Closing in on mass degenerate dark matter scenarios

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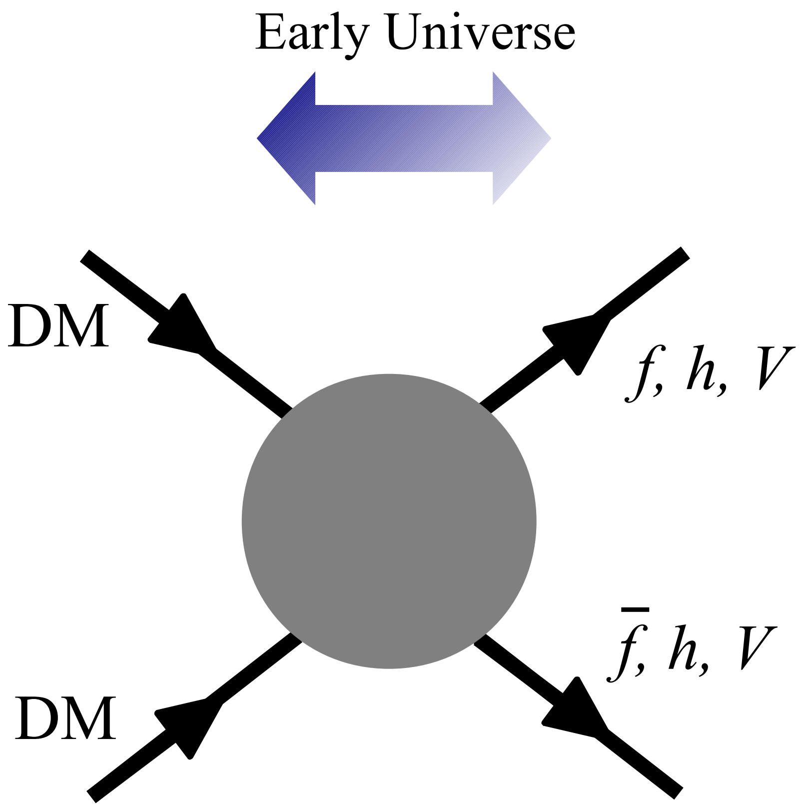
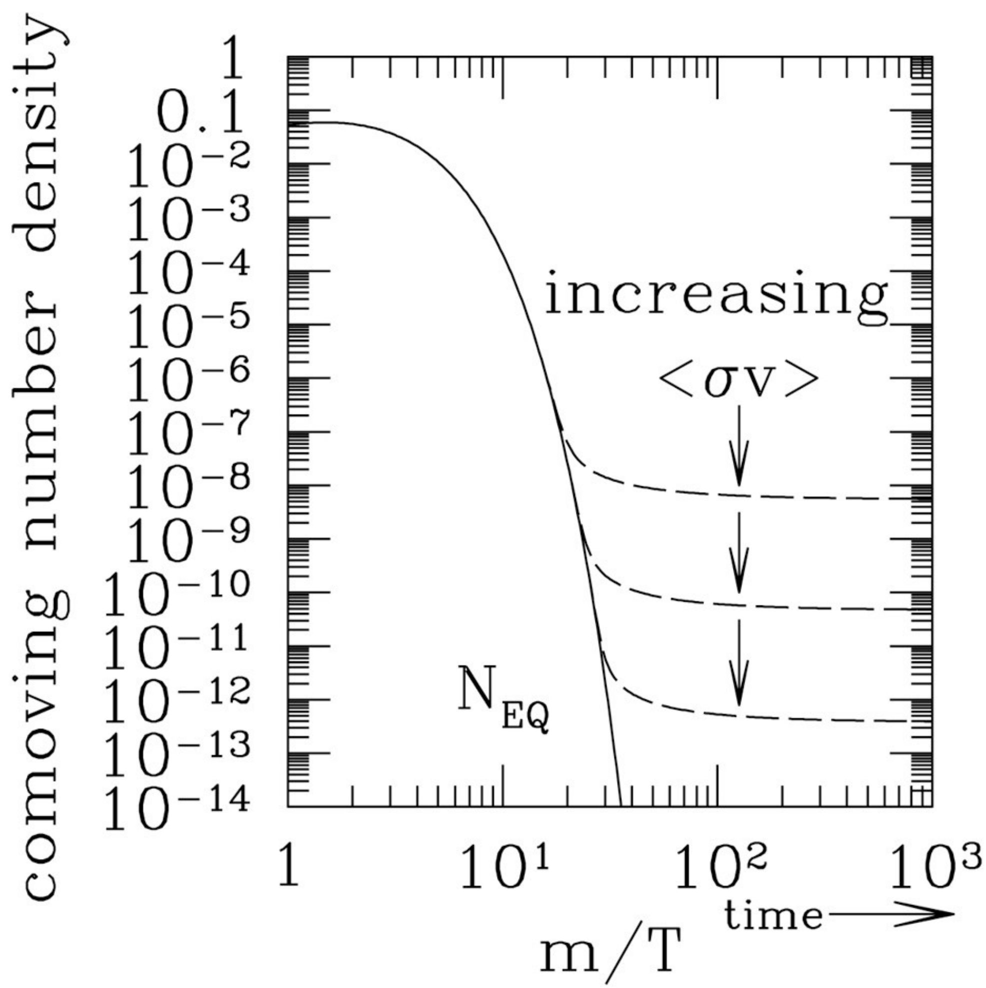
Based on M. Garny, AI, S. Vogl, JCAP **1107** (2011) 028
M. Garny, AI, S. Vogl, JCAP **1204** (2012) 033
T. Bringmann, X. Huang, AI, S. Vogl, C, Weniger, JCAP **1207** (2012) 054
M. Garny, AI, M. Pato, S. Vogl, JCAP **1211** (2012) 017

Portoroz
17 March 2013

Dark matter annihilations: standard picture

Thermal production of WIMPs

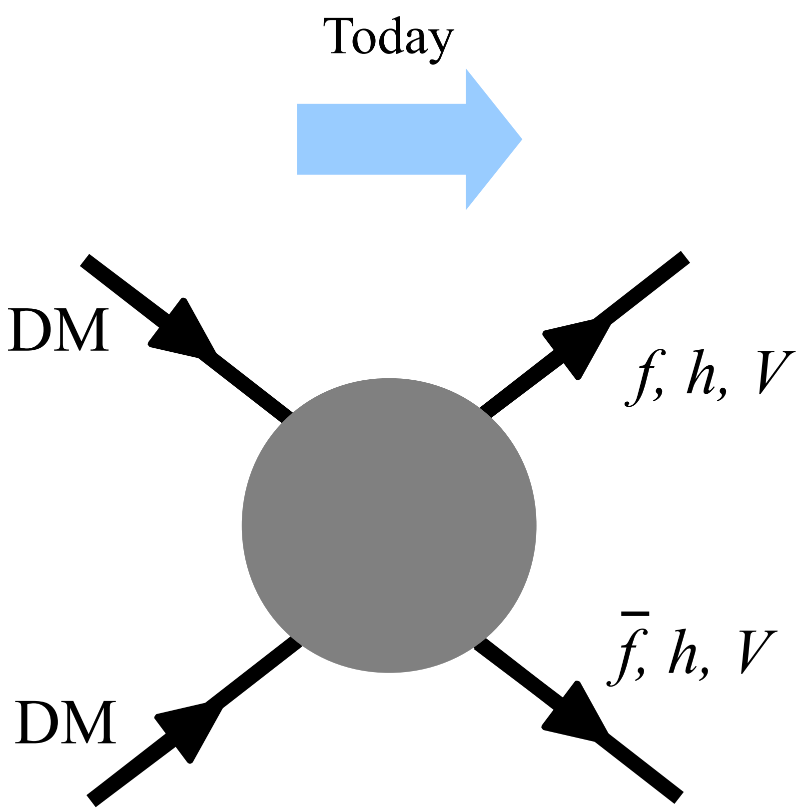




$$\Omega_{\rm DM}h^2 \simeq 0.11 \times \frac{3 \times 10^{-26}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

Dark matter annihilations: standard picture

Annihilations in galactic dark matter haloes



Canonical value of the velocity weighted annihilation cross-section

$$\langle \sigma_{\rm ann} v \rangle \simeq 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Target value for experiments

However, here it has been implicitly assumed that the velocity weighted annihilation cross section does not depend on the velocity.

Decompose the annihilation cross section as:

$$\langle \sigma v \rangle = a + b v^2$$

$a,b \longrightarrow$ calculable in a given DM model
$v \longrightarrow$ depends on the astrophysical conditions

Freeze-out $\langle v^2 \rangle \sim \frac{6 T_{\rm f.o.}}{m_{\rm DM}} \sim 0.3$ $\leftarrow$ $T_{\rm f.o.} \sim \frac{m_{\rm DM}}{20}$

Galactic center $v \sim 10^{-3}$

$a \gg b v^2 \Longrightarrow \frac{\langle \sigma v \rangle_{\rm G.C.}}{\langle \sigma v \rangle_{\rm f.o.}} \sim 1$

$a \ll b v^2 \Longrightarrow \frac{\langle \sigma v \rangle_{\rm G.C.}}{\langle \sigma v \rangle_{\rm f.o.}} \sim 3 \times 10^{-6}$

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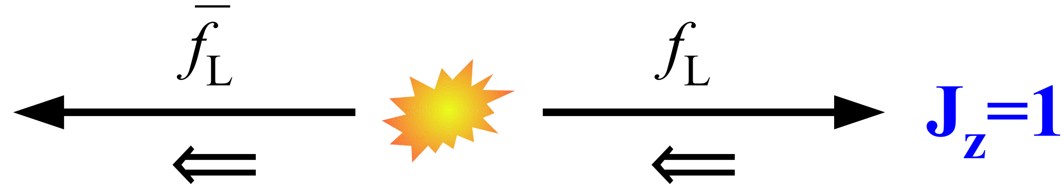
??? $a \ll bv^2$ ➡ $\frac{\langle \sigma v \rangle_{\rm G.C.}}{\langle \sigma v \rangle_{\rm f.o.}} \sim 3 \times 10^{-6}$

• Consider the annihilation DM DM $\to f\bar{f}$, with DM a Majorana fermion or a scalar particle



In the limit $v \to 0$,
no preferred direction

J_z=0

- Consider the annihilation DM DM $\rightarrow f\bar{f}$, with DM a Majorana fermion or a scalar particle

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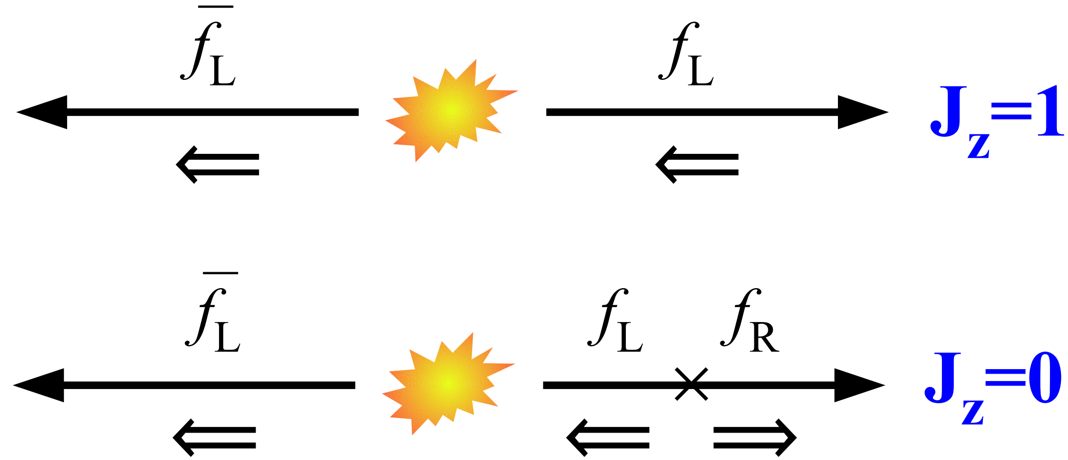

