A general approach for testing "non-cold" dark matter at small cosmological scales

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based on:
Murgia et al. (2017) [arXiv:1704.07838]

ASTRO-TS
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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 power spectra: "non-cold" DM (nCDM)

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

nCDM $\Leftrightarrow$ 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 $T(k)$:

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

i.e. the square root of the ratio of the power spectrum in the presence of nCDM with respect to that in the presence of CDM only

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DIFFERENT nCDM 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:

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

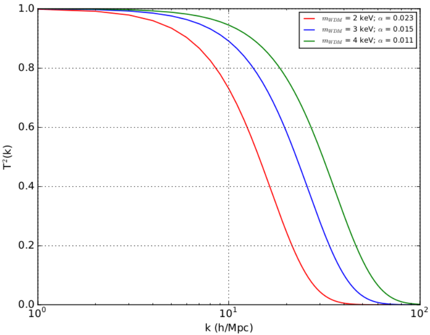
with:

$$\nu = 1.12 \;;$$

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

$\Downarrow$

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, several viable DM candidates do not have a thermal momentum distribution $\Longrightarrow$ the corresponding transfer functions may have non-trivial features!

Standard approach		**New general approach**
$T(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$	$\Rightarrow$	$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$

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

Standard approach $\Rightarrow$ **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

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

$\Rightarrow$

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

Standard approach

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

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

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

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

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

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

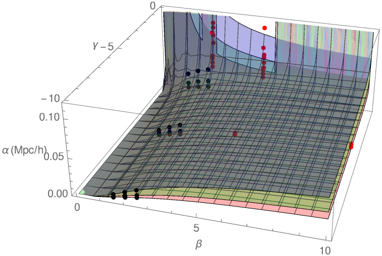
$\Rightarrow$

New general approach

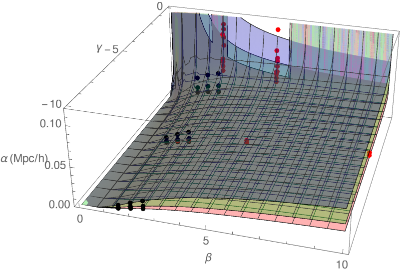
$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

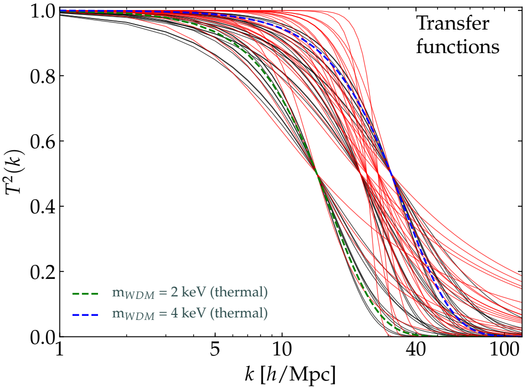
$$T^2(k) = 0.5$$
$$\Updownarrow$$
$$k_{1/2} = ((0.5)^{1/2\gamma} - 1)^{1/\beta})\alpha^{-1}$$

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



A new, general approach: method and parametrisation (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 popular non-thermal DM scenarios provided by theoretical particle physics:

- **Sterile neutrinos by resonant production**
- **Sterile neutrinos from particle decay production**
- **Mixed (cold + warm) DM**
- **Fuzzy DM**

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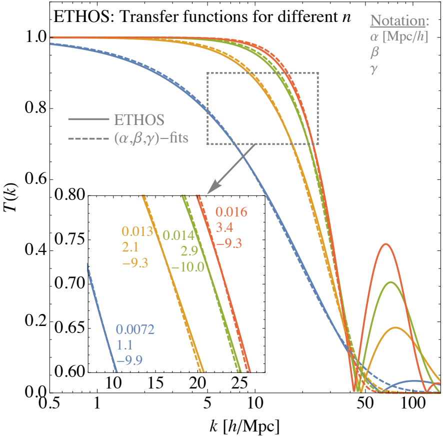
- **Effective THeory Of Structure formation (ETHOS)***



