DM "Transporting" Mechanism for Cosmic-Ray Excesses

D. Kim, **JCP** & S. Shin [arXiv:1702.02944]
& Work in progress

Jong-Chul Park

CNU 충남대학교
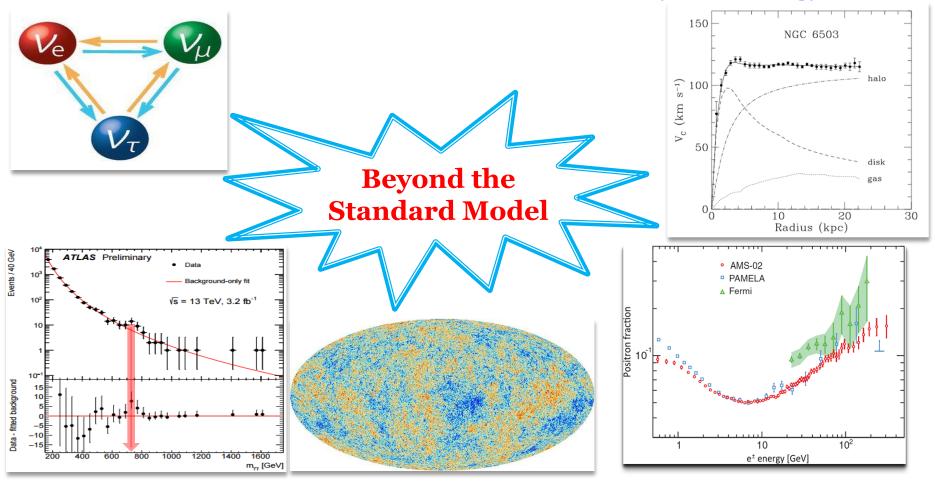CHUNGNAM NATIONAL UNIVERSITY

Things to Do/See/Eat ~

How many things

have you completed?

Need for New Physics

❖ On top of theory motivation, there are various real & hopefully-real motivations for new physics.
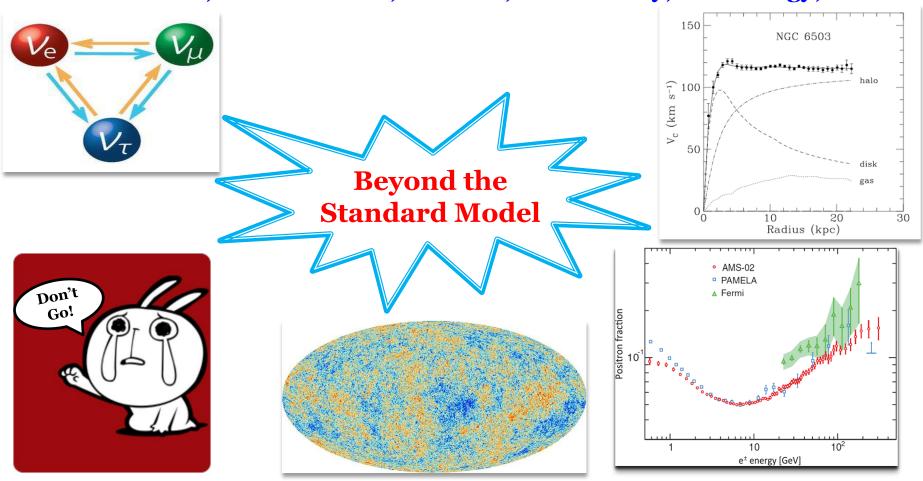
Neutrino, Dark Matter, Collider, Cosmic-Ray, Cosmology, ...

Beyond the Standard Model

Need for New Physics

❖ On top of theory motivation, there are various real & hopefully-real motivations for new physics.

Neutrino, Dark Matter, Collider, Cosmic-Ray, Cosmology, ...

Beyond the Standard Model

Don't Go!

Need for New Physics

❖ On top of theory motivation, there are various real & hopefully-real motivations for new physics.

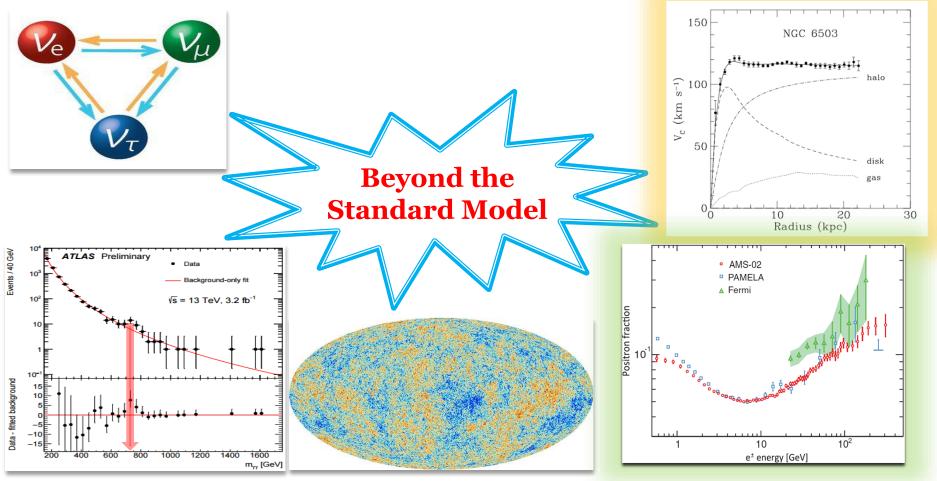**Neutrino, Dark Matter, Collider, Cosmic-Ray, Cosmology, ...**

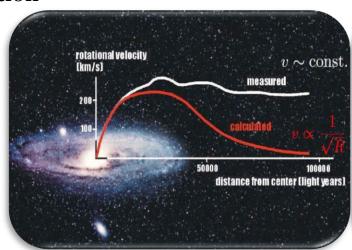**Beyond the Standard Model**

Dark Matter (DM)

