High energy cosmic rays from dark matter decay

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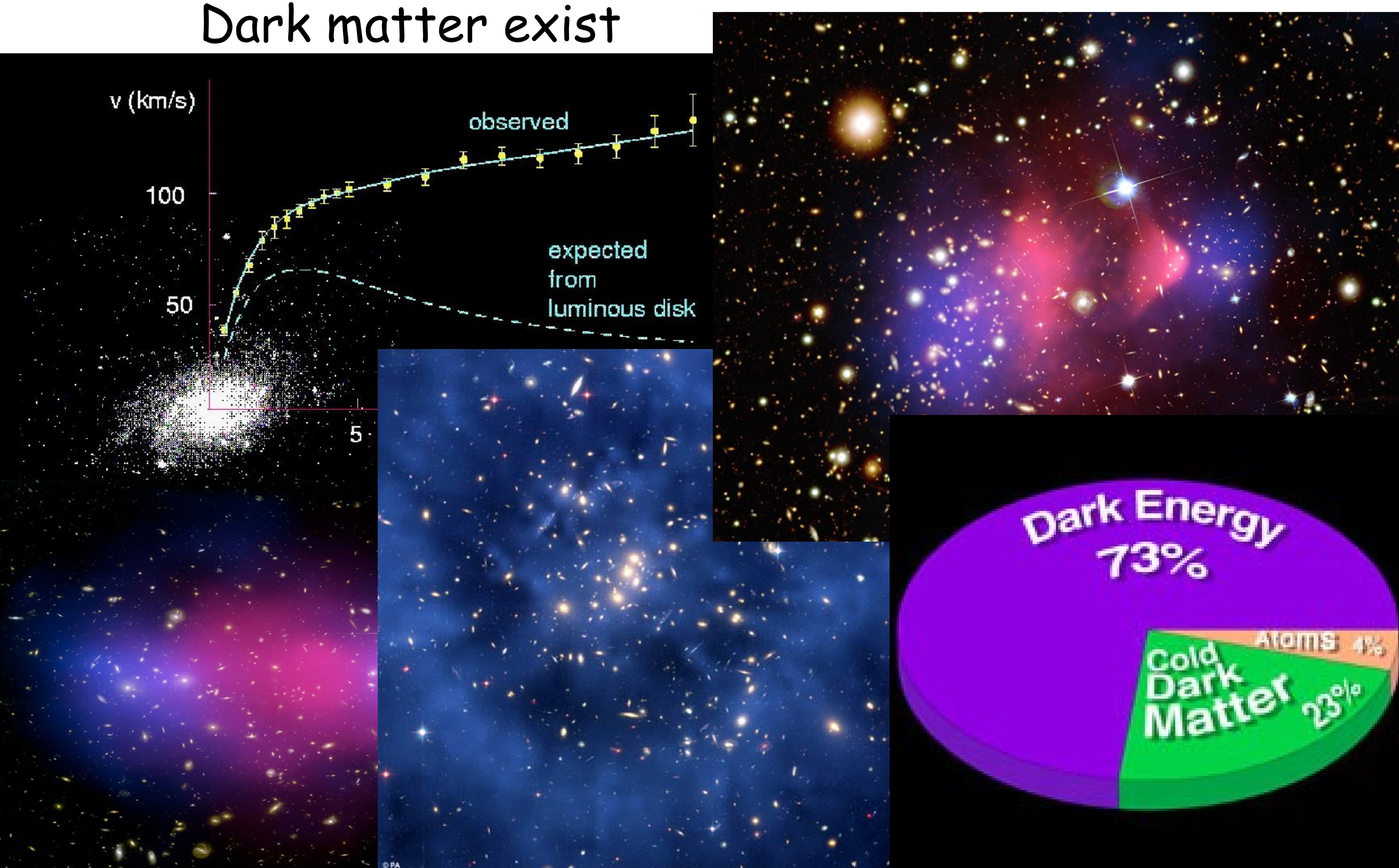
Technical University of Munich

Based on collaborations with Laura Covi, Michael Grefe, David Tran and Christoph Weniger.

BCTP Workshop
Bad Honnef
4th October 2010

Introduction

Dark matter exist



Introduction

Dark matter exist

What is the dark matter?

The dark matter is constituted by particles which have:

- Interactions with nuclei not stronger than the weak interaction.
- No baryon number.
- Low velocity at the time of decoupling (“cold” or may be “warm”).
- Lifetime longer than the age of the Universe.

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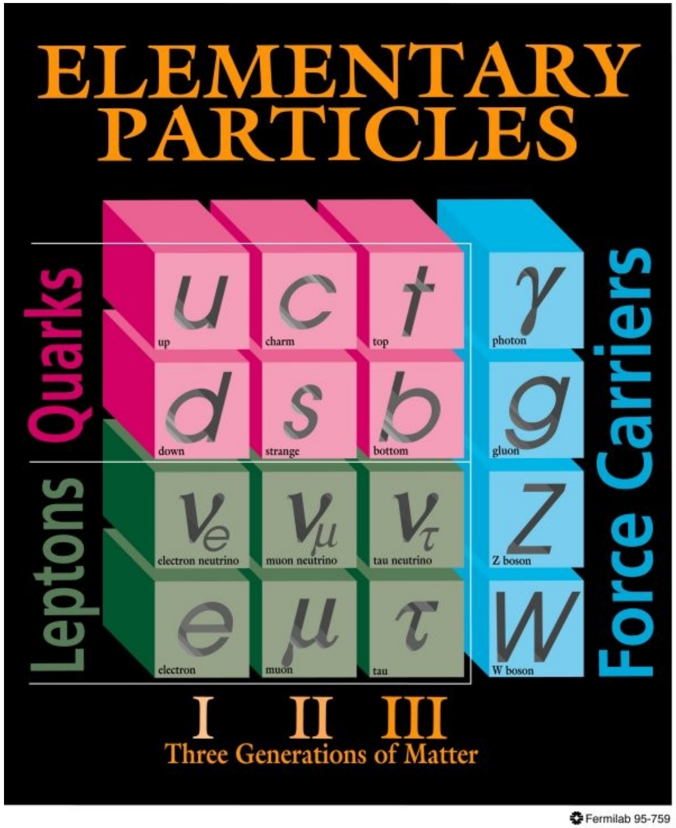

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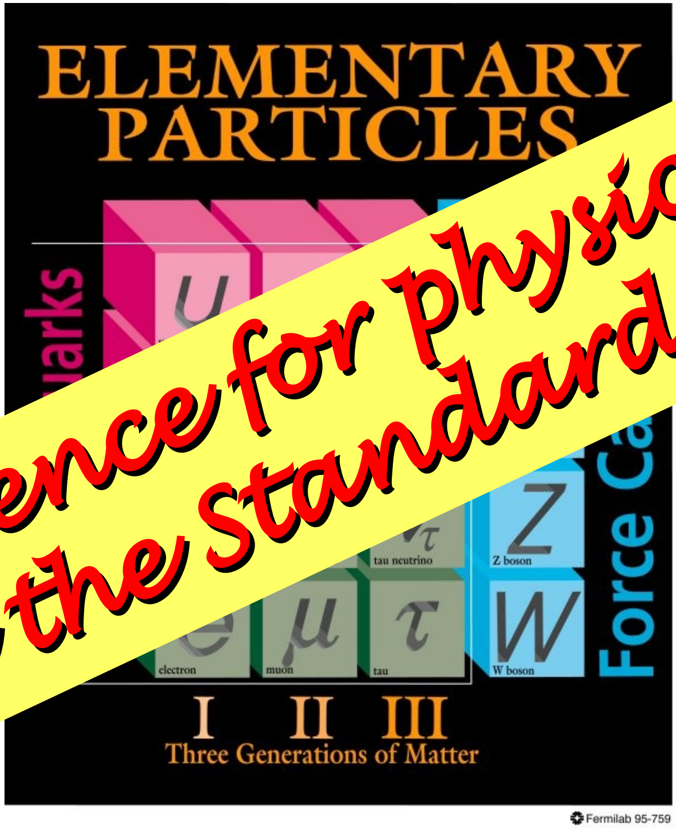


Evidence for physics beyond the Standard Model

Citation: K. Nakamura *et al.* (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	(2.00 ± 0.25) $\times 10^{-4}$		30
$e^+\nu_e$	[b]	(1.230 ± 0.004) $\times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	(7.39 ± 0.05) $\times 10^{-7}$		70
$e^+\nu_e\pi^0$		(1.036 ± 0.006) $\times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		(3.2 ± 0.5) $\times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		< 5 $\times 10^{-6}$	90%	70

DARK MATTER

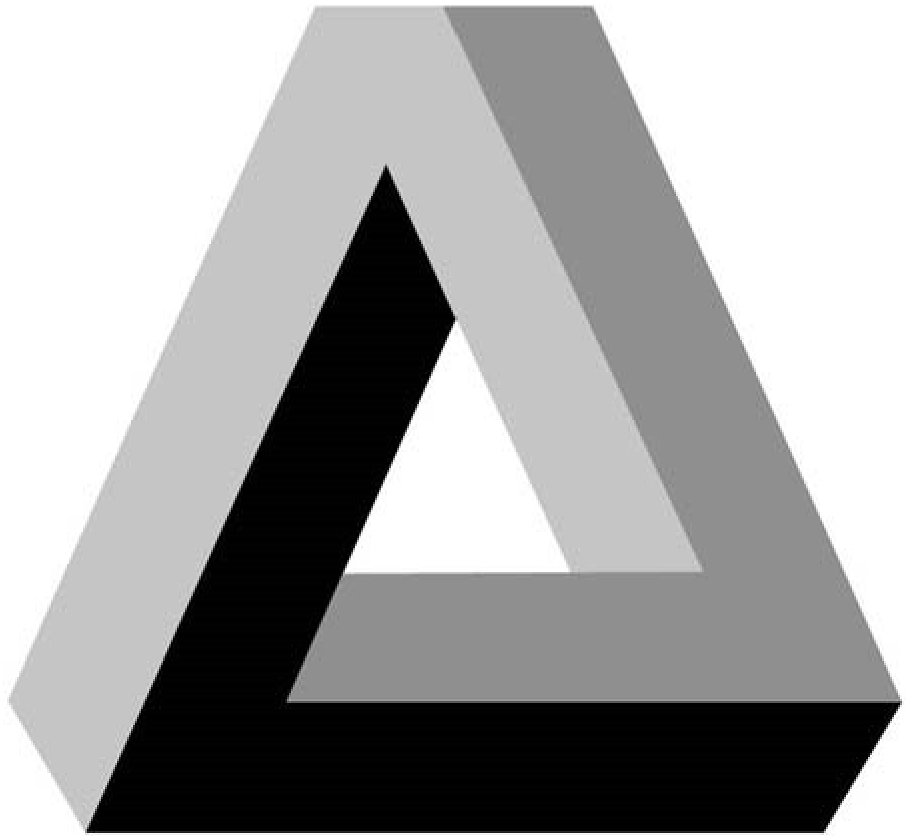
$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

Direct detection

DM nucleus $\rightarrow$ DM nucleus



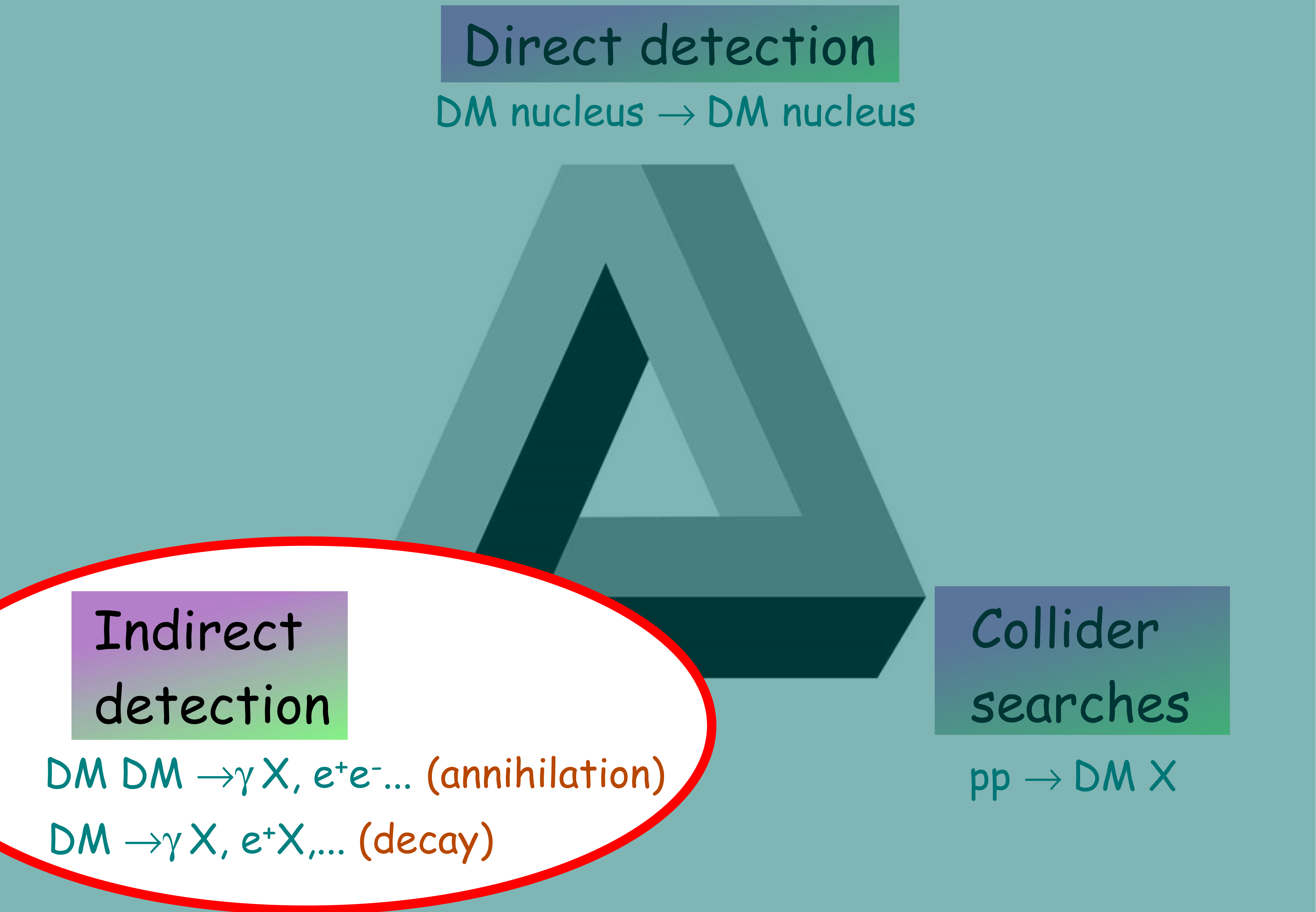
Indirect detection

DM DM $\rightarrow \gamma$ X, e^+e^-... (annihilation)

DM $\rightarrow \gamma$ X, e^+X,... (decay)

Collider searches

pp $\rightarrow$ DM X


Direct detection
DM nucleus → DM nucleus
Indirect detection
DM DM →γ X, e+e-... (annihilation)
DM →γ X, e+X,... (decay)
Collider searches
pp → DM X

nature

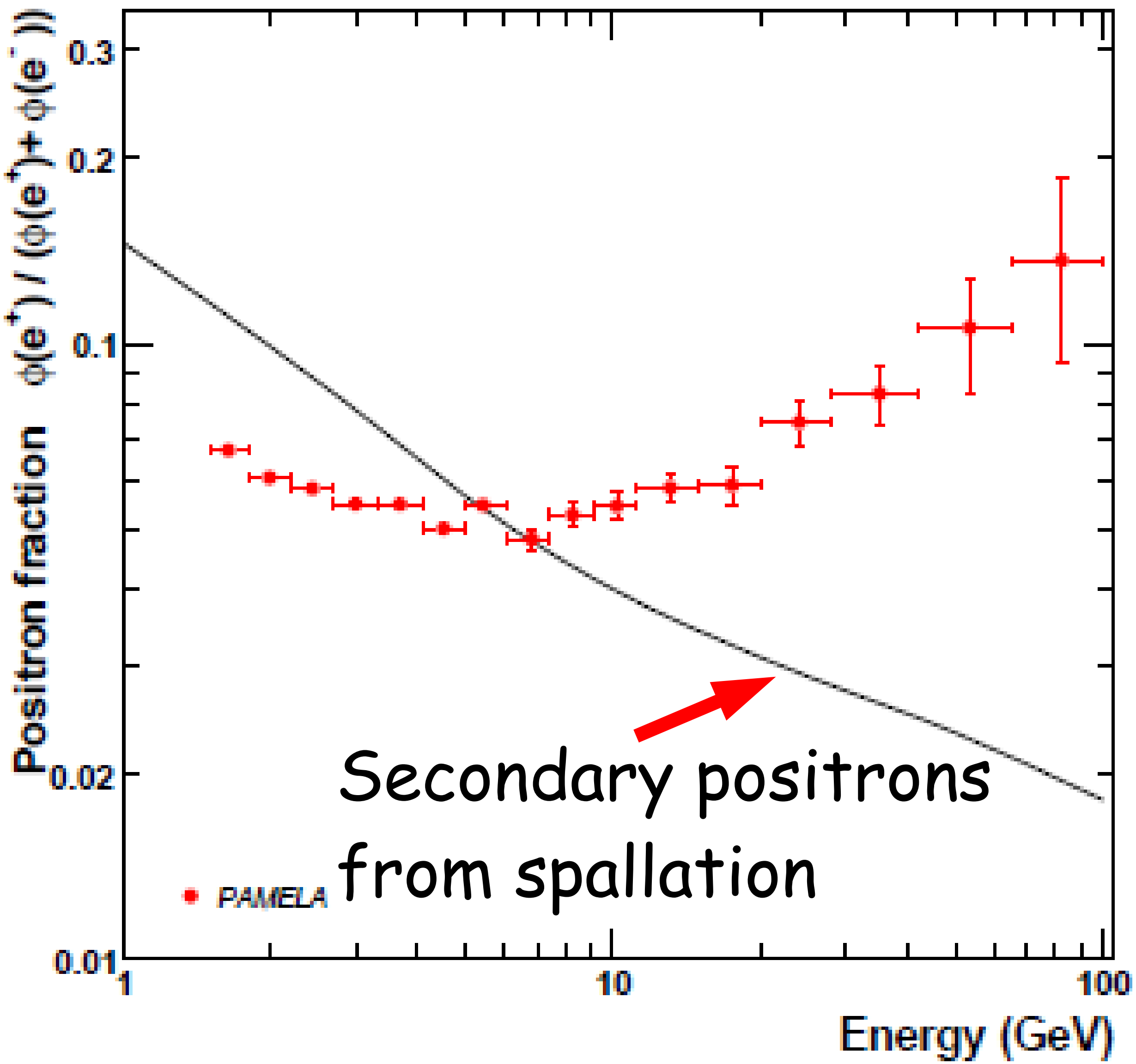
LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

Antiparticles account for a small fraction of cosmic rays and are known to be produced in interactions between cosmic-ray nuclei and atoms in the interstellar medium[1], which is referred to as a 'secondary source'. Positrons might also originate in objects such as pulsars[2] and microquasars[3] or through dark matter annihilation[4], which would be 'primary sources'. Previous statistically limited measurements[5–7] of the ratio of positron and electron fluxes have

calorimeter data. The proton-to-positron flux ratio increases from approximately 10^3 at 1 GV to approximately 10^4 at 100 GV. Robust positron identification is therefore required, and the residual proton background must be estimated accurately. The imaging calorimeter is 16.3 radiation lengths (0.6 nuclear interaction lengths) deep, so electrons and positrons develop well contained electromagnetic showers in the energy range of interest. In contrast, the majority of



Positron fraction φ(e⁺) / (φ(e⁺)+φ(e⁻))
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
PAMELA
Secondary positrons from spallation

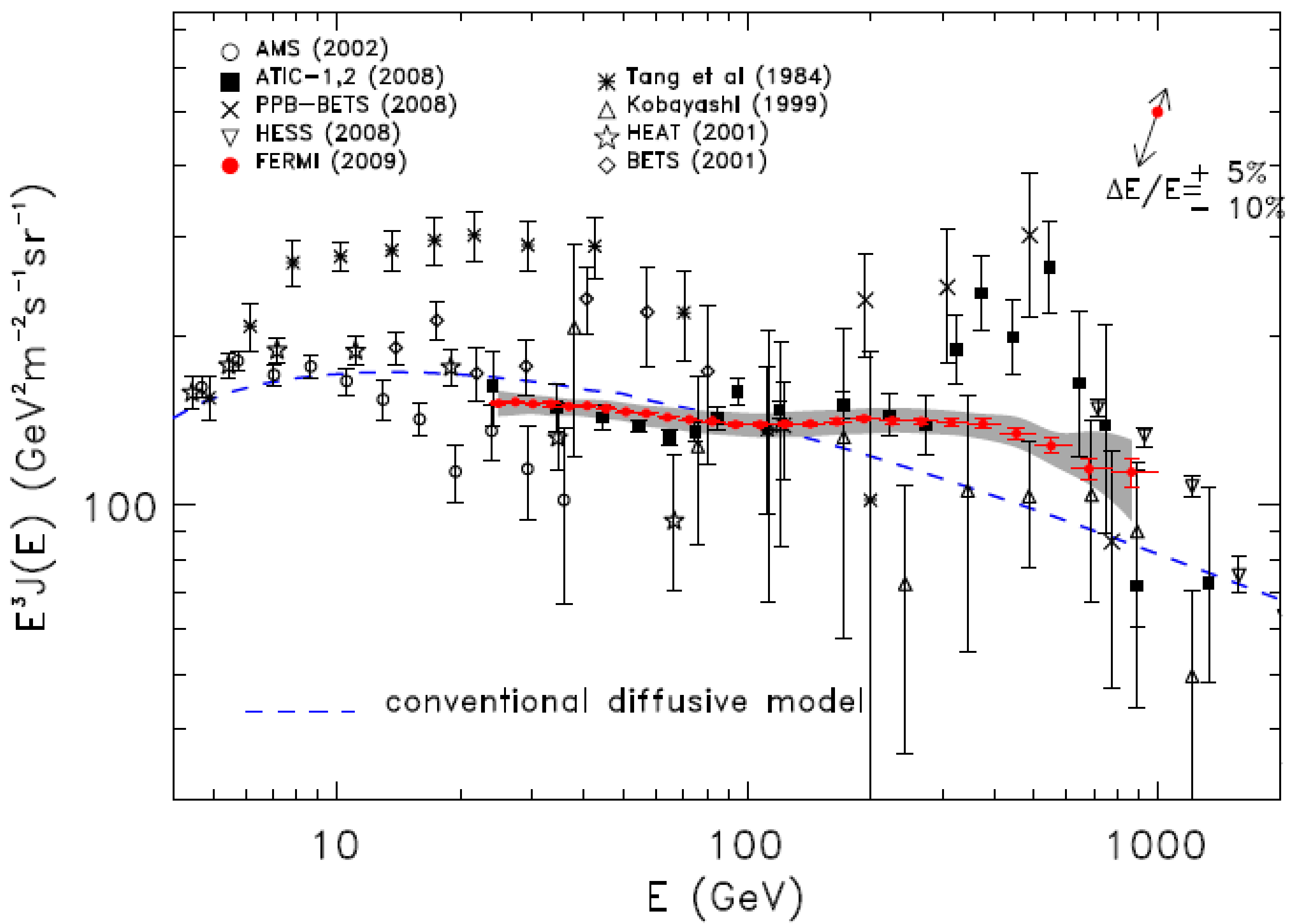
Selected for a Viewpoint in *Physics*
PRL **102,** 181101 (2009) PHYSICAL REVIEW LETTERS week ending 8 MAY 2009

Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope

A. A. Abdo,[1,2] M. Ackermann,[3] M. Ajello,[3] W. B. Atwood,[4] M. Axelsson,[5,6] L. Baldini,[7] J. Ballet,[8] G. Barbiellini,[9,10] D. Bastieri,[11,12] M. Battelino,[5,13] B. M. Baughman,[14] K. Bechtol,[3] R. Bellazzini,[7] B. Berenji,[3] R. D. Blandford,[3] E. D. Bloom,[3] G. Bogaert,[15] E. Bonamente,[16,17] A. W. Borgland,[3] J. Bregeon,[7] A. Brez,[7] M. Brigida,[18,19] P. Bruel,[15] T. H. Burnett,[20] G. A. Caliandro,[18,19] R. A. Cameron,[3] P. A. Caraveo,[21] P. Carlson,[5,13] J. M. Casandjian,[8] C. Cecchi,[16,17] E. Charles,[3] A. Chekhtman,[22,2] C. C. Cheung,[23] J. Chiang,[3] S. Ciprini,[16,17] R. Claus,[3] J. Cohen-Tanugi,[24] L. R. Cominsky,[25] J. Conrad,[5,13,26,27] S. Cutini,[28] C. D. Dermer,[2] A. de Angelis,[29] F. de Palma,[18,19] S. W. Digel,[3] G. Di Bernardo,[7] E. do Couto e Silva,[3] P. S. Drell,[3] R. Dubois,[3] D. Dumora,[30,31] Y. Edmonds,[3] C. Farnier,[24] C. Favuzzi,[18,19] W. B. Focke,[3] M. Frailis,[29] Y. Fukazawa,[32] S. Funk,[3] P. Fusco,[18,19] D. Gaggero,[7] F. Gargano,[19] D. Gasparrini,[28] N. Gehrels,[23,33] S. Germani,[16,17] B. Giebels,[15] N. Giglietto,[18,19] F. Giordano,[18,19] T. Glanzman,[3] G. Godfrey,[3] D. Grasso,[7] I. A. Grenier,[8] M.-H. Grondin,[30,31] J. E. Grove,[2] L. Guillemot,[30,31] S. Guiriec,[34] Y. Hanabata,[32] A. K. Harding,[23] R. C. Hartman,[23] M. Hayashida,[3] E. Hays,[23] R. E. Hughes,[14] G. Jóhannesson,[3] A. S. Johnson,[3] R. P. Johnson,[4] W. N. Johnson,[2] T. Kamae,[3] H. Katagiri,[32] J. Kataoka,[35] N. Kawai,[36,37] M. Kerr,[20] J. Knödlseder,[38] D. Kocevski,[3] F. Kuehn,[14] M. Kuss,[7] J. Lande,[3] L. Latronico,[7,*] M. Lemoine-Goumard,[30,31] F. Longo,[9,10] F. Loparco,[18,19] B. Lott,[30,31] M. N. Lovellette,[2] P. Lubrano,[16,17] G. M. Madejski,[3] A. Makeev,[22,2] M. M. Massai,[7] M. N. Mazziotta,[19] W. McConville,[23,33] J. E. McEnery,[23] C. Meurer,[5,26] P. F. Michelson,[3] W. Mitthumsiri,[3] T. Mizuno,[32] A. A. Moiseev,[39,33,†] C. Monte,[18,19] M. E. Monzani,[3] E. Moretti,[9,10] A. Morselli,[40] I. V. Moskalenko,[3] S. Murgia,[3] P. L. Nolan,[3] J. P. Norris,[41] E. Nuss,[24] T. Ohsugi,[32] N. Omodei,[7] E. Orlando,[42] J. F. Ormes,[41] M. Ozaki,[43] D. Paneque,[3] J. H. Panetta,[3] D. Parent,[30,31] V. Pelassa,[24] M. Pepe,[16,17] M. Pesce-Rollins,[7] F. Piron,[24] M. Pohl,[44] T. A. Porter,[4] S. Profumo,[4] S. Rainò,[18,19] R. Rando,[11,12] M. Razzano,[7] A. Reimer,[3] O. Reimer,[3] T. Reposeur,[30,31] S. Ritz,[23,33] L. S. Rochester,[3] A. Y. Rodriguez,[45] R. W. Romani,[3] M. Roth,[20] F. Ryde,[5,13] H. F.-W. Sadrozinski,[4] D. Sanchez,[15] A. Sander,[14] P. M. Saz Parkinson,[4] J. D. Scargle,[46] T. L. Schalk,[4] A. Sellerholm,[5,26] C. Sgrò,[7] D. A. Smith,[30,31] P. D. Smith,[14] G. Spandre,[7] P. Spinelli,[18,19] J.-L. Starck,[8] T. E. Stephens,[23] M. S. Strickman,[2] A. W. Strong,[42] D. J. Suson,[47] H. Tajima,[3] H. Takahashi,[32] T. Takahashi,[43] T. Tanaka,[3] J. B. Thayer,[3] J. G. Thayer,[3] D. J. Thompson,[23] L. Tibaldo,[11,12] O. Tibolla,[48] D. F. Torres,[49,45] G. Tosti,[16,17] A. Tramacere,[50,3] Y. Uchiyama,[3] T. L. Usher,[3] A. Van Etten,[3] V. Vasileiou,[23,51] N. Vilchez,[38] V. Vitale,[40,52] A. P. Waite,[3] E. Wallace,[20] P. Wang,[3] B. L. Winer,[14] K. S. Wood,[2] T. Ylinen,[53,5,13] and M. Ziegler[4]

(Fermi LAT Collaboration)

