Decaying Dark Matter in SUSY SU(5) models

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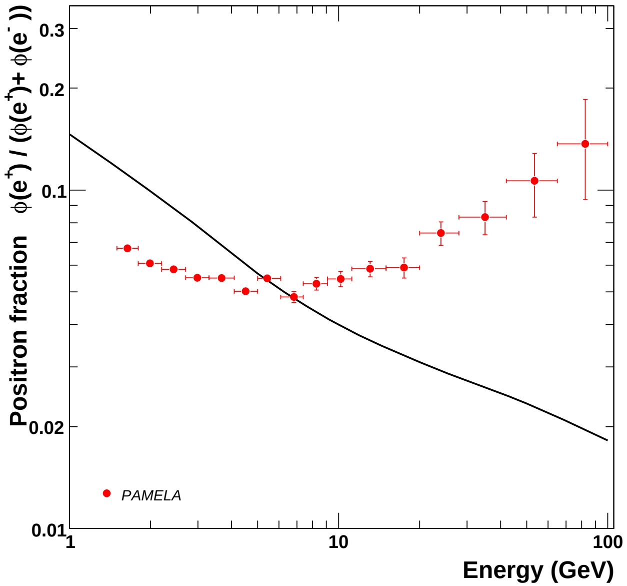
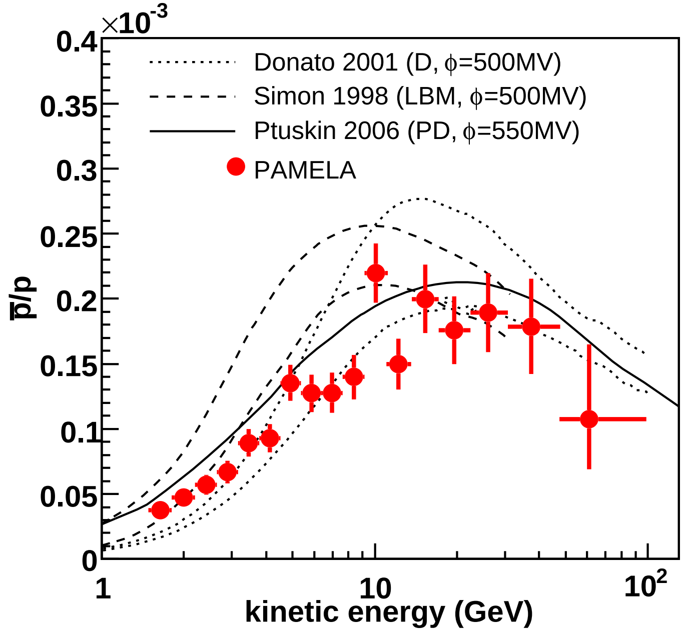
Outline

