
Non-minimal Dark Sector Phenomenology:
DM "Transporting" Mechanism
Phenomenology 2017 Symposium
arXiv: 1702.02944 with Doojin Kim & Seodong Shin
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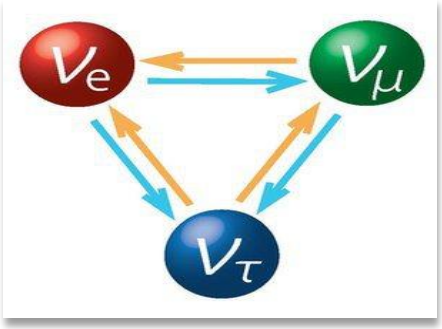
THE DARK WORLD
05.09.2017

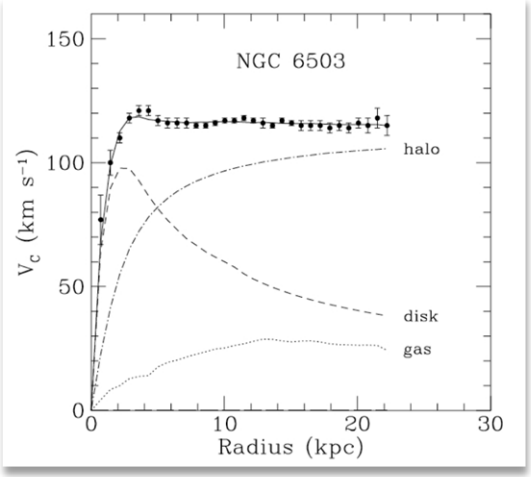
Need for New Physics

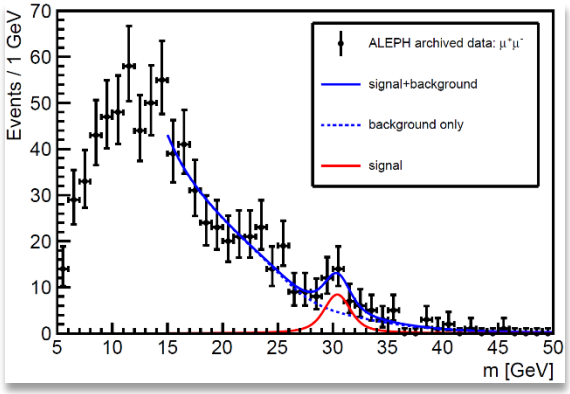
- On top of theory motivation, there are various real & hopefully-real motivations for new physics.

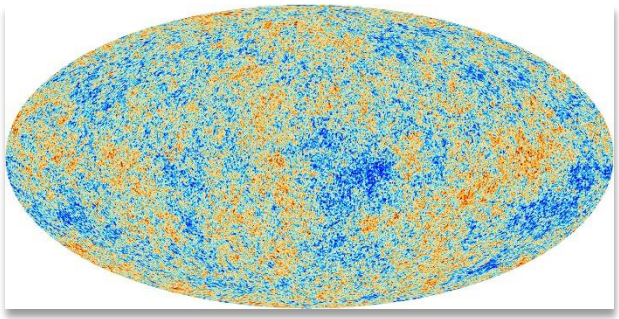
Neutrino, Dark Matter, Collider, Cosmic-Ray, Cosmology, …

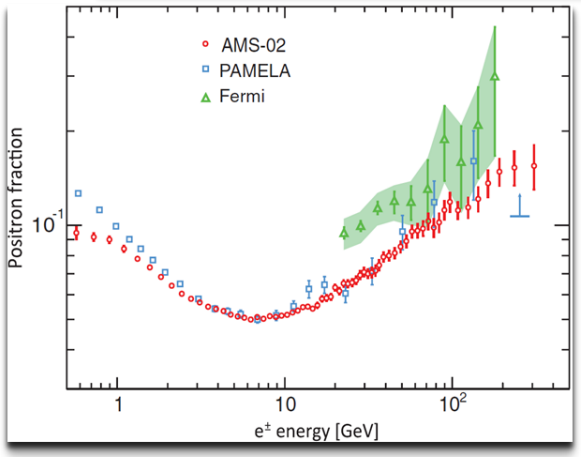


Beyond the Standard Model









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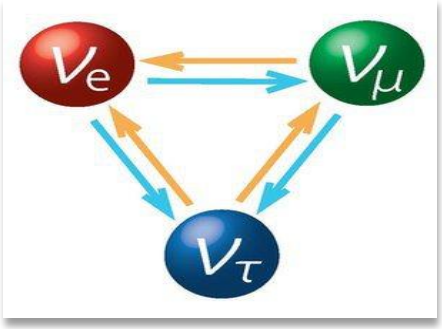

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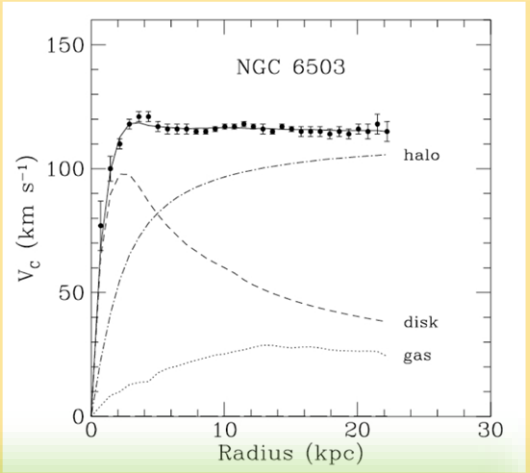
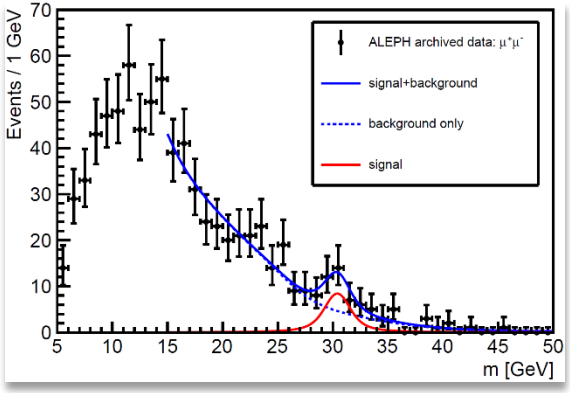
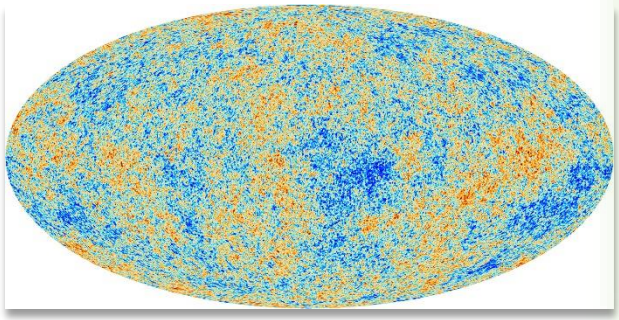
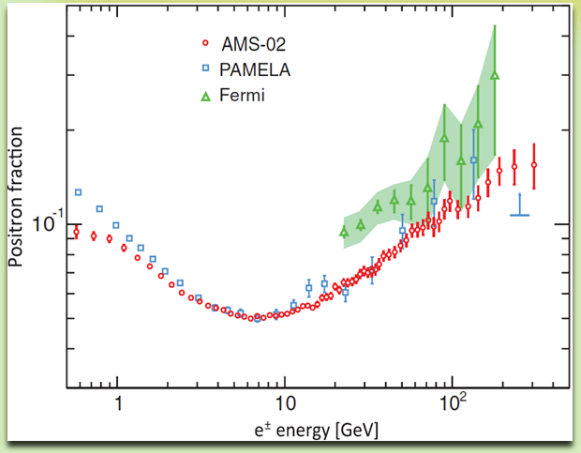
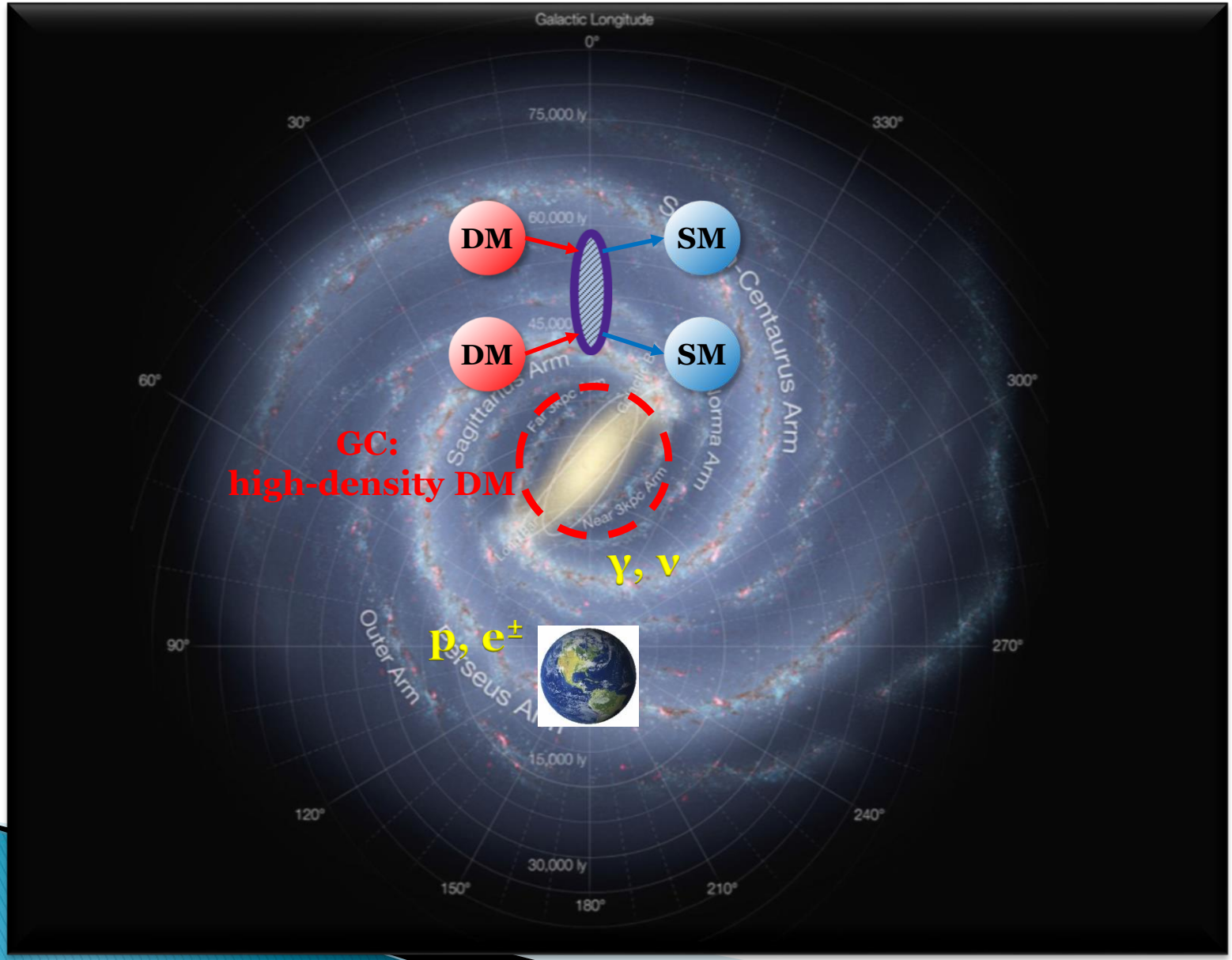








