Cosmology with the Lyα forest

Matteo Viel - SISSA (Trieste, Italy)

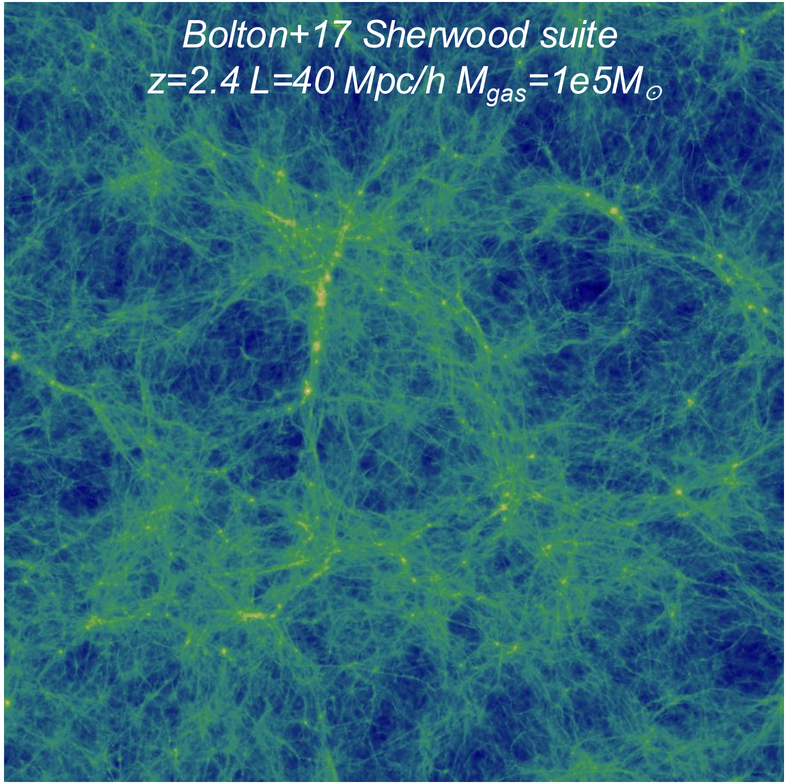
GGI - 30/9/2025

MA PER SEGUIR VIRTUTE E CANOSCENZA

ifpU

Intro: the simple physics of the cosmic web

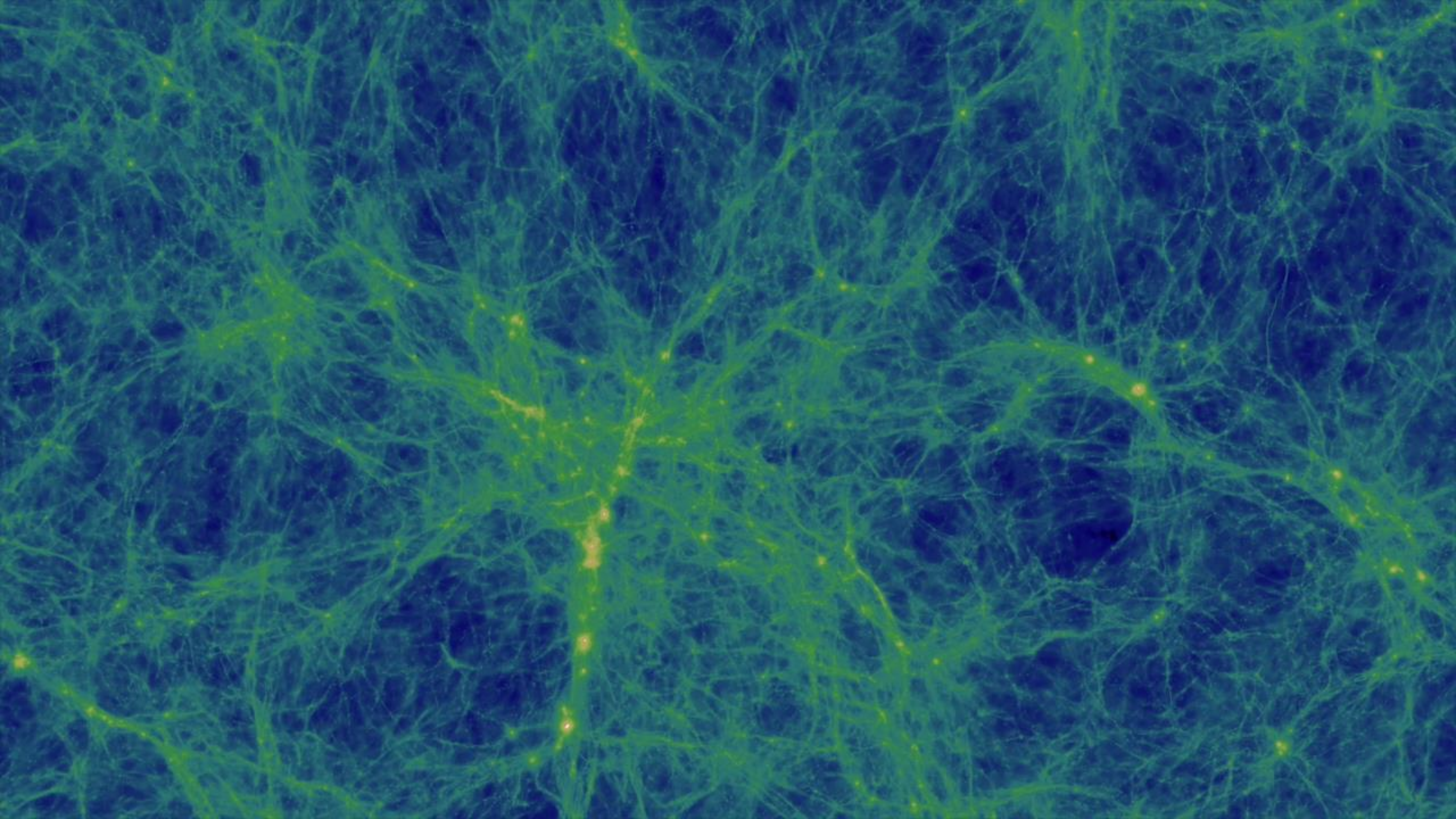
Physics of the gas



<u>Intergalactic Cosmic Web</u>

- ✓ Filamentary gaseous cosmic web as predicted in ΛCDM hydro sims
- ✓ Key physics relatively simple: **gas cooling** and **heating** by a (uniform) **UV background** in an **expanding Universe**
- ✓ Physical properties can be derived by assuming two physical fluids (DM and gas) evolving, with the latter having its pressure (Jeans scale)

Bi & Davidsen 1997, Schaye 2001, Gnedin & Hui 98



Physics of the gas: filtering scale

DM

$$\frac{d^2\delta_X}{dt^2} + 2H\frac{d\delta_X}{dt} = 4\pi G\bar{\rho}(f_X\delta_X + f_b\delta_b),$$

GAS

$$\frac{d^2\delta_b}{dt^2} + 2H\frac{d\delta_b}{dt} = 4\pi G\bar{\rho}(f_X\delta_X + f_b\delta_b) - \frac{c_S^2}{a^2}k^2\delta_b$$

$$k_J = \frac{a}{c_S}\sqrt{4\pi G\bar{\rho}}.$$

Thermal history

Equation of motion of gas element

$$\frac{d\boldsymbol{v}}{dt} + H\boldsymbol{v} = -\nabla\phi - \frac{1}{\rho}\nabla P,$$

$$\psi = \phi + \mathcal{H}$$

$$\frac{d\boldsymbol{v}}{dt} + H\boldsymbol{v} = -\nabla\psi$$

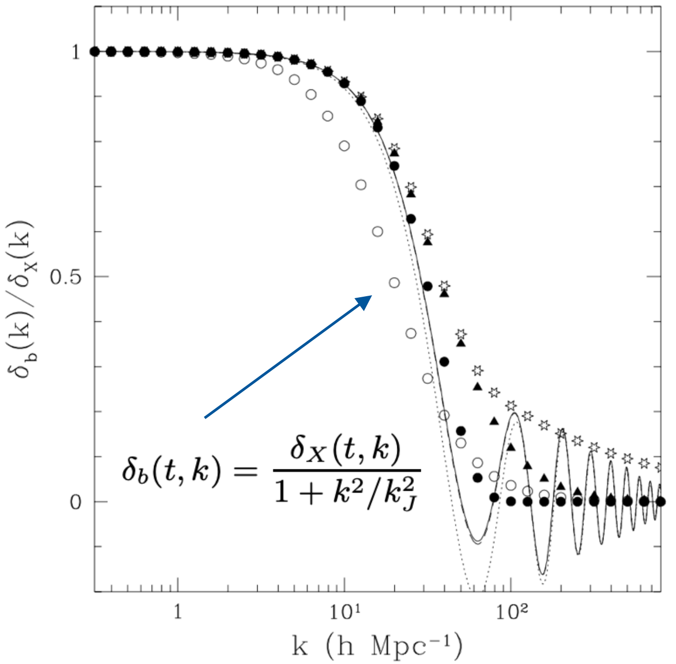
$$\mathcal{H}(\rho) = \frac{P(\rho)}{\rho} + \int_1^\rho \frac{P(\rho')}{\rho'}\frac{d\rho'}{\rho'}$$

Specific enthalpy

Filtering scale

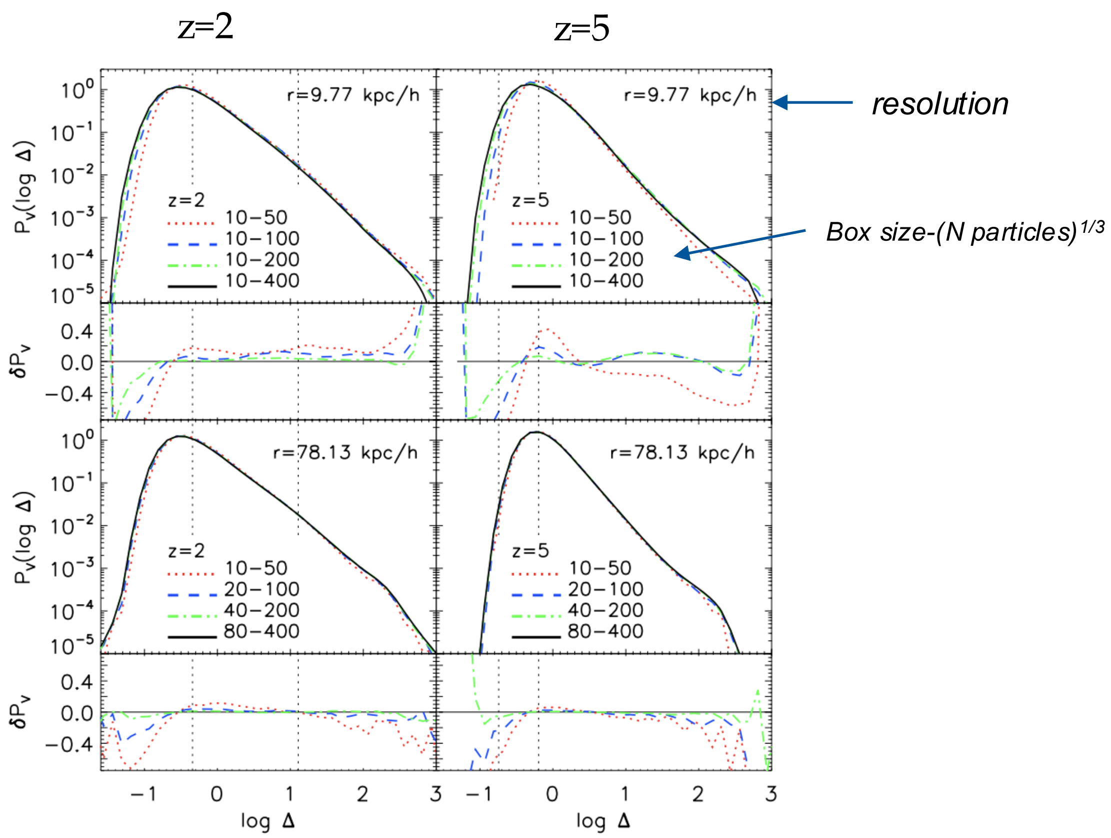
$$\frac{1}{k_F^2(t)} = \frac{1}{D_+(t)}\int_0^t dt' a^2(t')\frac{\ddot{D}_+(t') + 2H(t')\dot{D}_+(t')}{k_J^2(t')}\int_{t'}^t \frac{dt''}{a^2(t'')}$$

Filtering scale k_F rather than k_J is used
And k_F depends on the **whole thermal history** (unlike k_J)



Gnedin & Hui 1998, Gnedin 2000, He & Gnedin 2020

Physics of the gas: the gas PDF



Bolton & Becker 2009, Bi & Davidsen 97

- ✓ Volume-weighted gas pdf is a skewed Gaussian – **Lognormal** fit works reasonably well
- ✓ 8th order polynomali fit provided in Becker&Bolton 2009, but earlier models are also in agreement (Bi, Miralda-Escude' et al. 97)
- ✓ Unfortunately, this is not observable….

Physics of the gas: the gas thermal state

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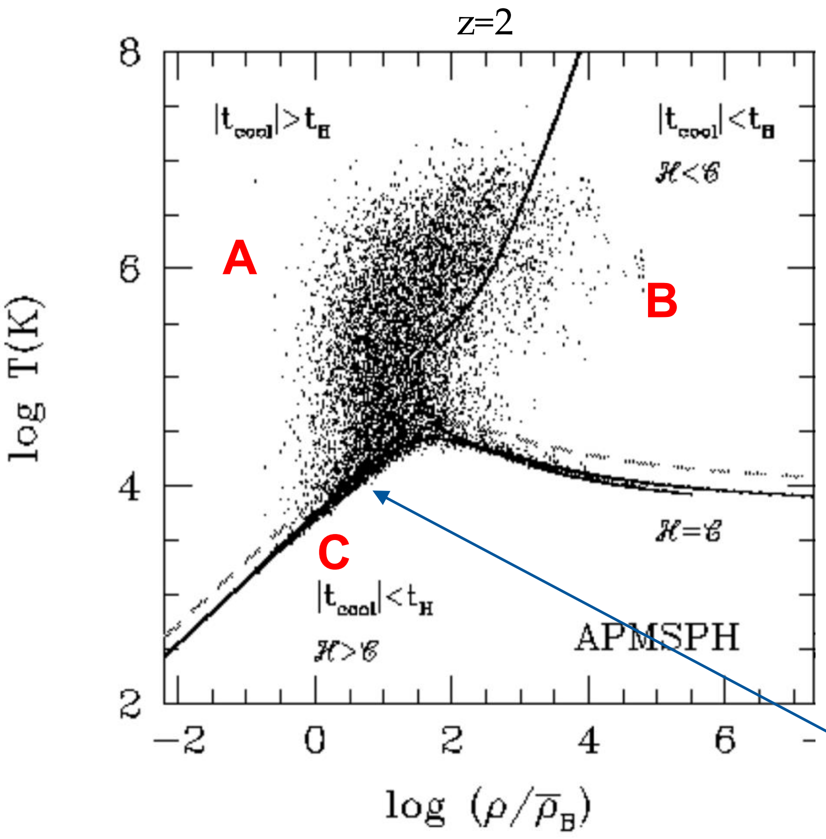


Theuns+98

$$t_{\rm cool} = \frac{u}{|\dot{u}|} = \frac{3k_BT}{2\mu}\frac{m_H}{\rho(1-Y)^2(\mathcal{C}-\mathcal{H})}$$

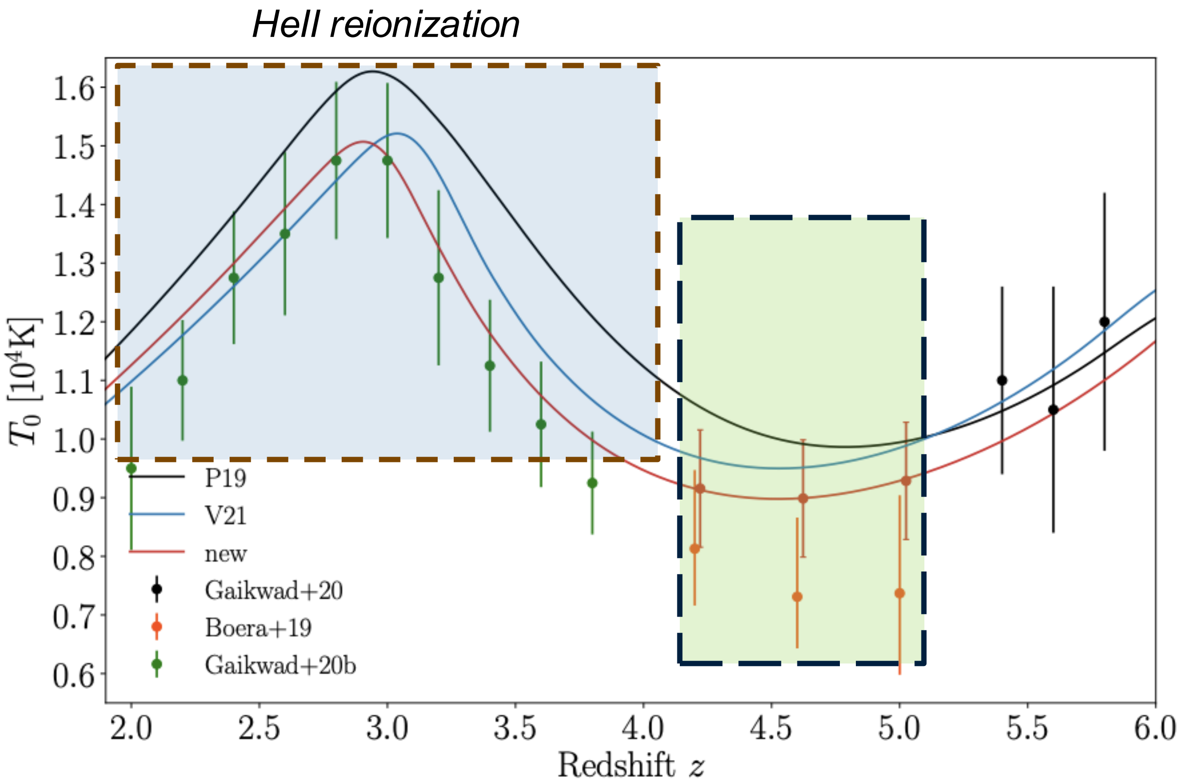
t_{cool}: cooling time with *C* an *H* are normalized cooling and heating rates

✓ 3 regions in the T-ρ plane:
- **A**) cooling time much longer than Hubble time: *C* and *H* are not effective
- **B**) Bremsstrahlung and line cooling are effective → $t_{cool}<t_H$
- **C**) Region with efficient photoheating (HI and HeII)

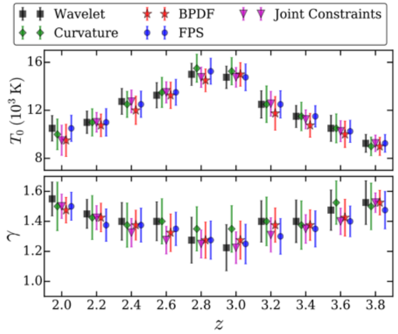
✓ $T=T_0(1+\delta)^{\gamma-1}$ for the low-density region

✓ Most of the gas in a cool/cold phase

The IGM thermal state

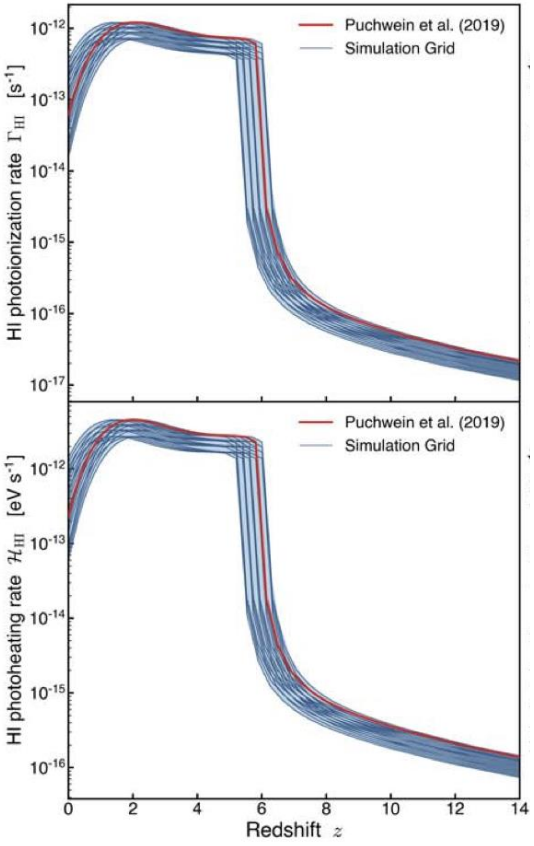


Walter+19

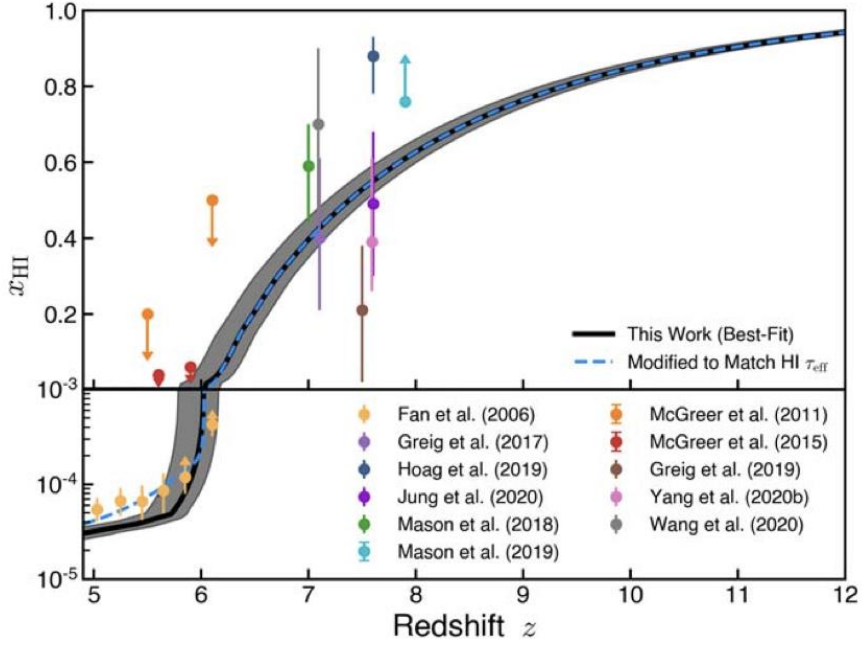


- ➢ Constraints obtained with a variety of data and methods
- ➢ Sensitive to lines rather than the lines' clustering
- ➢ HeII bump quite well detected

Ionization history



Villasenor+22



Most of this "global" uncertainty is captured by requiring the sims to reproduce a given mean flux value (which is very well measured by data)

Part 2

"New" astrophysics in the cosmic web

Patchy reionization

Simulating the high-redshift cosmic web

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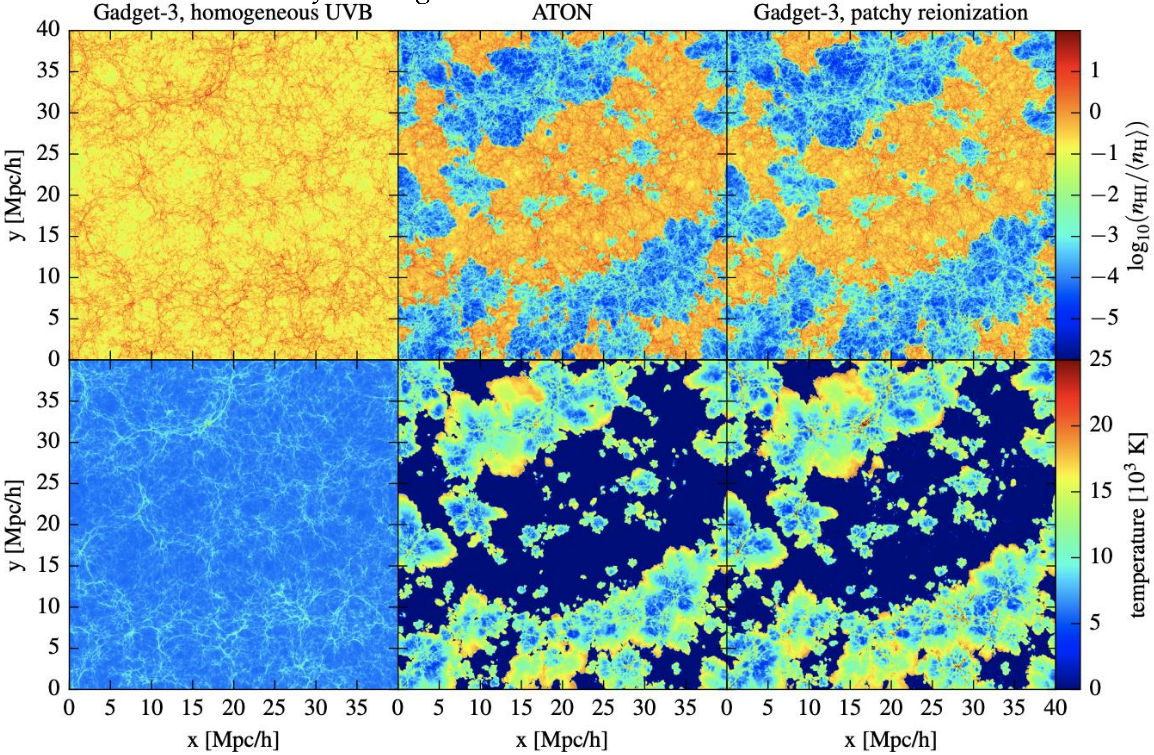
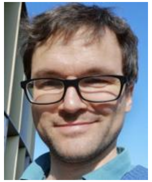
https://www.nottingham.ac.uk/astronomy/sherwood/

