Cosmic Ray Signatures of Dark Matter Decay

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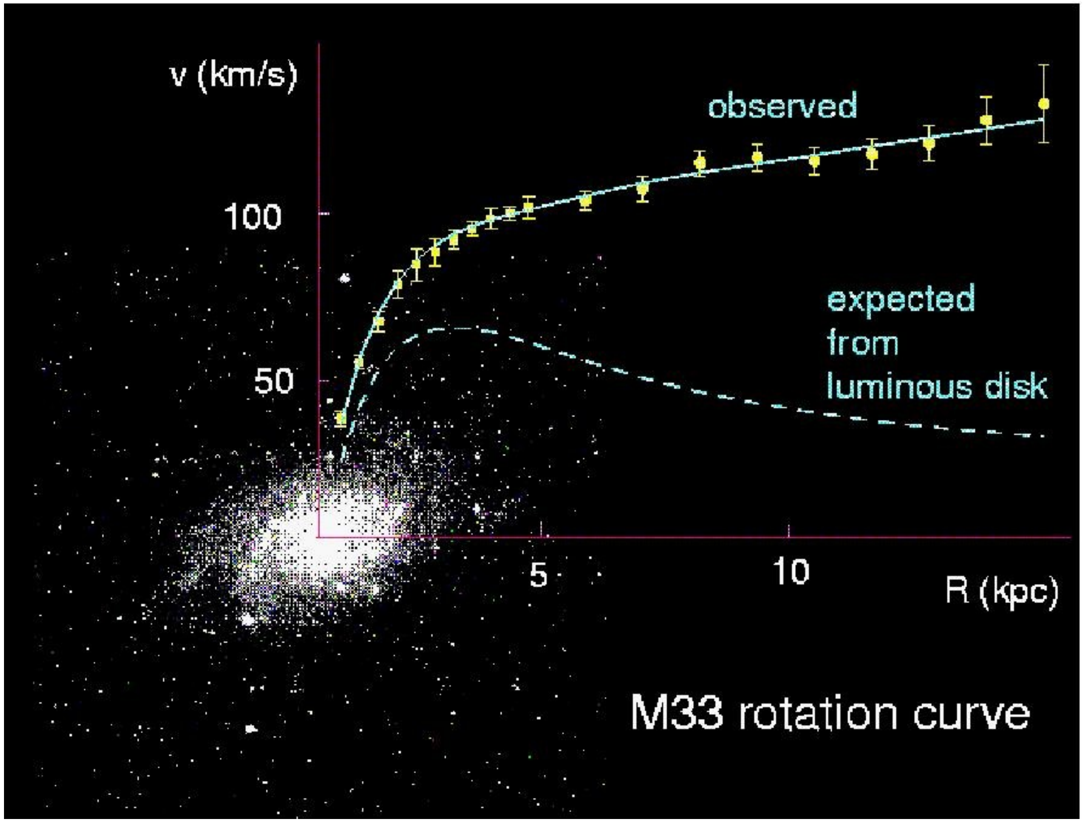
Many thanks to Wilfried Buchmüller, Gianfranco Bertone, Laura Covi, Michael Grefe, Koichi Hamaguchi, Tetsuo Shindou, Fumihiro Takayama, **David Tran**, Andreas Ringwald, **Christoph Weniger**, Tsutomu Yanagida.

IPMU

7th December 2009

Introduction

Dark matter exist



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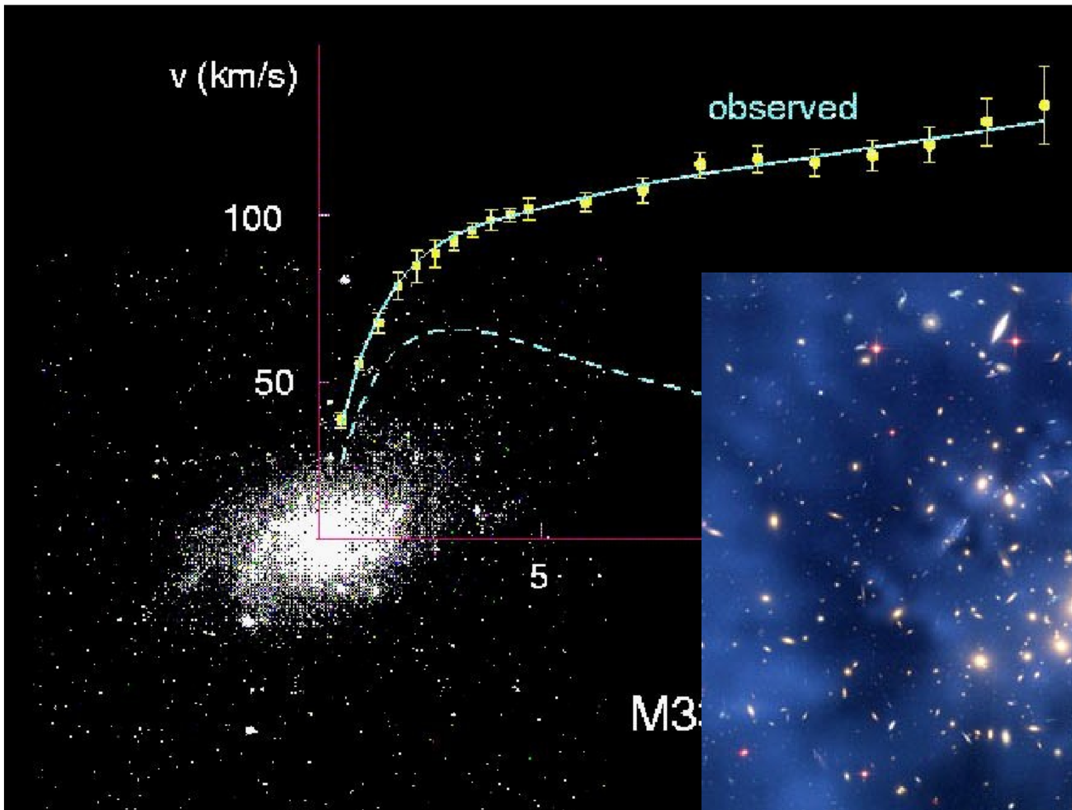

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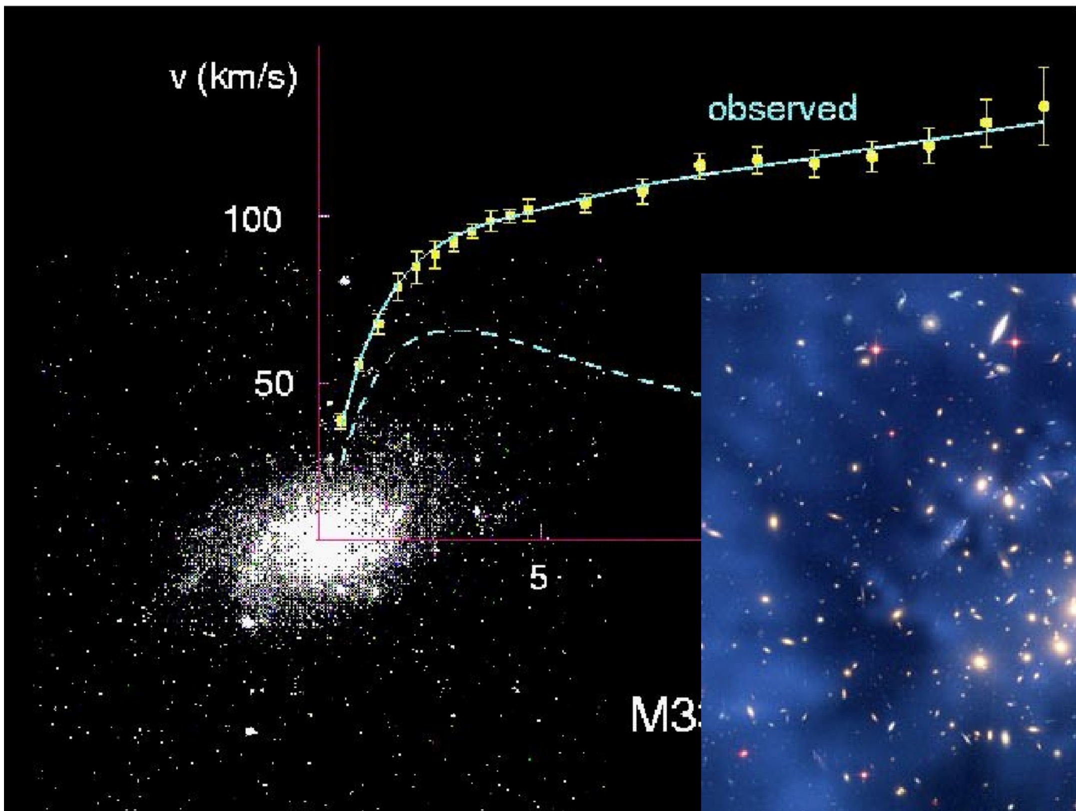

