Self Interacting Dark Matter

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Contents

Small scale structure problems

The ΛCDM model reproduces the large scale cosmic stucture very well. At small ($\lesssim 10^{11} M_\odot$) scales there are long standing issues:

- **Missing satellites problem**: CDM predicts hierarchial stucture down to very small scales. The Milky Way should host hundreds of satellite galaxies, but $\mathcal{O}(10)$ are found.

- **Core-cusp problem**: CDM simulations produce density profiles that scale as $\rho_{DM} \sim r^{-1}$ towards the center of the halo. However, some observations seem to prefer a nearly constant density core.

- **Too big to fail problem**: The central densities of the brigtest dwarf satellites of the MW, as inferred from velocity dispersion, are too low compared to the largest subhaloes predicted in CDM. The largest subhaloes should always host galaxies, as they are too big to fail at forming stars.

- **Diversity problem**: CDM predicts self-similar structure formation, with very litle scatter in the profile parameters for a given mass halo. More scatter is observed.

Solution?

The proposed solutions to the small scale structure problems include:

- ▶ **Baryons**: The problems were initially recognized in comparison of DM-only simulations to the observed structure. The effect of star formation, supernovas etc. could perhaps alleviate the problems.

- ▶ **Self interacting DM**: Elastic scattering between DM particles could resolve the issues, as initially proposed by Spergel and Steinhardt [astro-ph/9909386].

- ▶ **Warm DM**: Warm dark matter reduces structure at small scales, but is in contrast with observations of small scale structure from Lyman-α data. However, similar effects could be achieved with late kinetic decoupling or fuzzy DM (ultralight bosons, e.g. axions).

Unquestionably, baryonic effects must be understood to make the final verdict. The complete solution could be a combination of baryon physics and a modification of the collisionless CDM model.

Missing satellites

- The Milky Way should host thousands of subhaloes with $M \gtrsim 10^7 M_\odot$, but only ~ 50 satellite galaxies are known.
- Most likely the subhaloes exist, but fail at forming stars and are thus invisble.
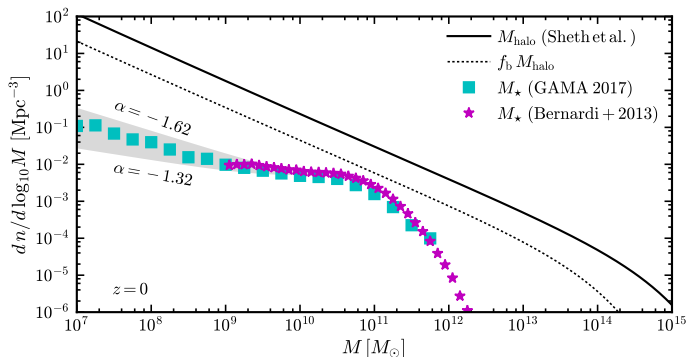- Star formation is suppressed for low-mass haloes e.g. due to reionization UV-radiation.
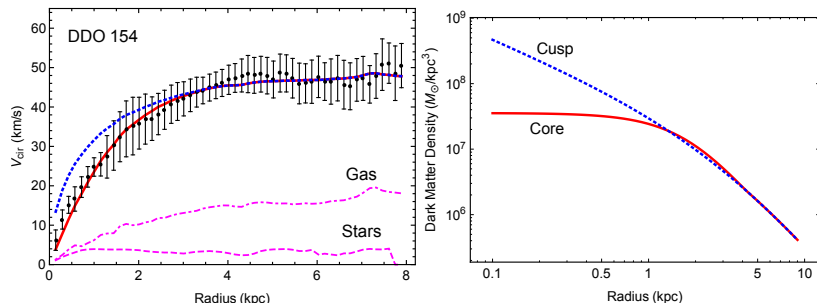

Figure from Bullock and Boylan-Kolchin, arXiv:1707.04256

Core vs cusp

Measurements of rotation curves and velocity distributions in dwarf galaxies seem to favor a constant density core over a NFW-like cusp. But see Read, Walker and Steger, arXiv:1805.06934 who find evidence for a DM cusp in Draco dSph.

