Cosmic rays from decaying of multi-component dark matter

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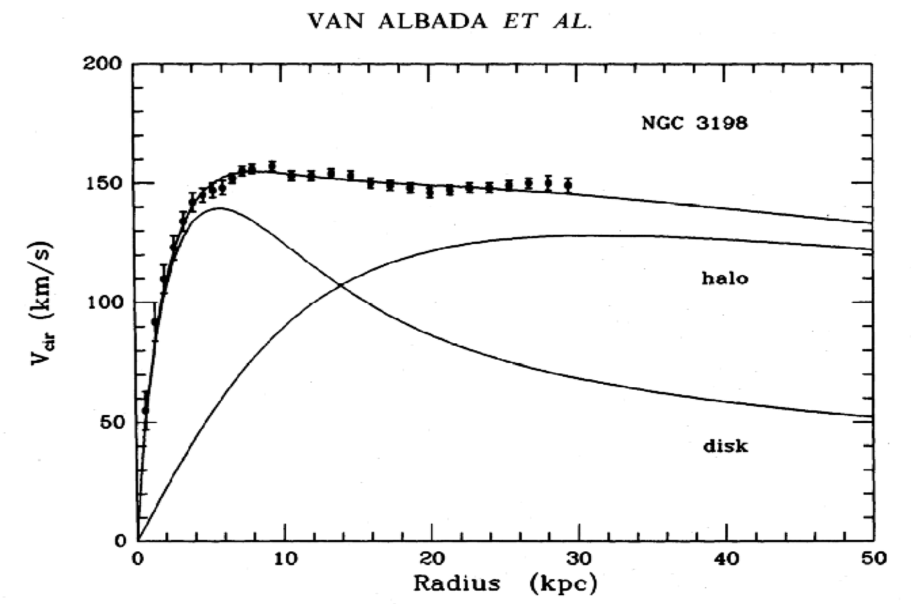
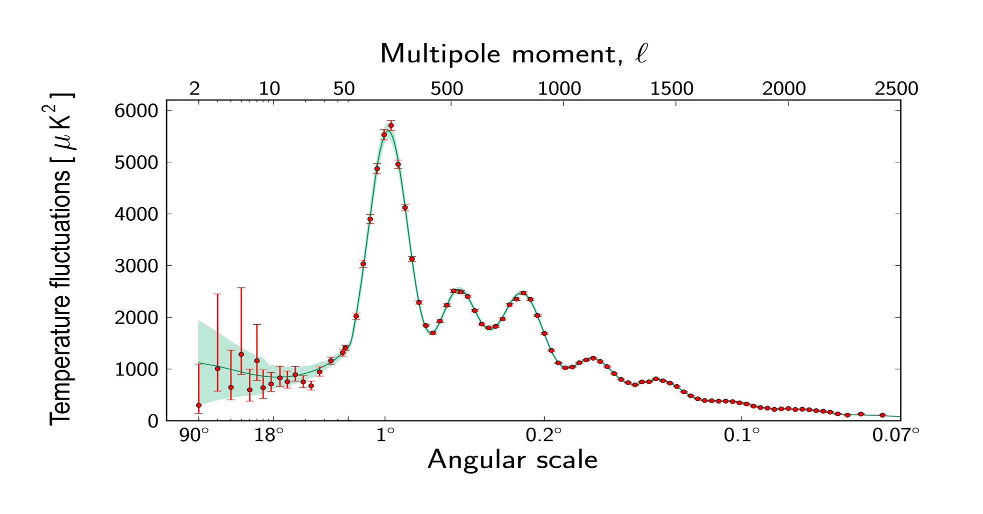
Outline

- The multi-component dark matter model
- Cosmic $e^{\pm}$ fluxes from multi-component dark matter decaying
- Conclusion

A multiple dark matter model

Dark matter evidence





The universe is consists of 4.9% ordinary matter, 26.8% dark matter (DM), and 68.3% dark energy Planck (2013)

Dark matter can be referred to a single type of stable particles thermalized with standard model (SM) particles in early universe.

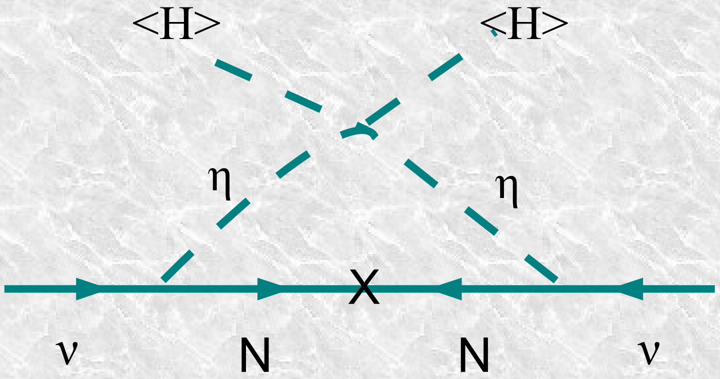
The weak interacting massive particle (WIMP) is a good dark matter candidate to satisfy the relic abundance and in the range of interest for direct search

Basically, the stability of DM is necessary by the indirect search, unless the decay rate is extremely small (life time > 10^{26}s)

Single or multiple DM? related to the number of symmetries

A Majorana heavy neutrino Model

The radiative neutrino model by E. Ma can have both small neutrino mass and stable dark matter



new interaction $\overline{L_{Ll}} Y_{li} N_i \eta,$

Z_2 symmetry is imposed

If the active neutrino masses are generated radiatively, then at least two *N* 's are necessary.

