Cosmological and astrophysical probes of dark matter annihilation

Institute for Cosmic Ray Research,
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J.Hisano, M.Kawasaki, K.Kohri and KN, Phys.Rev.D79,063514(2009)[0810.1892]
J.Hisano, M.Kawasaki, K.Kohri and KN, Phys.Rev.D79,043516(2009)[0812.0219]
M.Kawasaki, K.Kohri and KN, to appear in Phys.Rev.D [0904.3626]
J.Hisano, KN, and M.J.S.Yang, Phys.Lett.B678,101(2009)[0905.1552]

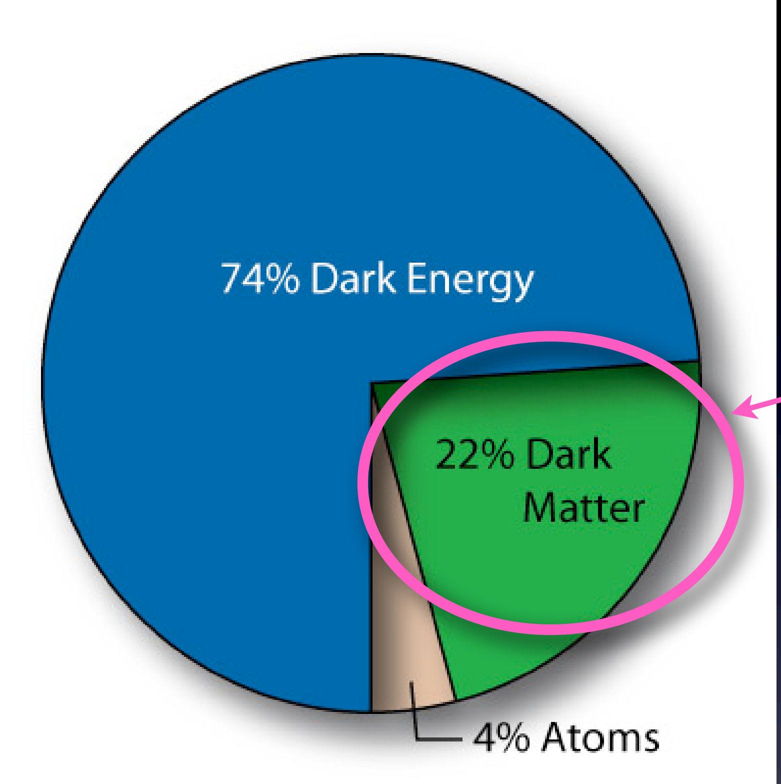
ACP Seminar@ IPMU (2009/07/02)

Contents

- First part
  - PAMELA/Fermi results & constraints on DM annihilation scenario
- Second part
  - Neutrino signals from GC
  - Diffuse gamma-ray background

First Part : Quick Summary

Energy content of the Universe after WMAP



What is the dark matter?

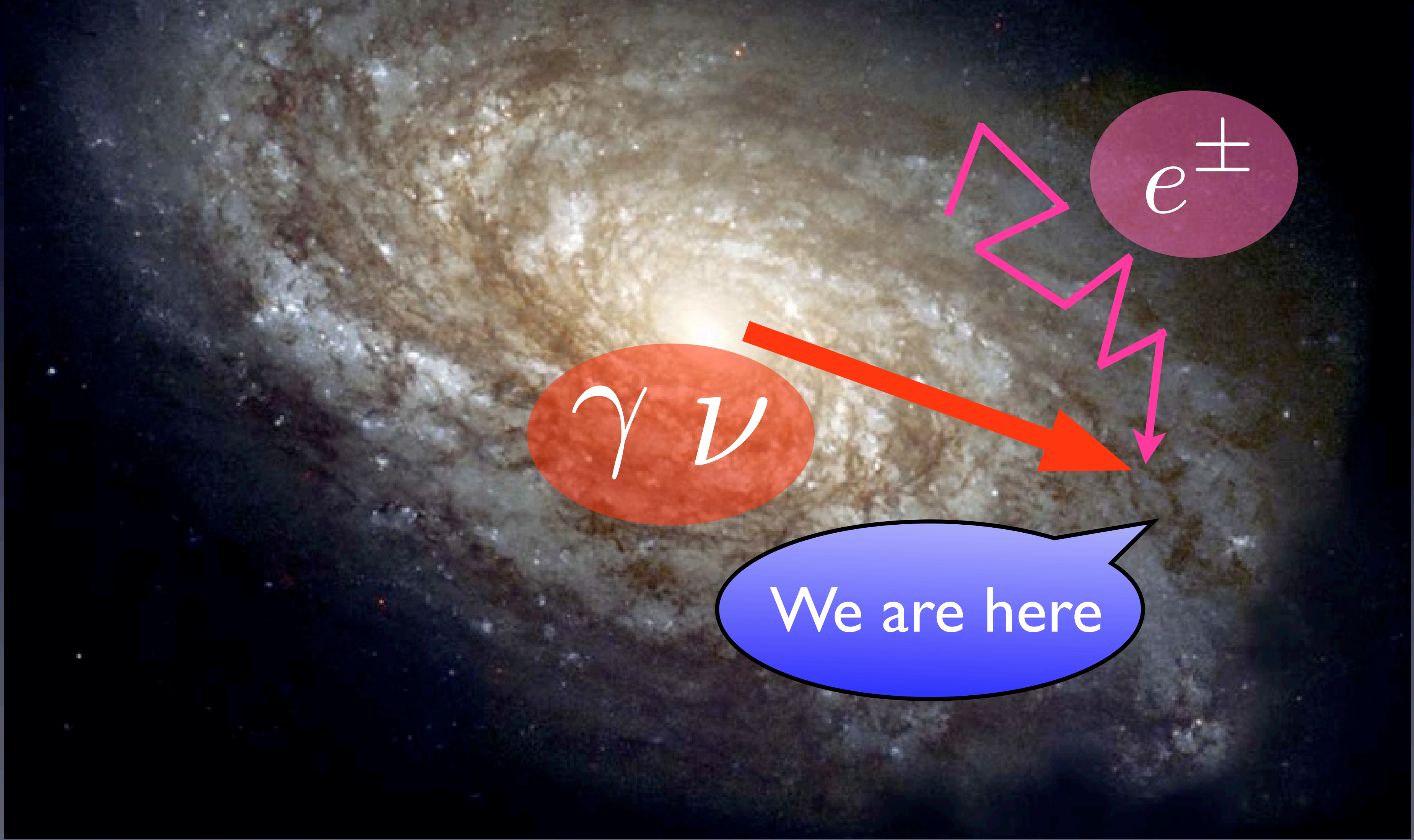
Can it be detected?

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

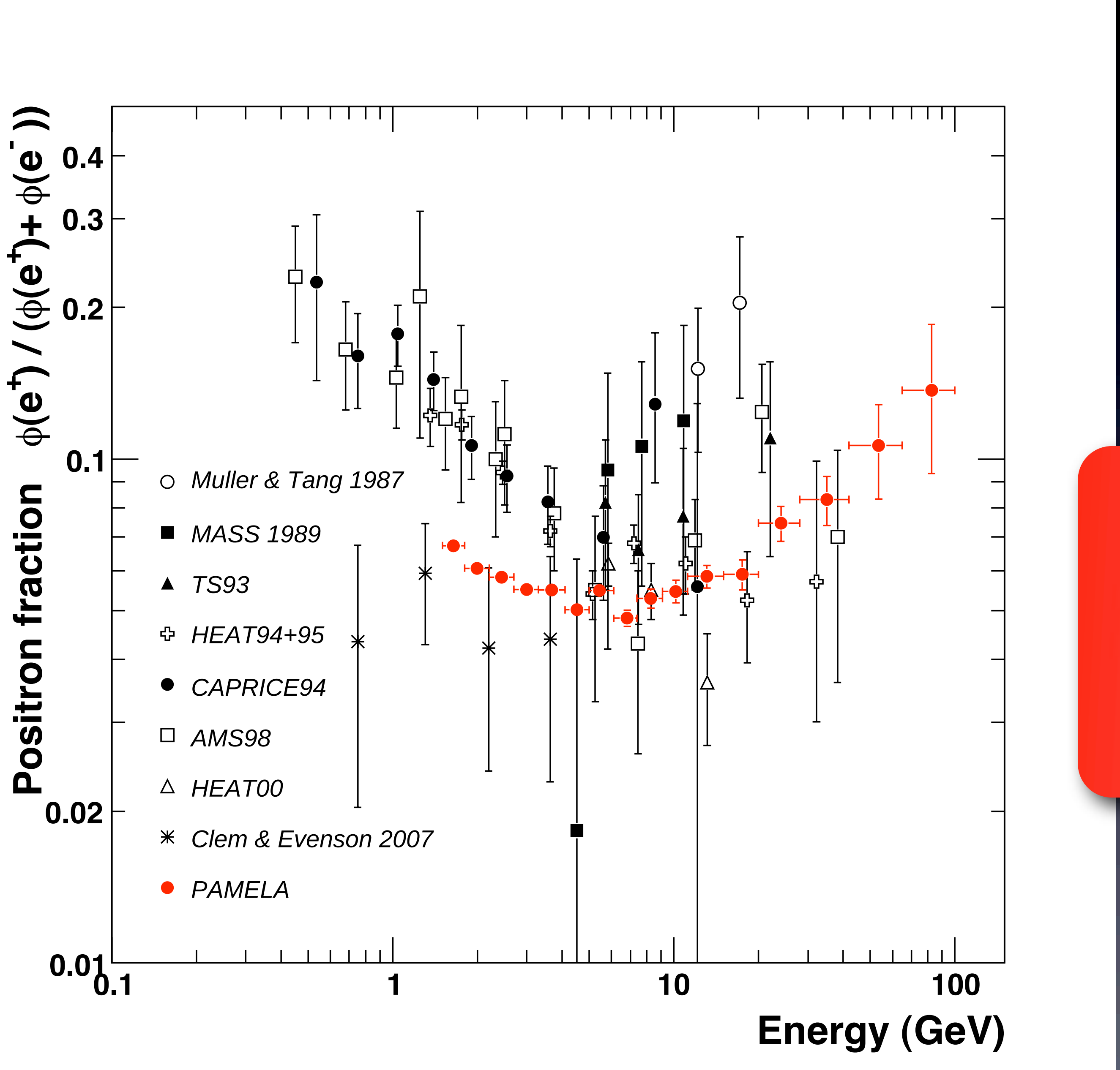
→ Cosmic Ray Signals

Detecting dark matter signal

$$\mathrm{DM} + \mathrm{DM} \to e^{\pm}, \gamma, \bar{p}, \nu, \ldots$$



PAMELA observation

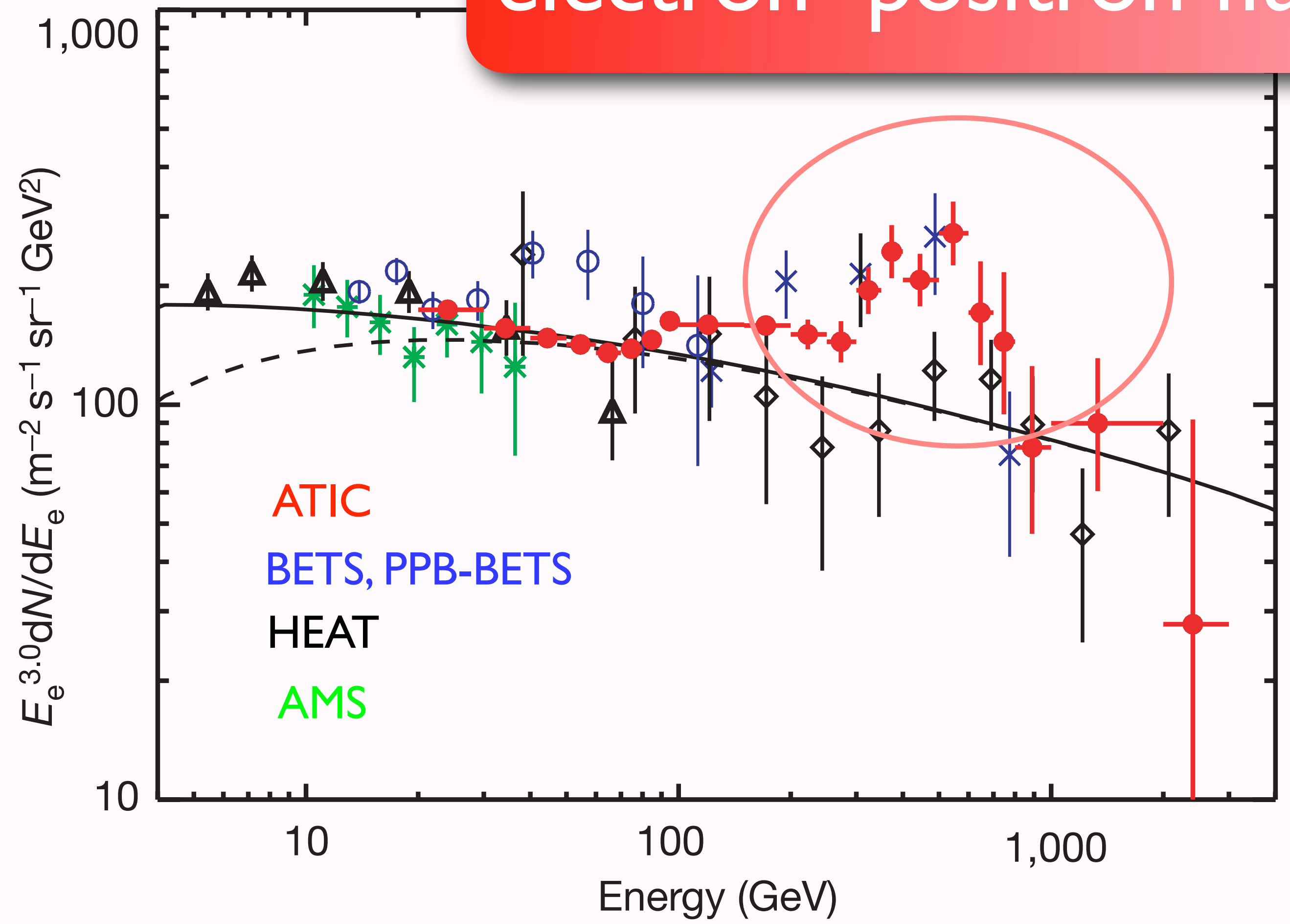


excess in cosmic-ray positron flux

Adriani et al.,arXiv:0810.4995

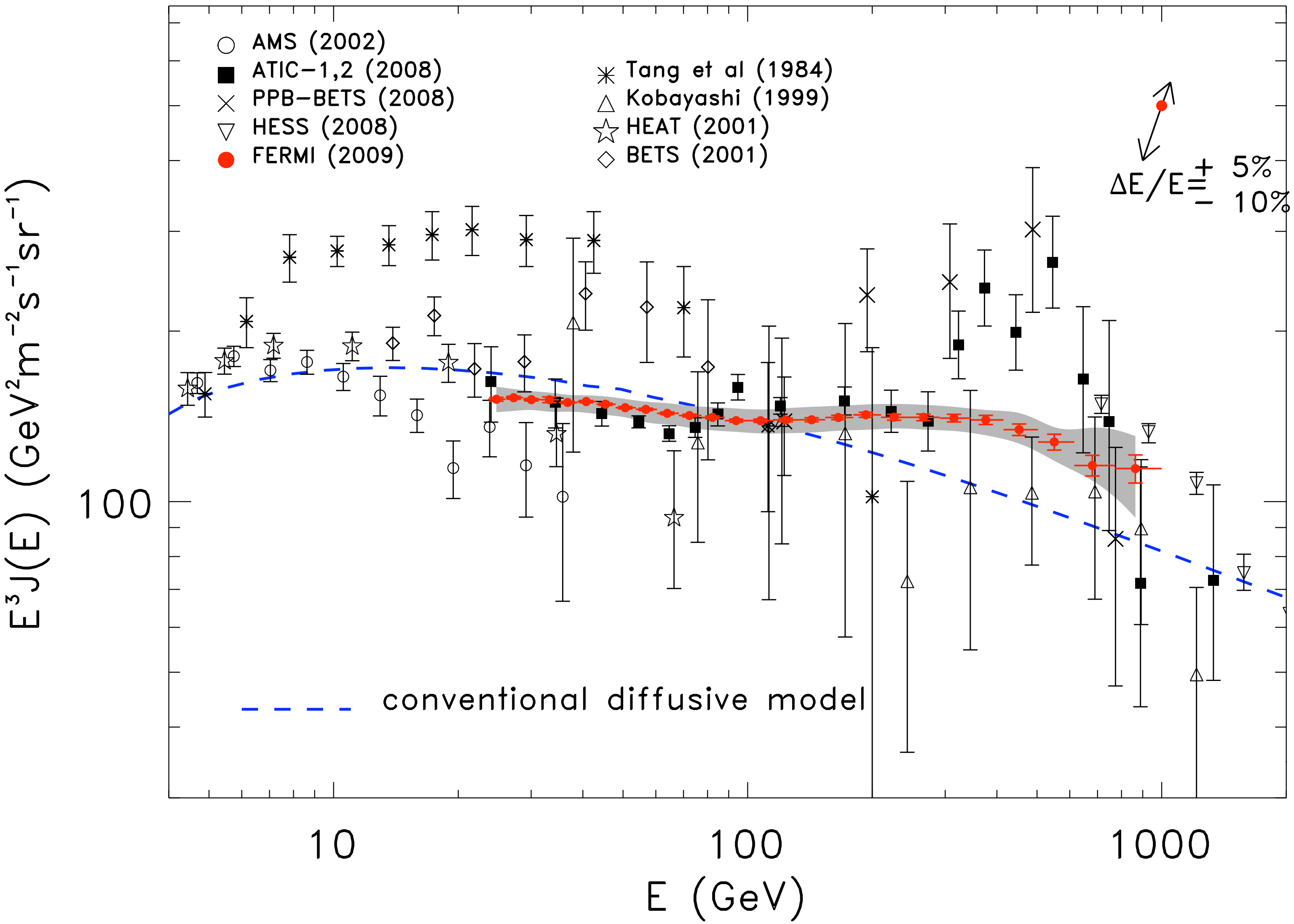
ATIC/PPB-BETS observations

excess in
electron+positron flux



J.Chang et al. Nature (2008)

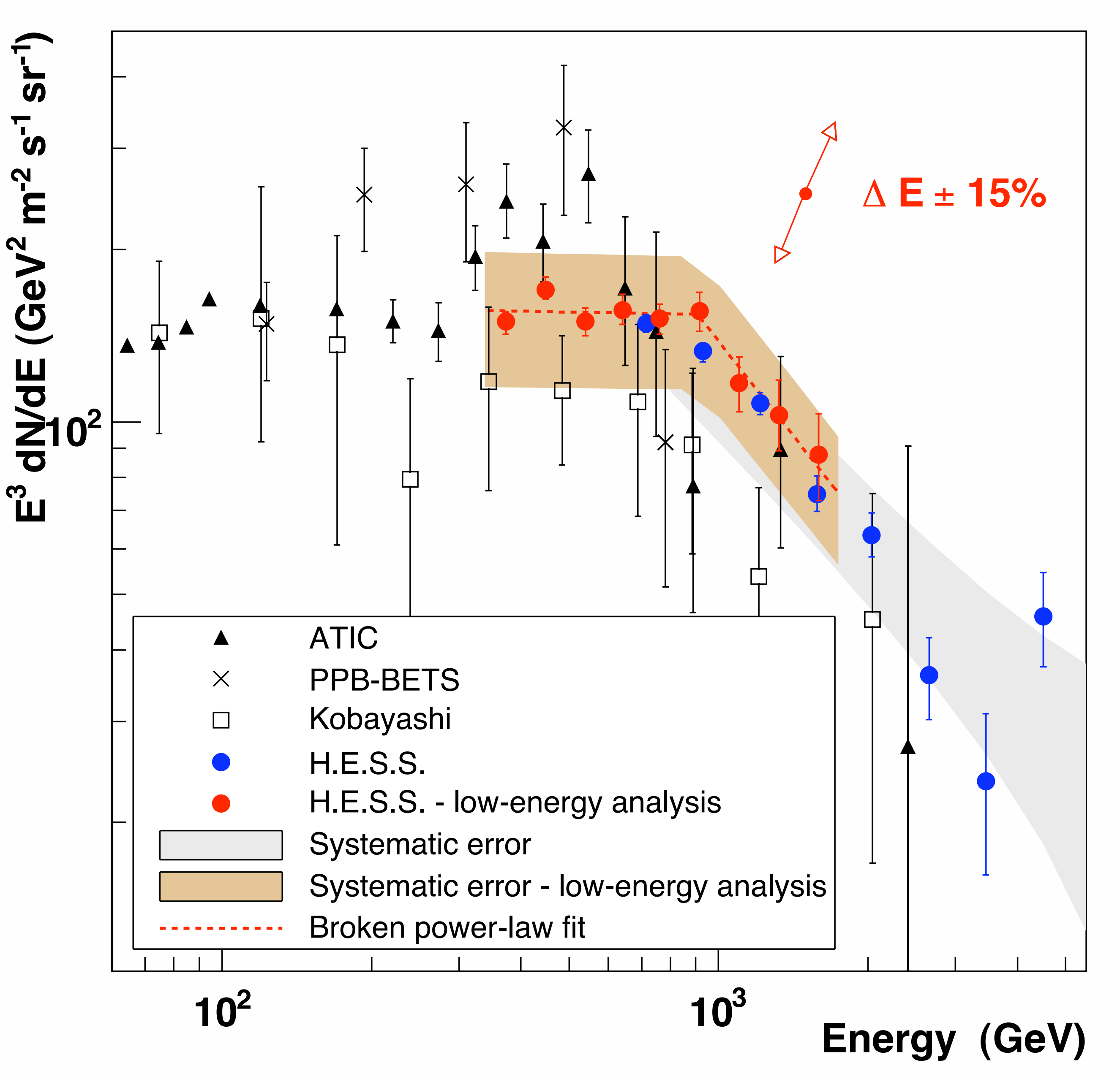
Fermi observation

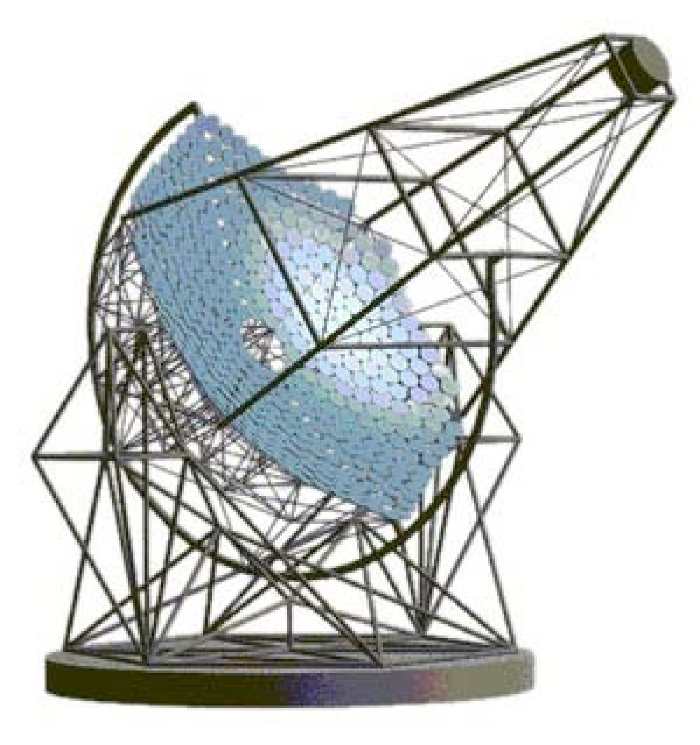


Inconsistent with ATIC results. Still there may be excess.

Fermi LAT collaboration, 0905.0025

HESS observation





Consistent with Fermi results.

HESS collaboration, 0905.0105

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.

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

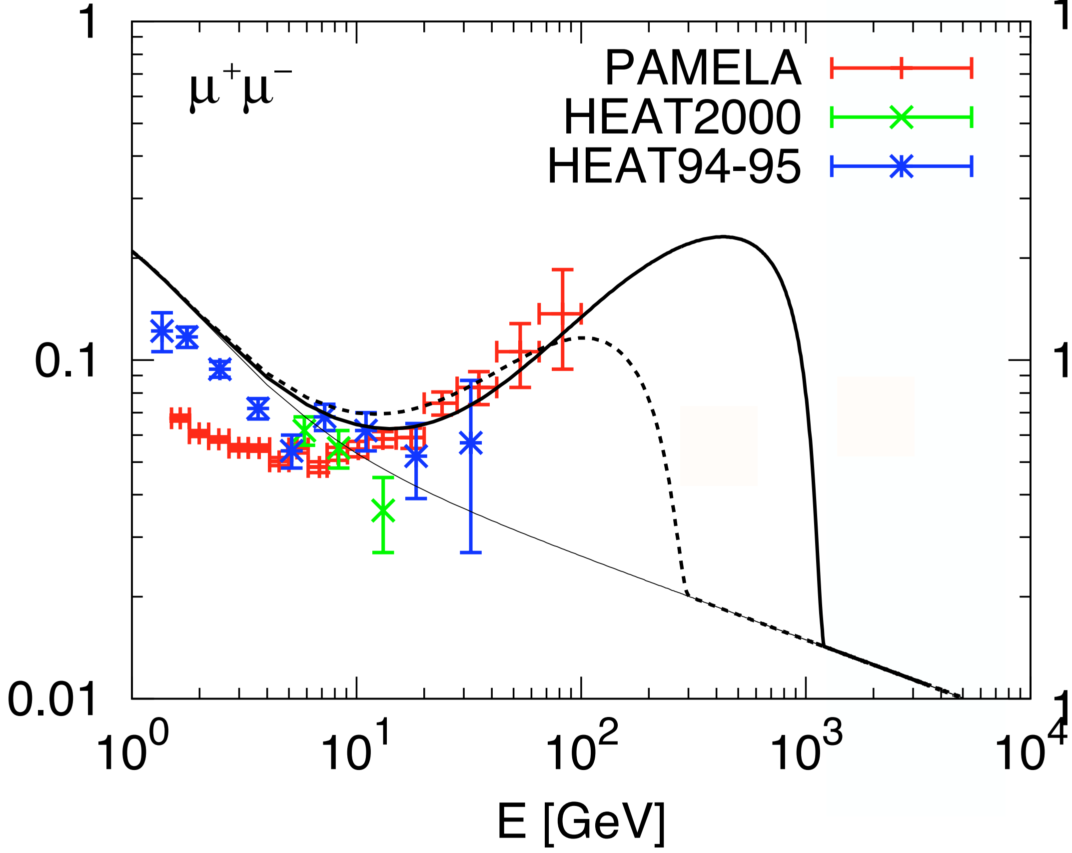
- Annihilating DM

  DM may have weak scale annihilation cross section.