[1]*National Research Council Research Associate*

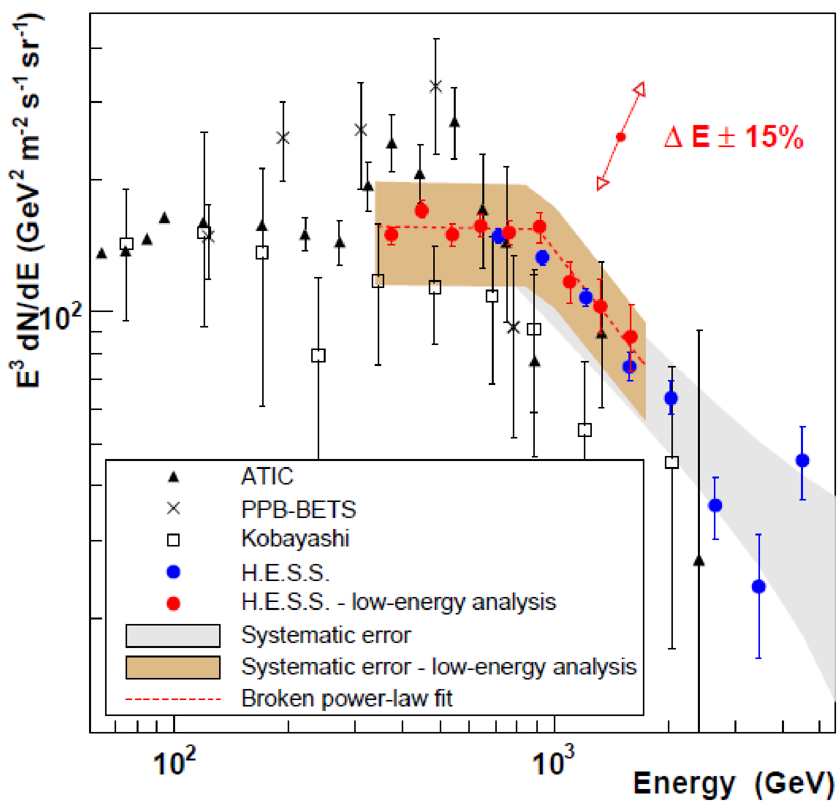


AMS (2002)
ATIC-1,2 (2008)
PPB-BETS (2008)
HESS (2008)
FERMI (2009)
Tang et al (1984)
Kobayashi (1999)
HEAT (2001)
BETS (2001)
ΔE/E = + 5% − 10%
conventional diffusive model
E³J(E) (GeV²m⁻²s⁻¹sr⁻¹)
100
10
100
1000
E (GeV)

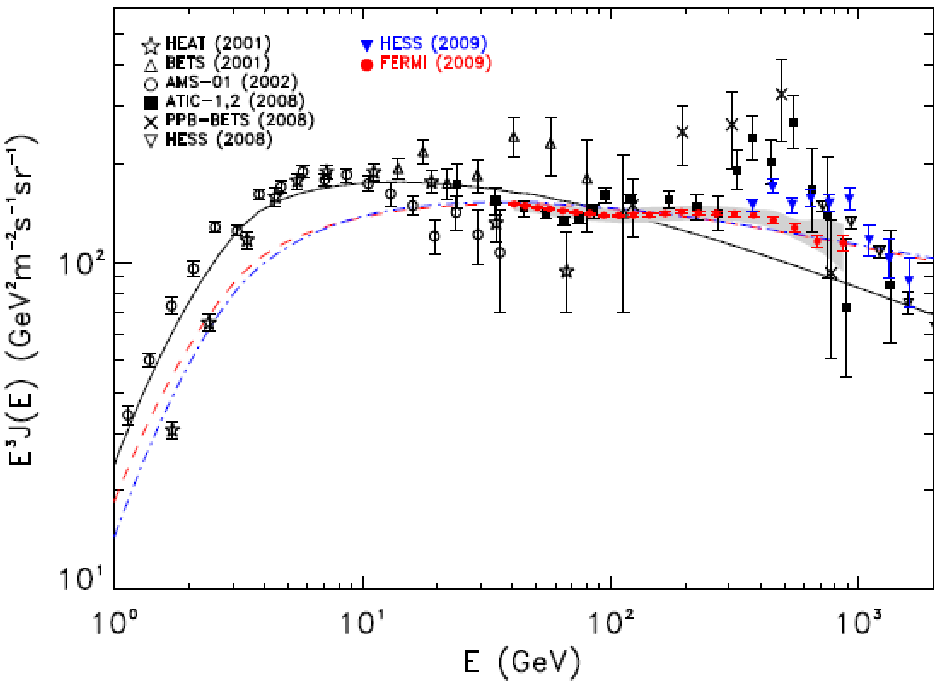
H.E.S.S.
High Energy Stereoscopic System

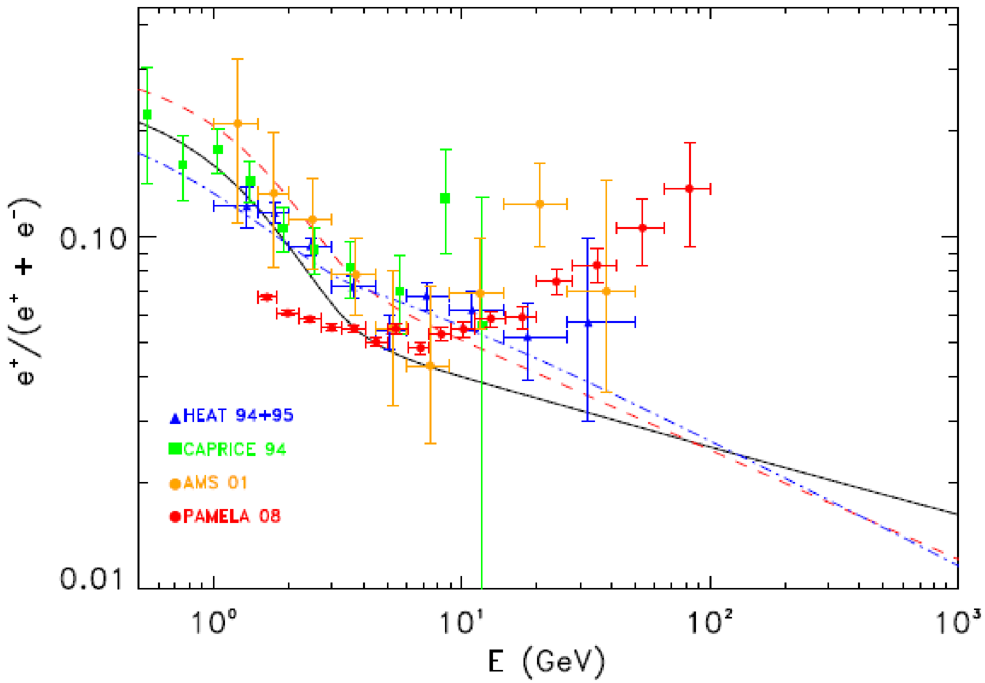
Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S.

F. Aharonian[1,13], A.G. Akhperjanian[2], G. Anton[16], U. Barres de Almeida[8,*], A.R. Bazer-Bachi[3], Y. Becherini[12], B. Behera[14], K. Bernlöhr[1,5], A. Bochow[1], C. Boisson[6], J. Bolmont[19], V. Borrel[3], J. Brucker[16], F. Brun[19], P. Brun[7], R. Bühler[1], T. Bulik[24], I. Büsching[9], T. Boutelier[17], P.M. Chadwick[8], A. Charbonnier[19], R.C.G. Chaves[1], A. Cheesebrough[8], L.-M. Chounet[10], A.C. Clapson[1], G. Coignet[11], M. Dalton[5], M.K. Daniel[8], I.D. Davids[22,9], B. Degrange[10], C. Deil[1], H.J. Dickinson[8], A. Djannati-Ataï[12], W. Domainko[1], L.O'C. Drury[13], F. Dubois[11], G. Dubus[17], J. Dyks[24], M. Dyrda[28], K. Egberts[1,†], D. Emmanoulopoulos[14], P. Espigat[12], C. Farnier[15], F. Feinstein[15], A. Fiasson[11], A. Förster[1], G. Fontaine[10], M. Füßling[5], S. Gabici[13], Y.A. Gallant[15], L. Gérard[12], D. Gerbig[21], B. Giebels[10], J.F. Glicenstein[7], B. Glück[16], P. Goret[7], D. Göring[16], D. Hauser[14], M. Hauser[14], S. Heinz[16], G. Heinzelmann[4], G. Henri[17], G. Hermann[1], J.A. Hinton[25], A. Hoffmann[18], W. Hofmann[1,‡], M. Holleran[9], S. Hoppe[1], D. Horns[4], A. Jacholkowska[19], O.C. de Jager[9], C. Jahn[16], I. Jung[16], K. Katarzyński[27], U. Katz[16], S. Kaufmann[14], E. Kendziorra[18], M. Kerschhaggl[5], D. Khangulyan[1], B. Khélifi[10], D. Keogh[8], W. Kluźniak[24], T. Kneiske[4], Nu. Komin[15], K. Kosack[1], R. Kossakowski[11], G. Lamanna[11], J.-P. Lenain[6], T. Lohse[5], V. Marandon[12], J.M. Martin[6], O. Martineau-Huynh[19], A. Marcowith[15], J. Masbou[11], D. Maurin[19], T.J.L. McComb[8], M.C. Medina[6], R. Moderski[24], E. Moulin[7], M. Naumann-Godo[10],



Present situation:





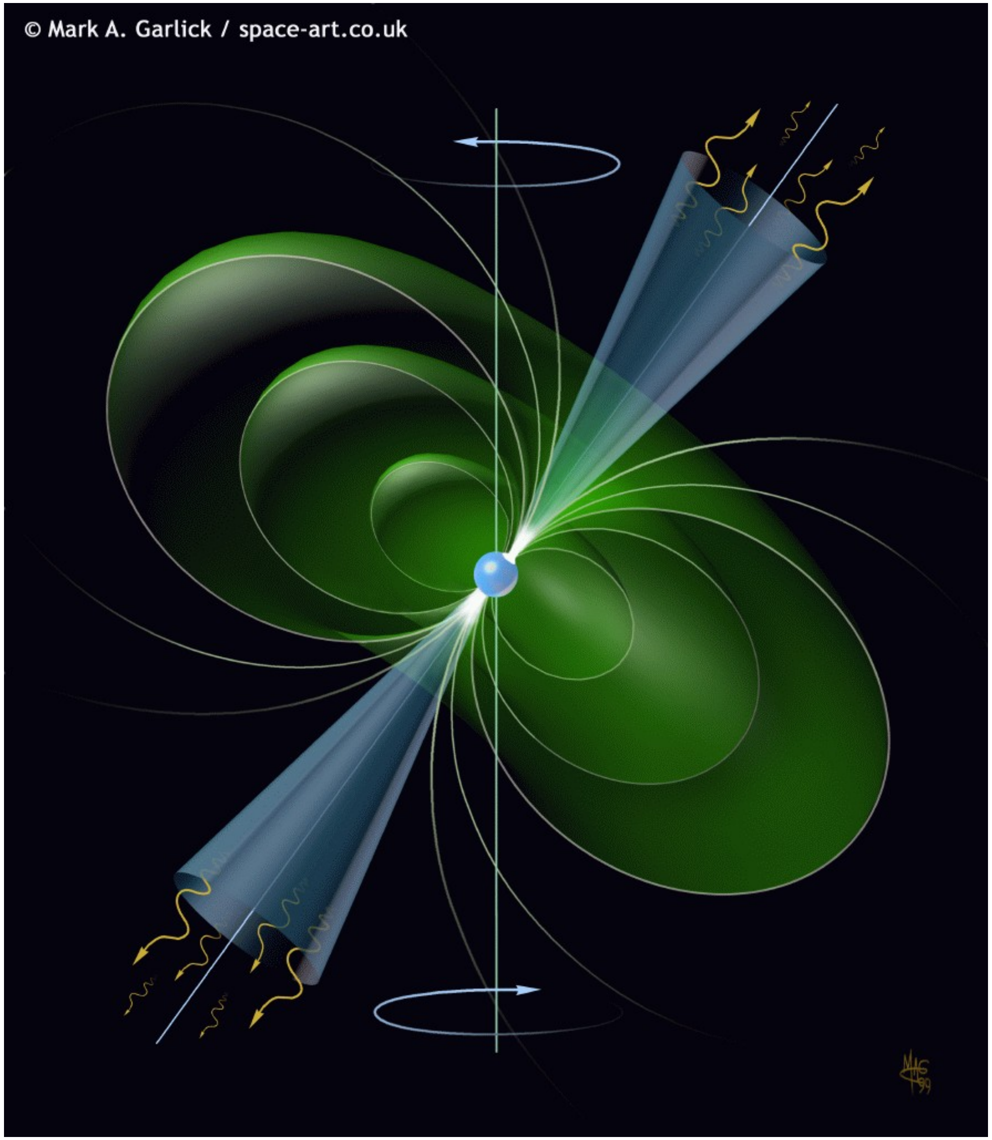
Evidence for a primary component of positrons
(possibly accompanied by electrons)

astrophysical sources? Pulsars, SN remnants...
new Particle Physics? DM annihilation, DM decay.

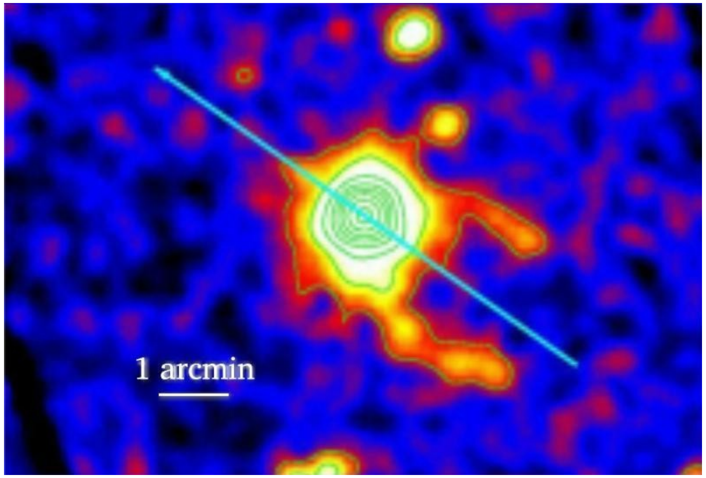
Astrophysical interpretations

Pulsars <u>are</u> sources of high energy electrons & positrons

Atoyan, Aharonian, Völk;
Chi, Cheng, Young;
Grimani



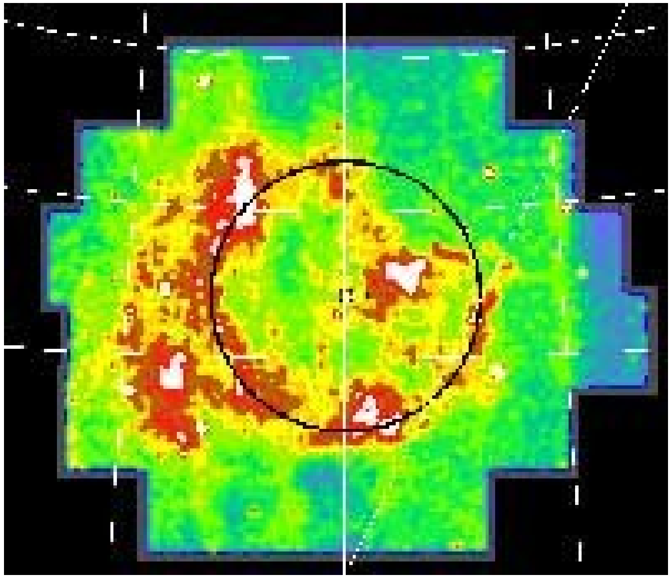
Pulsar explanation I: Geminga + Monogem



Geminga

T=370 000 years

D=157 pc



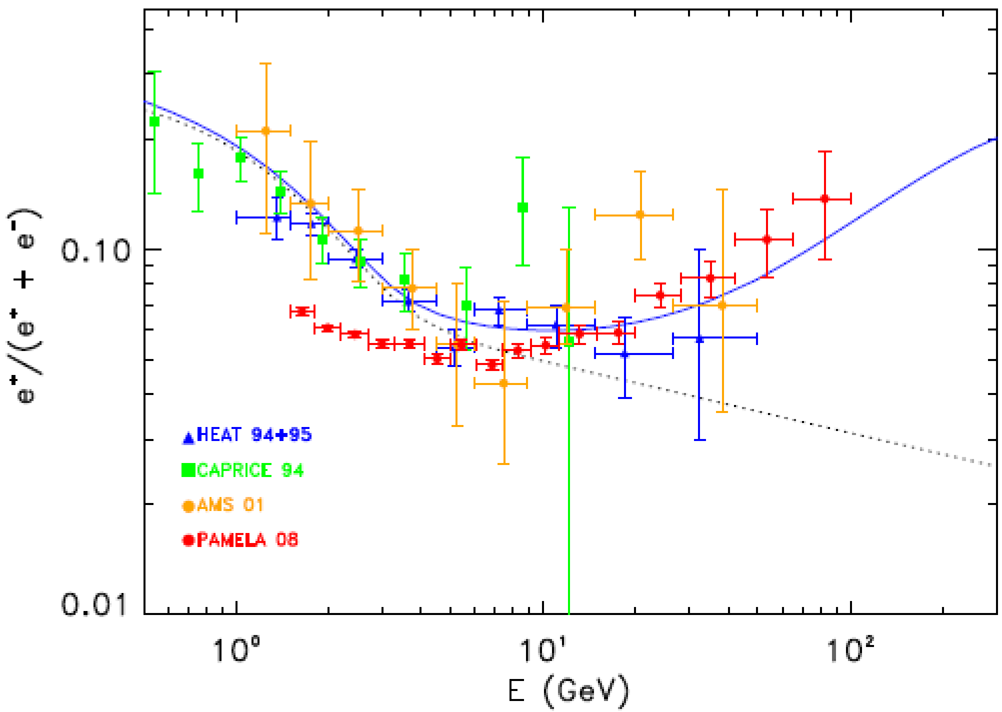
Monogem (B0656+14)

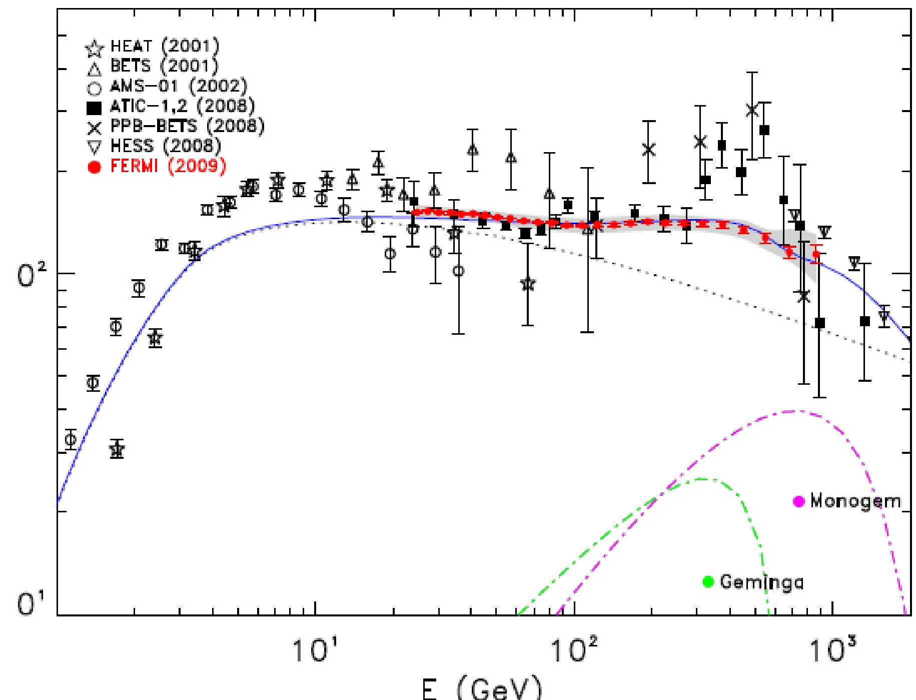
T=110 000 years

D=290 pc

Pulsar explanation I: Geminga + Monogem

Grasso et al.



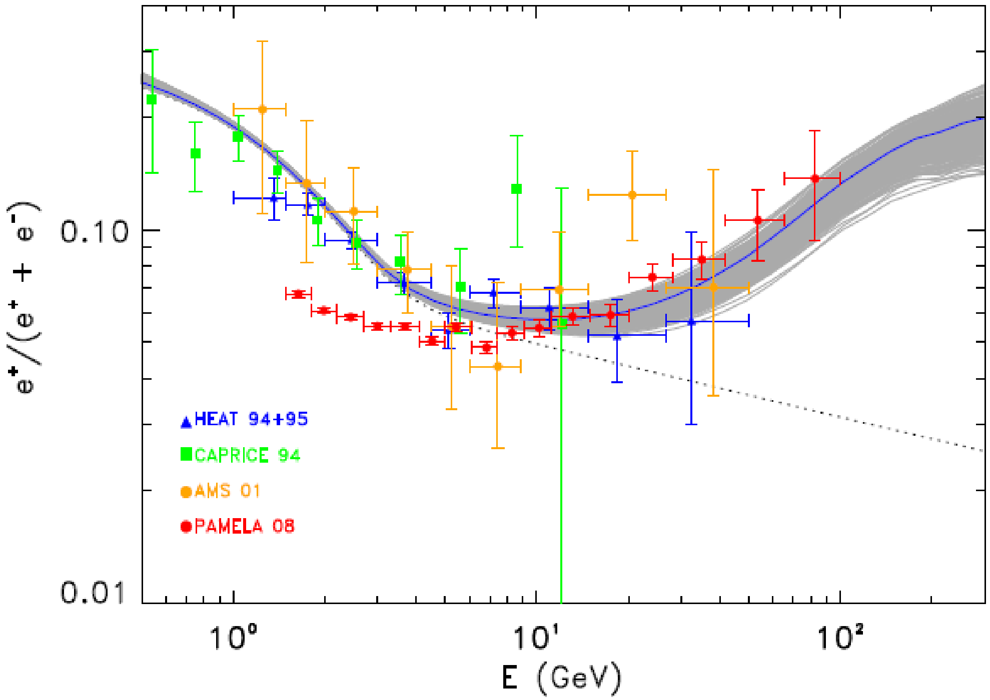


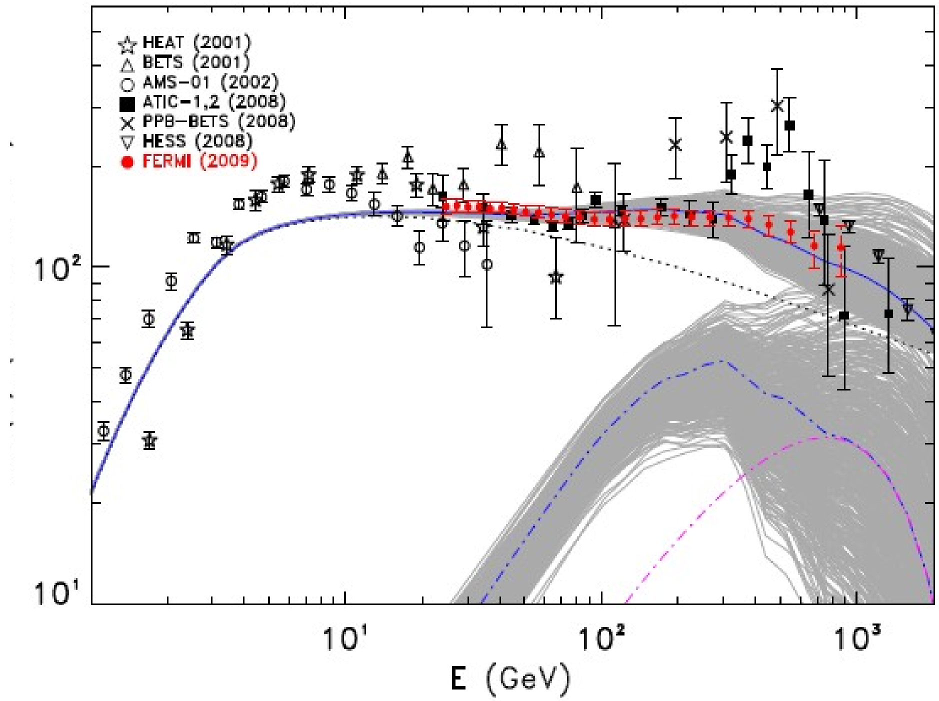
Nice agreement. However, it is not a prediction!

- $dN_e/dE_e \propto E_e^{-1.7} \exp(-E_e/1100\ \mathrm{GeV})$
- Energy output in e+e- pairs: 40% of the spin-down rate (!)

Pulsar explanation II: Multiple pulsars

Grasso et al.





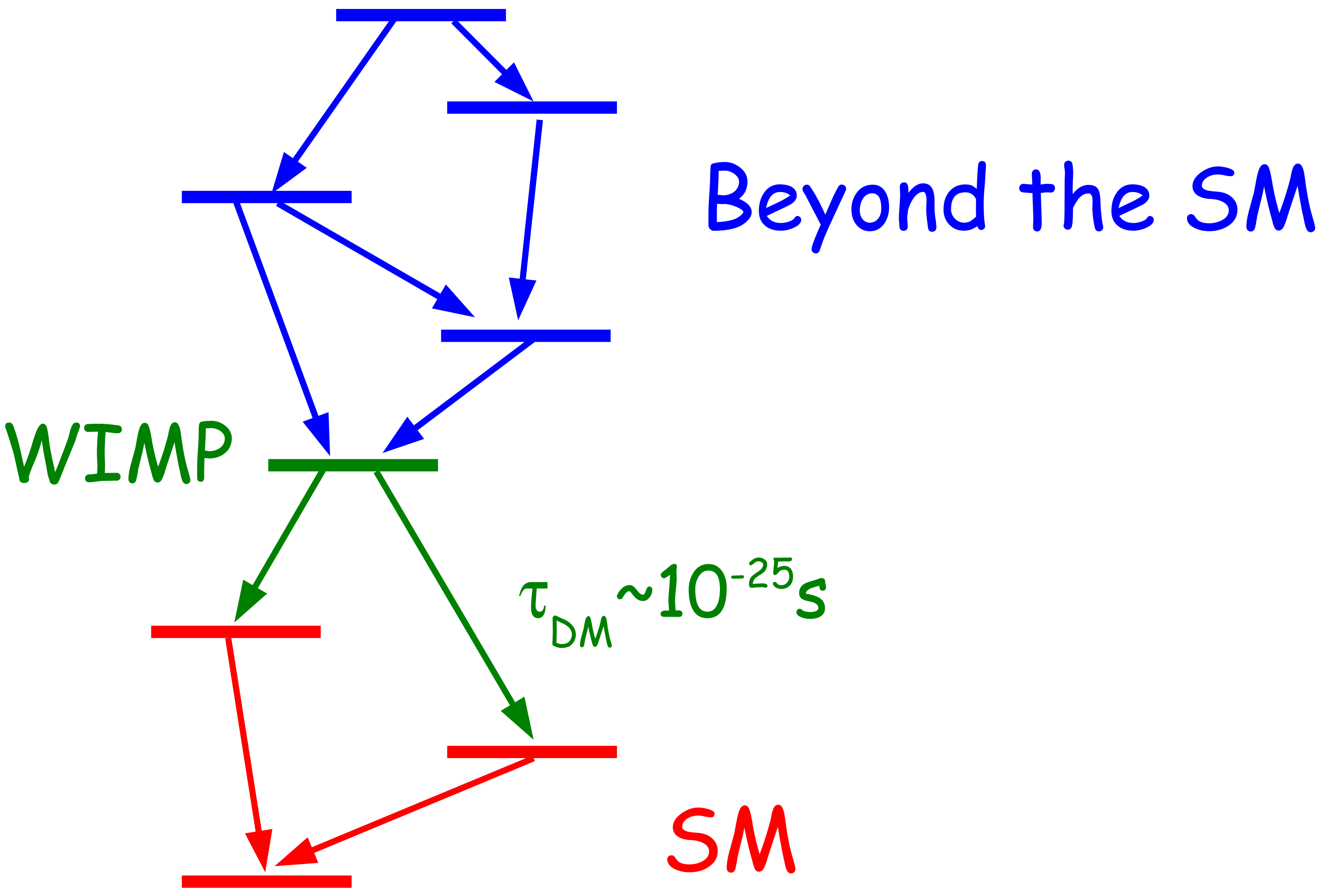
- $dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/E_0)$, $1.5 < \alpha < 1.9$, 800 GeV < E0 < 1400 GeV
- Energy output in e+e- pairs: between 10-30% of the spin-down rate

Dark matter decay

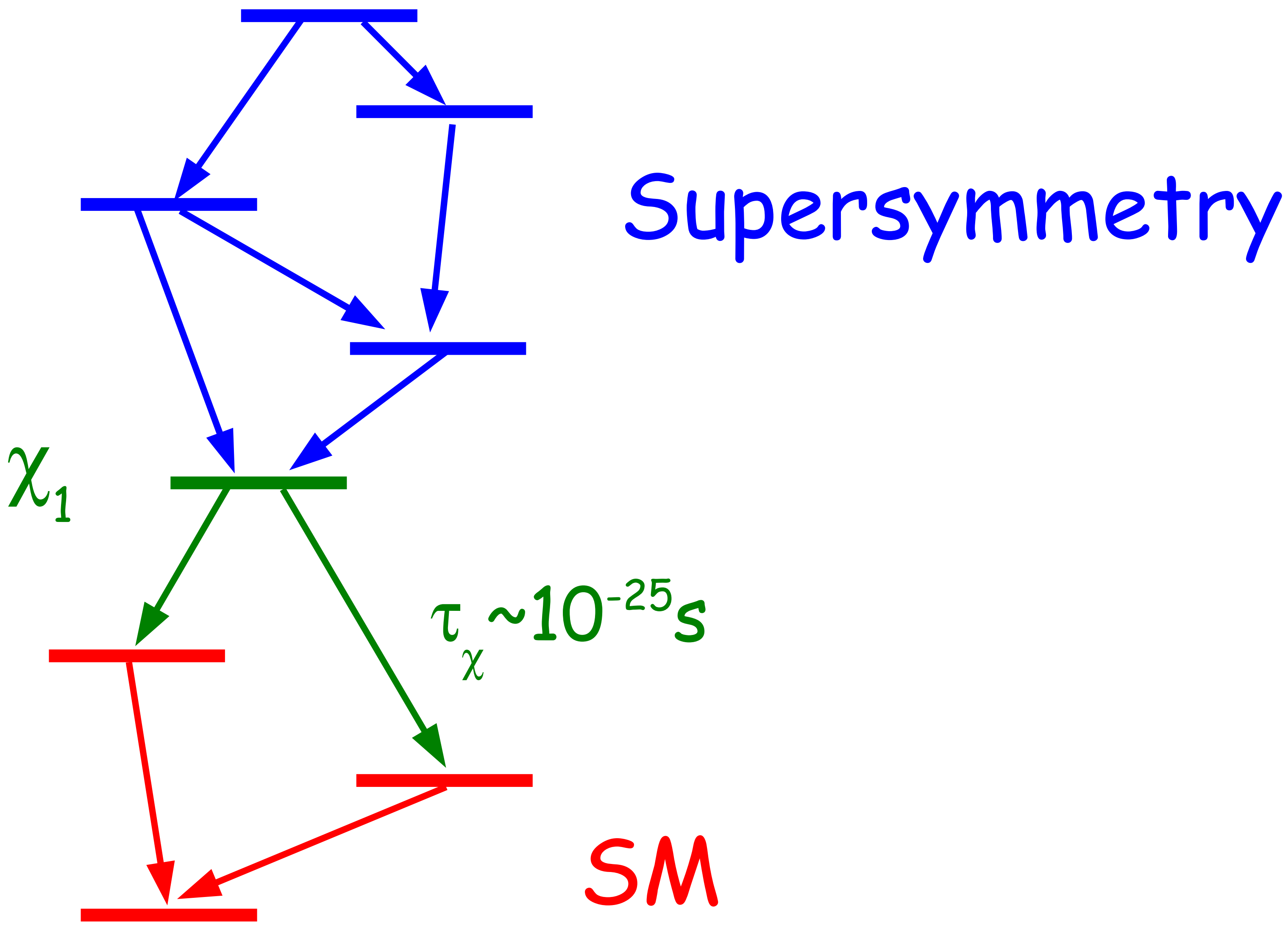
- No fundamental objection to this possibility, provided $\tau_{DM}>10^{17}$ s.
- Not as thoroughly studied as the case of the dark matter annihilation.

