# Early kinetic decoupling of dark matter with resonant annihilation

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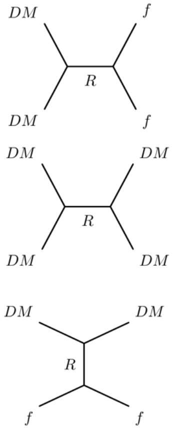
MD, B. Grządkowski, „Resonant dark matter annihilation with early kinetic decoupling", in preparation.

**Breit-Wigner resonance $2M_{DM} \approx M_R$**

**enhanced annihilation ⇒ suppressed coupling**




- enhancement of low velocity annihilation rates

  *Ibe et al., 2009, Guo, Wu 2009*

- special methods to treat resonantly enhanced annihilation

  *Gondolo, Gelmini 1991, Griest, Seckel 1991*

- insensitive to direct detection
- kinetic decoupling **?**
- enhancement of the self-interaction cross-section **?**

**Boltzmann equation for DM** $\int \mathbf{L}[f_{DM}]d^3p = \int \mathbf{C}[f_{DM}]d^3p$

$$\frac{dY}{dx} = -\alpha\frac{\langle\sigma v_{\rm rel}\rangle}{x^2}(Y^2 - Y_{\rm EQ}), \qquad \text{DM yield } Y = n/\mathbf{s}, \qquad \alpha = \frac{s(m)}{H(m)}$$

- $x = m/T$ dimensionless parameter
- **s** – entropy density ← conserved in the comoving volume

**Chemical decoupling** $x = x_d$

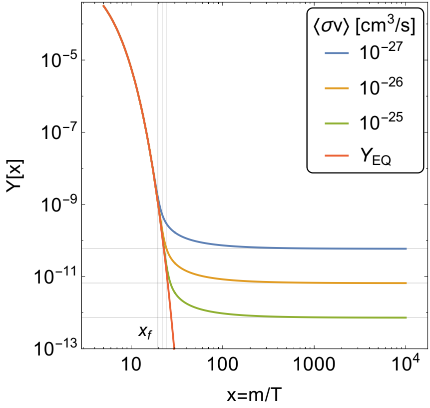
$$\Gamma = n_{EQ}\langle\sigma v_{\rm rel}\rangle \lesssim H(x)$$

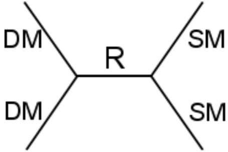
**Approximate solutions**

$\langle\sigma v_{\rm rel}\rangle = const$

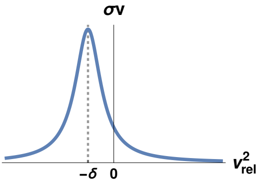
$$\frac{1}{Y_\infty} - \frac{1}{Y(x_d)} = \alpha\int_{x_d}^{\infty}\frac{\langle\sigma v_{\rm rel}\rangle}{x^2}$$

$$Y_\infty \approx \frac{x_d}{\alpha\langle\sigma v_{\rm rel}\rangle_0}$$






$$\sigma \sim \frac{1}{(s-M_R^2)^2+M_R^2\Gamma_{tot}^2}$$




**Annihilation cross-section - s-wave**

$$\sigma v_{\rm rel} = \sum_{f\neq i} \frac{64\pi\omega}{M^2} \frac{\eta_i \eta_f \beta_f}{(\delta + v_{\rm rel}^2/4)^2 + \gamma^2}$$

**Dimensionless parameters:**

$$\eta_{i/f} = \frac{\Gamma B_{i/f}}{M_R \bar{\beta}_{i/f}}, \qquad \delta = \frac{4M_{DM}^2}{M_R^2} - 1, \qquad \gamma = \frac{\Gamma_R}{M_R}$$

