Indirect and Direct Detection of Dark Matter and Flavor Symmetry

Takashi Toma

Kanazawa University
Max-Planck Institute for Nuclear Physics

FLASY11@Valencia in Spain
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In collaboration with: Yuji Kajiyama and Hiroshi Okada

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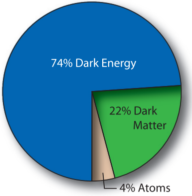
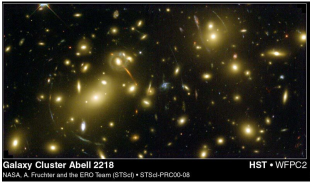
Introduction

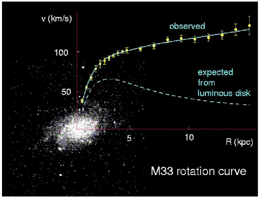
There are many experimental evidences for dark matter (DM).

- rotation curves of spiral galaxy
- CMB observation by WMAP
- gravitational lensing
- large scale structure of the universe

The existence of DM is crucial.

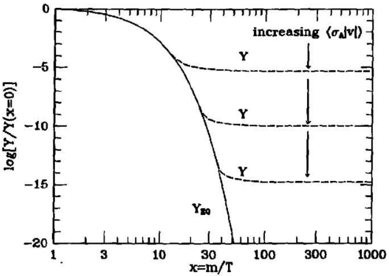






The Nature of DM

- Zero electric charge
- Non-relativistic particle
- Stable or extremely long lifetime



$\chi\chi \to$ SM particles

$$\Omega h^2 \simeq 0.11 \times \left(\frac{3.0 \times 10^{-26}}{\langle \sigma v \rangle \, [\mathrm{cm}^3/\mathrm{s}]} \right)$$

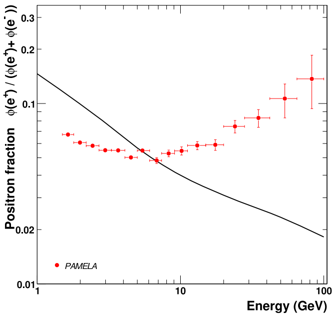
Required annihilation cross section

$$\begin{aligned} \langle \sigma v \rangle &\sim 3 \times 10^{-26} [\mathrm{cm}^3/\mathrm{s}] \\ &\sim 10^{-9} [\mathrm{GeV}^{-2}] \end{aligned}$$

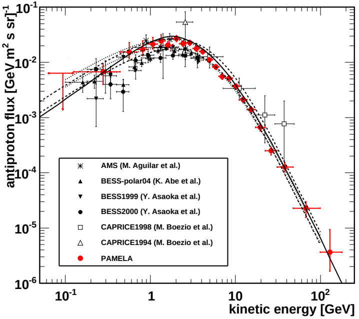
Indirect detection of DM (DM,DM$\to$ SM,SM)
DM annihilates to SM particles at the present universe.
The produced particles are observed as the cosmic ray ($e^{\pm}, \gamma, p, \nu$ etc).

PAMELA O. Adriani et al. arXiv:0810.4995, arXiv:1007.0821

$e^{\pm}$ observation



anti-proton observation



The positron excess might be produced by annihilation of DM. Leptophilic DM is favorable to explain the observation of the positron excess and no excess of anti-proton.

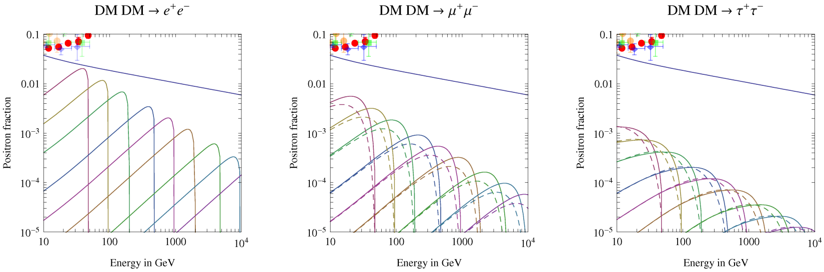
However large annihilation cross section is required.