We introduce two additional gauge singlet fermions N_H and N_L to the model as the double-component DM. The two-body decaying processes can be

$$\overline{L_L}\left(Y_h N_h + Y_l N_l\right)\eta, \quad \eta \text{ is a SU(2) doublet scalar}$$

We can further consider the models with non-stable $N_{h,l}$

In general, to make DM $N_{h,l}$ exist longer than 10^{26}s, the coupling constant should be $Y_{h,l}<10^{-25}$

To make the size of Yukawa coupling more natural, impose another doublet ζ. The very heavy η with small mixing with light doublet ζ can suppress the decay rate

$, \mu^2 \eta^+ \cdot \zeta$

Also has the three body decay channel $N_h \to N_l + l' + l''$

If one hope the two-body decay channel to be dominated

Take $M_N > M_\zeta \approx$ TeV, $M_\eta \approx 10^{10}$ TeV, $\mu \approx 1$ GeV, $Y_{h,l} \approx 10^{-6}$

Take $M_\zeta = 300$ GeV, then $N_h = 3030$ GeV, $N_l = 416$ GeV $\Rightarrow \tau_N > 10^{26}$ s

	N_{R1}	N_{R2}	η	ζ
Z_2	$-$	$-$	$-$	$+$
Z_2'	$+$	$+$	$+$	$-$

The Z_2 symmetries are required to make the DM quasi stable.

The soft-breaking term breaks both Z_2 and Z_2', but their combination is still conserved.

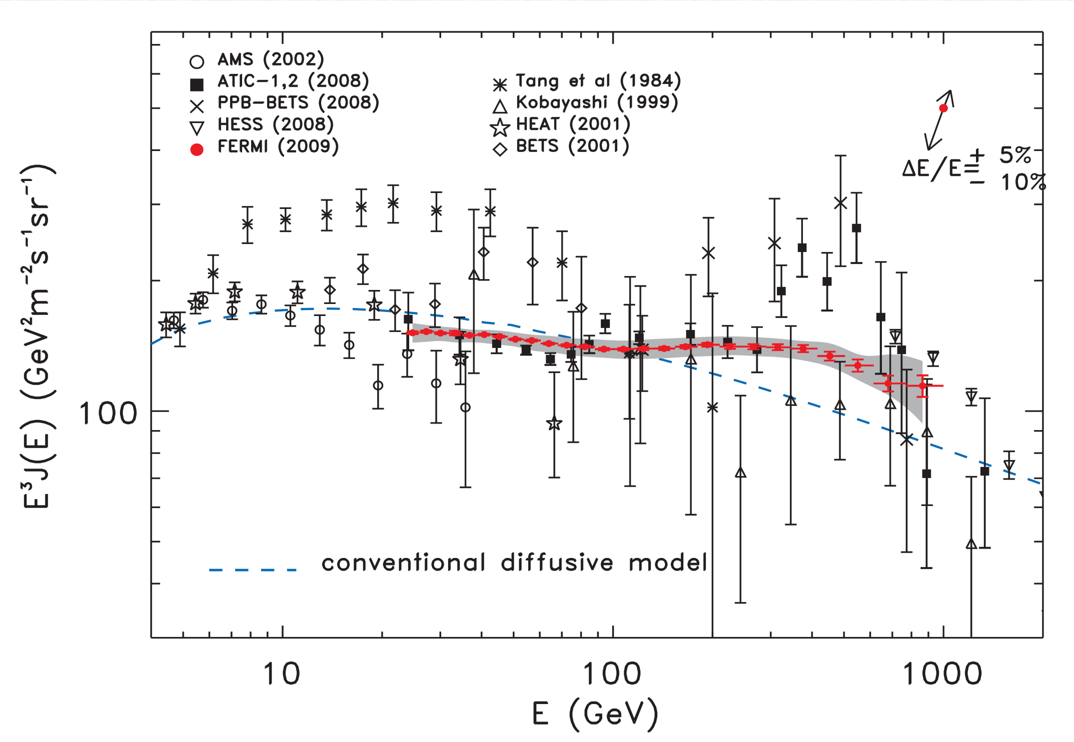
$$L = -\bar{L}_{Li}(Y_{1i}N_{R1} + Y_{2i}N_{R2})\eta - \frac{M_1}{2}\overline{(N_{R1})^c}N_{R1} - \frac{M_2}{2}\overline{(N_{R2})^c}N_{R2} - \mu^2\zeta^\dagger\eta - V$$