**couplings** **position** **width**

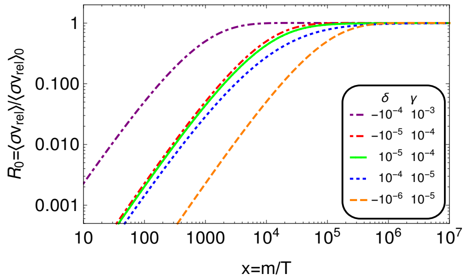
statistical spin-dependent factor

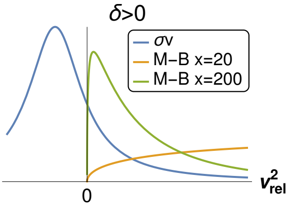
$$\omega = \frac{2s_R + 1}{(s_{DM}+1)^2}$$

# Thermally averaged annihilation cross-section

**Averaged cross section $\langle \sigma v_{\rm rel} \rangle$ normalized to $\langle \sigma v_{\rm rel} \rangle_{T=0}$**

$$R(x) = \frac{\langle \sigma v_{\rm rel} \rangle}{\langle \sigma v_{\rm rel} \rangle_{T=0}} = \frac{x^{3/2}}{2\sqrt{\pi}} \int_0^\infty dv v^2 e^{-xv^2/4} \frac{\delta^2 + \gamma^2}{(\delta + v^2/4)^2 + \gamma^2}$$

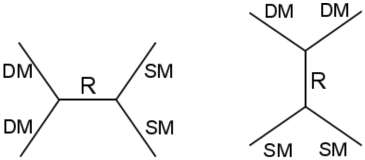



**$\langle \sigma v_{\rm rel} \rangle$ grows for smaller temperatures**

**Condition $T_{DM} = T_{SM}$ is not always fulfilled.**

Thermal equilibrium is maintained by the scattering of DM on the abundant light SM states.




- proper relic abundance requires small coupling of $DM$ to SM
- scattering process is not resonantly enhanced

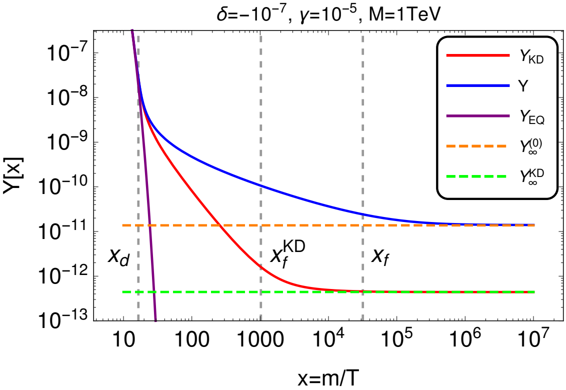
**Comparision of the Hubble rate to the scattering rate**

*Bi at al, 2011*

$$H(T_{kd}) \sim \Gamma_{\rm scat}(T_{kd}) \Rightarrow x_{kd} \lesssim \left( \frac{\max[\delta, \gamma]^{3/2}}{10^{-6}} \right)^{\frac{1}{4}} \Longrightarrow \mathbf{T_{kd} \sim T_{d}}.$$

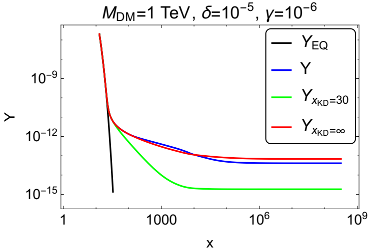
**Kinetic and chemical decoupling temperatures are comparable**

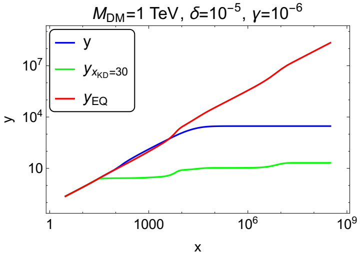
$$T_{DM} = \begin{cases} T_{SM}, & \text{if } T \geqslant T_{kd} \\ T_{SM}^2/T_{kd}, & \text{if } T < T_{kd}. \end{cases}$$