- Motivation
- SUSY SU(5) effective operators
- Phenomenologies
- Summary

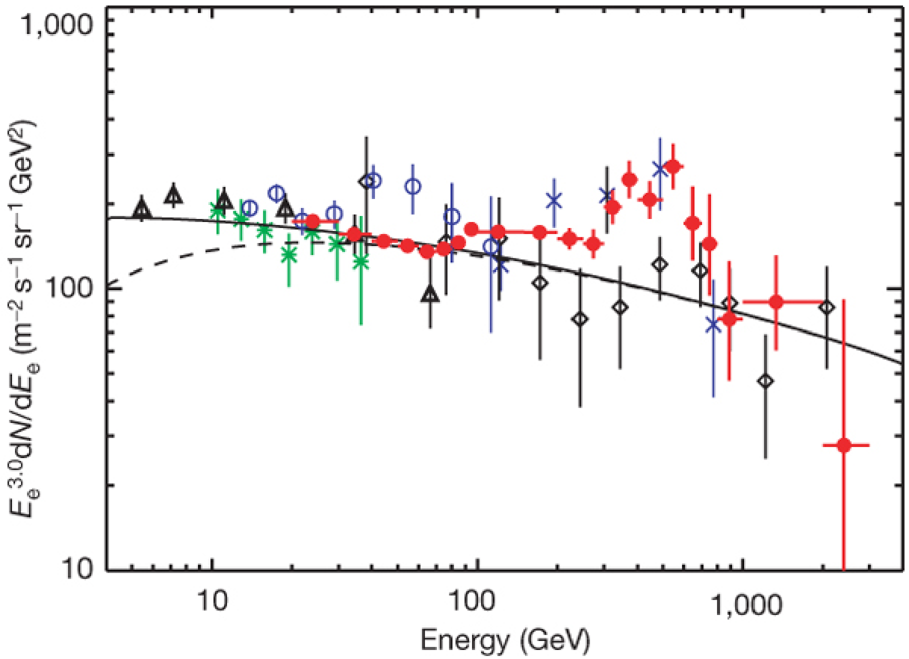
Motivation-1





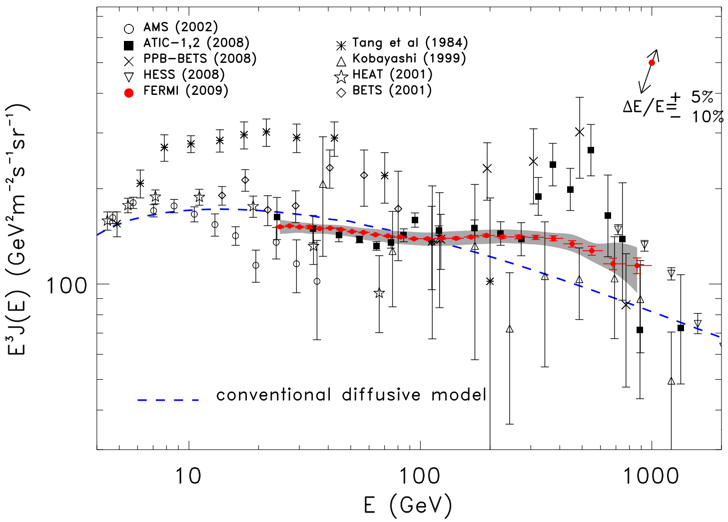
- **Pamela observation on** $\frac{e^+}{e^- + e^+}$ **and** $\bar{p}/p$

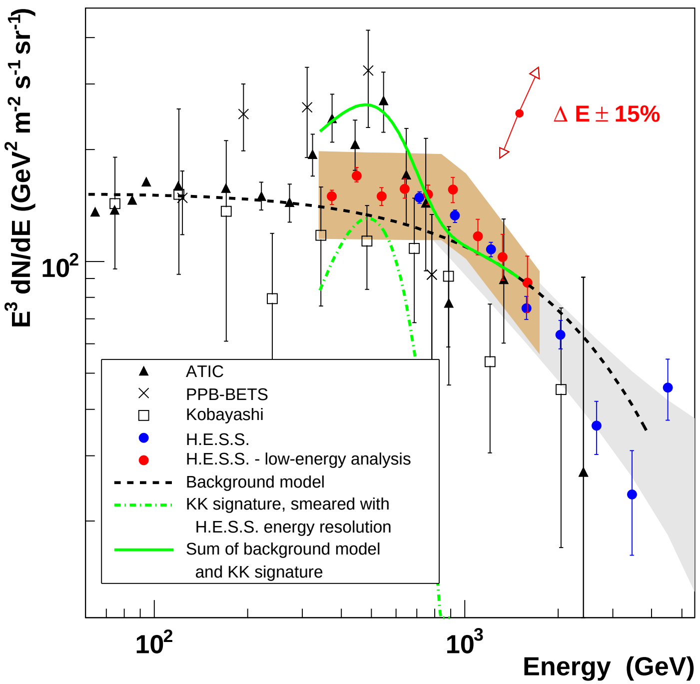
Motivation-2



- **Attic measurement on total $e^+ + e^-$ flux**

Motivation-3





- **Fermi-LAT and HESS measurements on total $e^+ + e^-$ flux**

Motivation-4

These excesses could be due to

- Unidentified astrophysical sources, e.g. nearby pulsars
- More exciting possibility: dark matter annihilation/decay

To determine the origin

- e^- and e^+ spectra with higher precision don't help much
- Gamma ray signals: the energy spectrum and its angular distribution
- Neutrino telescope: SuperK, IceCube DeepCore,...
- LHC, CDMS, Xenon,...

Motivation-5

Dark matter (DM) Interpretation

- $m_{DM} \sim 1$ TeV or even heavier (Fermi-LAT and HESS)
- Neutralino LSP unlikely (Pamela $\bar{p}/p$)

For DM Annihilation

- Non-thermal production of DM
- A large boost factor $\sim 10^2 - 10^3$ required
  - Astrophysical boost unlikely to be large enough
  - Nonperturbative Sommerfeld or Breit-Wigner enhancement
  - stringent constraints from gamma ray measurements

For DM Decay

Motivation-6

For DM decays via GUT-suppressed dim-6 operators

$$\tau \sim 8\pi \frac{M_{GUT}^4}{m_{DM}^5} = 3 \times 10^{27} s \left(\frac{\text{TeV}}{m_{DM}}\right)^5 \left(\frac{M_{GUT}}{2 \times 10^{16}\text{GeV}}\right)^4$$

This lifetime is being probed by Pamela, Fermi, ...

