Asymmetric WIMP dark matter and DM/antiDM oscillations

M. Cirelli, P. Panci, G. Servant, GZ.

Asymmetric Dark Matter

Motivation:

$$\frac{n_b}{n_\gamma} \sim 6.5\ 10^{-10}$$

the baryon relic density arises from a tiny *baryon- antibaryon asymmetry* which is of the order of 10^{-10}.

$$\frac{\Omega_{DM}}{\Omega_b} \sim 5.86$$

In contrast, in *the WIMP picture*, relic density of DM is determined by the *freeze- out* of its annihilations to standard model particles.

$n_b \leftrightarrow$ baryogenesis

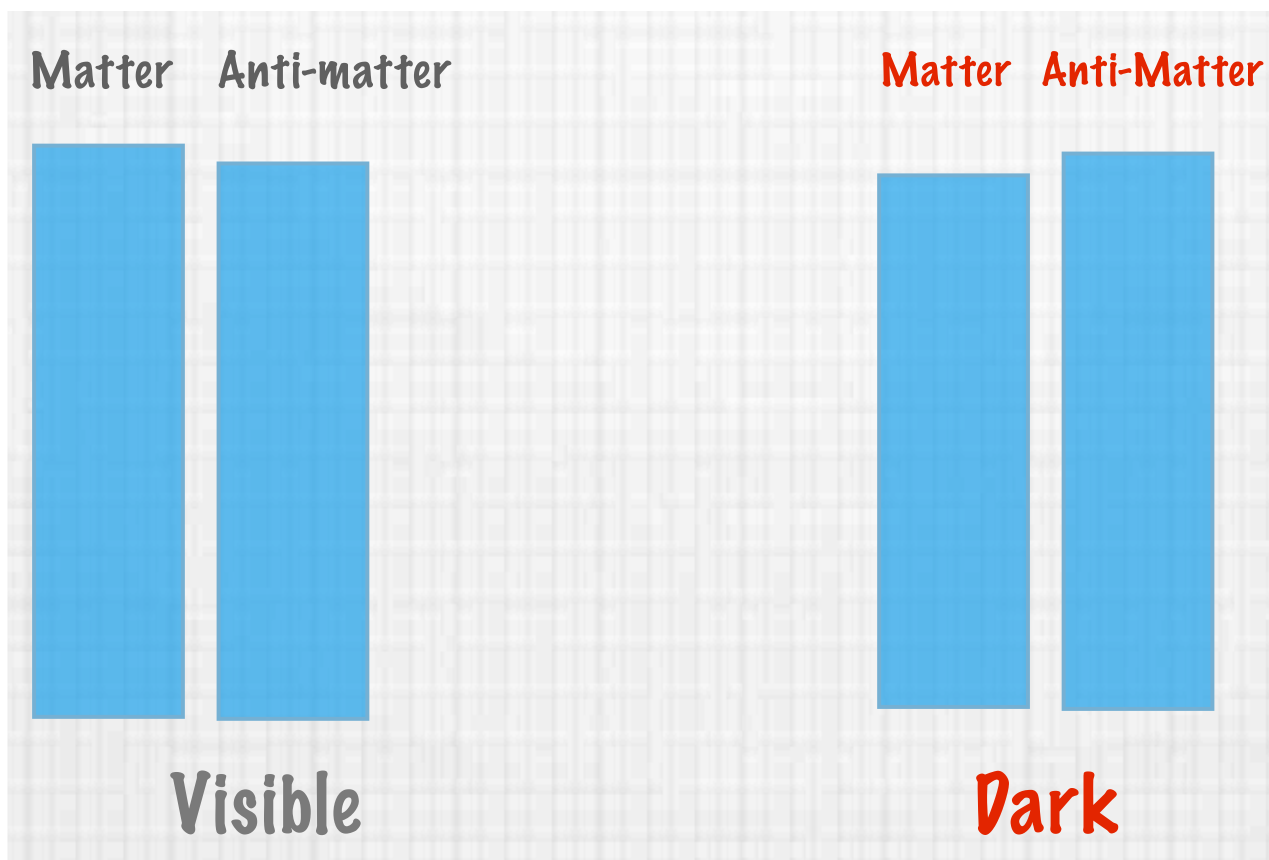
$n_{DM} \leftrightarrow$ relic freeze-out

Why are Ω_{DM} and Ω_b similar?

Asymmetric Dark Matter

Idea:

Ω_{DM} and Ω_b dynamically related?



[courtesy K. Zurek]

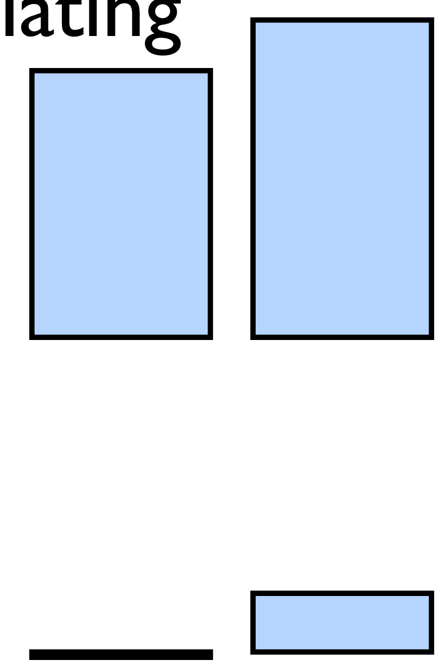
ADM models generally involve the *co-generation of an asymmetry* in both dark matter and baryonic sectors or *a transfer of asymmetries* between the two through higher-dimensional operators.

Asymmetric Dark Matter

For example...

- In most of the models, it is assumed that a *baryon/lepton asymmetry is created well above the electroweak scale.*
- and *transferred to dark matter* through B/L number violating operators as

$$\mathcal{L}_{\rm asym} = \frac{1}{{M'}_{ij}^{4}} \bar{X}^2 (L_i\, H)(L_j\, H) + {\rm h.c.}, \qquad \bar{X}\,\bar{X} \leftrightarrow \bar{\nu}\,\bar{\nu}$$



- *Symmetric interactions* stay in equilibrium longer and essentially *wipe out all remaining population* → Ω_{DM} depends only of asymmetry.

$$\mathcal{L}_{\rm sym} = \frac{1}{M_{ij}^2} \bar{X}\, X\, \bar{L}_i\, L_j + {\rm h.c.}, \qquad \bar{X}\, X \leftrightarrow \ell^+\, \ell^-,\ \bar{\nu}\, \nu$$

[K. Zurek et al, PhysRevLett.104.101301]

~100 papers on the ADM idea have been published since the 80ties [S. Nussinov,PLB(1985)].

Asymmetric Dark Matter

General features:

- DM is naturally light:

$$n_{\rm DM} \sim n_B \qquad \Omega_{\rm DM} \sim (m_{\rm DM}/m_B)\Omega_B.$$

→ *mDM~5 GeV!*

If DM is non-relativistic when the B/L-violating operators which transfer the asymmetry decouple (Td), n_{DM} is exponentially suppressed, and higher DM masses are possible (arguably less natural).

