# Cosmic rays and sub-GeV hidden U(1) model

Based on : JCAP 02 (2009) 026

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1. Motivation
2. SUSY and dark sector with a hidden $U(1)_X$
3. Interactions
4. Relic density, $e^+ \& e^-$ excess, direct detection and LHC
5. Conclusion

# New physics signals from cosmic ray?

- Positron excess

  HEAT — S. Barwick et al., ApJ **482**, L191 (1997)

  AMS-01 — M. Aguilar et al., PLB **646**, 145 (2007)

  PAMELA — O. Adriani et al., Nature **458**, 607 (2009)

- $e^+ + e^-$ excess

  PPB-BETS — S. Torii et al., arXiv:0809.0760 [astro-ph]

  ATIC — J. Chang et al., Nature **456**, 362 (2008)

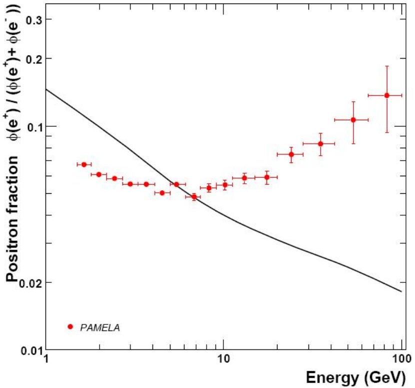
  H.E.S.S. — F. Aharonian et al., PRL **101**, 261104 (2008) & arXiv:0905.0105 [astro-ph]

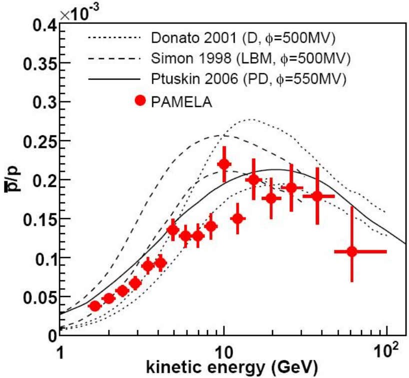
  Fermi/LAT — A. Abdo et al., PRL **102**, 181101 (2009)

- No excess in the antiproton fraction

  PAMELA — O. Adriani et al., PRL **102**, 051101 (2009)

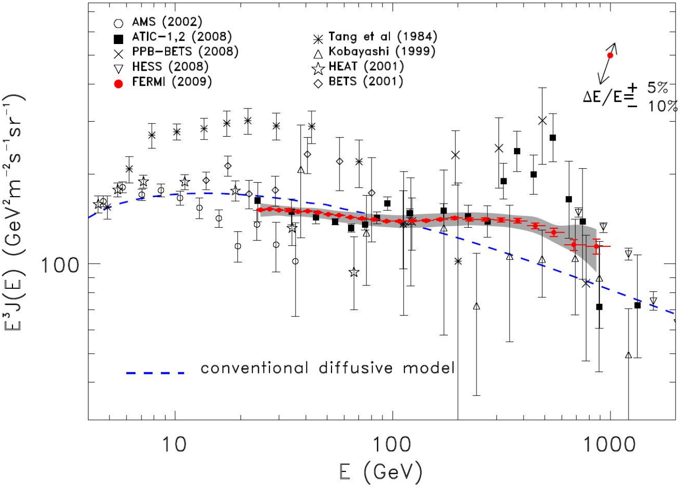
# Positron and anti-proton fractions




[PAMELA] Nature **458**, 607 (2009) & PRL **102**, 051101 (2009)

# $e^+ + e^-$ spectrum




[Fermi/LAT] PRL **102**, 181101 (2009)

# The origin of excessive energetic $e^+$ & $e^-$?

# Candidates of $e^+ \& e^-$ source

- Nearby mature pulsars
  In order to contribute significantly, not too young and old.
  $\Longrightarrow$ B0656+14 (290pc, 110000yr) and Geminga (157pc, 370000yr)