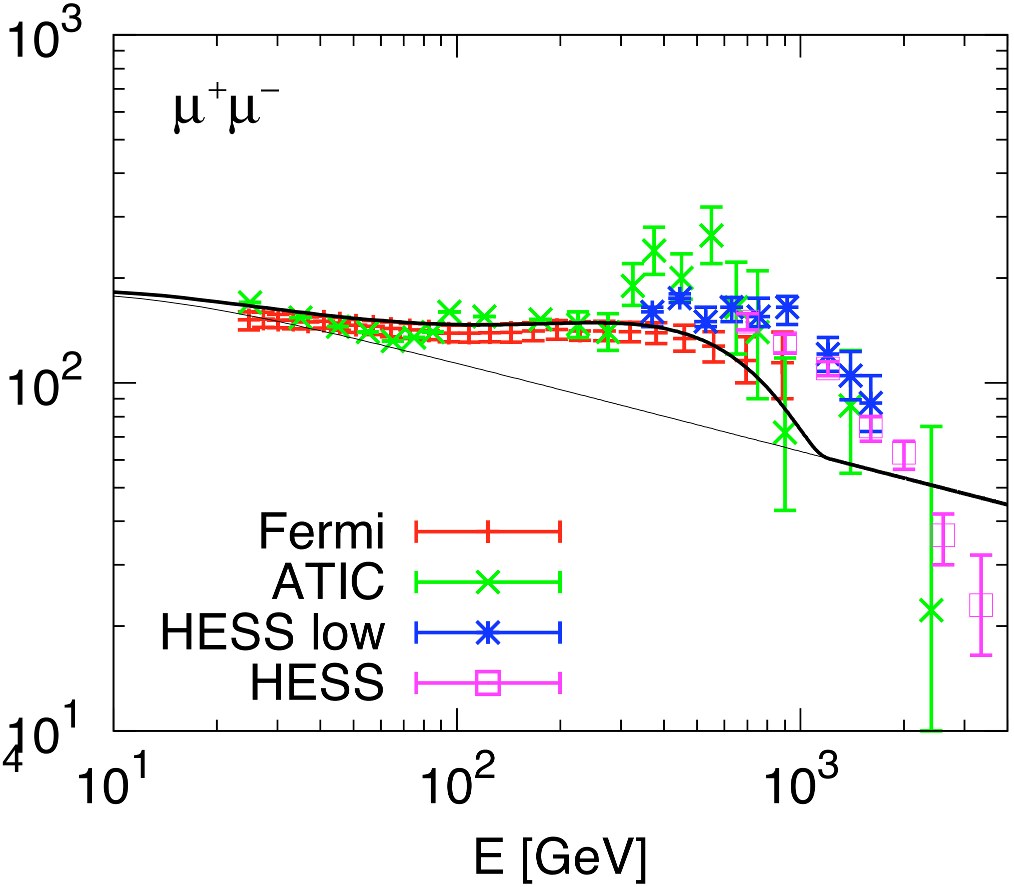
  Cross section with $\langle \sigma v \rangle \sim 10^{-24} - 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$ can explain PAMELA.

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

Positron fraction

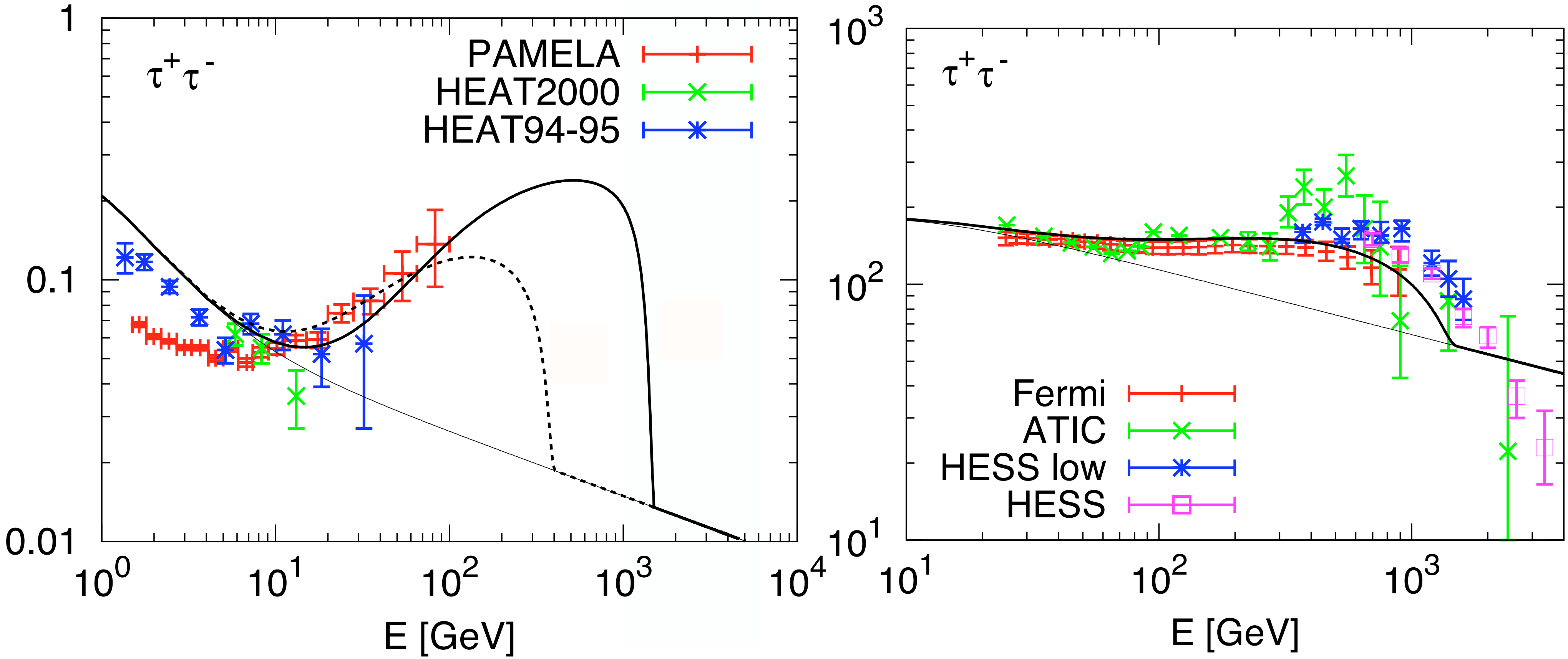


Total flux $[\mathrm{GeV}^2\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$



$$\chi\chi \to \mu^+\mu^- : m_\chi = 1.2\mathrm{TeV}, \langle\sigma v\rangle = 1.2 \times 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$$

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

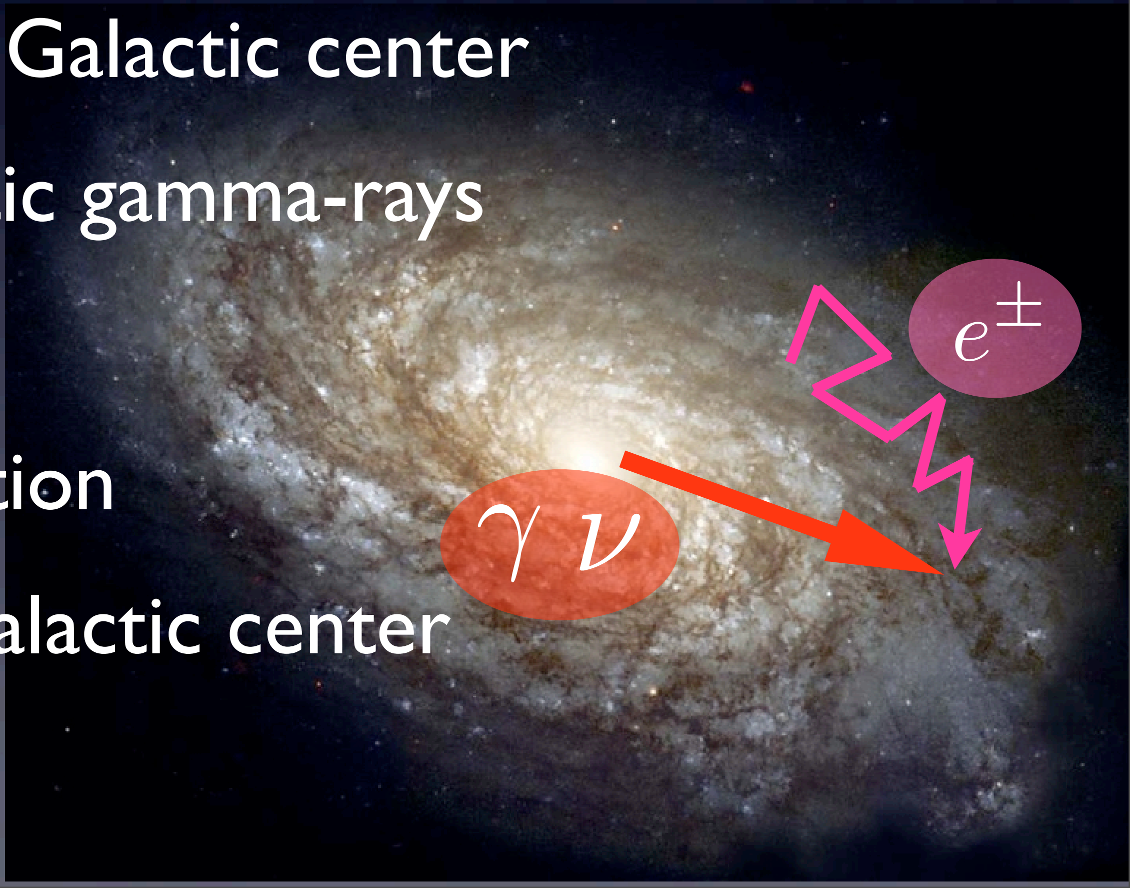


$$\boxed{\chi\chi \to \tau^+\tau^- \ : m_\chi = 1.5\mathrm{TeV}, \langle\sigma v\rangle = 3.5 \times 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}}$$

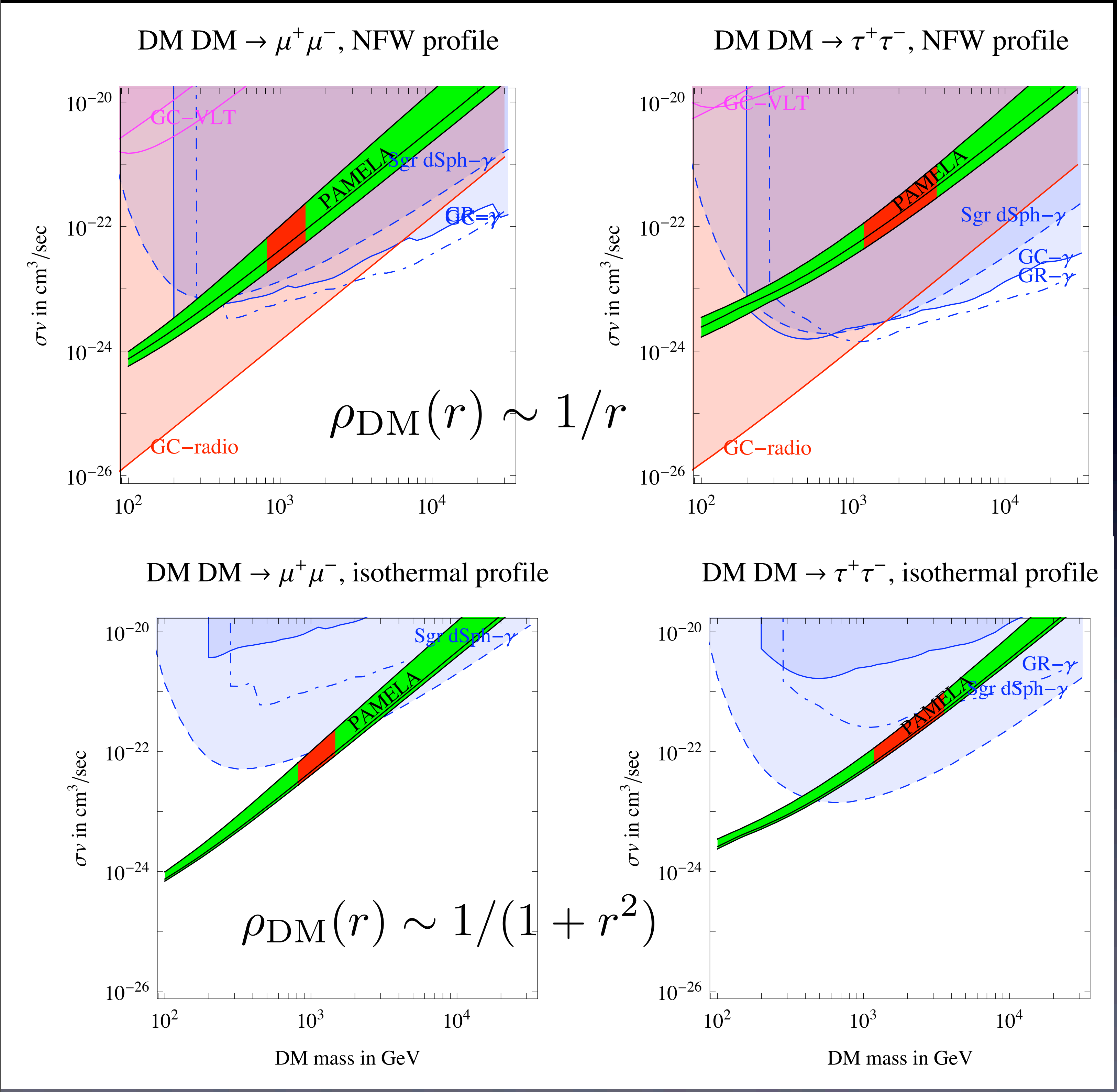
It is important to investigate

Relation to other signals

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



Constraints on DM ann models.



$$\rho_{\rm DM}(r) \sim 1/r$$

$$\rho_{\rm DM}(r) \sim 1/(1+r^2)$$

Sensitively depends on DM halo profile.

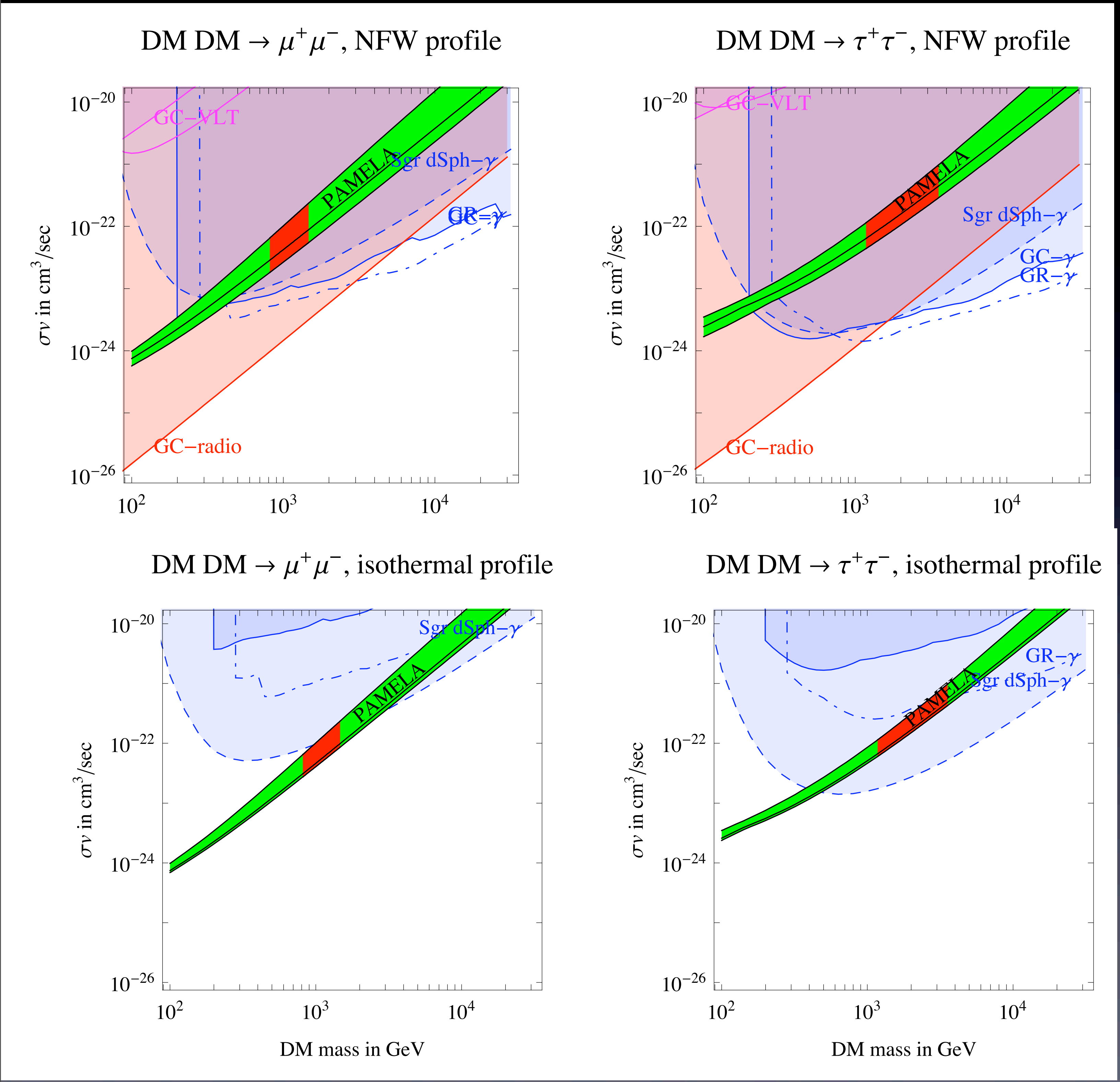
G.Bertone et al., 0811.3744

What we have done :

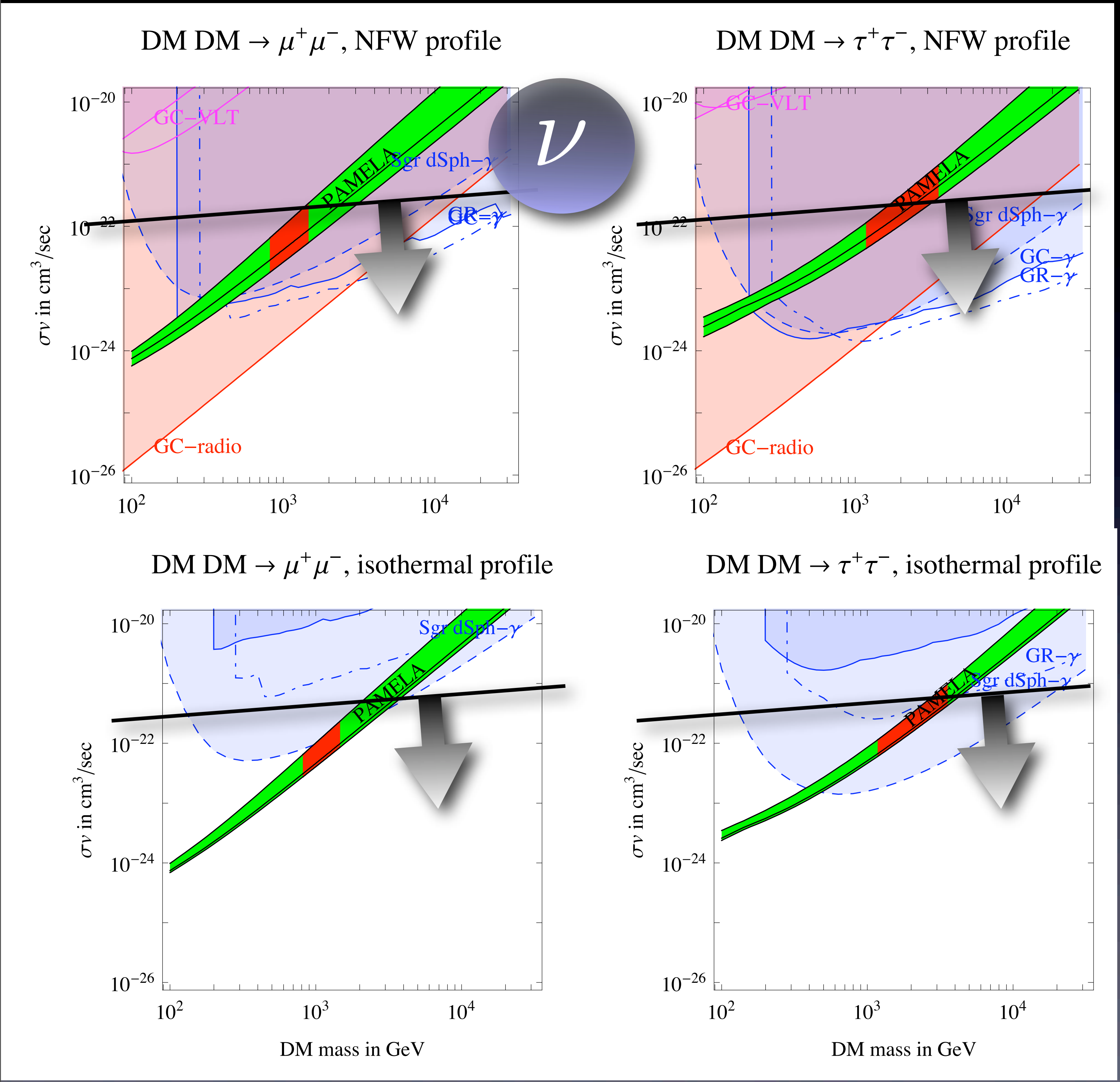
- Neutrino-induced muon flux from Galactic center
- Diffuse extragalactic gamma-rays from dark matter annihilation

Both give useful constraints on DM models, rather insensitive to DM halo profile

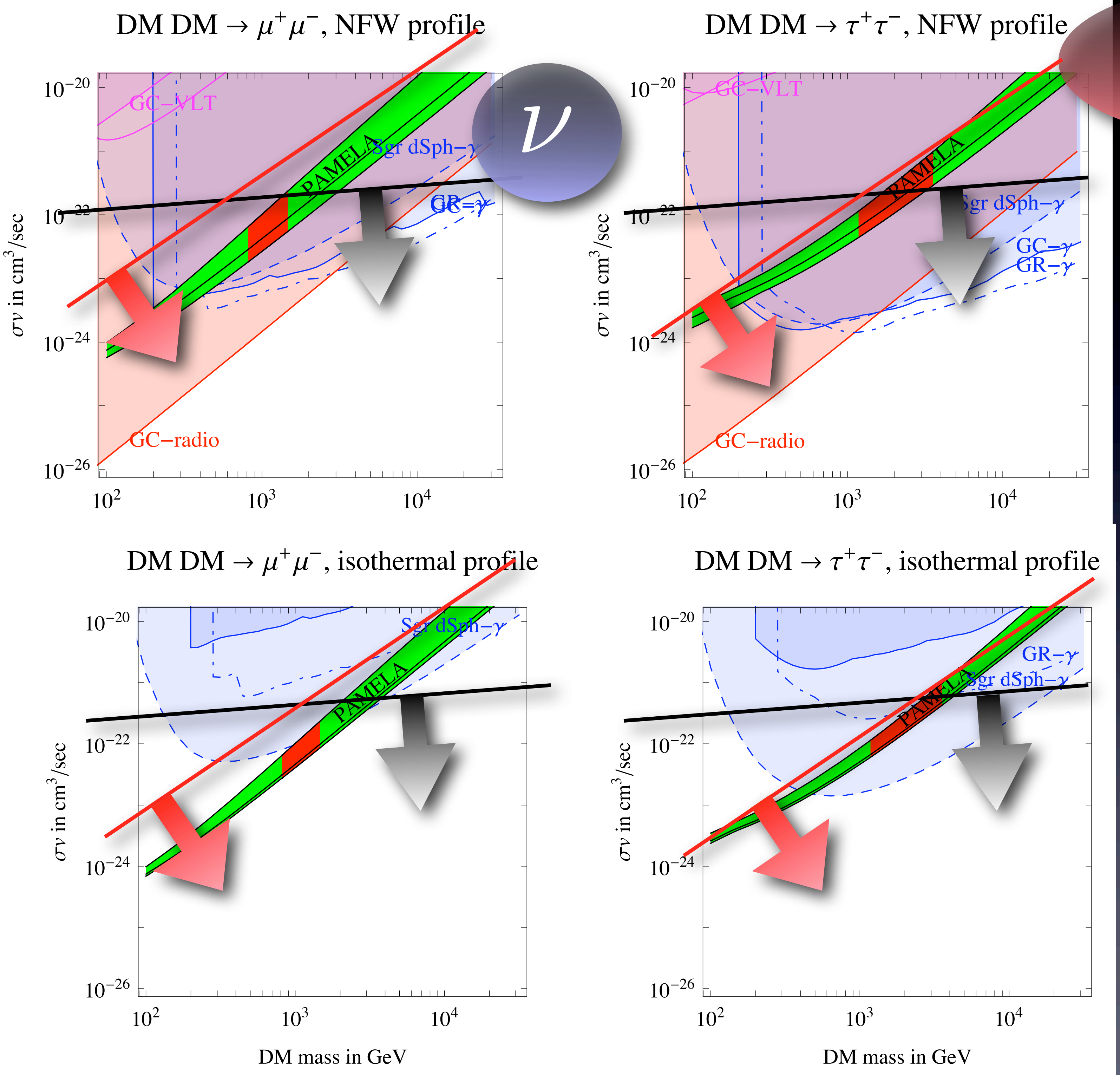
J.Hisano, M.Kawasaki, K.Kohri and KN, arXiv:0812.0219
M.Kawasaki, K.Kohri and KN, arXiv:0904.3626
J.Hisano, KN, and M.J.S.Yang, arXiv:0905.1552



