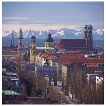
Gamma-Ray Lines from Radiative Dark Matter Decay

Mathias Garny (TU München)

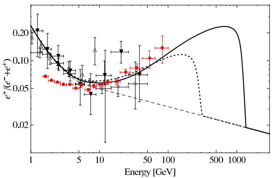


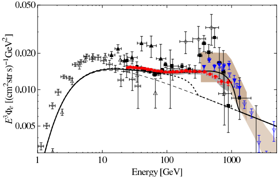
DESY, Workshop on Indirect Dark Matter Searches, 17.06.11

based on JCAP 1101 (2011) 032 (arXiv:1011.3786)

with Alejandro Ibarra, David Tran, Christoph Weniger

- Decaying dark matter has been proposed as explanation for PAMELA/Fermi $e^{\pm}$ measurements, e.g. $\psi_{DM} \to \ell^+ \ell^- \nu$





$m_{DM} = 600\,\text{GeV}$ (dotted), 2.5TeV (solid) *Ibarra, Tran, Weniger 0906.1571*

- Typical required life-times $\tau_{DM} \sim 10^{26}\text{sec}$

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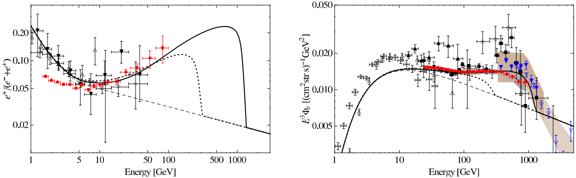

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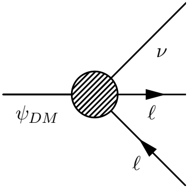
- Typical required life-times $\tau_{DM} \sim 10^{26}$sec
- $\psi_{DM} \to \ell^+\ell^-\nu$ via effective dim-6 operator $\frac{1}{M^2}\psi_{\rm DM}\ell\ell\nu$



$$\tau_{\psi_{\rm DM}\to\ell^+\ell^-\nu} \sim 10^{26}\,\text{sec}\left(\frac{1\ \text{TeV}}{m_{\psi_{\rm DM}}}\right)^5\left(\frac{M}{10^{15}\ \text{GeV}}\right)^4$$

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or: Can we constrain the dark matter scenario?

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- No excess in $\bar{p}$ observed $\Rightarrow$ leptophilic dark matter
- Baryons and photons can be produced by higher-order processes or interactions with the medium
  - ICS, synchrotron emission
  - electromagnetic/electroweak bremsstrahlung
  - ...
  - Gamma-ray line
    $\longrightarrow$ smoking gun signal
    $\longrightarrow$ generically induced by loop-corrections

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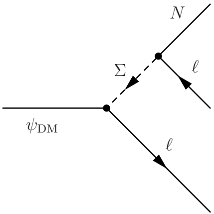
Model-independent analysis of loop-induced gamma-ray lines

- fermionic dark matter decaying into leptons
- scalar dark matter decaying into leptons

Fermionic Dark Matter

$$\psi_{DM} \to \ell^+ \ell^- \nu$$



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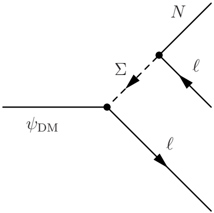
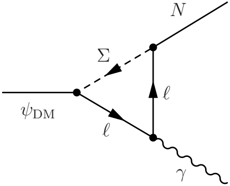


$$\psi_{DM} \to \gamma \nu$$



- Monoenergetic photons $E_\gamma = (m^2_{\psi_{DM}} - m^2_N)/2m_{\psi_{DM}}$

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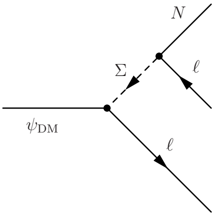

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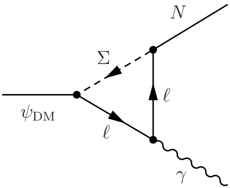

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- decay product $N = \nu$, neutralino, sterile neutrino, ...