  D. Hooper et al., JCAP **01**, 025 (2009)

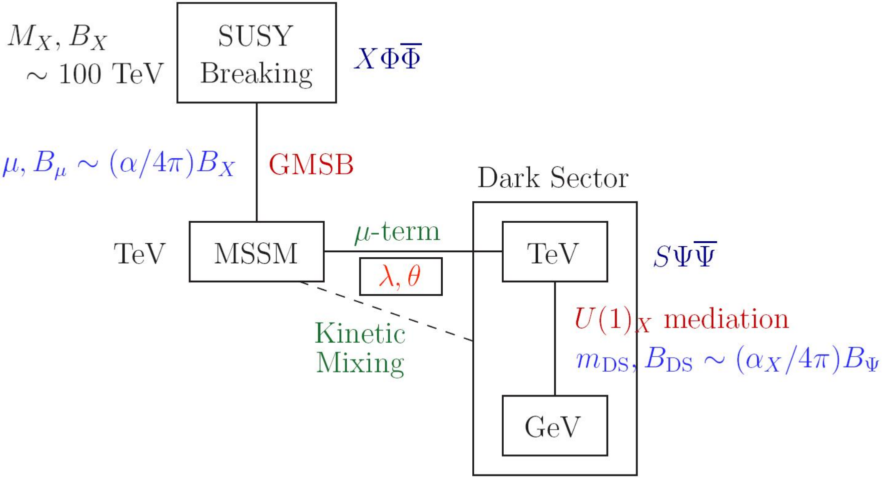
  S. Profumo, arXiv:0812.4457 [astro-ph]
- Supernova remnants — N. J. Shaviv et al., arXiv:0902.0376 [astro-ph.HE]
- Dark matter decay
  Required lifetime $\sim \mathcal{O}(10^{26}\mathrm{s})$
- Dark matter annihilation
  1. Excesses in $e^+ \& e^-$ but not in $\overline{p}$
  2. $\frac{\langle \sigma v \rangle_{\rm Gal}}{\langle \sigma v \rangle_{\rm Relic}} \sim 10^2 \left( \frac{M_{\rm DM}}{500 \rm GeV} \right)^2$

# New DM ideas

- Leptophilic property
  1. DM couplings to only leptons
  2. DM annihilates to sub-GeV mediator. $\Longrightarrow$ Decay to $p\&\bar{p}$ is kinematically forbidden. N. Arkani-Hamed et al., PRD **79**, 015014 (2009)
- Enhanced annihilation in the galaxy
  1. Non-thermal DM
  2. Local clumps in DM distribution: $\Lambda$CDM $N$-body simulations $\Longrightarrow$ BF $< 10$ J. Lavalle et al., Astron. Astrophys. **479**, 427 (2008)
  3. Breit-Wigner mechanism:
     DM annihilation through exchange of a particle in the s-channel with mass close to $2m_{\rm DM}$ M. Ibe et al., PRD **79**, 095009 (2009)
  4. Sommerfeld enhancement:
     Particles with a light attractive force carrier ($m_\phi < \alpha m_\chi$). Slow incident particles feel potential more at $r = 0$. $\Longrightarrow$ Enhanced cross section depending on $1/v$ A. Sommerfeld, Ann. Phys. **11**, 257 (1931)

# Our framework

E.J.Chun & JCP, JCAP **02**, 026 (2009)



# $\mu$-term and dark matter

1. Standard sector

$$W_{\rm standard} = y_u Q U^c H_u + y_d Q D^c H_d + y_e L E^c H_d + \lambda_H S H_u H_d + \frac{\lambda_S}{3} S^3$$

- NMSSM and GMSB

$$\mu = \lambda_H v_S \quad , \quad B = \lambda_S v_S \ , \quad \widetilde{m} = \frac{\alpha}{4\pi}\frac{F_X}{M_X}$$

2. Dark sector

$$W_{\rm dark} = \lambda_\Psi S \Psi_{+1}\Psi_{-1} + \lambda_1 \Phi_0 \Phi_z \Phi_{-z} + \lambda_p \Phi_0 \Phi_{pz} \Phi_{-pz} + \frac{\lambda_0}{3}\Phi_0^3$$

- DM as a TeV messenger in DS: $S\Psi_{+1}\Psi_{-1}$ (cf. $X\Phi\overline{\Phi}$)

$$m_\psi = \lambda_\Psi v_S \ , \quad V_{soft} = B m_\psi \tilde{\psi}_{+1}\tilde{\psi}_{-1} + h.c.$$

