Leptophilic Dark Matter

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Based on 0811.1646 in collaboration with P. Ko

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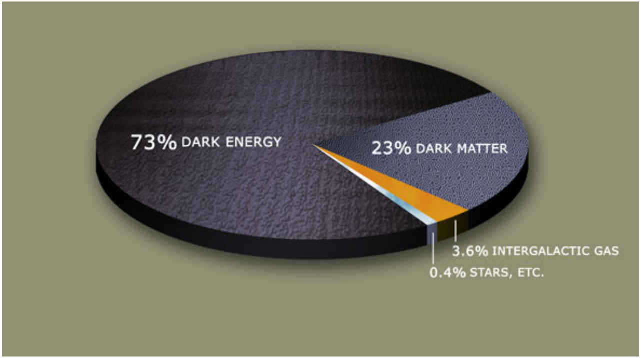
Outline

1. Introduction to the recent indirect DM searches
2. DM in the $L_\mu - L_\tau$ model
3. Fit to the PAMELA, Fermi LAT, and HESS data
4. Constraints from the gamma-ray and neutrino data
5. Conclusions

DM in the Universe

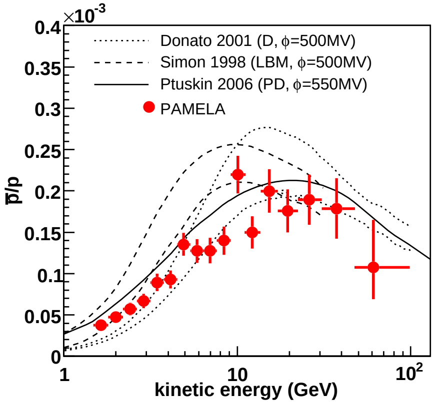
Although 23% of the universe is composed of DM, we do not know its nature yet!!



Cosmic ray detection

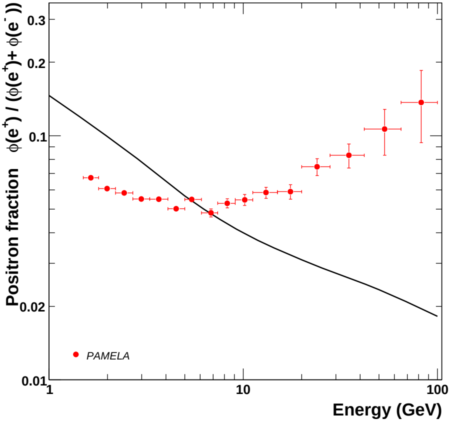
- The antiproton distribution ($\overline{p}/p$) is consistent with theory

  PAMELA cn, PRL(2009) (arXiv:0810.4994)



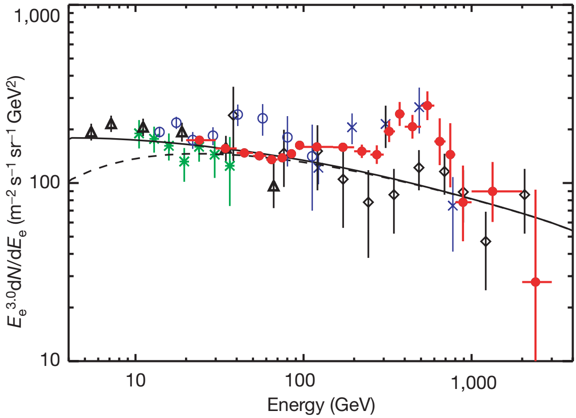
Cosmic ray detection

- Positron excess in $e^+/(e^+ + e^-)$ for the energy range 10–100 GeV
  PAMELA cn, Nature(2009) (arXiv:0810.4995)



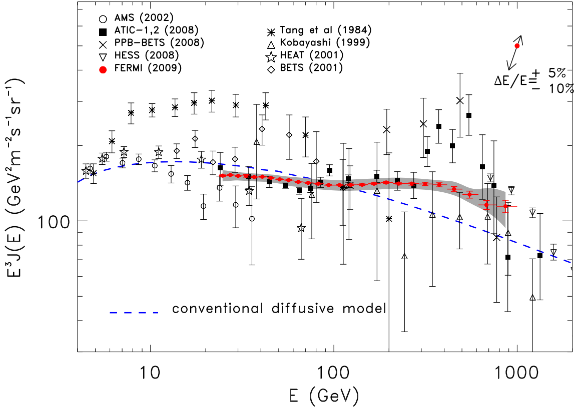
Cosmic ray detection

- ATIC has seen $e^+ + e^-$ peak in 300–800 GeV ATIC cn, Nature (2008)



