



A general framework for modeling the small-scale power in non-standard cosmologies

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(mainly) based on:

RM,Merle,Viel,Totzauer,Schneider, 2017, **JCAP 1711 046 (2017)** [arXiv:1704.07838]

RM,Viel,Iršič, 2018, **PRD 98 8 083540 (2018)** [arXiv:1806.08371]

Archidiacono,Hooper,RM,Bohr,Lesgourgues,Viel, 2019 **submitted to JCAP** [arXiv:1907.01496]

EPS-HEP Conference
Gent, July 12th, 2019

“Non-Cold” Dark Matter (nCDM)

CDM \Leftrightarrow velocity dispersion so small that the corresponding free-streaming length λ_{fs} is negligible for cosmological structure formation

nCDM \Leftrightarrow suppression of the matter power spectrum $P(k)$ on scales smaller than its free-streaming length, which is NON-negligible for structure formation ($\lambda_{\text{fs}} \approx \text{Mpc}$)

The small-scale suppression is described by the so-called transfer function $T(k)$:

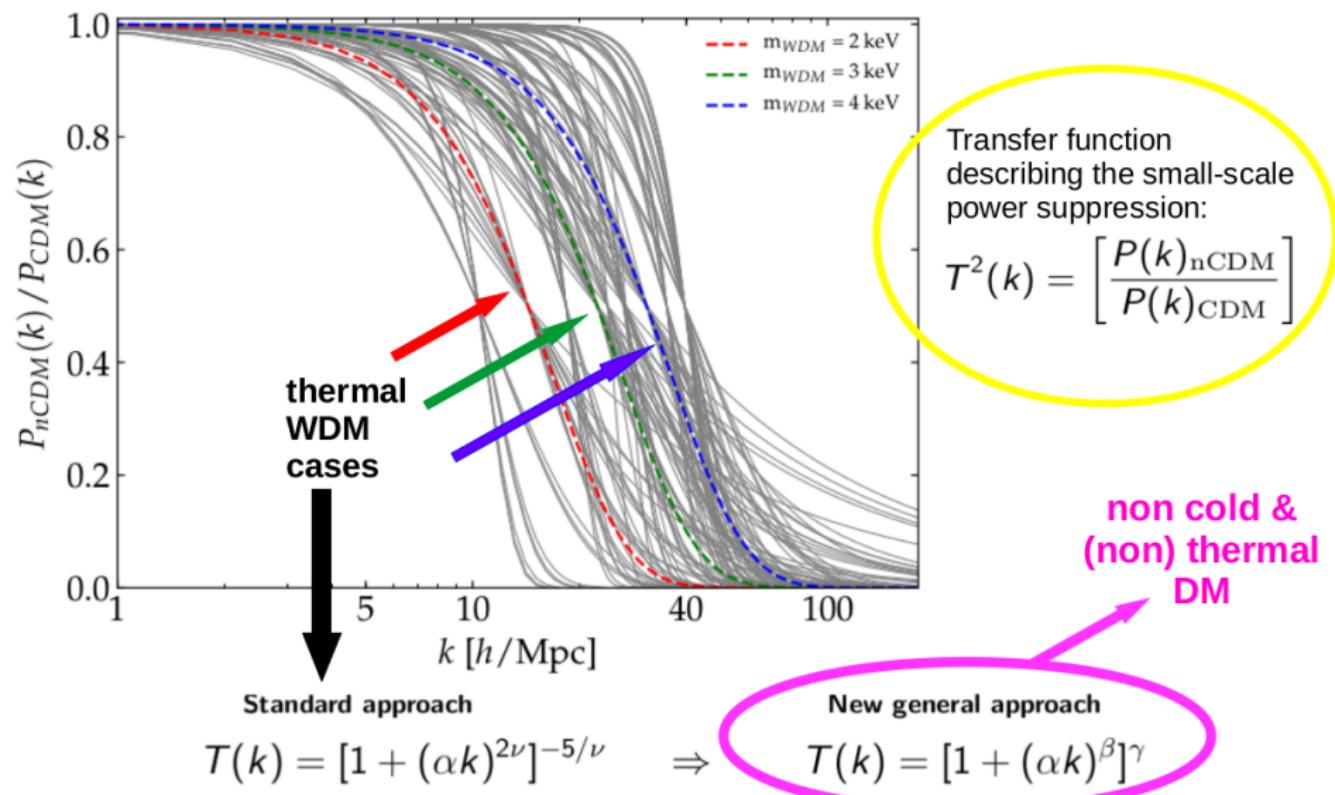
$$T^2(k) = \left[\frac{P(k)_{\text{nCDM}}}{P(k)_{\text{CDM}}} \right]$$

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 standard CDM only

DIFFERENT nCDM SCENARIOS
 \Downarrow

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

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



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

Standard approach

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

New general approach

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

Standard approach

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New general approach

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

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

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

Standard approach

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

New general approach

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

$$T^2(k) = 0.5$$



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

$$T^2(k) = 0.5$$

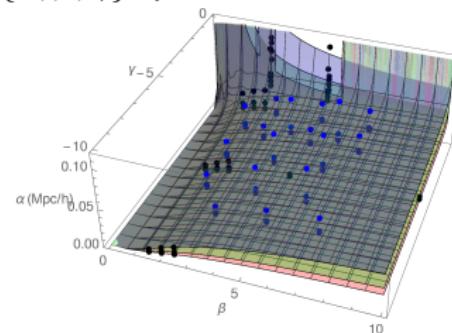


$$k_{1/2} = ((0.5)^{1/2\gamma} - 1)^{1/\beta} \alpha^{-1}$$

- one-to-one correspondence

$$\alpha \leftrightarrow m_{\text{WDM}} \leftrightarrow k_{1/2}$$

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



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

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

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

Connection with particle physics models

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:

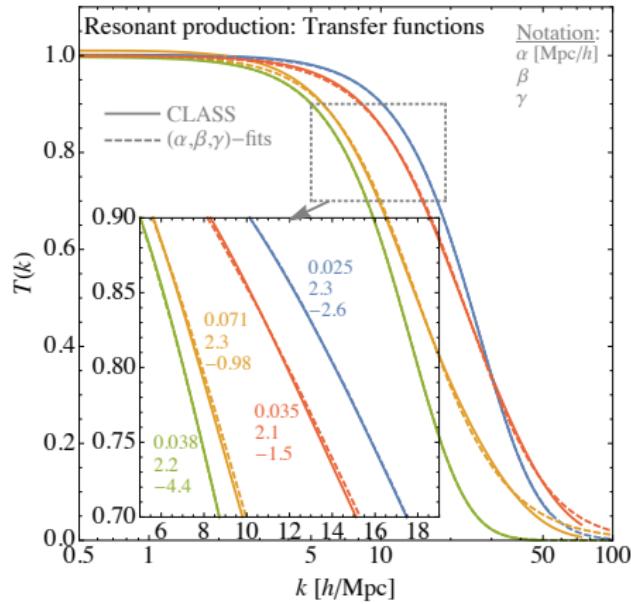
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- Sterile neutrinos by resonant production

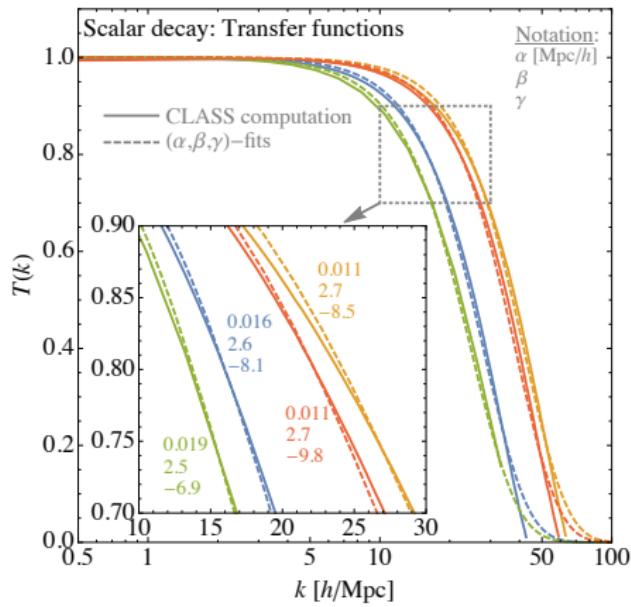


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- **Sterile neutrinos by resonant production**
- **Sterile neutrinos from particle decay production**

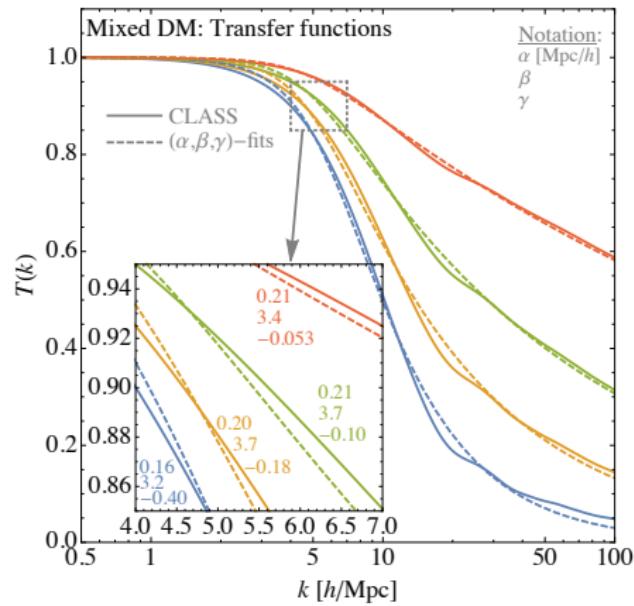


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- **Sterile neutrinos from particle decay production**
- **Mixed (cold + warm) DM**

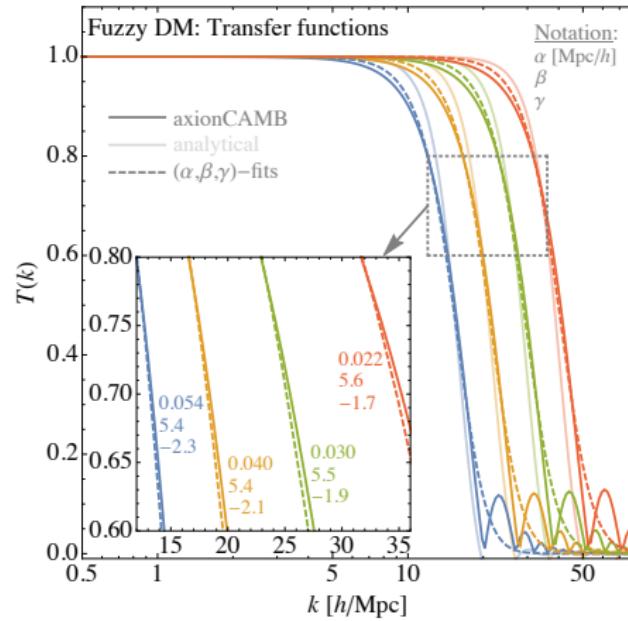


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- **Sterile neutrinos by resonant production**
- **Sterile neutrinos from particle decay production**
- **Mixed (cold + warm) DM**
- **Fuzzy DM**