Rate of DM DM $\rightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

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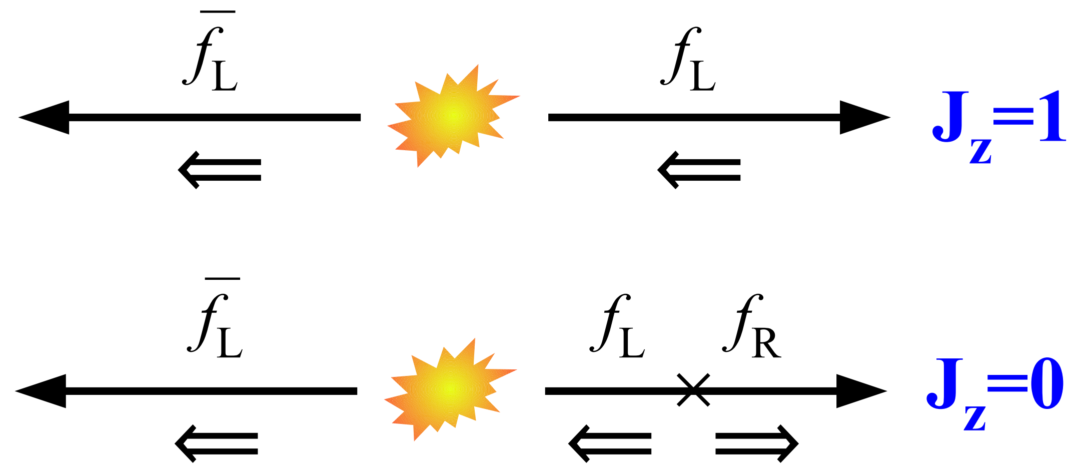


Rate of DM DM $\rightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

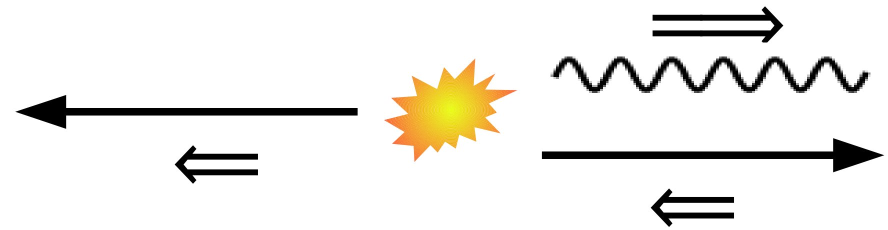
• Relative contributions to the velocity weighted annihilation cross section $\langle \sigma v \rangle = a + b v^2$ for annihilations into light fermions:

For m=300 GeV, $$\frac{a}{bv^2} \sim \frac{m_f^2}{m_{\rm DM}^2 v^2} \sim \begin{cases} 10^{-6} & \text{for electrons} \\ 0.1 & \text{for muons} \\ 10^{-5} & \text{for up-type quarks} \end{cases}$$

$$\Rightarrow \langle \sigma v \rangle_{\rm G.C.} \sim 3 \times 10^{-6} \langle \sigma v \rangle_{\rm f.o.} \sim 10^{-31}\, {\rm cm^3 s^{-1}}$$

Indirect detection hopeless?? Not really... higher order effects become important.

• Consider the annihilation DM DM $\rightarrow f\bar{f}V$, with DM a Majorana fermion or a scalar particle and V a vector



In the limit $v \rightarrow 0$,
no preferred direction

J_z=0

J_z=0

No suppression by mass insertion. Suppressed, however, by the extra coupling constant and by the 3-body phase space (and by the mass of the mediator of the interaction).

Bergström
Flores, Olive, Rudaz

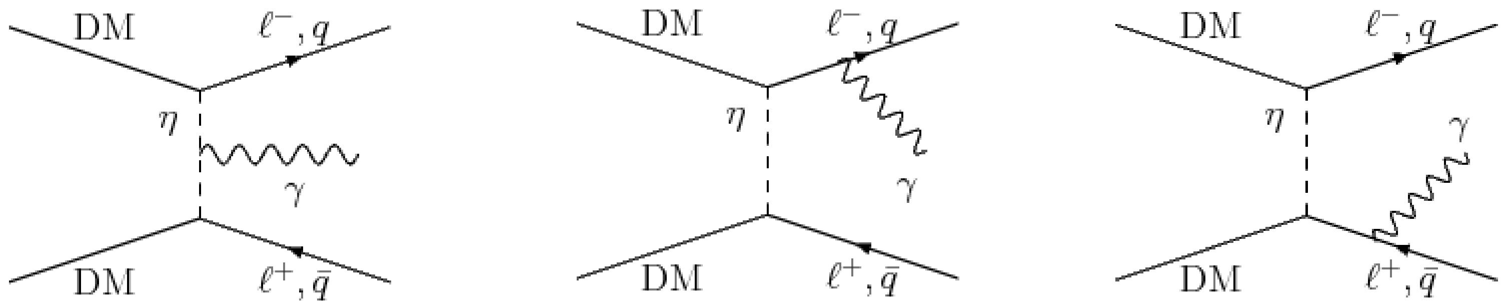
In the mass degenerate scenario, the dominant annihilation channel *today* can be DM DM $\rightarrow f\bar{f}V$, while at the time of freeze-out, DM DM $\rightarrow f\bar{f}$

$$\langle\sigma v\rangle^{2\rightarrow 3}_{G.C.} \sim \frac{\alpha}{0.3\pi}\langle\sigma v\rangle^{2\rightarrow 2}_{f.o.} \sim 10^{-28}\mathrm{cm}^3\mathrm{s}^{-1}$$

Target cross section for this class of scenarios, instead of $3\times10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$.

Outline

1- Search for signatures of DM DM $\rightarrow f\bar{f}\gamma$ with the Fermi-LAT



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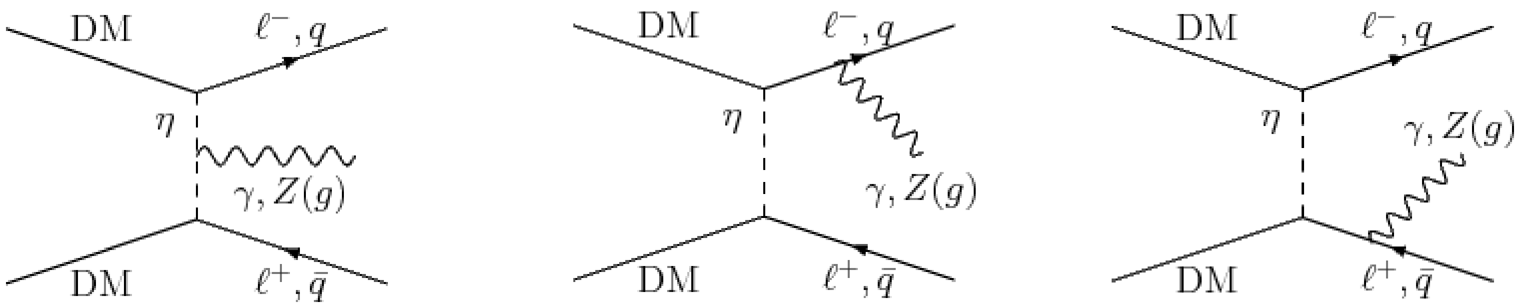
1- Search for signatures of DM DM $\rightarrow f\bar{f}\gamma$ with the Fermi-LAT

2- Antiproton limits on 2 $\rightarrow$ 3 processes



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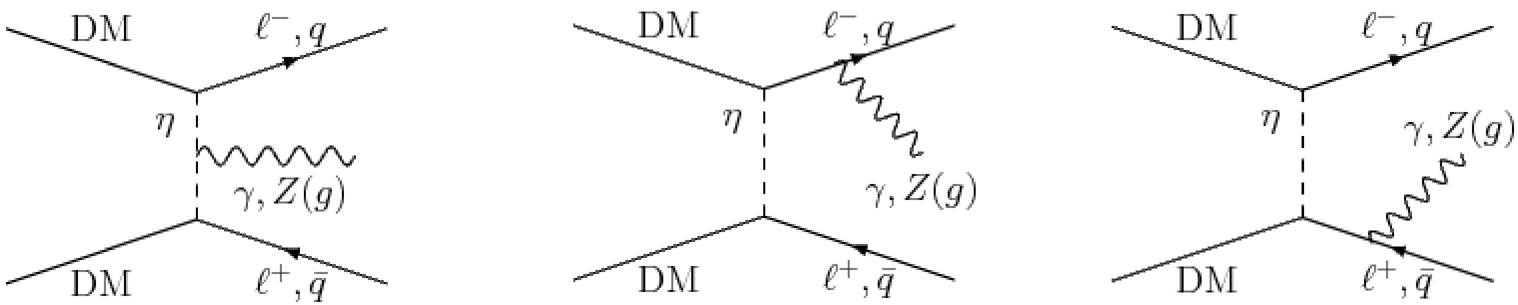

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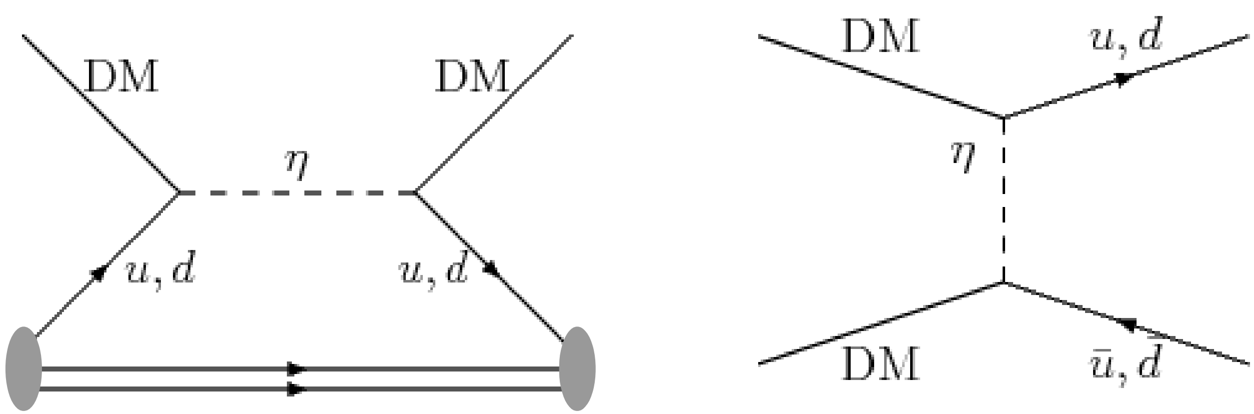

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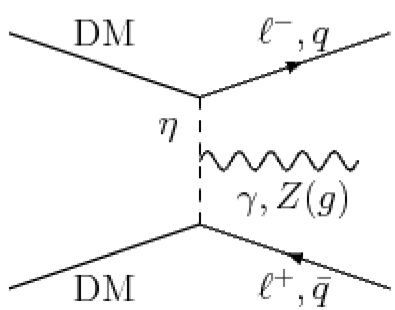