Possible reason: the most popular dark matter candidates are weakly interacting (can be detected in direct searches and can be produced in colliders). If the dark matter is a WIMP, absolute stability has to be normally imposed.

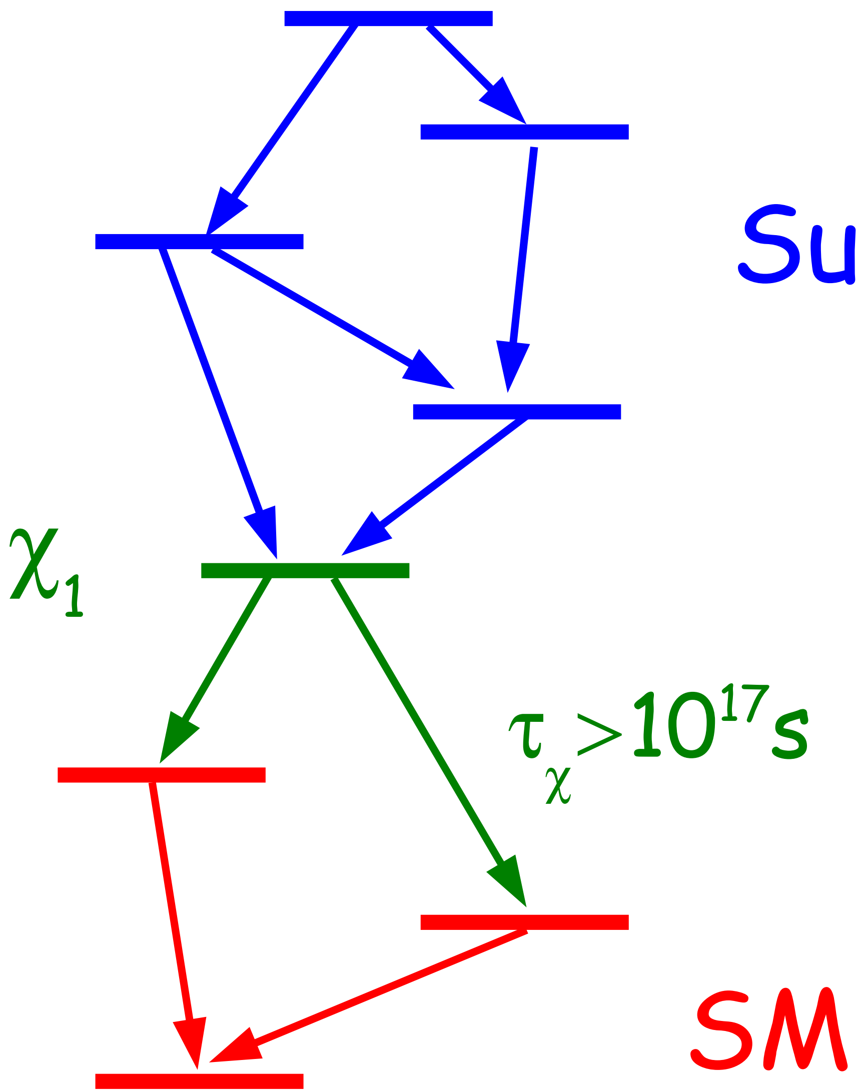
Sketch of a WIMP dark matter model:



Sketch of a WIMP dark matter model:

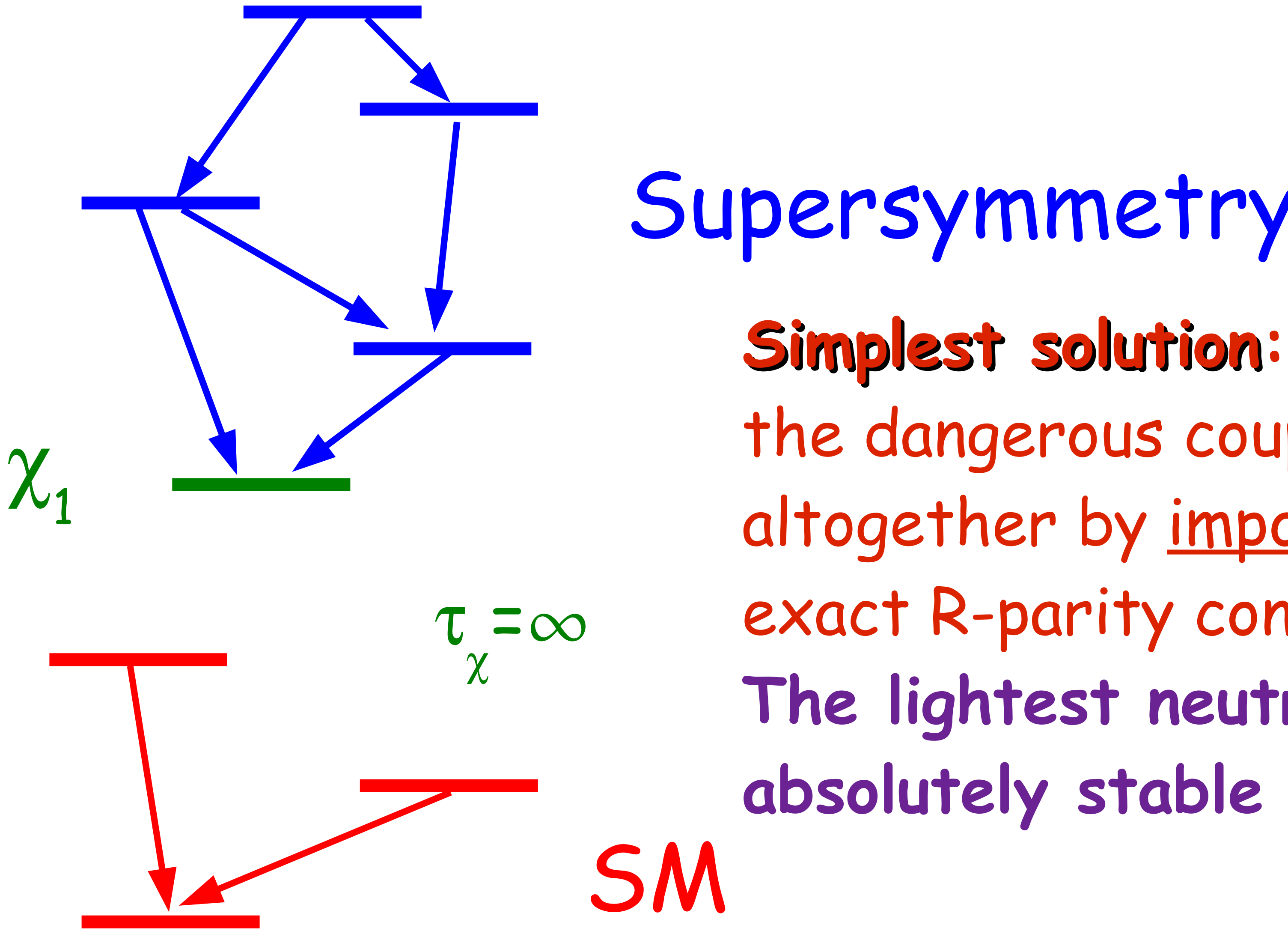


Sketch of a WIMP dark matter model:



Requires a suppression of the coupling of at least 22 orders of magnitude!

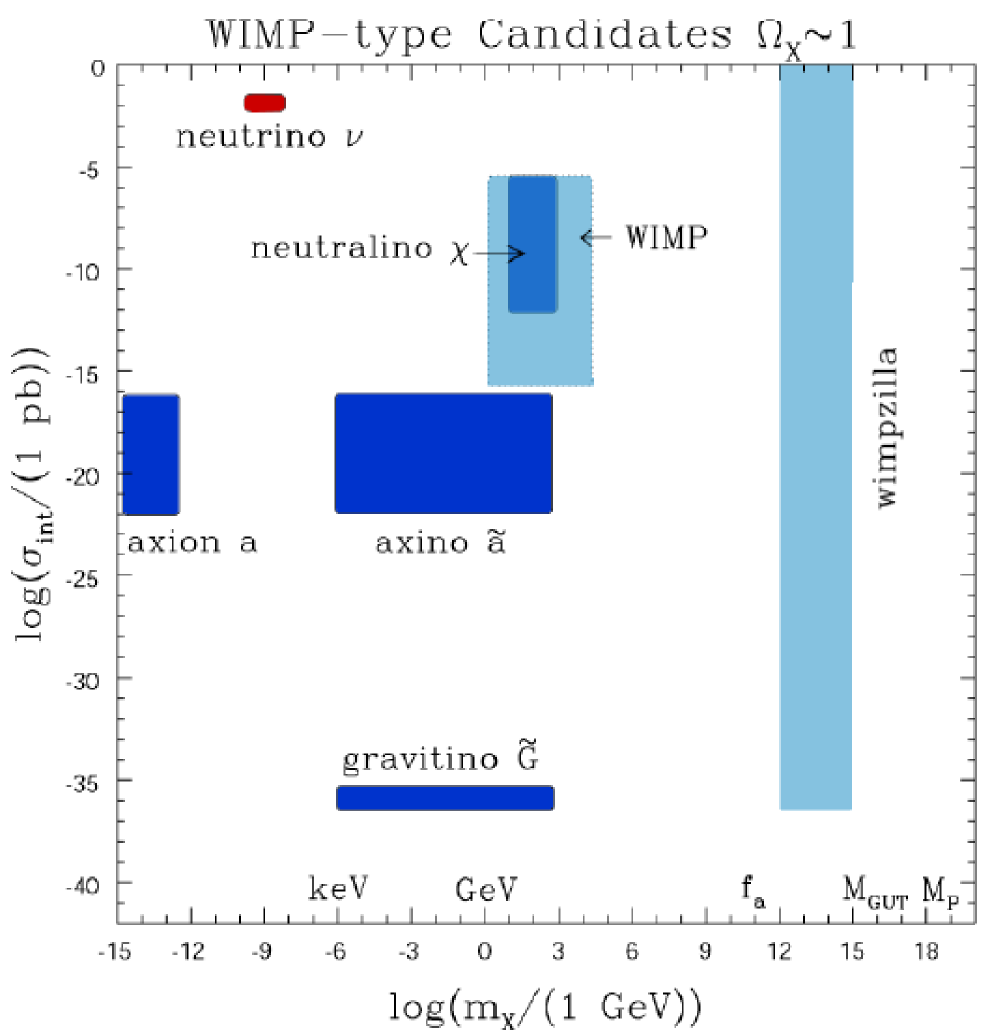
Sketch of a WIMP dark matter model:



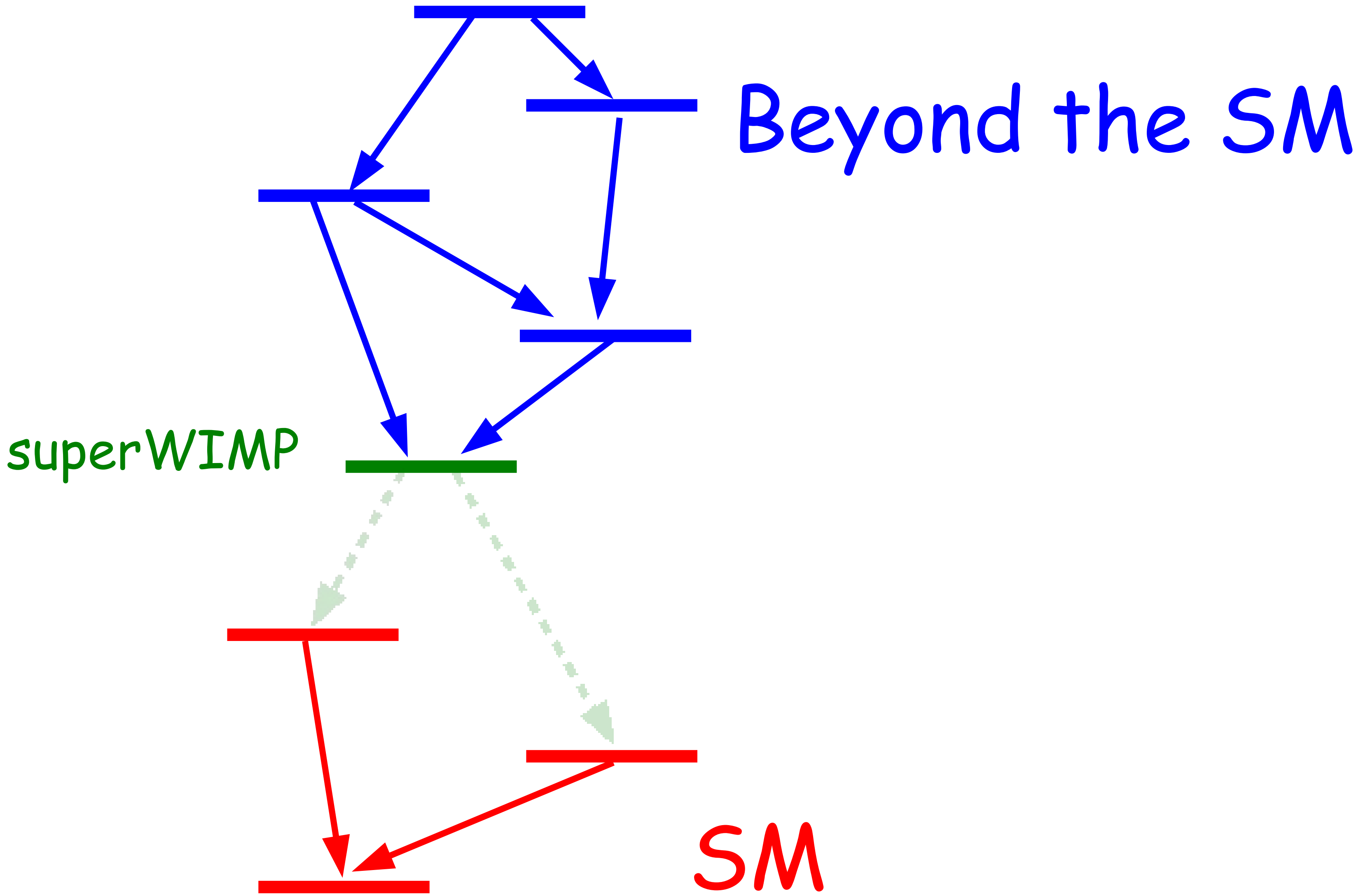
Simplest solution: forbid the dangerous couplings altogether by <u>imposing</u> exact R-parity conservation.

The lightest neutralino is absolutely stable

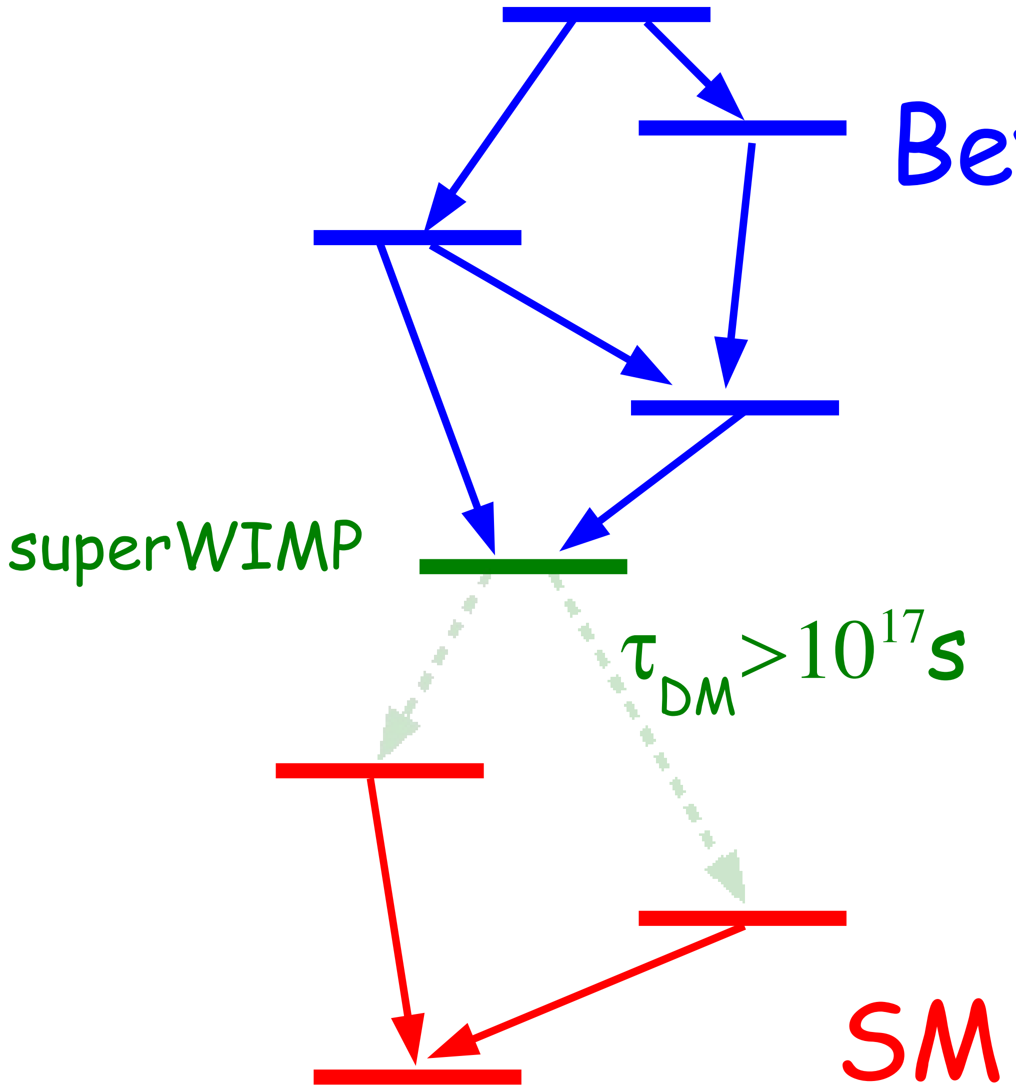
WIMP dark matter is not the only possibility: the dark matter particle could also be <u>superweakly interacting</u>



Sketch of a superWIMP dark matter model:

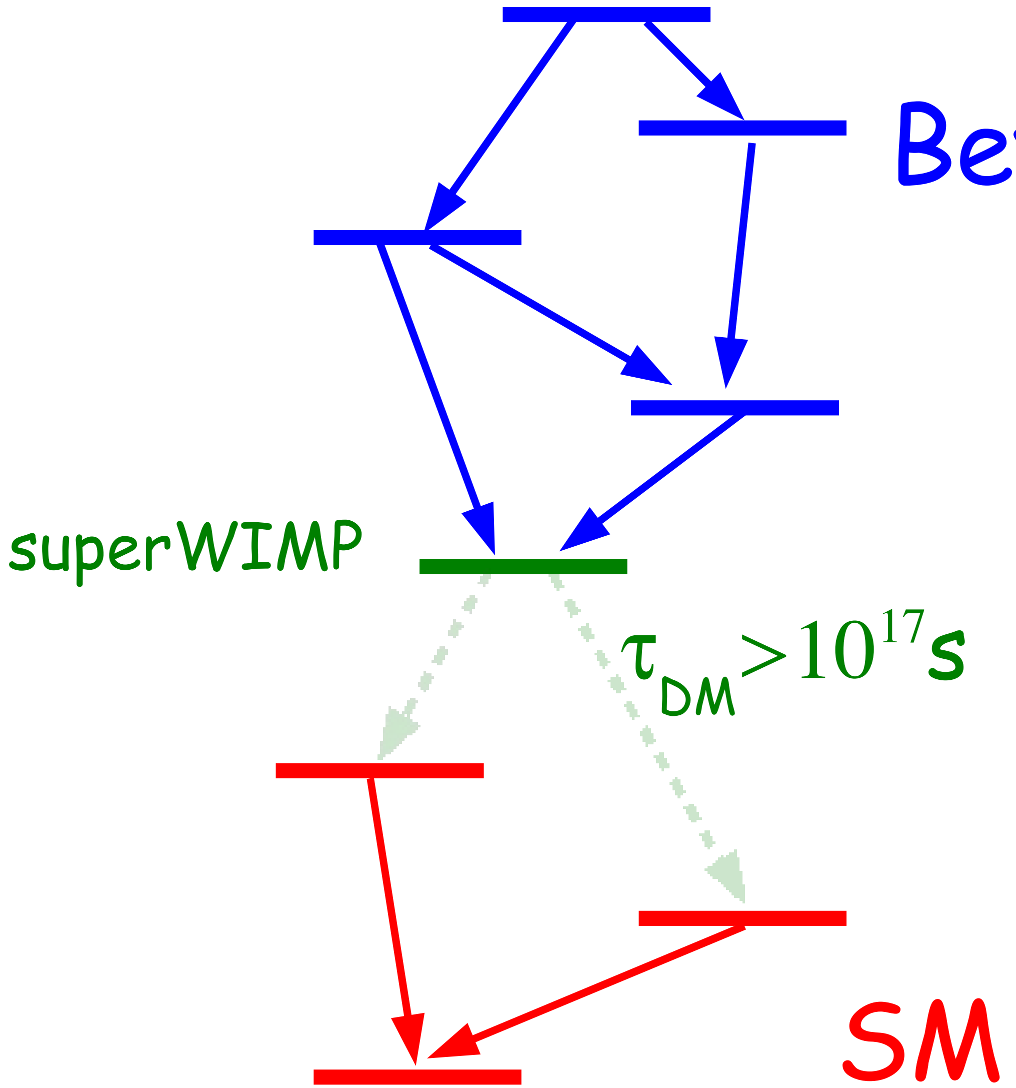


SuperWIMP DM particles are naturally very long lived. Their lifetimes can be larger than the age of the Universe, or perhaps a few orders of magnitude smaller.



It is enough a moderate suppression of the coupling to make the superWIMP a viable dark matter candidate.

SuperWIMP DM particles are naturally very long lived. Their lifetimes can be larger than the age of the Universe, or perhaps a few orders of magnitude smaller.



It is enough a moderate suppression of the coupling to make the superWIMP a viable dark matter candidate.

Eventually the dark matter decays!

Candidates of decaying dark matter

- Gravitinos in general SUSY models (without imposing R-parity conservation).

  Decay rate doubly suppressed by the SUSY breaking scale and by the small R-parity violation.

  Takayama, Yamaguchi; Buchmüller, et al.; AI, Tran; Ishiwata et al.; Choi et al., Lola et al.

- Hidden sector gauge bosons/gauginos.

  Decay rate suppressed by the small kinetic mixing between $U(1)_y$ and $U(1)_{hid}$

  Chen, Takahashi, Yanagida; AI, Ringwald, Weniger;

- Right-handed neutrinos/sneutrinos.

  Decay rate suppressed by a tiny coupling between left and right sectors.

  Babu, Eichler, Mohapatra Pospelov, Trott

- Hidden sector particles.

  Decay rate suppressed by the GUT scale.

  Eichler; Arvanitaki et al.; Hamaguchi, Shirai, Yanagida; Arina, Hambye, AI, Weniger

- Bound states of strongly interacting particles.

  Decay rate suppressed by the GUT scale.

  Hamaguchi et al.; Nardi et al

Positron fraction from decaying dark matter: model independent analysis

Possible decay channels

AI, Tran'08
AI, Tran, Weniger'09

fermionic DM

$\psi \to Z^0 \nu$

$\psi \to W^{\pm} \ell^{\mp}$

$\psi \to \ell^+ \ell^- \nu$

scalar DM

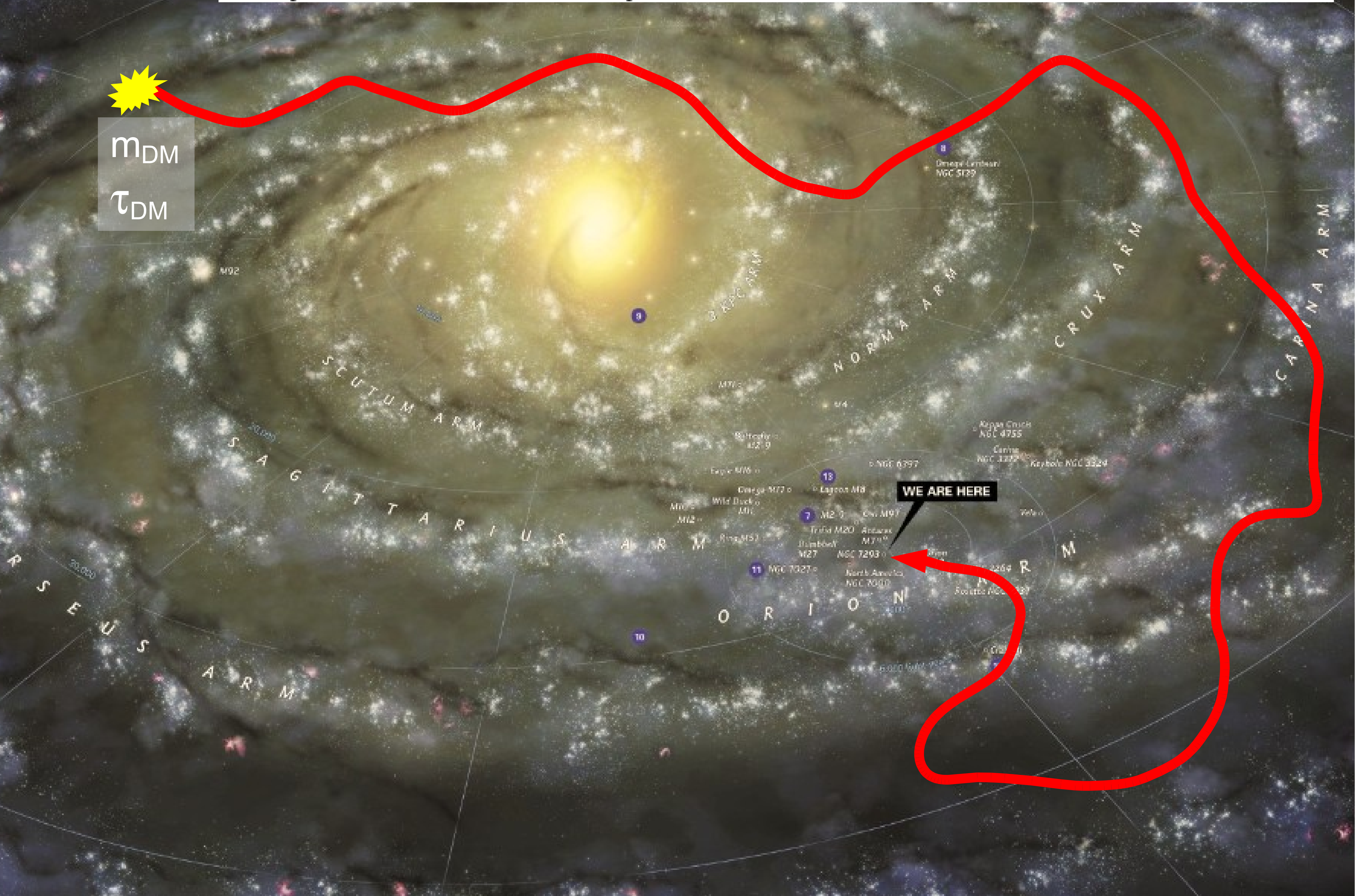
$\phi \to Z^0 Z^0$

$\phi \to W^+ W^-$

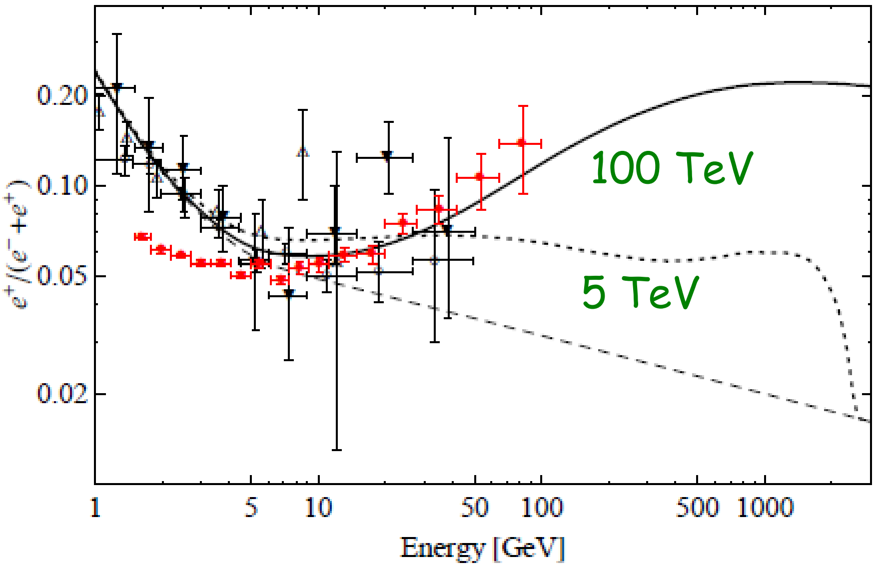
$\phi \to \ell^+ \ell^-$

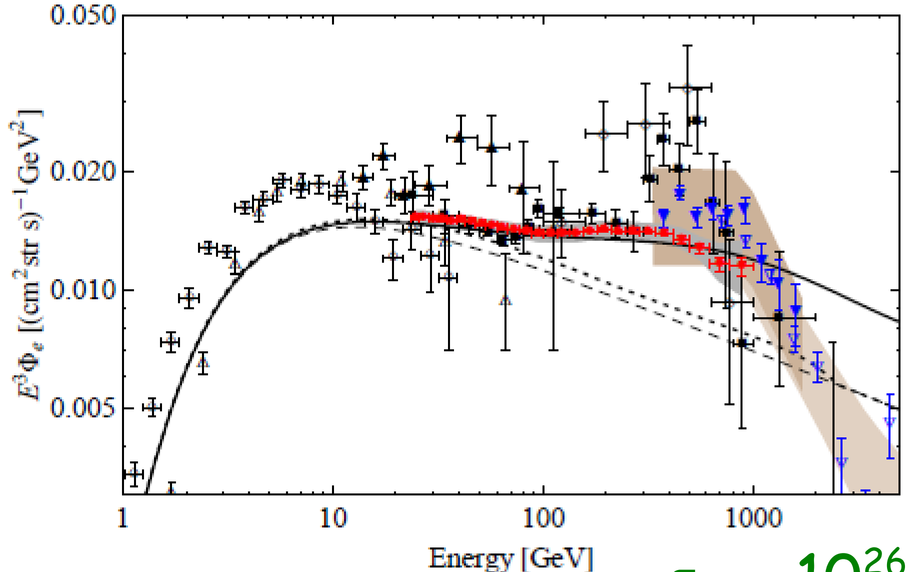
m_{DM}
τ_{DM}
WE ARE HERE
SCUTUM ARM
SAGITTARIUS ARM
NORMA ARM
CRUX ARM
CARINA ARM
ORION ARM
RSEUS ARM
3 KPC ARM
M92
M80
NGC 5139

$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r})$$



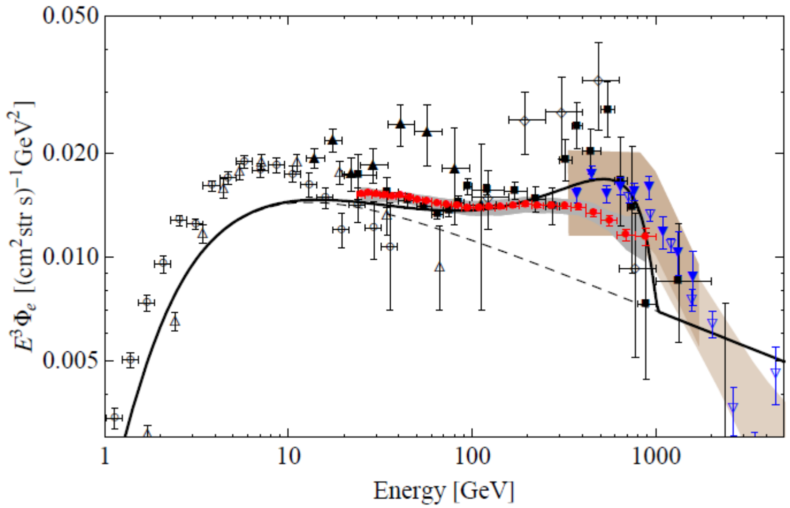
$\psi \rightarrow Z^0 \nu$





$\tau_{DM} \sim 10^{26}$s

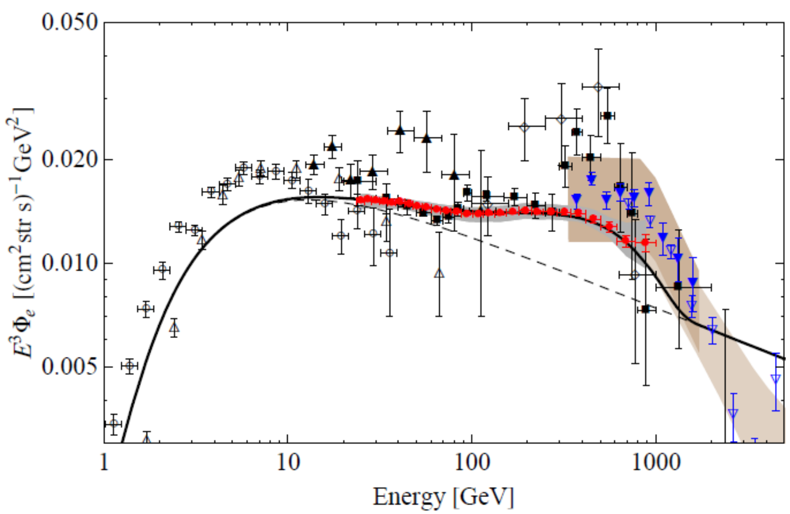
For "low" DM mass: conflict with PAMELA (spectrum too flat)
For "high" DM mass: agreement with PAMELA, but conflict with H.E.S.S.



