Gamma-ray spectral features in light of direct detection and colliders

Alejandro Ibarra
Technische Universität München

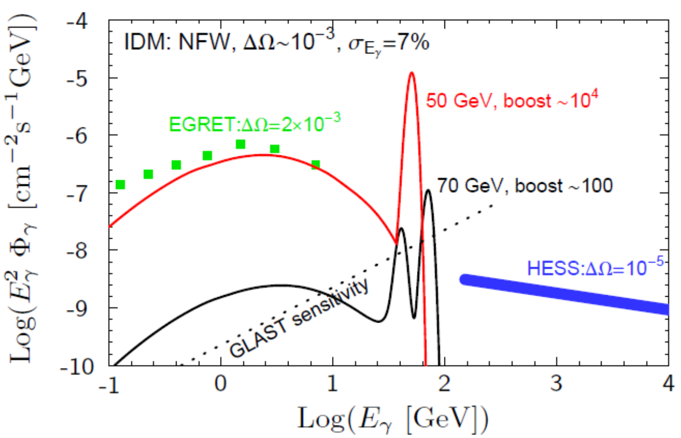
Based on
M. Garny, AI, S. Vogl, JCAP **1107** (2011) 028
M. Garny, AI, S. Vogl, JCAP **1204** (2012) 033
T. Bringmann, X. Huang, AI, S. Vogl, C, Weniger JCAP **1207** (2012) 054
M. Garny, AI, M. Pato, S. Vogl, JCAP **1211** (2012) 017

KITP
Santa Barbara
16 May 2013

Gamma-ray sharp spectral features

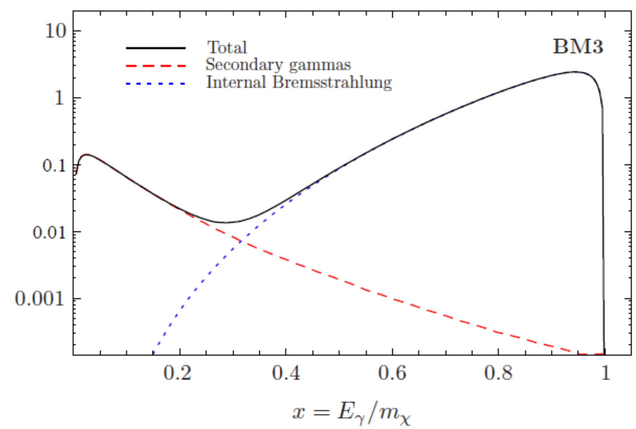
Some dark matter scenarios predict the existence of sharp spectral features in the gamma-ray sky.

Gamma-ray line



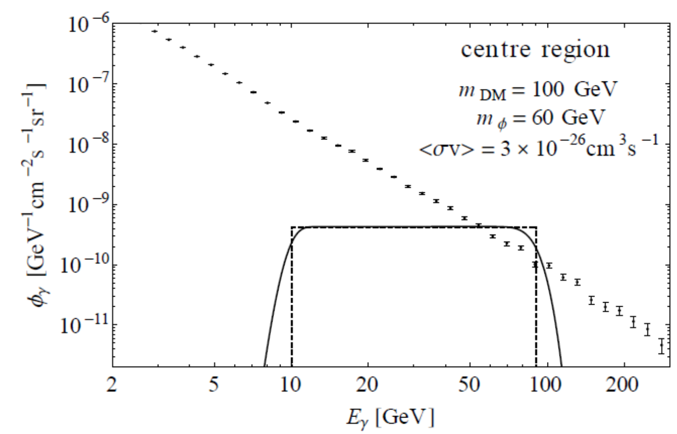
Gustafsson et al., astro-ph/0703512

Internal Bremsstrahlung



Bringmann, Bergström, Edsjö arXiv:0710.3169

Gamma-ray box



AI, Lopez-Gehler, Pato arXiv:1205.0007

Important question: what are the prospects to observe gamma-ray spectral features in view of present limits from other indirect detection, direct detection and collider experiments?

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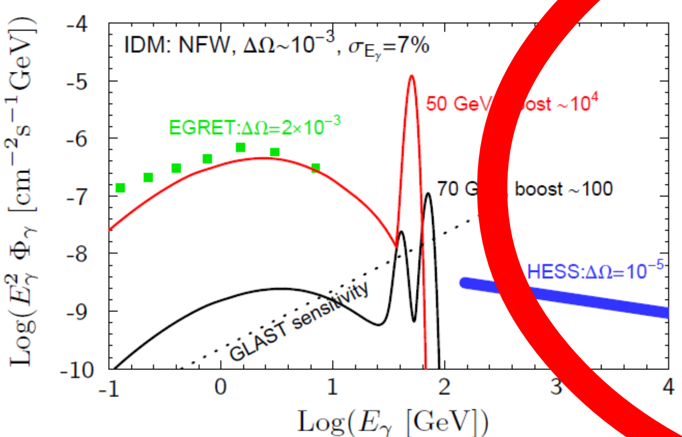

Gustafsson et al., astro-ph/0703512

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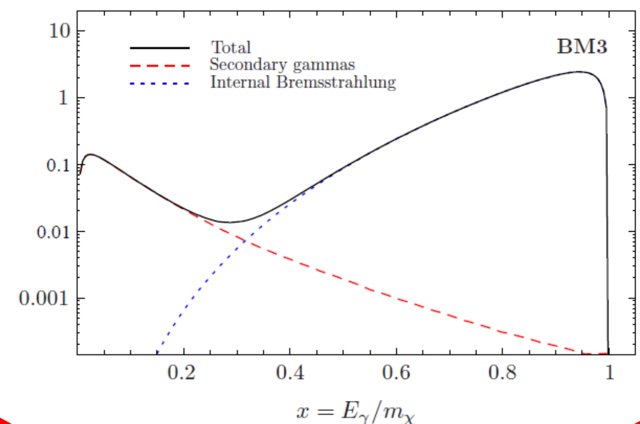
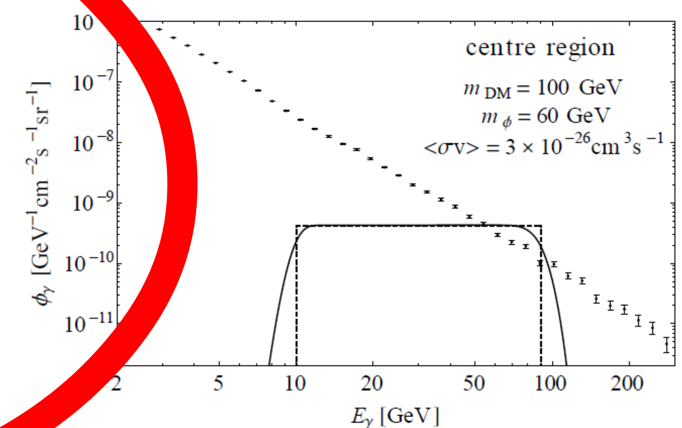


Bringmann, Bergström, Ed...
arXiv:0710.3169

Gamma-ray box



AI, Lopez-Gehler, Pato
arXiv:1205.0007

Important question: what are the prospects to observe gamma-ray spectral features in view of present limits from other indirect detection, direct detection and collider experiments?

Simplified models with large internal Bremsstrahlung

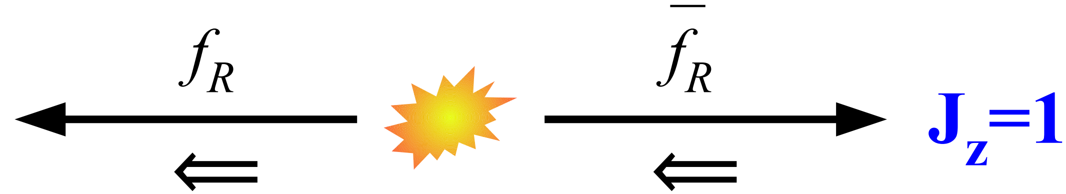
Consider a toy model consisting on a Majorana dark matter particle, χ, an intermediate charged scalar particle, η, and a light SM fermion, f_R.

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

Indirect detection a priori challenging: the annihilation process DM DM $\rightarrow \bar{f} f$ has a very small rate today

$$\langle \sigma v \rangle_{\rm G.C.} \sim \frac{\langle v^2 \rangle_{\rm G.C}}{\langle v^2 \rangle_{\rm f.o}} \langle \sigma v \rangle_{\rm f.o.} \sim 10^{-31}\,{\rm cm}^3\,{\rm s}^{-1}$$

- Consider the annihilation DM DM $\rightarrow f\bar{f}$



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

J_z=0

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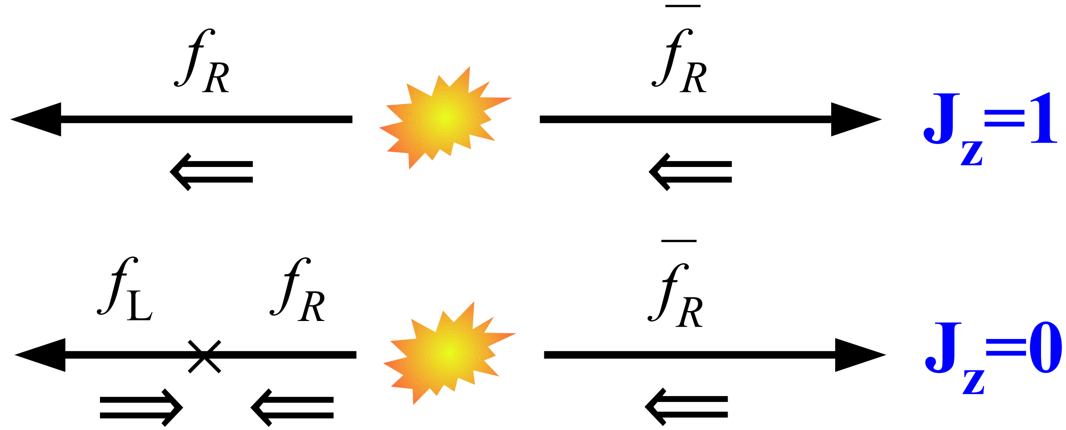

Rate of DM DM $\rightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

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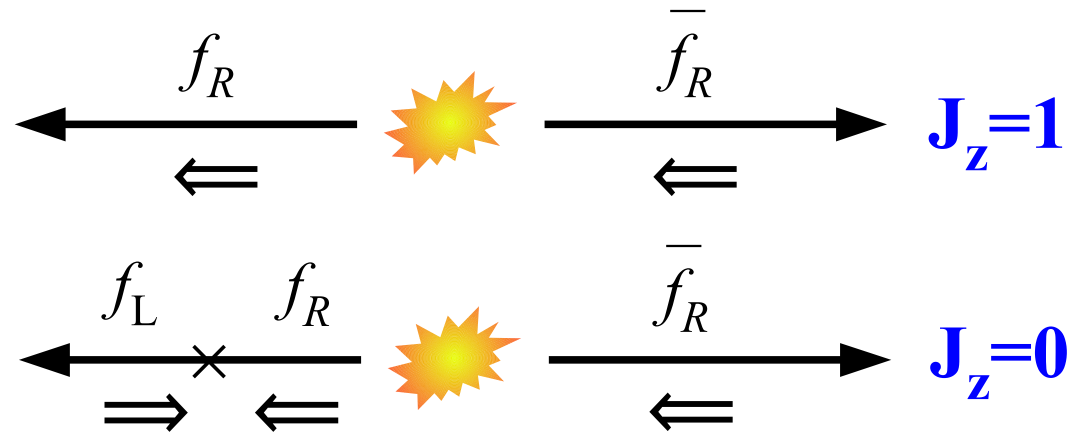


Rate of DM DM $\rightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

- Decomposing the velocity weighted annihilation cross section as $\langle\sigma v\rangle = a + bv^2$, the relative contributions of the two terms are:

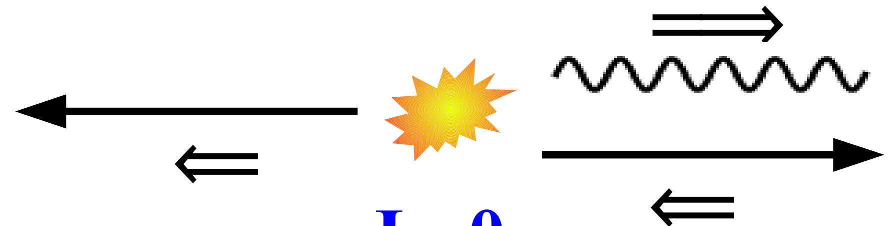
For m=300 GeV, $$\frac{a}{bv^2} \sim \frac{m_f^2}{m_{DM}^2 v^2} \sim \begin{cases} 10^{-6} & \text{for electrons} \\ 0.1 & \text{for muons} \\ 10^{-5} & \text{for up-type quarks} \end{cases}$$

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

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

- Consider the annihilation DM DM $\to f\bar{f}V$, with V a vector

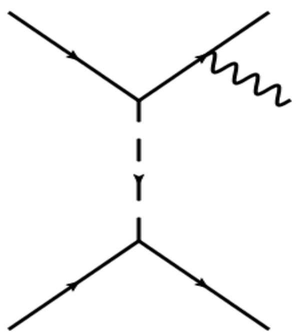
In the limit $v \to 0$,
no preferred direction
$J_z=0$



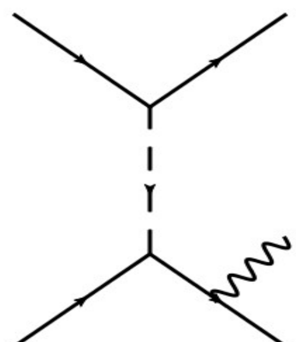
$J_z=0$

No suppression by mass insertion. Suppressed, however, by the extra coupling constant, by the 3-body phase space and by $(m_{DM}/m_\eta)^8$

Bergström
Flores, Olive, Rudaz



Final state radiation



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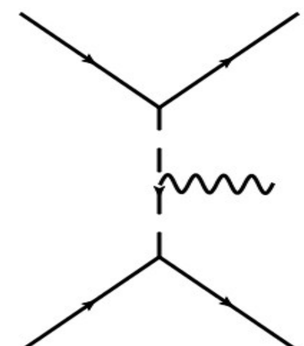

Virtual Internal Bremsstrahlung

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

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

- Consider the annihilation DM DM $\rightarrow f\bar{f}V$, with V a vector

In the limit $v \rightarrow 0$,
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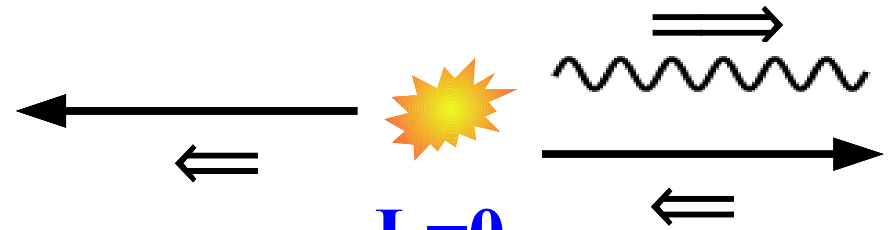
J_z=0



