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Kinetic decoupling and gauge invariance of the resonant annihilation in a vector dark matter model

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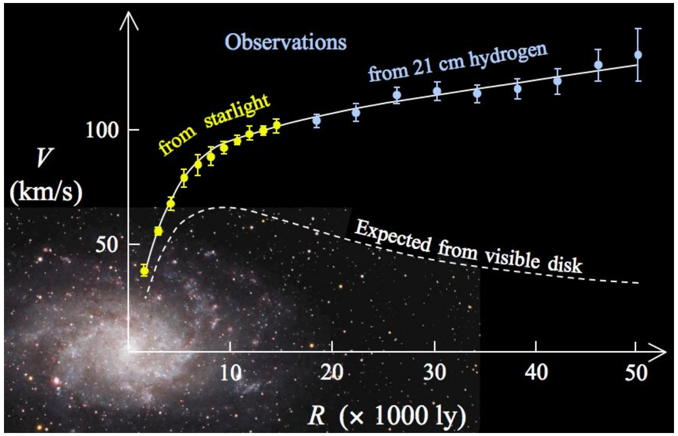
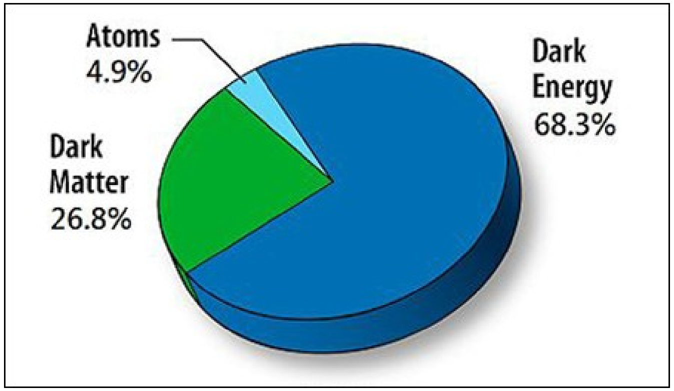
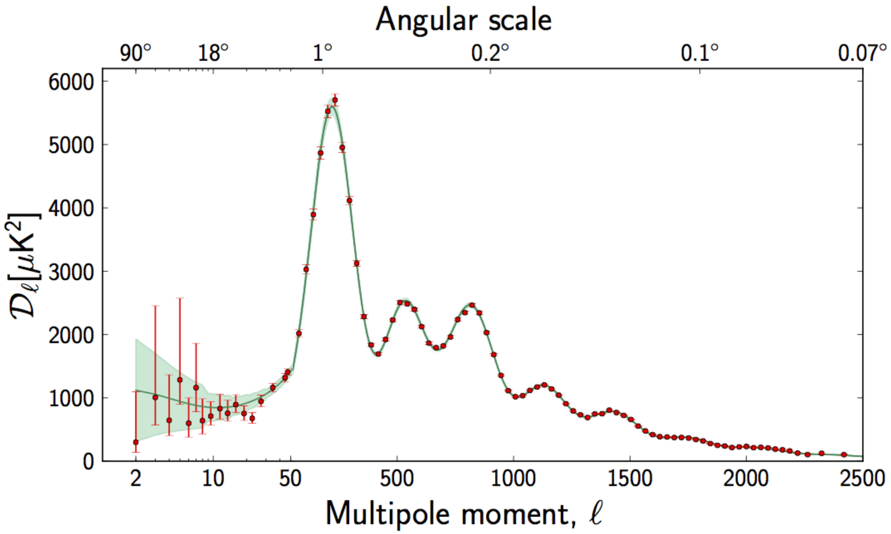
MD, Bohdan Grzadkowski, JHEP 1709 (2017) 159 [1705.10777]
MD, Bohdan Grzadkowski, Apostolos Pilaftsis, Gauge-dependence of the dark matter resonant annihilation amplitudes, in preparation.

