Title: Cosmic ray anomaly and metastable dark matter particles

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Abstract: TBA

Cosmic ray anomaly and metastable dark matter particles

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CERN

CR anomaly

- cosmic ray anomaly seen by PAMELA, ATIC, FERMI, HESS
- due to annihilating DM, decaying DM, astrophysics?
- if DM $\Rightarrow$ several interesting features
  - large annihilation xsec
  - preferentially into leptons
- this talk: how the discussion changes if dark sector includes metastable particles

The scales

- χ DM, but dark sector also includes $\phi \Leftarrow$ metastable
- assume that ϕ decays through higher dim operators
- for guidance use "see-saw" scale

$$m_\nu = y^2 \frac{v^2}{\Lambda} \quad \Rightarrow \quad \Lambda = 6 \cdot 10^{12}\,\mathrm{GeV} \left(\frac{y}{0.1}\right)^2 \left(\frac{0.1\,\mathrm{eV}}{m_\nu}\right)$$

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- if ϕ decays through dim 5 ops, $\frac{1}{\Lambda} O$

$$\tau \simeq 16\pi \frac{\Lambda^2}{m_\phi^3} = 0.1 \mu s \left(\frac{\Lambda}{10^{13}\mathrm{GeV}}\right)^2 \left(\frac{3\mathrm{TeV}}{m_\phi}\right)^3$$

- possibly relevant for early universe, explain the large boost factors?

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- if ϕ decays through dim 6 ops, $\frac{1}{\Lambda^2} O$

$$\tau \simeq 16\pi \frac{\Lambda^4}{m_\phi^5} = 1.4 \cdot 10^{12} s \left(\frac{\Lambda}{10^{13}\mathrm{GeV}}\right)^4 \left(\frac{3\mathrm{TeV}}{m_\phi}\right)^5$$

- decays after it flies $\lambda \simeq 1.3\ \mathrm{kpc} \left(\frac{v\gamma}{0.1}\right) \left(\frac{10^{13}\mathrm{GeV}}{\Lambda}\right)^4 \left(\frac{m_\phi}{3\mathrm{TeV}}\right)^3$
- propagation on galactic distances

Outline

- large boost factors
- gamma rays from galactic center
- conclusions

Large cross sections

Boost factor

- if simple thermal relic then
  $\Omega_{\rm DM} \propto 1/\langle \sigma_A v \rangle_{\rm F} \Rightarrow \langle \sigma_A v \rangle_{\rm F} \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
- cosmic ray flux

$$\Phi_{e^+} \propto \langle \sigma_A v \rangle \rho_{\rm DM}^2 / m_{\rm DM}^2$$

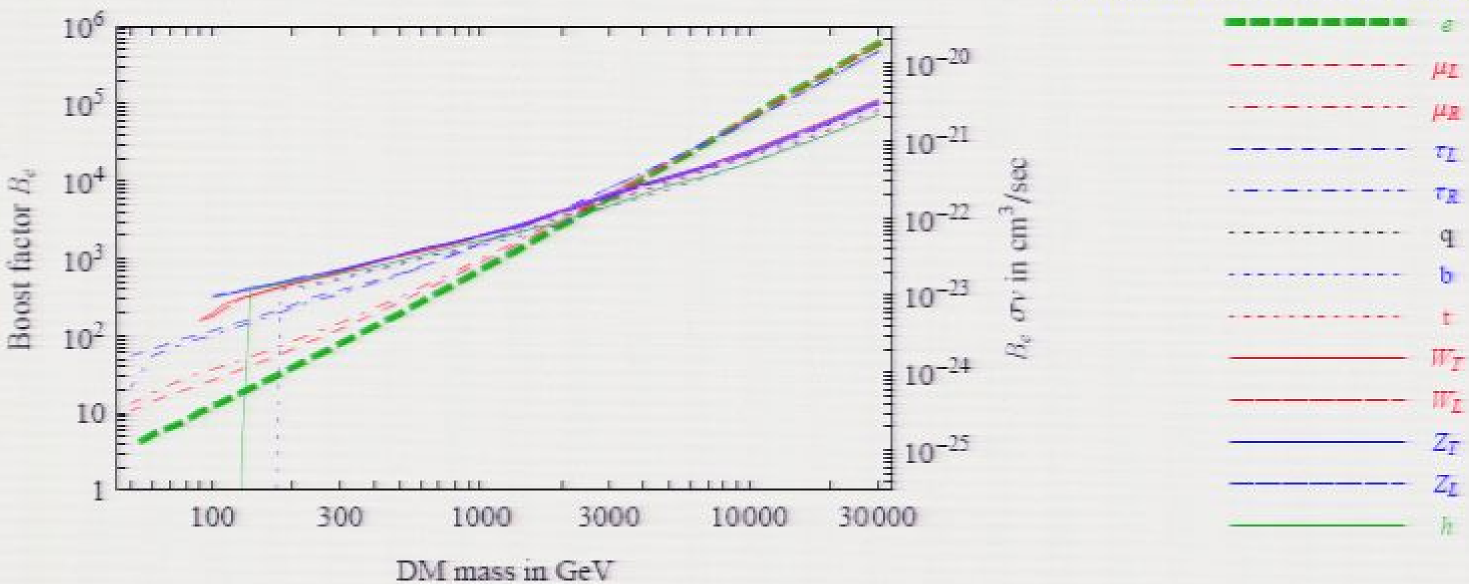
- define a "boost factor"

$$B \equiv \frac{\langle \sigma_A v \rangle \rho_{\rm DM}^2}{\langle \sigma_A v \rangle_F (\bar{\rho}_{\rm DM})^2}$$

Boost factors

- model independent analysis for Pamela

Cirelli, Kadastik, Raidal, Strumia 2008



- very large "boost factors"