$\langle \sigma v \rangle \sim 10^{-7} [\mathrm{GeV}^{-2}]$ for $e^{\pm}$ excess of PAMELA
$\langle \sigma v \rangle \sim 10^{-9} [\mathrm{GeV}^{-2}]$ for correct relic abundance
$\mathcal{O}(100)$ difference

How do you explain the difference?

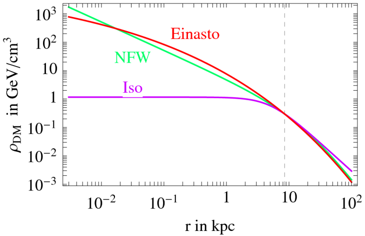
- Breit-Wigner enhancement
- Sommerfeld enhancement
- Non-thermal production of DM
- (Decaying DM)

Flavor dependence on $e^{\pm}$ flux M. Cirelli et al., arXiv:0809.2409



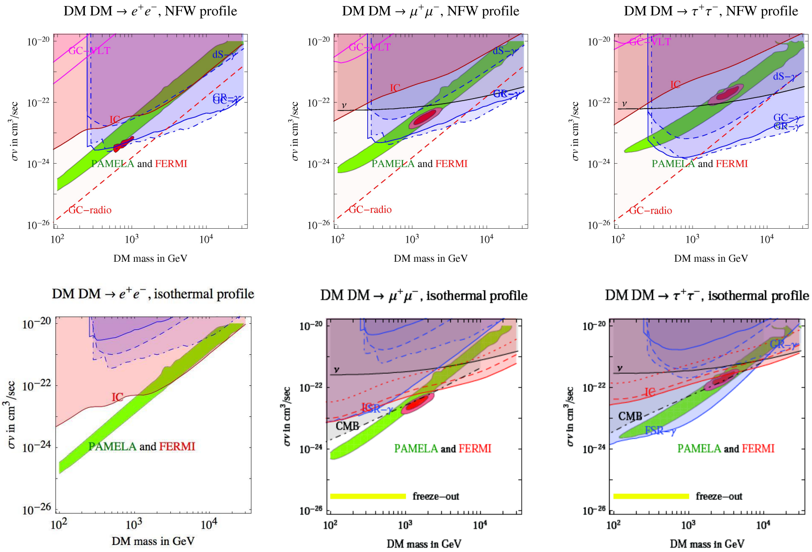
There is also DM density profile dependence for gamma ray flux.

M. Cirelli and P. Panci, arXiv:0904.3830



Constraint from gamma ray

P. Meade et al., arXiv:0905.0480; M. Papucci et al., 0912.0742



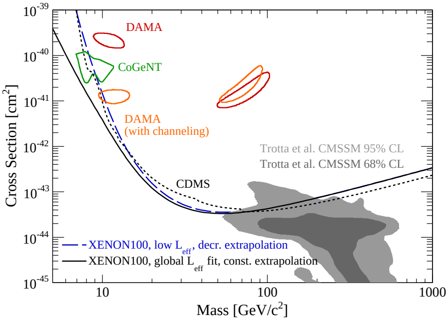
Direct Detection

Elastic scattering between DM and nucleus $\chi N \to \chi N$

detection rate

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int v f(v) \frac{d\sigma}{dE_R} dv$$

$f(v)$: velocity distribution of DM, E_R : recoil energy



ρ_0 : local DM density $\simeq 0.3[\mathrm{GeV/cm^3}]$

Upper bound of elastic cross section

$\sigma_0^{\mathrm{SI}} \lesssim 3.4 \times 10^{-44}[\mathrm{cm}^2]$

XENON100 Collaboration arXiv:1005.0380

D_6 Flavor Symmetric Model

- Field contents
  SM $+ n_i$, η and φ

$D_6 \times \hat{Z}_2 \times Z_2$ symmetry is imposed.

