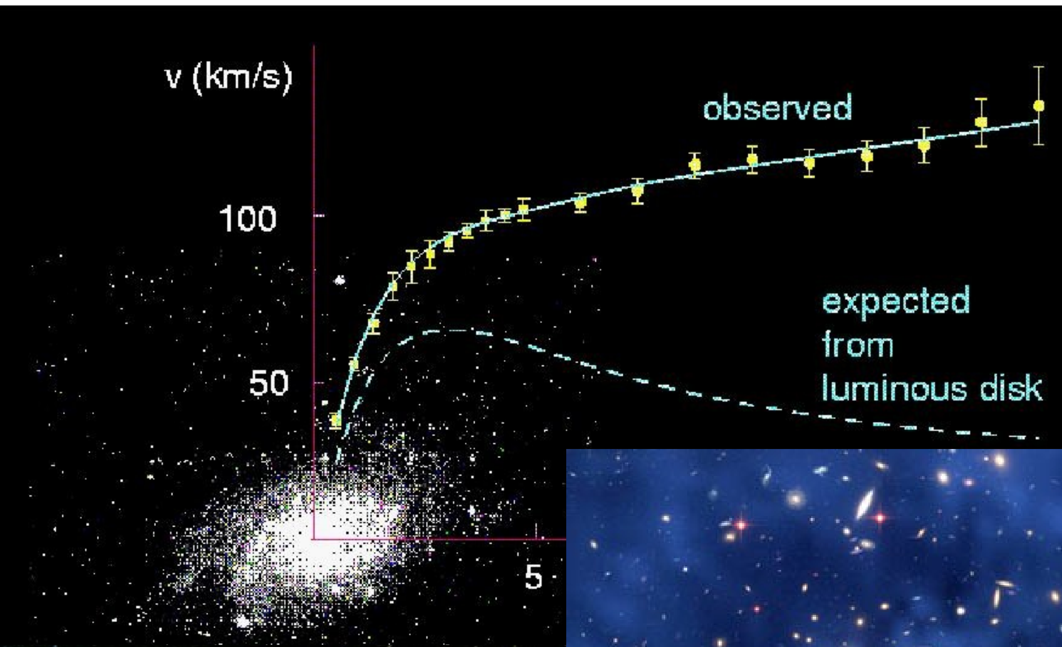
Indirect detection of decaying dark matter

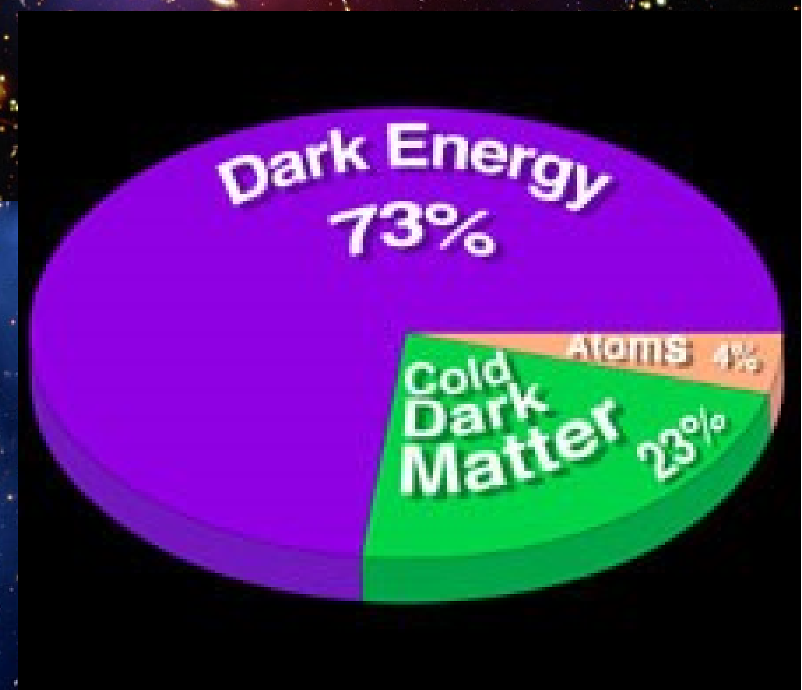
Alejandro Ibarra
Technical University of Munich

IDMS
Hamburg,
17th June 2011

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 structure formation ("cold" or may be "warm").
- Lifetime longer than the age of the Universe.

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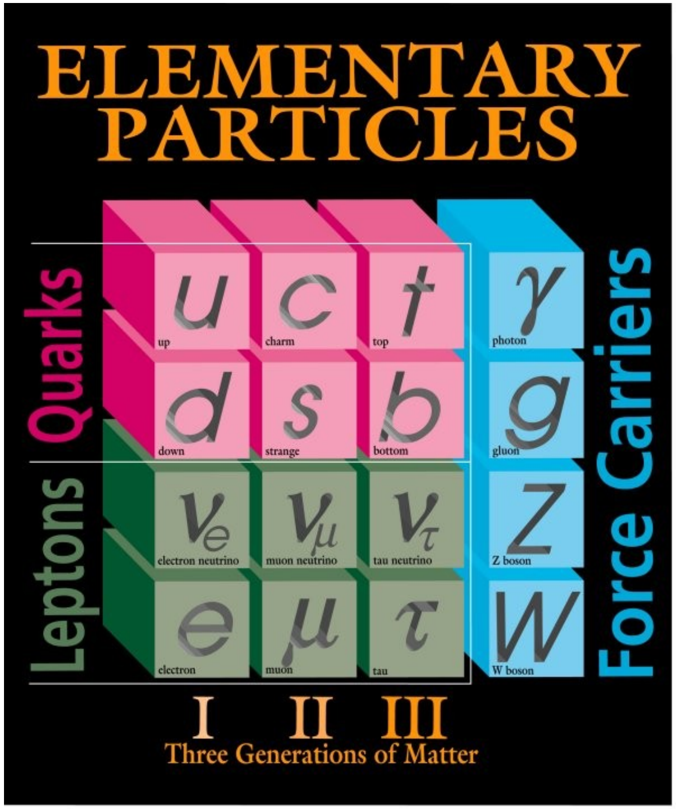

Fermilab 95-759

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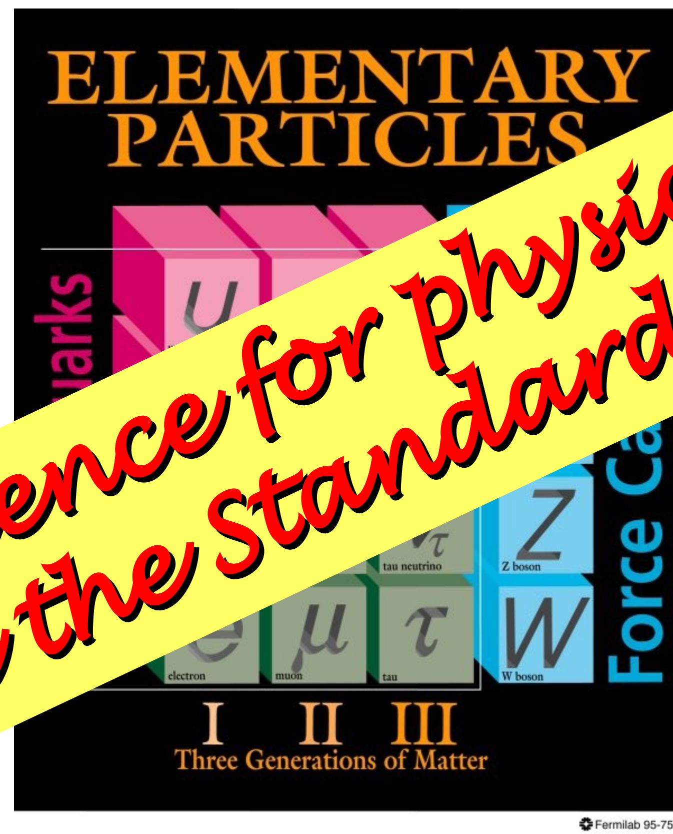


Evidence for physics beyond the Standard Model

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 $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

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

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]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

DARK MATTER

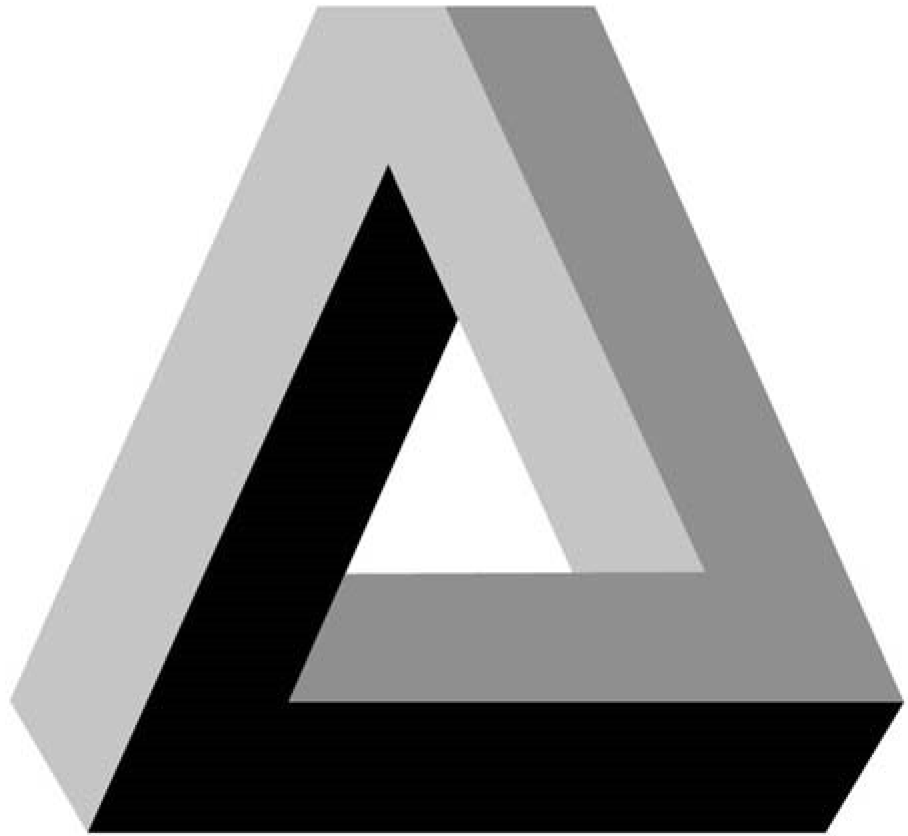
$J =$?

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

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Collider searches

pp $\rightarrow$ DM X

Matter stability in the Standard Model

particle	Lifetime	Decay channel	Theorerical explanation
proton	$\tau > 8.2\times10^{33}$ years	$p\rightarrow e^{+}\pi^{0}$	Lightest baryon. Stability related to baryon number conservation
electron	$\tau > 4.6\times10^{26}$ years	$e\rightarrow\gamma\,\nu$	Lightest charged particle. Stability related to electric charge conservation
neutrino	$\tau \gtrsim 10^{12}$ years	$\nu\rightarrow\gamma\,\gamma$	Lightest fermion. Stability related to Lorentz symmetry conservation
neutron	$\tau = 885.7\pm0.8$ s	$n\rightarrow p\,\bar{\nu}_e\,e^{-}$	Next-to-lightest baryon. Isospin symmetry mildly broken.

Matter stability in the Standard Model+DM

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Dark matter	$\tau > 10^9$ years	???	???

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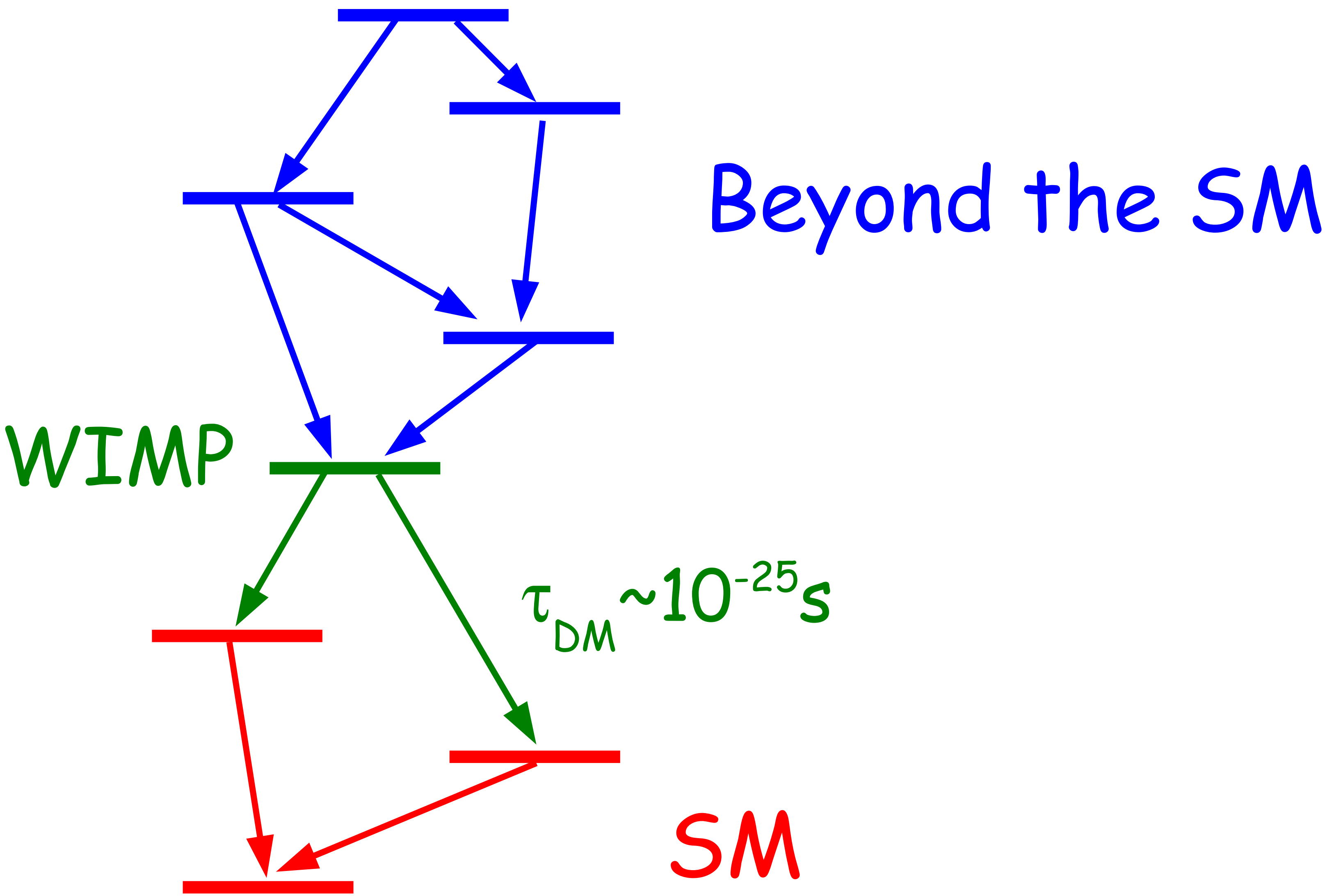
neutron	τ=885.7±0.8 s	$n \to p\, \bar{\nu}_e\, e^-$	Next-to-lightest baryon. Isospin symmetry mildly broken.
Dark matter	τ >10^9 years	???	???

Accidental symmetry of the Standard Model renormalizable Lagangian

Local symmetries

A priori, no symmetry principle that guarantees absolute stability of the dark matter particle.

Sketch of a WIMP dark matter model:



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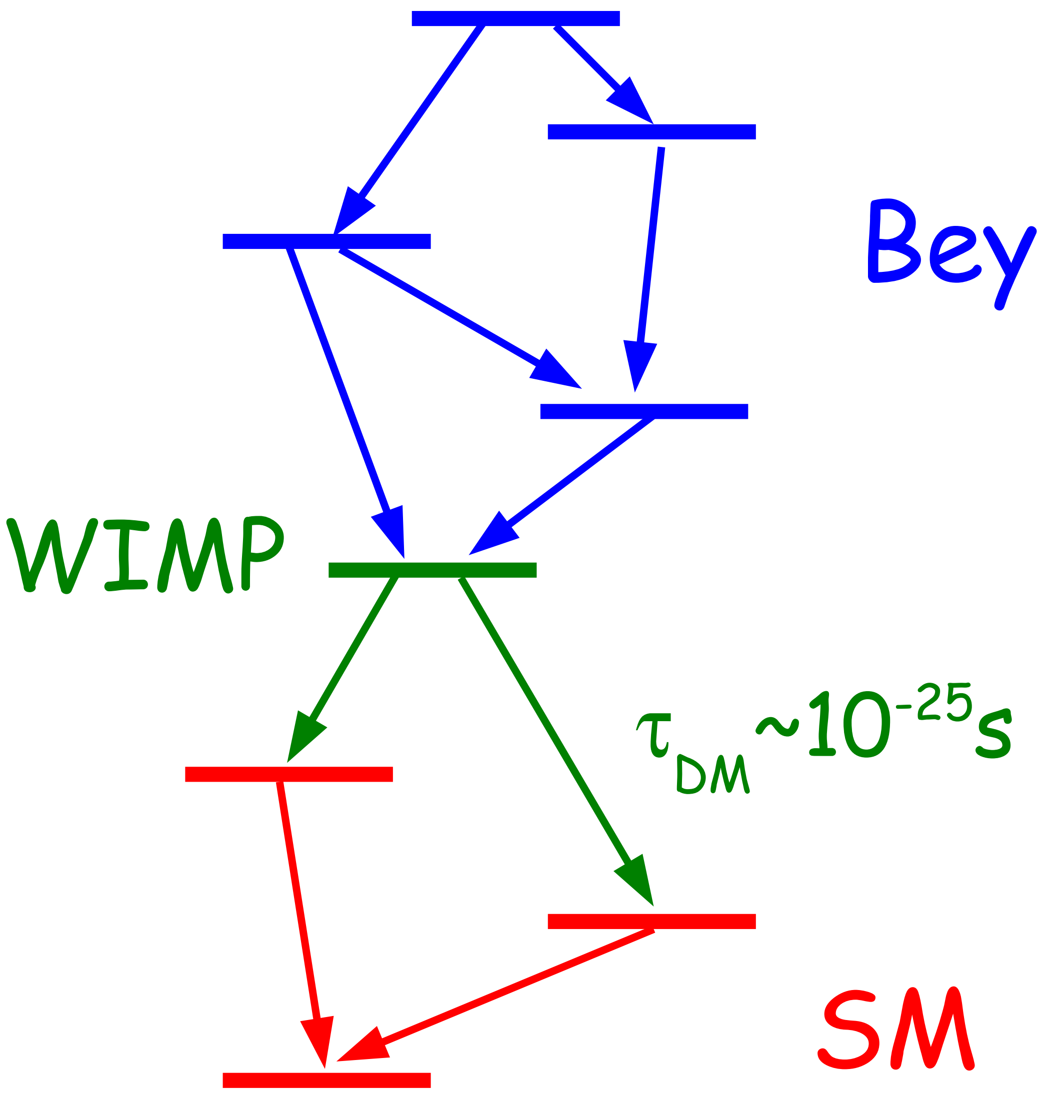

$\phi \to e^+e^-$

$\psi \to \gamma\, \nu,\ W^+e^-$

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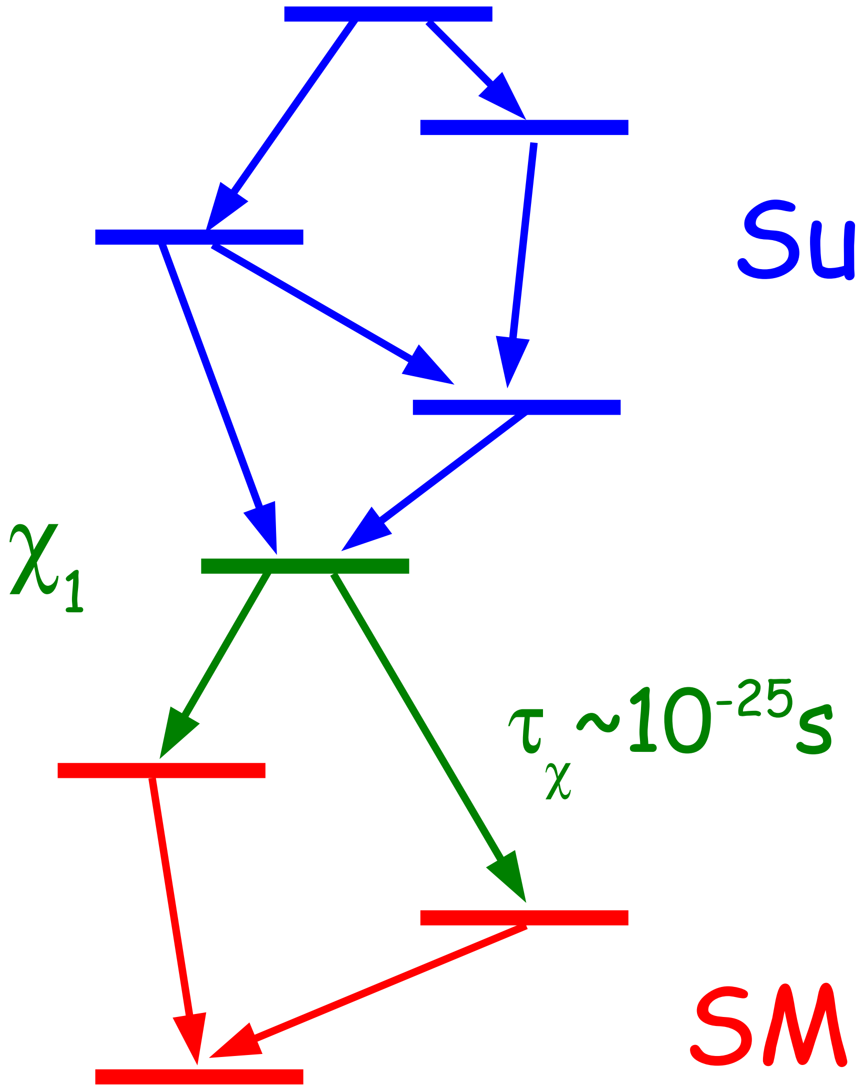
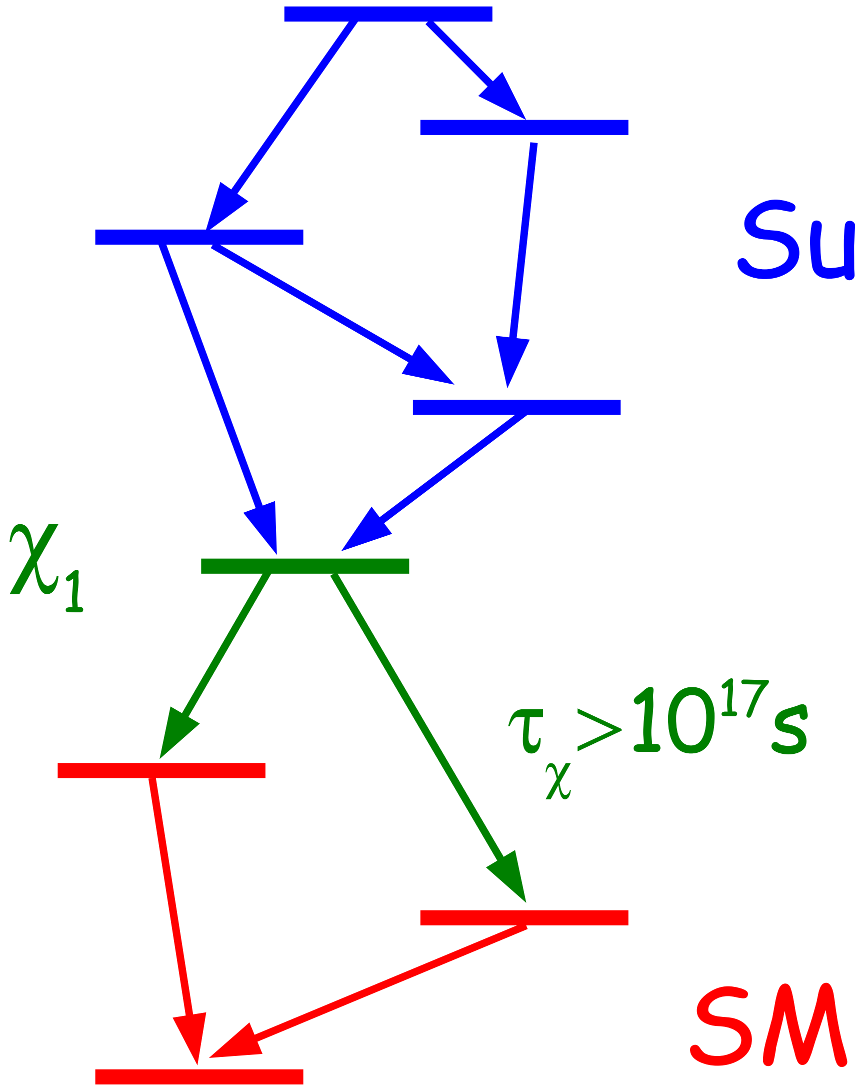


