# PAMELA, decaying dark matter and leptons

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CERN
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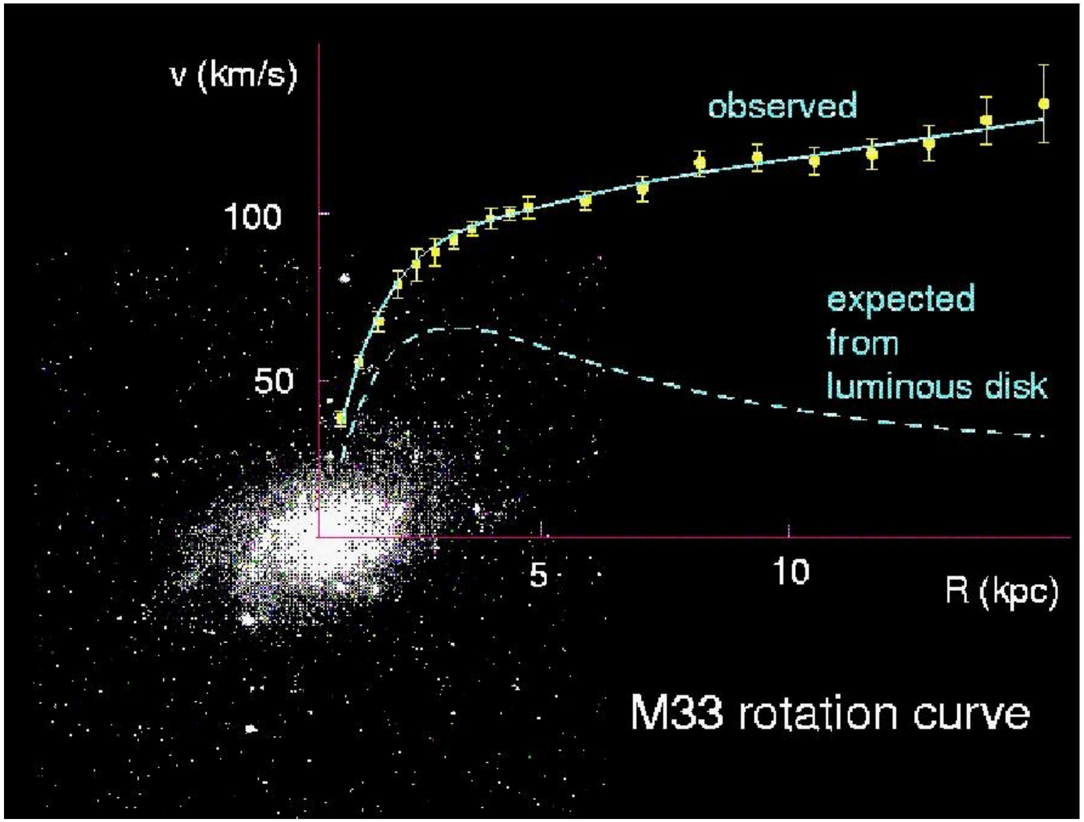
# Introduction

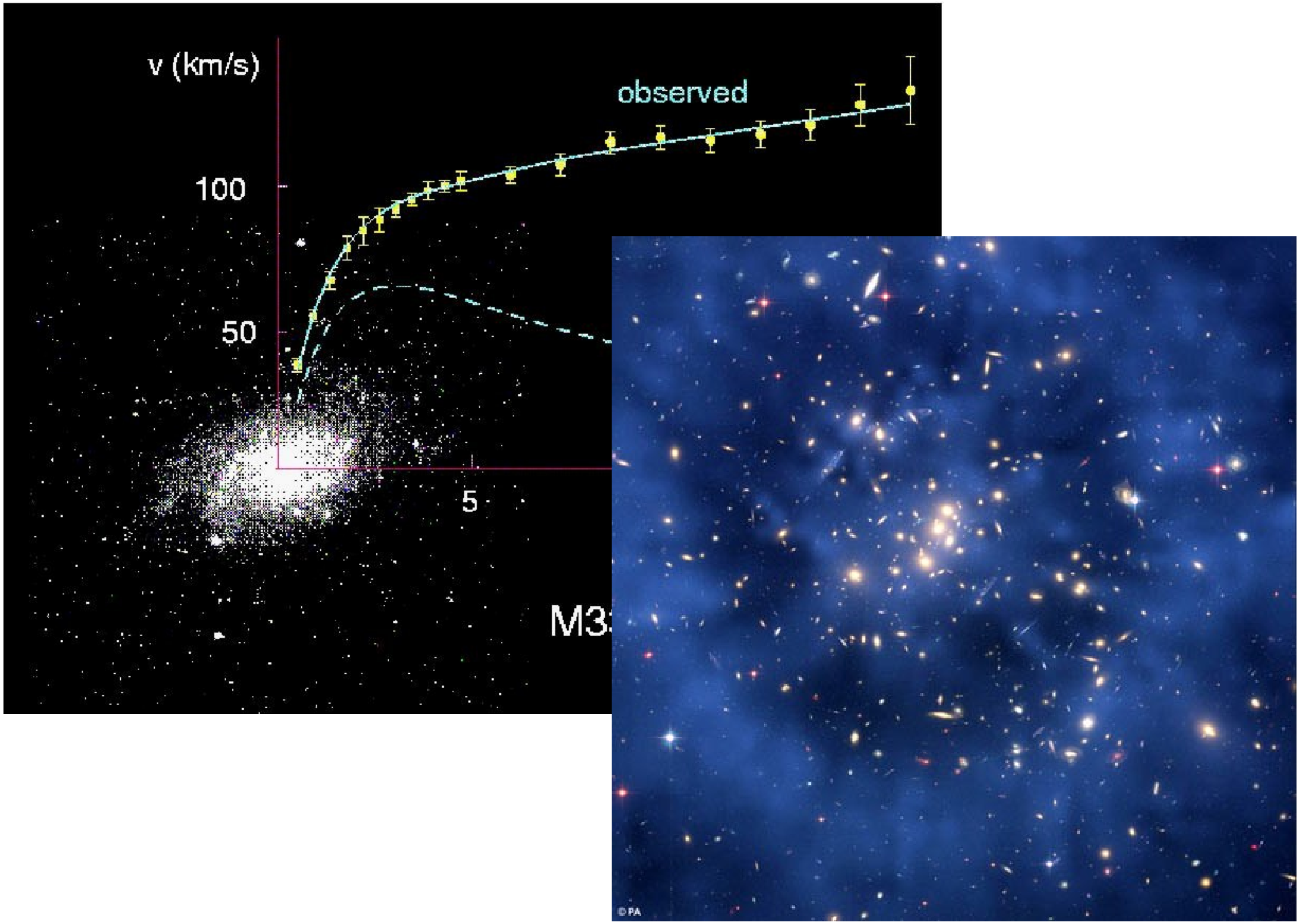
Dark matter exist



M33 rotation curve

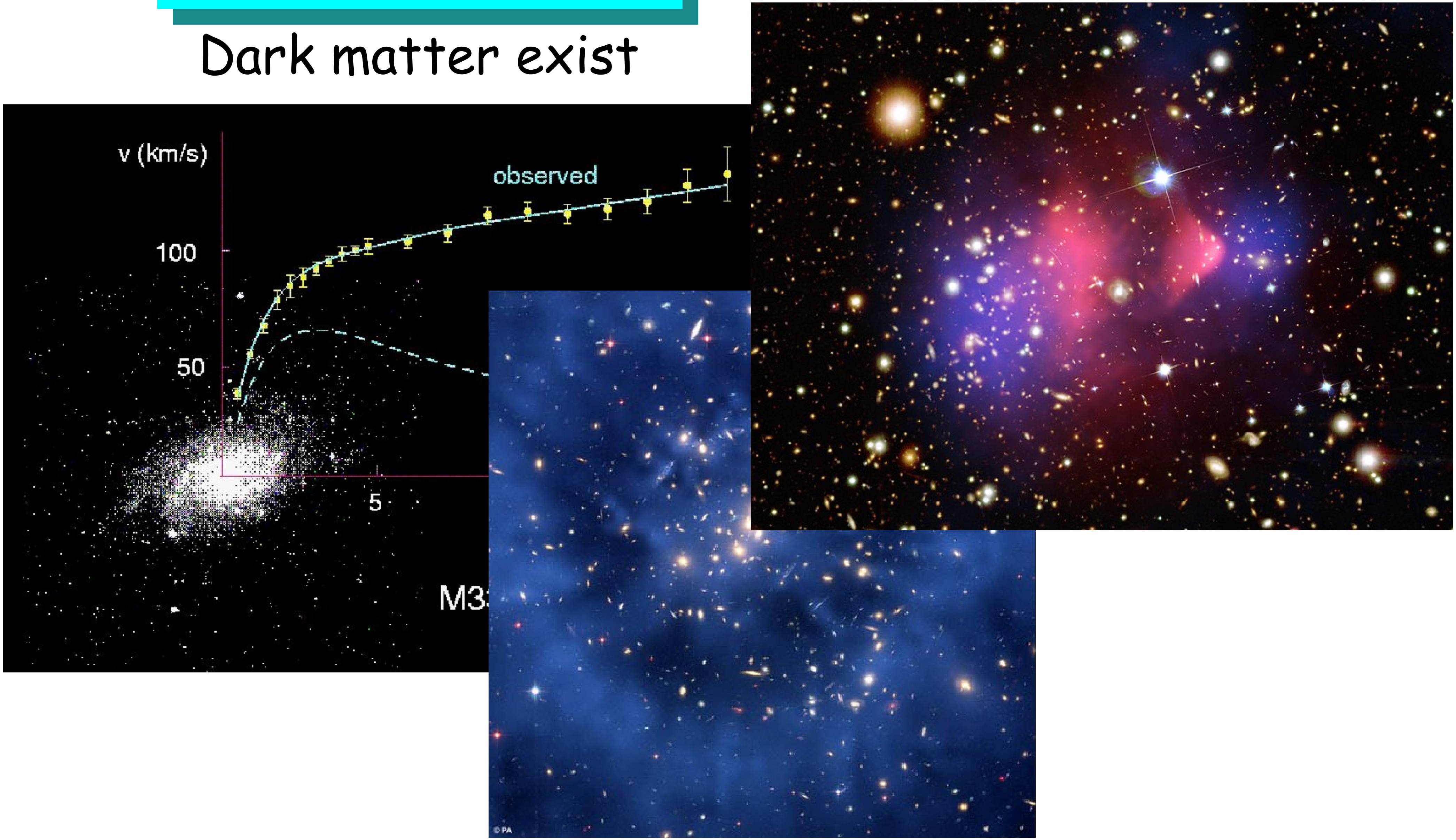
# Introduction

## Dark matter exist



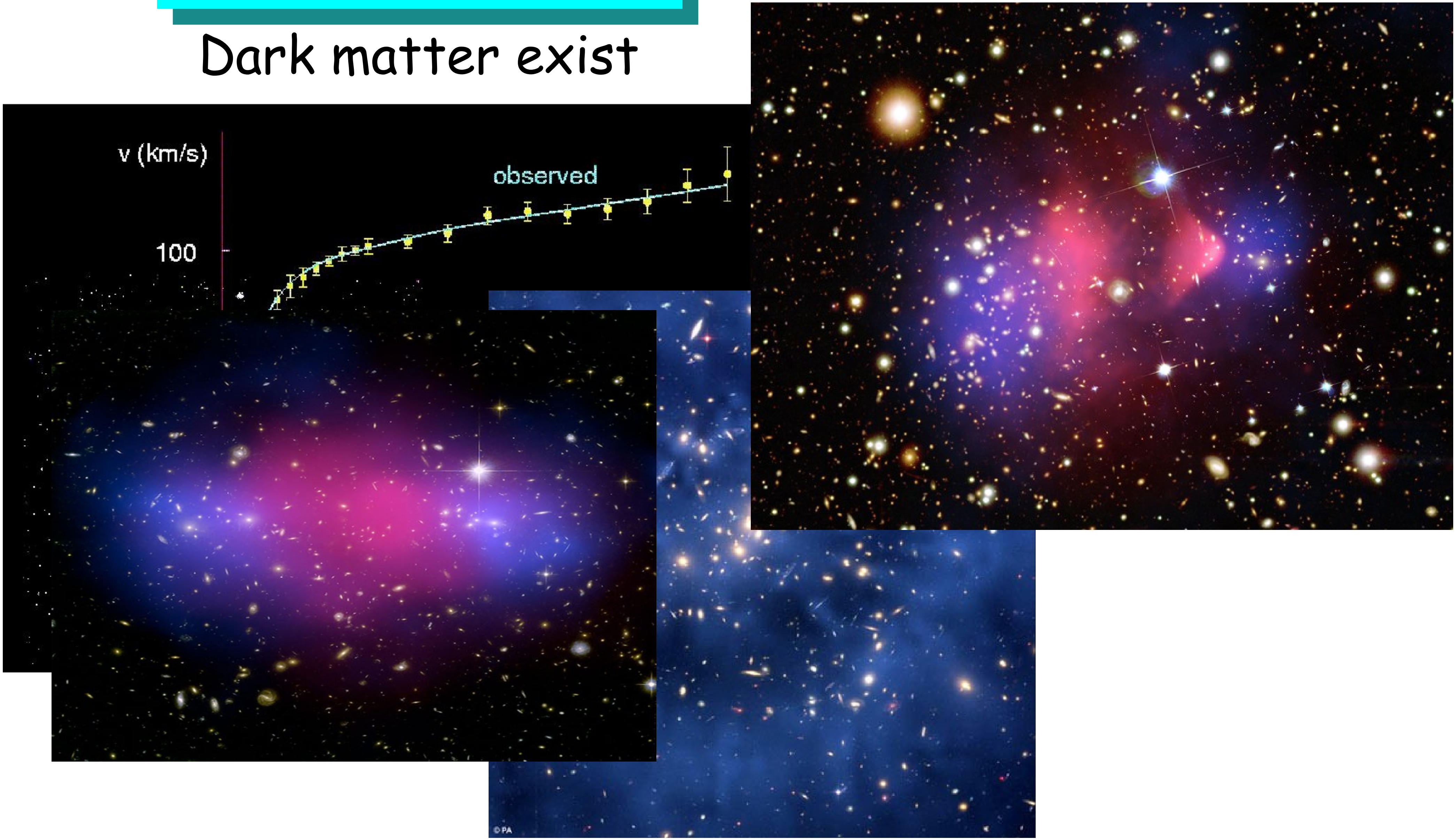
# Introduction

Dark matter exist



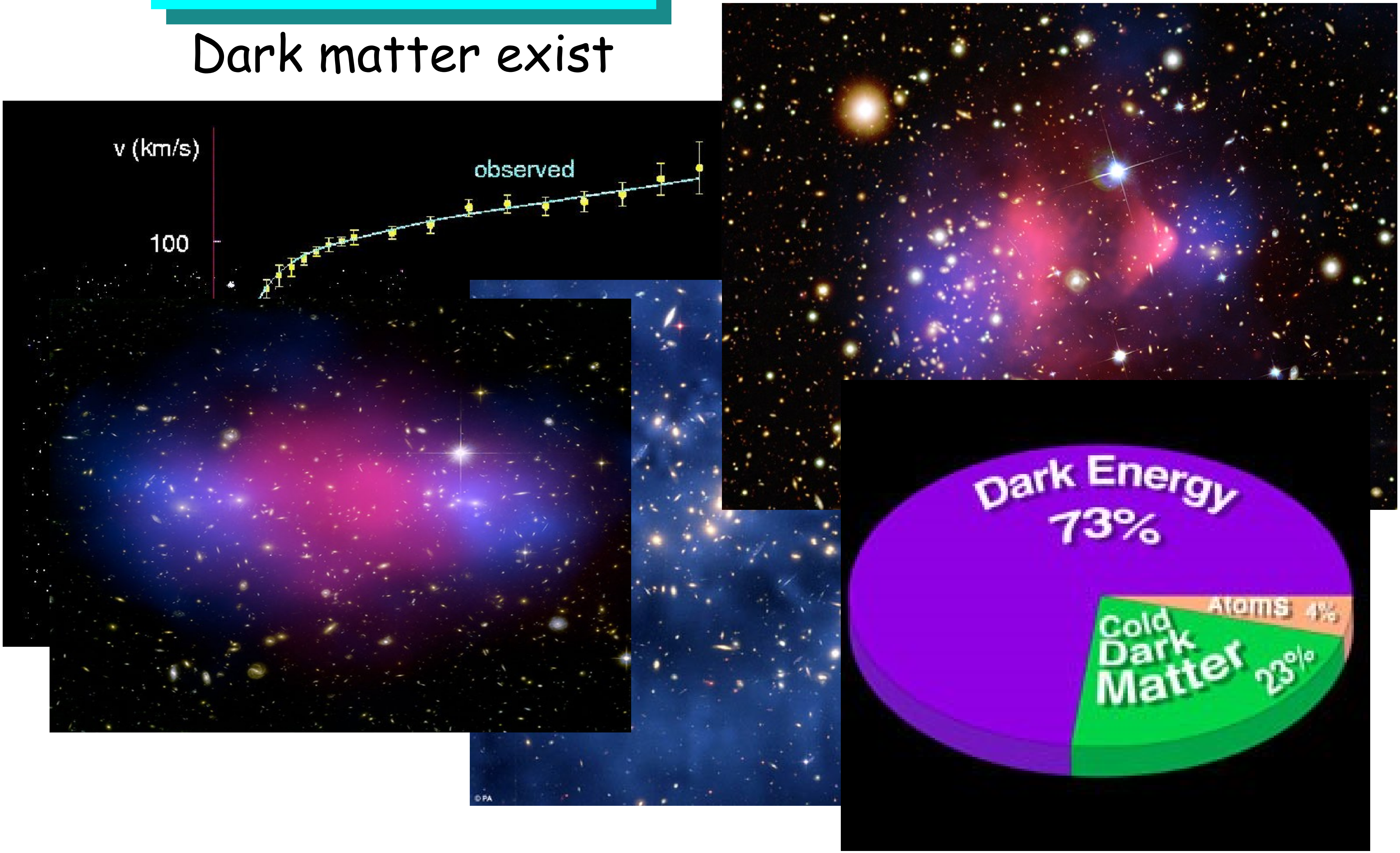
# Introduction

Dark matter exist



# Introduction

Dark matter exist



Observations indicate that the dark matter is a particle which is:

- Non baryonic
- Weakly interacting
- Slow moving ("cold" or perhaps "warm")
- Long lived (not necessarily stable!)