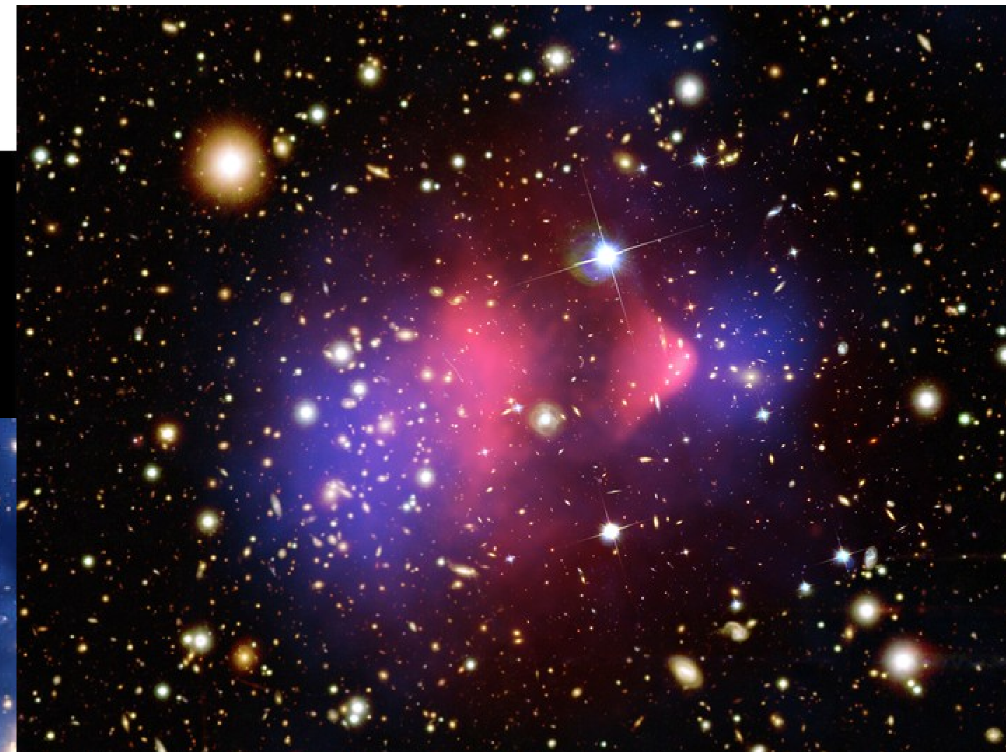

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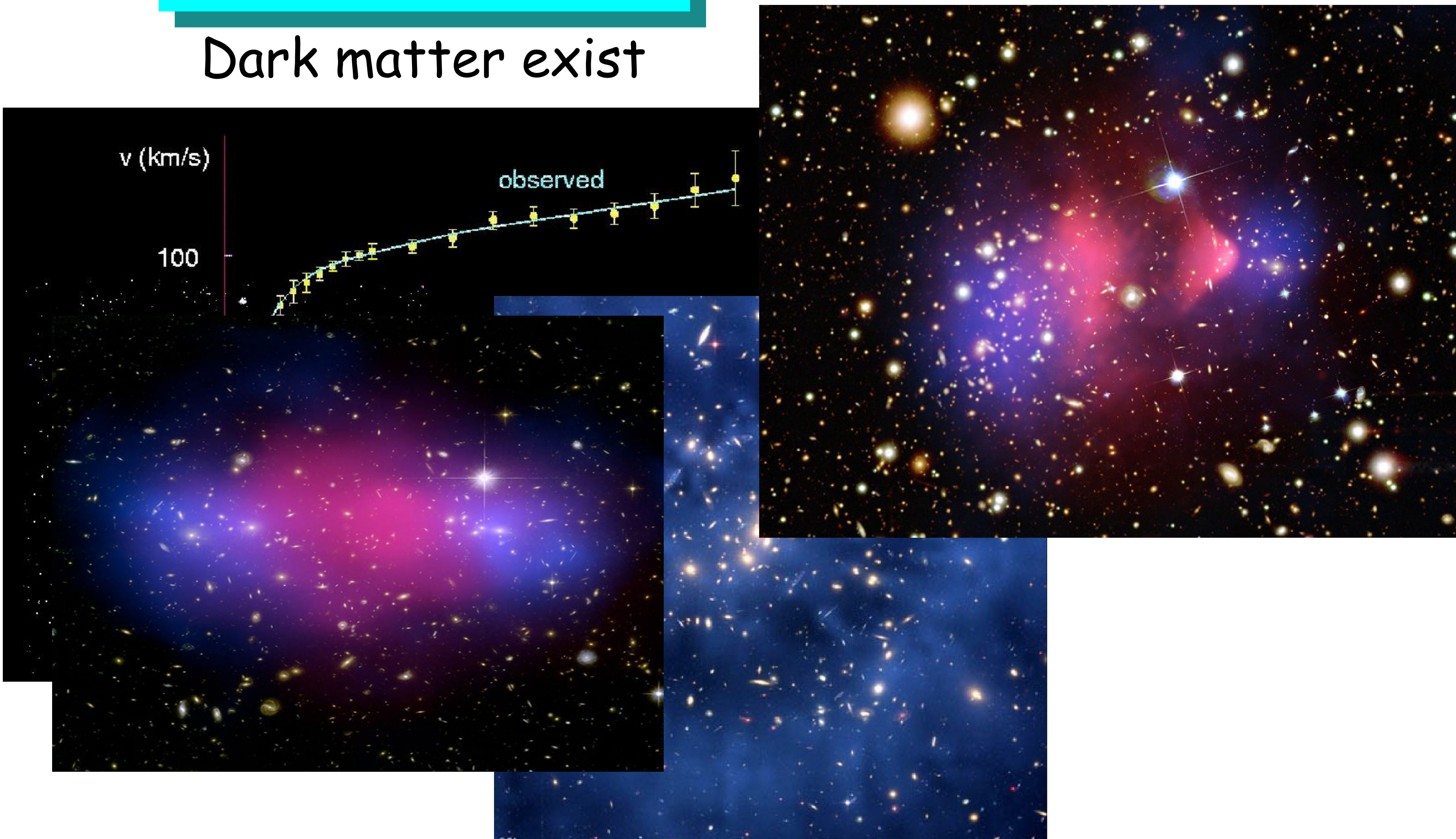

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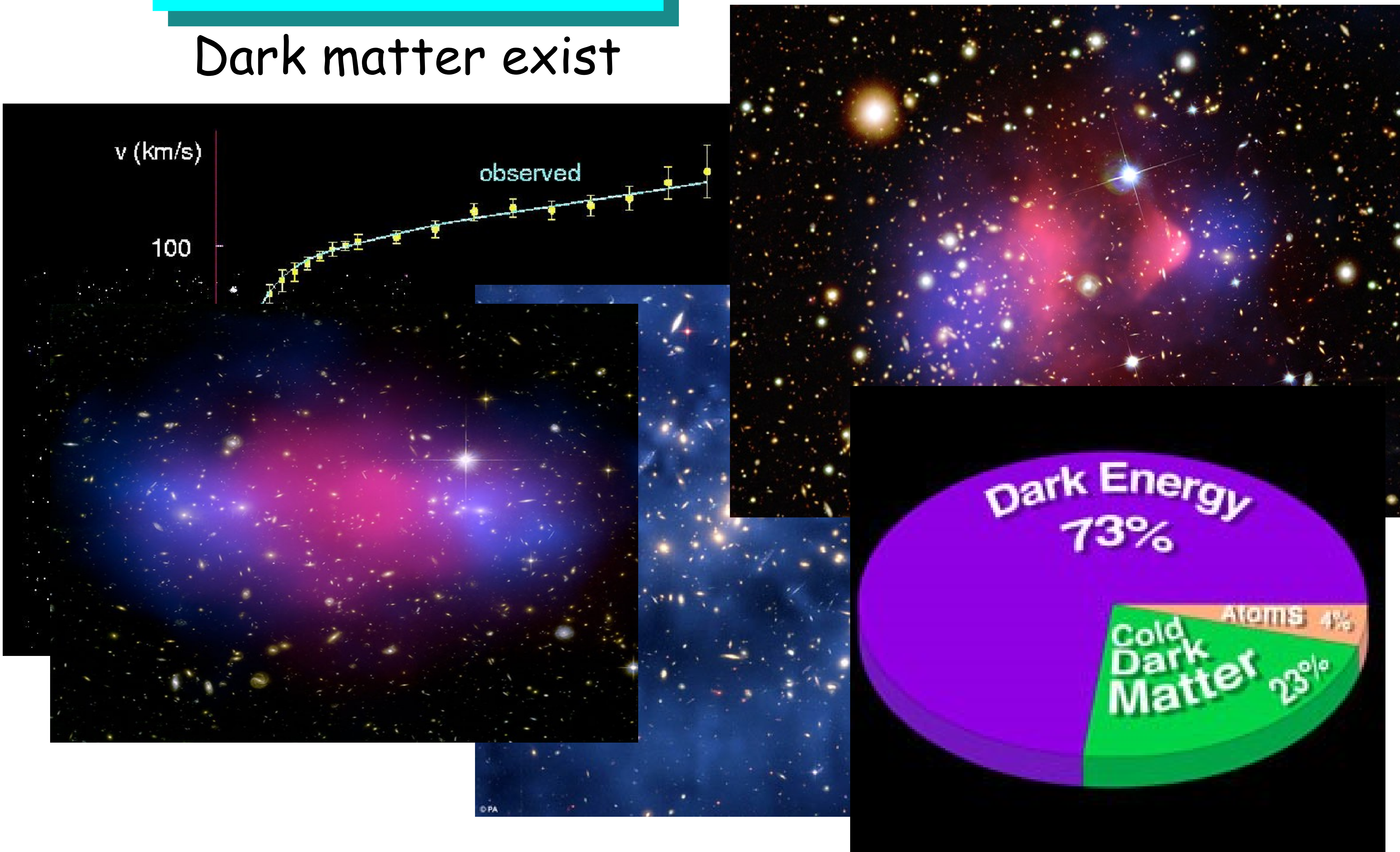


What is
the dark matter?