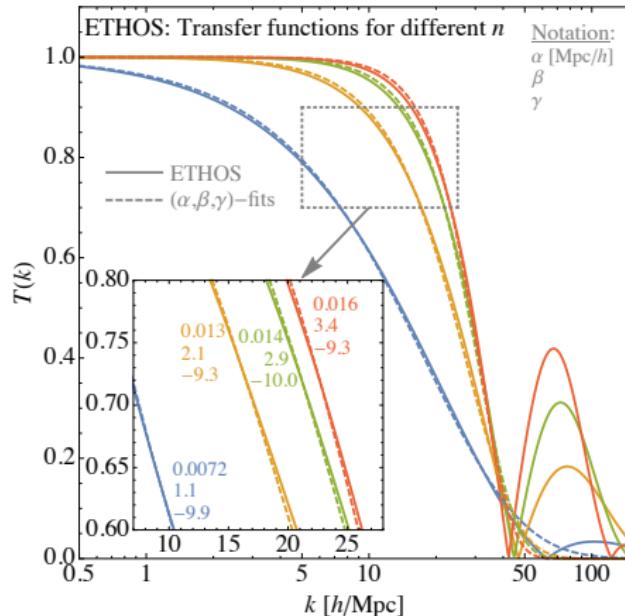


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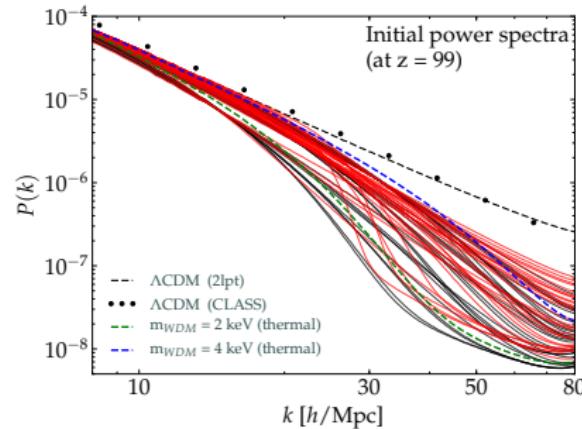
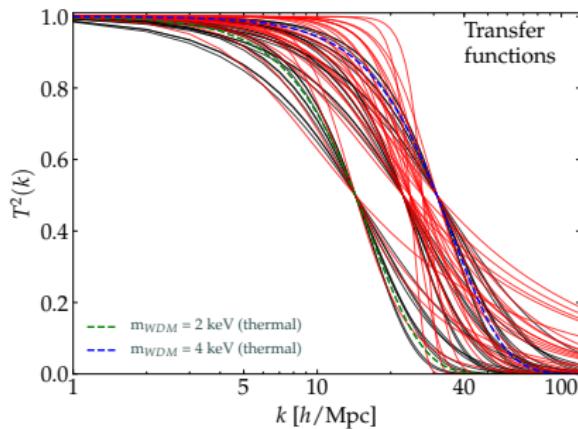
- Sterile neutrinos by resonant production
- Sterile neutrinos from particle decay production
- Mixed (cold + warm) DM
- Fuzzy DM
- Effective Theory Of Structure formation (ETHOS)*



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

Hydrodynamical simulations (I)

- We modified the numerical code 2LPTic¹, which generates initial conditions (ICs) for cosmological simulations, by implementing the new transfer function: now it takes as inputs $\{\alpha, \beta, \gamma\}$ instead of m_{WDM} , and it computes the corresponding $T(k)$ with the new, general fitting formula

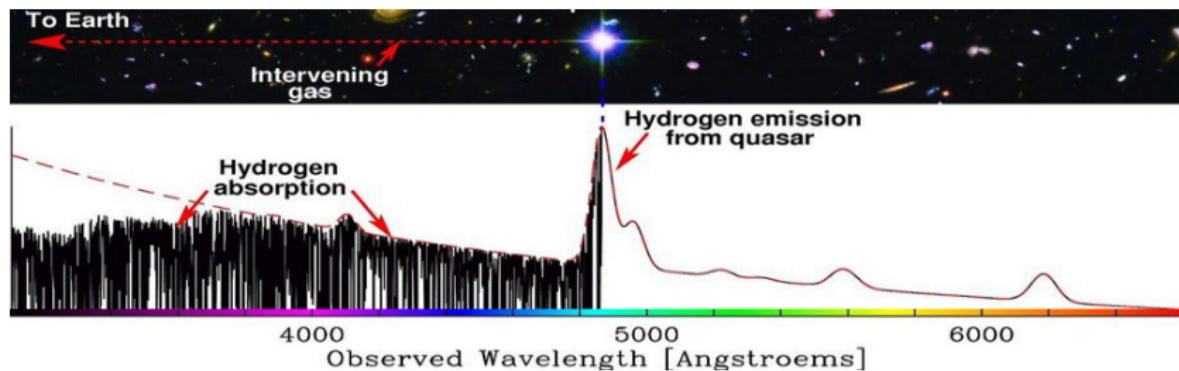


- We used these initial conditions for building a grid of hydrodynamical simulations efficiently sampling the $\{\alpha, \beta, \gamma\}$ -space, performed with GADGET-3² (512^3 particles in a $20 \text{ Mpc}/h$ box, up to redshift $z = 2$).

¹Crocce et al. (2006)

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

Hydrodynamical simulations (II)



- The goal is to confront our set of simulations against structure formation data, in order to put constraints on α , β and γ
- From each simulation, we extract the **1D flux power spectrum** $P_F(k, z)$, which is the physical observable for Lyman- α forest experiments.



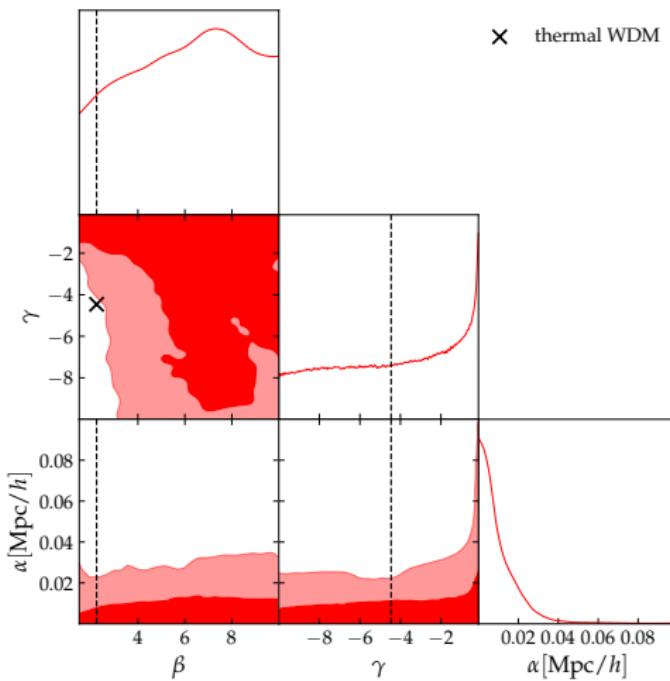
$$P_F(k, z, \alpha, \beta, \gamma, \bar{F}(z), T_{\text{IGM}}(z), \sigma_8, z_{\text{reio}}, n_{\text{eff}}, f_{\text{UV}})$$