Figures from Tulin and Yu, arXiv:1705.02358

Newman et. al. [arXiv:1209.1392] find evidence for $\sim 10 - 20$ kpc cores in DM haloes of relaxed galaxy clusters, using BCG stellar kinematics and weak lensing.

Core vs cusp

Baryon feedback could explain the core formation in dwarf galaxies, but cored cluster haloes are more difficult to explain with baryons (perhaps with AGN powered gas outflows).
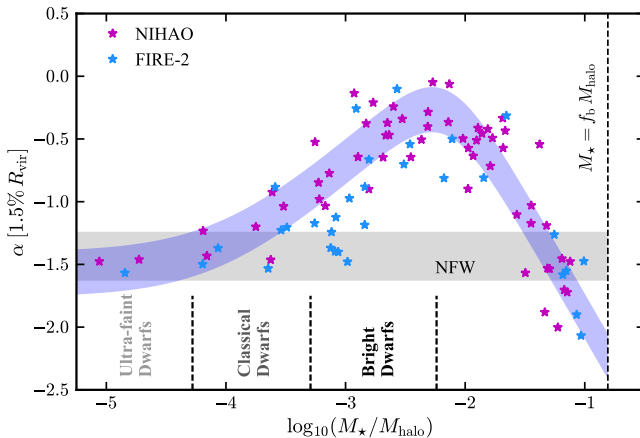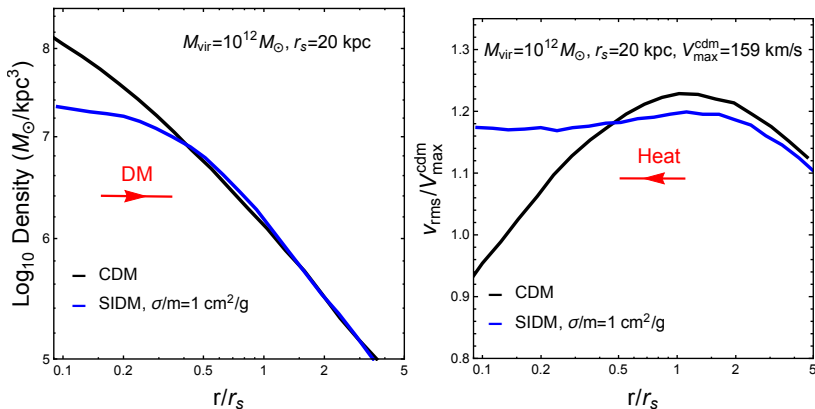

Figure from Bullock and Boylan-Kolchin, arXiv:1707.04256

Core vs cusp

SIDM enables heat transfer towards the center of the halo, creating an isothermal core.

Figures from Tulin and Yu, arXiv:1705.02358

Too big to fail

- If the missing satellites problem is simply resolved by abundance matching (i.e. small haloes are less effective at forming stars), the brightest observed satellites should inhabit the largest subhaloes.
- The rotation velocities of bright MW satellites are too low compared to CDM expectations.
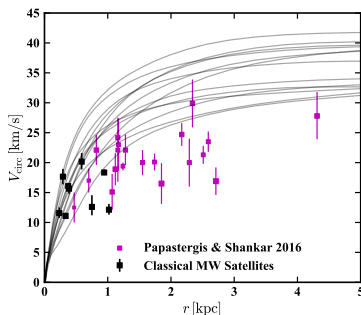- The problem also appears in satellites of Andromeda, and to some extent in local field galaxies.

Figure from Bullock and Boylan-Kolchin, arXiv:1707.04256

Too big to fail

- Too big to fail problem is at least partly resolved if DM haloes indeed have cores and thus overall lower central densities.
- Additionally, environmental effects, i.e. interaction with the MW halo and the MW disc, could produce lower central densities for the satellites.
- The problem may still persist in isolated field dwarfs, where environmental effects should play no role, and where stellar density is too low to induce cores by baryon feedback. More detailed observations and simulation of these systems are needed.
- SIDM could be the favored solution, since it can produce cores also in isolated faint dwarfs.

