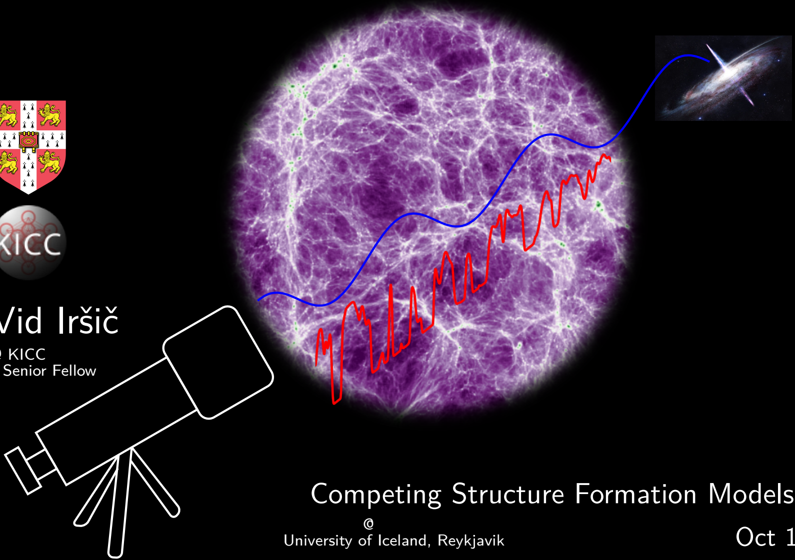
The IGM as a probe of the nature of dark matter



Vid Iršič

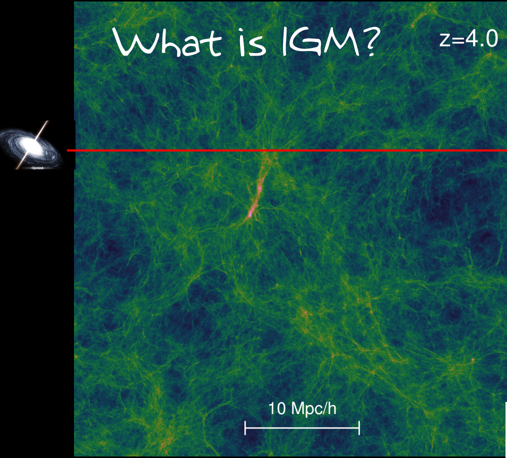
@ KICC
Kavli Senior Fellow

Competing Structure Formation Models

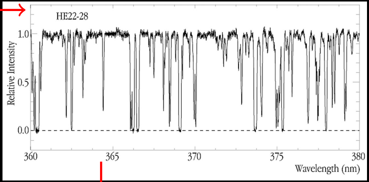
@
University of Iceland, Reykjavik

Oct 1, 2019

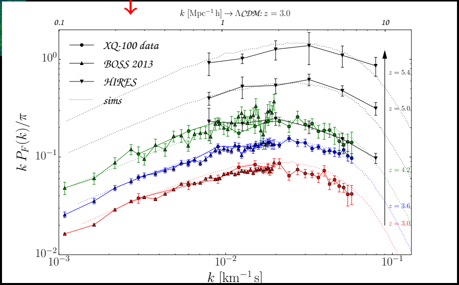
What is IGM?



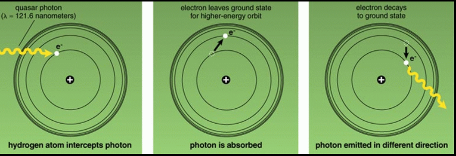
Absorption in Quasar spectra along the line of sight



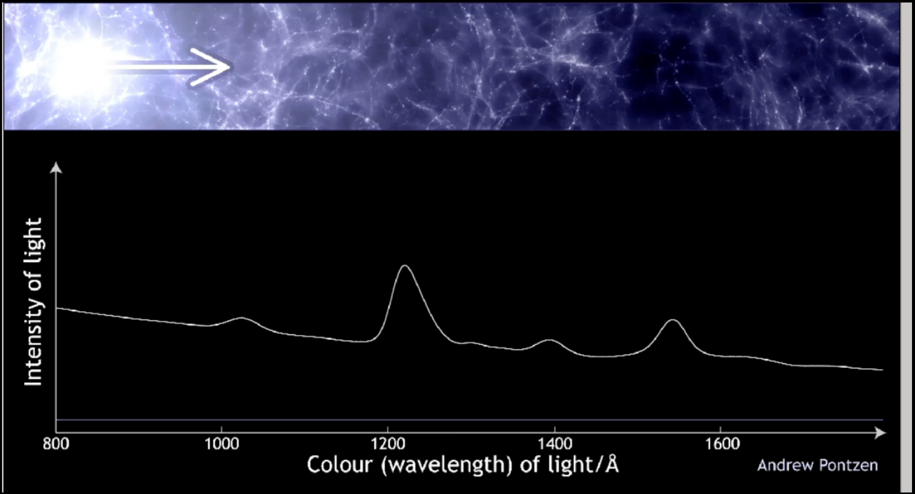
Flux power spectrum



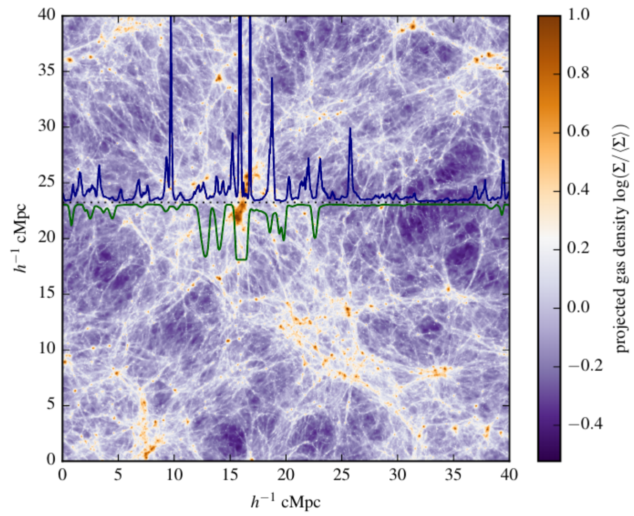
Scattering of the photon on $n = 1 \rightarrow n = 2$ Hydrogen transition (Lyman series)



Observable of the IGM



Why should we care about IGM?



ρ_g -gas density

F -observed flux

Flux is a biased tracer of the density:

$$F \sim b\,\rho_g$$

Sensitive to fluctuations, along the line-of-sight, on scales $\sim 0.1 - 10\ \mathrm{Mpc/h}$

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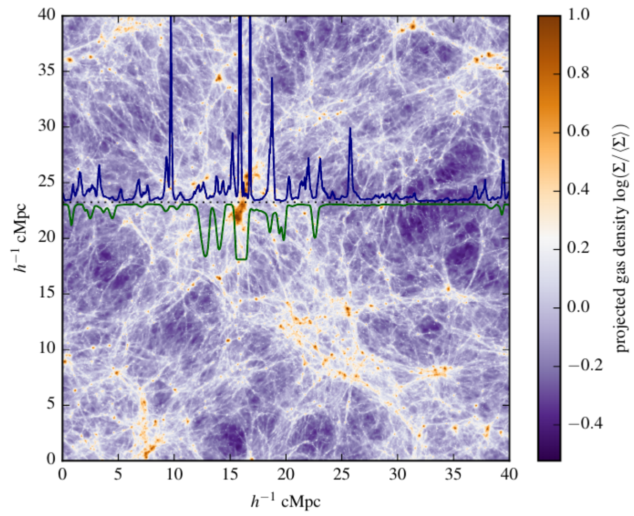

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small scales

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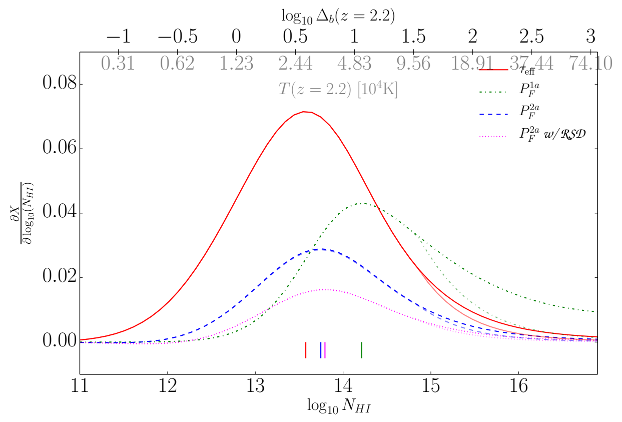


P_F^{2a} - cosmological

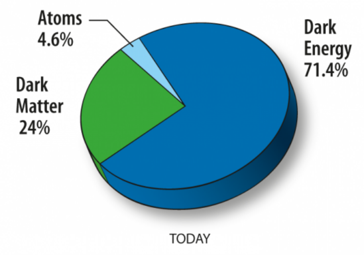
P_F^{1a} - thermal gas

Flux is a biased tracer of the density:

$$F \sim b\,\rho_g$$

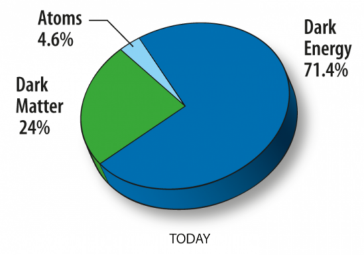
Sensitive to mildly non-linear density fluctuations, along the line-of-sight, on scales $\sim 0.1 - 10\ \mathrm{Mpc/h}$

Cold Dark Matter problems (?)