- The experiment acceptances of

$$\sim (1\text{m}^2)(1\text{yr})(1\text{sr}) \simeq 3 \times 10^{11}\text{cm}^2\text{s sr}$$

- The incident particles from decaying DM

$$\sim \int^{10\text{kpc}} \frac{d^3r}{r^2} \frac{0.3\text{GeV cm}^{-3}}{m_{DM}} 10^{-27}\text{s}^{-1} \simeq 10^{-9}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

- $\mathcal{O}(100)$ events per year

References: Phys. Rev. D79 (2009) 105022;
Phys. Rev. D80 (2009) 055011

SUSY SU(5) models

DM candidate in Minimal SUSY SU(5): LSP

- R-parity conservation: absolute stable
- R-parity violation: typically $m_{LSP} \sim \mathcal{O}$(100 GeV), too light

Minimal extension: SU(5) singlet S as DM candidate

- Gauge coupling unification intact
- if R-parity conserved, LSP could be (minor) part of DM
- Z_2 symmetry: S is odd, others are even,
  to suppress dim-5 operators

Effective operators

All possible dim-6 operators

$$\frac{S^{+}S\overline{5}^{+}\overline{5}}{M_{GUT}^{2}}, \quad \frac{S^{+}STr(10^{+}10)}{M_{GUT}^{2}}, \quad \frac{S^{+}SW_{\alpha}W^{\alpha}}{M_{GUT}^{2}}, \quad \frac{S^{+}SH_{u(d)}^{+}H_{u(d)}}{M_{GUT}^{2}}$$

- Superfields: $S(y) = \tilde{s}(y) + \sqrt{2}\theta s(y) + \theta^{2}F_{s}(y)$
- W_{α}: SUSY field strengths of SM gauge fields
- $H_{u,d}$: SUSY chiral fields for Higgs

$$\overline{5}^{T} = (d^{c}, d^{c}, d^{c}, e, -\nu)_{L}$$

$$10 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u^{c} & -u^{c} & u & d \\ -u^{c} & 0 & u^{c} & u & d \\ u^{c} & -u^{c} & 0 & u & d \\ -u & -u & -u & 0 & e^{c} \\ -d & -d & -d & -e^{c} & 0 \end{pmatrix}_{L}$$

Effective operators-2

$S^+SH^+_{u(d)}H_{u(d)}$, $S^+SW_\alpha W^\alpha$ **should be suppressed:**

- Significant number of quarks in final states, constrained by Pamela $\bar{p}/p$ measurement
- mono-energetic gamma ray lines

For $S^+S\overline{5}^+\overline{5}$, $S^+STr(10^+10)$

- Assuming the vev $\langle\tilde{s}\rangle \sim 1\text{TeV}$, Z_2 symmetry is spontaneously broken and both components $(\tilde{s}, s)$ in S can decay

Operators in component fields

$$\sum_{\Phi} \frac{1}{M_{GUT}^2} \left(i < \widetilde{s} > \widetilde{s}^* (\partial_\mu \psi \sigma^\mu \bar{\psi}) + i < \widetilde{s} > \widetilde{\psi}^* (\partial_\mu \psi \sigma^\mu \bar{s}) - < \widetilde{s} > \widetilde{s}^* \widetilde{\psi}^* \Box \widetilde{\psi} \right) + h.c. + ...$$

... denotes the terms which can be dropped

- Total divergence terms
- Operators from F terms
  - suppressed by the leptonic Yukawa coupling constant
  - leading to many body decays which are further suppressed by phase spaces

Operators in component fields-2

$\tilde{s}$ decays dominantly via $\tilde{s}^* \tilde{\psi}^* \Box \tilde{\psi}$

- For $\tilde{s}^* (\partial_\mu \psi \sigma^\mu \bar{\psi})$, $\Gamma \propto m_\psi^2$
  - dominant decay channel is $\tilde{s} \to t\bar{t}$
  - suppressed by m_t^2/m_s^2
- For $\tilde{\psi}^* (\partial_\mu \psi \sigma^\mu \bar{s})$, $\Gamma \propto m_\psi^2$
  - dominant decay channel is $s \to \tau\tilde{\tau}$
  - suppressed by m_τ^2/m_s^2

$\tilde{s}$ decays dominantly into a slepton pair if

- the squark masses are heavier than the DM mass $m_{\tilde{s}}$
- the slepton masses to be around several hundred GeV

Operators in component fields-3

the operator can be rewritten as

$$\sum_{\tilde{l}} \frac{-1}{M_{GUT}^2} < \tilde{s} > \tilde{s}^* (\widetilde{l_L}^* \Box \widetilde{l_L} + \widetilde{l_R} \Box \widetilde{l_R}^*), \quad (\tilde{l} = \tilde{e},\ \tilde{\mu},\ \tilde{\tau})$$

with the decay width

$$\Gamma_{\tilde{l}} = \frac{\sqrt{M_s^2 - 4M_{\tilde{l}}^2} < \tilde{s} >^2 M_{\tilde{l}}^4}{16\pi M_s^2 M_{GUT}^4}$$

