Evolution of dark matter density considering kinetic decoupling

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Matter To The Deepest, Podlesice

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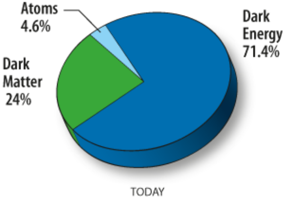
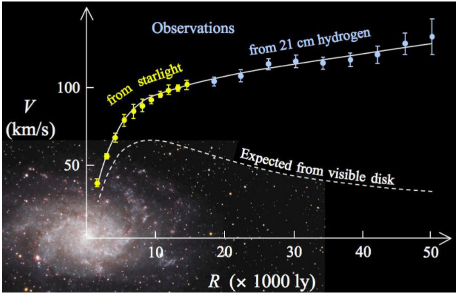
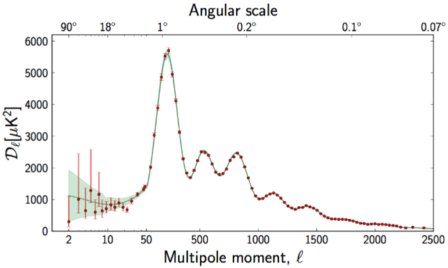
MD, Bohdan Grządkowski, 1705.10777, to appear in JHEP

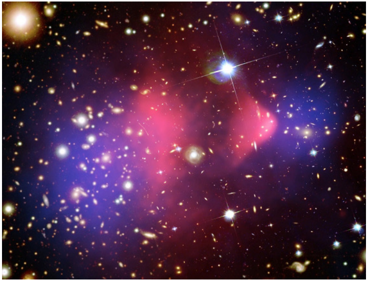
Motivation – Dark Matter





Convicing evidence on various astrophysical and cosmological scales



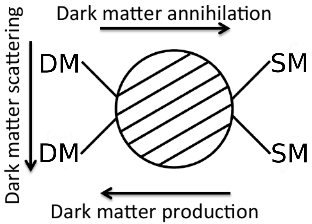


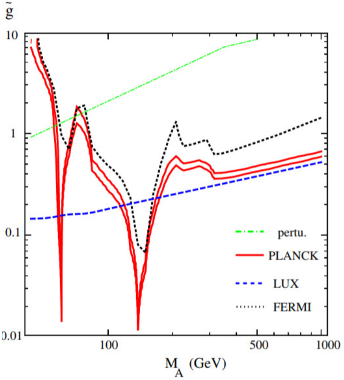
Properties of dark matter:

- electrically neutral (non luminous)
- non-relativistic (cold) (structure formation)
- stable or long-lived
- weakly interacting with ordinary matter

Dark matter interactions

- annihilation – production in the early universe and indirect detection (FERMI, MAGIC, H.E.S.S, ...)
- scattering on nucleons – direct detection (LUX, XENON, PANDA, ...) **strong constraints**
- production – collider searches

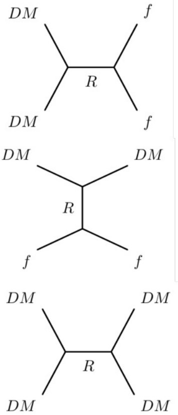




Gross, Lebedev, Mambrini, 2015

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

enhanced annihilation $\Rightarrow$ suppressed coupling



- insensitive to direct detection, but constrained by indirect searches

  enhancement of annihilation rate at low velocity

  Ibe et al., 2009, Guo, Wu 2009

- kinetic decoupling ($T_{DM} \neq T_{SM}$) **?**
- enhancement of the self-interaction cross-section **?**

Standard freeze-out mechanism

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

$$\boxed{\frac{dn}{dt} + 3Hn = -\langle \sigma v_{\rm rel}\rangle (n^2 - n_{EQ}^2)}$$

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

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

Chemical decoupling $x = x_d$

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

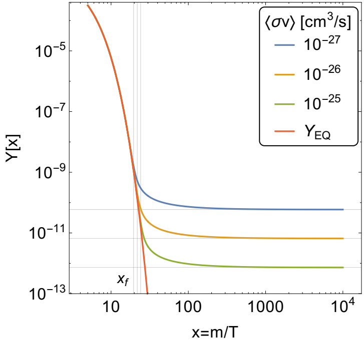
Approximate solutions

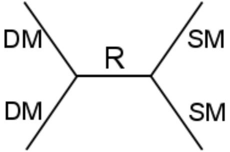
$\langle \sigma v_{\rm rel}\rangle(T) = const$

