Dark matter at small scales: a general approach

Riccardo Murgia
(SISSA, Trieste)

in collaboration with:

Matteo Viel (SISSA, Trieste)
Aurel Schneider (ETH, Zurich)
Alexander Merle (MPP, Munich)
Maximilian Totzauer (MPP, Munich)

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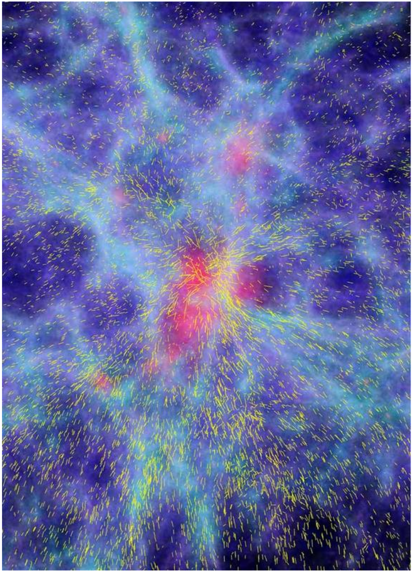
Outline

- ΛCDM small-scale "crisis"
  - Baryon physics VS "non-cold" dark matter
  - Thermal warm dark matter: the standard approach
- A new, general approach
  - Method and parametrisation
  - Connection with particle physics models
- Constraints from structure formation data
  - Milky Way satellite counts
  - Lyman-α forest data
- What next



Credits: ESO

Overview

Cosmic microwave background (CMB) and large scale structure (LSS) data $\Longrightarrow$ $\Longrightarrow$ present Universe mainly composed by a cosmological constant (Λ) and by cold dark matter (CDM) $\Longrightarrow$ ΛCDM model

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However, ΛCDM model shows some limits at sub-galaxy scales:

- *Missing satellite* problem
  Cosmological N-body simulations predict too many substructures around the Milky Way (MW) with respect to the observed number of MW satellites
- *Cusp-core* problem
  Cosmological N-body simulations predict too much dark matter (DM) in the innermost regions of galaxies
- *Too-big-to-fail* problem
  The dynamical properties of massive MW satellites are not reproduced in cosmological simulations

This small-scale "crisis" could be solved either by baryon physics, still not perfectly understood and implemented in cosmological simulations, or by modifying the nature of DM

Models with suppressed matter power spectra: "non-cold" DM

CDM $\Longleftrightarrow$ velocity dispersion so small that the corresponding free-streaming length is negligible for cosmological structure formation

"non-cold" DM $\Longleftrightarrow$ suppression of the matter power spectrum $P(k)$ on scales smaller than their free-streaming lenght, which is NON-negligible for structure formation ($m \sim$ keV $\Rightarrow \lambda_{\rm fs} \sim$ Mpc)

This phenomenon is described by the so-called transfer function $T(k)$:

$$T^2(k) = \left[\frac{P(k)_{\rm noncold}}{P(k)_{\Lambda{\rm CDM}}}\right]$$

i.e. the square root of the ratio of the power spectrum in the presence of "non-cold" DM with respect to that in the presence of CDM only

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DIFFERENT "NON-COLD" SCENARIOS

$\Downarrow$

DIFFERENT SHAPES OF THE POWER SUPPRESSION (i.e. of $T(k)$)

Thermal warm dark matter (WDM): the standard approach

Thermal WDM $\Leftrightarrow$ DM candidates with a Fermi-Dirac momentum distribution

$$\Downarrow$$

Very specific shape of the power suppression
(i.e. of the transfer function $T(k)$)

The transfer function is well described by:

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

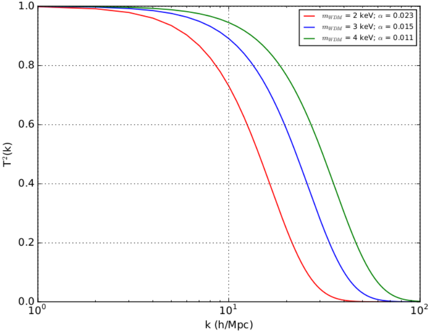
with:

$$\nu = 1.12 \; ;$$

$$\alpha = 0.049 \left(\frac{m_x}{1\ \mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_x}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$$

$$\Downarrow$$

one-to-one correspondence
$\alpha \leftrightarrow m_{\mathrm{WDM}}$



Bode et al. (2001)
Viel et al. (2005)

A new, general approach: method and parametrisation (I)

Most of the astrophysical constraints obtained so far, refer to thermal WDM. Nonetheless, most of the viable DM candidates do not have a thermal momentum distribution $\Longrightarrow$ the corresponding transfer functions may be non-trivially shallower!

