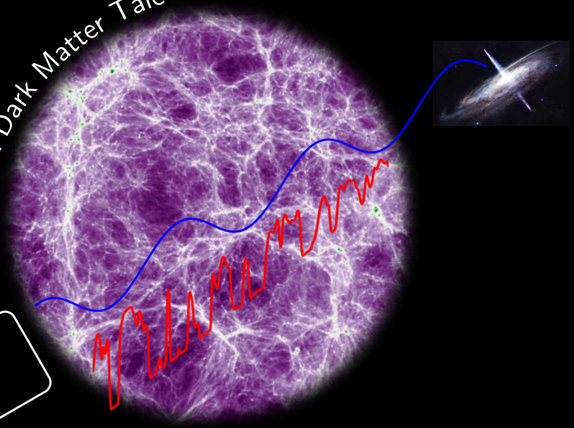
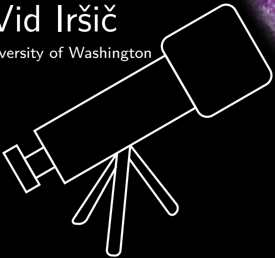
Small scale structure of the IGM:

A Dark Matter Tale





Vid Iršič

@ University of Washington

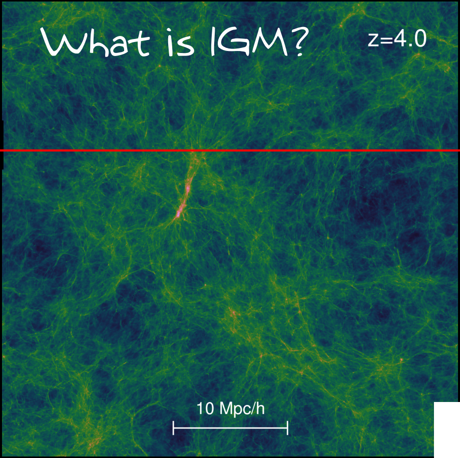
INPA Seminar

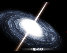
@

Lawrence Berkeley National Laboratory

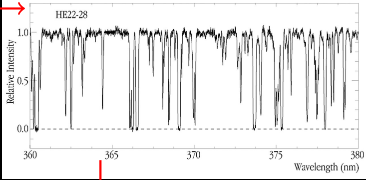
May 24, 2019

What is IGM?

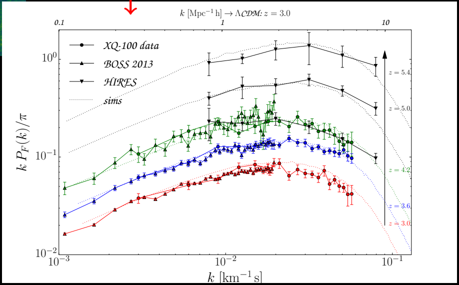




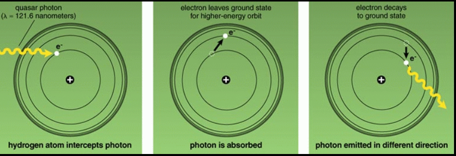
Absorption in Quasar spectra along the line of sight



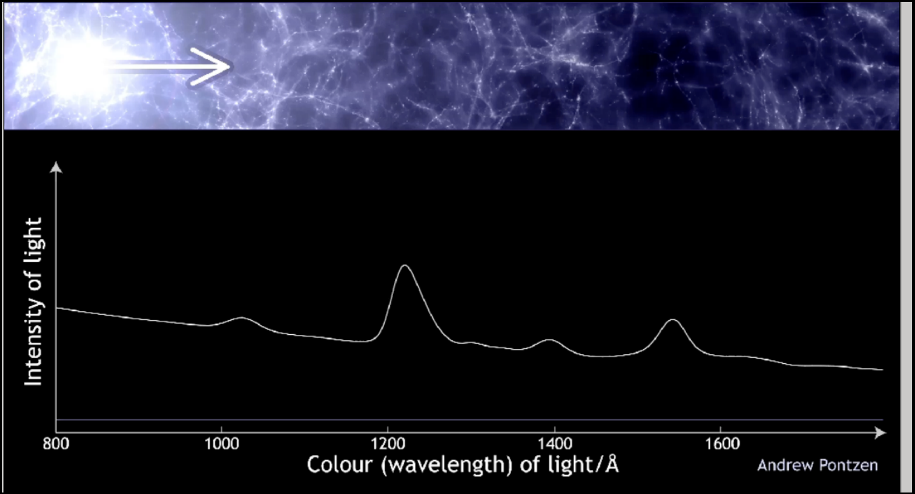
Flux power spectrum



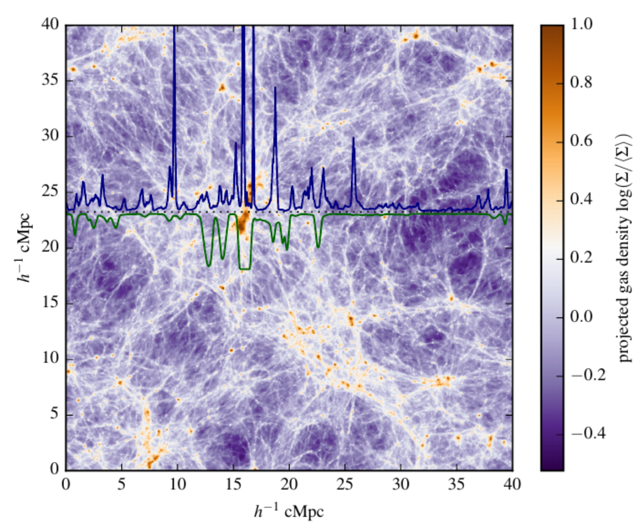
Scattering of the photon on $n = 1 \rightarrow n = 2$ Hydrogen transition (Lyman series)