* **Vogelsberger et al. (2015), Cyr-Racine et al. (2015)**

Connection with particle physics models (II)

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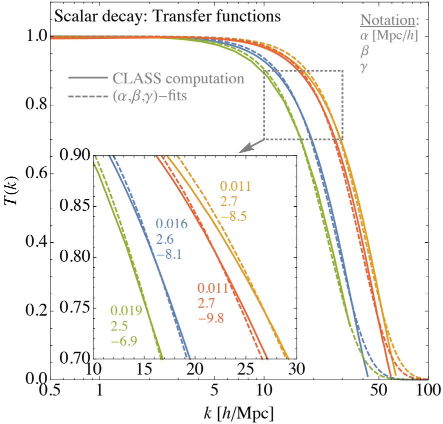

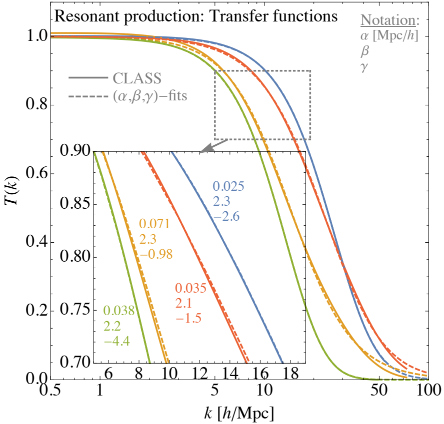

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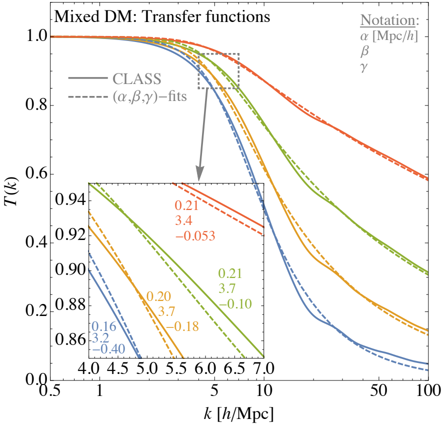
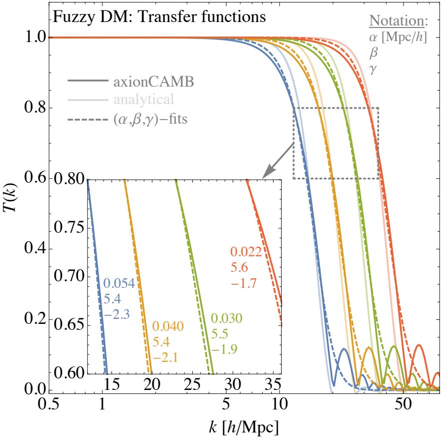
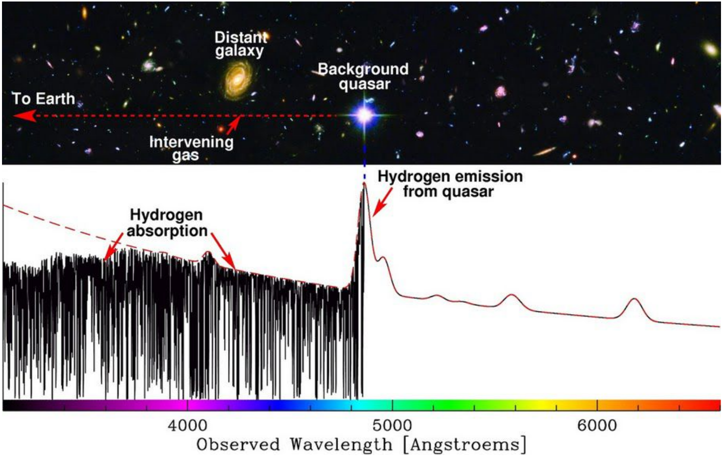