G.Bertone et al., 0811.3744



G.Bertone et al., 0811.3744



diffuse γ

G.Bertone et al., 0811.3744

Second part :
Neutrino Flux

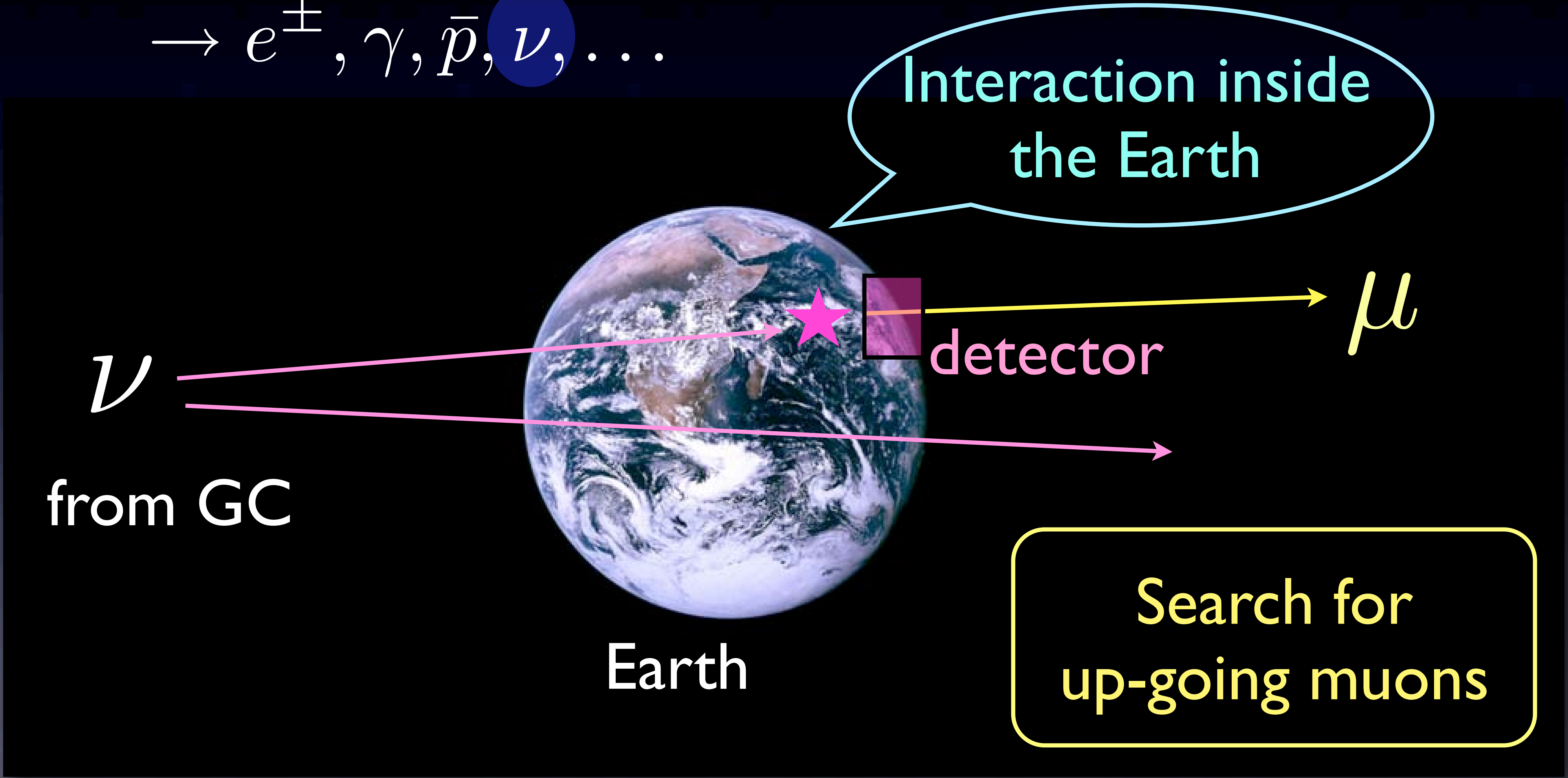
J.Hisano, M.Kawasaki, K.Kohri and KN, Phys.Rev.D79,043516(2009)[0812.0219]
J.Hisano, KN, and M.J.S.Yang, Phys.Lett.B678,101(2009)[0905.1552]

Neutrino Signal from DM Annihilation

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

$$\chi\chi \to W^+W^-, b\bar{b}, l^+l^-, \ldots$$

$$\to e^\pm, \gamma, \bar{p}, \nu, \ldots$$



Interaction inside the Earth

ν

from GC

Earth

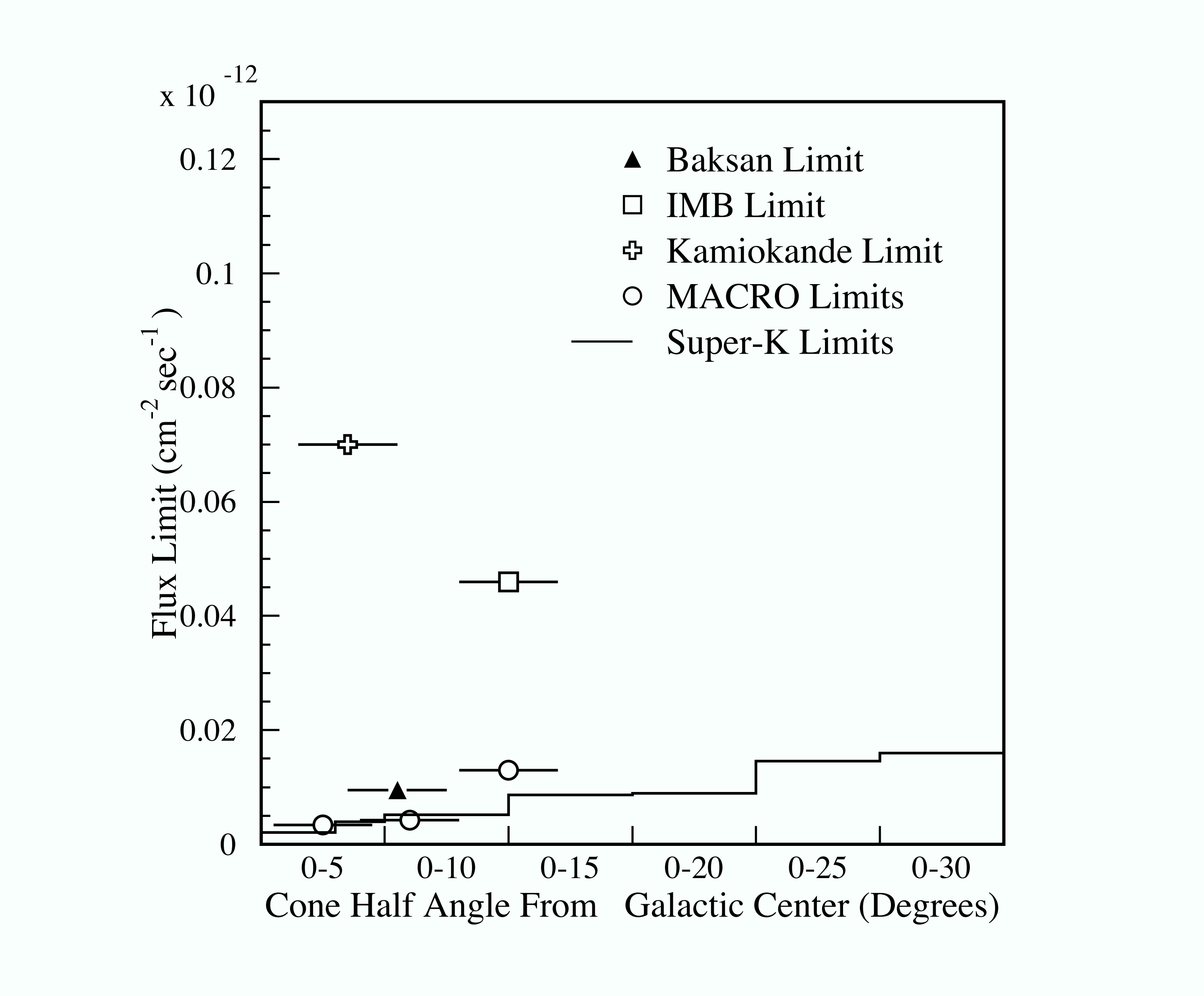
detector

μ

Search for up-going muons

→ 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

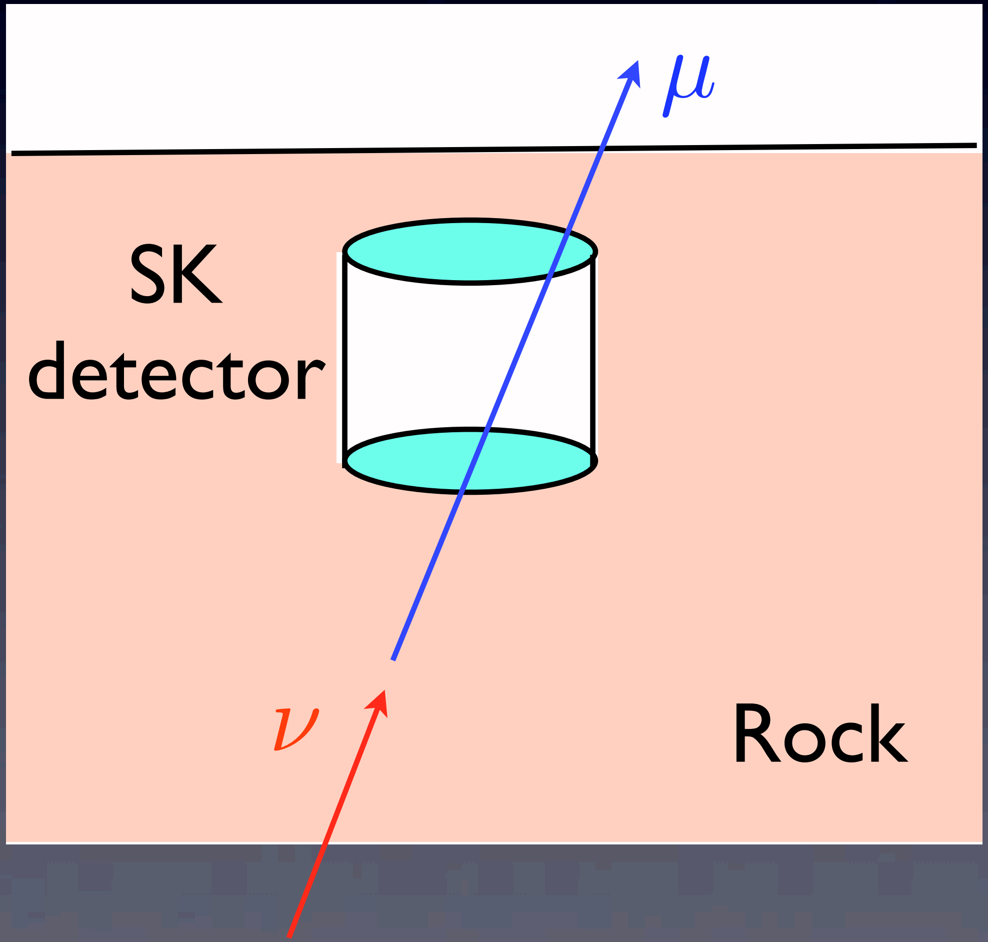
$$N_\mu = \int dE_{\nu_\mu} \frac{dF_{\nu_\mu}}{dE_{\nu_\mu}} f(E_{\nu_\mu})$$

(a) Neutrino flux from DM:

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

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

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



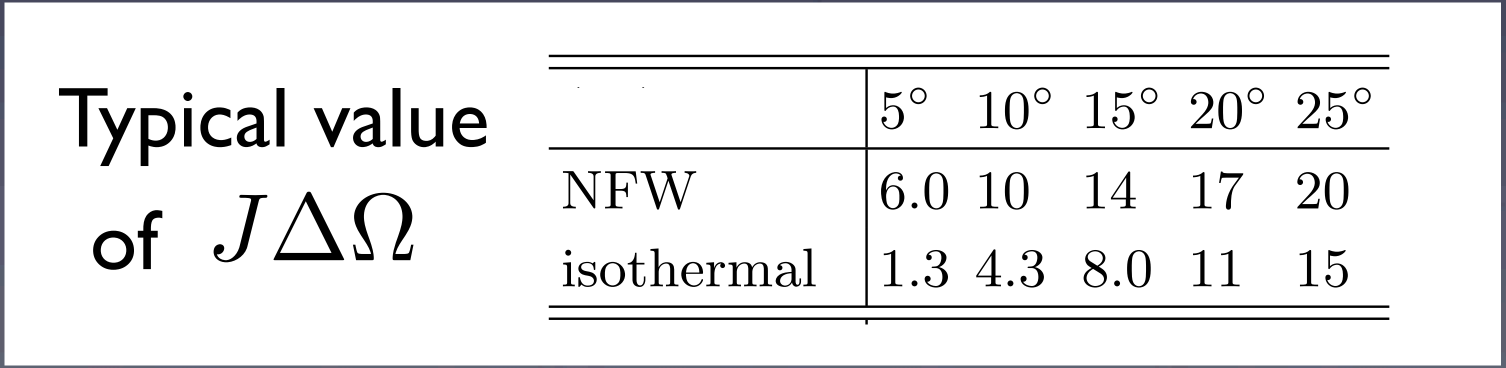
(a) Neutrino flux from GC

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

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

Neutrino oscillation

- DM halo profile dependent part : $\displaystyle J\Delta\Omega = \int \frac{d\Omega}{\Delta\Omega} \int_{\text{l.o.s.}} \frac{dl(\psi)}{R_\odot} \left(\frac{\rho(l)}{\rho_\odot}\right)^2$



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

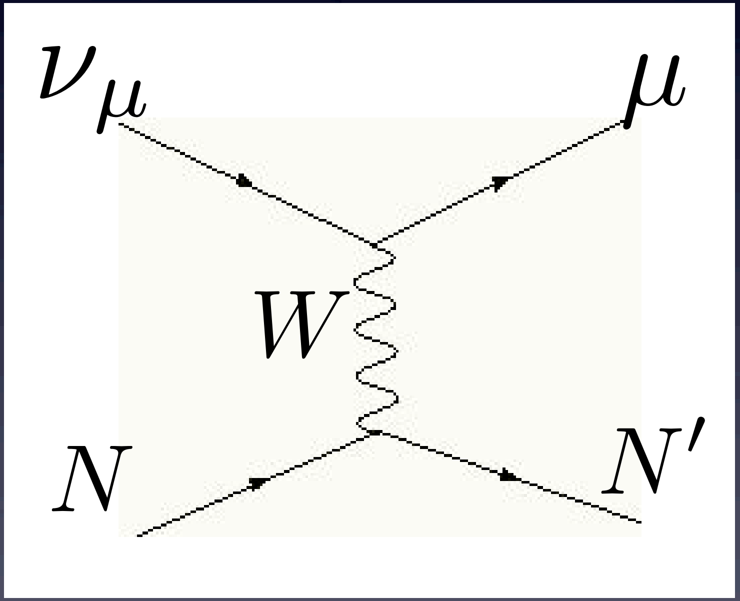
(b) Probability of $\nu_\mu \to \mu$

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

- 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 : $R(E_\mu)$



Energy loss of muon in matter

Dutta, Reno, Sarcevic, Seckel, Phys.Rev.D63,094020 (2001)

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

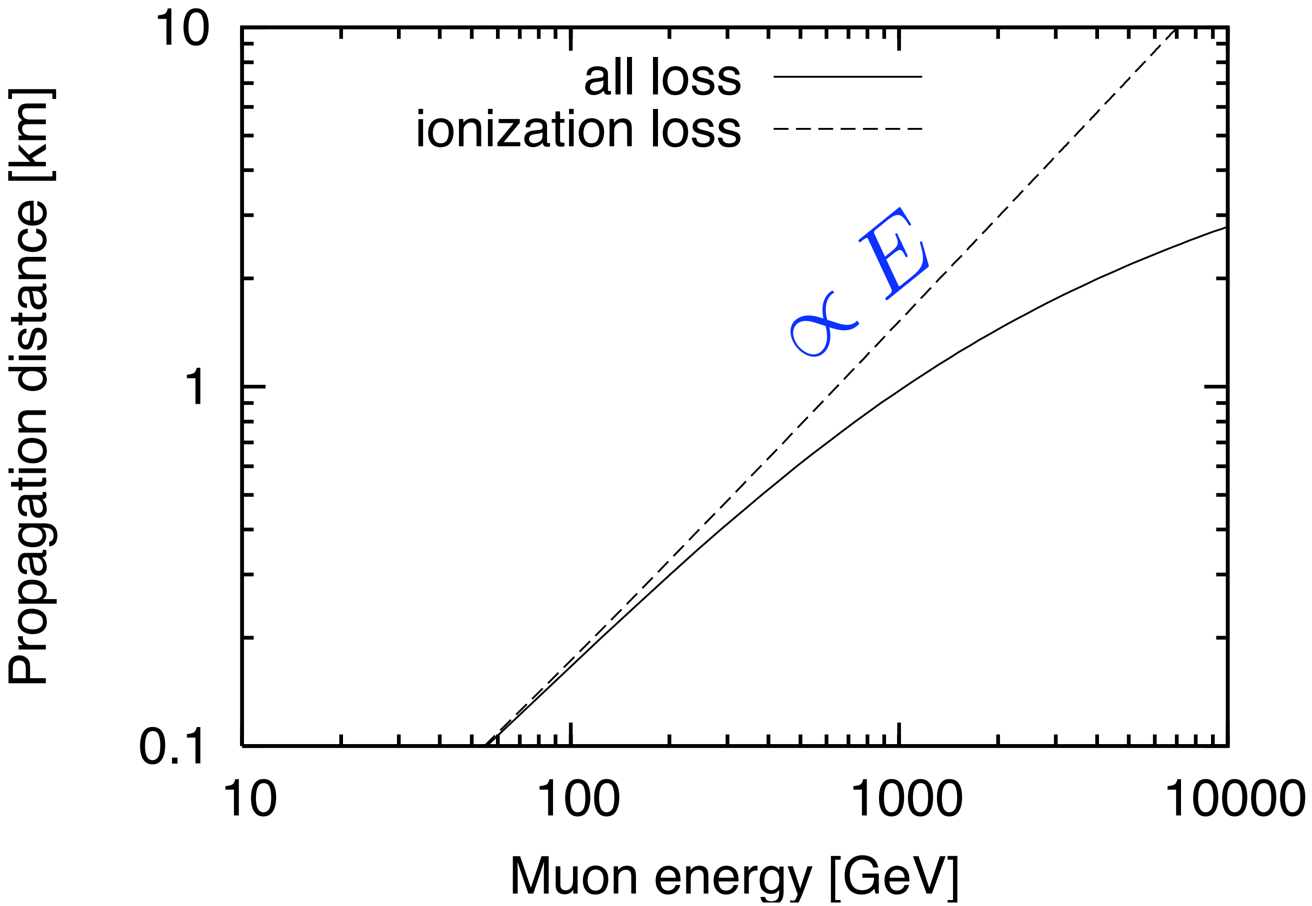
Ionization loss : $\alpha(E_\mu) \simeq 2\ \mathrm{MeVcm^2g^{-1}}$

Radiative loss : $\beta(E_\mu) \simeq 10^{-6}\ \mathrm{cm^2g^{-1}}$
(Brems, pair creation, ...)

→ Typical propagation distance :

$$R_\mu \sim \frac{E_\mu}{\alpha(E_\mu)\rho_{\mathrm{rock}}} \sim 1\ \mathrm{km}(E_\mu/1\mathrm{TeV})$$

Muon range in the rock



- $E_\mu \ll 1\ \mathrm{TeV}$ $R_\mu \sim 1\ \mathrm{km}(E_\mu/1\mathrm{TeV})$
- $E_\mu \gtrsim 1\ \mathrm{TeV}$ deviation from linearity

Probability of $\nu_\mu \longrightarrow \mu$

$$f(E_{\nu_\mu}) \sim \int \underbrace{dE_\mu \frac{d\sigma_{\nu_\mu p \to \mu X}}{dE_\mu}}_{\sim \frac{G_F^2 s}{\pi} \propto E_{\nu_\mu}} n_p^{(\mathrm{rock})} \underbrace{R(E_\mu)}_{\propto E_\mu}$$

➡ $\boxed{f(E_{\nu_\mu}) \propto E_{\nu_\mu}^2}$

Higher energy neutrinos are more likely converted into muon

Monochromatic neutrino : $\chi\chi \longrightarrow \nu\bar{\nu}$

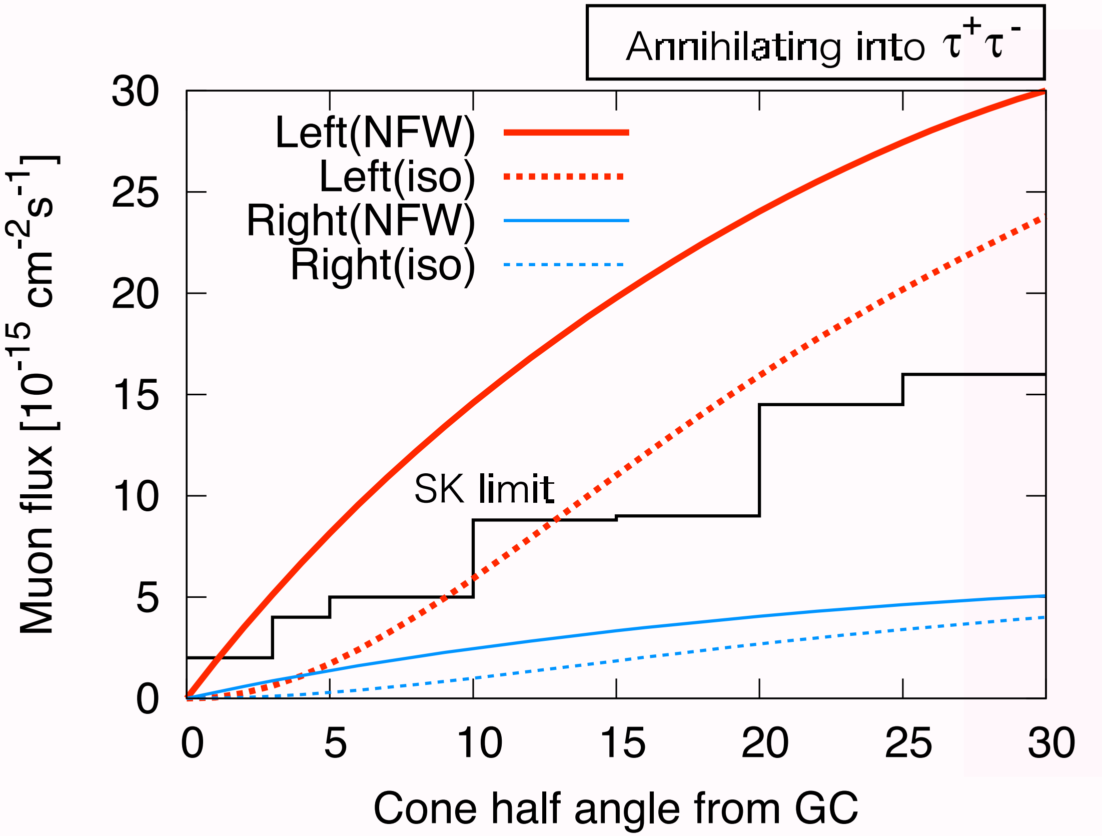
is constrained more severely than

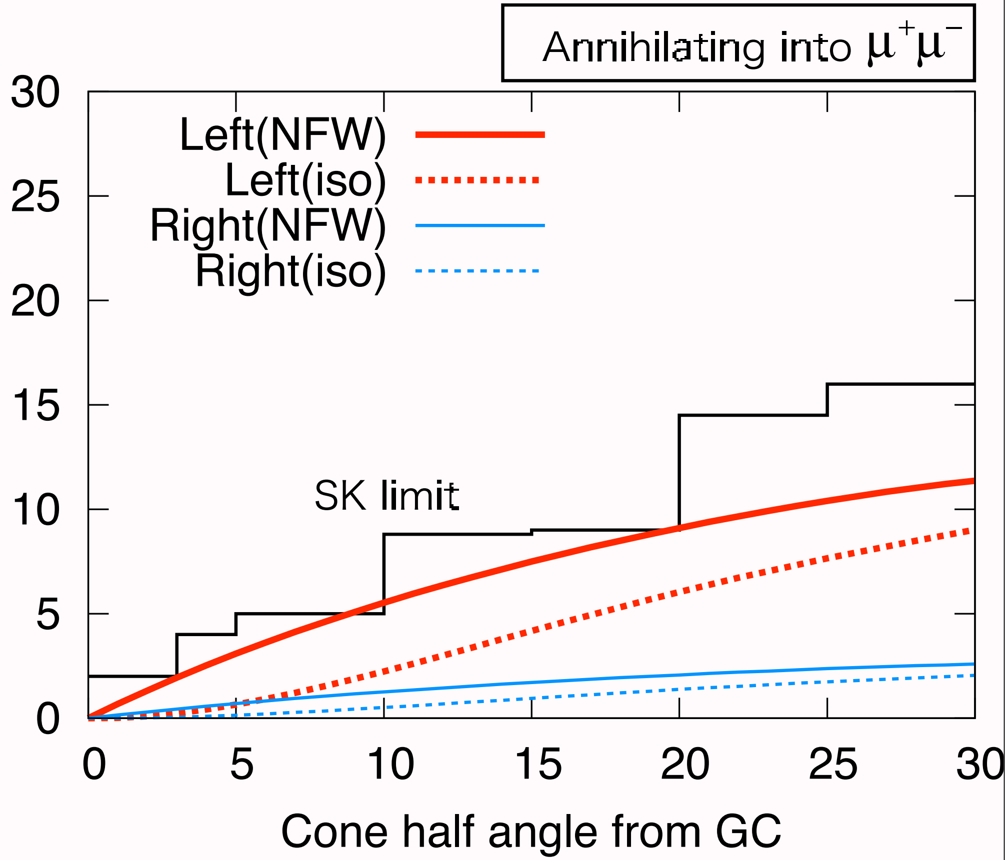
secondary neutrino : $\chi\chi \longrightarrow \mu^+\mu^-, \quad \mu^- \longrightarrow \nu_\mu \bar{\nu}_e e$

