Cuspy to cored galaxy profiles from late-time dark matter oscillations ★

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Motivation

ΛCDM is extremely successful, but there are some disagreements between observations and N-body simulations at scales smaller than $\sim$ Mpc.

Core-cusp problem

Simulations prefer cuspy DM halos, while observations of dwarf galaxies point to more cored profiles. Cores are less pronounced in galaxy clusters.

Popular solutions in literature: baryonic physics; self-interacting DM (SIDM) with elastic velocity-independent or dependent scattering cross section $\sigma/m \lesssim \mathcal{O}(1)$ cm^2/g.

Idea

DM annihilation is an exothermic process like velocity-dependent scattering. To avoid challenges in the early Universe, annihilation has to freeze-out and then reactivate during structure formation to solve the core-cusp problem.

Our solution

Asymmetric DM with a small number-violating mass $\boldsymbol{\delta m}$, causing oscillations between particle χ and anti-particle $\bar\chi$ at late times.

Oscillation formalism: idea

The distinction between χ and $\bar\chi$ is time-dependent in the context of particle oscillation. If

$$\mathcal{L} \supset \mathcal{L}_m = \frac{1}{2}\delta m(\bar\chi\chi^c + \text{h.c.})$$

each state is labeled by a phase φ, evolving as $\varphi = \delta m\, t$ if no interaction occurs.

We have to solve **quantum Boltzmann equations** for the density matrix to describe $\chi - \bar\chi$ evolution.

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Oscillation formalism: two models

- **Model 1** (flavor-sensitive): vector mediator V^μ

$$\mathcal{L}_1 \supset -\frac{1}{2}m_V^2 V_\mu^2 - g'\bar\chi \not{V}\chi$$

$$\Longrightarrow \boxed{\chi\bar\chi \to VV} \;:\; \Gamma_{\rm ann} \propto \sin^2(\varphi - \varphi')\,, \quad \Gamma_{\rm scatt} \propto v\,, \qquad \sin(2\varphi)_t \sim e^{-\Gamma_{\rm scatt}\,t}\sin(2\varphi)_0$$

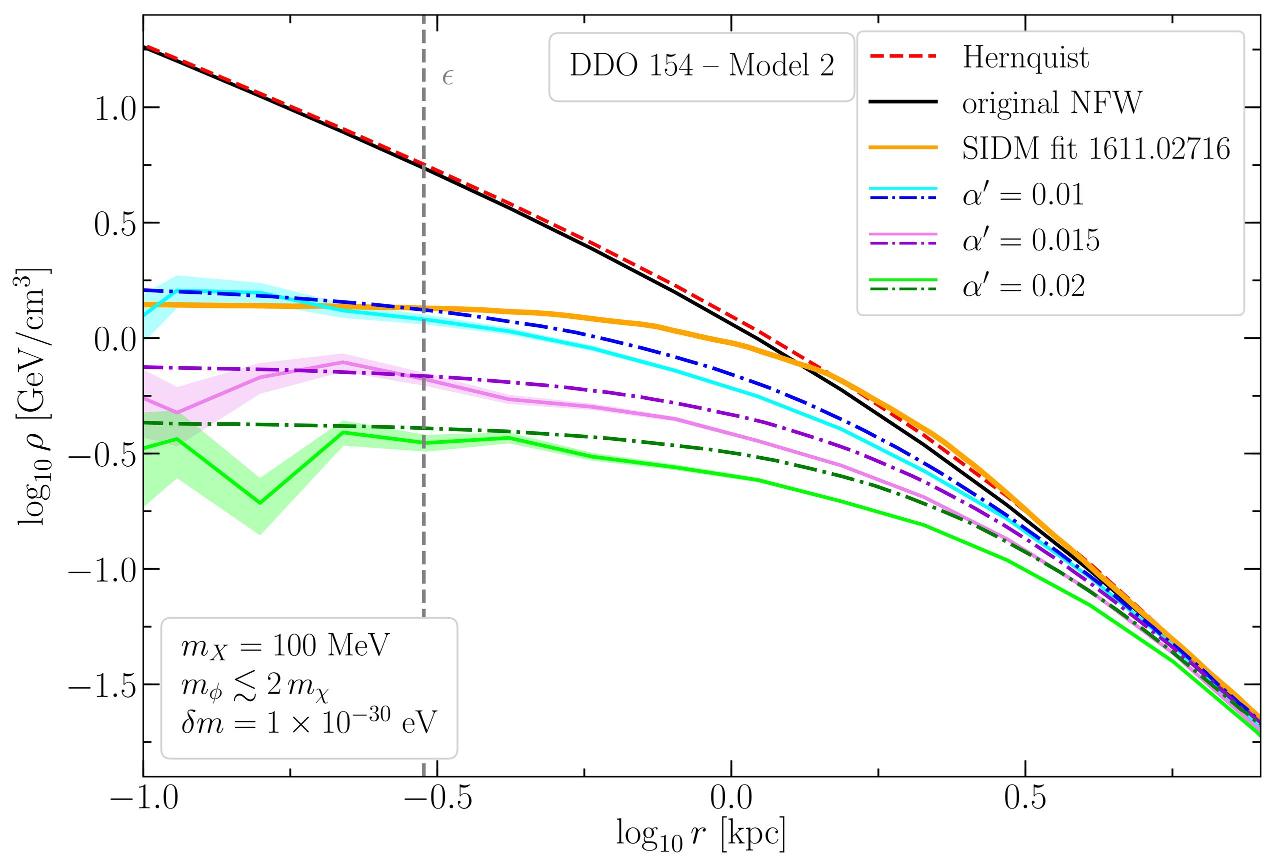
- **Model 2** (flavor-blind): scalar mediator $\Phi = \phi + ia$