	L_S	n_S	e^c_S	L_I	n_I	e^c_I
$SU(2)_L \times U(1)_Y$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 0)$	$(\mathbf{1}, 1)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 0)$	$(\mathbf{1}, 1)$
D_6	$\mathbf{1}$	$\mathbf{1'''}$	$\mathbf{1}$	$\mathbf{2'}$	$\mathbf{2'}$	$\mathbf{2'}$
$\hat{Z}_2$	$+$	$+$	$-$	$+$	$+$	$-$
Z_2	$+$	$-$	$+$	$+$	$-$	$+$

	ϕ_S	ϕ_I	η_S	η_I	φ
$SU(2)_L \times U(1)_Y$	$(\mathbf{2}, -1/2)$	$(\mathbf{2}, -1/2)$	$(\mathbf{2}, -1/2)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 0)$
D_6	$\mathbf{1}$	$\mathbf{2'}$	$\mathbf{1'''}$	$\mathbf{2'}$	$\mathbf{1}$
$\hat{Z}_2$	$+$	$-$	$+$	$+$	$+$
Z_2	$+$	$+$	$-$	$-$	$+$

- D_6 → predict the lepton mixing, **restrict annihilation channels of DM**
- $\hat{Z}_2$ → suppress FCNC of the quark sector
- Z_2 → forbid Dirac neutrino masses and stabilize DM candidate

$$\begin{aligned}\mathcal{L}_{\rm lepton} \quad = \quad & \sum_{a,b,d=1,2,S} \left[Y^{ed}_{ab}(L_a i\sigma_2 \phi_d) e^c_b + Y^{\nu d}_{ab}(\eta^\dagger_d L_a) n_b \right] \\ & - \sum_{I=1,2} \frac{M_1}{2} n_I n_I - \frac{M_S}{2} n_S n_S \\ & - \sum_{I=1,2} \frac{\mathfrak{S}_1}{2} \varphi n_I n_I - \frac{\mathfrak{S}_S}{2} \varphi n_S n_S + \text{h.c.}\end{aligned}$$

In the model, neutrino masses are generated radiatively.

$$m_\nu \sim \frac{Y^\nu Y^\nu \kappa}{(4\pi)^2} \frac{v^2}{M_S} I_1 \left(\frac{M_S^2}{M_\eta^2} \right)$$

$$\kappa \ll 1, \quad Y^\nu \sim 1, \quad M_S, M_\eta \sim 1 \text{ [TeV]}.$$

MNS matrix at the leading order,

$$V_{MNS} \simeq \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\frac{1}{\sqrt{2}}\sin\theta_{12} & \frac{1}{\sqrt{2}}\cos\theta_{12} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}}\sin\theta_{12} & \frac{1}{\sqrt{2}}\cos\theta_{12} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- The maximal mixing of atmospheric neutrino is derived.
- Inverted hierachy is only allowed. ($|\Delta m_{21}^2| < |\Delta m_{23}^2|$)

DM candidates :Z_2 odd particles
$\to \eta_I^0,\ \eta_S^0,\ n_I,\ n_S$
We assume n_S to be DM. It is interesting because there are only a few parameters due to D_6 flavor symmetry.

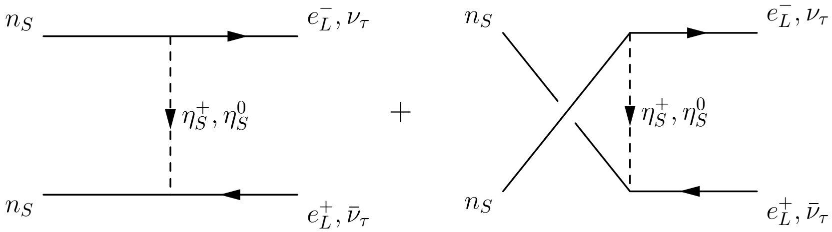
We have to study whether n_S can satisfy the correct relic abundance.

$$\begin{array}{ccc} n_1, & n_2, & n_S \end{array}$$

$$\mathcal{L} \supset \eta_S^+ \overline{\ell_i} Y_{ij} n_j, \quad Y \simeq \begin{pmatrix} 0 & 0 & h \\ 0 & 0 & \frac{m_e}{m_\mu} h \\ 0 & 0 & 0 \end{pmatrix} \begin{array}{c} e \\ \mu \\ \tau \end{array} \quad \text{for charged leptons}$$

$$\mathcal{L} \supset \eta_S^0 \overline{\ell_i} Y_{ij} n_j, \quad Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h \end{pmatrix} \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \quad \text{for neutrinos}$$