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



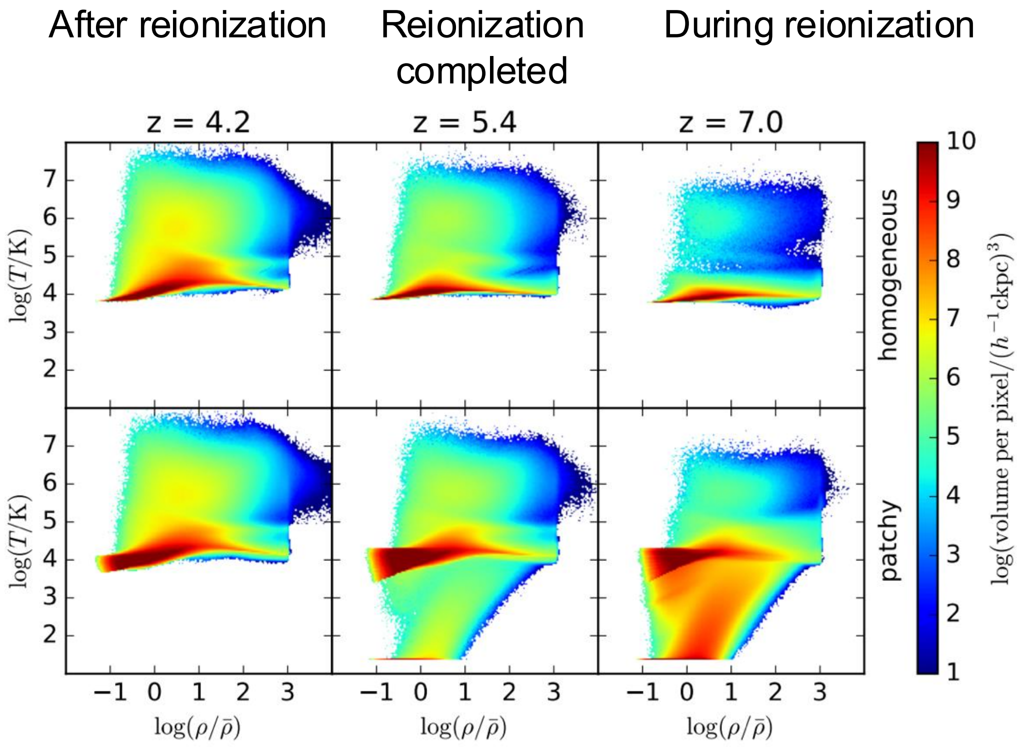
Bolton+17
Puchwein, Bolton+23



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
- ✓ G3 code + ATON to perform radiative transfer for patchy reionization
- ✓ Focus (and model calibration) on the high-z (z>4) forest

Physics of the gas: the gas thermal state at high-z



Puchwein+23

- ✓ T-ρ relation somewhat flatter at high-z – moving closer to reionization
- ✓ … and prone to the effects of a patchy reionization

Patchy Reionization

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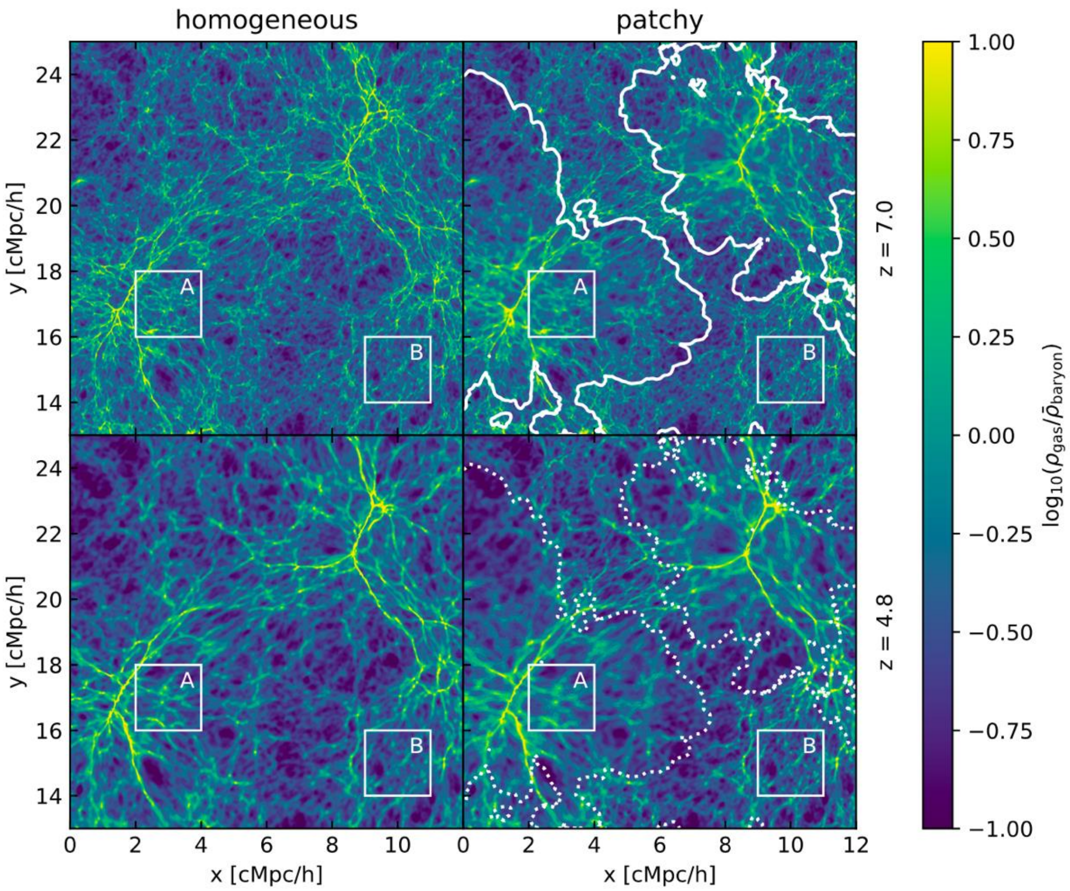
Puchwein+23



During reionization

After reionization is complete

Note: Reionization ends at z =5.3

Patchy reionization - II

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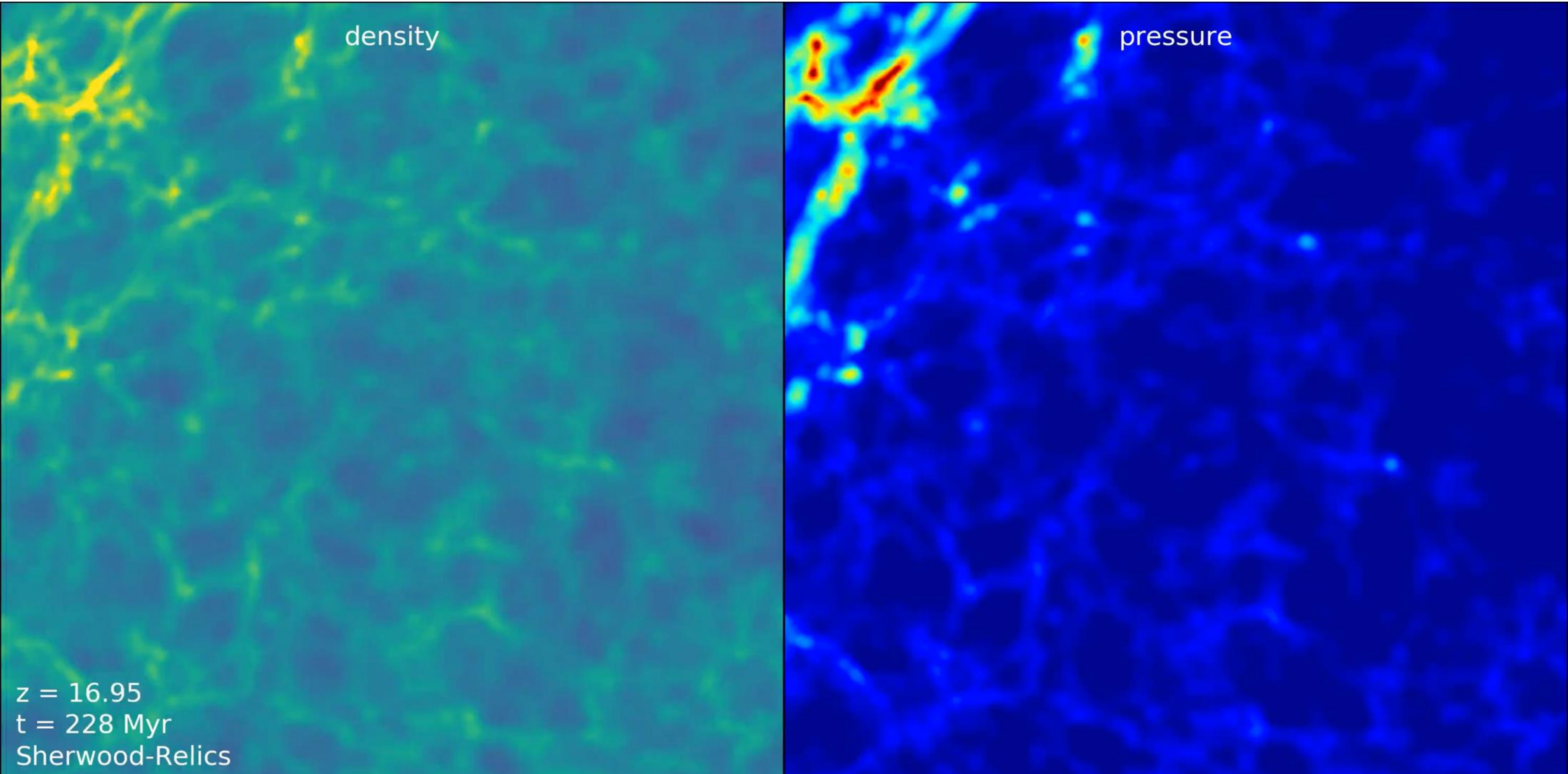


Summary

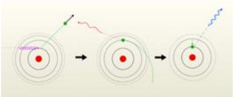
- ✓ There is a physical model of the low-density cosmic web based on gravitational instability, hydrostatic equilibrium (Jeans scale) + UV background, at z=2-5.
- ✓ Cosmic filaments do trace underlying gravitational (DM) potential above the filtering scale
- ✓ Thermal and ionization history are reasonably constrained and support: **patchy reionization**, HeII "heating" bump
- ✓ Feedback effects are small, impact more the low z regime, no evidence for turbulence
- ✓ Any astrophysical or fundamental physical process able either to:
  - dump heat in the low density IGM
  - or modify the matter power spectrum

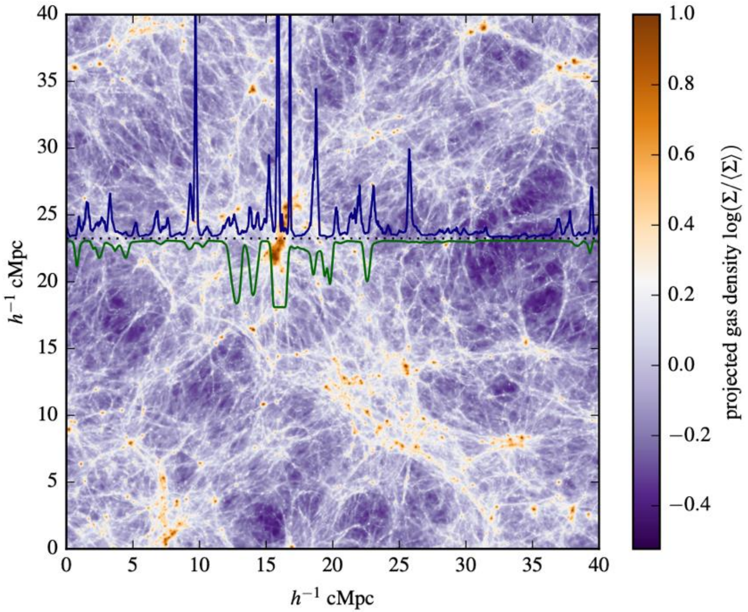
  could have an impact
- ✓ How can we observe this?

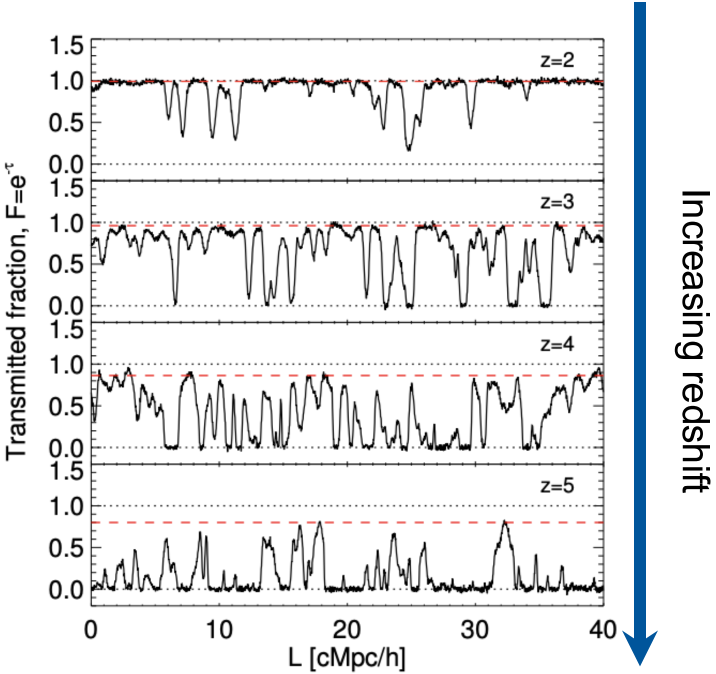
Lyman-α forest as a manifestation of the cosmic web

Modelling
Cosmology

The Lyman-α forest





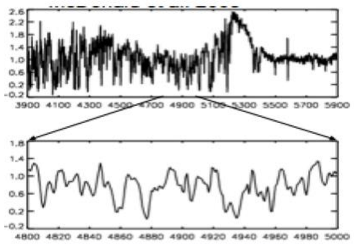


Most of the flux statistics are in agreement with ΛCDM – 216,000 flux models fed into MCMC analysis

Increasing z → increasing HI → more Absorption – at high z even underdense gas can produce absorption

Data

DESI **BOSS/SDSS-III**



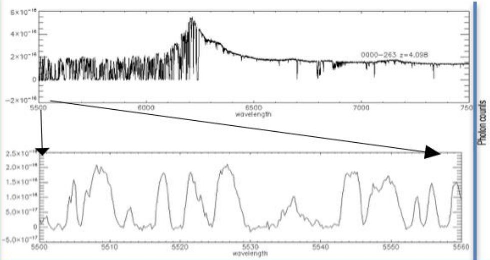
Low resolution BOSS and SDSS-III spectra S/N~2-3 - 160,000 spectra

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



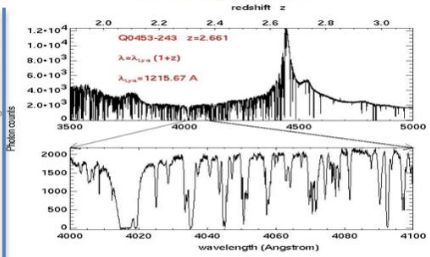
Medium resolution X-Shooter VLT spectra S/N ~ 30

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

Modelling the 3D flux power

Matteo Viel

3D flux power — Linear power

$$P_F(k,\mu) = b_\delta^2(1+\beta\mu^2)^2 P_L(k)\, D(k,\mu)$$

$$\beta = \frac{b_{F\eta} f(\Omega)}{b_{F\delta}}$$

See Seljak 12 for analytical understanding of Lya bias

Linear tracer

$$\delta_F = b_{F\delta}\delta + b_{F\eta}\eta$$

$$b_{F\delta} = \frac{\partial \delta_F}{\partial \delta}\,;\quad b_{F\eta} = \frac{\partial \delta_F}{\partial \eta} \qquad \eta = -\frac{1}{aH}\frac{\partial v_p}{\partial x_p}$$

Density bias — Velocity grad. bias — Pec. Vel. Grad.

Non linearities

See Desjacques+18 for bias expansion

McDonald 2003

$$D(k,\mu) \equiv \exp\left\{\left[\frac{k}{k_{\rm NL}}\right]^{\alpha_{\rm NL}} - \left[\frac{k}{k_P}\right]^{\alpha_P} - \left[\frac{k_\parallel}{k_V(k)}\right]^{\alpha_V}\right\}$$

Non-linear power — Pressure smoothing — RSD and thermal broadening

Arinyio-i-prats+ 2015

$$D_1(k,\mu) = \exp\left\{\left[q_1\Delta^2(k) + q_2\Delta^4(k)\right]\left[1 - \left(\frac{k}{k_v}\right)^{a_v}\mu^{b_v}\right] - \left(\frac{k}{k_p}\right)^2\right\}$$

Fewer params, better behaved at small k

k_{NL} ~ 5 h/Mpc k_p~10 h/Mpc k_v ~ 5-10 h/Mpc q_1~0.5-1.5

Modelling the 3D flux power

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$$\delta_F(\mathbf{x}) = b_1\,\delta_m(\mathbf{x}) + b_\eta\,\eta(\mathbf{x}) + \sum_i b_{\mathcal{O}_i}\,\mathcal{O}_i(\mathbf{x}) \;+ \delta_{\rm ctr}(\mathbf{x}) + \epsilon(\mathbf{x})$$

- ✓ EFT for the forest (Ivanov 23) 3D flux power with 15 params: 8 free parameters + analytical marginalization on other 7 param
  Good fit up to k_{max}=3 h/Mpc (z=2.8)

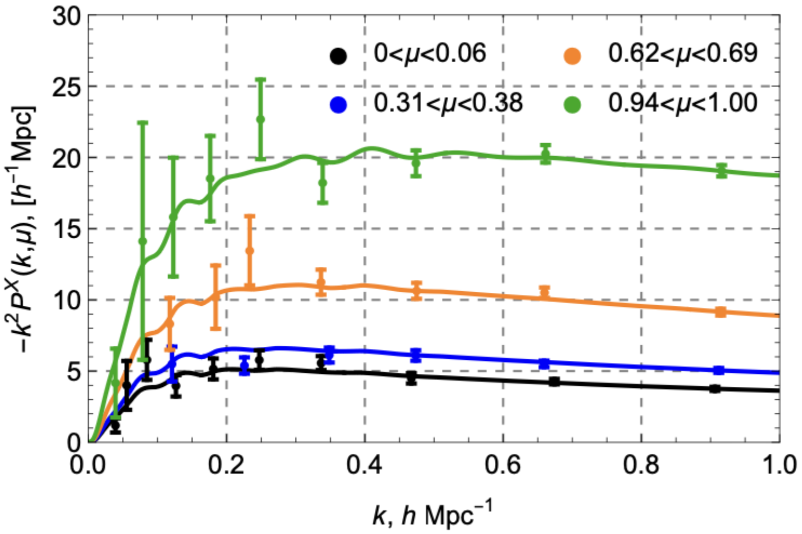
- ✓ Extended also to cross-correlation (Chudaykin & Ivanov 25) – good fit to k_{max} = 1h/Mpc

- ✓ Extended to **1D flux power**, tested on sims and applied to data to constrain PBH
  Ivanov & Trifinopolous 25

$$P_F(k_\parallel, z) = \frac{1}{2\pi}\int_{k_\parallel}^{\infty} \mathrm{d}k\, k\, P_F^{\rm 3D}(k, k_\parallel, z)$$

- ✓ And also to 3D flux power estimate from cross power in transverse direction *Abdul-Karim+25*

Cross-correlation forest-haloes

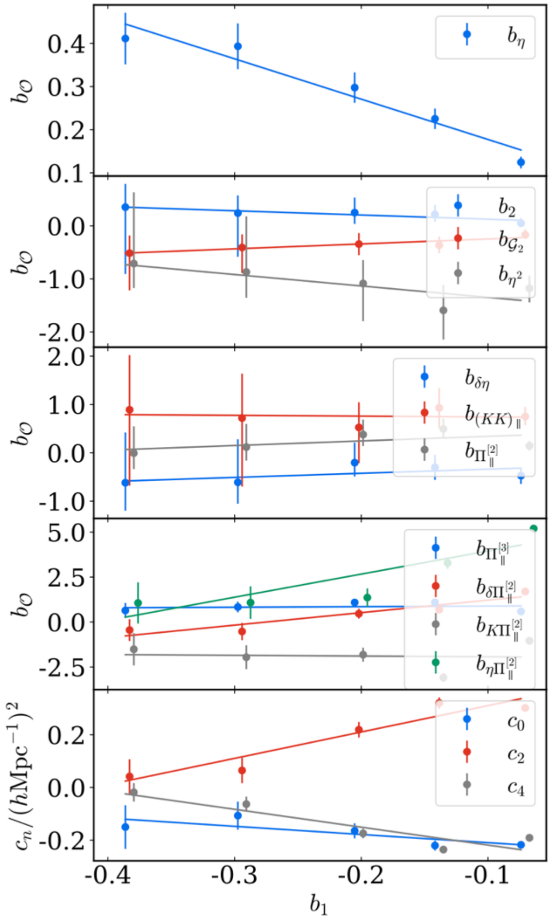


Chudaykin & Ivanov 25

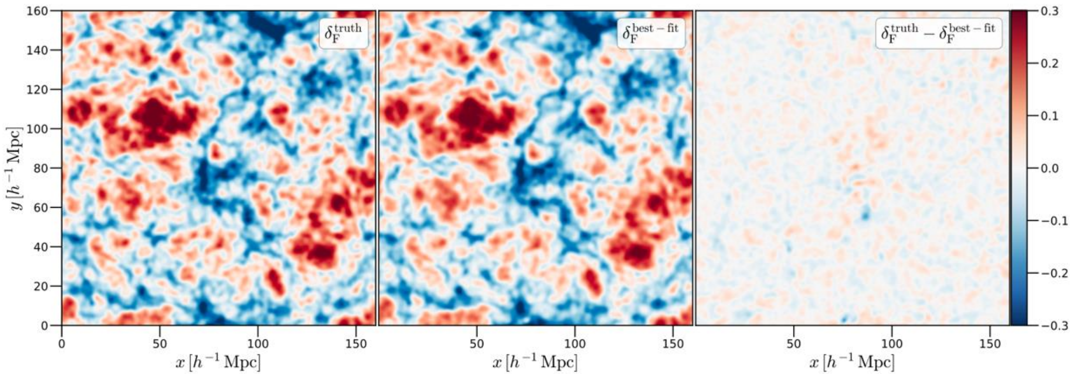
Modelling the 3D flux power

- ✓ Nyx code (Adaptive Mesh Refinement and grid based). DeBelsunce+24 – k_{max}=2h/Mpc
- ✓ Degeneracies between the many parameters are crucial

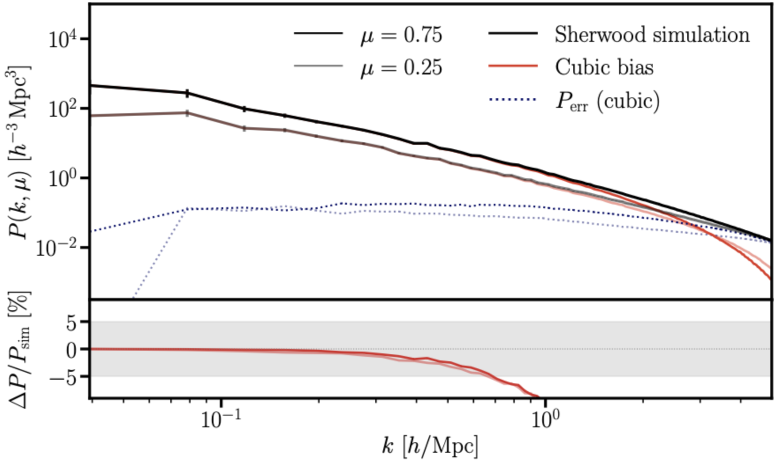
EFT Parameter (Sampled)	Prior	EFT Parameter (Marginalized)	Prior
b_1	$\mathcal{U}(-2,2)$	$\frac{c_{0,2,4,6}}{[h^{-1}\mathrm{Mpc}]^2}$	$\mathcal{N}(0,1^2)$
b_η	$\mathcal{U}(-2,2)$	P_{shot}	$\mathcal{N}(0,5^2)$
b_2	$\mathcal{N}(0,2^2)$	$\frac{a_{0,2}}{[h^{-1}\mathrm{Mpc}]^2}$	$\mathcal{N}(0,5^2)$
$b_{\mathcal{G}_2}$	$\mathcal{N}(0,2^2)$	$b_{(K\Pi^{[2]})_\parallel}$	$\mathcal{N}(0,2^2)$
$b_{(KK)_\parallel}$	$\mathcal{N}(0,2^2)$	$b_{\delta\Pi^{[2]}_\parallel}$	$\mathcal{N}(0,2^2)$
$b_{\Pi^{[2]}_\parallel}$	$\mathcal{N}(0,2^2)$	$b_{\eta\Pi^{[2]}_\parallel}$	$\mathcal{N}(0,2^2)$
$b_{\delta\eta}$	$\mathcal{N}(0,2^2)$	$b_{\Pi^{[3]}_\parallel}$	$\mathcal{N}(0,2^2)$
b_{η^2}	$\mathcal{N}(0,2^2)$		



Modelling the 3D flux power at the field level

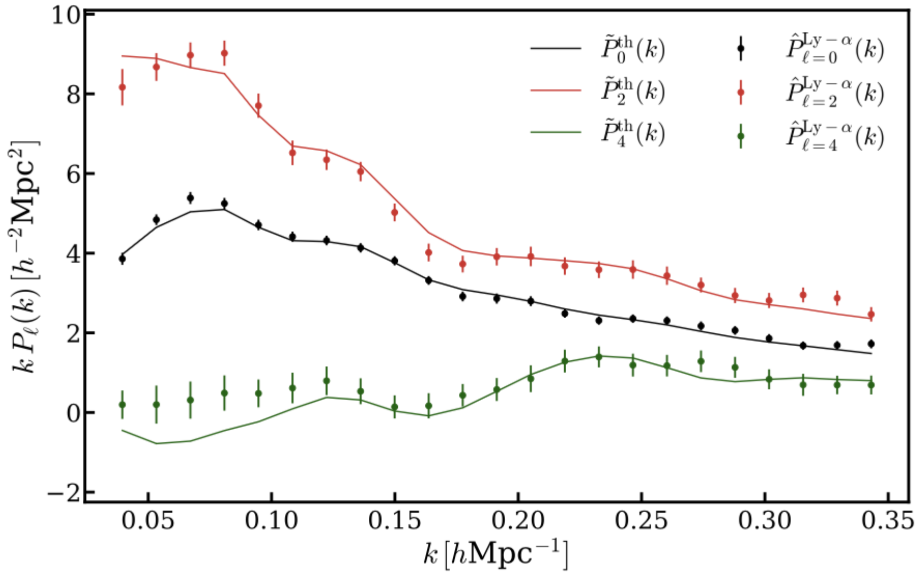


$$\delta_F^{\rm model}(\mathbf{k}) = \beta_1^F(k,\mu)\tilde{\delta}_1(\mathbf{k})$$
$$+\,\beta_\eta^F(k,\mu)\left(\delta_Z(\mathbf{k}) - \frac{3}{7}f\mu^2\tilde{\mathcal{G}}_2\right)^{\perp}$$
$$+\,\beta_2^F(k,\mu)(\tilde{\delta_1^2})^{\perp}(\mathbf{k}) + \beta_{\mathcal{G}_2}^F(k,\mu)\tilde{\mathcal{G}_2}^{\perp}(\mathbf{k})$$
$$+\,\beta_{\delta\eta}^F(k,\mu)[\tilde{\delta\eta}]^{\perp}(\mathbf{k})$$
$$+\,\beta_{\eta^2}^F(k,\mu)\tilde{\eta}^{2,\perp}(\mathbf{k}) + \beta_{KK_\parallel}^F(k,\mu)(\tilde{KK})_\parallel^{\perp}(\mathbf{k})$$