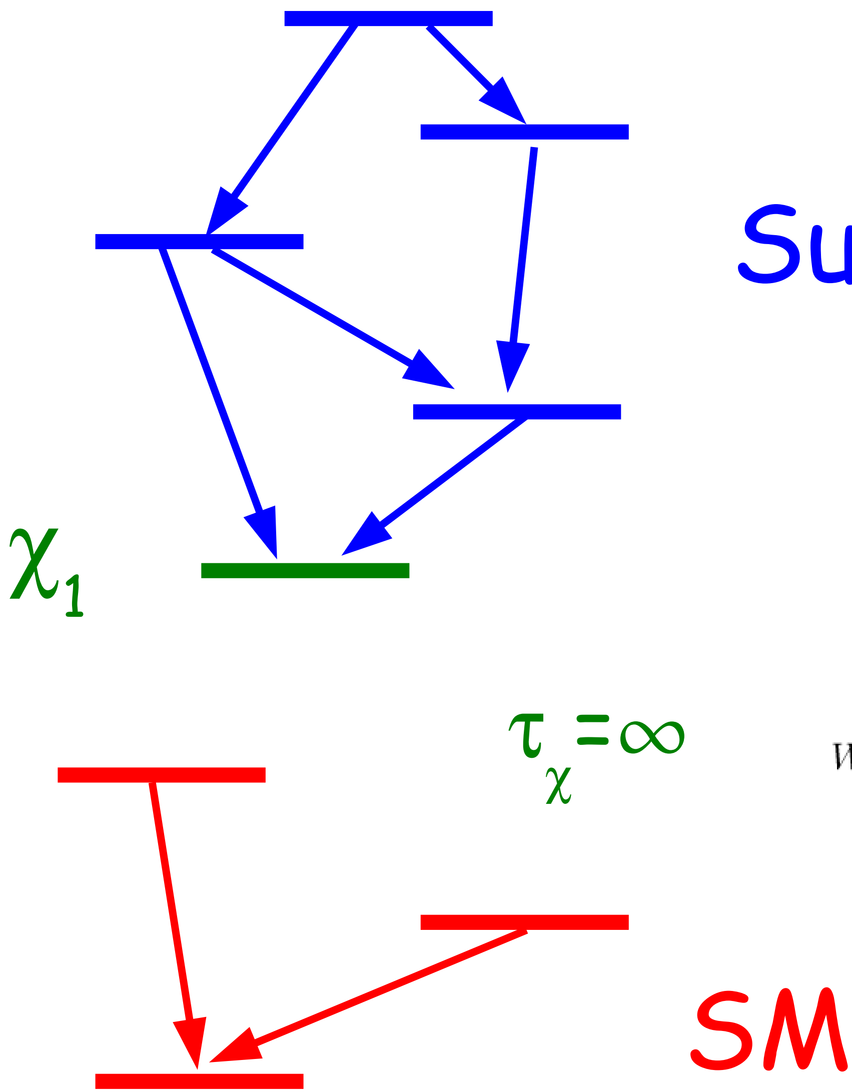
$$\chi_1 \rightarrow \gamma\,\nu,\ W^+e^-$$

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:



Supersymmetry

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

$$W_{MSSM} = \mathbf{Y}^e_{ij} e^c_{Ri} L_j H_d + \mathbf{Y}^d_{ij} d^c_{Ri} Q_j H_d + \mathbf{Y}^u_{ij} u^c_{Ri} Q_j H_u + \mu H_u H_d + \cancel{\frac{1}{2}\lambda_{ijk} L_i L_j e^c_k} + \cancel{\lambda'_{ijk} L_i Q_j d^c_k} + \cancel{\frac{1}{2}\lambda''_{ijk} u^c_i d^c_j d^c_k} + \cancel{\mu'_i L_i H_u}.$$

The lightest neutralino is absolutely stable

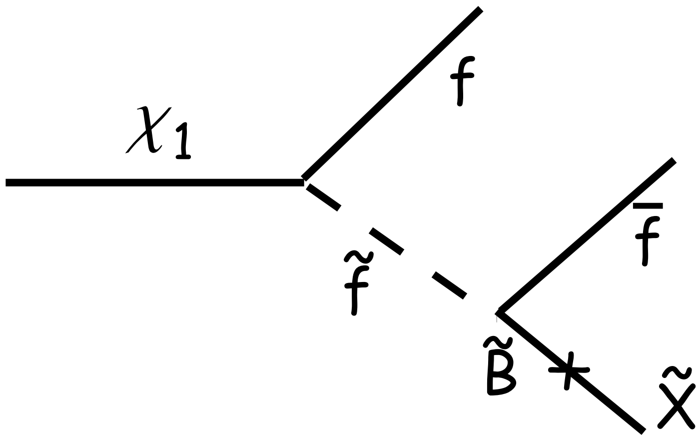
Unstable WIMPs: some examples

- Gauge boson of a hidden SU(2) symmetry, which is spontaneously broken.

Accidental SO(3) symmetry in the renormalizable part of the Lagrangian
↪ Dark matter particle long lived. Hambye
SO(3) symmetry broken by dimension-6 operators. e.g $\frac{1}{\Lambda^2}\mathcal{D}_\mu\phi^\dagger\phi\,\mathcal{D}_\mu H^\dagger H$

$$\Gamma(A\to\gamma h)^{-1} = 1.5\times 10^{28}\,\mathrm{s}\left(\frac{\Lambda}{2\times 10^{15}\,\mathrm{GeV}}\right)^4\left(\frac{1\,\mathrm{TeV}}{v_\phi}\right)^2\left(\frac{100\,\mathrm{GeV}}{M_A}\right)$$ Arina et al.

- Lightest neutralino decaying into a hidden U(1) gaugino. AI, Ringwald, Weniger

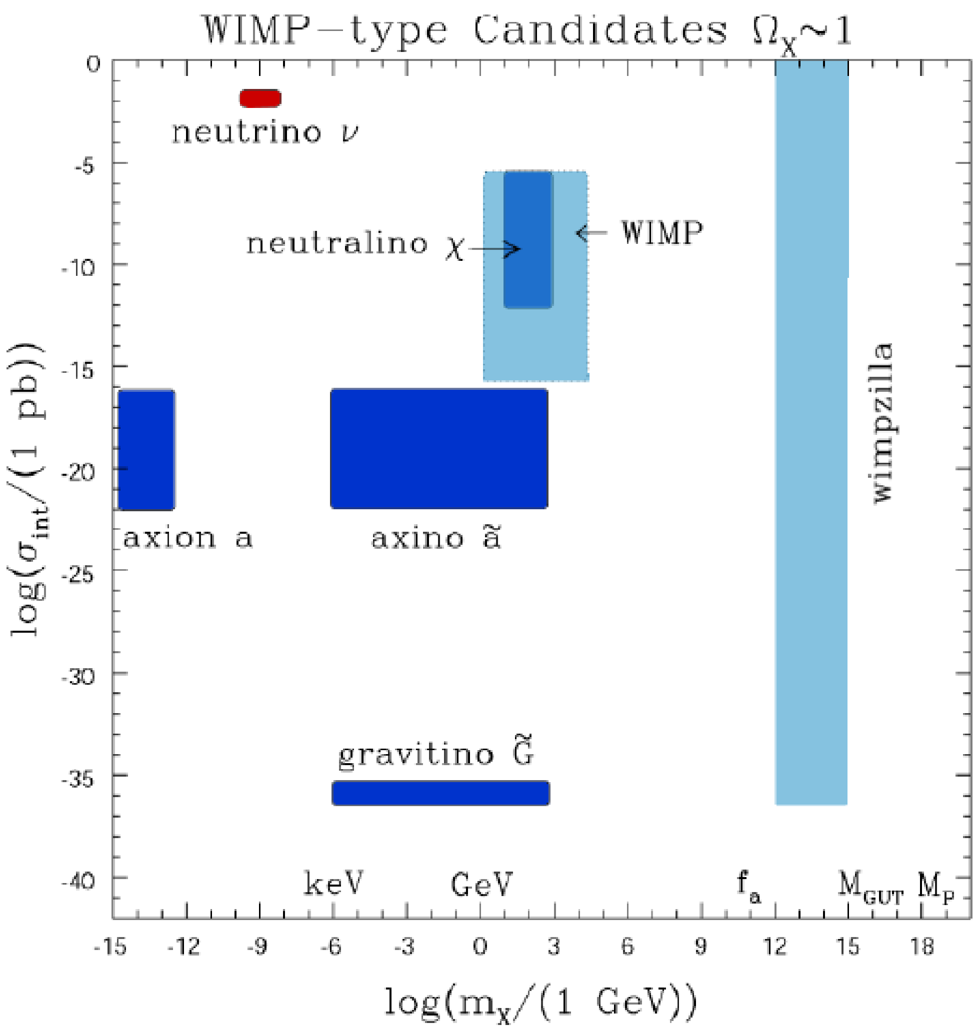


$$\Gamma(\chi_1^0\to f\bar{f}\tilde{X})\simeq 10^{-4}g'^4\Theta^2\frac{M_\chi^5}{m_{\tilde{f}}^4}$$

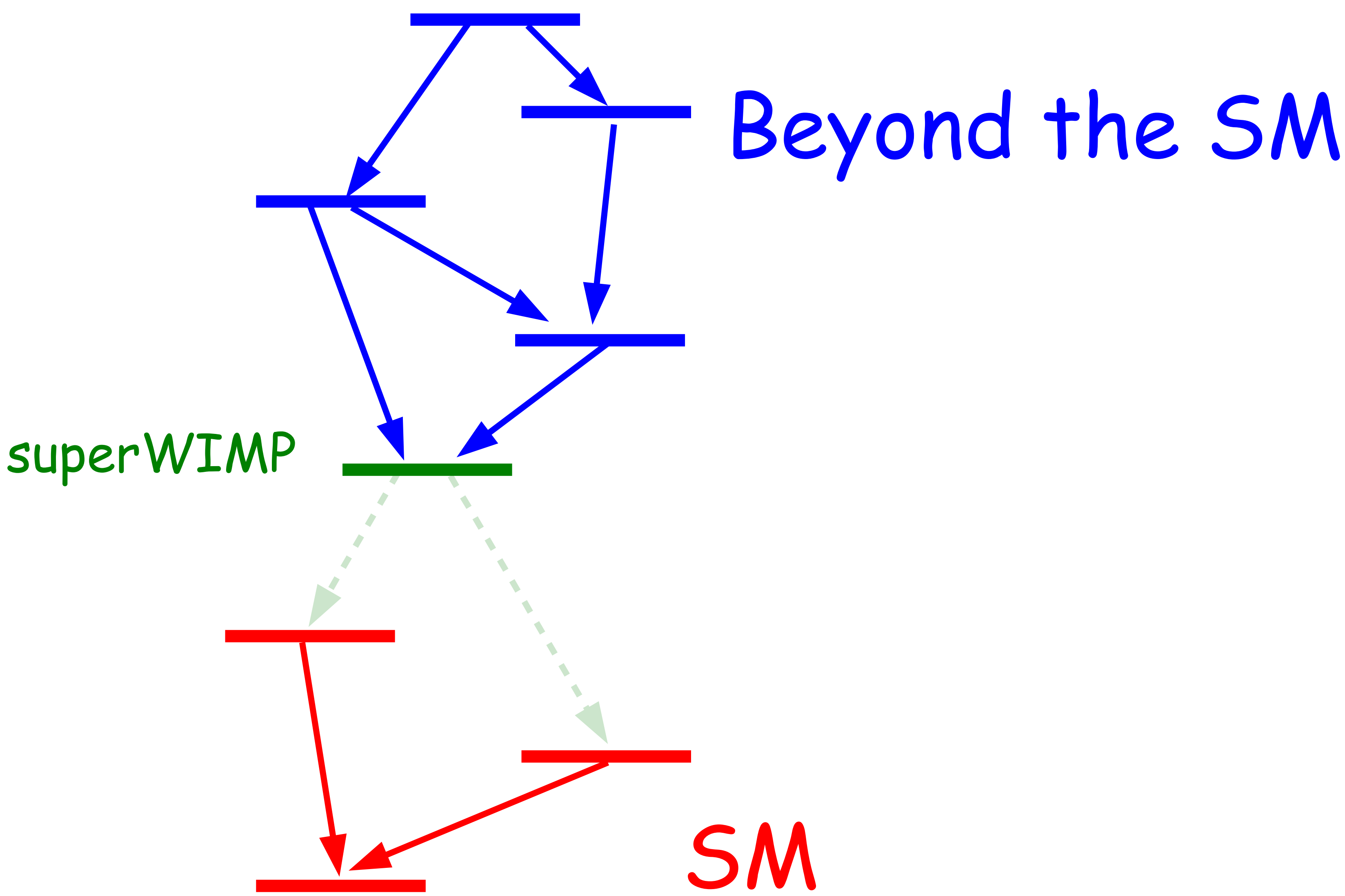
Note: $\frac{\Gamma(\chi_1^0\to q\bar{q}\tilde{X})}{\Gamma(\chi_1^0\to \ell\bar{\ell}\tilde{X})}\sim\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{q}}}\right)^4$ usually <<1
↪ "leptophilic"

- WIMP decaying via instanton effects Carone, Erlich, Primulando

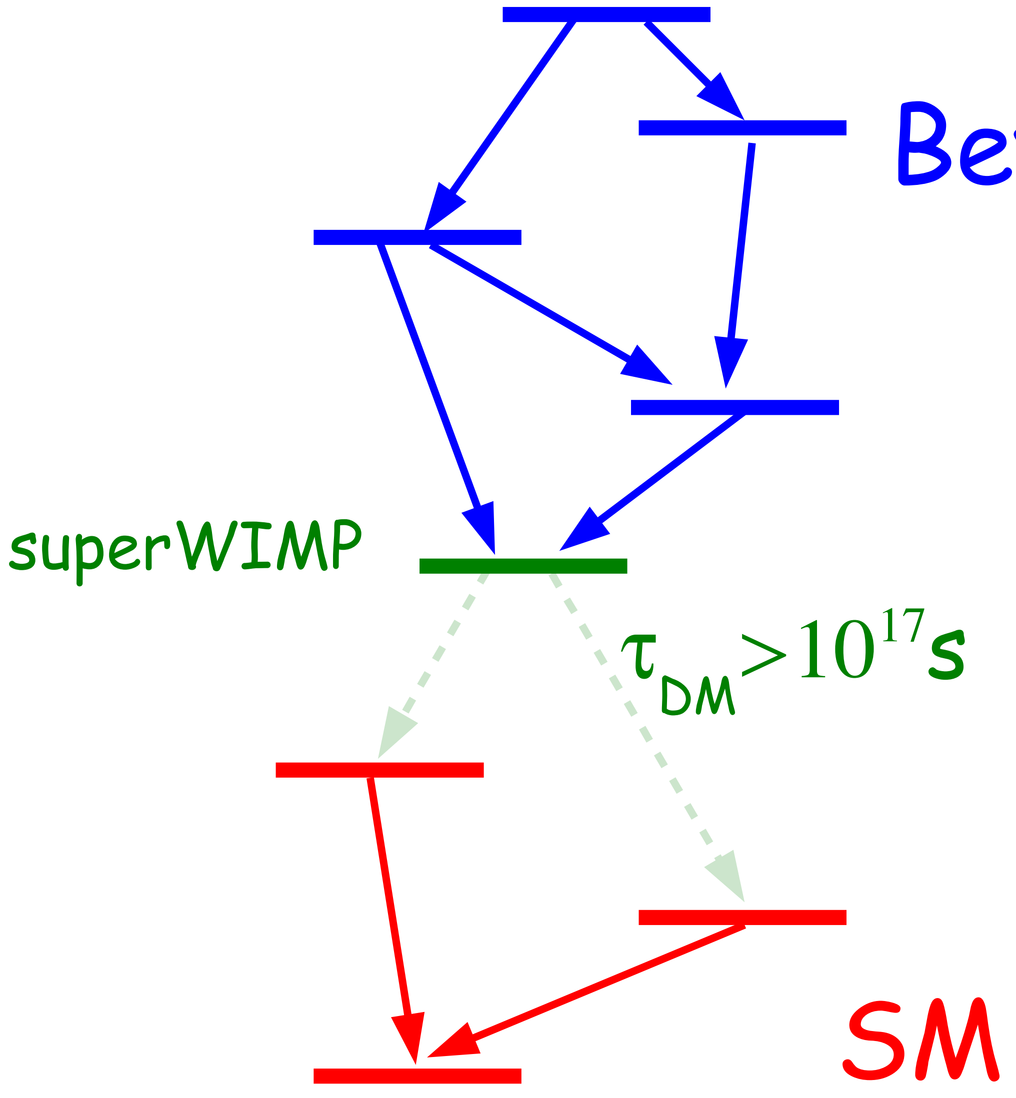
WIMP dark matter is not the only possibility: the dark matter particle could also be <u>superweakly interacting</u>



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.

Unstable superWIMPs: some examples

- 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.
  Talk by M. Grefe

- 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;

- Bound states of strongly interacting particles.
  Decay rate suppressed by the GUT scale.

  Hamaguchi et al.; Nardi et al

Indirect detection

Source term: $$Q(E,\vec{r}) = \frac{\rho(\vec{r})}{m_{\rm DM}\tau_{\rm DM}}\frac{dN}{dE}$$

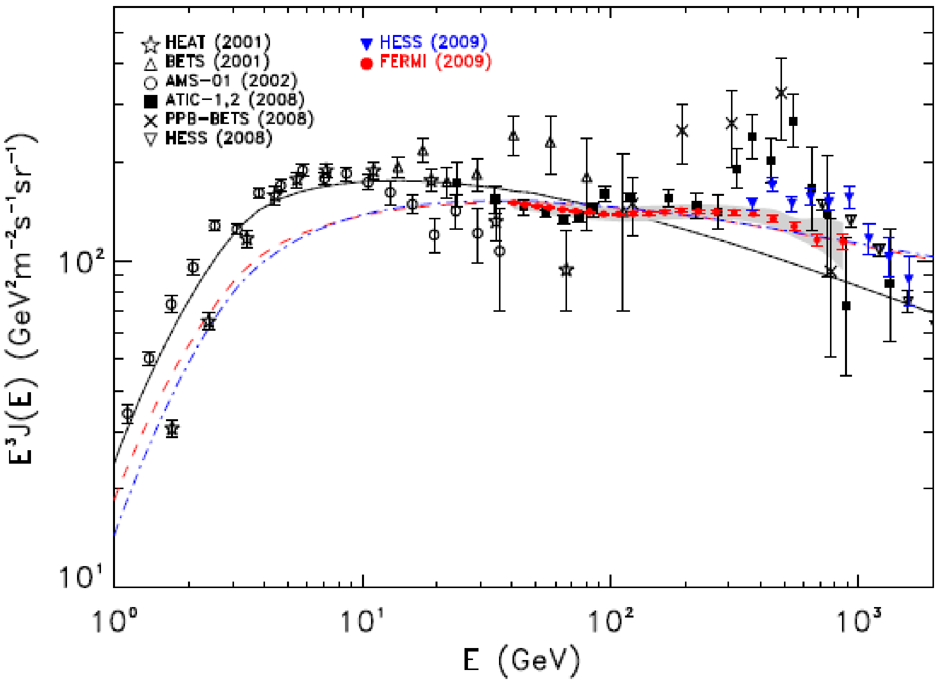
Indirect detection

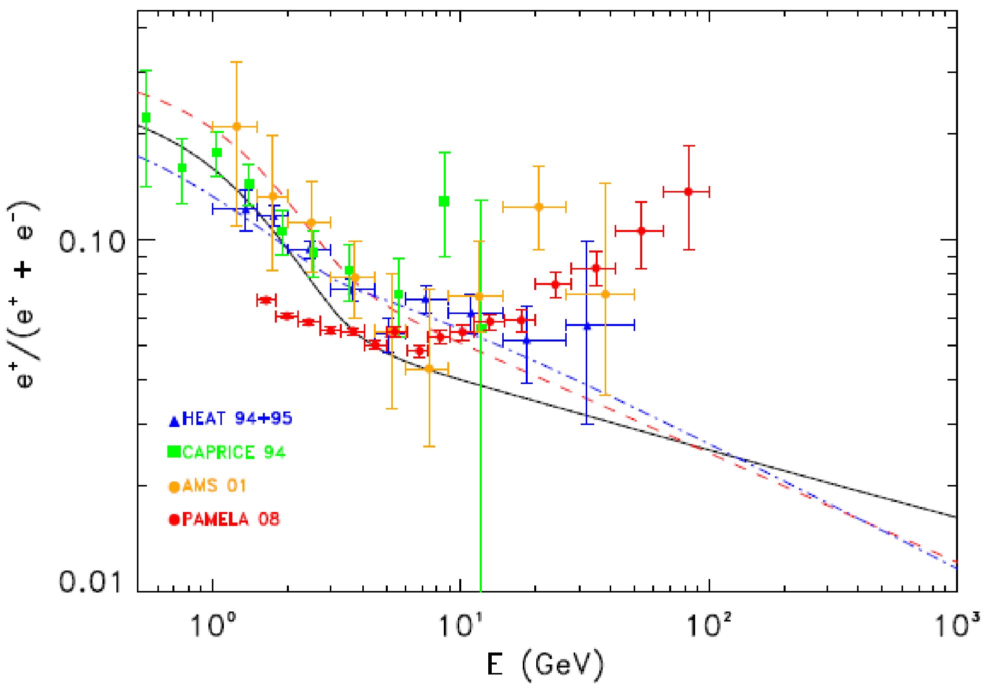
Uncertainties in the halo profile
are usually not critical

Source term: $$Q(E,\vec{r}) = \frac{\rho(\vec{r})}{m_{\rm DM}\tau_{\rm DM}}\frac{dN}{dE}$$

Fluxes controlled by the lifetime.
Even for thermal relics the fluxes
can be sizable (no boost factors needed)

Electron and positron fluxes





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

astrophysical sources? Pulsars, SN remnants...

new Particle Physics? DM annihilation, DM decay.

