Higher Order Effects in Dark Matter Annihilations

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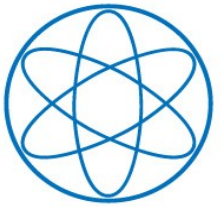
Technische Universität München

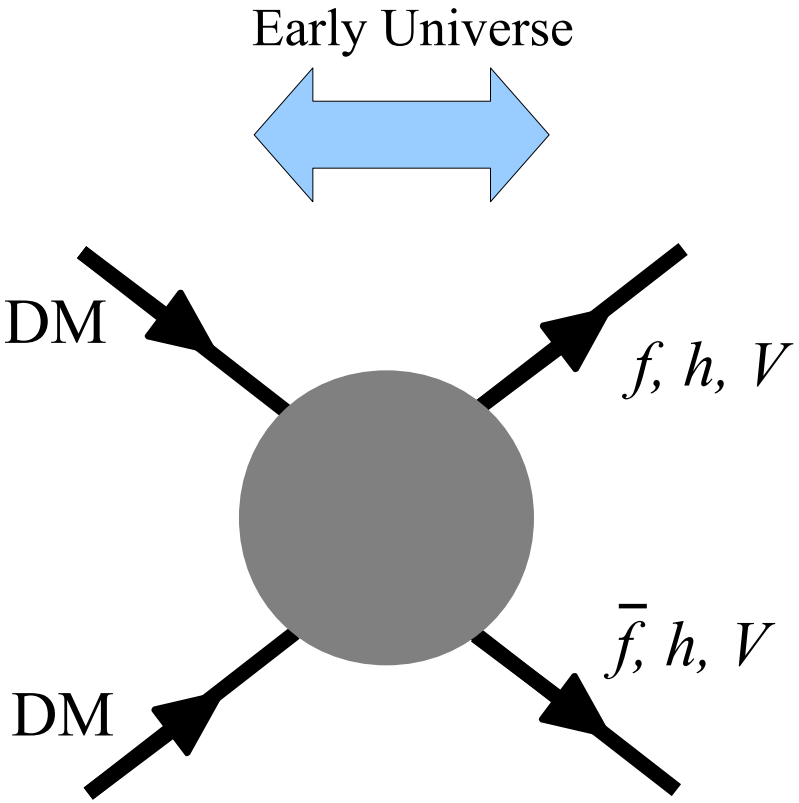


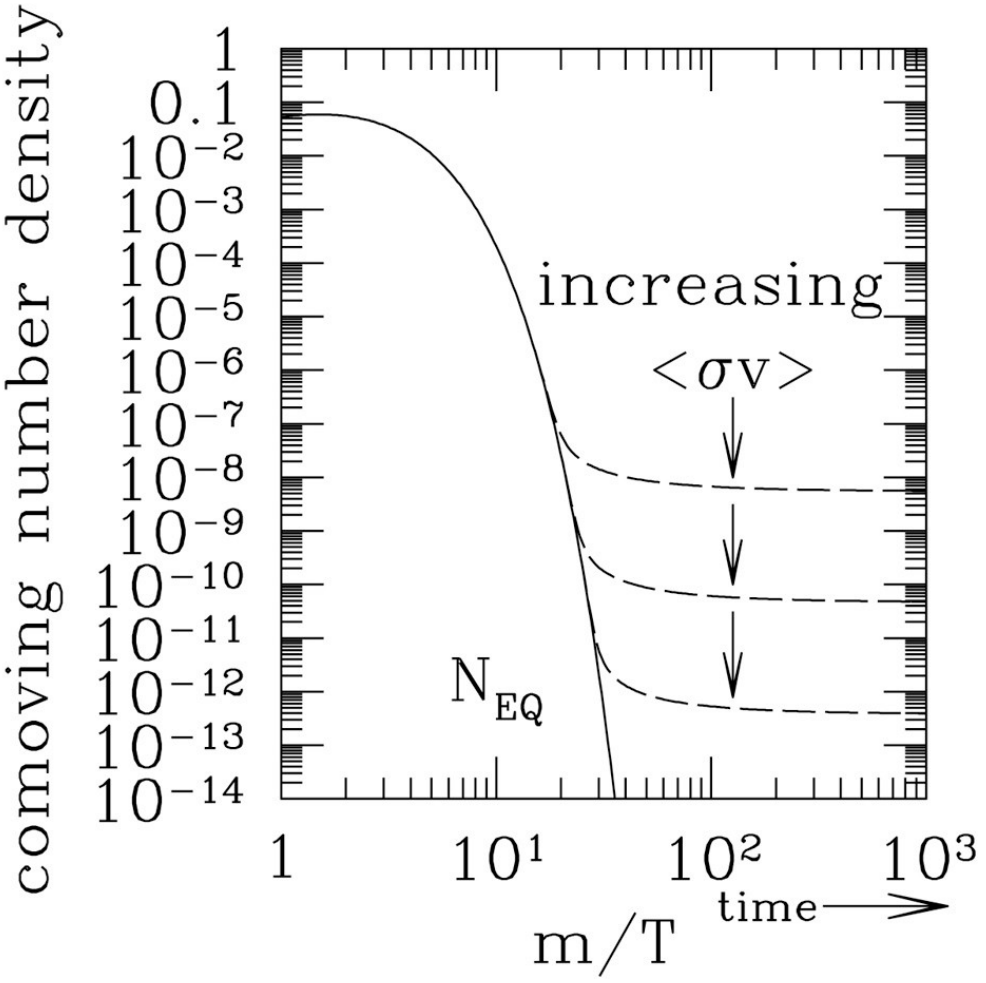
Based on M. Garny, AI, S. Vogl, JCAP **1107** (2011) 028
M. Garny, AI, S. Vogl, JCAP **1204** (2012) 033
T. Bringmann, X. Huang, AI, S. Vogl, C, Weniger JCAP **1207** (2012) 054
M. Garny, AI, M. Pato, S. Vogl, arXiv:1207.1431

IPP12, Tehran
1 October 2012

Dark matter self-annihilation: standard picture

Thermal production of WIMPs

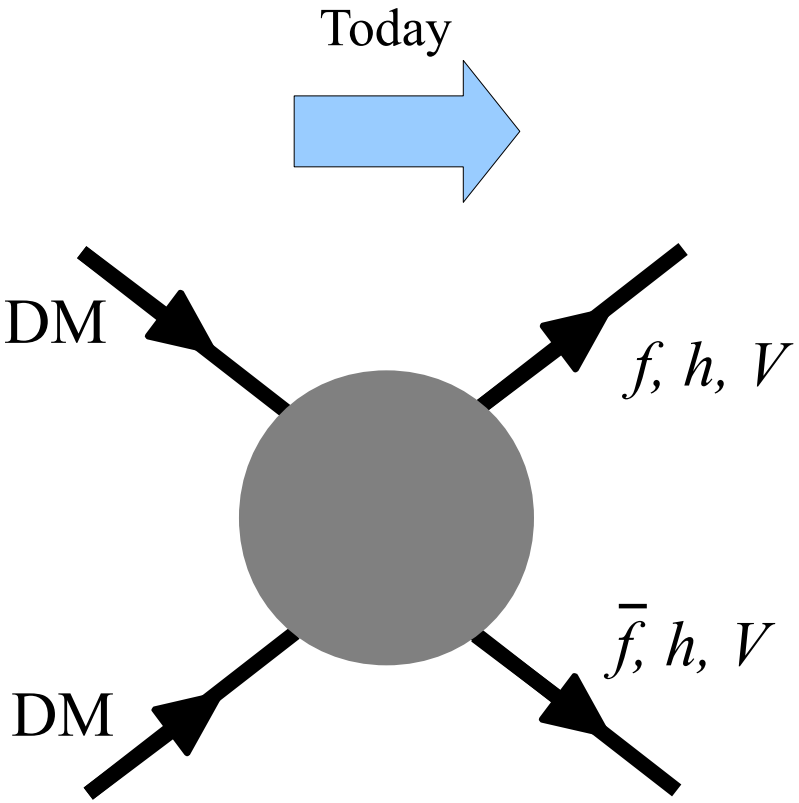




$$\Omega_{\rm DM} h^2 \simeq 0.11 \times \frac{3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

Dark matter self-annihilation: 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:

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

$a,b \rightarrow$ calculable in a given DM model

$v \rightarrow$ depends on the astrophysical conditions

Freeze-out $\quad \langle v^2 \rangle \sim \dfrac{6 T_{\rm f.o.}}{m_{\rm DM}} \sim 0.3$, with $T_{\rm f.o.} \sim \dfrac{m_{\rm DM}}{20}$

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

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

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

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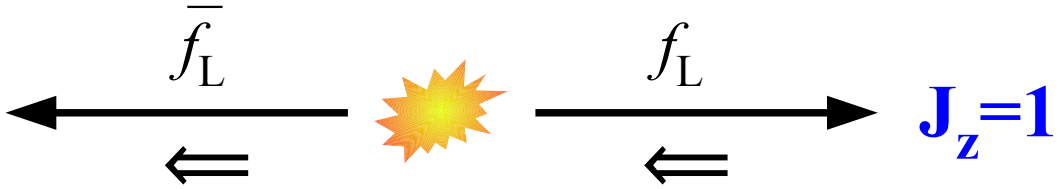
• Consider the annihilation DM DM $\to f\bar{f}$, with DM a Majorana fermion or a scalar particle

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

J_z=0



J_z=1

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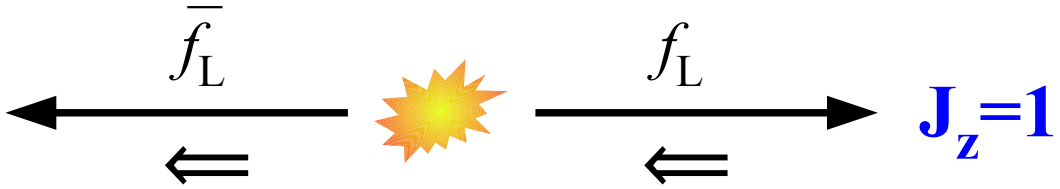

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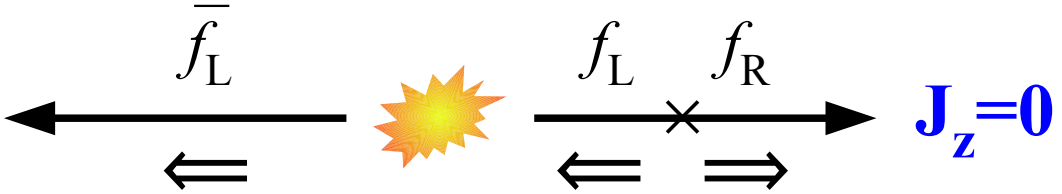

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Rate of DM DM $\to f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

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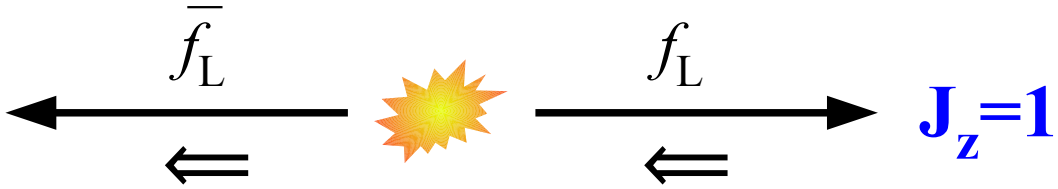

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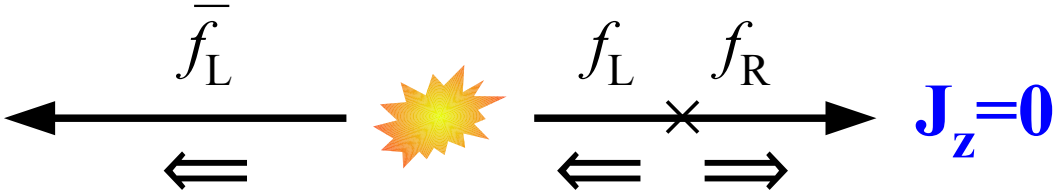