Cold Dark Matter (CDM):
heavy, non-interactive particle(s) → WIMPs

Cold Dark Matter problems (?)



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CDM problems of small-scale physics:

- Missing satellites
- Core/Cusp problem
- ...

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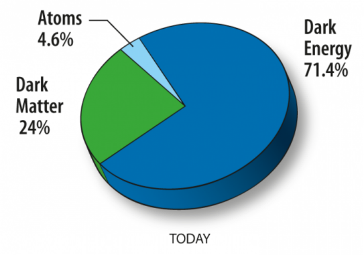

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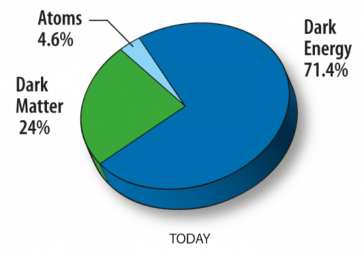

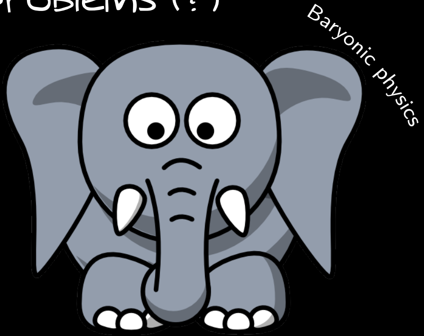

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CDM problems of small-scale physics:

- Missing satellites
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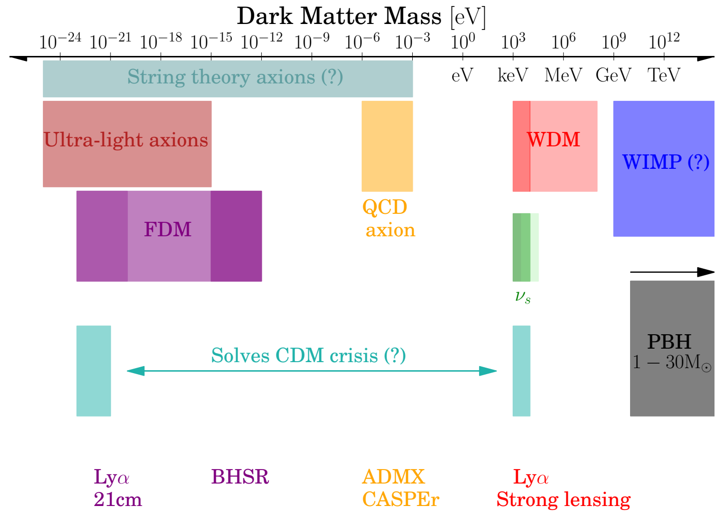
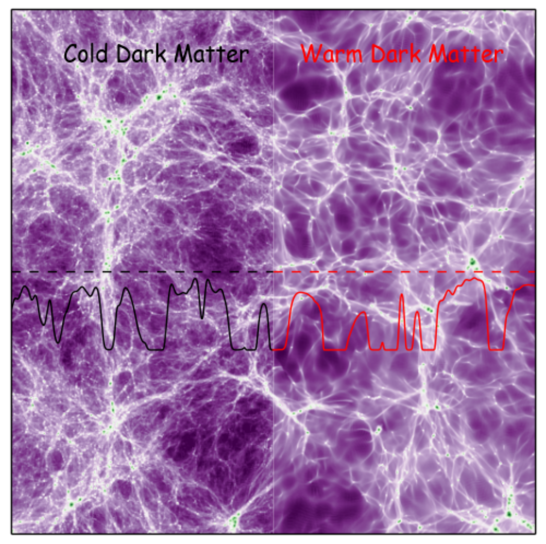
→ Alternative DM models (Warm DM, Fuzzy DM, Self-interacting DM, ...)

Where to look for DM?



Non-CDM erases small scale structure



Warm Dark Matter (WDM):

Free-streaming of DM particles

(From the time they decouple

until they become non-relativistic)

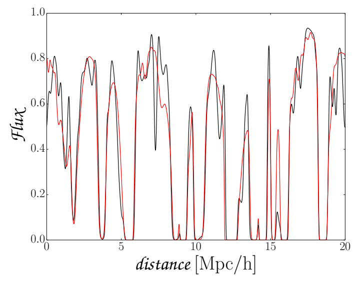
Fuzzy Dark Matter (FDM):

de-Broglie wavelength

of ultra-light DM scalar

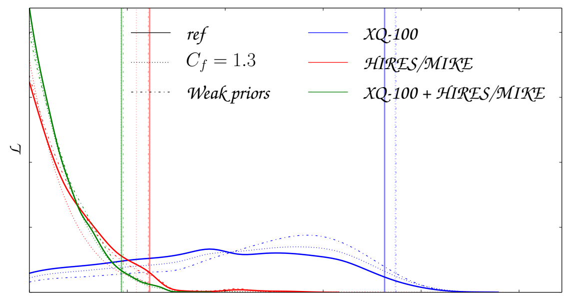
$\Longrightarrow$ erases small scale structure

Typical $\lambda_{\mathrm{FS}} \sim \mathrm{Mpc/h}$



Typical DM particle mass from local small-scale structure

- $m_{\mathrm{WDM}} \sim 2-3\ \mathrm{keV}$ (WDM)
- $m_{\mathrm{FDM}} \sim 1-10\ \times\ 10^{-22}\ \mathrm{eV}$ (FDM)



'realistic' thermal history:

$\rightarrow \boxed{m_{\rm FDM} > 37 \times 10^{-22}\ {\rm eV}\ @\ 2\sigma}$

conservative thermal history model:

$\rightarrow \boxed{m_{\rm FDM} > 20 \times 10^{-22}\ {\rm eV}\ @\ 2\sigma}$

VI, Viel, Haehnelt, Bolton, Becker (2017c)

TRAILER

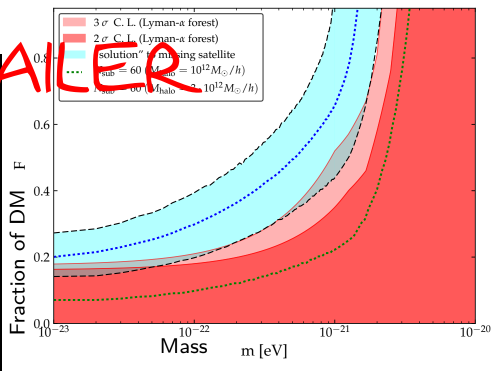
'realistic' thermal history:

$\rightarrow \boxed{m_{\rm WDM} > 5.3\ {\rm keV}\ @\ 2\sigma}$

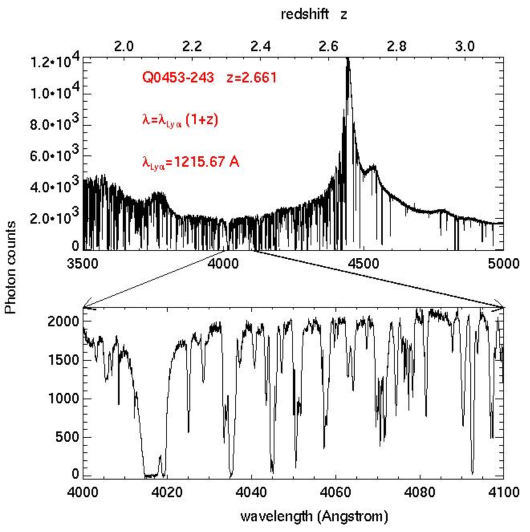
conservative thermal history model:

$\rightarrow \boxed{m_{\rm WDM} > 3.5\ {\rm keV}\ @\ 2\sigma}$

VI, Viel, Haehnelt, Bolton, et al. (2017B)



What do we measure?



