Cosmic Ray Excess From Multi-Component Dark Matter

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In collaboration with C.-Q. Geng, L.-H. Tsai and C. Lai

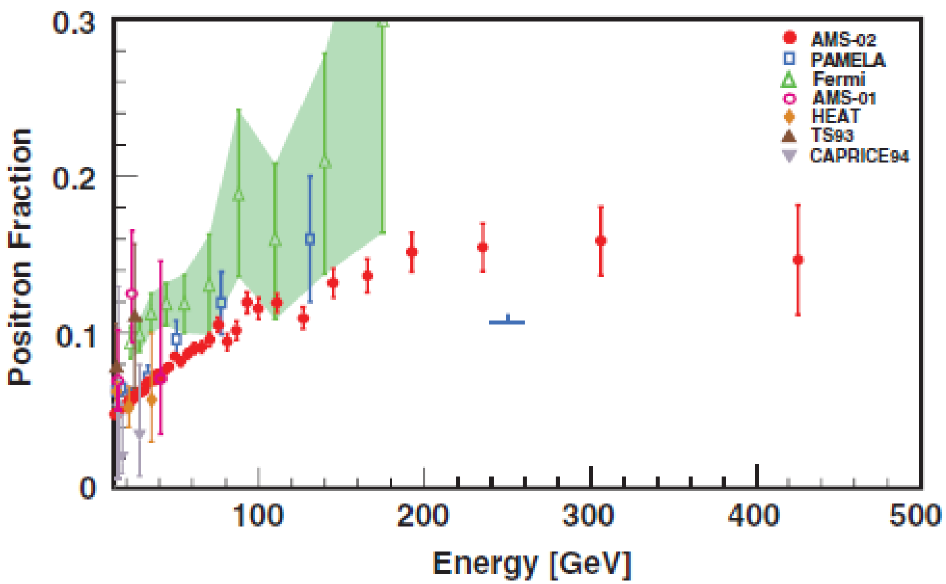
Content

- Motivation and Review of Experimental Status
- General Phenomenological Analysis–Two- Component Decaying DM
- Diffuse γ-ray Prediction
- Summary

Motivation

➢ Recently, AMS-02 published a series of new measurements of the positron fraction spectrum , showing an uprise above 10 GeV.

AMS-02 Positron Fraction Spectrum



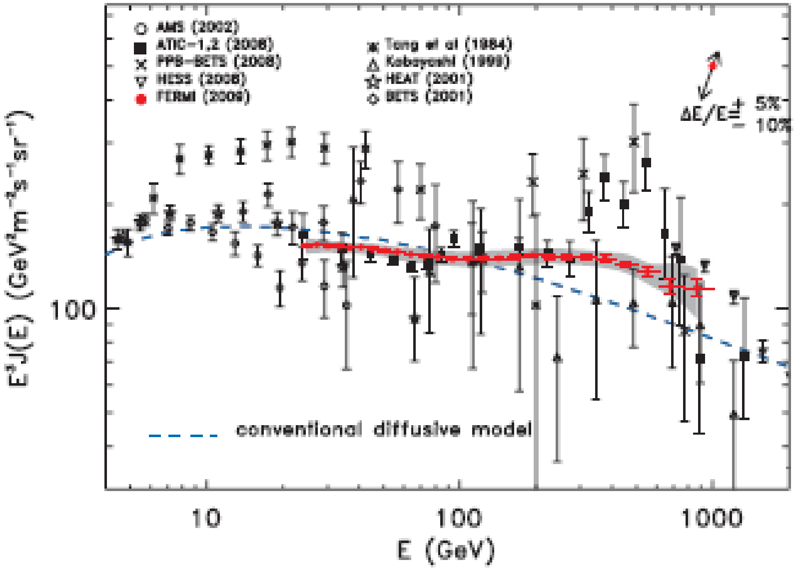
➢ Confirm the observation by many previous experiments, such as PAMELA, Fermi-LAT, AMS-01, et al..

➢ Different from usual astrophysical expection: decreasing power law

Motivation

- The excess was also observed in the total $e^{+}+e^{-}$ flux spectrum by PAMELA, Fermi-LAT and AMS-02.

Femi-LAT $e^{+}+e^{-}$ Spectrum

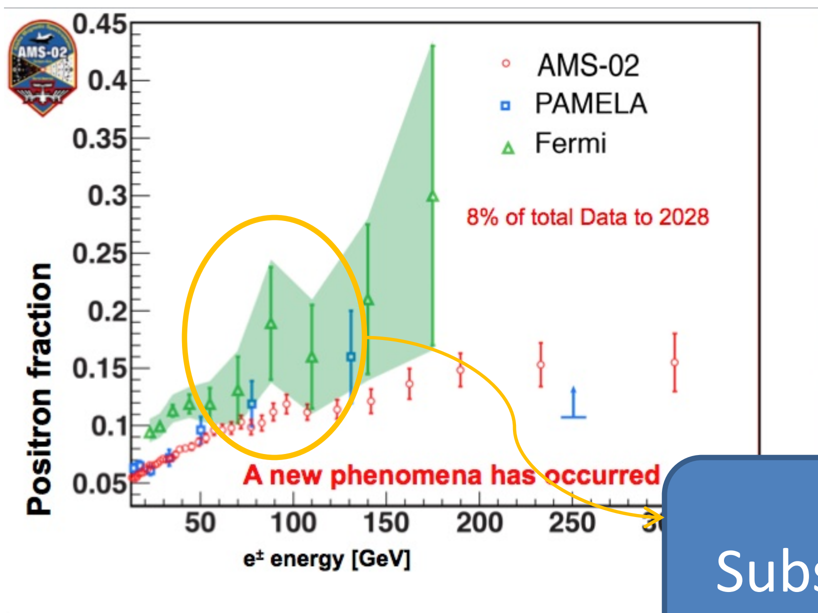


- Conventional expectation: decreasing power law

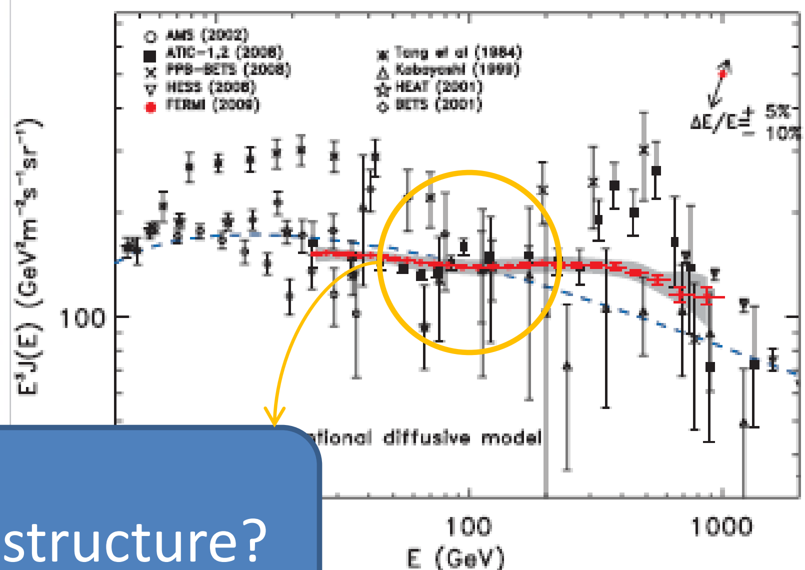
Motivation

➢ Moreover, both the **AMS-02** positron fraction spectrum and the **Femi-LAT** total $e^+ + e^-$ flux spectrum showed some substructure around 100 GeV.