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

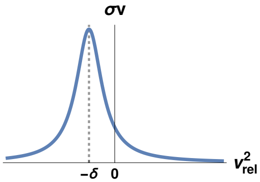
Standard assumption

DM is kinetically coupled to SM (has the same temperature) during freeze-out





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



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:

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

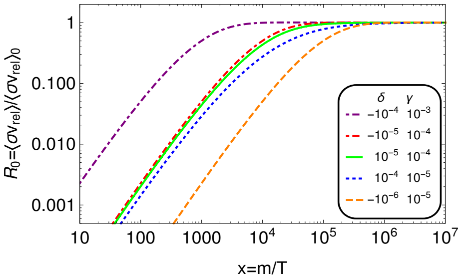
couplings **position** **width**

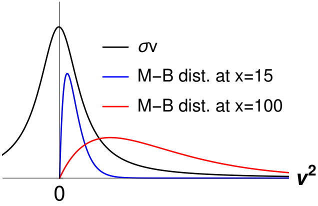
statistical spin-dependent factor

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

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

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

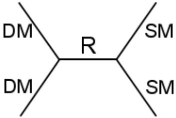


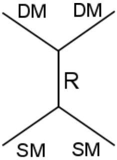


$\langle \sigma v_{\rm rel} \rangle$ grows for smaller temperatures

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

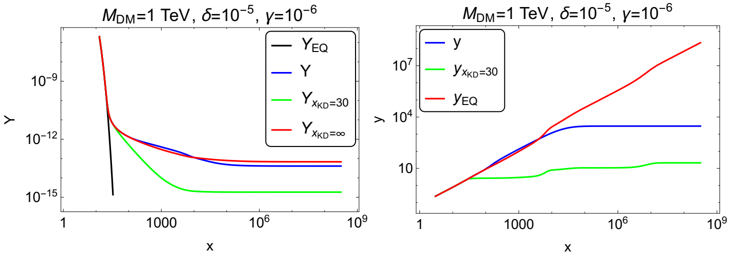
Comparision of the Hubble rate to the scattering rate

Bi at al, 2011

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

Kinetic and chemical decoupling temperatures are comparable

Kinetic decoupling – detailed description



Temperature parameter

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

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

after decoupling: $y \approx const$

Bringmann, 0903.0189

Second moment of Boltzmann equation

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

Coupled Boltzmann equation

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

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

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

Aarssen, Bringmann, Goedecke 2012

Scattering and annihilation have both influence on temperature

scattering rate c(T)

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

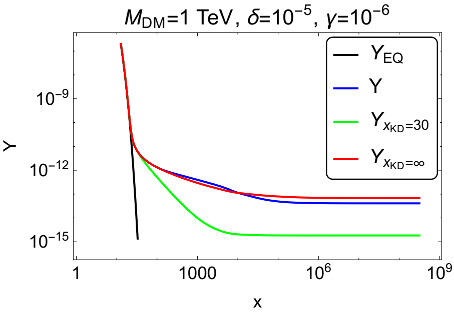
the averaged cross section $\langle\sigma v_{\rm rel}\rangle_2$

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

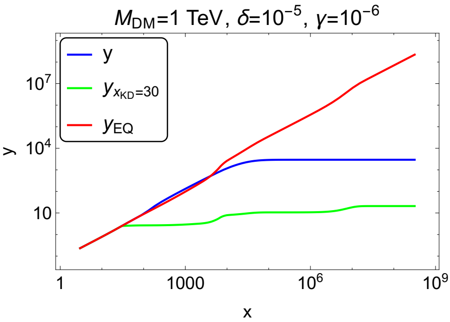
Boltzmann distribution maintained by DM self-interactions

departure from Boltz. dist.– Binder, Bringmann, Gustafsson, Hryczuk 1706.07433

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 $U(1)_X$

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

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

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_μ

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

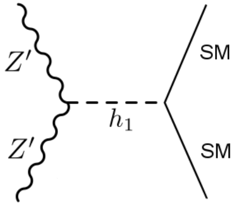
  $\mathcal{Z}_2 : V_\mu \to -V_\mu$, $S \to S^*$, $S = \phi e^{i\sigma}$: $\phi \to \phi$, $\sigma \to -\sigma$
- Higgs mechanism in the hidden sector $M_{Z'} = g_x v_x$

