Title: Dark Matter Interpretations of the Electron/Positron Excesses after FERMI

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Abstract: The cosmic-ray excess observed by PAMELA in the positron fraction and by FERMI and HESS in the electron + positron flux can be interpreted in terms of DM annihilations or decays into leptonic final states. Final states into tau's or 4mu give the best fit to the excess. However, in the annihilation scenario, they are incompatible with photon and neutrino constraints, unless DM has a quasi-constant density profile. Final states involving electrons are less constrained but poorly fit the excess, unless hidden sector radiation makes their energy spectrum smoother, allowing a fit to all the data with a combination of leptonic modes. In general, DM lighter than about a TeV cannot fit the excesses, so PAMELA should find a greater positron fraction at higher energies. The DM interpretation can be tested by FERMI gamma observations above 10 GeV: if the electronic excess is everywhere in the DM halo, inverse Compton scattering on ambient light produces a well-predicted gamma excess that FERMI should soon detect.

The galactic DM density profile

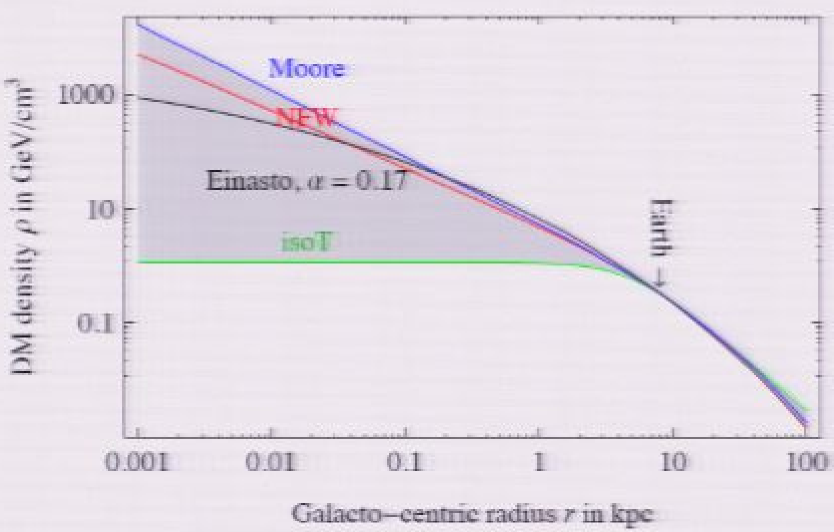
DM velocity: $\beta \approx 10^{-3}$. DM is spherically distributed with uncertain profile:

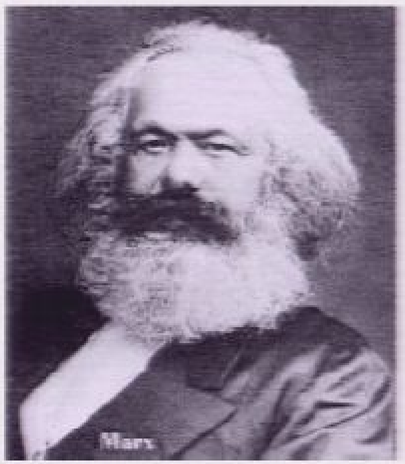
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

$r_\odot = 8.5\,\mathrm{kpc}$ is our distance from the Galactic Center, $\rho_\odot \equiv \rho(r_\odot) \approx 0.3\,\mathrm{GeV/cm^3}$,

DM halo model		α	β	γ	r_s in kpc
Isothermal	'isoT'	2	2	0	5
Navarro, Frenk, White	'NFW'	1	3	1	20

$\rho(r)$ is uncertain because DM is like capitalism according to Marx: a gravitational system (slowly) collapses to the ground state $\rho(r) = \delta(r)$. Maybe our galaxy is communist: $\rho(r) \approx$ low constant, as in isoT.





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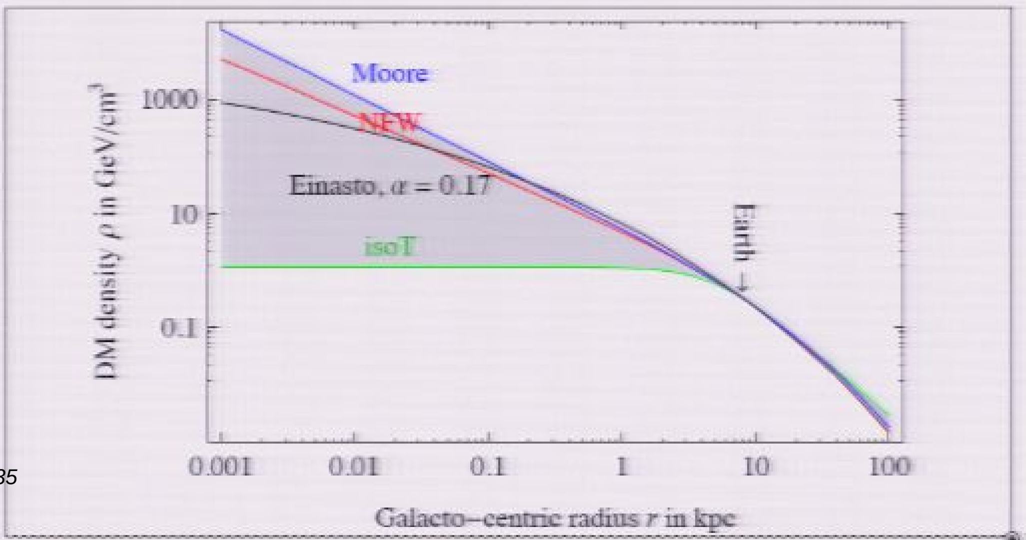

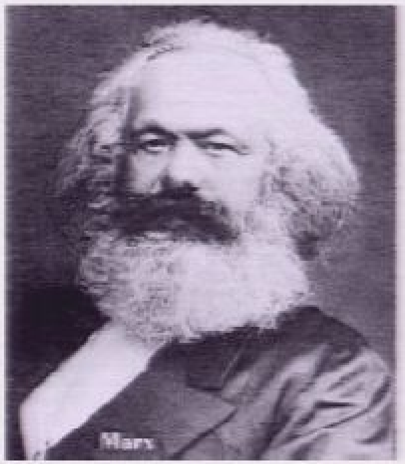

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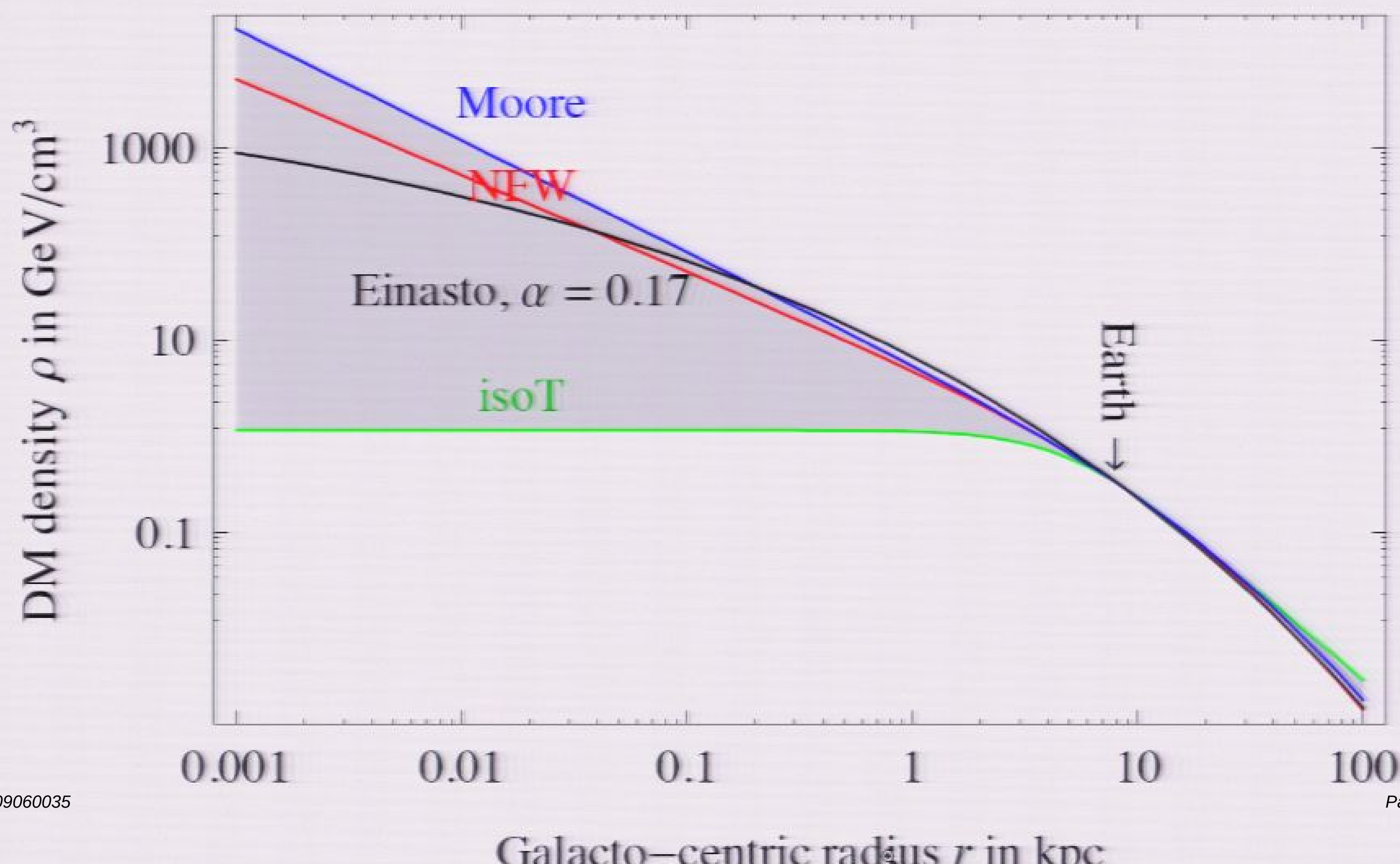

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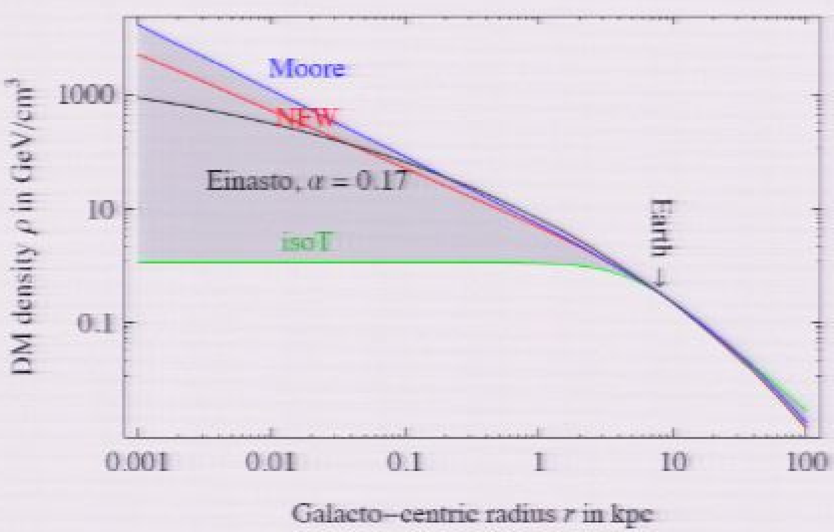
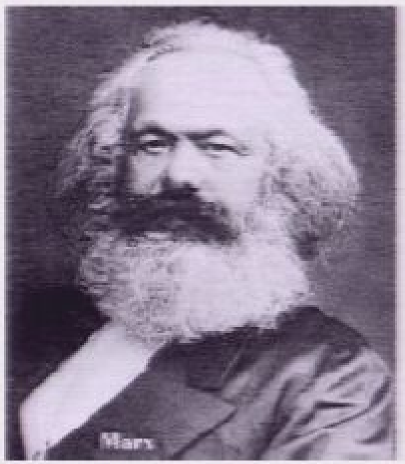
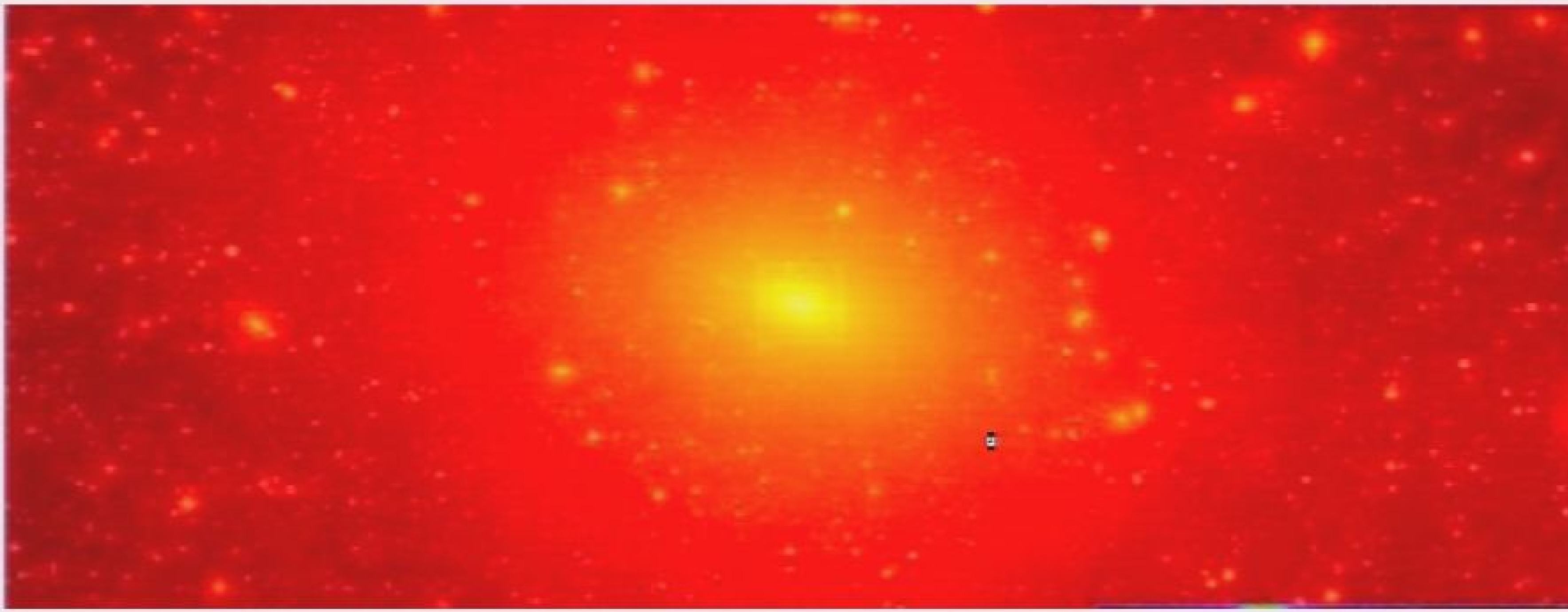




DM DM signal boosted by sub-halos?

N-body simulations suggest that DM might clump in subhalos:



Annihilation rate $\propto \int dV\ \rho^2$ increased by a boost factor $B = 1 \leftrightarrow 100 \sim$ a few

Simulations neglect normal matter, that locally is comparable to DM.

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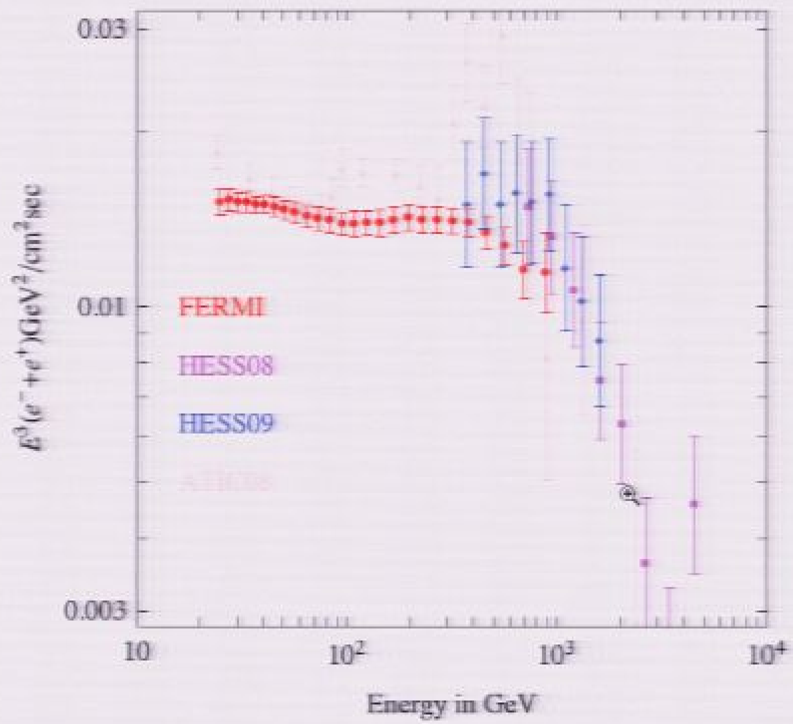
Model-independent theory of DM indirect detection

$e^+ + e^-$: FERMI and HESS

These experiments cannot discriminate e^+/e^-, but probe higher energy.



Hardening at 100 GeV + softening at 1 TeV

Are these real features? Likely yes. Hardening also in ATICs.

Systematic errors, not yet defined, are here (conservatively?) incoherently added bin-to-bin to the smaller statistical error, allowing for a power-law fit.

DM annihilations into fermions f

- $\mathscr{D}$ can only couple as

$$\mathscr{D} f_L f_R + \text{h.c.} = \mathscr{D} \bar{\Psi}_f \Psi_f$$

with $\Psi_f = (f_L, \bar{f}_R)$ in Dirac notation. It means zero helicity on average, and is typically suppressed by m_f/M.

- $\mathscr{D}_\mu$ can couple as

$$\mathscr{D}_\mu [\bar{f}_L \gamma_\mu f_L] = \mathscr{D}_\mu [\bar{\Psi}_f \gamma_\mu P_L \Psi]$$

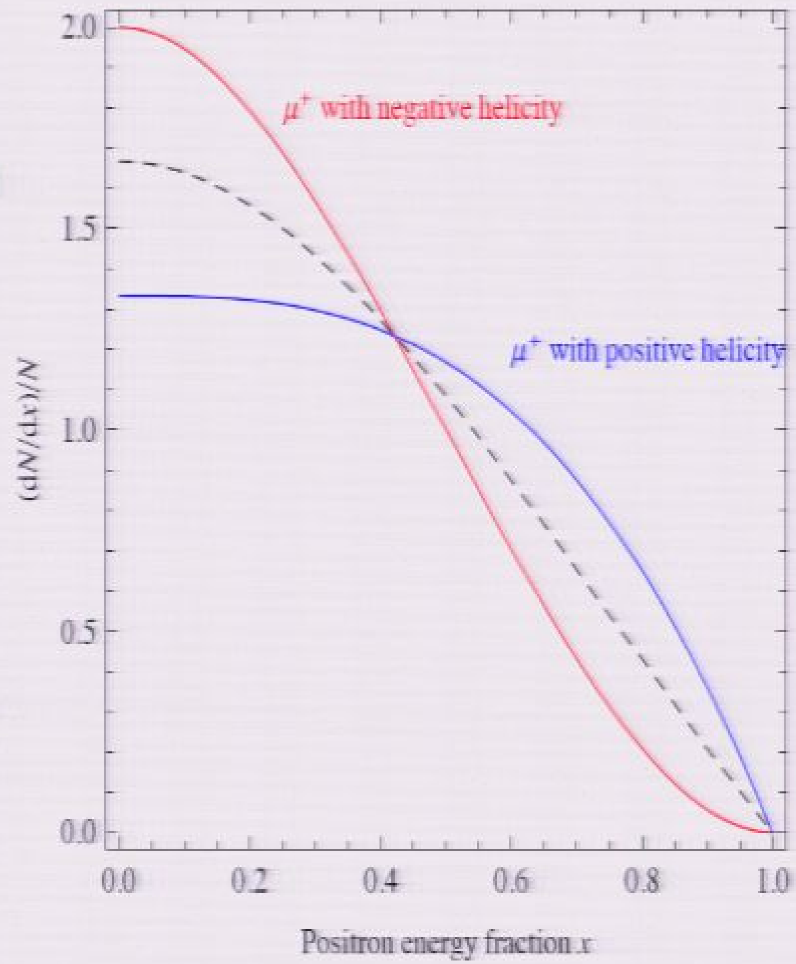
or

$$\mathscr{D}_\mu [\bar{f}_R \gamma_\mu f_R] = \mathscr{D}_\mu [\bar{\Psi}_f \gamma_\mu P_R \Psi]$$

i.e. fermions with Left or Right helicity. Decays like $\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$ give e^+ with