↔ non-standard DM
 ↔ astrophysical
 ↔ cosmological

Constraints from Lyman- α forest data on $\{\alpha, \beta, \gamma\}$

We performed a Monte Carlo Markov Chain (MCMC) analysis of the high resolution and high-z MIKE-HIRES Lyman- α data, and extract absolute constraints on $\{\alpha, \beta, \gamma\}$

RM,Viel,Iršič, 2018, PRD 98 8 083540 [arXiv:1806.08371]



Constraint on the SHAPE of the power suppression

$$\begin{array}{c} |\beta/\gamma| < 14 \\ \alpha < 0.03 \text{ Mpc}/h \end{array}$$

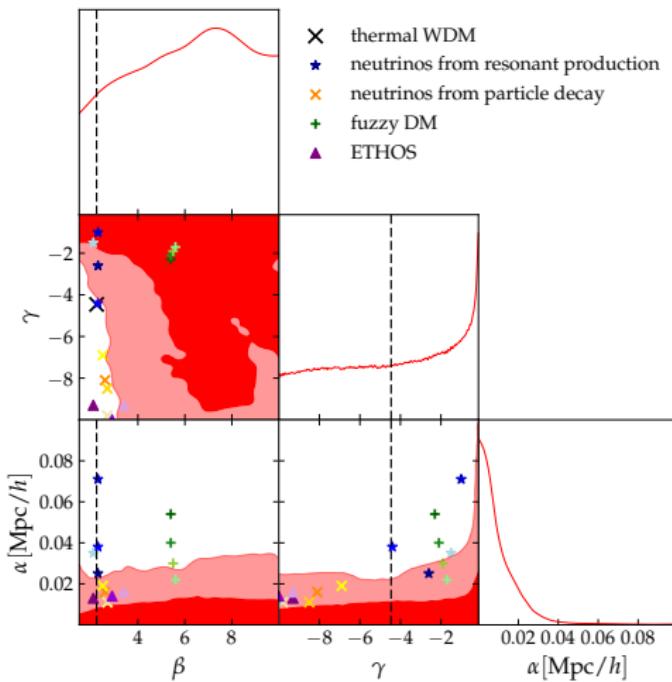
(2 σ C.L.)

Constraint on the SCALE of the power suppression

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Take-home message

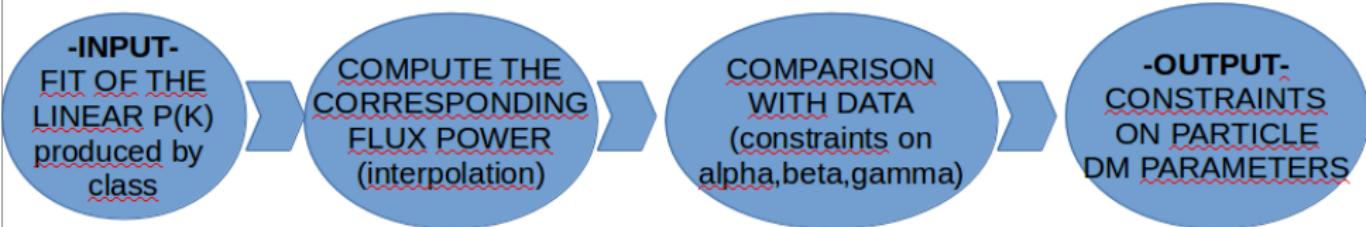


IF YES...

...no need to run new simulations to test the corresponding nCDM model with Lyman- α !

OK, but how can I systematically explore the DM particle parameter space?

Through a **new likelihood*** for the cosmological parameter inference code MontePython³, which translates the $\{\alpha, \beta, \gamma\}$ -limits to constraints on the fundamental DM scenario

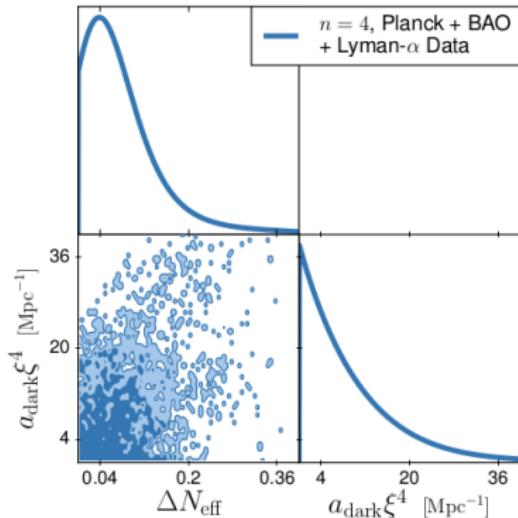
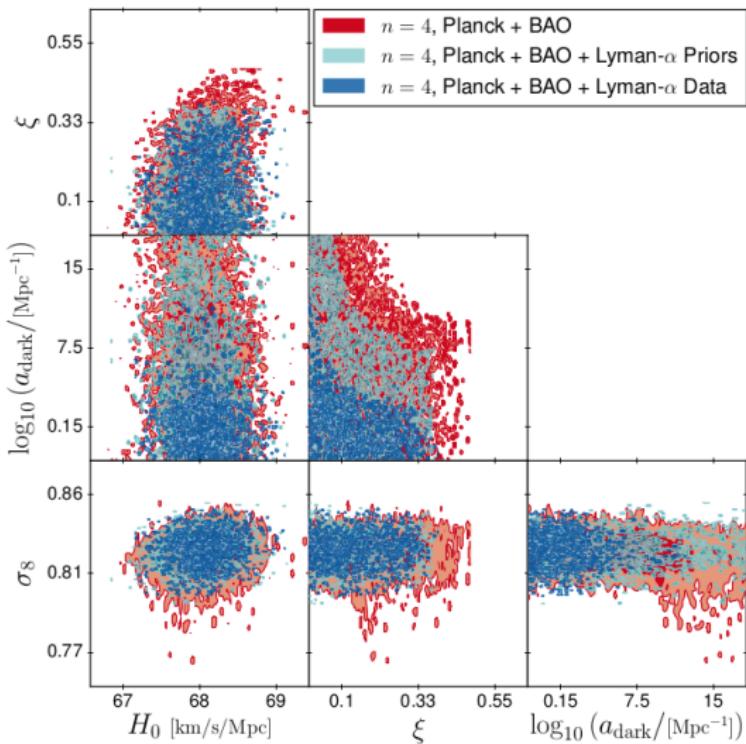


