Asymmetric WIMP dark matter and DM/antiDM oscillations

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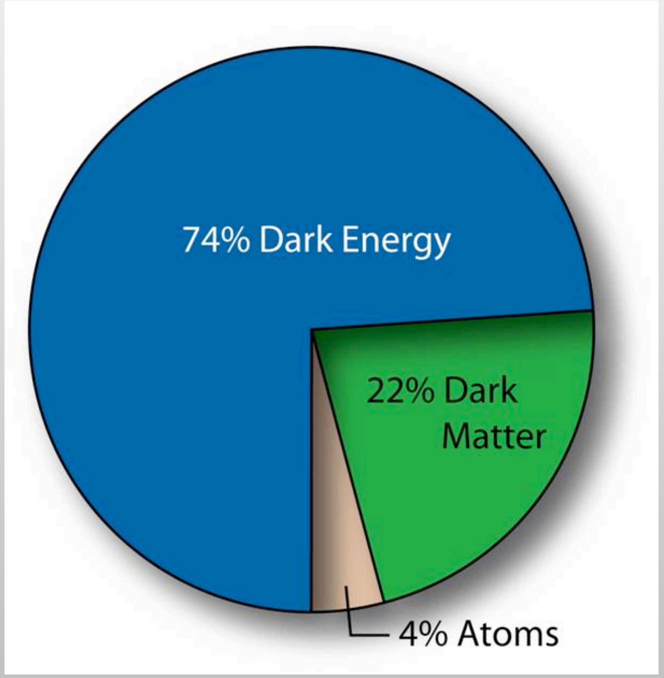
w M. Cirelli, P. Panci, G. Servant.

24th Recontre de Blois, 2012.

Cosmic Pie

The energy content of the Universe:

Ω_{DM}~22% (CMB, rotational curves, X rays from clusters...)
Ω_b~4% (CMB, BBN, ...)
Ω_Λ~74% (CMB+SNIa observations)

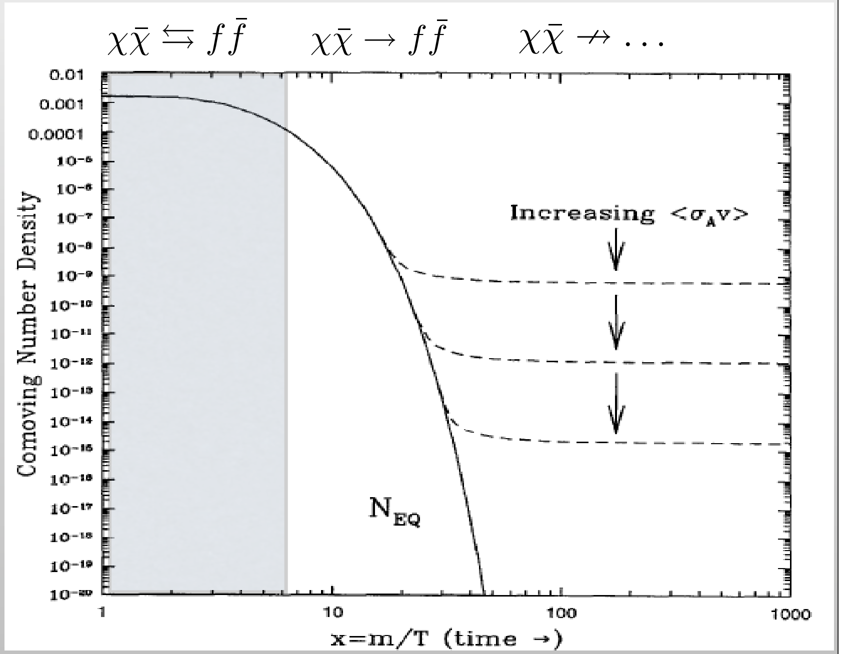


1) Most of the Universe is unknown/Dark.
☞ 2) Ω_{DM}, Ω_b (and Ω_Λ) are of a *comparable* magnitude.

What determines Ω_{DM} and Ω_b?

$\Omega_{DM} \leftrightarrow$ thermal decoupling (WIMPs):

- initially DM is in equilibrium with thermal plasma;



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  → DM interaction rates drops below the expansion rate of the Universe,
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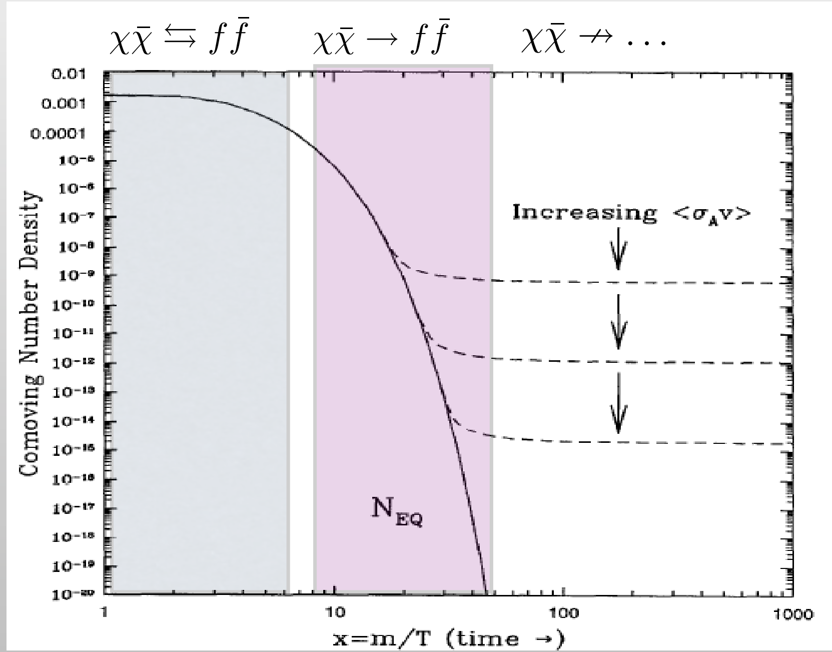

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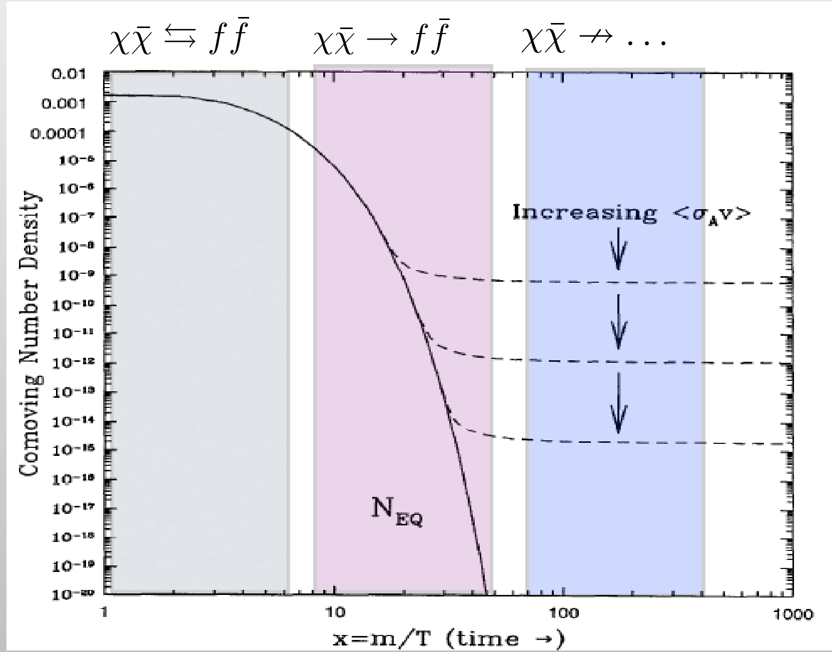

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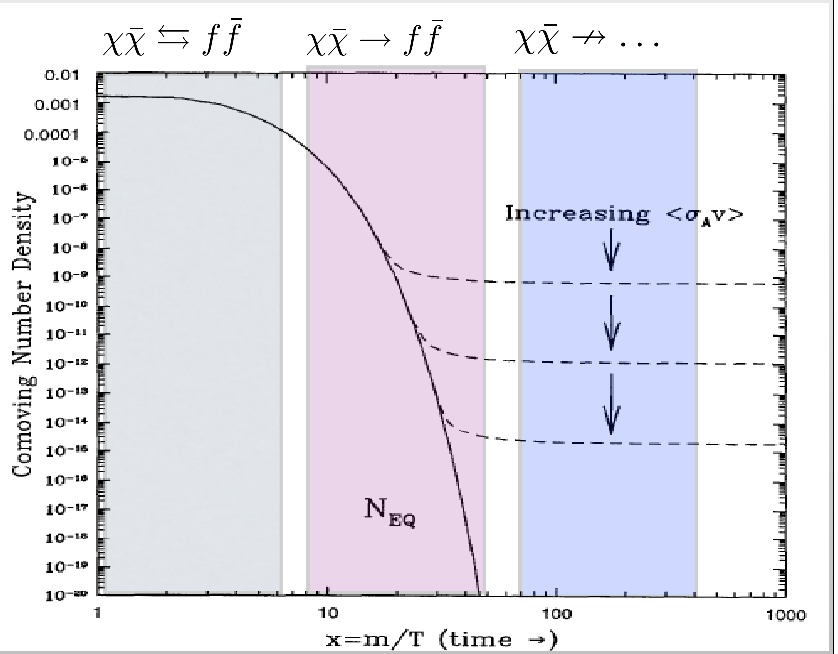
  (weak cross section → *WIMP miracle*)



$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV^2}} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

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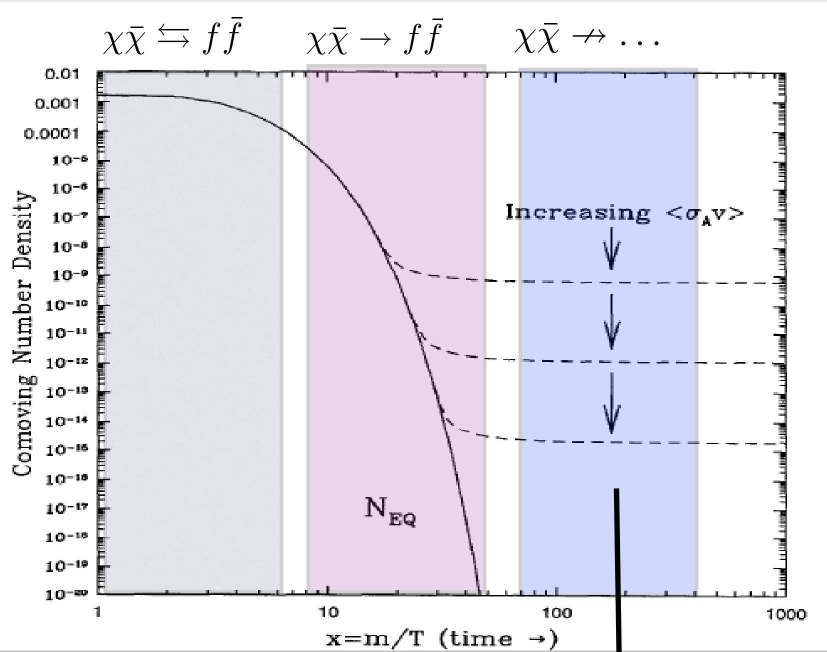

