Indirect dark matter detection in mass degenerate scenarios

Alejandro Ibarra

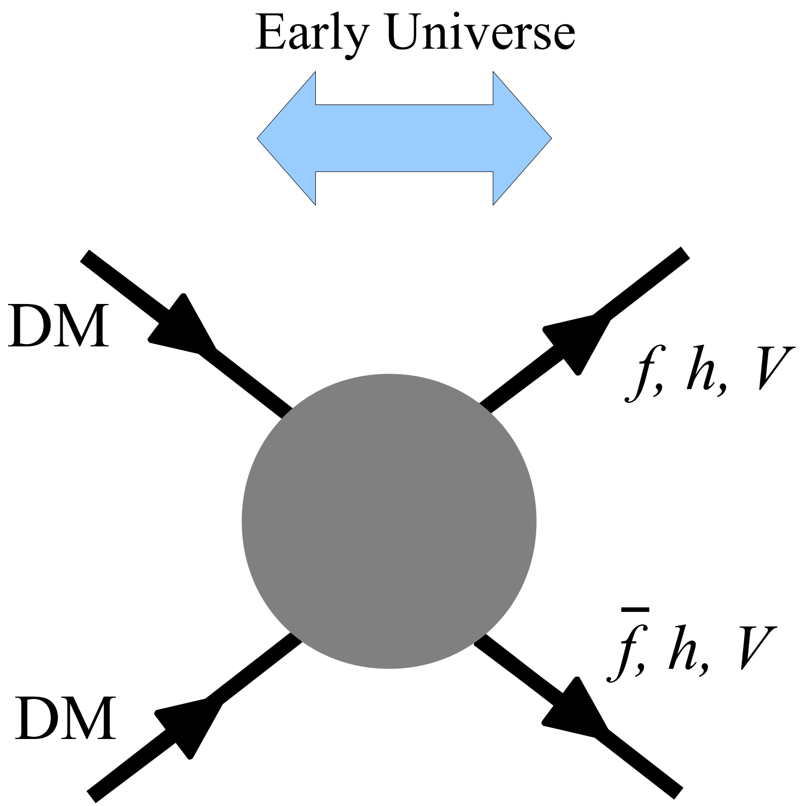
Technische Universität München

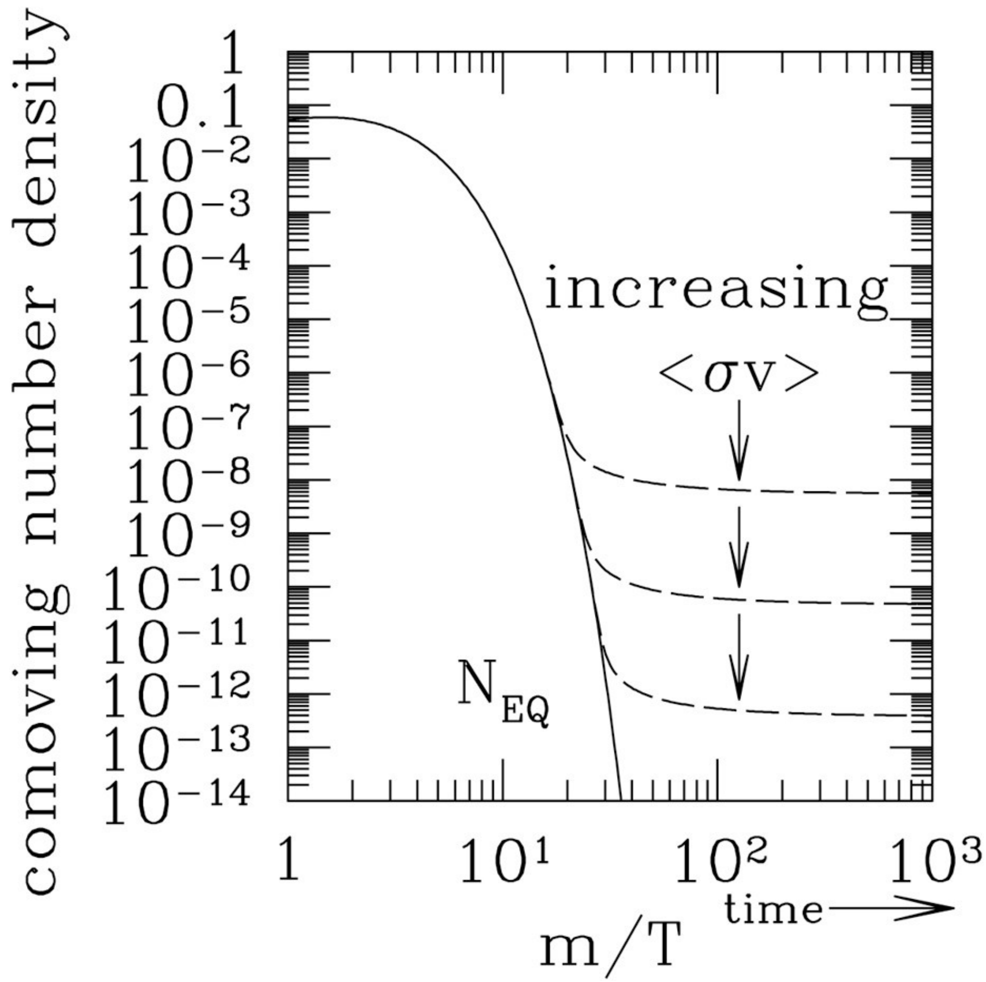
Based on
M. Garny, AI, S. Vogl, JCAP **1107** (2011) 028
M. Garny, AI, S. Vogl, JCAP **1204** (2012) 033
T. Bringmann, X. Huang, AI, S. Vogl, C, Weniger, JCAP **1207** (2012) 054
M. Garny, AI, M. Pato, S. Vogl, JCAP **1211** (2012) 017

HAP Dark Matter meeting
Münster
18-20 February 2013

Dark matter annihilations: standard picture

Thermal production of WIMPs

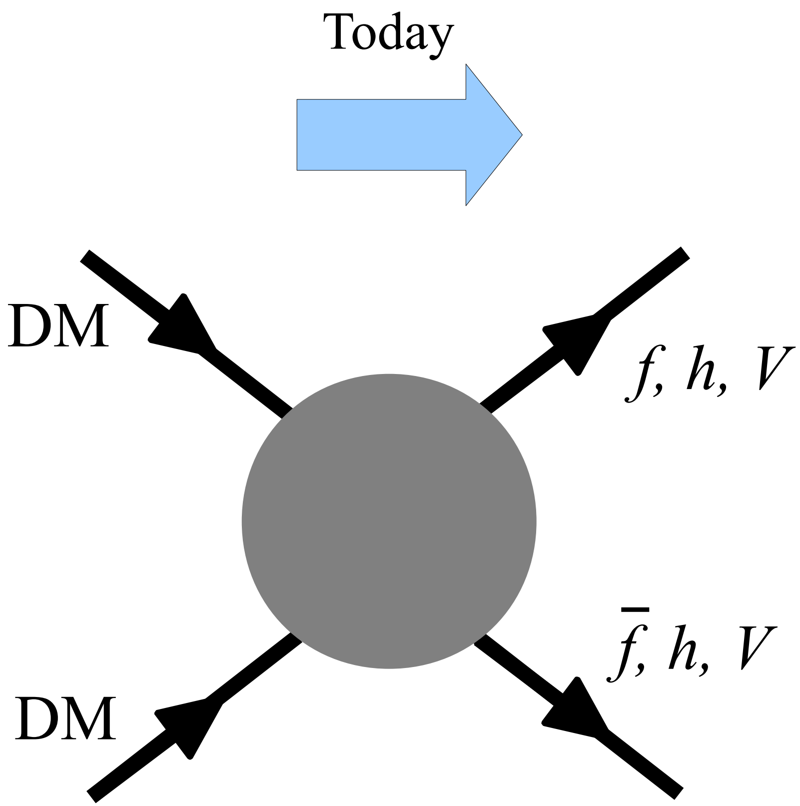




$$\Omega_{\rm DM} h^2 \simeq 0.11 \times \frac{3\times 10^{-26}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

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

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

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

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

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???

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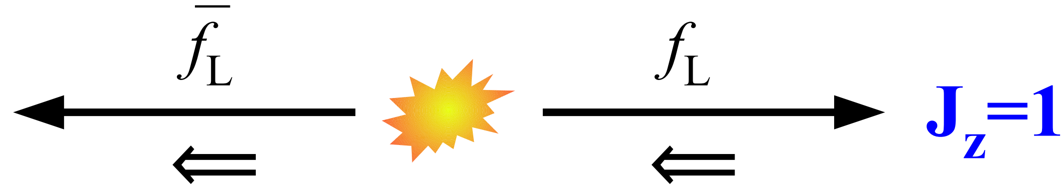
• Consider the annihilation DM DM $\rightarrow f\bar{f}$, with DM a Majorana fermion or a scalar particle



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

$J_z=0$

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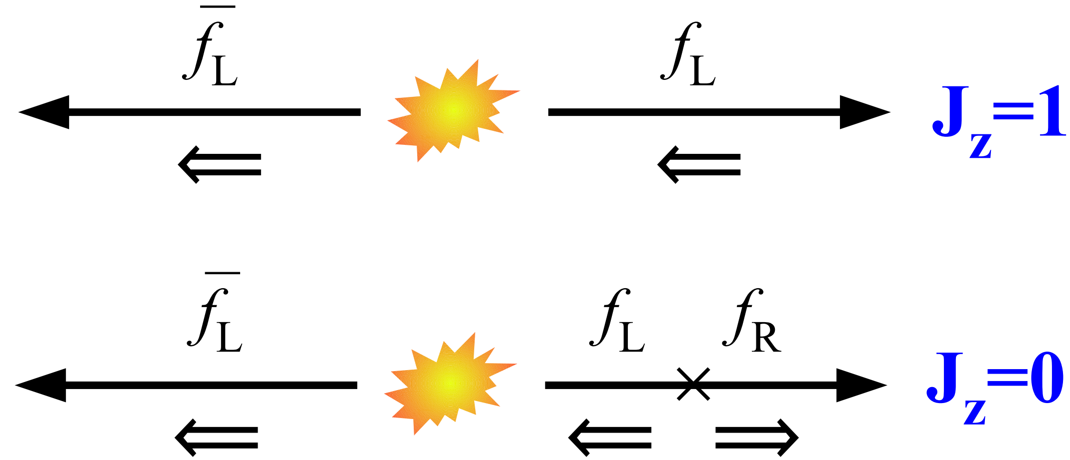

Rate of DM DM $\rightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

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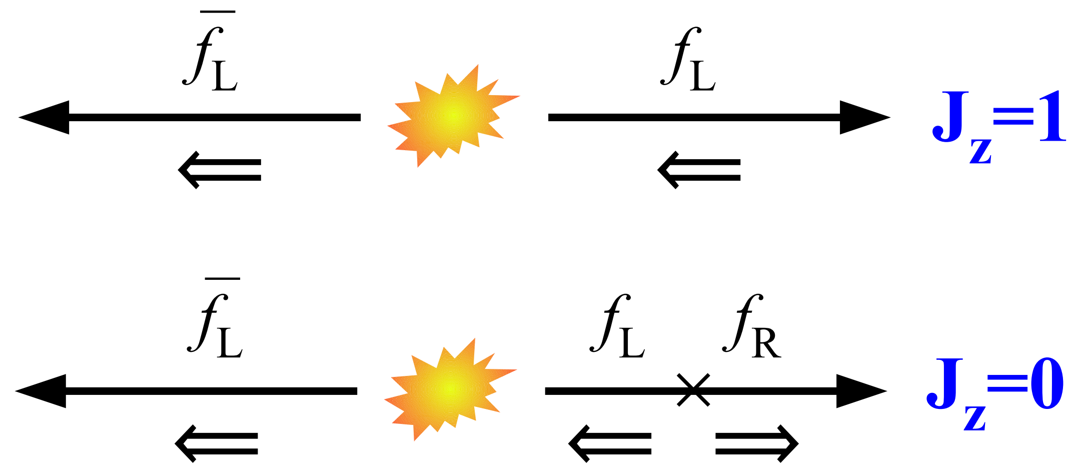


Rate of DM DM $\rightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

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

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

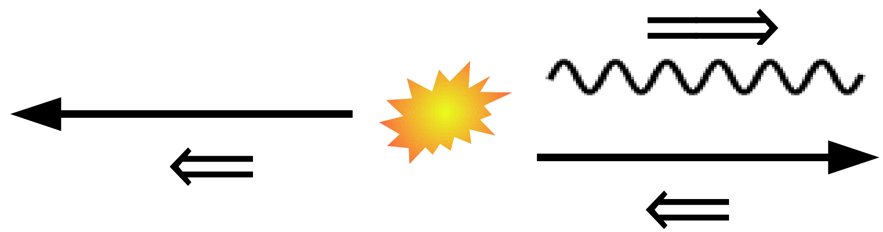
$$\Longrightarrow \langle \sigma v \rangle_{G.C.} \sim 3 \times 10^{-6} \langle \sigma v \rangle_{f.o.} \sim 10^{-31}\, \mathrm{cm^3 s^{-1}}$$

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

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 $\to f\bar{f}V$, while at the time of freeze-out, DM DM $\to f\bar{f}$

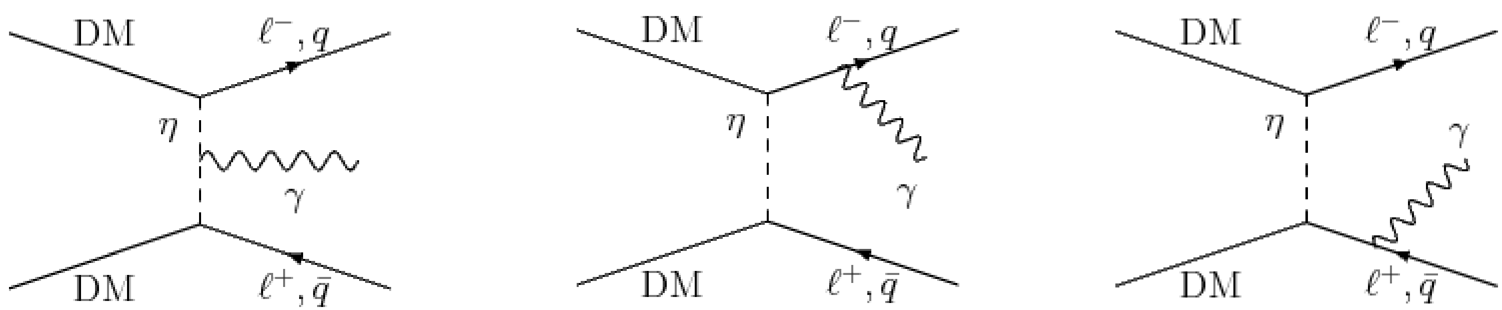
$$\langle \sigma v \rangle^{2\to 3}_{G.C.} \sim \frac{\alpha}{0.3\pi} \langle \sigma v \rangle^{2\to 2}_{f.o.} \sim 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Target cross section for this class of scenarios, instead of 3×10^{-26} $\mathrm{cm}^3\mathrm{s}^{-1}$.

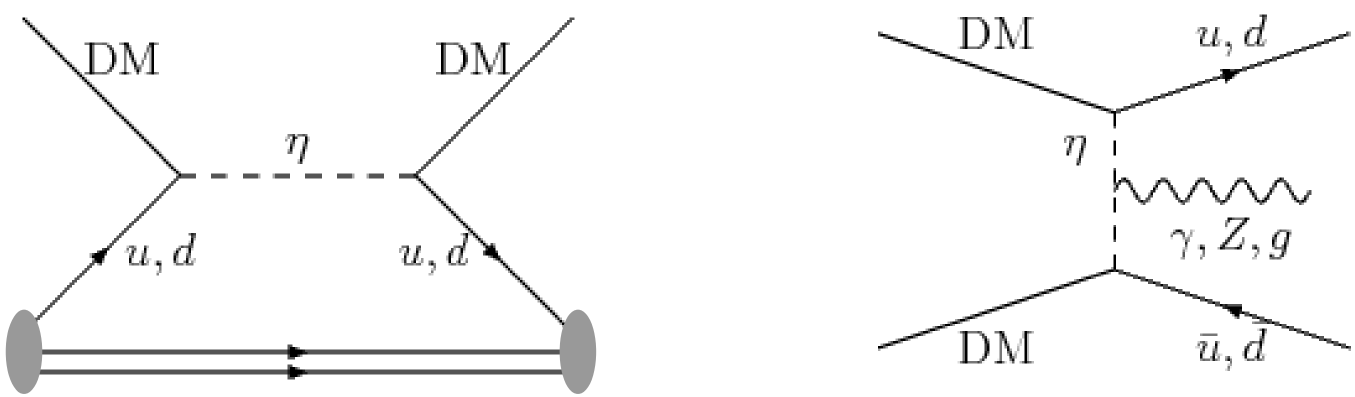
Outline

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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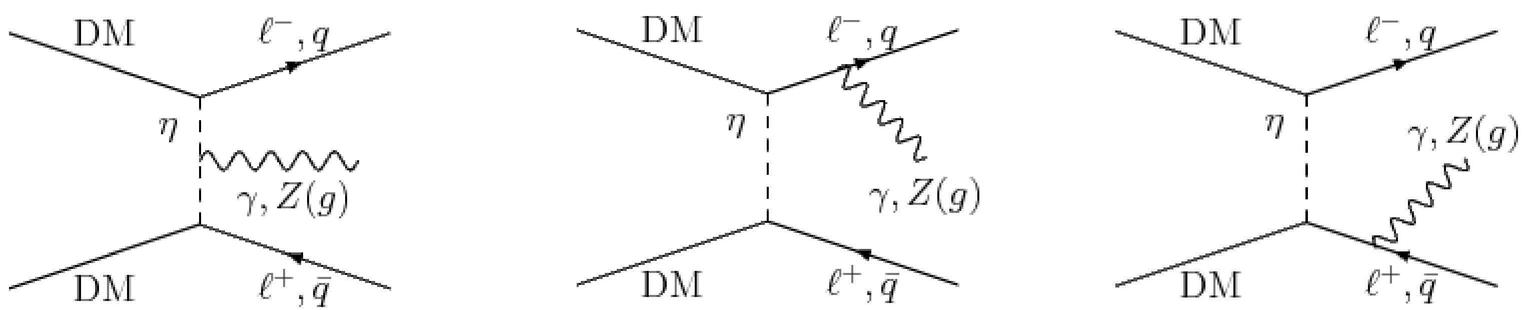

