Neutrino/gamma-ray signals from annihilating/decaying dark matter

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J.Hisano, M.Kawasaki, K.Kohri and KN, Phys.Rev.D79,043516(2009)[0812.0219]

M.Kawasaki, K.Kohri and KN, Phys.Rev.D80,023517(2009)[0904.3626]

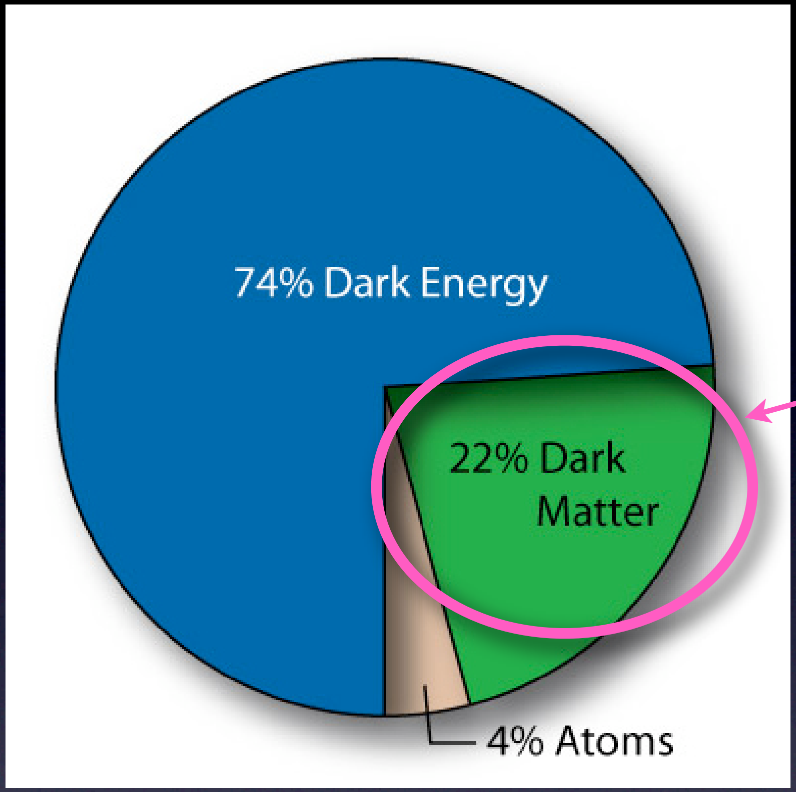
J.Hisano, KN, and M.J.S.Yang, Phys.Lett.B678,101(2009)[0905.1552]

Focus week on Indirect Dark Matter Search @ IPMU (2009/12/08)

Contents

- PAMELA/Fermi results & DM annihilation/decay scenario
- Neutrino signals from DM
- Diffuse gamma-rays from DM
- Summary of constraints on DM

Energy content of the Universe after WMAP



What is the dark matter?

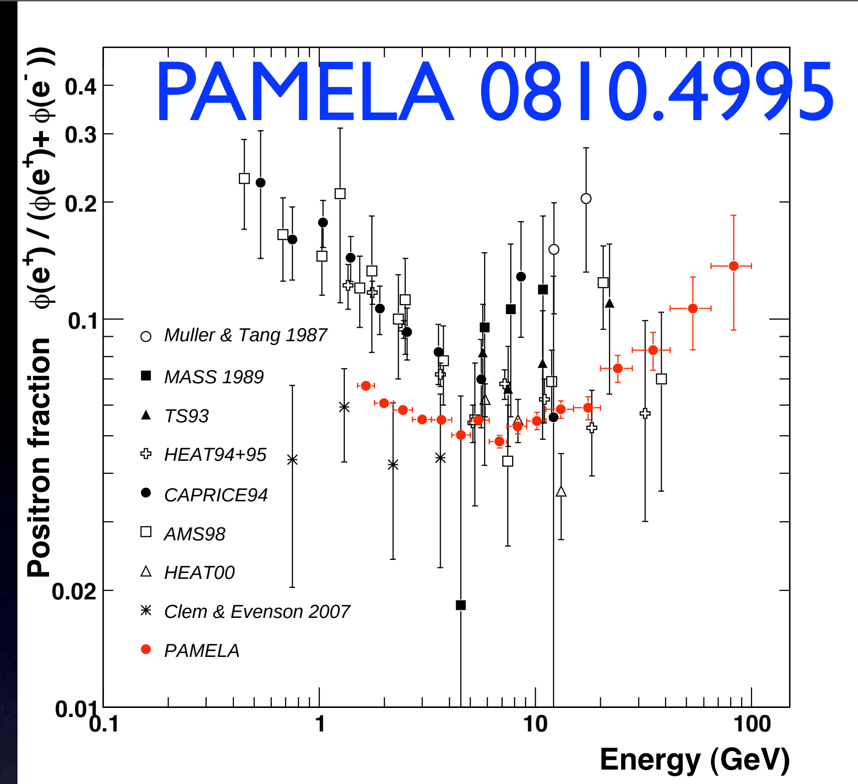
Can it be detected?

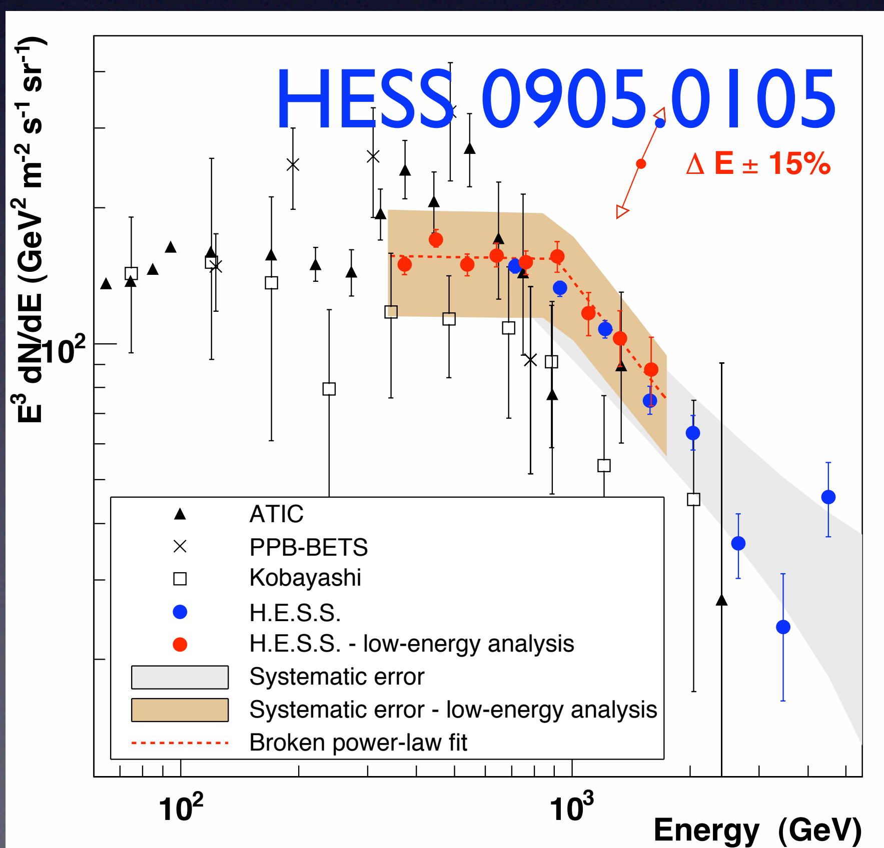
- Collider
- Direct detection — DM-nucleon Scattering
- Indirect detection — DM annihilation

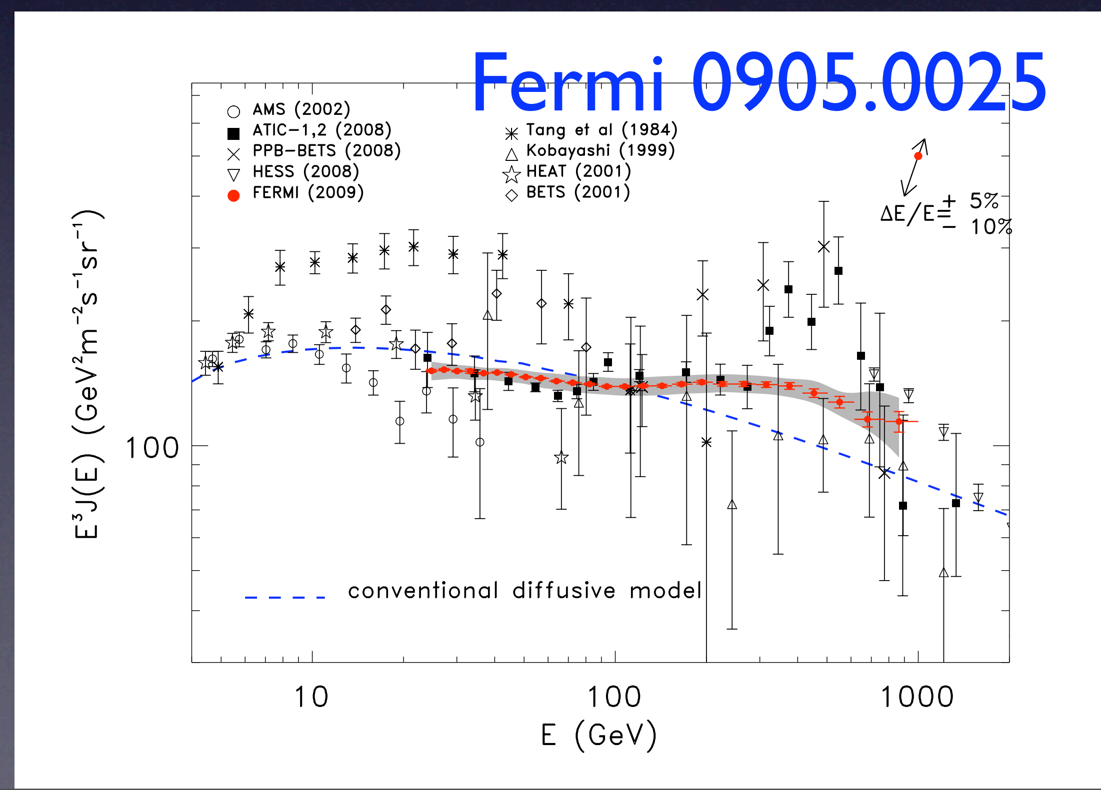
→ Cosmic Ray Signals

Signatures from DM?

- Positron excess by PAMELA
- Electron+positron excess by Fermi & HESS







Dark Matter : Decay or Annihilate

- **Decaying DM**

  DM need not be completely stable.

  DM lifetime with $\tau \sim 10^{26}\mathrm{sec}$ can explain PAMELA.

  $$\boxed{\mathrm{Flux} \propto \frac{n_{\mathrm{DM}}}{\tau} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}}$$

- **Annihilating DM**

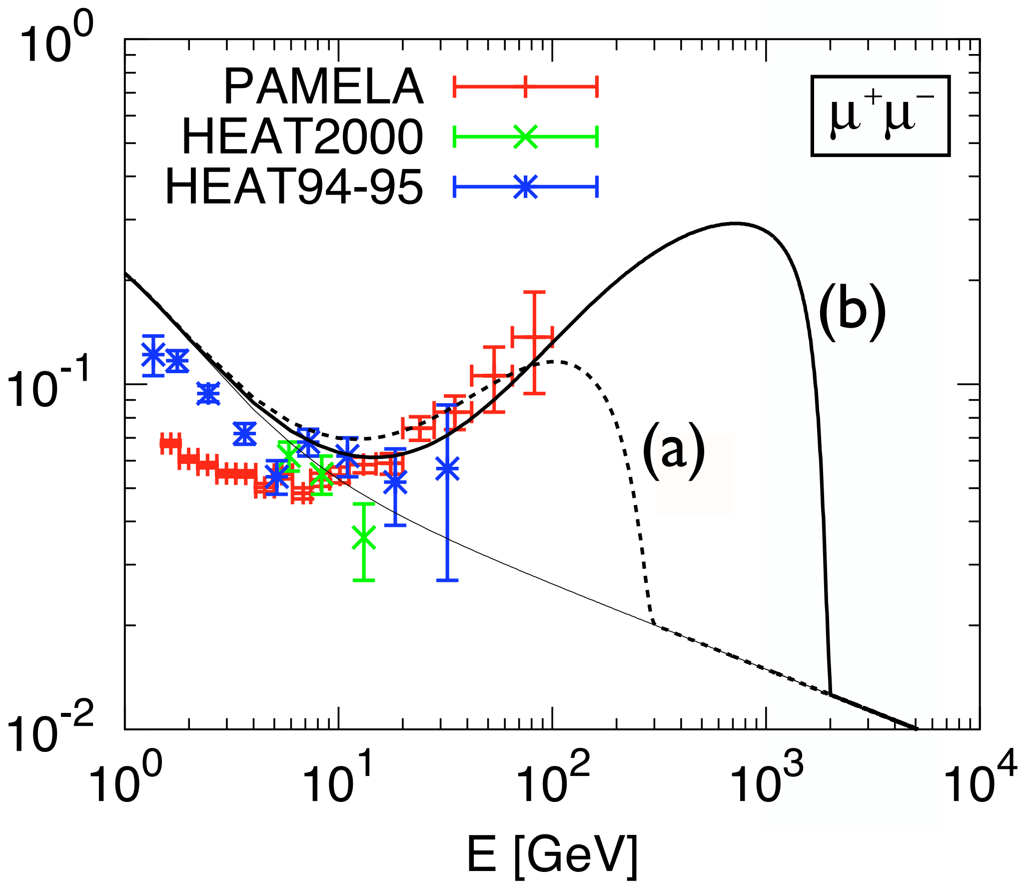
  DM may have weak scale annihilation cross section.

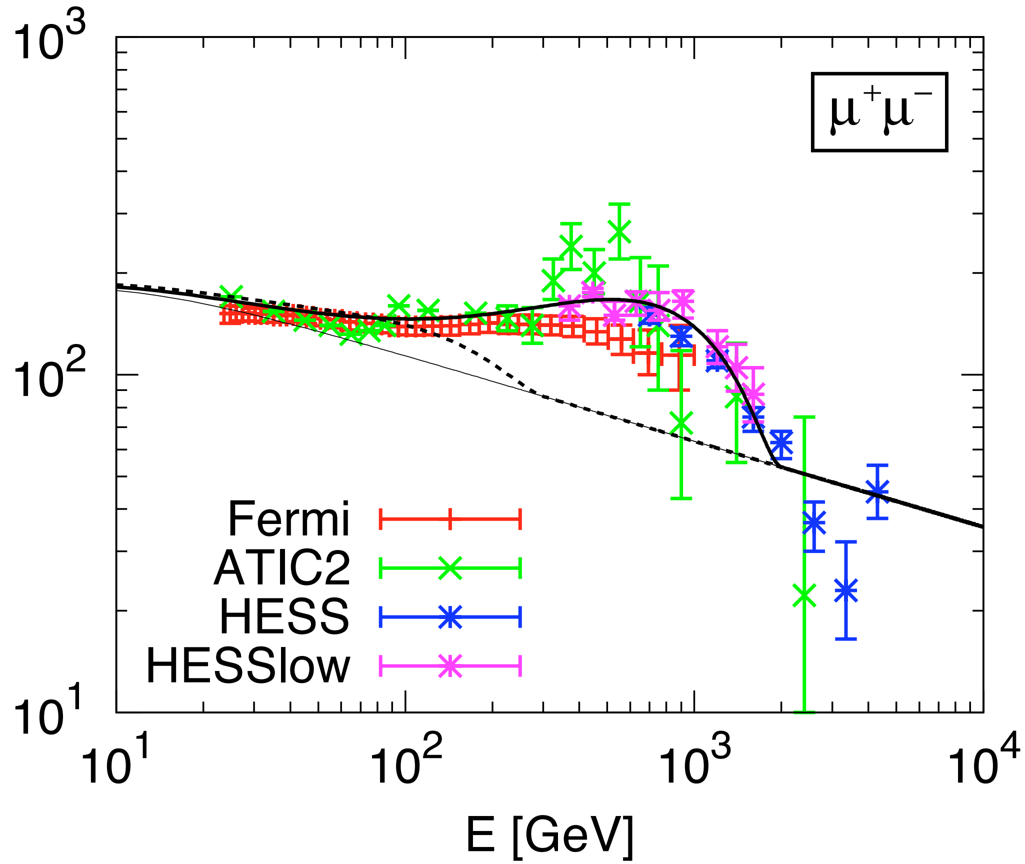
  Cross section with $\langle \sigma v \rangle \sim 10^{-24} - 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$ can explain PAMELA.

  $$\boxed{\mathrm{Flux} \propto n_{\mathrm{DM}}^2 \langle \sigma v \rangle \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}}$$

Positron fraction

Total flux $[\mathrm{GeV}^2\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$