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

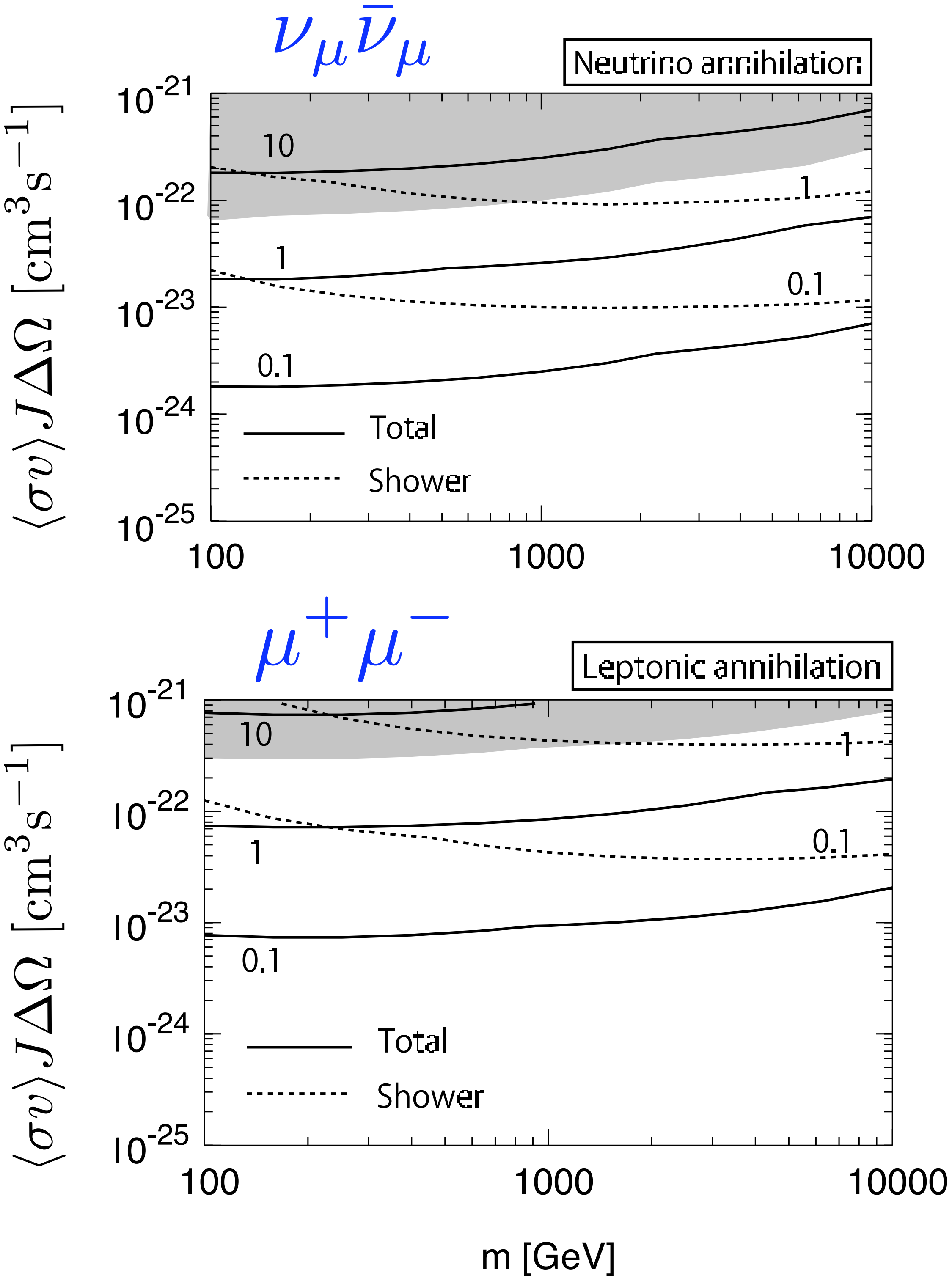
— Annihilate into left handed leptons $(\nu\bar{\nu} + l_L^- l_R^+)$

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





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



Contour : Muon flux

$(\times 10^{-15}\ \mathrm{cm^{-2}s^{-1}})$

Gray : current SK bound

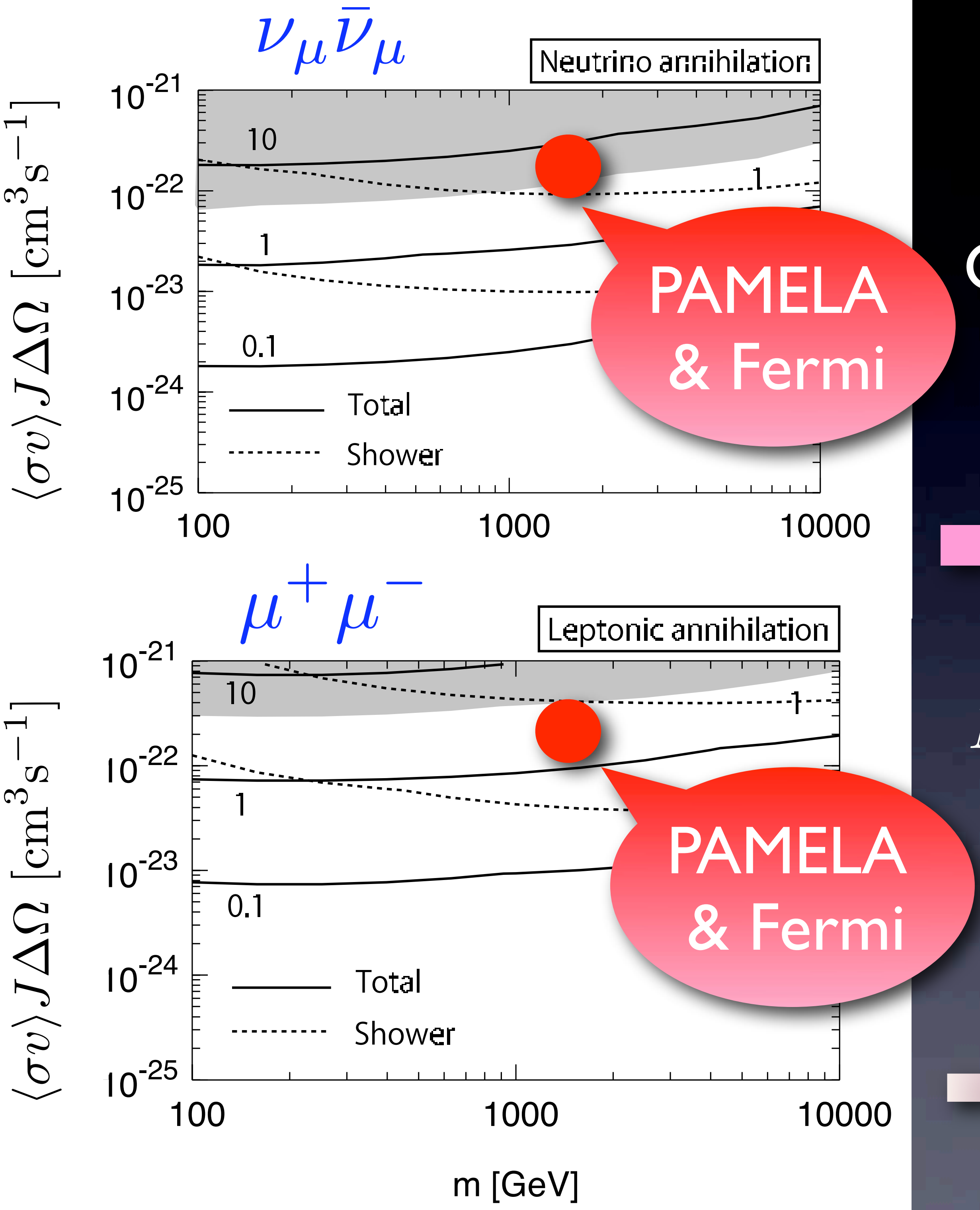
$(\text{for } \theta = 5^\circ)$

- Total muon flux

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

$$\propto m_\chi^{-2}$$

$$\rightarrow \boxed{N_\mu \sim \text{const.}}$$



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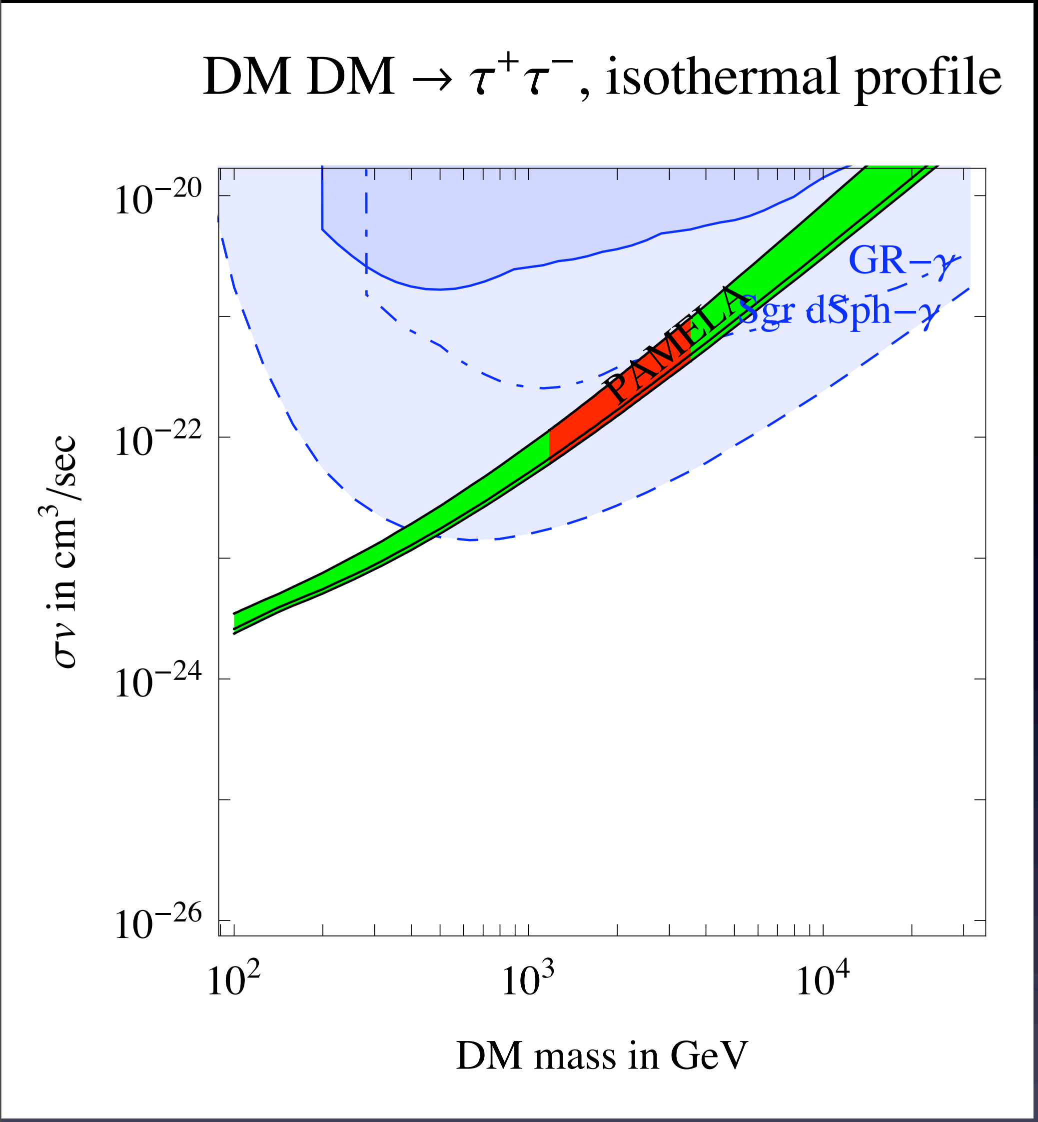
$$\propto m_\chi^{-2}$$

→ $\boxed{N_\mu \sim \text{const.}}$

Lesson from neutrino

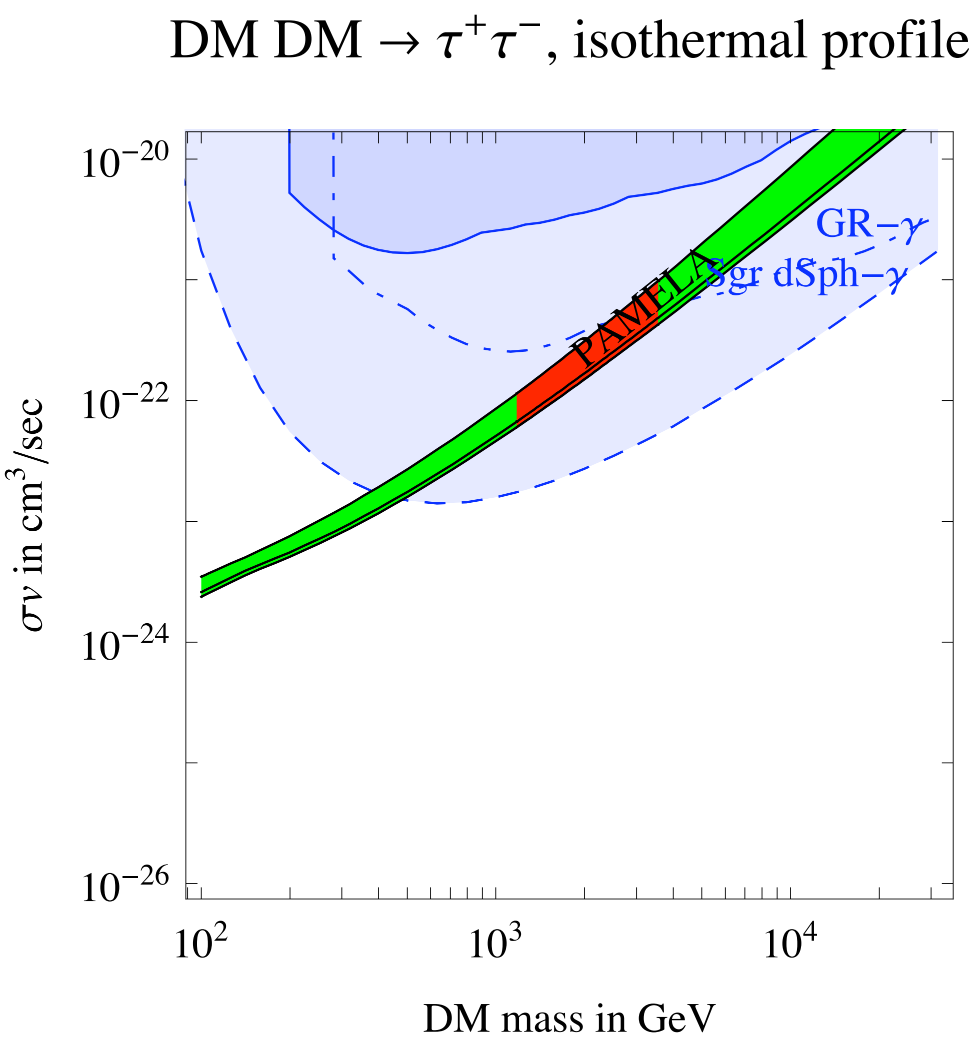
- Construct a DM model which fits PAMELA/Fermi data (either ann or decay)
- Check if your model produce monochromatic neutrinos with similar rate or not
- If yes, your model may conflict with SK bound irrespective of DM density profile

→ Check carefully the SK bound!



DM DM → $\tau^+\tau^-$, isothermal profile

G.Bertone et al., 0811.3744



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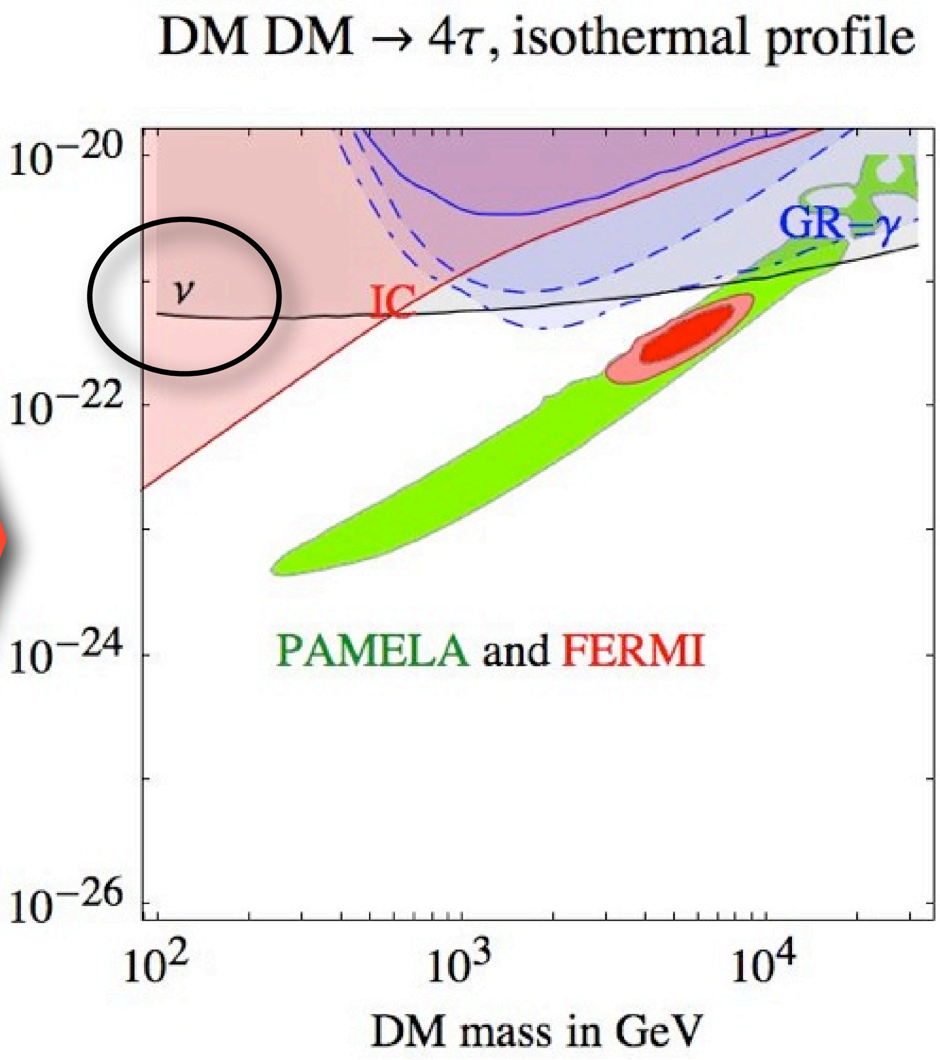
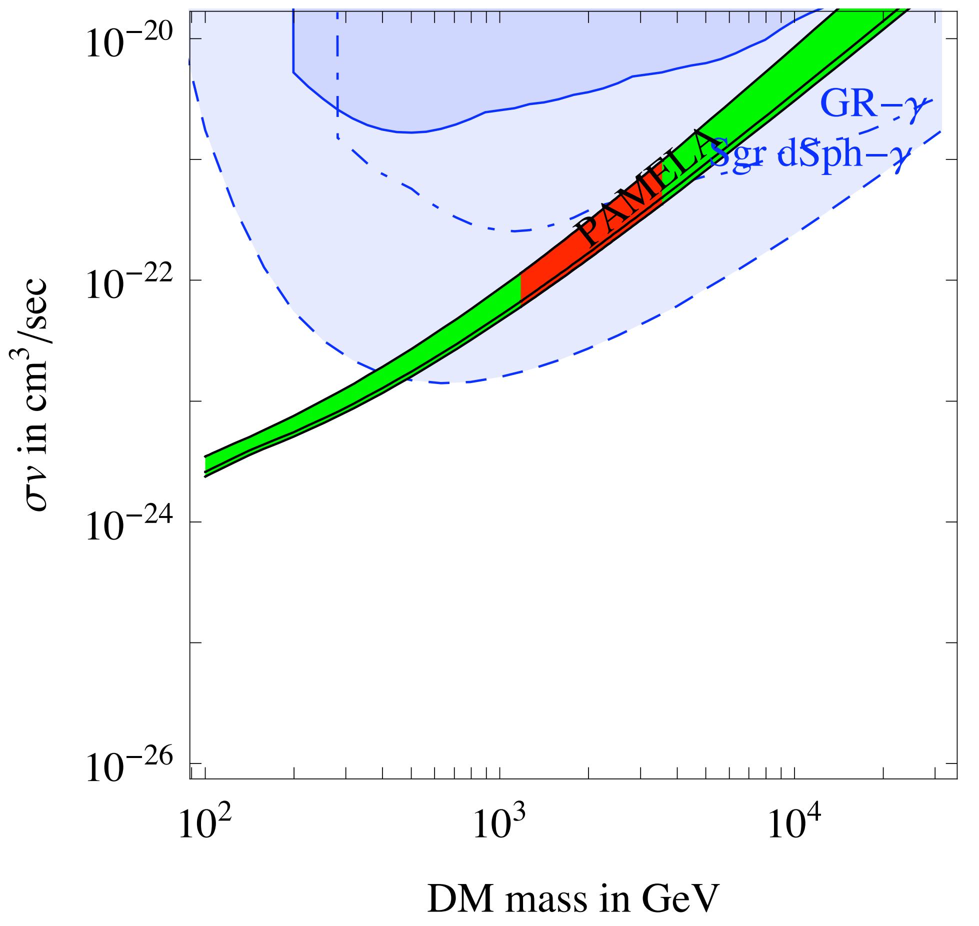
G.Bertone et al., 0811.3744