Indirect Detection: Cosmic-Rays



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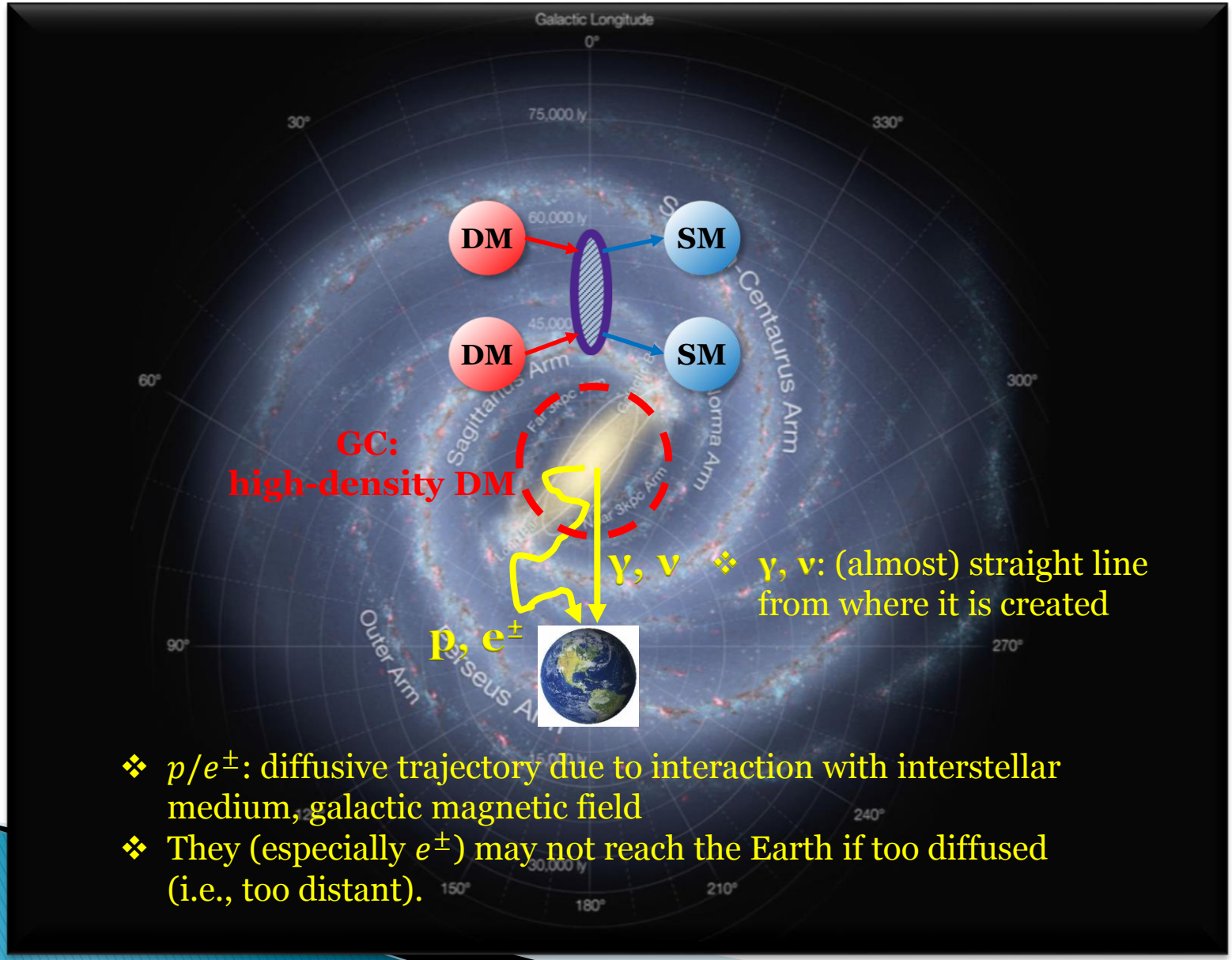
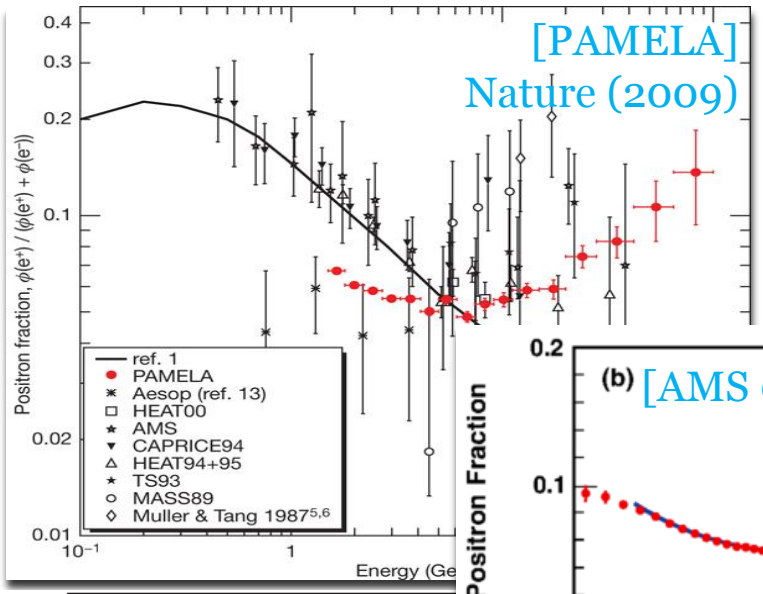
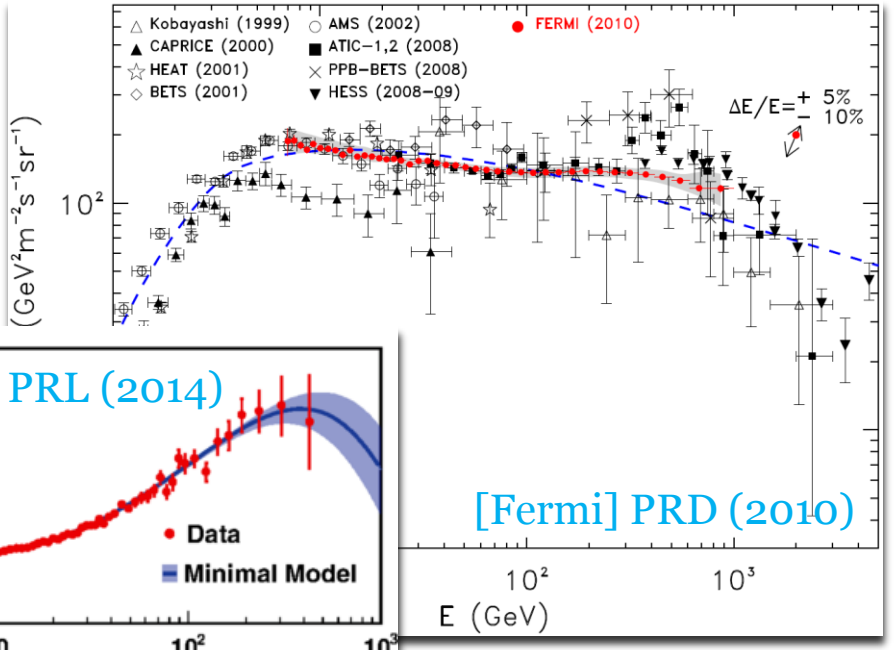


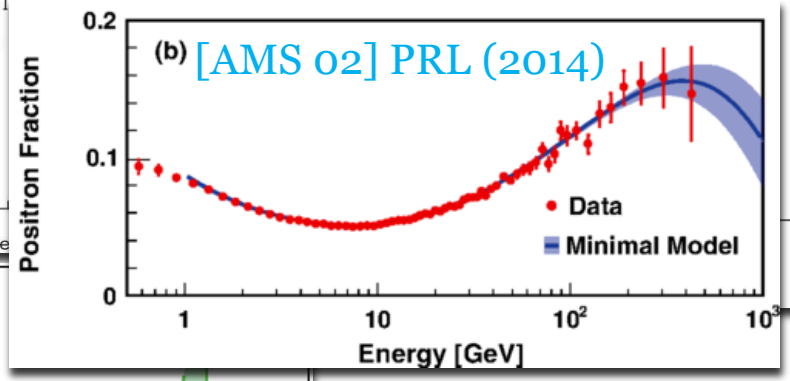
- γ, ν: (almost) straight line from where it is created