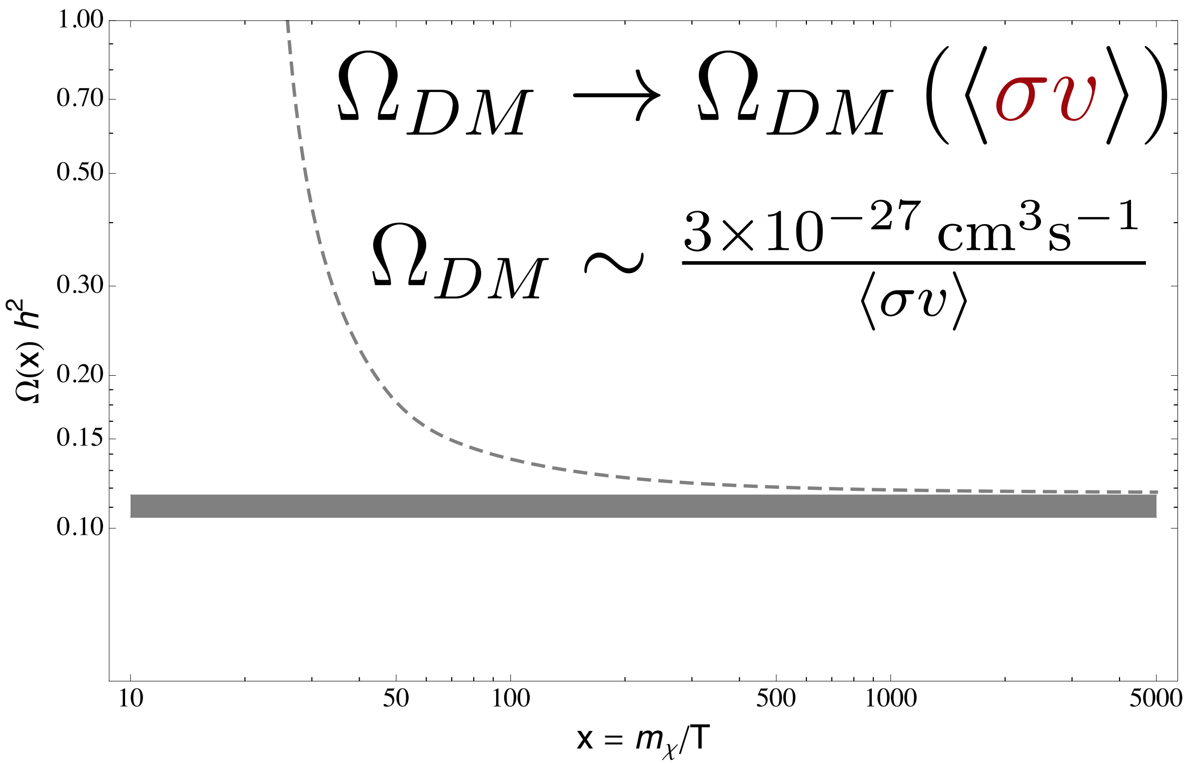
$$(n_X - n_{\bar{X}}) \sim (n_\ell - n_{\bar{\ell}})\, e^{-m_X/T_d}$$

- *No indirect detection signatures* of DM (it does not self-annihilate).
- Bounds on ADM models typically set from an effect of accumulation in (neutron/white dwarf) stars.

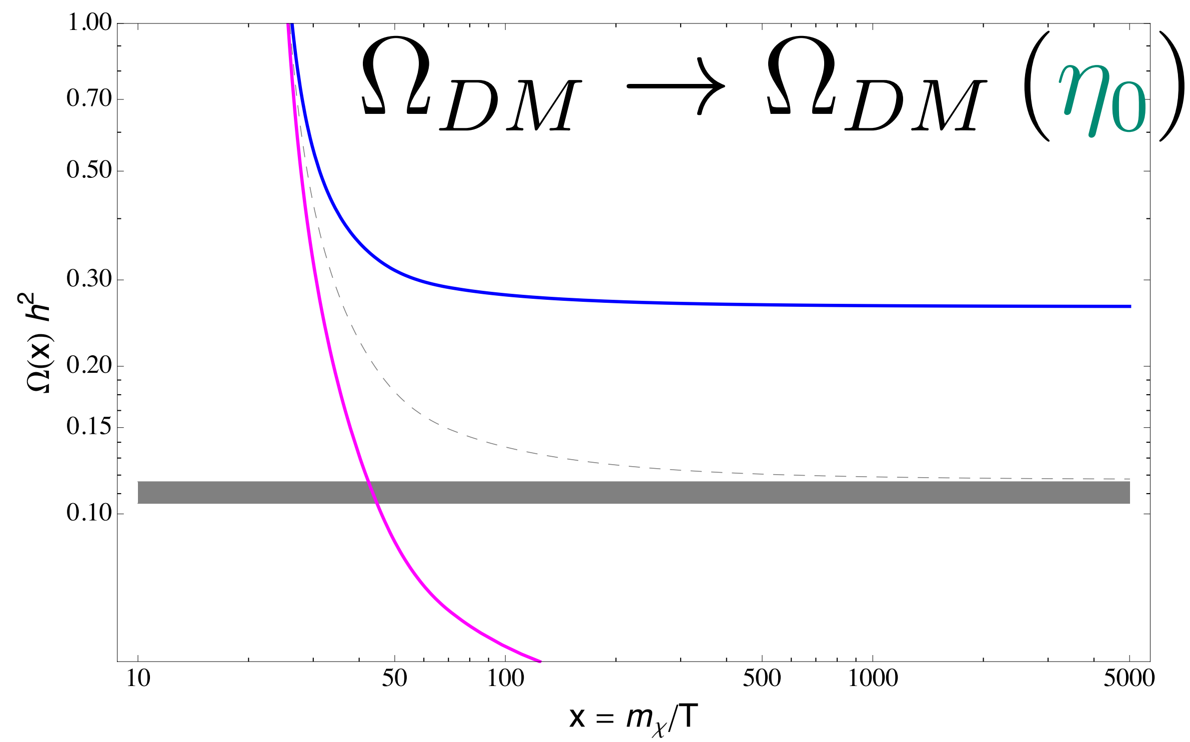
Asymmetric Dark Matter

Why consider DM/anti-DM oscillations?

Standard WIMP picture



Asymmetric DM picture



1. It *fills a gap* between the standard freeze out prediction (where Ω_{DM} depends only on the annihilation cross section σ), and the aDM prediction where Ω_{DM} depends only on the primordial DM asymmetry.

Asymmetric Dark Matter

Why consider DM/anti-DM oscillations?

2. *Higher masses* >~100 GeV are therefore ‘naturally’ available in this framework
3. *Phenomenological bounds modified*: traditional ADM bounds do not apply while standard WIMP bounds become relevant.