$\psi \rightarrow e^+ e^- \nu$

m_{DM}=2000 GeV

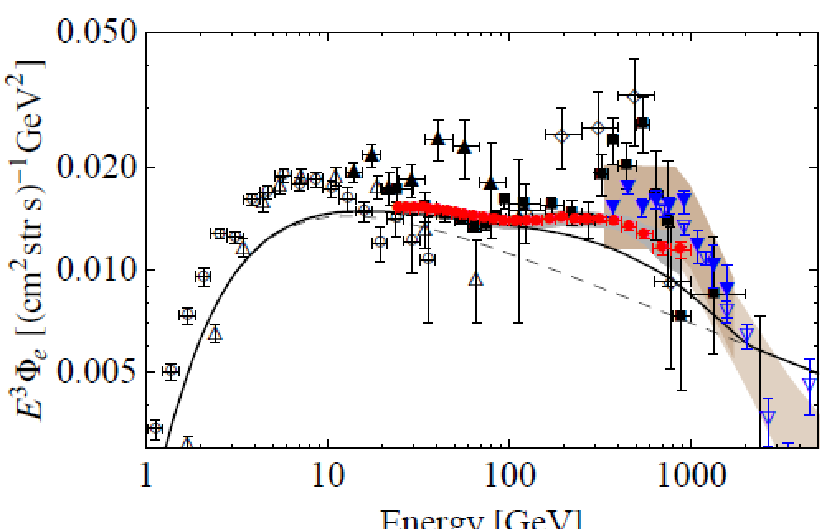
τ_{DM}~10^{26} s



$\psi \rightarrow \mu^+ \mu^- \nu$

m_{DM}=3500 GeV

τ_{DM}~10^{26} s



$\psi \rightarrow \tau^+ \tau^- \nu$

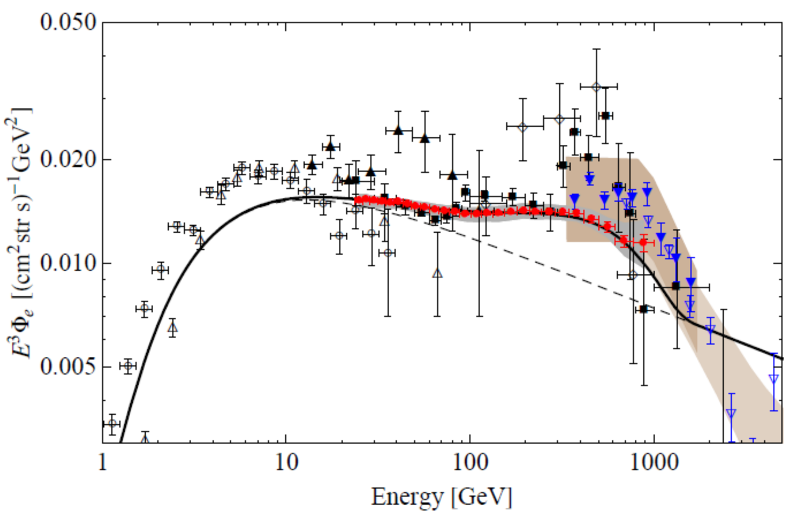
m_{DM}=5000 GeV

τ_{DM}~10^{26} s

$\Psi \rightarrow e^+ e^- \nu$

m_{DM}=2000 GeV

τ_{DM}~10^{26} s



$\Psi \rightarrow \mu^+ \mu^- \nu$

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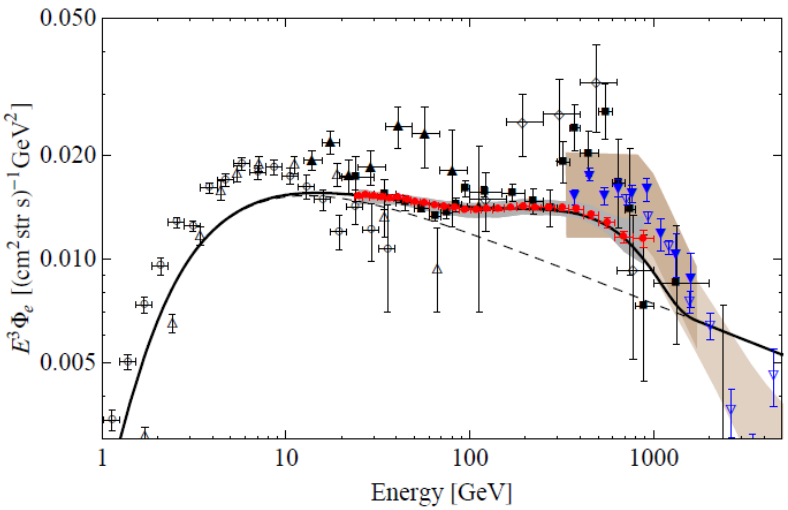

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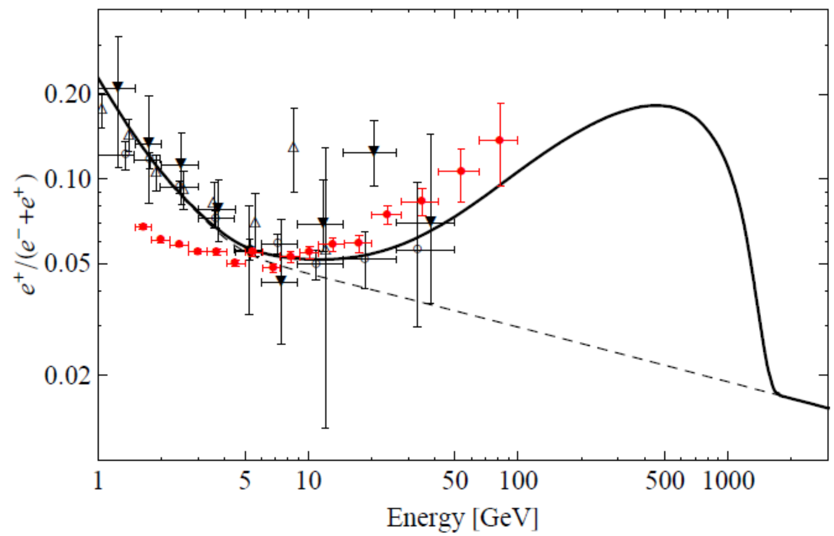


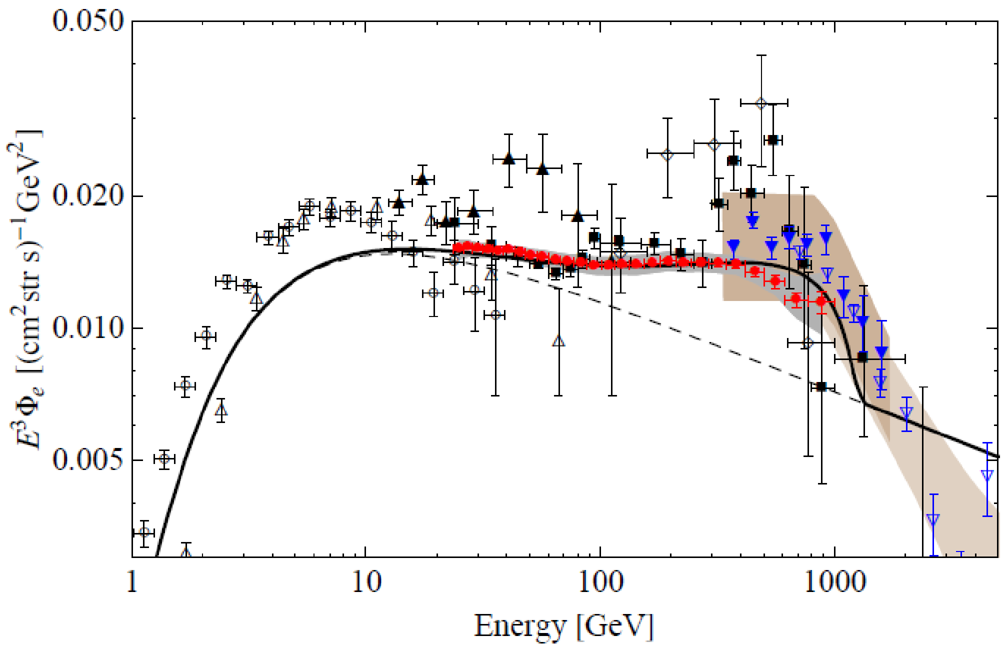
$\psi \to \tau^+ \tau^- \nu$

m_{DM}=5000 GeV

τ_{DM}~10^{26} s

Democratic decay $\psi \to \ell^+ \ell^- \nu$

m_{DM}=2500 GeV
τ_{DM}=1.5×10^{26} s



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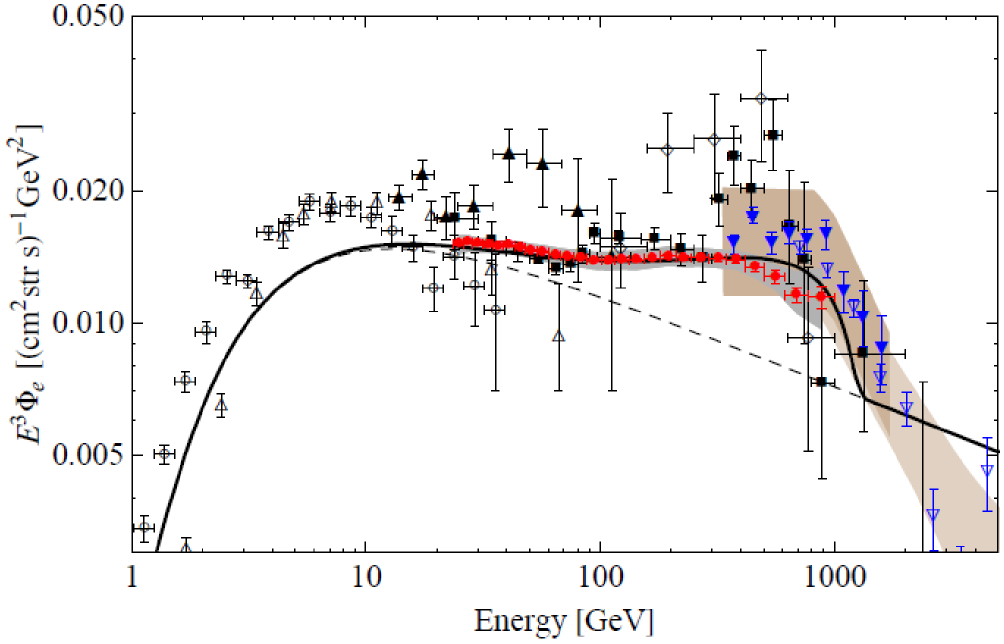
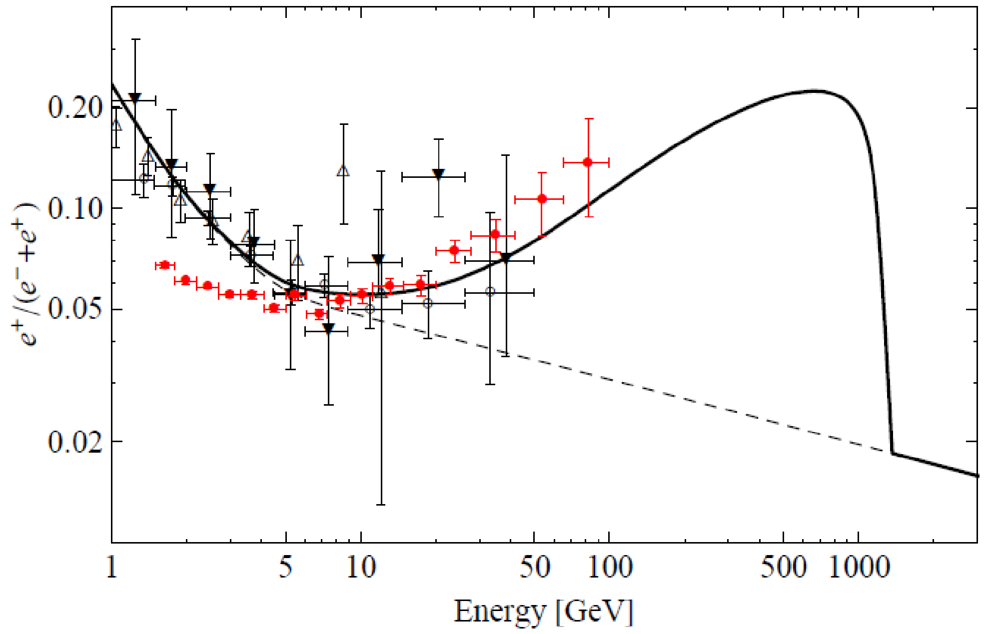




Some decay channels can explain simultaneously the PAMELA, Fermi LAT and H.E.S.S. observations

Decay Channel	$M_{\rm DM}$ [GeV]	$\tau_{\rm DM}$ $[10^{26}\rm s]$
$\psi_{\rm DM} \to \mu^+\mu^-\nu$	3500	1.1
$\psi_{\rm DM} \to \ell^+\ell^-\nu$	2500	1.5
$\psi_{\rm DM} \to W^\pm\mu^\mp$	3000	2.1
$\phi_{\rm DM} \to \mu^+\mu^-$	2500	1.8
$\phi_{\rm DM} \to \tau^+\tau^-$	5000	0.9

10^{26} seconds??

The lifetime of a TeV dark matter particle which decays via a dimension six operator suppressed by M^2 is

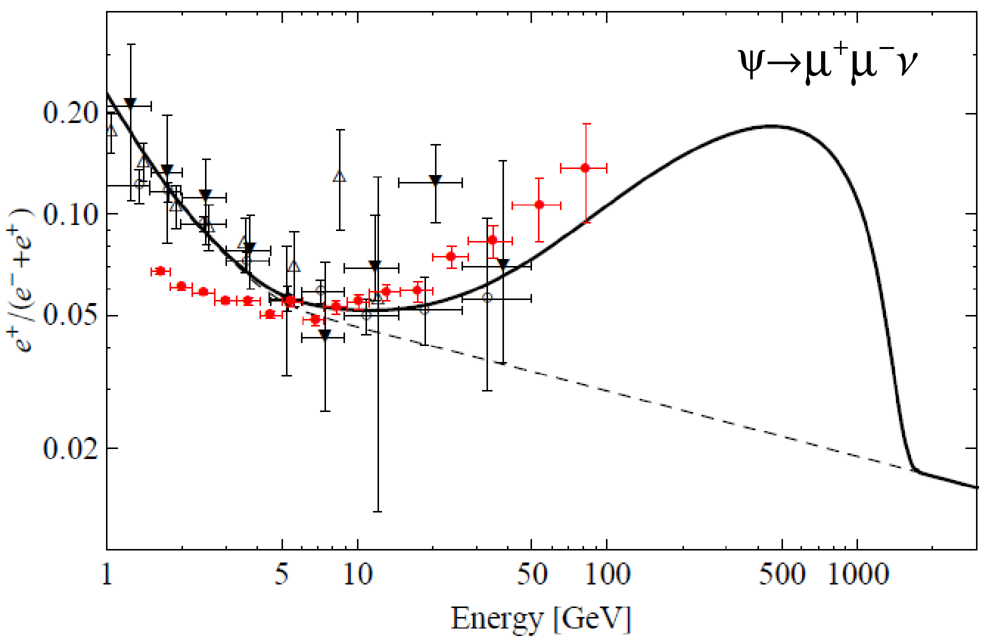
$$\tau_{\rm DM} \sim 10^{26}{\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M}{10^{15}{\rm GeV}}\right)^4$$

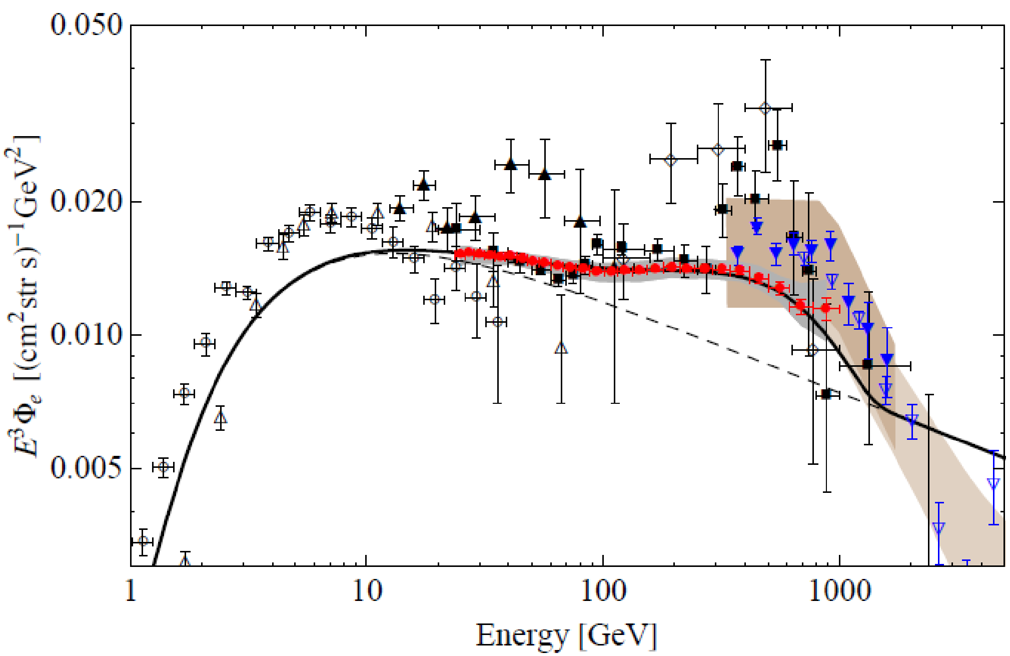
M is remarkably close to the Grand Unification Scale

Indirect dark matter searches can probe models at very high energies.

Conclusion so far:

the electron/positron excesses can be naturally explained by the decay of dark matter particles.





Is this the first non-gravitational evidence of dark matter?

"Extraordinary claims require extraordinary evidence"
Carl Sagan

More tests needed!

Decay Channel	$M_{\rm DM}$ [GeV]	$\tau_{\rm DM}$ [10^{26}s]
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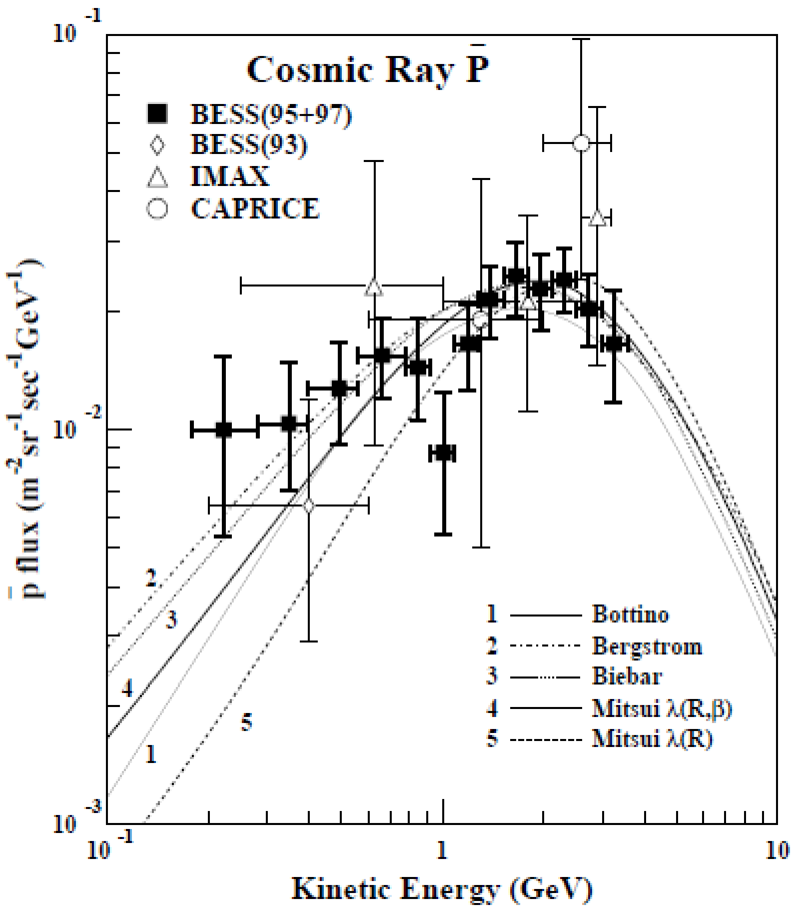
$\phi_{\rm DM} \to \mu^+\mu^-$	2500	1.8
$\phi_{\rm DM} \to \tau^+\tau^-$	5000	0.9

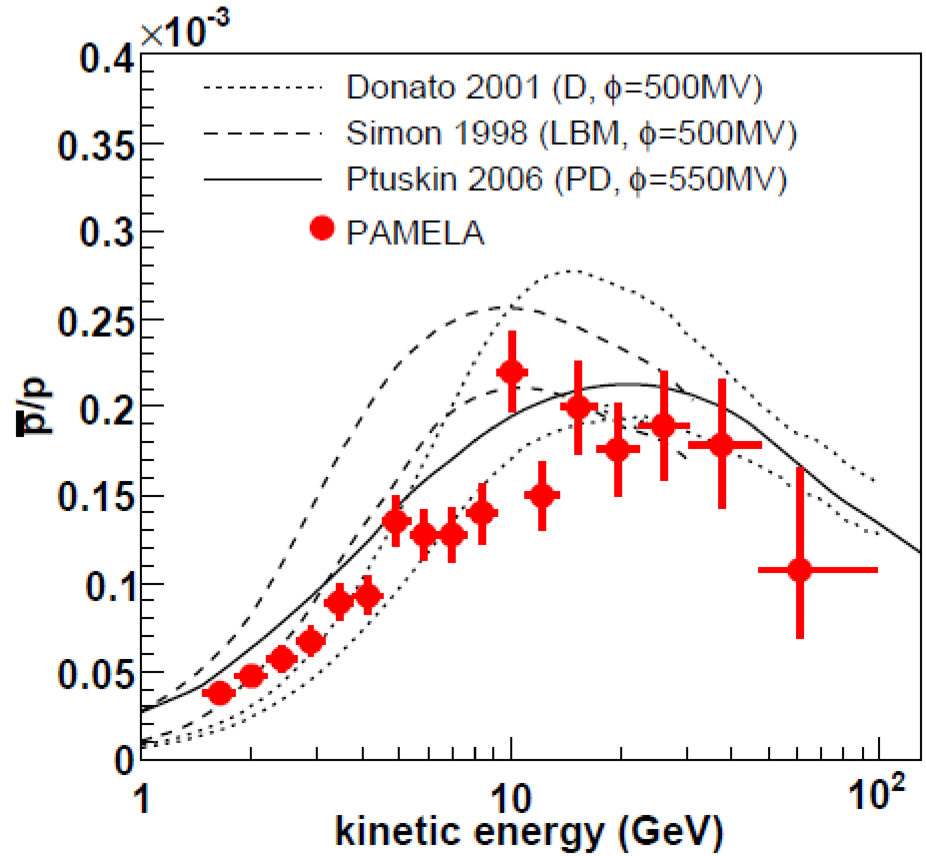
No free parameters from Particle Physics

Prediction for the fluxes of:

- Antiprotons
- Gamma rays
- Neutrinos
- Antideuterons

Antiproton flux





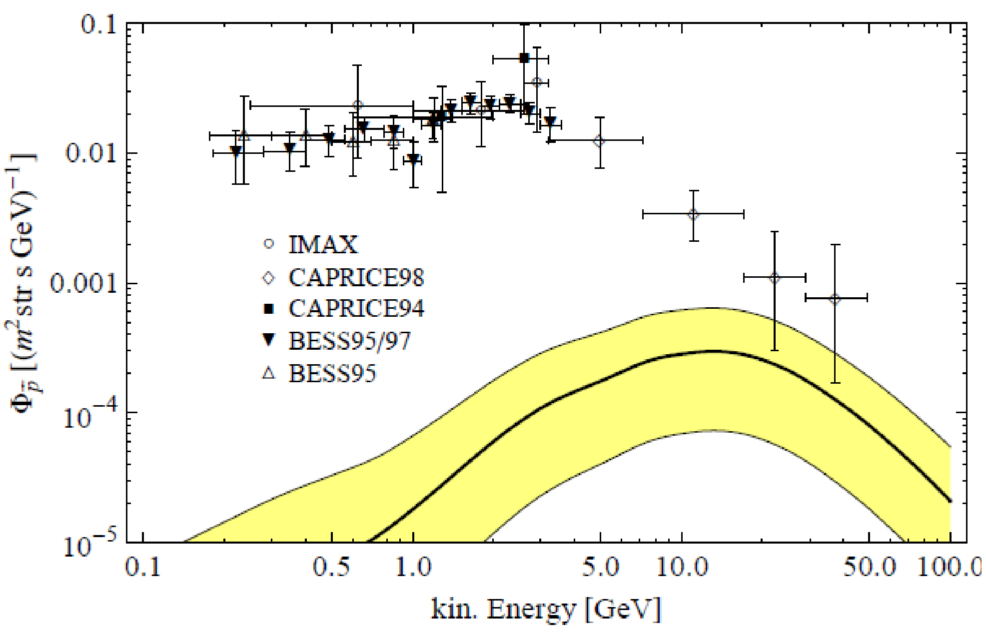
Good agreement of the theory with the experiments: no need for a sizable contribution to the primary antiproton flux. Purely leptonic decays (*e.g.* $\psi \rightarrow \mu^+\mu^-\nu$) are favoured over decays into weak gauge bosons.