AMS-02 Positron Fraction Spectrum



Femi-LAT $e^+ + e^-$ Spectrum

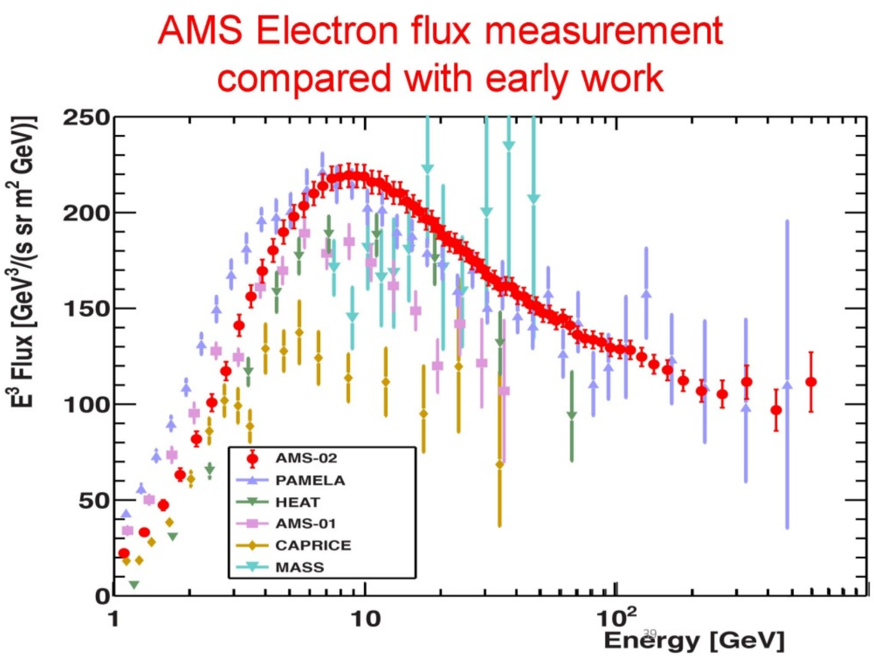


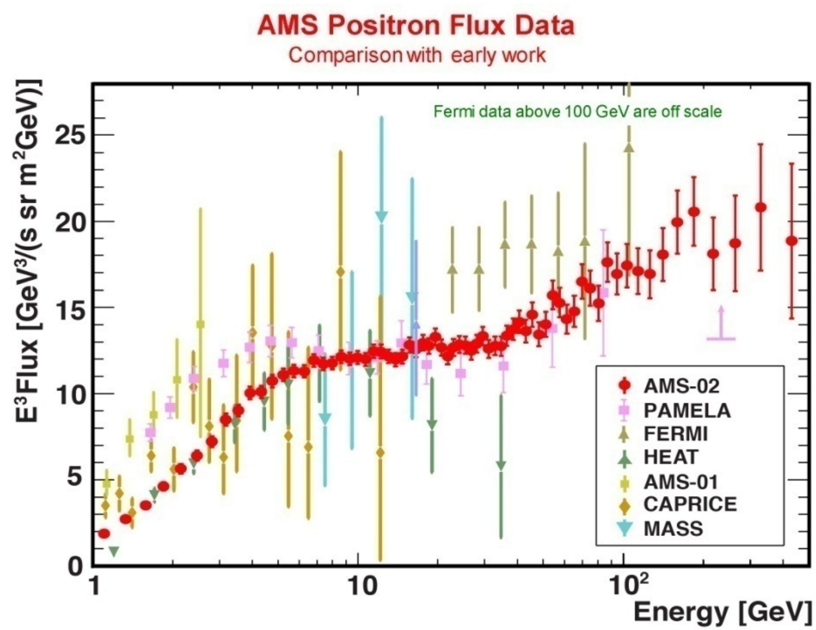
Substructure?

Motivation

- In the new release, **AMS-02** also gave the spectra of e^{+} (e^{-}) flux and total ($e^{+}+e^{-}$) flux.

- e^{+} (e^{-}) flux: Spectrum hardening above ~30 GeV

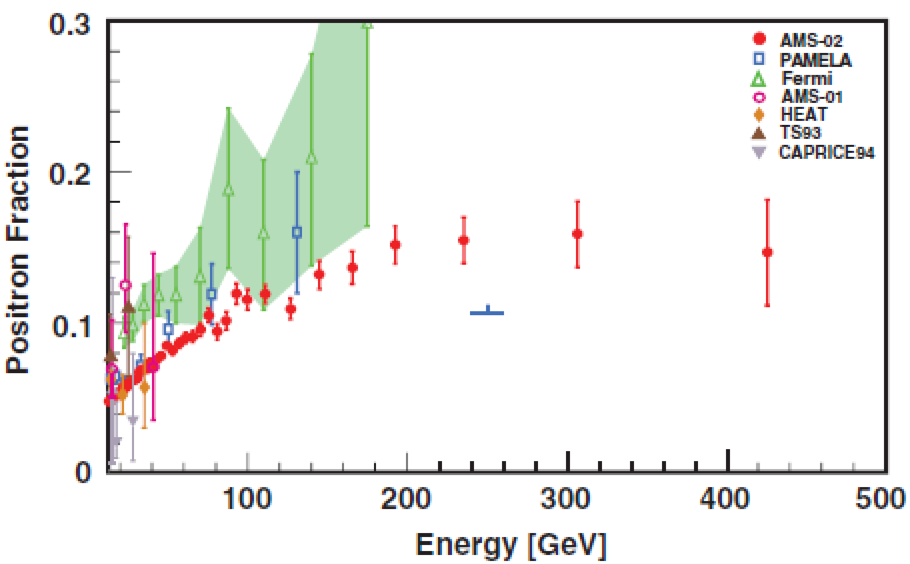




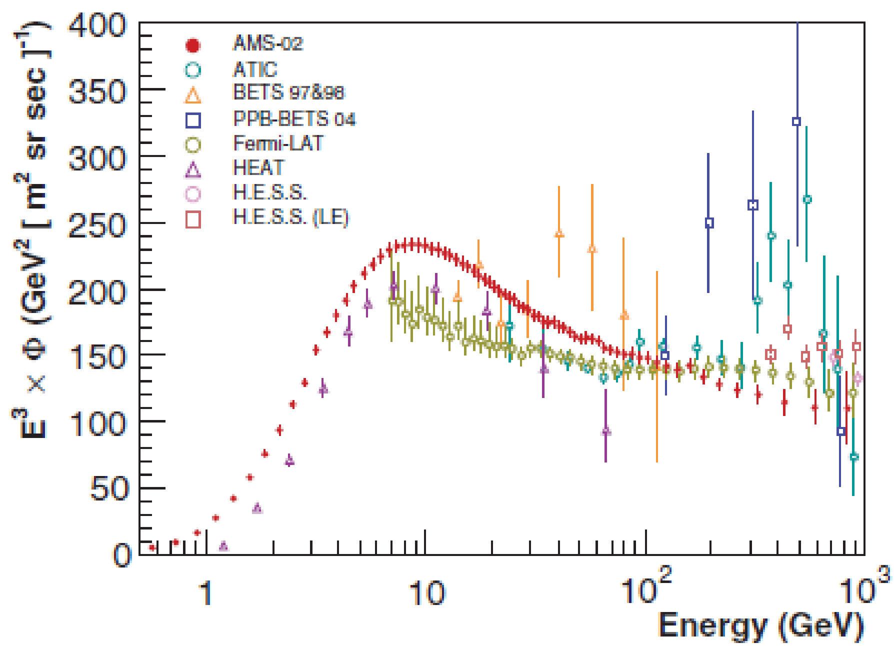
Motivation

- Positron fraction : first evidence that positron fraction stops increasing with energy above ~200 GeV
- Total $e^{+}+e^{-}$ flux: good fit with a single power law at high energy

AMS-02 Positron Fraction Spectrum



AMS-02 Spectrum of $(e^{+}+e^{-})$ flux



Motivation

- All the excesses indicate that there are additional positron and/or electron sources beyond our current knowledge, either in astrophysical or particle physical origin.

- In literature, there are two compelling candidate origin for these excesses: **Pulsars** and **Dark Matter.**

- In this talk, I concentrate on the decaying dark matter interpretation for this AMS-02/Fermi-LAT excess

Requirement	the TeV DM lifetime $\tau_{DM} \sim O(10^{26})$s >> $\tau_{Universe} \sim O(10^{17})$s

Decaying DM: Status

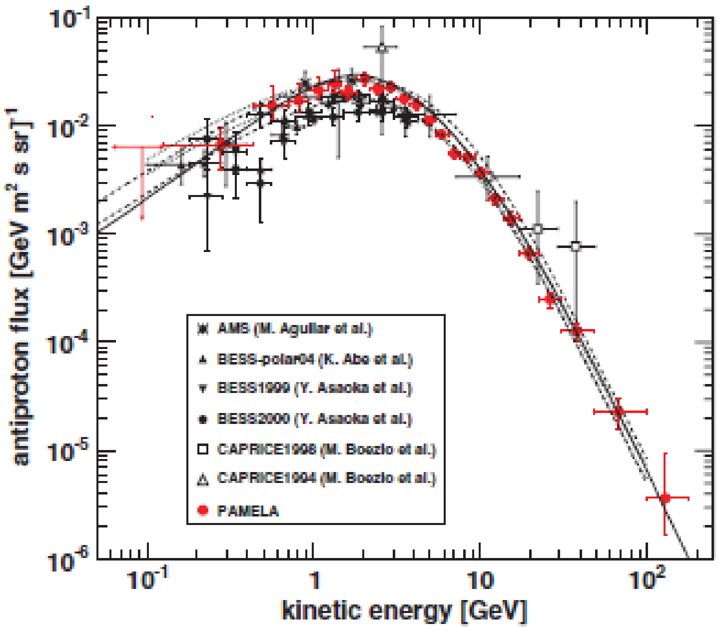
- Previous Studies concentrated on the Single-Component Decaying DM models with the dominant decay channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^-, b^+b^-, … Their general conclusion is that such models cannot explain the AMS-02 positron fraction and Fermi-LAT total $e^+ + e^-$ flux simultaneously.