All these evidences for dark matter are of gravitational origin

Impossible to determine the nature and properties of the dark matter particle from these observations

Independent (non-gravitational) evidences for dark matter are necessary

# Indirect detection of dark matter

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

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

# Indirect detection of dark matter

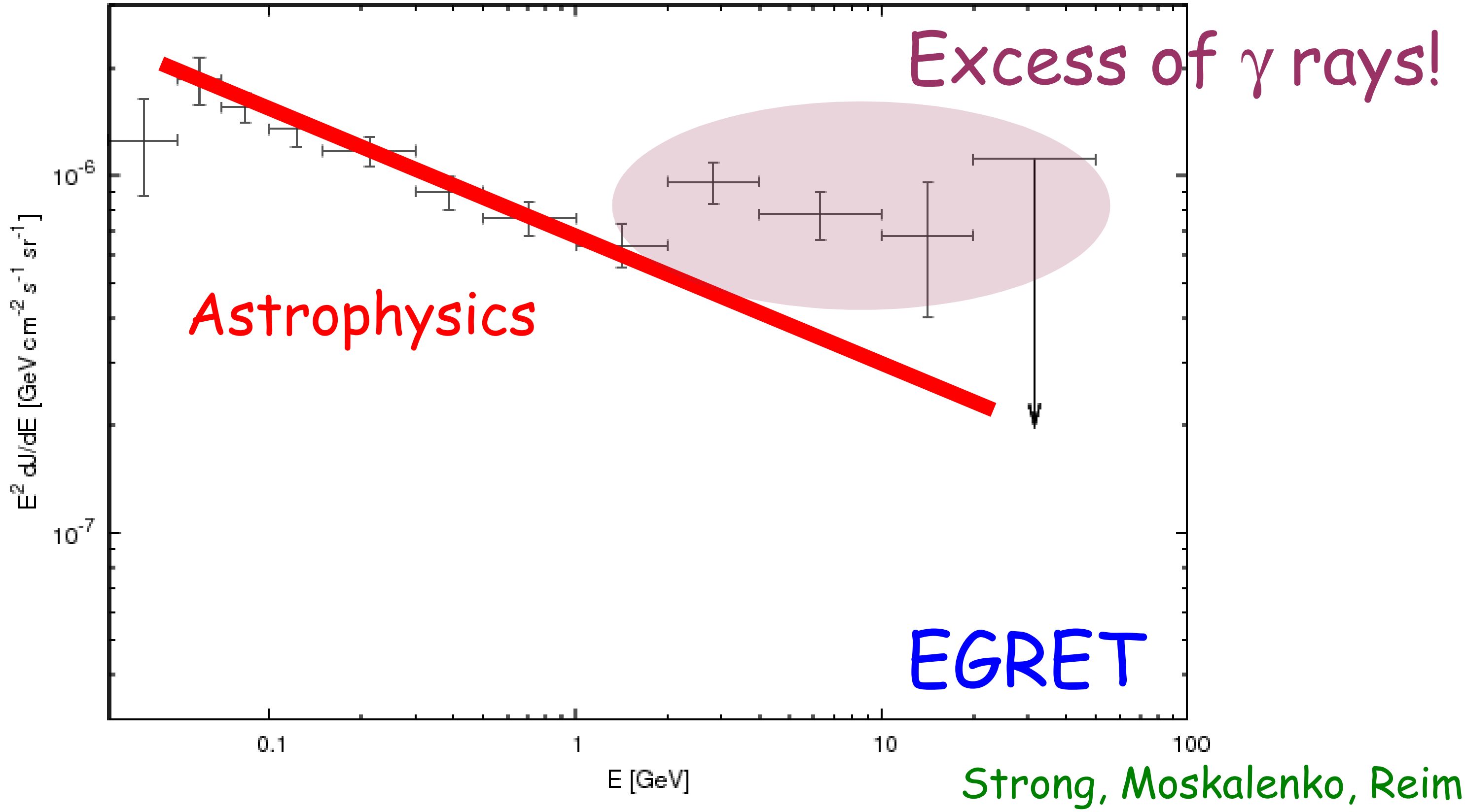
$\mathrm{DM\ DM} \rightarrow \gamma\, X,\ e^{+} X\ldots$ (annihilation)

$\mathrm{DM} \rightarrow \gamma\, X,\ e^{+}X,\ldots$ (decay)

Exciting possibility!

There have been indications in the past for dark matter annihilation/decay in the high energy cosmic ray fluxes.

# Extragalactic flux of gamma rays

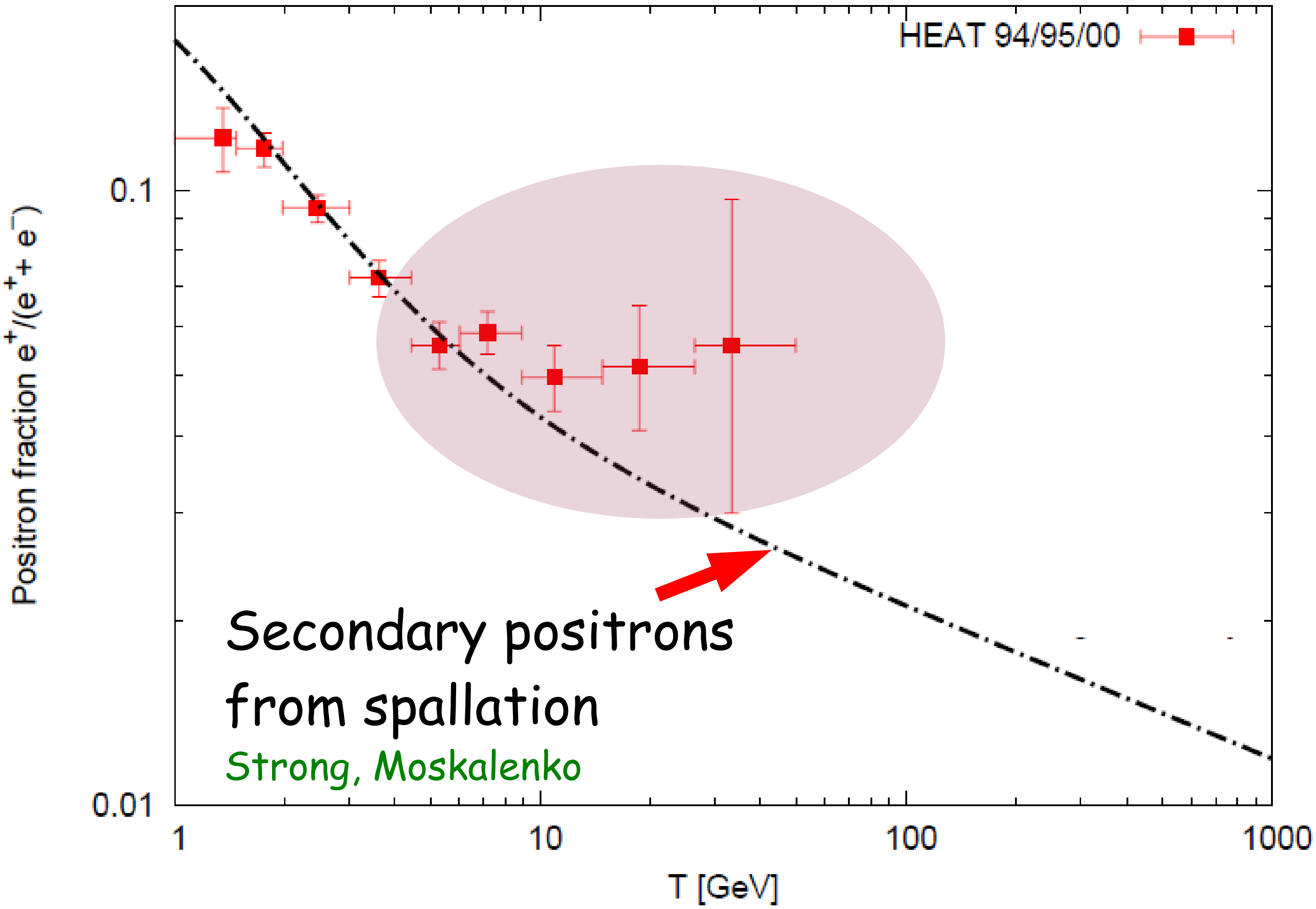


Strong, Moskalenko, Reimer

Many open questions:

- Extraction of the signal from the galactic foreground
- Is the signal isotropic/anisotropic
- Precise shape of the energy spectrum