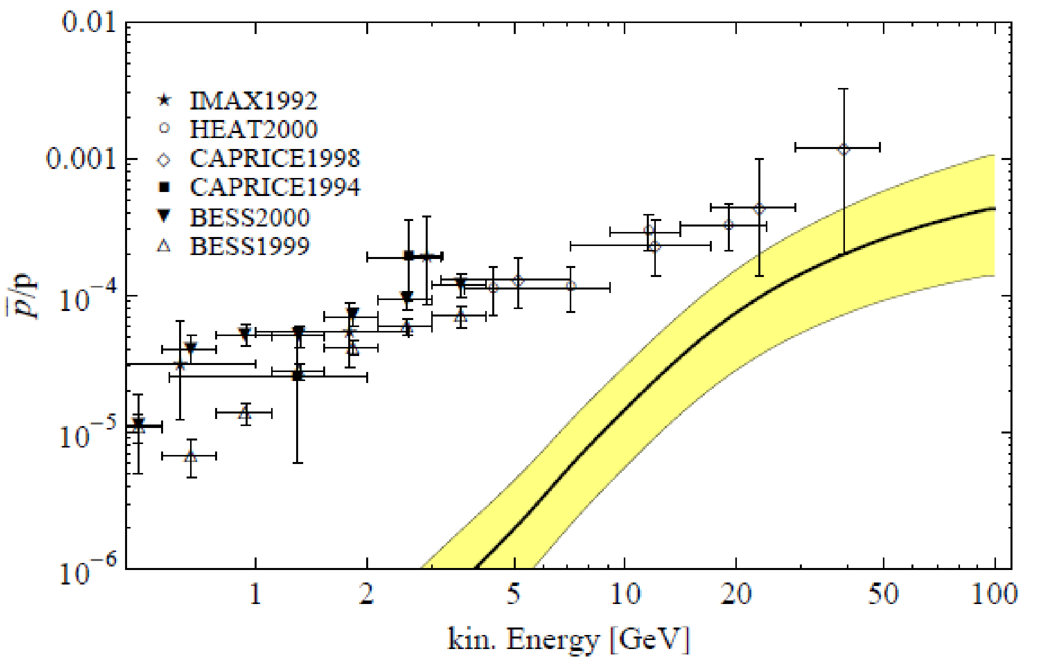
Antiproton flux from dark matter decay

Propagation mechanism more complicated than for the positrons.

The predicted flux suffers from huge uncertainties due to degeneracies in the determination of the propagation parameters

$\psi \to W^{\pm}\mu^{\mp}$





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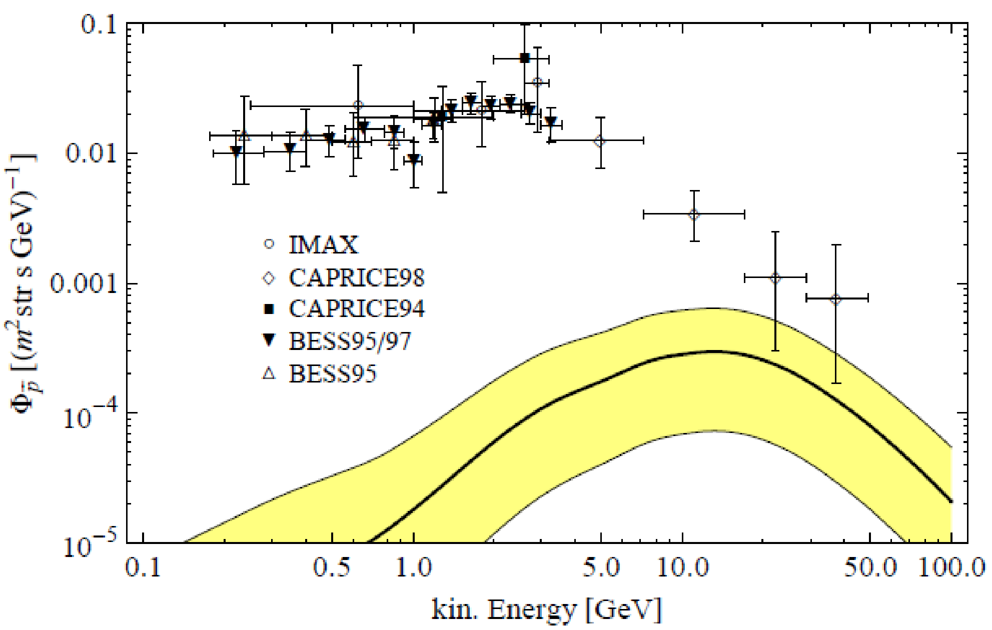
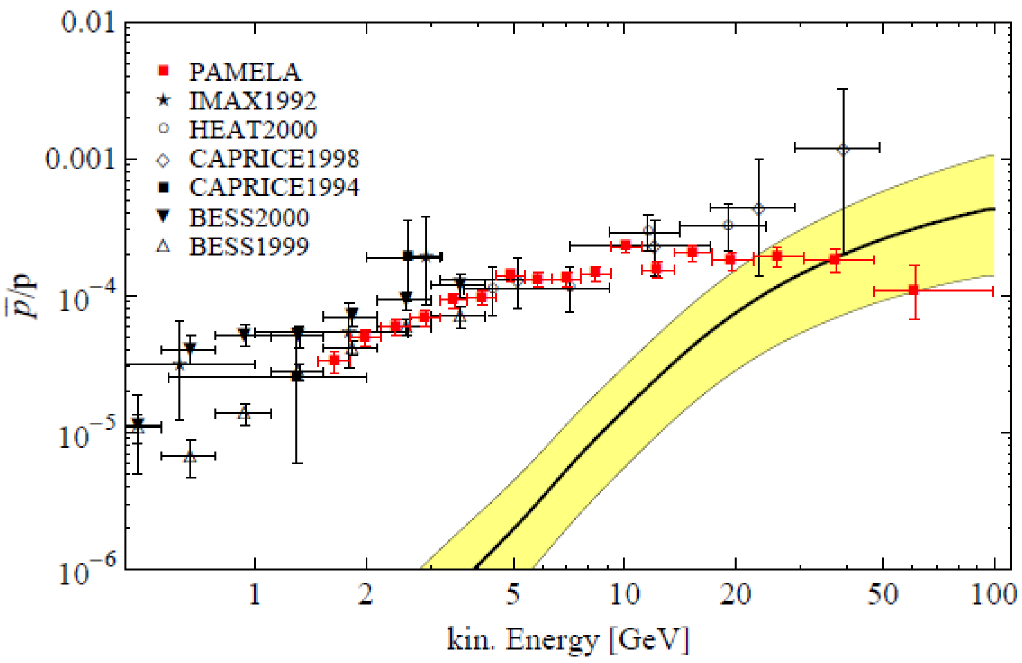




Diffuse gamma ray flux from DM decay

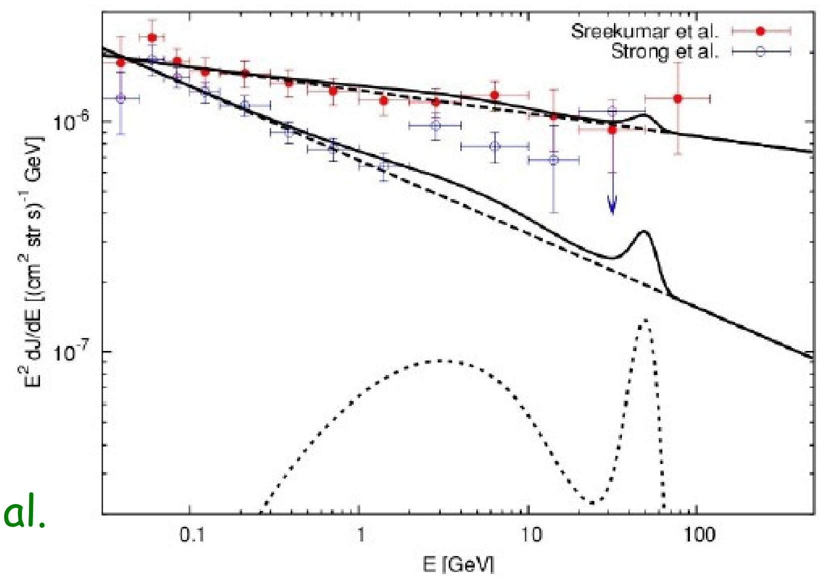
The gamma ray flux from dark matter decay has two components:

- Inverse Compton Scattering radiation of electrons/positrons produced in the decay.
- Always smooth spectrum.

- Prompt radiation of gamma rays produced in the decay (final state radiation, pion decay...)
- May contain spectral features.

e.g. gravitino in SUSY models without R-parity conservation

Buchmüller et al.



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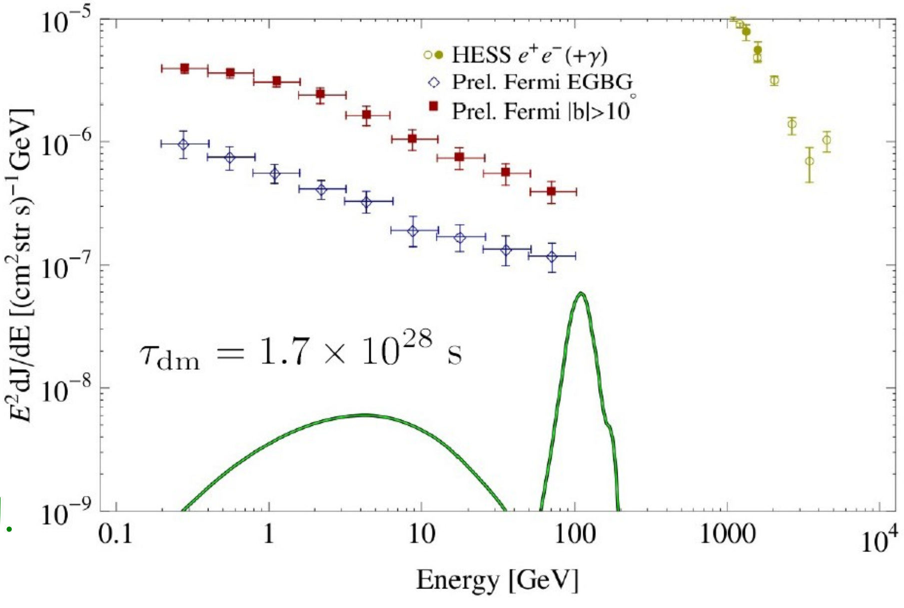
e.g. Hidden vector dark matter

Arina et al.



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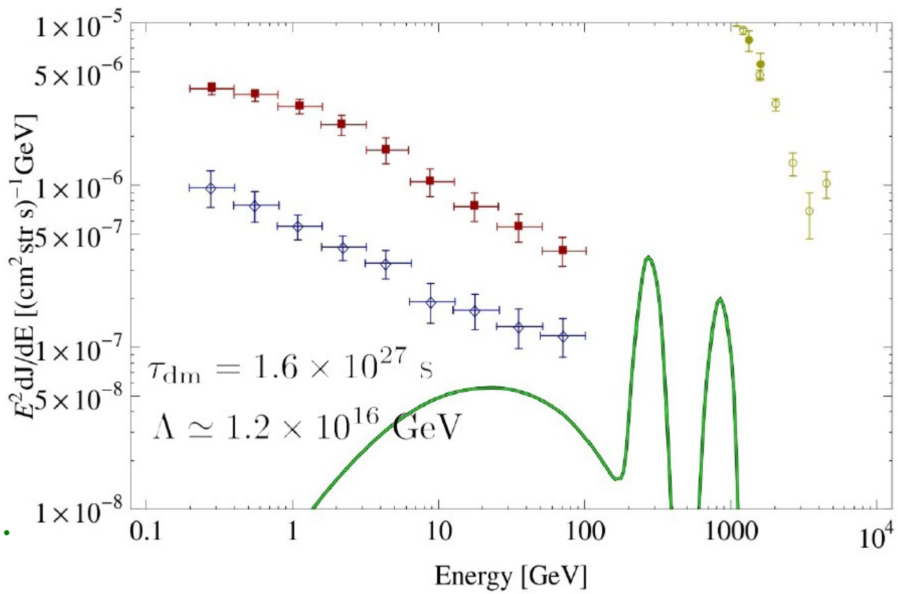


Prompt radiation

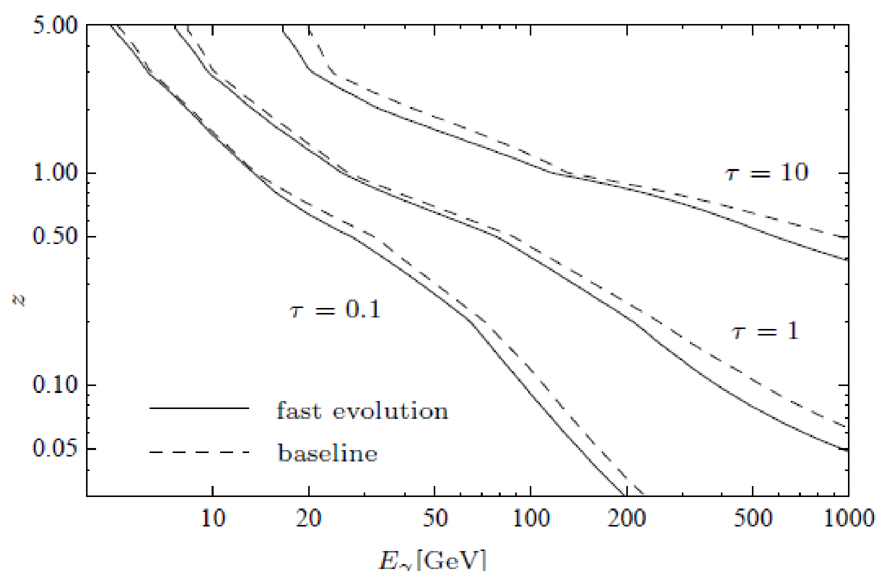
$$\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\rm halo}}{dE_\gamma}(\Omega) + \frac{dJ_{eg}}{dE_\gamma}$$

Halo component

- Depends on the dark matter profile. Strong dependence in the direction of the galactic center and mild at high latitudes (|b|>10°)
- Even if the profile is spherically symmetric, the flux at Earth is anisotropic (more later)

Extragalactic component

- Assumed to be isotropic
- It is attenuated at high energies due to scattering with the intergalactic background light.



Stecker et al.

Prompt radiation

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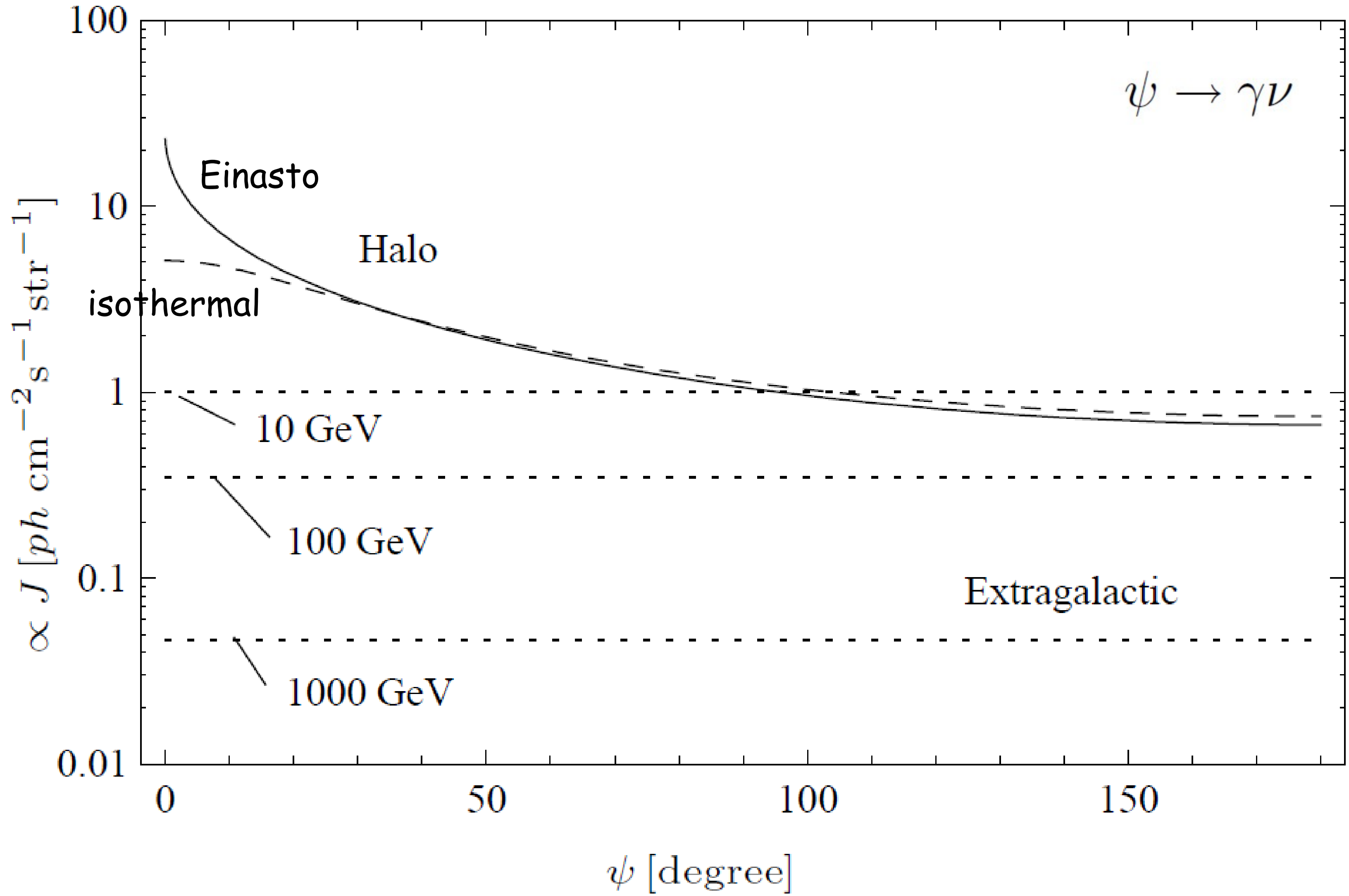


Inverse Compton Scattering radiation

The inverse Compton scattering of electrons/positrons from dark matter decay with the interstellar and extragalactic radiation fields produces gamma rays.

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma^{*}$$

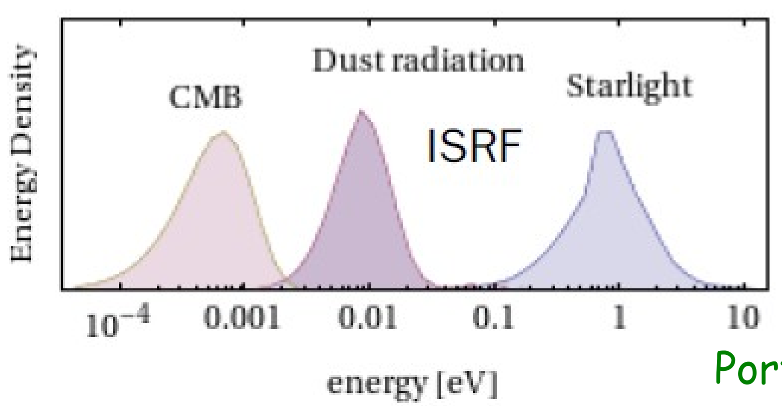
$e^{\pm}$ from dark matter decay
$E_e \lesssim 1$ TeV

Interstellar radiation field (Galactic)
CMB (extragalactic)

Upscattered photon

$$E_{\gamma^*} \leq 4 \left(\frac{E_e}{m_e} \right)^2 E_\gamma$$

This produces
$E_{\gamma*} \lesssim 100$ GeV

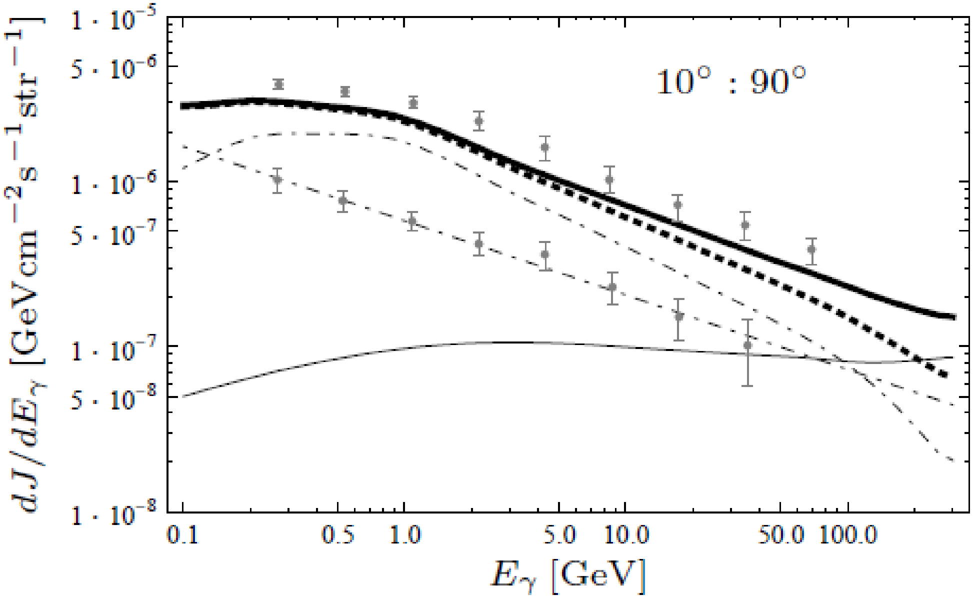


Porter et al.

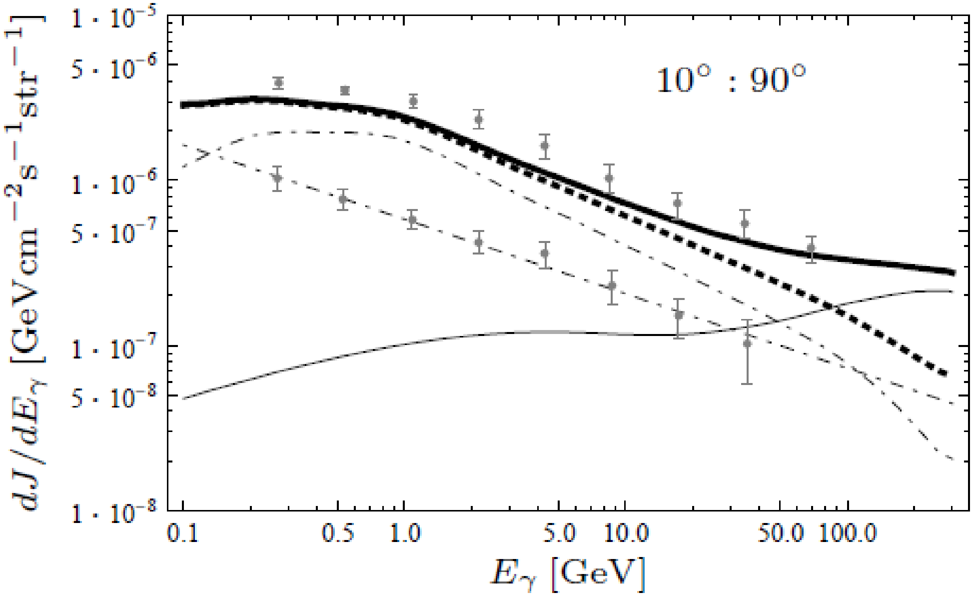
Diffuse gamma ray flux from DM decay

AI, Tran, Weniger
arXiv: 0909.3514

(Data taken from M. Ackermann, talk given at TeV Particle Astrophysics 2009)



$\psi \to \mu^+ \mu^- \nu$



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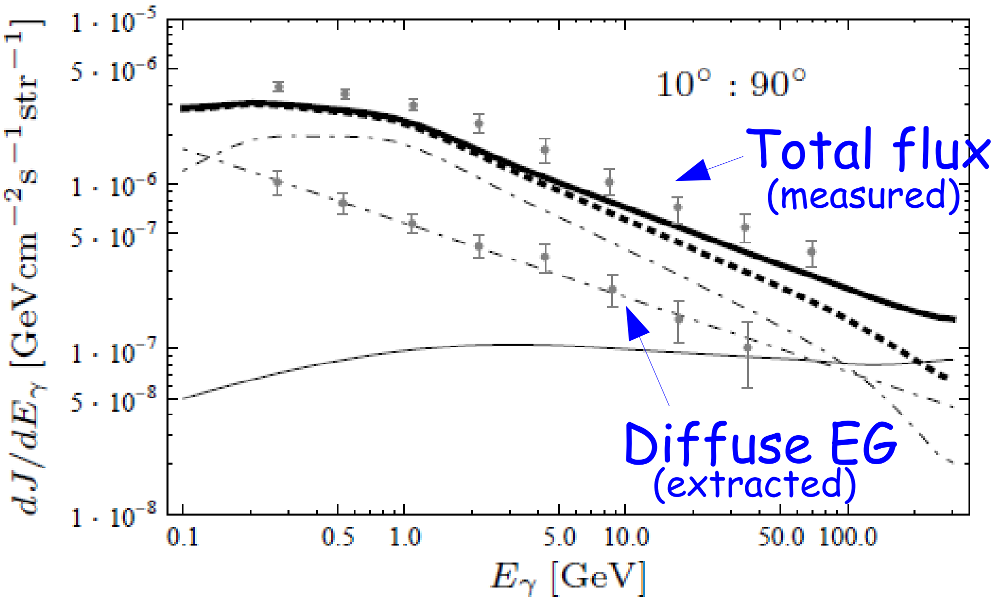

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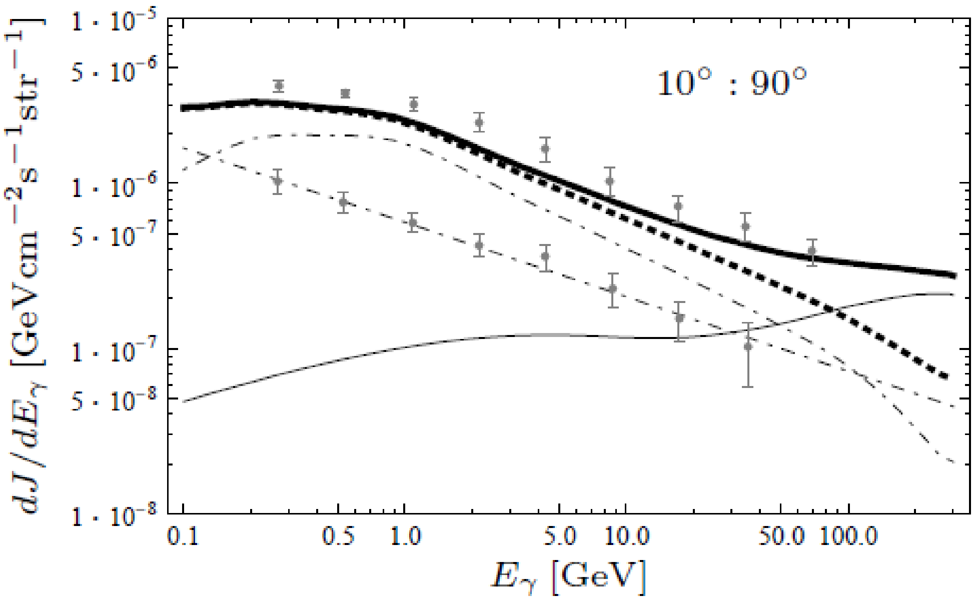

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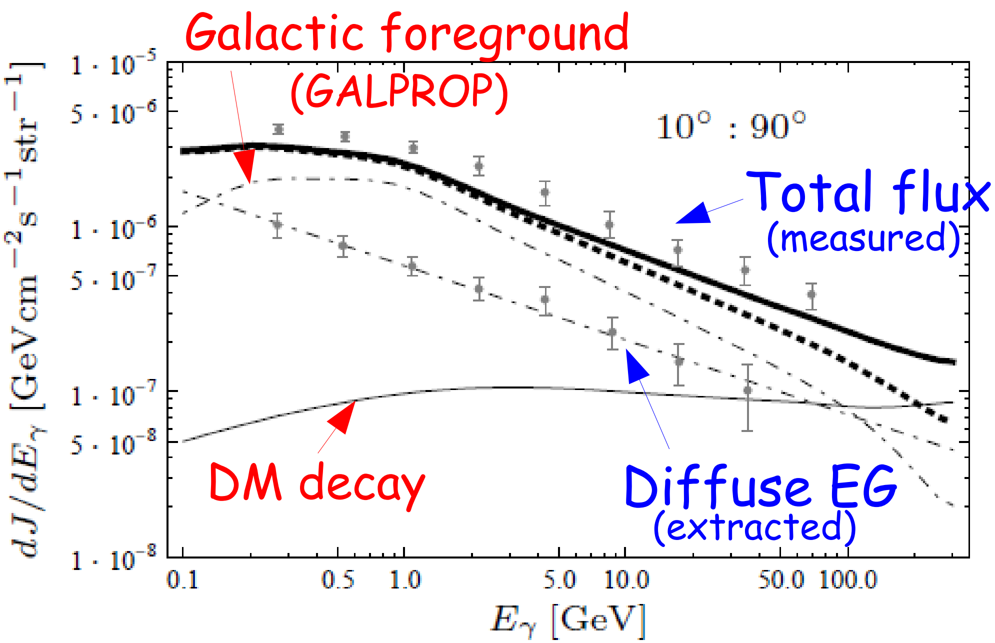

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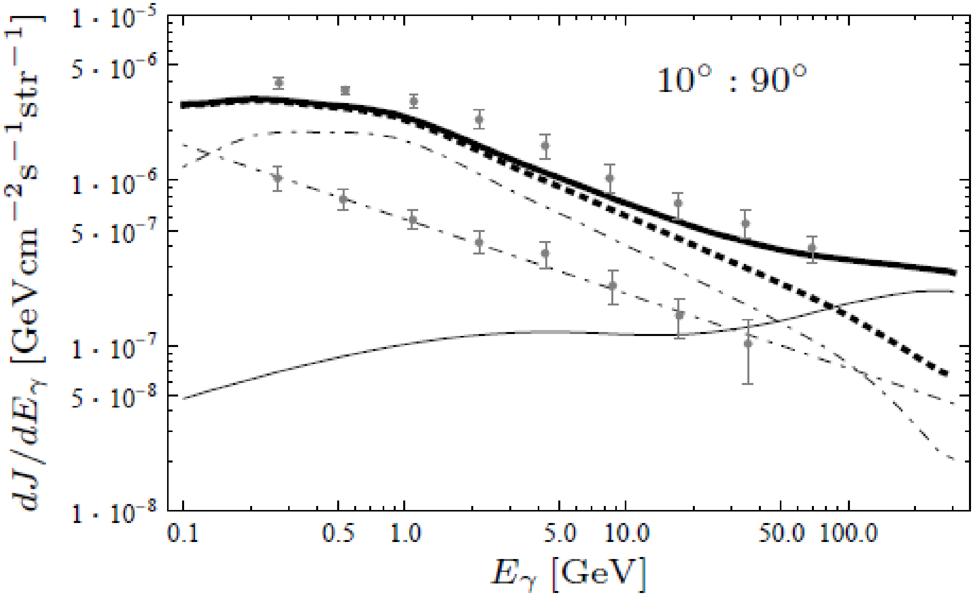