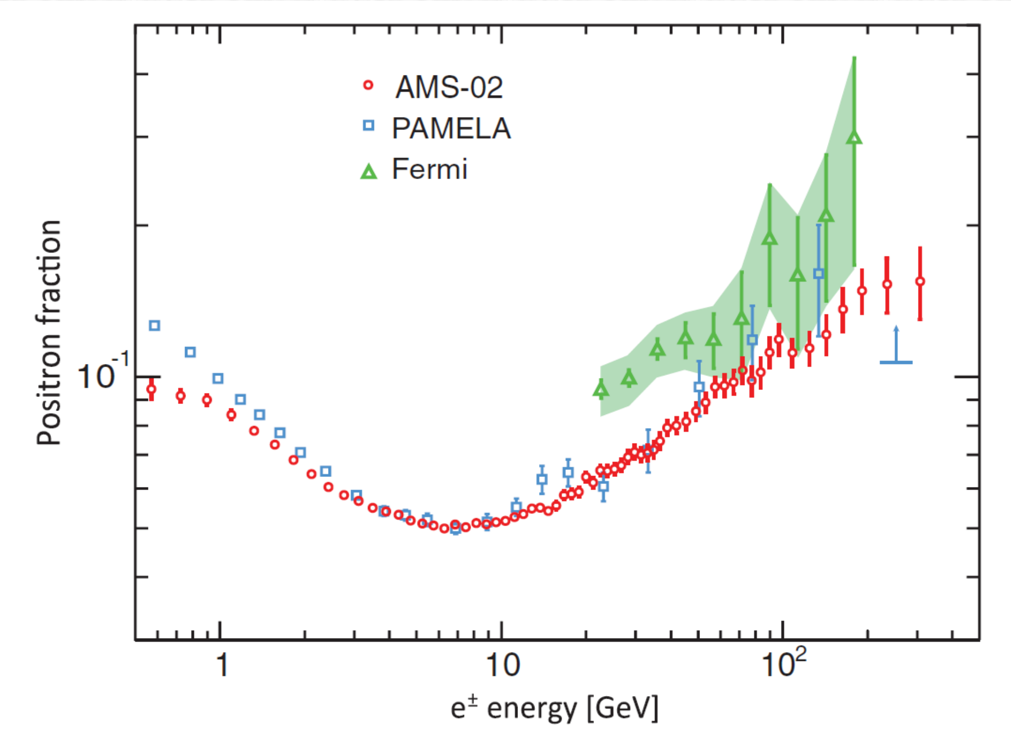
We will study the DM indirect signal in this model

Geng, Huang, and LHT (2013)

e± fluxes from multi-component DM decay

Fermi-LAT and AMS-02 observation





The propagation of $e^{\pm}$ in the Galaxy

$\Phi_e = \frac{c}{4\pi} f(E)$, f: energy density of CR in differential energy range

Diffusion equation describe the time evolution, spatial diffusion, and energy loss of CR propagating in the Galaxy.

$$\frac{\partial f}{\partial t} = \vec{\nabla} \cdot [K(E,\vec{r}) \vec{\nabla} f] + \frac{\partial}{\partial E}[b(E,\vec{r}) f] + Q(E,\vec{r}) = 0$$

Source of $e^{\pm}$

$K = D_0 \left(\frac{E}{E_0}\right)^{\delta}$ is the diffusion coefficient

If the flux is steady and assuming the boundary for our Galaxy is set to zero, then the electron/positron flux can be expressed by

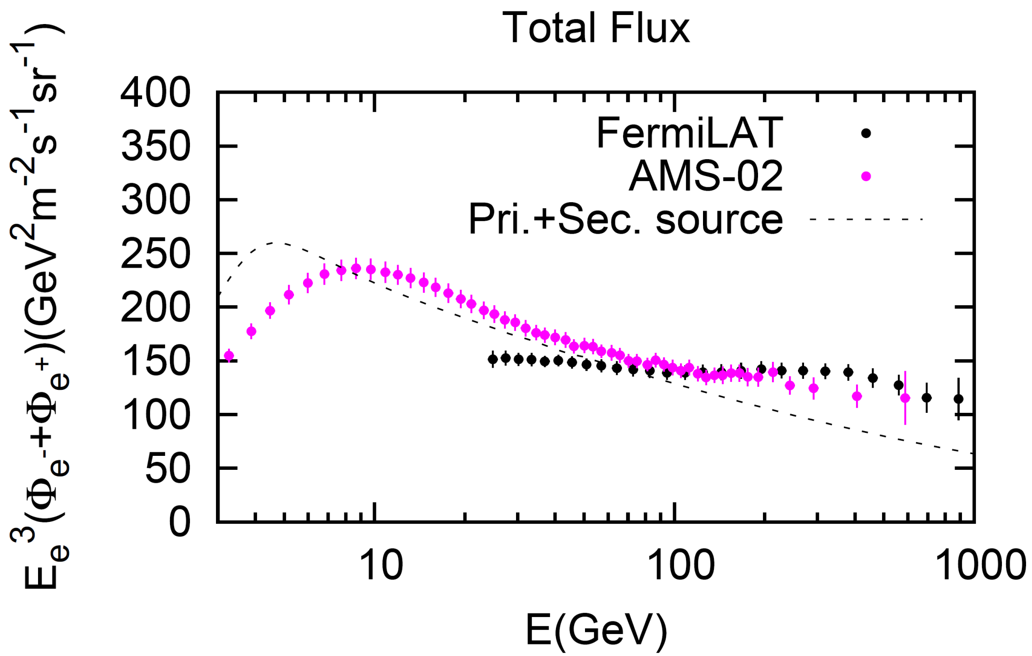
$$\Phi_e = \frac{c}{4\pi} f(E) = \frac{c}{4\pi} \int G(E, E') Q(E') dE'$$