❖ **DM**: ~25% of our Universe

❖ **Compelling paradigm**:
massive, non-luminous & stable particles

❖ **Evidence**
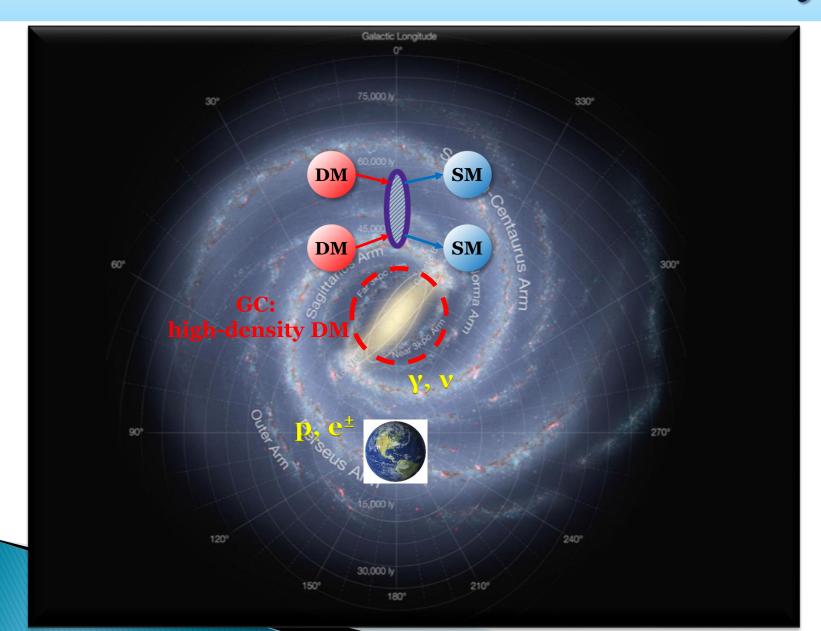
- ✓ Galaxy rotation curve
- ✓ Bullet cluster
- ✓ Gravitational lensing
- ✓ Structure formation
- ✓ CMB
- ✓ Coma Cluster
- ✓ Sky surveys
- ✓ …

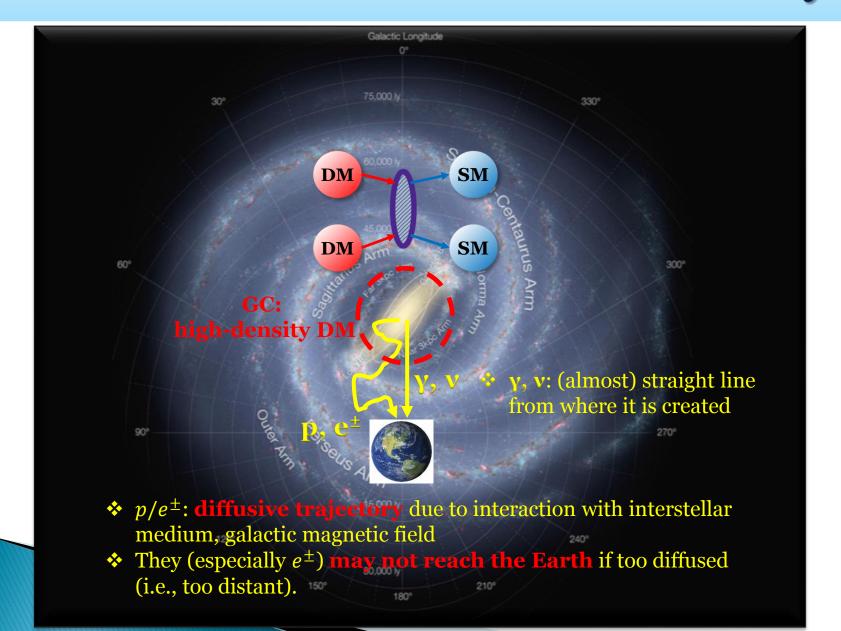5% Visible Matter

25% Dark Matter

70% Dark Energy

rotational velocity [km/s]

$v \sim$ const.

measured

200

100

calculated

$v \propto \dfrac{1}{\sqrt{R}}$

50000   100000

distance from center [light years]

Indirect Detection: Cosmic-Rays

Indirect Detection: Cosmic-Rays

DM — SM

DM — SM

GC: high-density DM

γ, ν

$p, e^{\pm}$

❖ γ, ν: (almost) straight line from where it is created

❖ $p/e^{\pm}$: **diffusive trajectory** due to interaction with interstellar medium, galactic magnetic field

❖ They (especially $e^{\pm}$) **may not reach the Earth** if too diffused (i.e., too distant).

Cosmic-Ray Experiments

❖ **Ground-based**
MAGIC, HESS, CTA, IceCube, Super-K, Hyper-K, …

❖ **Balloon-based**:
ATIC, PPB-BETS, …

❖ **Satellite-based**:
AMS, Chandra, Fermi-LAT, PAMELA, XMM-Newton, Hitomi, ASTROGAM, …

✓ Great sensitivity to cosmic-ray signals

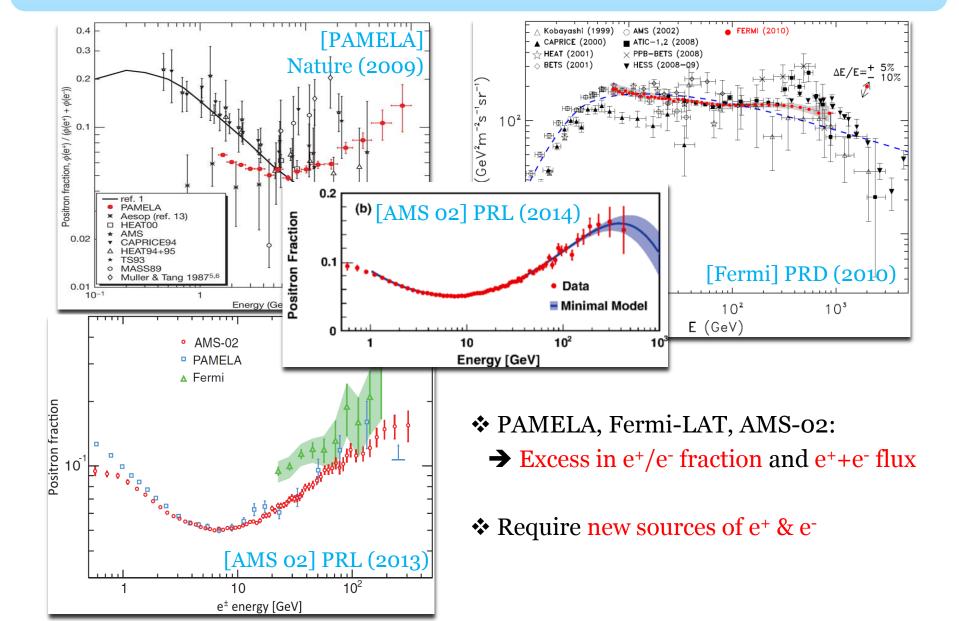✓ Better chance to have the information for extracting DM properties

IceCube

ATIC

CTA

Fermi-LAT

Hints from Cosmic-Rays?

