Cosmic ray anomaly

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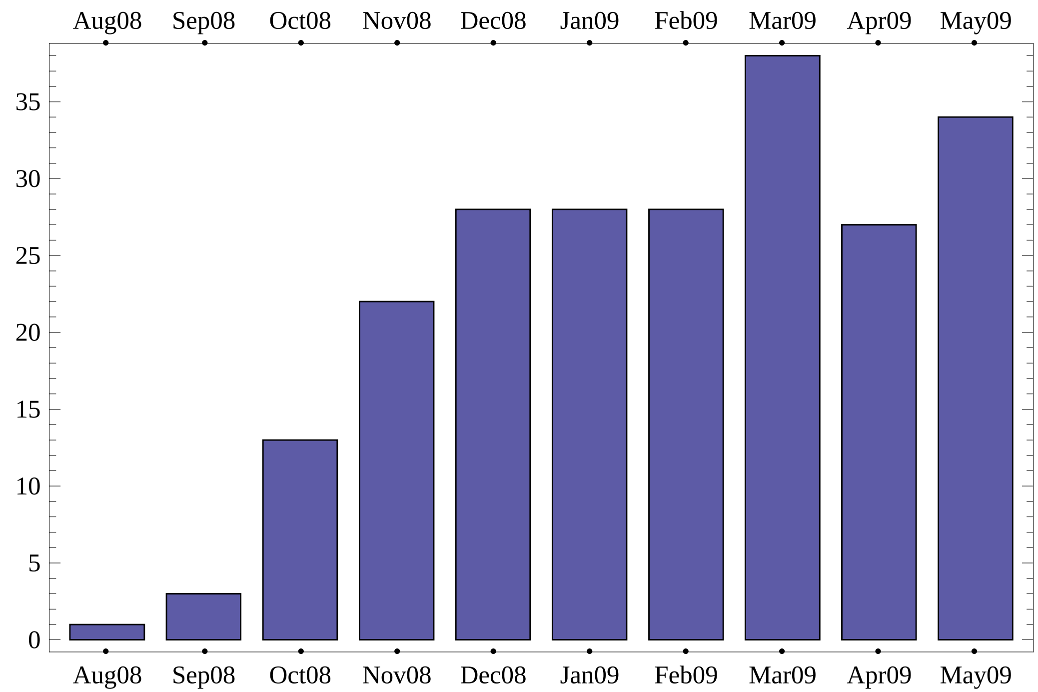
CERN

Lots of activity

- Pamela data (0810.4995) appeared on arXiv Oct. 28
- by now 200+ citations



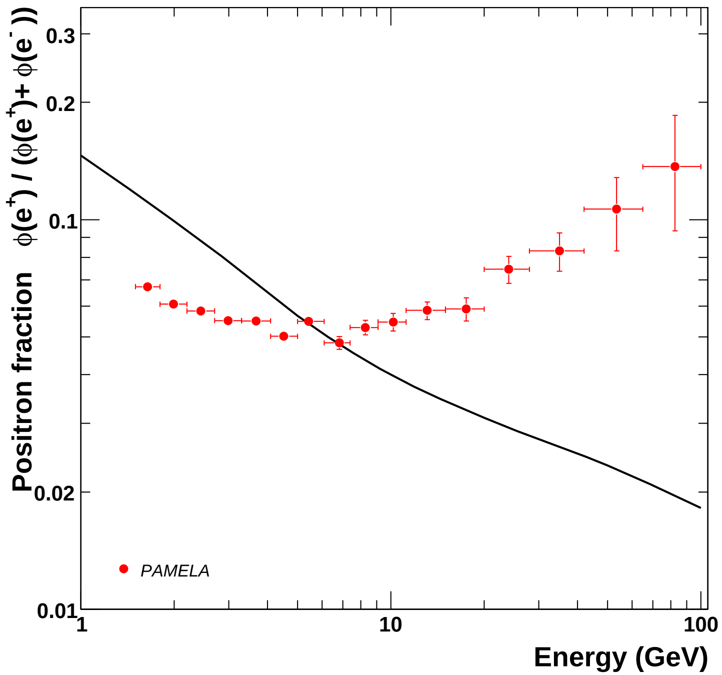
- my excuse: Fairbairn, JZ (0810.4147)
  Rothstein, Schwetz, JZ (0903.3116)

Outline

- Data: Pamela, ATIC, Fermi, HESS
- explanations
  - astrophysics
  - dark matter (annihilating, decaying)
- challenges for annihilating DM
  - boost factors
  - annihilation modes
  - photon flux constraints
- proposed solutions

Pamela-positrons

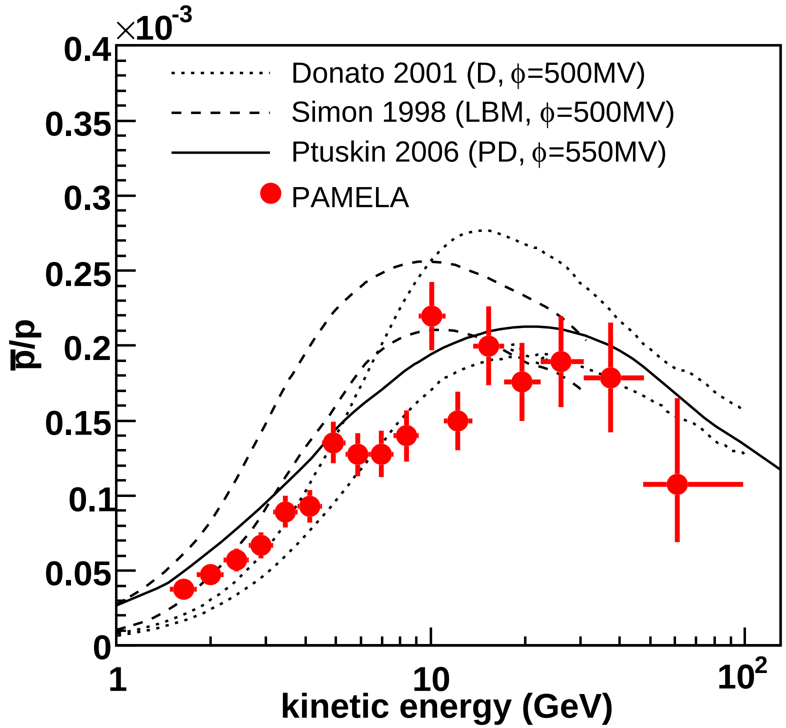
- PAMELA - satelite mission, start June 2006 0810.4995
- turn-up in the positron fraction above $10\mathrm{GeV}$
- comparison with the expected background (secondary production - Moskalenko& Strong [Galprop])
- low energy (< 10 GeV) sensitive to solar modulation