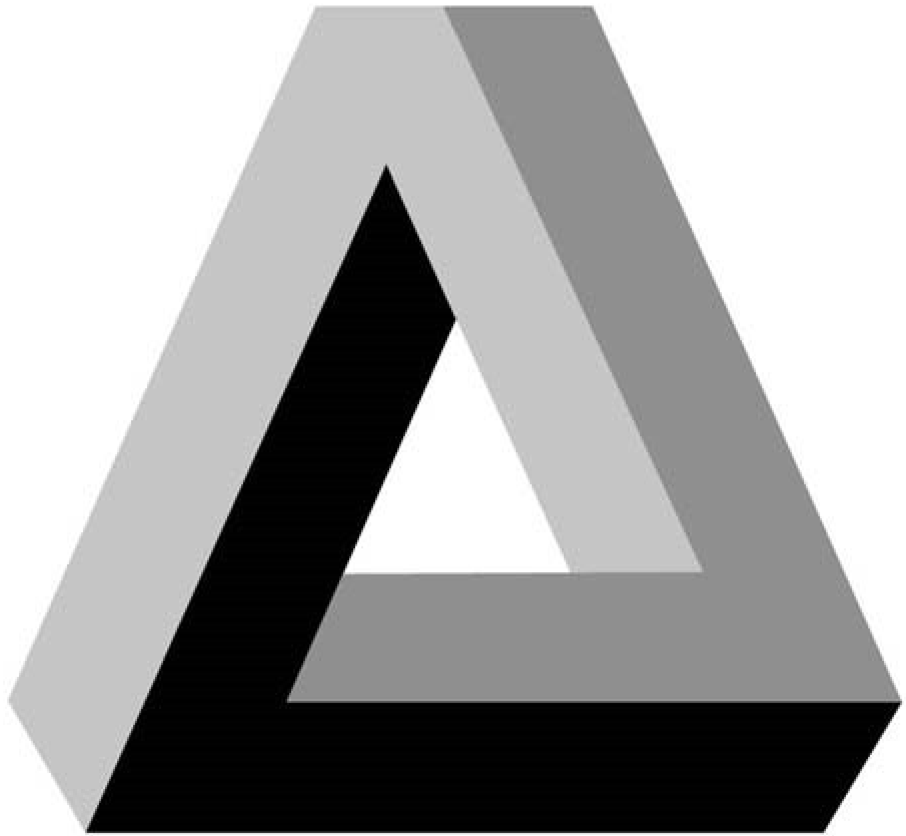
All these evidences for dark matter are of gravitational origin

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

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

Direct detection

DM nucleus → DM nucleus



Indirect detection

DM DM →γγ, e+e-... (annihilation)

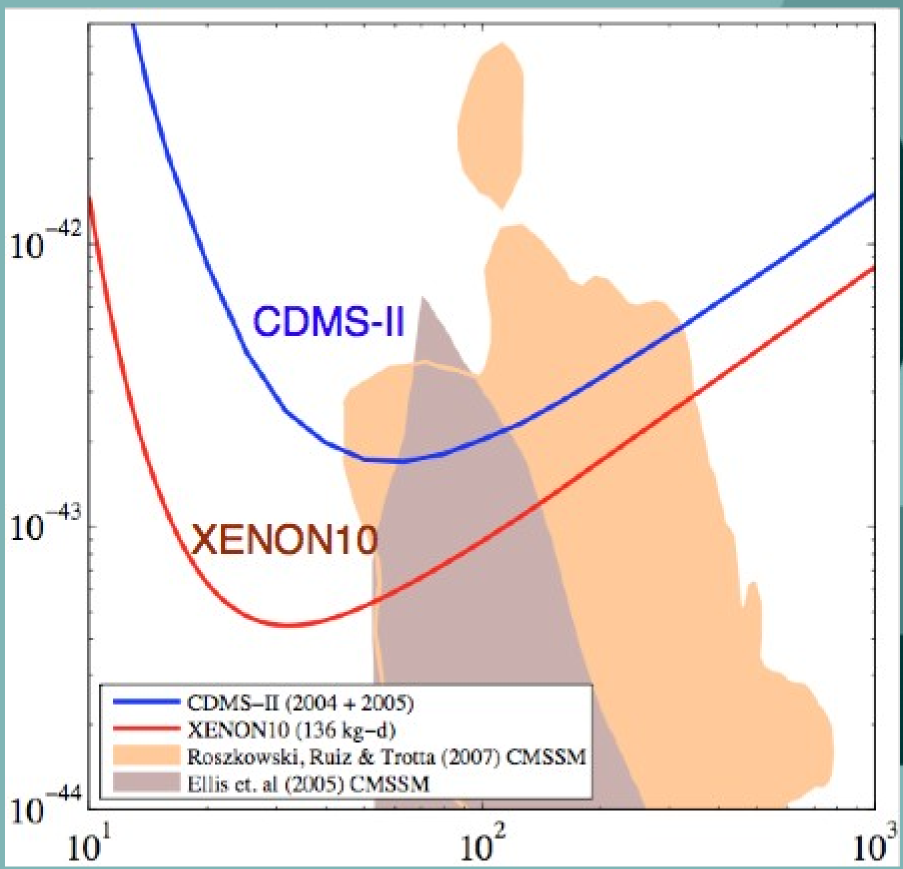
DM →γ X, e+X,... (decay)

Collider searches

pp → DM X

Direct detection

DM nucleus → DM nucleus



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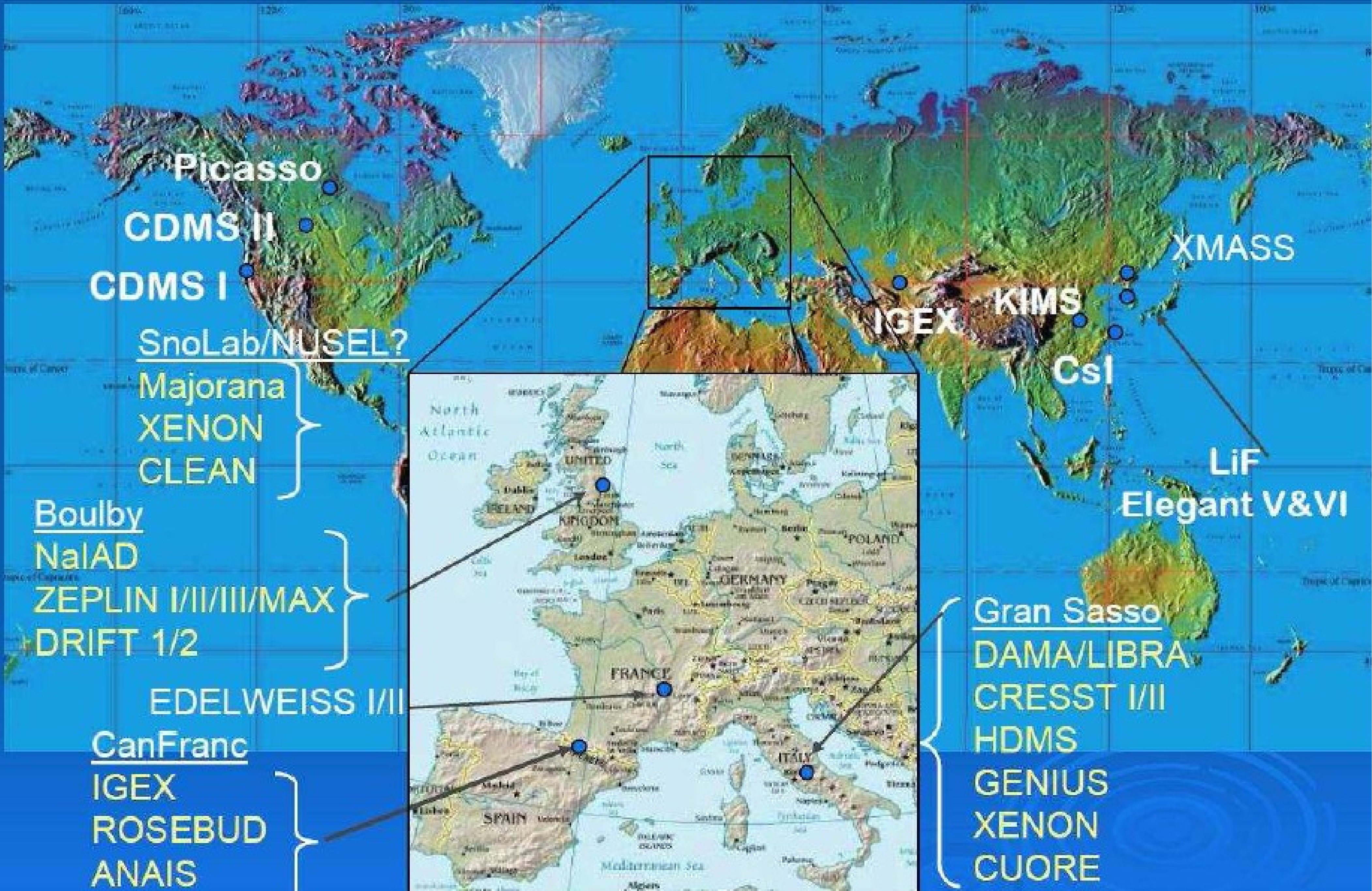
DM →γ X, e+X,... (decay)