*Archidiacono, Hooper, RM, Bohr, Lesgourgues, Viel, 2019 [arXiv:1907.01496]

³Audren et al. (2013), Brinckmann & Lesgourgues (2018)

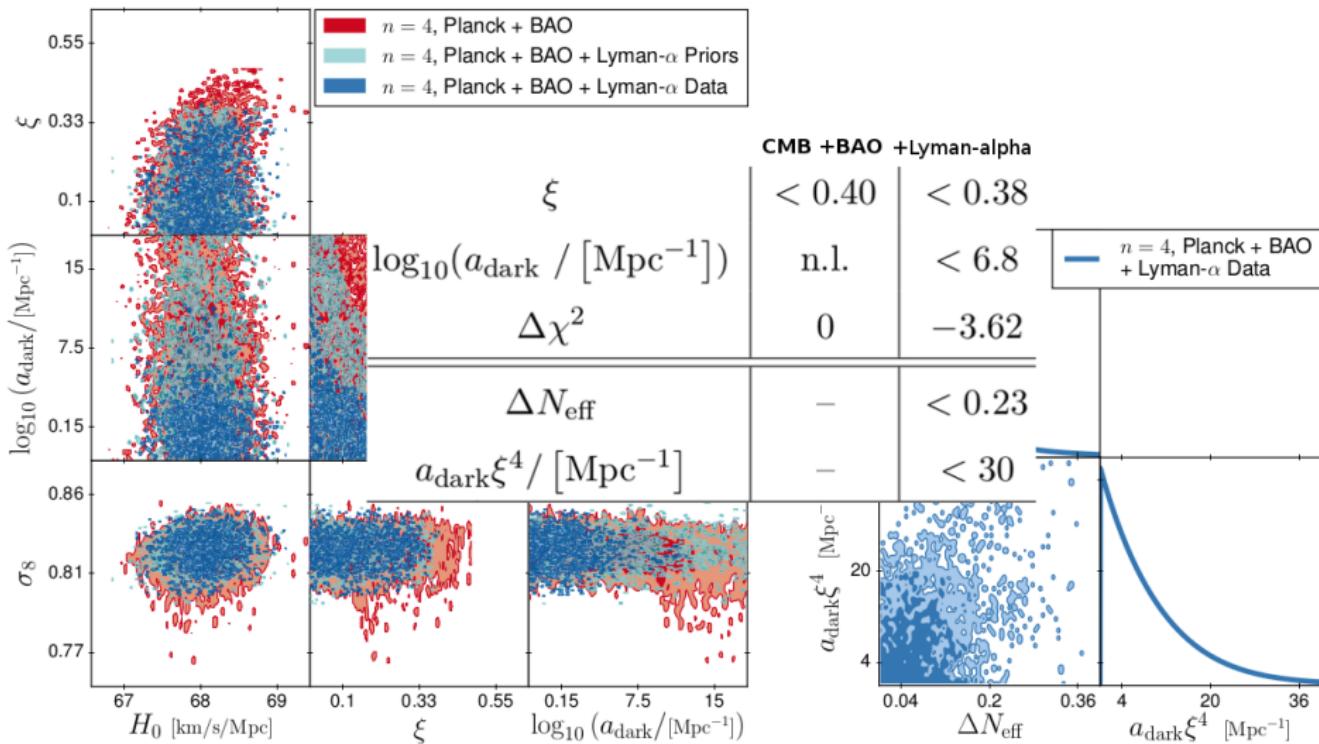
Constraints on DM-Dark Radiation interactions (ETHOS n=4)

Archidiacono, Hooper, RM, Bohr, Lesgourges, Viel, 2019 [arXiv:1907.01496]



