HYDROGEN AS A COSMOLOGICAL PROBE

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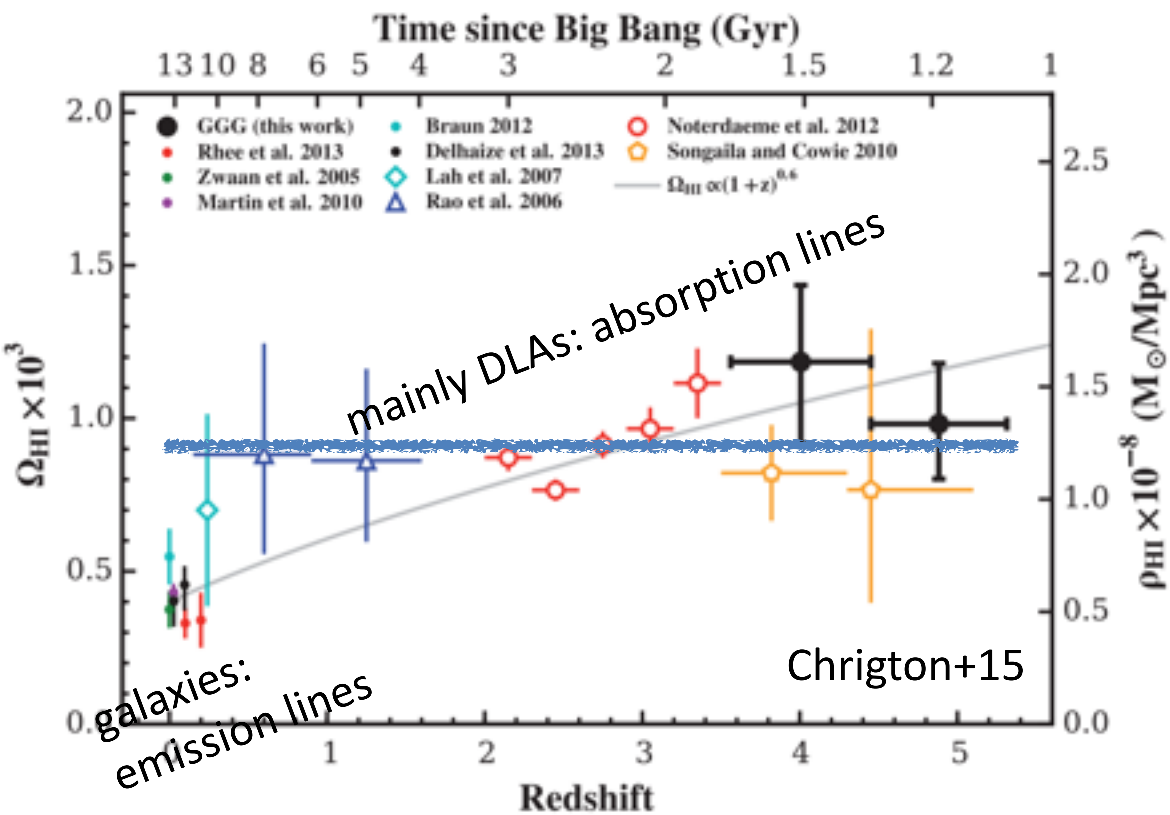
Neutral Hydrogen (HI) as a cosmic tracer

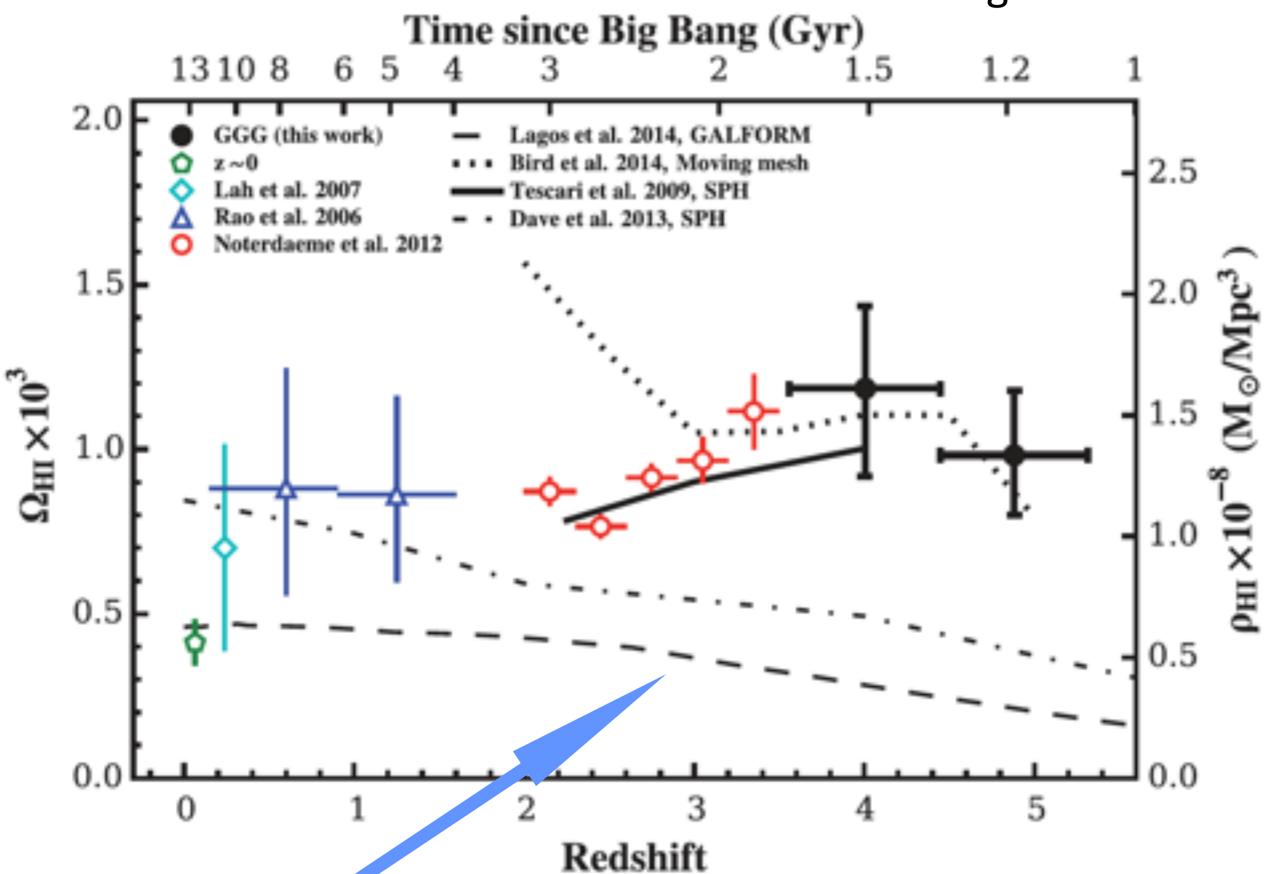
$$\Omega_{\rm HI} \sim \Omega_{\nu} \sim \Omega_{\star}$$



- **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.

Neutral Hydrogen (HI) as a cosmic tracer - II

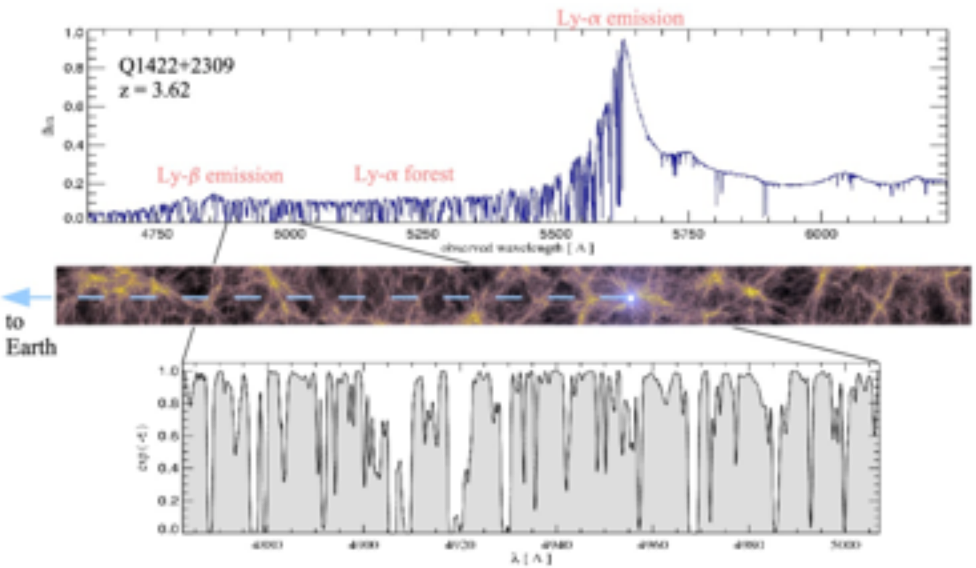
Chrigton+15

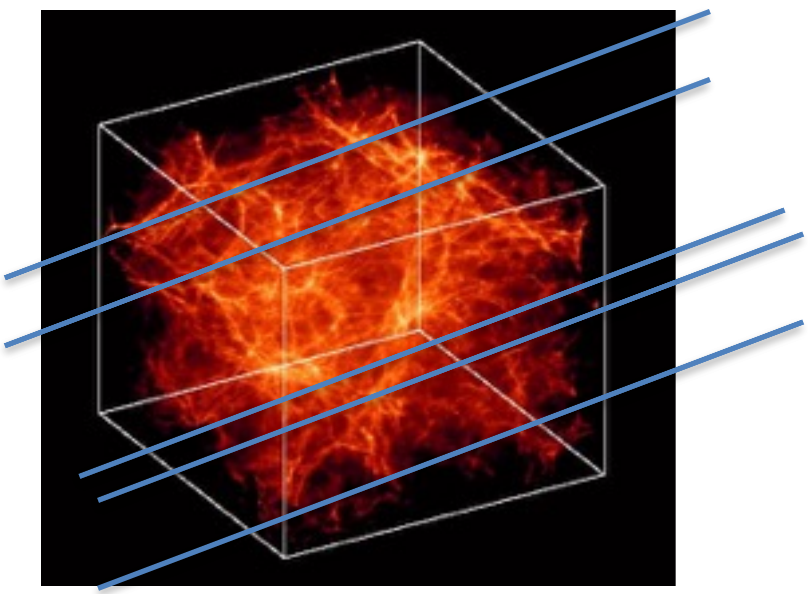


“typical" semi-analytical galaxy formation trend

- Fitting this simple statistics is already challenging for model builders: both SAMs or hydro sims do require some **fine tuning**.
- **Post processing** is needed (i.e. neutral hydrogen self shielding, galactic feedback, radiative transfer, etc.) and also accurate tests of numerical convergence.

The Lyman-alpha forest





- **Intergalactic medium:** filaments at low density (outside galaxies) - distances spanned 0.1-100 Mpc/h

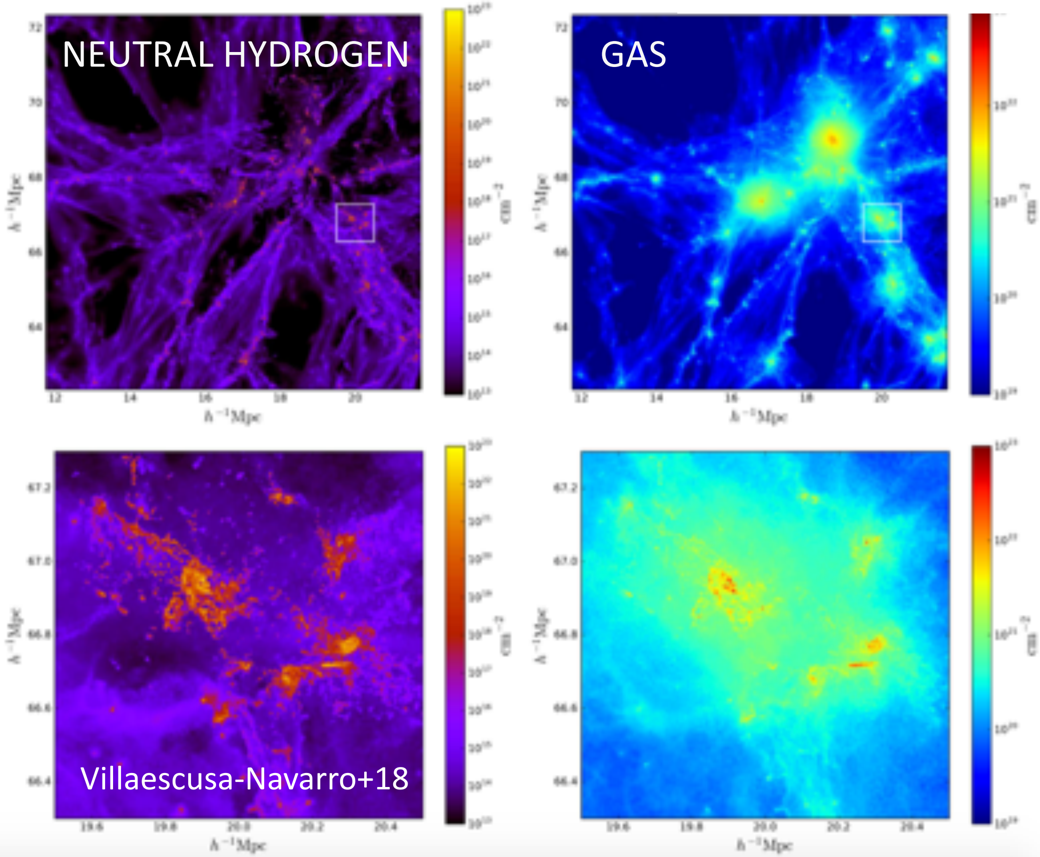
- Lyman-alpha forest its the main manifestation of the IGM

- High redshift observable, 1D projected power (but also 3D)

Intensity mapping

Linear theory model:

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



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

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

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

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

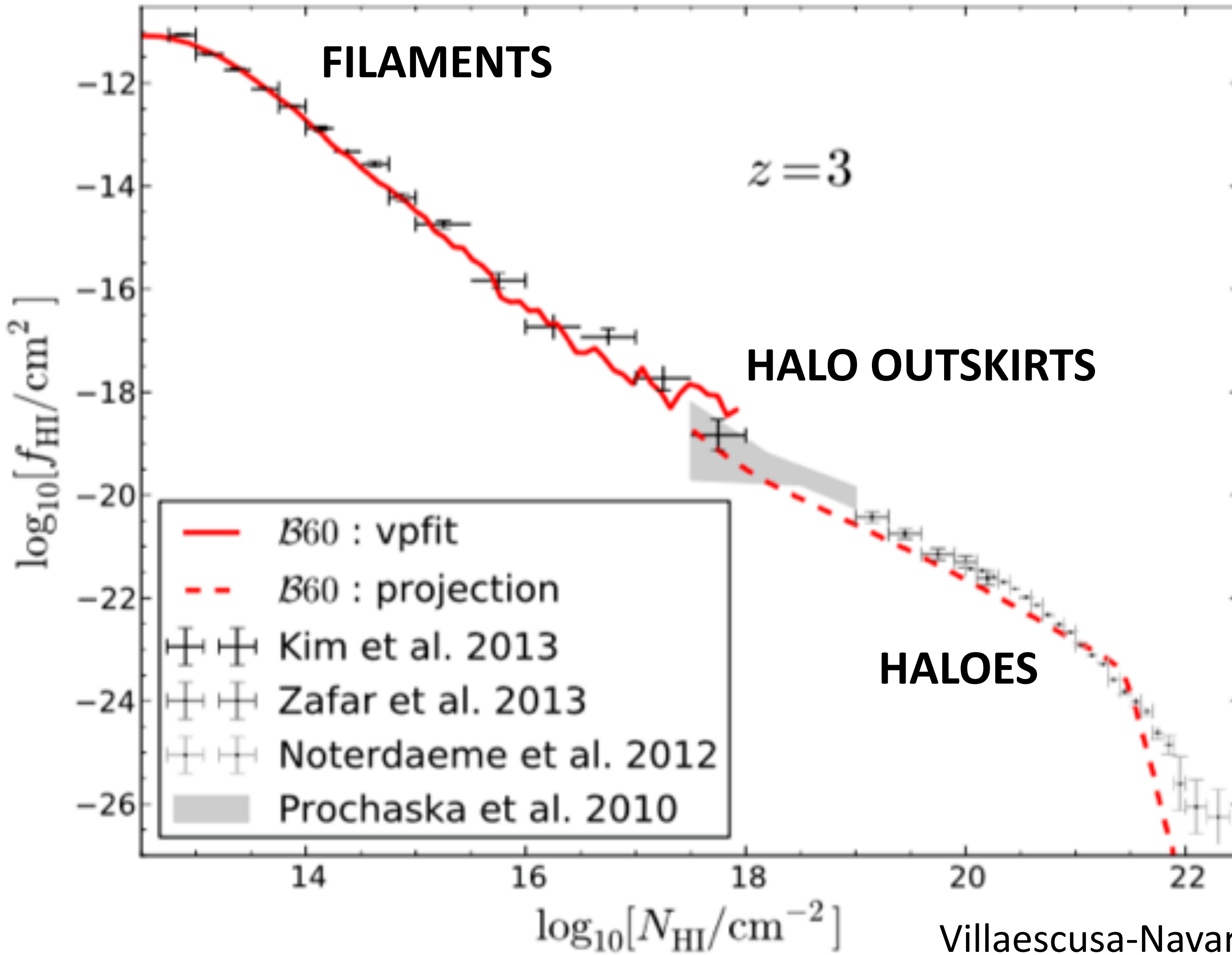
$$M_{\mathrm{H\,I}}(M,z) = M_0\left(\frac{M}{M_{\mathrm{min}}}\right)^\alpha \exp(-(M_{\mathrm{min}}/M)^{0.35}).$$

M_{min} decreases with redshift
alpha increases with redshift

- degeneracy between b_{HI} and 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)
- **IM signal:** main ingredient is the function $M_{HI}(M_{halo})$ with its scatter.

Towards a consistent model

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



Villaescusa-Navarro,MV+14

Some key questions

- Is there a consistent model of HI evolution from z=1100 to z=0?

  what are the observables we *cannot* fit?

- To what extent HI traces the underlying structure formation process?

  scale dependent bias? HI halo model? Shot noise?

- To what extent HI evolution is influenced by galaxy formation?

- Can we constrain feedback models?

- Is there evidence of new physics?

  NEUTRINO MASSES, GEOMETRY OF THE UNIVERSE, DARK MATTER NATURE?