$\Omega_b \sim 0.$

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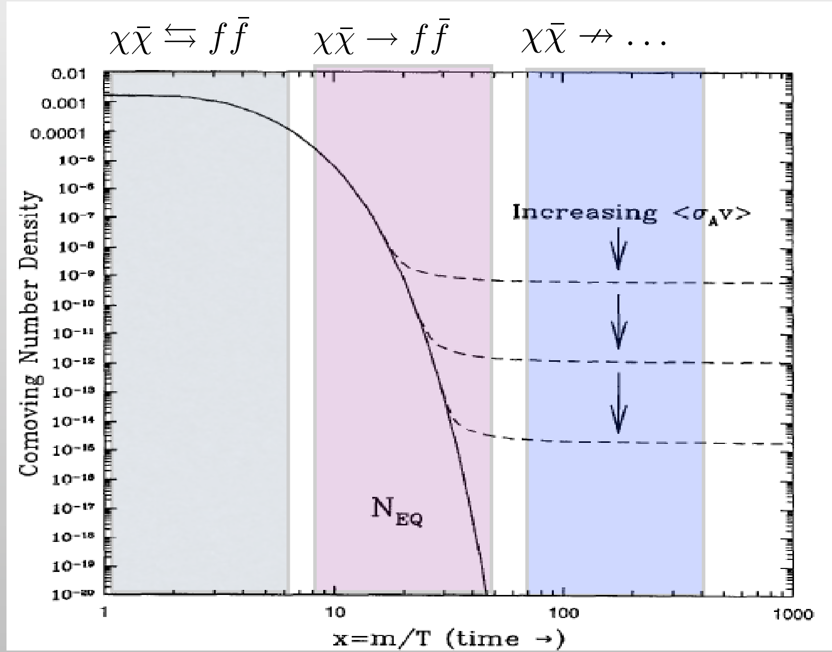
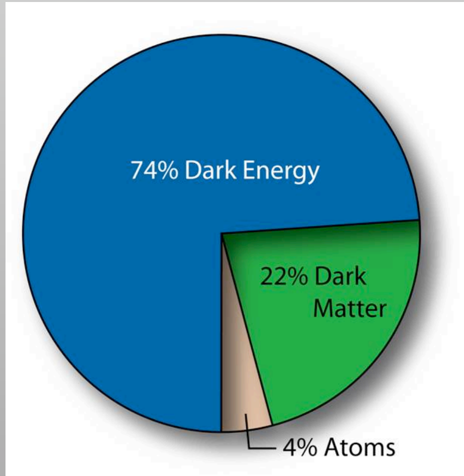


Ω_b ↔ <u>primordial asymmetry;</u>
baryons freeze-out due to a lack of anti-baryons! (otherwise, due to the high cross section they would annihilate away).

Motivation for Asymmetric DM models

n_{DM} ↔ relic freeze-out
n_b ↔ baryogenesis
(lack of anti-baryons)



Two sectors, with mutually weak interactions and different time evolution, ...

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

Just a coincidence?
Or signal of a link?

General *idea* of ADM:

DM carries a charge and is 'asymmetric' (like the visible sector)
+ there is a connection between ΔB(X) and ΔB(B,L) causing $n_{DM} \sim n_b$.

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.

General *features* of ADM:

1) ADM is naturally light.

$$a\ (n_{DM} - n_{\overline{DM}})\ =\ (n_B - n_{\overline{B}})$$

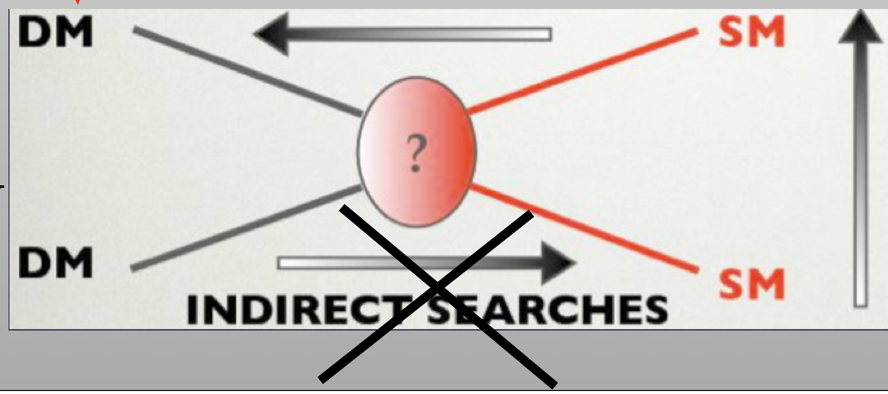
$$\frac{\Omega_{DM}}{\Omega_B} = \frac{n_{DM}}{n_B}\frac{m_{DM}}{m_B}$$

→ $m_{DM} \sim 5a$ GeV!

2) ADM does not self-annihilate: No standard indirect detection signatures.

✓ COLLIDER SEARCHES

✓ DIRECT DETECTION



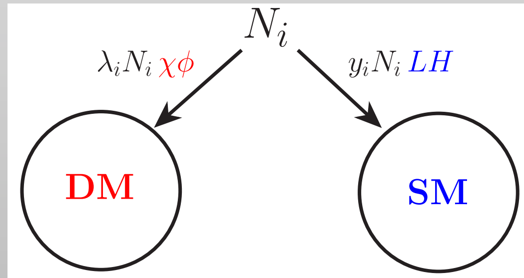
Particle physics framework(s) - a brief overview of ideas

~100 papers on the ADM idea have been published since the 80ties.

1) Co-generation of asymmetry in dark and our sectors:

- Embed in EW baryogenesis via sphalerons/DM charged under the SU(2)(Nussinov, 1985, Barr, Chivukula&Farhi, 1990, Kaplan, 1992...).

- Generalized GUT-baryogenesis or leptogenesis: (Davoudiasl et. al, 1008.2399, Blennow et al., 1009.3159, Falkowski et. al, 1101.4936, ...) CP-violating decays of heavy states lead to a lepton number asymmetry in both the SM and hidden sectors.



(Falkowski et. al, 1101.4936: 'Two sector leptogenesis')

- leptogenesis triggered by WIMP freeze-out (Cui, Randall, Shuve, 1112.2704; Chowdhury et al., 1110.5334).

Particle physics framework(s) - a brief overview of ideas

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2) Asymmetry transfer: asymmetry generated in one sector and *transferred* to the other one:

- through (temperature dependent) mass mixing between X and L: (Cui, Randall, Shuve, 1106.4834.)
- through higher-dim operators (Kaplan et. al 0901.4117, Cohen&Zurek,0909.2035)

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

Asymmetry fixed after transfer operators freeze-out (T_D).

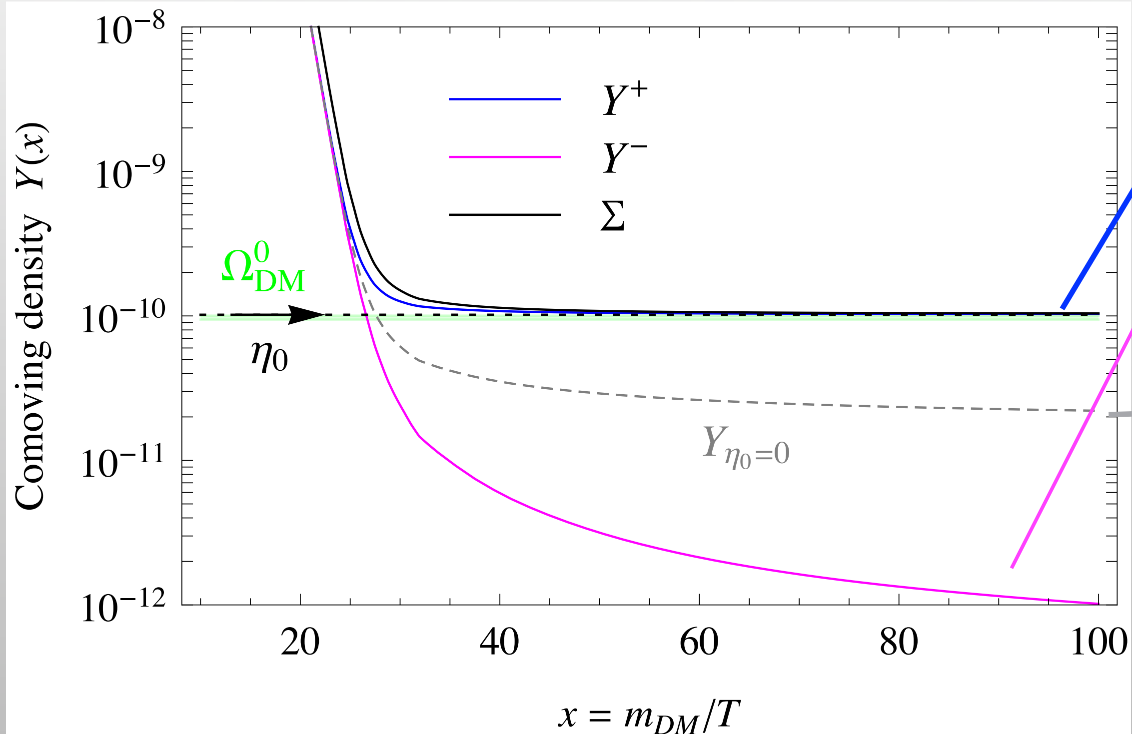
$$\frac{n_X}{n_b} \sim \frac{n_X^{eq}(T_D)}{n_b^{eq}(T_D)}$$

DM/anti-DM oscillations?

The ADM story can change significantly in the presence of tiny *majorana mass term* which gives rise to DM particle-antiparticle oscillations.

Oscillating ADM provides a generalization of typical symmetric and asymmetric DM freeze-out cosmologies. (The asymmetric limit corresponds to oscillations slower than the lifetime of the Universe, while the symmetric limit corresponds to fast oscillations that turn on long before DM freeze-out.)

DM/anti-DM oscillations:
A different relic decoupling scenario



Asymmetric DM picture

$\Omega_{DM} \to \Omega_{DM}(\eta_0)$

Standard WIMP picture

$\Omega_{DM} \to \Omega_{DM}(\langle\sigma v\rangle)$

η_0- primordial asymmetry.

Y^+/Y^- DM particle/antiparticle.