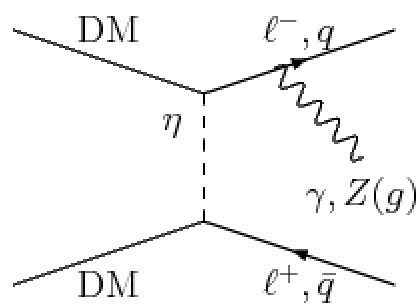

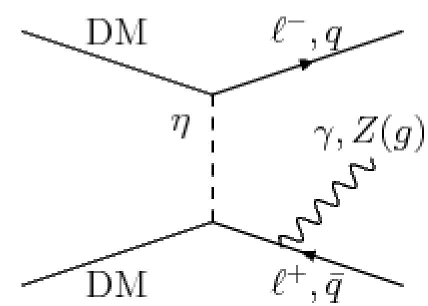

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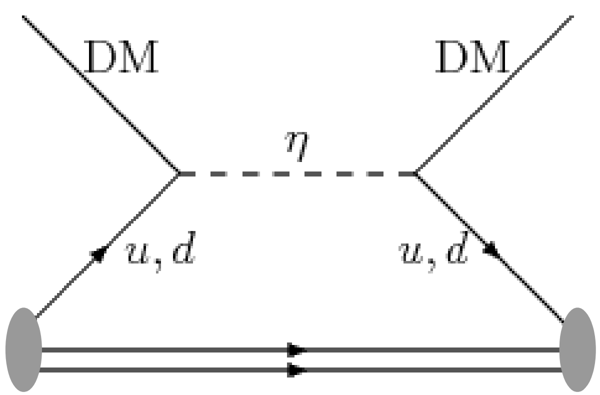
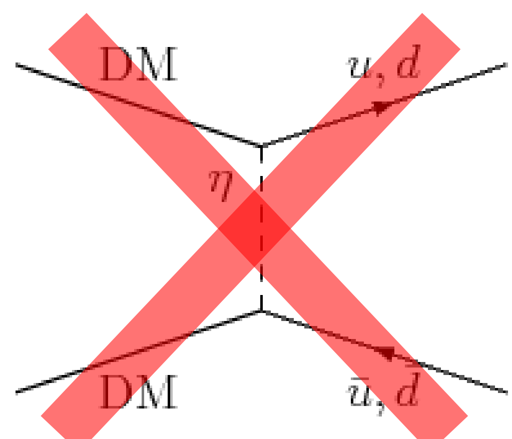
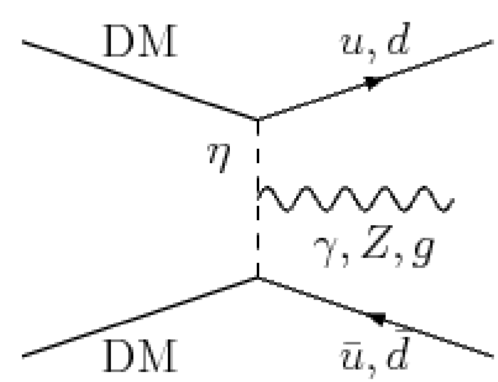




Very suppressed!

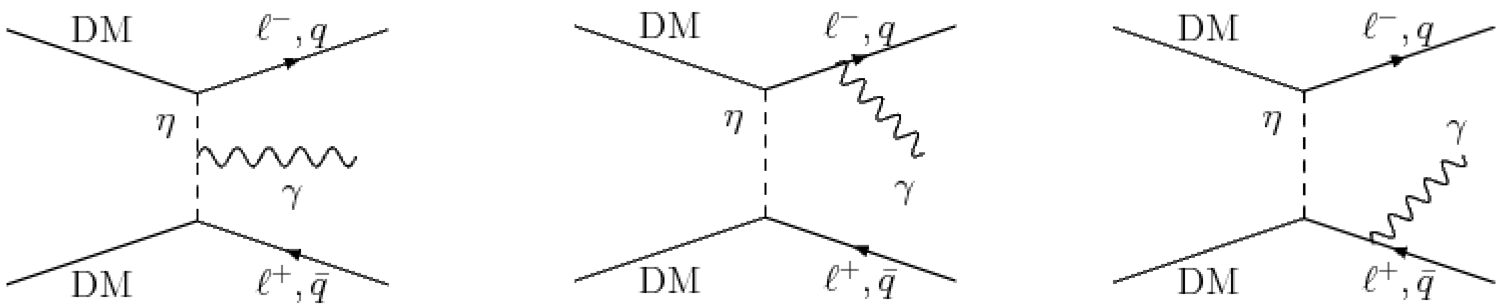
$\langle \sigma v \rangle \propto (m_{u,d}/m_{\rm DM})^2$



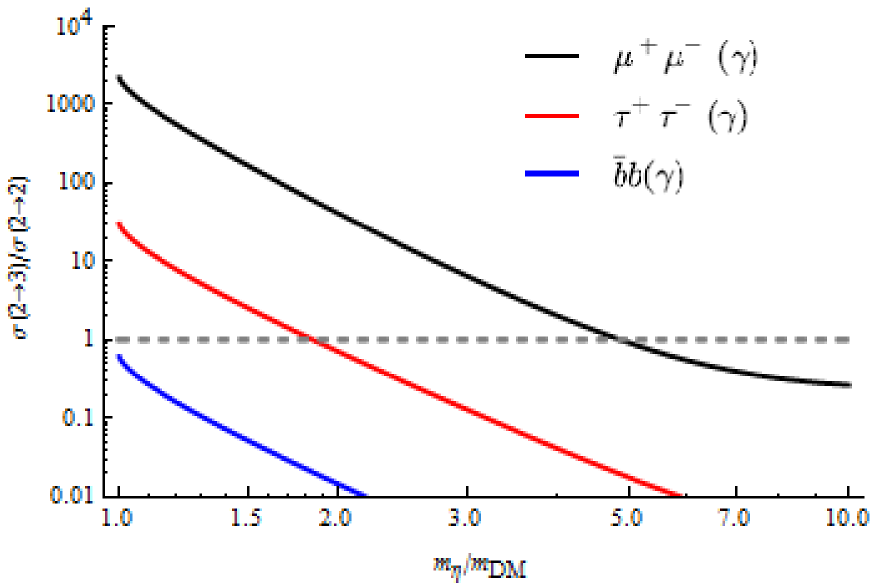
1- Search for signatures of internal Bremsstrahlung with the Fermi-LAT

Consider a toy model with a Majorana dark matter particle, χ, an intermediate scalar particle η, and a right-handed SM fermion $\Psi = \mu,\ \tau,\ b$.

Interaction Lagrangian: $\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + {\rm h.c.}$

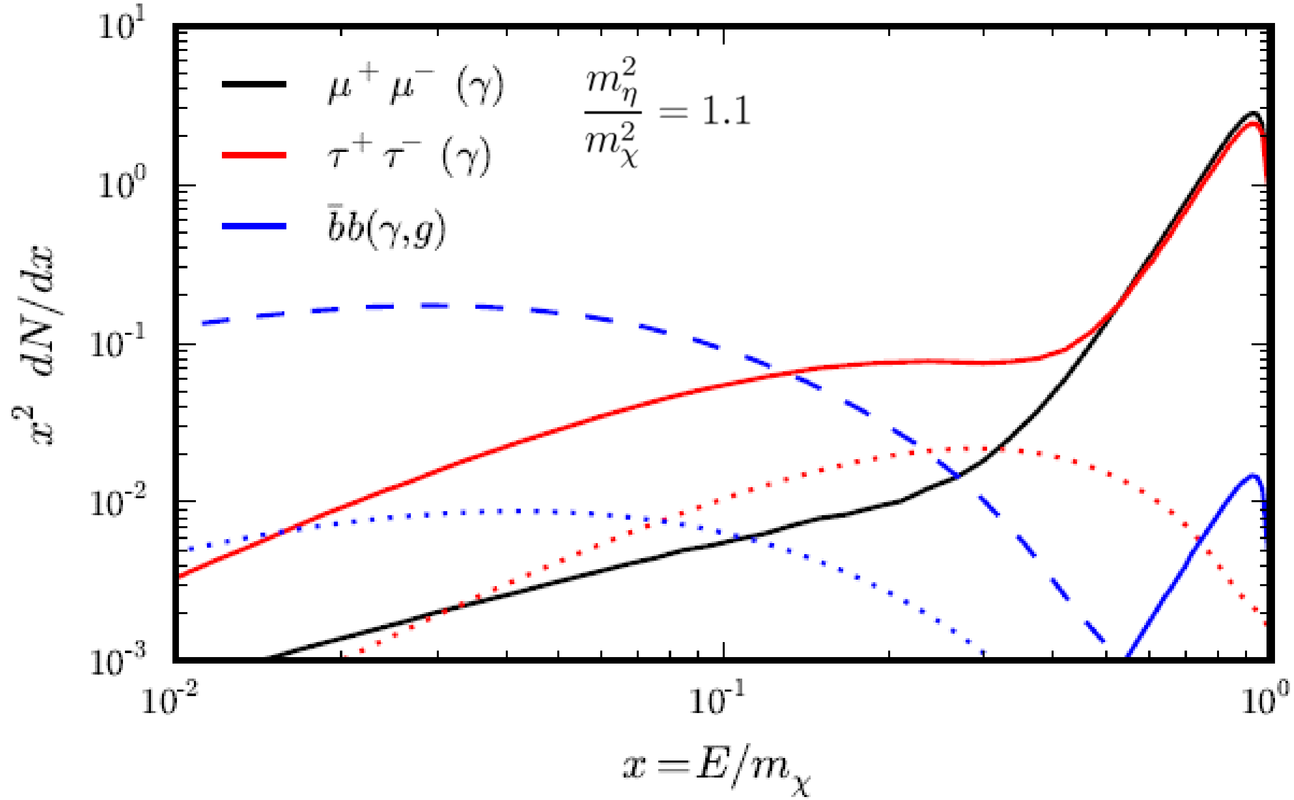


The cross section of the $2 \rightarrow 3$ process is enhanced as $m_\eta/m_{DM} \rightarrow 1$.