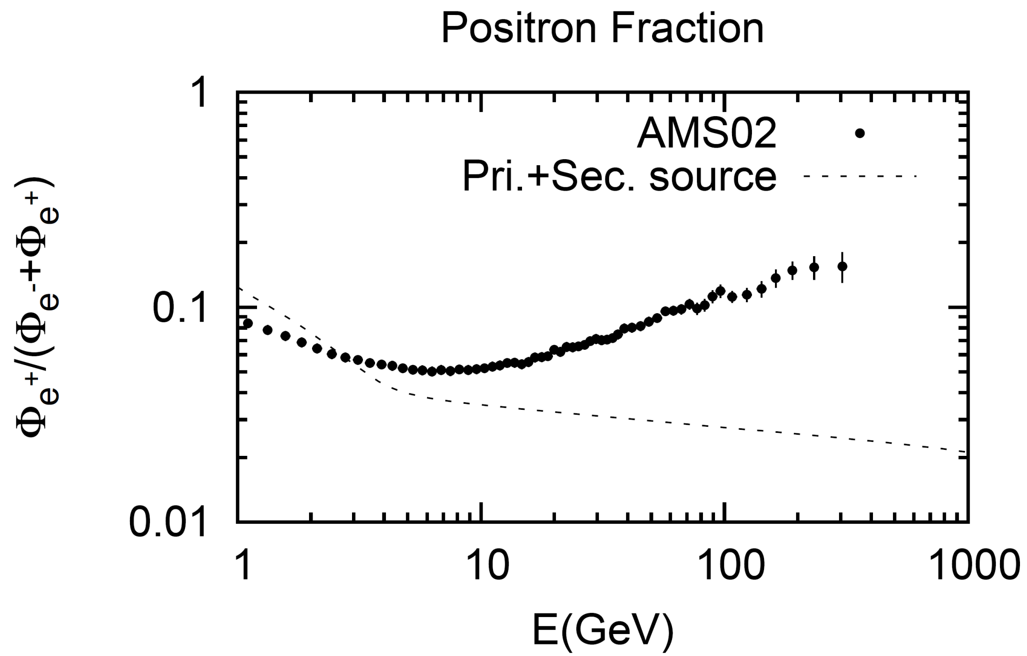
Primary electrons come from the explosion of supernovae, active galactic nuclei and Gamma-ray burst

$$q^{n,e}(\rho) \propto \left(\frac{\rho}{\rho_{br}^{n,e}}\right)^{-\gamma_1^{n,e}(\gamma_2^{n,e})},$$

$$f(R,z) \propto \left(\frac{R}{R_\odot}\right)^a \exp\left[-\frac{b(R-R_\odot)}{R_\odot}\right] \exp\left(-\frac{|z|}{z_s}\right),$$

diffuse coefficient				primary electron			primary proton		
$D_0(\mathrm{cm^2 s^{-1}})$	$\rho_r(\mathrm{MV})$	δ	$v_A(\mathrm{km\,s^{-1}})$	$\rho^e_{\mathrm{br}}(\mathrm{MV})$	γ^e_1	γ^e_2	$\rho^p_{\mathrm{br}}(\mathrm{MV})$	γ^n_1	γ^n_2
5.3×10^{28}	4.0×10^3	0.33	33.5	4.0×10^3	1.54	2.6	11.5×10^3	1.88	2.39





The dark matter (DM) as the source of $e^{\pm}$

One possible solution: The electron (positron) accelerated by pulsars

$$f(r,z) \propto \left(\frac{R}{R_s}\right)^a \exp(-bR/R_s)\exp(|z|/z_s)$$

$$\frac{dN}{dE} = AE^{-\alpha}\exp(-E/E_c)$$

There are two ways to generate electron/positron from DM

1. annihilation: DM+ DM → $l^{\pm}$+ X
2. DM decay: DM → $l^{\pm}$+ X

The source term Q is the number density CR generated in unit time in differential energy

$$Q_{\text{annihilation}} = \langle \sigma v \rangle \frac{\rho^2}{M^2}\left(\frac{dN}{dE}\right) \qquad Q_{\text{decay}} = \frac{\rho}{\tau M}\left(\frac{dN}{dE}\right)$$

We take the isothermal profile $\rho(R) = \rho_0 \frac{R_c^2 + R_s^2}{R_c^2 + R^2}$

$$\rho_0 = 0.43\ \text{GeV cm}^{-3},\ R_c = 2.8\ \text{kpc}$$

DM with two-body decaying into $e^{\pm}$

Since the proton and antiproton excess was not found from observation, the fermionphilic DM is favored,