Pamela-antiprotons

0810.4994

- no excess seen in the antiproton fraction spectrum

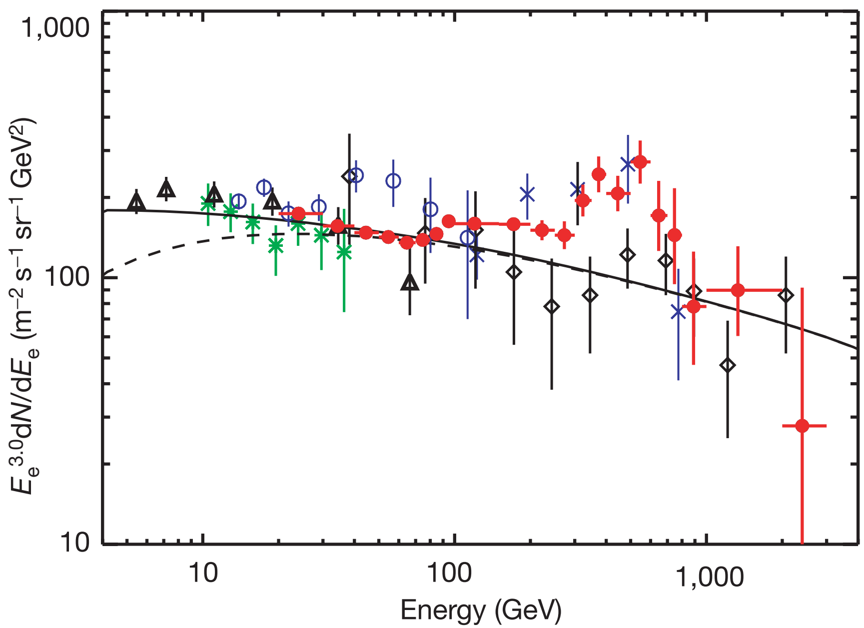


LBM=Leaky Box Model, D=Diffusion model, PD=Plain Diffusion model [Galprop]

ATIC-electrons+positrons

Nature, 456, 07477

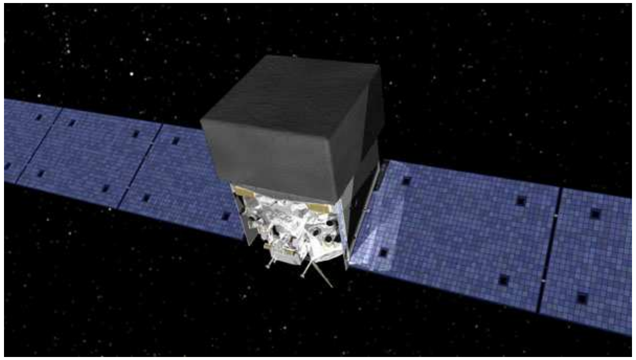
- long duration balloon flights over Antarctica
- released data Nov.08: $\gtrsim 4\sigma$ excess in $\Phi(e^+ + e^-)$



- ● ATIC 1+2
- $*$ AMS
- △ HEAT
- ○ BETS
- × PPB-BETS
- ◇ emulsion chambers
- — GALPROP prediction
- – – estimate of solar modulation

New data

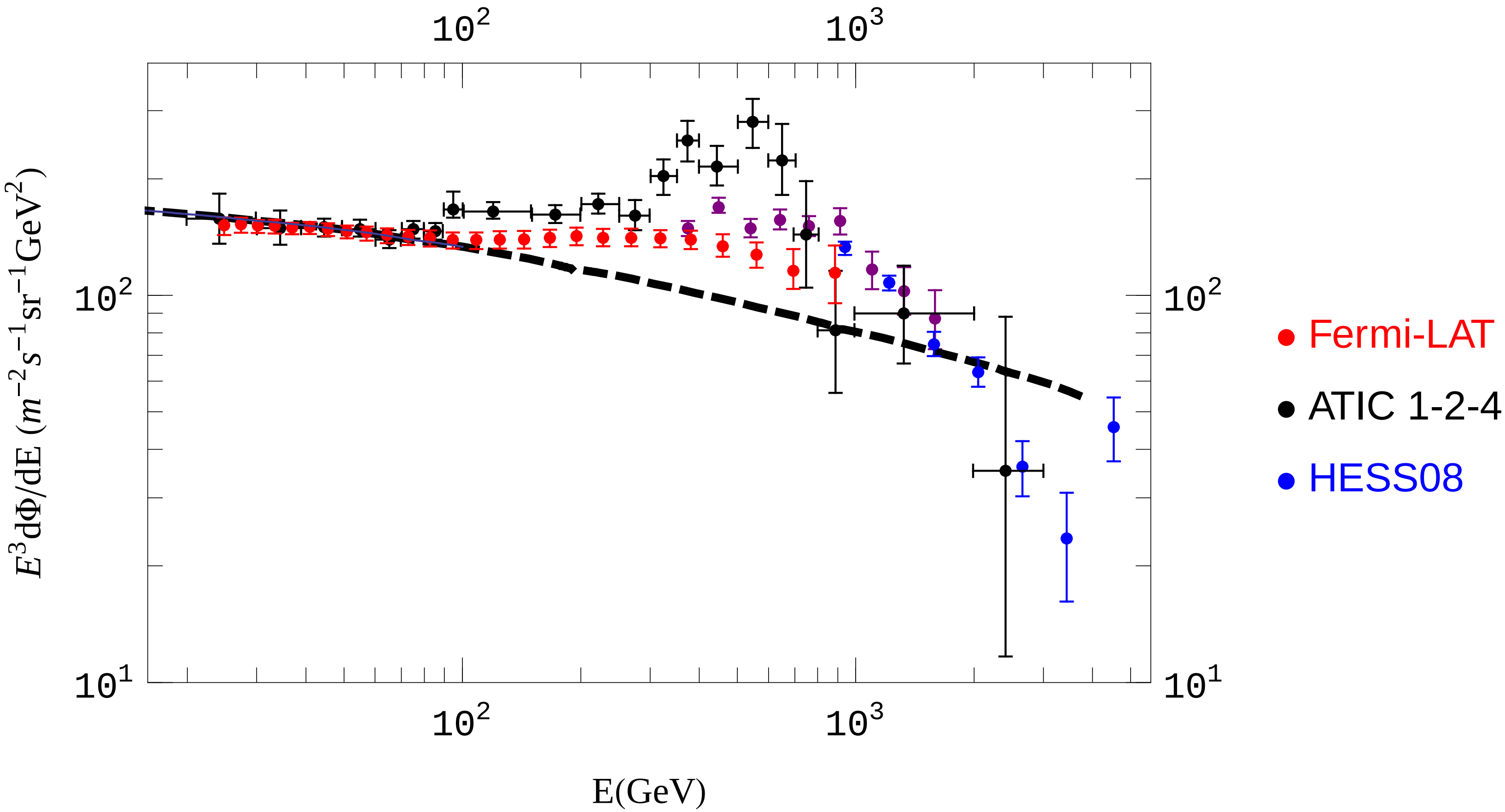
- Fermi-LAT:
  satellite mission, start June 2008, will run 5+ years, released $e^+ + e^-$ data, 0905.0025



- H.E.S.S.: 4 Čerenkov telescopes in Namibia, $E_{\text{thr}} > 100\text{GeV}$, 0811.3894,0905.0105

- ATIC-4: preliminary results shown at "Tango in Paris" worshop, May09, significance increased to 5.1σ

