Constraints on the Dark Matter Properties from Radiative Decays

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In collaboration with Mathias Garny, David Tran and Christoph Weniger
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Introduction

Many pieces of evidence for particle dark matter. However, very little is known about the properties of the dark matter particle:

Spin: 0 or 1/2 or 1 or 3/2 (possibly higher if composite)

Parity: + or −

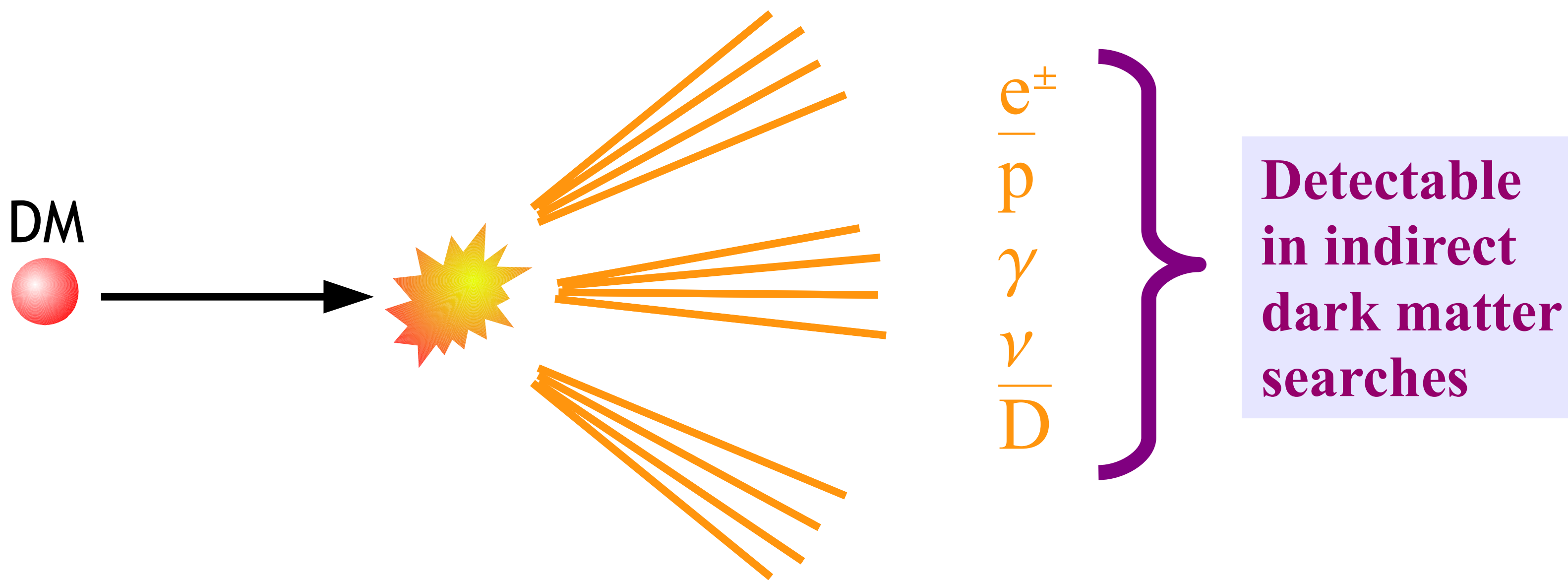
Mass: 10^{-15} GeV $\longrightarrow$ 10^{15} GeV
(axions) (WIMPzillas)

Interaction cross section with nucleons: 10^{-40} pb $\longrightarrow$ 10^{-5} pb
(gravitinos) (neutralinos)

Lifetime: 10^{9} years $\longrightarrow$ infinity

Introduction

Goal: constrain the lifetime of a dark matter particle with mass in the TeV range



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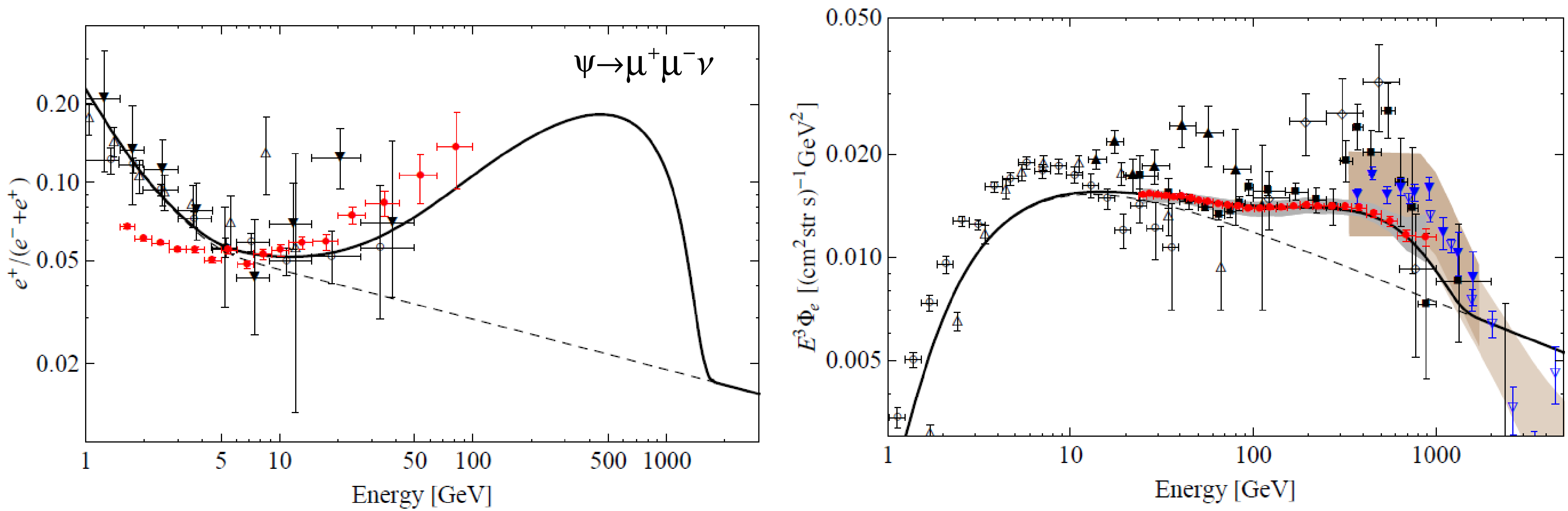
Phenomenological motivation: Electron/positron excesses could be explained by the decay of dark matter particles



AI, Tran, Weniger
0906.1571

$m_{DM} \approx 3500$ GeV, $\tau_{DM} \approx 1.1 \times 10^{26}$ s

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Decay Channel	$M_{\rm DM}$ [GeV]	$\tau_{\rm DM}$ [10^{26}s]
$\psi_{\rm DM} \to \mu^+\mu^-\nu$	3500	1.1
$\psi_{\rm DM} \to \ell^+\ell^-\nu$	2500	1.5
$\psi_{\rm DM} \to W^\pm\mu^\mp$	3000	2.1
$\phi_{\rm DM} \to \mu^+\mu^-$	2500	1.8
$\phi_{\rm DM} \to \tau^+\tau^-$	5000	0.9

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Theoretical motivation: No matter particle is guaranteed to be stable

particle	Lifetime	Decay channel	Theoretical justification
proton	$\tau > 8.2 \times 10^{33}$ years	$p \to e^+ \pi^0$	Baryon number conservation
electron	$\tau > 4.6 \times 10^{26}$ years	$e \to \gamma \nu$	Electric charge conservation
neutrino	$\tau \gtrsim 10^{12}$ years	$\nu \to \gamma \gamma$	Lorentz symmetry conservation
neutron	$\tau = 885.7 \pm 0.8$ s	$n \to p \, \bar{\nu}_e \, e^-$	Isospin symmetry mildly broken.

} Accidental symmetry (proton)

} Local symmetry (electron, neutrino)

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dark matter	$\tau \gtrsim 10^9$ years	???	???

} Accidental symmetry (proton)

} Local symmetry (electron, neutrino)

It is conceivable that the dark matter particle is long lived due to an accidental symmetry of the renormalizable Lagrangian (as for the proton).

Higher dimensional operators may induce the dark matter decay (as for the proton). For a dimension six operator suppressed by a large scale M,

$$\tau_{\rm DM} \sim 10^{26}{\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M}{10^{15}{\rm GeV}}\right)^4$$

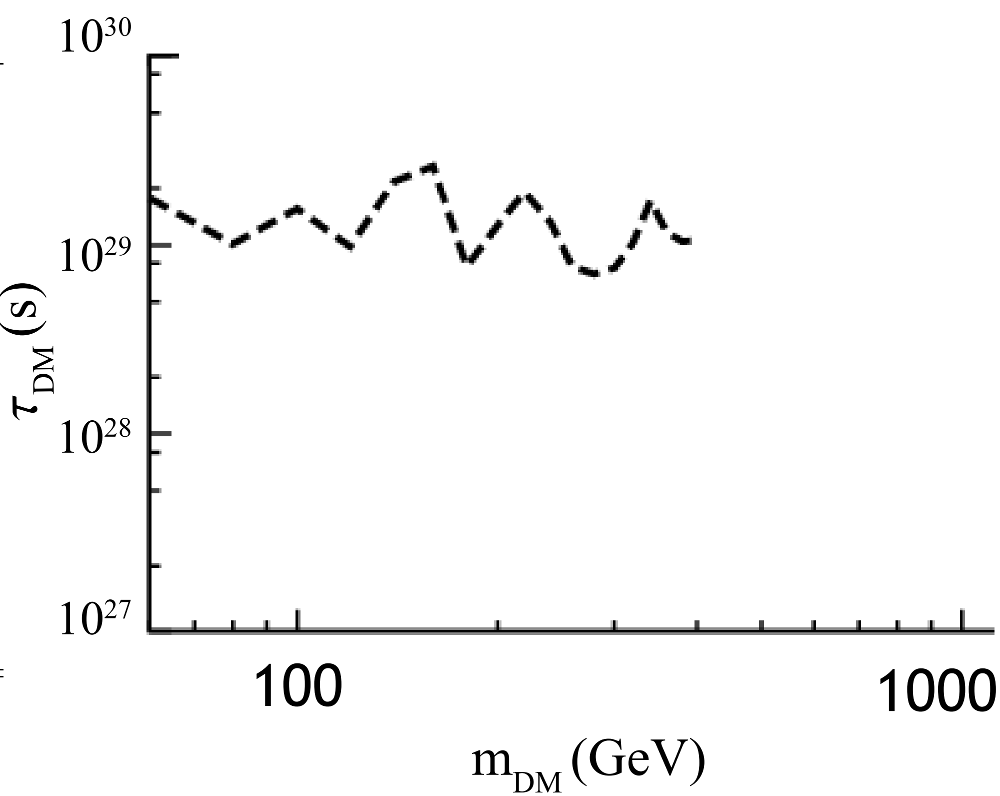
Gamma-ray lines

Gamma ray lines constitute an inequivocal sign of dark matter: No (known) astrophysical source can produce a gamma-ray line in the multi-GeV range