Electron and positron fluxes

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

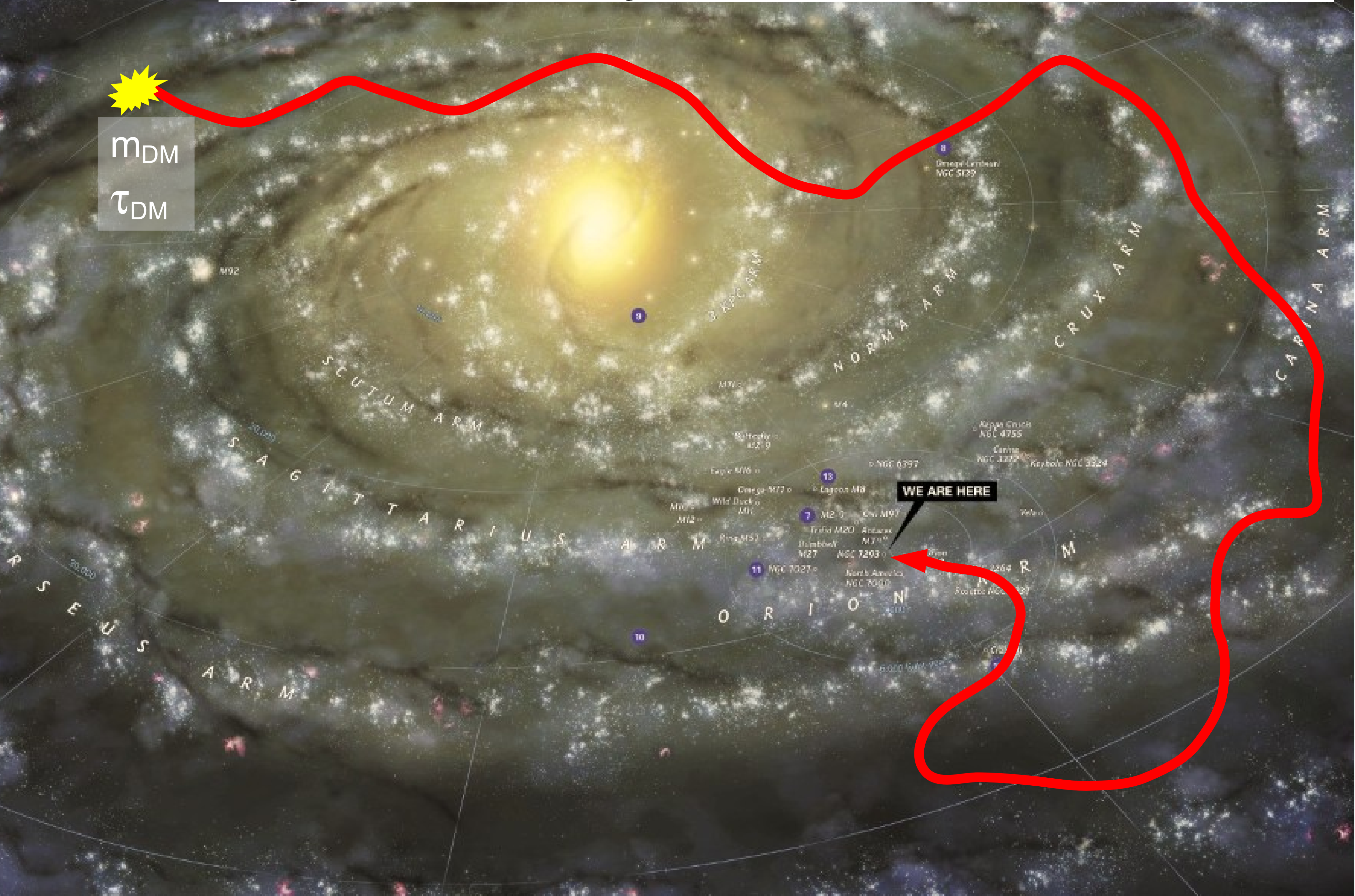
$\phi \to Z^0 Z^0$

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

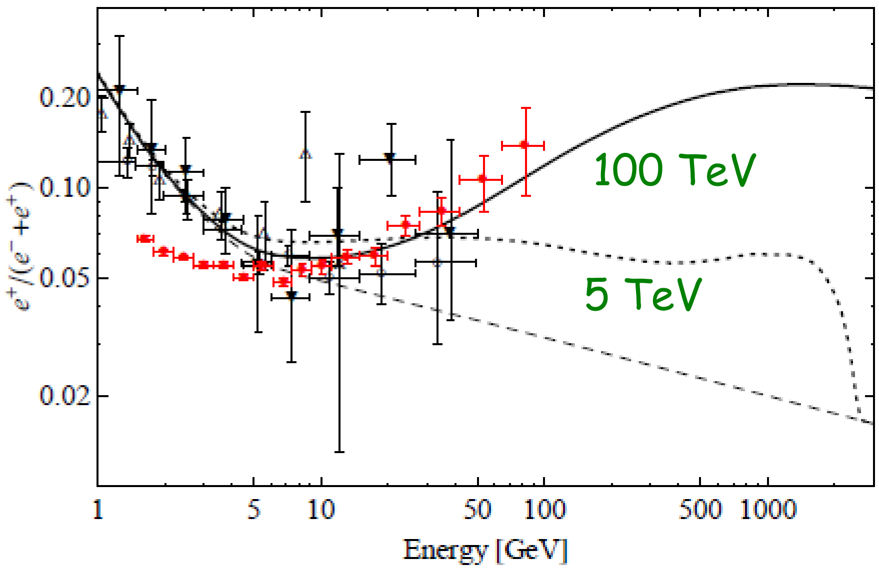
$\phi \to \ell^+ \ell^-$

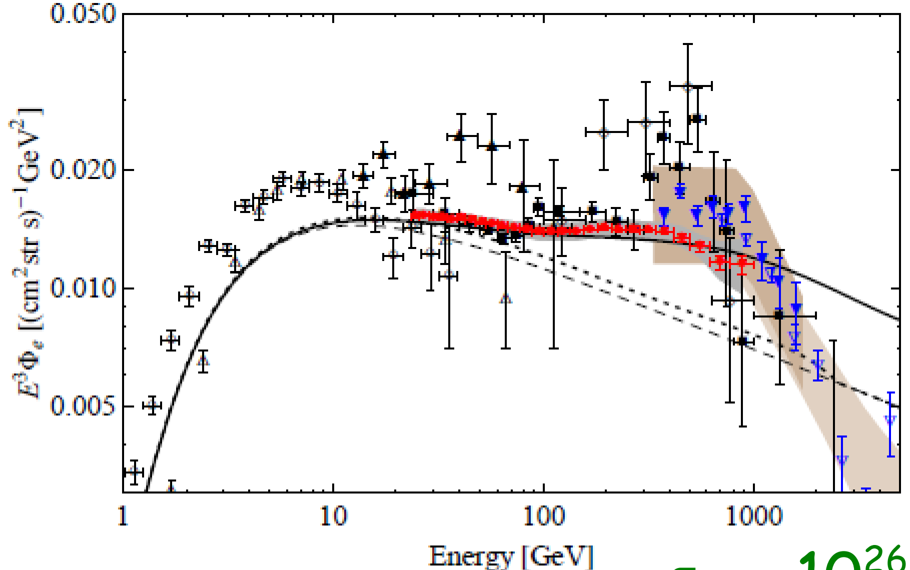

m_{DM}
τ_{DM}
WE ARE HERE
3 KPC ARM
NORMA ARM
CRUX ARM
CARINA ARM
SCUTUM ARM
SAGITTARIUS ARM
ORION ARM
RSEUS ARM
M80
M92
NGC 6397
Keyhole NGC 3324
Lagoon M8
Omega M17
NGC 7293
NGC 7027
North America NGC 7000

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



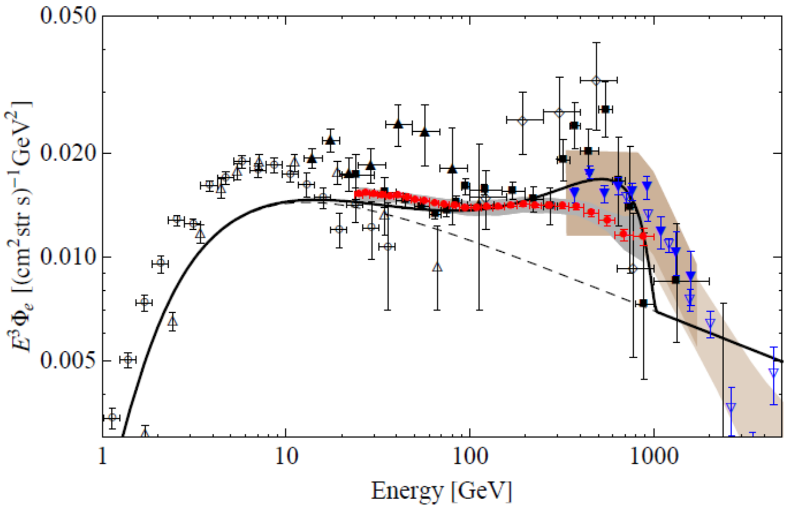
$\psi \to Z^0 \nu$





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

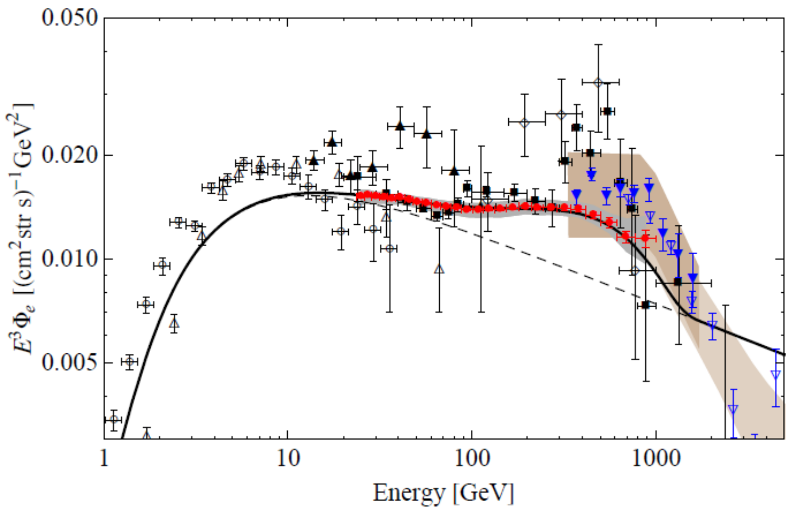
For "low" DM mass: conflict with PAMELA (spectrum too flat)
For "high" DM mass: agreement with PAMELA, but conflict with H.E.S.S.



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

m_{DM}=2000 GeV

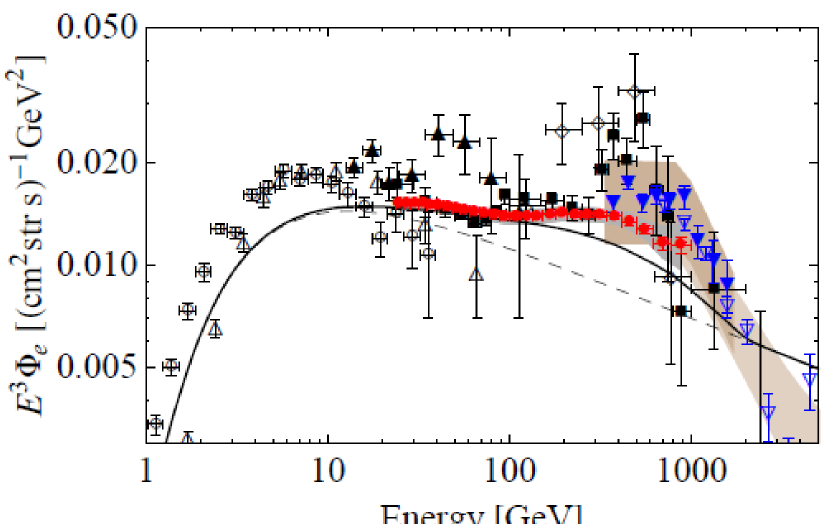
τ_{DM}~10^{26} s



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

m_{DM}=3500 GeV

τ_{DM}~10^{26} s



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

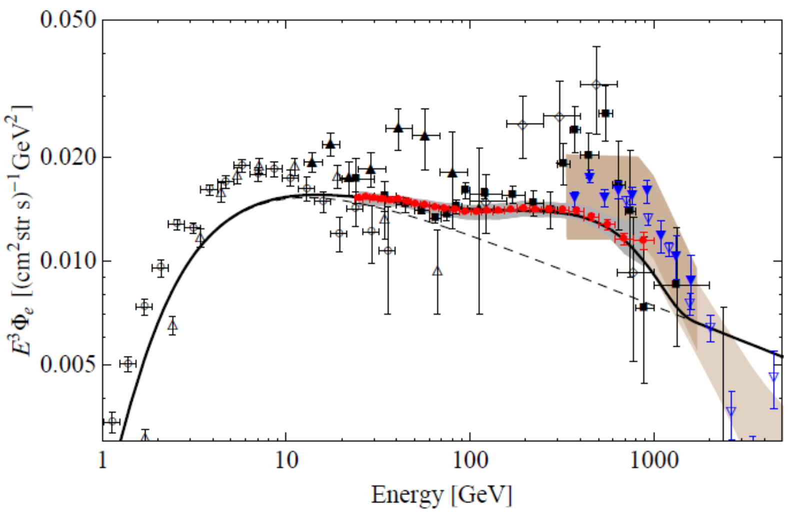
m_{DM}=5000 GeV

τ_{DM}~10^{26} s

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

m_{DM}=2000 GeV

τ_{DM}~10^{26} s



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

m_{DM}=3500 GeV

τ_{DM}~10^{26} s

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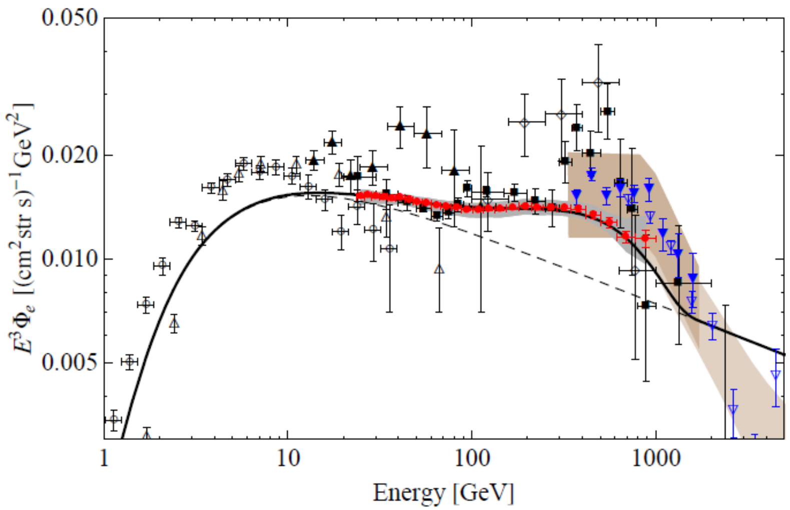

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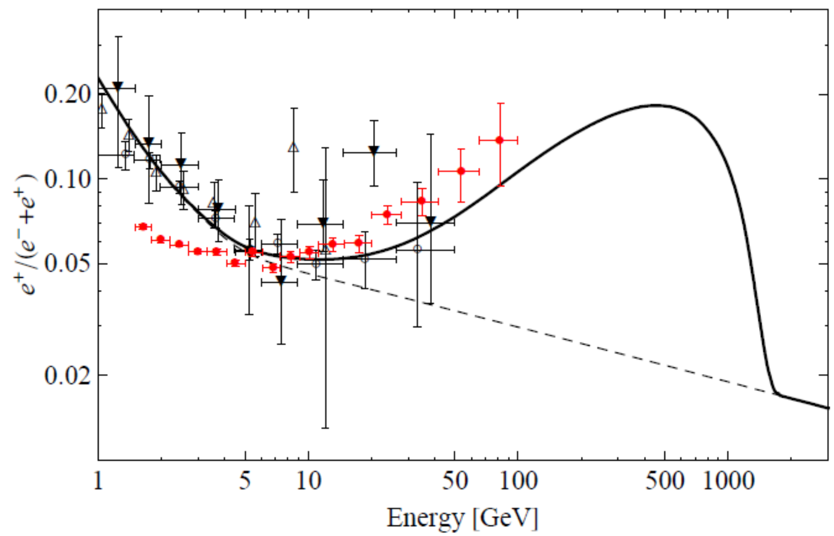


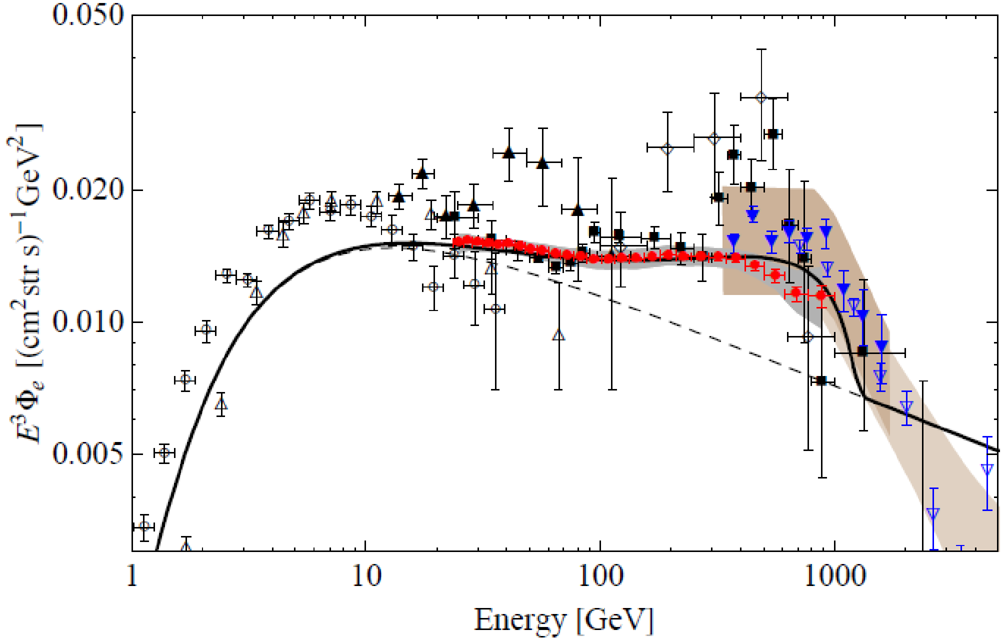
$\psi \to \tau^+ \tau^- \nu$

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



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

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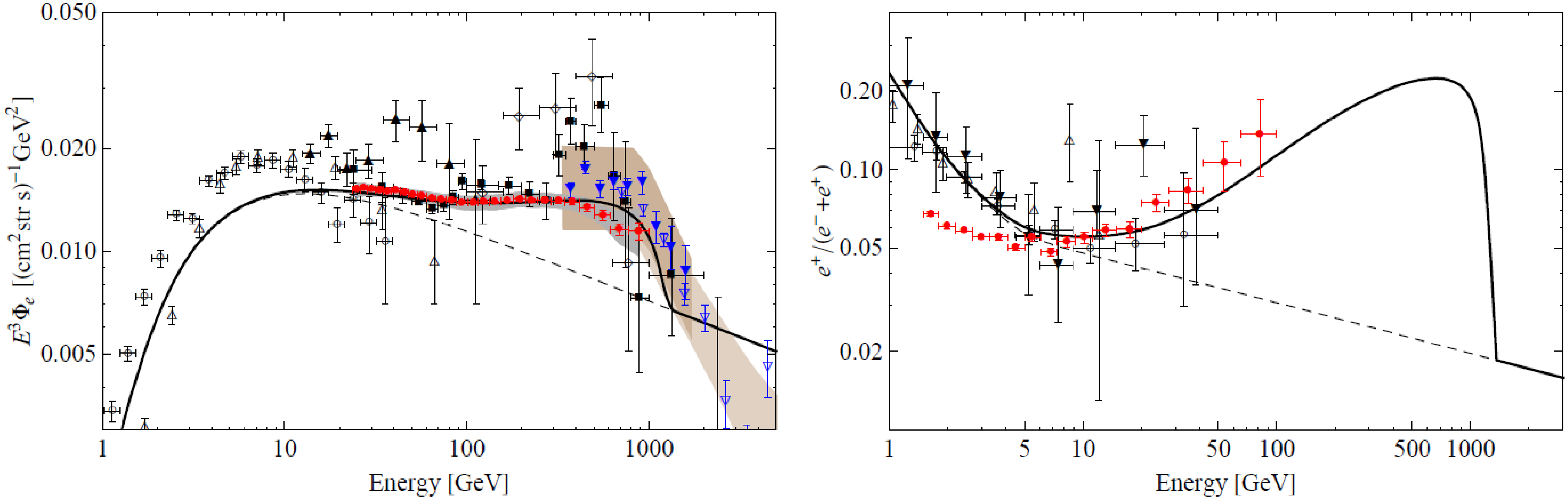
τ_{DM}=1.5×10^{26} s



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}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

No need of boost factors!

