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Light Dark Matter annihilation in model independent approach.

Based on work done by A.B, Alexey A. Petrov and Gagik. K. Yeghiyan

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Outline

- Motivation
- Generic description of DM->γγ process
- Connection to the observed data
- Model independent description of particle dynamics in DM->γγ and resulting constrains
- Application of this approach to several models as an example

Motivation

- Nature of Dark Matter is still unknown
- WIMP’s?
- DAMA results – WIMPless DM with mass as low as 2 GeV
- Lower bound on DM particle mass can be as low as 1-6keV[1,2]

[1] Faustin Munyaneza arXiv:astro-ph/0702167v1
[2] Alexey Boyarsky *et al* JCAP03(2009)005

Model independent consideration of DM annihilation

$$\mathcal{L} = A_1(m_\phi, s)\phi\phi F^{\mu\nu}F_{\mu\nu} + A_2(m_\phi, s)\phi\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

There are no other contributions because:

- will have operators dimension higher than 6 and they will be suppressed
- Operators involving derivatives vanish for self-conjugated DM

Leads to the following squared amplitude of process

$$|\mathcal{M}(\phi\phi \to \gamma\gamma)|^2 = 2s^2(|A_1|^2 + 2|A_2|^2)$$

$$\sigma = \frac{s^{3/2}(|A_1|^2 + 2|A_2|^2)}{8\pi\sqrt{s - 4\mu^2}}$$

$$s \approx 4\mu^2 + (\vec{p_1} - \vec{p_2})^2 = (2\mu)^2 (1 + \left(\frac{\vec{v_1} - \vec{v_2}}{2}\right)^2)$$

$$\sigma v = \frac{s^{3/2}(|A_1|^2 + 2|A_2|^2)}{8\pi\mu}$$

Considering non-relativistic DM we expand around relative velocity $|\vec{v_1} - \vec{v_2}| = 0$, and average assuming Maxwell-Boltzman distribution of velocities.

$$\sigma v = A + B(\vec{v}_1 - \vec{v}_2)^2 \qquad \langle \sigma v \rangle = A + B\frac{6kT}{\mu}$$

$$A = \mu^2(|A_1(s = 4\mu^2)|^2 + 2|A_2(s = 4\mu^2)|^2)$$

$$B = \mu^2(\tfrac{3}{8}(|A_1(s = 4\mu^2)|^2 + 2|A_2(s = 4\mu^2)|^2) + \\ + \mu^2(2Re[A_1 \tfrac{\partial A_1}{\partial s}(s = 4\mu^2)] + 4Re[A_2 \tfrac{\partial A_2}{\partial s}(s = 4\mu^2)]))$$

We assume DM to be relatively cold $\approx 10000K$[1]

[1] J. T. Kleyna et al arXiv:astro-ph/0507154v2

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Photon flux from DM annihilation

$$I(E,\psi) = \frac{dN_\gamma}{dE}\frac{\langle\sigma v\rangle}{2\mu^2}J(\psi) \qquad \mathrm{J}(\psi) = \int_{l.o.s} ds\,\frac{\rho^2[r(s,\psi)]}{4\pi}$$

There are various profile models for $r(s,\psi)$ as well as different approximations of $J(\psi)$. Results can vary depending on profile and on additional effects taken into account. It was argued in [1] that maximum flux will be in the direction of galactic center. And $J(0)$ can be considered instead.In our calculations we use the Navarro-Frenk-White profile which gives us a following result

$$I(E,\psi) = 7.3\times10^{-5}\frac{dN_\gamma}{dE}\frac{\sigma v}{2\mu^2}cm^{-1}s^{-1}sr^{-1}GeV^{-1}$$

In this result dependence on particle physics dynamics is separated from the structure of halo. To proceed further we need to introduce mechanism of DM annihilation

[1] Lars Bergstrom, Piero Ulio and James H. Buckley Astropart.Phys. 9 (1998) 137-162

