From warm dark matter to dark radiation: General cosmological constraints on a second dark component in the Universe

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Based on work done in collaboration with:

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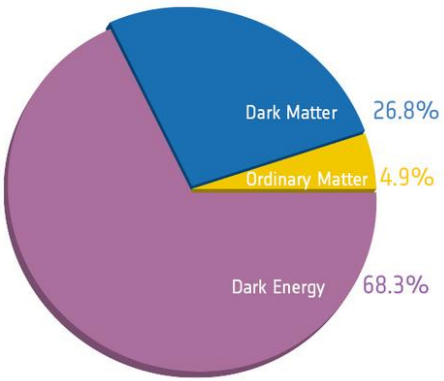
- Stefano Gariazzo - INFN - Universitá di Torino
- Olga Mena - IFIC - Universidad de Valéncia

[IN PREPARATION]

Outline

Cosmology (1)



[Planck Collaboration, 2015]

The simplest Standard Model Lambda Cold Dark Matter (ΛCDM) is described by 6 parameters:

- $\omega_b = \Omega_b h^2$ baryon density;
- $\omega_c = \Omega_c h^2$ CDM density;
- τ reionization optical depth;
- θ angular scale of acoustic peaks;
- n_s scalar spectral index;
- A_s curvature fluctuation amplitude.

Cosmology (2)

ΛCDM $\rightarrow$ radiation dominated at the beginning.

The density of relativistic species in the Universe:

- the photon contribution ρ_γ;
- the contribution of all the other relativistic species:

  $N_{\rm eff} \rightarrow$ all radiation contribution not given by photons;

The energy density of the total radiation component reads:

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = [1 + 0.227 N_{\rm eff}]\rho_\gamma$$

$N_{\rm eff} = 3.046 \rightarrow$ three active neutrino contribution.

Cosmology (3)

Additional extra radiation:

$$\Delta N_{\rm eff} = N_{\rm eff} - 3.046$$

non-standard value of $N_{\rm eff}$ may affect:

- Big Bang Nucleosynthesis $\rightarrow$ production of light nuclei
- Matter-Radiation equality:

$$1 + z_{eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{\omega_\gamma} \frac{1}{[1 + 0.227 N_{\rm eff}]\rho_\gamma}$$

- Change in the expansion rate at decoupling
  - $\rightarrow$ the CMB peaks position
- increased Silk damping at small scales.

Beyond ΛCDM Model (1)

Mixed Dark Matter (DM) model:

cold DM

+

non-cold DM

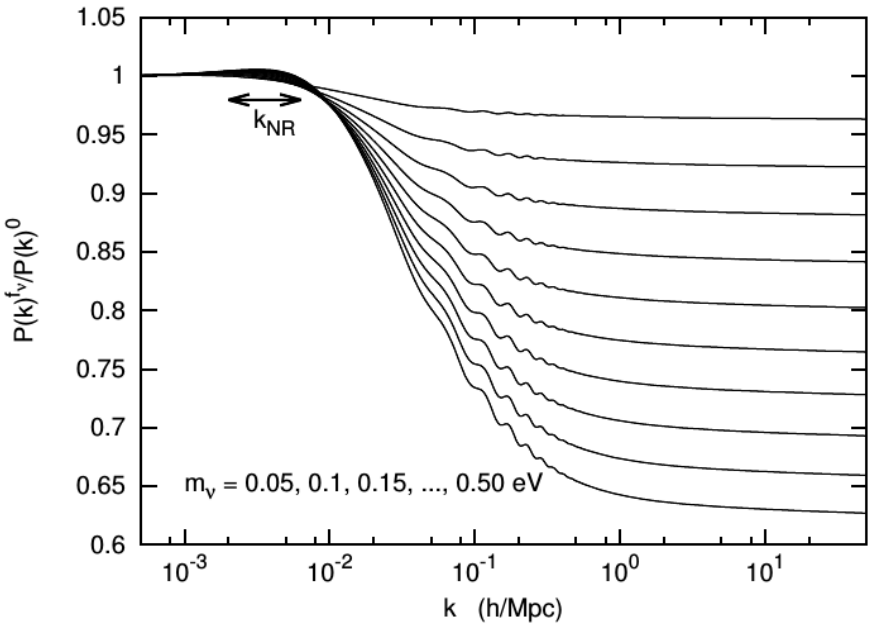
Warm DM , Hot DM or Dark Radiation ...