Asymmetric Dark Matter

In our study, δm is a free parameter that can range orders of magnitude. An example:

- δm can be connected to neutrino mass through the seesaw Lagrangian:

$$\mathcal{L} \supset -m_\chi \chi\tilde{\chi} + \frac{1}{2} M_{N_1} N_1^2 + \lambda\, N_1 \chi \langle \phi \rangle + y\, N_1 L \langle h \rangle + h.c.$$

$$\mathcal{L} \supset -m_\chi\, \chi\tilde{\chi} - \frac{\mu_\chi}{2}\chi^2 - \frac{m_\nu}{2}\nu^2 - \mu_{\chi\nu}\, \chi\nu + h.c.$$

$$\mu_\chi = \lambda^2 \frac{v_\phi^2}{M_{N_1}}\,, \qquad m_\nu = y^2 \frac{v_{\rm EW}^2}{M_{N_1}}\,, \qquad \mu_{\chi\nu} = \left(\frac{\lambda}{y}\frac{v_\phi}{v_{\rm EW}}\right) m_\nu\,.$$

After integrating out the heavy right-handed neutrino, N generates a small Majorana mass for χ ($\mu_\chi \ll m_\chi$).

[A. Falkowski et al, JHEP05(2011)106]

- a natural value in the fermionic case is obtained from the dimension-5 operator: $\frac{XXH^\dagger H}{\Lambda}$ δm~10^{-6} eV

Formalism

We study a system of χ^+ and χ^-, which possess *an initial asymmetry* ($n+ > n-$) and are subject to *simultaneous*:

i) oscillations $\chi^+ \leftrightarrow \chi^-$

ii) annihilations $\chi^+ \chi^- \leftrightarrow$ SMSM and

iii) elastic scatterings χ SM $\leftrightarrow$ χ SM.

'Density matrix formalism' (originally developed for ν oscillations in the Early Universe) provides a framework to treat an interplay between a *coherent* process such as oscillations with incoherent processes such as annihilations and scatterings.

Formalism

$$\mathcal{Y}(x) = \left(\begin{array}{cc} Y^{+}(x) & Y^{+-}(x) \\ Y^{-+}(x) & Y^{-}(x) \end{array} \right)$$

Y: co-moving DM abundance; diagonal elements are *physical states* while off diagonal elements are their superposition.

$$Y_0^{\pm} \equiv Y^{\pm}(x_0) = Y_{\rm eq}(x_0)\, e^{\pm\xi_0}$$

$$\begin{aligned} \mathcal{Y}'(x) \;=\; & -\frac{i}{x\,H(x)}\Big[\mathcal{H}, \mathcal{Y}(x)\Big] \\ & -\frac{s(x)}{x\,H(x)}\left(\frac{1}{2}\Big\{\mathcal{Y}(x), \Gamma_{\rm a}\,\bar{\mathcal{Y}}(x)\,\Gamma_{\rm a}^{\dagger}\Big\} - \Gamma_{\rm a}\,\Gamma_{\rm a}^{\dagger}\,\mathcal{Y}_{\rm eq}^{2}\right) \\ & -\frac{1}{x\,H(x)}\Big\{\Gamma_{\rm s}(x), \mathcal{Y}(x)\Big\}. \end{aligned}$$

oscillations DM ↔ DM

annihilations DMDM ↔ SMSM

elastic scatterings DM SM ↔ DM SM

Formalism

Oscillations only:

$$\mathcal{Y}'(x) = -\frac{i}{x\,H(x)}\Big[\mathcal{H}, \mathcal{Y}(x)\Big].$$

$$\mathcal{H} = \begin{pmatrix} m_{\rm DM} & \delta m \\ \delta m & m_{\rm DM} \end{pmatrix}.$$

$$\begin{cases} \Sigma'(x) = 0, \\ \Delta'(x) = -2\dfrac{\Gamma_{\rm osc}(x)}{x\,H(x)}\Delta(x). \end{cases}$$

The total number of particles (Σ) stays constant, while the difference (Δ) oscillates,

$\Delta = \Delta_0 \mathrm{Cos}(\delta m/2H(x))$

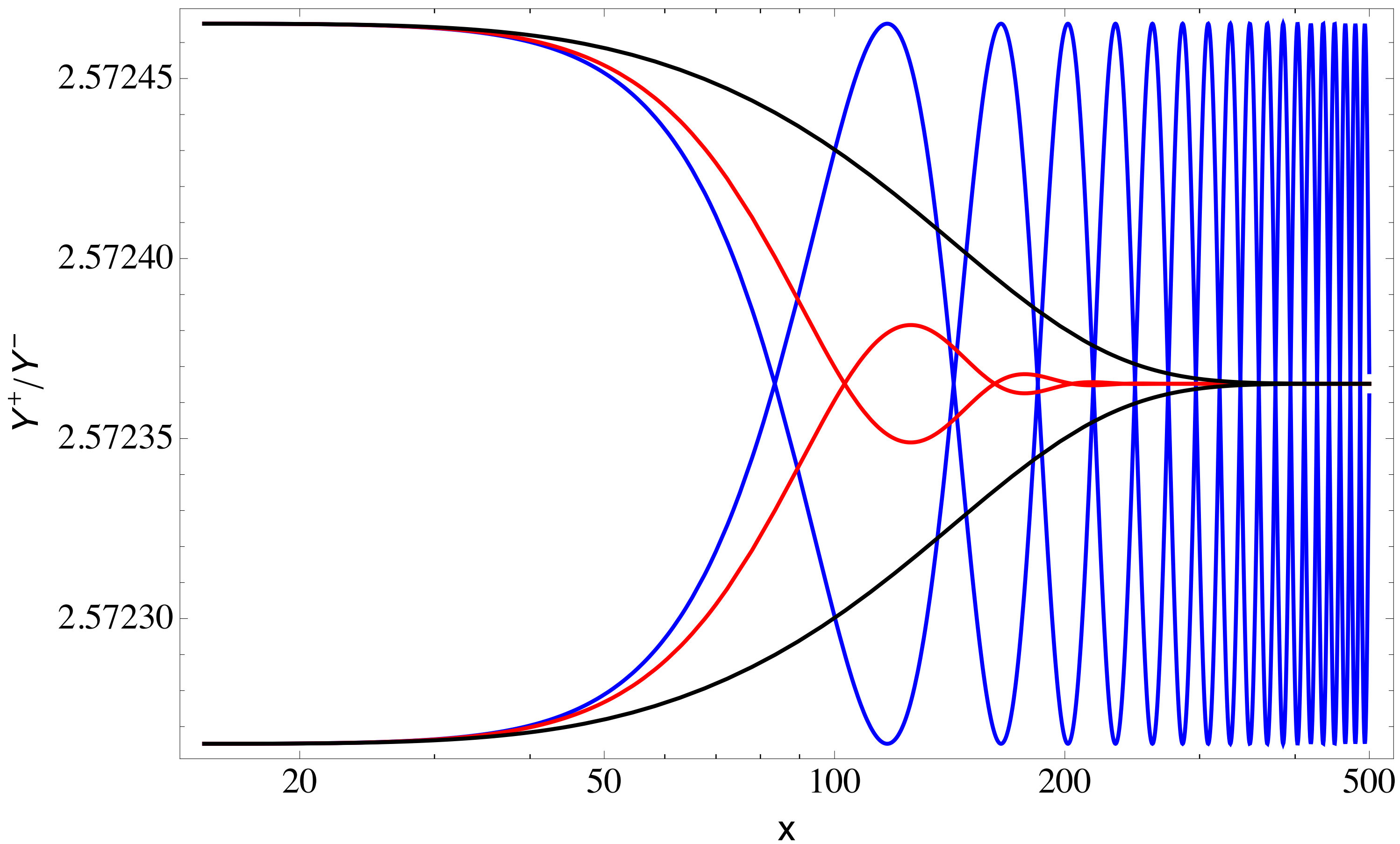
$$x_{\rm osc} \simeq \; 2\cdot 10^{-4}\left(\frac{m_{\rm DM}}{10\ {\rm GeV}}\right)\left(\frac{\rm eV}{\delta m}\right)^{1/2}$$