The discrepancy



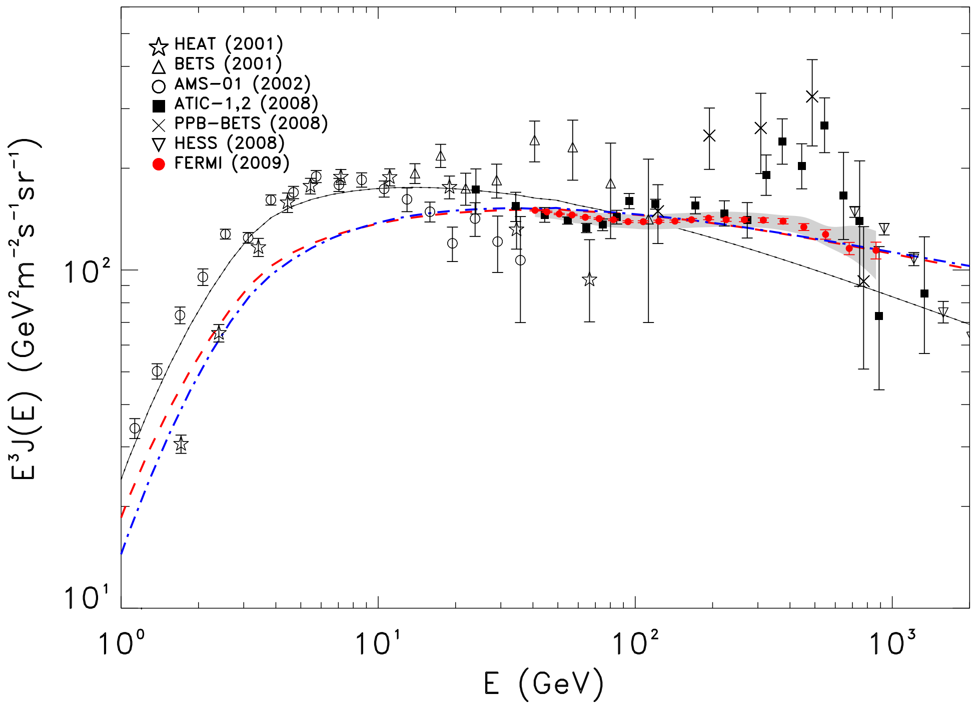
Interpretations

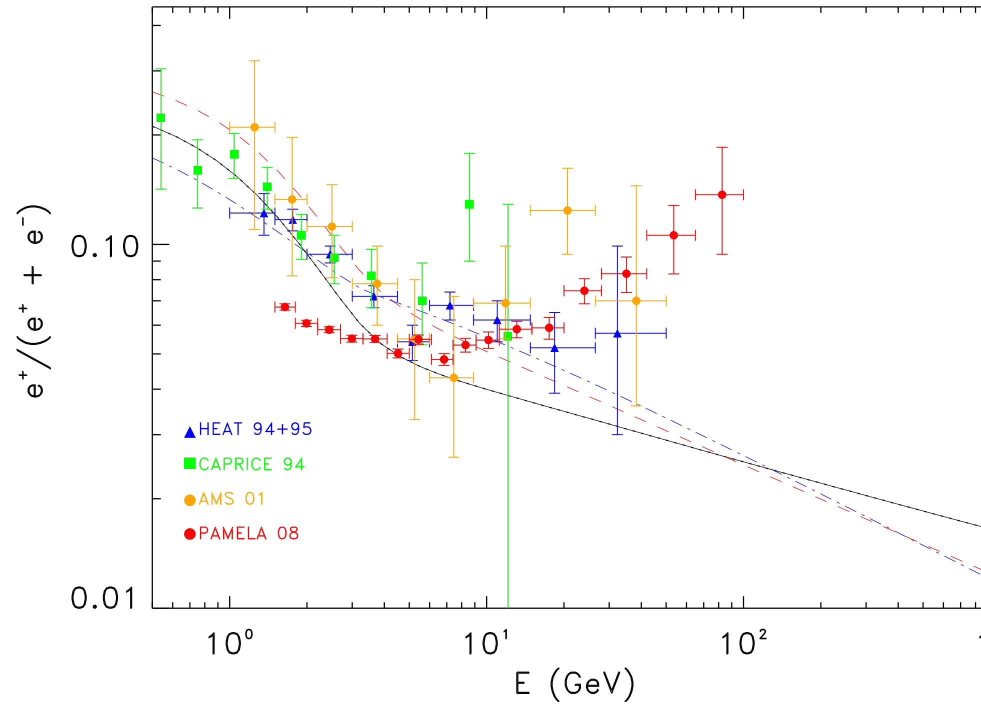
- astrophysical sources: local supernovae remnants (pulsars)?
- signal of nongravitational dark matter interactions?

Astrophysical source?

- change the el. injection spectrum (make harder)
  - problem with low energy $e^+ + e^-$ (below 10GeV)
  - PAMELA rise completely unexplained

Grasso et al., 2009





Astrophysical source?

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Grasso et al., 2009

- a local pulsar suggested as a source

Hooper, Blasi, Serpico, 2008; Serpico 2008;+ refs in

  - mature pulsars with age $\sim 10^5$ years, $d \sim \mathrm{few}100pc$
  - Monogem, Geminga require relatively high eng. conversion to e^+e^- flux
- in addition more distant mature pulsars
- new reacceleration mechanism at production suggested

Blasi, 2009; Blasi, Serpico, 2009

DM signal?

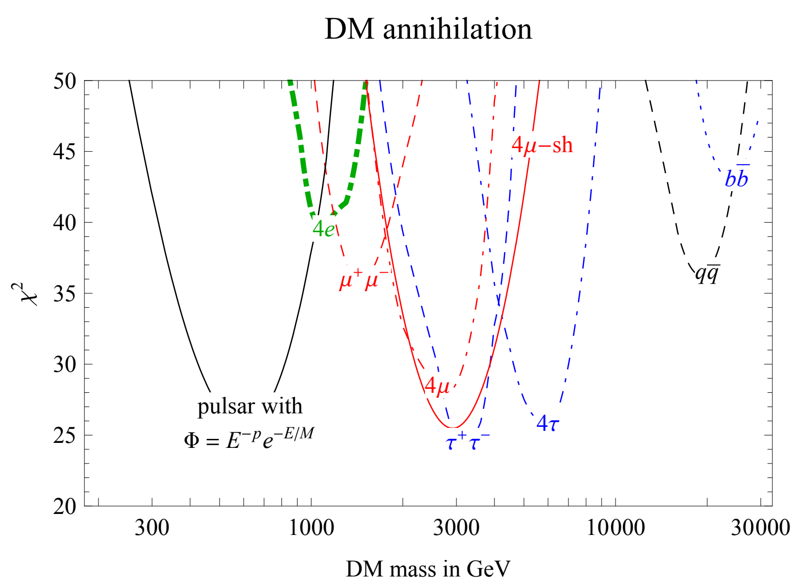
- assume that the signal due to annihilation

$$\chi + \chi \to X_{SM}$$

where $X_{SM} = e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \bar{q}q, \bar{b}b, \bar{t}t, WW, ZZ, hh$

- recent model independent analysis
  - $\sim 1\text{TeV}$ DM with $\chi + \chi \to l^+l^-$
  - for $\chi + \chi \to \text{hadrons}$ one has $m_{DM} > 10\text{TeV}$