❖ DM signatures in cosmic-ray observations?

- ➢ SPI/INTEGRAL ($\gamma \rightarrow e^+$): 511 keV line

- ➢ PAMELA ($e^\pm$, $p^\pm$, ...): e^+ excess

- ➢ ATIC (e^-e^+): e^-e^+ excess

- ➢ Fermi-LAT (e^-e^+, γ): e^-e^+ excess, 130 GeV line, GeV excess

- ➢ AMS-02 ($e^\pm$, $p^\pm$, ...): e^+ excess

- ➢ XMM-Newton (X-ray): 3.5 keV line

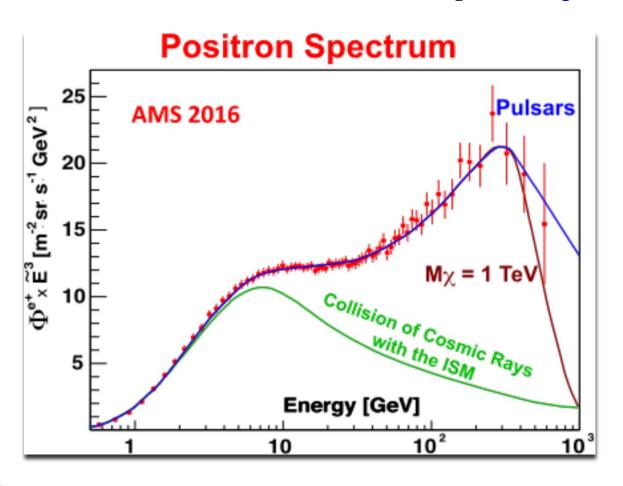- ➢ IceCube (ν): PeV events

- ➢ ...

Hints from Cosmic-Rays?

❖ DM signatures in cosmic-ray observations?

- ➤ SPI/INTEGRAL ($\gamma \rightarrow e^+$): 511 keV line

- ➤ PAMELA ($e^\pm$, $p^\pm$, ...): e$^+$ excess

- ➤ ATIC (e^-e^+): e$^-$e$^+$ excess

- ➤ Fermi-LAT (e^-e^+, γ): e$^-$e$^+$ excess, 130 GeV line, GeV excess

- ➤ AMS-02 ($e^\pm$, $p^\pm$, ...): e$^+$ excess

- ➤ XMM-Newton (X-ray): 3.5 keV line

- ➤ IceCube (ν): PeV events

- ➤ ...

DM Indirectly Detected? (e±)

[PAMELA] Nature (2009)

[AMS 02] PRL (2014)

[Fermi] PRD (2010)

[AMS 02] PRL (2013)

❖ PAMELA, Fermi-LAT, AMS-02:
  ➔ Excess in e+/e- fraction and e++e- flux

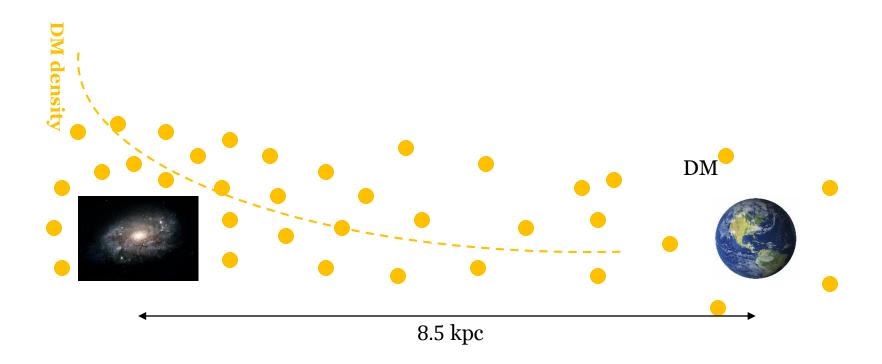❖ Require new sources of e+ & e-

e⁺ Excesses: AMS-02 in 2016

❖ I will talk about a New Mechanism for e⁺ excesses having DM interpretations in mind.

Typical DM Interpretation
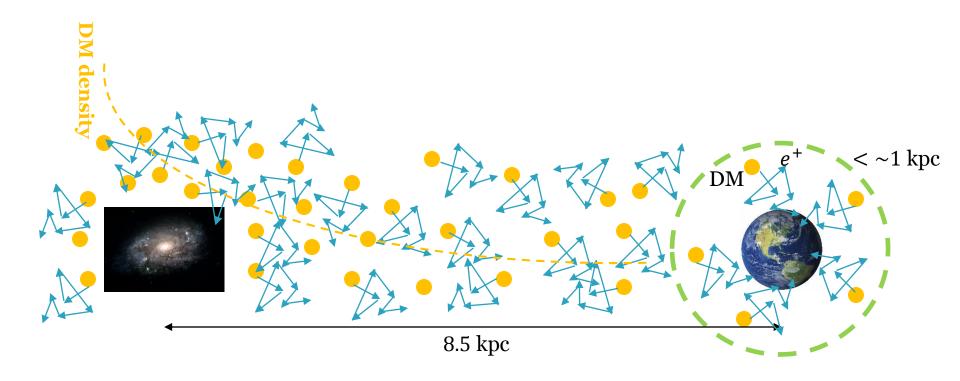
❖ DM particles most densely populate around the GC in our galaxy.