Measured quantity:

$$f = C \cdot \bar{F}\,(1 + \delta_F) + n$$

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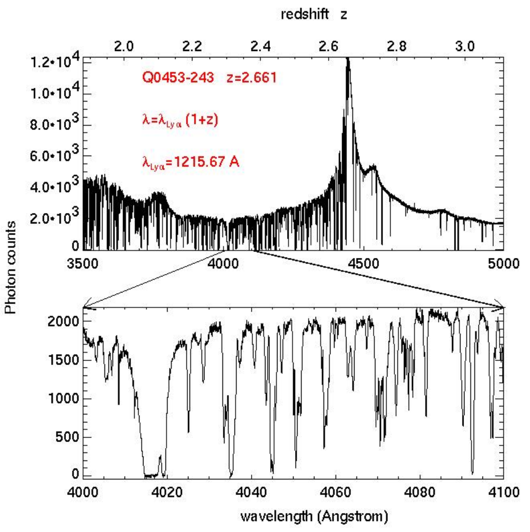

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observed flux

absorption

continuum

noise

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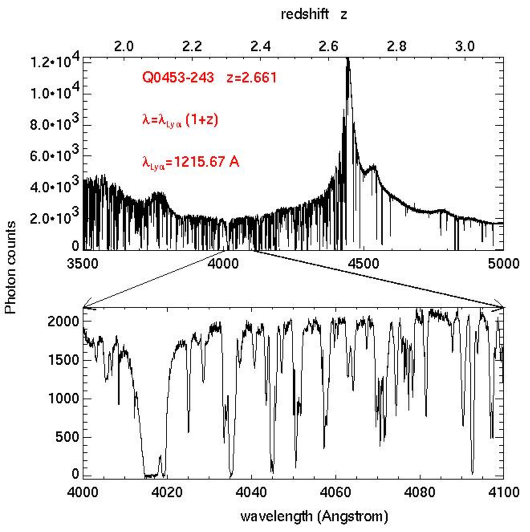

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$\bar{F}$

δ_F

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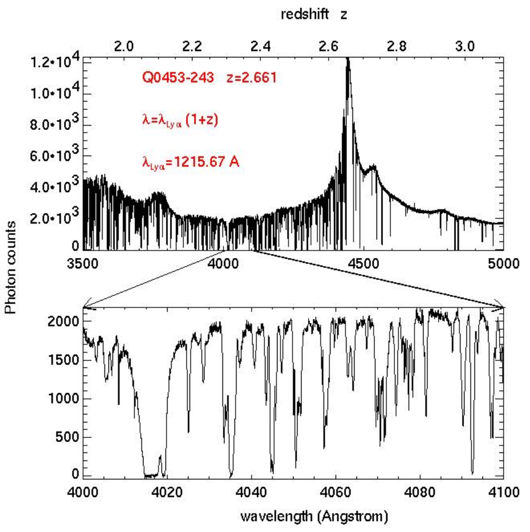

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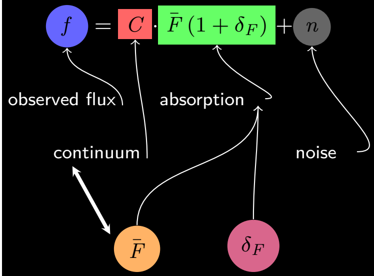

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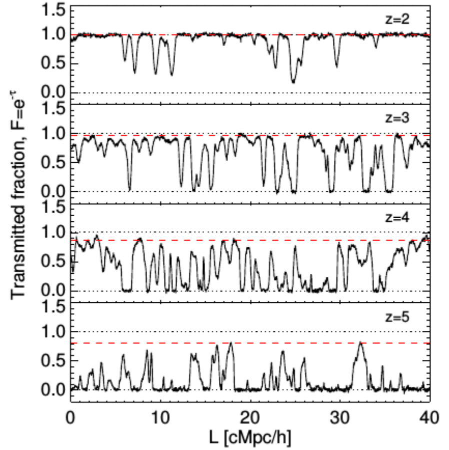

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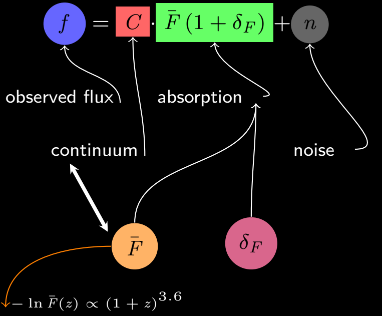

$$f = C \cdot \bar{F}\left(1+\delta_F\right) + n$$

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noise

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δ_F

$-\ln \bar{F}(z) \propto (1+z)^{3.6}$

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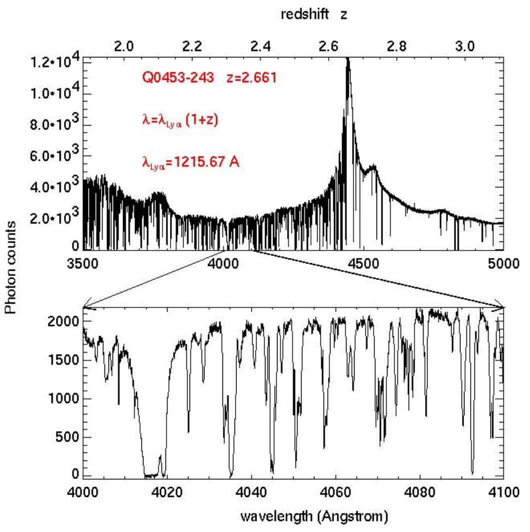

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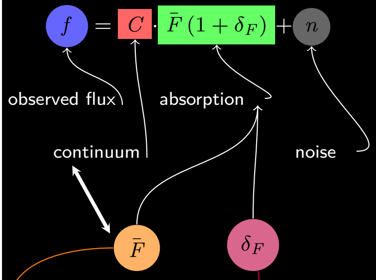

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$$\langle \delta_F(x)\delta_F(x+r)\rangle \equiv \xi_F(r)$$

$$\xi_F(r) = \frac{1}{2\pi}\int P_F(k)e^{-ikr}\,dk$$

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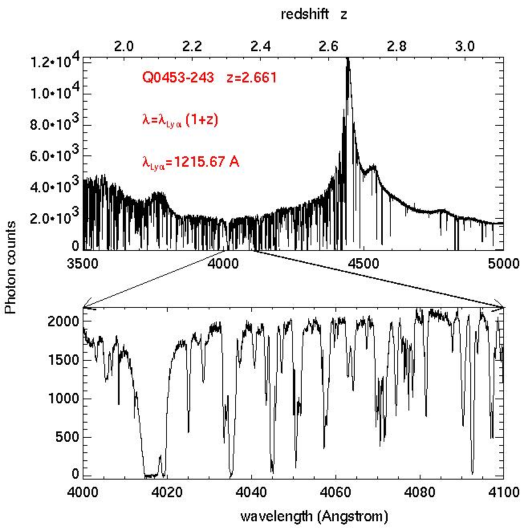

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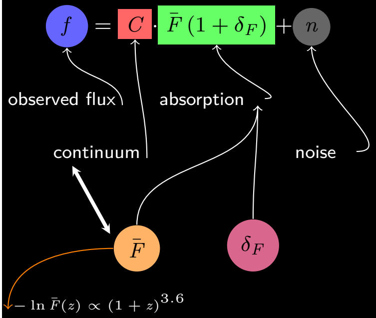

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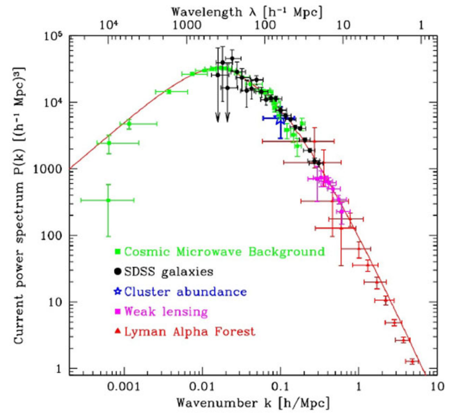
1D

Matter $\leftrightarrow$ Lyman-α

3D: Matter Power spectrum $P_m(k,z)$



Matter ↔ Lyman-α

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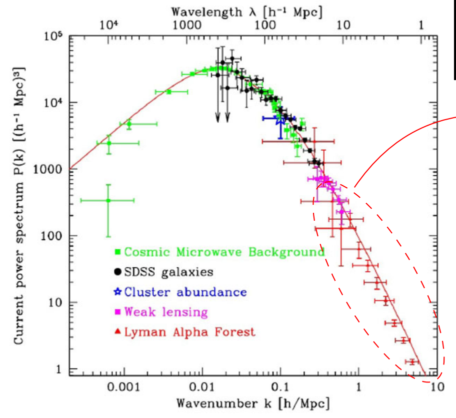
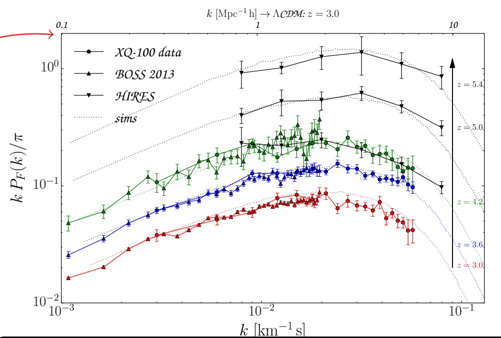


1D: Flux Power spectrum $P_F(k,z)$



1D: small scales, gas physics, m_{wdm}, ...

$F(\rho_g)$: Complex non-linear relationship

Flux fluctuations in Lyα forest trace matter density fluctuations

$$F = \exp\left[-\tau(\delta)\right]$$

- Intergalactic medium (IGM) is mainly highly ionized hydrogen gas (Gunn & Petterson)
- UV photo-ionization in equilibrium with recombination
- Data & simulations suggest the state of IGM: 10^4 K and low densities $10^{-4}\ cm^{-3}$
- Equation of state of the IGM can be approximately described by $T \propto \rho^\gamma$

Highly nonlinear relation between flux and density

$$F = \exp\left[-A\,(1+\delta)^p\right]$$

But that is not all... Temperature + peculiar velocity effects:

strength of the UV background

peculiar velocity shift

$$F(v) = \exp\left[-A(\bar{z};\Omega_i)\int ds\,\left(1+\delta_b(s)\right)^2\,T(s)^{-0.7}\,\Gamma^{-1}_{\gamma,HI}\,V\left(v-s-v_p(s);T(s)\right)\right]$$

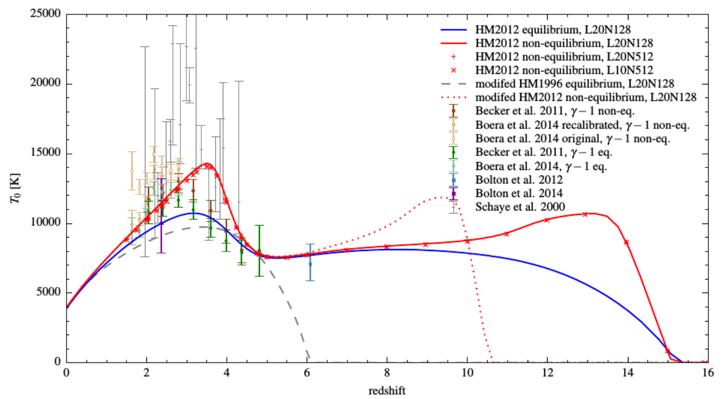
UV photoion. equil. is 2 body process

and has T depend.