- ✓ De Belsunce et al. 2025: Field level, EFT inspired reconstruction of the flux field (and cross with haloes)
- ✓ Tested on flux power but also on flux pdf (very difficult to fit)

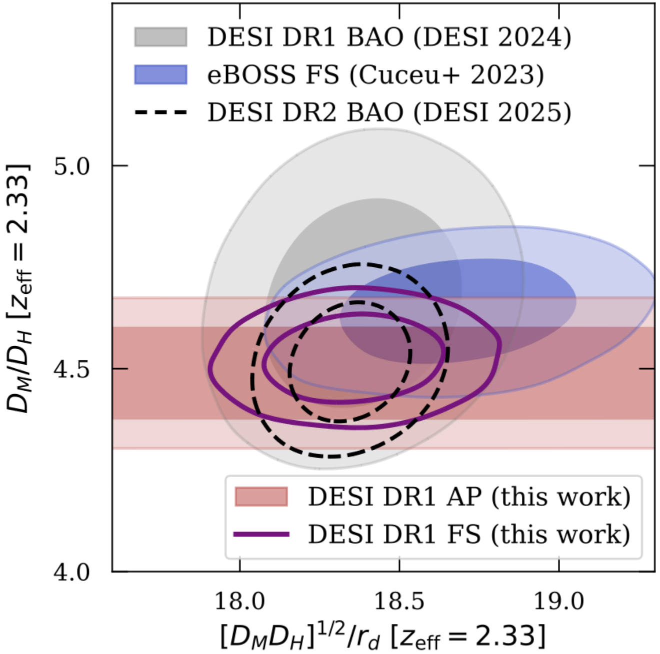
3D flux power from eBOSS DR16



- ✓ De Belsunce+24: 205,000 QSOs with <z> = 2.33 - Pair-count estimator in real space (good for window)
- ✓ Tested against Gaussian mocks and CoLoRe.
- ✓ Kaiser formula + non-linear correction is a good fit for 0.02-0.35 h/Mpc

3D correlation function from DESI

$$P_F(\mathbf{k}) = b_F'^2(1+\beta_F'\mu_k^2)^2\ G(\mathbf{k})F_{NL}(\mathbf{k})P_{\rm fid}(k)$$
$$P_{F\times Q}(\mathbf{k}) = b_F'(1+\beta_F'\mu_k^2)(b_Q+f\mu_k^2)\ G(\mathbf{k})X_{NL}(\mathbf{k})P_{\rm fid}(k)$$



- ✓ Full-shape analysis of DESI DR1 (Cuceu+25) measurement of Alcock-Paczynski (AP) and RSD - about 750,000 QSOs at z>1.7
- ✓ β parameter marginalized over. Fit for b_F, b_Q and f
- ✓ Tightest AP constraints at z>1, 2.4 times improvement over BAO only
- ✓ First measurement of $f\sigma_8$ from cross

3D corr. function from DESI: dynamical dark energy

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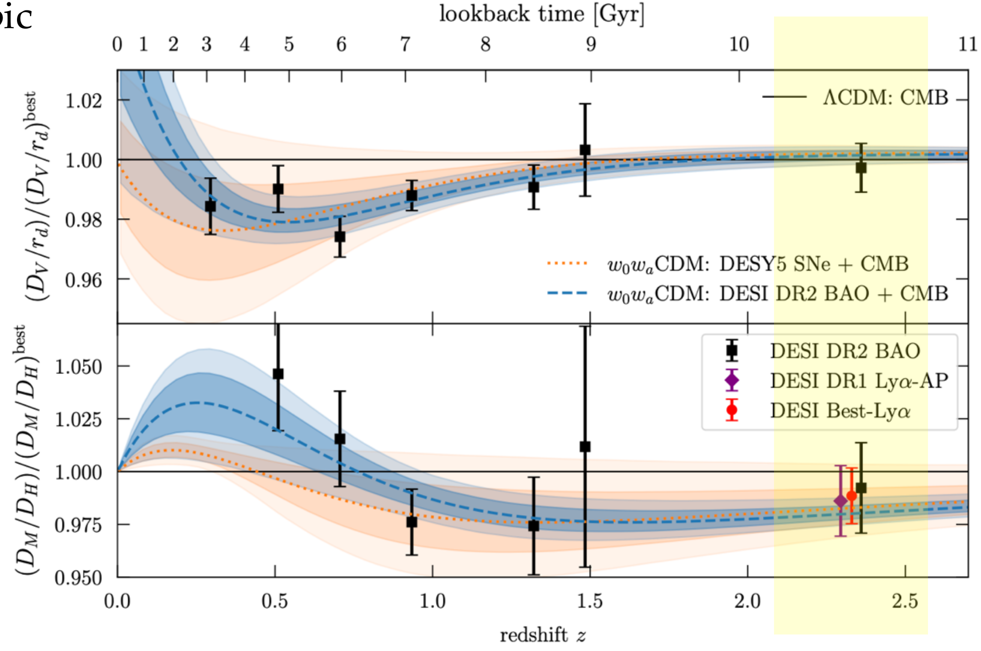
Cuceu+25

Isotropic BAO

AP



- ✓ Consistent with both CMB and galaxy BAOs
- ✓ Lyα is good at measuring D_H
- ✓ 2.7σ tension with SHOES
- ✓ Slightly reduced tension in w_0-w_a plane w.r.t. LCDM when Lyα is combined (3.3σ→3.1σ)
- ✓ 1.7% on the AP at z=2.33 (could go down to 0.3% at DESI yr5)

$$\sum m_\nu < 0.0638\ \text{eV}\ (95\%,\ \text{Ly}\alpha\text{-AP+BAO+CMB})$$

Particle physics in the cosmic web

Neutrino interactions
Warm Dark Matter
Cold+Warm Dark Matter

Promises of the post-reionization Universe

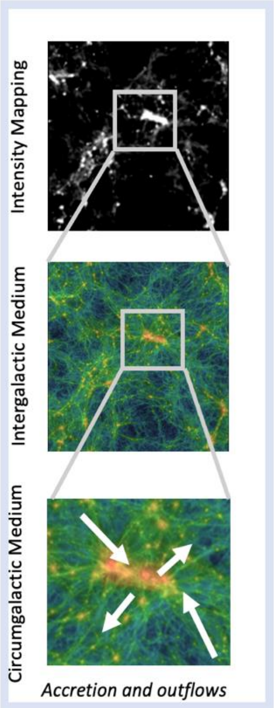
Matteo Viel

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

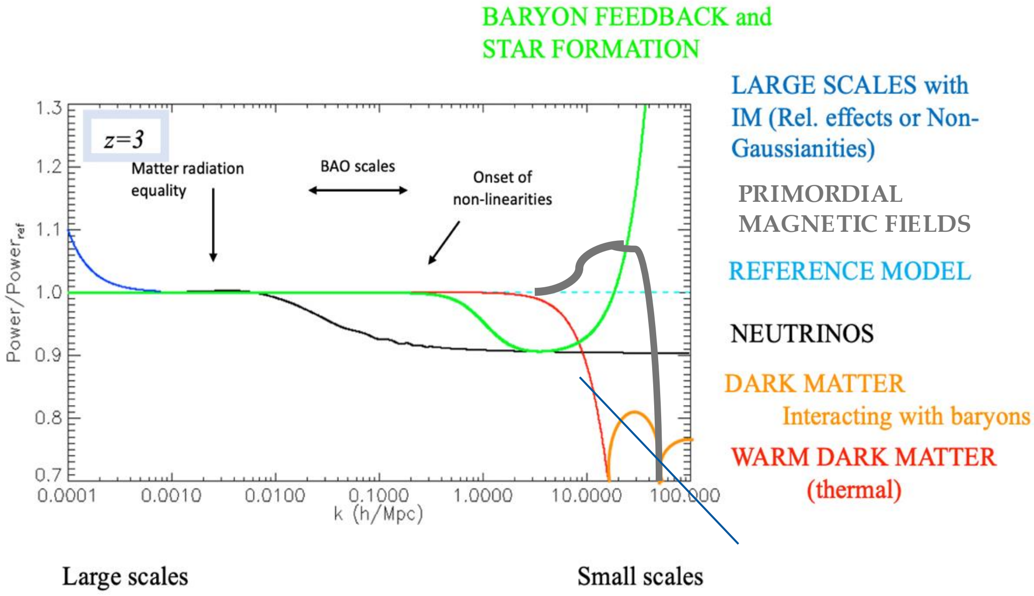
- **Power spectrum**
- **cross-correlations** of different tracers
- **new estimators** (e.g. 1-point function, bispectrum, Machine Learning)

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

Environments



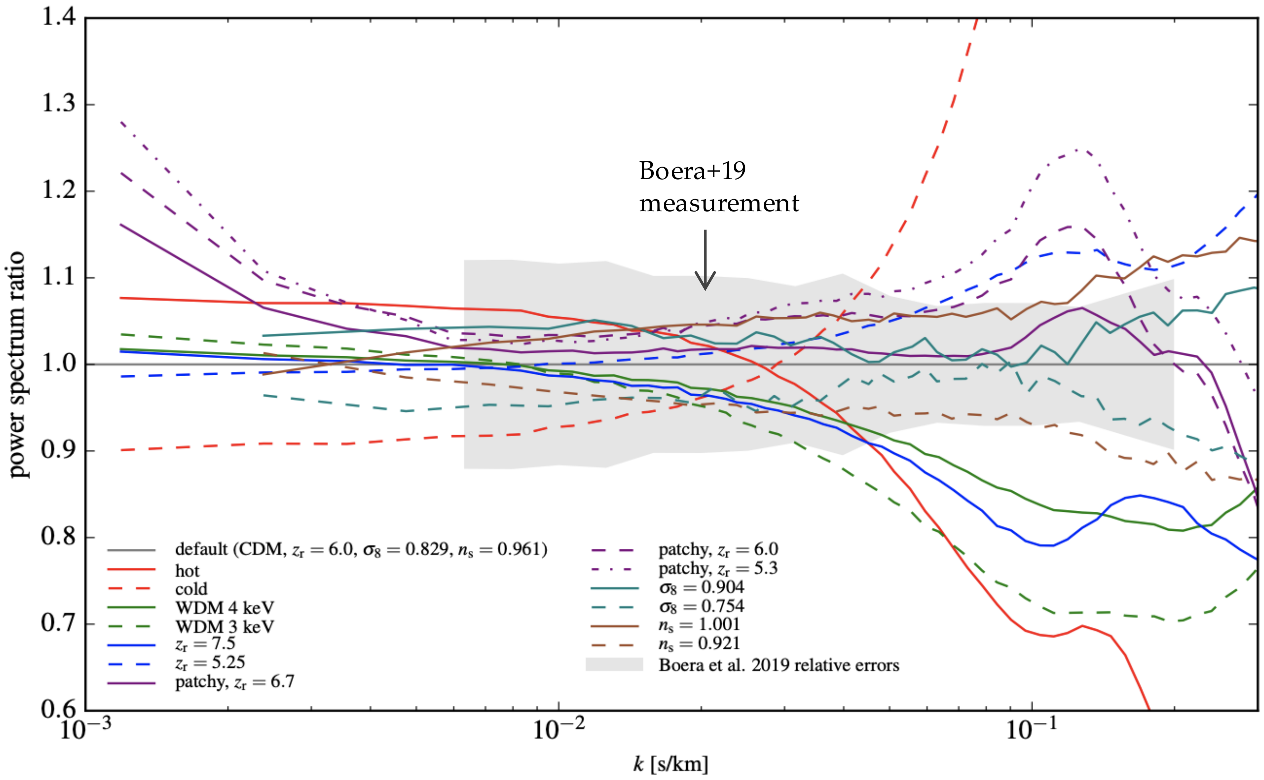
Physical Scales



HI measures density perturbations in a matter dominated regime!

Impact on 1D flux power

Simulated 1D flux power @ z=4.6



More power

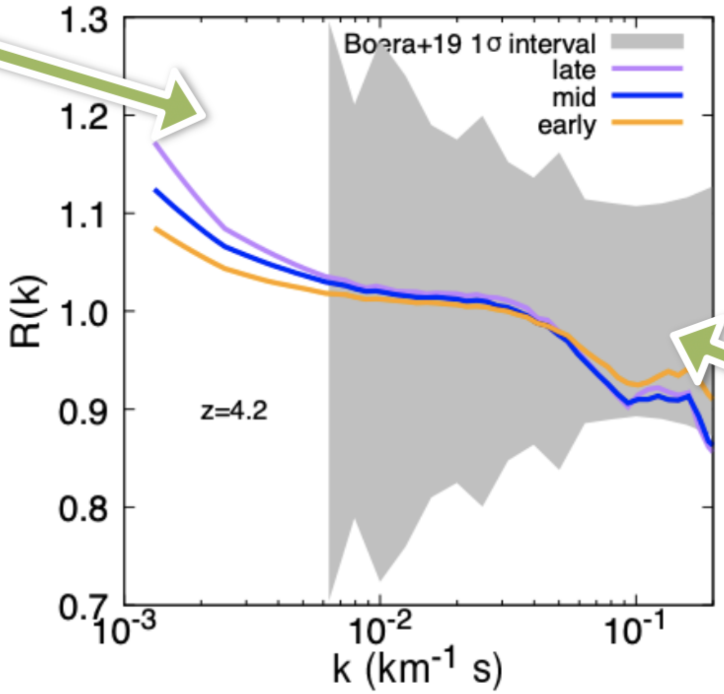
Less power

Large scales

Small scales

Patchy Reionization – Impact on 1D flux power

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

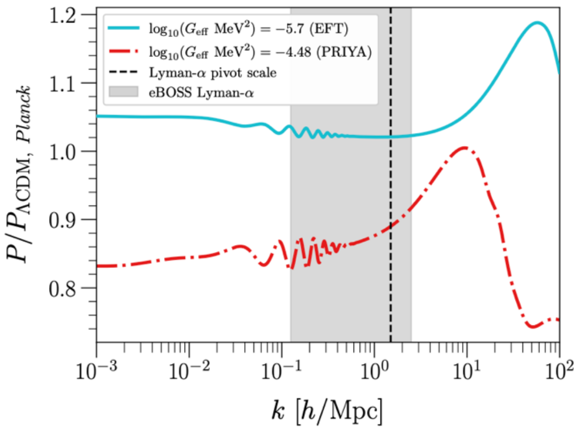


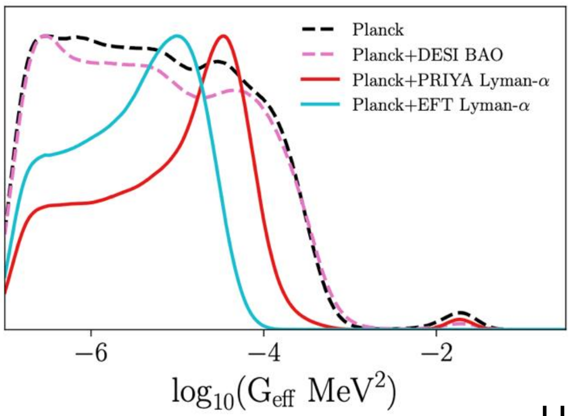
Molaro+23
“Detected” this
increase of power at 2.7σ
from KODIAQ, SQUAD,
XQ100 sample of 538 QSOs

Suppression
due to thermal broadening
of recently ionised regions

Molaro, Bolton, Irsic,… MV 2021&2023

EFT 1D flux power models and applications





He+25

- ✓ He+24: strong preference for neutrino self interactions (delayed onset of free streaming) from BOSS full shape analysis of forest (and other data) pointed to Geff=0.01 at 5s, with a compressed likelihood (based on LCDM)
- ✓ New likelihood either EFT based or based on a new suite of simulations (Bird et al.) and applied to eBOSS data: result goes away

A warm cosmic web?

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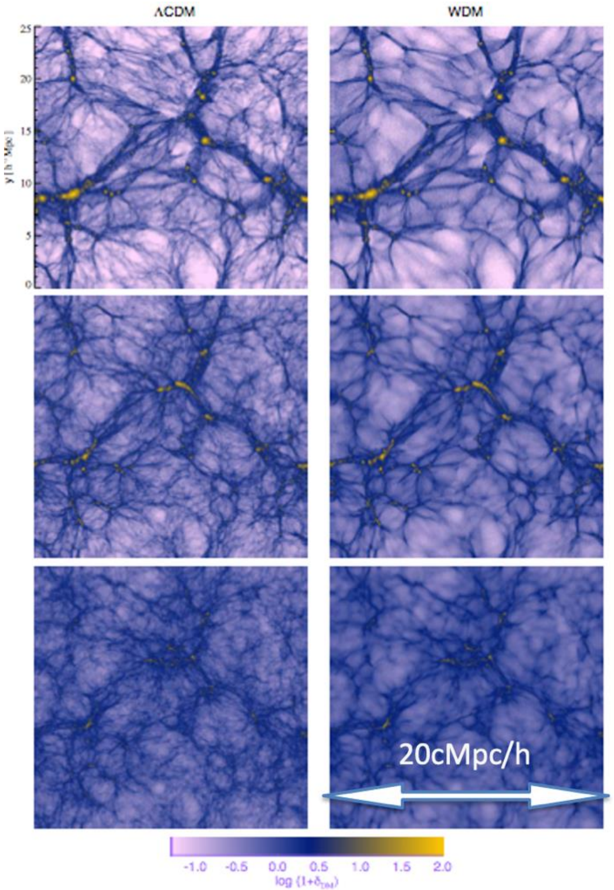


z=0

z=2

z=5

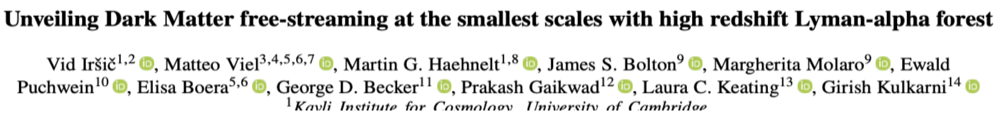
$$k_{\rm FS} \sim 15.6 \frac{h}{\rm Mpc} \left(\frac{m_{\rm WDM}}{1 \rm keV}\right)^{4/3} \left(\frac{0.12}{\Omega_{\rm DM} h^2}\right)^{1/3}$$

Free streaming scale of thermal warm dark matter

Viel et al 2005

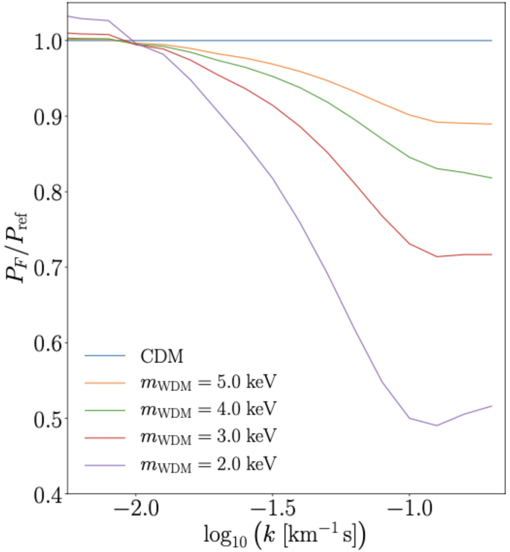
The smoothing scales

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 streaming



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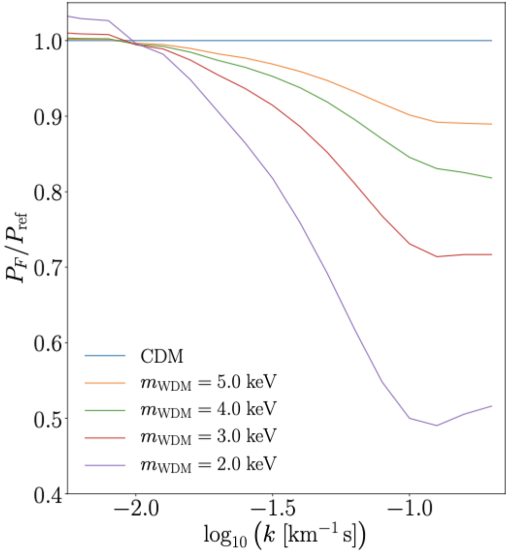
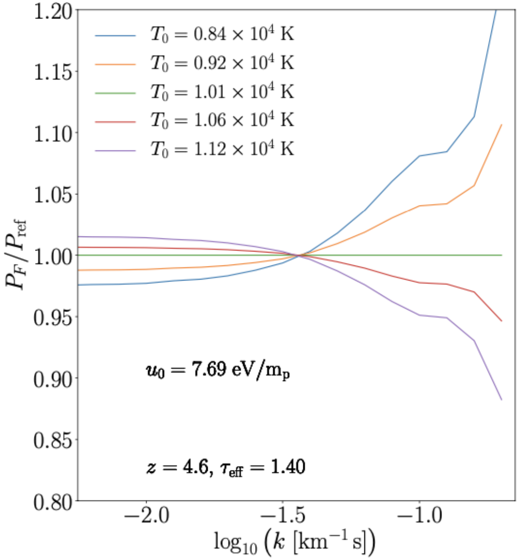


Thermal broadening



The smoothing scales

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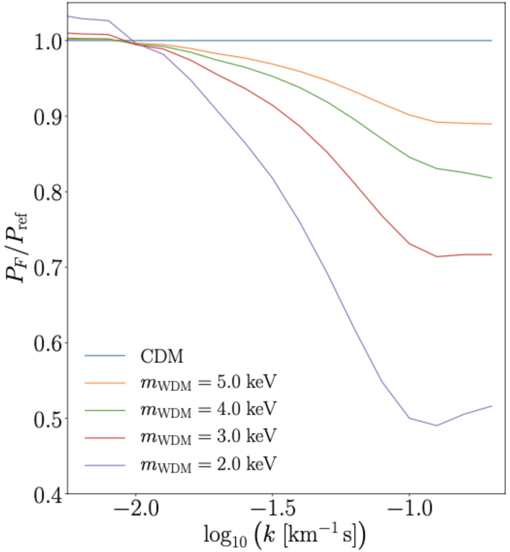

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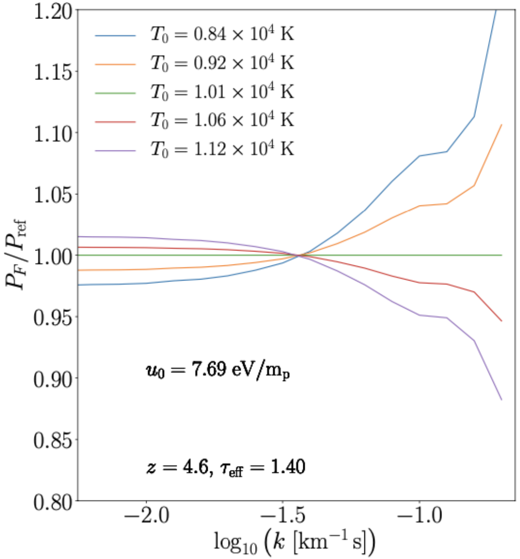
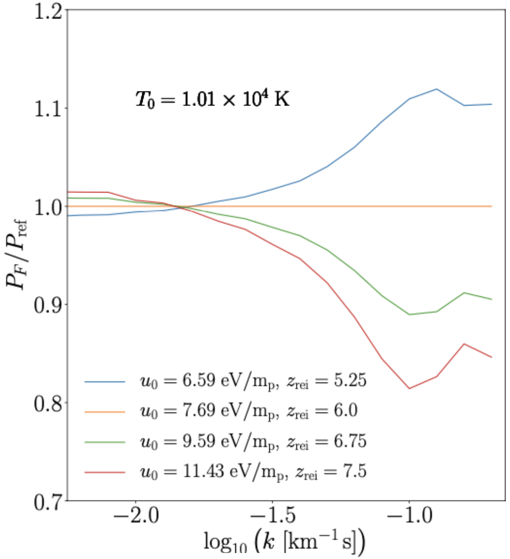


