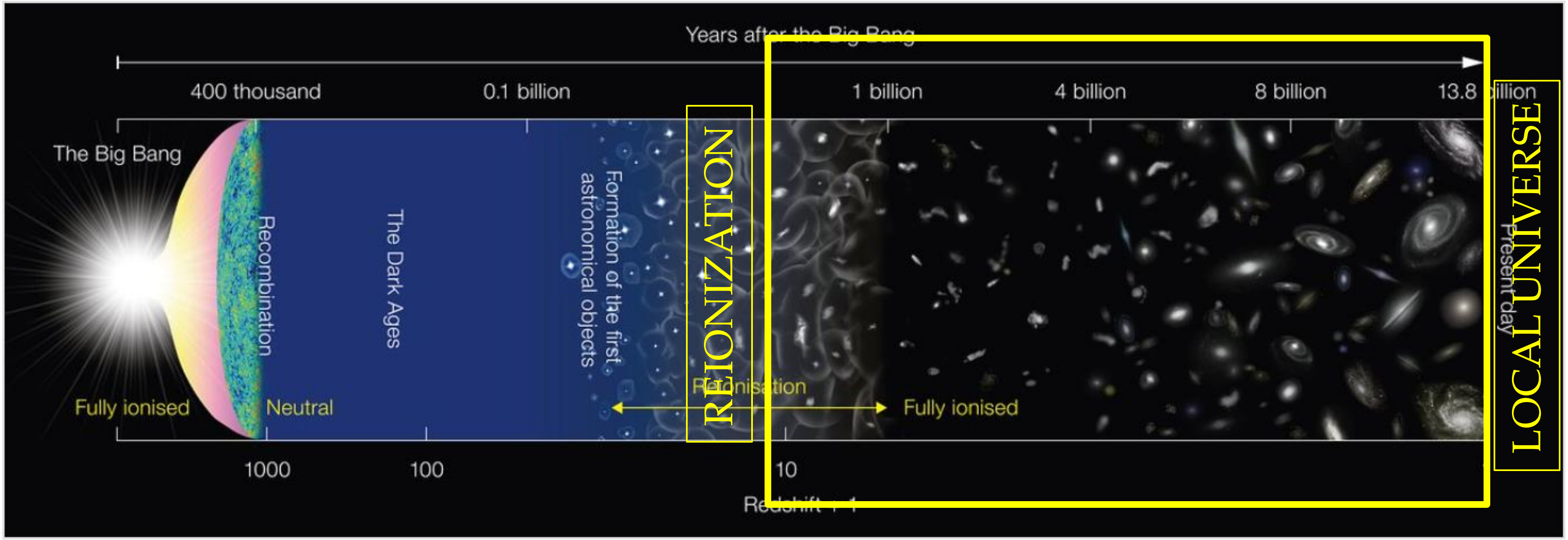
Fundamental Physics with Hydrogen in emission and in absorption

Matteo Viel - SISSA (Trieste, Italy)

12/06/25
COSMOFONDUE

Promises of the post-reionization Universe

Matteo Viel



- Ideal place to test **structure formation** processes
- and cosmological models in and beyond **ΛCDM** (Universe being more linear)

Promises of the post-reionization Universe

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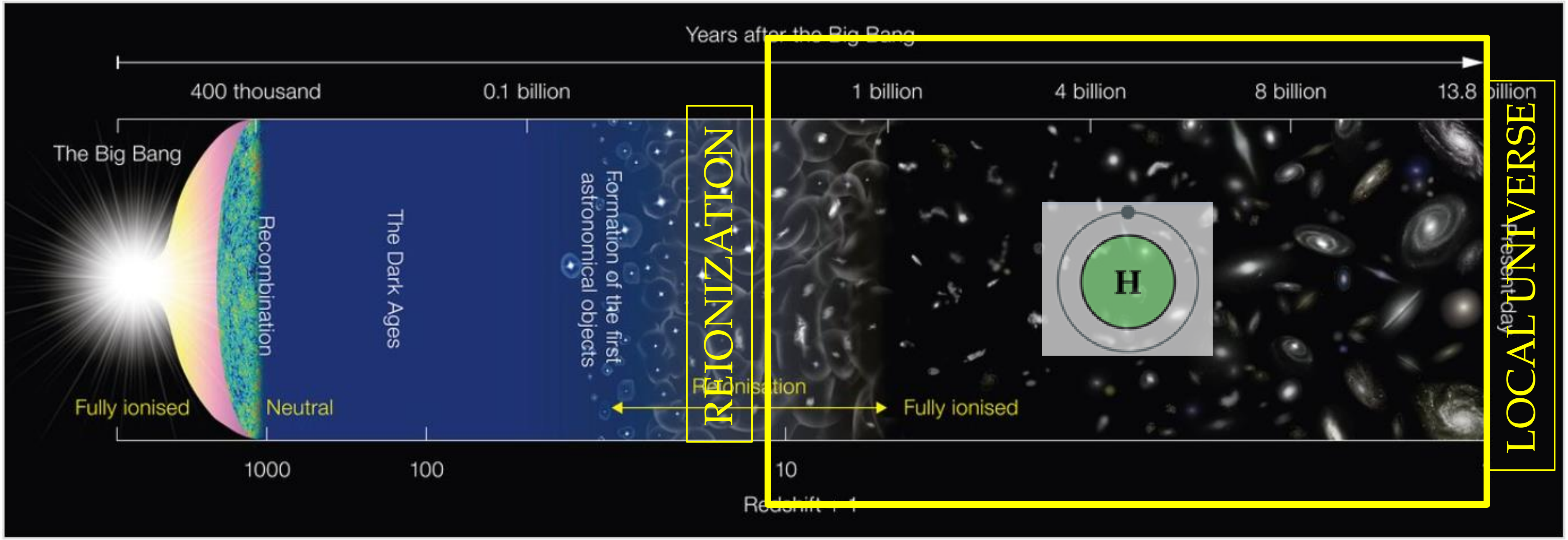
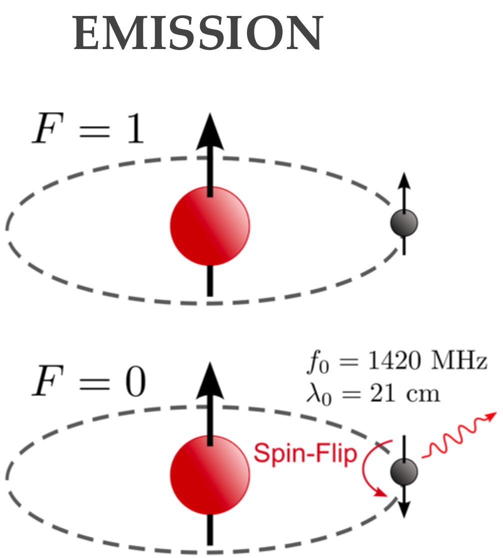


- Ideal place to test **structure formation** processes
- and cosmological models in and beyond **ΛCDM** (Universe being more linear)
- **Large volume** to be probed
- … but HI tracer is sensitive **to small scale** (astro) physics (intrinsically no threshold)
- And can probe **underdense regions** far from galaxies too

Clustering of LSS tracers (>Mpc) is coupled to the astrophysics at scales: *O*(10 pc)-*O*(100 kpc)

Atomic processes in place



- Spin-flip electron transition
- In the post-reio epoch HI is mainly in haloes
- Which dominate the emission signal

- **Mass weighted view** of the HI distribution

- Need to specify $M_{HI}(M_{halo})$ or Line luminosity as a function of M_{halo}

Atomic processes in place

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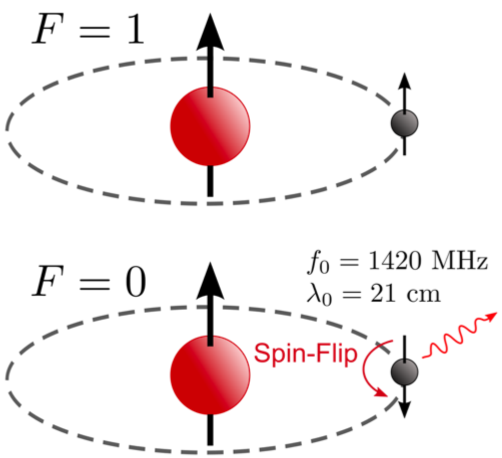
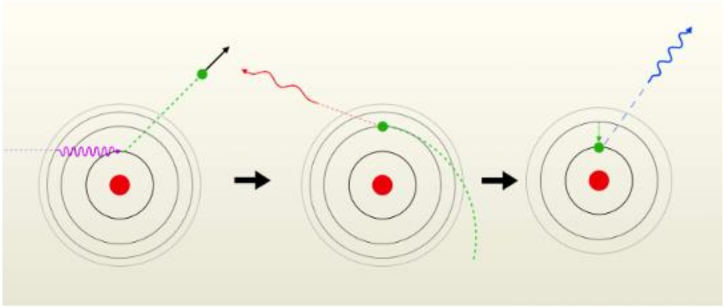
EMISSION



ABSORPTION

HI



$$\lambda = \lambda_0(1+z)$$
$$\lambda_0 = 1215.67\,\text{Å}$$

- Spin-flip electron transition
- In the post-reio epoch HI is mainly in haloes
- Which dominate the emission signal

- **Mass weighted view** of the HI distribution

- Need to specify $M_{HI}(M_{halo})$ or Line luminosity as a function of M_{halo}

- Lyman-α scattering
- Need a bright source behind
- Neutral fraction in most of the volume is <1.e-5

- **Volume weighted view** of the HI distribution

- Need to model Flux-DM density relation (very non-linear transform)

Holistic view on HI distribution

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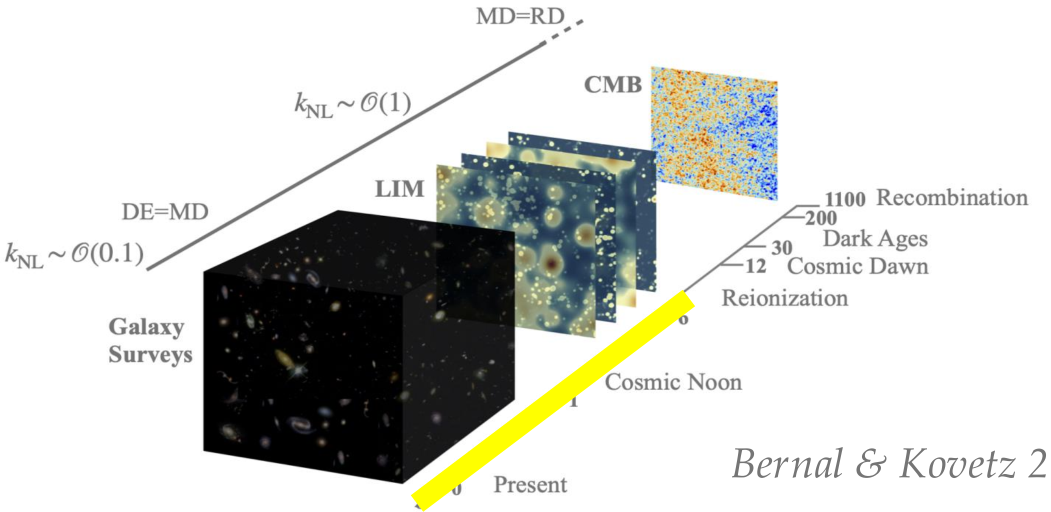
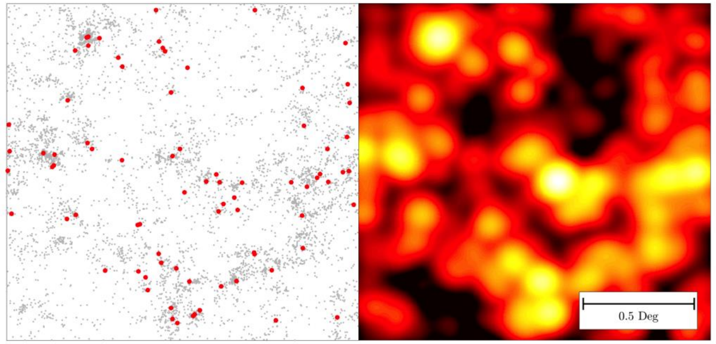
EMISSION Knots of the cosmic web



Bernal & Kovetz 2022

GALAXIES



LIM INTENSIY

Kovetz+18

Holistic view on HI distribution

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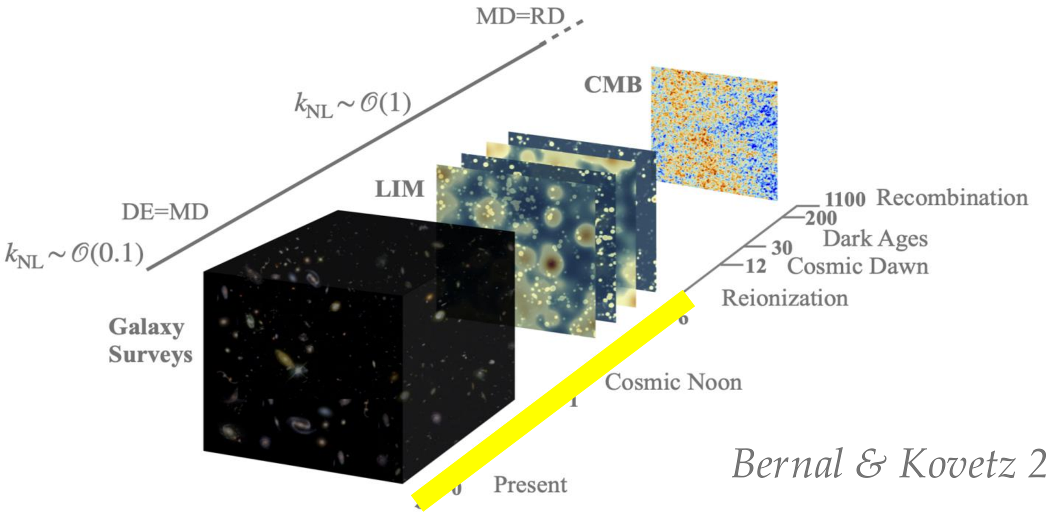
EMISSION Knots of the cosmic web



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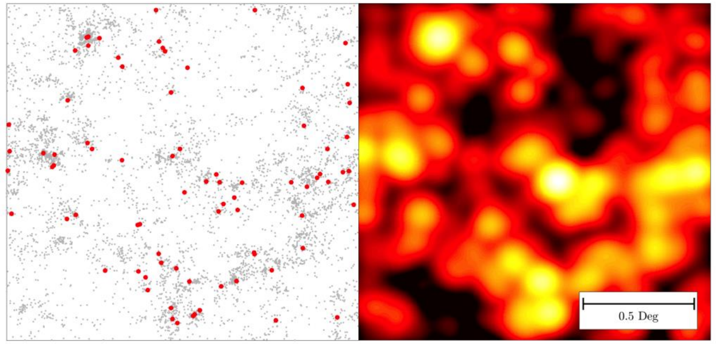

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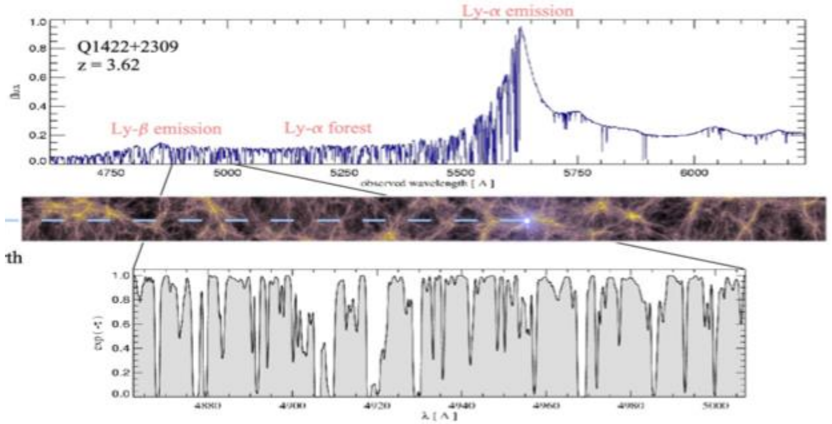
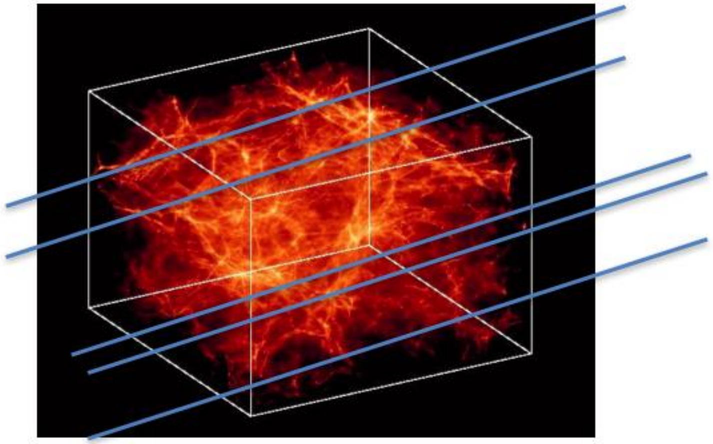




Quasars

Bolton+18, Puchwein+23

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?

What are the big questions?

- 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*

Promises of the post-reionization Universe

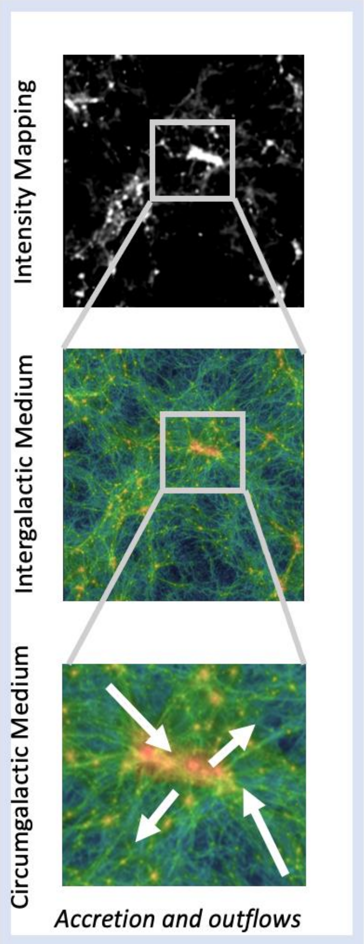
Matteo Viel

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

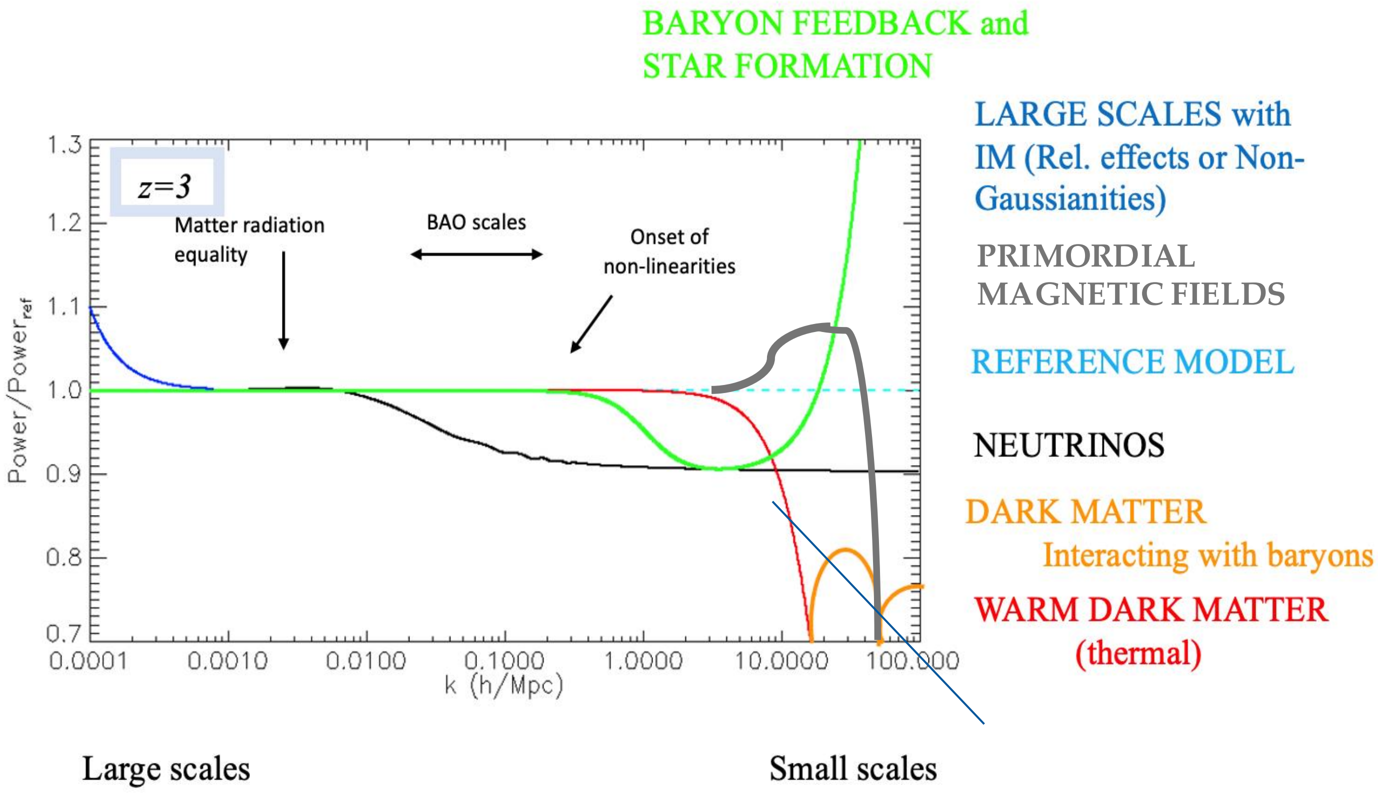
- **Power spectrum**
- **cross-correlations** of different tracers
- **new estimators** (e.g. 1-point function, bispectrum, Machine Learning)

It is an "active phase" of structure formation processes (feedback, star formation, black holes, cosmic bayron cycle etc.)

Environments



Physical Scales



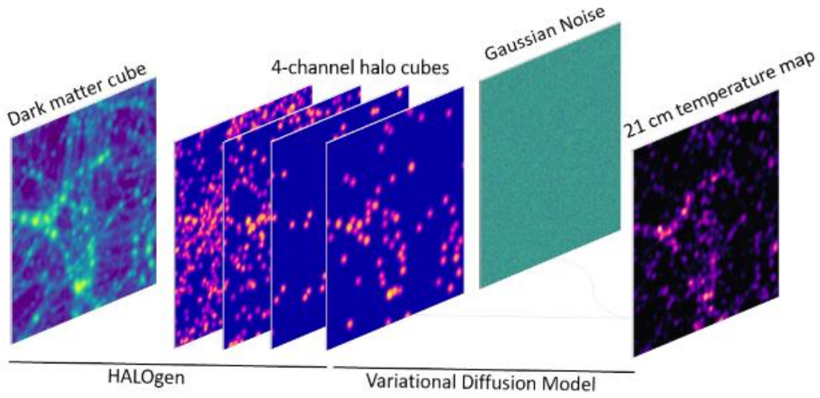
HI measures density perturbations in a matter dominated regime!

INTENSITY MAPPING

1) Modelling
2) Small scales
3) BAO

Methods: Learning LIM with diffusion models

LODI: **L**atent **O**verlap **D**iffusion for **I**ntensity Mapping



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

Mishra, Trotta, Viel, 2025 - arXiv:2506.08086

Methods: Learning LIM with diffusion models

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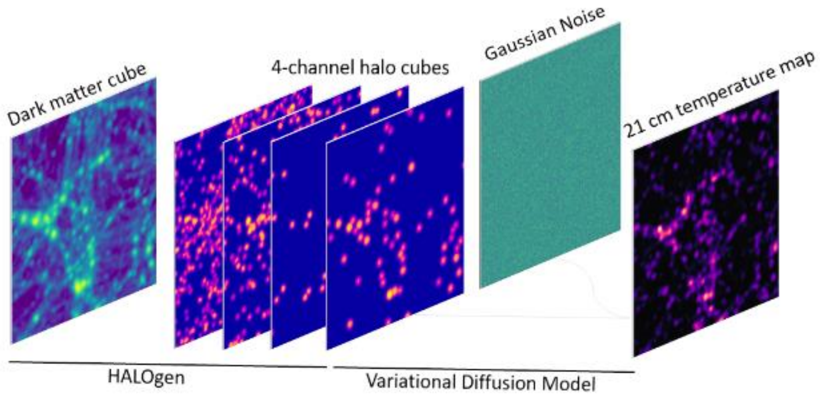
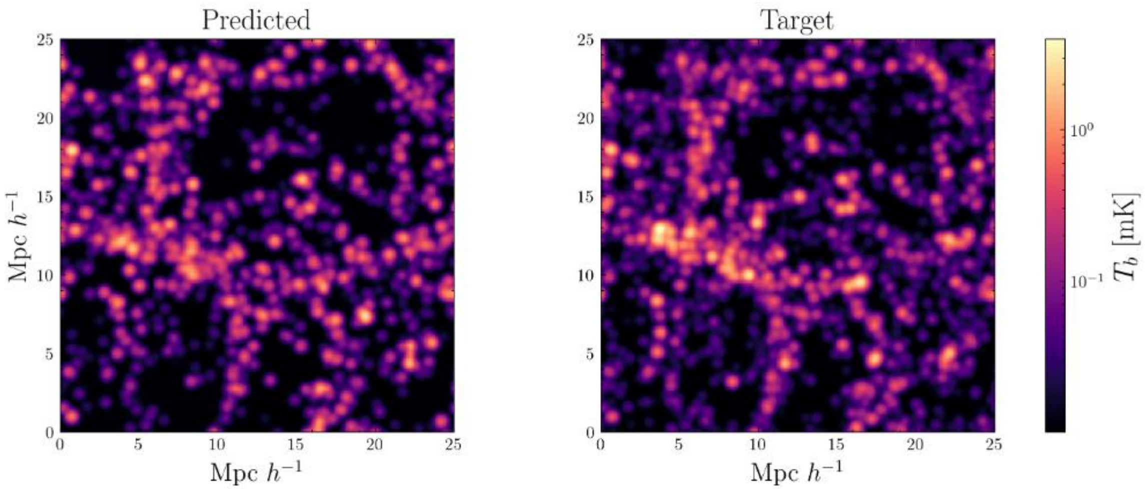
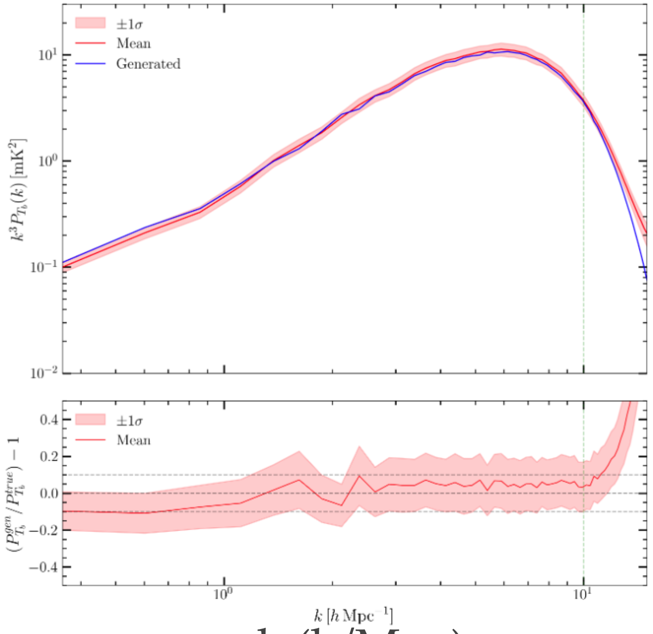




1st step: DM → haloes (via U-Net)
2nd step: Haloes → Intensity voxel map (via Diffusion model)

- Trained on CAMELS simulations
- Agreement up to k = 10 h/Mpc
- Extendable to other LIM lines
- Good for likelihood free field-level inference

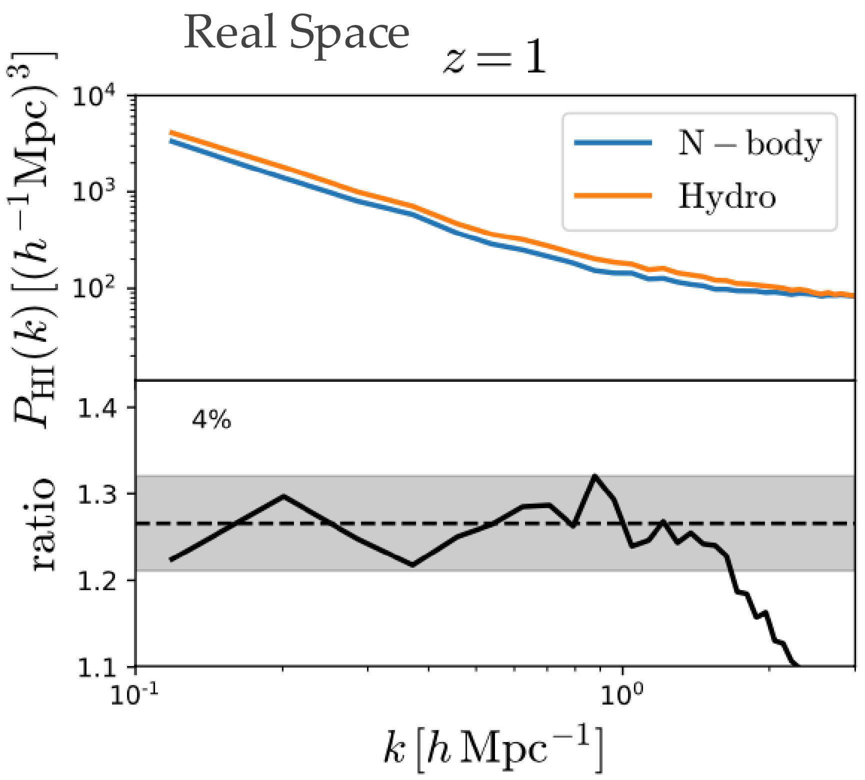
21cm power spectrum



k (h/Mpc)