COMPUTATIONAL METHODS

ABSORPTION

Investigated with hydro sims. down to M_{gas} = 1.e4 M_{sun}. (DM only not working).

High resolution needed, combination of low-res high-res very interesting for future and present 1D/3D flux power self consistent modelling.

Semi-analytical models could achieve a 10% agreement with observations.

Halo-model of forest absorption also developed (Irsic & McQuinn 17).

1D flux power fit: typically ~20 parameters fit done with MCMC with a likelihood built on **O(tens) accurate hydro sims.**

EMISSION

Investigated with hydrosims down to M_{gas} = 1.e6-7M_{sun}. DM only simulations also working and still used.

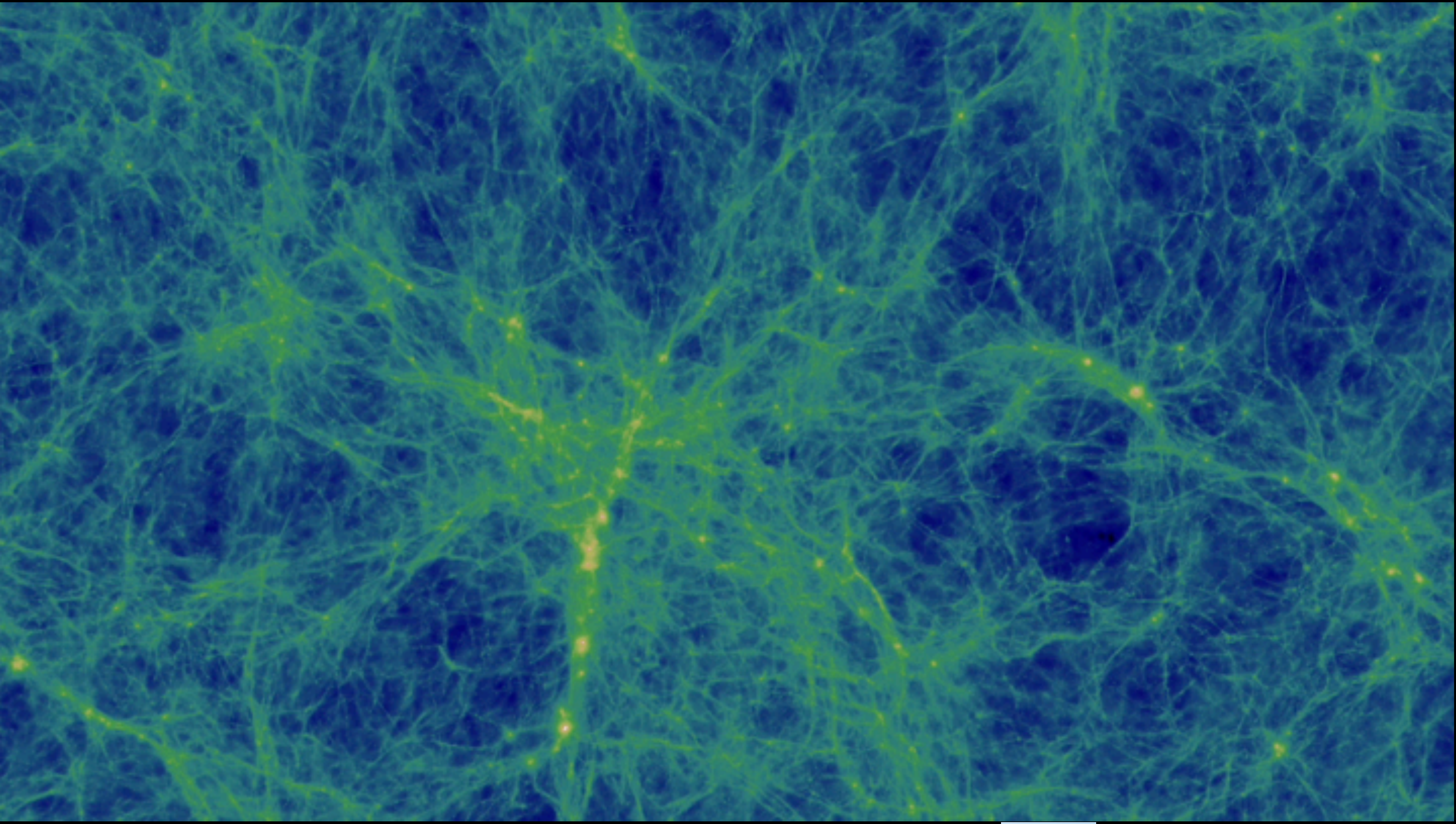
High res. hydro needed for accurate predictions on 21 cm power amplitude (shape is fine only with DM)

HI halo models quite used by the community (allow to explore parameter space faster).

Forecast made using Fisher Matrix. Very little data available that are either able to constrain some parameters of the model or get an evidence for LSS contribution with cross-correlation.

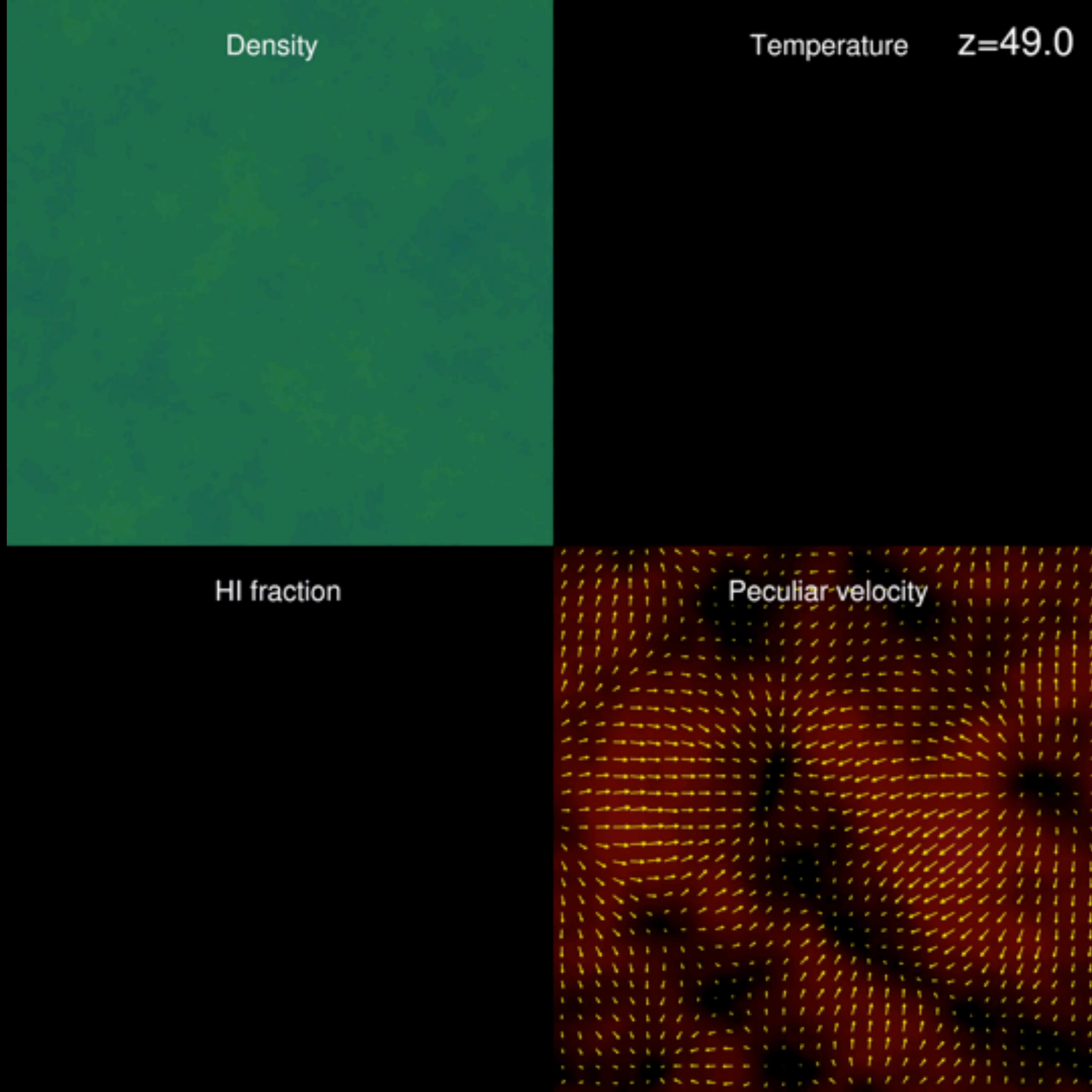
ABSORPTION

IGM SIMULATIONS



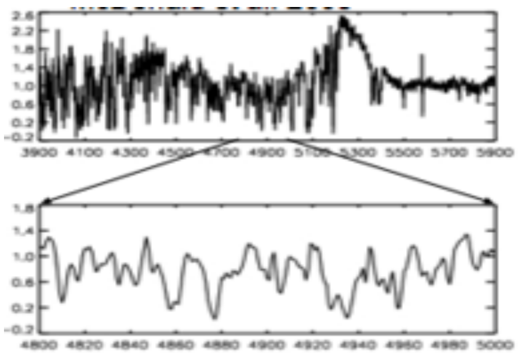
Bolton+17, Sherwood simulation suite (PRACE call: 15 CPU Mhrs)
Puchwen+19, New simulations (PRACE call: 23 CPU Mhrs)

New
PRACE runs
down to
M_gas=10^4 M_sun



COSMOLOGY WITH QSOs

BOSS/SDSS-III



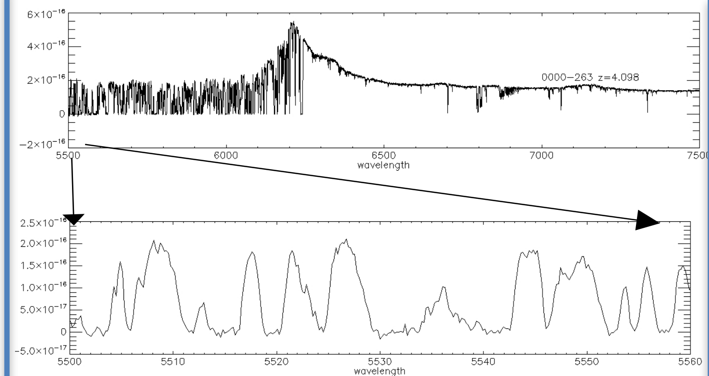
Low resolution BOSS and SDSS-III spectra S/N~2-3 – 160,000 spectra

Used to detect BAOs at z=2.3 and correlations in the transverse direction

Used to place stringent constraints on neutrino masses <0.12 eV

Busca+13, Slosar+14, Font-Ribera+14
Palanque-Delabrouille+15
Seljak+06, Baur+16, Yeche+17 etc.

XQ-100



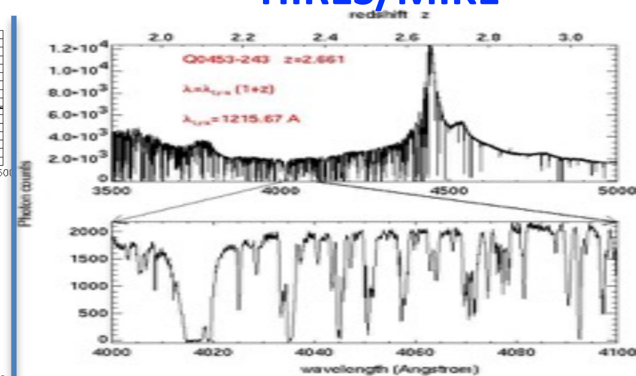
Medium resolution X-Shooter VLT spectra S/N ~ 30

100 spectra at z>3.5

Used to place stringent constraints on Warm Dark Matter in combination with high res. spectra

Irsic, MV+ 17a,17b
Lopez+16, Irsic+16

HIRES/MIKE



High resolution VLT or Keck spectra S/N ~100 – ~hundreds of spectra

Used for WDM, astrophysics of the IGM and galaxy formation, variation of fundamental constants

MV+05,08,13, ***Becker****+11*
Yeche+17, Garzilli+18 ,
Bosman+18

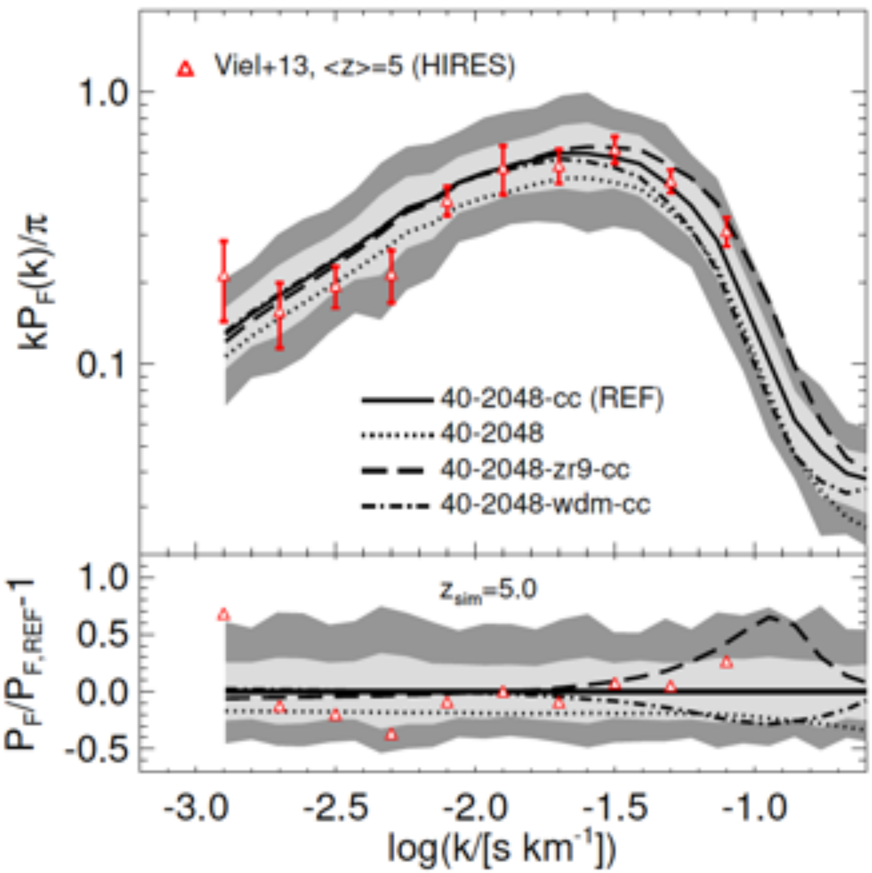
High vs low-z Lyman-alpha flux power

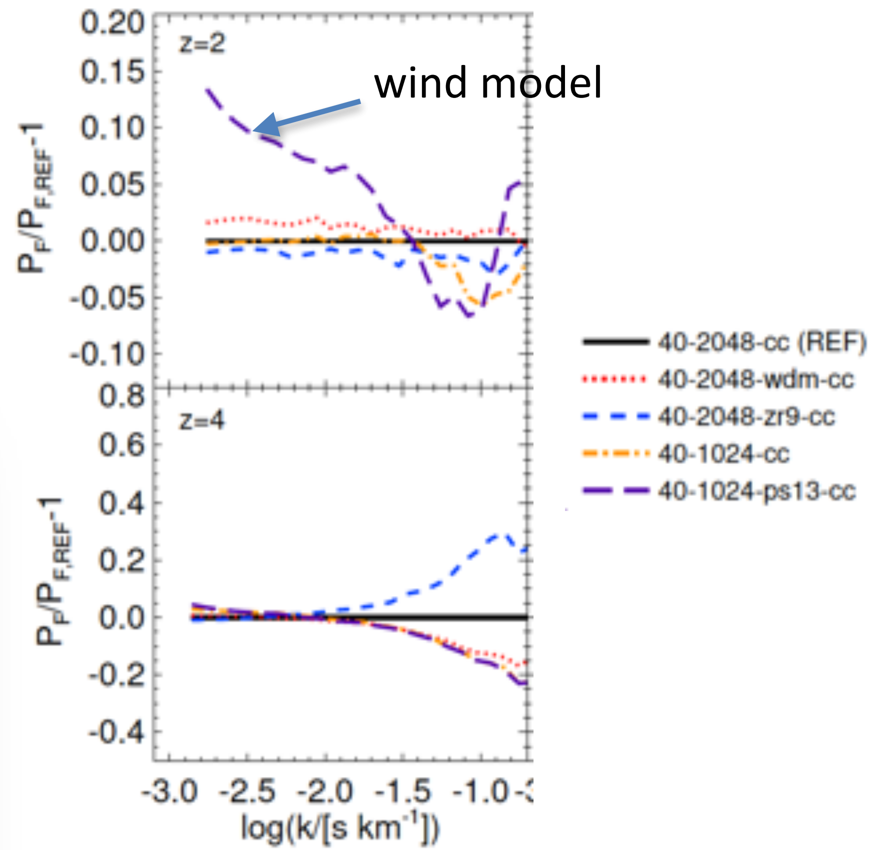
High redshift:
constraining reionization

Statistical error usually comparable or larger than known systematic errors

Low redshift:
constraining feedback

Known systematic errors usually larger than statistical errors





Lyman-alpha forest open issues

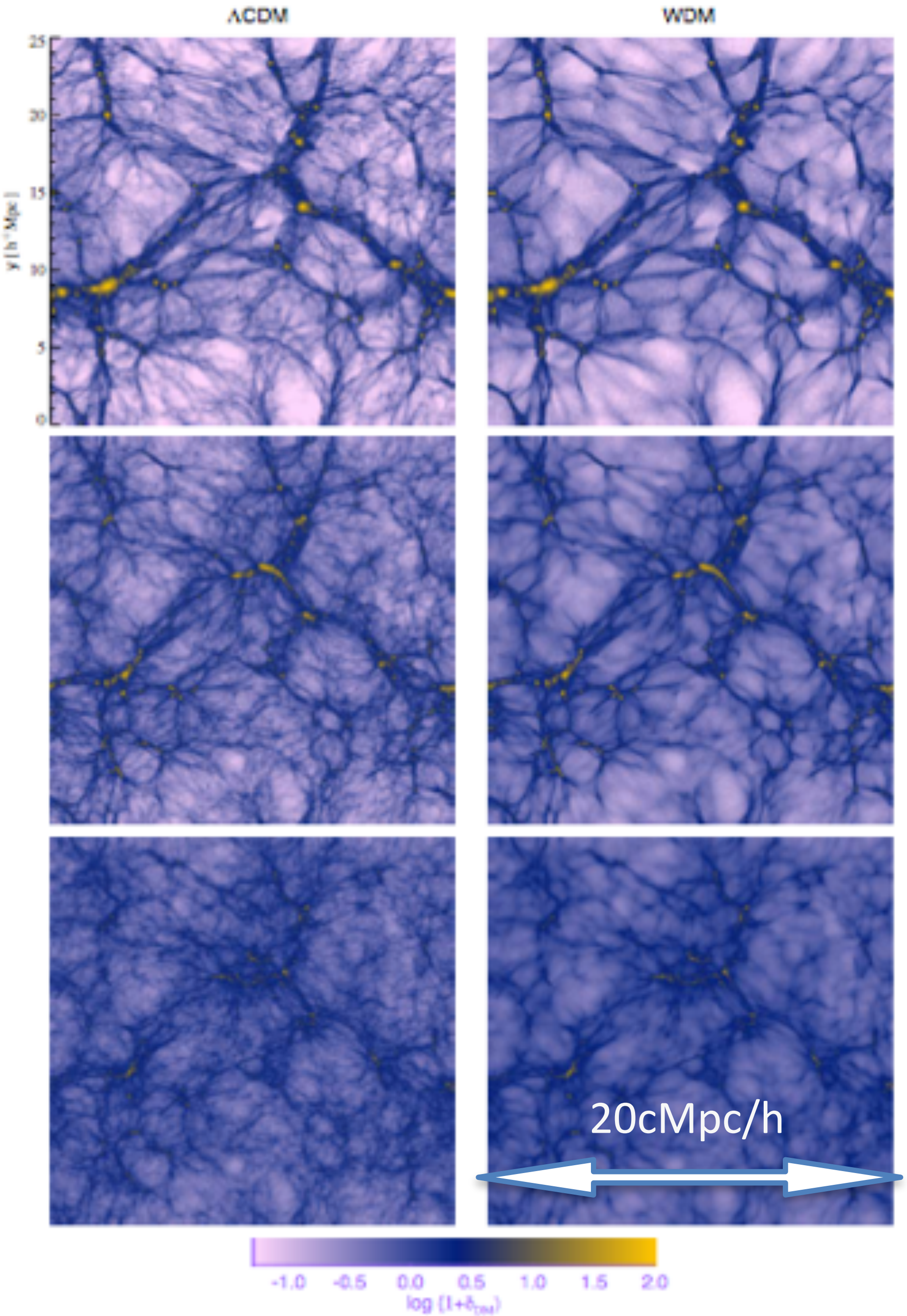
Overall broad consistency between LCDM model and Lyman-alpha flux statistics.