J_z=0

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

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

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

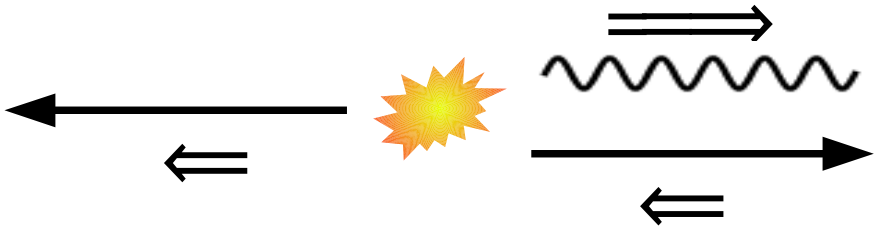
$$\Rightarrow \langle\sigma v\rangle_{\rm G.C.} \sim 3 \times 10^{-6} \langle\sigma v\rangle_{\rm f.o.} \sim 10^{-31}\,{\rm cm}^3{\rm s}^{-1}$$

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

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

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

$\mathbf{J_z=0}$



$\mathbf{J_z=0}$

No suppression by mass insertion.
Suppressed, however, by the extra coupling constant and by the 3-body phase space. Bergström
Flores, Olive, Rudaz

For annihilations into light fermions, the dominant annihilation channel *today* can be DM DM $\to f\bar{f}V$, while at the time of freeze-out, DM DM $\to f\bar{f}$

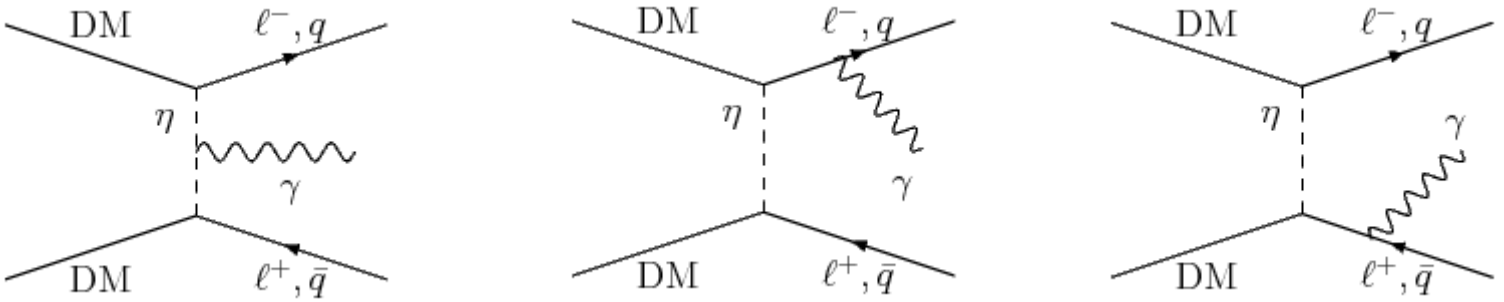
$$\langle\sigma v\rangle^{2\to3}_{G.C.} \sim \frac{\alpha}{0.3\pi}\langle\sigma v\rangle^{2\to2}_{f.o.} \sim 10^{-28}\mathrm{cm}^3\mathrm{s}^{-1}$$

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

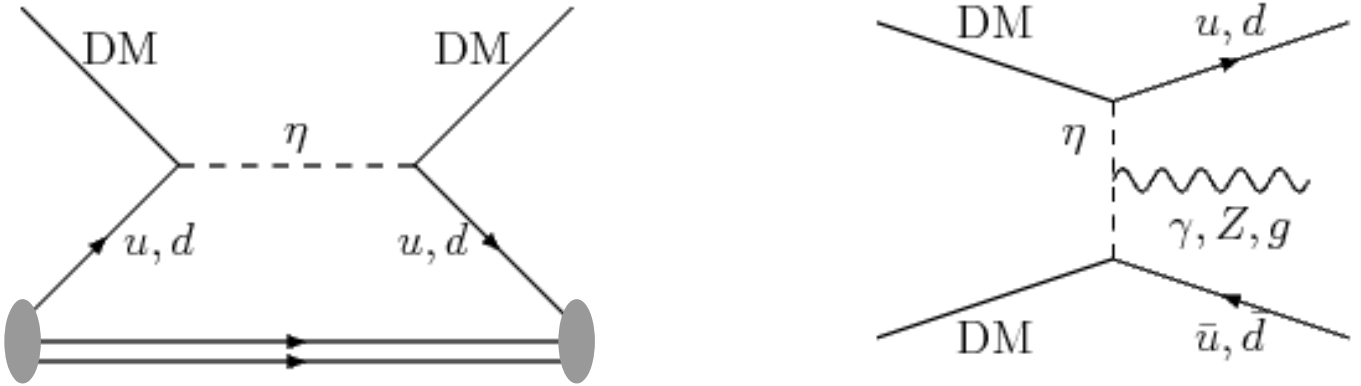
Outline

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

2- Antiproton limits on 2 → 3 processes



3- Interplay direct detection – indirect detection



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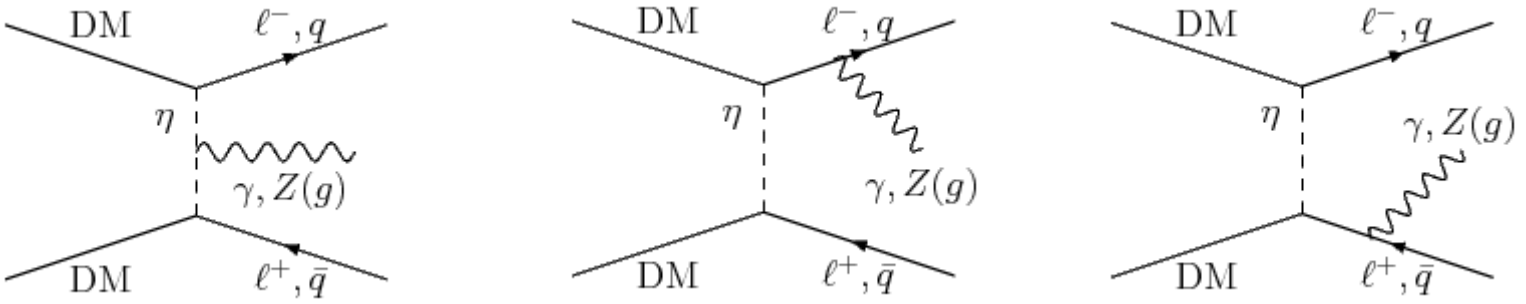

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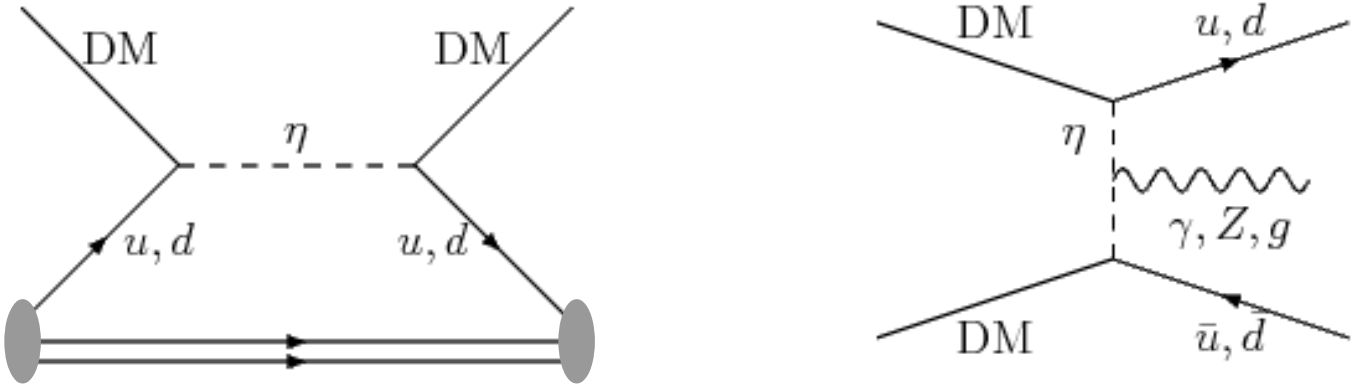
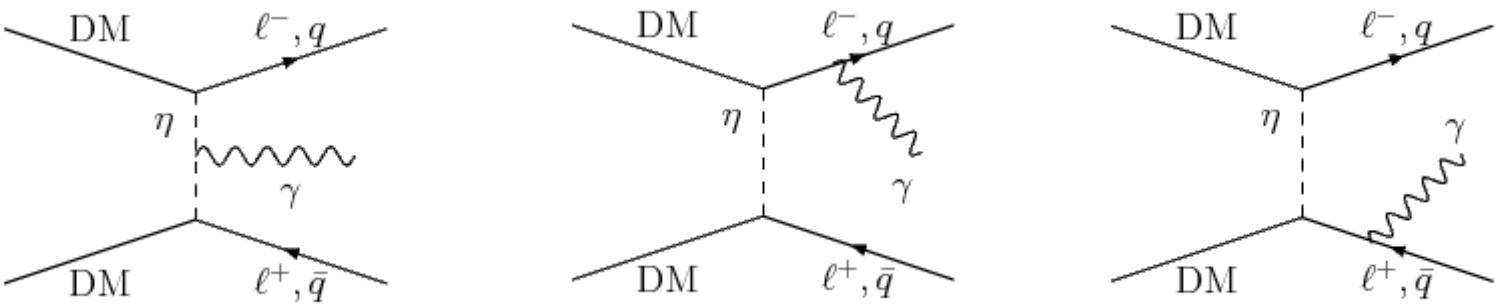


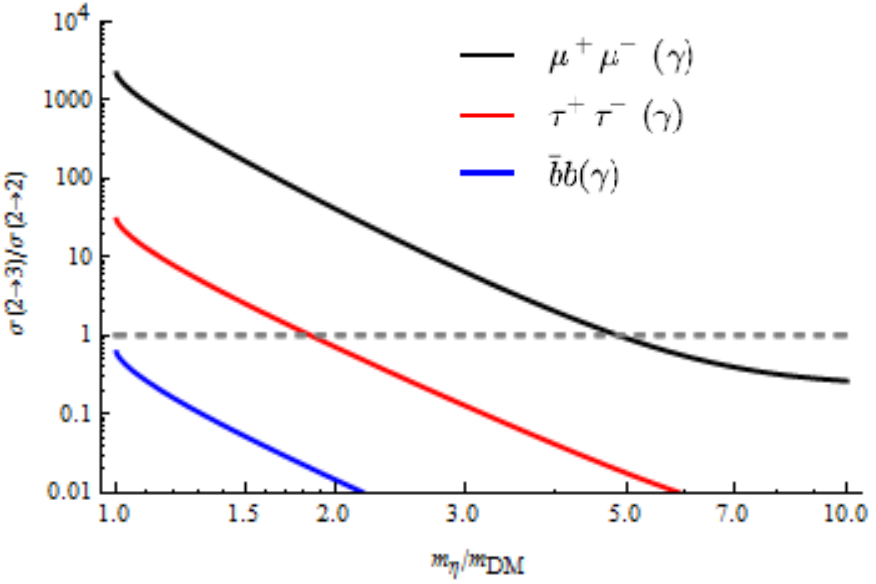
1- Search for signatures of internal bremsstrahlung with the Fermi-LAT

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



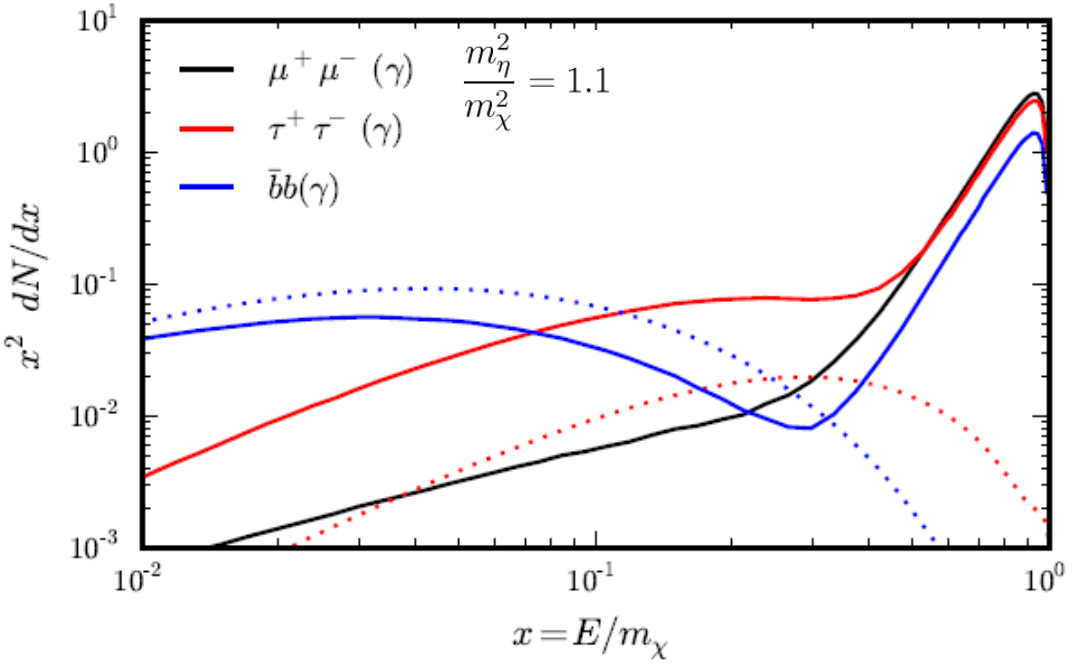
The cross section of the $2 \to 3$ process is enhanced when $m_\eta/m_{DM} \simeq 1$.



