Cannibal dark matter decoupled from standard model: cosmological constraints

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Indian Association for the Cultivation of Science

International Conference on High Energy Particle & Astroparticle Physics (ICHEPAP2023), SINP, Kolkata

Abstract

We have considered an **internally thermalized dark matter(DM)** consisting of a real scalar particle with only gravitational interaction with the standard model (SM) particles. This DM may undergo **3→2** processes when it is non-relativistic, **cannibalizes itself to cool at much slower rate than standard NR matter**. We solve coupled evolution equations of DM temperature and number density to determine the abundance for different DM-self couplings. We determine constraints on parameters from CMB power spactrum, BBN bounds on relativistic species, Lyman-α limits on DM free-streaming length and unitarity limits on $3 \to 2$ cross-section. We show that, cannibal DM decoupled from the SM, with mass around **80 eV to 700 TeV** can be a viable candidate satisfying all the constraints when the initial DM temperature (T_{DM}) lies between $\boldsymbol{T_{SM}/9100 \lesssim T_{DM} \lesssim T_{SM}/1.1}$.

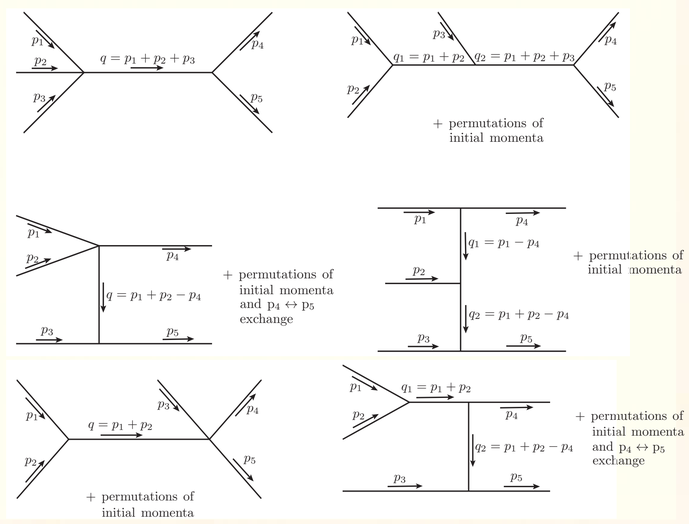
The Model and Diagrams

- Our low-energy toy model for a real scalar cannibal DM,

$$\mathcal{L}_{int} \supset -\frac{\mu}{3!}\chi^3 - \frac{\lambda}{4!}\chi^4$$

- For the process $\chi(\mathbf{p}_1) + \chi(\mathbf{p}_2) + \chi(\mathbf{p}_3) \to \chi(\mathbf{p}_4) + \chi(\mathbf{p}_5)$:

$$|\mathcal{M}|^2 \simeq \frac{25\,\mu^2}{64\,m_\chi^4}\left(3\lambda - \frac{\mu^2}{m_\chi^2}\right)^2.$$



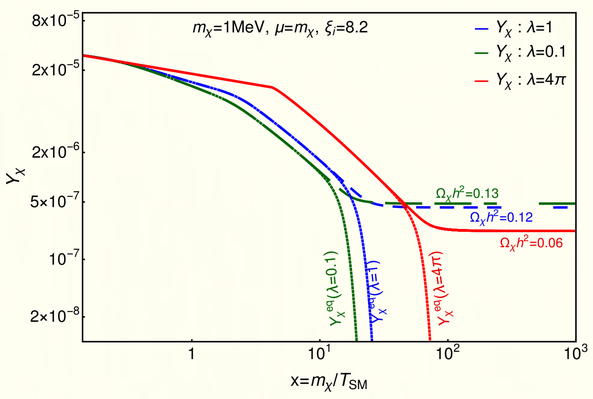
Boltzmann Equation & Collision terms

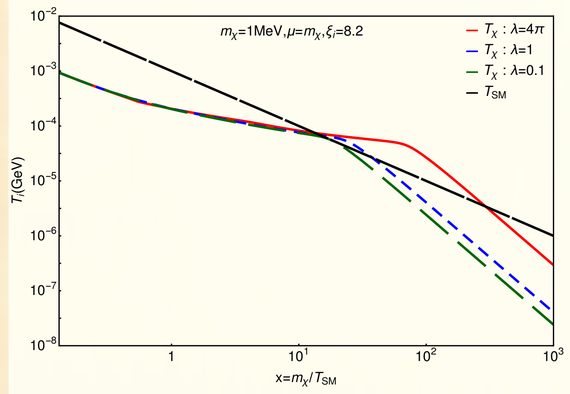
- Equation for the evolution of DM phase-space density $f_\chi(\mathbf{p}, t)$:

$$\frac{\partial f_\chi(\mathbf{p},t)}{\partial t} - H\mathbf{p}.\nabla_{\mathbf{p}} f_\chi(\mathbf{p},t) = C[f_\chi]$$