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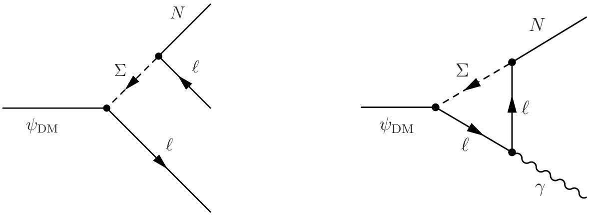
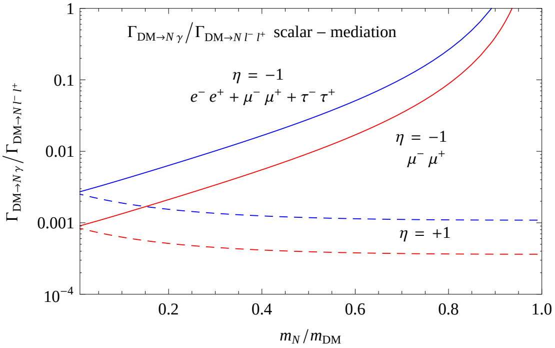
$\psi_{DM} \to \ell^+\ell^-\nu$ $\psi_{DM} \to \gamma\nu$



- Monoenergetic photons $E_\gamma = (m^2_{\psi_{DM}} - m^2_N)/2m_{\psi_{DM}}$
- decay product $N = \nu$, neutralino, sterile neutrino, ...
- decay mediated by heavy scalar Σ (e.g. $\tilde{\ell}$) or vector V_μ (e.g. W_R)

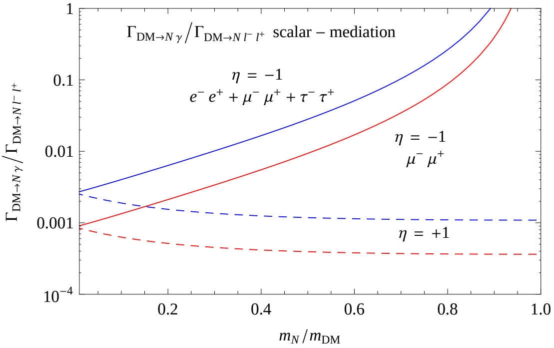
$$\mathcal{L}^{\Sigma}_{\text{eff}} = -\bar{\psi}_{\text{DM}} \left[\lambda^L_{\ell\psi} P_L + \lambda^R_{\ell\psi} P_R\right] \ell\, \Sigma^\dagger - \bar{N} \left[\lambda^L_{\ell N} P_L + \lambda^R_{\ell N} P_R\right] \ell\, \Sigma^\dagger$$
$$\mathcal{L}^{V}_{\text{eff}} = -\bar{\psi}_{\text{DM}}\gamma^\mu \left[\lambda^L_{\ell\psi} P_L + \lambda^R_{\ell\psi} P_R\right] \ell\, V^\dagger_\mu - \bar{N}\gamma^\mu \left[\lambda^L_{\ell N} P_L + \lambda^R_{\ell N} P_R\right] \ell\, V^\dagger_\mu$$

Intensity of the gamma-ray line: intermediate scalar



- gamma-line suppressed by $\alpha_{\text{em}}/\pi \sim 10^{-3}$

$$\frac{\Gamma(\psi_{\text{DM}} \to \gamma N)}{\sum_\ell \Gamma(\psi_{\text{DM}} \to \ell^+\ell^- N)} \simeq \frac{3\alpha_{\text{em}}}{8\pi} \times \underbrace{R_\eta^\Sigma(\lambda^L_{\ell N}, \lambda^L_{\ell\psi}, \lambda^R_{\ell N}, \lambda^R_{\ell\psi})}_{\lesssim \begin{cases} 3 & \text{democratic decay} \\ 1 & \text{single-flavor decay} \end{cases}}$$