$\Sigma = Y^+ + Y^-$

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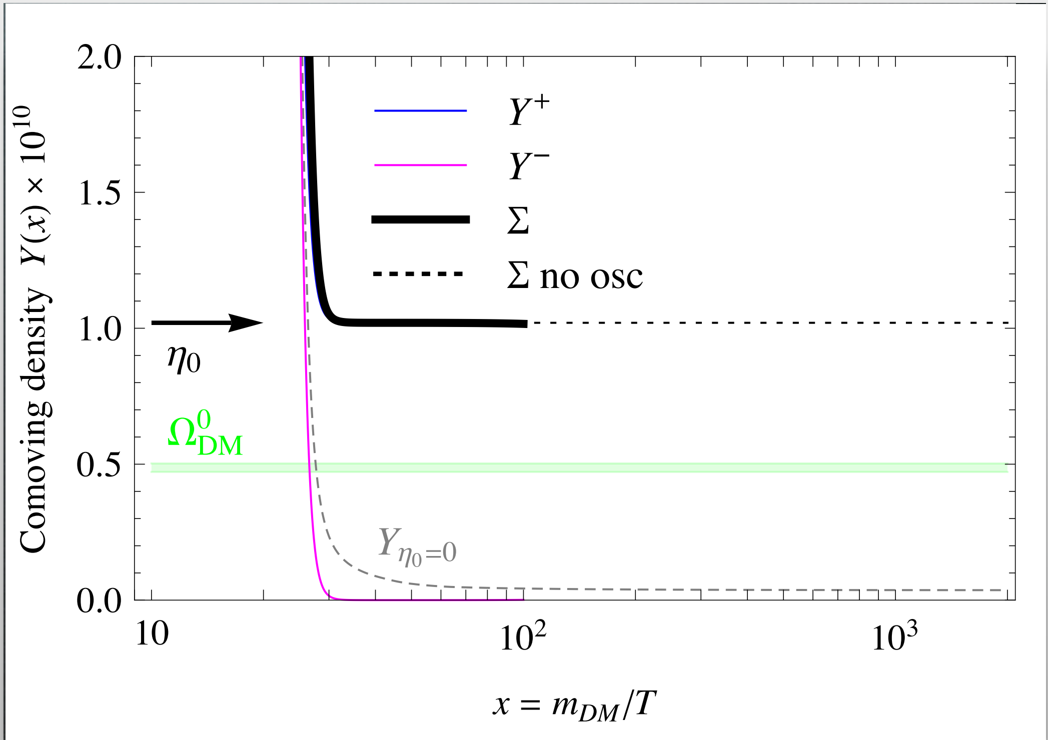

General features of ADM WIMP decoupling:

1. Asymmetric 'freeze-out'

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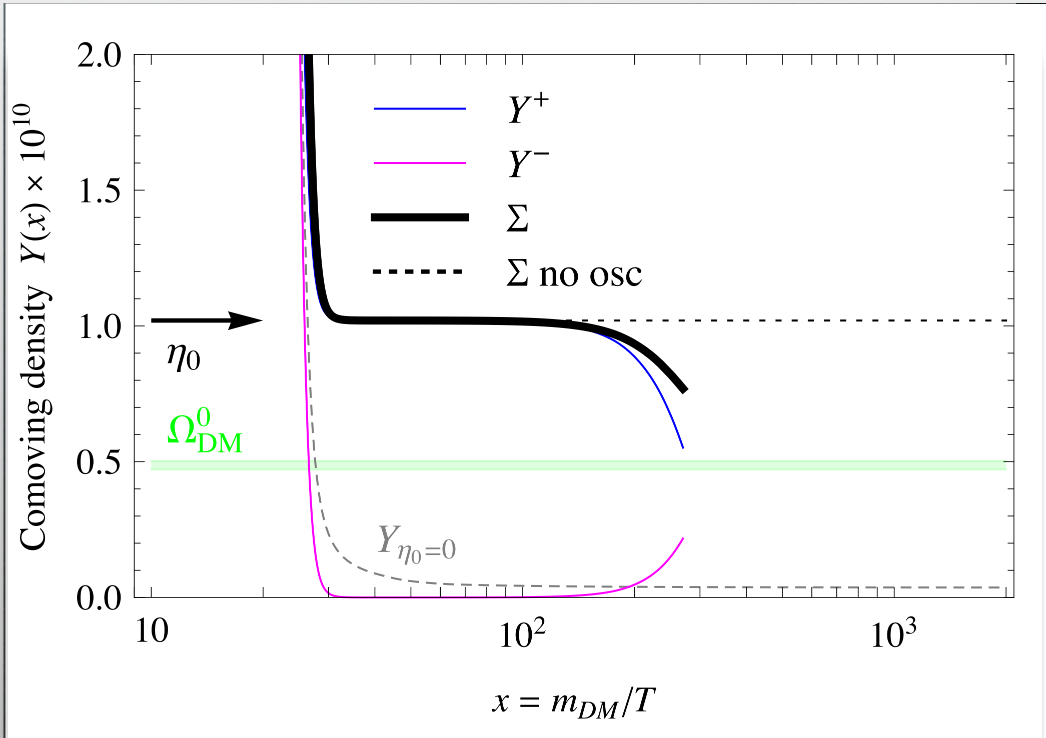

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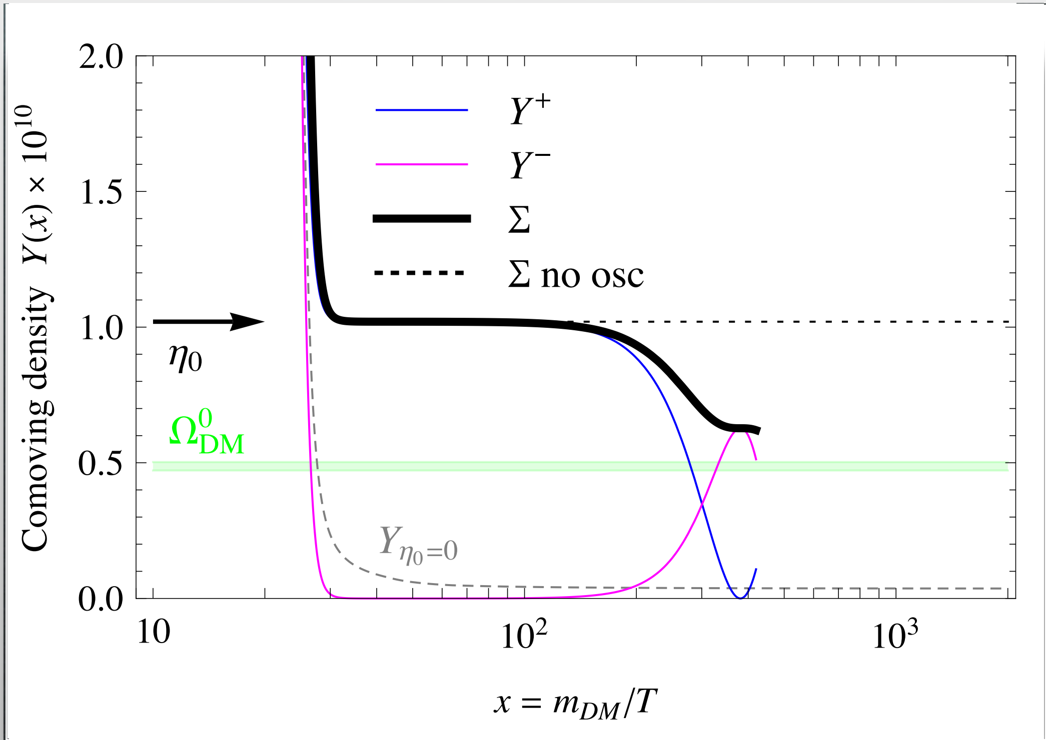

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1. Asymmetric 'freeze-out'
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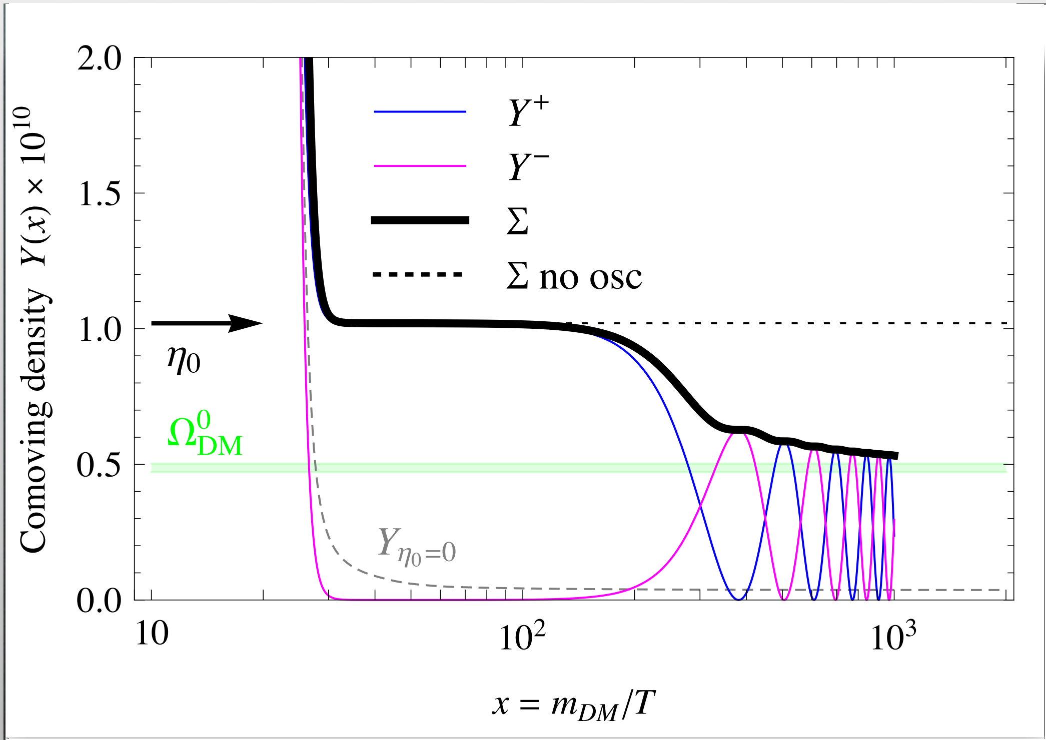

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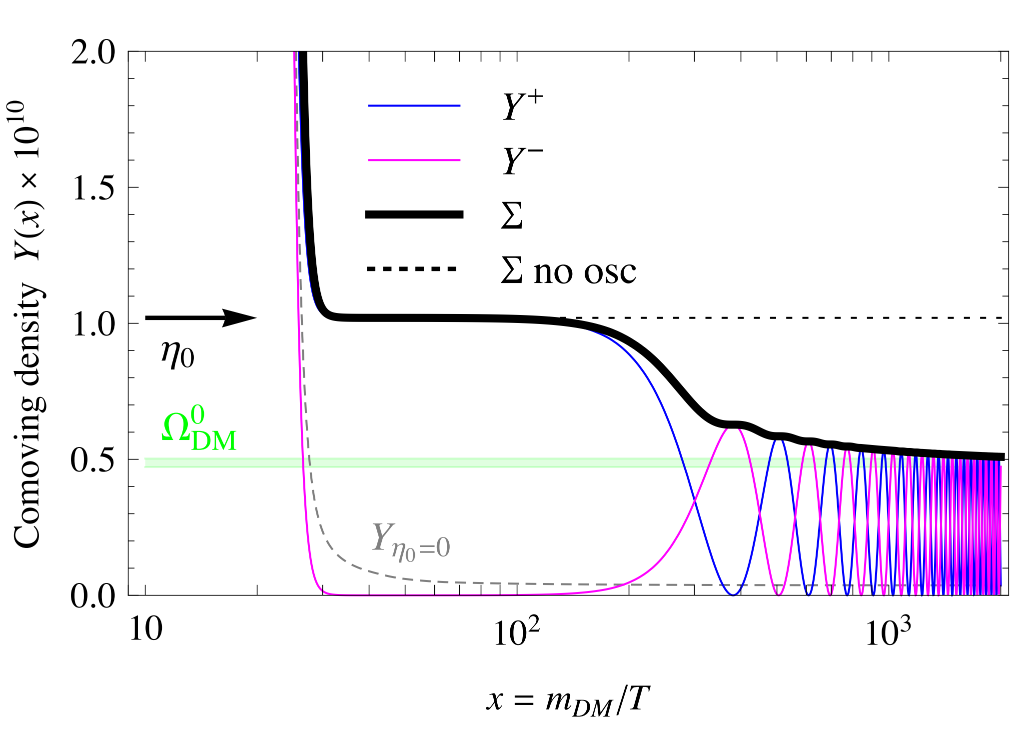


General features of ADM WIMP decoupling:

1. Asymmetric 'freeze-out'
2. Oscillations repopulate Y^-
3. Annihilations recouple and lower the total DM density.
4. Process repeats in a series of plateaux.
5. Correct relic abundance can be achieved and it now depends on:

η_0- primordial asymmetry.
Y^+/Y^- DM particle/antiparticle.
$\Sigma = Y^+ + Y^-$

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

DM/anti-DM oscillations: A different relic decoupling scenario

1. →Oscillations *fill 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.