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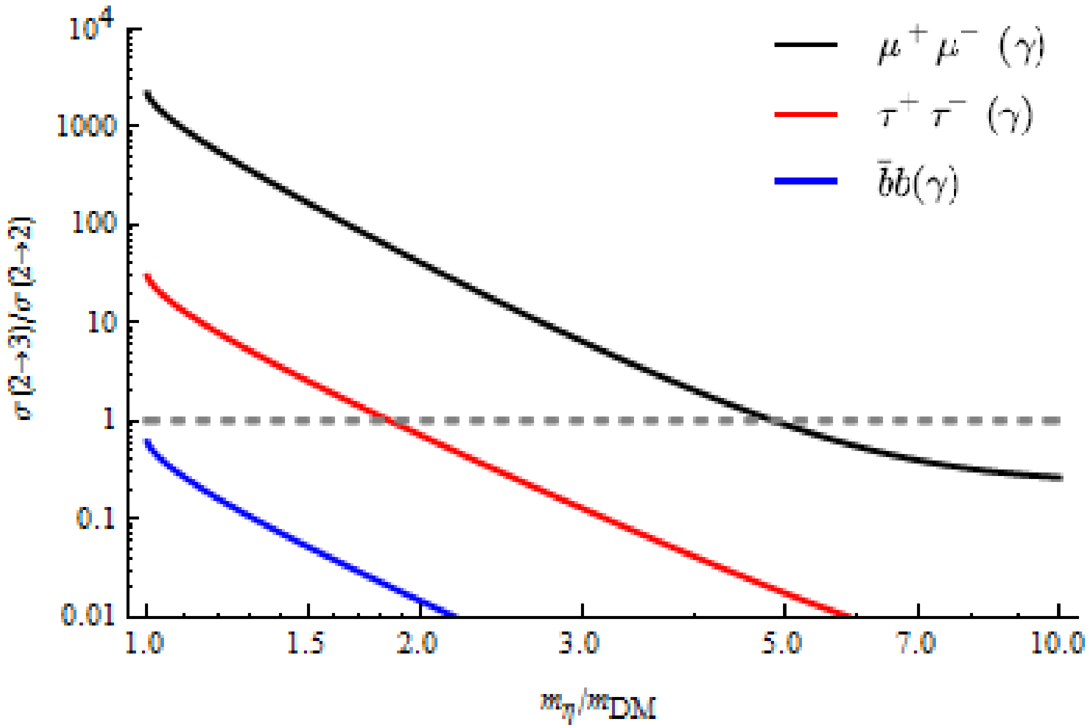

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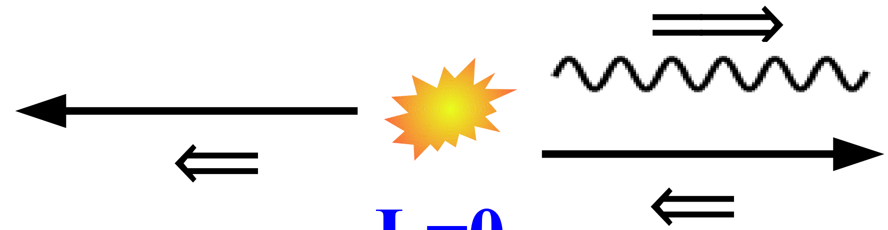

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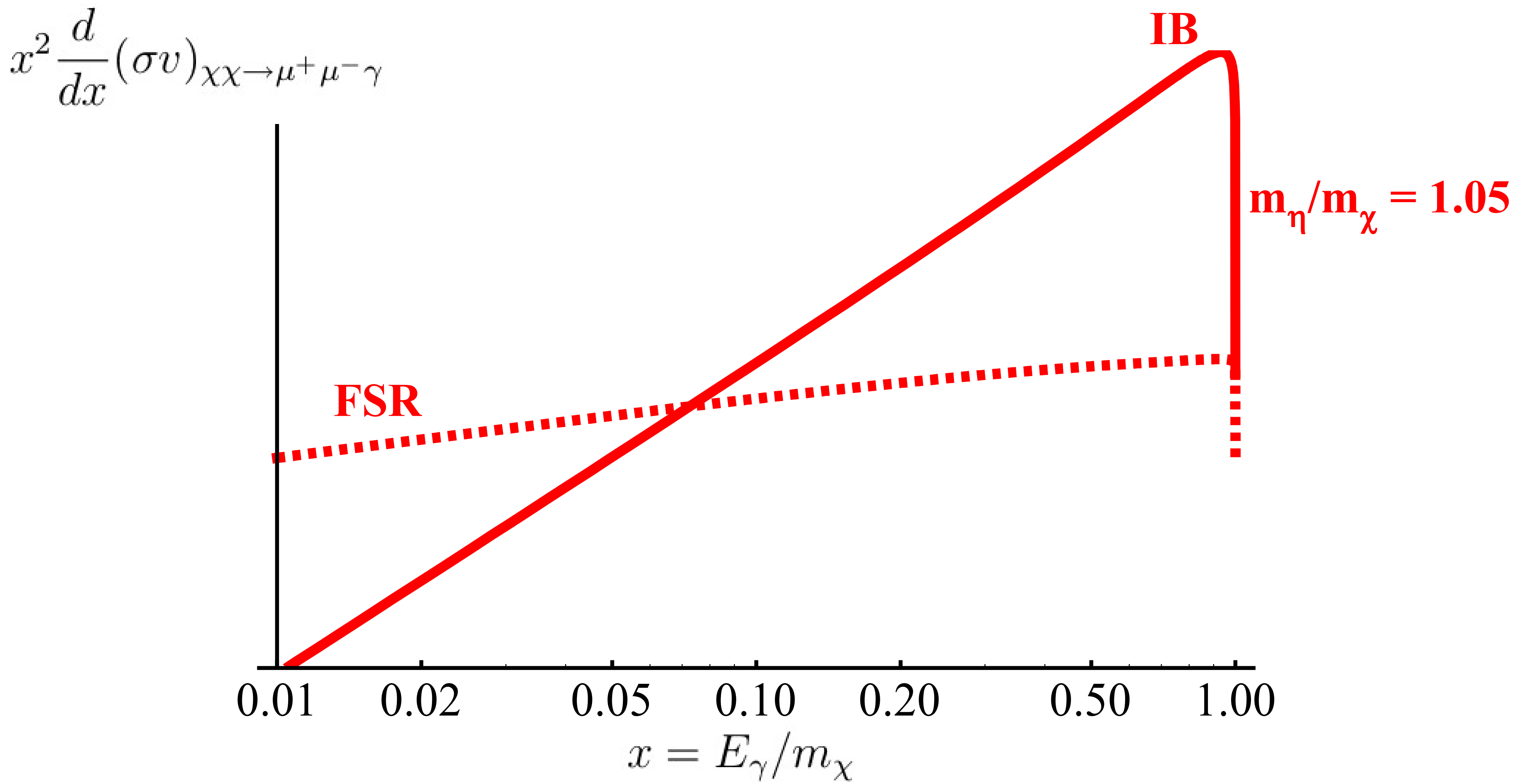
Bergström
Flores, Olive, Rudaz

In the 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 $\to f\bar{f}$

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

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

Bringmann, Bergström, Edsjö



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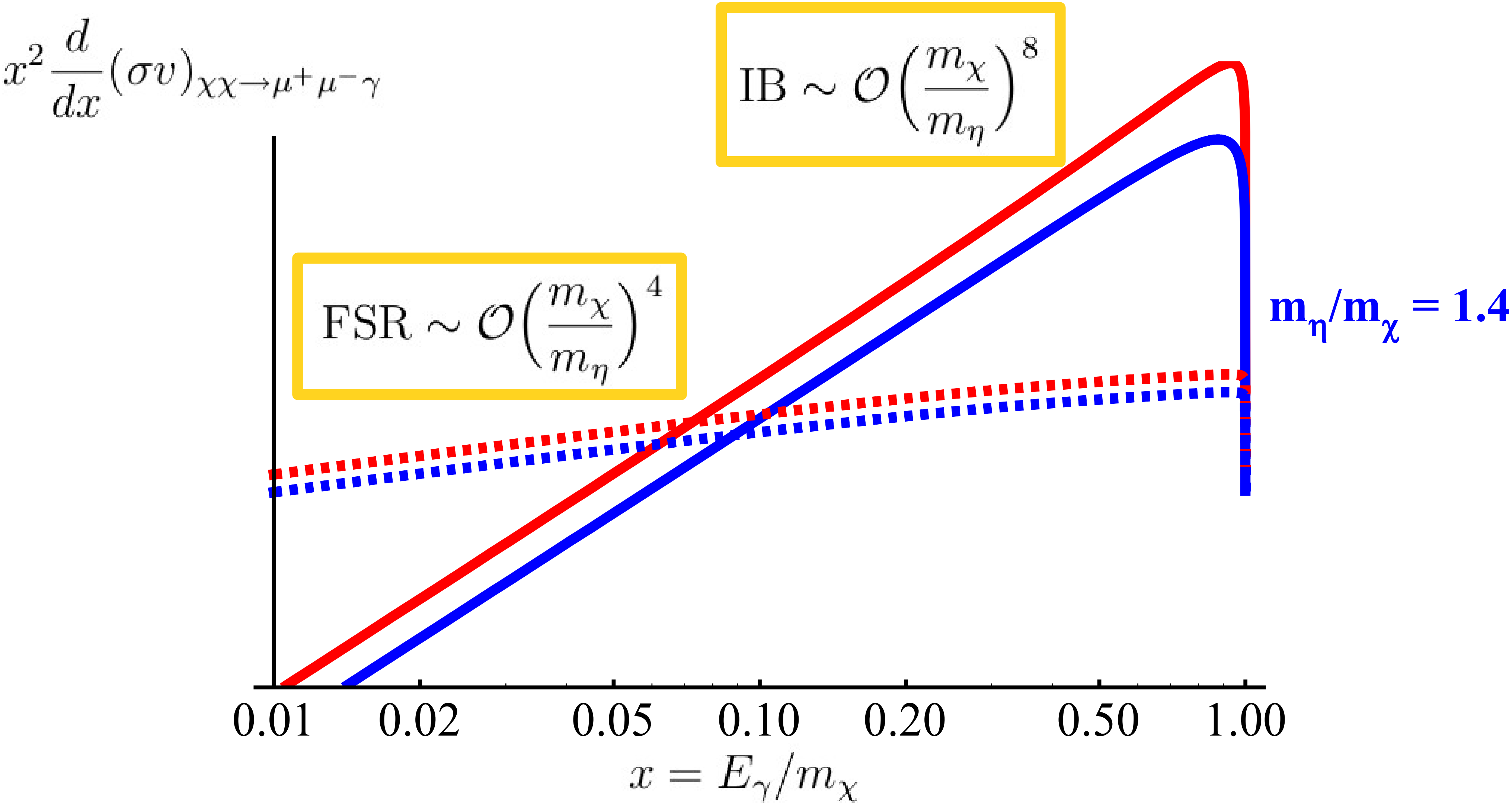

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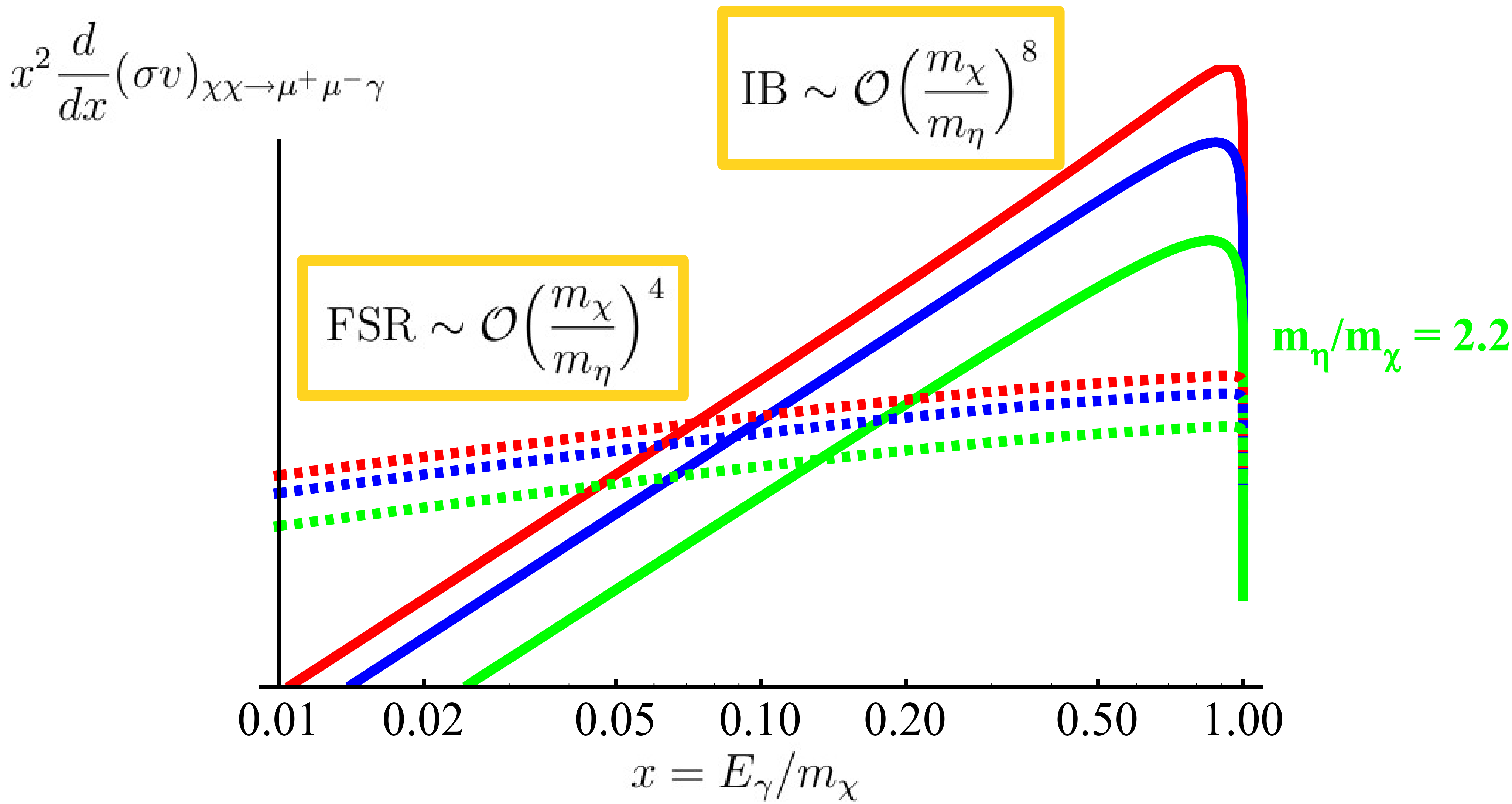