Very stringent constraints on the dark matter lifetime (assuming 100% decays into monochromatic gamma-rays)

E_γ (GeV)	95%CLUL (10^{-9} cm^{-2}s^{-1})	$\tau_{\gamma\gamma}$ [γZ] (10^{28} s) NFW	Einasto	Isothermal
30	3.5	17.6 [4.2]	17.8 [4.2]	17.5 [4.2]
40	4.5	10.1 [2.9]	10.3 [2.9]	10.0 [2.9]
50	2.4	15.5 [5.0]	15.7 [5.1]	15.4 [5.0]
60	3.1	9.8 [3.5]	10.0 [3.5]	9.7 [3.5]
70	1.2	21.6 [8.2]	21.9 [8.3]	21.5 [8.1]
80	0.9	26.0 [10.4]	26.4 [10.5]	25.8 [10.3]
90	2.6	7.7 [3.2]	7.8 [3.2]	7.6 [3.1]
100	1.4	12.6 [5.4]	12.8 [5.4]	12.5 [5.3]
110	0.9	18.9 [8.2]	19.2 [8.3]	18.8 [8.2]
120	1.1	13.3 [5.9]	13.5 [6.0]	13.2 [5.9]
130	1.8	7.6 [3.4]	7.8 [3.5]	7.6 [3.4]
140	1.9	7.0 [3.2]	7.1 [3.3]	7.0 [3.2]
150	1.6	7.5 [3.5]	7.6 [3.5]	7.4 [3.4]
160	1.1	10.2 [4.8]	10.4 [4.8]	10.1 [4.7]
170	0.6	17.0 [8.0]	17.2 [8.1]	16.9 [7.9]
180	0.9	11.6 [5.5]	11.8 [5.6]	11.6 [5.4]
190	0.9	10.4 [4.9]	10.5 [5.0]	10.3 [4.9]
200	0.9	10.6 [5.1]	10.8 [5.1]	10.5 [5.0]

Fermi coll.
1001.4836



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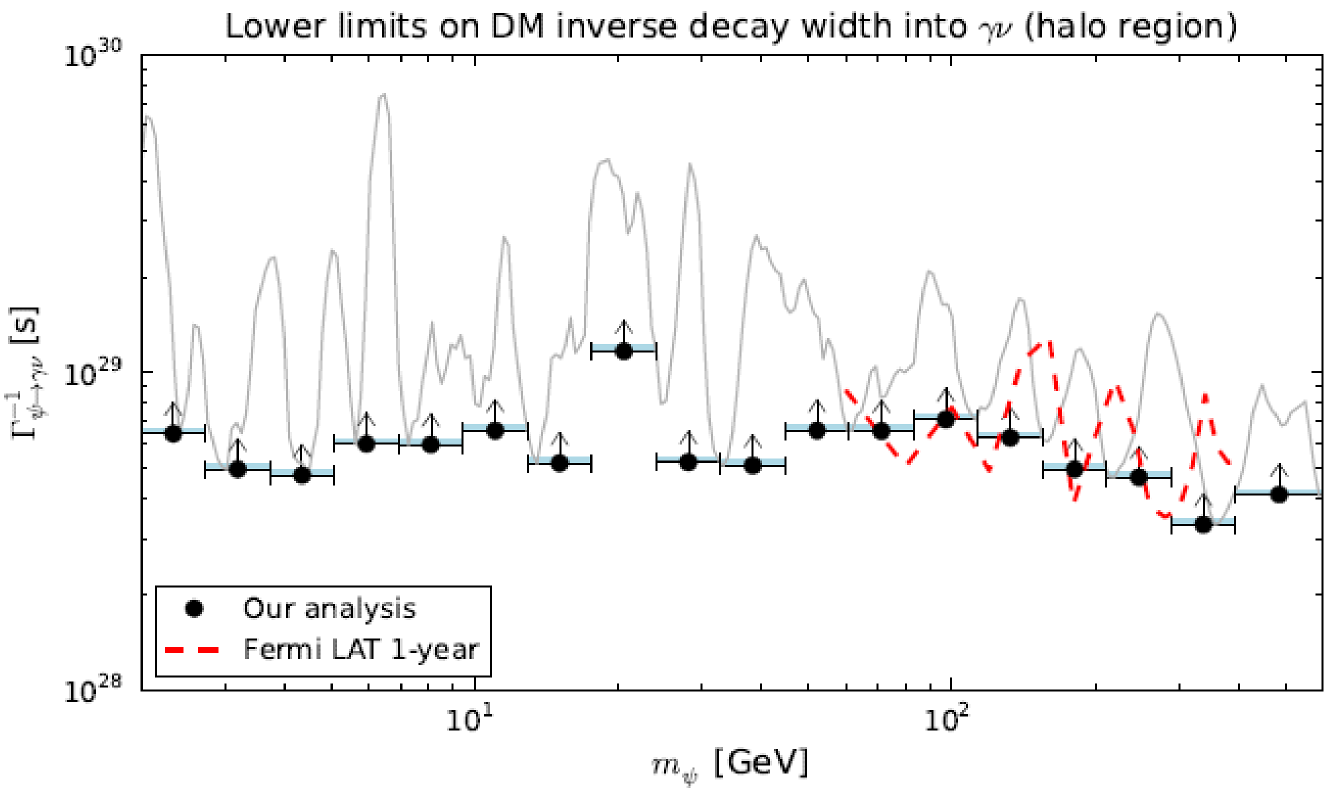

Vertongen, Weniger
1101.2610

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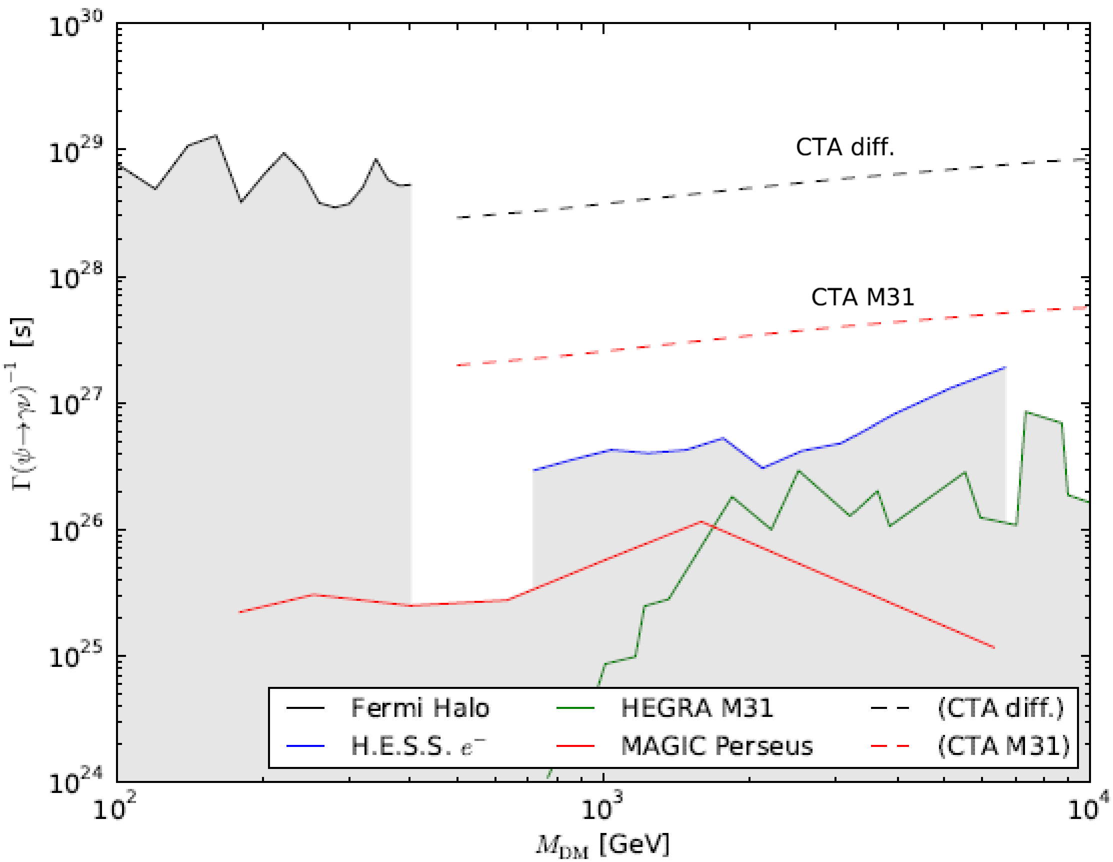


Garny et al.
1011.3786

Present constraint for Fermi-LAT:

$$\Gamma^{-1}(\psi\rightarrow\gamma\nu)\gtrsim 5\times10^{28}-10^{29}\ \mathrm{s},\ \text{for } m_\psi \text{ between 1 and 600 GeV}$$