2. *Higher masses* >~100 GeV are therefore 'naturally' available in this framework

3. *Phenomenological bounds modified*: DM is symmetric today, so it self-annihilates! Traditional ADM bounds do not apply while standard WIMP bounds become relevant.

DM/anti-DM oscillations:
The formalism

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

i) oscillations $Y^{+,-} \leftrightarrow Y^{-,+}$
ii) annihilations $Y^+ Y^- \leftrightarrow$ SMSM and
iii) elastic scatterings $Y^{+,-}$ SM $\leftrightarrow$ $Y^{+,-}$ SM.

It is an interplay between a coherent process such as oscillations with incoherent processes such as annihilations and scatterings.

'Density matrix formalism' (originally developed for ν oscillations in the Early Universe) provides a framework to account for quantum coherence between particle and antiparticle states (Dolgov, 1981; Sigl&Raffelt, 1993; Dolgov et al., hep-ph/0202122v2, ...)

DM/anti-DM oscillations: The formalism

$$\mathcal{Y}(x) = \begin{pmatrix} Y^{+}(x) & Y^{+-}(x) \\ Y^{-+}(x) & Y^{-}(x) \end{pmatrix}$$

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

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

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

mass hamiltonian acts as source of oscillations
$Y^+ \leftrightarrow Y^-$

annihilations
$Y^+ Y^- \leftrightarrow$ SMSM

elastic scatterings
Y SM $\leftrightarrow$ Y SM

$$\mathcal{H} = \begin{pmatrix} m & \delta m \\ \delta m & m \end{pmatrix}$$

and we take $\Gamma_a \sim \langle \sigma_a v \rangle I$, $\Gamma_s \sim \sigma_s I$.

DM/anti-DM oscillations: Results:

Parameters of the system: m_{DM}, σ_0, δm, η_0, ξ.

δm: oscillation parameter: tiny! typically $10^{-14} \rightarrow 10^{-2}$ eV
If δm *too large*: oscillations occur too early, system is symmetric.
If δm *too small*: oscillations occur too late, system is totally asymmetric.

η_0: primordial DM asymmetry: free, but naturally ~ η_b

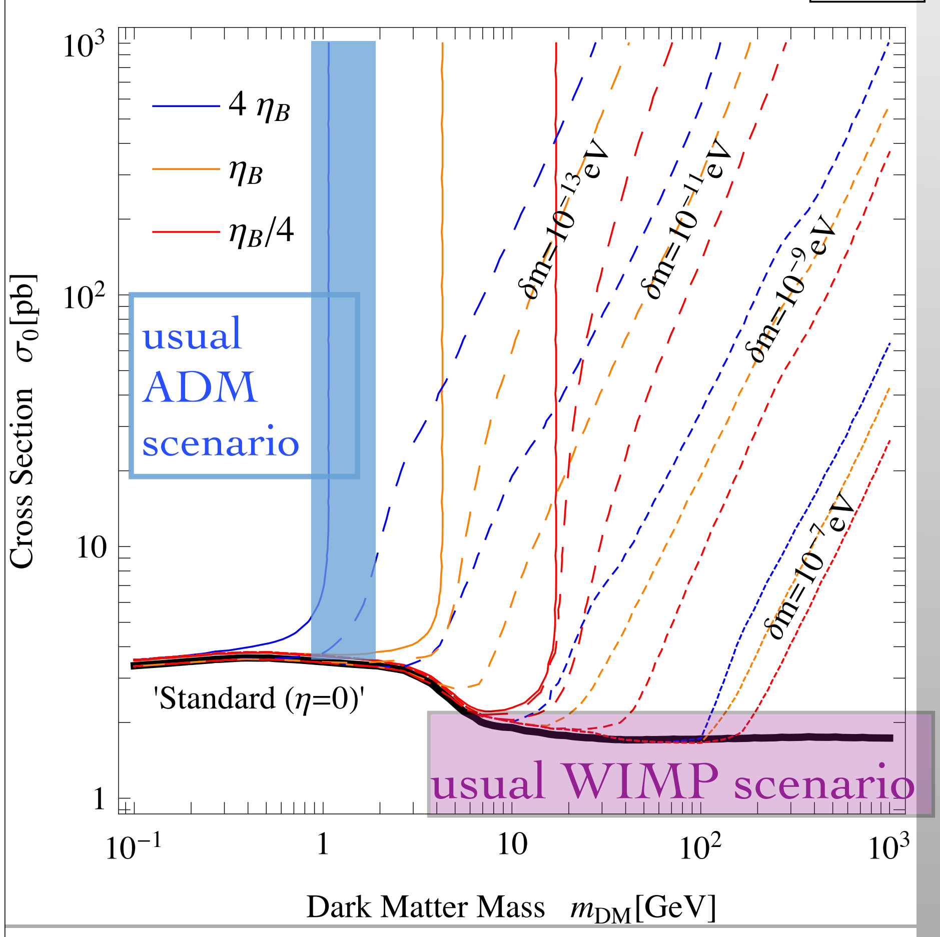
ξ: strength of scattering on normal matter wrt naive ~G_F expectations.
Direct detection experiments impose $\xi < 10^{-2}$

DM/anti-DM oscillations:
Results: σ_0 vs m_{DM} plane.

w isolines of correct Ω_{DM}, for different values of δm and η_0.

ann+osc

ξ = 0



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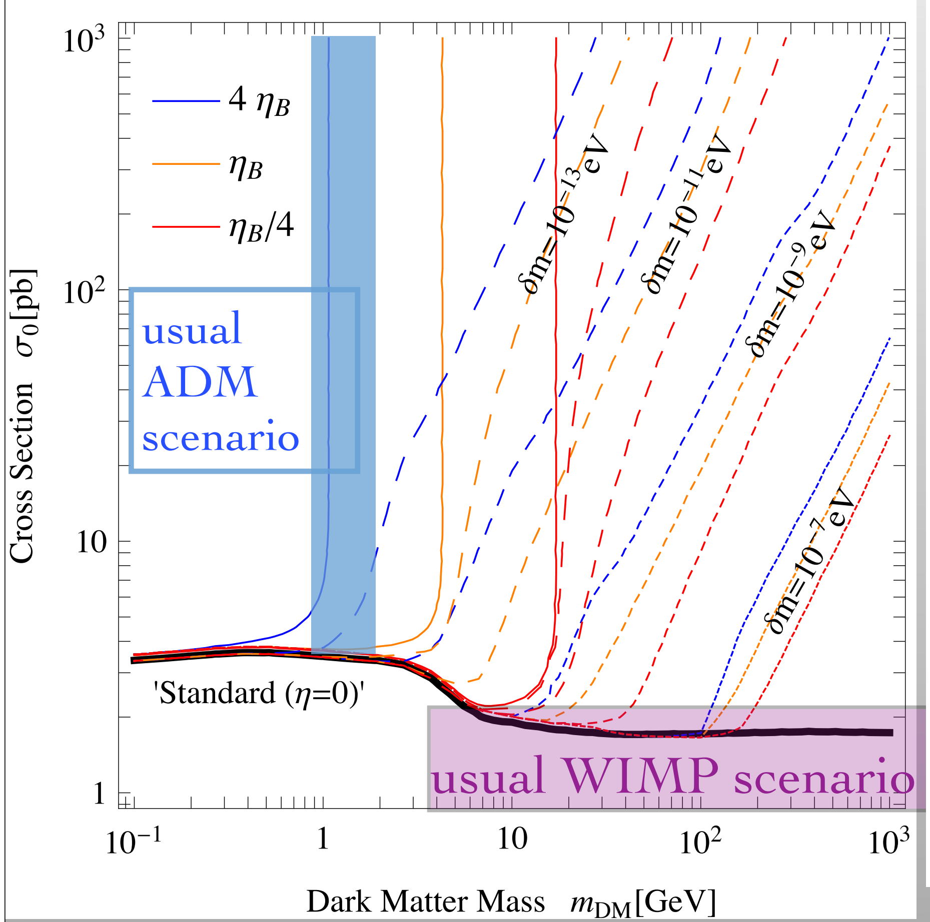
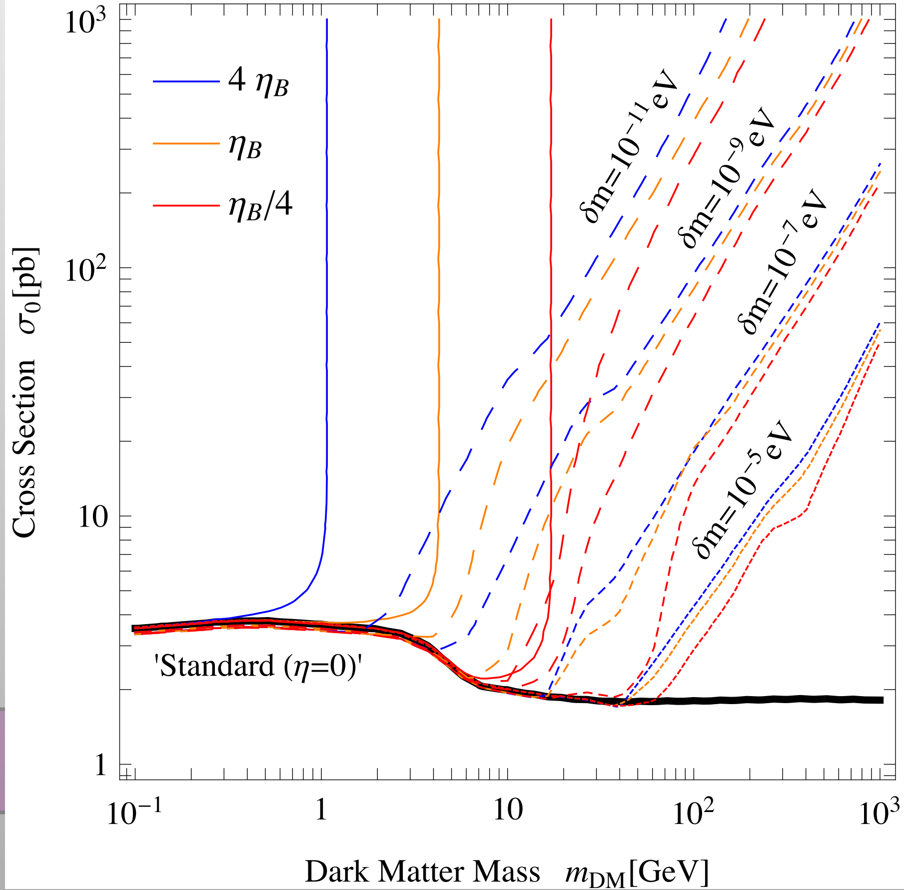


ann+osc+ el scatterings $\xi = 10^{-2}$



DM/anti-DM oscillations:

Results: Parameter space with phenomenological constraints.

Oscillations symmetrize dark sector→ constraints on WIMP annihilations apply.