Mishra, Trotta, Viel, 2025 - arXiv:2506.08086

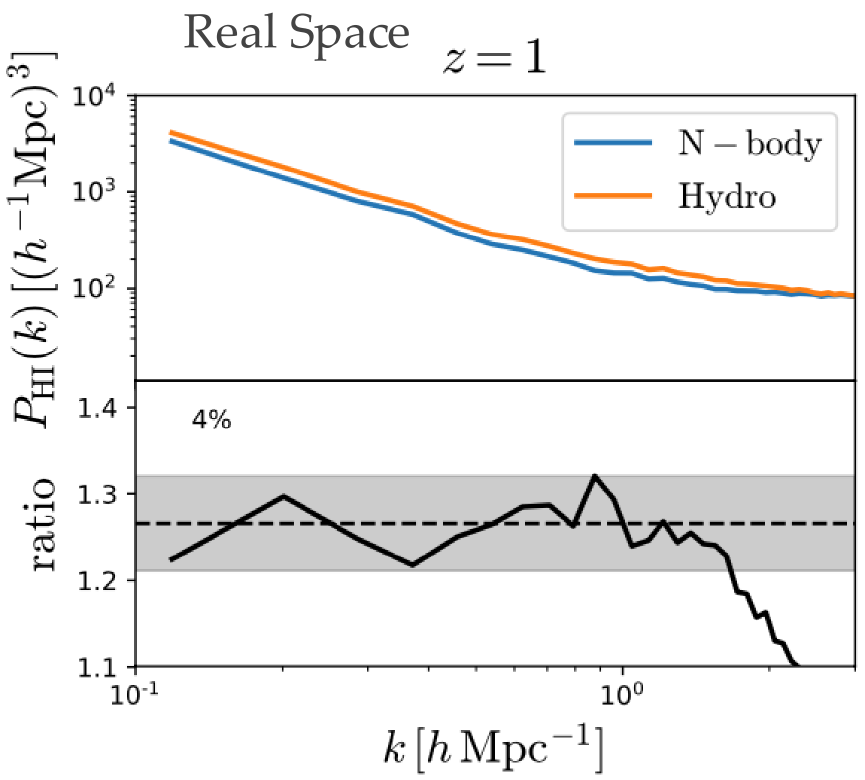
Modelling: populating haloes with HI

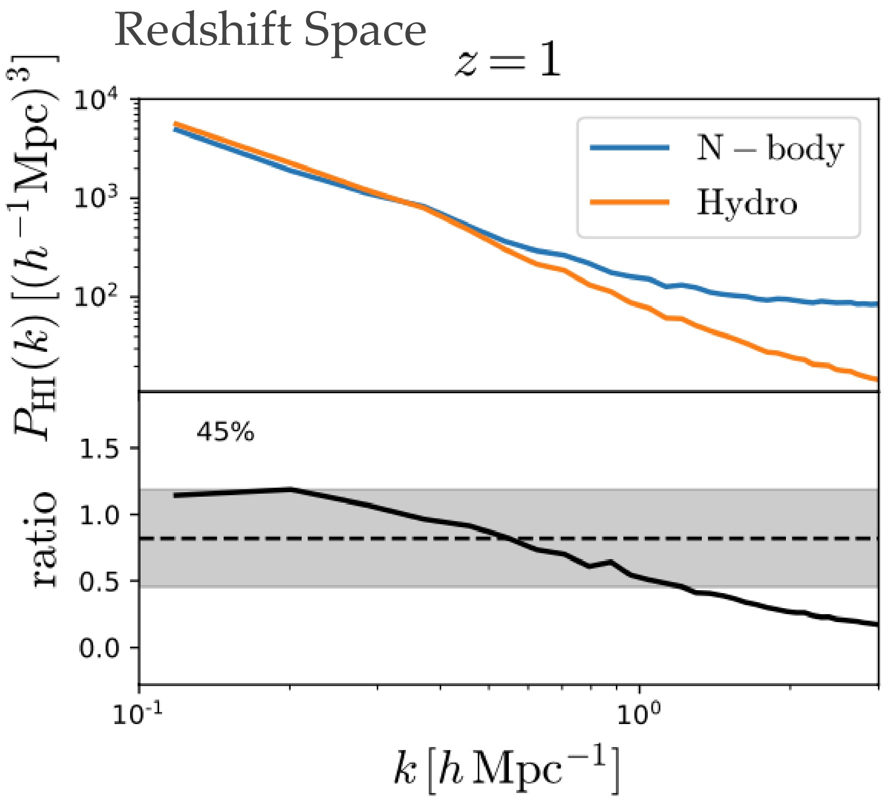


Villaescusa-Navarro+ 2018

Modelling: populating haloes with HI

Matteo Viel



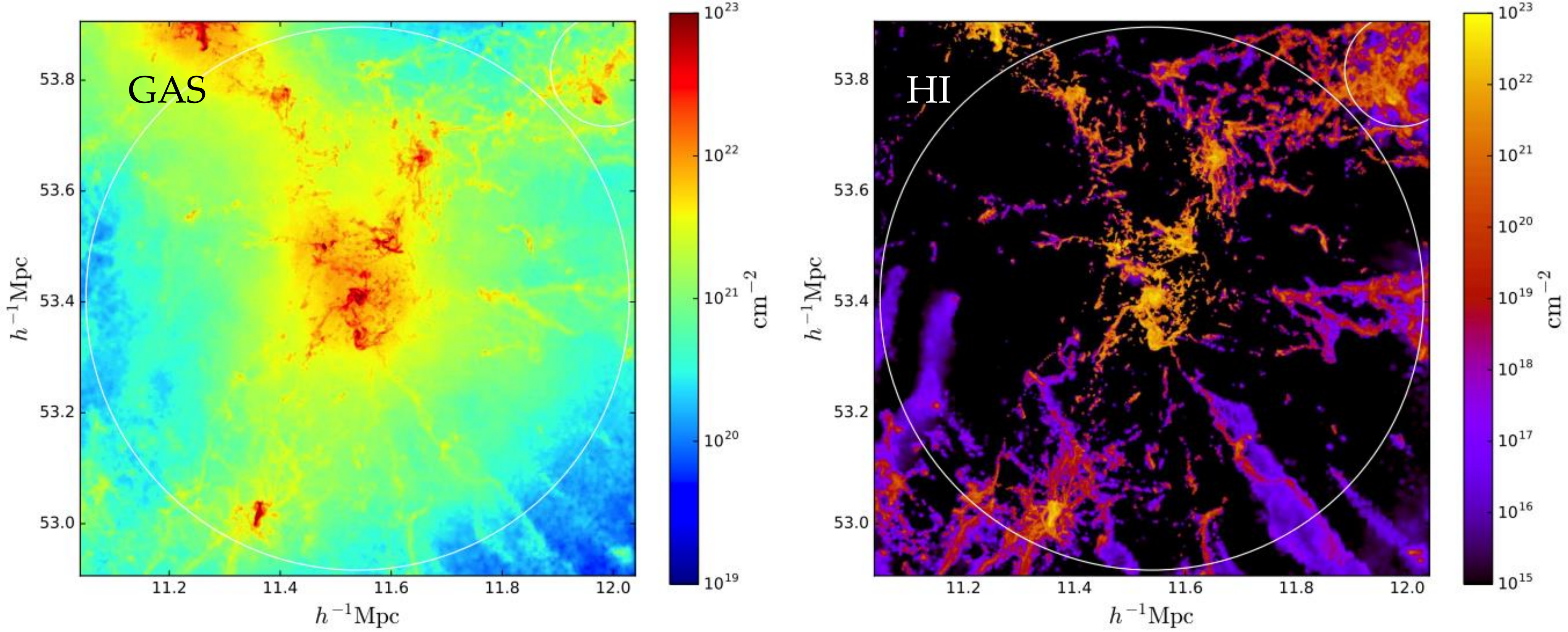


- N-body (all HI is in the center of the halo) vs. full hydro HI power spectrum (effectively there is a 1-halo term). Normalization is quite different but shape is reasonable.
- Kaiser effect (boosts power at large scales) vs. Finger of Gods (suppresses power at small scales but not so small). Behaviour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

Villaescusa-Navarro+ 2018

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?

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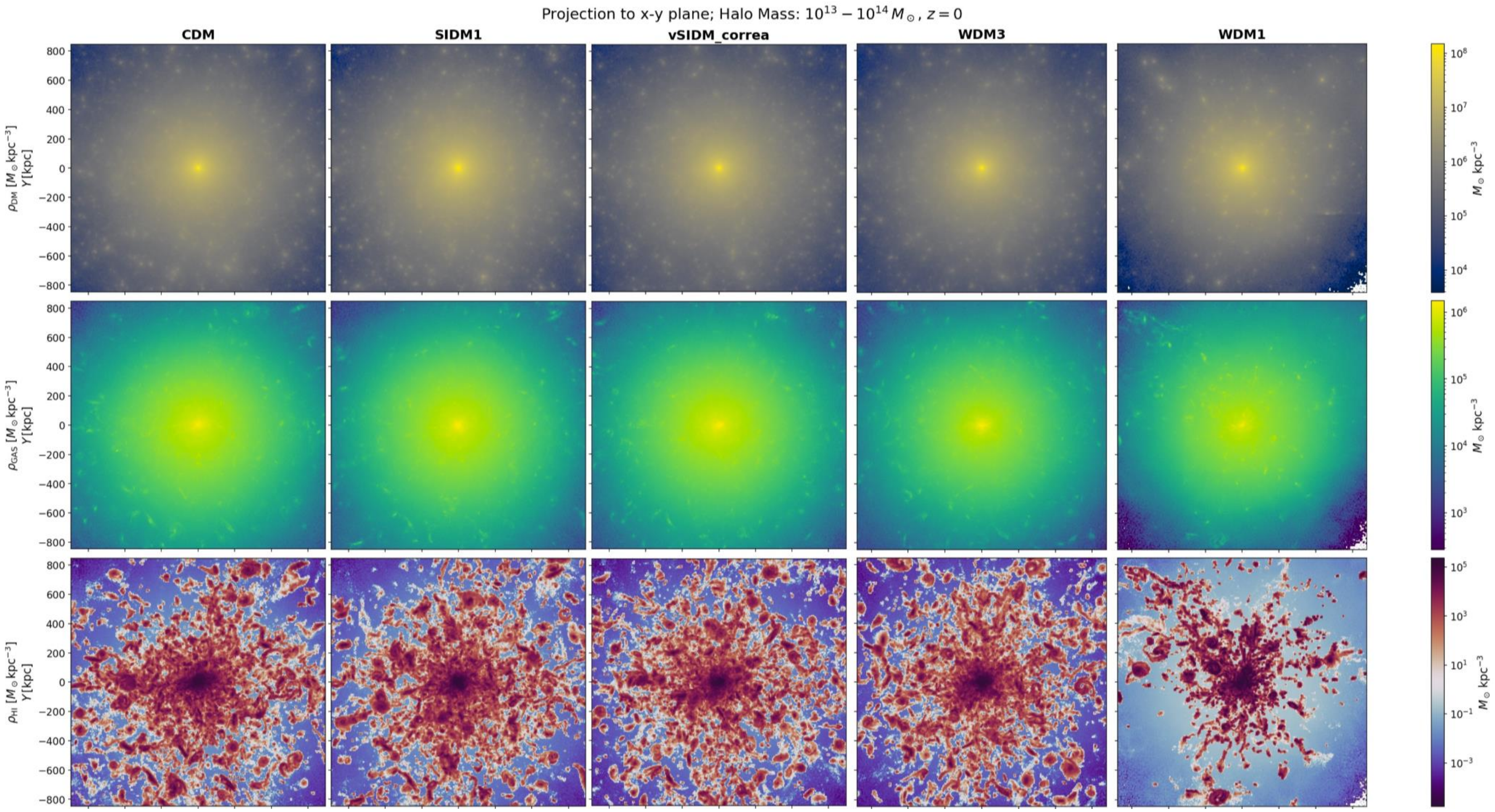
Redshift z=0 stacking of 100 haloes 10^{13}-10^{14} $M_\odot$

DM SIDM vSIDM WDM3keV WDM1keV

DM

GAS

HI



Zhang, Garaldi, Despali, Viel 2025 in prep.

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

Matteo Viel

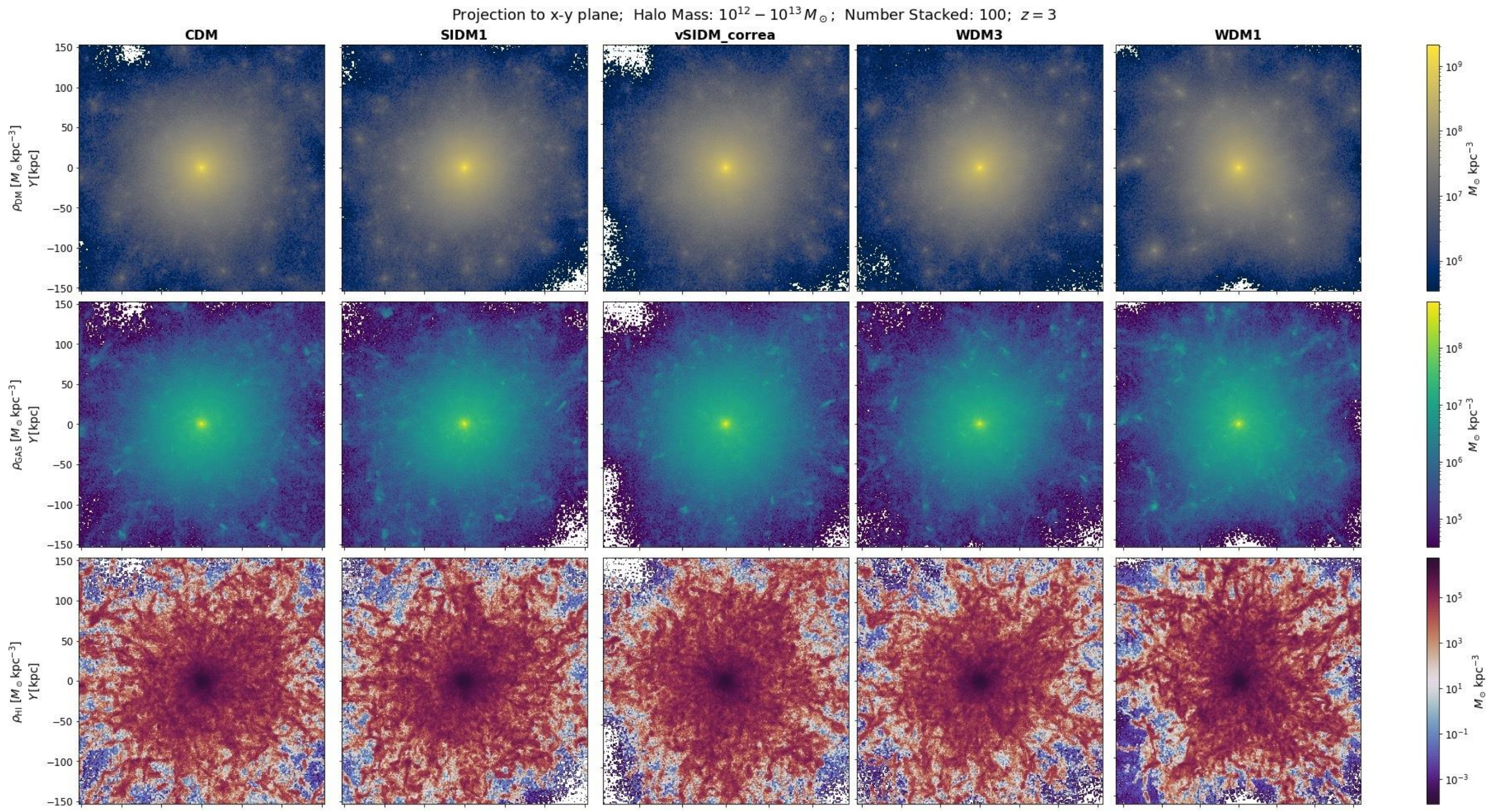
Redshift z=3
stacking of 100
haloes 10^{12}-10^{13} $M_\odot$

DM | SIDM | vSIDM | WDM3keV | WDM1keV

DM

GAS

HI

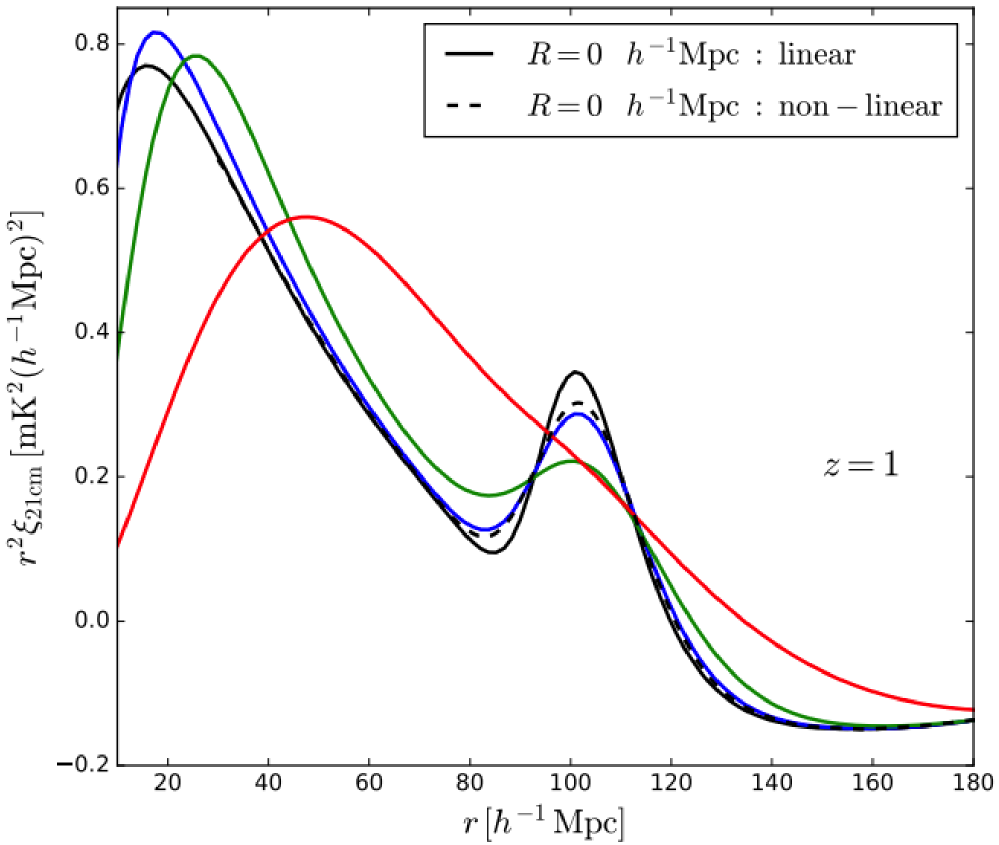


Zhang, Garaldi, Despali, Viel 2025 in prep.

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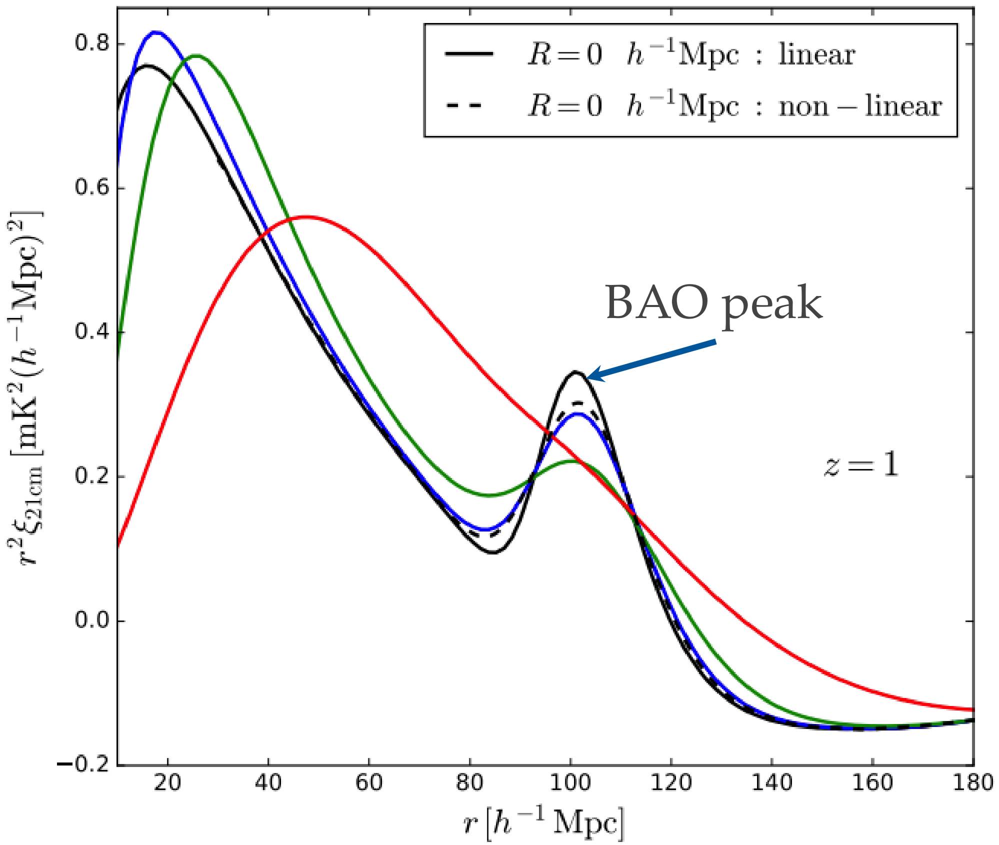
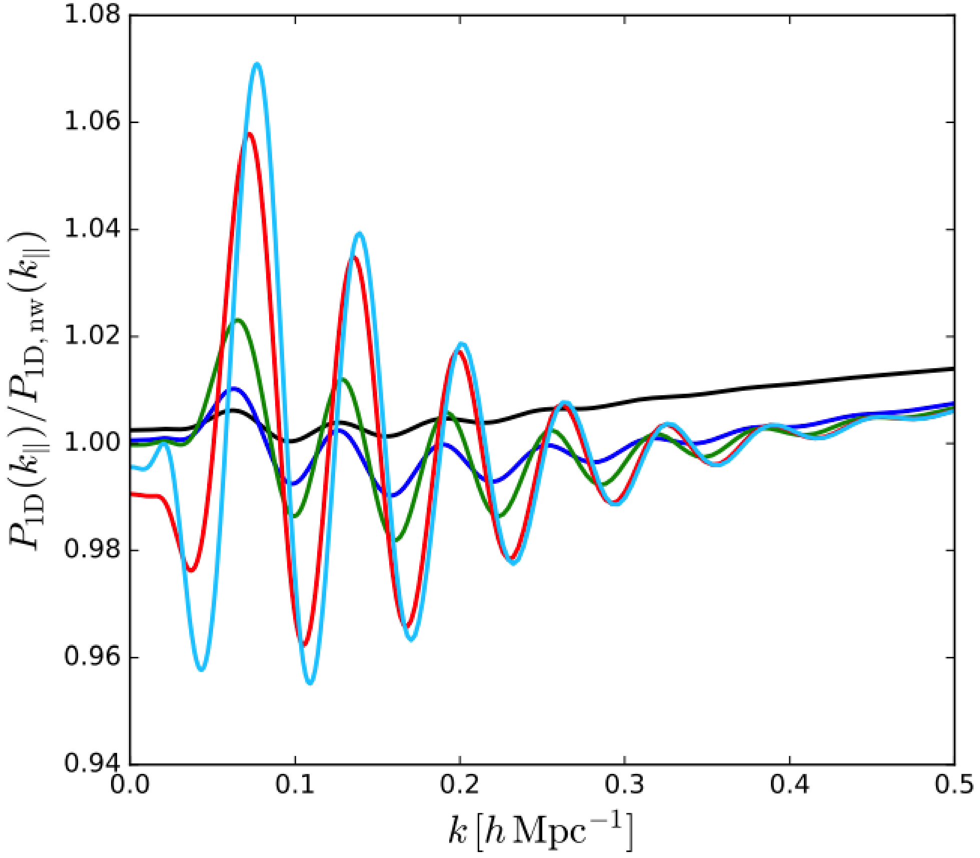
$$\lim_{R\to\infty} P_{21\mathrm{cm,obs,1D}}(k_\parallel, z) = \frac{1}{4\pi R^2} P_{21\mathrm{cm}}(k_\parallel, z)$$

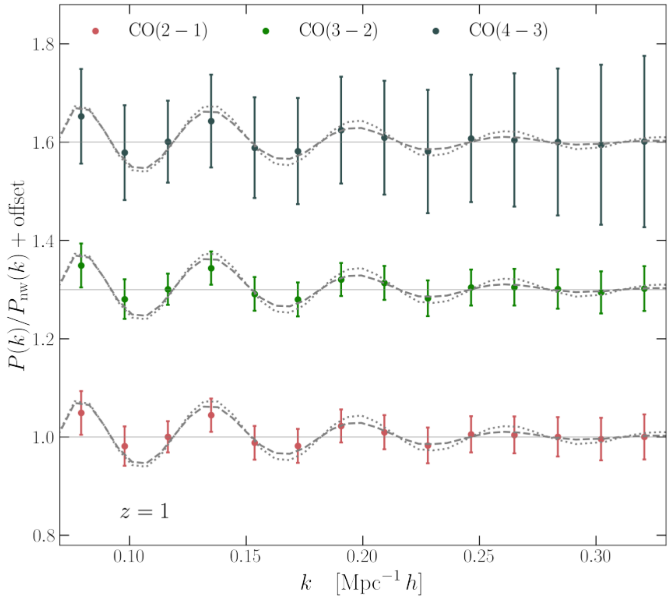




Villaescusa-Navarro, Alonso, MV 2017

BAO with other LIM experiments

- 3% error on BAO peak position at z=2.5 with noise and foregrounds for SKA
- This could improve to 1.7% with BAO pixel-reconstruction
- And other IM lines could be used to (different systematics)



Moradinezhad Dizgah, Nikakthar, Keating, Castorina 22

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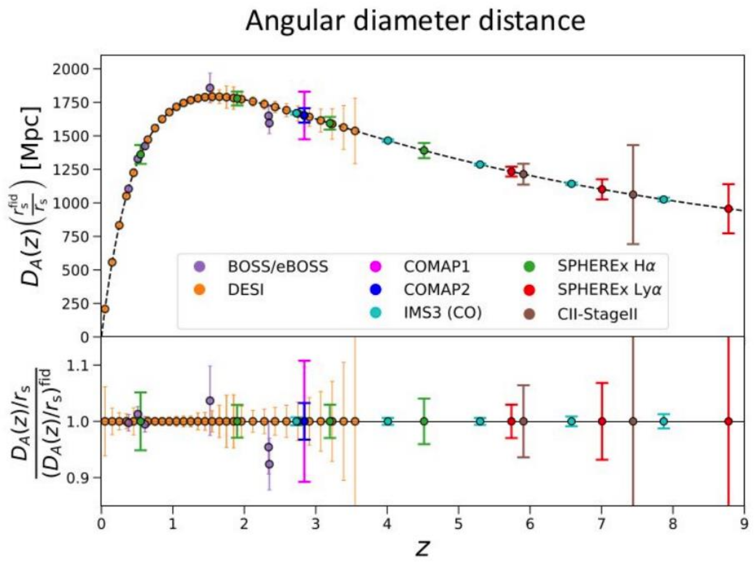

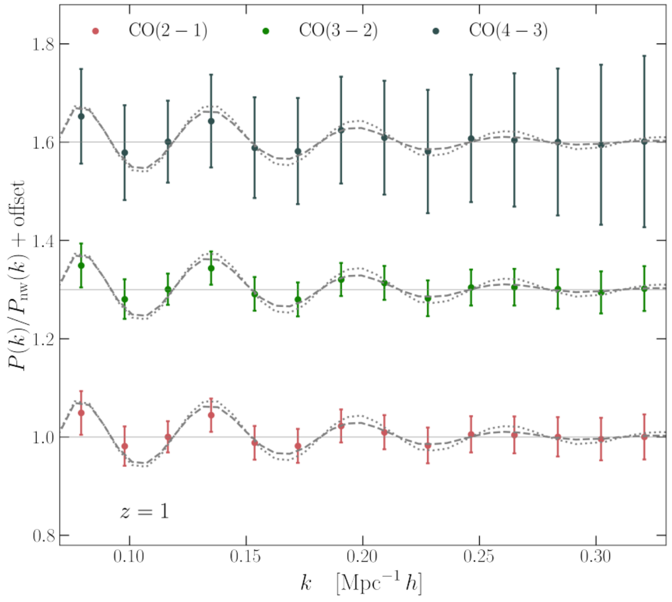

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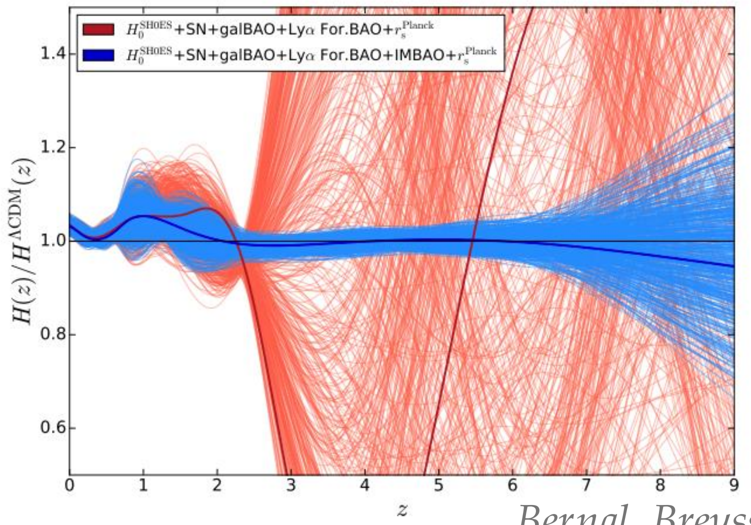


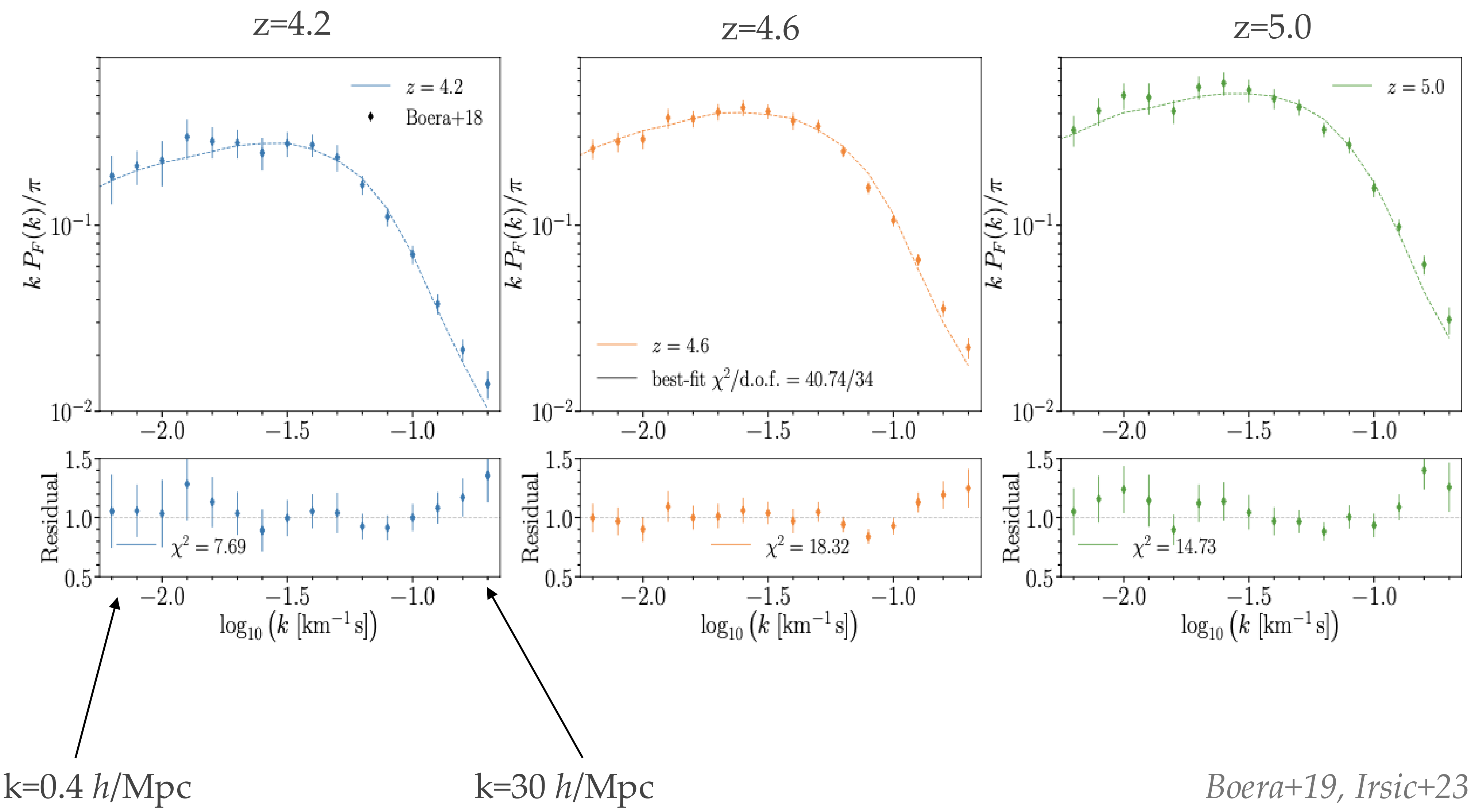
Bernal, Breysse, Kovetz 2019

LYMAN-α FOREST

1) Modelling relics of reionization
2) Warm Dark Matter
3) Primordial Magnetic Fields
4) Heath injections