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 $\sim 0.1 - 10$ Mpc/h

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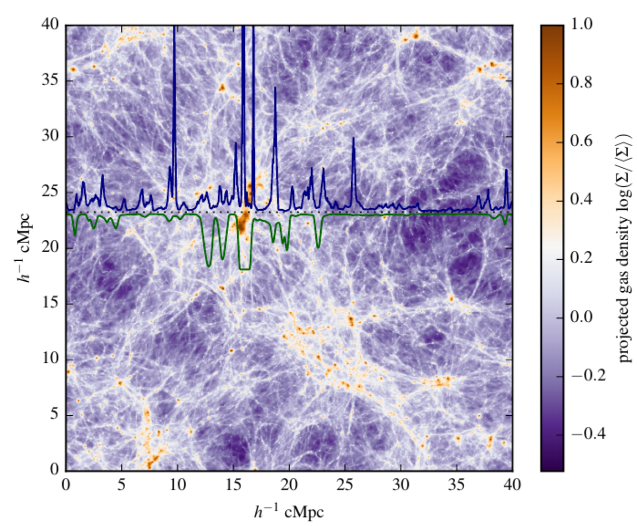

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small scales

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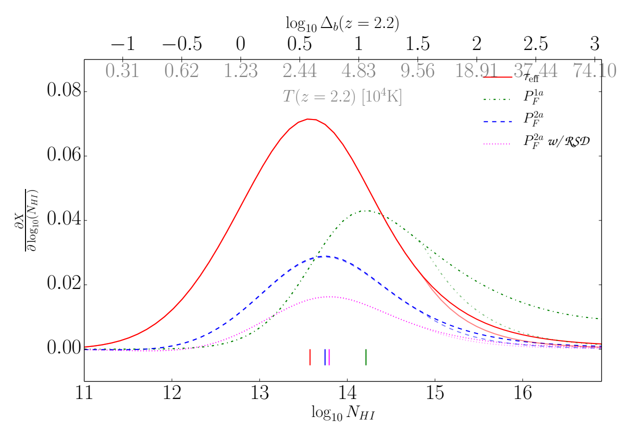


ρ_g -Gas density

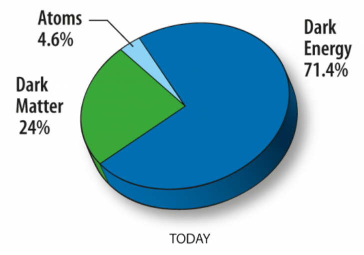
F -Observed flux

Flux is a biased tracer of the density:

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

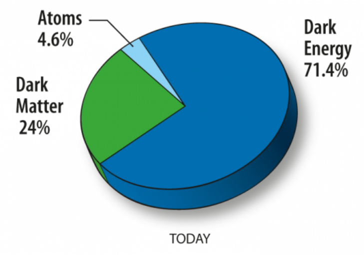
Sensitive to mildly non-linear density fluctuations, along the line-of-sight, on scales $\sim 0.1 - 10\ \mathrm{Mpc/h}$

Cold Dark Matter problems (?)



Cold Dark Matter (CDM):
heavy, non-interactive particle(s) $\rightarrow$ WIMPs

Cold Dark Matter problems (?)



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CDM problems of small-scale physics:

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

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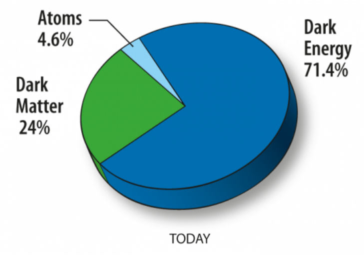

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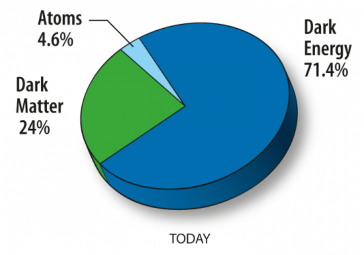

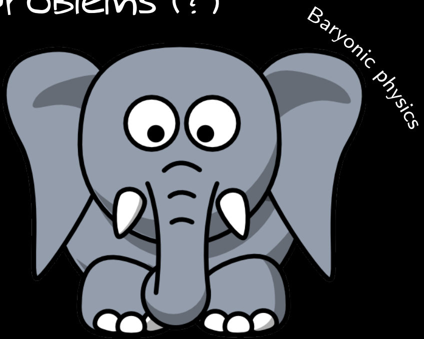

Cold Dark Matter (CDM):
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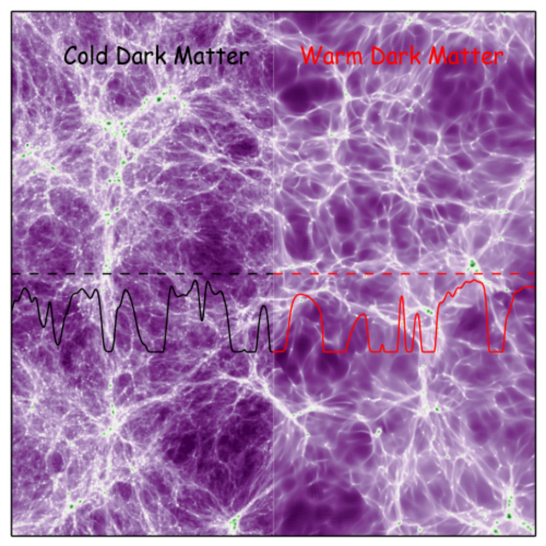
CDM problems of small-scale physics:

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

$\rightarrow$ Alternative DM models (Warm DM, Fuzzy DM, Self-interacting DM, ...)