Several different groups running hydro sims for quantitative cosmological analysis of forest data (Lukic, Onorbe, Palanque-Delabrouille, etc.).

Critical areas for modelling/simulations:

1) high-redshift regime: UV/temperature fluctuations.
2) low and intermediate redshifts: galactic feedback, HeII reionization.
3) modelling several statistics at once (PDF, 1D, 3D, bispectrum) - self-consistent model of 3D and 1D flux power not addressed.
4) resolution under control @ k=0.1 s/km roughly scales of k ~ 10-20 h/Mpc @ z=2-6?

THE COSMIC WEB in WDM/LCDM scenarios



z=0

$$\frac{T_x}{T_\nu} = \left(\frac{10.75}{g_*(T_D)}\right)^{1/3} < 1$$

$$k_{\rm FS} = \frac{2\pi}{\lambda_{\rm FS}} \sim 5\,{\rm Mpc}^{-1}\left(\frac{m_x}{1\,{\rm keV}}\right)\left(\frac{T_\nu}{T_x}\right)$$

$$\omega_x = \Omega_x h^2 = \beta\left(\frac{m_x}{94\,{\rm eV}}\right)$$

$$\beta = (T_x/T_\nu)^3$$

z=2

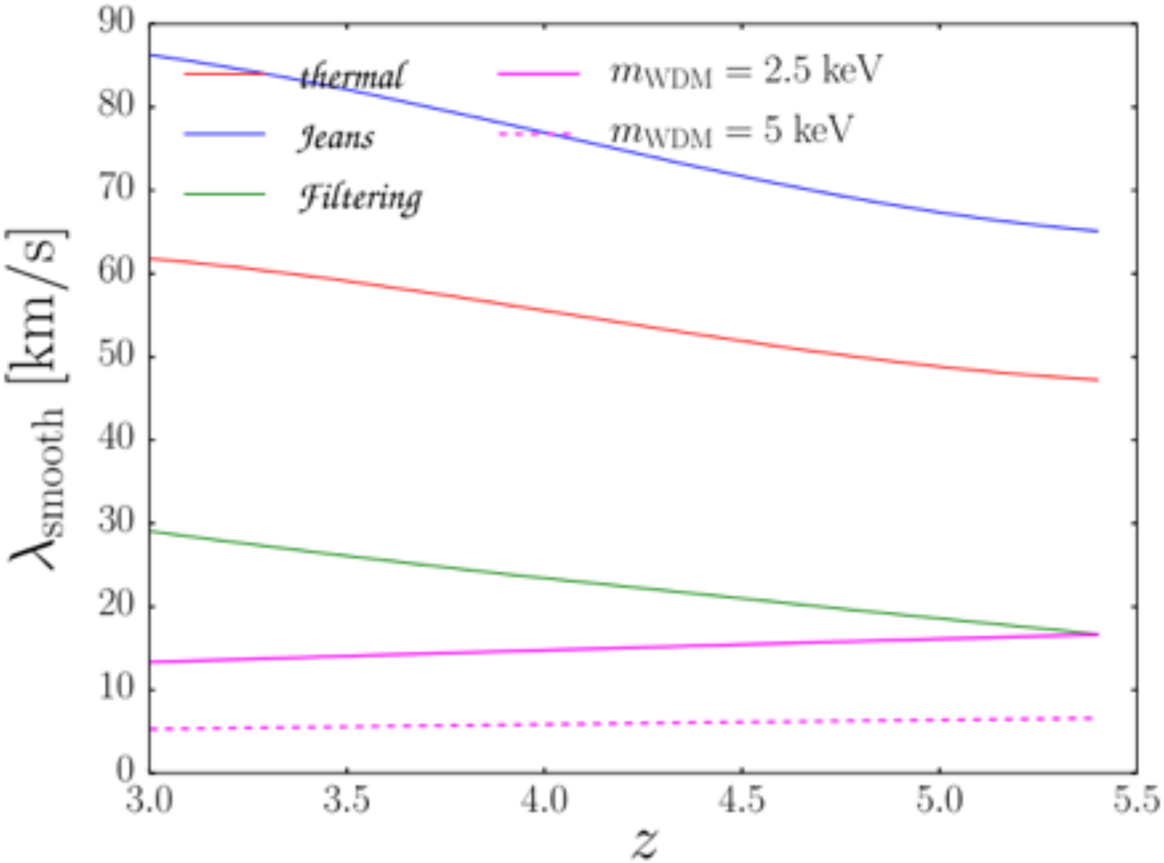
$$k_{\rm FS} \sim 15.6\frac{h}{\rm Mpc}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{4/3}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)^{1/3}$$

z=5

WARNING:
Numerical fragmentation is less of an issue for the Lyman-alpha forest flux, but still reaching convergence especially at high-z is demanding (voids contribute).

MV, Markovic, Baldi & Weller 2013
Markovic & MV, 2014

Smoothing scales

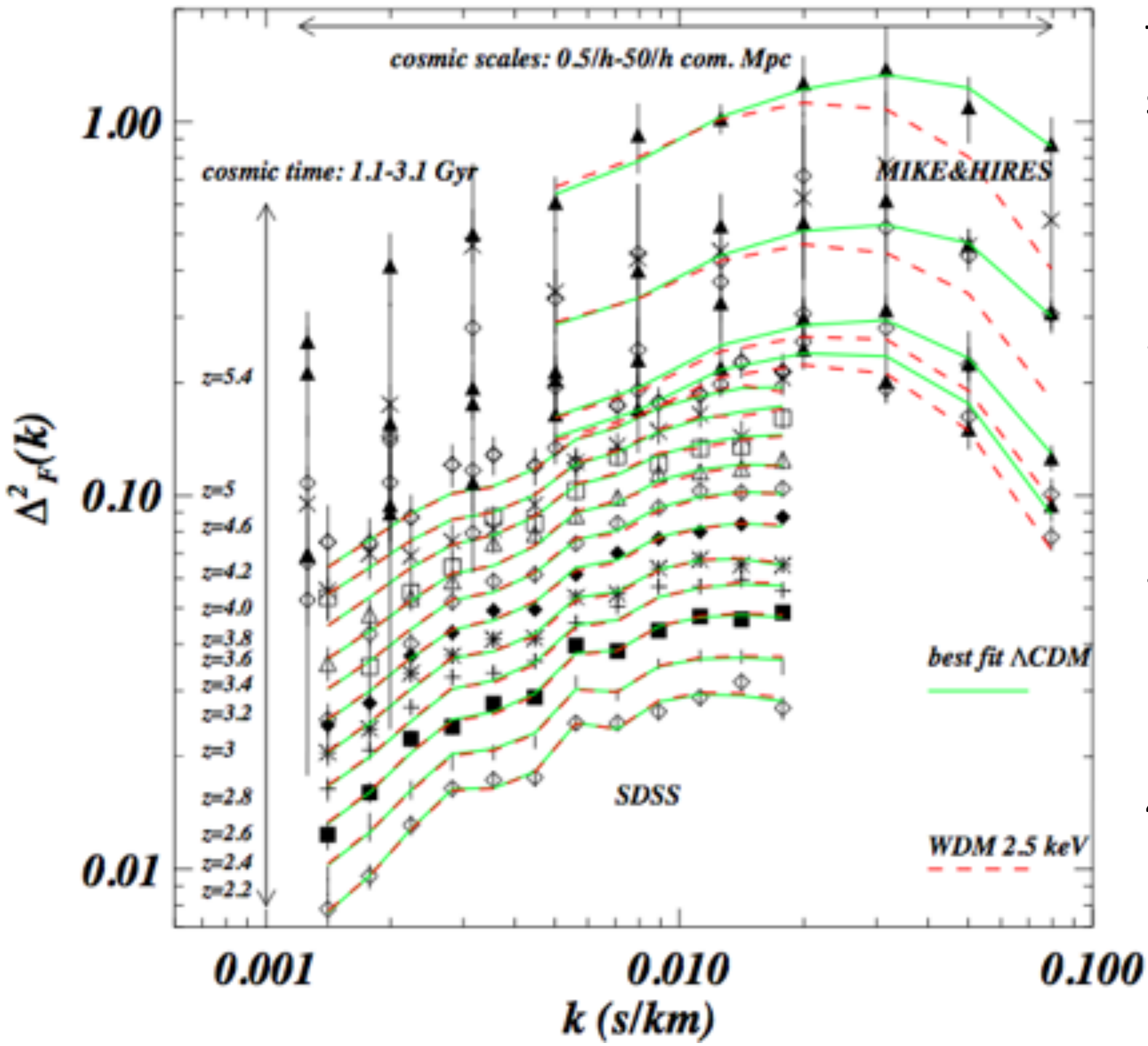


Irsic,MV+17

- Different physical scales (on top of instrumental resolution) affect the power spectrum cutoff:
- **thermal**: instataneous temperature at that redshift;
- **Jeans:** scale due to gas pressure;
- **filtering scale**: depends on all the previous thermal history;
- WDM cutoffs are basically redshift independent
- Constraints are obtained from a full shape of the 1D fux power.

STATUS in 2013

$M_{\text{thermal WDM}} > 3.3$ keV (2σ C.L.)



This lower limit is derived under some assumptions

1) Bayesian analysis

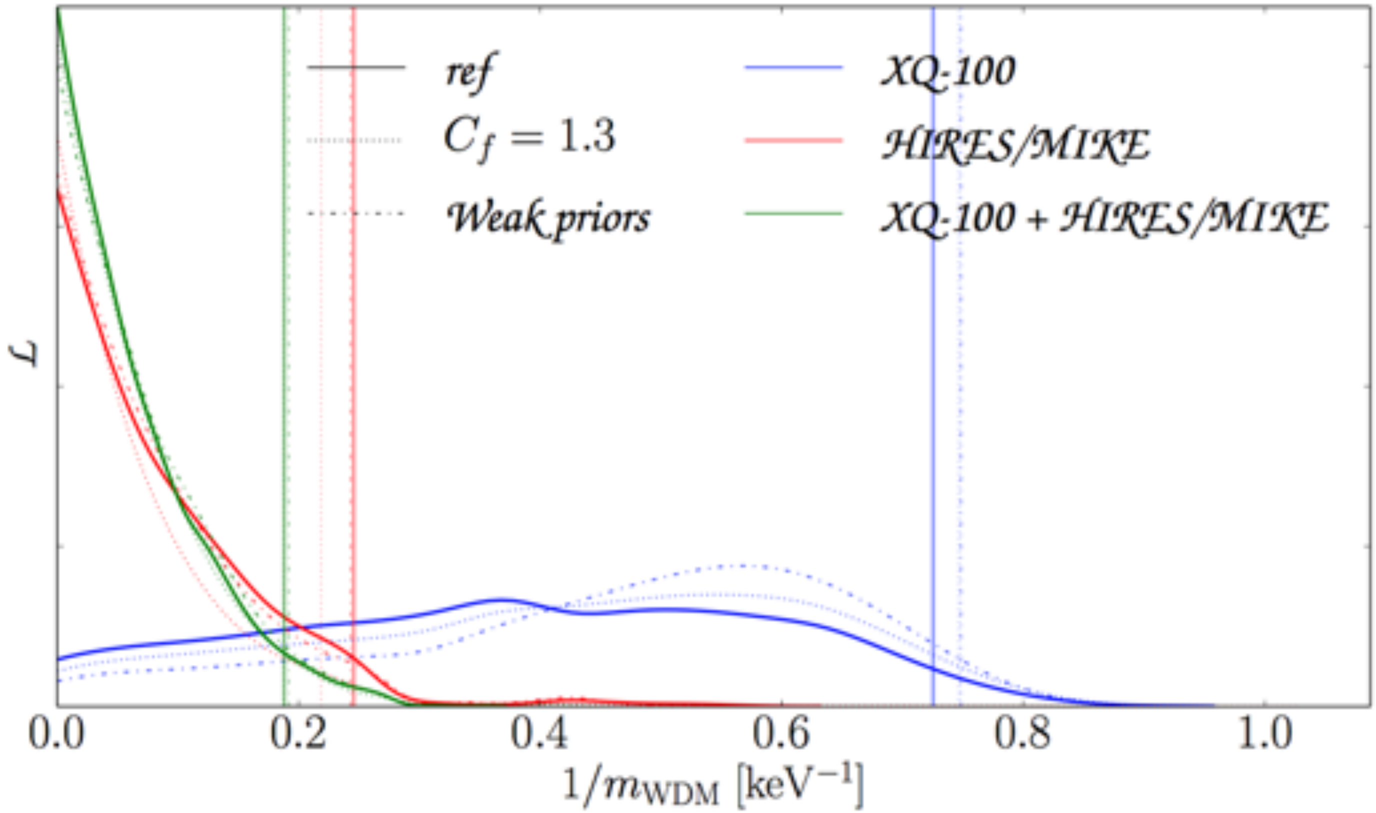
2) Bootstrap-derived covariance matrix from mock QSO sample with entries multiplied by 1.3

3) resolution corrections performed and particularly important at high-z & small-scales

4) limited exploration of z_reio Jeans smoothing

2017/18 status: the X-Shooter sample and new results for WDM (thermal)

Irsic, MV+, 2017b, arxiv: 1702.01764

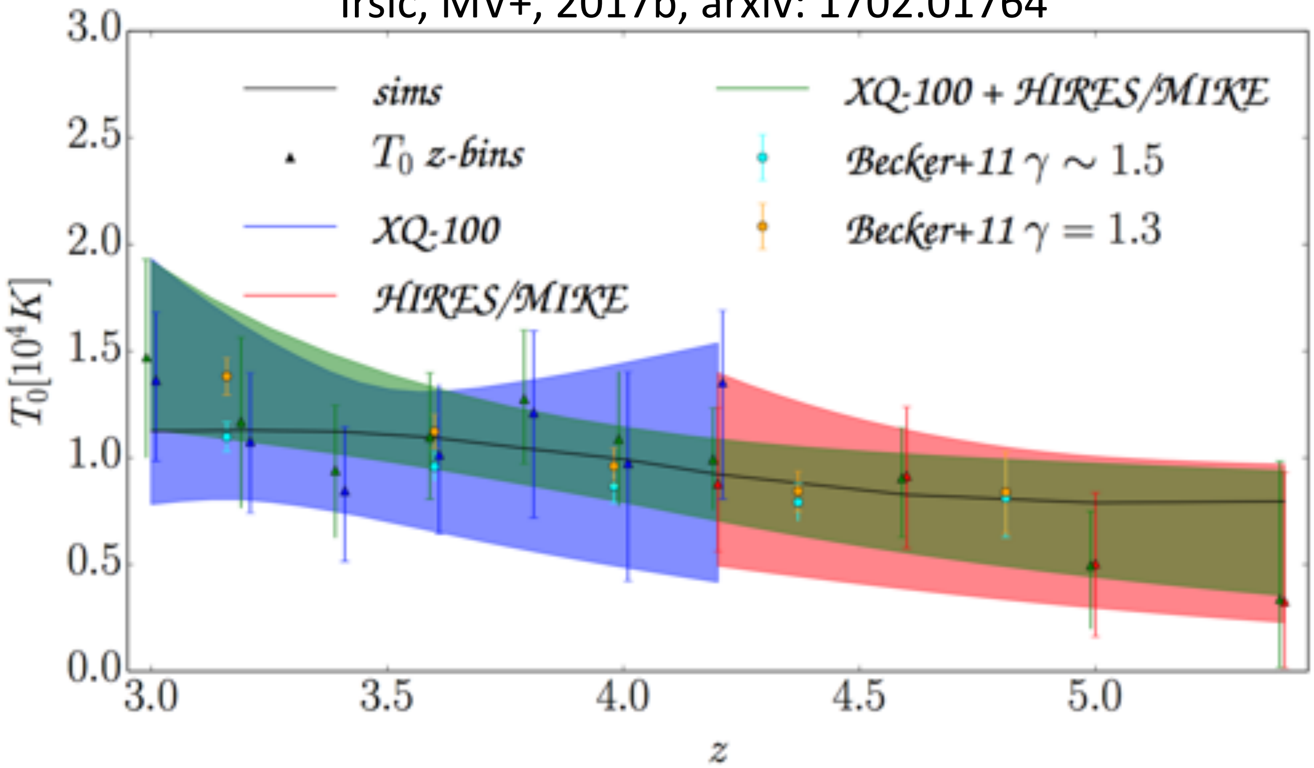


Irsic

- Likelihood greatly improves (shrinks) when combined with HIRES, pushing towards LCDM (cold).
- **Increasing covariance matrix by 1.3 (for XQ-100) or applying weak priors on cosmo paramete does not impact (this is good)**.
- Limits are then: > 1.4, > 4.1, > 5.3 keV for the reference cases for XQ-100 (medium res.), HIRES/Keck (high res.) and combined, respectively.