The data

1D FLUX POWER



Boera+19, Irsic+23

Theory: patchy reionization

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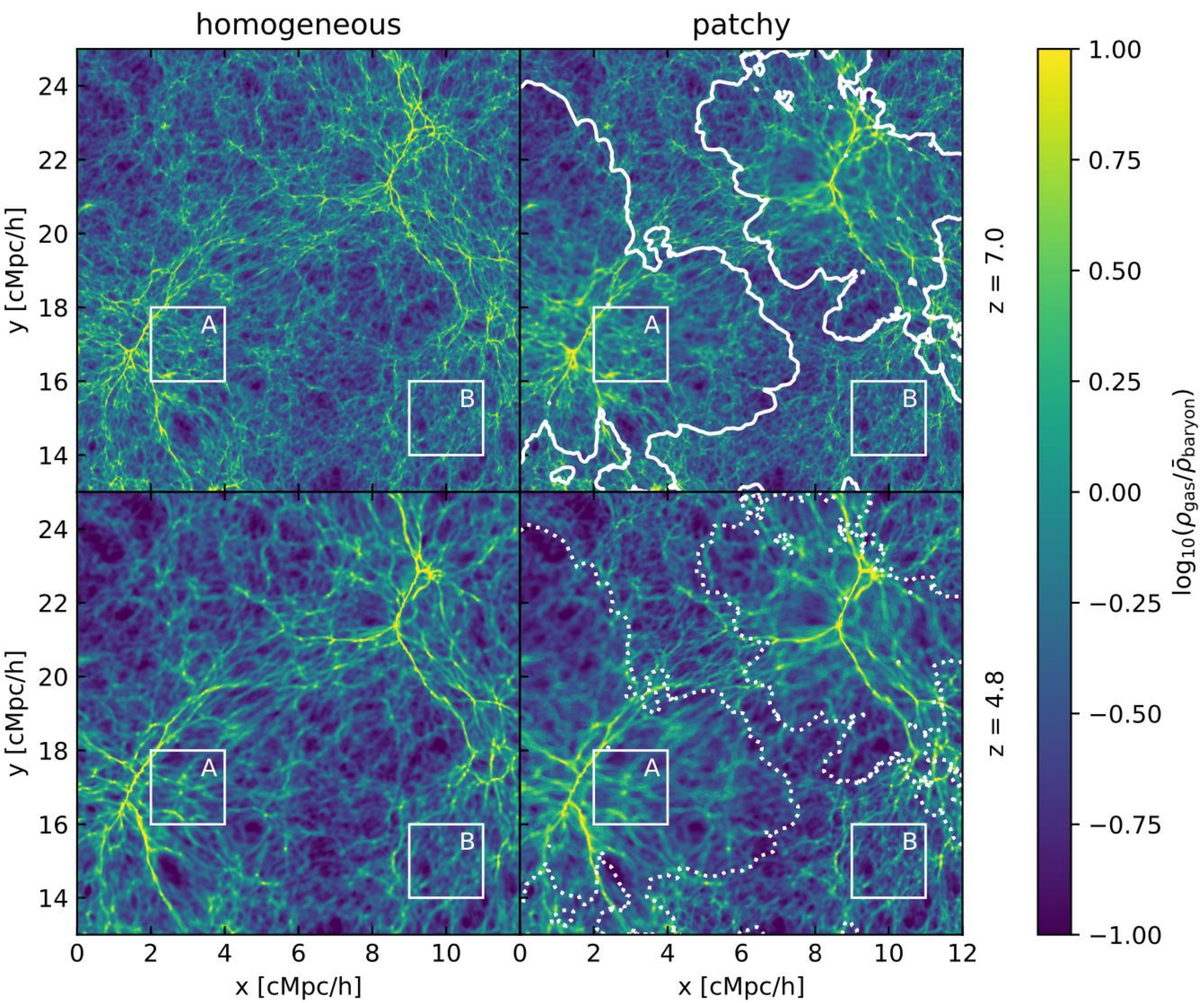


During reionization z=7

Note:
Reionization ends at z =5.4

After reionization z=4.8

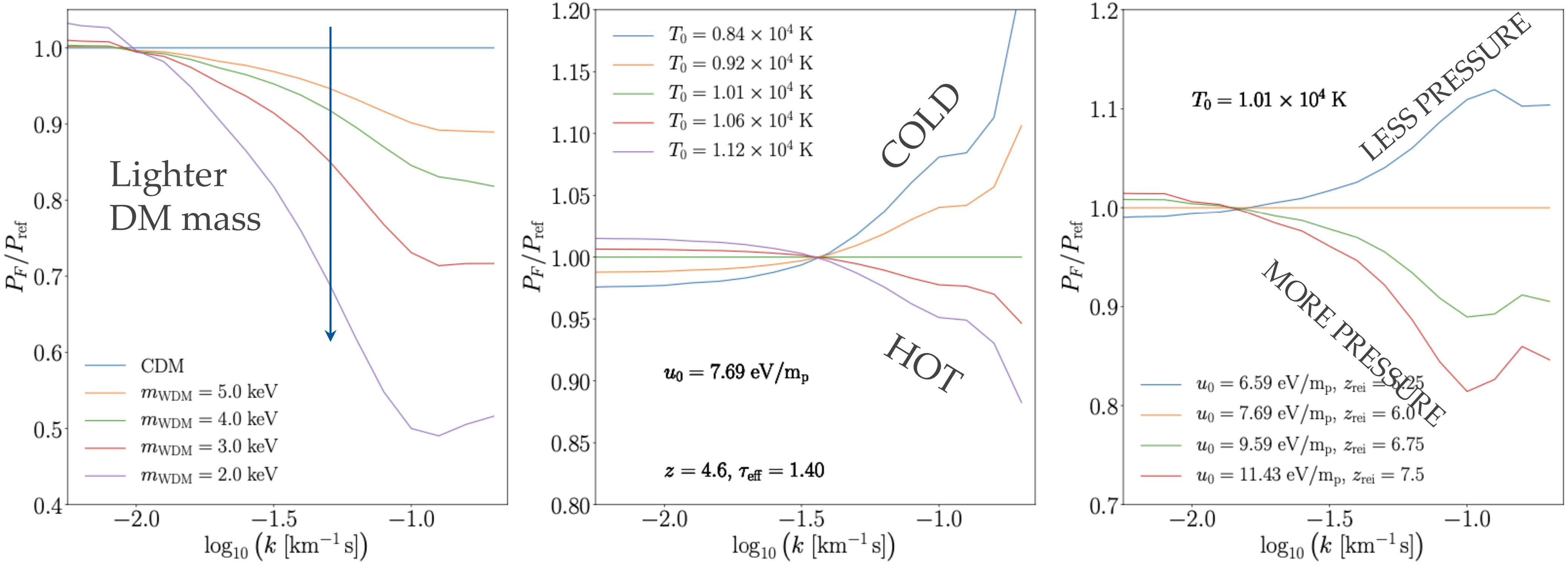
Puchwein+23

The smoothing scales

Unveiling Dark Matter free-streaming at the smallest scales with high redshift Lyman-alpha forest

Vid Iršič[1,2], Matteo Viel[3,4,5,6,7], Martin G. Haehnelt[1,8], James S. Bolton[9], Margherita Molaro[9], Ewald Puchwein[10], Elisa Boera[5,6], George D. Becker[11], Prakash Gaikwad[12], Laura C. Keating[13], Girish Kulkarni[14]
[1]Kavli Institute for Cosmology, University of Cambridge

WDM free streaming | Thermal broadening | Gas pressure



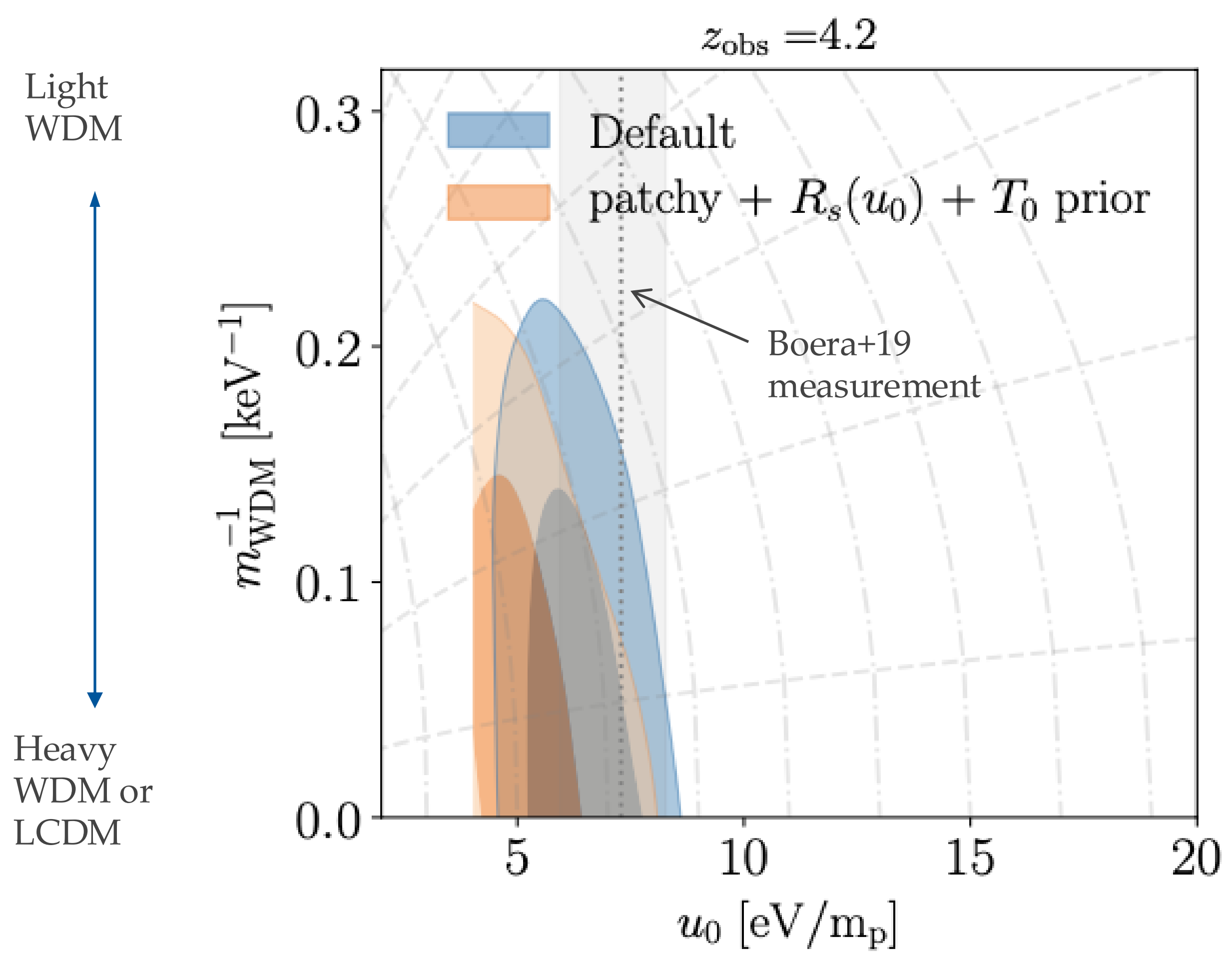
$$u_0(t) = \int_0^t dt\, \frac{\mathcal{H}}{\bar{\rho}_m} \frac{3k_B}{2\mu}$$

H is heating rate

Thermal WDM - II

Light
WDM

Heavy
WDM or
LCDM

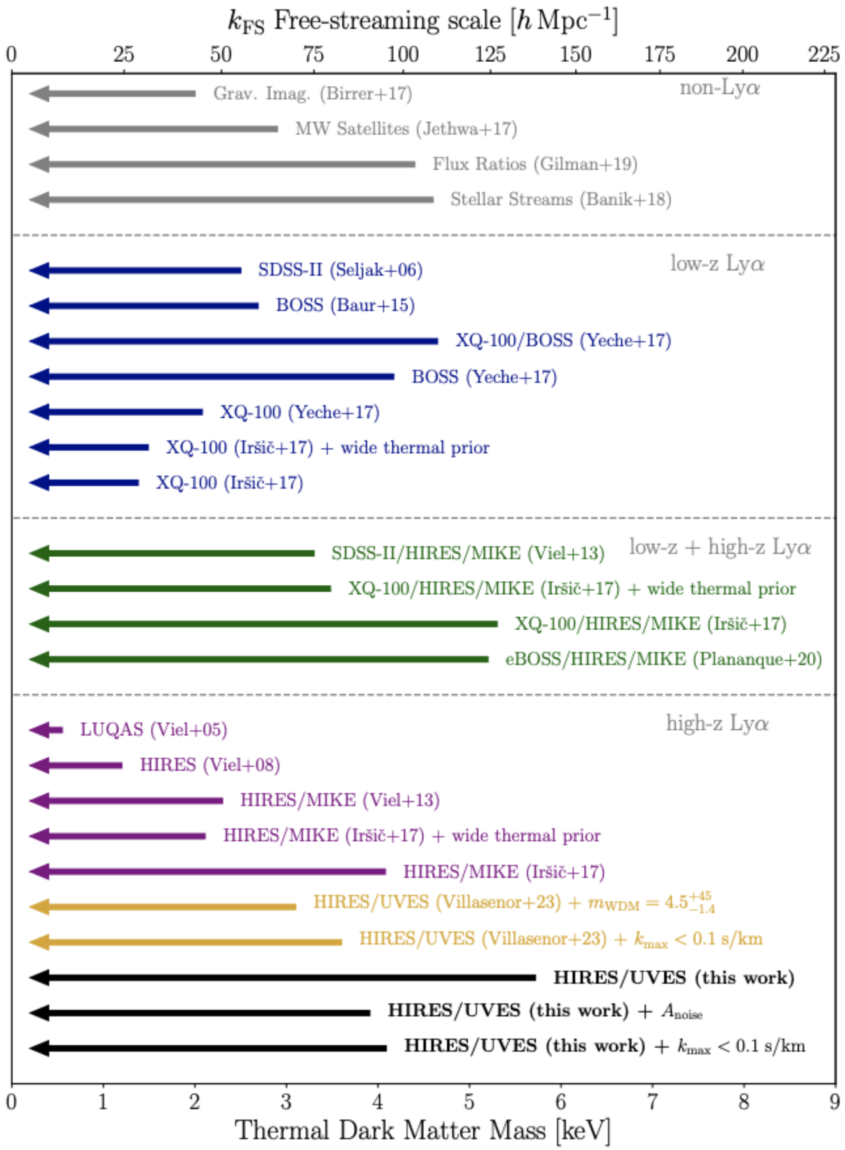


Injected heat proxy for GAS pressure

Irsic, MV +23

Thermal Warm Dark Matter Constraints

Matteo Viel



Tests made:

Cut small scales

Marginalize over data noise

Assume/Remove T_0 priors

Correct for a model dependent resolution

Patchy reionization models

Name	m_{WDM} [keV] (2σ)
Default	> 5.72
$k_{max} < 0.1$ km^{-1} s	> 4.10
A_{noise}	> 3.91
T_0 prior	> 5.85
$R_s(u_0)$ mass resolution	> 4.44
patchy reion.	> 5.10
$R_s(u_0) + T_0$ prior	> 4.24
patchy + $R_s(u_0) + T_0$ prior	> 5.90

If f_{WDM} is allowed to vary for m_{WDM}=3 keV

f_{WDM}<0.5

Irsic, MV +23-
Garcia-Gallego, Irsic+25

arXiv:2504.06367

The IGM as a thermometer

- Dark photon Dark Matter: simple extension of the SM of particle physics

$$\mathcal{L}_{\gamma A'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_{\mu}$$

- Dark photon converts into standard photon when a resonance condition is met

$$E_{A'\to\gamma} \sim 2.5\,\mathrm{eV}\left(\frac{\epsilon_{-14}}{0.5}\right)^2 \left(\frac{3}{1+z_{\rm res}}\right)^{3/2} \left(\frac{m_{-13}}{0.8}\right)$$

Bolton, Caputo, Liu, MV, PRL, 2022 - Trost, Bolton, Caputo, Liu, Viel PRD 2025

The IGM as a thermometer (low redshift)

- Dark photon Dark Matter: simple extension of the SM of particle physics

$$\mathcal{L}_{\gamma A'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_{\mu}$$

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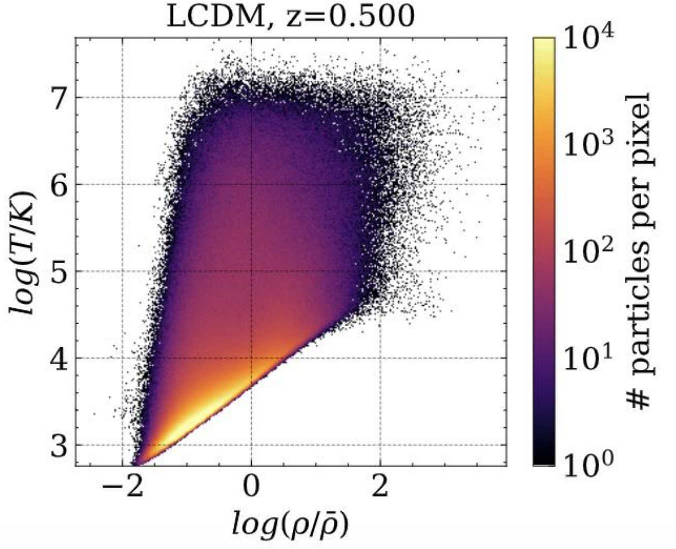
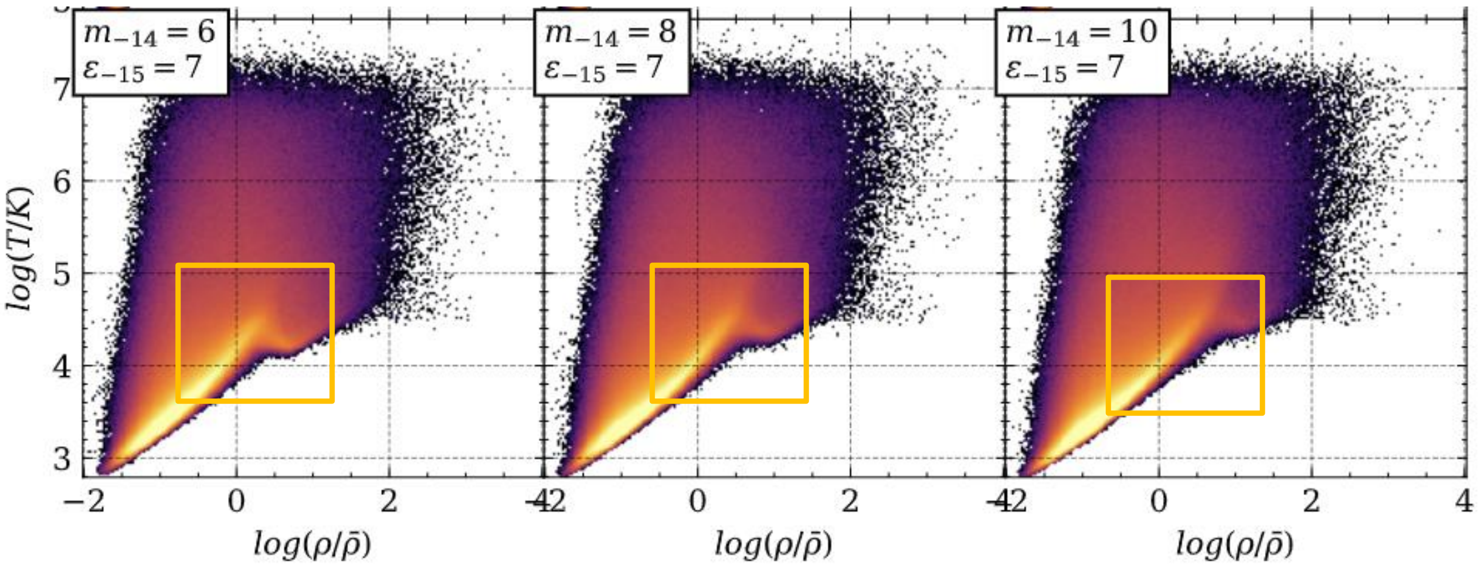
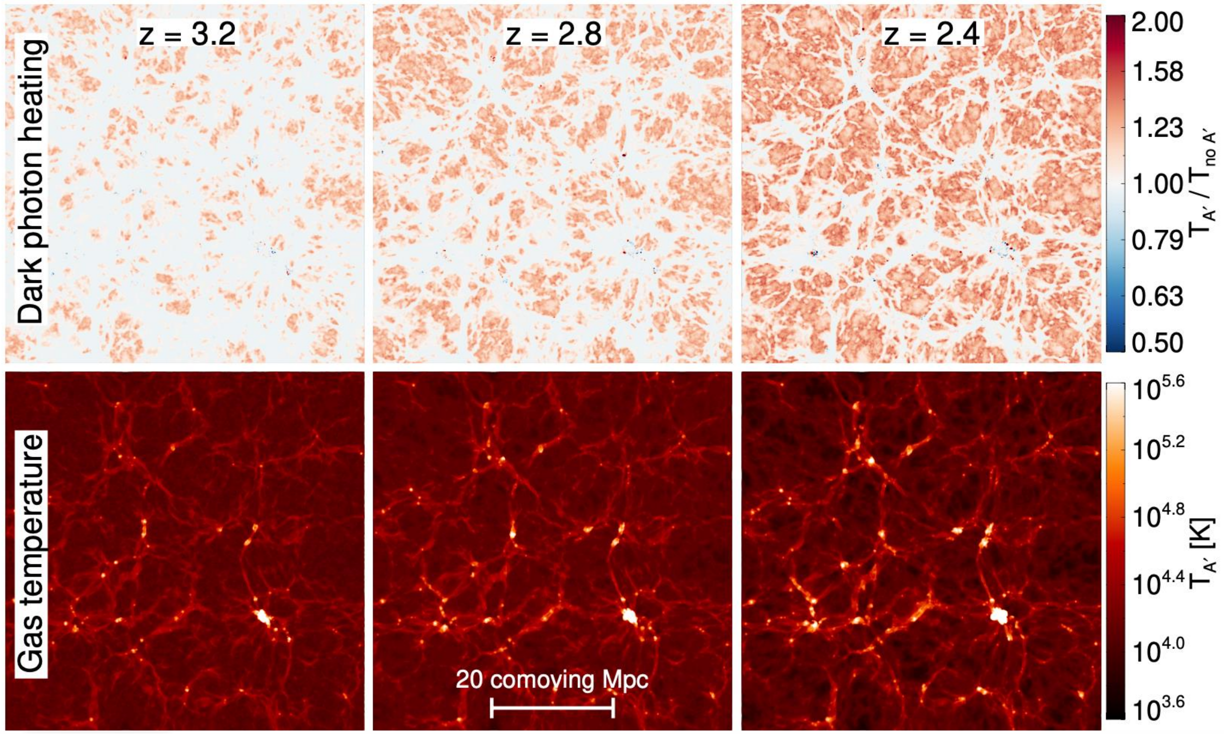




Bolton, Caputo, Liu, MV, PRL, 2022 - Trost, Bolton, Caputo, Liu, Viel PRD 2025

The IGM as a thermometer (high redshift)

Distinctive heating mechanism happening far away from complex astrophysics



Trost+25

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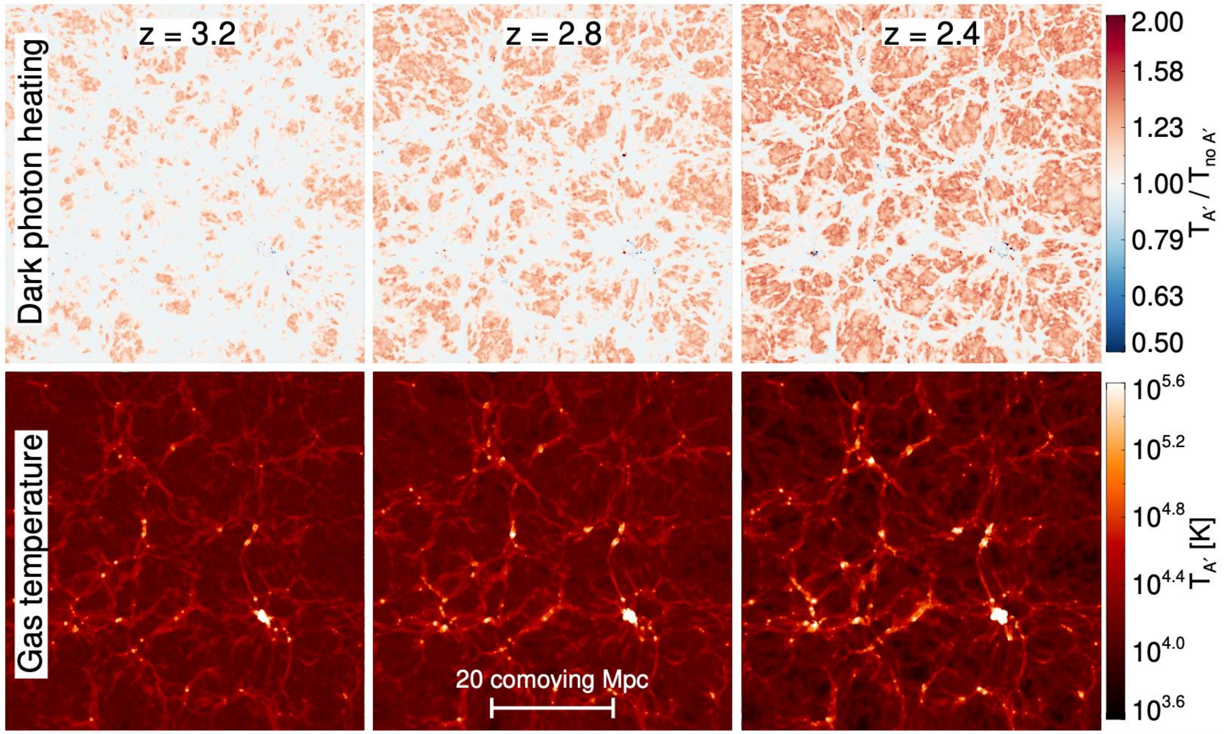

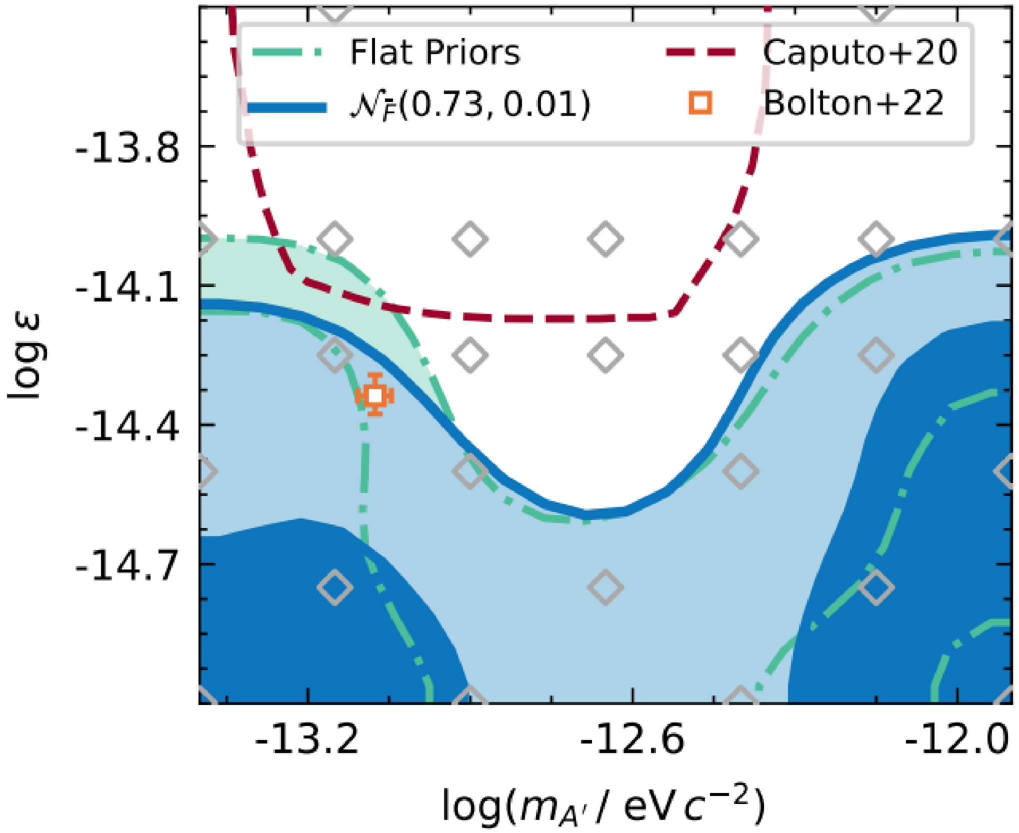

Trost+25

Ideal MHD in the postrecombination Universe

Matteo Viel

$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

Comoving Magnetic field is conserved

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a \partial a} = -\frac{\nabla\cdot(\nabla\times\vec{B})\times\vec{B}}{(4\pi a^3 \rho_b)a^5 H^2} + \frac{\nabla^2 \phi}{(a^2 H)^2}$$

Baryon perturbations driven by magnetic field and gravity

$$\nabla^2 \phi = \frac{a^2}{2M_{Pl}^2}(\rho_b \delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2 \phi}{(a^2 H)^2}$$

Gravity has the usual form

Ideal MHD in the postrecombination Universe

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$$\frac{\partial(\vec{B})}{\partial t} = 0$$

S_0/a^3H^2

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a \partial a} = -\frac{\nabla\cdot(\nabla\times\vec{B})\times\vec{B}}{(4\pi a^3\rho_b)a^5H^2} + \frac{\nabla^2\phi}{(a^2H)^2}$$

$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

$$S_0 = \frac{\nabla\cdot[(\nabla\times\vec{B})\times\vec{B}]}{4\pi a^3\rho_{\rm b}}$$

Key ingredient is the S_0 source term

Ideal MHD in the postrecombination Universe

Matteo Viel

$$a^2\frac{\partial^2\delta_b}{\partial a^2}+a\frac{3}{2}\frac{\partial\delta_b}{\partial a}-\frac{3}{2}\frac{\Omega_b}{\Omega_m(1+a_{eq}/a)}\delta_b=-\frac{S_0}{a^3H^2}+\frac{3}{2}\frac{\Omega_{DM}}{\Omega_m(1+a_{eq}/a)}\delta_{DM}$$

$$a^2\frac{\partial^2\delta_{DM}}{\partial a^2}+a\frac{3}{2}\frac{\partial\delta_{DM}}{\partial a}-\frac{3}{2}\frac{\Omega_{DM}}{\Omega_m(1+a_{eq}/a)}\delta_{DM}=\frac{3}{2}\frac{\Omega_b}{\Omega_m(1+a_{eq}/a)}\delta_b.$$

DM

baryons

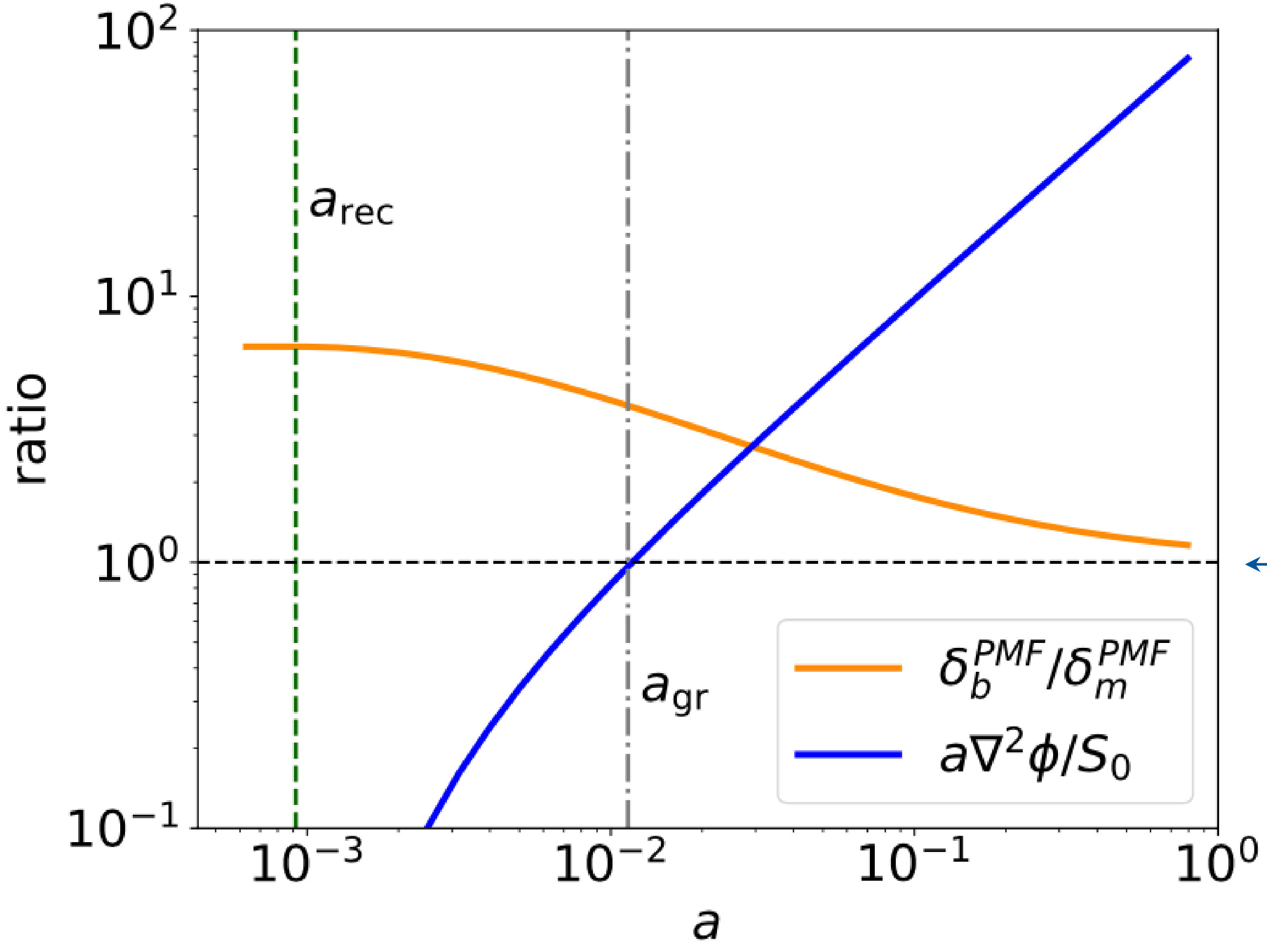
Coupled differential equations

$$\delta_b^{PMF}=-\xi_b(a)\frac{S_0}{a^3H^2}\qquad \delta_{DM}^{PMF}=-\xi_{DM}(a)\frac{S_0}{a^3H^2}.$$

$$P_b^{PMF}\propto P_{S0}$$

Power spectrum of Lorentz force
For n_B~ -3 (scale invariant) this returns
P_{matter} ~ k