Bounds from the Lyman-α forest - Overview

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)

Bounds from the Lyman-α forest - The "Area Criterion" (I)

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

$$P_{\rm F}(k) = b^2(k) P_{\rm 1D}(k) \qquad \text{with} \quad P_{\rm 1D}(k) = \frac{1}{2\pi}\int_k^{\infty} dk' k' P_{\rm 3D}(k')$$

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

– The bias $b^2(k)$ differs very little between standard CDM and our nCDM models, thus:

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

– Estimator of the suppression of the power spectrum, with respect to standard CDM:

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

– 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:

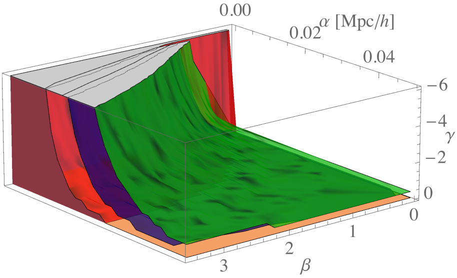
$$\delta A > \delta A_{\rm REF}$$

Bounds from the Lyman-α forest - The "Area Criterion" (II)

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)

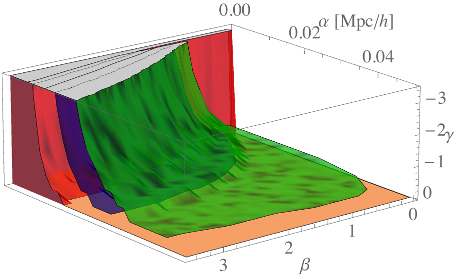
$$m_{\mathrm{WDM}} = 3.5\ \mathrm{keV} \Rightarrow \delta A_{\mathrm{REF}} = 0.38$$



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

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

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



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

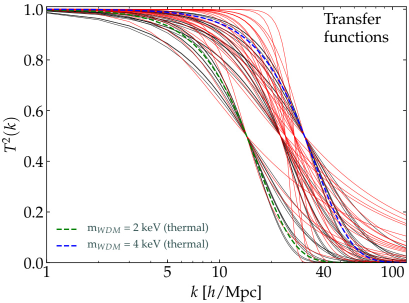
Reality-check

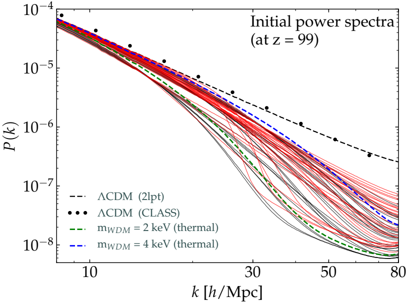
The fitting formula reproduces the true results to a very high degree!

	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%]	✓

Bounds from the Lyman-α forest - Towards a full MCMC analysis (I)

- We modified the numerical code `2LPT`[1], which generates initial conditions for cosmological simulations, by implementing the new transfer function: now it takes as inputs $\{\alpha, \beta, \gamma\}$ instead of $m_{\rm WDM}$, and it computes the corresponding $T(k)$ with the new, general fitting formula





- We used these initial conditions for running 55 full hydrodynamical simulations (512^3 particles in a 20 Mpc/h box, up to redshift $z = 2$) with `GADGET-3`[2], in order to extract the corresponding flux power spectra

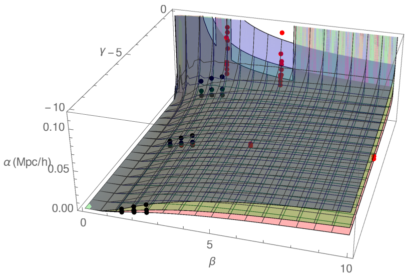
[1] Crocce et al. (2006)

[2] Springel et al. (2000), Springel (2005)