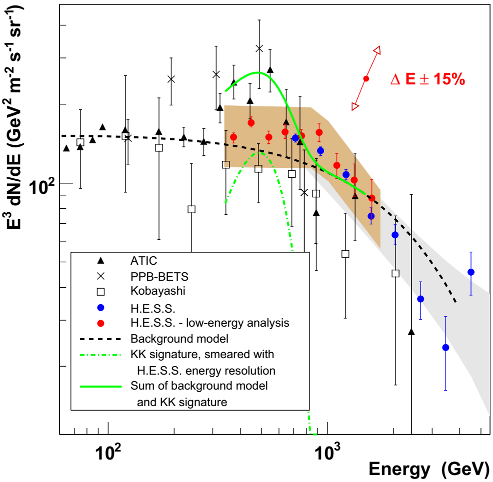
Cosmic ray detection

- Recent Fermi LAT data which is much more precise do not confirm the ATIC $e^+ + e^-$ peak in 100–1000 GeV. But still $e^+ + e^-$ excess. Fermi LAT cn, arXiv:0905.0025



Cosmic ray detection

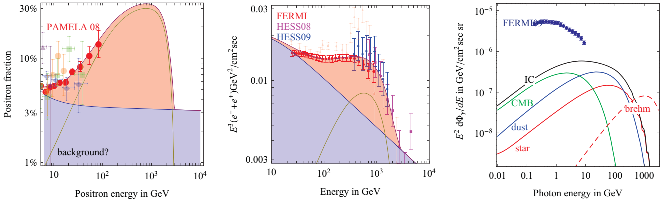
- HESS data also shows possible $e^+ + e^-$ excess compared to the background. HESS cn, arXiv:0905.0105



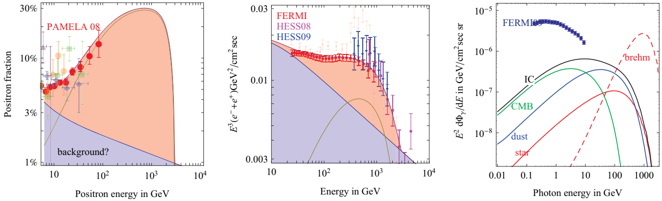
DM interpretation

Meade, Papucci, Strumia, Volansky, arXiv:0905.0480

DM with $M = 3.$ TeV that annihilates into 4μ with $\sigma v = 8.8 \times 10^{-23}\ \mathrm{cm}^3/\mathrm{s}$



DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 2.0 \times 10^{-22}\ \mathrm{cm}^3/\mathrm{s}$



DM interpretation

- We need leptophilic DM annihilating preferentially into $\mu^+\mu^-$ or $\tau^+\tau^-$
- π^0 from τ decays into $\gamma\gamma$. Need to consider gamma-ray constraints.
- In general there can be associated ν productions. Need to consider ν constraints.

Gauged $U(1)_{L_\mu - L_\tau}$

- Anomaly-free $U(1)'$ groups that can be gauged without extending the SM fermions

$$U(1)_{L_e - L_\mu}, \quad U(1)_{L_\mu - L_\tau}, \quad U(1)_{L_e - L_\tau}, \quad U(1)_{B-L}.$$

- $U(1)_{L_\mu - L_\tau}$ not strongly constrained from collider exp. yet
- Generation-dependent $U(1)'$ charges

He, Joshi, Lew, Volkas (1991)

Gauged $U(1)_{L_\mu - L_\tau}$

Quantum number assignments

	SU(3)	SU(2)	U(1)$_Y$	U(1)$_{L_\mu - L_\tau}$
Q	3	2	1/6	0
u^c	$\overline{3}$	1	-2/3	0
d^c	$\overline{3}$	1	1/3	0
L	1	2	-1/2	(0,1,-1)
e^c	1	1	1	(0,-1,1)
H	1	2	1/2	0

Gauged $U(1)_{L_\mu - L_\tau}$: FCNC

- Generic FCNC problems

$$
\begin{aligned}
\mathscr{L} &= -g' Z'_\mu \left[\begin{pmatrix} \overline{e^0} & \overline{\mu^0} & \overline{\tau^0} \end{pmatrix}_L \begin{pmatrix} 0 & & \\ & 1 & \\ & & -1 \end{pmatrix} \begin{pmatrix} e^0 \\ \mu^0 \\ \tau^0 \end{pmatrix}_L + (L \leftrightarrow R) \right] \\
&= -g' Z'_\mu \left[\begin{pmatrix} \overline{e} & \overline{\mu} & \overline{\tau} \end{pmatrix}_L V_L^e \begin{pmatrix} 0 & & \\ & 1 & \\ & & -1 \end{pmatrix} V_L^{e\dagger} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_L + (L \leftrightarrow R) \right],
\end{aligned}
$$

where $V_R^e Y_e V_L^{e\dagger} = \frac{\sqrt{2}}{v} m_E$.

- The FCNC is dependent on the flavor model.
- We evade the problem, by assuming $V_L^e = V_R^e = 1$. So $U_{\rm MNS} = V_L^e V^{\nu\dagger} = V^{\nu\dagger}$.

Gauged $U(1)_{L_\mu - L_\tau}$: $Z - Z'$ mixing

- Kinetic mixing

$$\mathscr{L} = -\frac{1}{4}\sin\chi B_{\mu\nu} Z'^{\mu\nu}$$

: can be eliminated by embedding $U(1)'$ to non-abelian gauge groups.

- No DM scattering off the proton or neutron.

Gauged $U(1)_{L_\mu - L_\tau}$: 3 classes of the model

(a) $U(1)'$ symmetry is exact. Z' is massless.