Collider searches

pp → DM X

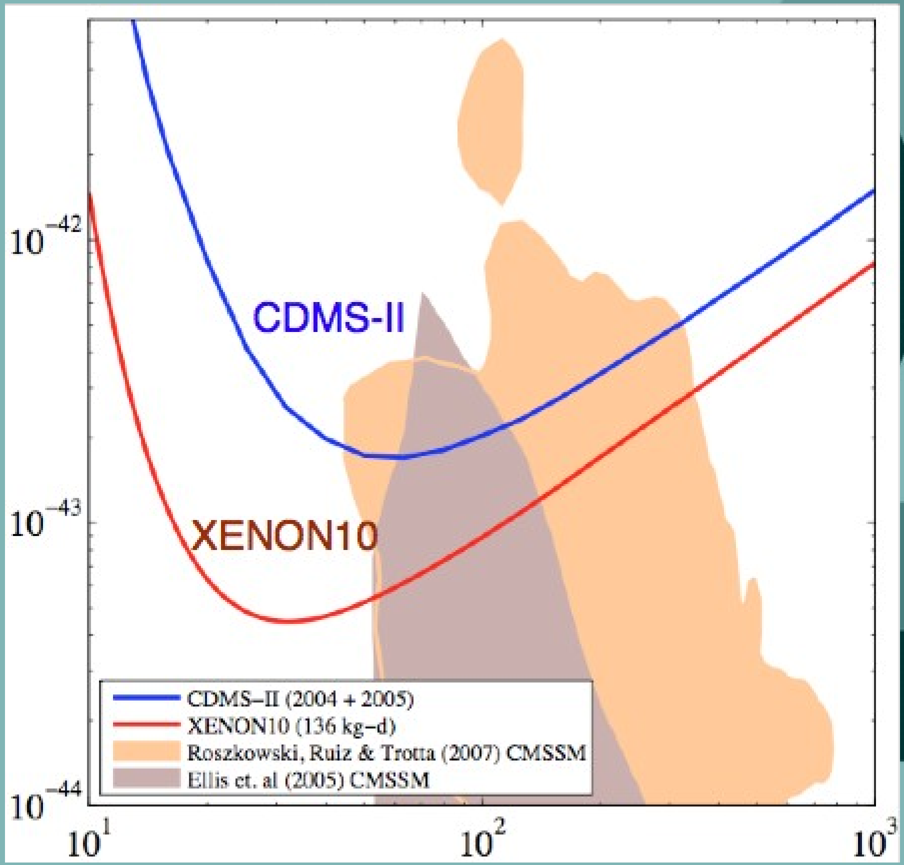
World Wide WIMP Search

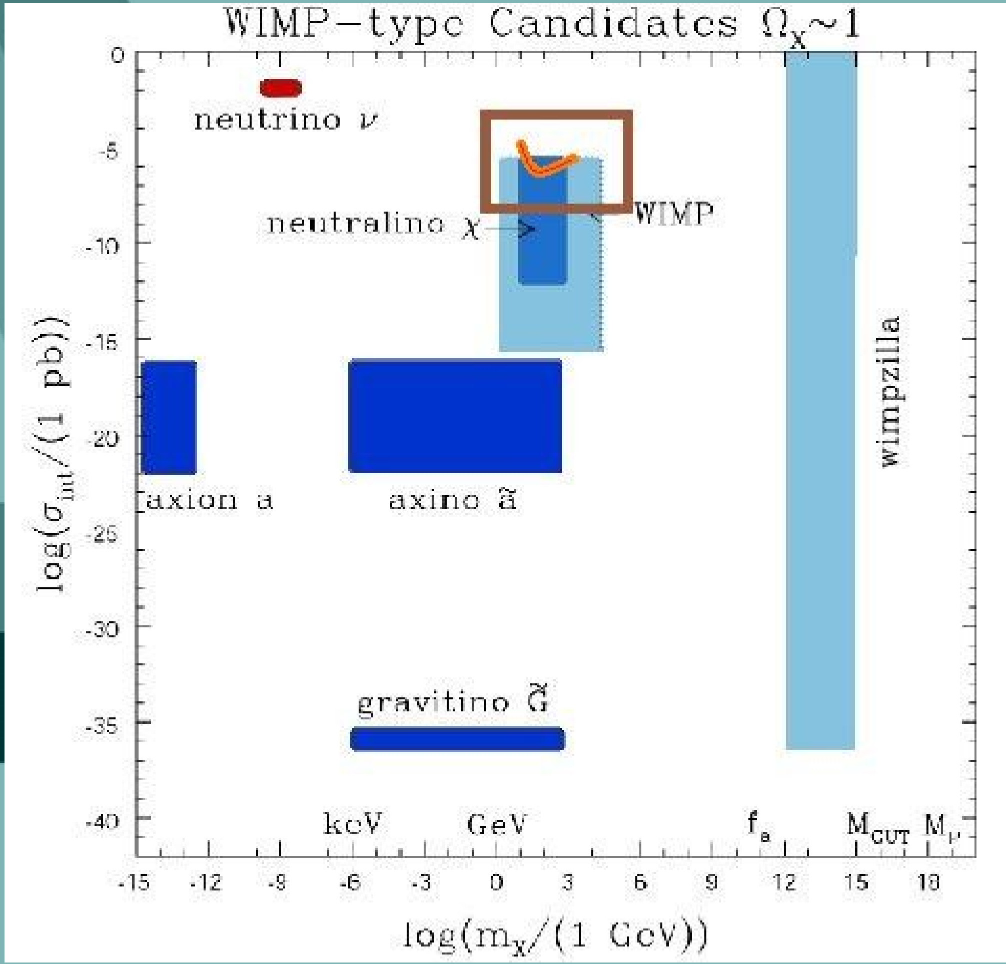


From Laura Baudis

Direct detection

DM nucleus → DM nucleus





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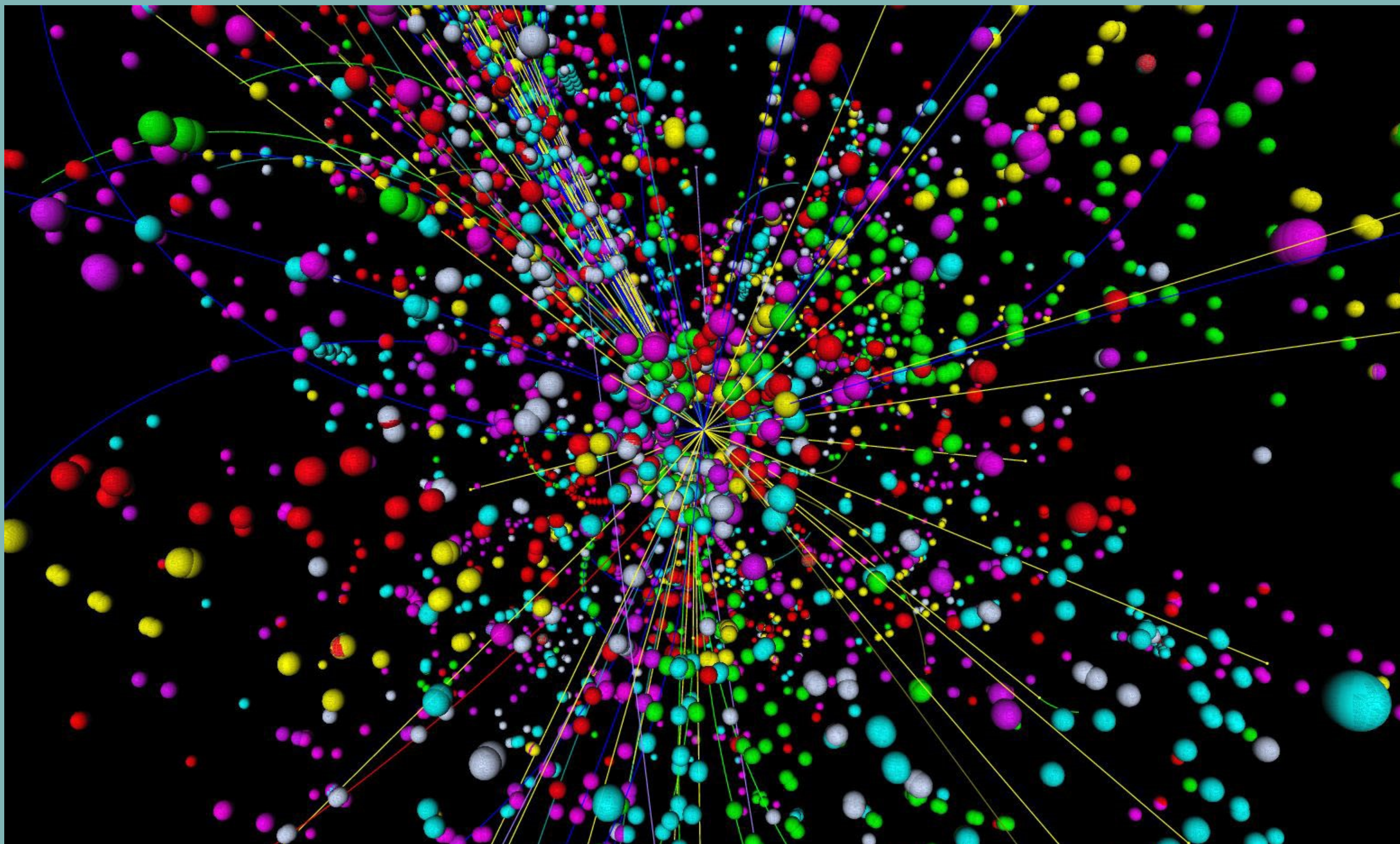


Indirect detection

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

