Coannihilation without chemical equilibrium

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Heidelberg, LAUNCH, 15.09.17

based on 1705.09292

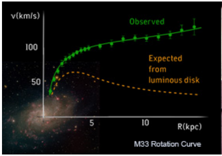
with Jan Heisig, Benedikt Lülf, Stefan Vogl

Dark Matter

- Galactic (rotation curves)

  Vera Rubin, Kent Ford 1970

  Pato, Iocco, Bertone 1504.06325



- Galaxy clusters

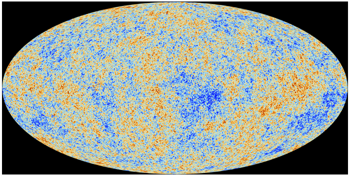
  Fritz Zwicky 1933

  Bullet Cluster, Clowe et al astro-ph/0608407

- Cosmic microwave background

$$\Omega_{cdm} h^2 = \frac{\rho_{cdm}}{10.50\,\mathrm{GeV}/\mathrm{m}^3} = 0.1198 \pm 0.0015$$

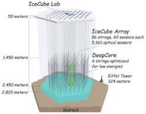
Planck 1502.01589



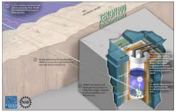
Testing the WIMP hypothesis

Fermi, H.E.S.S., AMS02, IceCube, Planck. . . , CTA

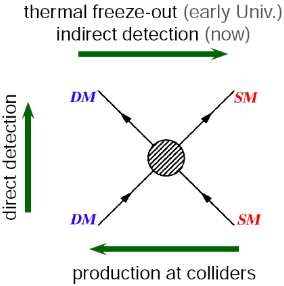


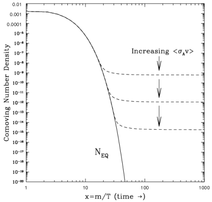



XENON1T
LUX
. . .



XENONnT
DARWIN
LZ





LHC, HL-LHC

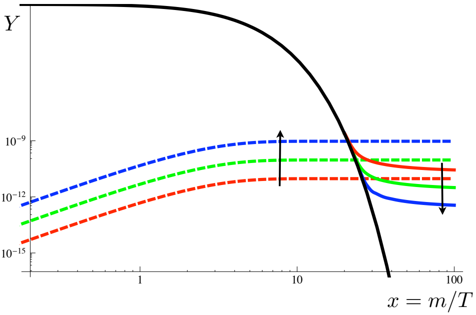
More possibilities

interaction with SM	mass		
	Super Light	Light	Heavy
Strong	x	x	MACHOs, black holes
Weak	x	WIMP	WIMPZILLA
Super Weak	Axion, sterile	gravitino, FIMP	PIDM

not complete!

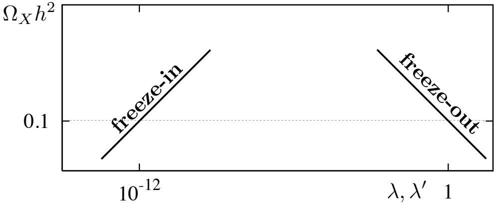
credit M. Sloth

FIMP vs WIMP



Hall, Jedamzik, March-Russell, West 0911.1120

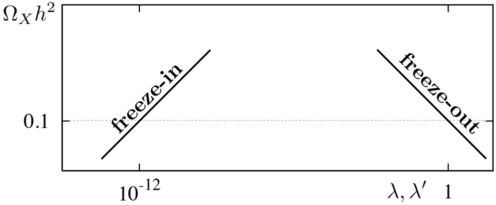
FIMP vs WIMP



interaction strength with SM

Hall, Jedamzik, March-Russell, West 0911.1120

FIMP vs WIMP

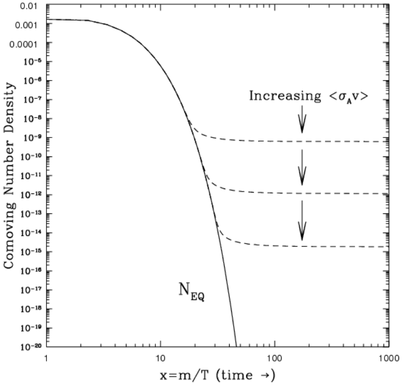


interaction strength with SM

Hall, Jedamzik, March-Russell, West 0911.1120

Can we be in between?

