Decaying Dark Matter

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Introduction

Common lore in indirect dark matter detection:

dark matter particles are stable and annihilate:

$$DM\ DM \rightarrow \gamma\gamma,\ e^+e^- \ldots$$

cif. talk by Marco Cirelli

Introduction

Common lore in indirect dark matter detection:

dark matter particles are stable and annihilate:

DM DM $\rightarrow \gamma\gamma$, e+e-... cif. talk by Marco Cirelli

Why? Astrophysical and cosmological evidences for dark matter just require a lifetime longer than the age of the Universe.

In the most conservative scenario, dark matter could decay (and possibly also annihilate)

If the decays occur at a sufficiently large rate, the decay products DM $\rightarrow \gamma$ X, e+X could be detected as an anomalous contribution to the high energy cosmic ray fluxes.

In this talk we will discuss that:

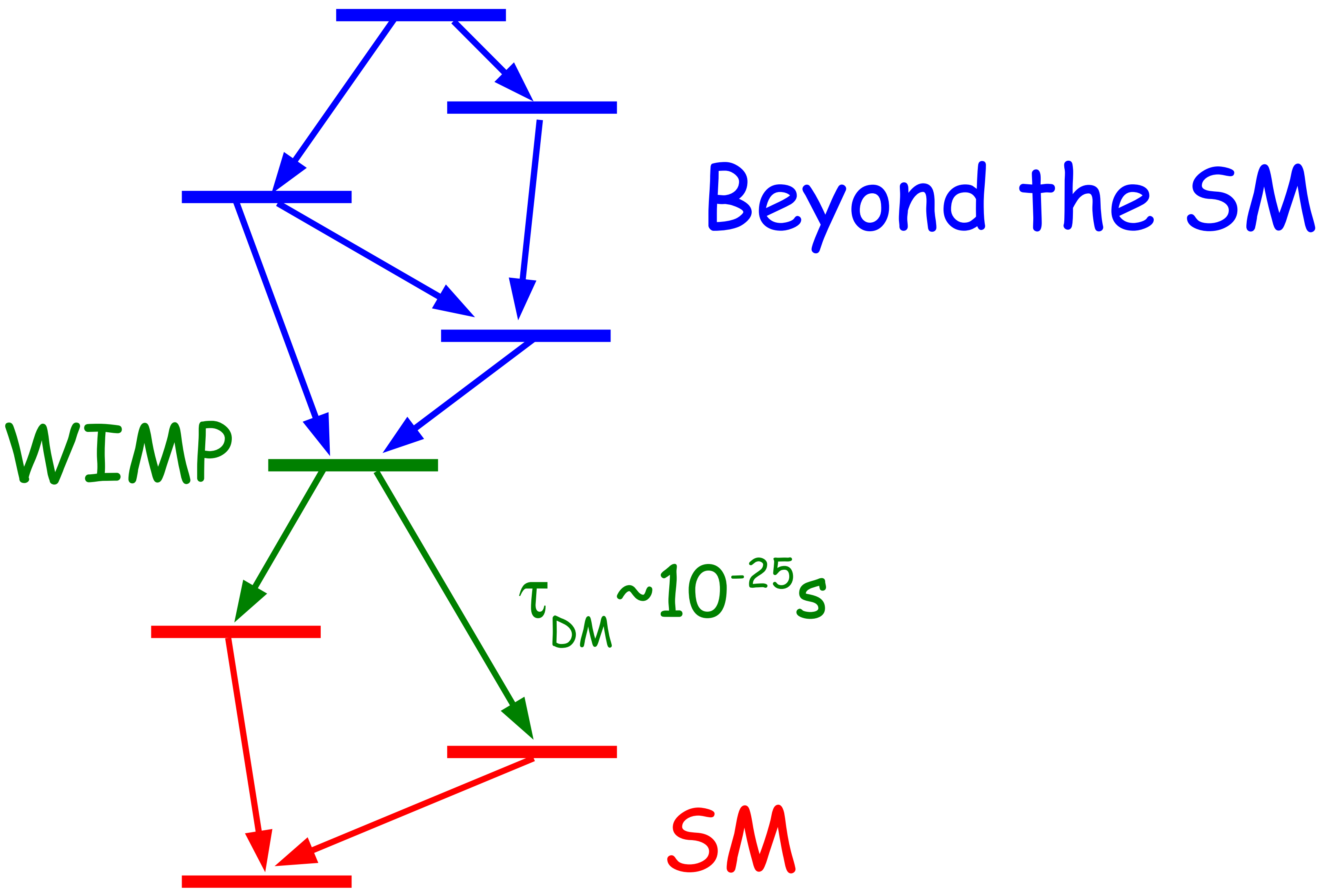
- decaying dark matter is a very well motivated scenario from the particle physics point of view,
- can be constrained by indirect DM detection experiments,
- provides a natural explanation to the PAMELA e^+ excess,
- provides signatures qualitatively different to the case of dark matter annihilation.

Decaying dark matter: a particle physicist's perspective

- No fundamental objection to this possibility, provided τ_{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:



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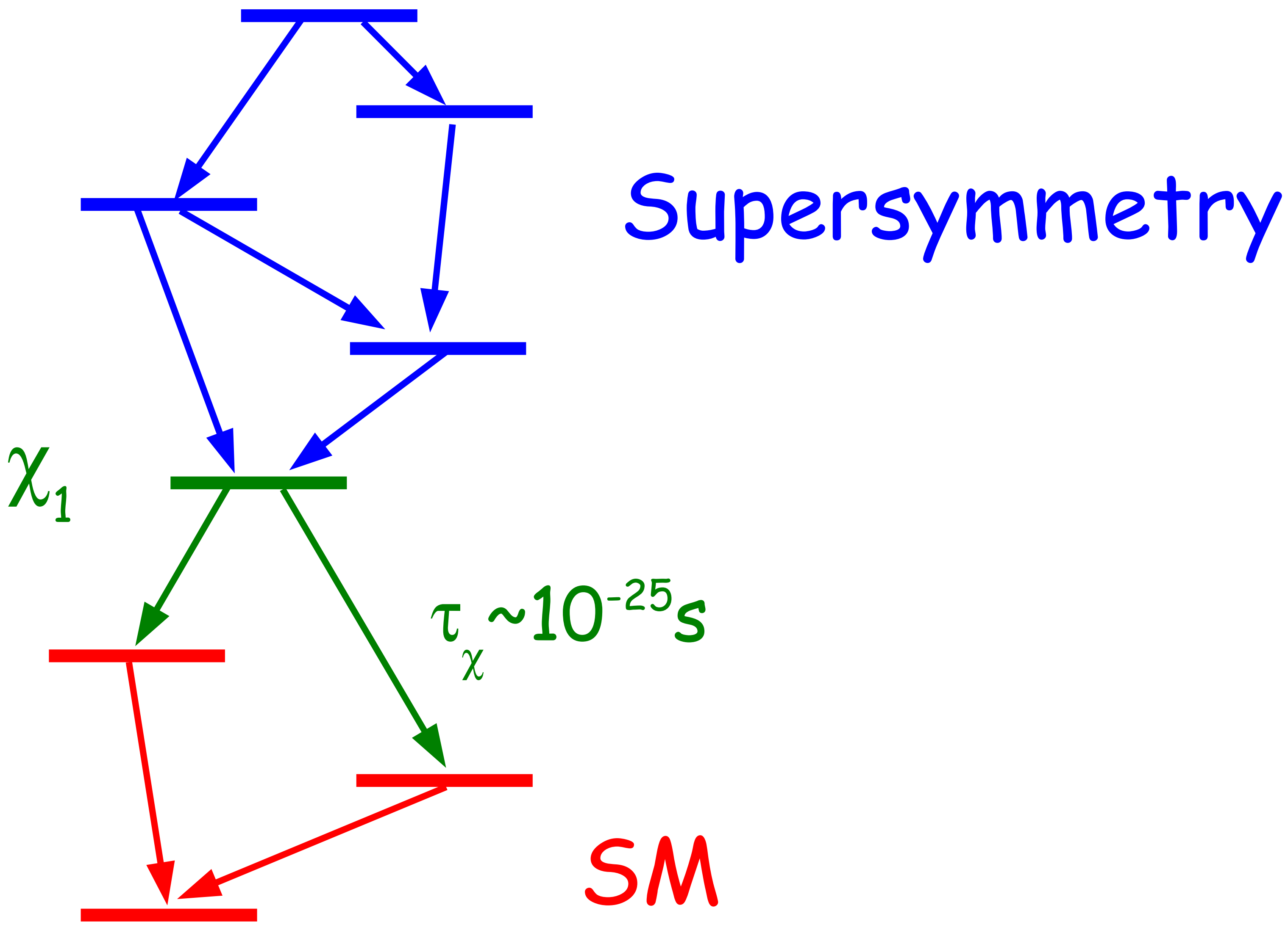

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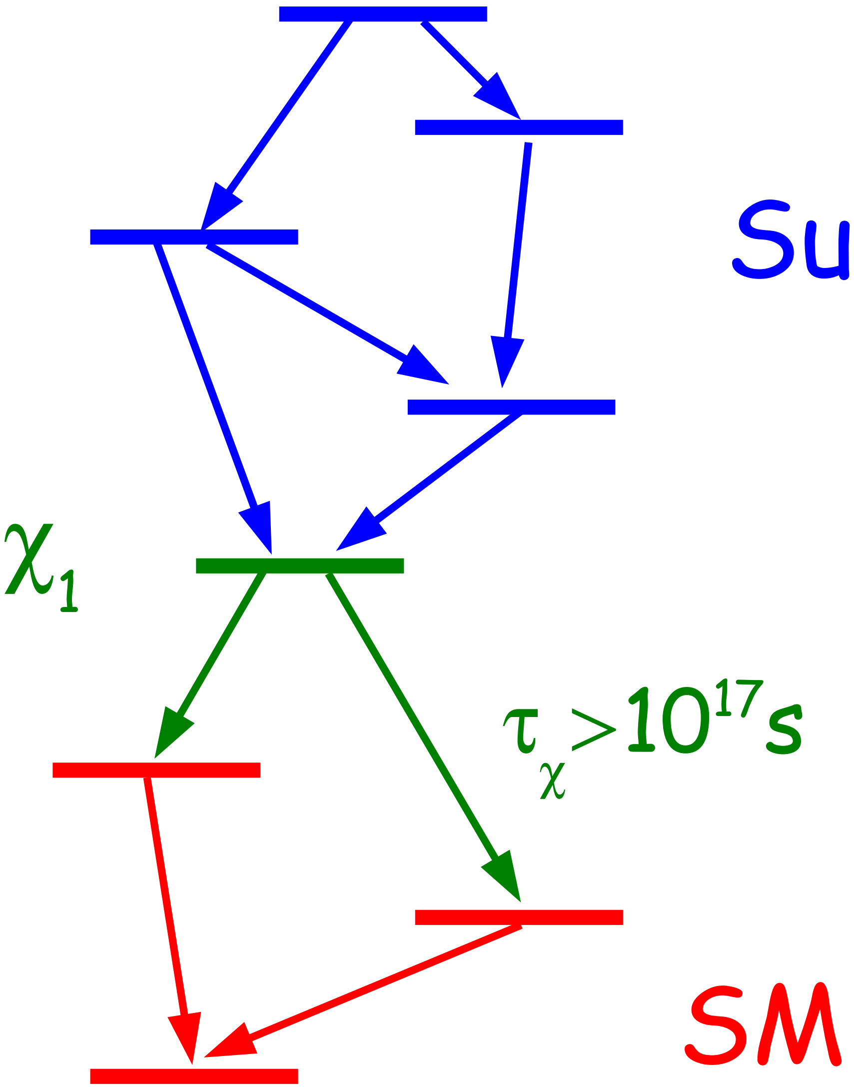
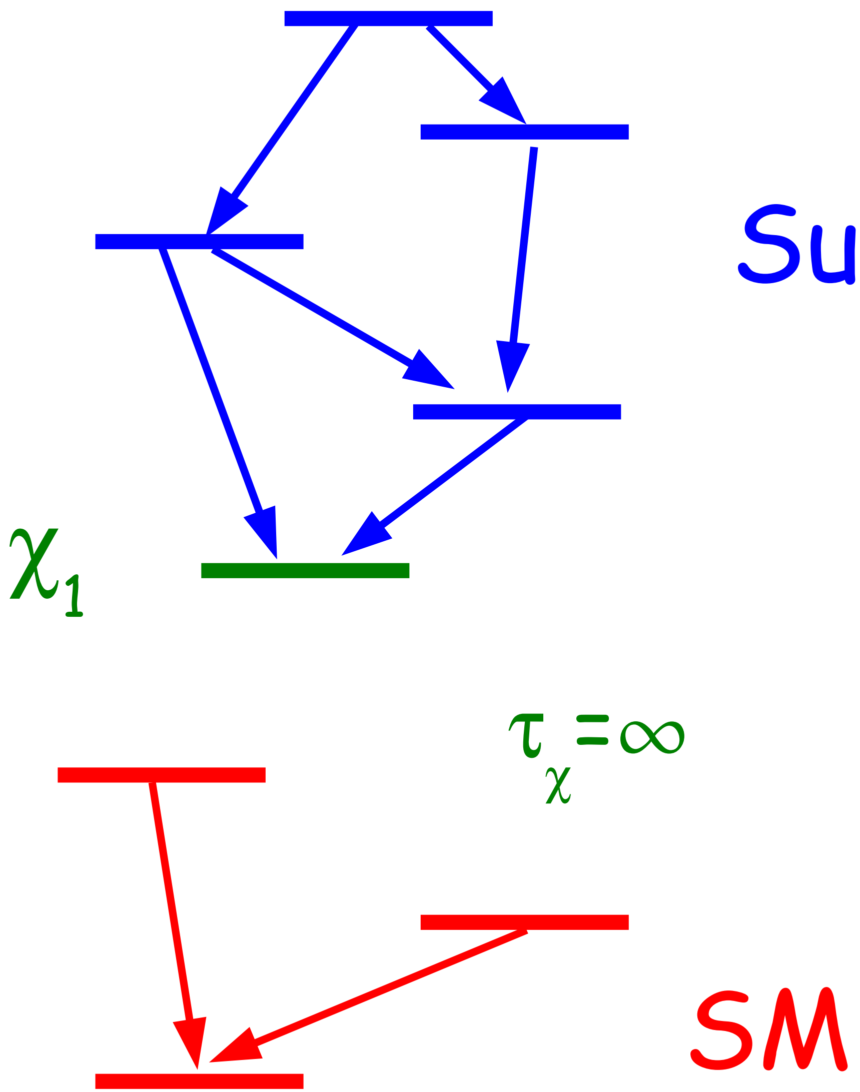


Requires a suppression of the coupling of at least 22 orders of magnitude!