Generic interaction of DM with SM fields

To proceed further we need to specify dependence of A_i on s. The most general way to do it is by introduction of generic lagrangian describing Interaction of DM with ordinary matter. The most simple one is as follows:

$$\mathcal{L} = \frac{2}{\Lambda^2} \sum_i C_i \hat{O}_i$$

$$O_1 = m_\psi \phi^* \phi \bar{\psi} \psi$$

$$O_2 = \imath m_\psi \phi^* \phi \bar{\psi} \gamma_5 \psi$$

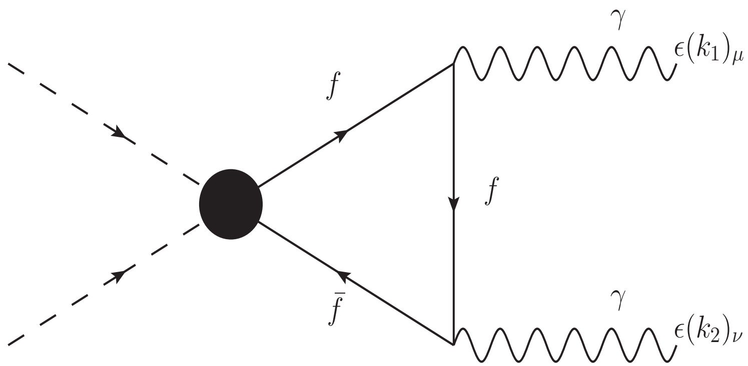
$$O_3 = \phi^* (\overleftarrow{\partial} - \overrightarrow{\partial}) \phi \bar{\psi} \gamma_\mu \psi$$

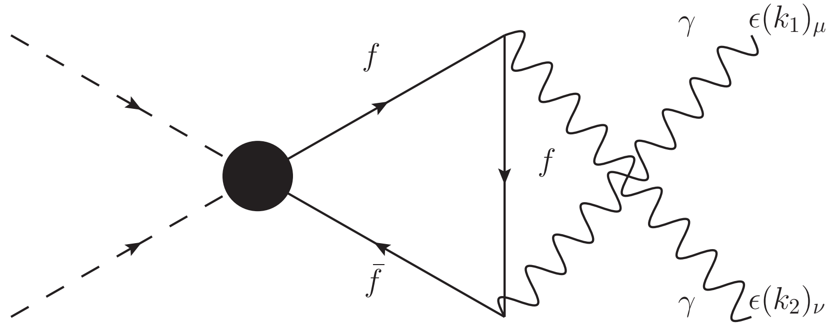
$$O_4 = \phi^* (\overleftarrow{\partial} - \overrightarrow{\partial}) \phi \bar{\psi} \gamma_\mu \gamma_5 \psi$$

Give 0 for self conjugated DM (O_3, O_4)

Sum over all fermions (quarks, leptons) is assumed (O_1–O_4)

Possible operators describing interaction of DM with gauge bosons are not considered here. Their contribution will be negligable due to large mass of bosons in the loop





$$A_1 = \frac{8C_1 m_f^2 \pi^2 Q_f^2}{s}((4m^2 - s)C_0(0,0,s,m^2,m^2,m^2) + 2)$$

$$A_2 = -8\imath C_2 m_f^2 \pi^2 Q_f^2 C_0(0,0,s,m^2,m^2,m^2)$$

$$C_0(p_1^2,(p_1-p_2)^2,p_2^2,m_1^2,m_2^2,m_3^2) = \int \frac{d^4q}{\imath\pi^2}\frac{1}{(q^2-m_1^2)((q+p_1)^2-m_2^2)((q+p_2)^2-m_3^2)}$$

When transferred energy is about $4m_f^2$ it can result in some resonance states which are not considered here

These results reproduce result of A.I.Vainstein et al in Sov.J.Nucl. Phys. 30(5)Nov.1979

EGRET results can be parametrized as follows [1]

$$I = I_{gal} + I_{ex}$$

$$I_{ex} = (7.32 \pm 0.34) \times 10^{-6} \left(\frac{E}{0.451 GeV}\right)^{-2.10\pm0.03} cm^{-2} s^{-2} sr^{-2} GeV^{-1}$$

$$I_{gal} = N_0(l,b) \times 10^{-6} \left(\frac{E}{GeV}\right)^{-2.7} cm^{-2} s^{-1} sr^{-1} GeV^{-1}$$

$$-180 \leq l \leq 180 \text{ and } -90 \leq b \leq 90$$

$$N_0(l,b) \begin{cases} = 0.5 + \frac{85.5}{\sqrt{1+(l/35)^2}\sqrt{1+[b/(1.1+0.022|l|)]^2}} & |l| \geq 30 \\ = 0.5 + \frac{85.5}{\sqrt{1+(l/35)^2}\sqrt{1+(b/1.8)^2}} & |l| \leq 30 \end{cases}$$