DM density

DM

8.5 kpc
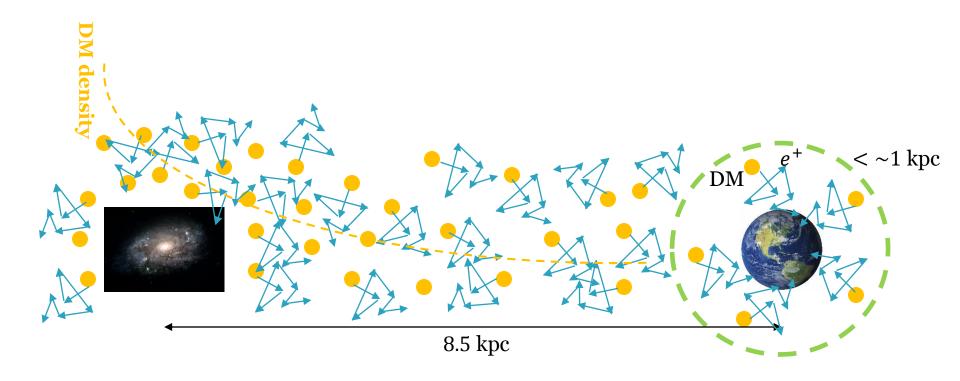
Typical DM Interpretation

❖ Dominant contribution by e⁺'s from DM annihilation near the Earth (< ~1 kpc)
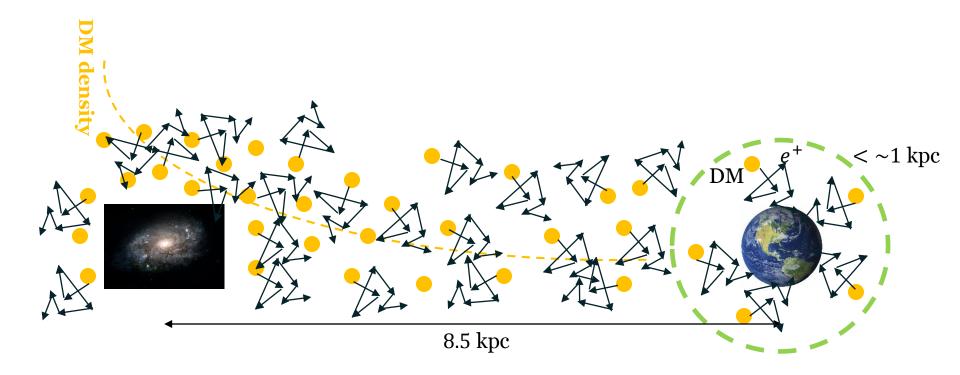
Typical DM Interpretation

❖ Dominant contribution by e$^+$'s from DM annihilation near the Earth (< ~1 kpc)

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: not enough flux expected from known ρ & $\langle \sigma v \rangle$ (~10^{-3} -10^{-4} smaller)
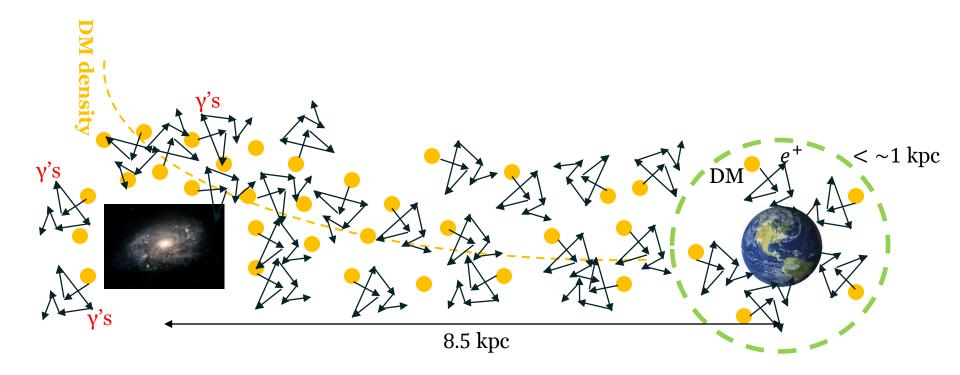
$\rho_\odot \sim$ 0.3-0.4 GeV/cm^3 $\langle \sigma v \rangle_{FO} \sim$ (2-3)×10^{-26} cm^3/s

DM density

DM

e^+ < ~1 kpc

8.5 kpc

Previous Mechanisms: Enhancing <σv>

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: **Enhancing $\langle \sigma v \rangle$**

➢ Only in the current universe: Sommerfeld enhancement [Hisano et. al. (2002), Arkani-Hamed et. al. (2008)]

➢ Even in the early universe: Relic from late decays of other dark-sector particles [Fairbairn & Zupan (2008)]
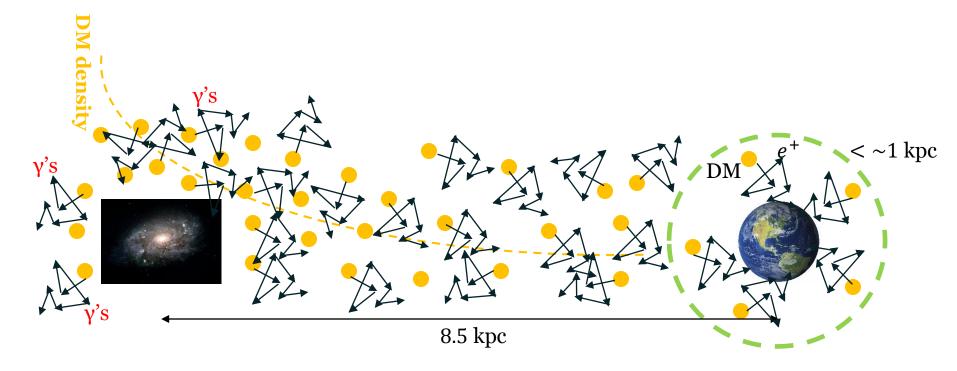
Previous Mechanisms: Enhancing <σν>

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: **Enhancing $\langle \sigma v \rangle$**

  ➢ Only in the current universe: Sommerfeld enhancement [Hisano et. al. (2002), Arkani-Hamed et. al. (2008)]

  ➢ Even in the early universe: Relic from late decays of other dark-sector particles [Fairbairn & Zupan (2008)]
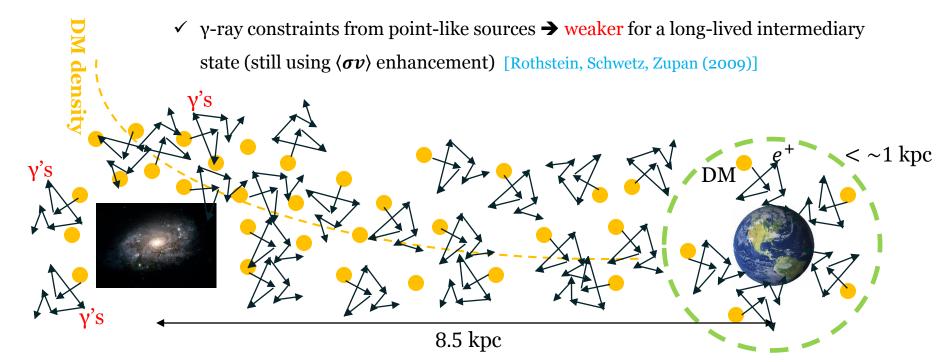
❖ Strong constraints from γ-ray flux (in particular, from GC & dwarfs)