Formalism

Oscillations + scatterings: effect of decoherence:

$$\mathcal{Y}'(x) = -\frac{i}{x\,H(x)}\Big[\mathcal{H}, \mathcal{Y}(x)\Big] - \frac{1}{x\,H(x)}\Big\{\Gamma_s(x), \mathcal{Y}(x)\Big\}.$$

$$\Gamma_s = \begin{pmatrix} \gamma_s & 0 \\ 0 & \gamma_s \end{pmatrix}$$



$\Gamma = 0$

$\Gamma = \delta m$

$\Gamma = 5\delta m$

Scatterings have an effect of *delaying* and *damping* oscillations!

Formalism

Elastic scatterings: DM SM ↔ DM SM

$$\mathcal{H} = \begin{pmatrix} m_{\rm DM} + V(x) + \Delta V(x) & \delta m \\ \delta m & m_{\rm DM} + V(x) \end{pmatrix} \quad \text{and} \quad \Gamma_{\rm s} = \begin{pmatrix} \gamma_{\rm s} & 0 \\ 0 & \gamma_{\rm s} \end{pmatrix}.$$

Two-fold effect: the one just described + ΔV represents the effective energy shift of DM versus anti-DM induced by the baryon asymmetry of the medium (it leads to a non-maximal mixing angle, *reducing the oscillation probability* in the vacuum.)

$$\Delta V = \xi \sqrt{2}\, G_{\rm F}\, \underline{\eta_{\rm B}}\, \big(g_{*\rm s}(x) - 2\big)\, n_\gamma \quad \text{and} \quad \gamma_{\rm s} = \xi^2\, \frac{45}{\pi^3} \zeta(5)\, G_{\rm F}^2\, \big(g_{*\rm s}(x) - 2\big) \frac{m_{\rm DM}^5}{x^5},$$

We consider **ξ=0** (no effect of scatterings) and **ξ=10^{-2}** (corresponds to sigma~ 10^{-41}cm^2, somewhat stronger than current DD bounds).

Formalism

Annihilations only:

$$\mathcal{Y}'(x) = -\frac{s(x)}{x\,H(x)}\left(\frac{1}{2}\left\{\mathcal{Y}(x), \Gamma_{\mathrm{a}}\,\bar{\mathcal{Y}}(x)\,\Gamma_{\mathrm{a}}^{\dagger}\right\} - \Gamma_{\mathrm{a}}\,\Gamma_{\mathrm{a}}^{\dagger}\,\mathcal{Y}_{\mathrm{eq}}^{2}\right).$$

$$\Gamma_{\mathrm{a}}\,\Gamma_{\mathrm{a}}^{\dagger} = \langle\sigma v\rangle\,\mathbb{I}$$

$$\bar{\mathcal{Y}} = \mathrm{CP}^{-1}\cdot\mathcal{Y}\cdot\mathrm{CP}$$

Reduces to the usual
Boltzmann equation.

Results

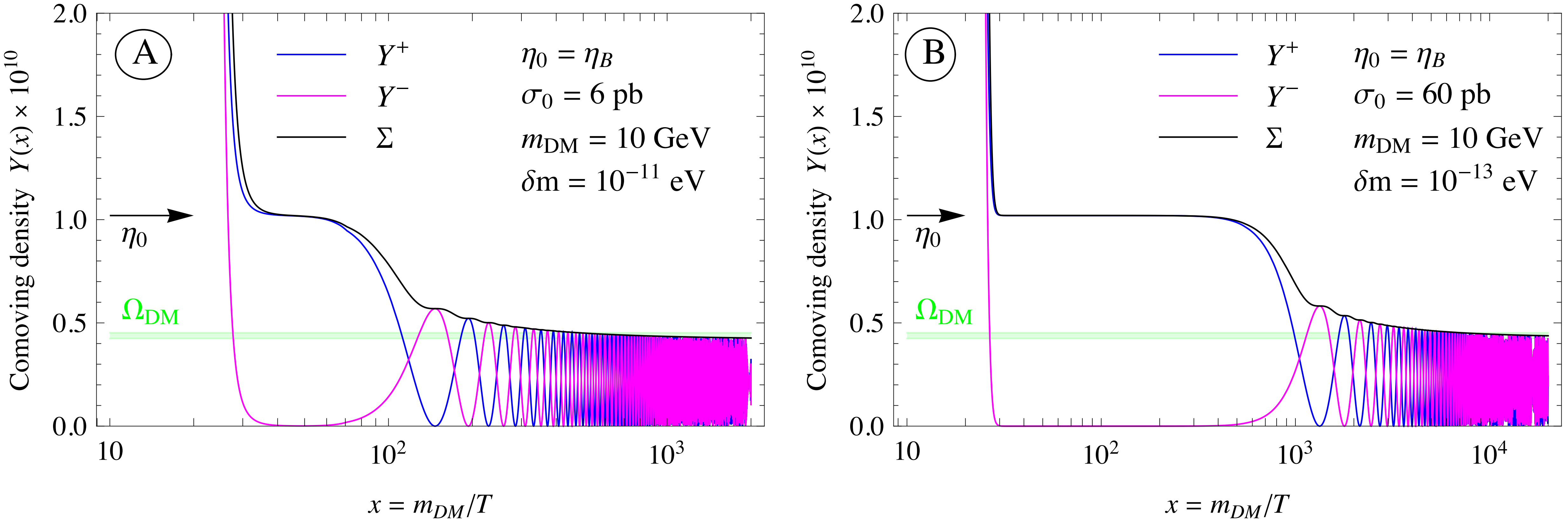
Oscillations + Annihilations:

1. Y^+ sits only temporarily on the plateau determined by η_0, as in the usual ADM scenarios.
2. oscillations start at x ~ 600 and Y^- gets repopulated.
3. Given the relatively **large** annihilation cross section σ_0 = 60 pb, *annihilations then resume* and the total population Σ decreases.
4. In the later stages, Σ goes through a rapid *series of plateaux and drops*, until it rests on its asymptotic value, determined by the freeze-out of annihilations.

$$\Omega_{DM} \to \Omega_{DM}\left(\langle \sigma v \rangle, \eta_0, m_{DM}, \delta m\right)$$