10^{26} seconds??

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

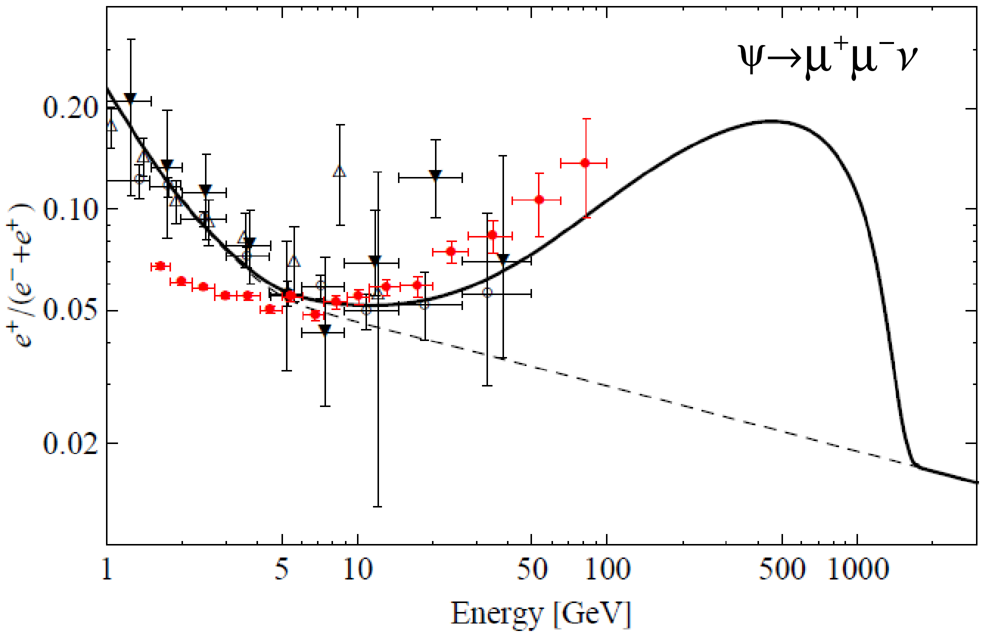
$$\tau_{\rm DM} \sim 10^{26}{\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M}{10^{15}{\rm GeV}}\right)^4$$

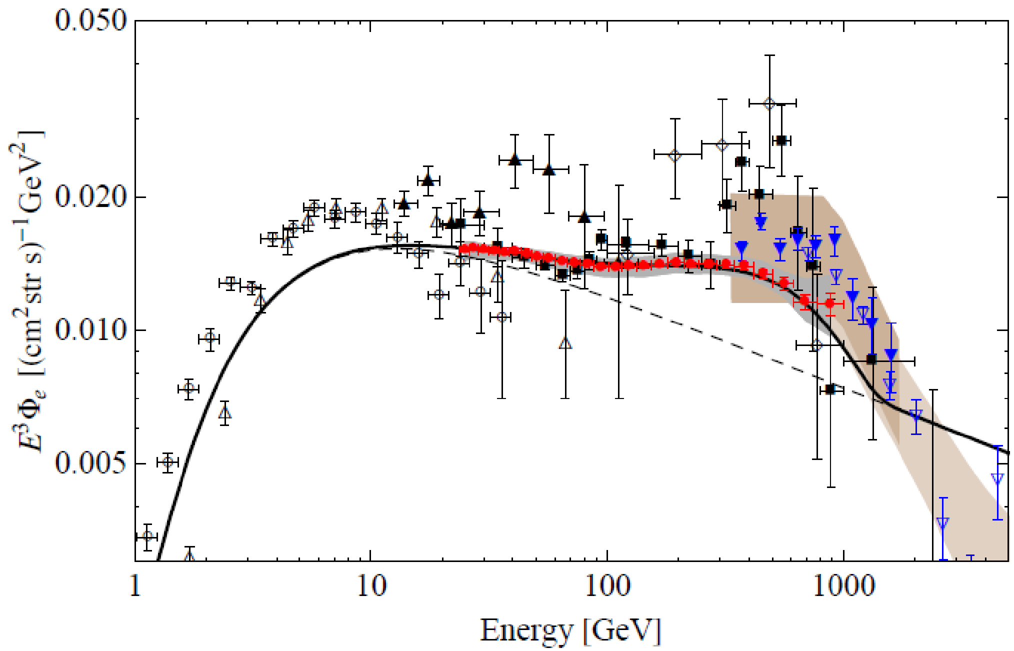
M is remarkably close to the Grand Unification Scale

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

Exciting conclusion

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



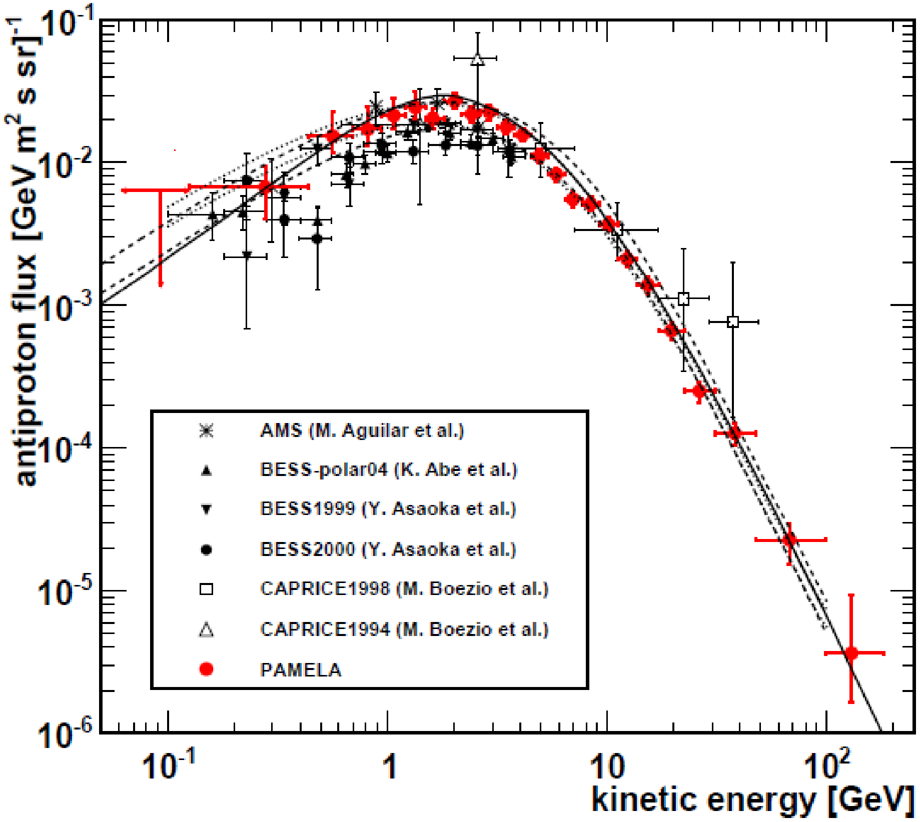


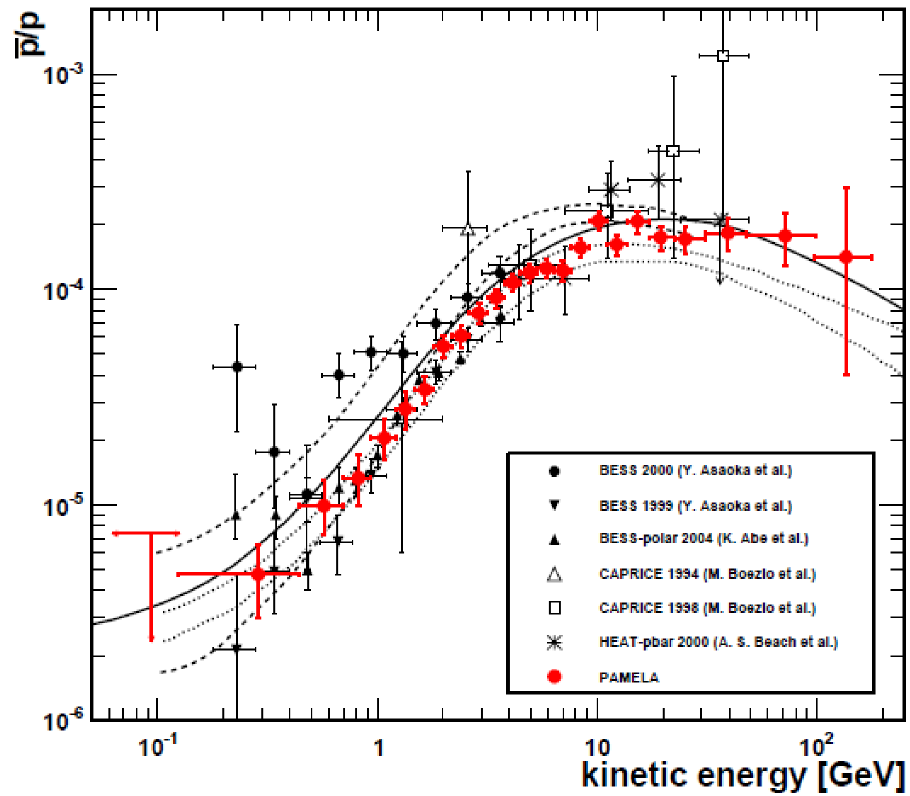
Is this the first non-gravitational evidence of dark matter?

"Extraordinary claims require extraordinary evidence"
Carl Sagan

More tests needed

Antiproton flux





Good agreement of the theory with the experiments.

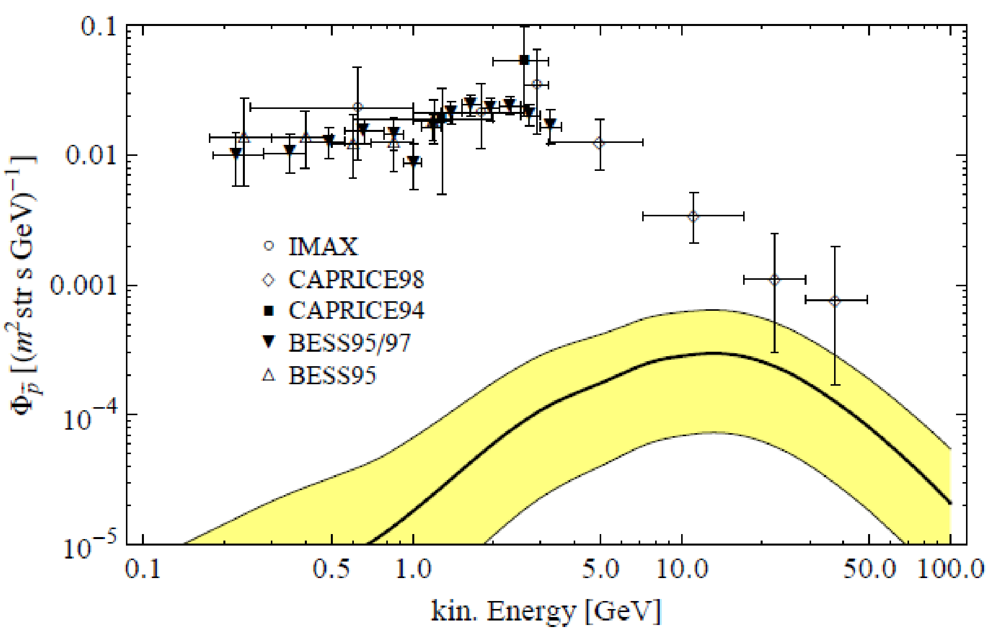
Stringent constraints on the existence of an exotic component.

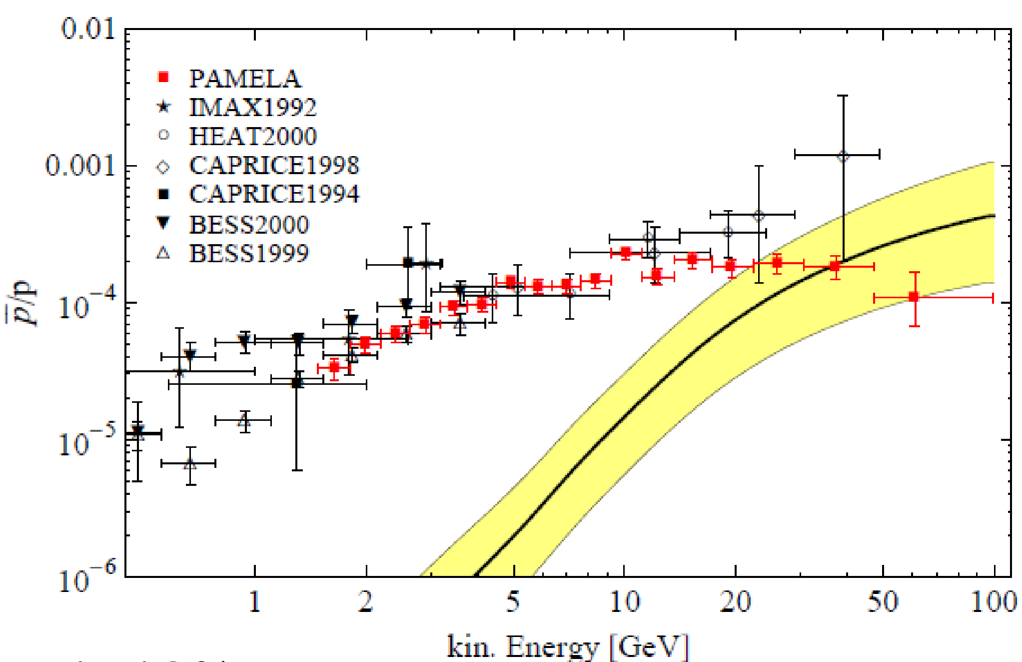
Antiproton flux from dark matter decay

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

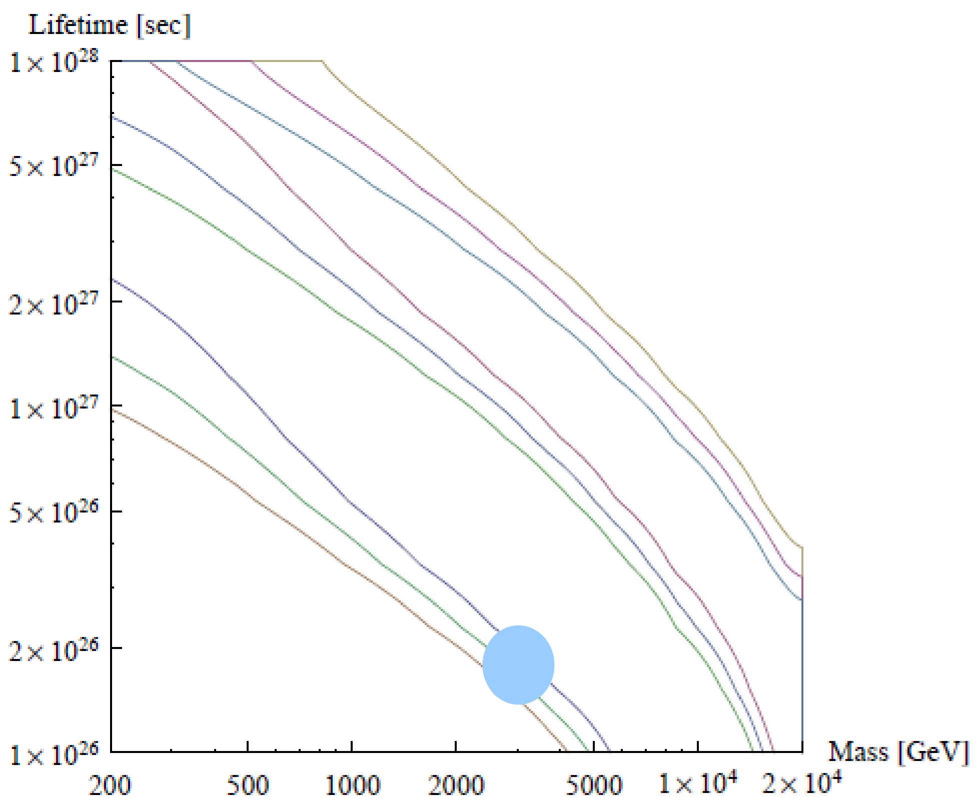
$\psi \to W^{\pm}\mu^{\mp}$



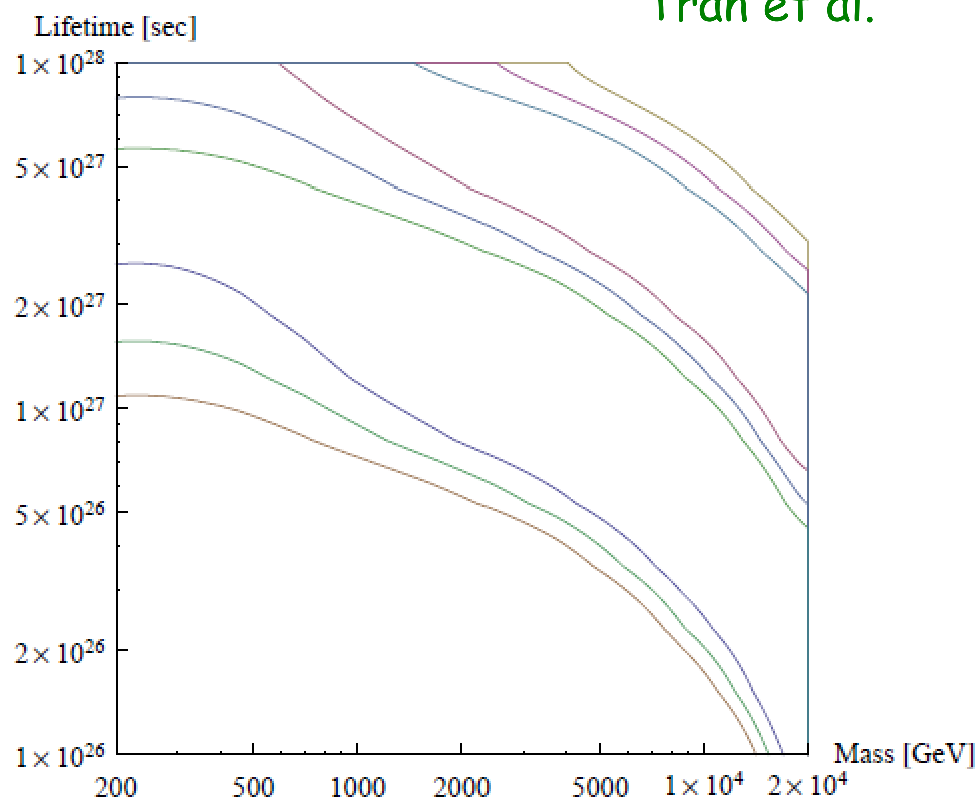


m=3TeV, τ=2.1×10^{26}s

Tran et al.

