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Exploring the Universe with Unstable Dark Matter

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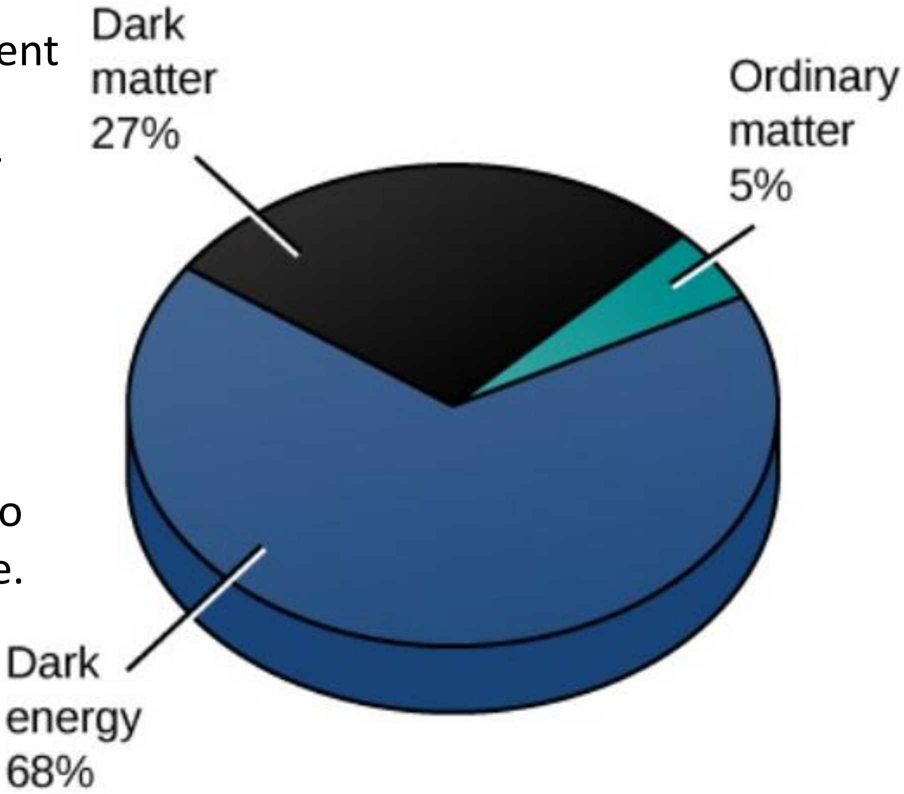
Composition of the Universe

All visible matter accounts for only about 5 percent of the total energy content of the universe. The rest is dark matter and dark energy. Dark matter makes up approximately 25-27 percent of the universe.

We know it exists because we can observe its gravitational effects on galaxies and the cosmic microwave background.

However, despite decades of research, we still do not know what dark matter particles actually are.



The standard model

The standard model of cosmology, known as the ΛCDM model, has been very successful in describing the evolution of the universe. In this model, dark matter is assumed to be **stable**, meaning it does not decay over time. The model includes several components: radiation, ordinary matter, cold dark matter, and dark energy. Each of these components evolves differently as the universe expands.

$$\frac{d\rho}{dt} + 3H(\rho + p) = 0$$

For a component with equation of state parameter $w=p/\rho$:

$$\rho(z) = \rho_0(1+z)^{3(1+w)}$$

Component	Equation of state	Density evolution
Radiation	$w = 1/3$	$\rho_r(z) = \rho_{r,0}(1+z)^4$
Matter	$w = 0$	$\rho_m(z) = \rho_{m,0}(1+z)^3$
Dark energy	$w = -1$	$\rho_\Lambda(z) = \rho_{\Lambda,0}$

Stable DM

$$\dot{\rho}_{DM} + 3H\rho_{DM} = 0$$

$$\boxed{\rho_{dm}(z) = \rho_{dm,0} \cdot (1+z)^3}$$

- Idealized, reference behavior of a non-relativistic substance in a changing universe
- Explicit expression