- GeV masses for $X$-gaugino & DS scalars

$$m_{\tilde{X}} = \frac{\alpha_X}{4\pi} B \ , \quad m^2_{\phi_x} = 2x^2 m^2_{\tilde{X}}$$

# DM and Higgs

- The lighter scalar $\widetilde{\psi}_1$ as a DM

$$V = m_\psi^2(|\widetilde{\psi}_{+1}|^2 + |\widetilde{\psi}_{-1}|^2) + Bm_\psi(\tilde{\psi}_{+1}\tilde{\psi}_{-1} + h.c.)$$

$$m^2_{\tilde{\psi}_{1,2}} = m_\psi^2 \mp Bm_\psi$$

- DM-DM-$H$ interaction

$$\mathcal{L} = -\frac{1}{2}\lambda_H \lambda_\Psi H_u H_d \widetilde{\psi}_1 \widetilde{\psi}_1^* + h.c.$$

$$\mathcal{L} = \lambda v h^0 \widetilde{\psi}_1 \widetilde{\psi}_1^* , \quad \text{where } \lambda \equiv \frac{1}{2} s_\beta c_\beta \lambda_H \lambda_\Psi$$

# Kinetic mixing

- $U(1)_Y$ and $U(1)_X$ can mix

$$\mathcal{L}_{\rm kinetic} = -\frac{1}{4}(\hat{W}^i_{\mu\nu}\hat{W}^{i\mu\nu} + \hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \hat{X}_{\mu\nu}\hat{X}^{\mu\nu}) - \frac{\sin\theta}{2}B^{\mu\nu}\hat{X}_{\mu\nu}$$

- Physical basis

$$\begin{pmatrix} \hat{W}^3_\mu \\ \hat{B}_\mu \\ \hat{X}_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W & -\frac{c_W s_W m_Z^2}{m_Z^2 - m_X^2}\,\theta \\ -s_W & c_W & -\frac{c_W^2 m_Z^2 - m_X^2}{m_Z^2 - m_X^2}\,\theta \\ \frac{s_W m_Z^2}{m_Z^2 - m_X^2}\,\theta & 0 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \\ X_\mu \end{pmatrix} + \mathcal{O}(\theta^2)$$

# Gauge interactions

- Gauge interactions

$$\mathcal{L} = ig_X(X_\mu + s_W \theta Z_\mu)(\widetilde{\psi}_1^* \partial^\mu \widetilde{\psi}_1 - \partial^\mu \widetilde{\psi}_1^* \widetilde{\psi}_1) + g_X^2 X^\mu X_\mu \widetilde{\psi}_1^* \widetilde{\psi}_1$$

$$\mathcal{L} = g' Q_f c_W^2 \theta X_\mu \overline{f} \gamma^\mu f$$

- Assume the dominance of DM-$X$ over DM-$H$ coupling

$$\lambda_H \lambda_\Psi < g_X^2$$

# Relic density

- Annihilation through $\widetilde{\psi}_1 \widetilde{\psi}_1^* \to XX$

$$\langle \sigma v \rangle_{XX} \simeq \frac{4\pi\alpha_X^2}{m_{\widetilde{\psi}_1}^2}$$

- Relic density of $\widetilde{\psi}_1$

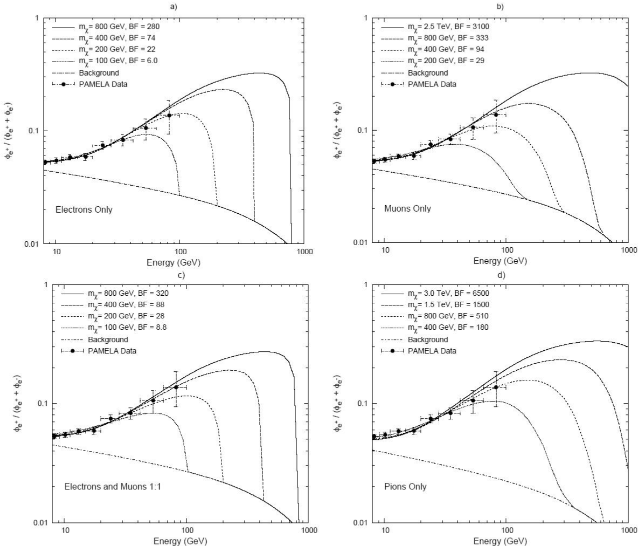
$$\Omega_{\widetilde{\psi}_1} h^2 \simeq \frac{1.07 \times 10^9 \ \mathrm{GeV}^{-1}}{M_{pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{\langle \sigma v \rangle_{XX}}$$

$$\approx \frac{2.17 \times 10^{-10} \ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle_{XX}}$$