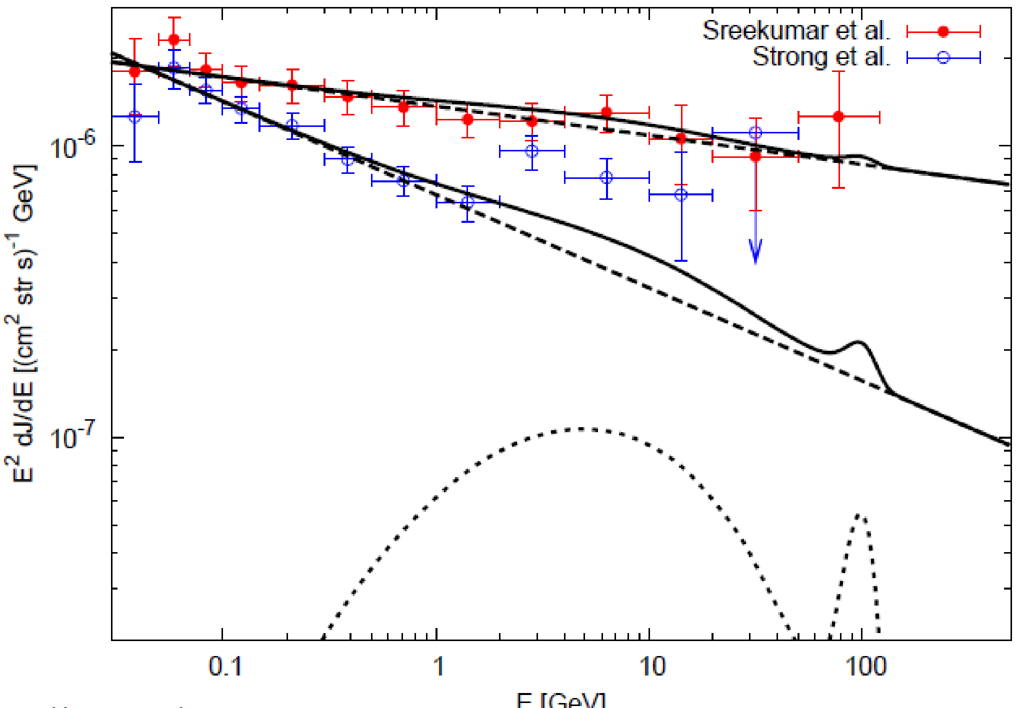
Projected senstivity at CTA:

$$\Gamma^{-1}(\psi\rightarrow\gamma\nu)\gtrsim 5\times10^{28}-10^{29}\ \mathrm{s},\ \text{for } m_\psi \text{ between 600 GeV and 10 TeV}$$

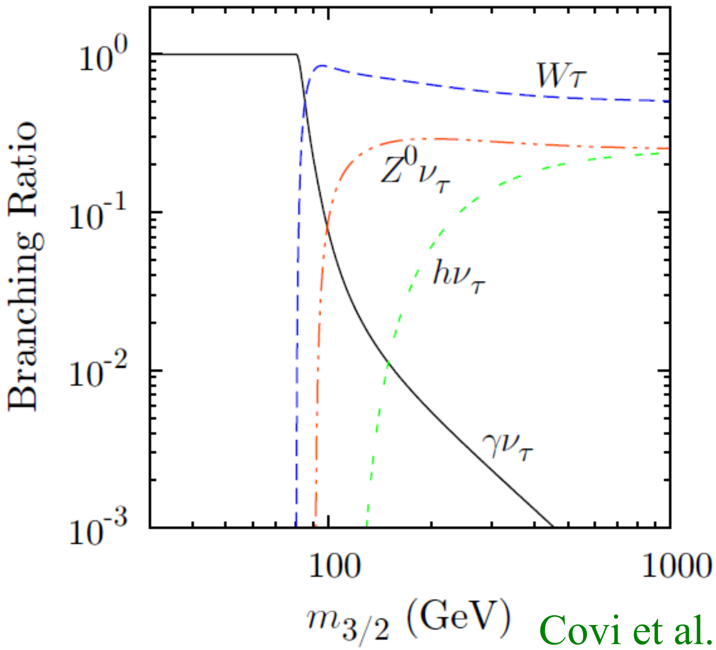
Very stringent constraints on dark matter particles which decay *at tree level* into monoenergetic gamma-rays

Gravitino in SUSY models without R-parity conservation

m=200 GeV
$\tau=7\times10^{26}$ s



Buchmüller et al.
0906.1187



Covi et al.
0809.5030

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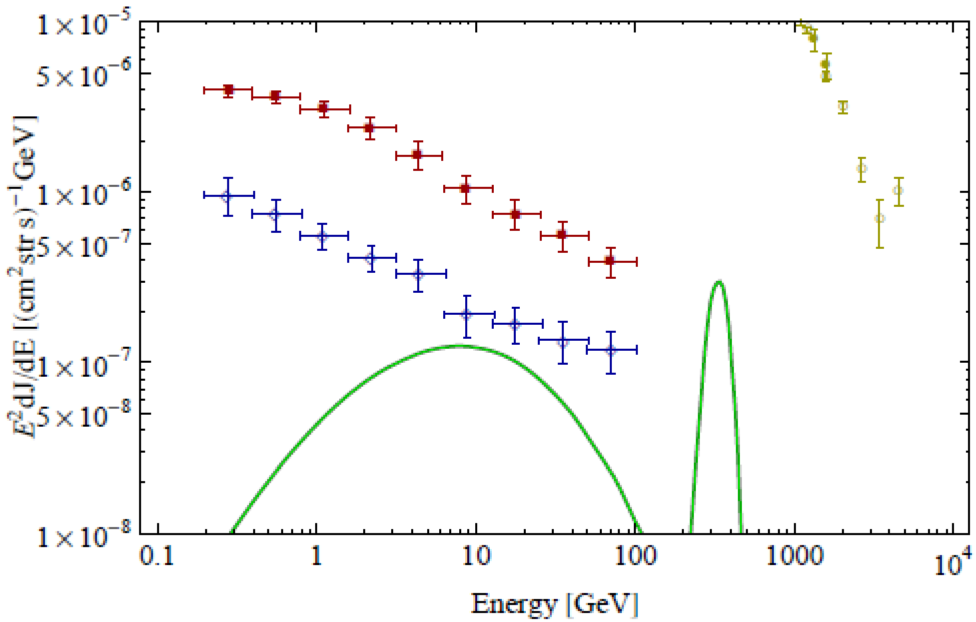
Vector of a hidden SU(2) gauge group



m=600 GeV

$\tau=1.1\times10^{27}$ s

Arina et al 0912.4496

	$\eta\eta$	$h\eta$	hh	$\gamma\eta$	$Z\eta$	γh	Zh
Branching Ratios	-	0.04	0.62	0.002	0.003	0.15	0.18

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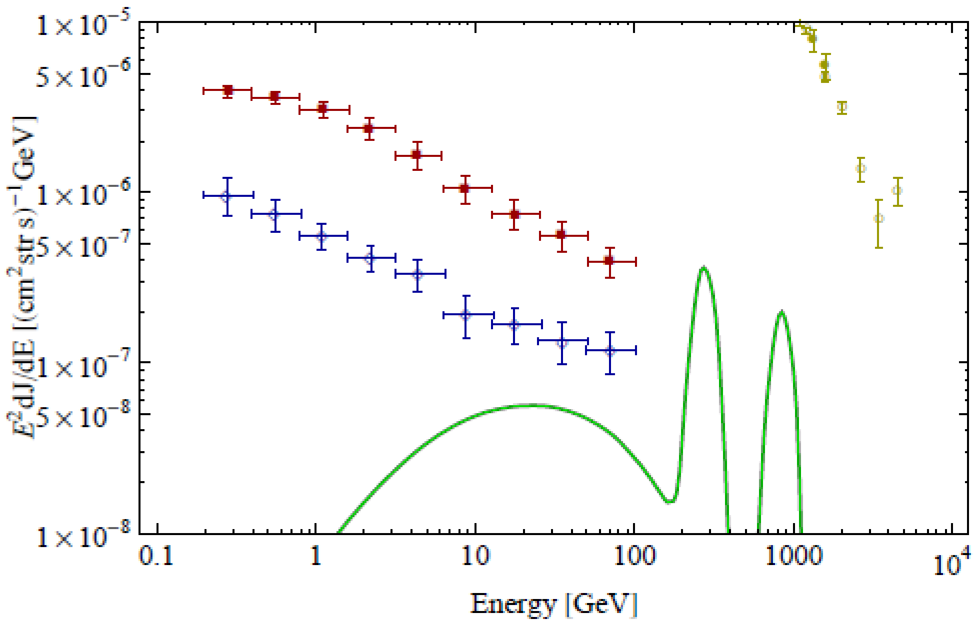

m=1550 GeV
$\tau=1.6\times10^{27}$ s

Arina et al
0912.4496

	$Z\eta$	$\gamma\eta$	Zh	γh
Branching Ratios	0.028	0.79	0.041	0.14

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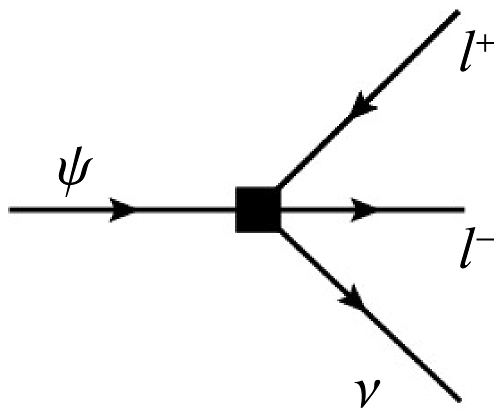
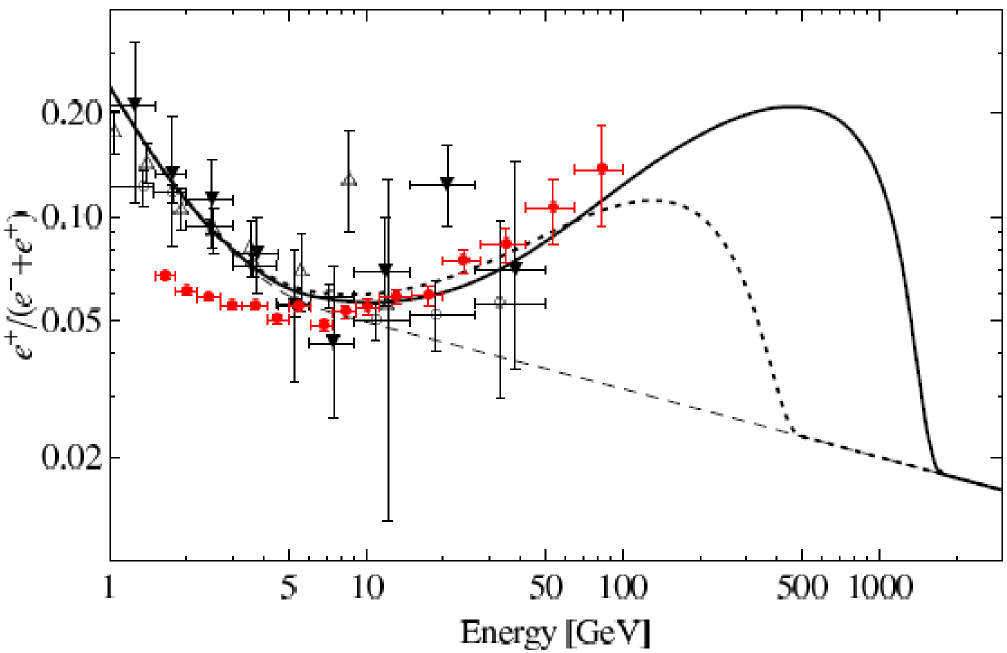
Constraints on models where the gamma lines appear at the *one loop level*