Dark matter – motivation

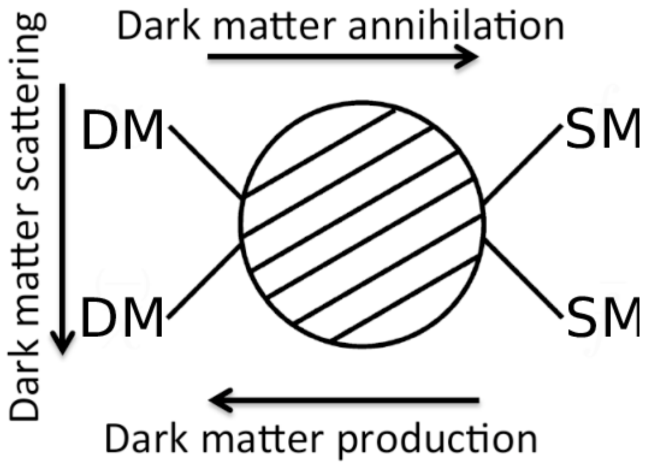




Convincing evidence on various astrophysical and cosmological scales



Dark matter – motivation

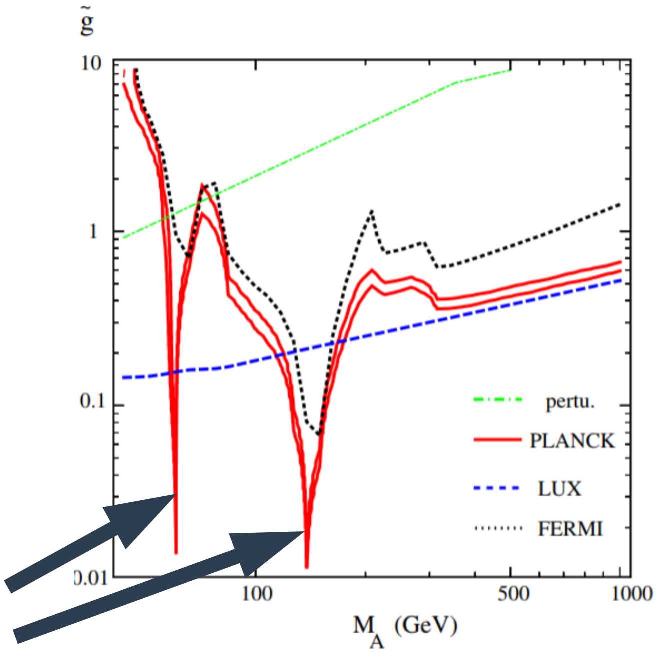


Properties of dark matter:

- 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-LAT, MAGIC, H.E.S.S, ...)
- production – collider searches
- scattering on nucleons – direct detection (LUX, PANDA, XENON 1T)



Gross, Lebedev, Mambrini, 2015

STRONG CONSTRAINTS

↓

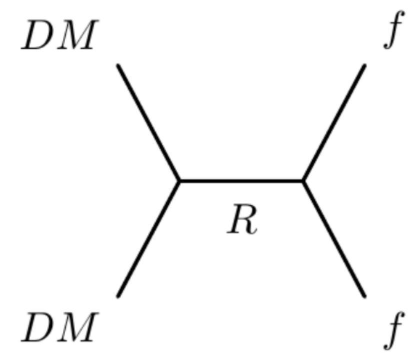
SMALL COUPLING REGIONS ARE RELEVANT

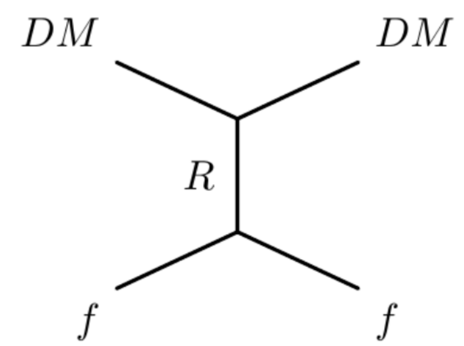
Breit-Wigner resonance

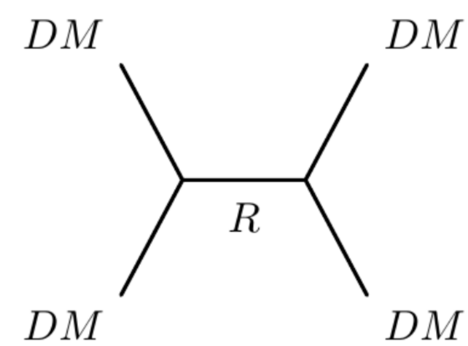
Breit-Wigner resonance $2M_{\mathrm{DM}} \approx M_{\mathrm{R}}$

enhanced annihilation → suppressed coupling

- low sensitivity to direct detection
- velocity dependent cross-section → possibility of enhanced indirect detection signals
- kinetic decoupling $T_{\mathrm{DM}} \neq T_{\mathrm{SM}}$?
- large self-interaction cross-section ?