Bergström
Flores, Olive, Rudaz

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 Bergstrom

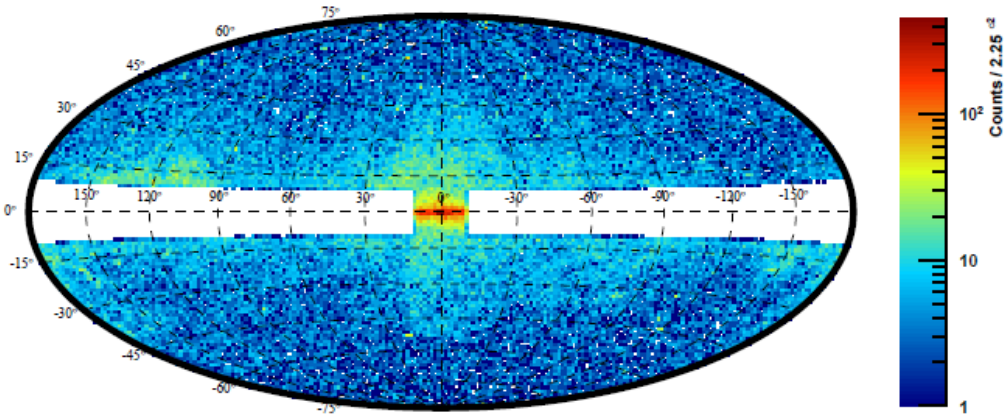


Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

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

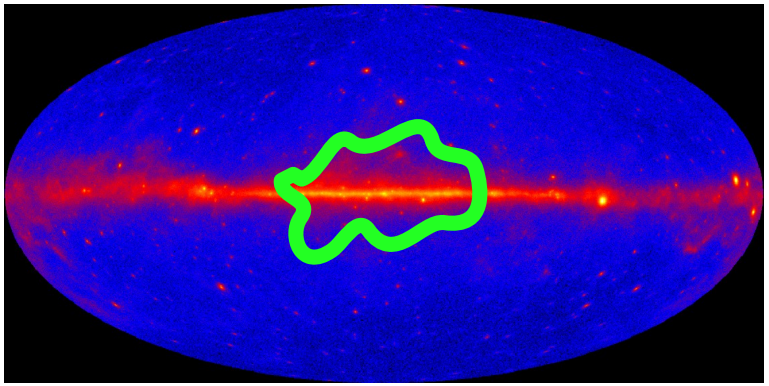
Traditional approach: select a fixed region of the sky and search for features.

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



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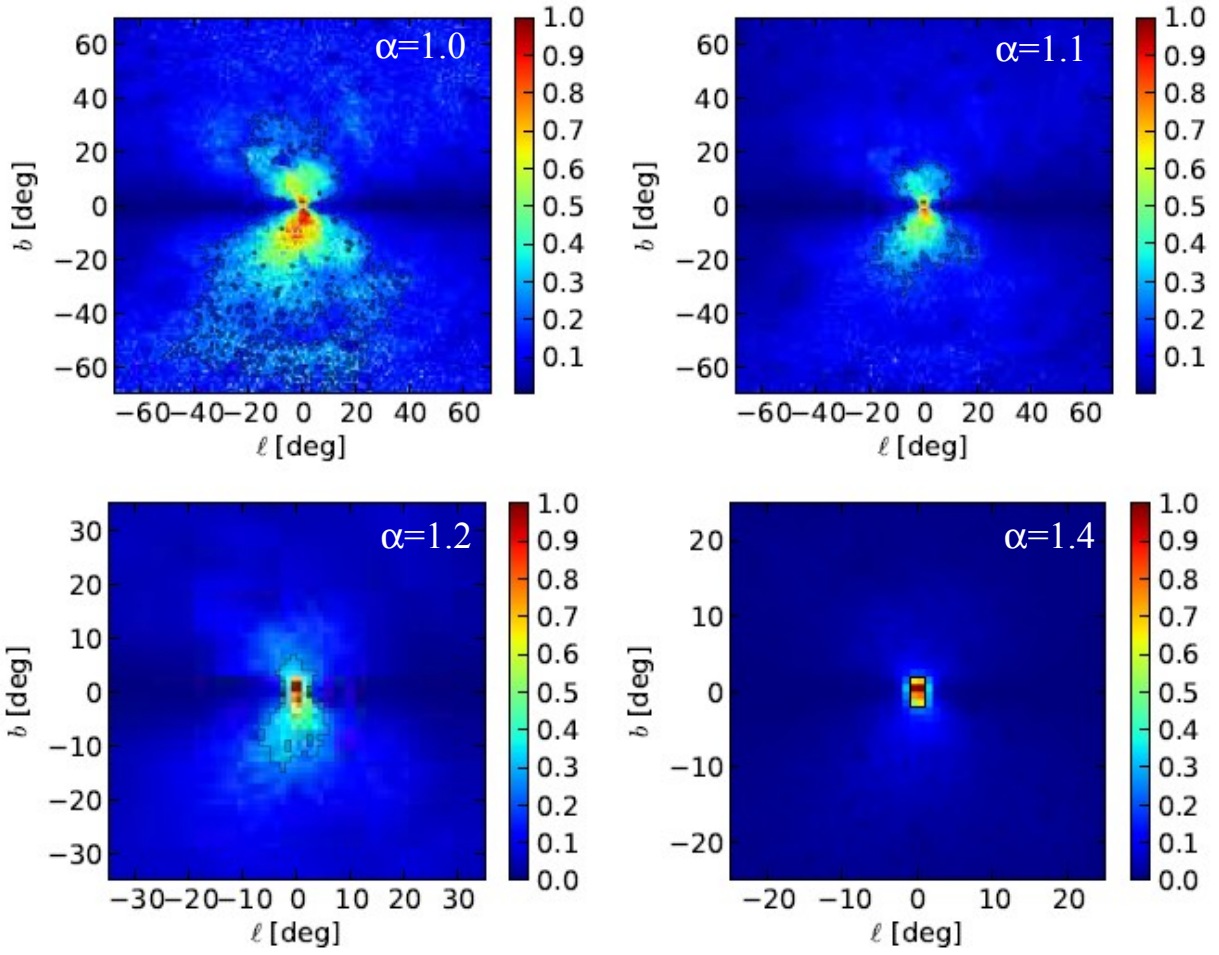
Consider a generalized NFW profile

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

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



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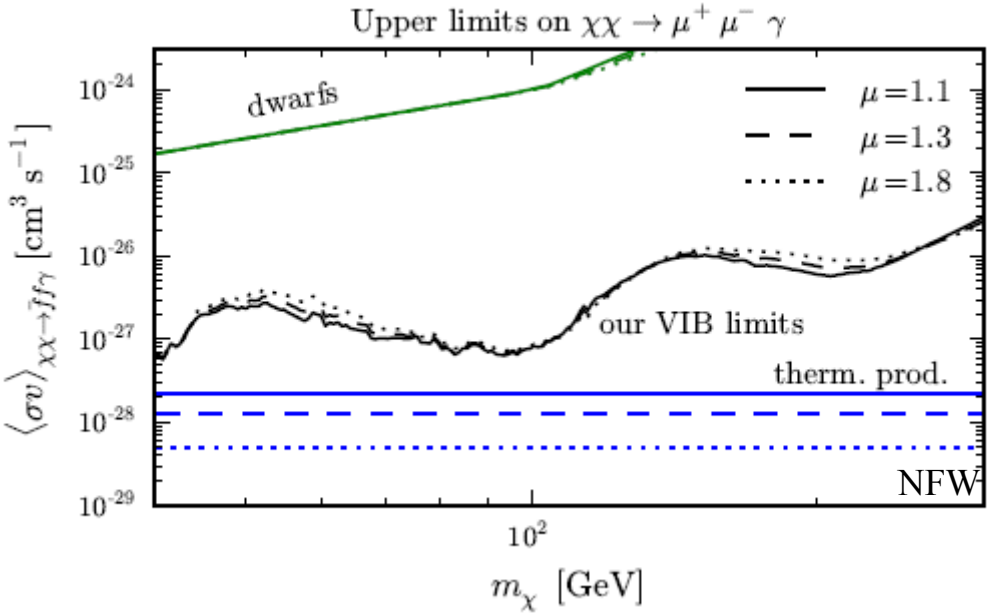

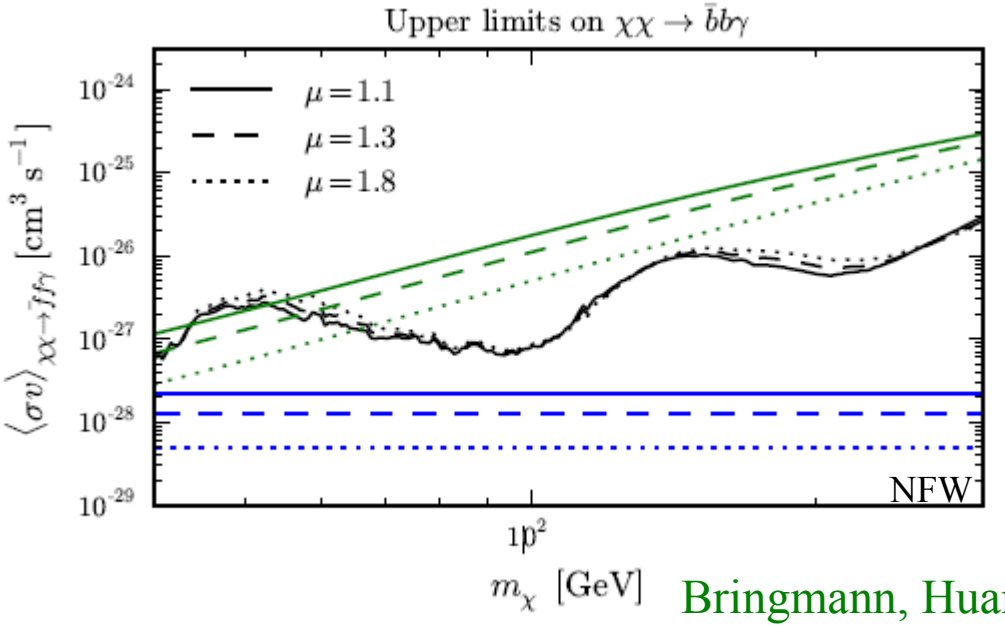

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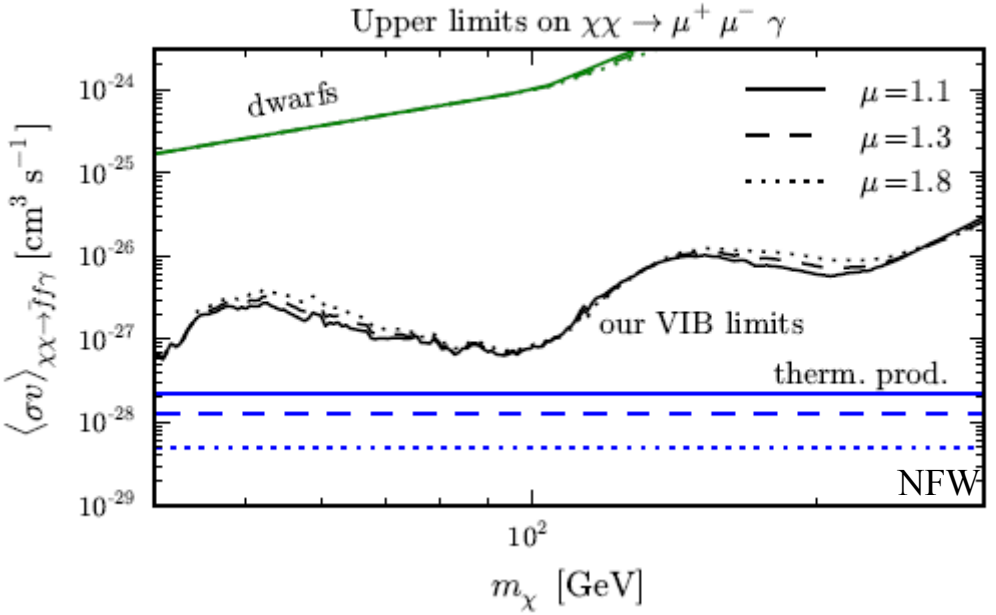