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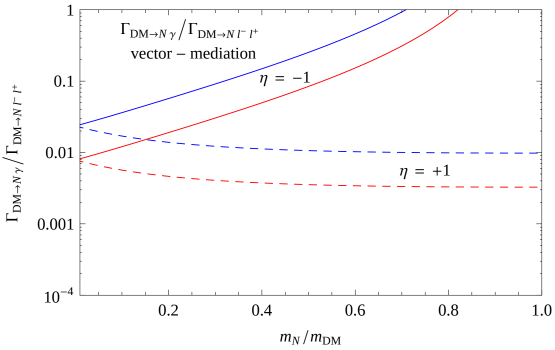
- enhancement when ψ/N have opposite CP parity $(\eta = -1)$

Intensity of the gamma-ray line: intermediate vector



- gamma-line suppressed by $\sim 10^{-2}$

$$\frac{\Gamma(\psi_{DM} \to \gamma N)}{\sum_\ell \Gamma(\psi_{DM} \to \ell^+\ell^- N)} \simeq \frac{27\alpha_{em}}{8\pi} \times \underbrace{R^V_\eta(\lambda^L_{\ell N}, \lambda^L_{\ell\psi}, \lambda^R_{\ell N}, \lambda^R_{\ell\psi})}_{\lesssim \begin{cases} 3 & \text{democratic decay} \\ 1 & \text{single-flavor decay} \end{cases}} \times \underbrace{S_\eta(m_N/m_{\psi_{DM}})}_{\to 1 \text{ for } m_N \to 0}$$

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Examples

- Decay into left-handed neutrinos (via scalar mediation)

$$\frac{\Gamma(\psi_{\mathrm{DM}} \to \gamma\nu)}{\sum_\ell \Gamma(\psi_{\mathrm{DM}} \to \ell^+\ell^-\nu)} \simeq \frac{3\alpha_{\mathrm{em}}}{8\pi} \underbrace{\frac{\left[\sum_\ell \lambda^R_{\ell\nu}\lambda^R_{\ell\psi}\right]^2}{\sum_\ell \left(\left|\lambda^L_{\ell\psi}\right|^2 + \left|\lambda^R_{\ell\psi}\right|^2\right)\left|\lambda^R_{\ell\nu}\right|^2}}_{= R_\eta \leq N_\ell \leq 3}$$

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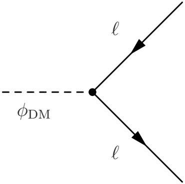
- Hidden sector: unbroken $U(1)_X$ with kinetic mixing to $U(1)_Y$
  ψ_{DM} =neutralino, N =hidden gaugino, $\Sigma =$ sleptons $\tilde{\ell}_{L;R}$
  see Ibarra, Ringwald, Weniger 08

$$\frac{\Gamma(\psi_{\rm DM}\to\gamma N)}{\sum_\ell \Gamma(\psi_{\rm DM}\to\ell^+\ell^- N)} \simeq \frac{3\alpha_{\rm em}}{8\pi}\times R_\eta\times S_\eta(m_N/m_{\psi_{\rm DM}})$$

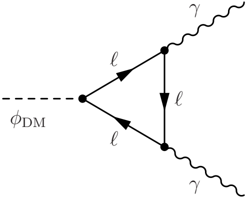
$$R_\eta = \begin{cases} 1.6 & \text{for } \eta\equiv\eta_{CP}(\psi_{DM})\cdot\eta_{CP}(N)=+1 \\ 4.4 & \text{for } \eta\equiv\eta_{CP}(\psi_{DM})\cdot\eta_{CP}(N)=-1 \end{cases}$$

Scalar Dark Matter

$\phi_{DM} \to \ell^+\ell^-$



$\phi_{DM} \to \gamma\gamma$



$$\frac{\Gamma(\phi_{\mathrm{DM}} \to \gamma\gamma)}{\Gamma(\phi_{\mathrm{DM}} \to \ell^+\ell^-)} \simeq \frac{\alpha_{\mathrm{em}}^2}{2\pi^2}\frac{m_\ell^2}{m_{\phi_{\mathrm{DM}}}^2}\left|2 - \frac{1}{2}\left(\ln(m_\ell^2/m_{\phi_{DM}}^2) + i\pi\right)^2\right|^2$$

$$\simeq 10^{-9}\left(\frac{m_\ell}{106\ \mathrm{MeV}}\right)^2\left(\frac{1\ \mathrm{TeV}}{m_{\phi_{\mathrm{DM}}}}\right)^2$$