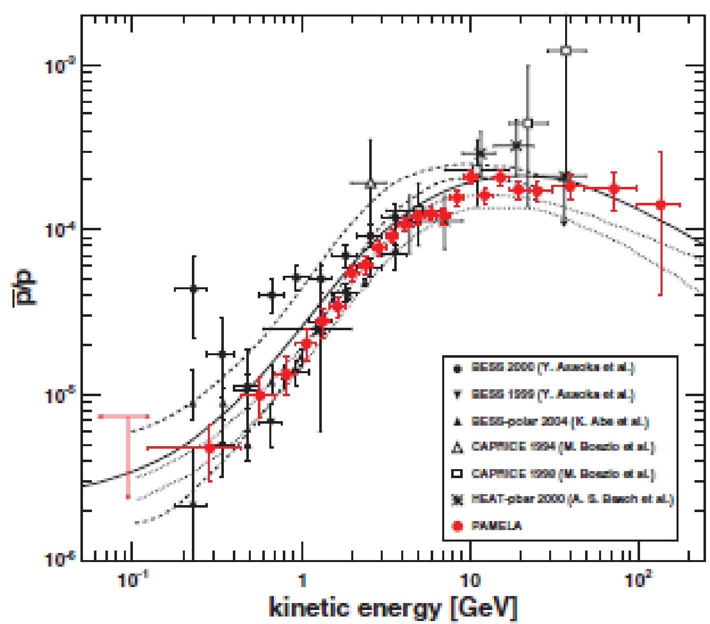
Jin et al APJ (2013) arXiv: 1304.1997; Yuan, et .al. arXiv: 1304.1482 …

Multi-Component DM

Further Constraints on Decaying DM

- The measured antiproton spectrum agrees with the prediction of the conventional astrophysical theory well

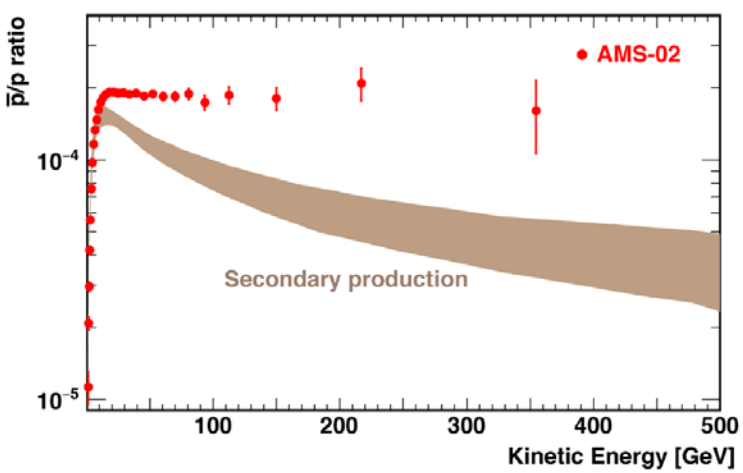


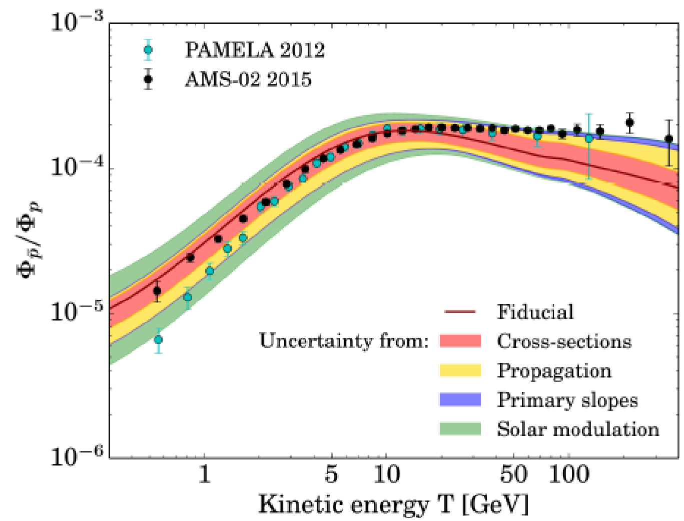


Further Constraints on Decaying DM

➢ Recent analysis with the new AMS-02 data confirmed this conclusion.

Giesen et al ICAP(2015);
lin et al. PRD (2015);
Kappl et al JCAP(2015) .





Leptophilic DM

Decaying DM: General Formula

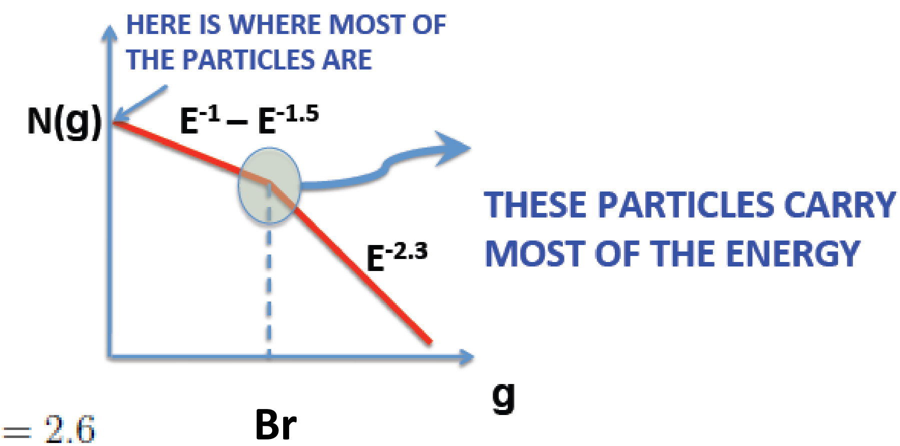
$e^{-}(e^{+})$ flux:

$$\Phi_e^{(\mathrm{tot})} = \kappa_1 \Phi_e^{(\mathrm{primary})} + \kappa_2 \Phi_e^{(\mathrm{secondary})} + \Phi_e^{\mathrm{DM}},$$

$$\Phi_p^{(\mathrm{tot})} = \kappa_2 \Phi_p^{(\mathrm{secondary})} + \Phi_p^{\mathrm{DM}},$$

$\Phi_e^{(\mathrm{primary})}$

Primary electron flux: assumed to be broken power law



$\mathrm{Br} = 4.0 \times 10^{3}\mathrm{MV},\ \gamma_1 = 1.54,\ \gamma_2 = 2.6$

$\Phi_e^{(\mathrm{secondary})} = \Phi_p^{(\mathrm{secondary})}$: Secondary $e^{-}(e^{+})$ produced in propagation, computed by GALPROP

$\kappa_{1,2}$ denotes the uncertainty in normalization of backgrounds.

Two-Component Decaying DM

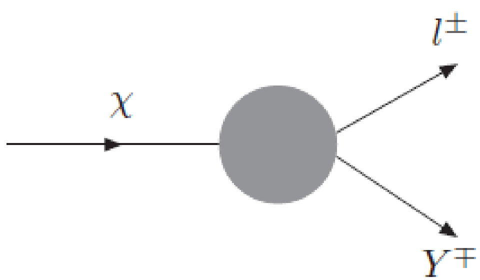
➢ DM Source Term: $Q(\mathbf{x}) = \frac{\rho(\mathbf{x})}{2}\left[\frac{1}{\tau_1 M_1}\left(\frac{dN}{dE}\right)_1 + \frac{1}{\tau_1 M_2}\left(\frac{dN}{dE}\right)_2\right]$

Half Density

ρ(x): DM density distribution, here we use isothermal profile

τ_i: DM lifetime M_i: DM Mass

➢ DM decay process :