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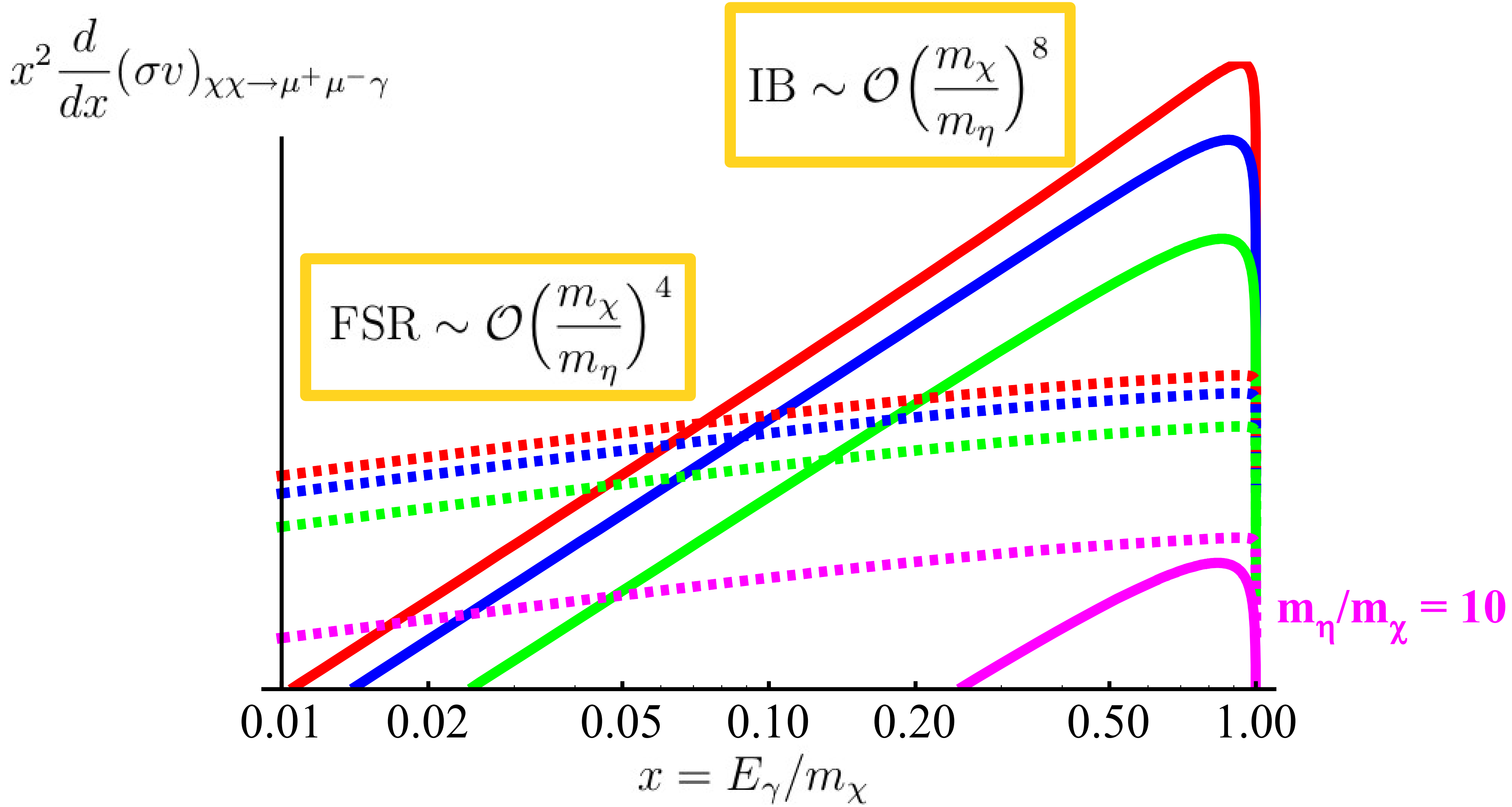
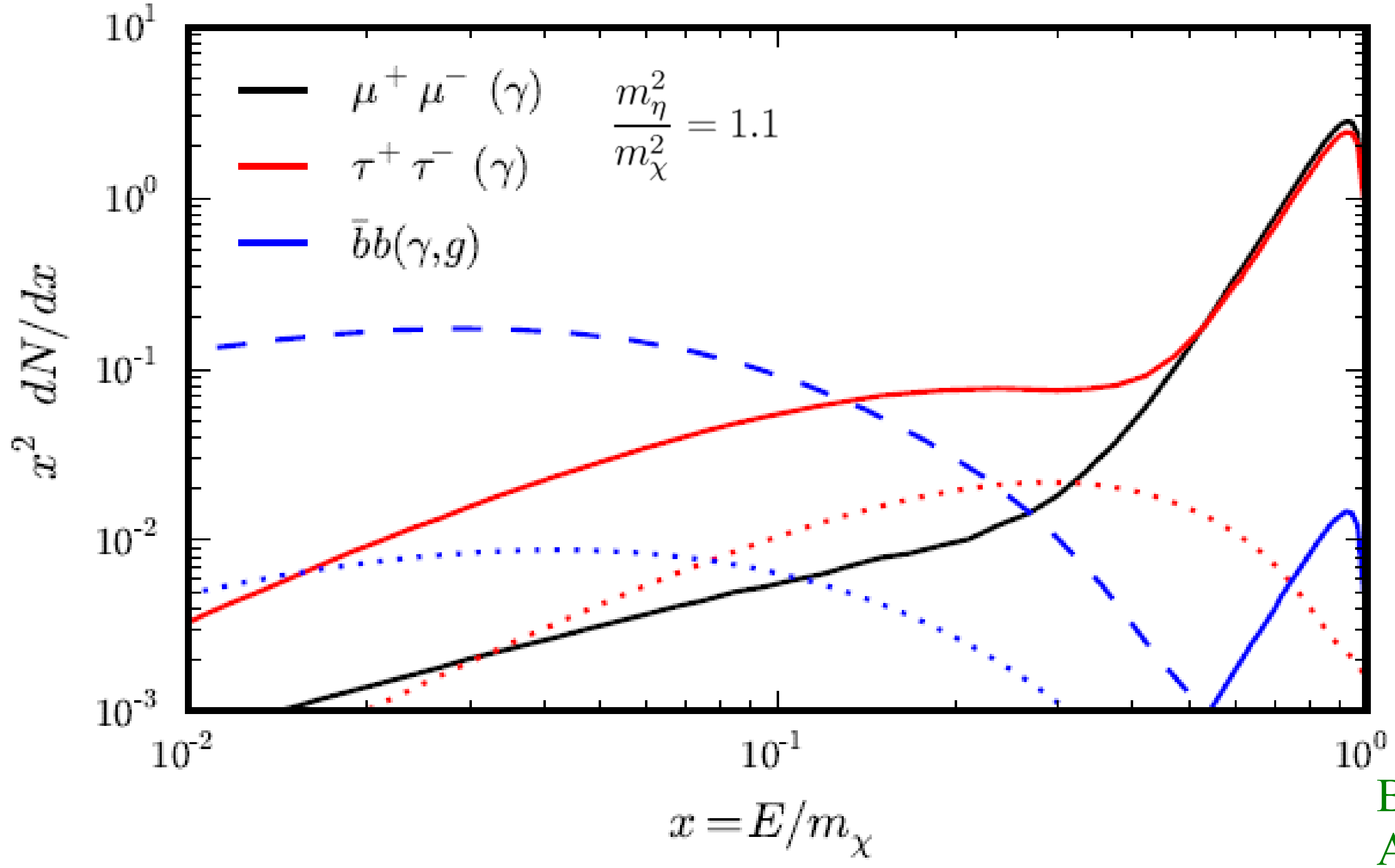


Bonus: if η is sufficiently degenerate in mass with the dark matter particle, the gamma-ray spectrum displays a characteristic spectral feature

Prompt gamma-ray spectrum from dark matter annihilations

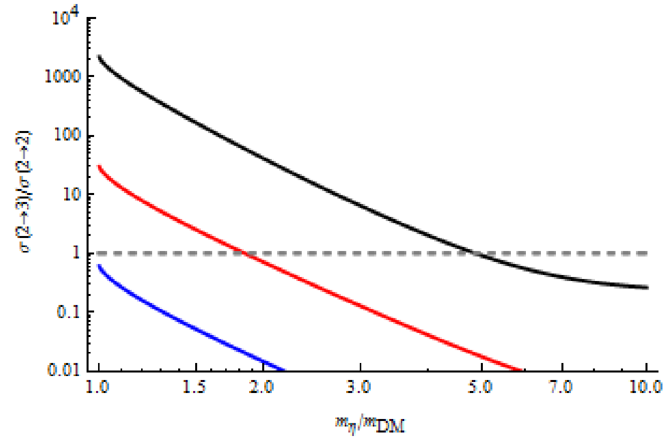


Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

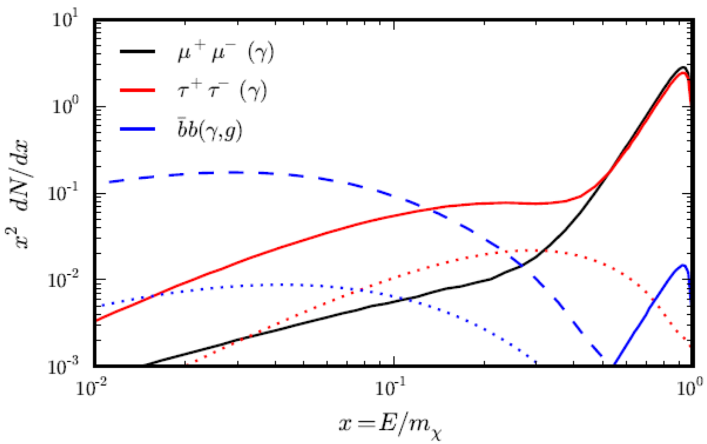
Message to take home:

In scenarios where the dark matter is a Majorana fermion that couples to a light fermion and a scalar, when $m_{DM} \sim m_\eta$,

1) The annihilation channel DM DM $\rightarrow f \bar{f} \gamma$, can have a sizable cross section (and can even be the dominant annihilation channel today)

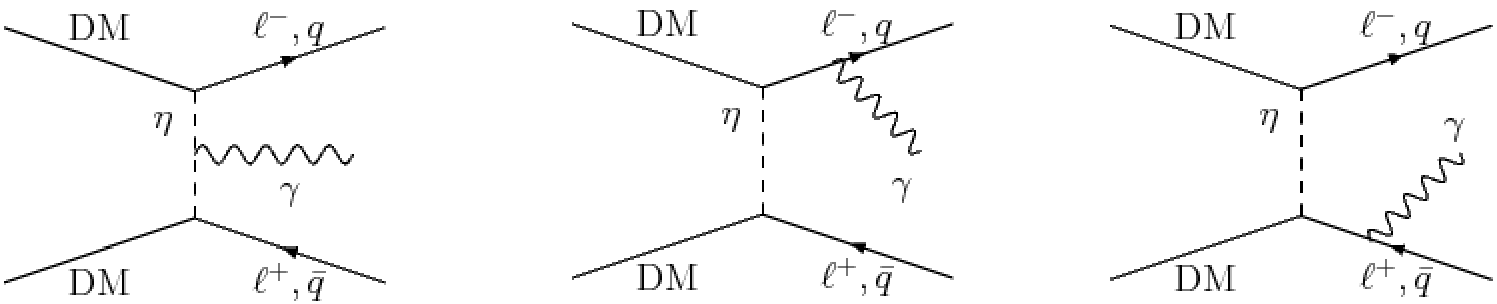


2) The energy spectrum of photons presents a sharp gamma ray feature that resembles a “distorted line”



Outline

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



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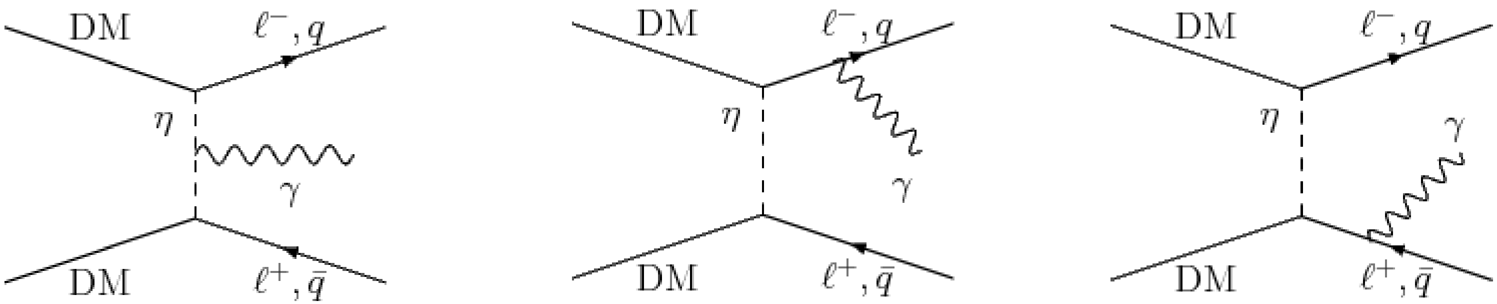
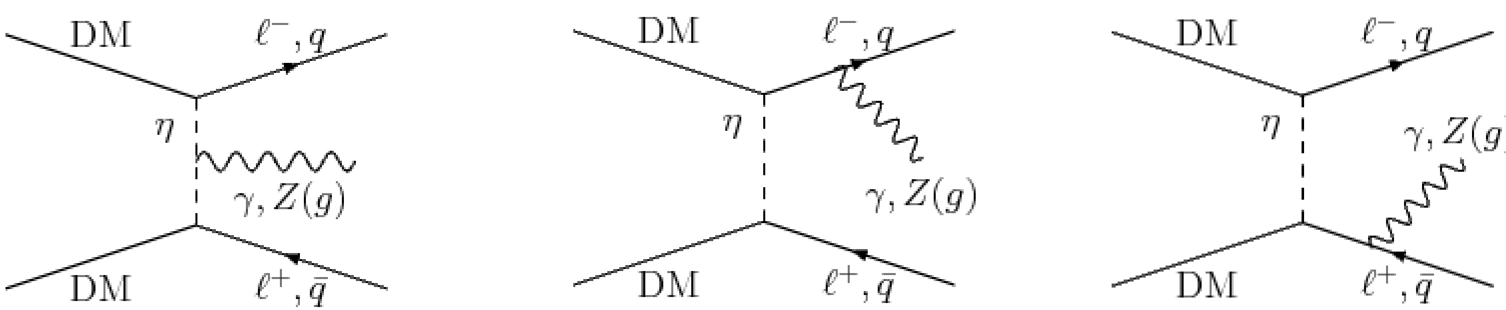
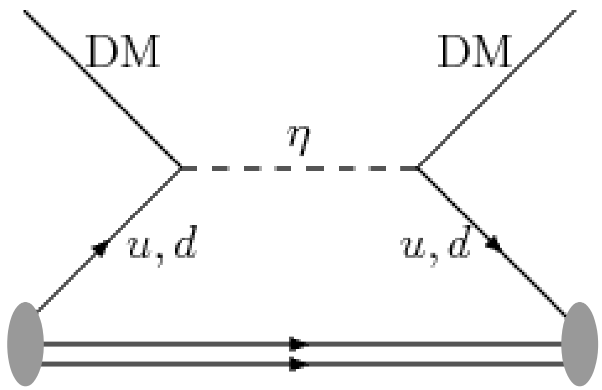


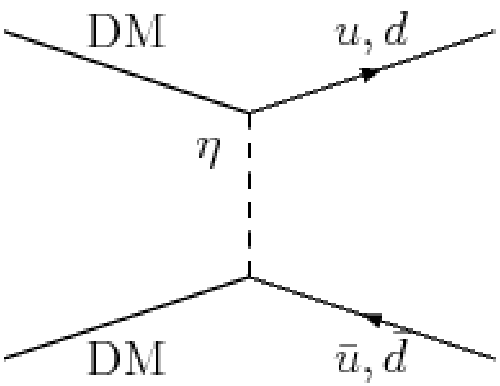
2- Antiproton limits on 2 → 3 processes



Outline (cont.)