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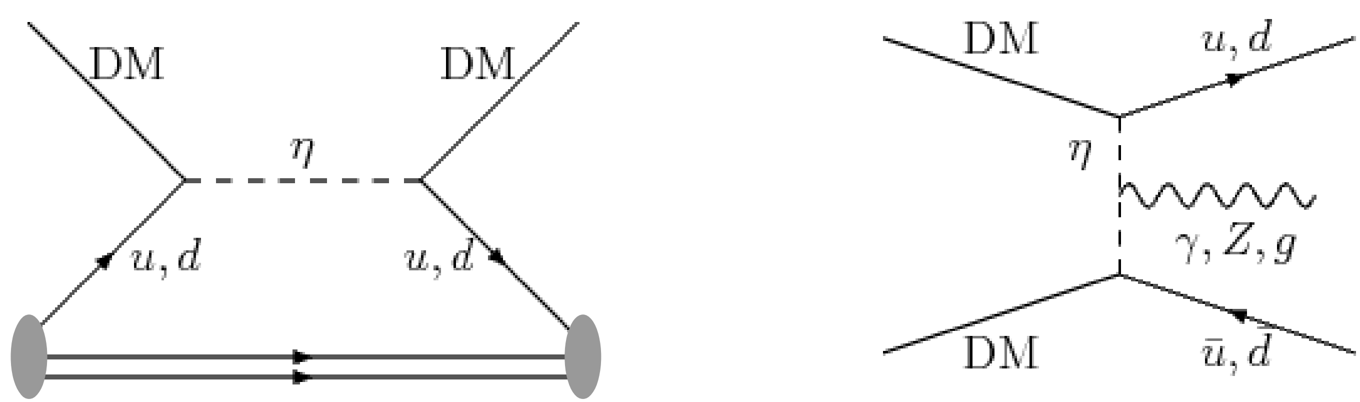
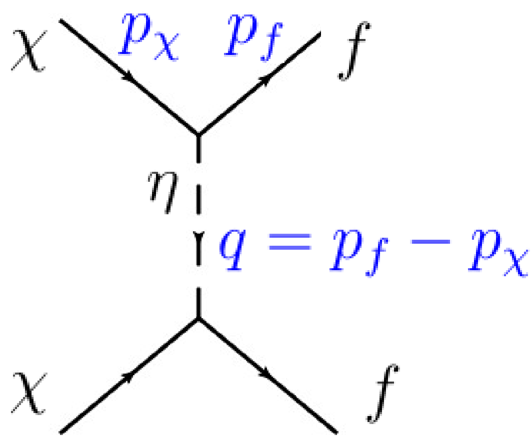


1- Search for signatures of internal bremsstrahlung with the Fermi-LAT

Consider a toy model with a Majorana dark matter particle, χ, an intermediate charged scalar particle, η, and a light SM fermion, f.

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

$2 \rightarrow 2$ annihilations



$$\Delta_F \sim \frac{1}{q^2 - m_\eta^2}$$

Annihilation cross section for 2→2 annihilations:

$$(\sigma v)_{\chi\chi\to f\bar{f}} = \Big[\qquad\qquad\qquad\qquad \Big] \mathcal{O}\left(\frac{m_\chi}{m_\eta}\right)^4$$

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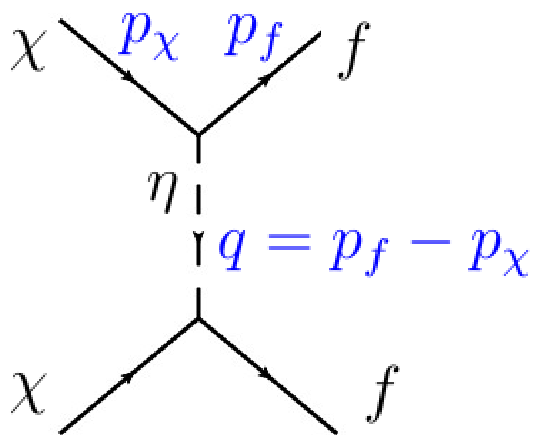

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$$(\sigma v)_{\chi\chi\to f\bar{f}} = \left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_f^2}{m_\chi^2}\right) + \mathcal{O}(v^2)\right]\mathcal{O}\left(\frac{m_\chi}{m_\eta}\right)^4$$

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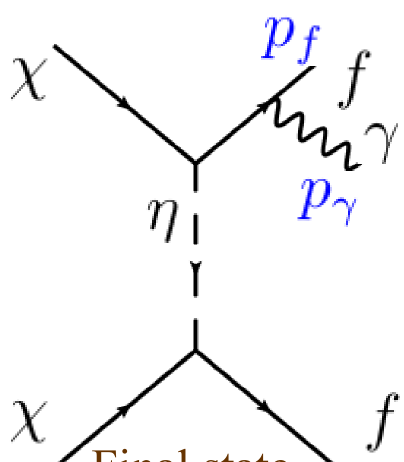
$2 \to 3$ annihilations via nearly on-shell final fermions



Final state radiation

$$S_F \sim \frac{1}{(p_f + p_\gamma)^2 - m_f^2} = \frac{1}{2 p_f p_\gamma}$$

Collinear/soft divergence

Annihilation cross section for FSR:

$$(\sigma v)^{\rm FSR}_{\chi\chi \to f\bar{f}\gamma} \simeq \frac{\alpha_{\rm em}}{\pi} \int_0^1 dx \frac{1 + (1-x)^2}{x} \log\left[\frac{4 m_\chi^2 (1-x)}{m_f^2}\right] (\sigma v)_{\chi\chi \to f\bar{f}}$$

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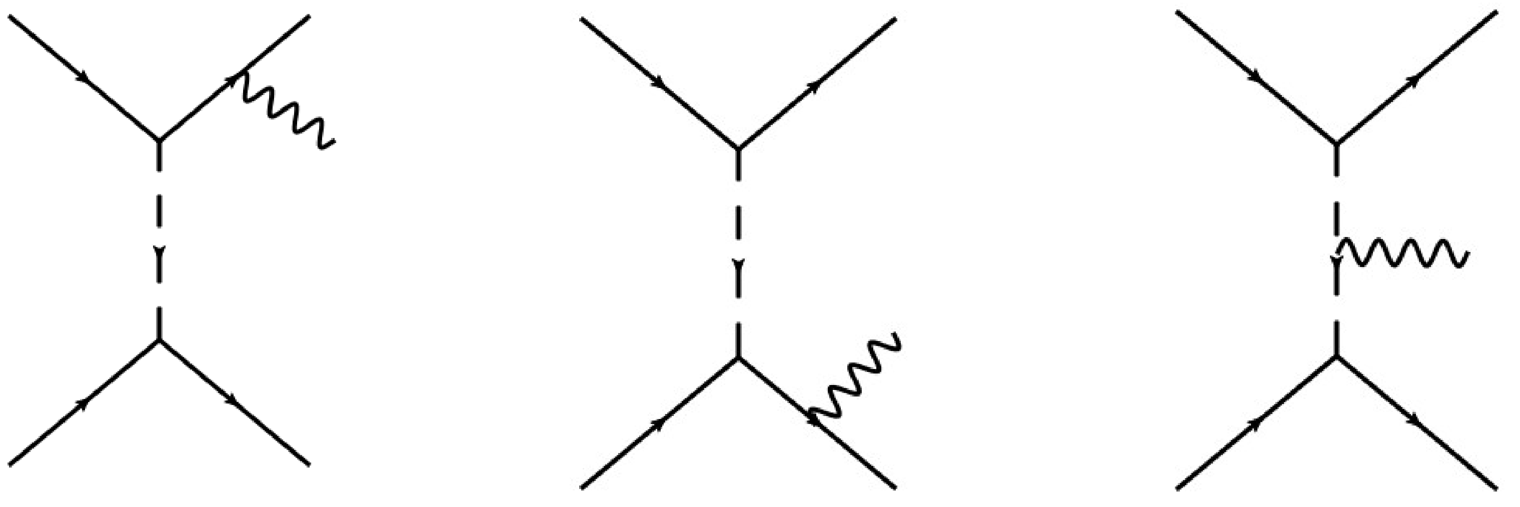
2 → 3 annihilations via off-shell final fermions



Annihilation cross section for internal Bremsstrahlung (FSR+VIB):

$$(\sigma v)_{\chi\chi\to f\bar{f}\gamma} = \frac{\alpha_{\rm em}}{\pi}\left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_\chi}{m_\eta}\right)^8 + \mathcal{O}(v^2)\mathcal{O}\left(\frac{m_\chi}{m_\eta}\right)^4\right]$$

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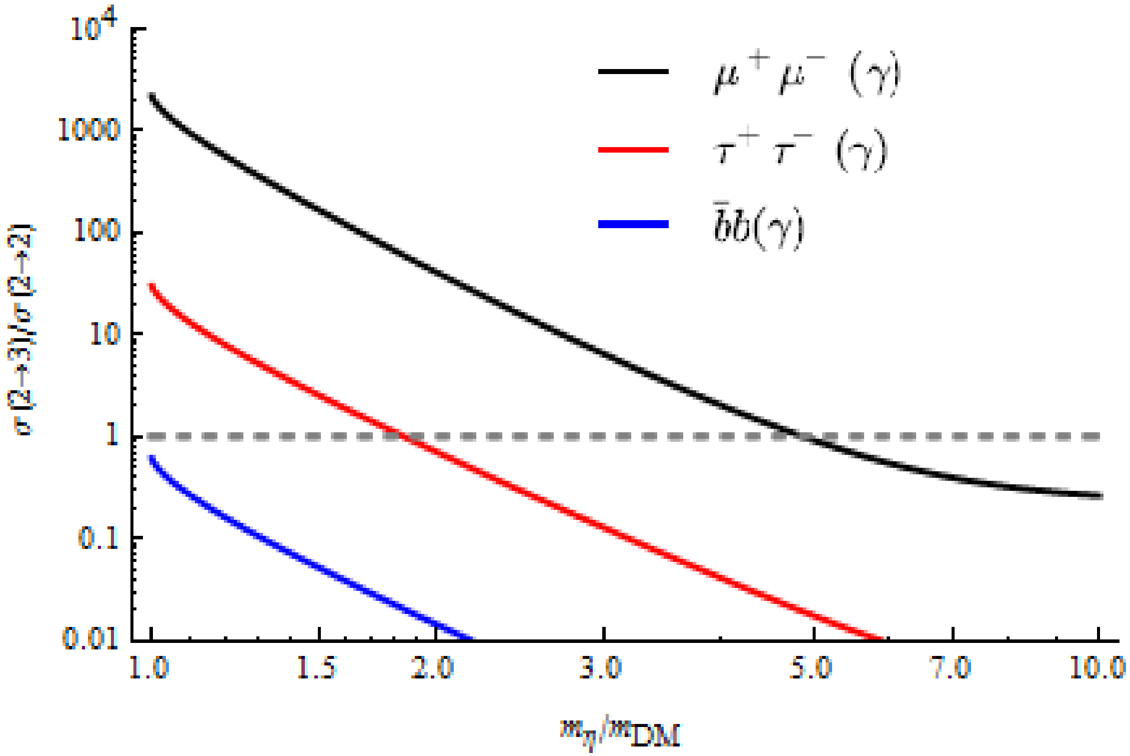
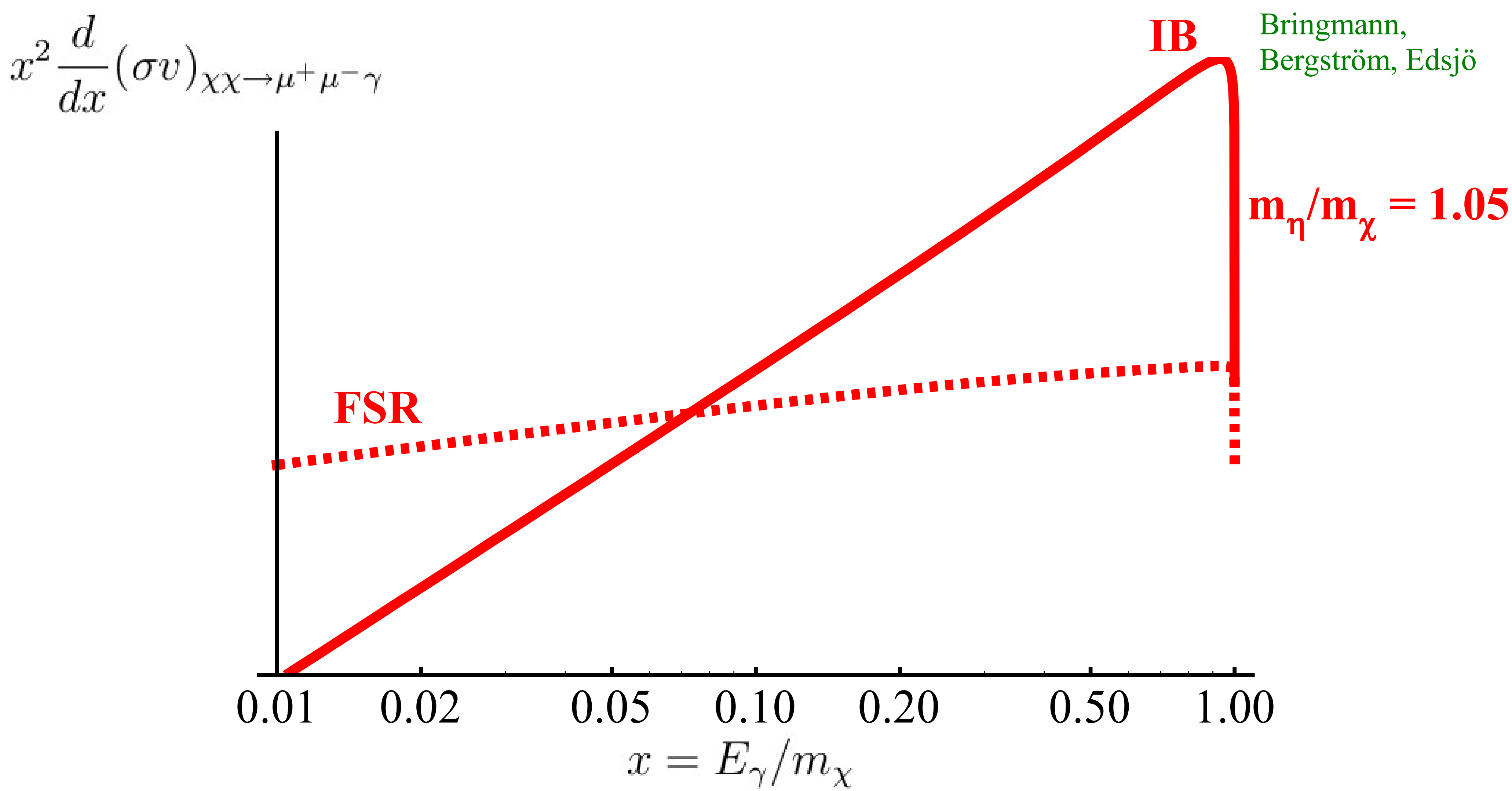


The cross section of the $2 \to 3$ process is enhanced when $m_\eta/m_{DM} \simeq 1$.

Bergström
Flores, Olive, Rudaz

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

The γ-ray spectrum from VIB display a prominent spectral feature!



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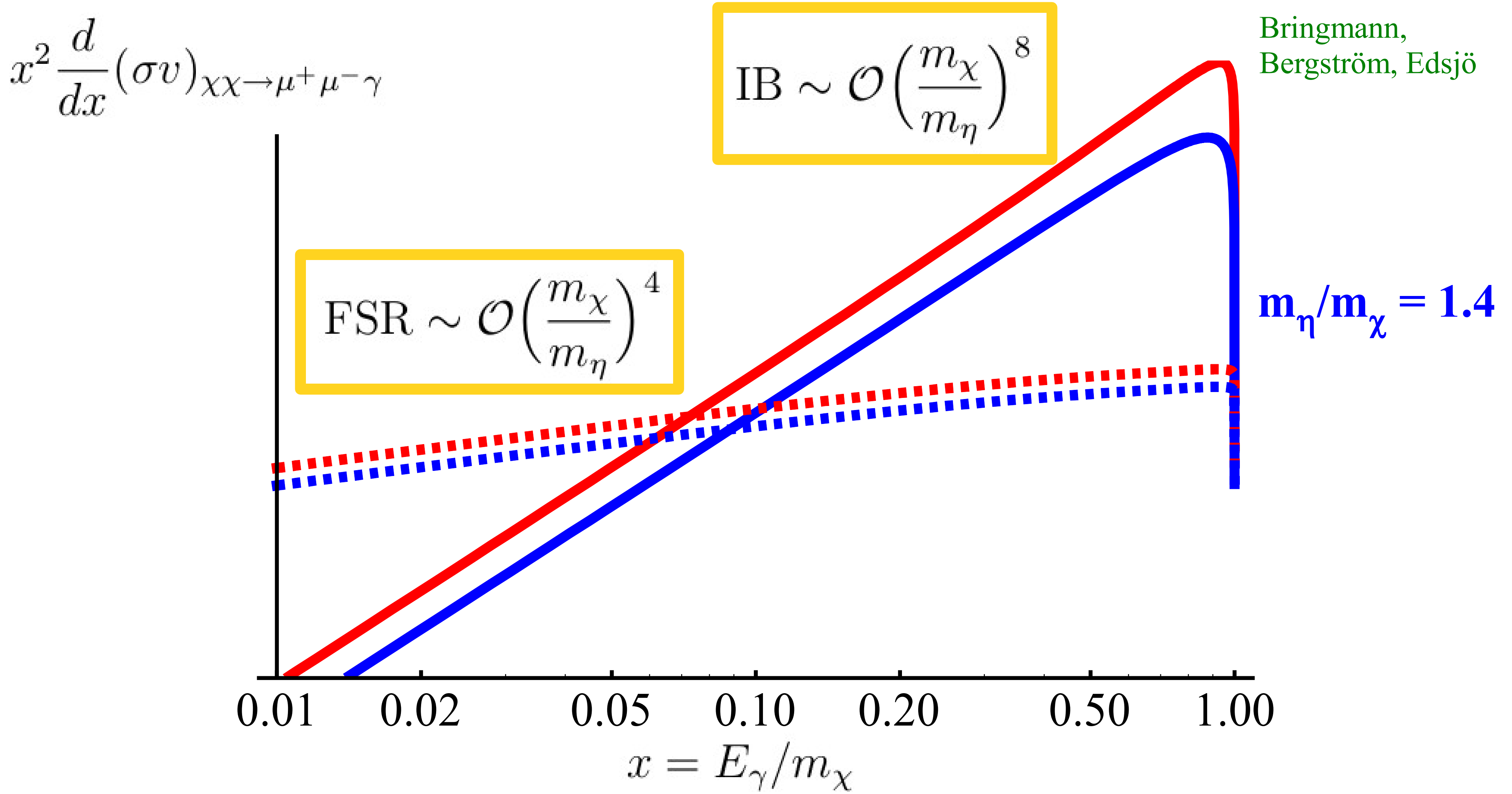