1- Search for signatures of internal Bremsstrahlung with the Fermi-LAT

Bonus: if η is sufficiently degenerate in mass with the dark matter particle, the gamma-ray spectrum displays a characteristic feature

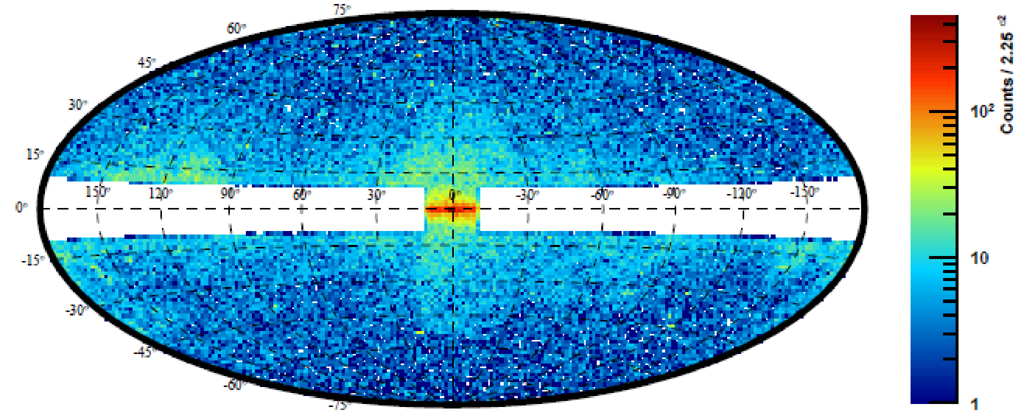


Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

1- Search for signatures of internal Bremsstrahlung with the Fermi-LAT

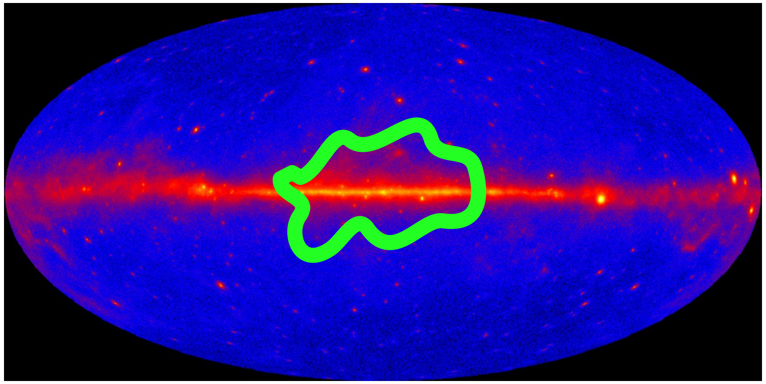
Traditional approach: select a fixed region of the sky and search for features.

e.g region |b|>10° plus a 20°×20° square centered at the Galactic Center (Fermi coll.)



Disadvantage: in the chosen region the background could be too large and bury the signal

Our approach: choose regions where, for a given dark matter profile, the signal-to-background ratio is maximized

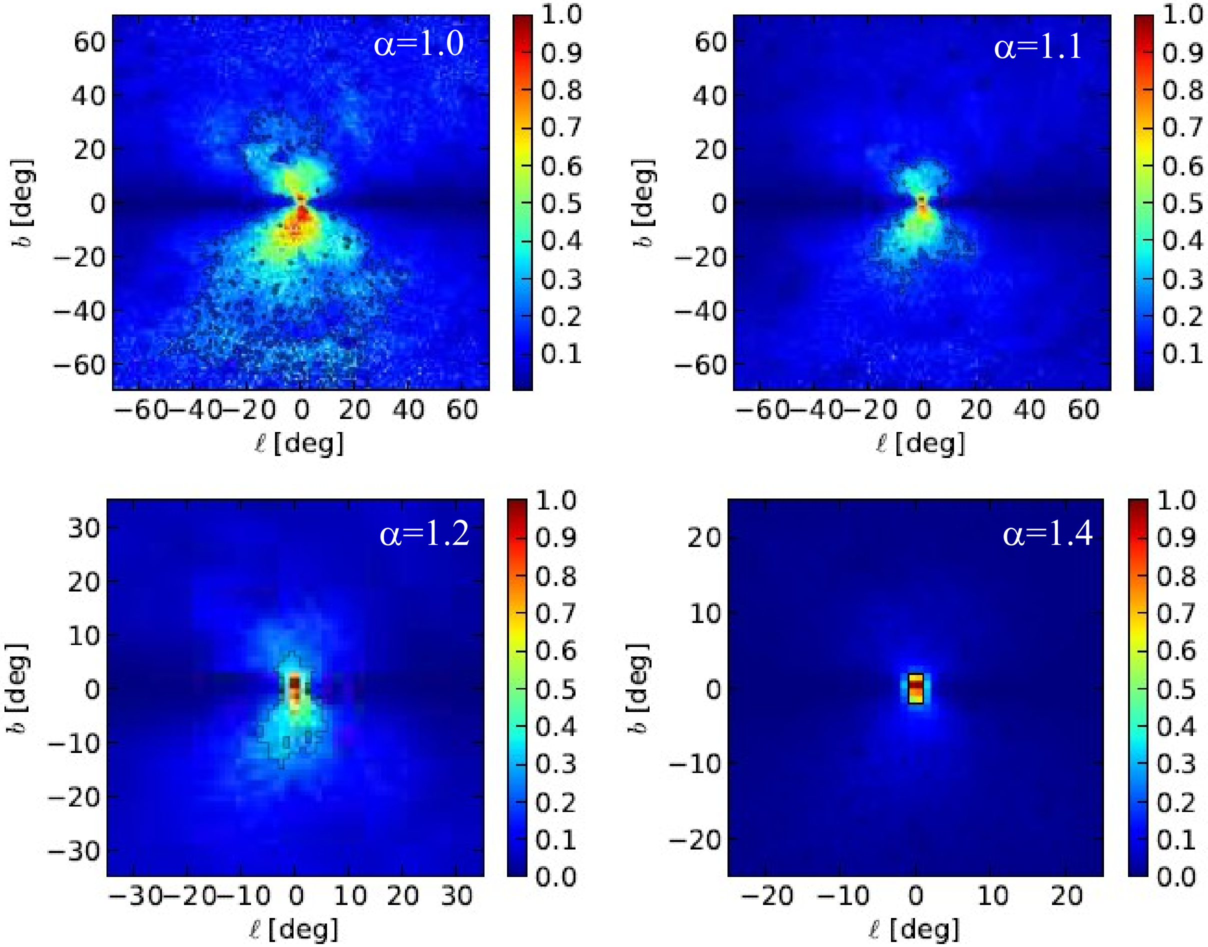


1- Search for signatures of internal Bremsstrahlung with the Fermi-LAT

Consider a generalized NFW profile

$$\rho_\chi(r) \propto \frac{1}{(r/r_s)^\alpha \,(1+r/r_s)^{3-\alpha}}$$

Target regions which maximize the signal-to-background ratio:



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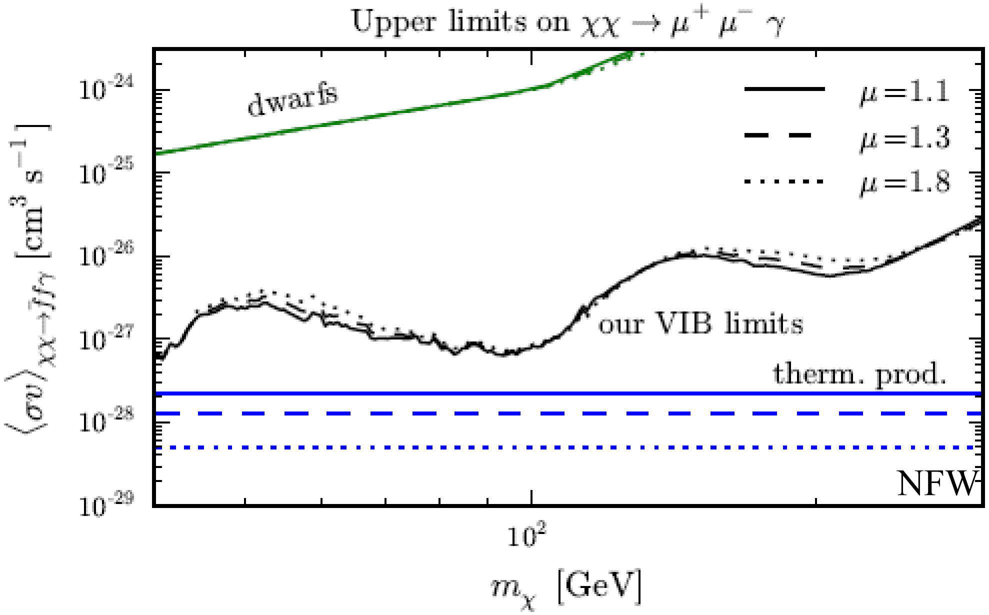