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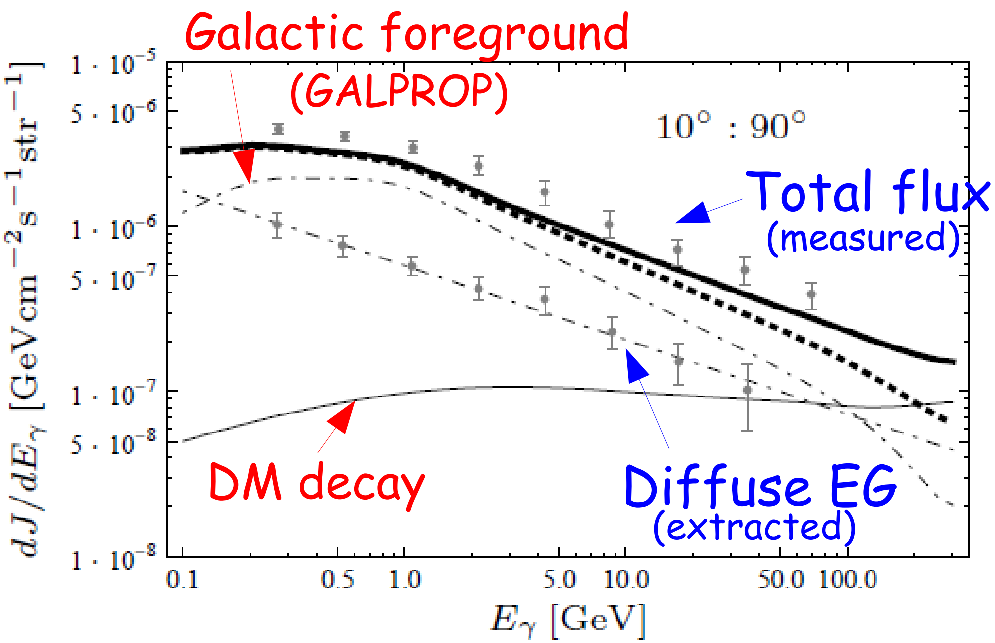

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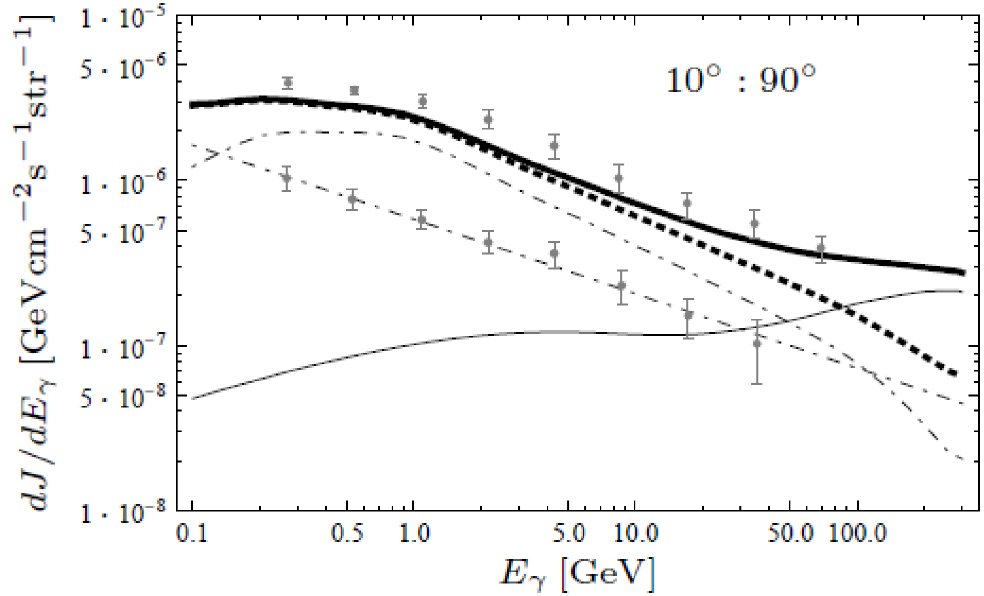

$\psi \to \ell^+\ell^-\nu$

- Crucial test: the contribution from DM decay to the total flux should not exceed the measured one.

Diffuse gamma ray flux from DM decay

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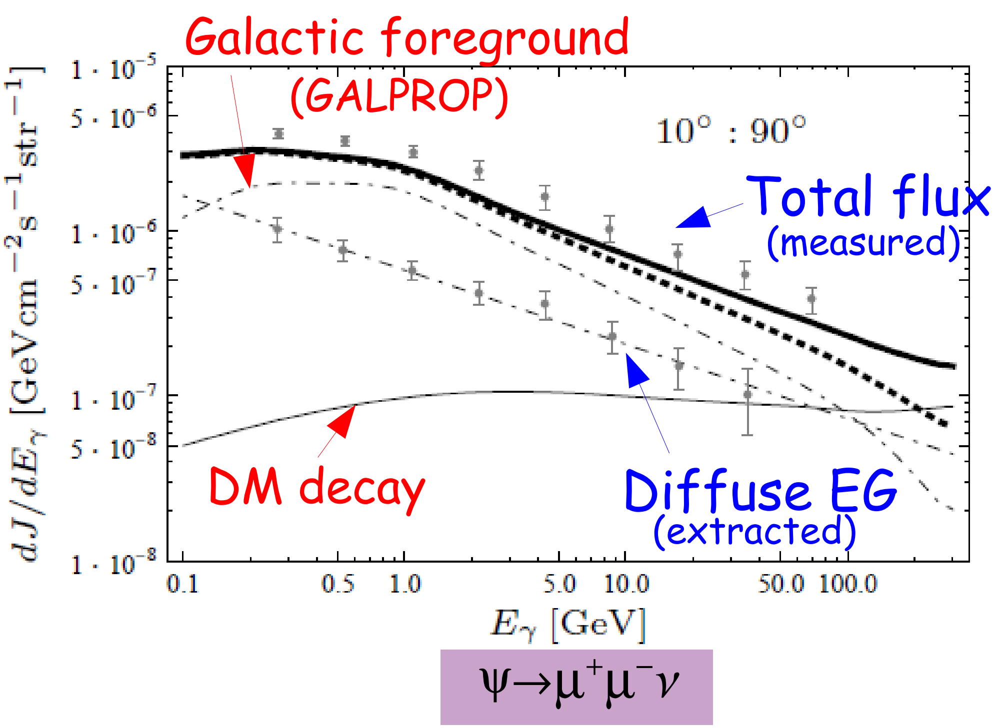
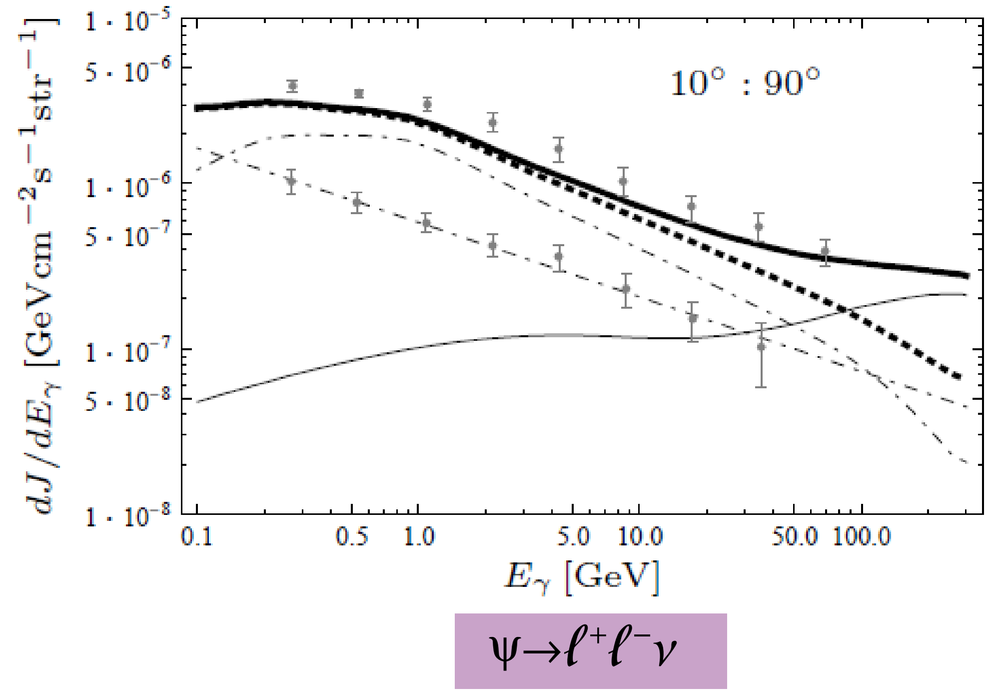


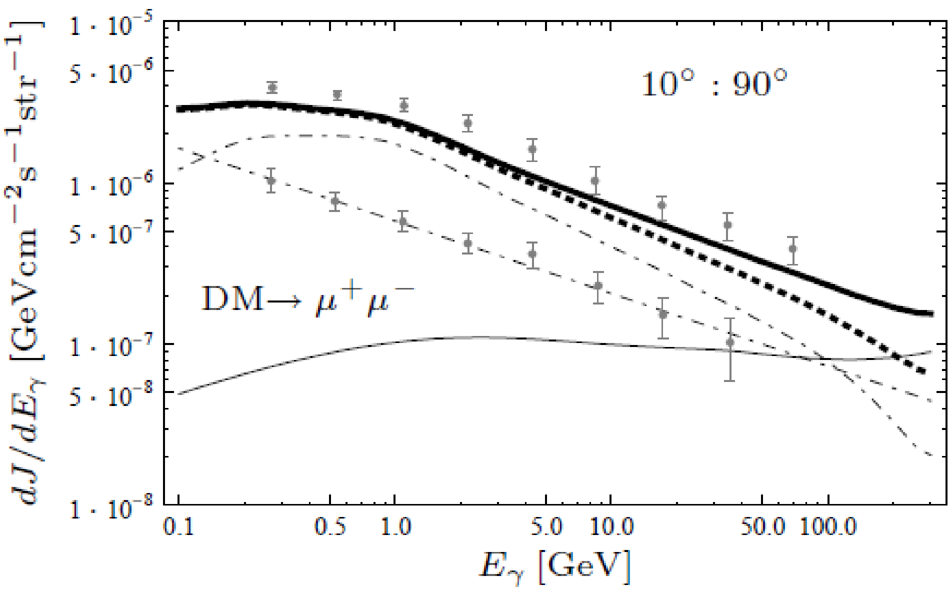


- Crucial test: the contribution from DM decay to the total flux should not exceed the measured one.
- In some channels, there starts to be a deviation from the power law in the diffuse EG flux at higher energies.

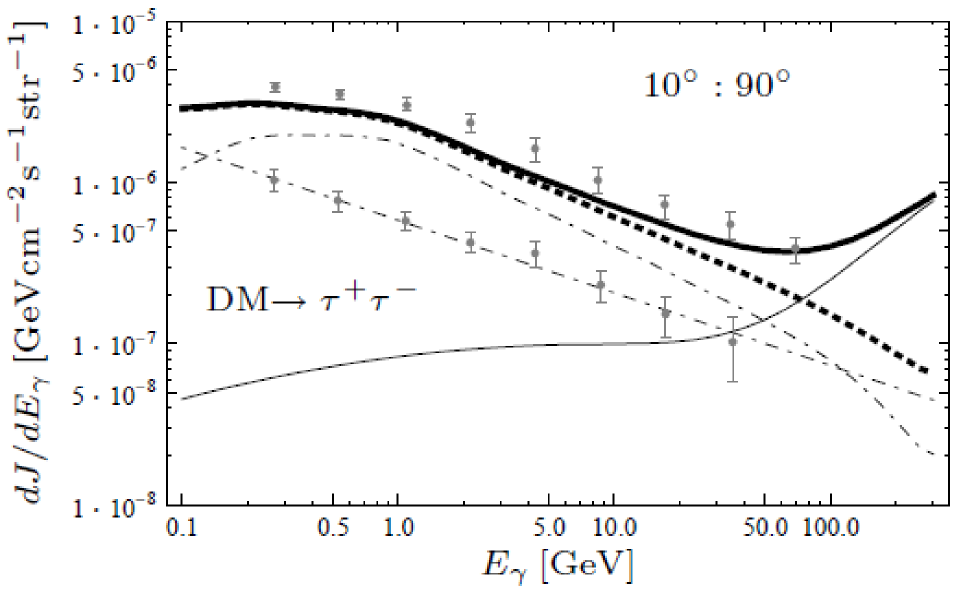
Diffuse gamma ray flux from DM decay

AI, Tran, Weniger
arXiv: 0909.3514

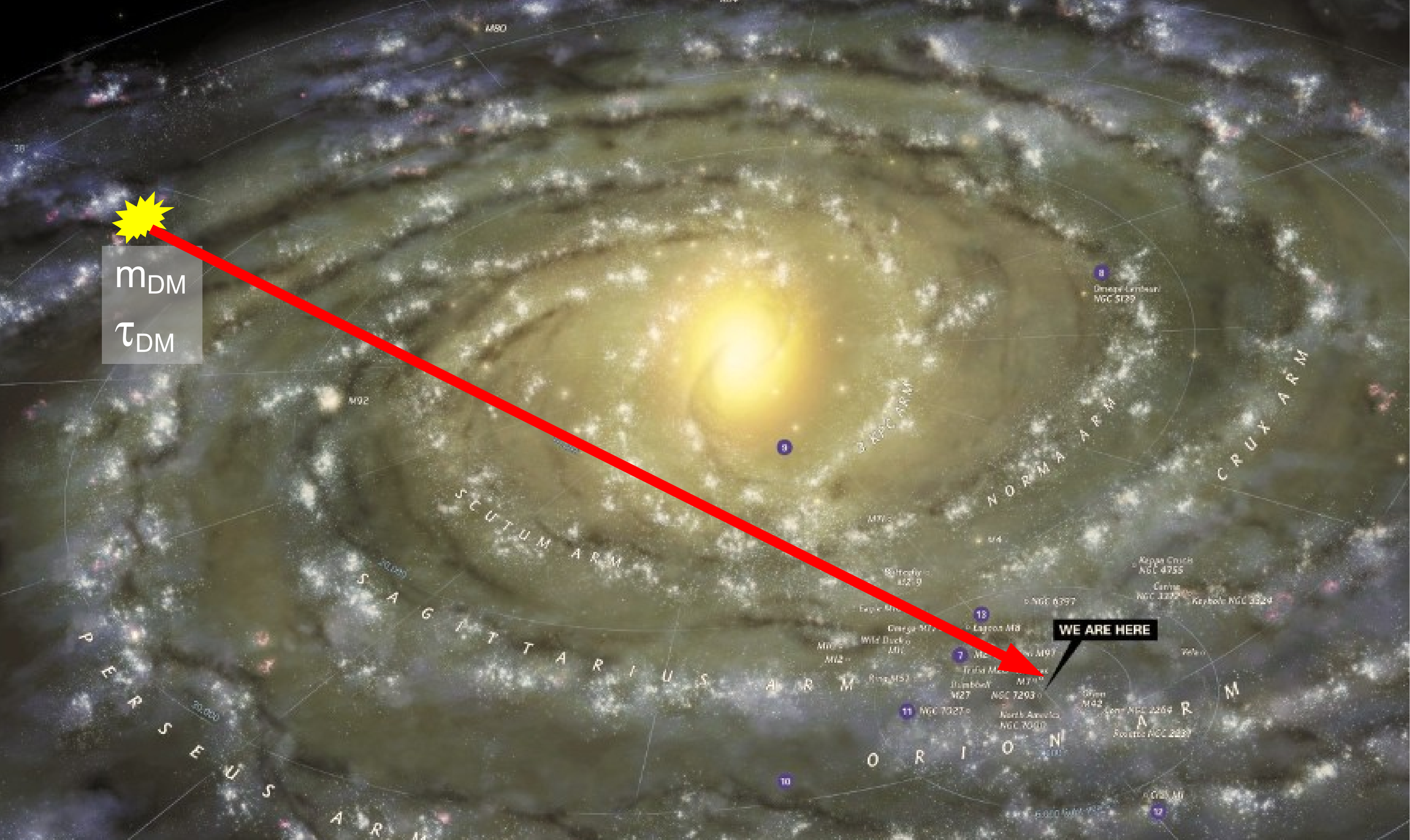
(Data taken from M. Ackermann, talk given at TeV Particle Astrophysics 2009)



$\phi \to \mu^+\mu^-$

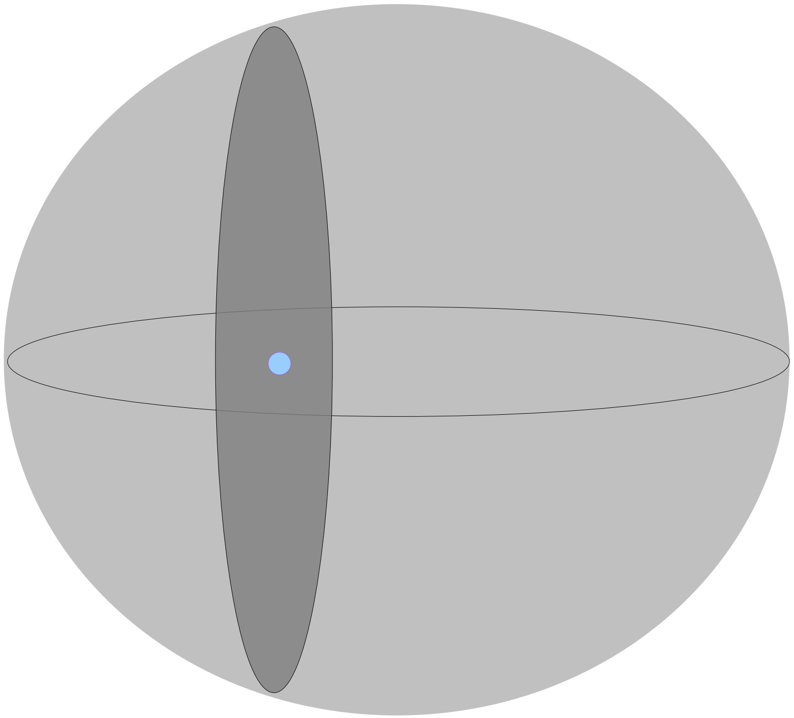


$\phi \to \tau^+\tau^-$



Gamma rays do not diffuse and point directly to the source.
More indications for or against the decaying dark matter scenario arise from the angular distribution of gamma-rays.

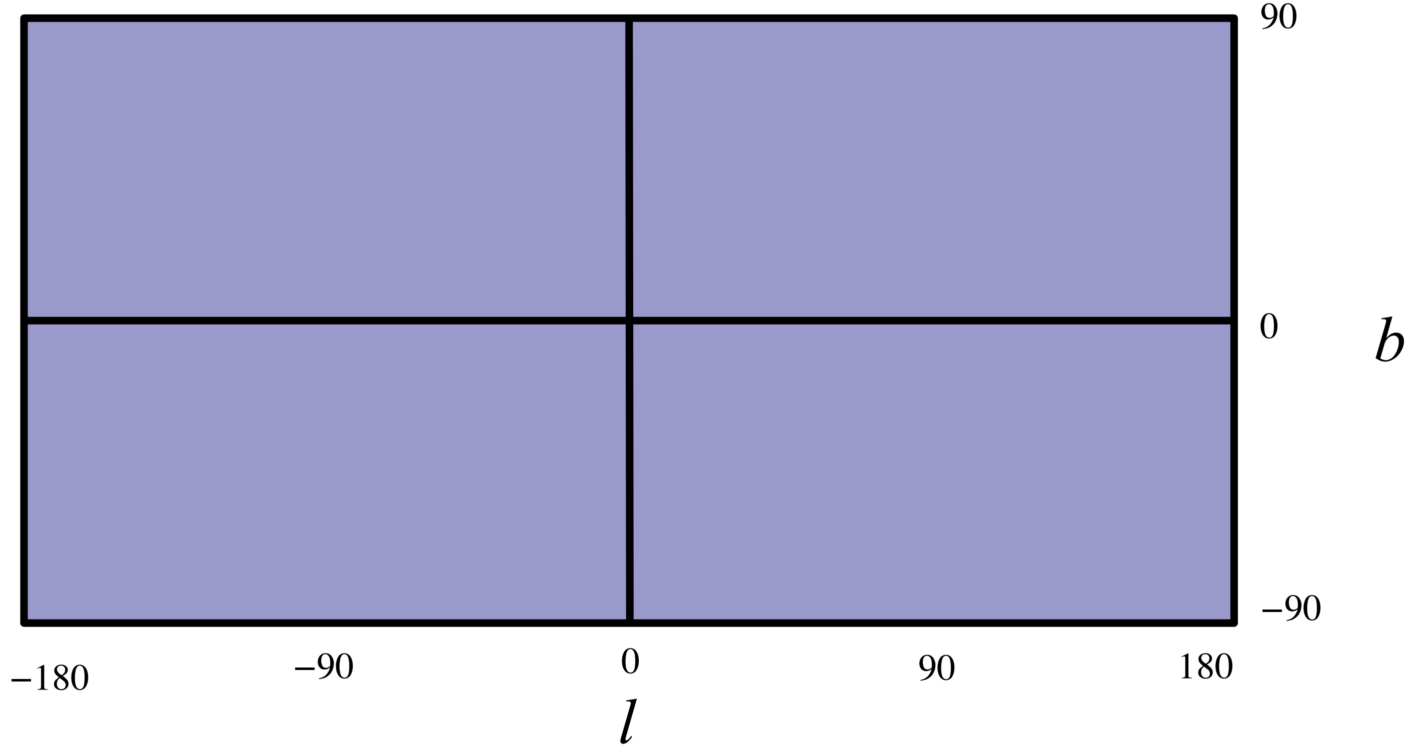
<u>A crucial test</u>: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.



(but no North-South anisotropy)

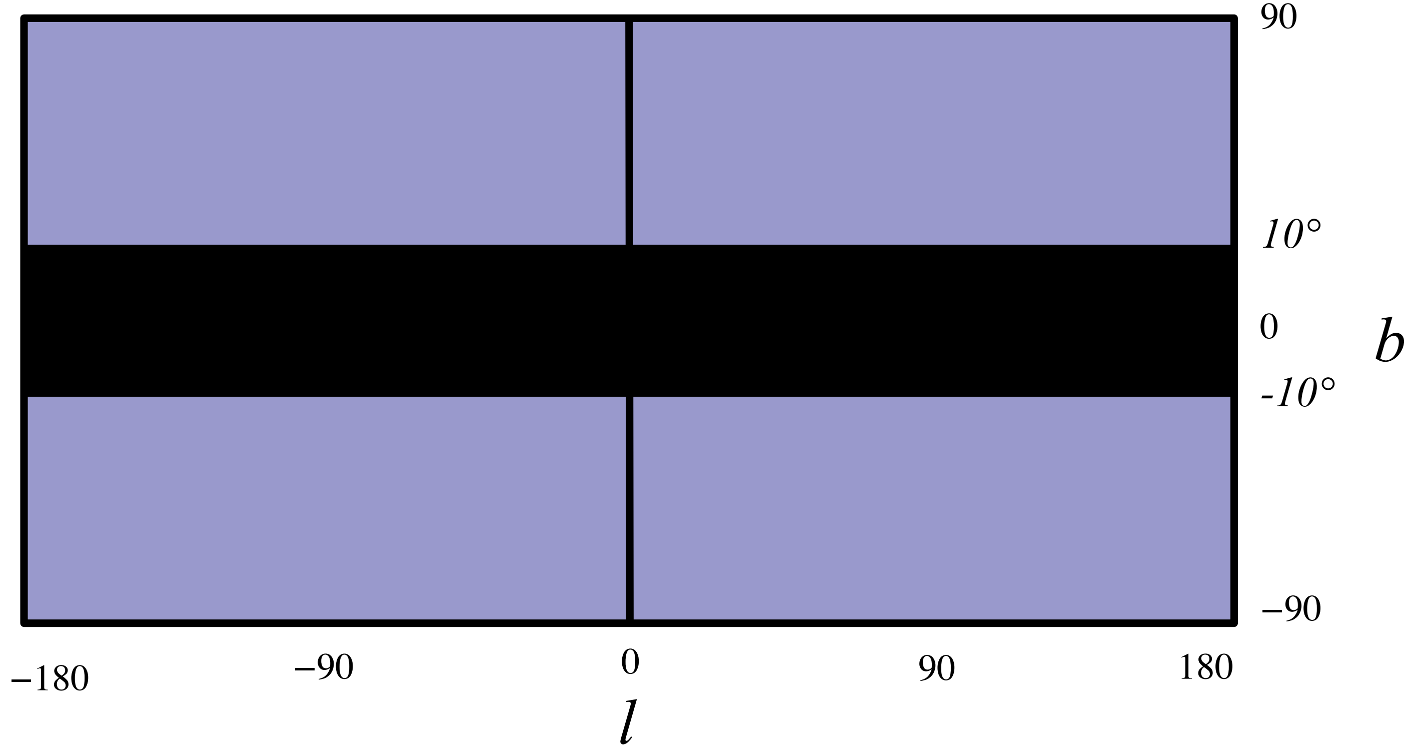
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 1) For a certain energy, take the map of the total diffuse gamma ray flux



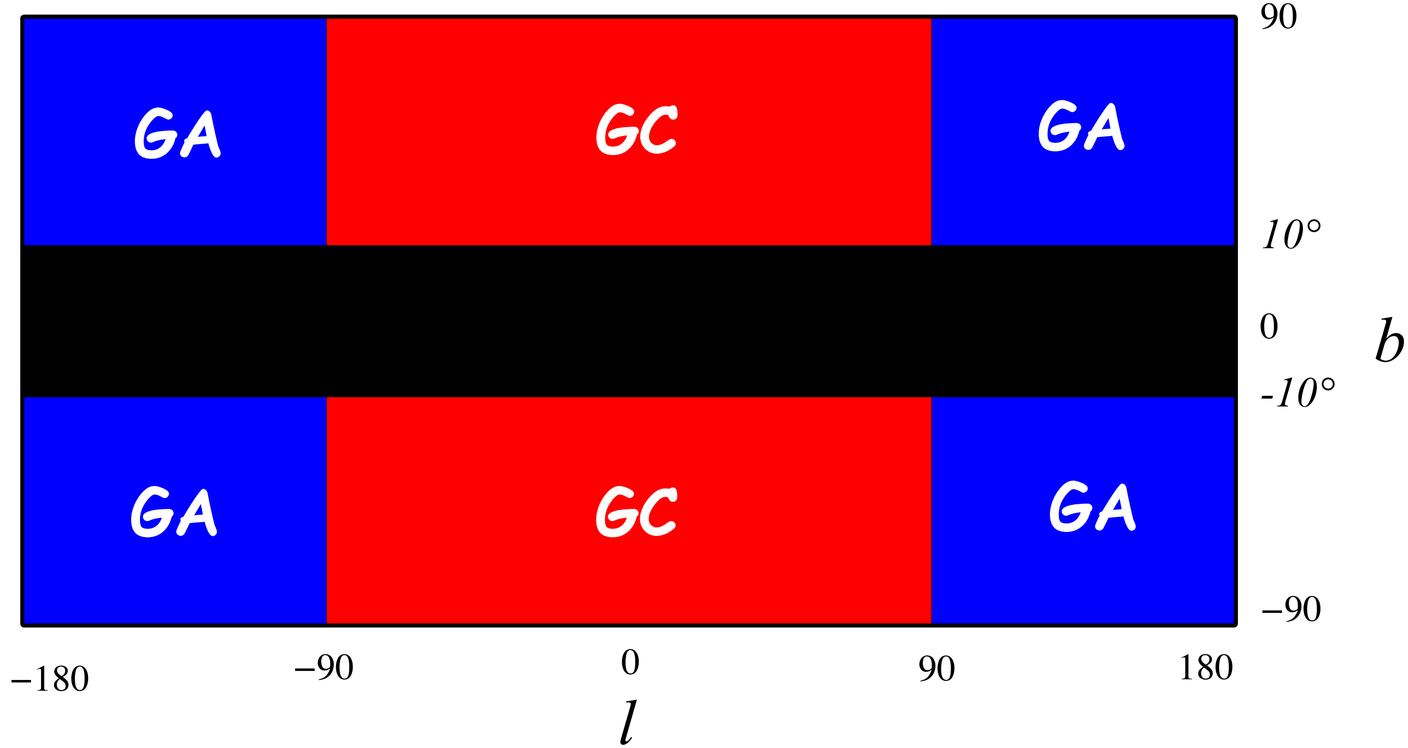
<u>A crucial test</u>: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 2) Remove the galactic disk



A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 3) Take the total fluxes coming from the direction of the galactic center (J_{GC}) and the galactic anticenter (J_{AC}).