3- Interplay indirect detection - direct detection





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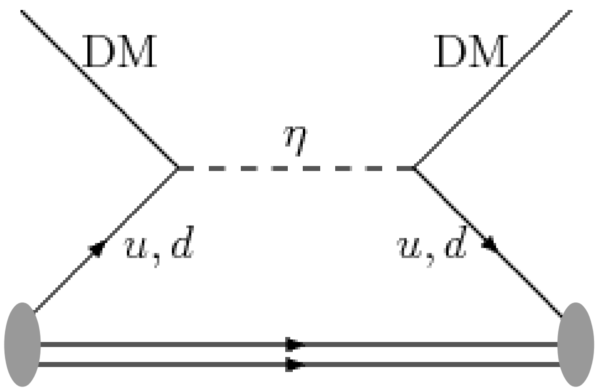
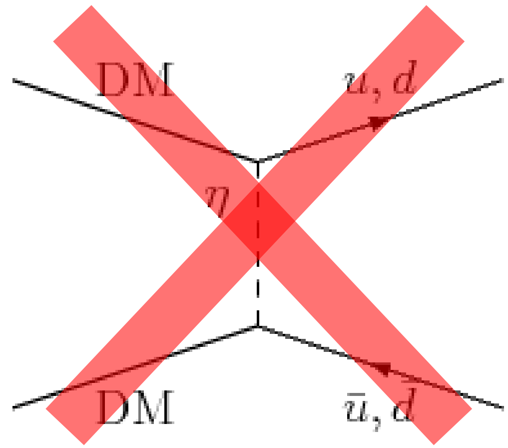
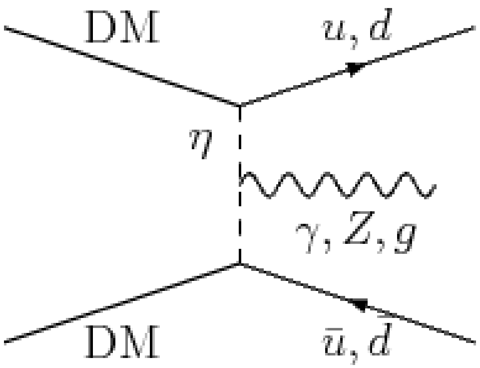




Very suppressed!

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



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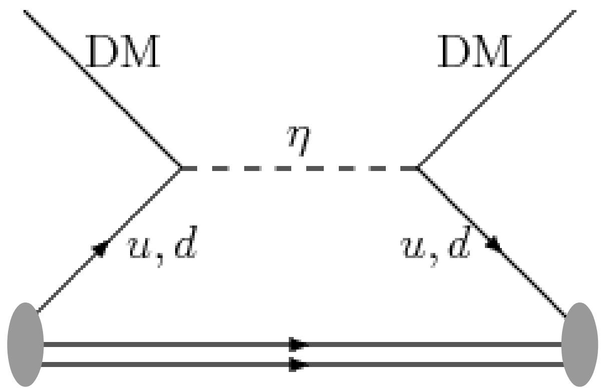

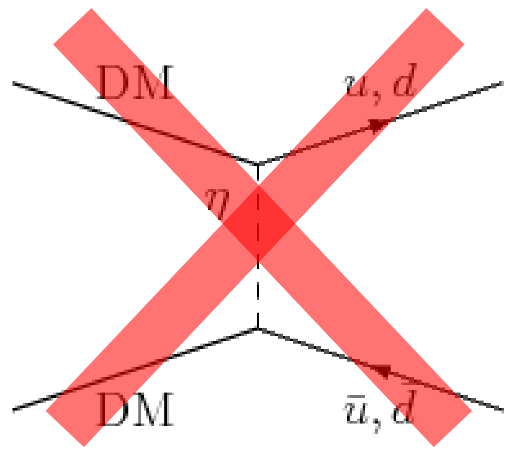

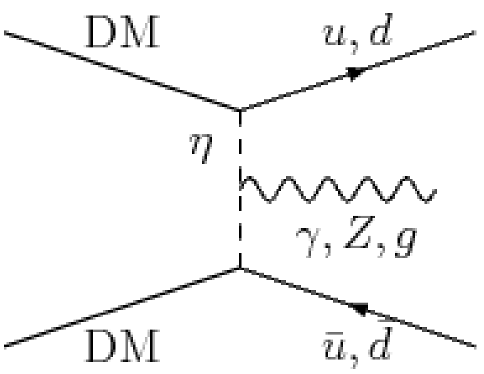

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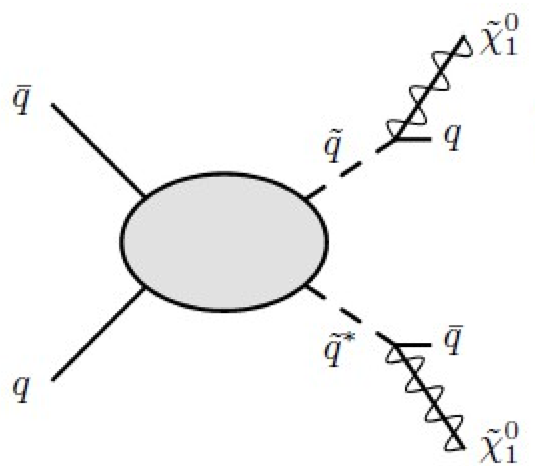
4- Collider limits



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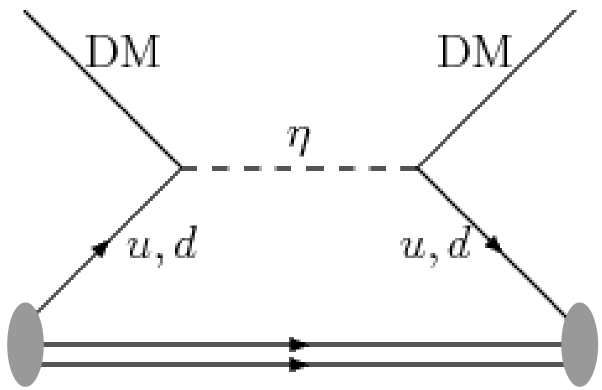

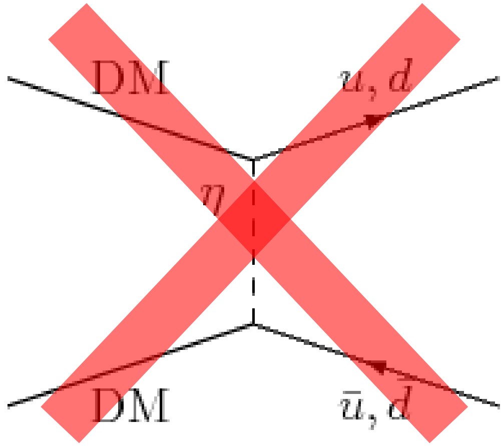

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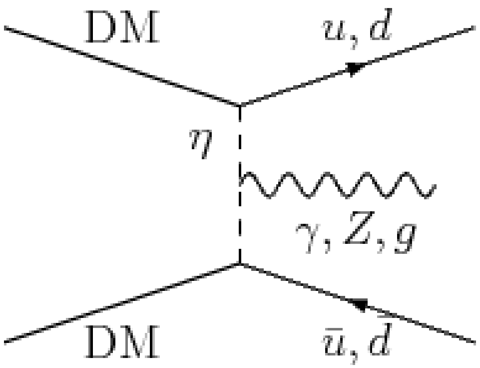

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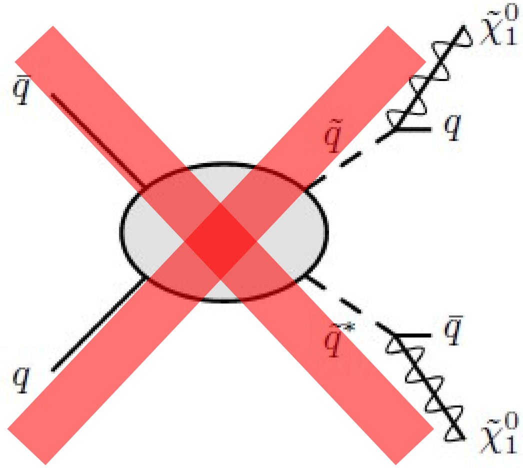
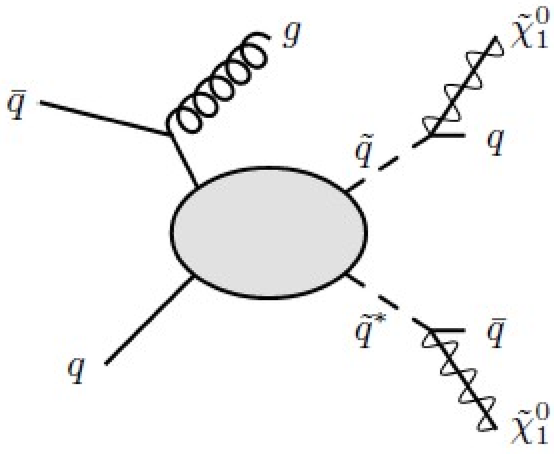


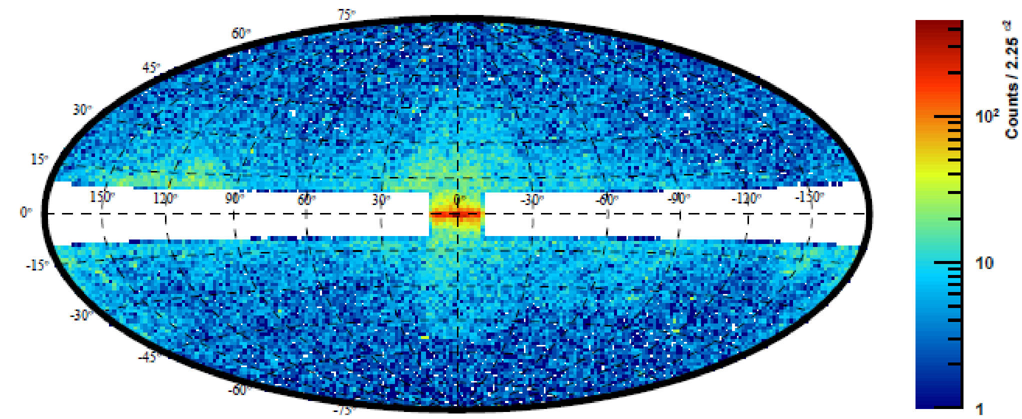
Invisible final state!



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

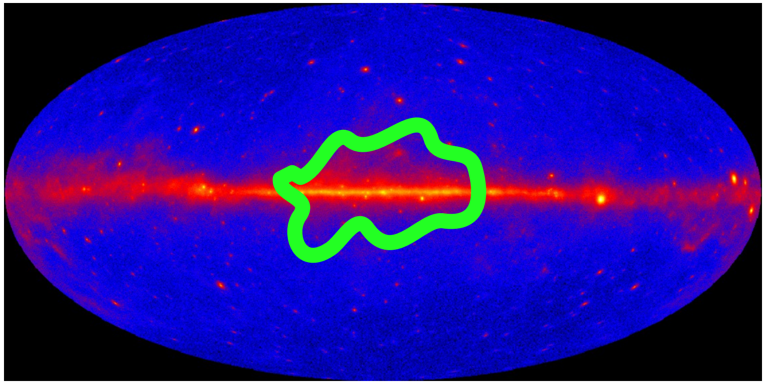
Traditional approach: select a fixed region of the sky and search for features.

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

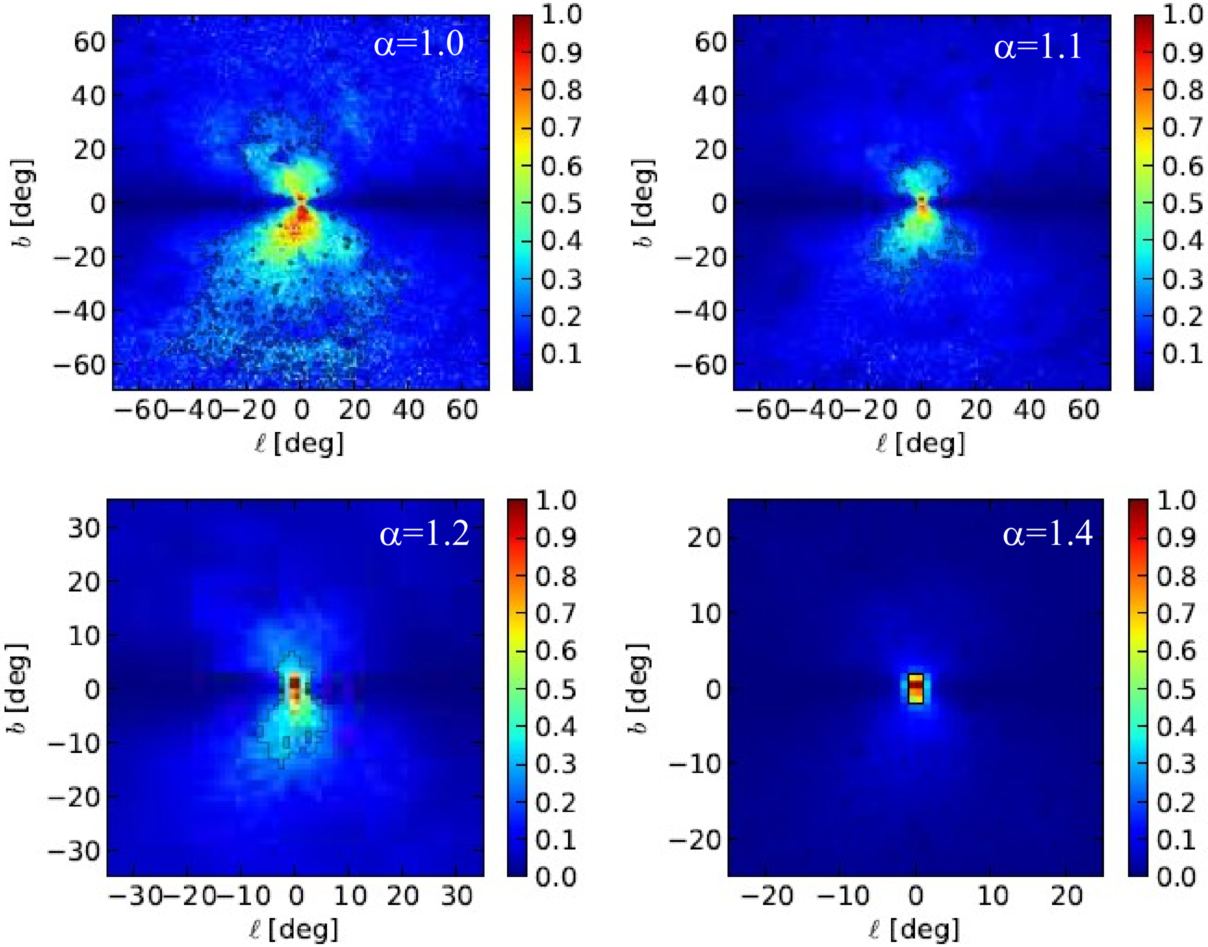


1- Search for signatures of internal bremsstrahlung with the Fermi-LAT

Consider a generalized NFW profile

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

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



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

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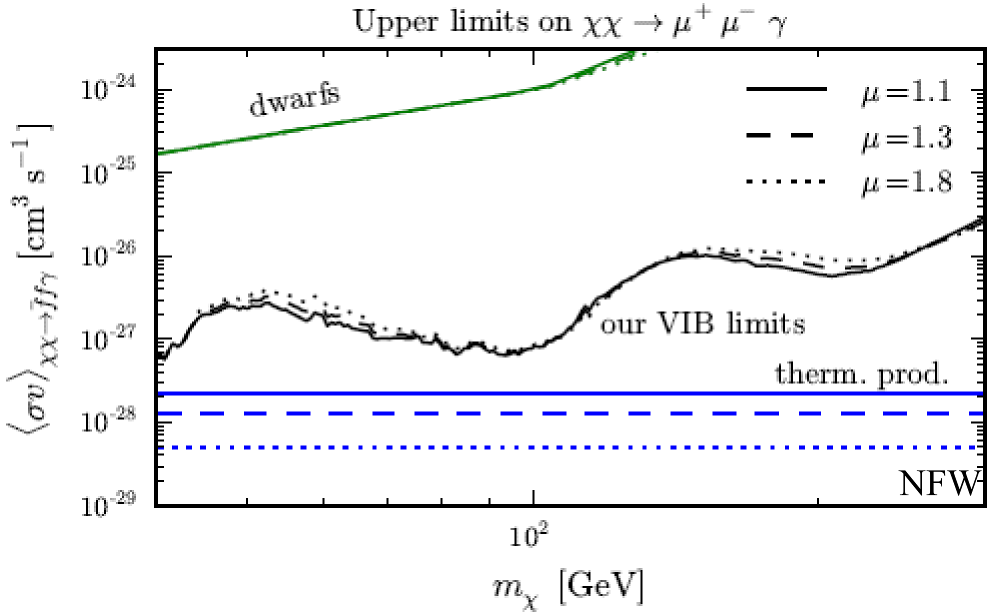