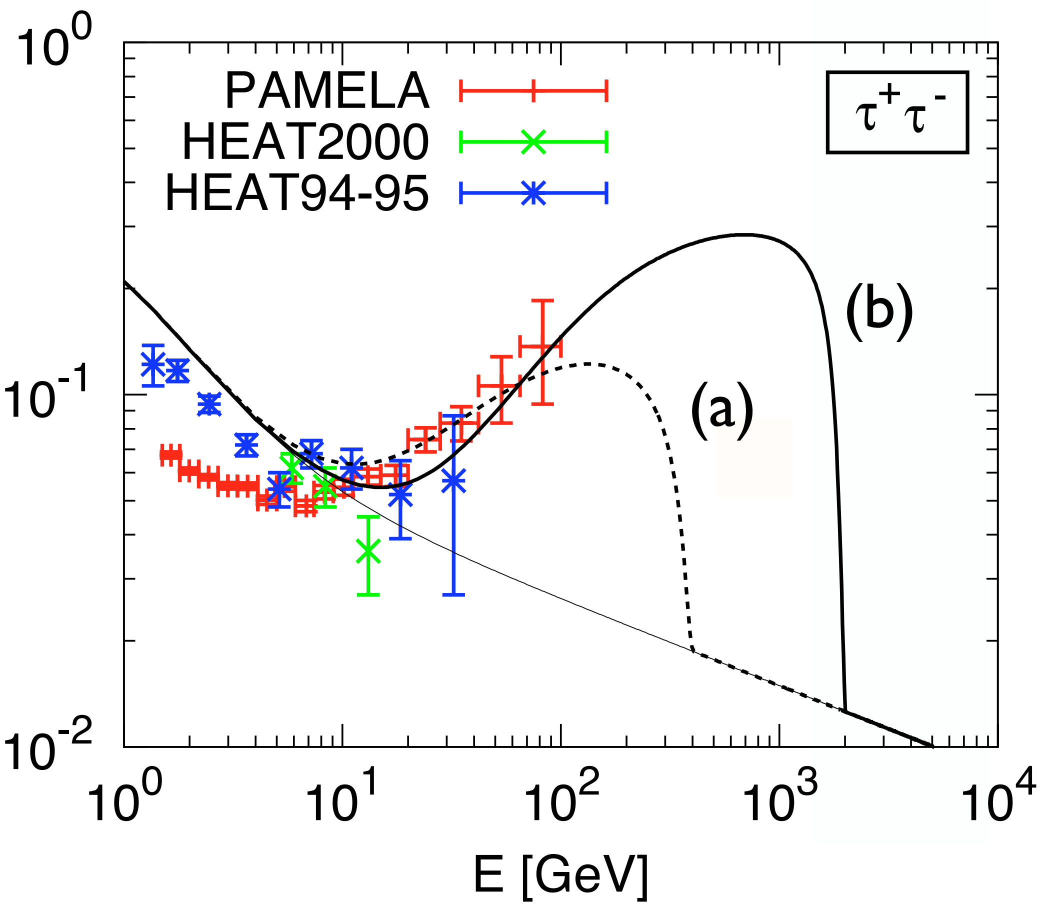


$$\chi\chi \to \mu^+\mu^-$$

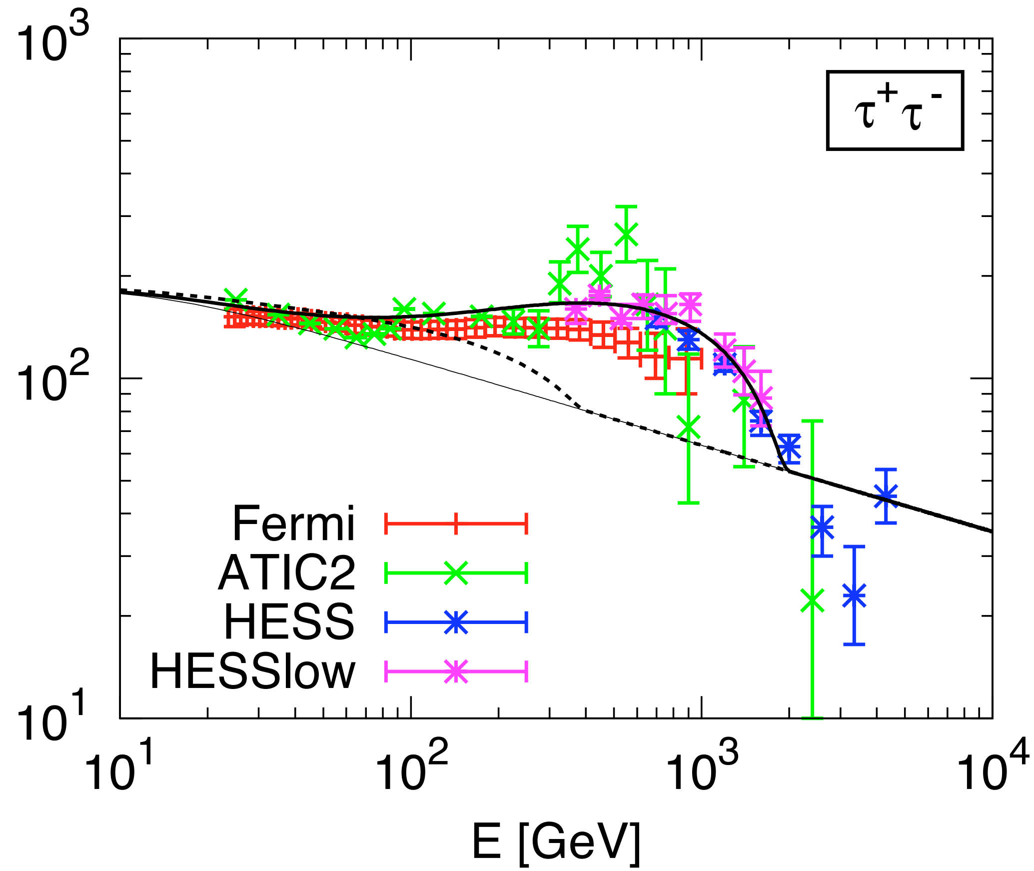
$$(a): m_\chi = 300\mathrm{GeV}, \langle\sigma v\rangle = 2\times 10^{-24}\mathrm{cm}^3\mathrm{s}^{-1}$$

$$(b): m_\chi = 2\mathrm{TeV}, \langle\sigma v\rangle = 5\times 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$$

Positron fraction



Total flux $[\mathrm{GeV^2 m^{-2} s^{-1} sr^{-1}}]$

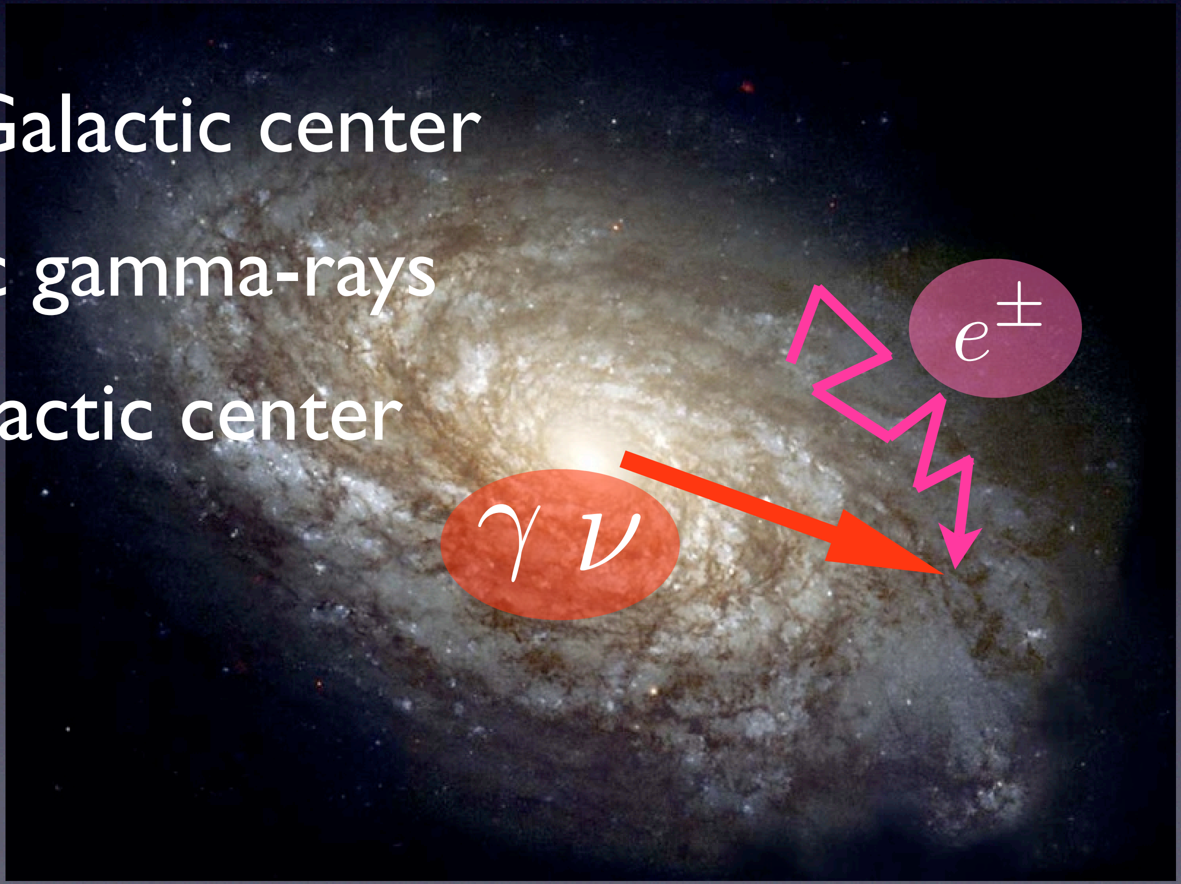


$$\chi\chi \to \tau^+\tau^- \quad \begin{array}{l} (a) : m_\chi = 400\mathrm{GeV}, \langle \sigma v \rangle = 1 \times 10^{-23} \mathrm{cm^3 s^{-1}} \\ (b) : m_\chi = 2\mathrm{TeV}, \langle \sigma v \rangle = 1 \times 10^{-22} \mathrm{cm^3 s^{-1}} \end{array}$$

Relation to other signals ?

DM annihilation/decay yields not only positron/electrons, but also ...

- Gamma-rays from Galactic center
- Diffuse extragalactic gamma-rays
- Neutrinos from Galactic center
- Anti-protons



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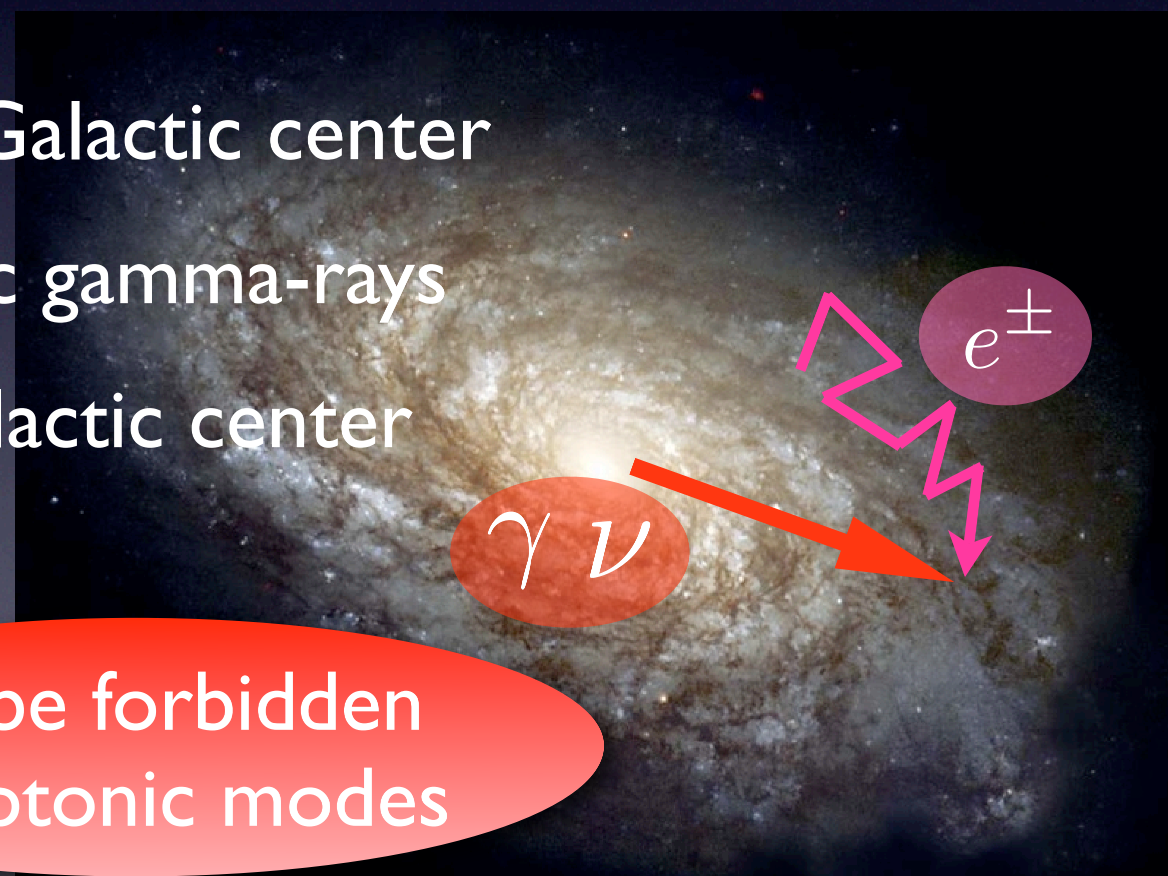

Can be forbidden for leptonic modes

Relation to other signals ?

DM annihilation/decay yields not only
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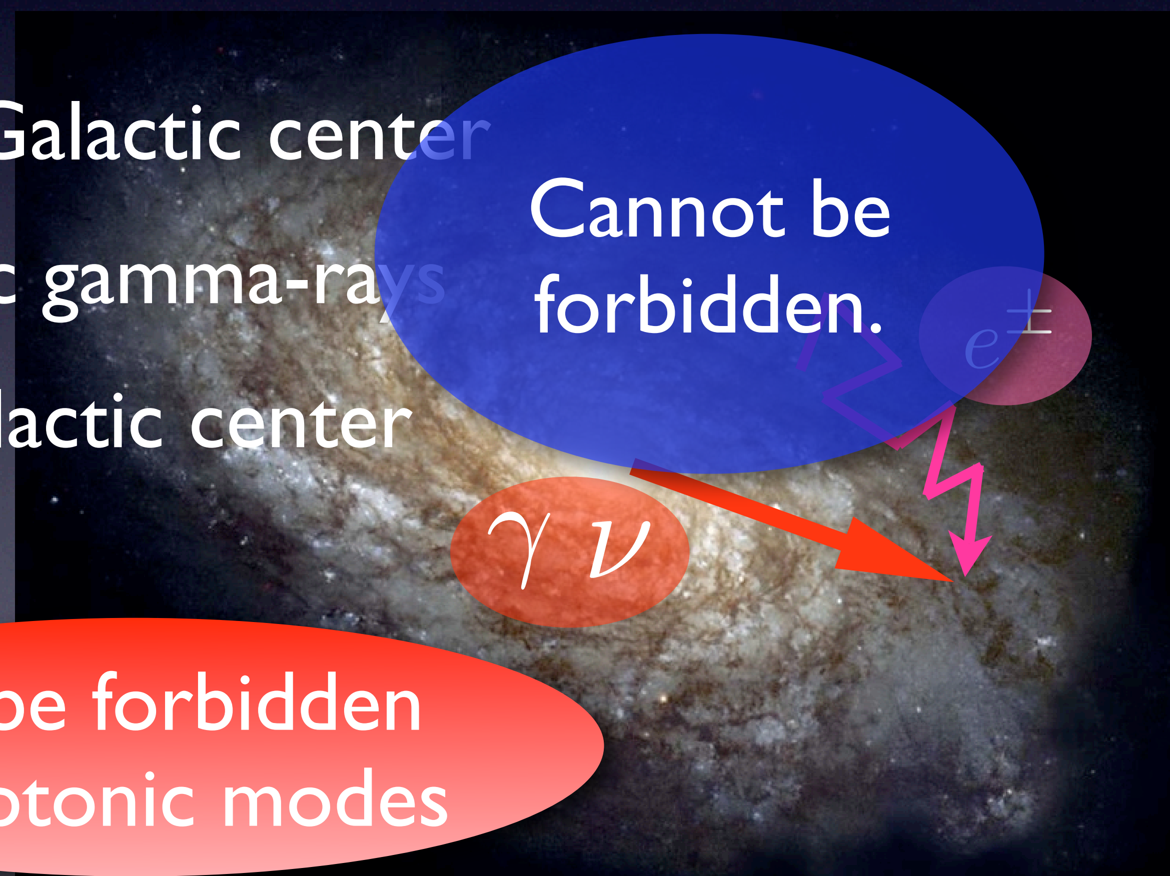


Can be forbidden for leptonic modes

Neutrino Flux

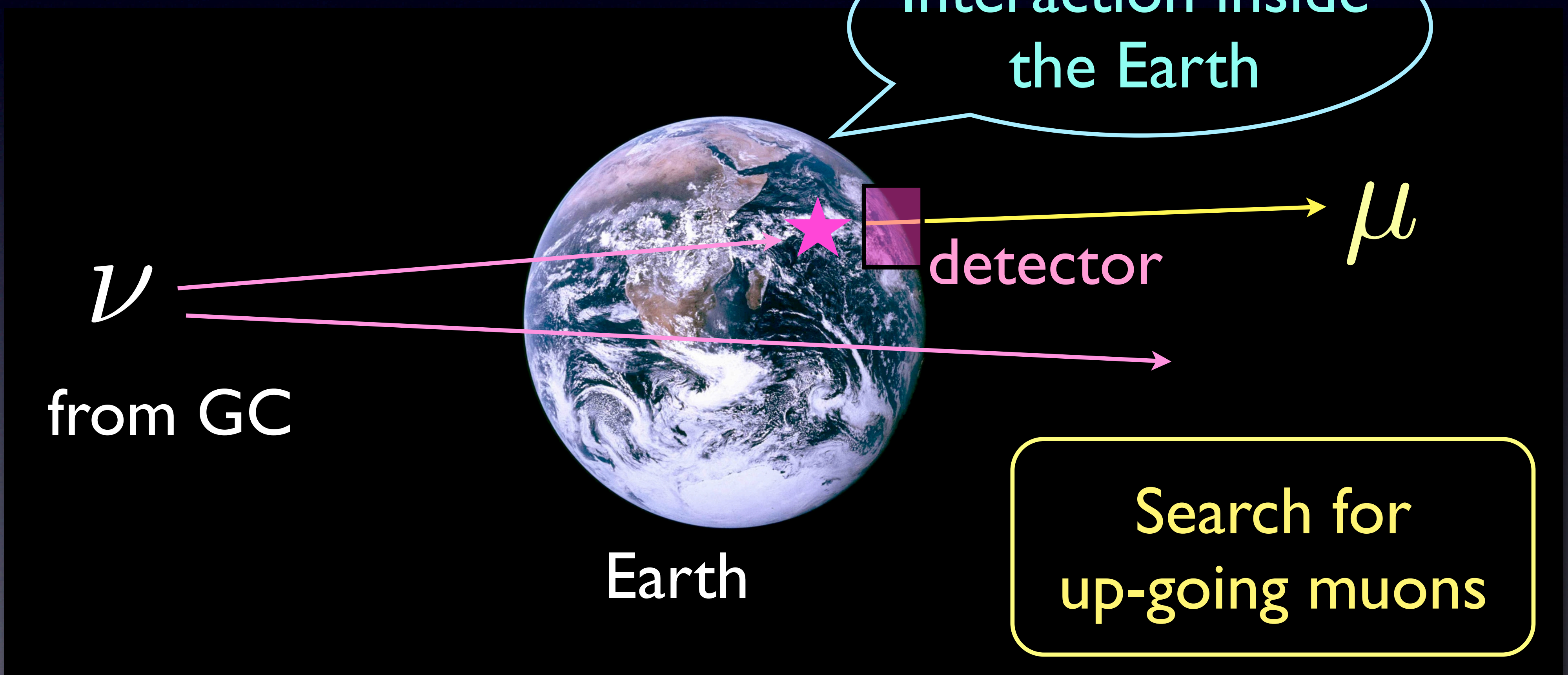
J.Hisano, M.Kawasaki, K.Kohri and KN, Phys.Rev.D79,043516(2009)[0812.0219]

