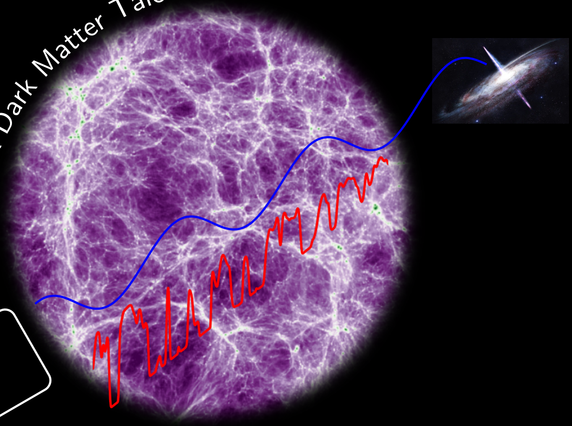
Small scale structure of the IGM:

A Dark Matter Tale



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@ University of Washington

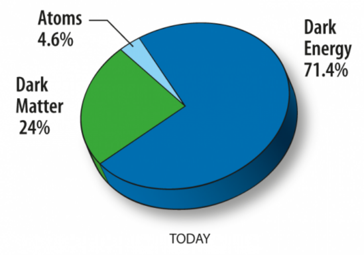
Intergalactic Interconnections

@

Aix-Marseille Université

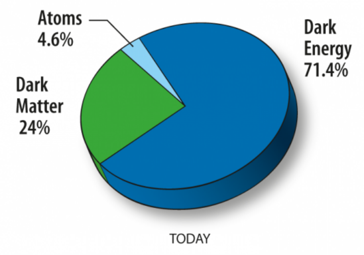
July 13, 2018

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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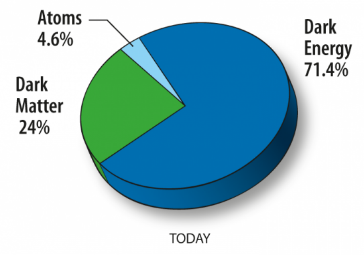

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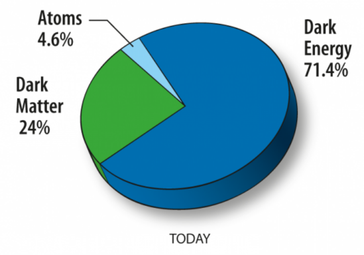
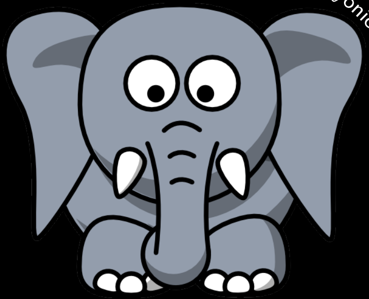
→ Alternative DM models (Warm DM, Fuzzy DM, Self-interacting DM, ...)

Cold Dark Matter problems (?)





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CDM problems of small-scale physics:
- Missing satellites
- Core/Cusp problem
- ...

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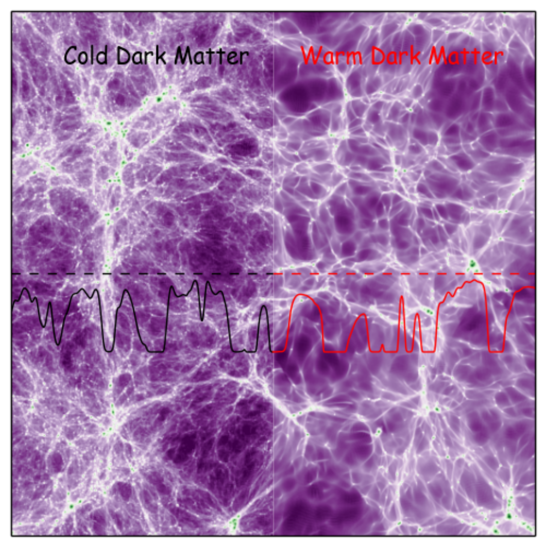
Non-CDM erases small scale structure



Warm Dark Matter (WDM):

Free-streaming of DM particles

(From the time they decouple

until they become non-relativistic)

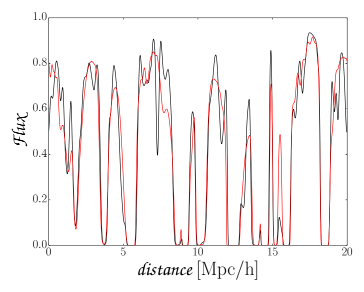
Fuzzy Dark Matter (FDM):

de-Broglie wavelength

of ultra-light DM scalar

$\Longrightarrow$ erases small scale structure

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



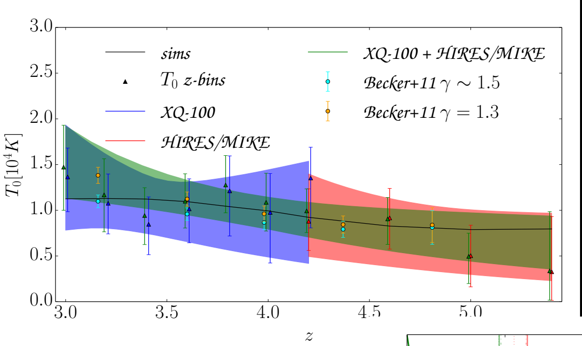
Cosmological parameter inference - WDM

- Parameters (p): $\bar{F}(z)$, $T_0\,(T^A, T^S)$, $\gamma\,(\gamma^A, \gamma^S)$, σ_8, $n_{\rm eff}$, $z_{\rm rei}$, $f_{\rm UV}$ + $m_{\rm WDM}$
- A grid of simulations (3x, 3x3 + 3x4, 3x3, 3, 3, 3x4, 3, 4x3 + 4x3)
- Interpolation scheme among the grid points
- run (4) MCMC chains for each model we desire to test (e.g. different data-set, different priors, adding systematic errors, etc.) $\rightarrow$ maximizing the likelihood $\mathcal{L}(p|d)$