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

Collider searches

pp $\rightarrow$ DM X

Direct detection

DM nucleus $\rightarrow$ DM nucleus

Indirect detection

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

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

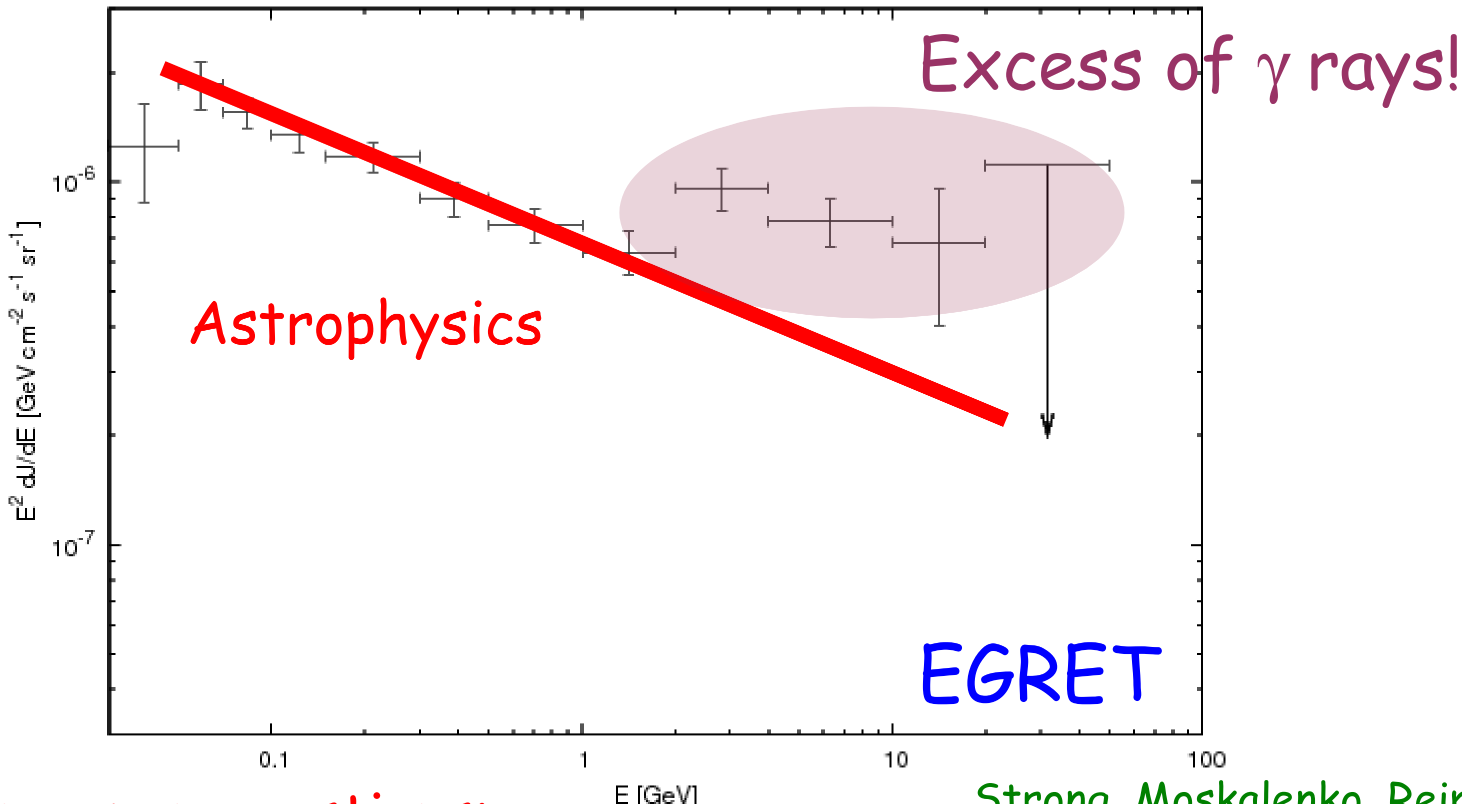
Collider searches

pp $\rightarrow$ DM X

Exciting possibility!