Standard freeze-out mechanism

Boltzmann equation for DM phase space density $f_{DM}(\vec{p},t)$ $\quad L[f]=C[f]$

$$g\int L[f_{DM}]\frac{d^3p}{2\pi^3}\rightarrow \qquad \frac{dn}{dt}+3Hn=-\langle\sigma v_{\rm rel}\rangle(n^2-n_{\rm EQ}^2) \qquad \leftarrow g\int C[f_{DM}]\frac{d^3p}{2\pi^3}$$

DM yield $\quad Y=n/s, \quad x=M_{\rm DM}/T \quad$ n – number density, s – entropy density

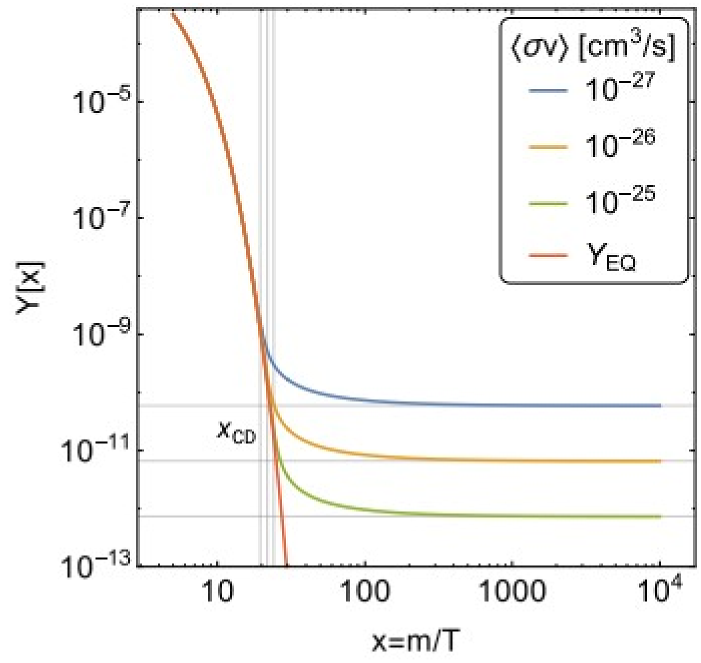
$$\frac{dY}{dx}=-\alpha\frac{\langle\sigma v_{\rm rel}\rangle}{x^2}(Y^2-Y_{\rm EQ}^2), \qquad \alpha=\frac{s(M_{\rm DM})}{H(M_{\rm DM})}$$

DM chemical decoupling

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

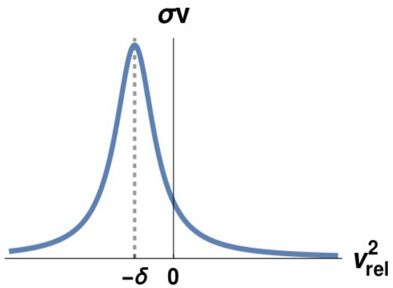
Approximate solution

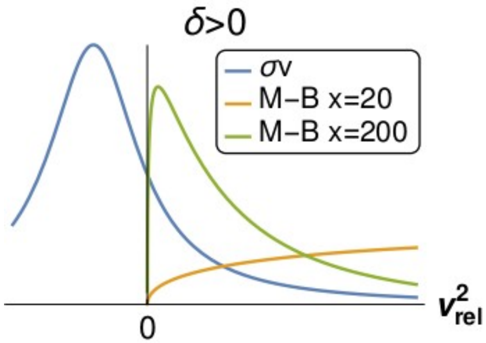
$$Y_\infty\approx\frac{x_{CD}}{\alpha\langle\sigma v_{\rm rel}\rangle}$$