Parametrization for galactic flux is calibrated around GeV while intesity of extra-galctic one is valid from $E \sim 10 MeV$ to $E \sim 100 GeV$

Since NO single peaks observed, they must have intesity lower than I and this gives us perfect chance to limit parameter space for Wilson coefficients C_i

We compare experimental results with our estimates for flux from galactic center and thus we use values of I at $l, b = 0$

[1] M. Kachelrieß and P.D. Serpico arXiv:0707.0209v2

Model independent analysis

$$\frac{I_{theory}}{UpperBound(I_{ex}+I_{gal})} \leq 1$$

$$E_\gamma = \mu_{DM}$$

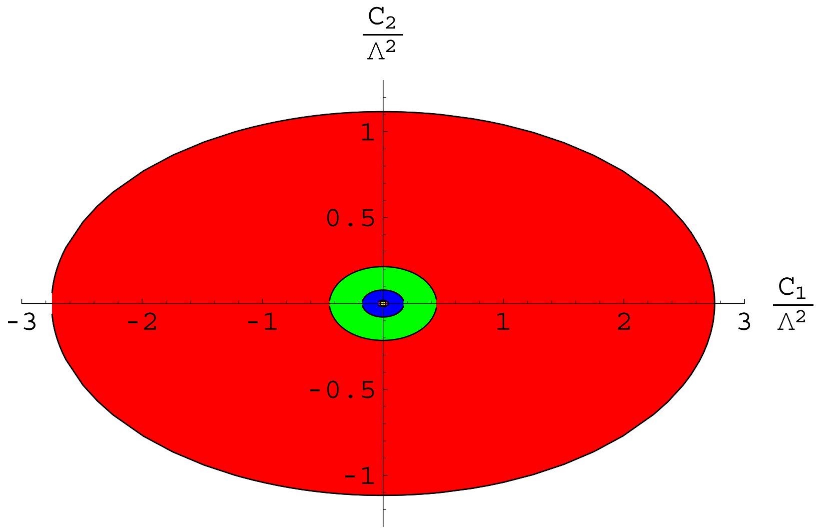
$$\mu = 0.1GeV \qquad 0.132\left(\frac{C_1}{\Lambda^2}\right)^2 + 0.802\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