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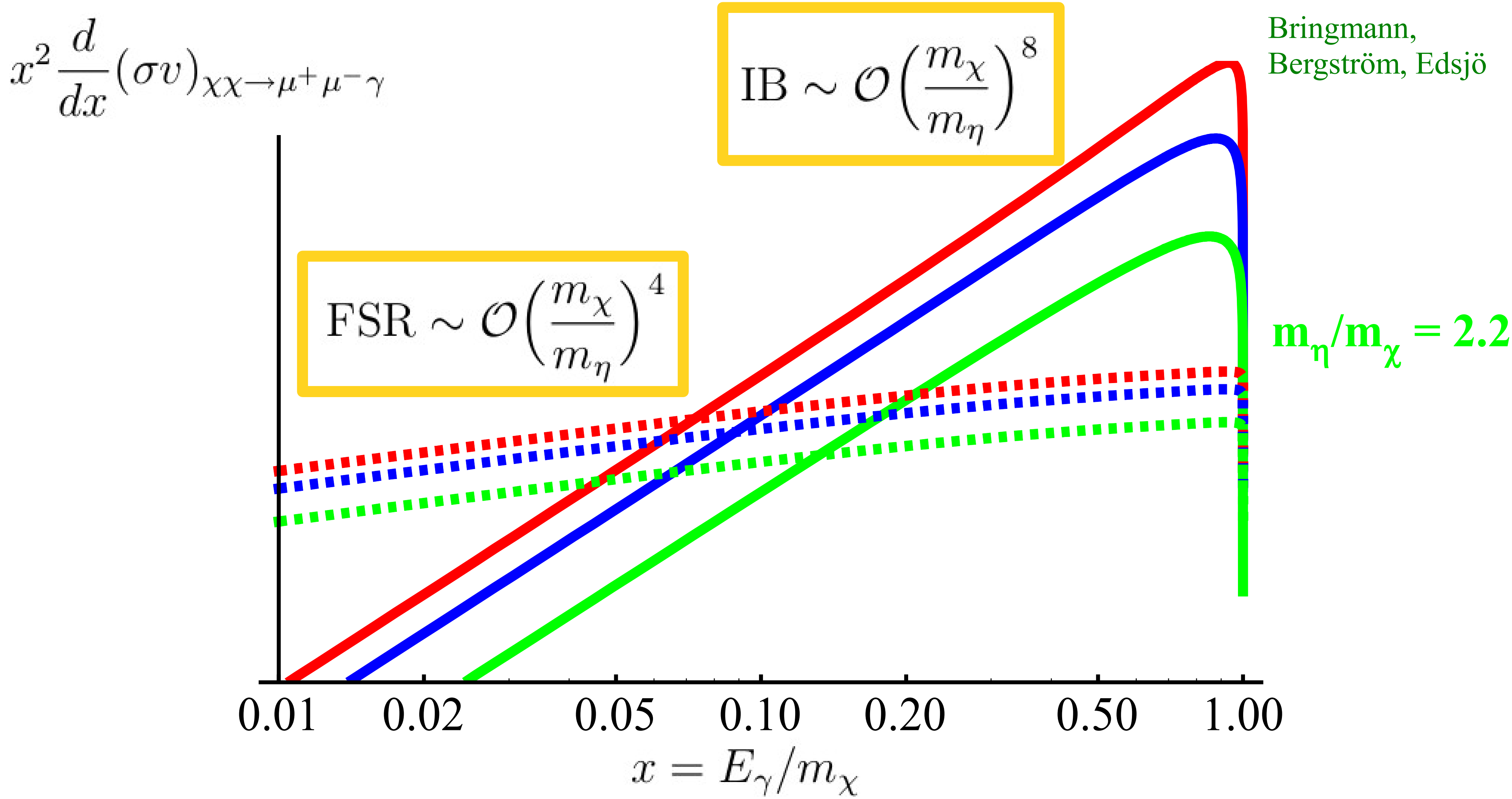

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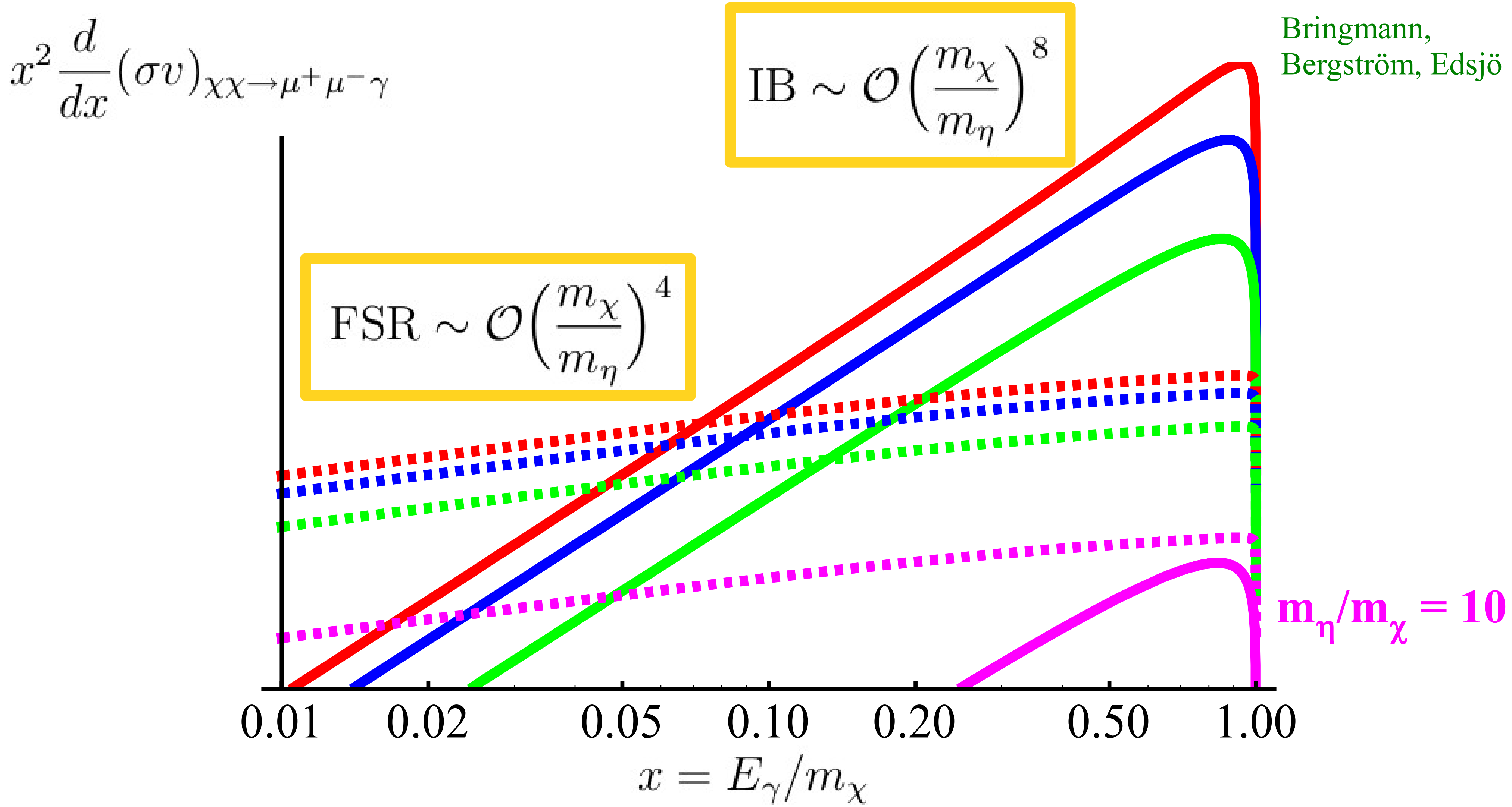

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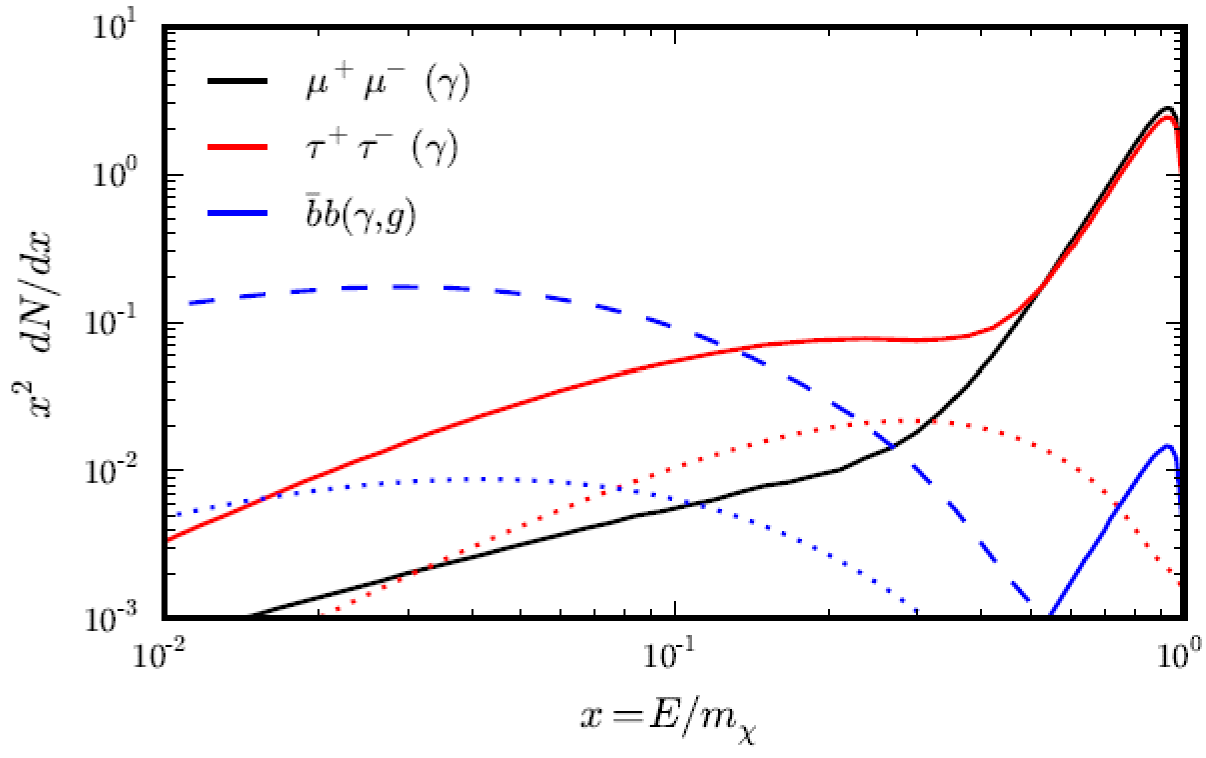
Prompt gamma-ray spectrum from dark matter annihilations

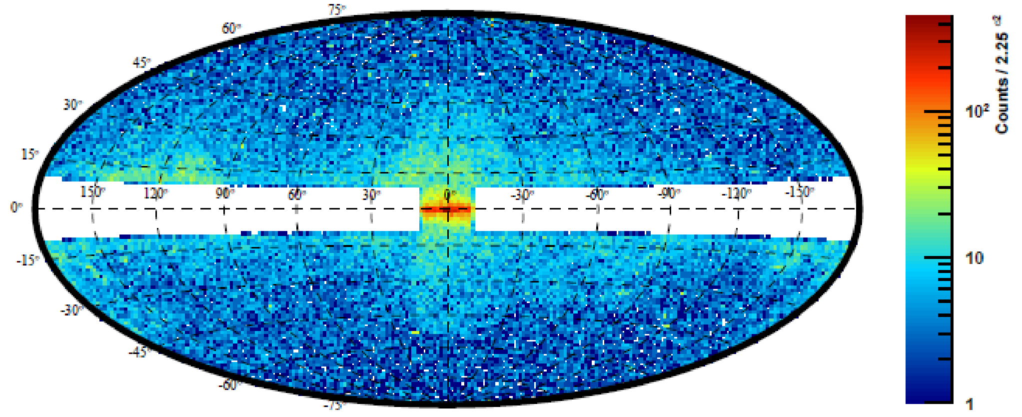


Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

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

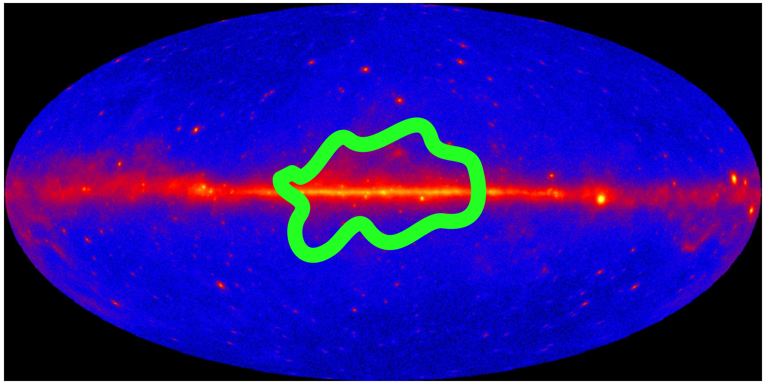
Traditional approach: select a fixed region of the sky and search for features.

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

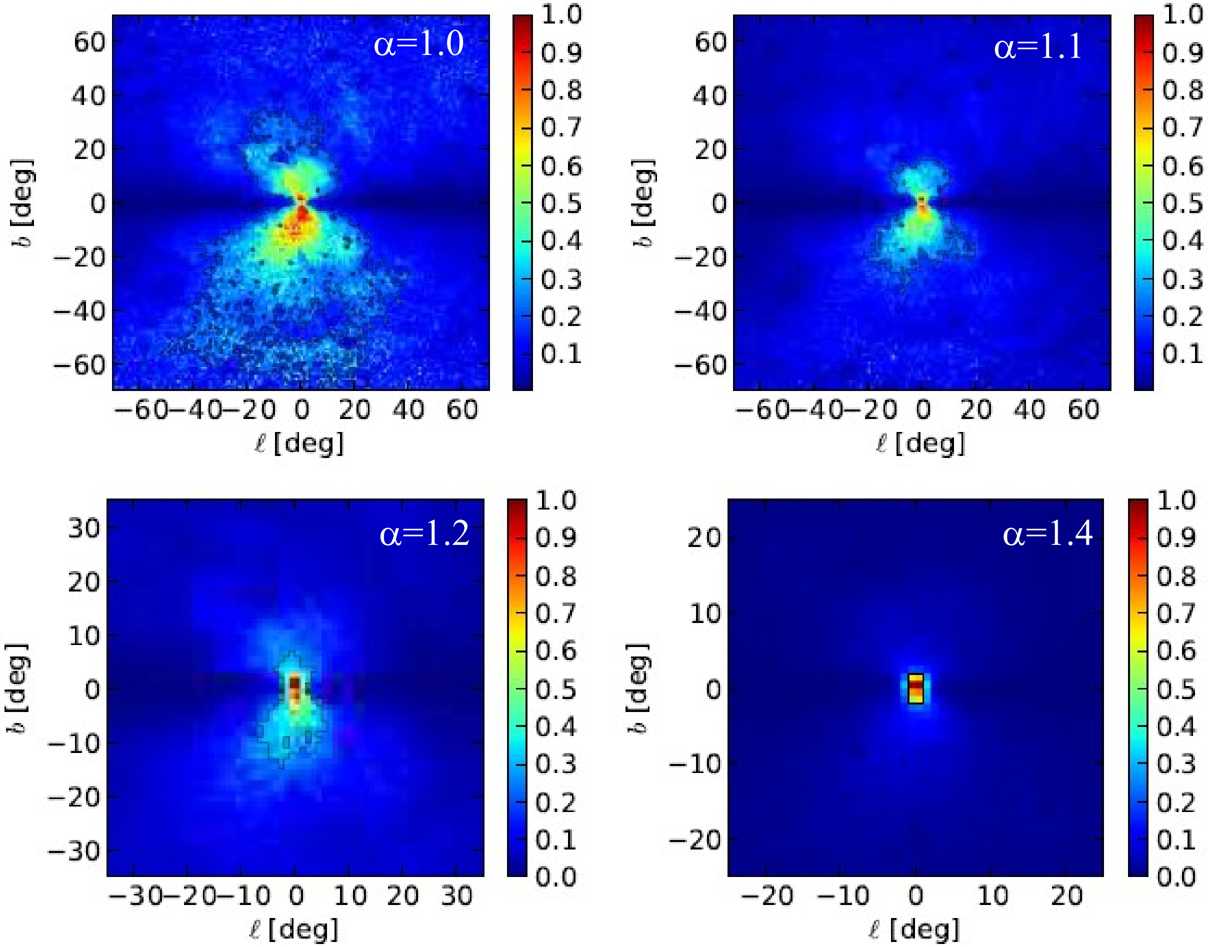


1- Search for signatures of internal bremsstrahlung with the Fermi-LAT

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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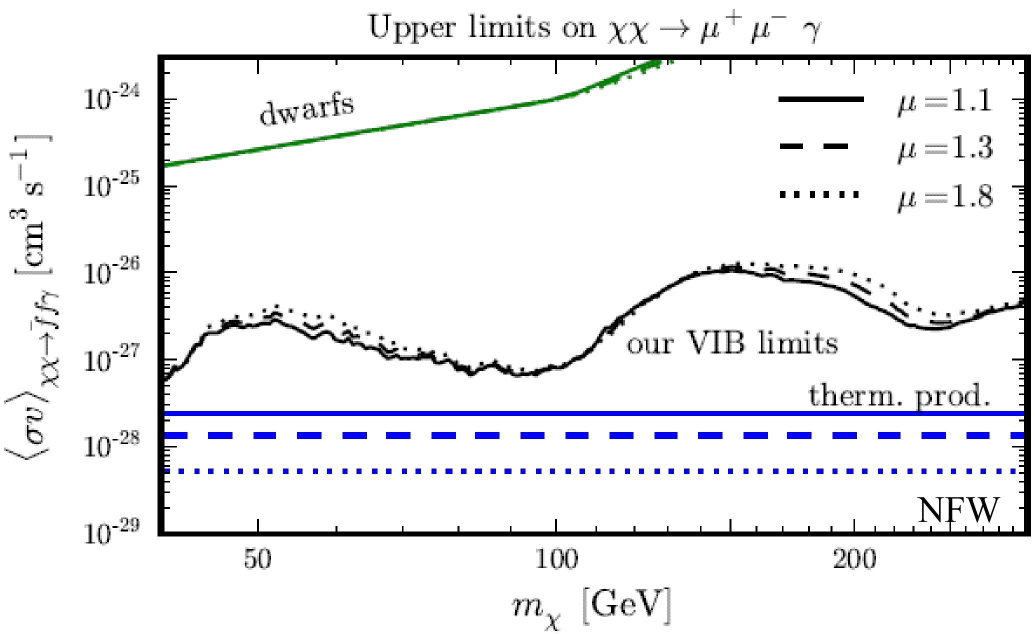