- $\tau_{\tilde{s}} \sim 10^{26}$s with $m_s \sim < \tilde{s} > \sim 1$ TeV and $M_{\tilde{l}} \sim$ several hundred GeV
- The decay width $\Gamma_{\tilde{l}} \propto M_{\tilde{l}}^4$: slightly different masses between $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$ may lead to quite different branching ratios.

the DM decay

With R-parity conservation, $e^{\pm}$ can be produced from $\tilde{s} \to \tilde{l}^{+}\tilde{l}^{-}$

- selectron chain: $\tilde{s} \to \tilde{e} \to e$
- smuon chain: $\tilde{s} \to \tilde{\mu} \to \mu \to e$
- stau chain: $\tilde{s} \to \tilde{\tau} \to \tau \to e$ (using PYTHIA)

In total, the $e^{\pm}$ fluxes due to DM decays at the source are

$$Q_e^{DM}(\vec{r}, E) = \sum_{\tilde{l}} \frac{\Gamma_{\tilde{l}}^{DM} \rho^{DM}(\vec{r})}{m_{DM}} \frac{dN_{\tilde{l}\to e}^{DM}}{dE}$$

The NFW halo model

$$\rho^{DM}(r) = \frac{\rho_{\odot} r_{\odot}}{r} \left(\frac{1 + r_{\odot}/r_s}{1 + r/r_s}\right)^2$$

with the DM density at earth $\rho_{\odot} = 0.3$ GeV/cm^3 and $r_s = 20$ kpc

$e^{\pm}$ fluxes at the Earth

Semi-analytical description on $e^{\pm}$ propagation

$$\Phi_e^{DM}(r_\odot, E) = \frac{c}{4\pi B(E)} \sum_{\tilde{l}} \frac{\rho_\odot \Gamma_{\tilde{l}}^{DM}}{m_{DM}} \int_E^{m_{DM}/2} dE' I(\lambda_D(E, E')) \frac{dN_{\tilde{l}\to e}^{DM}}{dE'}$$

- Effective energy loss coefficient $B(E) = E^2/(\text{GeV} \cdot \tau_E)$
- $\tau_E = 10^{16} s$: The energy loss of $e^{\pm}$ due to ICS on the ISRF and synchrotron radiation
- $\lambda_D(E, E')$: The diffusion length from energy E' to E

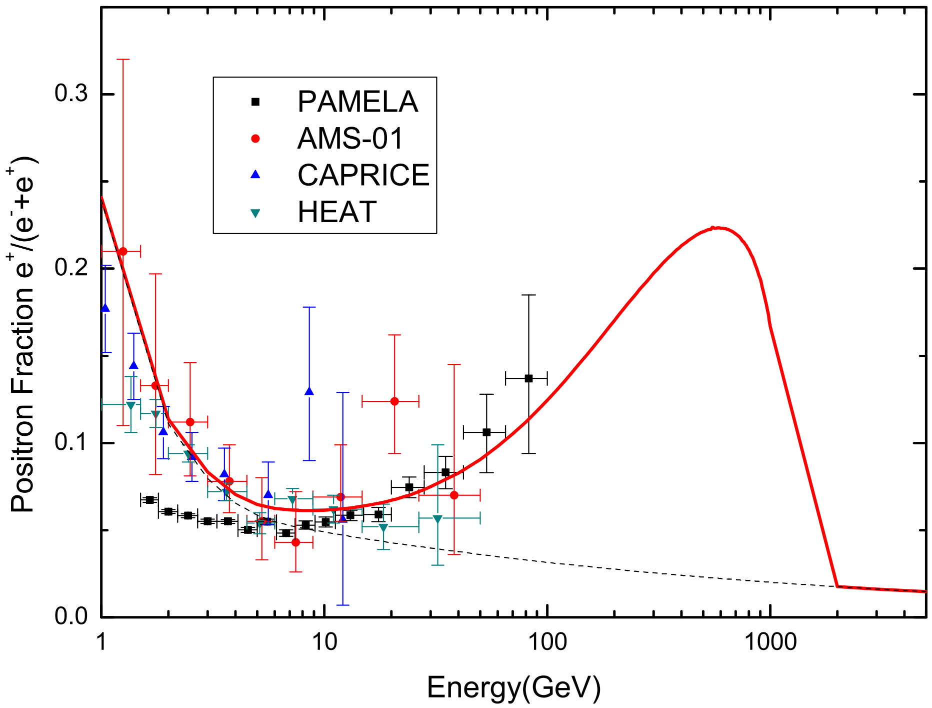
$$\lambda_D^2 = 4K_0\tau_E \left(\frac{(E/\text{GeV})^{\delta-1} - (E'/\text{GeV})^{\delta-1}}{1-\delta} \right)$$