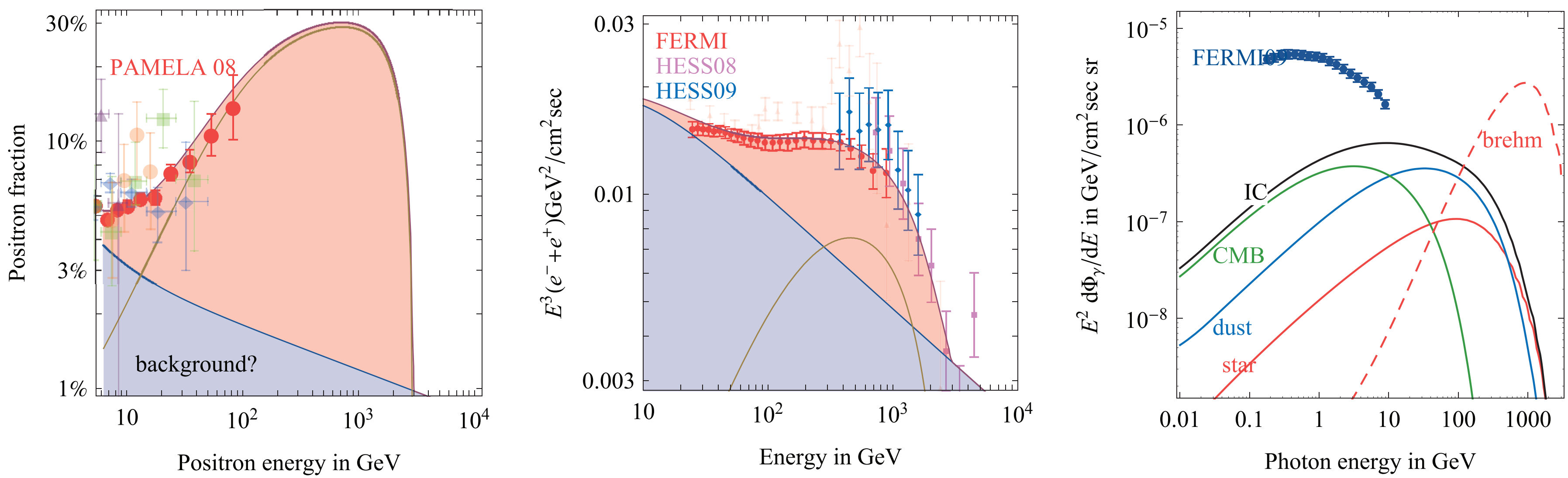
Meade et al. 0905.0480



~ TeV DM

Meade et al. 09

DM with $M = 3.$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 2.0 \times 10^{-22}$ cm^3/s



Challenges

several challenges if DM annihilation $\chi\chi \to X_{SM}$

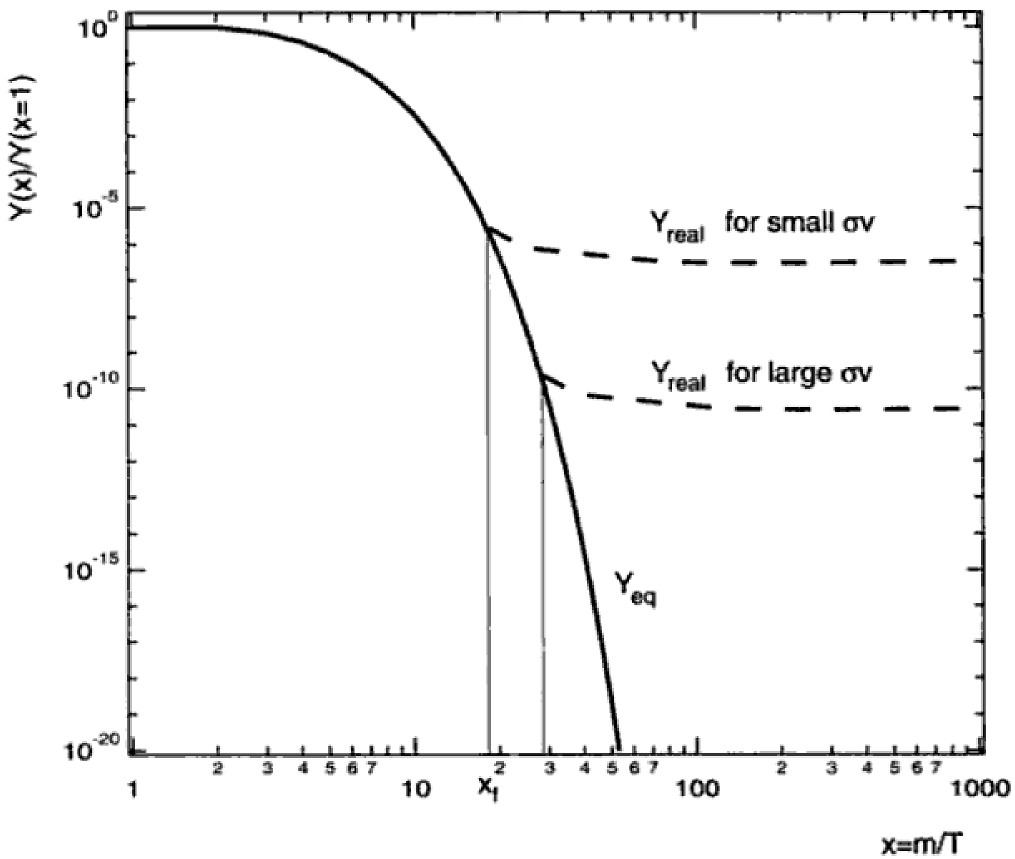
- signal in leptons (e^+) but not in quarks ($\bar{p}$)
- the annihilation cross section larger than expected for a thermal relic
- electrons in the final state $\to$ energetic photons
  - problem with HESS observations of galactic center, galactic ridge

Large cross sections

Thermal relic

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

$Y = n/s$



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

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

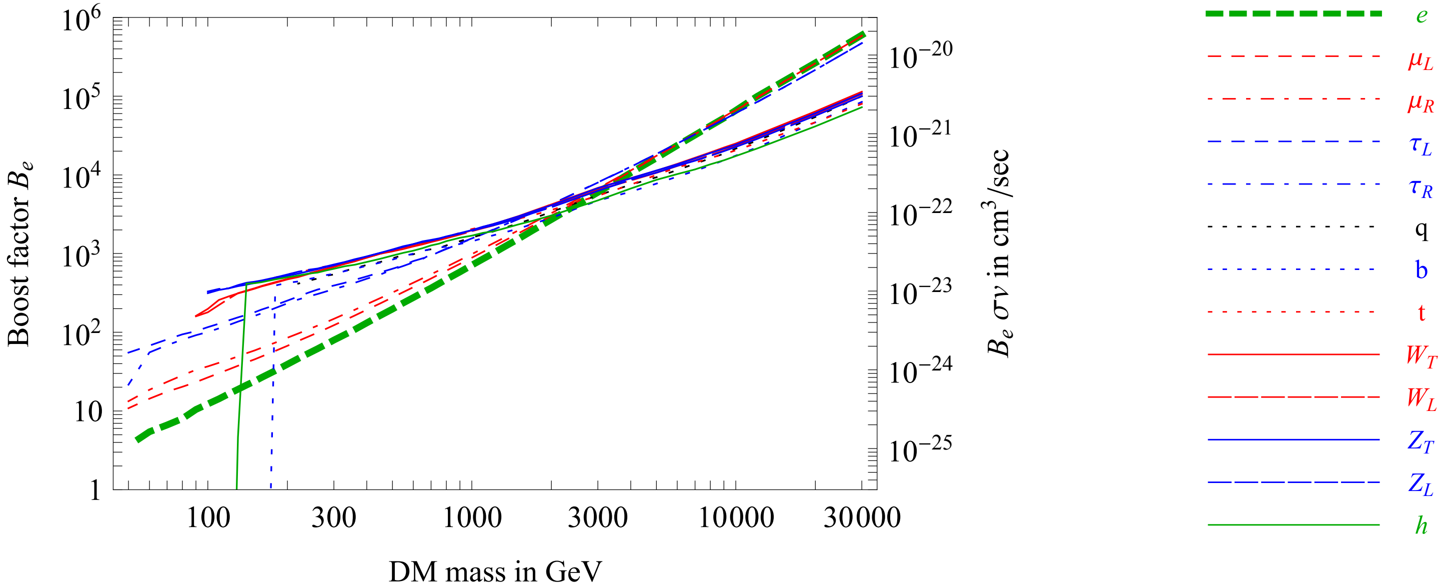
- define a "boost factor"

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

Boost factors

- model independent (EFT) analysis for Pamela

Cirelli, Kadastik, Raidal, Strumia 2008



- astrophysical boost factor (due to DM halo substructure) below 10
- $\Rightarrow$ if DM annihilation then not a simple thermal relic