Standard assumption: DM is kinetically coupled to SM during freeze-out, i.e. it has the same temperature as the SM thermal bath

Annihilation near the resonance





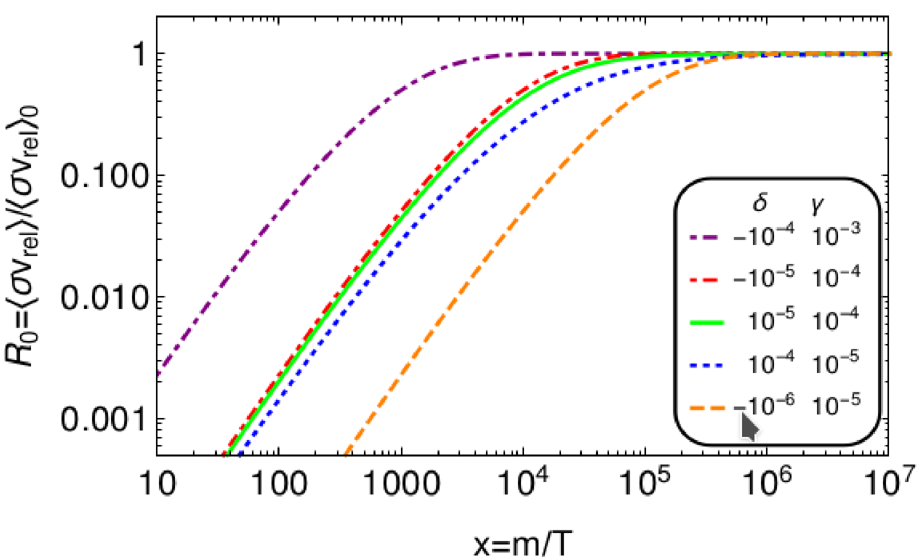
Non-relativistic annihilation cross-section – s-wave case

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

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

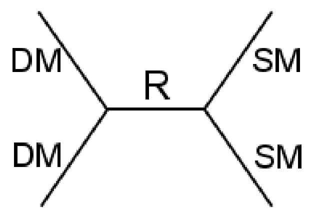


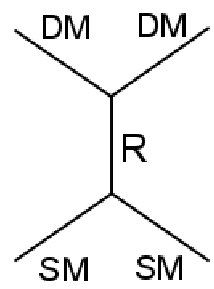
- cross section grows with falling temperature
- prolonged period of effective annihilation
- strong temperature dependence

$$T_{\rm DM} \neq T_{\rm SM} \quad ???$$

Kinetic decoupling – simplified picture

Scatterings on the abundant relativistic SM states → thermal equilibrium





- relic abundance requires small coupling between DM and SM
- scattering process is not resonantly enhanced

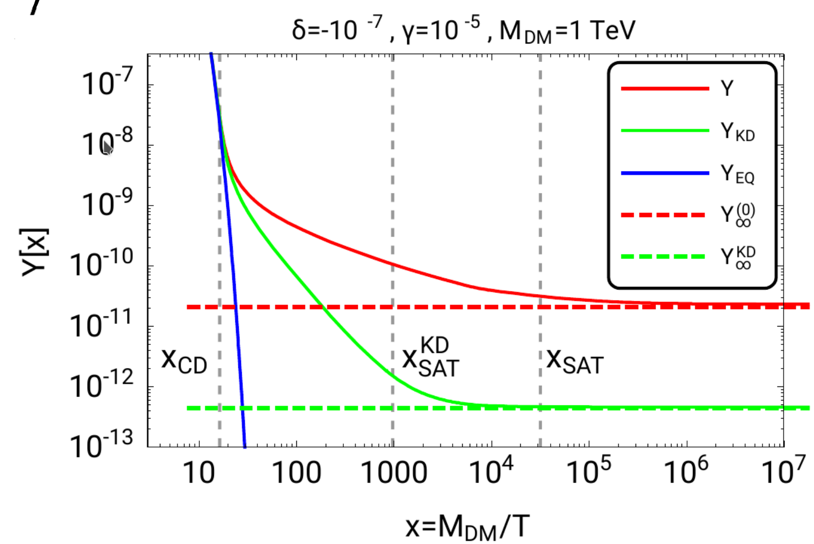
Comparision of the Hubble rate to scattering rate