Unitarity bound

- unitarity bound also imposes the upper bound on DM mass
- s-wave annihilation: $\sigma v \leqslant 4\pi/(vM^2)$
- this bounds the possible boost factor

$$B \leqslant \frac{4\pi}{vM^2\langle\sigma v\rangle_F} = 5\cdot 10^6\left(\frac{1\mathrm{TeV}}{M}\right)^2\left(\frac{10^{-3}}{v}\right)$$

- from model indep. bound on previous slide for leptonic decays

$$M \leqslant 8-9\ \mathrm{TeV}$$

($M \leqslant 12\mathrm{TeV}$ for hadronic decays)

Boost factors

- model independent analysis for Pamela

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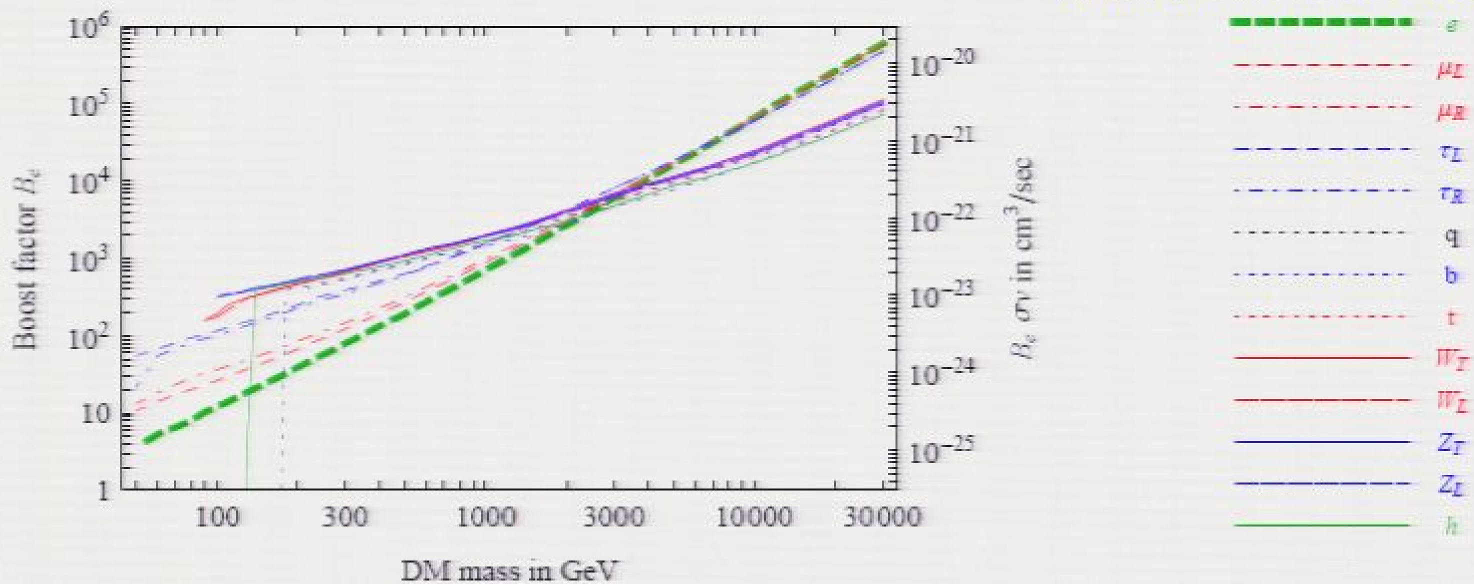

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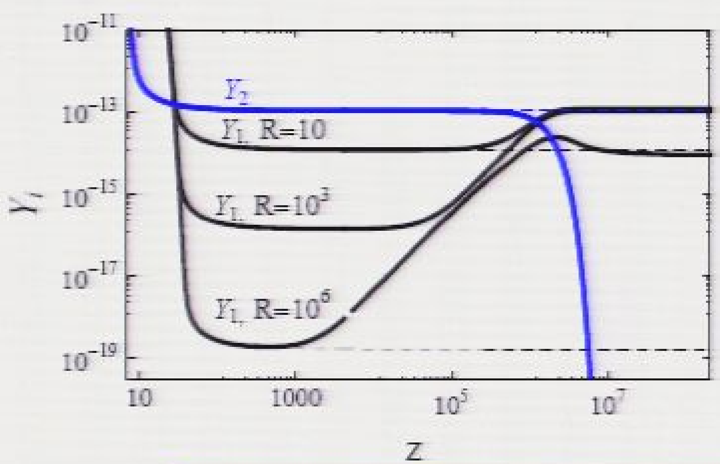
Large boost factors

- Sommerfeld enhancement due to a new long range attractive interaction between WIMPs
  Hisano et al. 03-06; Cirelli et al. 07-08; Pospelov, Ratz 08;Arkani-Hamed et al. 08; Fox, Poppitz 08; Pospelov 08; Bai, Hambye 08; Nomura, Thaler 08; Ackerman et al 08;
- annihilation through resonances
- recombination through WIMP-onium — Pospelov, Ratz 2008
- nonthermal DM: 2 component dark sector (2CDS) model — Fairbairn, JZ, 2008
- decaying DM
  Chen, Takahashi, Yanagida, 08; Ibarra, Tran 08; Hamaguchi, Nakamura, Shirai Yanagida 08; Yin, Yuan, Liu, hang, Bi, Zhu 08
- different temperature in the DM sector and in the visible sector — Nelson and Spitzer

2-component dark sector

Fairbairn, JZ, 0810.4147

- an example of DM not a simple thermal relic
- two components: χ_2, χ_1
  - χ_2 is metastable, decays after freeze-out
    $\chi_2 \to \chi_1 + X_{SM}$
  - χ_1 is the DM that we observe now - and also gives Pamela/ATIC/FERMI/HESS signal
  - this setup decouples $\langle \sigma_A v \rangle_F$ from $\Omega_{\rm DM}$



$$B \simeq \frac{Y_1(\infty)}{Y_1^{\rm Th.rel.}} \simeq N_{\rm dec} R$$

$R = \frac{m_1}{m_2} \frac{\langle \sigma_{A1} v_1 \rangle}{\langle \sigma_{A2} v_2 \rangle}$, $z = m_1/T$, $Y_i(z) = n_i(z)/s(z)$