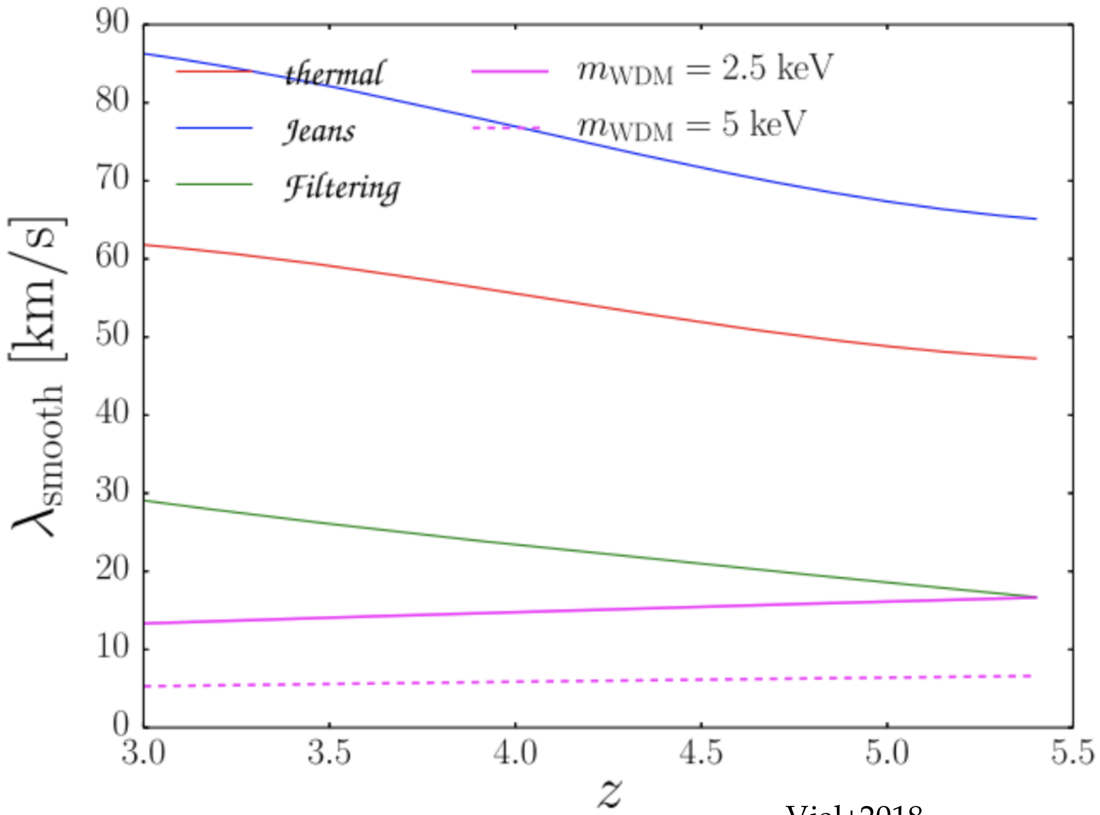
Gas pressure



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

H is heating rate

The smoothing scales - II

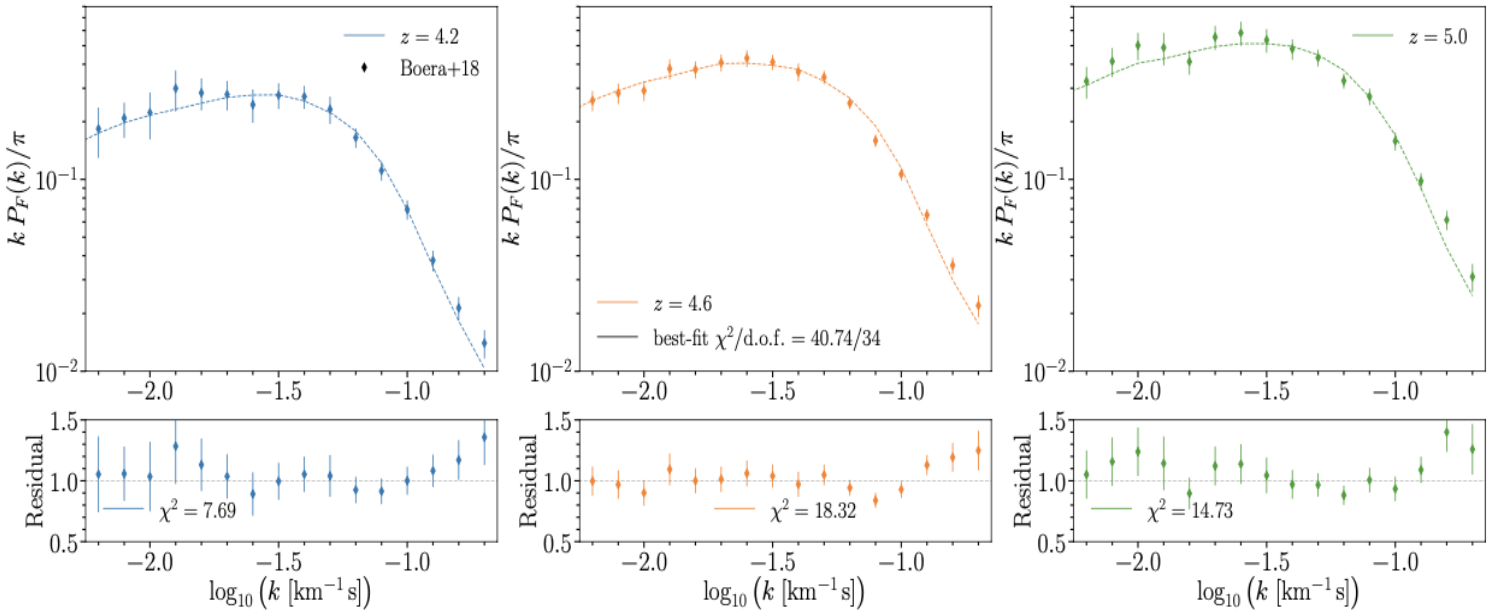


Viel+2018

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 data at z=4-5

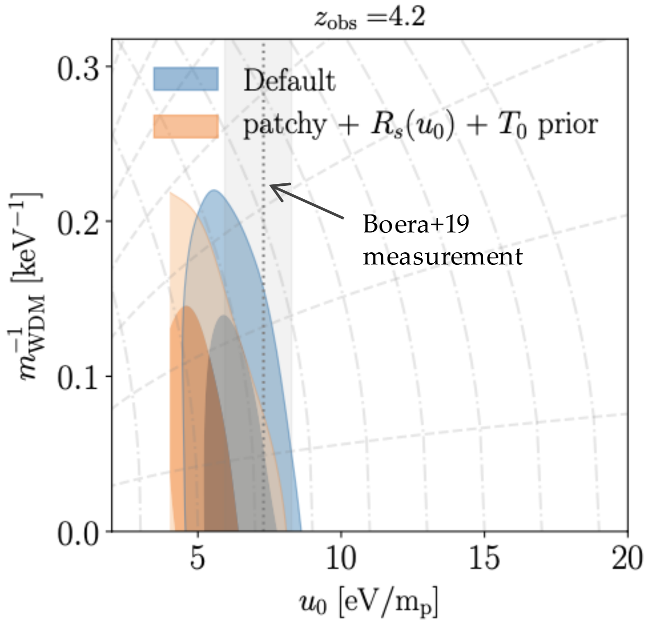


Boera+19, Irsic+23

Thermal WDM

Light WDM

Heavy WDM or LCDM



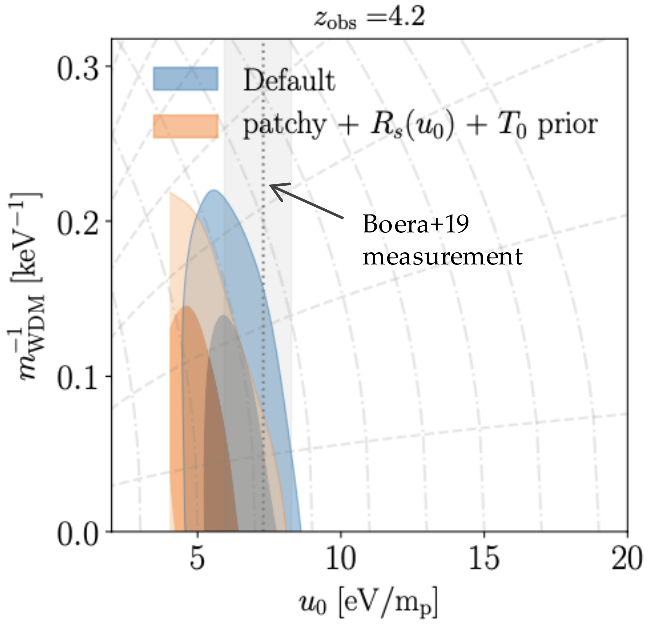
Injected heat

Irsic, MV +23

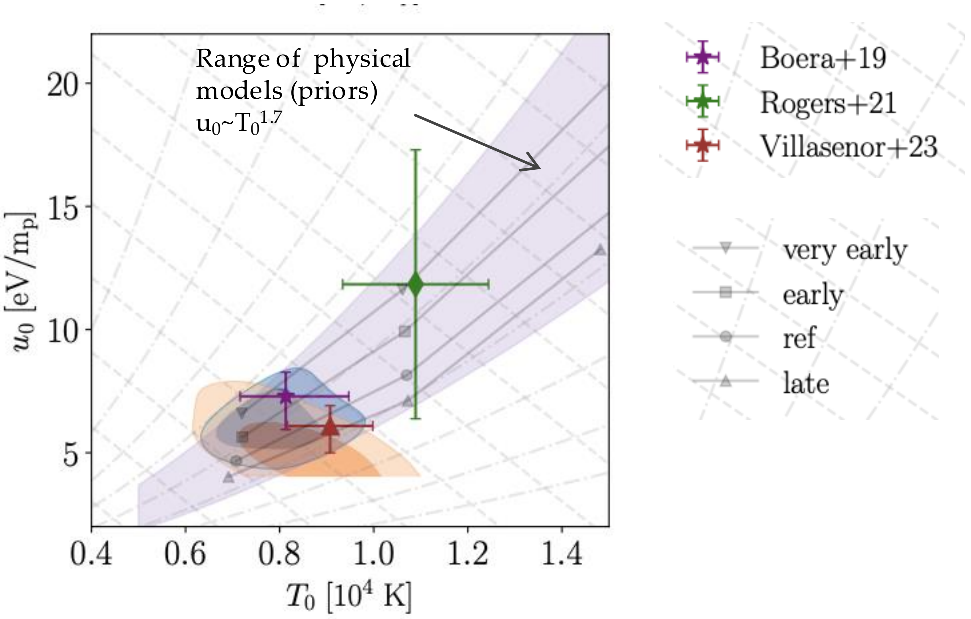
Thermal WDM - II

Light WDM

Heavy WDM or LCDM



Injected heat

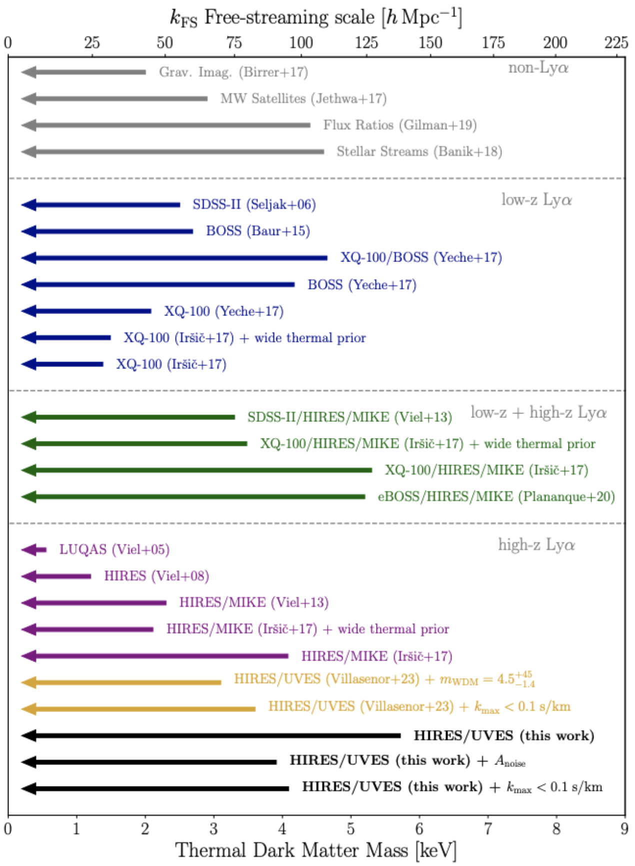


IGM temperature

Irsic, MV +23

Thermal WDM

Matteo Viel



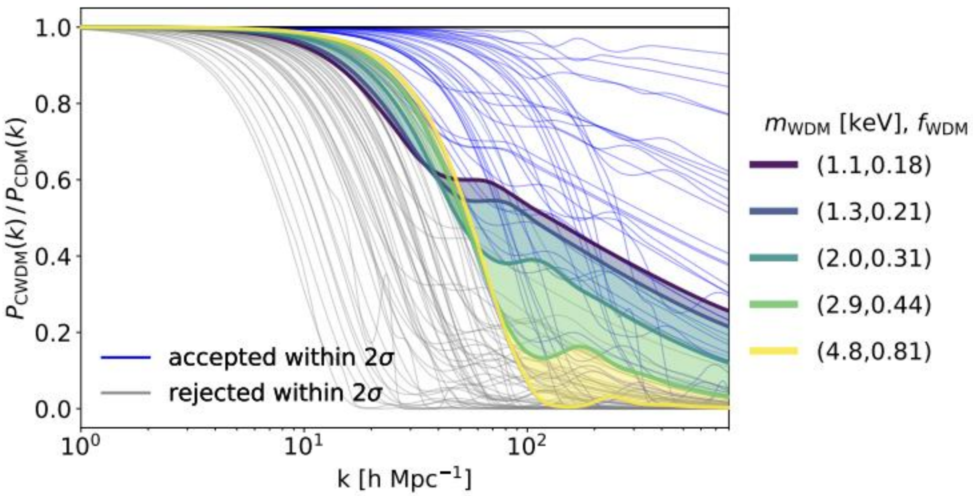
Tests made:
Cut small scales
Marginalize over data noise
Assume/Remove T_0 priors
Correct for a model dependent resolution
Patchy reionization models

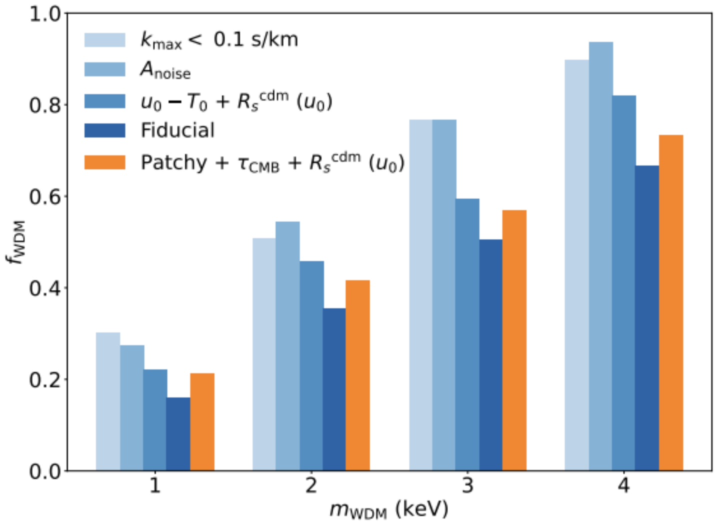
Name	m_{WDM} [keV] (2σ)	$\tau_{eff}(z=4.6)$	$T_0(z=4.6)$ [10^4 K]	$\gamma(z=4.6)$	$u_0(z=4.6)$ [eV/m$_p$]	$A_{noise}(z=4.6)$	χ^2/dof
Default	> 5.72	$1.502^{+0.061}_{-0.061}$	$0.743^{+0.041}_{-0.075}$	$1.35^{+0.24}_{-0.19}$	$6.19^{+0.68}_{-0.68}$	-	40.7/34
$k_{max} < 0.1$ km^{-1} s	> 4.10	$1.501^{+0.060}_{-0.074}$	$0.840^{+0.095}_{-0.340}$	$1.28^{+0.09}_{-0.28}$	$8.91^{+1.57}_{-5.26}$	-	10.2/20
A_{noise}	> 3.91	$1.458^{+0.053}_{-0.074}$	$0.966^{+0.156}_{-0.466}$	$1.23^{+0.06}_{-0.23}$	$5.93^{+0.38}_{-2.28}$	$1.12^{+0.49}_{-0.29}$	18.4/31
T_0 prior	> 5.85	$1.494^{+0.062}_{-0.077}$	$0.770^{+0.110}_{-0.120}$	$1.31^{+0.10}_{-0.31}$	$6.50^{+1.00}_{-1.60}$	-	47.6/34
$R_s(u_0)$ mass resolution	> 4.44	$1.531^{+0.073}_{-0.064}$	$0.617^{+0.007}_{-0.118}$	$1.38^{+0.28}_{-0.13}$	$7.90^{+1.70}_{-2.30}$	-	30.7/34
patchy reion.	> 5.10	$1.486^{+0.058}_{-0.068}$	$0.686^{+0.046}_{-0.080}$	$1.33^{+0.17}_{-0.26}$	$5.32^{+0.58}_{-0.52}$	-	41.0/34
$R_s(u_0) + T_0$ prior	> 4.24	$1.473^{+0.056}_{-0.076}$	$0.83^{+0.11}_{-0.11}$	$1.28^{+0.09}_{-0.28}$	$5.53^{+0.73}_{-1.2}$	-	39.4/34
patchy + $R_s(u_0) + T_0$ prior	> 5.90	$1.450^{+0.051}_{-0.070}$	$0.828^{+0.098}_{-0.098}$	$1.26^{+0.08}_{-0.26}$	$4.87^{+0.52}_{-0.71}$	-	40.8/34

Irsic+23

Mixed (Cold + Warm) dark matter models

Matteo Viel





- ✓ 5 CWDM models allowed by the data and their suppression in terms of matter power

- ✓ Constraints

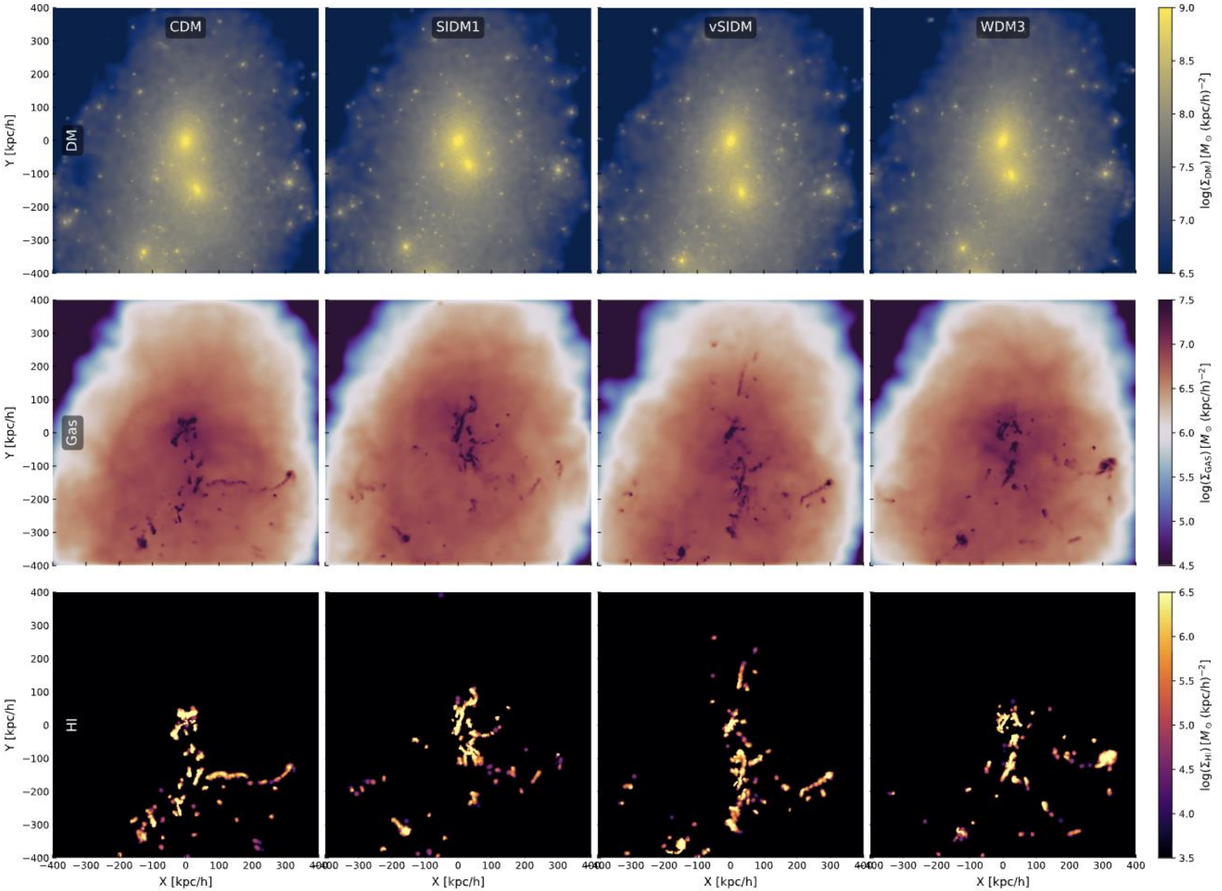
$$f_{WDM} = 0.14\ (1\text{keV}/m_{WDM})^{-1.1}.$$

Garcia-Gallego, Irsic, Haehnelt, Viel, Bolton 2025

DM + galaxy formation halo environments

Matteo Viel

4.3 x 1e13 $M_\odot$ halo
At z=0
50 Mpc/h box
M_{gas}=6.8e5$M_\odot$



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} $M_\odot$

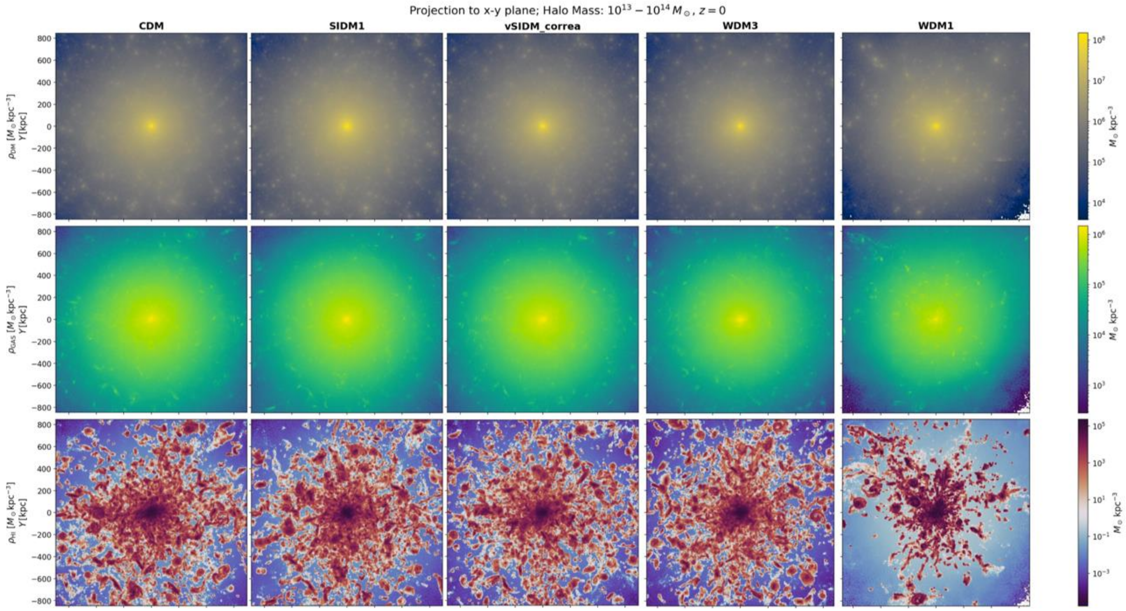
DM SIDM vSIDM WDM3keV WDM1keV

DM

GAS

HI

Temperature



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} $M_\odot$

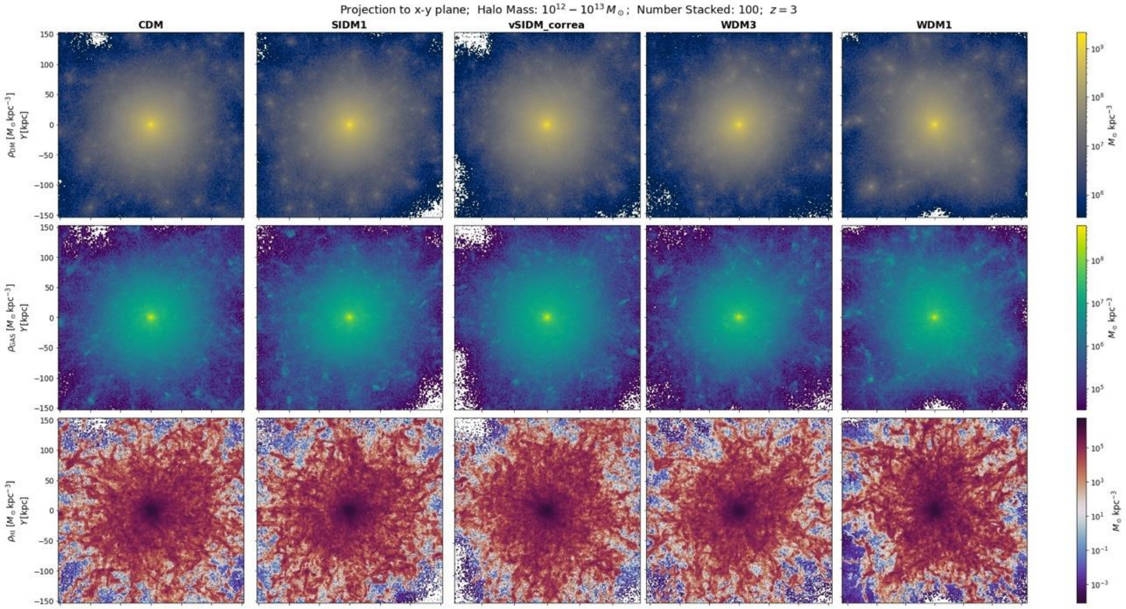
DM SIDM vSIDM WDM3keV WDM1keV

DM

GAS

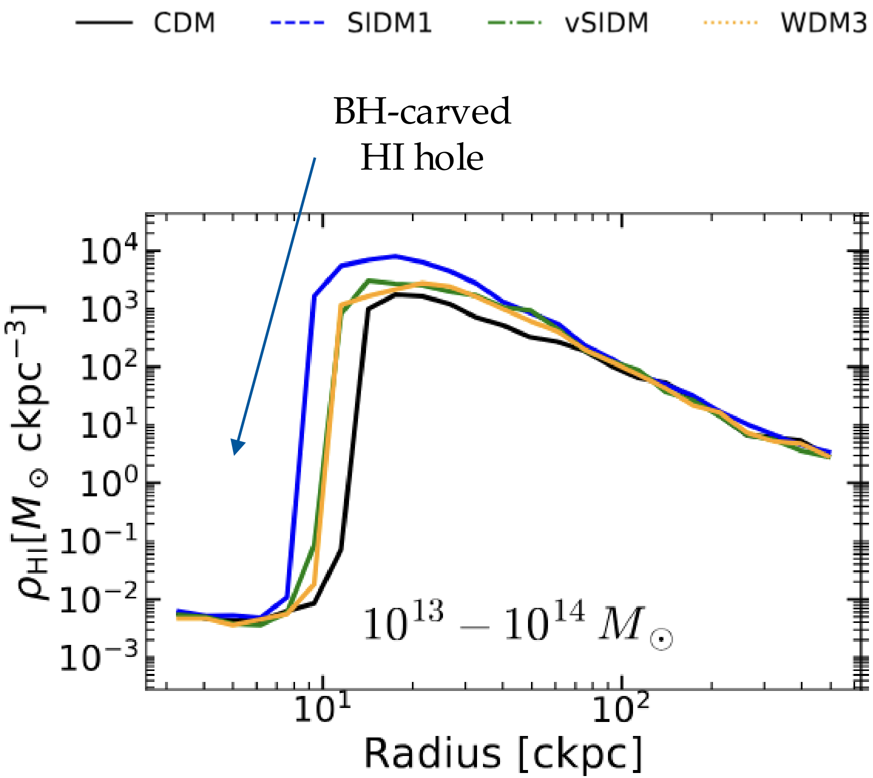
HI

Temperature



Zhang, Garaldi, Despali, Viel 2025 in prep.