Unstable DM

$$\dot{\rho}_{\mathrm{udm}} + 3H\rho_{\mathrm{udm}} = -\Gamma\rho_{\mathrm{udm}}$$

$$\boxed{\rho_{\mathrm{udm}}(z) = \rho_{\mathrm{udm},0} \cdot (1+z)^3 \, e^{-\Gamma \int_z^0 \frac{dz'}{H(z')(1+z')}}}$$

- The integral = the proper time interval from z to now
- Γ=1/τ = the decay rate
- Implicit expression

Energy lost by decaying UDM does not disappear - it is transferred to relativistic products.

$$\dot{\rho}_{rel} + 4H\,\rho_{rel} = +\Gamma\,\rho_{\mathrm{UDM}}$$

For the relativistic decay products, the solution is more complex:

$$\rho_{rel}(z) = (1+z)^4\rho_{rel,0} - \rho_{udm}(z) + \\ + \rho_{udm,0}(1+z)^4\left[1 - \int_0^z \frac{1}{(1+z')^2}\exp\left(\int_0^{z'}\frac{\Gamma(H(z''))}{H(z'')(1+z'')}dz''\right)dz'\right]$$

The total energy density is the sum of all components:

$$\rho_{\mathrm{all}}(z) = \rho_{\mathrm{r}}(z) + \rho_b(z) + \rho_\Lambda(z) + \rho_{\mathrm{udm}}(z) + \rho_{\mathrm{rel}}(z)$$

Substituting this expression into the Friedmann equation gives the modified Hubble parameter