➡ Energy injected from DM annihilation during recombination (z~1100), results in an increased amount of free electrons, which survive to lower redshifts and affect the CMB anisotropies. [Galli et al., PRD (2011)]

➡ Present time annihilations (*producing gamma rays*)

Fermi-LAT observation (non-detection) of dwarf spheroidal Galaxies. [Fermi-LAT collaboration, PRL (2011)]

HESS observation of the Galactic Center halo region. Due to the high energies covered by ACTs these limits are specially relevant for heavy >~1TeV DM.
[H.E.S.S. Collaboration, arXiv:1103.3266]

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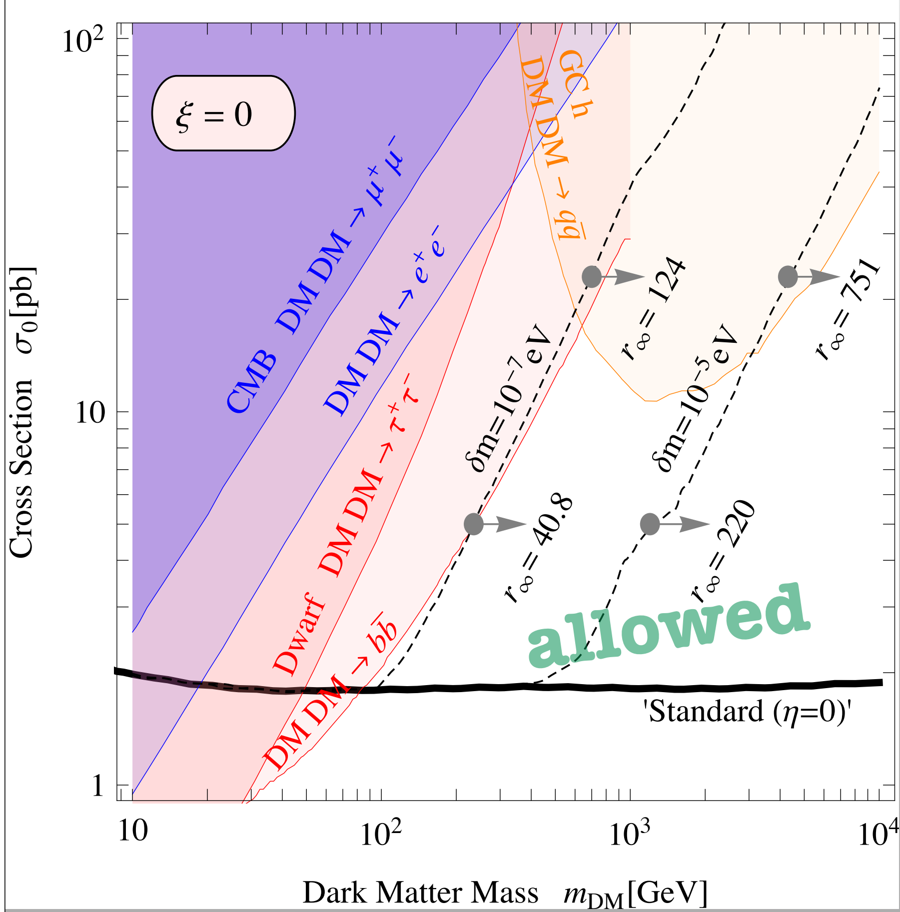
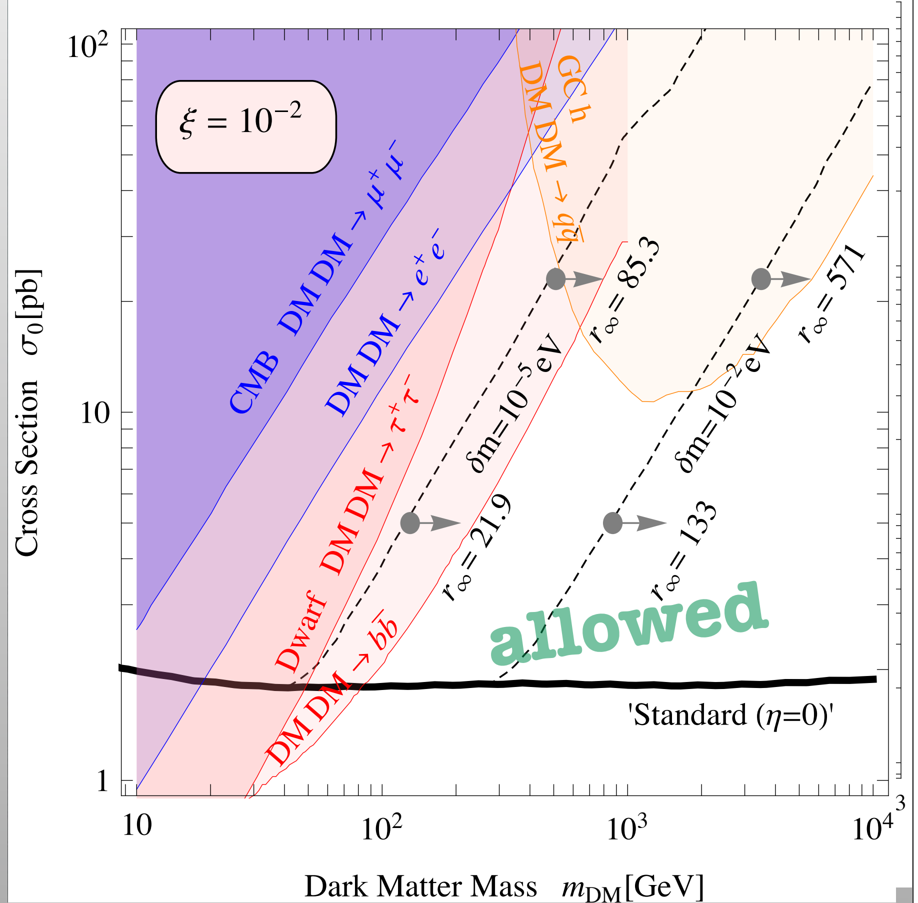


ann+osc+ el scatterings

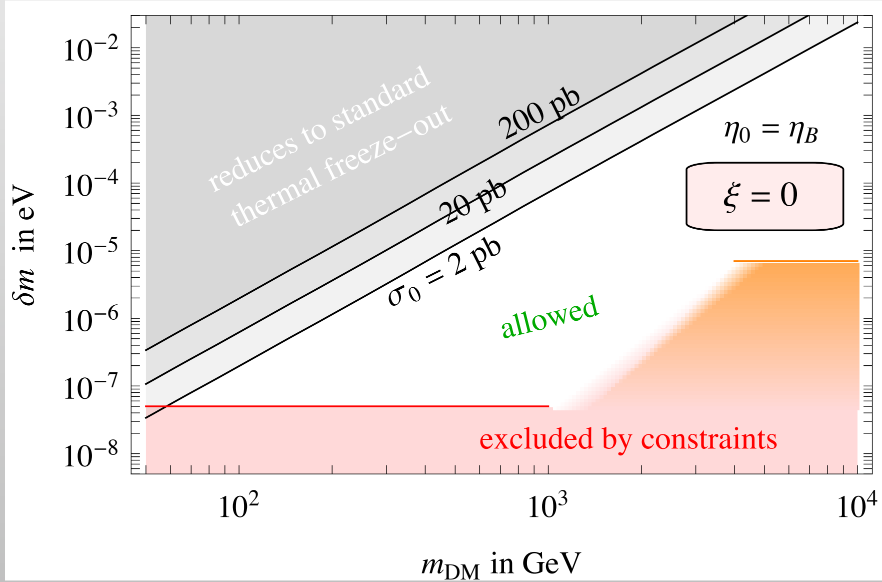


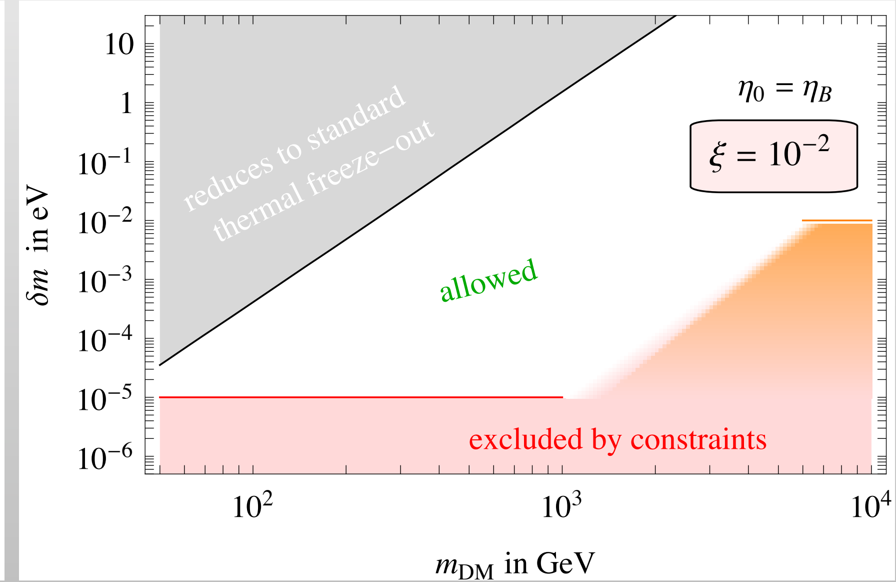
DM/anti-DM oscillations:
Results: δm vs mDM plane.

As oscillations symmetrize dark sector, usual WIMP constraints apply.

ann+osc

ann+osc+ el scatterings





Note: a natural value in the fermionic case is obtained from the dimension-5 operator:

$$\frac{XXH^\dagger H}{\Lambda}$$

taking Λ~Mp, <H> → δm~10^{-6} eV.