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

Kinetic and chemical decoupling temperatures are comparable

$$T_{\rm DM} = \begin{cases} T_{\rm SM}, & \text{for } T \geq T_{\rm KD} \;\; = T_{\rm CD} \\ T_{\rm SM}^2/T_{\rm KD}, & \text{for } T < T_{\rm KD} \;\; = T_{\rm CD} \end{cases}$$

non-relativistic expanding gas



Kinetic decoupling – detailed description

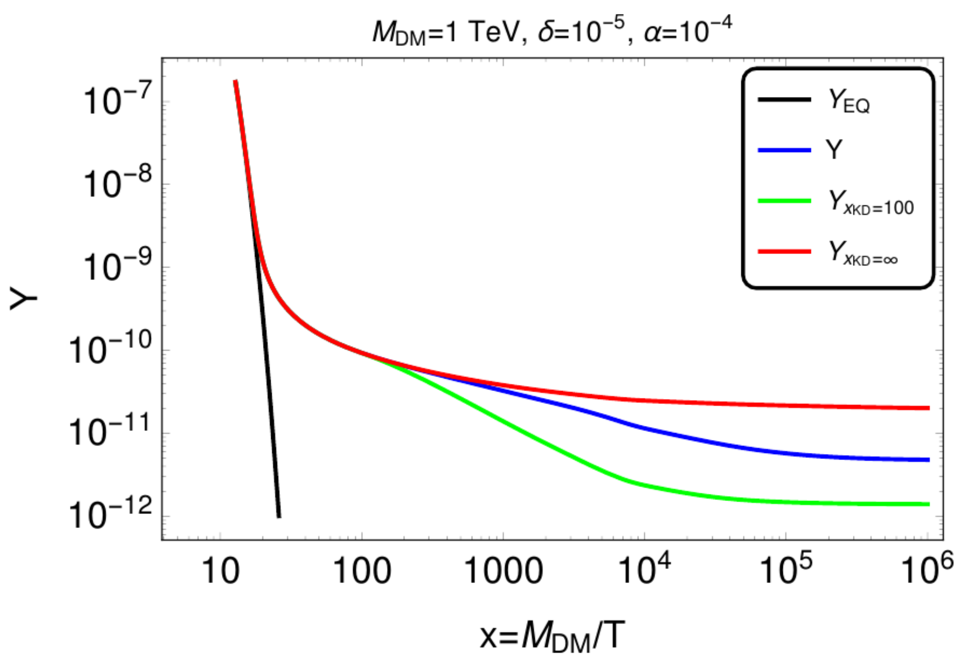
Second moment of Boltzmann equation $\int p^2 L[f] = \int p^2 C[f]$

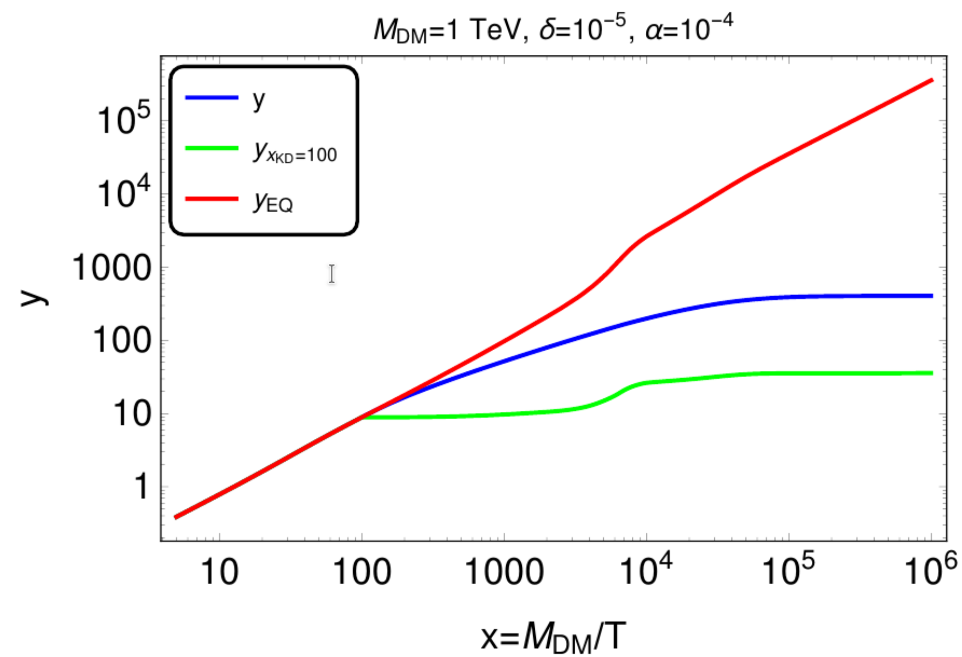
Temperature parameter $T_{DM} \propto \int p^2 f(p) d^3 p \qquad y \equiv \frac{M_{DM} T_{\rm DM}}{s^{2/3}}$