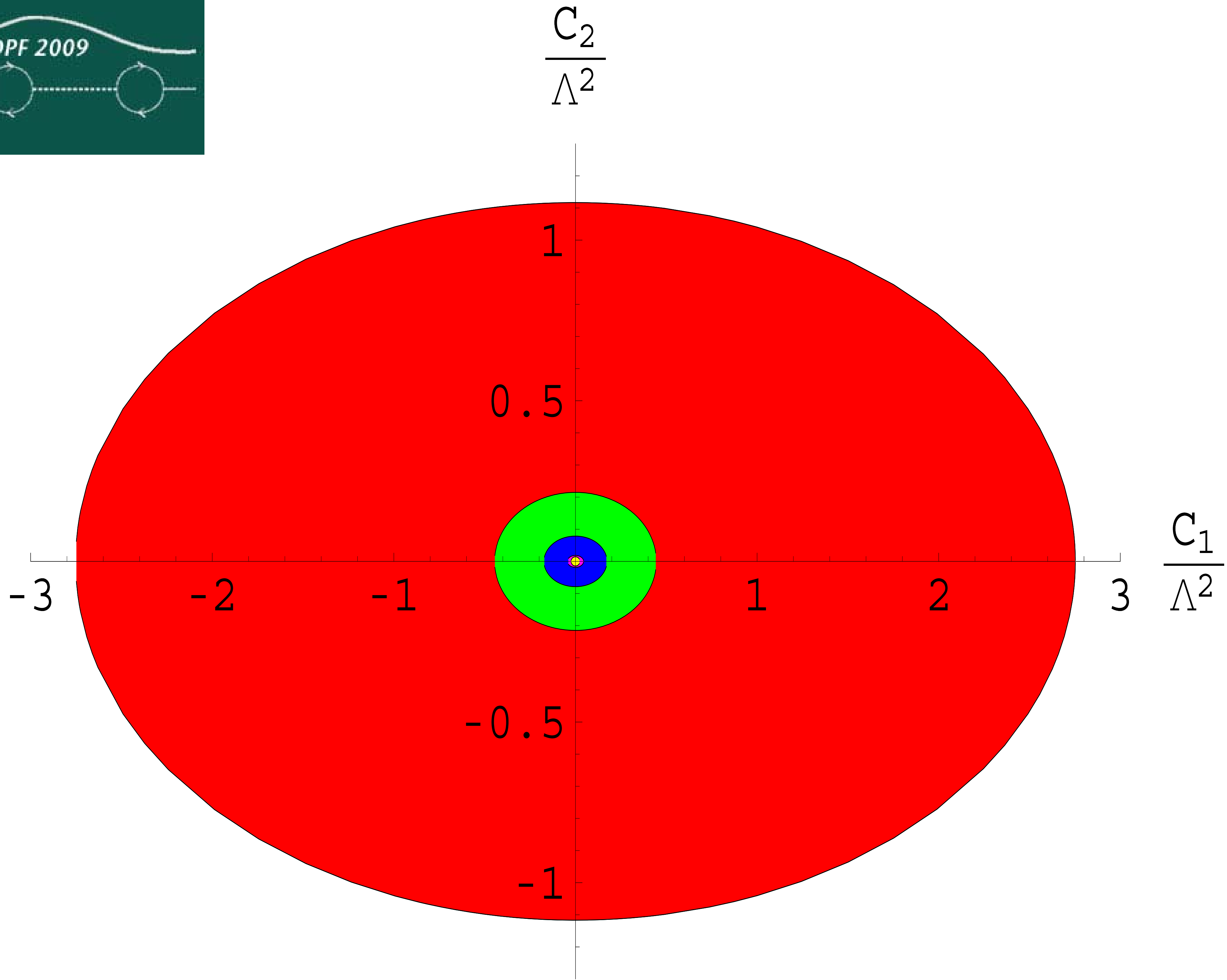
$$\mu = 0.5GeV \qquad 5.041\left(\frac{C_1}{\Lambda^2}\right)^2 + 21.67\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

$$\mu = 1GeV \qquad 33.18\left(\frac{C_1}{\Lambda^2}\right)^2 + 161.8\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

$$\mu = 2GeV \qquad 489.3\left(\frac{C_1}{\Lambda^2}\right)^2 + 2931\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

$$\mu = 5GeV \qquad 1600\left(\frac{C_1}{\Lambda^2}\right)^2 + 4843\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$





C2/Λ2
1
0.5
-0.5
-1
C1/Λ2
-3
-2
-1
1
2
3

Example model

The simplest possible DM model involves scalar DM interacting with SM fields via Higgs exchange. This model is very restricted based on relic abundance calculations however it is the simplest possible DM model and is perfect for testing of our approach

$$C_1 = -\frac{\lambda}{2},\ C_2 = 0,\ \Lambda = M_h \text{ with } M_h \geq 115 GeV$$

$$\mu = 0.1 GeV \qquad \|\lambda\| \leq 7.284 \times 10^4 \left(\frac{M_h}{115}\right)^2$$

$$\mu = 0.5 GeV \qquad \|\lambda\| \leq 1.178 \times 10^4 \left(\frac{M_h}{115}\right)^2$$

$$\mu = 1 GeV \qquad \|\lambda\| \leq 4.592 \times 10^3 \left(\frac{M_h}{115}\right)^2$$

$$\mu = 2 GeV \qquad \|\lambda\| \leq 1.196 \times 10^3 \left(\frac{M_h}{115}\right)^2$$

$$\mu = 5 GeV \qquad \|\lambda\| \leq 6.613 \times 10^2 \left(\frac{M_h}{115}\right)^2$$

Not very restrictive and helpful ☹

Corrections due to motion of DM particles

In the real case energy spectrum of photons will be smeared due to relative motion of DM particles, motion of detector with Earth etc. So instead of δ-function spectrum will be described by the peak of finite width and finite height. This way having good resolution of detector we might be able to detect this peak.