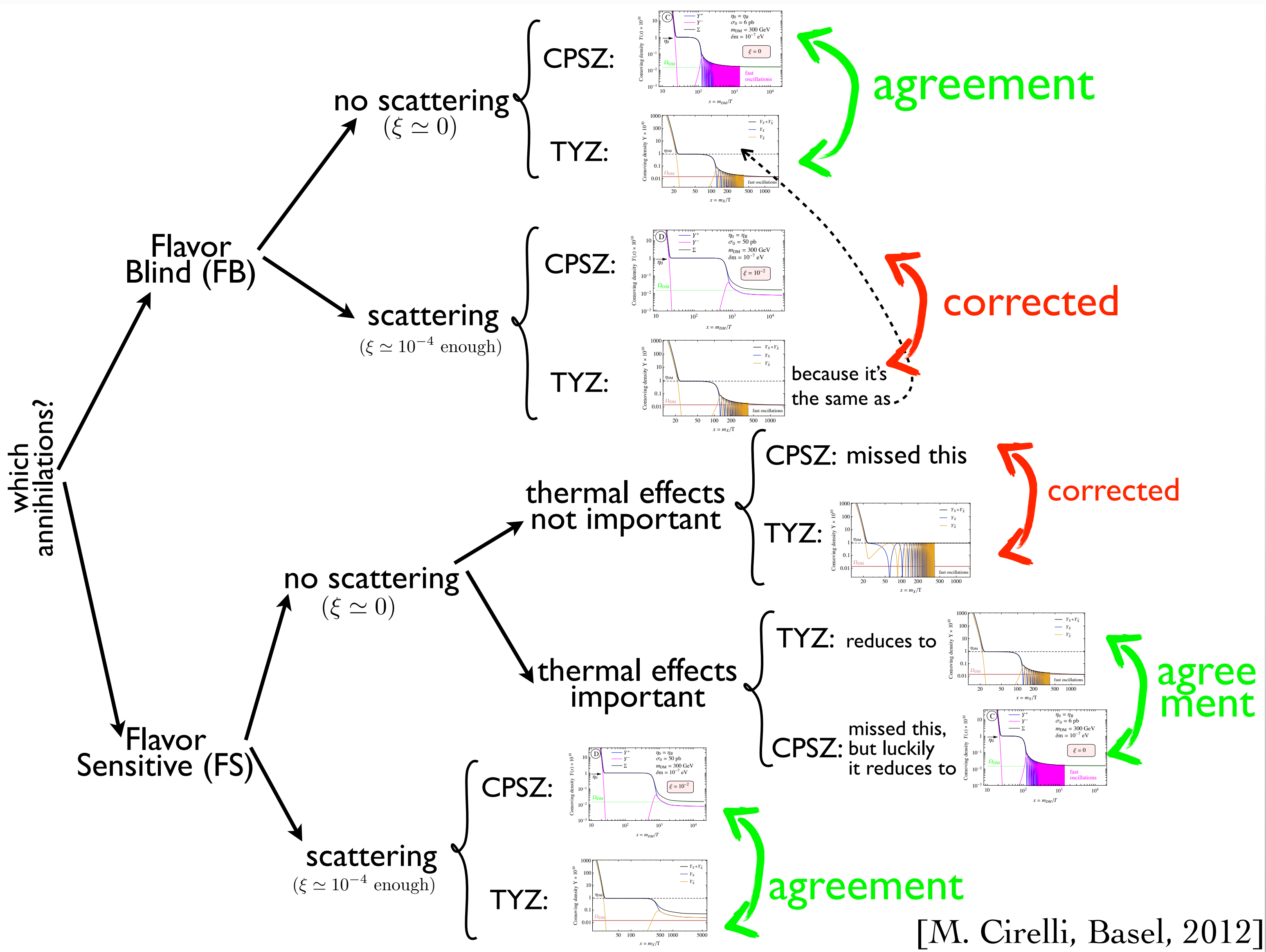
Comparing

Tulin, Yu, Zurek, 1202.0283	This work, 1110.3809
✓ full formalism from first principles: • non-equilibrium QFT	• full matrix formalism
✓ extends to include • flavor sensitive interactions • precise effects of scatterings	• scattering on plasma
• only specific examples	✓ scans parameter space

Quantitatively:

results unchanged for some particle physics cases

some new cases appear (next page)



FB/FS refers to a transformation property of a L under C.
If DM/fermions coupled through contact interaction: flavor blind (scalar, pseudo scalar, axial vector)/sensitive (vector and tensor).

Summary

- Scenarios with DM anti-DM oscillations *preserve the attractive feature of ADM*, that relates the DM primordial asymmetry and the baryon asymmetry and at the same time *preserve also the appeal of weak scale DM mass and cross-sections*.

- We *suggest 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 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.

- Work on particular particle physics cases in progress.

Extra slides

General features of ADM:

Phenomenological probes/constraints:

Stars can accumulate far more ADM particles than usual WIMPs, which can *alter their dynamics*.

- ADM captured in neutron stars can become *self-gravitating*, forming a black hole that will eventually destroy the host stars. *Observation of old pulsars in globular clusters* then sets the limit on DM capture rate (elastic cross section) competitive w.r.t. direct detection experiments. (McDermott et al., 1103.5472)

(Panci, Cirelli, Servant, Zaharijas, 1110.3809)

DM/anti-DM oscillations?

A small χ^+/χ^- mass splitting induces $\chi^+ \leftrightarrow \chi^-$ oscillations.

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

fermionic DM

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

scalar DM

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

Δ is a term which violates a global $U(1)_{DM}$ and its non-zero value is responsible for the oscillations between Y⁺ and Y⁻.

Natural to assume: 'Majorana' mass Δ << 'Dirac' mass m.

DM/anti-DM oscillations: δm

In our study, δm is a free parameter that can range orders of magnitude. *Could the Majorana masses of neutrinos and dark matter have a common origin*?

(Cohen&Zurek, 0909.2035, Falkowski, 1101.4936),

extra *hidden scalar φ* links *right handed N* and DM (leptogenesis framework)

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

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

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

if φ *acquires a vev*, it *generates a Majorana mass* for DM but also *induces a mixing between DM and neutrinos* that can lead to DM *decay* depending on the choice of parameters.

- Note: a natural value in the fermionic case is obtained from the dimension-5 operator:

$$\frac{XXH^\dagger H}{\Lambda}$$

taking Λ~Mp, <H> → δm~10^{-6} eV.

Formalism: Consider *only* DM annihilations

The density matrix equation reads:

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

annihilations

$$\Gamma_{\mathrm{a}}\, \Gamma_{\mathrm{a}}^{\dagger} = \langle \sigma v \rangle\, \mathbb{I} \qquad\qquad \bar{\mathcal{Y}} = \mathrm{CP}^{-1} \cdot \mathcal{Y} \cdot \mathrm{CP}$$

In this case the matrix form reduces to the usual Boltzmann eqn:

$$Y^{\pm\prime}(x) = -\frac{\langle \sigma v \rangle\, s(x)}{x\,H(x)} \left[Y^{+}(x)\, Y^{-}(x) - Y_{\mathrm{eq}}^{2}(x) \right].$$

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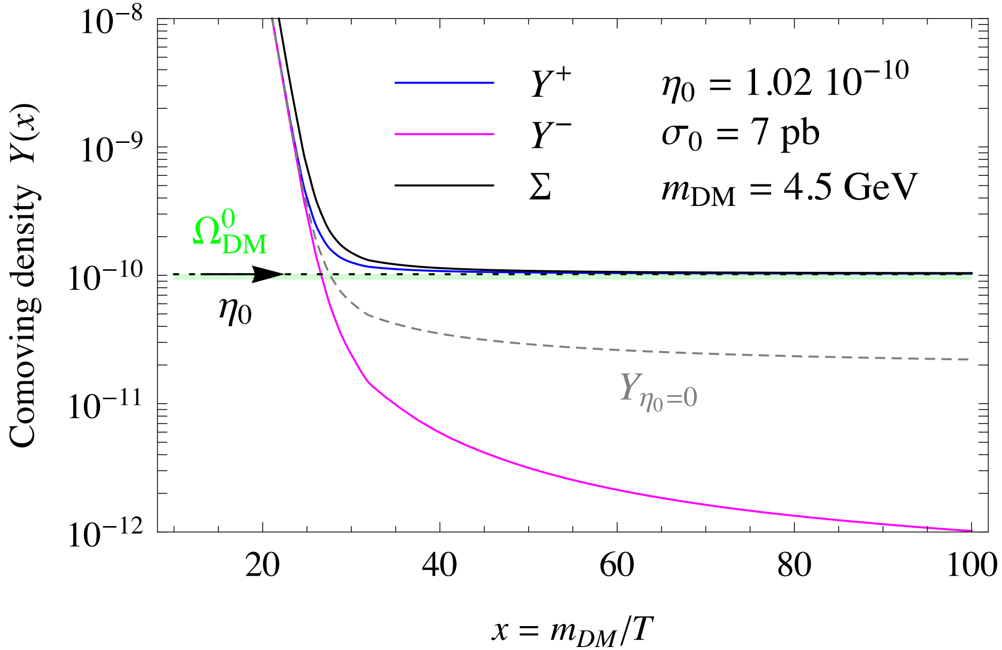


Formalism: Consider *only* oscillations

The density matrix equation reads:

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

mass hamiltonian acts as source of oscillations

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

And is equivalent to a simple set of two equations:

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

Σ- the total number of particles
Δ - the difference

$$\Gamma_{\rm osc} \to \delta m\, \tan(\delta m / H(x))$$

Formalism: Consider *only* oscillations

And is equivalent to a simple set of two equations:

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

Solutions are simple oscillations:

- Σ stays constant,
- Δ oscillates,

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

$$\Gamma_{\rm osc} \to \delta m\, \tan(\delta m/H(x))$$

oscillation period: H~1/2t; t_{osc}~$2\pi/\delta m$.

Formalism: *Oscillations* + *elastic scatterings*

Now we can study an effect of *decoherence* of scattering on DM oscillations

$$\mathcal{Y}'(x) = -\frac{i}{x\,H(x)}\left[\mathcal{H}, \mathcal{Y}(x)\right] - \frac{1}{H(x)}\left\{\Gamma_{\rm s}(x), \mathcal{Y}(x)\right\}.$$

$$\mathcal{H} = \begin{pmatrix} m_{\rm DM} & \delta m \\ \delta m & m_{\rm DM} \end{pmatrix}. \qquad \Gamma_{\rm s} = \begin{pmatrix} \gamma_{\rm s} & 0 \\ 0 & \gamma_{\rm s} \end{pmatrix}$$

mass hamiltonian acts as source of oscillations

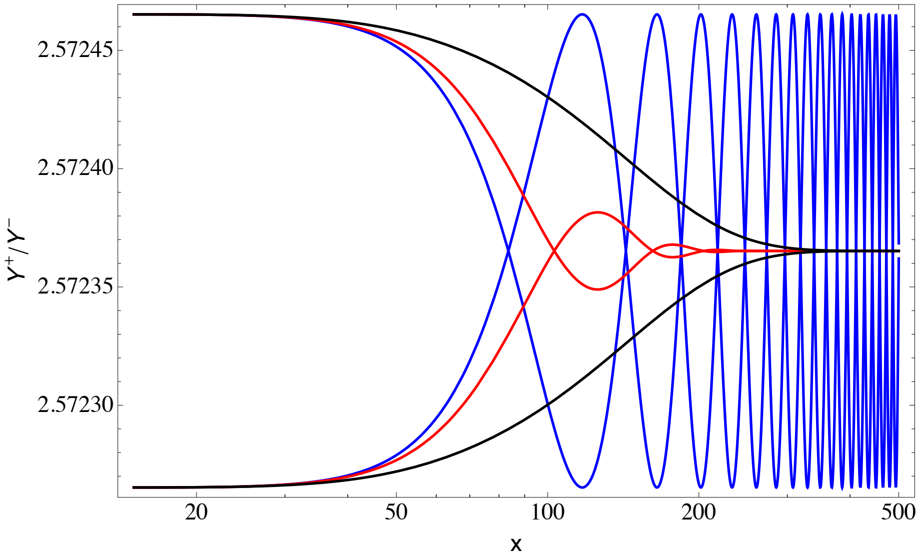
elastic scatterings described by a diagonal matrix.

Formalism: *Oscillations* + *elastic scatterings*

Now we can study an effect of *decoherence* of scattering on DM oscillations

$$\mathcal{Y}'(x) = -\frac{i}{x\,H(x)}\left[\mathcal{H}, \mathcal{Y}(x)\right] - \frac{1}{H(x)}\left\{\Gamma_{\rm s}(x), \mathcal{Y}(x)\right\}.$$

numerical solution of DMeq:



Scatterings *delay* and *damp* oscillations!

The same holds for annihilations.