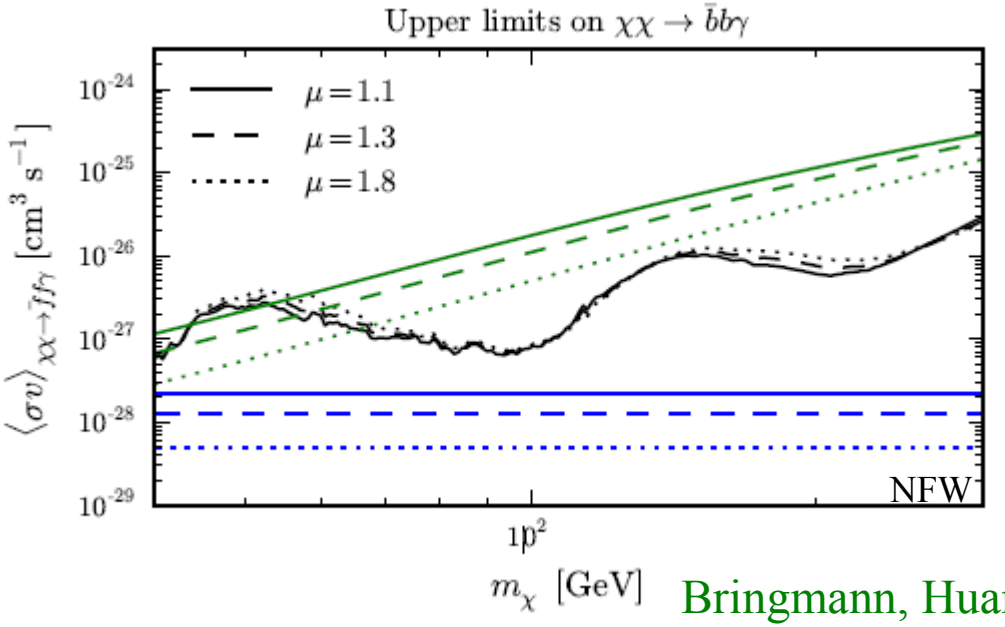

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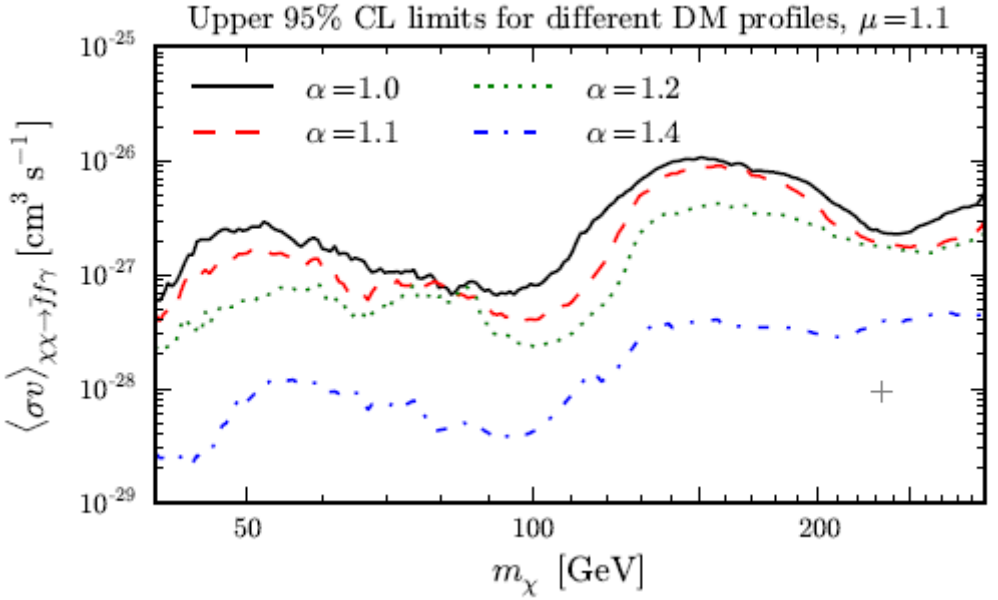

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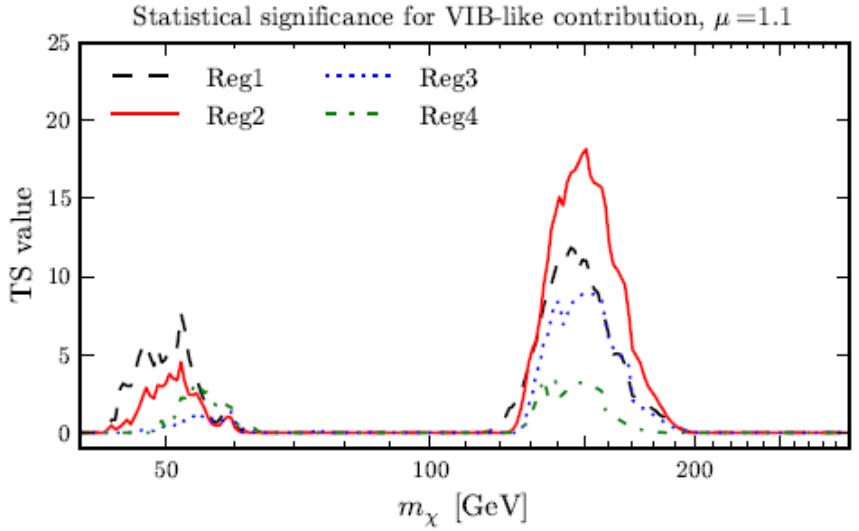
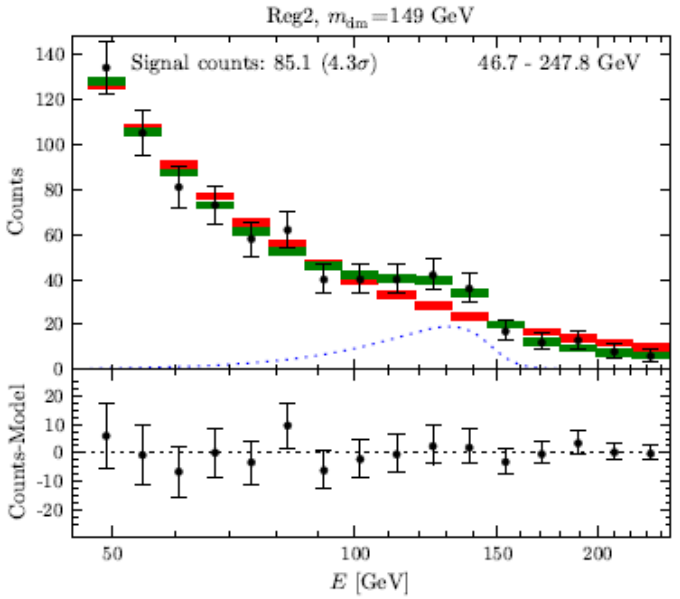
A possible hint of dark matter annihilations?





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

4.3 σ (3.1 σ with LEE) in Reg2

Bringmann, Huang, AI, Vogl, Weniger
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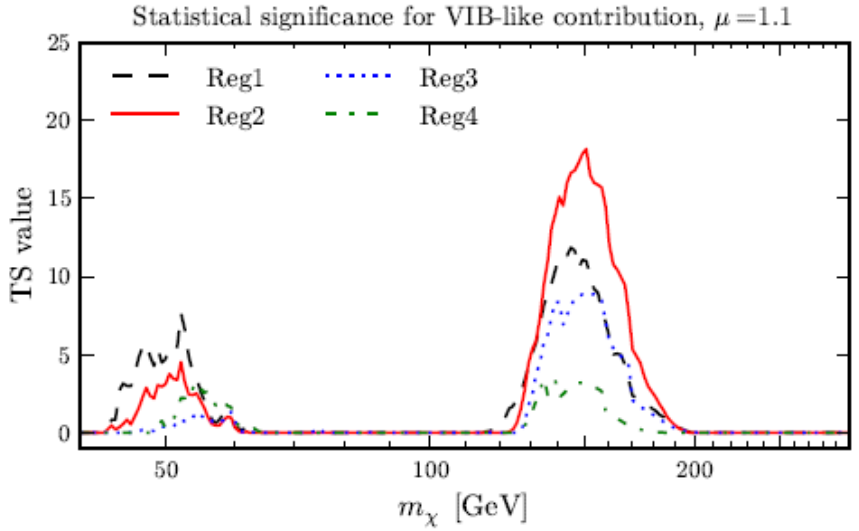

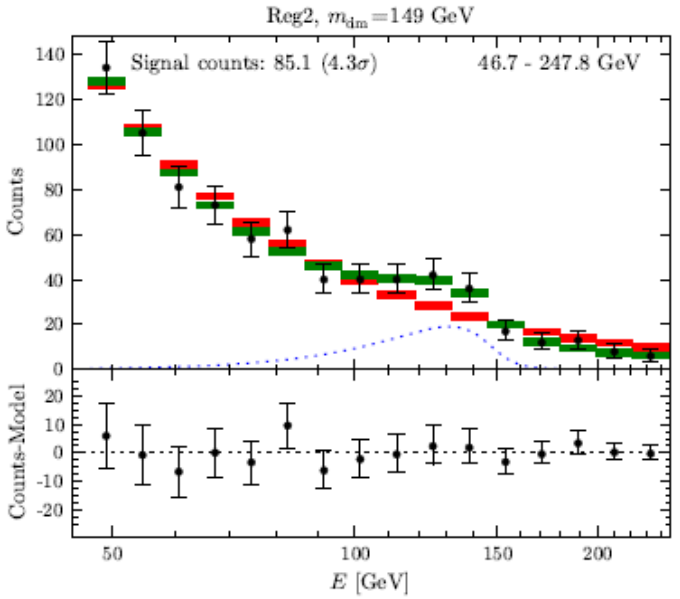

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Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

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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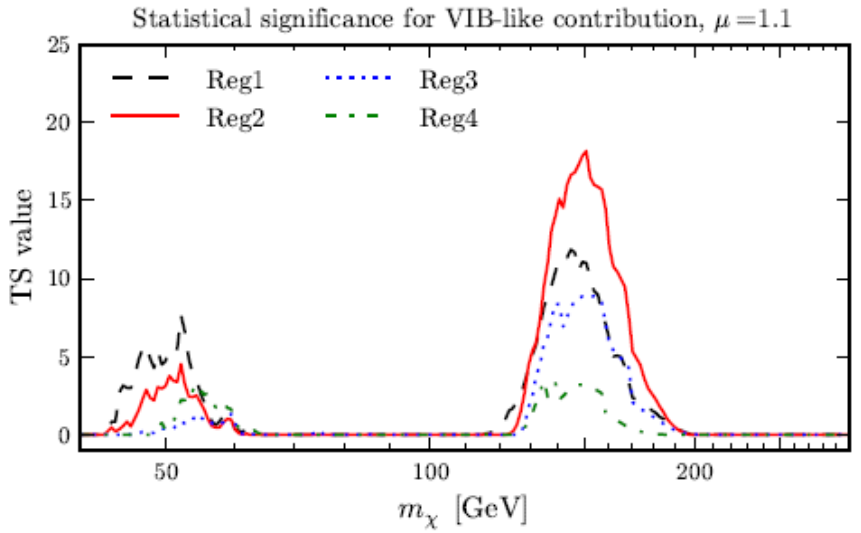