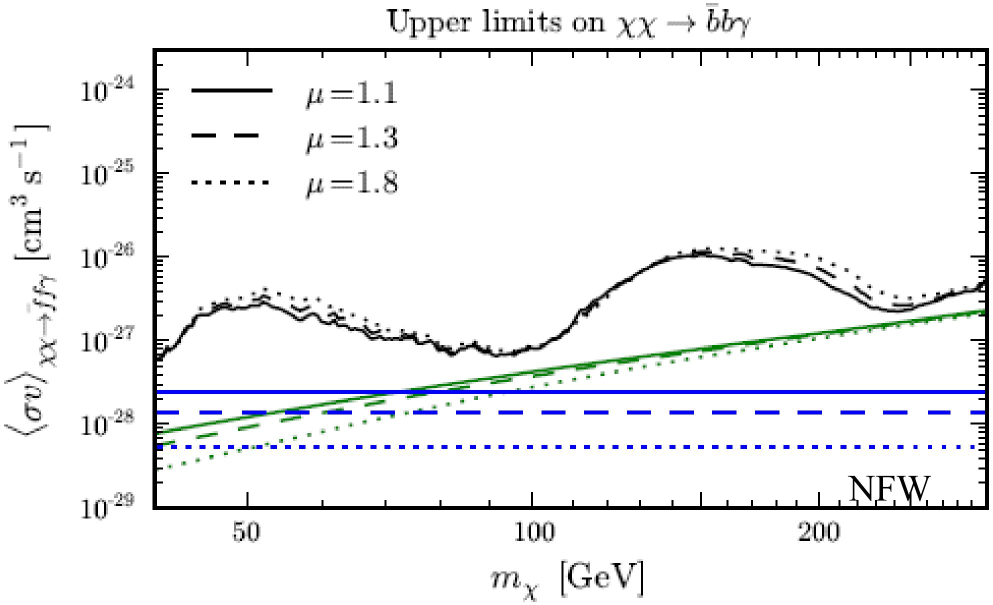

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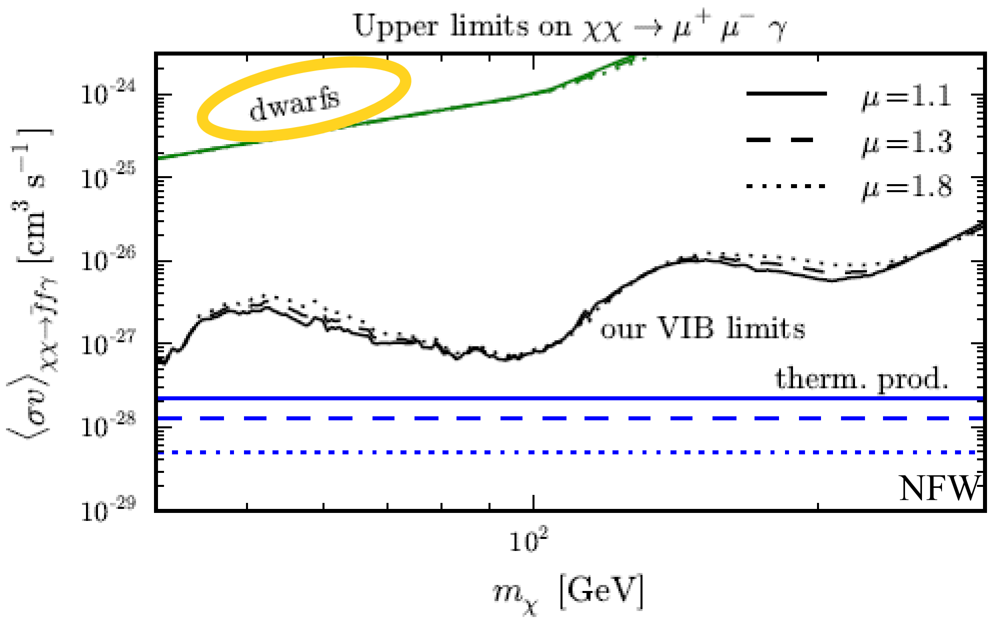
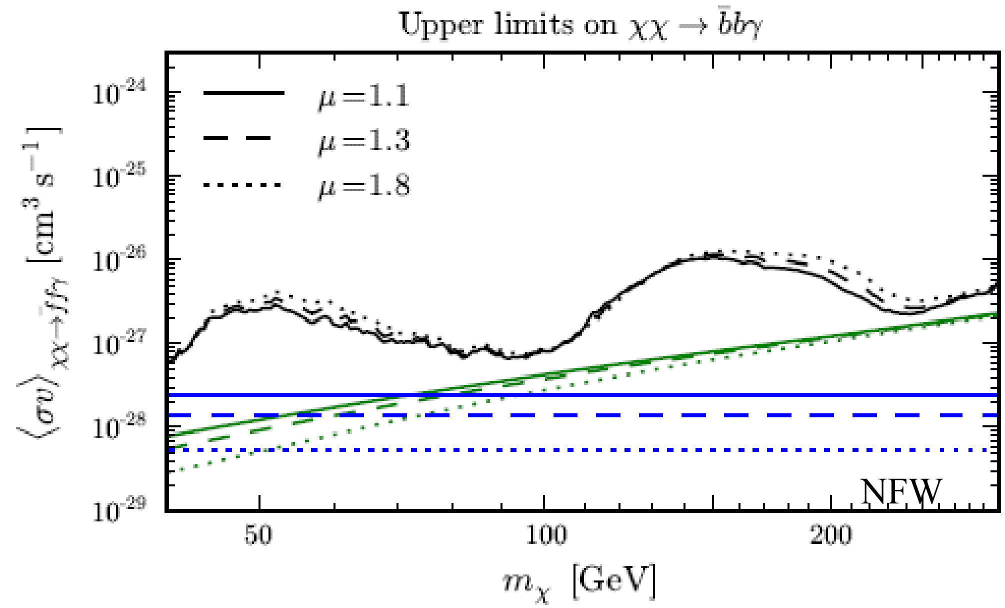


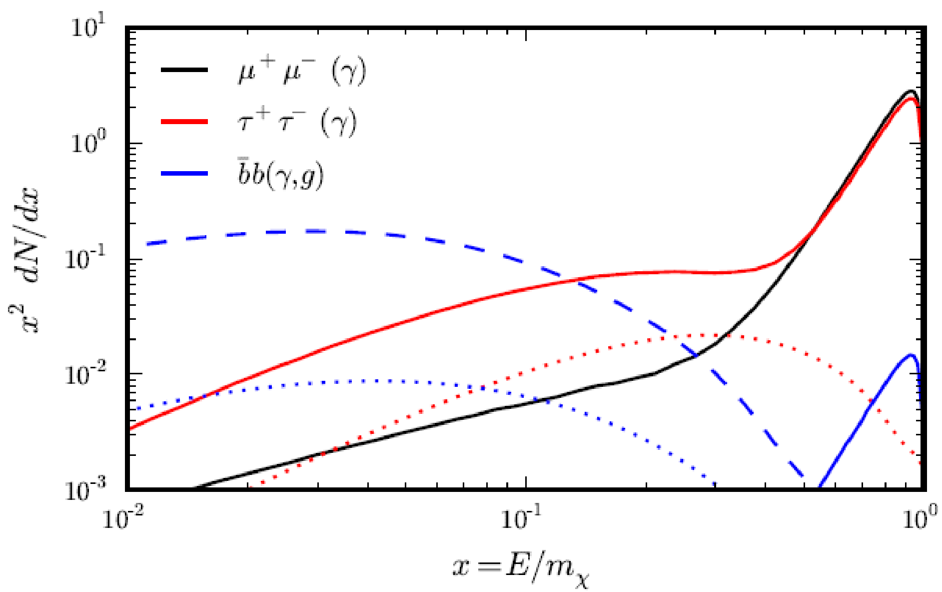


Limit on the total annihilation cross section from dwarf galaxy observations

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

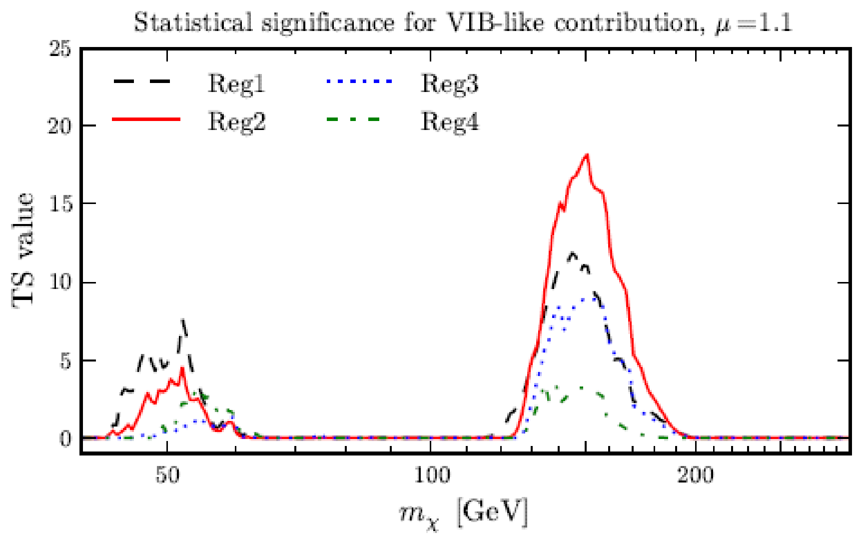
N_γ^{tot}= Number of photons with E=1-100 GeV

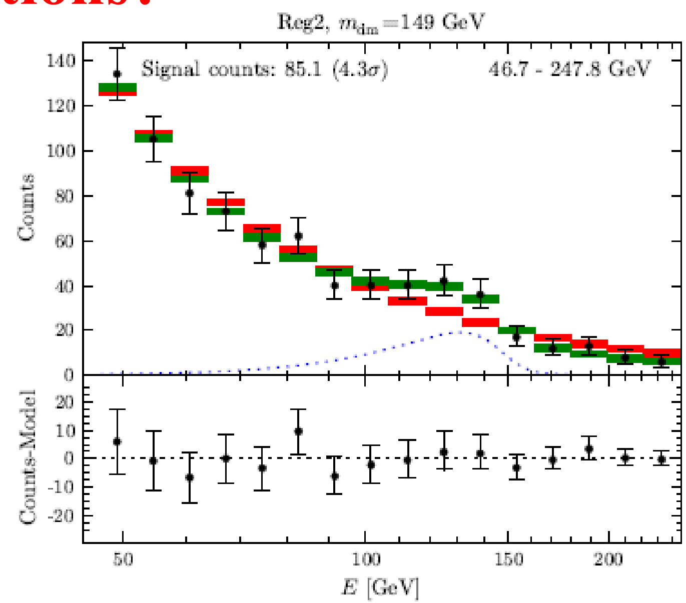
Geringer-Sameth, Koushiappas, arXiv:1108.2914



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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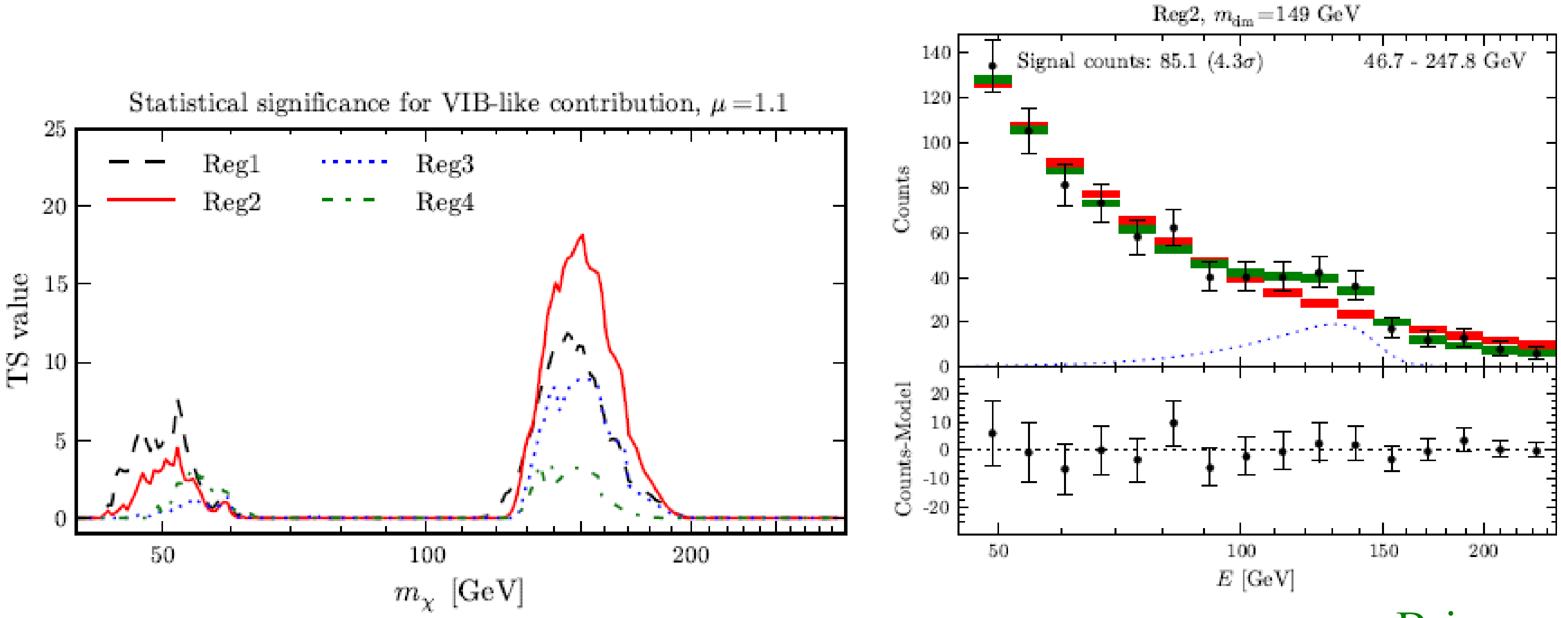

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4.3 σ (3.1 σ with LEE) in Reg2