DM DM → 4τ, isothermal profile

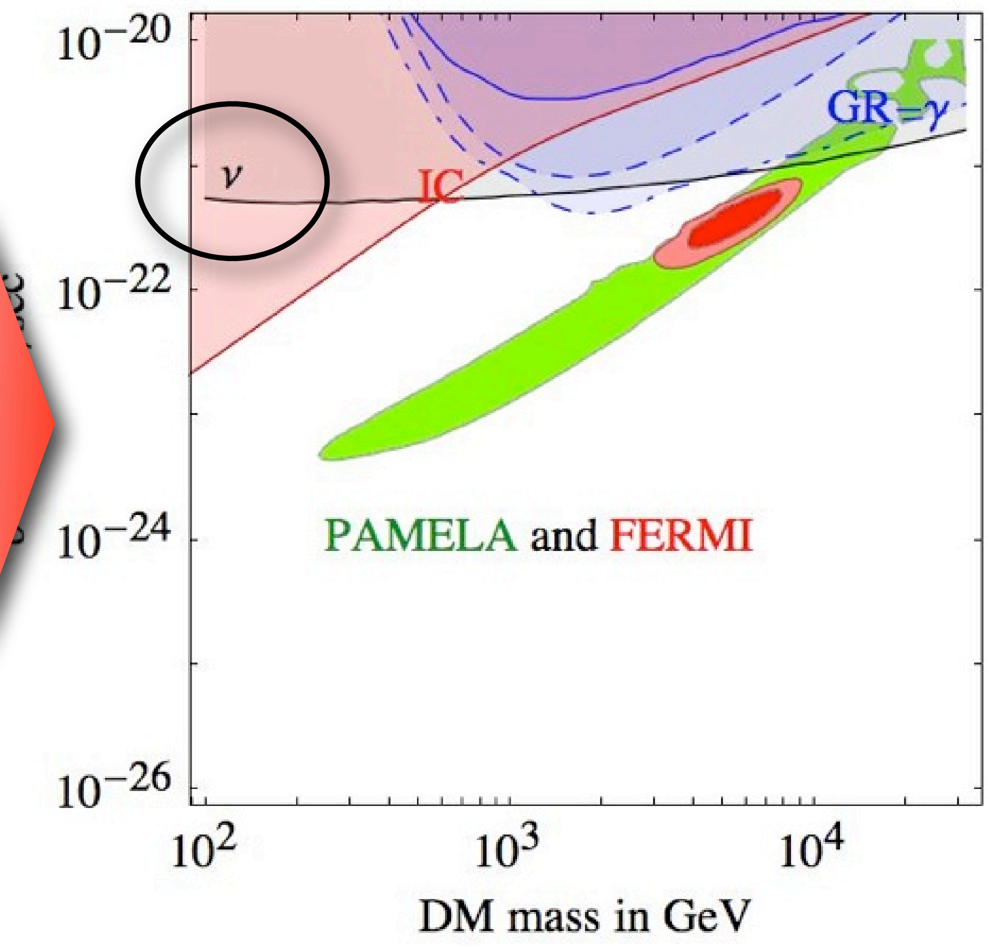
P.Maede et al., 0905.0480

DM DM $\to \tau^+\tau^-$, isothermal profile



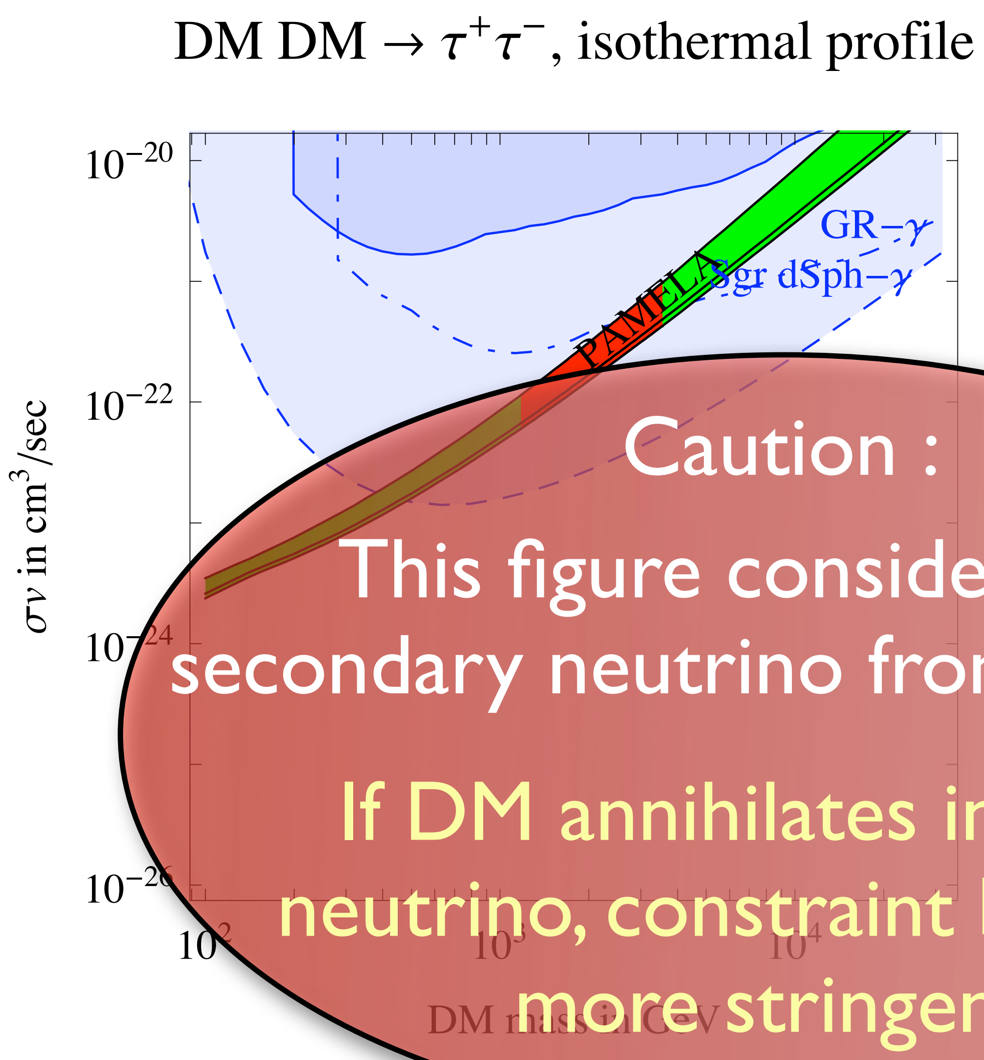
G.Bertone et al., 0811.3744

DM DM $\to 4\tau$, isothermal profile

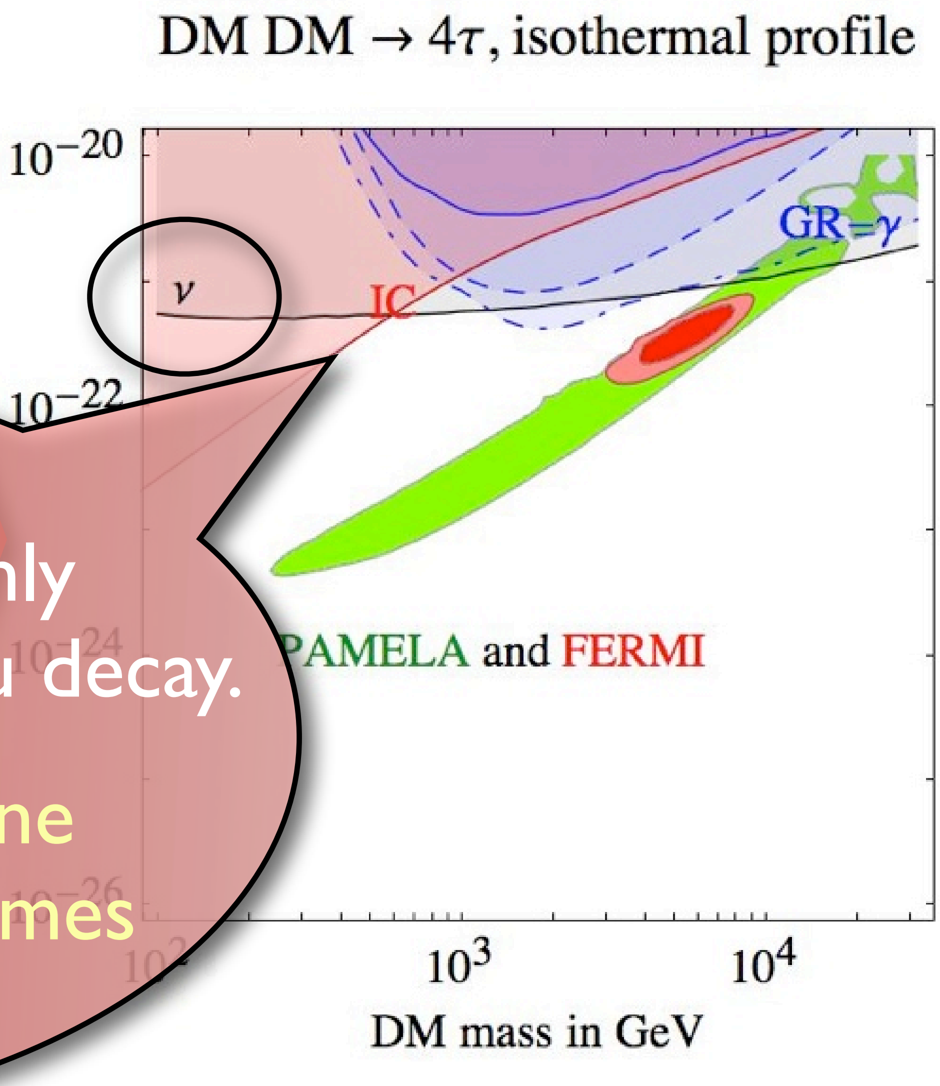


P.Maede et al., 0905.0480

Neutrino constraint becomes standard.



G.Bertone et al., 0811.3744



P.Maede et al., 0905.0480

Caution :

This figure considers only secondary neutrino from tau decay.

If DM annihilates into line neutrino, constraint becomes more stringent.

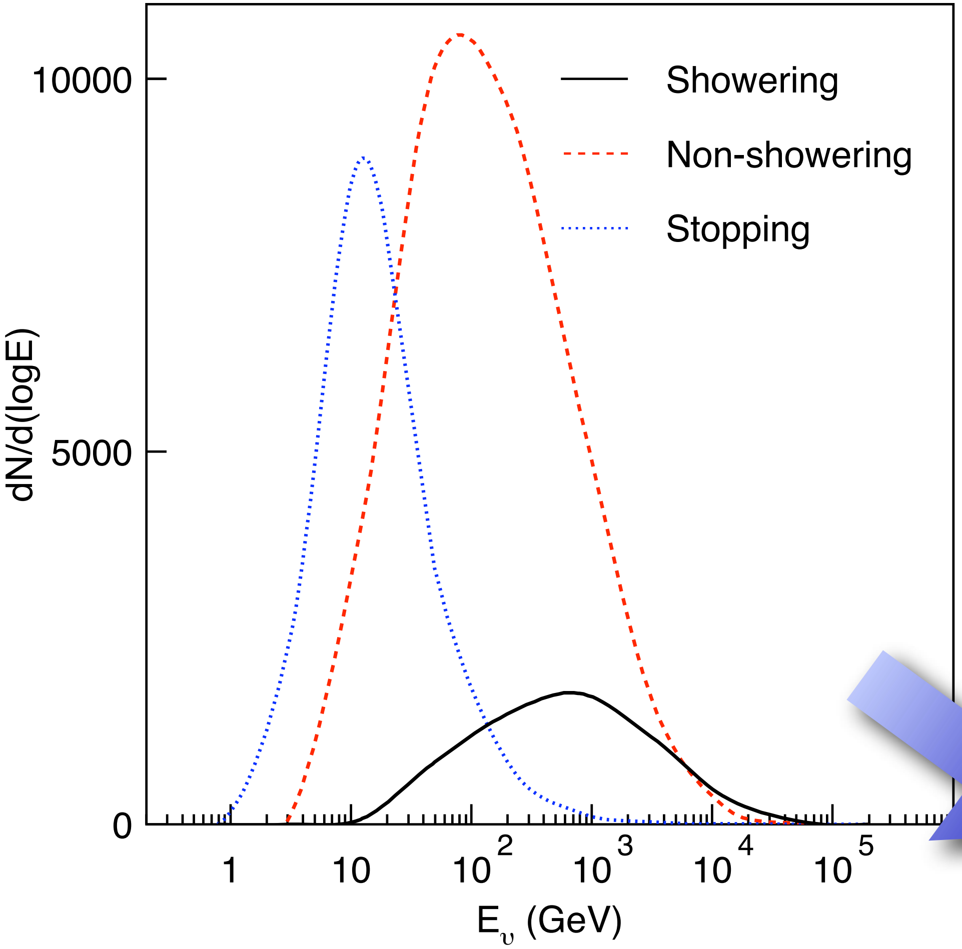
Neutrino constraint becomes standard.

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

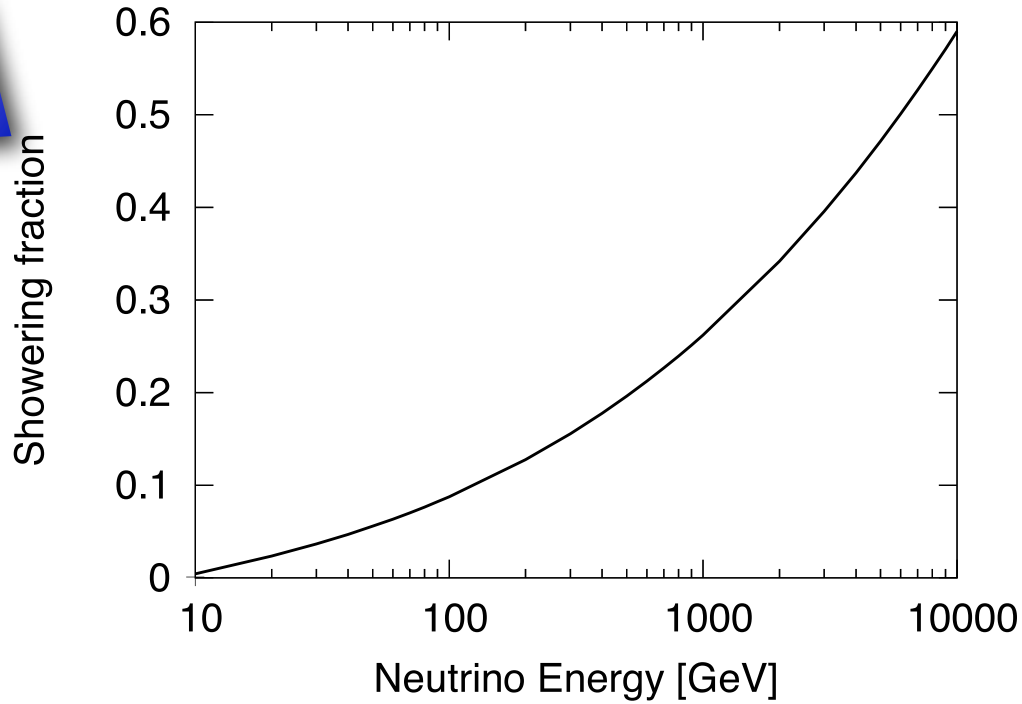
Simulation



3 kind of muon events :

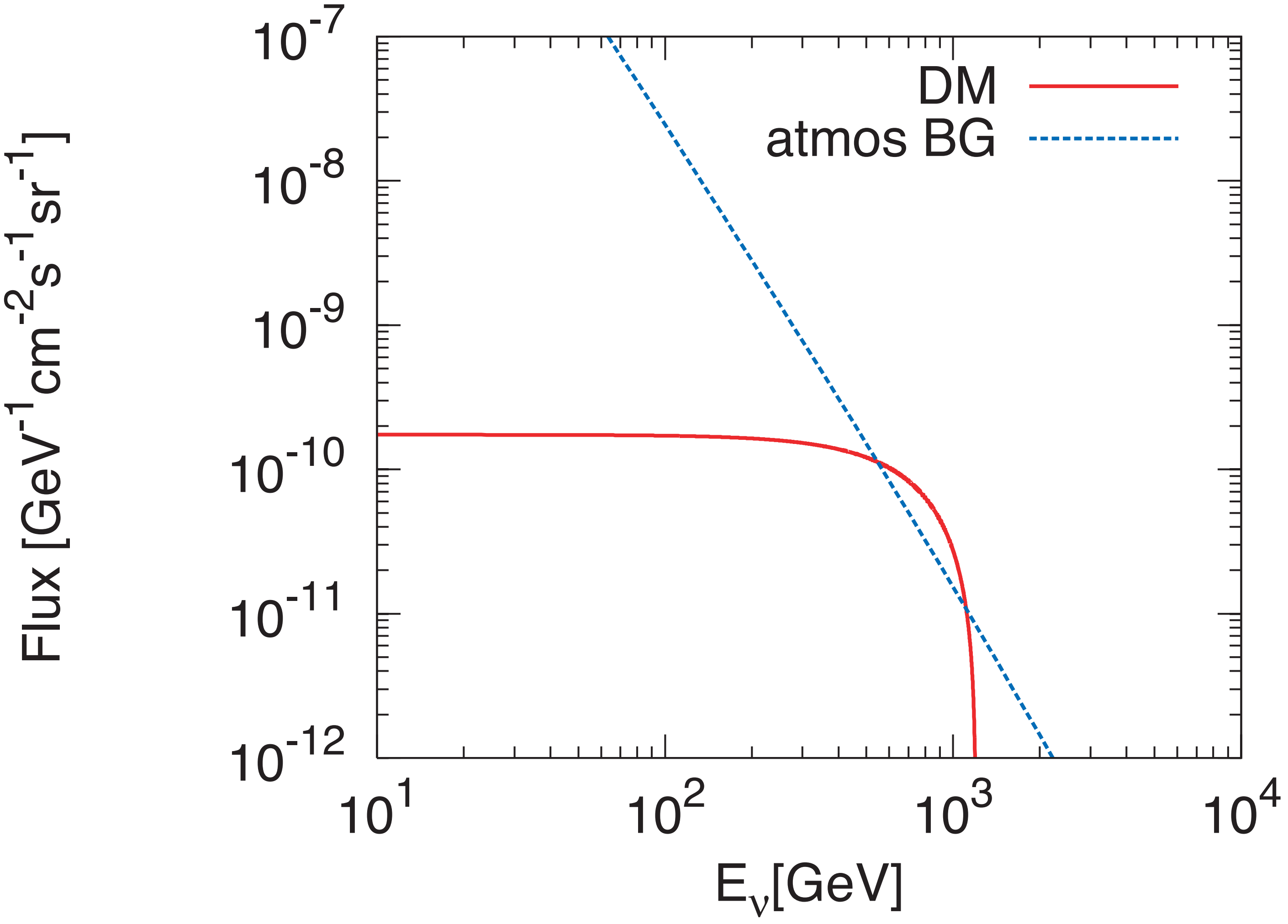
- Through-going shower mu
- Through-going nonshower mu
- Stopping mu

Probability for shower

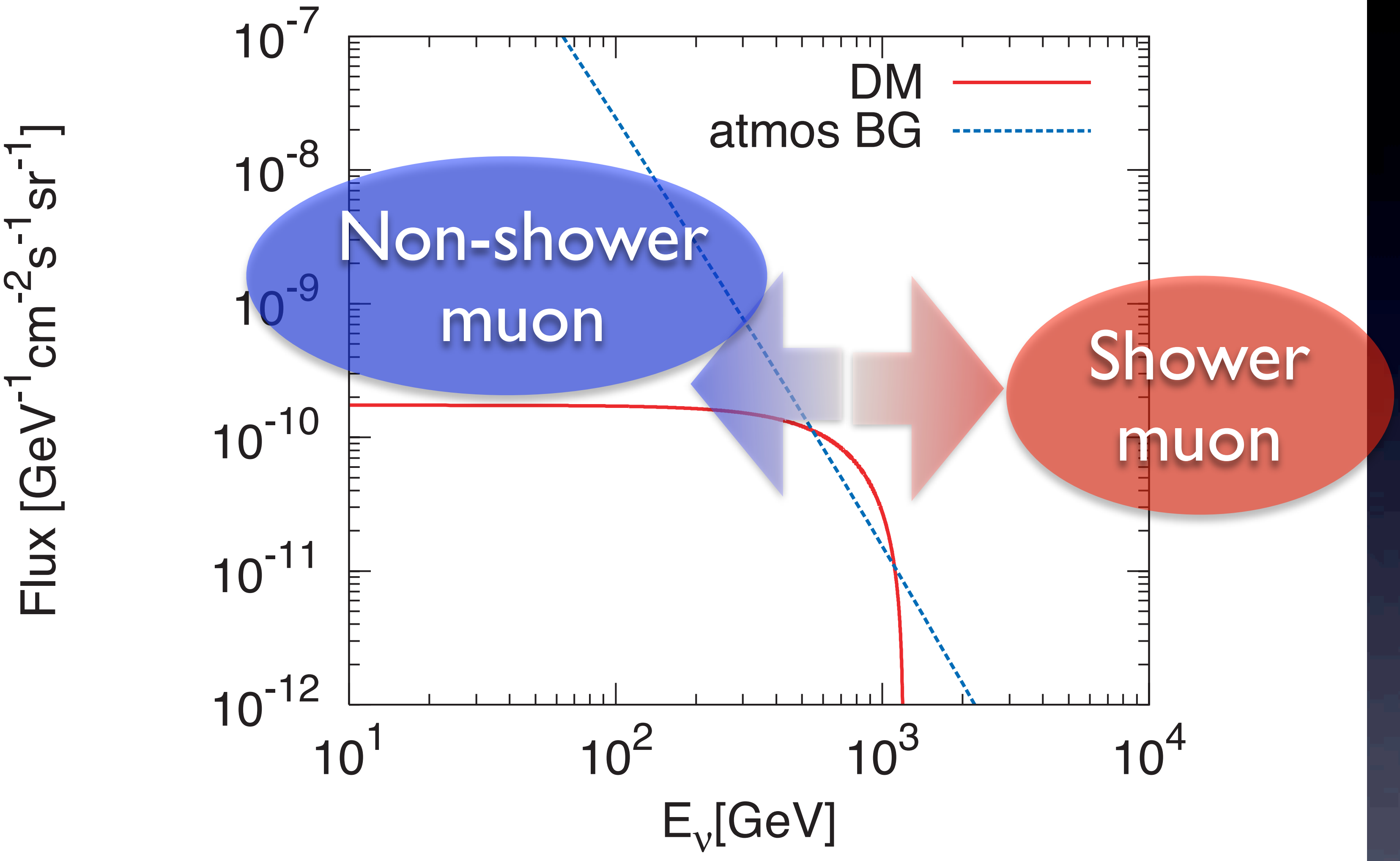


S.Desai et al.,
Astropart.Phys.29,42 (2008)