Results

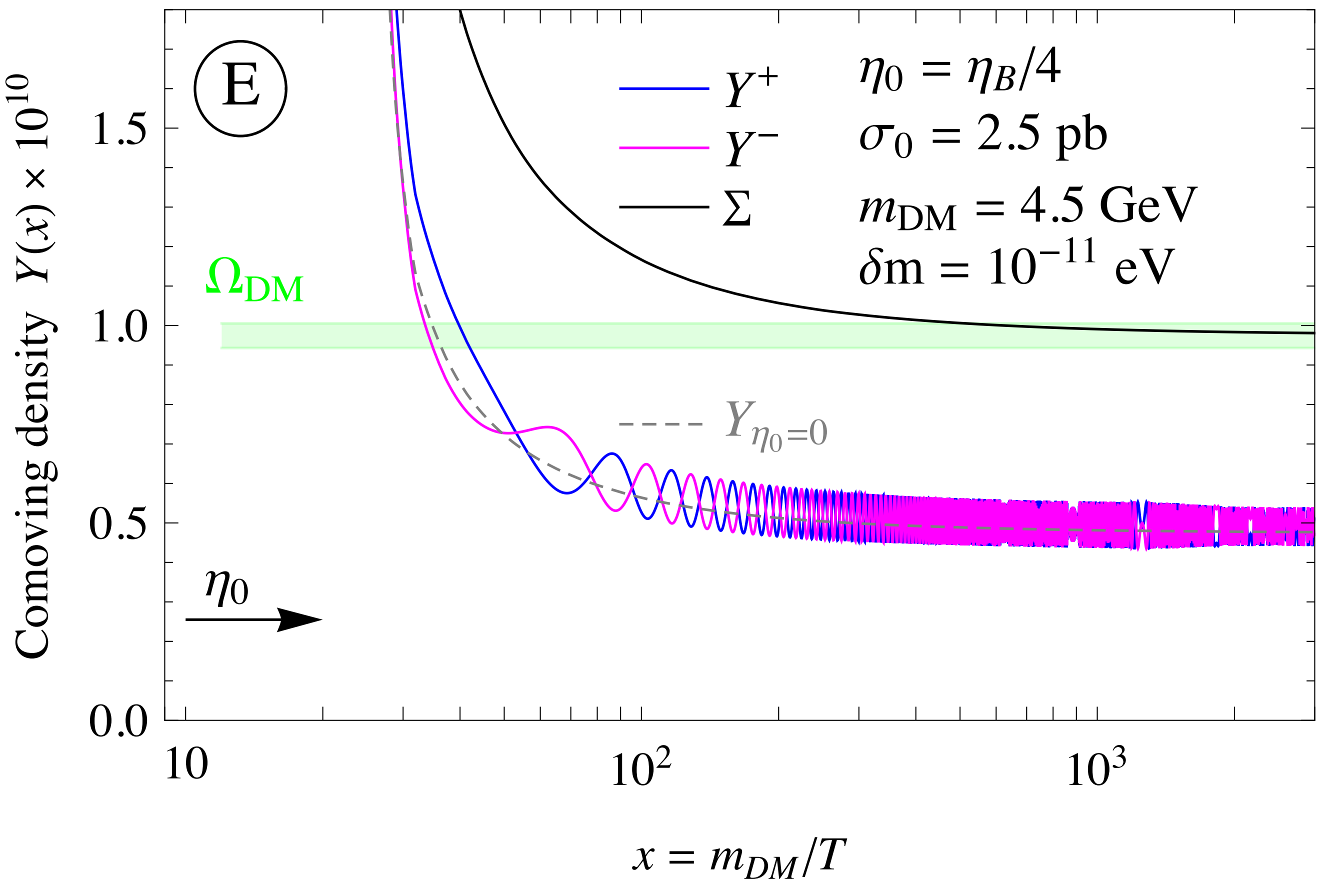
Oscillations + Annihilations: impact of varying δm.



A: the same mDM as in B, but we adopt a much *larger δm*. The co-moving population of DM therefore sits for a shorter time on the plateau determined by the initial asymmetry η0. Lower value of σ0 = 6 pb is now needed to reach the correct relic abundance.

Results

Oscillations + Annihilations: 'maximal' δm.



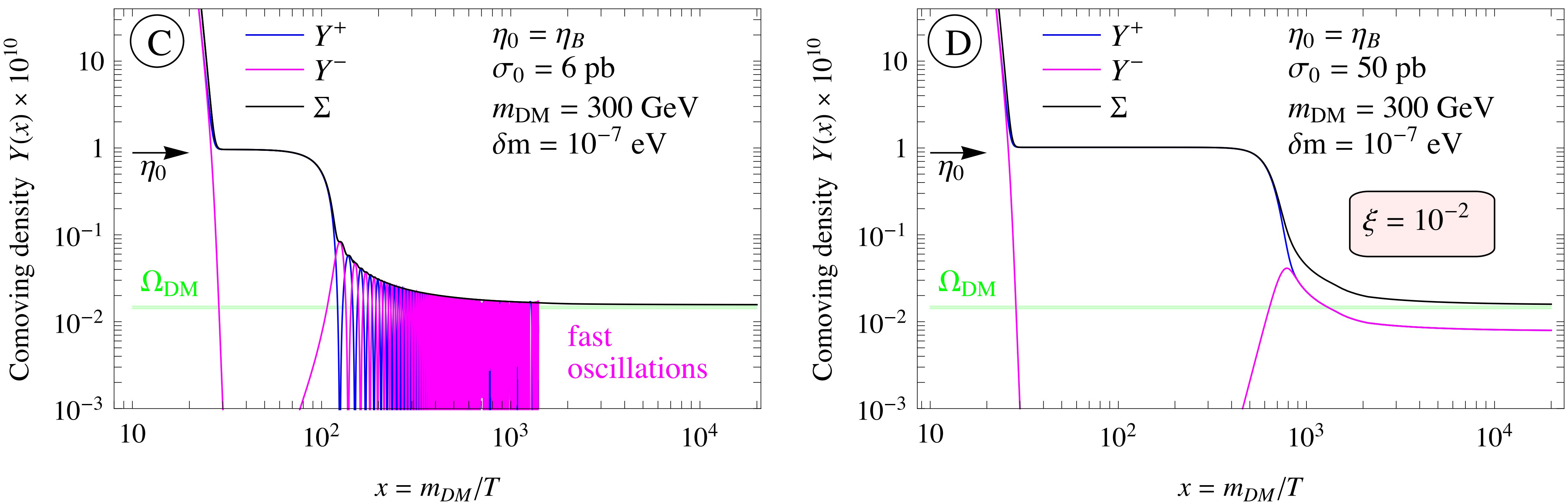
For too large δm oscillations start too early and symmetrize the dark sector such that decoupling proceeds as in the standard thermal freeze-out scenario.

$$\delta m_{\rm max} = 2\pi\ H(m)/x^2_{\rm decoupl,\ asym.} \sim 10^{-11}\sqrt{g_*}\,(m_{\rm DM}/1\ {\rm GeV})^2\ \ {\rm eV},$$

m_{DM}~1 TeV, $\delta m < 10^{-5}$ eV (when there is no elastic scatterings, $\xi < 10^{-2}$!).

Results

Oscillations + Annihilations + Scatterings:



Case D corresponds to same situation as C (in terms of m_{DM} and δm), except that now we *include elastic scatterings* ($\xi = 10^{-2}$). The effect of *incoherent scatterings* that delay and damp the oscillations is very much apparent with respect to case C. A *larger cross section* is needed to keep the annihilations active at late times and thus reach the right abundance.