...depending on its free-streaming length

$$\lambda_{FS} = \int_{t_0}^{t_{eq}} \frac{v(t)}{a(t)}\, dt$$

Beyond ΛCDM Model (2)

Free-streaming length λ_{FS}
and
Matter power spectrum $P(k)$:



[Lesgourgues et al. "Neutrino Cosmology", 2013]

Beyond ΛCDM Model (3)

The density of CDM in the Universe: Ω_{cdm}

$$\Omega_{tot} = \Omega_{cdm} + \Omega_{ncdm} \text{ and } \Omega_{cdm} = (1 - f_{ncdm})\Omega_{tot}$$

$$f_{ncdm} = \frac{\Omega_{ncdm}}{\Omega_{cdm} + \Omega_{ncdm}}$$

- We simulate the non-cold DM component by fixing the temperature to $T_{ncdm} \sim 4000\, T^0_{cmb}$

  $\rightarrow T_{ncdm} = 1$ eV (today);

- The non-cold DM mass varies between 0.1 and 10^8 eV;

- The velocity today varies between 10^{-8} and 1

  $\rightarrow$ between <u>cold dark matter</u> and <u>dark radiation</u>;

Data

We perform our analysis by using:

Planck TT+lowP+lensing datasets:

bounds on the amount of energy density of relativistic species

+

bounds on m_{ncdm}

Small Scales Measurements of P(k)
(Satellite Number Counts)

+

BAO dataset:

bounds on the amount and on m_{ncdm} of non-cold DM

Tools

- `CLASS` for the computation of Boltzmann equations;

  [J. Lesgourgues, 1104.2932]

- `MontePython` for the computation of the likelihoods;

  [B. Audren et al., 1210.7183]

  Implemented `SAT` likelihood to obtain the number of satellites galaxies with constrain: predicted number $\geq$ observed number.

  [A. Schneider, 1412.2133]

- `Multinest` for an efficient sampling.

  [F. Feroz et al., 0809.3437]

Satellites counts

Estimate the number of satellites

Relation based on the **conditional mass function**:

$$\frac{dN_{sat}}{d\ln M_{sat}} = \frac{1}{45}\,\frac{1}{6\pi^2}\left(\frac{M_{hh}}{M_{sat}}\right)\frac{P(1/R_{sat})}{R_{sat}^3\sqrt{2\pi(S_{sat}-S_{hh})}}$$

hh = host halo $\quad sat$ = satellites

[A. Schneider, 1601.07553]

Variance & Mass:

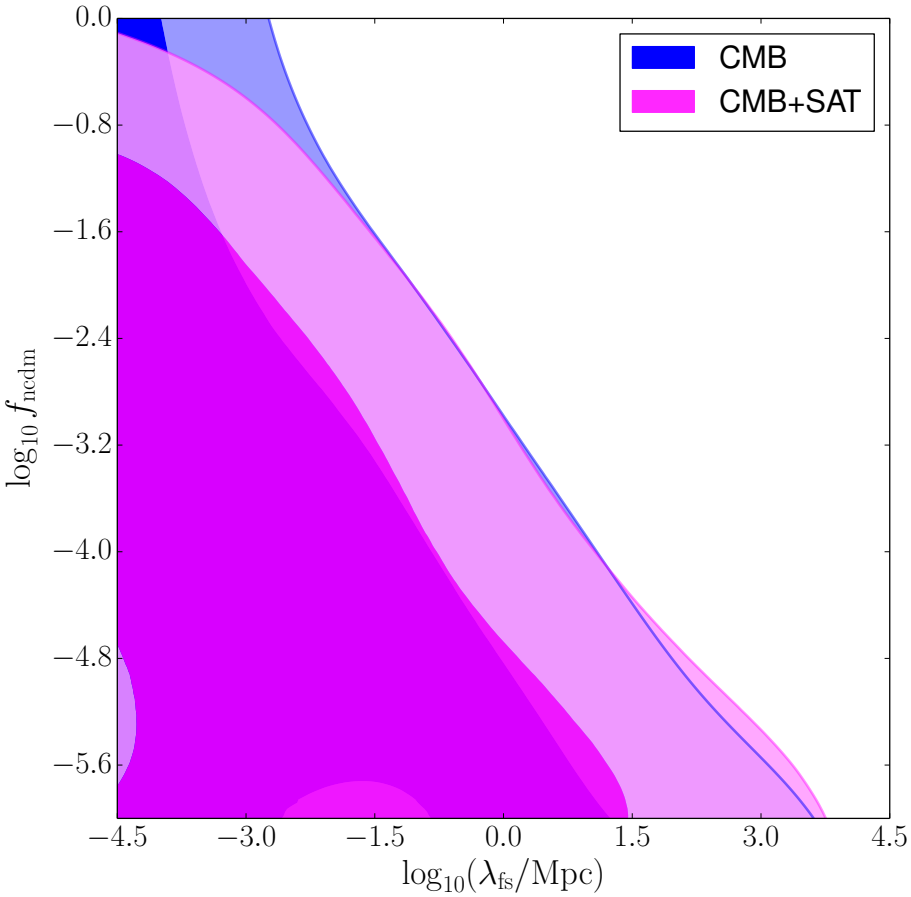
$$S_i = \frac{1}{2\pi^2}\int_0^{1/R_i} dk\,k^2\,P(k)\,, \quad M_i = \frac{4\pi}{3}\,\Omega_m\rho_c(cR_i)^3\,, \quad c = 2.5$$