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

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

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

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

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

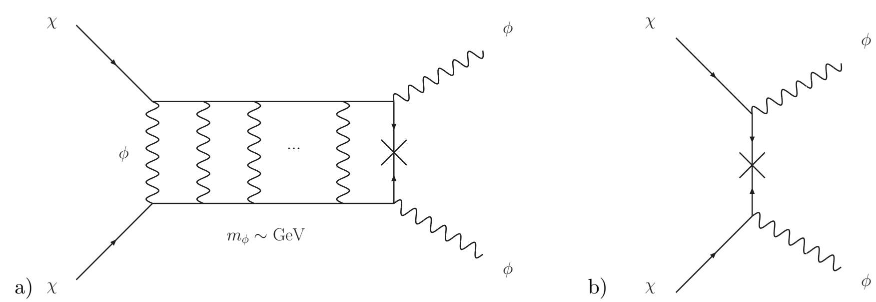
Large boost factors

- 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: 2DM 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

Sommerfeld enhancement

Hisano et al. 03-06; Cirelli et al. 07-08; Pospelov, Ratz 08;Arkani-Hamed et al. 08; Han 08; Fox, Poppitz 08; Pospelov 08; Bai, Hambye 08; Nomura, Thaler 08; Ackerman et al 08;

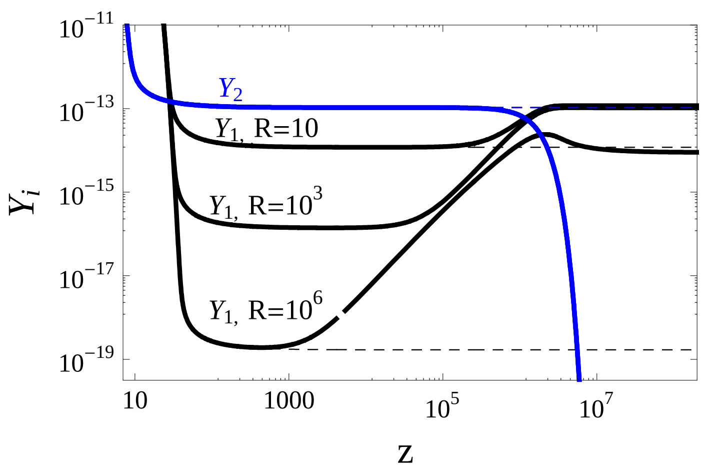
- seems the most popular model-builders' choice
- attractive interaction enhances annihilation in NR limit



- leads to a Yukawa potential $V(r) = -\alpha e^{-m_\phi r}/r$
- annihil. $\chi + \chi \to X_{\rm SM}$: $\sigma v \sim \pi \alpha'^2/M^2$
  - from relic abundance $\alpha' \sim 0.03(M/1{\rm TeV})$
- $v^2 \gg \alpha m_\phi/M$: $\Rightarrow 1/r$ potential $\Rightarrow S = \frac{\pi\alpha}{v} \sim 10^2 \frac{\alpha}{0.03}\frac{10^{-3}}{v}$
- larger boost possible, if zero energy resonance

2-component DM

- an example of DM not a simple thermal relic Fairbairn, JZ, 08
- 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 signal
  - this setup decouples $\langle \sigma_A v \rangle_F$ from $\Omega_{\rm DM}$



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

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

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

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

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

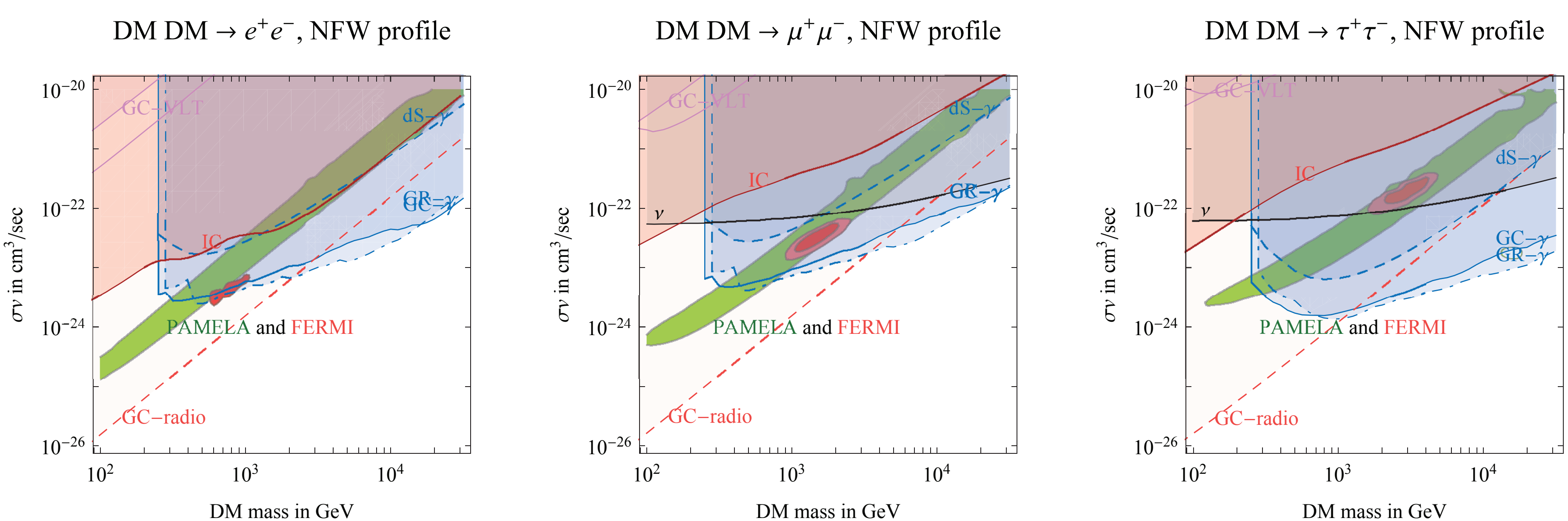
- note: the allowed range includes see-saw scale
- if produced at LHC would fly macroscopic distance

Gammas from galactic center

High energy photons

- annihilation into charged particles ⇒ inevitably high energy gamma from bremsstrahlung
- a curse and a blessing
  - a signal of DM (escpecially 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