DM Injection Spectra: $$\left(\frac{dN}{dE}\right) = \epsilon_e \frac{dN_e}{dE} + \epsilon_\mu \frac{dN_\mu}{dE} + \epsilon_\tau \frac{dN_\tau}{dE}$$

with condition: $$\epsilon_e + \epsilon_\mu + \epsilon_\tau = 1$$

Two-Component Decaying DM

- Normalized Injection Spectra for Electrons :

$$\frac{dN_e}{dE} = \frac{1}{E_c}\delta(1-x) \,, \qquad \text{where } x = E/E_c$$

$$\frac{dN_\mu}{dE} = \frac{1}{E_c}[3(1-x^2) - \frac{4}{3}(1-x)]\theta(1-x) \,,$$

dN_τ/dE : obtained with the simulation by PYTHIA

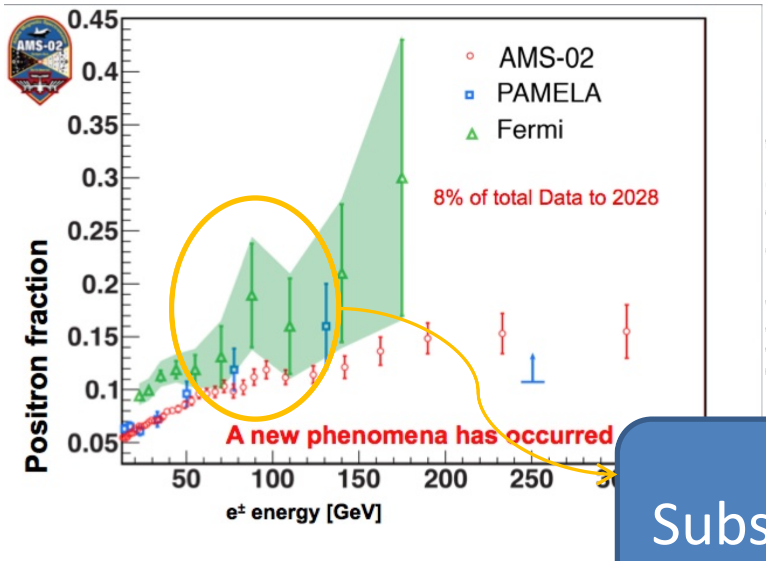
- After e^+/e^- are produced from DM decays, they would propagate in the Galaxy, which is solved numerically by GALPROP

Two-Component Decaying DM

Observations:

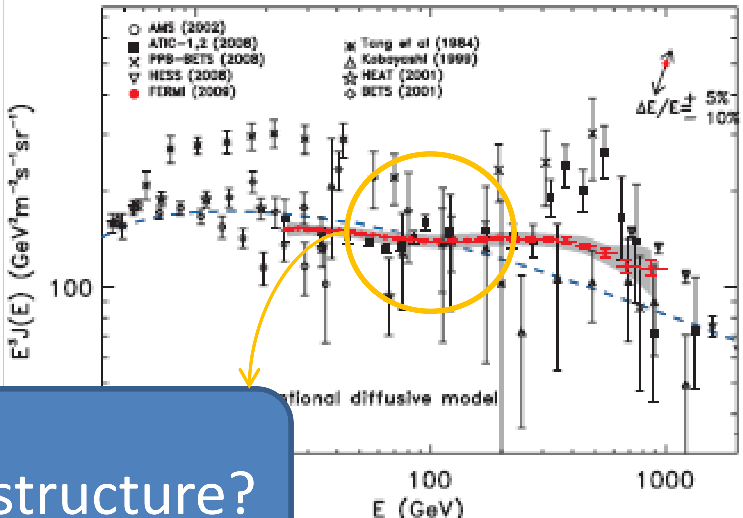
- The excess of total $e^{+}+e^{-}$ flux by Fermi-LAT extends to 1 TeV, so at least one DM cutoff should be larger than 1 TeV;
- The substructure at around 100 GeV observed by both AMS-02 and Fermi-LAT

AMS-02 Positron Fraction Spectrum



Femi-LAT $e^{+}+e^{-}$ Spectru

One DM drop at 100GeV



Substructure?

Two-Component Decaying DM

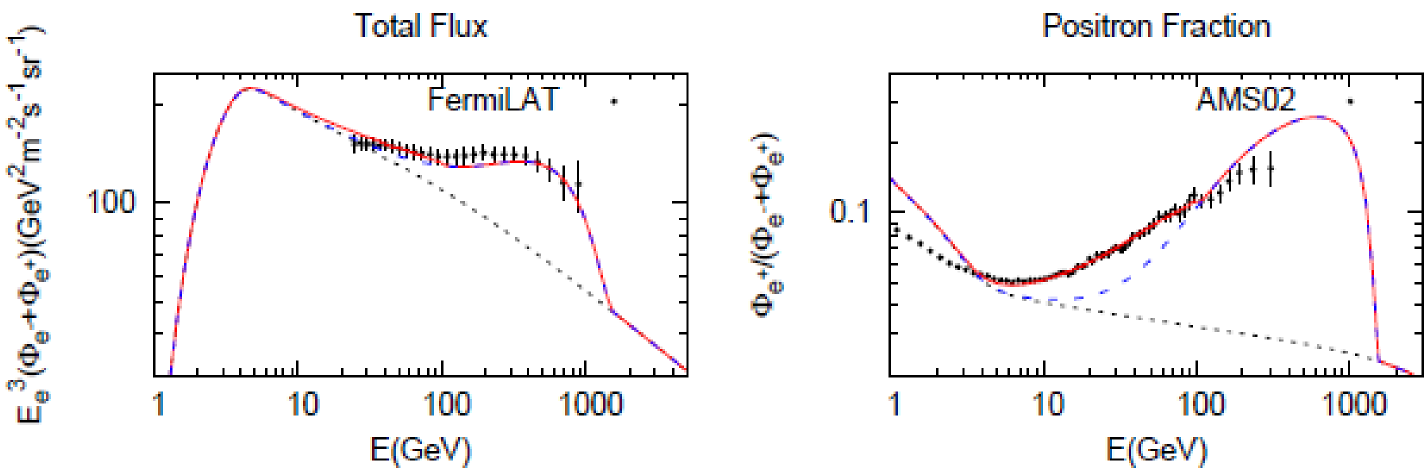
- The observations above indicates that DM at least contains two components, with E_{c1} > 1000 GeV and E_{c2} ≈100 GeV. For generic discussion, we take two DMs' cutoffs E_{ci} and masses M_i as follows:

E_{c1}	M_1	E_{c2}	M_2
1500 GeV	3030 GeV	100 GeV	416 GeV

Two-Component Decaying DM

- Fitting Results:

κ	ϵ_{e1}	$\epsilon_{\mu 1}$	$\epsilon_{\tau 1}$	$\tau_1(10^{26}\mathrm{s})$	ϵ_{e2}	$\epsilon_{\mu 2}$	$\epsilon_{\tau 2}$	$\tau_2(10^{26}\mathrm{s})$	χ^2	$\chi^2/d.o.f.$
0.844	0	1	0	0.92	0.018	0	0.982	0.81	62.3	1.06



- Conclusion: Double-Component DM decaying mainly via two-body leptonic decay CAN fit to AMS-02 positron fraction and Fermi-LAT total flux simultaneously.

Update with New AMS-02 Data

- Recently, we update our analysis of two-component decaying DM model with the AMS-02 positron fraction and total $(e^+ + e^-)$ flux. C. Lai, DH, C. Q. Geng, MPLA 30 (2015) 35, 1550188

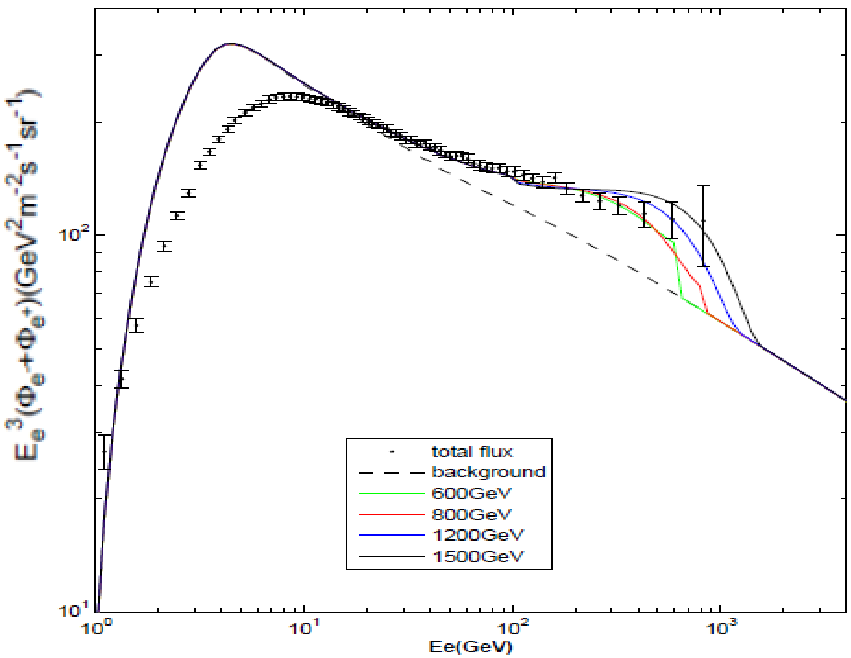
  - Advantage: reduce the systematic uncertainties of fit

TABLE III. Parameters leading to the minimal values of χ^2 with the cutoffs of the heavy DM being 600, 800, 1200, and 1500 GeV, respectively.