DM $\rightarrow l^-(l^+) + X$ with a specific charged leton energy E_c

The energy distribution of $e^{\pm}$ source – DM two-body decaying is given by

$$\left(\frac{dN}{dE}\right)_{\text{tot}} = \epsilon_e \left(\frac{dN_e}{dE}\right) + \epsilon_\mu \left(\frac{dN_\mu}{dE}\right) + \epsilon_\tau \left(\frac{dN_\tau}{dE}\right), \text{ with } \epsilon_e + \epsilon_\mu + \epsilon_\tau = 1$$

$$\left(\frac{dN_e}{dE}\right) = \frac{1}{E_c}\delta(x-1),\ x = E/E_c$$

$$\left(\frac{dN_\mu}{dE}\right) = \frac{1}{E_c}\left[3(1-x^2) - \frac{4}{3}(1-x)\right]\theta(1-x), \text{ from } \mu \rightarrow e\nu\bar{\nu}$$

Single DM as a new source of $e^{\pm}$

The total flux of electron/positron can be expressed by

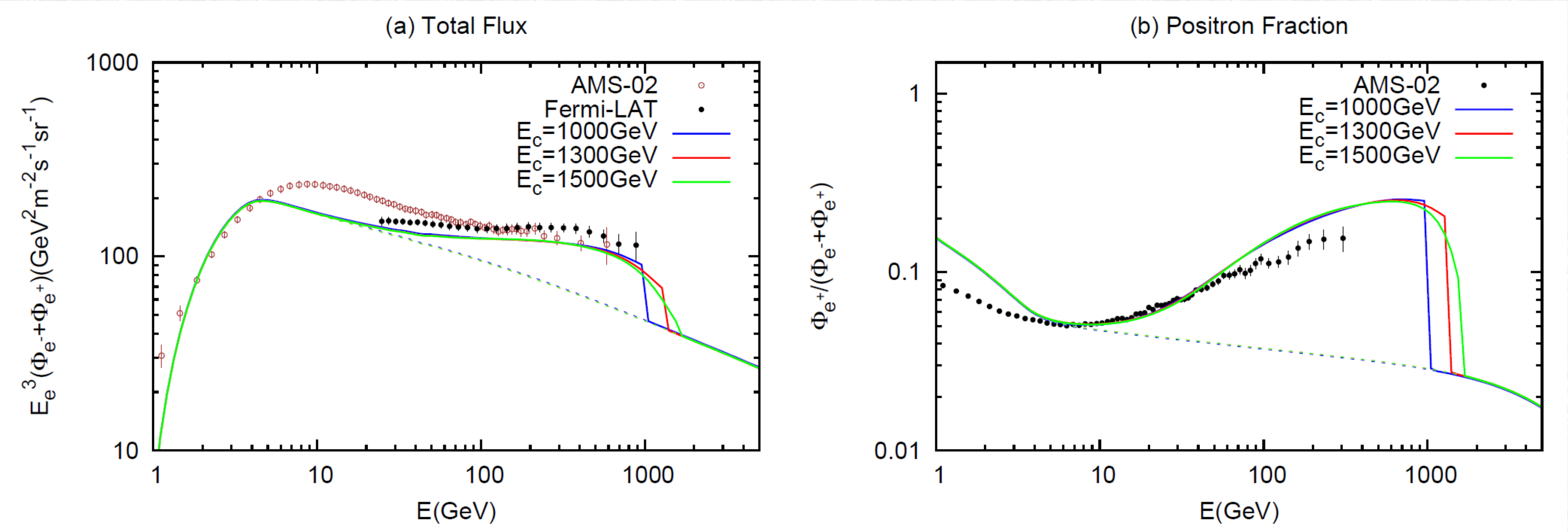
$$\Phi_e^{tot} = \kappa\,\Phi_e^{primary} + \Phi_e^{secondary} + \Phi_e^{DM}$$

$$\Phi_p^{tot} = \Phi_p^{secondary} + \Phi_p^{DM}$$

Takeing $M = 3030$ GeV, fit $\{\kappa, \epsilon_\mu, \epsilon_\tau, \tau, E_c\}$

68 data points of AMS-02(42 points)+Fermi-LAT(26 points)

E_c	κ	ϵ_e	ϵ_μ	ϵ_τ	$\tau(10^{26}\,s)$	χ^2
1000	0.73	0.09	0	0.91	0.66	463
1300	0.72	0.04	0	0.96	0.71	516
1500	0.71	0.02	0	0.98	0.74	541



DM with two-body decaying is not good for fitting to Fermi-LAT and AMS-02 results, As pointed out in many literature (Jin *et .al*, ….)

Single decaying channels of e μ τ are too 'hard'.