Ideal MHD in the postrecombination Universe



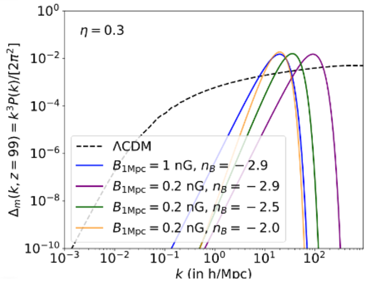
- Ratio of perturbations is equivalent to baryon fraction and starts very high and only now reaches the cosmic mean 0.17 value

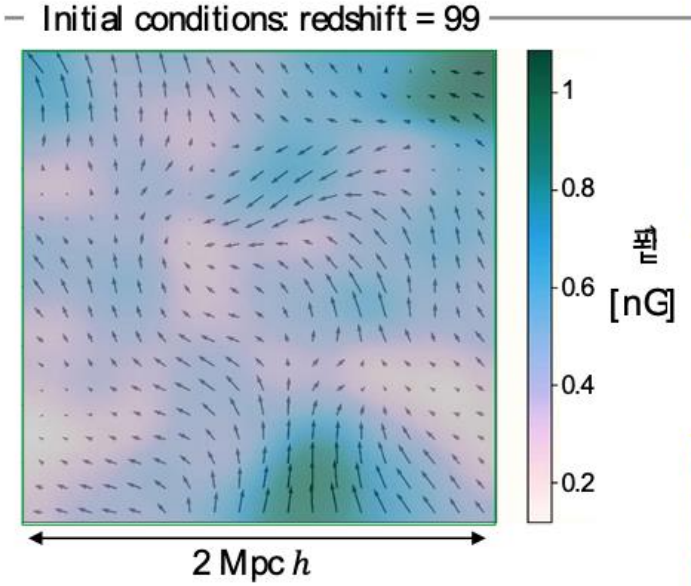
← Cosmic mean

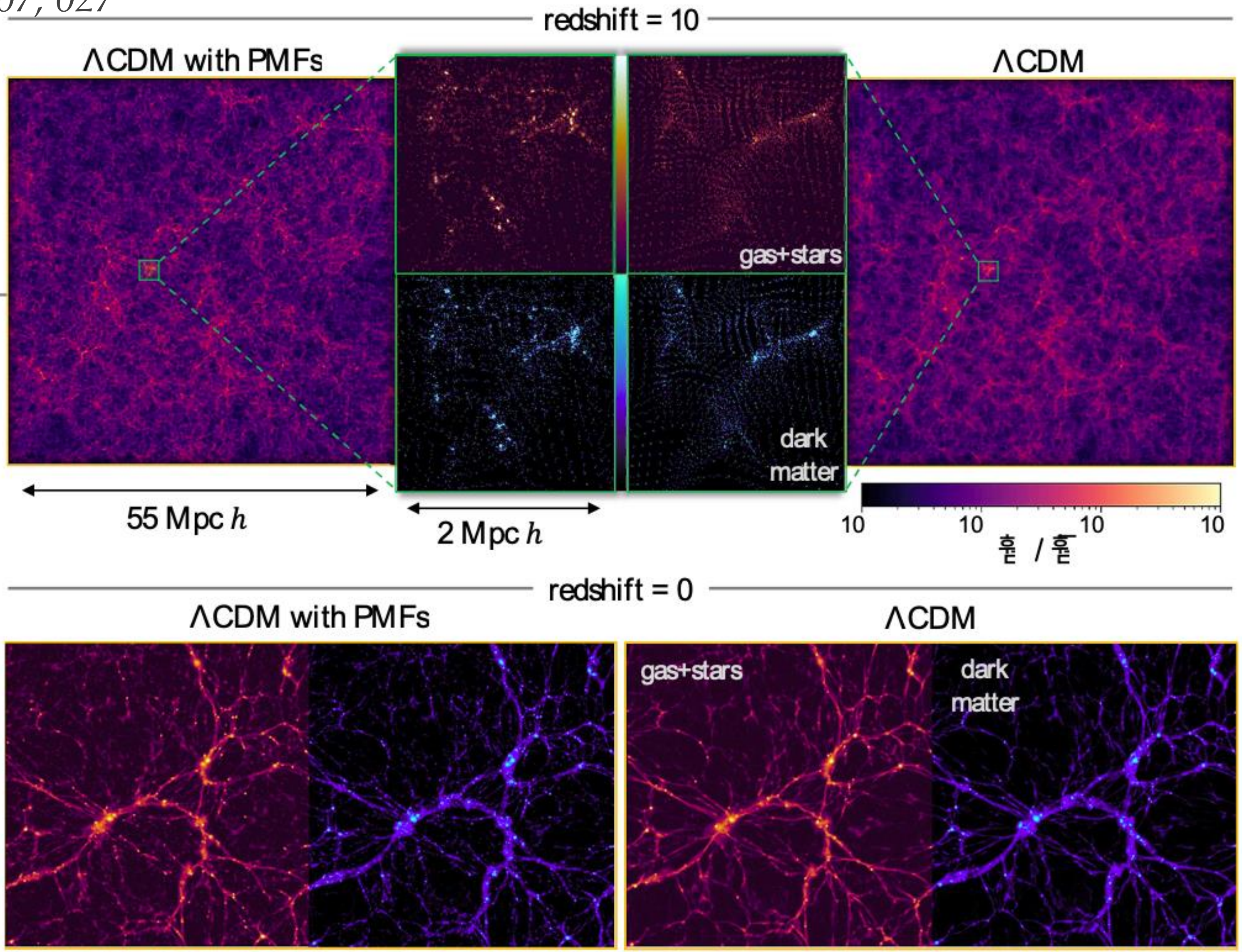
Raleganker, Pavicevic, Viel, 2024, JCAP, 07, 027

Hydro sims with extra PMFs-induced power

Raleganka r, Pavicevic, Viel, 2024, JCAP, 07, 027



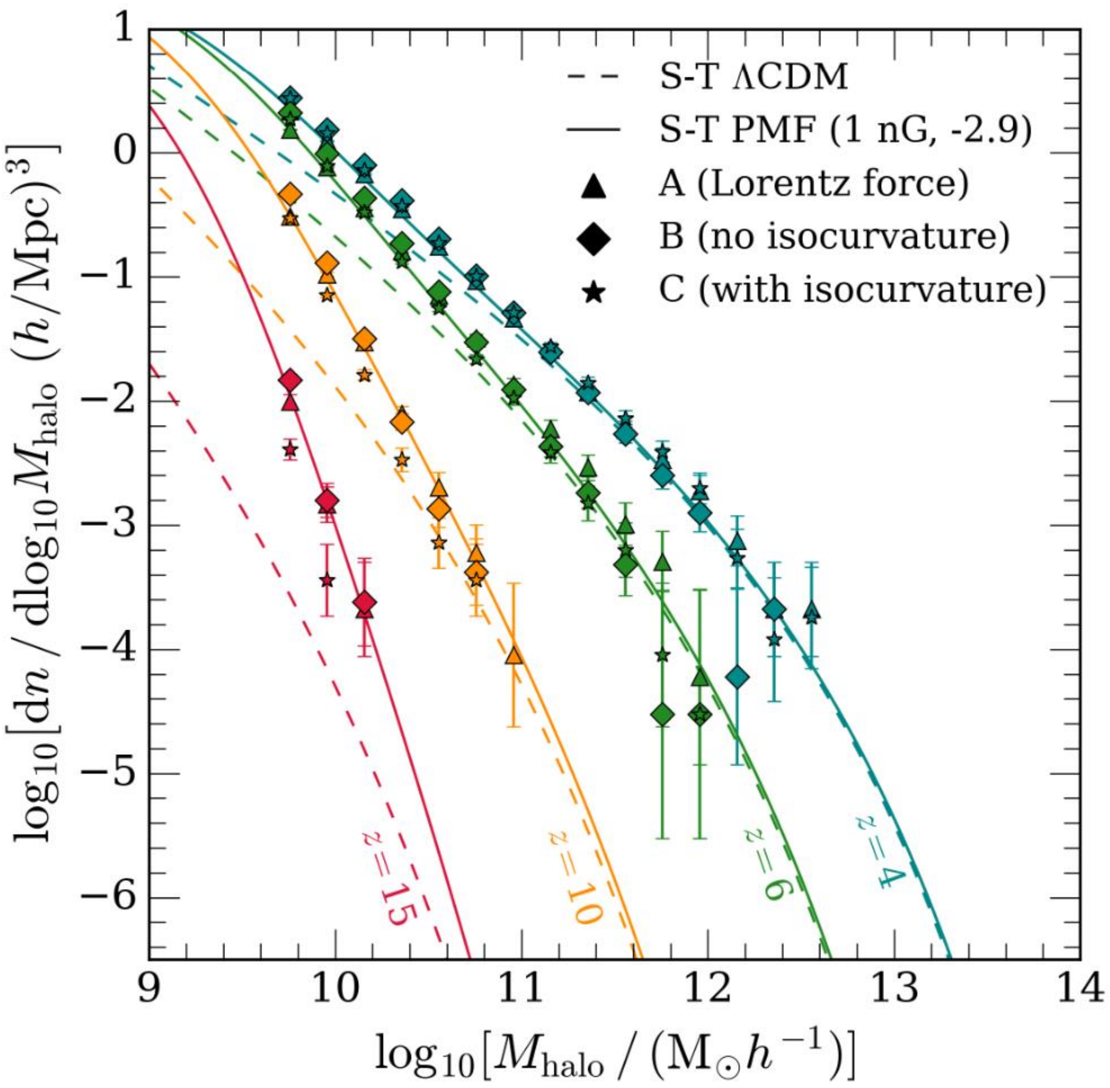




NEW IMPLEMENTATION

1) Baryons displaced according to Lorentz force
2) Different transfer function for baryons and DM

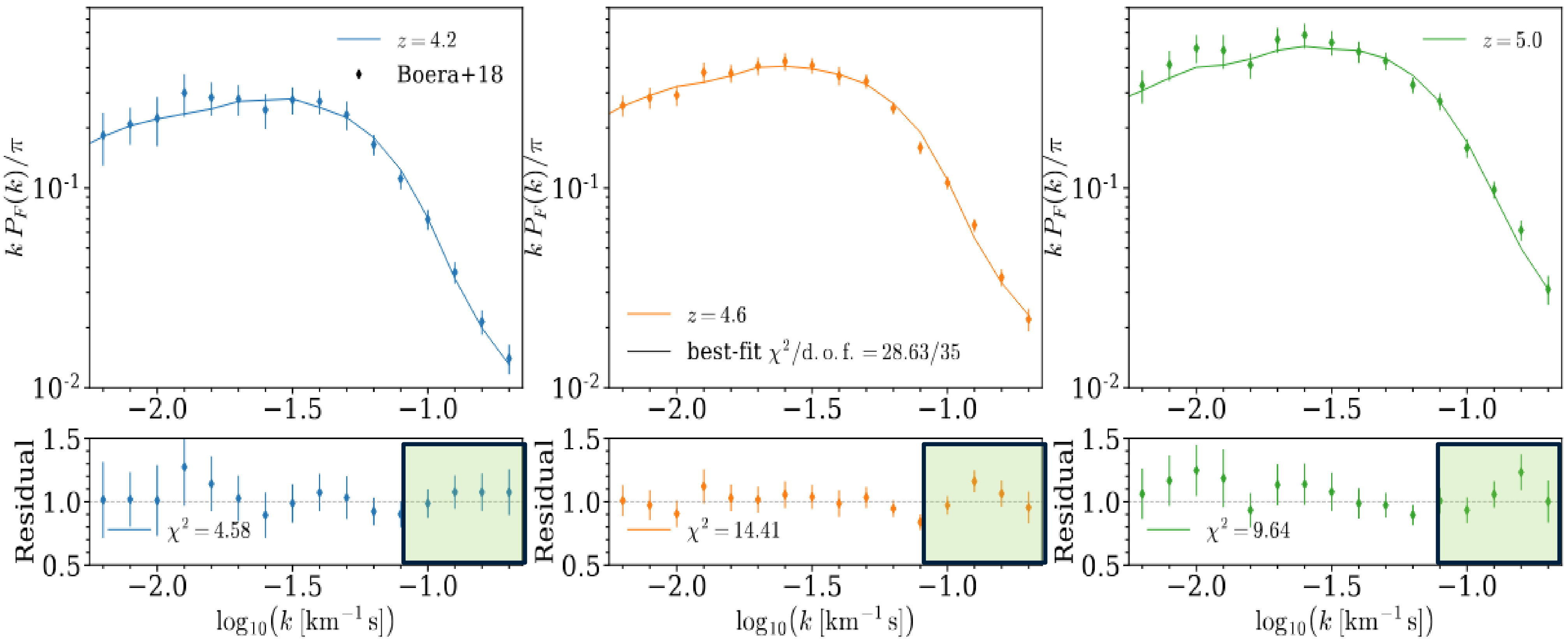
Halo Mass Function



- Extra PMFs power produces more haloes, at "low" mass
- With lower B values (< 1 nG) the enhancement will move to lower masess
- Below 0.05 nG effect is probably too small at any scale

Ralegankar, Pavicevic, Viel, 2024, JCAP, 07, 027

Best fit PMF models



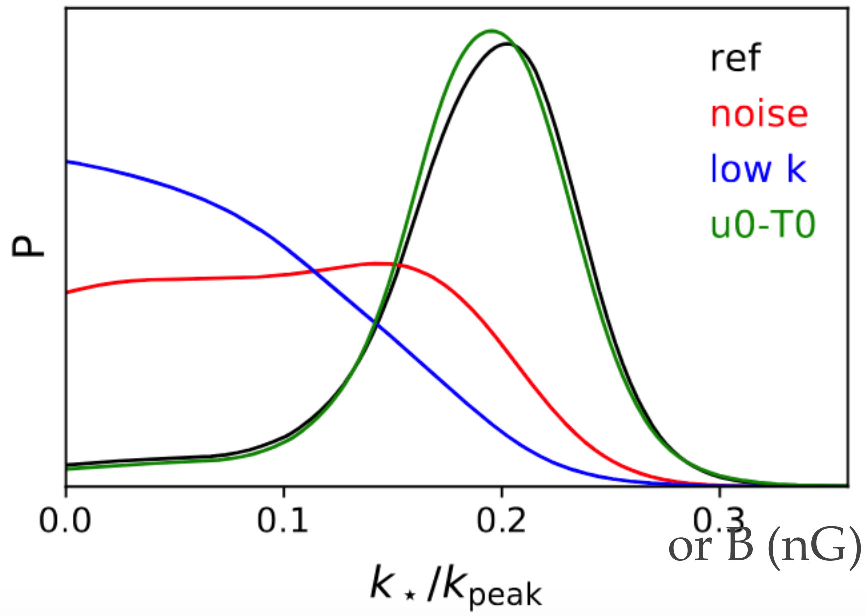
$$\chi^2_{\Lambda\mathrm{CDM}} = 40.8 \ \text{for} \ 36 \ \text{d.o.f.}$$

$$\chi^2_{\mathrm{PMF}} = 28.63 \ \text{for} \ 35 \ \text{d.o.f.}$$

Constraints on peak position

$$k_{\rm peak} = \lambda_{\rm D}^{-1}\sqrt{\frac{n_{\rm B}+5}{2}}\ {\rm Mpc}^{-1} \qquad k_\star = 10\,{\rm Mpc}^{-1}$$

- Measurement of extra power in the data interpreted in the context of PMFs
- Effectively probing underdense high-redshift regions



or B (nG)

- Voids/filaments in the local Universe are also magnetized (see Garg, Durrer, Schober 25)

Detection → B=0.2 ± 0.05 nG (1σ)
Upper limit → B=0.3 nG (3σ)

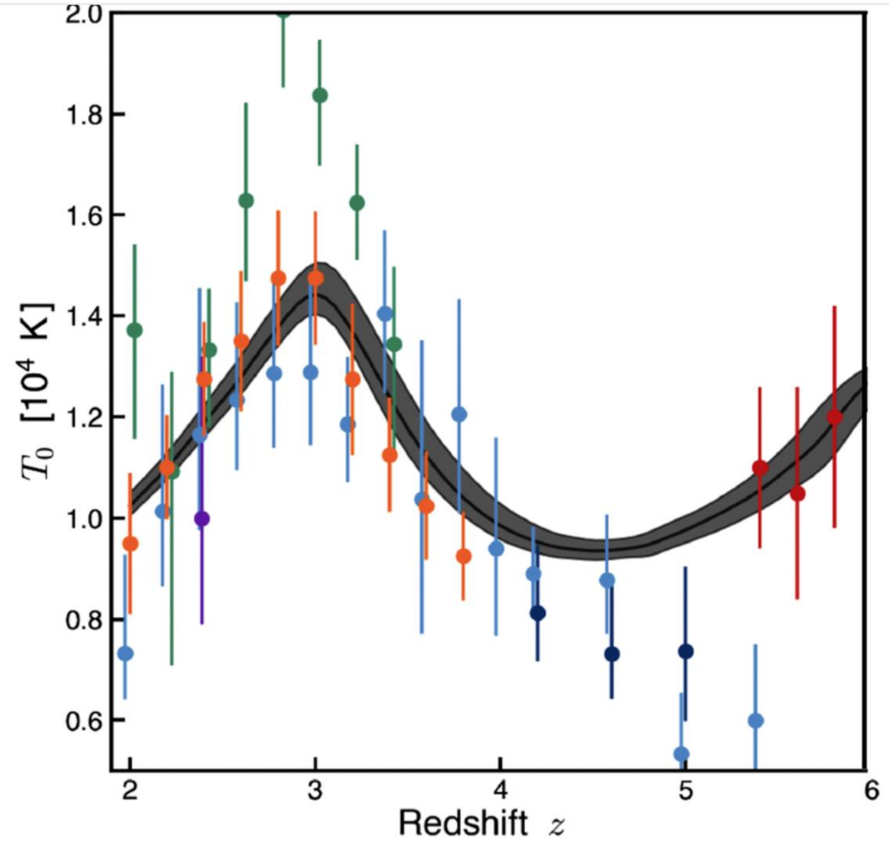
Summary

- 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 with IM and k~ 30 *h*/Mpc with forest
- With intensity mapping 1D radial BAO will constrain geometry
- Power spectrum will constrain growth (and thus neutrino masses – Autieri's talk)
- Warm dark matter constraints m > 5.72 keV – constraints on Cold +Warm DM models too
- Hint of extra power in the data is well fitted with PMF at 0.2 nG, robust upper limit 0.3 nG

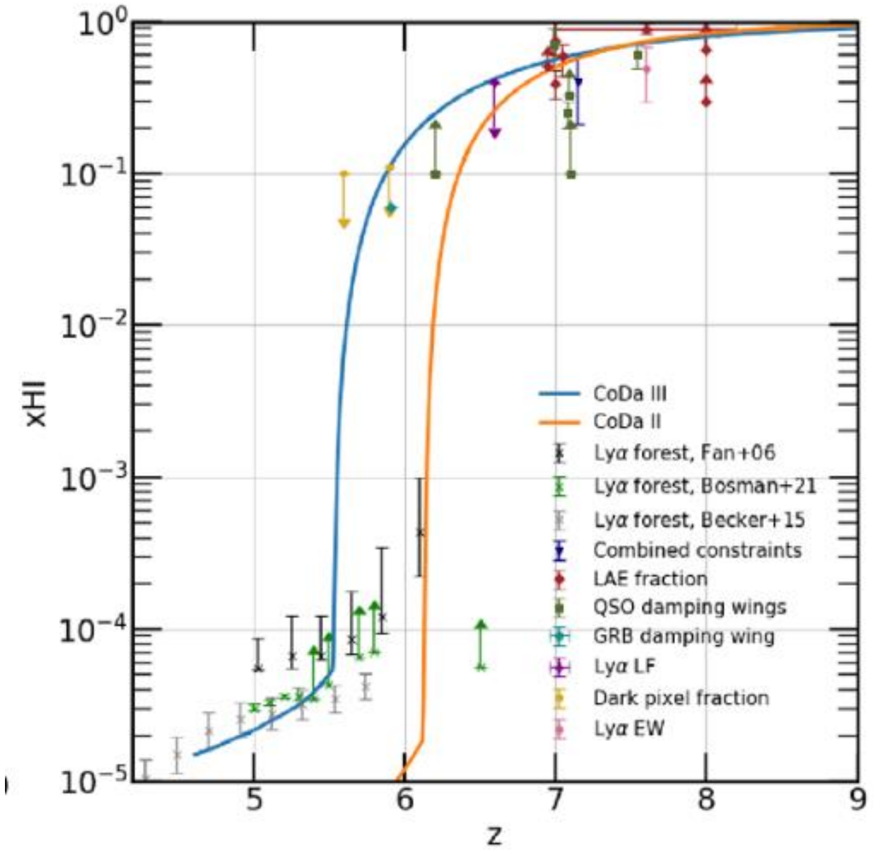
Extra slides

Extra slides

Thermal state of baryons at mean density



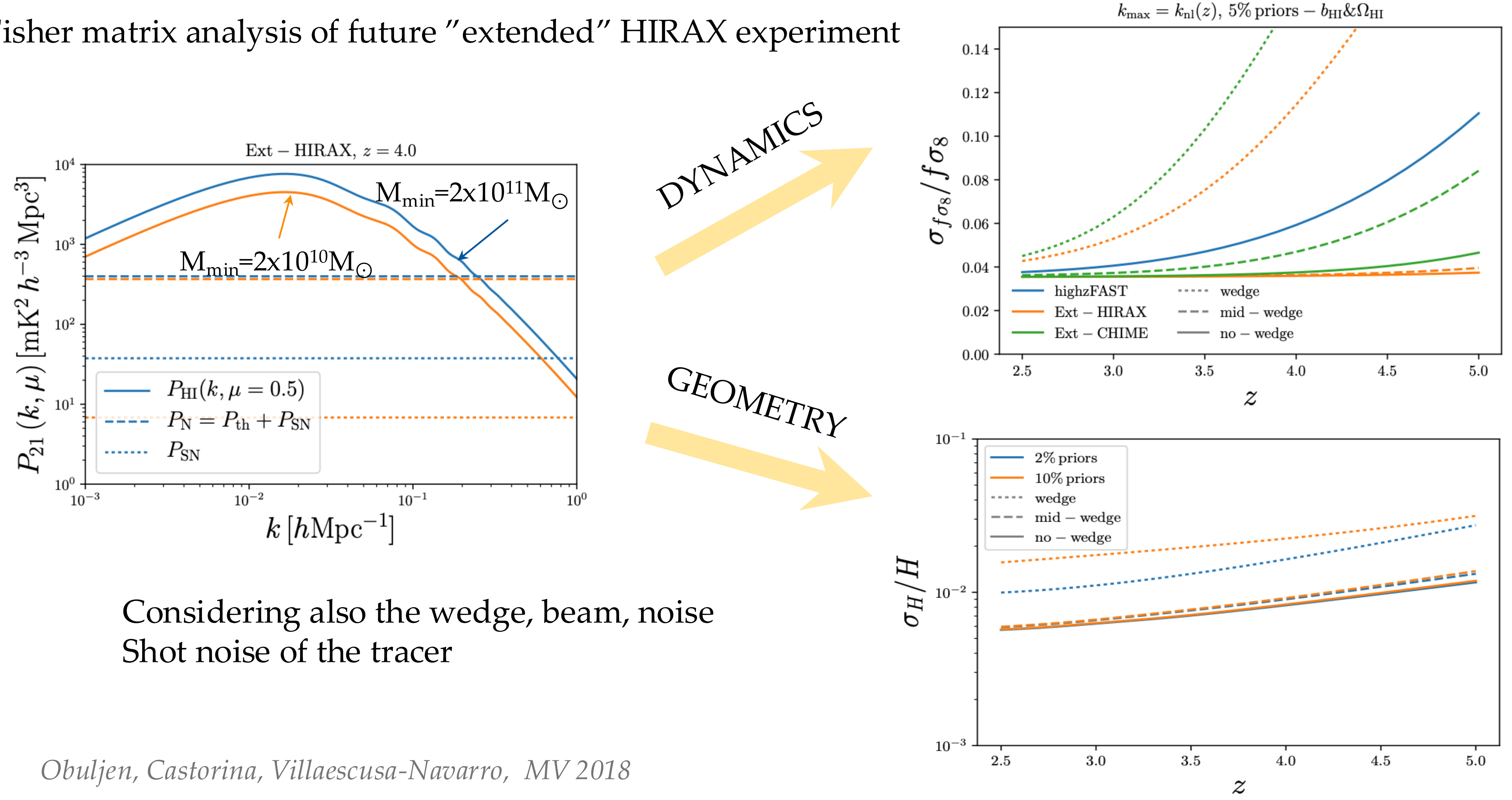
Neutral fraction evolution



Gnedin & Madau 22, Lewis +22

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

Modelling LIM power to linear order

Matteo Viel

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

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

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

HI bias

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

Shot-Noise power spectrum

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

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

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

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

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

COSMOLOGY

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

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

COSMOLOGY

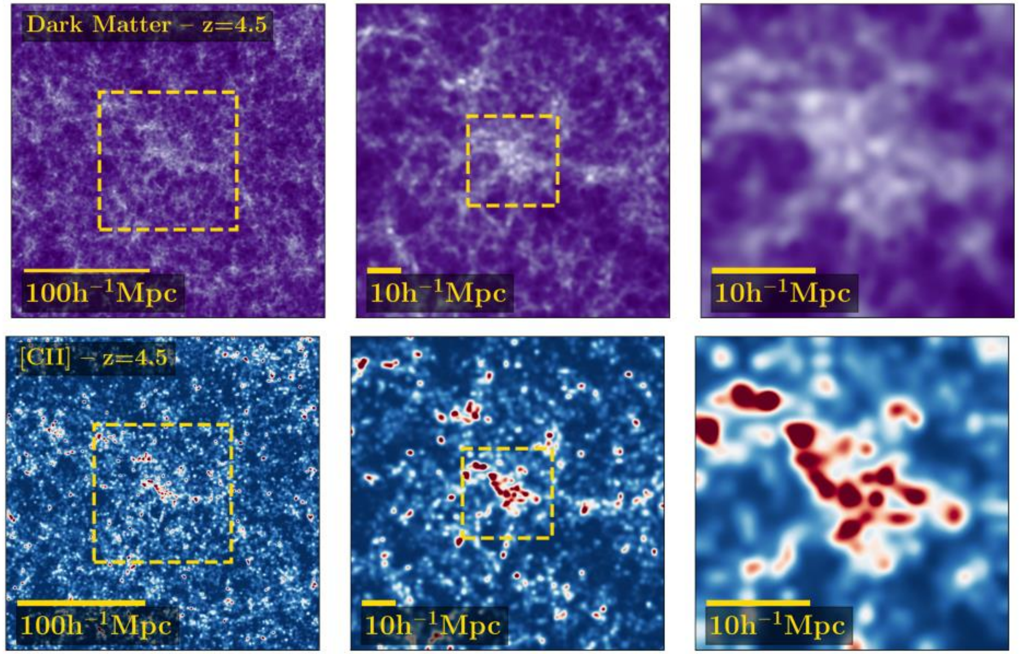
ASTROPHYSICS OF THE HALOES

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

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

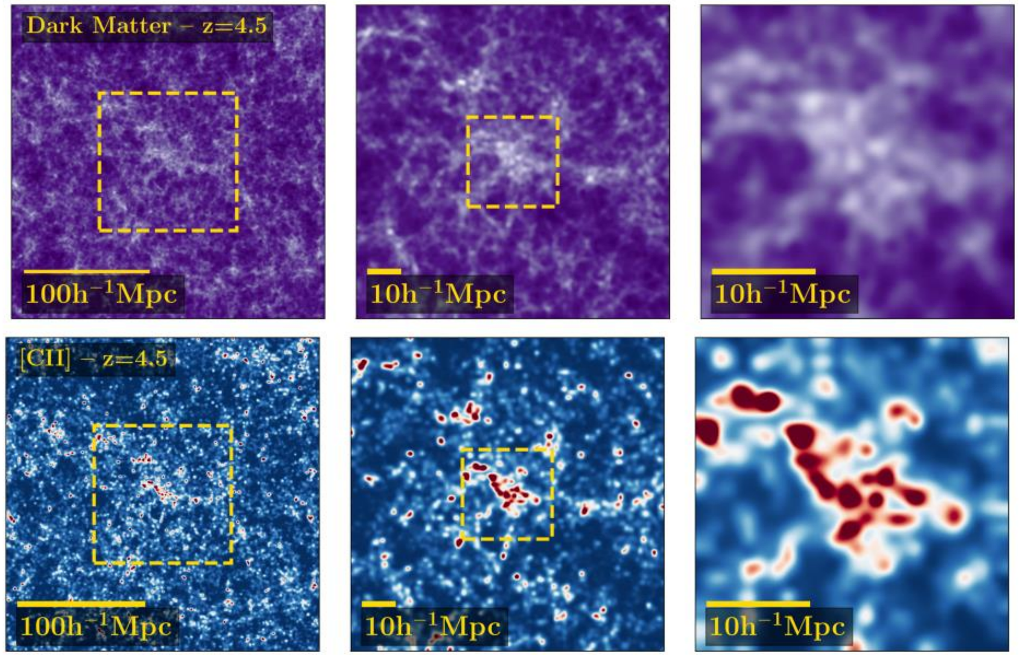


- Alcock-Paczynski parameters and BAO wiggles
- State-of-the-art treatment of (non) Poisson shot noise
- Bias of the different lines [CII] and CO
- EFT inspired perturbation theory at 1-loop
- Comparison with large scale/high res. (DM only) mocks

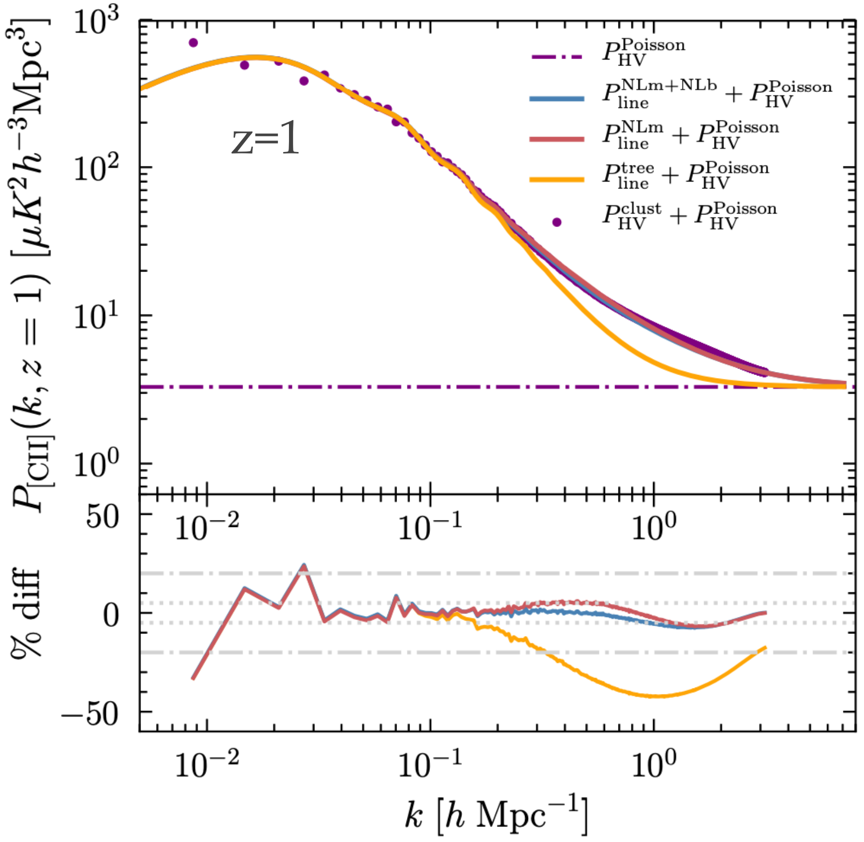
Moradinezhad Dizgah, Nikakthar, Keating, Castorina 22