Non-CDM erases small scale structure

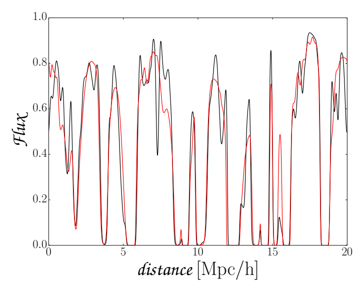


Warm Dark Matter (WDM):
Free-streaming of DM particles
(From the time they decouple
until they become non-relativistic)

Fuzzy Dark Matter (FDM):
de-Broglie wavelength
of ultra-light DM scalar

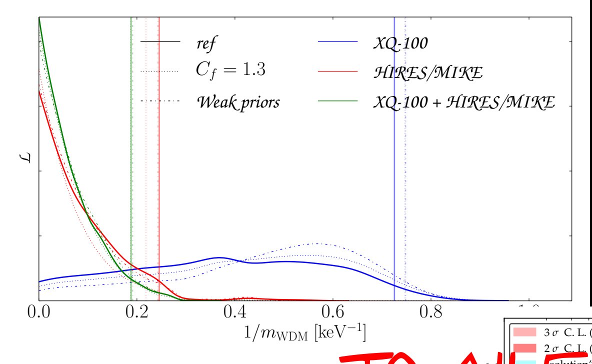
$\Longrightarrow$ erases small scale structure

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



Typical DM particle mass from local small-scale structure

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

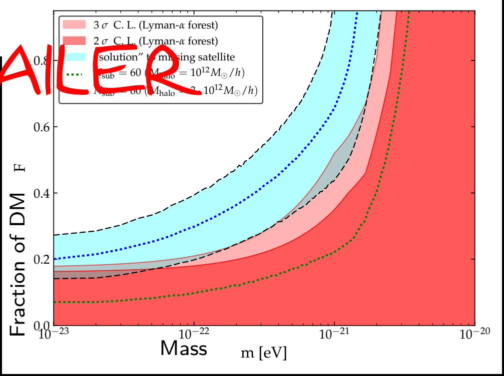


'realistic' thermal history:

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

conservative thermal history model:

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



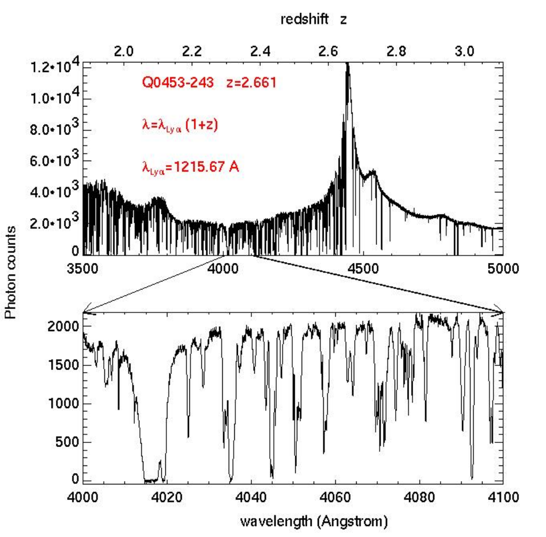
'realistic' thermal history:

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

conservative thermal history model:

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

What do we measure?



Measured quantity:

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

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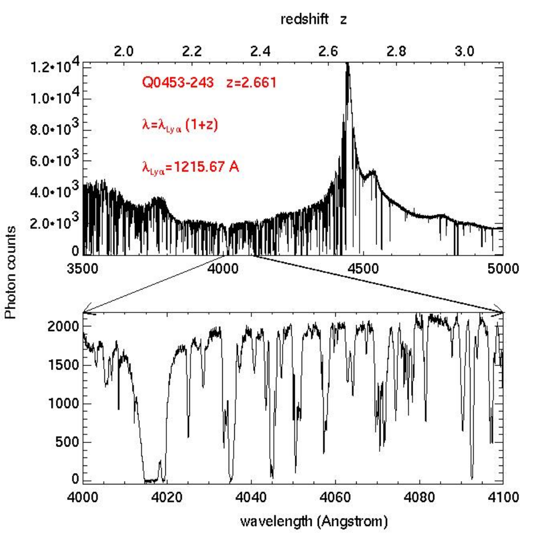

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- f: observed flux
- C: continuum
- $\bar{F}\,(1+\delta_F)$: absorption
- n: noise

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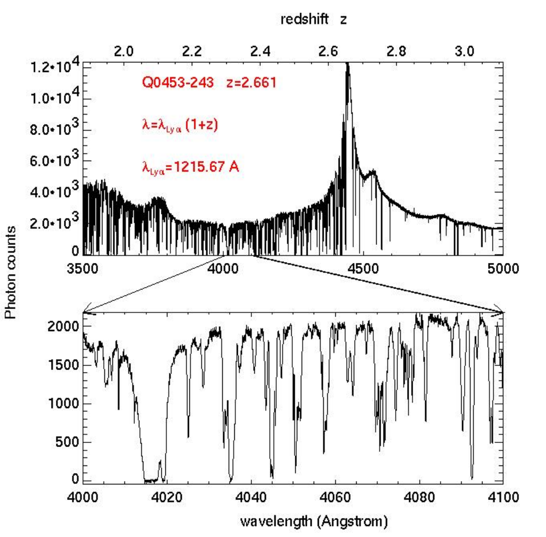

Measured quantity:

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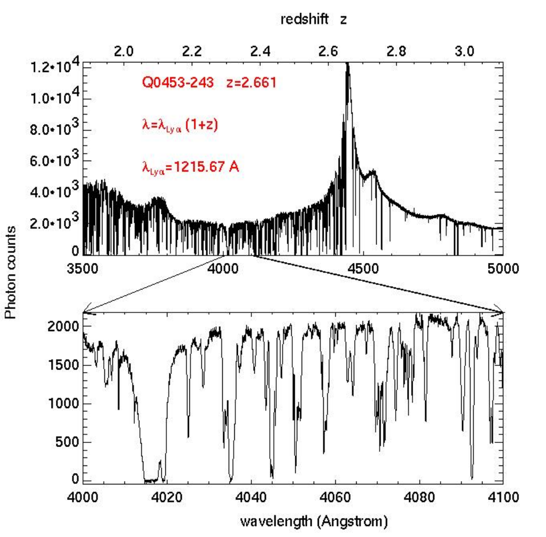
observed flux (f), continuum (C), absorption ($\bar{F}\,(1+\delta_F)$: $\bar{F}$ and δ_F), noise (n)

What do we measure?