$$H^2(z) = \frac{8\pi G}{3}\rho_{all}(z)$$

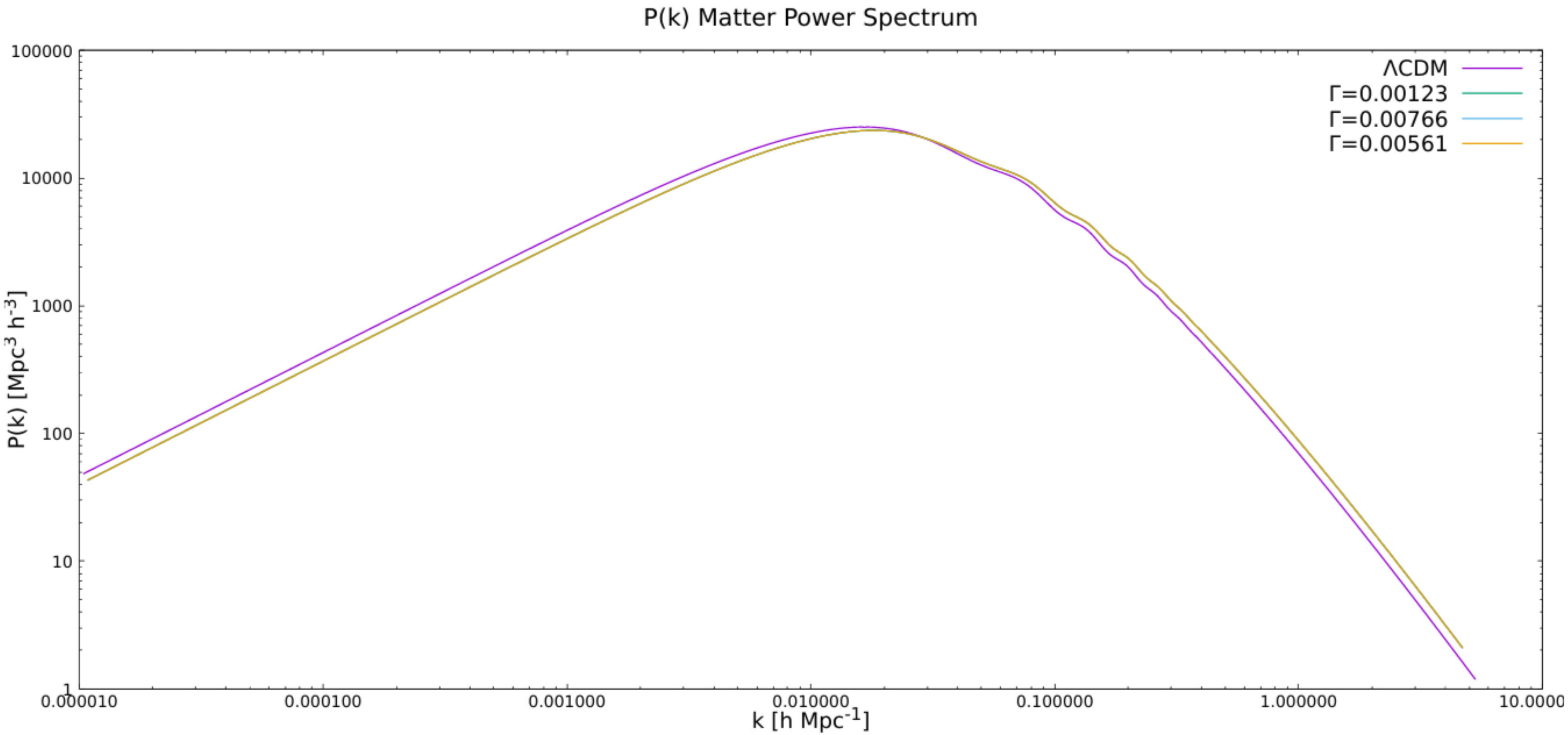
Numerical calculations

The standard ΛCDM model was used as a baseline for comparison. Then we considered three models with unstable dark matter, each with a different value of the decay rate Γ.

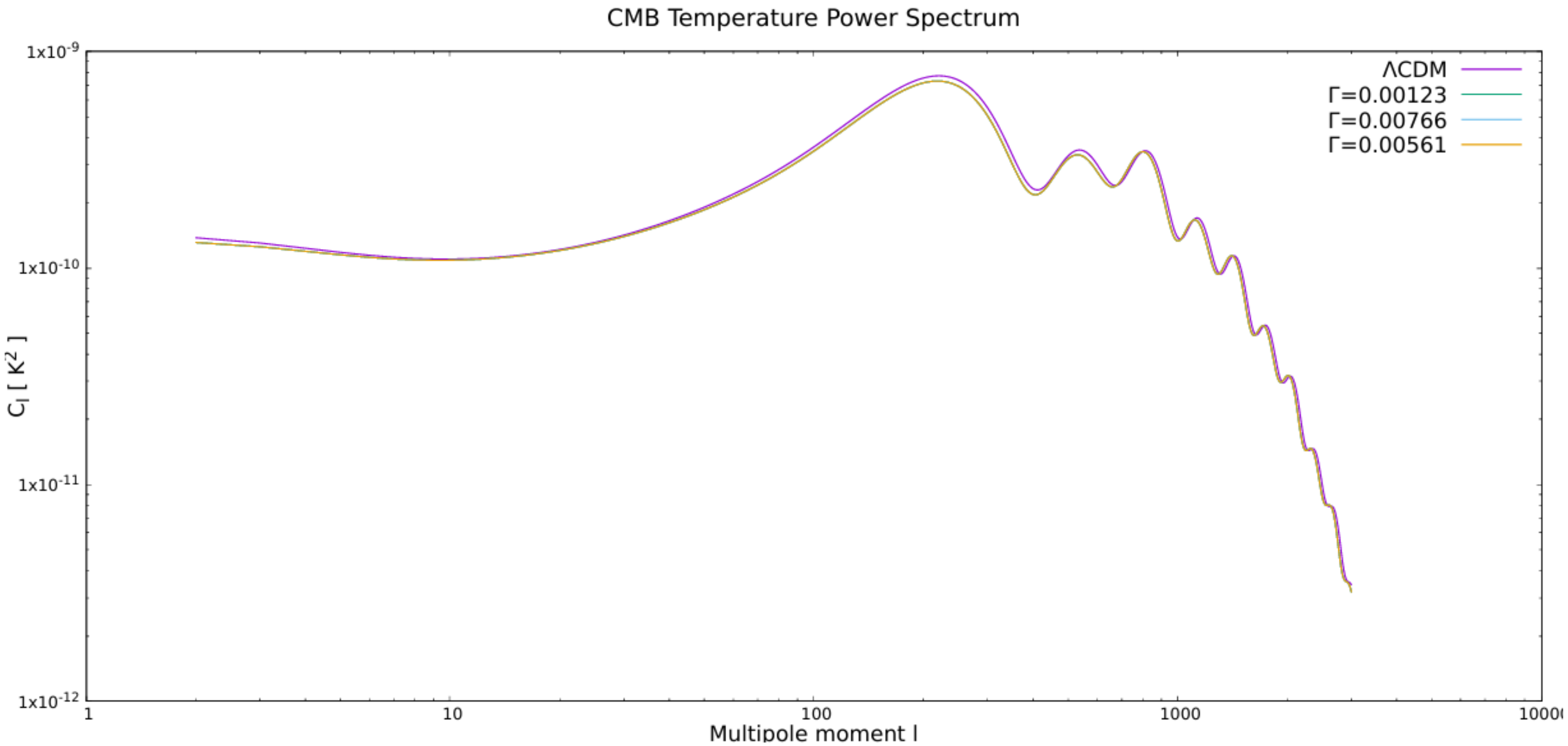
Table II: Marginalized constraints at 95% C.L.