J.Hisano, KN, and M.J.S.Yang, Phys.Lett.B678,101(2009)[0905.1552]

Neutrino Signal from DM Annihilation

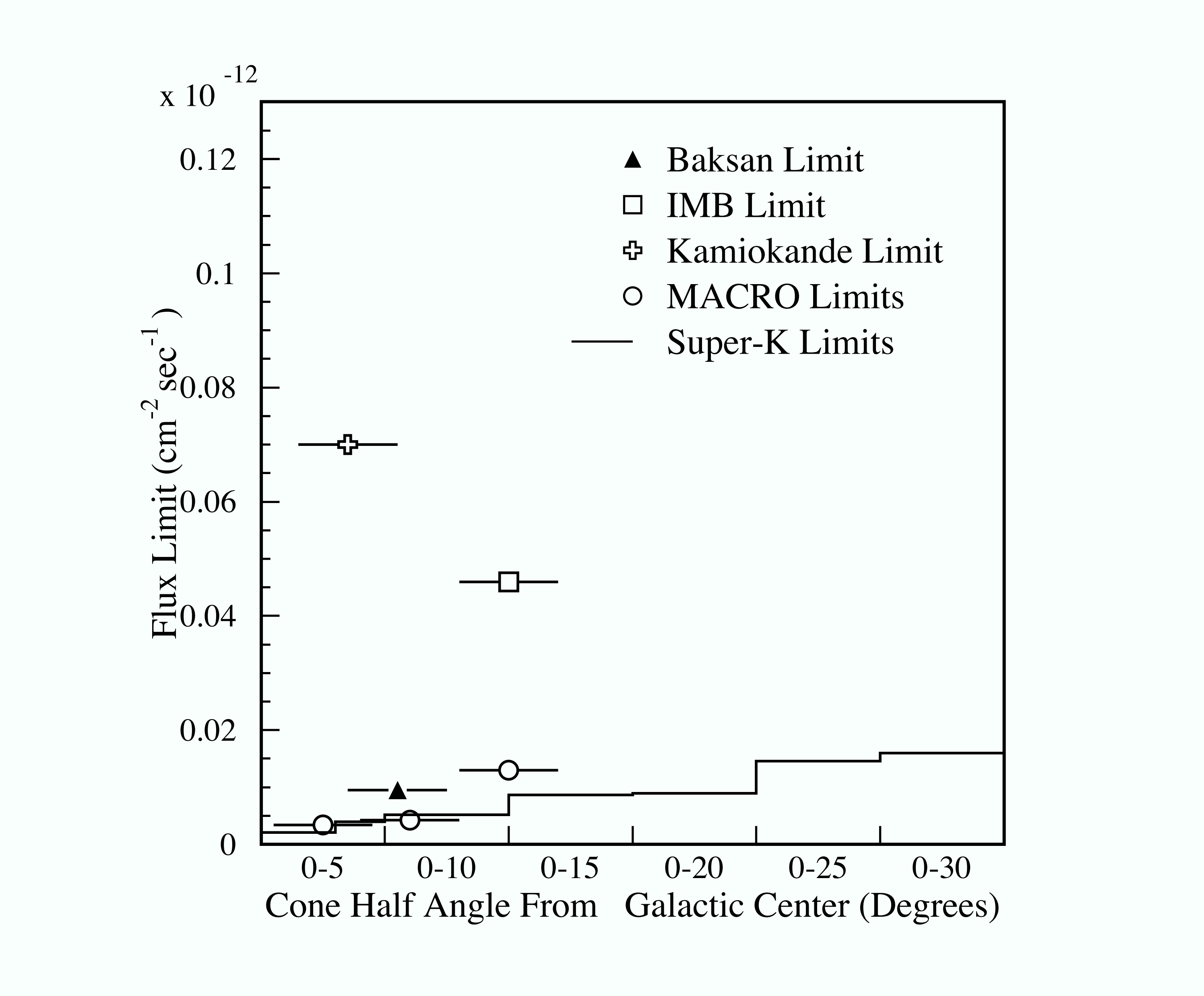
Ritz, Seckel (88),Kamionkowski (90),...
Bertone,Nezri,Orloff,Silk (04),
Yuksel,Horiuchi,Beacom,Ando(07)

$$\chi\chi \to W^+W^-, b\bar{b}, l^+l^-, \ldots$$
$$\to e^\pm, \gamma, \bar{p}, \nu, \ldots$$



→ Limits from Super-K

SK limit on upward muon flux from GC direction



S.Desai et al., Phys.Rev.D70,083523 (2004)

Muon flux from DM

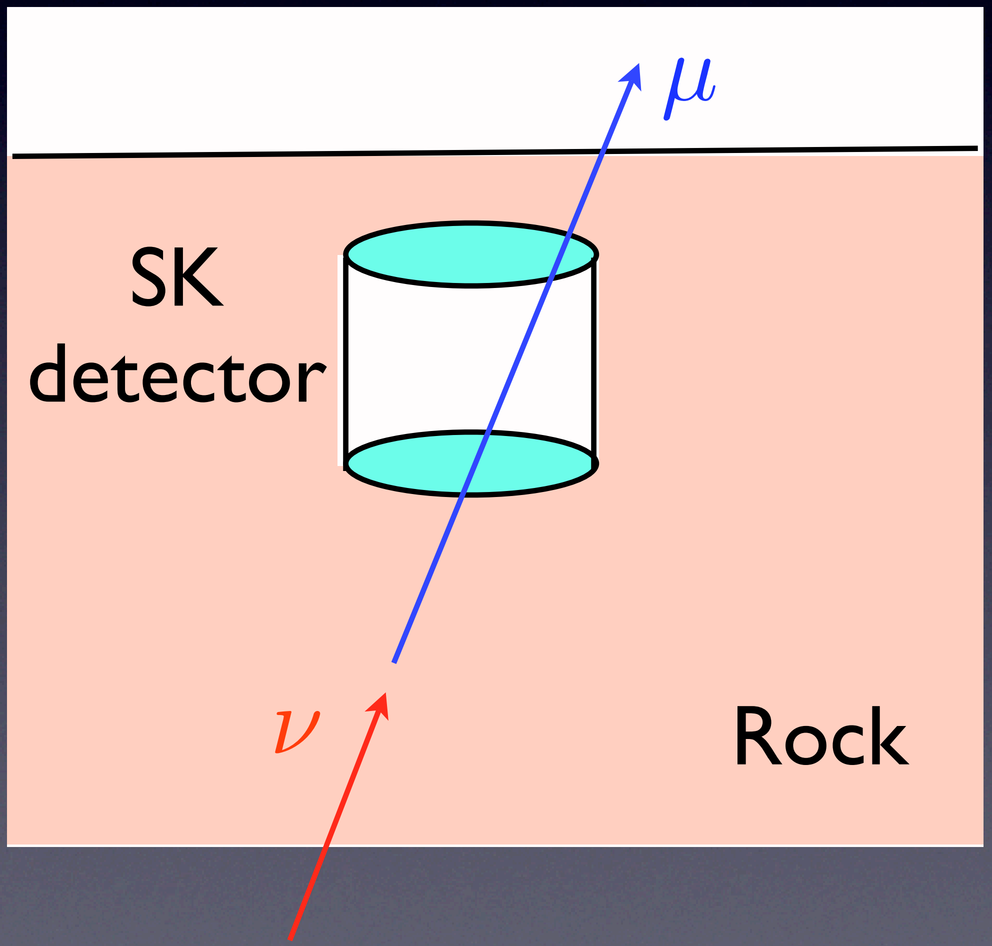
$$N_\mu = \int dE_{\nu_\mu} \frac{dF_{\nu_\mu}}{dE_{\nu_\mu}} f(E_{\nu_\mu})$$

(a) Neutrino flux from DM:

$$\frac{dF_{\nu_\mu}}{dE_{\nu_\mu}}$$

(b) Probability of $\nu_\mu \to \mu$:

$$f(E_{\nu_\mu})$$



(a) Neutrino flux from GC

$$\boxed{\frac{dF_{\nu_\mu}}{dE_{\nu_\mu}} = \frac{R_\odot \rho_\odot^2}{8\pi m^2} \left(\sum_F \langle \sigma v \rangle_F \frac{dN_F^{(\nu_\mu)}}{dE_{\nu_\mu}} \right) J\Delta\Omega}$$

- Neutrino spectra :

$$\frac{dN_F^{(\nu_\mu)}}{dE_{\nu_\mu}} = \sum_i \left(P_{\nu_i \nu_\mu} \frac{dN_F^{(\nu_i)}}{dE_{\nu_i}} \right)_{E_{\nu_i} = E_{\nu_\mu}}$$

Neutrino oscillation

- DM halo profile dependent part :

$$J\Delta\Omega = \int \frac{d\Omega}{\Delta\Omega} \int_{\text{l.o.s.}} \frac{dl(\psi)}{R_\odot} \left(\frac{\rho(l)}{\rho_\odot} \right)^2$$

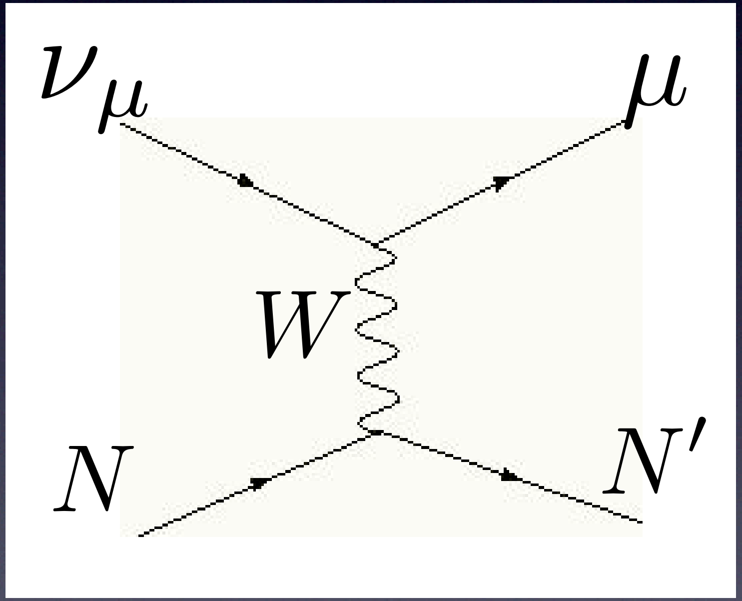
Typical value of $J\Delta\Omega$

	5°	10°	15°	20°	25°
NFW	6.0	10	14	17	20
isothermal	1.3	4.3	8.0	11	15

(b) Probability of $\nu_\mu \to \mu$

$$\boxed{f(E_{\nu_\mu}) \sim \int dE_\mu \frac{d\sigma_{\nu_\mu p \to \mu X}}{dE_\mu} n_p^{(\mathrm{rock})} R(E_\mu)}$$

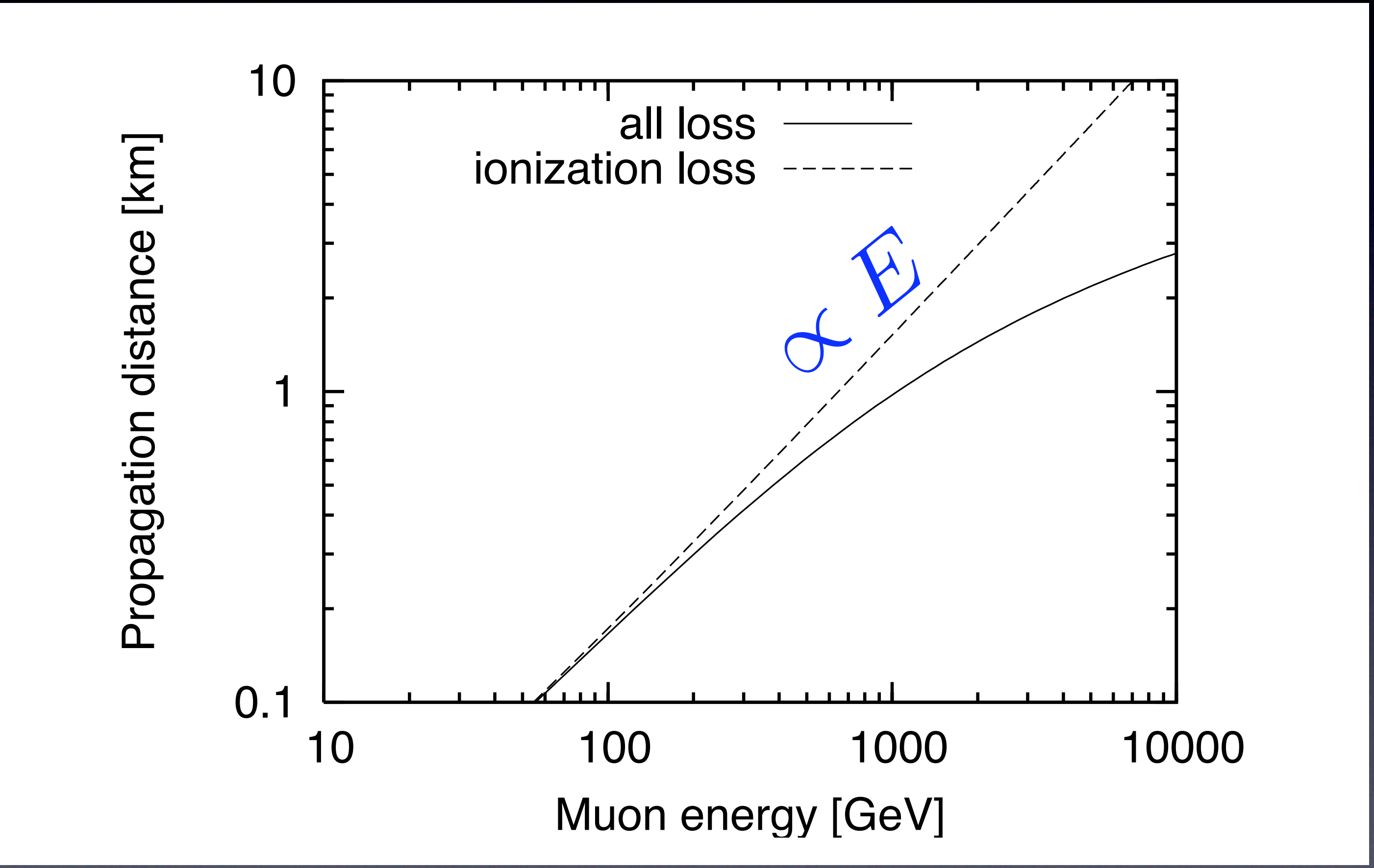
- Cross section : $\sim \dfrac{G_F^2 s}{\pi} \propto E_{\nu_\mu}$
- Number density of proton in the rock :
  $$n_p^{(\mathrm{rock})} = 1.3 N_A \ \mathrm{cm}^{-3}$$
- Muon range : $R(E_\mu)$



Muon energy loss

$$\boxed{\frac{dE_\mu}{dX} = -\alpha(E_\mu) - \beta(E_\mu)E_\mu}$$

$\alpha(E_\mu) \simeq 2\ \mathrm{MeVcm^2g^{-1}}$ $\quad \beta(E_\mu) \simeq 10^{-6}\ \mathrm{cm^2g^{-1}}$

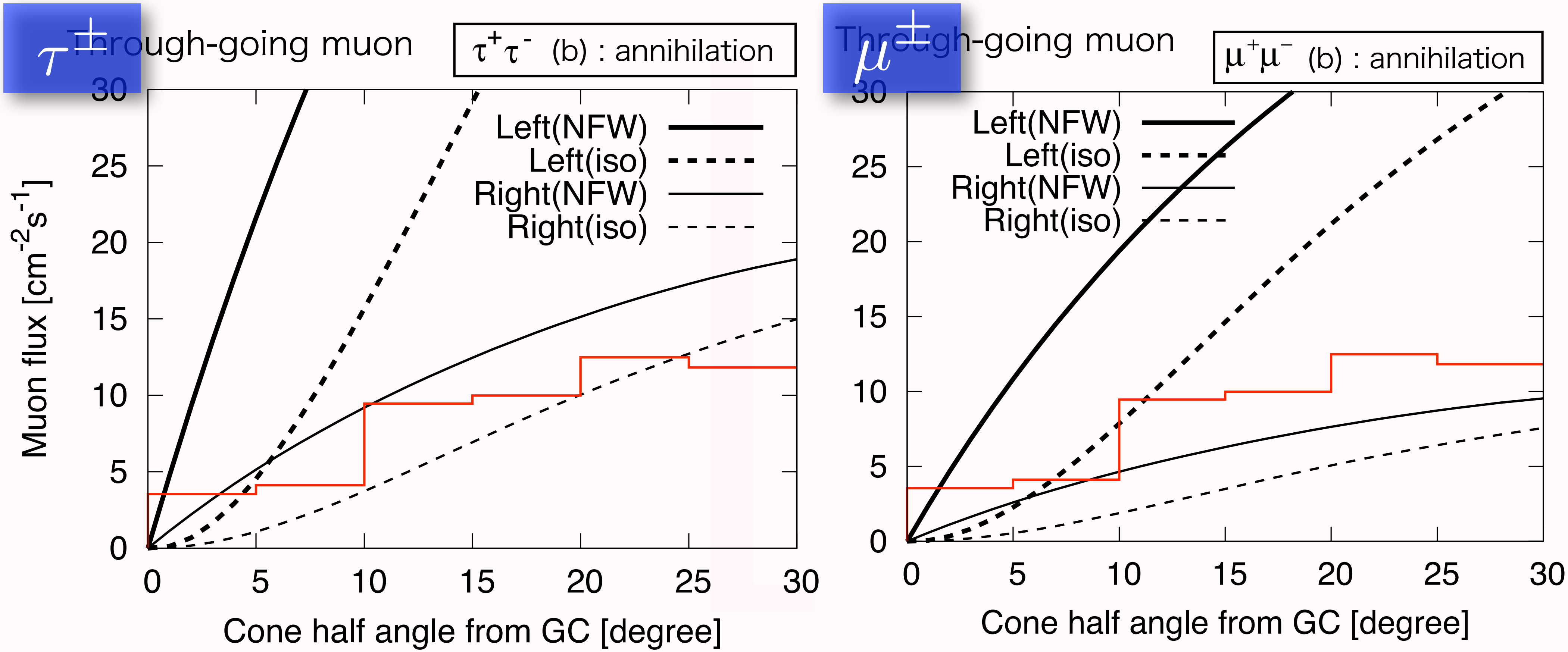


- $E_\mu \ll 1\ \mathrm{TeV}$ $\quad R_\mu \sim 1\ \mathrm{km}(E_\mu/1\mathrm{TeV})$
- $E_\mu \gtrsim 1\ \mathrm{TeV}$ $\quad$ Radiative loss

Limits from SK : Annihilation into left-handed leptons is not favored.