Coupled set of Boltzmann equations

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

$$\frac{dy}{dx} = -\frac{1 - \frac{x}{3}\frac{g'_{*s}}{g_{*s}}}{Hx} \left[2 M_{DM} c(T)(y - y_{EQ}) - sy \Big(Y \left(\langle \sigma v_{\rm rel} \rangle_{x_{DM}} - \langle \sigma v_{\rm rel} \rangle_2 |_{x_{DM}} \right) - \frac{Y_{EQ}^2}{Y} \left(\langle \sigma v_{\rm rel} \rangle_x - \frac{y_{EQ}}{y} \langle \sigma v_{\rm rel} \rangle_2 |_x \right) \Big) \right]$$





Abelian vector dark matter

Additional complex scalar field S

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

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

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

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_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 $M_{Z'} = g_x v_x$

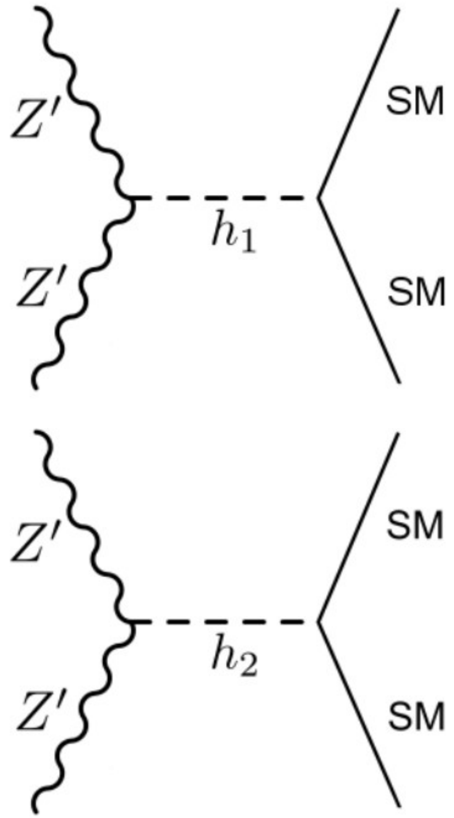
Higgs couplings – mixing angle α, $M_{h_1} = 125$ GeV

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

Resonance with a Higgs scalars

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

Small α required by relic abundance



Resonance with the SM-like Higgs

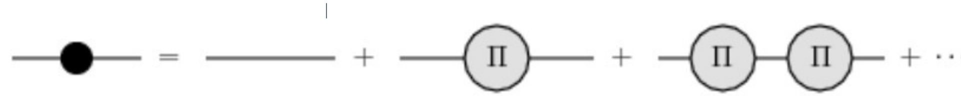
- $M_{Z'} \approx 125/2$ GeV
- decay channel $h_1 \to Z'Z'$, if open suppressed by $\sin^2\alpha$ and by phase space

