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

[J. M. Cline, G. Gambini, S. D. McDermott, **MP**, JHEP 2021, 223 (2021)]

Matteo Puel

Physics Department, McGill University

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McGill Space Institute
Institut Spatial de McGill

Introduction: Core-cusp problem

Some disagreements between observations and N-body CDM-only simulations based on ΛCDM cosmology at small scales (below Mpc).

[D.H. Weinberg et al., Proc. Nat. Acad. Sci. 112, 40 (2015)]

Core-cusp problem

Simulations prefer cuspy DM halos, while observations of dwarf galaxies seem to point out more cored profiles. Cores are less pronounced in galaxy clusters. [W.J.G. de Block, Adv in Astronomy 789293 (2010)]

Popular solutions:

- Include baryonic physics in simulations
- Self-interacting DM (SIDM) with elastic scattering cross section $\sigma/m_\chi \sim (0.1 - 1)\ \mathrm{cm}^2/\mathrm{g}$ [S. Tulin & H.-B. Hu, Phys Rept 730, 1-57 (2018)]
- SIDM possibly with $\sigma \sim 1/v$ at high v and $\sigma \sim$ constant at low v

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Idea: DM annihilation is also an exothermic process with $\langle \sigma v \rangle_a \to$ constant as $v \to 0$.

Our solution: Asymmetric DM with a small number-violating mass δm, causing oscillations between χ and $\bar{\chi}$ at late times

Models: Quasi-Dirac fermionic DM χ of mass m_χ

- Model 1 : χ couples to a lighter vector boson V^μ

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

- Model 2 : χ couples to a lighter complex scalar $\Phi = \phi + ia$

$$\mathcal{L}_2 \supset -\frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2} m_a^2 a^2 - g' \bar{\chi}(\phi + i\, a\, \gamma_5)\chi \quad \Longrightarrow \quad \boxed{\chi\bar{\chi} \to \phi a}$$

Assumptions

1. $m_a \ll m_\phi$
2. $m_\chi \sim \mathcal{O}(100)$ MeV
3. annihilation $\gg$ scattering

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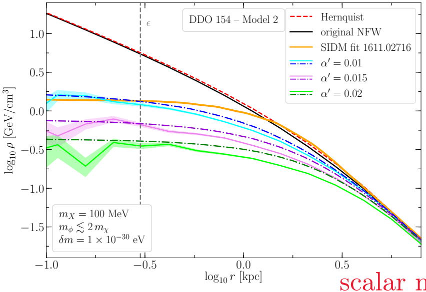
The DM-number-violating mass term for both models is $[\alpha' \equiv g'^2/4\pi]$

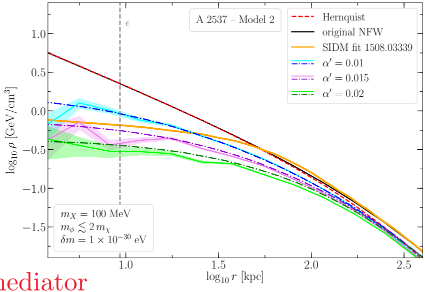
$$\mathcal{L}_m = \frac{1}{2}\,\delta m\,(\bar{\chi}\chi^c + \text{h.c.})$$

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

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

Effects: structure formation





scalar mediator

↑ dwarf galaxy

↑ galaxy cluster

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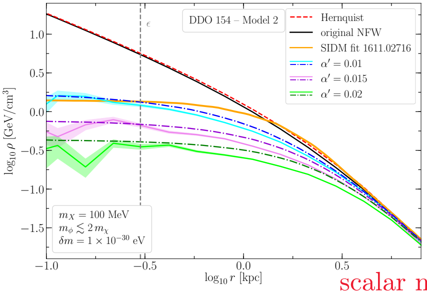