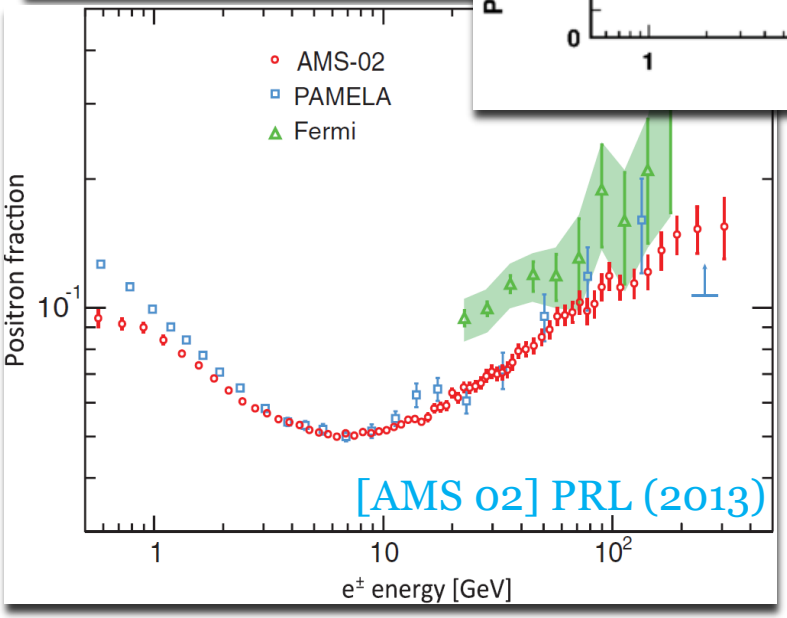
- $p/e^{\pm}$: diffusive trajectory due to interaction with interstellar medium, galactic magnetic field
- They (especially $e^{\pm}$) may not reach the Earth if too diffused (i.e., too distant).

DM Indirectly Detected? ($e^{\pm}$)





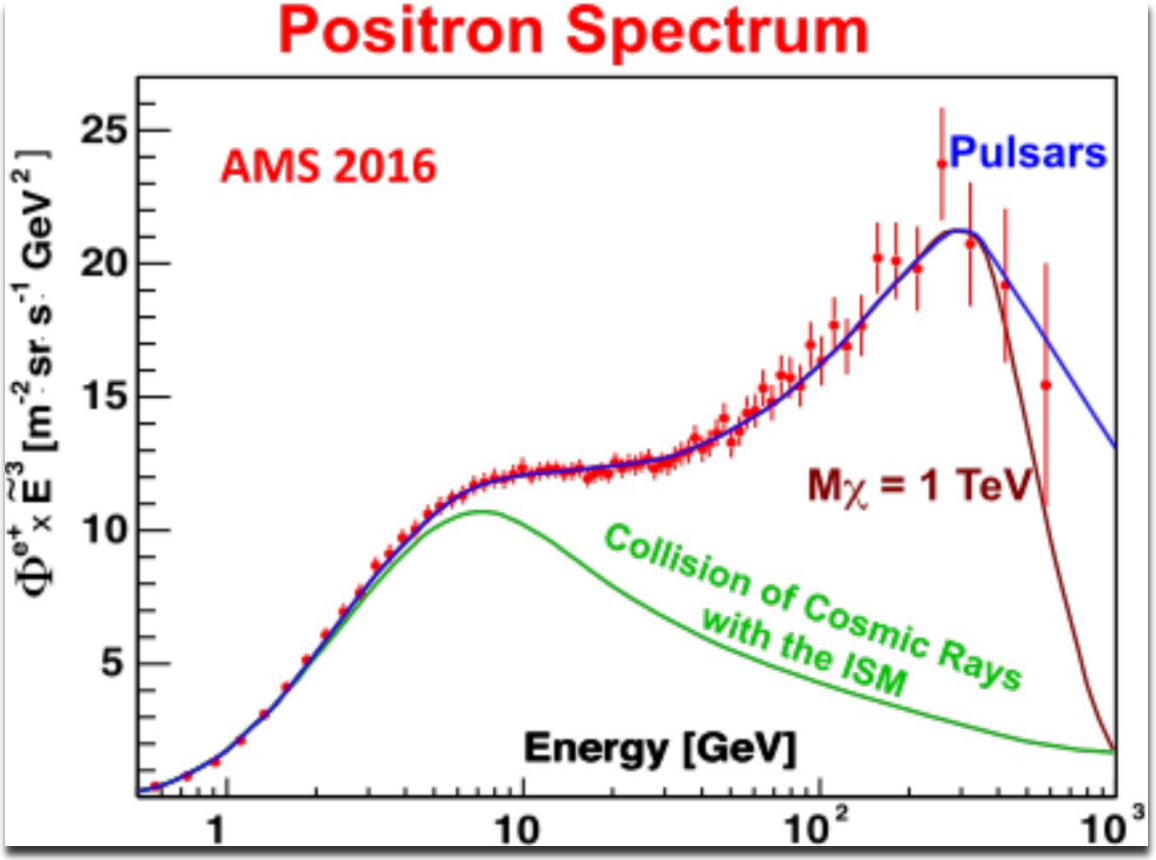




- PAMELA, Fermi-LAT, AMS-02:
  - ➔ Excess in e^+/e^- fraction and $e^+ + e^-$ flux
- Require new sources of e^+ & e^-

e^+ Excesses: AMS-02 in 2016

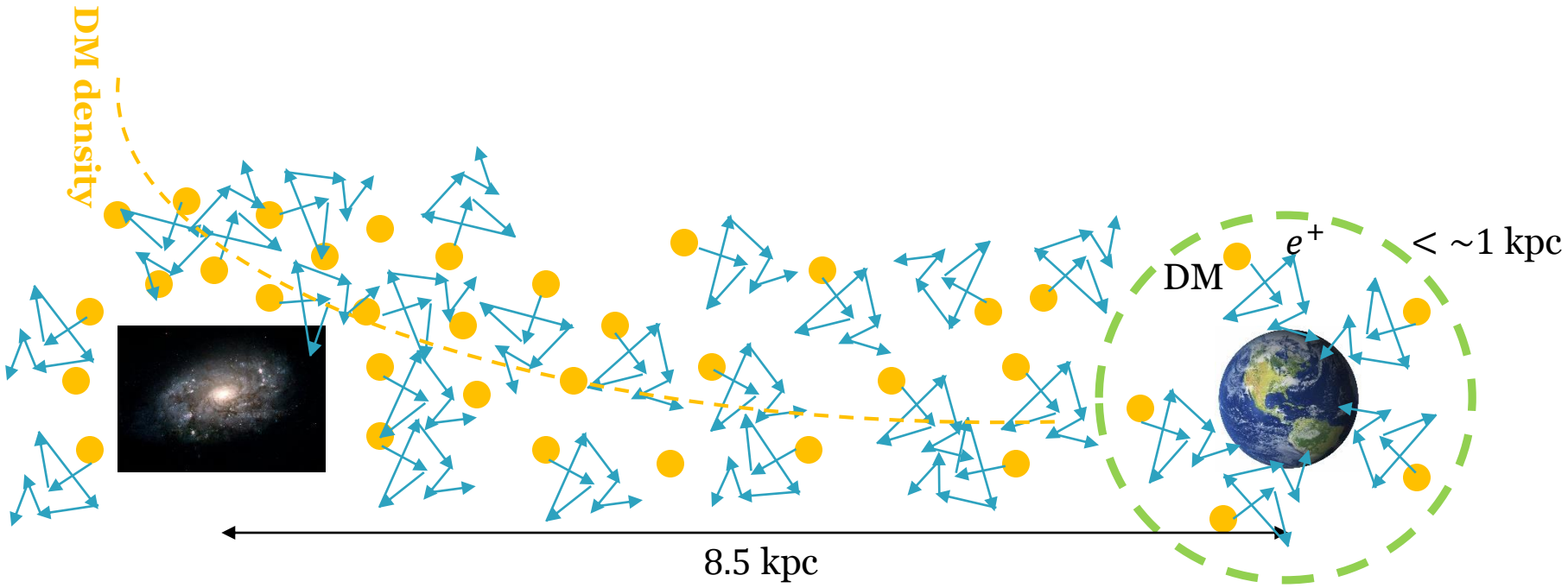
❖ I will talk about a New Mechanism for e^+ excesses having DM interpretations in mind.