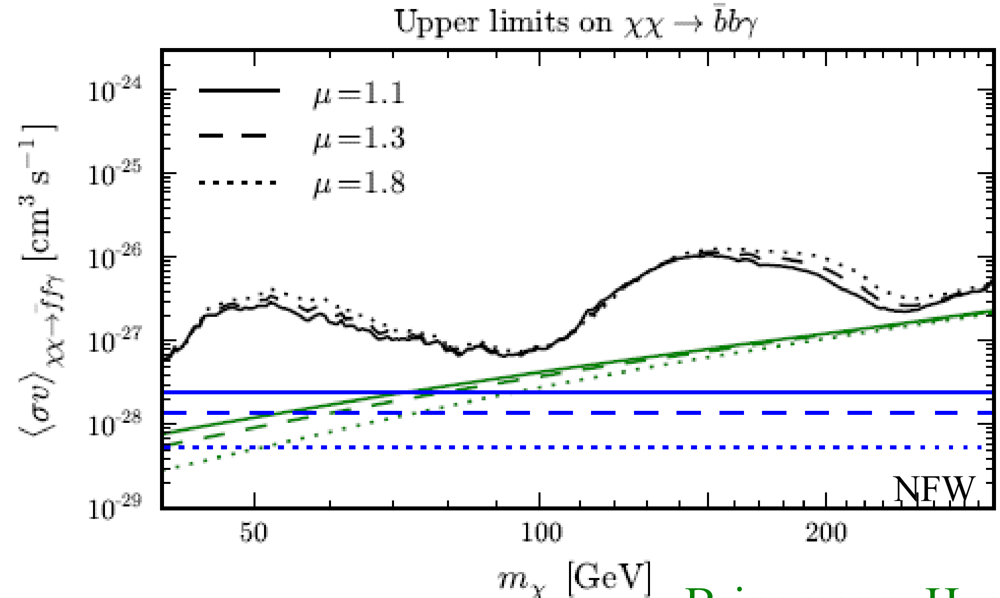

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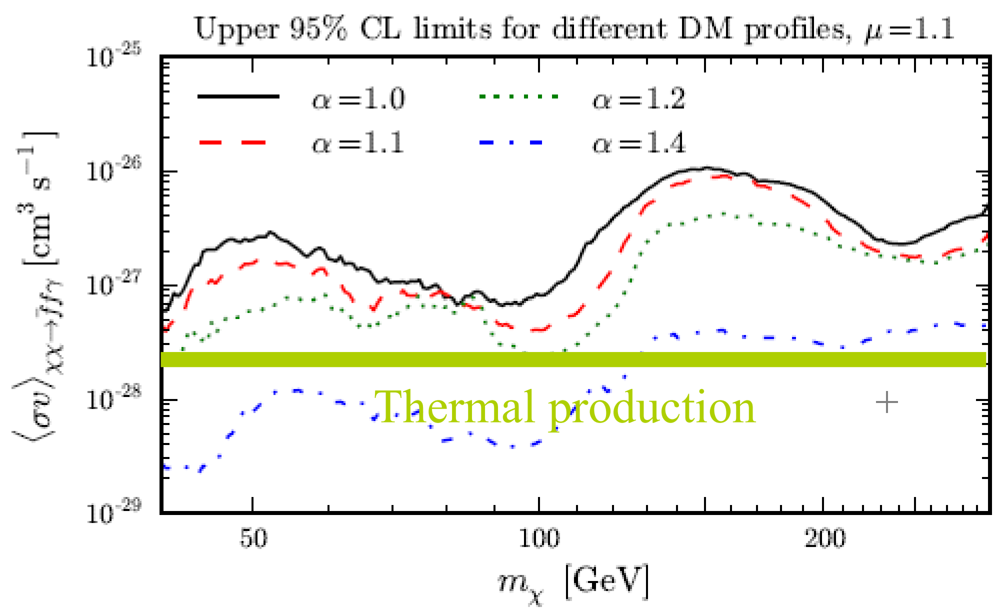
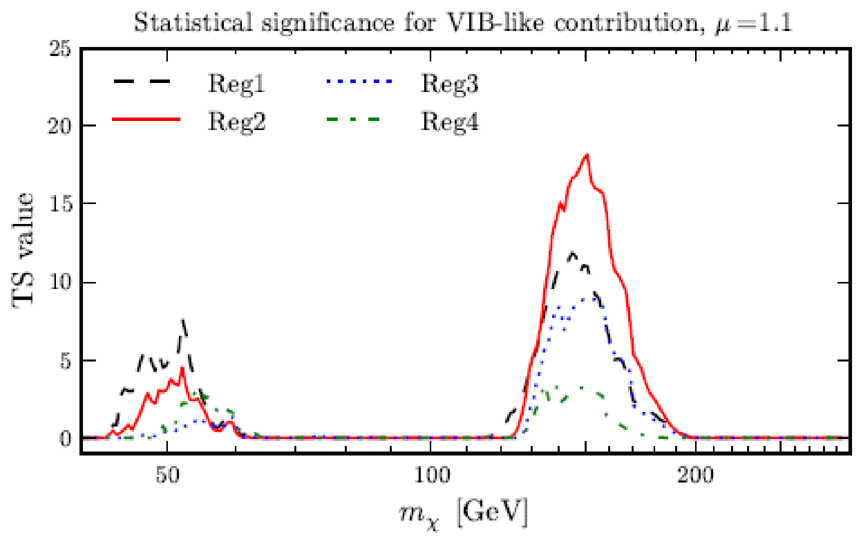
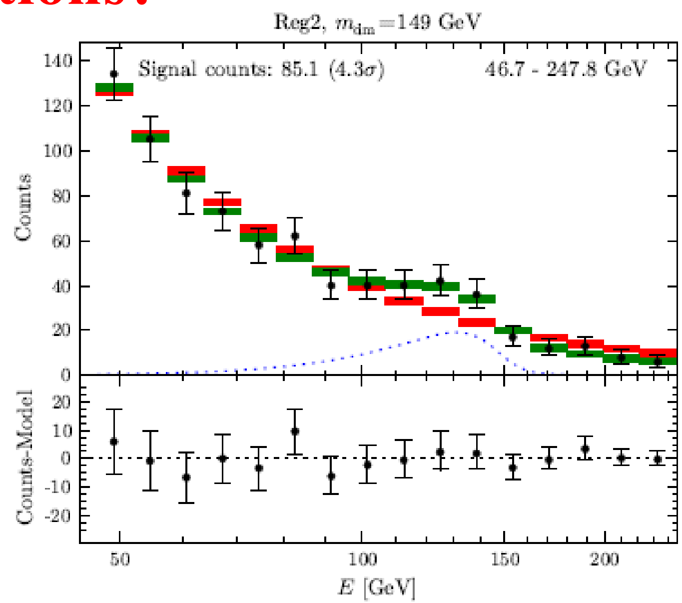


1- Search for signatures of internal Bremsstrahlung with the Fermi-LAT

A possible hint of dark matter annihilations?





$$m_\chi = (149 \pm 4)\ \text{GeV}$$
$$\langle \sigma v \rangle = (5.7 \pm 1.4) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

4.3 σ (3.1 σ with LEE) in Reg2

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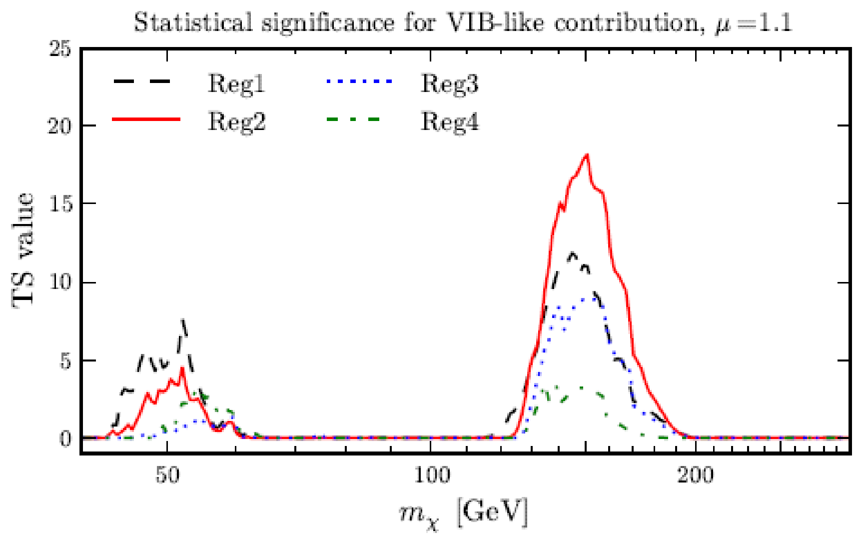

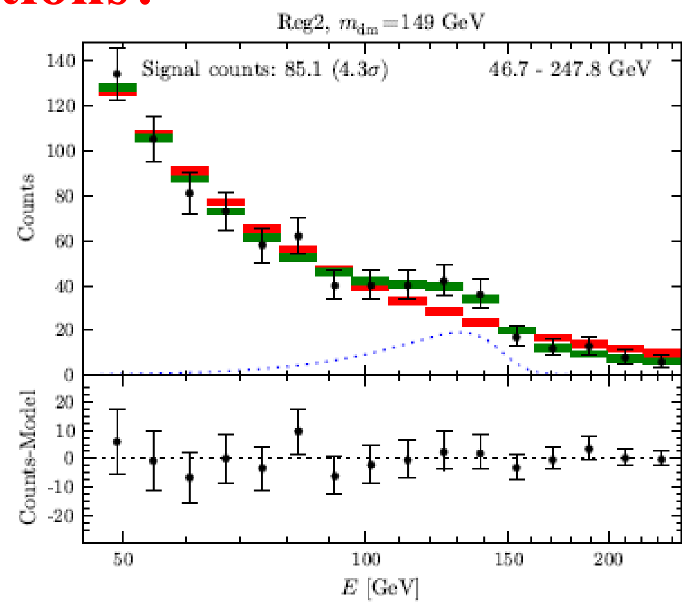

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Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

The excess can also be fitted by a line $\begin{cases} m_\chi \sim 130\ \text{GeV} \\ \langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \sim 10^{-27}\ \text{cm}^3\ \text{s}^{-1} \end{cases}$

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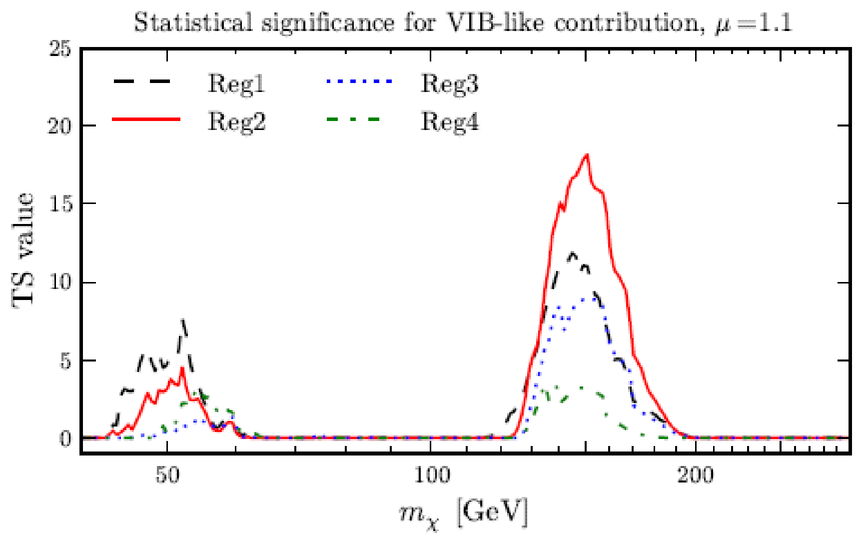

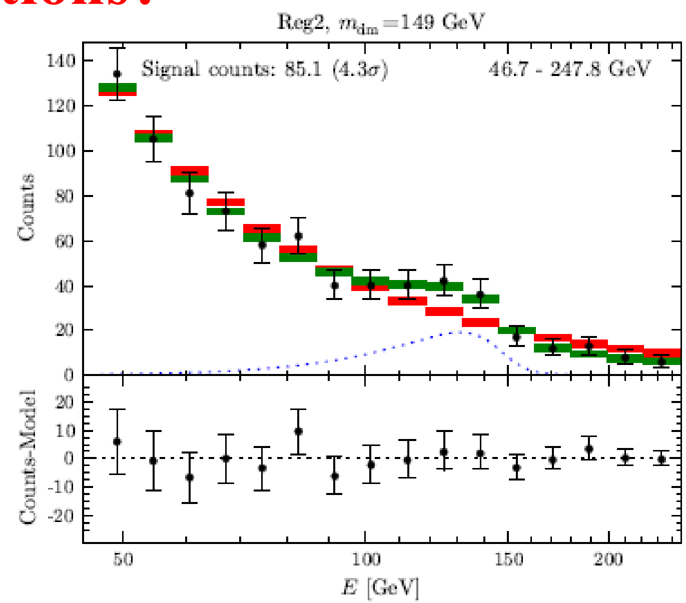

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4.3 σ (3.1 σ with LEE) in Reg2

Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

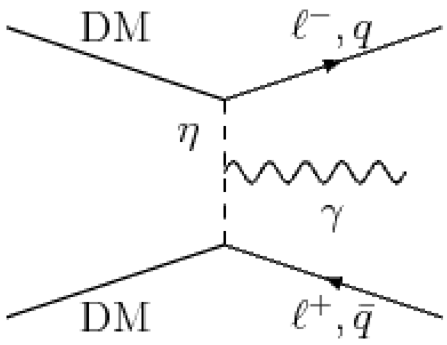
The excess can also be fitted by a line

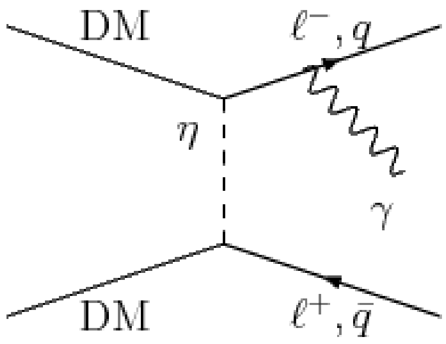
$$m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}\ \mathrm{GeV}$$
$$\langle \sigma v \rangle = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