Parameter	XQ-100	HIRES/MIKE	Combined
$m_{\rm WDM}$ [keV]	> 1.4	> 4.1	> 5.3
σ_8	$[0.75, 0.92]$	$[0.75, 1.32]$	$[0.83, 0.95]$
$n_{\rm eff}$	$[-2.42, -2.25]$	$[-2.53, -2.11]$	$[-2.43, -2.32]$
$T^A(z_{\rm p})$ [10^4 K]	$[0.73, 1.27]$	$[0.46, 1.12]$	$[0.74, 1.06]$
$T^S(z_{\rm p})$	$[-4.39, 1.89]$	$[-4.78, -1.80]$	$[-3.22, -0.82]$
$\gamma^A(z_{\rm p})$	$[1.12, 1.45]$	$[1.08, 1.52]$	$[1.23, 1.69]$
$\gamma^S(z_{\rm p})$	$[-1.89, 0.17]$	$[-1.18, 1.77]$	$[-0.07, 1.81]$
$z_{\rm rei}$	$[6.5, 15.66]$	$[6.26, 14.88]$	$[6.25, 13.43]$
$f_{\rm UV}$	$[0.06, 0.96]$	$[0.05, 0.96]$	$[0.05, 0.94]$
$\chi^2/d.o.f.$	134/124	33/40	185/173

Marginalized constraints at 95 %, obtained from the MCMC analysis. The pivot redshifts for different data sets are: $z_p = 3.6$ for XQ-100, $z_p = 4.5$ for HIRES/MIKE and $z_p = 4.2$ for XQ-100 + HIRES/MIKE.

WDM mass constraints

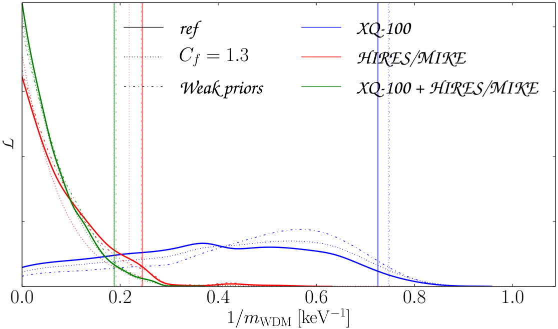


$T_0(z), \gamma(z)$ are power-laws

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

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

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



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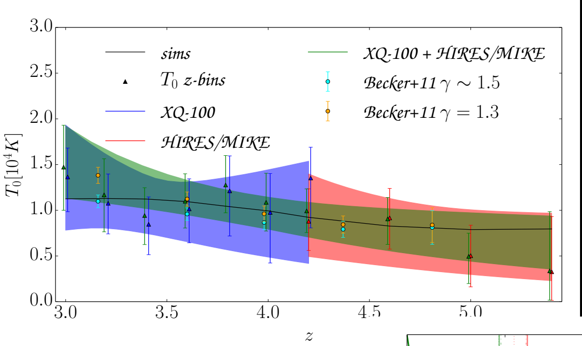

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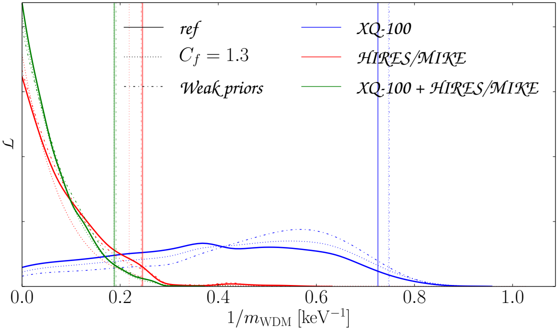
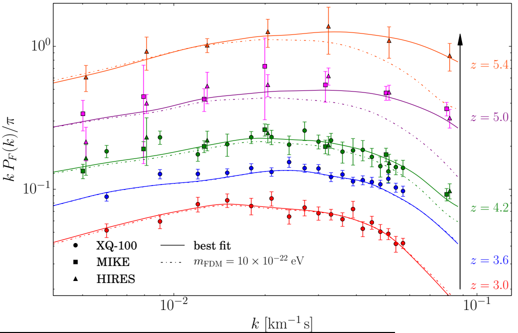
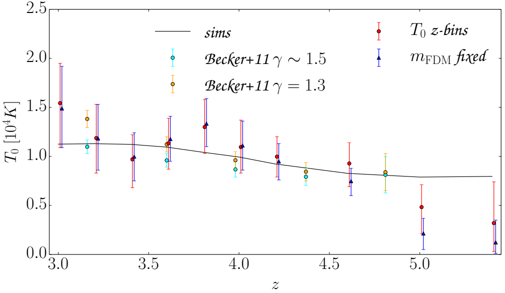


How cold is too cold?





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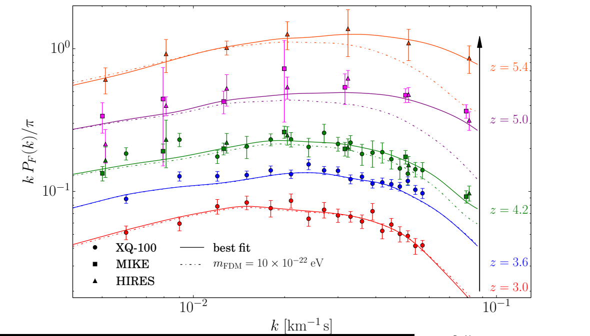

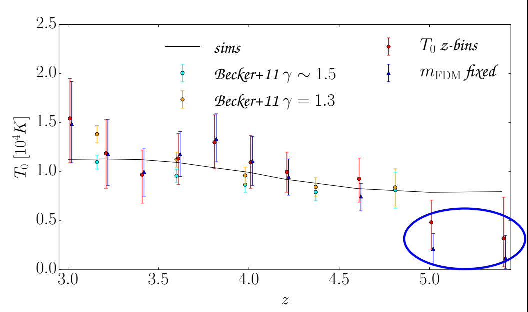

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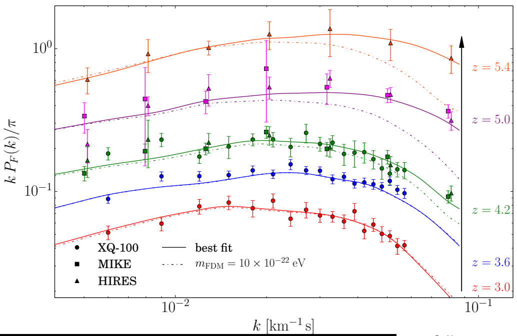


Simple model:

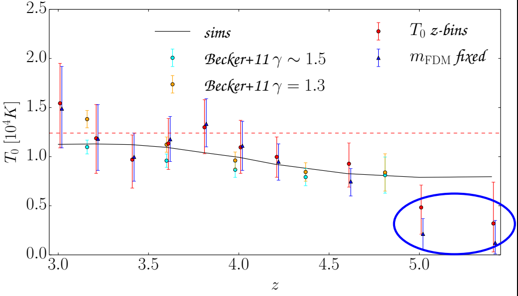
- instantaneous H reionisation at $z_{\rm rei} = 9$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 0$
- Compton cooling + adiabatic expansion

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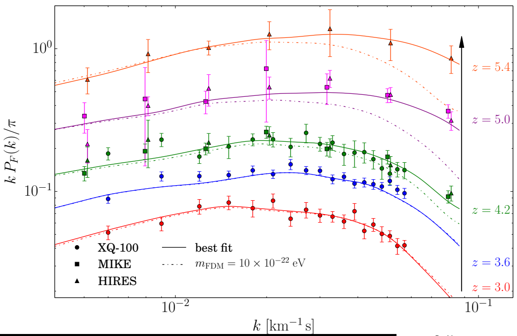

Simple model:

- instantaneous H reionisation at $z_{\rm rei} = 9$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 2$
- Compton cooling + adiabatic expansion

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

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

Other things assumed:

- T fluctuations increase above this temperature
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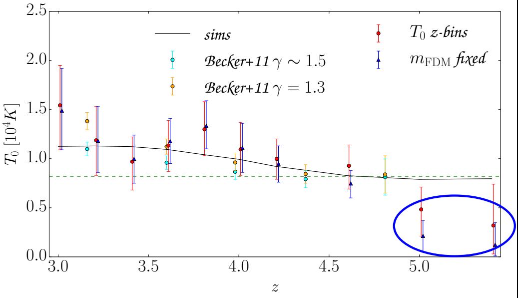

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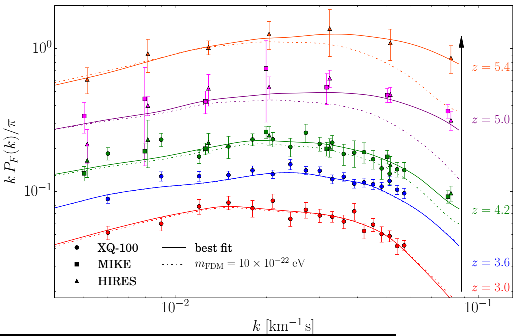


Simple model:

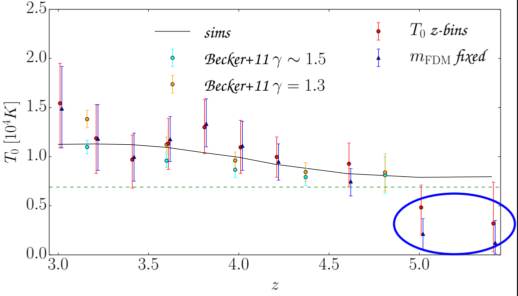
- instantaneous H reionisation at $z_{\rm rei} = 15$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 2$
- Compton cooling + adiabatic expansion

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

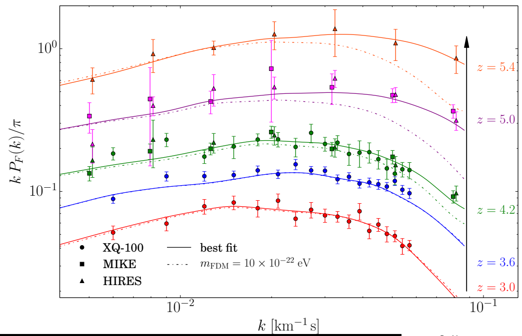
McQuinn & Upton Sanderback (2015), Upton Sanderback et al. (2016)

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:

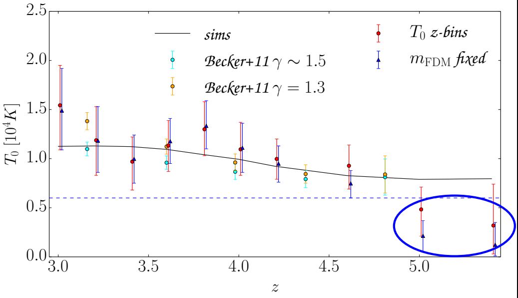
- instantaneous H reionisation at $z_{\text{rei}} = 15$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 3$
- Compton cooling + adiabatic expansion

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



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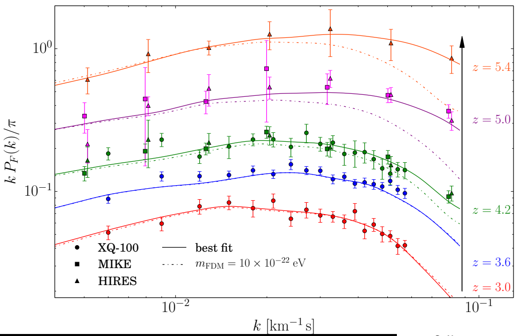


Simple model:

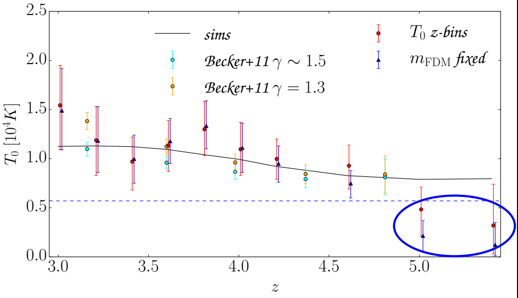
- instantaneous H reionisation at $z_{\rm rei} = 20$
- HI photo-heating, depends on spectral index of UV intensity $\alpha_{bk} = 3$
- Compton cooling + adiabatic expansion