X-Shooter sample: IGM thermal priors

Irsic, MV+, 2017b, arxiv: 1702.01764



- Thermal history is the main nuisance. It is marginalized over but still quite sensitive to priors.
- For reference case $T_{IGM}(z)$ assumed to be a power-law (motivated by IGM physics), having this assumption lifted weakens the combined constrained to 3.5 keV.
- Key-aspect here: wide redshift range that allows to break degeneracies between WDM cutoff, Jeans pressure, filtering scale (all suppress power but differently in z).

Different data sets allow to break degeneracies

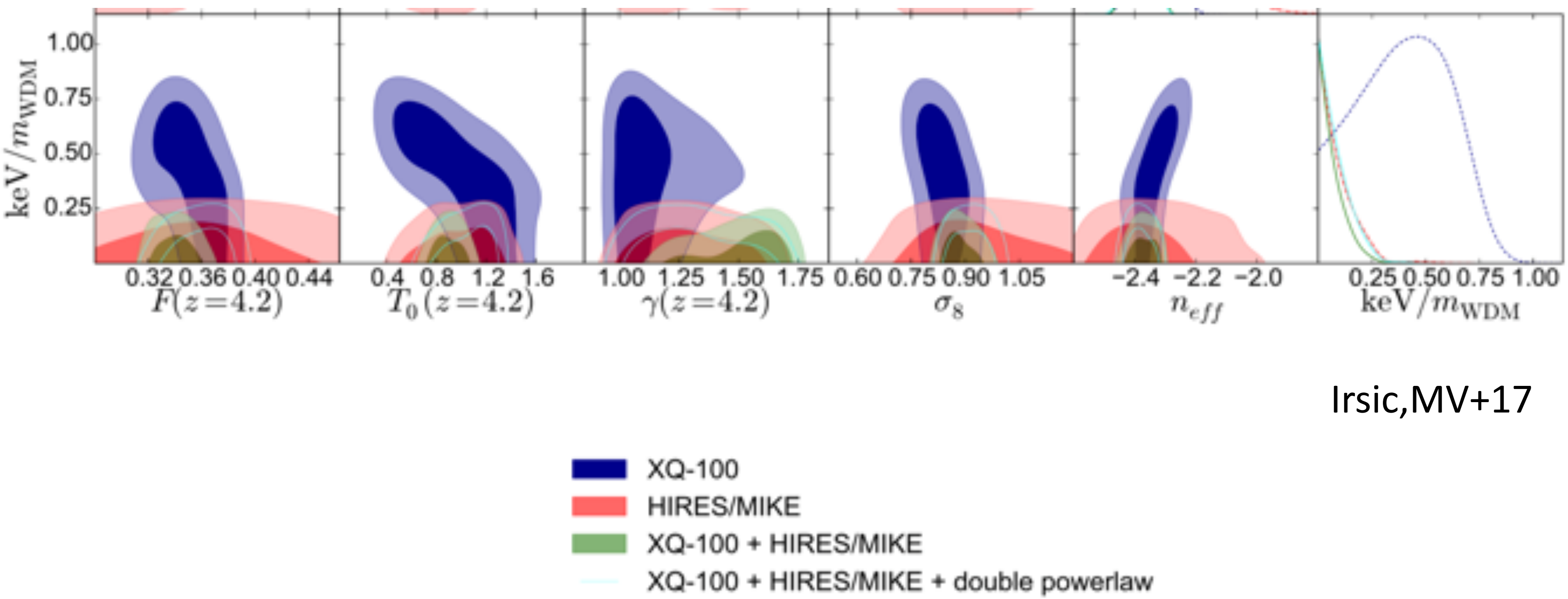
MEAN FLUX (quite constrained by obs.)

TEMPERATURE AT MEAN DENSITY

ANOTHER TEMPERATURE PARAM.

AMPLITUDE OF LINEAR POWER

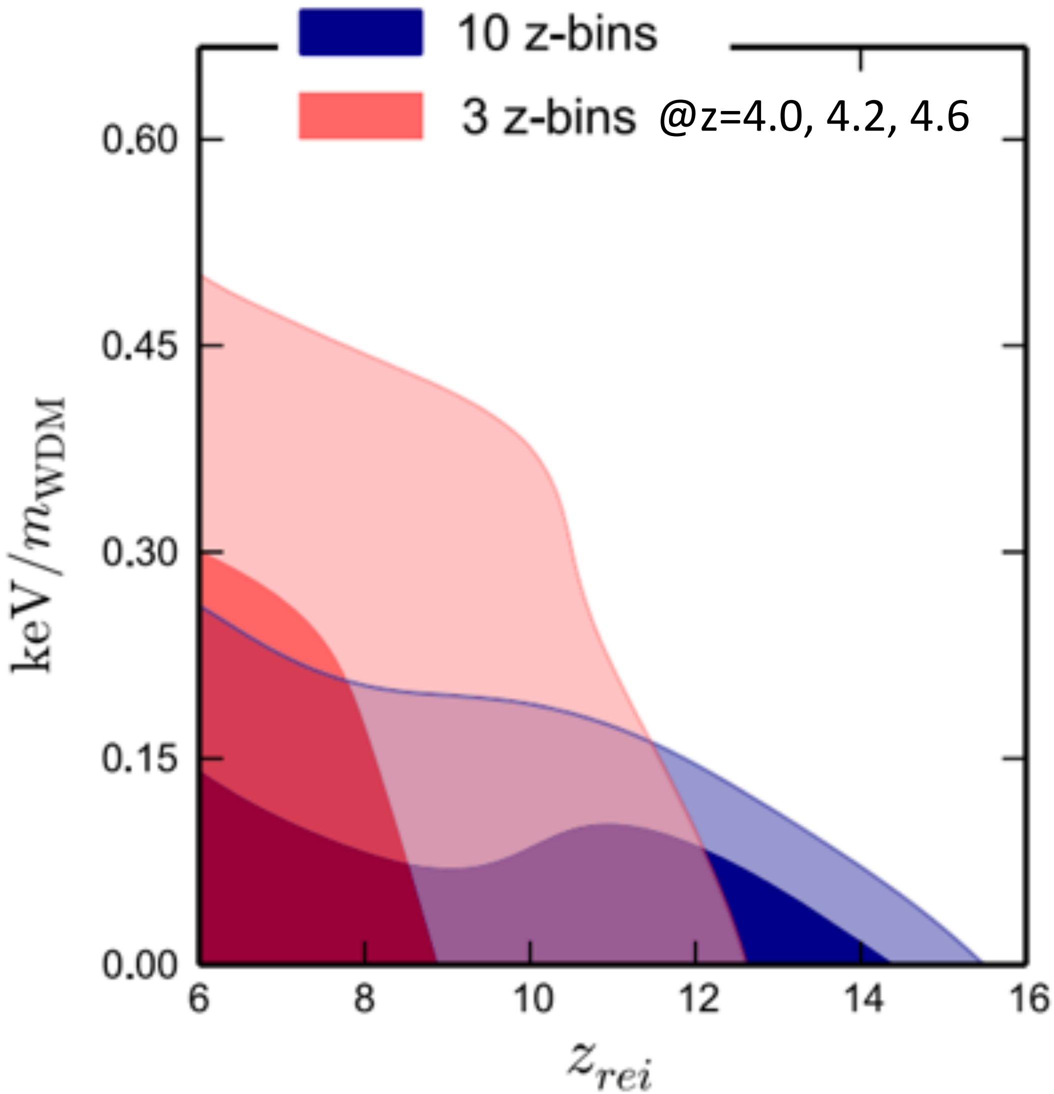
SLOPE OF LINEAR POWER



Irsic,MV+17

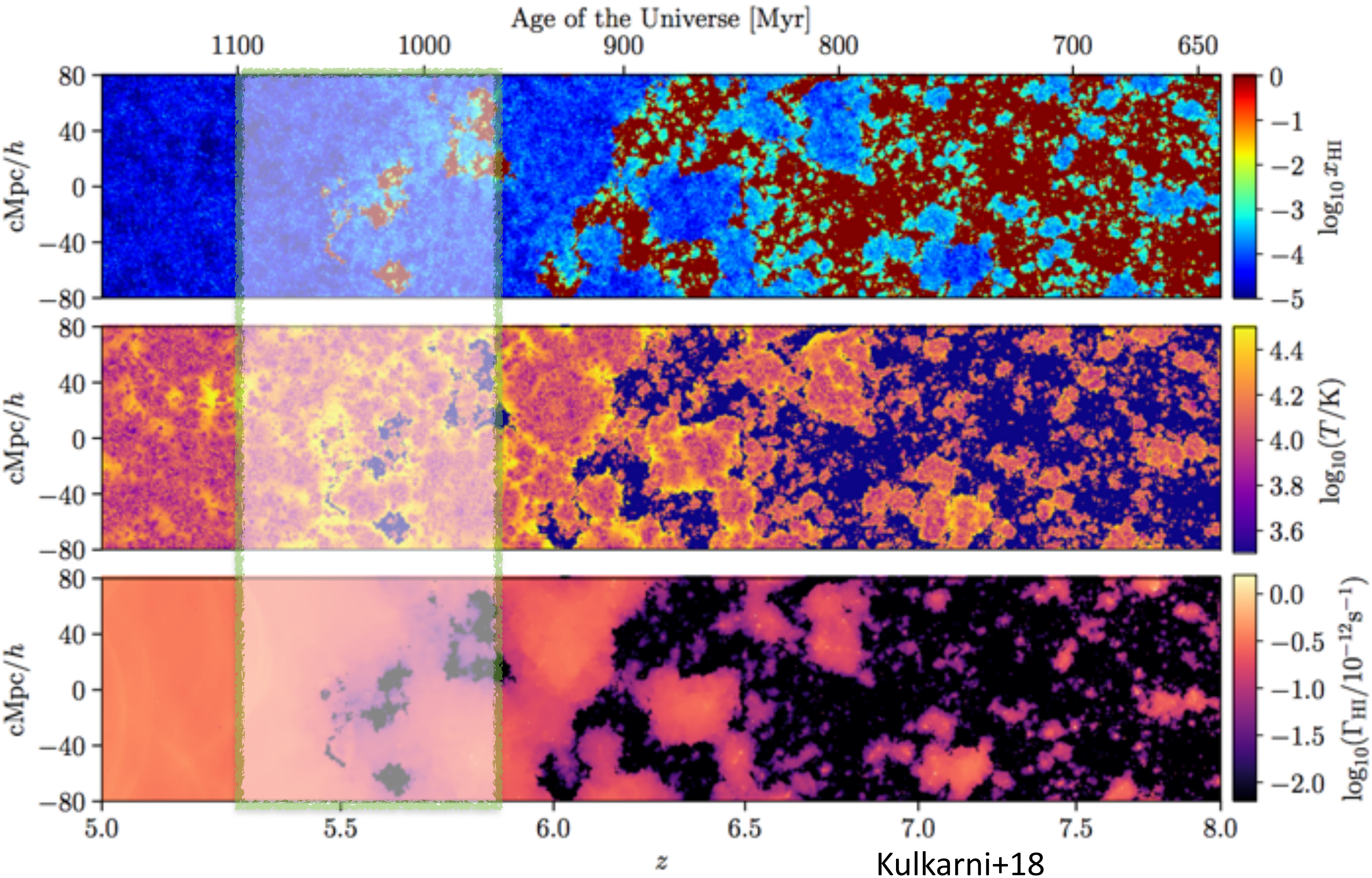
Redshift coverage is important

Since it allows to break degeneracies



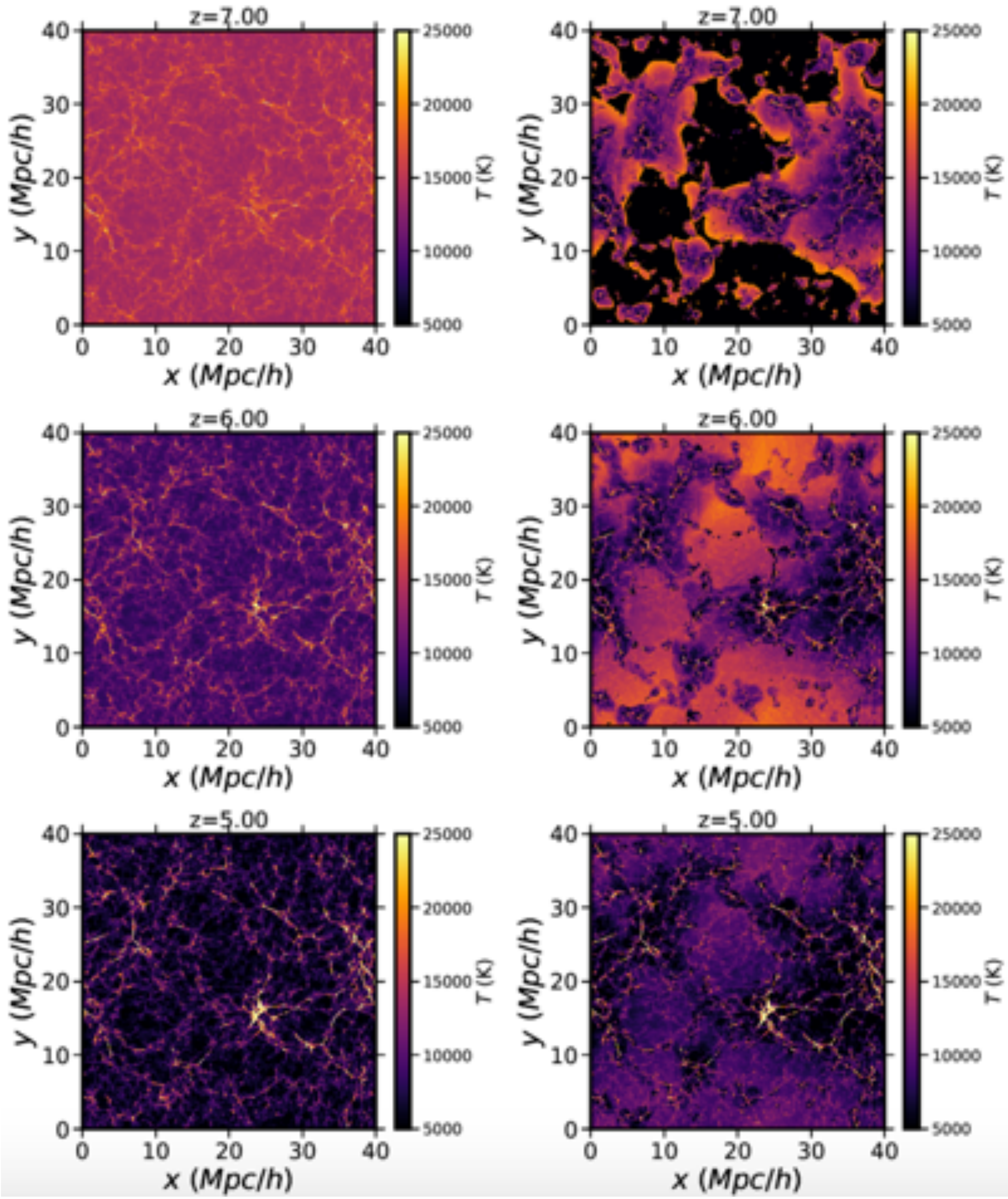
Irsic,MV+17

Reionization - I: islands of neutral hydrogen surviving?



Kulkarni+18

Reionization - II: temperature fluctations



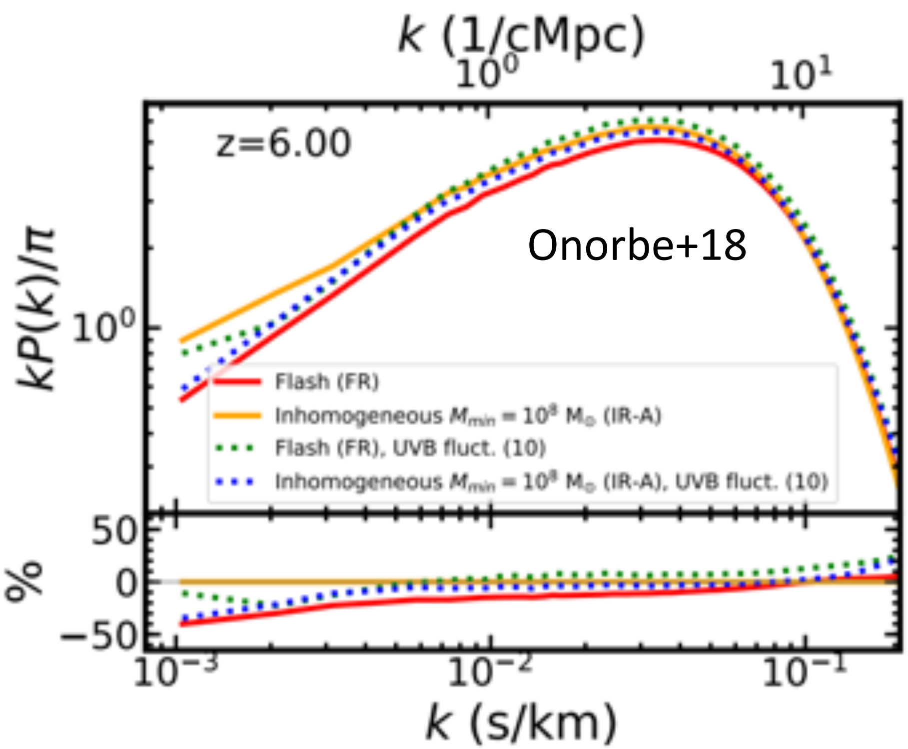
Onorbe+18: homogenous (left) vs. patchy reionization (right) with temperature fluctuations

UVB fluctuations decrease opacity in overdense regions with more sources of ionizing photons, and increase the opacity in underdense regions that are distant from sources.