$P(k)$ = linear power spectrum

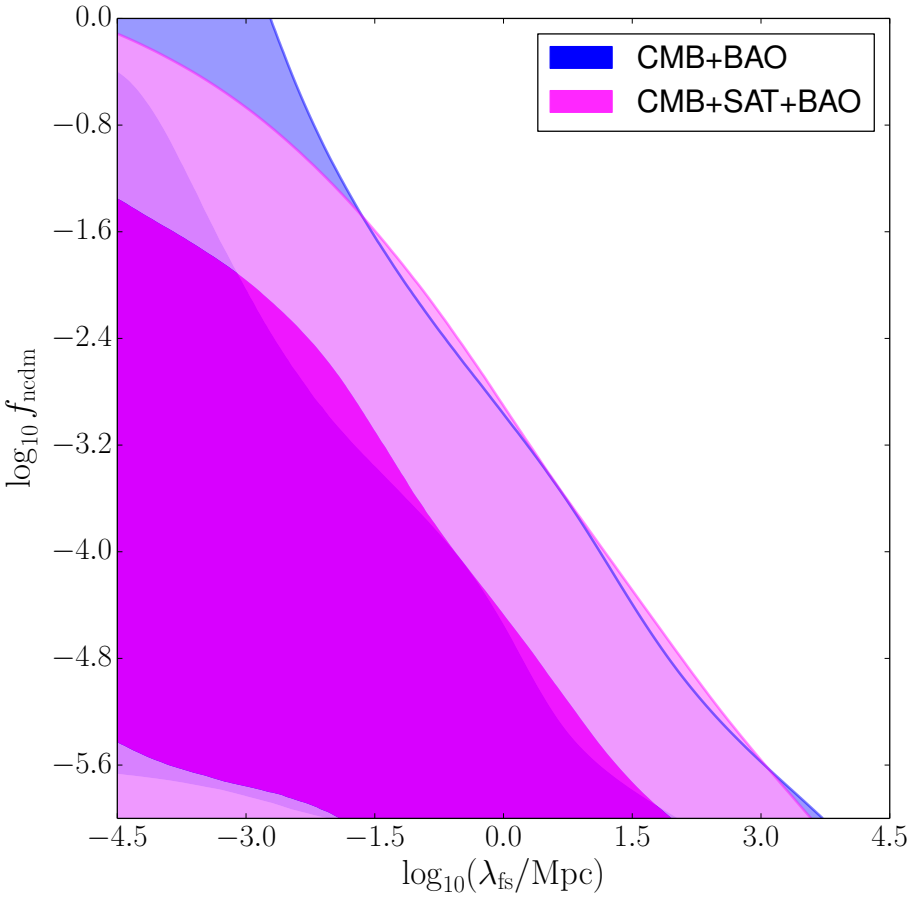
Approach based on the **sharp-k filter**:

$\rightarrow$ cut of $k < 1/R_{sh}$

Results (1)


CMB
CMB+SAT
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$\log_{10} f_{\rm ncdm}$
−4.5
−3.0
−1.5
0.0
1.5
3.0
4.5
$\log_{10}(\lambda_{\rm fs}/{\rm Mpc})$