Results

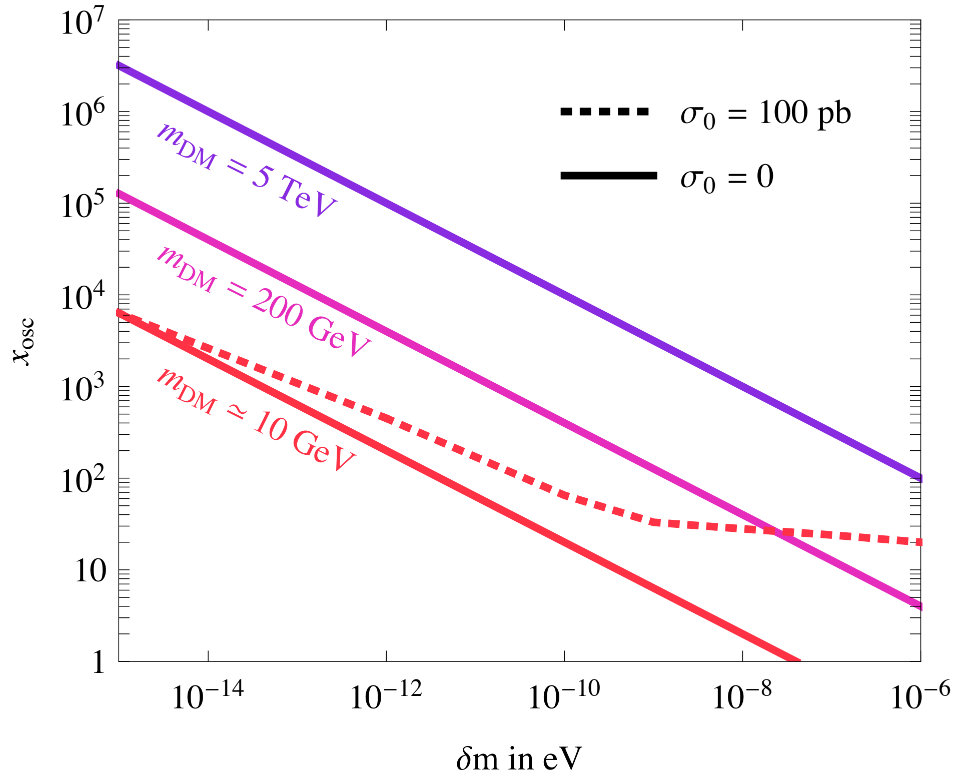
Overview of general features:

1.higher cross sections than usual σ_0 are needed to reach the correct abundance!

2. these effects are present for $\delta m < \delta m_{max}$.

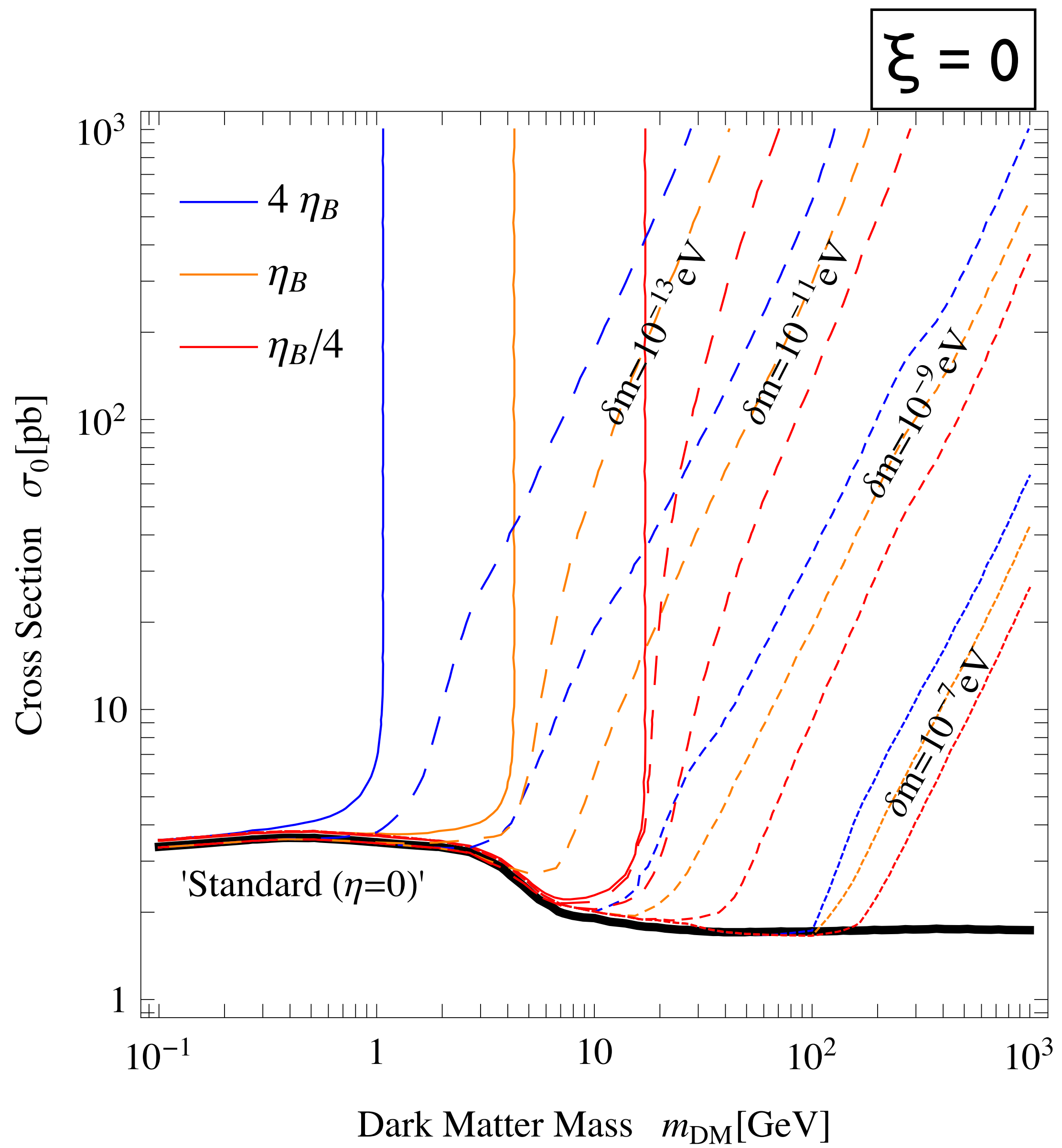
$$\delta m_{\rm max} = 2\pi\ H(m)/x^2_{\rm decoupl,\ asym.} \sim 10^{-11}\sqrt{g_*}\,(m_{\rm DM}/1\ {\rm GeV})^2\ {\rm eV}$$