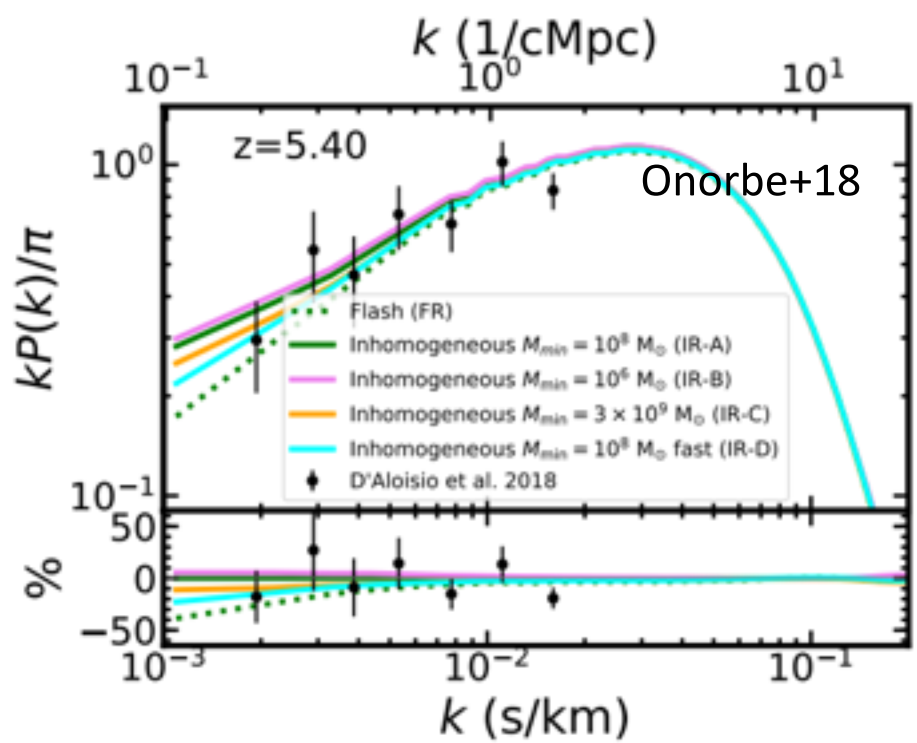
Temperature fluctuations: overdense regions reionize early and are cold and opaque, while underdense regions reionize late and are hot and transparent.

Reionization - III: effects on 1D flux power

UVB fluctuations effects



Temperature fluctuations



- Small scale effects seem to be small (if any) and are likely not to spoil WDM constraints.

- Large scale effects will be constrained by data and significantly affect 3D and 1D power. However, BAO constraints are at z=2.3.

Scalar Dark Matter - I

$$\nabla_\mu \nabla^\mu \phi = m^2 \phi, \quad G_{\mu\nu} = 8\pi G T_{\mu\nu},$$

KG and Einstein equations

$$T^\phi_{\mu\nu} = g_{\mu\nu}\left(-\frac{1}{2}\partial_\rho\phi\partial^\rho\phi - \frac{1}{2}m^2\phi^2\right) + \partial_\mu\phi\partial_\nu\phi.$$

Energy momentum tensor for the scalar field

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)d\boldsymbol{x}^2$$

Metric

$$\phi = \frac{1}{\sqrt{2m}}\left(\varphi e^{-imt} + \varphi^* e^{imt}\right)$$

Oscillating field

$$i\left(\dot{\varphi} + \frac{3}{2}H\varphi\right) = -\frac{\partial^2\varphi}{2a^2m} + m\Phi\varphi,$$

Dropping higher order and averaging over one oscillating period: Schrodinger type eq.

$$\rho_\phi \equiv m\varphi\varphi^*, \quad v_i \equiv \frac{\partial_i\{\arg(\varphi)\}}{am} = -\frac{i}{2am}\left(\frac{\partial_i\varphi}{\varphi} - \frac{\partial_i\varphi^*}{\varphi^*}\right)$$

Defining density and velocities of the fluid

$$\dot{v}_i + Hv_i + \frac{v_j\partial_j v_i}{a} = -\frac{\partial_i\Phi}{a} + \boxed{\frac{1}{2a^3m^2}\partial_i\left(\frac{\partial^2\sqrt{\rho_\phi}}{\sqrt{\rho_\phi}}\right)}$$

Euler eq. NOTE the pressure term

$$\dot{\rho}_\phi + 3H\rho_\phi + \frac{\partial_i(\rho_\phi v_i)}{a} = 0.$$

Continuity

Hui+16 for a review, Mocz & Succi 15 for SPH implementation, Marsh+15, Nori&Baldi 18

Scalar Dark Matter - II

$$\delta_{\rm m} = F\delta_\phi + (1-F)\delta_{\rm c}.$$

$$\ddot{\delta}_{\phi k} + 2H\dot{\delta}_{\phi k} + \frac{c_s^2 k^2}{a^2}\delta_{\phi k} - \frac{3}{2}H^2\delta_{{\rm m}k} = 0,$$

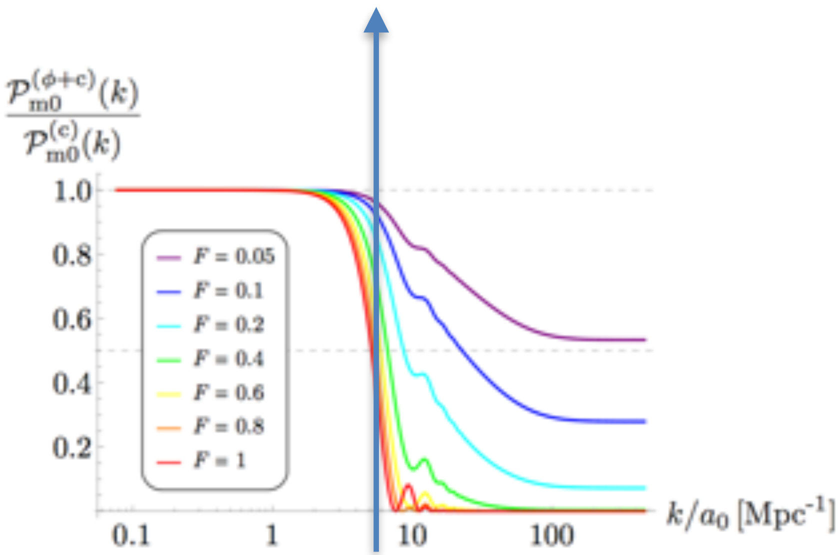
$$\ddot{\delta}_{{\rm c}k} + 2H\dot{\delta}_{{\rm c}k} - \frac{3}{2}H^2\delta_{{\rm m}k} = 0.$$

Linear perturbation theory in CDM+scalar field model

$$c_s^2 \equiv \frac{k^2}{4a^2m^2}, \qquad \frac{k_{\rm J}}{a} = \sqrt{Hm},$$

$$\boxed{\frac{k_{\rm Jeq}}{a_0} = \frac{a_{\rm eq}}{a_0}\sqrt{H_{\rm eq}m} \approx 7\,{\rm Mpc}^{-1}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{1/2}}$$

Sound speed of scalar DM and Jeans scale definition



At $k<k_J$ no pressure

At $k>k_J$ pressure and oscillations

no growth

Comoving Jeans $k_J \sim a^{1/4}$ in MD

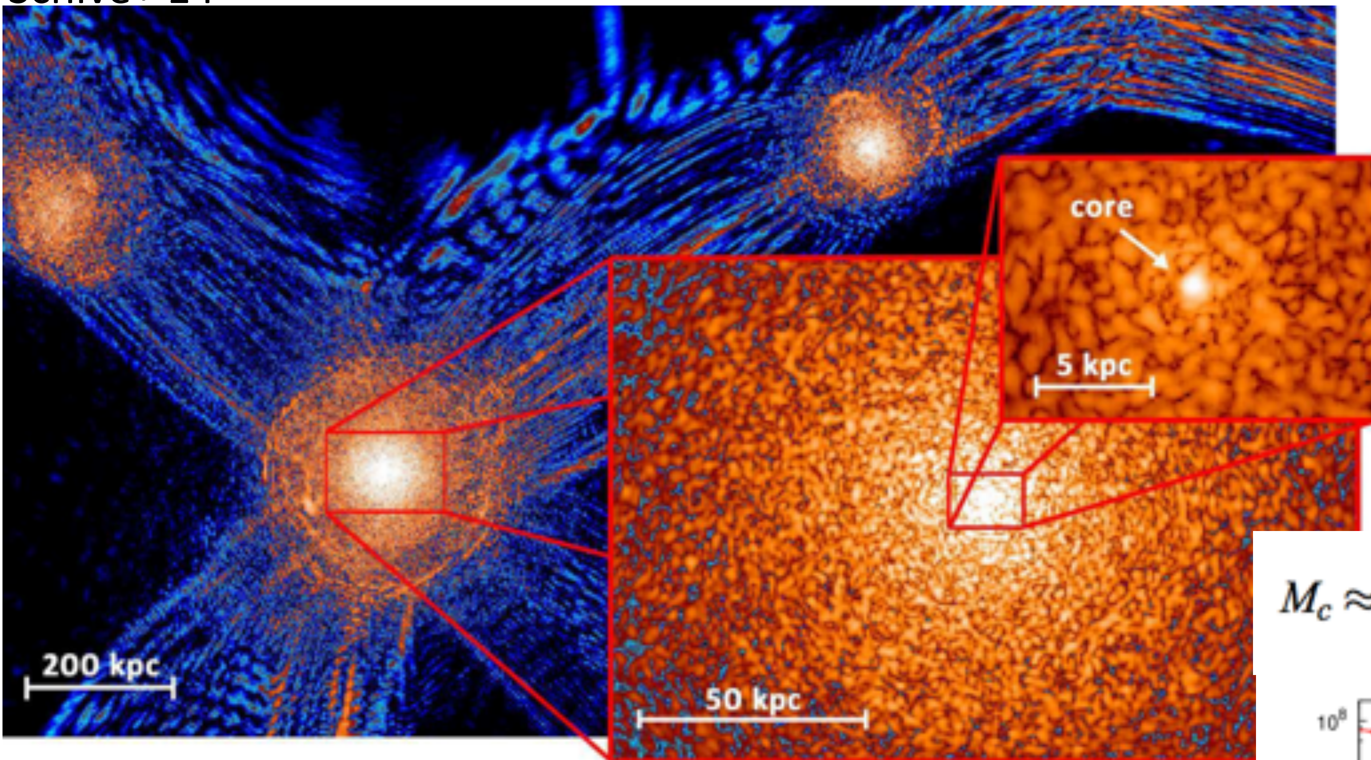
Important quantity is k_J at equival.

Plateau is set by FDM fraction

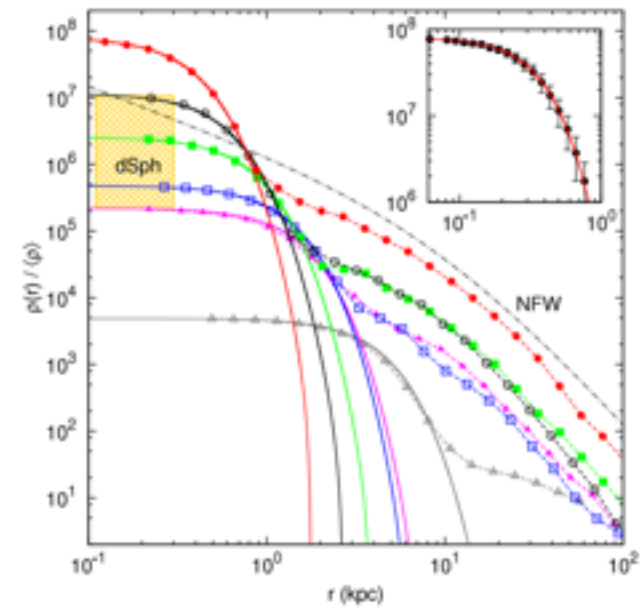
Cutoff scale set by FDM mass

Simulating Scalar Dark Matter

Schive+ 14



$$M_c \approx \frac{5.5 \times 10^9}{(m_B/10^{-23}\ \mathrm{eV})^2 (\mathrm{r_c}/\mathrm{kpc})} M_\odot$$

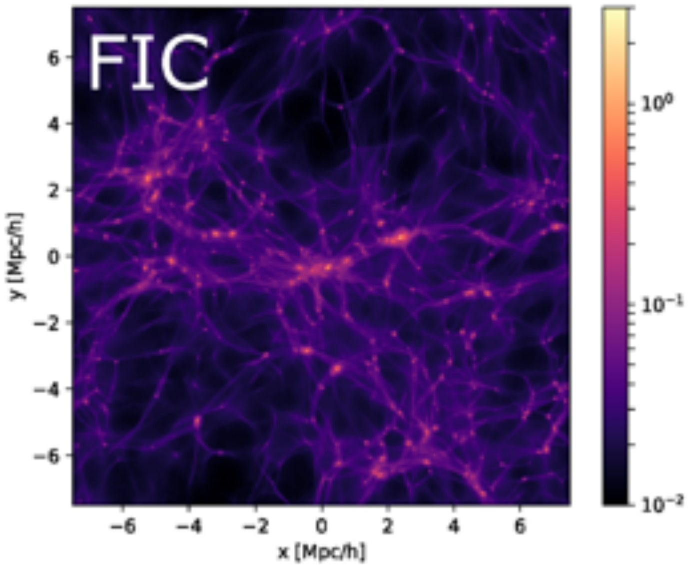


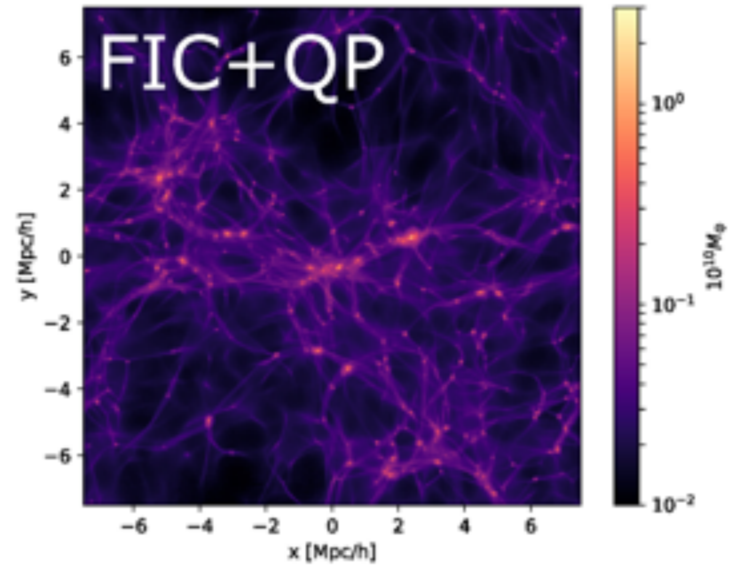
- Very **distintictive prediction: solitonic core** (steep jump in density) with a simple numerical solution (e.g. Mocz+17, Schive +17, Marsh+15, Nori & Baldi 18).
- Stability of the core over cosmological times still an open issue.
- Size of the core $M_{core} \sim M_{galaxy}^{1/3}$.
- Claimed detection at 10^{-22} eV from Phornax.
- Searched in galaxies but not seen, however baryon might be an issue (Blum+17).

Simulating Scalar Dark Matter - II

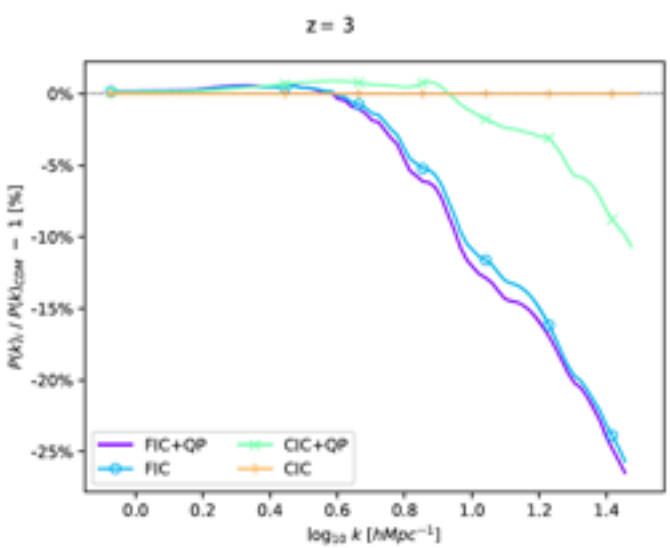
Nori&Baldi18

Nori, Baldi,
Murgi, MV+ 19





$$Q = \frac{\hbar^2}{2m_\chi^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}} = \frac{\hbar^2}{2m_\chi^2}\left(\frac{\nabla^2\rho}{2\rho} - \frac{|\nabla\rho|^2}{4\rho^2}\right)$$

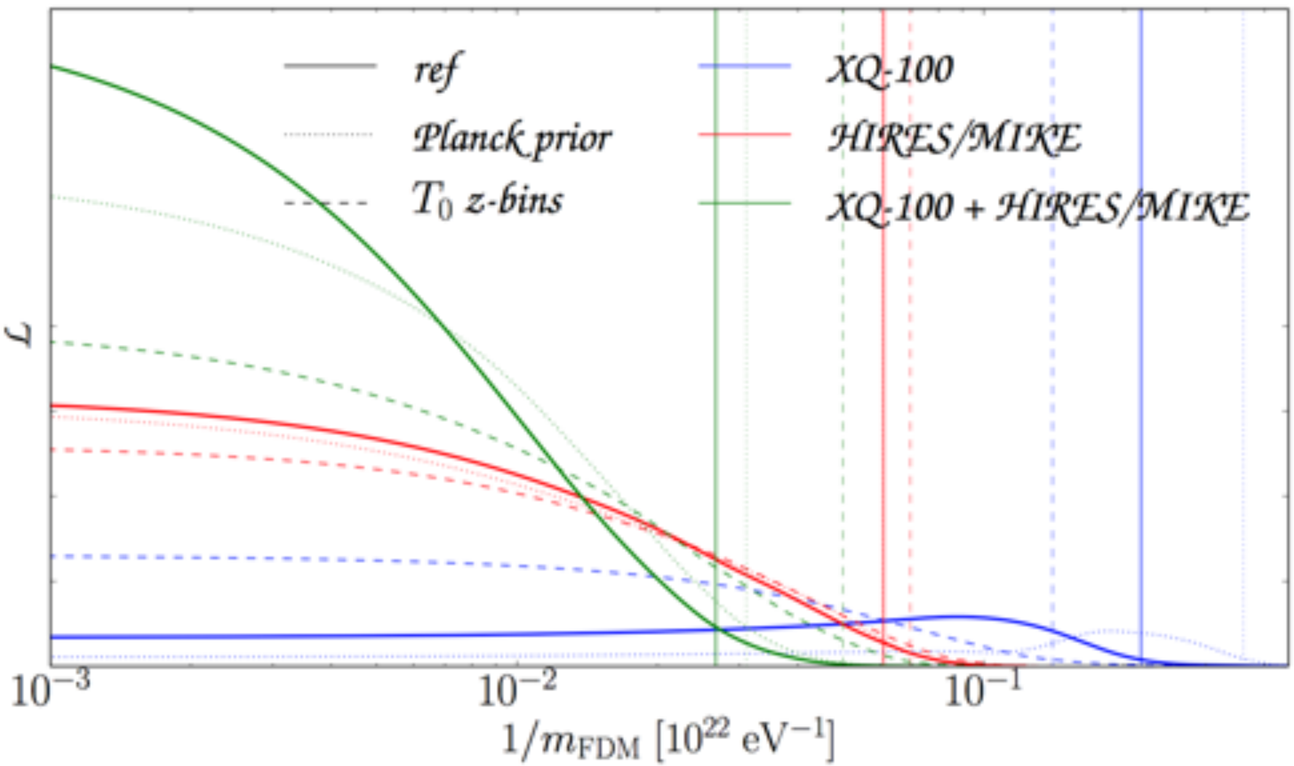


- Quantum potential not small for matter power spectrum, especially at high redshift.