Garny et al. 1011.3786

$$-\mathcal{L}_{\rm eff}=\frac{1}{\Lambda^2}(\bar\psi\ell)(\bar\ell\nu)+\frac{1}{\Lambda^2}(\bar\psi\gamma^\mu\ell)(\bar\ell\gamma_\mu\nu),\ \ldots$$



$$\Gamma(\psi\to\ell^+\ell^-\nu)\sim\frac{1}{512\pi^3}\frac{m_\psi^5}{\Lambda^4}$$



$$\Gamma^{-1}(\psi\to\ell^+\ell^-\nu)\gtrsim10^{26-27}\text{ s}$$

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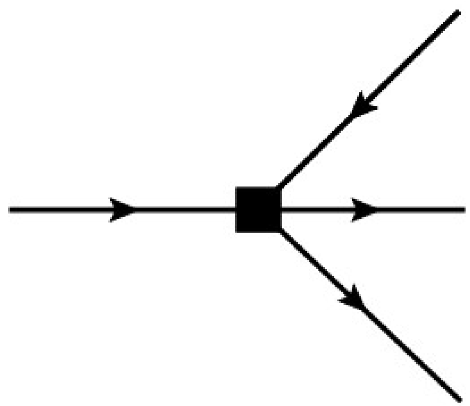

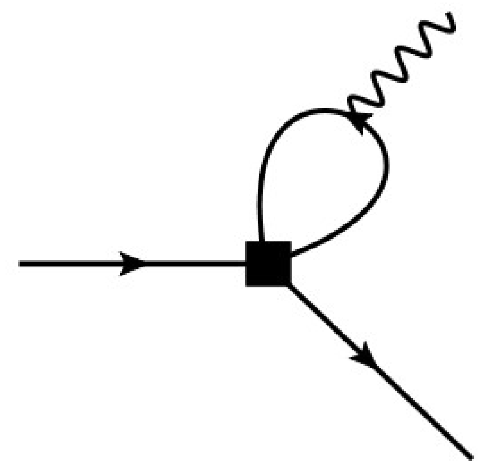

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$$\Gamma(\psi\to\gamma\nu) \sim \frac{1}{16\pi}\left(\frac{e}{16\pi^2}\right)^2\frac{m_\psi^5}{\Lambda^4}$$

$$\Gamma(\psi\to\gamma\nu) \sim \frac{\alpha}{2\pi}\Gamma(\psi\to\ell^+\ell^-\nu)$$

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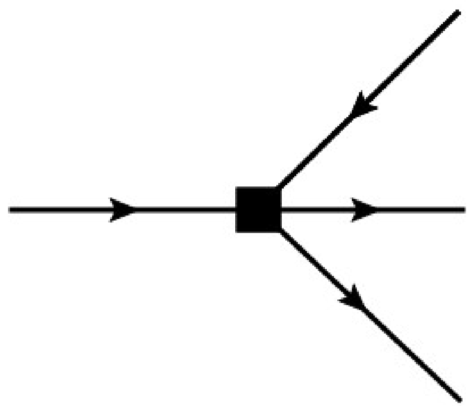

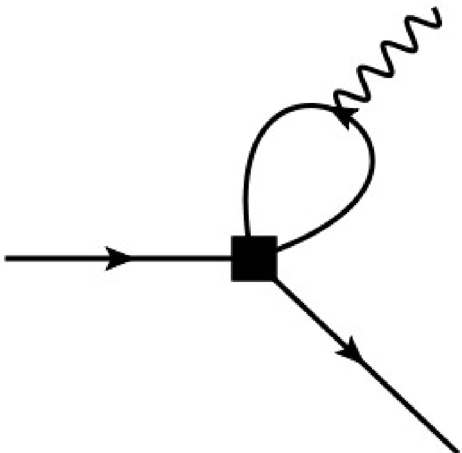

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$$\Gamma^{-1}(\psi\to\gamma\nu)\sim 8\times10^{28}\ \text{s}\left(\frac{\Gamma^{-1}(\psi\to\ell^+\ell^-\nu)}{10^{26}\ \text{s}}\right)$$

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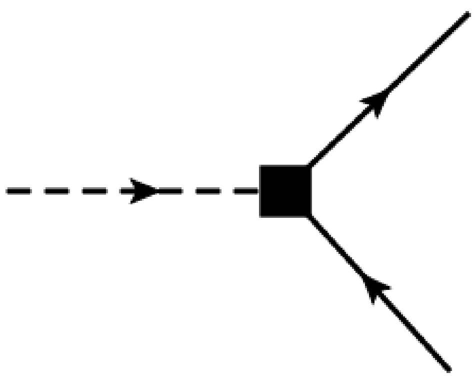

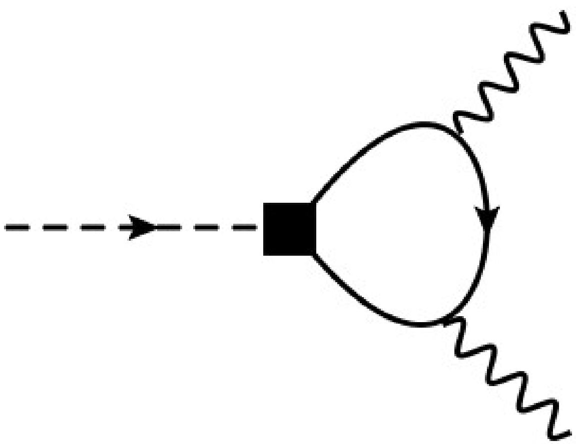

$$\Gamma(\phi\to\ell^+\ell^-)\sim\frac{1}{16\pi}m_\phi|\lambda|^2 \qquad \Gamma(\phi\to\gamma\gamma)\sim\frac{1}{16\pi}m_\phi|\lambda|^2\left(\frac{e^2}{16\pi^2}\right)^2\left(\frac{m_\ell}{m_\phi}\right)^2$$

$$\Gamma(\phi\to\gamma\gamma)\sim\frac{\alpha^2}{16\pi^2}\left(\frac{m_\ell}{m_\phi}\right)^2\Gamma(\phi\to\ell^+\ell^-)$$

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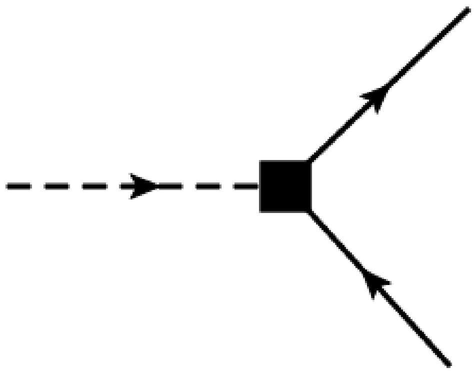
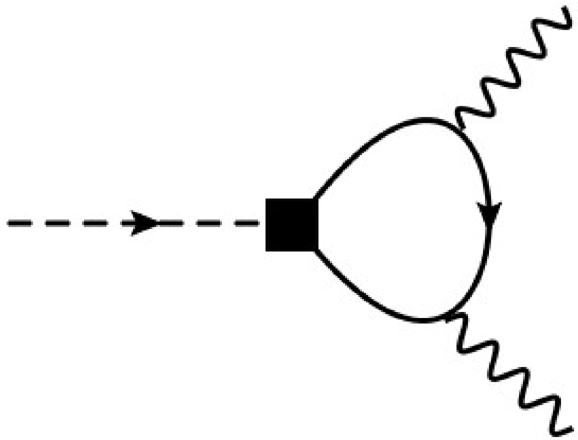


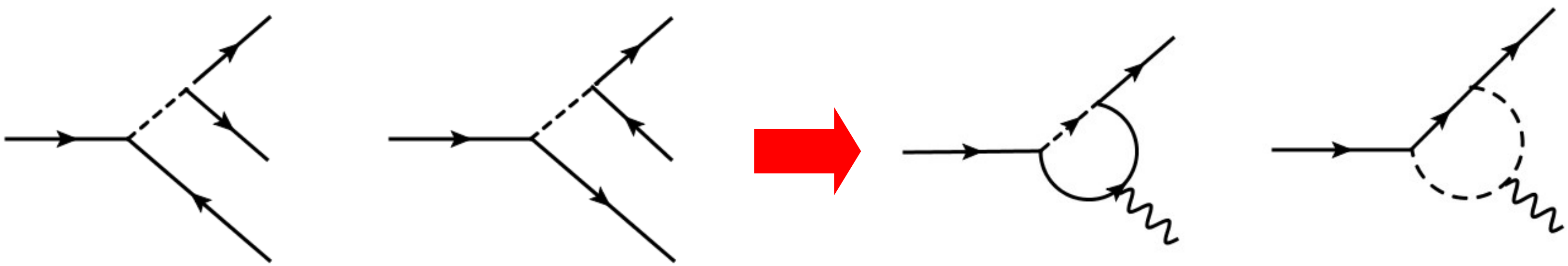


$$\Gamma(\phi \to \ell^+\ell^-) \sim \frac{1}{16\pi} m_\phi |\lambda|^2$$

$$\Gamma(\phi \to \gamma\gamma) \sim \frac{1}{16\pi} m_\phi |\lambda|^2 \left(\frac{e^2}{16\pi^2}\right)^2 \left(\frac{m_\ell}{m_\phi}\right)^2$$

$$\Gamma^{-1}(\phi \to \gamma\gamma) \sim 10^{38}\ \mathrm{s} \left(\frac{\Gamma^{-1}(\phi \to \ell^+\ell^-)}{10^{26}\ \mathrm{s}}\right)\left(\frac{m_\phi}{1\ \mathrm{TeV}}\right)^{-2}$$