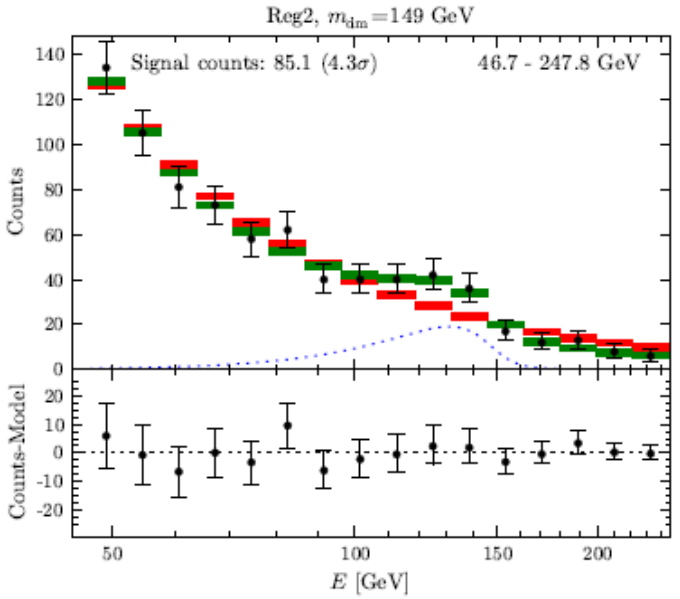

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4.3 σ (3.1 σ with LEE) in Reg2

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

The excess can also be fitted by a line

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

Weniger, arXiv:1204.2797

4.6 σ (3.3 σ with LEE) for Einasto

2- Antiproton limits on 2 → 3 processes

• We consider a Majorana dark matter particle which couples to a light SM fermion and a complex scalar, η.

Various possibilities for the SU(3)×SU(2)×U(1) quantum numbers of η, from requiring an electrically neutral and colorless DM particle.

	RH lepton	LH lepton
SU(2) singlet DM	(1,1,1)	(1,2,-1/2)
SU(2) doublet DM	(1,2,-1/2)	(1,1,1)

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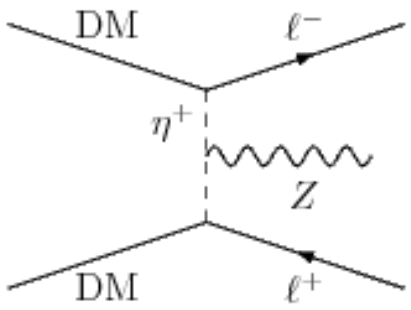

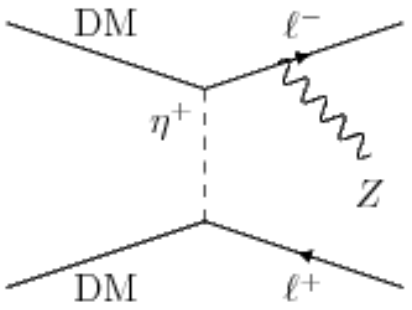

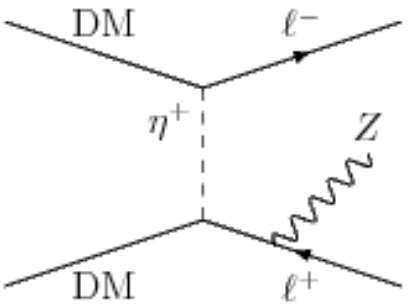

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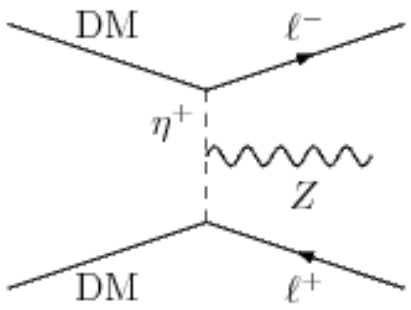

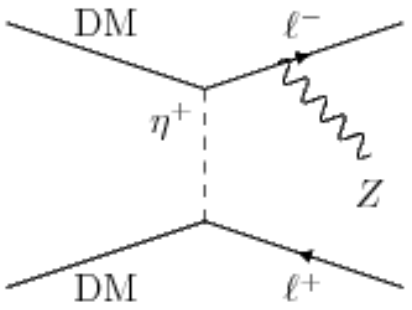

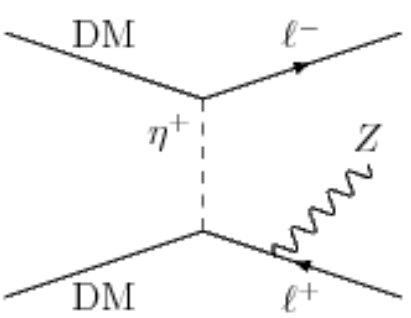

2- Antiproton limits on 2 → 3 processes

• We consider a Majorana dark matter particle which couples to a light SM fermion and a complex scalar, η.

Various possibilities for the SU(3)×SU(2)×U(1) quantum numbers of η, from requiring an electrically neutral and colorless DM particle.

	RH lepton	LH lepton
SU(2) singlet DM	(1,1,1)	(1,2,-1/2)
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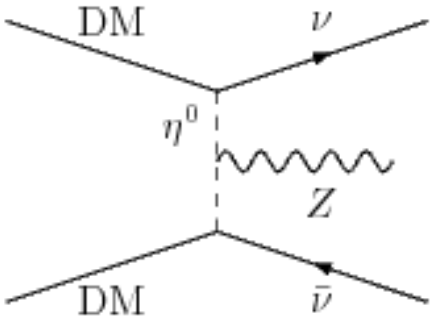
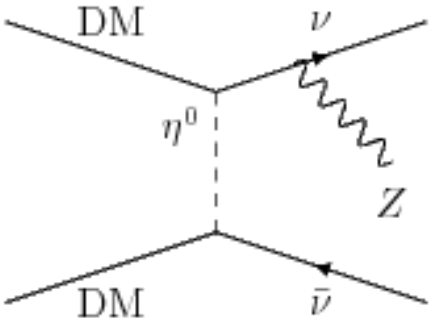
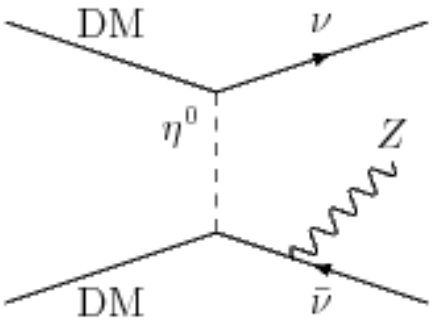
• For a light SM fermion, the 2 → 3 processes producing antiprotons can have a sizeable cross section.







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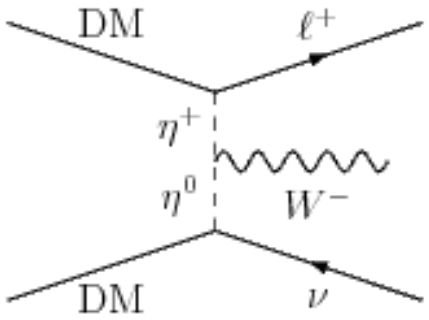
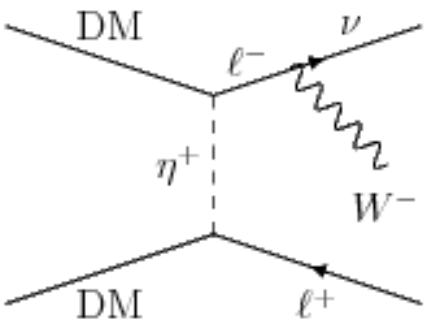
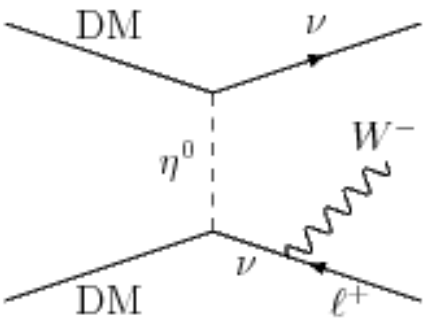