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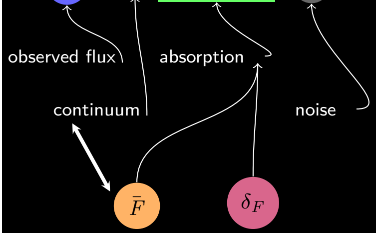

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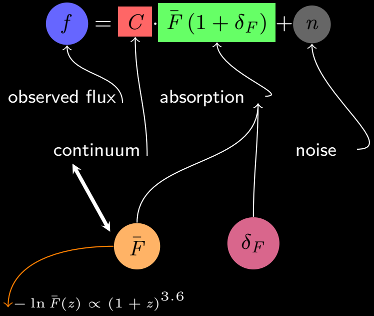

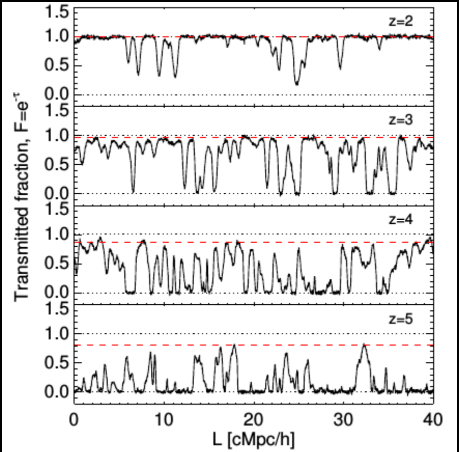

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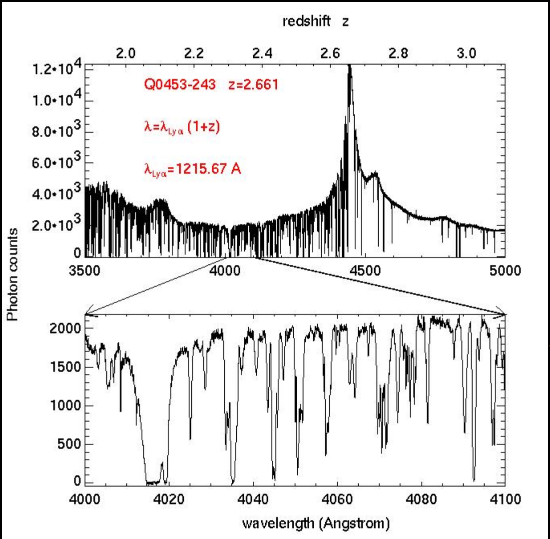


Measured quantity:

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

observed flux — continuum — absorption — noise

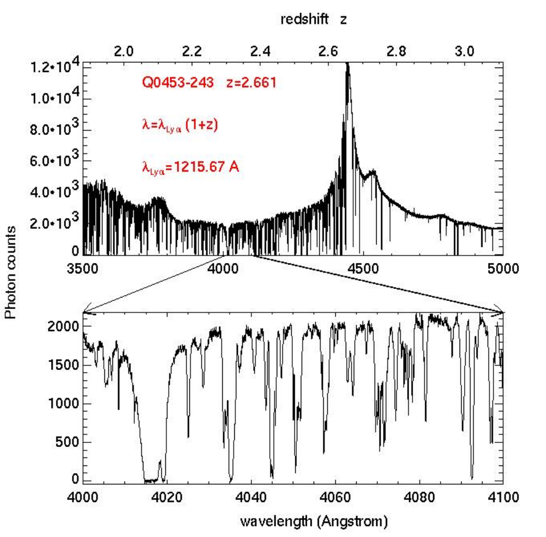
$\bar{F}$ ↔ continuum

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

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

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

What do we measure?



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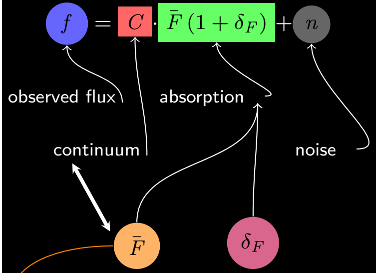

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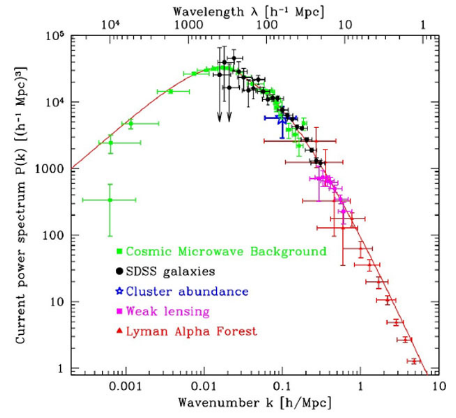
1D