Line profile with broadening:
Doppler, pressure, ...

$F(\rho_g)$: Complex non-linear relationship

Flux



- Petterson)
-
- cm^{-3}
-

High

But t

strength of the UV background

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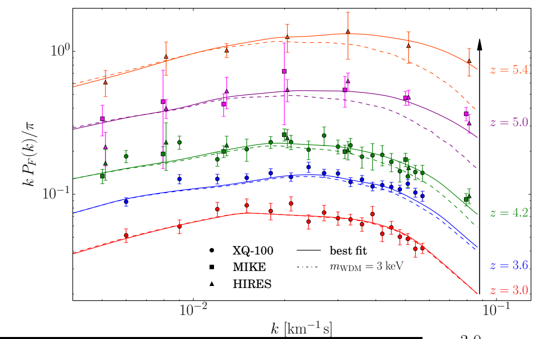
WDM mass constraints



Low-z data:

XQ-100 ($3 < z < 4.2$)

High-z data:

HIRES/MIKE ($4.2 < z < 5.4$)

Typical DM mass:

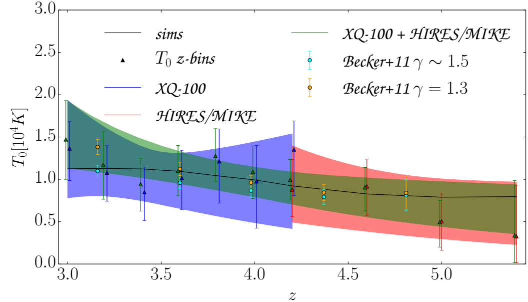
$m_{\rm WDM} \sim 2 - 3$ keV

$T_0(z)$ is power-law - Realistic prior

$\rightarrow m_{\rm WDM} > 5.3$ keV @ 2σ

$T_0(z)$ free + $\dfrac{\partial T_0}{\partial z}$ bounded - Simple physical prior

$\rightarrow m_{\rm WDM} > 3.5$ keV @ 2σ



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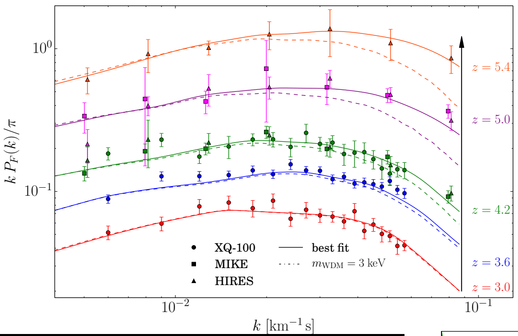

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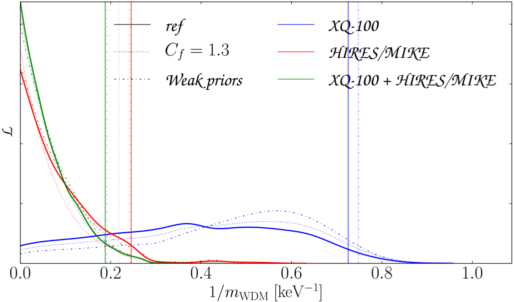
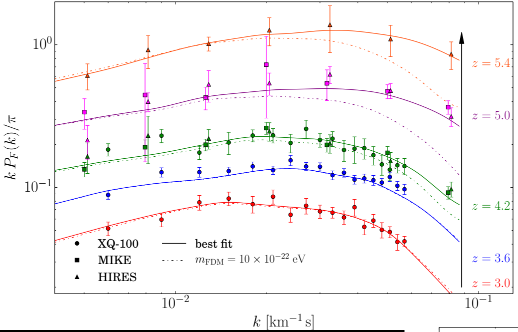


FDM mass constraints



Results later confirmed by independent groups:

Yeche et al. 2017 (WDM)

Armengaud et al. 2017 (FDM)

Garzilli et al. 2018 (WDM - ν_s)

Typical DM mass:

$m_{\rm FDM} \sim 1 - 10 \ \times \ 10^{-22}$ eV

$T_0(z)$ is power-law - Realistic prior

$\rightarrow \boxed{m_{\rm FDM} > 37.5 \ \times \ 10^{-22} \ {\rm eV}}$ @ 2σ

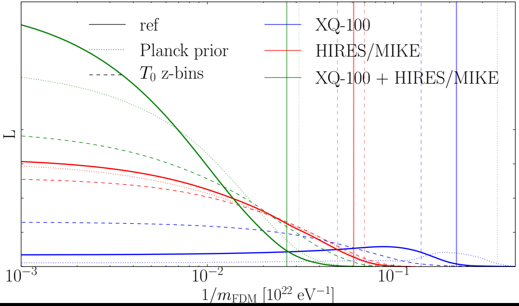
$T_0(z)$ free + $\dfrac{\partial T_0}{\partial z}$ bounded - Simple physical prior

$\rightarrow \boxed{m_{\rm FDM} > 20.4 \ \times \ 10^{-22} \ {\rm eV}}$ @ 2σ

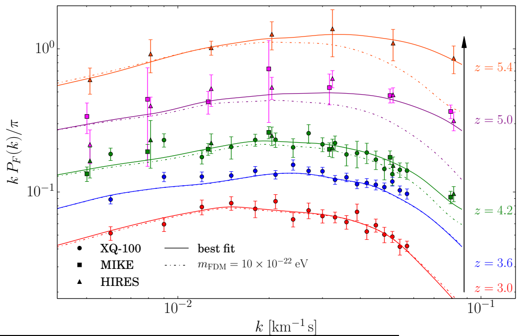
FDM + Quantum Pressure - Simple physical prior

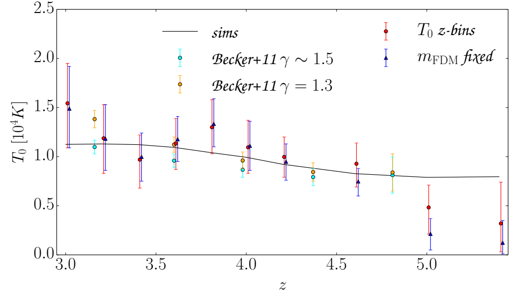
$\rightarrow \boxed{m_{\rm FDM} > 21.1 \ \times \ 10^{-22} \ {\rm eV}}$ @ 2σ

Nori, Murgia, VI, Baldi, Viel (2018)



How cold is too cold?





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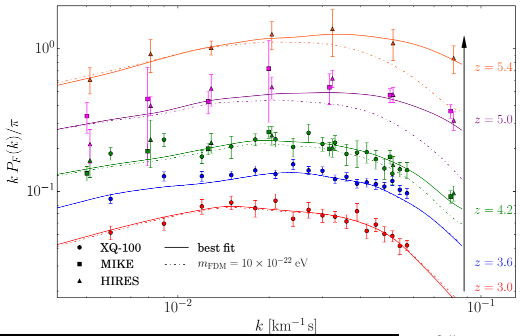

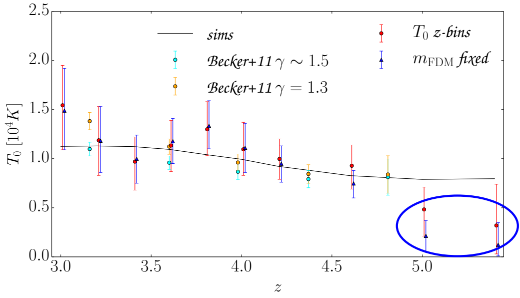

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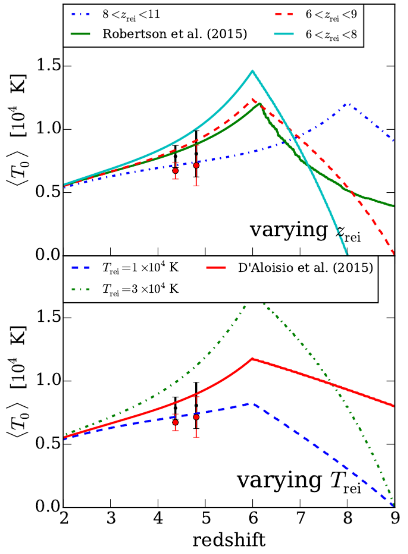
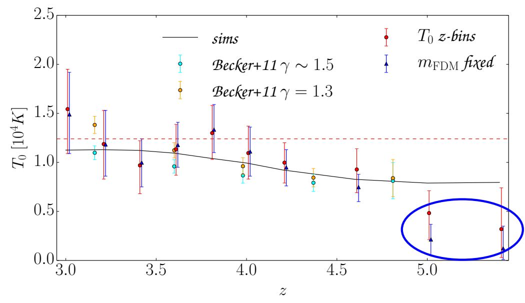