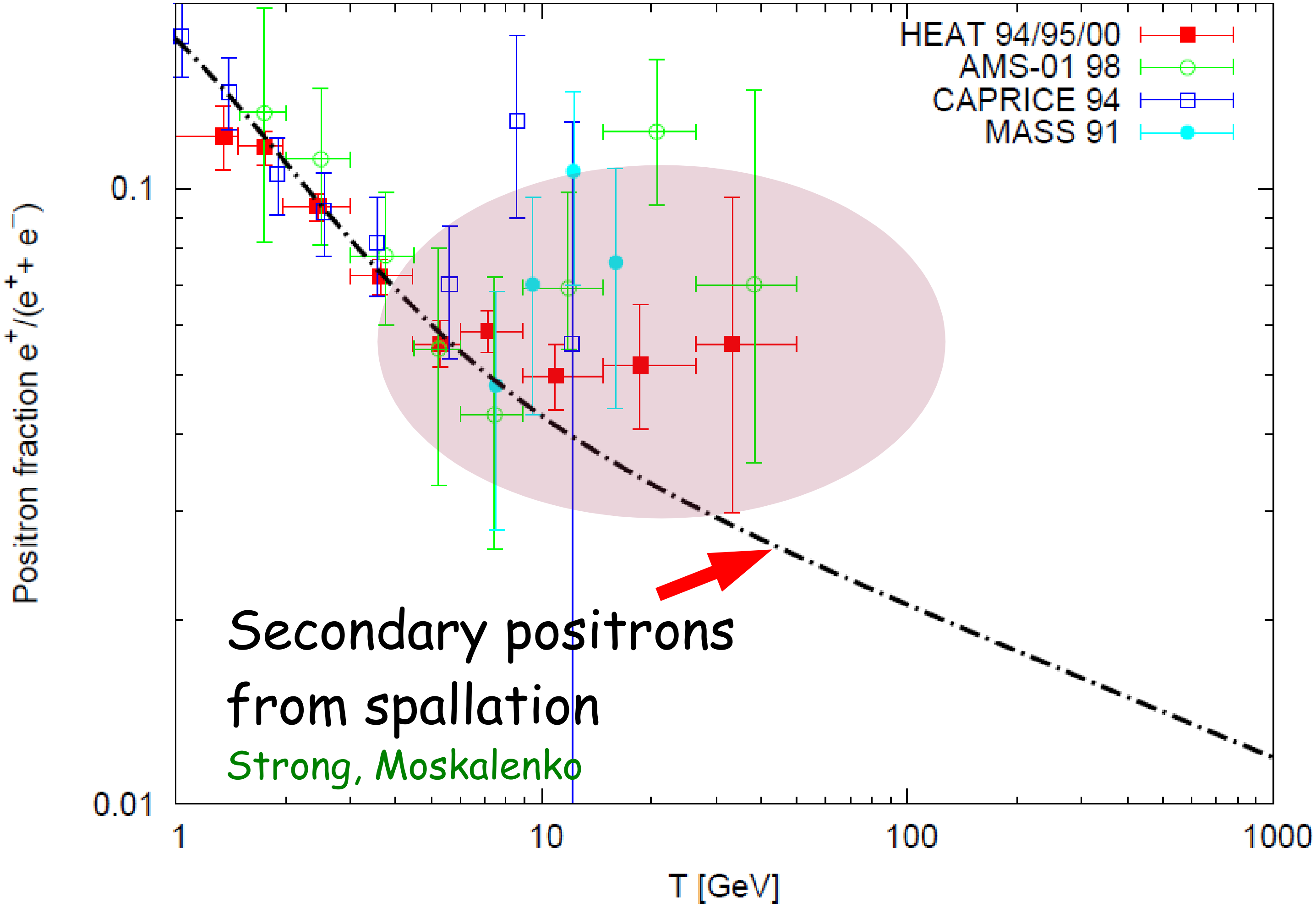
# Positron Fraction



Secondary positrons from spallation

Strong, Moskalenko

# Positron Fraction

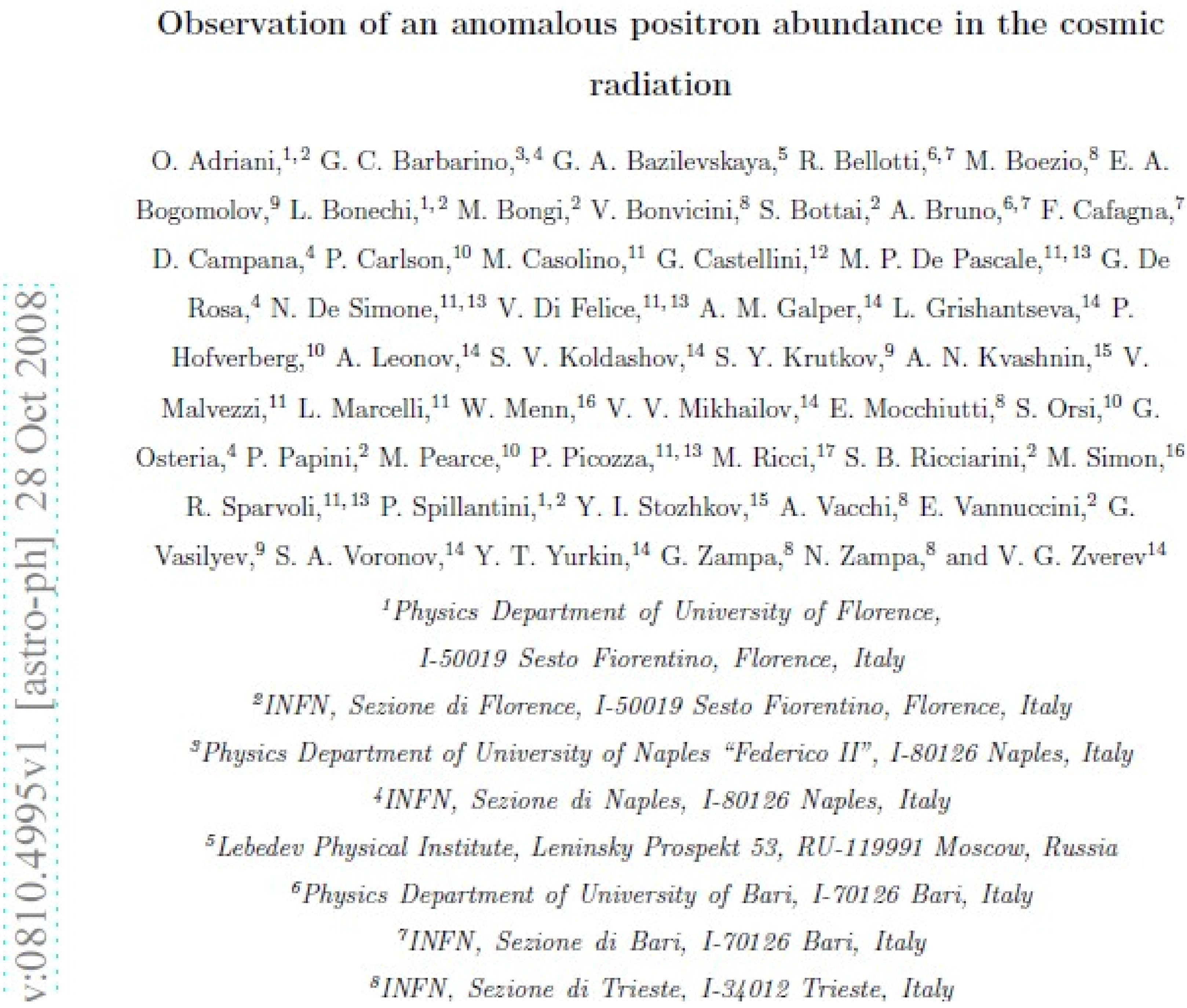


Secondary positrons from spallation

Strong, Moskalenko

Spectacular experimental progress over the last months

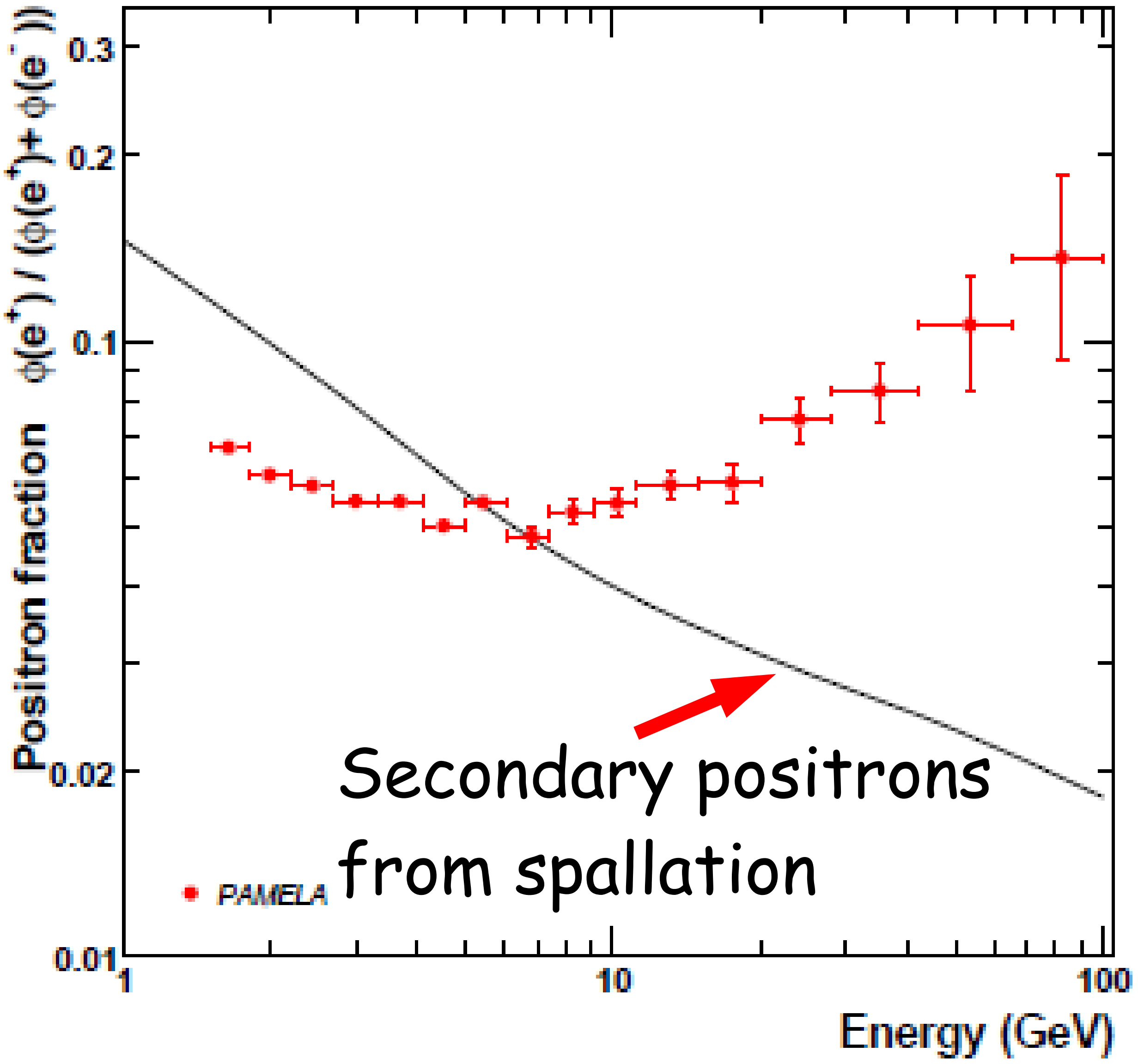
# PAMELA collaboration



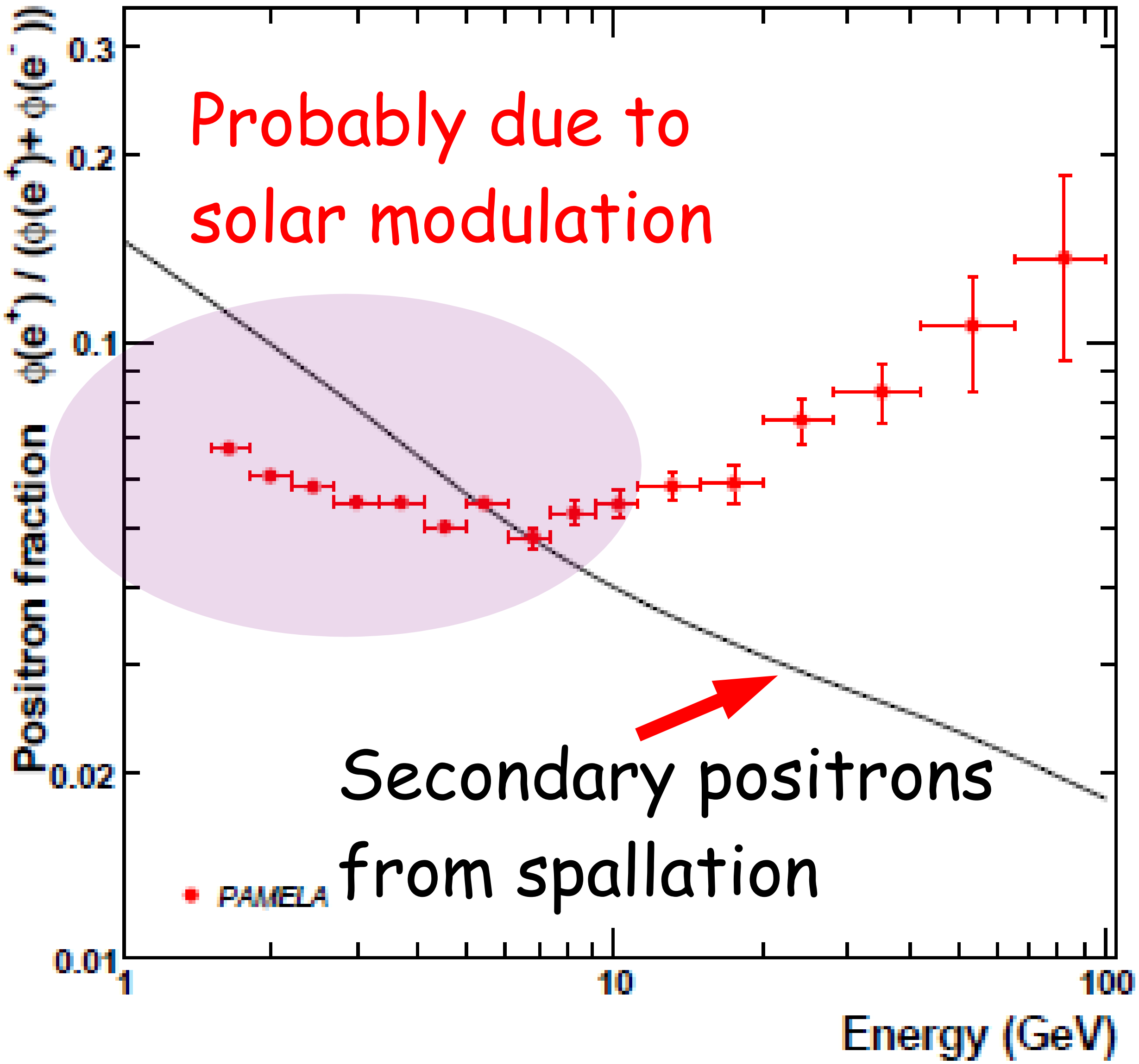
## Observation of an anomalous positron abundance in the cosmic radiation

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] A. Leonov,[14] S. V. Koldashov,[14] S. Y. Krutkov,[9] A. N. Kvashnin,[15] V. Malvezzi,[11] L. Marcelli,[11] W. Menn,[16] V. V. Mikhailov,[14] E. Mocchiutti,[8] S. Orsi,[10] G. Osteria,[4] P. Papini,[2] M. Pearce,[10] P. Picozza,[11,13] M. Ricci,[17] S. B. Ricciarini,[2] M. Simon,[16] R. Sparvoli,[11,13] P. Spillantini,[1,2] Y. I. Stozhkov,[15] A. Vacchi,[8] E. Vannuccini,[2] G. Vasilyev,[9] S. A. Voronov,[14] Y. T. Yurkin,[14] G. Zampa,[8] N. Zampa,[8] and V. G. Zverev[14]

[1]*Physics Department of University of Florence,*
*I-50019 Sesto Fiorentino, Florence, Italy*
[2]*INFN, Sezione di Florence, I-50019 Sesto Fiorentino, Florence, Italy*
[3]*Physics Department of University of Naples "Federico II", I-80126 Naples, Italy*
[4]*INFN, Sezione di Naples, I-80126 Naples, Italy*
[5]*Lebedev Physical Institute, Leninsky Prospekt 53, RU-119991 Moscow, Russia*
[6]*Physics Department of University of Bari, I-70126 Bari, Italy*
[7]*INFN, Sezione di Bari, I-70126 Bari, Italy*
[8]*INFN, Sezione di Trieste, I-34012 Trieste, Italy*

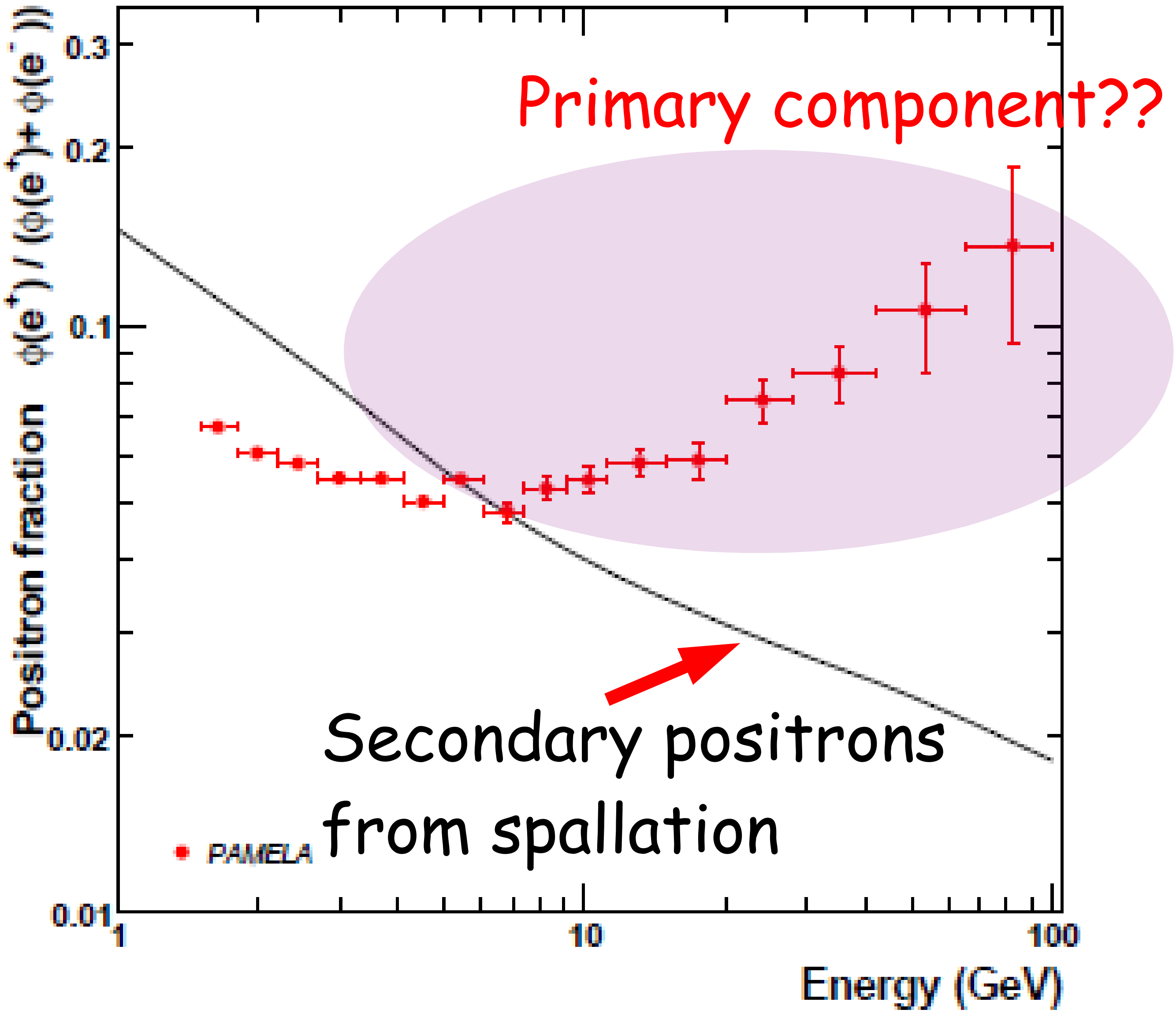


Secondary positrons from spallation



Probably due to solar modulation

Secondary positrons from spallation



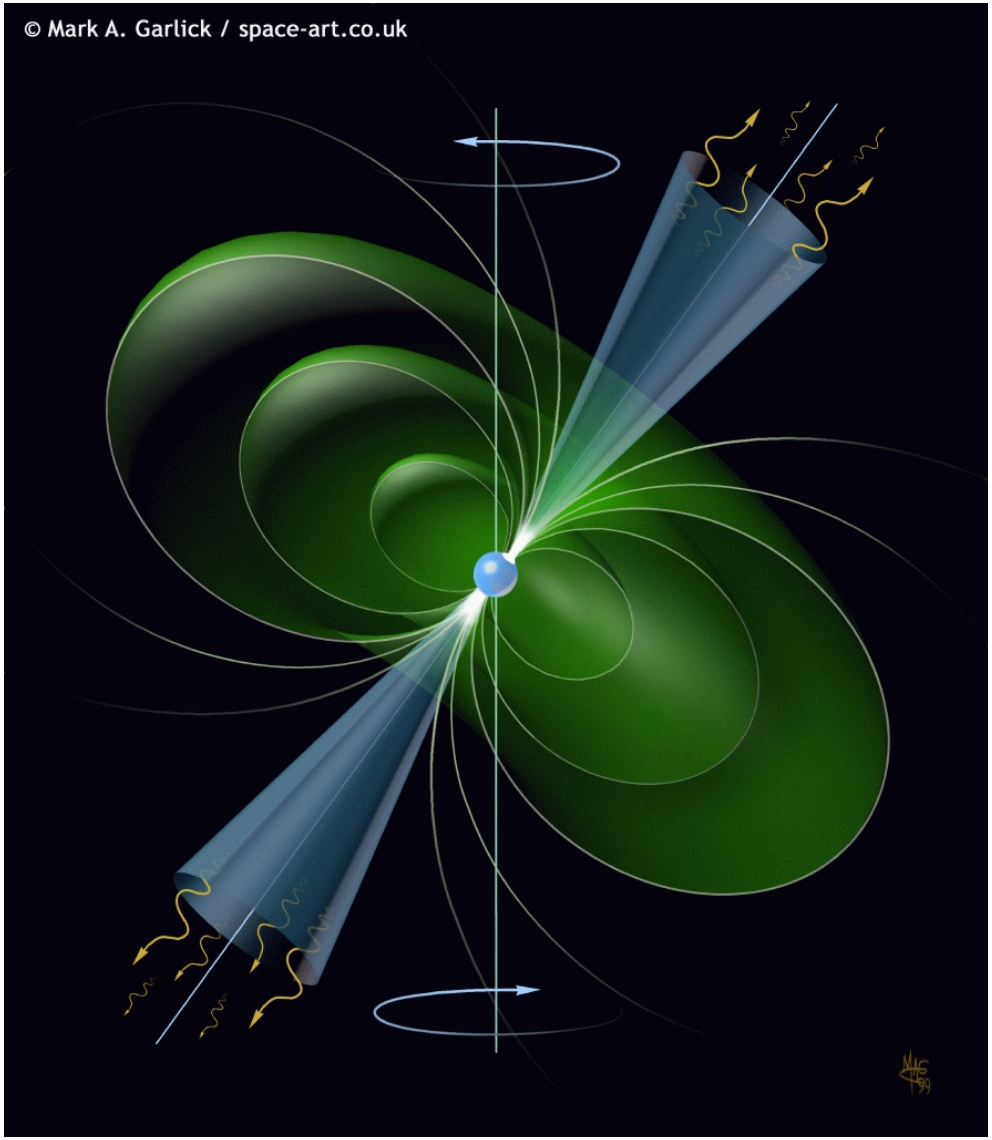
Primary component??