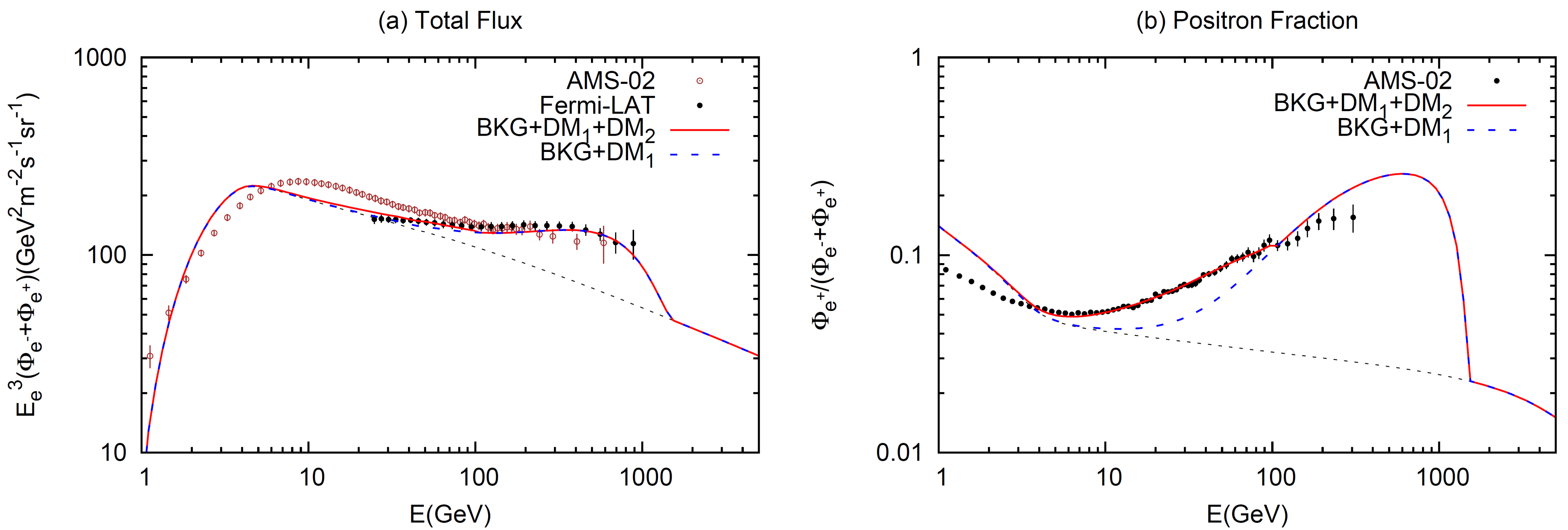
Two component DM decaying scenario

Take $M_1 = 3030\,\text{GeV}$, $M_2 = 416\,\text{GeV}$, $E_{c1} = 1500\,\text{GeV}$, $E_{c2} = 100\,\text{GeV}$

In the two DM scenario, we only open the muon two-body decay for DM_1, and electron and tau channels for DM_2

$$\kappa = 0.844,\quad \tau_1 = 0.76\times10^{26}\,s,\quad \tau_2 = 0.82\times10^{26}\,s,\quad \epsilon_{e2} = 0.018,\quad \epsilon_{\tau 2} = 0.982$$

$$\chi^2_{\text{min}}/d.o.f = 62.3/(26+42-7) \approx 1$$



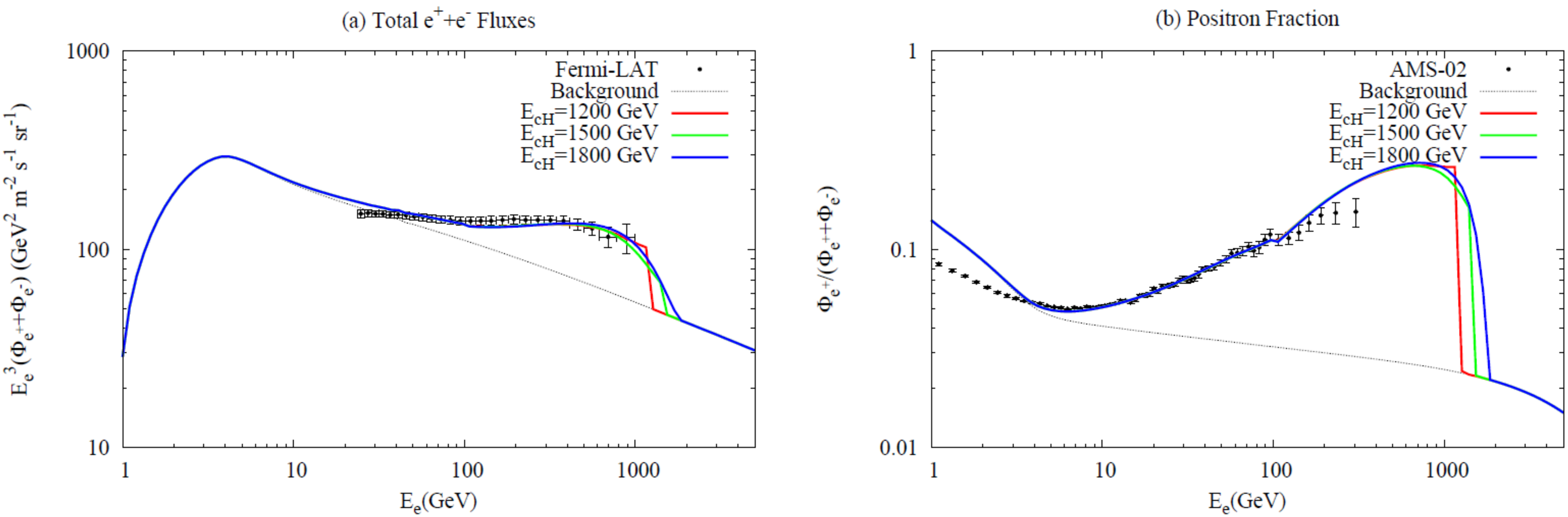


Table 1. Parameters leading to the minimal values of χ^2 with the cutoffs of heavy DM being 1200, 1500 and 1800 GeV, respectively.