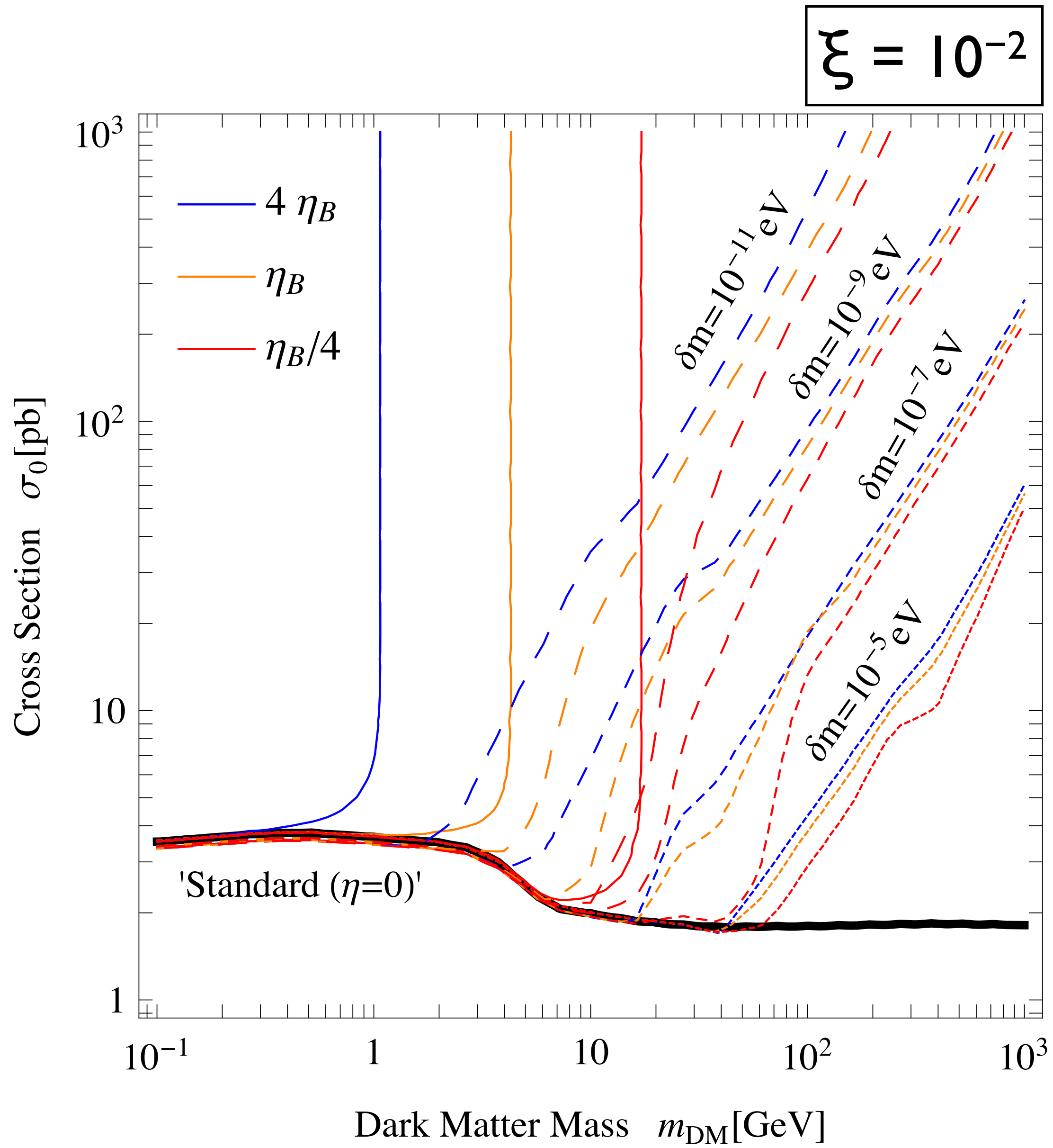
3. osc start later than a simple guess ~1/δm, due to decoherence.



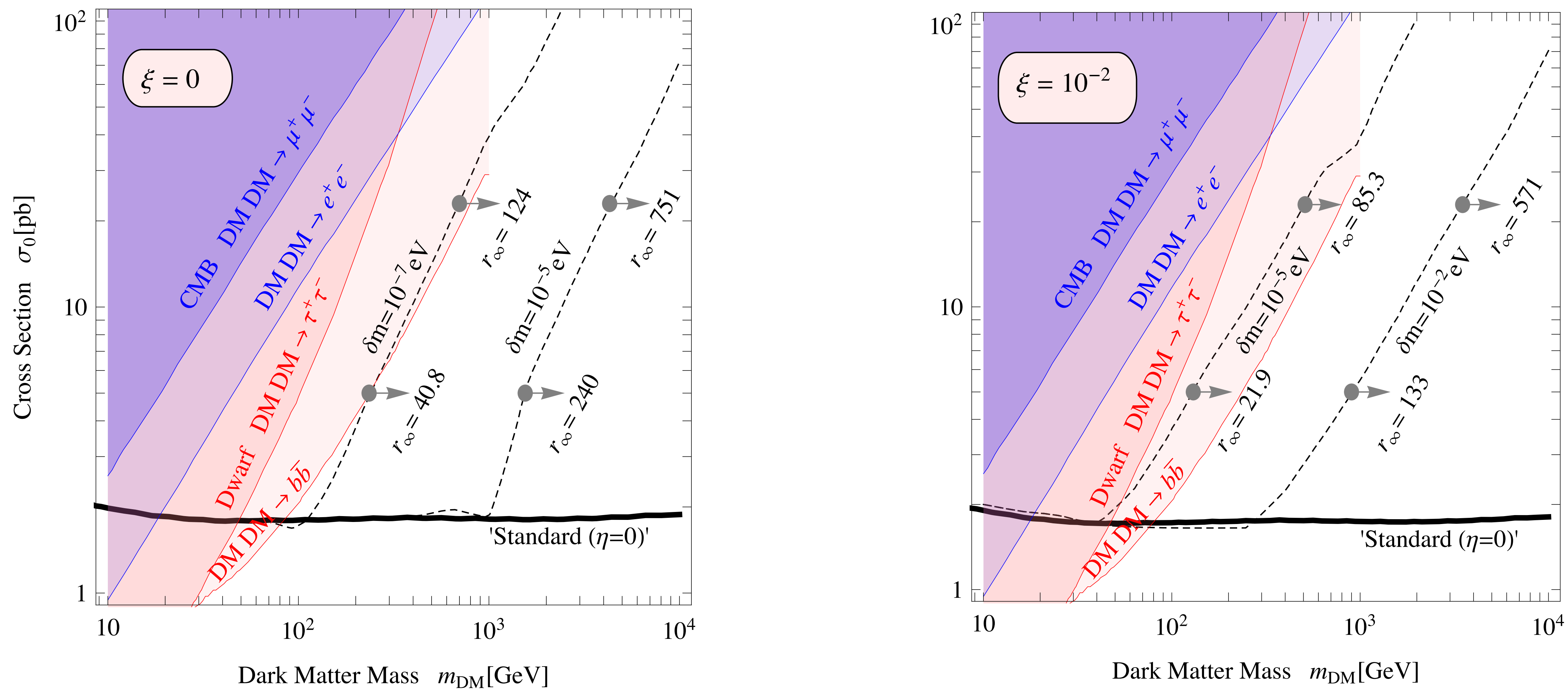
$$x_{\rm osc} \simeq 2\cdot 10^{-4}\left(\frac{m_{\rm DM}}{10\ {\rm GeV}}\right)\left(\frac{\rm eV}{\delta m}\right)^{1/2}$$

Parameter Space





Parameter Space



In these scenarios DM consists of equal portions of DM and anti-DM and can self-annihilate at late epochs, as in usual WIMP scenarios. We plot current constraints from: i) energy injection from DM annihilation during recombination, and its impact on the CMB anisotropies, [F. Iocco et al., Phys.Rev.D84 (2011)] and ii) Fermi-LAT observation (non-detection) of dwarf spheroidal Galaxies [Fermi-LAT collaboration, arXiv:1108.3546v2].