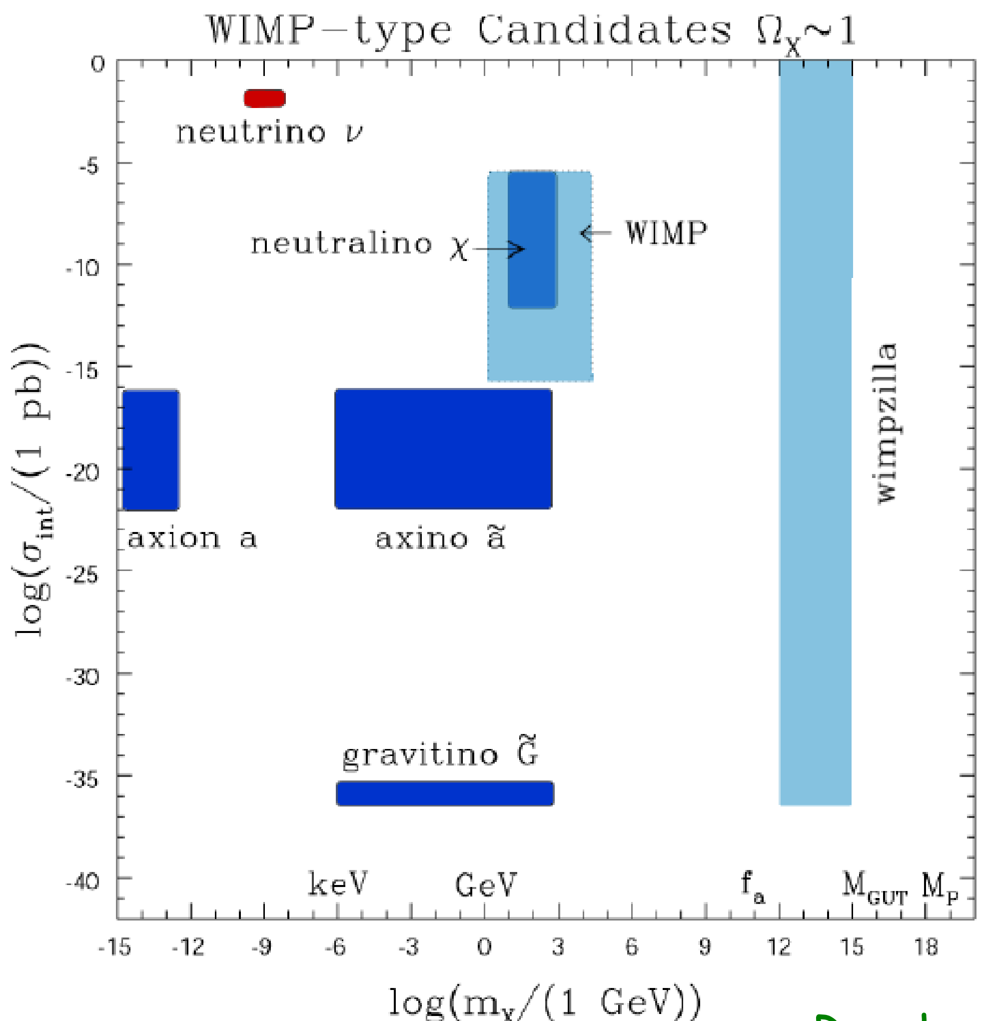
Sketch of a WIMP dark matter model:



Simplest solution: forbid the dangerous couplings altogether by imposing 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>



Roszkowski

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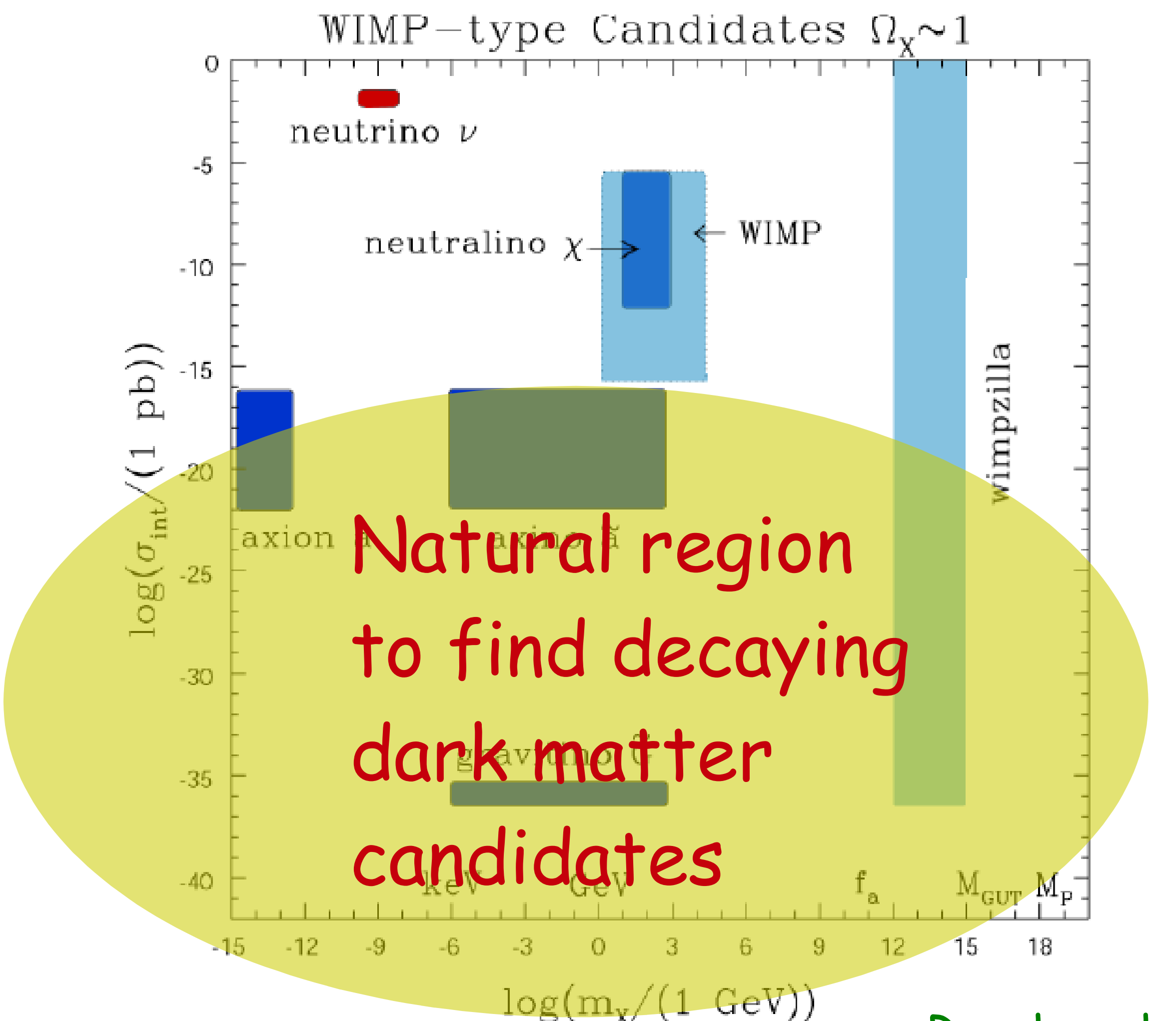
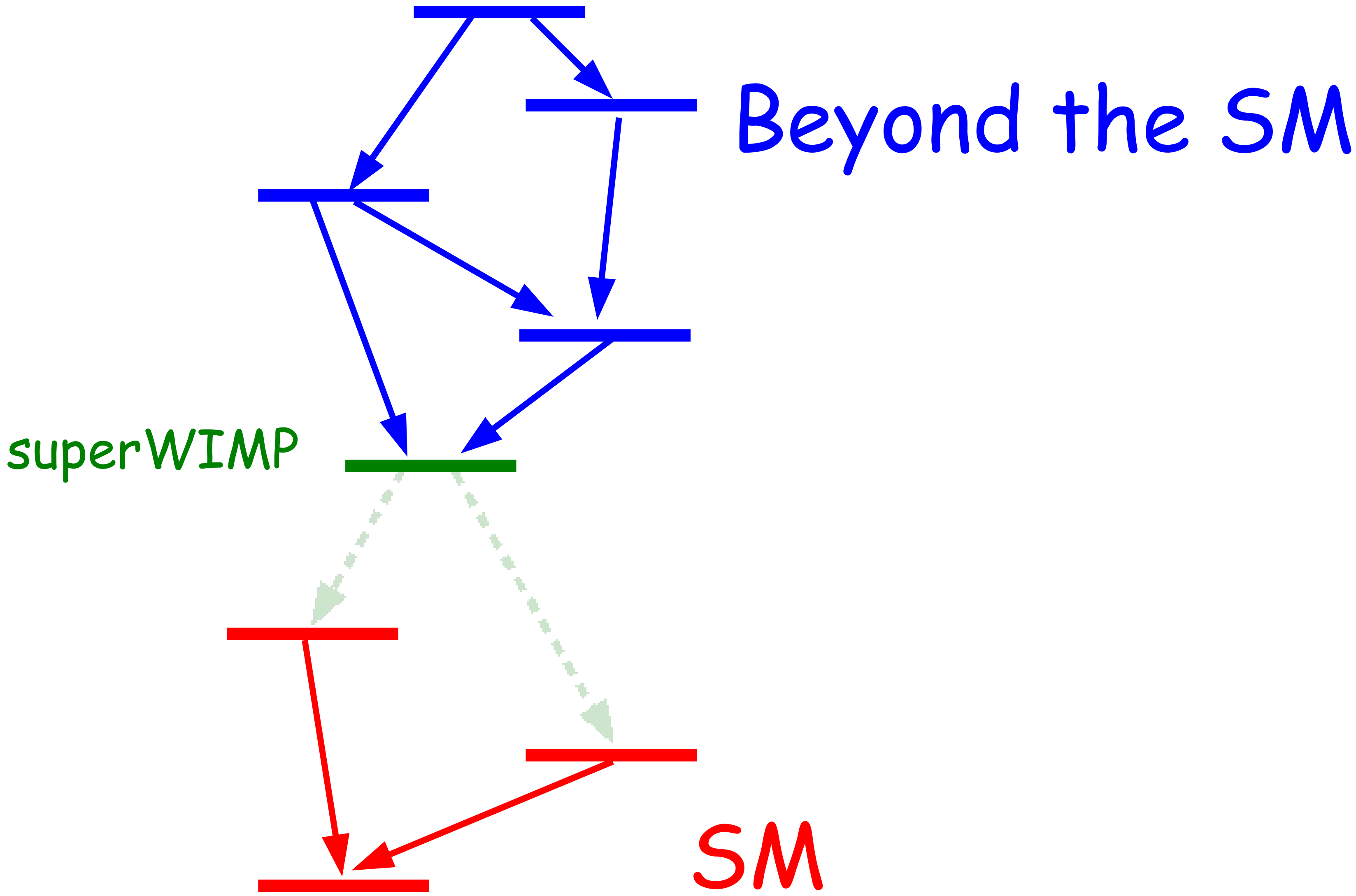
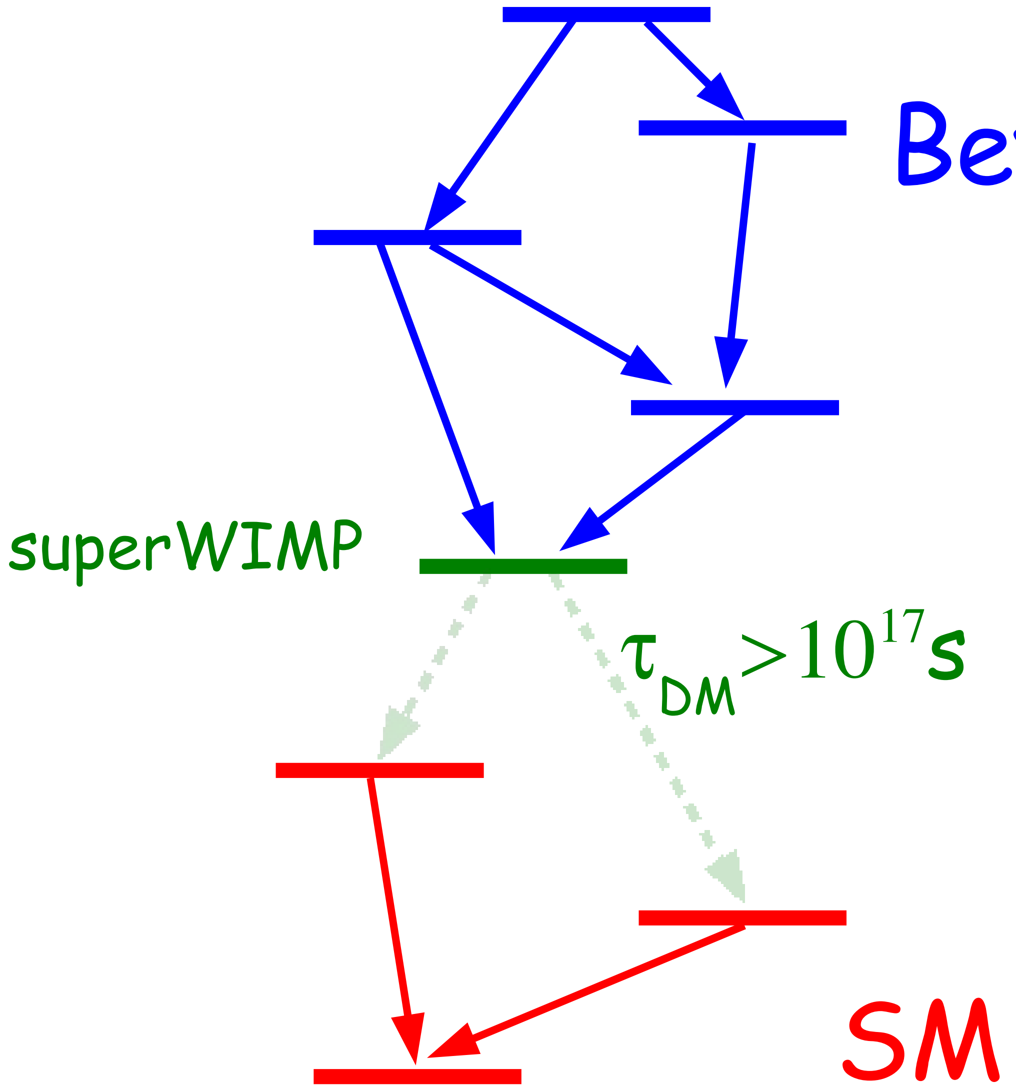


Roszkowski

Sketch of a superWIMP dark matter model:

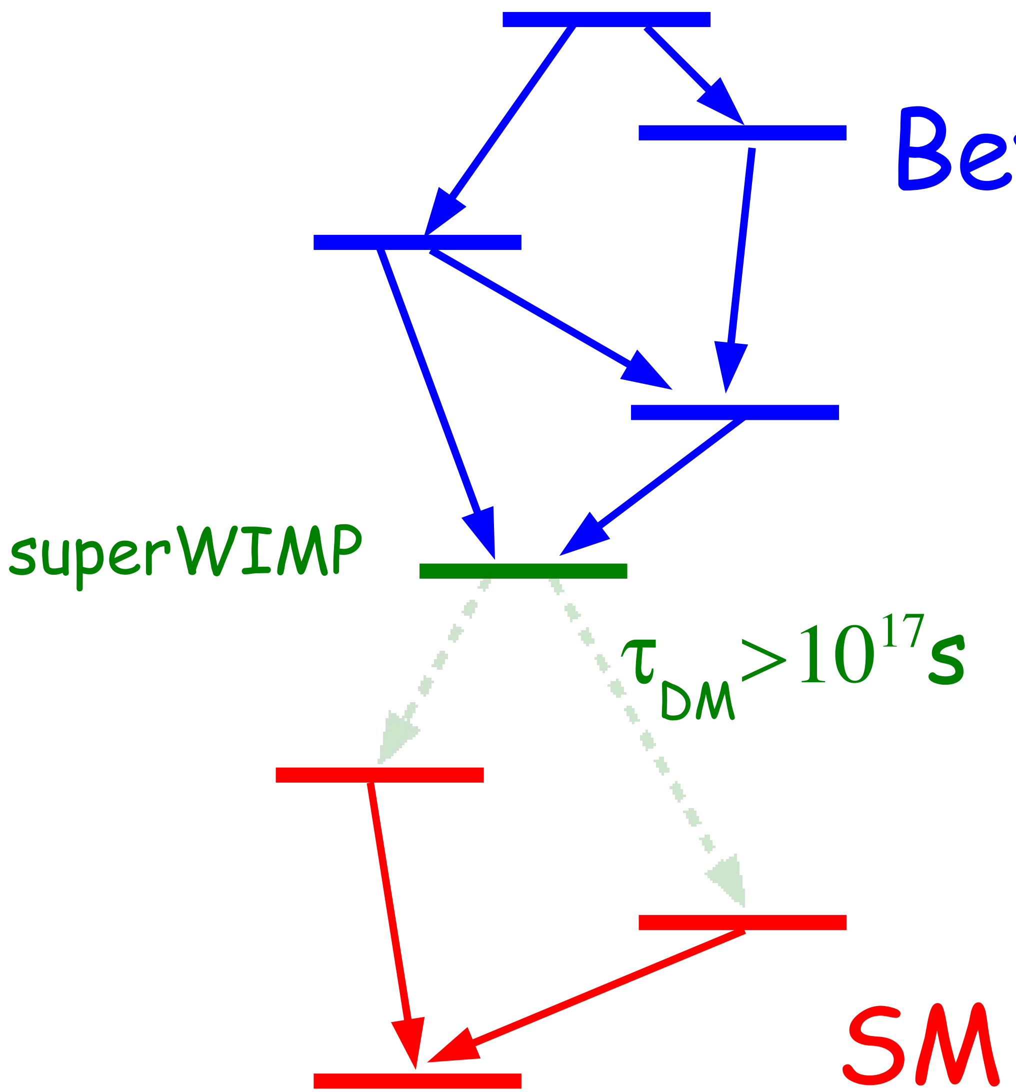


SuperWIMPs are naturally very long lived. Their lifetimes can be larger than the age of the Universe, or perhaps a few orders of magnitude smaller.



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

SuperWIMPs are <u>naturally very long lived</u>. 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 R-parity breaking vacua.

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

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

Poster by David Tran

- Hidden sector gauge bosons/gauginos.

Interactions suppressed by the small kinetic mixing between $U(1)_{hid}$ and $U(1)_{Y}$.

Chen, Takahashi, Yanagida; AI, Ringwald, Weniger; Chun, Park.

- Right-handed sneutrinos in scenarios with Dirac neutrino masses. Pospelov, Trott

Interactions suppressed by the tiny Yukawa couplings.

- Hidden sector fermions. Arvanitaki et al.; Hamaguchi, Shirai, Yanagida

Interactions suppressed by the GUT scale.

- Bound states of strongly interacting particles. Hamaguchi et al.; Nardi et al

Interactions suppressed by the GUT scale.