New modelling of LIM power with the halo model

Matteo Viel



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)

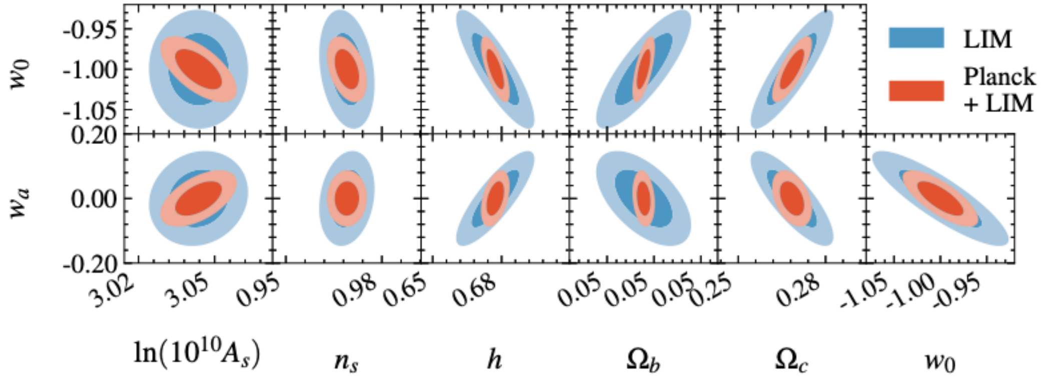
Moradinezhad Dizgah, Nikakthar, Keating, Castorina 22

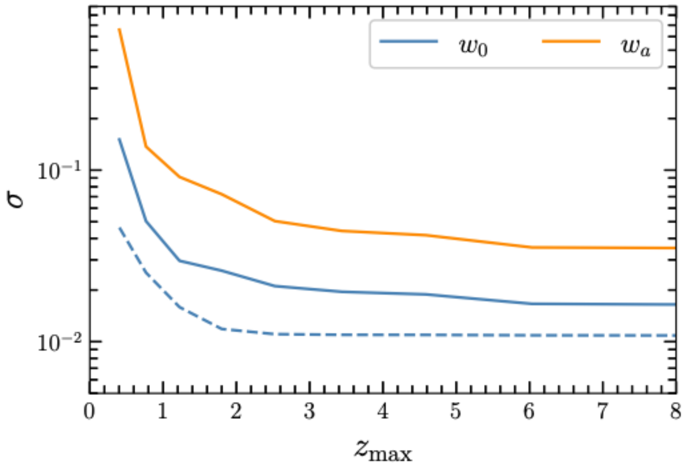
Evolving Dark Energy - II

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

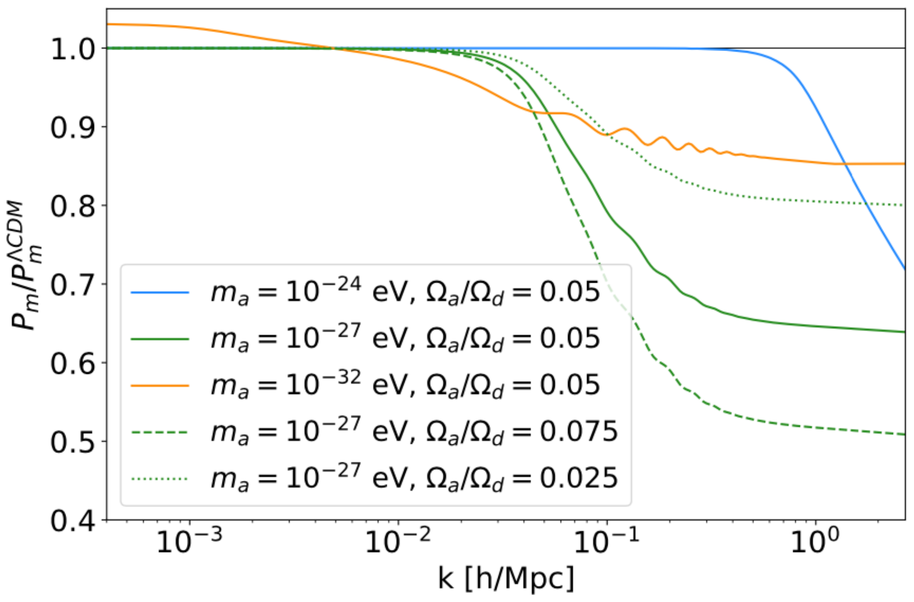
cosmology

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

astrophysics

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

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



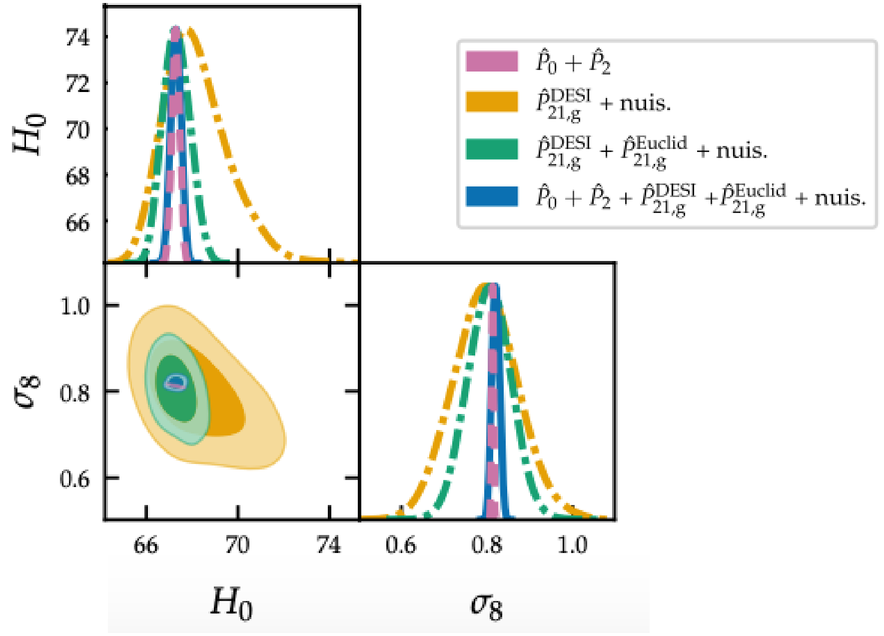
- Pheno model that captures axion + cold DM
- COMAP-Y5 experiment (z=2.9)
- Monopole of the power spectrum + Voxel intensity distribution (VID) – this is important to capture non gaussian nature of signal

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

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

$$P_{\rm g}(z,k,\mu) = \left(b_{\rm g}(z) + f(z)\,\mu^2\right)^2 P_{\rm m}(z,k) + \frac{1}{\bar{n}_{\rm g}(z)}$$

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

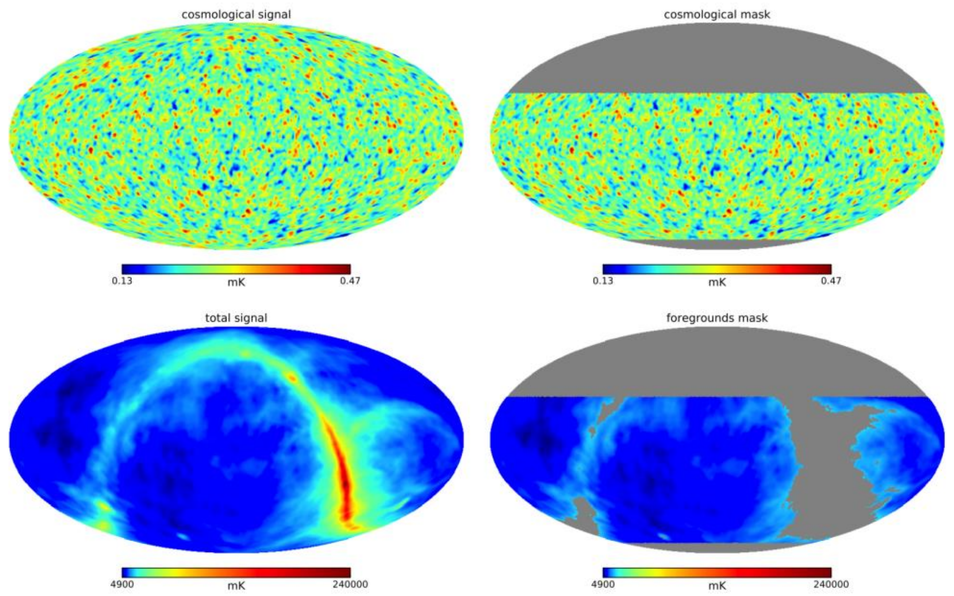


Parameter	$\hat{P}_0 + \hat{P}_2$	$\hat{P}^{\rm DESI}_{21,g}$	$\hat{P}^{\rm DESI}_{21,g}$ + nuis.	$\hat{P}^{\rm Euclid}_{21,g}$	$\hat{P}^{\rm Euclid}_{21,g}$ + nuis.	$\hat{P}^{\rm DESI}_{21,g} + \hat{P}^{\rm Euclid}_{21,g}$ + nuis.	$\hat{P}_0 + \hat{P}_2 + \hat{P}^{\rm DESI}_{21,g} + \hat{P}^{\rm Euclid}_{21,g}$ + 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

- 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

Matteo Viel

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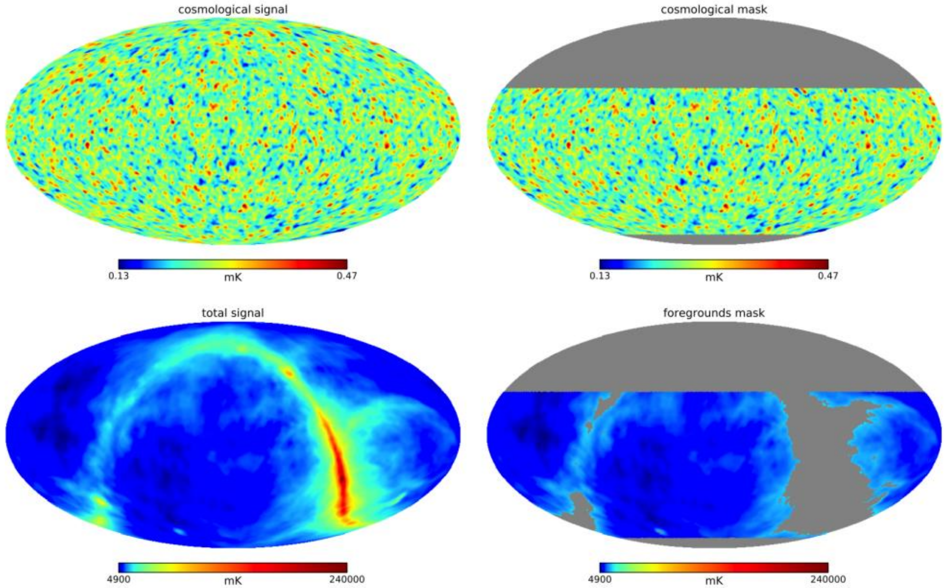
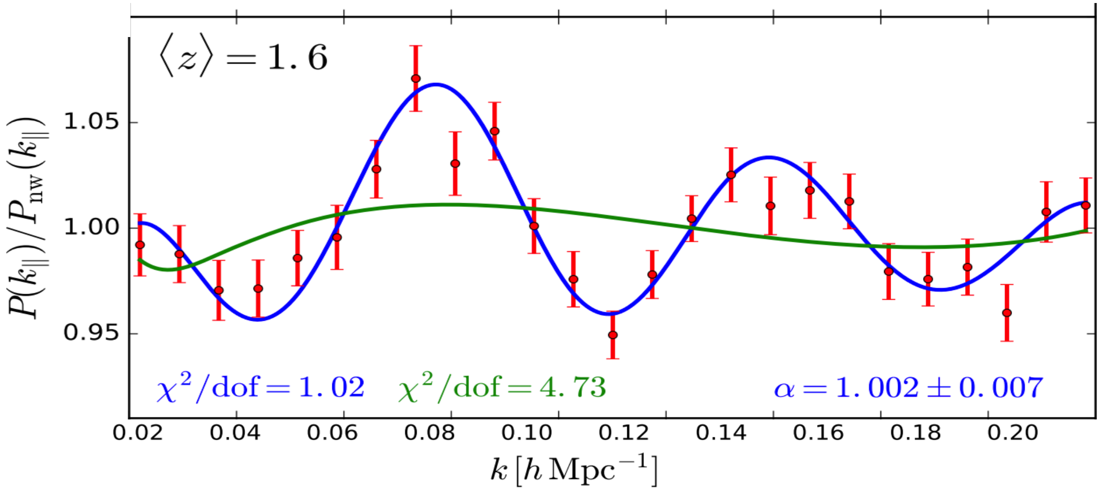
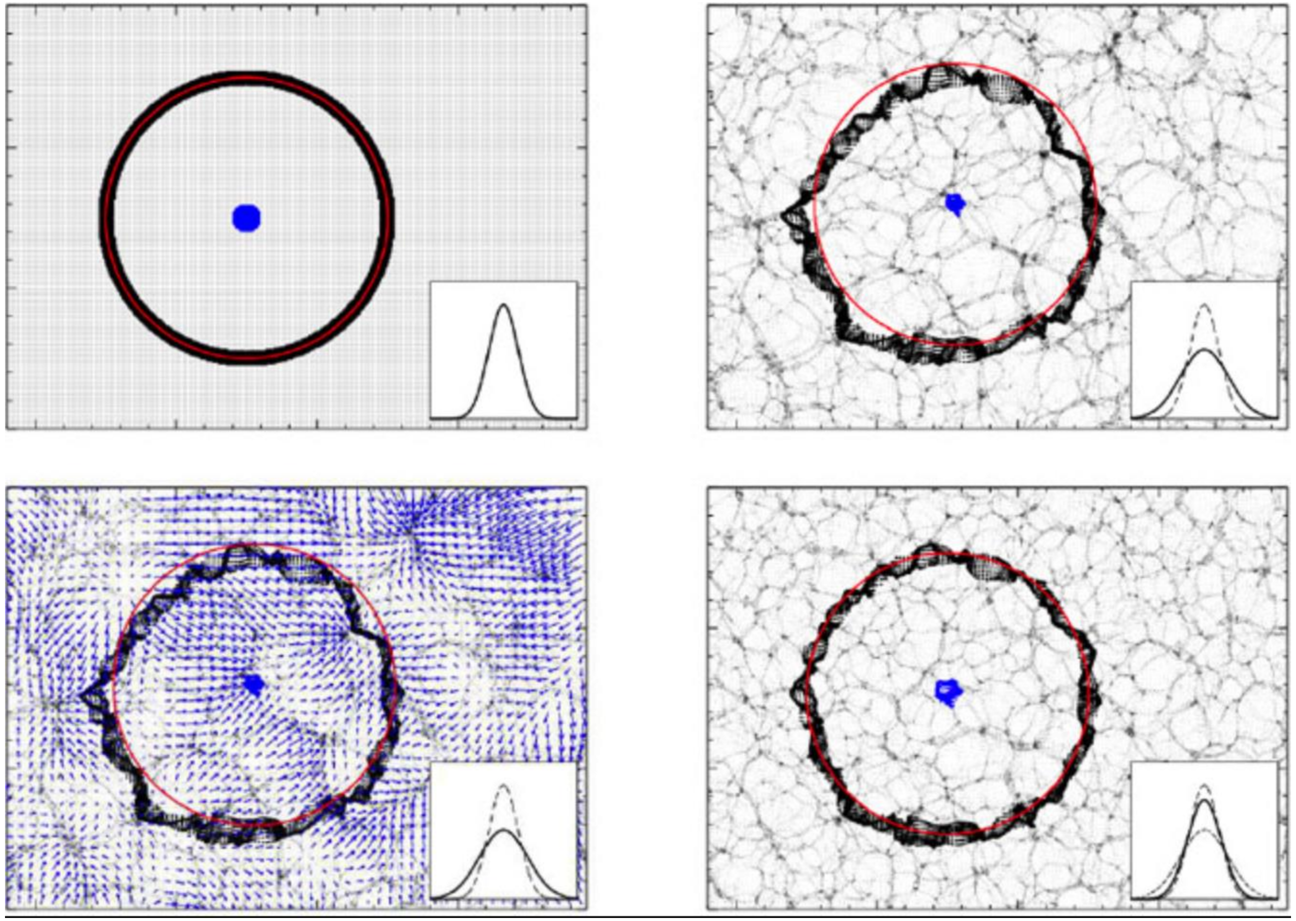




z range	$\langle z \rangle$	mask	σ_α (C)	(C+N)	(C+N+FG)
[0.36-0.75]	0.6	no	1.008 ± 0.016	1.008 ± 0.016	1.007 ± 0.016
		yes	1.006 ± 0.020	1.006 ± 0.021	1.006 ± 0.024
[0.75-1.26]	1.0	no	0.996 ± 0.010	0.997 ± 0.011	0.996 ± 0.011
		yes	0.997 ± 0.012	0.997 ± 0.013	0.998 ± 0.015
[1.26-1.98]	1.6	no	1.001 ±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

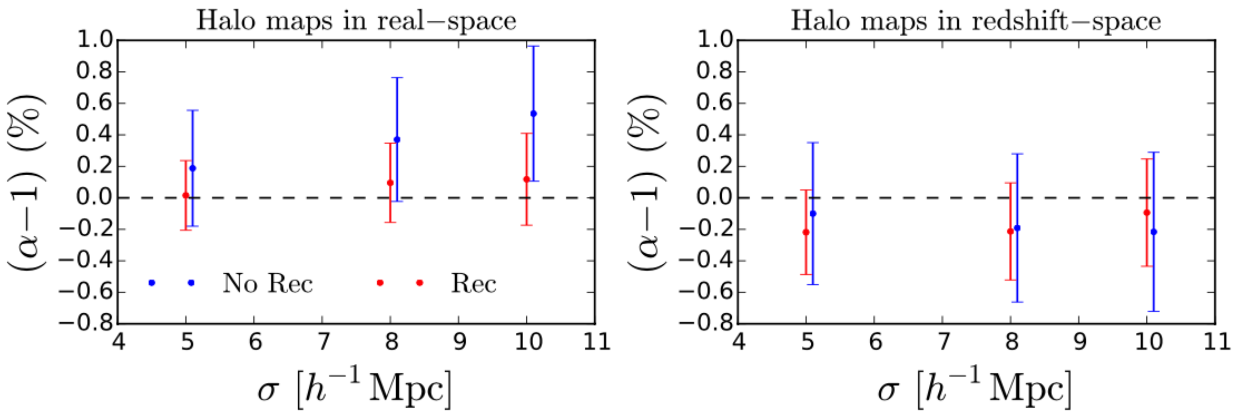
Obuljen, Villaescusa-Navarro, Castorina, MV 2017

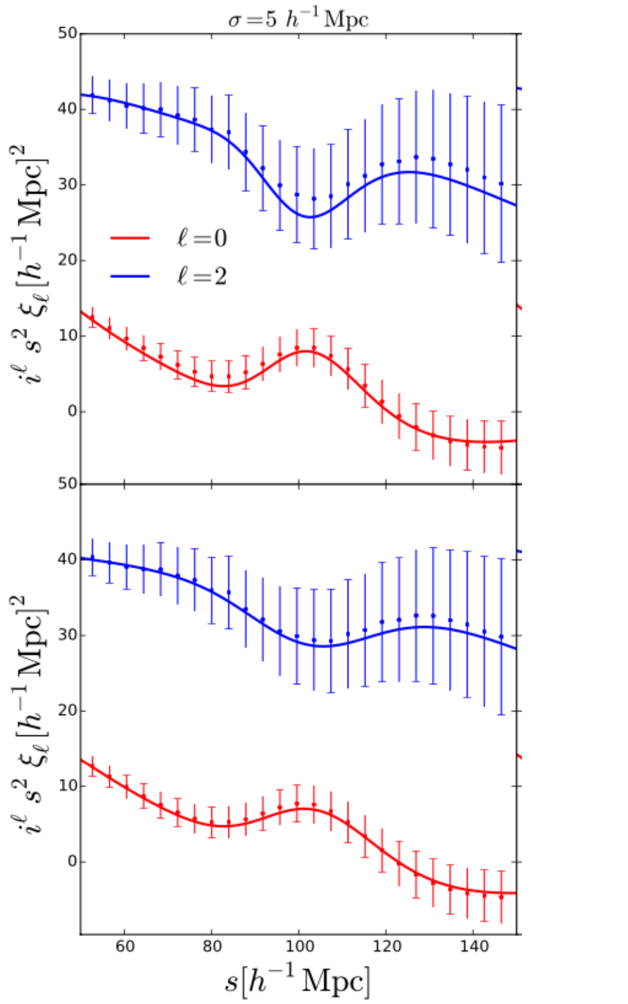
Reconstruction of the BAO peak with pixels

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

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

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



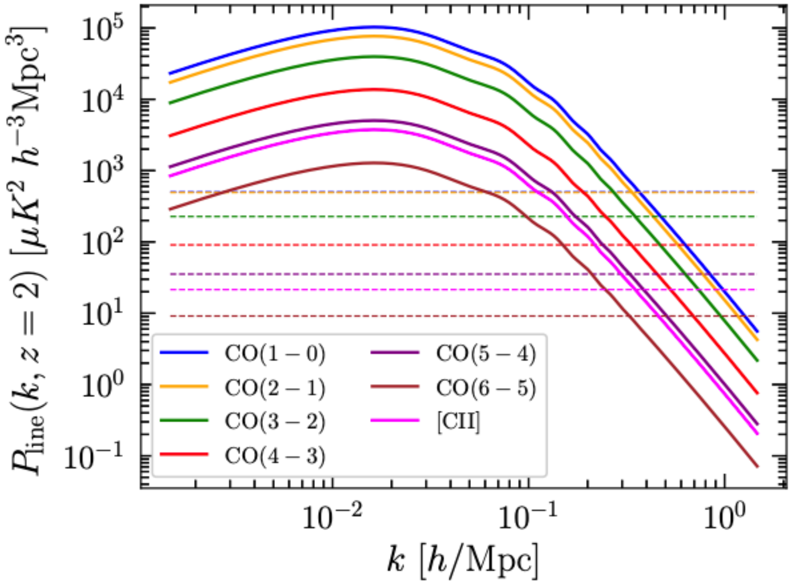


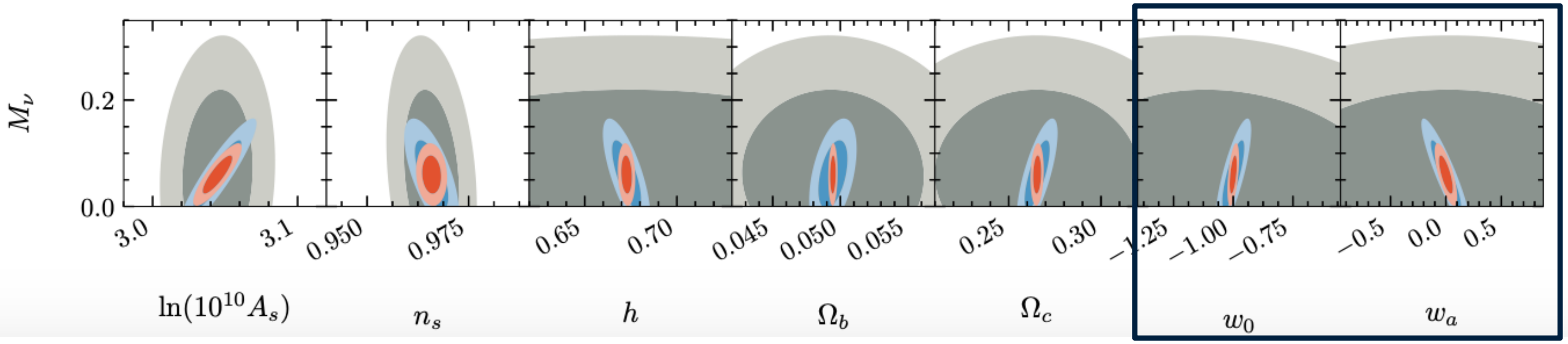
Obuljen, Villaescusa-Navarro, Castorina, MV 2017

Post-reionization cosmology: 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

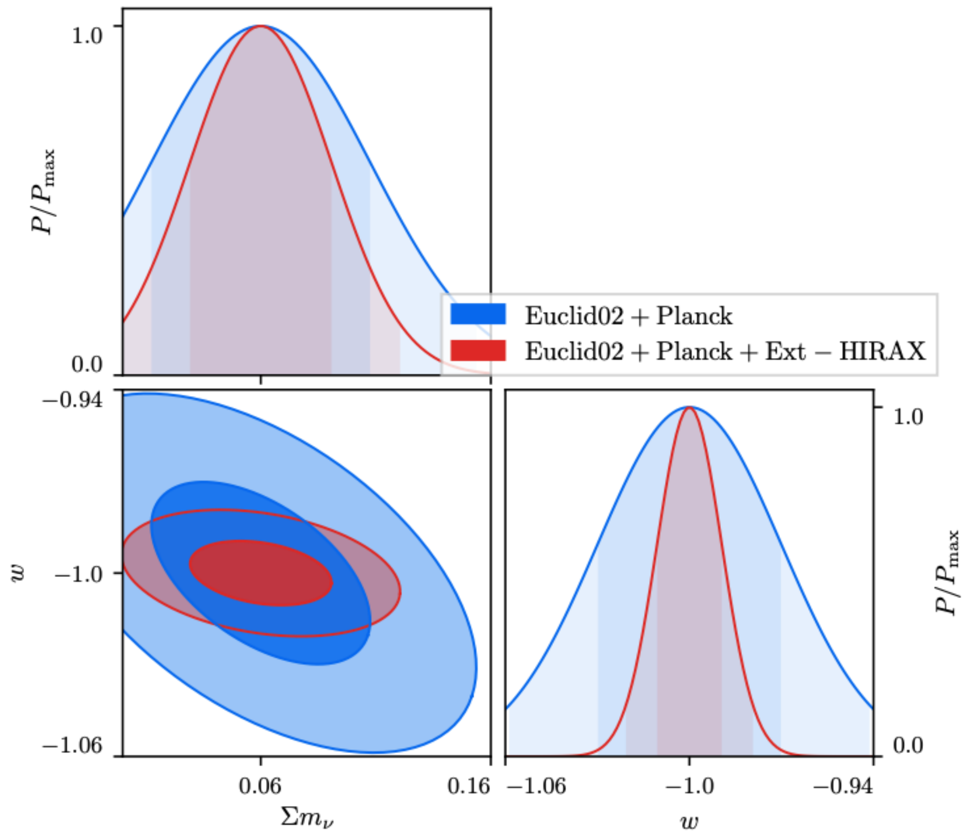


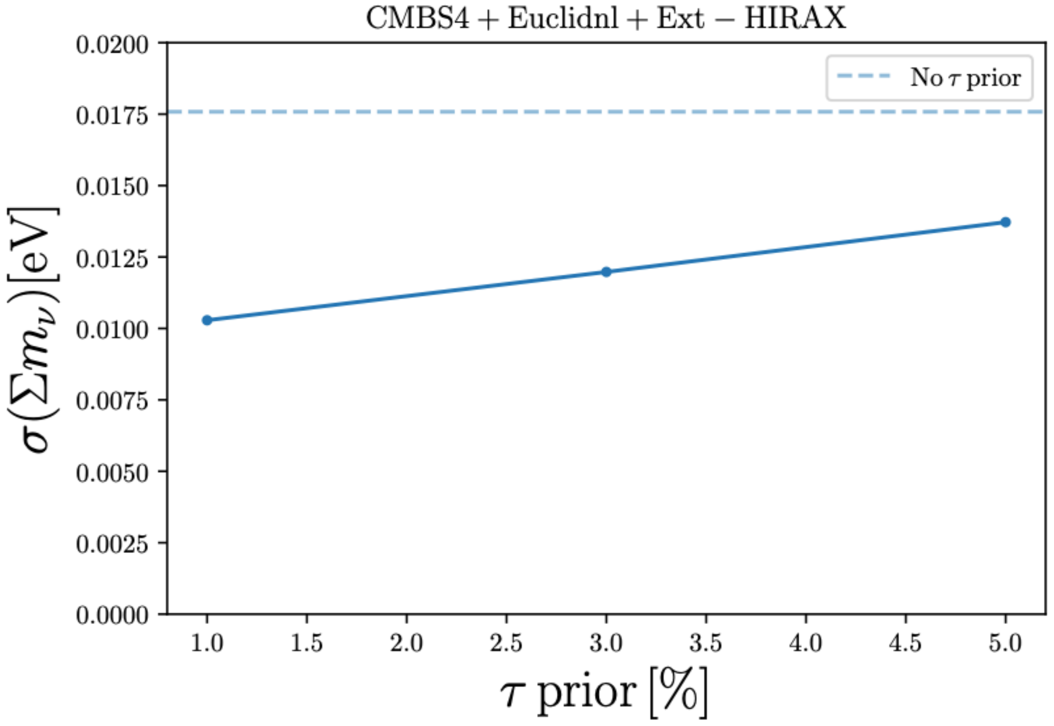


Moradinezahd Dizgah+2022

Post-reionization cosmology: neutrino masses

Obuljen, Castorina, Villaescusa-Navarro, MV 2018



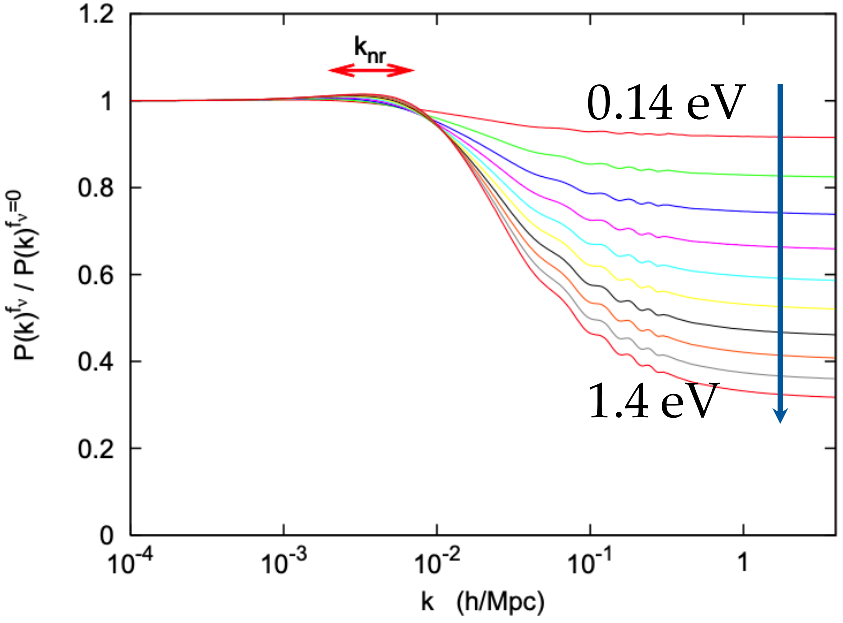


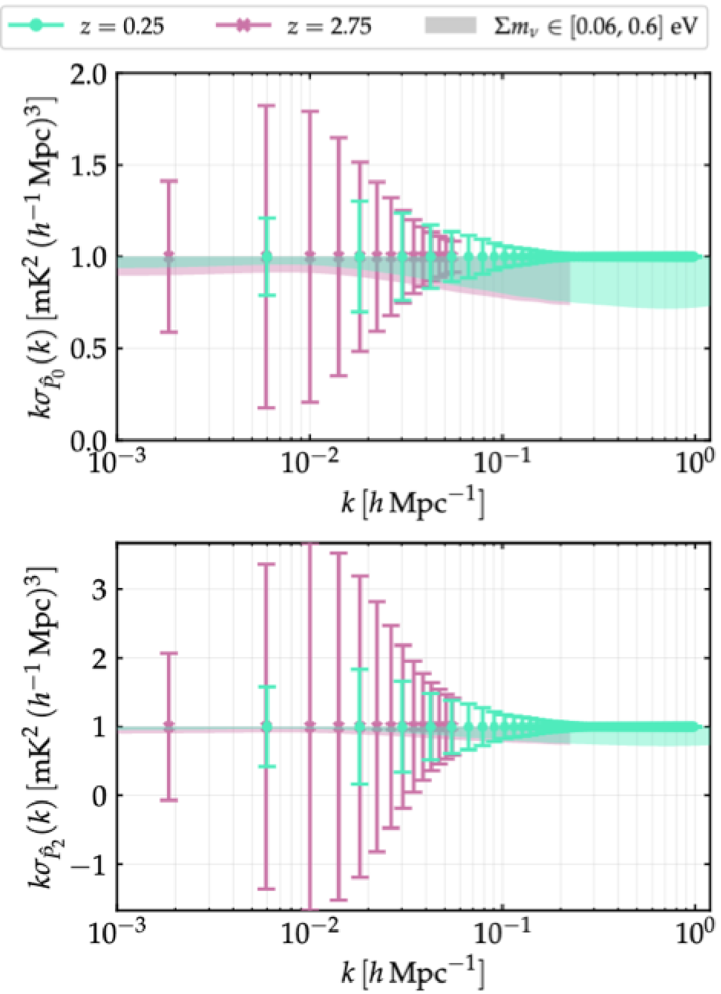
Prior on the CMB optical depth somehow fixes large scale amplitude inferred from the CMB… and helps measuring neutrino free streaming