Previous Mechanisms: Enhancing $\langle \sigma v \rangle$

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: **Enhancing $\langle \sigma v \rangle$**

  ➢ Only in the current universe: Sommerfeld enhancement [Hisano et. al. (2002), Arkani-Hamed et. al. (2008)]

  ➢ Even in the early universe: Relic from late decays of other dark-sector particles [Fairbairn & Zupan (2008)]

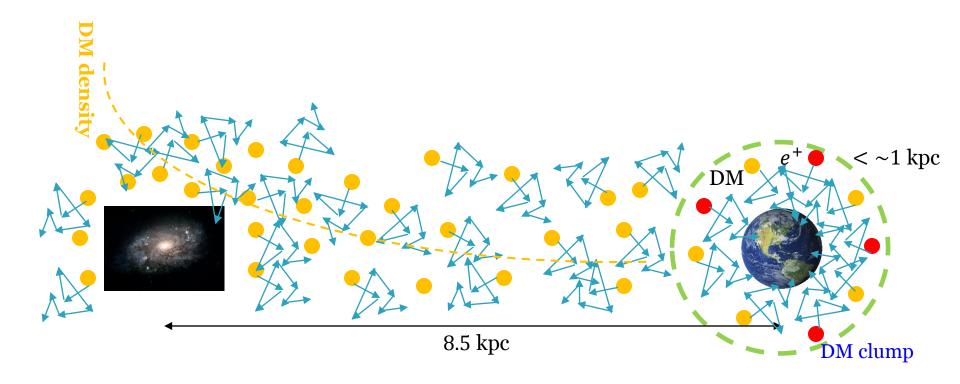❖ Strong constraints from γ-ray flux (in particular, from GC & dwarfs)

  ➢ Cf. decaying DM models: $\Phi \sim \rho \Gamma$ ($\tau \sim 10^{26}$ sec) [Chen, Takahashi, Yanagida (2008)]

Previous Mechanisms: Enhancing <σv>

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: **Enhancing $\langle \sigma v \rangle$**

  ➤ Only in the current universe: Sommerfeld enhancement [Hisano et. al. (2002), Arkani-Hamed et. al. (2008)]

  ➤ Even in the early universe: Relic from late decays of other dark-sector particles [Fairbairn & Zupan (2008)]

❖ Strong constraints from γ-ray flux (in particular, from GC & dwarfs)

  ➤ Cf. decaying DM models: $\Phi \sim \rho \Gamma$ ($\tau \sim 10^{26}$ sec) [Chen, Takahashi, Yanagida (2008)]

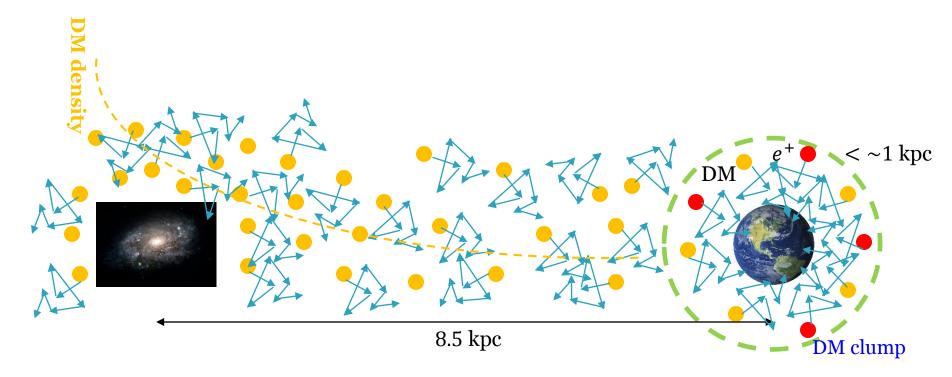   ✓ γ-ray constraints from point-like sources ➜ weaker for a long-lived intermediary state (still using $\langle \sigma v \rangle$ enhancement) [Rothstein, Schwetz, Zupan (2009)]

Previous Mechanisms: Enhancing $\rho_\odot$

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: **Enhancing DM density** itself

  ➤ Local DM clumps near the Earth
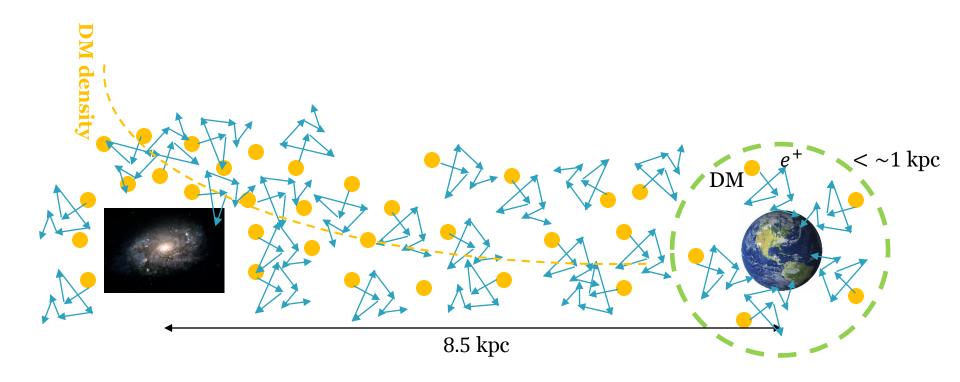
Previous Mechanisms: Enhancing $\rho_\odot$

❖ $\Phi_{e+} \propto \rho^2 \langle \sigma v \rangle$: **Enhancing DM density** itself

  ➤ Local DM clumps near the Earth

❖ Not enough local clumps to produce the observed e+ flux

  ➤ N-body simulation ➔ enhancement by a factor of < ~10 [Lavalle et al. (2007)]

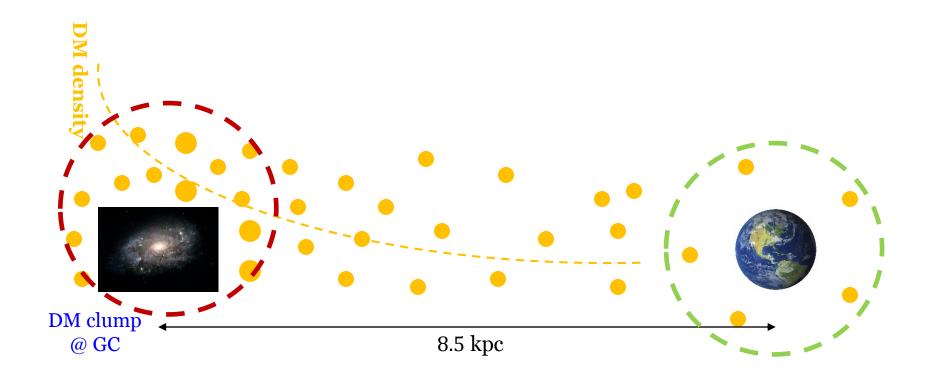 ➤ Subhalos ➔ 1/3 of the required enhancement can be explained [Cline, Vincent, Xue (2010)]

Previous Mechanisms

"Challenging" to explain e+ excesses

with typical (minimal) DM scenarios!