HI in non-cold DM models



Zhang, Garaldi, Despali, Viel 2025 in prep.

Summary

- ✓ The low-density cosmic web as seen in the high redshift Lyman-α forest allows to constrain DM properties through 1D flux power
- ✓ WDM mass is constrained (<3-5 keV)
- ✓ WDM fraction is also constrained (f<0.2 – depending on mass)
- ✓ Cosmic web is relatively cold consistent with CDM
- ✓ No sign of neutrino interactions
- ✓ Small scale HI distribution inside haloes could be impacted by DM nature

What about increase in power?

Primordial Magnetic Fields (PMFs)

- ✓ Why do we care: observed in the Universe from planet scales up to cosmological scales even in cosmic voids (!)
- ✓ What can they tell us: they could be of astro or primordial origin (produced during inflation or phase transitions in the early Universe)
- ✓ When considered: strong implications for structure formation

Primordial Magnetic Fields (PMFs)

Matteo Viel

Durrer and Neronov 2013

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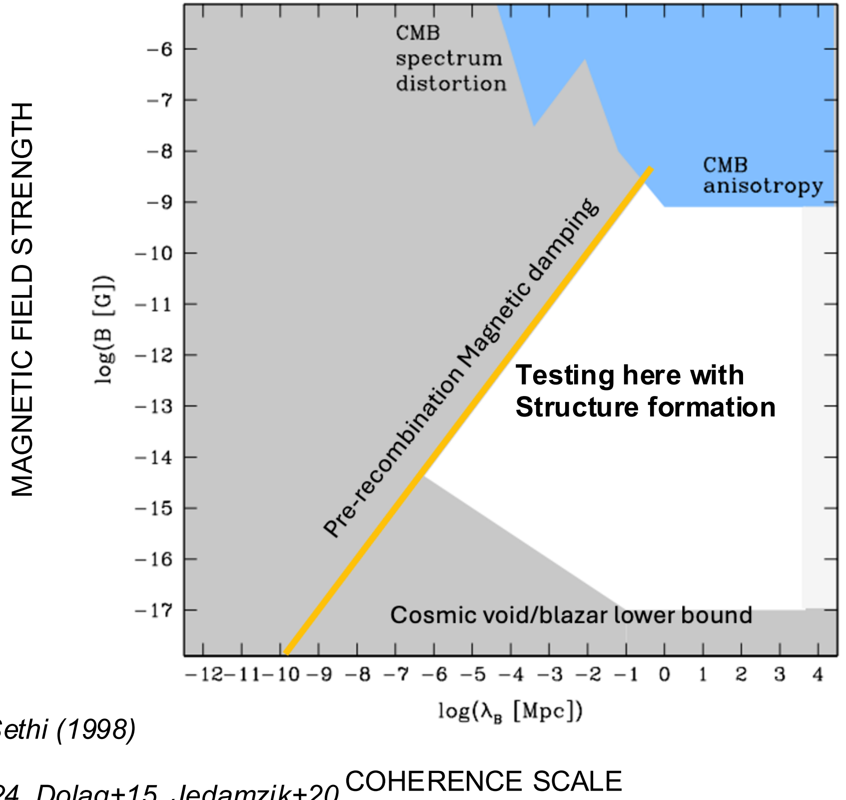


Wasserman (1978); Kim+ (1996); Subramanian & Barrow (1997); Gopal&Sethi (1998)

Kanhashvili+15, Sanati+20, Katz+21, Mtchelidze+22, Paoletti+22, Vazza+24, Dolag+15, Jedamzik+20

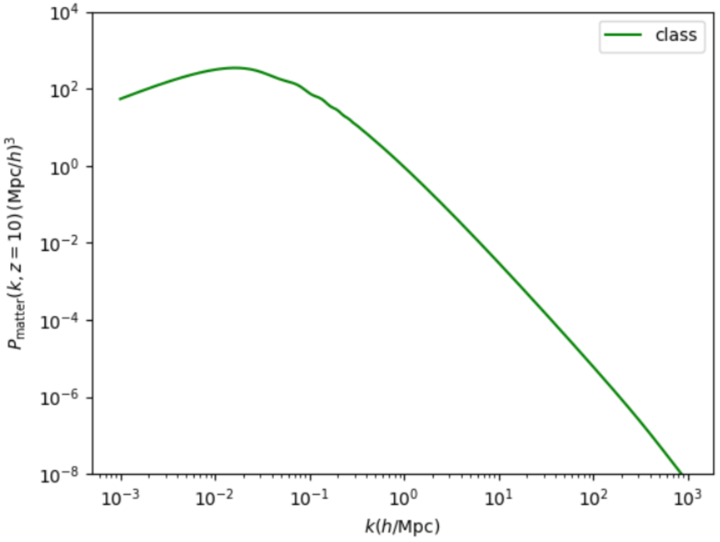
Setting the stage

Matteo Viel

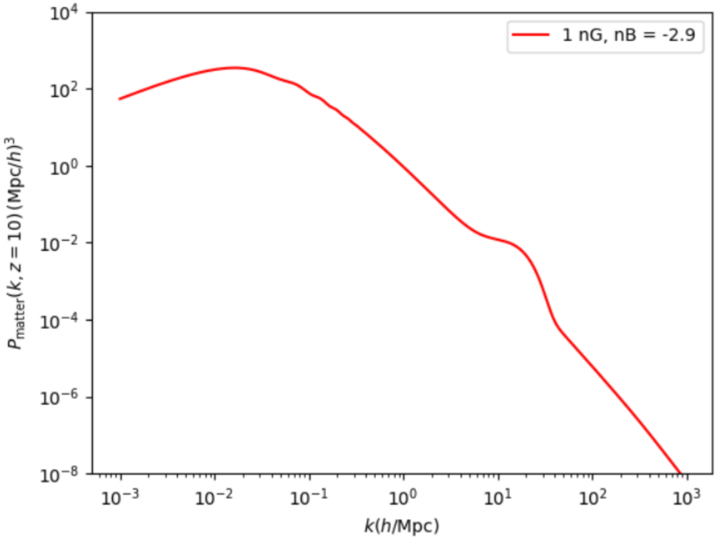
$$\langle B_i(k) B_j^*(k') \rangle = (2\pi)^3 \delta^3(k - k') \left(\delta_{ij} - \frac{k_i k_j}{k^2} \right) \frac{P_B(k)}{2}$$

$$P_B(k) \propto B_{1Mpc}^2 k^{n_B}$$

$$P_{\Lambda CDM}$$



$$P_{\Lambda CDM} + P_{PMF}$$



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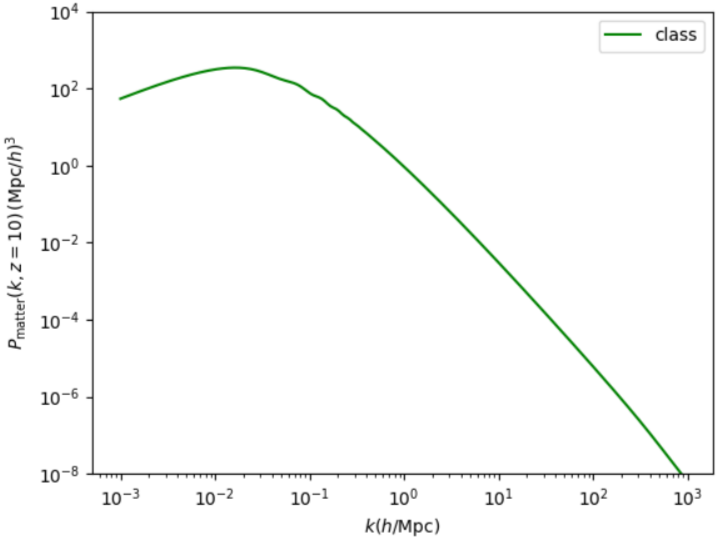

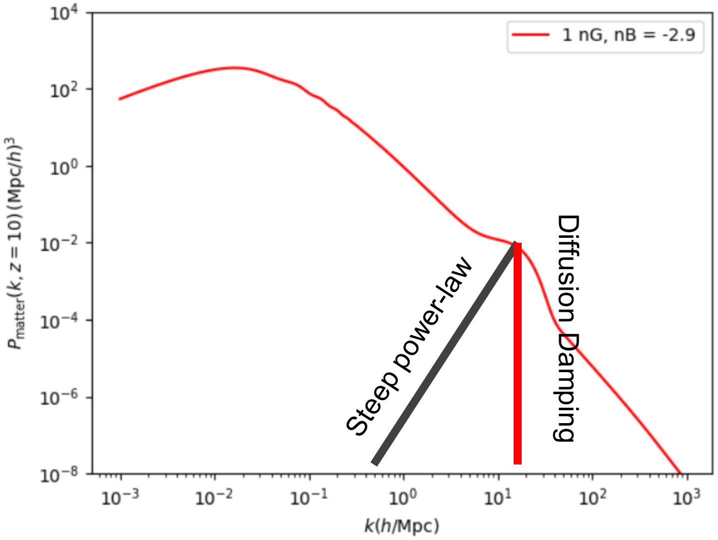

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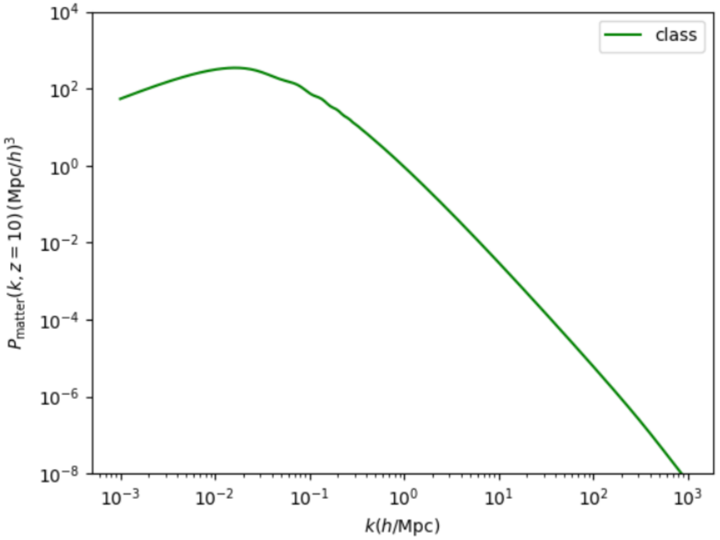

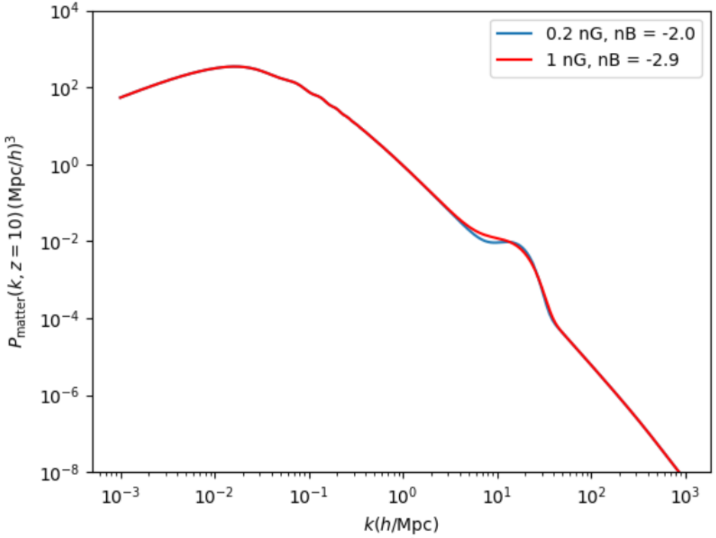

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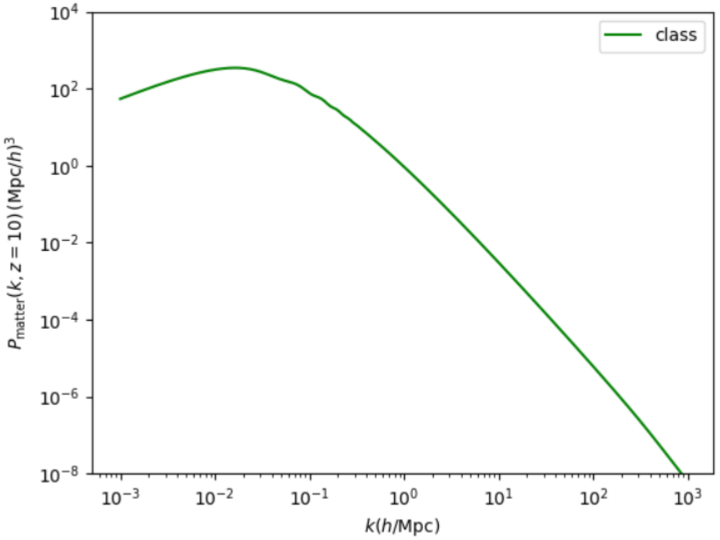
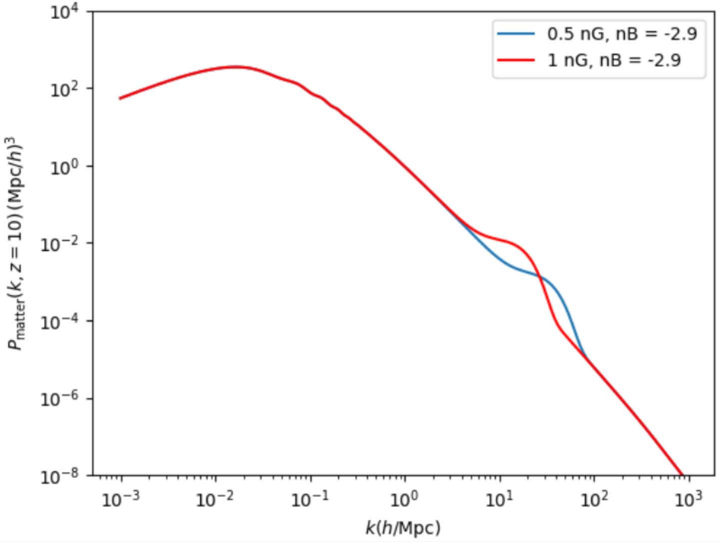


$$P_{\Lambda CDM} + P_{PMF}$$



Ideal MHD in the postrecombination Universe

$$\frac{\partial\,(\vec{B})}{\partial t} = \frac{\nabla\times(\vec{v}_b\times\vec{B})}{a}$$

$$\frac{\partial \vec{v}_b}{\partial t} + H\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{(\nabla\times\vec{B})\times\vec{B}}{4\pi a^5\rho_b} - \frac{c_b^2\nabla\delta_b}{a} - \frac{\nabla\phi}{a}$$

$$\frac{\partial\delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b\vec{v}_b)}{a}$$

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

$$\frac{\partial^2\delta_{DM}}{\partial a^2} + \left[\frac{\partial\ln(a^2H)}{\partial\ln a} + 1\right]\frac{\partial\delta_{DM}}{a\partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

Ralegankar, Pavicevic, Viel, 2024, JCAP, 07, 027 (Kim+96, Adi+24)

Ideal MHD in the postrecombination Universe

$$\frac{\partial\,(\vec{B})}{\partial t} = \cancel{\frac{\nabla\times(\vec{v}_b\times\vec{B})}{a}}$$

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At large scales

$\delta \ll 1$

$v_b \ll aH$

Velocity field is generated

$$\partial_t v_b \propto (\nabla\times B)\times B$$

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

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

S_0/a^3H^2

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

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

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

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

Key ingredient is the S_0 source term

Ideal MHD in the postrecombination Universe

Matteo Viel

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

$$a^2\frac{\partial^2\delta_{\rm DM}}{\partial a^2}+a\frac{3}{2}\frac{\partial\delta_{\rm DM}}{\partial a}-\frac{3}{2}\frac{\Omega_{\rm DM}}{\Omega_{\rm m}(1+a_{\rm eq}/a)}\delta_{\rm DM}=\frac{3}{2}\frac{\Omega_{\rm b}}{\Omega_{\rm m}(1+a_{\rm eq}/a)}\delta_{\rm b}.$$

DM

baryons

Coupled differential equations

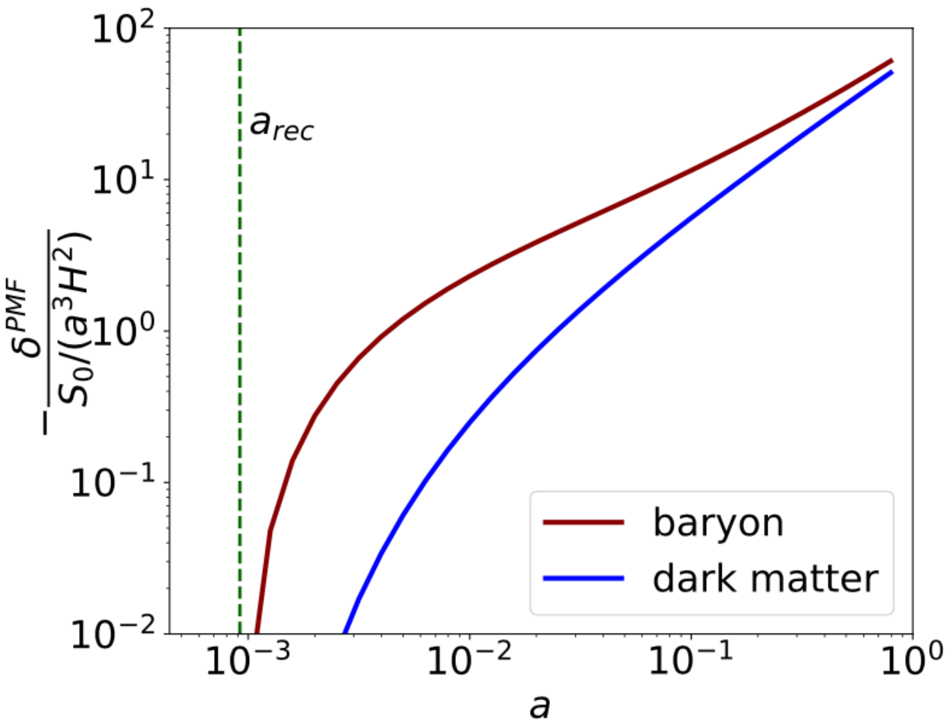
$$\delta_{\rm b}^{\rm PMF}=-\xi_{\rm b}(a)\frac{S_0}{a^3H^2}$$

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

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

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

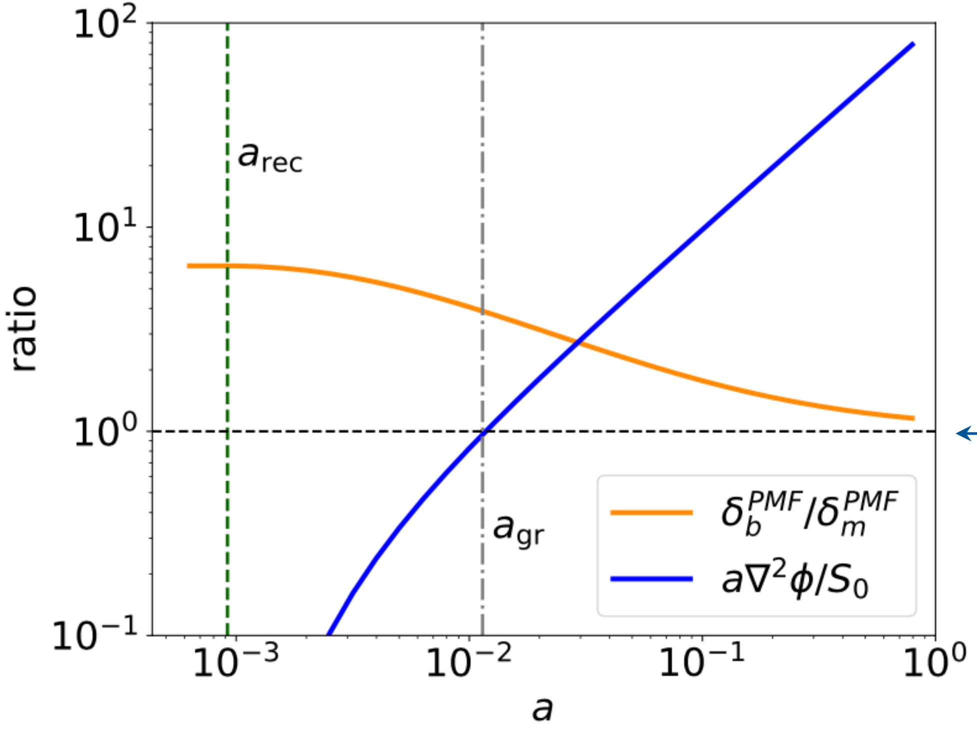
Ideal MHD in the postrecombination Universe



- ✓ Time evolution of perturbations (scale dependence is hidden in S0)
- ✓ Baryons are primarily enhanced
- ✓ DM is lagging behind and eventually catches up at z~0

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

Ideal MHD in the postrecombination Universe



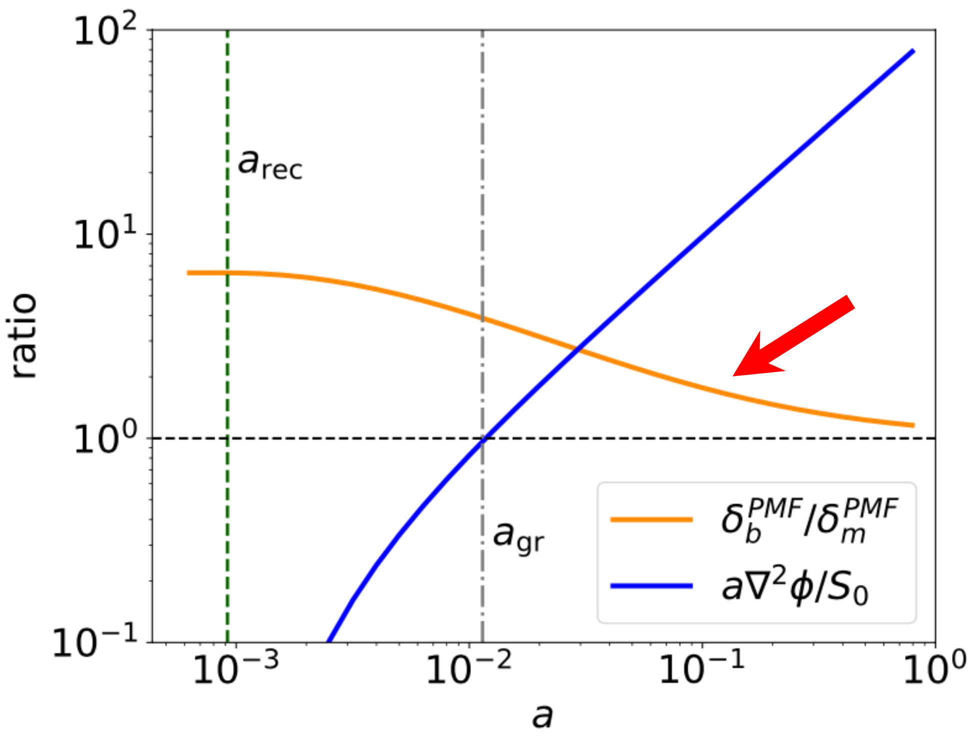
- ✓ Ratio of perturbations is equivalent to baryon fraction and starts very high and only now reaches the cosmic mean 0.17 value

← Cosmic mean

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

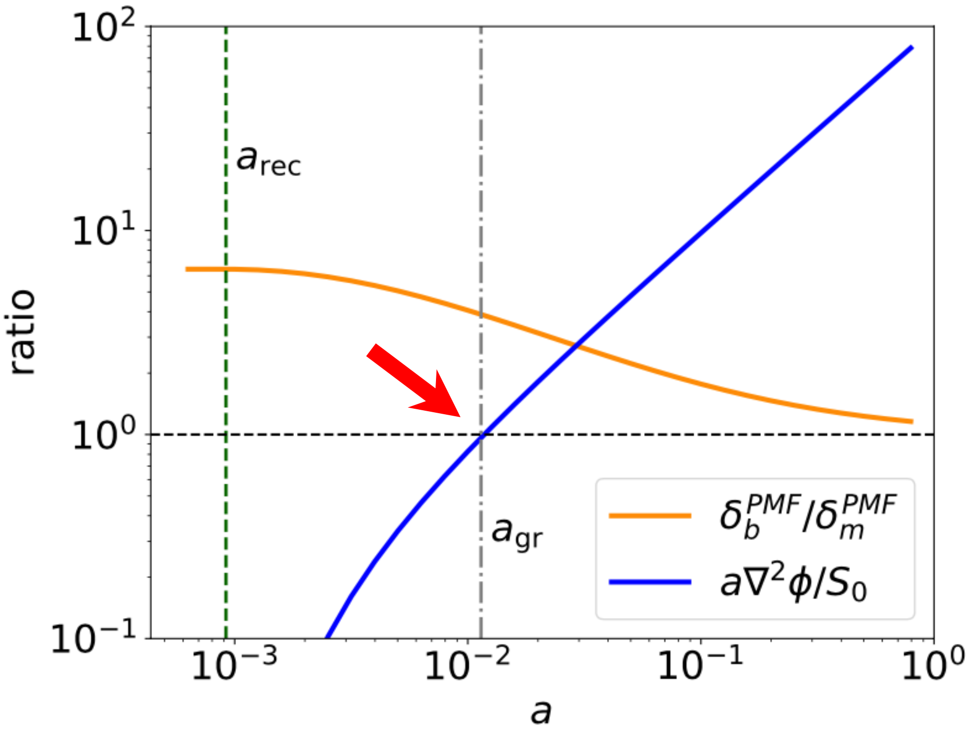
Ideal MHD in the postrecombination Universe

Matteo Viel



- ✓ Ratio of perturbations is equivalent to baryon fraction starts very high and only now reaches the cosmic mean 0.17 value
- ✓ At z=10 baryon fraction is 2 times the cosmic mean

Ideal MHD in the postrecombination Universe



- ✓ Ratio of perturbations is equivalent to baryon fraction starts very high and only now reaches the cosmic mean 0.17 value
- ✓ At z=10 baryon fraction is 2 times the cosmic mean
- ✓ At z=100 gravity overcomes Lorentz force (this is independent of B and at all scales)