Lepton loop helicity suppressed $\Rightarrow$ no observable gamma-ray line

Gamma Ray Line: Observational Constraints

- Milky Way halo:
  monochromatic gamma-ray flux from dark matter decay is given by the line-of-sight integral over the dark matter distribution (e.g. Bertone 2007)

$$\frac{dJ_{\rm dm}^{\rm halo}}{dE} = \frac{\Gamma(\psi_{\rm DM} \to \gamma N)}{4\pi\, m_{\psi_{\rm DM}}}\, \delta\left(E_\gamma - E\right) \int_{\rm l.o.s.} d\vec{l}\, \rho_{\rm DM}^{\rm MW}(\vec{l})$$

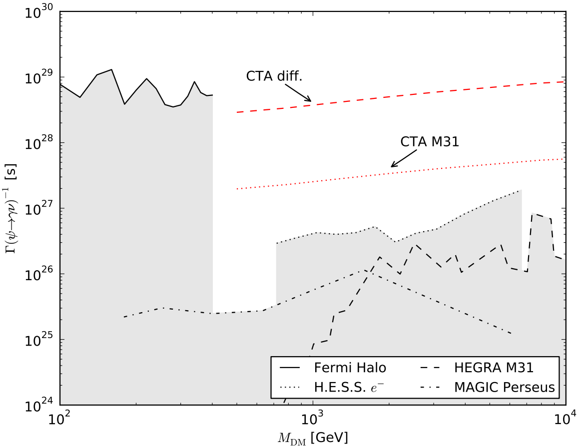
- M31: (or Perseus, ...)
  gamma-ray flux from dark matter decay in M31 within the opening angle $\theta_{\rm obs}$ (Hegra M31 0.105°; Magic Perseus 0.15°)

$$\frac{dJ_{\rm DM}^{\rm M31}}{dE} = \frac{\Gamma(\psi \to \gamma N)}{4\pi\, m_{\rm DM}}\, \delta(E_\gamma - E)\, 2\pi \int_0^{\theta_{\rm obs}} d\theta\, \sin\theta \int_{-\infty}^{\infty} ds\, \rho_{\rm DM}^{\rm M31}(\sqrt{s^2 + R^2})$$

where D is the distance to the target ($D = 770$ kpc in case of M31 and $D = 78$ Mpc for Perseus) and $R \simeq D\,\theta$

Gamma Ray Line: Observational Constraints

$$\Gamma(\psi_{DM} \to \gamma\nu)^{-1} \text{ [sec]}$$



Fermi 1001.4836; Hegra astro-ph/0302347 20h; Magic 0909.3267 25h; HESS 0811.3894 240h, 0905.0105 77h;

CTA $A_{eff} = 2km^2$ *at 5TeV,* $\Delta E/E \simeq 10\%$, $\epsilon_r = 0.01$ *(see 1008.3703), M31* 1° *20h, diffuse* $\pi(3^\circ)^2$ *1000h*

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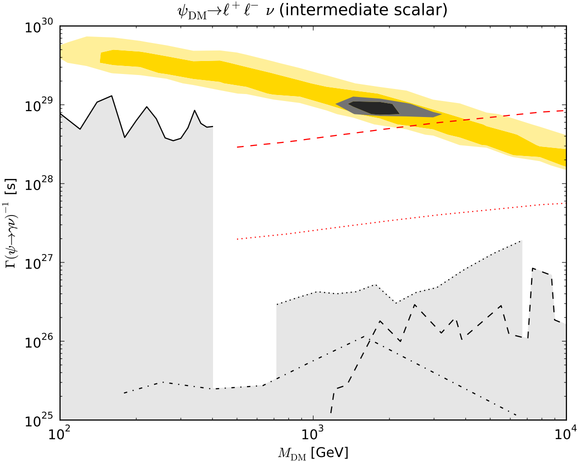