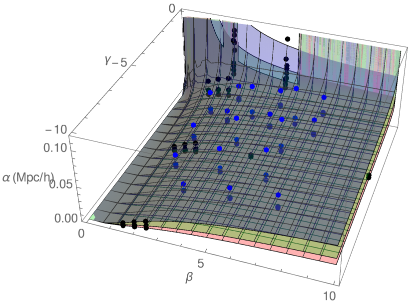
Bounds from the Lyman-α forest - Towards a full MCMC analysis (II)

What now:

- Performing 55 additional simulations, in order to refine the $\{\alpha, \beta, \gamma\}$ grid (**almost done**)



$\Rightarrow$



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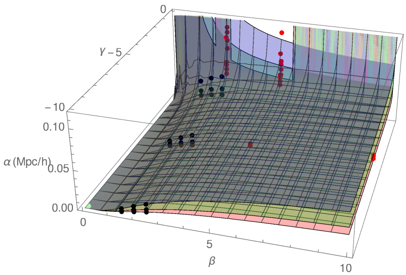

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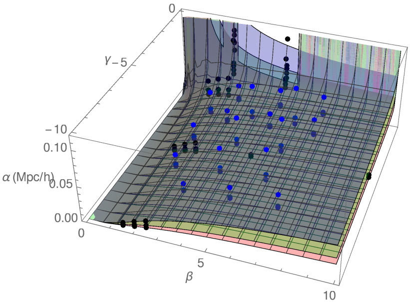

- Developing an accurate interpolation method for estimating the expected flux power spectrum in any $\{\alpha, \beta, \gamma\}$-point sampling the volume embraced by the grid of simulations (**work in progress**)

Bounds from the Lyman-α forest - Towards a full MCMC analysis (II)

What now:

- Performing 55 additional simulations, in order to refine the $\{\alpha, \beta, \gamma\}$ grid (**almost done**)
- Developing an accurate interpolation method for estimating the expected flux power spectrum in any $\{\alpha, \beta, \gamma\}$-point sampling the volume embraced by the grid of simulations (**work in progress**)

Ordinary Kriging method $\Rightarrow$ $P_F(k, z, \{\alpha, \beta, \gamma\}) = \sum_{i=1}^{110} \lambda_i P_F(k, z, \{\alpha, \beta, \gamma\}_i)$ with:

$$\lambda_i \equiv \frac{D(\{\alpha, \beta, \gamma\}_i, \{\alpha, \beta, \gamma\})^{-1}}{\sum_{j=1}^{110} D(\{\alpha, \beta, \gamma\}_j, \{\alpha, \beta, \gamma\})^{-1}};$$

$$\sum_{i=1}^{110} \lambda_i = 1;$$

$$D(\{\alpha, \beta, \gamma\}', \{\alpha, \beta, \gamma\}) \equiv ([(\alpha'_{norm} - \alpha_{norm})^2 + (\beta'_{norm} - \beta_{norm})^2 + (\gamma'_{norm} - \gamma_{norm})^2]^{1/2} + \epsilon)^{\xi};$$

$$\xi = 4; \quad \epsilon = 10^{-9}; \quad \alpha_{norm} \equiv \frac{\alpha}{\alpha_{max} - \alpha_{min}}, \ \ldots$$

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$$\xi = 4; \quad \epsilon = 10^{-9}; \quad \alpha_{norm} \equiv \frac{\alpha}{\alpha_{max} - \alpha_{min}}, \ \ldots$$

- Carrying out a comprehensive Monte Carlo Markov Chain (MCMC) analysis of the Lyman-α forest data, in order to extract absolute constraints on $\{\alpha, \beta, \gamma\}$ easily translatable to bounds on the fundamental nCDM properties, through the scheme that we have illustrated

Thanks for the attention!