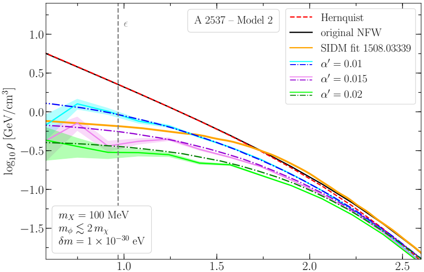

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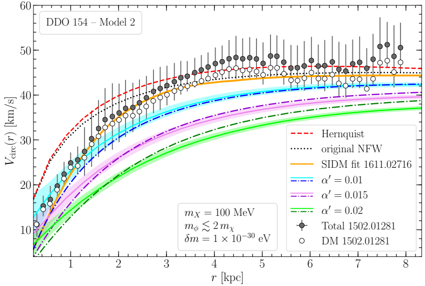
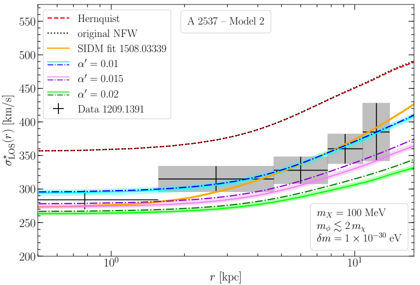
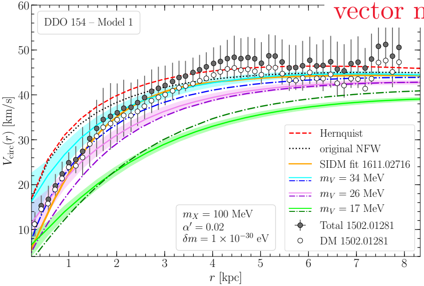
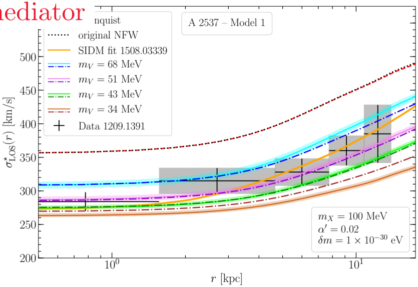


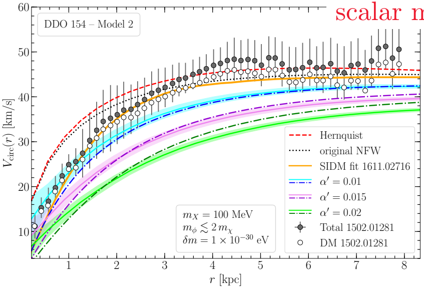


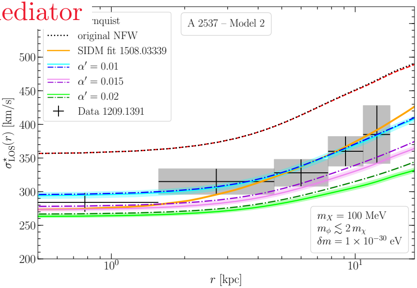
vector mediator





scalar mediator





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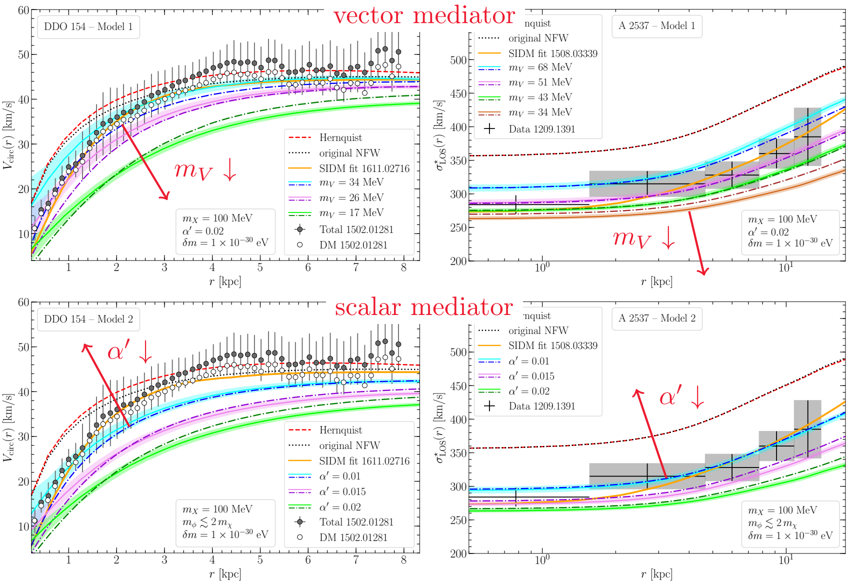