Magnetic Damping Scale

Matteo Viel

$$v_b \sim \frac{1}{aH\lambda_D}\frac{\vec{B}^2_{\rm phys}}{4\pi\rho_b}.$$

Baryon flow velocity from Euler Equation (Lorentz force)

$$v_b/\lambda_D \sim aH$$

Breaking of linearity

$$v_A^2 \equiv \frac{\langle \vec{B}^2_{\rm phys}\rangle}{4\pi\rho_b}$$

Alfven velocity def.

$$\lambda_D \sim \frac{v_A}{aH}$$

$$\lambda_D \sim 0.1{\rm Mpc}\left(\frac{B}{\rm nG}\right)$$

$$k_D \sim 3(nG/B_0){\rm Mpc}^{-1}$$

- ✓ Linear perturbation theory does not work at small scales
- ✓ Density perturbations backreact on the magnetic field
- ✓ MHD Turbulence suppresses perturbations

The baryon PMF induced power spectrum

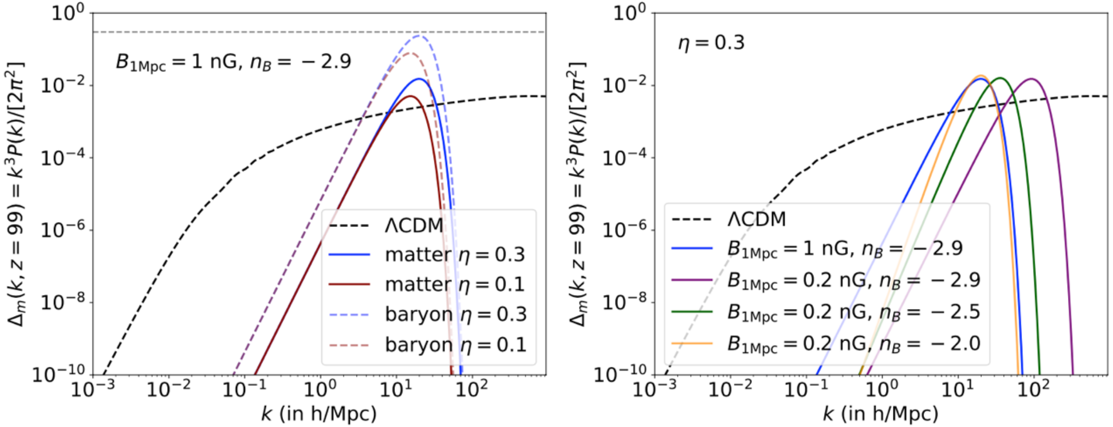
$$P_B(k) = A k^{n_B} e^{-k^2\lambda_D^2} \qquad B^2_{1\mathrm{Mpc}} \equiv \int \frac{d^3k}{(2\pi)^3} P_B(k) e^{-k^2\lambda^2_{\mathrm{Mpc}}} = \frac{A\lambda_{\mathrm{Mpc}}^{-(3+n_B)}}{4\pi^2}\Gamma([n_B+3]/2)$$

$$P_b^{\mathrm{PMF}}(k) = \xi_b^2(a)\frac{k^4}{8(4\pi a^3\rho_b[a^3H^2])^2}\int \frac{d^3q}{(2\pi)^3}\frac{P_B(q)P_B(k-q)}{(k-q)^2}\left[k^2+2q^2+4\frac{(q\cdot k)^4}{k^4q^2} - 4\frac{(q\cdot k)^2}{k^2} - 4\frac{(q\cdot k)^3}{k^2q^2} + \frac{(q\cdot k)^2}{q^2}\right]$$

$$\Delta_b^{\mathrm{PMF}}(k) \equiv \frac{k^3P_b^{\mathrm{PMF}}(k)}{2\pi^2} = 10^{-4}\xi_b^2(a)\left(\frac{k}{\mathrm{Mpc}^{-1}}\right)^{2n_B+10}\left(\frac{B_{1\mathrm{Mpc}}}{\mathrm{nG}}\right)^4 G_{n_B}e^{-2k^2\lambda_D^2}, \qquad (2.2$$

where G_{n_B} is a dimensionless number determined by

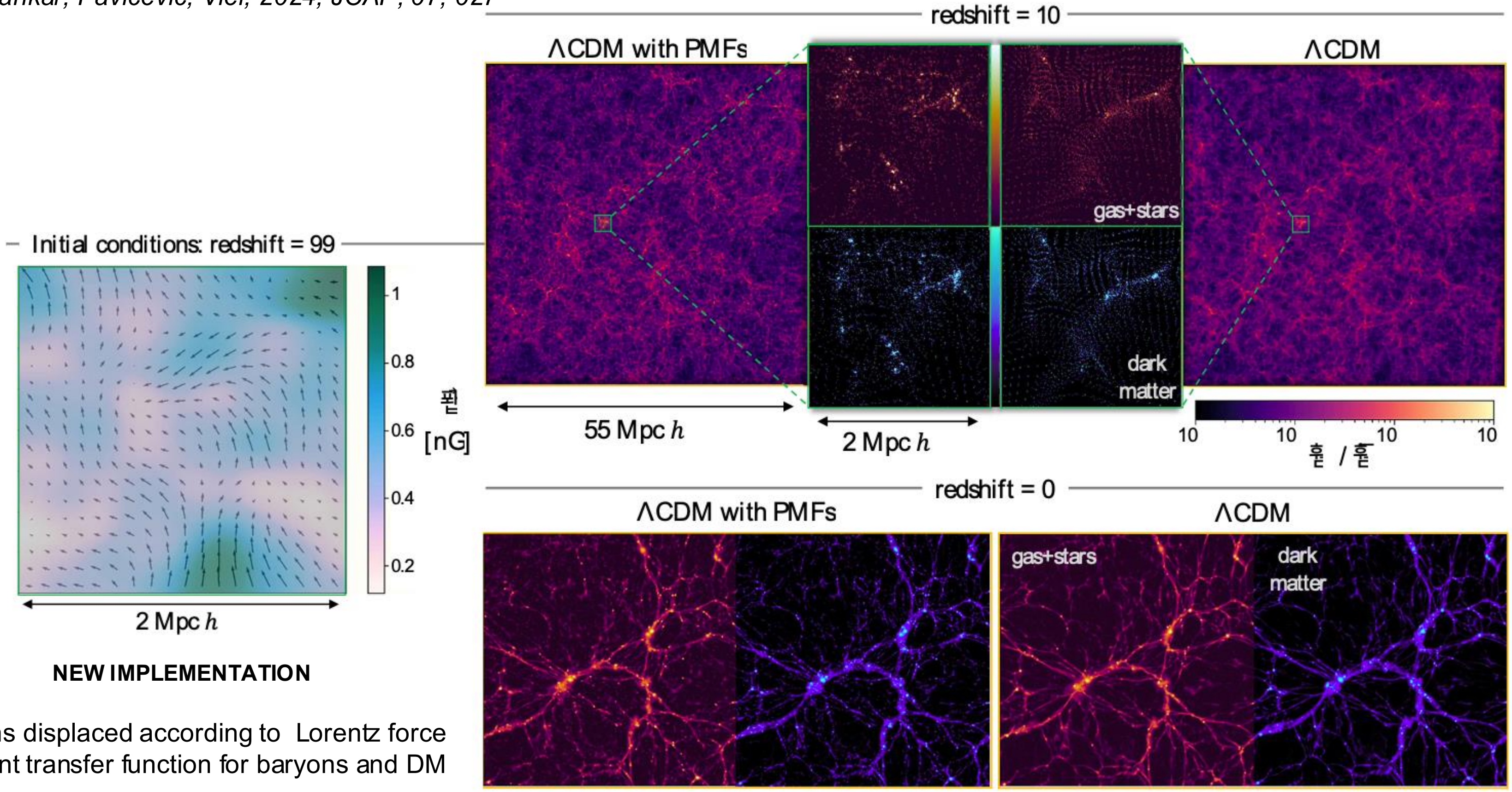
$$G_{n_B} = \int_0^\infty dx \int_{-1}^1 \frac{dy}{2} x^{n_B+2}(1+x^2-2xy)^{n_B/2-1}\frac{[1+2x^2+4y^4x^2-4y^2x^2-4y^3x+y^2]}{\Gamma^2([n_B+3]/2)}$$



Raleganker, Pavicevic, Viel 2024
Adi, Cruz, Kamionkowski 2024

Hydro sims

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

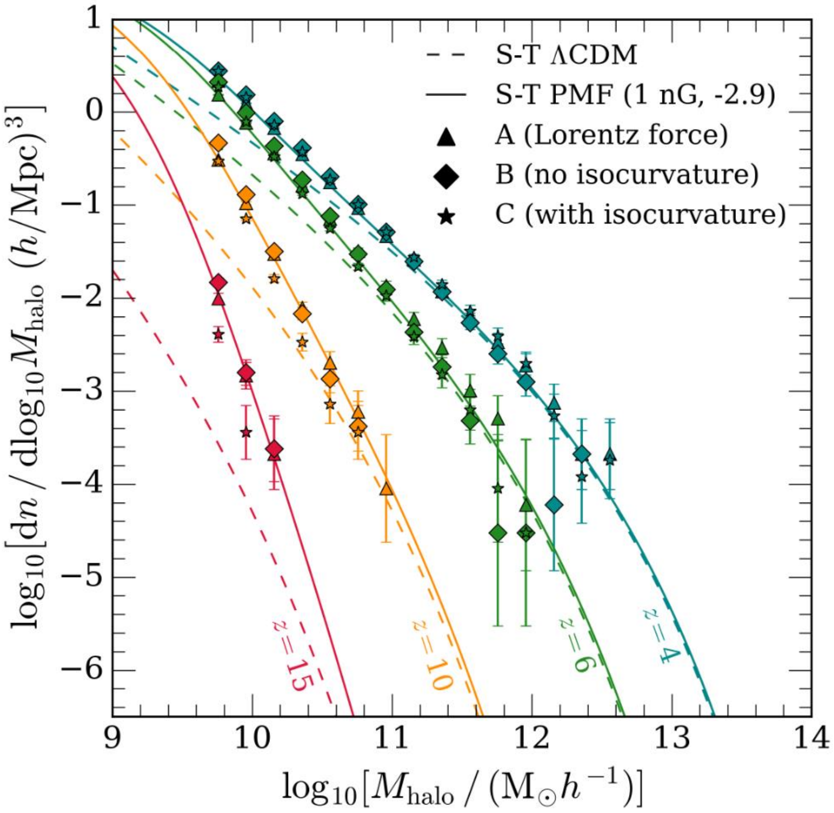


NEW IMPLEMENTATION

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

Halo Mass Function

Matteo Viel

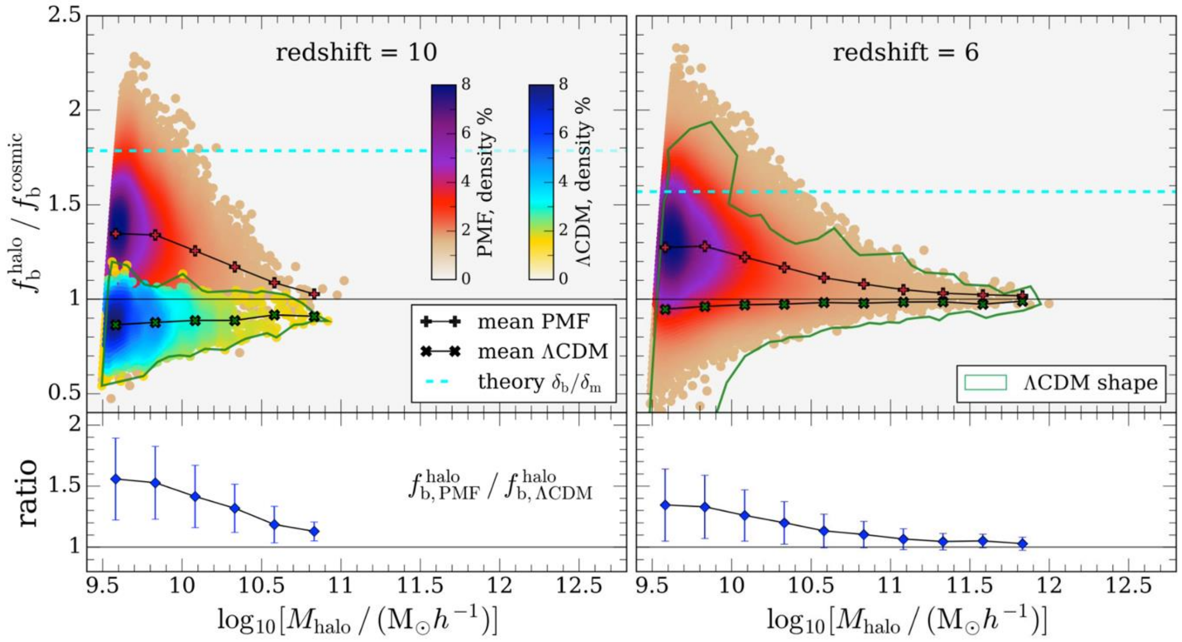


- ✓ Extra PMFs power produces more haloes, at "low" mass
- ✓ With lower B values (< 1 nG) the enhancement will move to lower masess
- ✓ Below 0.05 nG effect is probably too small at any scale

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

Halo Baryon Fractions at high redshift

Matteo Viel

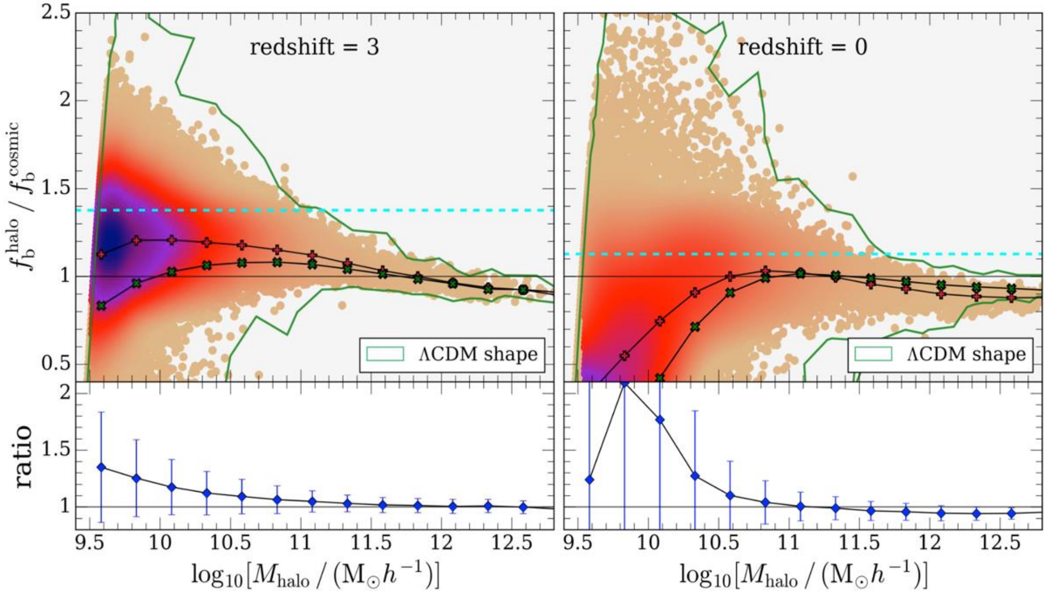


- ✓ Larger baryon fraction in haloes also shown in hydro sims
- ✓ At large masses (scales) cosmic values is recovered
- ✓ More scatter in PMF models

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

Halo Baryon fraction at lower redshift

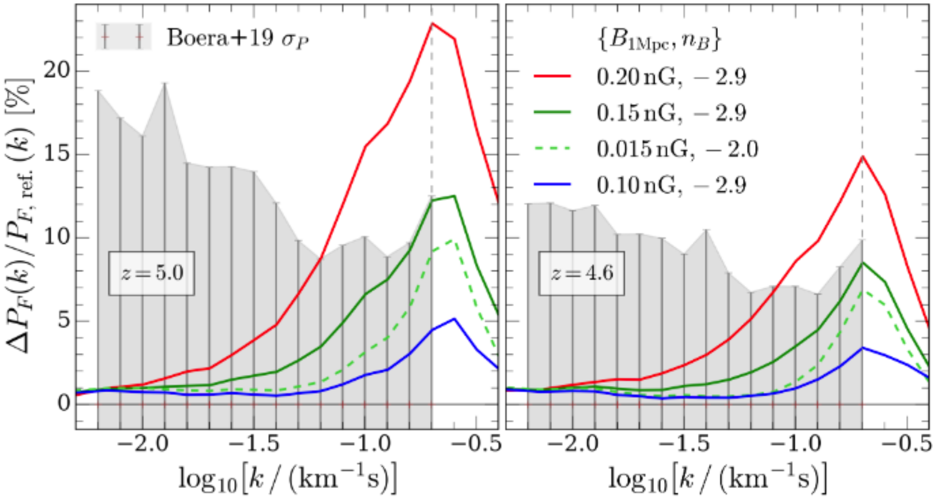
Matteo Viel



- ✓ At low (z<3) redshift the effect vanishes

Impact on flux power

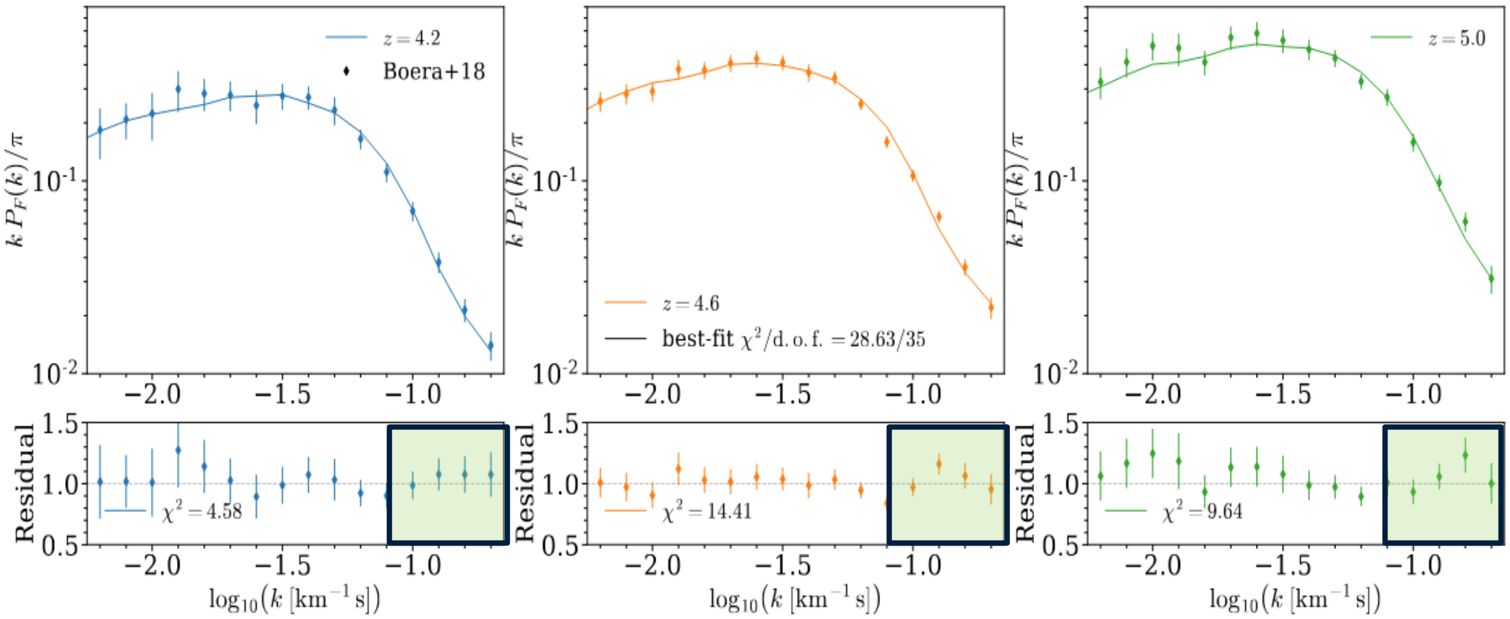
Pavicevic, Irsic, MV et al. 2025



✓ Strong scale/z dependent increase of power

Best fit PMF models

Pavicevic, Irsic, MV et al. 2025

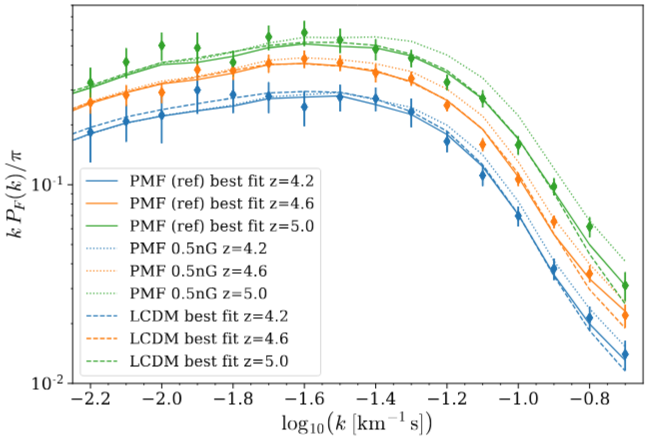


$$\chi^2_{\Lambda\text{CDM}} = 40.8 \text{ for } 36 \text{ d.o.f.}$$

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

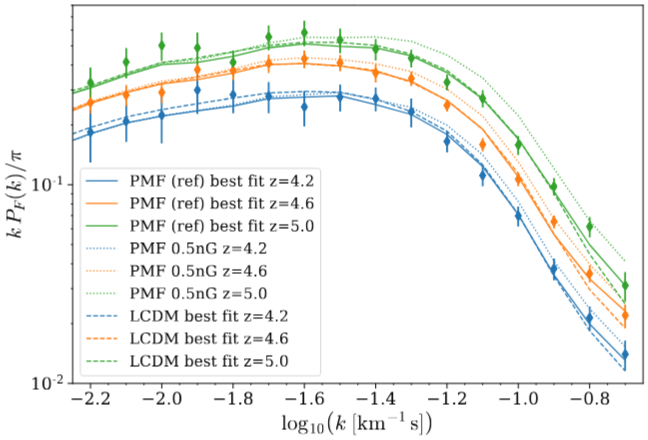
Constraints on peak position

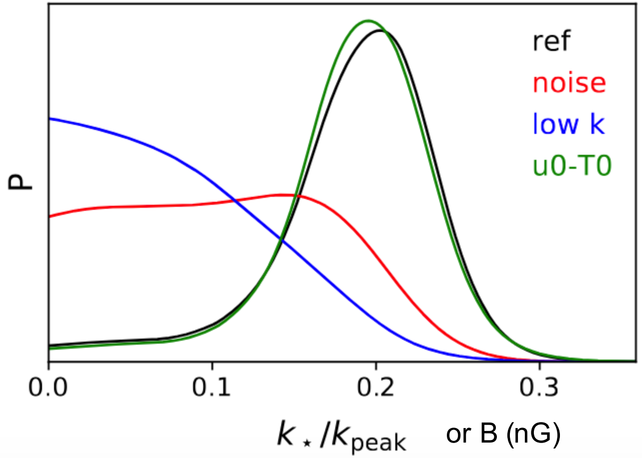
Matteo Viel



Constraints on peak position

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





Pavicevic, Irsic, MV et al. 2025

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

Part 6

IGM as a calorimeter

The IGM as a thermometer

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

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

- ✓ 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

The IGM as a thermometer

Matteo Viel

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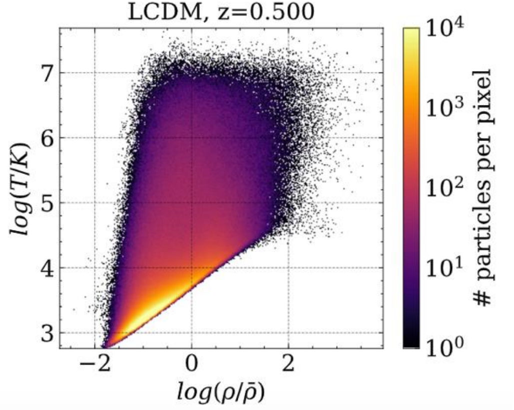
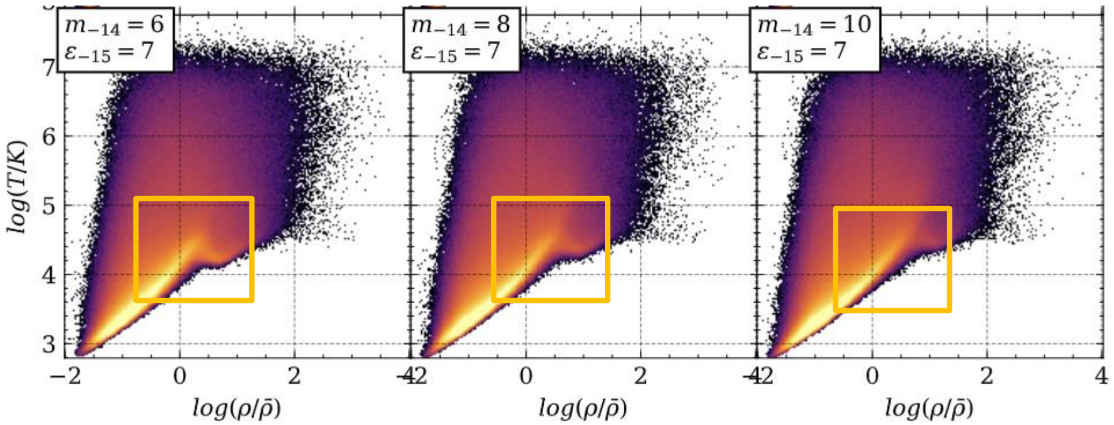
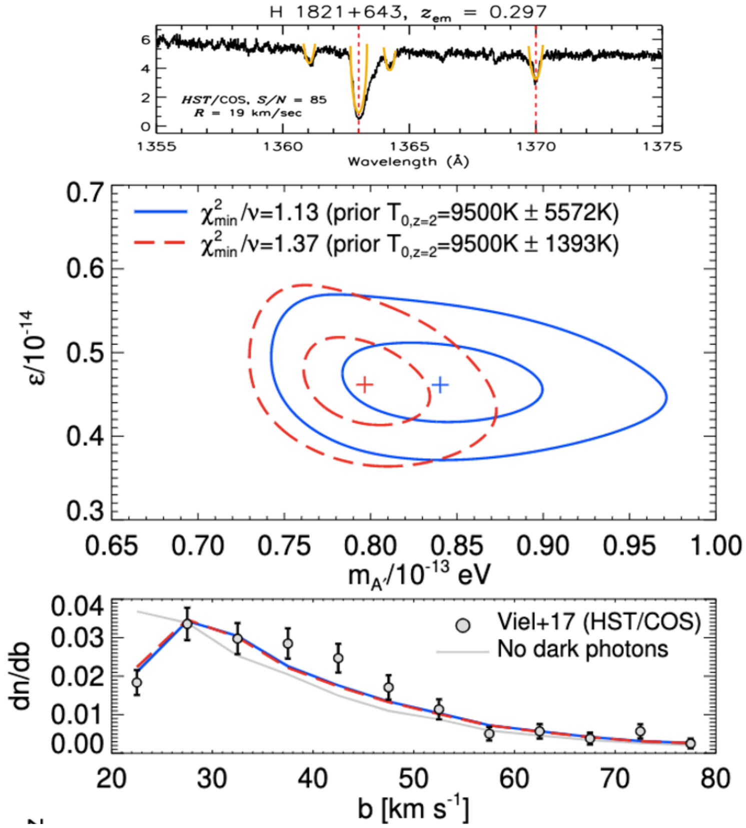




Bolton, Caputo, Liu, MV, PRL, 2022 - see also Trost+arXiv: 2410.02858

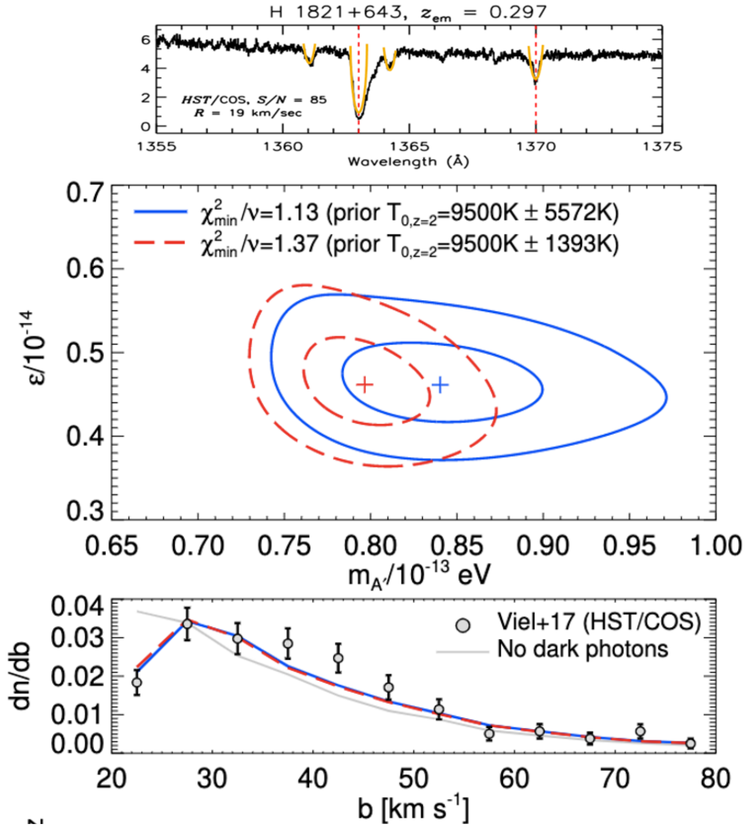
The IGM as a thermometer - II



- ✓ Effect is small but can be used to place constraints on extra-heating
- ✓ At z=0.1 COS/HST lines are broader than
- ✓ expected (feedback, turbulence?)