(b) $U(1)'$ symmetry is broken by SM singlet Higgs ϕ.

(c) $U(1)'$ symmetry is broken by Higgs fields charged under SM groups as well as $U(1)'$.

SB, Deshpande, He, Ko, PRD(2001)

Gauged $U(1)_{L_\mu - L_\tau}$: Case (a)

- The Z' couplings to matter

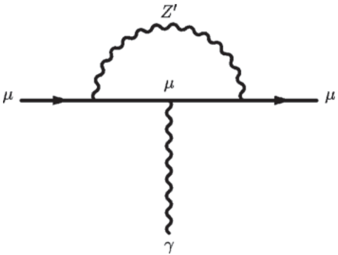
$$\mathscr{L} = -g' Z'_\mu \left(\overline{\mu} \gamma^\mu \mu - \overline{\tau} \gamma^\mu \tau \right)$$

- Constrained by $(g-2)_\mu$.

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (302 \pm 88) \times 10^{-11}$$

- The constraint on $\alpha' = g'^2/4\pi$:

$$\Delta a_\mu = \frac{\alpha'}{2\pi} \to \alpha' = (1.9 \pm 0.6) \times 10^{-8}.$$



- Too small DM annihilation cross section.

Ruled out by $\Omega_{\text{DM}} h^2 < 0.1099$.

Gauged $U(1)_{L_\mu - L_\tau}$: Case (b)

- SM singlet Higgs field ϕ is introduced

	SU(3)	SU(2)	U(1)$_Y$	U(1)$_{L_\mu - L_\tau}$
ϕ	1	1	0	1

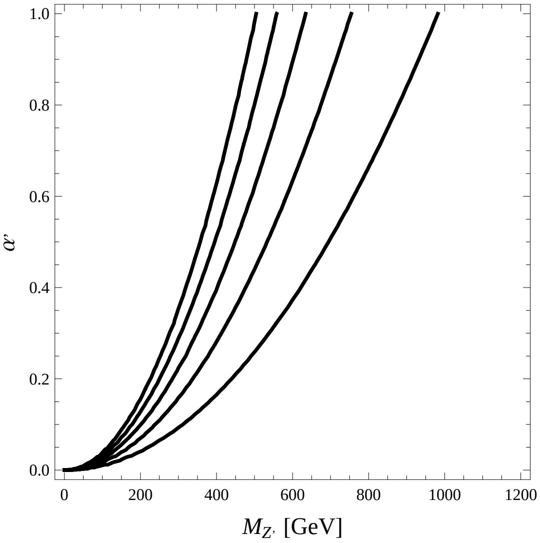
- The $U(1)'$ breaking scale is independent of the ew scale

$$m_{Z'} = g' v_\phi .$$

- $(g-2)_\mu$

$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2m_\mu^2}{3m_{Z'}^2} \quad (m_{z'} \gg m_\mu)$$

Gauged $U(1)_{L_\mu - L_\tau}$: Case (b)



Introduction of DM candidate

- Case (a,c) are too constrained to produce the correct thermal relic density
- For "Case (b)" we introduce vectorlike Dirac fermion as DM candidate

	SU(3)	SU(2)	$U(1)_Y$	$U(1)_{L_\mu - L_\tau}$
ϕ	1	1	0	1
ψ_D	1	1	0	1
ψ_D^c	1	1	0	-1

$$\begin{aligned}
\mathcal{L}_{\text{Model}} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{New}} \\
\mathcal{L}_{\text{New}} &= -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \overline{\psi_D} i D \cdot \gamma \psi_D - M_{\psi_D} \overline{\psi_D} \psi_D + D_\mu \phi^* D^\mu \phi \\
&\quad - \lambda_\phi (\phi^* \phi)^2 - \mu_\phi^2 \phi^* \phi - \lambda_{H\phi} \phi^* \phi H^\dagger H .
\end{aligned}$$

- Thermal relic density of the CDM ψ_D

$$\psi_D \overline{\psi}_D \to Z^{'*} \to \ell^+ \ell^-, \nu_\ell \overline{\nu}_\ell, \ (\ell = \mu, \tau),$$
$$\psi_D \overline{\psi}_D \to Z' Z'$$

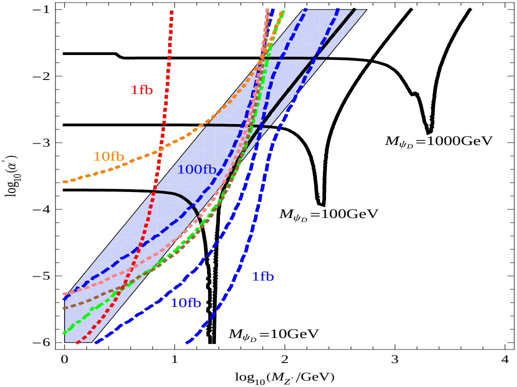
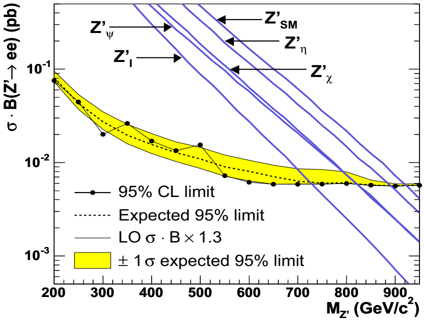