Freeze-out



Lee-Weinberg equation for a single dark matter species $\chi\chi \to \mathrm{SM}+\mathrm{SM}'$

$$\dot{n}_\chi + 3Hn_\chi = -(n_\chi^2 - n_{eq}^2)\langle\sigma v\rangle$$

Coannihilation

Dark matter + heavier BSM states χ_i $(m_i/m_{dm} \lesssim 1.5)$

- Annihilation $\chi_i + \chi_j \to \mathrm{SM} + \mathrm{SM'}$

$$\dot{n}_i + 3Hn_i = -\sum_j (n_i n_j - n_i^{eq} n_j^{eq}) \langle \sigma_{ij} v_{ij} \rangle$$

Edsjo, Gondolo 97

Coannihilation

Dark matter + heavier BSM states χ_i $(m_i/m_{dm} \lesssim 1.5)$

- Annihilation $\chi_i + \chi_j \to \mathrm{SM} + \mathrm{SM}'$
- Conversion via (inverse) decay $\chi_i \leftrightarrow \chi_j + \mathrm{SM}$
- Conversion via scattering $\chi_i + \mathrm{SM} \leftrightarrow \chi_j + \mathrm{SM}'$

$$\begin{aligned}
\dot{n}_i + 3Hn_i &= -\sum_j (n_i n_j - n_i^{eq} n_j^{eq}) \langle \sigma_{ij} v_{ij} \rangle \\
&\quad - \sum_{X \in \mathrm{SM}, j} \Gamma_{i \to jX} n_i^{eq} \left(\frac{n_i}{n_i^{eq}} - \frac{n_j}{n_j^{eq}} \right) - (i \leftrightarrow j) \\
&\quad - \sum_{X, Y \in \mathrm{SM}, j} \sigma_{iX \to jY} n_i^{eq} n_X^{eq} \left(\frac{n_i}{n_i^{eq}} - \frac{n_j}{n_j^{eq}} \right)
\end{aligned}$$

Edsjo, Gondolo 97

Coannihilation

$$\begin{aligned}
\sum_j n_i^{eq} n_j^{eq} \langle \sigma_{ij} v_{ij} \rangle \quad &\propto \quad \exp\left(-\frac{m_i + m_j}{T}\right) \\
\sum_{X \in \mathrm{SM},\, j} \Gamma_{i \to jX}\, n_i^{eq} \quad &\propto \quad \exp\left(-\frac{m_i}{T}\right) \\
\sum_{X, Y \in \mathrm{SM},\, j} \sigma_{iX \to jY}\, n_i^{eq} n_X^{eq} \quad &\propto \quad \exp\left(-\frac{m_i}{T}\right)
\end{aligned}$$

Coannihilation

$$\sum_j n_i^{eq} n_j^{eq} \langle \sigma_{ij} v_{ij} \rangle \quad \propto \quad \exp\left(-\frac{m_i + m_j}{T}\right)$$

$$\sum_{X \in \mathrm{SM},\, j} \Gamma_{i \to jX}\, n_i^{eq} \quad \propto \quad \exp\left(-\frac{m_i}{T}\right)$$

$$\sum_{X,Y \in \mathrm{SM},\, j} \sigma_{iX \to jY}\, n_i^{eq} n_X^{eq} \quad \propto \quad \exp\left(-\frac{m_i}{T}\right)$$