The IGM as a thermometer - II

Matteo Viel



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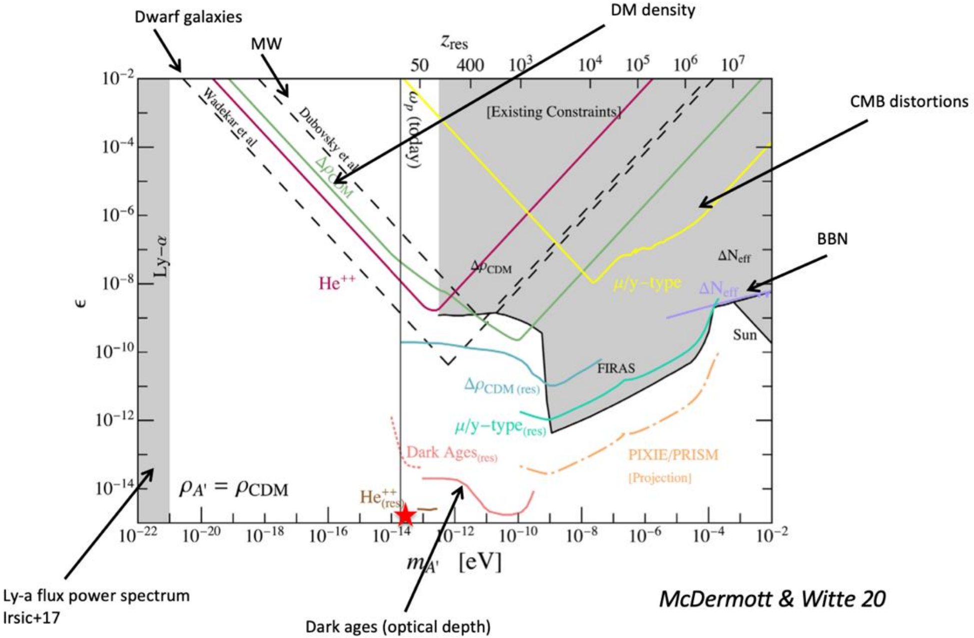
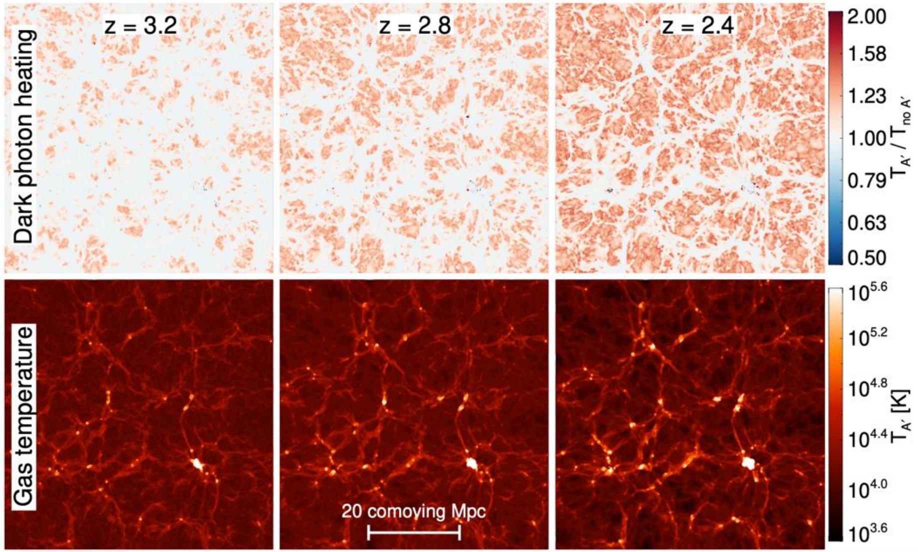


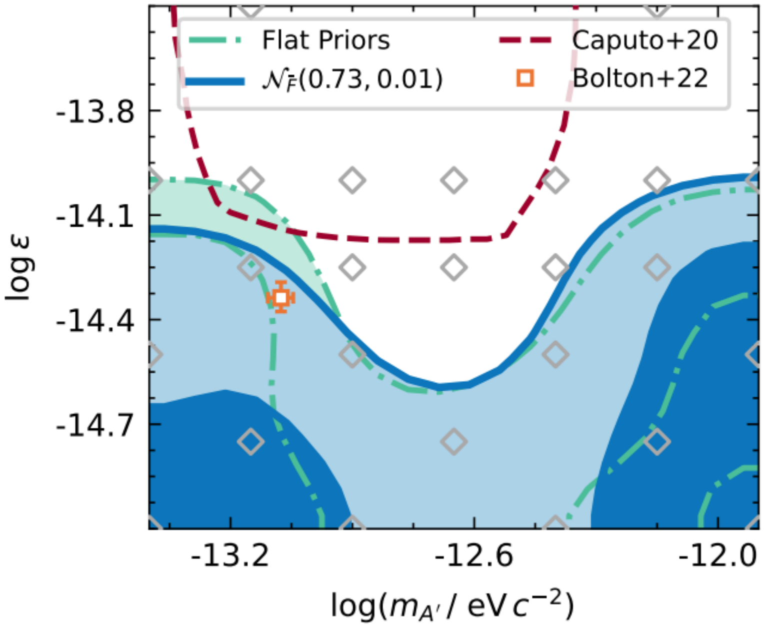
McDermott & Witte 20

The IGM as a thermometer - II

Matteo Viel

Distinctive heating mechanism happening far away from complex astrophysics





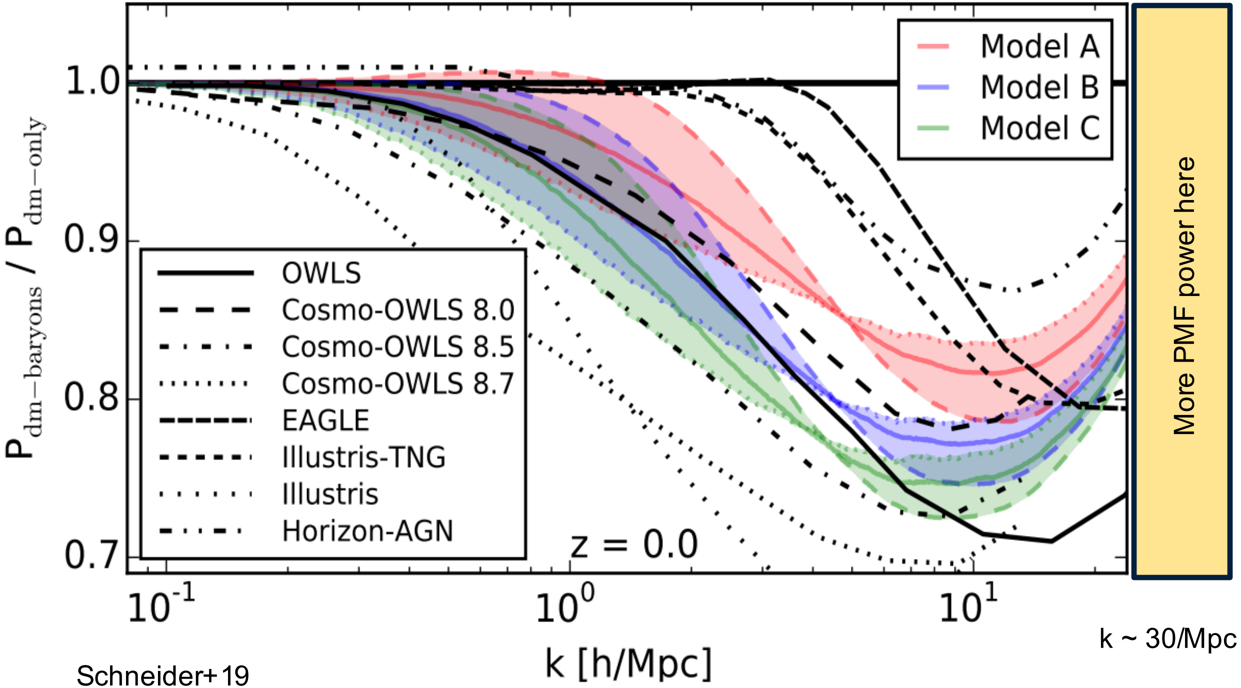
Trost+arXiv: 2410.02858

Summary

- ✓ PMFs can enhance baryon fraction apart from enhancing matter power spectrum
- ✓ Can affect **star formation/important for JWST**
- ✓ Observing **high baryon fraction** at high redshift will be smoking gun signal for PMFs
- ✓ **Lyα forest ideal probe** of PMFs, since it samples low density environments far from galaxies
- ✓ Constraints from Lyα forest point to **a detection at 0.2 nG** or more conservatively a tight 3σ **upper limit of 0.3 nG**

PMFs: interplay with baryonic corrections

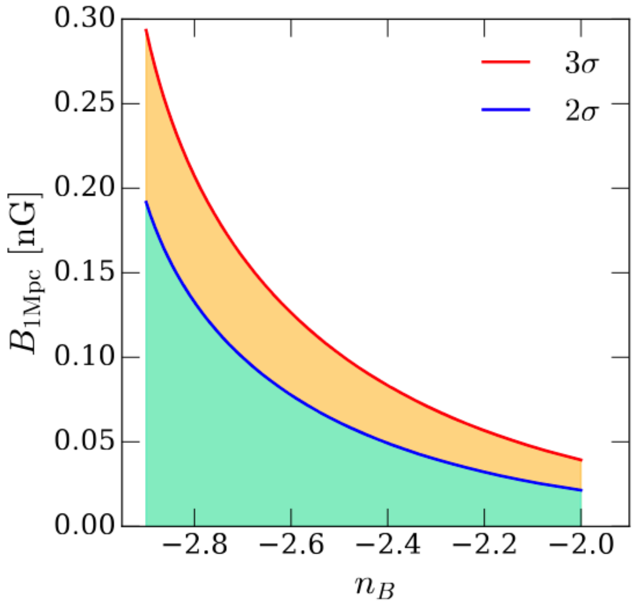
Matteo Viel



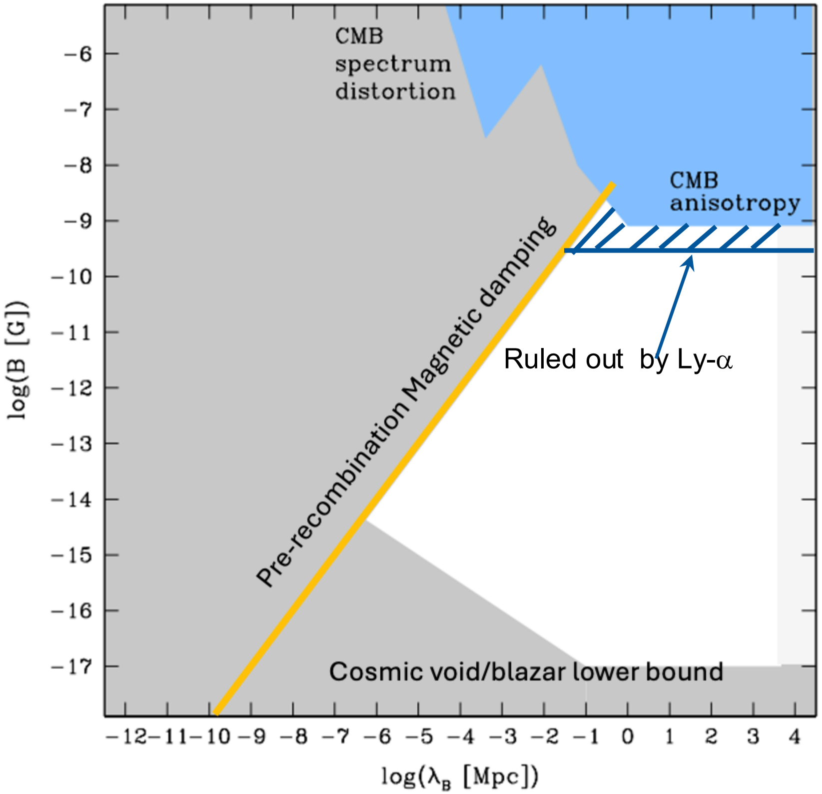
Schneider+19

Constraints on peak position

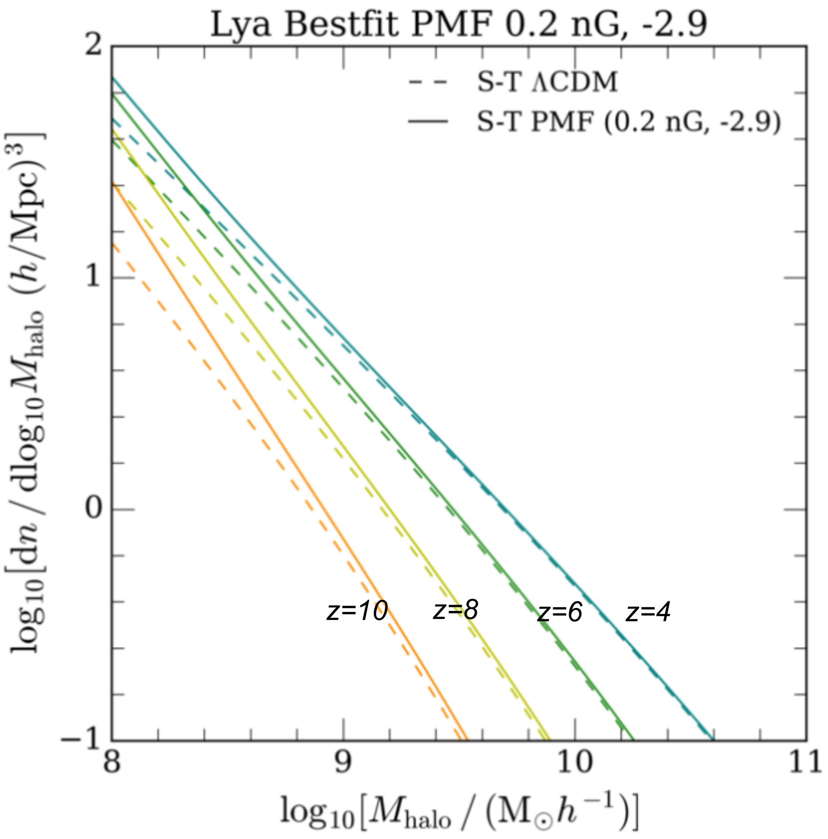
Matteo Viel



Extending to other n_B values

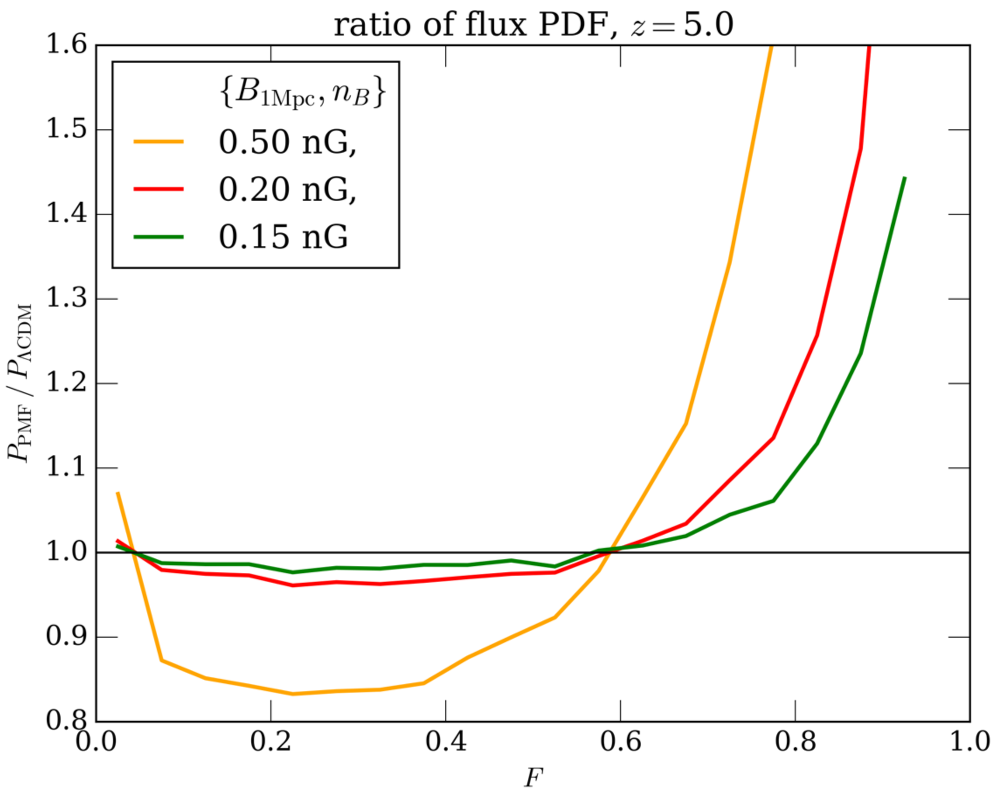


Implications for the detection



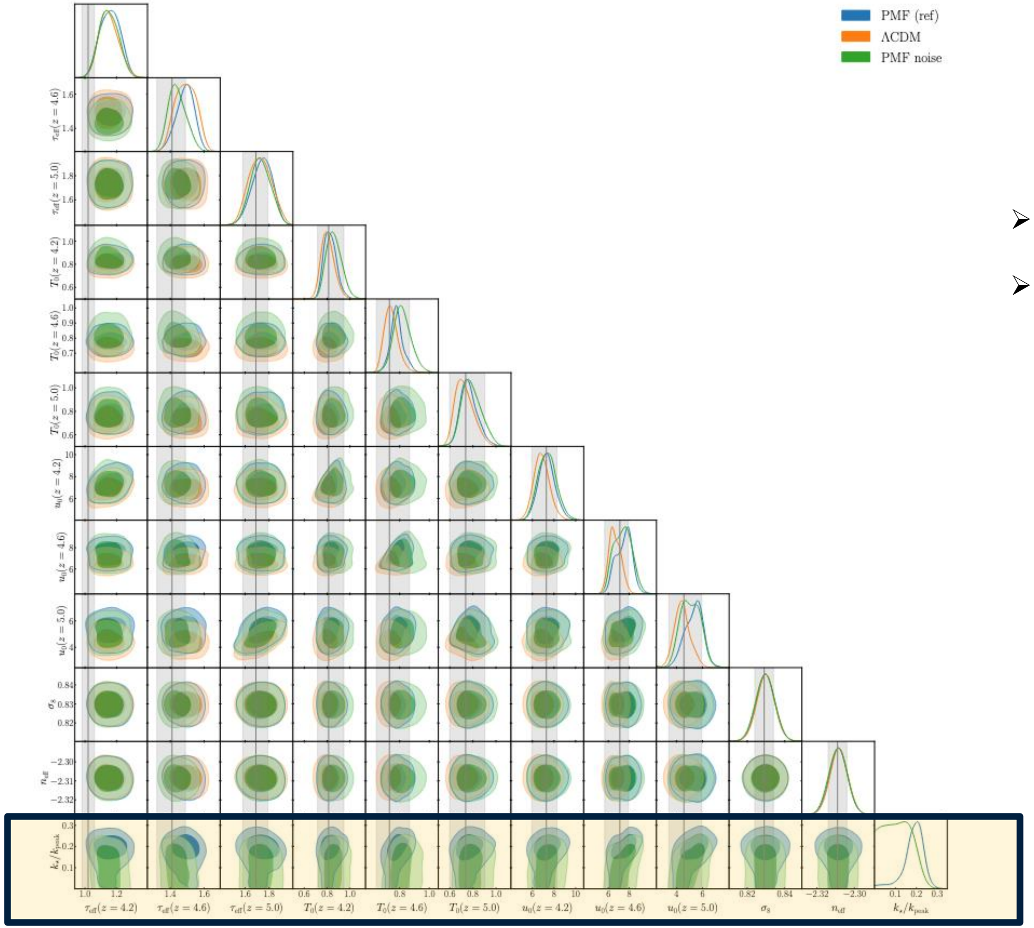
- MF is boosted at $M_{halo}<10^9\ M_\odot/h$
- ~2 more $10^8\ M_\odot/h$ haloes at z=10 expected compared to ΛCDM

PMFs: flux pdf



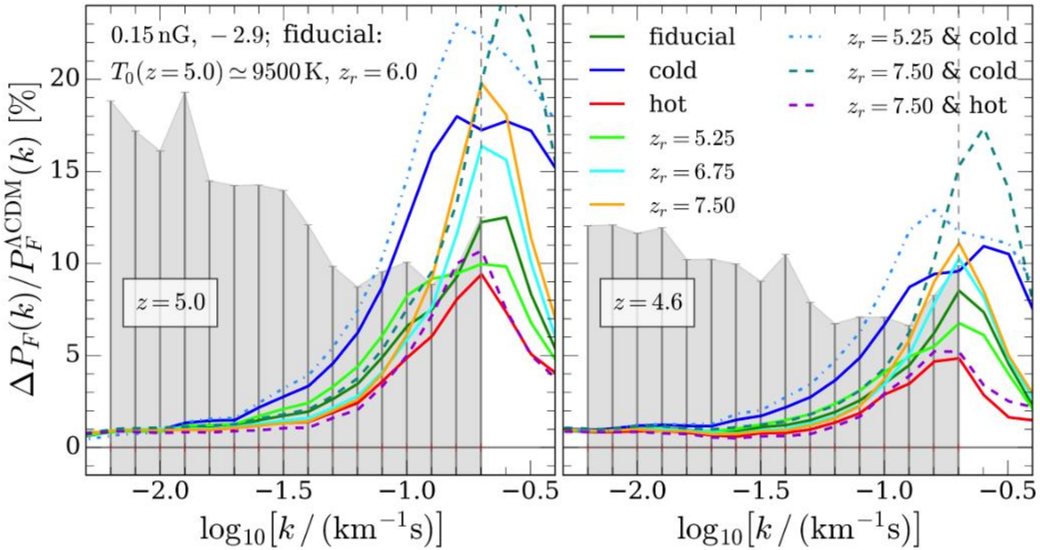
Extra slides: triangle plot

Matteo Viel



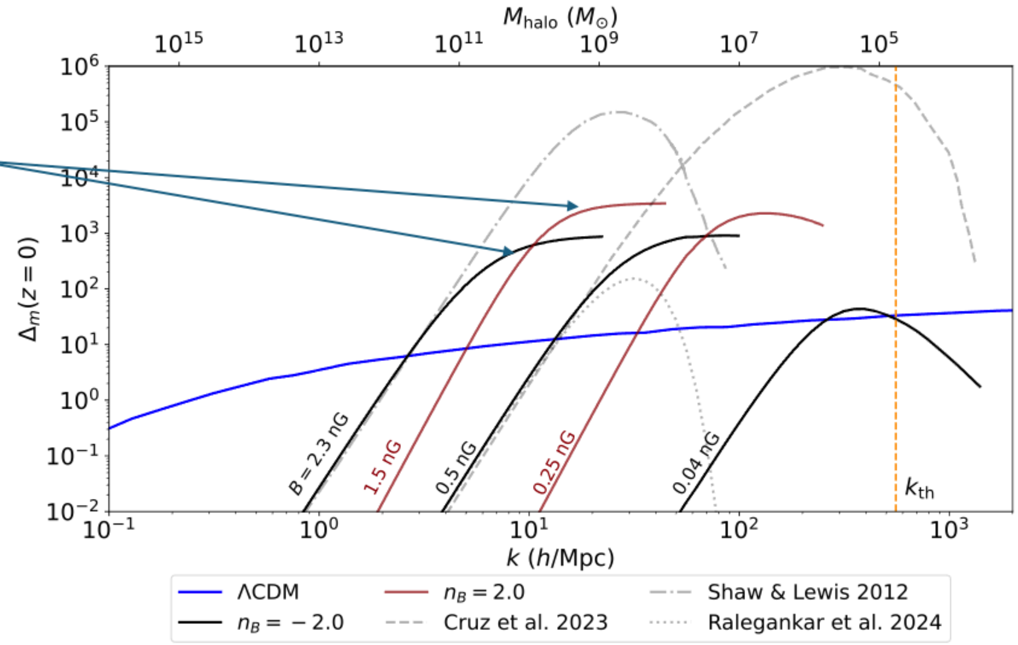
- Not strong degeneracies present
- Weak degeneracies with injected heat and noise modelling