Figure 1: The relic density of CDM (black), the muon $(g-2)_\mu$ (blue band), the production cross section at B factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the Z^0 decay width (2.5 $\times 10^{-6}$ GeV, brown dotted) in the $(\log_{10}\alpha^{'}, \log_{10} M_{Z'})$ plane. For the relic density, we show three contours with $\Omega h^2 = 0.106$ for $M_{\psi_D} = 10$ GeV, 100 GeV and 1000 GeV. The blue band is allowed by $\Delta a_\mu = (302 \pm 88) \times 10^{-11}$ within 3 σ.

$M_{Z'}$ bound from Tevatron



CDF cn, arXiv:0707.2524

- CDF searched for the Z' in the $p\bar{p} \to Z'^{*} \to e^{+}e^{-}$ and gave strong bound on the mass $M_{Z'} > 930$ GeV.
- The CDF bound on the $M_{Z'}$ does not apply here.
- The production cross section is suppressed.
- No $e^{+}e^{-}$ mode.

Current colliders, LHC

- Z'-strahlung

$$\begin{aligned} q\bar{q}\ (\text{or } e^+e^-) &\rightarrow \gamma^*, Z^* \rightarrow \mu^+\mu^- Z', \tau^+\tau^- Z' \\ &\rightarrow Z^* \rightarrow \nu_\mu \bar{\nu}_\mu Z', \nu_\tau \nu_\tau Z' \end{aligned}$$

- Vector boson fusion

$$\begin{aligned} W^+W^- &\rightarrow \nu_\mu \bar{\nu}_\mu Z' \quad (\text{or } \mu^+\mu^- Z'), \quad \text{etc.} \\ Z^0 Z^0 &\rightarrow \nu_\mu \bar{\nu}_\mu Z' \quad (\text{or } \mu^+\mu^- Z'), \quad \text{etc.} \\ W^+ Z^0 &\rightarrow \nu_\mu \bar{\mu} Z' \quad \text{etc.} \end{aligned}$$

Collider bounds

- Z' decay

$$Z^{'} \to \ell^+\ell^-, \nu_\ell\overline{\nu}_\ell, \psi_D\overline{\psi}_D, \ \ (\ell=\mu,\tau),$$

- For $m_{Z'} \gg m_\mu, m_\tau, M_{\psi_D}$,

$$\begin{aligned}\Gamma(Z^{'} \to \mu^+\mu^-) &= \Gamma(Z^{'} \to \tau^+\tau^-) = 2\Gamma(Z^{'} \to \nu_\mu\bar{\nu}_\mu) = 2\Gamma(Z^{'} \to \nu_\tau\bar{\nu}_\tau) \\ &= \Gamma(Z^{'} \to \psi_D\bar{\psi}_D)\end{aligned}$$

- Z' will decay inside the detector

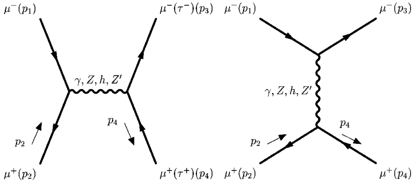
$$\Gamma_{\rm tot}(Z') = \frac{\alpha'}{3}M_{Z'} \times 4(3) \approx \frac{4(\text{or } 3)}{3} GeV \left(\frac{\alpha'}{10^{-2}}\right)\left(\frac{M_{Z'}}{100GeV}\right)$$

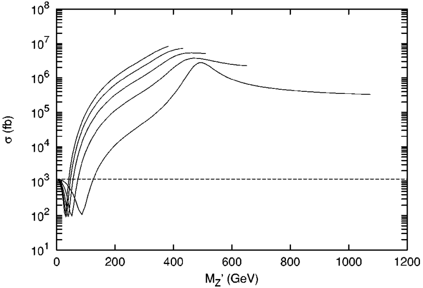
- Multi-muon(tau) events are characteristic signal of $U(1)_{L_\mu - L_\tau}$.

Muon collider

- We can see dramatic Z' production at a muon collider

$$\sigma(\mu\mu \to \mu\mu)$$





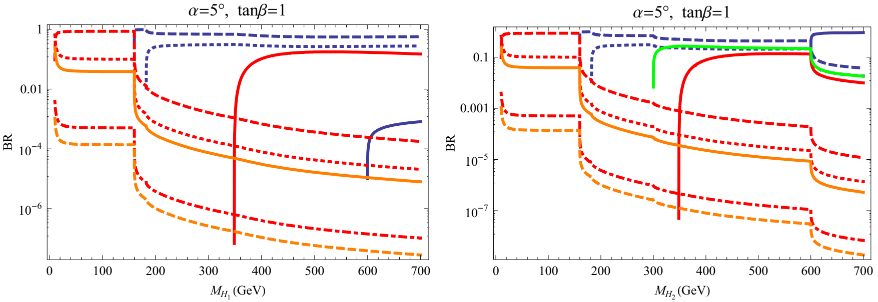
SB, Deshpande, He, Ko, PRD(2001)