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

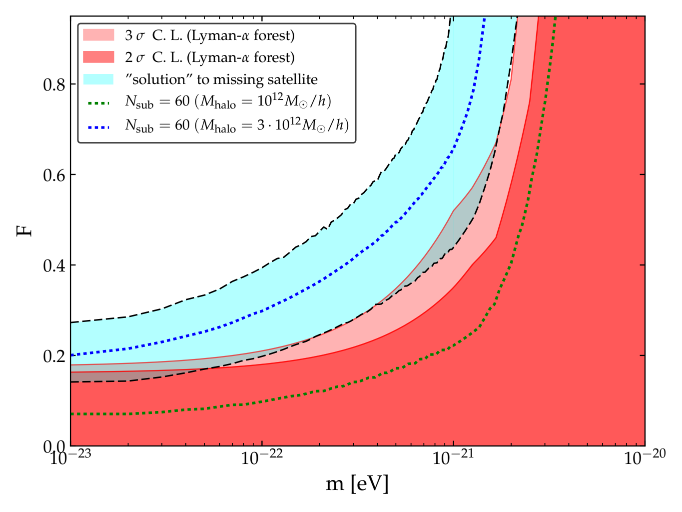
McQuinn & Upton Sanderback (2015), Upton Sanderback et al. (2016)

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)



FDM cannot solve missing satellite problem

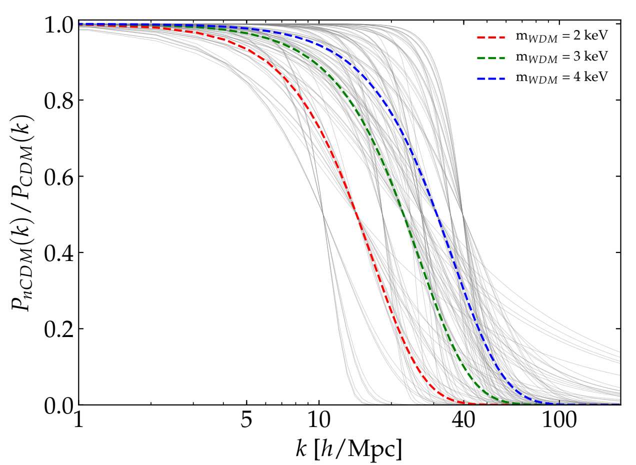


with T. Kobayashi (SISSA)

General non-CDM models

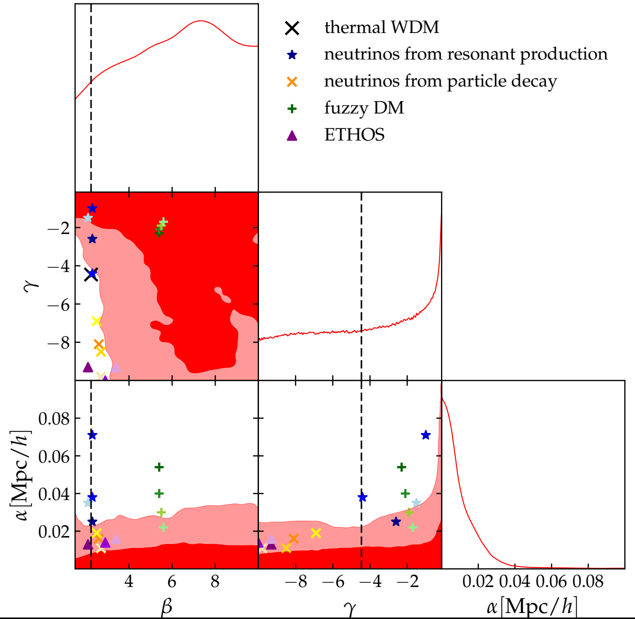
General transfer function for DM: $T(k) = \sqrt{\frac{P_{\rm nCDM}}{P_{\rm CDM}}} = \left[1 + (\alpha k)^{\beta}\right]^{\gamma},$

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



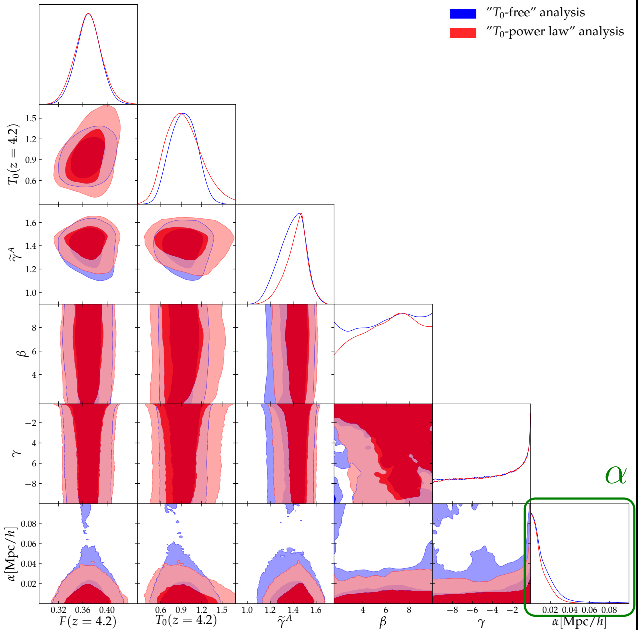
with R. Murgia (SISSA)

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

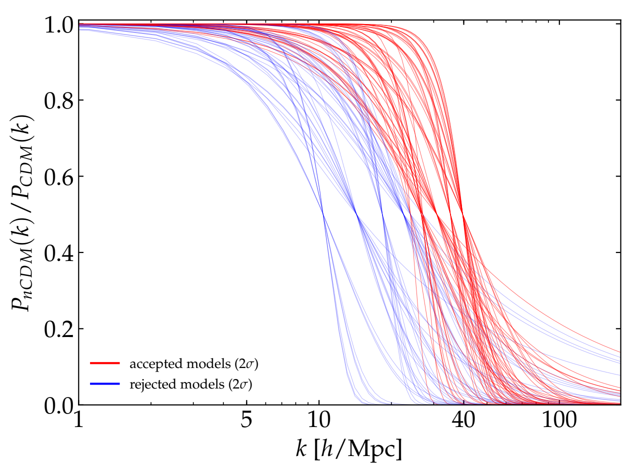
Stable limit on the scale of suppression



$\alpha < 0.03$ Mpc/h (2σ)

Stable limit on the scale of suppression

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



Conclusions

Cosmological & Astrophysical Constraints on WDM:

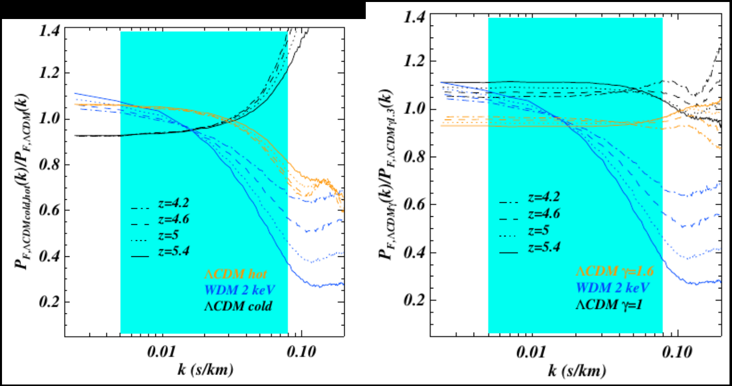
- Combined data: XQ-100 + HIRES/MIKE (high resolution, high redshift)
- Large redshift range and probing small scales
- Constraints on WDM from combined data: $m_{\mathrm{WDM}} > 5.3$ keV at 2σ.
- Constraints on WDM from combined data: $m_{\mathrm{WDM}} > 3.5$ keV at 2σ (conservative thermal history)
- Conservative thermal history perhaps too conservative?
- The paper: Iršič et al. (2017b) astro-ph/1702.01764

Cosmological & Astrophysical Constraints on FDM:

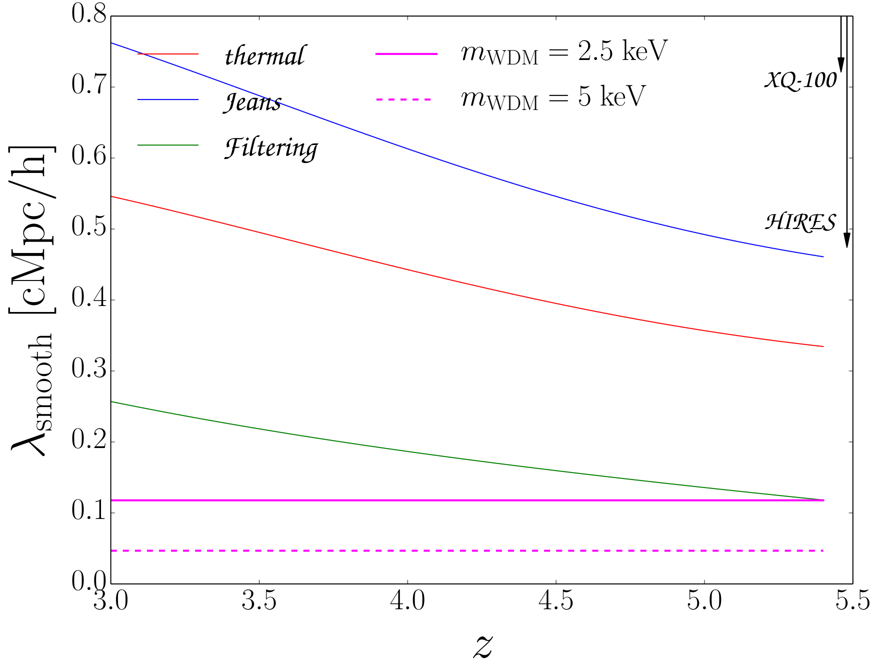
- Constraints on FDM from combined data: $m_{\mathrm{FDM}} > 37.5 \times 10^{-22}$ eV at 2σ.
- Constraints on FDM from combined data: $m_{\mathrm{FDM}} > 20.0 \times 10^{-22}$ eV at 2σ (conservative thermal history) high-z temperature
- FDM parameter space greatly constrained: it is hard to solve missing satellite problem and satisfy Lyα constraints.
- The papers: Iršič et al. (2017c) astro-ph/1703.04683, Kobayashi (VI incl) et al. (2017) astro-ph/1708.00015

Cosmological & Astrophysical Constraints on non-CDM:

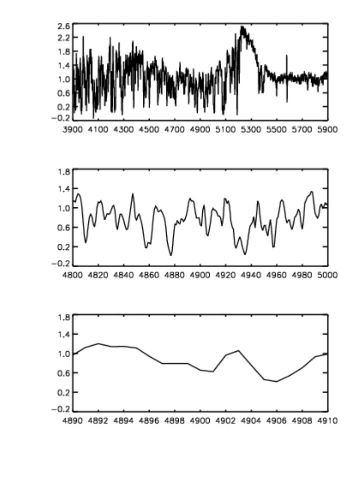
- General non-CDM model constraints scale of the suppression: $\alpha < 0.03$ Mpc$/h$ (2σ)
- Weak preference for non-thermal WDM
- The paper: Murgia (VI incl) et al. (2018) astro-ph/1806.08371

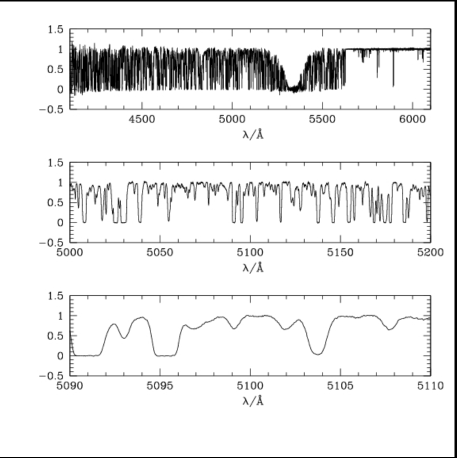


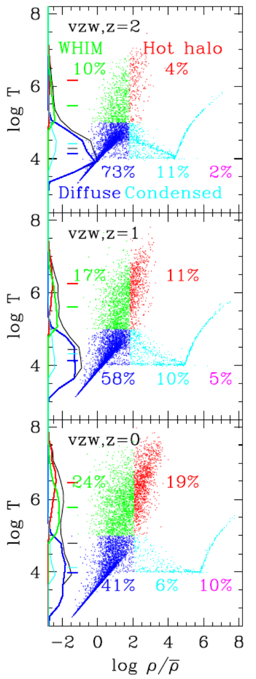
$P_{F,\Lambda CDM cold,hot}(k)/P_{F,\Lambda CDM}(k)$
z=4.2
z=4.6
z=5
z=5.4
ΛCDM hot
WDM 2 keV
ΛCDM cold
k (s/km)
$P_{F,\Lambda CDM\gamma}(k)/P_{F,\Lambda CDM\gamma 1.3}(k)$
ΛCDM γ=1.6
WDM 2 keV
ΛCDM γ=1