2CDS II

- for large boost factors $\langle \sigma_{A1} v_1 \rangle \gg \langle \sigma_{A2} v_2 \rangle$
- to avoid wash-out χ_2 should decay after freeze-out

$$\Gamma_2 \ll 10^{-17}\text{GeV} \cdot \left(\frac{10^3}{B}\right) \cdot \left(\frac{m_1}{1\text{TeV}}\right)^2$$

or $\tau_2 \gg (10^{-7}s) \times (B/10^3) \cdot (1\text{TeV}/m_1)^2$

- from nucleosynthesis $\tau_2 < 1s$
- if through dim 5 operators: $\Gamma_2 \simeq m_2^3/(16\pi\Lambda^2)$, then

$$5{\cdot}10^{15}\text{GeV}\left(\frac{m_2}{1\text{TeV}}\right)^{3/2} > \Lambda \gg 10^{12}\text{GeV}{\cdot}\left(\frac{B}{10^3}\right)^{1/2}\left(\frac{m_{1,2}}{1\text{TeV}}\right)^{1/2}$$

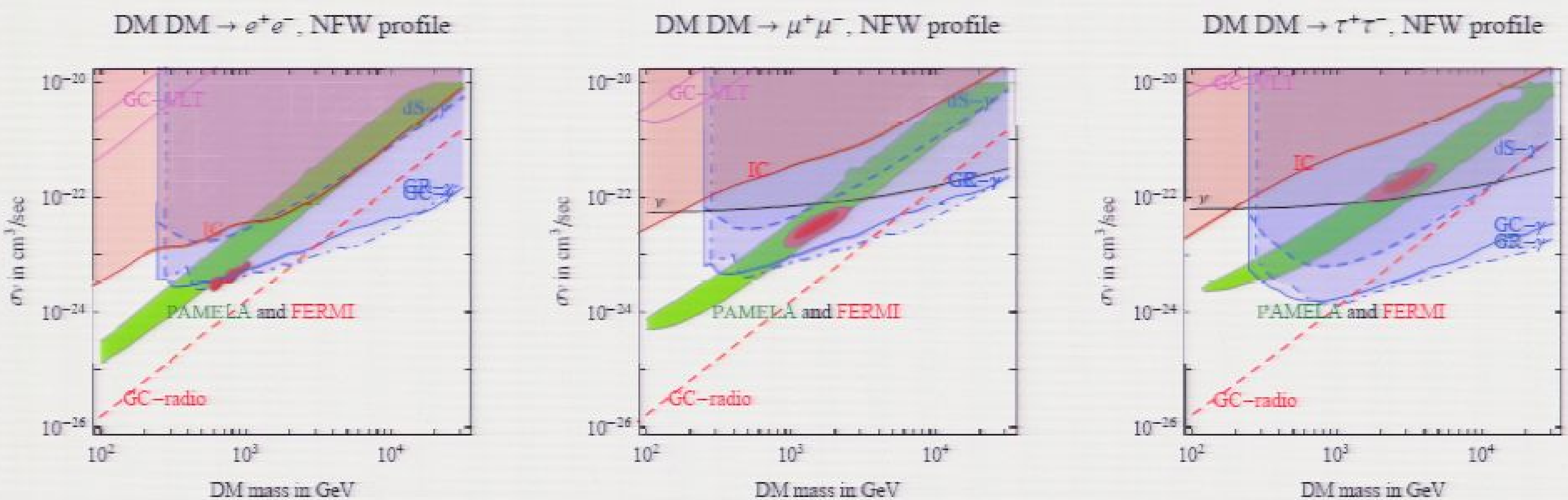
- note: the allowed range includes see-saw scale
- if produced at LHC would fly macroscopic distance

Gammas from galactic center

High energy photons

- annihilation into charged particles $\Rightarrow$ inevitably high energy gamma from bremsstrahlung
- a curse and a blessing
  - a signal of DM (especially if a line)
  - right now there is a tension between cosmic ray anomaly and gamma from galactic center

Meade et al. 0905.0480



Long lived intermediate states

ways out:

- less cuspy DM profiles in the galactic center?
- there is no problem if

$$\chi\chi \to \phi\phi \to 2\,\mathrm{SM}\,2\,\overline{\mathrm{SM}},$$ with ϕ long lived

Rothstein, Schwetz, JZ 0903.3116

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Rothstein, Schwetz, JZ 0903.3116

- if ϕ decays through dim 6 operators, $\tau \simeq 16\pi\Lambda^4/m_\phi^5$

$$\Lambda \sim \frac{2\times 10^{12}\,\mathrm{GeV}}{(\beta\gamma)^{1/4}}\left(\frac{\lambda}{10\,\mathrm{kpc}}\right)^{1/4}\left(\frac{m_\phi}{1\,\mathrm{TeV}}\right)^{5/4}$$

- for a see-saw scale $\Rightarrow$ propagation on galactic distances

Effective density

- for annihilating DM, the photon flux seen on earth

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{4\pi}\,\frac{r_\odot \rho_\odot^2}{m_\chi^2}\,\frac{dN_\gamma}{dE_\gamma}\,J\,\Delta\Omega$$

- the dimensionless J-factor is

$$J = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} \frac{ds}{r_\odot}\,\frac{\rho_{\text{DM}}^2(r)}{\rho_\odot^2}$$