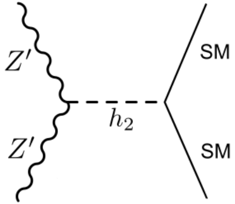
Higgs couplings – mixing angle α, $M_{h_1} = 125$ GeV

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

$\langle \sigma v_{\rm rel} \rangle \propto \sin^2\alpha \cos^2\alpha$

Small α 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

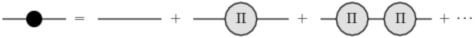
$$\sqrt{1 - 4M_{Z'}^2/M_{h_1}^2} = \sqrt{\delta} \ll 1 \qquad \Gamma_{h_1 \to Z'Z'} \ll \Gamma_{SM}$$

- Breit-Wigner approximation is sufficient

Resonance with the second Higgs

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

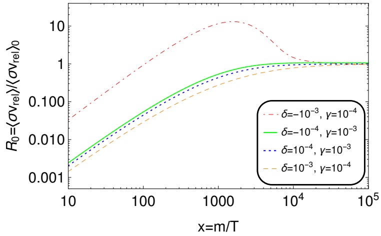
Beyond Breit-Wigner approximation – resummed propagator



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

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

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



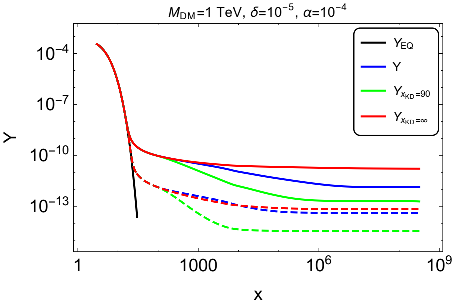
$$\sigma v(s) \sim \frac{1}{(\delta + v_{\rm rel}^2/4)^2 + (\gamma_{non-DM} + \eta v/2)^2}$$

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

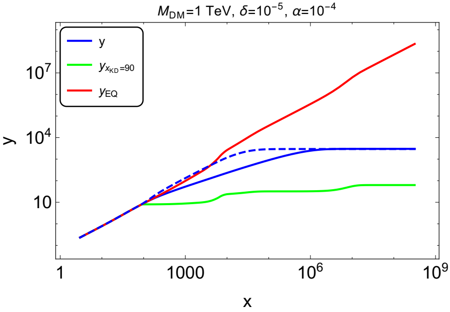
$$\sigma v(s) \sim \frac{1}{(\delta + v_{\rm rel}^2/4)^2 + \gamma^2}$$

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

Density



Temperature



dashed lines – Breit-Wigner approximation

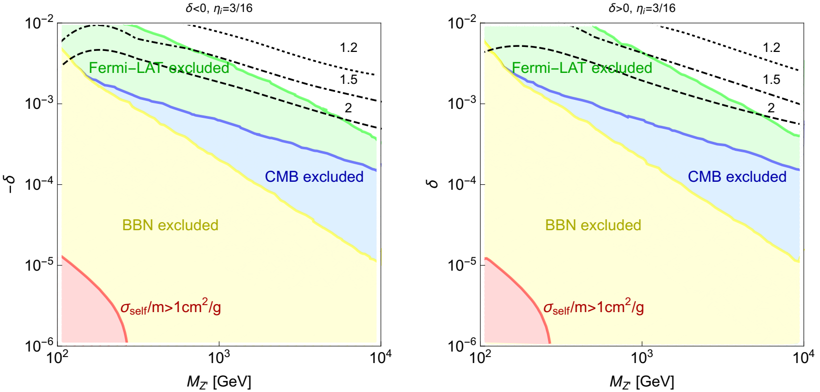
- earlier chemical decoupling
- annihilation lasts longer

- annihilation less effective in changing DM temperature

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

Bounds on the parameter space

Mixing angle α set by relic density



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

Summary

- When thermally averaged **cross-section is temperature dependent** and **scattering** on the SM states is **suppressed** kinetic decoupling effects are important
- 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.