- $I(\lambda_D)$ contains the whole information of the NFW halo model and MED propagation model (a_i, b_i, c_i are numerically known)
  $I(\lambda_D) = a_0 + a_1 \tanh\left(\frac{b_1 - l}{c_1}\right) \left[a_2 \exp\left(-\frac{(l-b_2)^2}{c_2} \right) + a_3 \right]$, $l = \log_{10} \frac{\lambda_D}{\text{kpc}}$

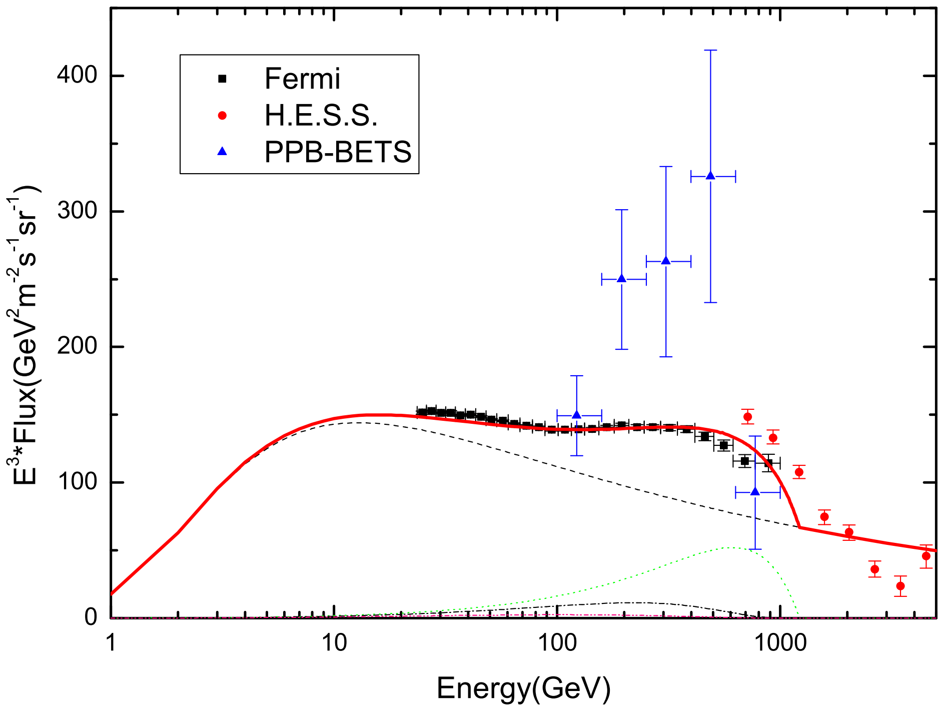
Fit to Pamela positron data

Parameter set

$M^{DM} = 6.5$ TeV, $M_{GUT} = 10^{16}$ GeV, $M_{\tilde{e}} = 380$ GeV, $M_{\tilde{\mu}} = 370$ GeV, $M_{\tilde{\tau}} = 330$ GeV, $M_{LSP} = 300$ GeV