Secondary positrons from spallation

# Astrophysics?

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

Atoyan, Aharonian, Völk;
Chi, Cheng, Young;
Grimani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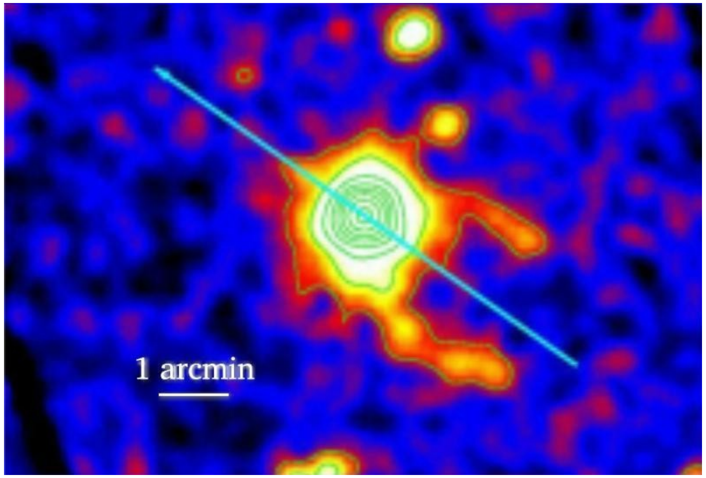
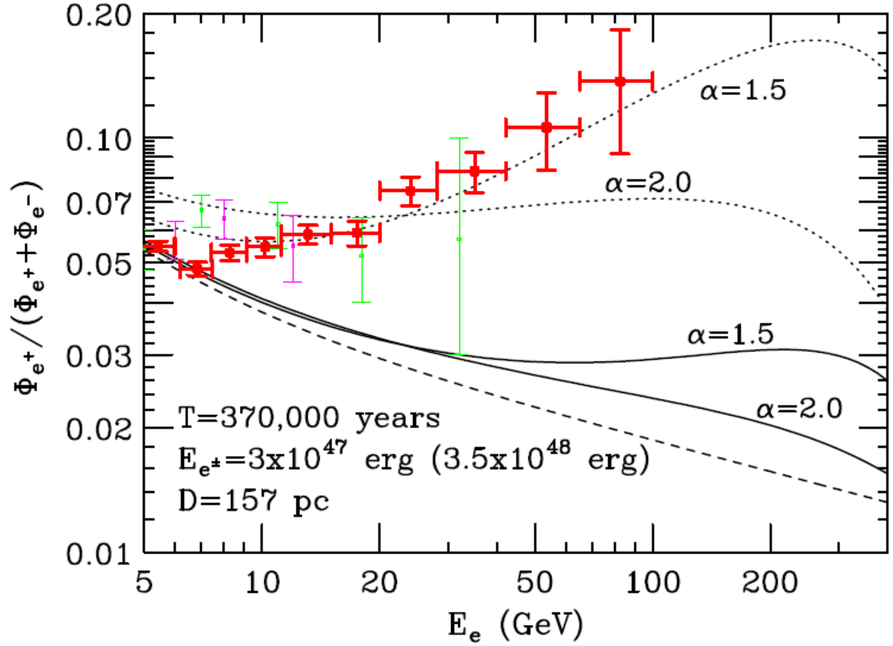
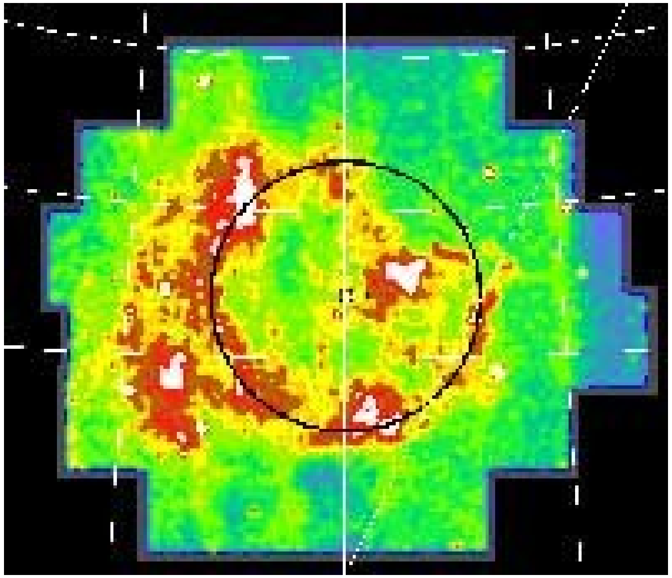
$$dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/600GeV)$$

Geminga







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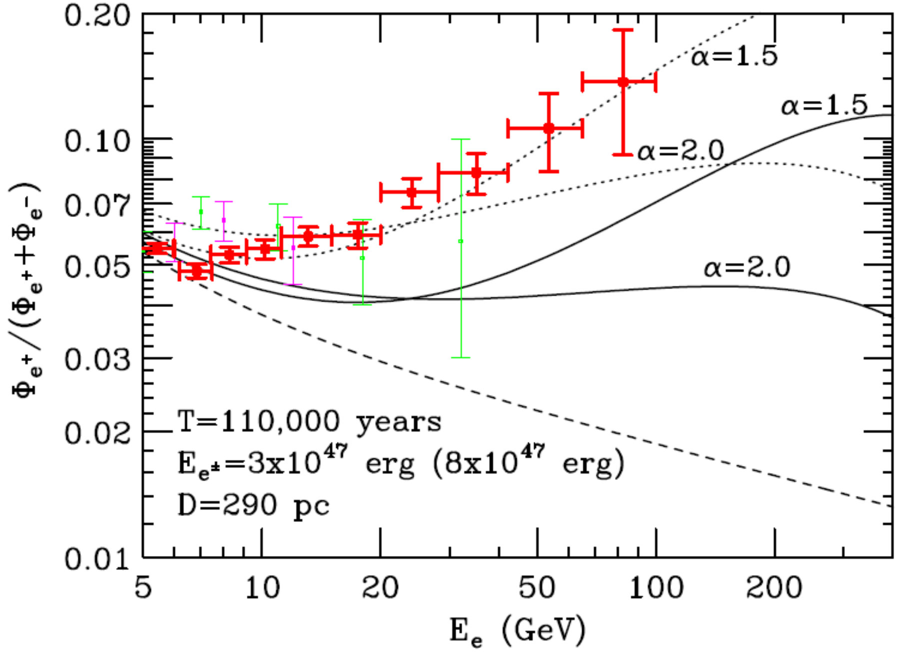
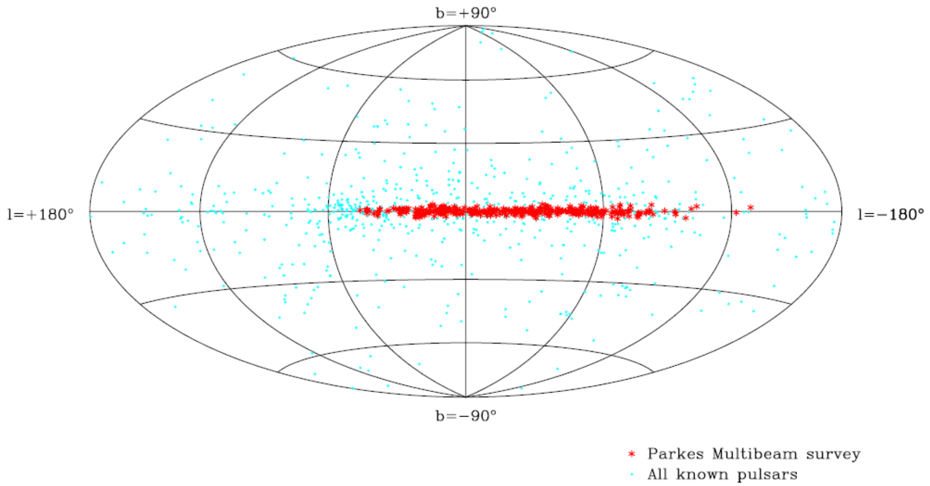


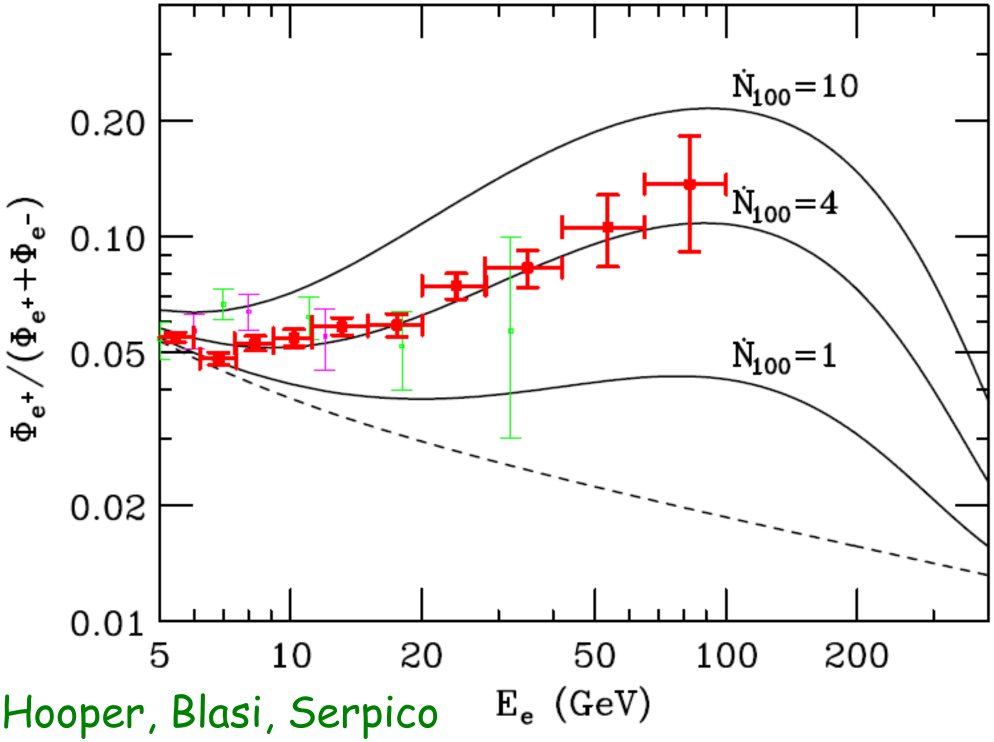
Hooper, Blasi, Serpico

We know around 1800 pulsars in our Galaxy




© Mark A. Garlick / space-art.co.uk

The combined positron emission from all of them could also produce a sizable primary flux



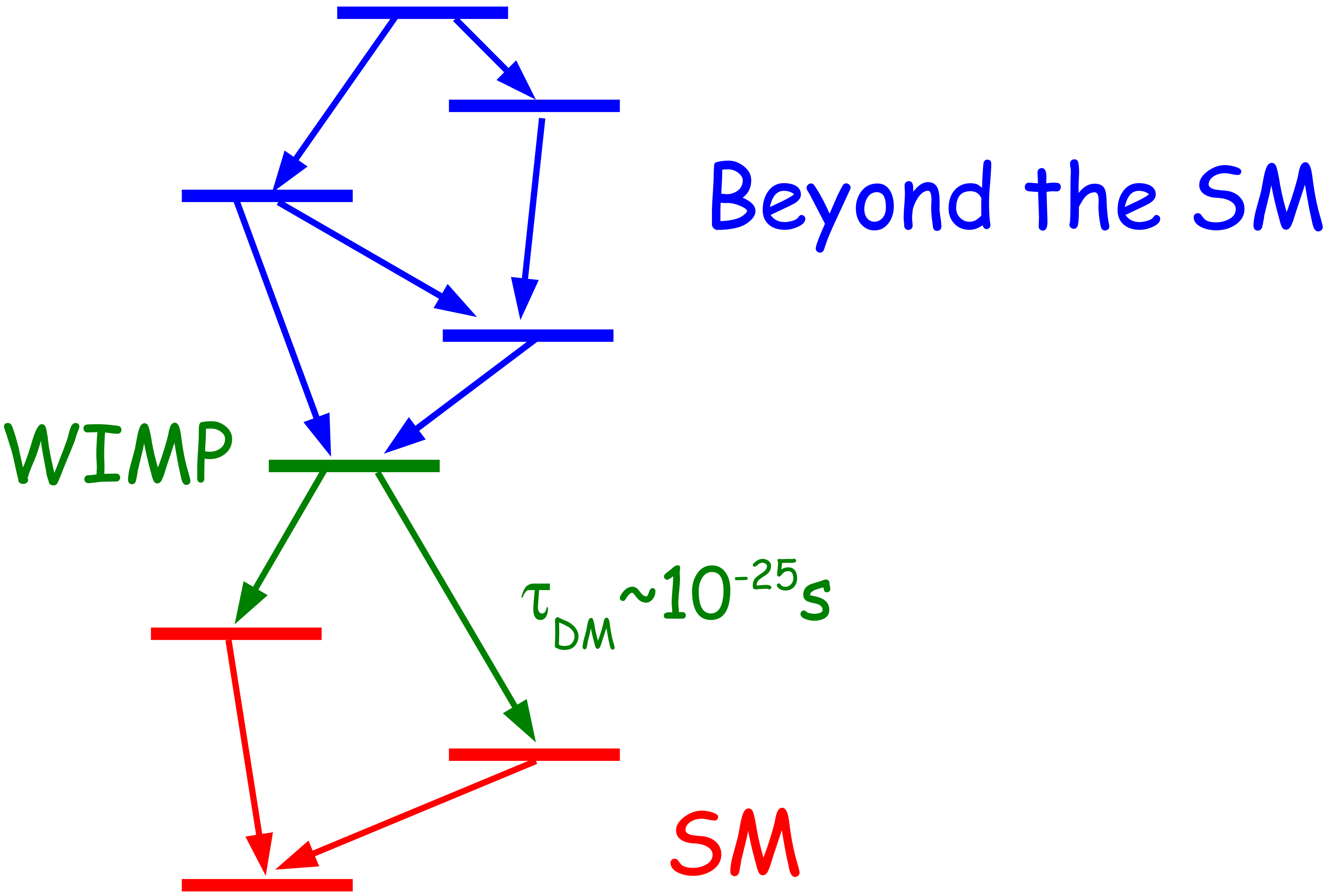
Hooper, Blasi, Serpico

# Dark matter decay

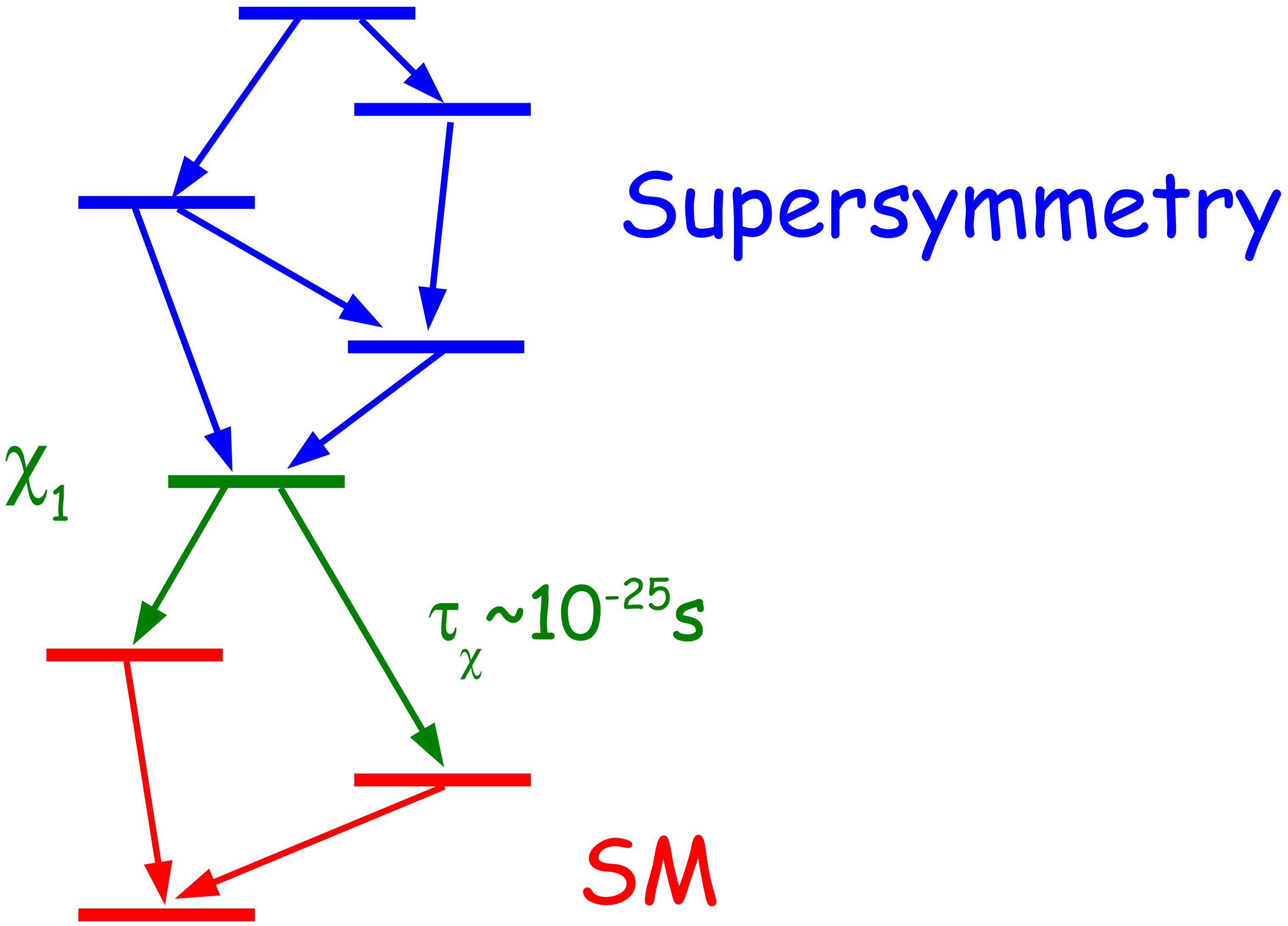
- No fundamental objection to this possibility, provided $\tau_{DM}>10^{17}$ s.
- Not as thoroughly studied as the case of the dark matter annihilation.