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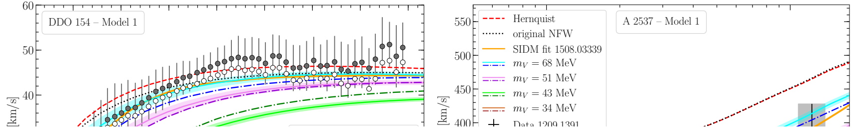
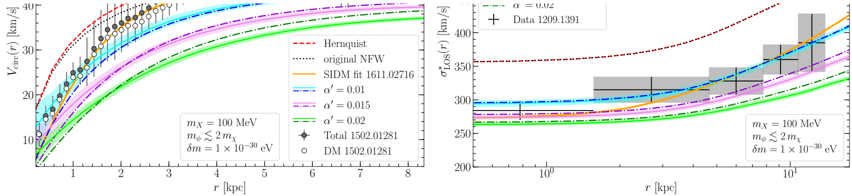


Qualitative trend

- cusp suppression in clusters (high-v) is more efficient in Model 1
- cusp suppression in dwarfs (high-ρ) is more efficient in Model 2

Possible solution: model with both mediators!



Thank you for your attention!

Backup slides

Models: analytical estimates

Annihilation cross section at threshold ($r_m = m_{V,\phi}/m_\chi$ and $\alpha' = g'^2/4\pi$)

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

Elastic scattering cross section at low velocities ($v = v_{\rm rel}/2$)

$$\sigma_s \cong 4\pi\alpha'^2\, m_\chi^2 \begin{cases} m_V^{-4} & \text{Model 1} \\ m_\phi^{-4} + (5/4)\, v^4\, m_a^{-4} & \text{Model 2} \end{cases}$$

Comparing $\langle \sigma v \rangle_a$ to $\sigma_{\rm SIDM} \sim 1.0\ {\rm cm}^2/{\rm g}$ for reference velocity $v_0 = 100$ km/s and requiring that $\sigma_s v_{\rm rel} < 0.3\,\langle \sigma_a v \rangle$ (for $m_a \ll m_\phi$)

$$\alpha' \cong 0.7\,\left(\frac{m_\chi}{\rm GeV}\right)^{3/2}$$

$0.6 < r_m < 0.94$ (Model 1)

$0.6 < r_m < 1.99$ (Model 2)

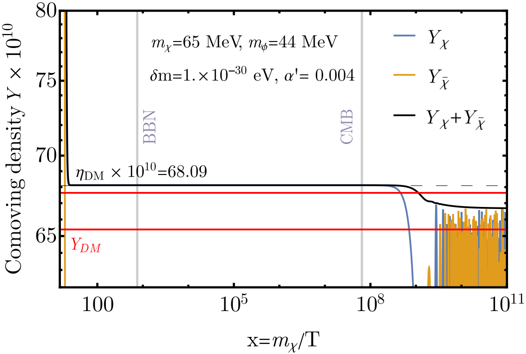


Figure: Cosmological evolution of χ and $\bar{\chi}$ and total abundances for Model 2. $\alpha' = g'^2/4\pi$

After oscillations commence at late times, annihilations recouple briefly before freezing-out again

- reduction of $Y = Y_\chi + Y_{\bar{\chi}}$ by $\lesssim \mathcal{O}(5\%)$
- implications for H_0 and σ_8 tensions?