Γ = 0 oscillations only

Γ = δm

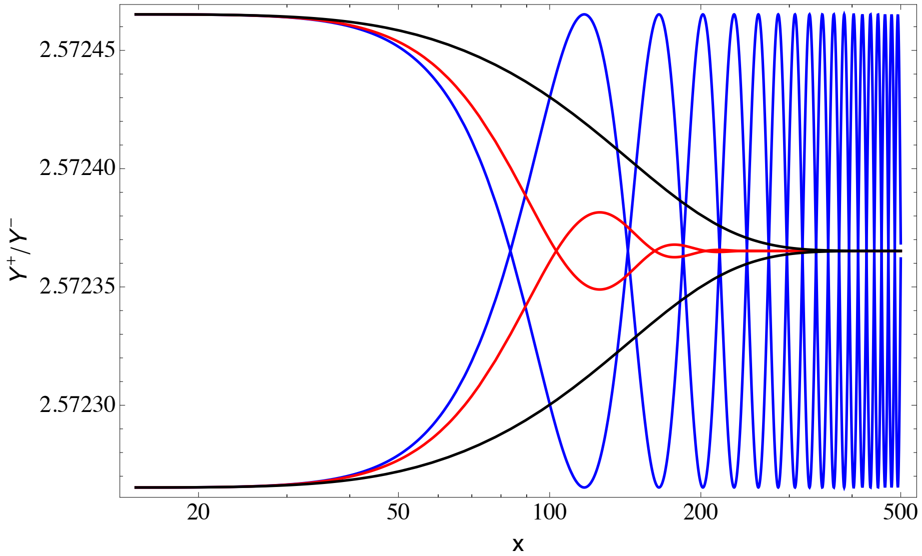
Γ = 5δm

Formalism: *Oscillations* + *elastic scatterings*

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

If scattering rates are >> δm, the solution is damped oscillator, with a decay time δm²/ϒ!

$$\Gamma_{\rm osc} \to 2\,\delta m^2/\gamma_{\rm s}$$



Γ = 0 oscillations only

Γ = δm

Γ = 5δm

Formalism: *Full Boltzmann equation*

Rephrased in terms of 4 new variables, rather than density matrices.

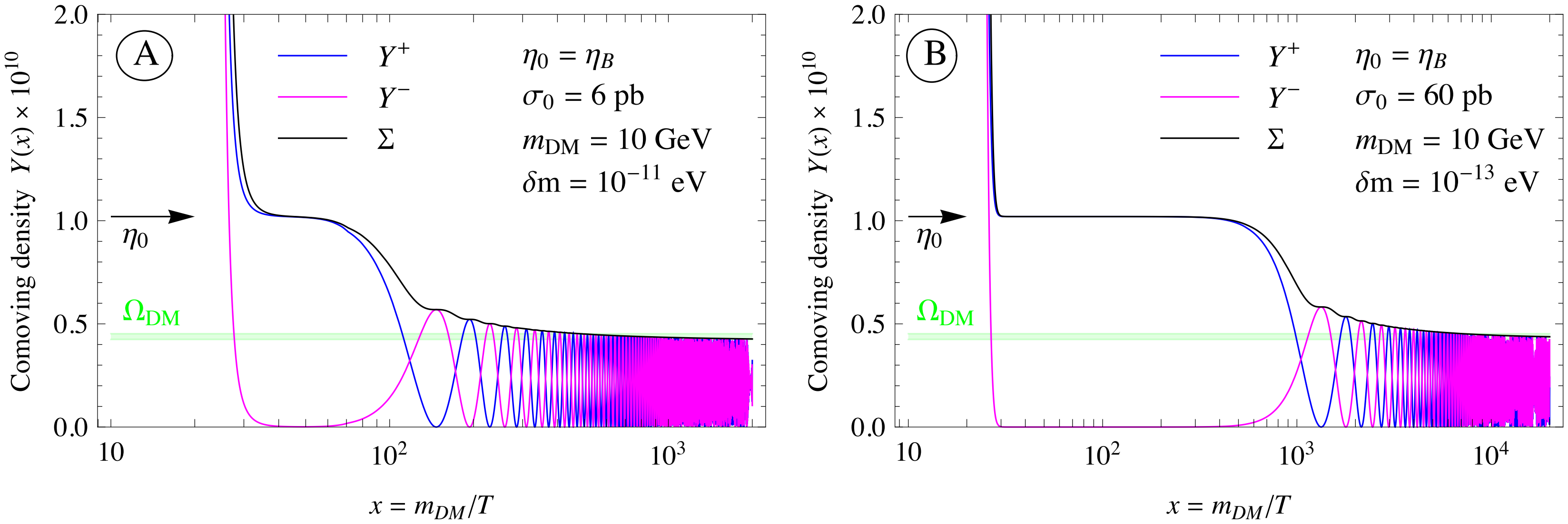
$$\begin{cases} \Sigma'(x) = -2\dfrac{\langle\sigma v\rangle\, s(x)}{x\,H(x)}\left[\dfrac{1}{4}\left(\Sigma^2(x) - \Delta^2(x) - \Xi^2(x) - \Pi^2(x)\right) - Y_{\rm eq}^2(x)\right], \\ \Delta'(x) = \dfrac{2i\,\delta m}{x\,H(x)}\,\Xi(x), \\ \Xi'(x) = \dfrac{2i\,\delta m}{x\,H(x)}\,\Delta(x) \;-\; \dfrac{i\,\Delta V}{x\,H(x)}\,\Pi(x) \;-\; \dfrac{\gamma_{\rm s}}{x\,H(x)}\,\Xi(x) - \dfrac{\langle\sigma v\rangle\, s(x)}{x\,H(x)}\Xi(x)\Sigma(x), \\ \Pi'(x) = -\dfrac{i\,\Delta V}{x\,H(x)}\,\Xi(x) - \dfrac{\gamma_{\rm s}}{x\,H(x)}\,\Pi(x). \end{cases}$$

$$\Pi(x) \;=\; Y^{+-}(x) + Y^{-+}(x)$$

$$\Xi(x) \;=\; Y^{+-}(x) - Y^{-+}(x)$$

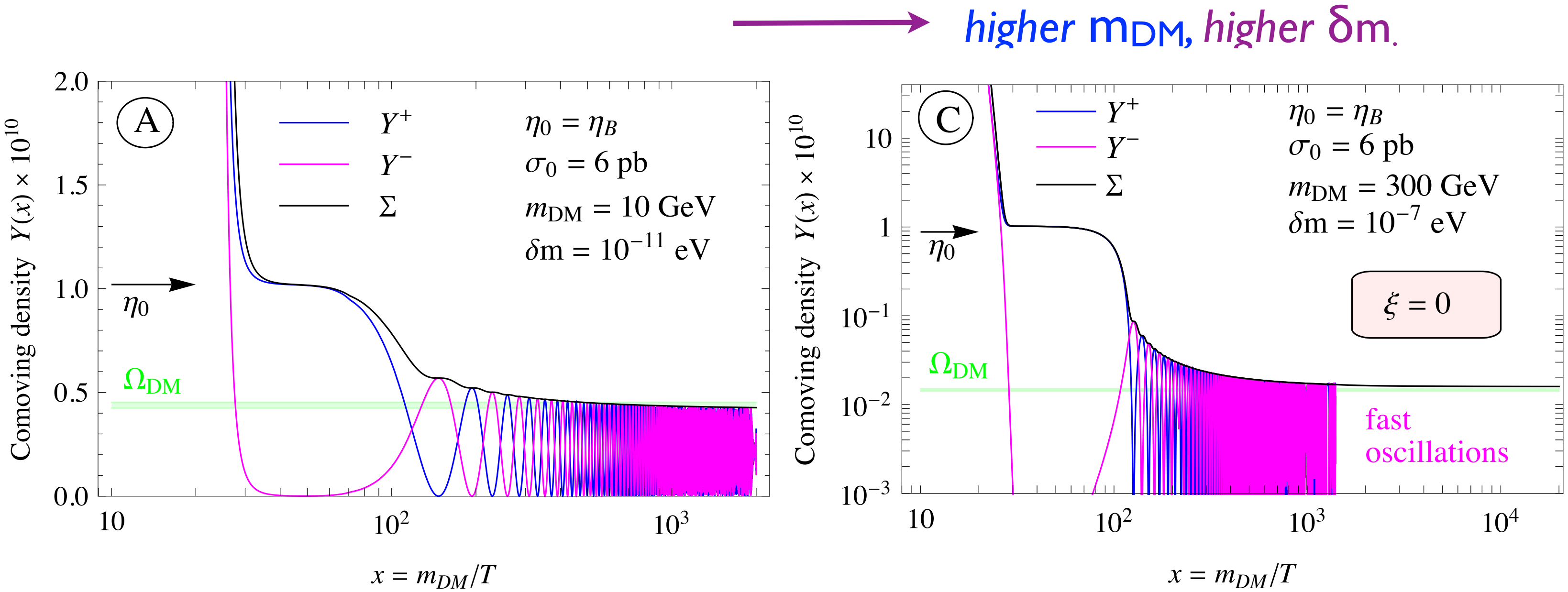
Results: Interplay among parameters: varying δm

→ *smaller δm, higher σ_0.*



To the right: a much *smaller δm*: the co-moving population of DM therefore sits for a *longer* time on the plateau determined by the initial asymmetry η_0. Higher value of σ_0 = 60 pb is now needed to reach the correct relic abundance.

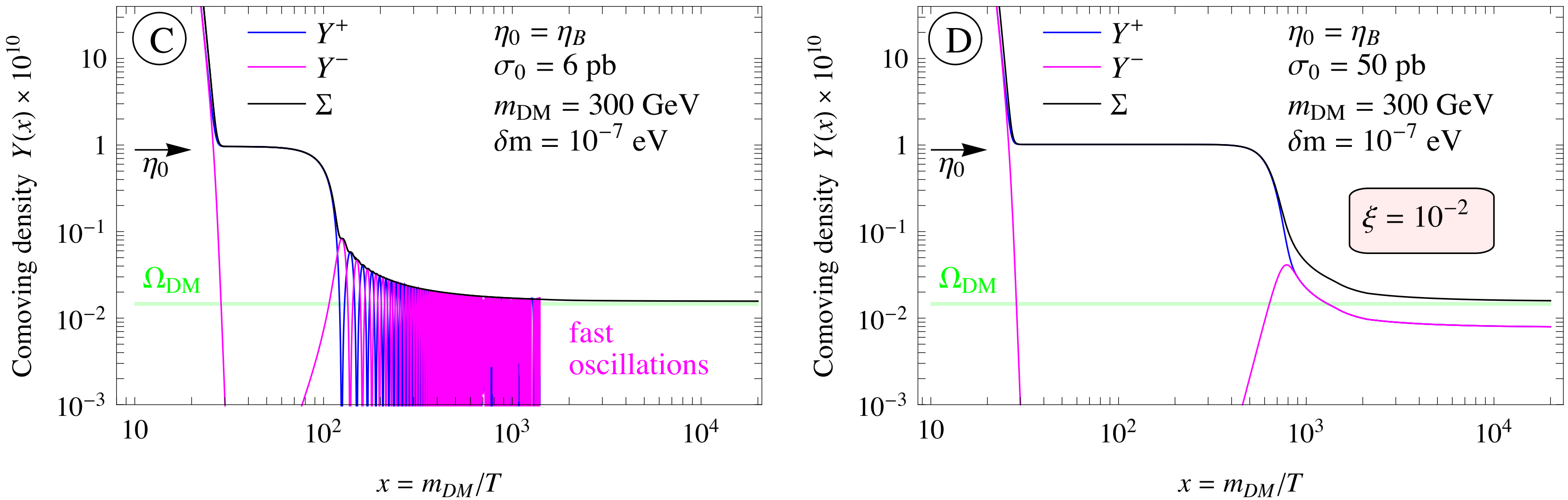
Results: Interplay among parameters: varying m_{DM}



To the right: a higher, roughly weak-scale value of the DM mass. The correct relic abundance is achieved by starting oscillations earlier (to deplete Y more efficiently!), i.e. by choosing a larger δm.

Results: Interplay among parameters: adding ξ.