Fermi and HESS $e^{\pm}$ spectra

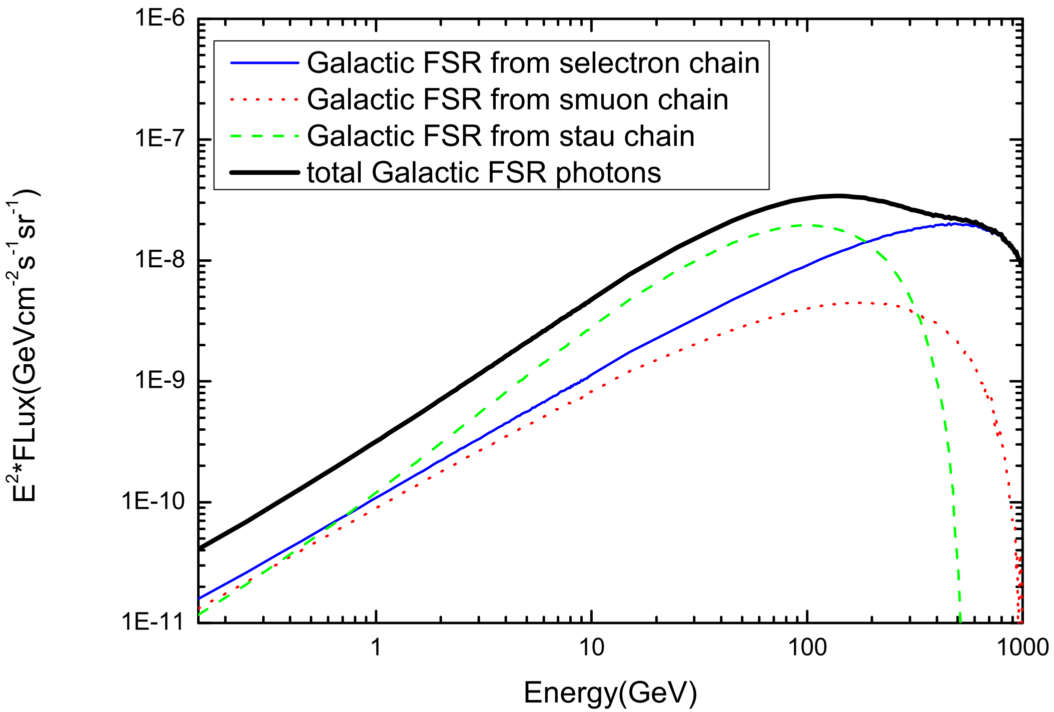


- $\tilde{s} \to \tilde{e}^+\tilde{e}^- \to e^+e^-$ smooth the $e^+ + e^-$ spectrum and naturally allowing for a good fit to the Fermi LAT measurement

Diffuse gamma-rays from the $e^{\pm}$ excesses

- Final state radiation (FSR): model dependent
  - The bremsstrahlung of $e^{\pm}$ fluxes
  - For the stau chain: $\tau \to \pi^0 \to \gamma\gamma$ dominant above 100 GeV
- Inverse Compton scattering (ICS) on ISRF: somewhat model independent
  - ISRF contains CMB, star light and infrared light
  - Typical photon energy around 10 GeV
- Synchrotron radiation in Galactic magnetic fields
  - Very soft (around 10^{-6} eV), will be neglected