If conversion rates $>$ Hubble expansion $\Rightarrow$ chemical equilibrium

$$\frac{n_i}{n_j} = \frac{n_i^{eq}}{n_j^{eq}}$$

Coannihilation in chemical equilibrium

Reduce effectively to single Lee-Weinberg equation for $n = \sum_i n_i$

$$\dot{n} + 3Hn = -(n^2 - (n^{eq})^2)\langle \sigma v_{eff} \rangle$$

Effective annihilation cross section

$$\sigma v_{eff} = \sum_{ij} \sigma_{ij} v_{ij} \frac{n_i^{eq} n_j^{eq}}{(n^{eq})^2}$$

Conversion terms dropped out, not sensitive as long as rates are large enough

Coannihilation

$$
\begin{aligned}
\sum_j n_i^{eq} n_j^{eq} \langle \sigma_{ij} v_{ij} \rangle &\propto |\mathcal{M}|^2_{ij \to SMSM'} \exp\left(-\frac{m_i + m_j}{T}\right) \\
\sum_{X \in \mathrm{SM},\, j} \Gamma_{i \to jX}\, n_i^{eq} &\propto |\mathcal{M}|^2_{i \to jSM} \exp\left(-\frac{m_i}{T}\right) \\
\sum_{X,Y \in \mathrm{SM},\, j} \sigma_{iX \to jY}\, n_i^{eq} n_X^{eq} &\propto |\mathcal{M}|^2_{iSM \to jSM'} \exp\left(-\frac{m_i}{T}\right)
\end{aligned}
$$

Rates depend also on matrix elements $\Rightarrow$ chemical equilibrium not guaranteed in general

Example

- Majorana fermion $\chi \equiv (1_c, 1_L, 0)$
- Coupling to RH quark q_R (e.g. bottom b_R)
- Scalar mediator $\tilde{b} \equiv (\bar{3}_c, 1_L, -Y_q)$

$$\mathcal{L}_{int}^{fermion} = \lambda_\chi \bar{\chi} q_R \tilde{b} + h.c.$$

- Three parameters: m_χ, $m_{\tilde{b}}$, coupling λ_χ

Example

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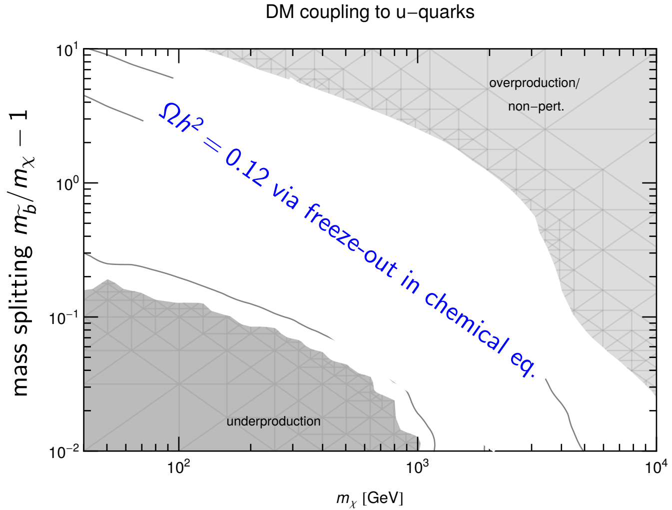
$$\mathcal{L}_{int}^{fermion} = \lambda_\chi \bar{\chi} q_R \tilde{b} + h.c.$$

- Three parameters: m_χ, $m_{\tilde{b}}$, coupling λ_χ
- Contains MSSM with bino-like neutralino, $\tilde{b} =$ squark

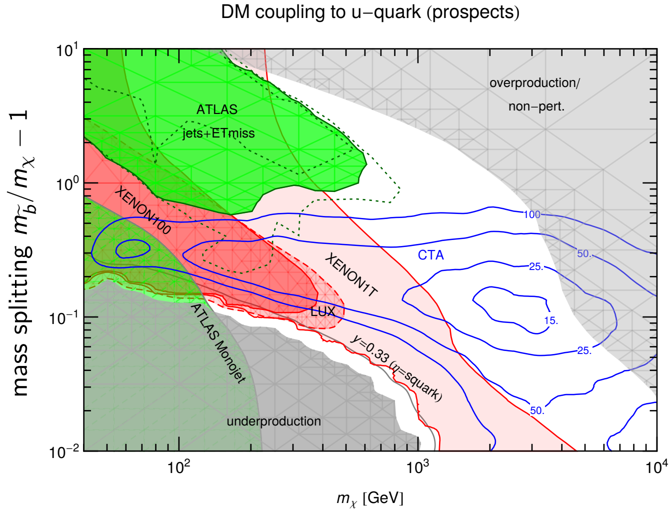
$$\lambda_\chi = \sqrt{2} g' Y_{\tilde{b}} \approx \begin{cases} 0.33 & \text{up-type} \\ 0.16 & \text{down-type} \end{cases}$$