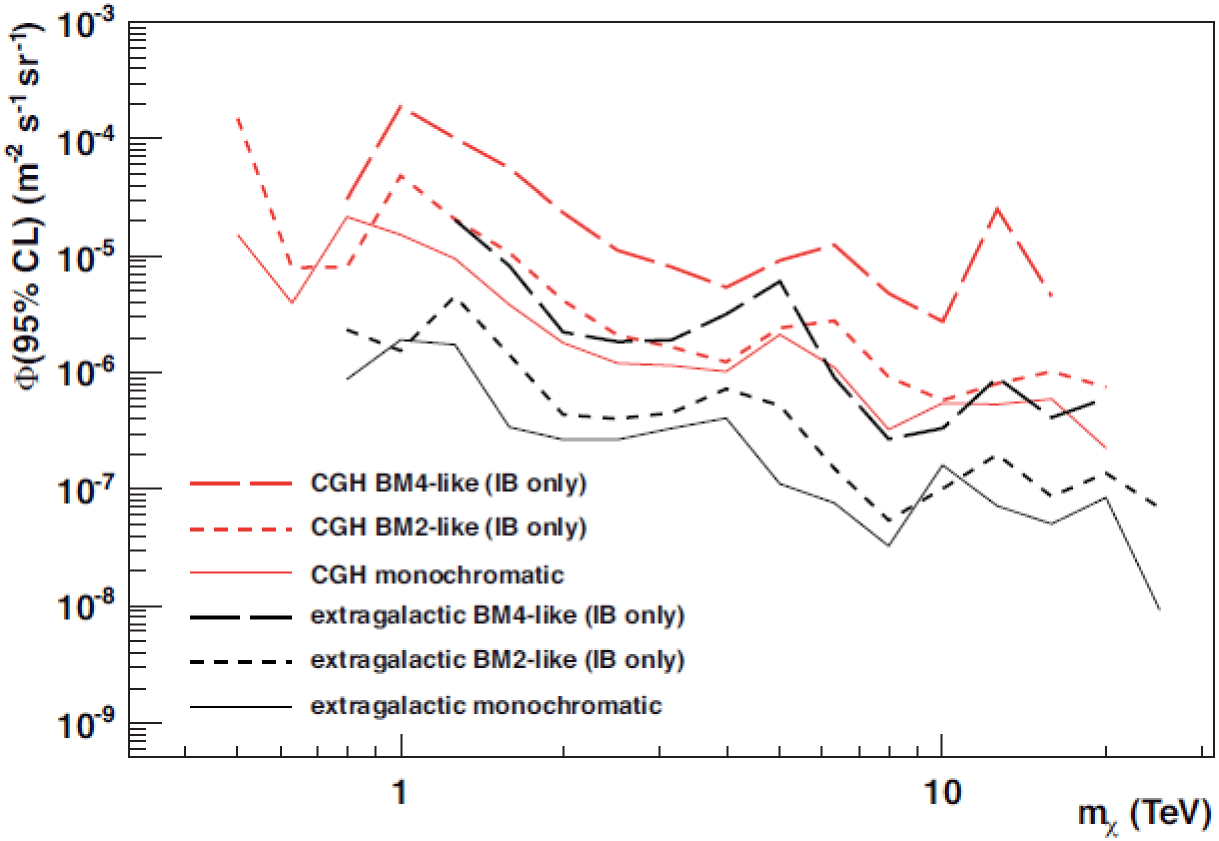
The excess can also be fitted by a line
$$\begin{cases} m_\chi = 129.8 \pm 2.4^{+7}_{-13}\ \text{GeV} \\ \langle \sigma v \rangle = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1} \end{cases}$$

Weniger, arXiv:1204.2797

4.6 σ (3.3 σ with LEE) for Einasto

Extending the search for internal Bremsstrahlung to larger DM masses

95% CL flux upper limits on spectral features



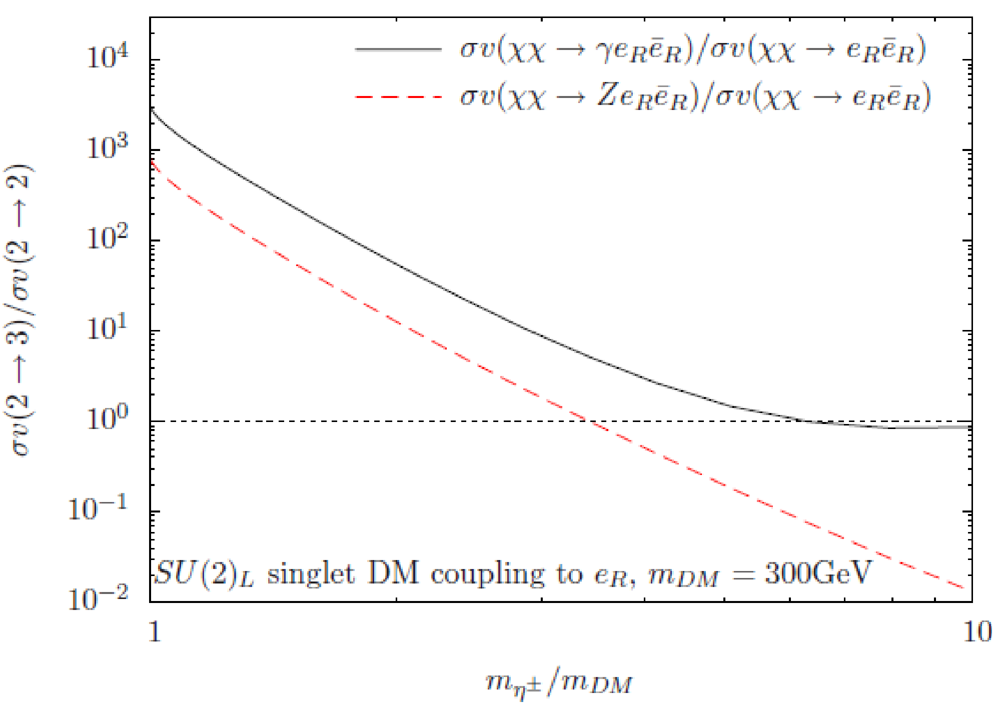
Abramowski et al.
H.E.S.S. Collaboration
arXiv:1301.1173

2- Antiproton limits on 2 → 3 processes

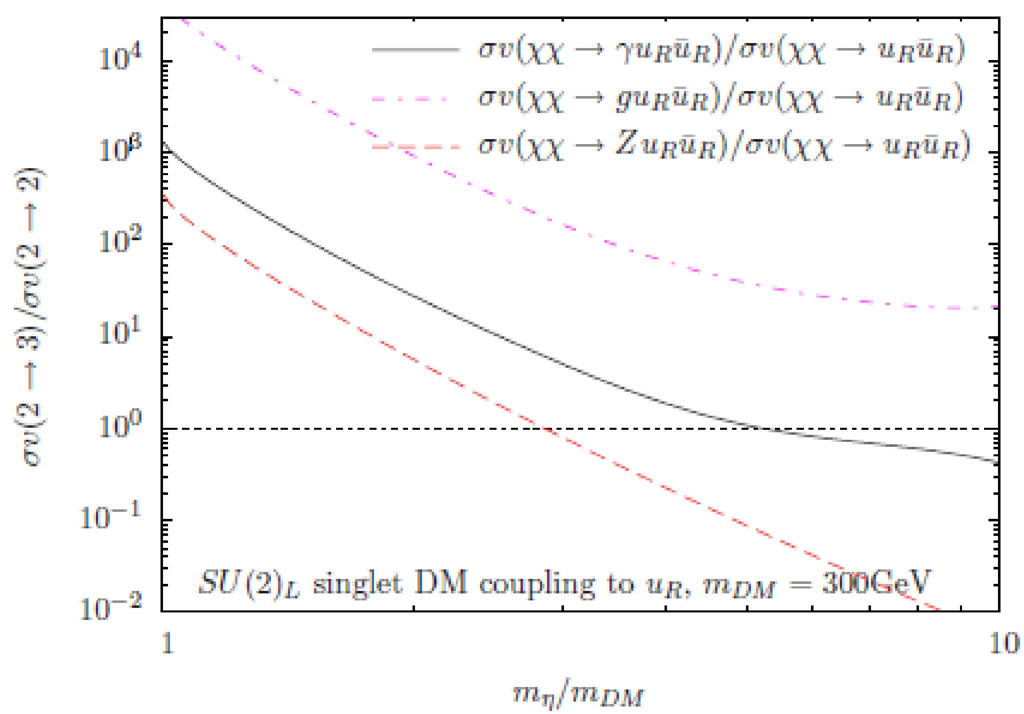
- In our toy model, the intermediate scalar η necessarily carries color charge and/or hypercharge. Antiproton production guaranteed.

- Furthermore, the 2 → 3 processes producing antiprotons can have a sizeable cross section.

Annihilations into $SU(2)_L$ singlet leptons

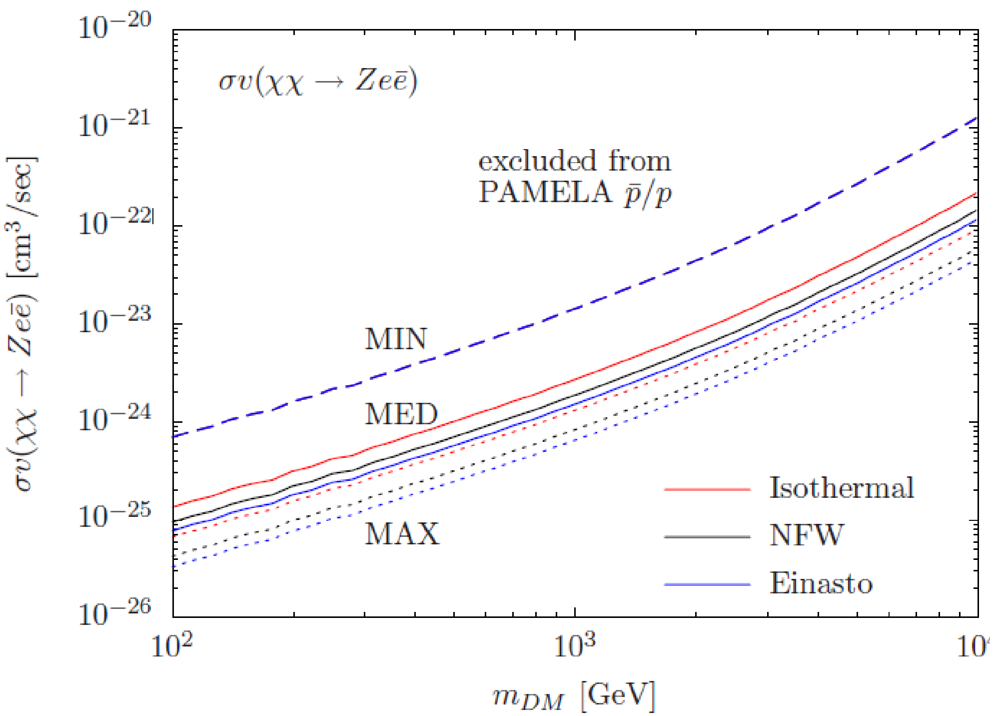


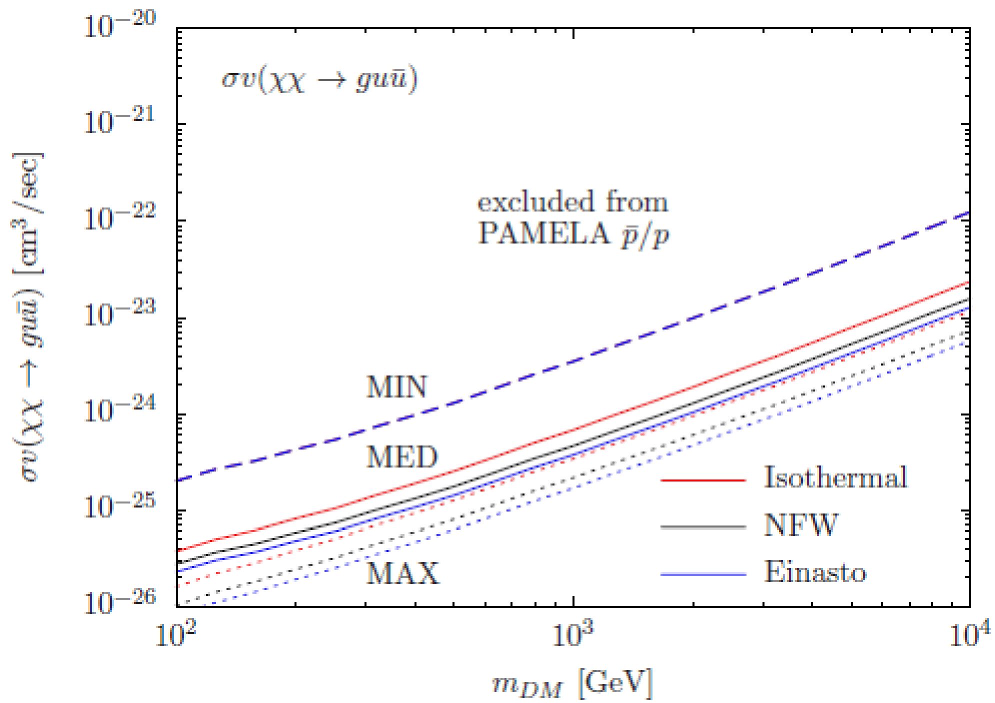
Annihilations into $SU(2)_L$ singlet quarks



2- Antiproton limits on 2 → 3 processes

Limits from the PAMELA p̄/p measurements

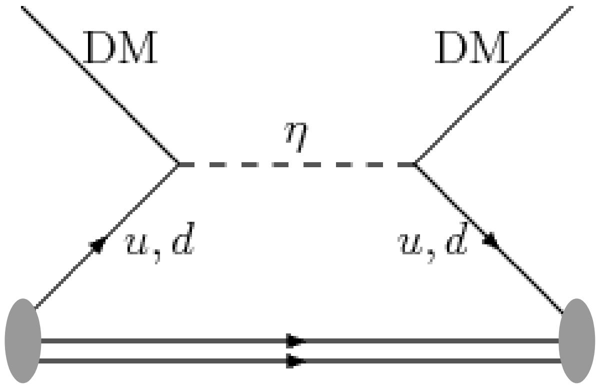


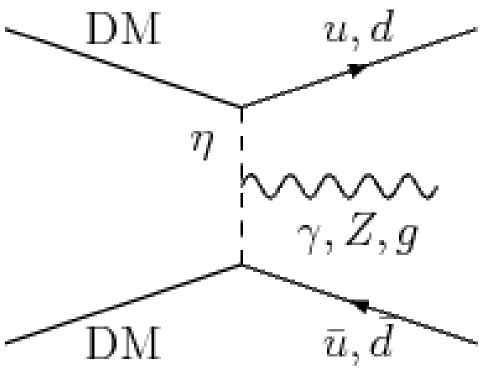


Garny, AI, Vogl
arXiv:1112.5155

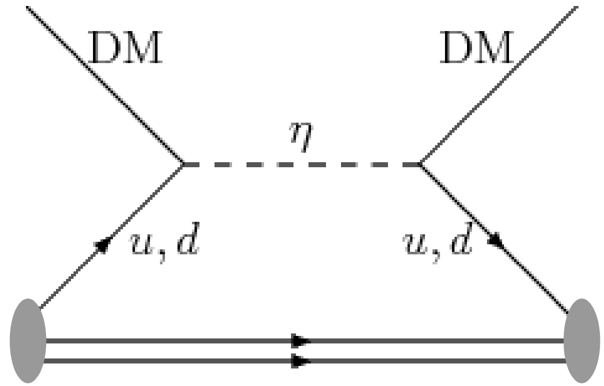
Limits for $\sigma v(\chi\chi \to We\nu)$ very similar, although with some (mild) dependence on $m_{\eta 0} - m_{\eta\pm}$.