$$dN/dx|_L = 2(1-x)^2(1+2x)$$

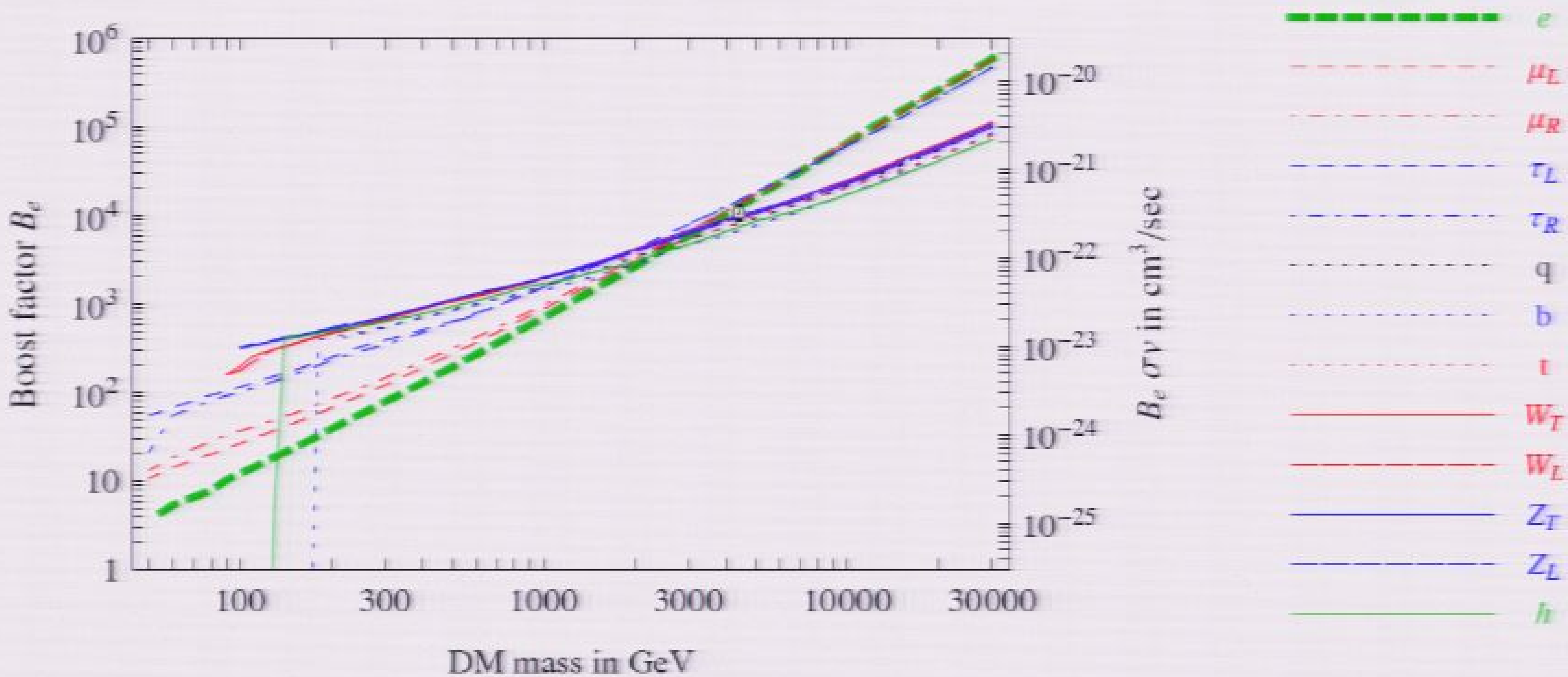
$$dN/dx|_R = 4(1-x^3)/3$$



Fitting procedure

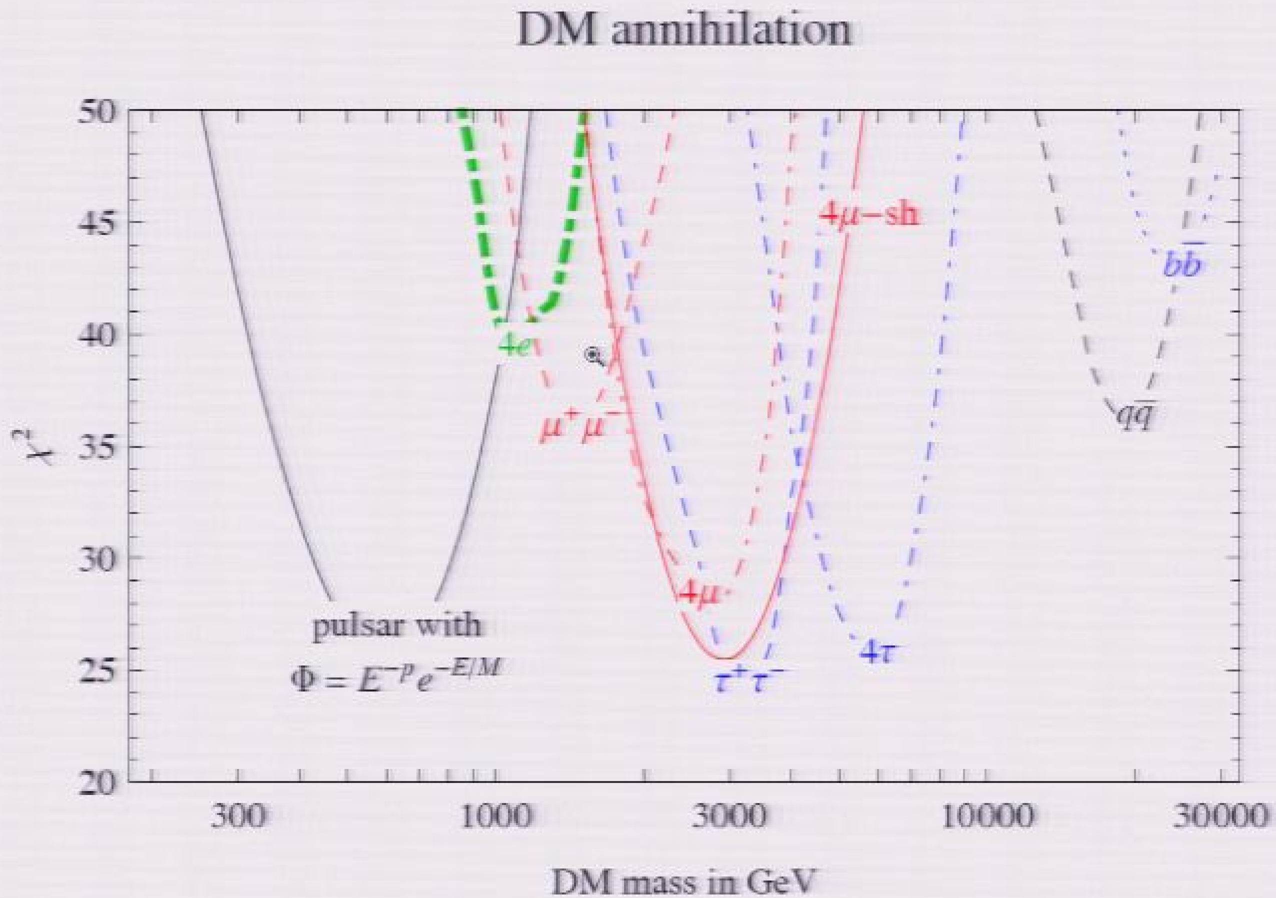
- **PAMELA** and **FERMI systematic uncertainties?**
- multiply each expected e^+, e^-, p^+/p^- **backgrounds** times $A_i E^{p_i}$ with free A_i and $p_i = 0 \pm 0.05$, and marginalize over A_i, p_i.
- **solar modulation** as uncorrelated uncertainty below 20 GeV: $\pm 6\%$ at 10 GeV, $\pm 30\%$ at 1 GeV.
- **DM halo**: marginalize over isoT/NFW/Moore with flat prior.
- **Propagation**: marginalize over MIN/MED/MAX with flat prior. (MED is favored?).
- Statistical techniques: as reviewed in appendix B of hep-ph/0606054.

The σv needed for PAMELA



σv larger than what suggested by cosmology by a factor B_e

Fitting PAMELA e^+ and FERMI $e^+ + e^-$

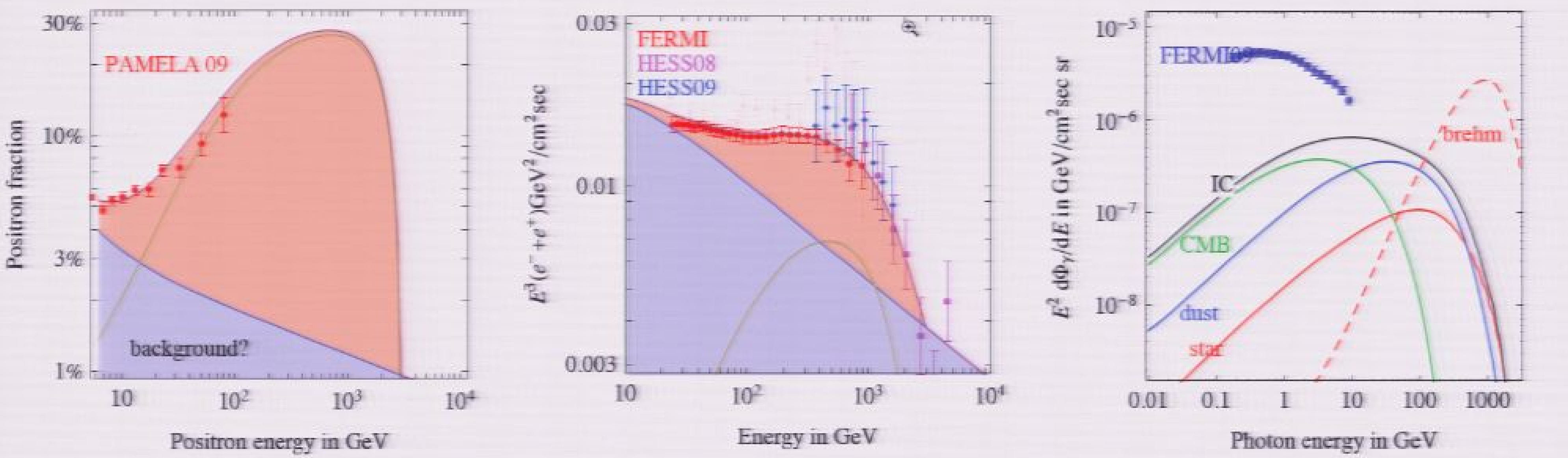


Compatible if DM has TeV mass and annihilates into some leptons.

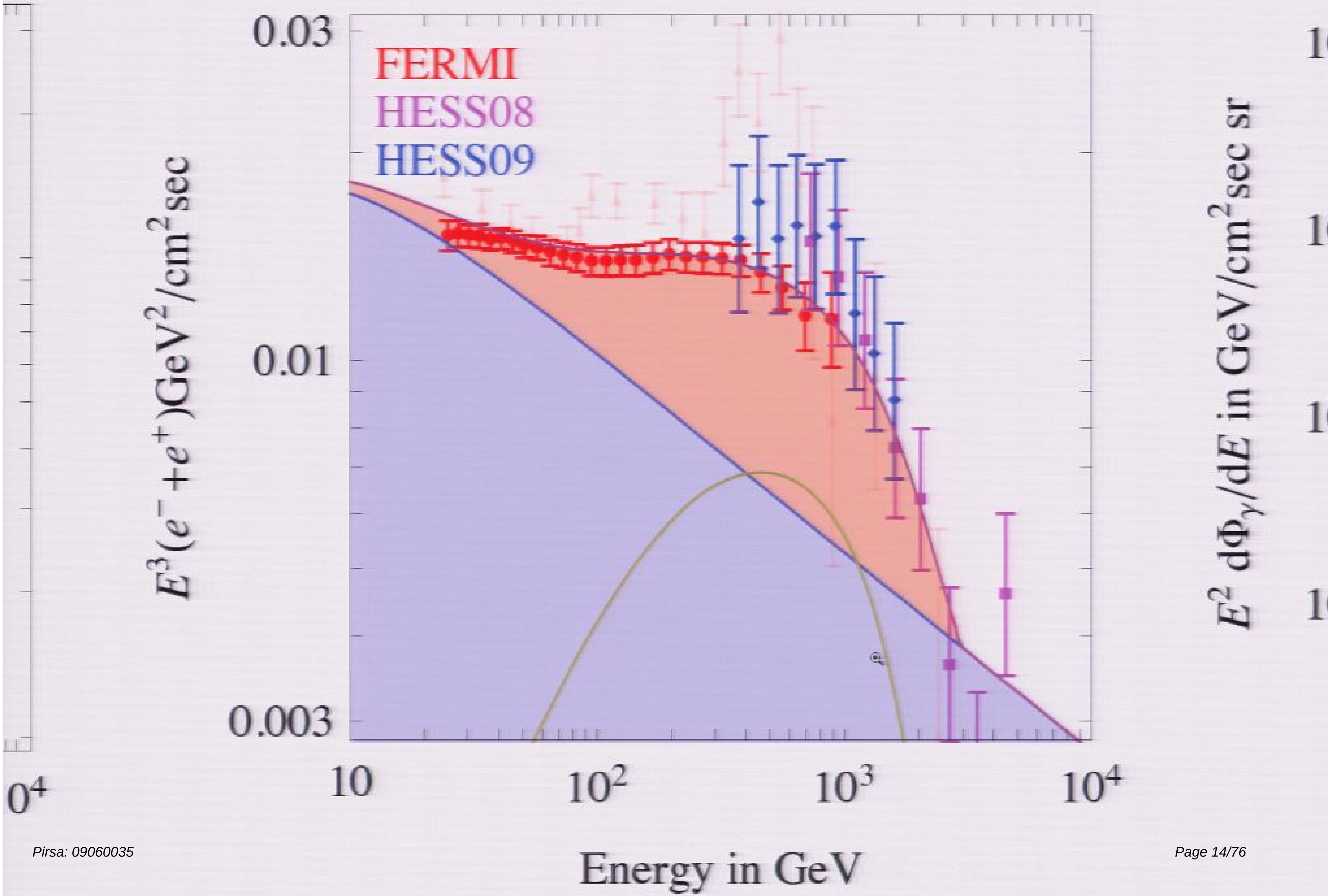
FERMI excludes that PAMELA is due to a DM lighter than about 1 TeV.

Dark Matter identified?

DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.9 \times 10^{-22}\ \text{cm}^3/\text{s}$



(The CDF μ anomaly motivates a hidden-sector that decays into $\tau^+\tau^-$)



0.03
FERMI
HESS08
HESS09
0.01
0.003
$E^3(e^- + e^+)\mathrm{GeV}^2/\mathrm{cm}^2\mathrm{sec}$
$E^2\, d\Phi_\gamma/dE$ in GeV/cm^{2}sec sr
10
10^2
10^3
10^4
Energy in GeV

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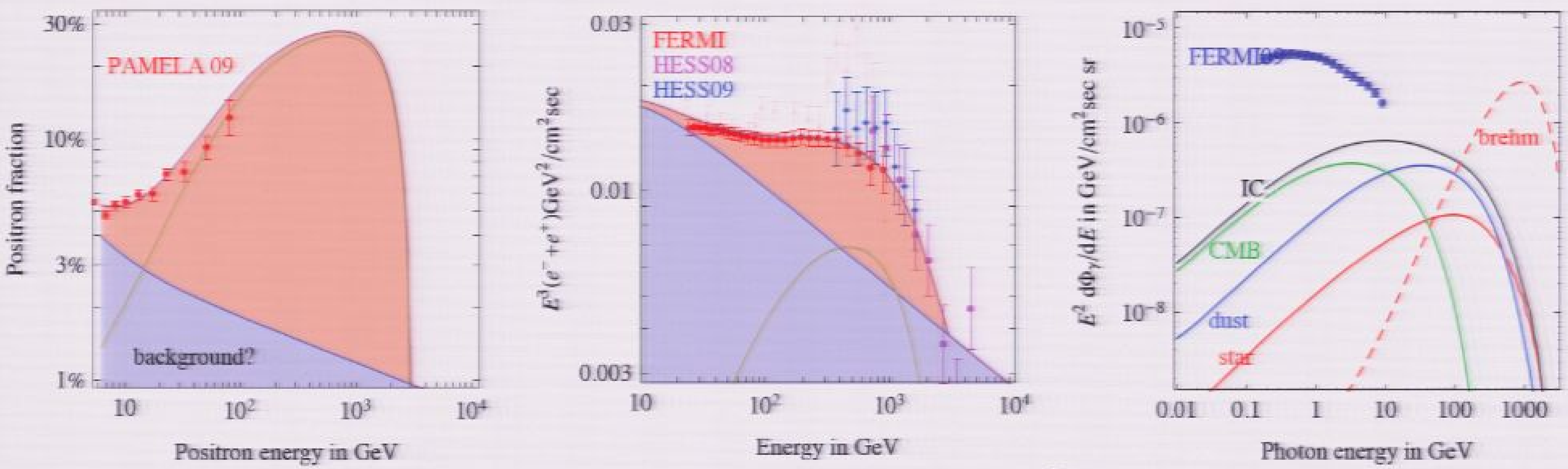

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New Dark Matter models

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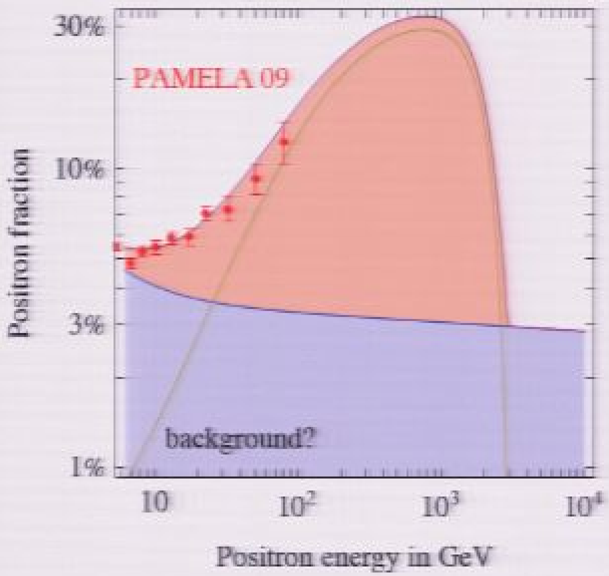

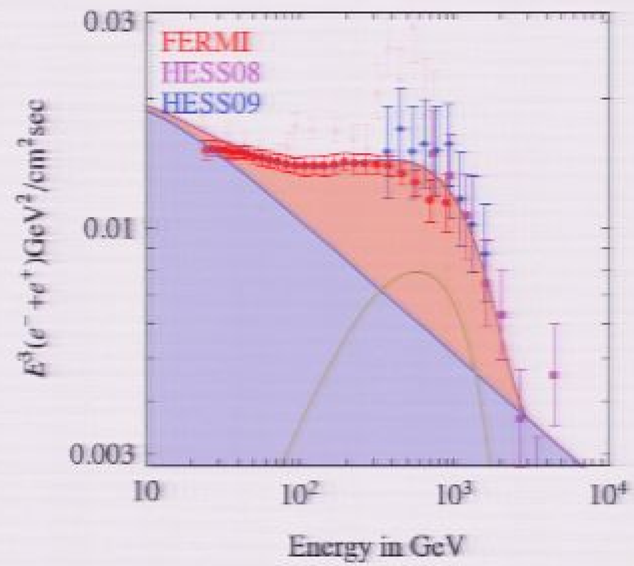

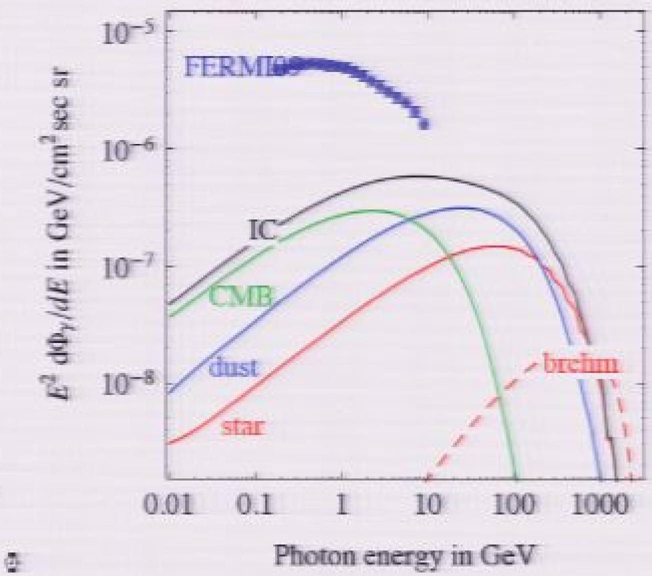

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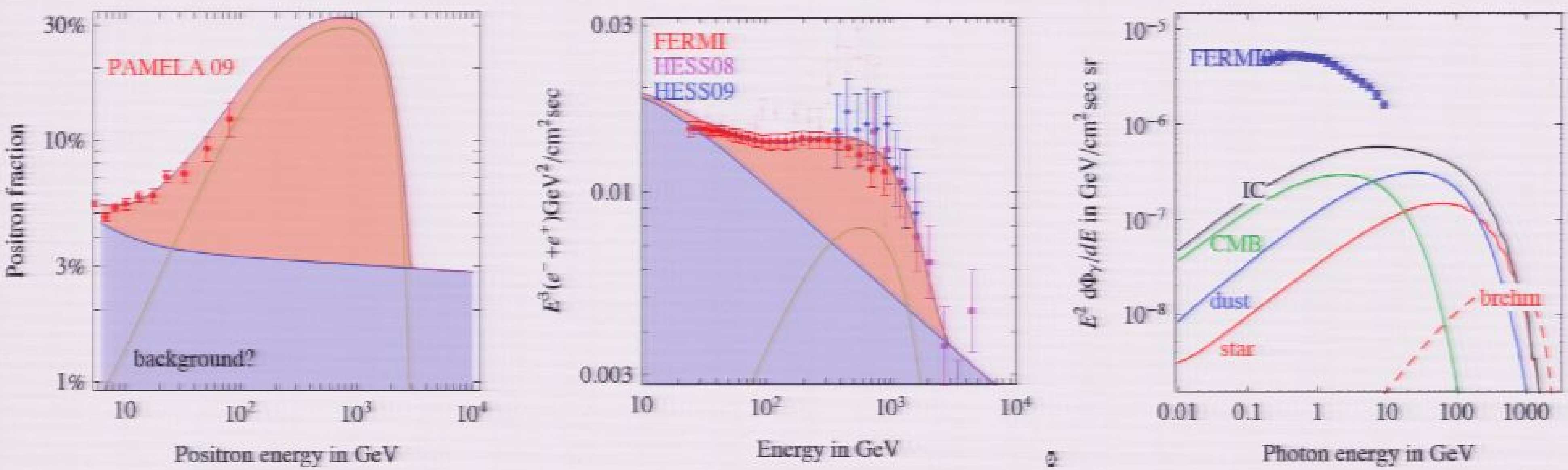

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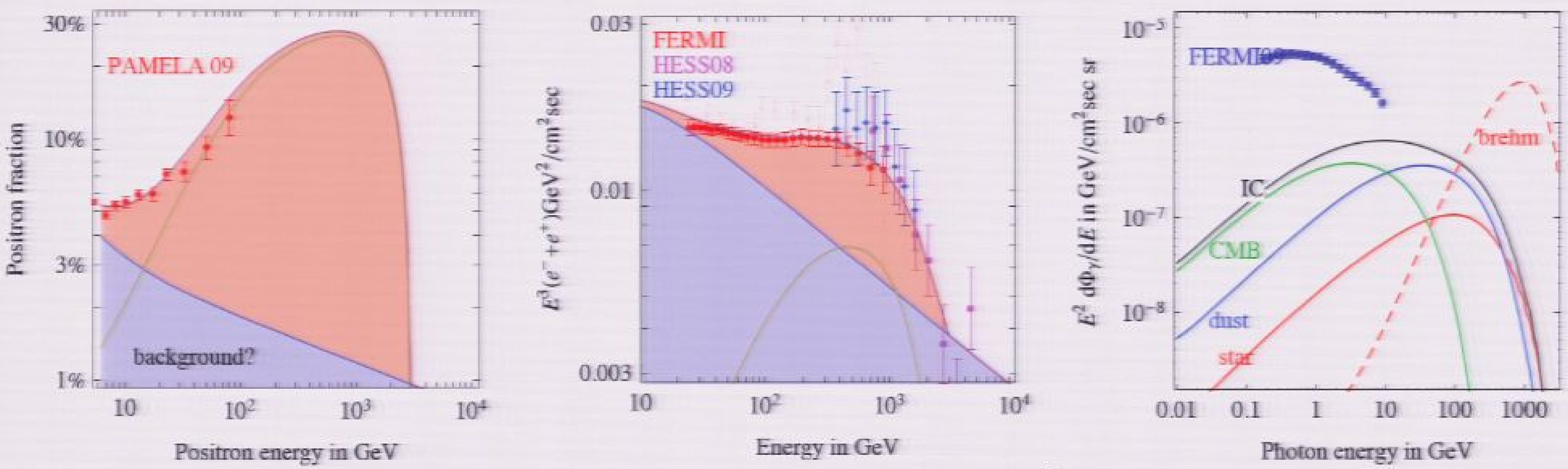