Standard approach **New general approach**

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu} \quad \Rightarrow \quad T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

A new, general approach: method and parametrisation (I)

Standard approach $\Rightarrow$ **New general approach**

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Standard approach

$$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

$$\Rightarrow$$

New general approach

$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

$$T^2(k) = 0.5$$
$$\Updownarrow$$
$$k_{1/2} = ((0.5)^{-\nu/10} - 1)^{1/2\nu})\alpha^{-1}$$

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$$k_{1/2} = ((0.5)^{1/2\gamma} - 1)^{1/\beta})\alpha^{-1}$$

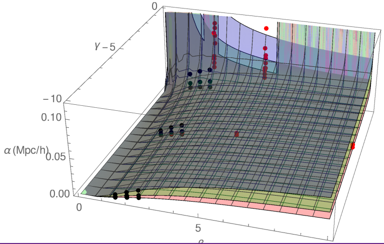
- one-to-one correspondence $\alpha \leftrightarrow m_{\mathrm{WDM}} \leftrightarrow k_{1/2}$

$$m'_{\mathrm{WDM}} = 2\ \mathrm{keV} \ \longleftrightarrow \ \mathrm{k}'_{1/2} = 14.323\ \mathrm{h/Mpc}$$

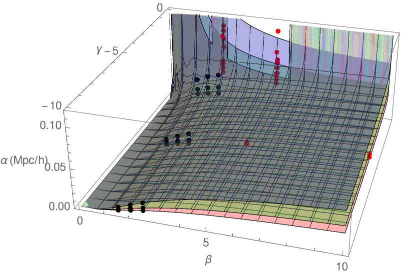
$$m''_{\mathrm{WDM}} = 3\ \mathrm{keV} \ \longleftrightarrow \ \mathrm{k}''_{1/2} = 22.463\ \mathrm{h/Mpc}$$

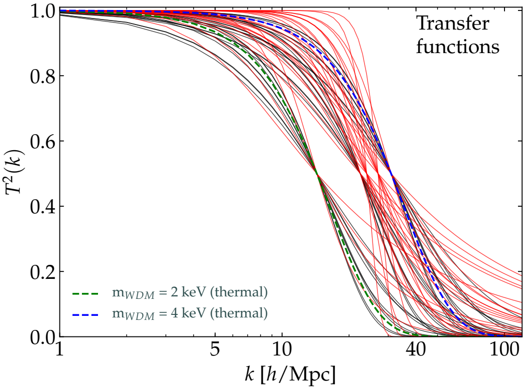
$$m'''_{\mathrm{WDM}} = 4\ \mathrm{keV} \ \longleftrightarrow \ \mathrm{k}'''_{1/2} = 30.914\ \mathrm{h/Mpc}$$

- constraints on m_{WDM} (or $k_{1/2}$) are mapped into 3D surfaces in the $\{\alpha, \beta, \gamma\}$-space



A new, general approach: method and parameterization (II)