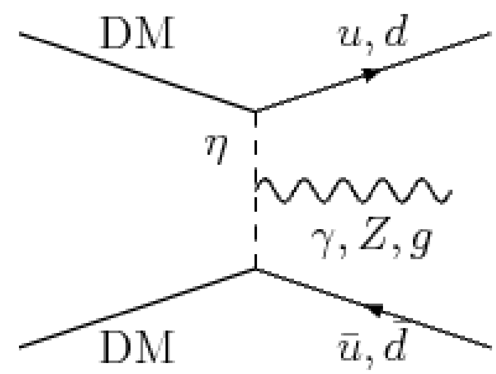
3- Interplay direct detection – indirect detection



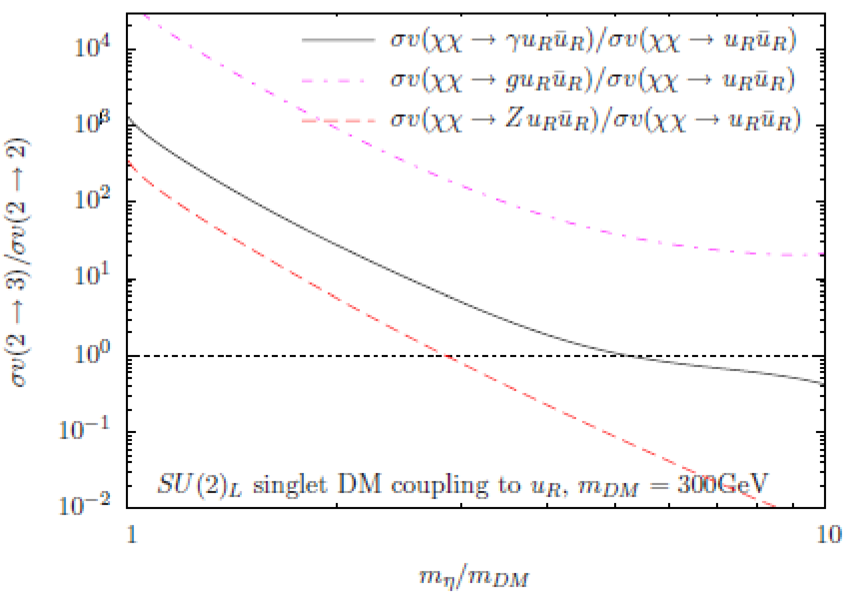


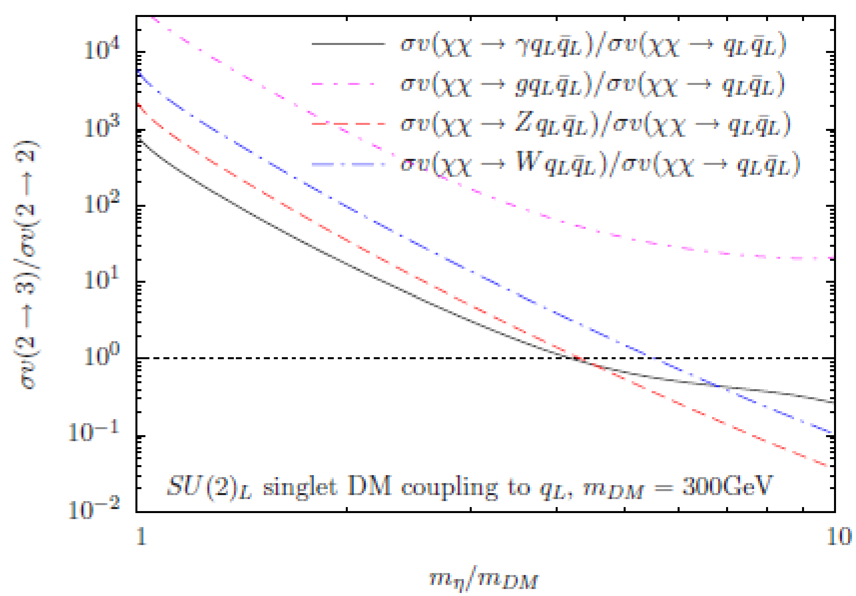
3- Interplay direct detection – indirect detection



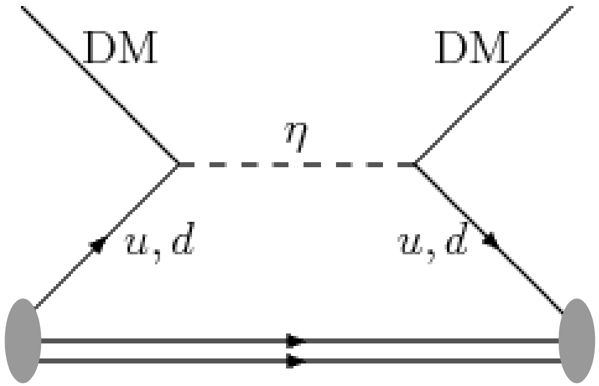


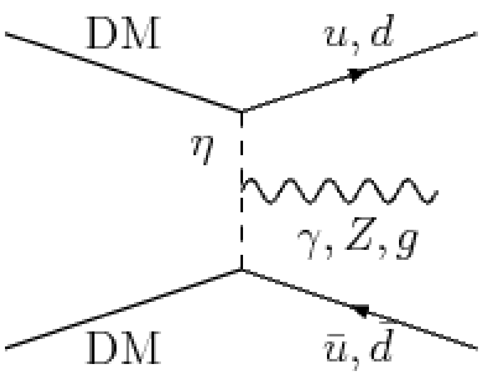
- Indirect detection limits become more stringent when η and χ are degenerate in mass, due to the larger $2 \to 3$ cross section.





3- Interplay direct detection – indirect detection





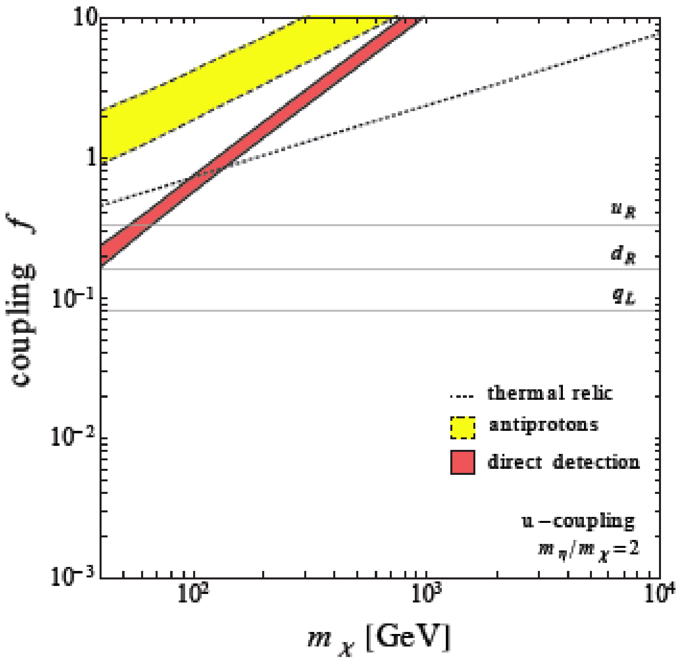
• Indirect detection limits become more stringent when η and χ are degenerate in mass, due to the larger 2 → 3 cross section.

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

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

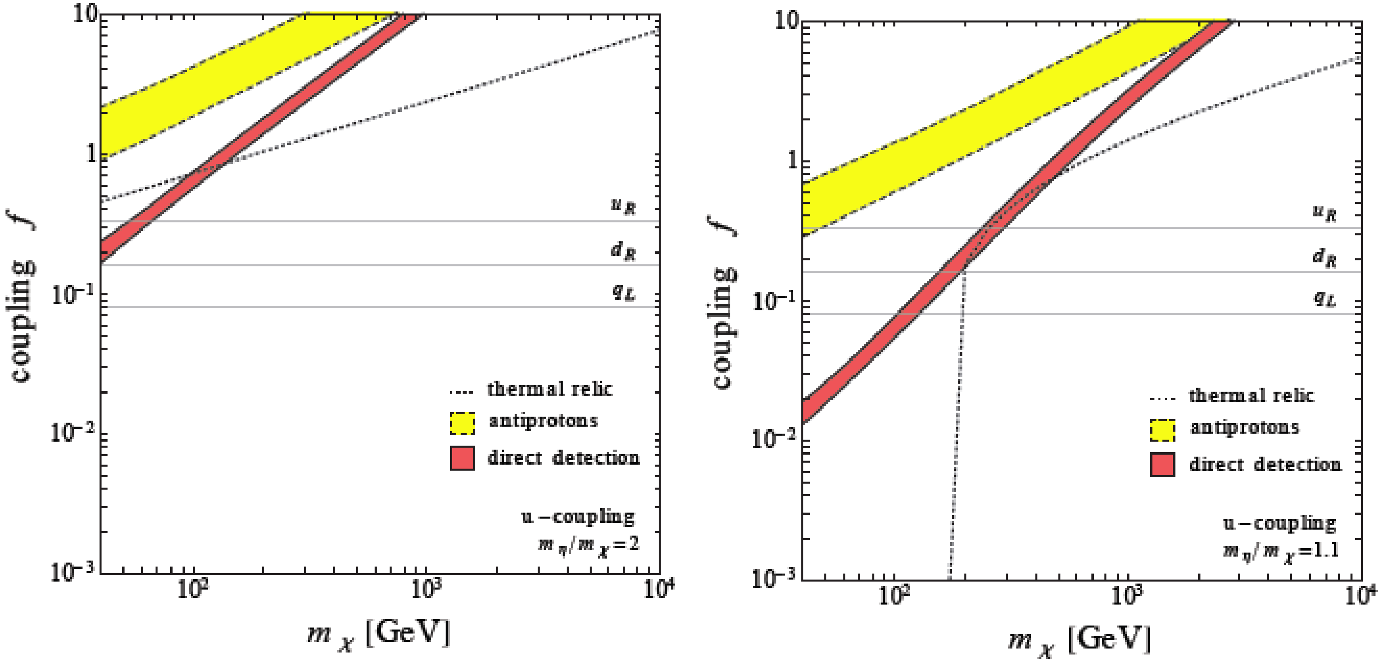
3- Interplay direct detection – indirect detection

Limits on the Yukawa coupling from PAMELA and XENON-100



3- Interplay direct detection – indirect detection

Limits on the Yukawa coupling from PAMELA and XENON-100



3- Interplay direct detection – indirect detection

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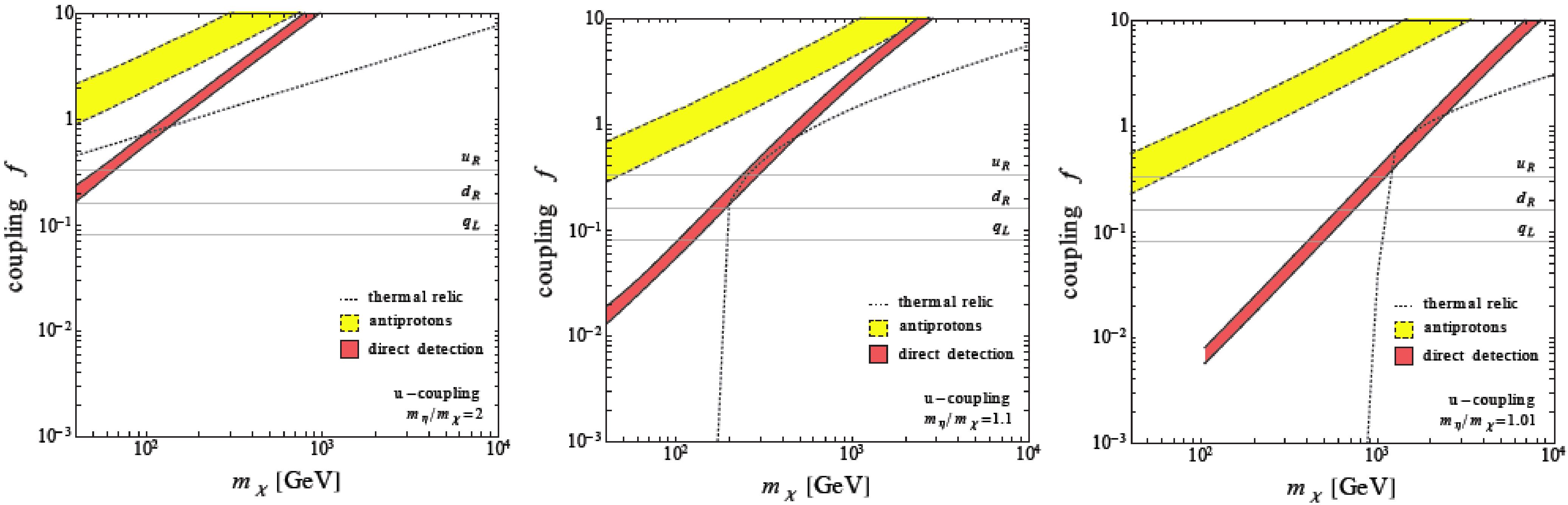
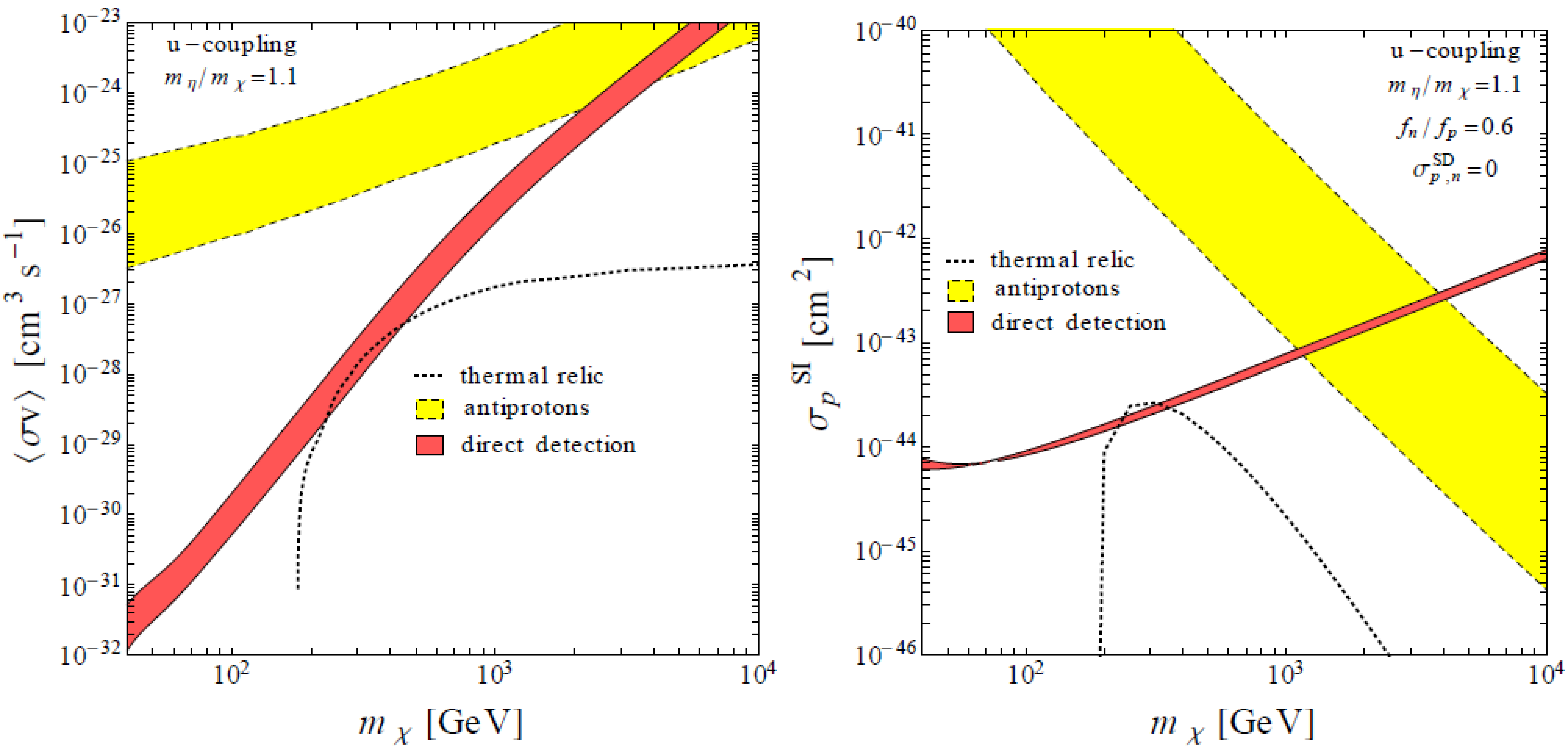