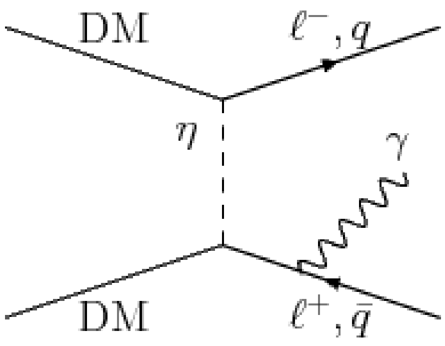
Weniger, arXiv:1204.2797

4.6 σ (3.3 σ with LEE) for Einasto

2- Antiproton limits on $2 \to 3$ processes







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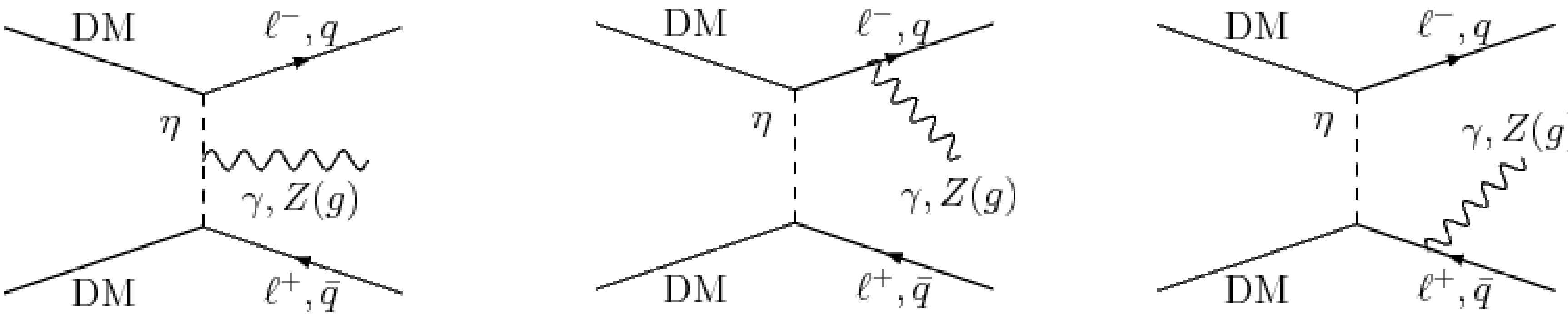
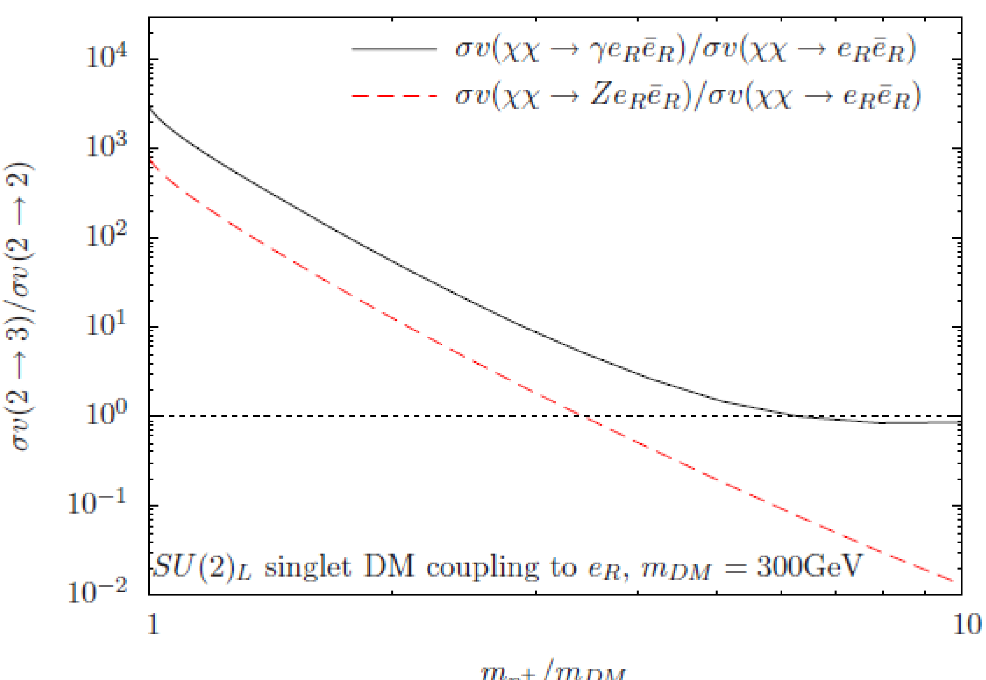
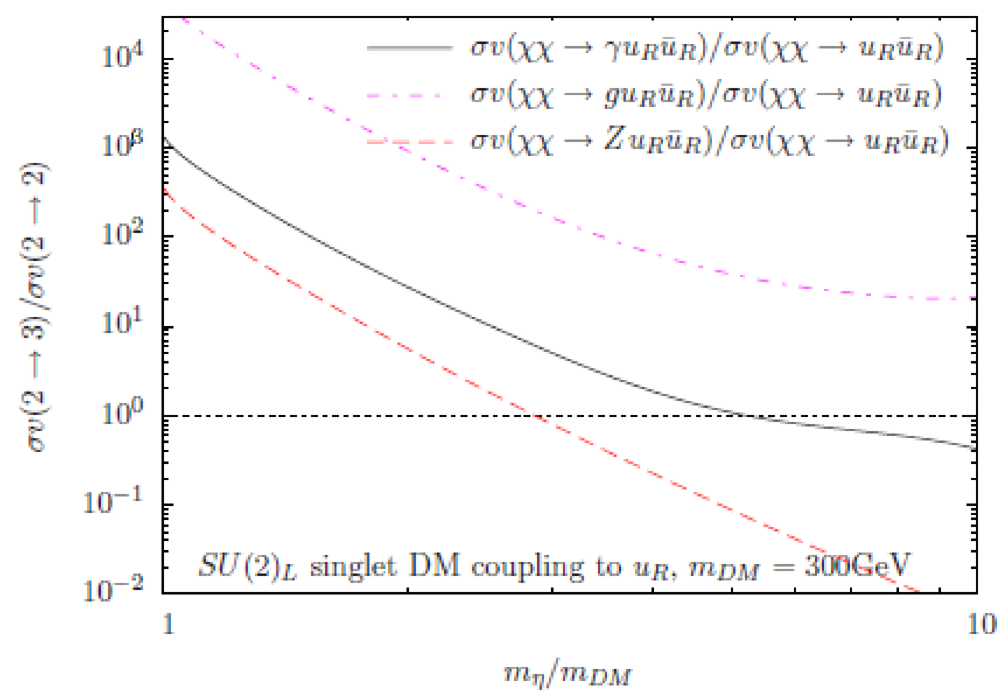


Singlet dark matter annihilating into right-handed electrons



Singlet dark matter annihilating into right-handed up-quarks



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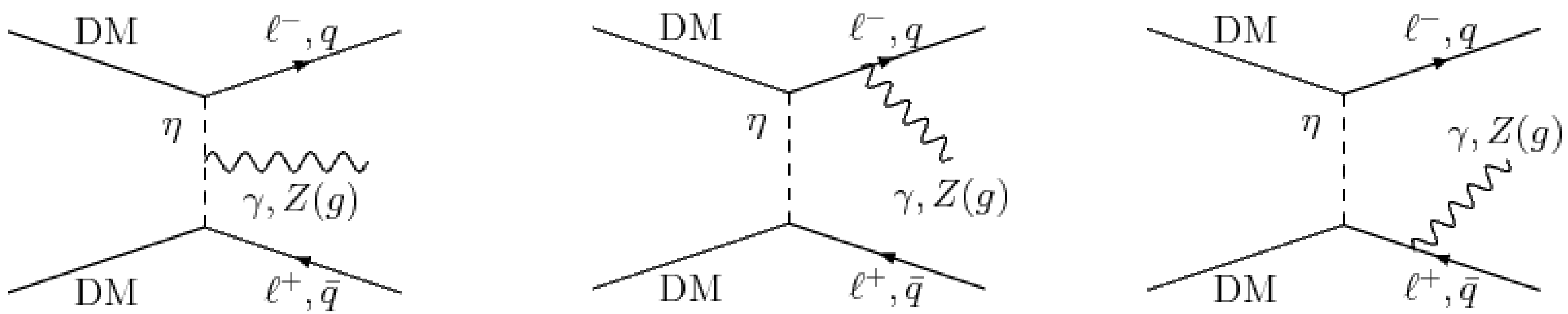

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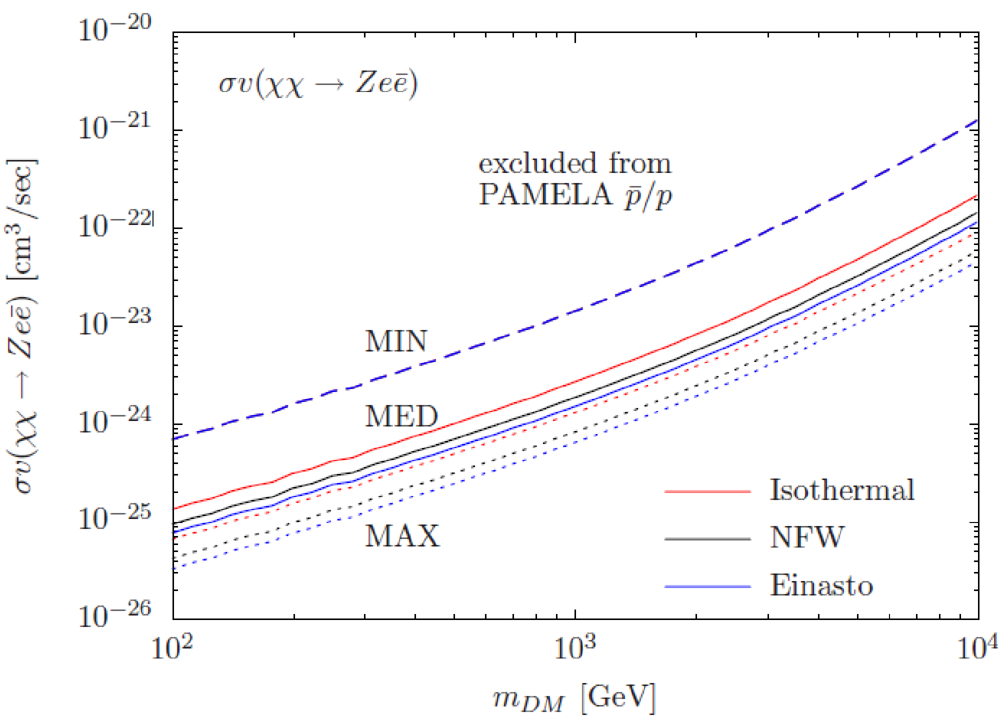