Conclusions

- *Scenarios with DM anti-DM oscillations preserve the attractive feature of aDM, that relates the DM primordial asymmetry and the baryon asymmetry in the first place, but at the same time preserve also the appeal of weak scale DM mass (and possibly cross-sections).*

- *We present a formalism needed to treat the system of particles that oscillate coherently but at the same time suffer coherence-breaking elastic scatterings on the plasma and annihilations among themselves.*

- *We have then applied such formalism to explore the phenomenologically available space, by varying the parameters of m_{DM}, σ_0, η_0, δm, for two discrete choices of the parameter ξ that sets the strength of the elastic scatterings on the plasma.*

- *We show that for motivated values of δm, predictions for σ_0 relevant for indirect DM searches are effected.*

extra

$$-\mathcal{L}_{mass} = m\ (\overline{X_R}X_L + \overline{X_L}X_R) +\ \Delta\ (\overline{X_L}(X_L)^c + \overline{(X_R)^c}X_R)$$

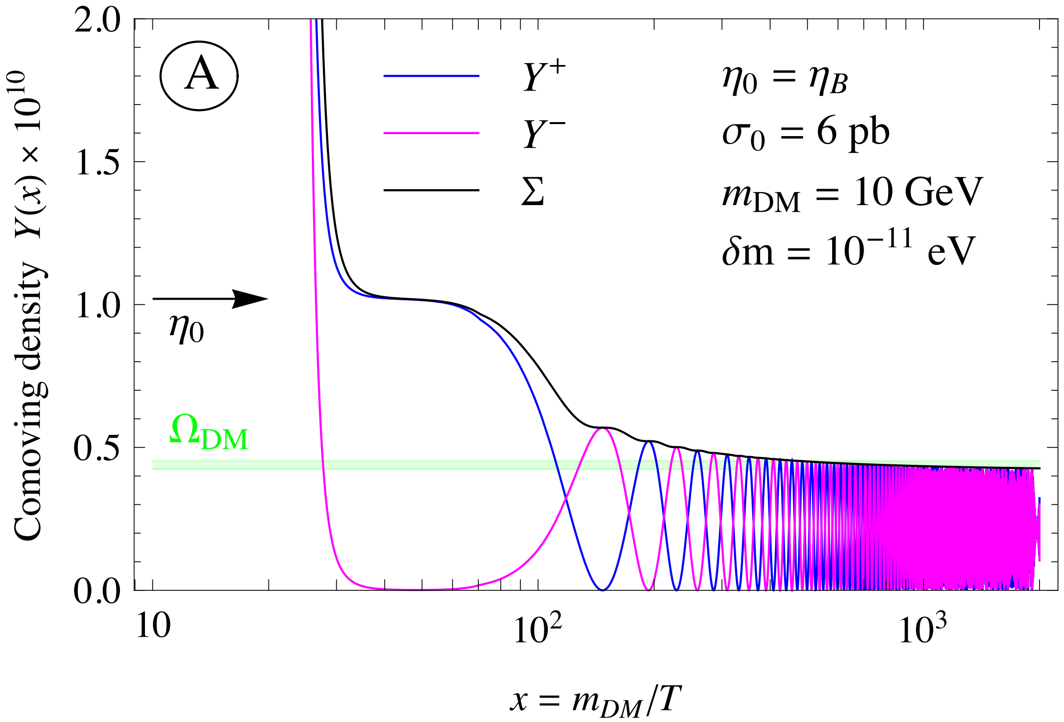
$$-\mathcal{L}_{mass} = \frac{1}{2}\ \overline{((X_L)^c \quad X_R)} \begin{pmatrix} \Delta & m \\ m & \Delta \end{pmatrix} \begin{pmatrix} X_L \\ (X_R)^c \end{pmatrix} + h.c.$$

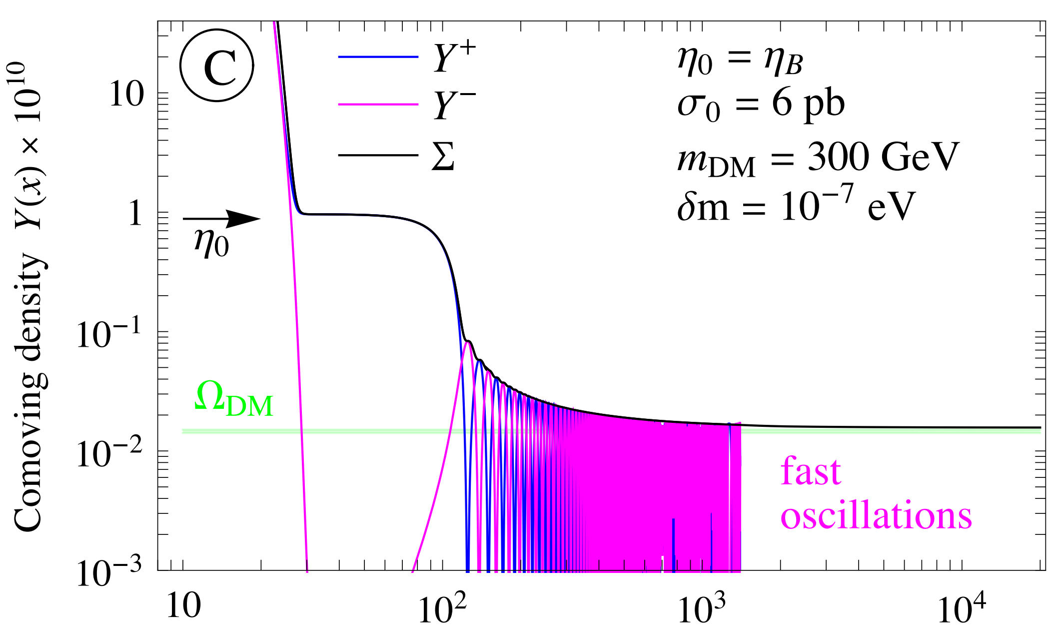
$$\mathcal{L}_{mass} = \frac{1}{2}\ (\varphi,\ \varphi^*)^* \begin{pmatrix} m^2 & \Delta^2/2 \\ \Delta^2/2 & m^2 \end{pmatrix} \begin{pmatrix} \varphi \\ \varphi^* \end{pmatrix}$$

$$\mathcal{H} = \begin{pmatrix} m & \delta m \\ \delta m & m \end{pmatrix} \quad \text{where} \quad \delta m = \begin{cases} \Delta & \text{if fermionic DM} \\ \Delta^2/(4M) & \text{if bosonic DM} \end{cases}$$

Results

Oscillations + Annihilations: impact of varying m_{DM}.





We keep instead the same annihilation cross section as in A, but we move to a *higher*, m_{DM} = 300 GeV.
The correct relic abundance is achieved by starting oscillations earlier than in A, i.e. by *choosing a much larger δm*.