Typical DM Interpretation

- 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)

$\rho_\odot$~ 0.3-0.4 GeV/cm^3 $\quad$ $\langle \sigma v \rangle_{FO}$ ~ (2-3)×10^{-26} cm^3/s



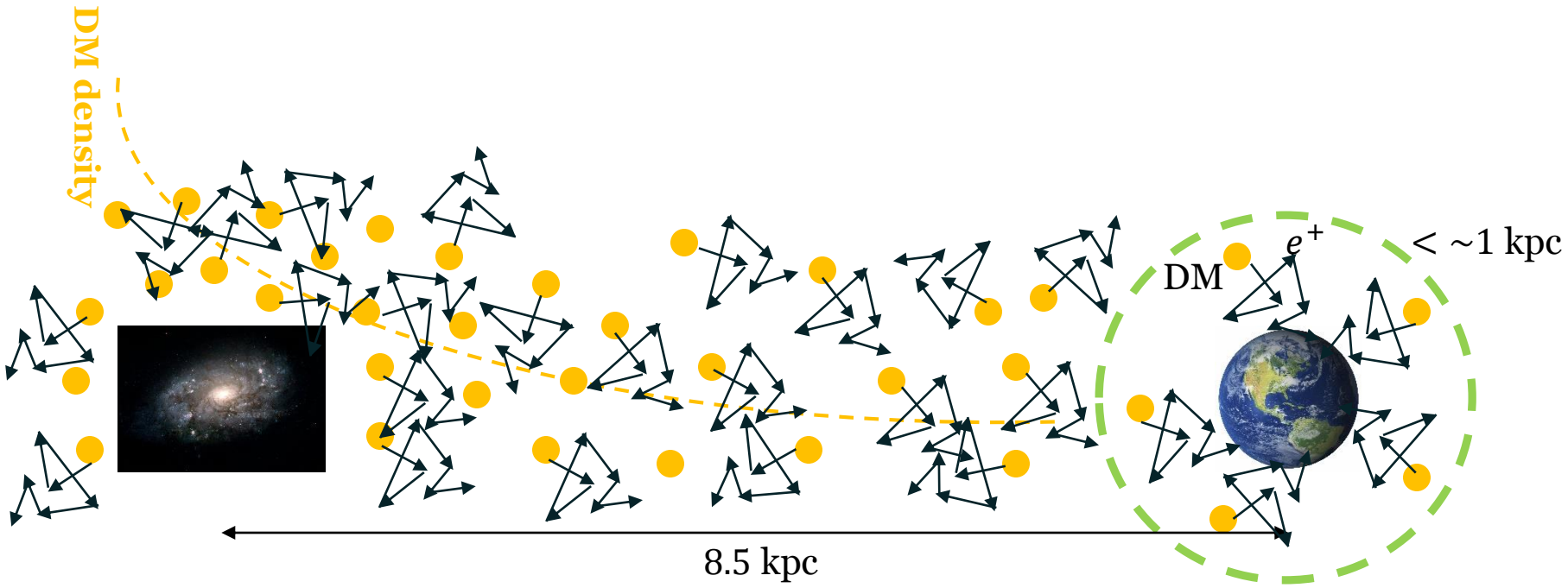
Previous Mechanisms: Enhancing <σv>

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

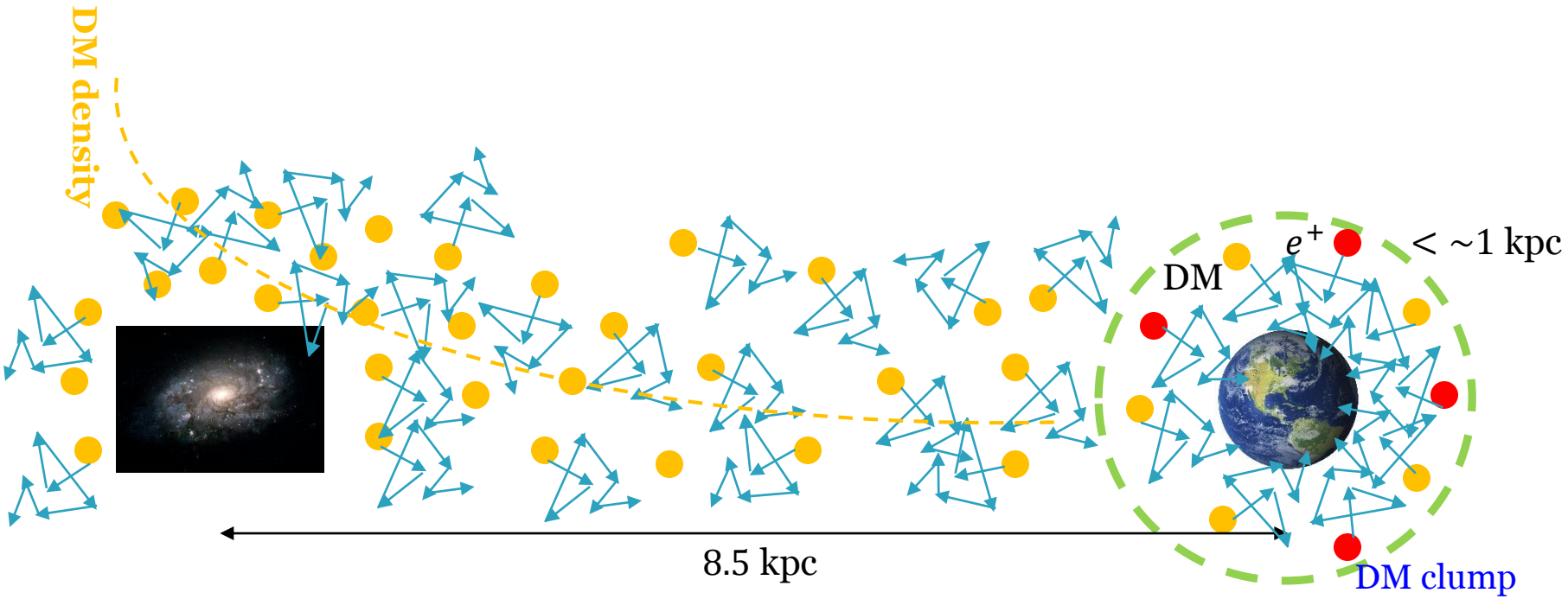
❖ Strong constraints from γ-ray flux (in particular, from GC & dwarfs)

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



Previous Mechanisms: Enhancing $\rho_\odot$

- $\Phi_{e+} \propto \boldsymbol{\rho^2}\langle\sigma v\rangle$: **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)]



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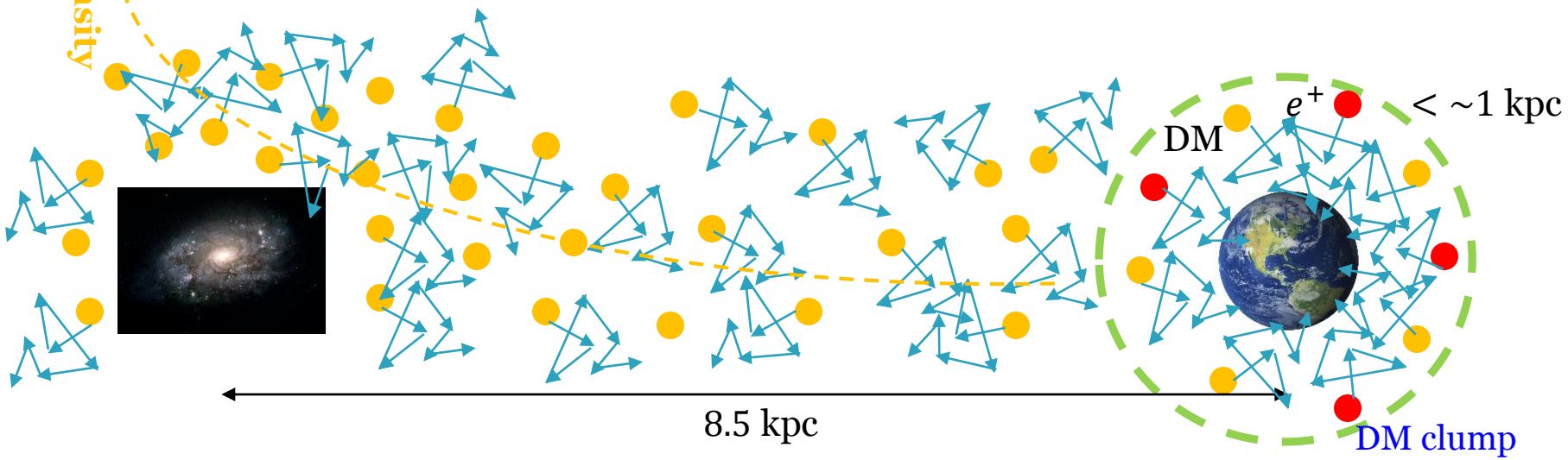
"Challenging" to explain e^+ excesses with minimal (typical) DM scenarios!



DM "Transporting" Mechanism

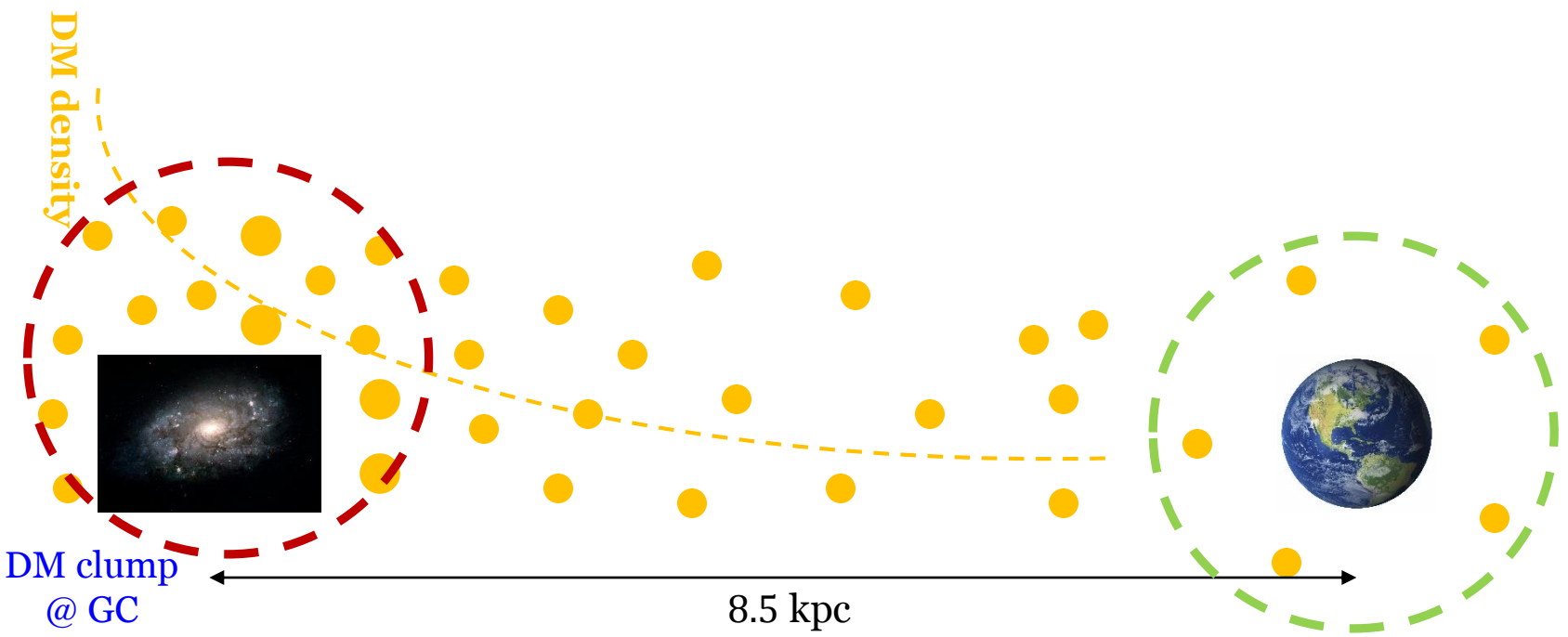
D. Kim, **JCP** & S. Shin [1702.02944]

❖ 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!