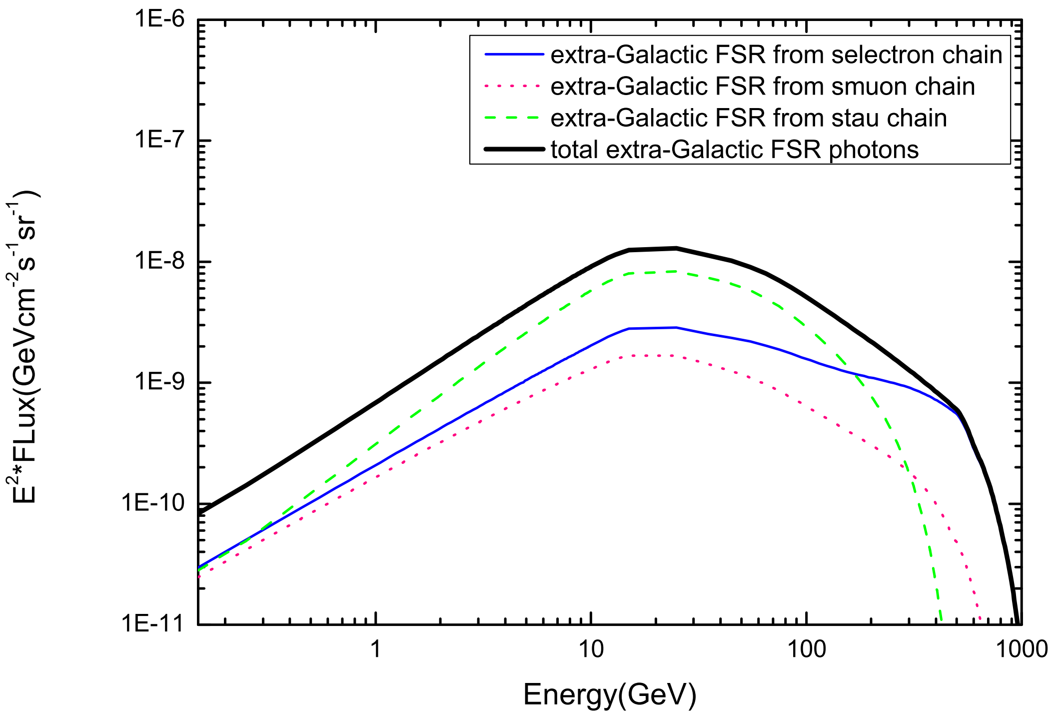
Galactic FSR spectra



Galactic FSR spectra in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$

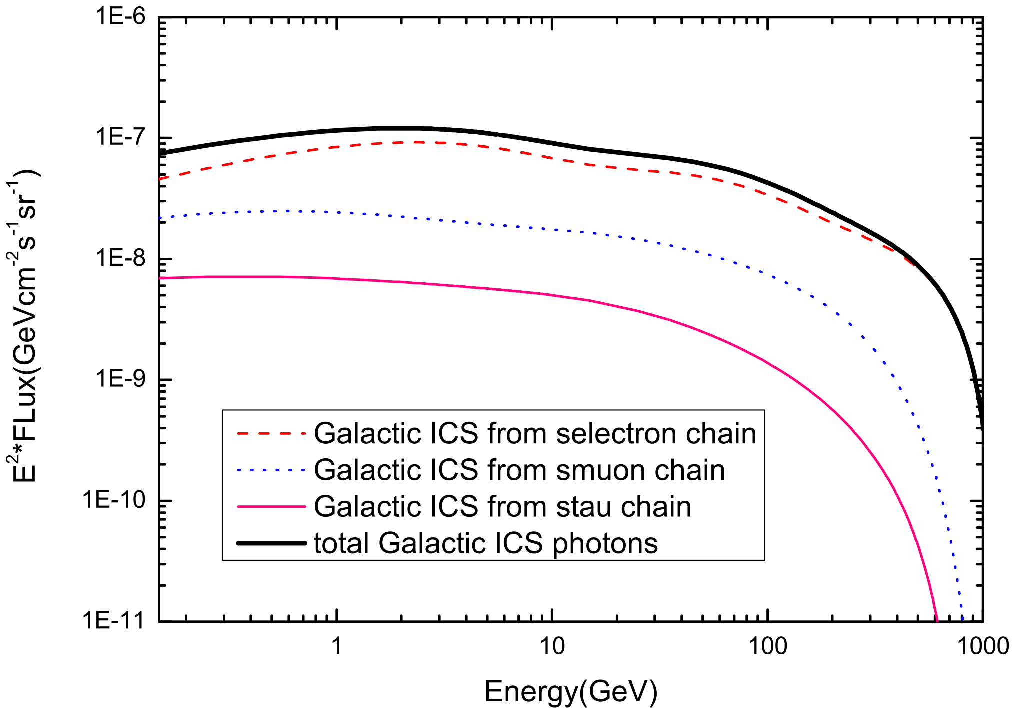
- The stau chain dominant due to $\tau \to \pi^0 \to \gamma\gamma$
- The spectra peak around several hundred GeV

Extra-galactic FSR spectra



Extra-galactic FSR spectra in the region $0^\circ \leq l \leq 360^\circ,\ 10^\circ \leq |b| \leq 20^\circ$

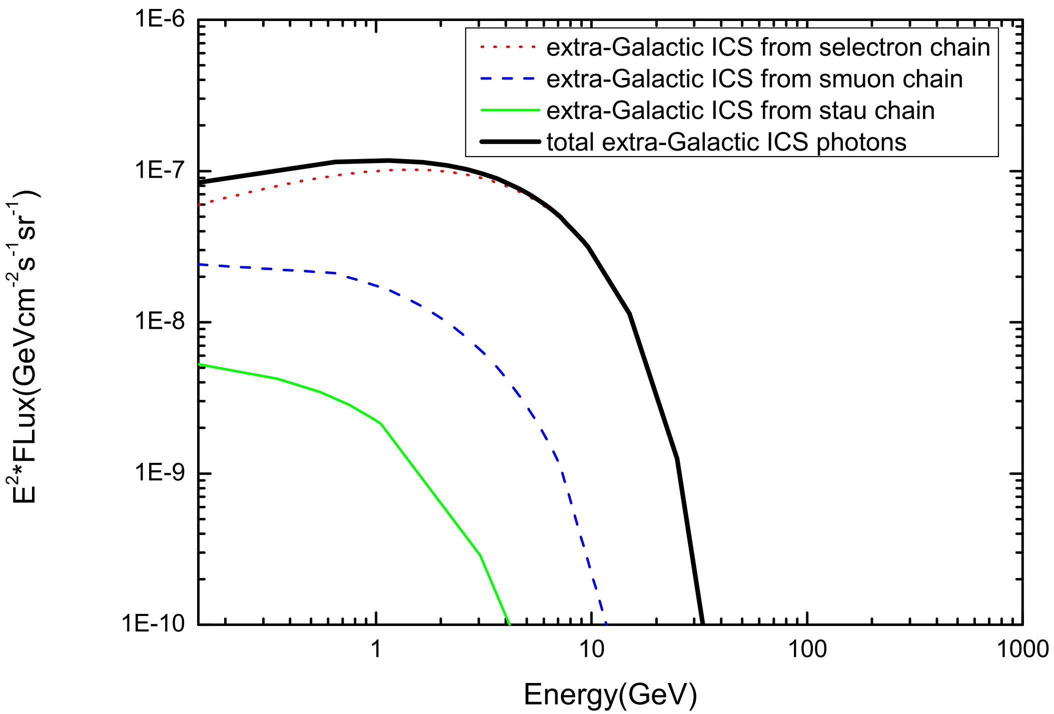
Galactic ICS spectra



Galactic ICS spectra in the region $0^\circ \leq l \leq 360^\circ,\ 10^\circ \leq |b| \leq 20^\circ$