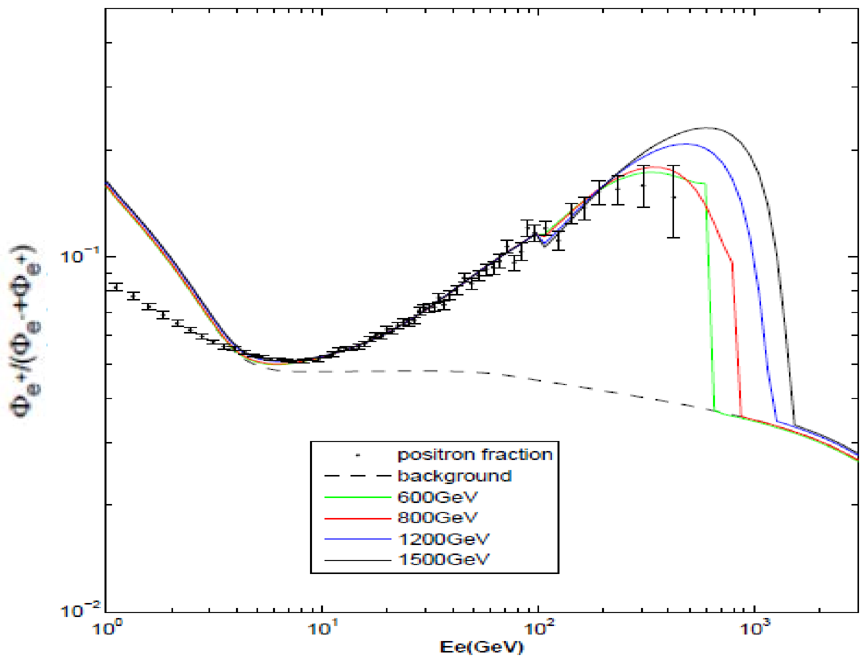
E_{cH}(GeV)	κ_1	κ_2	$\epsilon_L^{e,\mu,\tau}$	$\epsilon_H^{e,\mu}$	$\tau_L(10^{26}\mathrm{s})$	$\tau_H(10^{26}\mathrm{s})$	$\chi^2_{\min}$	$\chi^2_{\min}$/d.o.f.
600	0.94	1.51	0.02, 0, 0.98	0.18,0.82	1.43	1.60	94	1.09
800	0.94	1.52	0.04, 0.08, 0.88	0.05, 0.95	1.58	1.32	97	1.13
1200	0.94	1.57	0.12, 0.48, 0.40	0, 1	2.58	1.06	107	1.24
1500	0.94	1.60	0.20, 0.80, 0	0, 1	3.41	0.93	119	1.38

Update with New AMS-02 Data

Total $e^{+}+e^{-}$ Flux



Positron Fraction Spectrum



- All the cases fit the AMS-02 dataset very well.

Diffuse γ-ray Constraint

- Previous studies showed that the diffuse γ-ray measured by Fermi-LAT could already give strong constraint to decaying DM

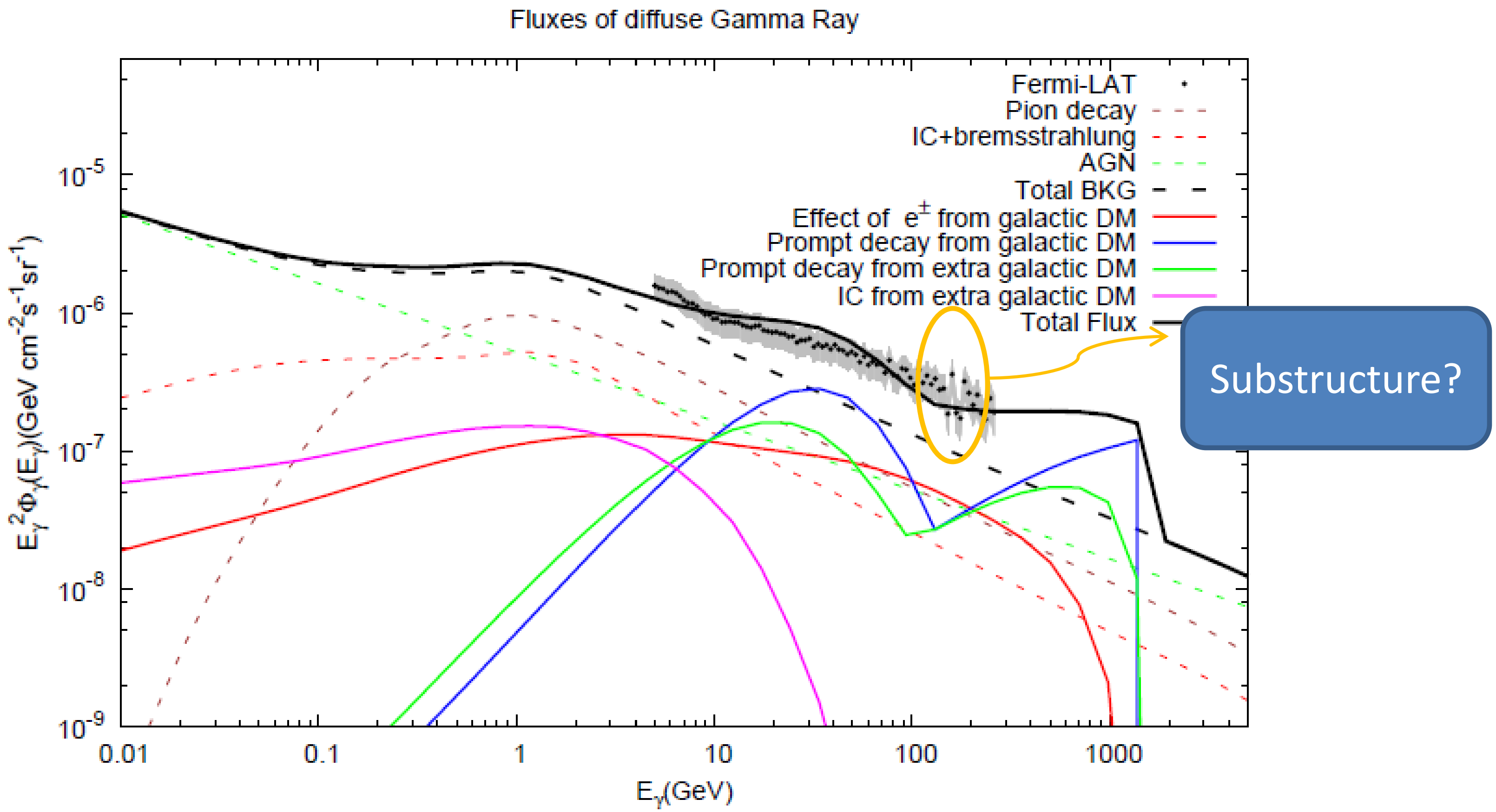
Cirelli et al PRD(2012); Essig et al. PRD (2009); Ibe et al(2013) , 1305.0084; Cirelli & Panci, NPB (2009); …

- Question: Does our two-component DM (or multi-component DM) scenario still survive after the consideration of diffuse γ-ray constraints?

- Strategy: We compute total various diffuse γ-ray spectrum, including the ones from two-component DM decays, which is compared with the Fermi-LAT data.

Total Predictions of Phen. Model !

Model Prediction to Diffuse γ-ray



Conclusion: With the parameters fitted by AMS-02 and Fermi-LAT, the predicted γ ray is still allowed by the Fermi-LAT measurement.

Summary

- In this talk we investigate the multi-component decaying Dark Matter model to explain AMS-02 and Fermi-LAT e^+/e^- excesses, and show that two DM components are enough to explain the data.

- We also use the AMS-02 2014 data to update our analysis of two-component DM model, and show that it can also provide a good fit.

- We also show that the predicted diffuse γ-ray spectrum agrees with that observed by Fermi-LAT.

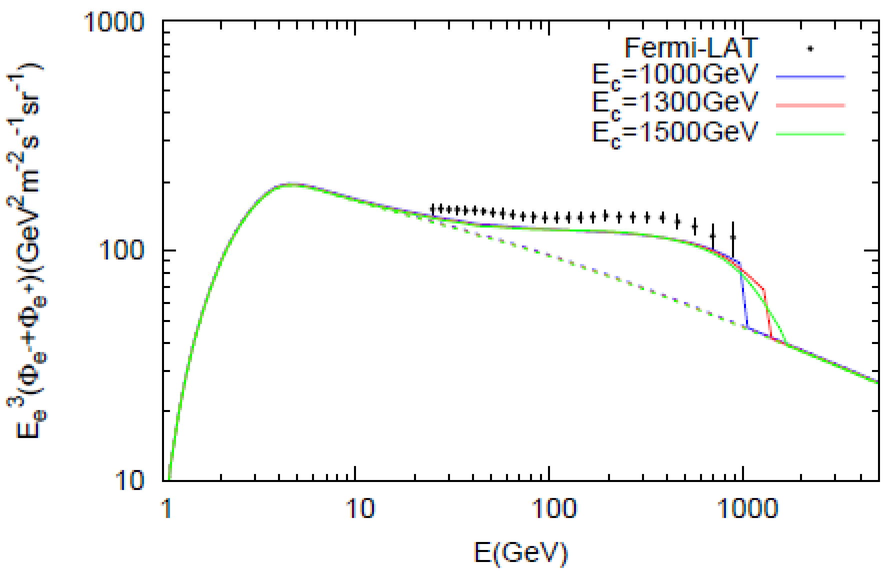
THANKS FOR YOUR ATTENTION!