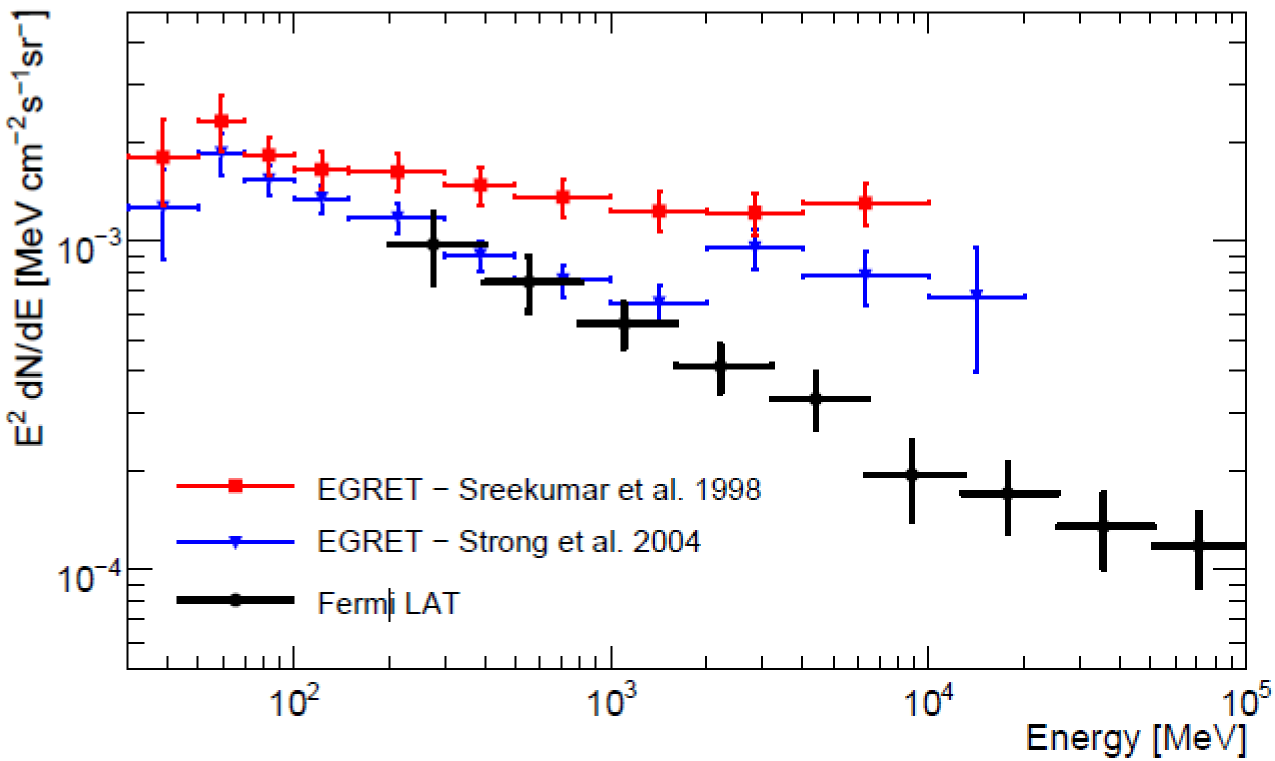


$$\psi \to W\ell$$



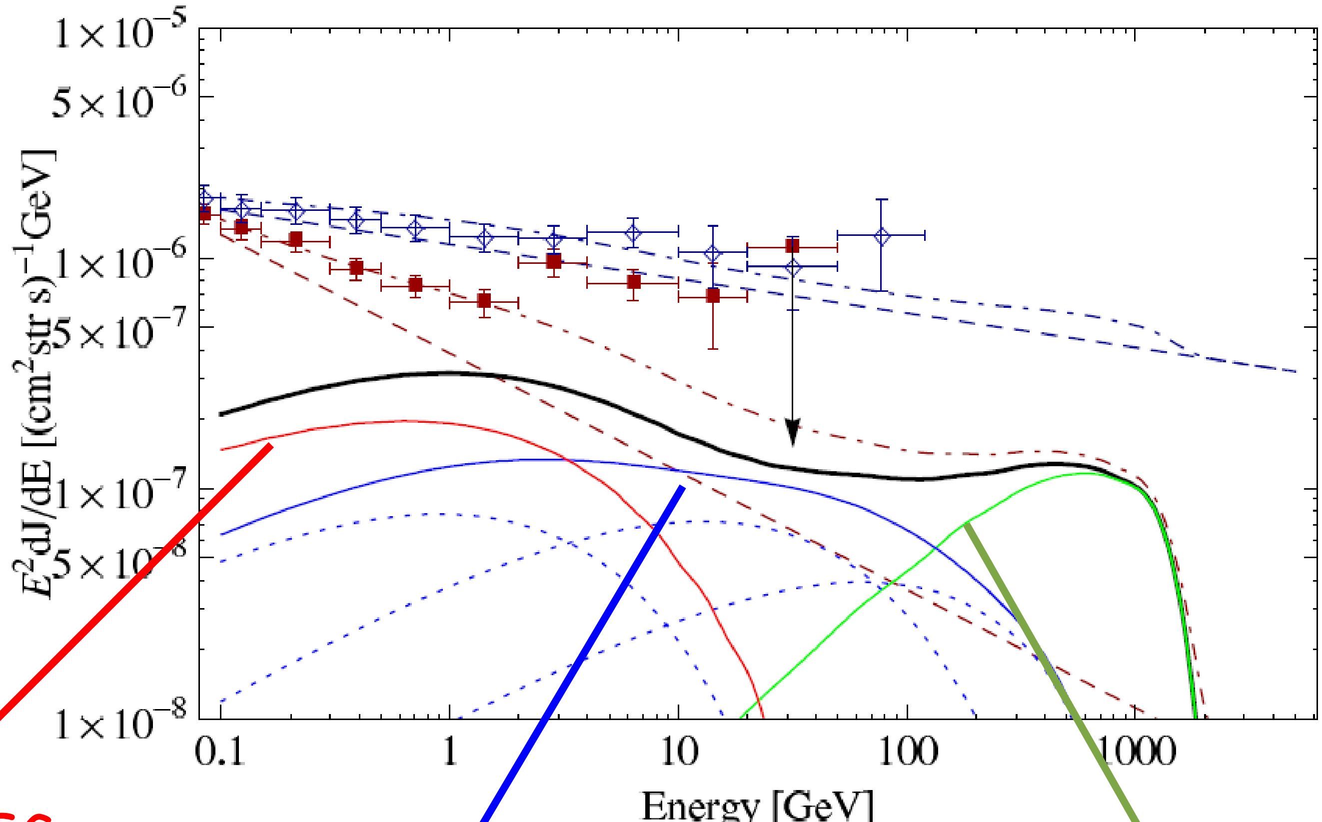
$$\psi \to b\bar{b}\nu$$

Diffuse "extragalactic" gamma ray flux from DM decay



Fermi coll.
arXiv:1002.3603

Diffuse "extragalactic" gamma ray flux from DM decay



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

m=3.5 TeV

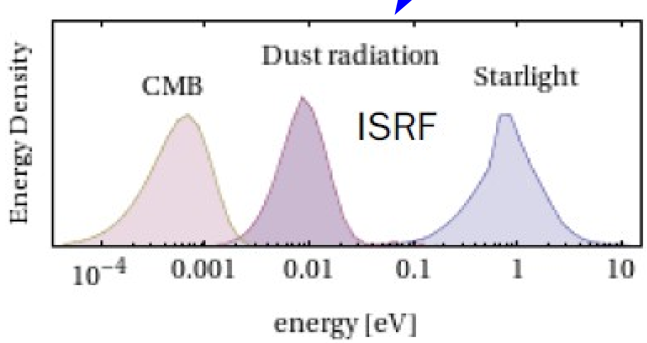
τ=1.1×10^{26}s

AI, Tran, Weniger
arXiv:0906.1571

ICS-EG

ICS

prompt



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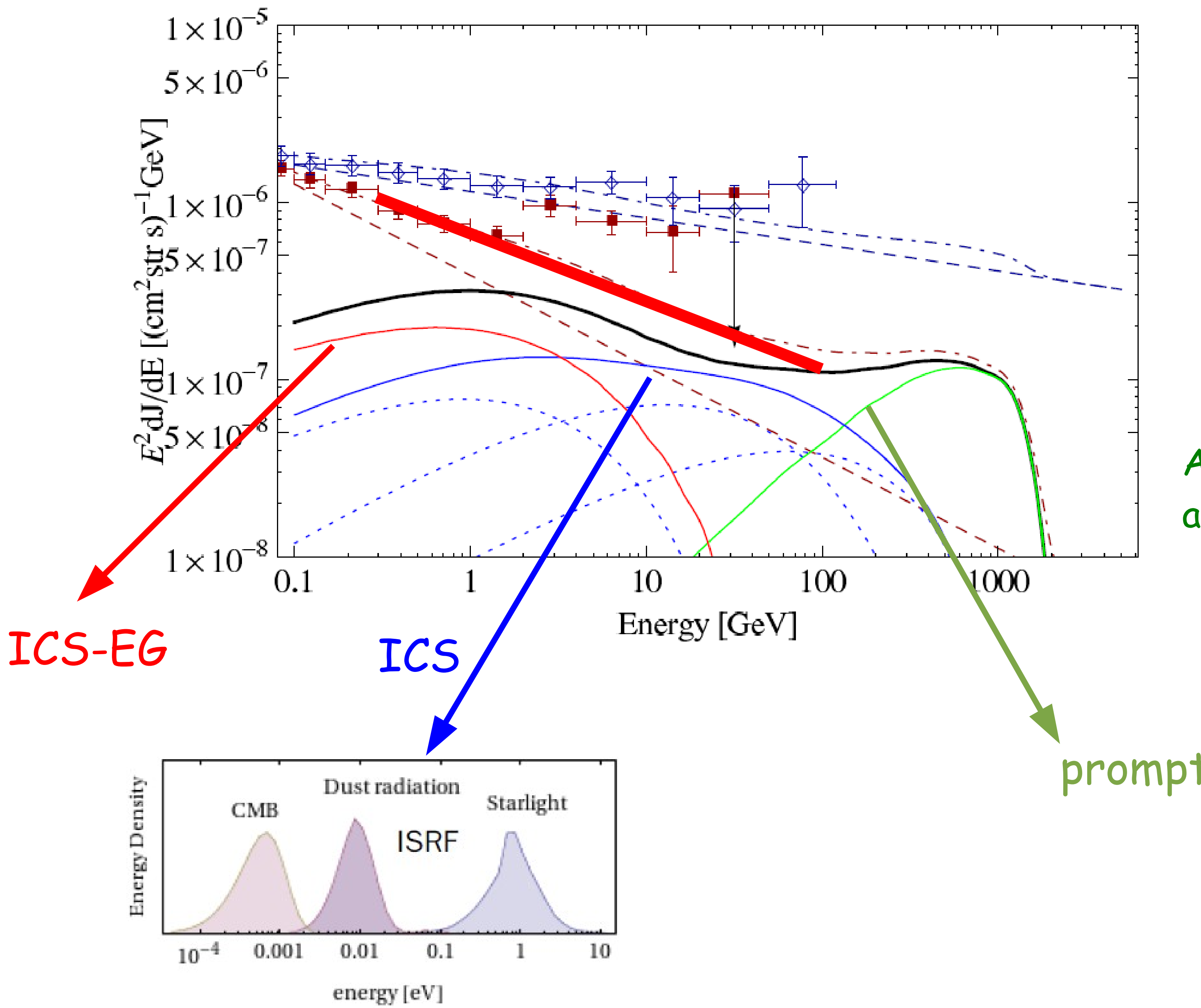

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AI, Tran, Weniger
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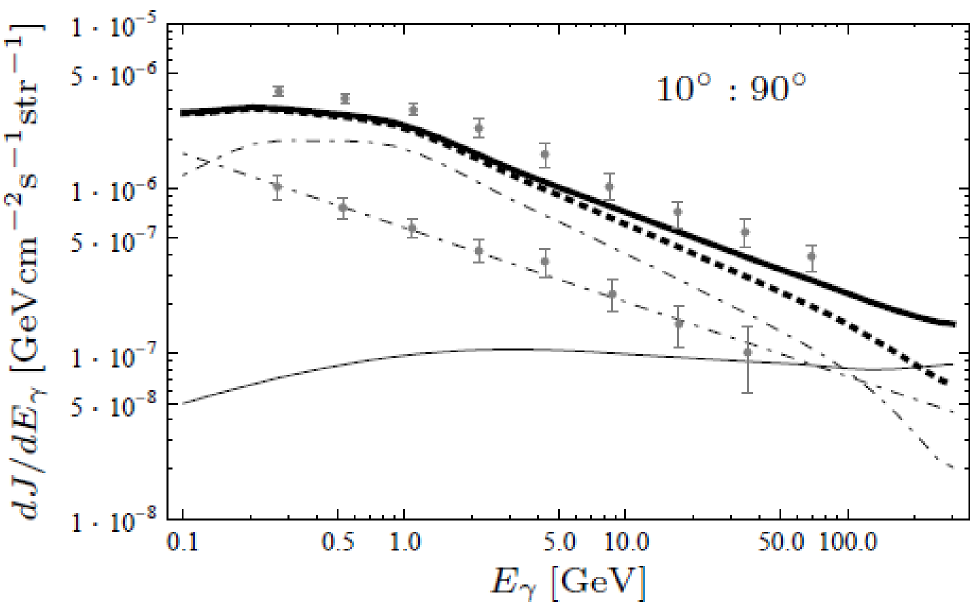
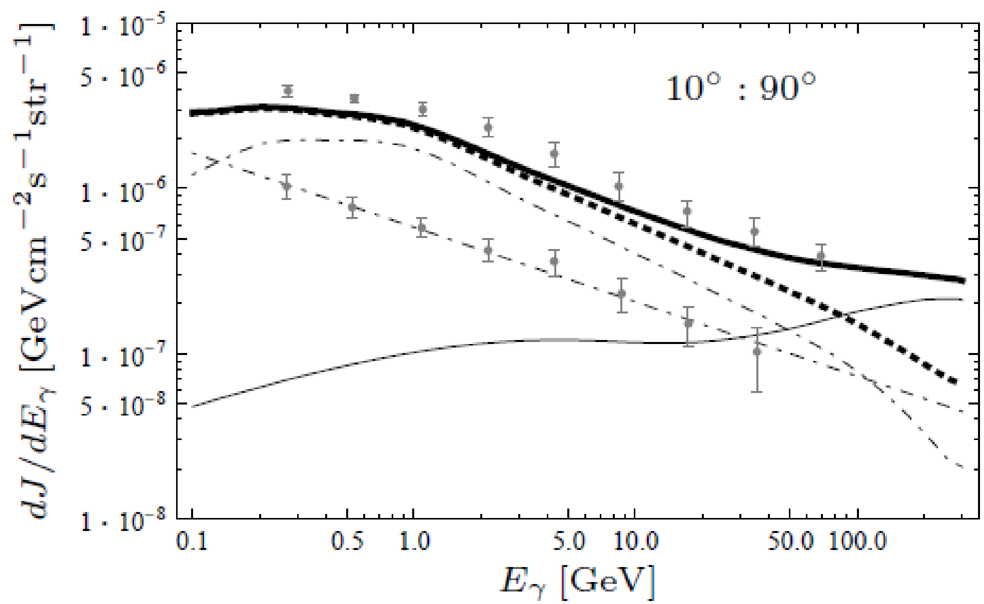
Diffuse gamma ray flux from DM decay

AI, Tran, Weniger
arXiv: 0909.3514

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



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



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

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

Diffuse gamma ray flux from DM decay

AI, Tran, Weniger
arXiv: 0909.3514

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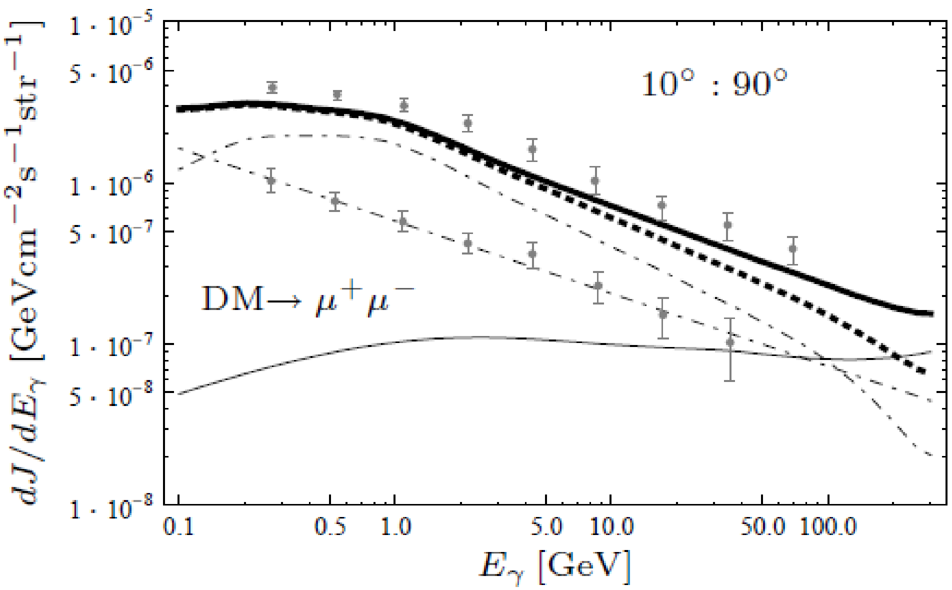
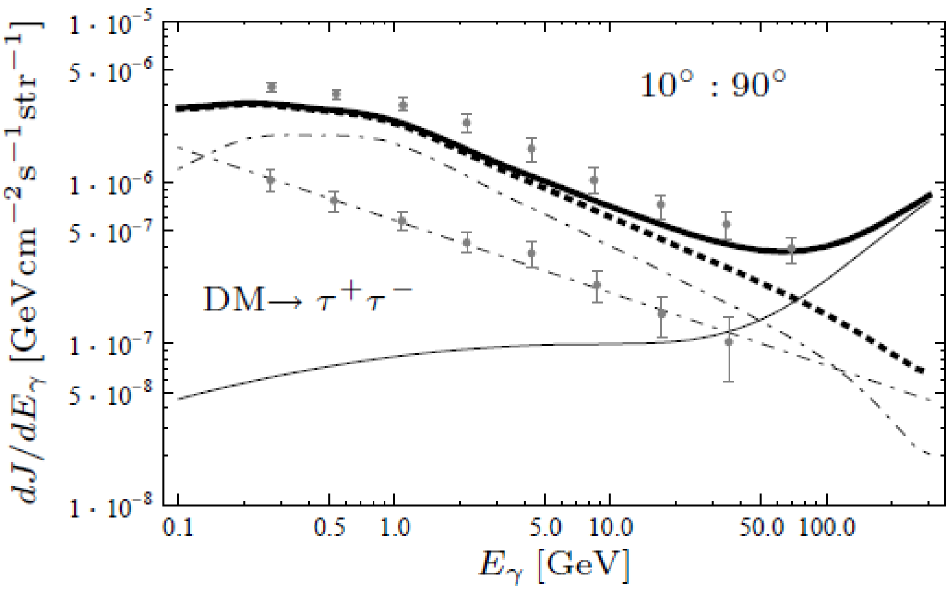
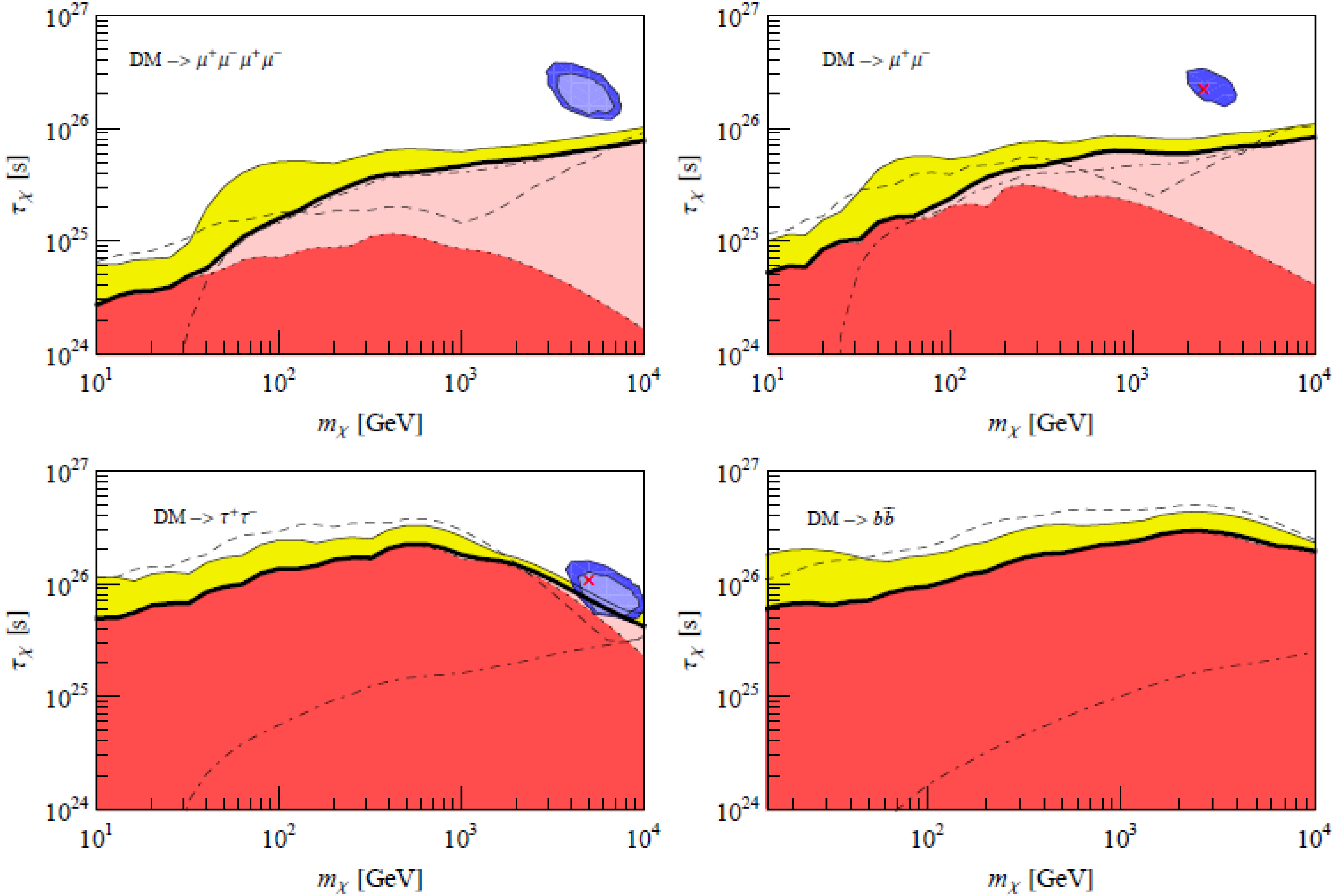