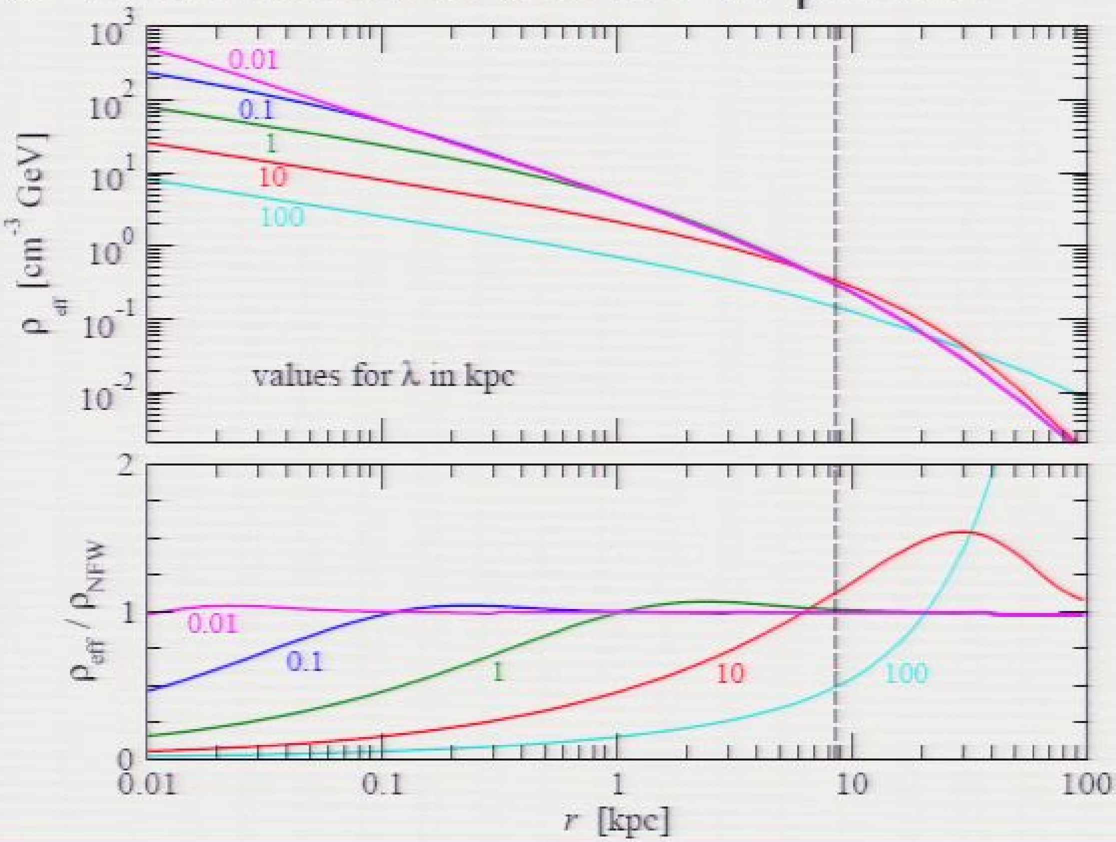
$\rho_\odot = 0.3\,\text{GeV}\,\text{cm}^{-3}$ and $r_\odot = 8.5$ kpc

- for simplicity assume that ϕ nonrelat.
- then the effect of ϕ: $\rho \to \rho_{\text{eff}}$

$$\rho_{\text{eff}}^2(r) = \int d^3r'\rho^2(r')\frac{1}{4\pi\lambda}\frac{e^{-|\vec{r}-\vec{r'}|/\lambda}}{|\vec{r}-\vec{r'}|^2}$$

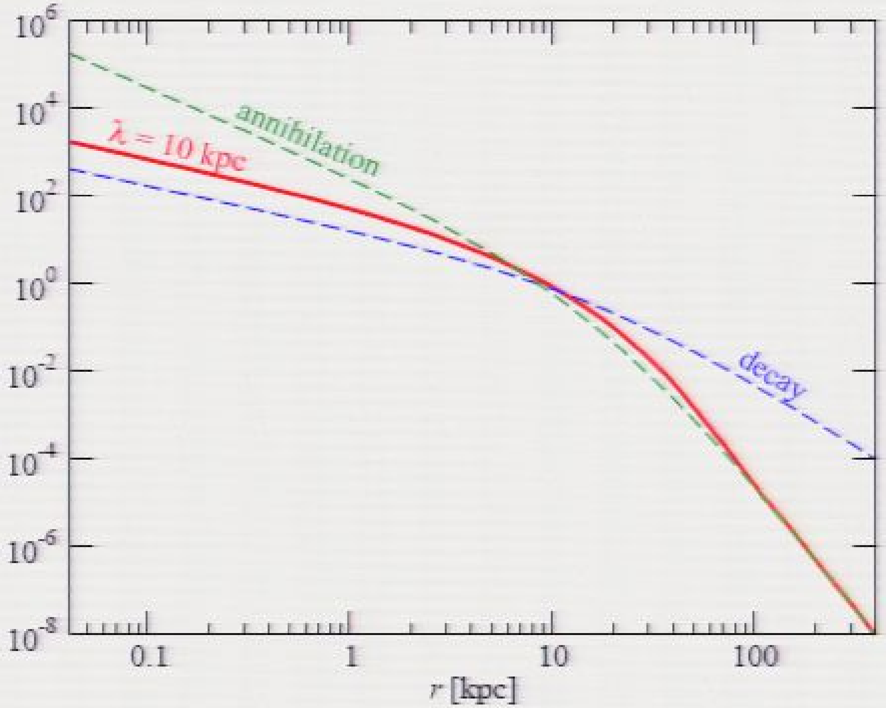
Effective density

- use NFW profile
  - for $r \lesssim \lambda$ supressed $\rho_{\rm eff}(r)$
  - for $r \gtrsim \lambda$ ϕ decays, so overproduction
  - for $r \gg \lambda$ we recover the NFW profile