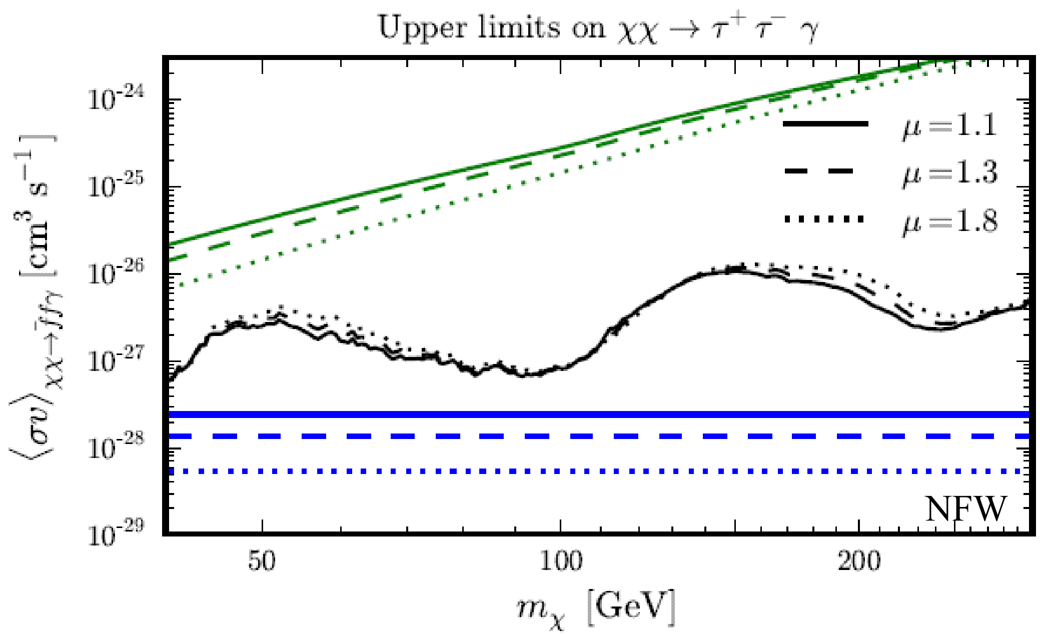

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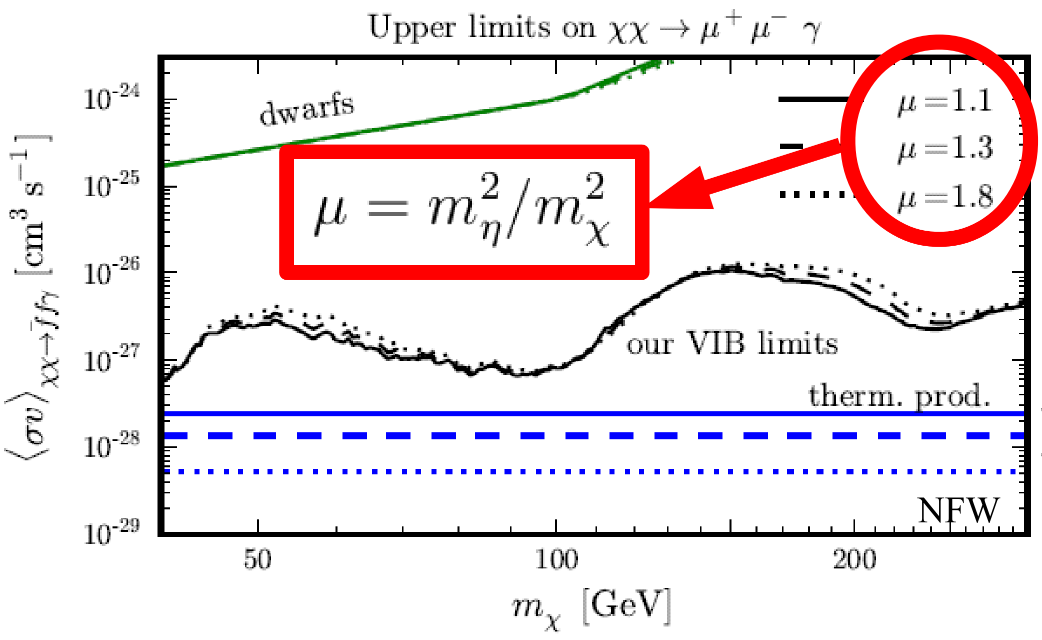

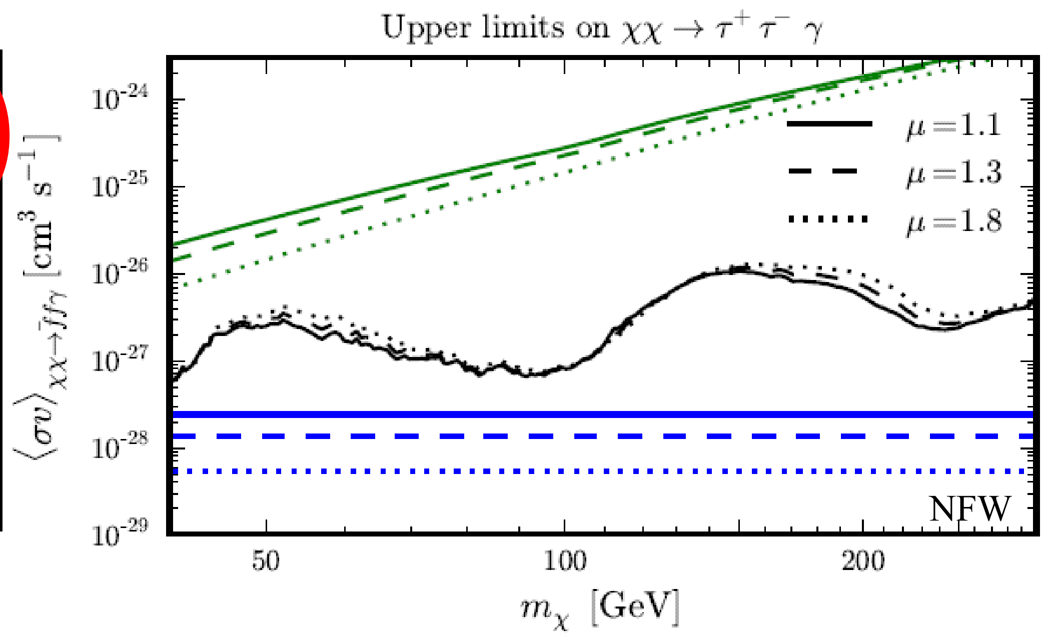

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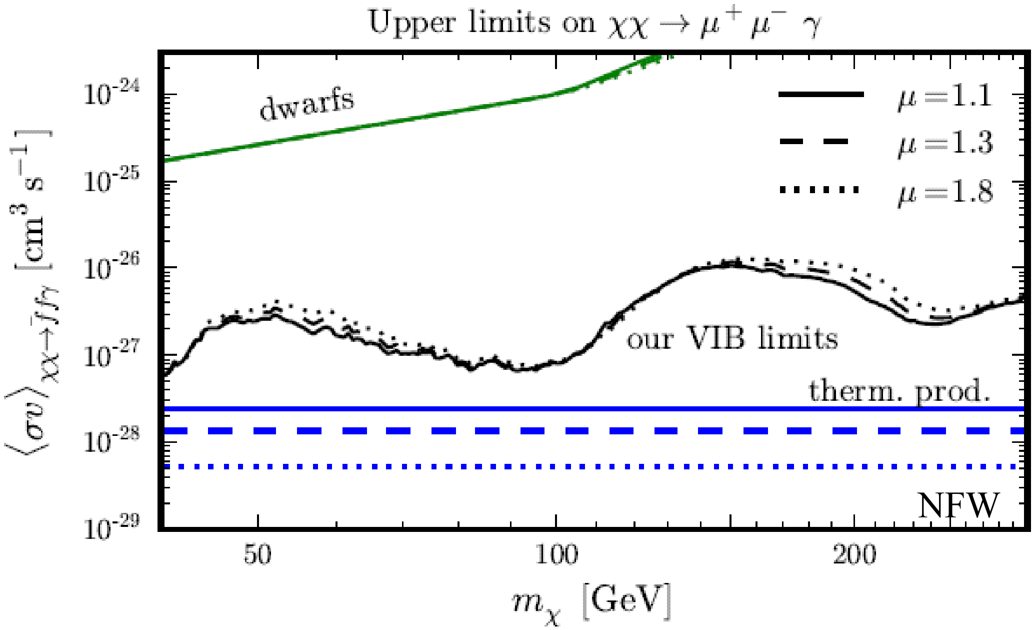

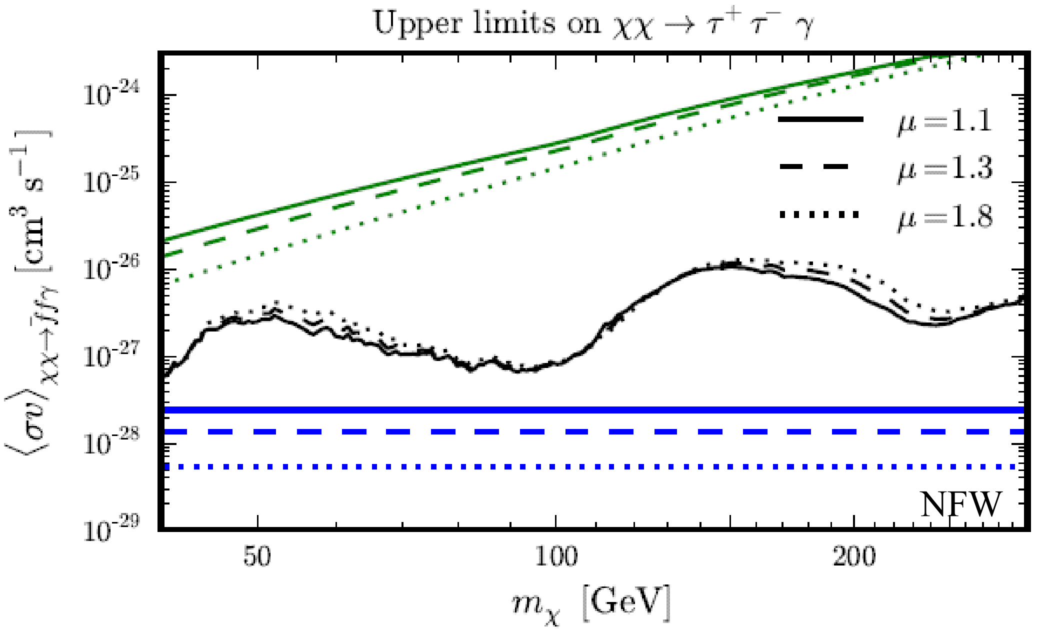

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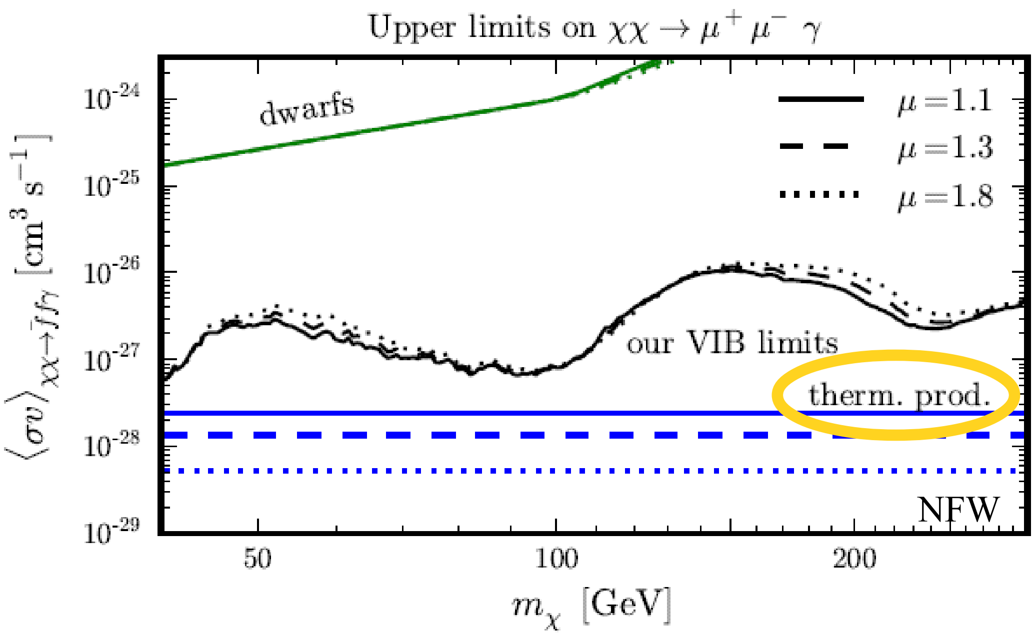

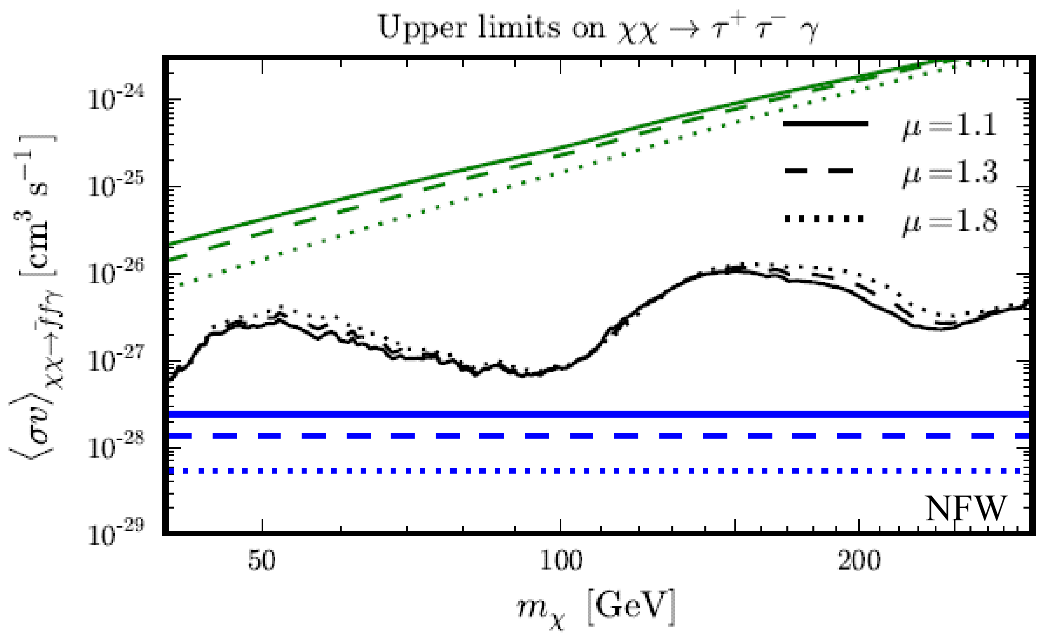

Dark matter relic density from $\chi\chi \leftrightarrow f\bar{f}$

$$\Omega_\chi h^2 \simeq 0.11 \frac{1}{N_c} \left(\frac{0.35}{y}\right)^4 \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2 \frac{(1+\mu)^4}{1+\mu^2}$$

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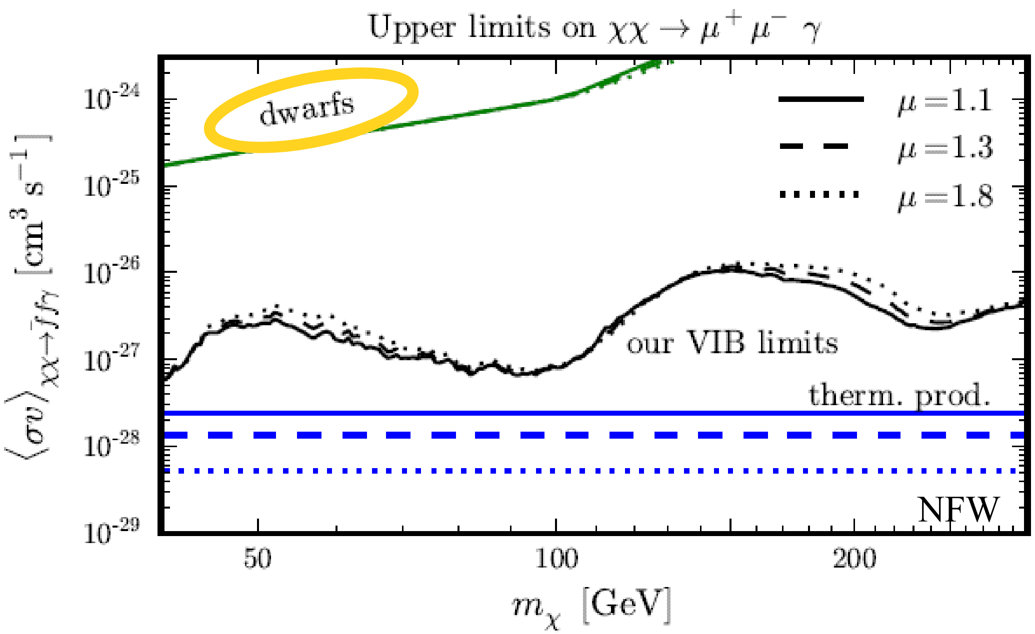