Post-reionization cosmology: neutrino masses - II

Matteo Viel

Neutrino free streaming





21cm power
SKA mid
Monopole and quadruopole

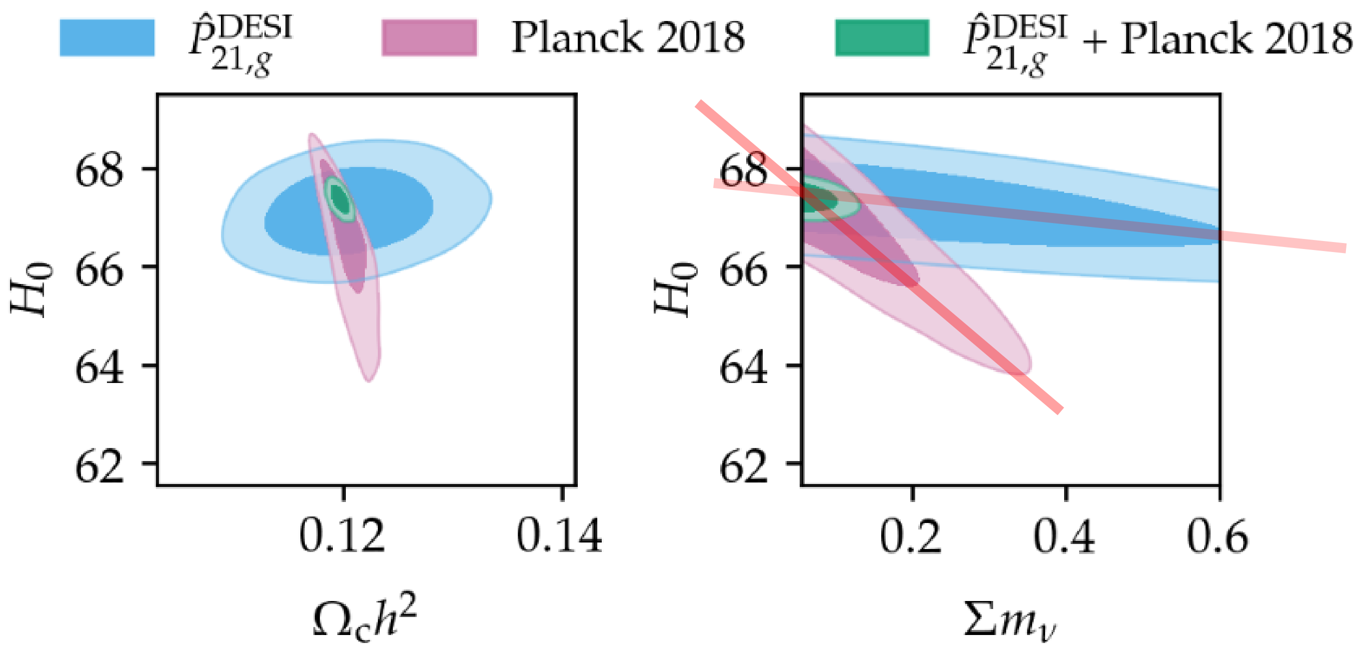
Autieri, Berti, Spinelli, Haridasu, MV (2025)

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



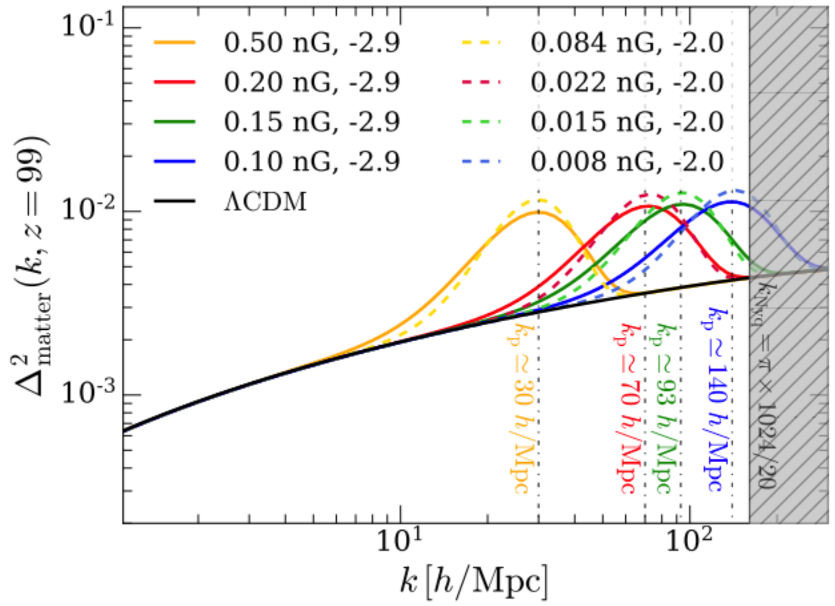
Likelihoods	$\Sigma m_\nu^{\mathrm{fid}} = 0.06\,\mathrm{eV}$	$\Sigma m_\nu^{\mathrm{fid}} = 0.1\,\mathrm{eV}$
$\hat{P}_0 + \hat{P}_2$	< 0.287	< 0.317
+ nuisances	< 0.425	< 0.452
Planck 2018		
$+ \hat{P}_0 + \hat{P}_2$	< 0.105	0.098 ± 0.022
+ nuisances	< 0.126	< 0.151
Planck 2018		
$+ \hat{P}^{\mathrm{DESI}}_{21,\mathrm{g}}$	< 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

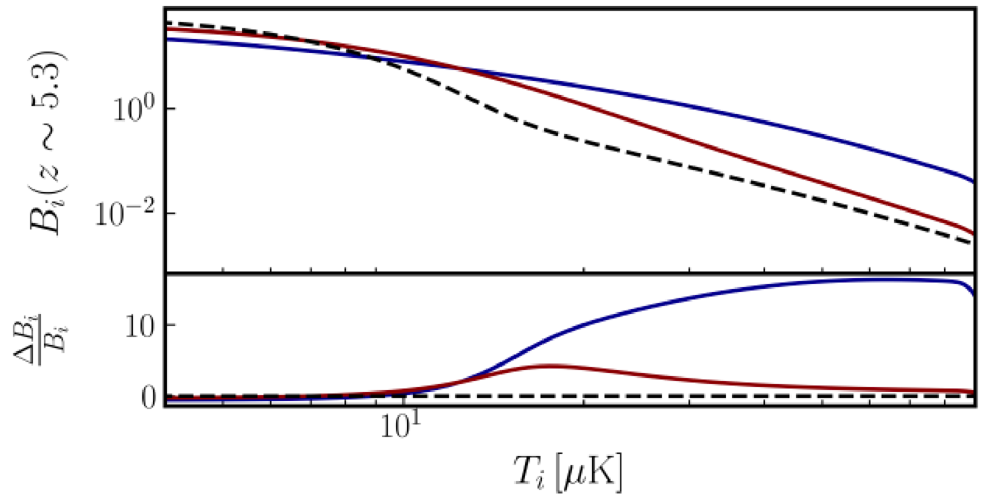
Increase of power in total matter power
Spectrum due to Lorentz force affecting
Baryons' clustering



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

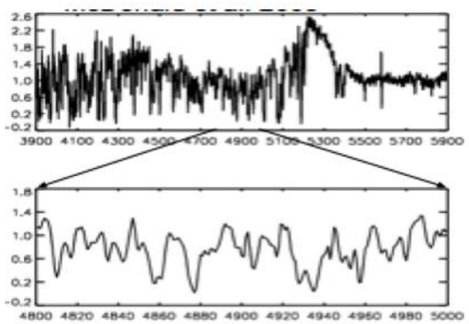
Pavicevic, Irsic, MV+ (2025) arXiv: 2501.06299

Adi, Libanore, Crutz, Kovetz 2024

Data

Matteo Viel

BOSS/SDSS-III



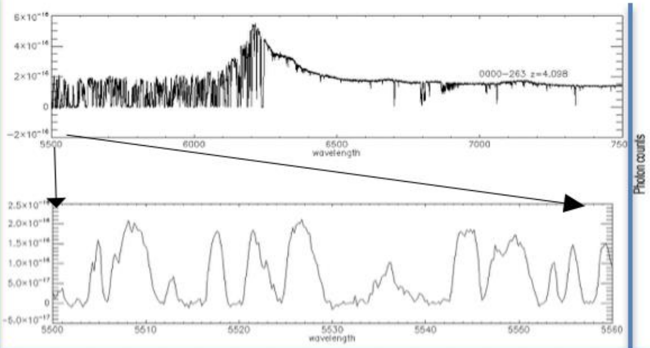
Low resolution BOSS and SDSS-III spectra S/N~2-3 - 160,000 spectra

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



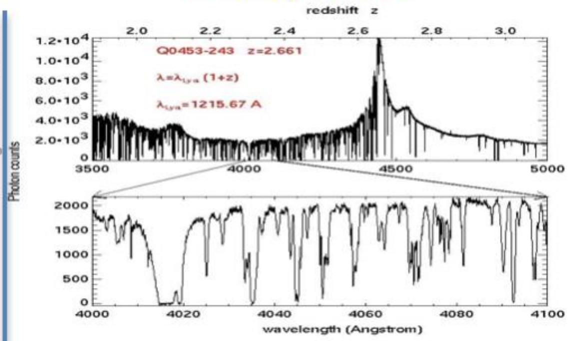
Medium resolution X-Shooter VLT spectra S/N ~ 30

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

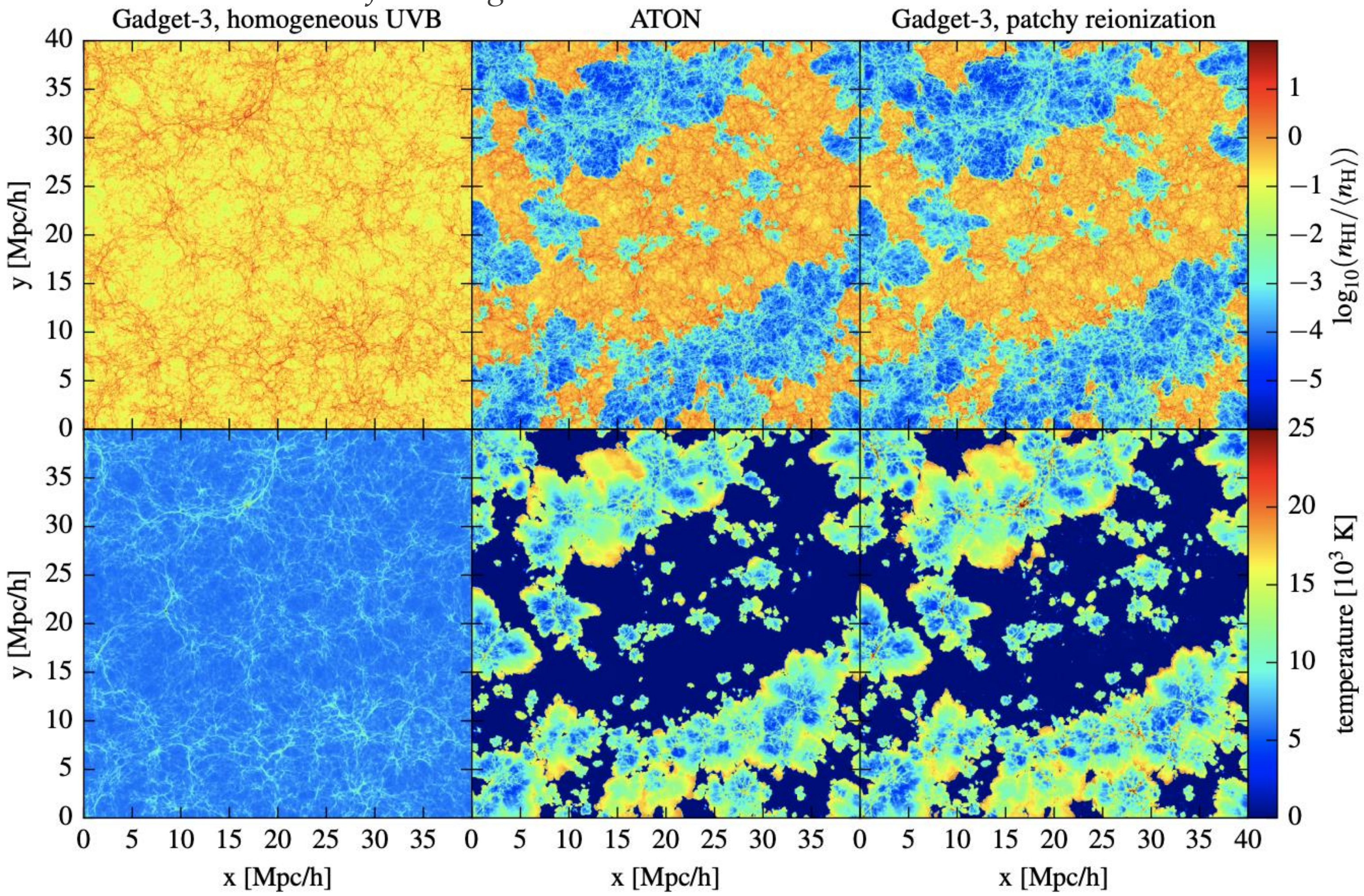
Used for WDM, astrophysics of the IGM and galaxy formation, variation of fundamental constants

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

The simulations - I

https://www.nottingham.ac.uk/astronomy/sherwood/

z=7 (with reionization finishing at z=5.3)



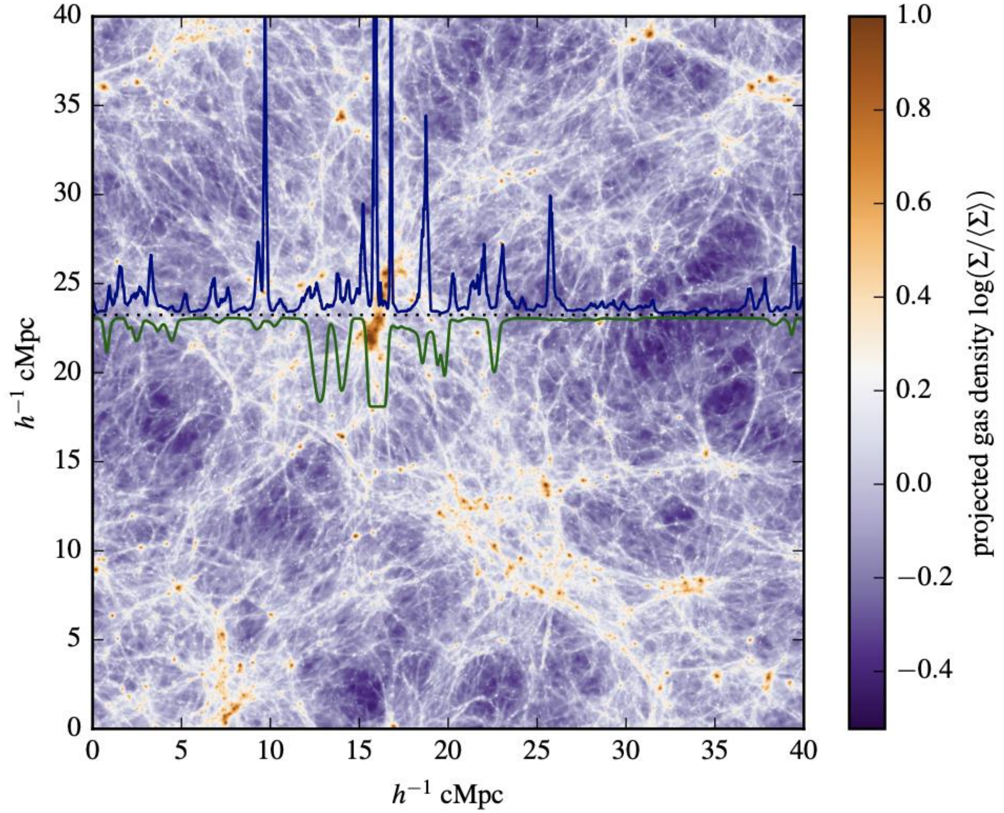
Bolton+17
Puchwein, Bolton+

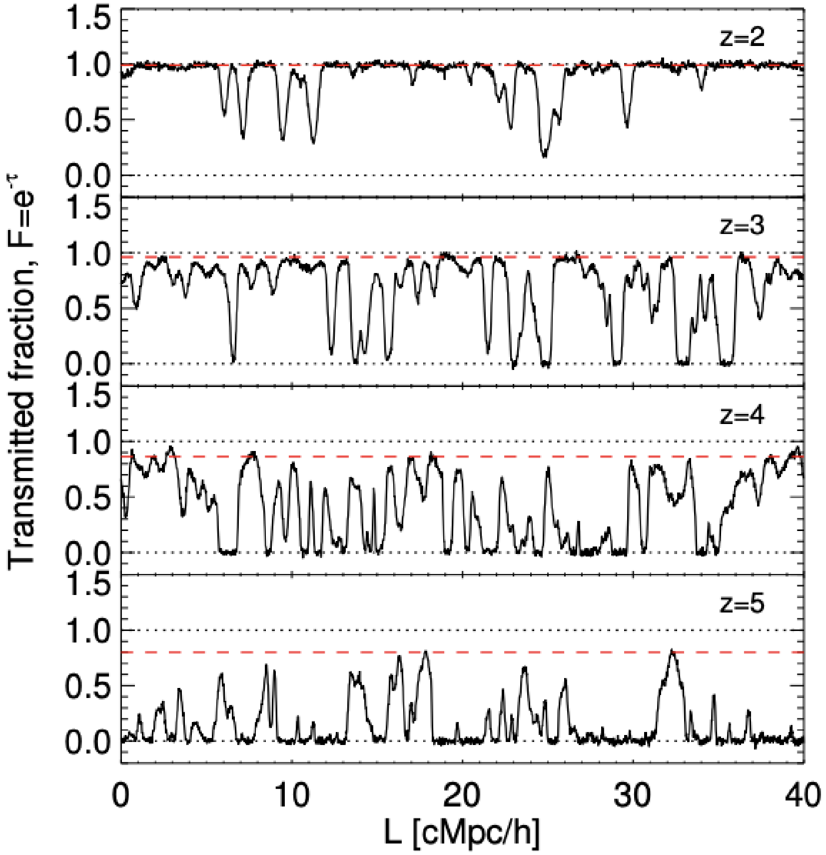
J. Bolton *E. Puchwein*

- **Sherwood-Relics suite** (>200 simulations: boxes 5-160 cMpc/h; M_{gas}=3.7e3-6.4e6 $M_\odot$) – about 75 Million CPU hrs (2017-now)

- G3 code + ATON to perform radiative transfer for patchy reionization

The simulations - III





of hyc

Cross-

- Most of the flux statistics are in agreement with ΛCDM – 216,000 flux models fed into MCMC analysis

Ratior

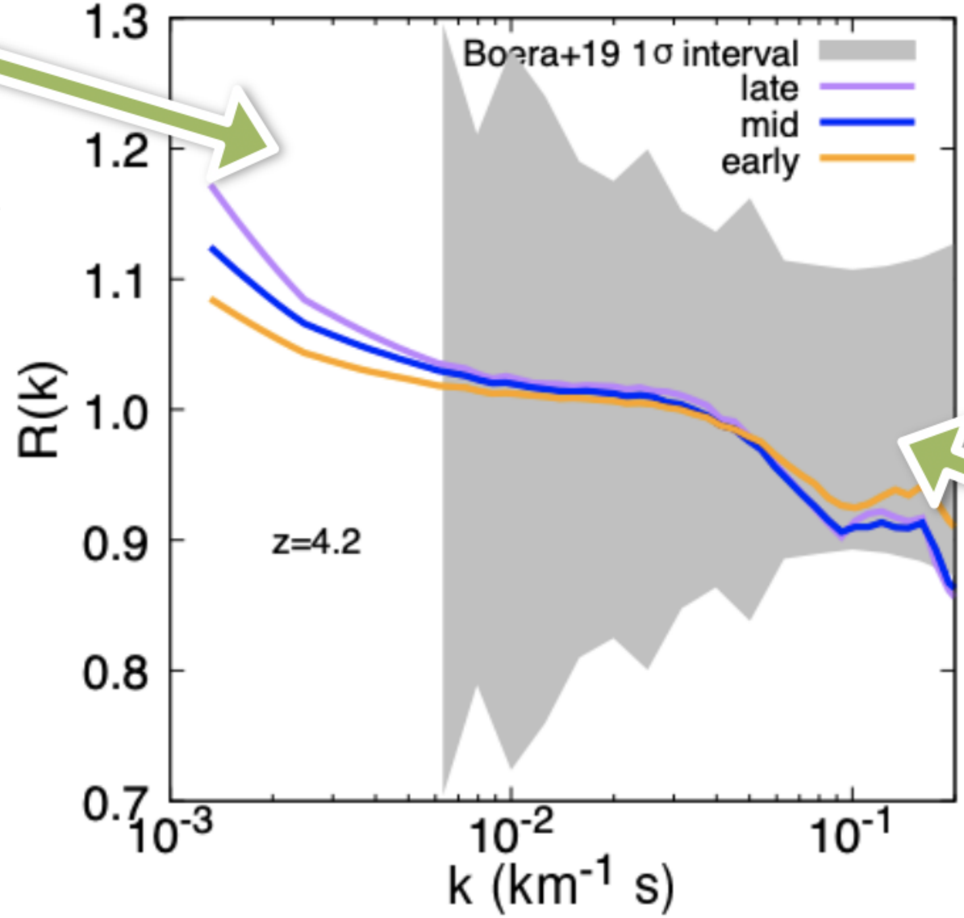
Increasing z → increasing HI → more absorption

eld

and bias parameters can be predicted and measured

Patchy Reionization - II

Boost
due to variation in neutral fraction from large scale temperature fluctuations



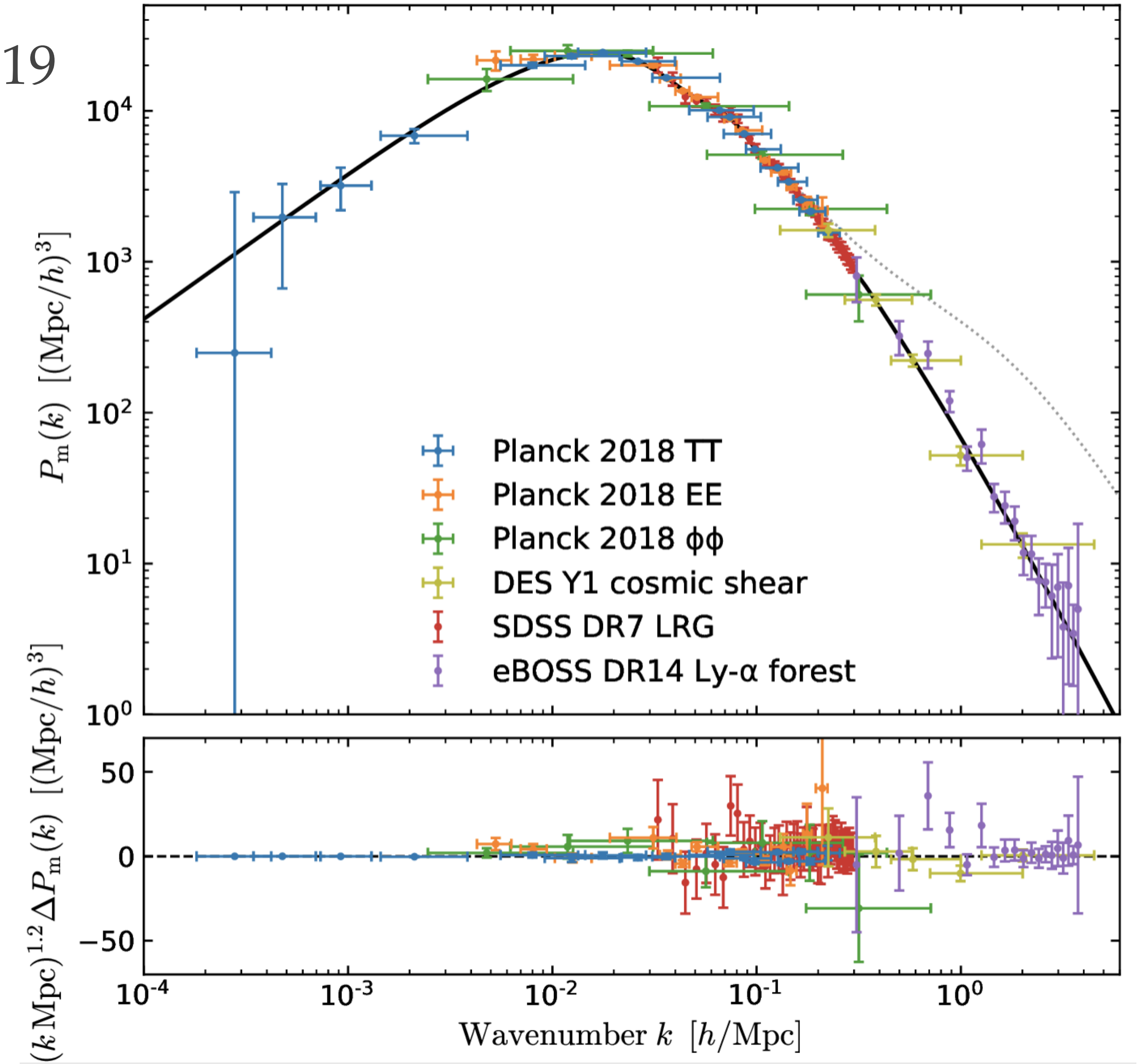
Suppression
due to thermal broadening of recently ionised regions

Molaro+23 "Detected" this increase of power at 2.7σ from KODIAQ, SQUAD, XQ100 sample of 538 QSOs

Molaro, Bolton, Irsic,… MV 2021&

Long lever arm of the linear power spectrum

Chabanier+19



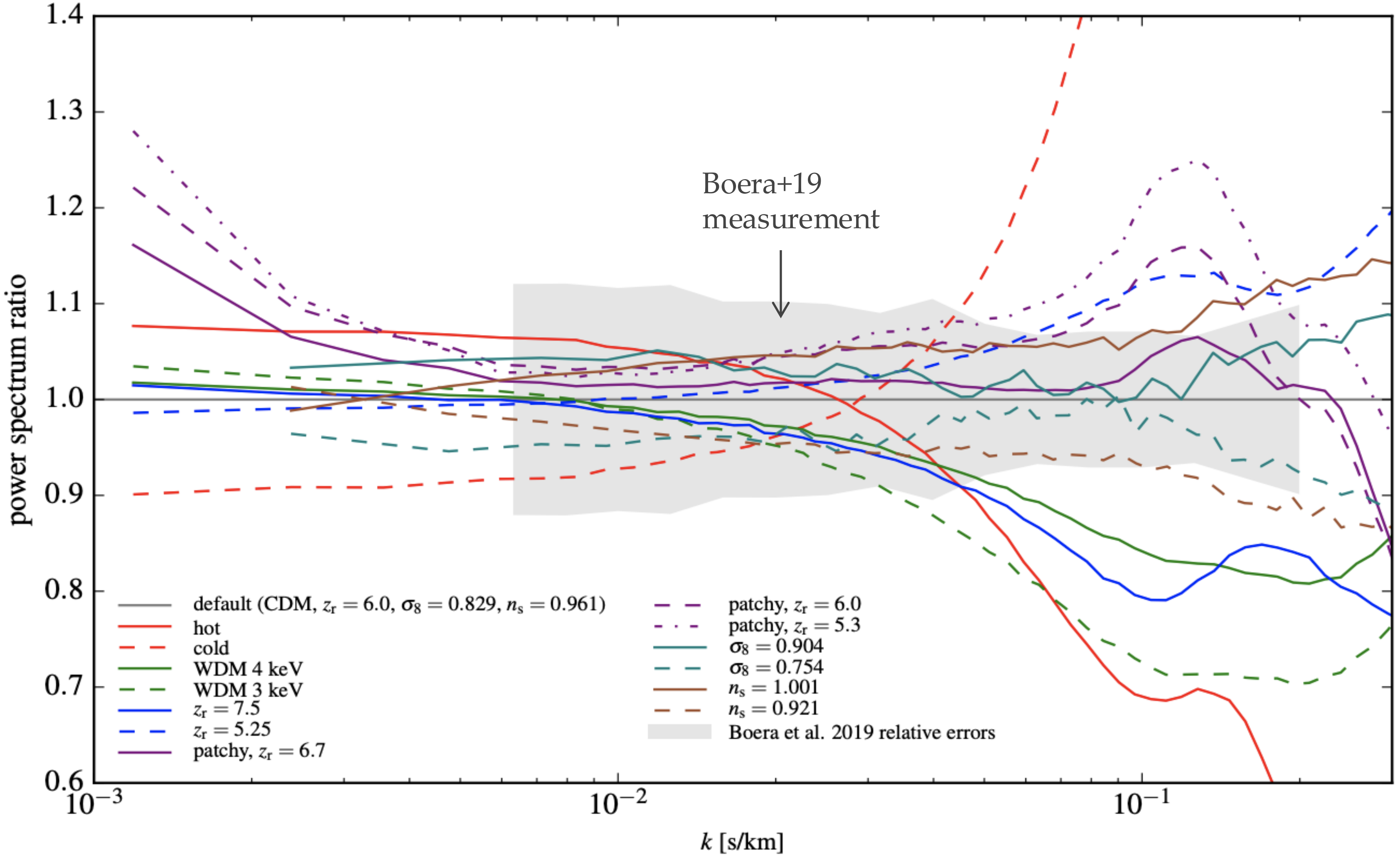
Two reasons for why Lyα is so constraining:

1) 1D is projected power
2) We are at high-z possibly closer to linear regime.