Higgs Searches

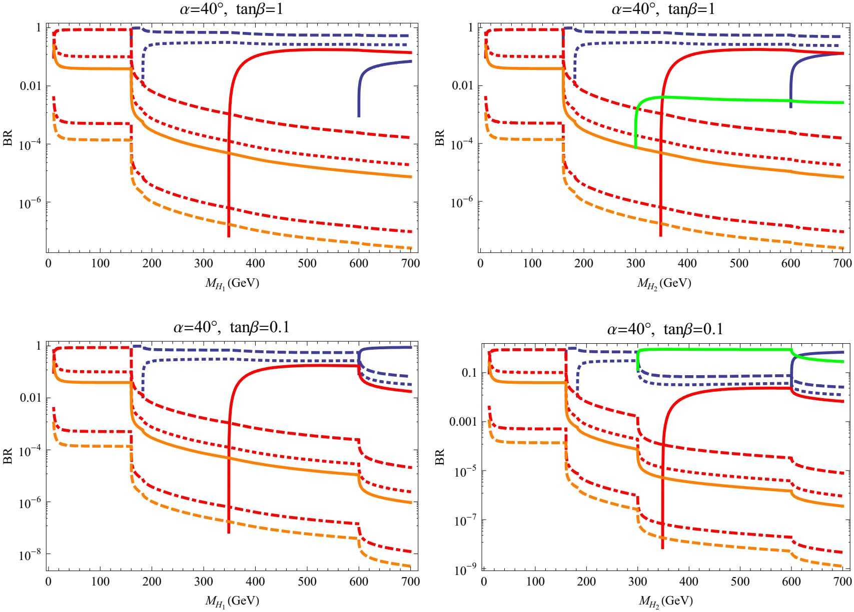
- The mixing term $\lambda_{H\phi}$ can make the Higgs search non-standard.

$$h_{SM} = H_1 \cos\alpha - H_2 \sin\alpha,$$
$$s = H_1 \sin\alpha + H_2 \cos\alpha,$$

- $\tan\beta = v_\phi / v_{SM}$.



Higgs Searches



Positron propagation

- The positron flux at Earth can be calcuated by solving the transport equation Delahaye, *et.al*, arXiv:0712.2312

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(\mathbf{x},E)\, \nabla \psi\} - \frac{\partial}{\partial E}\{b(E)\, \psi\} = q\,(\mathbf{x},E)\ .$$

- $\psi(\mathbf{x},t) =$ positron # density/Energy
- $K(\mathbf{x},E) = K_0\, \varepsilon^{\delta}(\varepsilon = E/E_0, E_0 = 1\,\mathrm{GeV})$: diffusion coef.
- $b(E) = E_0 \varepsilon^2/\tau_E(\tau_E = 10^{16}\mathrm{s})$: Energy loss through synchrotron radiation or ICS

Positron propagation

- $q(\mathbf{x},E) = \eta \langle \sigma v \rangle \left\{ \frac{\rho(\mathbf{x})}{m_\chi} \right\}^2 f(\varepsilon)$: source term ($\eta = 1/2$ (Majorana), $\eta = 1/4$ (Dirac))
- The positron flux at the Earth

$$\Phi_{e^+} = \frac{\beta_{e^+}}{4\pi} \psi(\odot, \varepsilon)$$

$$\psi(\odot, \varepsilon) = \kappa \frac{\tau_E}{\varepsilon^2} \int_{\varepsilon}^{+\infty} d\varepsilon_S f(\varepsilon_S) \tilde{I}(\lambda_D)$$

$$\lambda_{\mathrm{D}}{}^2 = 4 K_0 \tau_E \left\{ \frac{\varepsilon^{\delta-1} - \varepsilon_S^{\delta-1}}{1-\delta} \right\} .$$

Positron propagation

- Factor relevant to particle physics

$$\kappa = \eta \, \langle \sigma v \rangle \left\{ \frac{\rho_\odot}{m_\chi} \right\}^2 \quad .$$

- Factor relevant to astrophysics

$$\tilde{I}(\lambda_{\rm D}) = \int_{\rm DZ} d^3\mathbf{x}_S \, \tilde{G}\left(\odot, \varepsilon \leftarrow \mathbf{x}_S, \varepsilon_S\right) \, \left\{ \frac{\rho\left(\mathbf{x}_S\right)}{\rho_\odot} \right\}^2 \quad .$$

DM density profiles

$$\rho(r, r_s) = \frac{1}{r^\gamma} \frac{\rho_0}{(1 + (r/r_s)^\alpha)^{(\beta-\gamma)/\alpha}}$$

Halo model	α	β	γ	r_s [kpc]
Cored isothermal	2	2	0	5
Navarro, Frenk & White	1	3	1	20
Moore	1.5	3	1.3	30

Table: Dark matter distribution profiles in the Milky Way.