Parameter space



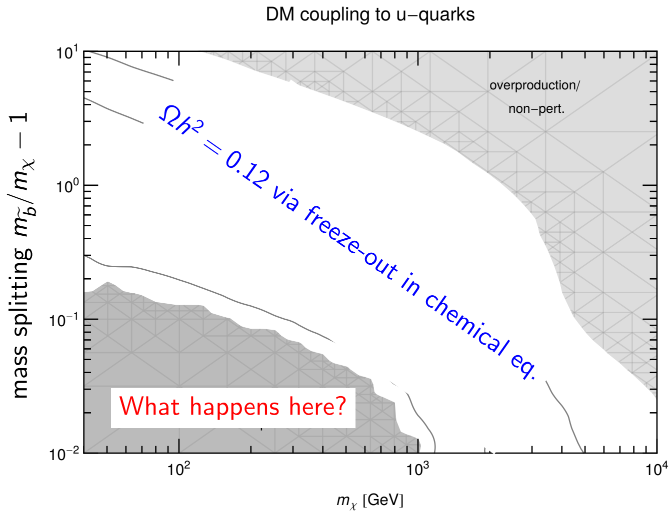
MG, Ibarra, Vogl 1503.01500

Parameter space



MG, Ibarra, Vogl 1503.01500

Parameter space



MG, Ibarra, Vogl 1503.01500

(Co-)annihilation processes

initial state		final state		scaling
χ	χ	b	$\bar{b}$	λ_χ^4
χ	$\widetilde{b}$	b	g, γ, Z, H	$\lambda_\chi^2 g_s^2$
		W^-	t, u, c	
$\widetilde{b}$	$\widetilde{b}^\dagger$	V	V	g_s^4
		q	$\bar{q}$	
		Z	H	
		l	$\bar{l}$	

Relic density if chemical equilibrium holds

$$\Omega_\chi h^2 \sim \frac{1}{\sigma v_{eff}} = \frac{m_\chi^2}{\lambda_\chi^4 \, C_{\chi\chi} + \lambda_\chi^2 \, g_s^2 \, C_{\chi\widetilde{b}} + g_s^4 \, C_{\widetilde{b}\widetilde{b}}}$$

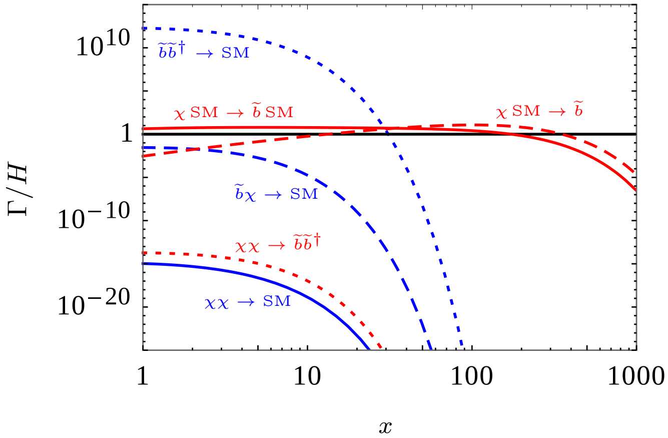
QCD-mediated channel $\propto g_s^4$ can lead to $\Omega_\chi h^2 < 0.12$ even for $\lambda_\chi \ll 1$