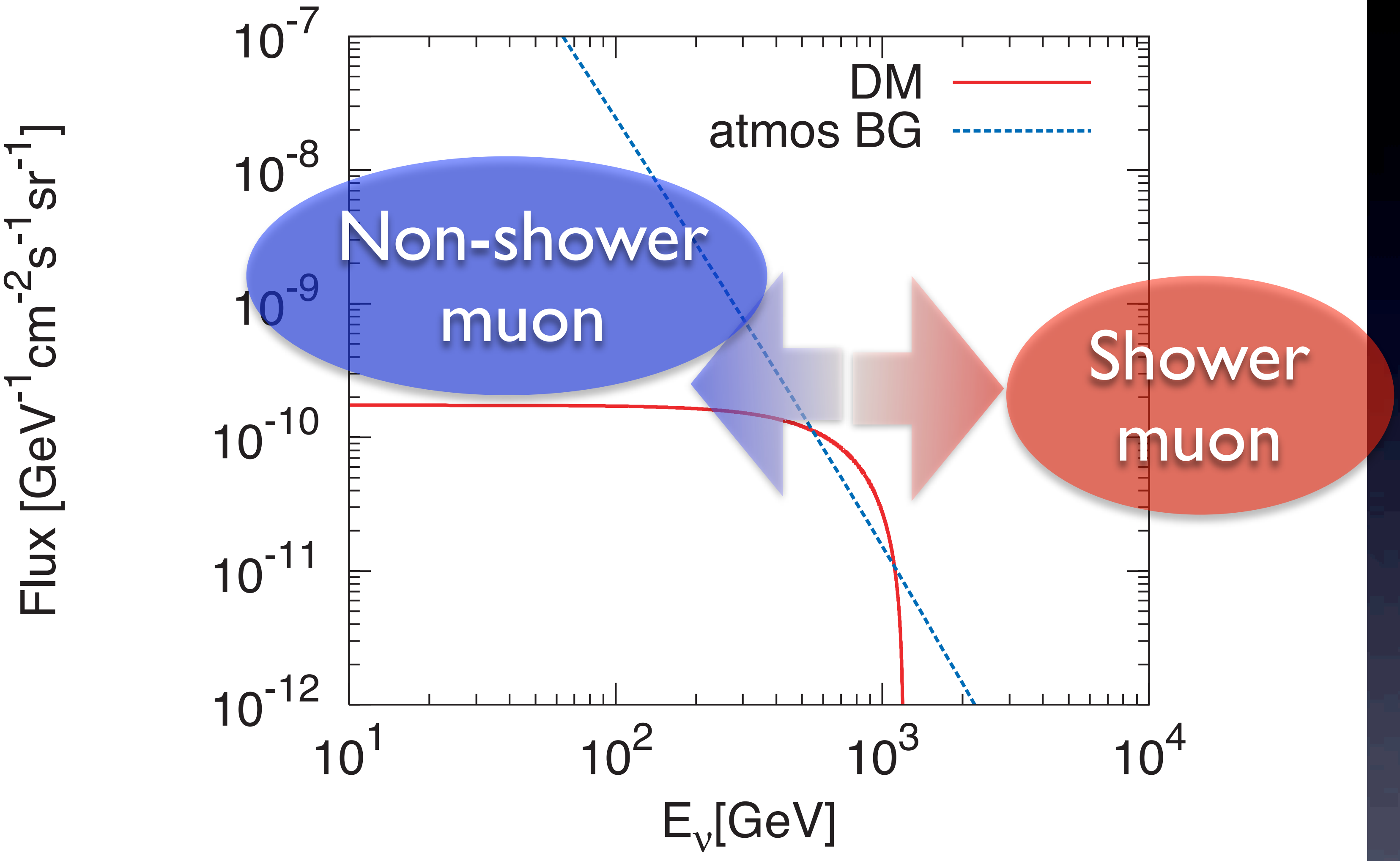
atmos : Honda et al.,2005



atmos : Honda et al.,2005

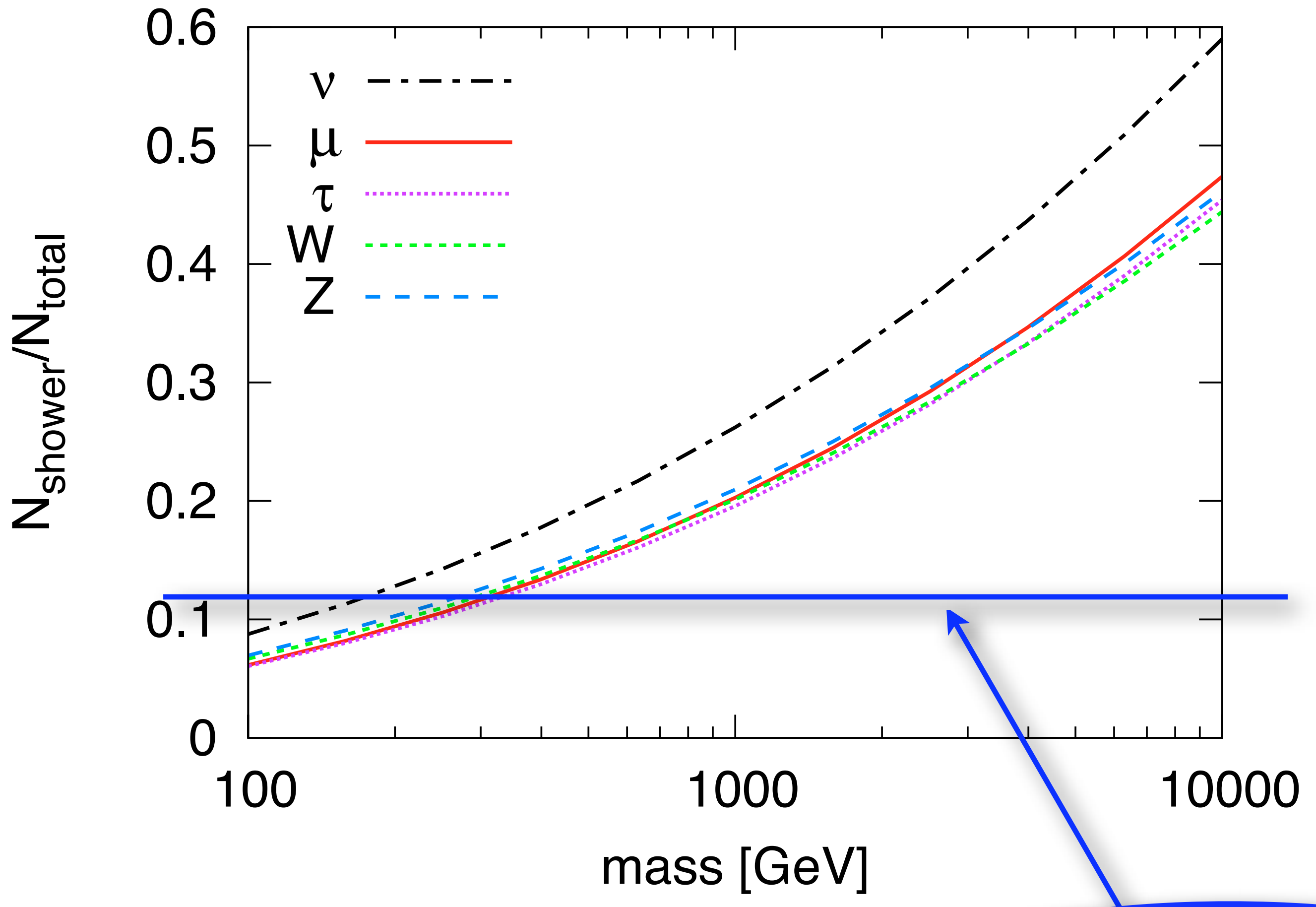


atmos : Honda et al.,2005



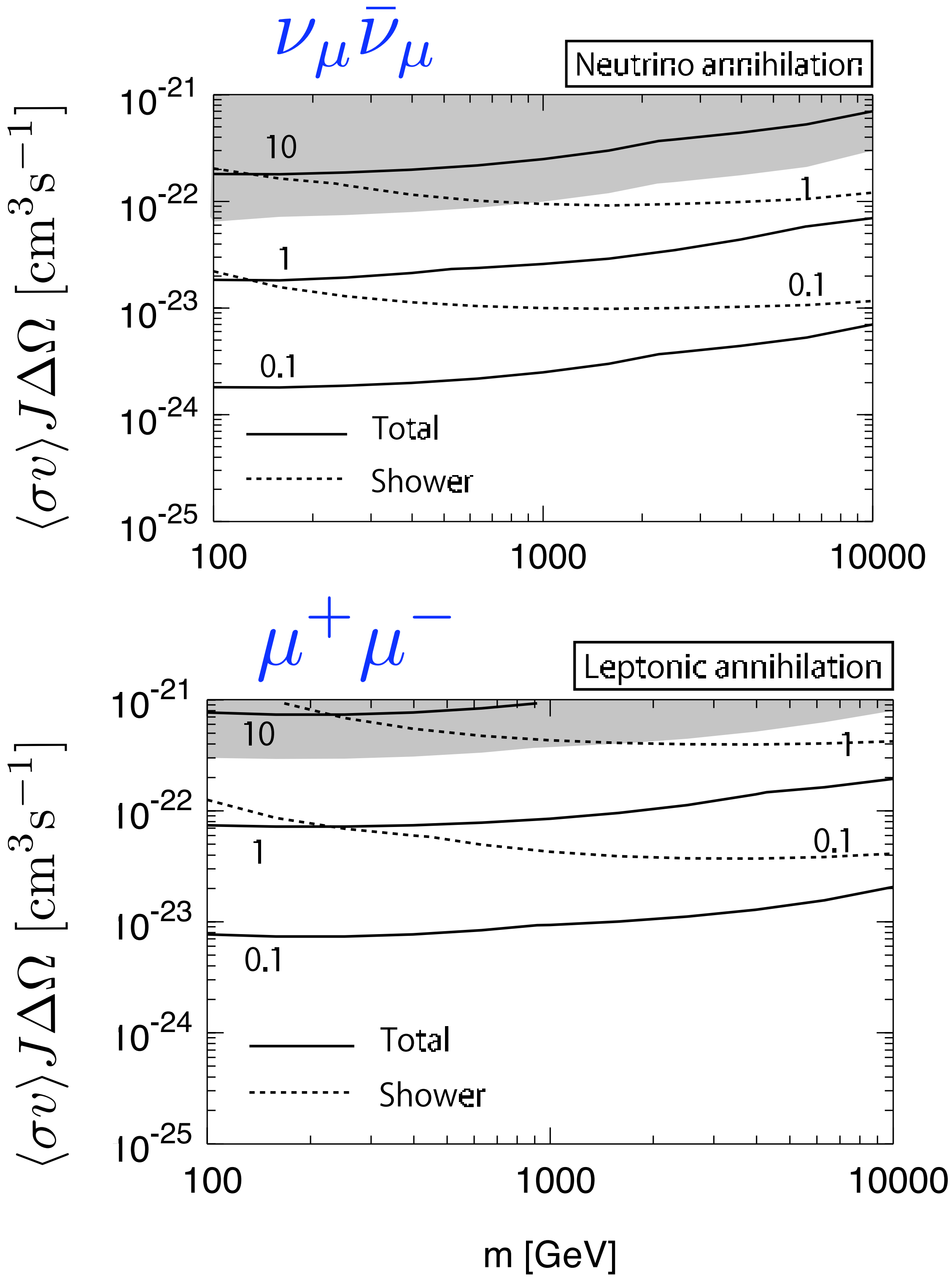
Shower muon events contain relatively large contribution from DM-produced neutrino

Ratio between Shower muon and Total muon



atmospheric :

$$N_\mu^{\text{shower}}/N_\mu^{\text{total}} \simeq 0.12$$



Contour : Muon flux

$(\times 10^{-15}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$

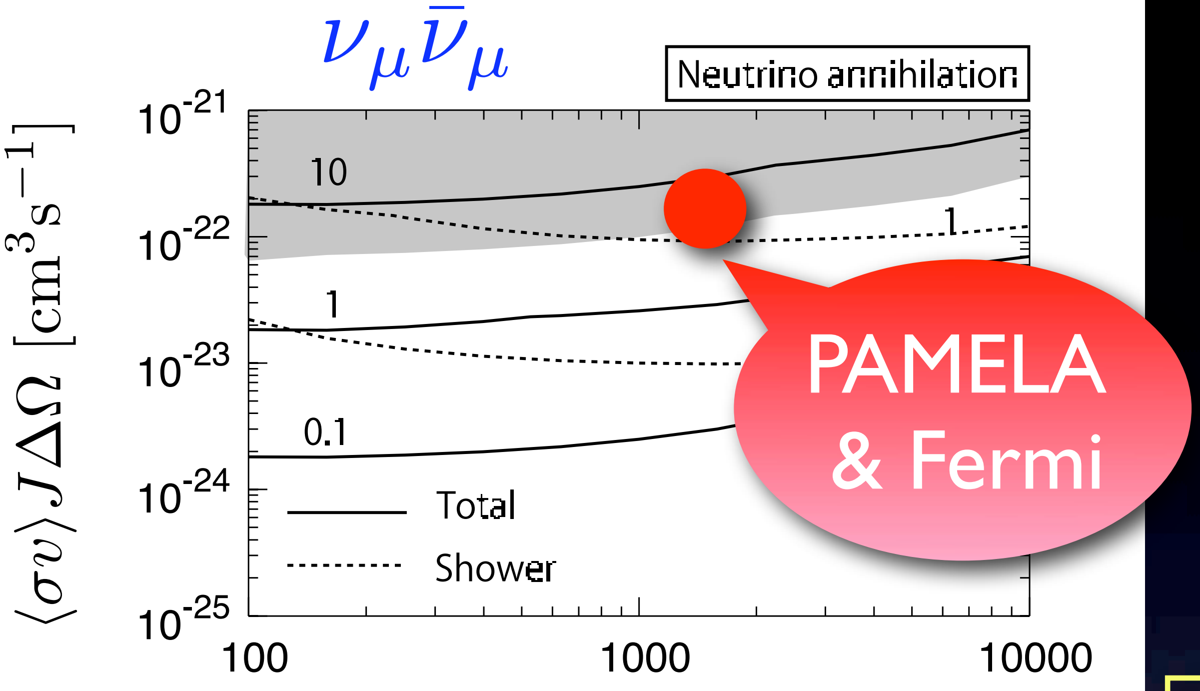
Gray : current SK bound

$(\mathrm{for}\ \theta = 5^\circ)$

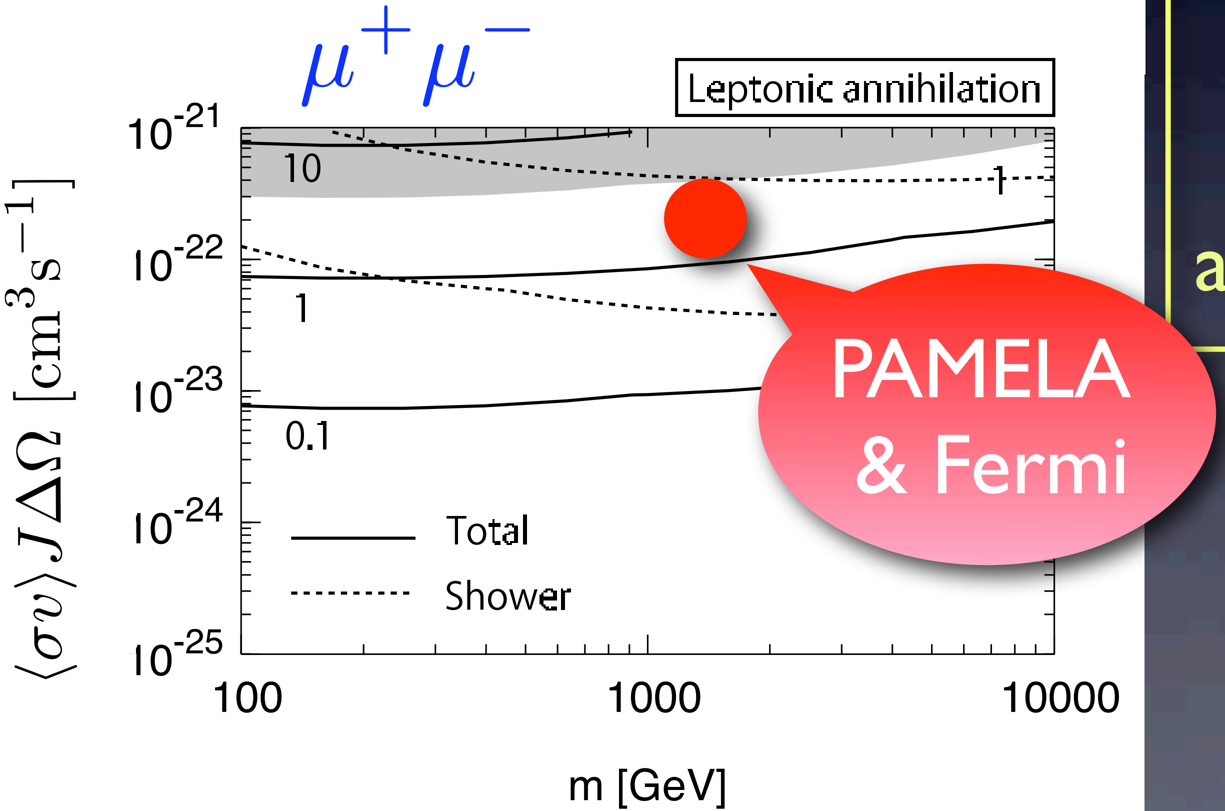
A factor improvement is expected on the annihilation cross section

May soon reach to PAMELA/Fermi region?

Hisano, KN, Yang 0905.2075



$\nu_\mu \bar{\nu}_\mu$



$\mu^+ \mu^-$

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Hisano, KN, Yang 0905.2075

Comments on IceCube

- Huge detector

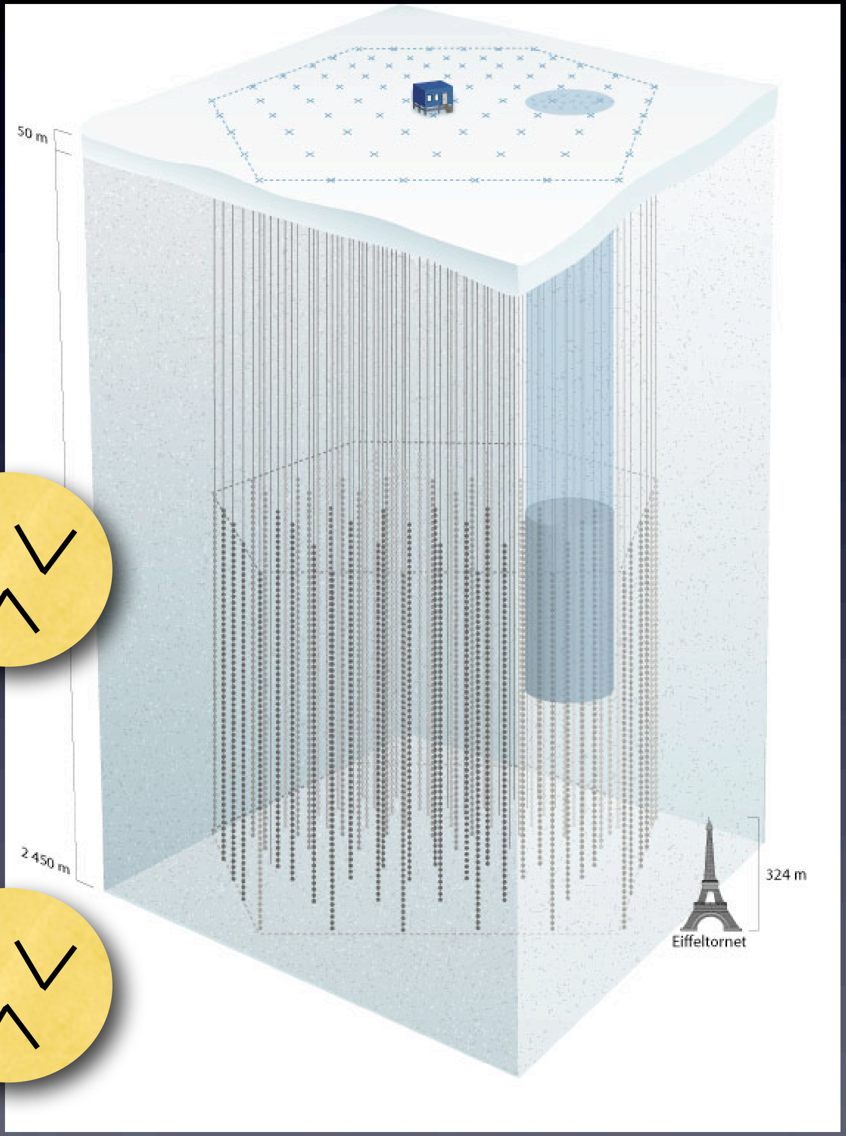
→ High statistics ☺

- Located at South Pole

→ cannot see Galactic center through upward muons ☹

- Use downward muons?

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



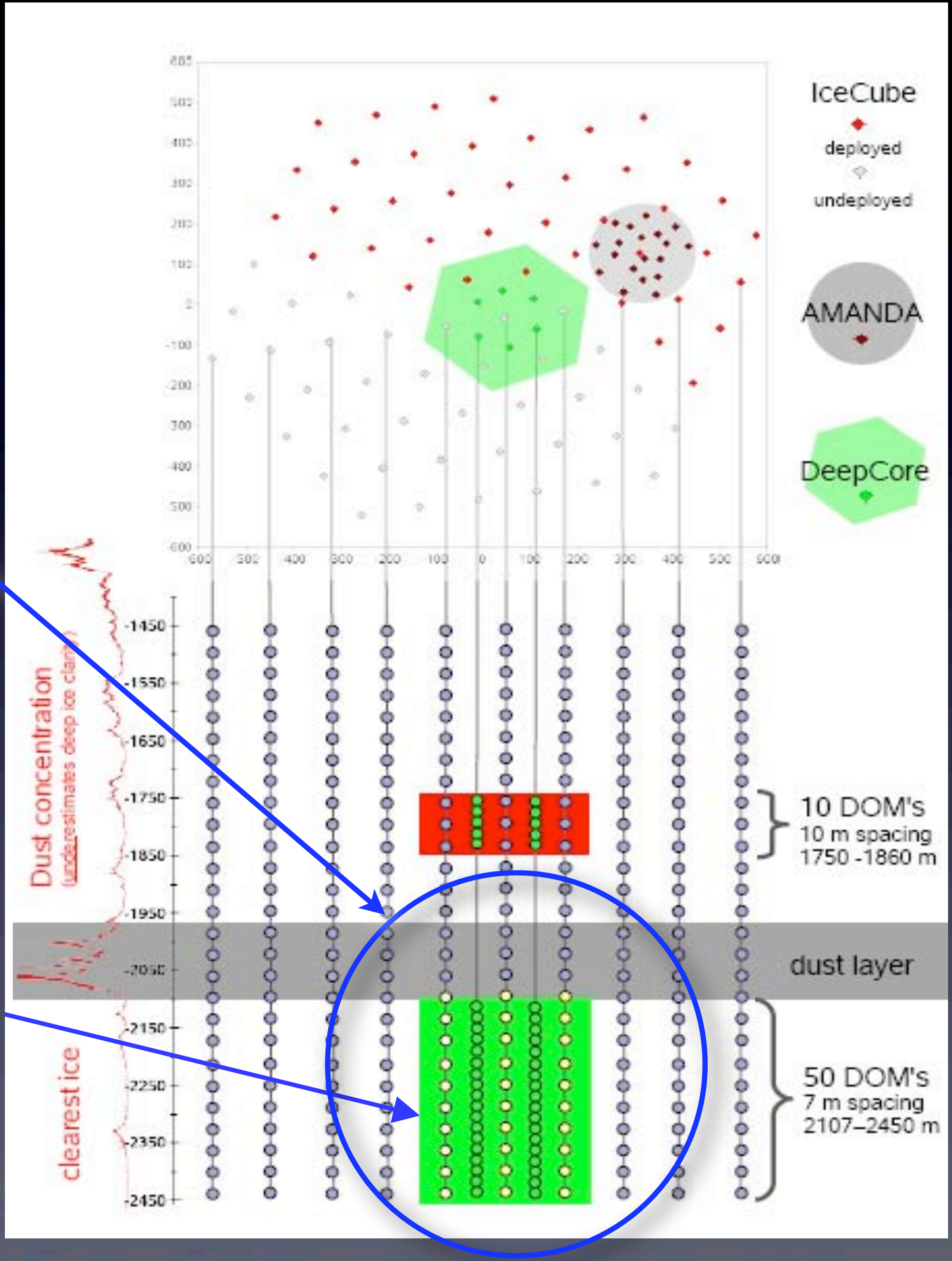
A planned extension : DeepCore

- Primary purpose : better sensitivity on low-energy neutrino

  Inner detector with denser instrumentation

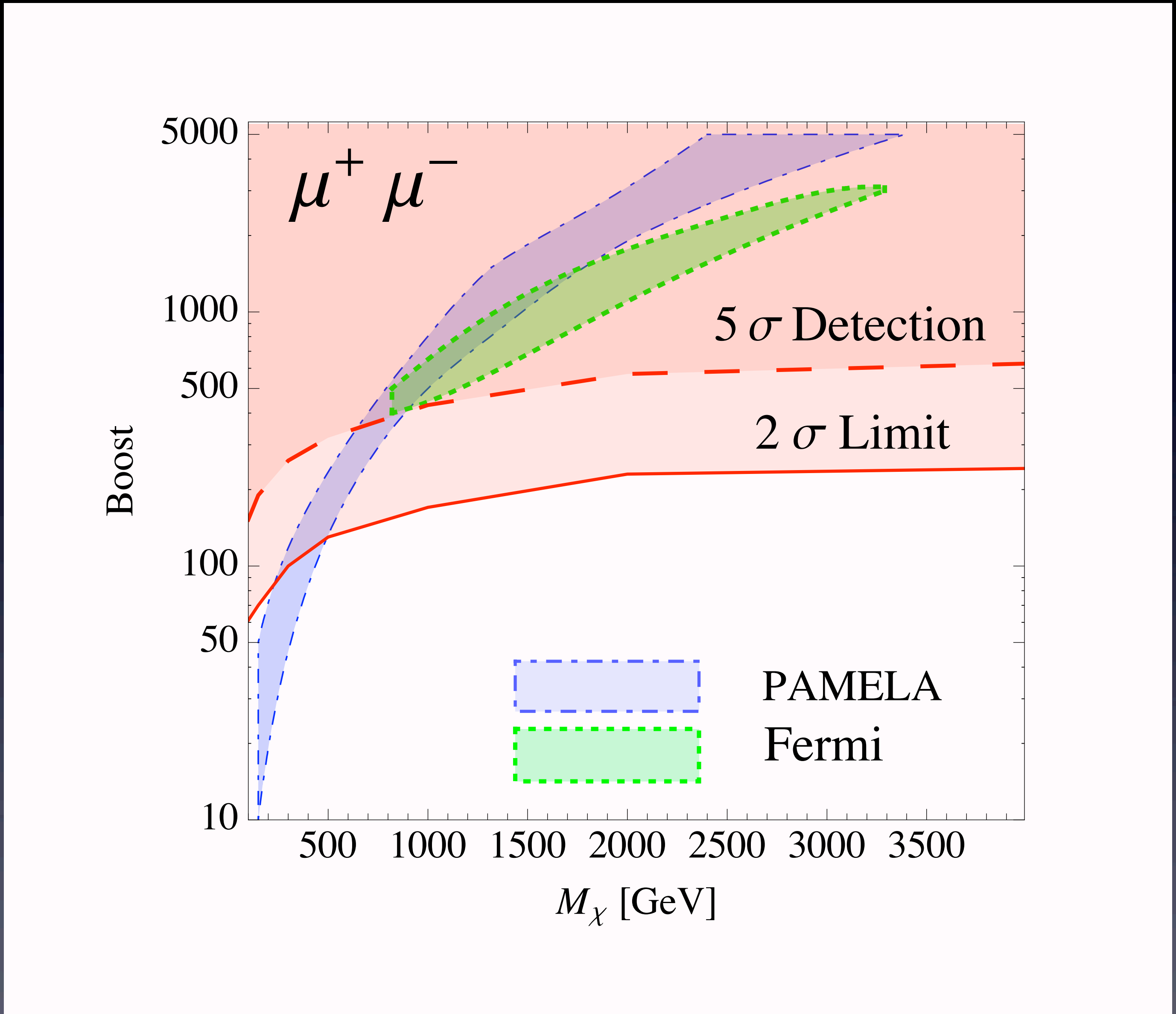
- Use original detector as muon veto

→ **Remove atmospheric muon BG**



S.Seo, Talk at Dark2009

Expected sensitivity of DeepCore (5yr)



Spolyar, Buckley, Freese, Hooper, Murayama, 0905.4764

Summary

DM interpretation of PAMELA/Fermi

→ Confirm/constrain by other signals

- Neutrino-induced muon Flux

  Useful constraints on annihilating/decaying DM.

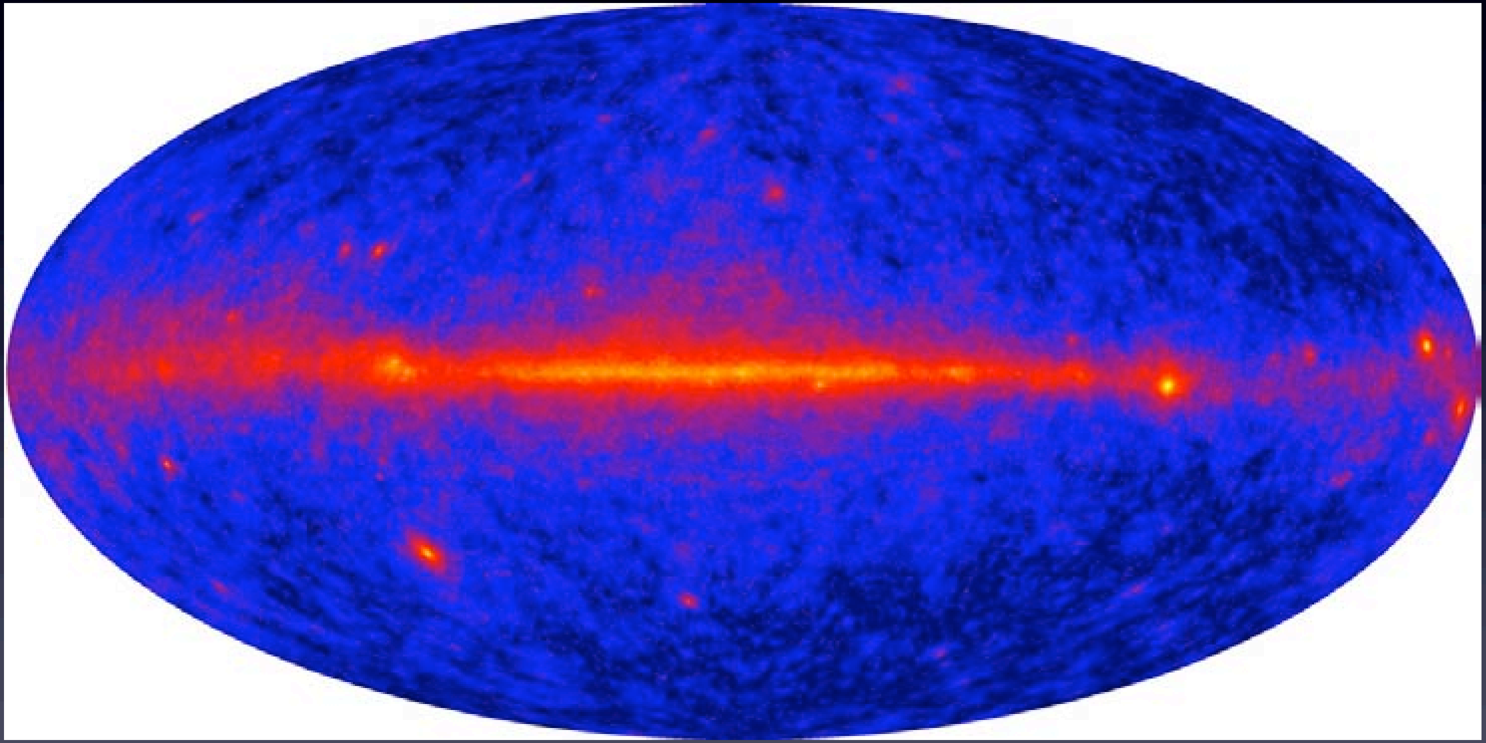
  Shower/non-shower separation may be
  a useful way to extract DM information.

