_{21,\mathrm{g}}(z,k,\mu) = \overline{T}_\mathrm{b}(z)\left(b_\mathrm{HI}(z) + f_\mathrm{CDM+b}(k,z)\mu^2\right)\left(b_\mathrm{g}(z) + f_\mathrm{CDM+b}(k,z)\mu^2\right) P_\mathrm{CDM+b}(z,k,\mu),$$

Note the different degeneracies



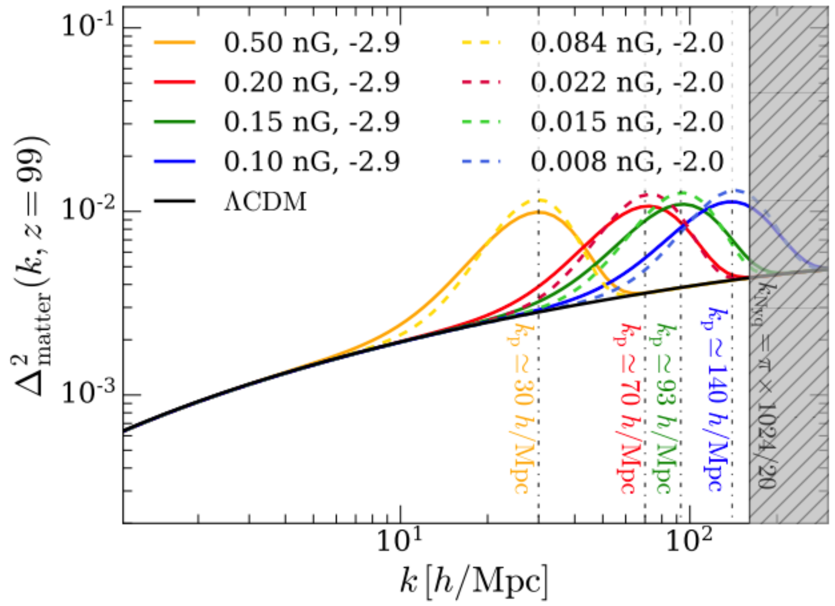
Likelihoods	$\Sigma m_\nu^{\mathrm{fid}} = 0.06\,\mathrm{eV}$	$\Sigma m_\nu^{\mathrm{fid}} = 0.1\,\mathrm{eV}$
$\hat{P}_0 + \hat{P}_2$	< 0.287	< 0.317
+ nuisances	< 0.425	< 0.452
Planck 2018		
$+ \hat{P}_0 + \hat{P}_2$	< 0.105	0.098 ± 0.022
+ nuisances	< 0.126	< 0.151
Planck 2018		
$+ \hat{P}^{\mathrm{DESI}}_{21,\mathrm{g}}$	< 0.116	$0.099^{+0.020}_{-0.033}$
+ nuisances	< 0.155	< 0.177
Planck 2018		
$+ \hat{P}^{\mathrm{Euclid}}_{21,\mathrm{g}}$	< 0.117	$0.100^{+0.021}_{-0.032}$
+ nuisances	< 0.156	< 0.180

- Cross-correlation data alone cannot constrain neutrino masses.
- When combined with CMB data, gives constraints competitive to the ones obtained with auto-power.

Autieri, Berti, Spinelli, Haridasu, MV (2025, arXiv:2504.18625)

Primordial Magnetic Fields and LIM

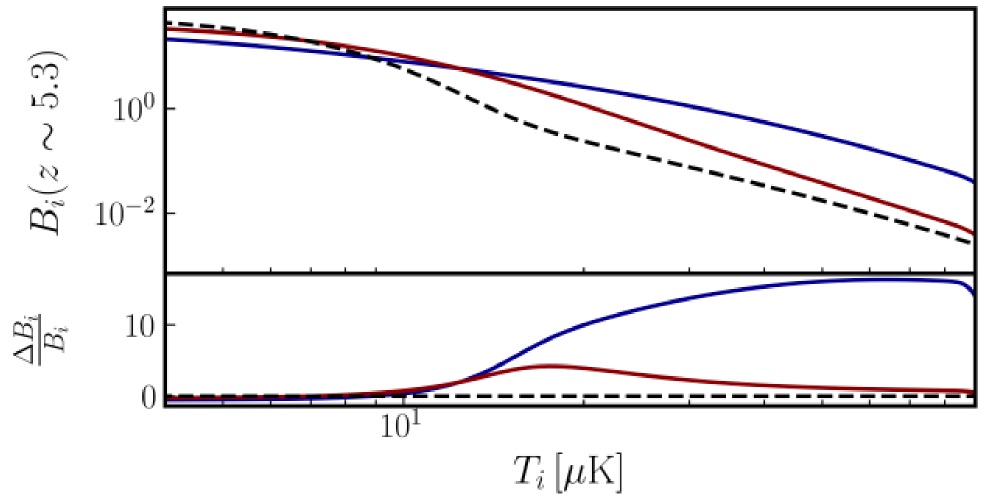
Increase of power in total matter power
Spectrum due to Lorentz force affecting
Baryons' clustering



From the forest: B ~ 0.2 nG "hint"