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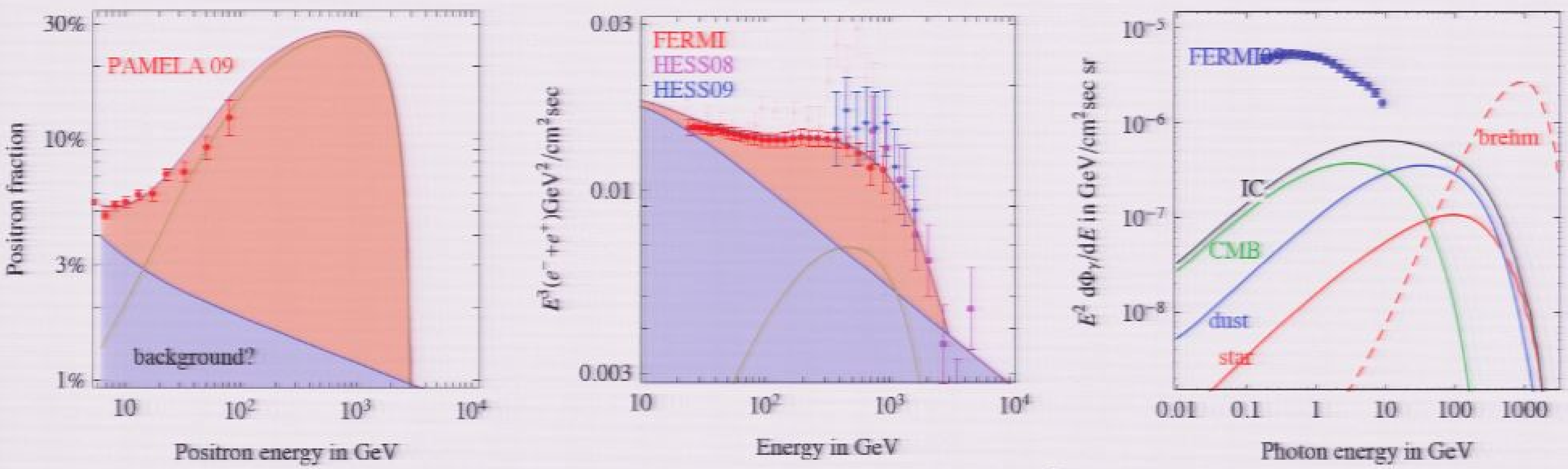

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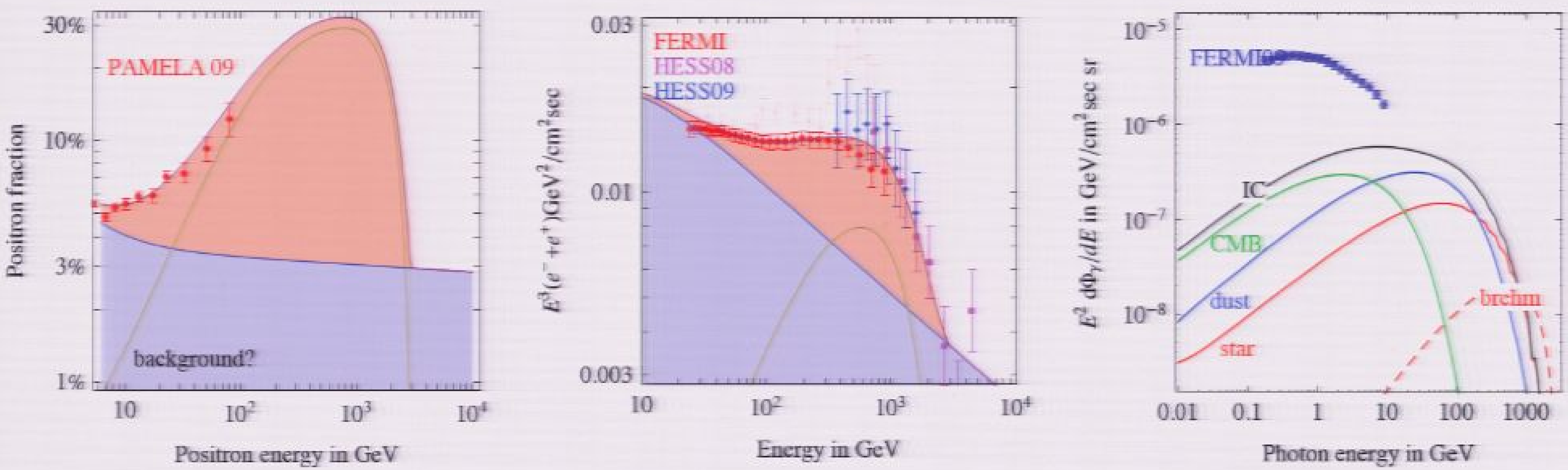

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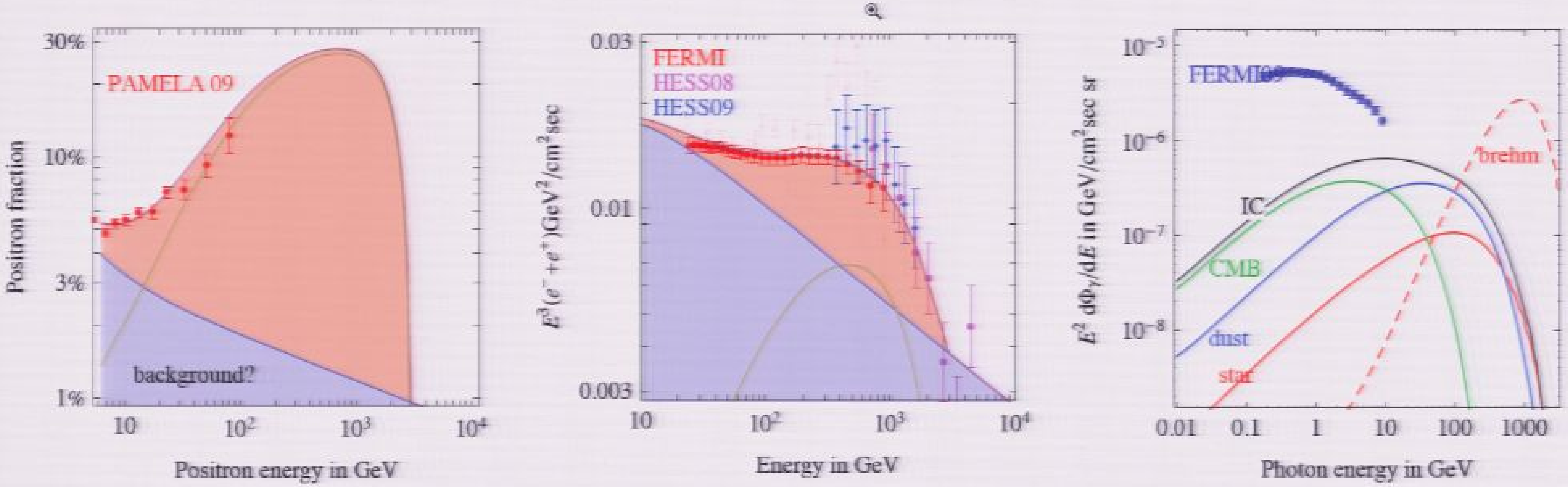

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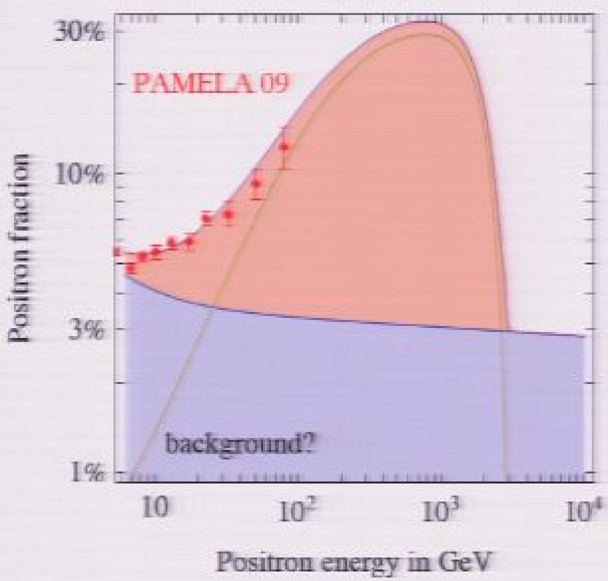

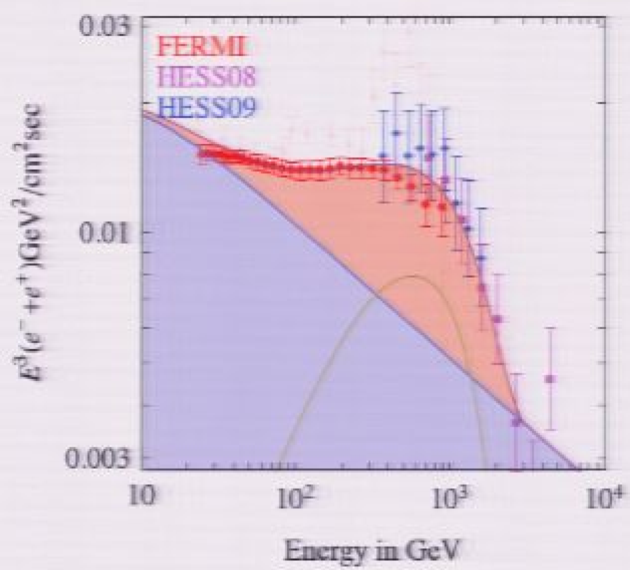

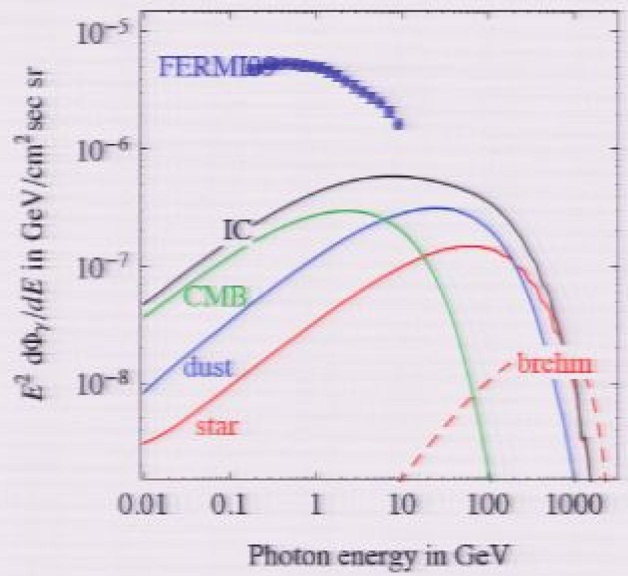

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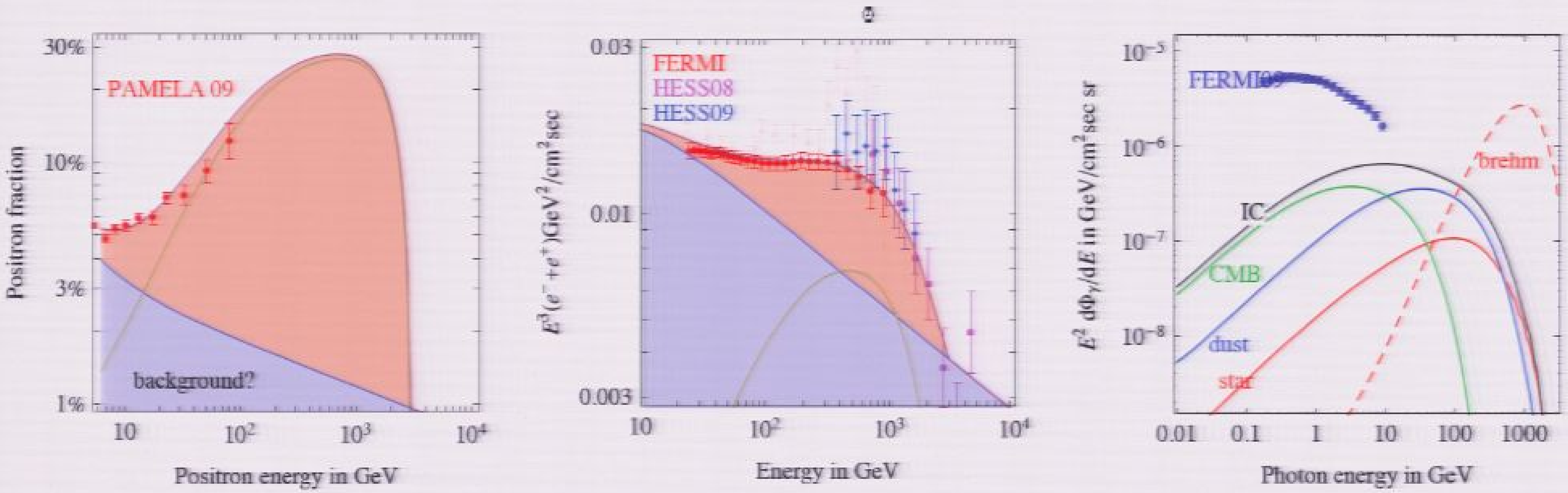

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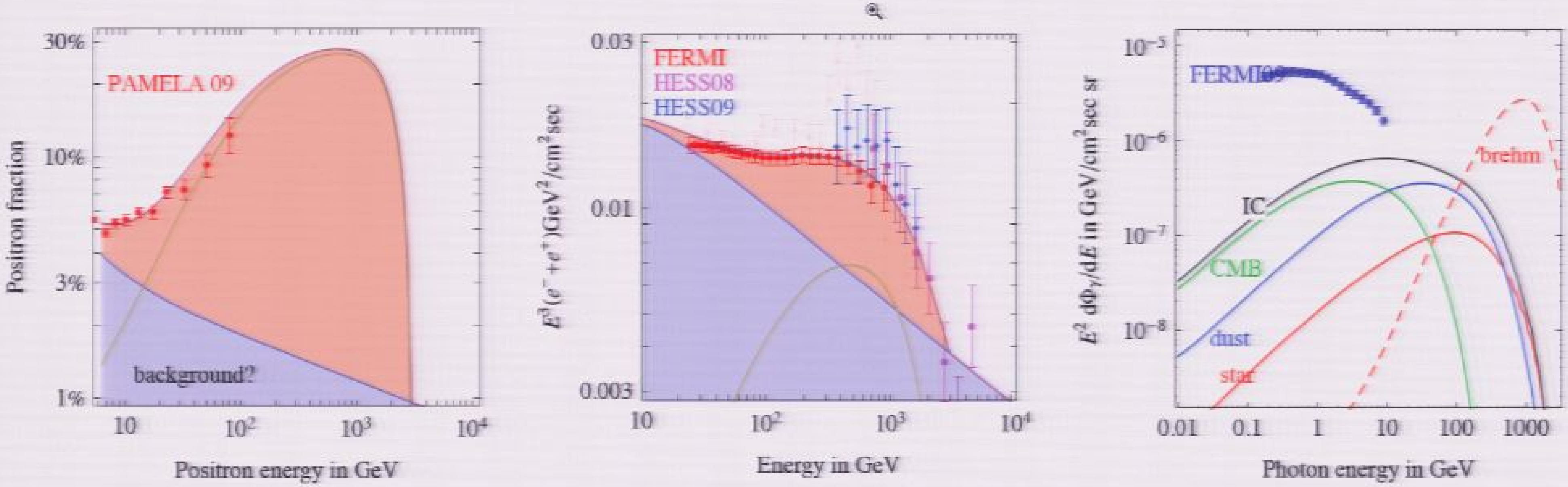

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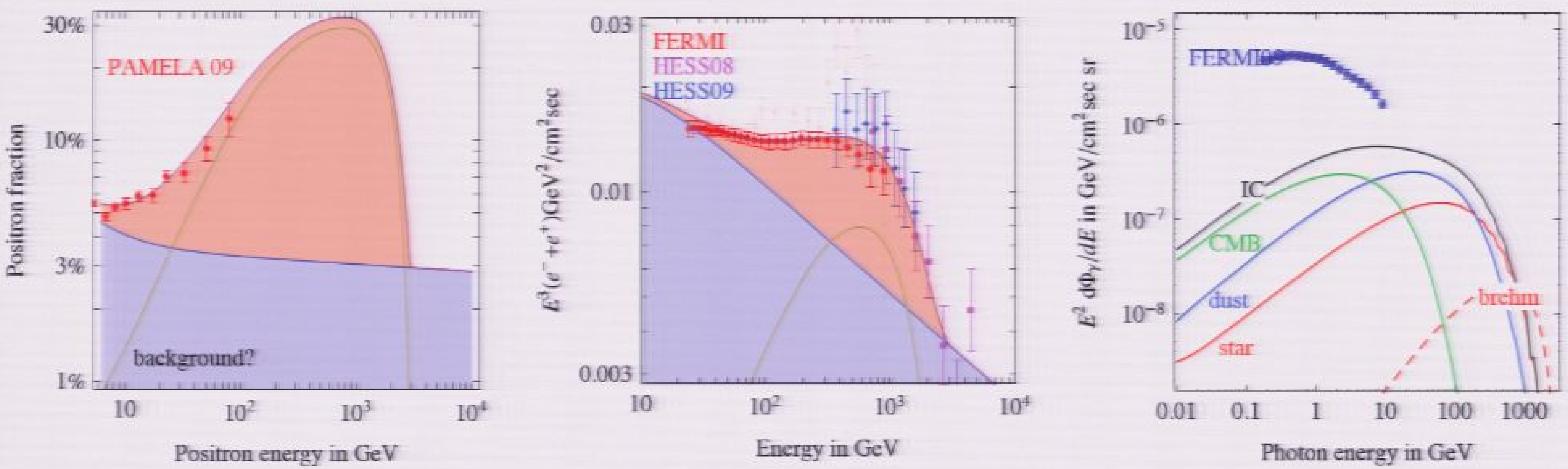

Photons from DM

DM DM $\to \ell^+\ell^-$ is **unavoidably** accompanied by photons:

- **Brehmstralung** from $\ell^\pm$ (if $\ell = \tau$ also $\pi \to \pi^0 \to \gamma\gamma$).
  Largest $E_\gamma \sim M_{\text{DM}}$, probed by HESS.

- **Inverse Compton**: $e^\pm\gamma \to e^\pm\gamma'$ scatterings on CMB and star-light: $\dot{E} \propto u_\gamma$.
  Intermediate $E_{\gamma'} \sim E_\gamma(E_e/m_e)^2 \sim 10\,\text{GeV}$ probed by FERMI.

- **Synchrotron**: $e^\pm$ in the galactic magnetic fit: $\dot{E} \propto u_B = B^2/2$.
  Small $E_\gamma \sim 10^{-6}\,\text{eV}$, probed by radio-observations: Davies, VLT, WMAP.

Problem: γ point to their source, and it is unclear which one is better for DM.
Solution: astrophysicists anyhow like to observe astrophysical backgrounds.

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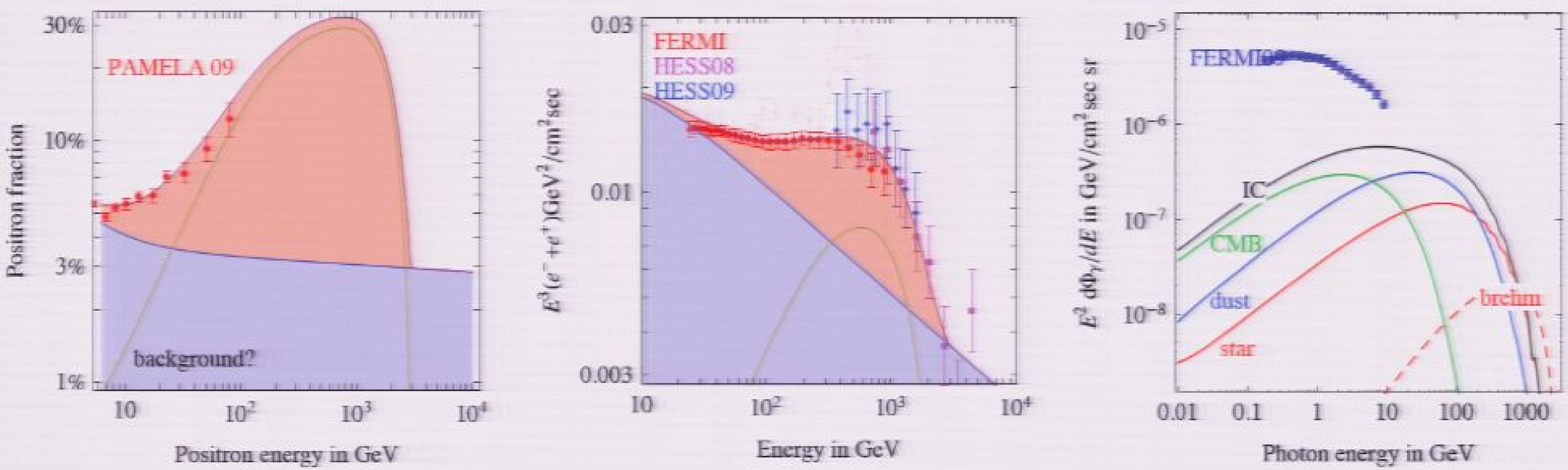

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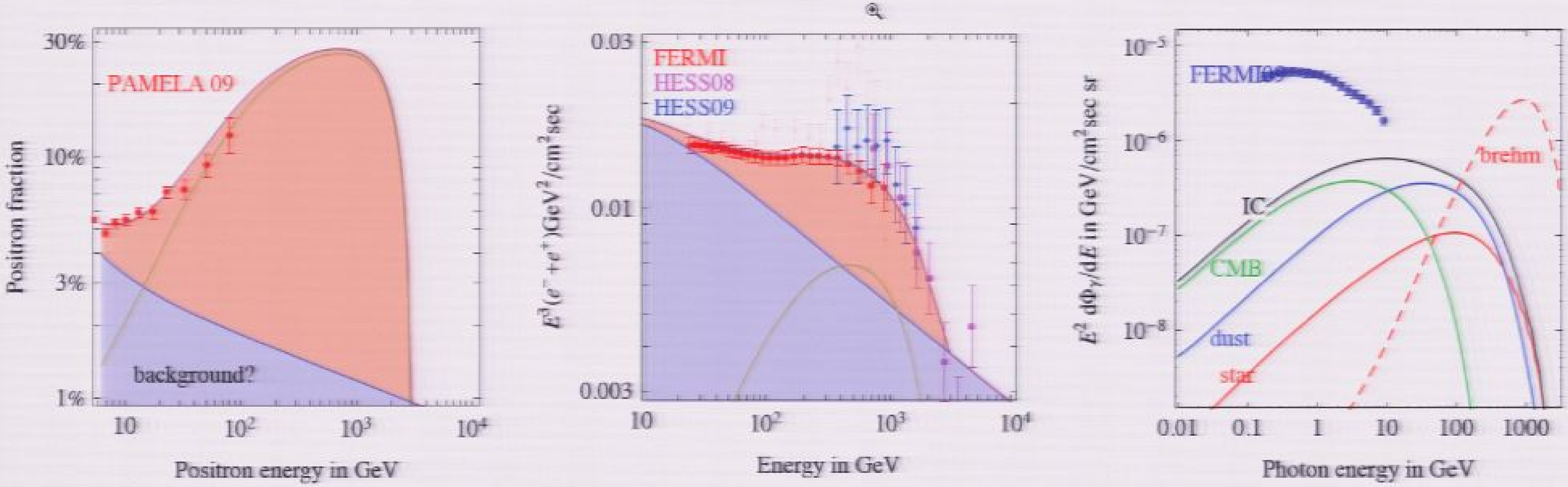