Conversion processes

initial state		final state		scaling
χ	b	$\widetilde{b}$	g, γ, Z, H	λ_χ^2
	g, γ, Z, H		$\bar{b}$	
	W^-		$\bar{t}, \bar{u}, \bar{c}$	
	t, u, c		W^+	
$\widetilde{b}$		χ	b	λ_χ^2

Conversions become inefficient for $\lambda_\chi \to 0 \Rightarrow$ deviation from chemical equilibrium needs to be taken into account for $\Gamma_{conv} \sim H$

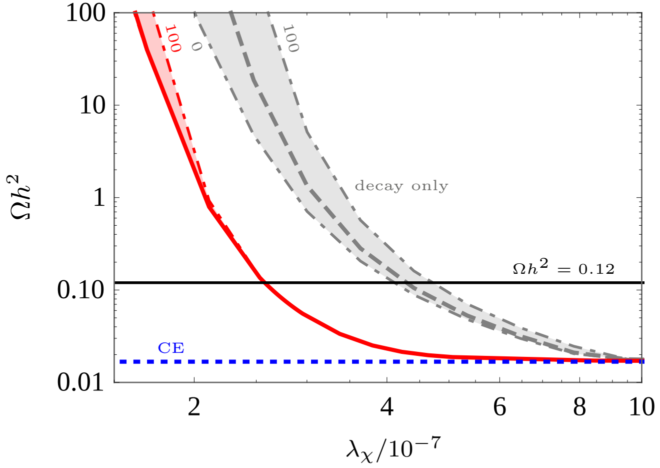
Rates vs $x = m_\chi / T$



$m_\chi = 500$ GeV, $m_{\tilde{b}} = 510$ GeV

MG, Heisig, Lülf, Vogl 1705.09292

Relic density vs coupling λ_χ



Measured abundance can be obtained by allowing the 'right' amount of contact between χ and $\widetilde{b}$

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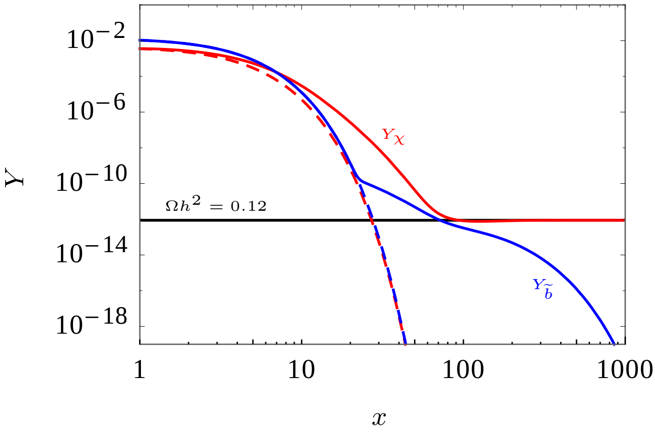
Freeze-out w/o chemical equilibrium



$m_\chi = 500$ GeV, $m_{\tilde{b}} = 510$ GeV

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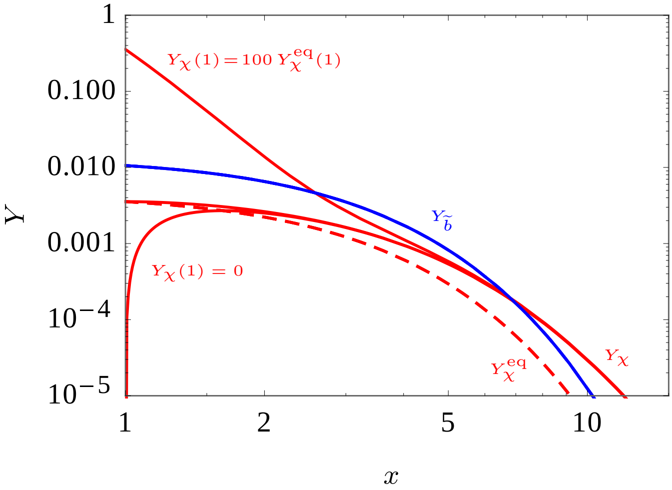
Independence of initial condition