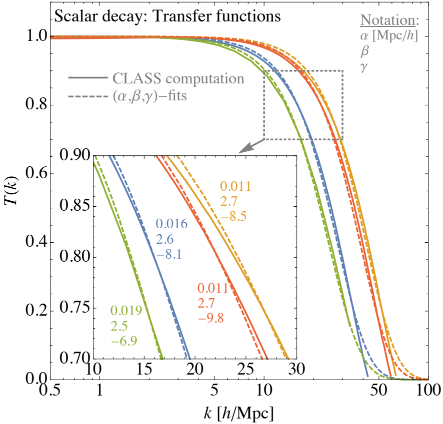


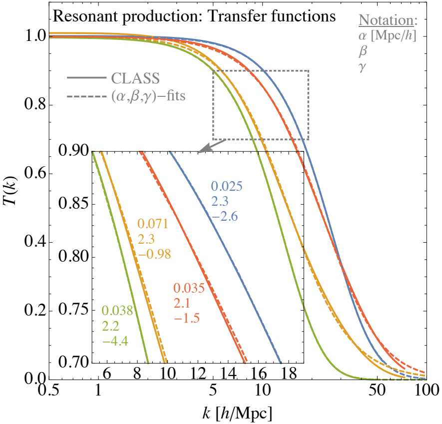


The position of $k_{1/2}$ is set by α, while β and γ are responsible of the slope of $T(k)$ before and after $k_{1/2}$, respectively. β must be positive in order to have meaningful transfer functions ($\beta < 0$ gives a $T(k)$ that differs from 1 at large scales). The larger is β, the flatter is $T(k)$ before $k_{1/2}$. The larger is the absolute value of γ, the sharper is the cut-off.

Connection with particle physics models (I)

Being able to reproduce a large variety of shapes in the suppression of the matter power spectrum, our general parametrisation accurately describes the most viable non-thermal DM scenarios, such as sterile neutrinos, mixed cold+warm models, fuzzy DM





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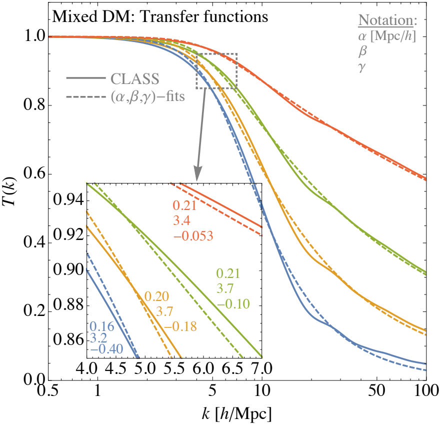
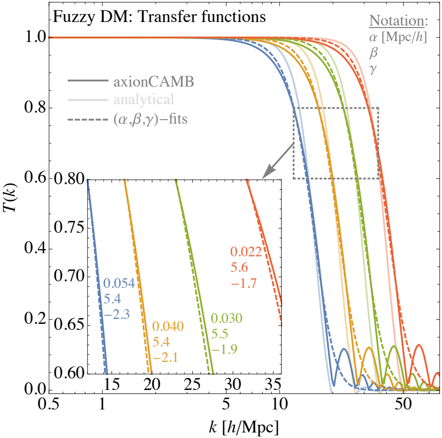


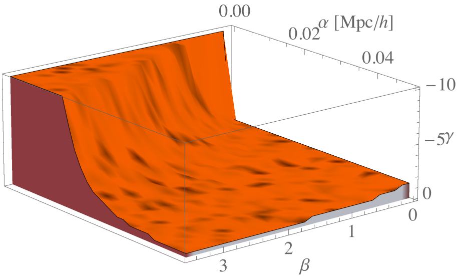


Constraints from MW satellite counts

Any "non-cold" DM model must predict a number of substructures within the MW virial radius not smaller than the actual number of MW satellites that we observe, i.e. $N_{\rm sub} < N_{\rm obs} \simeq 60 \quad (M_{\rm MW} = 1.7 \cdot 10^{12} M_{\rm sun})$

"Conservative" case (95% C.L. limit)

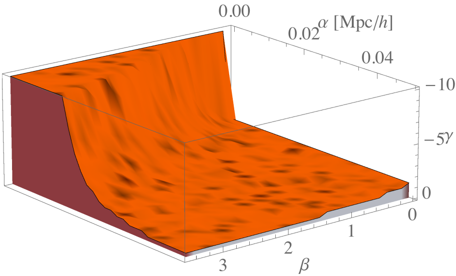
$N_{\rm sat} = 57$



$\alpha \leq 0.061\ {\rm Mpc}/h \quad (95\%\ {\rm C.L.})$

"Non-conservative" case (95% C.L. limit)