- Constraint from relic density

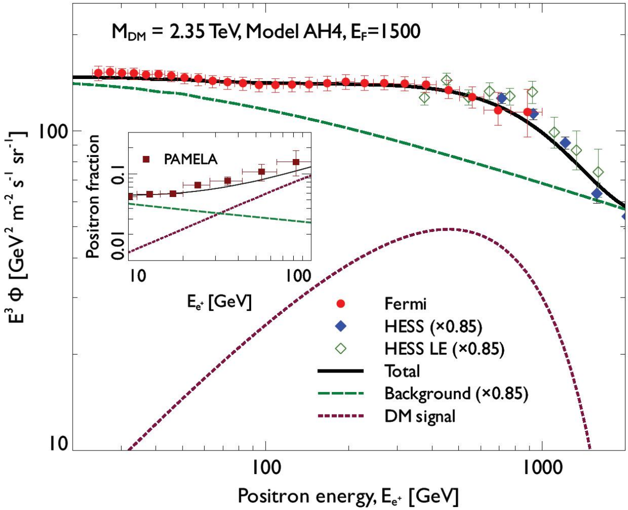
$\Omega_{\mathrm{DM}} h^2 \simeq 0.1143 \implies \alpha_X \simeq 1.58\,\alpha\,(m_{\widetilde{\psi}_1}/\mathrm{TeV})$

# Fit to the PAMELA data




I. Cholis et al., arXiv:0810.5344 [astro-ph]

# Fit to the Fermi and HESS data




$m_X = 0.25\text{GeV}$ & $\mu^+\mu^-$ : 100%

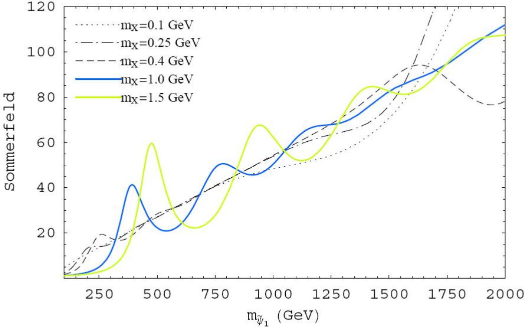
L. Bergstrom et al., arXiv:0905.0333 [astro-ph.HE]

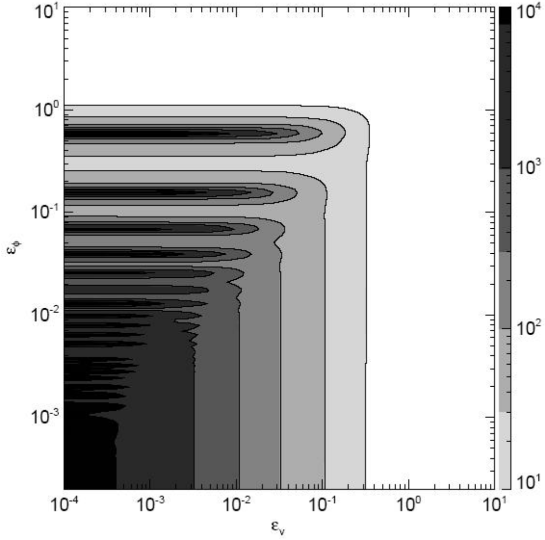
# Sommerfeld factor

$$-\frac{1}{m_{\tilde{\psi}_1}}\frac{d^2\tilde{\psi}_1(r)}{dr^2}-\frac{\alpha_X}{r}e^{-m_X r}\tilde{\psi}_1(r)=m_{\tilde{\psi}_1}\beta^2\tilde{\psi}_1(r)$$

$$S=|\tilde{\psi}_1(\infty)/\tilde{\psi}_1(0)|^2 \qquad \tilde{\psi}_1'(\infty)/\tilde{\psi}_1(\infty)=im_{\tilde{\psi}_1}\beta$$