The annihilation processes of n_S



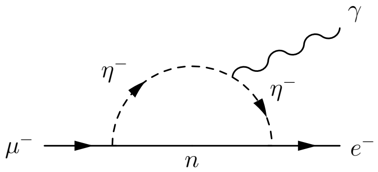
Only $e^\pm$ are generated as charged leptons because of the D_6 flavor symmetry.

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}, \qquad \langle \sigma v \rangle \simeq \frac{|h|^4}{4\pi} \frac{M_S^2 (M_S^4 + M_\eta^4)}{(M_S^2 + M_\eta^2)^4} \frac{T}{M_S}$$

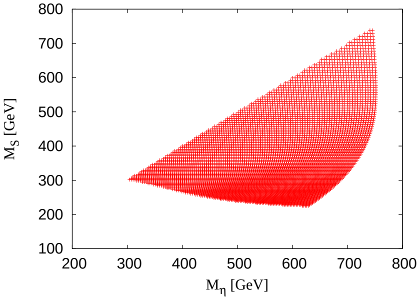
parameters : h, M_S, M_η

Constraint from $\mu \to e\gamma$

$$\mathrm{Br}(\mu \to e\gamma) \simeq \frac{3\alpha_{\rm em}}{64\pi G_F^2} \frac{m_e^2}{m_\mu^2} \frac{|h|^4}{M_\eta^4} F_2\left(\frac{M_S^2}{M_\eta^2}\right)$$



$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x}{6(1-x)^4}$$

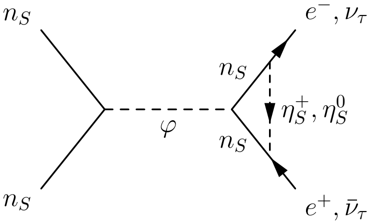


$\leftarrow$ The allowed region from the following constraints

- $\mathrm{Br}(\mu \to e\gamma) < 1.2 \times 10^{-11}$
- $|h| < 1.5$
- the relic abundace of n_S $(\Omega h^2 \simeq 0.11)$
- $M_S < M_\eta$.

$\to 230\mathrm{GeV} < M_S < 750\mathrm{GeV}$

Indirect Detection ($e^{\pm}$ excess)



The singlet φ mixes with the Higgses ϕ_I and ϕ_S.

$$\sigma_2 v \propto \frac{1}{(s - M_R^2)^2 + M_R^2 \Gamma_R^2},$$

$$s \simeq M_S^2 \left(1 + \frac{v^2}{4}\right),$$

R is the resonance particle $2M_S \simeq M_R$.

$$R = \mathcal{O}_I \phi_I + \mathcal{O}_S \phi_S + \mathcal{O}_\varphi \varphi \text{ (mass eigenstate)}$$

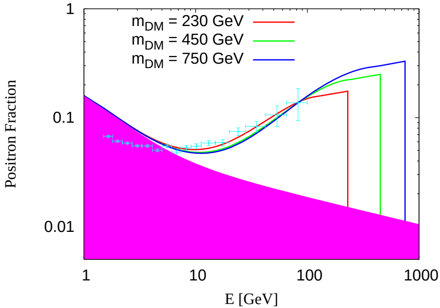
This process is enhanced by the Breit-Wigner enhancement, and effective at only the present universe, and neglected at the early universe.

Indirect Detection ($e^{\pm}$ excess)

$\langle \sigma_2 v \rangle \sim 10^{-7} [\mathrm{GeV}^{-2}]$ is needed.

$$BF \equiv \frac{\langle \sigma_2 v \rangle}{3.0 \times 10^{-9} [\mathrm{GeV}^{-2}]} \sim 100$$

DM profile is assumed to be Isothermal.