Annihilate into left handed leptons $(\nu\bar{\nu} + l_L^- l_R^+)$

Annihilate into right handed leptons $(l_R^- l_L^+)$

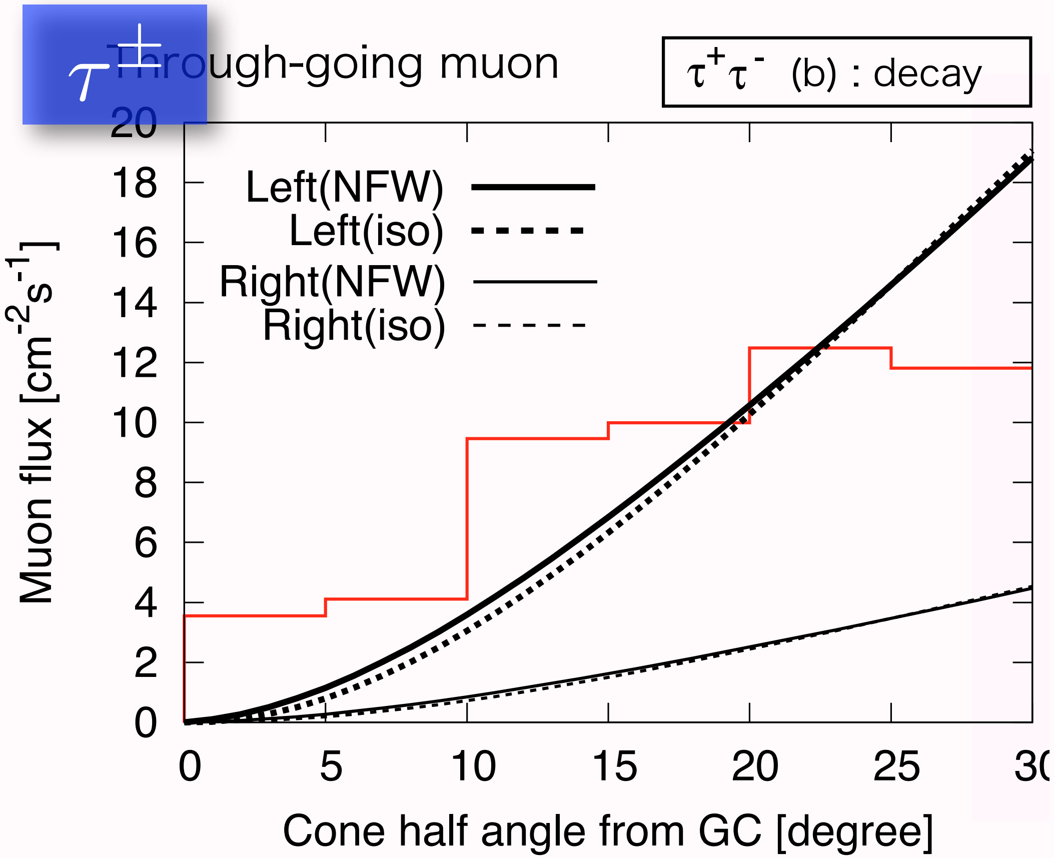


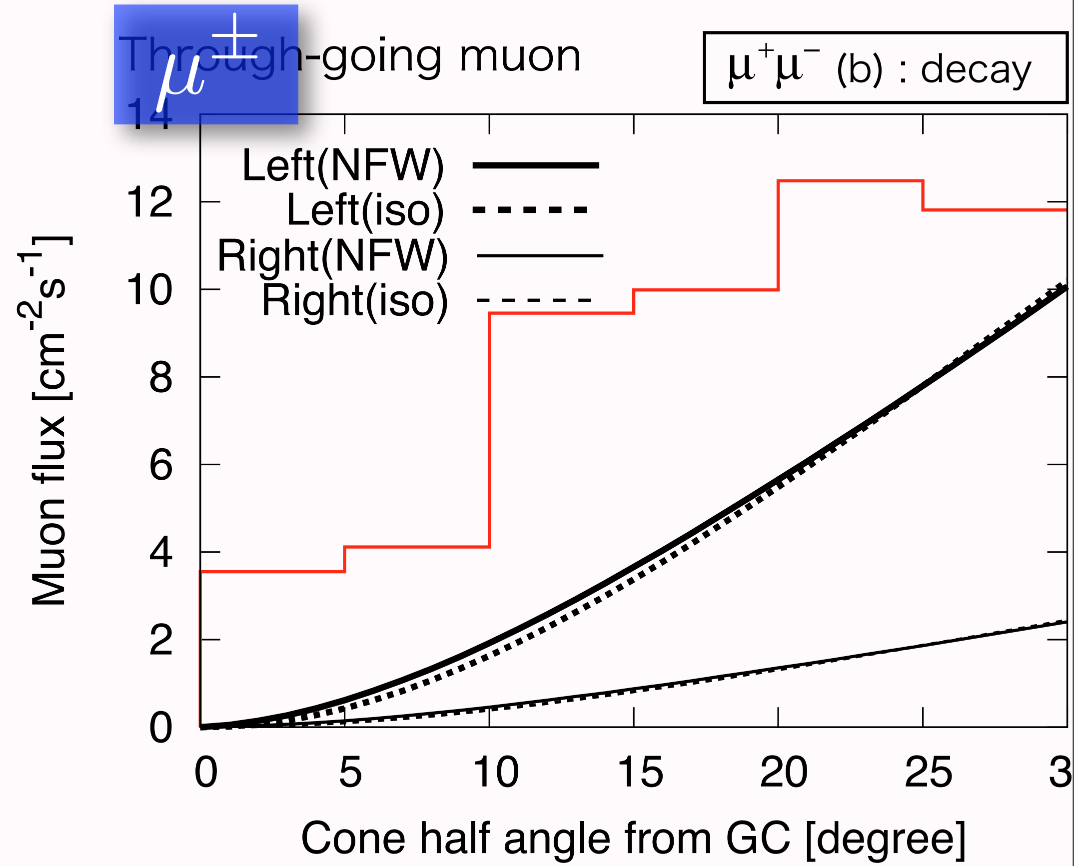
J.Hisano, M.Kawasaki, K.Kohri, KN (2008)

Case of Decaying DM

Decay into left handed leptons $(\nu\bar{\nu} + l_L^- l_R^+)$

Decay into right handed leptons $(l_R^- l_L^+)$





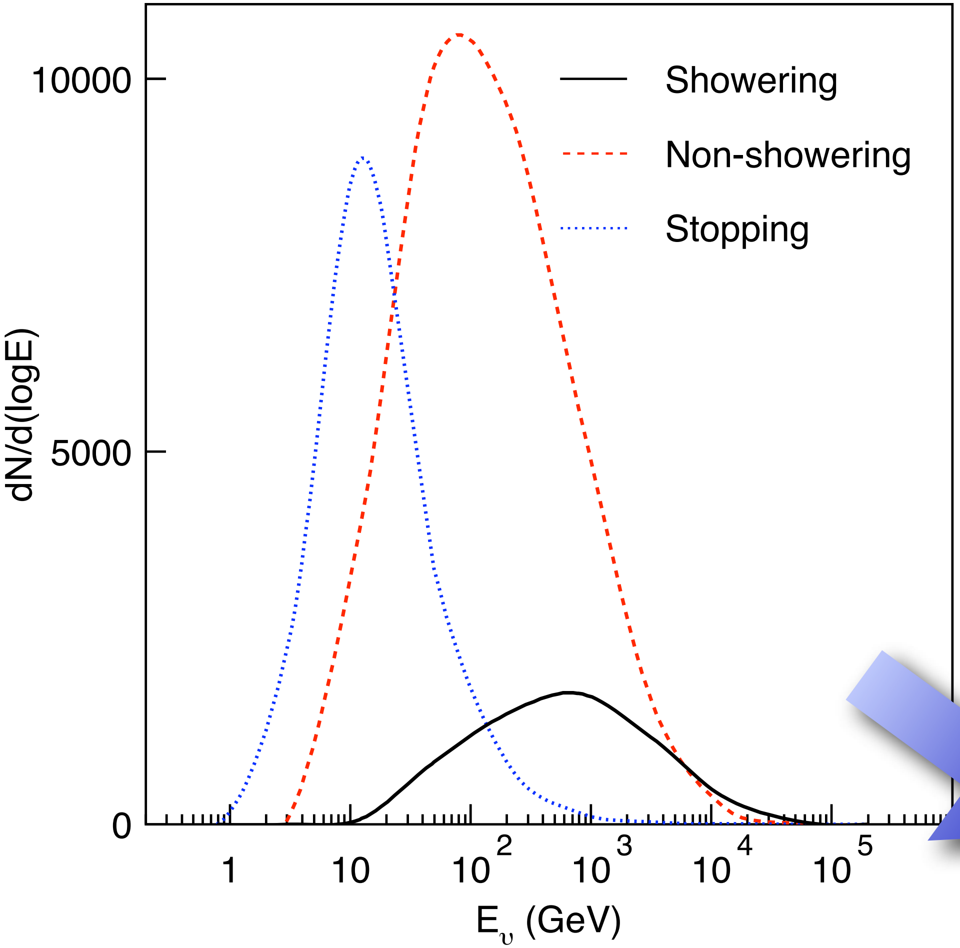
J.Hisano, M.Kawasaki, K.Kohri, KN (2008)

Possible improvement at SK

- High-energy neutrino-induced muons are detected through Cherenkov light
- Energy of each muon is not measured
- However, SK can distinguish muon events by event shape : shower and non-shower
- Higher energy muons more likely observed as showering muon

DM-originated neutrinos more likely produce shower events than atmospheric neutrinos

Simulation

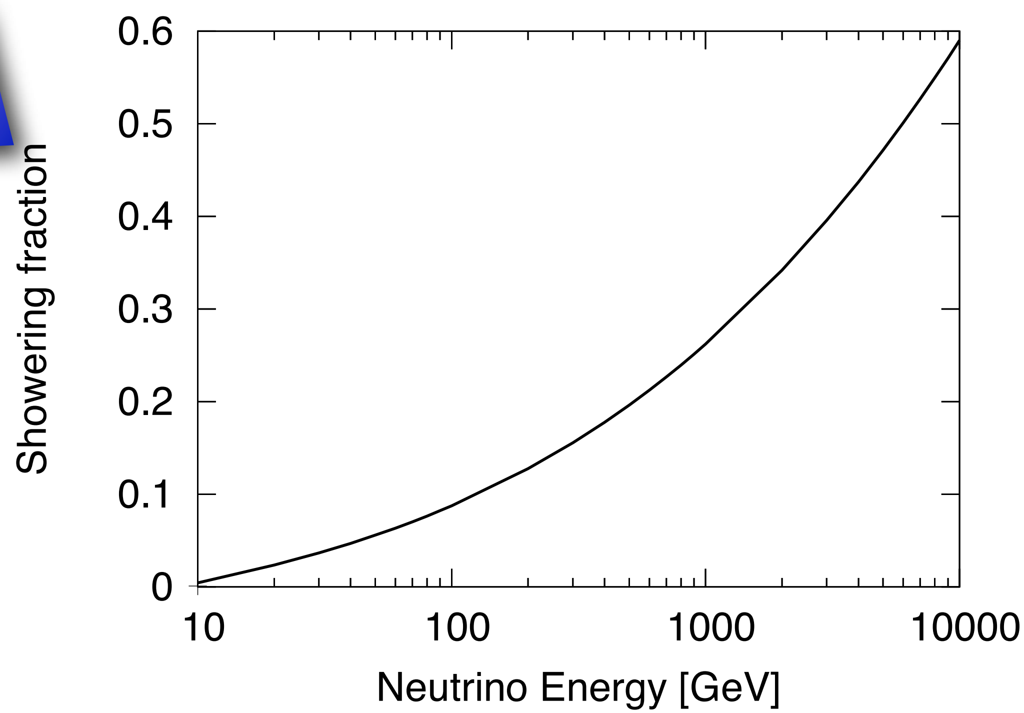


S.Desai et al.,
Astropart.Phys.29,42 (2008)

3 kind of muon events :

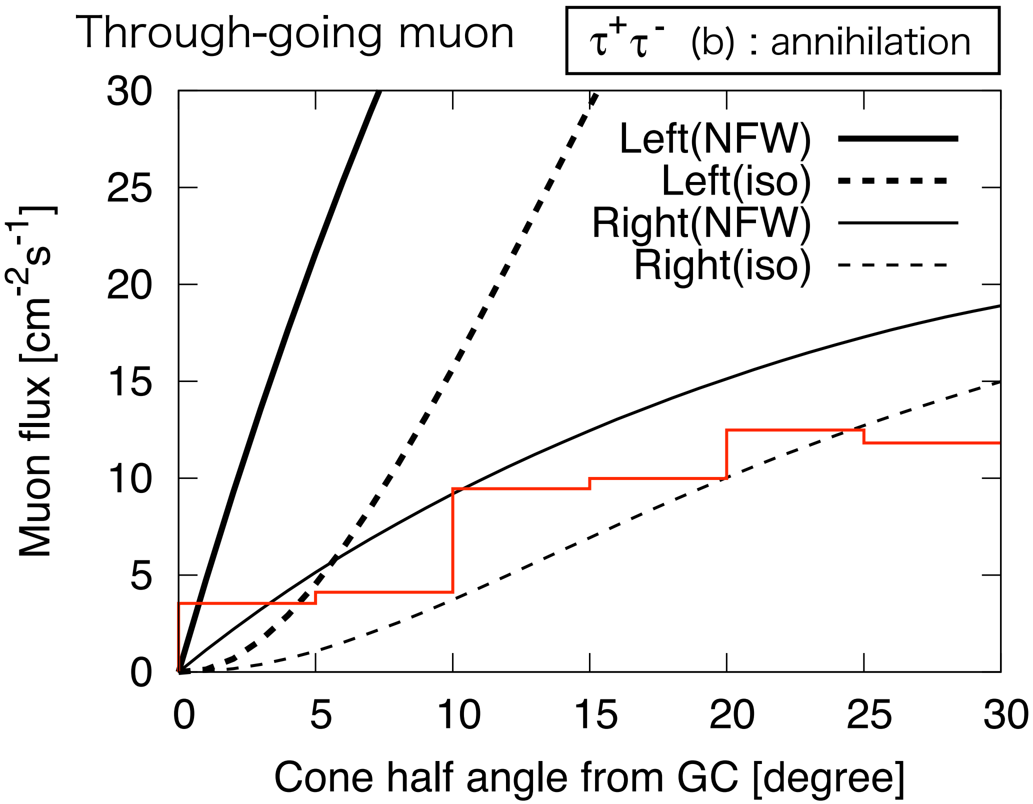
- Through-going shower mu
- Through-going nonshower mu
- Stopping mu

Probability for shower

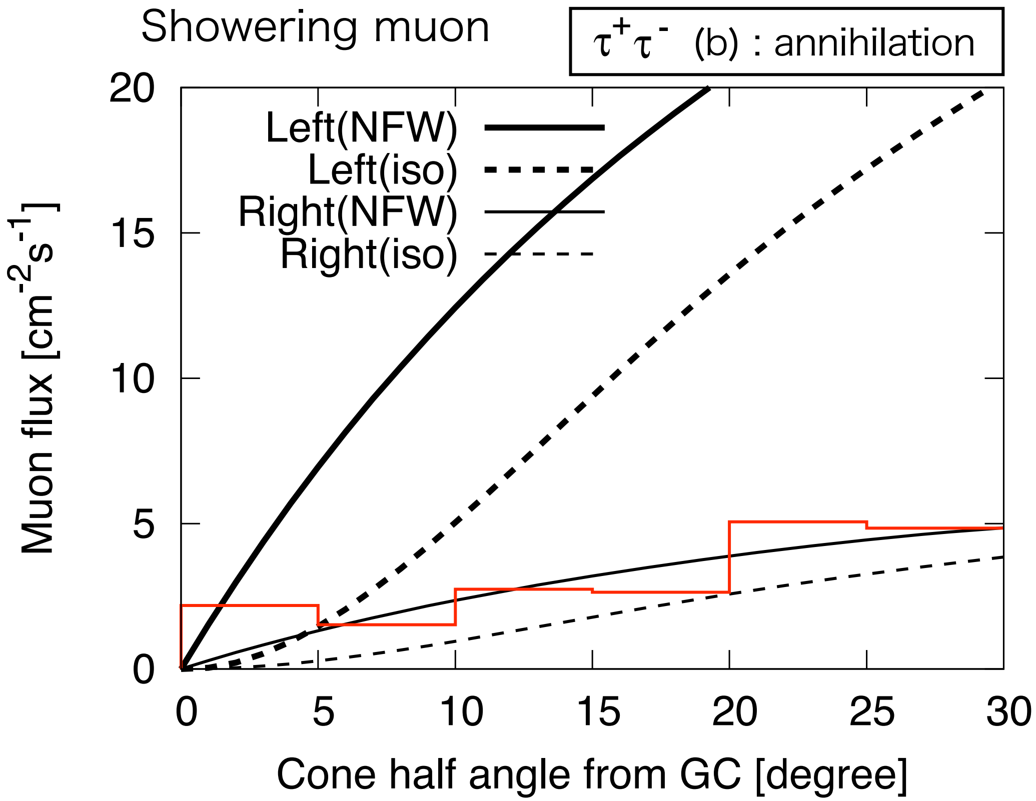


Up-going muon flux : shower and non-shower

Non-shower



Shower



Heavy DM ⟶ Shower muon is slightly better

[Data from SK-III preliminary (Y.Itow, private communication)]

Lesson from neutrino

- Construct a DM model which fits PAMELA/Fermi data (either ann or decay)
- Check if your model produce monochromatic neutrinos with similar rate or not
- If yes, your model may conflict with SK bound irrespective of DM density profile

→ Check carefully the SK bound!