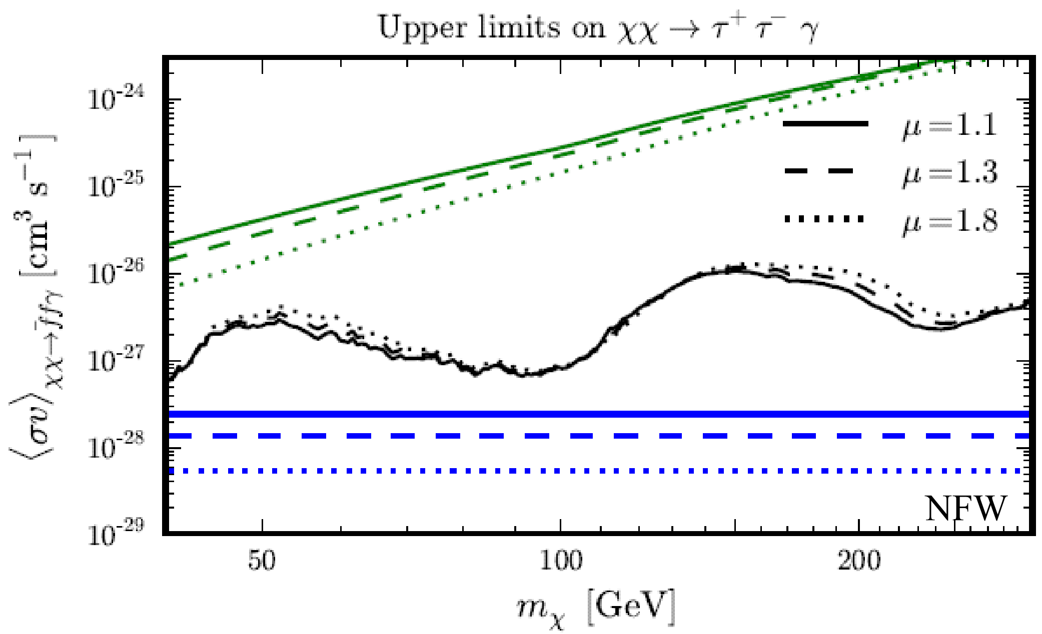

Limit on the total annihilation cross section from dwarf galaxy observations

$$\langle \sigma v \rangle < 8\pi \frac{m_\chi^2}{\underbrace{N_\gamma^{\text{tot}}}_{\text{between 1-100 GeV}}} \times 5.0 \times 10^{-30} \text{cm}^3 \text{s}^{-1} \text{GeV}^{-2}$$

Geringer-Sameth, Koushiappas
arXiv:1108.2914

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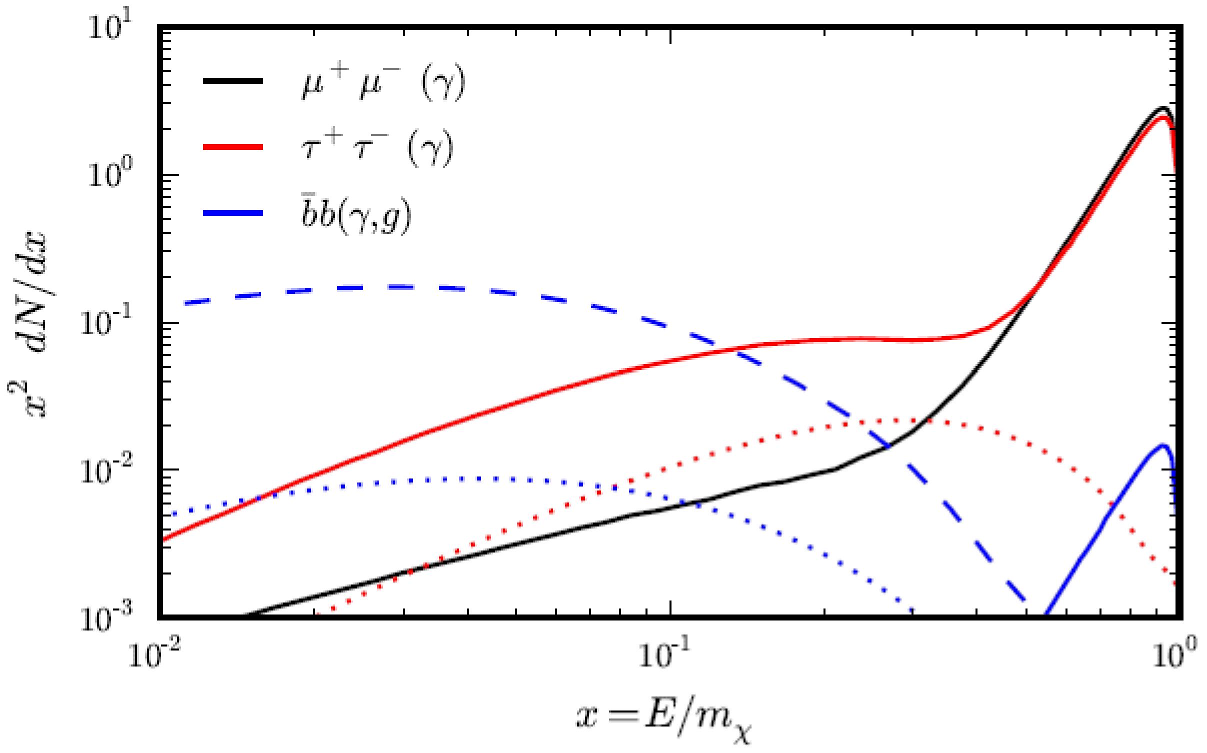

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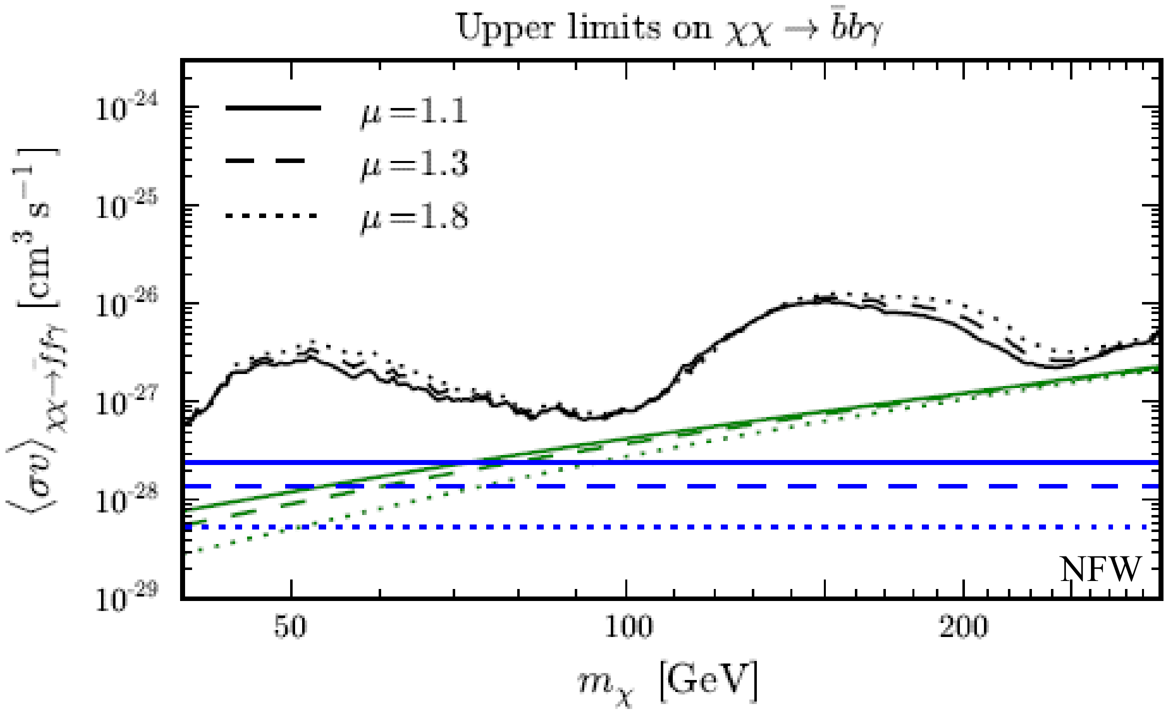

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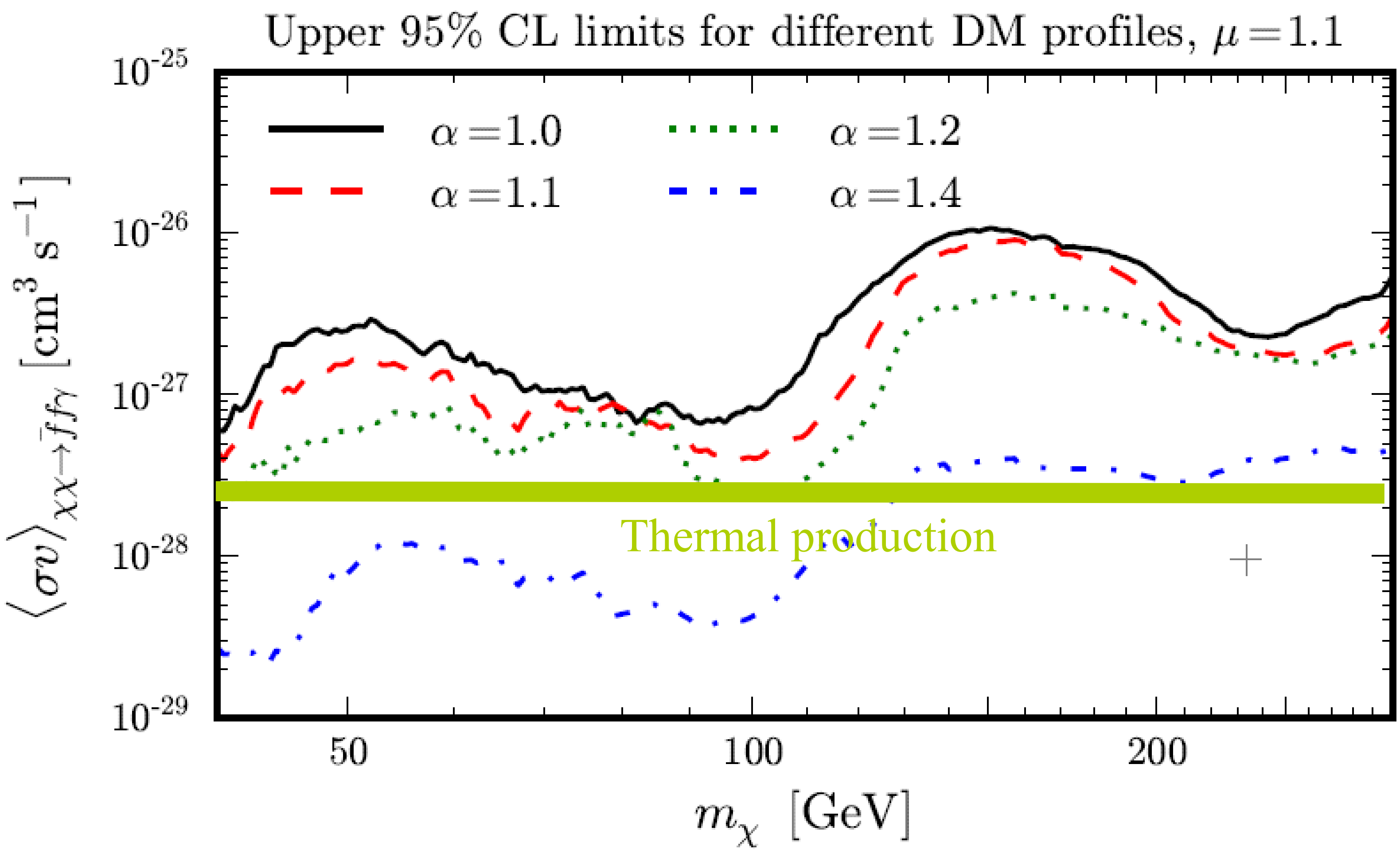
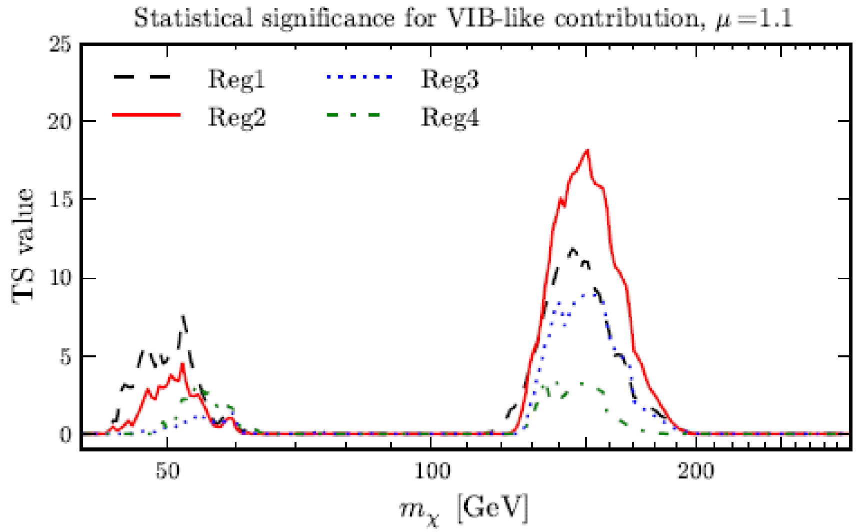
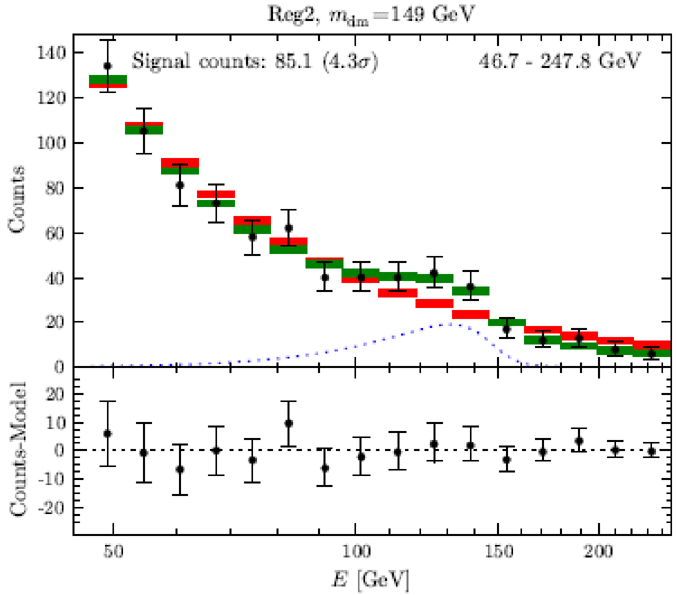


- Tension with very cuspy profiles from adiabatic contraction
- For NFW, the maximally allowed boost factor is 5-50.

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

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

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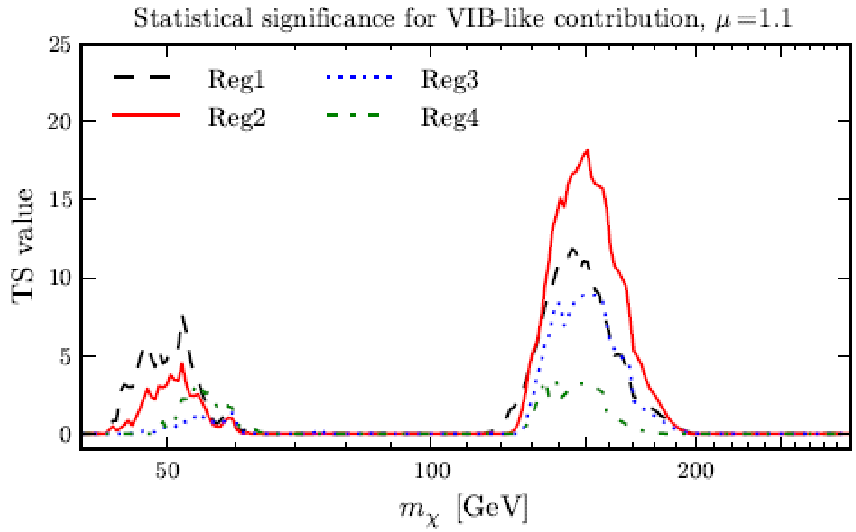

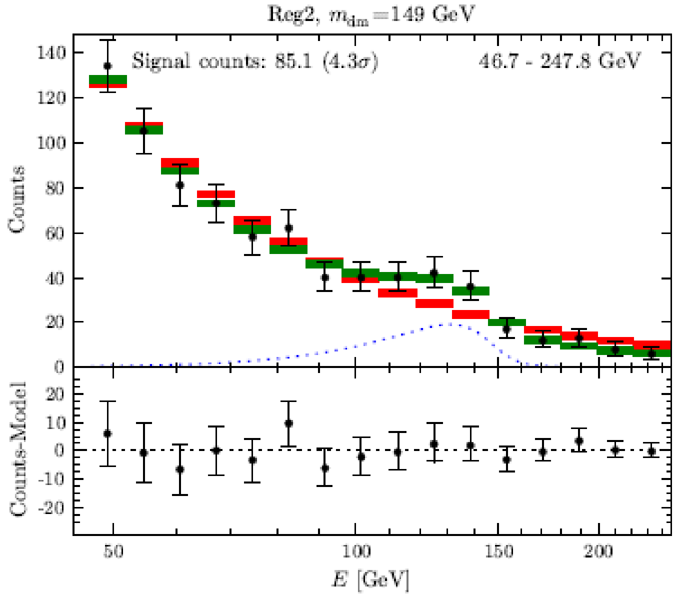

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4.3 σ (3.1 σ with LEE) in Reg2