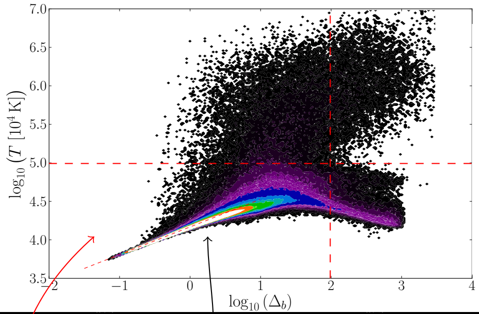


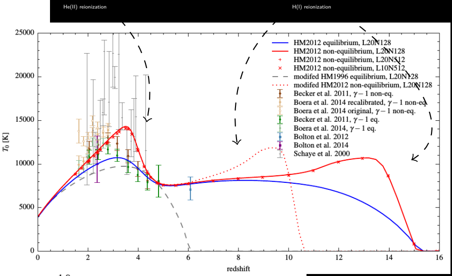
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
3.0
3.5
4.0
4.5
5.0
5.5
$\lambda_{\rm smooth}$ [cMpc/h]
z
thermal
Jeans
Filtering
$m_{\rm WDM} = 2.5$ keV
$m_{\rm WDM} = 5$ keV
XQ-100
HIRES

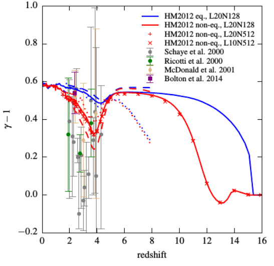



λ/Å
λ/Å
λ/Å


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
log $\rho/\bar{\rho}$

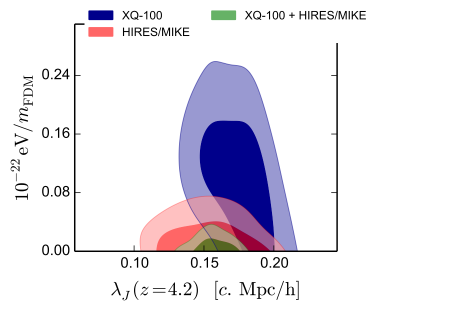


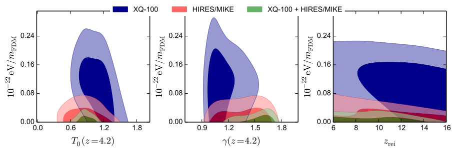


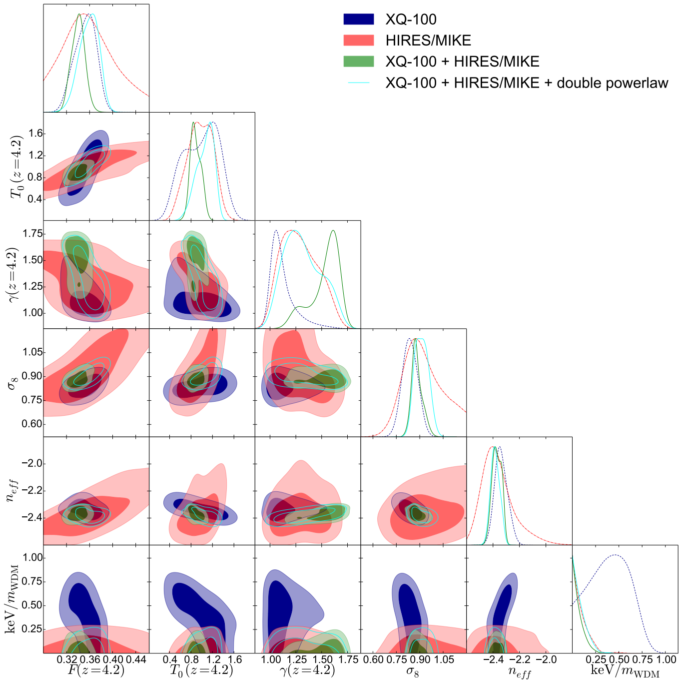


$$T = T_0 \Delta_b^{\gamma-1}$$

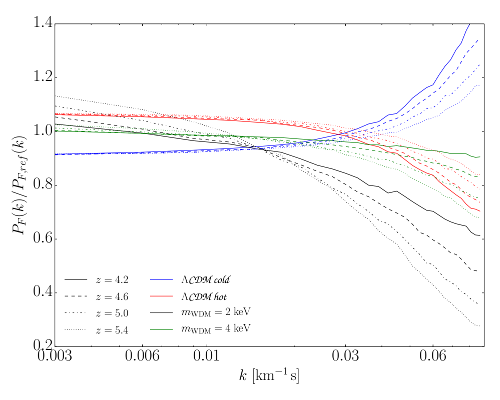
80-90% of baryons at $z \sim 3 - 4$


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]

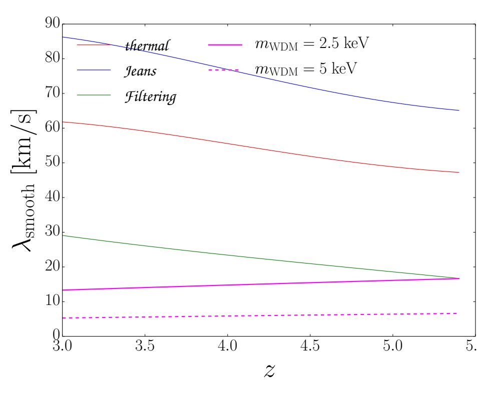

XQ-100
HIRES/MIKE
XQ-100 + HIRES/MIKE
$10^{-22}\,\mathrm{eV}/m_{\mathrm{FDM}}$
$T_0(z=4.2)$
$\gamma(z=4.2)$
z_{rei}


XQ-100
HIRES/MIKE
XQ-100 + HIRES/MIKE
XQ-100 + HIRES/MIKE + double powerlaw
$T_0(z=4.2)$
$\gamma(z=4.2)$
σ_8
n_{eff}
$\mathrm{keV}/m_{\mathrm{WDM}}$
$F(z=4.2)$