- < 5% extra suppression induced by the Quantum Potential w.r.t. to the same simulation with just a linear cut-off of power.

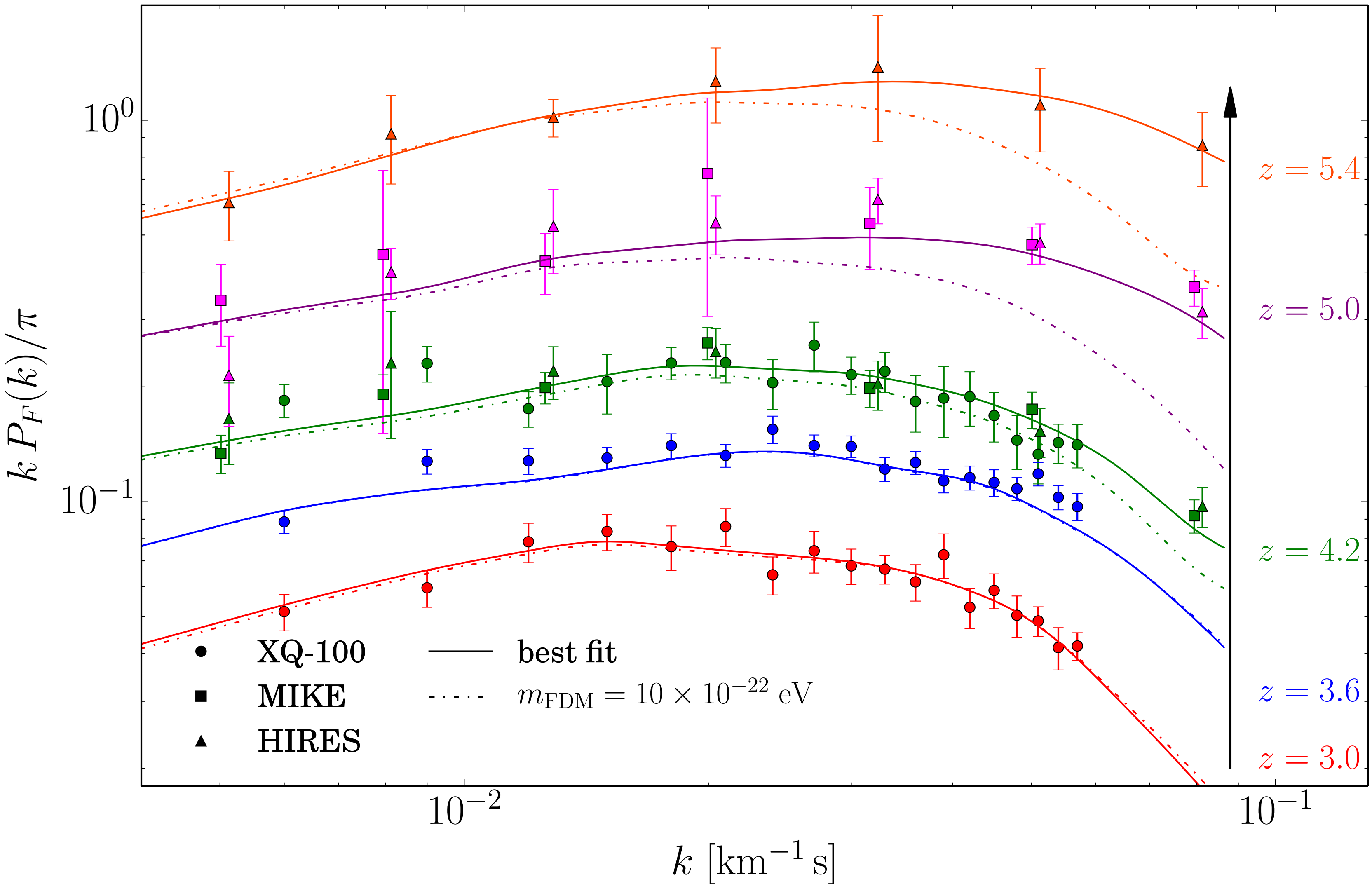
X-Shooter sample + HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)

Irsic, MV+, 2017c, arxiv: 1703.04683

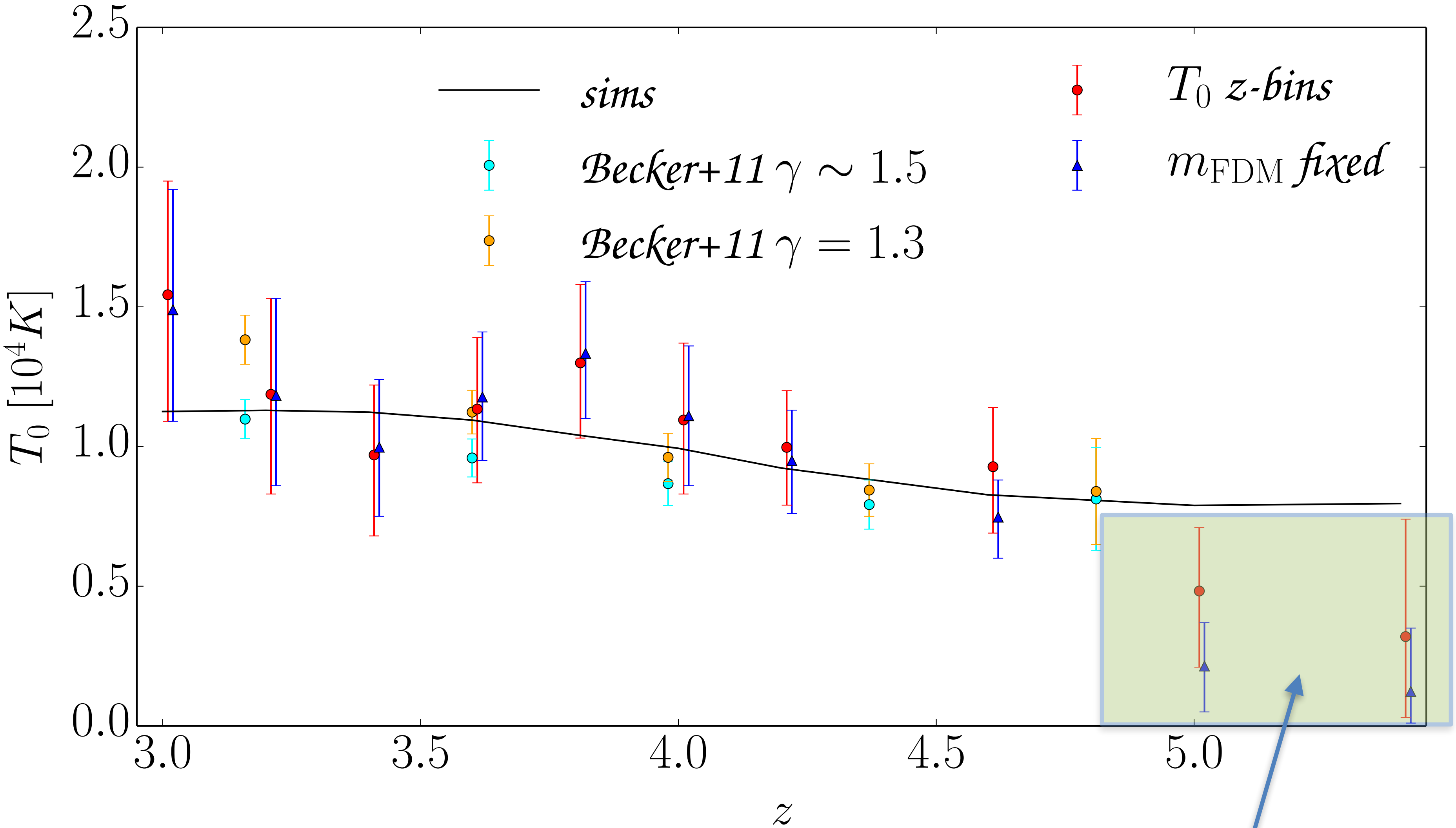


- New interest in FDM models. **VERY RICH IMPLICATIONS.**
- WDM thermal IGM constraints translated into FDM constraints by mapping $k_{1/2}$: poor approximation for large axion masses > 1.e-21.
- IGM constraints are **>2-4 x 10^{-21} eV** - ruling out the window range **0.1-1 x 10^{-21} eV** typically chosen to solve (putative) small scale LCDM crisis.

X-Shooter sample+HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)



X-Shooter sample+HIRES/MIKE: constraints on ultra-light axions (Fuzzy Dark Matter)



Unreasonably low temperatures?
Maybe not (e.g. Boera et al. finds 7000 K)
but then there is a “jump” at z=4.6

Non-cold Dark Matter at small scales - I: a new and more general approach

Standard approach

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

Applies to thermal WDM
(Fermi Dirac distribution)

$$\nu = 1.12\,;$$

$$\alpha = 0.049 \left(\frac{m_x}{1\ \mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_x}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$$

$\Rightarrow$

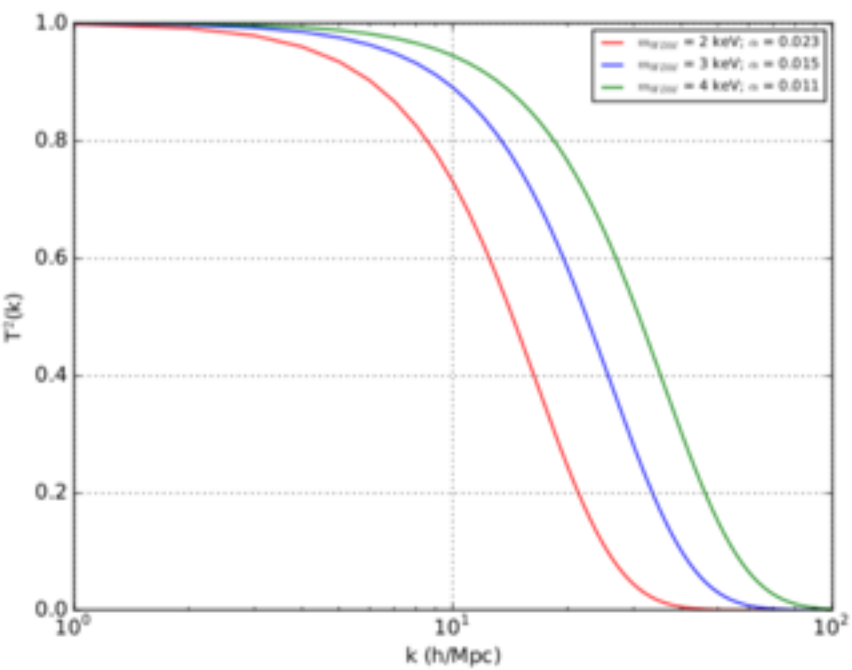
New general approach

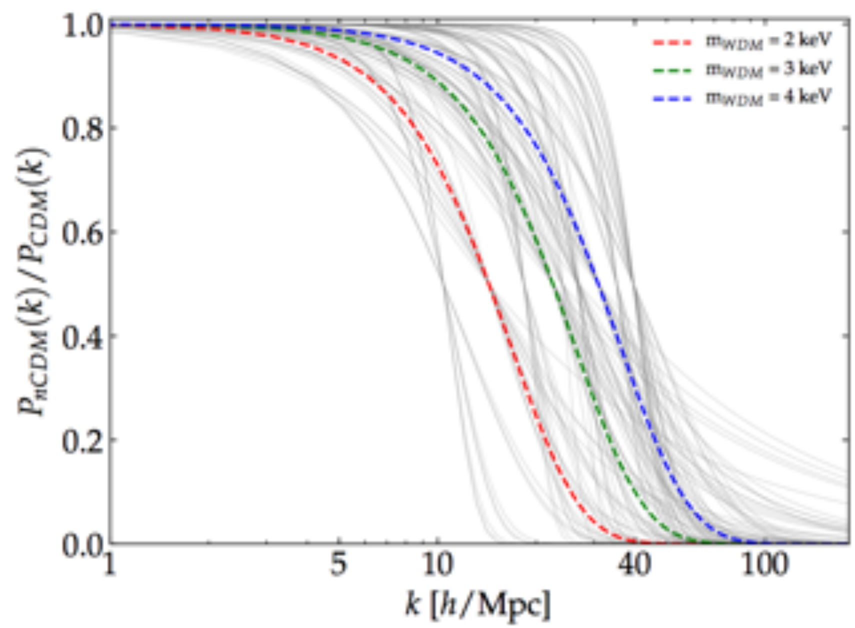
$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

Applies to ?

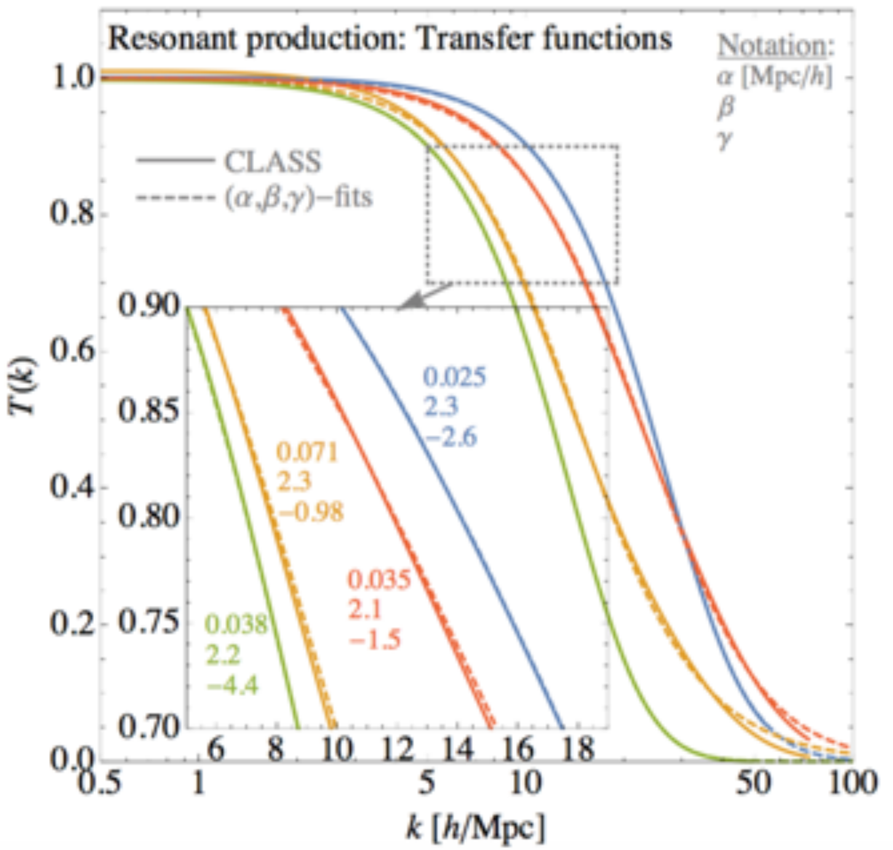
The larger is beta, the flatter is the shape for k < $k_{1/2}$; the larger is gamma, the steeper is the small-scale cutoff
.