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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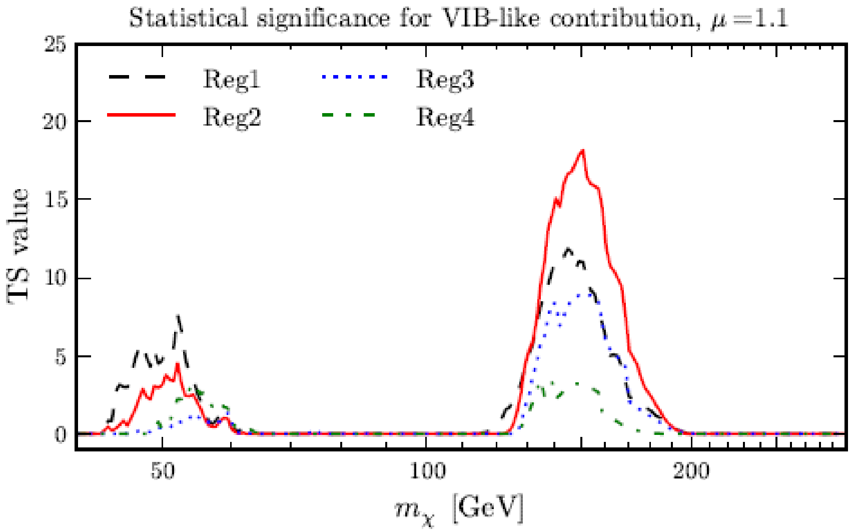

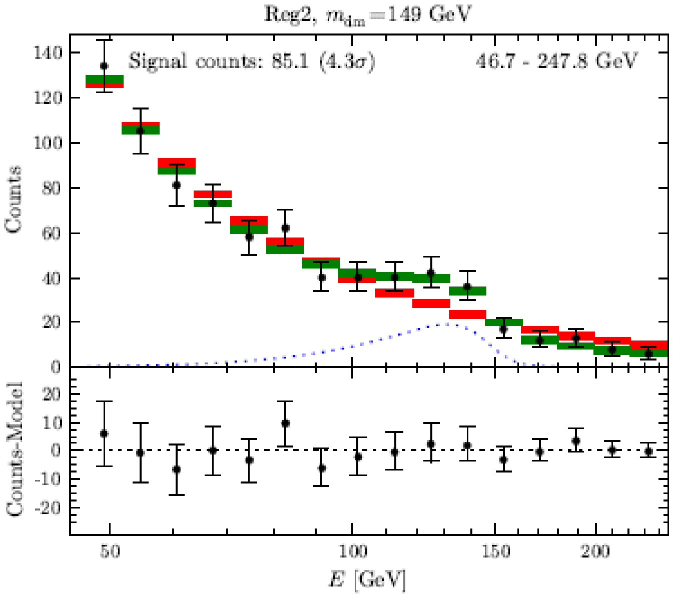

$$m_\chi = (149 \pm 4)\ \text{GeV}$$
$$\langle \sigma v \rangle = (5.7 \pm 1.4) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

4.3 σ (3.1 σ with LEE) in Reg2

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

The excess can also be fitted by a line
$$m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}\ \text{GeV}$$
$$\langle \sigma v \rangle = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

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)
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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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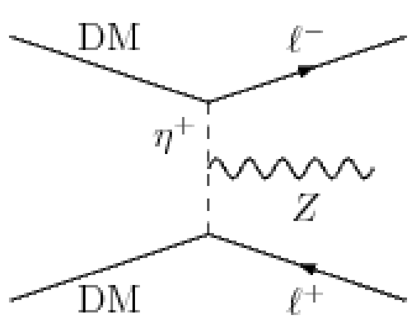

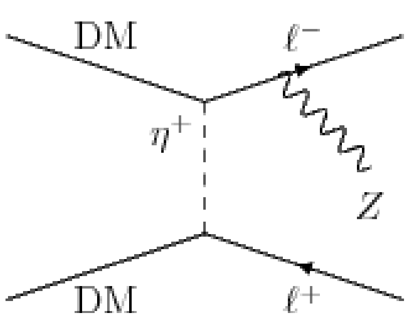

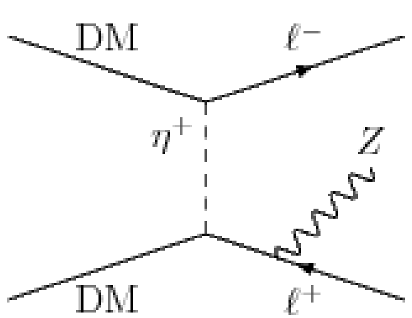

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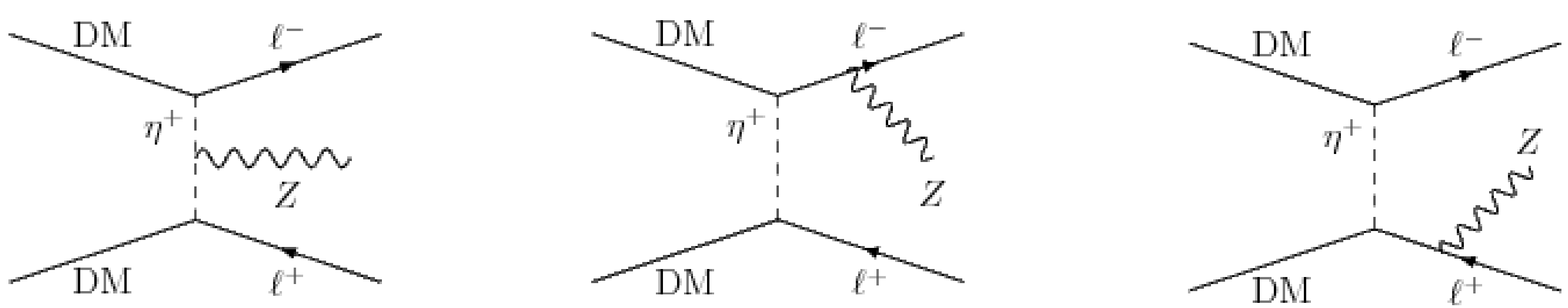

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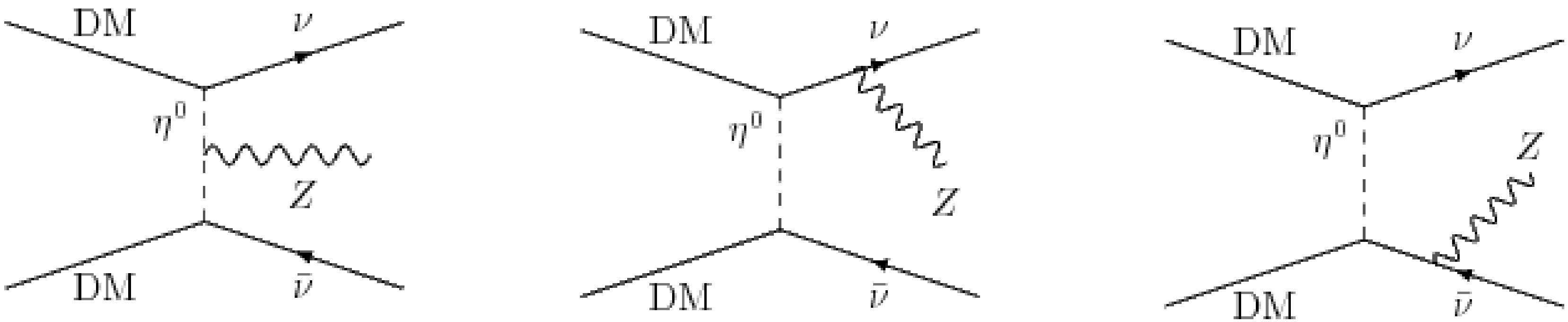

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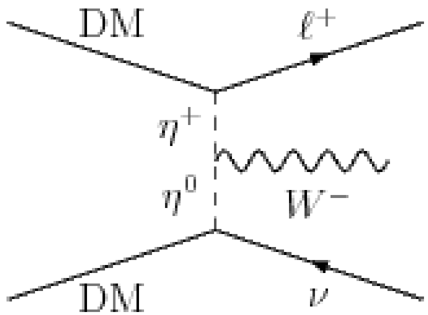
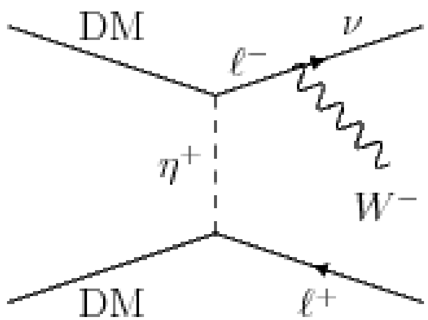
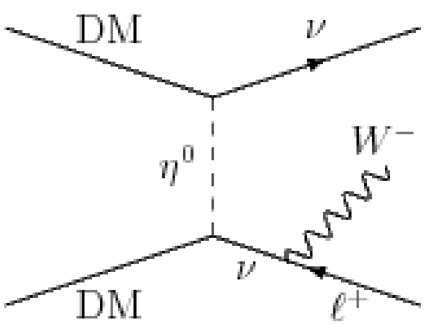




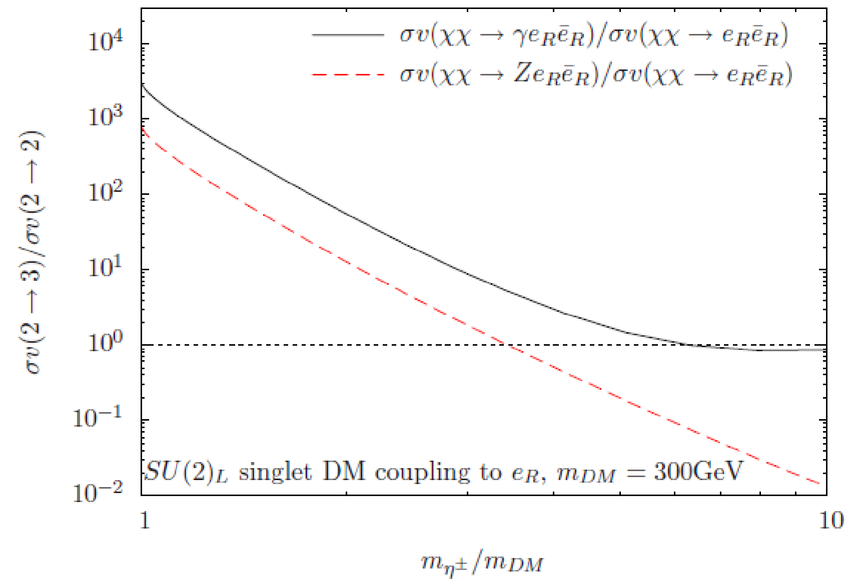


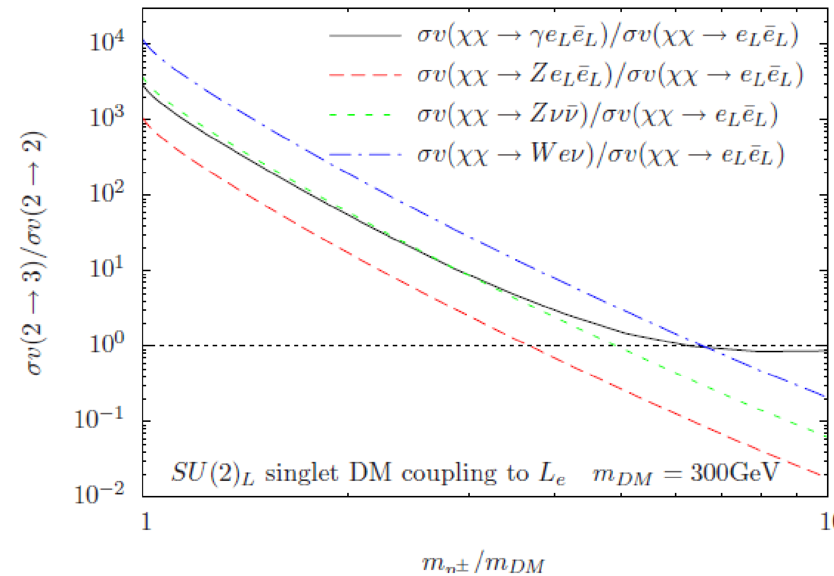
2- Antiproton limits on 2 → 3 processes

SINGLET DARK MATTER

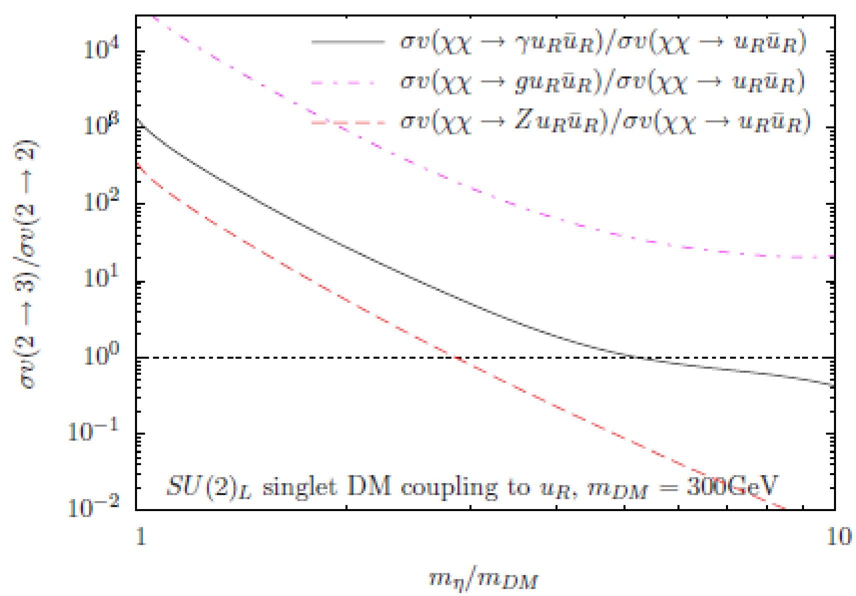
Annihilations into SU(2) singlets | Annihilations into SU(2) doublets