Positron fraction from decaying dark matter: model independent analysis

Possible decay channels

AI, Tran

fermionic DM

- $\psi \to Z^0 \nu$
- $\psi \to W^{\pm} \ell^{\mp}$
- $\psi \to \ell^+ \ell^- \nu$

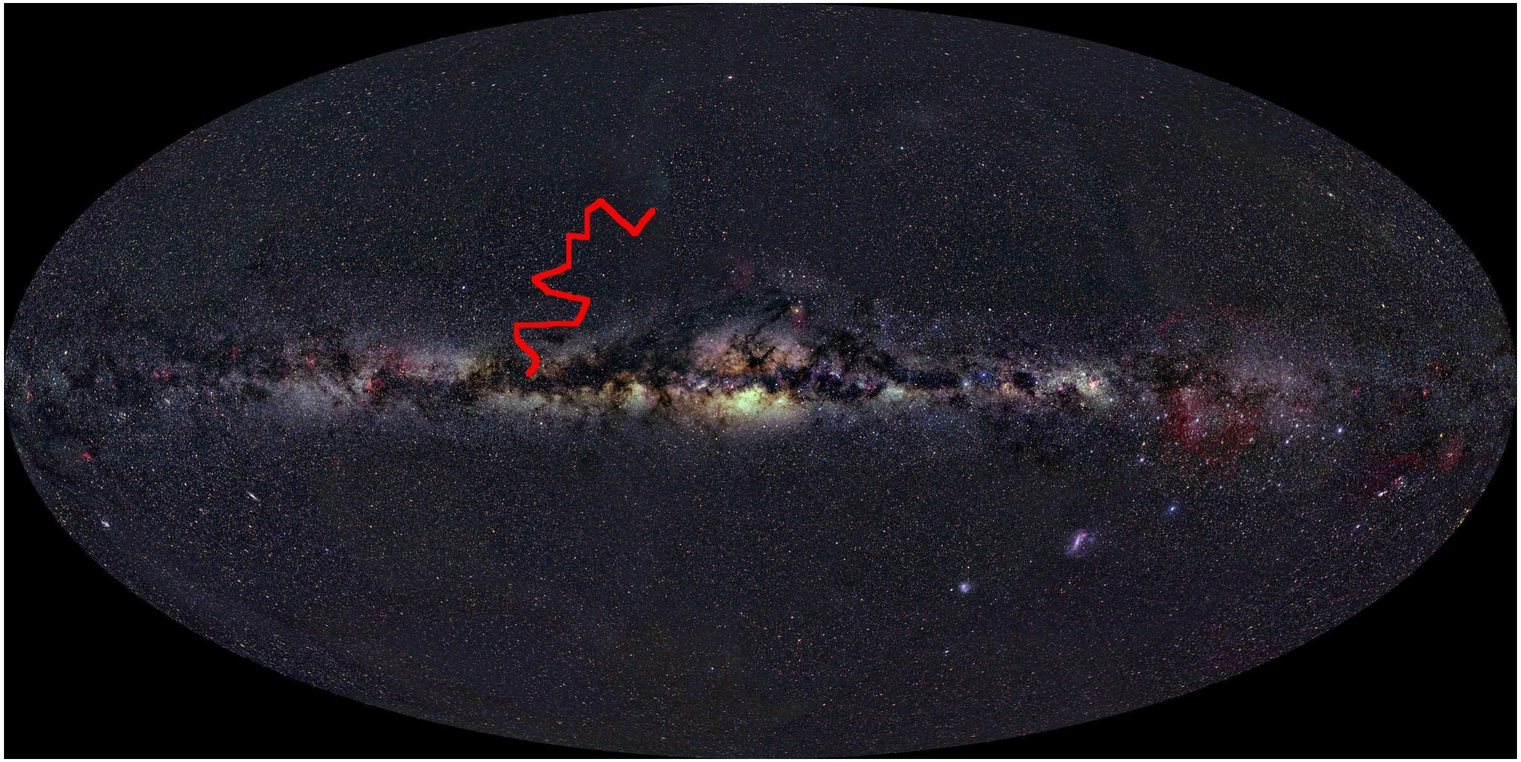
scalar DM

- $\phi \to Z^0 Z^0$
- $\phi \to W^+ W^-$
- $\phi \to \ell^+ \ell^-$

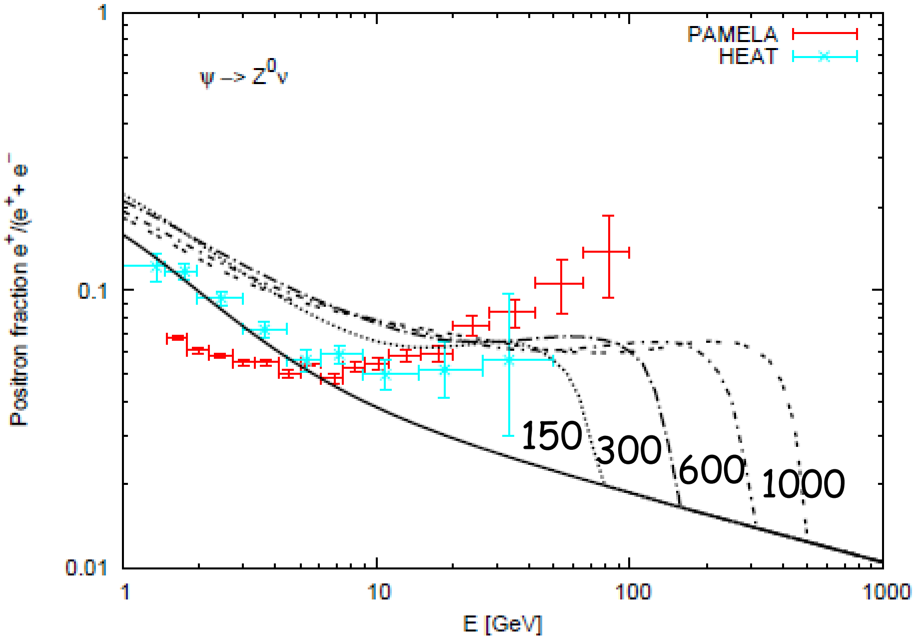
The injection spectrum of positrons depends just on two parameters: the dark matter mass and lifetime.

The positrons travel under the influence of the tangled magnetic field of the Galaxy and lose energy → complicated propagation equation

We follow the semi-analytical approach by Maurin *et al.*



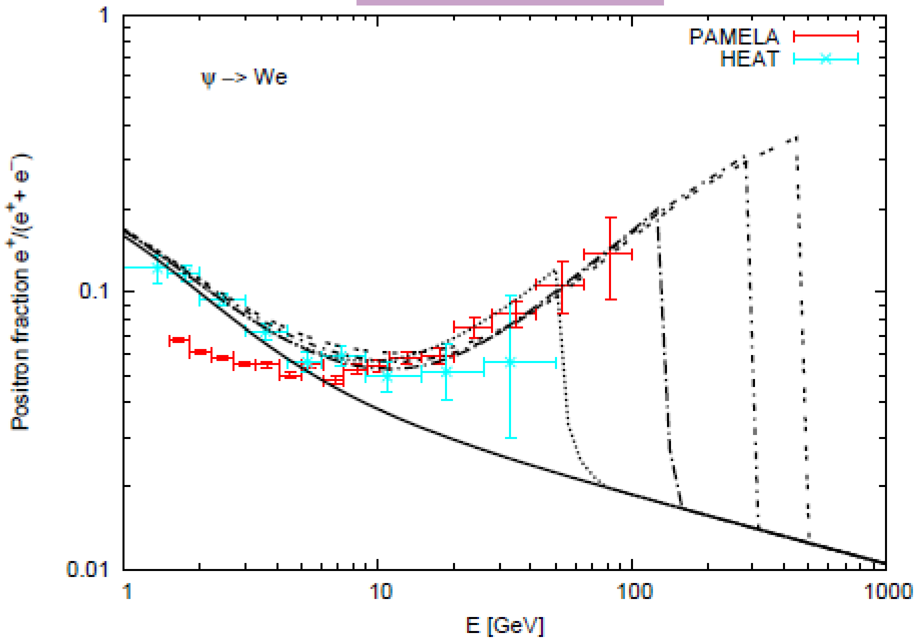
$\psi \rightarrow Z^0 \nu$



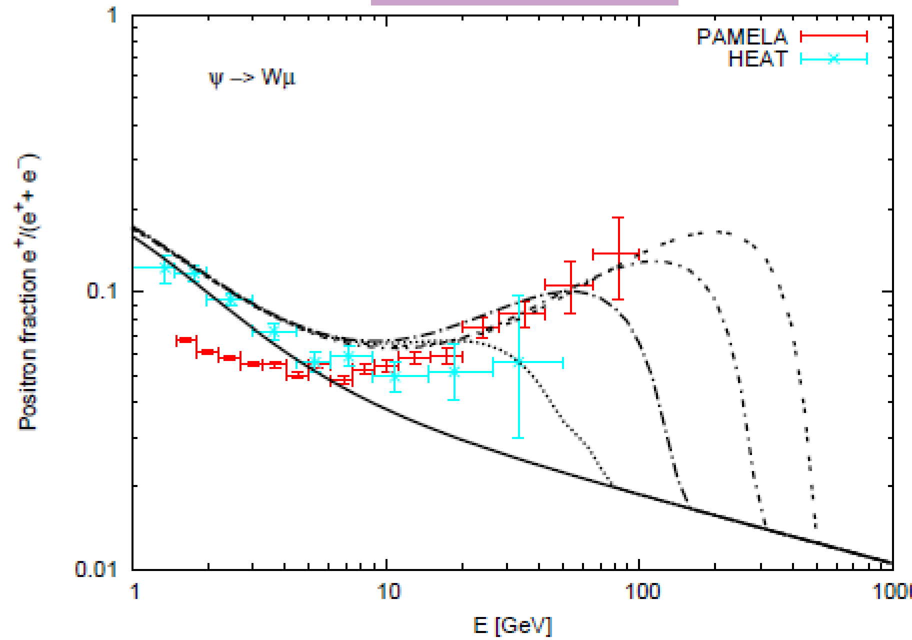
$\tau_{DM} \sim 10^{26}$s

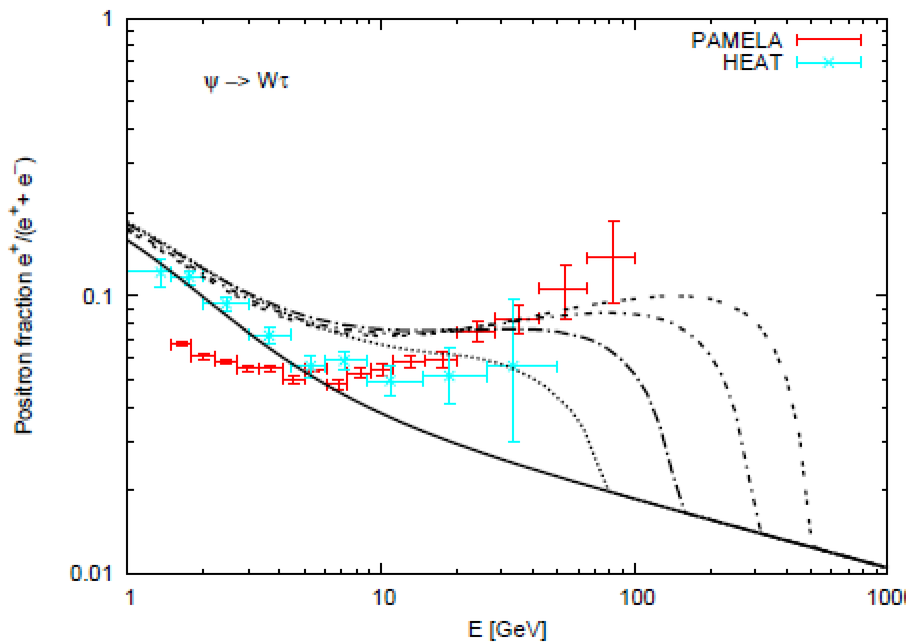
Positrons from gauge boson fragmentation produce a positron fraction which is too flat to explain the steep rise in the spectrum observed by PAMELA

$\psi \rightarrow W^{\pm} e^{\mp}$



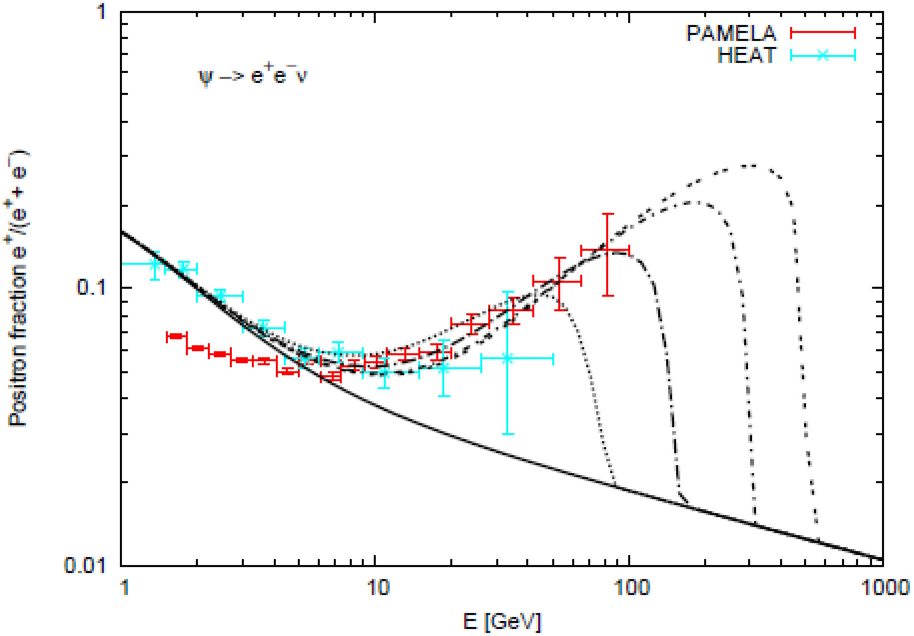
$\psi \rightarrow W^{\pm} \mu^{\mp}$



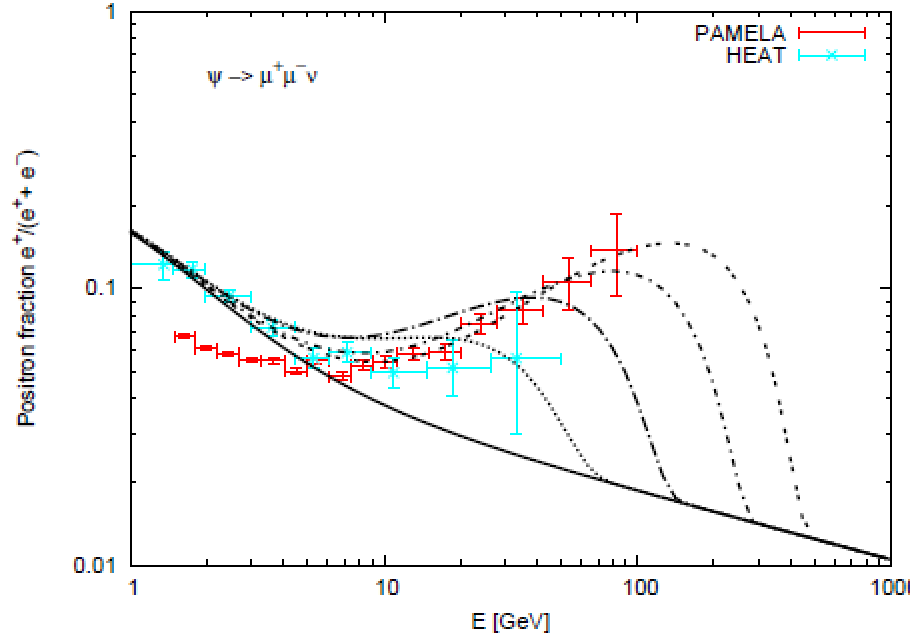


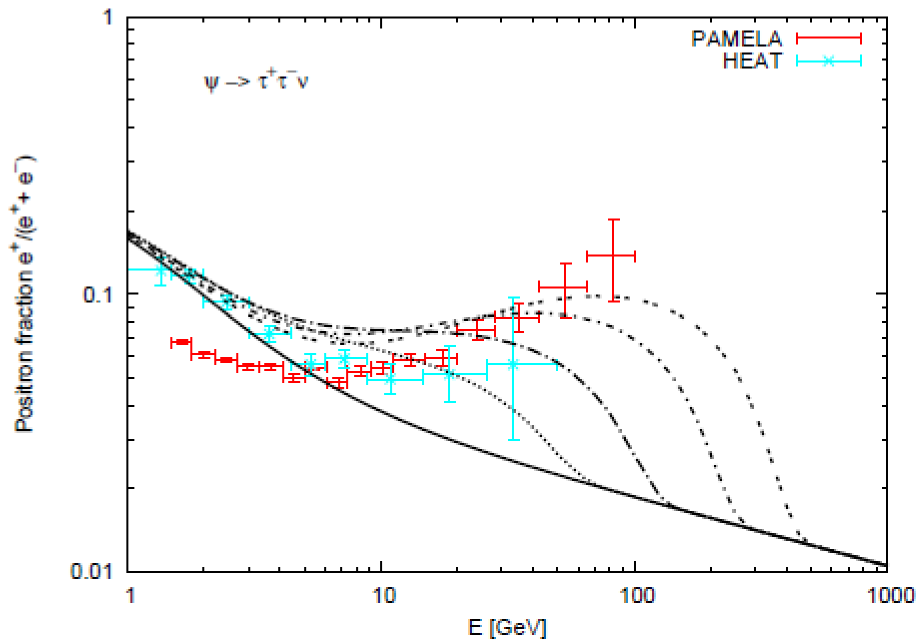
$\psi \rightarrow W^{\pm} \tau^{\mp}$

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



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





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

The PAMELA results on the positron fraction can be explained by the decay of a dark matter particle provided:

- **Has a mass larger than ~300 GeV,**
- **Has a lifetime around 10^{26} seconds,**
- **Decays preferentially into leptons of the first or second generation.**

10^{26} seconds??