Diversity problem

- In CDM haloes the characteristic density ρ_s and the scale radius r_s in the NFW profile $\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$ are tightly correlated, while more scatter in inferred profiles is observed.

- The problem persists in CDM $+$ hydro simulations, and in SIDM only simulations.

- Simulations with SIDM $+$ baryons produce more scatter, as the SIDM haloes are less robust against perturbations during mergers.
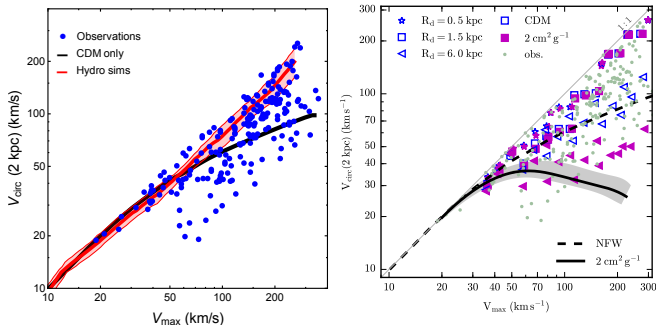
Figures from Tulin and Yu, arXiv:1705.02358 and Creasey et. al. arXiv:1612.03903

Small scale problems: recap

- **Missing satellites problem** is likely resolved by abundance matching: smaller haloes are increasingly inefficient at forming stars.

- **Core-cusp problem** could be resolved by baryon feedback, but only for a certain range of halo masses. If small and ultra-faint dwarfs have cores, SIDM may be needed. Cores in clusters, if confirmed, probably can not be explained with baryon feedback, and point to SIDM.

- **Too big to fail problem** is likely related to the core-cusp issue. Cored profiles reduce the central densities in satellites and field galaxies.

- **Diversity problem** seems to support SIDM. Simulations with SIDM and baryons produce more scatter in velocity curves than CDM + baryons, in line with observations.
  - However, it is not completely clear how the tight correlation between the circular velocity and the **baryonic** mass of galaxies, i.e. baryonic Tully-Fisher relation, (or similarly the radial acceleration relation) is resolved in face of this diversity in halo profiles.

Contents

Ellipticity of DM haloes

- The number of scattering events scales as $N \sim n_{DM}\sigma = \rho_{DM}\sigma/m$. Thus the relevant quantity for SIDM is the self scattering cross section divided by the DM mass, σ/m.

- Some of the first constraints for σ/m presented in the literature were based on the assumption that a DM halo becomes spherical as the number of scattering events per particle approaches one.

- The observed ellipticity of cluster haloes then yields a tight constraint $\sigma/m \lesssim 0.02$ cm^2/g.

- These initial approximations have turned out to be too simplistic, and SIDM simulations currently yield a constraint of roughly $\sigma/m \lesssim 1$ cm^2/g based on ellipticity of clusters. (Brinckmann et. al., arXiv:1705.00623)

Cluster density profiles

- SIDM is expected to produce a DM core in galaxy clusters.
- However, the overall density profile in the central region can be NFW-like, due to high density of baryons in the brightest cluster galaxy (BCG).
- Kaplinghat, Tulin and Yu [arXiv:1508.03339] match the profiles of 6 relaxed clusters inferred from stellar kinematics and gravitational lensing to SIDM and CDM profiles, and find $\sigma/m = 0.1(\pm0.03)$ cm^2/g, favoring a non-zero self scattering cross section.
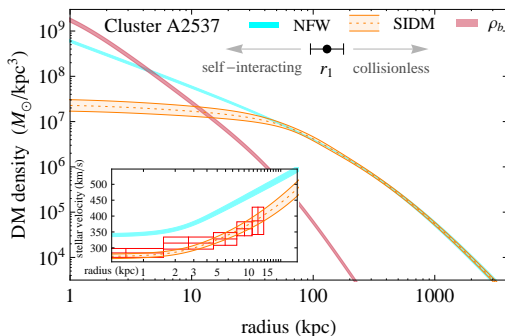
Cluster mergers