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

Long lived intermediate states

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

- 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

Some formalism

- 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

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

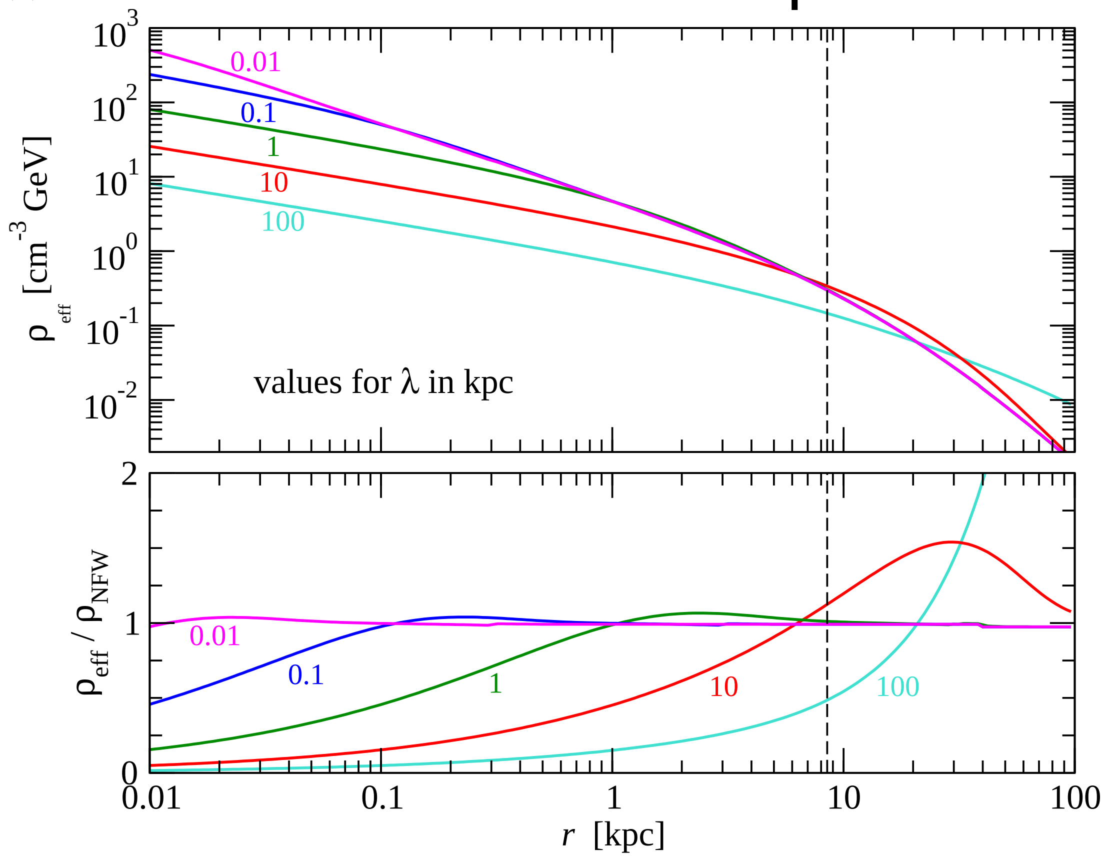
$\rho_\odot = 0.3\,\text{GeV}\,\text{cm}^{-3}$ and $r_\odot = 8.5$ kpc