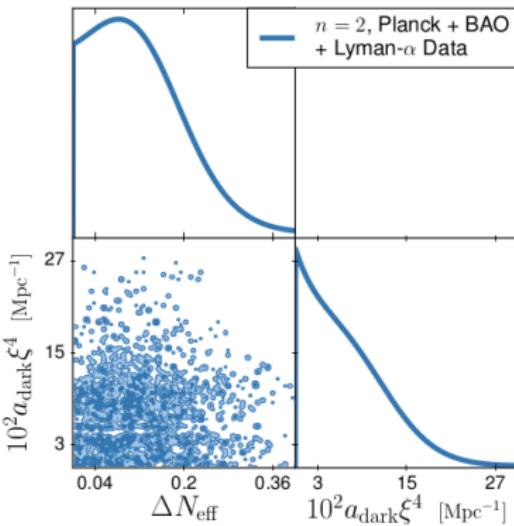
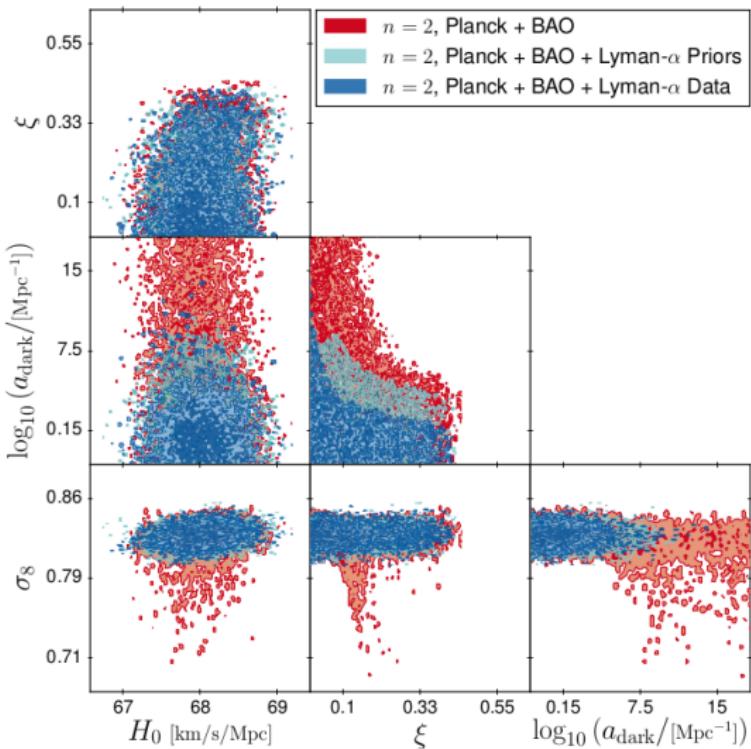
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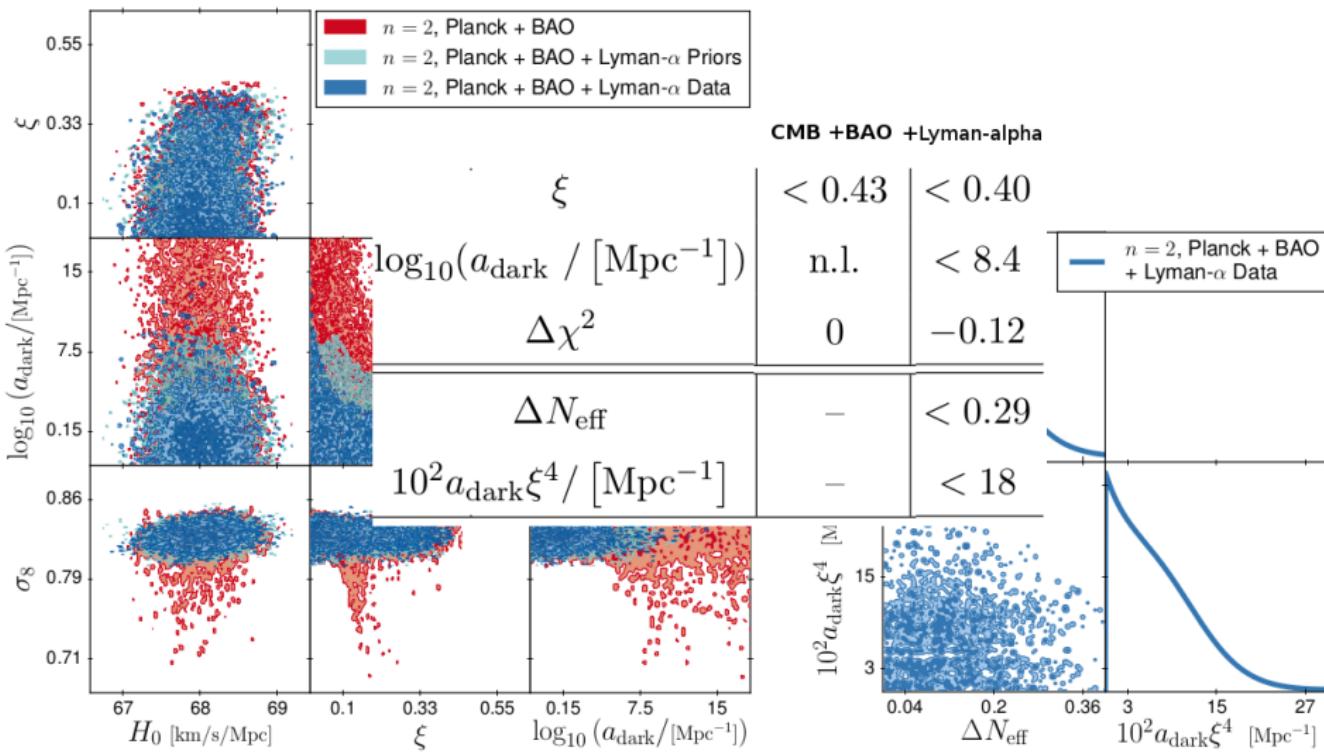
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Potential issues

- 1) Can we safely approximate the nCDM dynamics as standard, collisionless CDM during the non-linear structure evolution?
(e.g., for fuzzy DM models)

Nori, RM, Iršič, Baldi, Viel, 2018, MNRAS 482 3 [arXiv:1809.09619]

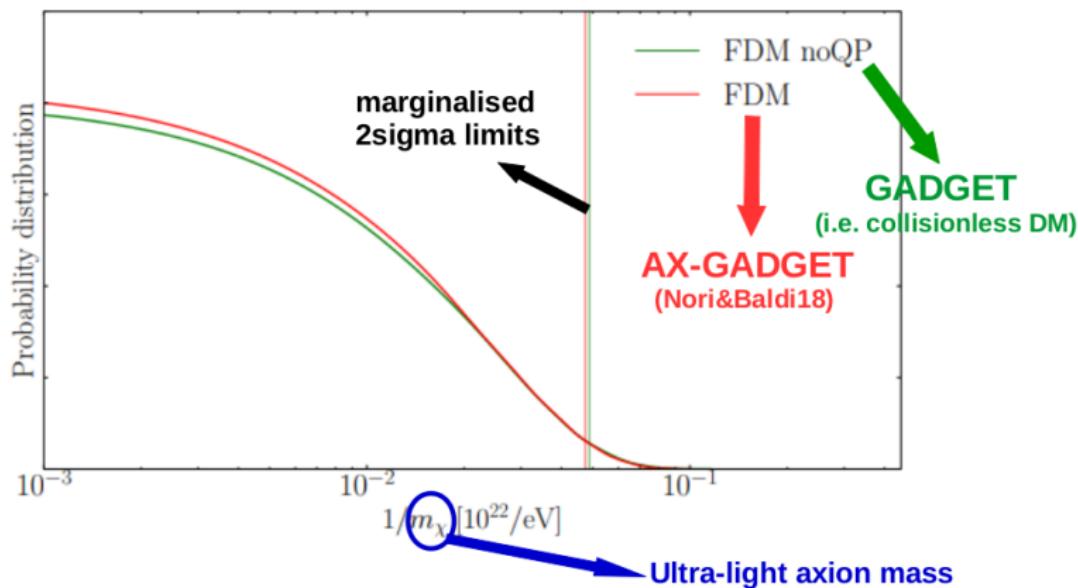
- 2) Can we safely neglect small-scale oscillations in the initial power spectra?
(e.g., in ETHOS models)

