Relaxed Dark Matter

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Based on: RC and M.Pietroni 2004, RC and M.Pietroni 2012

Outline

Thermal DM

WIMPs thermal production

- In the WIMP paradigm the dark matter relic abundance is found by solving the Boltzmann equation

$$\dot{n} + 3Hn = \langle \sigma v \rangle \left(n_{\rm eq}^2 - n^2 \right)$$

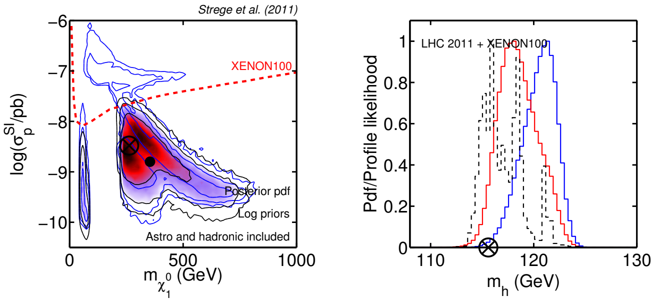
- When $\langle \sigma v \rangle n \sim H$ dark matter decouples and its density is diluted only by the Hubble expansion: thermal production.

- Order of magnitude estimations lead to approximately the correct relic abundance: "the WIMP miracle".

WIMPs & cMSSM

- Constrained MSSM global fit:

  Strege et al. 2011



- The WIMP paradigm is perfectly valid, but it might require a more sophisticated realization.
- It worths exploring alternative scenarios!

Asymmetric Dark Matter

Kaplan et al. 2009

- In this framework the dark matter relic abundance is determined by the baryon asymmetry.
- It provides a solution to the DM-baryon cosmic coincidence:[1]

$$\Omega_1 \sim \frac{m_1}{m_2}\Omega_2$$

- A solution to this coincidence constitutes a promising guiding principle to formulate an alternative to the WIMP paradigm.

[1] One refers to DM, two refers to baryons.

Relaxed Dark Matter

RDM: A dynamical solution to the ρ_1/ρ_2 cosmic coincidence

RC and M.Pietroni 2004, RC and M.Pietroni 2012

Assumptions

- A long range scalar field differently coupled to ρ_1 and ρ_2:

$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{1}{M^2}\left(\alpha_1\rho_1 + \alpha_2\rho_2\right)$$

- An attractor solution for the scalar field equation:

$$\alpha_1\rho_1 + \alpha_2\rho_2 = 0$$

Consequence

- Dark matter is produced by the relaxation of φ:

$$\Omega_1 = -\frac{\alpha_2}{\alpha_1} \times \Omega_2$$

Definition of relaxed dark matter

- Relaxed dark matter is:
  any DM candidate with Ω_1 produced by the relaxation of φ.

- This requires a Lagrangian of the form:

$$\mathcal{L}_\varphi = \frac{\sqrt{-g}}{2}\partial_\mu\varphi\partial^\mu\varphi + \sum_{i=1,2}\mathcal{L}_i[g_{\mu\nu}A_i^2(\varphi),\psi_i]$$

$$\alpha_i = \frac{\partial \log A_i}{\partial\varphi}$$

A specific realization

- We impose a Z_2 symmetry under which φ is odd. This implies:

1 $\alpha_i(\varphi) = \varphi \times g_i(\varphi^2)$

2 The properties of the attractor can be discussed in the context of the Z_2 symmetry breaking.

Background Equations

- The FRW equations take the form

$$H^2 = \frac{1}{3M_p^2}\sum_i \rho_i + \frac{1}{6}\frac{M^2}{M_p^2}\dot{\varphi}^2$$

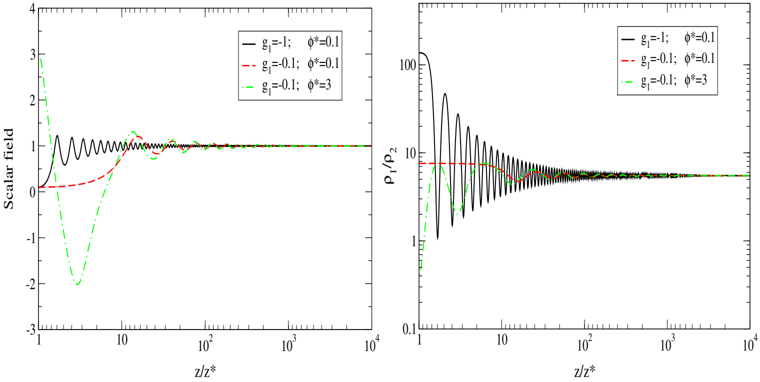
$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{1}{M^2}\sum_{i=1,2}\alpha_i\rho_i$$

$$\dot{\rho}_i + 3H\rho_i = \alpha_i\rho_i\dot{\varphi}$$

- The DM mass is φ-dependent $\longrightarrow$ it is density-dependent!