Arvanitaki et al.
Nardi, Sannino, Strumia
Chen, Takahashi, Yanagida

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

$$\tau \sim 2 \times 10^{26}\,\mathrm{s} \left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^5 \left(\frac{M}{10^{16}\,\mathrm{GeV}}\right)^4$$

M is remarkably close to the Grand Unification Scale ($M_{\mathrm{GUT}}=2\times10^{16}$ GeV).

Indirect dark matter searches are starting to probe the Grand Unification Scale!

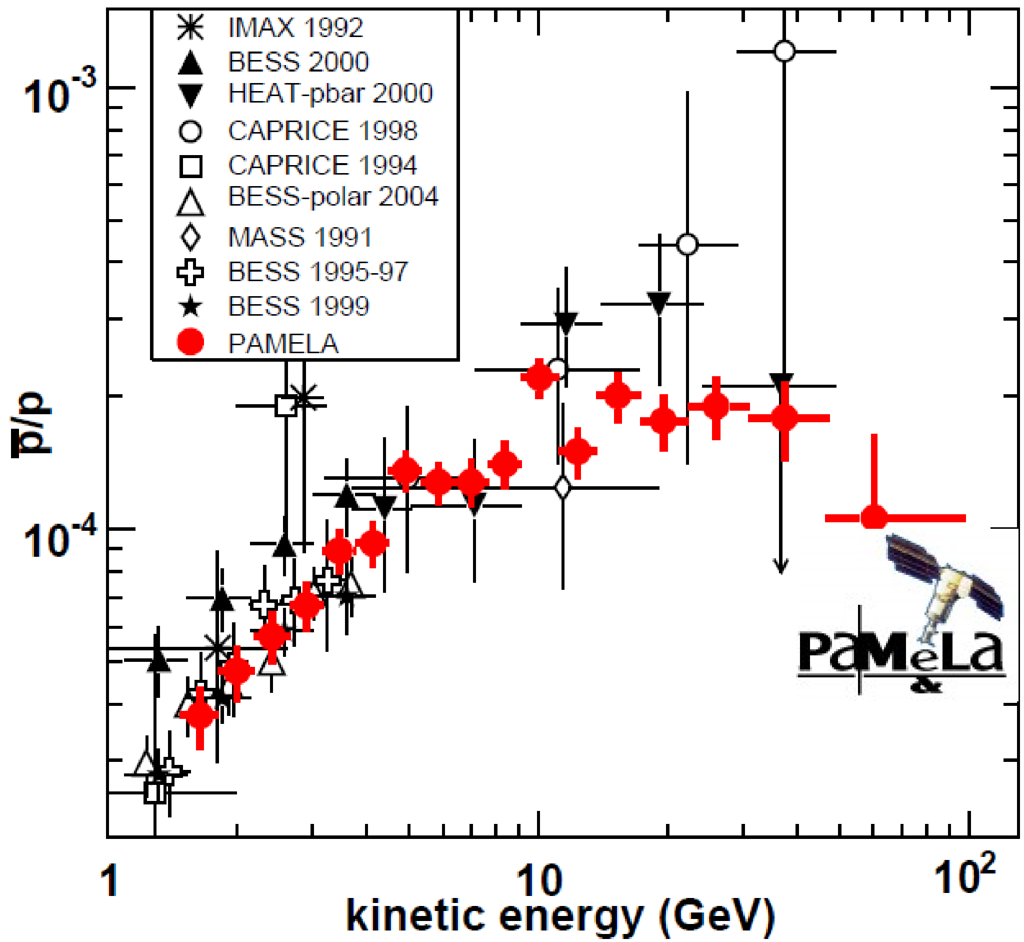
The decay of dark matter also predicts a flux of

- Antiprotons
- Gamma rays
- Neutrinos
- Antideuterons

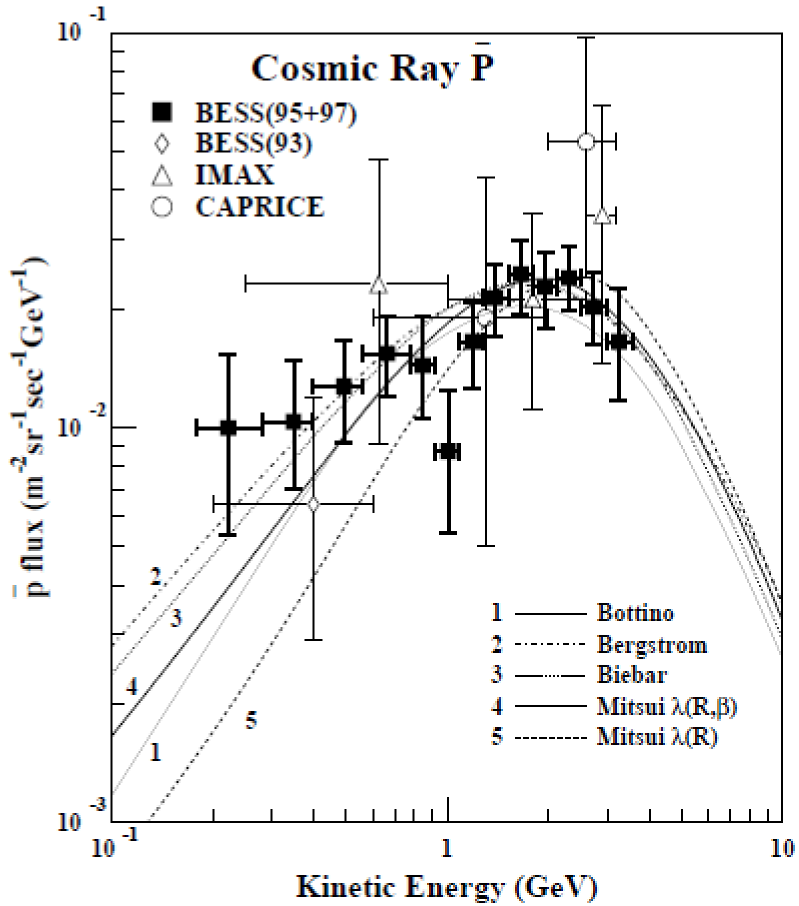
Additional constraints to the scenario!

Antiproton flux

Antiproton to proton ratio



Expectations from spallation



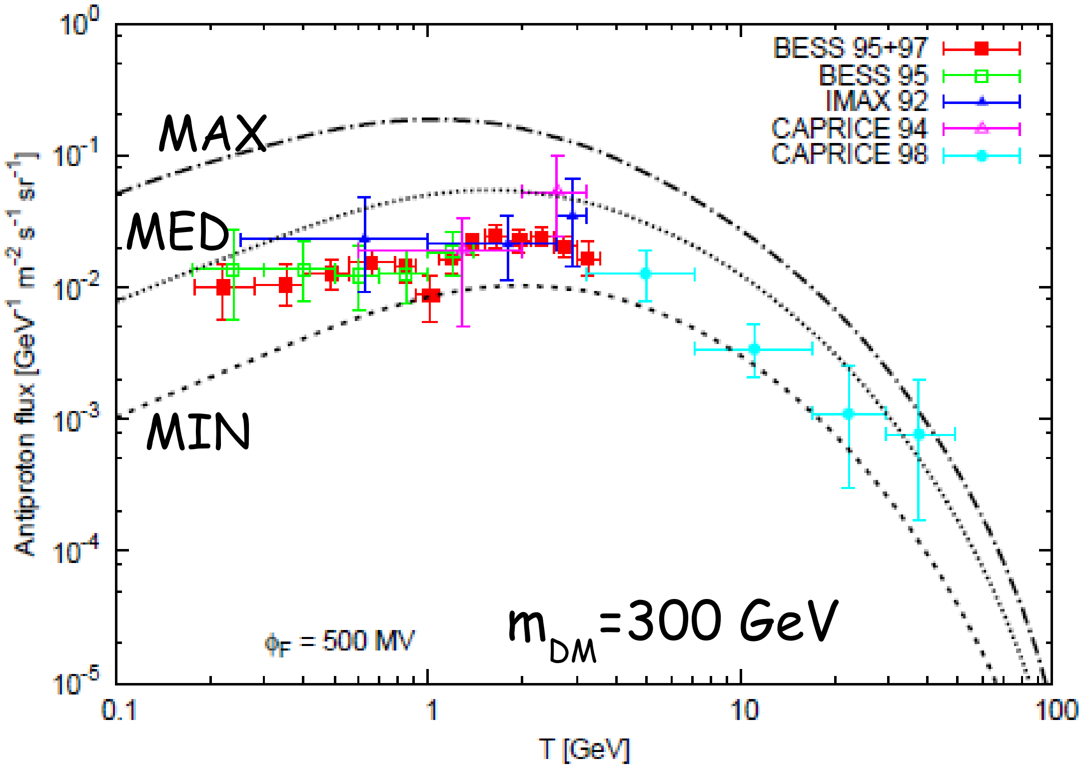
Good agreement of the theory with the experiments: no need for a sizable contribution to the primary antiproton flux.

Purely leptonic decays (*e.g.* $\psi \rightarrow e^+e^-\nu$) are favoured over decays into weak gauge bosons, but are not the only possibility.

Antiproton flux from dark matter decay

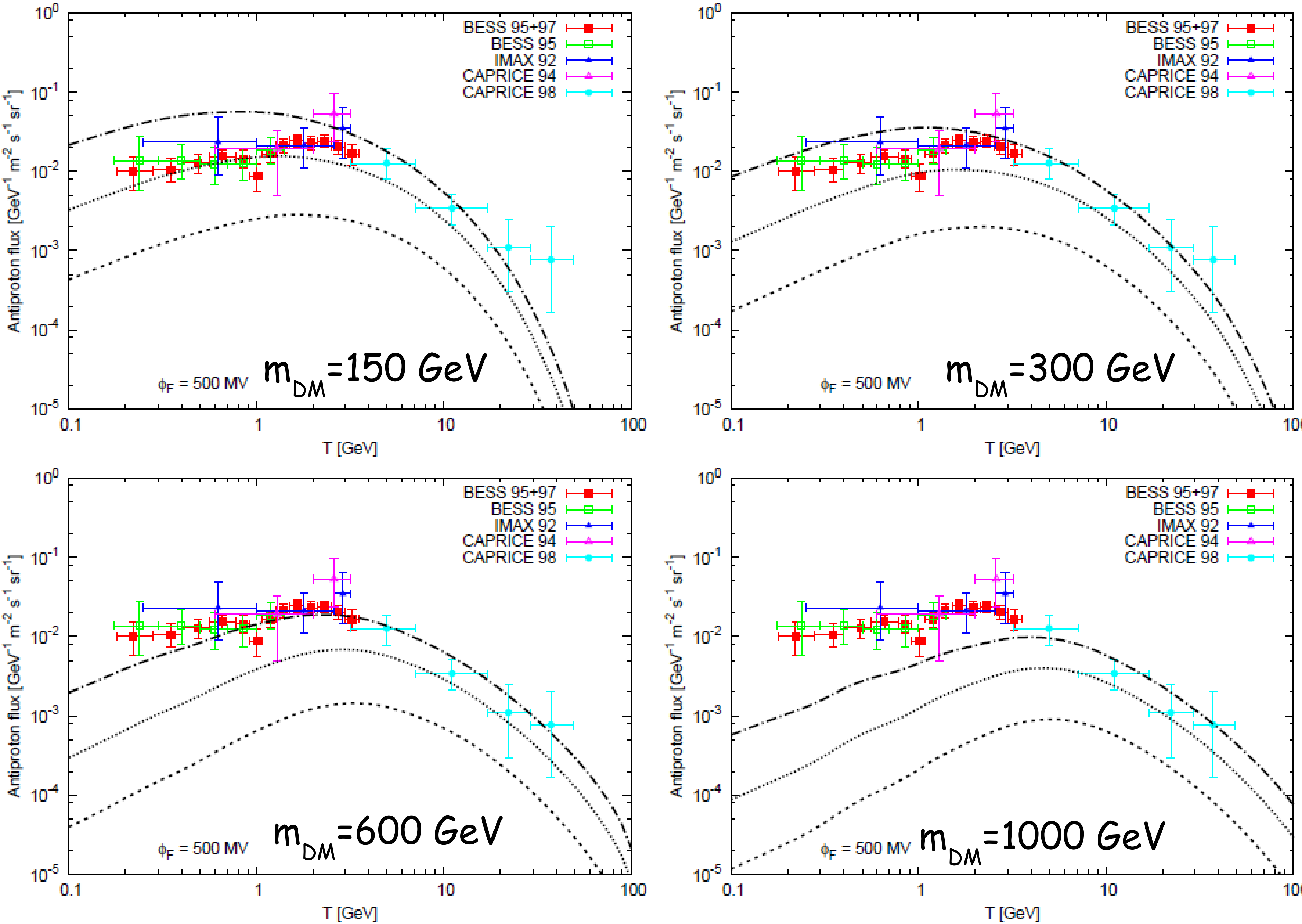
Propagation mechanism more complicated than for the positrons.
We neglect in our analysis reacceleration and tertiary contributions