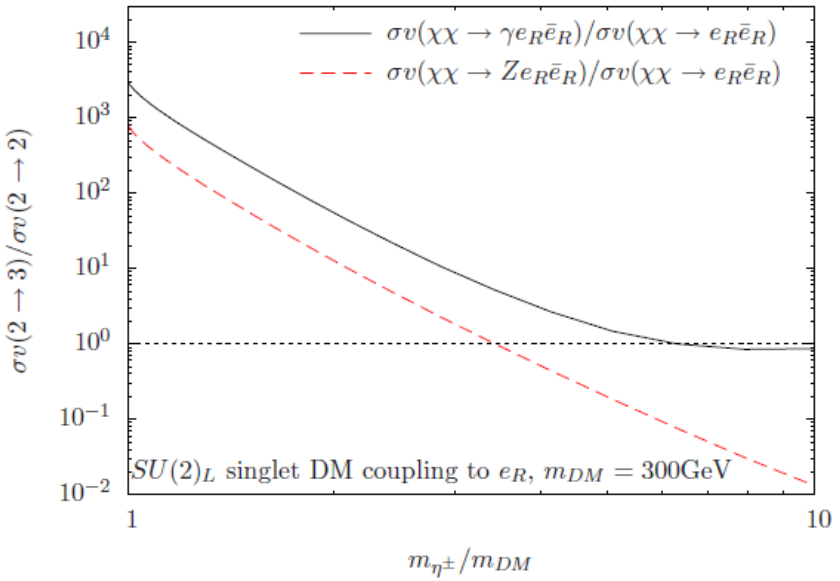
2- Antiproton limits on 2 → 3 processes

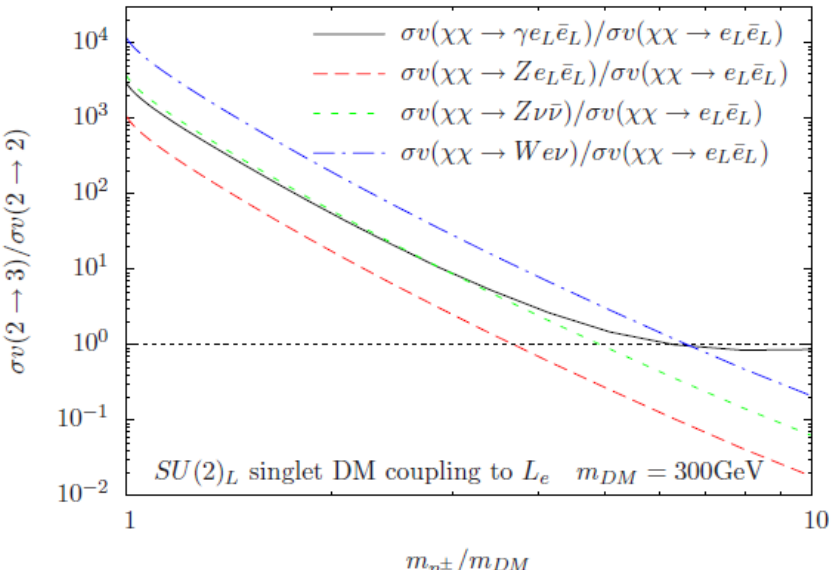
SINGLET DARK MATTER

Annihilations into SU(2) singlets

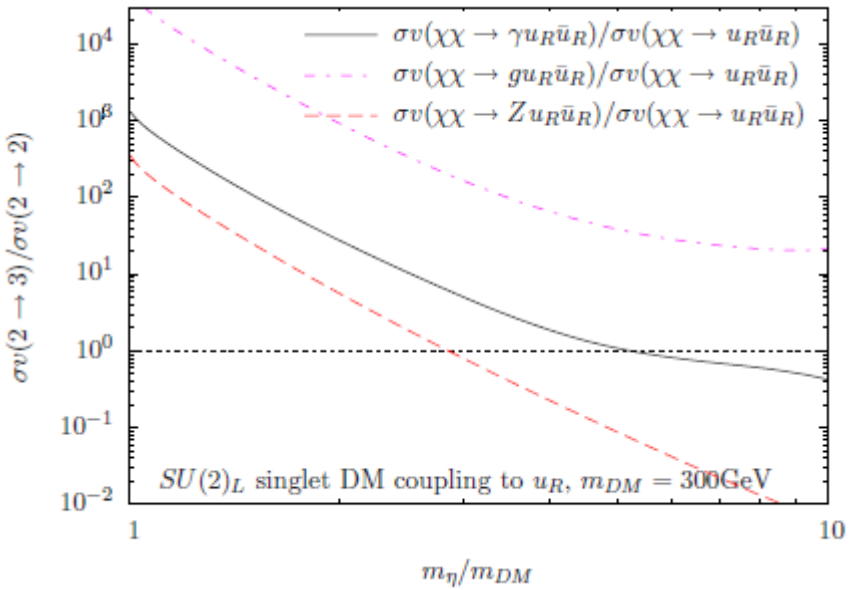
Annihilations into SU(2) doublets

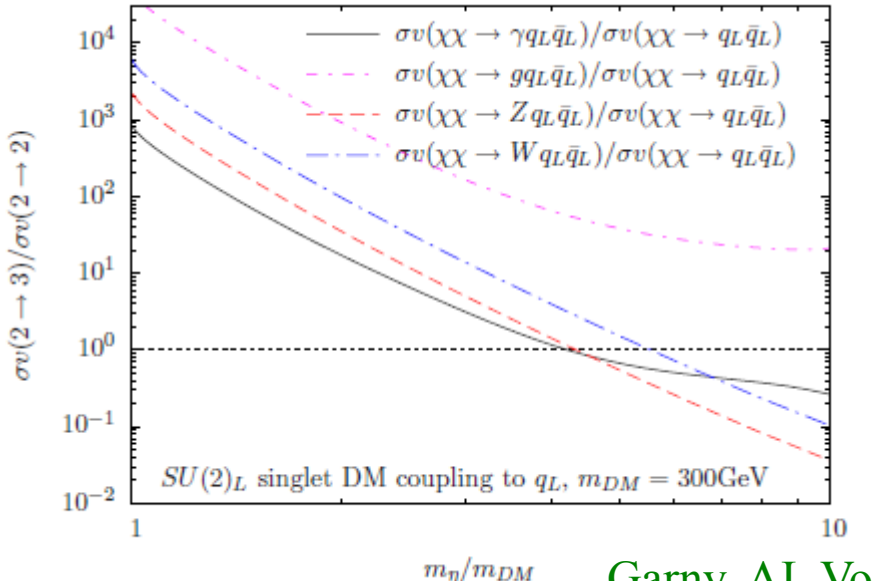
Coupling to leptons





Coupling to quarks

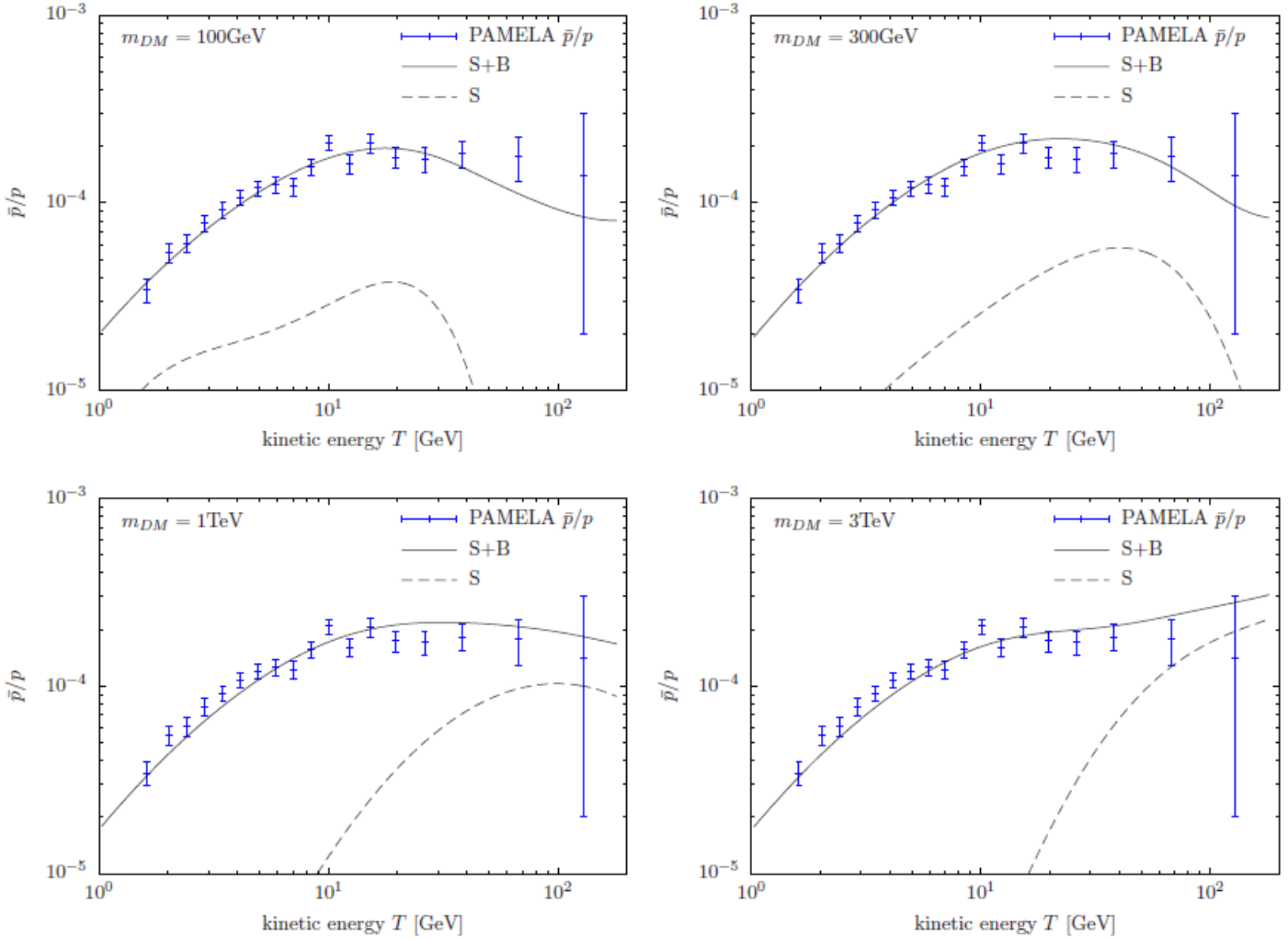




Garny, AI, Vogl

2- Antiproton limits on 2 → 3 processes

Limits from the PAMELA $\bar{p}/p$ measurements



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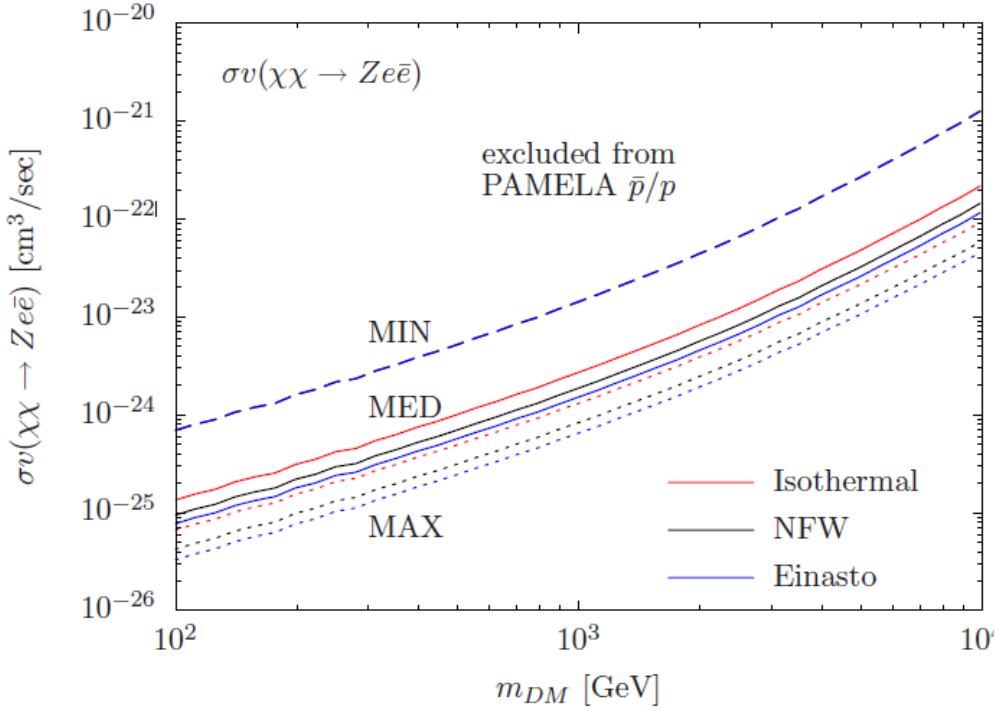
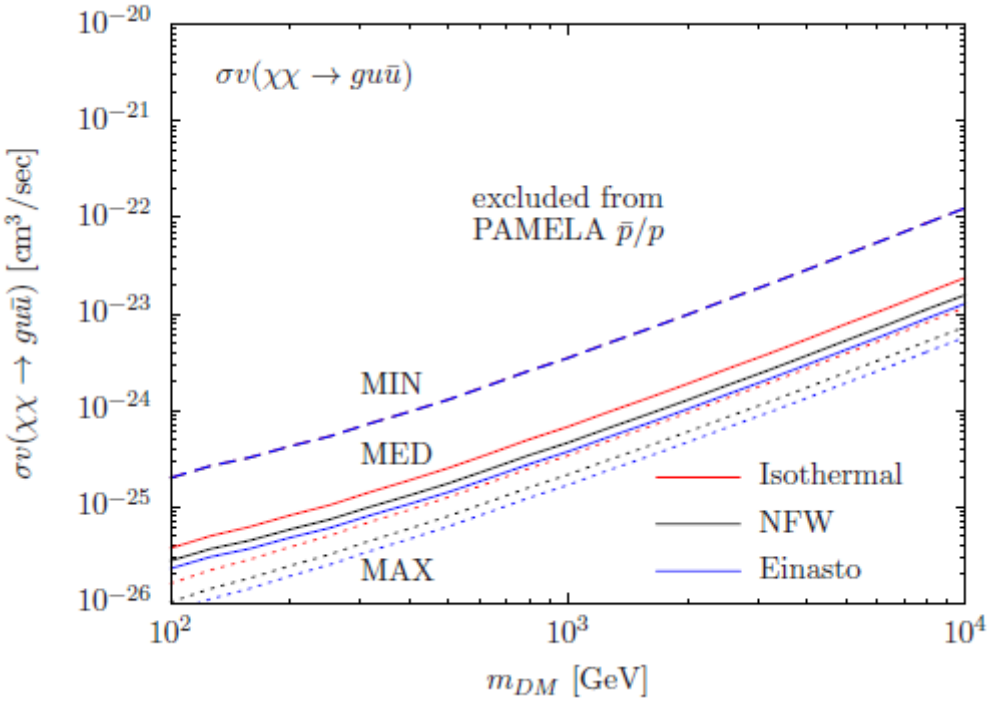


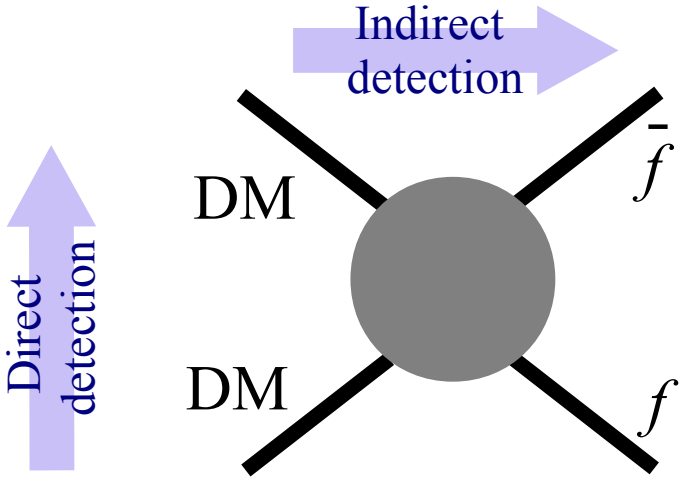


Garny, AI, Vogl

Limits for $\sigma v(\chi\chi \to W e\nu)$ very similar, although with some (mild) dependence on $m_{\eta 0} - m_{\eta \pm}$.