1. $S\sim 50$ for $m_{\tilde{\psi}_1}\approx 700$ GeV
2. Combined effect with BF $\lesssim 10$ from clumpy DM distribution

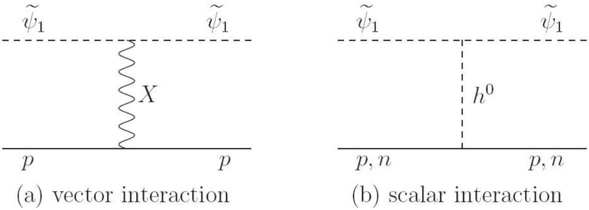


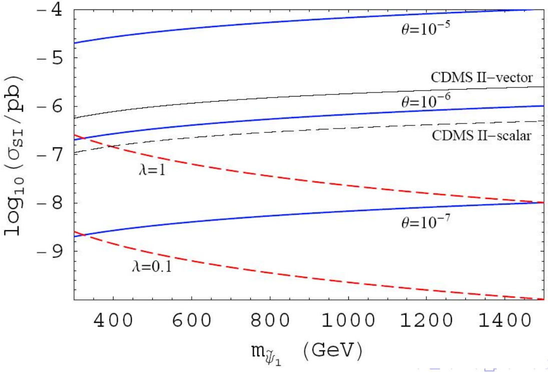



$\epsilon_v = v/\alpha$ & $\epsilon_v = m_\phi/\alpha m_\chi$

N. Arkani-Hamed et al., PRD **79**, 015014 (2009)

# Direct detection



# LHC signatures

- OLSP decay

$$\mathcal{L} = \frac{1}{2}(C_1 + C_2)\overline{\widetilde{X}}\sigma^{\mu\nu}\widetilde{S}X_{\mu\nu} \qquad C_i = \frac{m_\psi}{16\pi^2 m_i^2}\frac{\lambda_\Psi g_X^2}{\sqrt{2}}J(x_i)$$

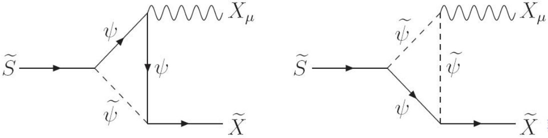
$$\Gamma(\widetilde{S} \to X\widetilde{X}) = \frac{1}{8\pi}\, m_{\widetilde{S}}^3\, (C_1 + C_2)^2 \approx \frac{\lambda_\Psi^2 \alpha_X^2}{2304\pi^3}\,\frac{m_{\widetilde{S}}^3}{m_\psi^2}$$

- Two decay gaps with $l\bar{l}$ and $\gamma$

$$l_{\chi_1^0 \to X\widetilde{X}} \approx \left(\frac{0.1}{c_{\widetilde{S}}}\right)^2 \left(\frac{0.1}{\lambda_\Psi^2}\right) \left(\frac{200\ \mathrm{GeV}}{m_{\widetilde{\chi}_1^0}}\right)^3 \times 10^{-3}\ \mathrm{cm}$$

$$l_{X \to f\bar{f}} \approx \left(\frac{1}{Q_f}\right)^2 \left(\frac{10^{-6}}{\theta}\right)^2 \left(\frac{0.4\ \mathrm{GeV}}{m_X}\right) \times 25\ \mathrm{cm}$$

$$l_{\chi_1^0 \to \gamma\psi_{3/2}} \approx \left(\frac{\sqrt{F}}{10^5\ \mathrm{GeV}}\right)^4 \left(\frac{200\ \mathrm{GeV}}{m_{\chi_1^0}}\right)^5 \times 3 \times 10^{-4}\ \mathrm{cm}$$



# Conclusion

- Leptonic excesses in cosmic rays may reveal the identity of DM.
  $\longrightarrow$ Require brand new ideas?
- Sub-GeV $U(1)_X$ dark sector can be realized in GMSB scheme.
- This model can give good fits for $e^+$ fraction and $e^+ + e^-$ spectrum.
- Required boost factor can be obtained from combination of Sommerfeld effect and DM clumps.
- LHC may have a chance to confirm this model through two distinctive decay signatures.

# Thank You!