Single-Component Decaying DM

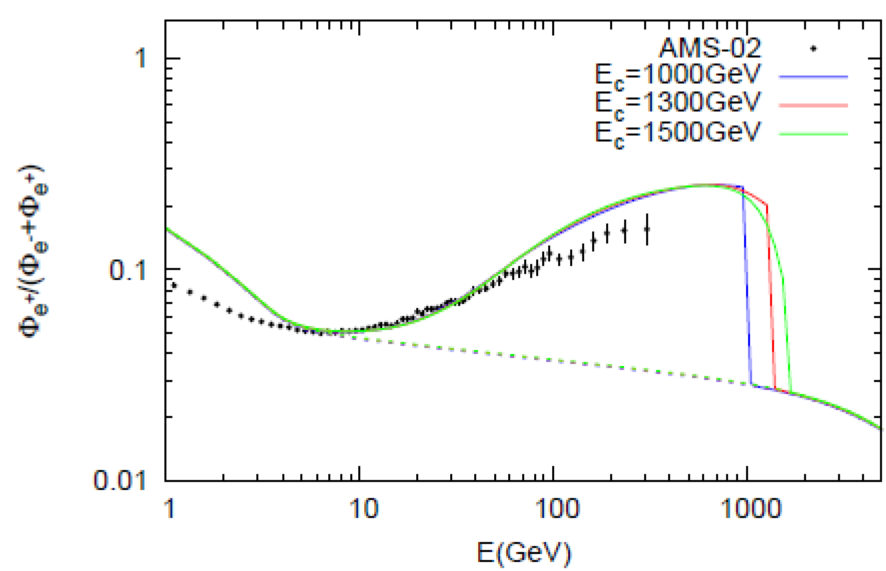
χ^2 Fitting Results:

E_c(GeV)	κ	ϵ^e	ϵ^μ	ϵ^τ	$\tau(10^{26}\mathrm{s})$	χ^2_{min}	$\chi^2_{\mathrm{min}}/d.o.f.$
1000	0.73	0.09	0	0.91	0.66	463	7.35
1300	0.72	0.04	0	0.96	0.71	516	8.19
1500	0.71	0.02	0	0.98	0.74	541	8.46

(a) Total Flux

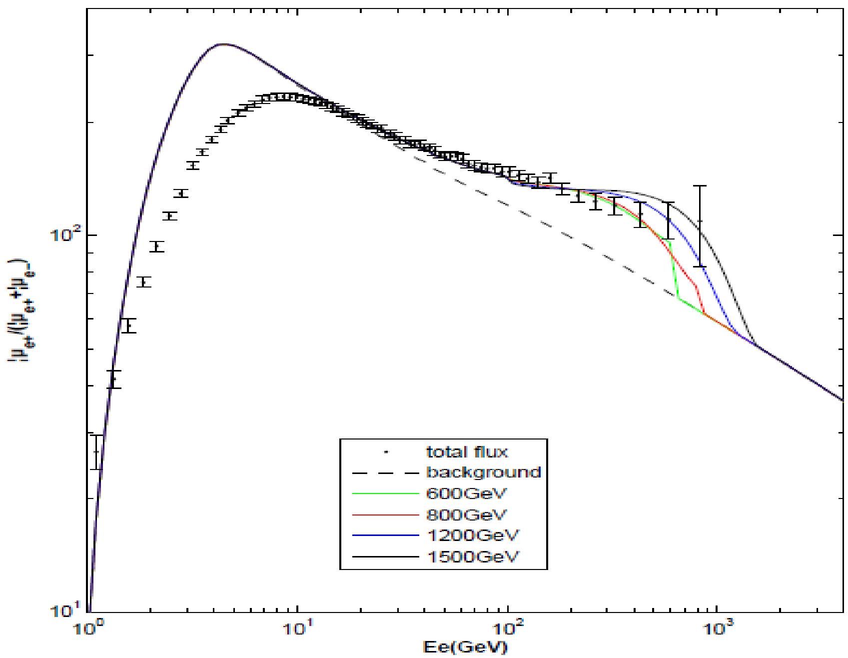


(b) Positron Fraction

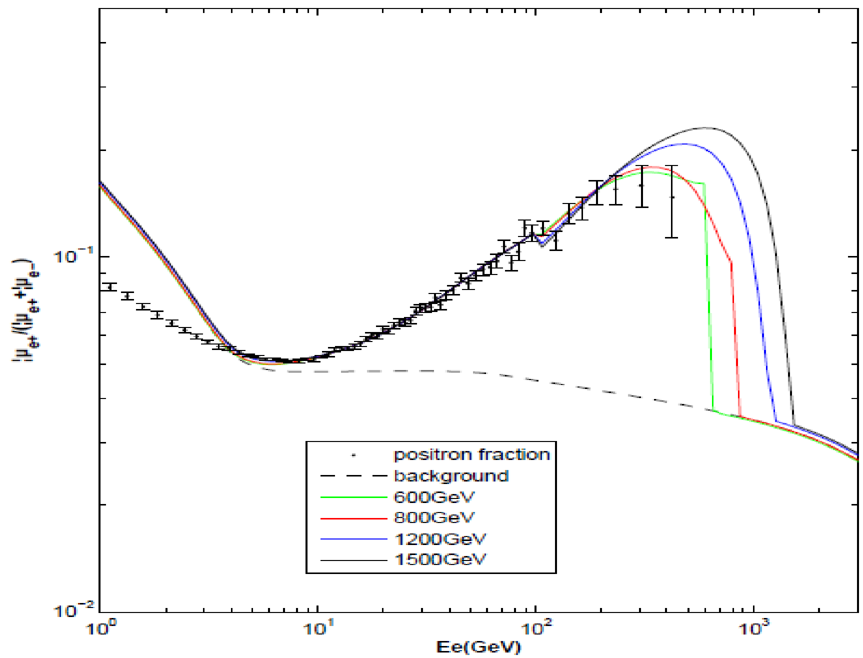


Update with New AMS-02 Data

Total $e^{+}+e^{-}$ Flux



Positron Fraction Spectrum



- All the cases fit the AMS-02 data very well → 2DM alive
- Observation: if E_{cH} < 1 TeV, the positron fraction begins decreasing at ~200 GeV, as claimed by AMS-02, but it cannot explain the total $(e^{+}+e^{-})$ flux at high energies.

Propagation Parameters

TABLE I. The parameters for the diffuse propagation, primary electron, and primary proton.

diffuse coefficient				primary electron			primary proton		
$D_0(\mathrm{cm}^2\mathrm{s}^{-1})$	$\rho_r(\mathrm{MV})$	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

Single-Component Decaying DM

χ^2 Fitting Results:

$E_c(\mathrm{GeV})$	κ	ϵ^e	ϵ^μ	ϵ^τ	$\tau(10^{26}\mathrm{s})$	χ^2_{min}	$\chi^2_{\mathrm{min}}/d.o.f.$
1000	0.73	0.09	0	0.91	0.66	463	7.35
1300	0.72	0.04	0	0.96	0.71	516	8.19
1500	0.71	0.02	0	0.98	0.74	541	8.46

Conclusion: Single-Component DM decaying mainly via two-body leptonic decay CANNOT give reasonable fit to AMS-02 positron fraction and Fermi-LAT total flux simultaneously.

wayout $\Rightarrow$ $\begin{cases} \text{Three-body or four-body decay channels} \\ \text{Multi-Component DM} \end{cases}$

Microscopic Realization of Multi-Component DM

- Particle Content

Particles	ζ	η	N_{R1}	N_{R2}
$SU(2)_L \times U(1)_Y$	(2,1)	(2,1)	(1,0)	(1,0)
Z_2	-	+	+	+
Z_2'	+	-	-	-