Decay mediated by a scalar

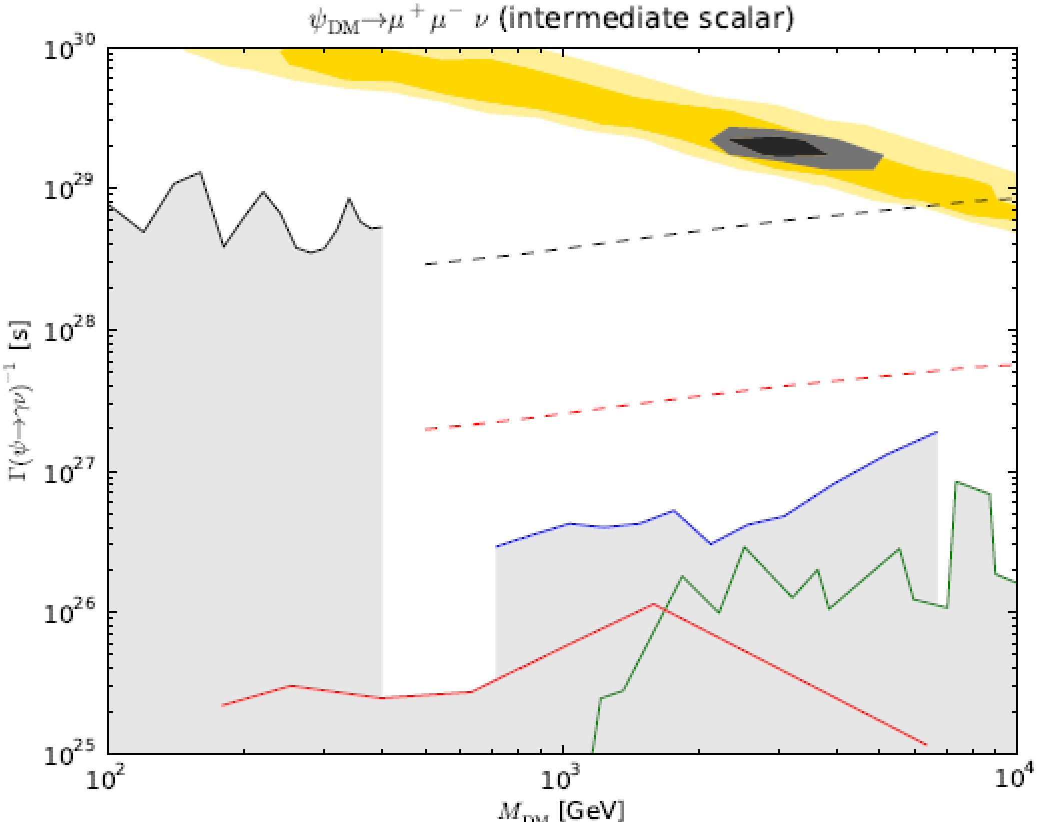


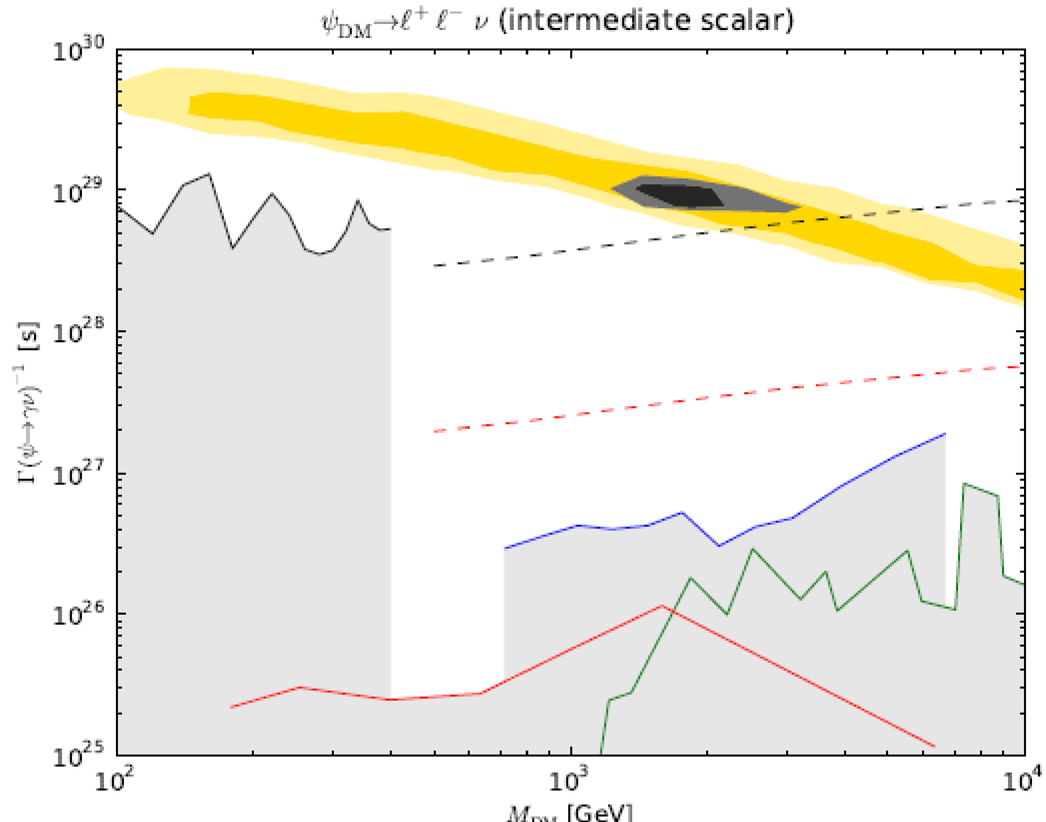
Decay into one flavour

$$\mathrm{BR}(\psi \to \gamma\nu) \simeq \frac{3\alpha}{8\pi}$$

"Democratic" decay

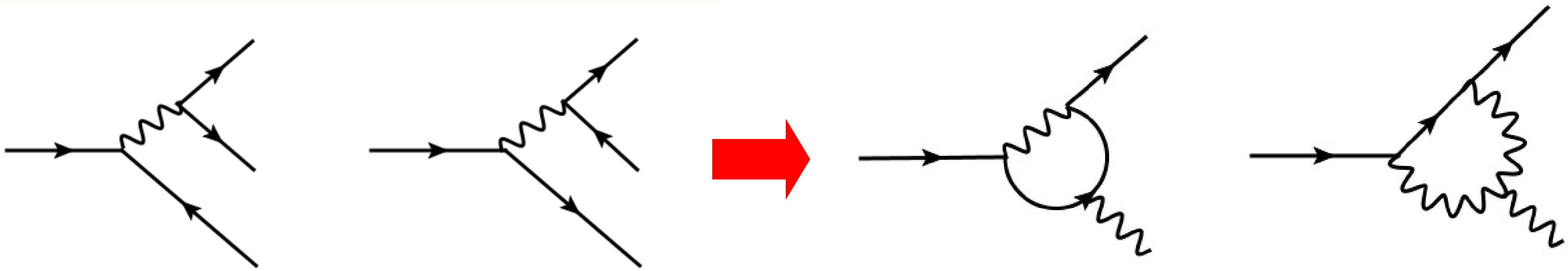
$$\mathrm{BR}(\psi \to \gamma\nu) \simeq 3 \times \frac{3\alpha}{8\pi}$$





Garny et al. arXiv:1011.3786

Decay mediated by a vector



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$$\mathrm{BR}(\psi \to \gamma\nu) \simeq \frac{27\alpha}{8\pi}$$

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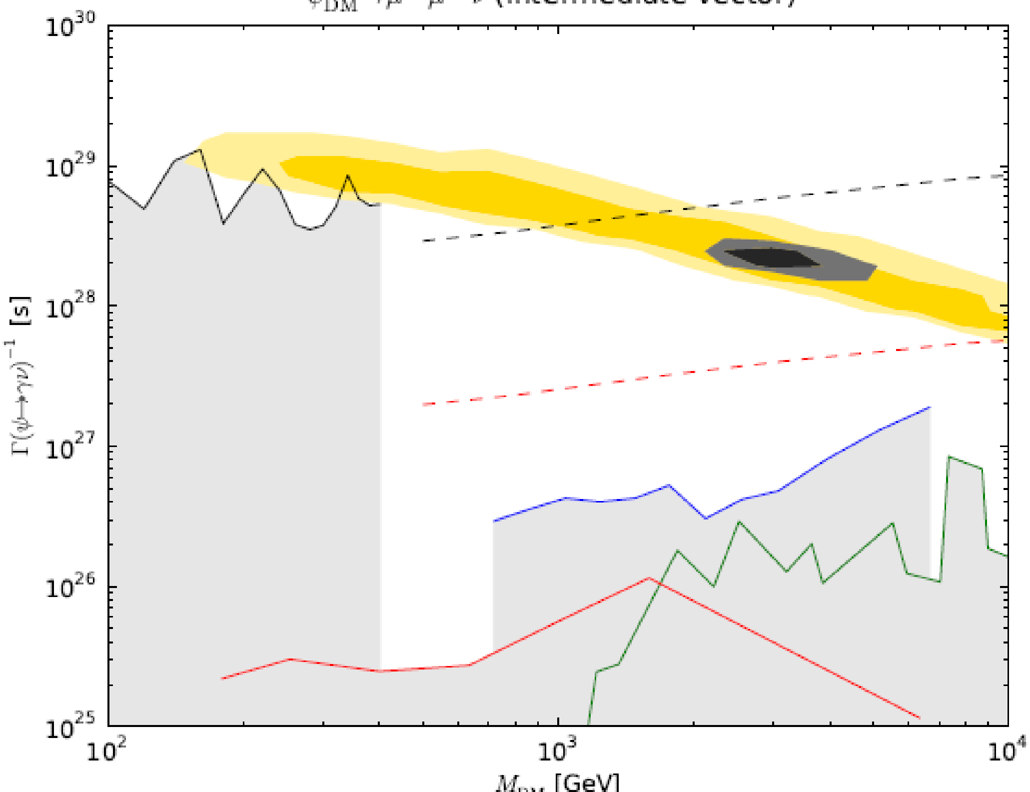
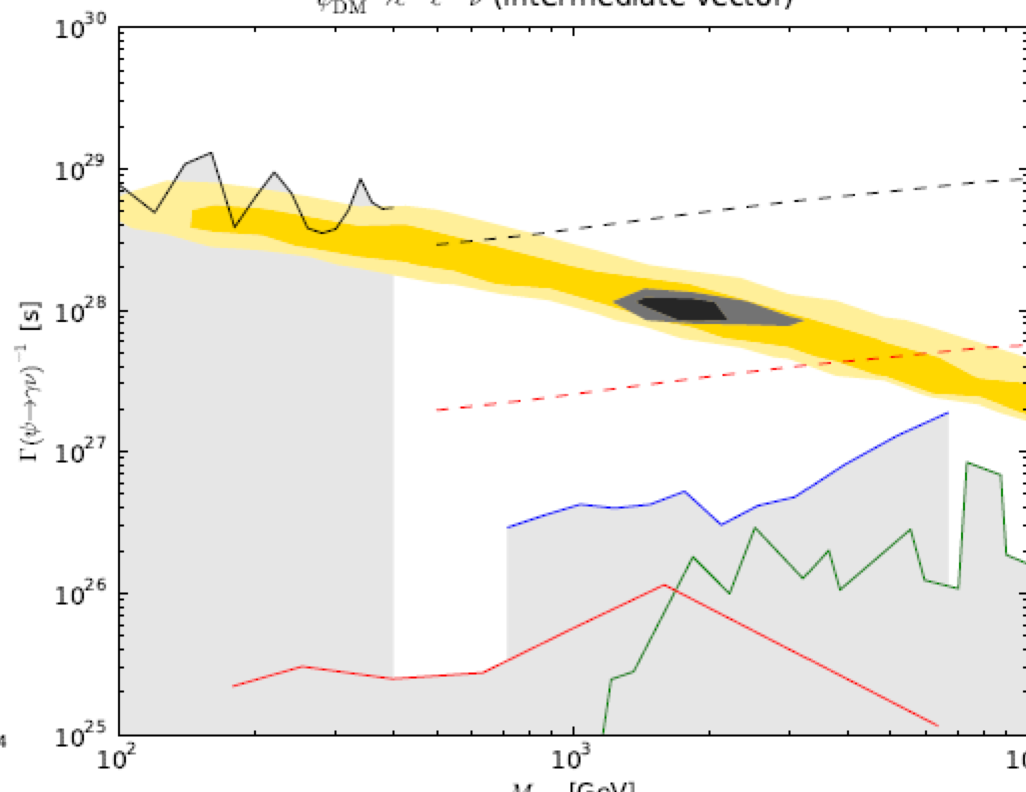