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

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**

Resummed propagator



gauge-independent

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

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

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

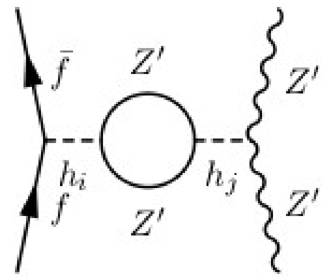
gauge-dependent

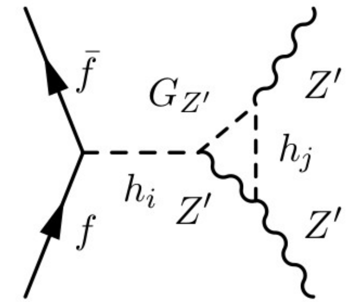
$$\Pi_{ij} = \frac{g_x^2 R_{2,i} R_{2,j}}{32\pi^2 M_{Z'}^2}\Big[\left(s^2 - 4M_{Z'}^2 s + 12 M_{Z'}^4\right) B_0(s, M_{Z'}^2, M_{Z'}^2) - (s^2 - m_i^2 m_j^2) B_0(s, \xi_X M_{Z'}^2, \xi_X M_{Z'}^2)\Big]$$

Depends explicitly on the gauge-fixing parameter
May grow with s^2 breaking unitarity

Pinch technique

One loop corrections to SM-DM process



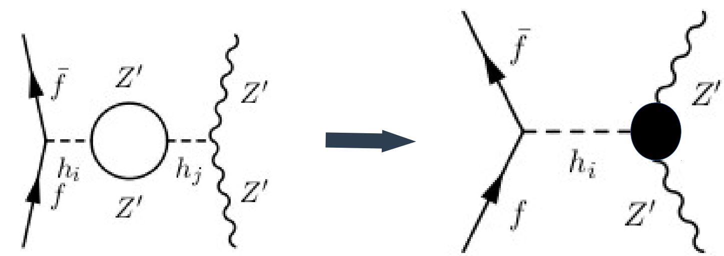


Tree-level Ward identities

$$r_2^\nu \hat{V}_{\mu\nu}^{h_i Z' Z'} + i M_{Z'} \hat{V}_\mu^{h_i Z' G'_Z} = -g_x R_{2,i} \hat{\Pi}_\mu^{G'_Z}(r_1),$$

$$r_1^\mu \hat{V}_\mu^{h_i Z' G'_Z} + i M_{Z'} \hat{V}^{h_i G'_Z G'_Z} = -g_x \left[\sum_j R_{2,j} \hat{\Pi}_{ji}(q^2) + R_{2,i} \hat{\Pi}^{G'_Z G'_Z}(r_2) \right],$$

$$r_1^\mu r_2^\nu \hat{V}_{\mu\nu}^{h_i Z' Z'} + M_{Z'}^2 \hat{V}^{h_i G'_Z G'_Z} = i g_x M_{Z'} [\sum_i R_{2,j} \hat{\Pi}_{ji}(q^2) + R_{2,i} \left(\hat{\Pi}^{G'_Z G'_Z}(r_1) + \hat{\Pi}^{G'_Z G'_Z}(r_2) \right)$$