Gamma-rays

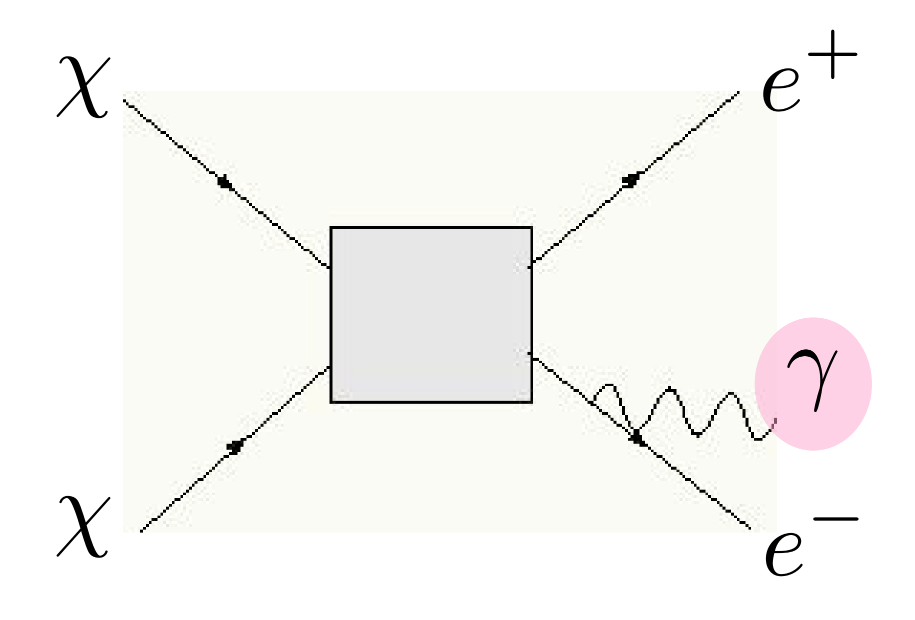
Continuum Gamma-Rays from DM ann.

Internal Brems.

Final state charged particle always emit photon.

$$\chi\chi \to l^+l^-$$

$$\chi\chi \to l^+l^-\gamma$$

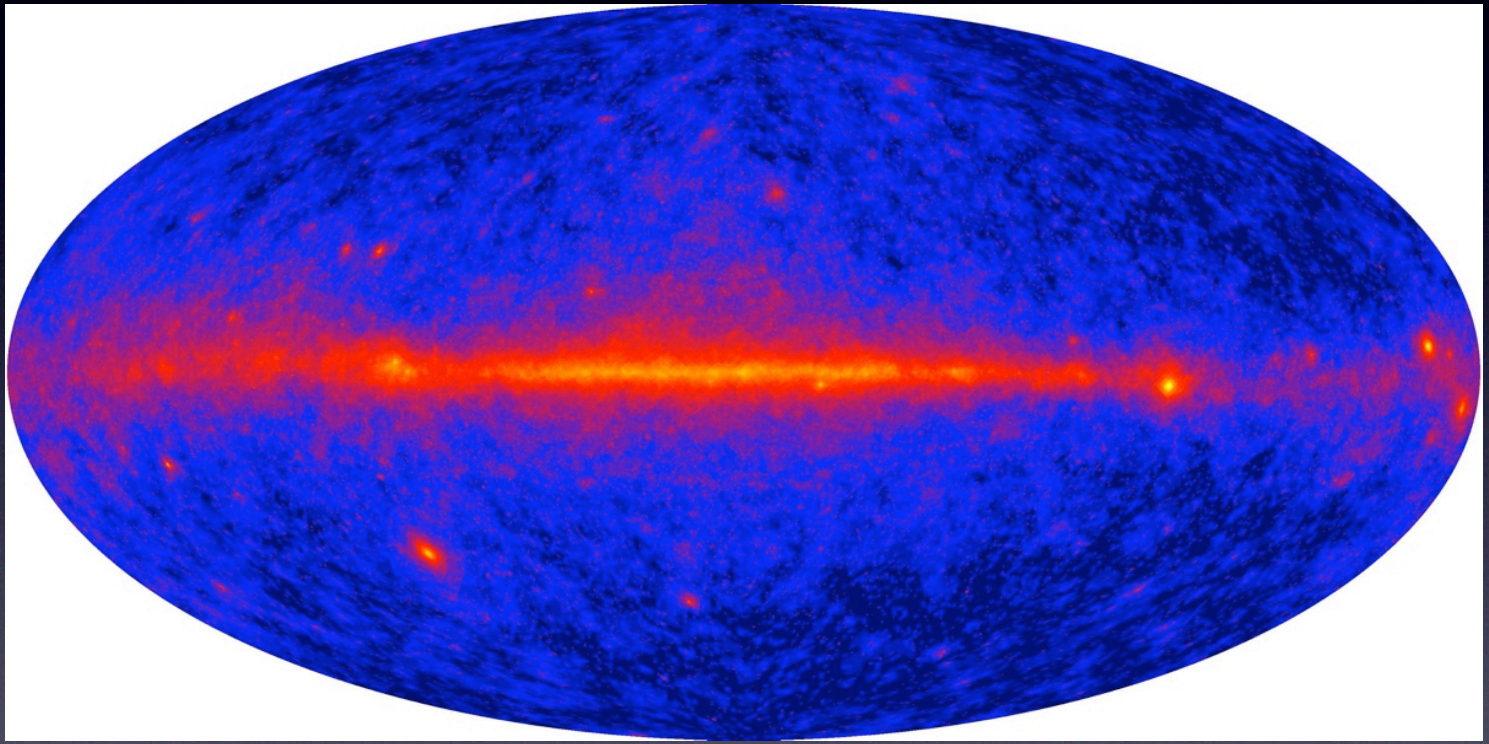


Cascade decay

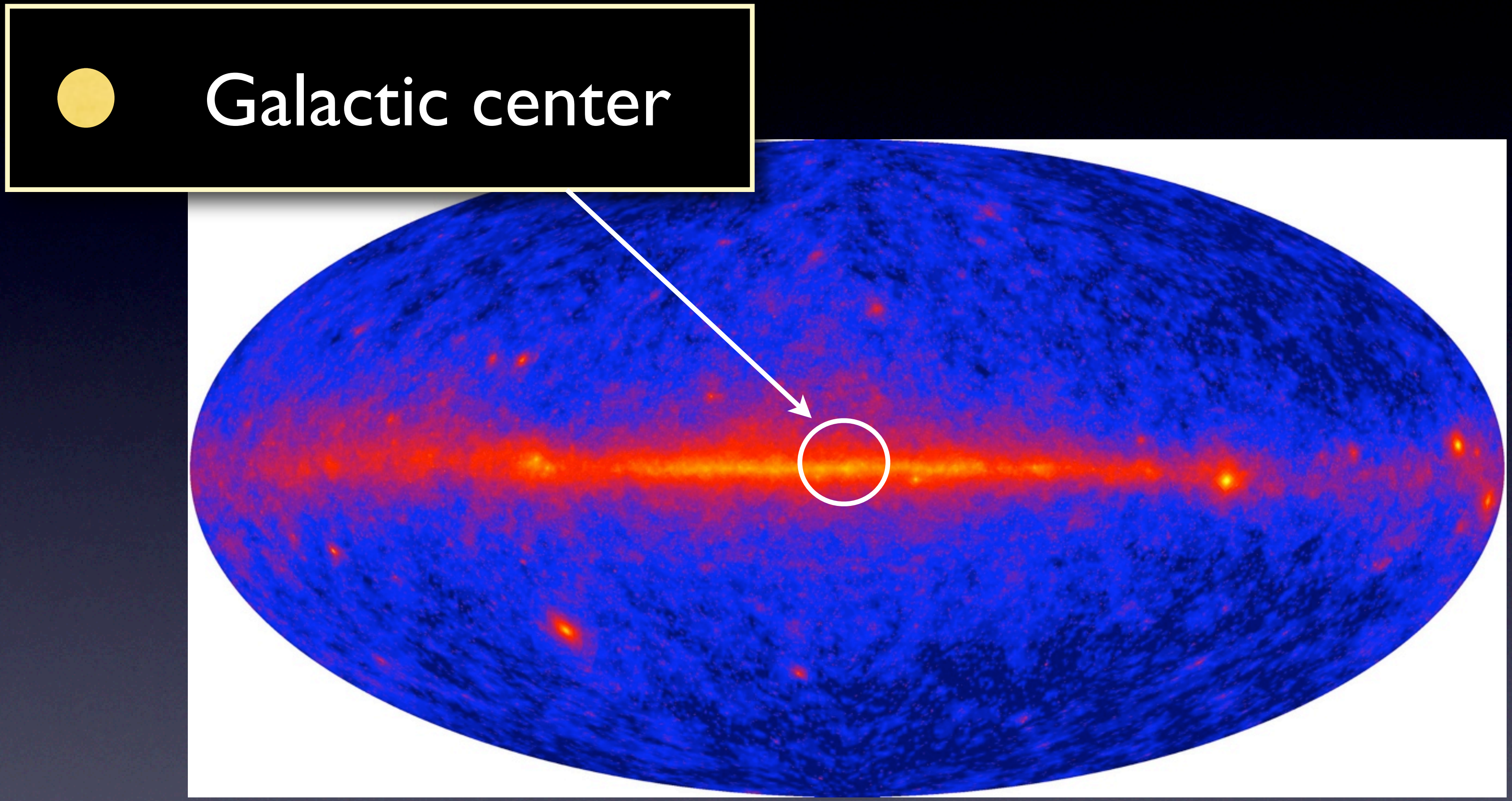
$$\chi\chi \to \tau^+\tau^-, W^+W^- \to \text{hadrons}(\pi^\pm, \pi^0, \rho, \ldots)$$