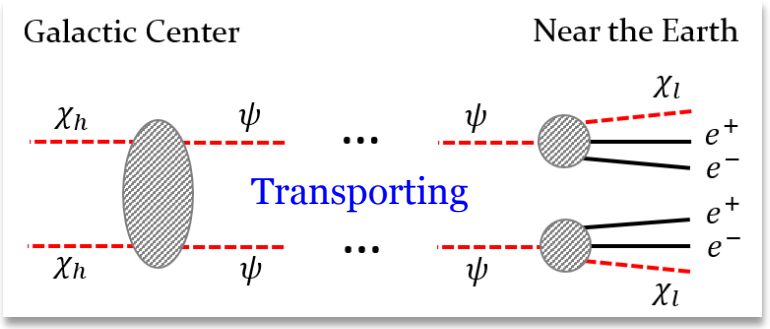
DM "Transporting" Mechanism

D. Kim, **JCP** & S. Shin [1702.02944]

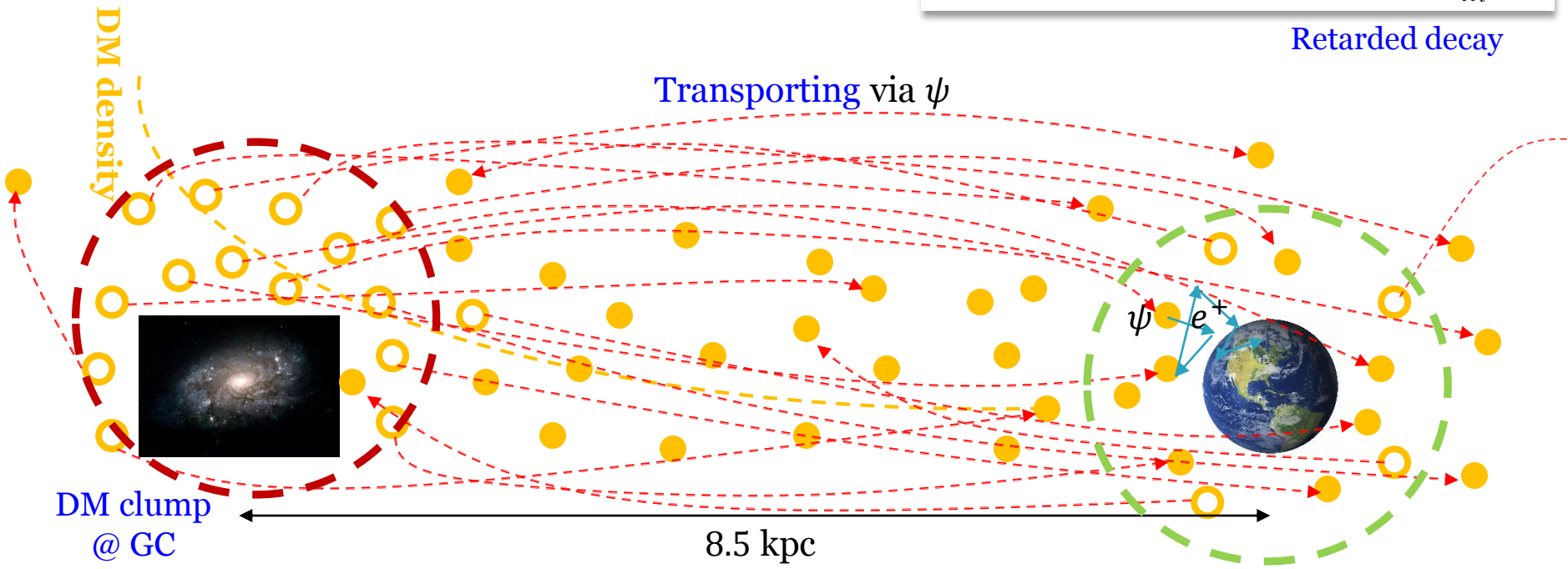
❖ "**Transporting**" (effectively) DM at the GC to the vicinity of the Earth via a "proxy" ψ

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

- 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



Retarded decay



Data Analysis

Parameter choice

- $\langle \sigma v \rangle \sim 3 \cdot 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ (conventional value: to be consistent with relevant observation)
- $\tau_\psi^{lab} = 1/\Gamma_\psi^{lab} = \sim 10^{12}$ s (~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:

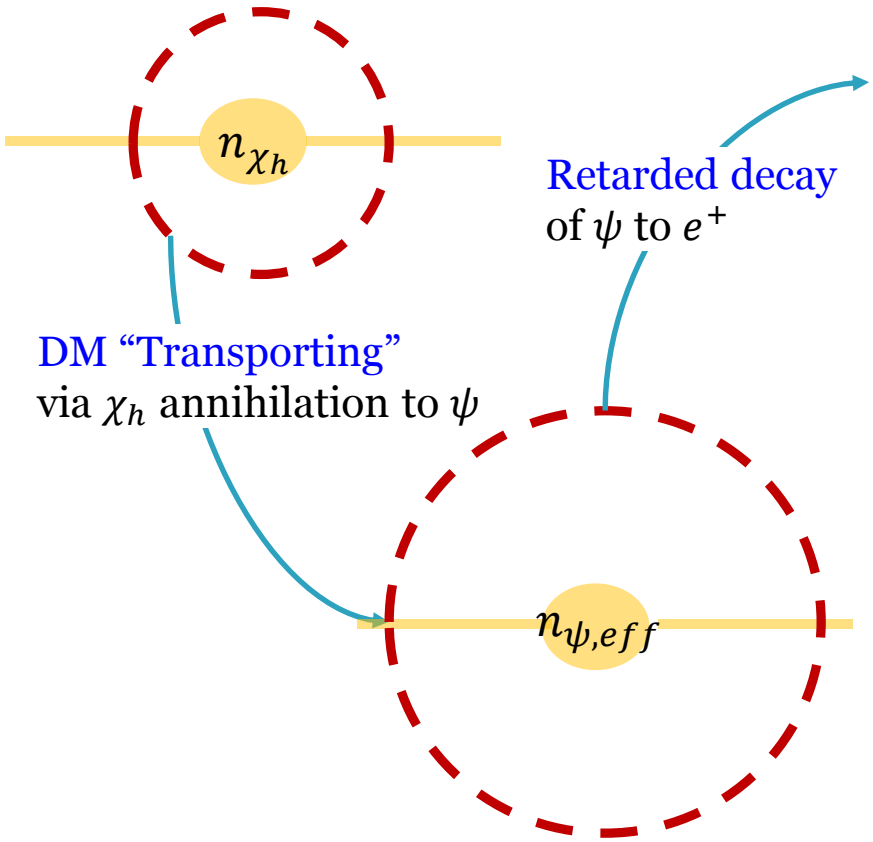
$$\rho_{\chi_A}(y) = \begin{cases} \rho_\odot \dfrac{(y/y_s)^{-1}}{(1+y/y_s)^2} \equiv \rho_{\mathrm{NFW}}(y) & \text{for } y \geq y_C \\ \mathcal{N} \times \rho_{\mathrm{NFW}}(y_C) & \text{for } y < y_C \end{cases}$$

