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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[IN PREPARATION]
Outline

1. Cosmology
2. MDM Model
3. Goals
4. Analysis
5. Results
Cosmology (1)

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;
- $\tau$ reionization optical depth;
- $\theta$ angular scale of acoustic peaks;
- $n_s$ scalar spectral index;
- $A_s$ curvature fluctuation amplitude.

[Planck Collaboration, 2015]
Cosmology (2)

ACDM $\rightarrow$ radiation dominated at the beginning.

The density of relativistic species in the Universe:

- the photon contribution $\rho_\gamma$;
- the contribution of all the other relativistic species:
  
  $N_{\text{eff}} \rightarrow$ all radiation contribution not given by photons;

The energy density of the total radiation component reads:

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

$N_{\text{eff}} = 3.046 \rightarrow$ three active neutrino contribution.
Cosmology (3)

Additional extra radiation:

\[ \Delta N_{\text{eff}} = N_{\text{eff}} - 3.046 \]

non-standard value of \( N_{\text{eff}} \) may affect:

- Big Bang Nucleosynthesis → production of light nuclei
- Matter-Radiation equality:

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

- Change in the expansion rate at decoupling
  - → 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 $\Lambda$CDM Model (2)

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

[Lesgourgues et al. “Neutrino Cosmology”, 2013]
Beyond ΛCDM Model (3)

The density of CDM in the Universe: $\Omega_{cdm}$

$$\Omega_{tot} = \Omega_{cdm} + \Omega_{ncdm}$$

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 $T_{ncdm} \sim 4000 T_{cmb}^0$
  $$\rightarrow T_{ncdm} = 1 \text{ eV (today)};$$

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

- The velocity today varies between $10^{-8}$ and $1$
  $$\rightarrow \text{between cold dark matter and dark radiation;}$$
Data

We perform our analysis by using:

**Planck TT+lowP+lensing datasets:**

- bounds on the amount of energy density of relativistic species
- \( m_{ncdm} \)

**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:

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

\(hh = \text{host halo} \quad sat = \text{satellites}\)

[A. Schneider, 1601.07553]

Variance & Mass:

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

\(P(k) = \text{linear power spectrum}\)

Approach based on the sharp-k filter:

\(\rightarrow \text{cut of } k < 1/R_{sh}\)
Results (1)

\[
\log_{10}(\lambda_{fs}/\text{Mpc})
\]

\[
\log_{10}(f_{n\text{cdm}})
\]

CMB

CMB+SAT

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Results (2)

\[
\text{CMB+BAO} \\
\text{CMB+SAT+BAO}
\]

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Results (3)
Frequentist Analysis (1)

$\log_{10} f_{\text{ncdm}}$ vs $\log_{10}(\lambda_{fs})$ only CMB

$\log_{10} f_{\text{ncdm}}$

$\log_{10}(\lambda_{fs} \text{ Mpc})$
Frequentist Analysis (2)

\[ \log_{10}(f_{\text{ncdm}}) \text{ vs } \log_{10}(\lambda_{fs} \text{ Mpc}) \]

CMB + SAT + BAO
Conclusions

- Constraints on the fraction, $f_{ncdm}$, in particular:
  - If $\lambda_{FS}$ too high ($\sim 1\text{Gpc}$, corresponding to a non-cold dark matter component which acts as dark radiation), the upper bound on $f_{ncdm}$ would be very low (lower than $10^{-5}$);
  - If $\lambda_{FS}$ too small ($\sim 10^{-5} \text{ Mpc} \sim 30 \text{ pc}$), 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!!!