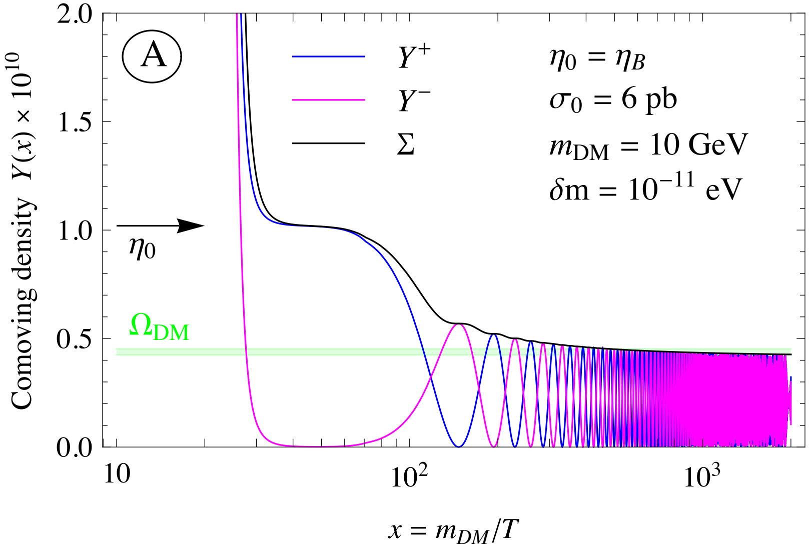
→ *added ξ, higher σ_0.*

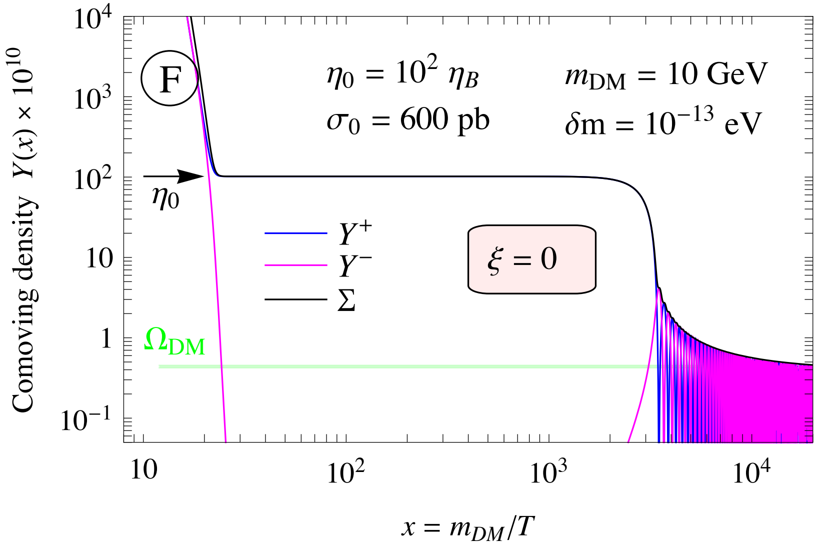


To the right: *elastic scatterings included* ($\xi = 10^{-2}$) - the effect of *incoherent scatterings* that delay and damp the oscillations. A *larger cross section* is needed to keep the annihilations active at late times and thus reach the right abundance.

Results: Interplay among parameters: adding η_0.

→ $\eta_0 >> \eta_B$, *higher* σ_0.



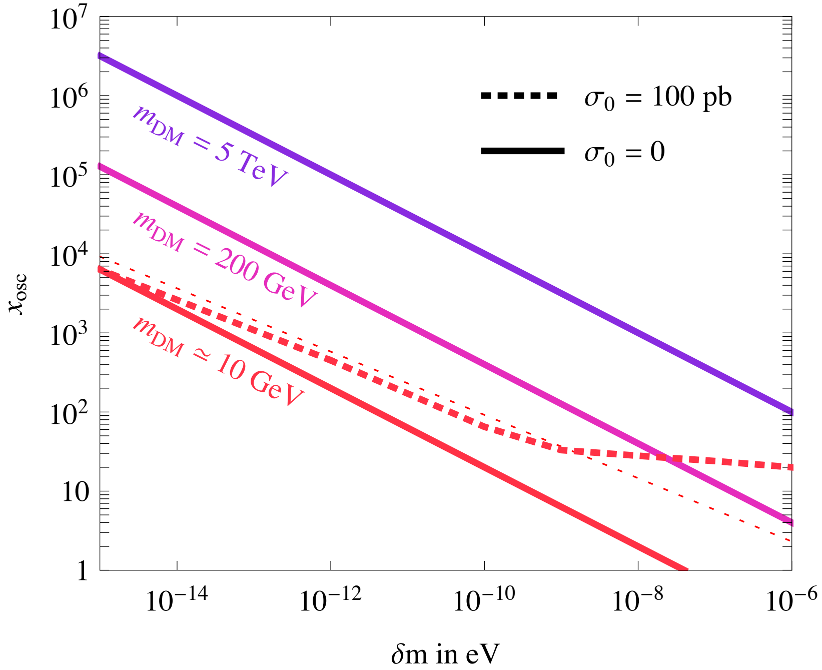


In case F a very large initial asymmetry is assumed. Having adopted a relatively small δm, oscillations start late but still efficient depletion is reached. Much higher asymmetry wrt η_B in the dark sector possible.

Overview of general features:

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

2. oscillations start *later* than a simple guess ~1/δm, due to decoherence effects.

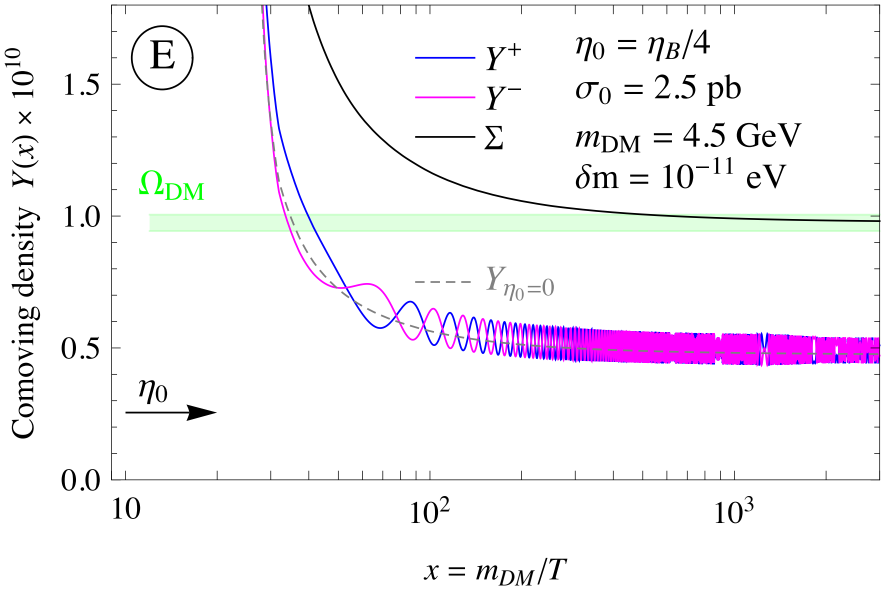


$$x_{\rm osc} \simeq \quad H/\delta m$$

$$x_{\rm osc,ann} \simeq \left(\frac{H_m\,\gamma_{\rm a}}{2\,\delta m^2}\right)^{1/2} \simeq \left(\frac{H_m\,\sigma_0\,s_m\,\eta_0/2}{\delta m^2}\right)^{1/5}$$

Overview of general features:

3. oscillations can modify DM thermal history only for sufficiently small $\delta m < \delta m_{max}$.

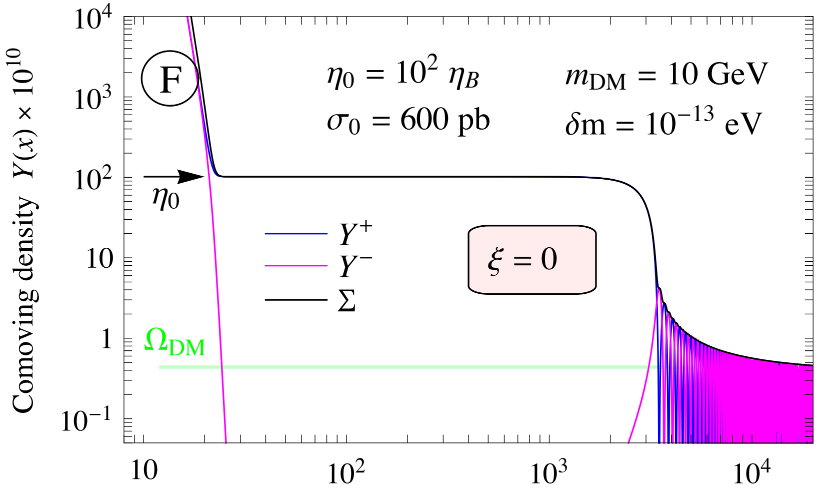


For too large δm oscillations start too early and symmetrize the dark sector → *usual WIMP scenario!*

Phenomenological constraints:

In these scenarios DM consists of equal portions of DM and anti-DM and can self-annihilate at late epochs.
Usual WIMP (+ novel) *indirect detection signatures.*

i) BBN: if oscillations start after the end of BBN, i.e. if $t_{osc} > t_{BBN}$, as annihilations recouple, a large amount of energy is injected into the plasma. The set-up is similar to the one of late-decaying heavy DM progenitor states. However, other constraints stronger and imply t_{osc}<~0.1 sec...



Phenomenological constraints:

In these scenarios DM consists of equal portions of DM and anti-DM and can self-annihilate at late epochs.
Usual WIMP (+ novel) *indirect detection signatures.*

i) CMB: energy injected from DM annihilation during recombination (z~1100), results in an increased amount of free electrons, which survive to lower redshifts and affect the CMB anisotropies.
Limits on σ_0 set using WMAP-7 data and ATACAMA telescope data, for DM annihilation channels to e^+e^- and $\mu^+\mu^-$.
[Galli et al., Phys.Rev.D84 (2011)]

Phenomenological constraints:

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.

iii) Present time annihilations: *Fermi-LAT observation (non-detection) of dwarf spheroidal Galaxies.* Stringent upper limits are derived by applying a joint likelihood analysis to 10 satellite galaxies with 2 years of FERMI-LAT data, and taking into account the uncertainty in the dark matter distribution in the satellites.

[Fermi-LAT collaboration, arXiv:1108.3546v2]

The limits are particularly strong for hadronic annihilation channels ($q\bar{q}$) and $\tau^+\tau^-$. These limits are somewhat weaker for e^+e^- and $\mu^+\mu^-$, as diffusion of leptons out of these systems is poorly constrained.

Phenomenological constraints:

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.

iii) Present time annihilations: *HESS observation of the Galactic Center halo region.*
Due to the high energies covered by ACTs these limits are specially relevant for heavy >~1TeV DM.
This refers to a $q\bar{q}$ annihilation channel and assumes that the DM distribution in the Galaxy follows a cuspy profile (~NFW). *These constraint are lifted in case of a cored profile!*
[H.E.S.S. Collaboration, arXiv:1103.3266]

Comparing

Buckley+Profumo, 1109.2164v1	This work, 1110.3809
• simplified **Boltzmann** formalism, with **constant oscillation rate**:	✓ full **matrix** formalism
- no oscillations	- oscillations
- no accounting for decoherence	- accounting for decoherence
• **no scatterings** on plasma	✓ **scatterings** on plasma
- no accounting for decoherence	- accounting for decoherence
• **not** concerned w obtaining **correct** $\Omega_{\rm DM} h^2$	✓ requires **correct** $\Omega_{\rm DM} h^2$

Quantitatively:

- evolution is almost always very different
- final abundances differ (a few to more than one order of magnitude)