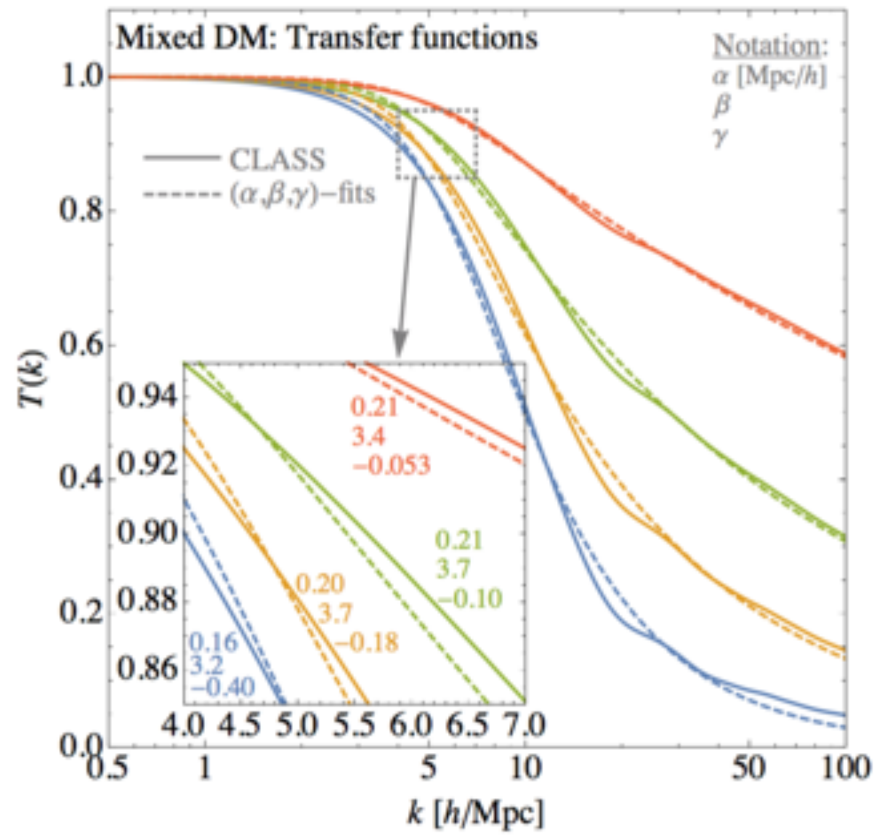
Murgia, Merle, MV +17





Non-cold Dark Matter at small scales - II: particle physics models

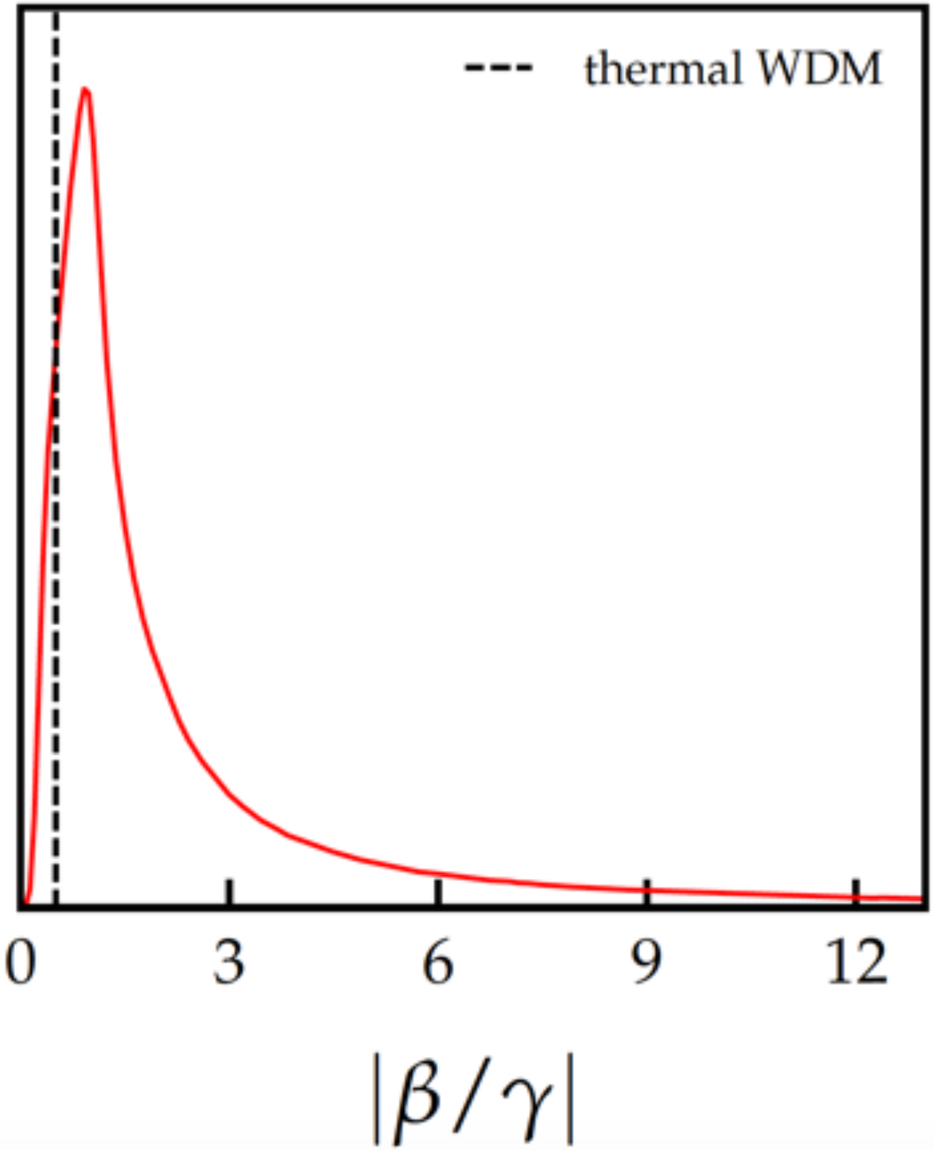




Simple parametrization proposed works well for:

- sterile neutrinos from scalar decays
- sterile neutrinos resonantly produced
- mixed models
- fuzzy dark matter
- ETHOS models

Non-Cold Dark Matter and constraints on the SHAPE of the cutoff



$$\alpha < 0.03\ \mathrm{Mpc}/h\ (2\sigma)$$

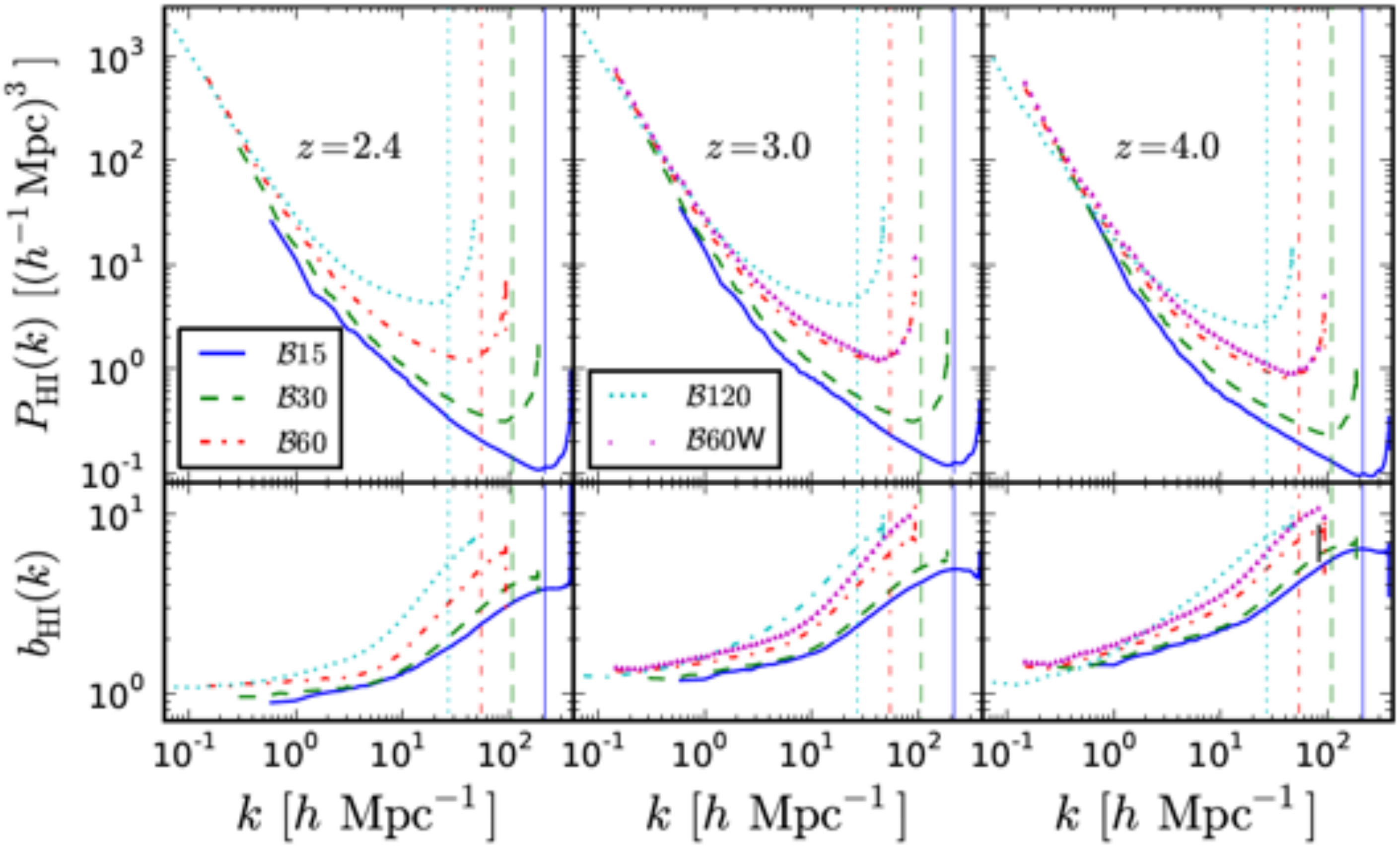
$$|\beta\,/\,\gamma| < 14$$

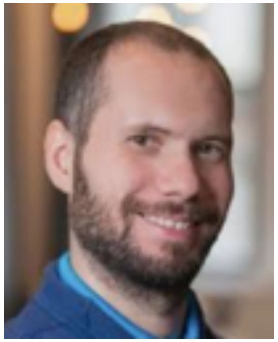
R. Murgia

Murgia, Irsic, MV, 2019

EMISSION

Simulating intensity mapping signal: the HI bias

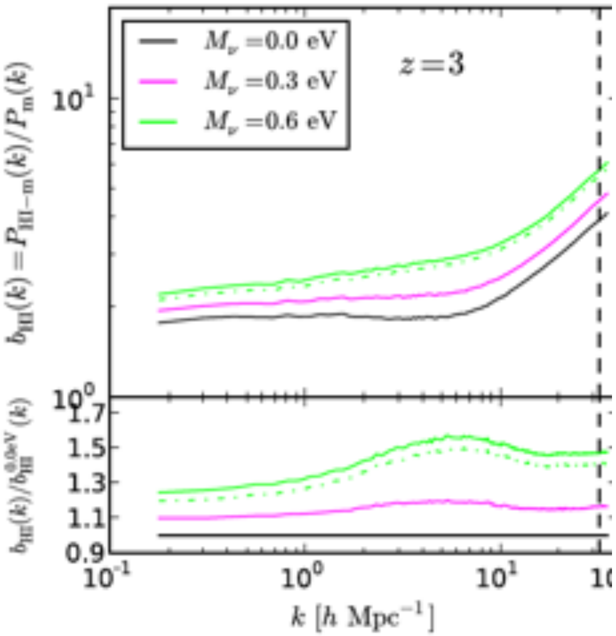




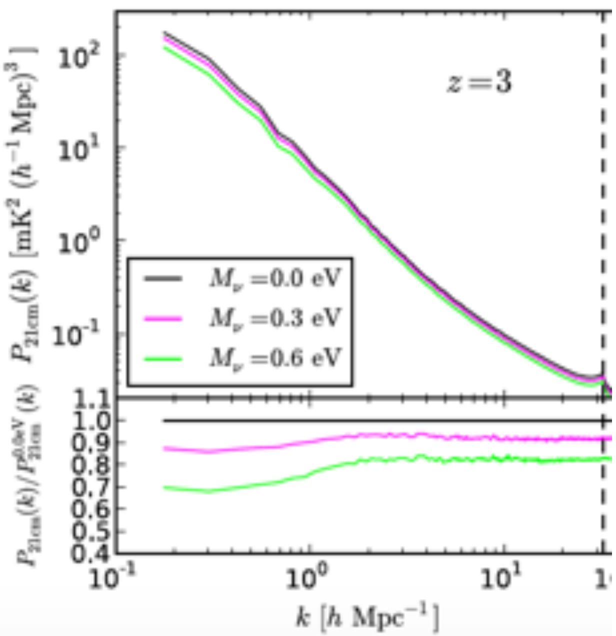
Villaescusa-Navarro, MV + 2014

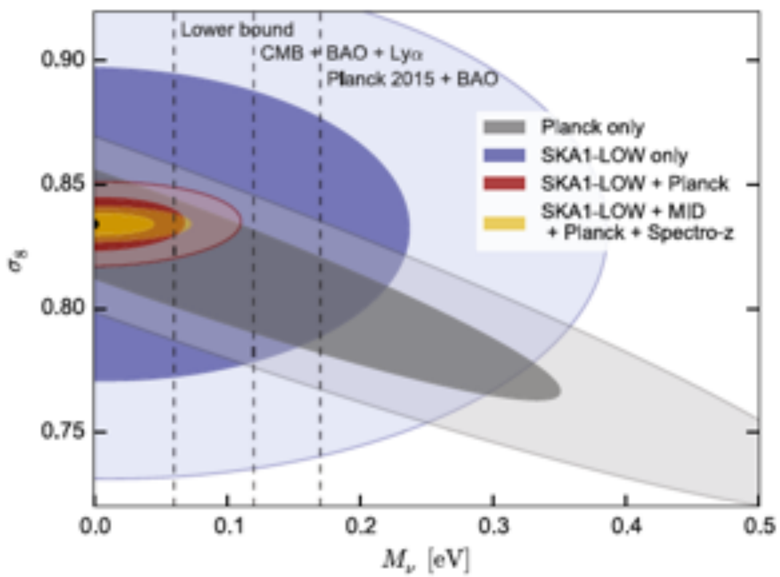
• Modelling of HI distribution based on particles and hydrosims of different box sizes of 15,30,60,120 Mpc/h linear size and different feedback implementation with and without galactic feedback (B60W with galatic winds, B60 without).

Simulating intensity mapping signal: large scales



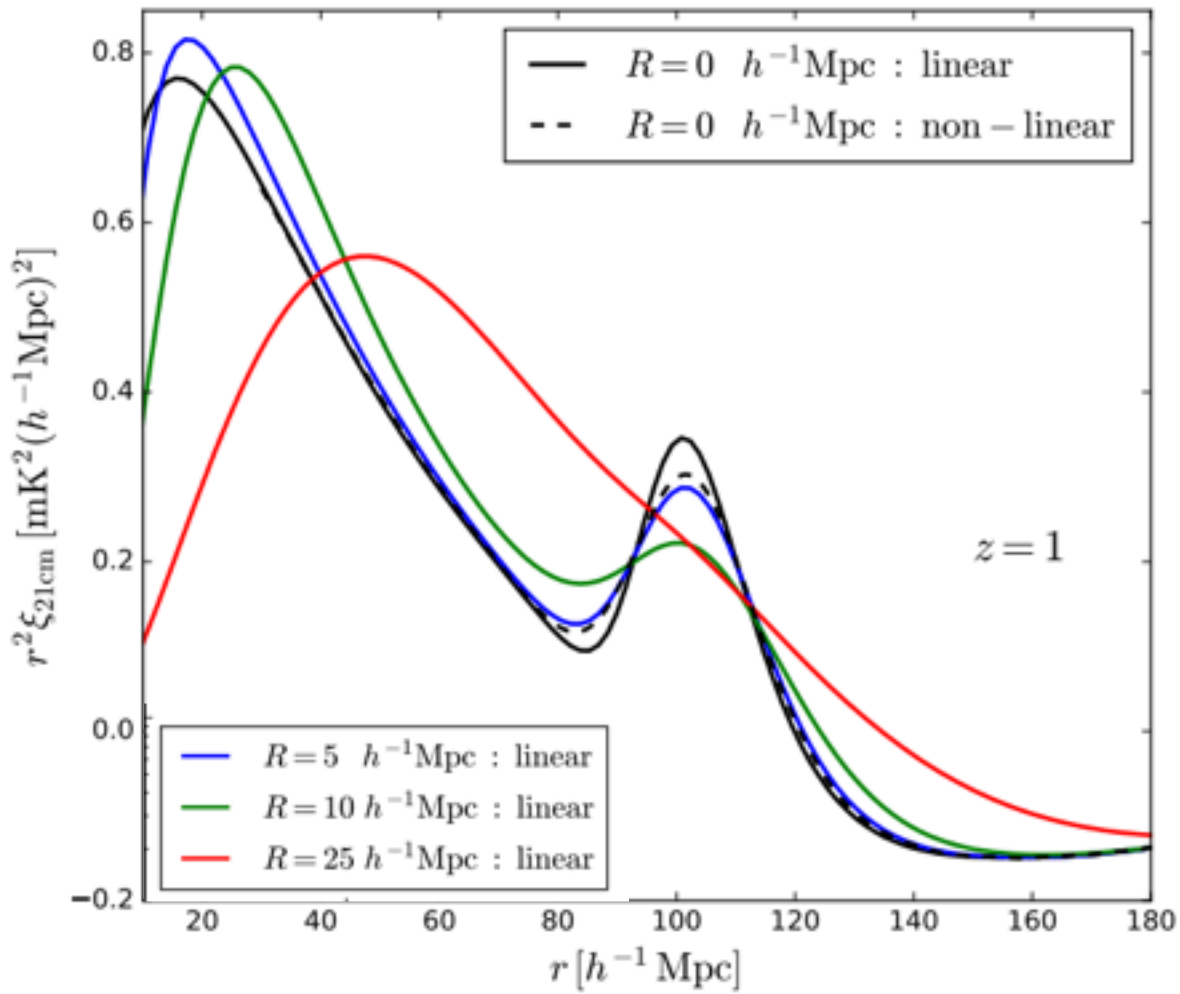
- Scale dependence bias also present in massive neutrino cosmologies.
- $M_{HI}(M)$ not affected by the presence of neutrinos.
- HI is more clustered in massive neutrino sims. (but $Omega_{HI}$ lower) - because small mass haloes are suppressed i.e. impact on $n_{HALO}(M)$.
- IM alone would provide constraint 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