$$\mathcal{L}_2 \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_a^2 a^2 - g'\bar\chi(\phi + ia\gamma_5)\chi$$

$$\Longrightarrow \boxed{\chi\bar\chi \to \phi a} \;:\; \Gamma_{\rm ann} \propto \sin^2(\varphi + \varphi')\,, \quad \Gamma_{\rm scatt} \propto \text{const}\,, \qquad \sin(2\varphi)_t \sim e^{-\Gamma_{\rm ann}\,t}\sin(2\varphi)_0$$

We assume $m_a \ll m_\phi$, $m_\chi \sim 0.1$ GeV and define the quantities: $r_m = m_{V,\phi}/m_\chi$, $\alpha' = g'^2/4\pi$ and $v_{\rm rel} = 2v$.

Results: Structure formation (for Model 2)



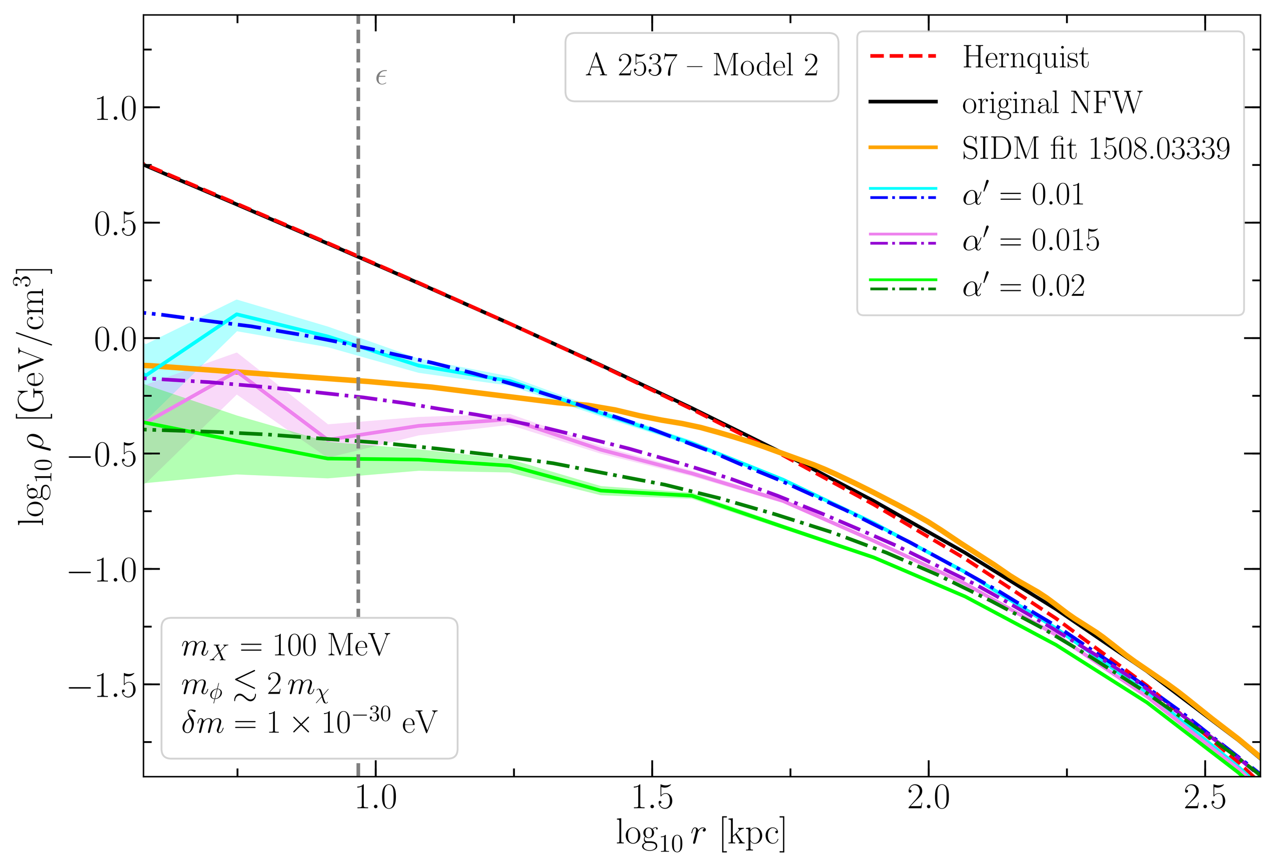
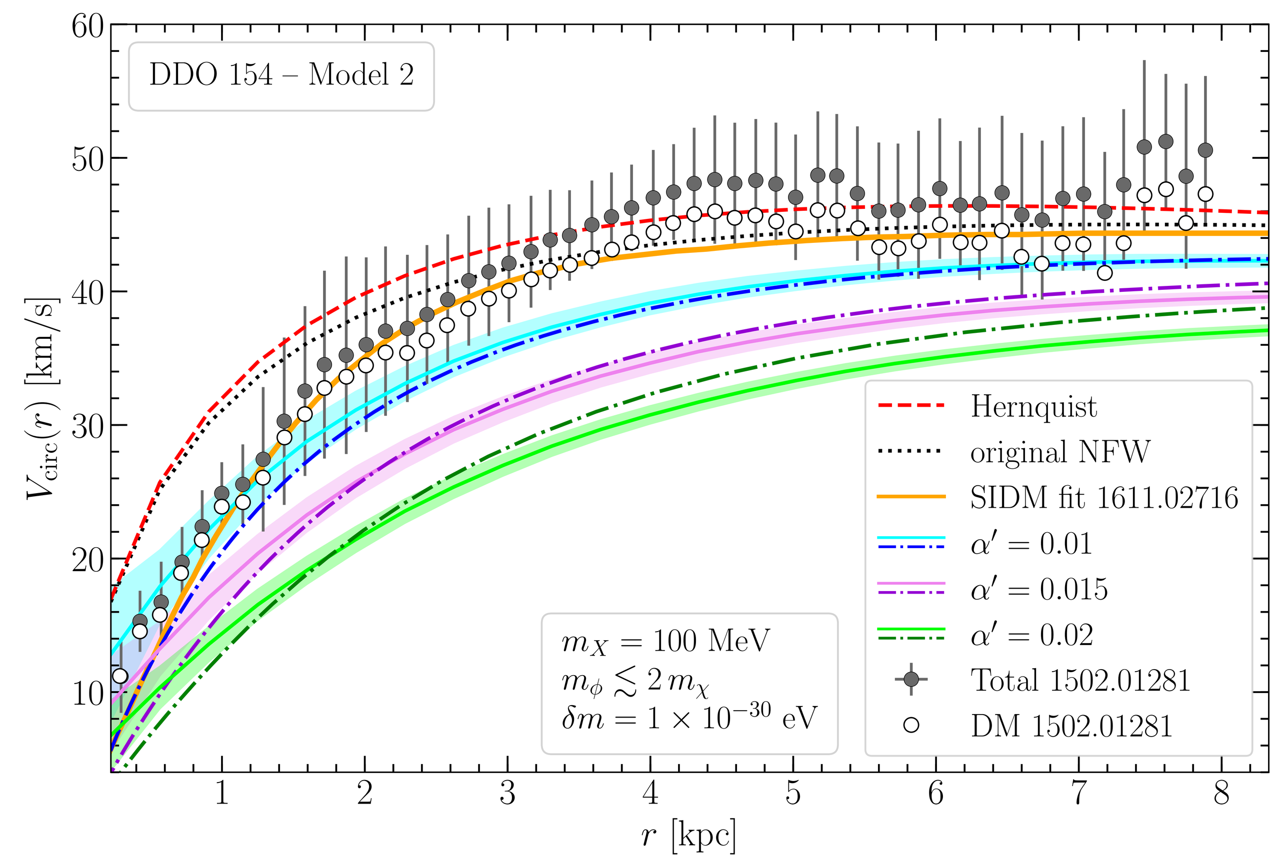


Figure: Density profile for dwarf galaxy DDO 154 (*left*) and galaxy cluster A 2537 (*right*) after $\sim$ 10 Gyr.