$$\pi^0 \to 2\gamma$$

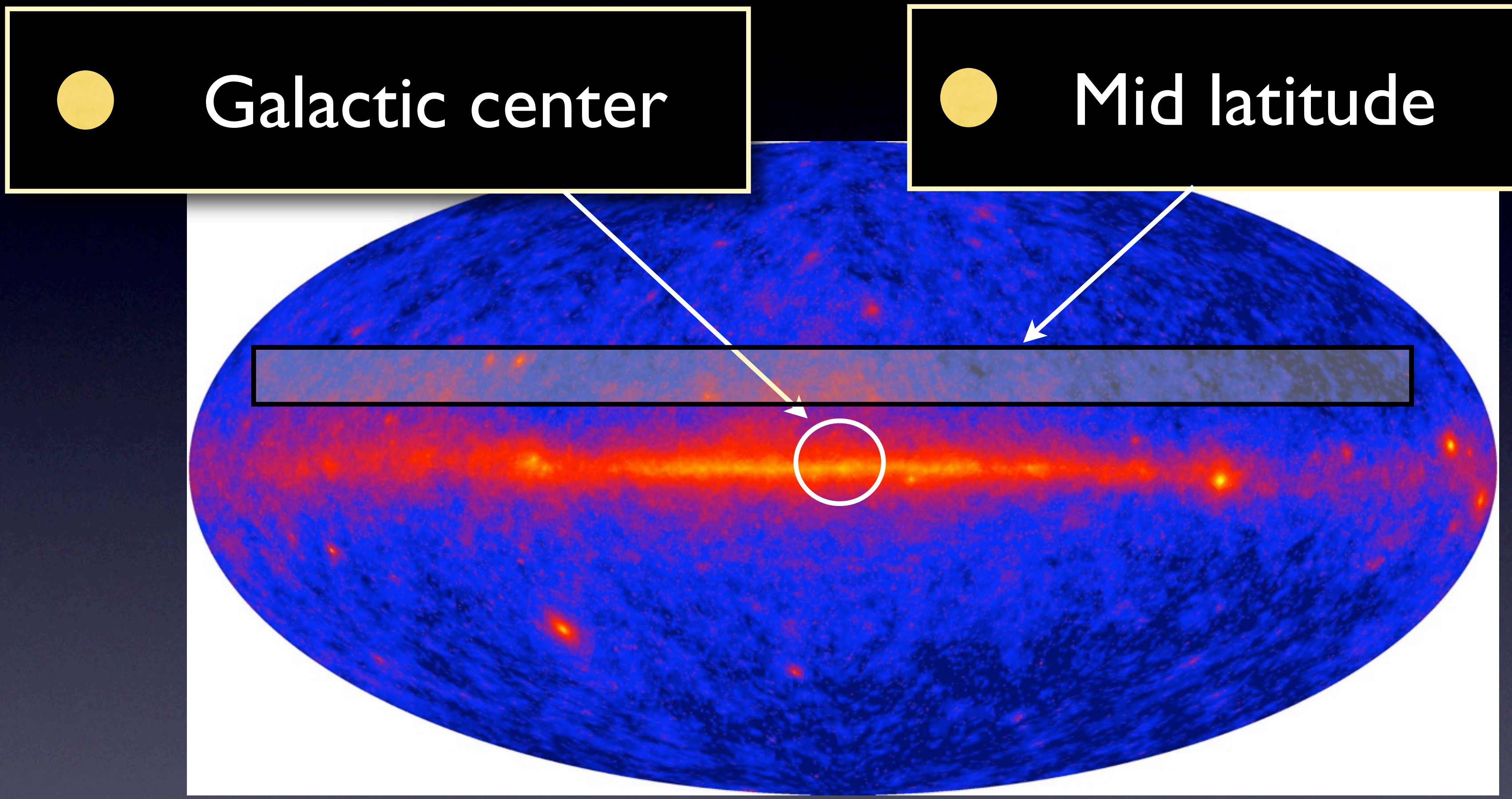
Observation regions



Observation regions

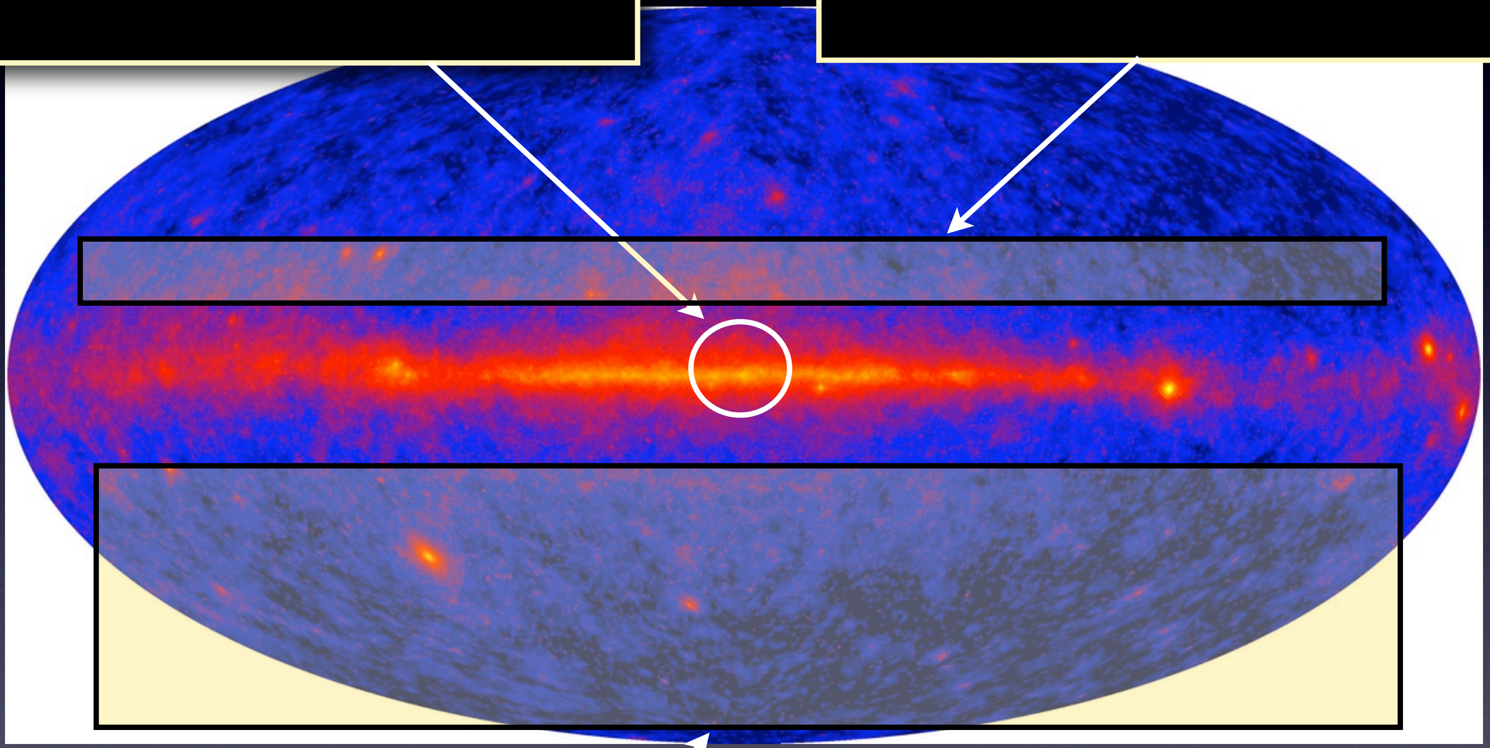


Observation regions



Observation regions

- Galactic center
- Mid latitude

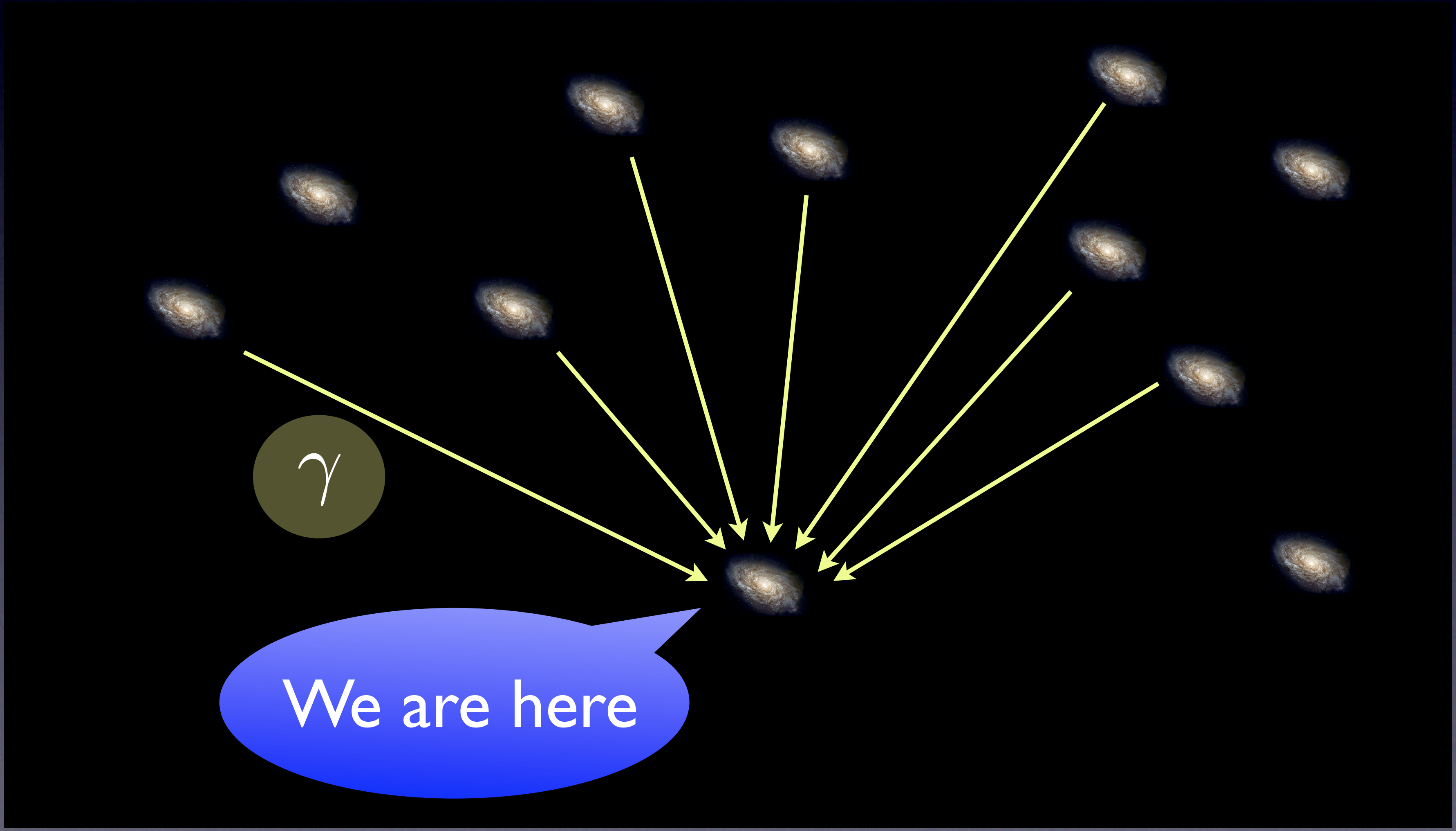


- Diffuse isotropic

Extra-Galactic component

Ullio, Bergstrom, Edsjo, Lacey (2002)

Dominant contribution is summation over the DM ann. in external clustering objects



$$\boxed{\left[\frac{d\Phi_\gamma}{dE}\right]_{\rm ext} = \frac{\langle\sigma v\rangle}{8\pi}\frac{\bar{\rho}_m^2}{m_\chi^2}\int\frac{dz(1+z)^3}{H(z)}\frac{dN^\gamma}{dE'}\Delta^2(z)}$$

$\Delta^2(z)$: Enhancement factor

($\Delta^2(z)=1$: homogeneous DM)

$$\Delta^2(z) \propto \int dM\, M\frac{dn(z)}{dM}\int dr\,\rho_M^2(r)$$

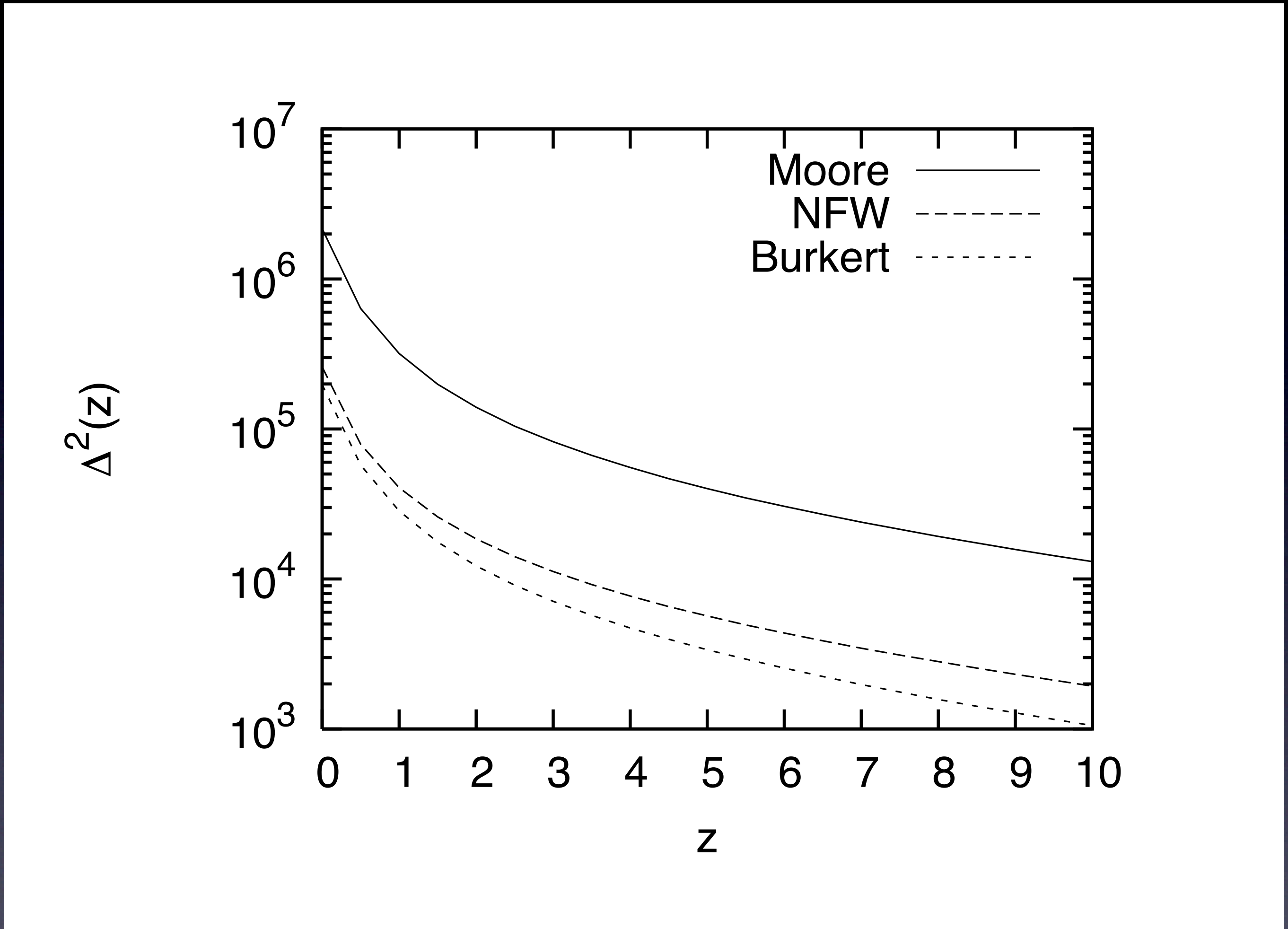
Number of clustering objects :

→ Press-Schechter theory

Press, Schechter (1974)
Sheth, Mo, Tormen (2001)

Universal DM halo profile
(Moore, NFW, ...)

Enhancement factor $\Delta^2(z)$



- **Moore**

$$\rho(r) \sim \frac{1}{r^{1.5}(1+r^{1.5})}$$

- **NFW**

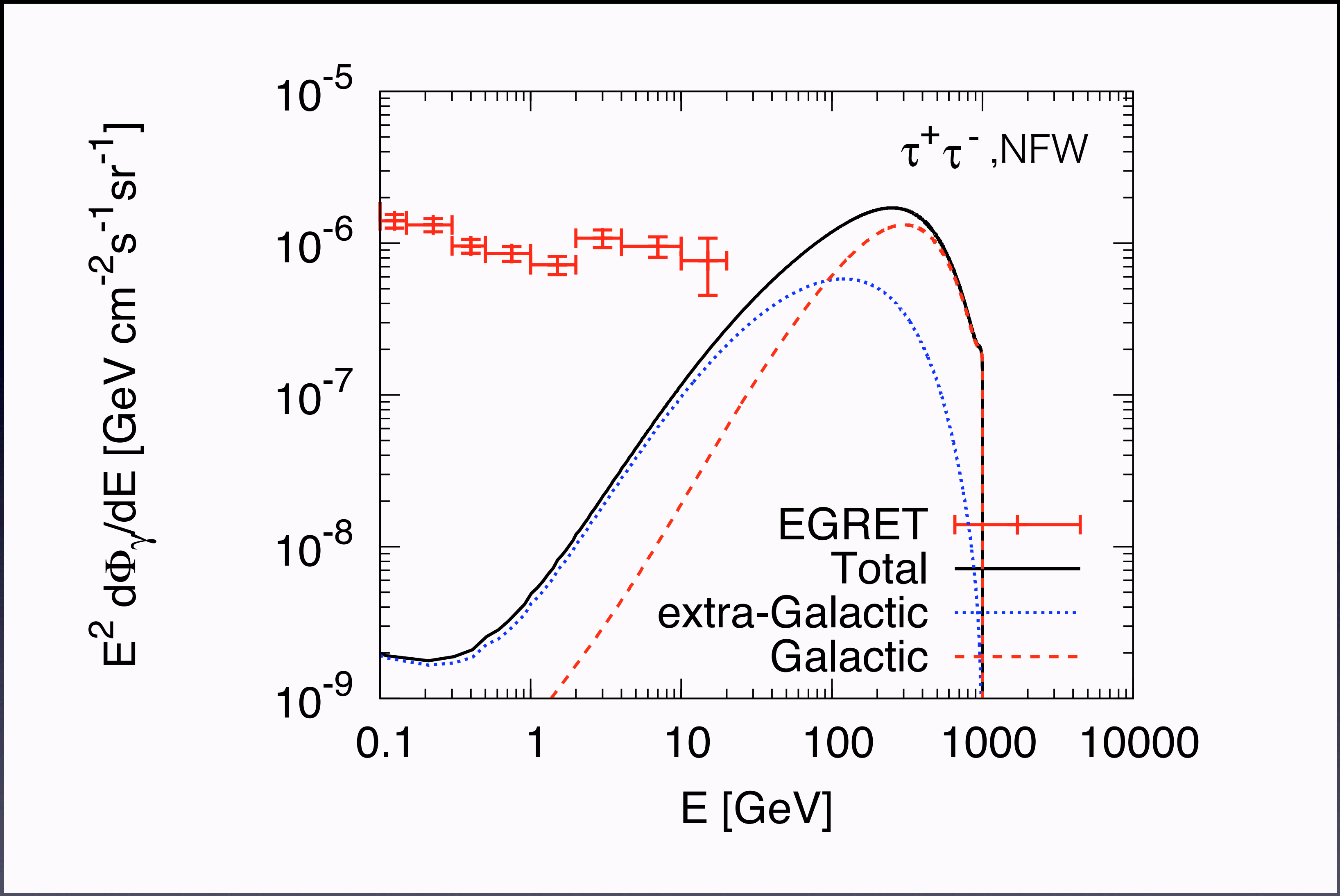
$$\rho(r) \sim \frac{1}{r(1+r)^2}$$

- **Burkert**

$$\rho(r) \sim \frac{1}{(1+r)(1+r^2)}$$

About 10^5-10^6 enhancement for DM annihilation rate

Gamma-rays from $10^\circ < |b| < 90^\circ$

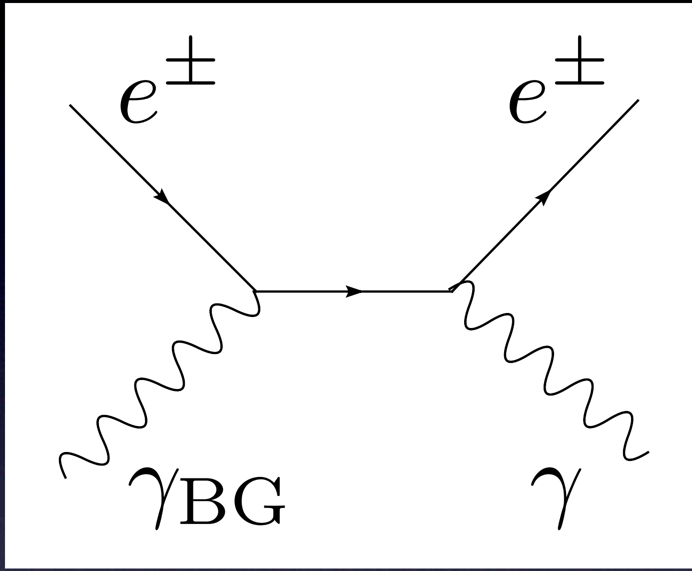


Extragalactic component is comparable to Galactic component

Inverse-Compton extragalactic Gamma-Rays

Profumo, Jeltema 0906.0001
Belikov, Hooper 0906.2251

High energy positron/electrons scatter off BG photon and yield gamma-rays



$$\chi\chi \to e^+e^-{}'\mathrm{s}$$

$$e^{\pm} + \gamma_{\rm BG} \to e^{\pm} + \gamma$$

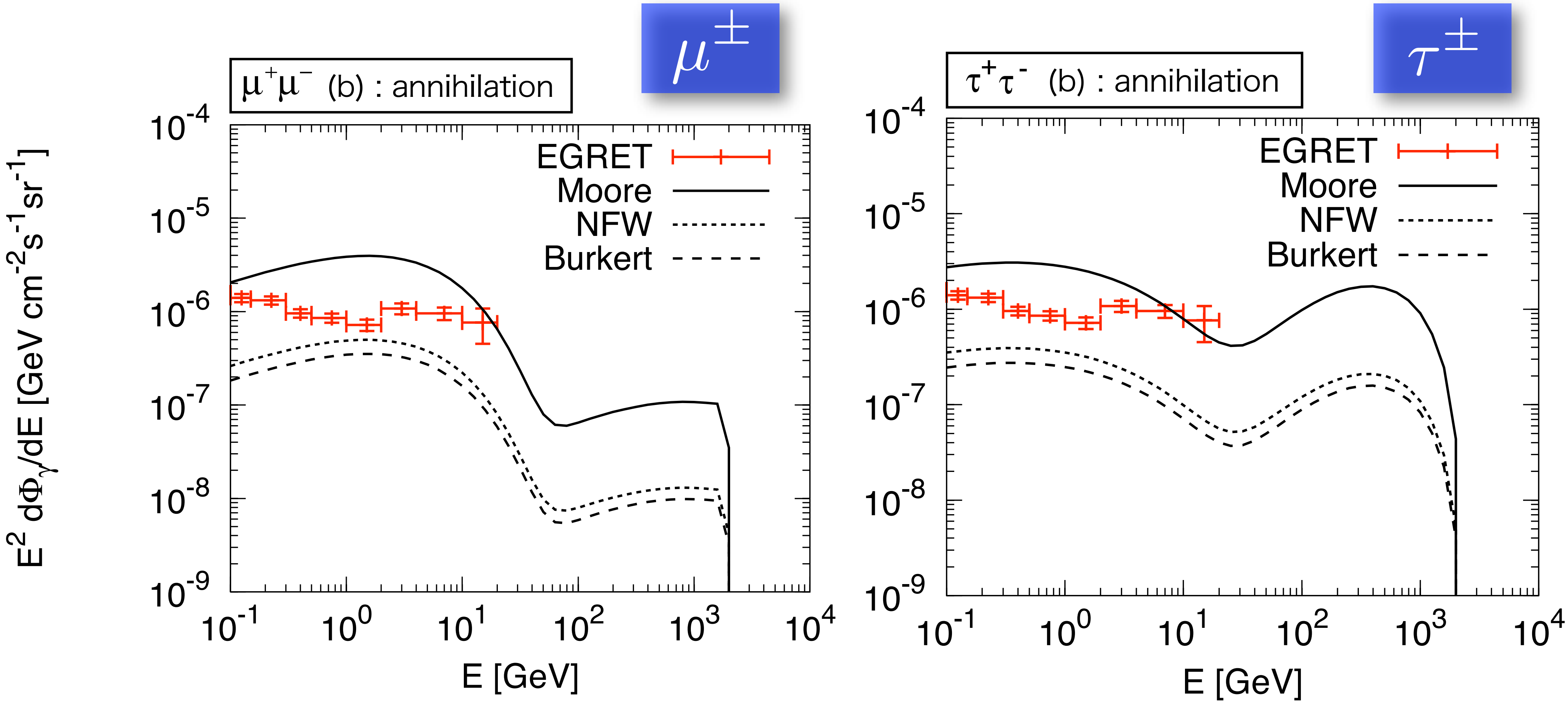
$$E_\gamma \sim \gamma_e^2 E_{\gamma(\rm BG)}$$