→ SK III, DeepCore, KM3NeT

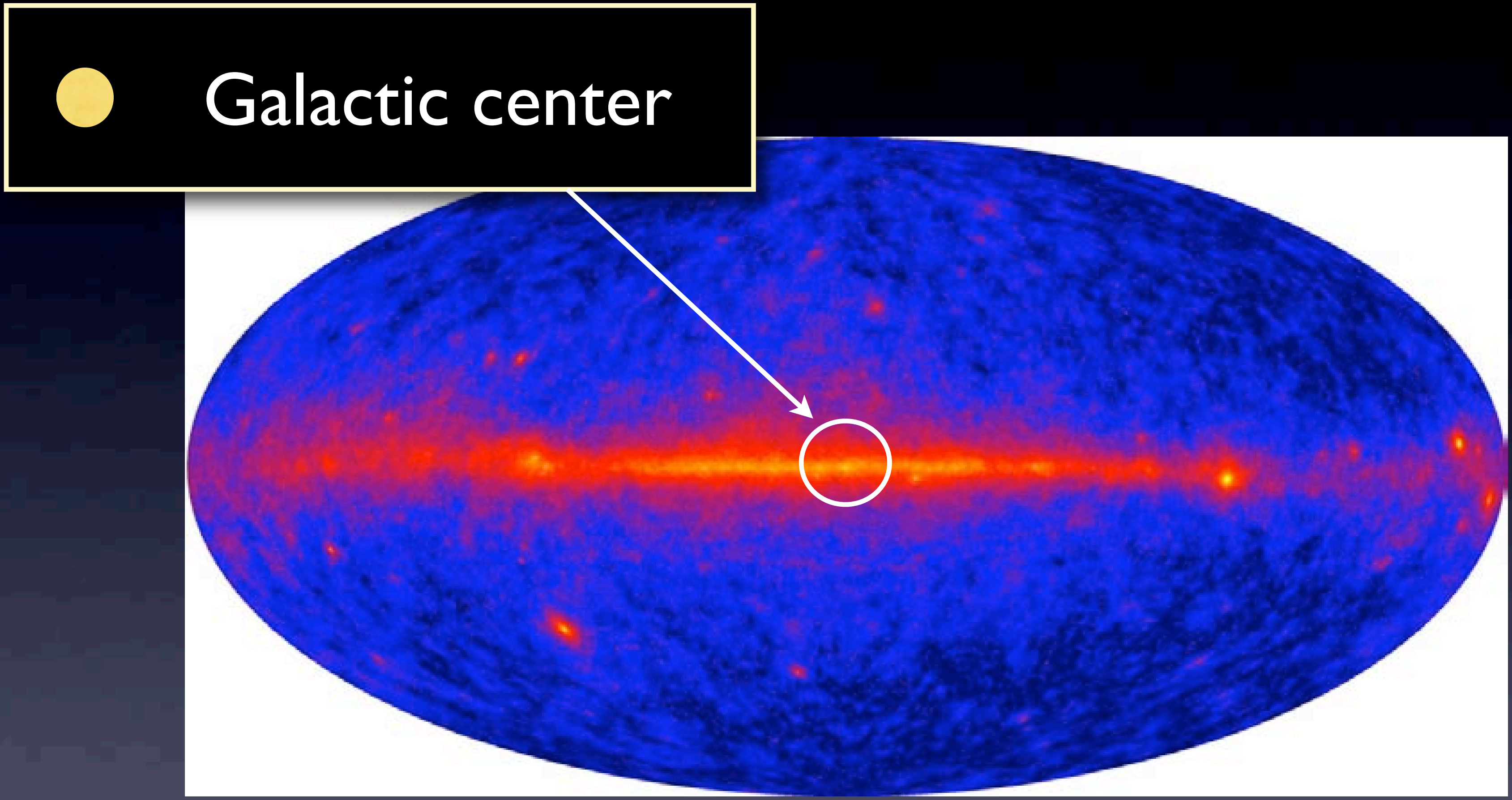
Second Part II : Diffuse gamma-rays

M.Kawasaki, K.Kohri and KN, to appear in Phys.Rev.D [0904.3626]

Gamma-Ray Flux

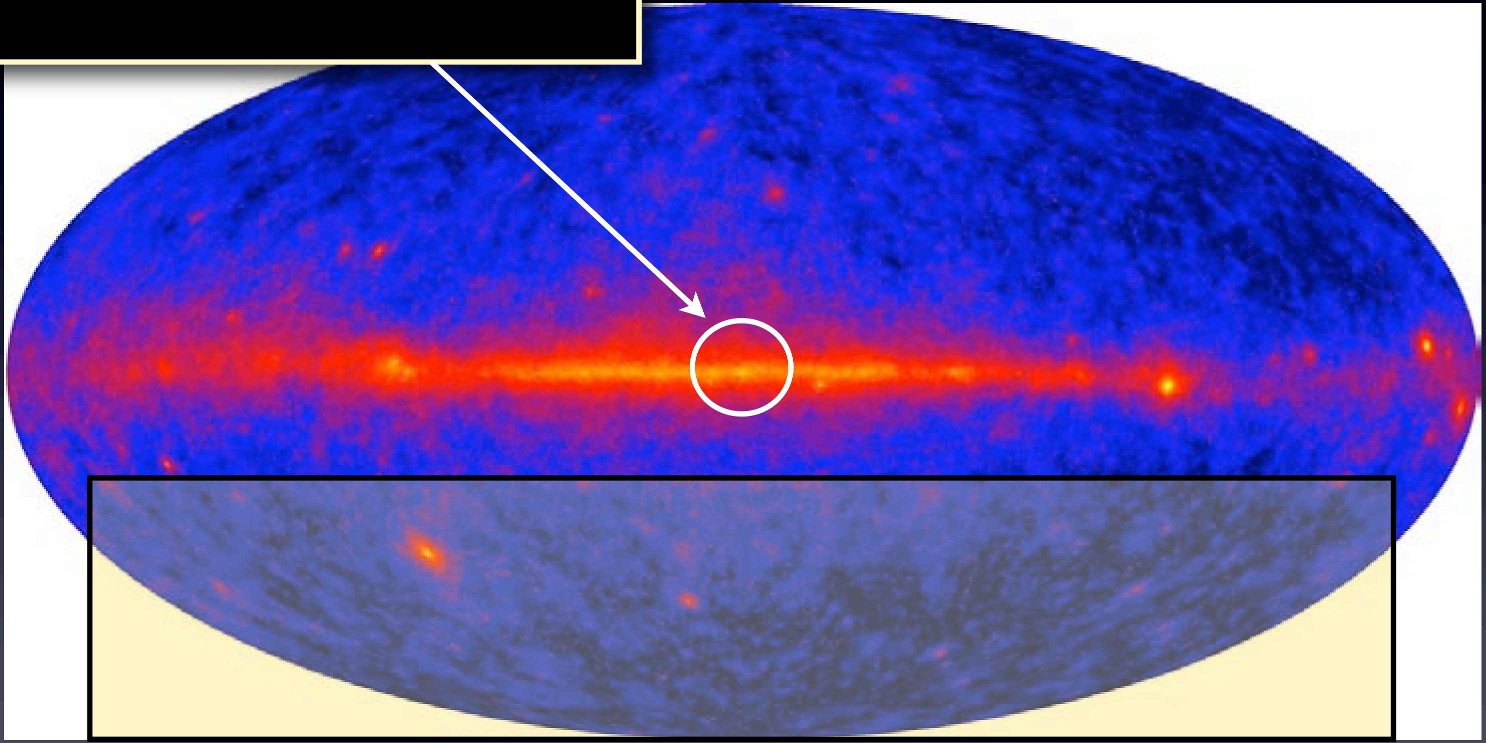


Gamma-Ray Flux



- Galactic center

Gamma-Ray Flux



- Galactic center

- Extra Galactic diffuse

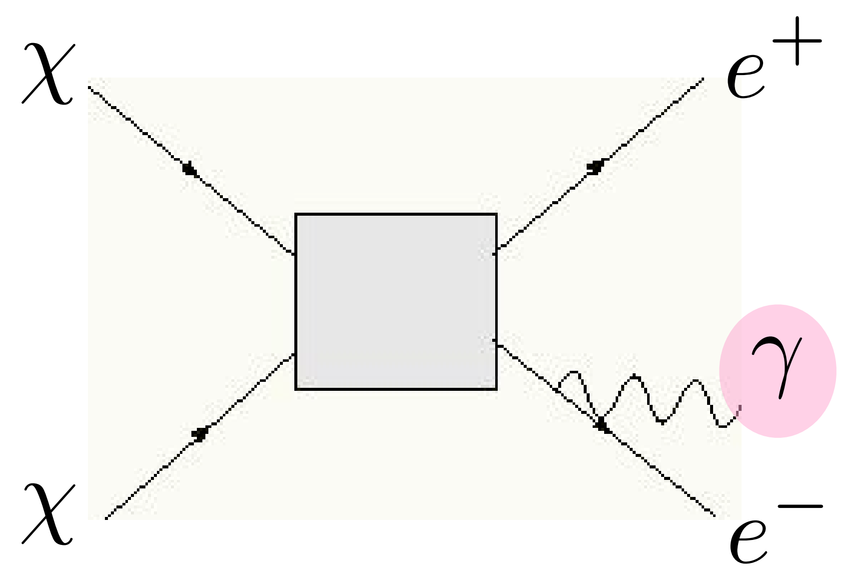
Continuum Gamma-Rays from DM ann.

Internal Brems.

Final state charged particle always emit photon.

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

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



Cascade decay

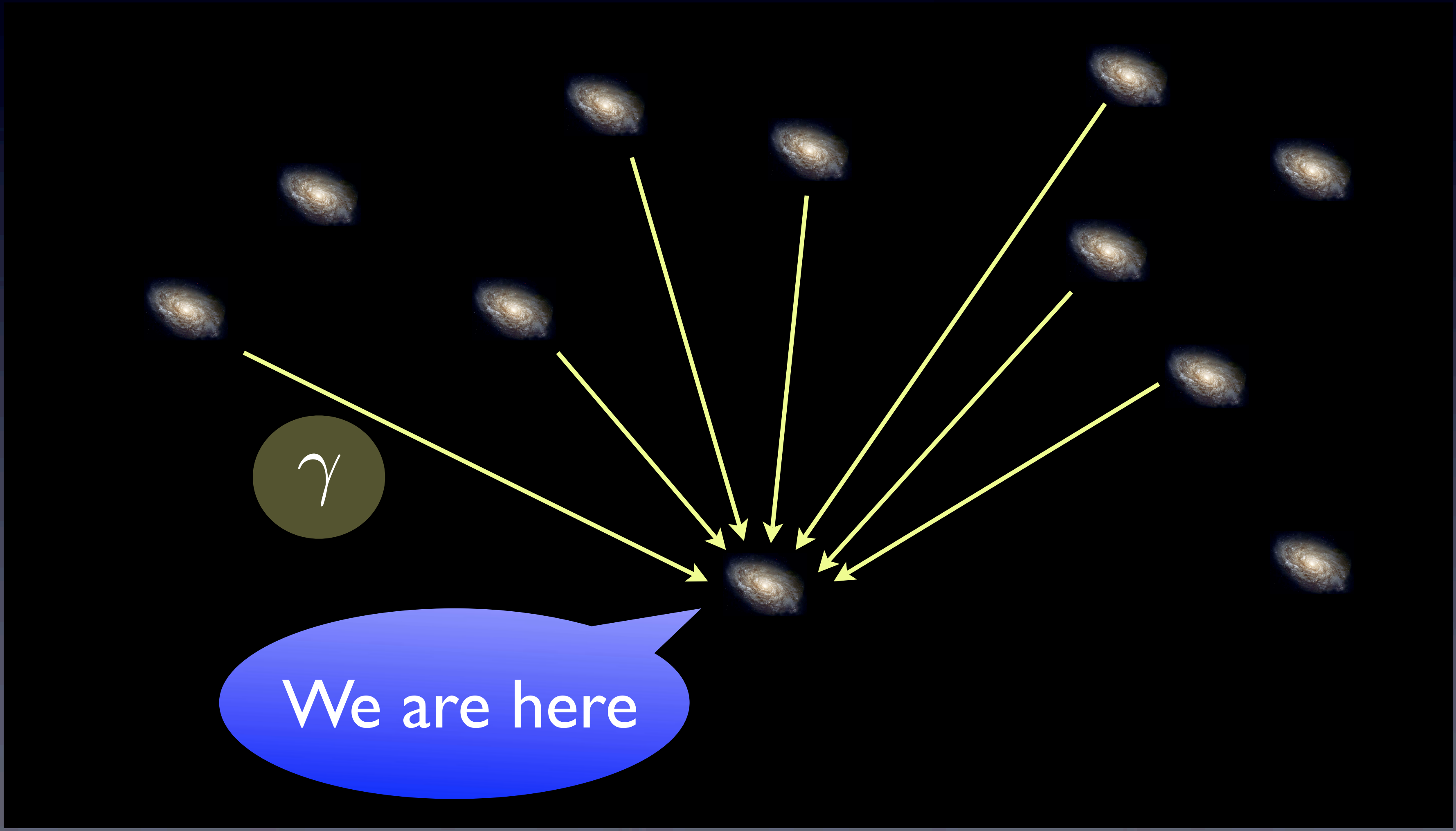
$$\chi\chi \to \tau^+\tau^-, W^+W^- \to \text{hadrons}(\pi^\pm, \pi^0, \rho, \dots)$$

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

Extra-Galactic component

Ullio, Bergstrom, Edsjo, Lacey (2002)

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



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

$\Delta^2(z)\ :\ \text{Enhancement factor}$

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

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

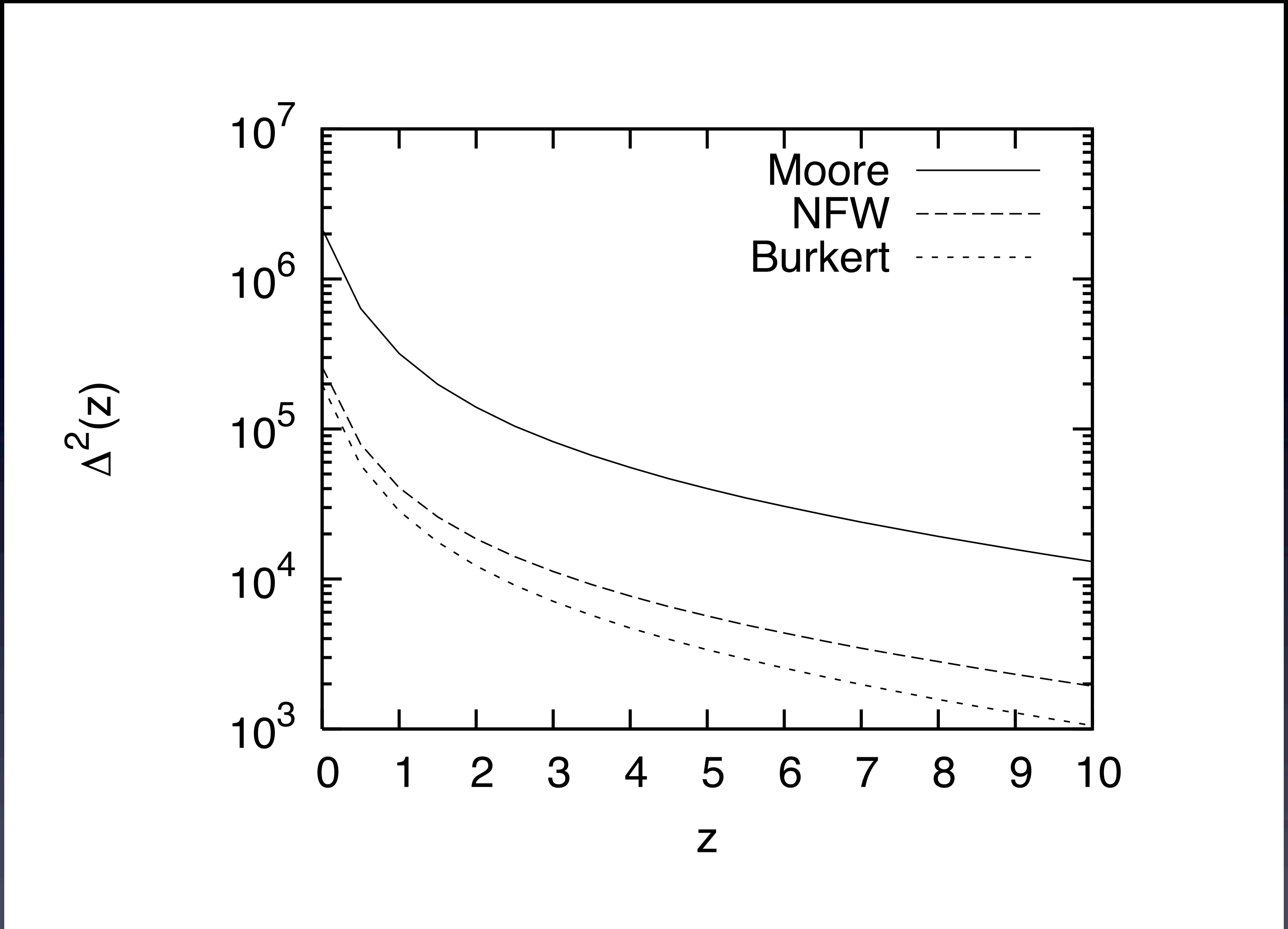
Number of clustering objects :