Extra slides: PMFs vs thermal parameters



Non-linear scales with MHD

Magnetic Jeans scale/ non-linear regime

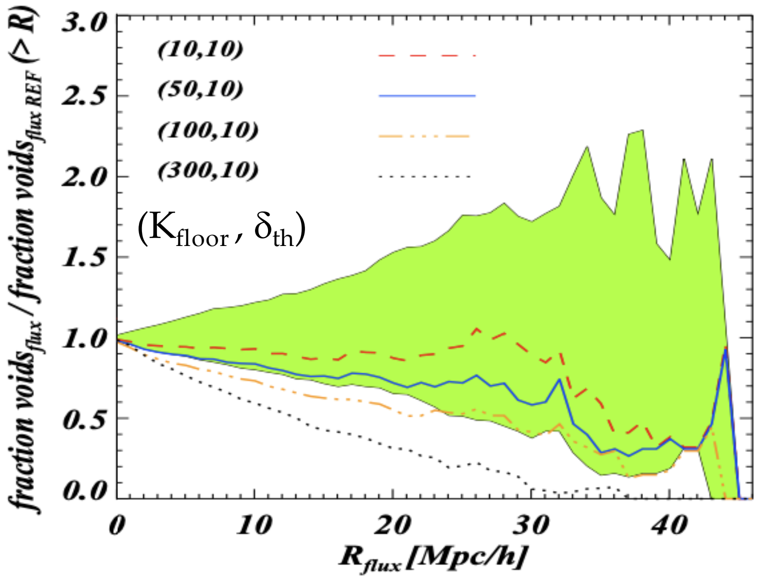


Ralegankar, Garaldi, Viel, 2024, arXiv:2410.02676

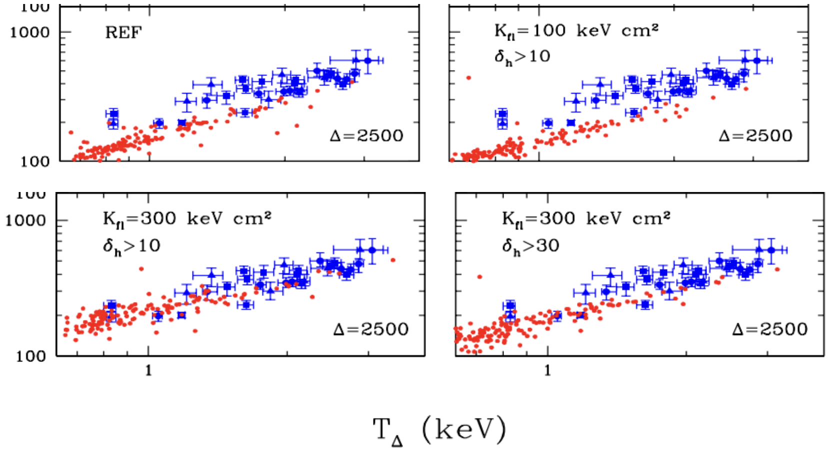
Connection to low z: entropy-temperature relation of groups

Matteo Viel

Forest Voids' statistics at z=2



CHANDRA entropy-temperature profiles

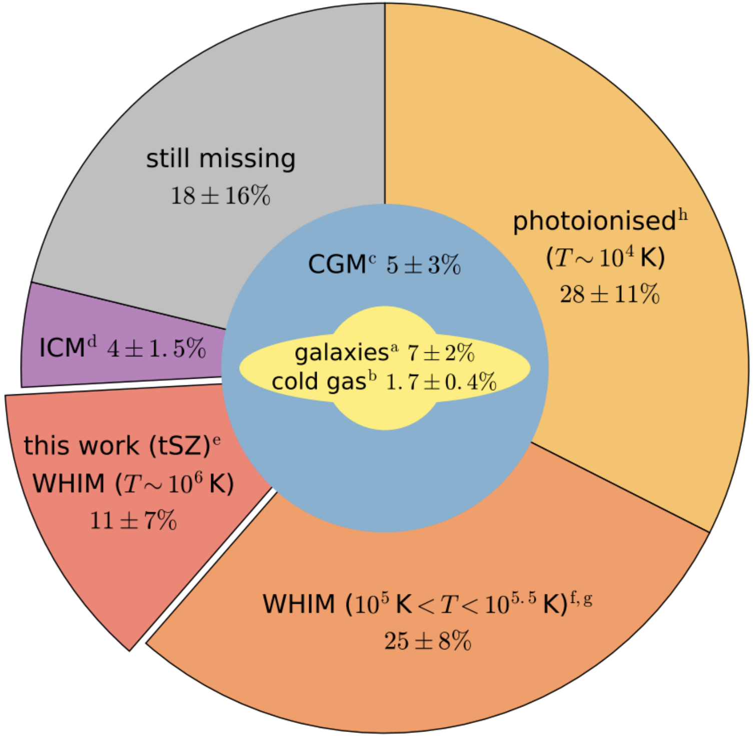


Pre-heating: gas at z=4 with $\delta>\delta_{th}$ and $K<K_{floor}$

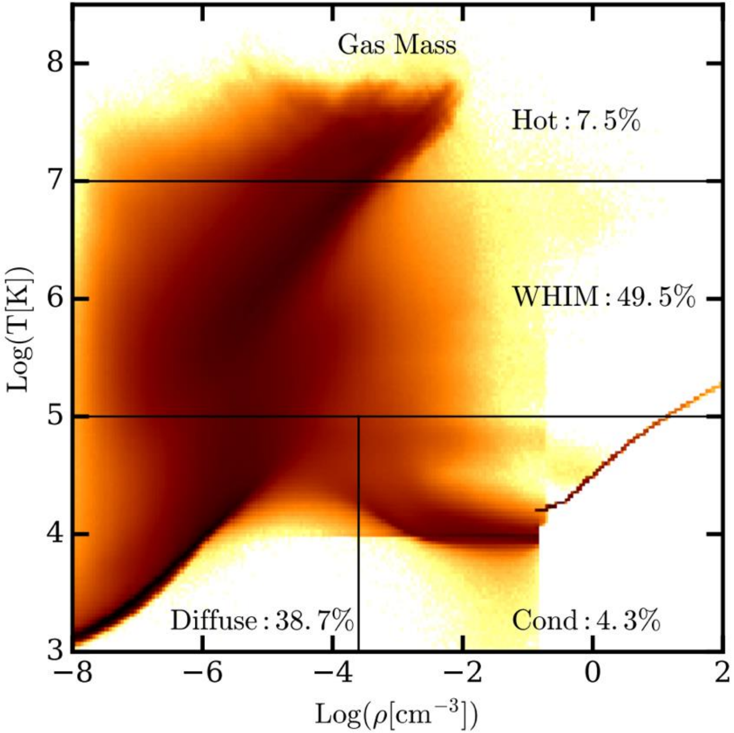
Must occur at δ>10-30 and/or at z<1

Borgani & Viel 2009

Connection to low z: census of the baryons at z=0



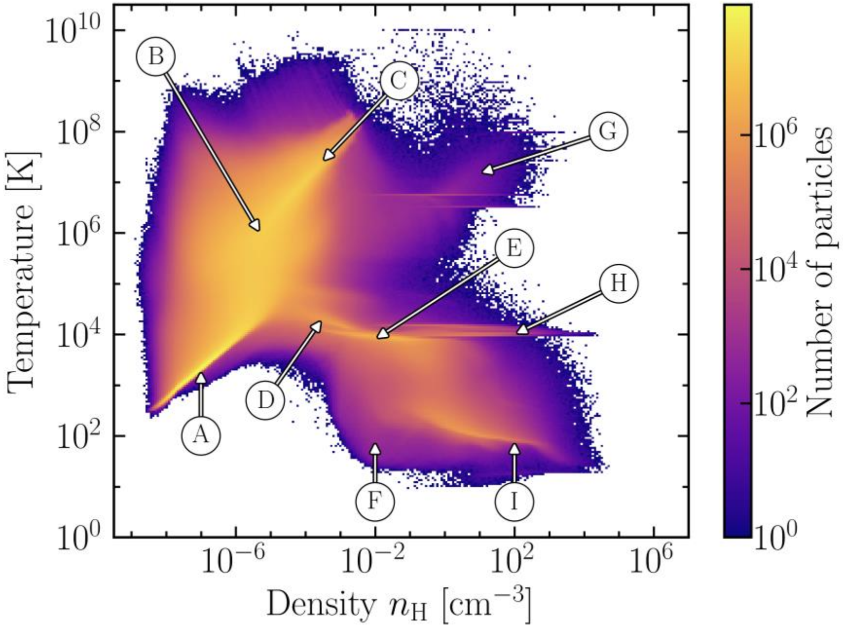
De Graaf et al. 2019
Parimbelli, Branchini, MV, Villaescusa-Navarro, ZuHone 2023



Torrey+19 [IllustrisTNG]

Connection to low-z: The physics of the T-ρ relation (z=0)

Matteo Viel



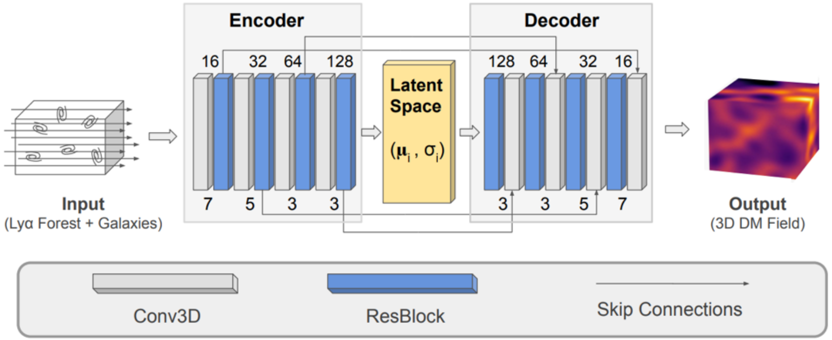
Schaye+25 COLIBRE simulations

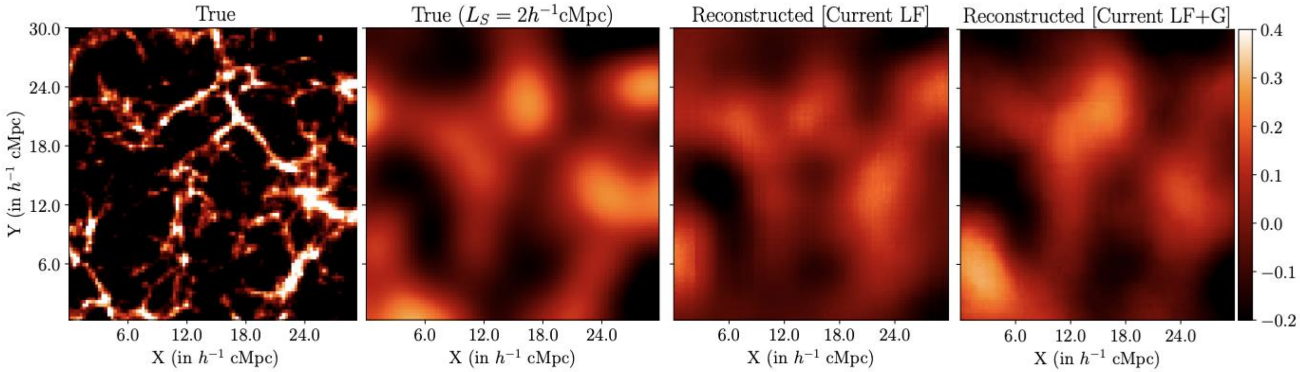
Impressive dynamical range

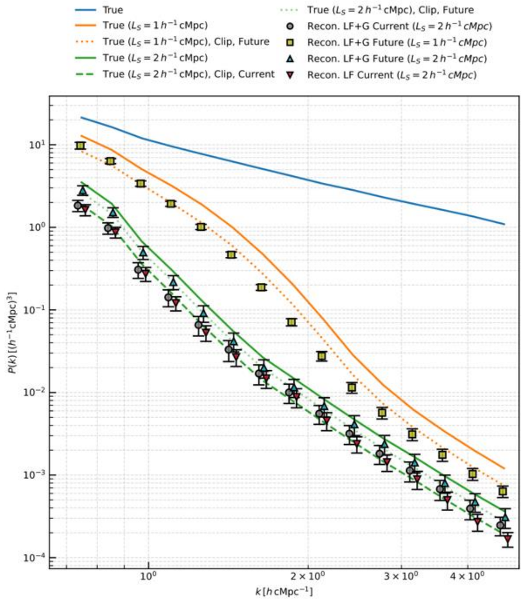
- ✓ A: diffuse IGM
- ✓ B: WHIM and CGM
- ✓ C: ICM
- ✓ D: cool CGM
- ✓ E: thermal equilibrium of low Z gas
- ✓ F: cold ISM
- ✓ G: hot ISM (from feedback)
- ✓ H: HII ionized regions
- ✓ I: very cold ISM

Reconstructing the 3D DM cosmic web with ML

Matteo Viel



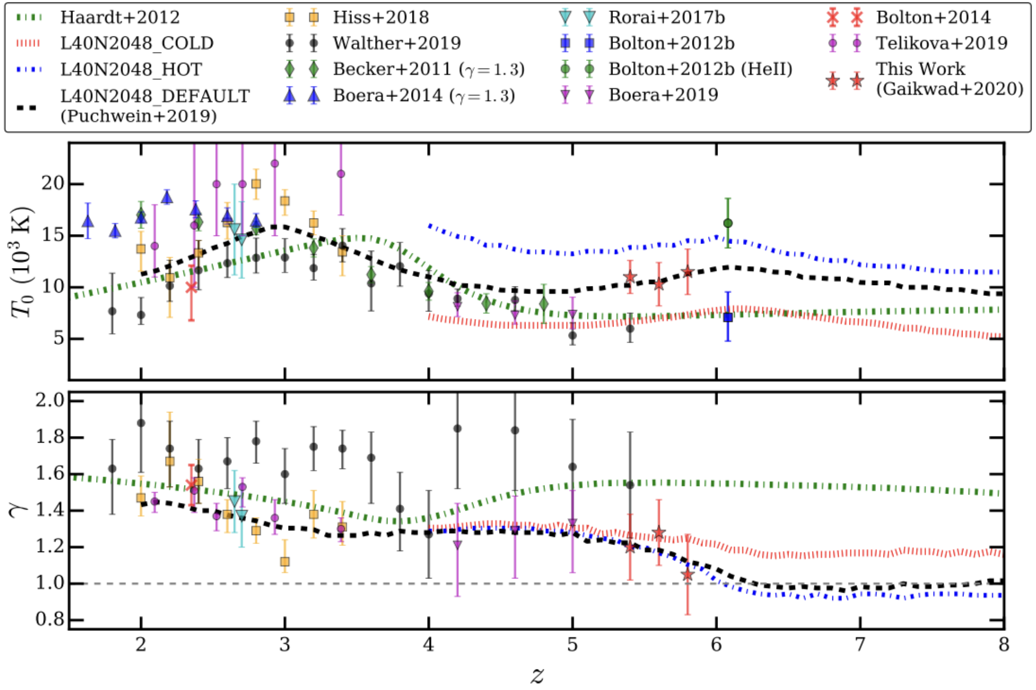




Maitra, Kulkarni, Viel 25

Physics of the gas: the gas thermal state

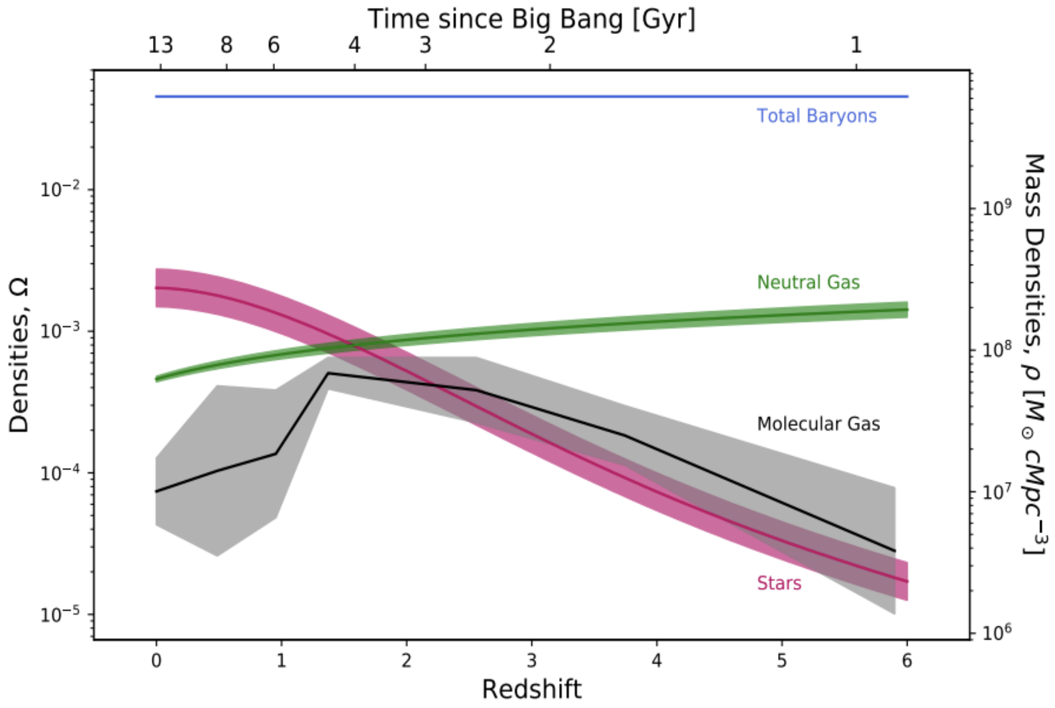
Matteo Viel



Gaikwad+20

- ✓ Temperature density relation can indeed be measured by using a variety of methods like wavelets, pdf of the gas, power spectrum, bispectrum, Voigt profile fitting.
- ✓ HeII bump quite "prominent"

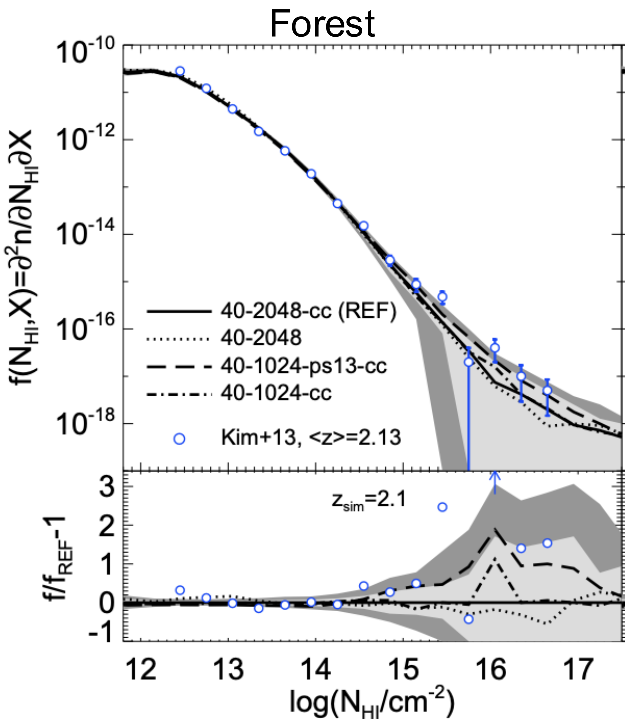
Evolution of the condensed phases



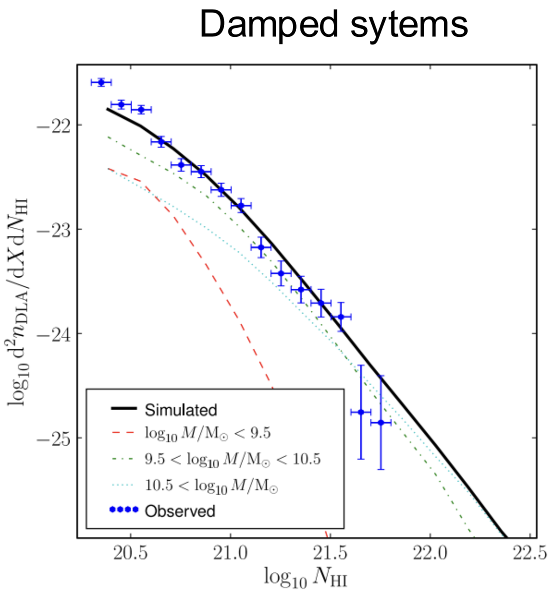
Peroux & Howk 2021

- ✓ Molecular gas traces star formation rate
- ✓ Neutral gas always dominating the budget at z>2 and always above the molecular
- ✓ Total budget is subdominant compared to total baryons

HI column densities



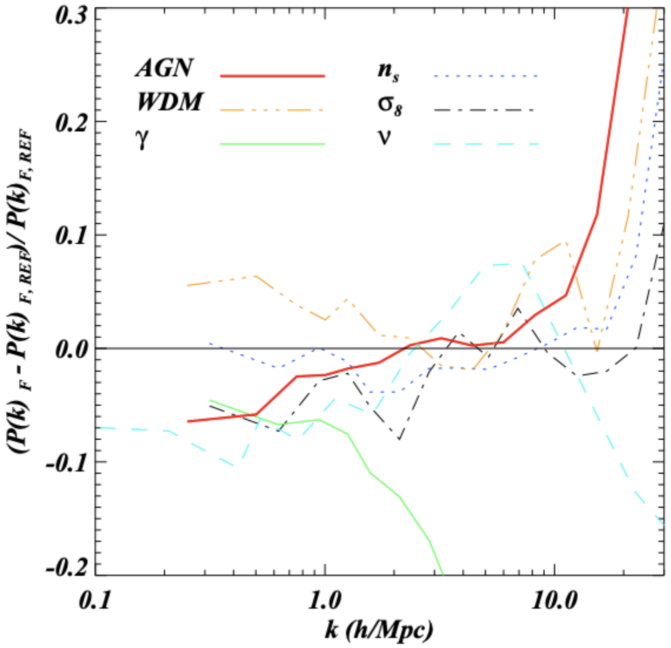
Bolton+17



Pontzen+09

- ✓ Fitting with Voigt profile allows to extract the HI column density
- ✓ Good agreement over about 10 orders of magnitude, spanning very underdense gas up to Damped systems (galaxies)
- ✓ Smaller scales are more complex and rich in physics (feedback, AGN, star formation, molecules, dust, metals)

Feedback and Lyman-α forest

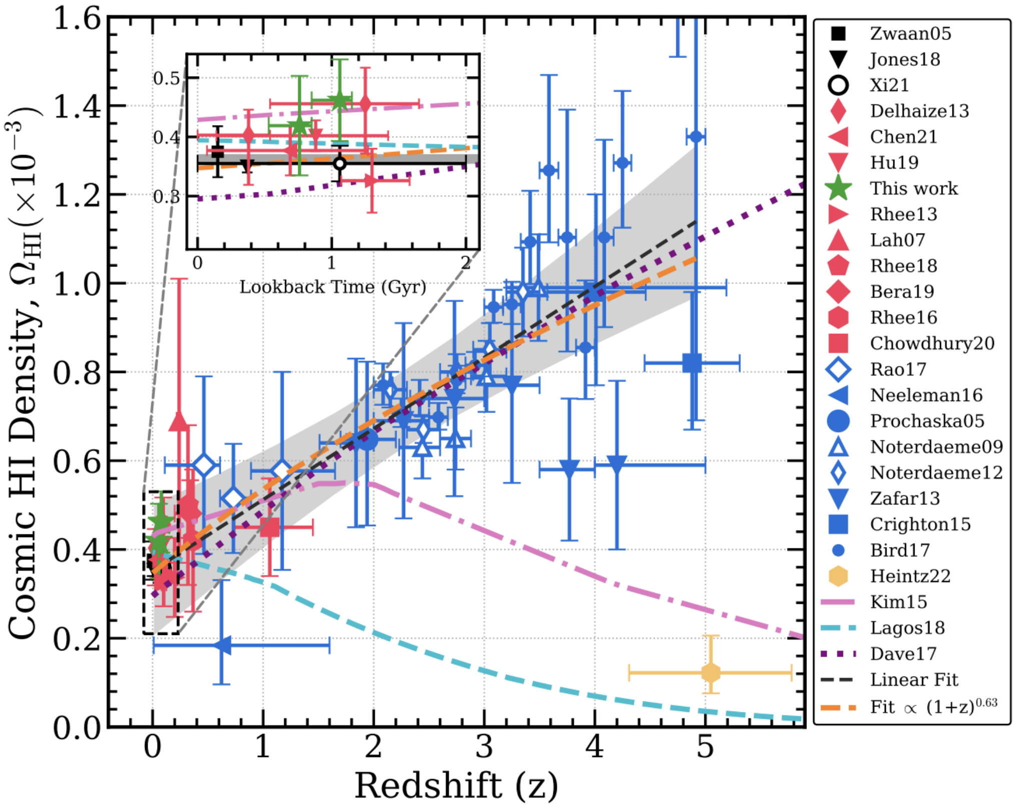


Viel, Schaye & Booth 2012
Chabanier+2025

- ✓ Impact of AGN feedback at low z (z~2) is of the same order of the cosmo params
- ✓ These effects can only partially be captured by changes in the Temp. density relation of photo-ionized gas
- ✓ Especially for AGN, changes in the density distribution and in the fraction of hot, collisionally ionised gas ($T>10^5$K)

HI evolution with redshift

Matteo Viel



Peroux & Nelson 2024

- ✓ Evolution of HI mass density is relatively mild compared to other physical quantities like SFR
- ✓ This quantity is dominated by DLAs and is important when 21cm intensity mapping models are built