$$m_\chi(\varphi) = \frac{A_1(\varphi)}{A_2(\varphi)} \times m_1$$

Numerical examples



Linear perturbations I

- Linear perturbation equations

$$\ddot{\delta}_i = -2H(\dot{\delta}_i + \alpha_i \dot{\varphi}) + \frac{3}{2}H^2 \sum_{j=1,2} \Omega_j \delta_j \gamma_{ij}$$

- γ_{ij} is the dark matter/baryon linear coupling function

$$\gamma_{ij} = 1 + 2\frac{M_p^2}{M^2}\alpha_i\alpha_j \left(1 + \frac{a^2 m_\varphi^2}{k^2}\right)^{-1}$$

- The mass of the scalar field is density-dependent

$$m_\varphi^2 = \frac{1}{M^2} \sum_{i=1,2} \rho_i \left(\frac{\partial \alpha_i}{\partial \varphi} + \alpha_i^2\right)$$

Linear perturbations II

- On the attractor, linear perturbations evolve as follows

$$\delta_1 = \delta_1^* \left(\frac{a}{a^*}\right)^m$$

$$\delta_2 = b \times \delta_1$$

with $b = 1$ and $m = 1$.

- Linear perturbations growths like in the ΛCDM!

Spherical Collapse I

- Equation for r_1 and r_2:
  radii of the spherical dark matter and baryon overdensities

$$\frac{\ddot{r}_i}{r_i} = \alpha_i \dot{\varphi} \left(H - \frac{\dot{r}_i}{r_i} \right) - \frac{1}{2} H^2 \sum_j \Omega_j \left(1 + \delta_j \Gamma_{ij}\right)$$

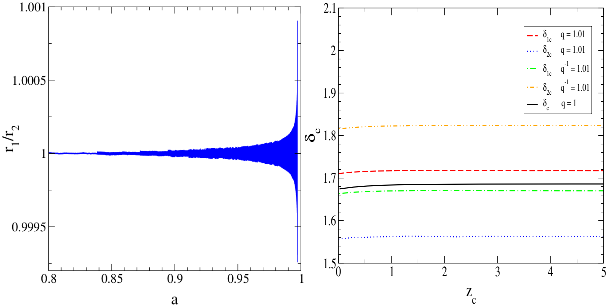
- The coupling function Γ_{ij} is given by (for $k^2 \gg a^2 m_\varphi^2$)

$$\Gamma_{ij} = \begin{cases} 1 + 2\frac{M_p^2}{M^2}\alpha_i\alpha_j & \text{if} \quad r_i < r_j \\ 1 & \text{otherwise.} \end{cases}$$

- On the attractor $\Gamma_{ij} \to 1$ and $\dot{\varphi} = 0$: ΛCDM evolution.

Spherical Collapse II

- If $\delta_1^* \neq \delta_2^*$ there are departures from the ΛCDM prediction.



- Results are similar to what found for dark energy models.
Pace et al. 2010

Implications for particle physics

- The DM relic abundance is independent from $\langle \sigma v \rangle$: the couplings determining $\langle \sigma v \rangle$ are not constrained by CMB.

- The dark matter mass is environment-dependent. Direct and indirect DM detection experiments measure different m_χ.
  Example: DM-induced γ-ray flux

$$\Phi(E,\theta) = \frac{\langle \sigma v \rangle_0}{8\pi} \sum_f \frac{dN_f}{dE} B_f \int_{\mathrm{l.o.s.}} dl(\theta)\, \rho_\chi^2(l) \times \frac{1}{m_\chi^2(l)}$$

- Present DM annihilations (*i.e.*$\langle \sigma v \rangle_0$) are unrelated to Ω_1.

Conclusions

- The WIMP paradigm is perfectly valid, but it could require realizations more sophisticated than the cMSSM.
- Relaxed Dark Matter is a class of theories where Ω_1/Ω_2 is determined by the relaxation of a long range scalar field.
- Its main features are:

1. The dark matter relic abundance is unrelated to $\langle \sigma v \rangle$.
2. m_χ is environment-dependent. This has a strong impact on the indirect/direct detection techniques.
3. Linear perturbations evolve like in the ΛCDM.
4. Non linear clustering can be affected if $\delta_1^* \neq \delta_2^*$.