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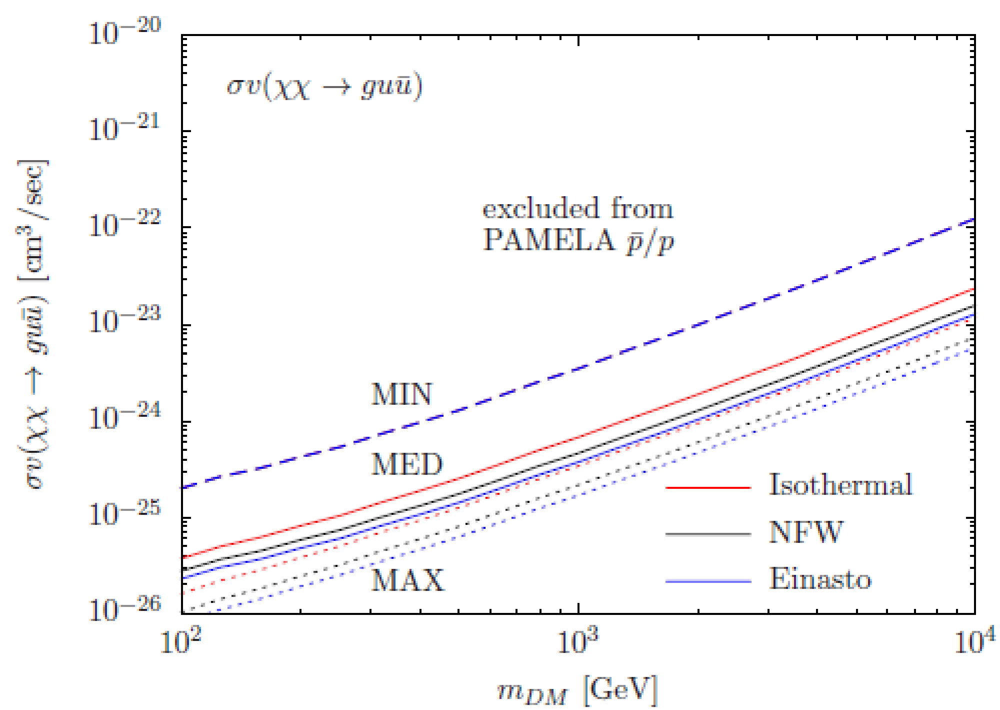
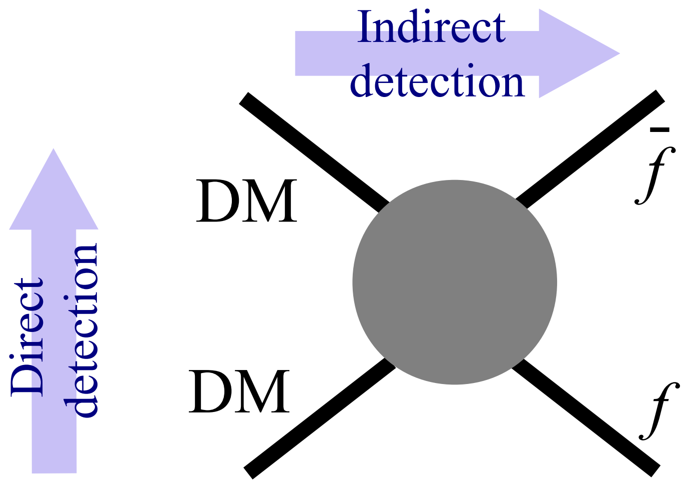


3- Interplay direct detection – indirect detection

Naive connection between direct detection and indirect detection:



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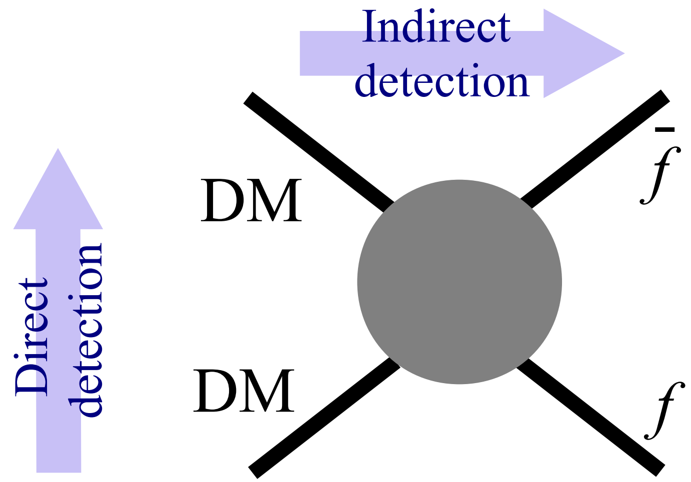
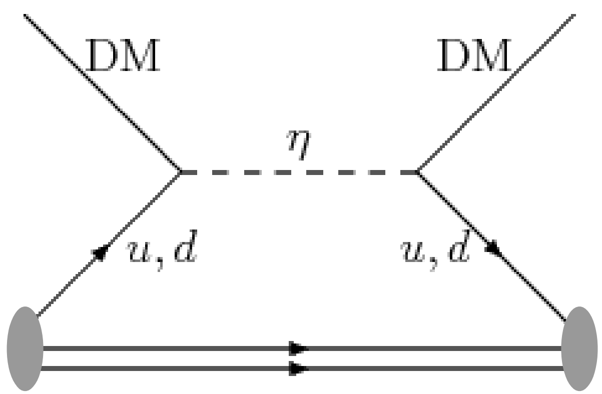
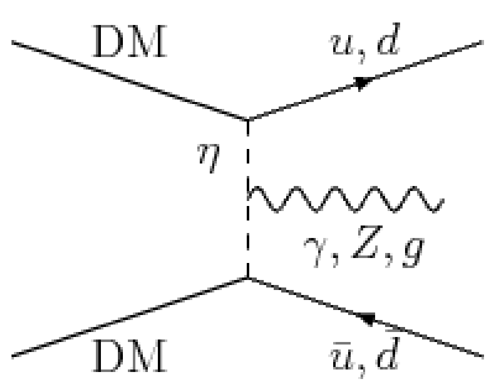


However, in direct search experiments it is probed the DM coupling to *a light quark.*

$\Longrightarrow$ The $2 \rightarrow 2$ annihilation into light quarks is suppressed.

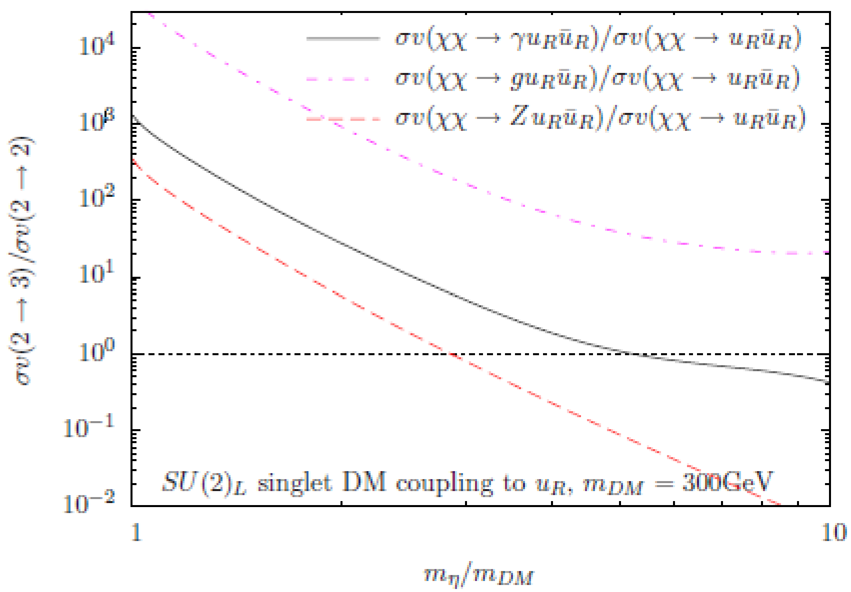
$\Longrightarrow$ **The $2 \rightarrow 3$ annihilation is usually the dominant channel**

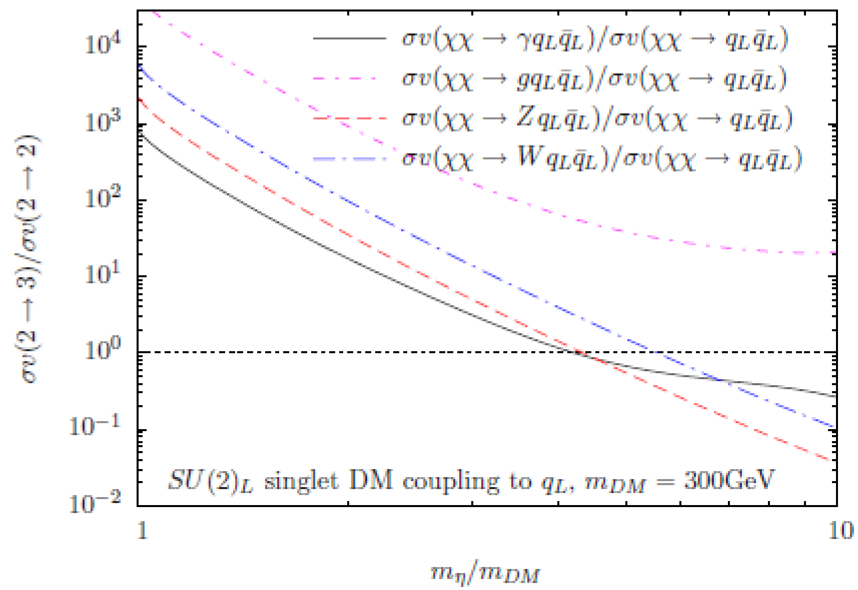




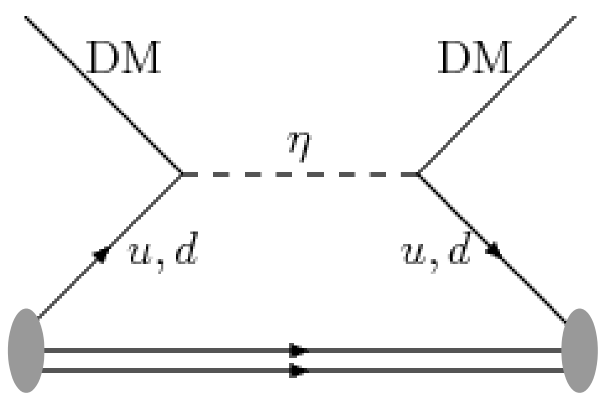
3- Interplay direct detection – indirect detection

• Indirect detection limits become more stringent when η and χ are degenerate in mass, due to the larger $2 \to 3$ cross section.





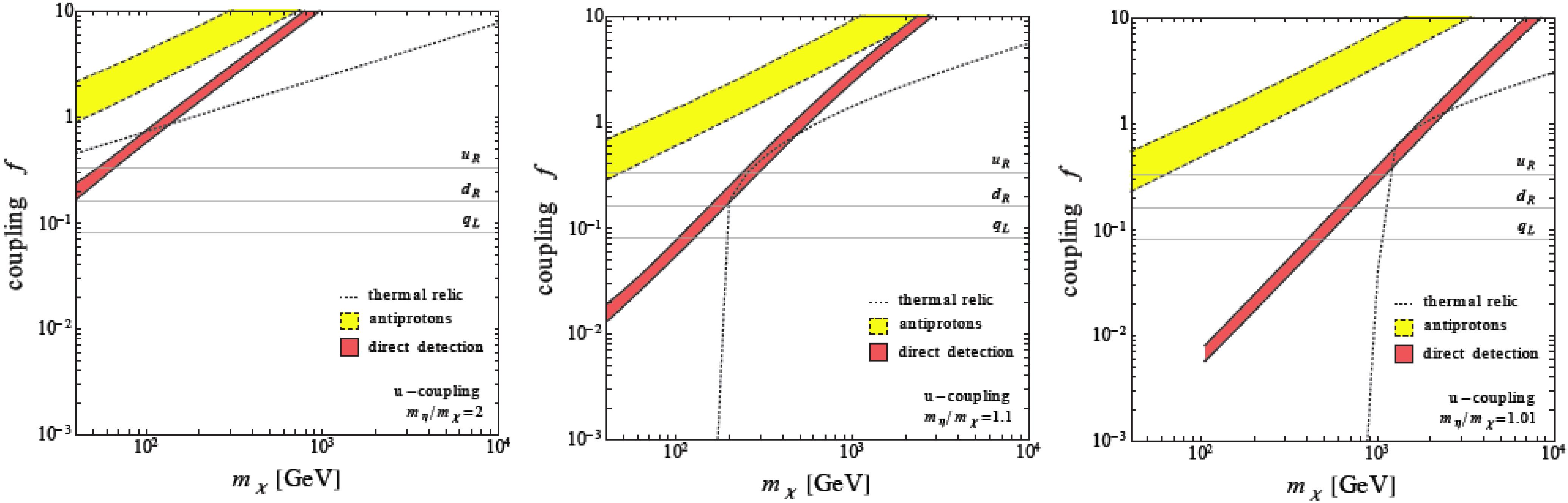
• Also the direct detection limits, due to an enhancement of the WIMP effective couplings in the degenerate limit.