Simple model:

- instantaneous H reionisation at $z_{\rm rei} = 9$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 0$
- Compton cooling + adiabatic expansion

$$T_0(z = 5.0) = 12,400 \text{ K}$$

McQuinn & Upton Sanderback (2015), Upton Sanderback et al. (2016)



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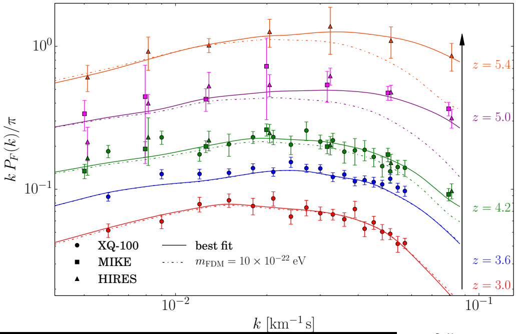

Simple model:

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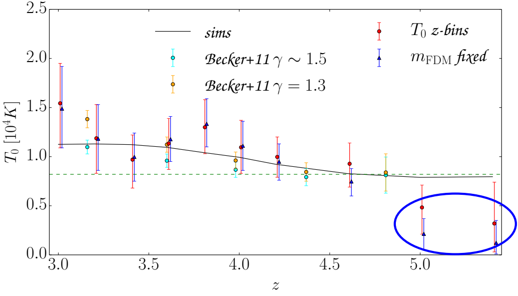
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 2$
- Compton cooling + adiabatic expansion

$$T_0(z = 5.0) = 8,200\ \mathrm{K}$$

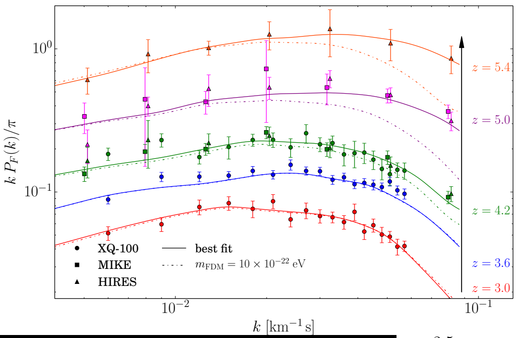
McQuinn & Upton Sanderback (2015),
Upton Sanderback et al. (2016)

Other things assumed:

- T fluctuations increase above this temperature
- He I and He II photo-heating only increases the temperature
- H II, He III recombination cooling decreases temperature by $\sim$ few %
- Planck ΛCDM Cosmology
- $T_{rei} = 10,000$ K (more realistic would be $20,000$ K)



How cold is too cold?



Simple model:

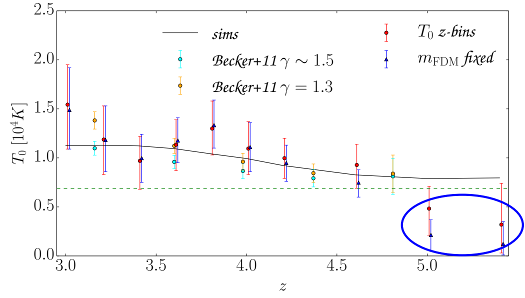
- instantaneous H reionisation at $z_{\mathrm{rei}} = 15$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 2$
- Compton cooling + adiabatic expansion

$$T_0(z = 5.0) = 6,900\ \mathrm{K}$$

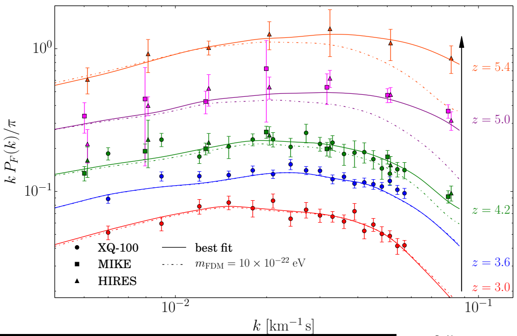
McQuinn & Upton Sanderback (2015),
Upton Sanderback et al. (2016)

Other things assumed:

- T fluctuations increase above this temperature
- He I and He II photo-heating only increases the temperature
- H II, He III recombination cooling decreases temperature by $\sim$ few %
- Planck ΛCDM Cosmology
- $T_{rei} = 10,000$ K (more realistic would be $20,000$ K)



How cold is too cold?



Simple model:

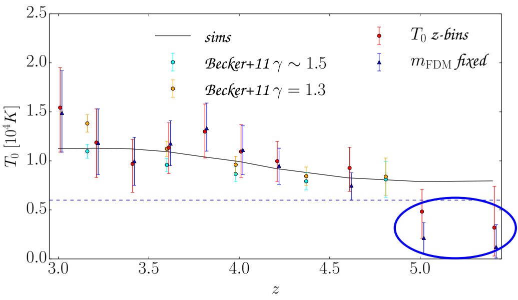
- instantaneous H reionisation at $z_{\rm rei} = 15$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 3$
- Compton cooling + adiabatic expansion

$T_0(z = 5.0) = 6,000$ K

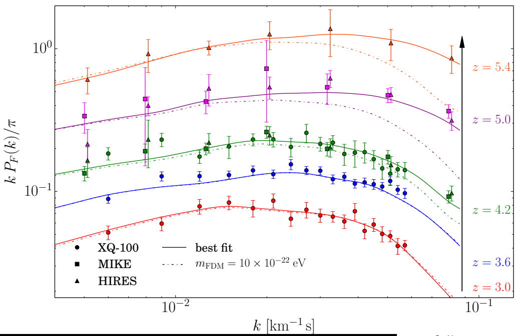
McQuinn & Upton Sanderback (2015),
Upton Sanderback et al. (2016)

Other things assumed:

- T fluctuations increase above this temperature
- He I and He II photo-heating only increases the temperature
- H II, He III recombination cooling decreases temperature by $\sim$ few %
- Planck ΛCDM Cosmology
- $T_{rei} = 10,000$ K (more realistic would be $20,000$ K)



How cold is too cold?



Simple model:

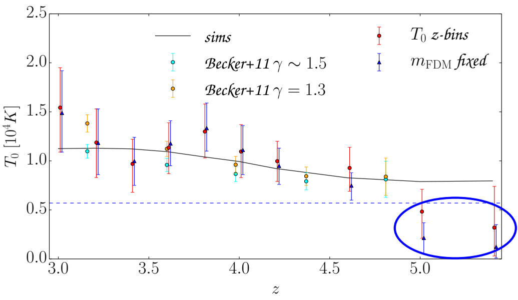
- instantaneous H reionisation at $z_{\rm rei} = 20$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 3$
- Compton cooling + adiabatic expansion

$T_0(z = 5.0) = 5,700$ K

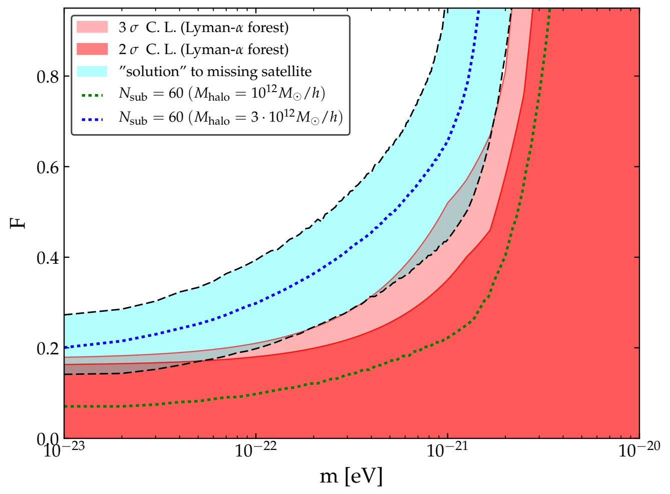
McQuinn & Upton Sanderback (2015), Upton Sanderback et al. (2016)

Other things assumed:

- T fluctuations increase above this temperature
- He I and He II photo-heating only increases the temperature
- H II, He III recombination cooling decreases temperature by $\sim$ few %
- Planck ΛCDM Cosmology
- $T_{rei} = 10,000$ K (more realistic would be $20,000$ K)



Overlapping constraints with different probes

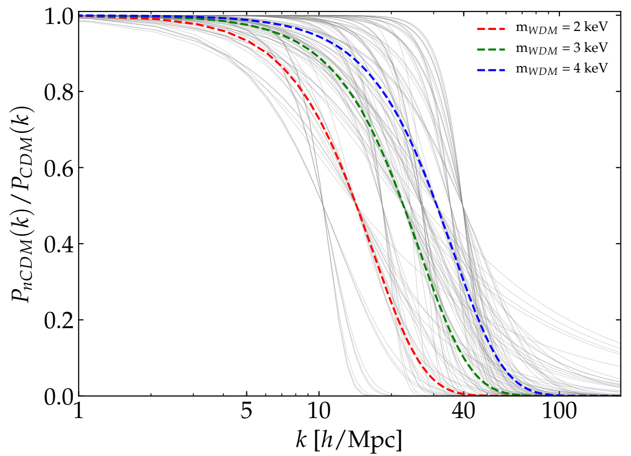


with T. Kobayashi
(SISSA)