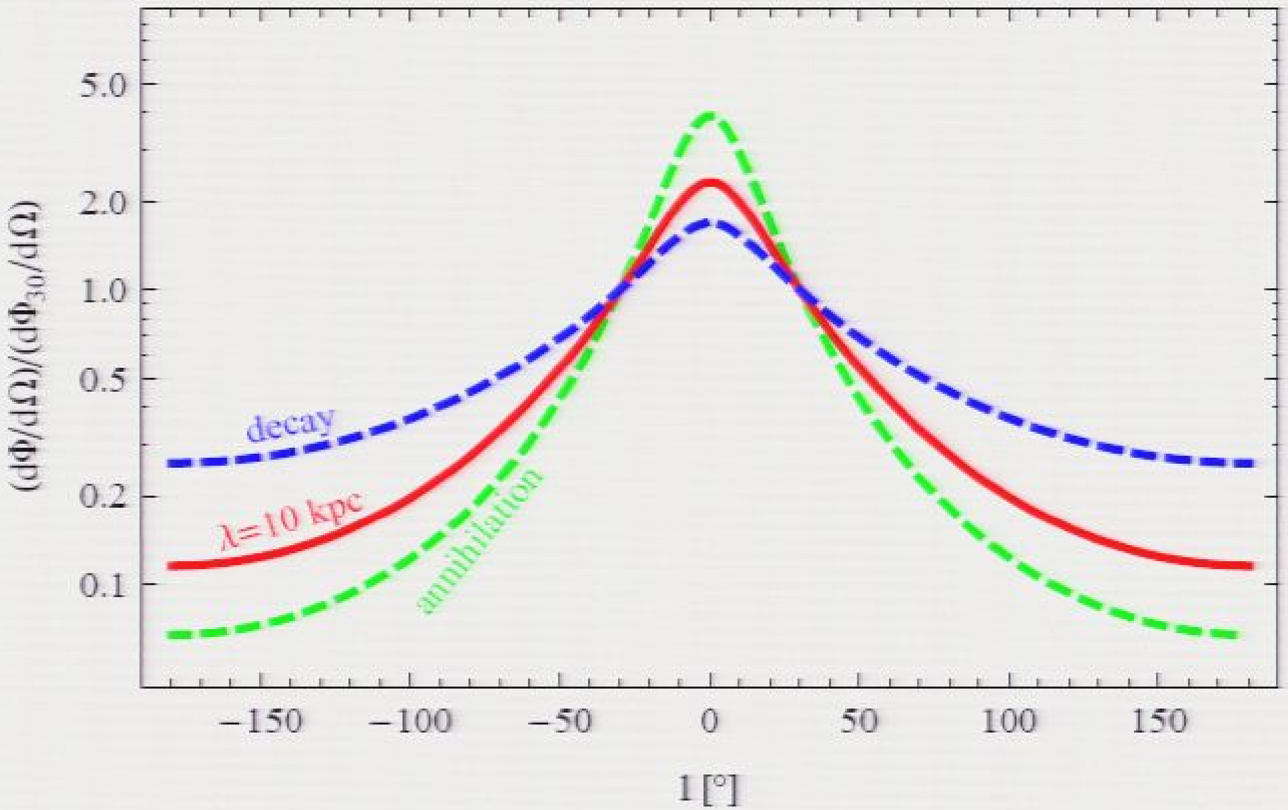
annih. vs decay

- the size of λ dials the model effects from $\sim$annihilating DM to $\sim$decaying DM
- eg., for $r \ll \lambda$ and profiles $\rho(r) \propto r^{-\gamma} \Rightarrow \rho_{\rm eff}^2(r) \propto 1/r^{2\gamma-1}$
  - for NFW ($\gamma = 1$): $\rho_{\rm eff}^2(r) \propto 1/\rho(r)$



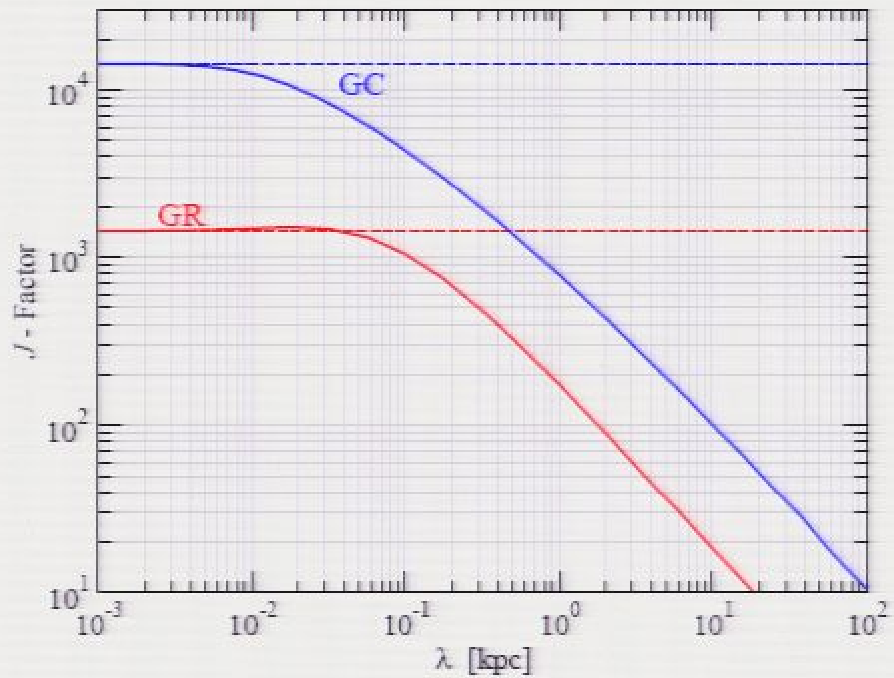
annih. vs decay

- comparing angular dependence



High energy photons

- the ϕ's decay outside the galactic center
- photon flux from galactic center suppressed