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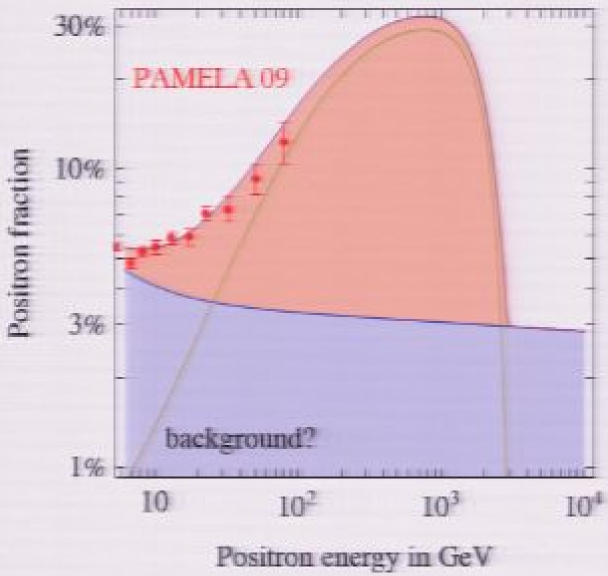

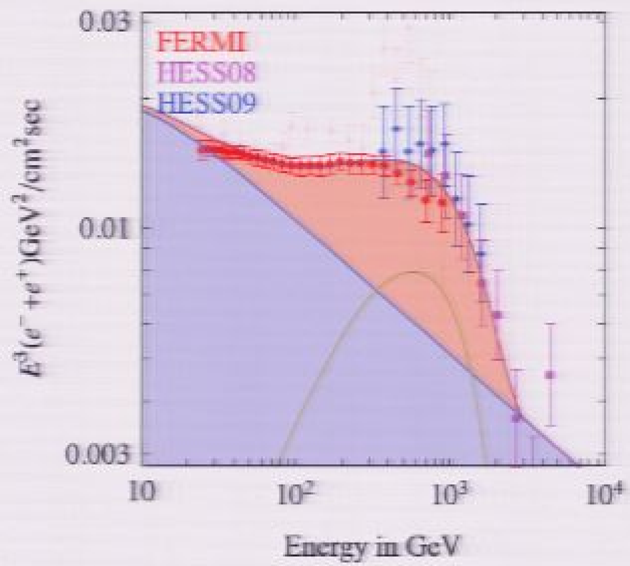

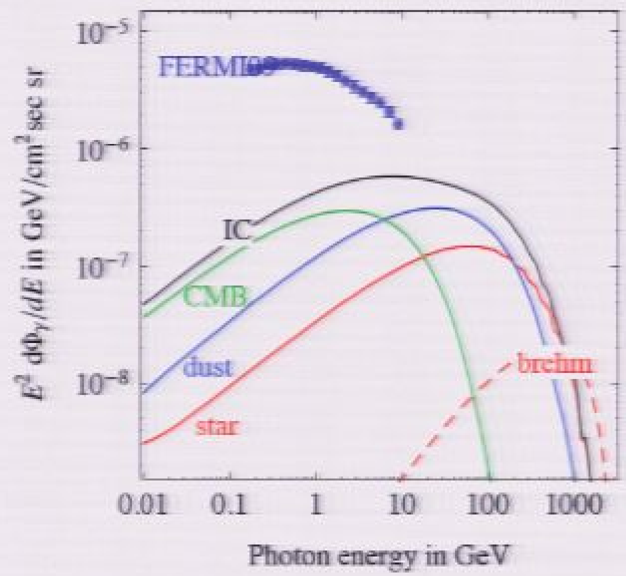

PAMELA vs SUSY & co

- Fit PAMELA with a neutralino at $M \sim 100\,\text{GeV}$ that annihilates into $e^+e^-\gamma$ thanks to a fine-tuned slepton mass, invoking a huuge boost $B_e \sim 10^6$;

- Unnatural SUSY at many TeV with σv enhanced by Sommerfeld;

- SUSY + ad hoc stable new particles. E.g. a $\tilde{\nu}_R$ lighter than M_W and with a large Yukawa $\nu_R LH$ annihilates into L;

- DM vectors or fermions suggested by wUED (would be Universal Extra Dimensions) or by LHT (Little Higgs with non-anomalous T-parity) annihilate $\sim 30\%$ into leptons, but $\sim 70\%$ into q, W.

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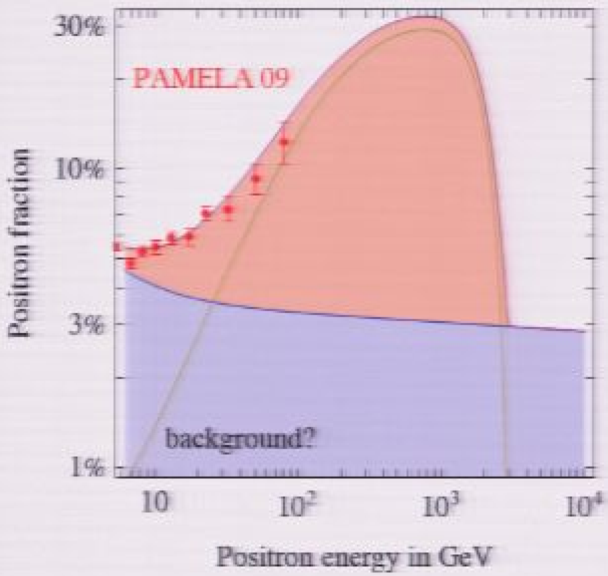

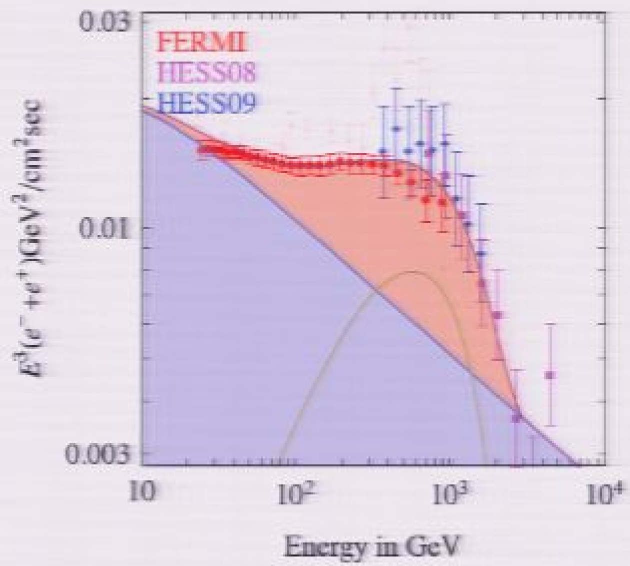

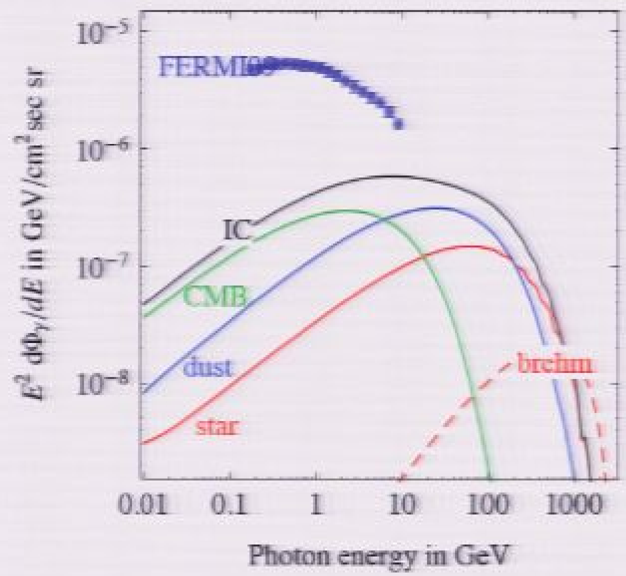

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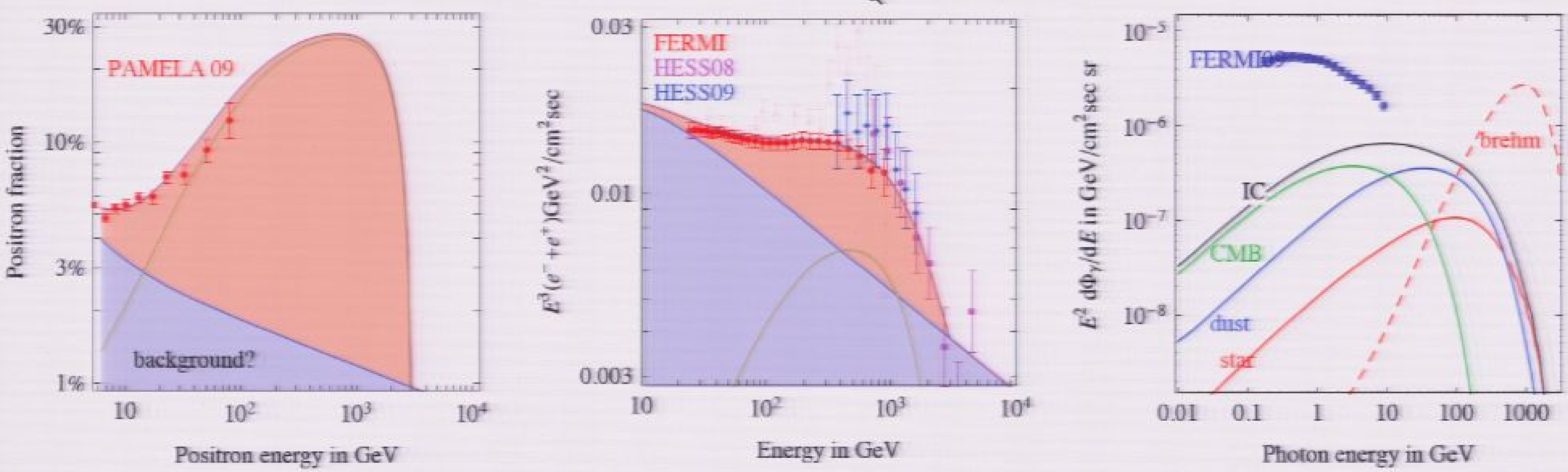

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DM models for PAMELA and FERMI

DM is charged under a dark gauge group, to get the Sommerfeld enhancement.

For PAMELA. We proposed that DM as a Dirac fermion with $M \approx 2\,\mathrm{TeV}$ and charge $q \approx 2$ under $L_\mu - L_\tau$ (suggested by $\theta_{23} \approx \pi/4$), gauged with $\alpha_V \approx 1/50$ (giving the correct thermal abundance) and mass $M_V \approx M_Z$, giving the $g_\mu - 2$ anomaly + Sommerfeld. At 1 loop $L_\mu - L_\tau$ mixes with the photon: $\theta \sim e g_V \ln(m_\tau/m_\mu)/6\pi^2 \sim 0.005$. Direct: $\sigma_{\rm SI} = 4\pi q^2 \alpha_V \alpha m_N^2 \theta^2 / M_V^4 \approx 10^{-42}\,\mathrm{cm}^2$

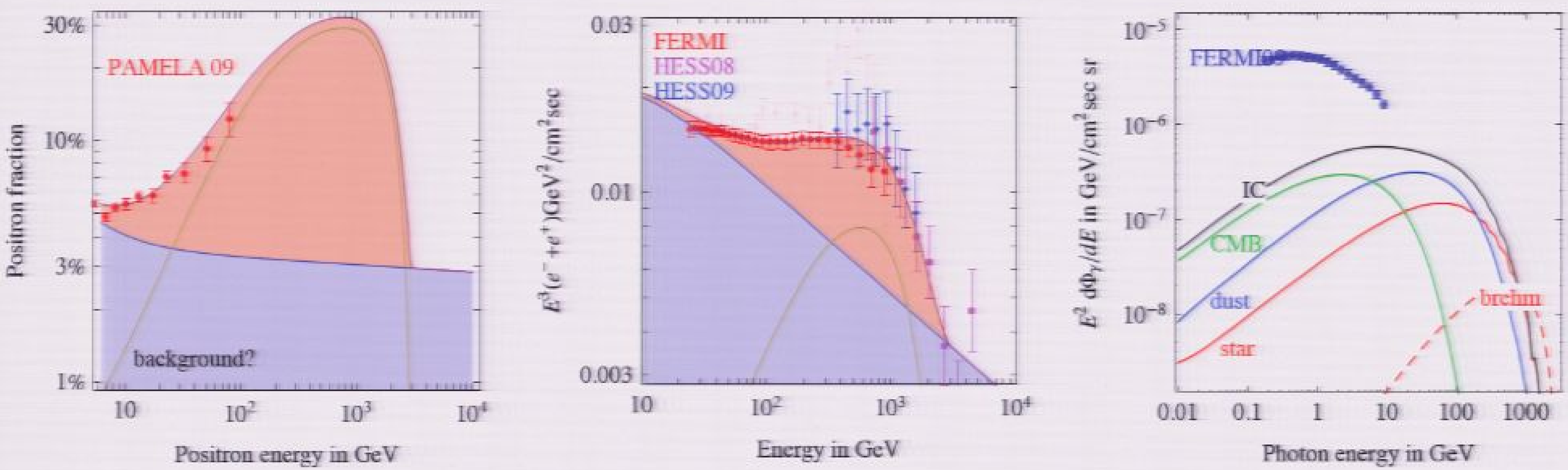
For PAMELA, ATIC (×), DAMA (?), INTEGRAL (×?) and EGRET (×?). [Arkani-Hamed, Weiner et al.] proposed that **the new vector is light** $m_V \lesssim m_N$ and couples to SM particles only via a mixing with the photon,

$$\theta \sim e g_V \ln(M_{\rm Pl}/M_?)/6\pi^2 \sim 10^{-2\div 3}$$

so that: • V automatically decays into light leptons $e, \mu, \pi^\pm$; • V gives a small $\delta a_\mu \sim \alpha\theta^2 (m_\mu/M_V)^2/\pi \sim 10^{-9}$ • V gives a 10^{-6} too large elastic $\sigma_{\rm SI}$. **If the DM gauge group is non abelian** and DM has multiple components with 100 keV ($\overset{?}{\sim} \alpha_V M_V$) mass splittings, one can instead get an **inelastic** $\sigma_{\rm dir}$ that can (?) explain DAMA

New Dark Matter models

DM with $M = 3.$ TeV that annihilates into 4μ with $\sigma v = 8.4 \times 10^{-23}$ cm^3/s



3

Bounds from γ, ν indirect detection

3

Bounds from γ, ν indirect detection

Photons from DM

DM DM $\to \ell^+\ell^-$ is **unavoidably** accompanied by photons:

- **Brehmstralung** from $\ell^\pm$ (if $\ell = \tau$ also $\tau \to \pi^0 \to \gamma\gamma$).
  Largest $E_\gamma \sim M_{\rm DM}$, probed by HESS.

- **Inverse Compton**: $e^\pm\gamma \to e^\pm\gamma'$ scatterings on CMB and star-light: $\dot{E} \propto u_\gamma$.
  Intermediate $E_{\gamma'} \sim E_\gamma(E_e/m_e)^2 \sim 10\,\text{GeV}$ probed by FERMI.

- **Synchrotron**: $e^\pm$ in the galactic magnetic fit: $\dot{E} \propto u_B = B^2/2$.
  Small $E_\gamma \sim 10^{-6}\,\text{eV}$, probed by radio-observations: Davies, VLT, WMAP.

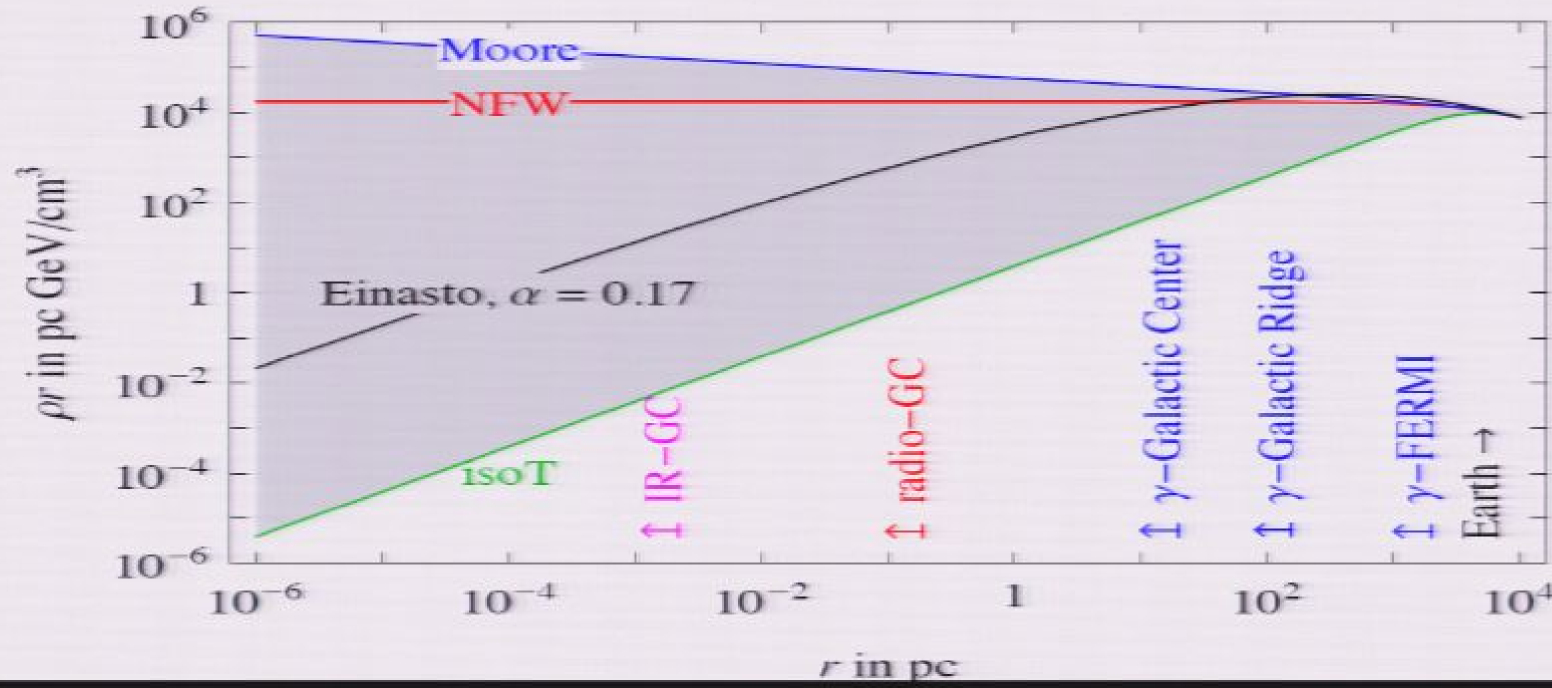
Problem: γ point to their source, and it is unclear which one is better for DM.
Solution: astrophysicists anyhow like to observe astrophysical backgrounds.

γ from brehmstralung

$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{24\pi}\frac{r_\odot\, \rho_\odot^2}{M_{\rm DM}^2} J \langle\sigma v\rangle \frac{dN_\gamma}{dE}, \qquad J = \int_{\rm line-of-sight} \frac{ds}{r_\odot}\left(\frac{\rho(r)}{\rho_\odot}\right)^2$$

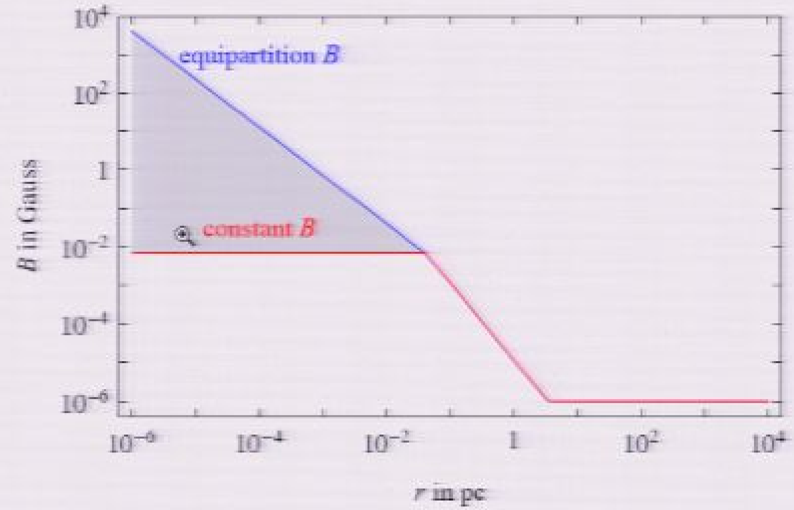
$\langle J\rangle_{\Delta\Omega} =$

NFW	Einasto	isoT/cored	region	$\Delta\Omega$
14700	7600	14	Galactic Center	$1\cdot 10^{-5}$
2400	3000	14	Galactic Ridge	$3\cdot 10^{-4}$
1000	–	140	Sagittarius dSph	$2\cdot 10^{-5}$



Radio observations

Around the GC magnetic fields B contain more energy than light, diffusion and advection seem negligible, so all the $e^{\pm}$ energy E goes into synchrotron radiation. The unknown B only determines the maximal ν_{syn}:



$$\frac{dW_{\text{syn}}}{d\nu} \approx \frac{2e^3 B}{3m_e}\delta\left(\frac{\nu}{\nu_{\text{syn}}} - 1\right) \qquad \text{where} \qquad \nu_{\text{syn}} = \frac{eBE^2}{4\pi m_e^3} = 1.4\,\text{MHz}\frac{B}{\text{G}}\left(\frac{p}{m_e}\right)^2.$$

Davies 1976 oservations at the lower $\nu = 0.408\,\text{GHz}$ give the robust and dominant bound as the observed GC radio-spectrum is harder than synchrotron:

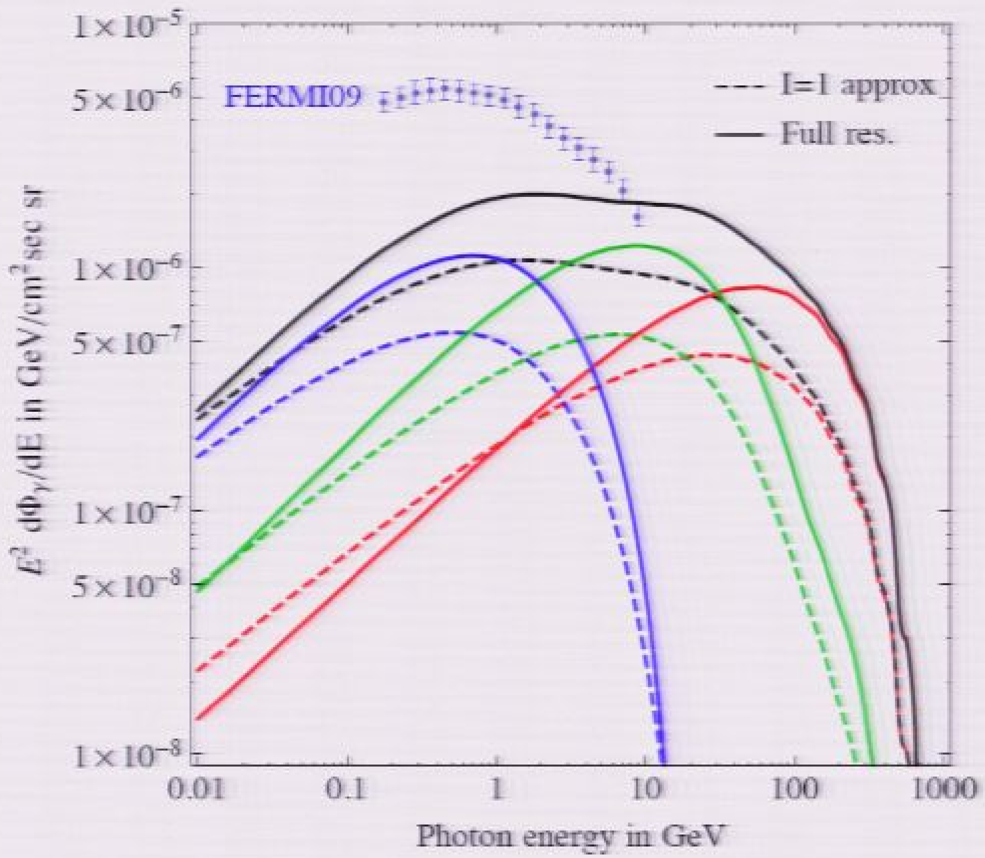
$$\nu\frac{dW_{\text{syn}}}{d\nu} = \frac{\sigma v}{2M^2}\int_{4'' \text{ cone}} dV\ \rho^2\ E(\nu)\ N_e(E(\nu)) < 4\pi r_{\odot}^2 \times 2\cdot 10^{-16}\,\frac{\text{erg}}{\text{cm}^2\,\text{s}}$$

BIG uncertainty in the DM density ρ at 1pc from the GC: NFW or ...?