DM "Transporting" Mechanism

❖ We already have a big DM clump at the GC.

DM density

DM clump
@ GC

8.5 kpc

DM "Transporting" Mechanism

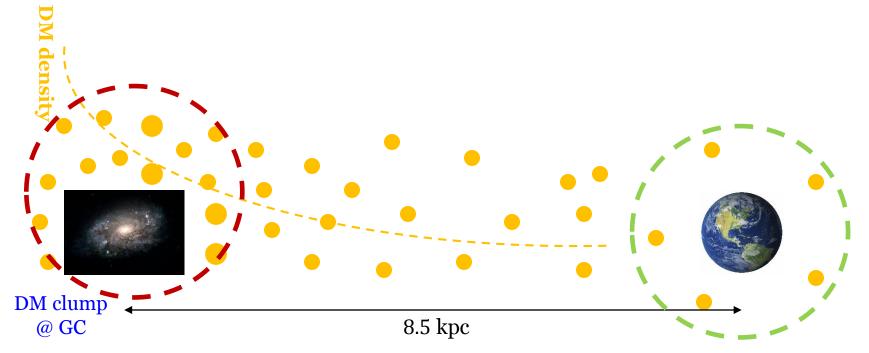❖ We already have a big DM clump at the GC.

Neither enhancing annihilation strength nor the introduction of additional DM clumps

(➔ no severe conflicts/issues associated with conventional mechanisms)
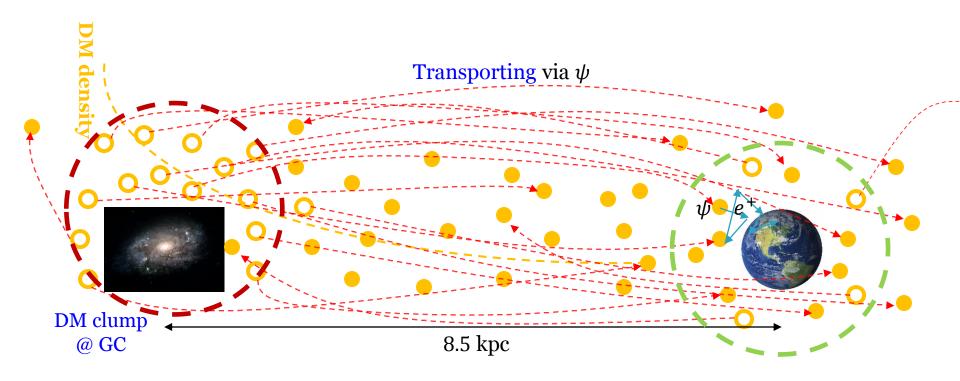
e+'s created near the GC can not reach the Earth!

DM density

DM clump
@ GC

8.5 kpc

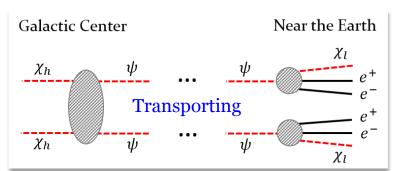# DM "Transporting" Mechanism

❖ "**Transporting**" (effectively) DM at the GC to the vicinity of the Earth via a "proxy" ψ

DM density

Transporting via ψ

ψ e^+

DM clump
@ GC

8.5 kpc

DM "Transporting" Mechanism

❖ "**Transporting**" (effectively) DM at the GC to the vicinity of the Earth via a "proxy" ψ

❖ $2\chi_h \rightarrow 2\psi$ & $\psi \rightarrow e^+e^-\chi_l + \ldots$

➤ χ_h: heavier DM, dominant relic, no direct coupling to SM

➤ ψ : heavy "meta"-stable dark sector state

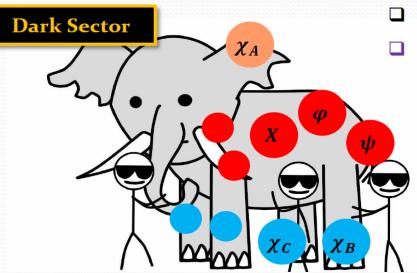➤ χ_l: lighter DM, subdominant relic, direct coupling to SM

Galactic Center   Near the Earth

Transporting

Retarded decay

Transporting via ψ

DM density

DM clump
@ GC

8.5 kpc

"Flavorful" Dark-sector Scenarios

● **In what sense?**

Dark Sector

☐ χ_A: **dominant relic** (as in the minimal setup)

☐ **More members** in the dark sector

   ✓ **Unstable members**, say $\psi,\ \varphi,\ X, \dots$ (e.g., cosmic ray excess interpretations [**DK** and J.-C. Park (2015)])

   ✓ **More dark matter species**, say $\chi_B, \chi_B \dots$ (e.g., dynamical dark matter models [K. Dienes and B. Thomas, (2011)])

☐ **Rising interest**

  ❖ Boosted dark matter scenarios [K. Agashe et al., (2014); K. Kong, G. Mohlabeng, J.-C. Park (2014)]

  ❖ Assisted freeze-out mechanism [G. Belanger and J.-C. Park (2011)]

  ❖ Dark matter "transporting" mechanism [**DK**, J.-C. Park and S. Shin (2017)]

Data Analysis

● **Parameter choice**

❖ $\langle \sigma v \rangle \sim 3 \cdot 10^{-26}$ cm^3/s (conventional value: to be consistent with relevant observation)

❖ $\tau_\psi^{lab} = 1/\Gamma_\psi^{lab} = \gamma_\psi \tau_\psi = \sim 10^{12}$ s with $\gamma_\psi = m_h / m_\psi$

(~time needed to travel from GC to the Earth, theoretically viable)

❖ With ordinary DM halo profiles, $O(1)$ enhancement (→ not enough to produce ψ?)