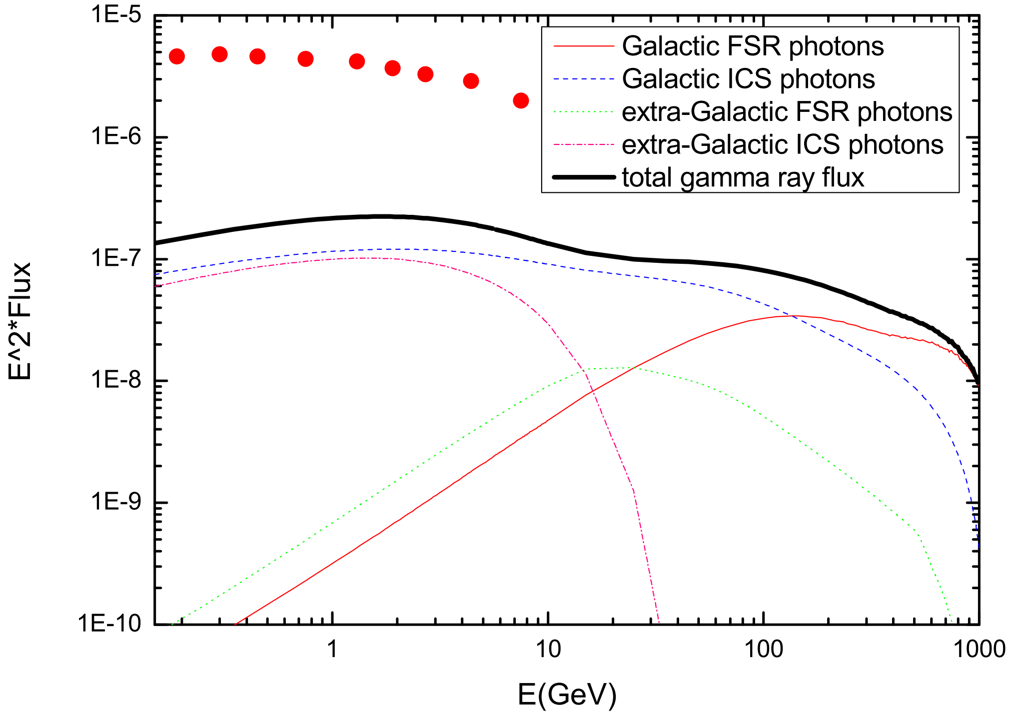
- The selectron chain dominant due to harder $e^{\pm'}$s produced

Extra-galactic ICS spectra



Extra-galactic ICS spectra in the region $0^\circ \leq l \leq 360^\circ,\ 10^\circ \leq |b| \leq 20^\circ$

Total diffuse gamma ray



Total diffuse gamma ray spectra: $0^\circ \le l \le 360^\circ,\ 10^\circ \le |b| \le 20^\circ$

- Consistent with preliminary Fermi LAT data below 10 GeV
- Could be tested soon above 100 GeV

Summary

- A SU(5) singlet S as dominant DM candidate
- S decays with lifetime around 10^{26}s
  - via GUT suppressed dim-6 effective operators
  - Spontaneously broken Z_2 symmetry by a TeV scale vev $\langle\tilde{s}\rangle$
- $\tilde{s}$ decays dominantly into a pair of sleptons as
  - $\tilde{s} \to q\bar{q}$, $l\bar{l}$: suppressed by m_q^2/m_s^2 or m_l^2/m_s^2
  - $s \to q\tilde{q}$, $l\tilde{l}$: suppressed by m_q^2/m_s^2 or m_l^2/m_s^2
  - Assuming the $\tilde{q}$ masses to be heavier than the DM mass
- $\tilde{s} \to \tilde{e}^+\tilde{e}^- \to e^+e^-$ smooth the $e^+ + e^-$ spectrum and naturally allowing for a good fit to the Fermi LAT measurement
- A simultaneously fit to Pamela can also be obtained
- The diffuse gamma ray spectrum is compared with the preliminary Fermi LAT data in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$
- Photon energies above 100 GeV may be tested soon by Fermi LAT