Inverse Compton and FERMI

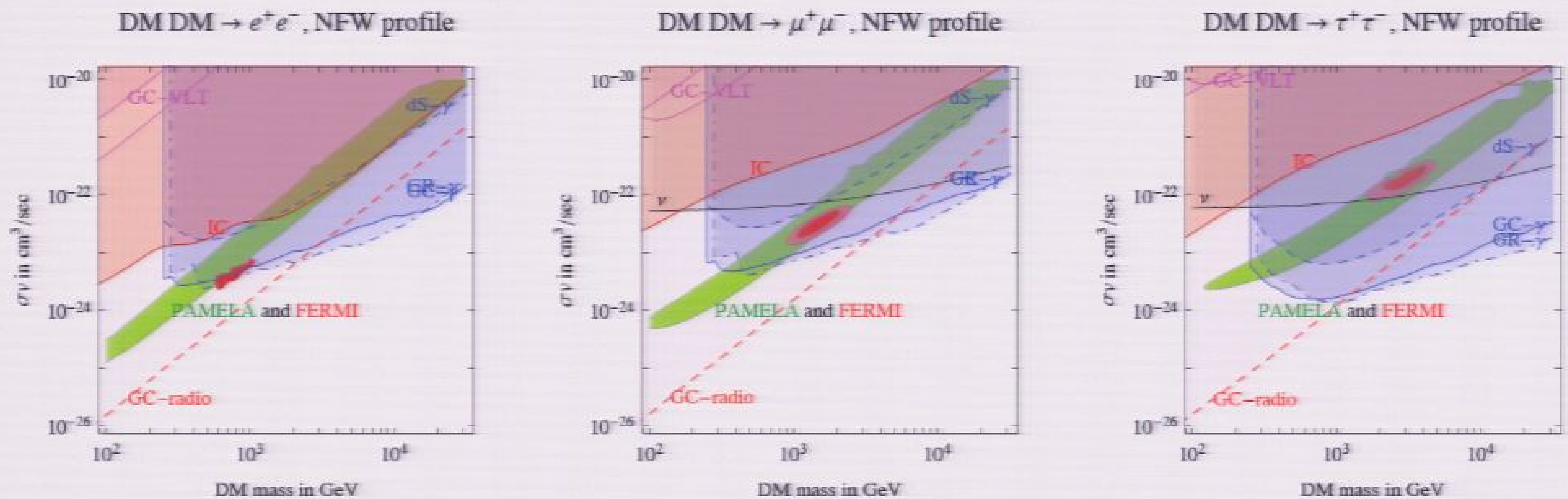
A fraction $u_\gamma/u_B \sim 1$ of the $e^\pm$ energy goes into $e\gamma \to e'\gamma'$.
Initial γ: $E_\gamma \sim$ eV from star-light and $E_\gamma \sim$ meV from CMB.
Final γ: $E_{\gamma'} \sim E_\gamma (E_e/m_e)^2 \sim 10\,\text{GeV}$. IC dominates of brehms at lower E.

EGRET excess not confirmed by FERMI, that agrees with astro background.
FERMI data shown only below 10 GeV, away from GC ($10^\circ <$ latitude $< 20^\circ$).



$e^{\pm}$ signals vs γ, ν bounds

Assuming NFW, **conservative** bounds from HESS γ observations of the Galactic Center, Galactic Ridge, Sagittarius Dwarf and from radio observations of the GC exclude the green (allowed by PAMELA) and red region (+FERMI):



(Way out: Sommerfeld × boosts can enhance GC γ less than $e^{\pm}$?)

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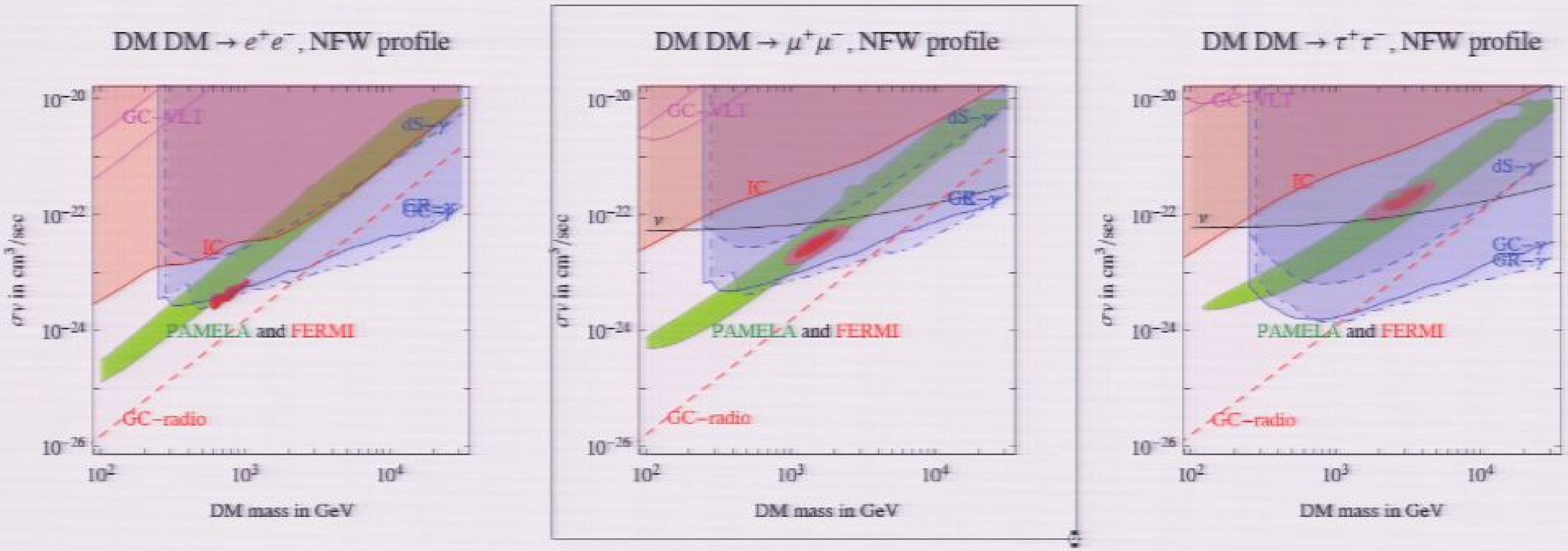

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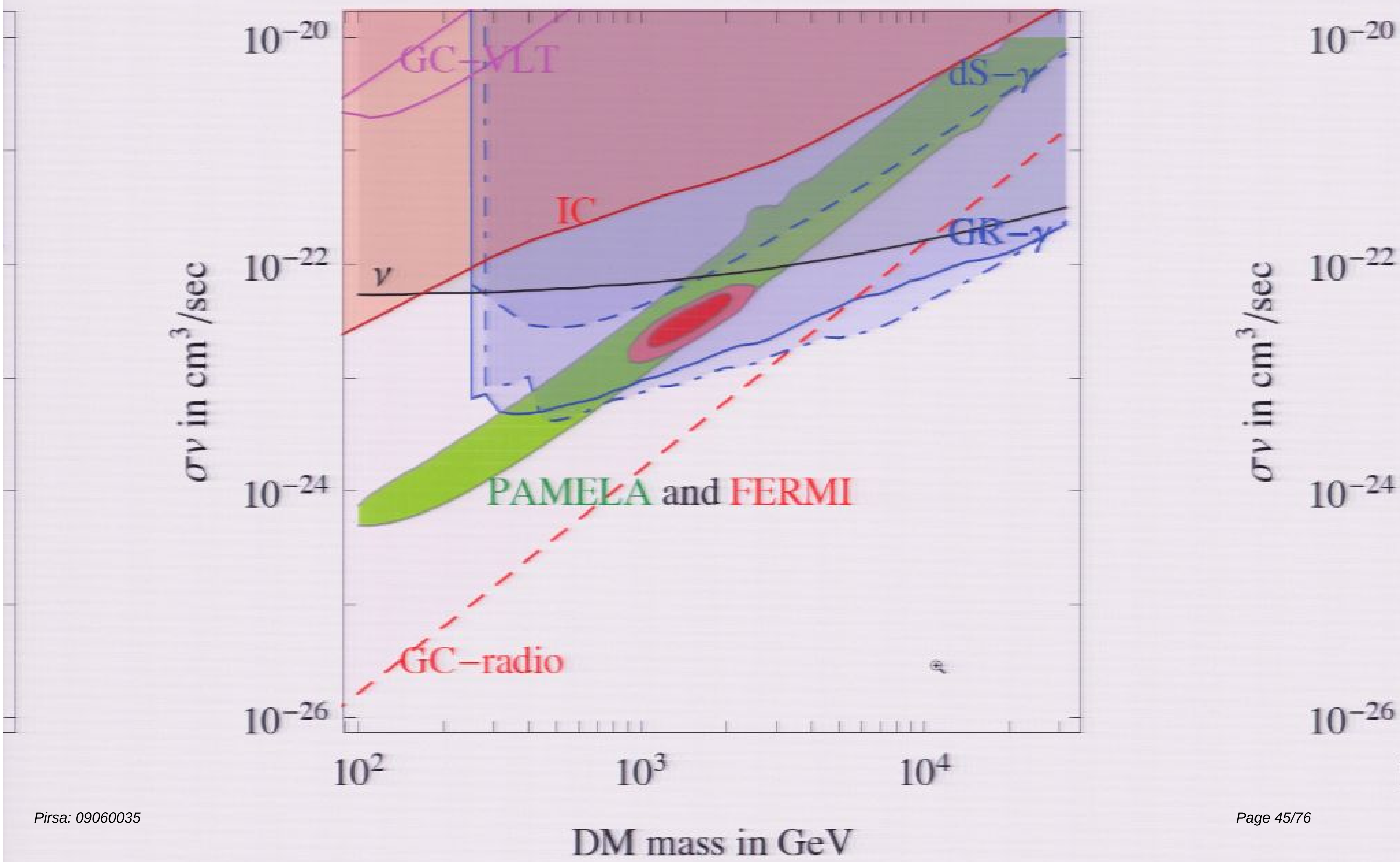
DM DM → $\mu^+\mu^-$, NFW profile



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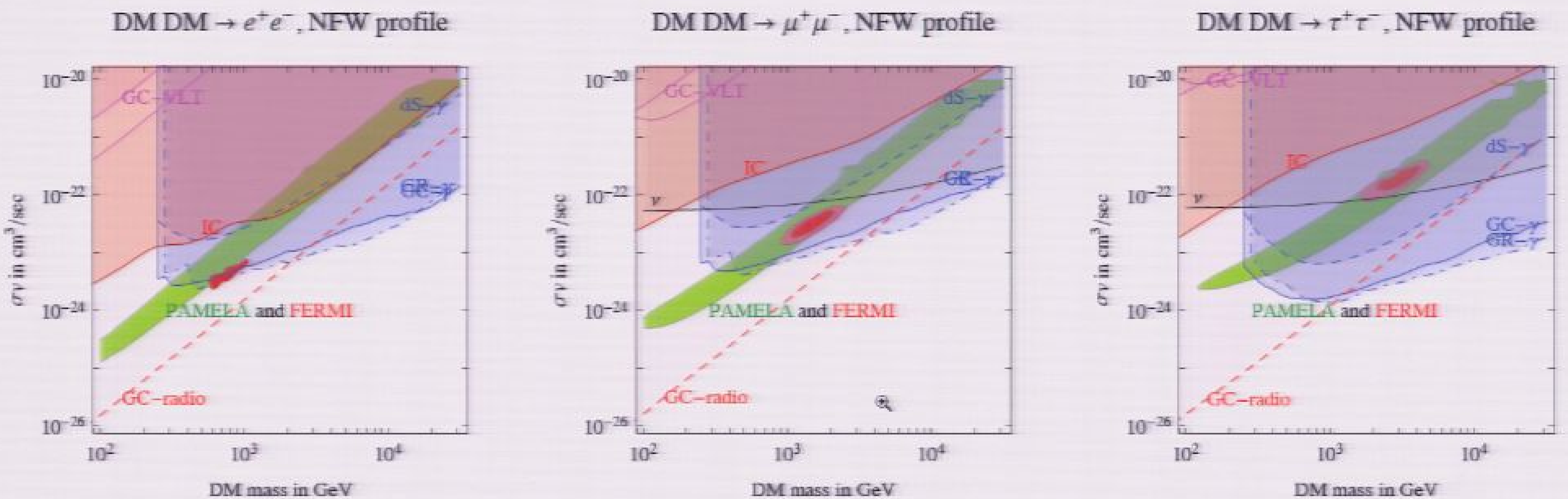

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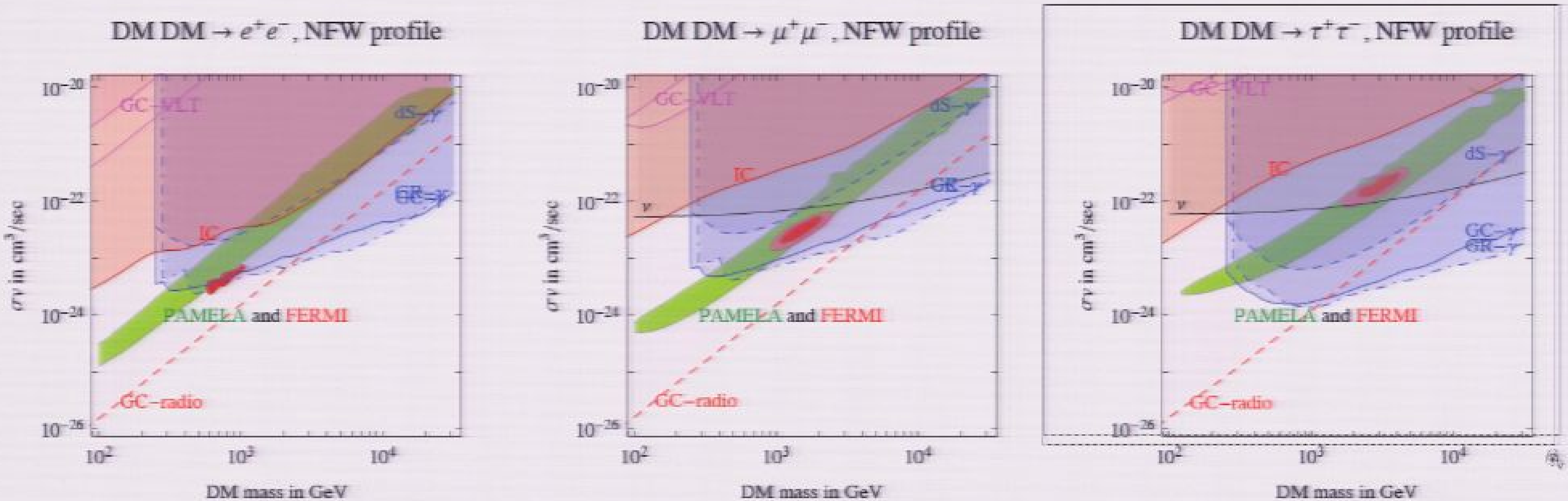

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profile

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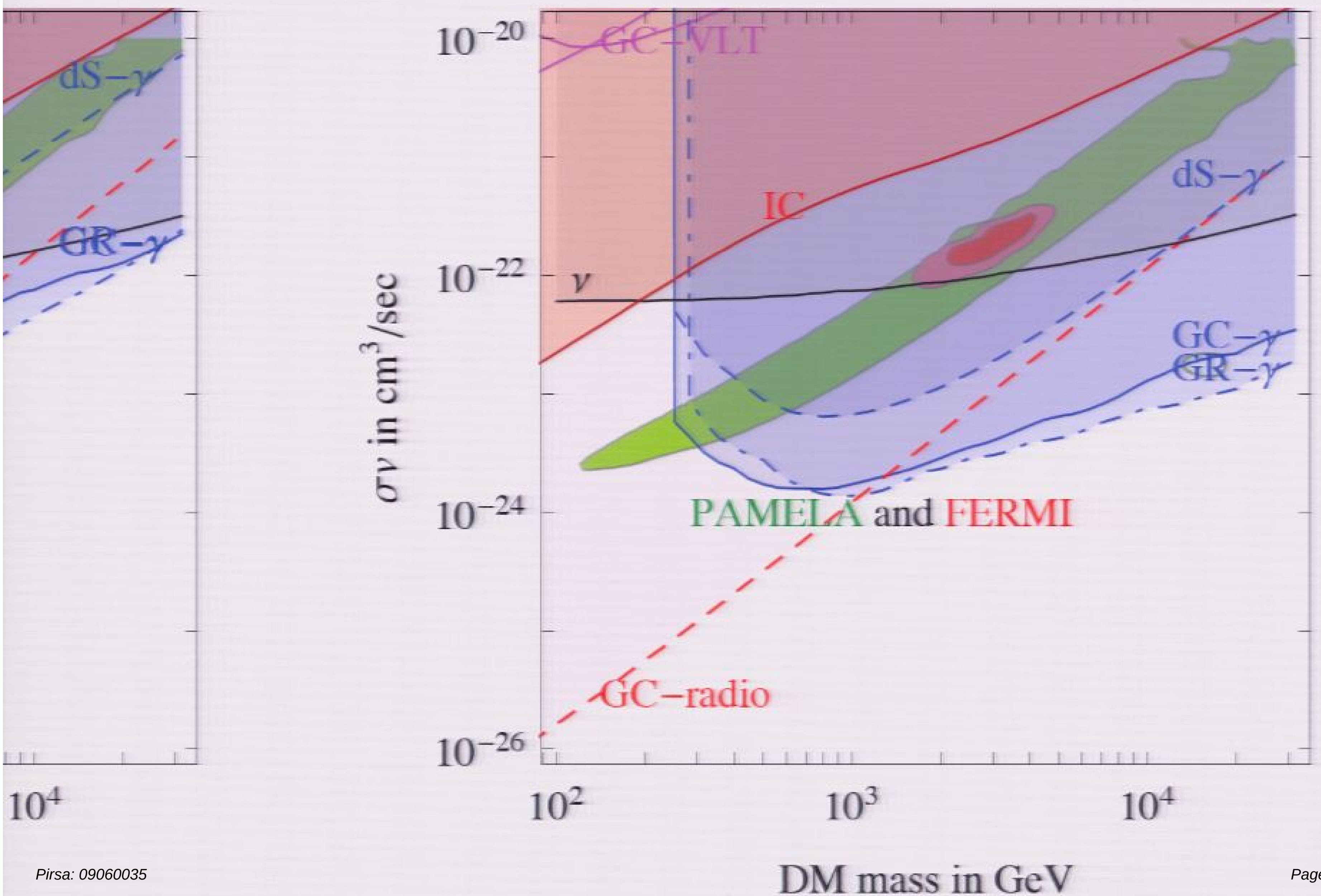