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:



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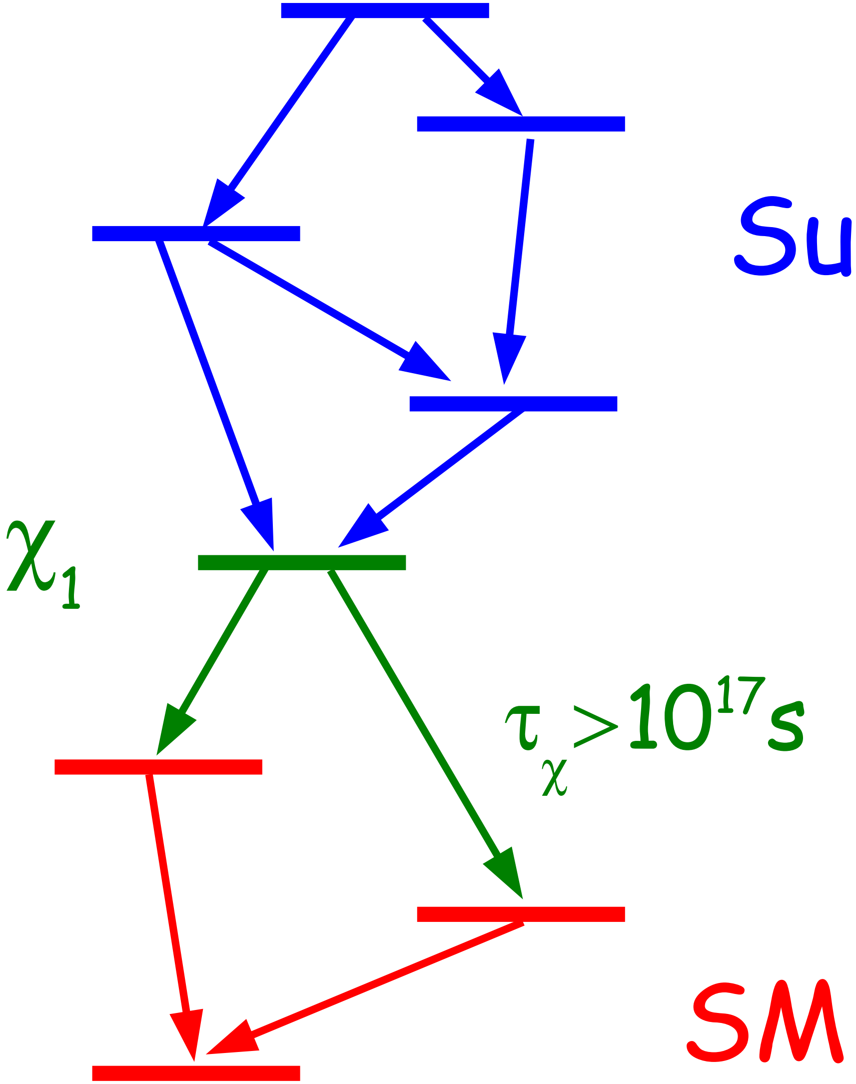
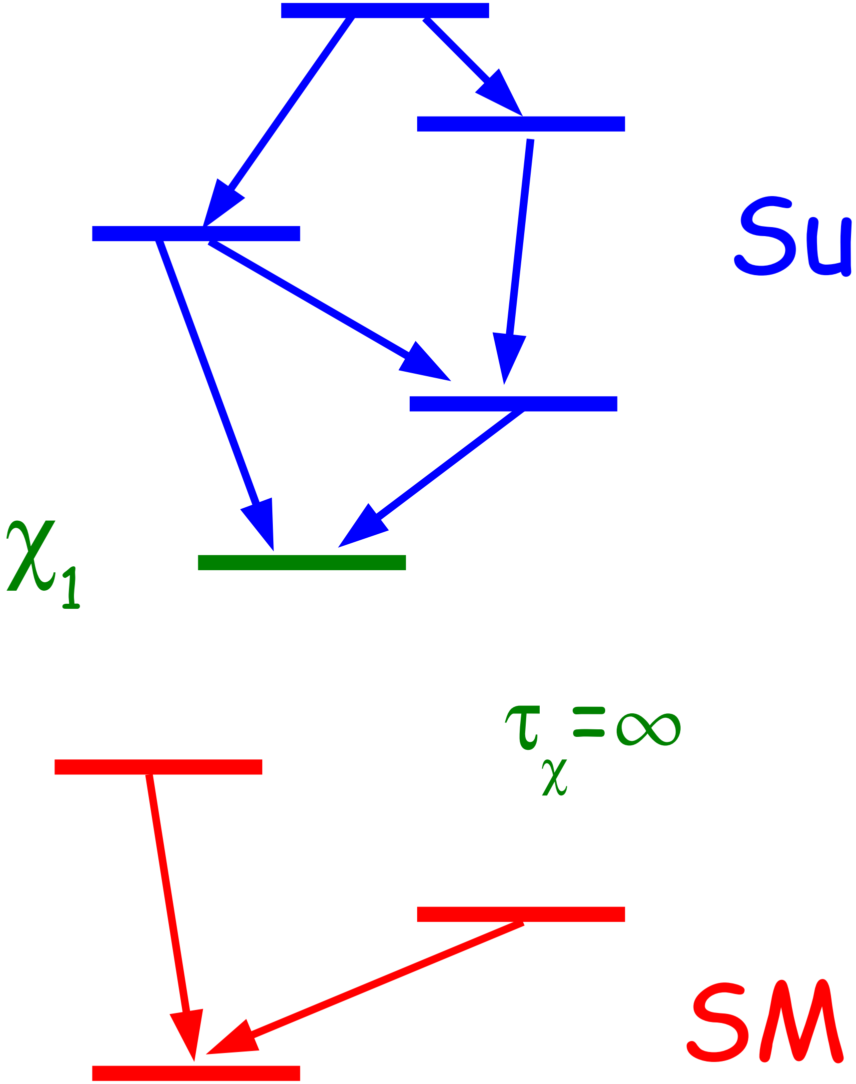


Supersymmetry

SM

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

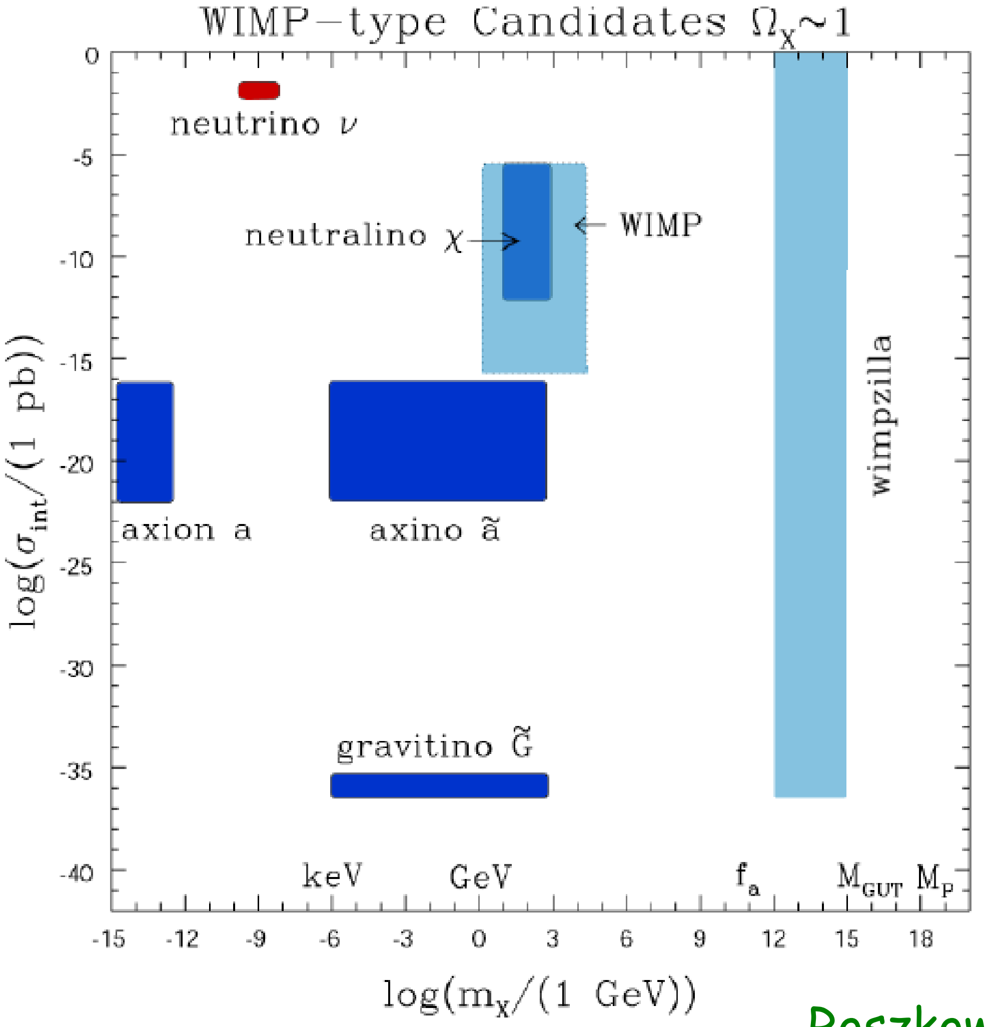
# Sketch of a WIMP dark matter model:



**Simplest solution**: forbid the dangerous couplings altogether by imposing exact R-parity conservation.

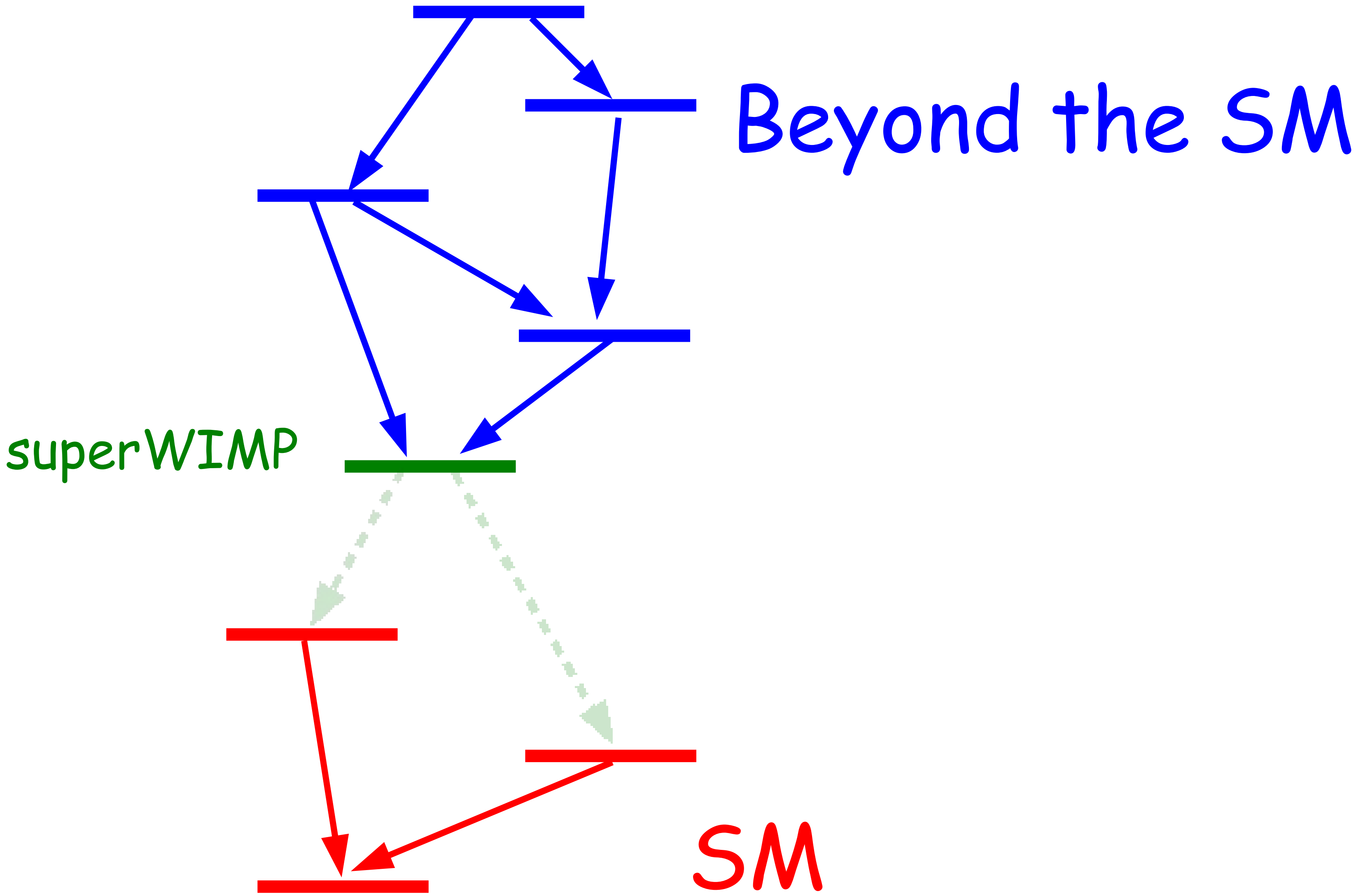
**The lightest neutralino is absolutely stable**