- Dissociative cluster mergers are a direct way of probing the self-interactions of DM.
- The individual galaxies behave as collisionless test particles.
- The hot intracluster medium (ICM) behaves as a collisional fluid, is shocked and slowed down. An offset between the luminous galaxies and the X-ray emitting ICM develops.
- The location of DM can be traced via gravitational lensing. Collisionless DM should remain coincident with the stars. An offset between the luminosity peak (stars) and the center of mass (DM) indicates self-interacting DM.
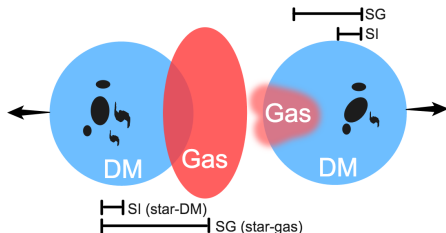

Figure from Wittmann, Golovich and Dawson, arXiv:1701.05877

Cluster mergers

- Using offsets from the Bullet cluster and other cluster mergers, Harvey et. al. [arXiv:1503.07675] find a constraint $\sigma/m \lesssim 0.5$ cm^2/g.
- Wittmann, Golovich and Dawson [arXiv:1701.05877] find the previous estimate to be overstated, and find $\sigma/m \lesssim 2$ cm^2/g.
- Kim, Peter and Wittman [arXiv:1608.08630] find no large offsets in simulated cluster mergers, and instead suggest to look for offset between the BCG and DM center of mass in the post-merger stage.
- Randall et. al. [arXiv:0704.0261] argue that the bullet in the Bullet cluster should not have lost more than 23% of it's mass during core passage, resulting in $\sigma/m \lesssim 0.7$ cm^2/g. However, it is unknown how the merger should affect the star formation rate and mass to light ratio of the subcluster.
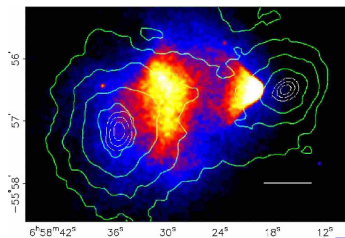
The curious case of Abell 520

Abell 520 is a complicated merger of several clusters. Jee et. al.
[arXiv:1401.3356] find a DM substructure coincident with the ICM, but
devoid of luminous galaxies.
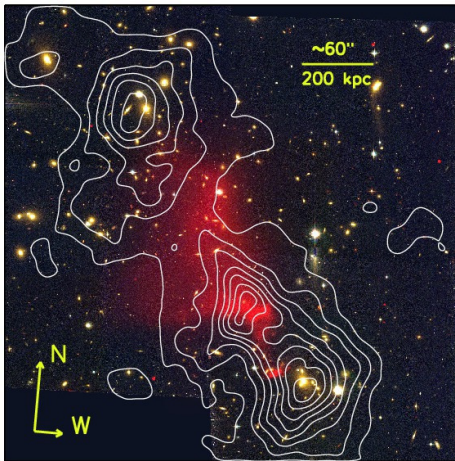
The curious case of Abell 520

- ▶ To explain the seemingly conflicting observations of the Bullet Cluster and Abell 520, Heikinheimo et. al. [1504.04371] have proposed a model of two-component DM: a dominant collisionless component, and a subdominant ($\sim 20 - 30\%$) self-interacting component, charged under a dark $U(1)$-interaction.

- ▶ Bullet cluster: Part of the self-interacting component of the bullet halo will be absorbed by the larger subcluster's halo. $\Rightarrow$ The fraction of self-interacting DM is limited by the observed constraints on mass loss.

- ▶ Abell 520: The self-interacting component forms the structure observed on top of the shocked ICM. $\Rightarrow$ The self-interacting component should effectively behave as a collisional fluid in the merger.

- ▶ Spethmann et. al. [arXiv:1603.07324] find agreement with both the Bullet cluster and Abell 520 in simulations with the SIDM and CDM components, but without baryons.