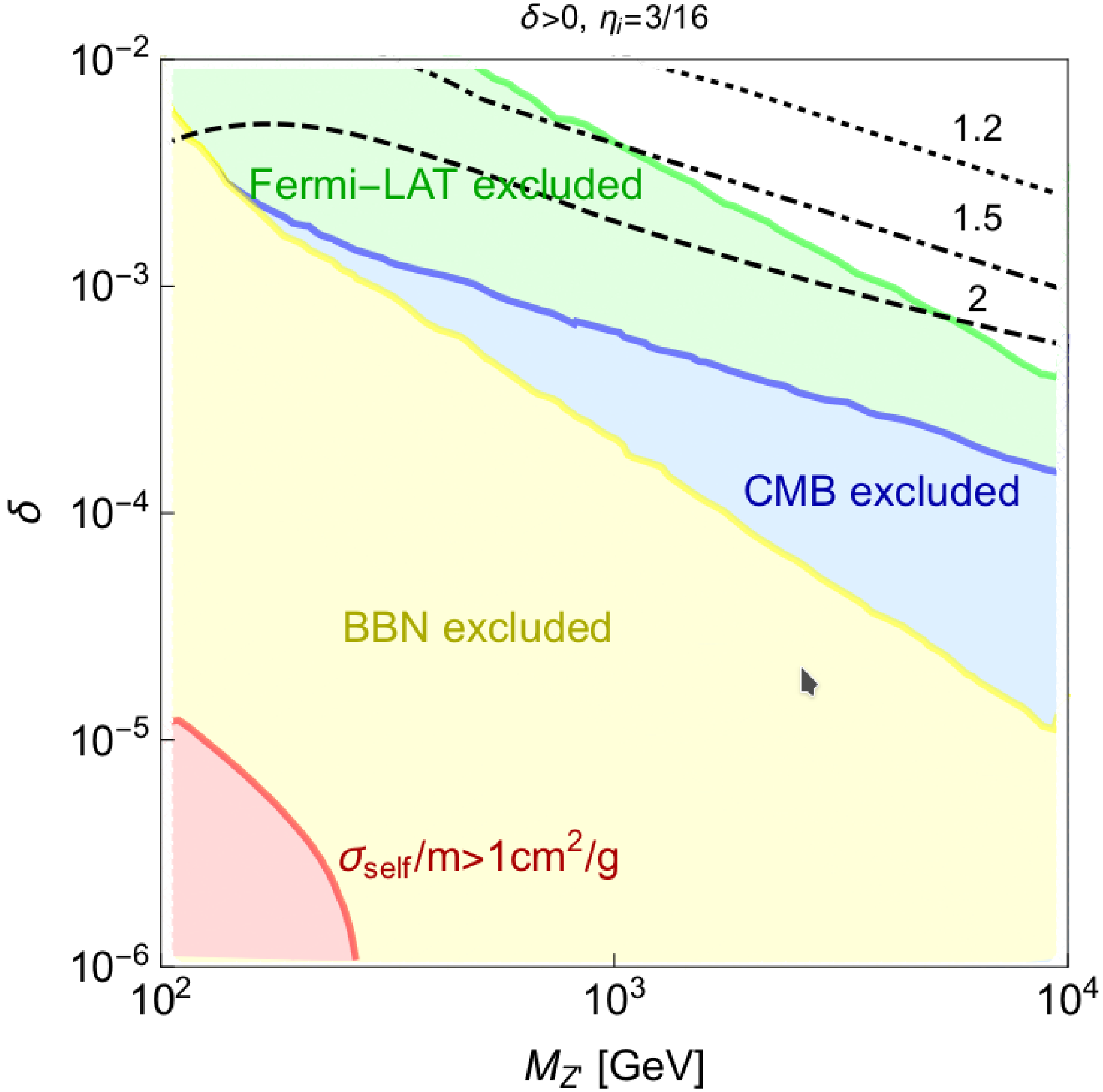
Pinch self-energy

$$\hat{\Pi}_{ij} = \frac{g_x^2 R_{2,i} R_{2,j}}{8\pi^2} \left[\frac{(m_i m_j)^2}{4 M_{Z'}^2} + \frac{m_i^2 + m_j^2}{2} - (2s - 3M_{Z'}^2) \right] B_0(s, M_{Z'}^2, M_{Z'}^2)$$

Condition that guaranties good high-energy behaviour of the process with resummed propagator

$$\lim_{s \to \infty} \frac{r_1^\mu r_2^\nu V_{\mu\nu}^{h_i Z' Z'}(q, r_1, r_2)}{s} = i g_x M_{Z'} \lim_{s \to \infty} \frac{\sum_i R_{2,j} \hat{\Pi}_{ji}(q^2)}{s}.$$

Bounds in the parameter space



- mixing angle set by relic density constraint
- maximal dark gauge coupling satisfying perturbative unitarity
- enhancement of low-velocity cross-section → strong bounds from indirect searches
- effects of early kinetic decoupling modify relic density by up to a factor of 2 in the allowed region

Summary

- resonant annihilation of dark matter has strong temperature dependence and leads to an early kinetic decoupling
- the evolution of dark matter density and temperature can be described with the set of coupled Boltzmann equations
- in vector dark matter models resonant annihilation requires gauge-independent treatment