RM, Viel, Iršič, 2018, PRD 98 8 083540 [arXiv:1806.08371]

Archidiacono, Hooper, RM, Bohr, Lesgourgues, Viel, 2019 [arXiv:1907.01496]

- 3) Can we fit nCDM scenarios featuring a plateau in the transfer function?
(e.g., models with a nCDM fraction $f_{\text{nCDM}} < 100\%$)

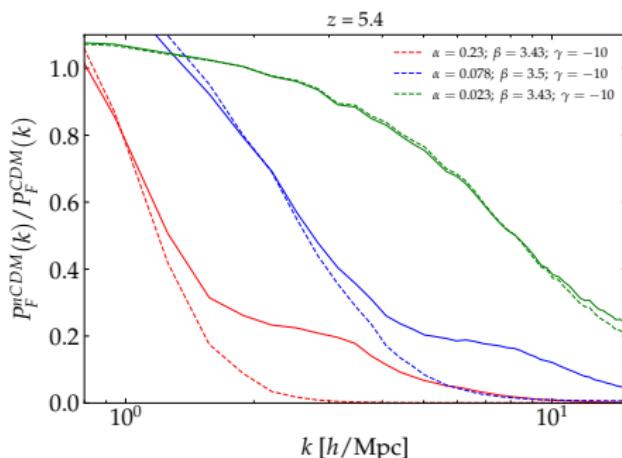
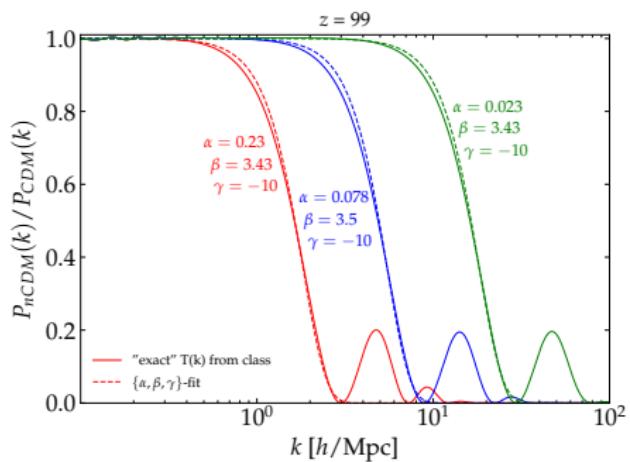
First potential issue: fuzzy DM dynamics (AX-GADGET)



QP → Quantum Pressure implemented in the non-linear dynamics (i.e. in AX-GADGET)

Nori, RM, Iršič, Baldi, Viel, 2018, MNRAS 482 3 [arXiv:1809.09619]

Second potential issue: small-scale oscillations (I)



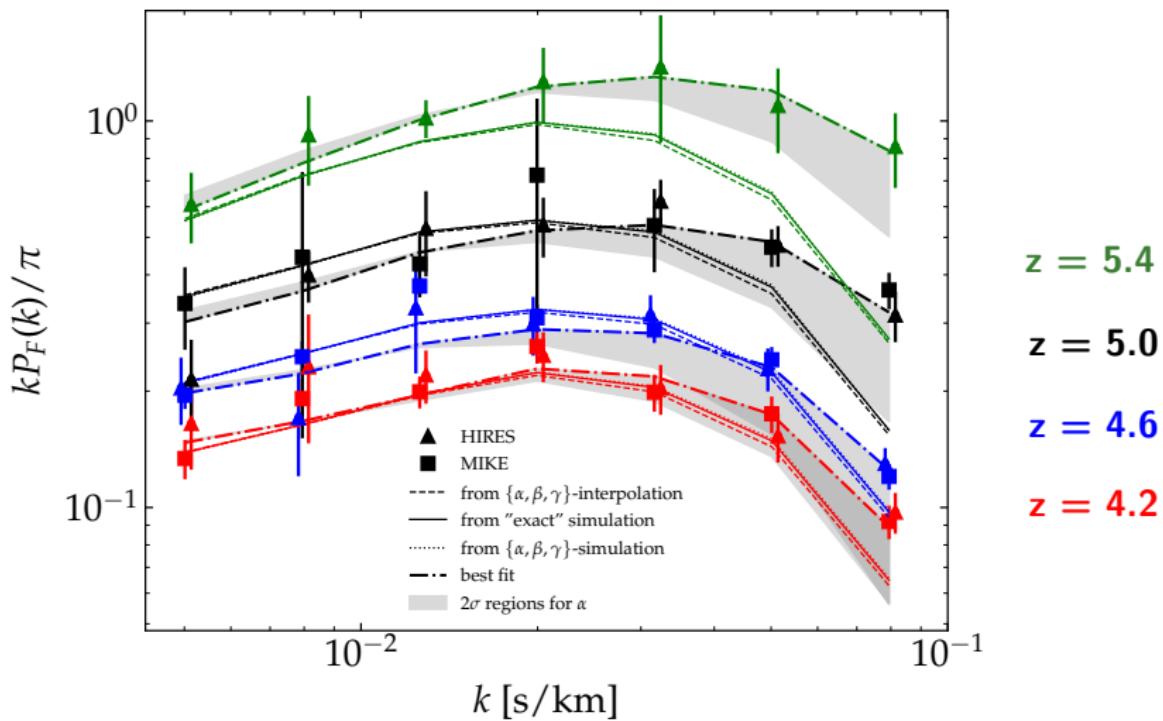
$$\begin{aligned} \alpha &= 0.23; \beta = 3.43; \gamma = -10; \\ \alpha &= 0.078; \beta = 3.5; \gamma = -10; \\ \alpha &= 0.023; \beta = 3.43; \gamma = -10 \end{aligned}$$



↑ DM-Dark Radiation interaction strength

RM,Viel,Iršič, 2018, PRD 98 8 083540 [arXiv:1806.08371]

Second potential issue: small-scale oscillations (II)