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



$$\psi \to Z^0 \nu$$

$\psi \rightarrow W^{\pm} e^{\mp}$



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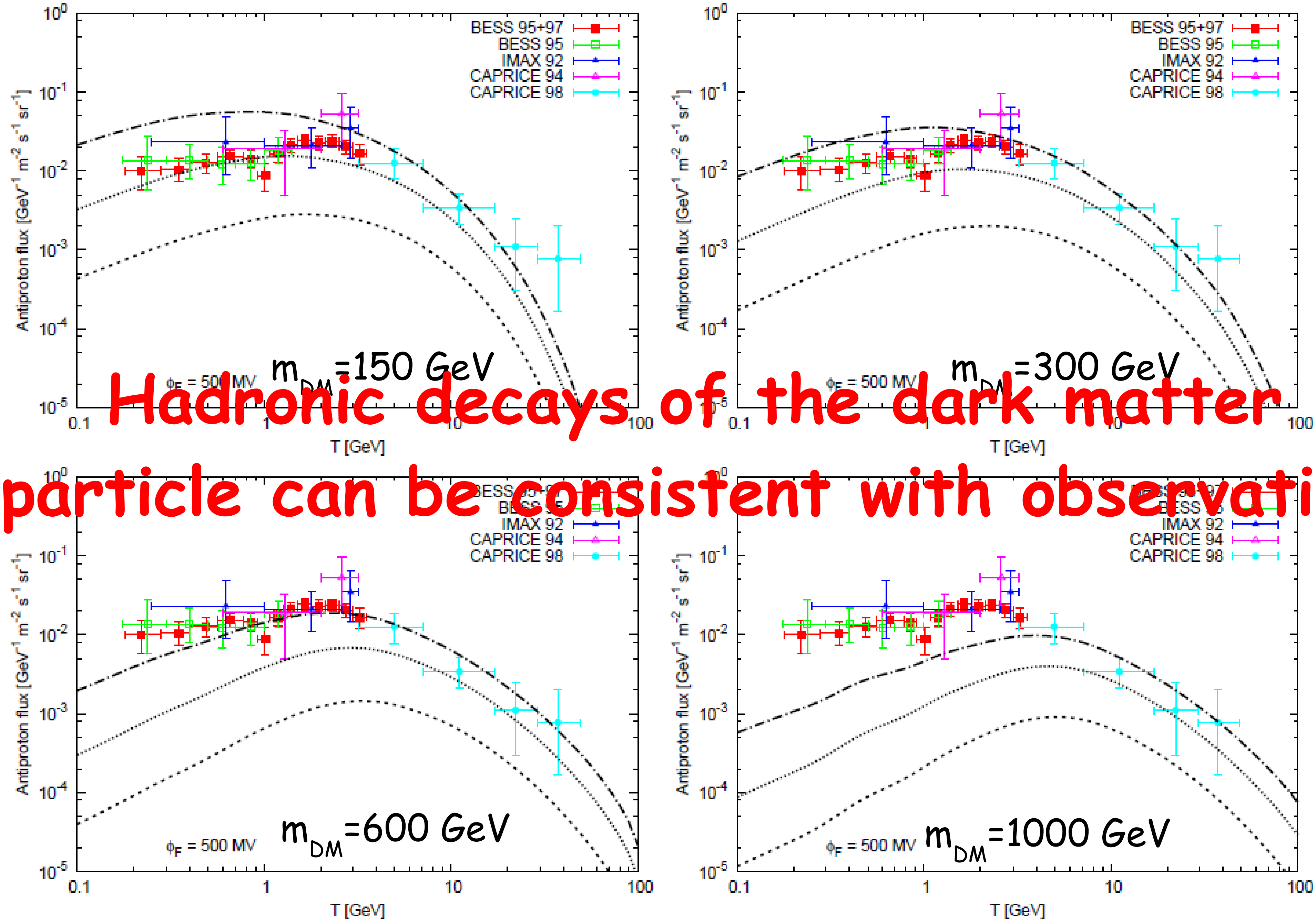
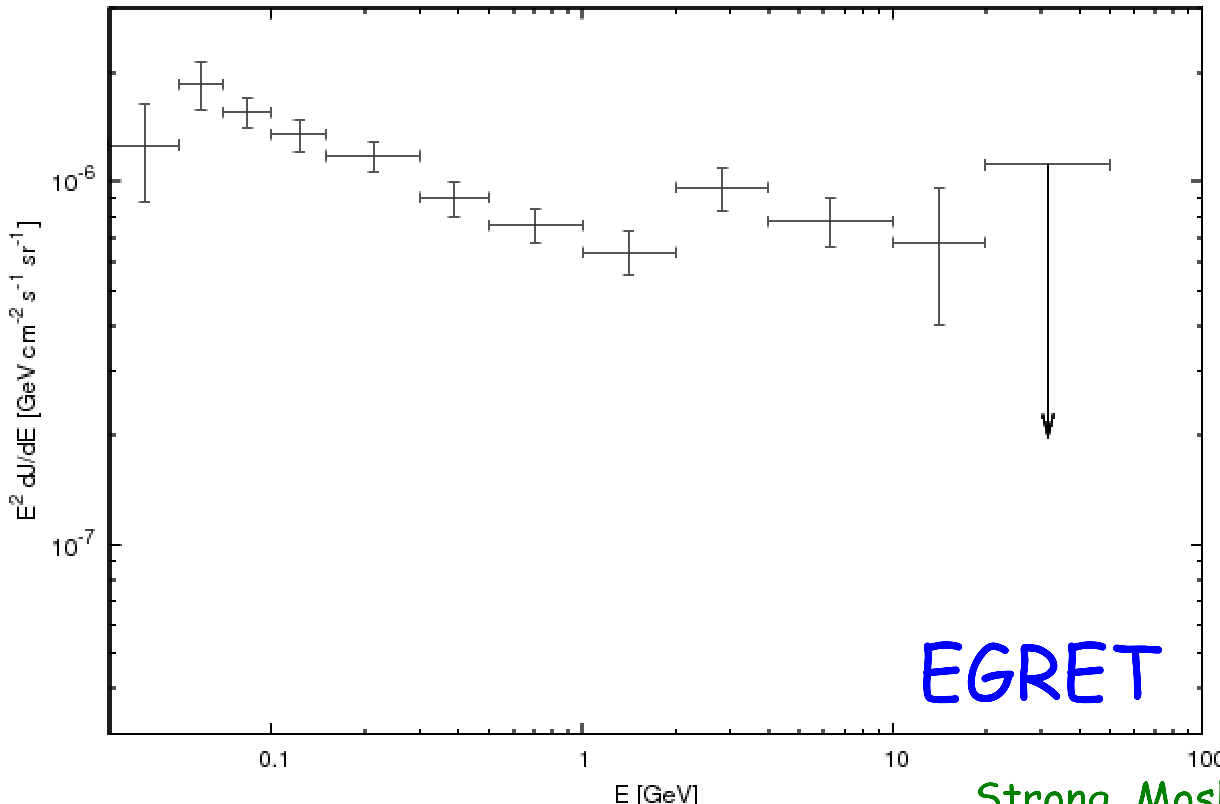


Hadronic decays of the dark matter particle can be consistent with observations

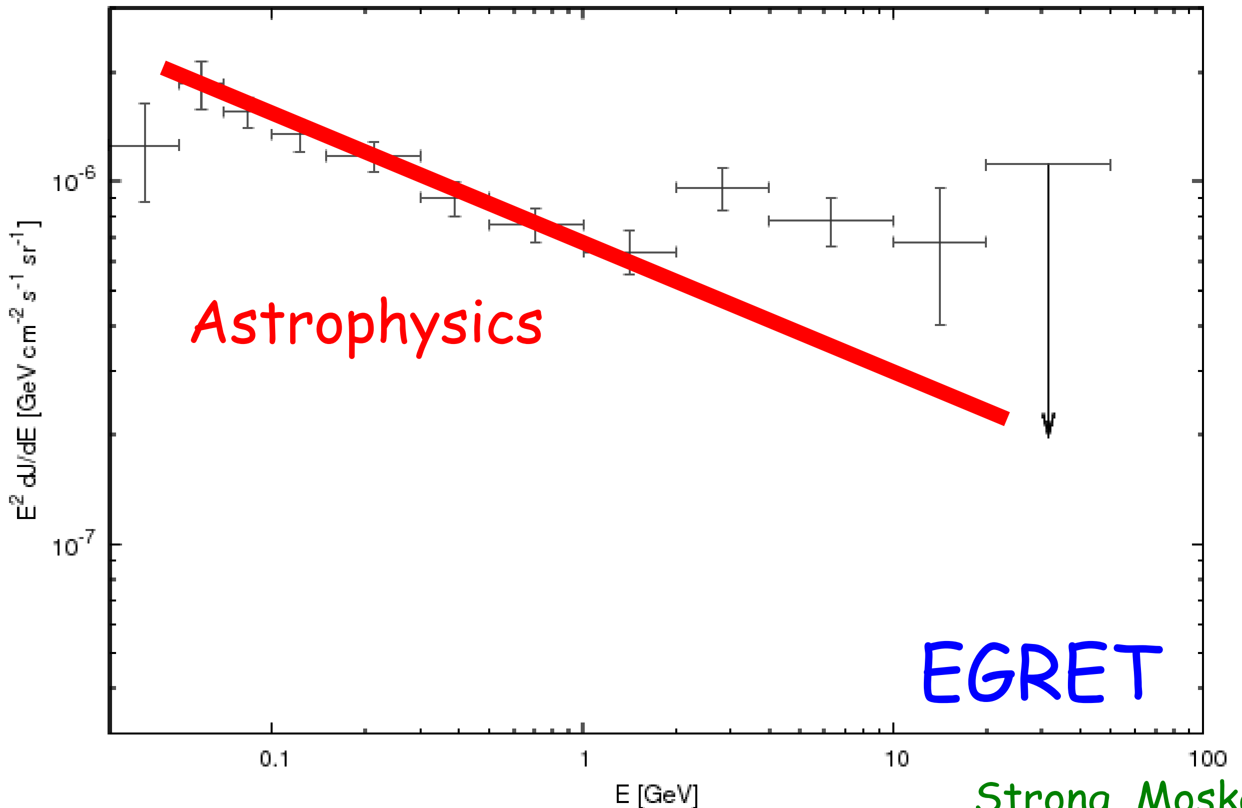
Diffuse gamma ray flux from EGRET



Strong, Moskalenko, Reimer '04

Constraint on the contribution from dark matter decay to the total gamma-ray flux.

Diffuse gamma ray flux from EGRET



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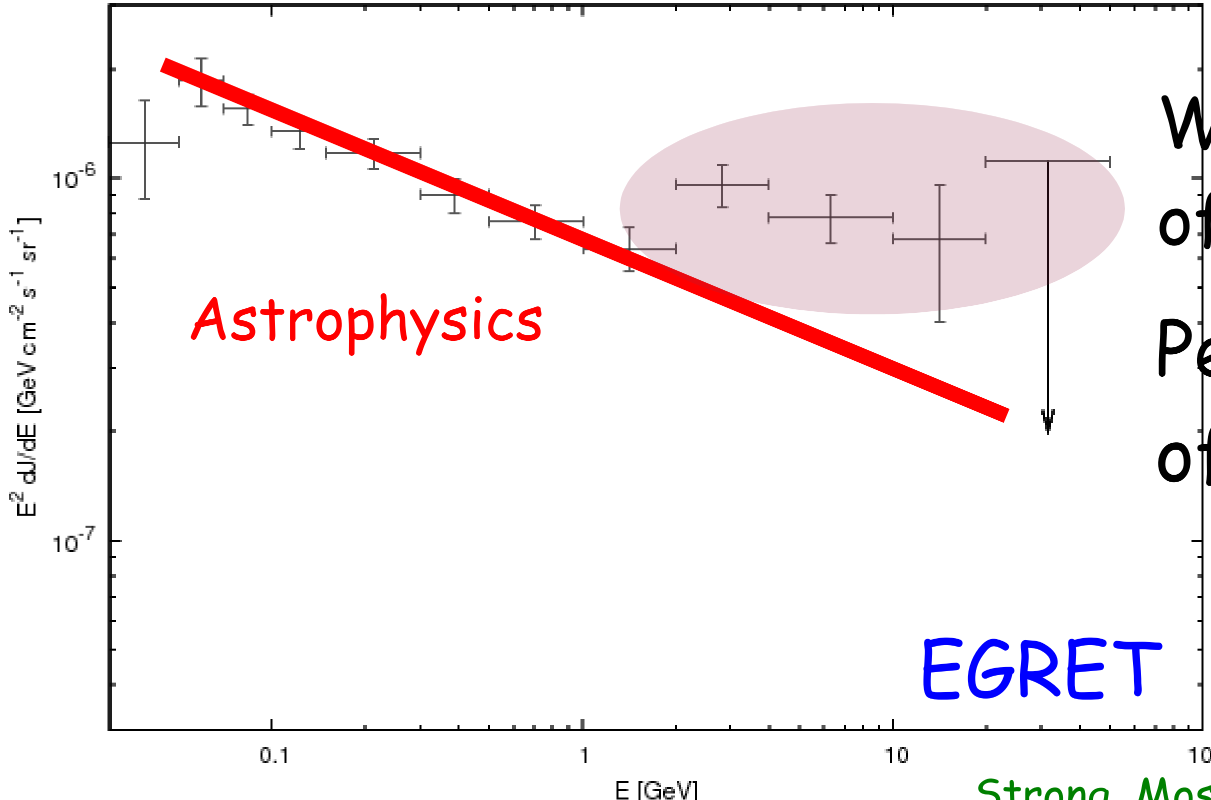

What is the origin of this bump?

Perhaps a hint of new physics?

Strong, Moskalenko, Reimer '04

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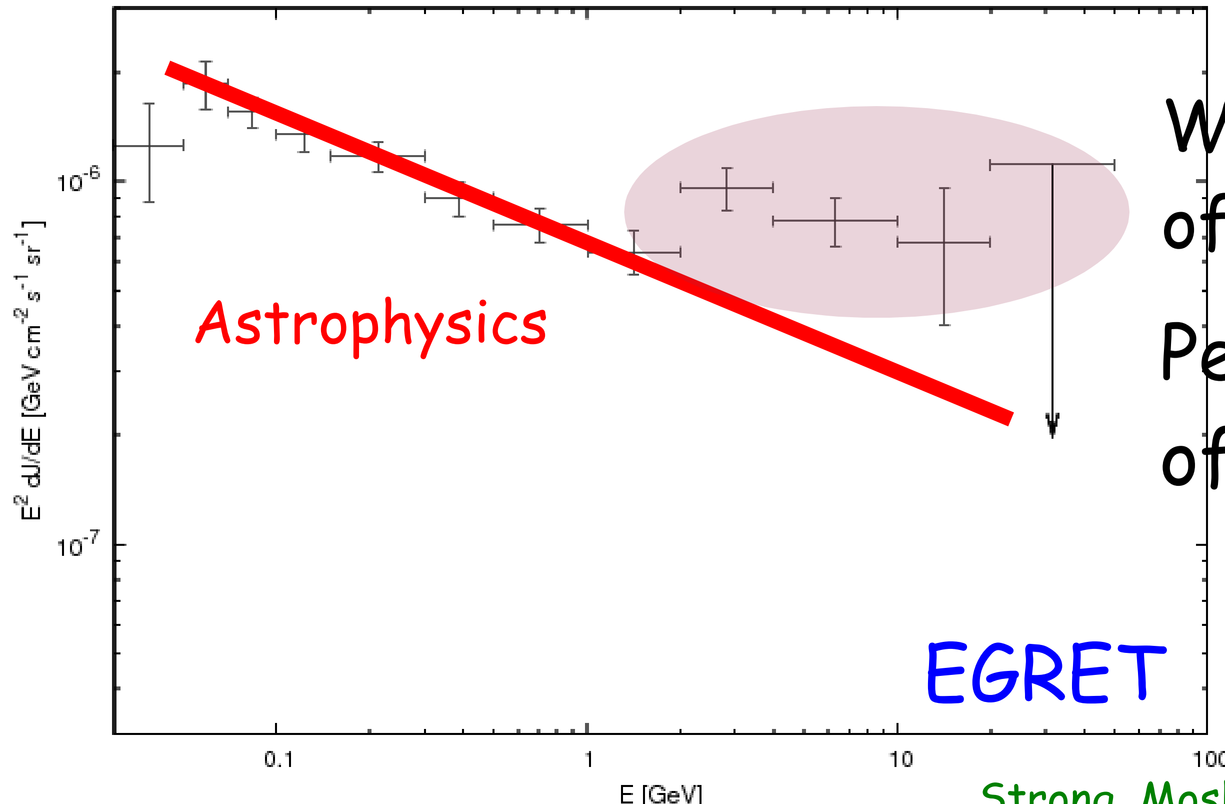

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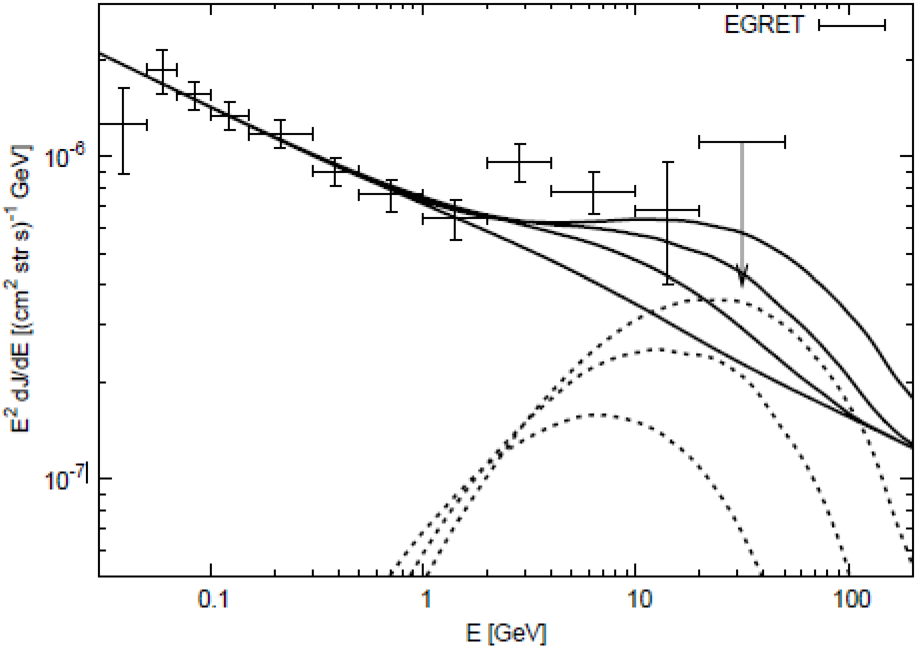
Strong, Moskalenko, Reimer '04

Many open questions:

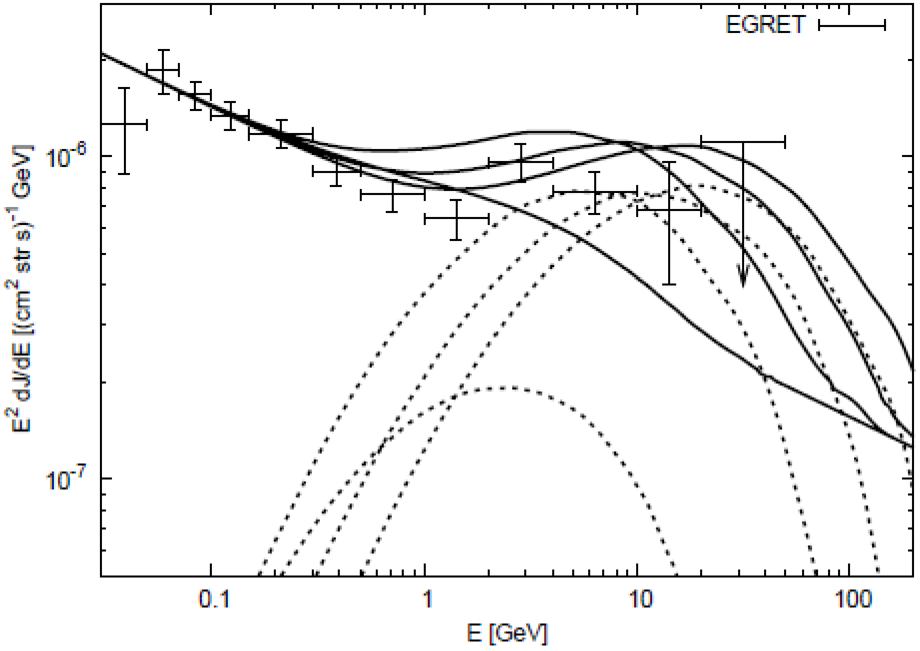
- Extraction of the signal from the galactic foreground
- Is the signal isotropic/anisotropic
- Precise shape of the energy spectrum
- Does the excess really exist?