Contents

Self scattering cross section

- The self scattering cross section per unit mass, σ/m should be $\mathcal{O}(1)$ cm^2/g to affect the small scale structure, while the tightest constraint arising from cluster cores implies $\sigma/m \lesssim \mathcal{O}(0.1)$ cm^2/g.

- The velocity dispersion in small scale structures is in the range $\mathcal{O}(10) - \mathcal{O}(100)$ km/s, and in clusters $\mathcal{O}(1000)$ km/s.

- A velocity-dependent cross section can fit the data at all scales. Velocity dependece typically arises in models with light mediators.
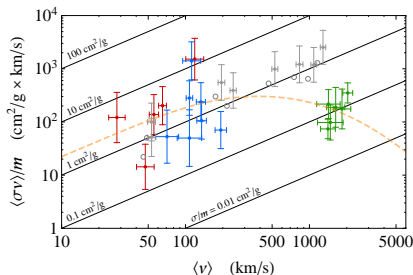

Figure from Kaplinghat, Tulin and Yu, arXiv:1508.03339

Vector mediator

- A simple model for velocity dependet SIDM scattering is given by DM interacting via a broken $U(1)$ gauge interaction, with the Yukawa potential $V(r) = \frac{\alpha_D}{r} e^{-m_\phi r}$.
- Kaplinghat, Tulin and Yu [arXiv:1508.0333] find a fit to cored DM profiles in dwarf galaxies, low surface brightness galaxies and clusters with $m_{DM} \sim 15$ GeV and $m_\phi \sim 17$ MeV.
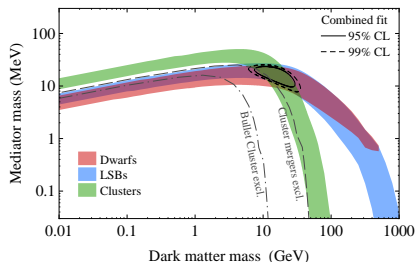

Figure from Kaplinghat, Tulin and Yu, arXiv:1508.03339

Producing the SIDM abundance

The usual Boltzmann equation for the DM number density is

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\mathrm{SM}\to\chi\chi}v\rangle(n_\chi^2 - (n_\chi^{\mathrm{eq}})^2).$$

The Freeze-in limit is given by $n_\chi \ll n_\chi^{\mathrm{eq}}$, and gives

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \left\{ \begin{array}{ll} \langle\sigma_{\psi\psi\to\chi\chi}v\rangle(n_\chi^{\mathrm{eq}})^2, & \text{Annihilations} \\ \langle\Gamma_{\psi\to\chi\chi}\rangle n_\psi^{\mathrm{eq}}, & \text{Decays} \end{array} \right.$$

i.e. the freeze-in limit is obtained by neglecting the back-scattering $\chi\chi \to \mathrm{SM}$. However, if number changing interactions $\chi\chi \to n\chi$, $n > 2$ are present, or if the hidden sector contains additional (light) particles ϕ so that $\chi\chi \to \phi\phi$ is relevant, the Bolzmann equation becomes

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle\sigma_{\mathrm{SM}\to\chi\chi}v\rangle_T(n_\chi^{\mathrm{eq}}(T))^2 - \langle\sigma_{\chi\chi\to\mathrm{HS}}v\rangle_{T_D}(n_\chi^2 - (n_\chi^{\mathrm{eq}}(T_D))^2).$$

Cannibal DM

Let's examine the simple case of a $\mathbb{Z}_2$ symmetric singlet scalar DM

$$V_\phi = \lambda_\phi \phi^4 + m_\phi^2 \phi^2 + \lambda_{\phi H} \phi^2 H^\dagger H.$$
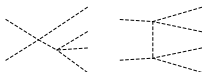
If $m_\phi < \frac{1}{2} m_H$ and $\lambda_{\phi H} \lesssim 10^{-7}$, the DM is produced via freeze-in from Higgs decays

$$n_\phi^{FI} \approx 3 \frac{n_h^{eq} \Gamma_{h \to \phi\phi}}{H} \bigg|_{T=m_h}.$$