- Integrating over $\mathbf{p}$, equation for DM number density obtained:

$$\frac{dn_\chi(t)}{dt} + 3Hn_\chi(t) = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3} C[f_\chi] \equiv C_0$$





- Define temperature as the average over $|\mathbf{p}|^2/3E$ over the distribution f^n :

$$T_\chi \equiv \frac{g_\chi}{n_\chi}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{|\mathbf{p}|^2}{3E} f_\chi(\mathbf{p},t).$$

- Evolution equation for the DM temperature :

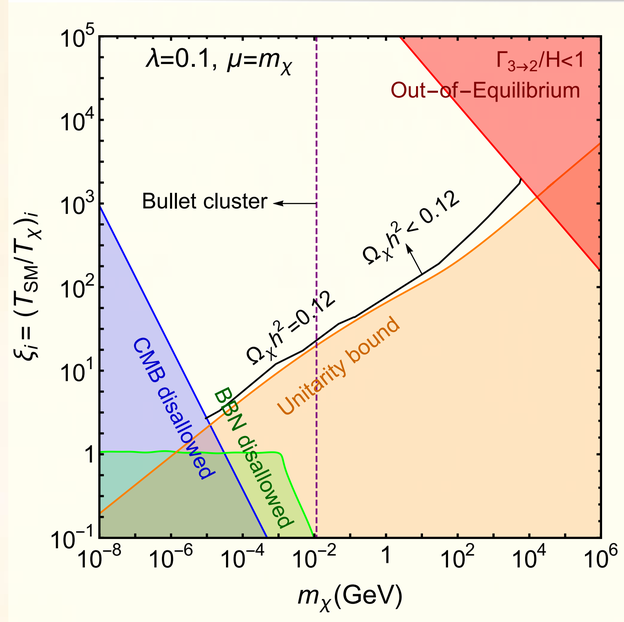
$$\frac{dT_\chi}{dt} + 2HT_\chi + \frac{T_\chi}{n_\chi}\left(\frac{dn_\chi}{dt} + 3Hn_\chi\right) - \frac{H}{3}\left\langle\frac{|\mathbf{p}|^4}{E^3}\right\rangle = \frac{1}{n_\chi}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{|\mathbf{p}|^2}{3E} C[f_\chi] \equiv \frac{1}{n_\chi} C_2$$

- The collision term for temperature evolution by symmetrizing the particle momenta :

$$C_2 = \frac{1}{3!2!}\int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_5 \left(\frac{|\mathbf{p}_1|^2}{3E_1} + \frac{|\mathbf{p}_2|^2}{3E_2} + \frac{|\mathbf{p}_3|^2}{3E_3} - \frac{|\mathbf{p}_4|^2}{3E_4} - \frac{|\mathbf{p}_5|^2}{3E_5}\right)$$
$$(2\pi)^4\delta^4(p_1+p_2+p_3-p_4-p_5)|\mathcal{M}|^2_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3\to\mathbf{p}_4,\mathbf{p}_5}\left(f_\chi(E_4)f_\chi(E_5) - f_\chi(E_1)f_\chi(E_2)f_\chi(E_3)\right)$$

- The DM cannibalizes itself via $3\chi \to 2\chi$ process to cool at much slower rate than standard NR matter.

Cosmological Constraints : Allowed parameter space



- **Constraints from the CMB power spectrum** :

$$\frac{T_\chi(a_{\rm LS})}{m_\chi} < 10^{-5}, \quad \text{at } T_{\rm SM}(a_{\rm LS}) \sim 0.26 \text{ eV}$$

- **Chemical equilibrium and freeze-out of cannibalism :** The region where $3\chi \to 2\chi$ freeze-out occurs when DM is still relativistic :