Problem of different smoothing scales

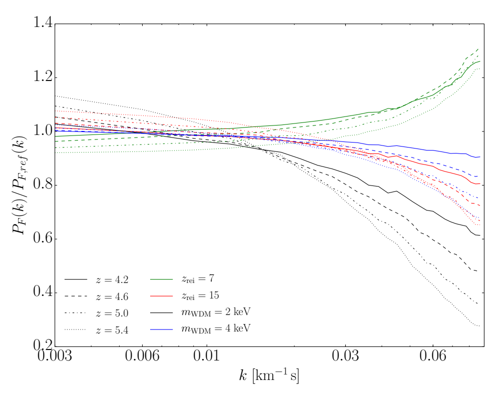


$m_{\rm WDM}$, T_0: different scale dependence

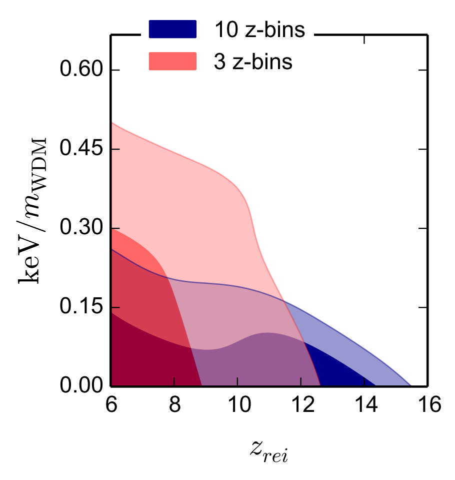


DM and thermal smoothing:
different redshift dependence

Redshift evolution breaks the degeneracies



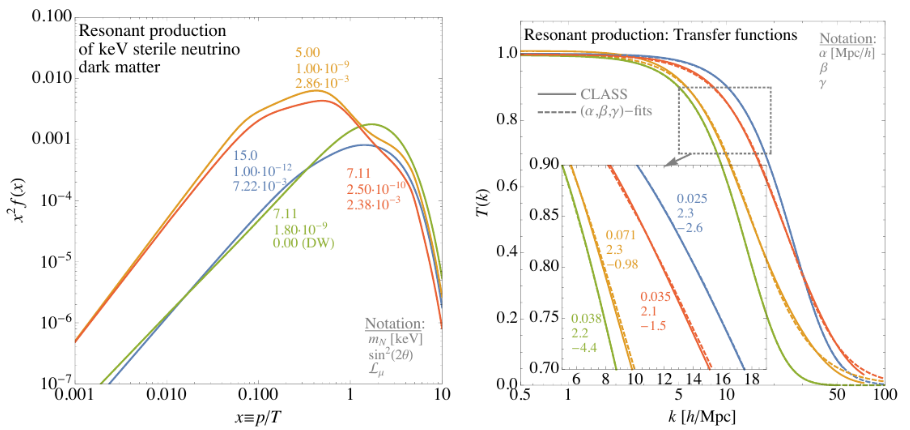
$m_{\rm WDM}, z_{\rm rei}$:
different scale/redshift dependence