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

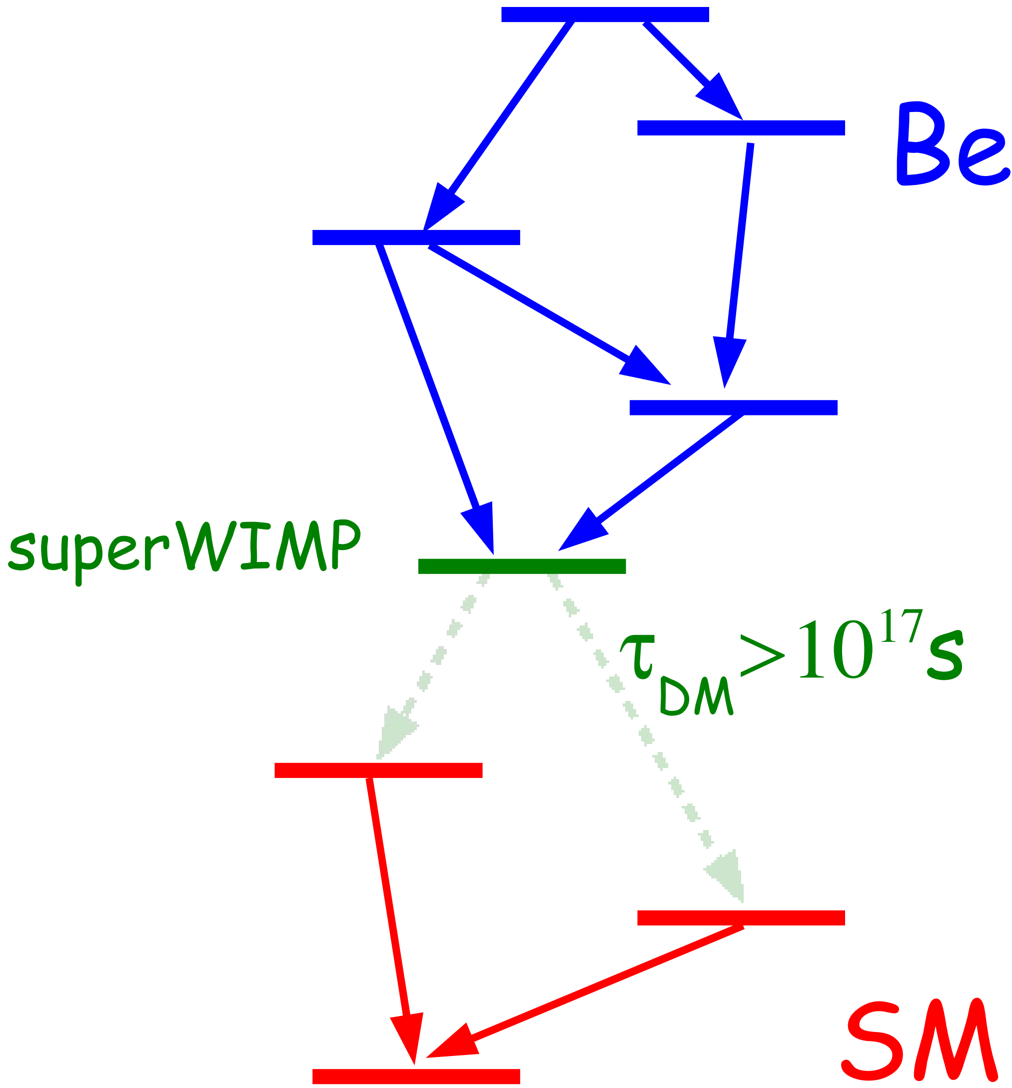


Roszkowski

# Sketch of a superWIMP dark matter model:

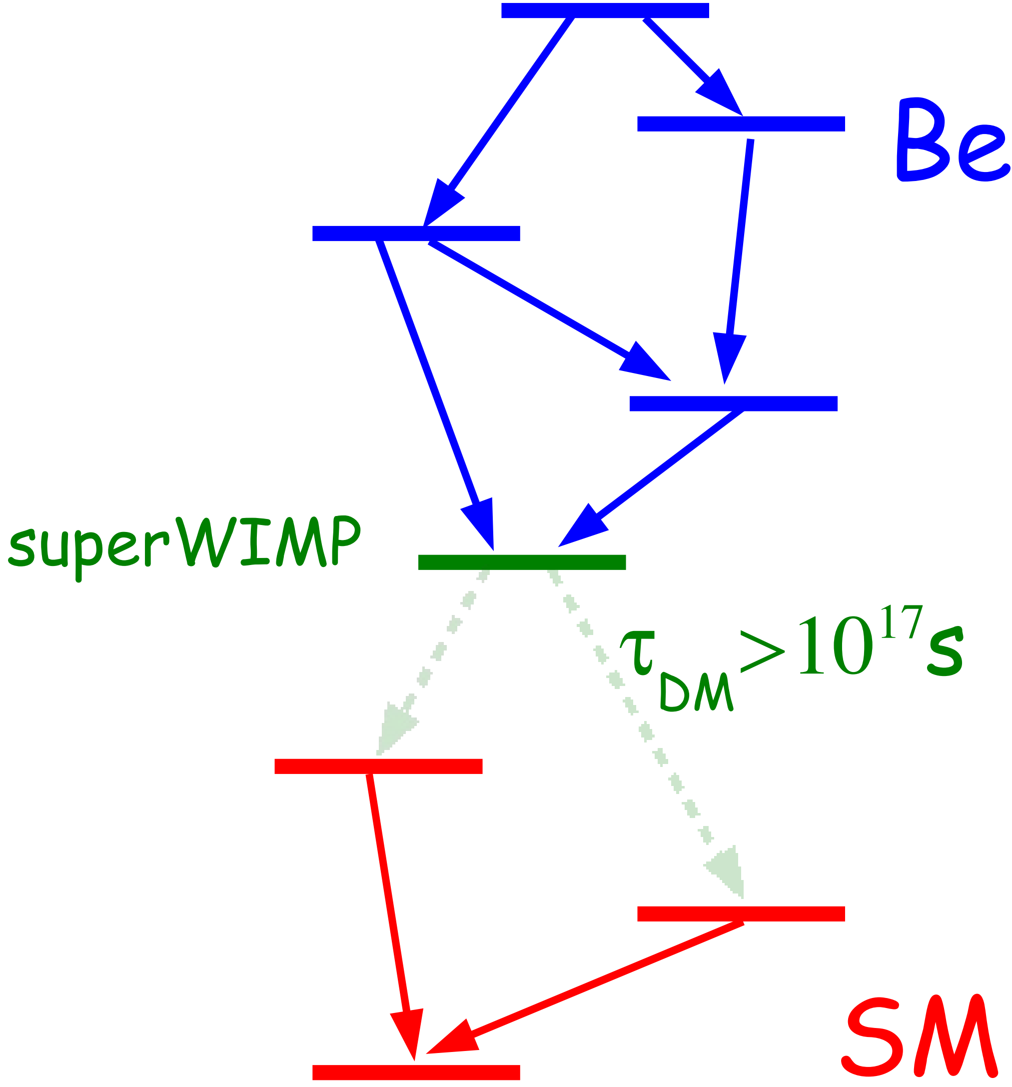


SuperWIMPs are <u>naturally very long lived</u>. Their lifetimes can be larger than the age of the Universe, or perhaps a few orders of magnitude smaller.



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

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.



Beyond the SM

superWIMP

$\tau_{DM} > 10^{17}$ s

SM

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.

- 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.