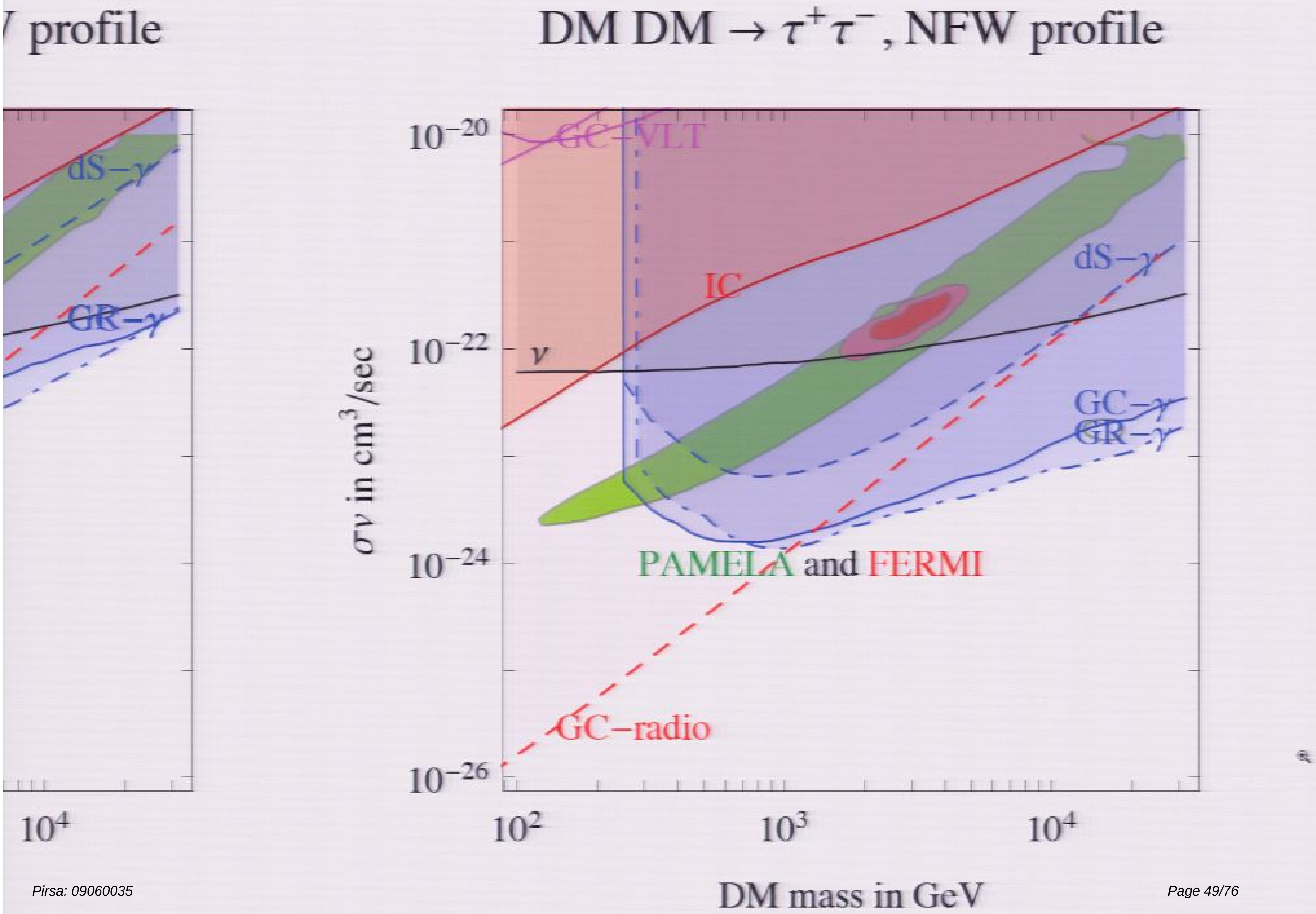

/ profile
dS−γ
GR−γ
10^4
DM DM → $\tau^+\tau^-$, NFW profile
GC−VLT
IC
ν
dS−γ
GC−γ
GR−γ
PAMELA and FERMI
GC−radio
10^{-20}
10^{-22}
10^{-24}
10^{-26}
σv in cm^3/sec
10^2
10^3
10^4
DM mass in GeV

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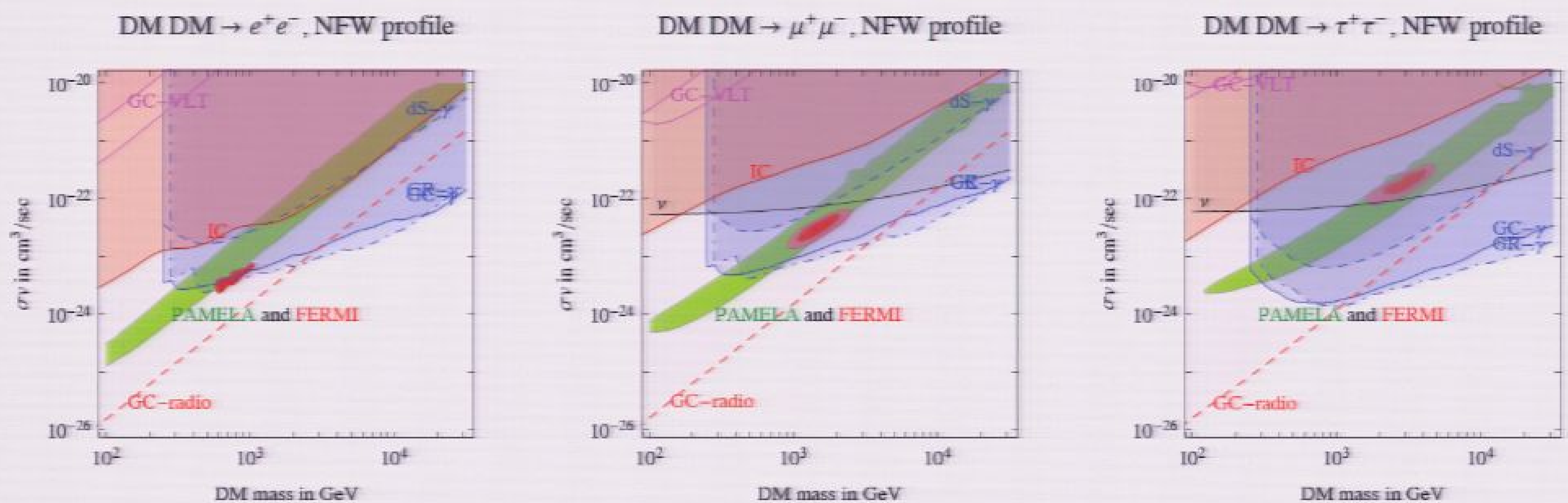

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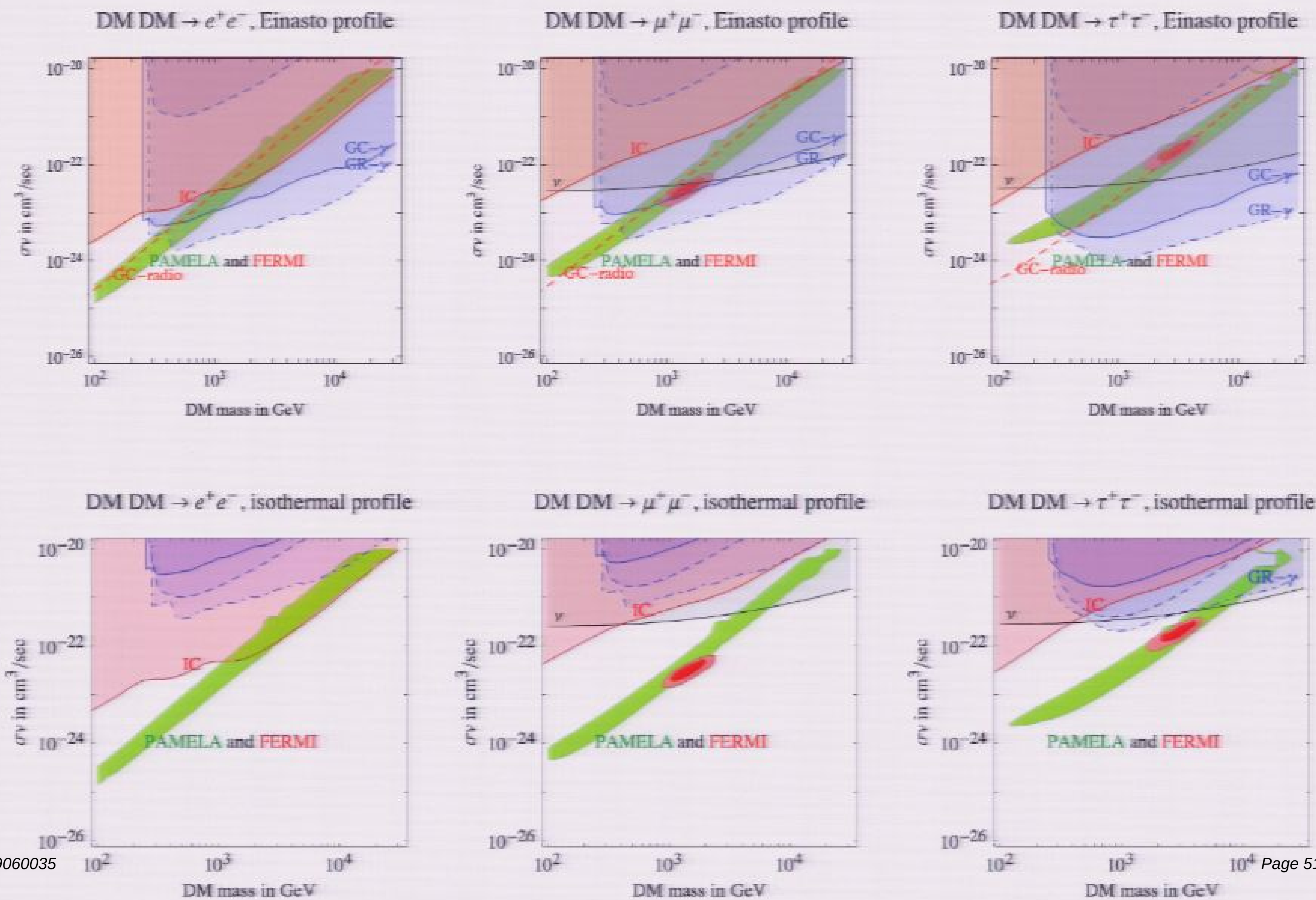

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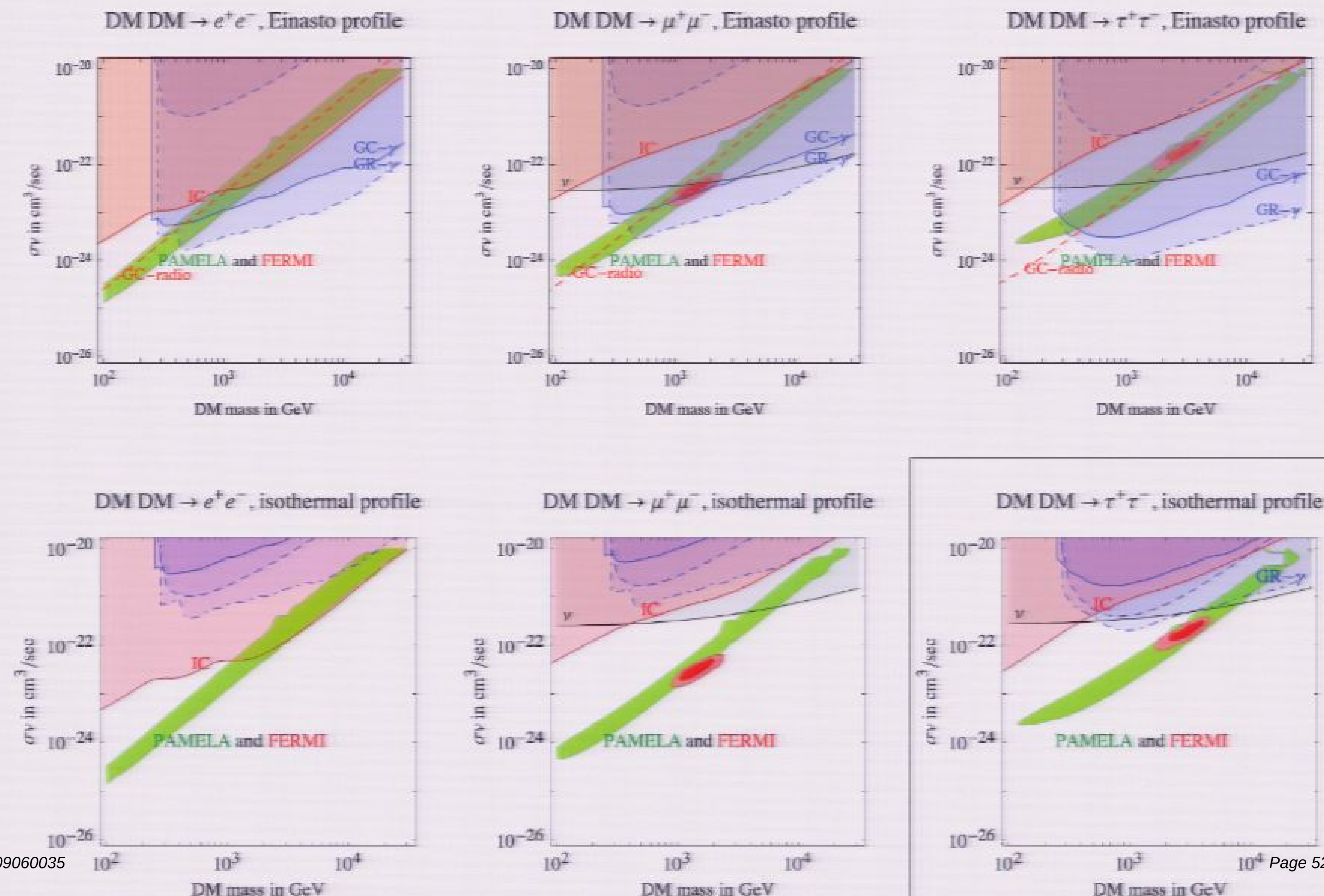
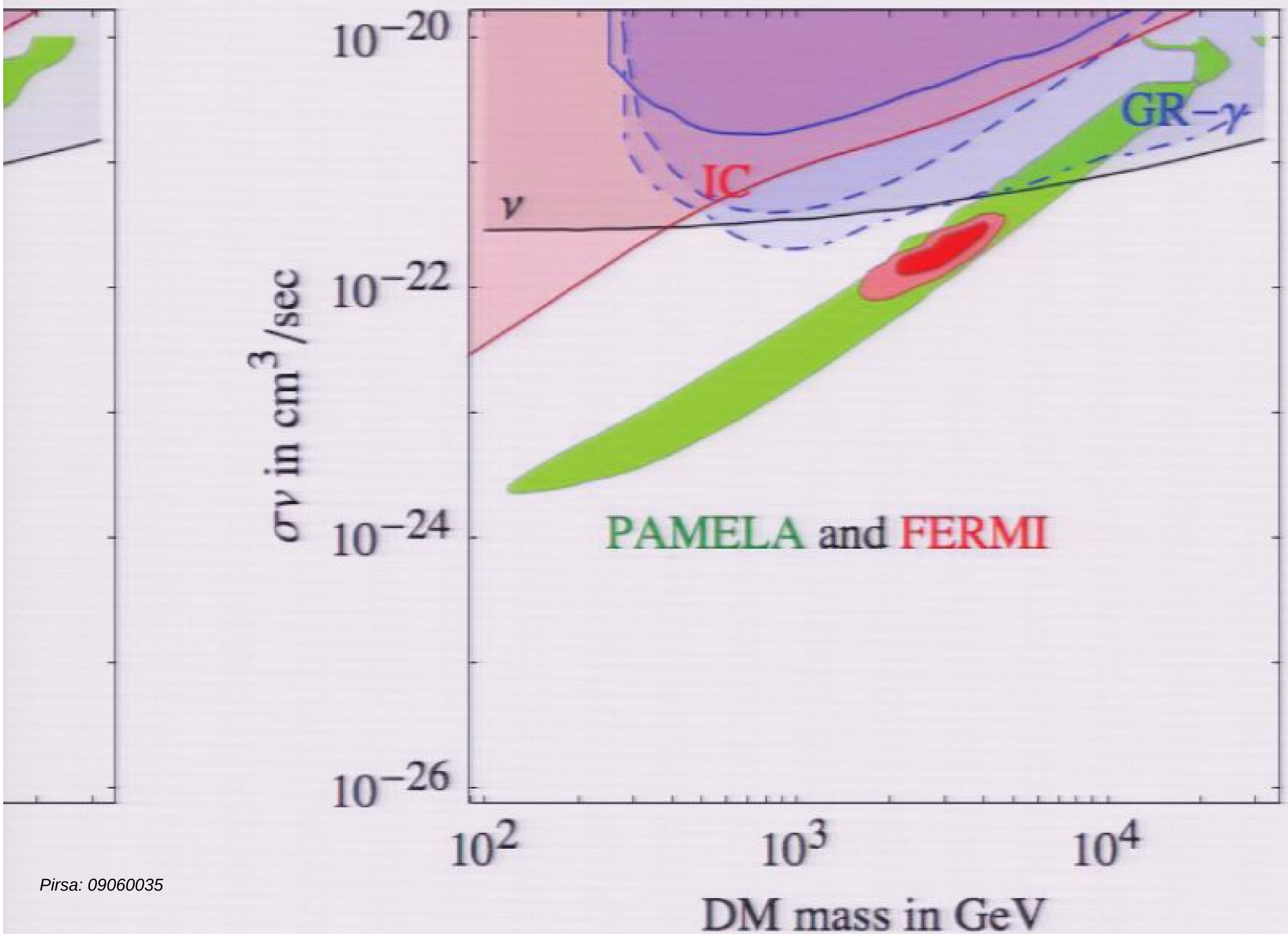


rofile

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



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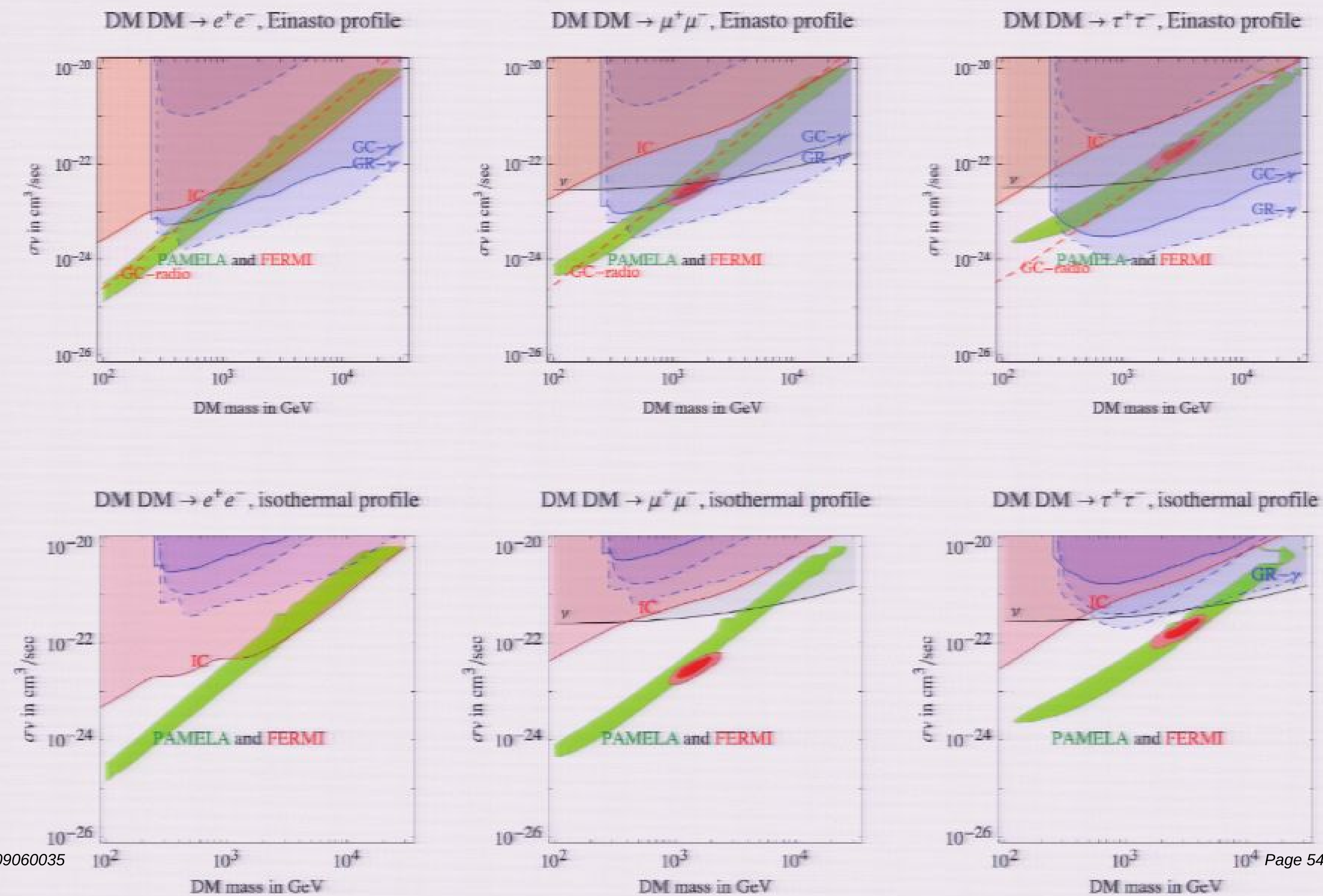
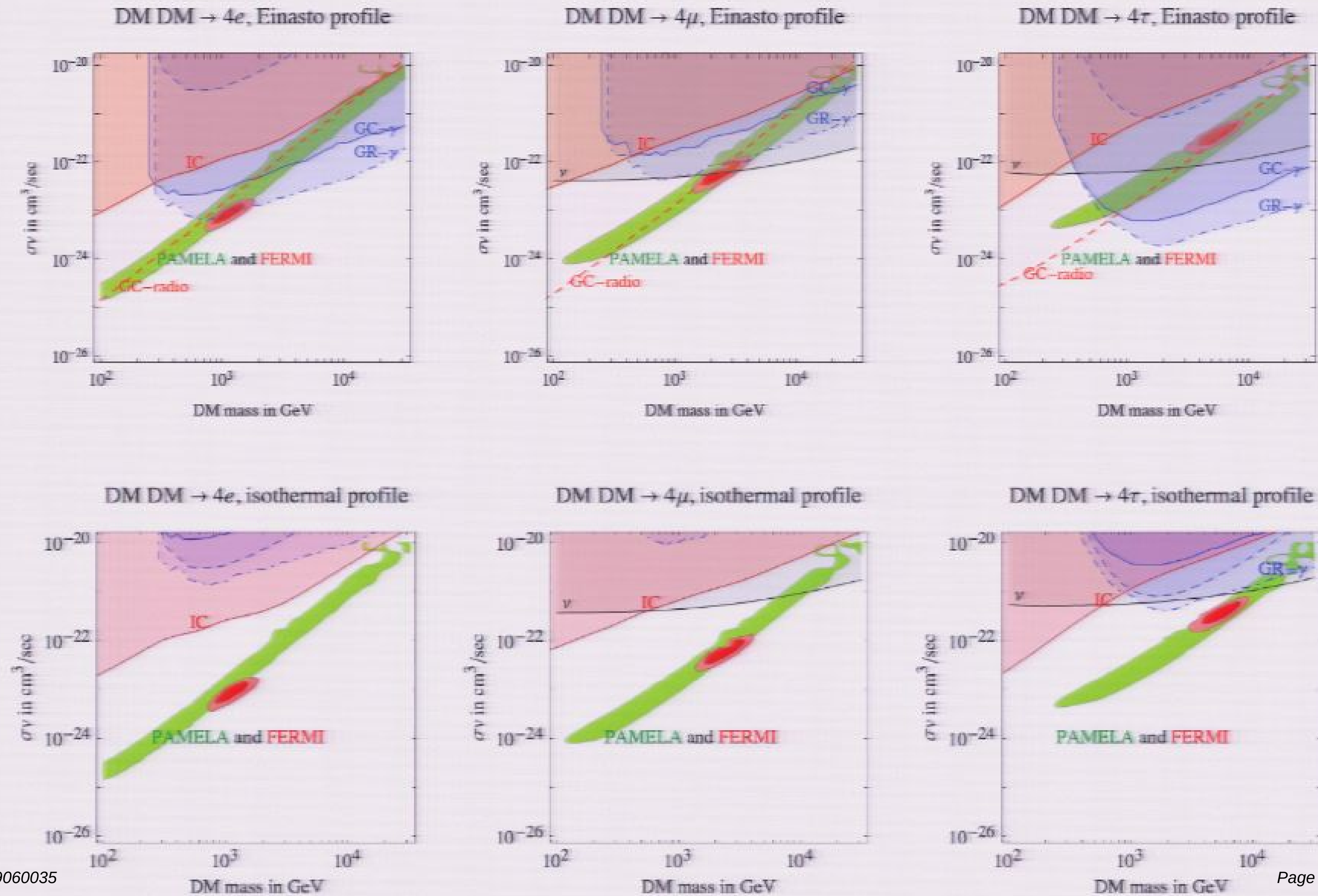
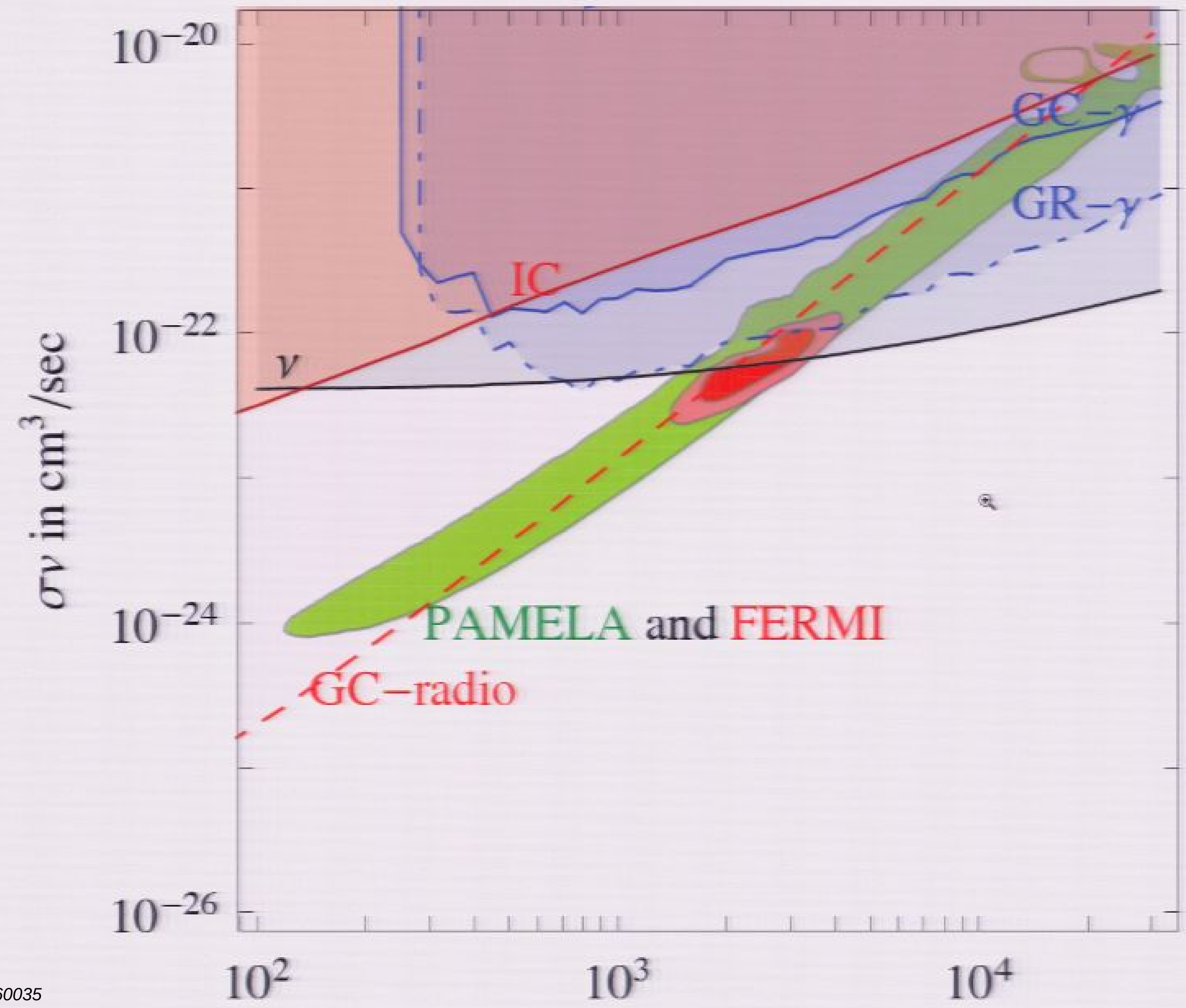