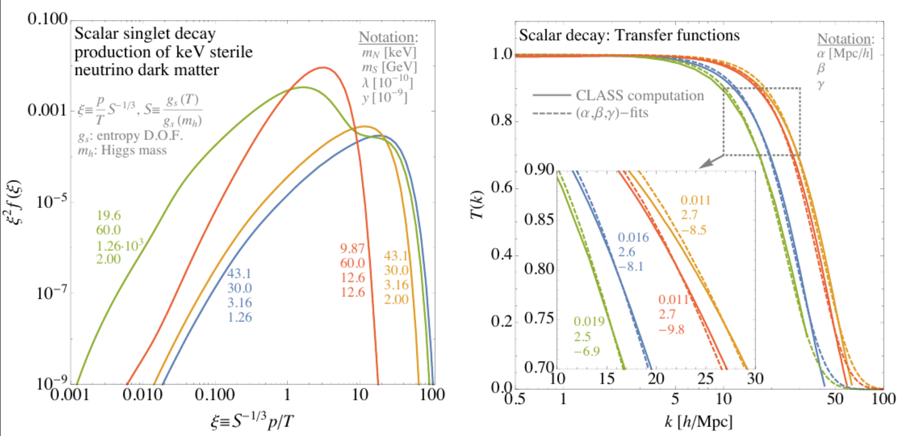


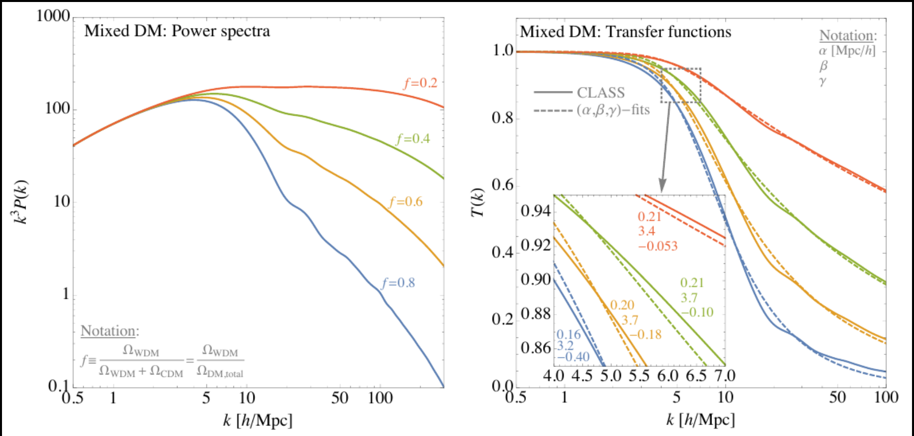
10 z-bins: $3.0 - 5.4$

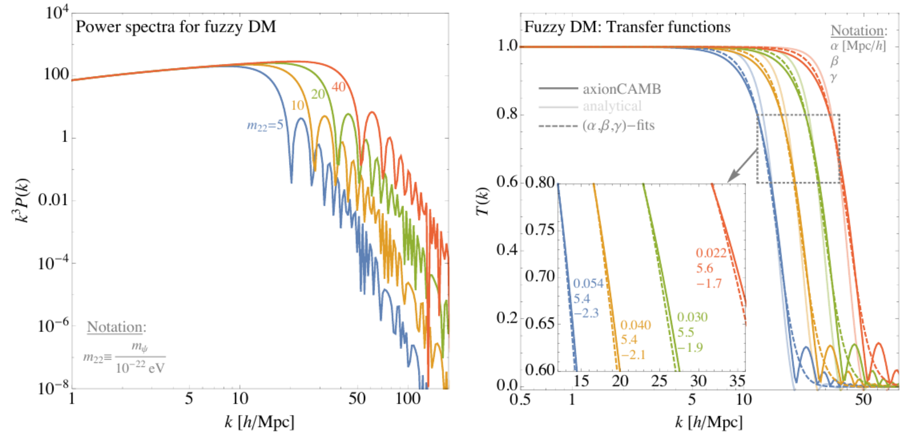
3 z-bins: $4.0, 4.2, 4.6$

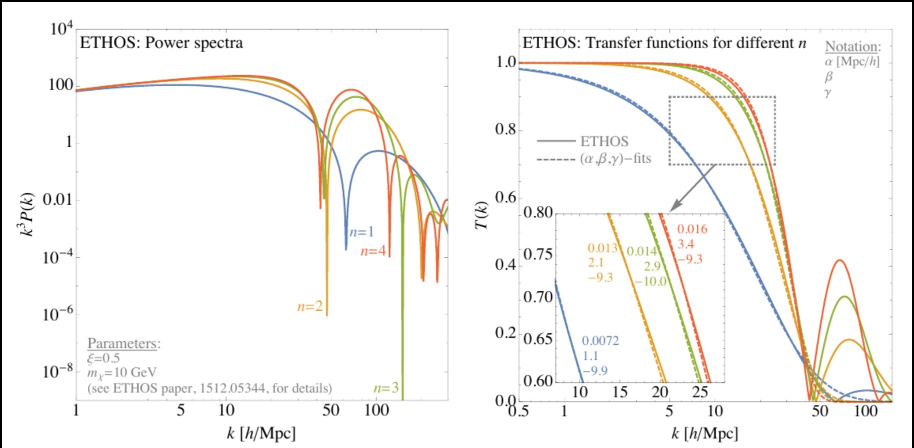
	α [Mpc/h]	β	γ	$k_{1/2}$ [h/Mpc]	χ^2
Neutrinos	0.025	2.3	-2.6	17.276	101
from	0.071	2.3	-1.0	9.828	266
resonant	0.038	2.3	-4.4	8.604	283
production	0.035	2.1	-1.5	15.073	149
Neutrinos	0.016	2.6	-8.1	19.012	104
from	**0.011**	**2.7**	**-8.5**	**28.647**	**38**
particle	0.019	2.5	-6.9	16.478	105
decay	**0.011**	**2.7**	**-9.8**	**26.31**	**45**
	0.16	3.2	-0.4	6.743	229
Mixed	0.20	3.7	-0.18	7.931	-
models	0.21	3.7	-0.1	11.36	-
	0.21	3.4	-0.053	33.251	-
	0.054	5.4	-2.3	13.116	169
Fuzzy	0.040	5.4	-2.1	18.106	104
DM	**0.030**	**5.5**	**-1.9**	**25.016**	**40**
	0.022	**5.6**	**-1.7**	**34.590**	**30**
	0.0072	1.1	-9.9	7.274	-
ETHOS	0.013	2.1	-9.3	16.880	153
models	0.014	2.9	-10.0	21.584	70
	0.016	3.4	-9.3	23.045	60


Resonant production of keV sterile neutrino dark matter
5.00
1.00·10^−9
2.86·10^−3
15.0
1.00·10^−12
7.22·10^−3
7.11
2.50·10^−10
2.38·10^−3
7.11
1.80·10^−9
0.00 (DW)
Notation:
m_N [keV]
sin^2(2θ)
L_μ
x^2 f(x)
x≡p/T
Resonant production: Transfer functions
Notation:
α [Mpc/h]
β
γ
CLASS
(α,β,γ)−fits
0.025
2.3
−2.6
0.071
2.3
−0.98
0.035
2.1
−1.5
0.038
2.2
−4.4
T(k)
k [h/Mpc]


Scalar singlet decay production of keV sterile neutrino dark matter
Notation:
m_N [keV]
m_S [GeV]
λ [10^{-10}]
y [10^{-9}]
$\xi \equiv \frac{p}{T} S^{-1/3}$, $S \equiv \frac{g_s(T)}{g_s(m_h)}$
g_s: entropy D.O.F.
m_h: Higgs mass
19.6
60.0
$1.26 \cdot 10^3$
2.00
43.1
30.0
3.16
1.26
9.87
60.0
12.6
12.6
43.1
30.0
3.16
2.00
$\xi^2 f(\xi)$
$\xi \equiv S^{-1/3} p/T$
Scalar decay: Transfer functions
Notation:
α [Mpc/h]
β
γ
CLASS computation
(α,β,γ)–fits
0.016
2.6
−8.1
0.011
2.7
−8.5
0.011
2.7
−9.8
0.019
2.5
−6.9
$T(k)$
k [h/Mpc]


Mixed DM: Power spectra
f=0.2
f=0.4
f=0.6
f=0.8
$k^3P(k)$
k [h/Mpc]
Notation:
$f \equiv \frac{\Omega_{WDM}}{\Omega_{WDM}+\Omega_{CDM}} = \frac{\Omega_{WDM}}{\Omega_{DM,total}}$
Mixed DM: Transfer functions
Notation:
α [Mpc/h]
β
γ
CLASS
(α,β,γ)–fits
$T(k)$
0.21
3.4
−0.053
0.21
3.7
−0.10
0.20
3.7
−0.18
0.16
3.2
−0.40
k [h/Mpc]


Power spectra for fuzzy DM
$k^3P(k)$
k [h/Mpc]
m_{22}=5
10
20
40
Notation:
$m_{22} \equiv \frac{m_\psi}{10^{-22}\,\text{eV}}$
Fuzzy DM: Transfer functions
$T(k)$
axionCAMB
analytical
(α,β,γ)−fits
Notation:
α [Mpc/h]
β
γ
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: Power spectra
$k^3P(k)$
k [h/Mpc]
n=1
n=2
n=3
n=4
Parameters:
ξ=0.5
m_χ=10 GeV
(see ETHOS paper, 1512.05344, for details)
ETHOS: Transfer functions for different n
$T(k)$
Notation:
α [Mpc/h]
β
γ
ETHOS
(α,β,γ)−fits
0.0072
1.1
−9.9
0.013
2.1
−9.3
0.014
2.9
−10.0
0.016
3.4
−9.3