3- Interplay direct detection – indirect detection

Naive connection between direct detection and indirect detection:



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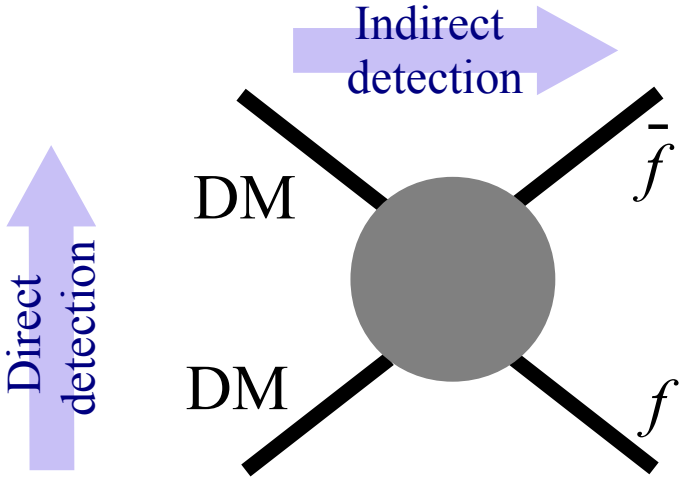
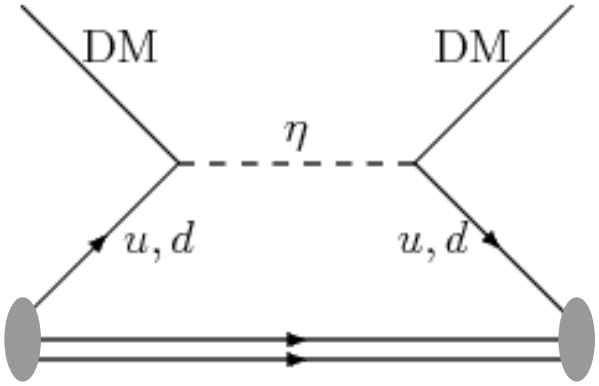
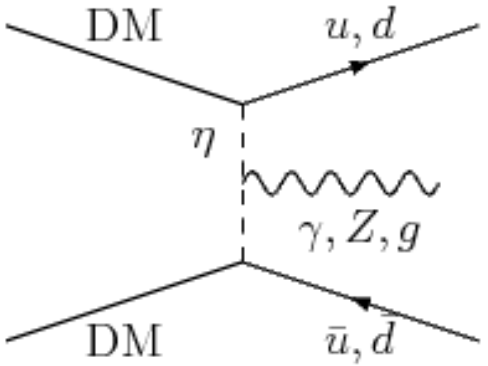


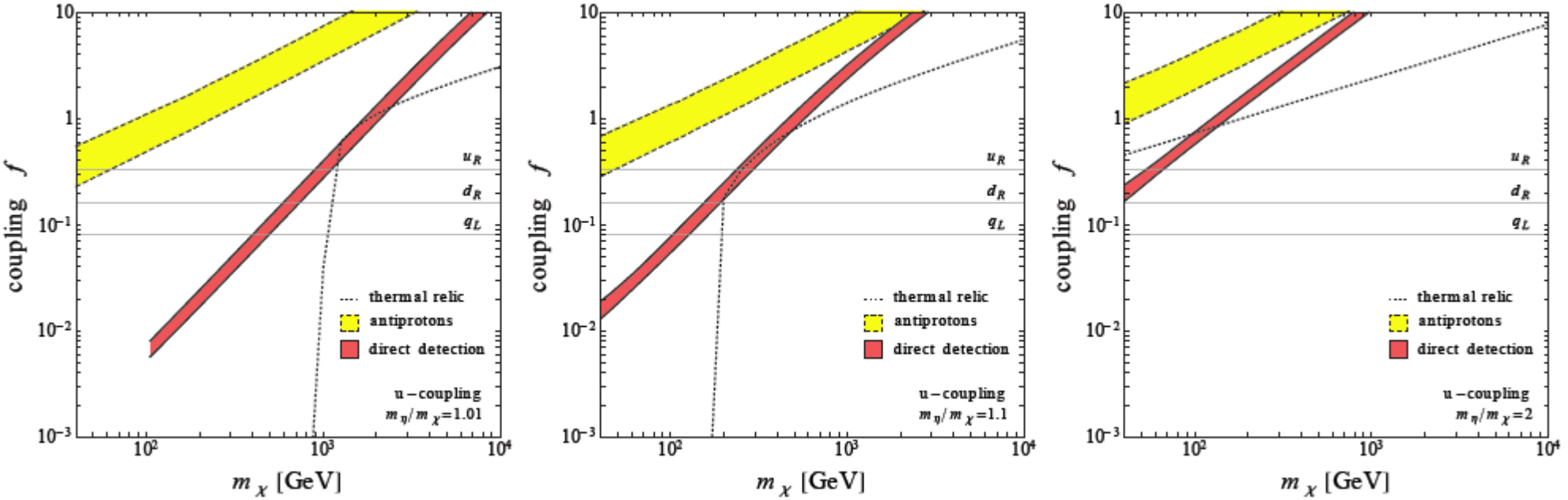
However, in direct search experiments it is probed the DM coupling to *a light quark*.
$\Longrightarrow$ The $2 \to 2$ annihilation into light quarks is suppressed.
$\Longrightarrow$ **The $2 \to 3$ annihilation is usually the dominant channel**





3- Interplay direct detection – indirect detection

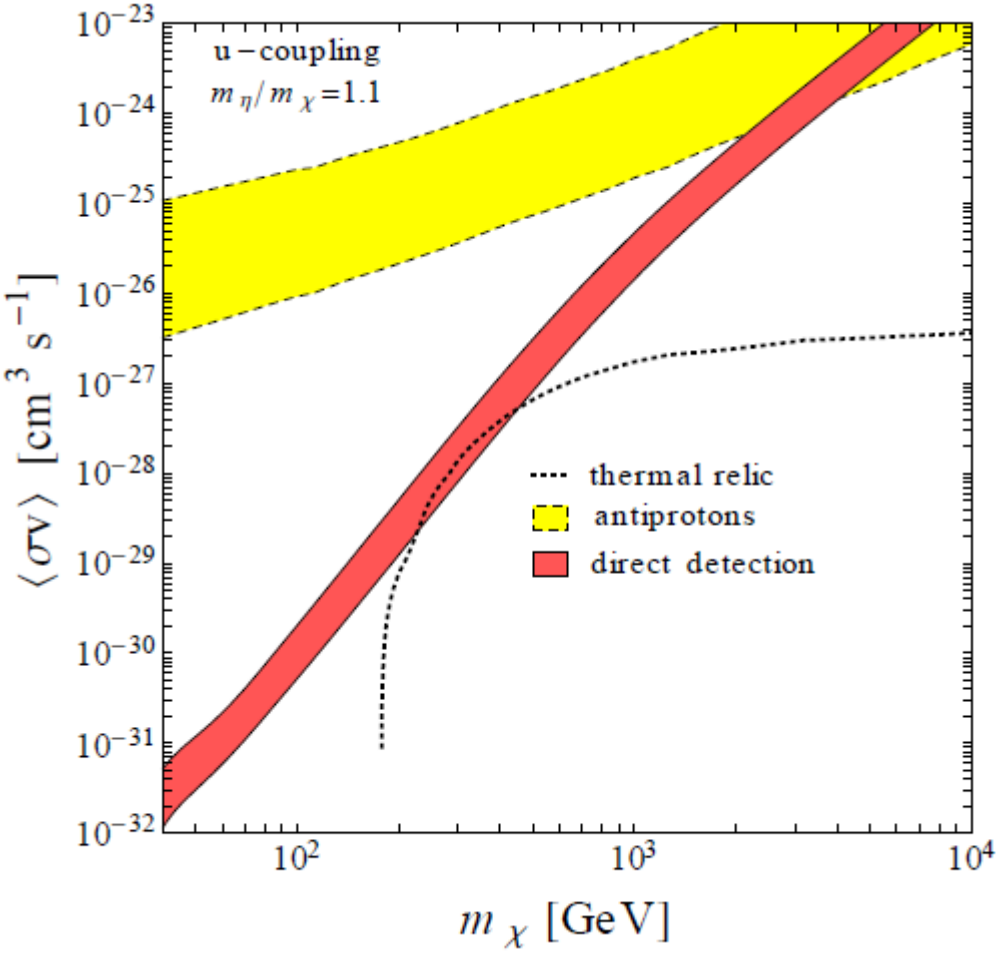
- We consider a toy model with $\mathcal{L}_{int} = -f\bar{\chi}\Psi_R\eta + \text{h.c.}$
- Limits on the coupling f from PAMELA and Xenon-100

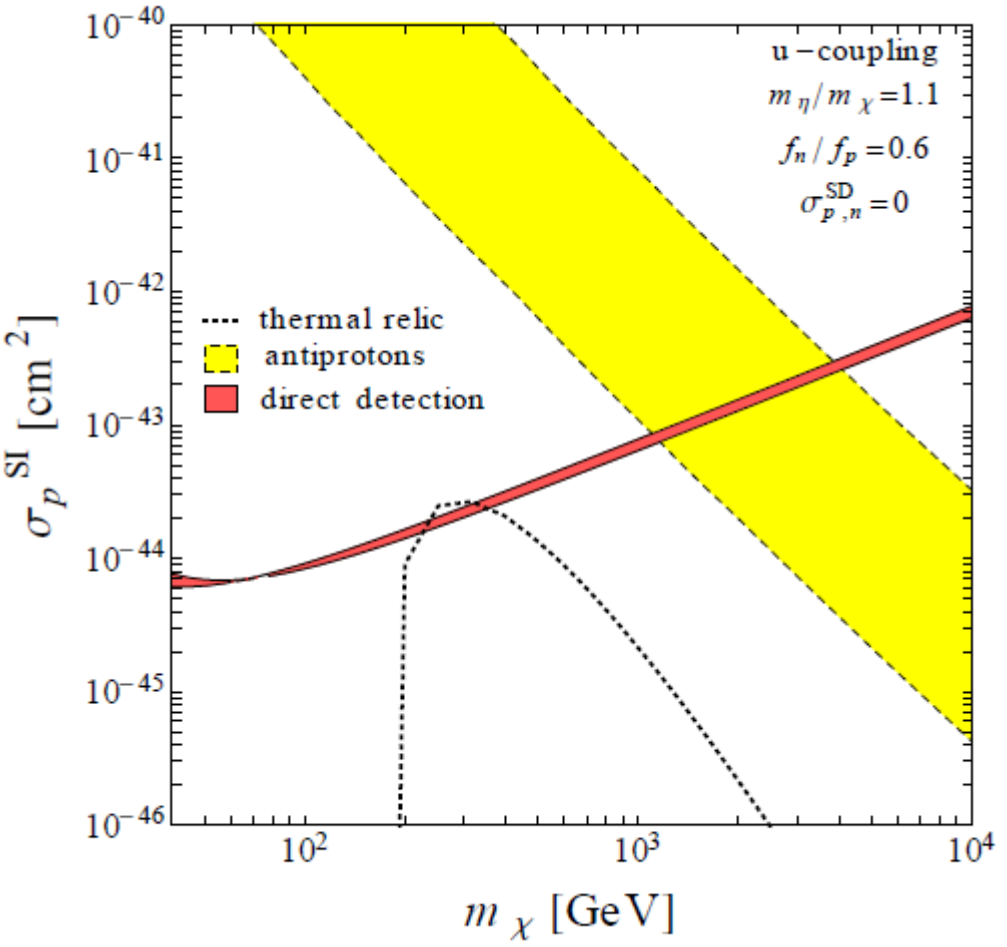


Garny, AI, Pato, Vogl

- 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 effective WIMP couplings in the degenerate limit. Hisano, Ishiwata, Nagata