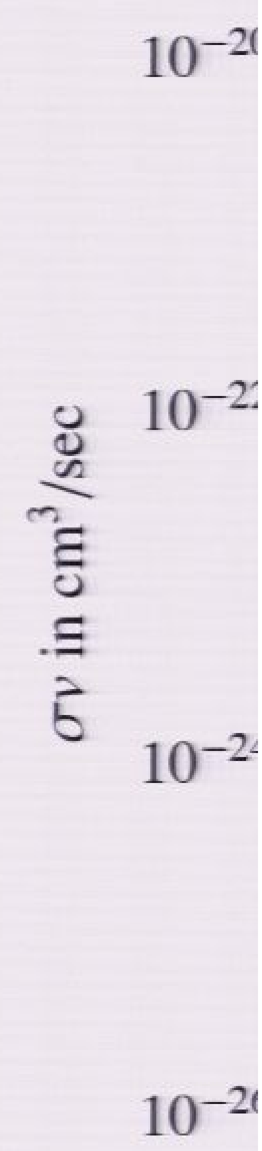
DM DM $\to VV \to \ell^+\ell^-\ell^+\ell^-$ is better

γ yield reduced from $\ln M/m_\ell$ to $\ln m_V/m_\ell$. And smoother $e^\pm$



DM DM $\to 4\mu$, Einasto profile





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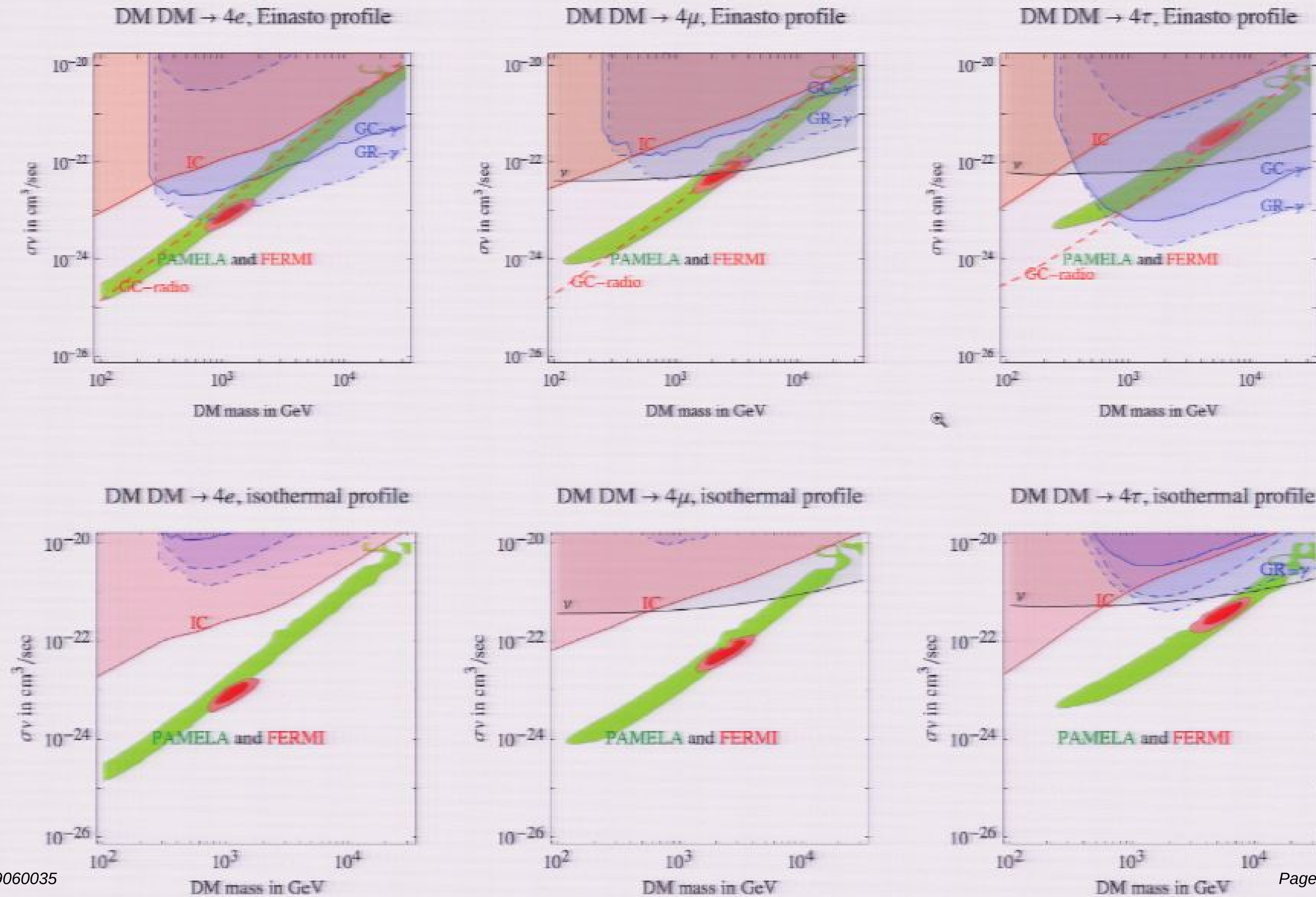
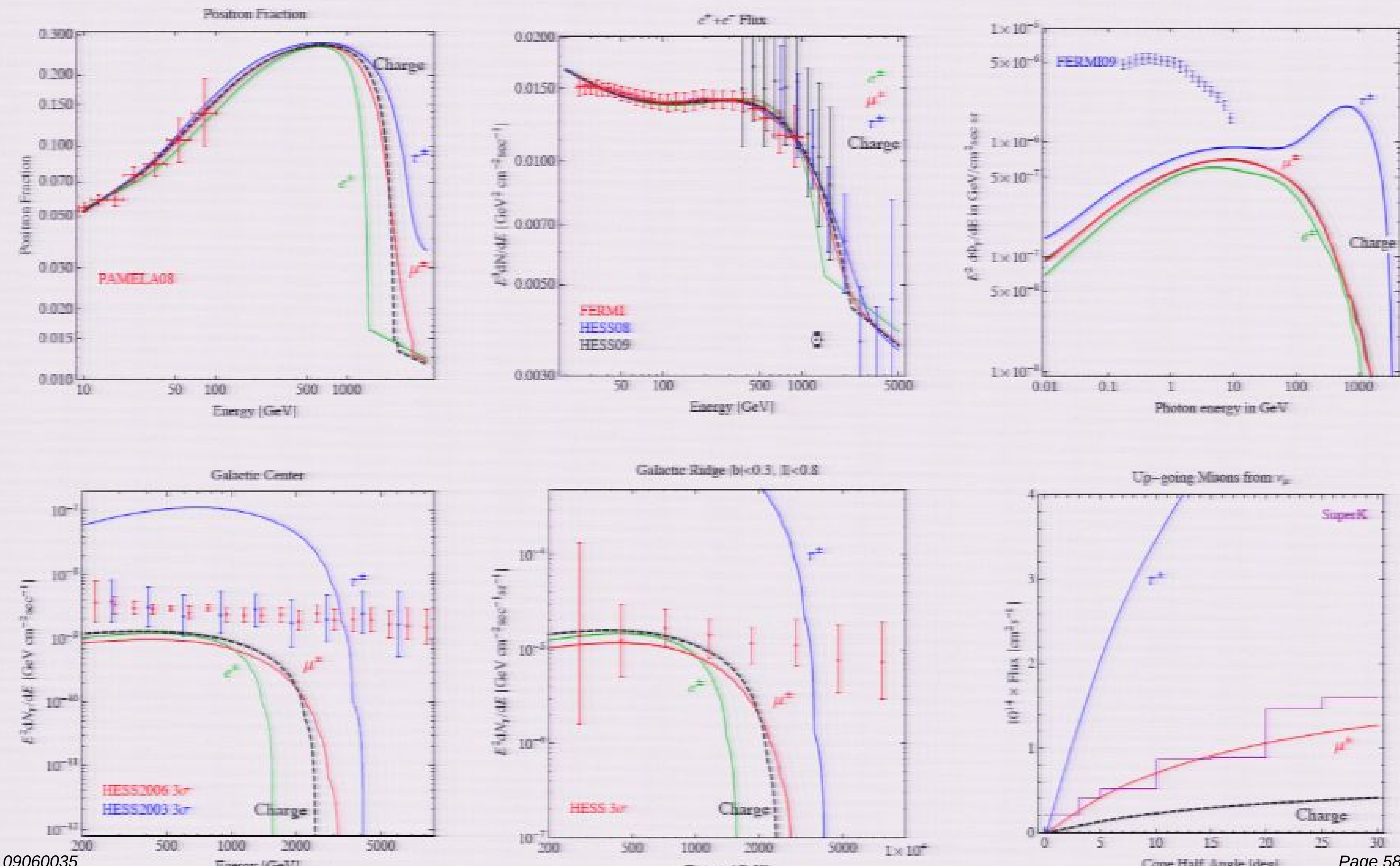


DM DM $\rightarrow 4e, 4\mu, 4\tau$

Best fits for Einasto MED. Charge is the coupling to electric charge:

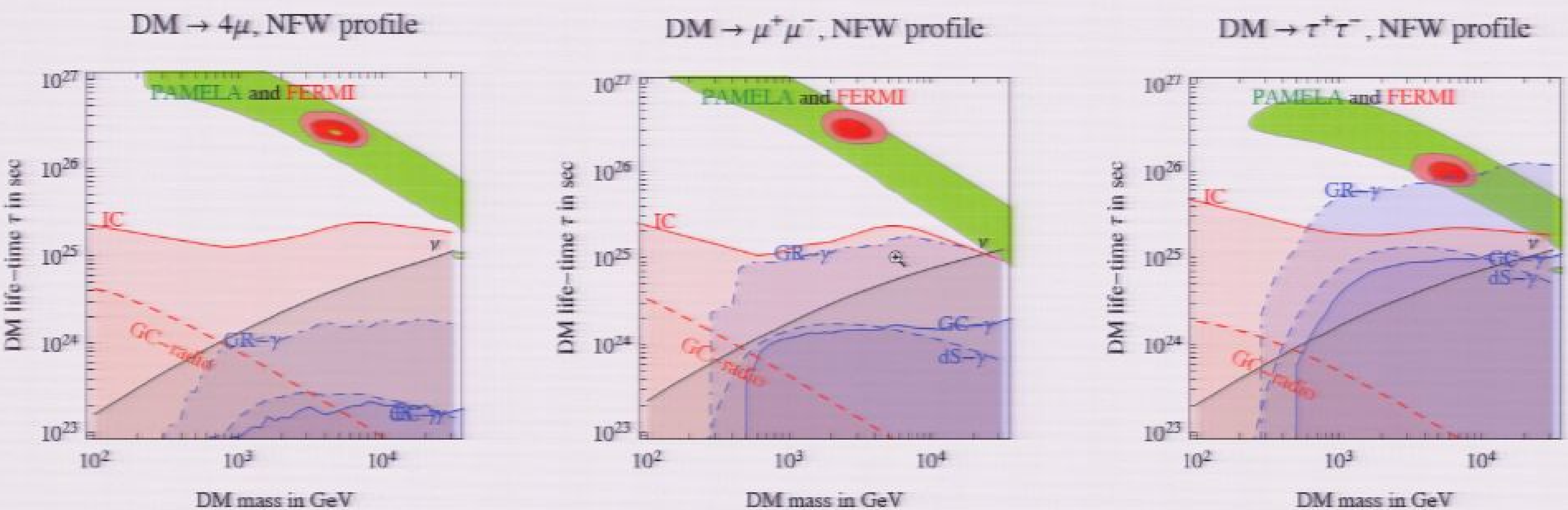


4

DM decays

DM decays are compatible with NFW

If instead DM **decays** with life-time τ, replace $\rho^2\sigma v/2M^2 \to \rho^1/M\tau$:



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DM decay not constrained by BBN, CMB

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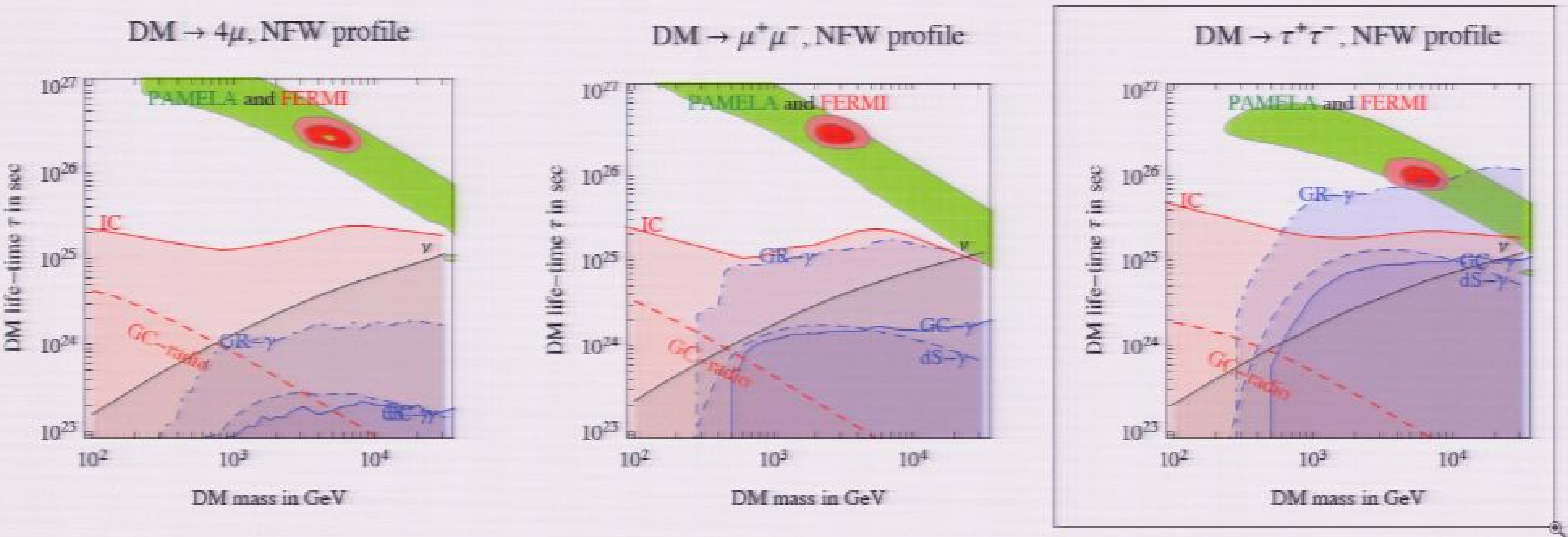

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ofile

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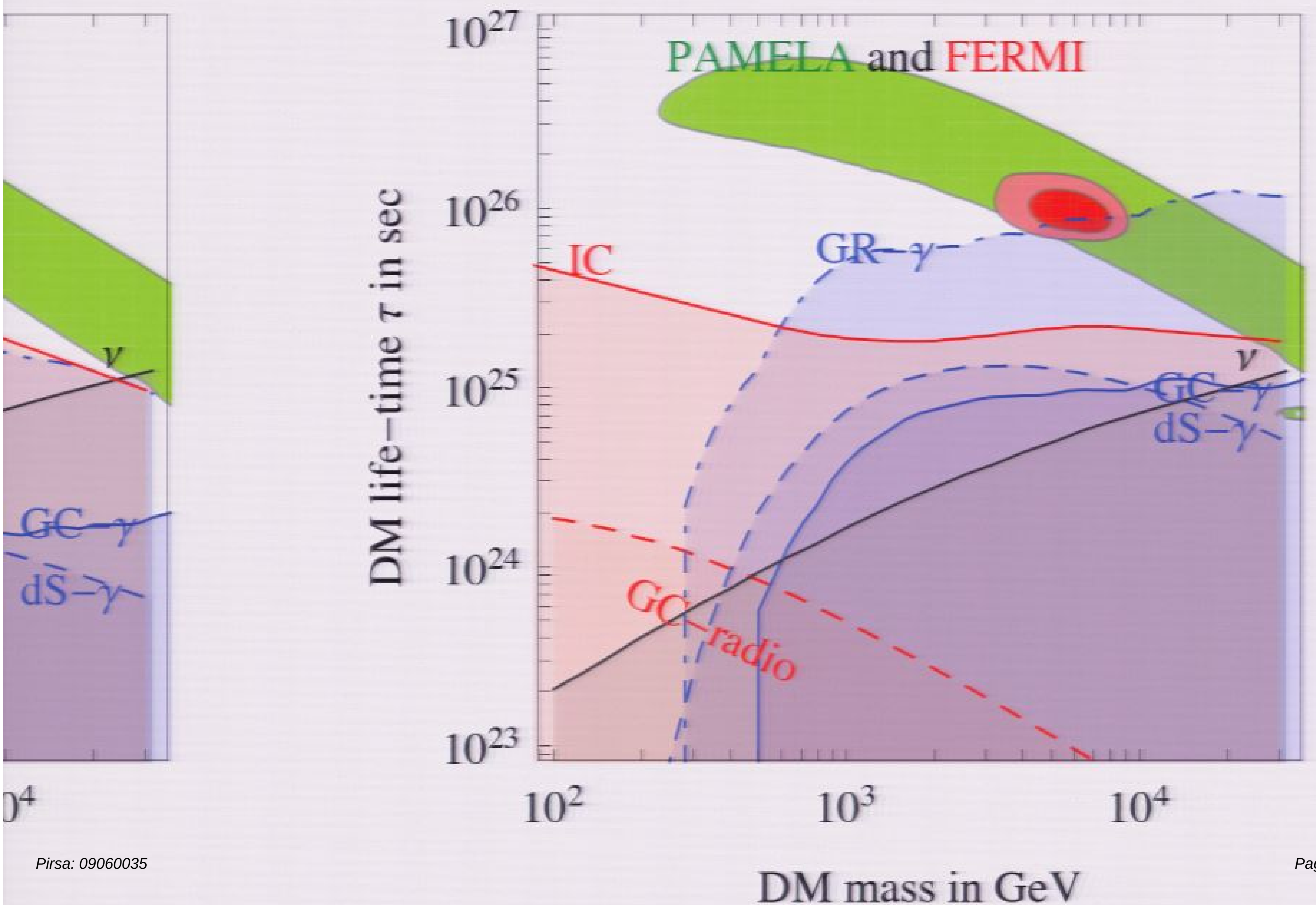