Parameter	CMB+DESI DR2 BAO	CMB+DESI DR2 BAO + Union3	CMB+DESI DR2 BAO+PantheonPluse
$\ln(10^{10}A_s)$	$3.08^{+0.0166}_{-0.0233}$	$3.09^{+0.0141}_{-0.0153}$	$3.08^{+0.0136}_{-0.0137}$
n_s	$0.999^{+0.00469}_{-0.00156}$	$0.997^{+0.00432}_{-0.00226}$	$0.998^{+0.00538}_{-0.00342}$
$100\theta_s$	$1.04^{+0.00017}_{-0.000265}$	$1.04^{+0.000344}_{-0.000366}$	$1.04^{+0.000185}_{-0.000433}$
$\Omega_b h^2$	$0.0231^{+0.000191}_{-0.00014}$	$0.0231^{+0.000168}_{-0.000124}$	$0.0231^{+0.000138}_{-0.000131}$
$\Omega_{udm} h^2$	$0.135^{+0.000766}_{-0.00053}$	$0.135^{+0.000706}_{-0.000817}$	$0.135^{+0.000685}_{-0.000828}$
Γ_{udm}	$0.00123^{+-6.76e-05}_{-0.00073}$	$0.00766^{+0.00198}_{-0.00716}$	$0.00561^{+-4.54e-05}_{-0.00511}$
H_0	$74^{+0.314}_{-0.375}$	$73.8^{+0.358}_{-0.337}$	$73.9^{+0.365}_{-0.362}$
Ω_m	$0.289^{+0.00337}_{-0.00257}$	$0.291^{+0.0036}_{-0.00419}$	$0.291^{+0.00341}_{-0.00385}$
σ_8	$0.852^{+0.00881}_{-0.00938}$	$0.854^{+0.00695}_{-0.00701}$	$0.854^{+0.0065}_{-0.00539}$
rs_{drag}	$138^{+0.116}_{-0.217}$	$138^{+0.154}_{-0.189}$	$138^{+0.176}_{-0.195}$
$S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$	$0.837^{+0.0101}_{-0.00986}$	$0.842^{+0.00988}_{-0.00933}$	$0.841^{+0.00827}_{-0.00806}$
$\chi^2_{\min}$	5467	6091	5282
AIC	5491	6115	5306
BIC	—	—	—

One of the main outputs of the simulations is the matter power spectrum P (k), which describes how matter is distributed on different scales.



CMB temperature power spectrum shows temperature fluctuations at different angular scales.



Conclusion and future work

In this research were derived analytical expressions for the densities of unstable dark matter and its relativistic decay products. Was performed numerical simulations using CLASS and computed the matter power spectrum and the CMB anisotropy spectrum for different values of the decay rate. The results show that the effects are small for the allowed range of parameters.

Interesting directions for future work include the study of the instantaneous decay limit and the exploration of an alternative parametrization of dark energy.

Thanks for your attention!