**quickly falling DM temperature ⇒ more effective annihilation**

# Kinetic decoupling – detailed description




## Temperature parameter

$$y \equiv \frac{M_{DM} T_{DM}}{s^{2/3}} \qquad T_{DM} \propto \int p^2 f(p) d^3p$$

before decoupling: $y \propto T_{SM}^{-1} \propto x$ $\qquad s \sim T_{SM}^3$

after decoupling: $y \approx const$

## Second moment of Boltzmann equation

$$\int p^2 \mathbf{L}[f_{DM}] d^3p = \int p^2 \mathbf{C}[f_{DM}] d^3p$$

**see also A. Hryczuk talk**

**Coupled Boltzmann equation**

$$\frac{dY}{dx} = -\frac{1-\frac{x}{3}\frac{g'_{*s}}{g_{*s}}}{Hx} s\left(Y^2\langle\sigma v_{\rm rel}\rangle_{x_{DM}} - Y_{EQ}^2\langle\sigma v_{\rm rel}\rangle_x\right)$$

$$\frac{dy}{dx} = -\frac{1-\frac{x}{3}\frac{g'_{*s}}{g_{*s}}}{Hx}\Big[2M_{DM}c(T)(y-y_{EQ})+$$

$$-sy\Bigg(Y\left(\langle\sigma v_{\rm rel}\rangle_{x_{DM}} - \langle\sigma v_{\rm rel}\rangle_2|_{x_{DM}}\right) - \frac{Y_{EQ}^2}{Y}\left(\langle\sigma v_{\rm rel}\rangle_x - \frac{y_{EQ}}{y}\langle\sigma v_{\rm rel}\rangle_2|_x\right)\Bigg)\Big]$$

*Aarssen, Bringmann, Goedecke 2012*

**Scattering and annihilation have both influence on temperature**

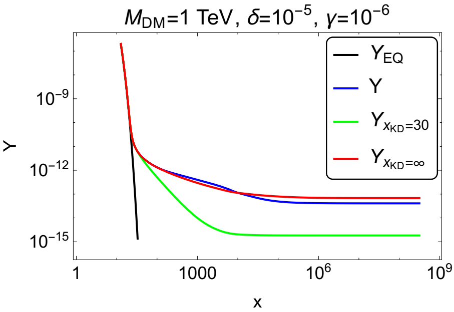
scattering rate c(T)

$$c(T) = \frac{1}{12(2\pi)^3)M_{DM}^4 T}\sum_f \int dk k^5 \omega^{-1} g|\mathcal{M}_f|^2_{t=0;s=M_{DM}^2+2M_{DM}\omega+M_f^2}$$

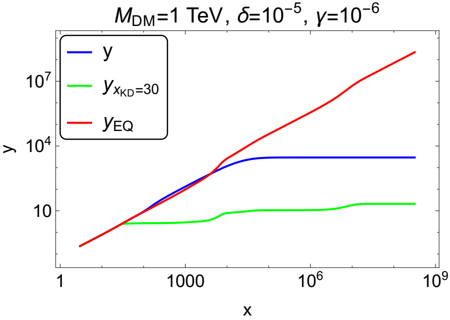
the averaged cross section $\langle\sigma v_{\rm rel}\rangle_2$

$$\langle\sigma v_{\rm rel}\rangle_2 = \int_0^\infty dv_{\rm rel}\frac{x^{3/2}}{4\sqrt{\pi}}\sigma v_{\rm rel}\left(1+\frac{1}{6}v_{\rm rel}^2 x\right)v_{\rm rel}^2 \exp^{-v_{\rm rel}^2 x/4}.$$

**Density**




**Temperature**




$\langle \sigma v_{\rm rel} \rangle$ **grows for smaller velocities $\Rightarrow$ annihilation heats up DM**

# Illustration - the Higgs portal with vector dark matter

## Additional complex scalar field S

- singlet of $U(1)_Y \times SU(2)_L \times SU(3)_c$, charged under $U(1)_X$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + (D_\mu S)^* D^\mu S + \tilde{V}(H, S)$$

$$V(H,S) = -\mu_H^2 |H|^2 + \lambda_H |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \kappa \mathbf{|S|^2 |H|^2}$$