Interactions 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

**fermionic DM**

$\psi \rightarrow Z^0 \nu$

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

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

**scalar DM**

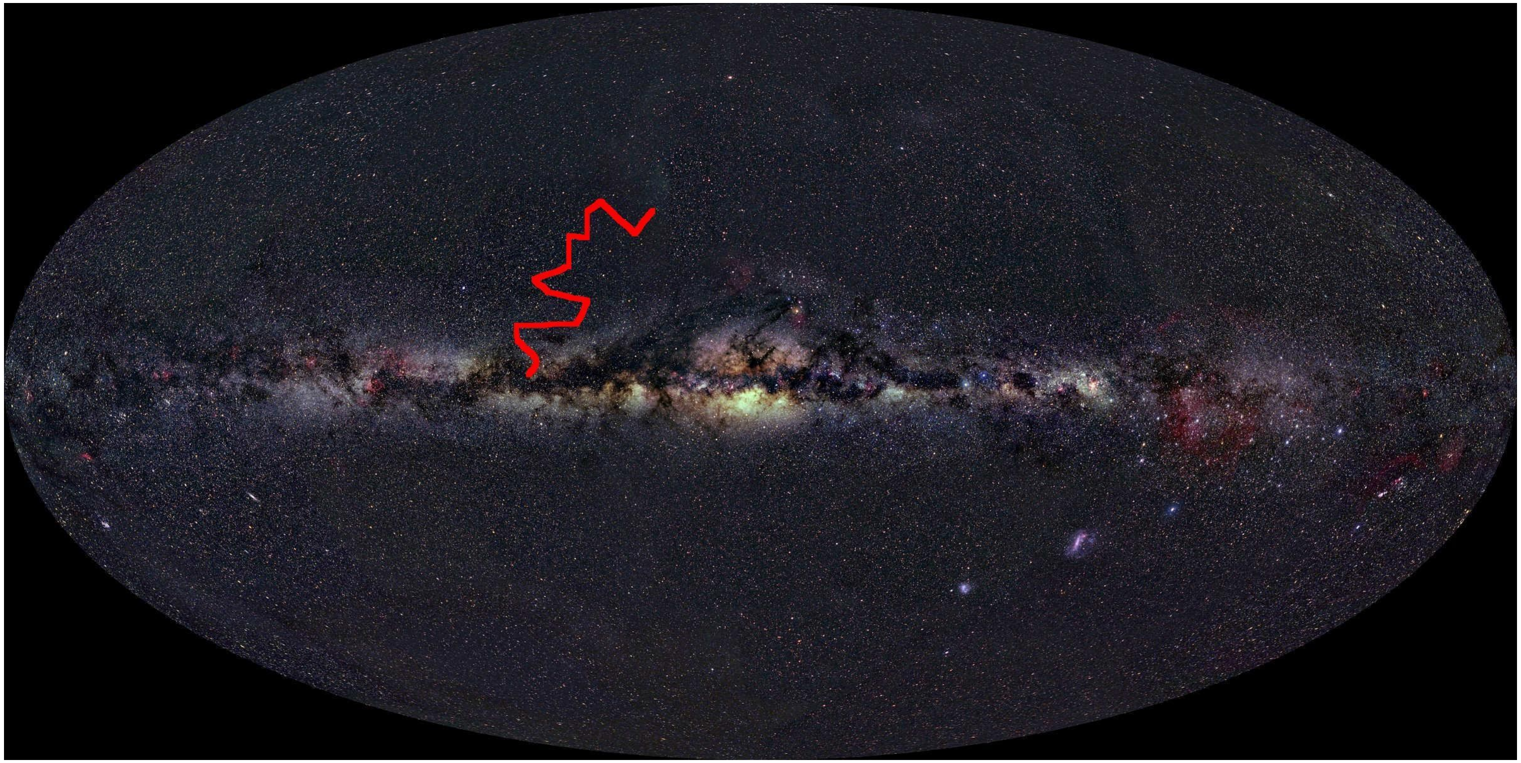
$\phi \rightarrow Z^0 Z^0$

$\phi \rightarrow W^+ W^-$

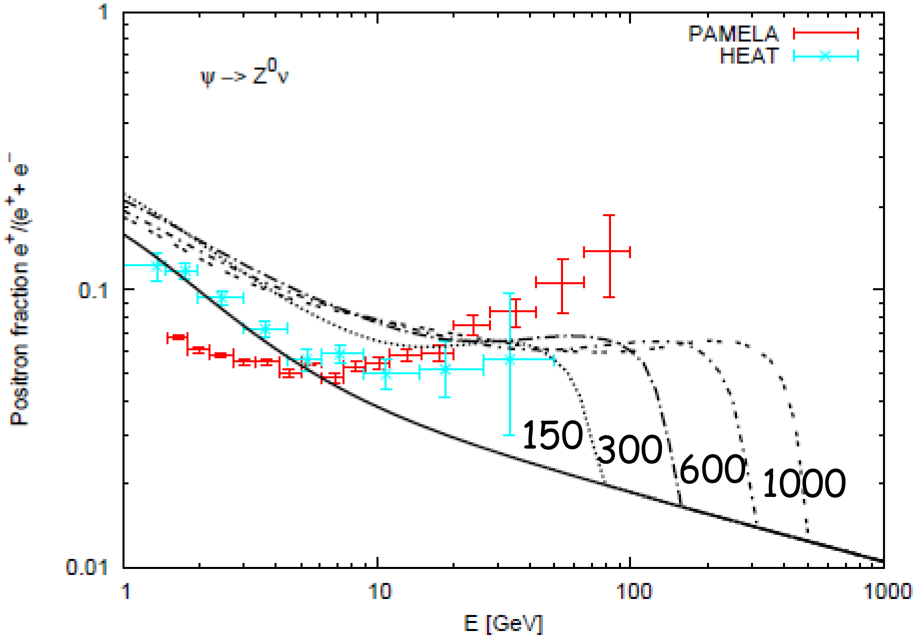
$\phi \rightarrow \ell^+ \ell^-$

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



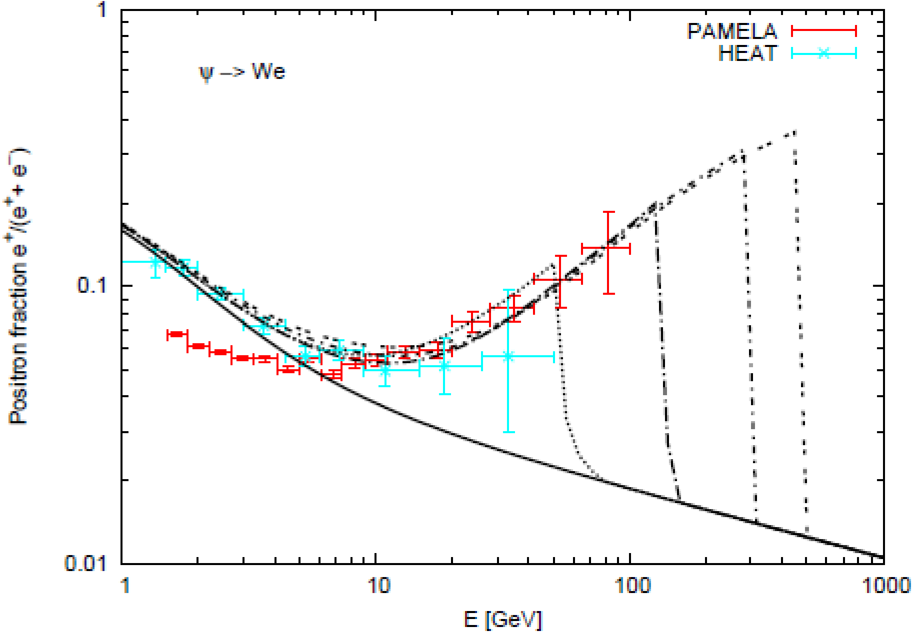
# $\psi \to Z^0 \nu$



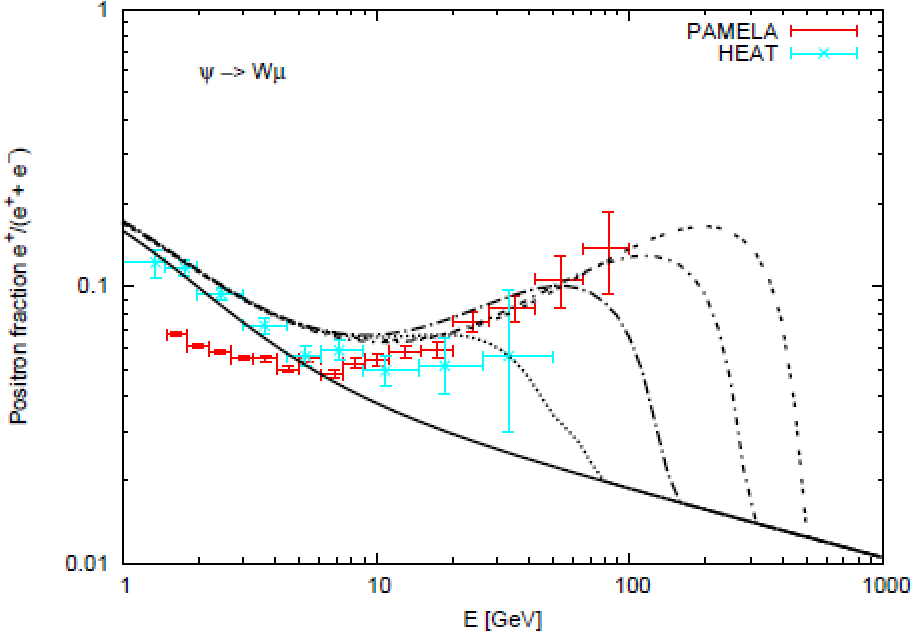
$\tau_{DM} \sim 10^{26}$s

Too flat to explain the steep rise
in the spectrum observed by PAMELA

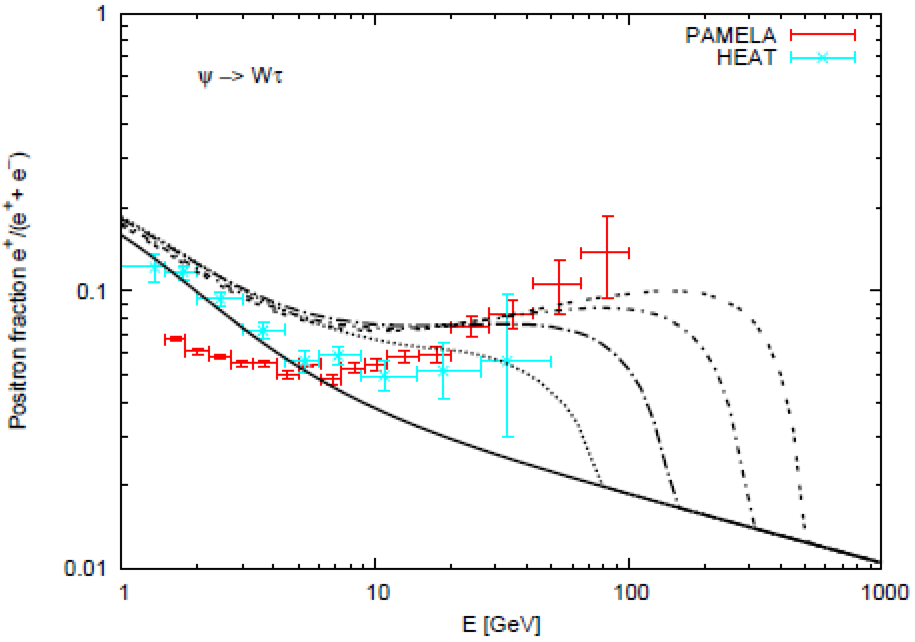
## $\psi \rightarrow W^{\pm}e^{\mp}$



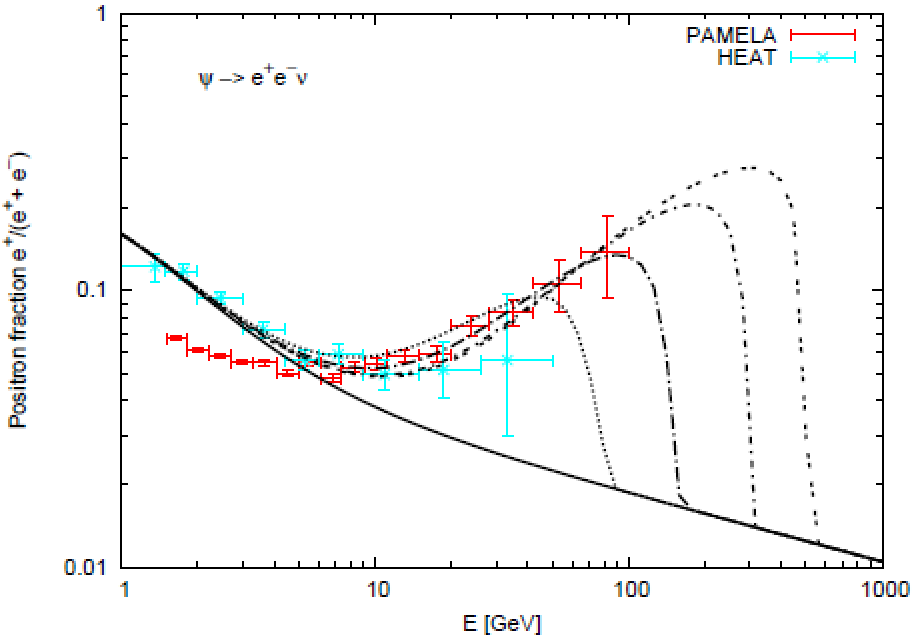
## $\psi \rightarrow W^{\pm}\mu^{\mp}$



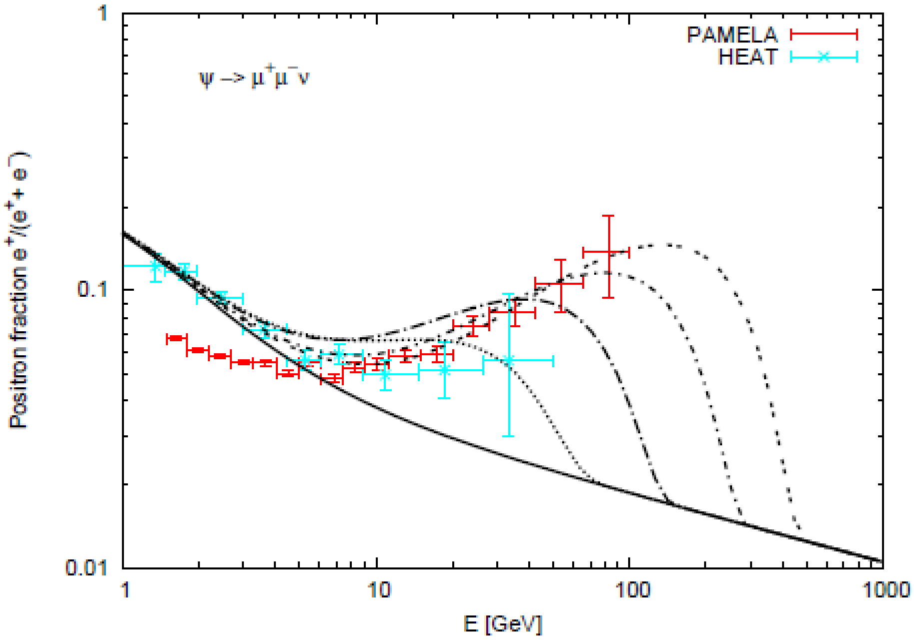
## $\psi \rightarrow W^{\pm}\tau^{\mp}$

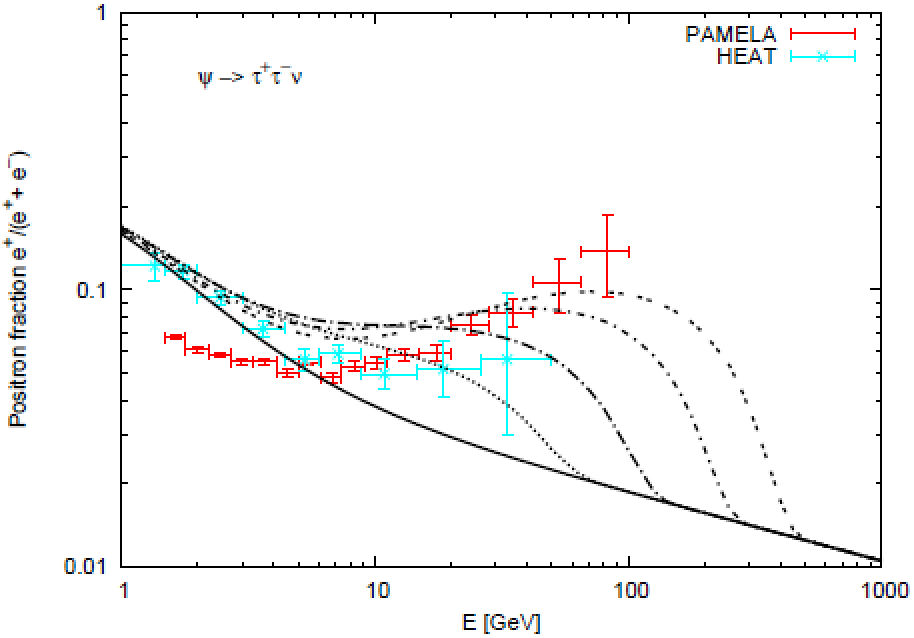


$\psi \rightarrow e^+ e^- \nu$



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





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

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

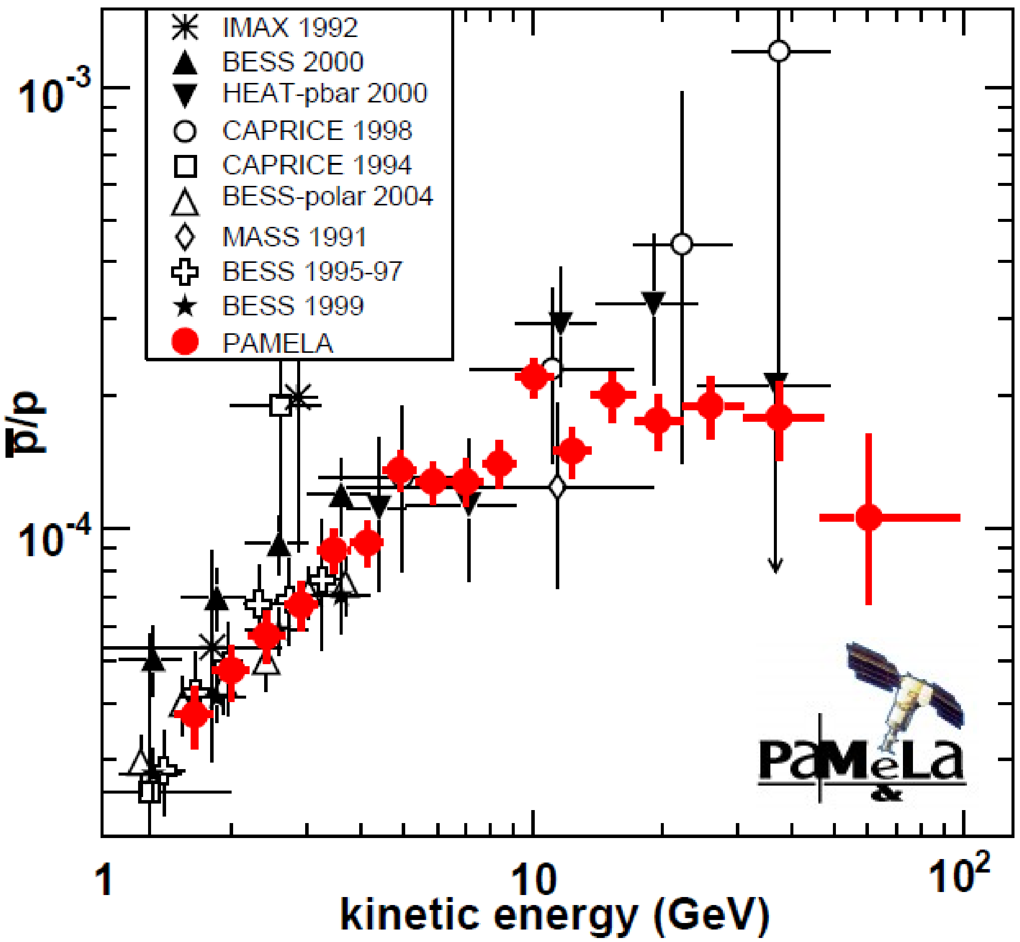
- **Has a mass larger than ~300 GeV,**
- **Has a lifetime around $10^{26}$ seconds,**
- **Decays preferentially into leptons of the first or second generation.**

The decay of dark matter also predicts a flux of

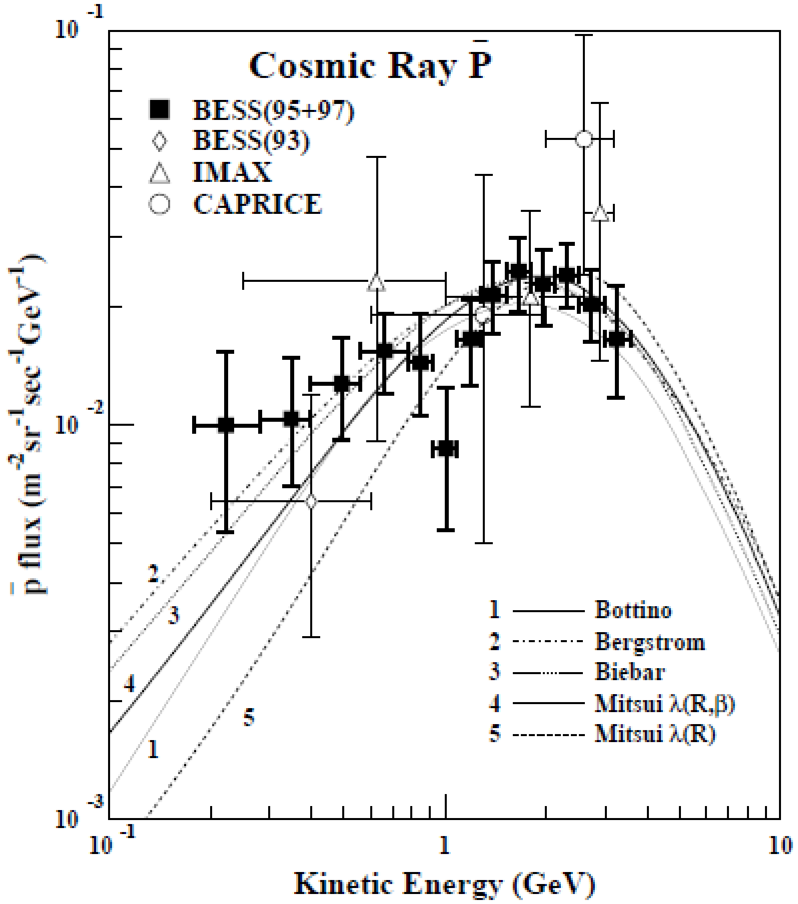
- Antiprotons
- Gamma rays
- Neutrinos

Additional constraints to the scenario!

# Antiproton flux from PAMELA



# Expectations from spallation

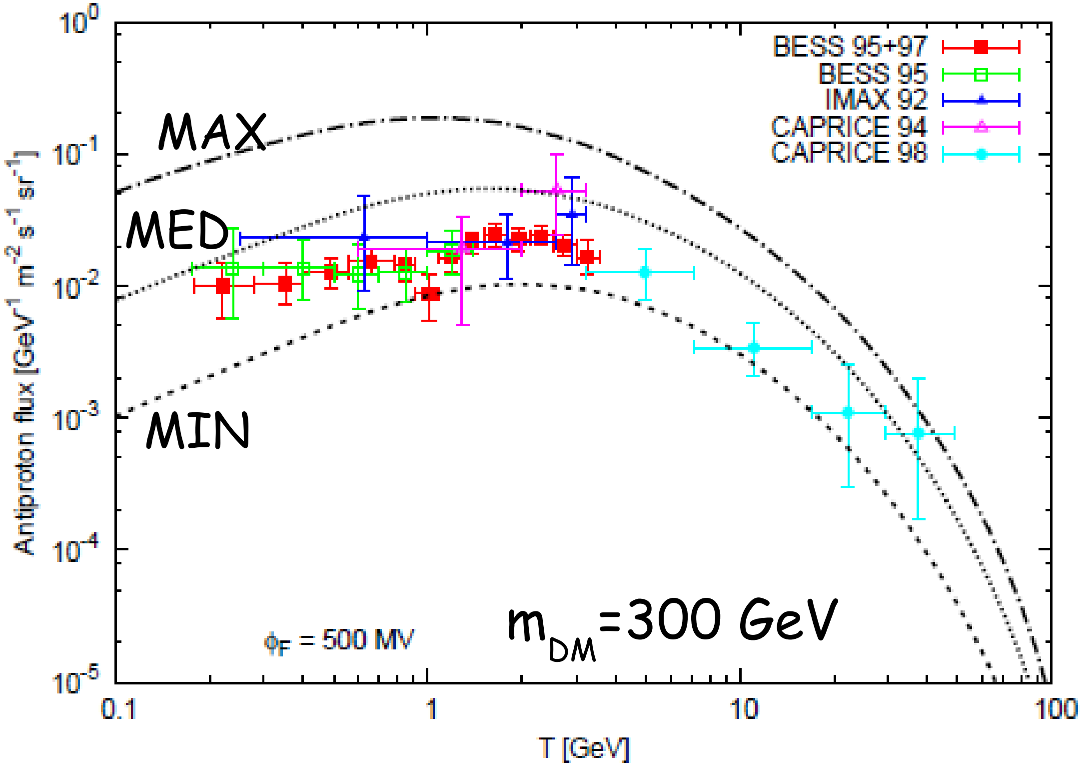


Good agreement of the theory with the experiments: no need for a sizable contribution to the primary antiproton flux. Purely leptonic decays (*e.g.* $\psi \to e^+e^-\nu$) are favoured over decays into weak gauge bosons.