3- Interplay direct detection – indirect detection





Garny, AI, Pato, Vogl

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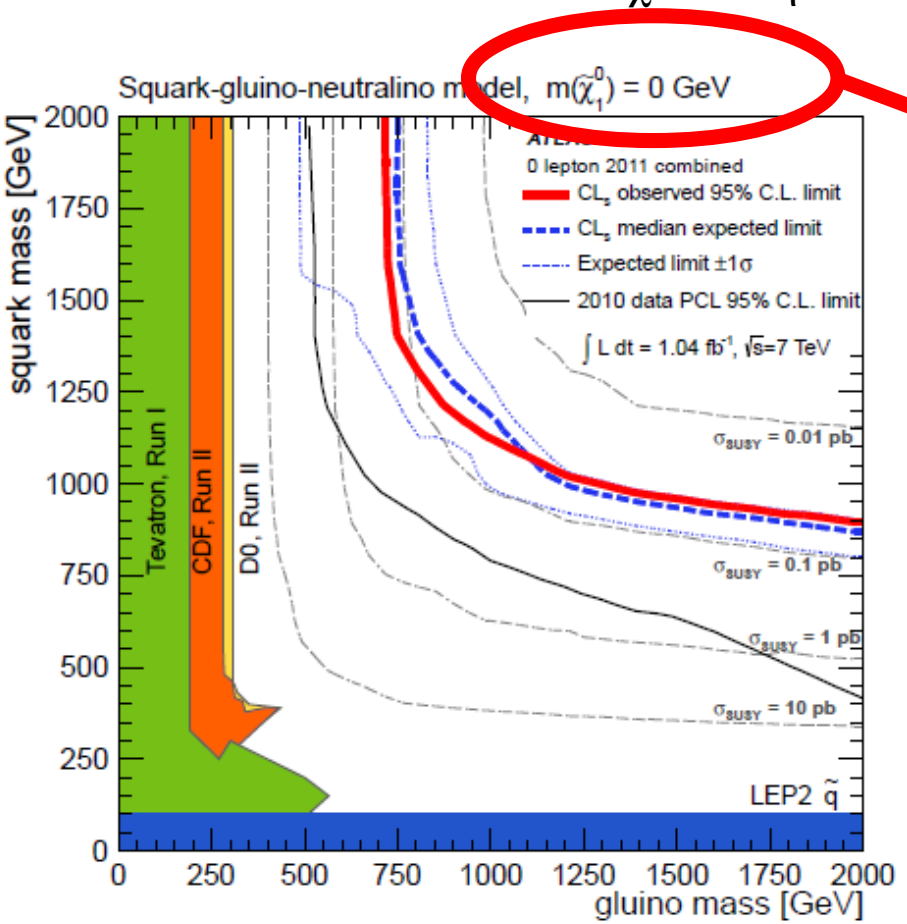
Note that in the limit $m_\chi \approx m_\eta$, the limits from collider searches are weak



Not our scenario!

ATLAS, arXiv:1109.6572

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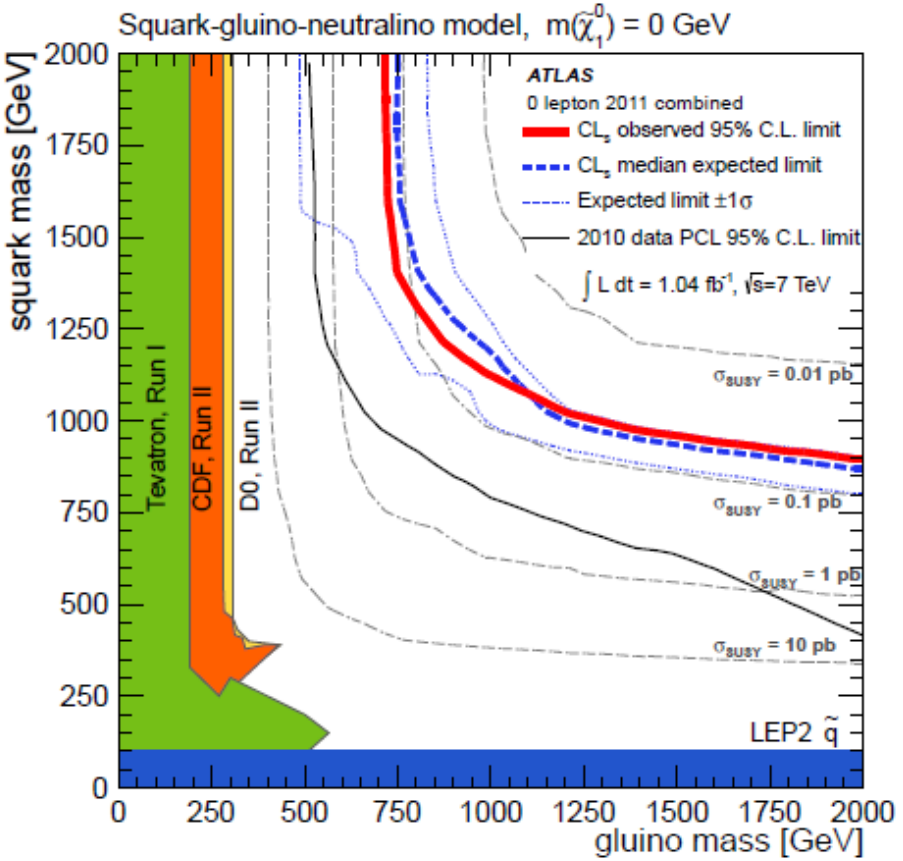

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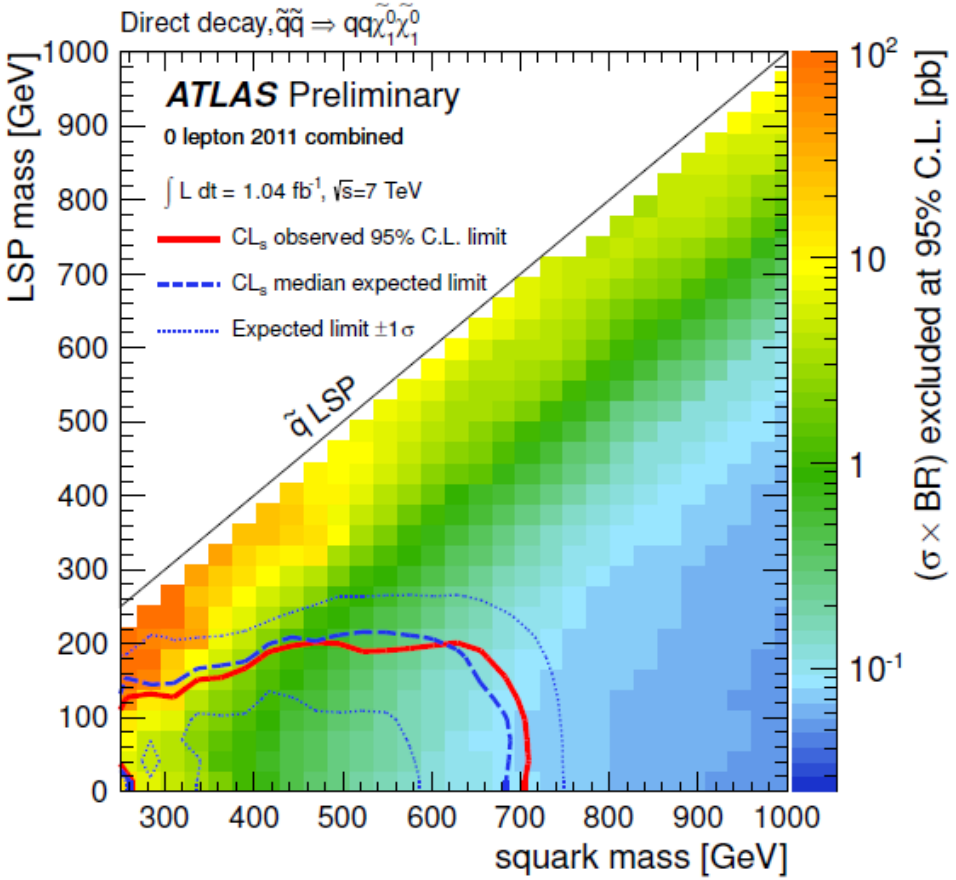
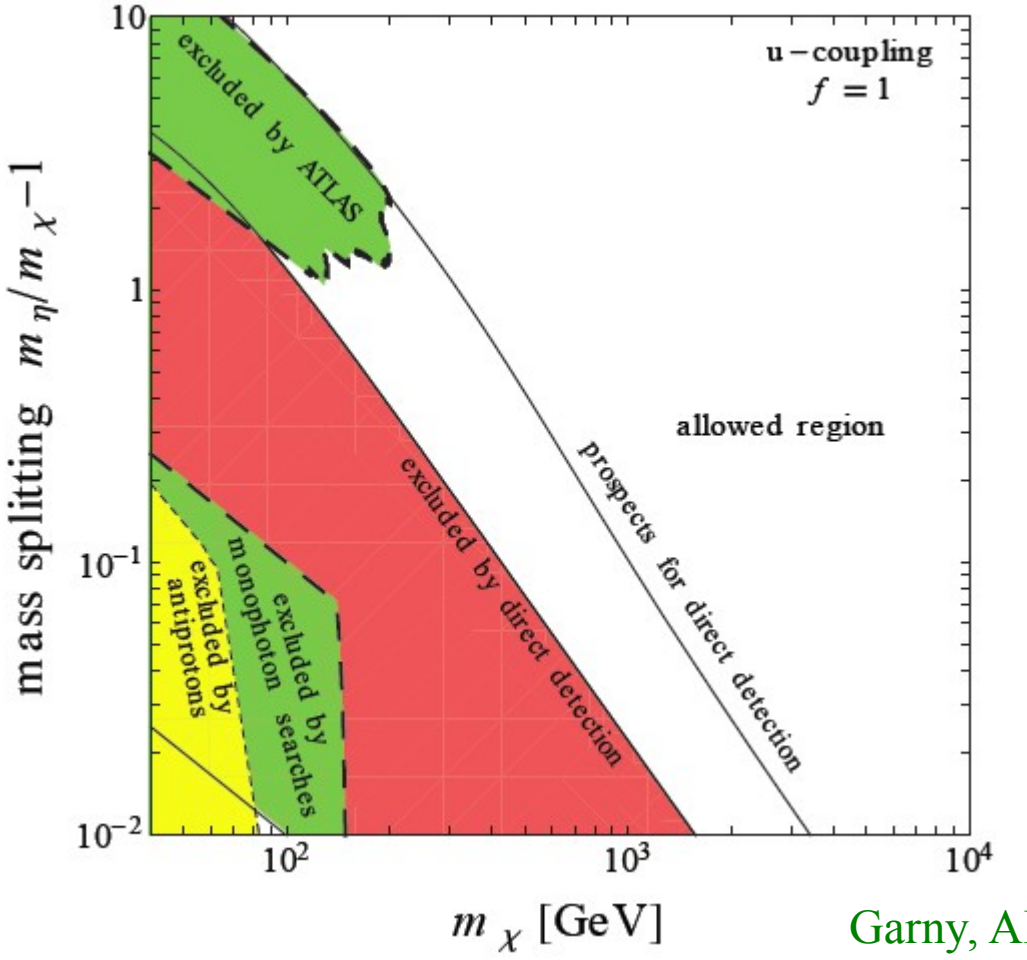


ATLAS-CONF-2011-155

The region $m_\eta - m_\chi < 10$ GeV is allowed for m_η even as low as 300 GeV.

Monojet searches? Work in progress

3- Interplay direct detection – indirect detection – collider searches



Garny, AI, Pato, Vogl

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. In fact, we already find a hint for a signal at $m_\chi \simeq 149$ GeV.

• We have calculated the limits on the process DM DM $\to f\bar{f}V$, from the Non observation of an excess in the PAMELA measurements of the $\bar{p}/p$ ratio.

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Thank you for your attention!