Assumptions

δ-function $\longrightarrow$ Gaussian distribution around $E = \mu$ with σ of energy spread.

Non-relativistic DM + Non-relativisitc orbital motion $\longrightarrow$ $E \approx \mu(1 \pm v/c) \quad v = v_{DM} + v_{orbit}$

$v_{DM} = 9km/s$ [1] $\quad v_{orbit} = 30km/s$

[1] J. T. Kleyna et al arXiv:astro-ph/0507154v2

Model independent analysis

$$\frac{I^{Mod}_{theory}}{UpperBound(I_{ex}+I_{gal})} \leq 1$$

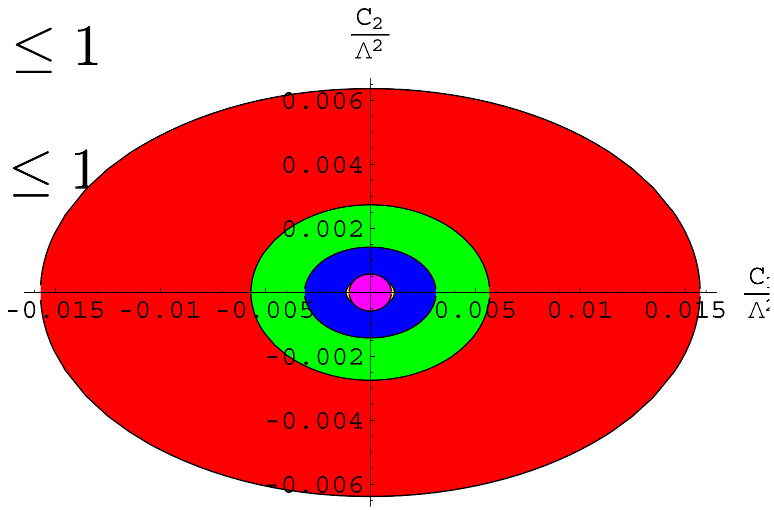
$$\mu = 0.1GeV \qquad 4051\left(\frac{C_1}{\Lambda^2}\right)^2 + 24612\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