However, if $\lambda_\phi \gtrsim 10^{-3}$, the $2 \leftrightarrow 4$ scattering becomes fast, $\langle \sigma_{2\to 4} v \rangle > H$, and the hidden sector reaches internal chemical equilibrium with temperature

$$T_D = \left(\frac{g_*^{\mathrm{SM}} \rho_{\mathrm{D}}}{g_*^{\mathrm{D}} \rho_{\mathrm{SM}}} \right)^{\frac{1}{4}} T, \quad \rho_D = \frac{1}{2} m_h n_\phi^{FI}$$

The final DM abundance is then set by the freeze-out of the $4 \to 2$ process.

Cannibal DM

- When T_D drops below m_ϕ, the DM becomes nonrelativistic and the $2 \to 4$ process becomes Boltzmann-suppressed.

- The number density n_ϕ follows the equilibrium density $n_\phi^{\rm eq}(T_D)$ as long as $\langle \sigma_{4 \to 2} v^3 \rangle > H$.

$$\frac{dn_\phi}{dt} + 3H(T)n_\phi = -\langle \sigma_{4 \to 2} v^3 \rangle n_\phi^2 (n_\phi^2 - (n_\phi^{\rm eq}(T_D))^2).$$

- During this period, the DM particles remain warm by eating each other: each $4 \to 2$ process converts $2m_\phi$ into kinetic energy, heating up the DM, and the hidden sector temperature evolves logarithmically in the scale factor:

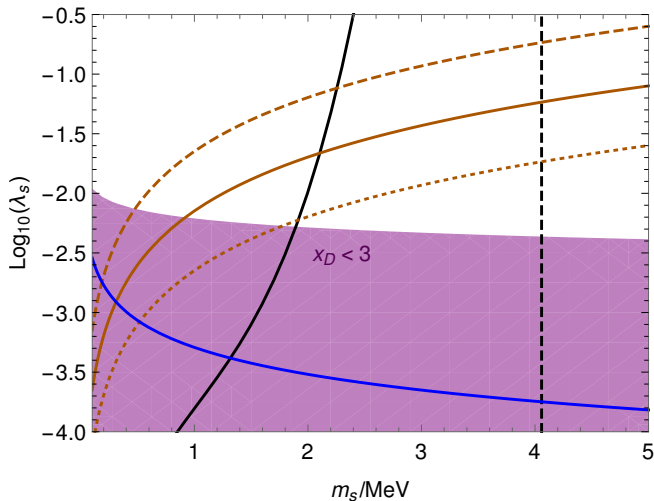$$\frac{T_D}{m_\phi} \sim \frac{1}{3 \log\left(\frac{a}{a_0}\right)}.$$

- The final DM abundance then depends both on the initial temperature of the hidden sector, controlled by $\lambda_{\phi H}$, and the freeze-out temperature $\langle \sigma_{4 \to 2} v^3 \rangle_{T_D^{FO}} \lesssim H(T)$, controlled by λ_ϕ.
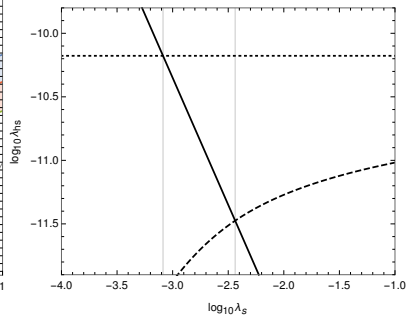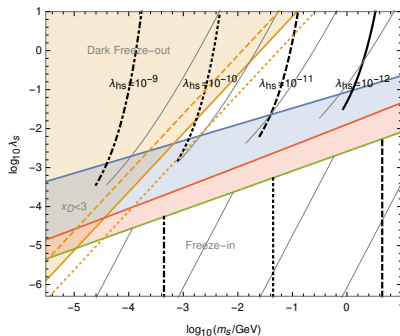
Cannibal DM

Cannibal DM with scale invariant potential

$$V_\phi = \lambda_\phi \phi^4 + \lambda_{\phi H} \phi^2 H^\dagger H.$$

Dark freeze-out

- ► Another possibility for dark sector freeze-out occurs, when the hidden sector contains a light particle ϕ in addition to the DM particle χ.