Impact on 1D flux power

Matteo Viel

Simulated 1D flux power @ z=4.6



More power

Less power

Large scales

Small scales

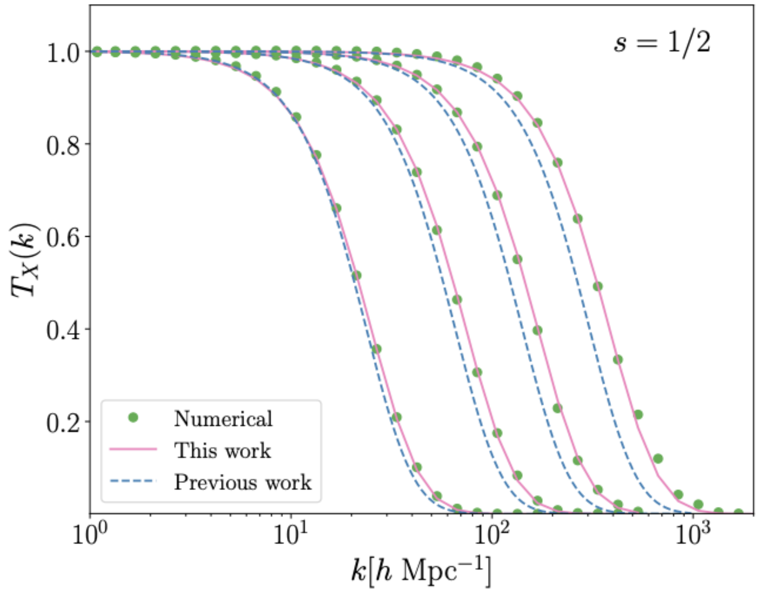
Matter power spectrum and WDM

Matteo Viel

$$T(k) \equiv [1 + (k/k_{break})^p]^{-10/p} \quad with\, p = 2.24$$

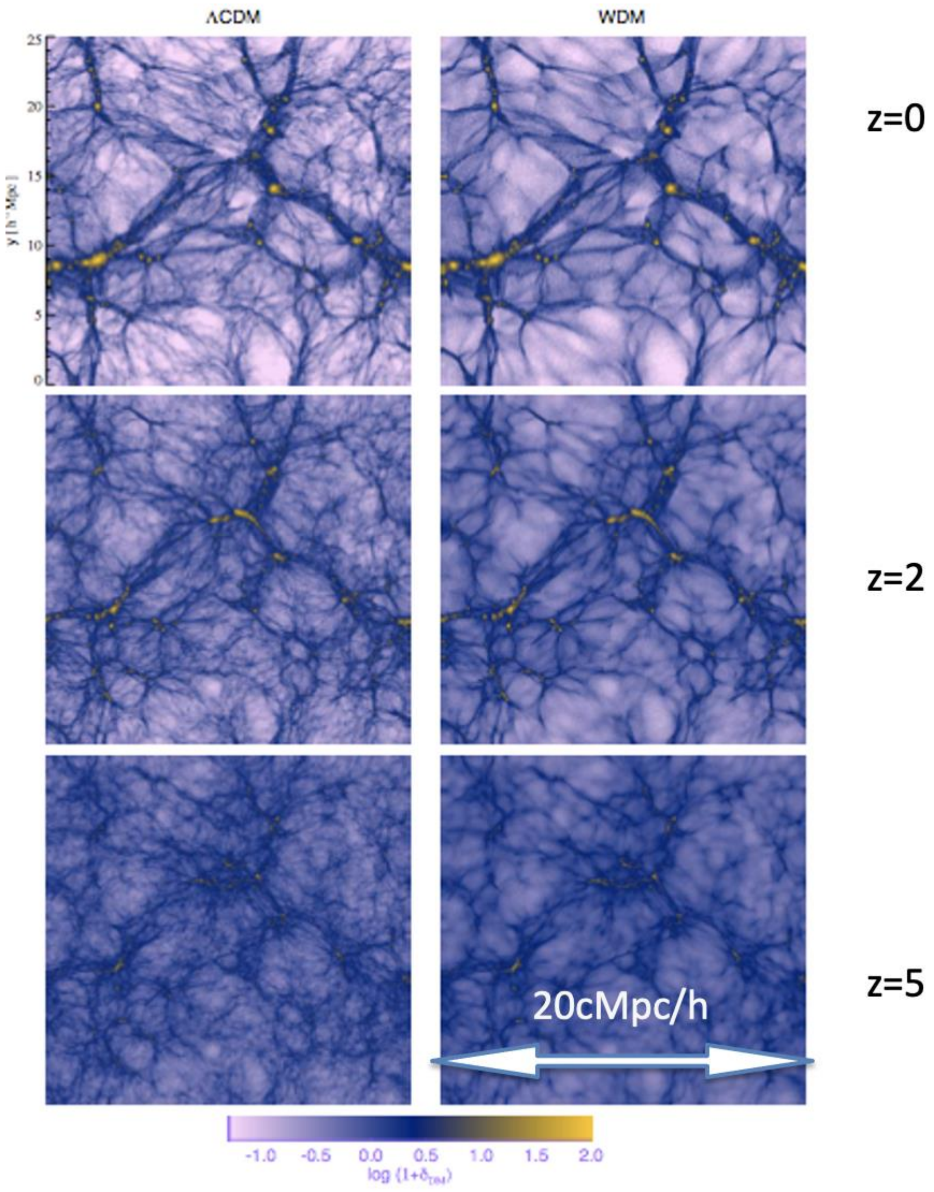
$$k_{break} = \frac{1}{0.24} X^{0.83} \left(\frac{\omega_X}{0.25 \times 0.7^2} \right)^{0.16} Mpc^{-1} \quad with\, X \equiv \frac{m_X/T_X}{1\, keV} T_\nu^a$$

Important: unlike active neutrinos this depends on both DM density and X
Because free streaming horizon depends on those



Viel+05;
Vogel&Abazajian https://arxiv.org/abs/2210.10753

A warm cosmic web?



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

Free streaming scale of thermal warm dark matter

Viel et al 2005

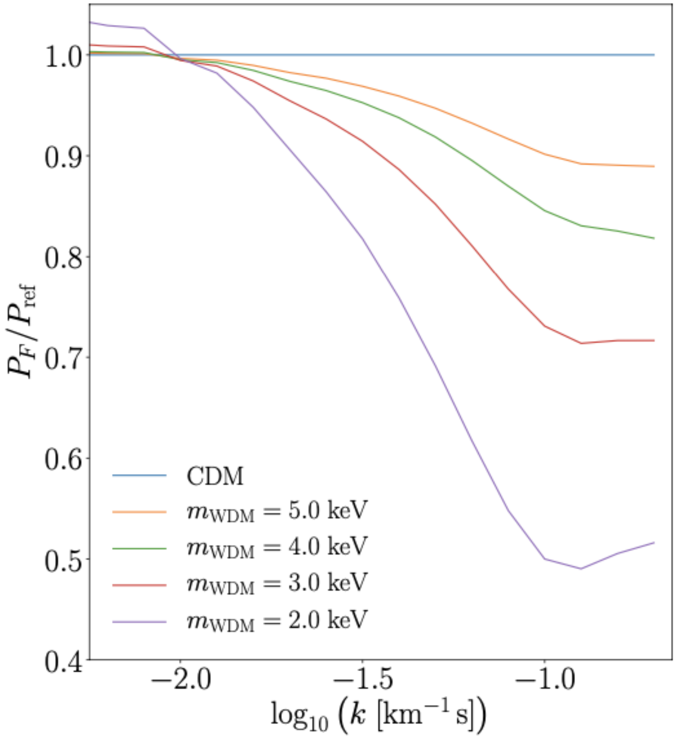
The smoothing scales

Vid Irsic

Unveiling Dark Matter free-streaming at the smallest scales with high redshift Lyman-alpha forest

Vid Iršič[1,2], Matteo Viel[3,4,5,6,7], Martin G. Haehnelt[1,8], James S. Bolton[9], Margherita Molaro[9], Ewald Puchwein[10], Elisa Boera[5,6], George D. Becker[11], Prakash Gaikwad[12], Laura C. Keating[13], Girish Kulkarni[14]
[1] Kavli Institute for Cosmology, University of Cambridge

WDM free streami



The smoothing scales

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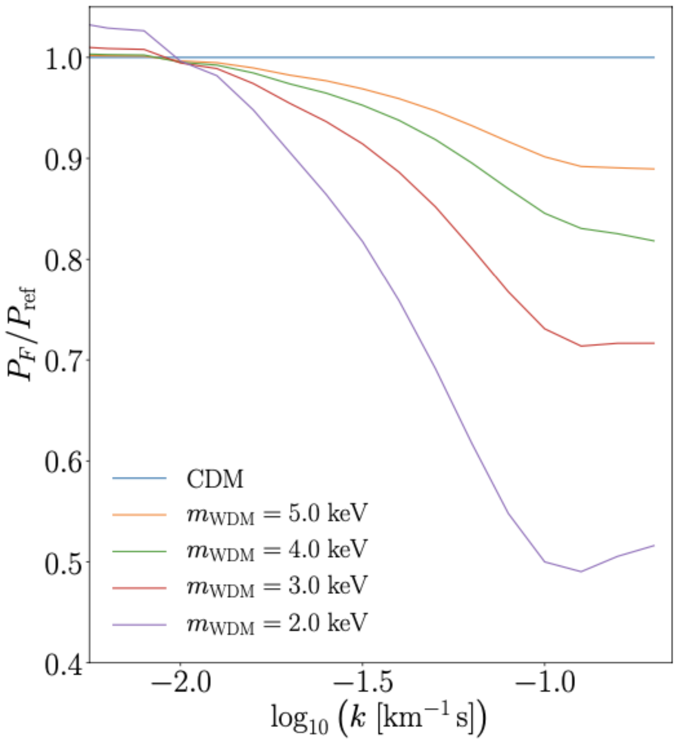
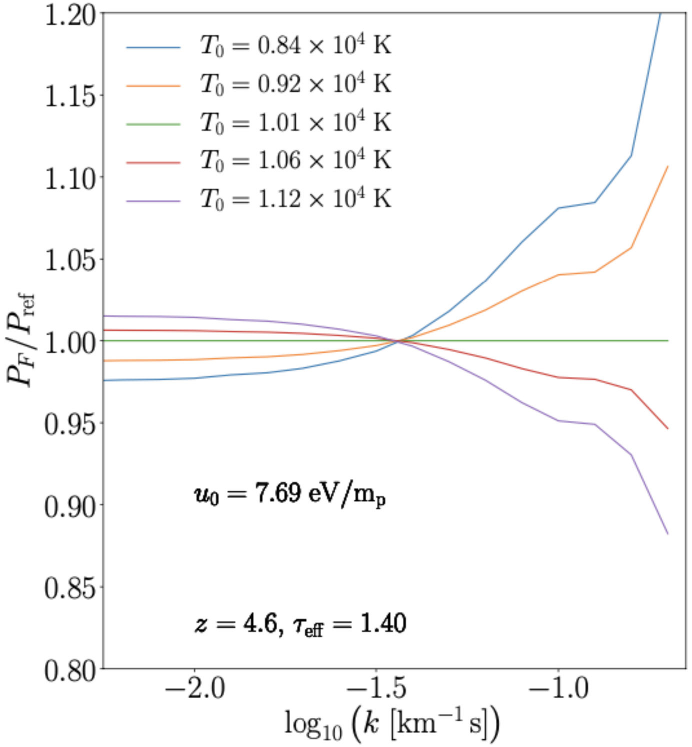
WDM free streaming



Thermal broadening



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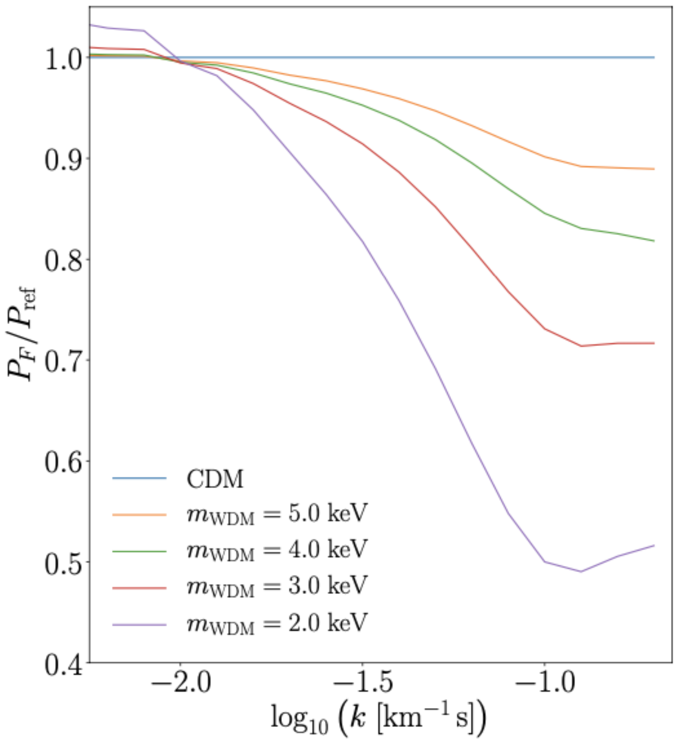
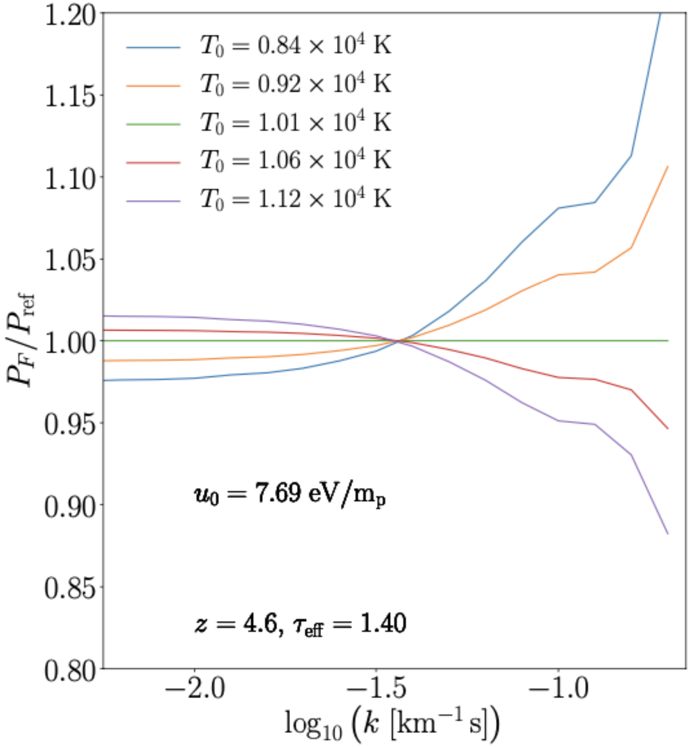
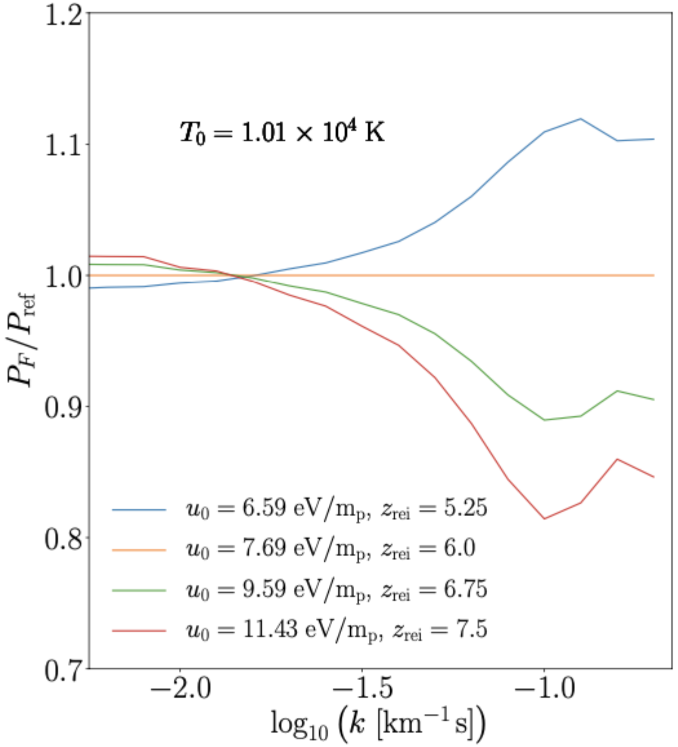
WDM free streaming



Thermal broadening



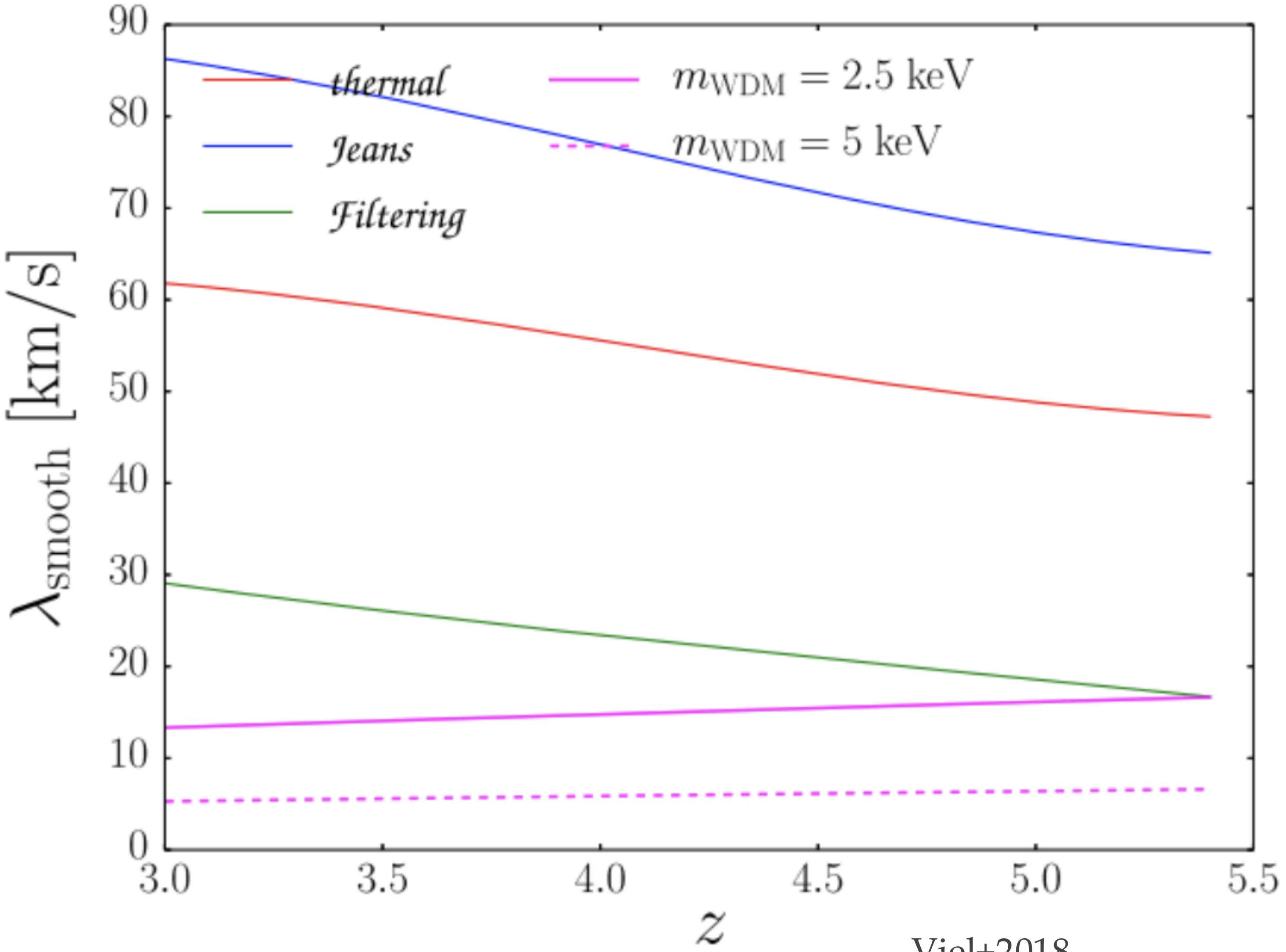
Gas pressure



$$u_0(t) = \int_0^t dt\, \frac{\mathcal{H}}{\bar{\rho}_m} \frac{3k_B}{2\mu}$$

H is heating rate

The smoothing scales - II

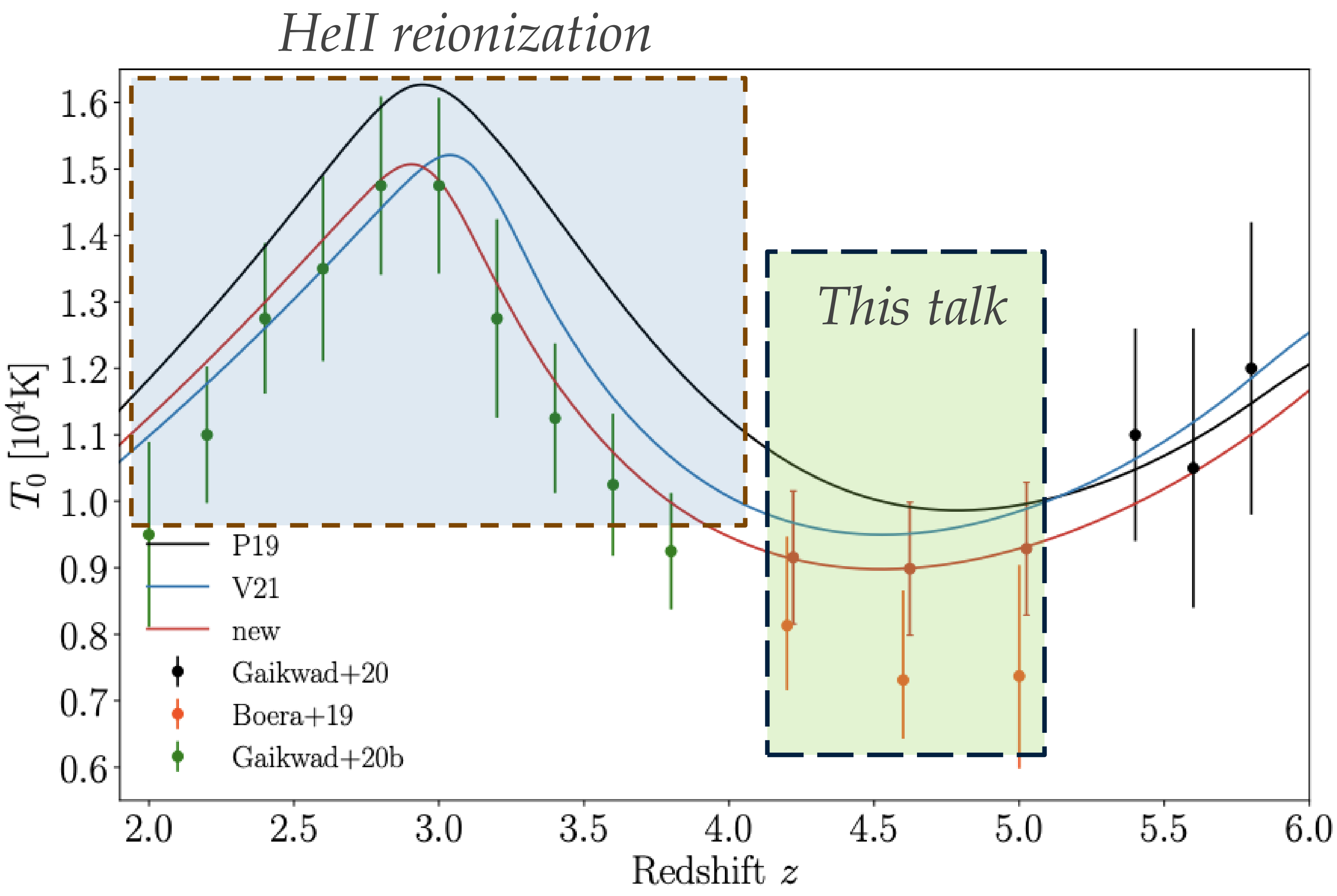


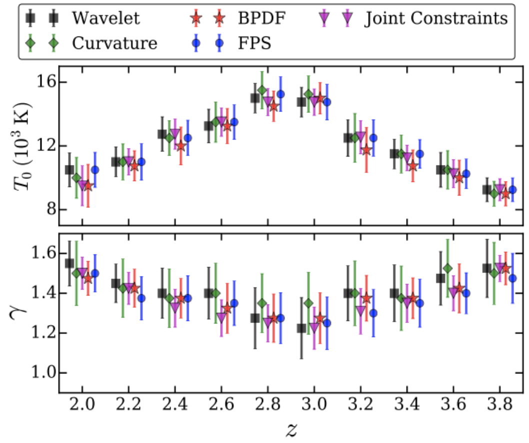
Viel+2018

Different physical scales (on top of instrumental resolution) affect the power spectrum cutoff:

- thermal: instataneous temperature at that redshift;
- filtering scale: depends on all the past thermal history – related to Jeans scale;
- WDM cutoffs are basically redshift independent

The IGM thermal state





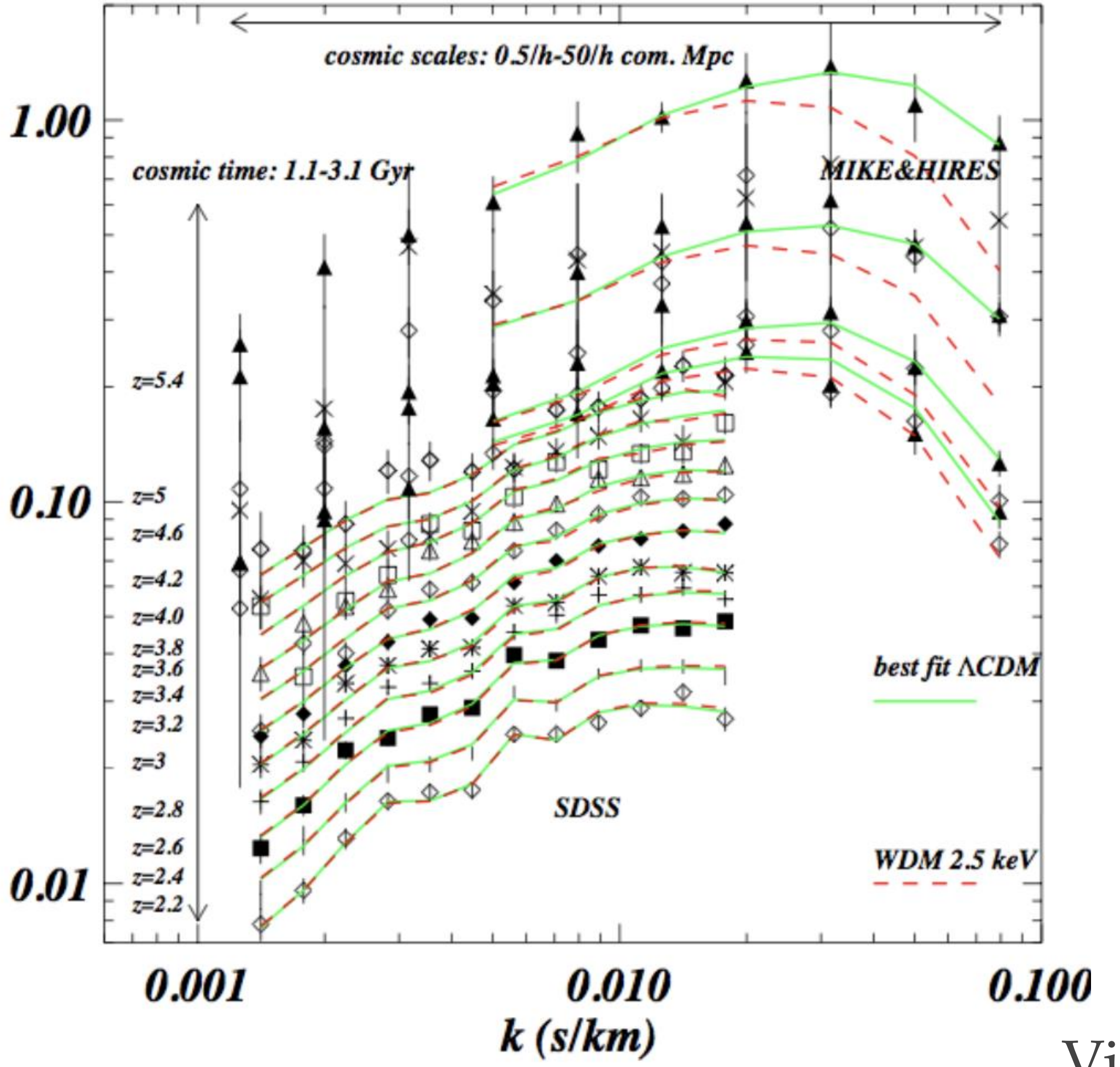
- Constraints obtained with a variety of data and methods
- Sensitive to lines rather than the lines' clustering

Status in 2013

Matteo Viel

Large scales — Small scales

1D flux power

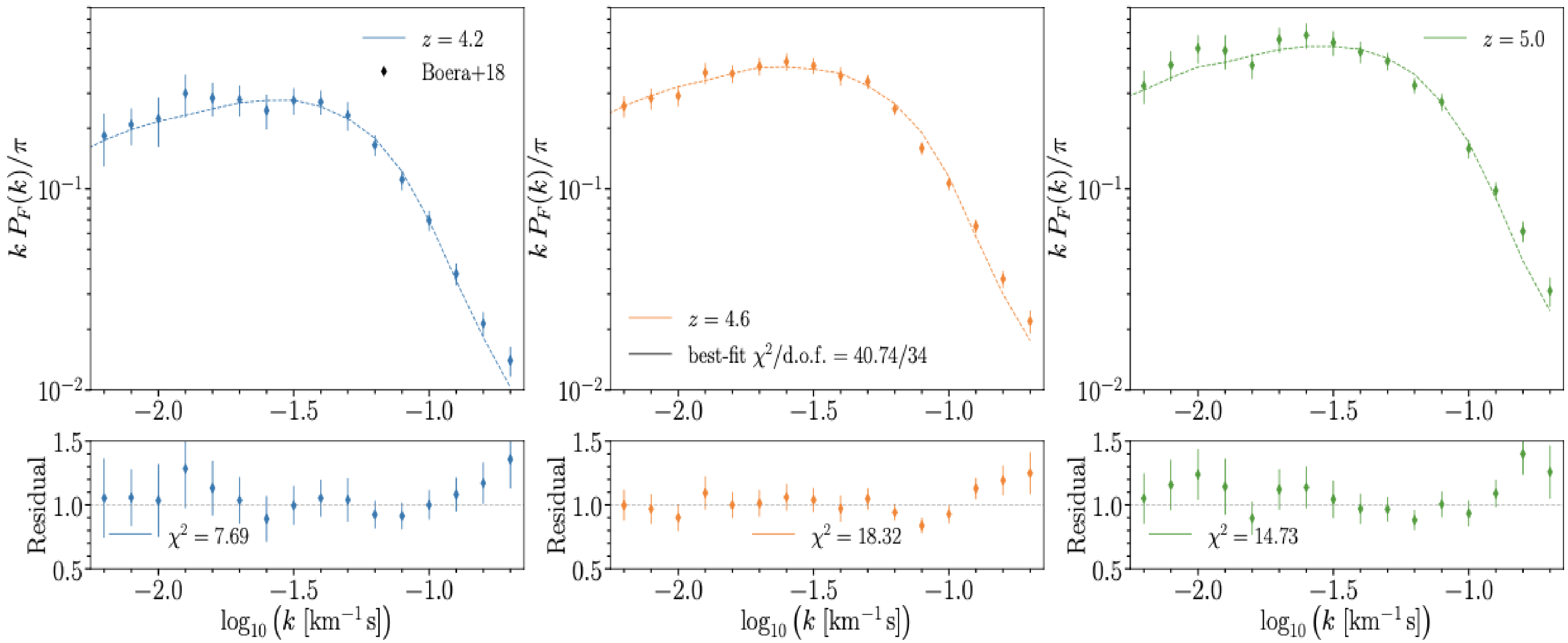


Viel+1

- Test of structure formation for a LCDM Universe in a **unique "pre-galactic" environment**
- m_{WDM} > 3.3 keV (2σ C.L.)