Sommerfeld enhancement

- If DM is a thermal relic, the relic abundance is approximately given by

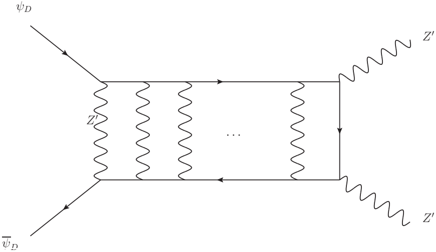
$$\Omega h^2 \simeq 0.1 \times \left(\frac{3 \times 10^{-26}\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v \rangle_{\mathrm{freeze}}} \right). \tag{1}$$

- The PAMELA, ATIC suggest $\sigma v \approx 10^{-23}\mathrm{cm}^3/\mathrm{sec}$

Sommerfeld enhancement

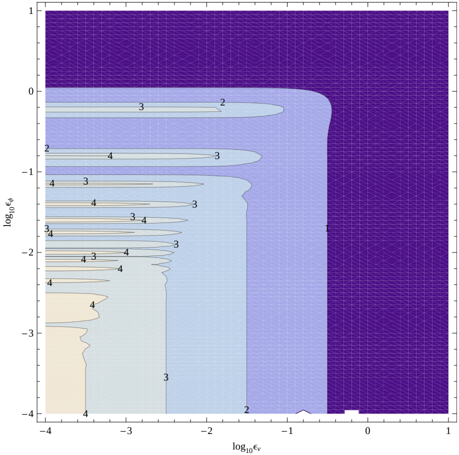
The large “boost factor” can come from

- the clumpy distribution of the dark matter
- or the “Sommerfeld enhancement” for long range force and small $v(\sim 10^{-3})$ (A. Sommerfeld (1931), Arkani-Hamed *et.al*, arXiv:0810.0713)



- By introducing $x = \alpha' M r$, $\varepsilon_v = v/\alpha'$, $\varepsilon_\phi = m_{Z'}/\alpha' M$

$$\chi'' + \left(\frac{1}{x}e^{-\varepsilon_\phi x} + \varepsilon_v^2\right)\chi = 0 \qquad (2)$$



(Arkani-Hamed *et.al*, arXiv:0810.0713)

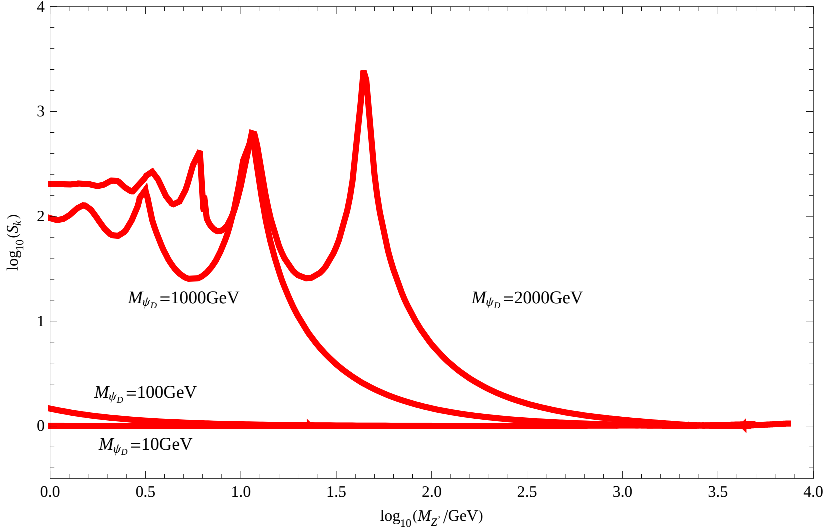
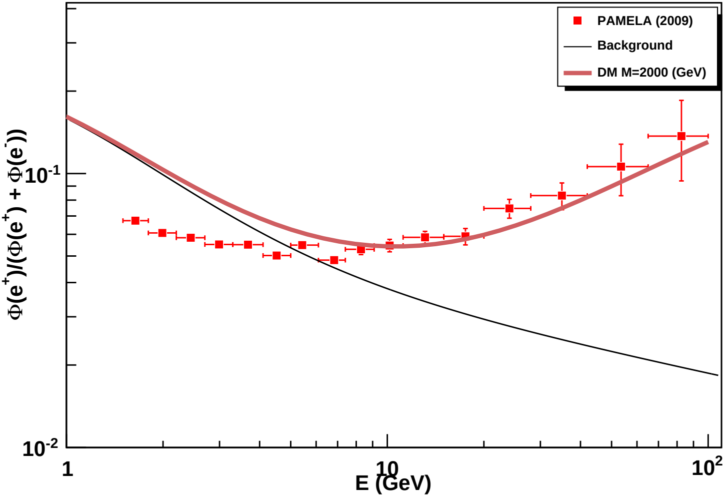


Figure: Sommerfeld enhancement factor along the constant relic density lines. $v = 200$ km/s.