Very weakly coupled, but still thermalized at early times $\Rightarrow$ no dependence on initial abundance

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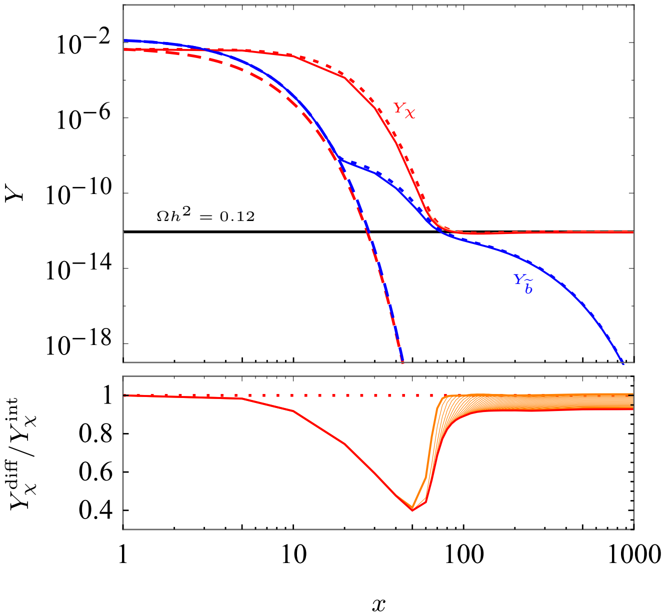
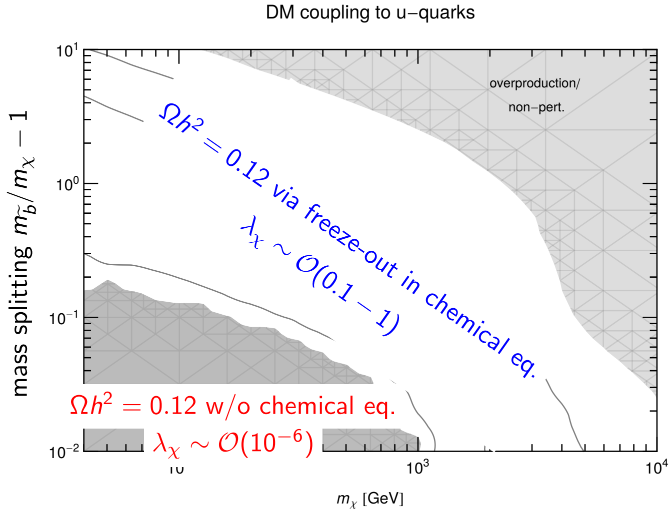
kinetic equilibrium



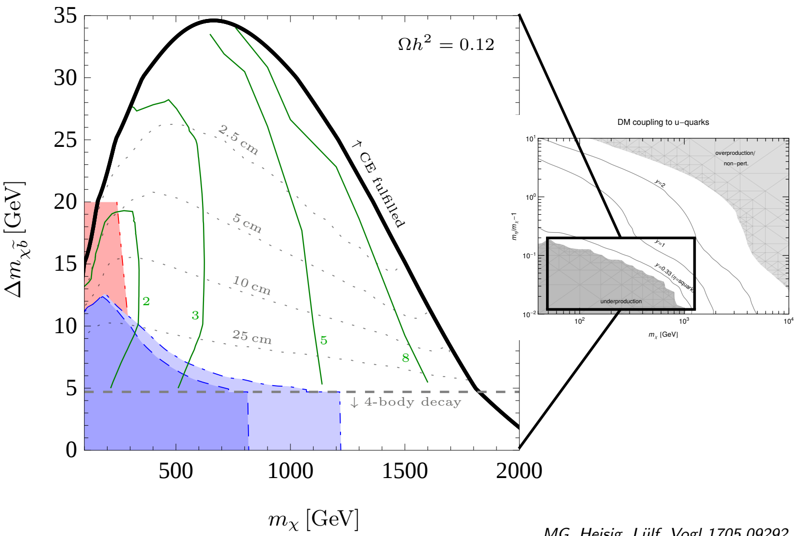
Parameter space



Signatures

- Small coupling avoids constraints from DD, ID
- Coloured mediator $\widetilde{b}$ produced at LHC, macroscopic decay length $\widetilde{b} \rightarrow \chi b$
- Ionizing track in detector (R-hadron)
- For $\Omega_\chi = 0.12$, decay length of order *cm* to *m*
- $\Rightarrow$ need to re-interpret R-hadron analyses to account for decay inside detector