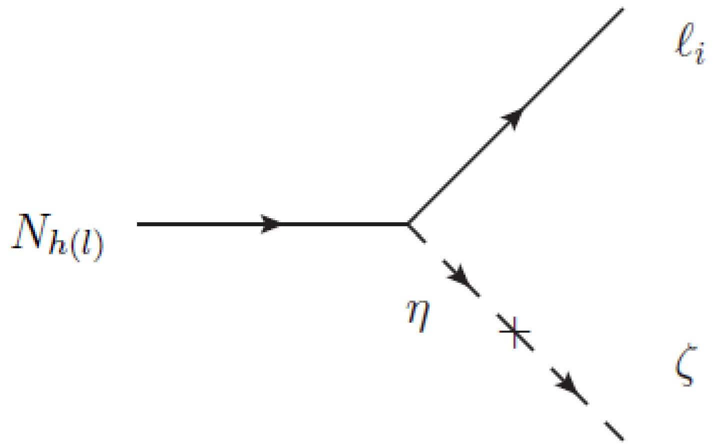
- Relevant Lagrangian

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

Break Z_2 and Z'_2

Microscopic Realization of Multi-Component DM

- Relevant Feynman Diagram



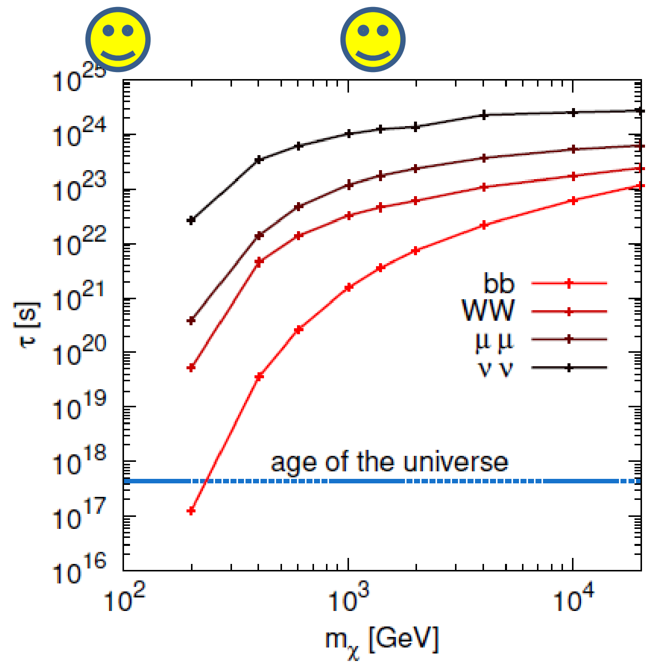
If $N_{h(l)}$'s lifetime is $O(10^{26})$s, then it only requires

$$Y_{1(2)i} \sim \mathcal{O}(10^{-6}),\ \mu \sim \mathcal{O}(1\ \mathrm{GeV})\ \ M_\eta \sim \mathcal{O}(10^{10}\ \mathrm{GeV})$$

Microscopic Realization of Multi-Component DM

- **Model Prediction**: Since the coupled leptons are left-handed, after $SU(2)_L$ transformation, the DM $N_{h(l)}$ can also decay into neutrinos, thus produce the same amount of neutrino flux, which can be observed by IceCube.

- Unfortunately, current IceCube's constraint is very loose for general decaying DM models.



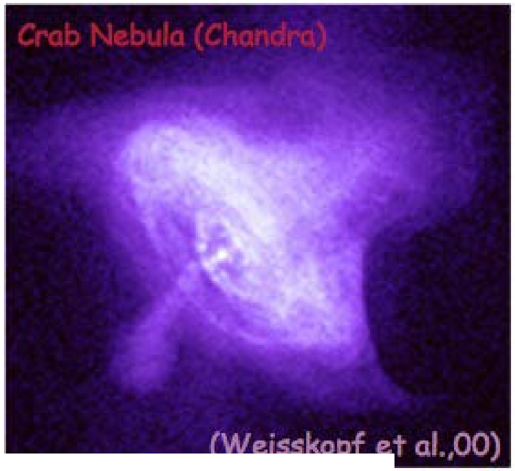
POSSIBLE EXPLANATION

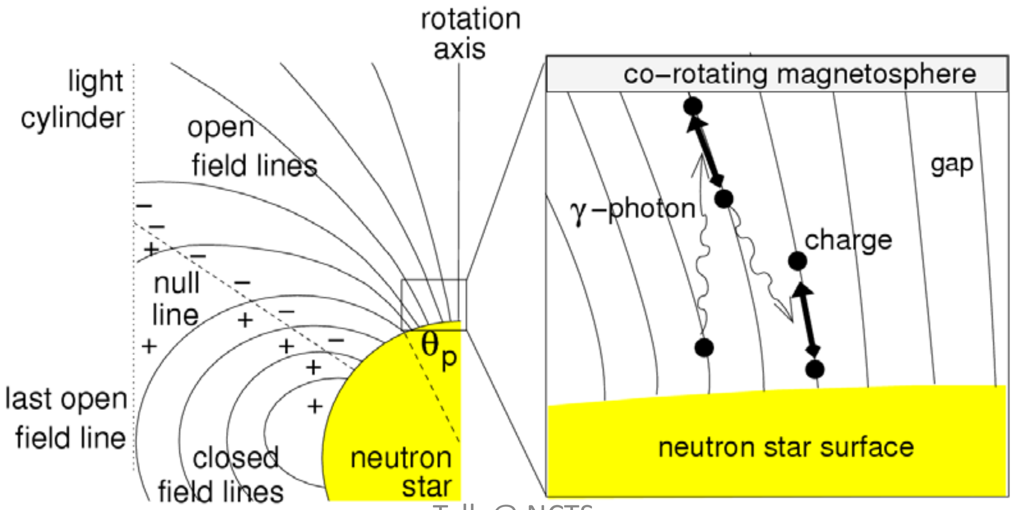
Possible Explanation of the Excess

➢ In literature, there are two compelling candidate origin for these excesses: **Pulsars** and **Dark Matter**.

Some Comments on Pulsars:

✓ Pulsars and their wind nebulae (PWN) are ideal electron-positron factories





Comments on Pulsar Scenario

In general, the extra source for e^+ and e^- can be a single nearby pulsar, or the total contribution of many pulsars

- Famous nearby pulsars:

  Geminga[J0633+1746], Monogem[B0656+14], ...

- Multiple pulsars:

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

Injection Spectrum: $q(p) = A_{\rm psr} p^{-\alpha} \exp(-p/p_c),$

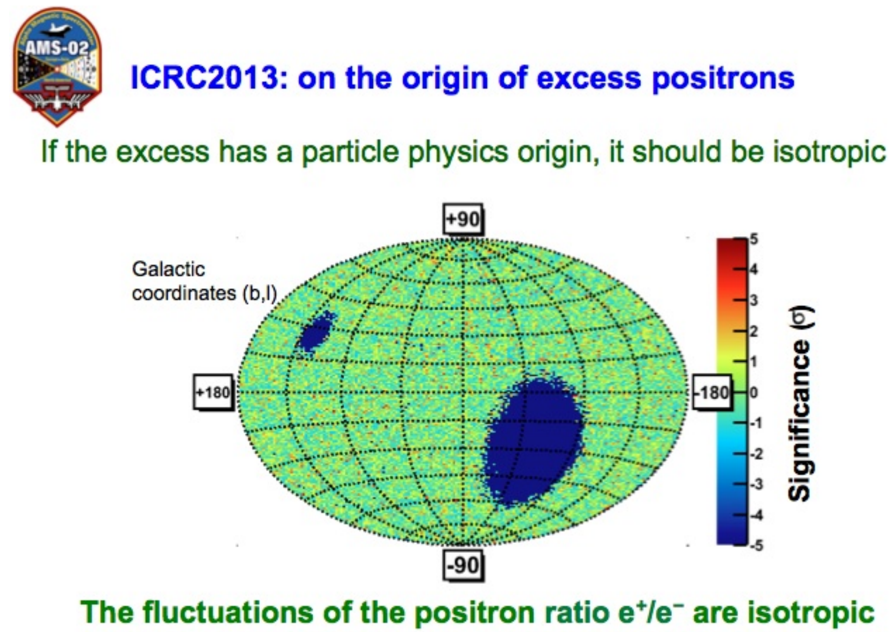
Both scenario can fit the AMS-02 and Fermi-LAT excess spectrum very well.