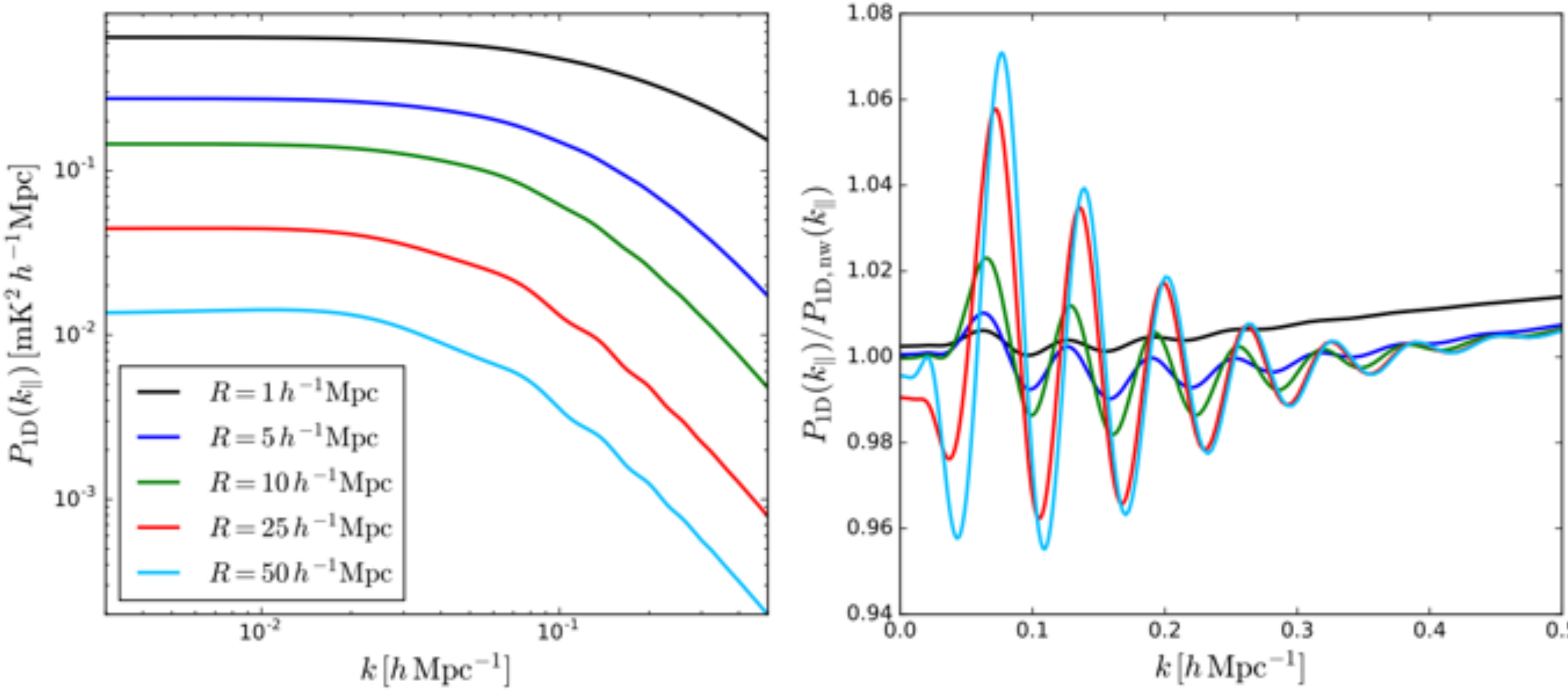
BAOs with SKA1-MID - I



Villaescusa-Navarro, Alonso, MV, 2017

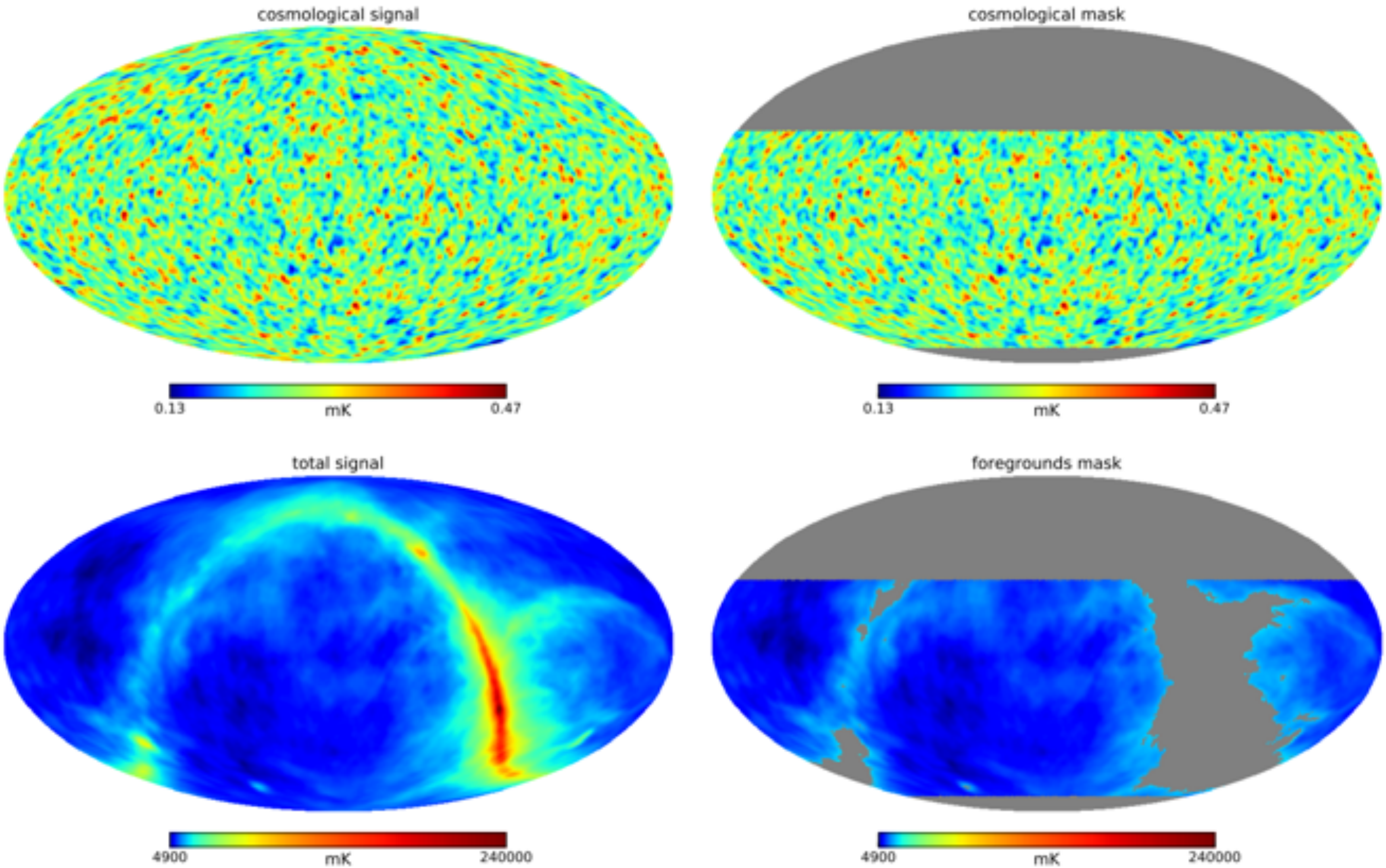
BAOs with SKA1-MID - II

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



Villaescusa-Navarro, Alonso, MV, 2017

BAOs with SKA1-MID - III



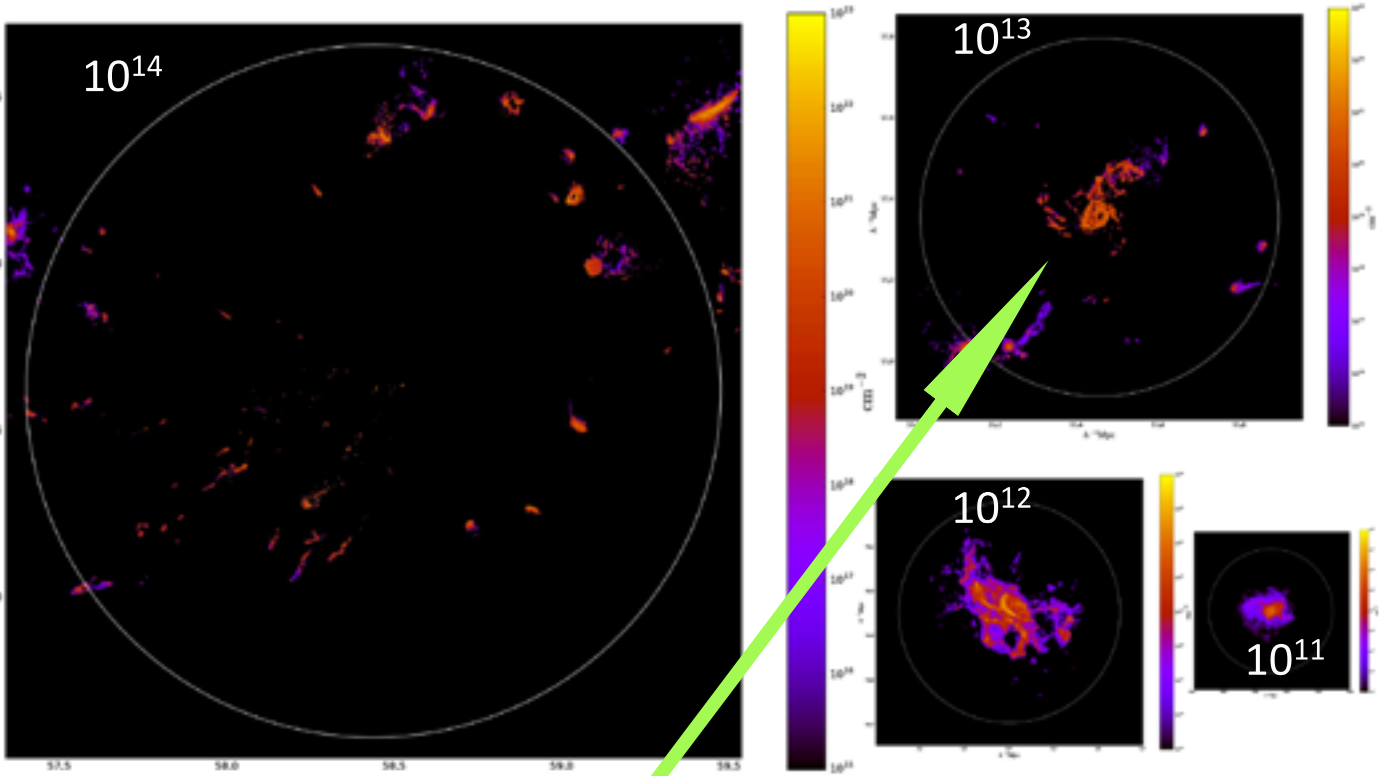
Villaescusa-Navarro, Alonso, MV, 2017

BAOs with SKA1-MID - IV

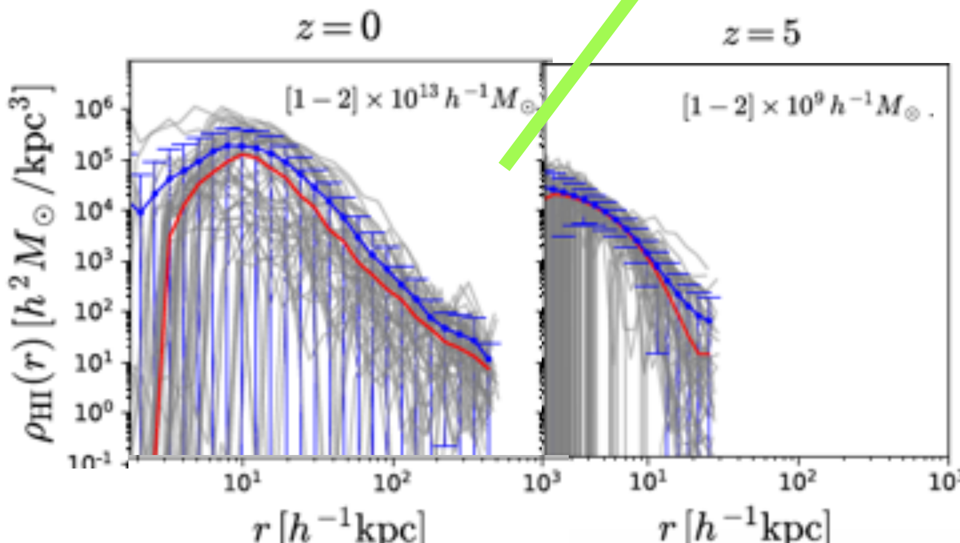
z range	$\langle z \rangle$	mask	σ_α (C)	(C+N)	(C+N+FG)
[0.36-0.75]	0.6	no	1.008 ± 0.016	1.008 ± 0.016	1.007 ± 0.016
		yes	1.006 ± 0.020	1.006 ± 0.021	1.006 ± 0.024
[0.75-1.26]	1.0	no	0.996 ± 0.010	0.997 ± 0.011	0.996 ± 0.011
		yes	0.997 ± 0.012	0.997 ± 0.013	0.998 ± 0.015
[1.26-1.98]	1.6	no	1.001 ±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

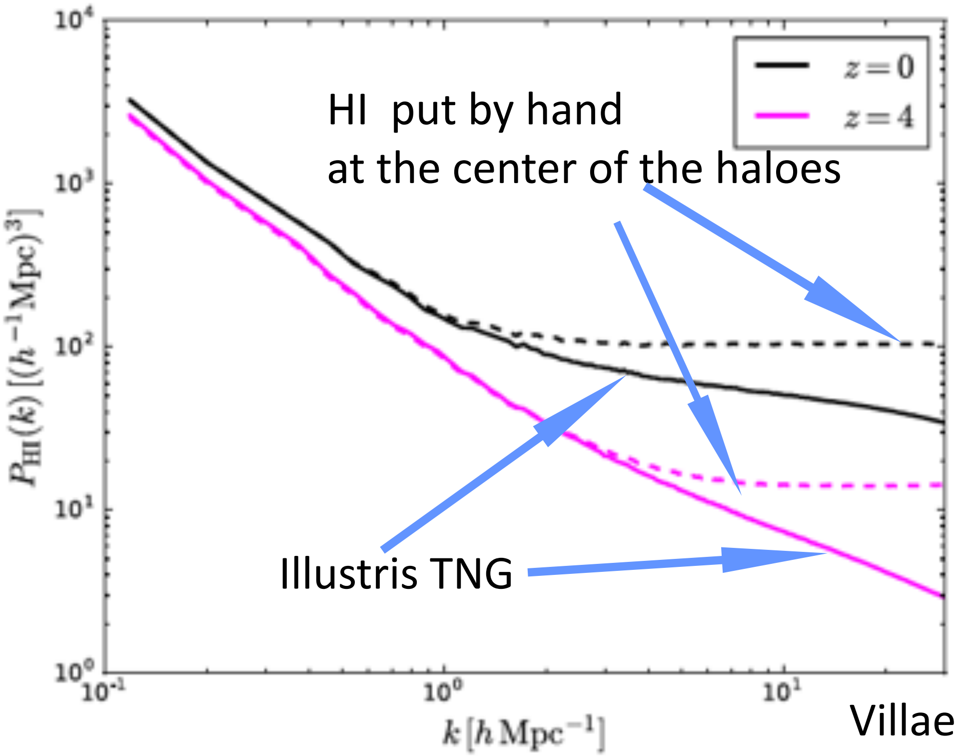


Villaescusa-Navarro+18
based on Illustris TNG



- 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



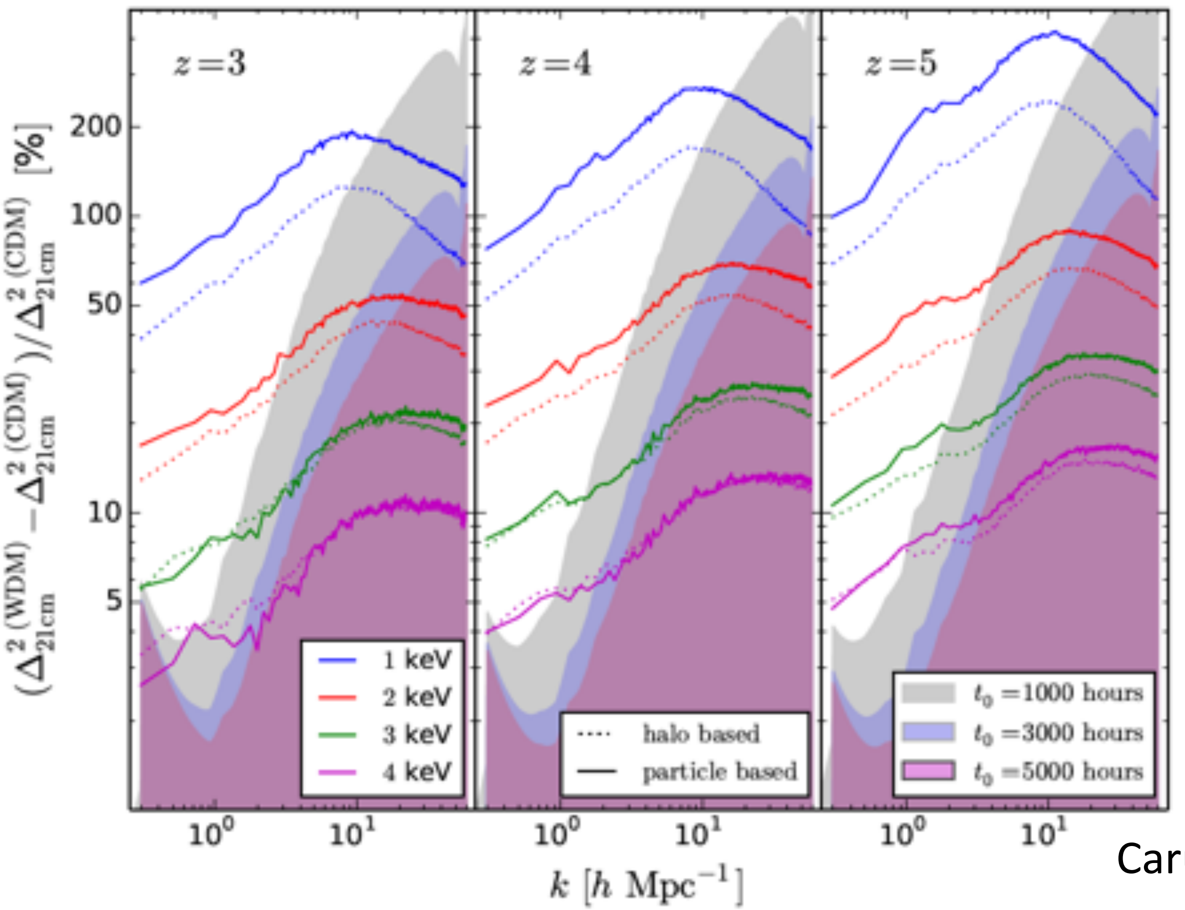
$$P_{\rm H\,I}^{\rm SN}(z) = \lim_{k\to 0} P_{\rm 1h,H\,I}(k,z) = \frac{1}{[\rho_c^0 \Omega_{\rm H\,I}(z)]^2} \times \int_0^\infty n(M,z) M_{\rm H\,I}^2(M,z)\, dM = \frac{\int_0^\infty n(M,z) M_{\rm H\,I}^2(M,z)\, dM}{\left[\int_0^\infty n(M,z) M_{\rm H\,I}(M,z)\, dM\right]^2}.$$

Villaescusa-Navarro+18

- 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



Isabella Carucci

Carucci, Villaescusa, MV, Lapi 15

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.*

SUMMARY

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

- From the forest: **no support for neutrino masses larger than zero or non cold dark matter.**

- New frontier for forest is the **high redshift** close to reionization and 3D/1D self consistent model.

- **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. However, Fingers of God effects would require modelling down to small scales.