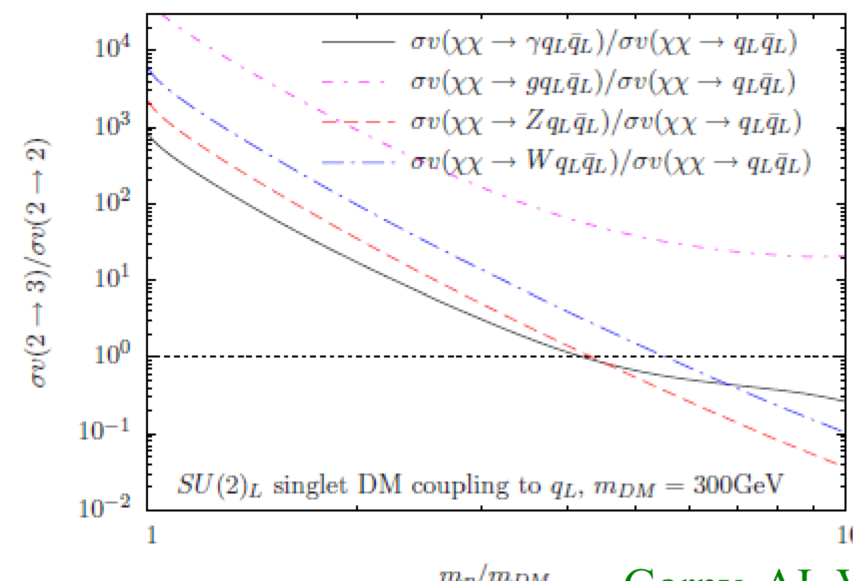
Coupling to leptons





Coupling to quarks

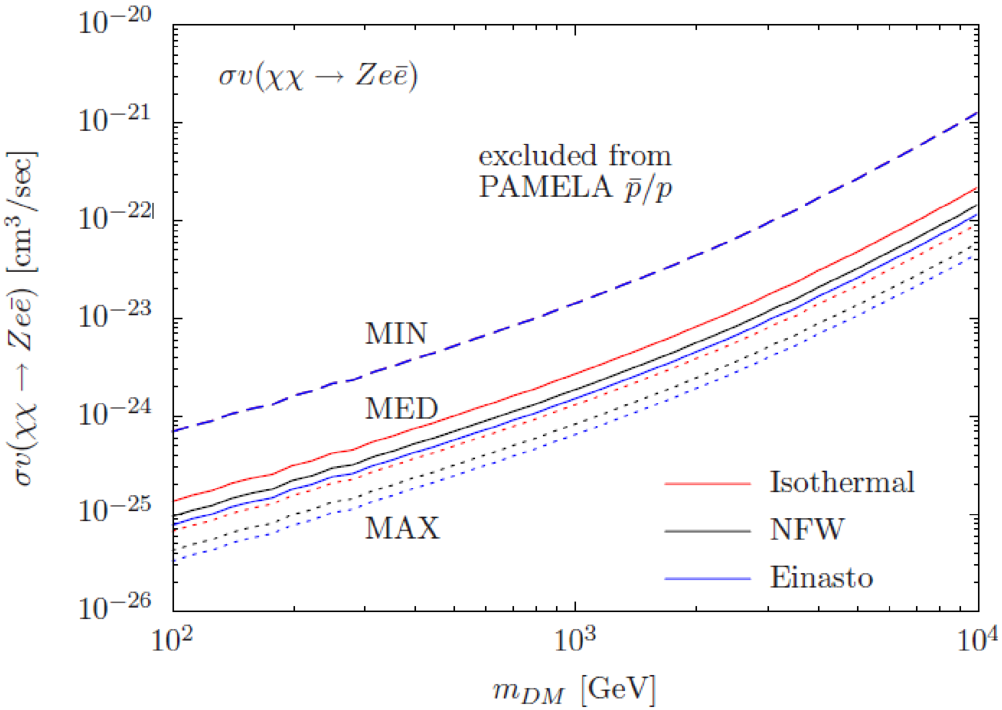


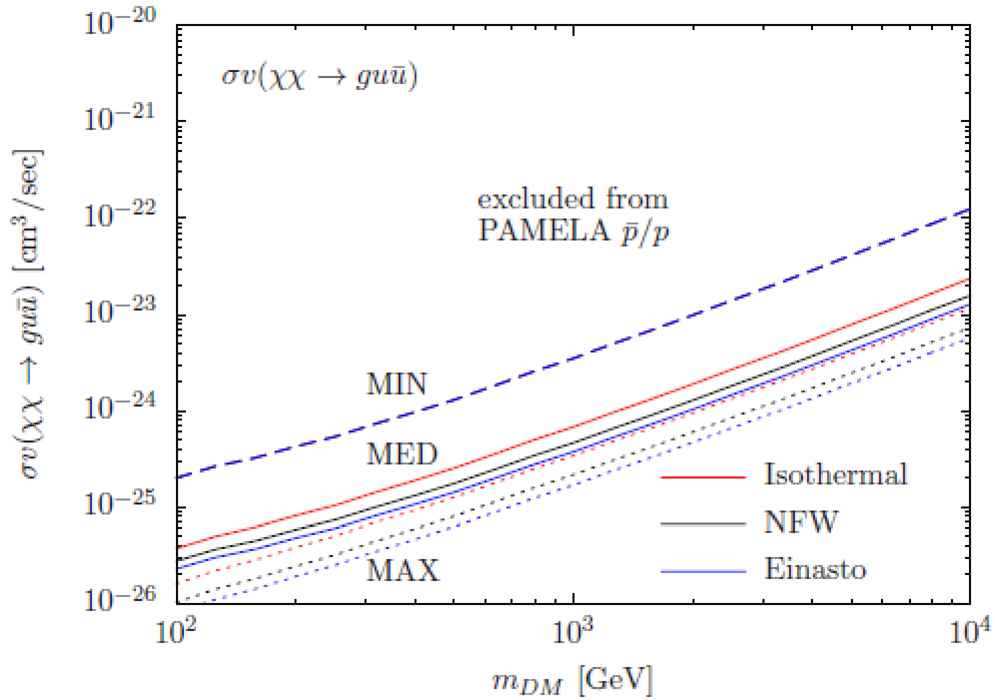


Garny, AI, Vogl

2- Antiproton limits on 2 → 3 processes

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



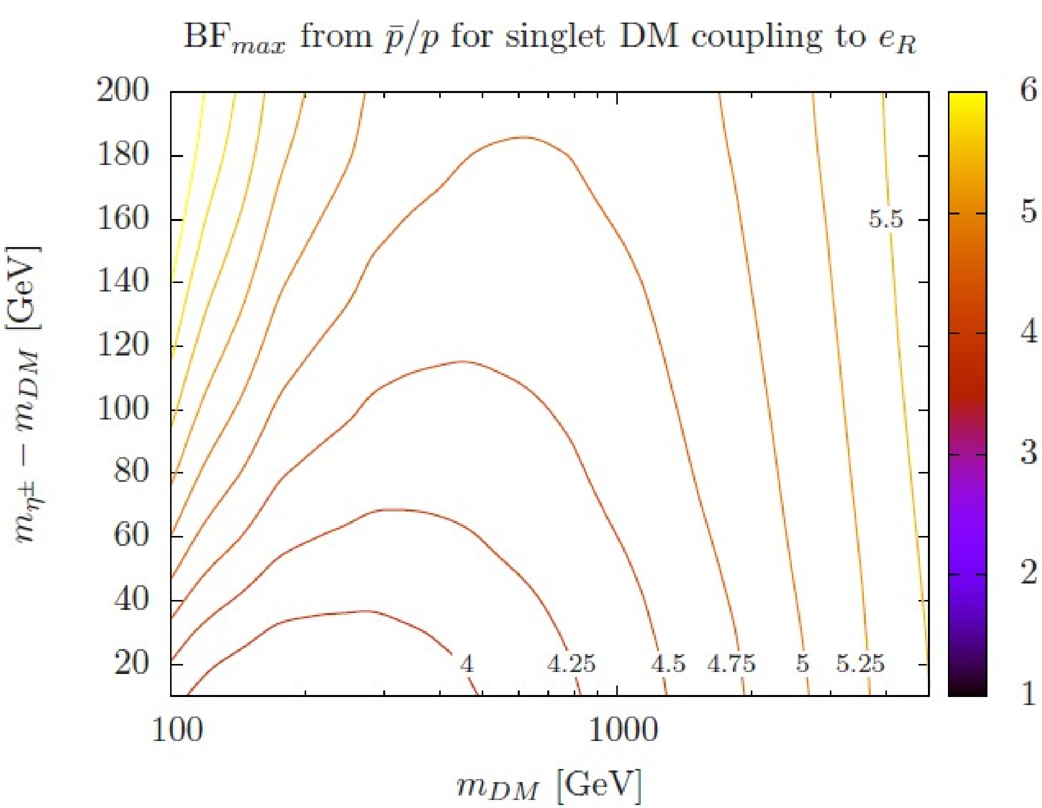


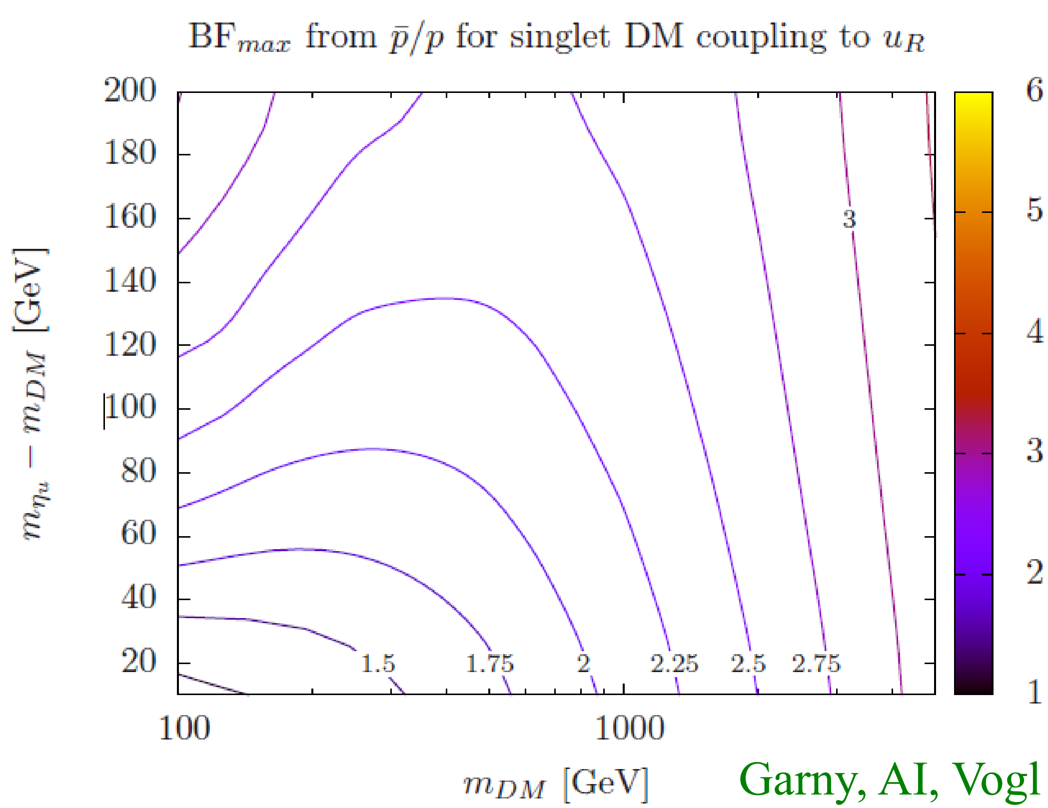
Garny, AI, Vogl

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

2- Antiproton limits on 2 → 3 processes

Limits on the astrophysical boost factor

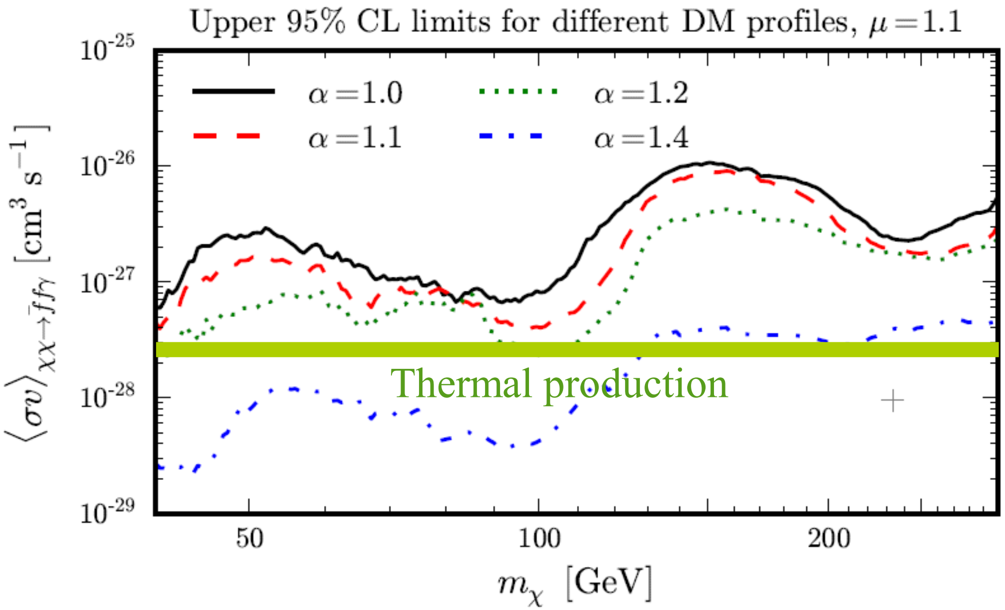


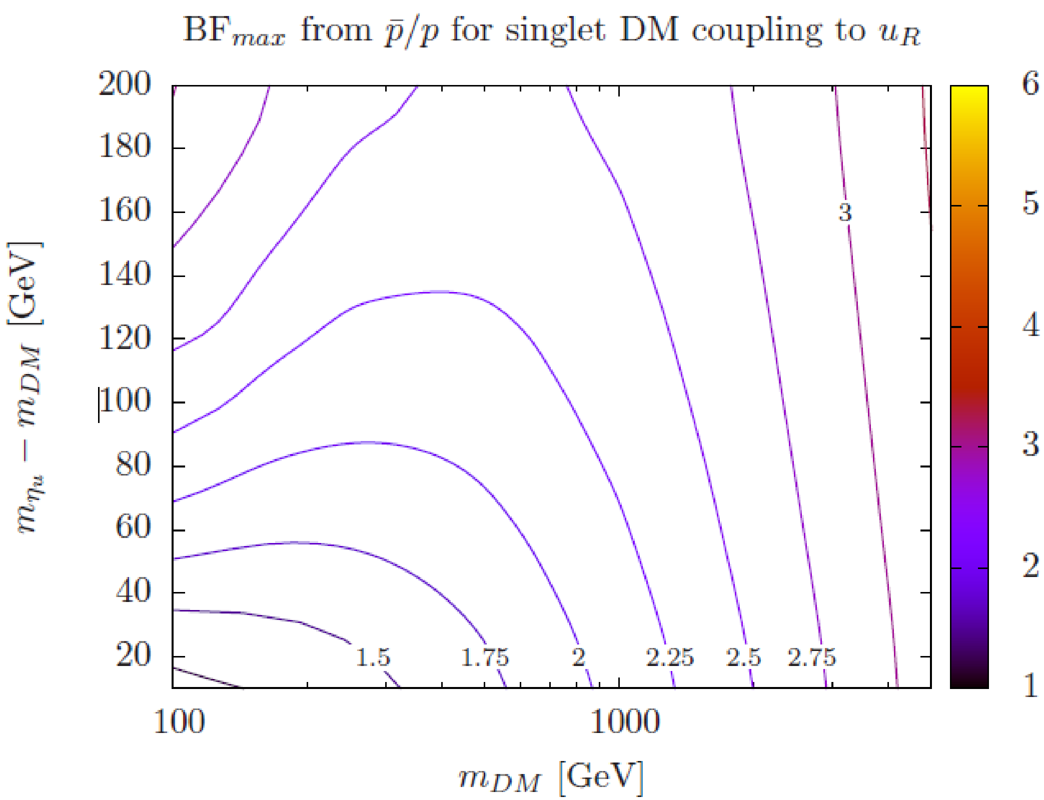


Garny, AI, Vogl

2- Antiproton limits on 2 → 3 processes

Interplay with gamma-ray limits





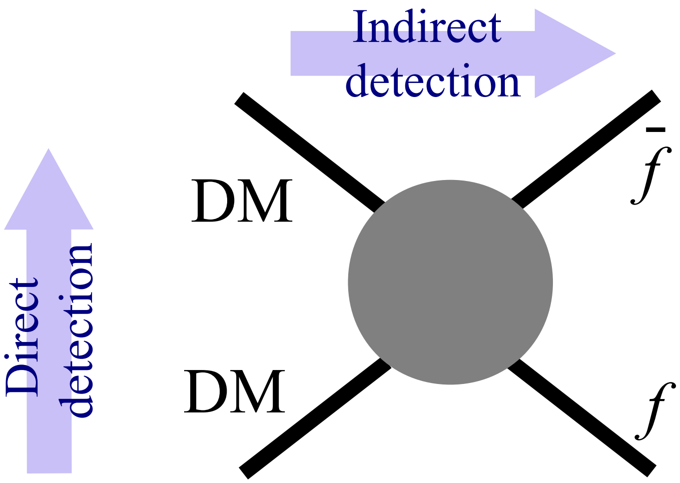
Maximal boost factor: 5-50

Maximal boost factor: 20-100

Limits on the annihilation cross section into light quarks from gamma rays and antiprotons are comparable.

3- Interplay direct detection – indirect detection

Naive connection between direct detection and indirect detection:



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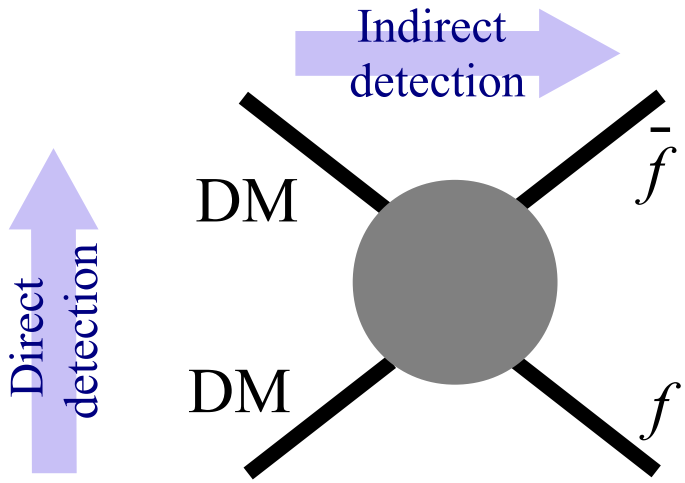
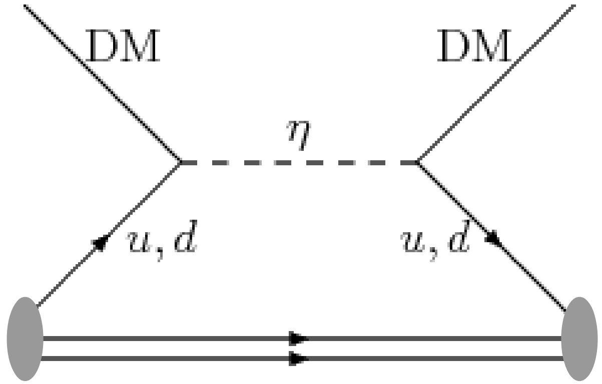
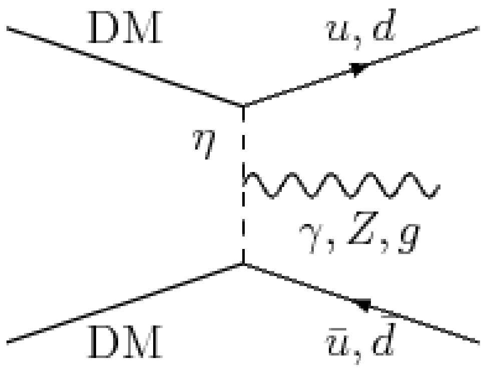


However, in direct search experiments it is probed the DM coupling to *a light quark.*

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

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

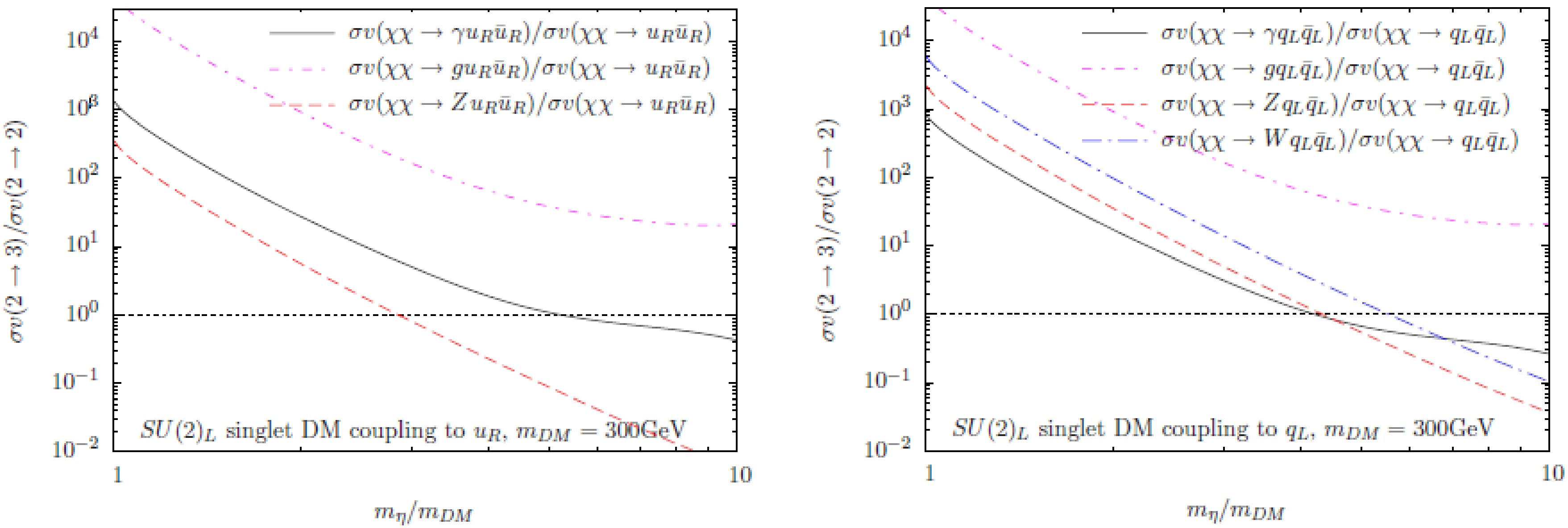




3- Interplay direct detection – indirect detection

- We consider a toy model with $\mathcal{L}_{int} = -f\bar{\chi}\Psi_R\eta + \text{h.c.}$