Vacuum expectation values: $\langle H \rangle = \frac{v_{SM}}{\sqrt{2}}$, $\langle S \rangle = \frac{v_x}{\sqrt{2}}$

## $U(1)_X$ vector gauge boson $V_\mu$

- Stability condition - no mixing of $U(1)_X$ with $U(1)_Y$ ~~$B_{\mu\nu} V^{\mu\nu}$~~

  $\mathcal{Z}_2 : V_\mu \to -V_\mu$, $S \to S^*$, $S = \phi e^{i\sigma}$: $\phi \to \phi$, $\sigma \to -\sigma$
- Higgs mechanism in the hidden sector $M_{Z'} = g_x v_x$

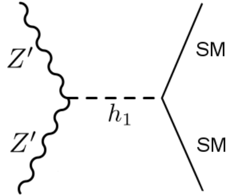
## Higgs couplings – mixing angle $\alpha$, $M_{h_1} = 125$ GeV

$$\mathcal{L} \supset \frac{h_1 \cos\alpha + h_2 \sin\alpha}{v} \left( 2 M_W W_\mu^+ W^{\mu -} + M_Z^2 Z_\mu Z^\mu - \sum_f m_f \bar{f} f \right)$$

# Resonance with a Higgs scalar

$\langle \sigma v_{\mathrm{rel}} \rangle \propto \sin\alpha \cos\alpha$

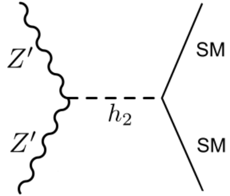
**Small $\alpha$ required by relic abundance**




### Resonance with the SM-like Higgs

- $M_{Z'} \approx 125/2$ GeV
- decay channel $h_1 \to Z'Z'$, if open
  suppressed by $\sin^2\alpha$ and by phase space

$$\sqrt{1 - 4M_{Z'}^2/M_{h_1}^2} = \sqrt{\delta} \ll 1 \qquad \Gamma_{h_1 \to Z'Z'} \ll \Gamma_{SM}$$




### Resonance with the second Higgs

- $M_{Z'} \approx M_{h_2}/2$ GeV
- $h_2 \to SMSM$ suppressed by $\sin^2\alpha$,
  $h_2 \to Z'Z'$ can dominate
- near threshold effects

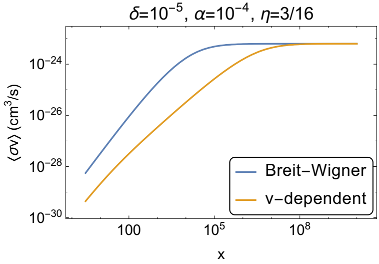
# Velocity dependent width

## Beyond Breit-Wigner approximation – resummed propagator


$$\frac{1}{s - m_h^2 + i\,\mathrm{Im}\,\Pi_h(s)}$$

$$\mathrm{Im}\,\Pi_h(s)/\sqrt{s} \approx \Gamma_{non-DM}(m_h^2) + \Gamma_{DM}(s)$$

$$\Gamma_{DM}(s) \approx \eta m_h \sqrt{1 - 4M_{Z'}^2/s} \approx \eta m_h v/2$$



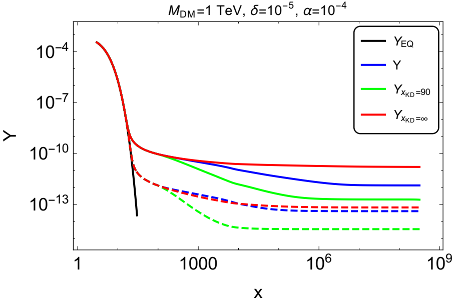

$$\sigma v(s) \sim \frac{1}{(\delta + v_{\mathrm{rel}}^2/4)^2 + (\gamma_{non-DM} + \eta v/2)^2}$$

- for larger $T$ scales like $1/v^2$
- saturates $\delta \sim \eta v/2$

$$\sigma v(s) \sim \frac{1}{(\delta + v_{\mathrm{rel}}^2/4)^2 + \gamma^2}$$

- for larger $T$ scales like $1/(\delta v^2)$
- saturates $\max[\delta, \gamma] \sim v^2/4$