Predictions from dark matter decay, for the masses and lifetimes suggested by PAMELA

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



$\psi \to Z^0 \nu$



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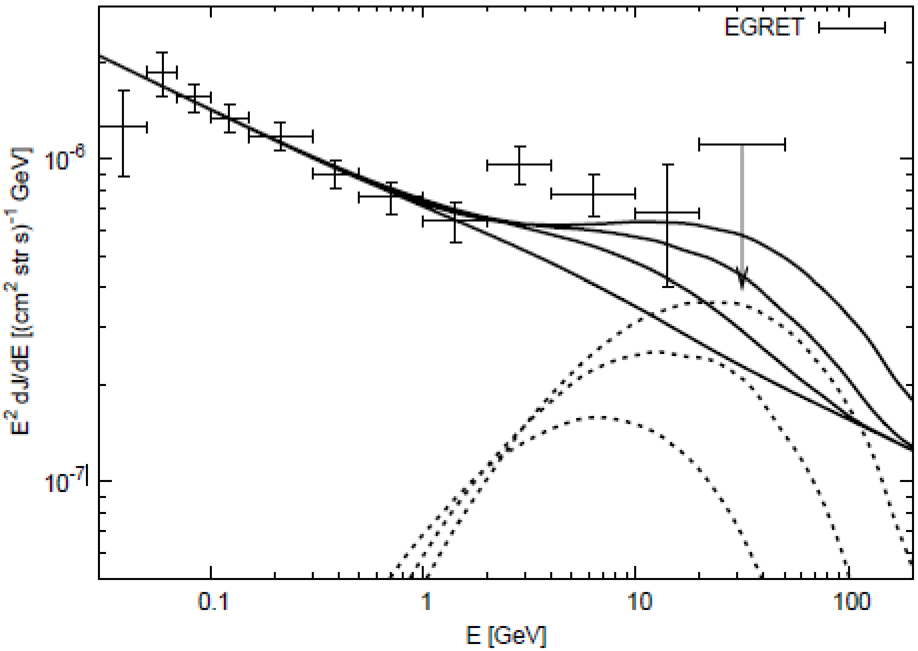

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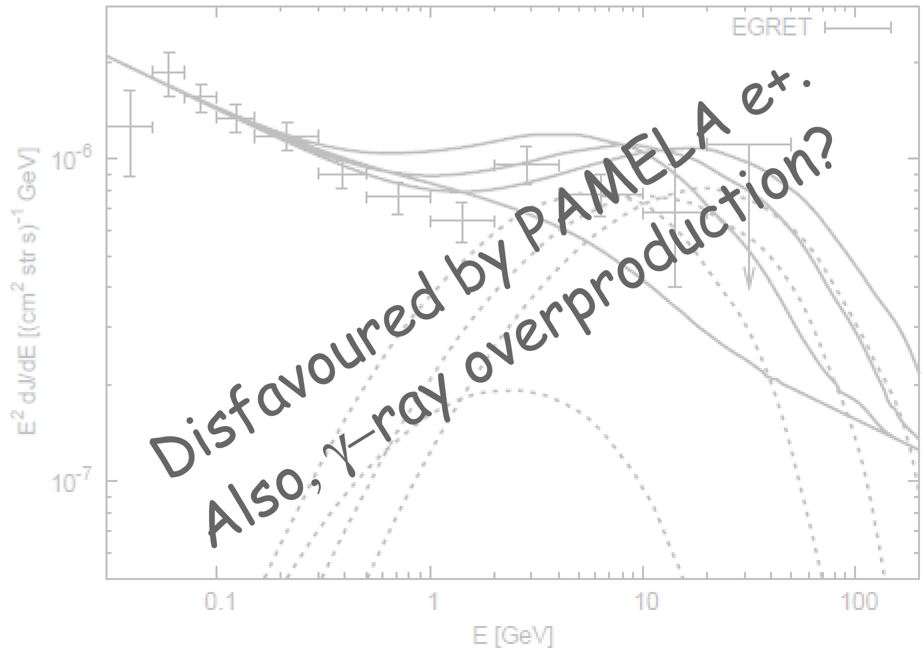
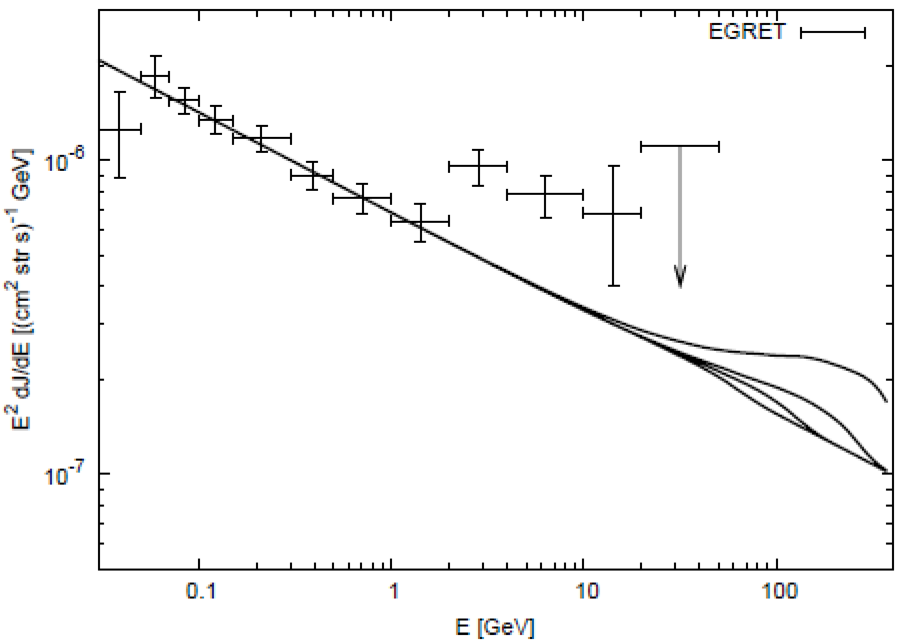
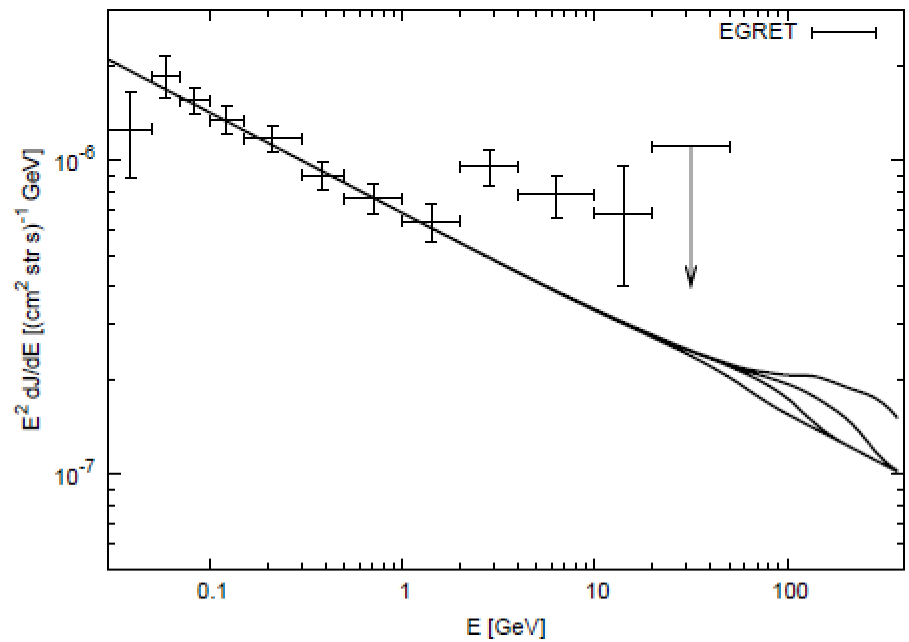
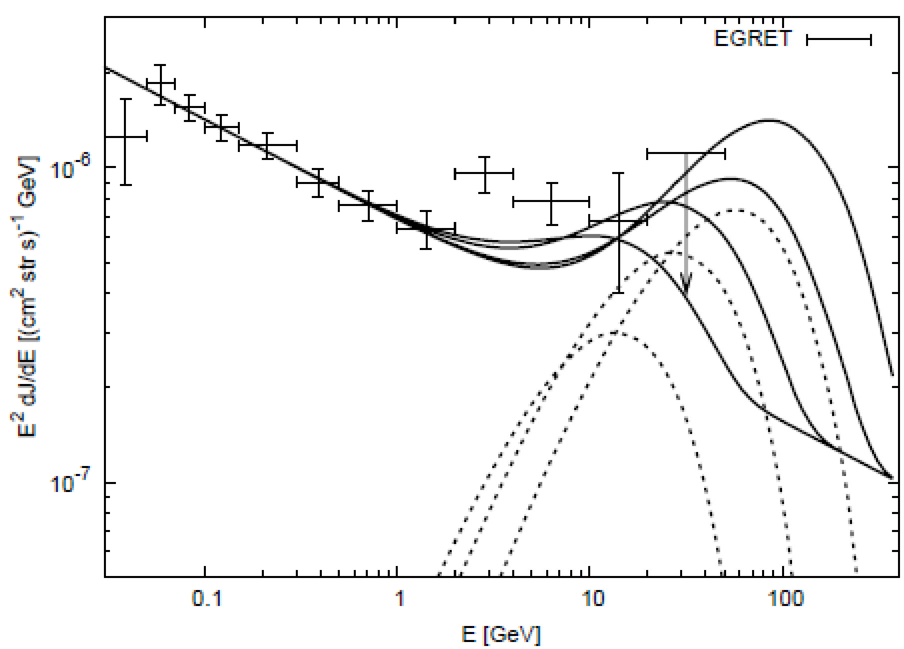