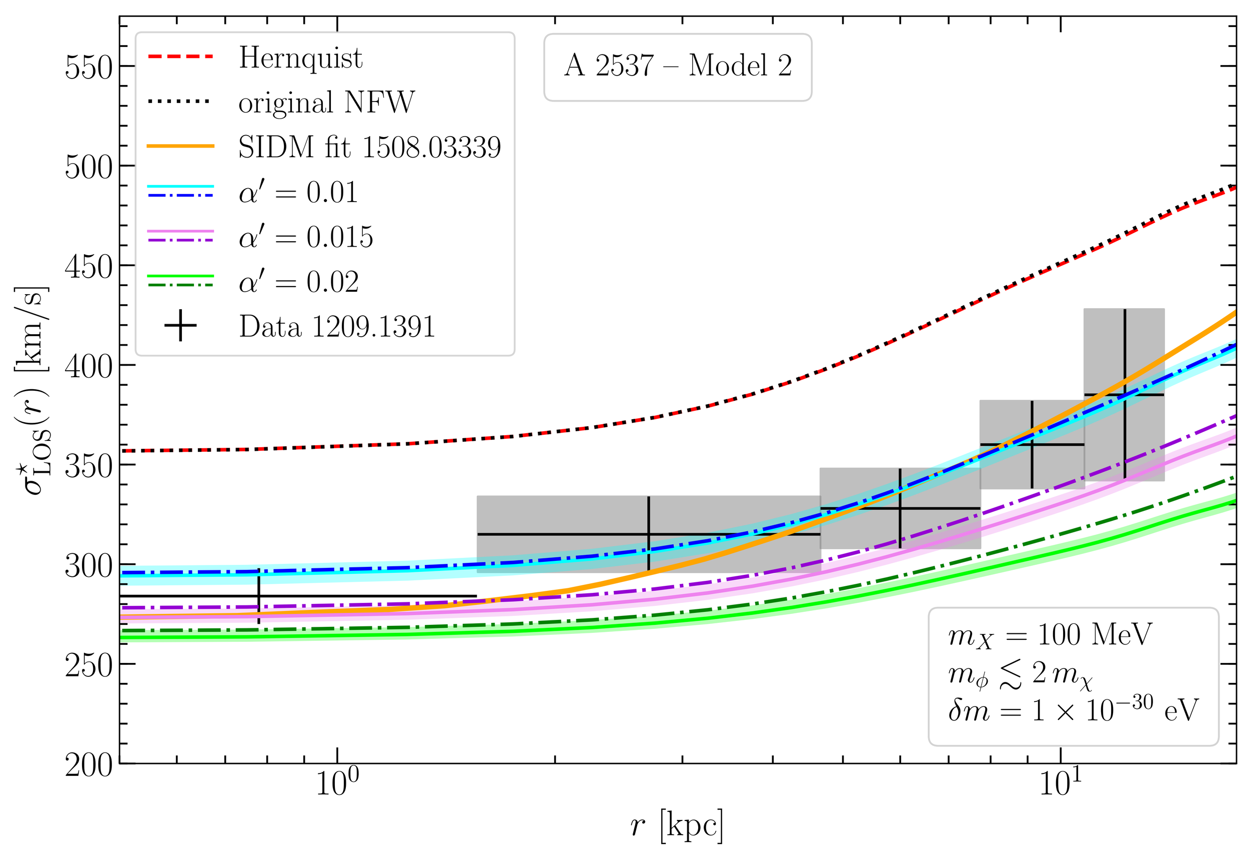


Figure: Circular velocity for DDO 154 (*left*) and stellar velocity dispersion along the line of sight for A 2537 (*right*).