There have been indications in the past for dark matter annihilation/decay

Diffuse "extragalactic" gamma ray flux



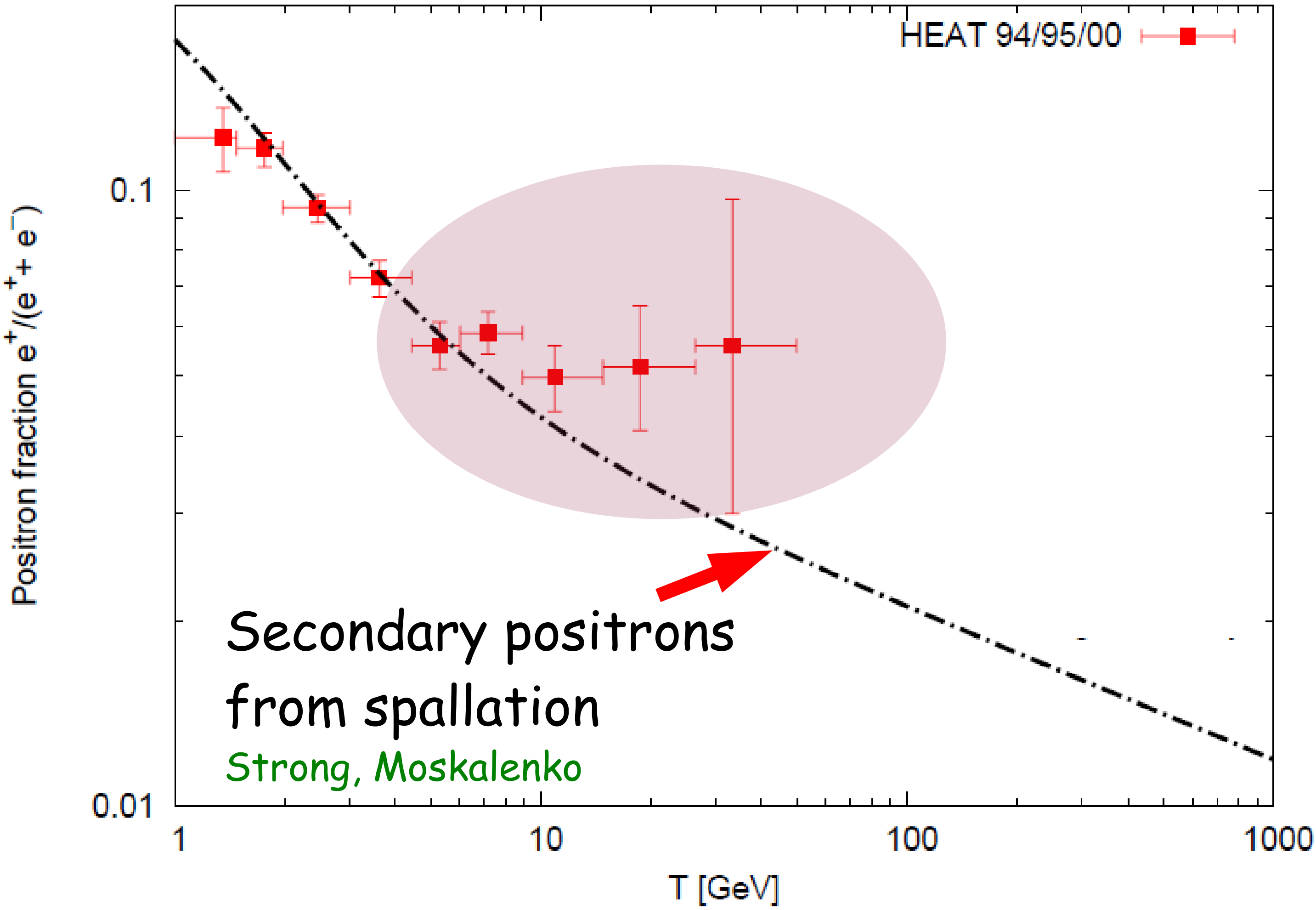
Strong, Moskalenko, Reimer

Many open questions:

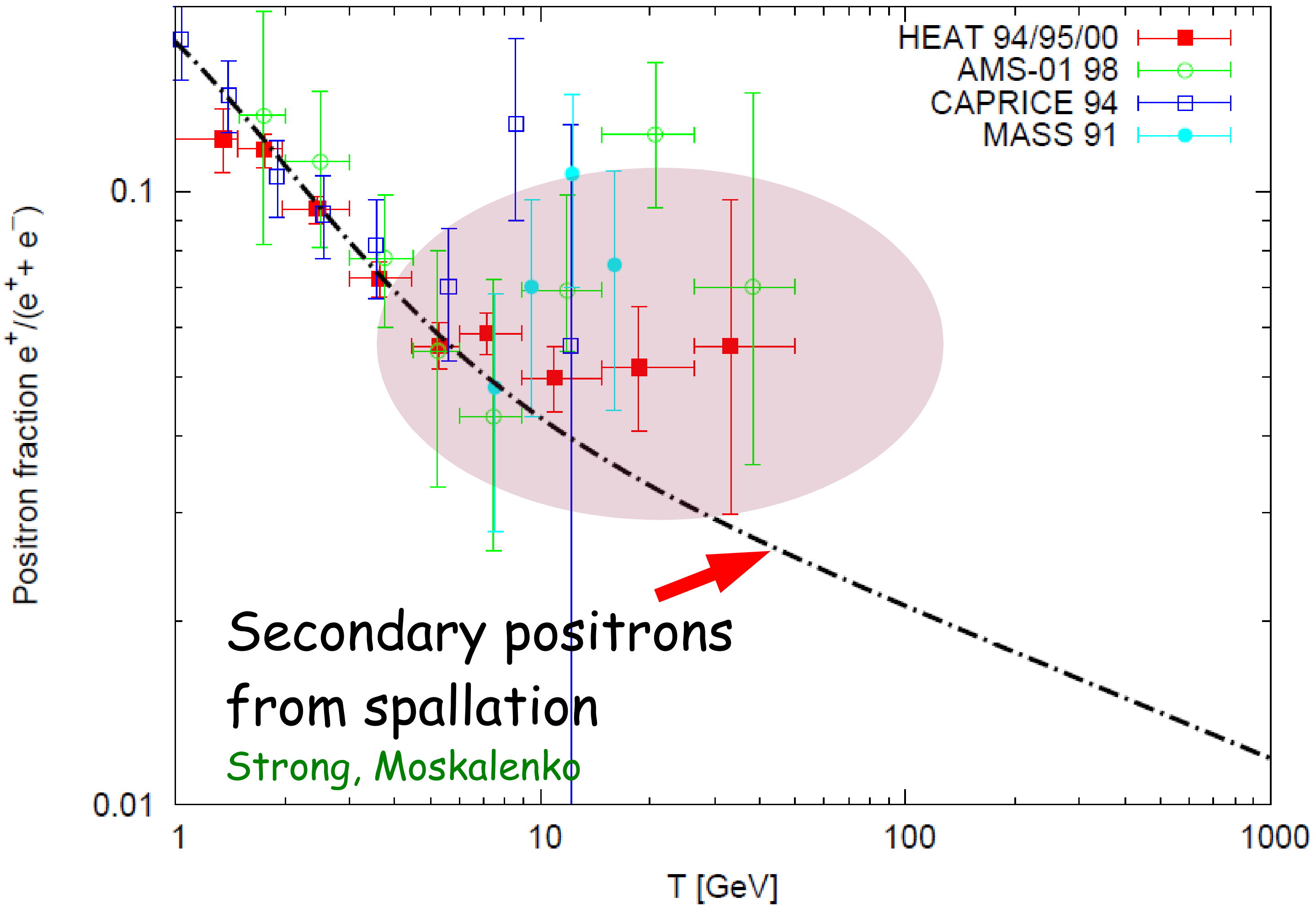
- Extraction of the signal from the galactic foreground
- Is the signal isotropic/anisotropic
- Precise shape of the energy spectrum
- Does this excess exist at all? Stecker, Hunter, Kniffen

(Possibly not, according to preliminary Fermi data)

Positron Fraction

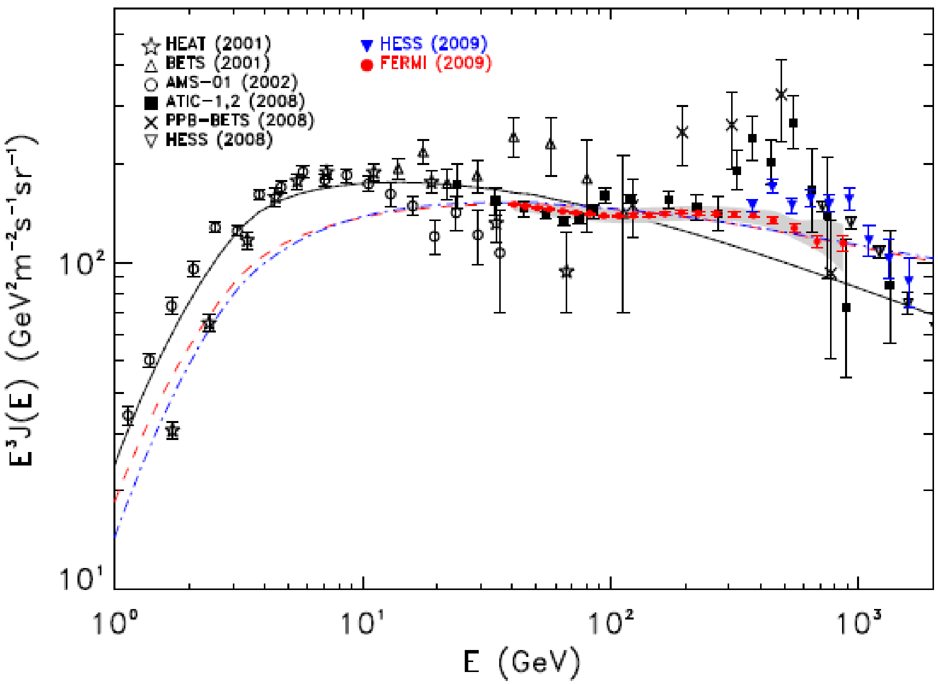


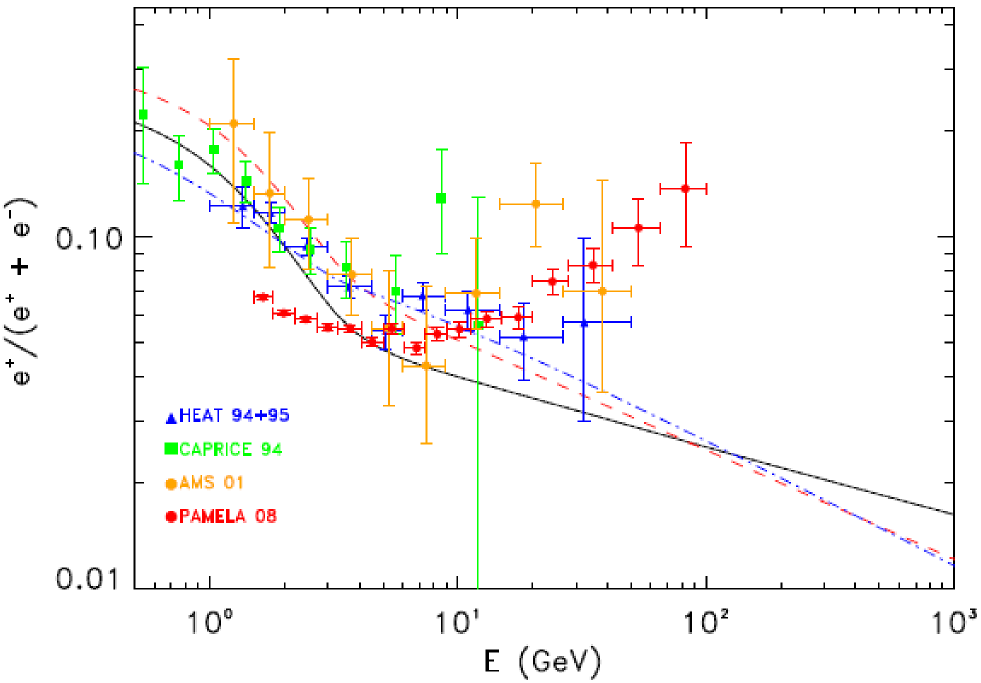
Positron Fraction



Spectacular experimental progress over the last year

Present situation:





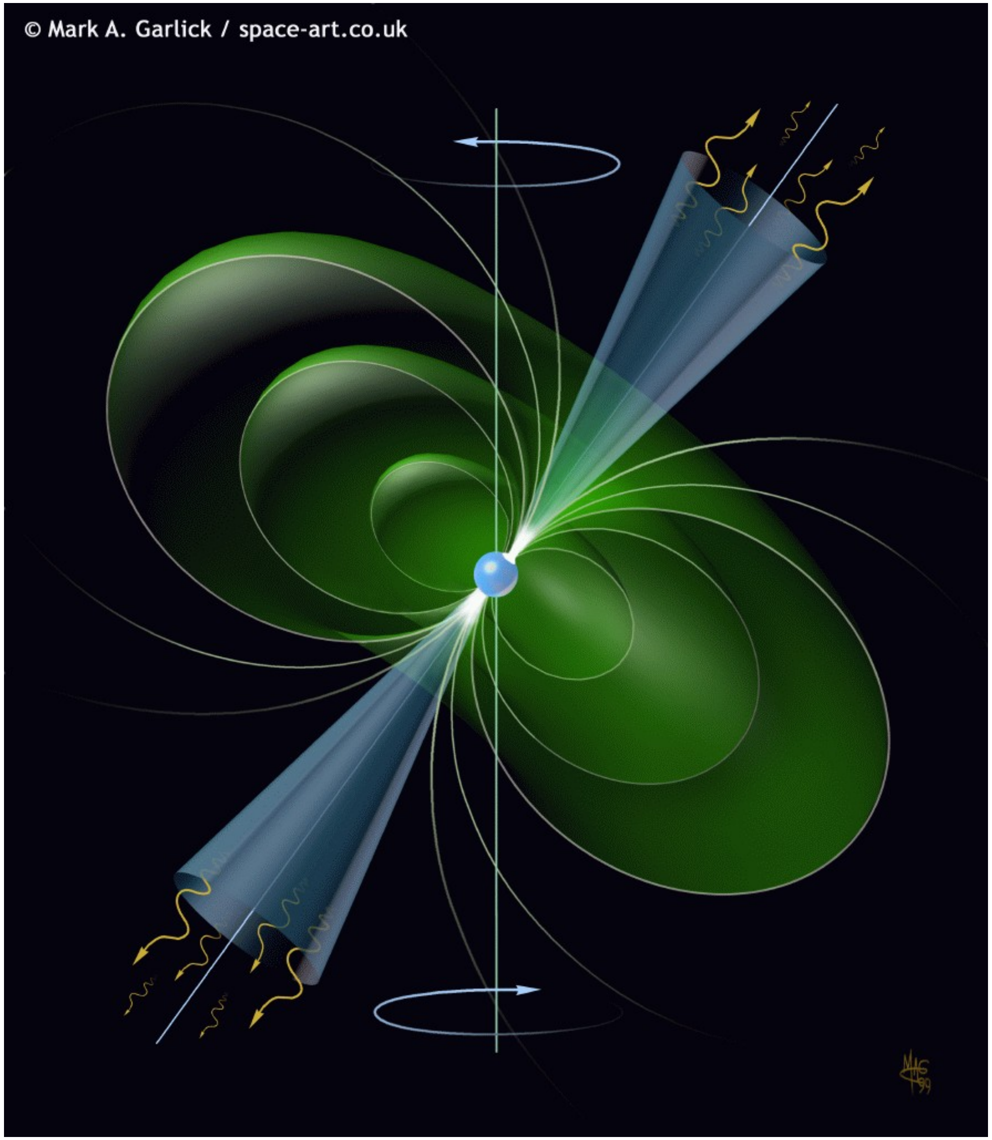
Evidence for a primary component of positrons
(possibly accompanied by electrons)

New astrophysics?

New particle physics?

Astrophysical interpretations

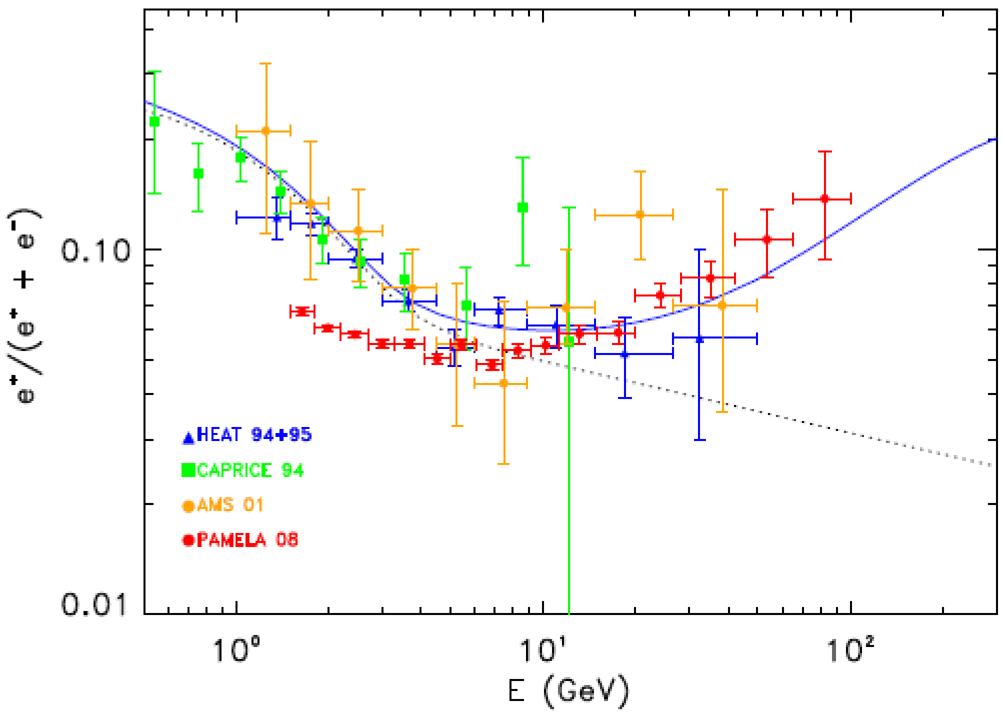
Pulsars are sources of high energy electrons & positrons

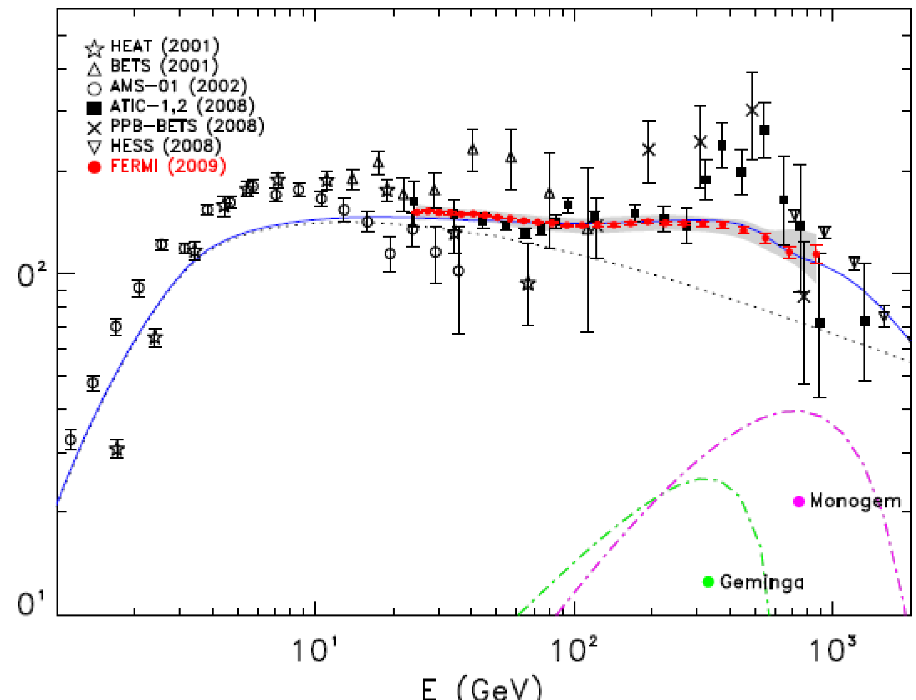


Atoyan, Aharonian, Völk;
Chi, Cheng, Young;
Grimani

For other astrophysical interpretations see talks by Pasquale Serpico, Philipp Mertsch and Masahiro Hoshino