R-hadron LHC constraints

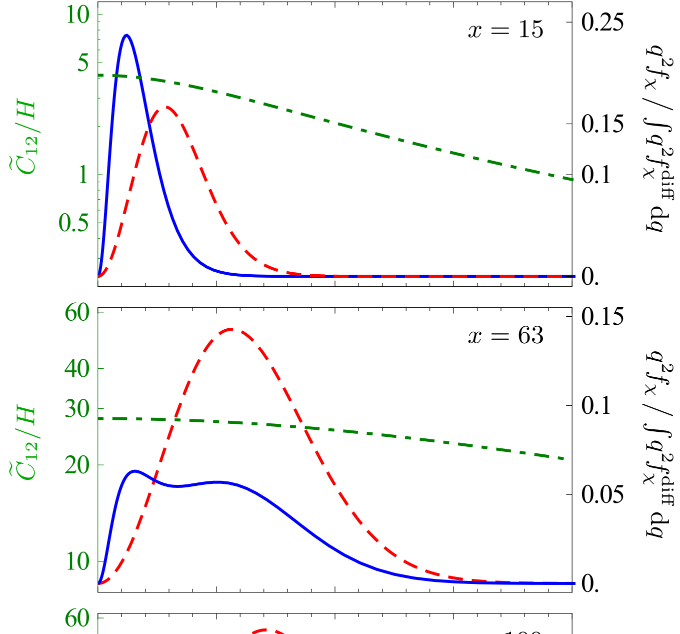


MG, Heisig, Lülf, Vogl 1705.09292

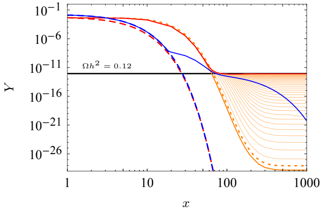
Conclusion

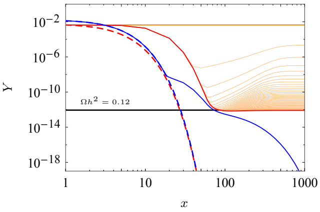
- Usual treatment of coannihilations relies on assumption of chemical equilibrium
- Often justified, but not always
- Freeze-out w/o chemical equilibrium can explain dark matter abundance for very weakly coupled dark matter particle, and strongly coupled mediator $\Rightarrow$ Long-lived states at LHC, no signal in DD/ID
- Required coupling lies between typical FIMP and WIMP
- Preserves predictivity of WIMPs (independence of ICs)
- Not limited to example shown here, 'co-scattering' *(see e.g. D'Agnolo, Pappadopulo, Ruderman 1705.08450)*