✓ Large uncertainty in DM density near the GC
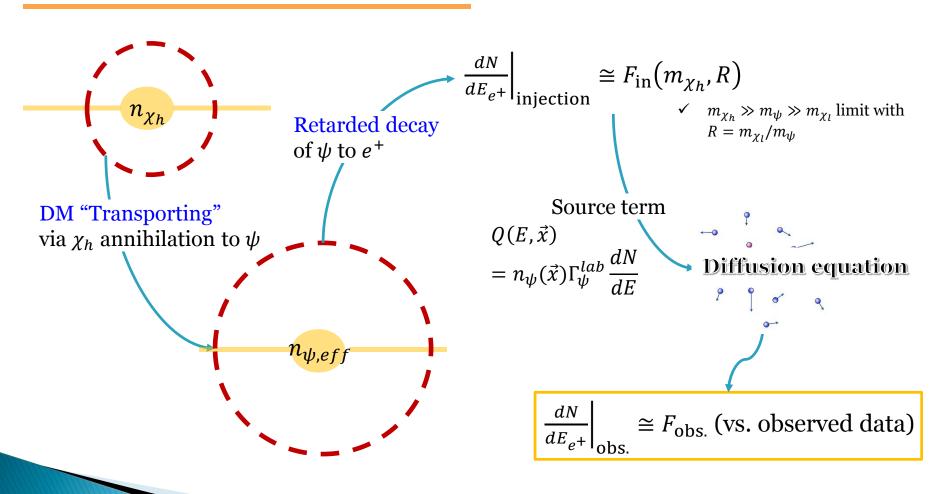
✓ Simple "toy" DM density profile:

$$\rho_{\chi_A}(y) = \begin{cases} \rho_\odot \dfrac{(y/y_s)^{-1}}{(1+y/y_s)^2} \equiv \rho_{\text{NFW}}(y) & \text{for } y \geq y_C \\ \mathcal{N} \times \rho_{\text{NFW}}(y_C) & \text{for } y < y_C \end{cases}$$

y_C: core size, y_s: scale radius

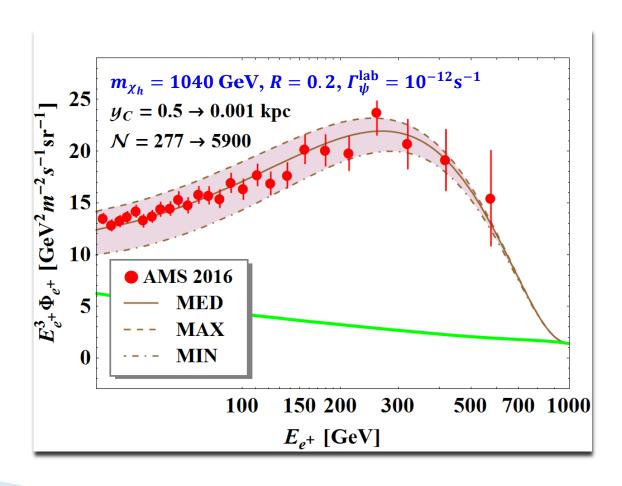ρ_{NFW}: Navarro-Frenk-White DM density profile

Data Analysis

● **Complete story in a nutshell**

n_{χ_h}

DM "Transporting"
via χ_h annihilation to ψ

Retarded decay
of ψ to e^+

$n_{\psi,eff}$

$$\left.\frac{dN}{dE_{e^+}}\right|_{\text{injection}} \cong F_{\text{in}}\left(m_{\chi_h}, R\right)$$

✓ $m_{\chi_h} \gg m_\psi \gg m_{\chi_l}$ limit with
$R = m_{\chi_l}/m_\psi$

Source term
$$Q(E, \vec{x})$$
$$= n_\psi(\vec{x})\Gamma_\psi^{lab}\frac{dN}{dE}$$

Diffusion equation

$$\left.\frac{dN}{dE_{e^+}}\right|_{\text{obs.}} \cong F_{\text{obs.}} \text{ (vs. observed data)}$$

Fit Results: AMS-o2 (2016)
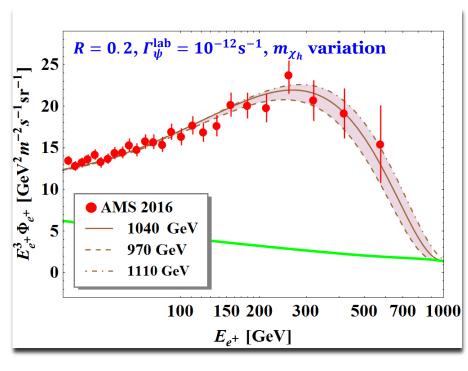
❖ The best-fit with the variations of y_C, N, and the propagation model

Fit Results: AMS-02 (2016)
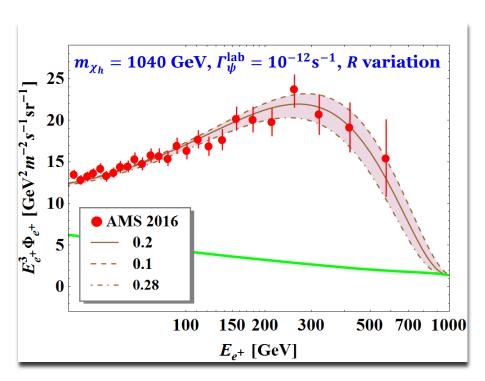
❖ The fit sensitivities to m_{χ_h} and $R = m_{\chi_l}/m_\psi$

Left plot: $R = 0.2$, $\Gamma_\psi^{\text{lab}} = 10^{-12} s^{-1}$, m_{χ_h} **variation**

Legend (left): AMS 2016; 1040 GeV; 970 GeV; 1110 GeV

Axes: $E_{e^+}^3 \Phi_{e^+}$ [GeV$^2 m^{-2} s^{-1} sr^{-1}$] vs E_{e^+} [GeV]

Right plot: $m_{\chi_h} = 1040$ GeV, $\Gamma_\psi^{\text{lab}} = 10^{-12} s^{-1}$, R **variation**

Legend (right): AMS 2016; 0.2; 0.1; 0.28

Axes: $E_{e^+}^3 \Phi_{e^+}$ [GeV$^2 m^{-2} s^{-1} sr^{-1}$] vs E_{e^+} [GeV]

➢ m_h ➜ maximum e$^+$ energy

➢ Larger R ➜ softer spectrum

Conclusions

❖ More interesting results from cosmic-ray measurements

❖ Rising interest in non-minimal dark sector physics (Doojins Kim's talk)

❖ Non-minimal/flavorful dark sector scenarios may provide dramatic phenomenology different from that in the minimal one.