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

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

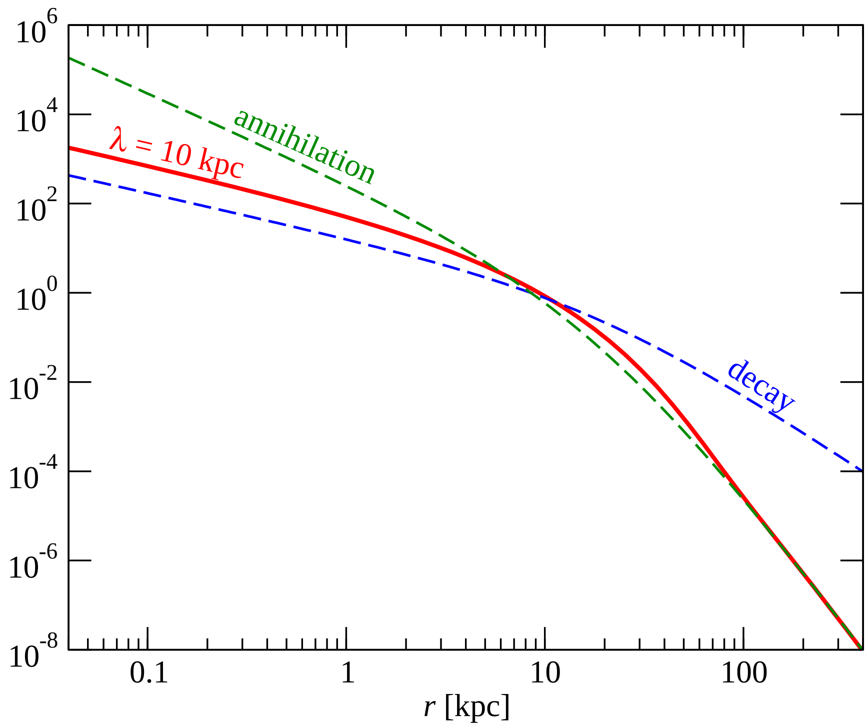
effective density

- 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



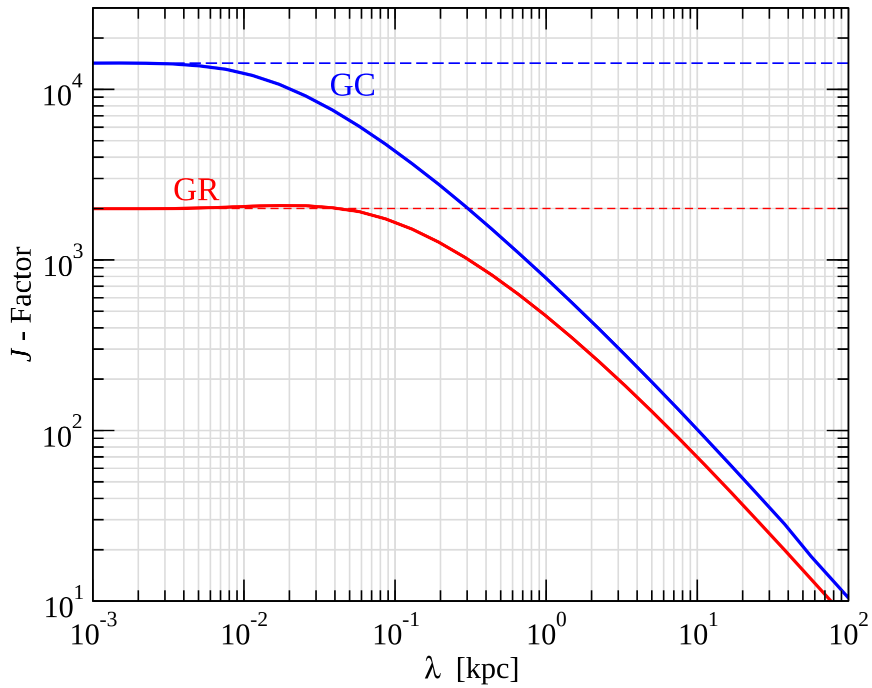
annih. vs decay

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



High energy photons

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

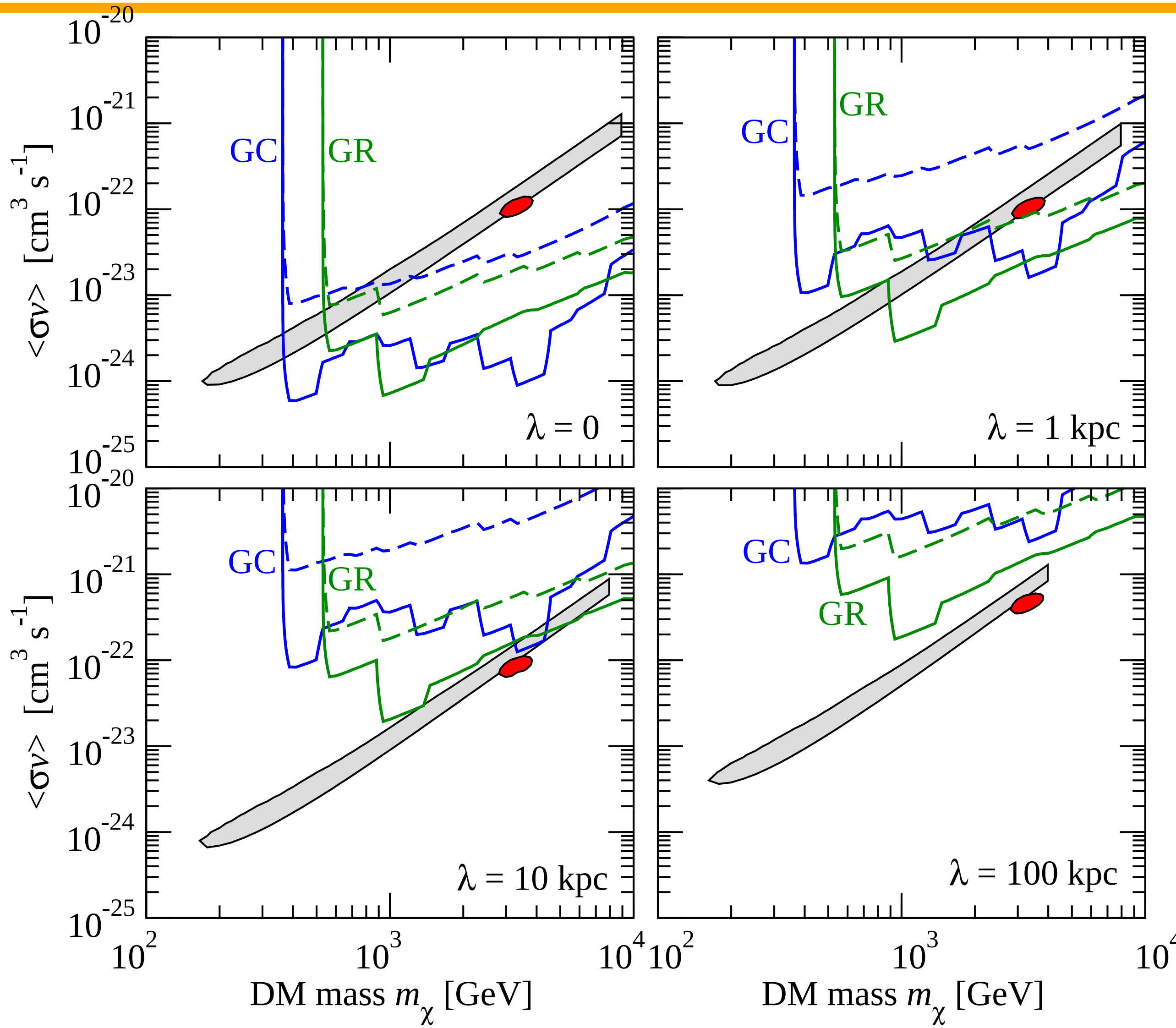


GC=Galactic center, GR=Galactic Ridge

effect on 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
- as an illustration on pre-Fermi data

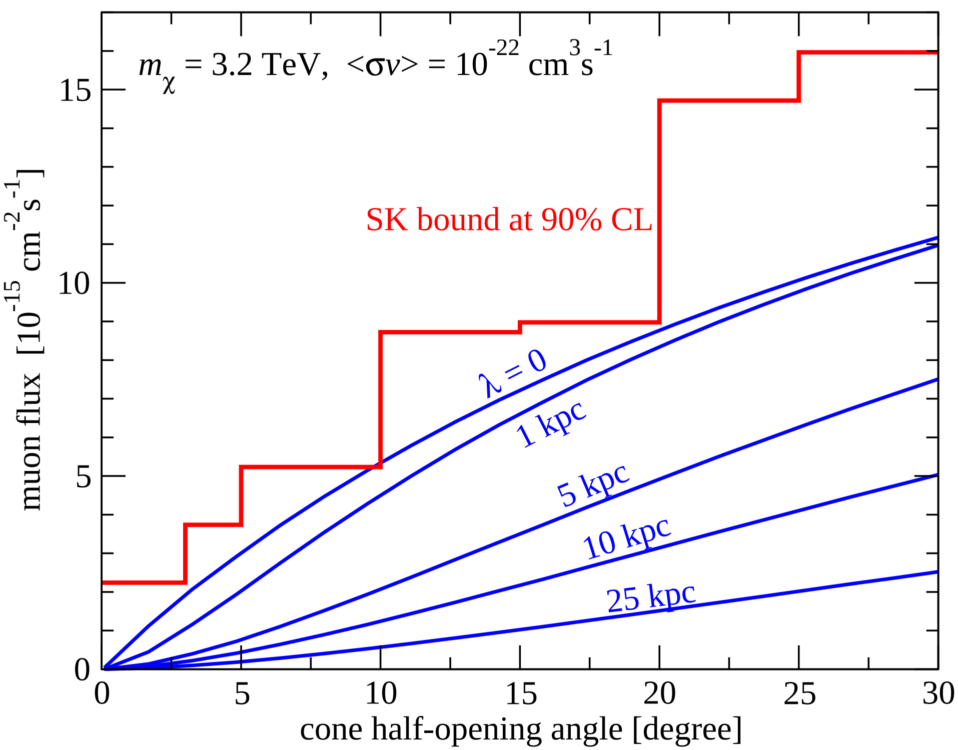
effect on fits



minimum $m_\chi = 3.3\mathrm{TeV}$, $\langle \sigma v \rangle 1.1 \times 10^{-22} \mathrm{cm}^3 \mathrm{s}^{-1}$

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?

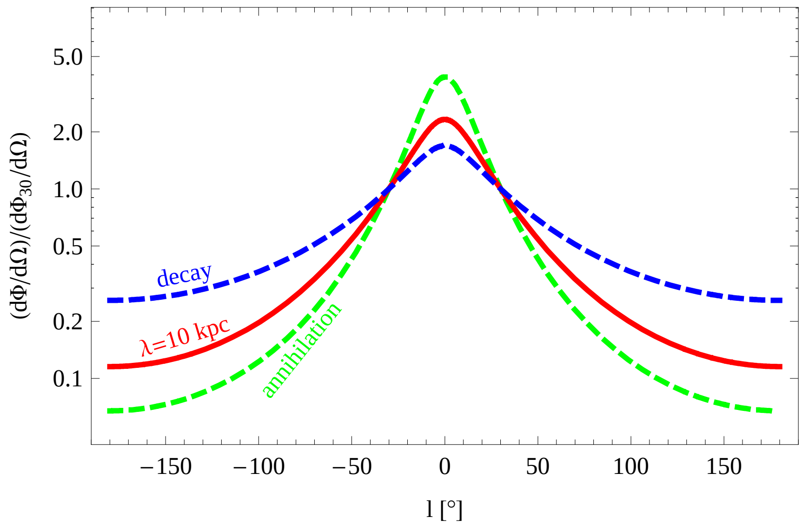
- other constraints if χ a thermal relic and ϕ a meta-stable thermal relic
- LLP scenario interesting if $\lambda \gtrsim 10$ kpc, then

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

- 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
  - good news for LHC, large cross sections
- an open exercise in model building

Distinguishing scenarios

- how can one distinguish DM explanations from pulsars?
  - anisotropy in cosmic electron flux (at 1% level measurable by FERMI)
  - diffuse gamma signal away from galactic plane
  - a line in photon signal at TeV
  - a signal in antideuterons or neutrinos
- distinguishing different DM explanations
  - precise measurement of diffuse gamma
  - collider signals



Concluding remarks

- 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

Decaying DM

Chen, Takahashi, Yanagida, 08; Ibarra, Tran 08; Hamaguchi, Nakamura, Shirai
Yanagida 08; Yin, Yuan, Liu, hang, Bi, Zhu 08

- a DM that is metastable on cosmological time scales
- typically $\tau \sim 10^{26} s \Leftrightarrow \Gamma \sim 10^{-51}\mathrm{GeV}$ needed to explain PAMELA/ATIC
- if from dim $n+4$ operator

$$\Gamma \sim \frac{m^{2n+1}}{16\pi\Lambda^{2n}}$$

- for dim 5 op.: $\Lambda \sim 10^{29}\mathrm{GeV}\left(\frac{m}{1\mathrm{TeV}}\right)^{3/2}$
- for dim 6 op.: $\Lambda \sim 10^{16}\mathrm{GeV}\left(\frac{m}{1\mathrm{TeV}}\right)^{5/4}$