Results (2)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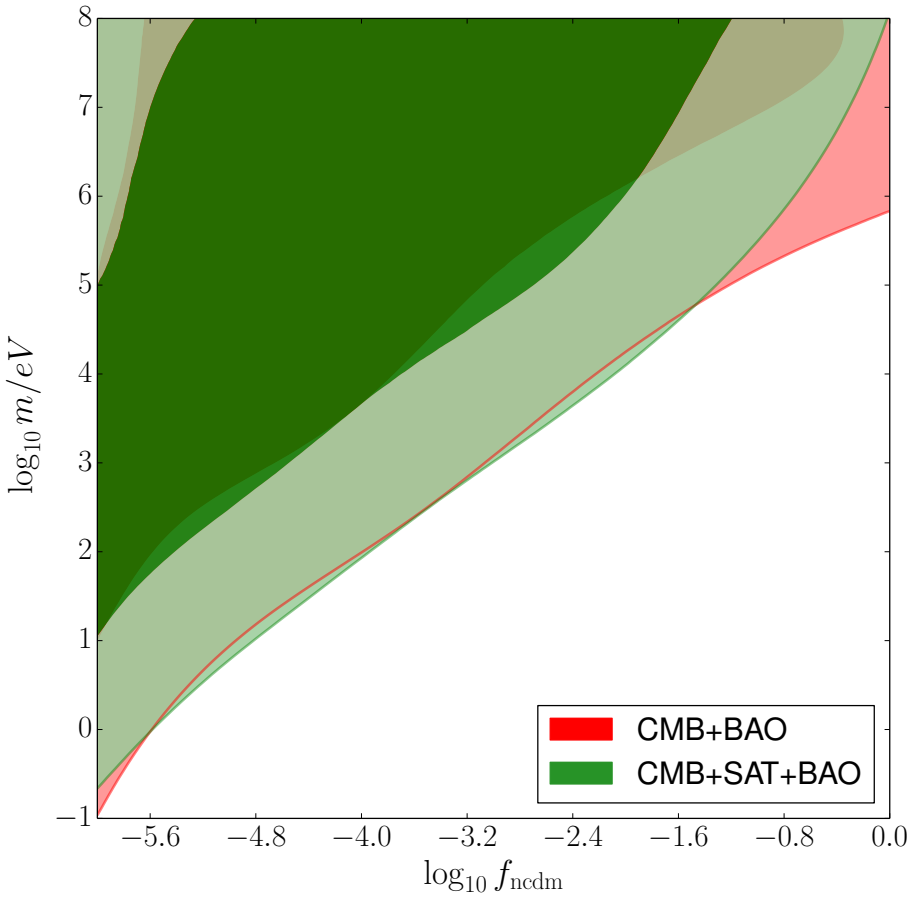
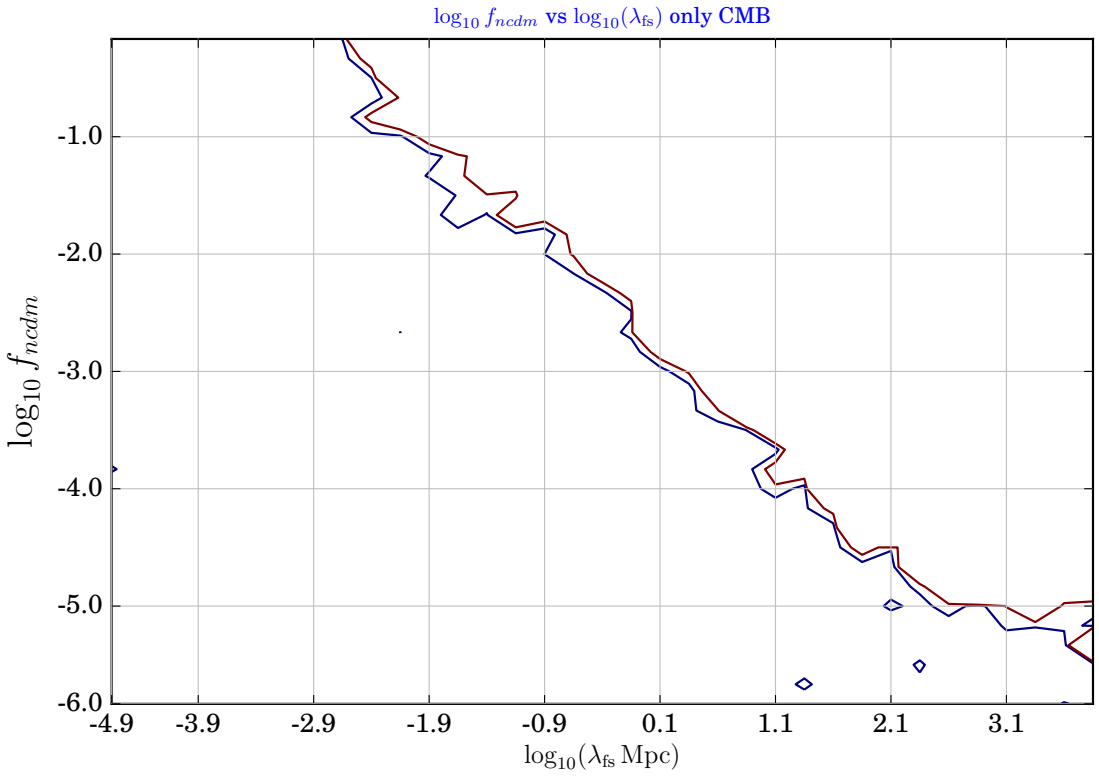
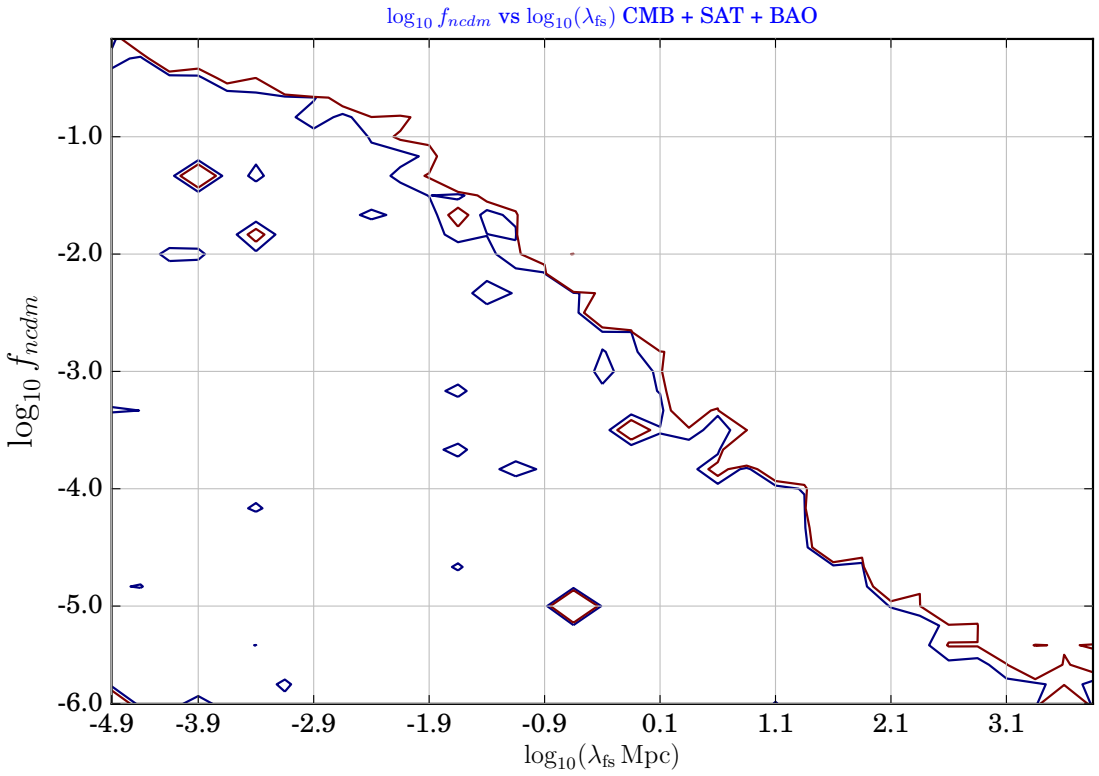
Results (3)


8
7
6
5
4
3
2
1
0
−1
$\log_{10} m/eV$
−5.6
−4.8
−4.0
−3.2
−2.4
−1.6
−0.8
0.0
$\log_{10} f_{\rm ncdm}$
CMB+BAO
CMB+SAT+BAO

Frequentist Analysis (1)



Frequentist Analysis (2)



Conclusions

- Constraints on the fraction, f_{ncdm}, in particular:
  - If λ_{FS} too high ($\sim$ 1Gpc, corresponding to a non-cold dark matter component which acts as dark radiation), the upper bound on f_{ncdm} would be very low (lower then 10^{-5});
  - If λ_{FS} too small ($\sim 10^{-5}$ Mpc $\sim$ 30 pc), the upper bound on f_{ncdm} would be high $\rightarrow$ "almost" 100% of the dark matter can be non-cold.
- For a relativistic component (v $\sim$ 1) the limit on f_{ncdm} is at values around a few times 10^{-5}:
  - As expected for dark radiation.
- **WORK STILL IN PROGRESS!!!**

MANY THANKS!!!