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Strategy: 4) Calculate the anisotropy, defined as:

$$A(E) = \frac{J_{GC} - J_{GA}}{J_{GC} + J_{GA}}$$

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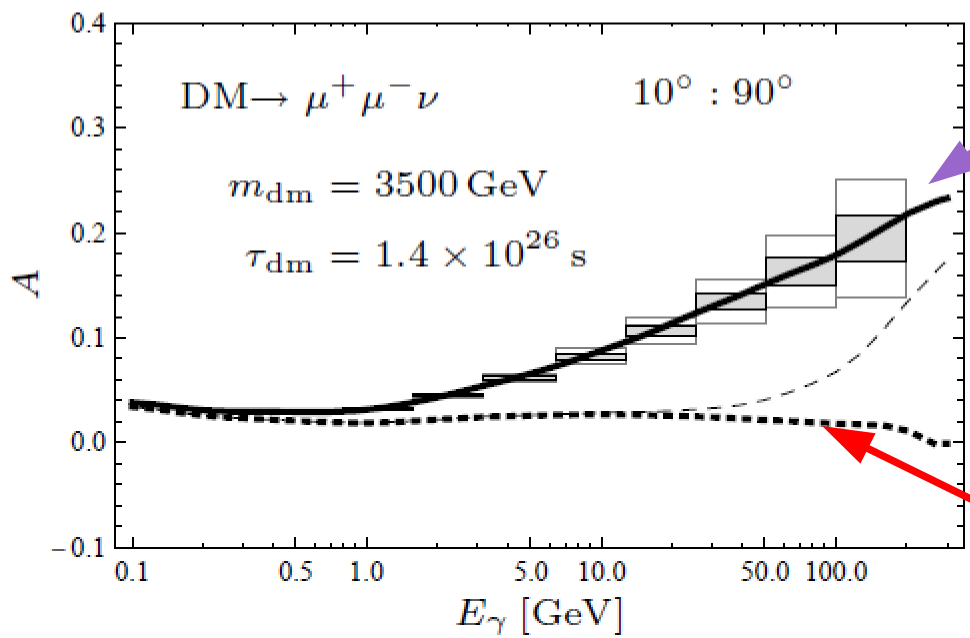
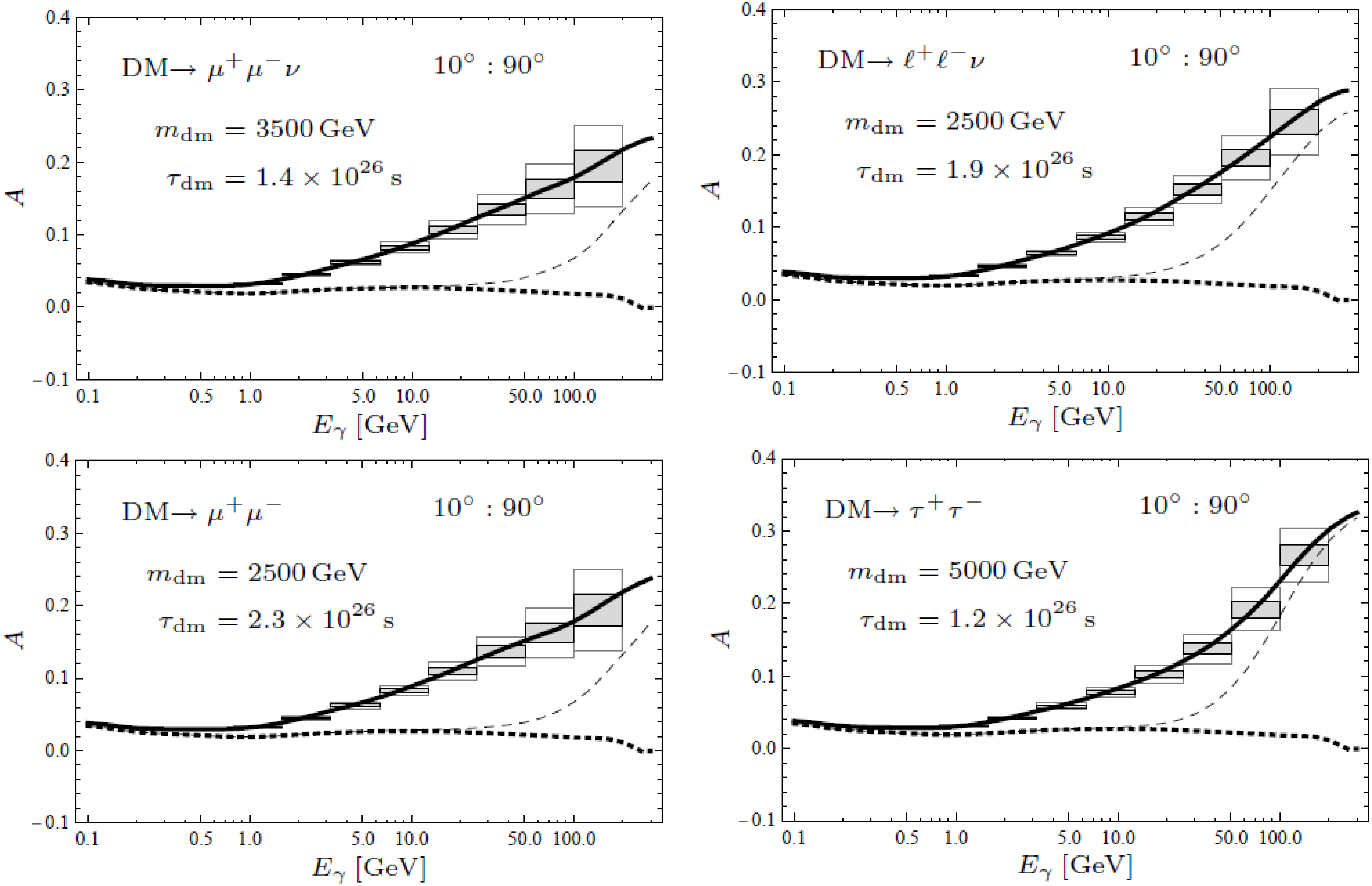


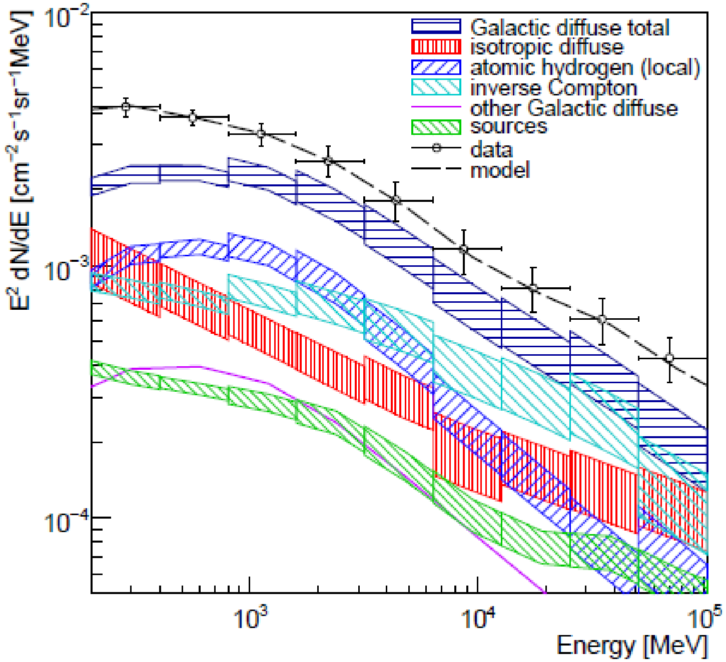
DM decay prediction: 15-20% at high energies!

"conventional" diffusive model

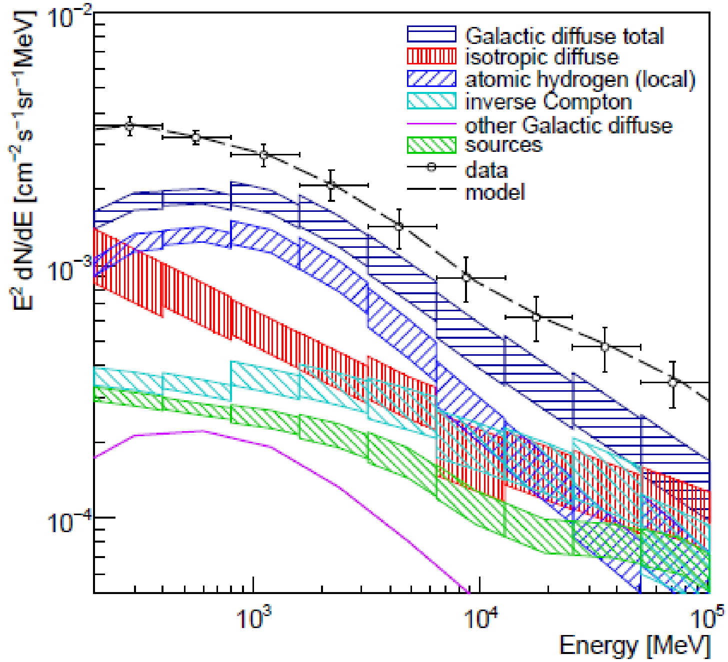
The same conclusion holds for all decaying DM scenarios that explain the electron/positron excesses.



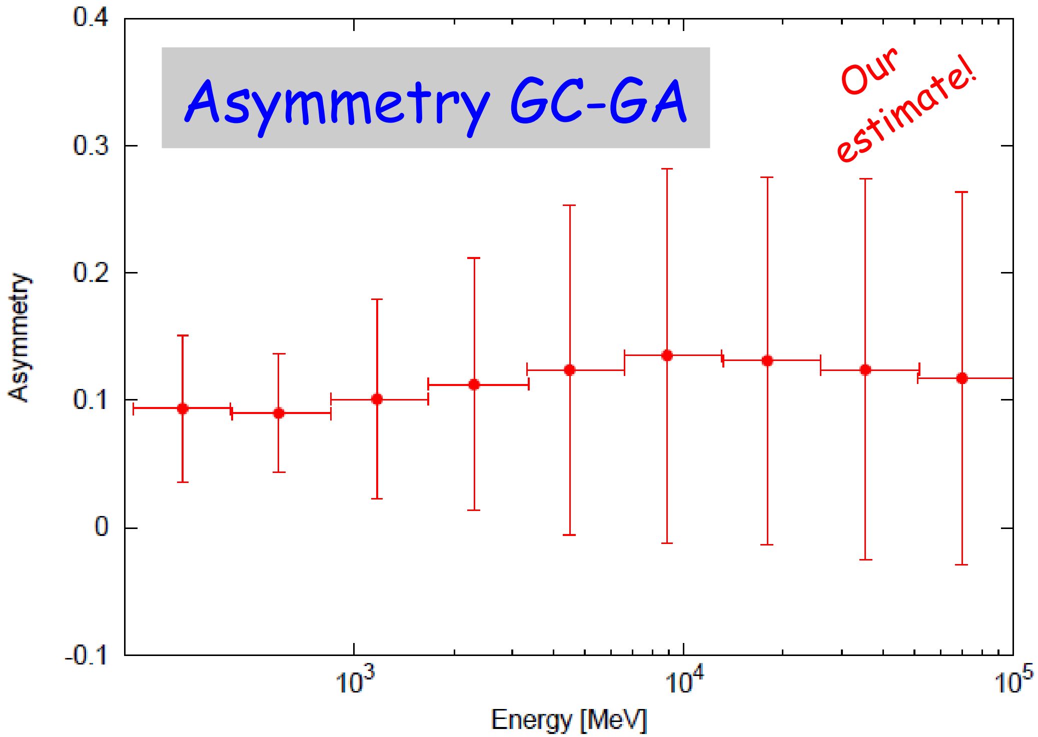
Galactic center



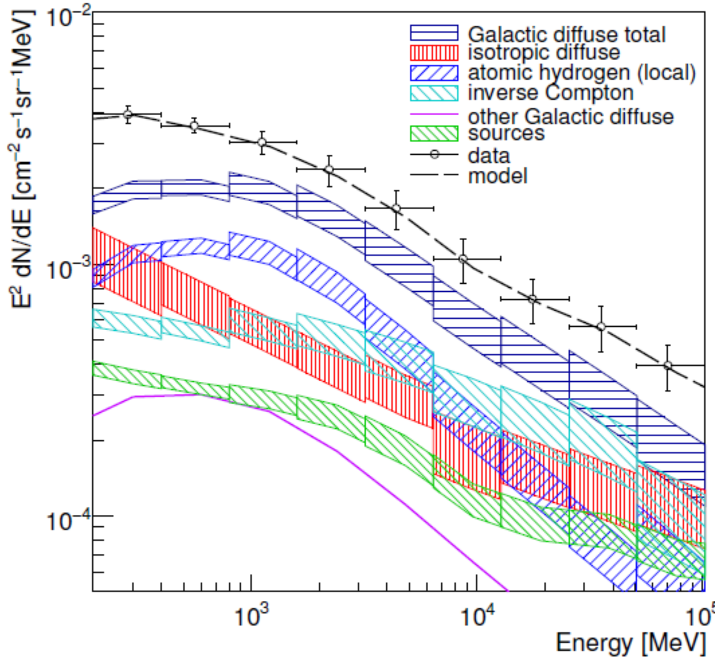
Galactic anticenter



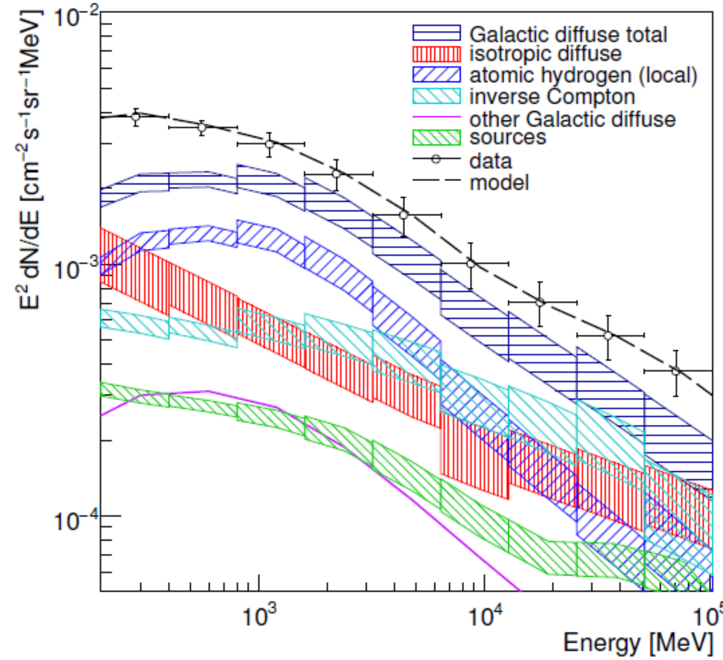
Fermi coll.



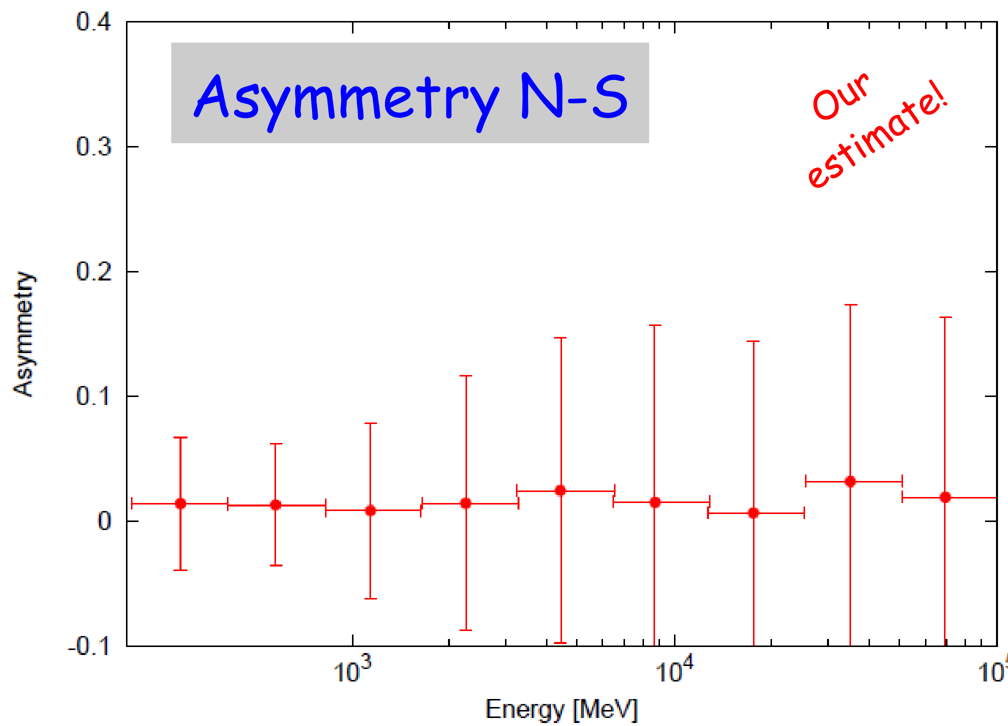
North hemisphere



South hemisphere

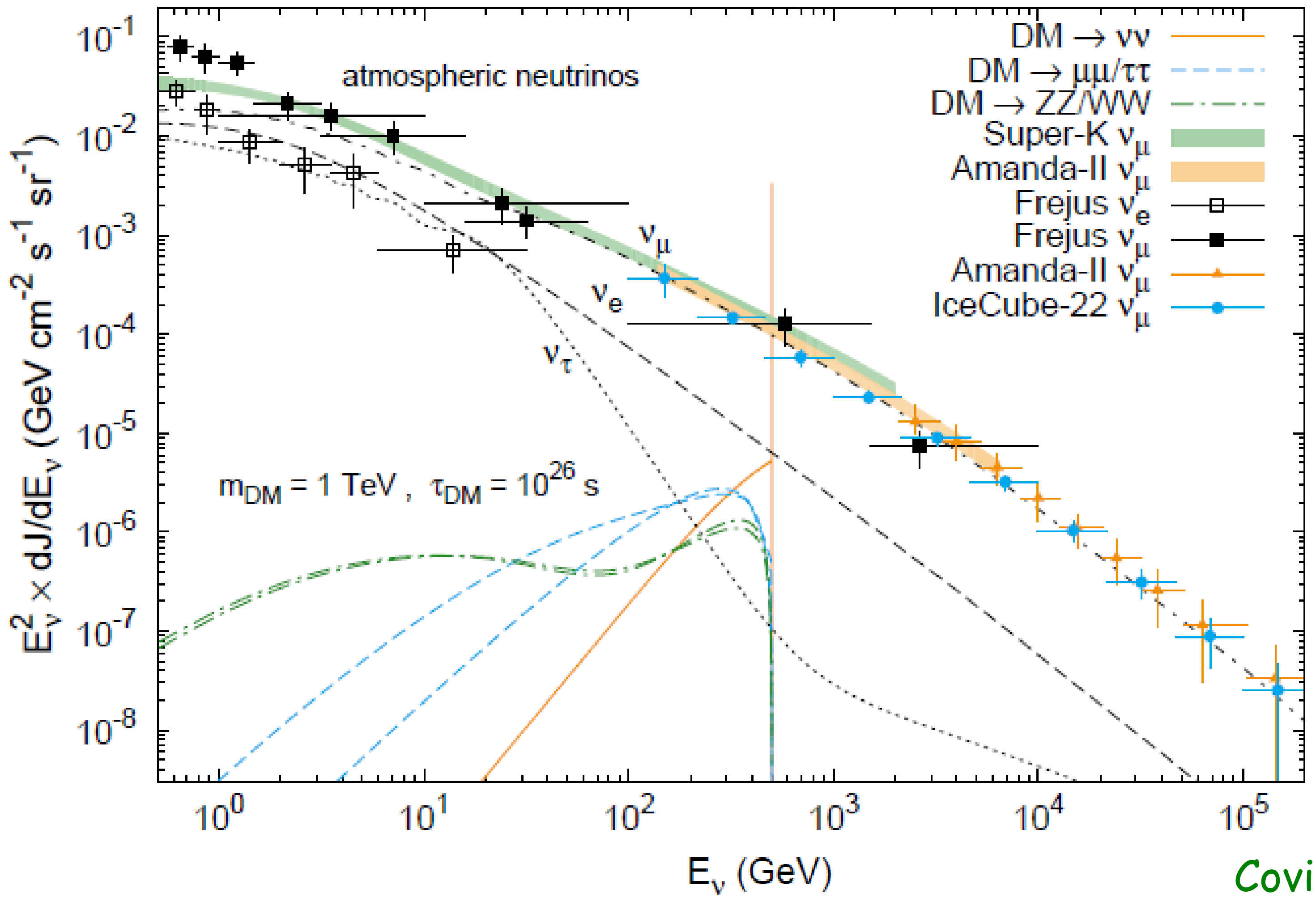


Fermi coll.



Neutrino flux

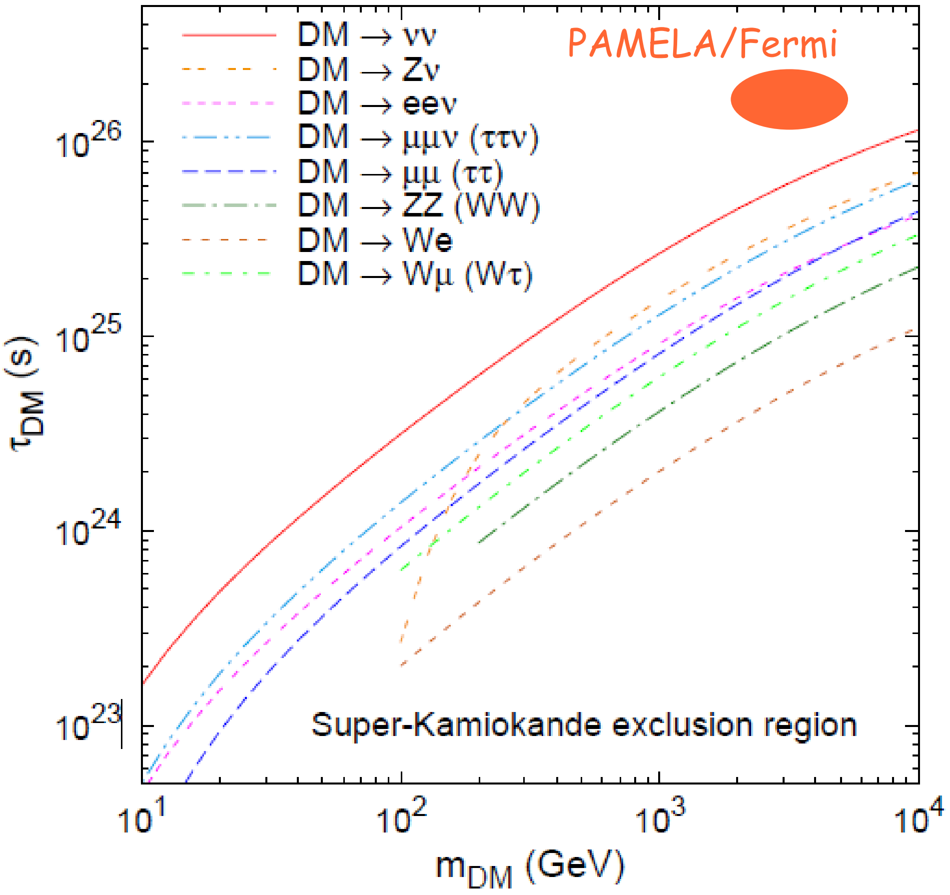
- Difficult to see due to large atmospheric backgrounds.



Covi et al.

Neutrino flux

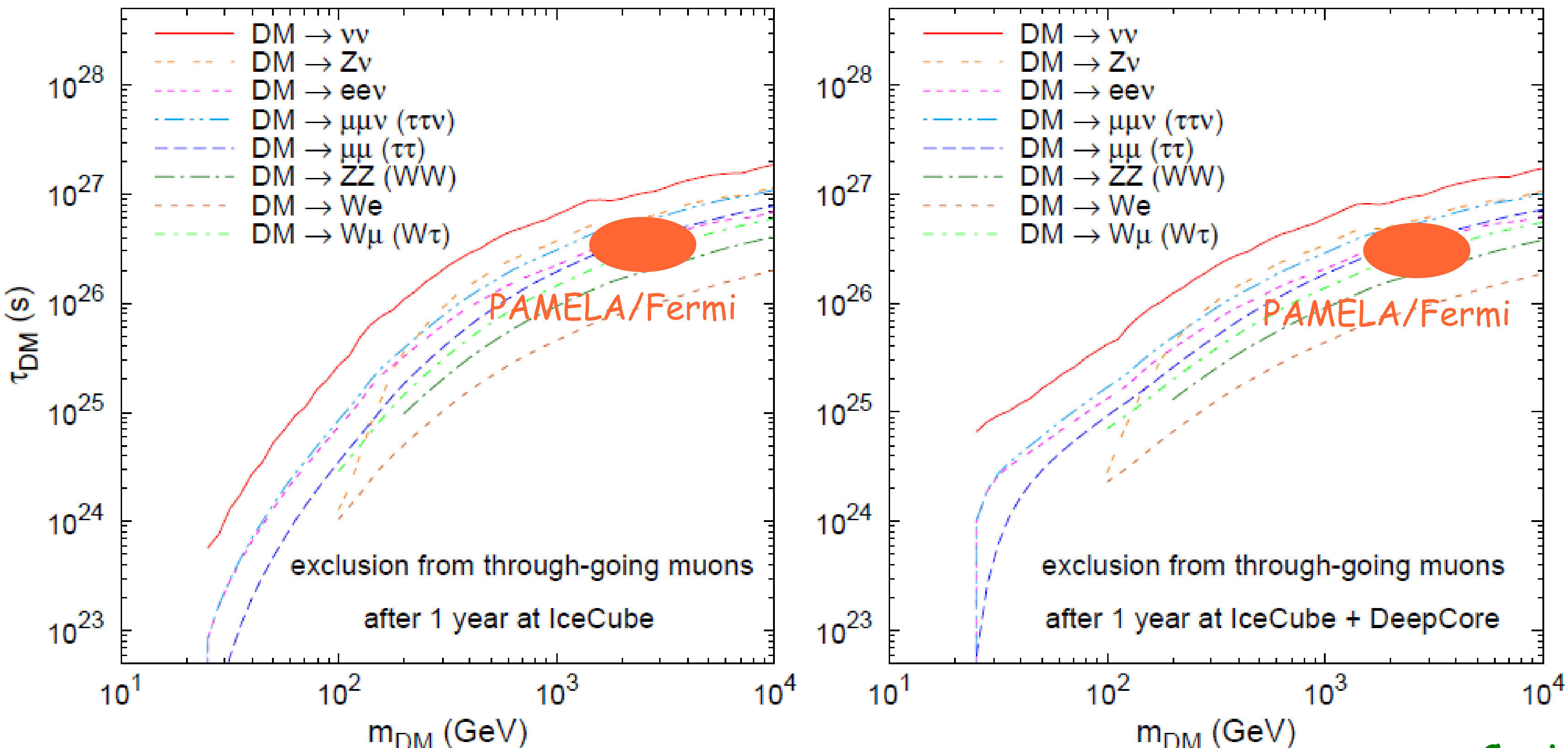
- Difficult to see due to large atmospheric backgrounds.



Covi et al.

Neutrino flux

- Difficult to see due to large atmospheric backgrounds.
- But not impossible: it may be observed by IceCube (+ DeepCore)



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Conclusions

• Some well motivated candidates for dark matter are predicted to decay with very long lifetimes. Their decay products could be detected in indirect search experiments.

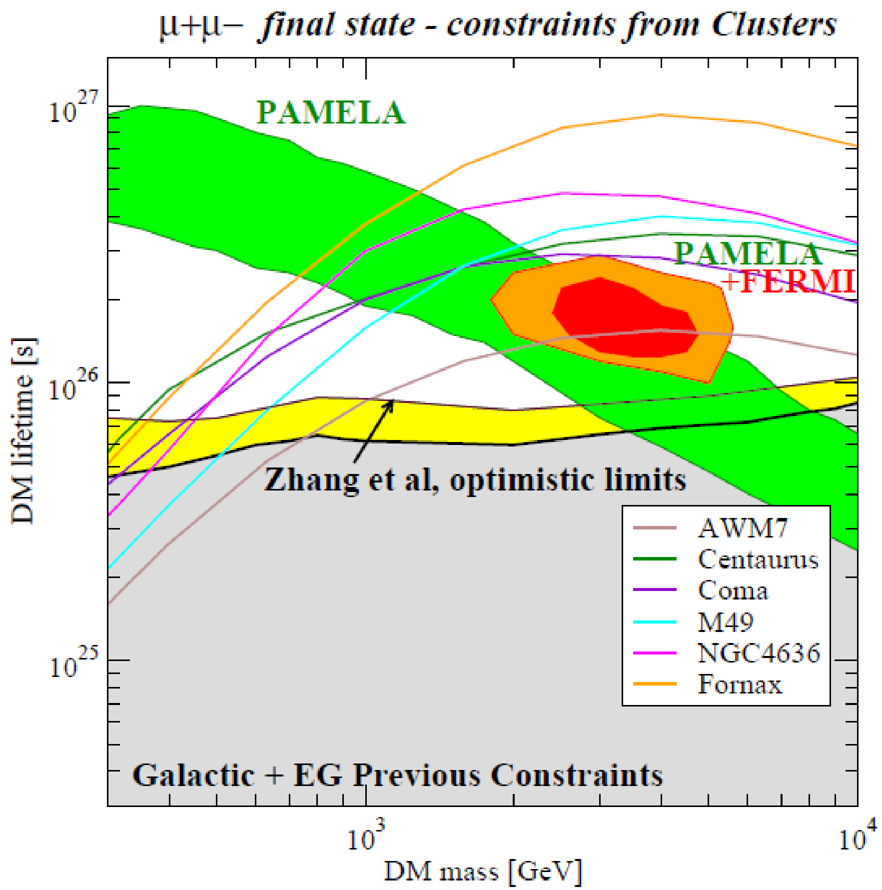
• Recent experiments have confirmed the existence of an excess of positrons at energies larger than ~7GeV.