The leptonic mode challenge

- kinematical suppression: used in "secluded" models of DM
  - two (or more) species of DM, one heavy χ and one light ϕ
  - the positrons signal from

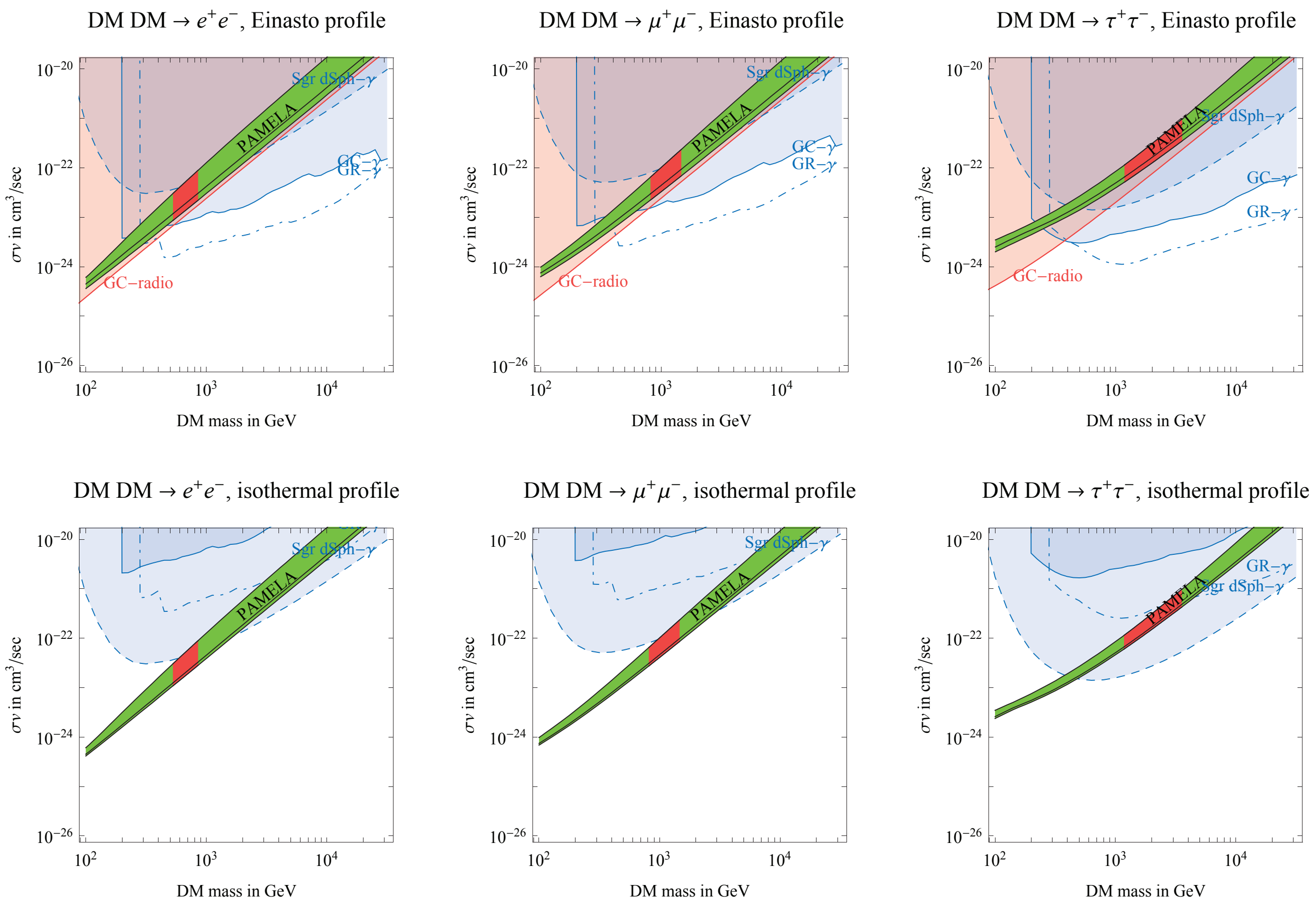
$$\chi + \chi \to \phi\phi \to X_{SM}$$

  - take $m_\phi < m_p$ then $\phi \to pX$ not possible
- leptophilic models: here the DM (or ϕ in "secluded" models) couples only to leptons due to a symmetry

DM annihilation and γ

Bertone, Cirelli, Strumia, Taoso, 0811.3894

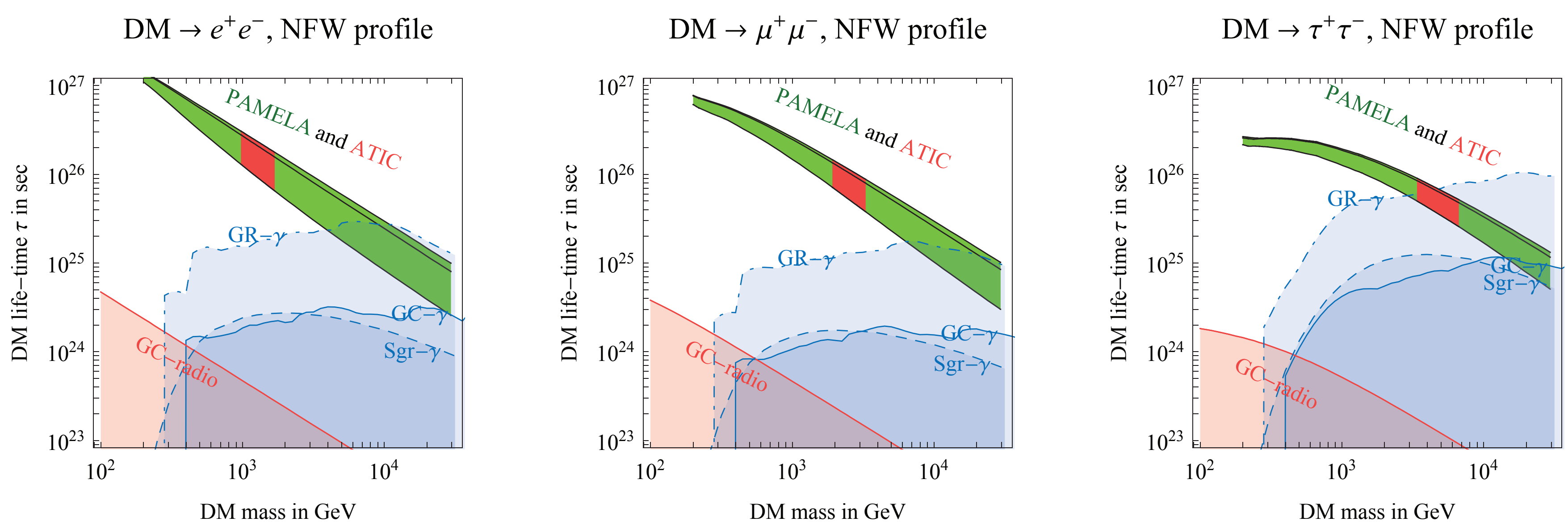
- $\chi\chi \to e^+e^-$ associated with bremsstrahlung+ sinchrotron radiation
- in conflict with HESS for most popular DM profiles



decaying DM and γ

Nardi, Sannino, Strumia, 0811.4153

- less problematic, the reason:
  - for decay $\Phi_{e^+} \propto \rho_{DM}$, while for annih. $\Phi_{e^+} \propto \rho_{DM}^2$
  - $\Rightarrow$ higher signal from dense regions (center of the galaxy, etc)
- for Navarro, Frenk and White profile:



Conclusions

- a very active field - are we seeing a DM signal?
- presented a 2 component DM model that can explain large "boost factors"