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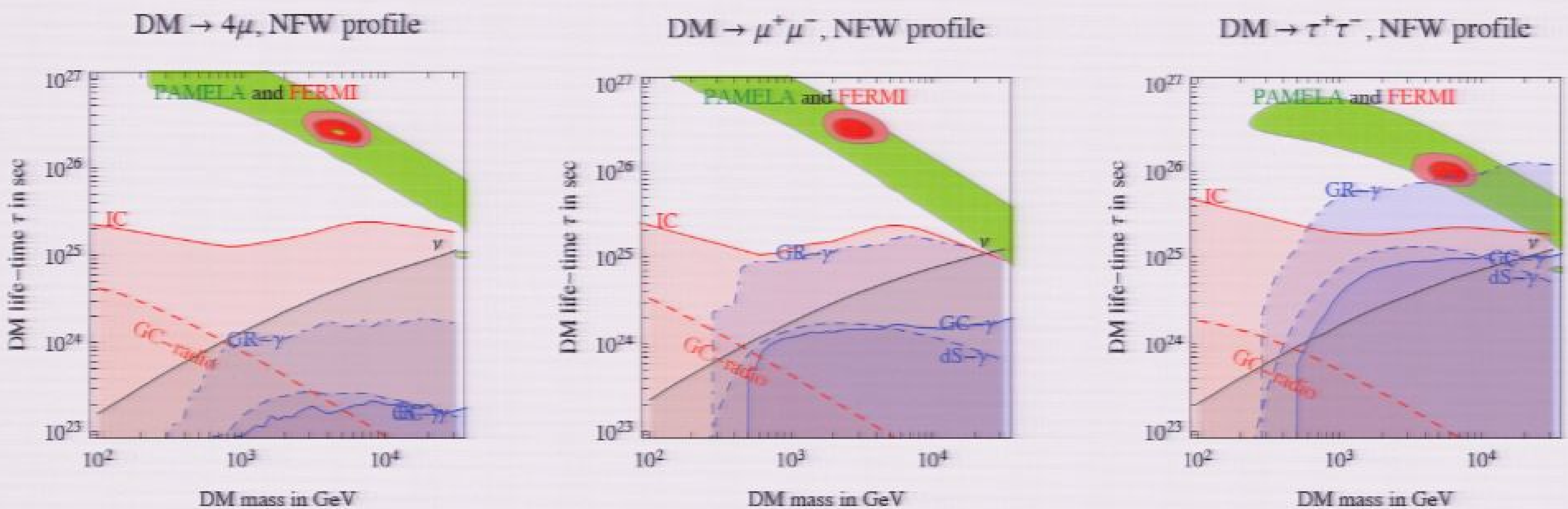

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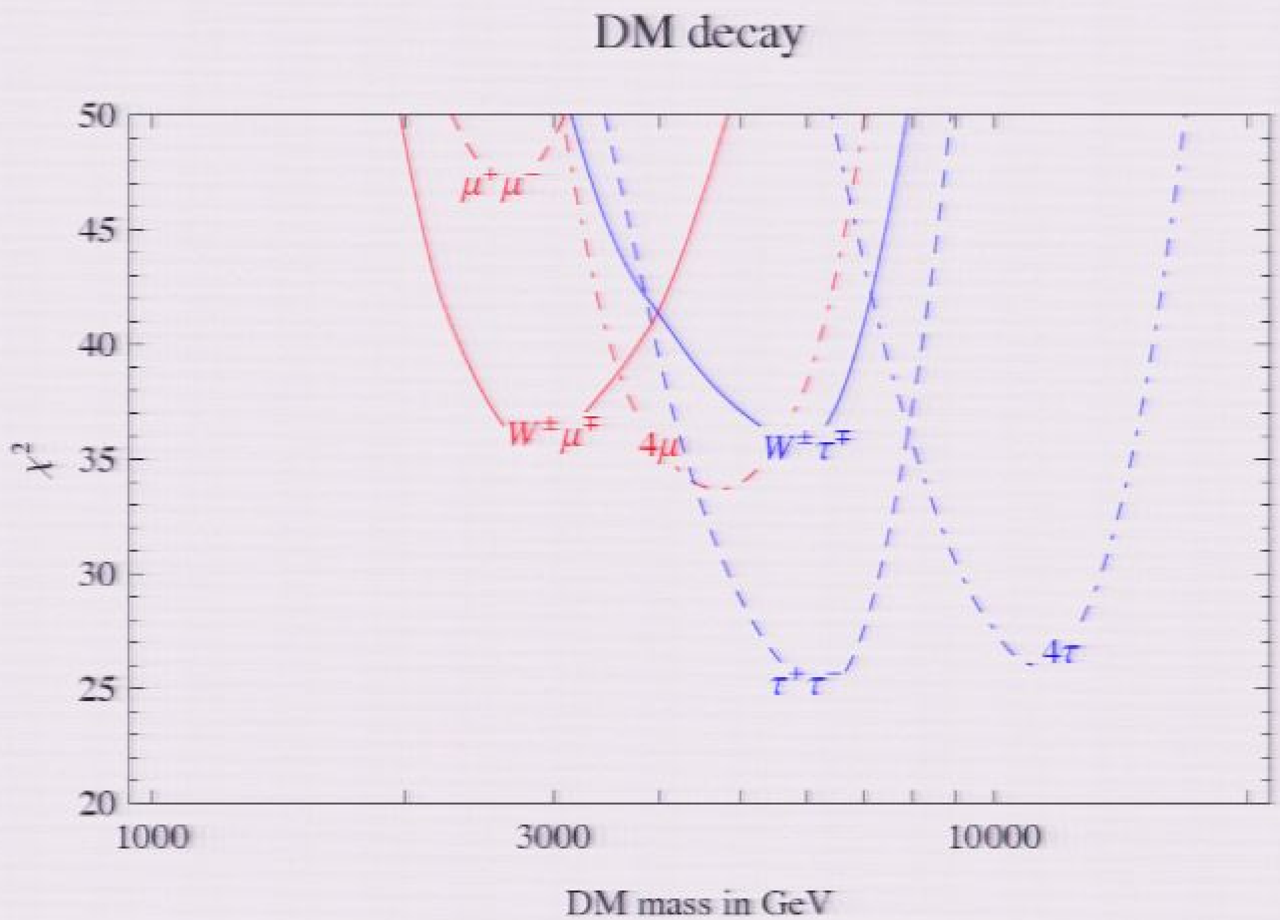
PAMELA and FERMI as DM decay



$e^{\pm}$ excesses suggest SU(2) technicolor!?

DM decays suggests $M \sim$ few TeV, which naturally implies the observed

$$5 \sim \frac{\rho_{\rm DM}}{\rho_b} \sim \frac{M}{m_p}\left(\frac{M}{T_{\rm dec}}\right)^{3/2} e^{-M/T_{\rm dec}}$$

if the DM density is due to a baryon-like asymmetry kept in thermal equilibrium by weak sphalerons down to $T_{\rm dec} \sim 200\,{\rm GeV}$.

Possible if DM is a chiral fermion or is made of chiral fermions.
The DM mass is $M \sim \lambda v \sim 2\,{\rm TeV}$ for $\lambda \sim 4\pi$: strong dynamics a-la technicolor.
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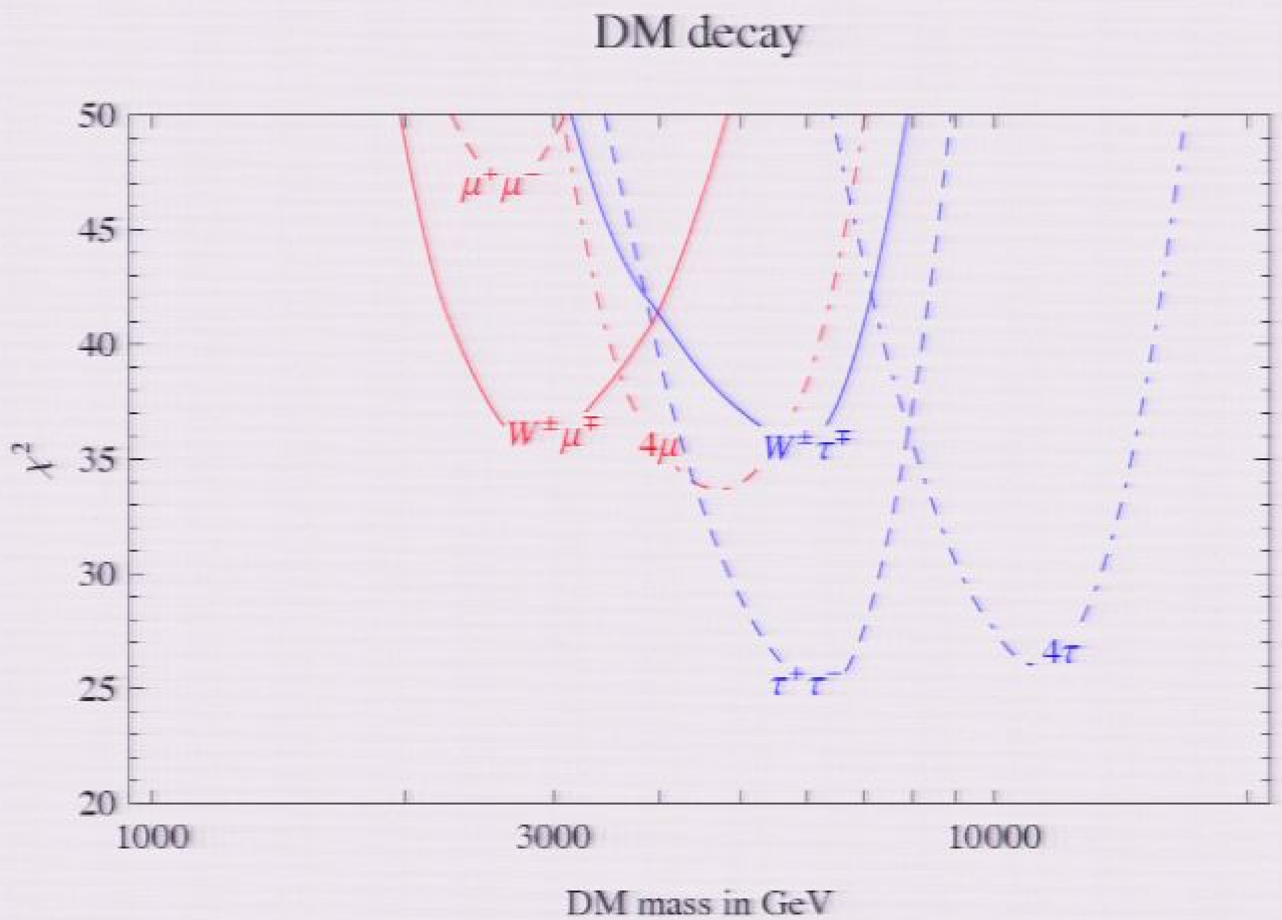

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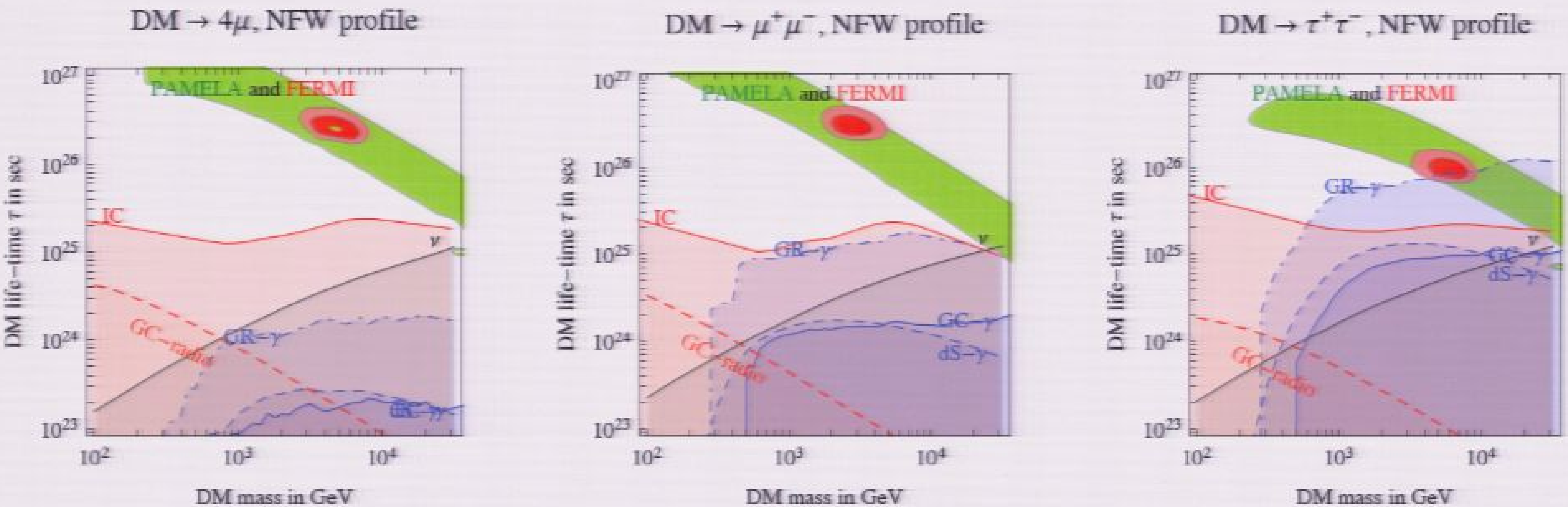

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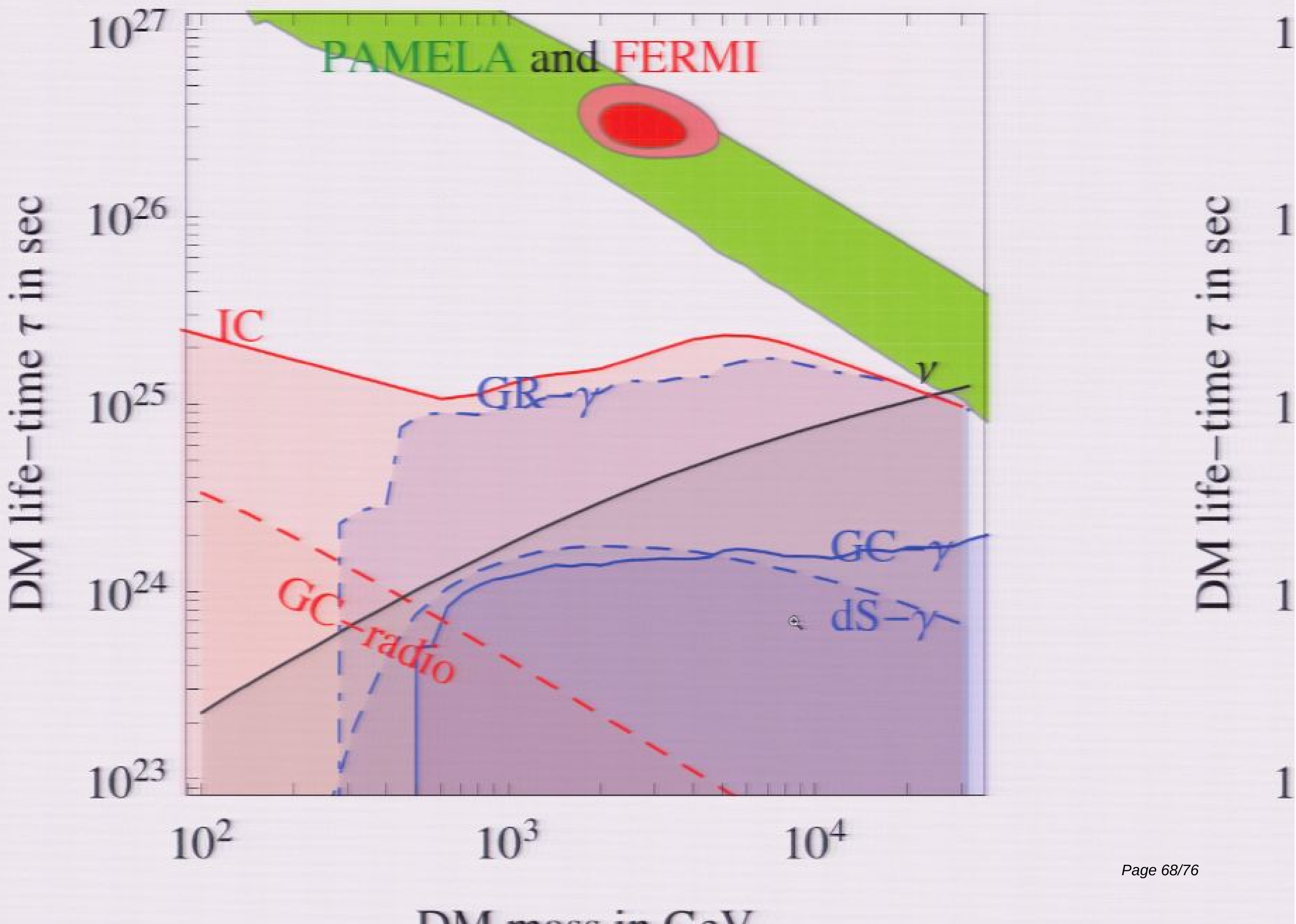

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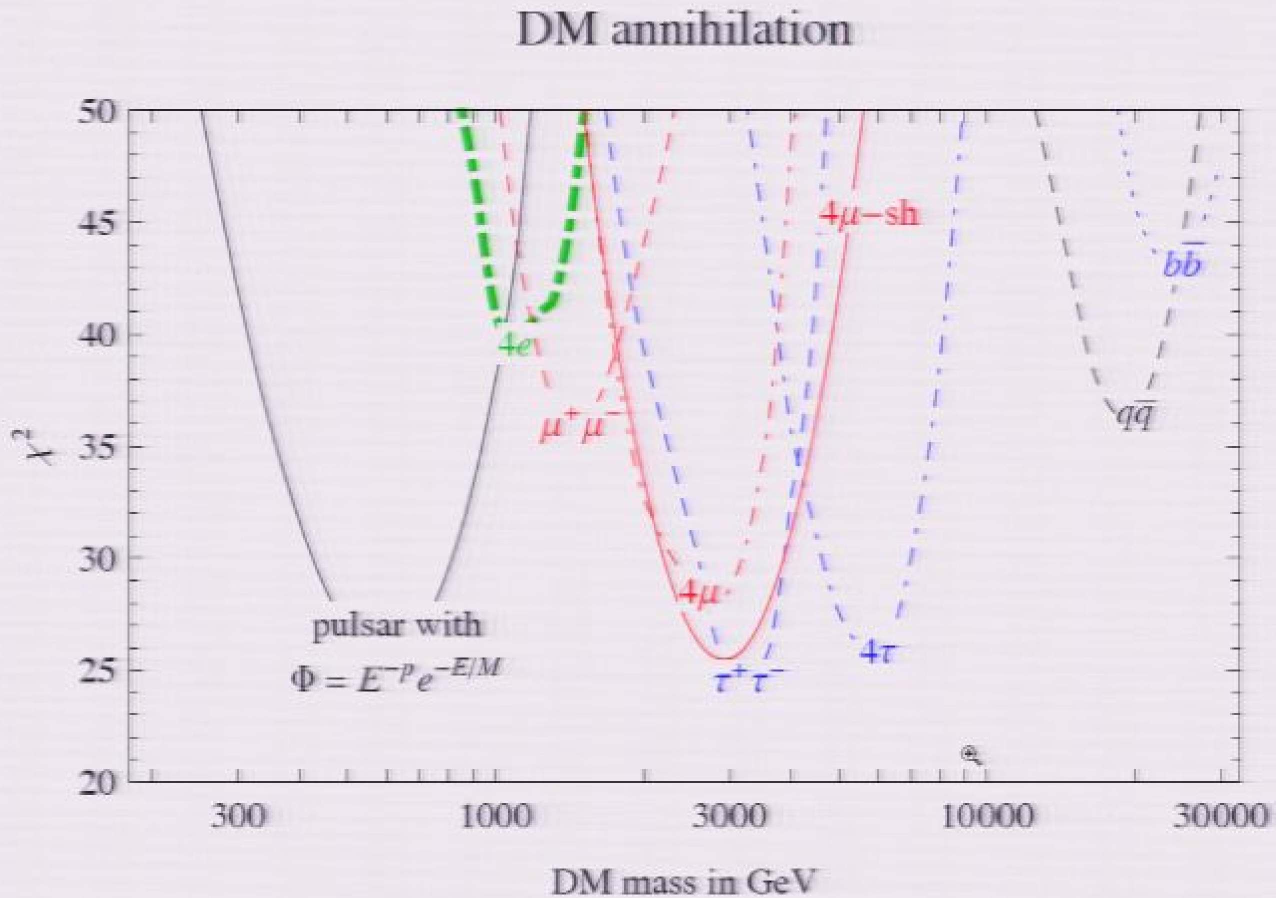
Implications of the positron/electron excesses on Dark Matter properties

1) The data
2) DM annihilations?
3) γ and ν constraints
4) DM decays?

Alessandro Strumia, talk at New Lights on DM, Perimeter Institute, 11/6/2009
From arXiv:0809.2409, 0811.3744, 0811.4153, 0905.0480 with
M. Cirelli, G. Bertone, M. Kadastik, P. Meade, M. Papucci, M. Raidal, M. Taoso
E. Nardi, F. Sannino, T. Volansky, www.cern.ch/astrumia/PAMELA.pdf

Fitting PAMELA e^+ and FERMI $e^+ + e^-$



Compatible if DM has TeV mass and annihilates into some leptons.

FERMI excludes that PAMELA is due to a DM lighter than about 1 TeV.

PAMELA vs SUSY & co

- Fit PAMELA with a neutralino at $M \sim 100$ GeV that annihilates into $e^+e^-\gamma$ thanks to a fine-tuned slepton mass, invoking a huuge boost $B_e \sim 10^6$;
- Unnatural SUSY at many TeV with σv enhanced by Sommerfeld;
- SUSY + ad hoc stable new particles. E.g. a $\tilde{\nu}_R$ lighter than M_W and with a large Yukawa $\nu_R LH$ annihilates into L;
- DM vectors or fermions suggested by wUED (would be Universal Extra Dimensions) or by LHT (Little Higgs with non-anomalous T-parity) annihilate $\sim 30\%$ into leptons, but $\sim 70\%$ into q, W.

DM models for PAMELA and FERMI

DM is charged under a dark gauge group, to get the Sommerfeld enhancement.

For PAMELA. We proposed that DM as a Dirac fermion with $M \approx 2\,\text{TeV}$ and charge $q \approx 2$ under $L_\mu - L_\tau$ (suggested by $\theta_{23} \approx \pi/4$), gauged with $\alpha_V \approx 1/50$ (giving the correct thermal abundance) and mass $M_V \approx M_Z$, giving the $g_\mu - 2$ anomaly + Sommerfeld. At 1 loop $L_\mu - L_\tau$ mixes with the photon: $\theta \sim e g_V \ln(m_\tau/m_\mu)/6\pi^2 \sim 0.005$. Direct: $\sigma_{\rm SI} = 4\pi q^2 \alpha_V \alpha m_N^2 \theta^2/M_V^4 \approx 10^{-42}\,\text{cm}^2$

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