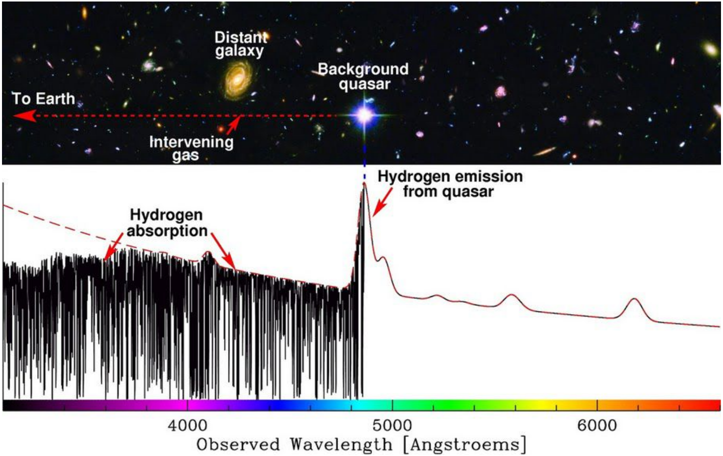
$N_{\rm sat} = 63$



$\alpha \leq 0.067\ {\rm Mpc}/h \quad (95\%\ {\rm C.L.})$

Constraints from Lyman-α forest data - Overview

Lyman-α forest $\equiv$ Lyman-α absorption produced by intergalactic neutral hydrogen in the spectra of distant quasars (thus a probe of the matter power spectrum on scales 0.5 $h/\mathrm{Mpc} < k < 50$ h/Mpc)



Credits: M. Murphy (www.futura-sciences.us)

Constraints from Lyman-α forest data - Method

- Flux power spectrum, the physical observable in Lyman-α forest experiments:

$$P_{\rm F}(k) = b^2(k) P_{\rm 1D}(k)$$

hydrodynamical simulations $\Rightarrow P_{\rm F}(k) \Rightarrow$ comprehensive data analysis

- The bias $b^2(k)$ differs very little between ΛCDM and our "non-cold" models, thus:

$$r(k) = \frac{P_{\rm 1D}^{\rm noncold}(k)}{P_{\rm 1D}^{\Lambda\rm CDM}(k)} \approx \frac{P_{\rm F}^{\rm noncold}(k)}{P_{\rm F}^{\Lambda\rm CDM}(k)}$$

- Estimator of the suppression of the power spectrum, with respect to ΛCDM model:

$$\delta A = \frac{A_{\Lambda\rm CDM} - A}{A_{\Lambda\rm CDM}} \qquad \text{with} \quad A = \int_{k_{\rm min}}^{k_{\rm max}} r(k)dk$$

- A model is excluded (at 95% C.L.) if it is characterised by a larger power suppression with respect to the most updated constraints on thermal WDM candidates (at 95% C.L.) obtained from comprehensive Lyman-α analyses, i.e. if:

$$\delta A > \delta A_{\rm REF}$$

Constraints from Lyman-α forest data - Results

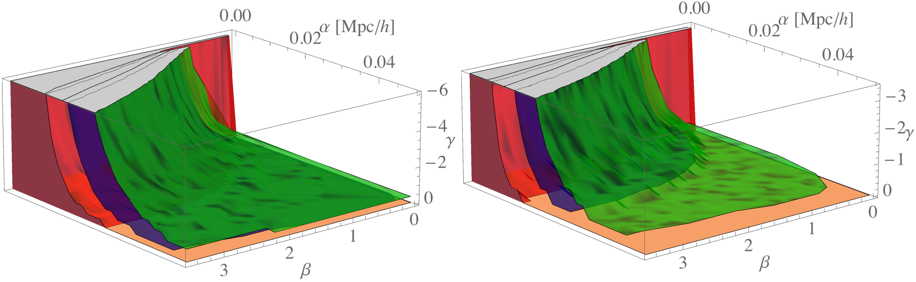
The most stringent constraints on thermal WDM masses from a full statistical analysis of Lyman-α forest data have been recently obtained by using the MIKE/HIRES+XQ-100 dataset ($0.5\ h/\mathrm{Mpc} < k < 20\ h/\mathrm{Mpc}$) **[Irsic et al. (2017)]**

"Conservative" case (95% C.L. limit)

$m_{\mathrm{WDM}} = 3.5\ \mathrm{keV} \ \Rightarrow\ \delta A_{\mathrm{REF}} = 0.38$

"Non-conservative" case (95% C.L. limit)

$m_{\mathrm{WDM}} = 5.3\ \mathrm{keV} \ \Rightarrow\ \delta A_{\mathrm{REF}} = 0.21$



$\alpha \leq 0.058\ \mathrm{Mpc}/h \quad (95\%\ \mathrm{C.L.})$

$\alpha \leq 0.044\ \mathrm{Mpc}/h \quad (95\%\ \mathrm{C.L.})$

Summarizing

The fitting formula reproduces the true results to a very high degree!