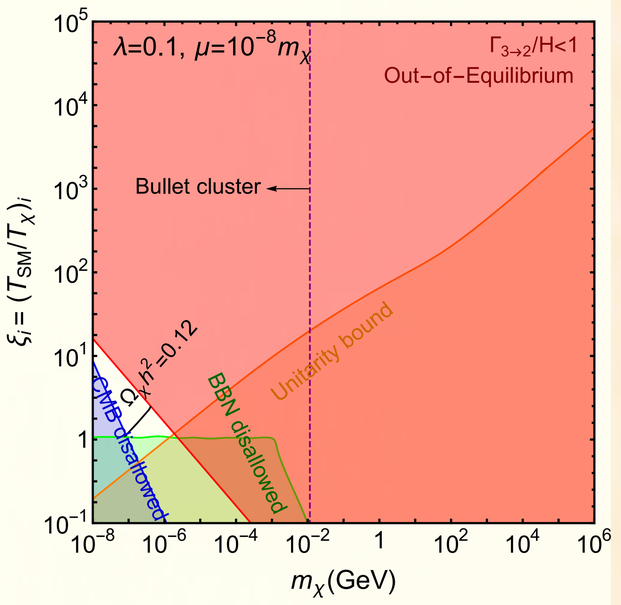
$$n^2_{\chi,\rm eq}\langle\sigma v^2\rangle_{3\chi\to2\chi} = H\Big|_{T_\chi = m_\chi}$$

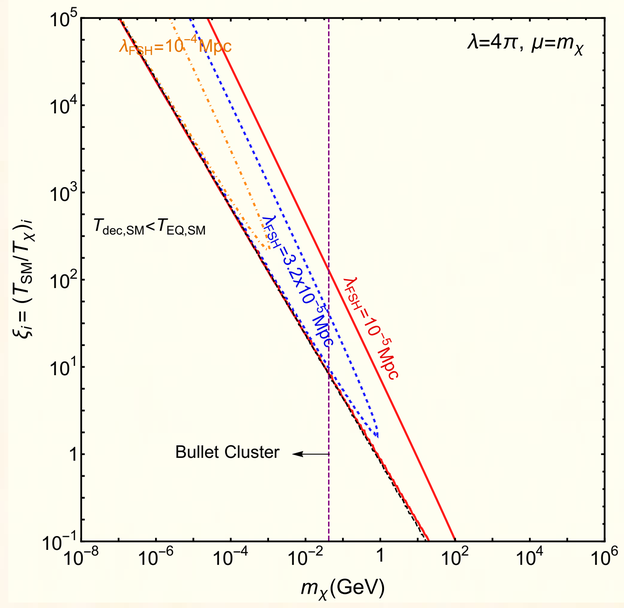
- **Constraints from BBN :** Bound from the contribution of DM to the effective number of neutrinos(ΔN_ν):

$$\xi_i \equiv \frac{T_{BBN}}{T_\chi} > 1.07, \quad \text{for } \mathrm{T}_\chi > \mathrm{m}_\chi$$

- **S-matrix unitarity limits :** Unitarity upper bound for thermal average of $3\to2$ s-wave annihilation rate :

$$\langle\sigma_{3\to2}v^2_{\rm rel}\rangle_{\rm max,\ s-wave} = \frac{8\sqrt{2}\,(\pi x')^2}{g_\chi m_\chi^5},$$





- **Constraints from Lyman-α :** Free streaming length of the DM upto the matter-radiation equality :

$$\lambda_{\rm FSH} = \frac{3M_{\rm Pl}T_0}{\sqrt{\rho_{R,0}}}\frac{\sqrt{x'_F}}{\xi_F m_\chi}\ln\left(\frac{x_{\rm EQ}}{x_{\rm dec}}\right)$$

where $\xi_F = T_{SM}/T_\chi$ at $3 \to 2$ decoupling

- **Bullet Cluster :** DM elastic self -scattering cross sections can be constrained using the observations of the bullet cluster : $\boldsymbol{\sigma_{2\chi\to2\chi}/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}}$

Results

- **In an internally thermalized sector, cannibal DM decoupled from the SM can be a viable possibility, consistent with all present cosmological constraints**
- **The CMB matter power spectrum and the requirement of chemical equilibrium when the DM is nonrelativistic leads to the strongest constraint on cannibal DM**
- **The availability of parameter space for a cannibal DM candidate leads to a lower bound on DM couplings with inflaton. In our case, $\mu \lesssim 10^{-9} m_\chi$ for $\lambda = 0.1$.**
- **Depending upon the DM self-couplings, DM mass of around 80 eV to 700 TeV can make up observed DM density with $T_{\rm SM}/9100 \lesssim T_{\rm DM} \lesssim T_{\rm SM}/1.1$.**

References

1. Avirup Ghosh, S. Gope, Satyanarayan Mukhopadhyay *"Cannibal dark matter decoupled from the standard model: Cosmological constraints"*, Phys. Rev. D **106**, no.10, 103515 (2022).

Acknowledgements

I would like to thank my collaborators Avirup Ghosh and Satyanarayan Mukhopadhyay for their contribution based on ref.[1]