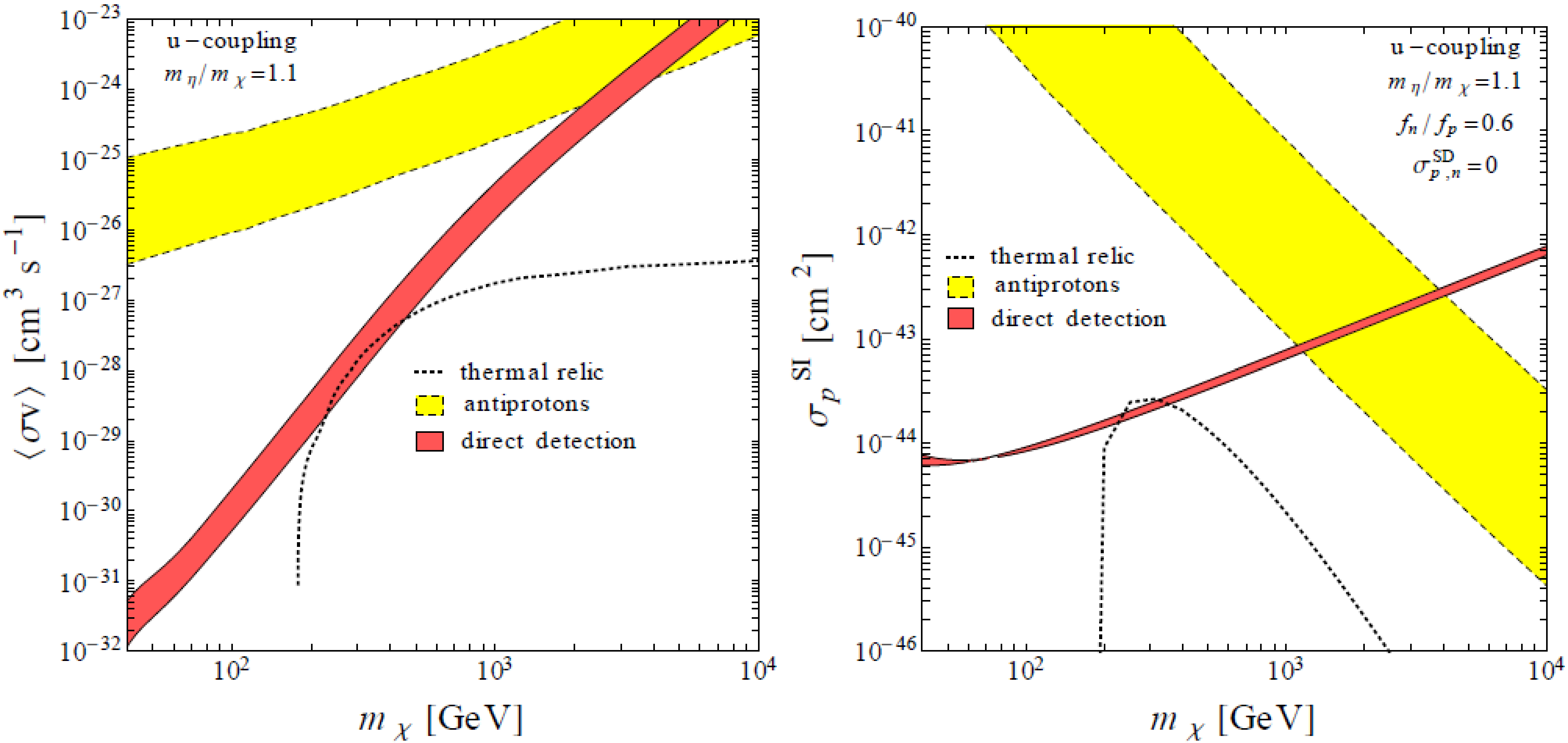
$$\Delta = \frac{1}{(p_\chi + p_q)^2 - m_\eta^2} \simeq \frac{1}{(m_\chi + m_q)^2 - m_\eta^2}$$

3- Interplay direct detection – indirect detection

Limits on the coupling f from PAMELA and XENON-100



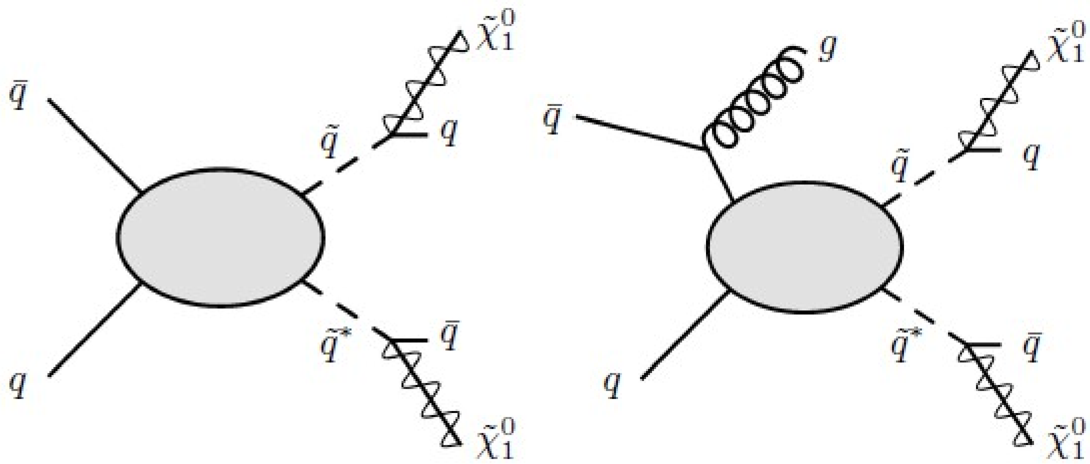
3- Interplay direct detection – indirect detection

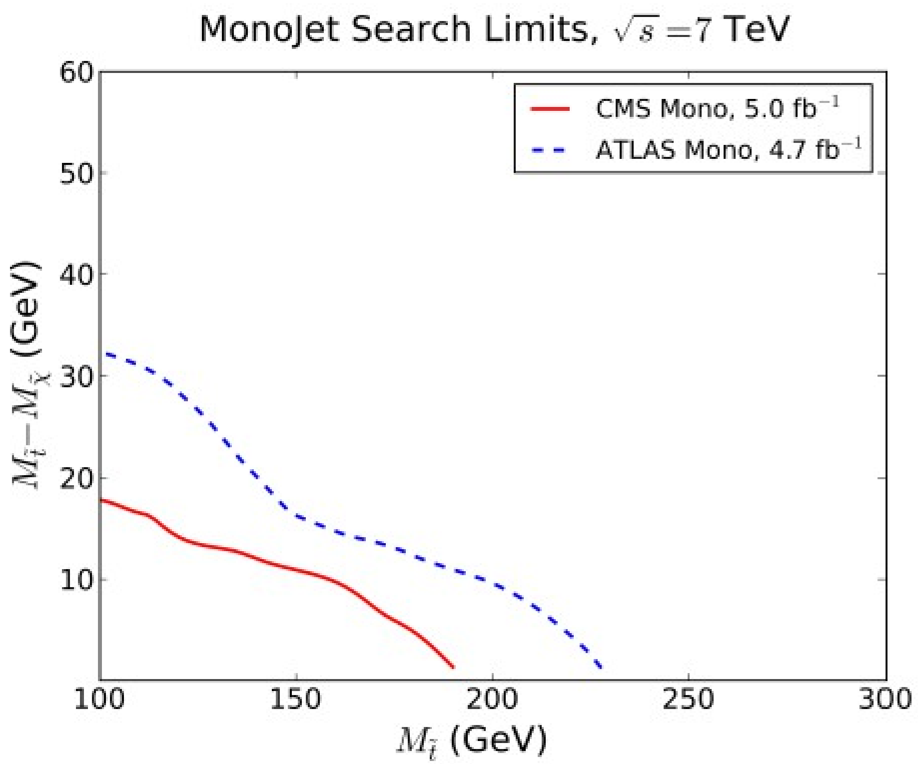


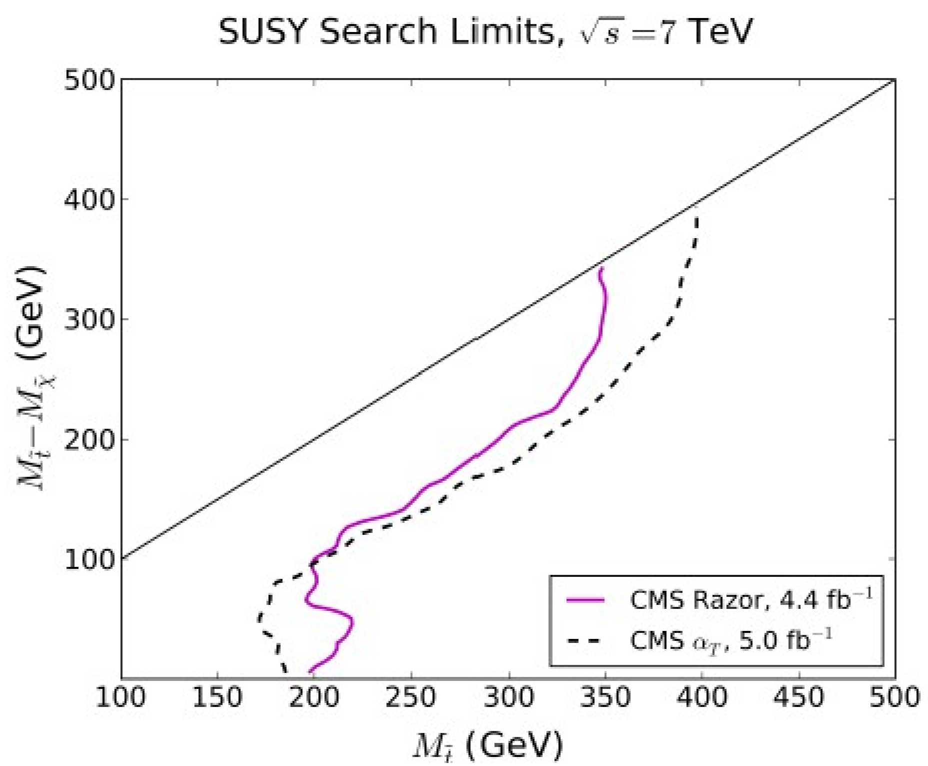
3- Interplay direct detection – indirect detection – collider searches

Hadronic
+
monojet searches

Dreiner, Krämer, Tattersal,
arXiv:1211.4981







Conclusions

• In scenarios with Majorana (or scalar) dark matter particles which couple to light fermions, the higher order annihilation process DM DM $\to f\bar{f}V$ can be important (even dominant).

• We have searched in the Fermi-LAT data for a signal from DM DM $\to f\bar{f}\gamma$. the limits are fairly stringent and are only one-two orders of magnitude above the cross sections expected from thermal production. The data analysis has also revealed a hint for a signal at $m_{DM}\simeq 149$ GeV.

• Interesting interplay between direct detection limits, antiproton limits, gamma-ray limits and collider limits in the case that the dark matter particle couples to light quarks.

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Thank you for your attention!