	α	β	γ	$k_{1/2}$ [h/Mpc]	$N_{\rm sub}^{\rm fit}$ ($N_{\rm sub}^{\rm true}$) [%]	Agree?	$\delta A_{\rm fit}$ ($\delta A_{\rm true}$) [%]	Agree?
RP neutrinos	0.025	2.3	−2.6	17.276	38 (39) [−2.6%]	✓	0.555 (0.571) [−2.8%]	✓
	0.071	2.3	−1.0	9.828	15 (14) [+7.1%]	✓	0.743 (0.754) [−1.5%]	✓
	0.038	2.3	−4.4	8.604	5 (5) [±0.0%]	✓	0.799 (0.810) [−1.4%]	✓
	0.035	2.1	−1.5	15.073	35 (37) [−5.4%]	✓	0.599 (0.613) [−2.3%]	✓
Neutrinos from particle decay	0.016	2.6	−8.1	19.012	38 (42) [−9.5%]	✓	0.521 (0.535) [−2.6%]	✓
	0.011	2.7	−8.5	28.647	**91** (**97**) [−6.2%]	✓	*0.339* (*0.360*) [−5.8%]	✓
	0.019	2.5	−6.9	16.478	27 (28) [−3.6%]	✓	0.582 (0.576) [+1.0%]	✓
	0.011	2.7	−9.8	26.31	**79** (**87**) [−9.2%]	✓	0.375 (*0.390*) [−3.8%]	✗
Mixed models	0.16	3.2	−0.4	6.743	9 (9) [±0.0%]	✓	0.823 (0.834) [−1.3%]	✓
	0.20	3.7	−0.18	7.931	28 (27) [+3.7%]	✓	0.738 (0.752) [−1.9%]	✓
	0.21	3.7	−0.1	11.36	*60* (*62*) [−3.2%]	✓	0.596 (0.610) [−2.3%]	✓
	0.21	3.4	−0.053	33.251	**110** (**114**) [−3.5%]	✓	*0.365* (*0.377*) [−3.2%]	✓
Fuzzy DM	0.054	5.4	−2.3	13.116	8 (9) [−11.1%]	✓	0.691 (0.708) [−2.4%]	✓
	0.040	5.4	−2.1	18.106	21 (23) [−8.7%]	✓	0.543 (0.565) [−3.9%]	✓
	0.030	5.5	−1.9	25.016	56 (60) [−6.7%]	✓	*0.376* (0.399) [−5.8%]	✗
	0.022	5.6	−1.7	34.590	**121** (**126**) [−4.0%]	✓	*0.228* (*0.250*) [−8.8%]	✓
ETHOS models	0.0072	1.1	−9.9	7.274	18 (19) [−5.3%]	✓	0.780 (0.788) [−1.0%]	✓
	0.013	2.1	−9.3	16.880	36 (39) [−7.7%]	✓	0.568 (0.581) [−2.2%]	✓
	0.014	2.9	−10.0	21.584	50 (53) [−5.7%]	✓	0.463 (0.477) [−2.9%]	✓
	0.016	3.4	−9.3	23.045	53 (56) [−5.4%]	✓	0.430 (0.439) [−2.1%]	✓

What next

- We have introduced a new analytical fitting formula for the transfer function, which is able to reproduce a large variety of shapes in the suppression of the matter power spectrum.
- We have shown that it covers the parameter space of the most viable DM candidates, such as sterile neutrinos (whether resonantly produced or from scalar decays), mixed cold+warm models, fuzzy dark matter.
- We have presented the first, preliminary, astrophysical constraints on its free parameters by using two key observables: the number of MW satellites and the Lyman-α forest.
- What now:
  - A full statistical analysis of Lyman-α forest data, by performing 55 hydrodynamical simulations in order to extract the flux power spectra for our "non-cold" scenarios and determine more accurate limits on $\{\alpha, \beta, \gamma\}$.
  - A weak lensing data analysis, which will provide another independent observable for constraining the parameter space.

Thanks for the attention!

Gratzias meda po s'attentzioni!

Results from N-body simulations

Non-linear power spectra and halo mass functions extracted from 55 DM-only simulations with 512^3 particles in a 20 Mpc/h box, each of them corresponding to a different $\{\alpha, \beta, \gamma\}$--combination, i.e. a different "non-cold" scenario