GC=Galactic center, GR=Galactic Ridge

effect on e^+e^- fits

- fix decay $\phi \to \mu^+\mu^-$, NFW profile, MED propagation model for el.
- injections spectra for photons, e^+, e^- from pythia
- background from Galprop + free scale, slope allowed to vary by ± 0.05
- split Fermi and ATIC data

A technical detail

- solution of diff. eq., source $q(\vec{x}, E) = \kappa\left(\frac{\rho(\vec{x})}{\rho_0}\right)^2 f(\epsilon)$

$$\Psi(r, z, \epsilon) = \kappa \frac{\tau_E}{\epsilon^2} \int_\epsilon^\infty d\epsilon_S f(\epsilon_S) \tilde{I}(\lambda_D, r, z),$$

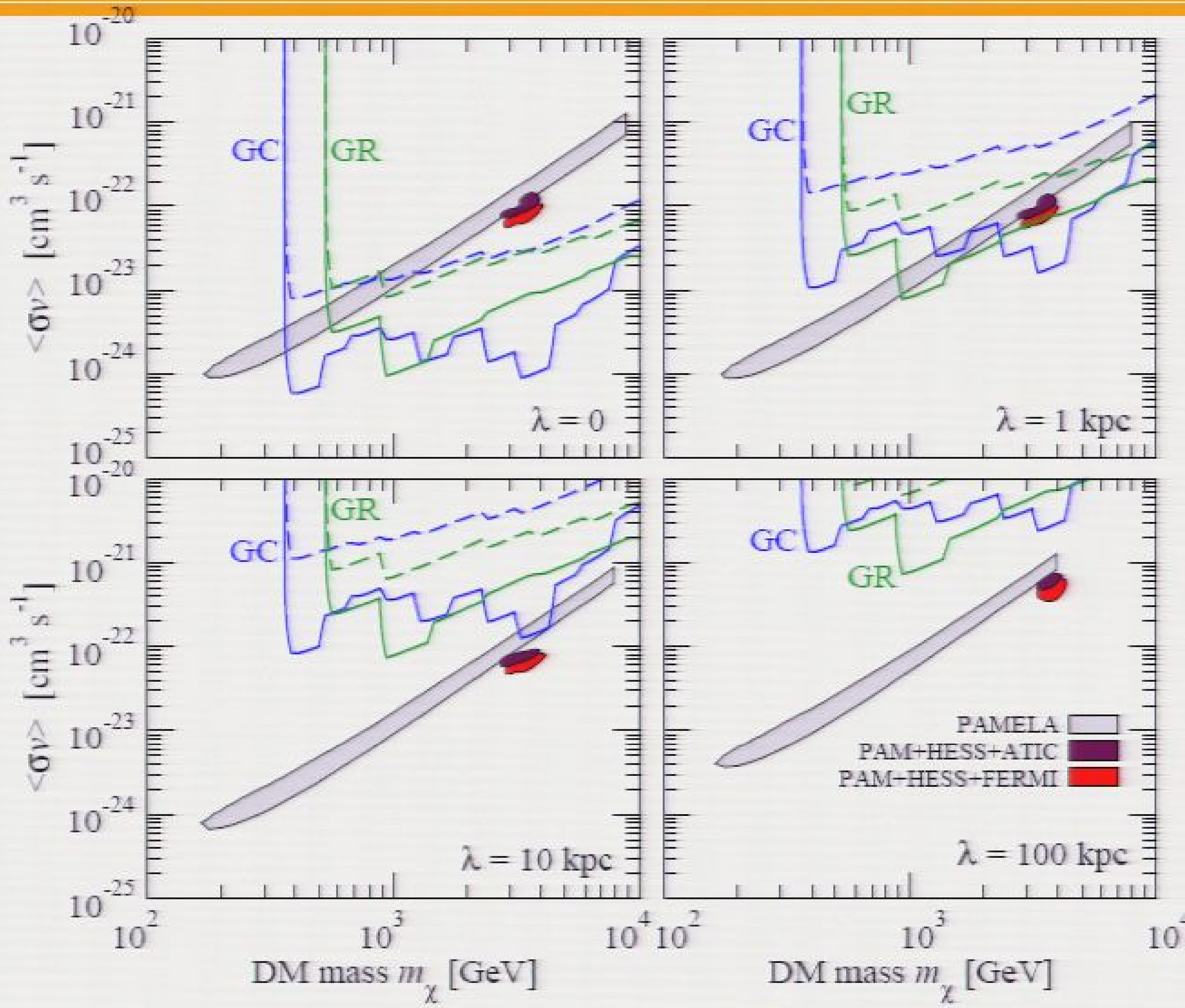
- astrophysics in $I(\lambda) \Rightarrow$ we need to wary it
  - if expanded in Bessel funcs., very slow converg.
  - can write a diff. eq., solved num. in ~10s on pc

$$\nabla^2 \tilde{I}(\lambda_D, r, z) - \tfrac{2}{\lambda_D} \partial_{\lambda_D} \tilde{I}(\lambda_D, r, z) = 0,$$

boundary conditions:

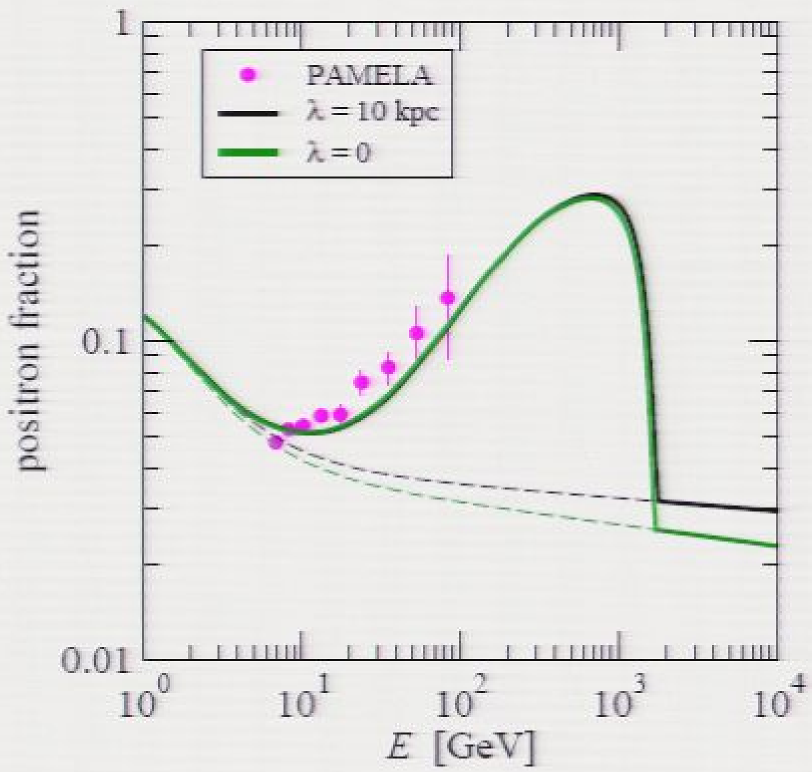
$$\tilde{I}(0, r, z) = \left(\tfrac{\rho(r,z)}{\rho_0}\right)^2, \qquad \tilde{I}(\infty, r, z) = 0,$$
$$\tilde{I}(\lambda_D, R_{\rm gal}, z) = 0, \qquad \tilde{I}(\lambda_D, r, \pm L) = 0.$$

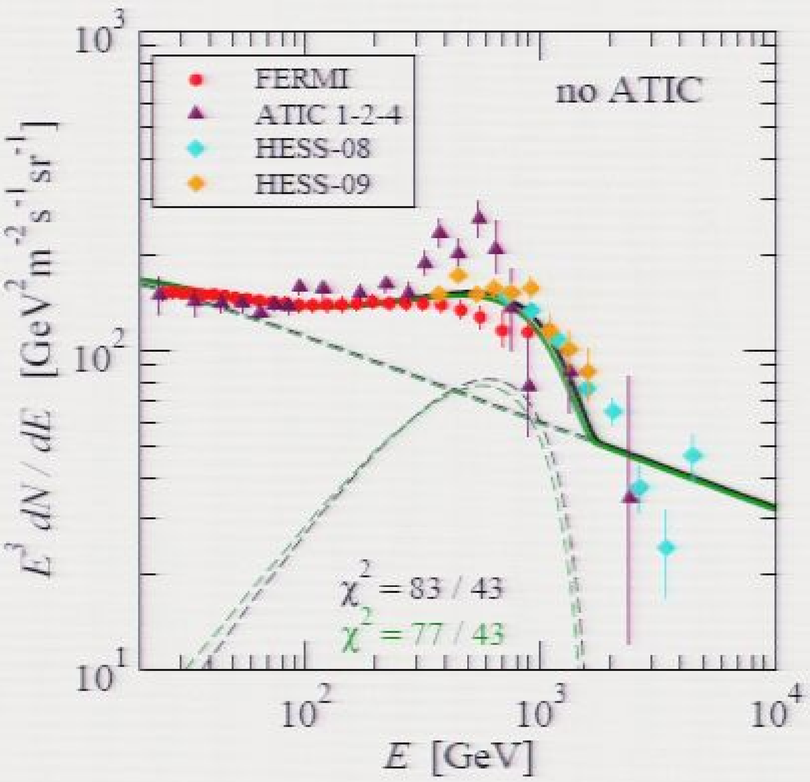
e^+e^- fits



minimum $m_\chi \simeq 3.6\mathrm{TeV},\ \langle\sigma v\rangle \sim 10^{-22}\mathrm{cm}^3\mathrm{s}^{-1}$