General non-CDM models

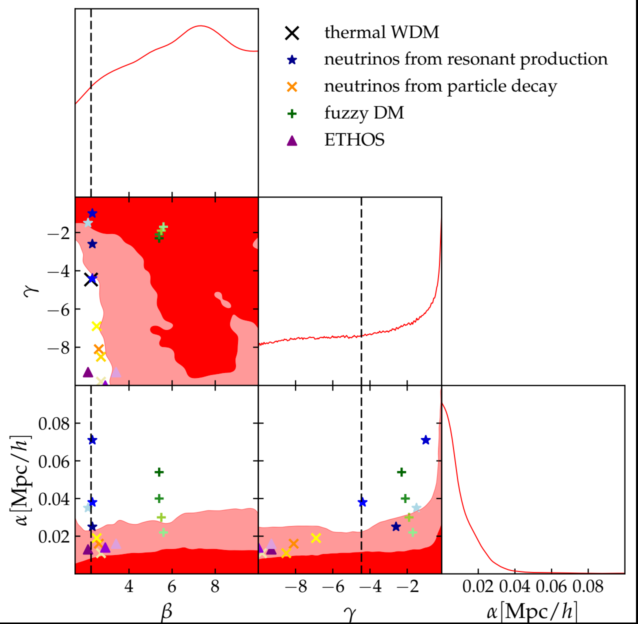
General transfer function for DM: $T(k) = \sqrt{\frac{P_{\mathrm{nCDM}}}{P_{\mathrm{CDM}}}} = \left[1 + (\alpha k)^{\beta}\right]^{\gamma}$,

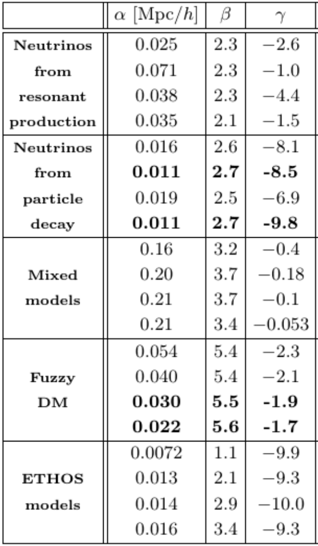
E.g. for thermal WDM: $\beta = 2.24$, $\gamma = -4.46$, $\alpha \propto 0.049 \left(\frac{m_{\mathrm{WDM}}}{1\ \mathrm{keV}}\right)^{-1.11}\ h^{-1}\ \mathrm{Mpc}$



with R. Murgia
(SISSA)

Constraints on the shape of the nCDM $T(k)$





	α [Mpc/h]	β	γ
Neutrinos from resonant production	0.025	2.3	−2.6
	0.071	2.3	−1.0
	0.038	2.3	−4.4
	0.035	2.1	−1.5
Neutrinos from particle decay	0.016	2.6	−8.1
	0.011	**2.7**	**-8.5**
	0.019	2.5	−6.9
	0.011	**2.7**	**-9.8**
Mixed models	0.16	3.2	−0.4
	0.20	3.7	−0.18
	0.21	3.7	−0.1
	0.21	3.4	−0.053
Fuzzy DM	0.054	5.4	−2.3
	0.040	5.4	−2.1
	0.030	**5.5**	**-1.9**
	0.022	**5.6**	**-1.7**
ETHOS models	0.0072	1.1	−9.9
	0.013	2.1	−9.3
	0.014	2.9	−10.0
	0.016	3.4	−9.3

What next?

With conservative thermal history:

$m_{\rm WDM} > 2.1~{\rm keV}~(2\sigma)$ (HIRES/MIKE) $\rightarrow m_{\rm WDM} > 3.5~{\rm keV}~(2\sigma)$ (HIRES/MIKE + XQ-100)

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$m_{\mathrm{WDM}} > 2.1$ keV (2σ) (HIRES/MIKE) → $m_{\mathrm{WDM}} > 3.5$ keV (2σ) (HIRES/MIKE + XQ-100)

New high-z QSOs in the future:

DESI (14,000 sq. deg.) ~ 25 QSO spectra at $z > 4.0$ (and $m < 18.5$)

SkyMapper (17,200 sq. deg.) ~ 30 QSO spectra at $z > 4.0$ (and $m < 18.5$)

LSST (30,000 sq. deg.) ~ 55 QSO spectra at $z > 4.0$ (and $m < 18.5$)

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QSO LF
Manti et al. 2016

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$\sim 8\mathrm{h}$ exposure time
@ Keck HIRES

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@ Keck HIRES

→ > 100 high-z $(4 < z < 6)$ QSOs in ~ 5 yrs

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QSO LF
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$\rightarrow$ > 100 high-z $(4 < z < 6)$ QSOs in ~ 5 yrs

with ELTs $\rightarrow$ > 1000 QSOs

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$\sim 8\mathrm{h}$ exposure time
@ Keck HIRES

$\rightarrow > 100$ high-z $(4 < z < 6)$ QSOs in ~ 5 yrs

with ELTs $\rightarrow > 1000$ QSOs

How much do we gain?

Simple forecast

With conservative thermal history:

$m_{\mathrm{WDM}} > 2.1$ keV (2σ) (HIRES/MIKE) → $m_{\mathrm{WDM}} > 3.5$ keV (2σ) (HIRES/MIKE + XQ-100)

↓

25 QSOs: $m_{\mathrm{WDM}} > 2.3$ keV

↓

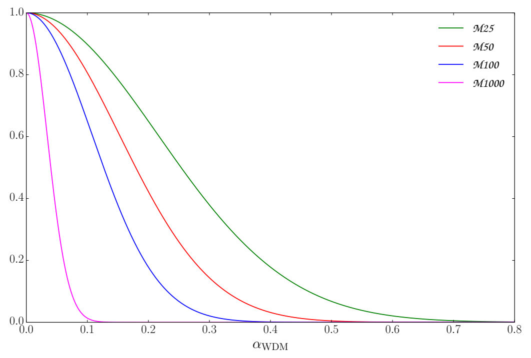
50 QSOs: $m_{\mathrm{WDM}} > 3.3$ keV

↓

100 QSOs: $m_{\mathrm{WDM}} > 4.6$ keV

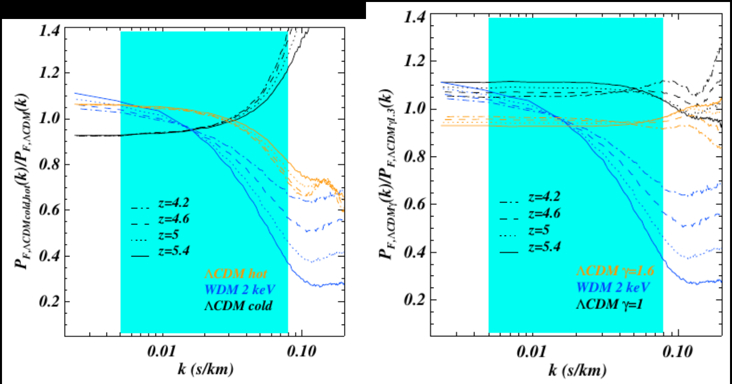
↓

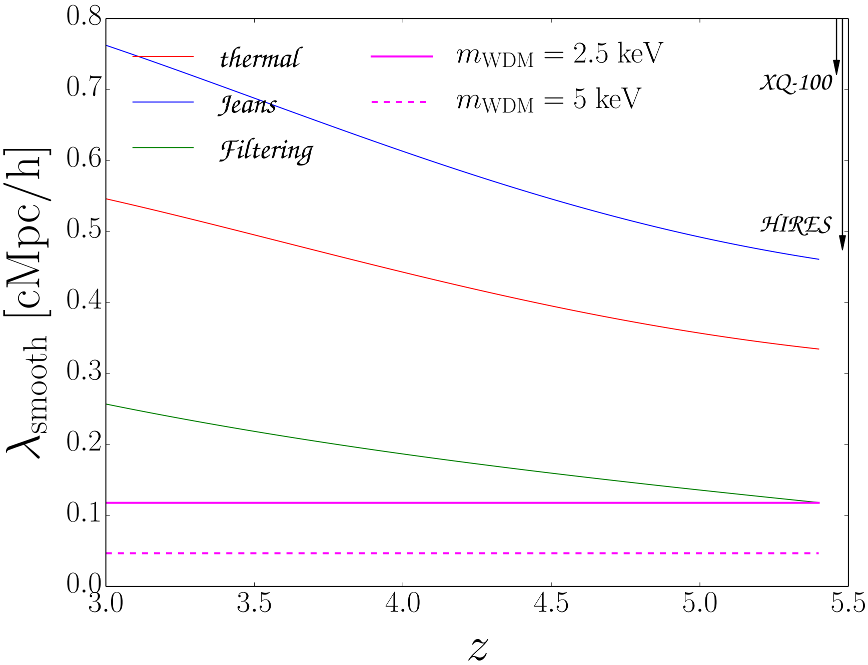
1000 QSOs: $m_{\mathrm{WDM}} > 14.7$ keV