Garny et al. arXiv:1011.3786

The degenerate scenario

In some models the final neutral particle is not a neutrino but a heavy fermion

$$\psi \rightarrow \ell^+ \ell^- N$$

(e.g. lightest neutralino decaying into a hidden gaugino and a fermion-antifermion pair)

Consequence 1: The radiatively induced gamma-ray line appears at an energy smaller than $m_\psi/2$:

$$E_\gamma = \frac{m_\psi}{2}\left(1 - \frac{m_N^2}{m_\psi^2}\right)$$

Consequence 2: The branching ratio into gamma-lines can be substantially enhanced:

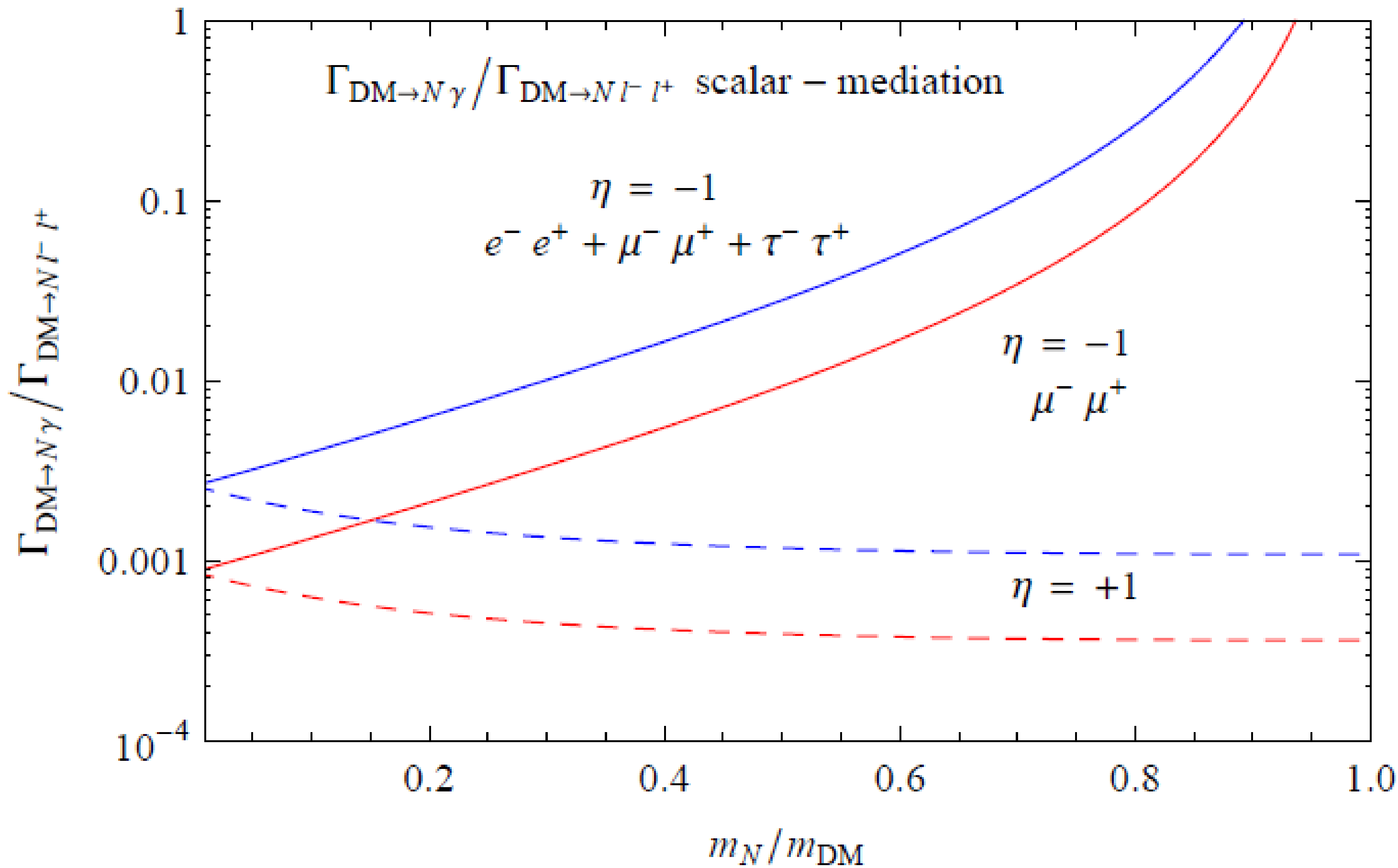
$$\Gamma(\psi \rightarrow \ell^+ \ell^- N) \propto \left(1 - \frac{m_N^2}{m_\psi^2}\right)^5$$

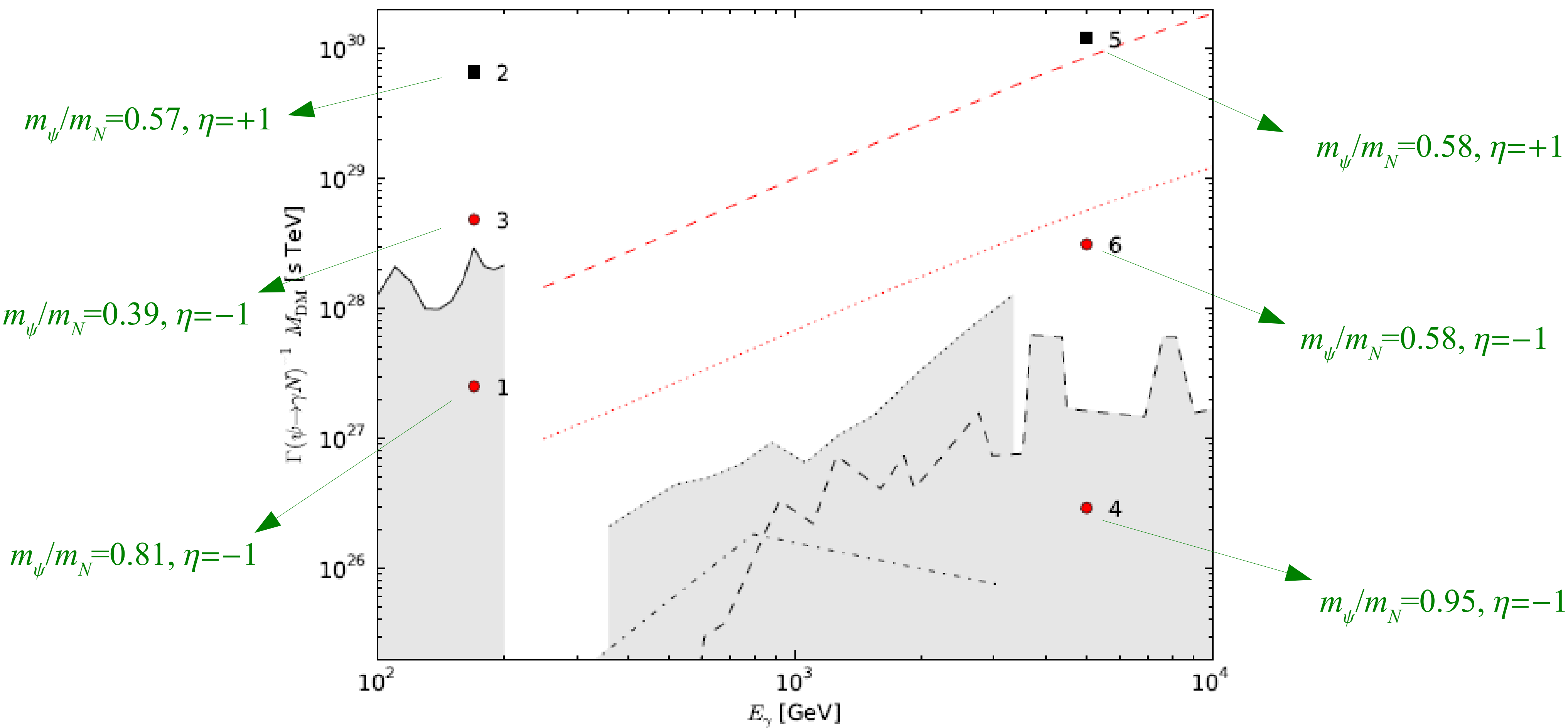
$$\Gamma(\psi \rightarrow \gamma N) \propto \left(1 - \frac{m_N^2}{m_\psi^2}\right)^3 \left(1 - \eta \frac{m_N}{m_\psi}\right)$$