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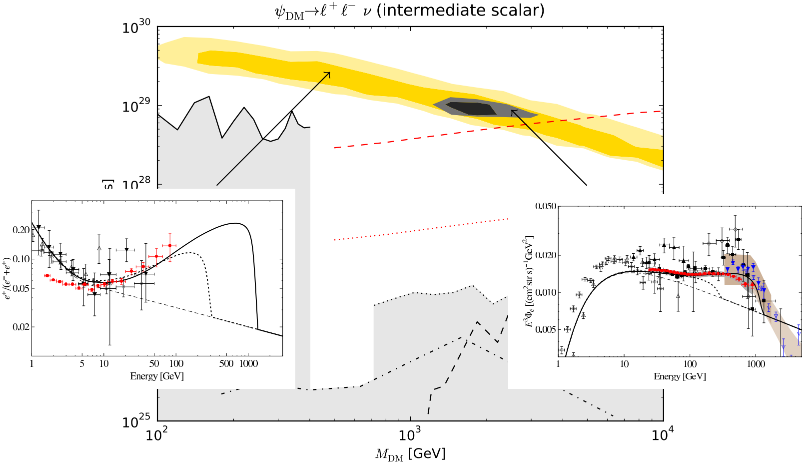

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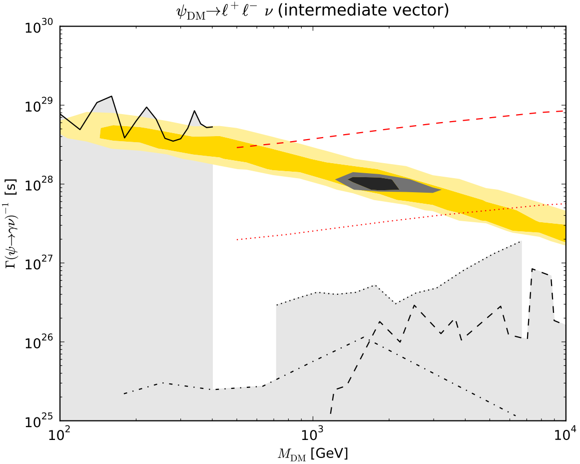


Gamma Ray Line: Enhancement

$\psi_{DM} \to e_L^+ e_L^- N$

$E_\gamma = 170$ GeV

#	m_{DM}	m_N
1	1.0	0.8
2	0.5	0.3
3	0.4	0.15

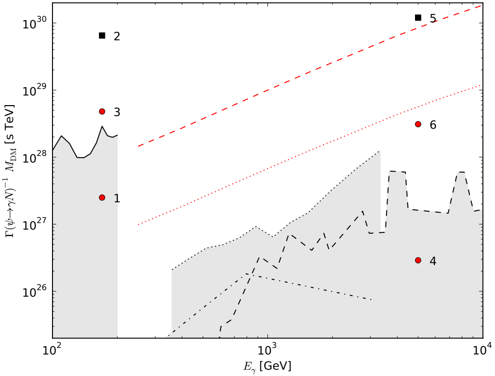
$\psi_{DM} \to \mu_L^+ \mu_L^- N$

$E_\gamma = 5$ TeV

#	m_{DM}	m_N
4	100	95
5	15	9
6	15	9

masses in TeV

$\Gamma(\psi_{DM} \to \gamma N)^{-1} m_{DM}$ [sec · TeV]



#1-6 fit PAMELA $e^+/e^\pm$, #4-6 fit Fermi $e^\pm$

$$\eta_{CP}(\psi_{DM}) \cdot \eta_{CP}(N) = \begin{cases} -1 & \#1, \#3, \#4, \#6 \\ +1 & \#2, \#5 \end{cases}$$

Conclusion

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