$\phi\rightarrow\mu^+\mu^-$

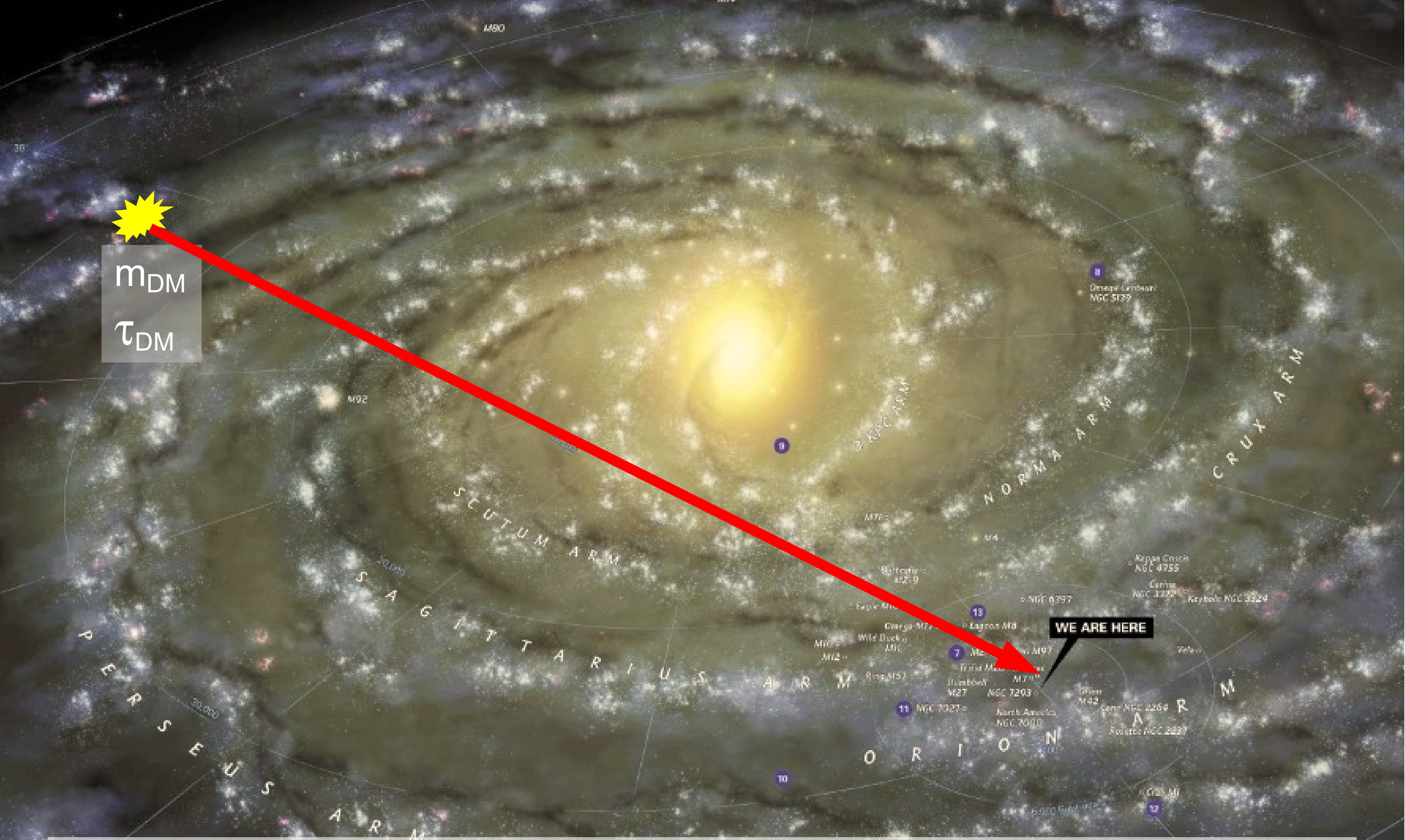


$\phi\rightarrow\tau^+\tau^-$

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



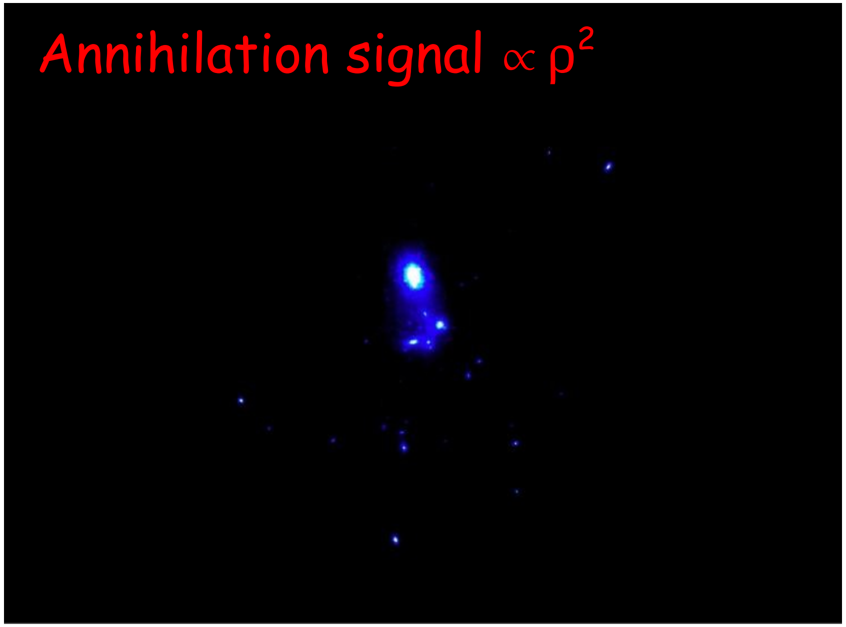
Zhang, Weniger, Maccione, Redondo, Sigl

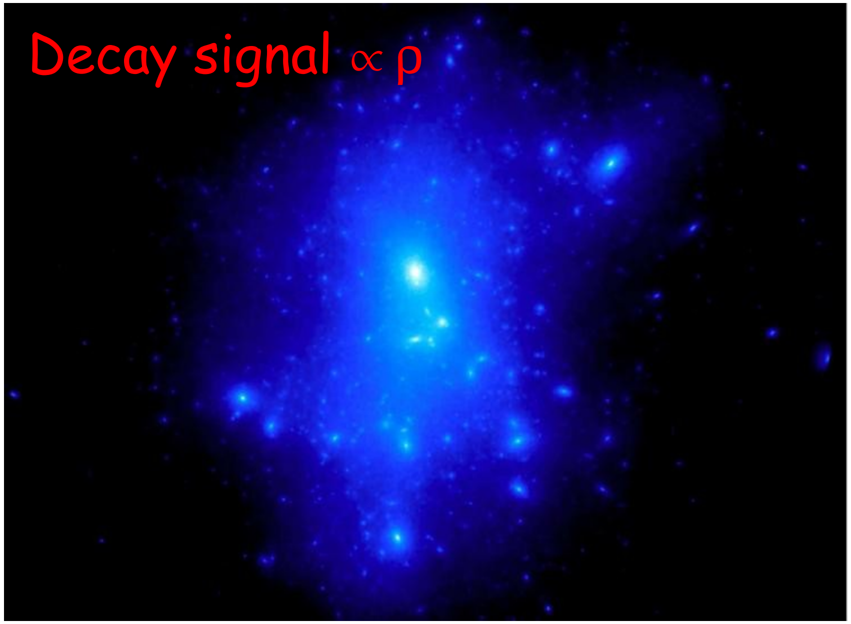


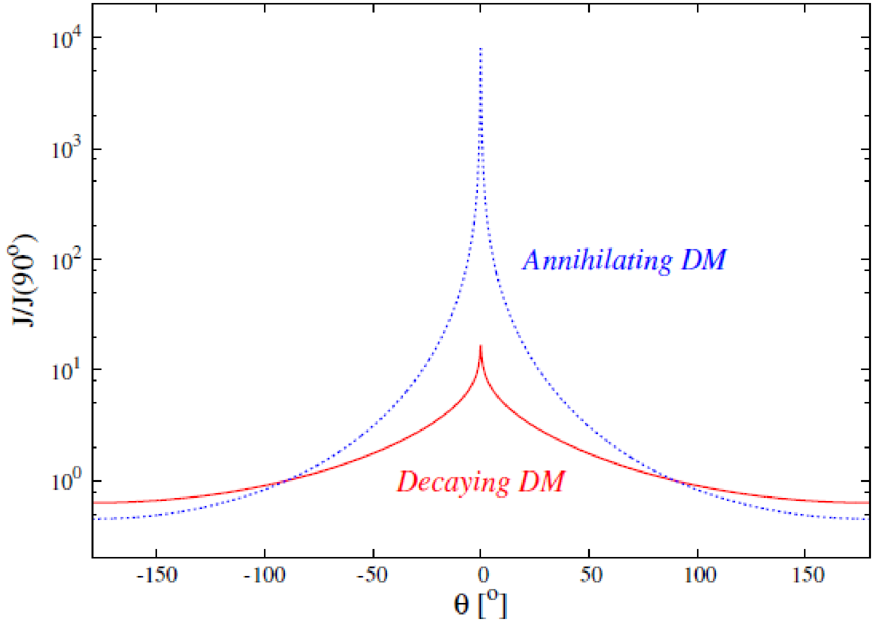
Gamma rays do not diffuse and point directly to the source.

More indications for or against the decaying dark matter scenario arise from the angular distribution of gamma-rays.

It is possible in principle to distinguish between annihilating dark matter and decaying dark matter

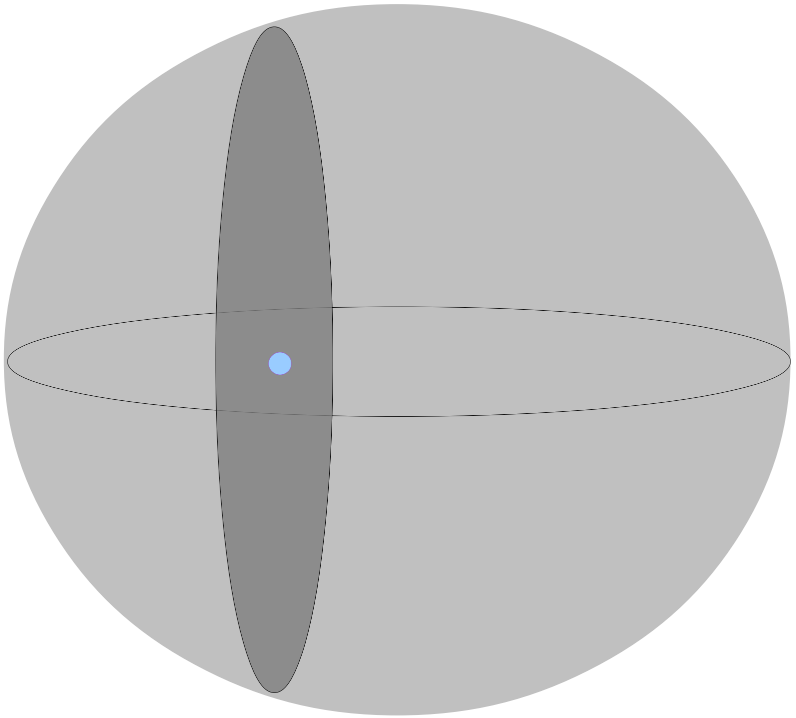






Bertone *et al.*

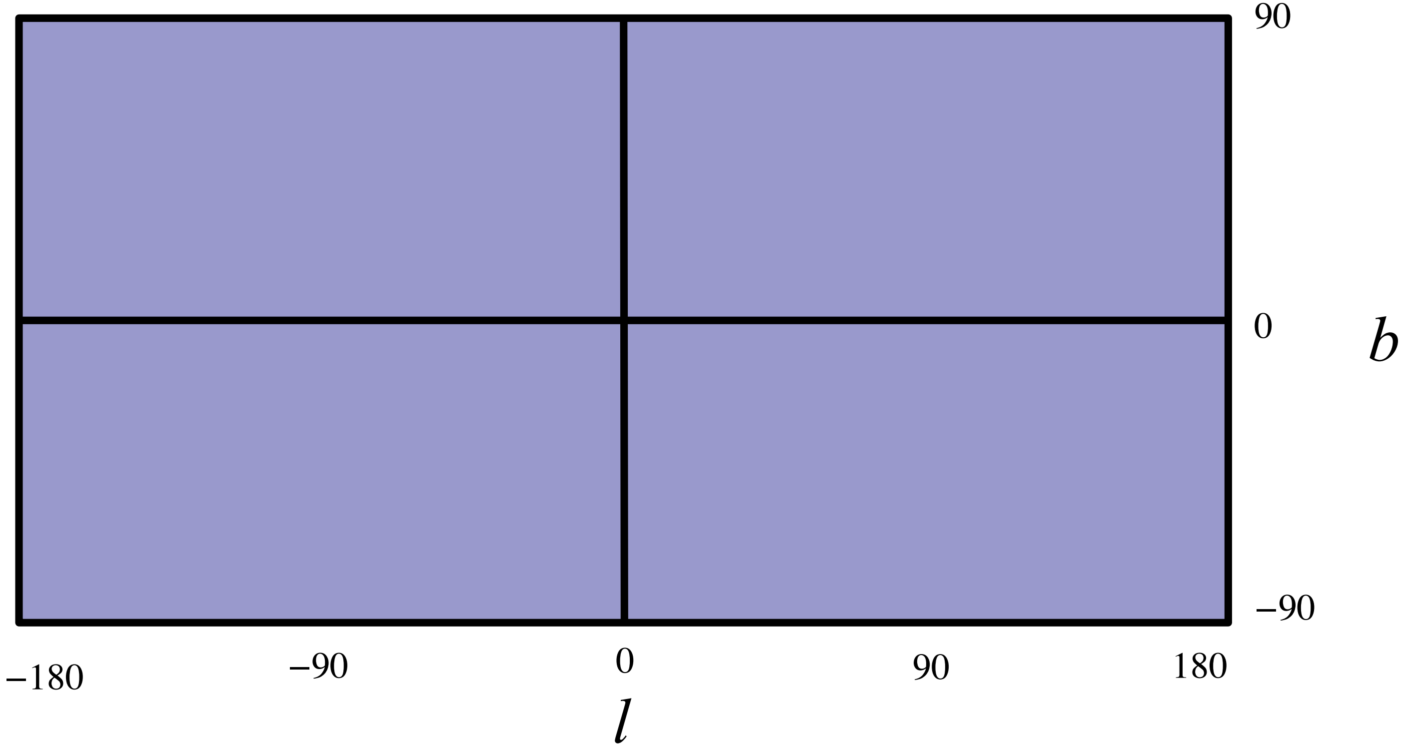
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.



(but no North-South anisotropy)

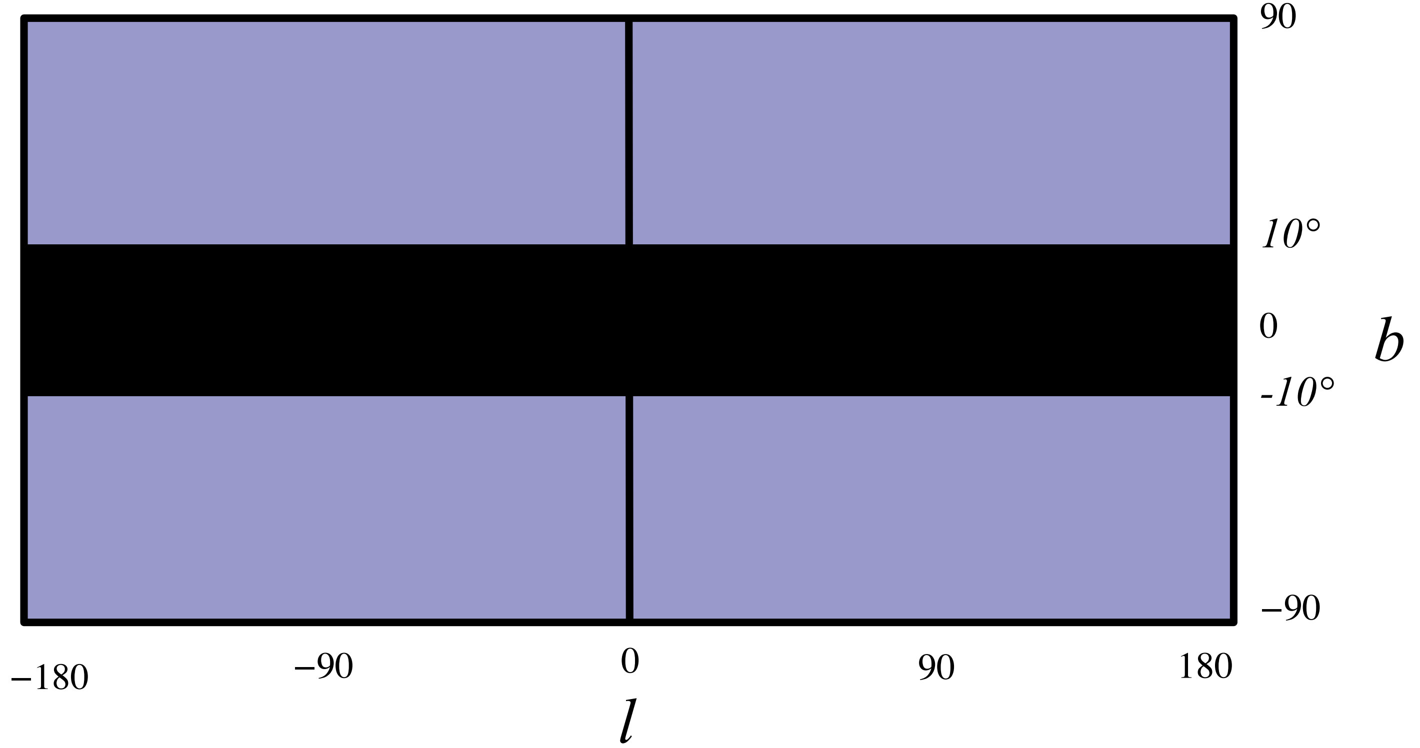
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

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



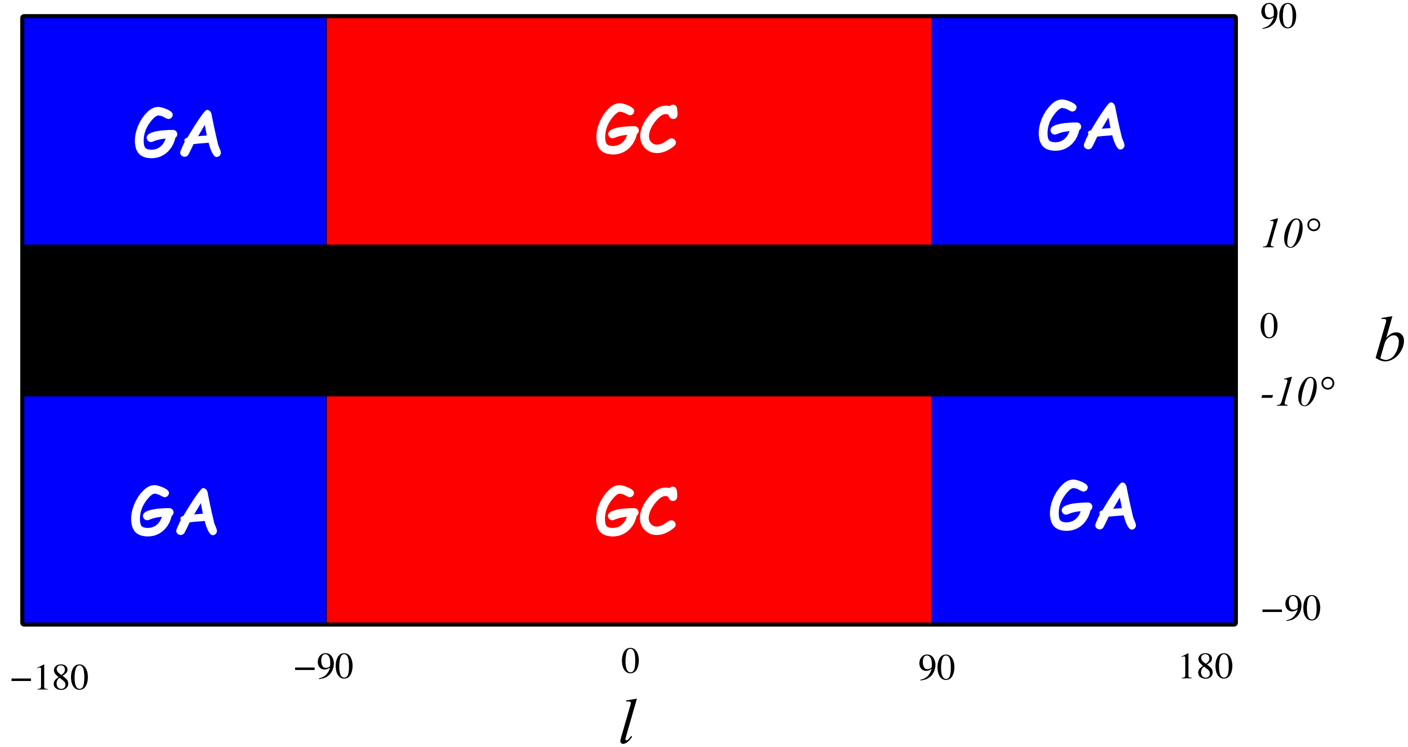
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 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}).



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: 4) Calculate the anisotropy, defined as:

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

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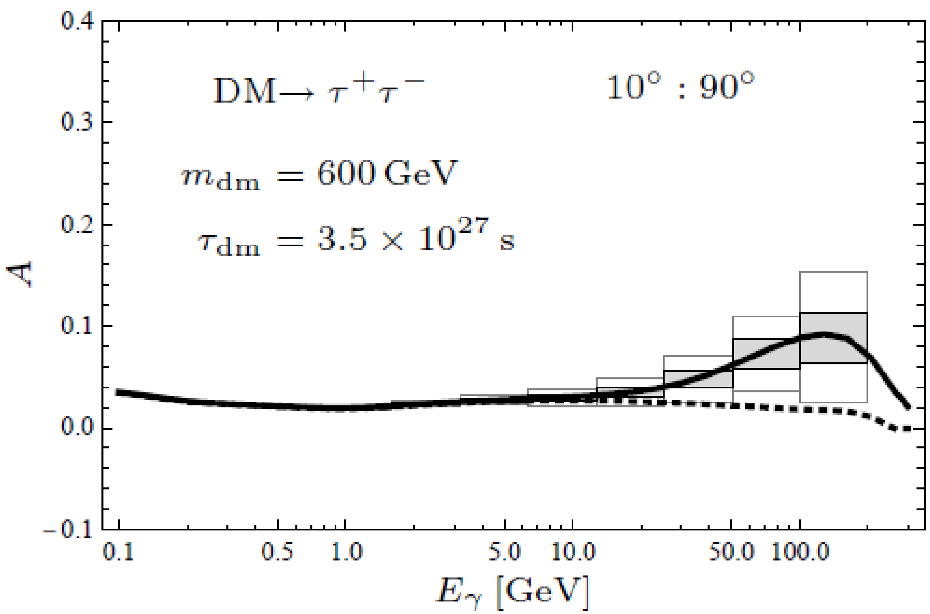

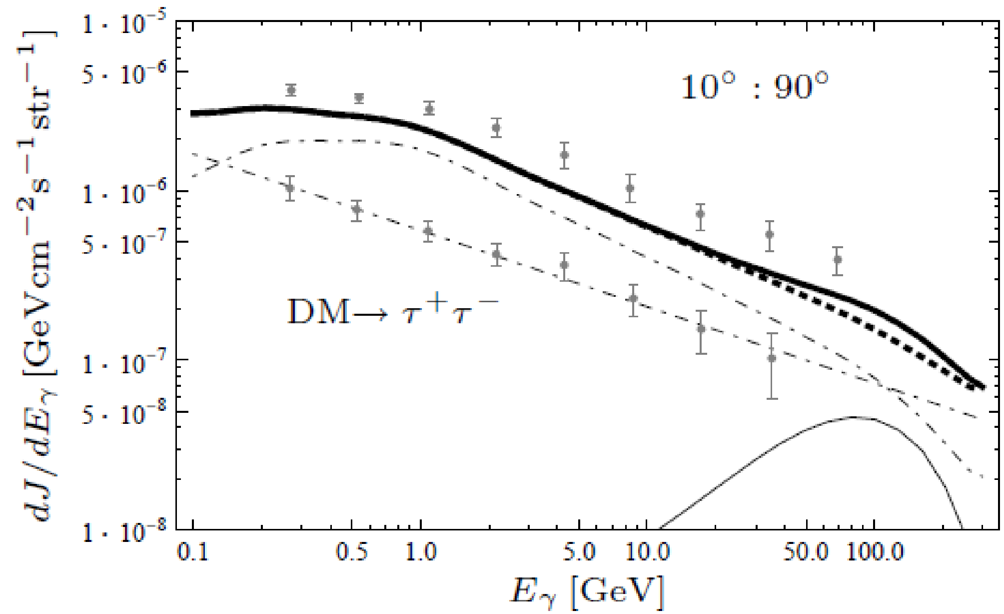

AI, Tran, Weniger
arXiv: 0909.3514

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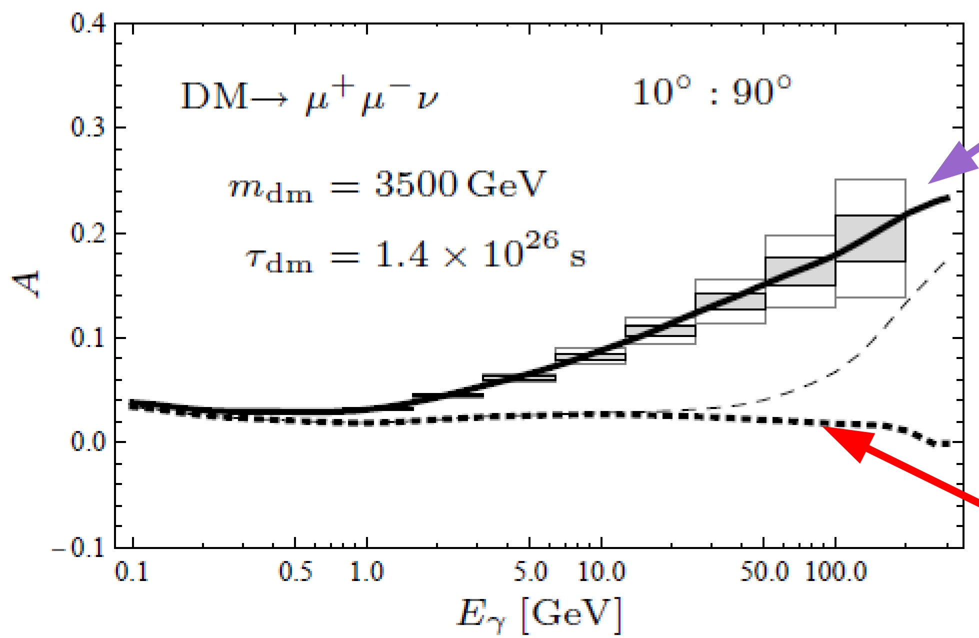


DM decay prediction: 15-20% at high energies!