E_{cH} (GeV)	κ	$\epsilon^{e}_{H,L}$	$\epsilon^{\mu}_{H,L}$	$\epsilon^{\tau}_{H,L}$	$\tau_{H,L}$ (10^{26}s)
1200	0.844	0.206,0.015	0.794,0	0,0.985	0.97,0.83
1500	0.844	0.058,0.020	0.942,0	0,0.980	0.78,0.82
1800	0.843	0,0.022	0.842,0	0.158,0.978	0.64,0.83

Geng, Huang, and LHT (2014)

Gamma-ray signals

Pion decaying $p+(\mathrm{H}_{\mathrm{I}},\mathrm{H}_{2},\ldots)\rightarrow\pi^{0}+X,\quad\pi^{0}\rightarrow 2\gamma$

Inverse Compton scattering (IC) and Bremsstrahlung

Isotropic extra galactic source (AGN)

$$\Phi_{\mathrm{extra}}=5.18\times10^{-7}E^{-2.499}\,\mathrm{GeV}^{-1}s^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-}$$

photon from prompt decaying of DM

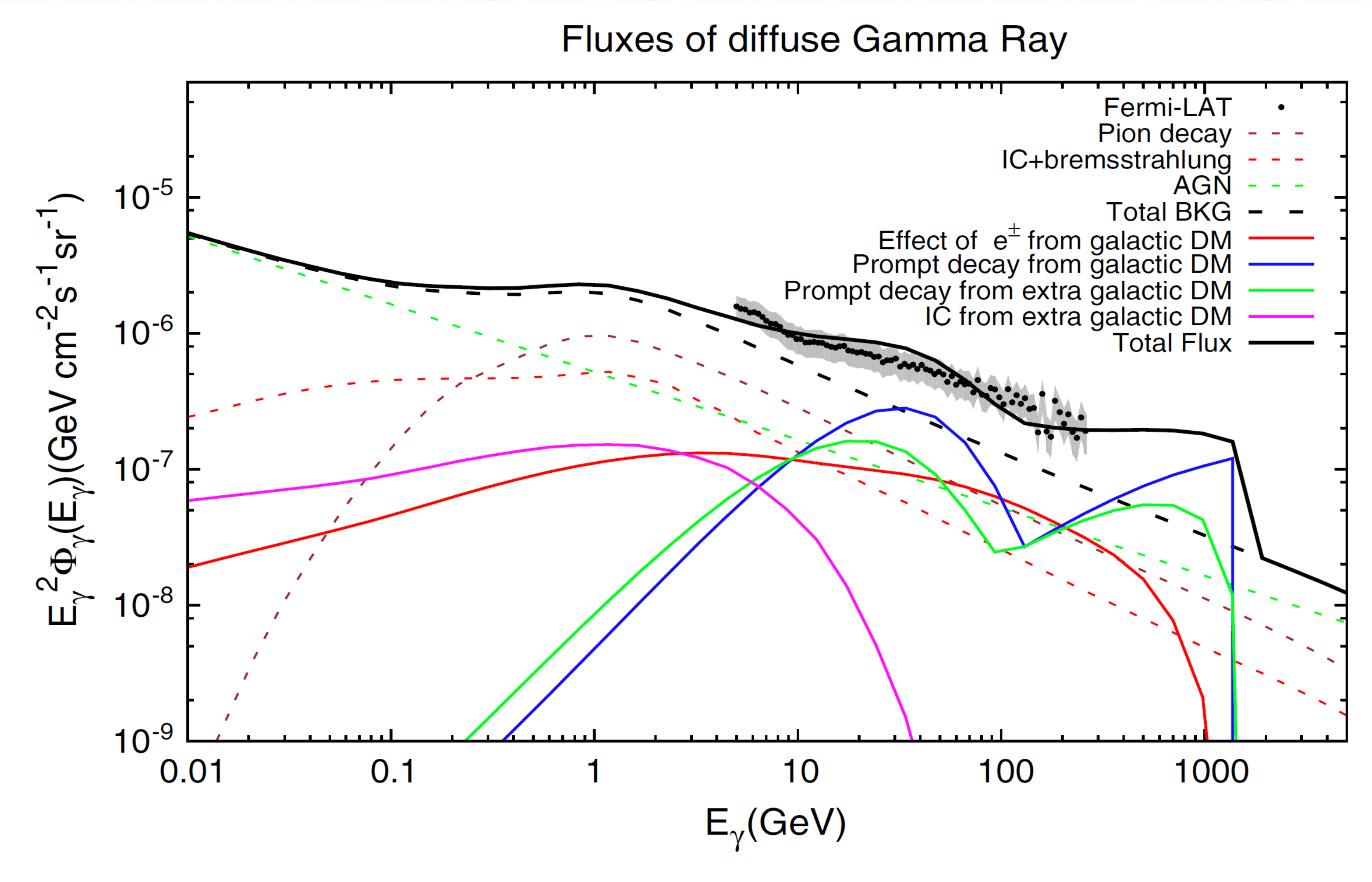
Final state radiation DM $\rightarrow X+l^{*}\rightarrow X+l+\gamma$