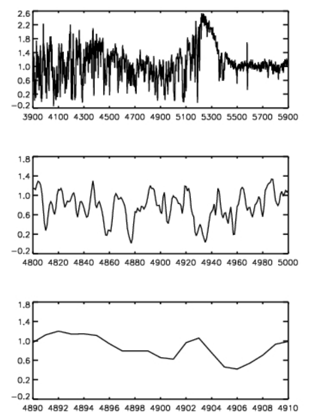
Conclusions

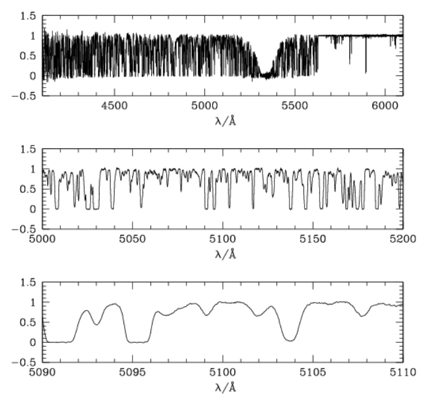
- Lyman-α forest is a unique probe of the IGM (in both redshift range and small scales access)
- Robust constraints on DM models (e.g. WDM, FDM)
  - astro-ph/1702.01764, astro-ph/1703.04683
- WDM/FDM mass values from "local" Universe leads to unphysically small high-z temperature
- WDM/FDM parameter space greatly constrained: it is hard to solve missing satellite problem and satisfy Lyα constraints
- Possibility to study DM model extensions (e.g. Quantum Pressure for FDM, production mechanisms of WDM)
  - astro-ph/1708.00015, astro-ph/1806.08371, astro-ph/1809.09619
- Statistically dominated at high-z – need more high quality QSO sightlines $z > 4.5$

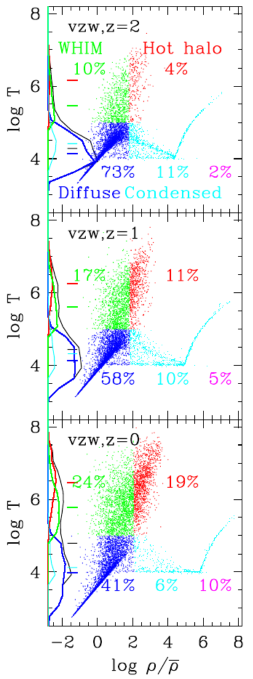

1.4
1.2
1.0
0.8
0.6
0.4
0.2
$P_{F,\Lambda CDM\,cold,hot}(k)/P_{F,\Lambda CDM}(k)$
z=4.2
z=4.6
z=5
z=5.4
ΛCDM hot
WDM 2 keV
ΛCDM cold
0.01
0.10
k (s/km)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$P_{F,\Lambda CDM\gamma}(k)/P_{F,\Lambda CDM\gamma 1.3}(k)$
z=4.2
z=4.6
z=5
z=5.4
ΛCDM γ=1.6
WDM 2 keV
ΛCDM γ=1
0.01
0.10
k (s/km)

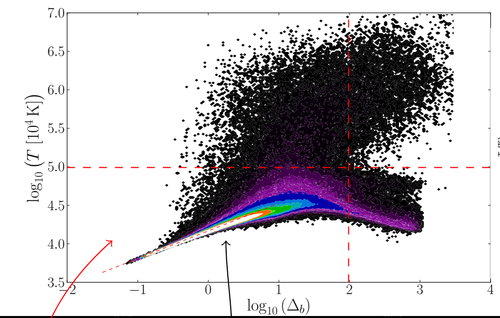


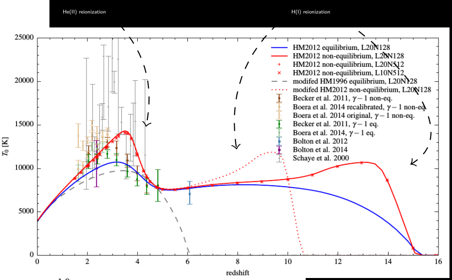
$\lambda_{\rm smooth}$ [cMpc/h]
z
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
3.0
3.5
4.0
4.5
5.0
5.5
thermal
Jeans
Filtering
$m_{\rm WDM} = 2.5$ keV
$m_{\rm WDM} = 5$ keV
XQ-100
HIRES


2.6
2.2
1.8
1.4
1.0
0.6
0.2
−0.2
3900 4100 4300 4500 4700 4900 5100 5300 5500 5700 5900
1.8
1.4
1.0
0.6
0.2
−0.2
4800 4820 4840 4860 4880 4900 4920 4940 4960 4980 5000
1.8
1.4
1.0
0.6
0.2
−0.2
4890 4892 4894 4896 4898 4900 4902 4904 4906 4908 4910


1.5
1
0.5
0
−0.5
4500 5000 5500 6000
λ/Å
1.5
1
0.5
0
−0.5
5000 5050 5100 5150 5200
λ/Å
1.5
1
0.5
0
−0.5
5090 5095 5100 5105 5110
λ/Å


vzw,z=2
WHIM
Hot halo
10%
4%
73%
11%
2%
Diffuse
Condensed
vzw,z=1
17%
11%
58%
10%
5%
vzw,z=0
24%
19%
41%
6%
10%
log T
8
6
4
−2
0
2
4
6
8
log $\rho/\overline{\rho}$

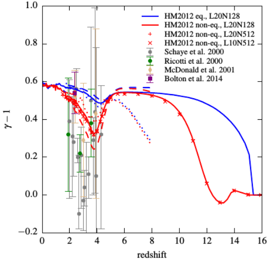


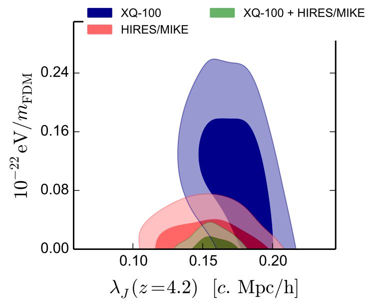


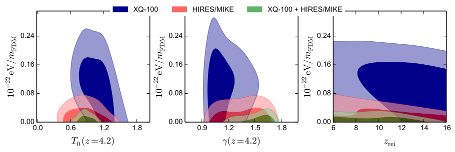
$$\Delta_b = \frac{\rho_b}{\bar{\rho}_b} = \delta_b + 1$$

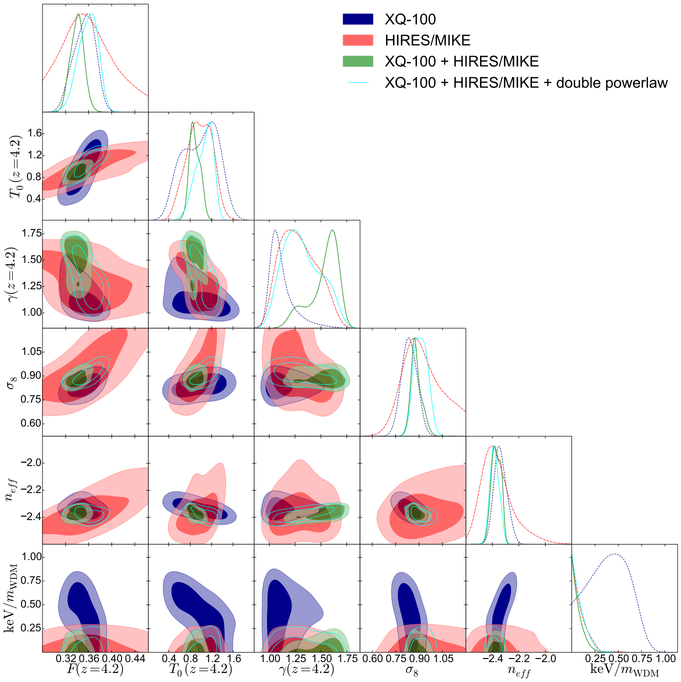
$$T = T_0 \Delta_b^{\gamma-1}$$

80-90% of baryons at $z \sim 3-4$

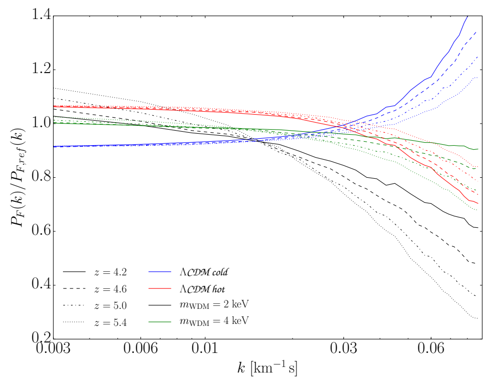



XQ-100
XQ-100 + HIRES/MIKE
HIRES/MIKE
$10^{-22}\mathrm{eV}/m_{\mathrm{FDM}}$
0.24
0.16
0.08
0.00
0.10
0.15
0.20
$\lambda_J(z\!=\!4.2)$ [$c.$ Mpc/h]


XQ-100
HIRES/MIKE
XQ-100 + HIRES/MIKE
$10^{-22}\,\mathrm{eV}/m_{\mathrm{FDM}}$
0.00
0.08
0.16
0.24
0.0
0.6
1.2
1.8
$T_0(z=4.2)$
0.9
1.2
1.5
1.8
$\gamma(z=4.2)$
6
8
10
12
14
16
z_{rei}