→ 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

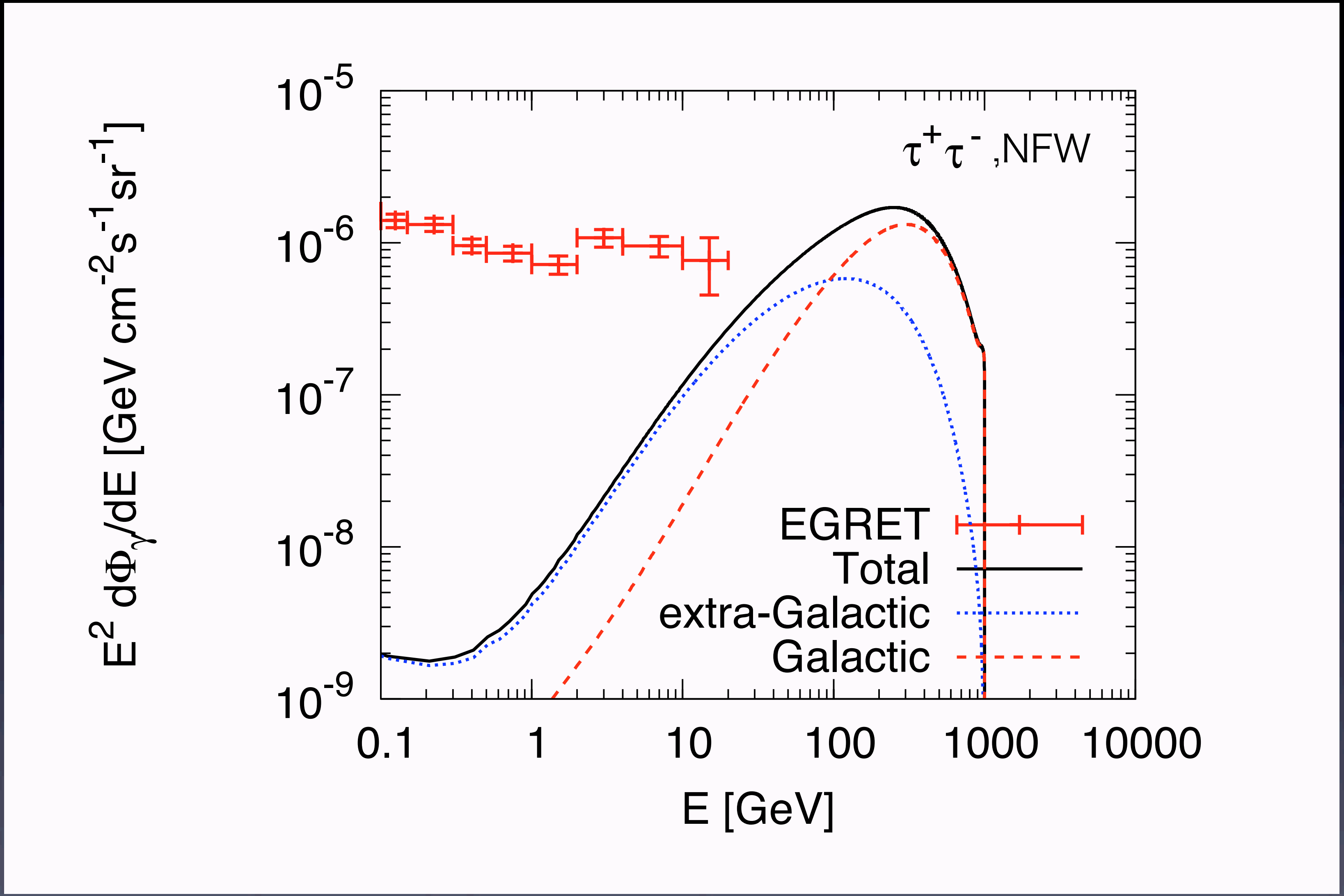
$$\rho(r) \sim \frac{1}{r(1+r)^2}$$

- Burkert

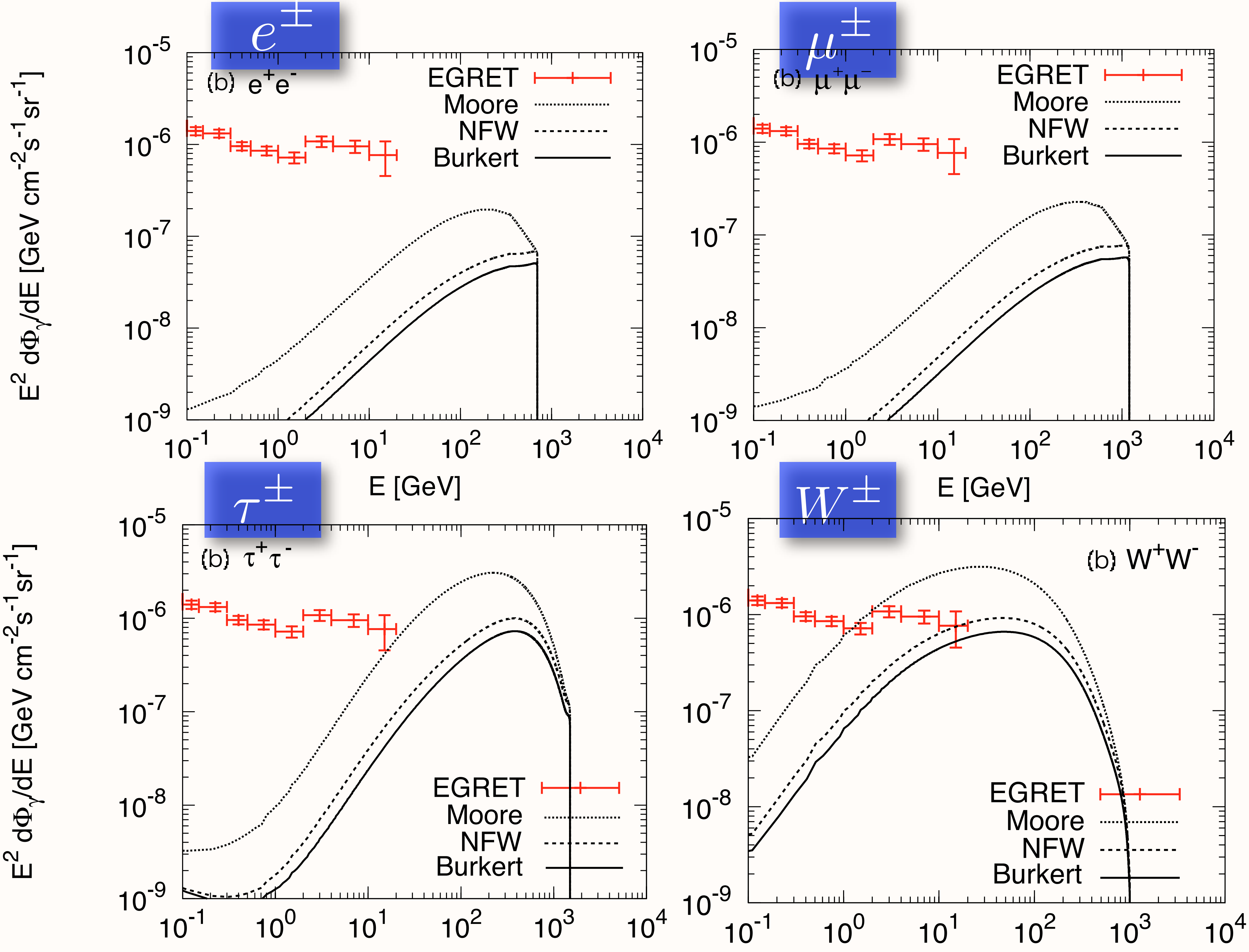
$$\rho(r) \sim \frac{1}{(1+r)(1+r^2)}$$

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

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

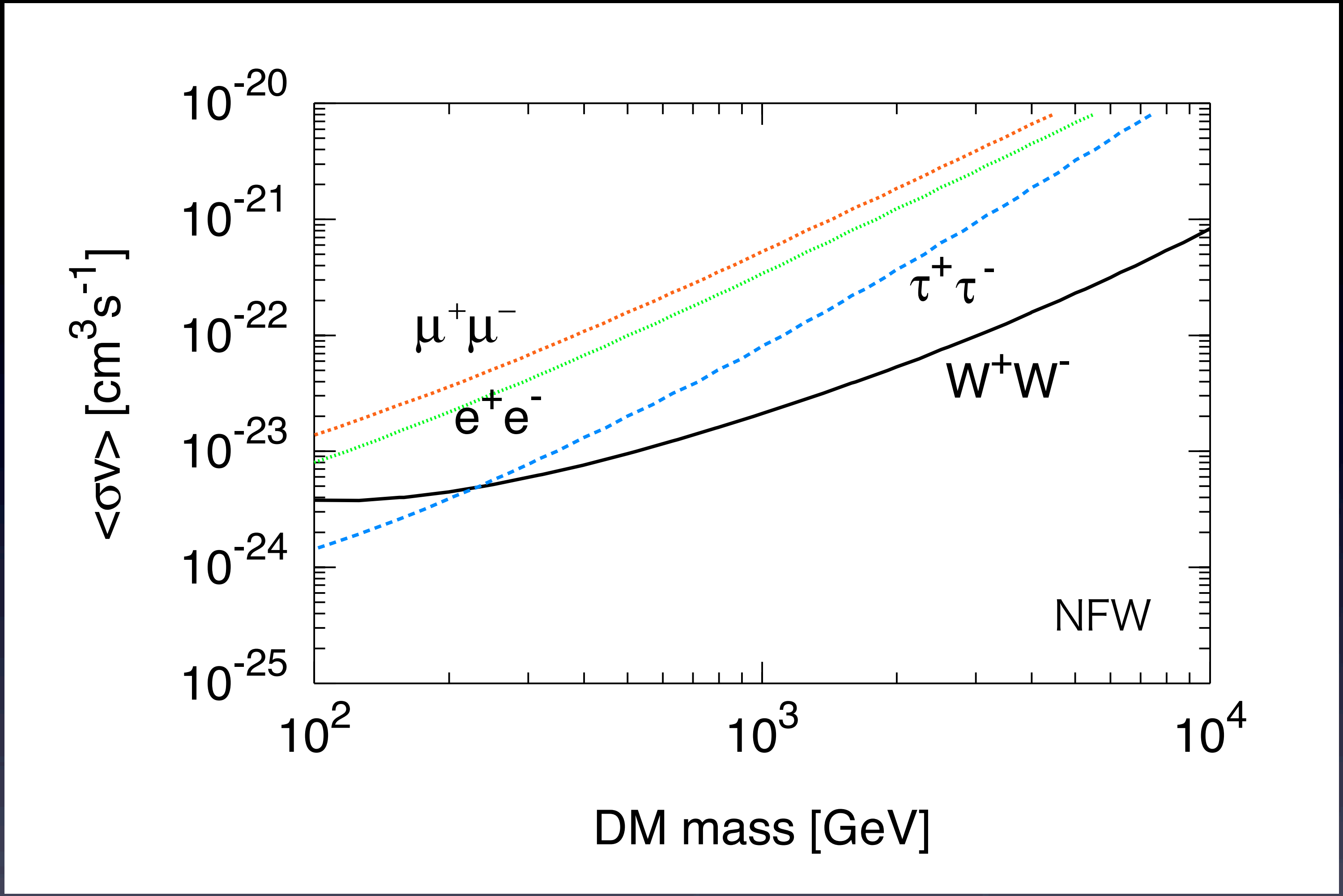


Extragalactic component is comparable to Galactic component



M.Kawasaki, K.Kohri, KN, 0904.3626

Constraints on annihilation cross section



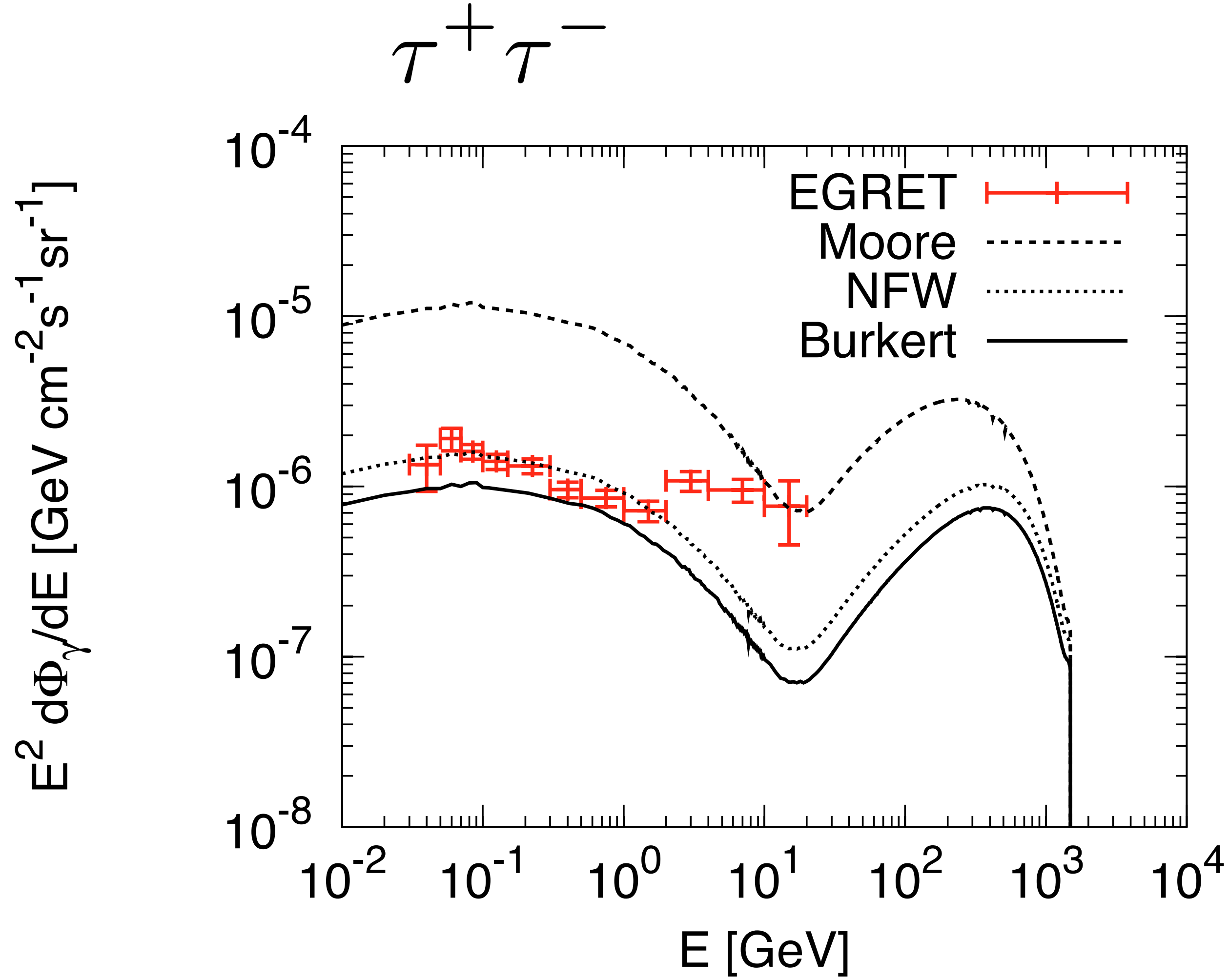
- Cuspy profile : extragalactic is weaker than GC bound
- Cored profile : extragalactic is stronger than GC bound

Fermi will soon make the bound stronger

Effects of Inverse Compton scattering CMB photon

Profumo, Jeltema,0906.0001
Belikov, Hooper, 0906.2251

$$e^{\pm} + \gamma_{\mathrm{CMB}} \to e^{\pm} + \gamma$$



Second peak around

$$E_\gamma^{(\mathrm{IC})} \sim \gamma_e^2 E_{\mathrm{CMB}}$$

$$\sim 0.1\ \mathrm{GeV} \left(\frac{m_{\mathrm{DM}}}{1\ \mathrm{TeV}}\right)^2$$

→ More stringent constraint

Summary

DM interpretation of PAMELA/Fermi

Confirm/constrain by other signals, as

- Neutrino-induced muon Flux

  Useful constraints on annihilating/decaying DM.

  → SK III, DeepCore, KM3NeT

- Gamma-ray Flux

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

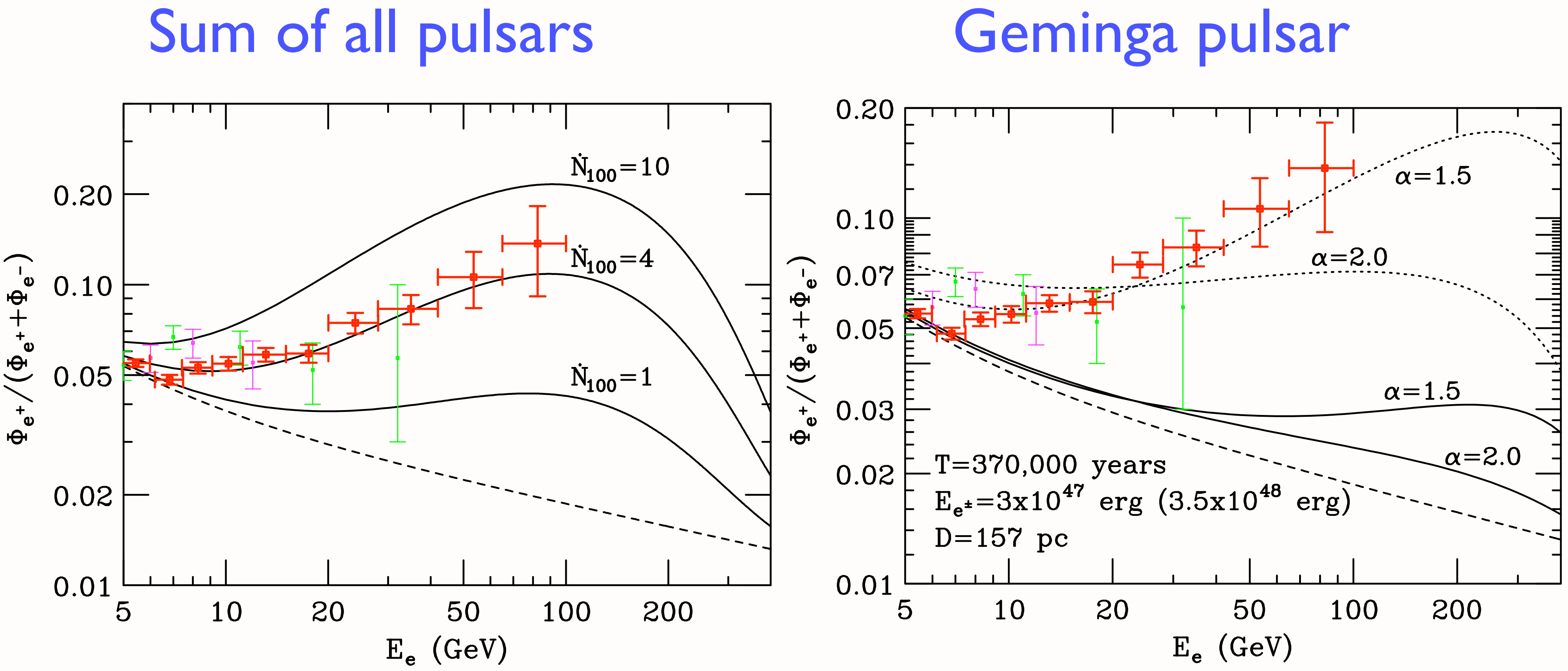
  → Fermi

Back-up Slides

Astrophysical source

- Pulsar (single or sum)
- Gamma-ray burst

Hooper, Blasi, Serpico, arXiv:0810.1527
Profumo, arXiv:0812.4457
K.Ioka, arXiv:0812.4851

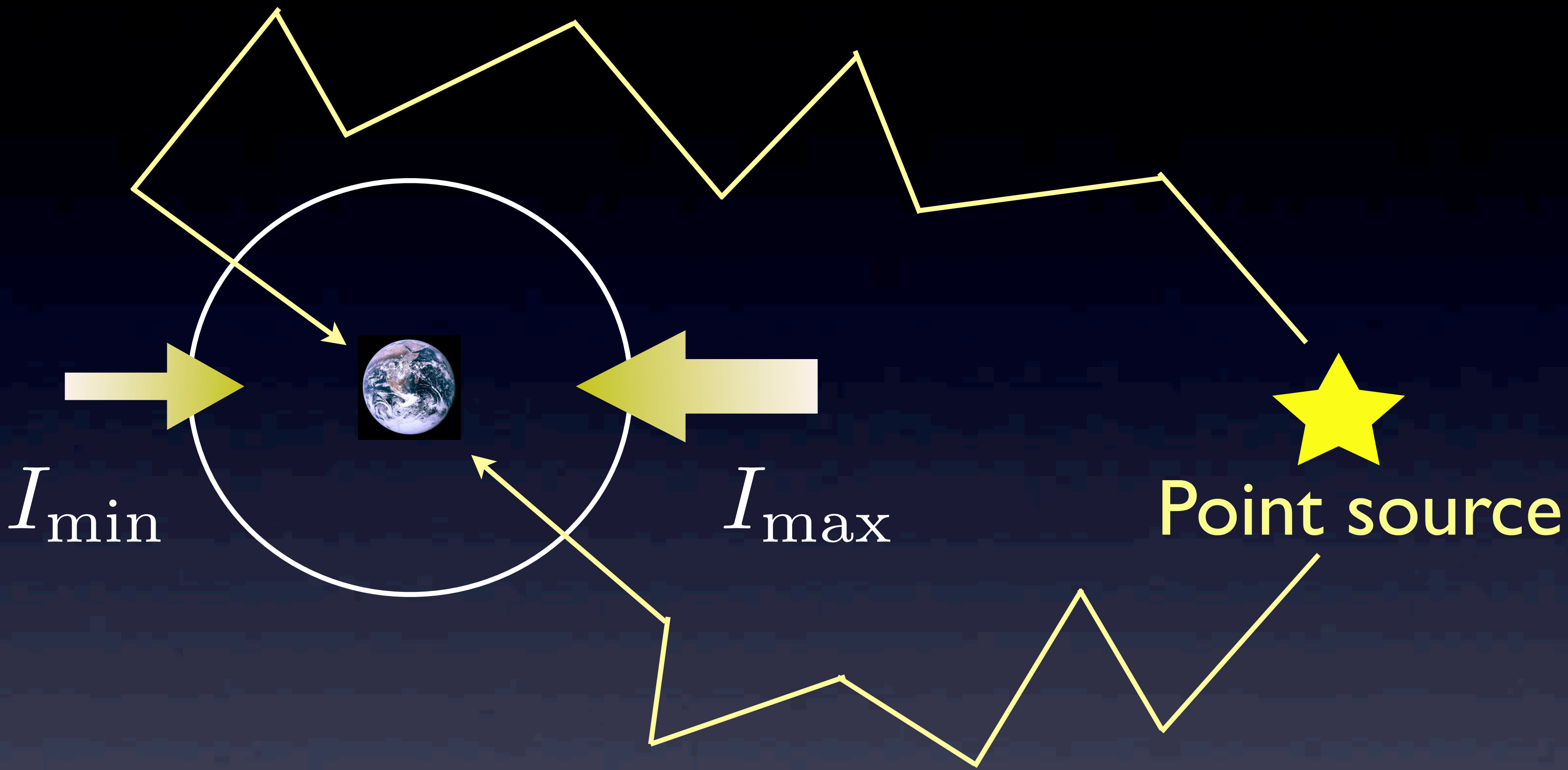


Sum of all pulsars

Geminga pulsar

Hooper, Blasi, Serpico, arXiv:0810.1527

DM or Astrophysics? → Anisotropy in CR flux



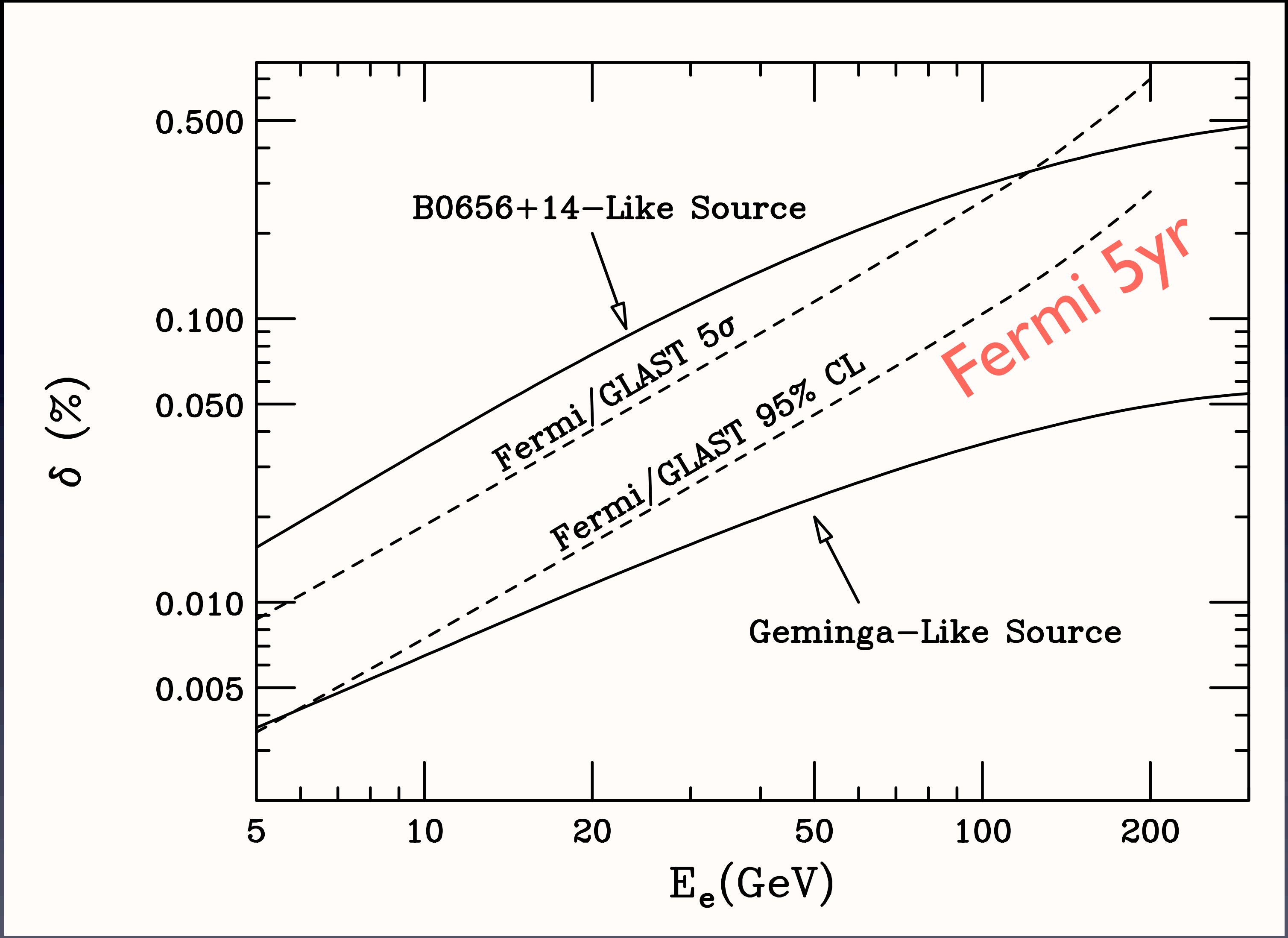
I_{min}

I_{max}

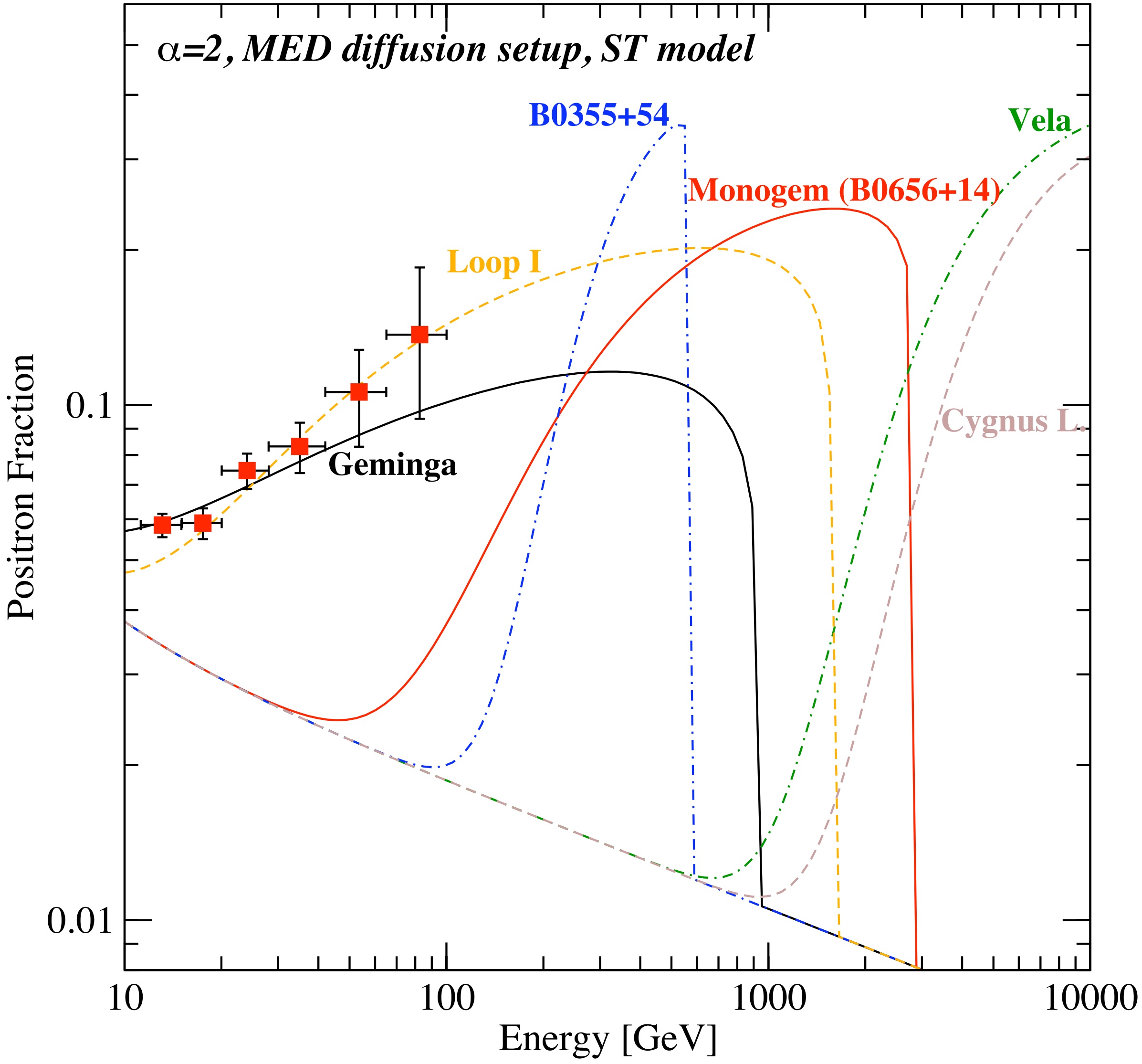
Point source

$$\delta = \frac{I_{\mathrm{max}} - I_{\mathrm{min}}}{I_{\mathrm{max}} + I_{\mathrm{min}}} \quad \sim \frac{K(E)}{Rc} \sim 0.01\% \left(\frac{1\ \mathrm{kpc}}{R}\right)\left(\frac{E}{1\ \mathrm{GeV}}\right)^{0.6}$$

Anisotropy from nearby Pulsar



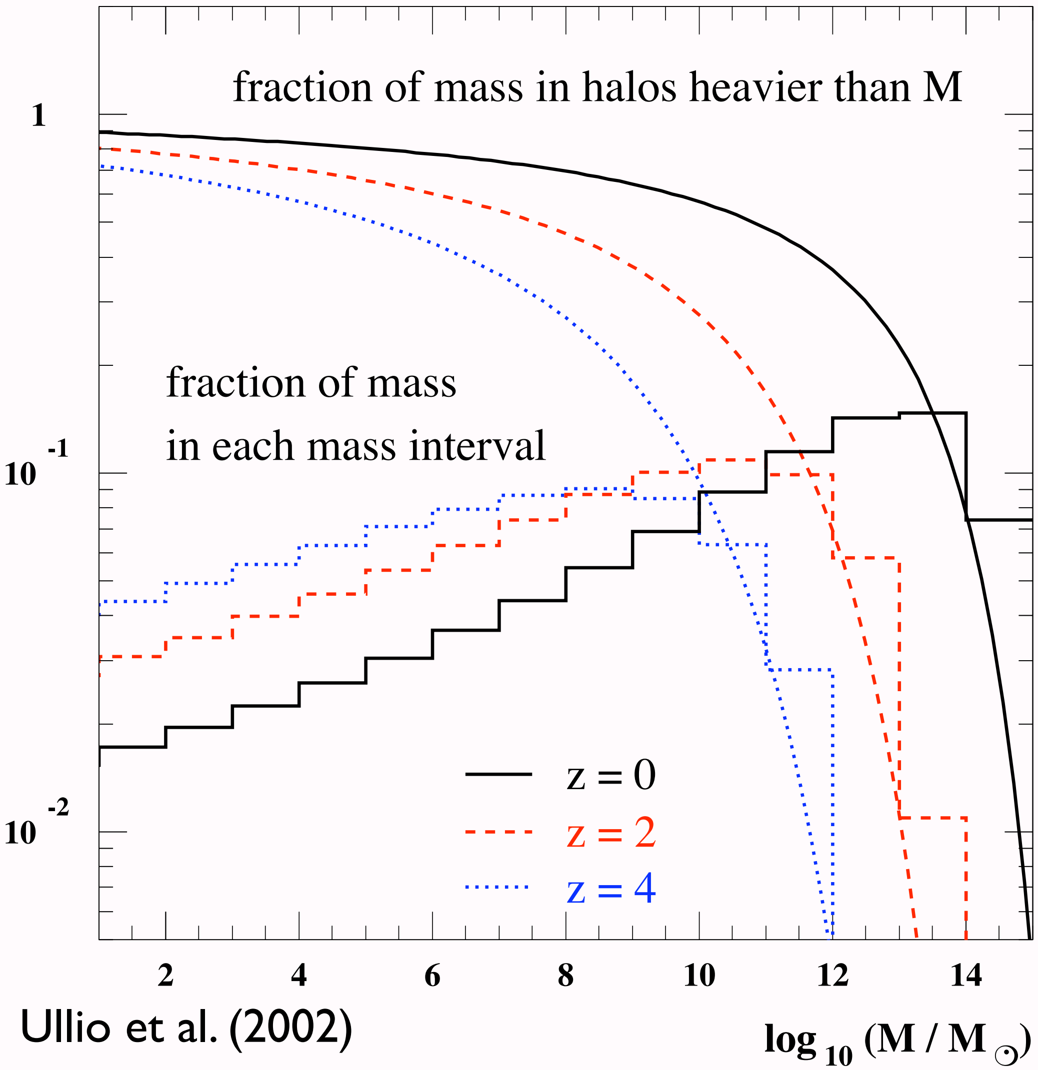
Hooper, Blasi, Serpico, arXiv:0810.1527



S.Profumo, arXiv:0812.4457

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

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

Predict number of collapsed objects with mass M