"conventional" diffusive model

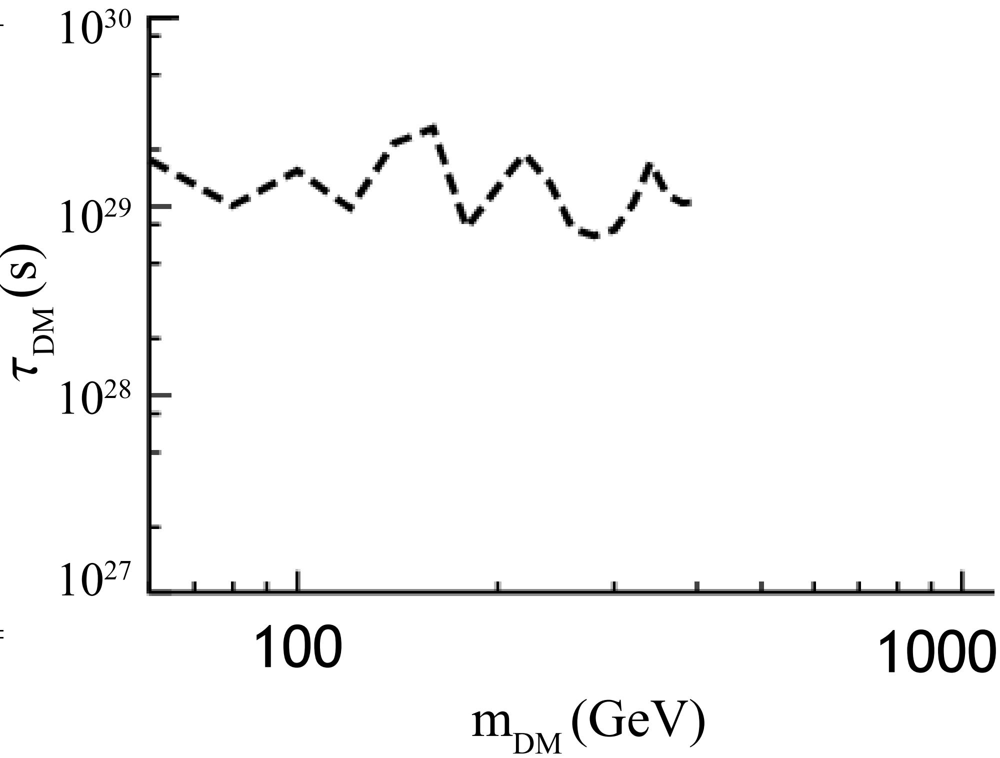
AI, Tran, Weniger
arXiv: 0909.3514

Gamma-ray lines

Inequivocal sign of dark matter. No (known) astrophysical source can produce a gamma-ray line in the multi-GeV range

E_γ (GeV)	95%CLUL (10^{-9} cm^{-2}s^{-1})	$\tau_{\gamma\gamma}$ [γZ] (10^{28} s) NFW	Einasto	Isothermal
30	3.5	17.6 [4.2]	17.8 [4.2]	17.5 [4.2]
40	4.5	10.1 [2.9]	10.3 [2.9]	10.0 [2.9]
50	2.4	15.5 [5.0]	15.7 [5.1]	15.4 [5.0]
60	3.1	9.8 [3.5]	10.0 [3.5]	9.7 [3.5]
70	1.2	21.6 [8.2]	21.9 [8.3]	21.5 [8.1]
80	0.9	26.0 [10.4]	26.4 [10.5]	25.8 [10.3]
90	2.6	7.7 [3.2]	7.8 [3.2]	7.6 [3.1]
100	1.4	12.6 [5.4]	12.8 [5.4]	12.5 [5.3]
110	0.9	18.9 [8.2]	19.2 [8.3]	18.8 [8.2]
120	1.1	13.3 [5.9]	13.5 [6.0]	13.2 [5.9]
130	1.8	7.6 [3.4]	7.8 [3.5]	7.6 [3.4]
140	1.9	7.0 [3.2]	7.1 [3.3]	7.0 [3.2]
150	1.6	7.5 [3.5]	7.6 [3.5]	7.4 [3.4]
160	1.1	10.2 [4.8]	10.4 [4.8]	10.1 [4.7]
170	0.6	17.0 [8.0]	17.2 [8.1]	16.9 [7.9]
180	0.9	11.6 [5.5]	11.8 [5.6]	11.6 [5.4]
190	0.9	10.4 [4.9]	10.5 [5.0]	10.3 [4.9]
200	0.9	10.6 [5.1]	10.8 [5.1]	10.5 [5.0]

Fermi coll.
arXiv:1001.4836



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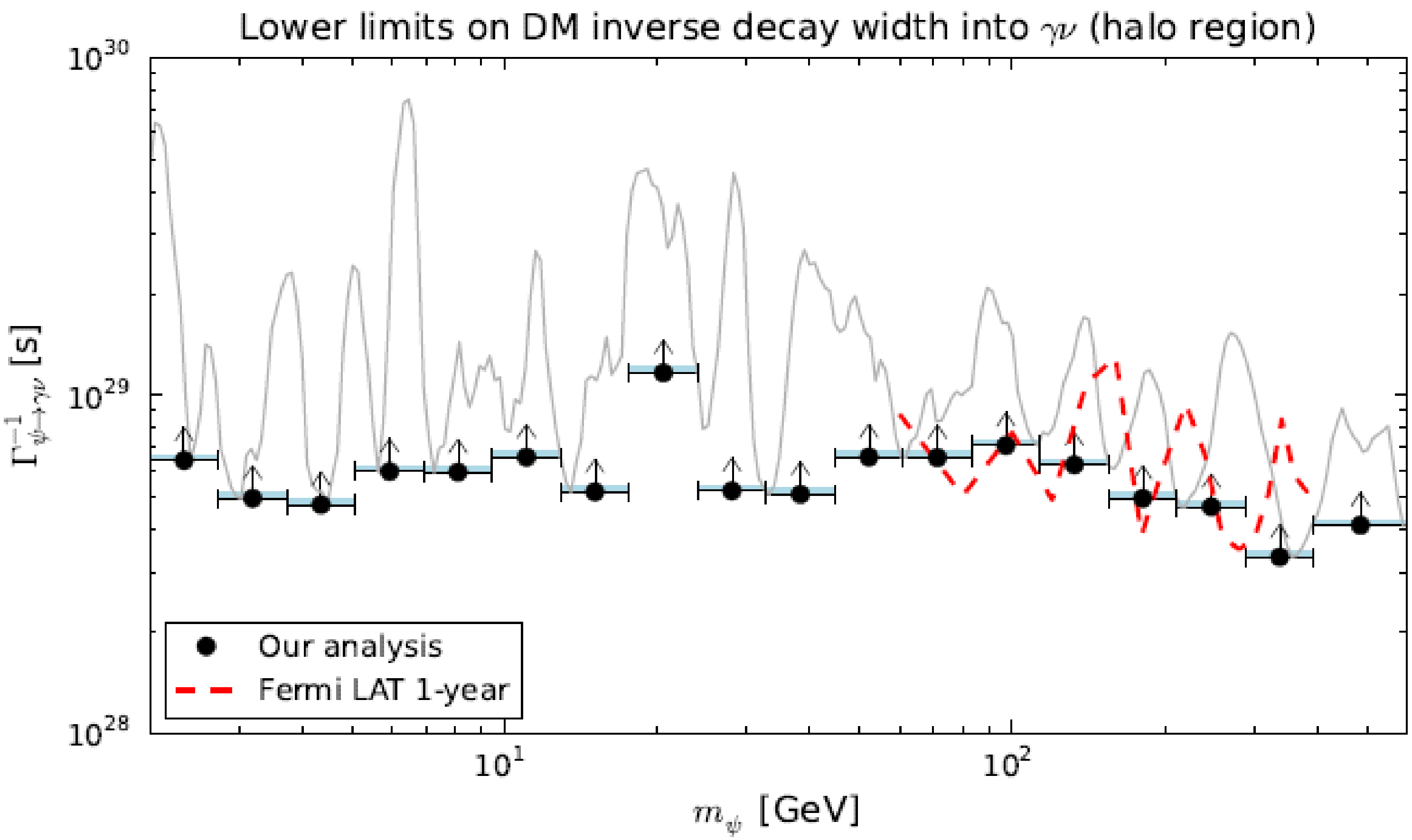
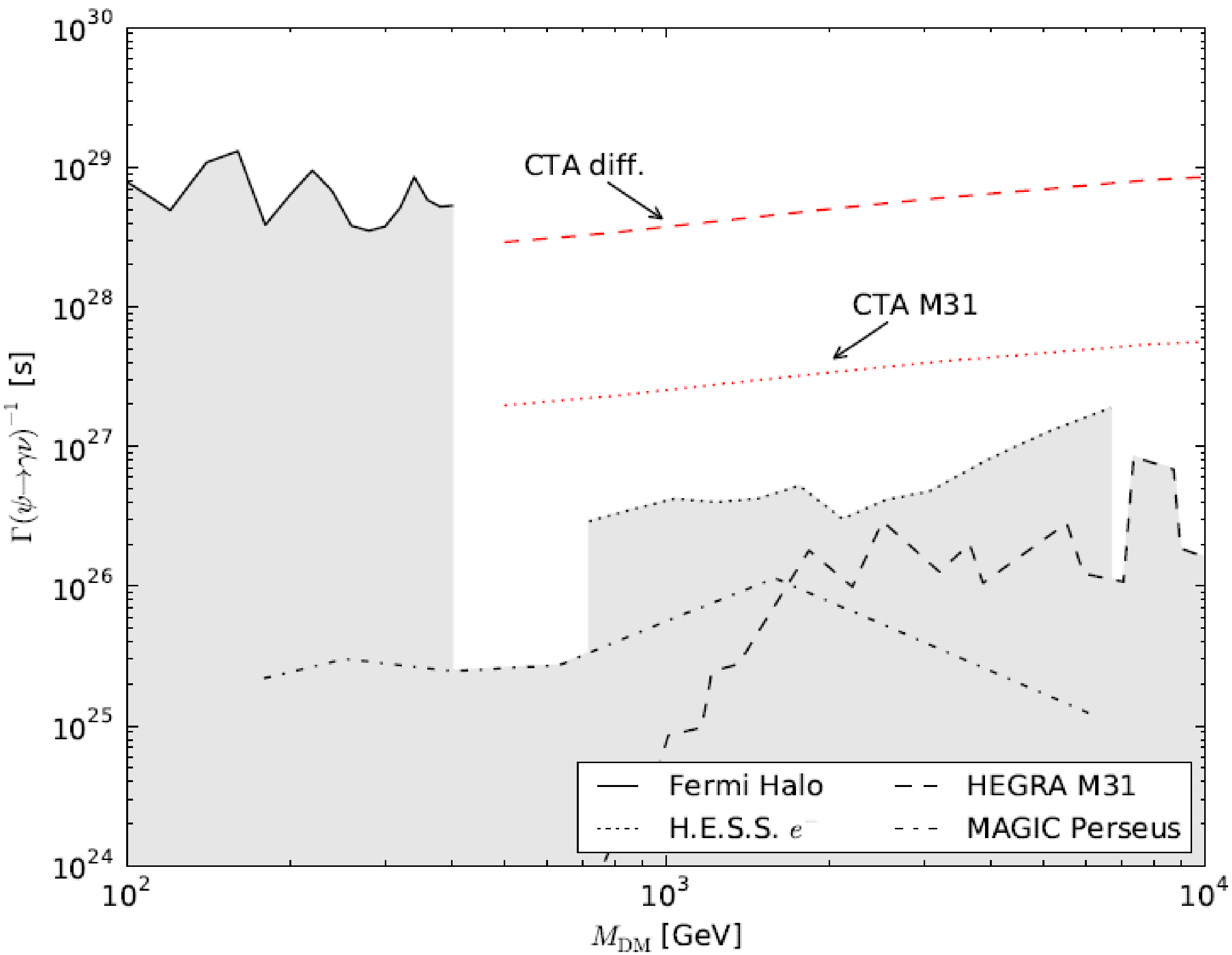


Vertongen, Weniger
arXiv:1101.2610

Talk by C. Weniger

Gamma-ray lines

Inequivocal sign of dark matter. No (known) astrophysical source can produce a gamma-ray line in the multi-GeV range



Garny et al.
arXiv:1011.3786

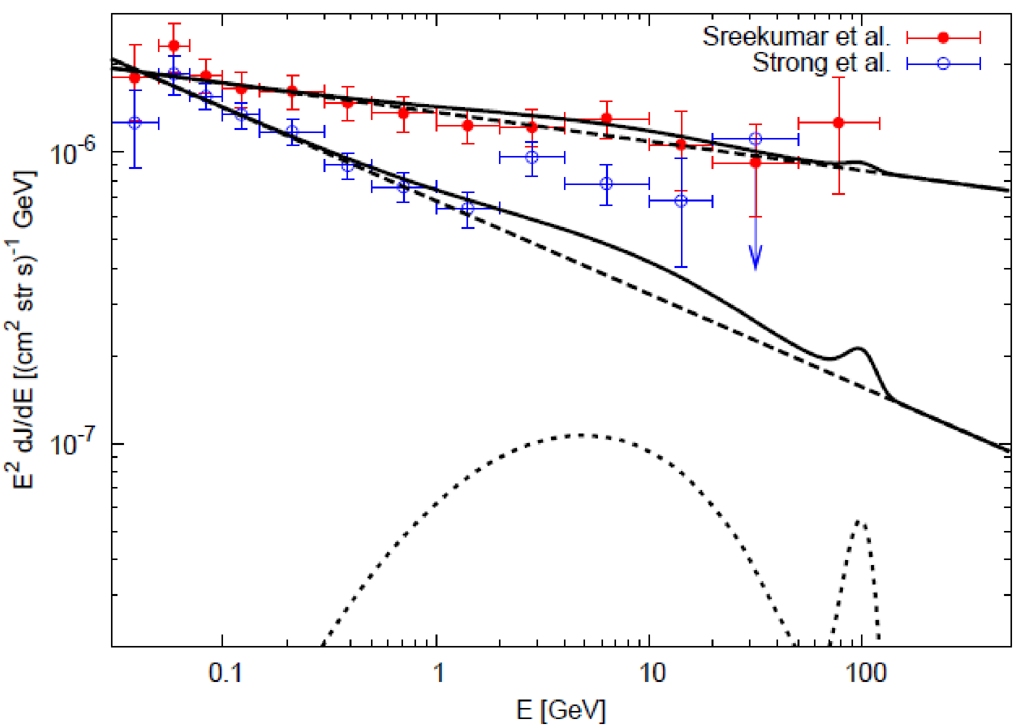
Talk by M. Garny

Gamma-ray lines

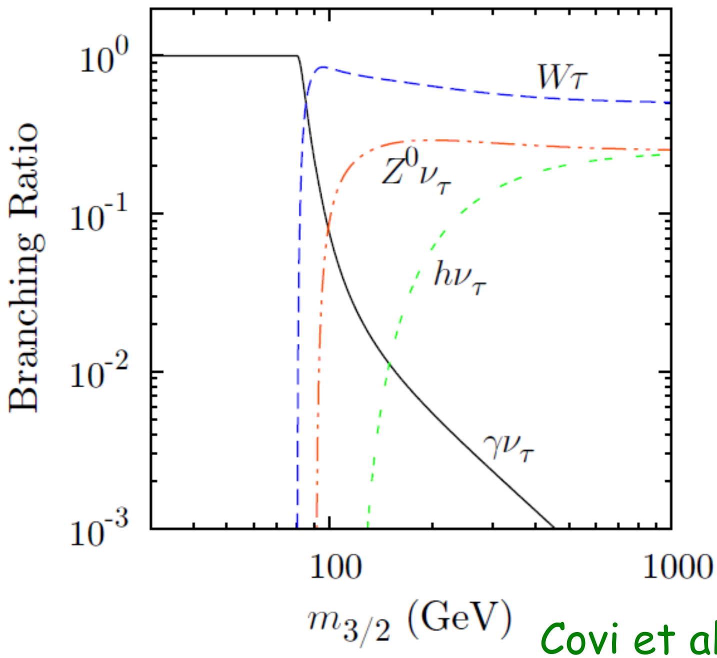
Predicted to be fairly intense in some concrete models

- Gravitino in general SUSY models

(without imposing R-parity conservation)



Buchmüller et al.



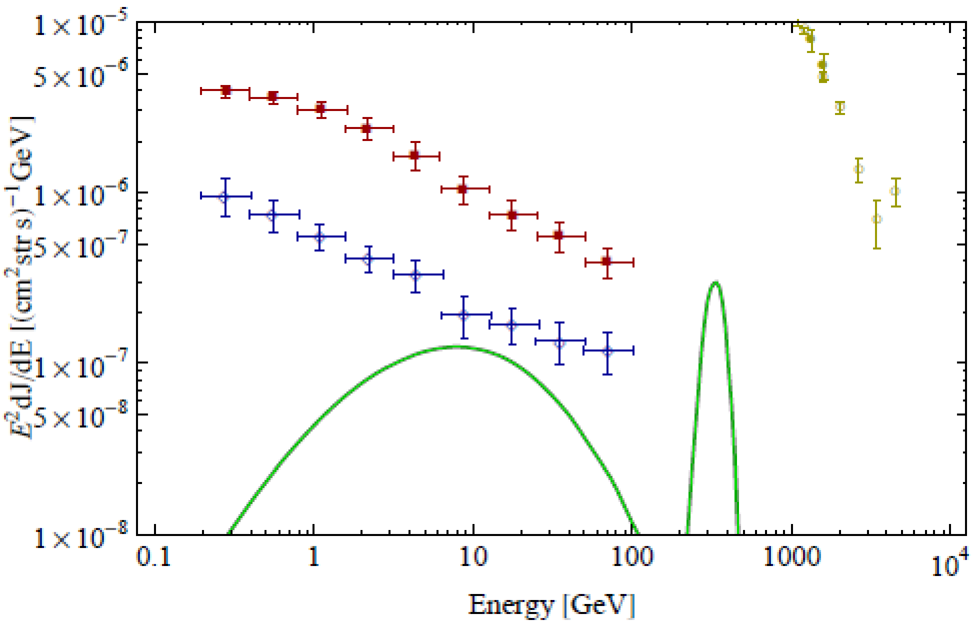
Covi et al.