HE electron from DM annihilation

CMB photon

Gamma-ray

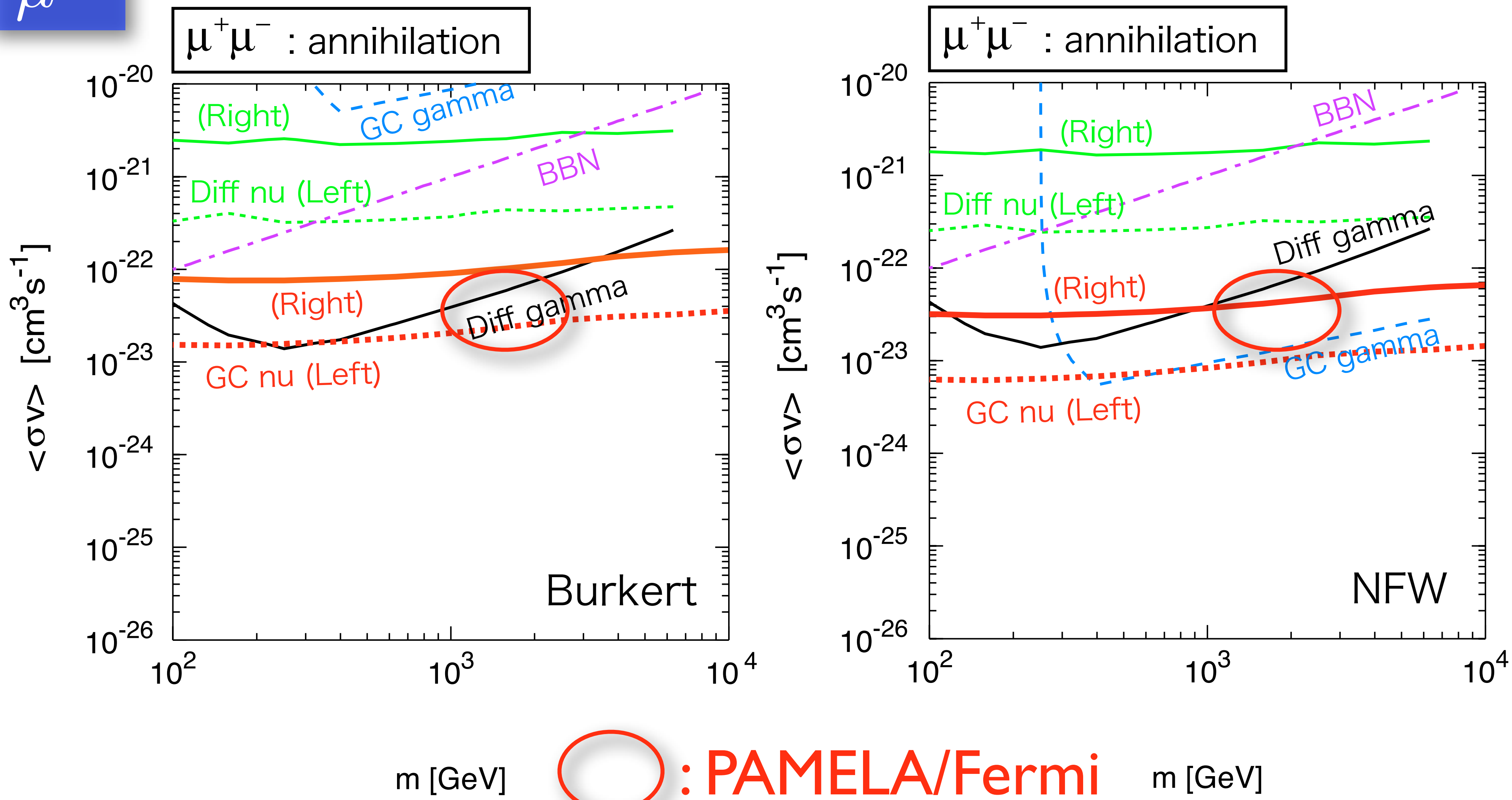
Extragalactic gamma-ray flux



Diffuse isotropic component gives the most stringent bound for cored profile.

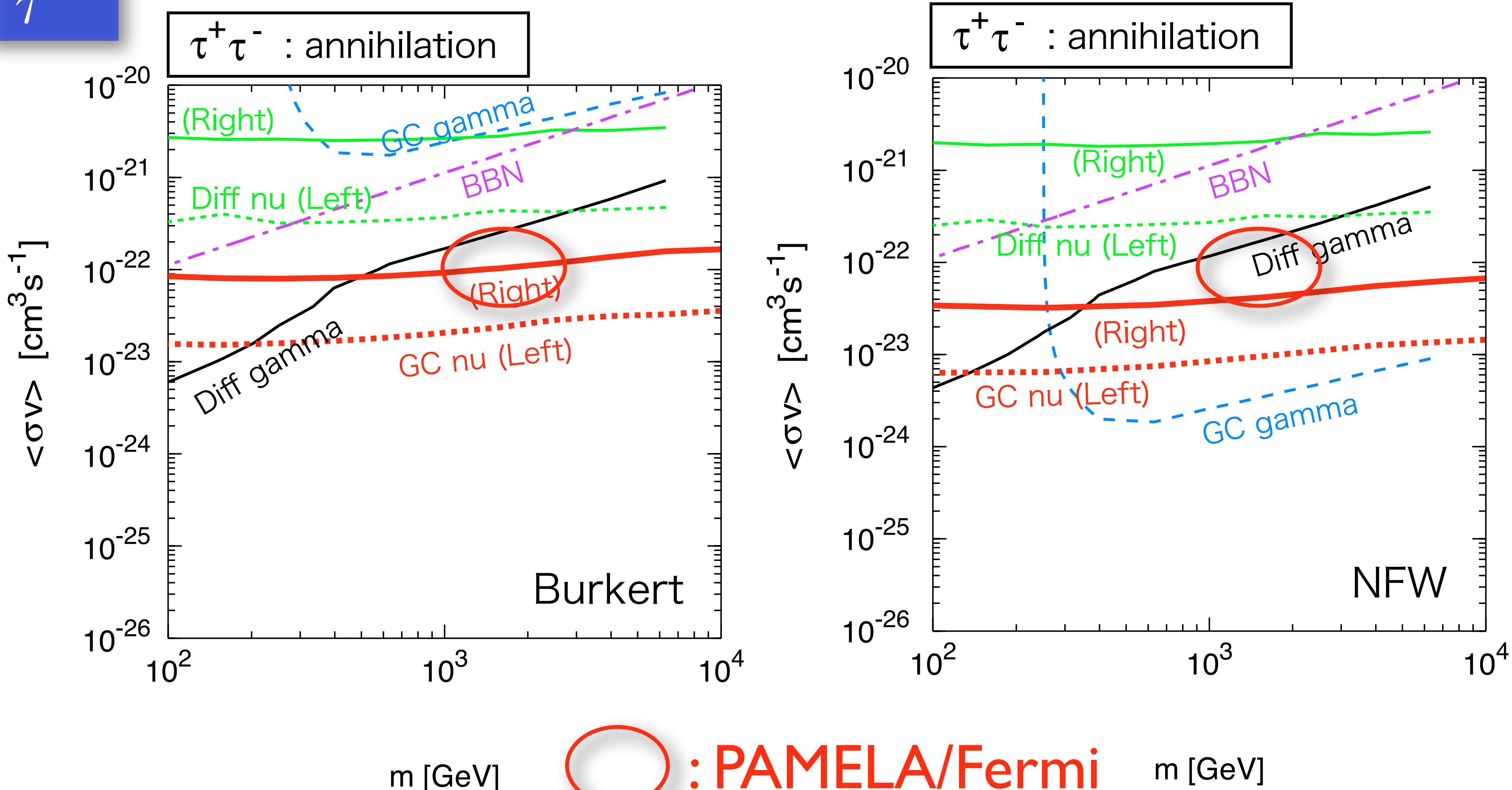
Summary of constraints

$\mu^{\pm}$



: PAMELA/Fermi

$\tau^{\pm}$



: PAMELA/Fermi

Diffuse gamma & neutrino constraints are important.

Summary

DM interpretation of PAMELA/Fermi

Constraints from other signals, such as

- Neutrino-induced muon Flux

  Useful constraints on annihilating/decaying DM.

  → IceCube(+DeepCore), KM3NeT

- Gamma-ray Flux

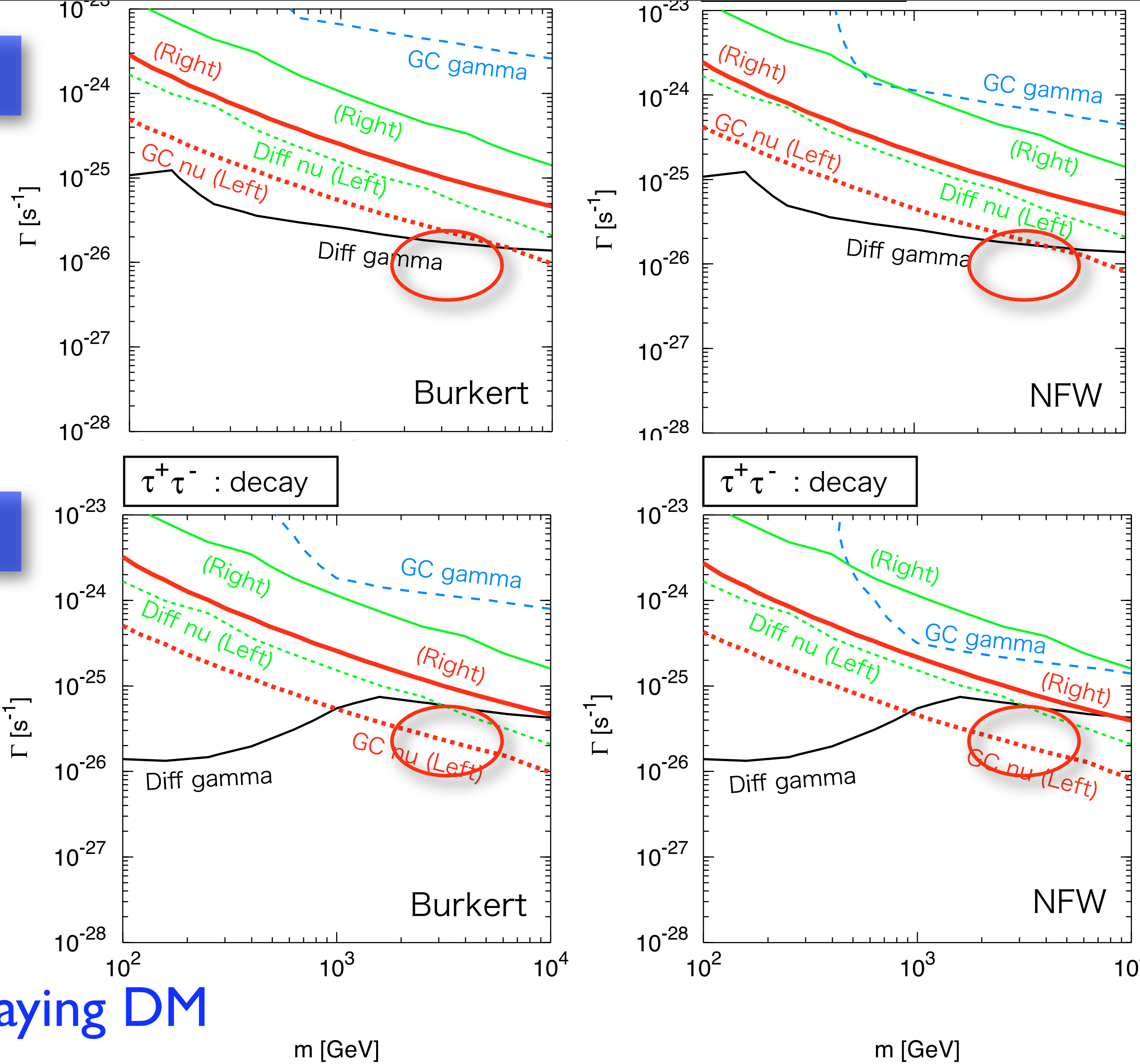
  Both Galactic and extra-Galactic gamma-rays may be significant in DM ann scenario.

  → Fermi

Decaying DM

$\mu^{\pm}$

$\tau^{\pm}$



Back-up Slides

Comments on IceCube

- Huge detector

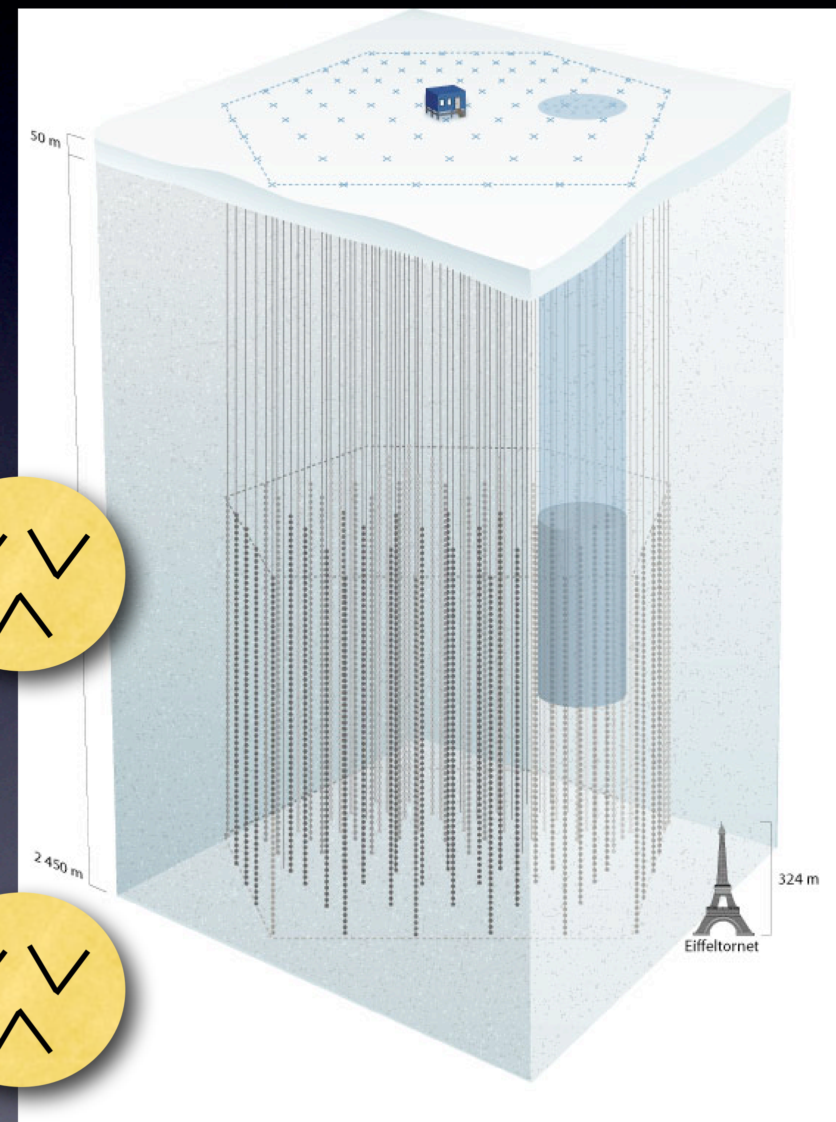
→ High statistics

- Located at South Pole

→ cannot see Galactic center through upward muons

- Use downward muons?