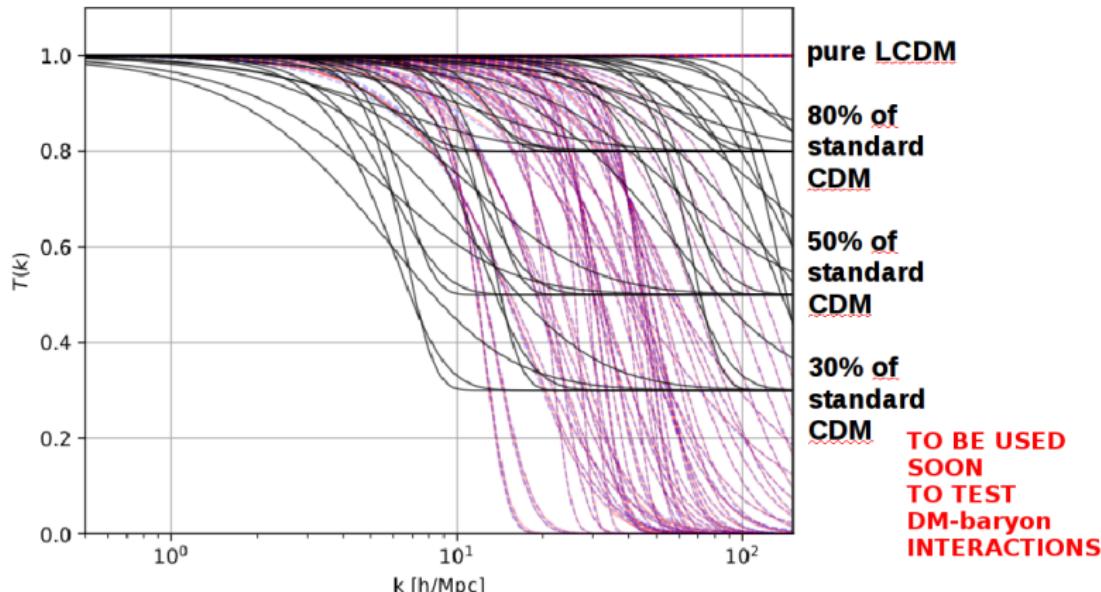


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Third potential issue: $f_{\text{nCDM}} < 100\%$

$$T(k) = [1 + (\alpha k)^\beta]^\gamma \quad \Rightarrow \quad T(k) = (1 - \delta) \cdot [1 + (\alpha k)^\beta]^{-1.5 \cdot \beta} + \delta$$

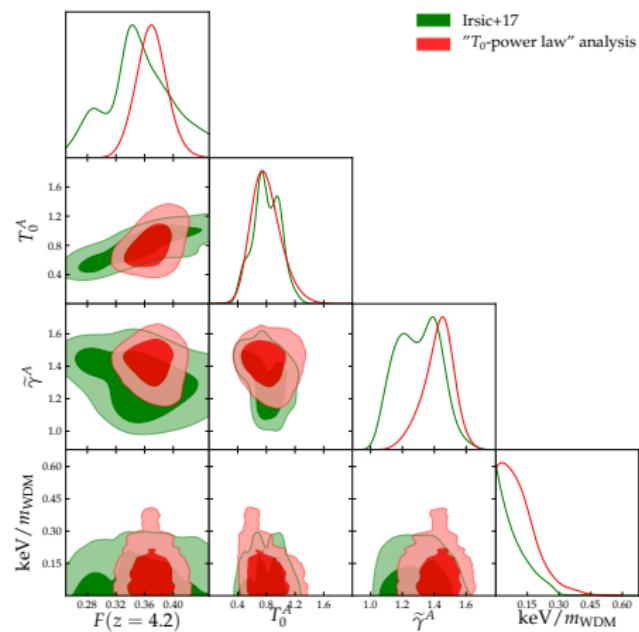
A better parameterization for fitting power suppressions featuring a plateau!



PRELIMINARY

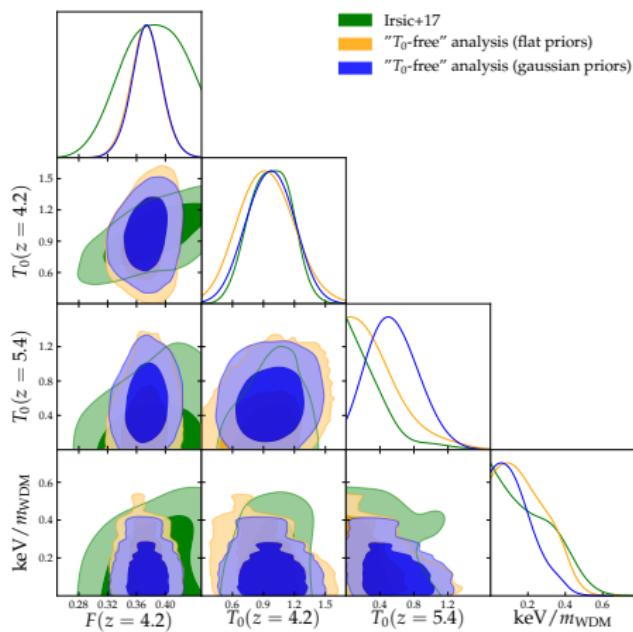
Thanks for the attention!

Reproducing the previous thermal WDM limits



Irsic+17: $m_{\text{WDM}} > 4.1 \text{ keV}$ (2σ)

RM+18: $m_{\text{WDM}} > 3.6 \text{ keV}$ (2σ)



Irsic+17: $m_{\text{WDM}} > 2.1 \text{ keV}$ (2σ)

RM+18: $m_{\text{WDM}} > 2.7 \text{ keV}$ ($m_{\text{WDM}} > 2.2 \text{ keV}$) (2σ)

RM,Viel,Irsič, 2018, PRD 98 8 083540 [arXiv:1806.08371]

Interpolation scheme & MCMC sampler

- 1) Accurate interpolation method for estimating the expected flux power spectrum in any $\{\alpha, \beta, \gamma\}$ -point sampling the volume embraced by the sparse, non-regular grid of simulations

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

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

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

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

$$\xi = 5; \quad \epsilon = 10^{-9}; \quad \alpha_{norm} \equiv \frac{\alpha}{\alpha_{max} - \alpha_{min}}, \dots$$

- 2) Comprehensive Monte Carlo Markov Chain (MCMC) analyses 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 (**emcee** sampler⁴)

⁴<http://dfm.io/emcee/current/>