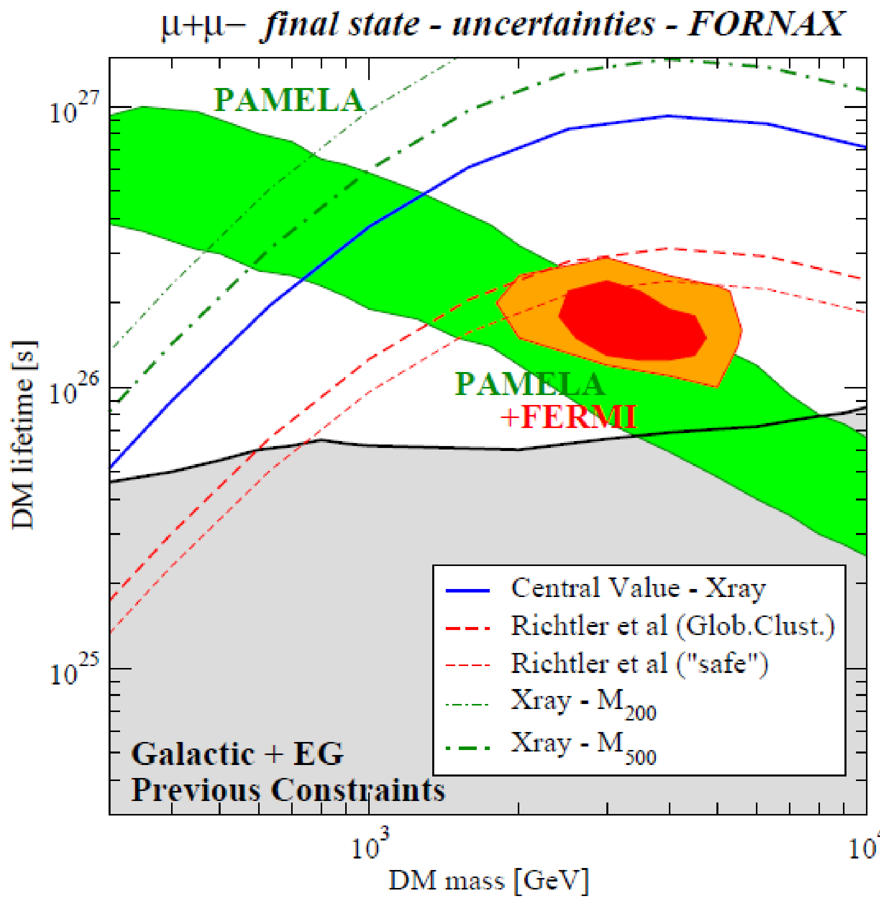
Evidence for a primary component:

astrophysics?

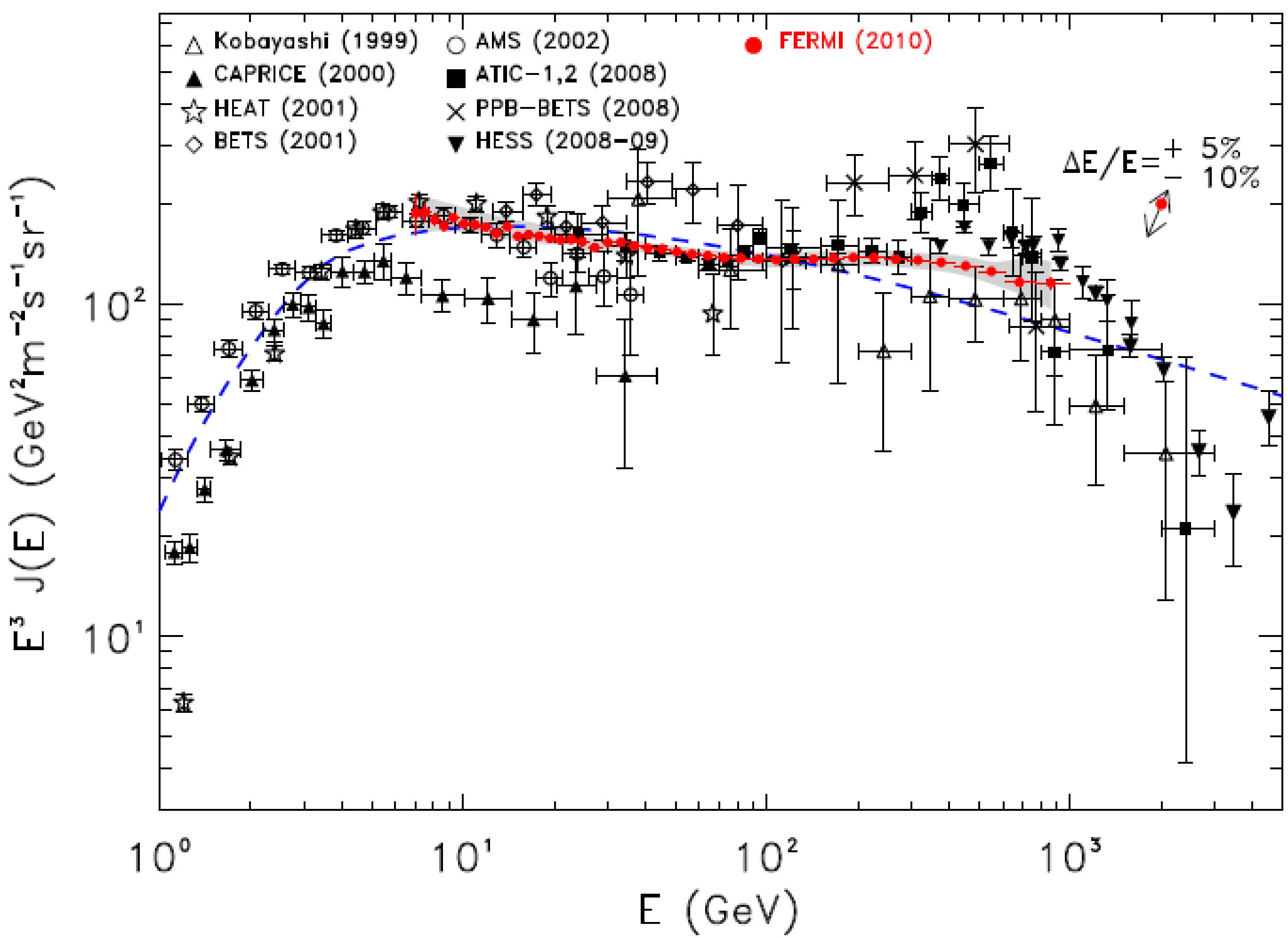
particle physics?

• Decaying dark matter can explain the electron/positron excesses observed by PAMELA and Fermi. Furthermore, these scenarios make predictions for future gamma-ray and neutrino observations, providing tests for this interpretation of the e+/e- excesses

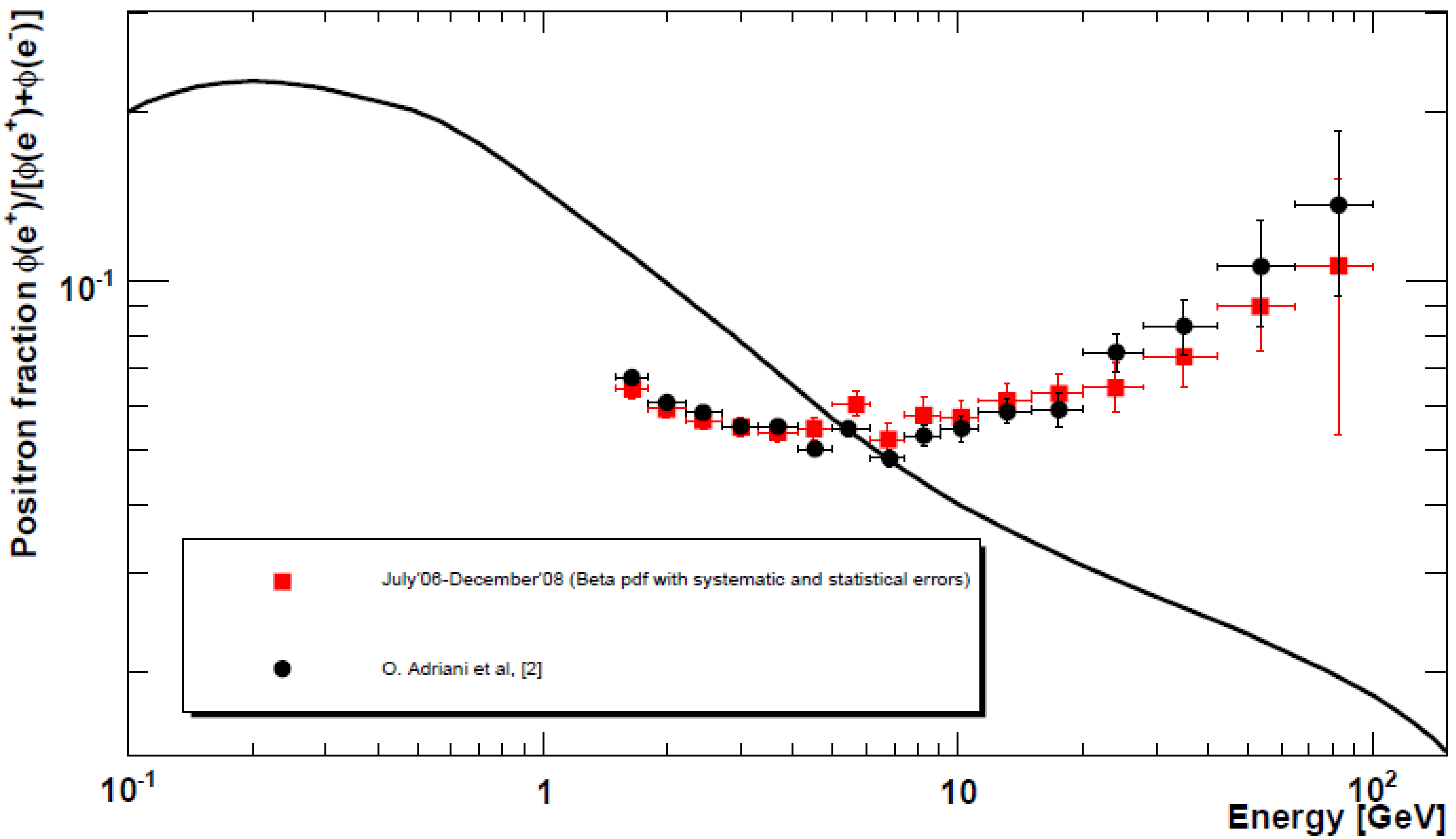




Dugger, Jeltema, Profumo
arXiv:1009.5999

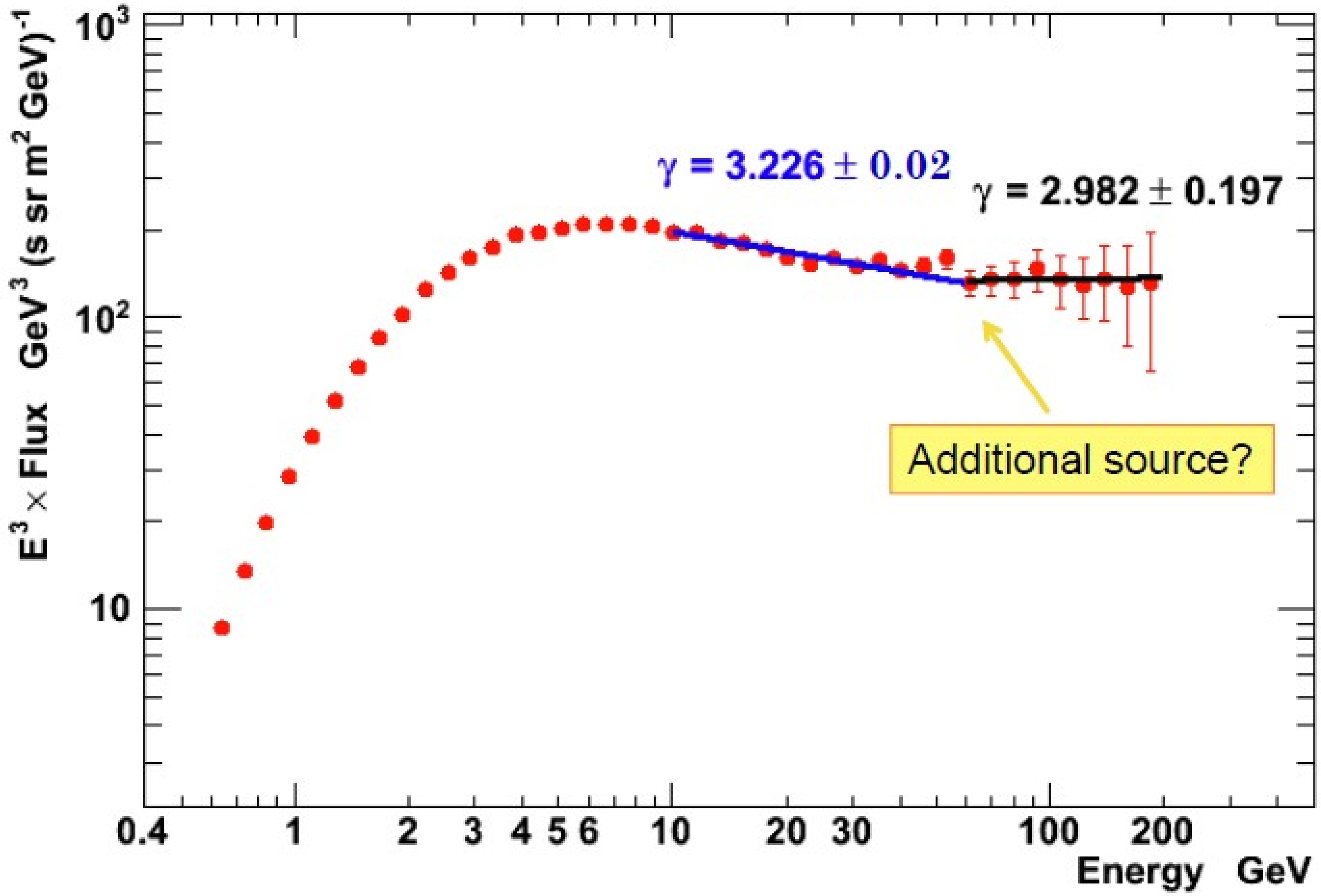


Fermi collaboration
arXiv:1008.3999



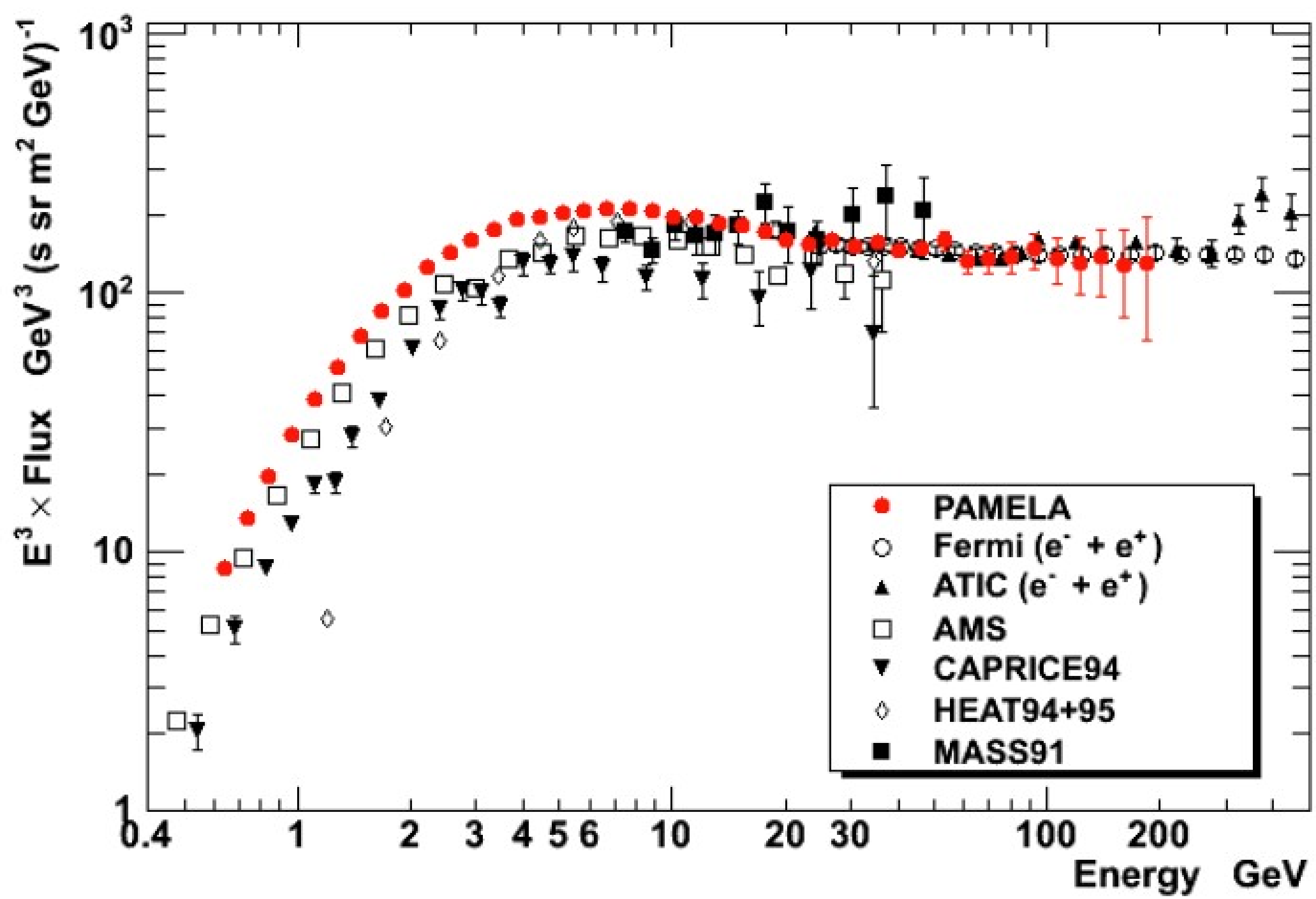
Adriani et al., 1001.3522

PAMELA ELECTRON (e^-) SPECTRUM



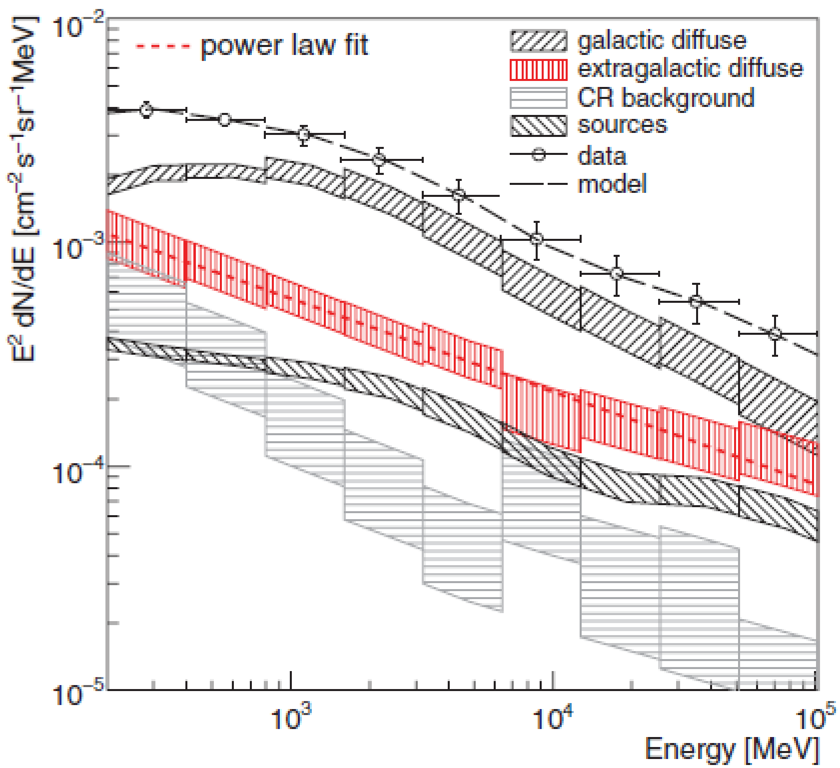
From Roberta Sparvoli
Les Rencontres de Physique
de la Vallée d'Aoste 2010

PAMELA Electron (e⁻) Spectrum



From Roberta Sparvoli
Les Rencontres de Physique
de la Vallée d'Aoste 2010

Diffuse gamma ray flux



Fermi coll.

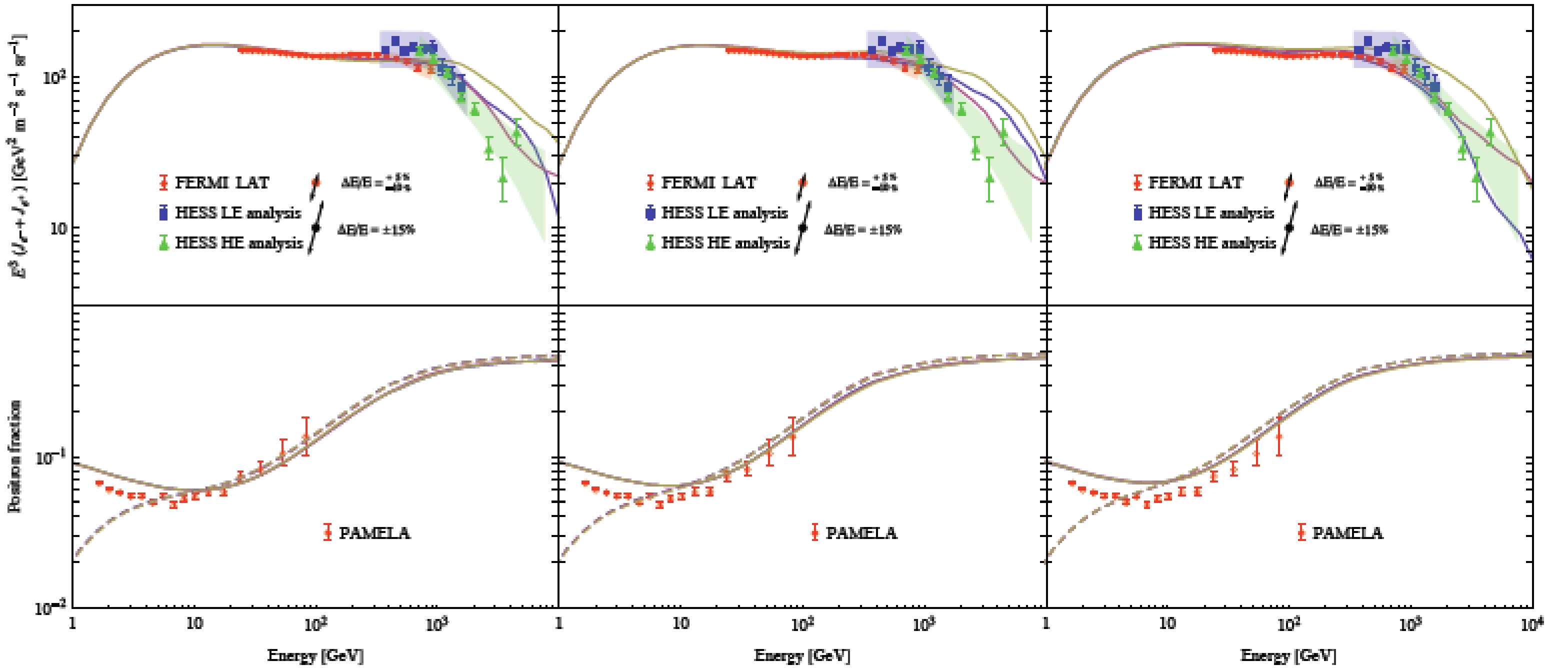
For the dominant high-latitude components, bremsstrahlung and π^0-decay emission from HI and HII in the local Galaxy (7.5 kpc $< R <$ 9.5 kpc) and IC emission, the intensities are fit to the LAT data via scale factors. We use the GALPROP sky maps as templates with the component normalizations per energy bin as fit parameters. The subdo-

TABLE I. Fit results and uncertainties for the EGB and other components for $|b| \geq 10°$.

	Intensity integrated over energy band (cm^{-2} s^{-1} sr^{-1})								
Energy in GeV	0.2–0.4	0.4–0.8	0.8–1.6	1.6–3.2	3.2–6.4	6.4–12.8	12.8–25.6	25.6–51.2	51.2–102.4
Intensity scale factor	$\times 10^{-6}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-8}$	$\times 10^{-8}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-9}$	$\times 10^{-10}$
EGB	2.4 ± 0.6	9.3 ± 1.8	3.5 ± 0.6	12.7 ± 2.1	5.0 ± 1.0	14.3 ± 4.0	6.3 ± 1.5	2.6 ± 0.7	11.1 ± 2.9
Galactic diffuse (fit)	4.9 ± 0.4	25.9 ± 1.8	12.6 ± 1.3	50.7 ± 7.2	17.0 ± 3.0	50.0 ± 10	17.1 ± 3.6	6.1 ± 1.4	19.1 ± 5.2
Galactic diffuse (model)	5.0	26.0	11.5	43.3	14.7	47.9	15.7	5.2	17.0
IC (fit)	1.5 ± 0.1	6.8 ± 0.5	3.5 ± 0.4	16.1 ± 2.3	6.6 ± 1.2	23.3 ± 4.9	9.3 ± 2.1	3.9 ± 1.0	10.6 ± 3.7
IC (model)	1.2	5.3	2.3	9.7	4.0	16.2	6.3	2.4	8.7
local HI (fit)	2.7 ± 0.2	15.4 ± 1.1	7.4 ± 0.8	28.3 ± 4.0	8.3 ± 1.5	20.6 ± 4.2	5.9 ± 1.2	1.6 ± 0.4	7.0 ± 2.2
local HI (model)	3.1	17.0	7.6	27.6	8.7	26.0	7.7	2.3	6.8
Sources	0.8 ± 0.1	3.8 ± 0.2	1.7 ± 0.1	7.2 ± 0.8	2.7 ± 0.4	9.0 ± 1.3	3.4 ± 0.5	1.5 ± 0.2	6.3 ± 1.0
CR background	1.4 ± 0.6	4.2 ± 1.7	1.0 ± 0.4	2.8 ± 1.2	0.8 ± 0.4	6.3 ± 3.0	1.4 ± 0.8	0.6 ± 0.4	0.9 ± 0.9
Solar	0.1 ± 0.01	0.4 ± 0.04	0.2 ± 0.02	1.0 ± 0.2	0.4 ± 0.2	1.7 ± 0.4	0.7 ± 1.6	0.1 ± 0.04	0.8 ± 0.5
LAT	9.6 ± 0.8	44.0 ± 3.0	18.8 ± 2.0	72.9 ± 10	25.3 ± 4.5	81.3 ± 16	28.3 ± 5.7	10.6 ± 2.1	37.9 ± 7.7
	Foreground modeling related uncertainty in cm^{-2} s^{-1} sr^{-1}								
HI column density	+0.1/−0.3	+0.1/−1.7	+0.1/−0.9	+0.1/−3.6	+0.1/−1.1	+0.1/−2.4	+0.1/−0.9	+0.1/−0.2	+0.1/−1.1
IC + halo size	+0.1/−0.2	+0.1/−0.8	+0.1/−0.5	+0.1/−1.8	+0.1/−0.5	+0.1/−0.7	+0.3/−0.3	+0.4/−0.1	+2.9/−0.5
CR propagation model	+0.1/−0.3	+0.1/−1.1	+0.1/−0.6	+0.1/−0.8	+0.1/−0.3	+0.1/−1.2	+1.4/−0.1	+0.4/−0.1	+3.0/−0.1
Subregions of $\lvert b \rvert > 10°$ sky	+0.2/−0.3	+0.8/−1.5	+0.4/−0.9	+1.9/−2.1	+0.7/−0.5	+2.5/−1.9	+1.0/−1.5	+0.5/−0.3	+2.7/−0.9

Acceleration in nearby sources Blasi, 0903.2794

$\Gamma = 2.4$



Ahlers, Mertsch, Sarkar

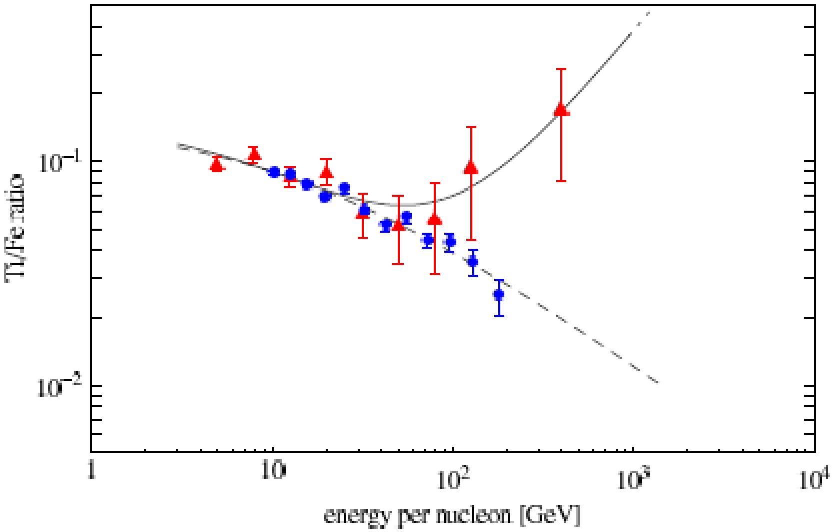


FIG. 1: The titanium-to-iron ratio in cosmic rays along with model predictions — the 'leaky box' model with production of secondaries during propagation only (dashed line), and including production and acceleration of secondaries in a nearby source (solid line - dotted beyond the validity of our calculation). The data points are from ATIC-2 (triangles) [27] and HEAO-3-C3 (circles) [34].

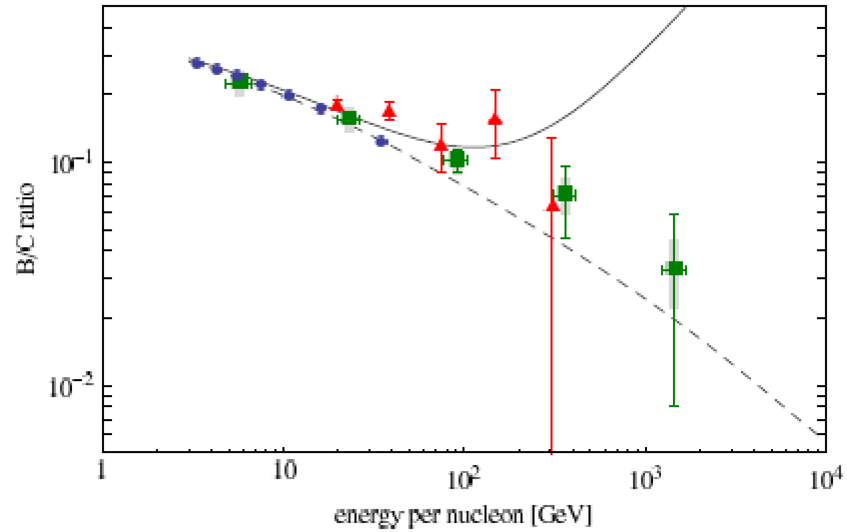


FIG. 2: The boron-to-carbon ratio in cosmic rays along with model predictions — the 'leaky box' model with production of secondaries during propagation only (dashed line), and including production and acceleration of secondaries in a nearby source (solid line). The data points are from HEAO-3-C2 (circles) [31], ATIC-2 (triangles) [35] and CREAM (squares) [36].

Mertsch, Sarkar