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



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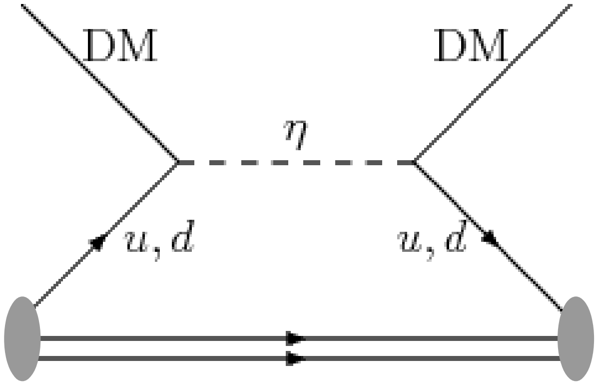
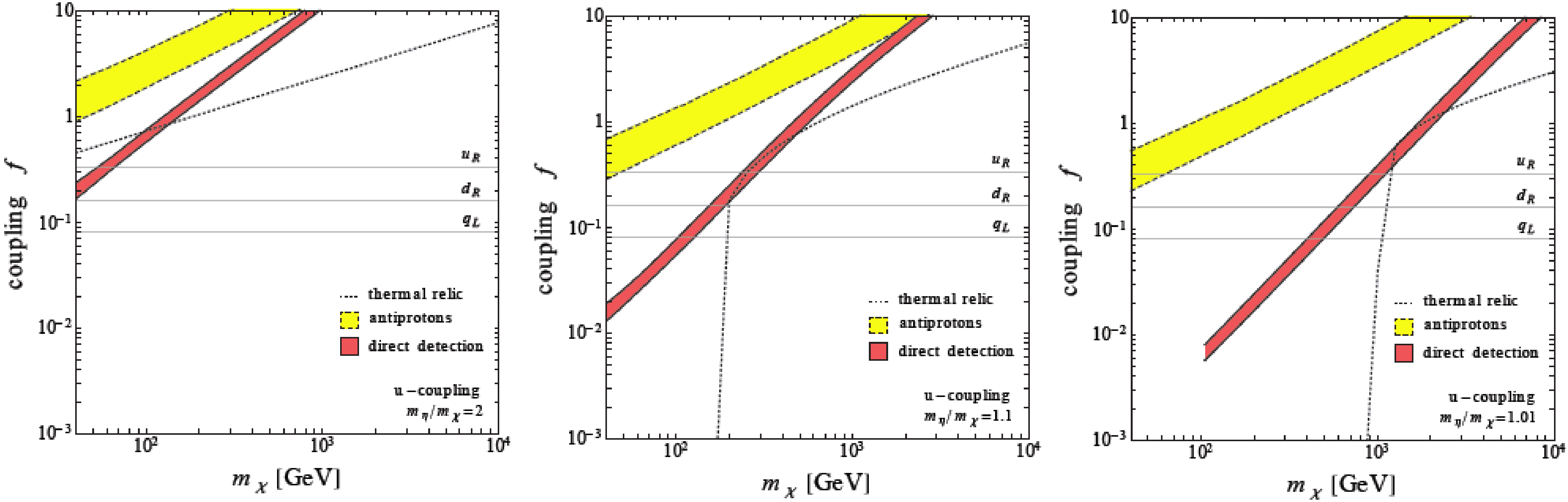
- Also the direct detection limits, due to an enhancement of the effective WIMP couplings in the degenerate limit.



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

3- Interplay direct detection – indirect detection

Limits on the coupling f from PAMELA and XENON-100



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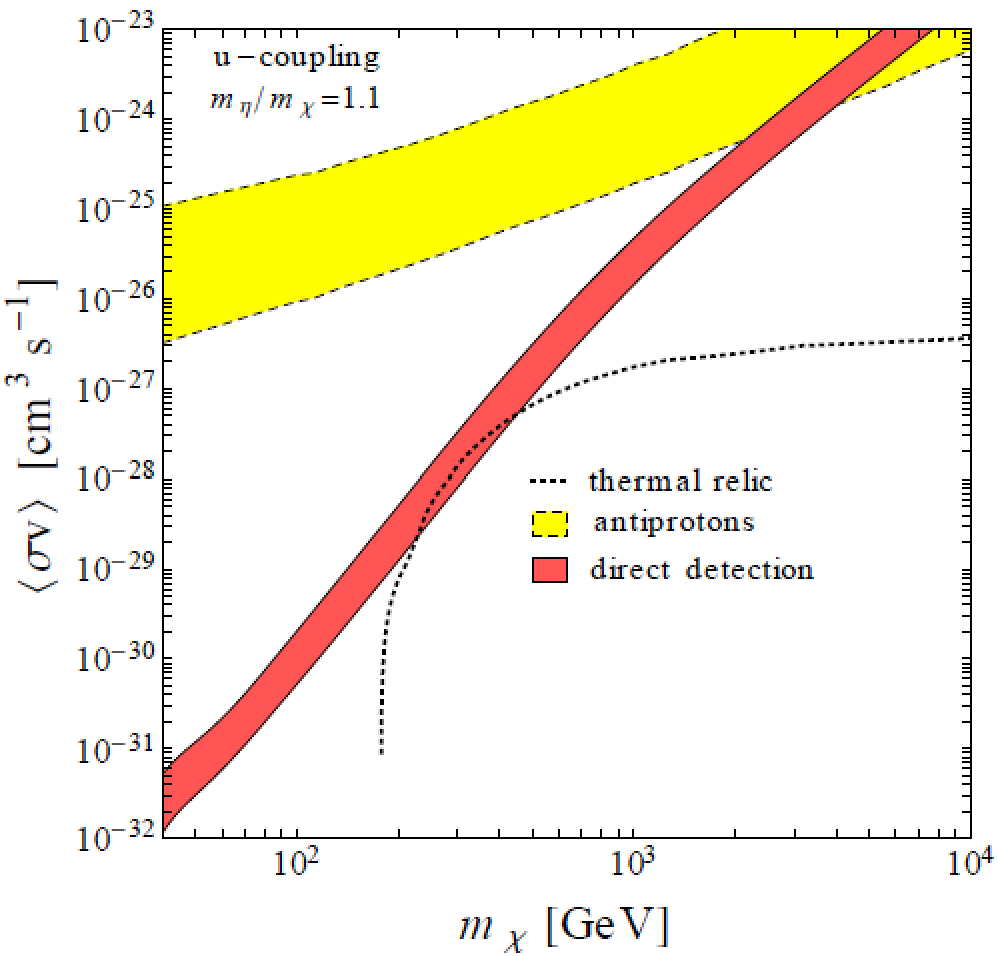
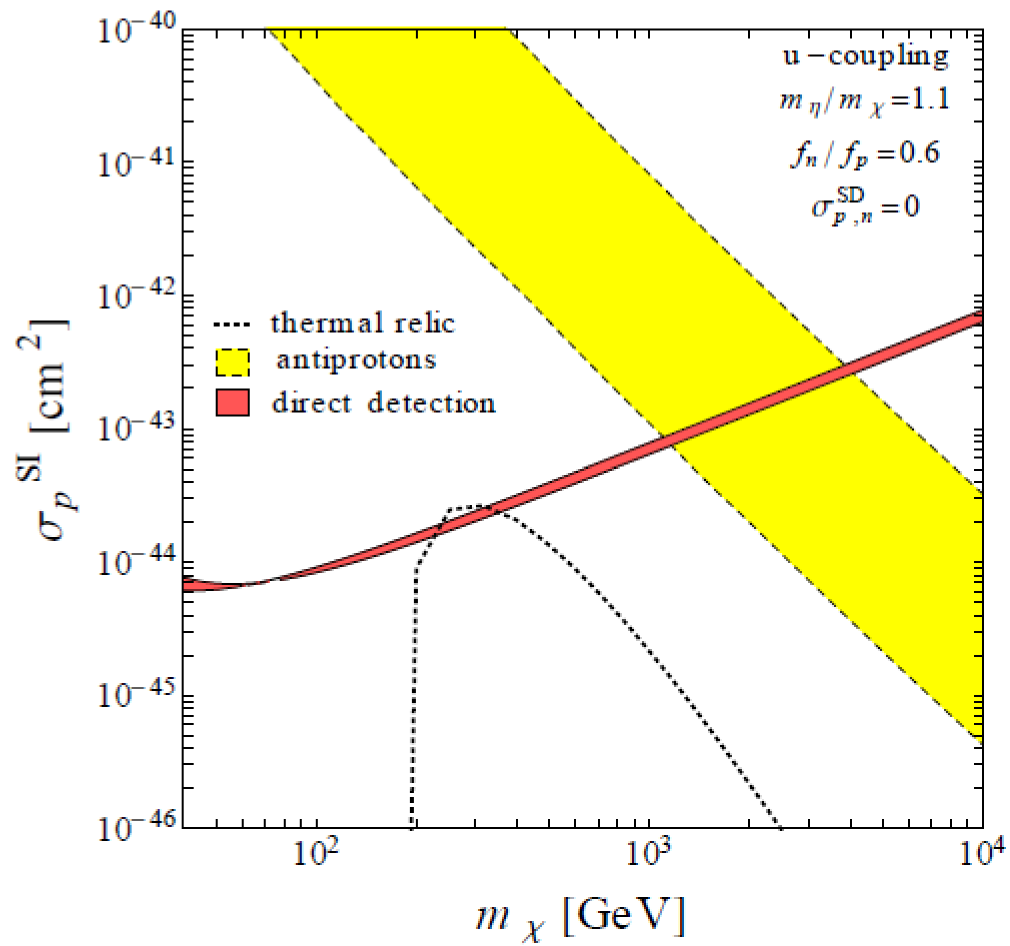




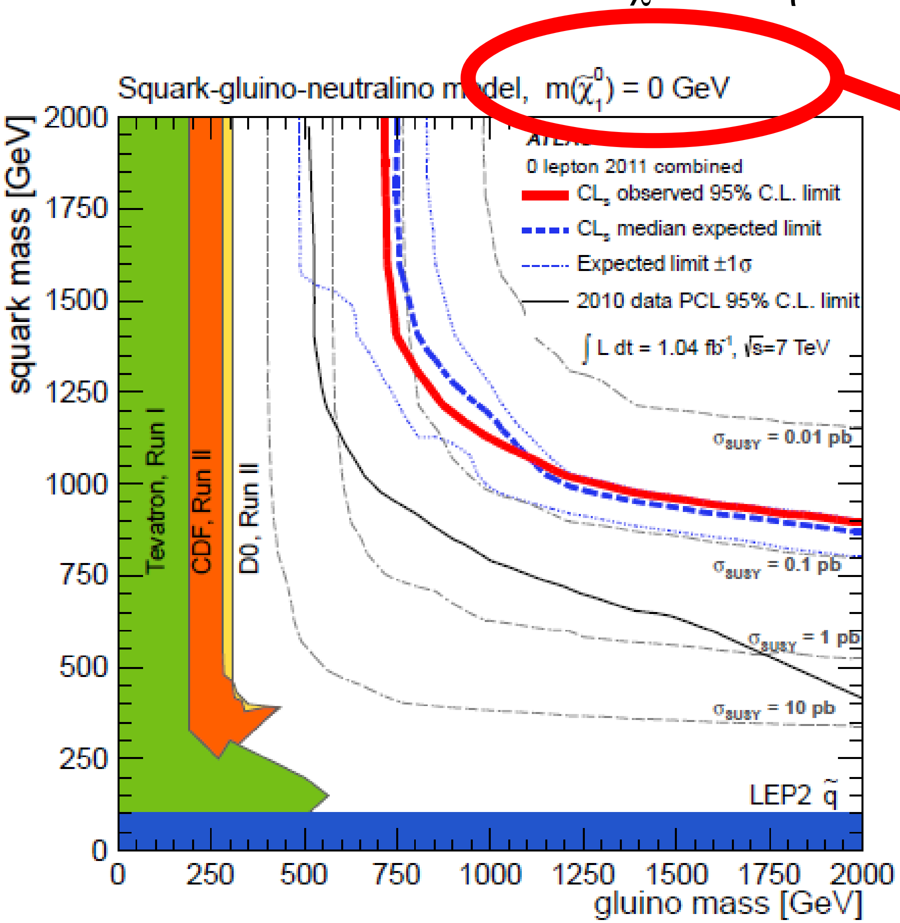
Direct detection can probe boost factors of O(1) in the range m_χ=200-600 GeV

Garny, AI, Pato, Vogl

Observation of γ-ray signals from $\chi\chi \rightarrow u \bar{u} \gamma$ are unlikely

3- Interplay direct detection – indirect detection – collider searches

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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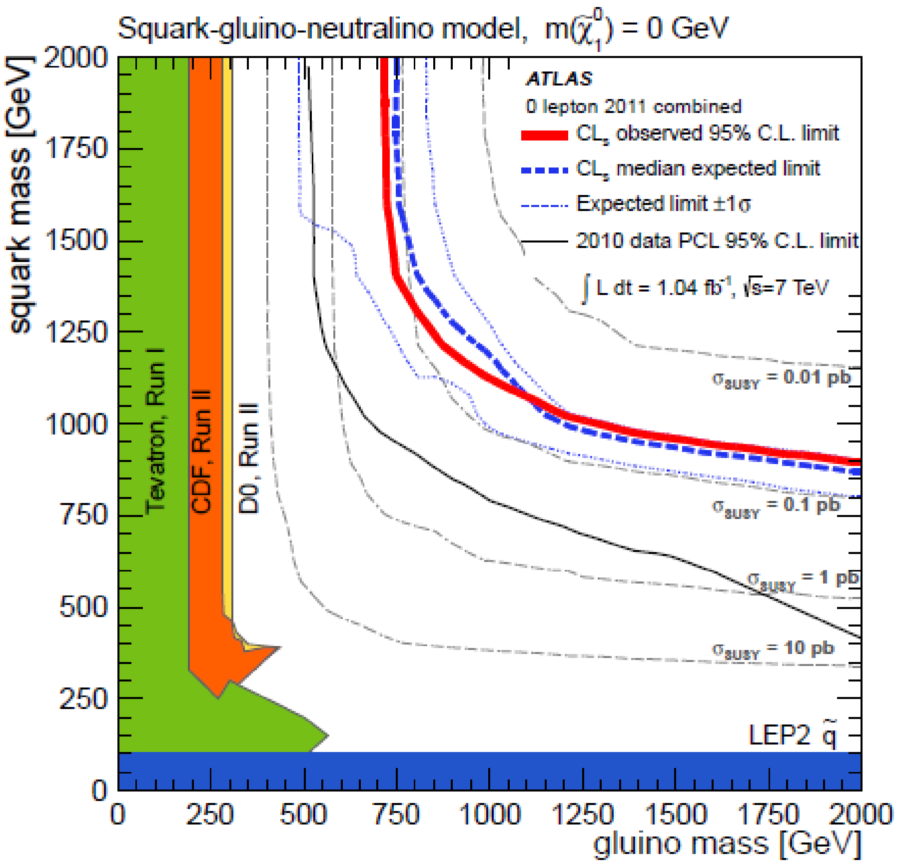
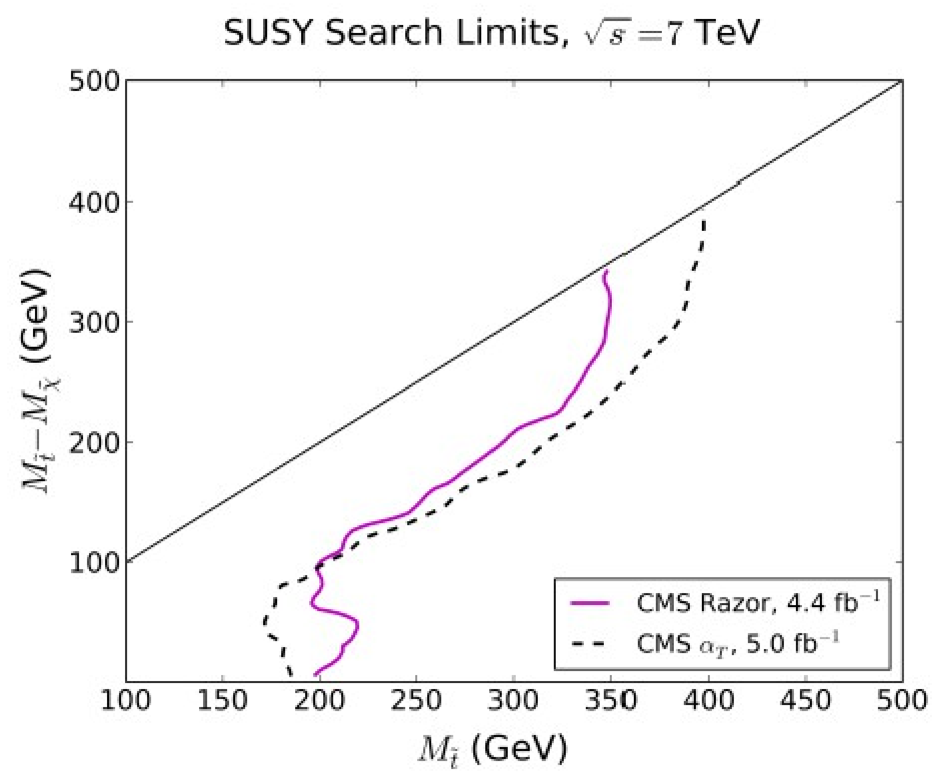


ATLAS, arXiv:1109.6572



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 $\rightarrow f\bar{f}V$ can be important (even dominant).

• We have searched in the Fermi-LAT data for a signal from DM DM $\rightarrow f\bar{f}\gamma$. 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.

• Limits on the process DM DM $\rightarrow f\bar{f}V$ also follow from the non observation of an excess in the PAMELA measurements of the $\bar{p}/p$ ratio.

• 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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Submission of proposals for 2015 is open!

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M. Krämer, S. Dittmaier, N. Glover, G. Heinrich

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