y_C: core size, y_s: scale radius

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

Data Analysis

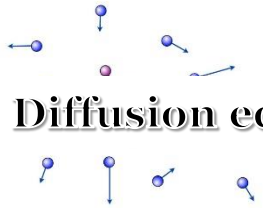
- Complete story in a nutshell



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

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

Source term



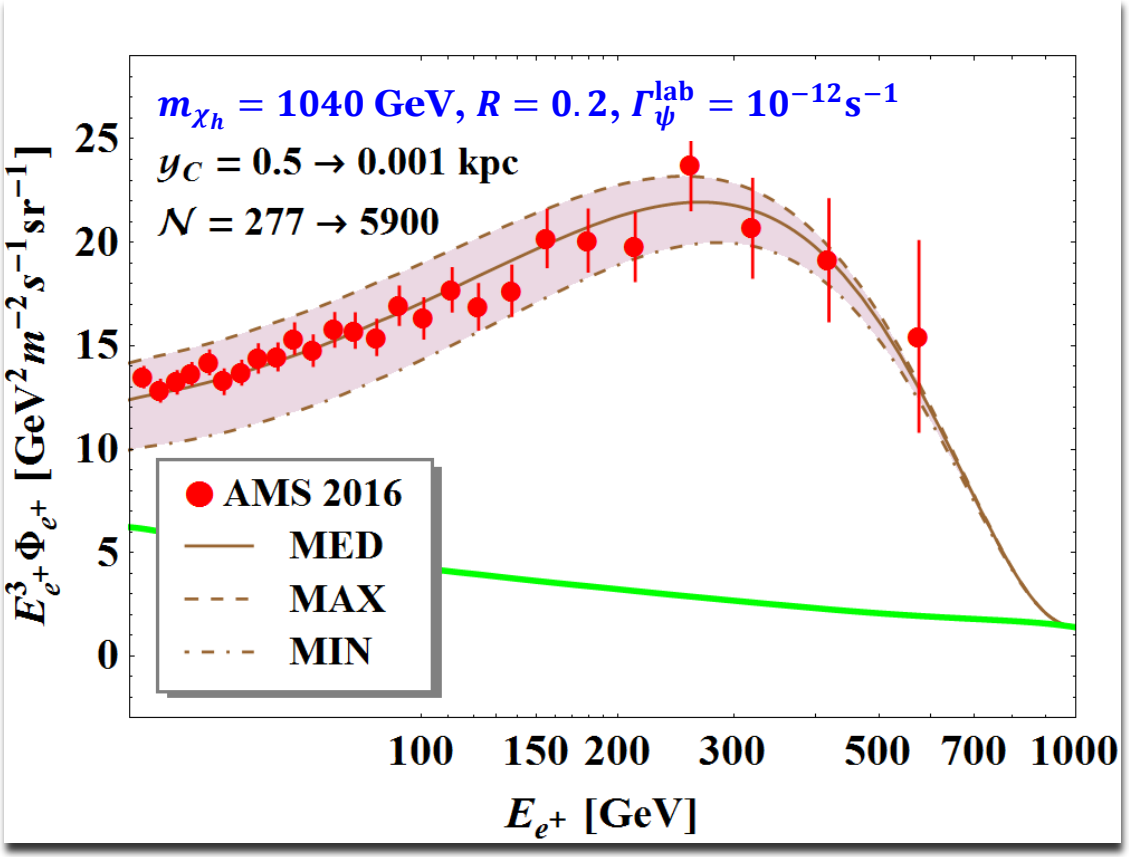
Diffusion equation

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

Fit Results: AMS-02 (2016)

D. Kim, **JCP** & S. Shin [1702.02944]

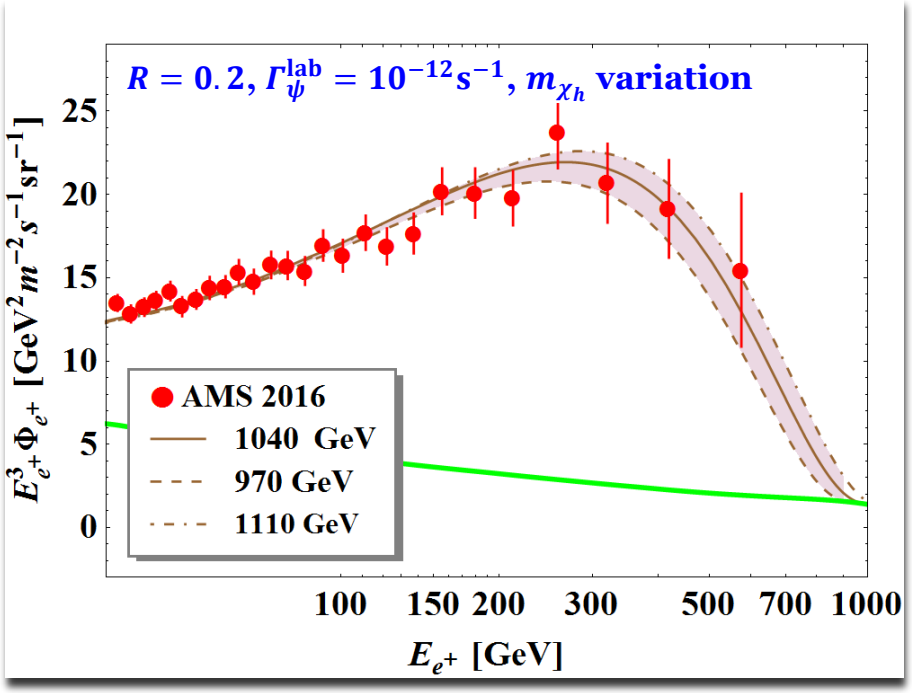
❖ The best-fit with the variations of y_C, N, and the propagation model



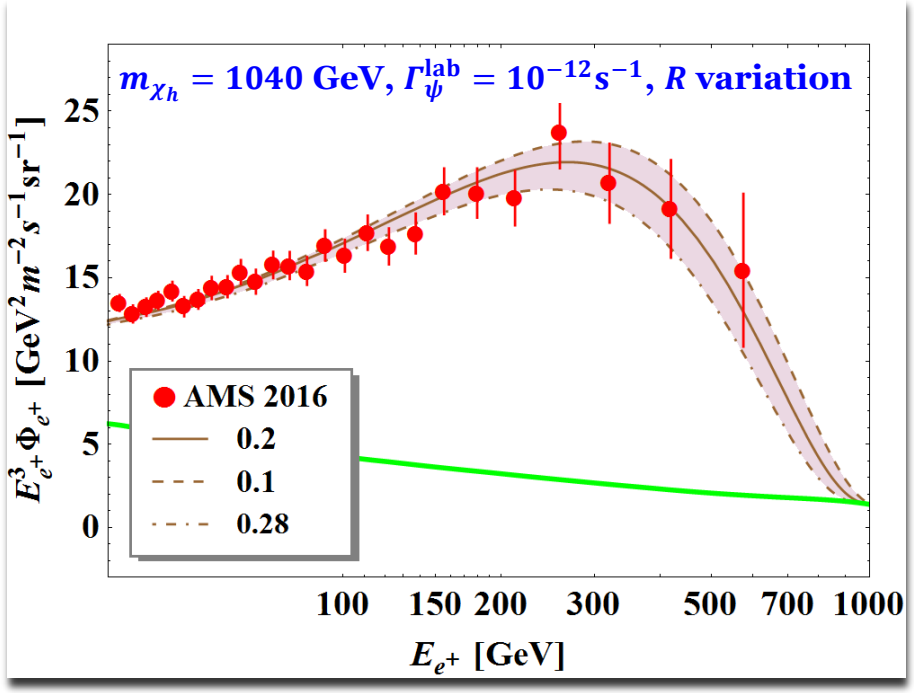
Fit Results: AMS-02 (2016)

D. Kim, **JCP** & S. Shin [1702.02944]

❖ The fit sensitivities to m_{χ_h} and $R = m_{\chi_l}/m_\psi$



➢ Affecting the region towards higher E



➢ Affecting the region towards lower E

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 (Seodong Shin's talk)
  - ✓ DM "transporting" mechanism: new mechanism for cosmic-ray excesses
    - ➔ We can use an already existing big DM clump at the GC.

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Thank you

Back-Up

Positron Spectrum

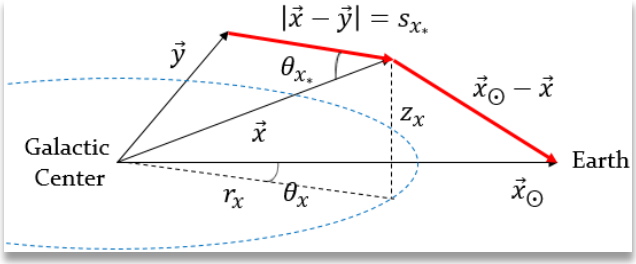
Positron spectrum from diffusion Eq.

- $\underbrace{\nabla(K(E,\vec{x})\nabla f)}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial E}(b(E,\vec{x})f)}_{\text{E loss}} + \underbrace{Q(E,\vec{x})}_{\text{source}} = 0, \frac{d\Phi}{dE} = \frac{v}{4\pi} f, v=c$

- $Q(E,\vec{x}) = n_\phi(\vec{x})\Gamma_\phi^{lab}\frac{dN}{dE}$

- $$\frac{d}{d\Omega_{x_\star} dE_\phi}\Phi_\phi(\vec{x}) = \left(\frac{1}{2}\right)\cdot\frac{1}{4\pi}\int_{l.o.s} ds_{x_\star}\frac{n_{\chi_h}^2(\vec{y})}{2}\langle\sigma v\rangle_{\chi_h\chi_h\to\phi\phi} e^{-\frac{|x-y|}{c}\Gamma_\phi^{lab}}\frac{dN_\phi}{dE_\phi}$$

$$\frac{dN_\phi}{dE_\phi} = 2\cdot\delta(E_\phi - m_{\chi_h}) \quad \& \quad y^2 = r_x^2 + z_x^2 + s_{x_\star}^2 - 2\sqrt{r_x^2+z_x^2}\, s_{x_\star}\cos\theta_{x_\star}$$