$\psi \rightarrow e^+ e^- \nu$



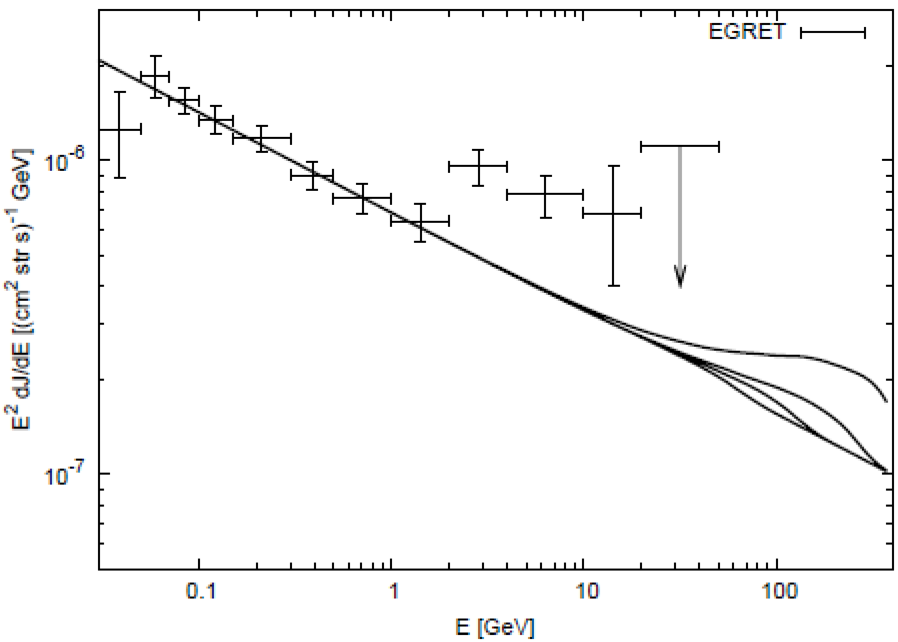
$\psi \rightarrow \mu^+ \mu^- \nu$



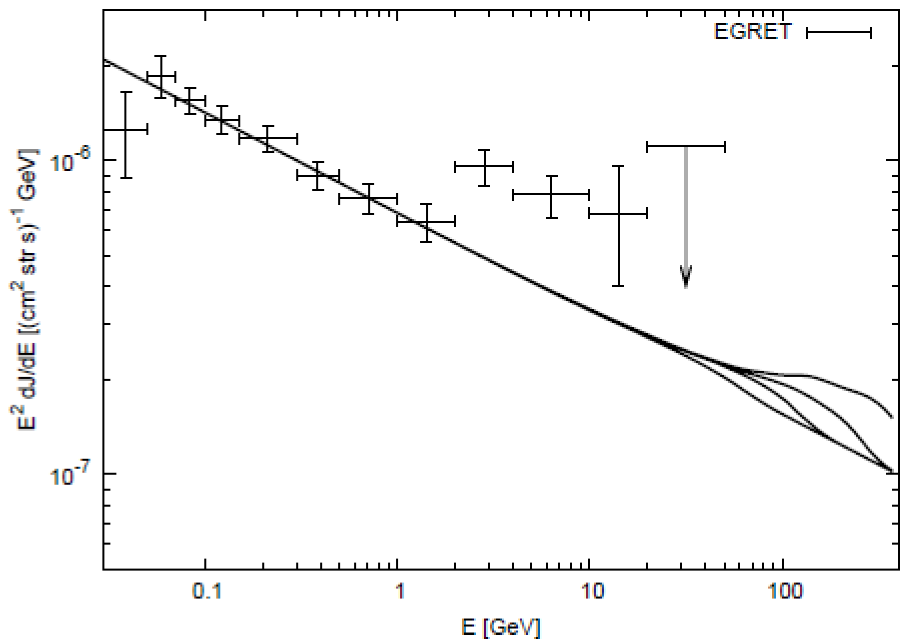


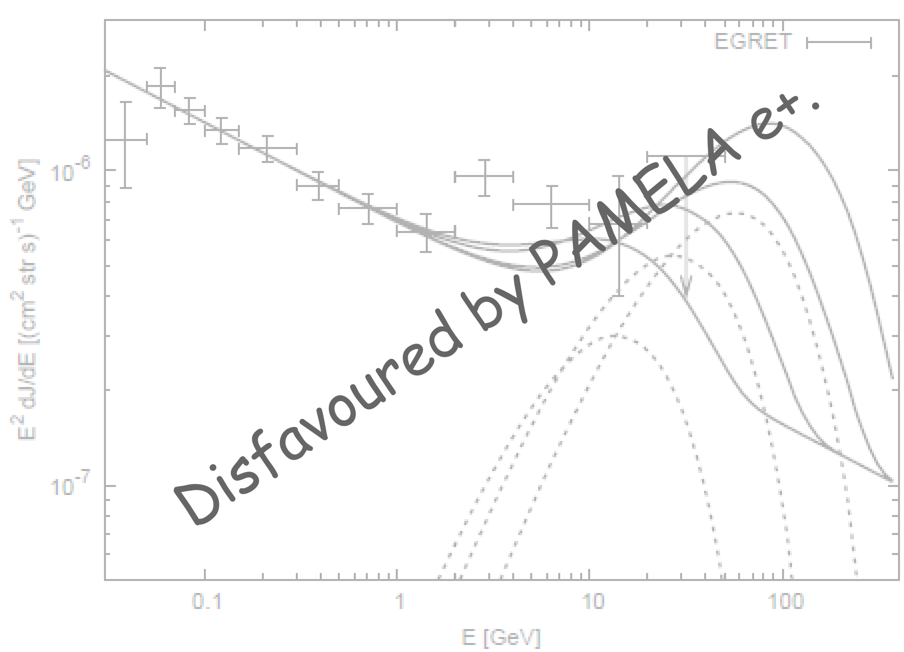
$\psi \rightarrow \tau^+ \tau^- \nu$

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



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



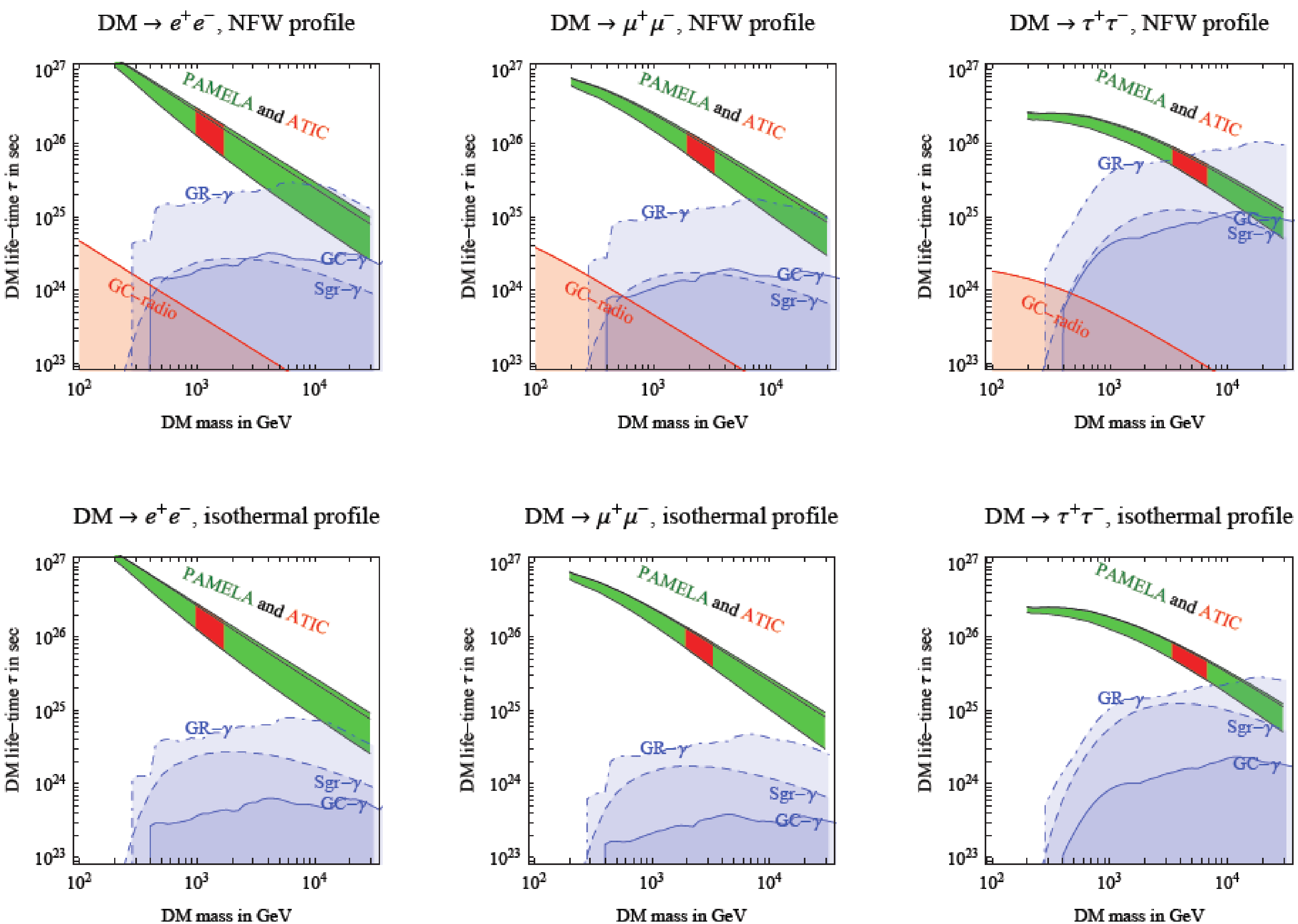


$\psi \to \tau^+ \tau^- \nu$

Summary of fermionic dark matter decays: from PAMELA to Fermi LAT

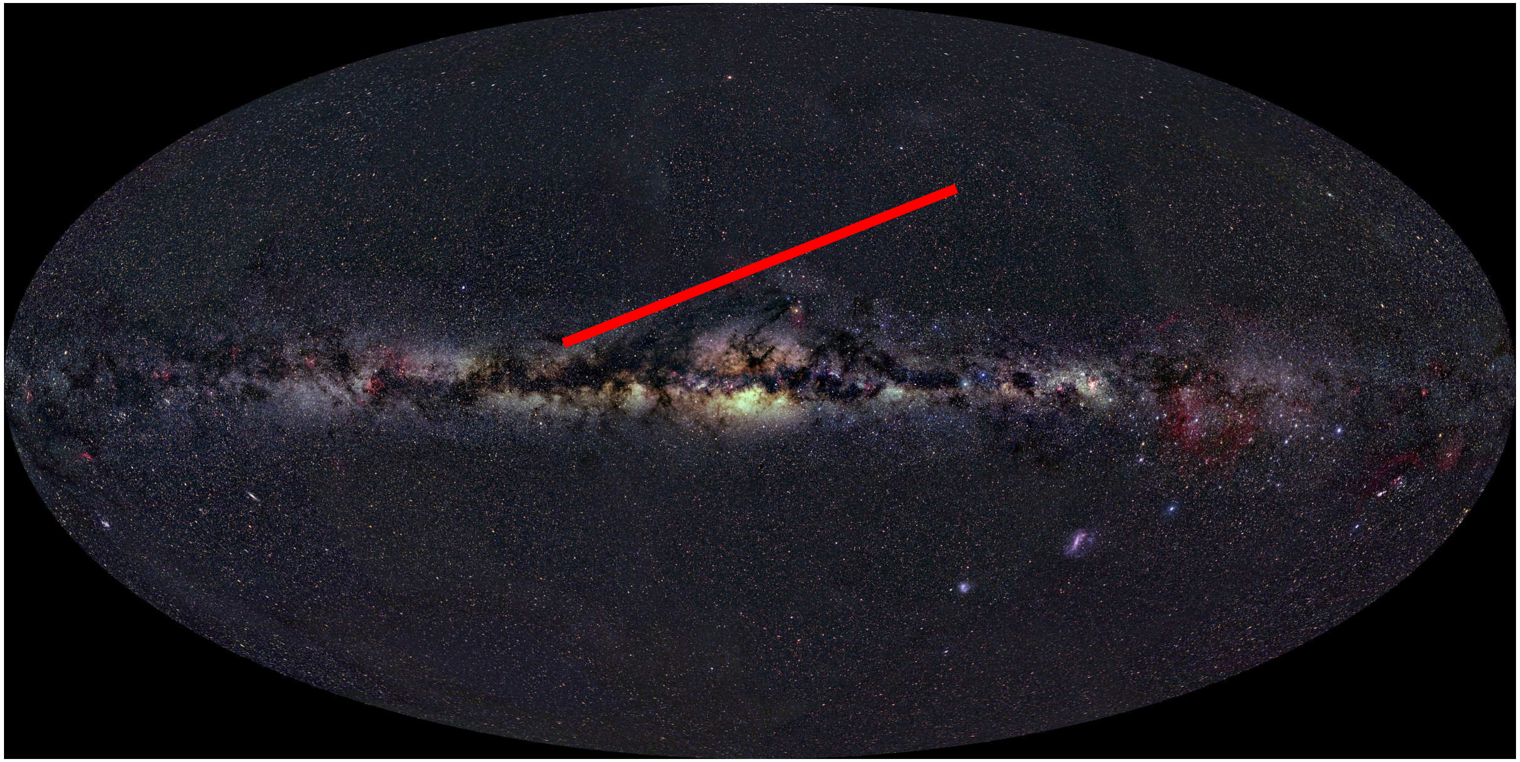
$\Psi \to Z^0 \nu$	Not promising. Positron spectrum too flat. Overproduction of gamma rays.
$\Psi \to W^{\pm} \ell^{\mp}$	Promising if ℓ=e, μ, and the DM mass is larger than ~300GeV. A sizable bump in the diffuse γ ray spectrum is predicted.
$\Psi \to \ell^+ \ell^- \nu$	Promising if ℓ=e, μ, and the DM mass is larger than 300GeV. No sizable bump is predicted.

Other gamma ray constraints: Nardi, Sannino, Strumia



Future observations in gamma rays will provide crucial tests to the scenario of decaying dark matter.

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



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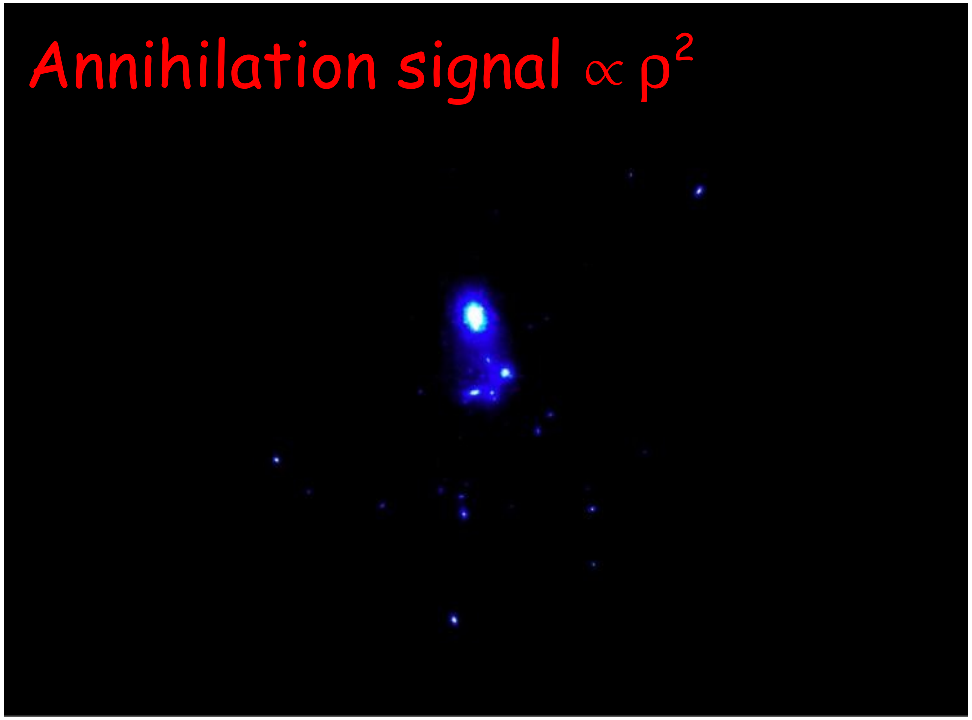
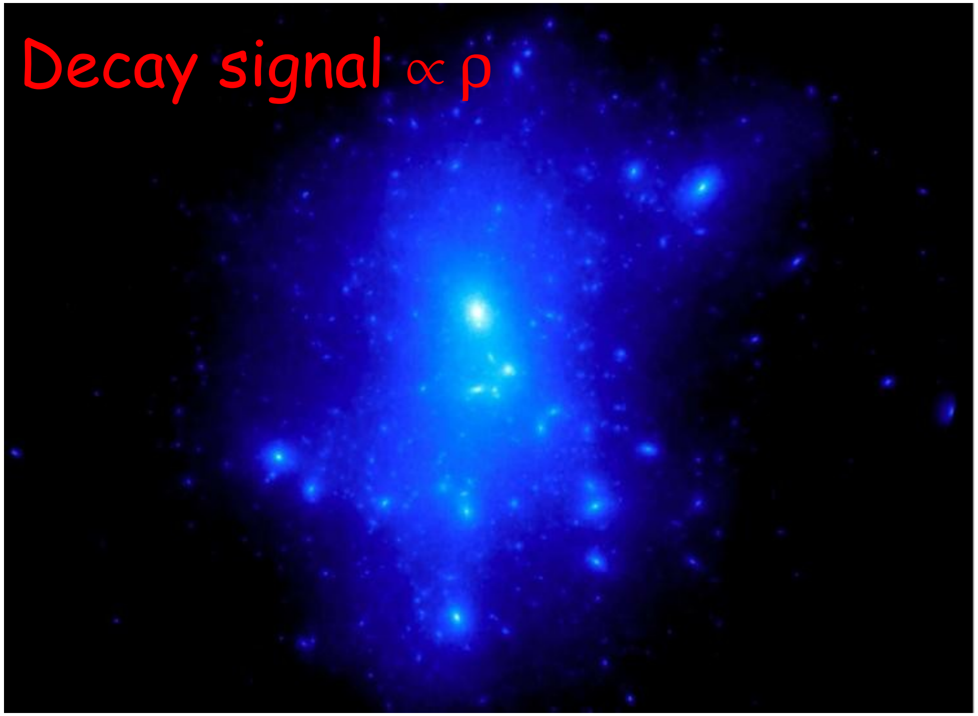
It will be possible to distinguish between annihilating dark matter and decaying dark matter





From B. Moore

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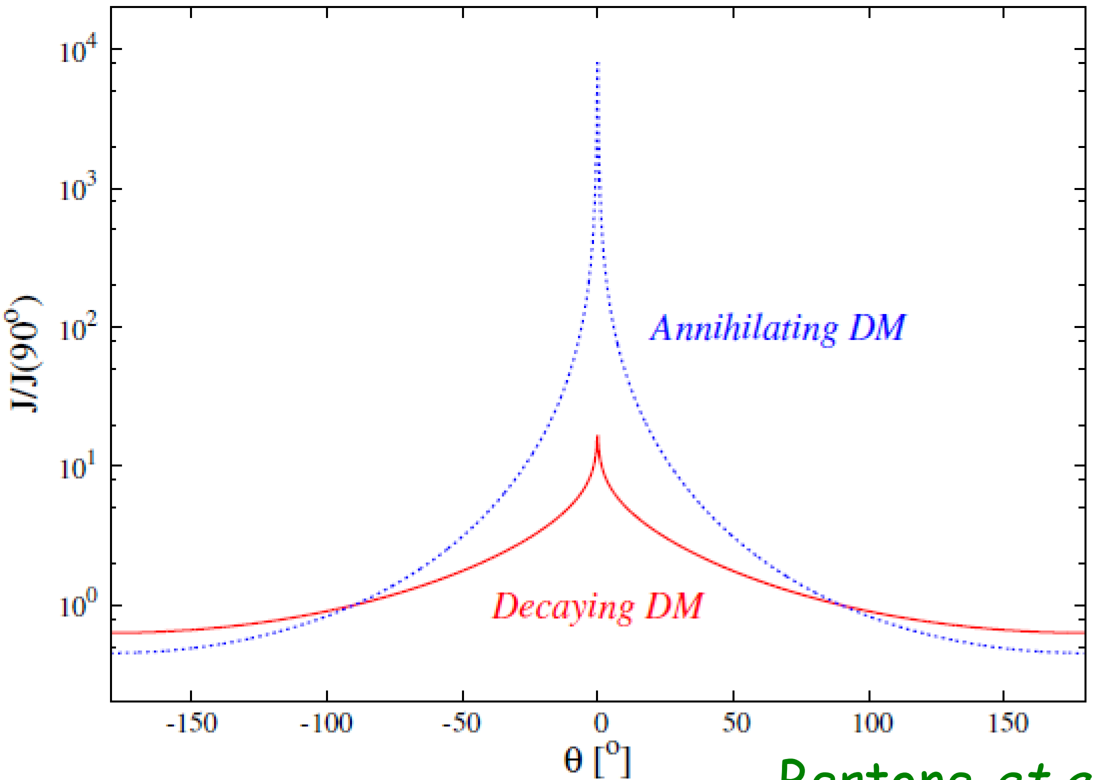
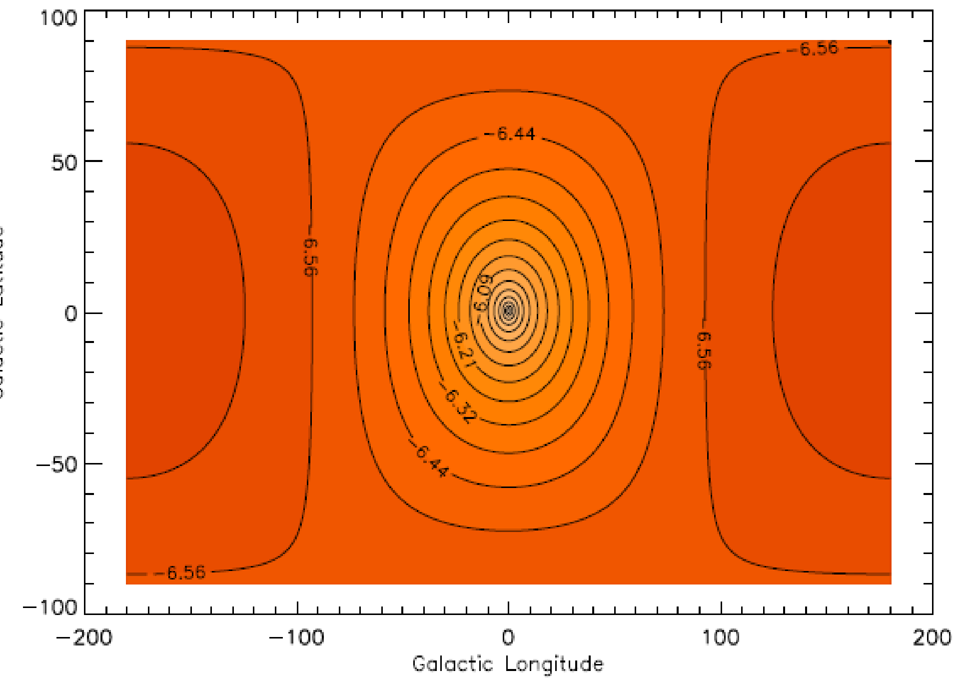