Matter ↔ Lyman-α

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



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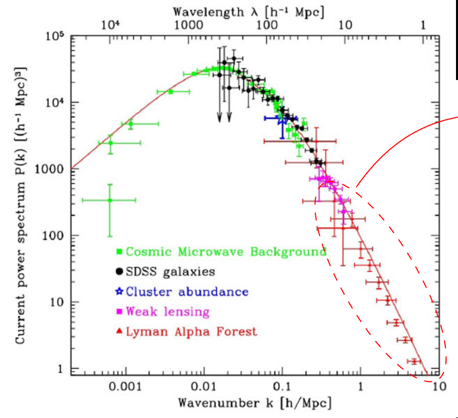
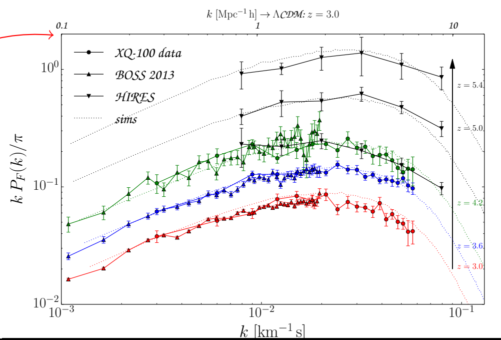


1D: Flux Power spectrum $P_F(k, z)$



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

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

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

strength of the UV background

peculiar velocity shift

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

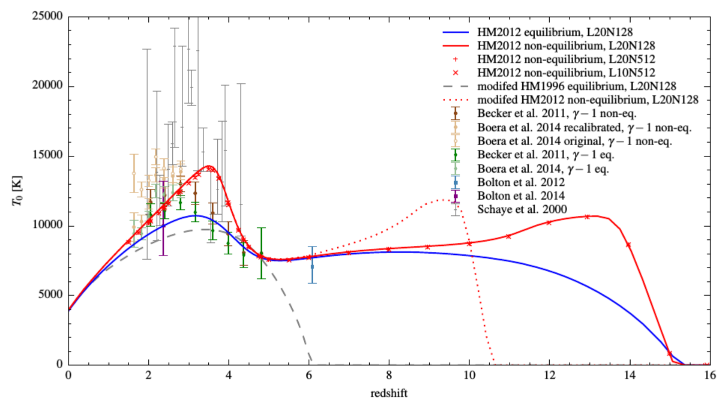
UV photoion. equil. is 2 body process

and has T depend.

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

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

Flux



Petterson)

cm^{-3}

High

But t

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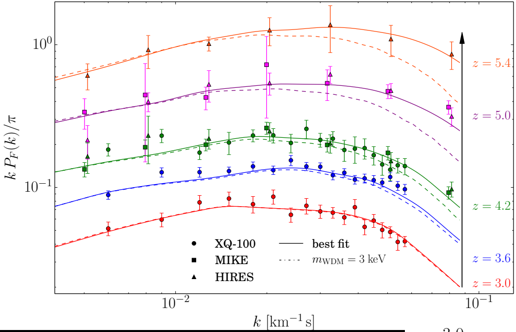
WDM mass constraints



Low-z data:

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

High-z data:

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

Typical DM mass:

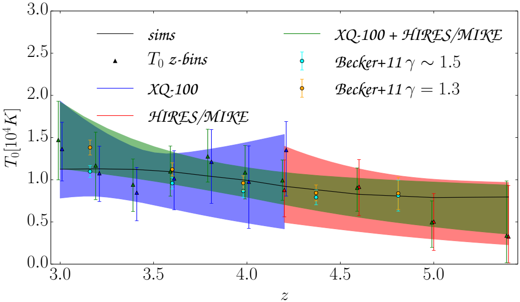
$m_{\rm WDM} \sim 2 - 3$ keV

$T_0(z)$ is power-law

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

$T_0(z)$ free + $\dfrac{\partial T_0}{\partial z}$ bounded

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



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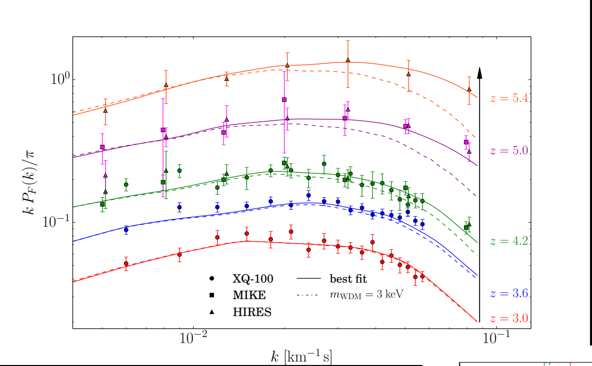

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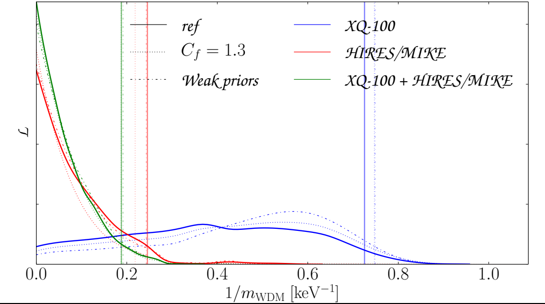
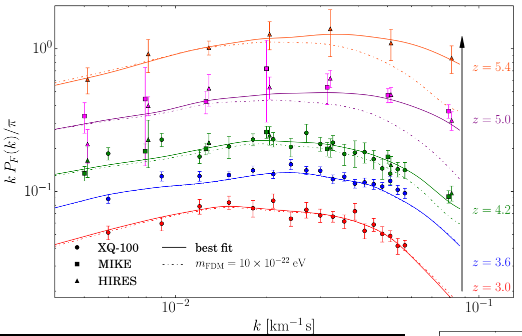


FDM mass constraints



Results later confirmed by independent groups:

Yeche et al. 2017 (WDM)

Armengaud et al. 2017 (FDM)

Typical DM mass:

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

$T_0(z)$ is power-law

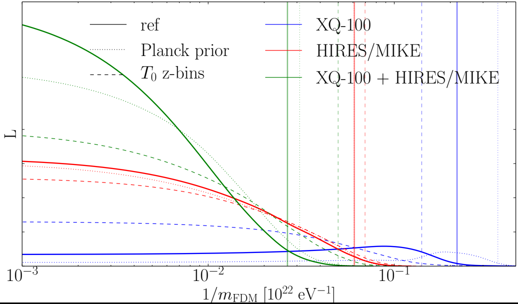
$\rightarrow m_{\rm FDM} > 37.5 \times 10^{-22}$ eV @ 2σ

$T_0(z)$ free + $\dfrac{\partial T_0}{\partial z}$ bounded

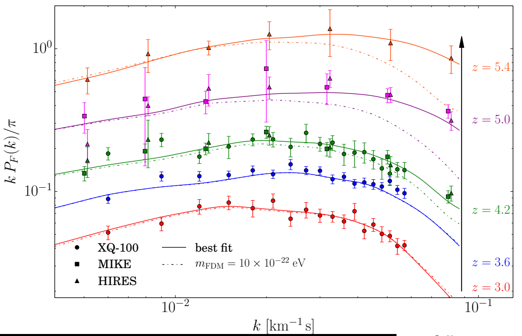
$\rightarrow m_{\rm FDM} > 20.4 \times 10^{-22}$ eV @ 2σ

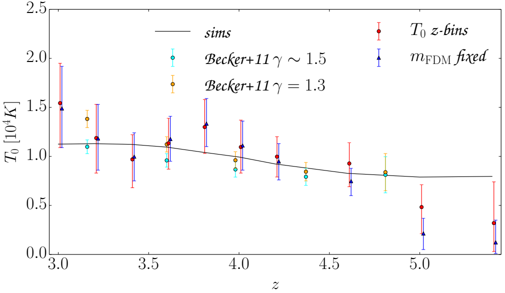
FDM + Quantum Pressure

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



How cold is too cold?





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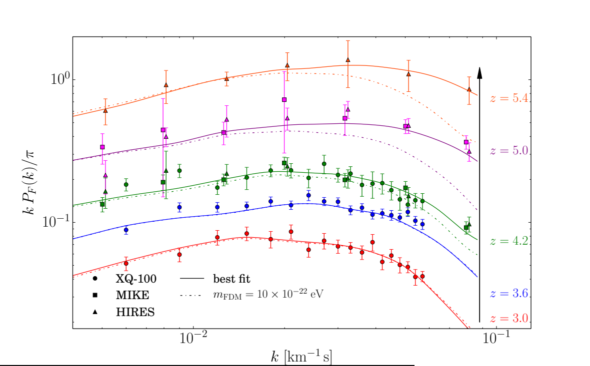

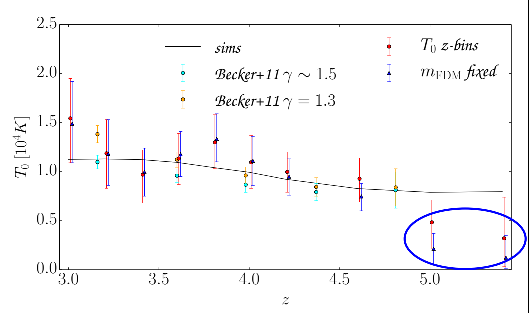

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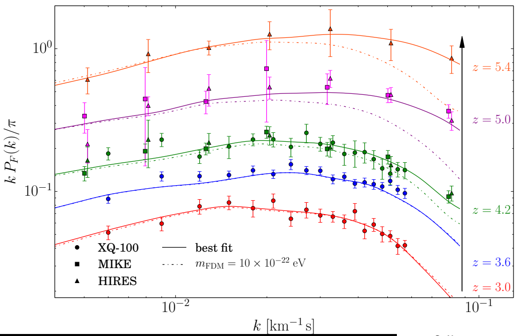


Simple model:

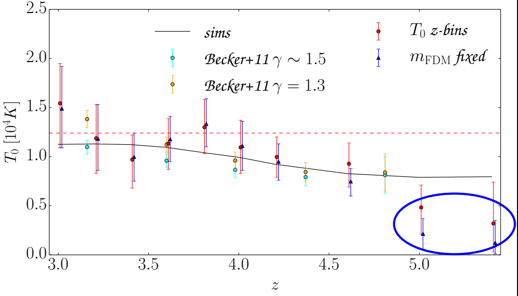
- instantaneous H reionisation at $z_{\rm rei} = 9$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 0$
- Compton cooling + adiabatic expansion

$T_0(z = 5.0) = 12,400$ 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)



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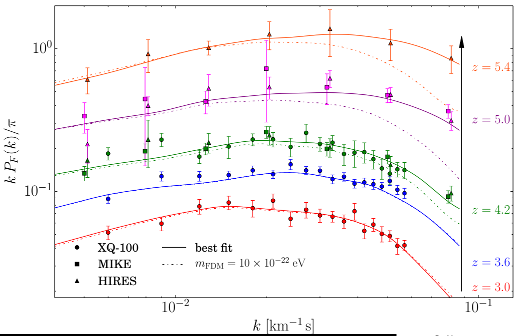

Simple model:

- instantaneous H reionisation at $z_{\rm rei} = 9$
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- Compton cooling + adiabatic expansion

$T_0(z = 5.0) = 8,200$ K

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

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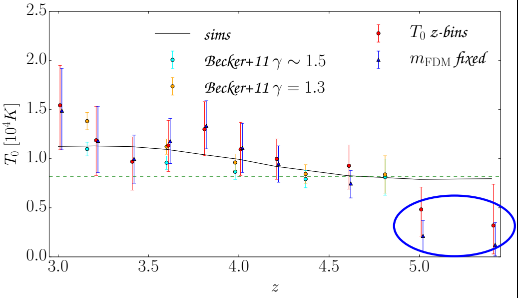