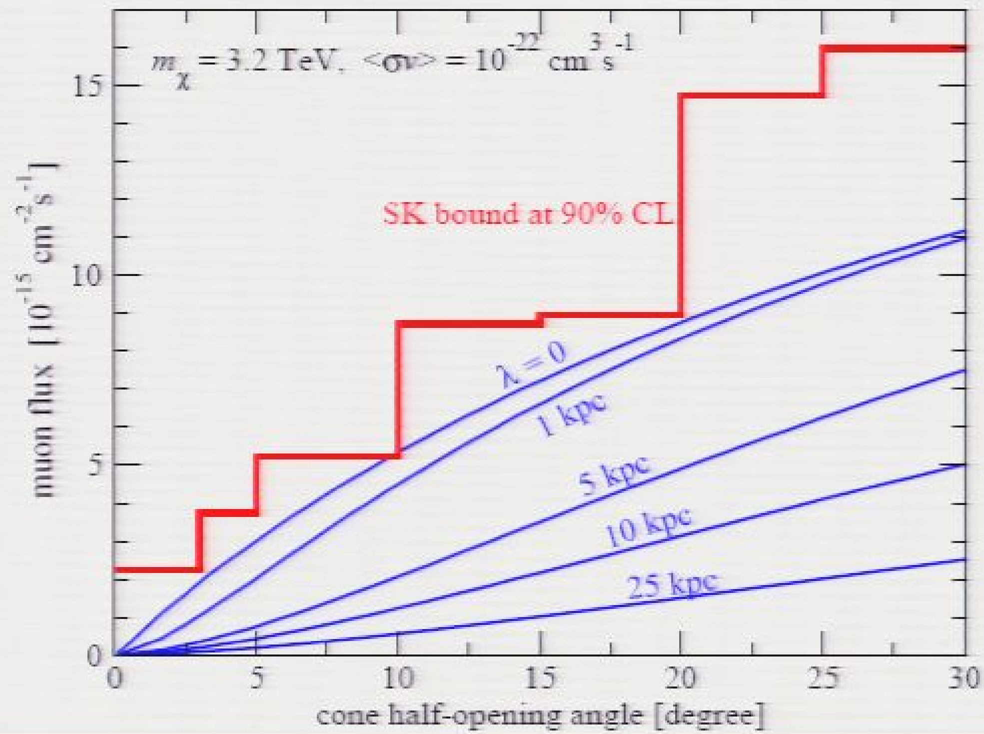
comparison with data





Neutrino bounds

- Super-Kamiokande: upper limit on ν induced upward going muon flux from various extra-terrestrial sources
- potentially relevant for LLP scenario since 8 neutrinos/DM annihilation ($\chi\chi \to \phi\phi \to 2\mu^+ 2\mu^-$)



Can χ, ϕ be thermal relics?

- other constraints if χ a thermal relic and ϕ a meta-stable thermal relic
- LLP scenario interesting if $\lambda \gtrsim 10$ kpc, then

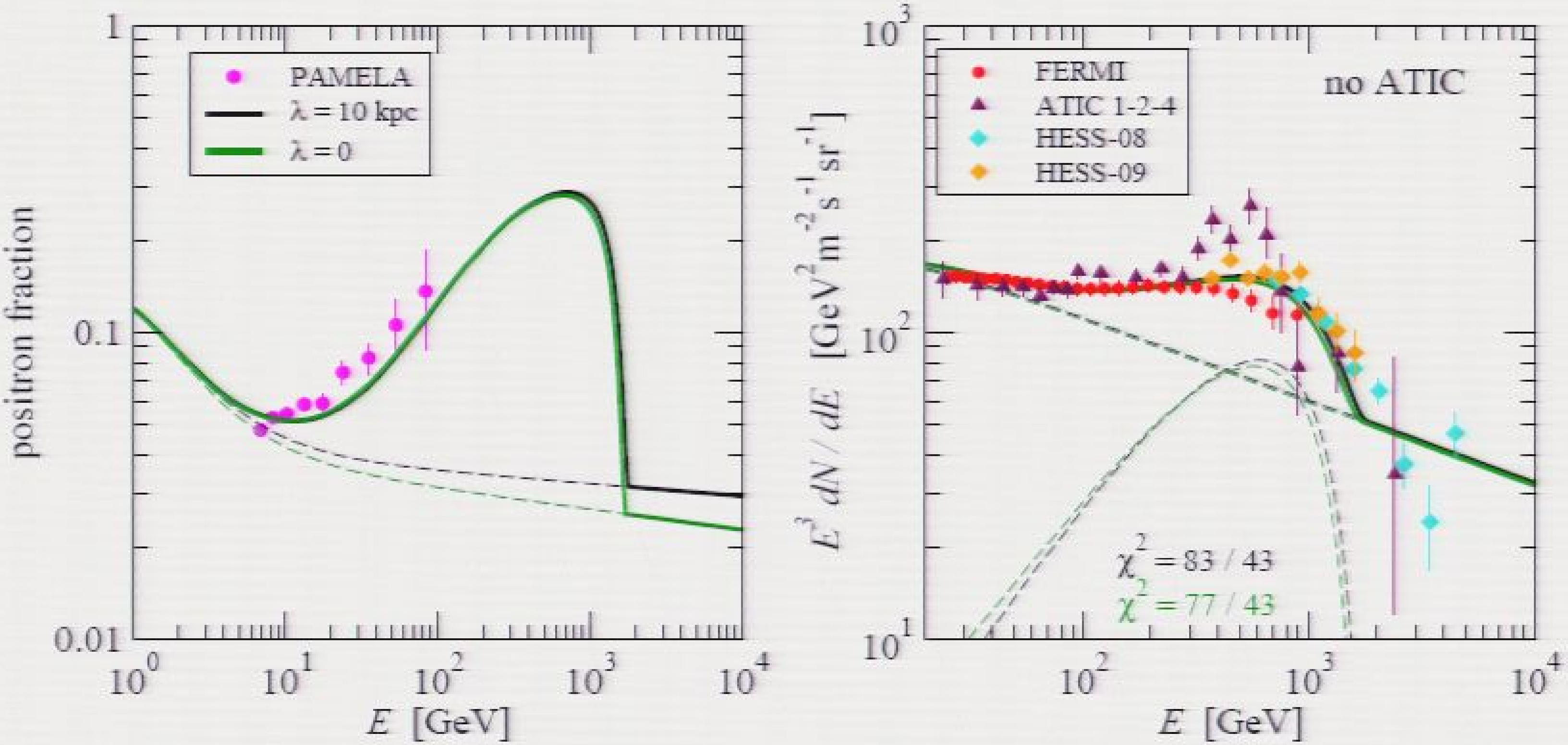
$$\tau_\phi = \frac{\lambda}{c\beta\gamma} \simeq \frac{10^{12}\,\mathrm{s}}{\beta\gamma}\left(\frac{\lambda}{10\,\mathrm{kpc}}\right).$$

- such late decaying relics modify light element abundances $\Rightarrow \rho_\phi \lesssim 10^{-3}\rho_\chi$
- for $\tau \gtrsim 10^{13}$ s constr. from diffuse gamma ray bckg.
- ratio $\sigma_\chi^{\mathrm{ann}}/\sigma_\phi^{\mathrm{ann}}$ must be of order 10^{-3} or smaller
- an open exercise in model building

Conclusions

- have provided two scenarios with metastable particles
- they solve the problems for annihilating DM explanation of cosmic ray anomaly
  - the large boost factors
  - the lack of DM photon signal from galactic center

comparison with data



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