Bertone *et al.*

Moreover, the decaying dark matter scenario makes a very definite prediction of the angular map of gamma rays

signal



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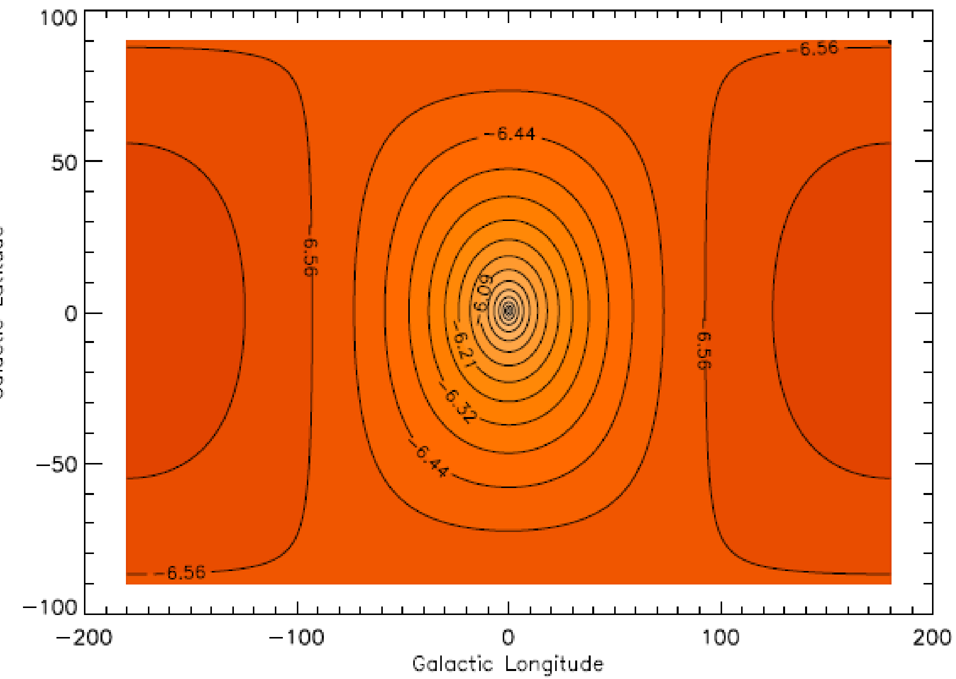
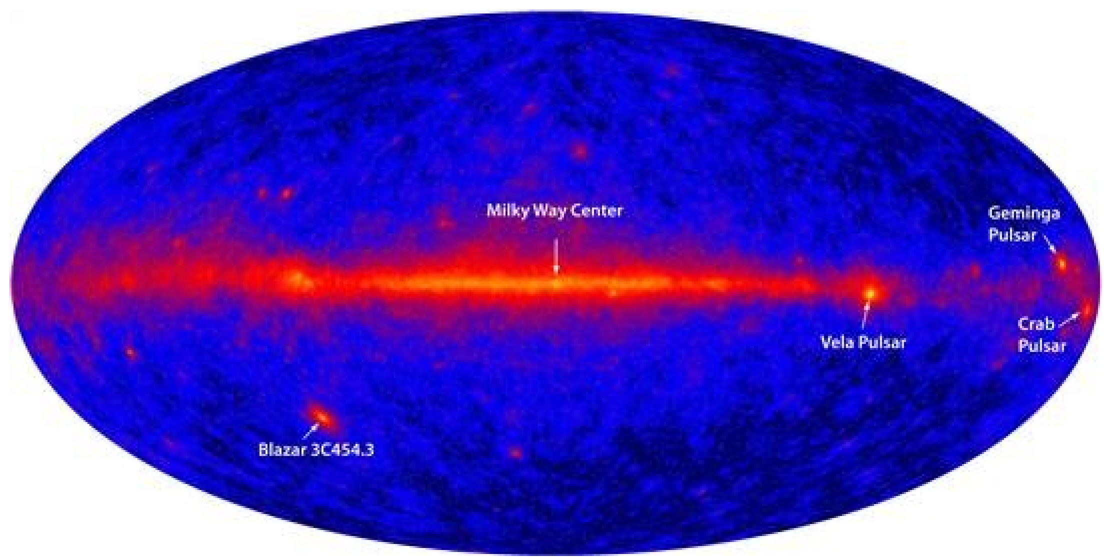


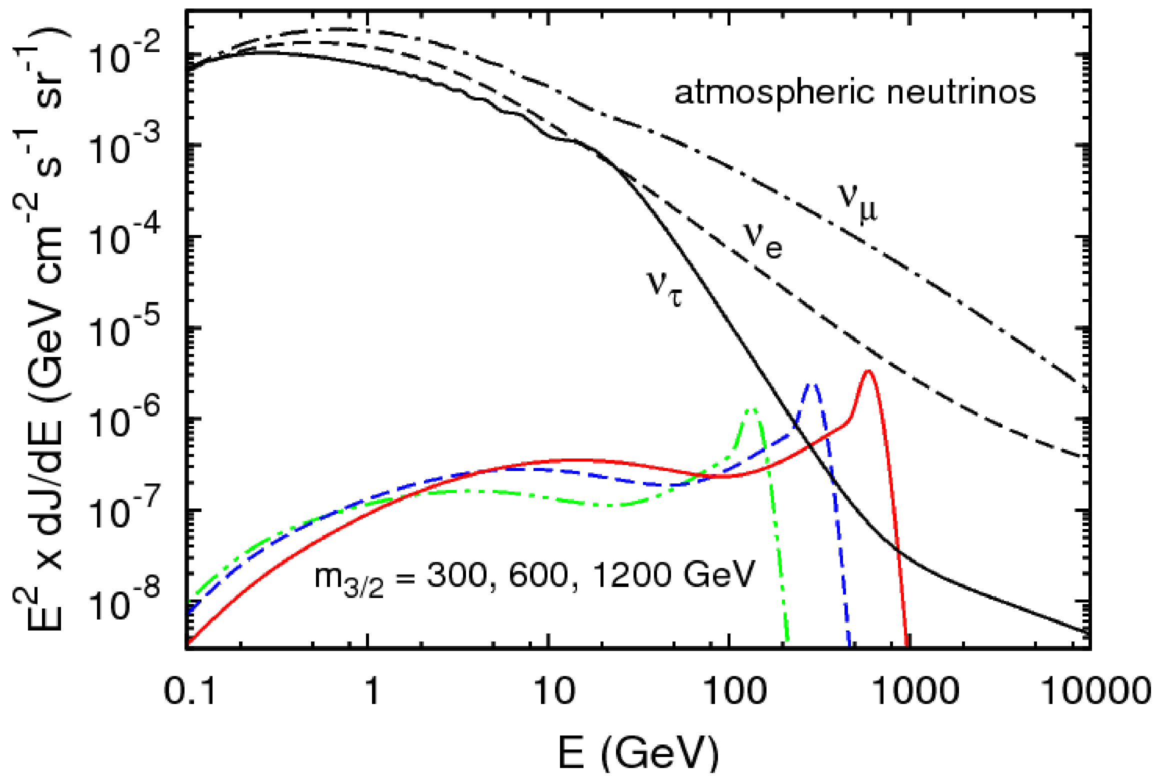
signal+background



Bertone *et al.*

Neutrino flux

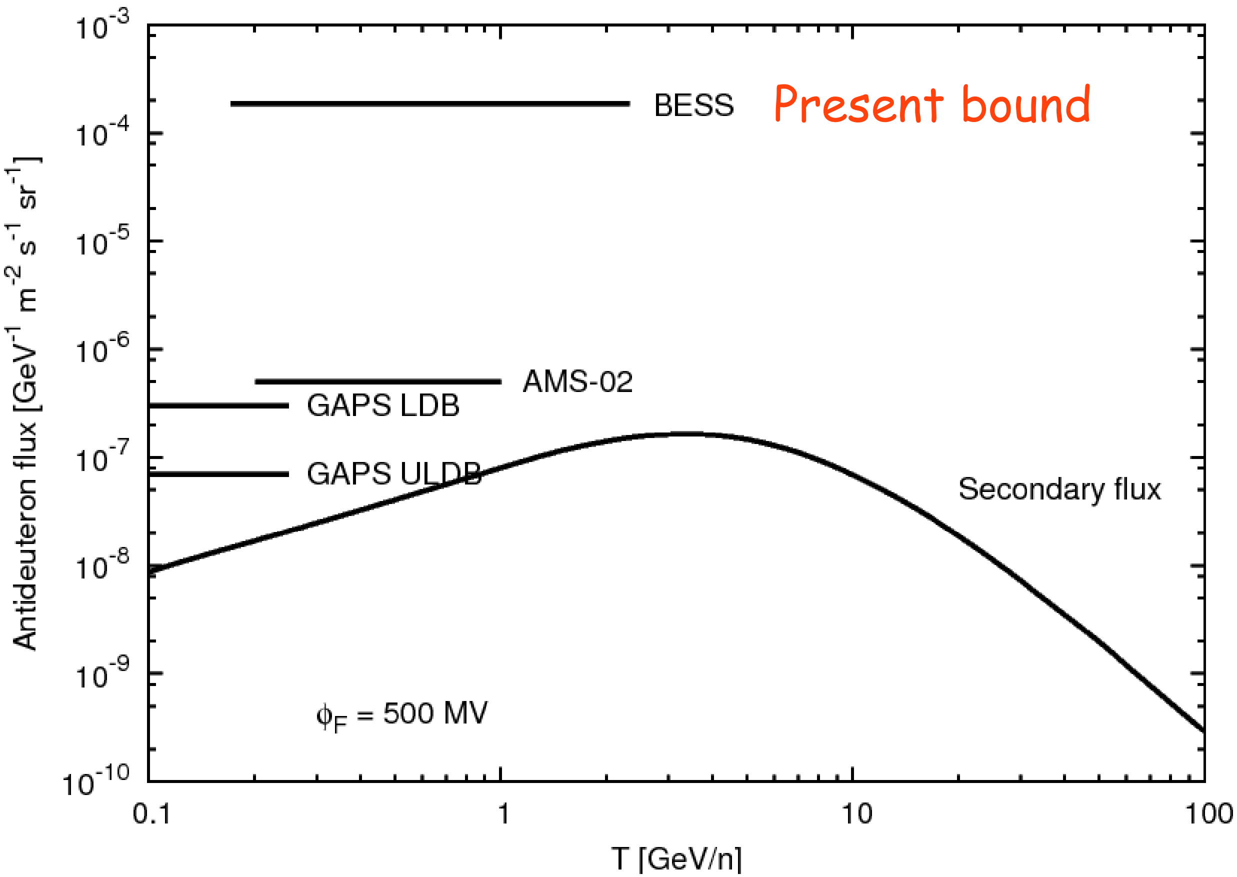
- Difficult to see due to large atmospheric backgrounds.
- If the dark matter mass is large, it may be observed by IceCube



Covi et al.

Antideuteron flux

- Antideuterons are very interesting targets for indirect dark matter detection. Donato, Fornengo, Maurin



A flux of antideuterons is necessarily accompanied by a flux of antiprotons, which is severely constrained by experiments.

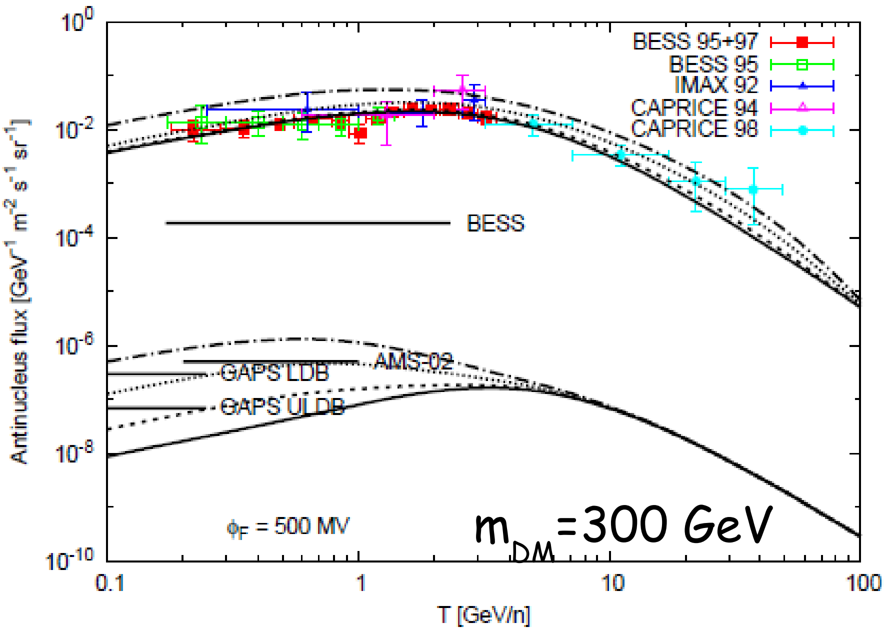
Interestingly, there are ranges of parameters where the primary antideuteron flux from dark matter decay could be observed by future experiments, being the antiproton flux consistent with present measurements.

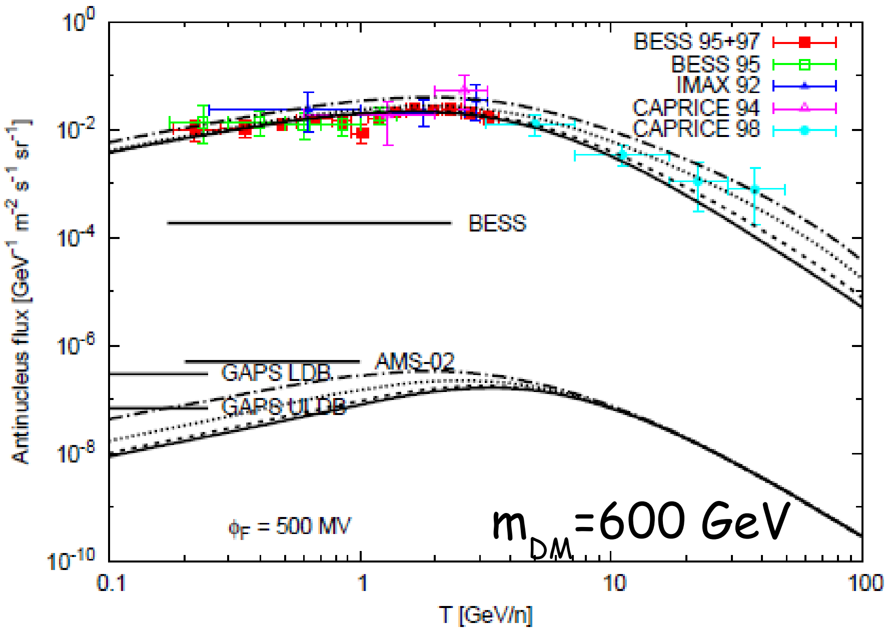
↓

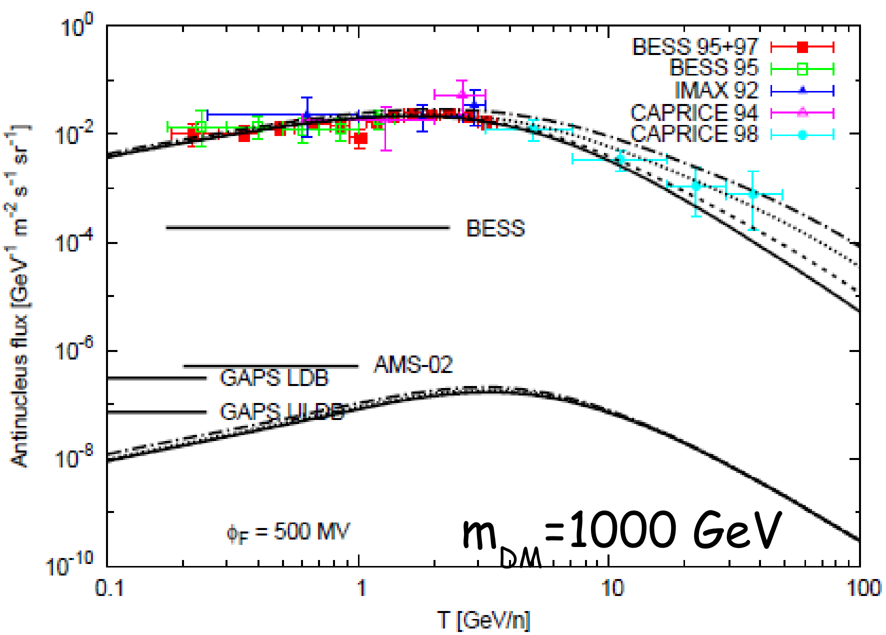
Signature for the hadronic decay of the dark matter

Total antiproton and antideuteron fluxes from $\psi \to W^{\pm} e^{\mp}$
Lifetime chosen to reproduce the PAMELA anomaly

AI, Tran







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.

•The PAMELA positron excess could be naturally explained by the decay of a dark matter particle, provided the mass is larger than ~300 GeV, the lifetime is around 10^{26}s and the particle decays preferentially into electrons or muons.

•This scenario makes predictions for the diffuse γ-ray flux, the neutrino flux and the antideuteron flux, which will be tested in the near future.