Garny, AI, Pato, Vogl
ArXiv:1207.1431

3- Interplay direct detection – indirect detection



Garny, AI, Pato, Vogl
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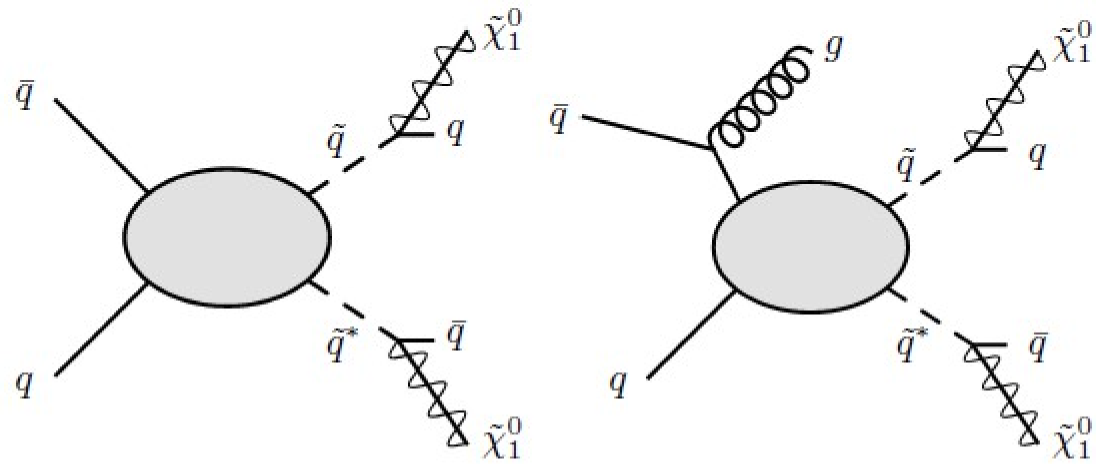
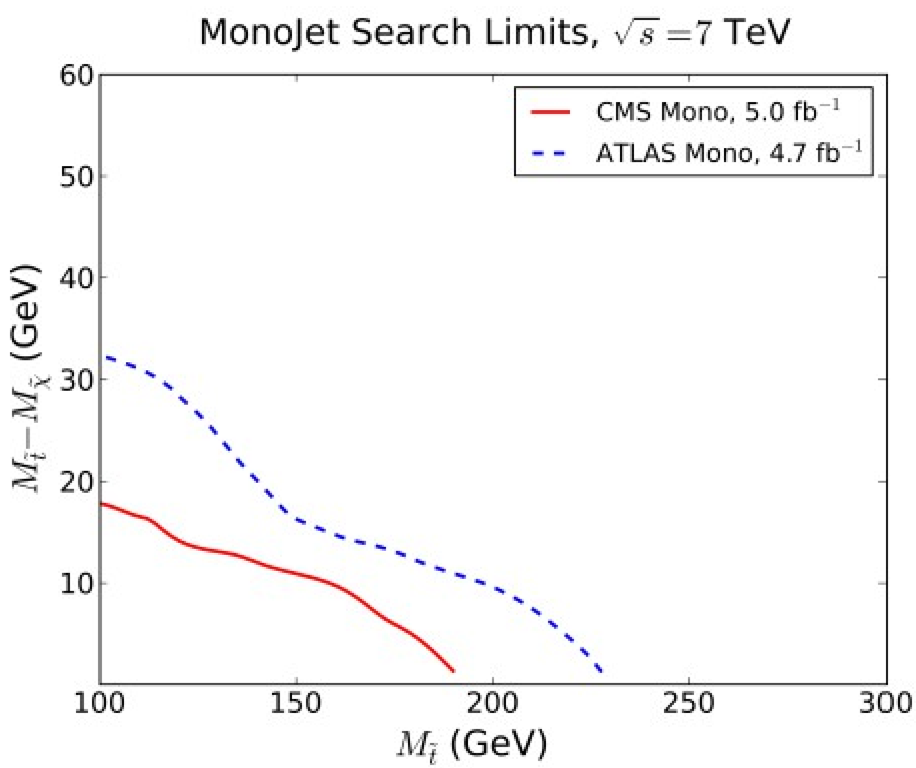
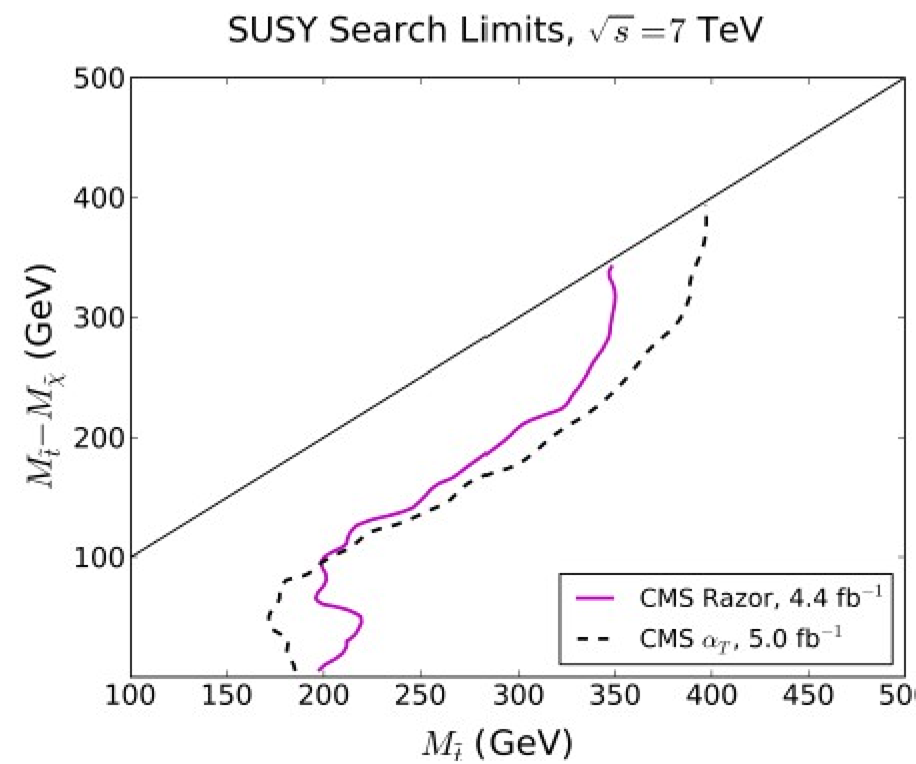
4- Collider limits

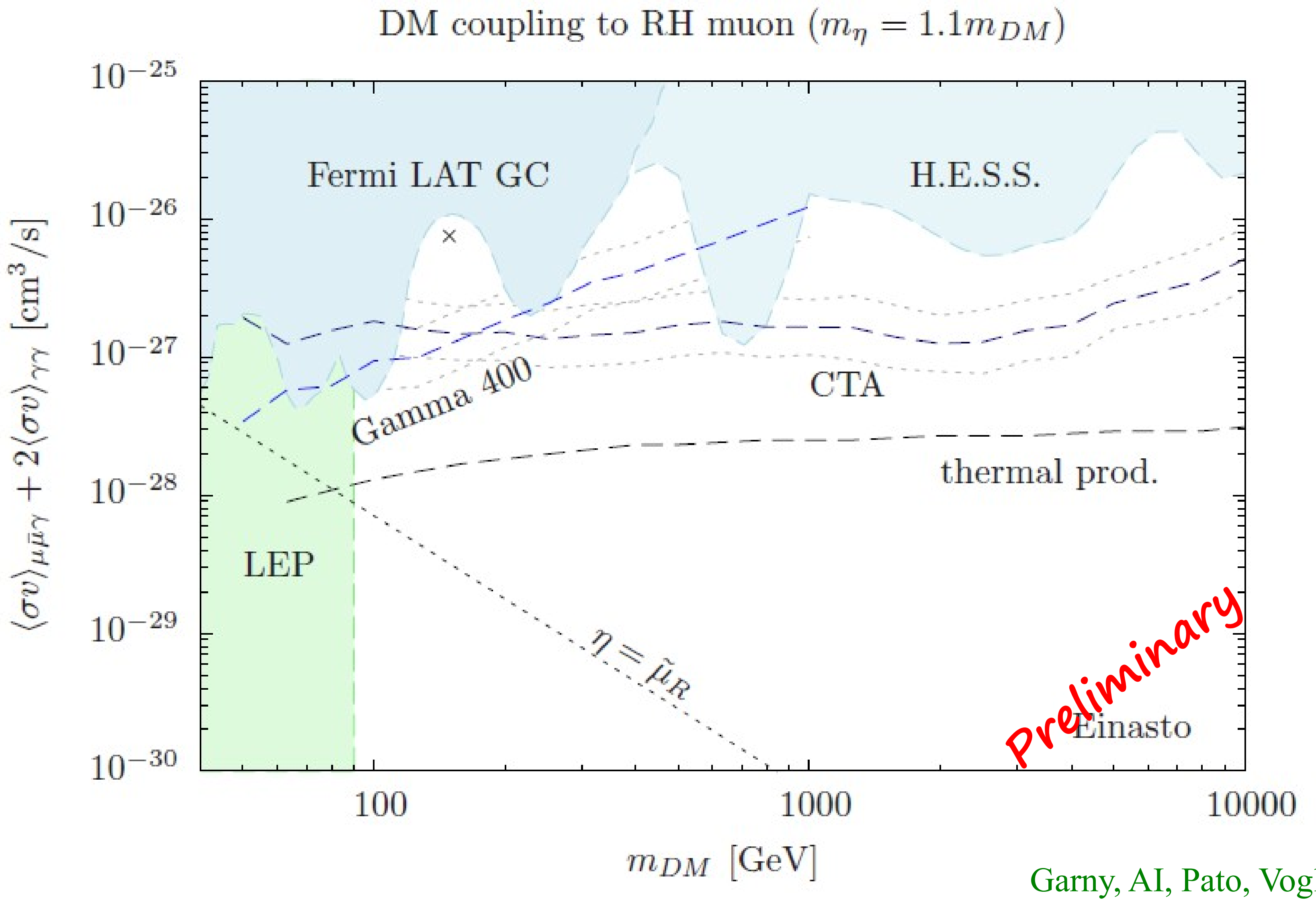






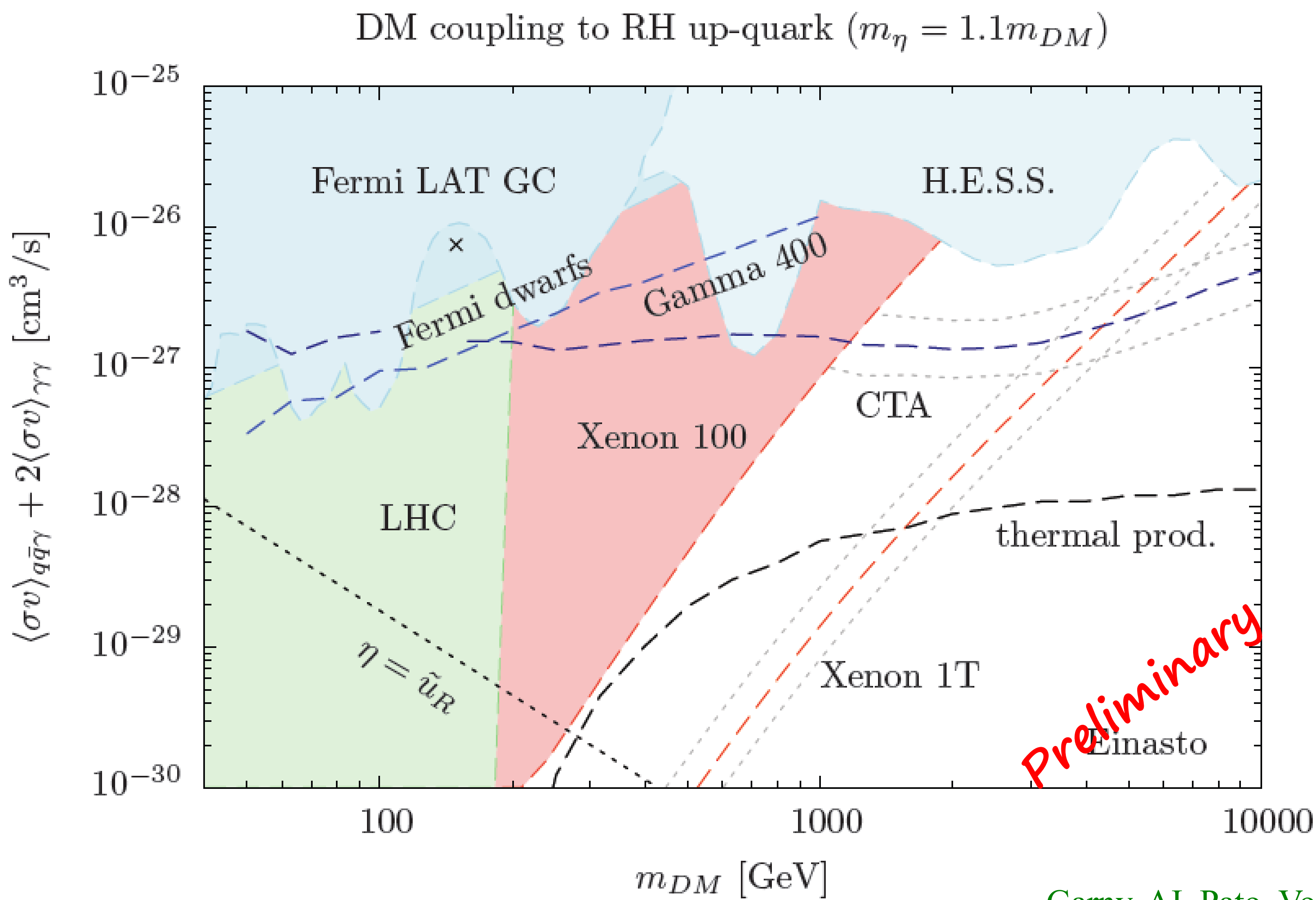
Dreiner, Krämer, Tattersal, arXiv:1211.4981
See also CMS coll., arXiv:1303.2985

5 - Gamma-ray spectral features in light of direct detection and colliders



Garny, AI, Pato, Vogl
in preparation

5 - Gamma-ray spectral features in light of direct detection and colliders



Garny, AI, Pato, Vogl
in preparation

Conclusions

• In scenarios with Majorana 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).

• The annihilation DM DM $\rightarrow f\bar{f}\gamma$ produces a sharp spectral feature that could be observed in gamma-ray telescopes. The Fermi-LAT and H.E.S.S. already impose strong limits on the annihilation cross section, which lie a factor of a few above the expected values from thermal production. An intriguing excess at ~130 GeV was found in the Fermi-LAT data which could be attributed to DM DM $\rightarrow f\bar{f}\gamma$ with $m_\chi \simeq 149$ GeV.

• Limits on these scenarios also follow from direct detection experiments, antiproton measurements and collider experiments, which are complementary to the gamma-ray limits.

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Thank you for your attention!