PAMELA, Fermi LAT, HESS, SK, HESS gamma-ray from GC

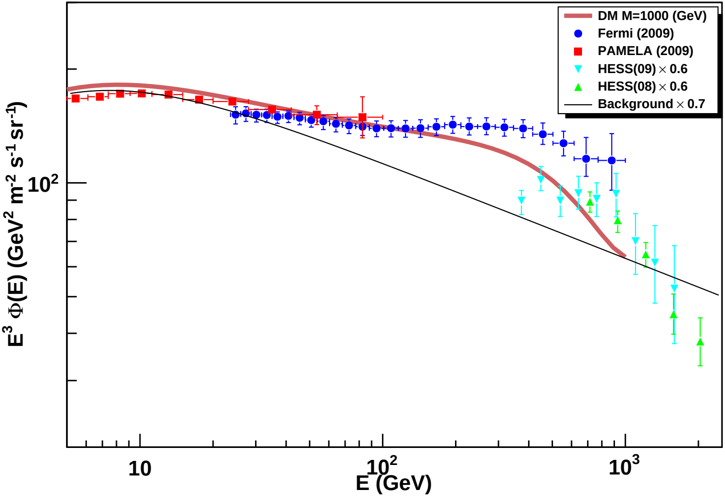
- Fit the BF, and scale parameters to the indirect detection data
- Used NFW DM profile with MED parameters
- For the background e^+ and e^- we used the results in Baltz and Edsjö (1998); Moskalenko and Strong (1998)
- Considered SK up-going neutrino-induced muon flux, HESS gamma-ray frux from the GC and GR

Fit to PAMELA data



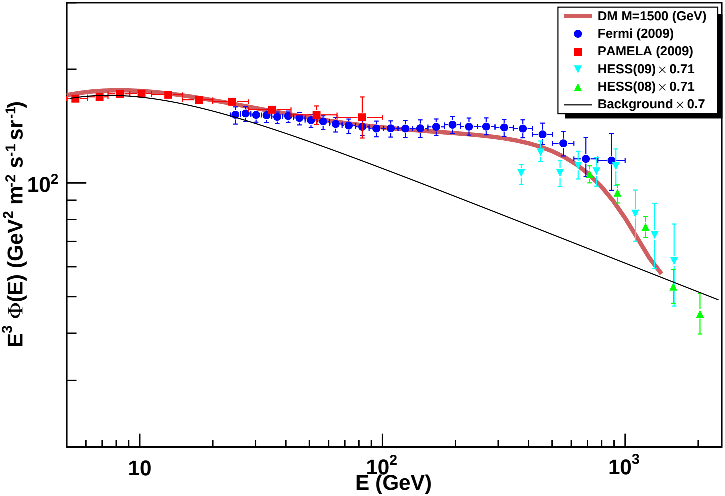
Fit to PAMELA, Fermi LAT, and HESS data

NFW MED, BF=1574, $\chi^2_{\min}/dof = 201/50$.



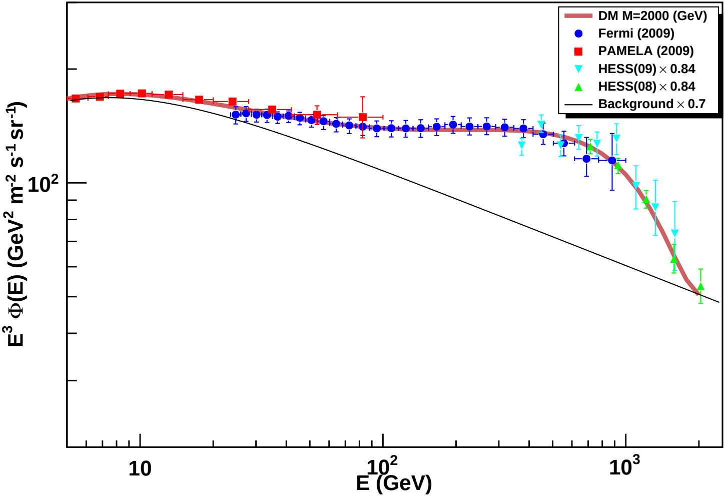
Fit to PAMELA, Fermi LAT, and HESS data

NFW MED, BF=3044, $\chi^2_{\min}/dof = 104/50$.



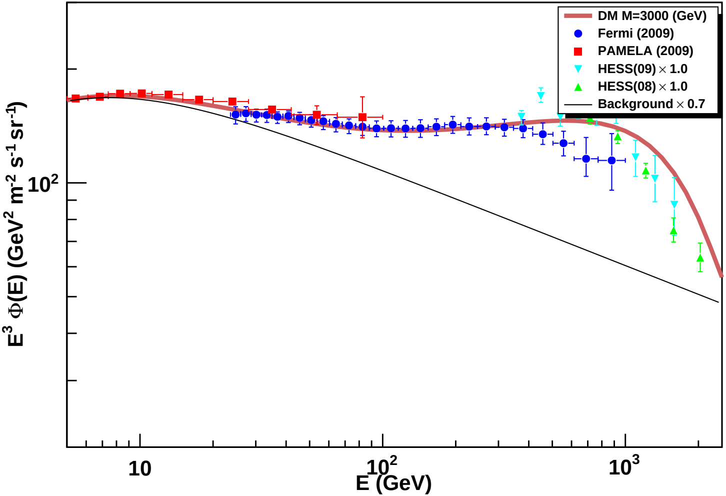
Fit to PAMELA, Fermi LAT, and HESS data

NFW MED, BF=5198, $\chi^2_{\min}/dof = 53/50$.