Relative CP parity of N and ψ

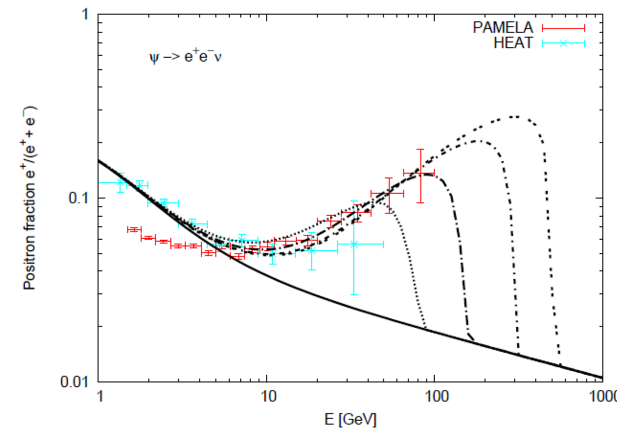
$$\mathrm{BR}(\psi \rightarrow \gamma N) \propto \begin{cases} \frac{1}{(1+m_N/m_\psi)^2} & \text{if } \eta = +1 \\ \frac{1}{(1-m_N/m_\psi)^2} & \text{if } \eta = -1 \end{cases}$$

The degenerate scenario

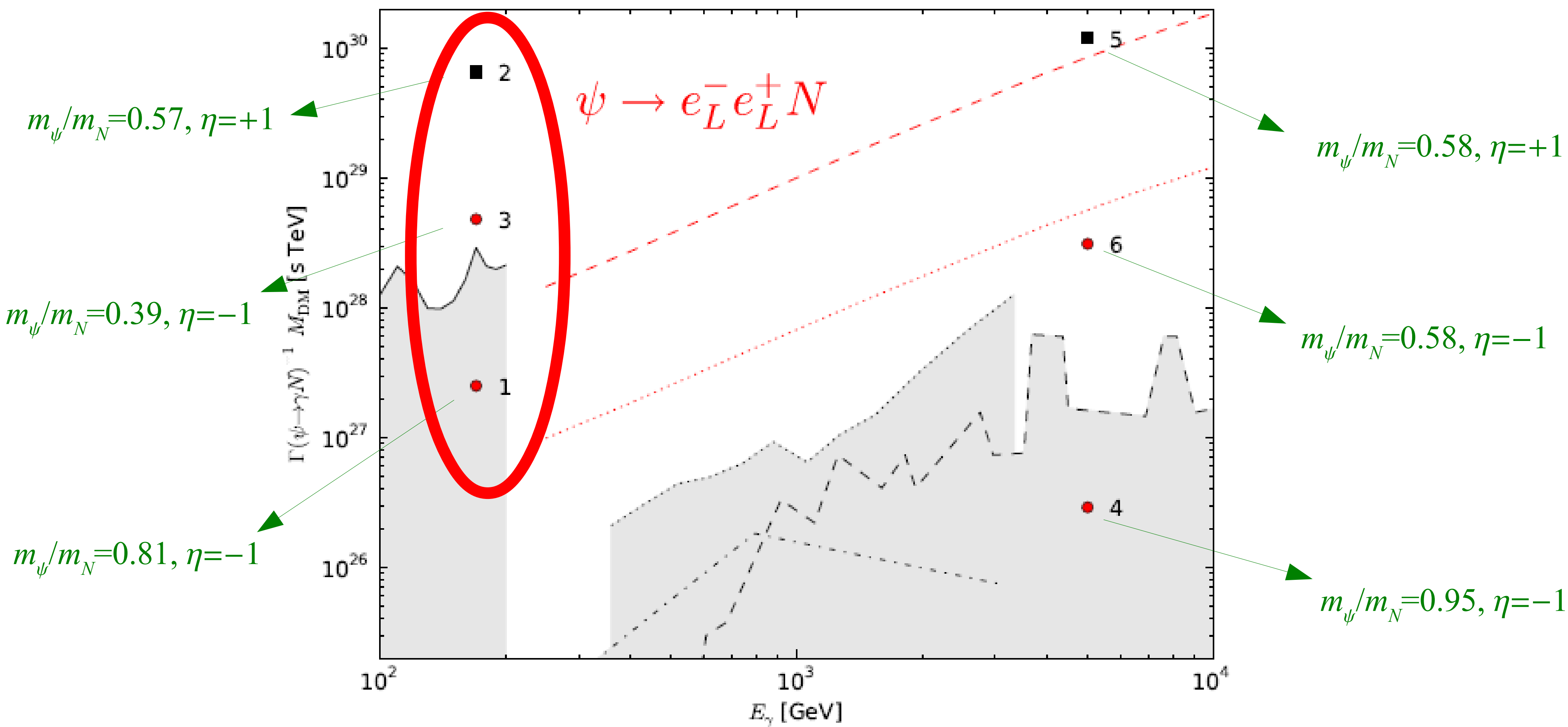




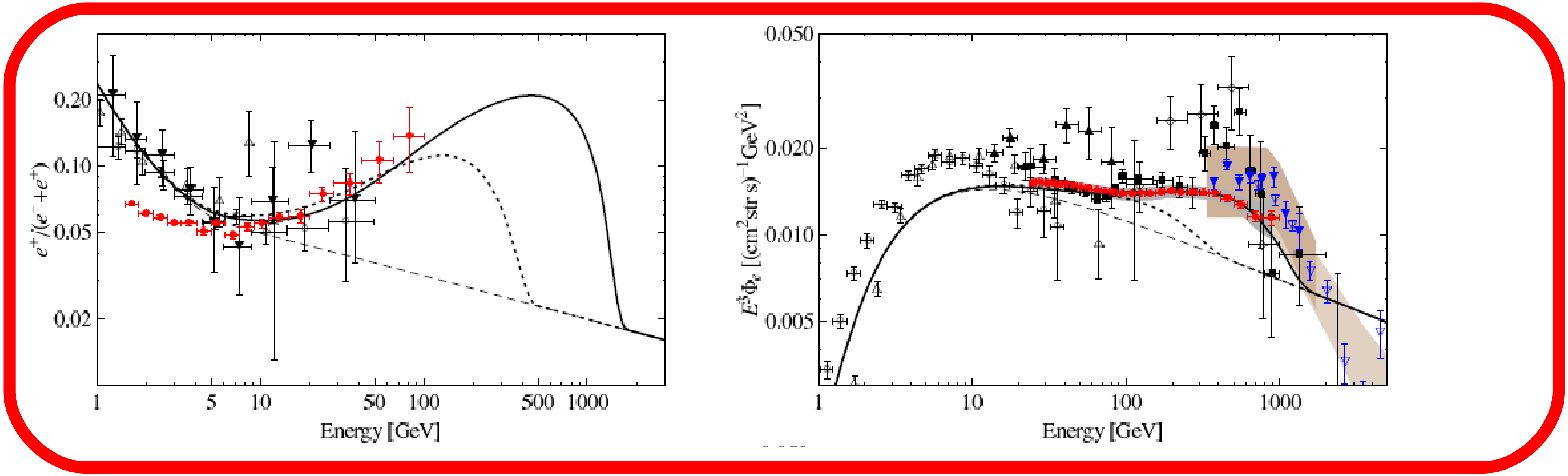
m_ψ/m_N=0.57, η=+1
m_ψ/m_N=0.39, η=−1
m_ψ/m_N=0.81, η=−1
m_ψ/m_N=0.58, η=+1
m_ψ/m_N=0.58, η=−1
m_ψ/m_N=0.95, η=−1
1
2
3
4
5
6
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{2}
10^{3}
10^{4}
$\Gamma(\psi\to\gamma N)^{-1}\ M_{\rm DM}$ [s TeV]
E_γ [GeV]



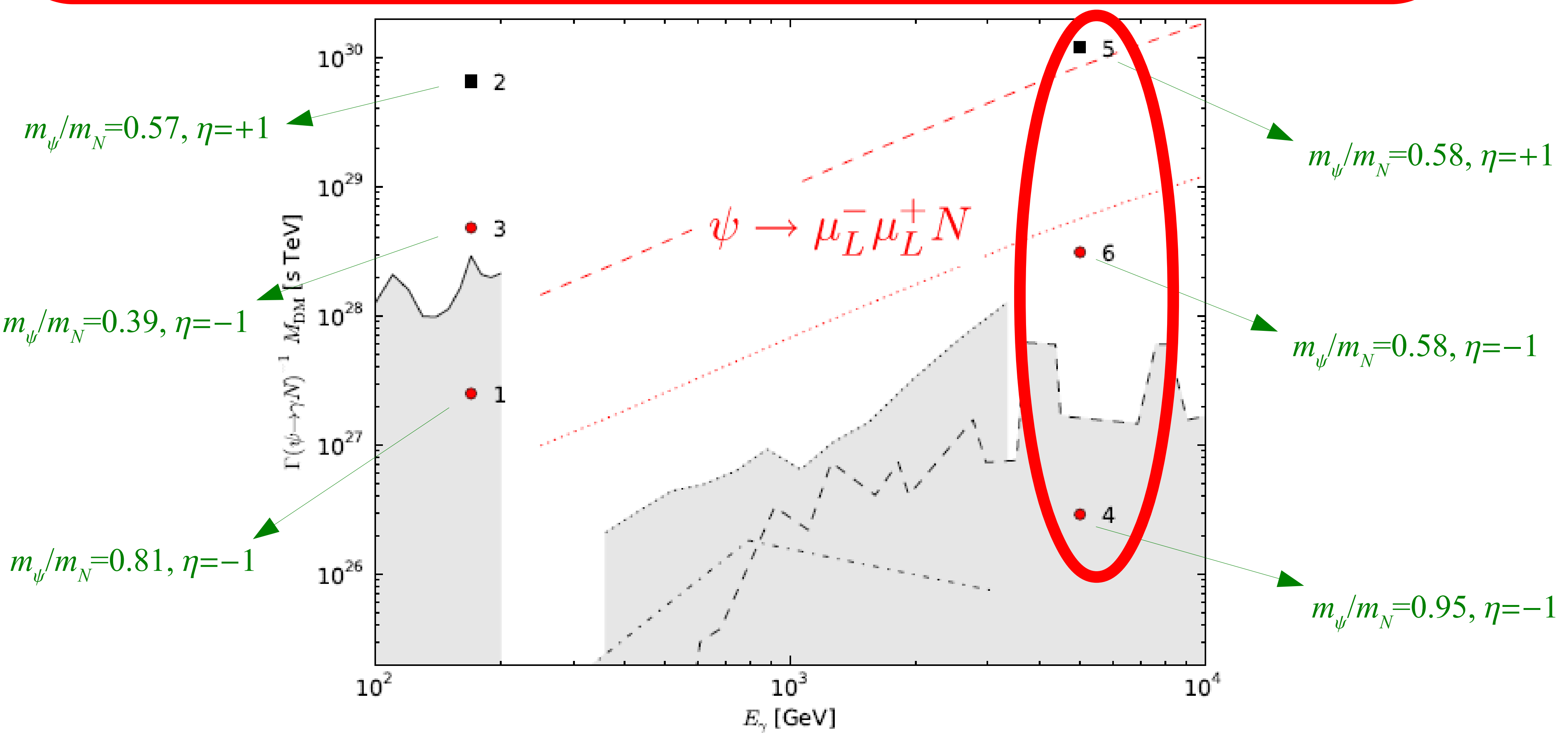
PAMELA
HEAT
ψ -> e+e−ν
Positron fraction e+/(e+ + e−)
1
0.1
0.01
1
10
100
1000
E [GeV]