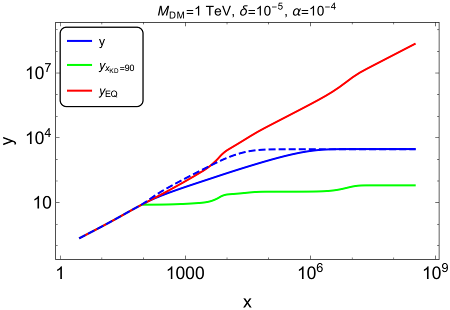
**Density**




dashed lines – Breit-Wigner approximation

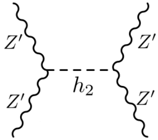
- earlier chemical decoupling
- annihilation lasts longer

**Temperature**




- annihilation less effective in changing DM temperature

**$\langle \sigma v_{\mathrm{rel}} \rangle$ grows for smaller velocities $\Rightarrow$ annihilation heats up DM**




## Core/cusp problem

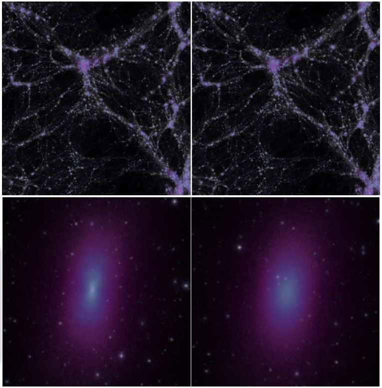
Simulated CDM halos contain more DM in the central region than indicated by the data from observations

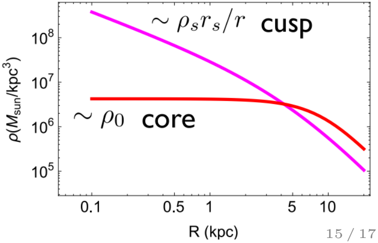
## Possible solution

**Large self-interaction cross-section**

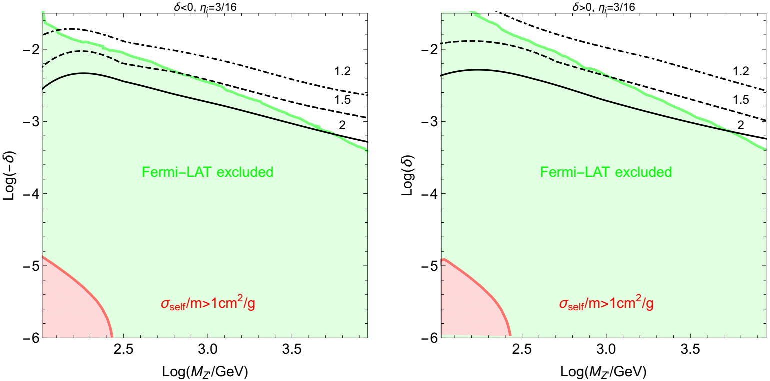
$$0.1\,\frac{\mathrm{cm}^2}{\mathrm{g}} \lesssim \frac{\sigma_{\mathrm{self}}}{M_{DM}} \lesssim 1\,\frac{\mathrm{cm}^2}{\mathrm{g}} \sim \frac{\mathrm{barn}}{\mathrm{GeV}} \gg \frac{\mathrm{pb}}{\mathrm{GeV}}$$

CDM SIDM





Mixing angle $\alpha$ set by relic density




Effects of kinetic decoupling may change the relic density by more than order of magnitude

# Summary

- Thermally averaged **cross-sections** for dark matter annihilation near the resonance **strongly depend on temperature**.
- **DM freeze-out is delayed** with respect to the non-resonant case
- To include the effects of **early kinetic decoupling** one has to solve the set of coupled Boltzmann equations
- If coupling between resonant mediator and DM is not suppressed then Breit-Wigner approximation is modified by near threshold effects.
- Large self-interactions are strongly constrained by the DM indirect searches.