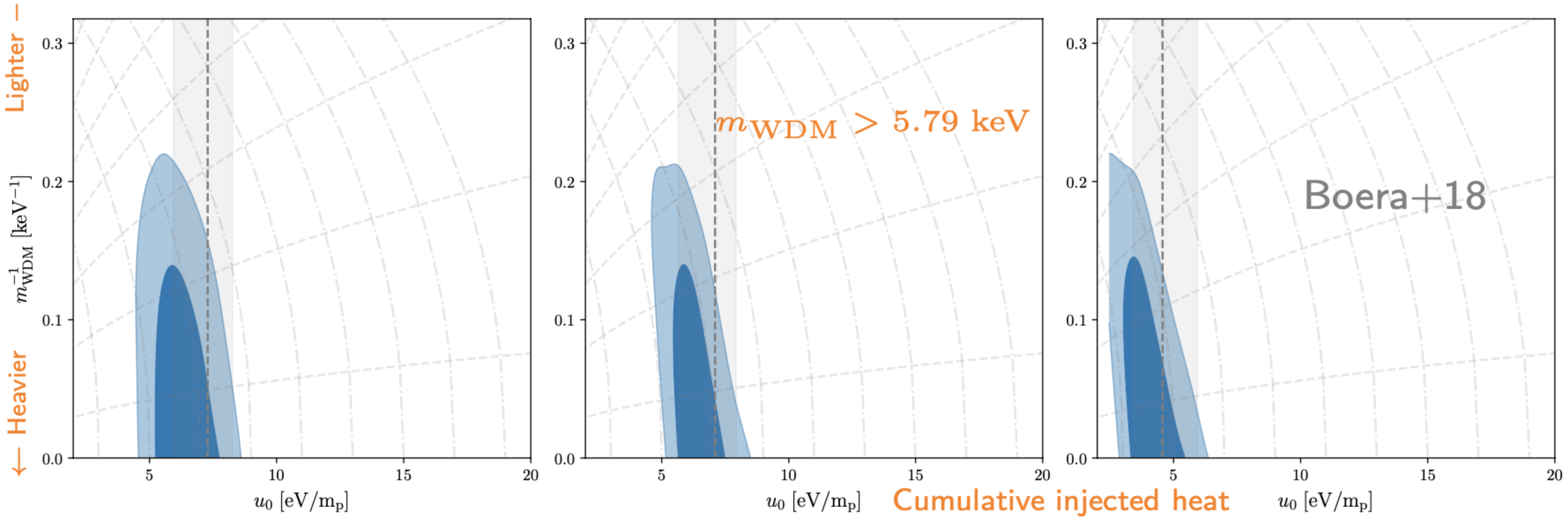
Note: 10 yrs later only a factor 2 more high z QSOs

The data



Boera+19, Irsic+23

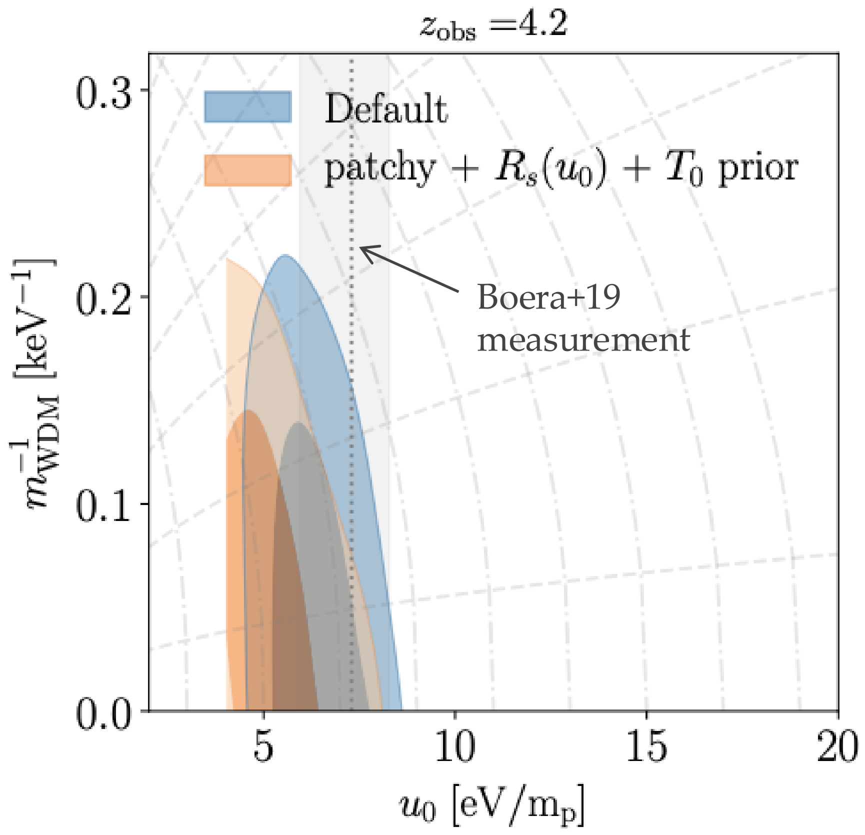
Thermal WDM



Irsic+23

Thermal WDM

Light WDM



Heavy WDM or LCDM

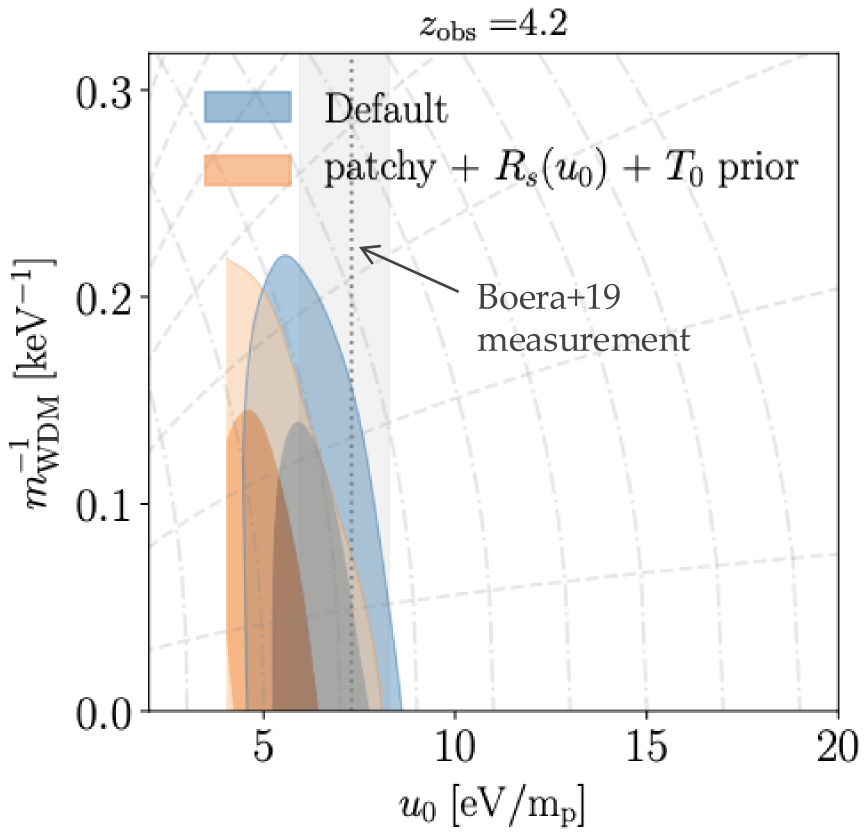
Injected heat

Irsic, MV +23

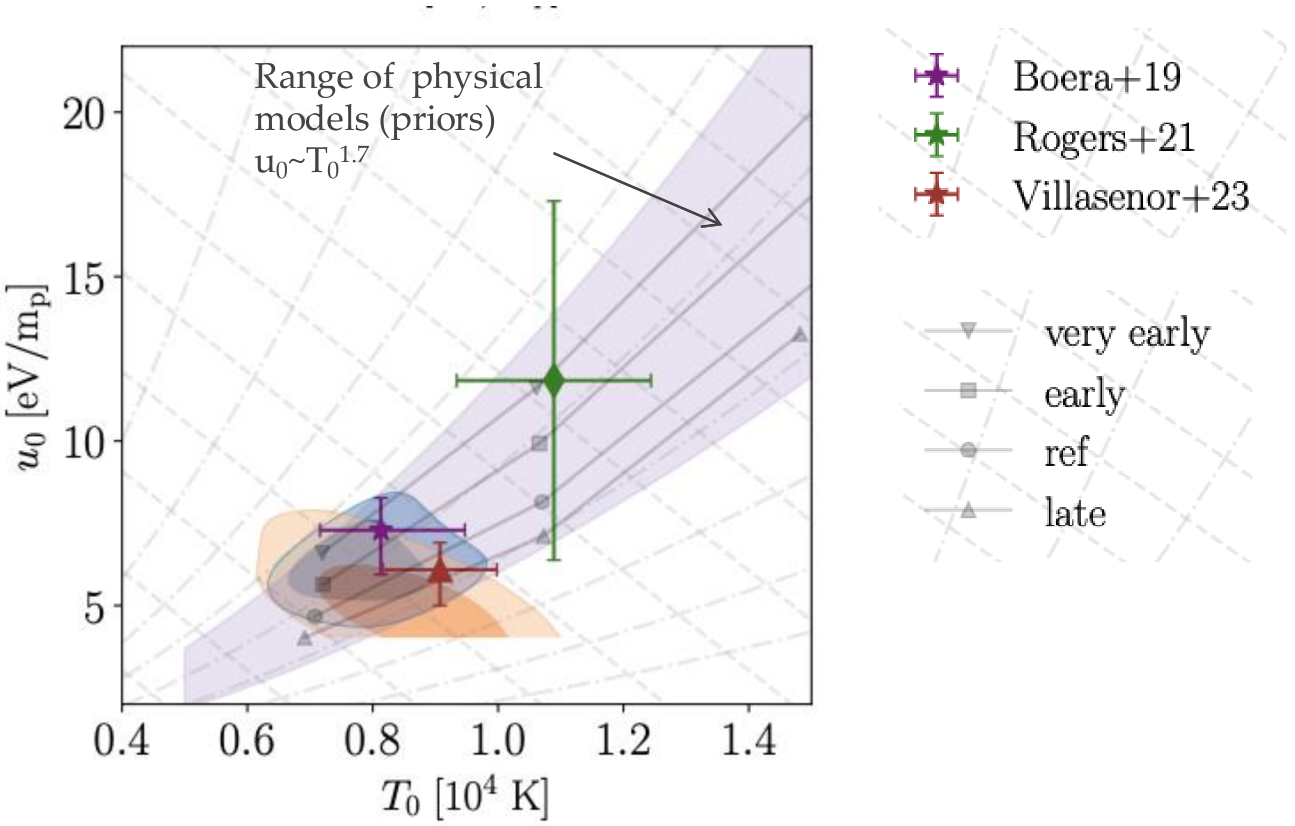
Thermal WDM - II

Light WDM

Heavy WDM or LCDM



Injected heat

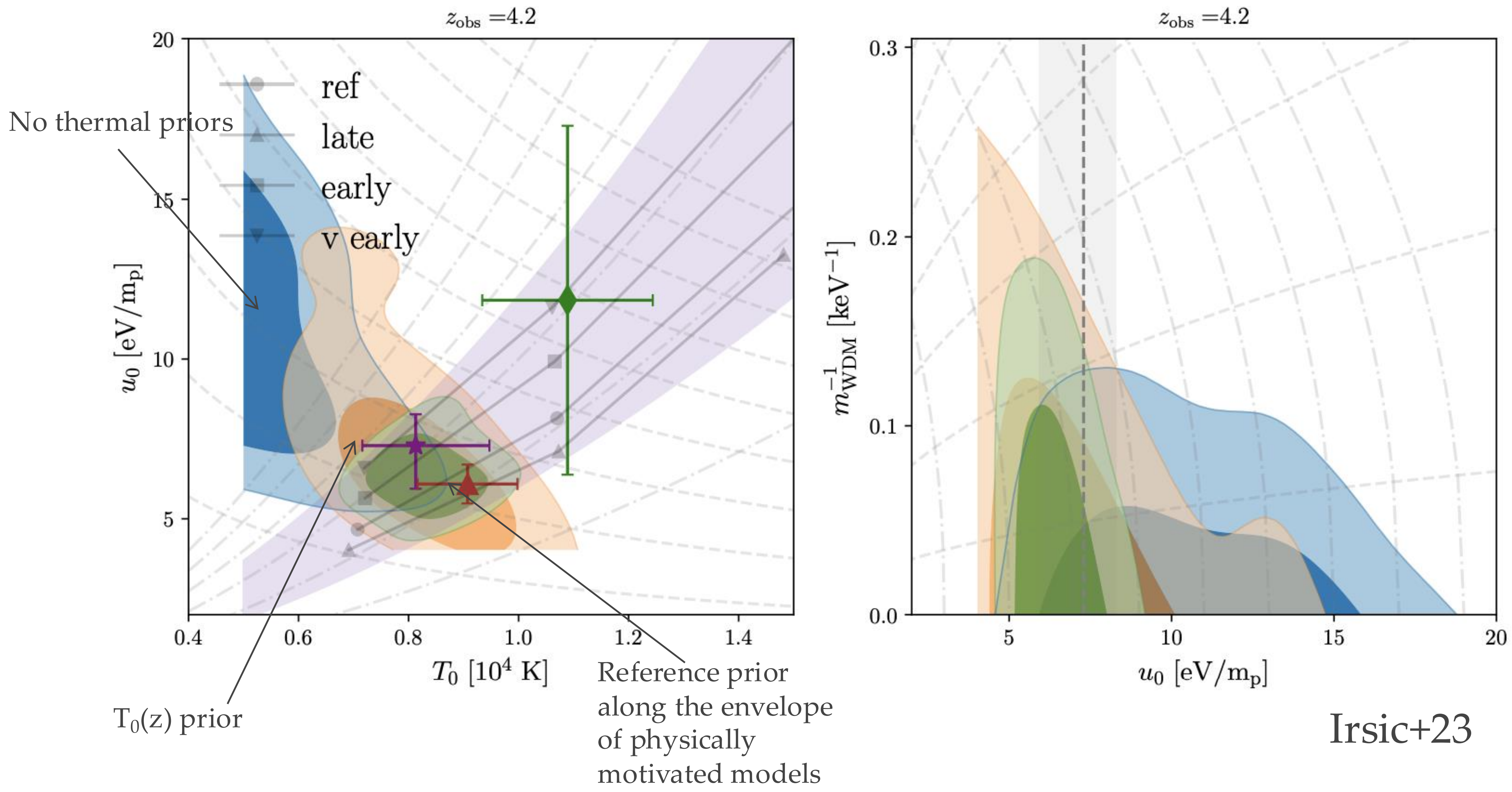


IGM temperature

Irsic, MV +23

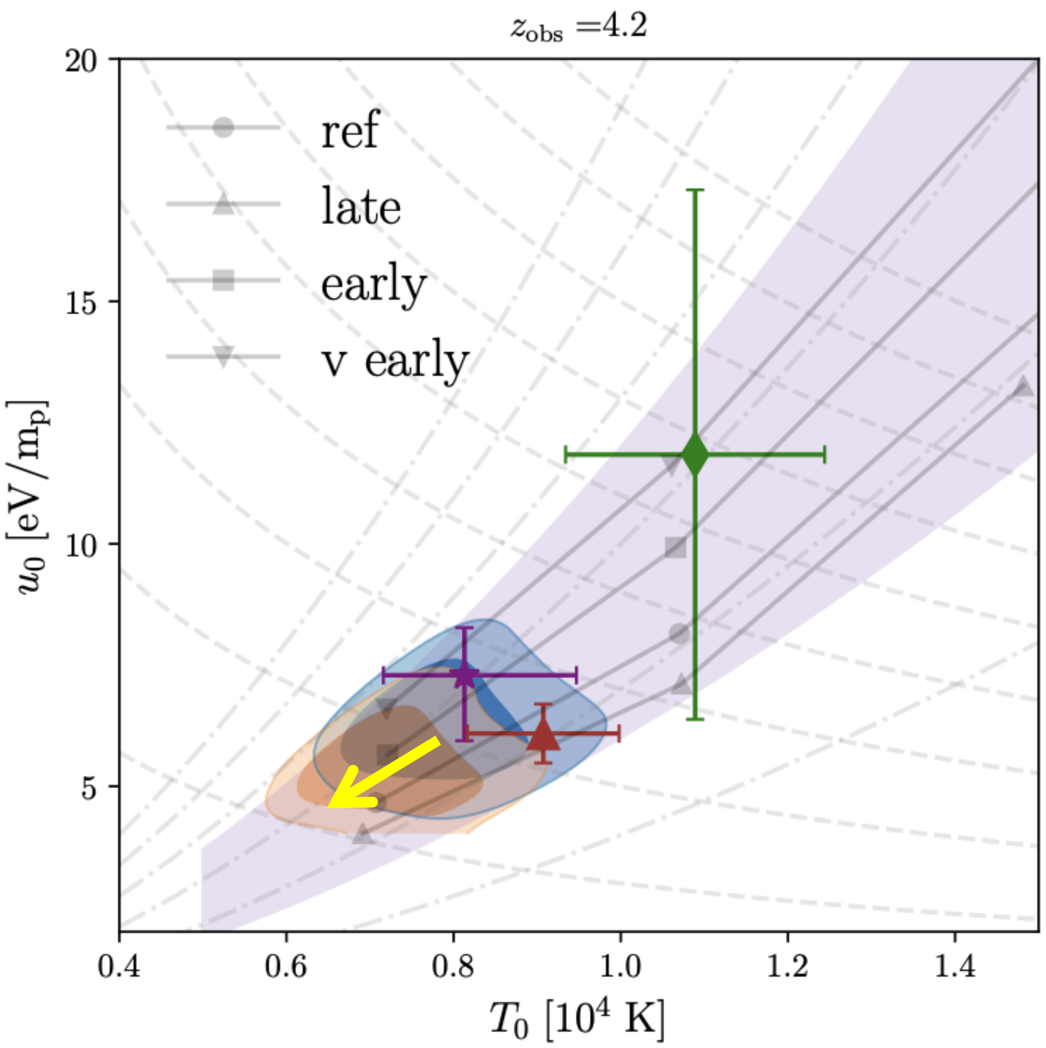
Thermal WDM – the effect of thermal priors

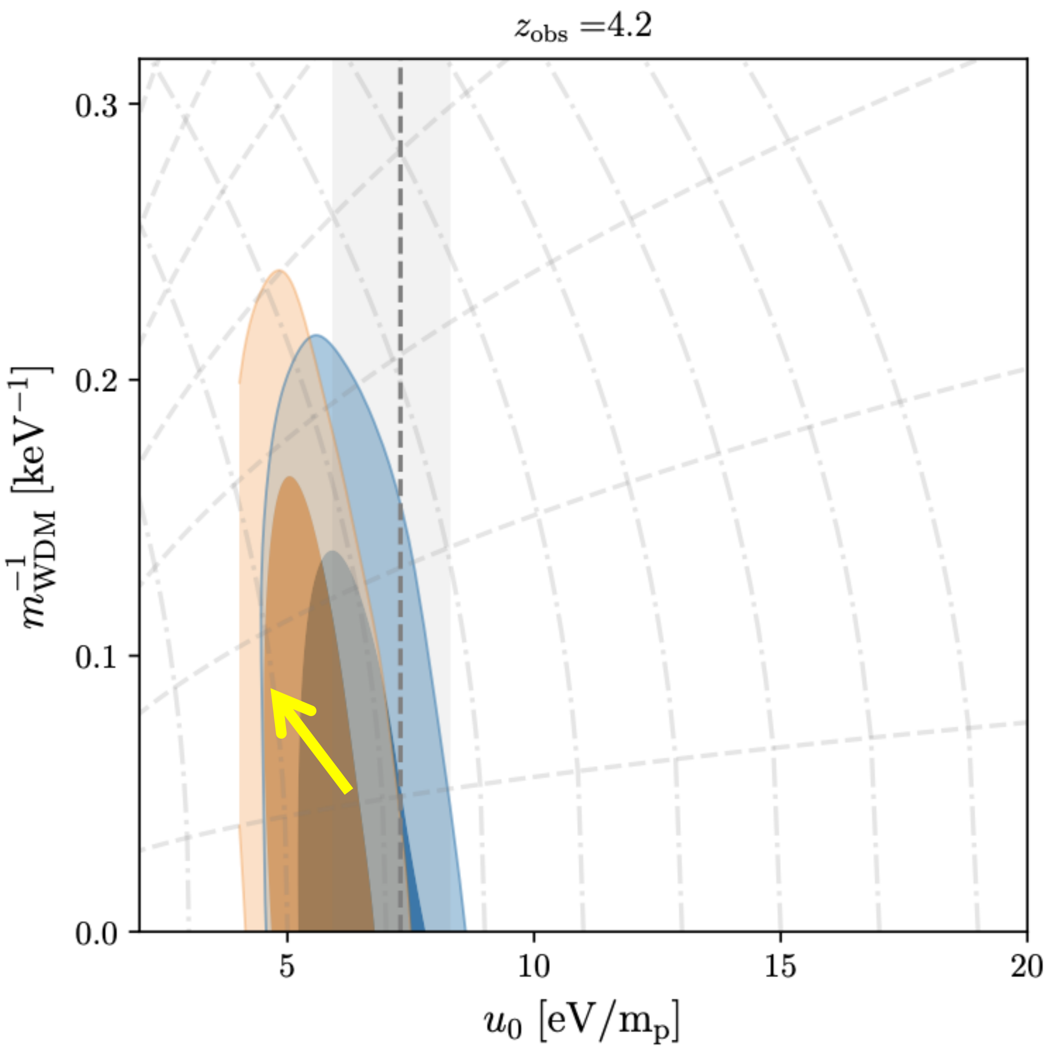
Matteo Viel



Irsic+23

Thermal WDM – inclusion of patchy correction





Irsic+23

Scalar Dark Matter

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

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

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Phi)dx^2$$

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

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

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

Matteo Viel

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

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

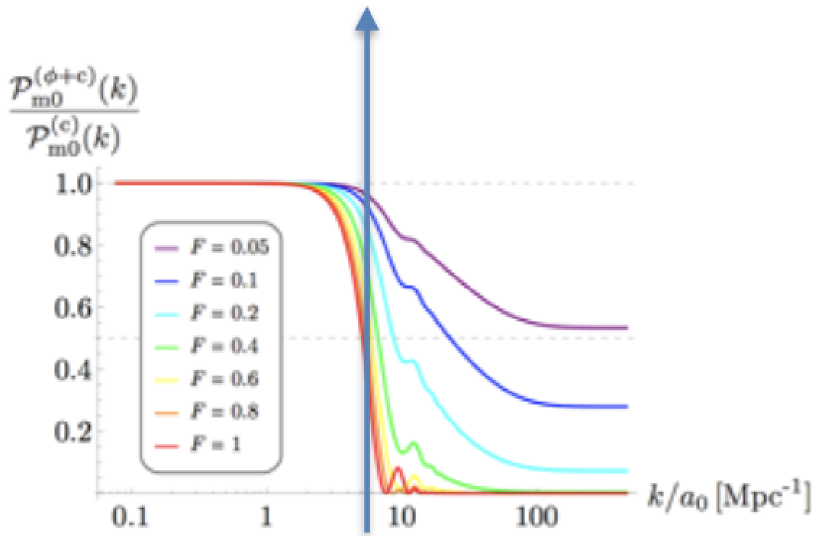
$$\ddot{\delta}_{{\rm c}k} + 2H\dot{\delta}_{{\rm c}k} - \frac{3}{2}H^2\delta_{{\rm m}k} = 0.$$

Linear perturbation theory in CDM+scalar field model

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

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

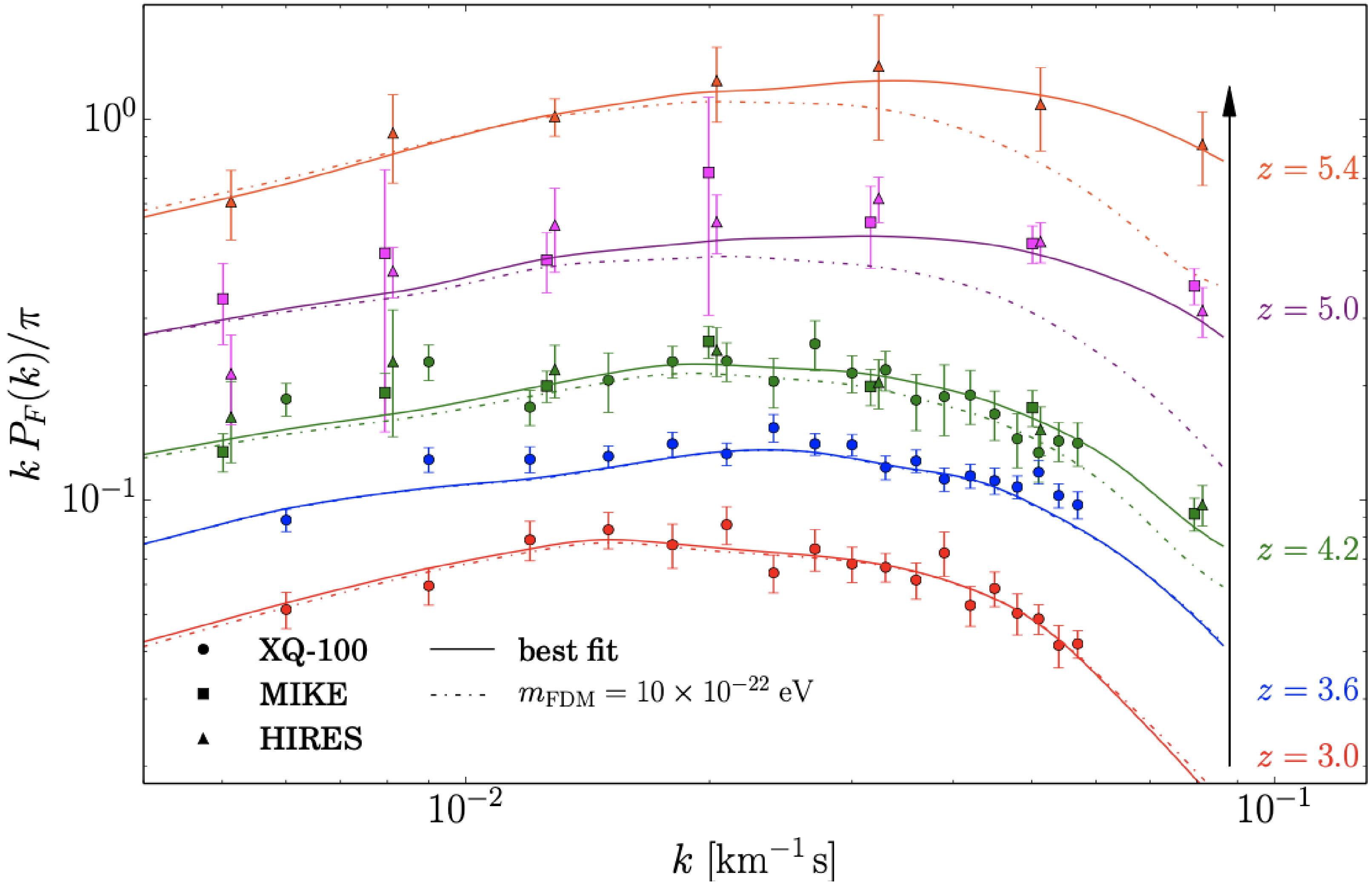
Sound speed of scalar DM and Jeans scale definition



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

Scalar Dark Matter - III



Irsic, Viel+ 2022 PRL

The IGM as a thermometer

- Dark Photon Dark Matter: simple extension of the SM of particle physics

$$\mathcal{L}_{\gamma A'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu$$

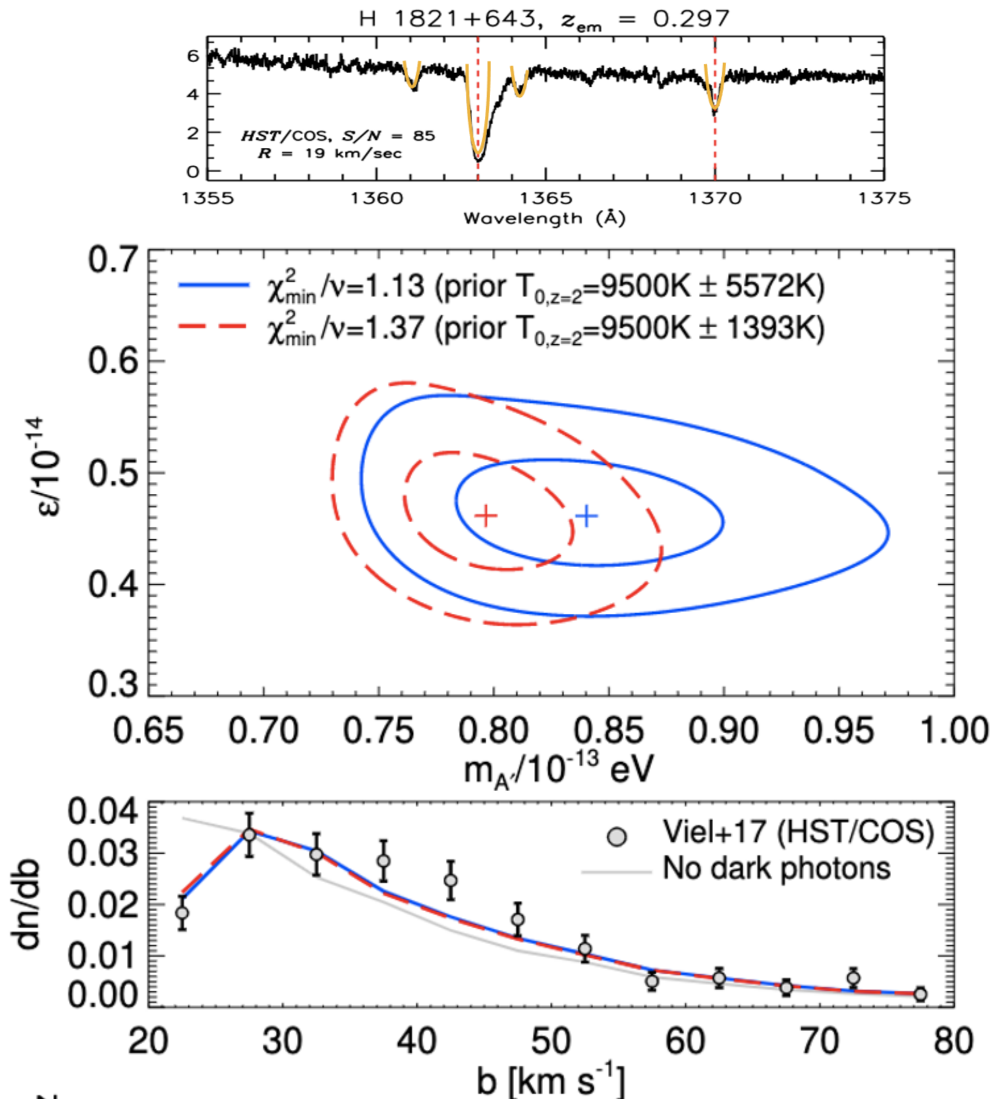
$$E_{A'\to\gamma} \sim 2.5\,\mathrm{eV}\left(\frac{\epsilon_{-14}}{0.5}\right)^2\left(\frac{3}{1+z_{\rm res}}\right)^{3/2}\left(\frac{m_{-13}}{0.8}\right)$$

- Dark photon converts into standard photon when a resonance

Bolton, Caputo, Liu, MV, PRL, 2022

The IGM as a thermometer - II

Matteo Viel

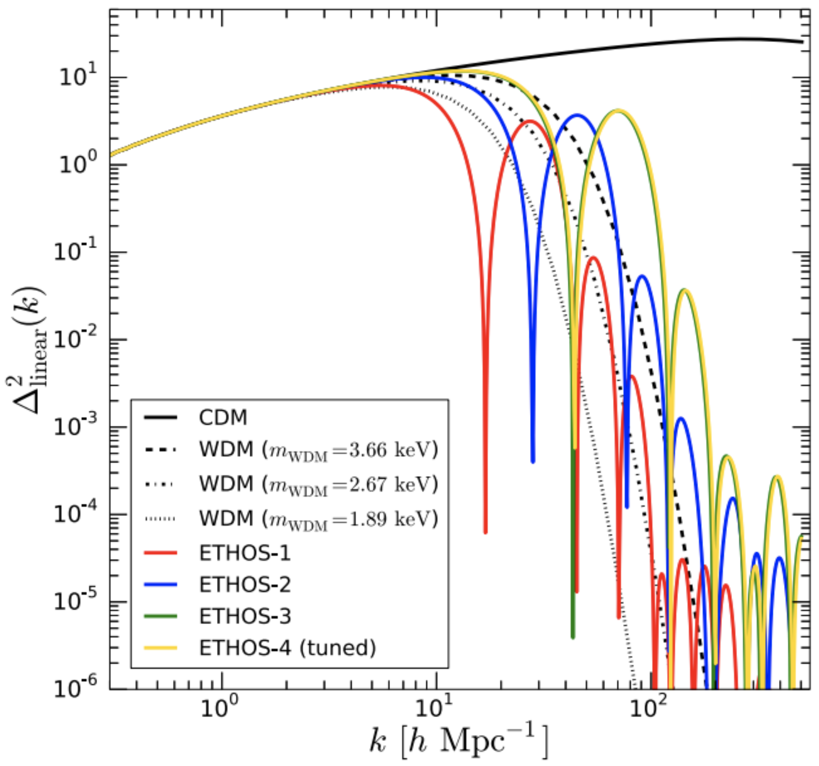


- Effect is small but can be used to place constraints on extra-heating

- At z=0.1 COS/HST lines are broader than

Baryon-DM or Dark radiation-DM interactions

Vogelsberger+16



- Dark Acoustic Oscillations are impacted by: 1) non-linearities; 2) projection in 1D power; 3) non-linear density-flux transformation