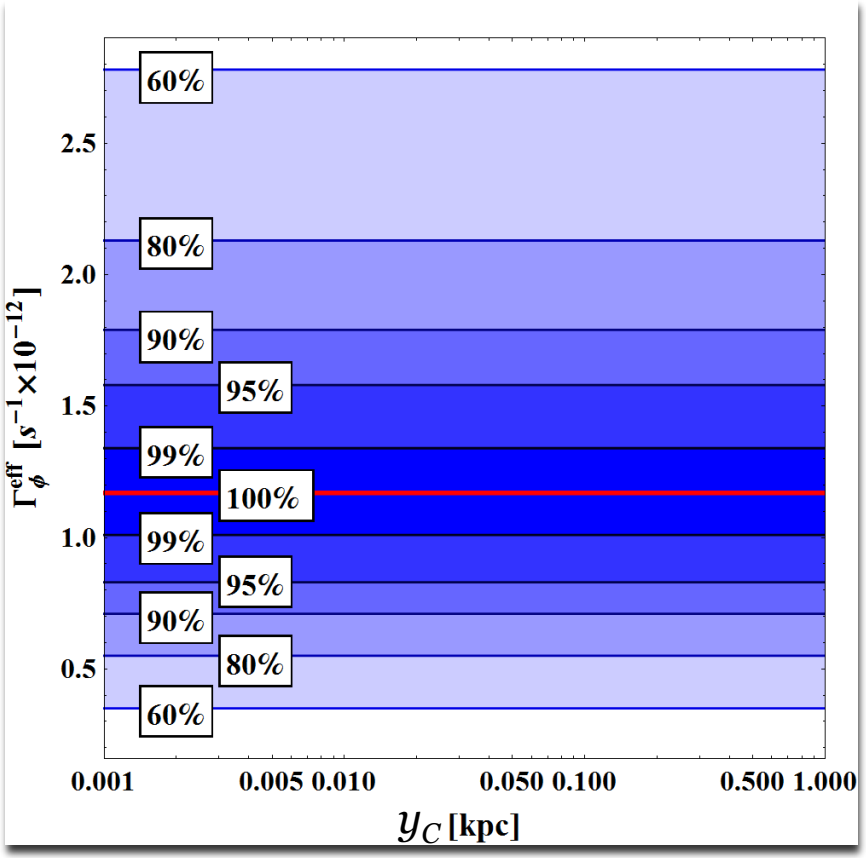


- $$\frac{dN}{dE} = \frac{1}{2\gamma_\phi\beta_\phi}\left[\frac{m_\phi^4 - m_{\chi_l}^2}{8m_\phi} + \frac{m_{\chi_l}^2 m_\phi}{2}\log\left(\frac{m_{\chi_l}}{m_\phi}\right)\right]^{-1}$$
$$\times\left[m_\phi(E^+ - E^-) + \frac{m_{\chi_l}^2}{2}\log\left(\frac{m_\phi - 2E^+}{m_\phi - 2E^-}\right)\right]$$

$$E^+ = \min\left[\frac{E}{\gamma_\phi(1-\beta_\phi)}, \frac{m_\phi^2 - m_{\chi_l}^2}{2m_\phi}\right]$$

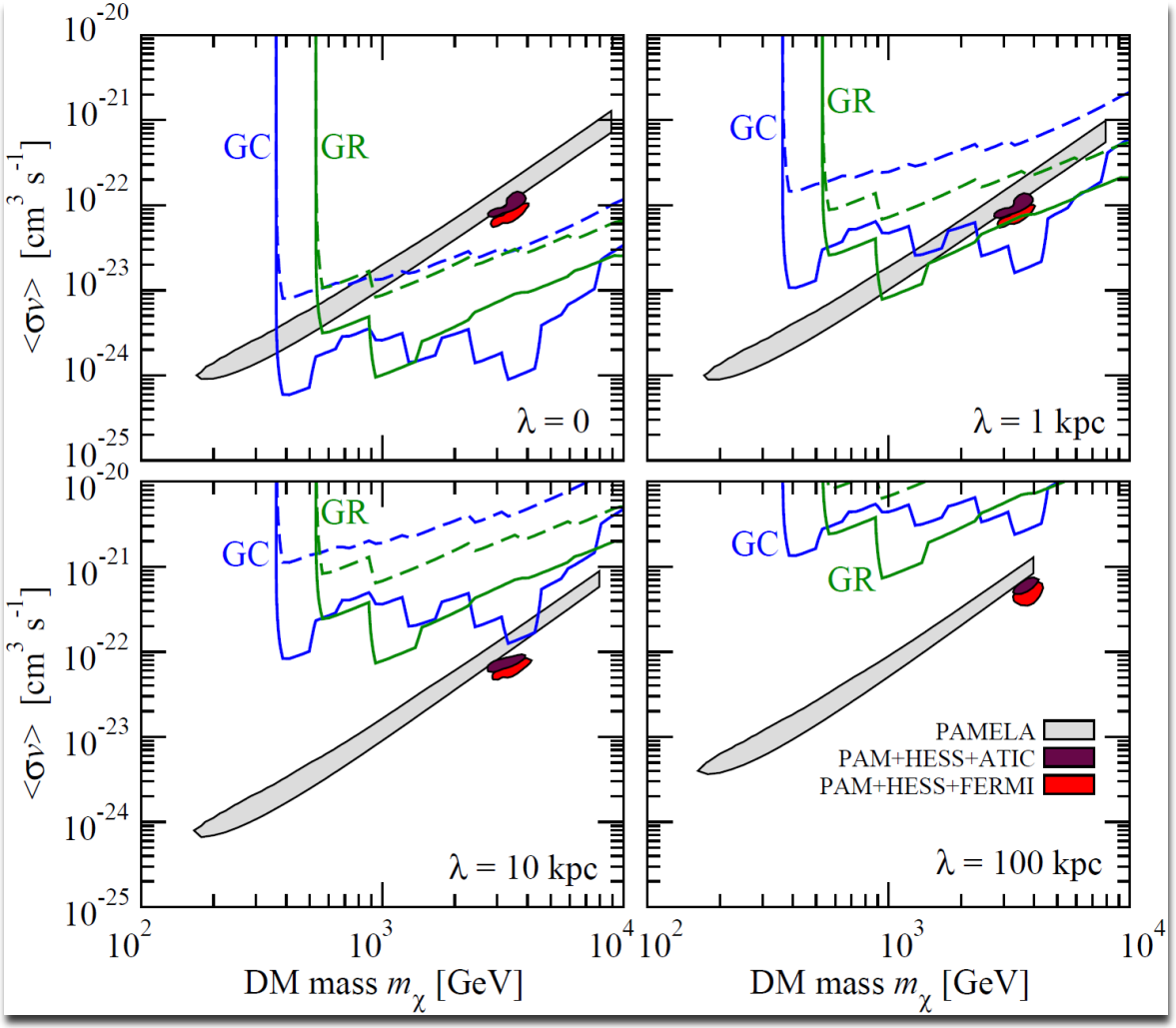
$$E^- = \frac{E}{\gamma_\phi(1+\beta_\phi)}.$$

Correlation/Tuning of y_C vs Γ_ϕ^{lab}



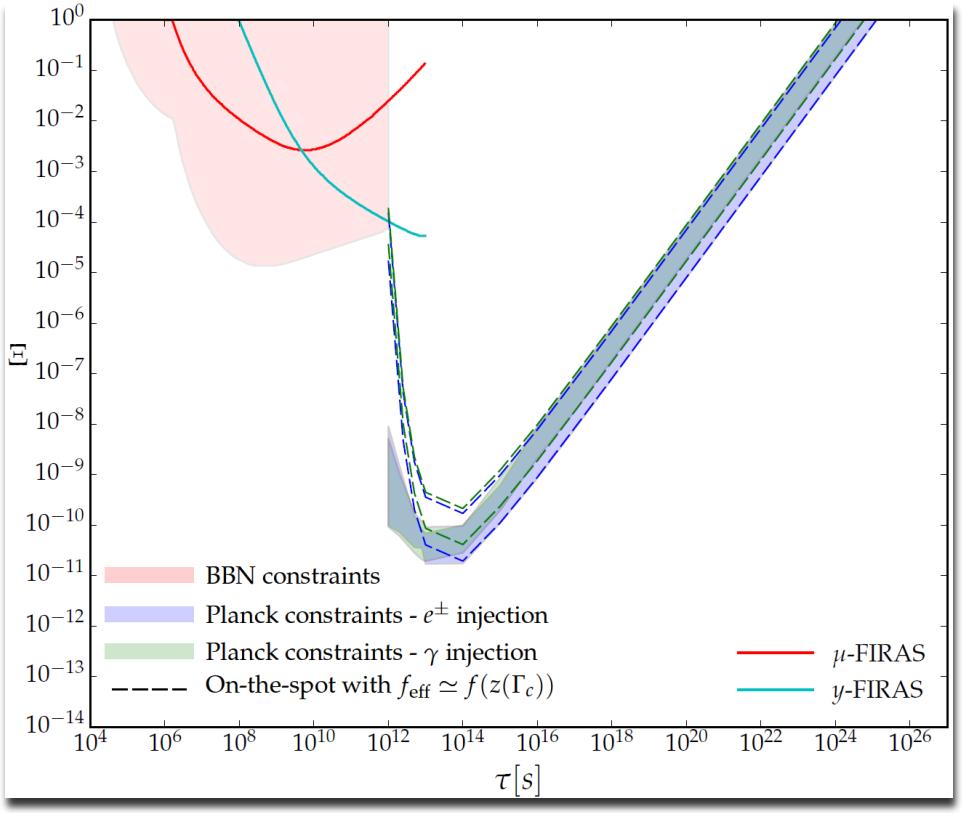
Gamma-ray Constraints

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



[Rothstein et al. (2009)]

BBN & CMB Constraints



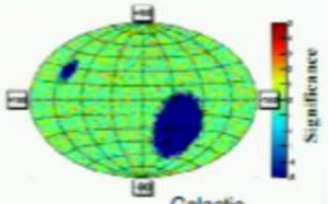
$\Xi=(\rho/\rho_{DM})\cdot$(Decay E into γ's & $e^{\pm}$)