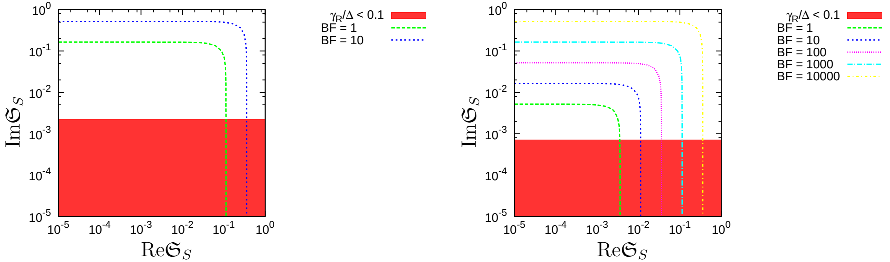


$$\langle \sigma_2 v \rangle = \frac{\int (\sigma_2 v) e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2}{\int e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2}$$

If $\Gamma_R / M_R \equiv \gamma_R \ll \Delta \ (\equiv 1 - 4M_S^2/M_R^2)$,

$$\langle \sigma_2 v \rangle \simeq \frac{\sqrt{\pi}}{10(4\pi)^4} |h|^4 \mathcal{O}_\varphi^2 \left(\mathrm{Re}\mathfrak{S}_S\right)^2 \frac{m_e^2}{M_\eta^4} \left(\frac{M_S}{T}\right)^{3/2} e^{-\Delta M_S/T}$$

for $\sqrt{\Delta} = 10^{-6}$ for $\sqrt{\Delta} = 10^{-7}$



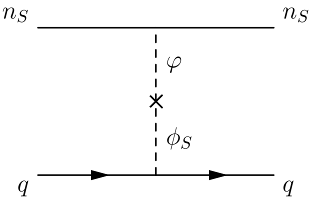
When $\mathrm{Re}\mathfrak{S}_S \ll \mathrm{Im}\mathfrak{S}_S$, Large boost factor is obtained.

The constraint from no excess of anti-proton flux

Due to the constraint from no anti-proton excess, $\langle \sigma_3 v \rangle / \langle \sigma_2 v \rangle \lesssim 10^{-2}$ is needed.

$$\longrightarrow \quad \frac{|\mathcal{O}_S|}{|\mathfrak{S}_S|} \lesssim 10^{-12}$$ It is the severe constraint!

Direct Detection

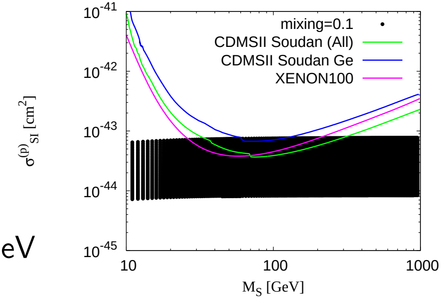


This process ocuurs through the Higgs mixing.
The largest contribution comes from the t-channel exchange of SM-Higgs.

$$\text{SM-Higgs} = \mathcal{U}_I \phi_I + \mathcal{U}_S \phi_S + \mathcal{U}_\varphi \varphi$$

$$\sigma^p_{\mathrm{SI}} \propto \left| \frac{\mathcal{U}_S \mathcal{U}_\varphi \mathfrak{S}_S Y_q}{m^2_{\mathrm{SM-Higgs}}} \right|^2$$

$$\mathcal{U}_S \mathcal{U}_\varphi \mathfrak{S}_S = 0.1$$
$$115 \text{ GeV} < m_{\mathrm{SM-Higgs}} < 200 \text{ GeV}$$



Summary

1. Leptophilic DM is favored from indirect detection.
2. $e^{\pm}$ flux has flavor dependence, in particular annihilation to $\tau^{\pm}$ is excluded by the constraint from gamma ray.
3. DM n_S in the D_6 symmetric model dominantly couples to $e^{\pm}$.
4. The $e^{\pm}$ excess in the cosmic ray is explained by the Breit-Wigner enhancement.
5. The elastic scattering between DM and quarks occurs through the Higgs mixing.
6. It is consistent with indirect and direct detection of DM since the mediate particle for indirect detection is different from direct detection.