photon from electron effect from DM

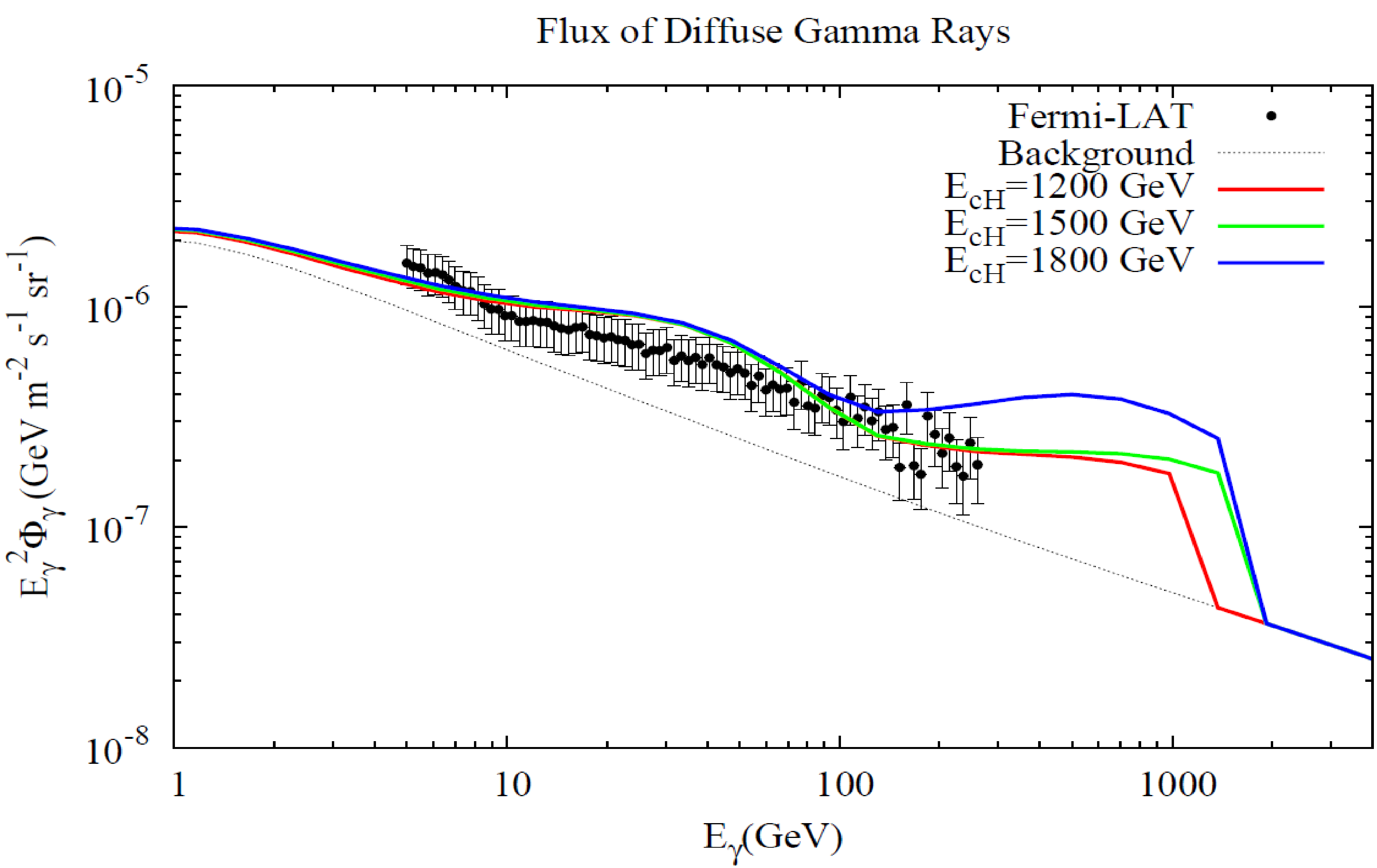
DM contribution to IC far away from our galaxy

$$\Phi_{\gamma}(b,l)=\frac{1}{4\pi}\int ds\,\epsilon(r),\quad\epsilon(r)=\frac{\rho(r)}{\tau M}\frac{dN}{dE}$$

We focus on the region |b|<10°, l < 10°, l>350°



Most of the constraints from gamma-ray is resulted by tau channel; while muon channel can release it.


Flux of Diffuse Gamma Rays
Fermi-LAT
Background
E_{cH}=1200 GeV
E_{cH}=1500 GeV
E_{cH}=1800 GeV
$E_\gamma^2\Phi_\gamma$(GeV m^{-2} s^{-1} sr^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
10
100
1000
E_γ(GeV)

Conclusion

- Double-component decaying DM model can explain the combined results of AMS-02 and Fermi-LAT.
- The flux of gamma ray can satisfy the constraints from Fermi-LAT measurement. The branching ratio of taun channel for DM is also constrained.
- Note that the neutrino mass matrix generating through one loop has zero elements $M_{\mu\tau}$. To be consistent with observation, another heavy neutrino N_{R3} should be imposed.

Thank you!