Analytic estimates

Annihilation cross section at threshold

$$\langle\sigma v\rangle_a = \frac{\pi\,\alpha'^2}{m_\chi^2}\begin{cases}(1-r_m^2)^{3/2}/(1-r_m^2/2)^2 & \text{Model 1}\\ (1-r_m^2/4) & \text{Model 2}\end{cases}$$

Elastic scattering cross section at low velocities

$$\sigma_s \simeq \frac{4\pi\alpha'^2}{m_\chi^2}\, r_m^{-4}$$

Comparing $\langle\sigma v\rangle_a$ to $\sim \mathcal{O}(1)$ cm^2/g with v_0 = 100 km/s and requiring that $\sigma_s v_{\rm rel} < 0.3\,\langle\sigma_a v\rangle$

$$\alpha' \simeq 0.7\left(\frac{m_\chi}{\text{GeV}}\right)^{3/2}, \qquad \begin{matrix} 0.6 < r_m < 0.94 & \text{(Model 1)}\\ 0.6 < r_m < 1.99 & \text{(Model 2)}\end{matrix}$$

For annihilations to recouple during structure formation and to be in agreement with CMB constraints on the change in the DM relic density

$$10^{-31}\,\text{eV} \lesssim \delta m \lesssim \begin{cases} 5\times 10^{-28}\,\text{eV}, & \text{Model 1}\\ 3\times 10^{-30}\,\text{eV}, & \text{Model 2}\end{cases}$$

Results: Early cosmology

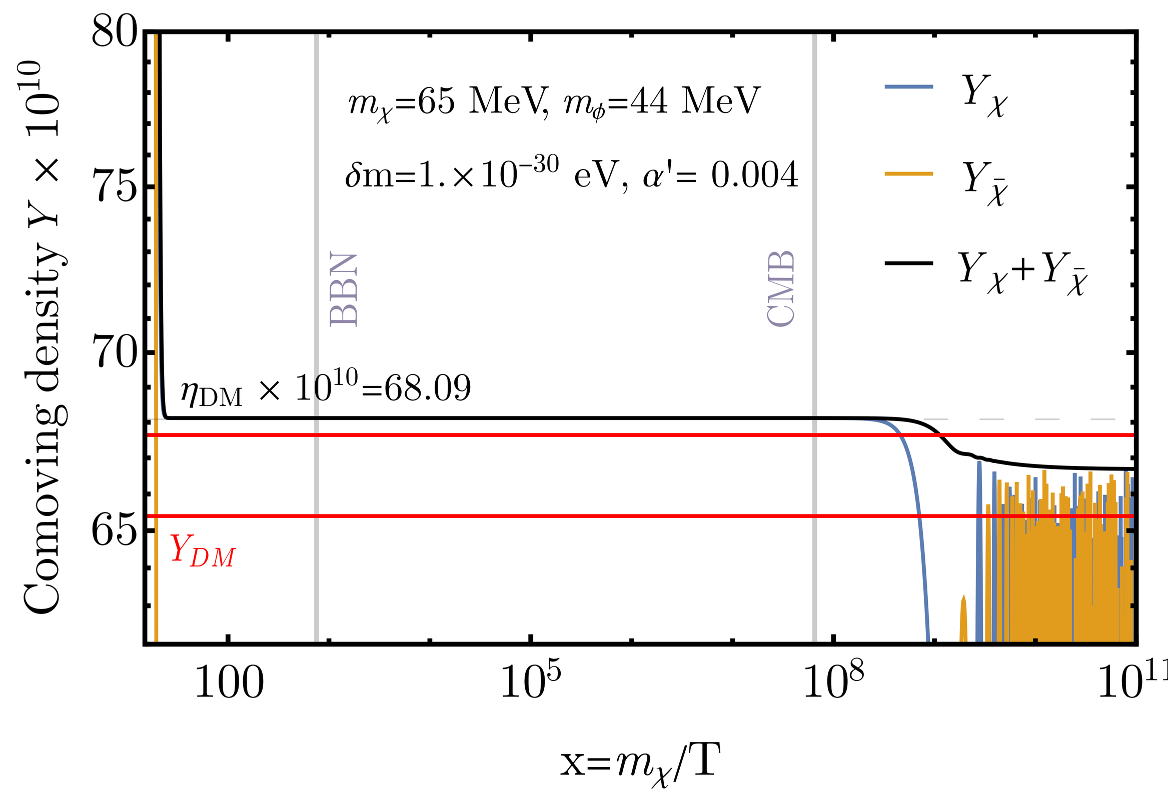


Figure: Cosmological evolution of χ and $\bar\chi$ and total abundances for Model 2, where $\eta_{\rm DM}$ is the DM asymmetry.

★ Based on

Cline, J. M., Gambini, G., McDermott S. D., **Puel, M.**, *Late-Time Dark Matter Oscillations and the Core- Cusp Problem*, JHEP 2021, 223 (2021) [arXiv:2010.12583]