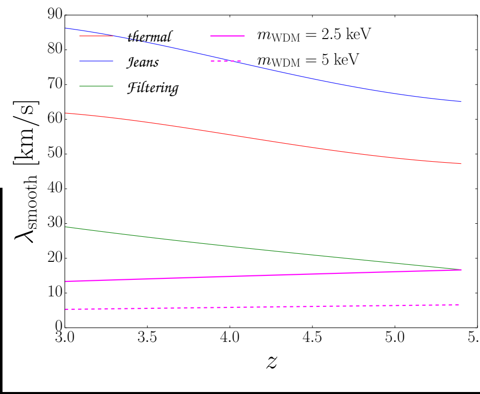

XQ-100
HIRES/MIKE
XQ-100 + HIRES/MIKE
XQ-100 + HIRES/MIKE + double powerlaw
$T_0(z=4.2)$
1.6
1.2
0.8
0.4
$\gamma(z=4.2)$
1.75
1.50
1.25
1.00
σ_8
1.05
0.90
0.75
0.60
n_{eff}
−2.0
−2.2
−2.4
$\mathrm{keV}/m_{\mathrm{WDM}}$
1.00
0.75
0.50
0.25
0.32 0.36 0.40 0.44
$F(z=4.2)$
0.4 0.8 1.2 1.6
$T_0(z=4.2)$
1.00 1.25 1.50 1.75
$\gamma(z=4.2)$
0.60 0.75 0.90 1.05
σ_8
−2.4 −2.2 −2.0
n_{eff}
0.25 0.50 0.75 1.00
$\mathrm{keV}/m_{\mathrm{WDM}}$

Problem of different smoothing scales

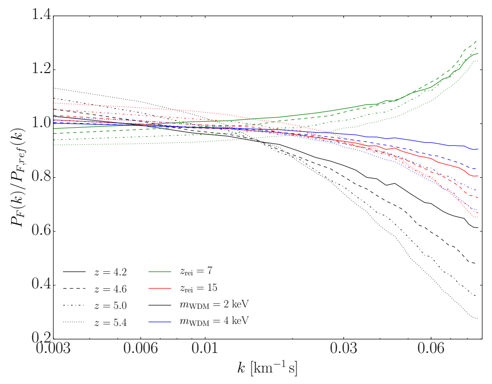


$m_{\rm WDM}, T_0$: different scale dependence

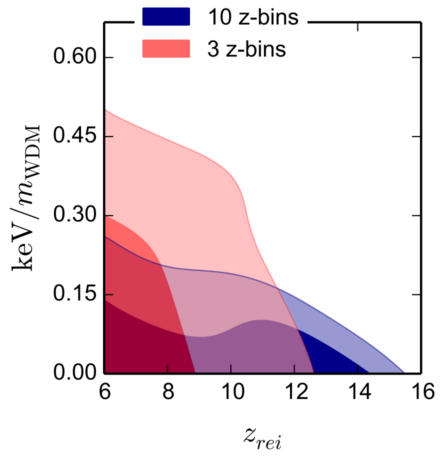
DM and thermal smoothing:
different redshift dependence



Redshift evolution breaks the degeneracies



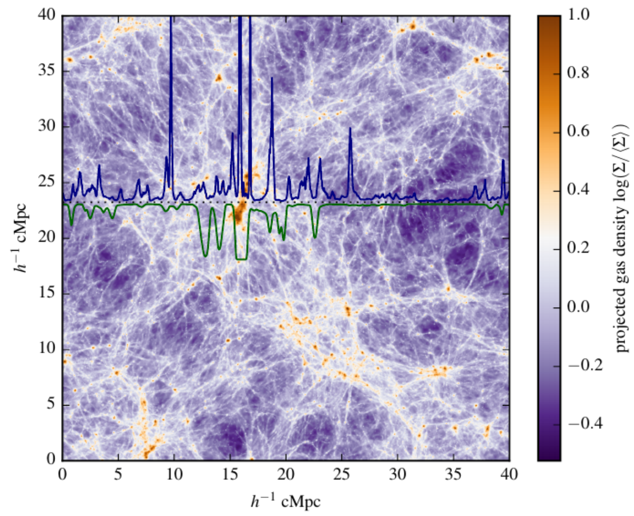
$m_{\rm WDM}, z_{\rm rei}$:
different scale/redshift dependence



10 z-bins: $3.0 - 5.4$

3 z-bins: $4.0, 4.2, 4.6$

Why should we care about IGM?



ρ_g -gas density

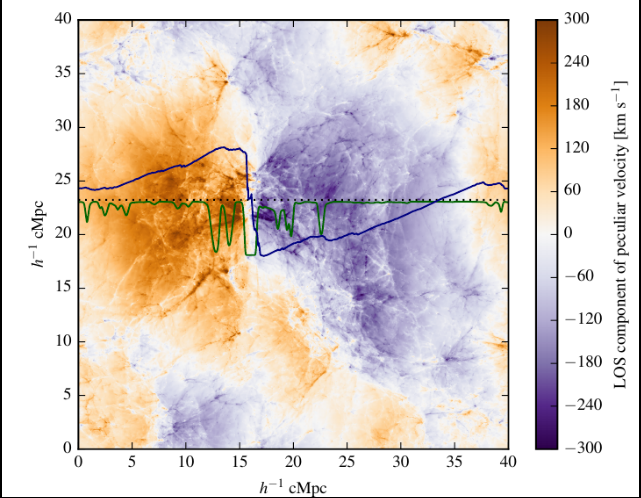
F -observed flux

Flux is a biased tracer of the density:

$$F \sim b\,\rho_g$$

Sensitive to fluctuations, along the line-of-sight, on scales $\sim 0.1 - 10$ Mpc/h

Why should we care about IGM?



peculiar velocity:

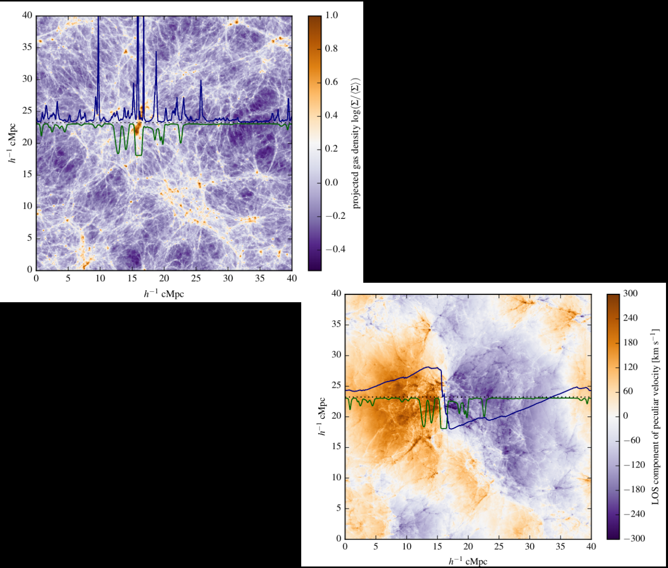
$v_p = v_{\parallel} - H(z)\, r(z)$

F -observed flux

Flux is a biased tracer of the density:

$$F \sim b\, \rho_g$$

Why should we care about IGM?



ρ_g -Gas density

F -Observed flux

v_p - peculiar velocity

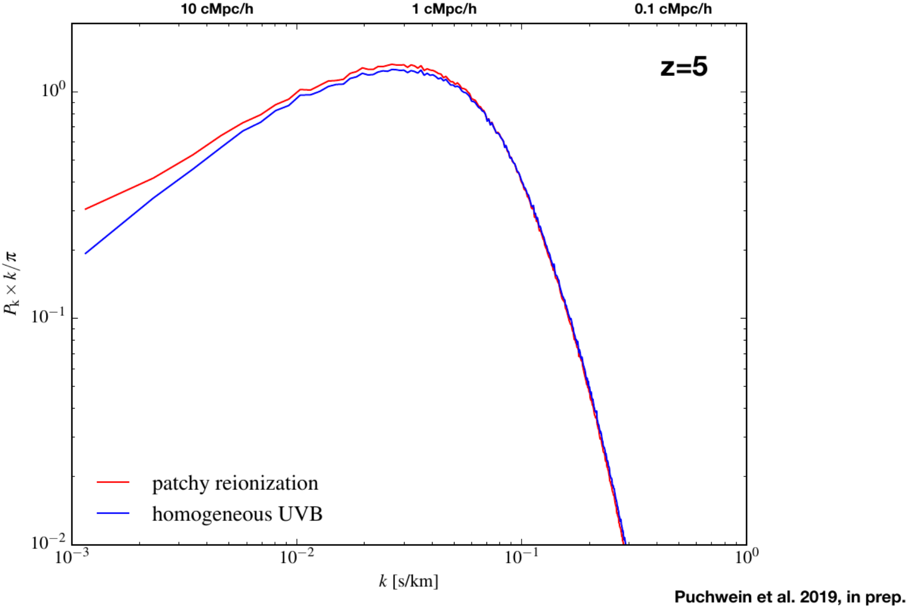
Flux is a Biased tracer of the density:

$$F \sim b\,\rho_g + b_v\,\nabla v_p$$

Sensitive to density fluctuations, along the line-of-sight, on scales $\sim 0.1 - 10\ \mathrm{Mpc/h}$

small scales

Effect of HI reionization



Puchwein et al. 2019, in prep.