   ✓ DM "Collider": new DM search strategies (Doojin Kim's talk)

   ✓ DM "Transporting" Mechanism: new mechanism for cosmic-ray excesses

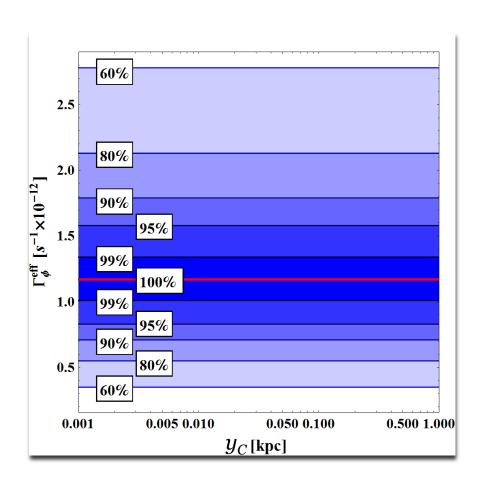   ➔ We can use an already existing big DM clump at the GC.

Conclusions

❖ More interesting results from cosmic-ray measurements

❖ Rising interest in non-minimal dark sector physics (Doojins Kim's talk)

❖ Non-minimal/flavorful dark sector scenarios may provide dramatic phenomenology different from that in the minimal one.

 ✓ DM "Collider": new DM search strategies (Doojin Kim's talk)

 ✓ DM "Transporting" Mechanism: new mechanism for cosmic-ray excesses
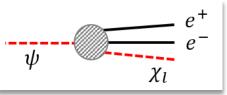
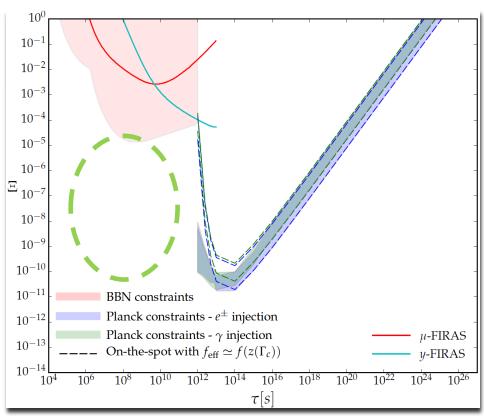 ➔ We can use an already existing big DM clump at the GC.
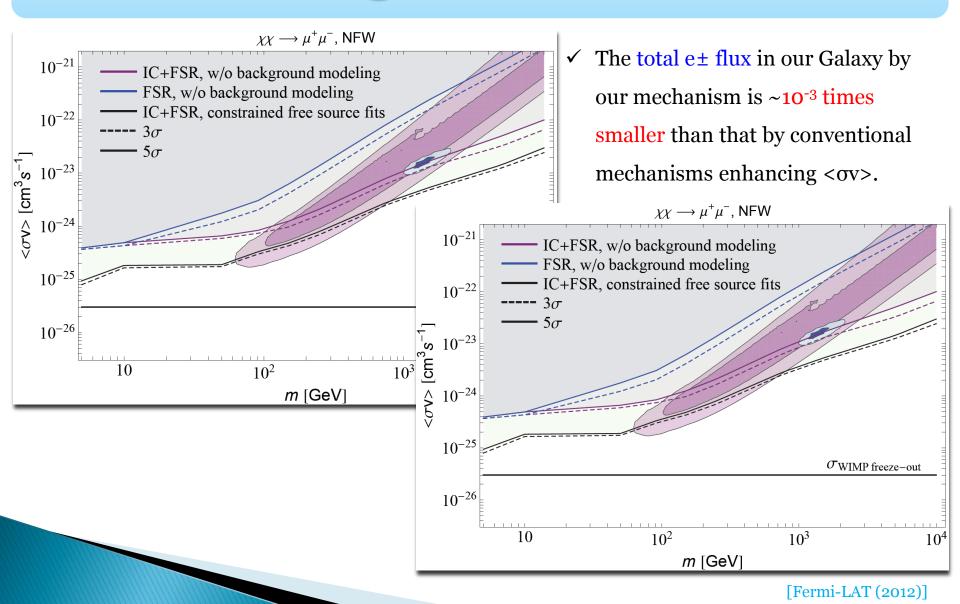
Thank you

Back-Up

Correlation/Tuning of y_C vs Γ_ϕ^{lab}

BBN & CMB Constraints

$\Xi = (\rho/\rho_{\mathrm{DM}}) \cdot (\text{Decay E into } \gamma\text{'s \& } e^{\pm})$

[Poulin et al. (2016)]

IC Scattering Constraints

$\chi\chi \to \mu^+\mu^-$, NFW

- IC+FSR, w/o background modeling
- FSR, w/o background modeling
- IC+FSR, constrained free source fits
- 3σ
- 5σ

✓ The total e± flux in our Galaxy by our mechanism is ~10^{-3} times smaller than that by conventional mechanisms enhancing <σv>.

[Fermi-LAT (2012)]
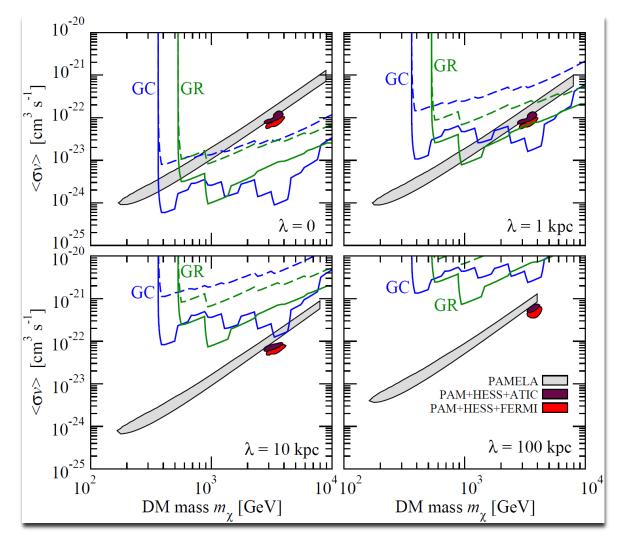
Gamma-ray Constraints

❖ γ-ray constraints from point-like sources become weaker for a long-lived intermediary state.

[Rothstein, Schwetz, Zupan (2009)]