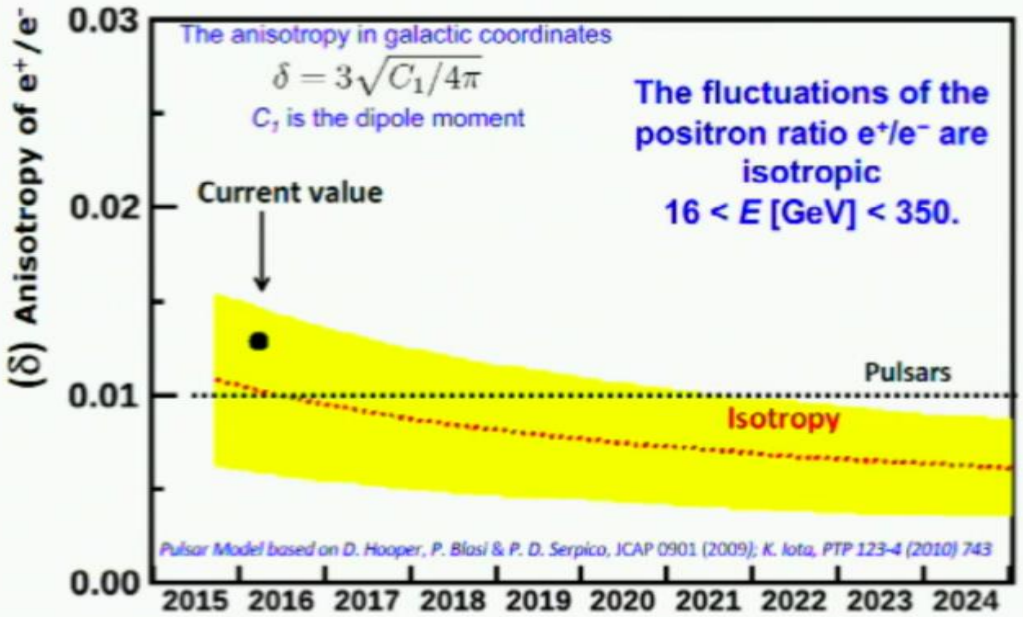
[Poulin et al. (2016)]

Anisotropy in e^+/e^-

Physics Result 4: Measurement of anisotropy

Astrophysical point sources like pulsars will imprint a higher level of anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.





Data taking to 2024 will allow to explore anisotropies of 1%

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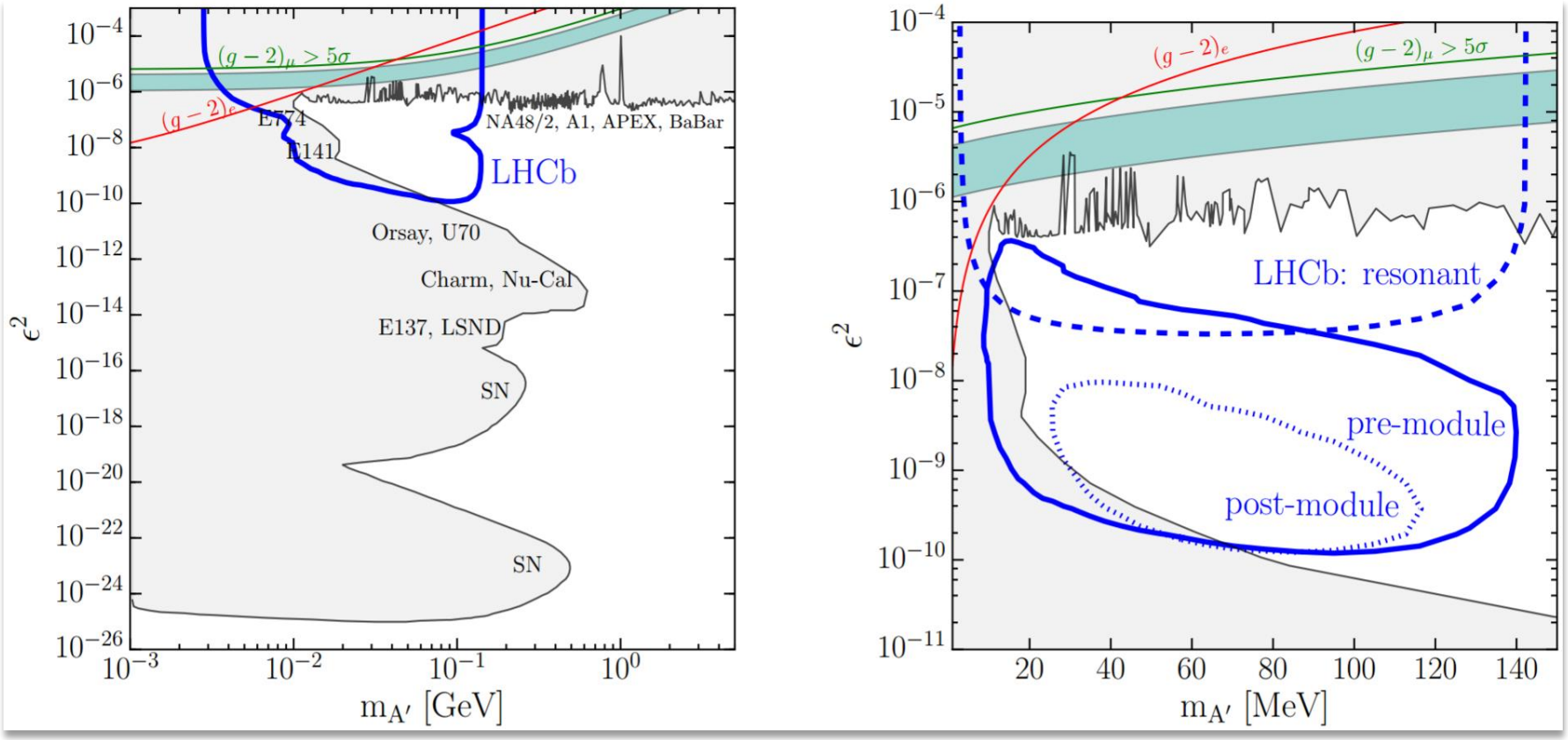
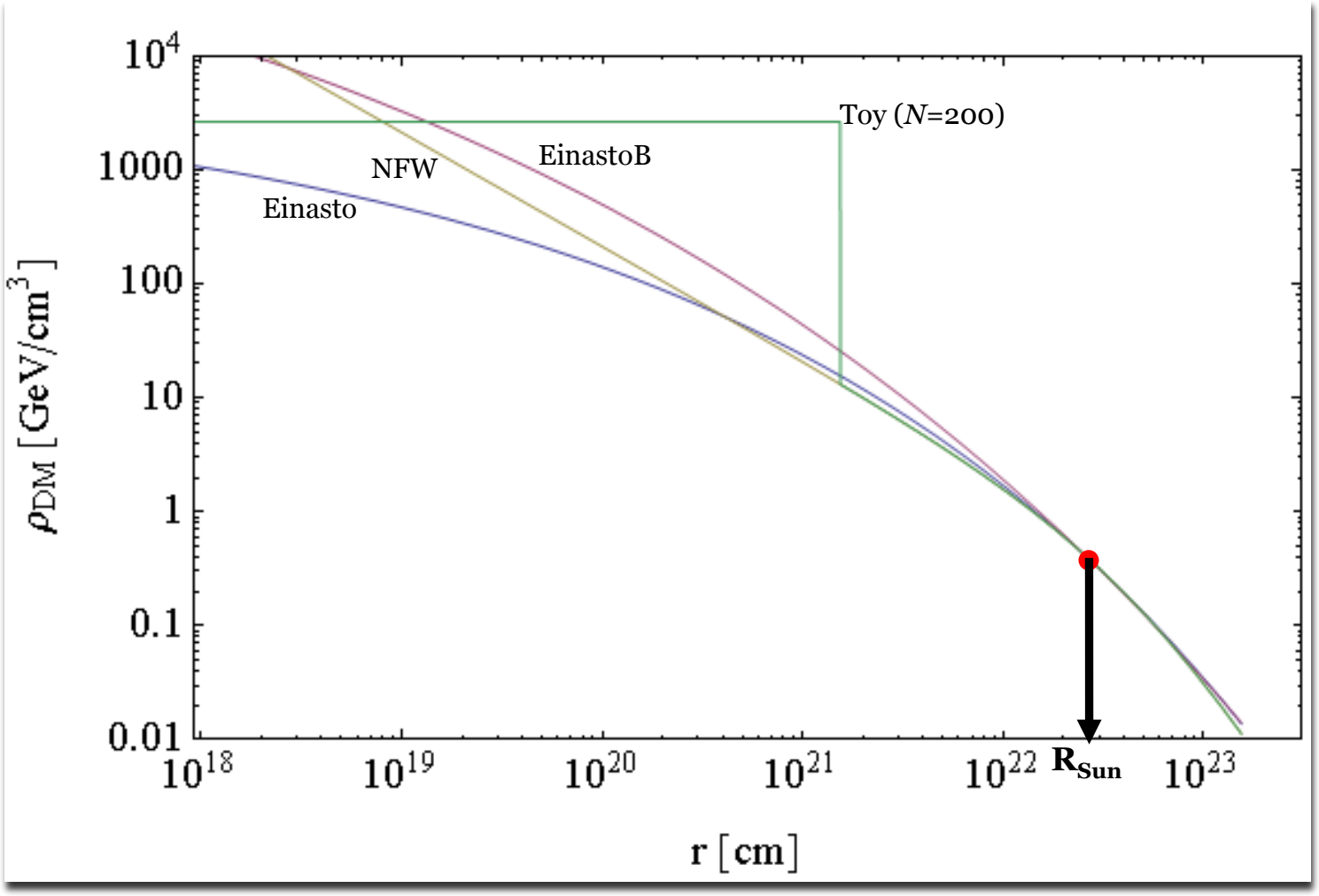
[AMS02 (2016)]

Constraints on Dark $U(1)_X$



[Ilten et al. (2015)]

DM Halo Profiles



Basic Framework: Assisted FO

G. Belanger & **JCP** (2011)

- Two species of DM: ψ_h, ψ_l with $m_h > m_l$ (e.g. $U(1)' \otimes U(1)''$, $Z_2' \otimes Z_2''$)
- ψ_h : dominant DM component, no direct coupling to the SM
  - ➔ Assisted Freeze-Out Mechanism: required!
- ψ_l: sub-dominant, direct coupling to the SM ($\mathcal{L} \supset -\frac{1}{2} \sin\epsilon X_{\mu\nu} F^{\mu\nu}$)

can be metastable
E. J. Chun & JCP (2011)