# Antiproton flux from dark matter decay

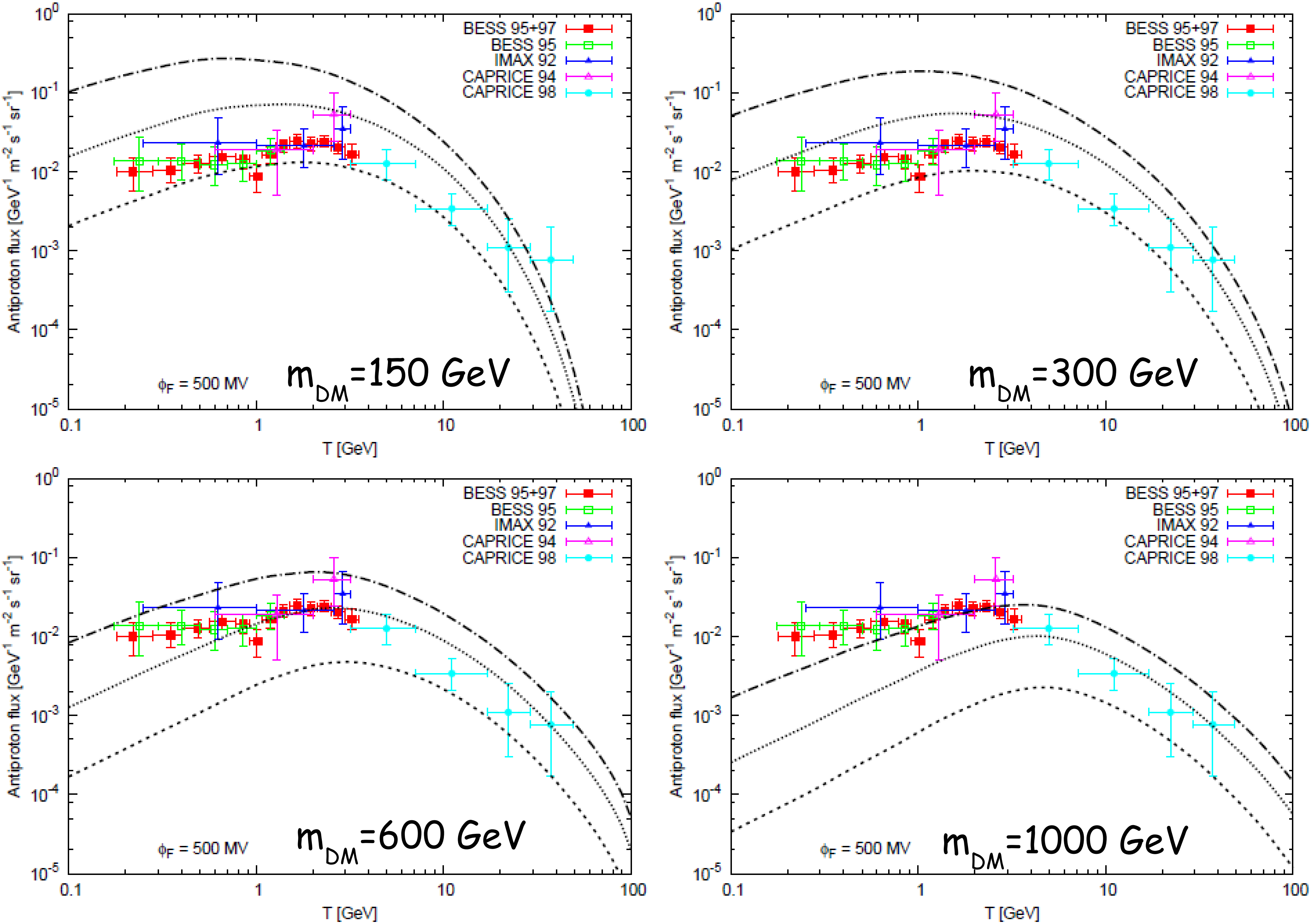
Propagation mechanism more complicated than for the positrons. We neglect in our analysis reacceleration and tertiary contributions

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

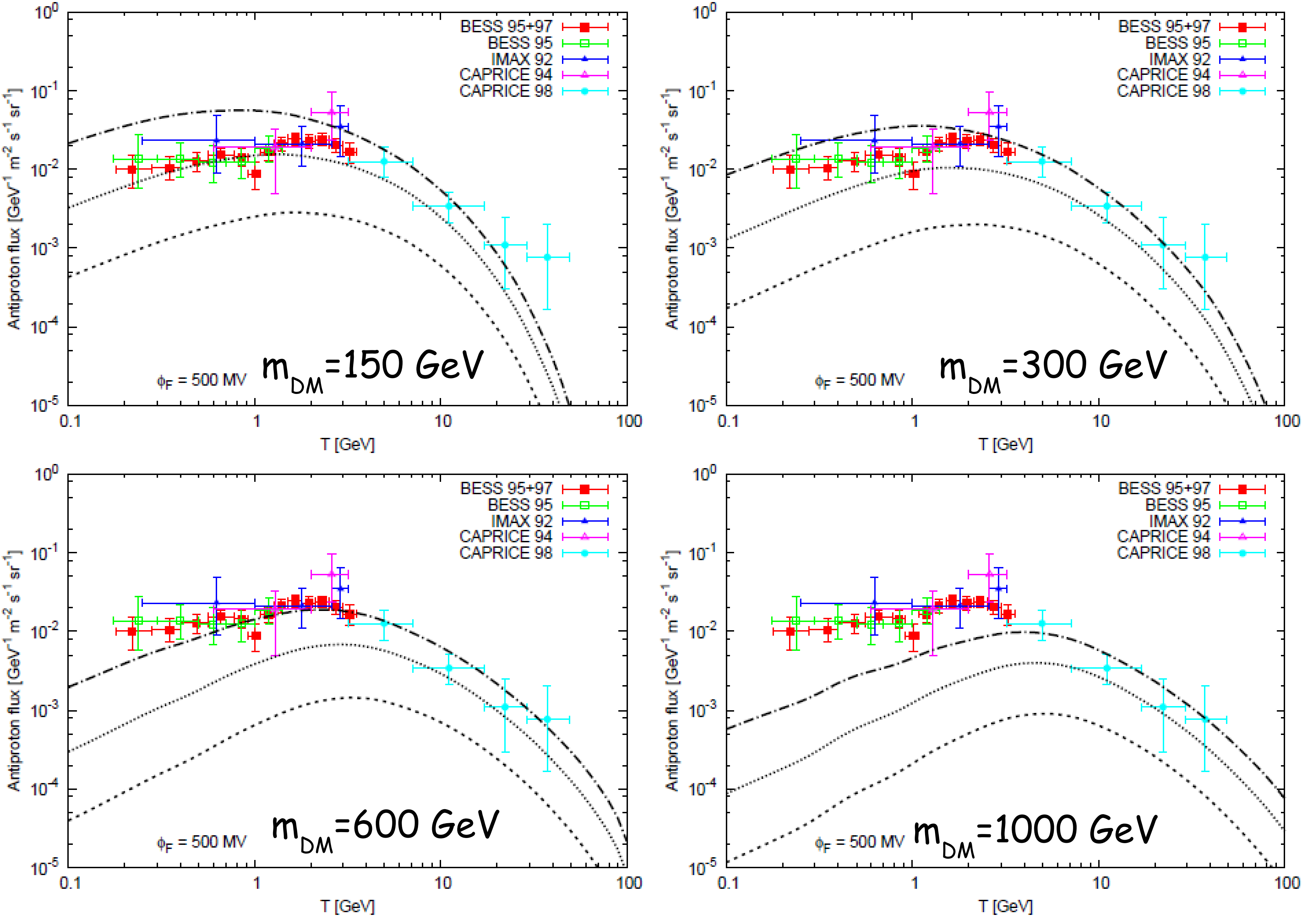


$$\psi \rightarrow Z^0\, \nu$$

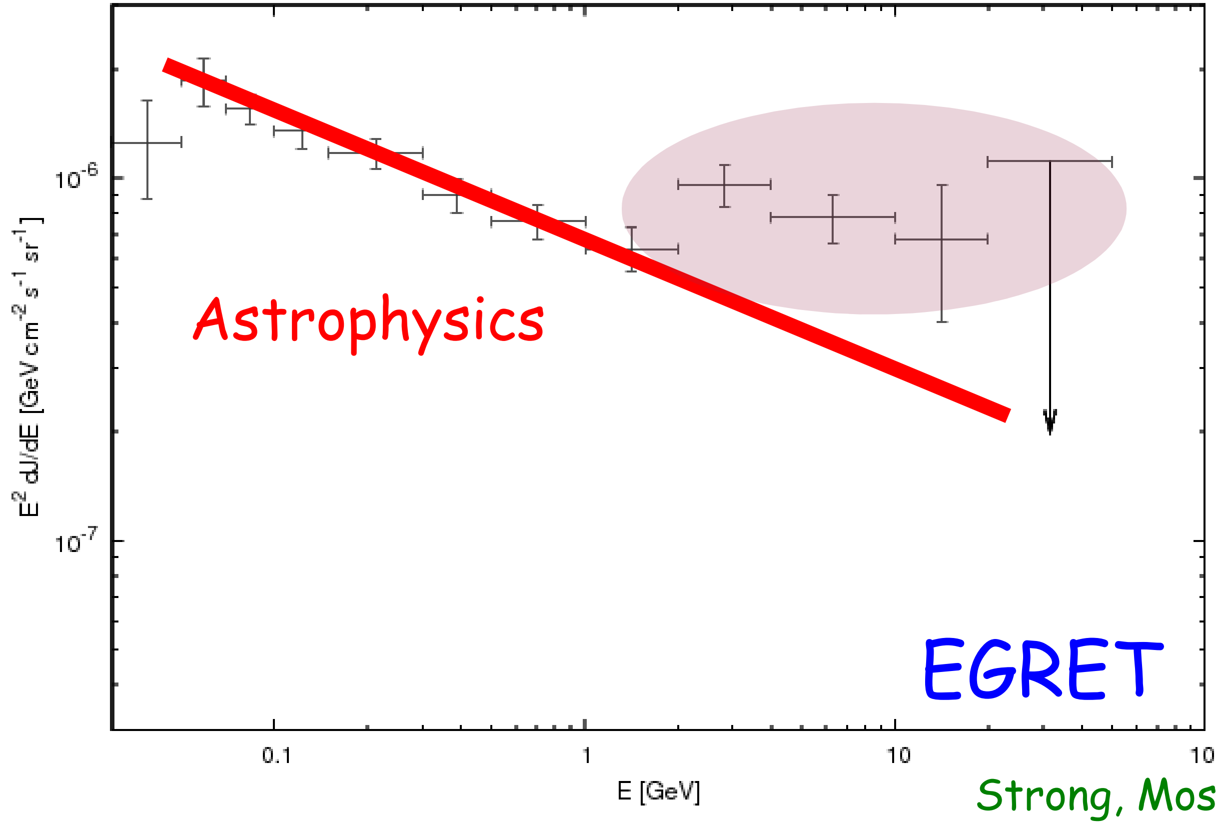
# $\psi \to Z^0 \nu$


BESS 95+97
BESS 95
IMAX 92
CAPRICE 94
CAPRICE 98
Antiproton flux [GeV$^{-1}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]
T [GeV]
10$^{0}$
10$^{-1}$
10$^{-2}$
10$^{-3}$
10$^{-4}$
10$^{-5}$
0.1
1
10
100
$\phi_F$ = 500 MV
$m_{DM}$=150 GeV
$m_{DM}$=300 GeV
$m_{DM}$=600 GeV
$m_{DM}$=1000 GeV

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



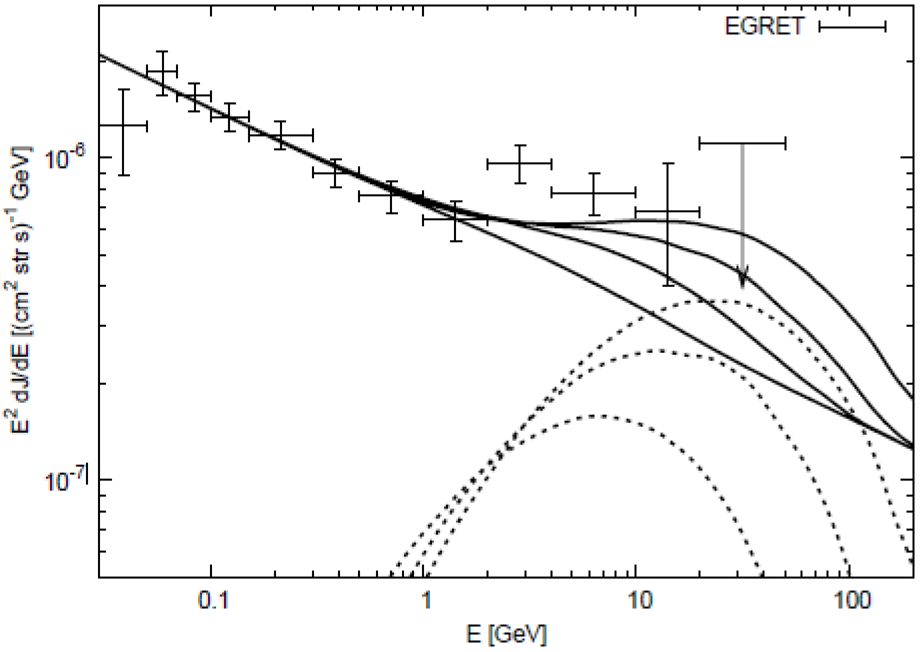
# Extragalactic gamma ray flux from EGRET



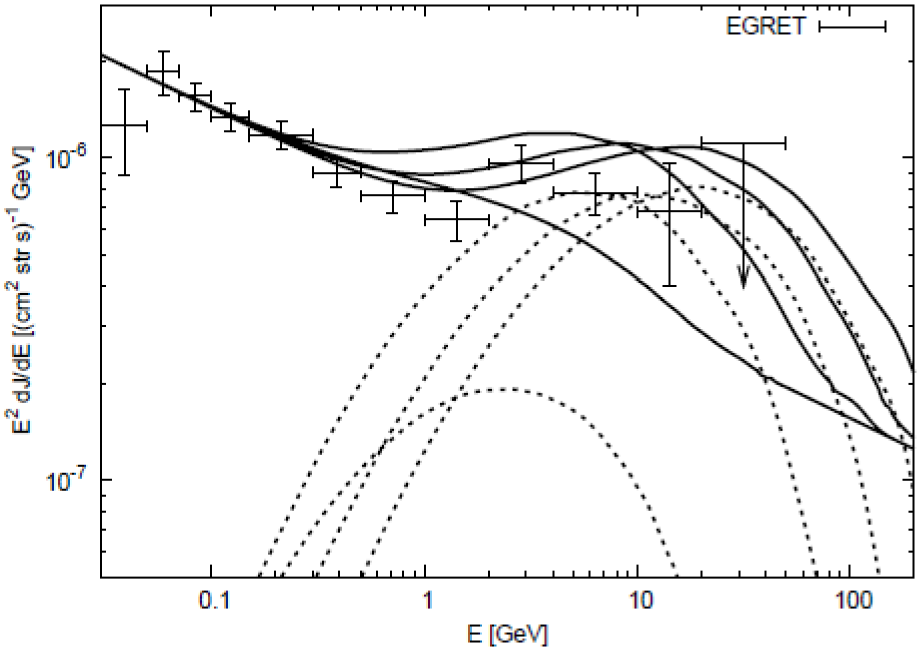
Strong, Moskalenko, Reimer

Hint for an exotic contribution in the extragalactic gamma ray flux

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

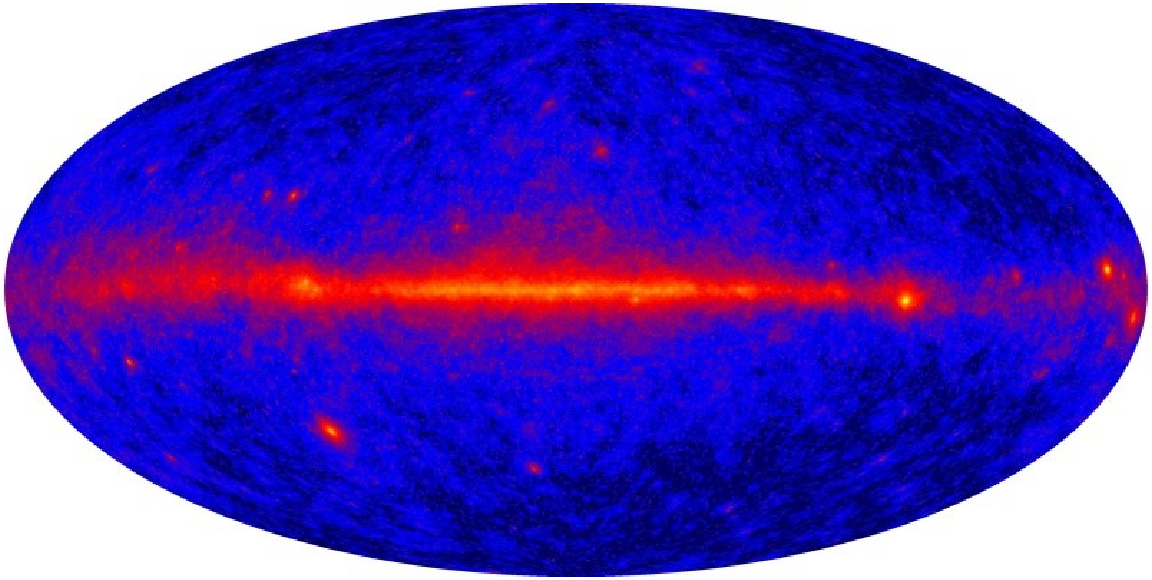


$\psi \to Z^{0}\, \nu$



# Better measurements will be available soon

Fermi
Gamma-ray
Space Telescope



# Summary of fermionic dark matter decay:

| | |
|---|---|
| $\Psi \to Z^0 \nu$ | Not promising. Positron spectrum too flat. |
| $\Psi \to W^\pm \ell^\mp$ | Promising if $\ell$=e, $\mu$, and the DM mass is larger than ~300GeV. A signal at Fermi is predicted! |
| $\Psi \to \ell^+ \ell^- \nu$ | Promising if $\ell$=e, $\mu$, and the DM mass is larger than 300GeV. No signal at Fermi. |

# Conclusions

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

Evidence for a primary component:

New astrophysics?

New particle physics?

- Decaying dark matter could naturally explain the positron excess observed by PAMELA provided the mass is larger than ~300 GeV, the lifetime is around $10^{26}$s, and the dark matter particle decays preferentially into electrons or muons.