Fit to PAMELA, Fermi LAT, and HESS data

NFW MED, BF=10287, $\chi^2_{\min}/dof = 120/50$.



Neutrino/gamma constraint

- The neutrino/gamma-ray flux at the Earth coming from the Galactic center by DM annihilation Hisano, *et.al.*, arXiv:0812.0219

$$\frac{dF_{\nu_i,\gamma}}{dE} = \frac{R_{sc}\rho_{sc}^2}{8\pi m_\chi^2} \left(\sum_F \langle \sigma v \rangle_F \frac{dN_{\nu_i,\gamma}}{dE} \right) \langle J_2 \rangle_\Omega \Delta\Omega$$

-

$$\langle J_n \rangle_\Omega = \int \frac{d\Omega}{\Delta\Omega} \int_{l.o.s} \frac{dl}{R_{sc}} \left(\frac{\rho(l)}{\rho_{sc}} \right)^n .$$

Neutrino/gamma constraint

- The neutrino-induced muon flux Hisano, *et.al.*, arXiv:0812.0219

$$F_{\mu^+\mu^+} \simeq 5.9 \times 10^{-15}\mathrm{cm}^{-2}\mathrm{s}^{-1} \sum_F S_F \left(\frac{\langle \sigma v \rangle}{10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}} \right) \left(\frac{\langle J_2 \rangle_\Omega \Delta\Omega}{10} \right)$$

- $$S_F = \sum_{\nu_i} \int_{E_{\mathrm{min}}}^{E_{\mathrm{in}}} \frac{dN_F^{(\nu_i)}}{dE} P_{\nu_i \nu_\mu} \left(\frac{E}{E_{\mathrm{in}}} \right)^2 dE$$

- $P_{\nu_i \nu_\mu}$: The probability that ν_i at the production is observed as ν_μ at Earth due to neutrino oscillation. $P_{\nu_i \nu_\mu} \sim (2/9, 7/18, 7/18)$
- E^2 in the integral $\rightarrow$ more sensitive to the energetic neutrinos

SK neutrino constraint

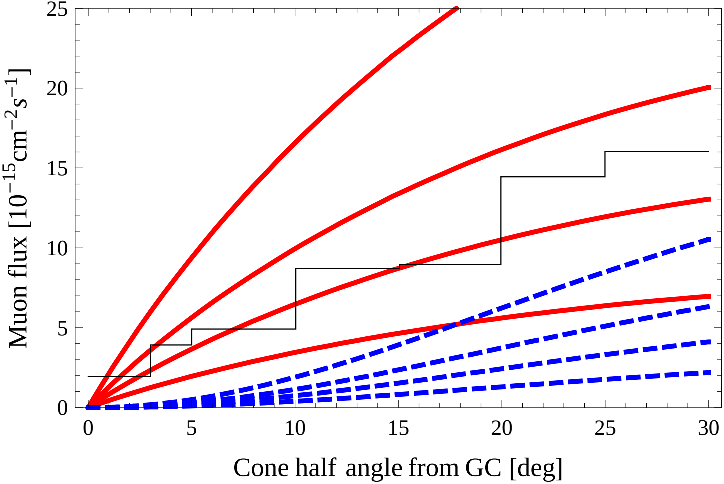
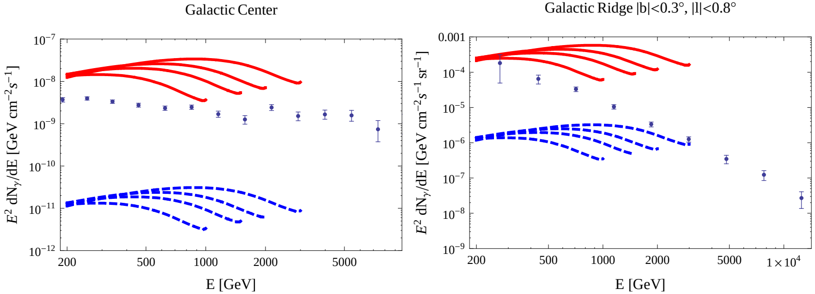


Figure: NFW (red), isothermal (blue) DM profiles. DM masses: 3, 2, 1.5, 1 (TeV) from above.

The gamma-ray from the GC (HESS)

HESS, PRL(2006); nature(2006)



Conclusions

- DM from leptophilic $U(1)_{L_\mu - L_\tau}$ model can be an explanation of positron/electron excess in PAMELA, Fermi LAT and HESS CR experiments.
  - the fit to the data is excellent when $M_{\rm DM} = 2000$ GeV
  - the required BF can be obtained from the Sommerfeld enhancement
  - NFW DM profile is disfavored by the neutrino and gamma data
- LHC can cover the large parameter space of $U(1)_{L_\mu - L_\tau}$ model through multi muon/tau events.
- The Higgs searches can be non-standard.