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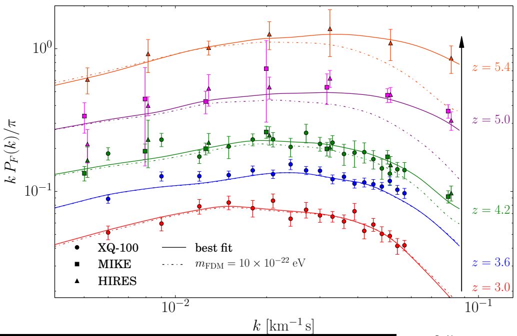


Simple model:

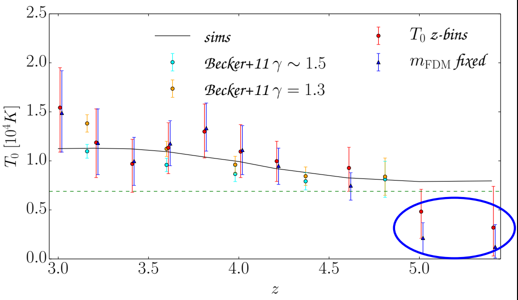
- instantaneous H reionisation at $z_{\rm rei} = 15$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 2$
- Compton cooling + adiabatic expansion

$T_0(z = 5.0) = 6,900$ K

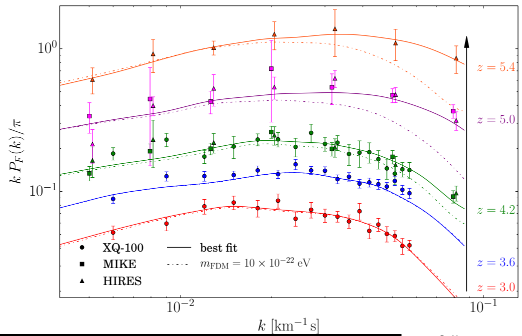
McQuinn & Upton Sanderback (2015),
Upton Sanderback et al. (2016)

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:

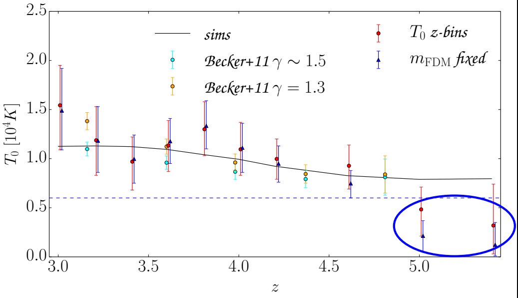
- instantaneous H reionisation at $z_{\rm rei} = 15$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 3$
- Compton cooling + adiabatic expansion

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

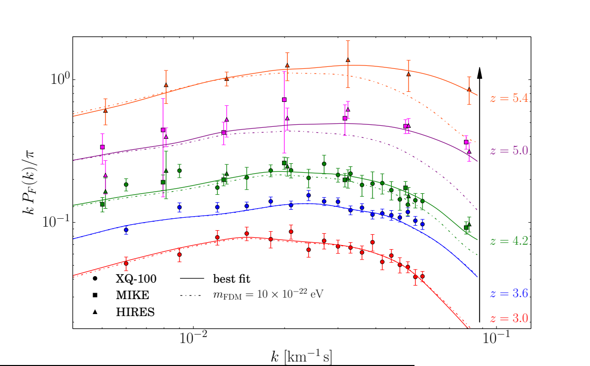
McQuinn & Upton Sanderback (2015), Upton Sanderback et al. (2016)

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:

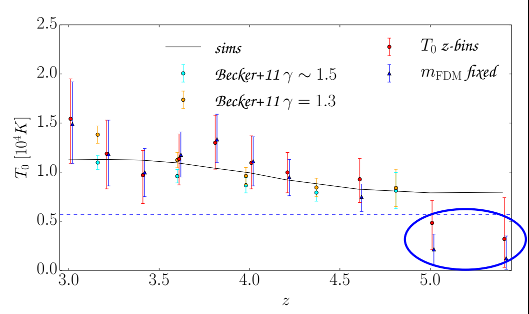
- instantaneous H reionisation at $z_{\rm rei} = 20$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 3$
- Compton cooling + adiabatic expansion

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

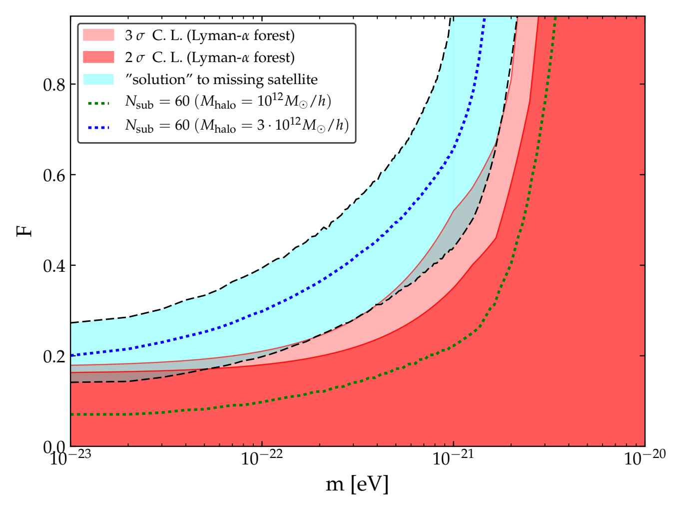
McQuinn & Upton Sanderback (2015), Upton Sanderback et al. (2016)