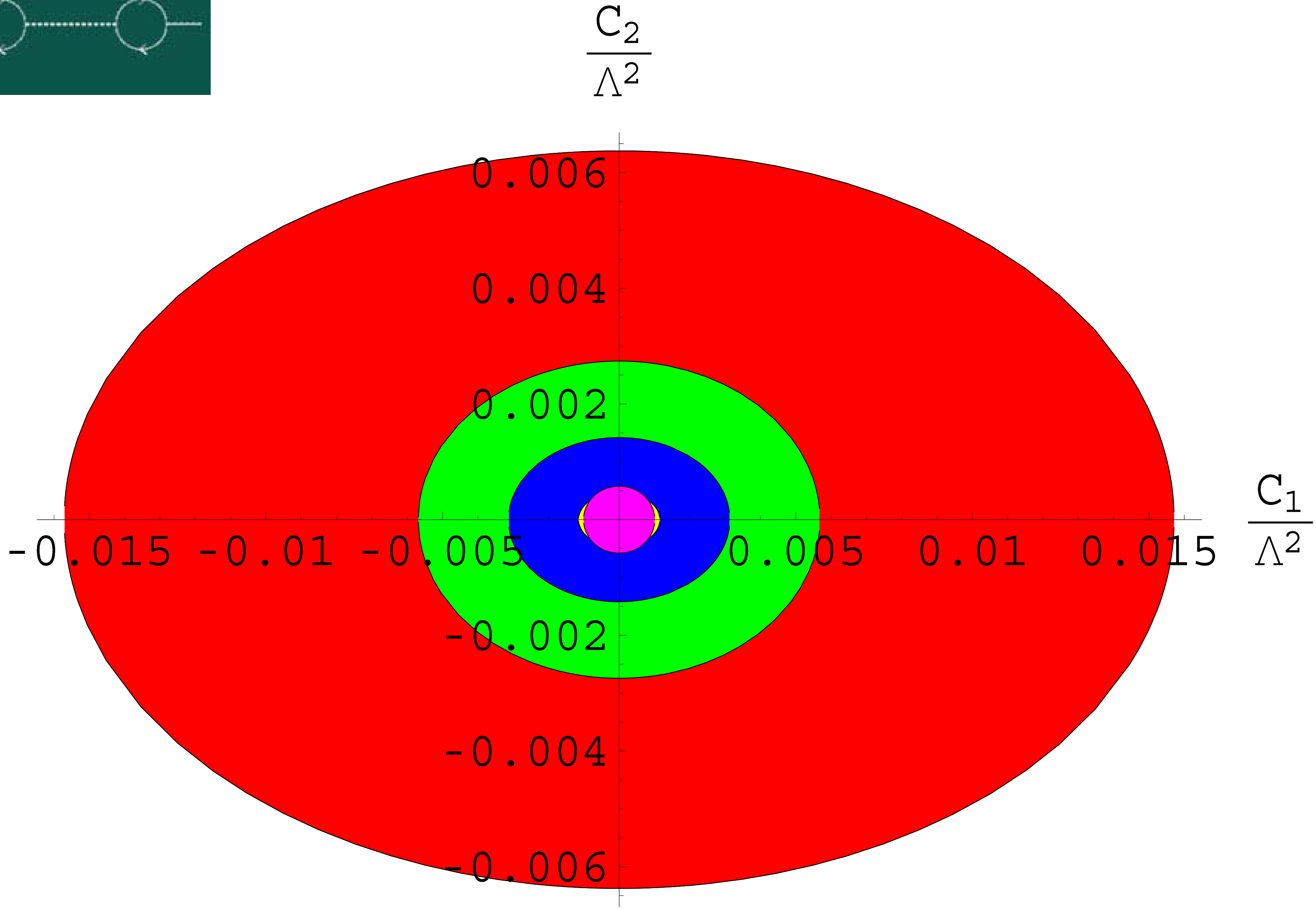
$$\mu = 0.5GeV \qquad 30940\left(\frac{C_1}{\Lambda^2}\right)^2 + 133001\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

$$\mu = 1GeV \qquad 101822\left(\frac{C_1}{\Lambda^2}\right)^2 + 496530\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

$$\mu = 2GeV \qquad 750779\left(\frac{C_1}{\Lambda^2}\right)^2 + 4.497 \times 10^6\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$

$$\mu = 5GeV \qquad 982012\left(\frac{C_1}{\Lambda^2}\right)^2 + 2.972 \times 10^6\left(\frac{C_2}{\Lambda^2}\right)^2 \leq 1$$





$\frac{C_2}{\Lambda^2}$
0.006
0.004
0.002
-0.002
-0.004
-0.006
$\frac{C_1}{\Lambda^2}$
-0.015
-0.01
-0.005
0.005
0.01
0.015

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Back to example model

$$C_1 = -\frac{\lambda}{2},\ C_2 = 0,\ \Lambda = M_h \text{ with } M_h \geq 115GeV$$

$$\mu = 0.1GeV \qquad \|\lambda\| \leq 416\left(\frac{M_h}{115}\right)^2$$

$$\mu = 0.5GeV \qquad \|\lambda\| \leq 150\left(\frac{M_h}{115}\right)^2$$

$$\mu = 1GeV \qquad \|\lambda\| \leq 82.9\left(\frac{M_h}{115}\right)^2$$

$$\mu = 2GeV \qquad \|\lambda\| \leq 30.5\left(\frac{M_h}{115}\right)^2$$

$$\mu = 5GeV \qquad \|\lambda\| \leq 26.7\left(\frac{M_h}{115}\right)^2$$

Better, but still not very restrictive ☹

Conclusions

- Annihilation of Dark Matter particles into pair of photon considered in the model independent way
- Model independent prediction for photon flux from halo derived and compared to the experimental data
- Model-independent constraints on parameters of DM derived and applied to the Minimal Dark Matter model as an example
- Resulting constrains on parameters of the model appear to be very weak and non-restrictive.
- For reasonable values of parameters of considered model, results appear to be at least order of magnitude less than current experimental bounds
- Models with enhancement factors (2HDM for example) will be more restricted