Comments on Pulsar Scenario

- General Pulsar Prediction: Anisotropy

- However, current exp. do not see any anisotropy

Not Support Pulsar Explanation



- DM Prediction: Isotropic Spectrum

Annihilating DM v.s. Decaying DM

- From the perspective of fitting both experimental results, both scenarios would give essentially the same degree of goodness of fitting, since fitting mainly depends on the injection spectra which can be the same.
- Problem for Annihilating DM:
  - Needing much larger annihilation cross section than that for WIMP relic abundance

  ⇨ Extraordinarily Large boosting factor b~O(1000), possibly due to Sommerfeld Enhancemnet or Resonance Enhancement

  - Such a large boosting factor is incompatible with the one obtained in numerical simulation of LSS formation

Annihilating DM v.s. Decaying DM

- Problem for Annihilating DM: (continued)
  - Due to DM density square dependence, the associated *γ-ray* produced by FSR and IC is enhanced much and already exceeds the Fermi-LAT and EGRET bounds for most channels

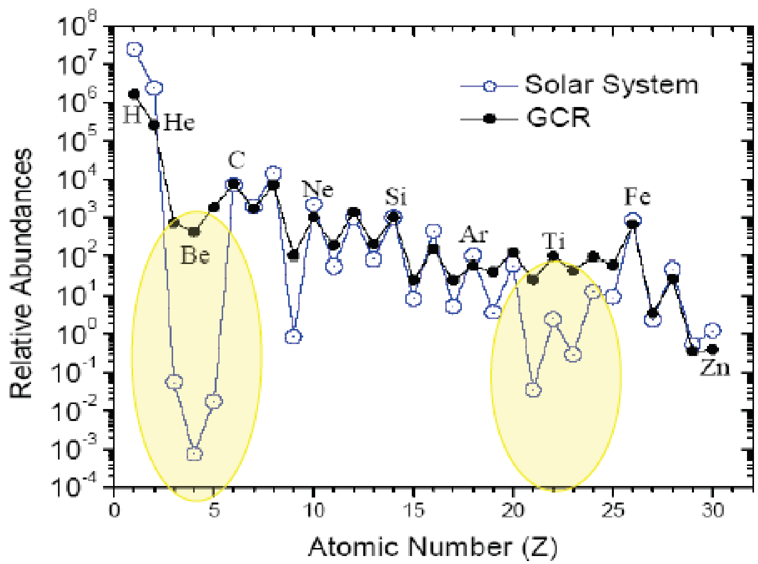
- Decaying DM:
  - Free of such problems, especially for the *γ-ray* bound since the final flux only depends on single power of DM density
  - In order to explain the observed flux, it generically needs the TeV DM lifetime $\tau_{DM} \sim O(10^{26})s$ >> $\tau_{Universe}$ ~ O(10^{17})s
  - Previous fitting shows it seems difficult in fitting AMS-02 and Fermi-LAT simultaneously with leptophilic decaying DM

Jin, Wu, Zhou (2013); Yuan et al. (2013); Bertone et al, PRL(2013); …

Motivation

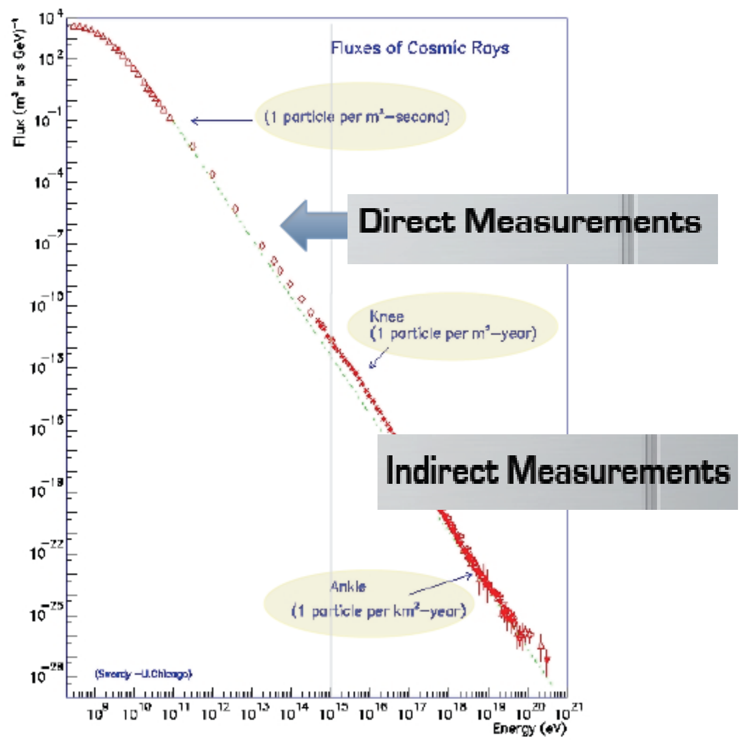
➢ Cosmic ray is an important probe to tell us a lot about the information of our Galaxy and our Universe.

➢ **Composition of CR:**



H	He	C,O,...	e
90%	9%	1%	1%

➢ **Energy Range of CR:**

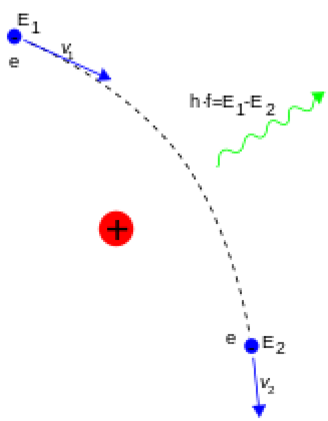


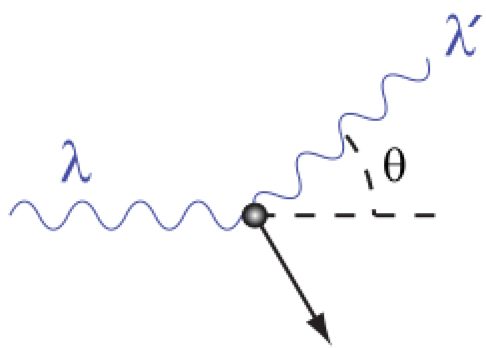
Diffuse γ-ray Origin

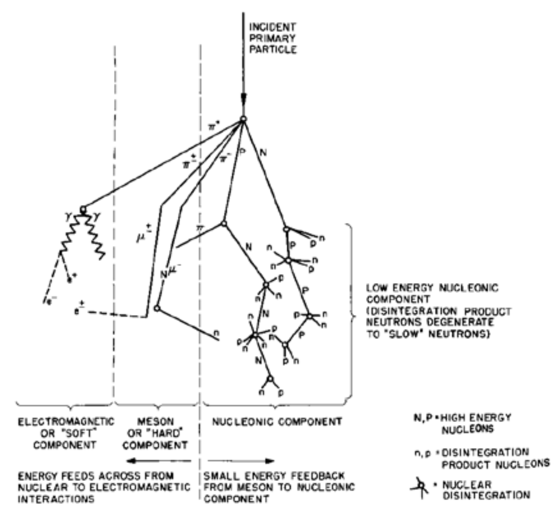
Conventional Contributions (Background):

- Inside the Galaxy:
  - Bremsstralung
  - Inverse Compton(IC) Scattering
  - π^0 decay

GALPROP







Schematic Diagram of Cosmic Ray Shower

Diffuse γ-ray Origin

- Outside the Galaxy: Active Galactic Nuclei (AGN)

$$E^2\Phi_\gamma(E) = 5.18 \times 10^{-7} E^{-0.499} (\mathrm{GeV\,cm^{-2}sr^{-1}s^{-1}})$$

obtained by fitting low energy spectrum of EGRET

K.Ishiwata, S. Matsumoto and T. Moroi PRD 78, 063505 (2008)

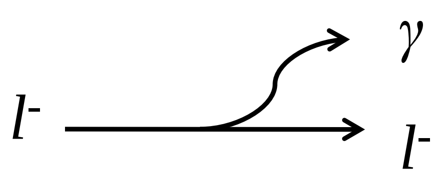
Diffuse γ-ray Origin

DM Contributions (Signal):

- Inside the Galaxy:
  - ✓ DM Electron Diffusion:
    - Bremsstralung
    - Inverse Compton(IC) Scattering

GALPROP

  - ✓ Prompt Decay
    - $e^-(e^+)$: FSR



    - $\mu^-(\mu^+)$: FSR + μ radiative decay ($\mu \rightarrow e\nu\nu\gamma$)
    - $\tau^-(\tau^+)$: FSR + π^0 decay

$$\frac{dN_\gamma}{dy} = y^{-1.31}(6.94y - 4.93y^2 - 0.51y^3)e^{-4.53y}, \text{ where } y = E/E_e$$

Diffuse γ-ray Origin

DM Contributions:

- Outside the Galaxy:
  - ✓ DM Electron Diffusion:
    - Inverse Compton(IC) Scattering: $e^-(e^+)$ with CMB
  - ✓ Prompt Decay
    - $e^-(e^+)$: FSR
    - $\mu^-(\mu^+)$: FSR + μ radiative decay ($\mu \rightarrow e\nu\nu\gamma$)
    - $\tau^-(\tau^+)$: FSR + π^0 decay

Cosmic Expansion: $\left[E^2 \frac{dJ_\gamma}{dE}\right]_{eg} = \frac{E^2 c \Omega_{A'} \rho_c}{4\pi m_{A'} \tau_{A'} H_0 \Omega_M^{1/2}} \int_1^{y_{eq}} dy \frac{dN_\gamma}{d(yE)} \frac{y^{-3/2}}{\sqrt{1 + \frac{\Omega_\Lambda}{\Omega_M} y^{-3}}},$