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

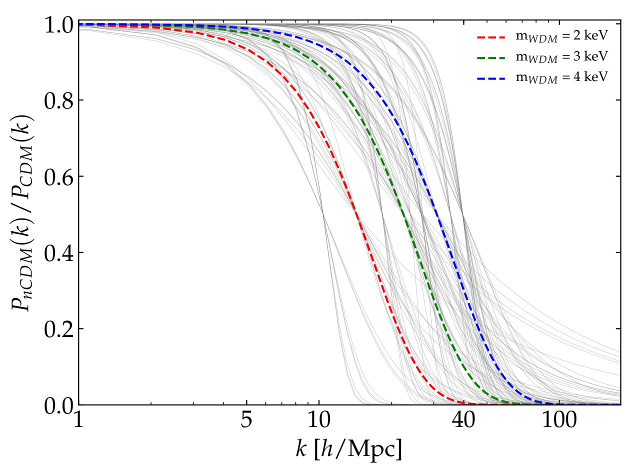


with T. Kobayashi (SISSA)

General non-CDM models

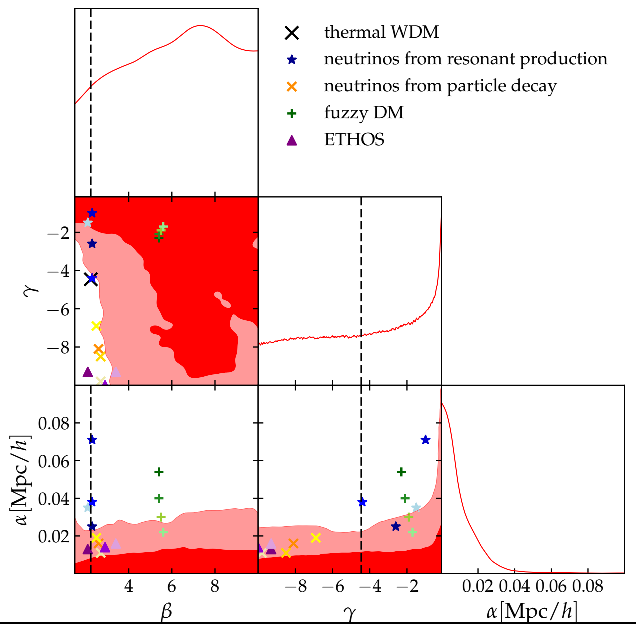
General transfer function for DM: $$T(k) = \sqrt{\frac{P_{\mathrm{nCDM}}}{P_{\mathrm{CDM}}}} = \left[1 + (\alpha k)^{\beta}\right]^{\gamma},$$

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



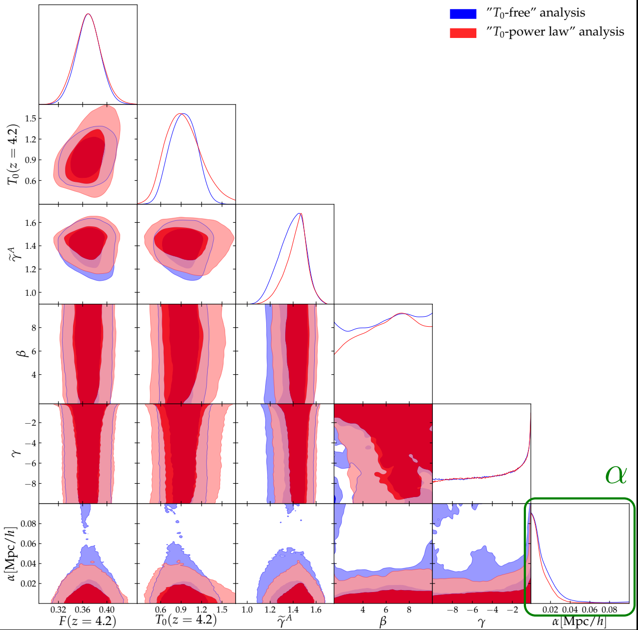
with R. Murgia (SISSA)

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

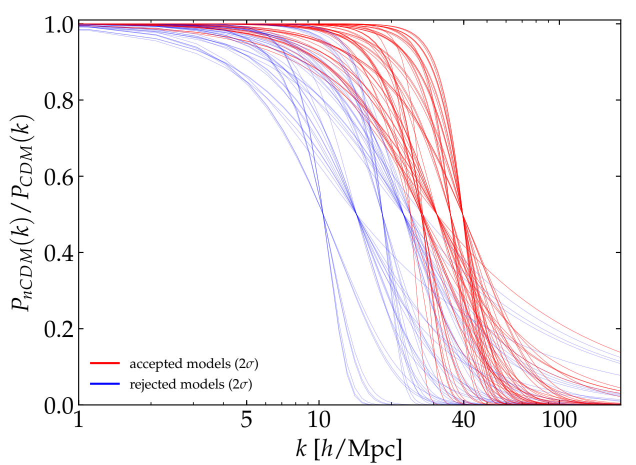
Stable limit on the scale of suppression



$\alpha < 0.03$ Mpc/h (2σ)

Stable limit on the scale of suppression

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



Conclusions

Cosmological & Astrophysical Constraints on WDM:

- Combined data: XQ-100 + HIRES/MIKE (high resolution, high redshift)
- Large redshift range and probing small scales
- Good agreement with thermal history evolution (a paper by Becker+11)
- Constraints on WDM from combined data: $m_{\rm WDM} > 5.3$ keV at 2σ.
- Constraints on WDM from combined data: $m_{\rm WDM} > 3.5$ keV at 2σ (conservative thermal history)
- The paper: astro-ph/1702.01764

Cosmological & Astrophysical Constraints on FDM:

- First FDM constraints from Lyman-α forest
- Constraints on FDM from combined data: $m_{\rm FDM} > 37.5 \times 10^{-22}$ eV at 2σ.
- Constraints on FDM from combined data: $m_{\rm FDM} > 20.0 \times 10^{-22}$ eV at 2σ (conservative thermal history)
- $m_{\rm FDM}$ value from "local" Universe leads to unphysically small high-z temperature
- FDM parameter space greatly constrained: it is hard to solve missing satellite problem and satisfy Lyα constraints.
- The papers: astro-ph/1703.04683, astro-ph/1708.00015