Talk by M. Grefe

Gamma-ray lines

Predicted to be fairly intense in some concrete models

- Vector of a hidden SU(2) gauge group



m=600 GeV
τ=1.1×10^{27} s

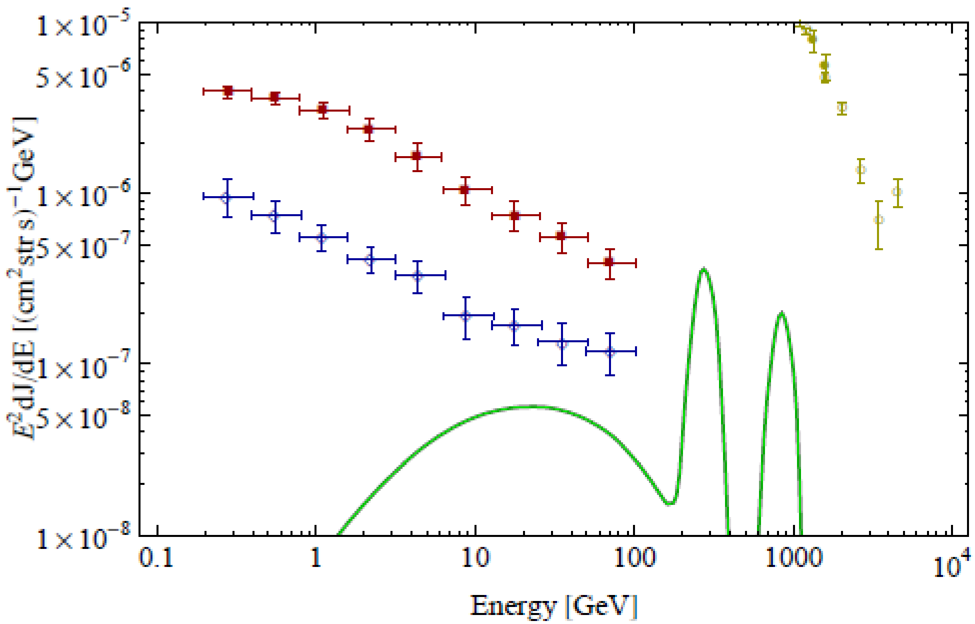
Arina, Hambye, AI, Weniger

	$\eta\eta$	$h\eta$	hh	$\gamma\eta$	$Z\eta$	γh	Zh
Branching Ratios	-	0.04	0.62	0.002	0.003	0.15	0.18

Gamma-ray lines

Predicted to be fairly intense in some concrete models

- Vector of a hidden SU(2) gauge group



m=1550 GeV

τ=1.6×10^{27} s

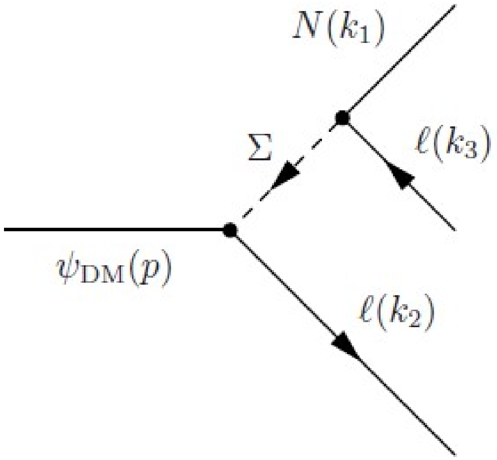
Arina, Hambye, AI, Weniger

	$Z\eta$	$\gamma\eta$	Zh	γh
Branching Ratios	0.028	0.79	0.041	0.14

Radiatively induced gamma-ray lines

Garny et al.
arXiv:1011.3786

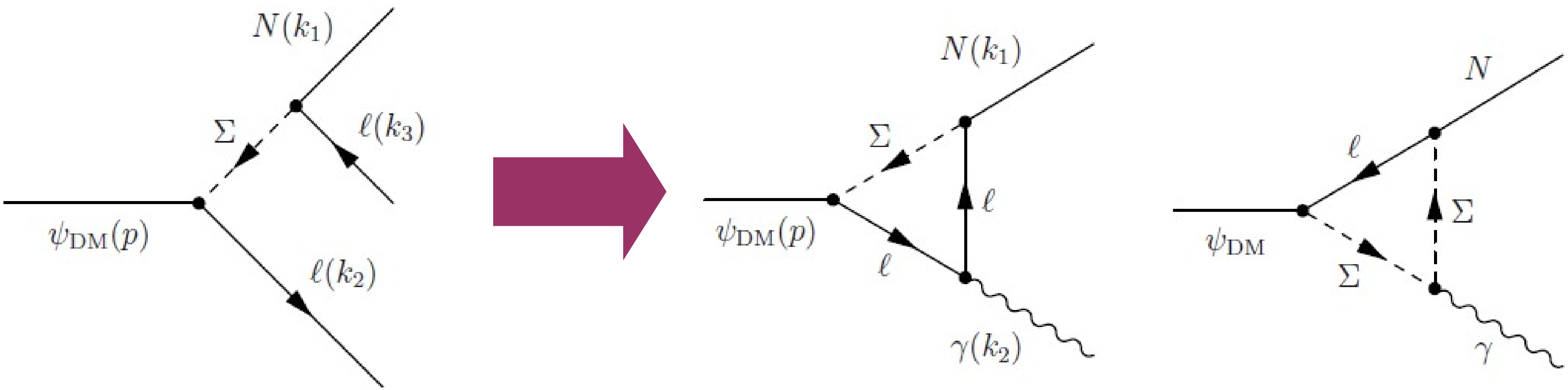
Three body decay mediated by a <u>scalar</u>

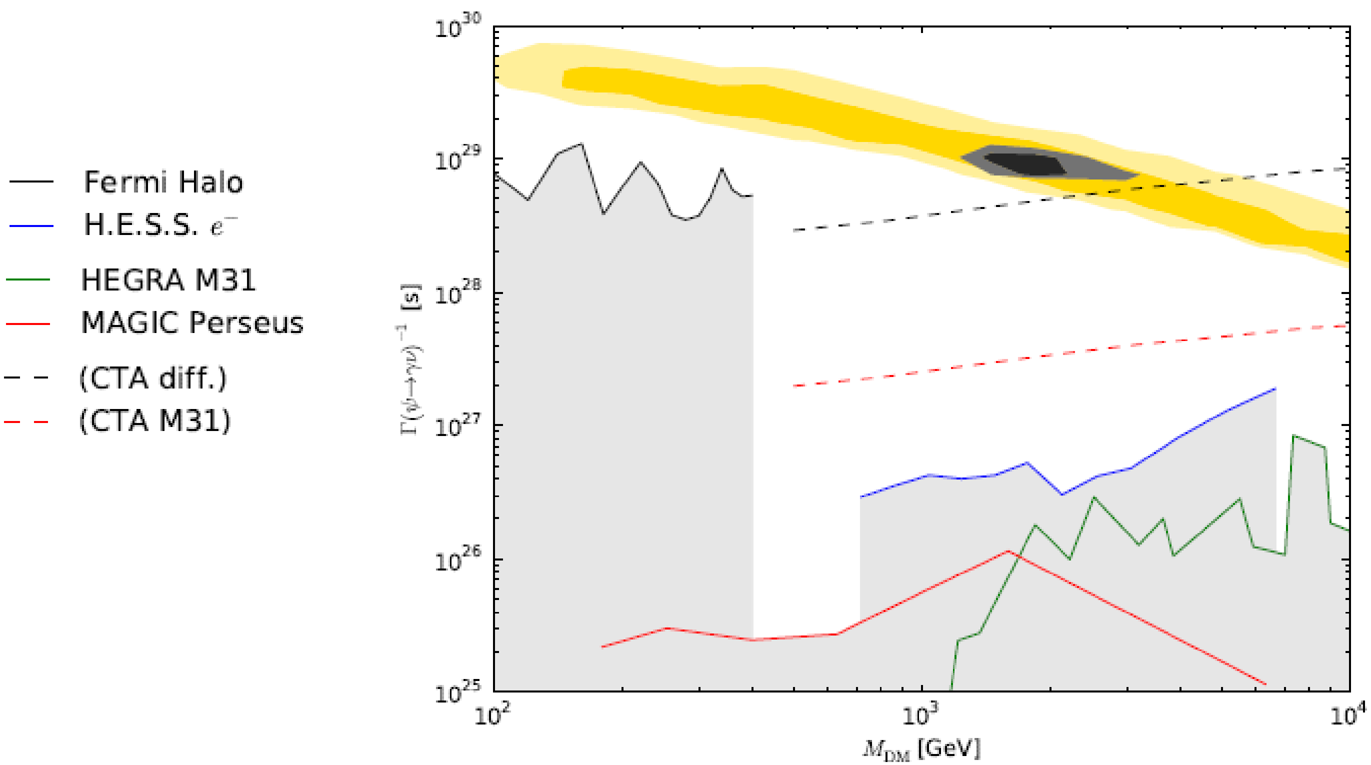


Gamma-ray lines

Garny, AI, Tran, Weniger

Three body decay mediated by a scalar



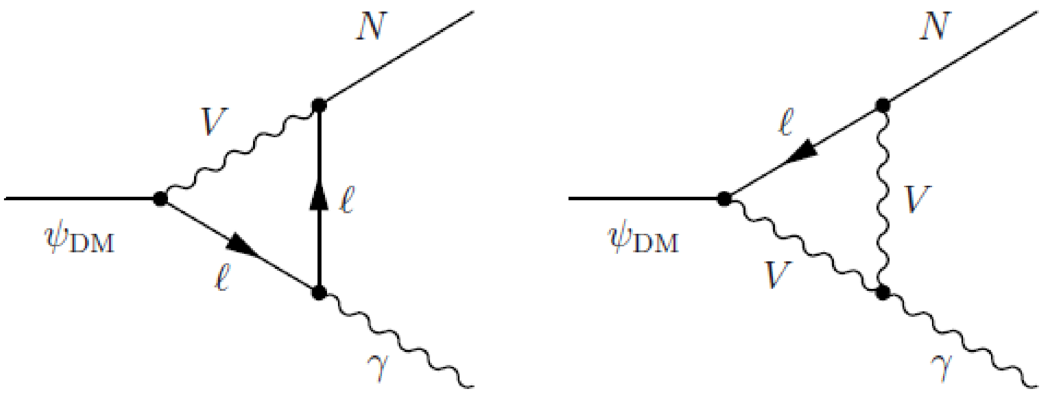


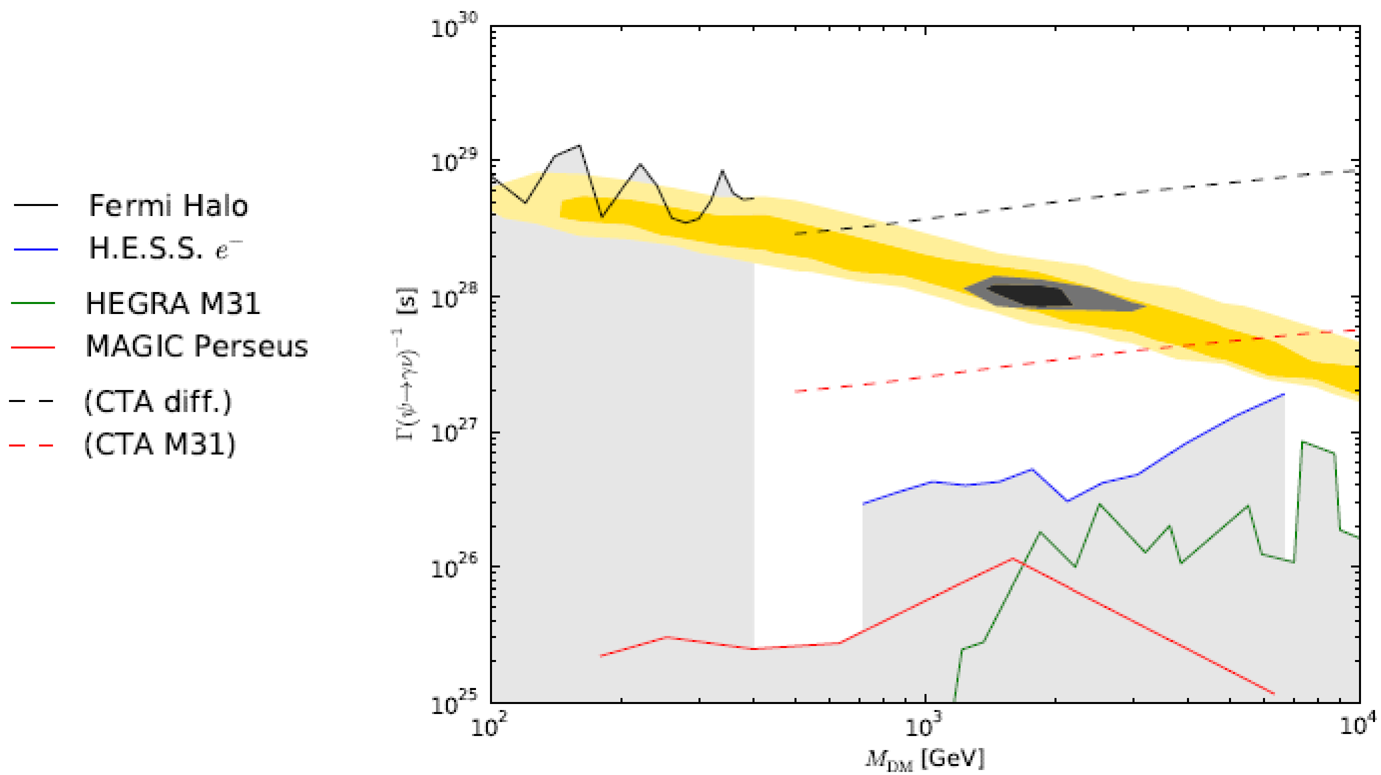
Democratic decay

Gamma-ray lines

Garny, AI, Tran, Weniger

Three body decay mediated by a vector



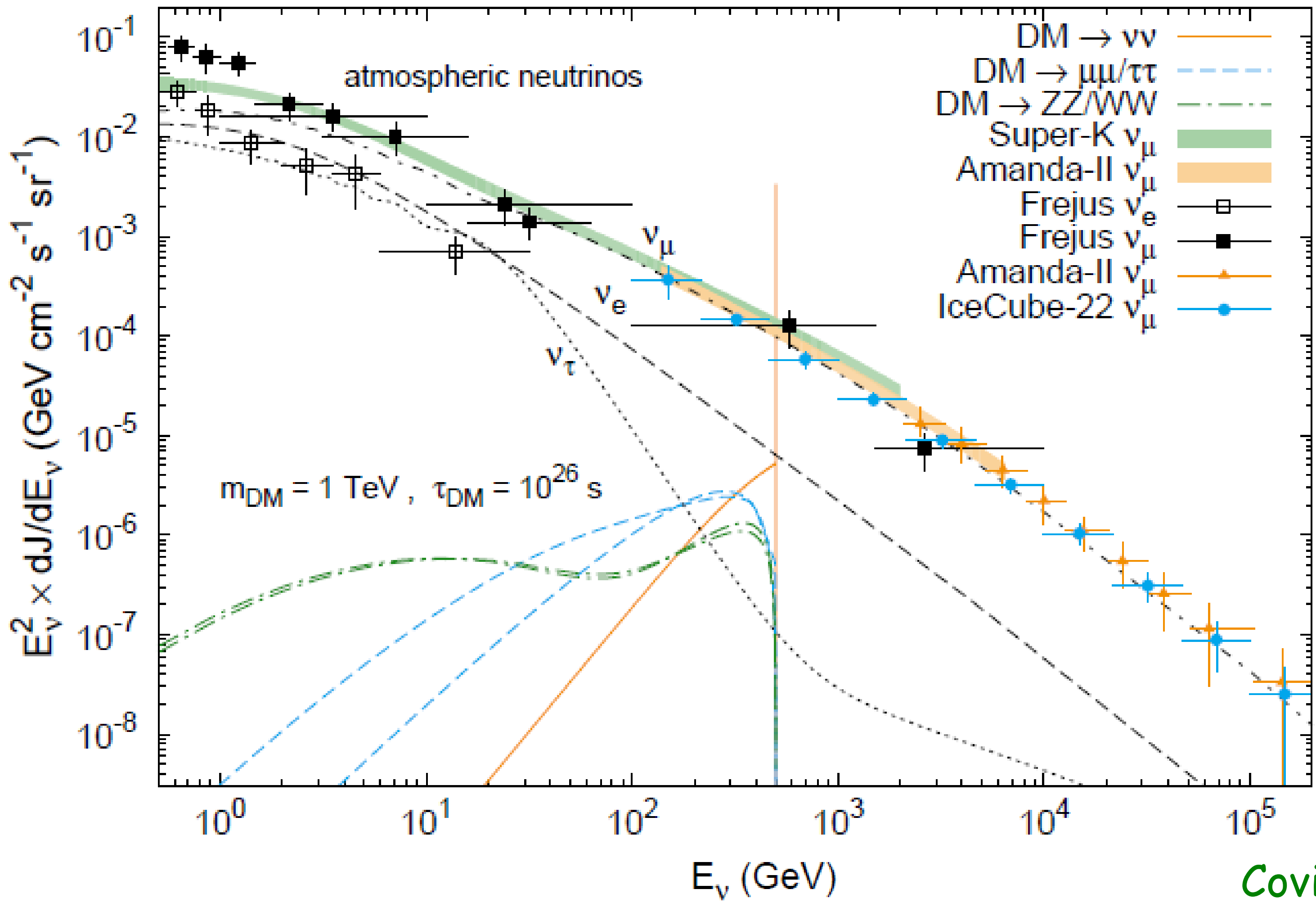


Democratic decay

Talk by M. Garny

Neutrino flux

- Difficult to see due to large atmospheric backgrounds.



Covi et al.

Neutrino flux

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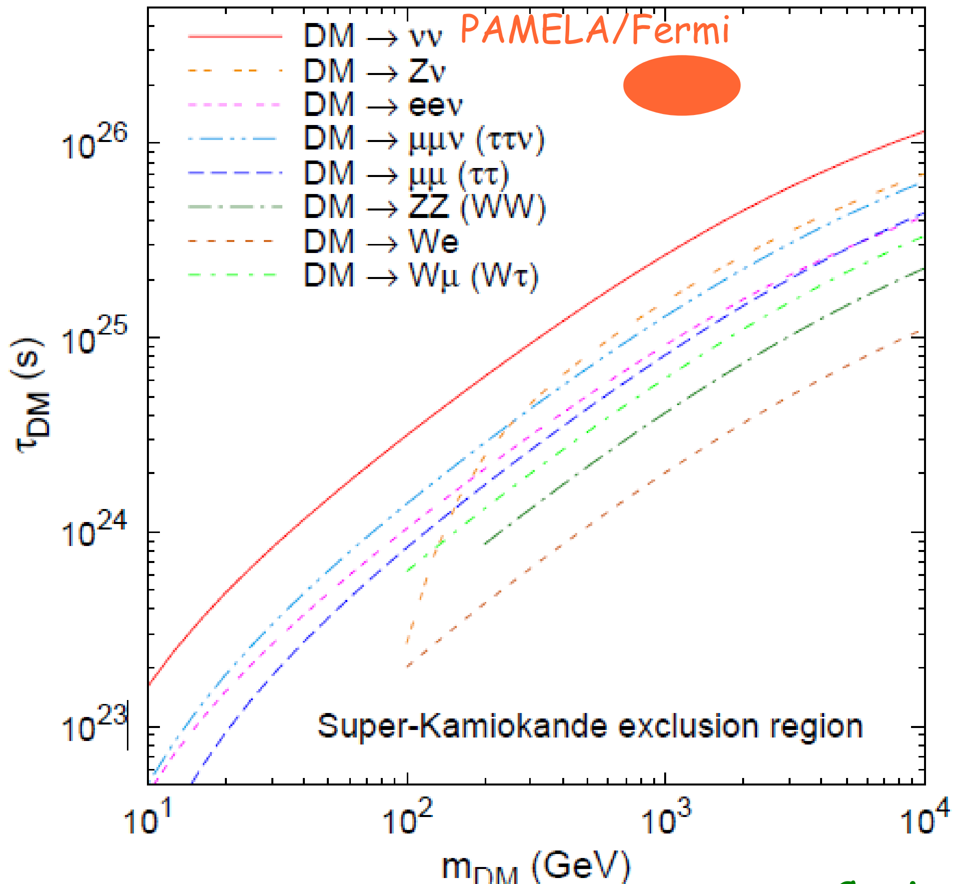
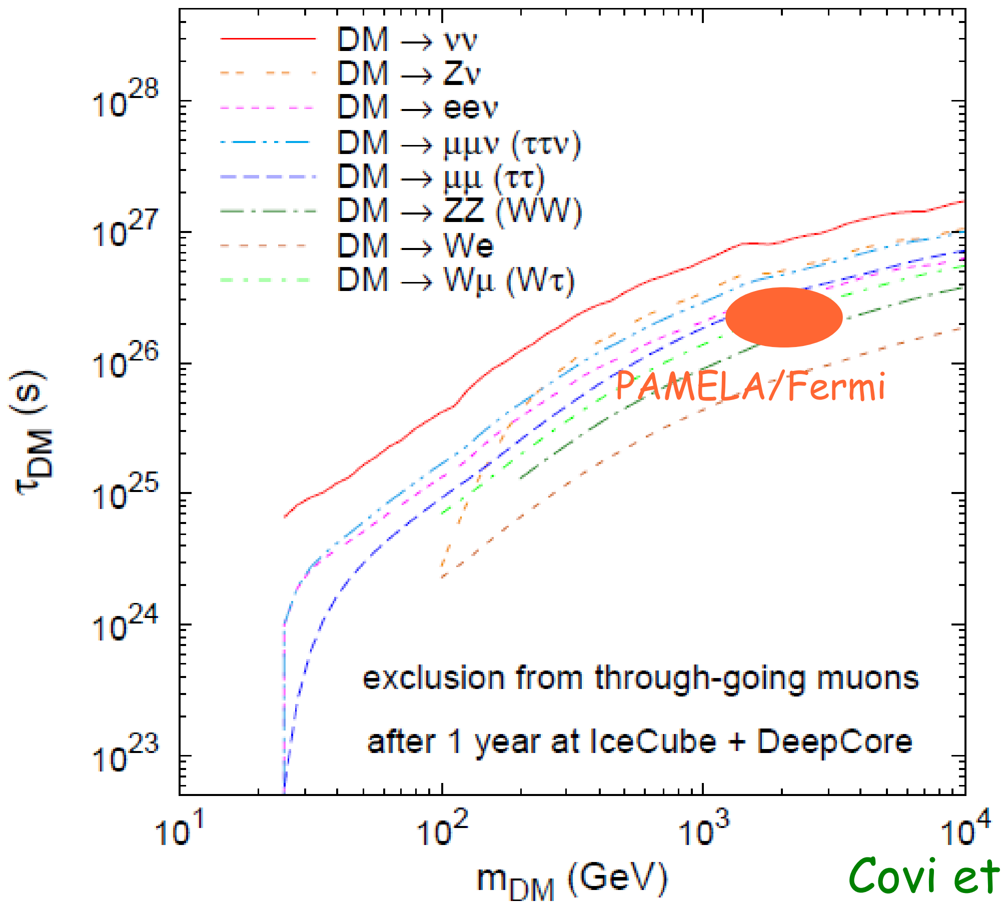


Covi et al.

Neutrino flux

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



Covi et al.

Conclusions

• Stability of the dark matter particle is an open question (as is proton stability). Indirect dark matter searches constrain the dark matter lifetime.

• Some well motivated candidates for dark matter are predicted to decay with very long lifetimes. Constraints on concrete models.

• 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