- ► Then the DM abundance is set by the freeze-out of the annihilation process $\chi\chi \to \phi\phi$,

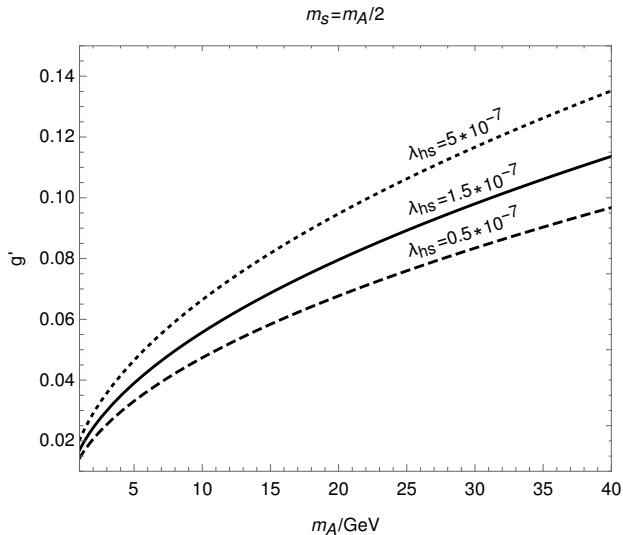$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\chi\chi \to \phi\phi} v \rangle_{T_D} (n_\chi^2 - (n_\chi^{\text{eq}}(T_D))^2).$$

- ► Again the DM abundance depends both on the temperature ratio $\xi = T_D/T$ and the annihilation cross section $\sigma_{\chi\chi \to \phi\phi}$.

$$\Omega_{\text{CDM}} h^2 = \frac{1.07 \times 10^9 \xi x^{\text{FO}} \text{ GeV}^{-1}}{\sqrt{g_*} m_P \langle \sigma_{\chi\chi \to \phi\phi} v \rangle},$$

$$x^{\text{FO}} = \log \left(\xi^2 \frac{m_P m_\chi \langle \sigma_{\chi\chi \to \phi\phi} v \rangle \sqrt{x^{\text{FO}}}}{1.66 \sqrt{g_*} (2\pi)^{\frac{3}{2}}} \right).$$

Dark freeze-out

$m_S = m_A/2$

Indirect detection from dark freeze-out

- If the lifetime of the mediator is below the BBN and CMB bounds, the decay products of $\phi \to \mathrm{SM}$ might still be observable today due to annihilations $\chi\chi \to \phi\phi$ taking place in regions with DM overdensities (Galactic center, dwarf galaxies, cluster haloes).

- The spectrum of the four-body indirect detection signal (e.g. $\chi\chi \to \phi\phi \to \bar{b}b\bar{b}b$) slightly differs from the standard two-body annihilation of WIMPS (e.g. $\chi\chi \to \bar{b}b$). (B. Dutta, Y. Gao, T. Ghosh and L. E. Strigari arXiv:1508.05989).

- For WIMPS, the annihilation cross section $\sigma_{\chi\chi\to\mathrm{SM}}$ is completely determined by the relic abundance.

- for dark freeze-out, the abundance is also a function of the temperature ratio ξ.

Indirect detection from dark freeze-out

Vector DM with Higgs portal coupling:

$$\mathcal{L}_{\text{hidden}} = \frac{1}{4}F^{'\mu\nu}F^{'}_{\mu\nu} + (D^{\mu}s)^{\dagger}(D_{\mu}s) - \mu_{\text{s}}^2 s^{\dagger}s + \lambda_{\text{s}}(s^{\dagger}s)^2 + \lambda_{\text{hs}}H^{\dagger}H s^{\dagger}s$$

Freeze-in via $H \to ss$, DM abundace from $AA \to ss$, $s \to \tau^+\tau^-$.