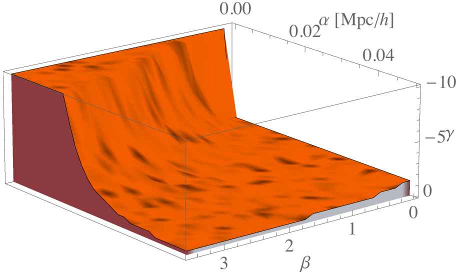
BACKUP SLIDES

Bounds from MW satellite counts (based on linear perturbation theory)

Any nCDM 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. $N_{\rm sub} < N_{\rm obs} \simeq 60$ $\quad (M_{\rm MW} = 1.7 \cdot 10^{12} M_{\rm sun})$ **[Schneider (2016)]**

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

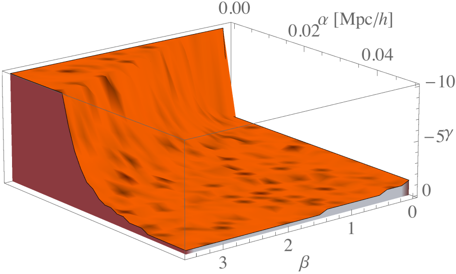
$N_{\rm sat} = 57$



$\alpha \leq 0.061$ Mpc/h (95% C.L.)

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

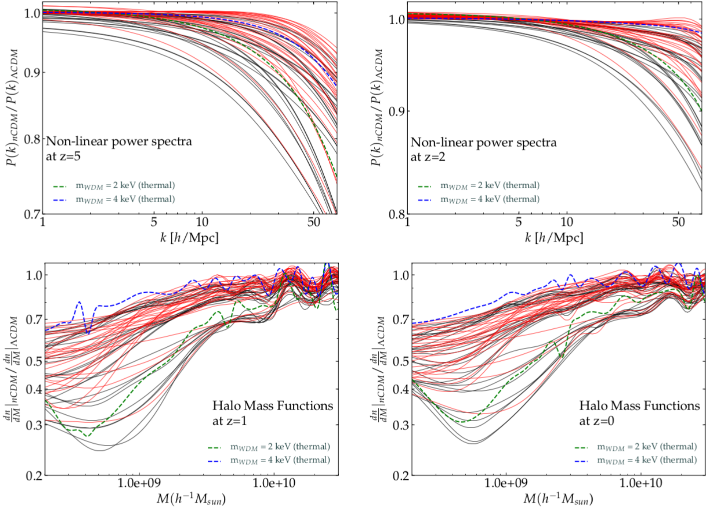
$N_{\rm sat} = 63$



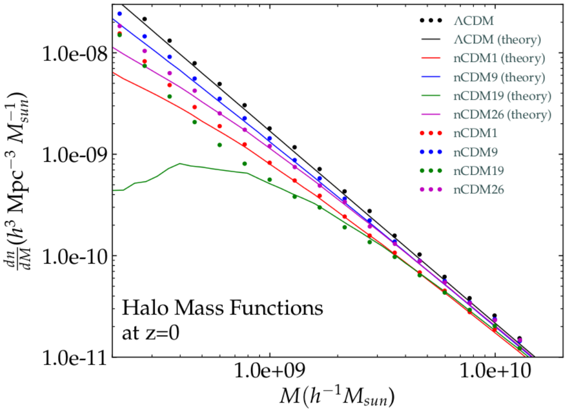
$\alpha \leq 0.067$ Mpc/h (95% C.L.)

DM-only simulations - Results

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 nCDM scenario.



DM-only simulations - Comparison with theoretical predictions



$$\frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{sub}}} = \frac{1}{44.5}\frac{1}{6\pi^2}\frac{M_{\mathrm{halo}}}{M_{\mathrm{sub}}^2}\frac{P(1/R_{\mathrm{sub}})}{R_{\mathrm{sub}}^3\sqrt{2\pi(S_{\mathrm{sub}}-S_{\mathrm{halo}})}}$$

[Schneider (2016)]