→ Atmospheric muon BG is 10^6 larger than DM signal



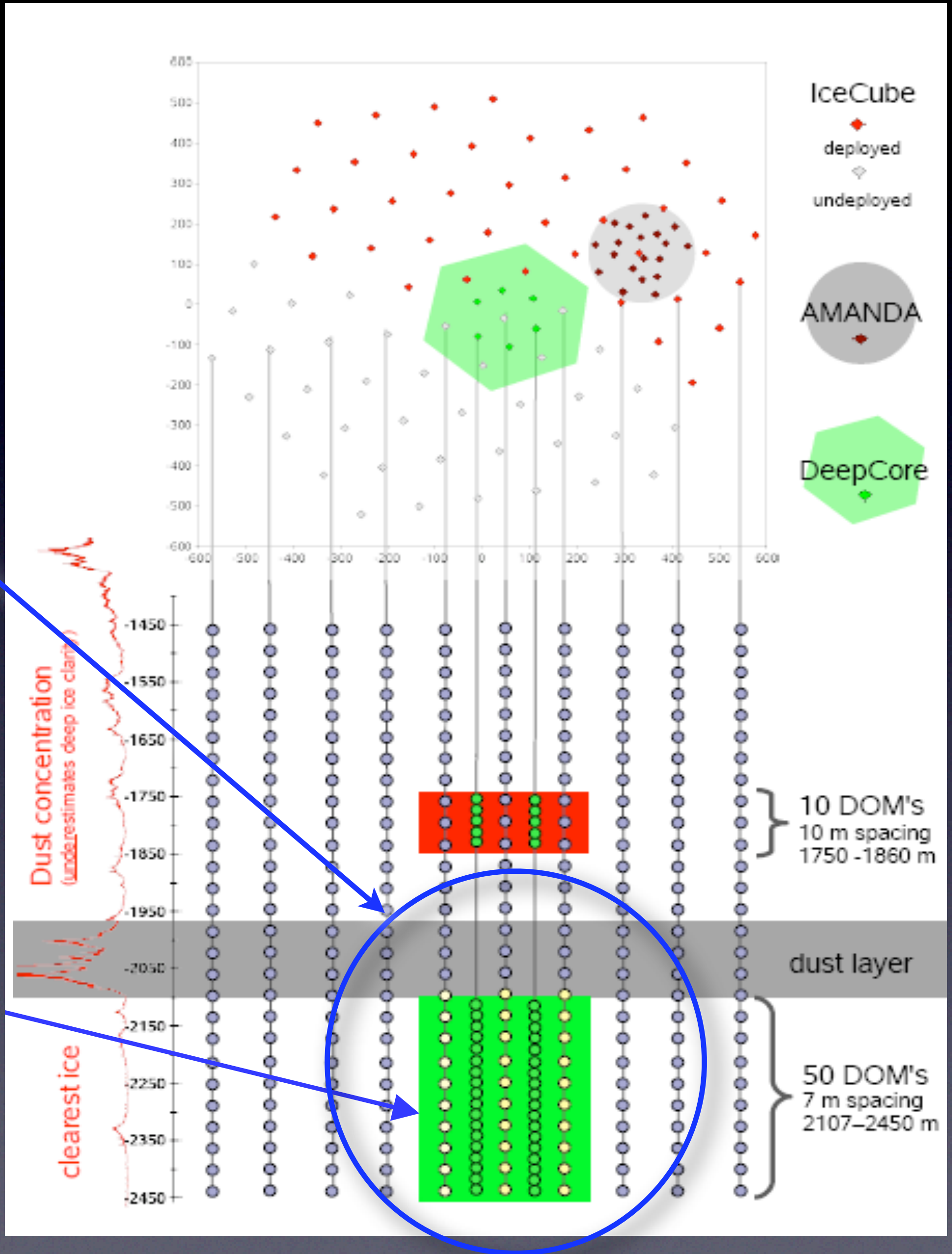
A planned extension : DeepCore

- Primary purpose : better sensitivity on low-energy neutrino

  Inner detector with denser instrumentation

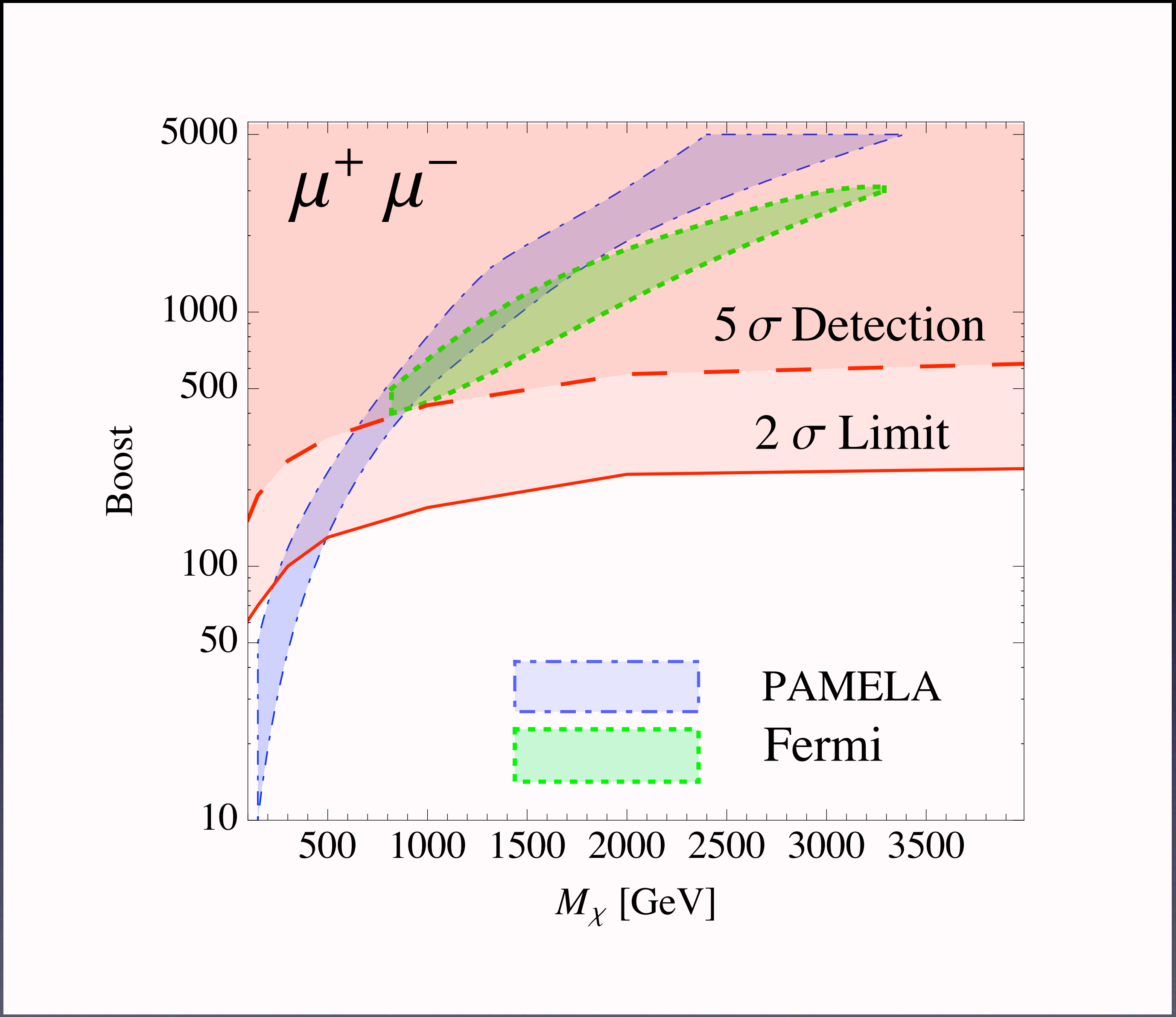
- Use original detector as muon veto

Remove atmospheric muon BG



S.Seo, Talk at Dark2009

Expected sensitivity of DeepCore (5yr)



Spolyar, Buckley, Freese, Hooper, Murayama, 0905.4764

Gamma-rays from DM annihilation

1. Galactic gamma

DM annihilation in the Galaxy

2. Galactic inverse-Compton gamma

Cholis et al. 0811.3641
Cirelli, Panci 0904.3830

DM annihilation in the Galaxy

Target photon : star light, dust emission, CMB

3. Extragalactic gamma

Sum of DM ann. in DM halos

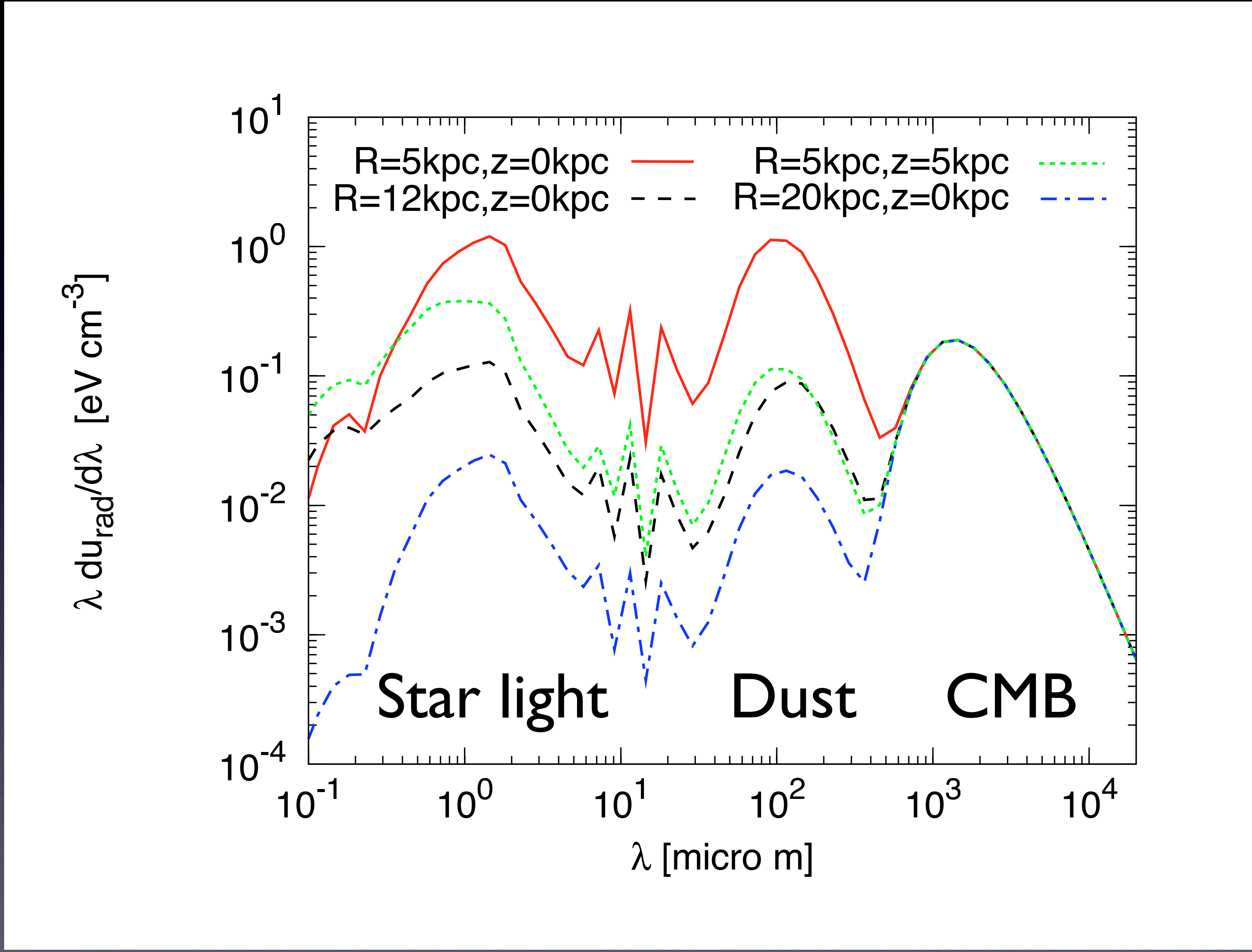
4. Extragalactic inverse-Compton gamma

Sum of DM ann. in DM halos

Profumo, Jeltema 0906.0001
Belikov, Hooper 0906.2251

Target photon : CMB

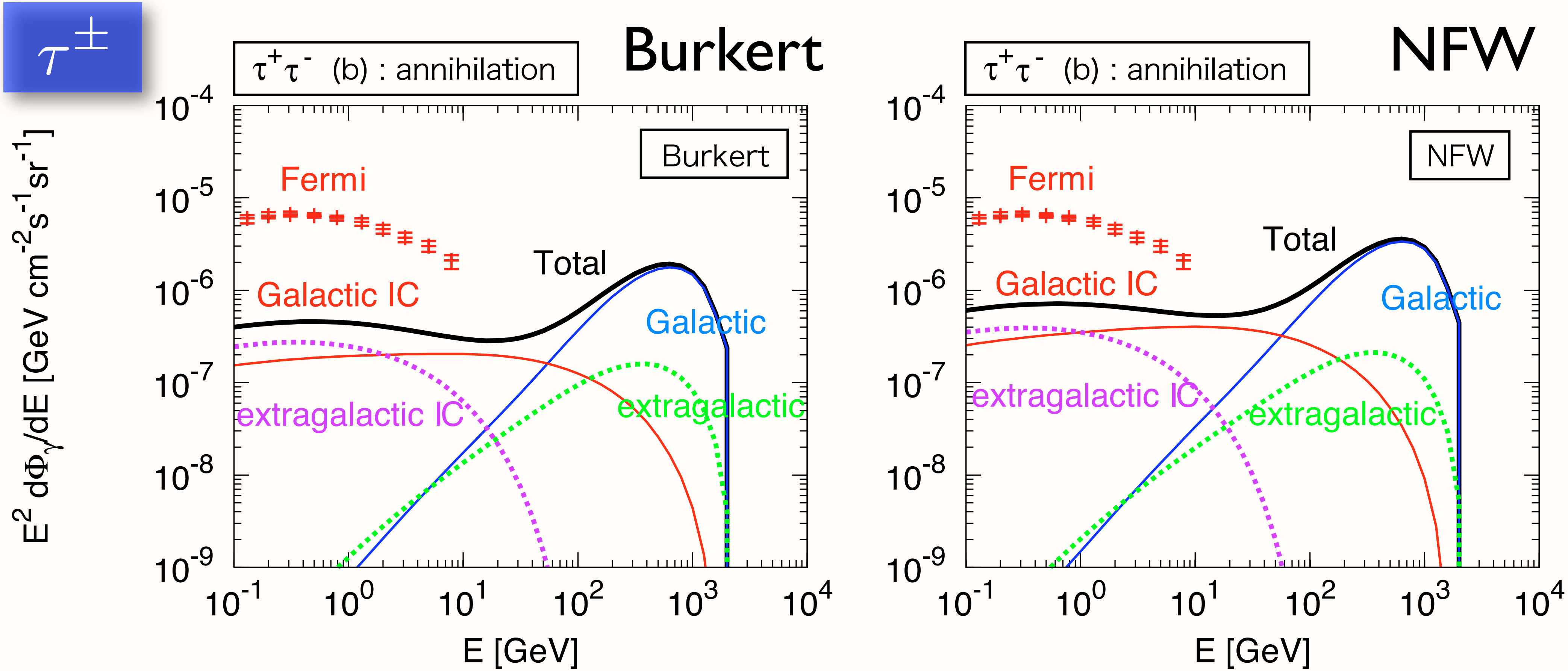
Intersteller radiation field



Porter & Strong (2005)

Gamma-rays from $10^\circ < |b| < 20^\circ$: each component

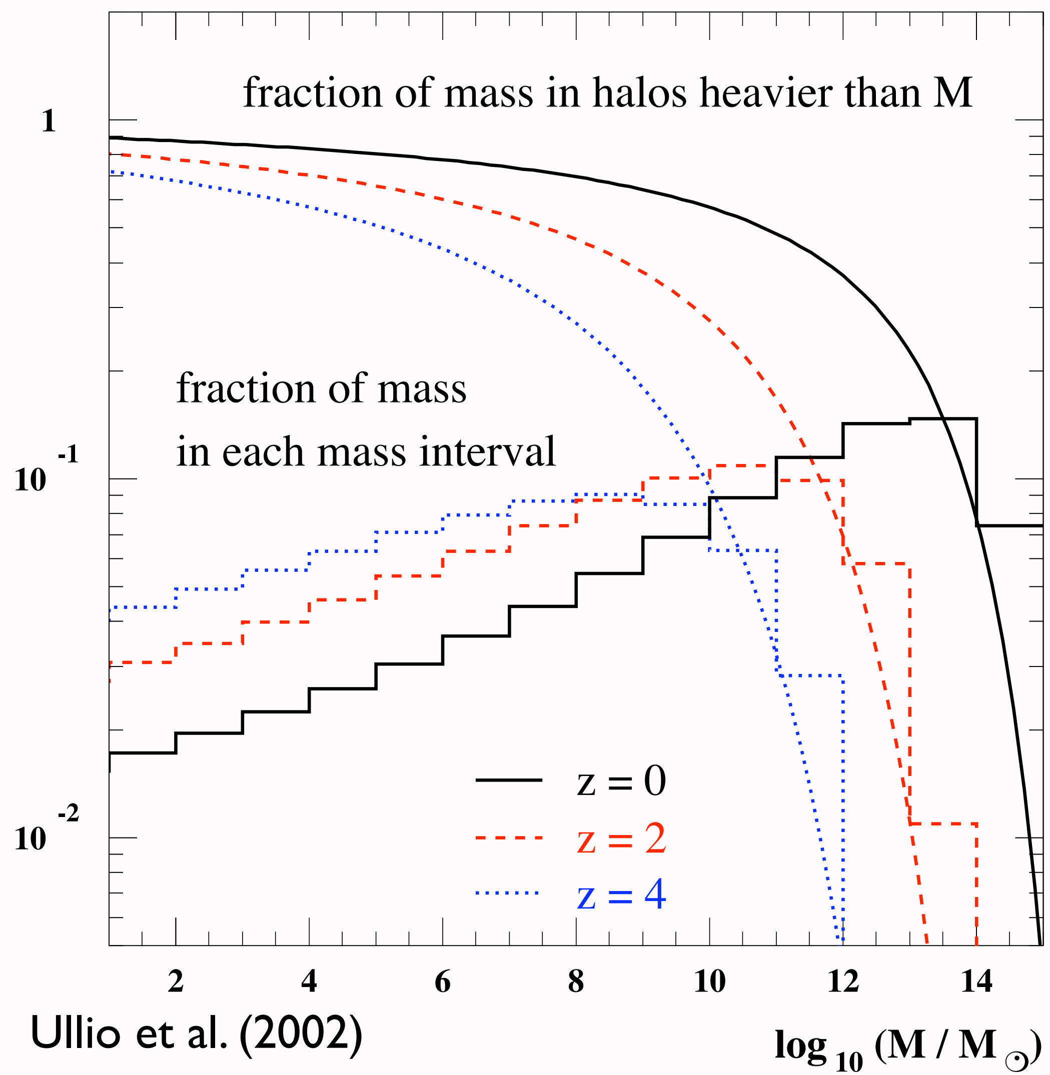
$\tau^{\pm}$



- All components are comparable
- Halo dependence is weak except for GC direction

Press-Schechter theory

$$\frac{dn}{dM} = \sqrt{\frac{2}{\pi}}\frac{\bar{\rho}_m \delta_c}{M}\left[-\frac{1}{\sigma(M)^2}\frac{d\sigma(M)}{dM}\right]\exp\left[-\frac{\delta_c^2}{2\sigma^2(M)}\right].$$



Ullio et al. (2002)

M : halo mass

$\sigma(M)$: dispersion of density field

$\delta_c \sim 1.686$: critical overdensity

$$\sigma^2(M) = \frac{1}{2\pi^2}\int W^2(k_M)P(k)k^2 dk$$

Predict number of collapsed objects with mass M