$\psi \to e_L^- e_L^+ N$
$\Gamma(\psi \to \gamma N)^{-1} \; M_{DM}$ [s TeV]
E_γ [GeV]
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^2
10^3
10^4
1
2
3
4
5
6
m_ψ/m_N=0.57, η=+1
m_ψ/m_N=0.39, η=−1
m_ψ/m_N=0.81, η=−1
m_ψ/m_N=0.58, η=+1
m_ψ/m_N=0.58, η=−1
m_ψ/m_N=0.95, η=−1



0.20
0.10
0.05
0.02
$e^+/(e^-+e^+)$
1
5
10
50
100
500
1000
Energy [GeV]
0.050
0.020
0.010
0.005
$E^3\Phi_e$ [(cm^{2}str s)$^{-1}$GeV^2]
1
10
100
1000
Energy [GeV]



10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
$\Gamma(\psi\to\gamma N)^{-1}$ M_{DM} [s TeV]
10^2
10^3
10^4
E_γ [GeV]
$\psi \to \mu_L^- \mu_L^+ N$
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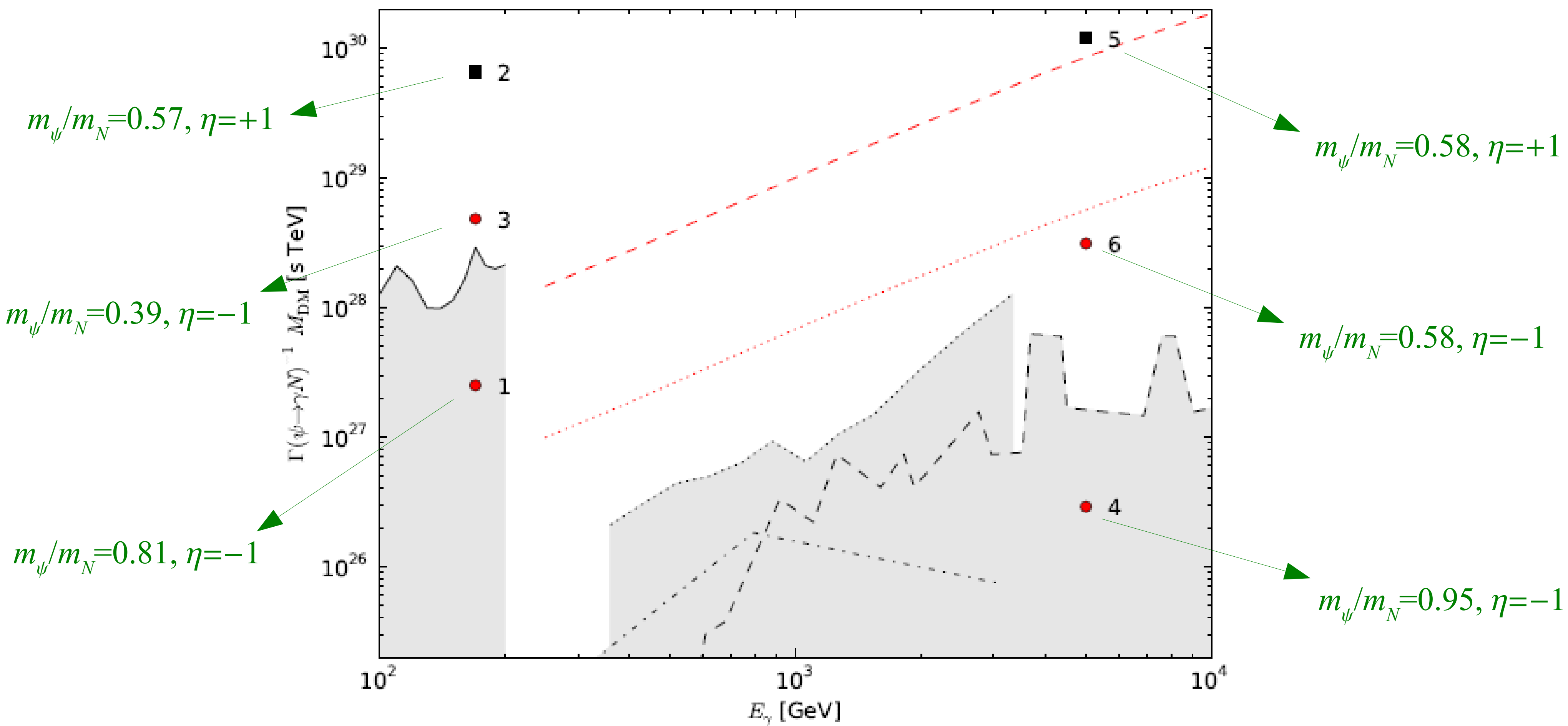
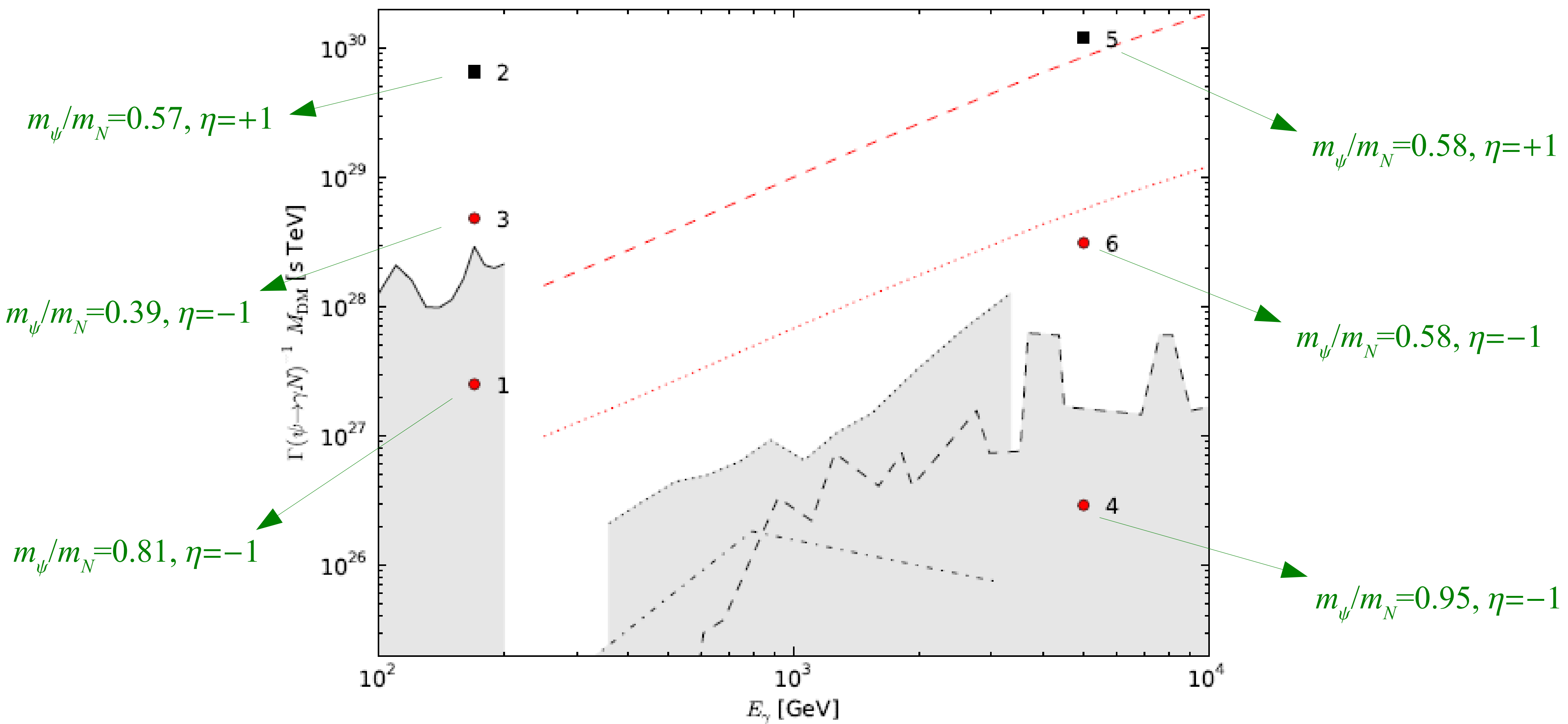
m_ψ/m_N=0.57, η=+1
m_ψ/m_N=0.39, η=−1
m_ψ/m_N=0.81, η=−1
m_ψ/m_N=0.58, η=+1
m_ψ/m_N=0.58, η=−1
m_ψ/m_N=0.95, η=−1

$\psi \to \mu_L^- \mu_R^+ N$ ★

BR($\psi \to \gamma N$) suppressed by $(m_\mu/m_N)^2$



Some decaying dark matter models of the type $\psi \rightarrow l^+ l^- N$ which are allowed by the electron/positron constraints are presently ruled out by gamma-line searches.



Conclusions

■ Stability of the dark matter particle is an open question (as is proton stability). Indirect dark matter searches constrain the dark matter lifetime.

■ The lower bound on the lifetime depends on the decay mode. The Fermi-LAT has set very stringent constraints on decays into monoenergetic gamma-rays for $m_{\rm DM}$=1 GeV– 600 GeV ($\tau \gtrsim 5\times10^{28} - 10^{-29}$ s). The CTA might set similar bounds on the lifetime for $m_{\rm DM}$=600 GeV – 10 TeV.

⬇

Very stringent constraints on models where the dark matter particle decays *at tree level* into monoenergetic gamma-rays.

■ In the interesting case where $\psi \to l^+ l^- \nu$, the constraints on the lifetime from loop induced gamma-ray lines are competitive with the (tree level) constraints from electron/positron measurements.

■ If the decay $\psi \to l^+ l^- \nu$ is the origin of the electron/positron excesses, a gamma-ray line might be observed in the diffuse flux at the CTA.

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Thank you for your attention!