Impact on VID
COMAP EoR survey + other instruments at z=2-3

$$B_i = N_{\rm vox} \int_{T_i}^{T_i+\Delta T_i} \mathcal{P}_{\rm tot}(T)\, dT,$$



From CO: IM B ~ 0.006 nG can be probed

Pavicevic, Irsic, MV+ (2025) arXiv: 2501.06299

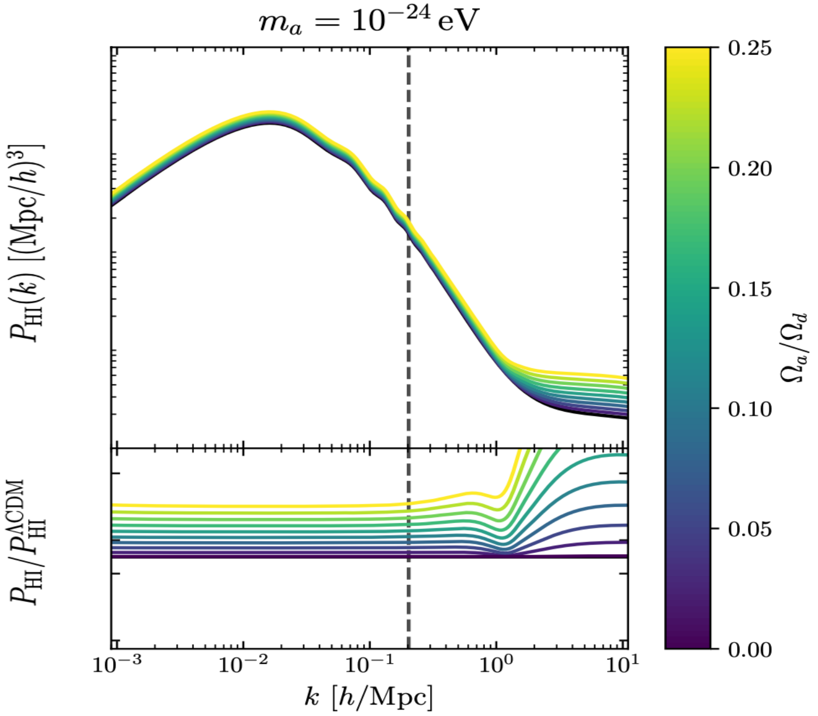
Adi, Libanore, Crutz, Kovetz 2024

Summary

- Post-reionization Universe: a new place to test structure (and galaxy) formation and probe fundamental physics
- Access to relatively small scales k~1 *h*/Mpc at high redshift (cool scientific cases)
- 1D radial BAO will constrain geometry
- Power spectrum will constrain growth (and thus neutrino masses)
- If auto-correlation is difficult, then cross-correlation will boost the signal and break degeneracies
- New statistics/methods
- Realistic mocks' production: there is a lot to learn

Axions

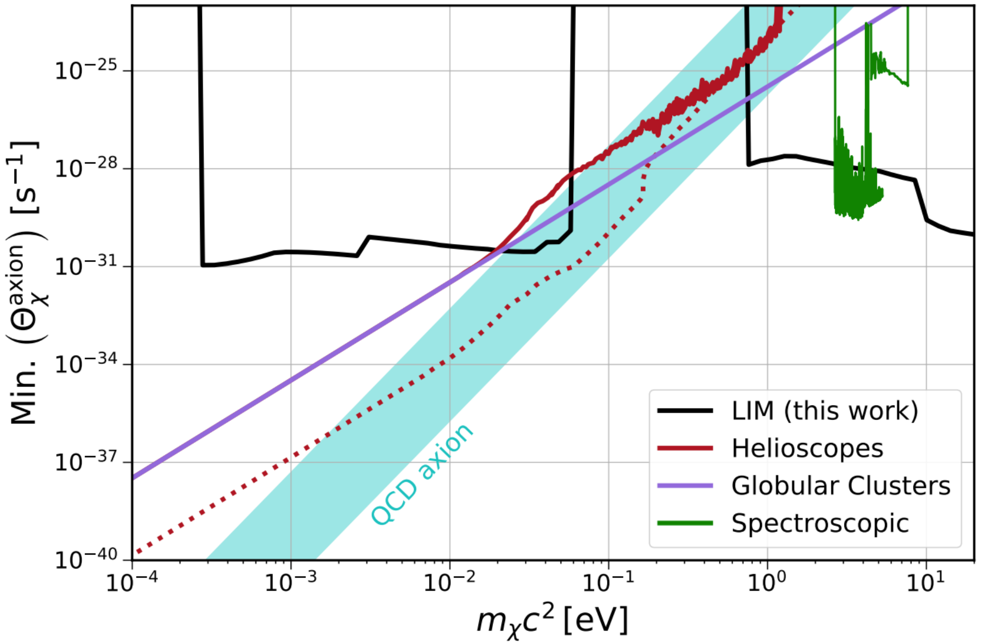
Axion as a fraction of DM



Impact on matter power spectrum

Detecting DM decay as a line interloper

$$\Theta_\chi \equiv f_\chi f_{\gamma\gamma} f_{\rm esc} \Gamma_\chi$$



Energy injection – estimate from COMAP+HERA+CHIME+HIRAX

Bauer+20

Bernal, Caputo, Kamionkowski 21