BE w/o chemical and kinetic equilibrium

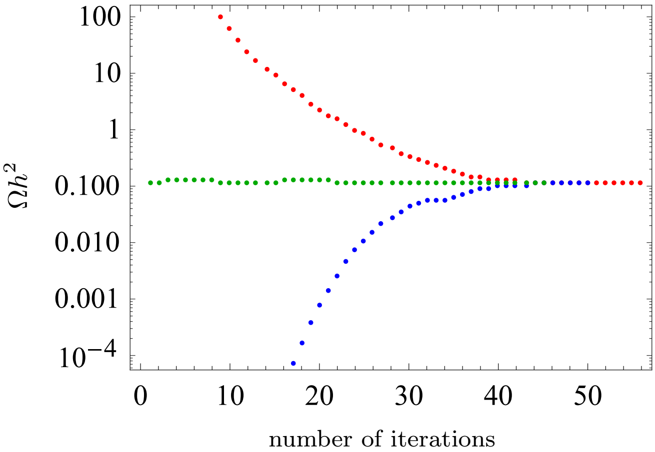


BE w/o chemical and kinetic equilibrium

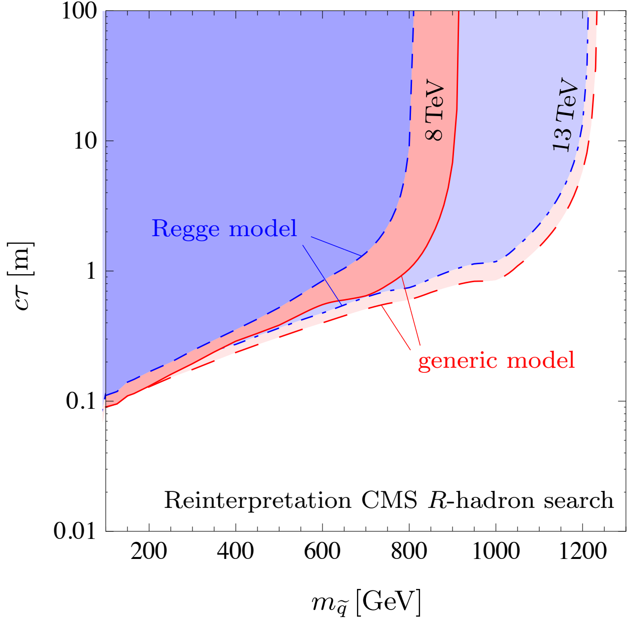




BE w/o chemical and kinetic equilibrium



CMS R-hadron reinterpretation



BE w/o chemical equilibrium

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x} \Bigg[\langle\sigma_{\chi\chi} v\rangle \left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \left\langle \sigma_{\chi\widetilde{b}} v\right\rangle \left(Y_\chi Y_{\widetilde{b}} - Y_\chi^{\mathrm{eq}} Y_{\widetilde{b}}^{\mathrm{eq}}\right)$$

$$+ \frac{\Gamma_{\chi\to\widetilde{b}}}{s}\left(Y_\chi - Y_{\widetilde{b}}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\widetilde{b}}^{\mathrm{eq}}}\right) - \frac{\Gamma_{\widetilde{b}}}{s}\left(Y_{\widetilde{b}} - Y_\chi\frac{Y_{\widetilde{b}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)$$

$$+ \left\langle \sigma_{\chi\chi\to\widetilde{b}\widetilde{b}^\dagger} v\right\rangle \left(Y_\chi^2 - Y_{\widetilde{b}}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\widetilde{b}}^{\mathrm{eq}\,2}}\right)\Bigg]$$

$$\frac{\mathrm{d}Y_{\widetilde{b}}}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x} \Bigg[\frac{1}{2}\langle\sigma_{\widetilde{b}\widetilde{b}^\dagger} v\rangle \left(Y_{\widetilde{b}}^2 - Y_{\widetilde{b}}^{\mathrm{eq}\,2}\right) + \left\langle \sigma_{\chi\widetilde{b}} v\right\rangle \left(Y_\chi Y_{\widetilde{b}} - Y_\chi^{\mathrm{eq}} Y_{\widetilde{b}}^{\mathrm{eq}}\right)$$

$$- \frac{\Gamma_{\chi\to\widetilde{b}}}{s}\left(Y_\chi - Y_{\widetilde{b}}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\widetilde{b}}^{\mathrm{eq}}}\right) + \frac{\Gamma_{\widetilde{b}}}{s}\left(Y_{\widetilde{b}} - Y_\chi\frac{Y_{\widetilde{b}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right)$$

$$- \left\langle \sigma_{\chi\chi\to\widetilde{b}\widetilde{b}^\dagger} v\right\rangle \left(Y_\chi^2 - Y_{\widetilde{b}}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\widetilde{b}}^{\mathrm{eq}\,2}}\right)\Bigg]$$