Pulsar explanation I: Geminga + Monogem

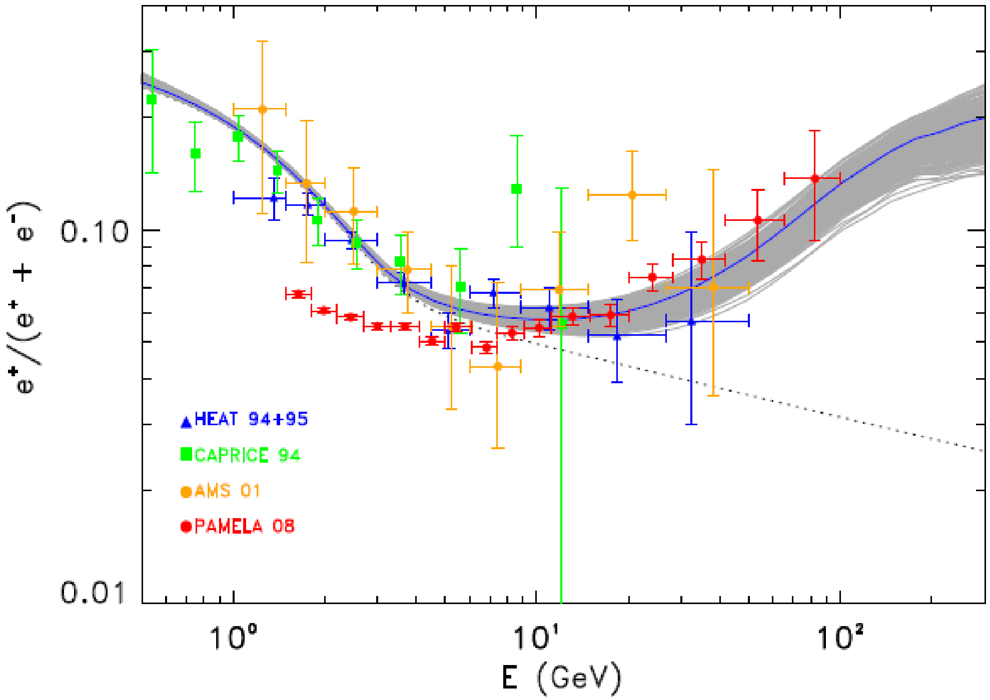


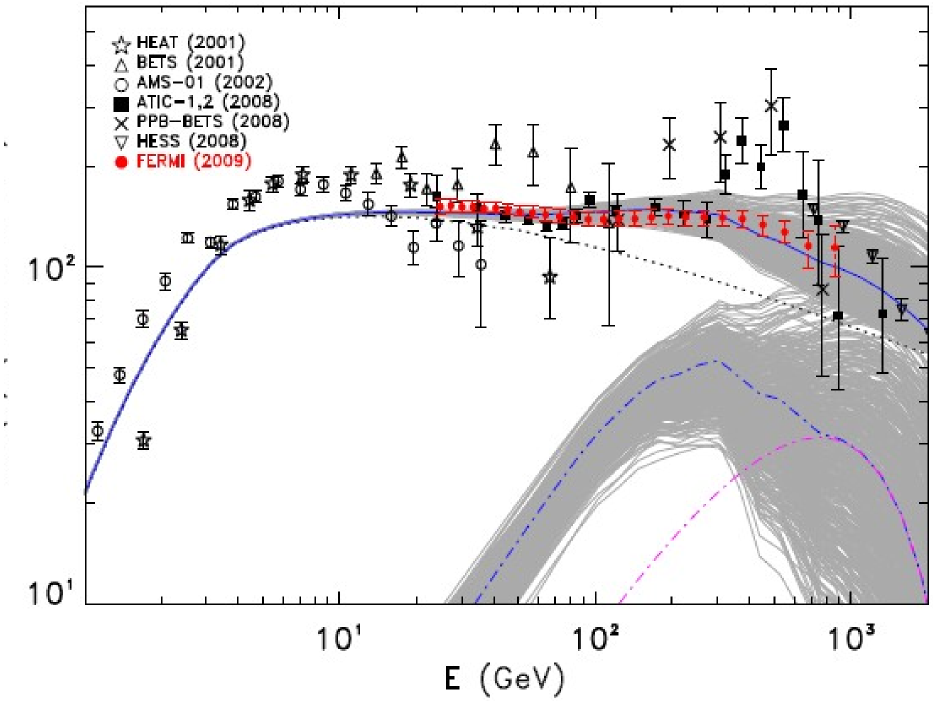


Nice agreement. However, it is not a prediction!

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

Pulsar explanation II: Multiple pulsars





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

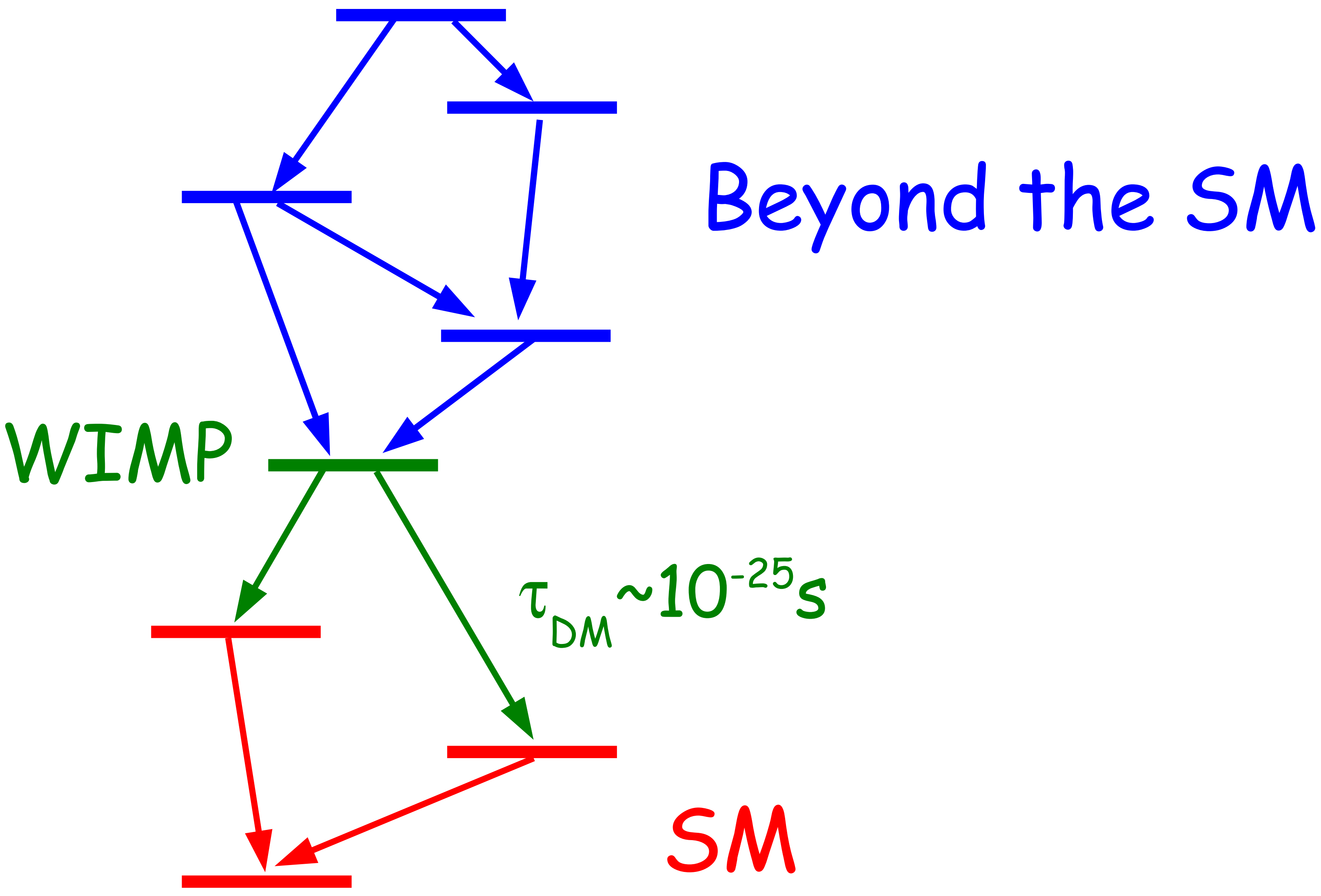
$\longrightarrow$ Talks by Pasquale Serpico, Stefano Profumo

Dark matter decay

- 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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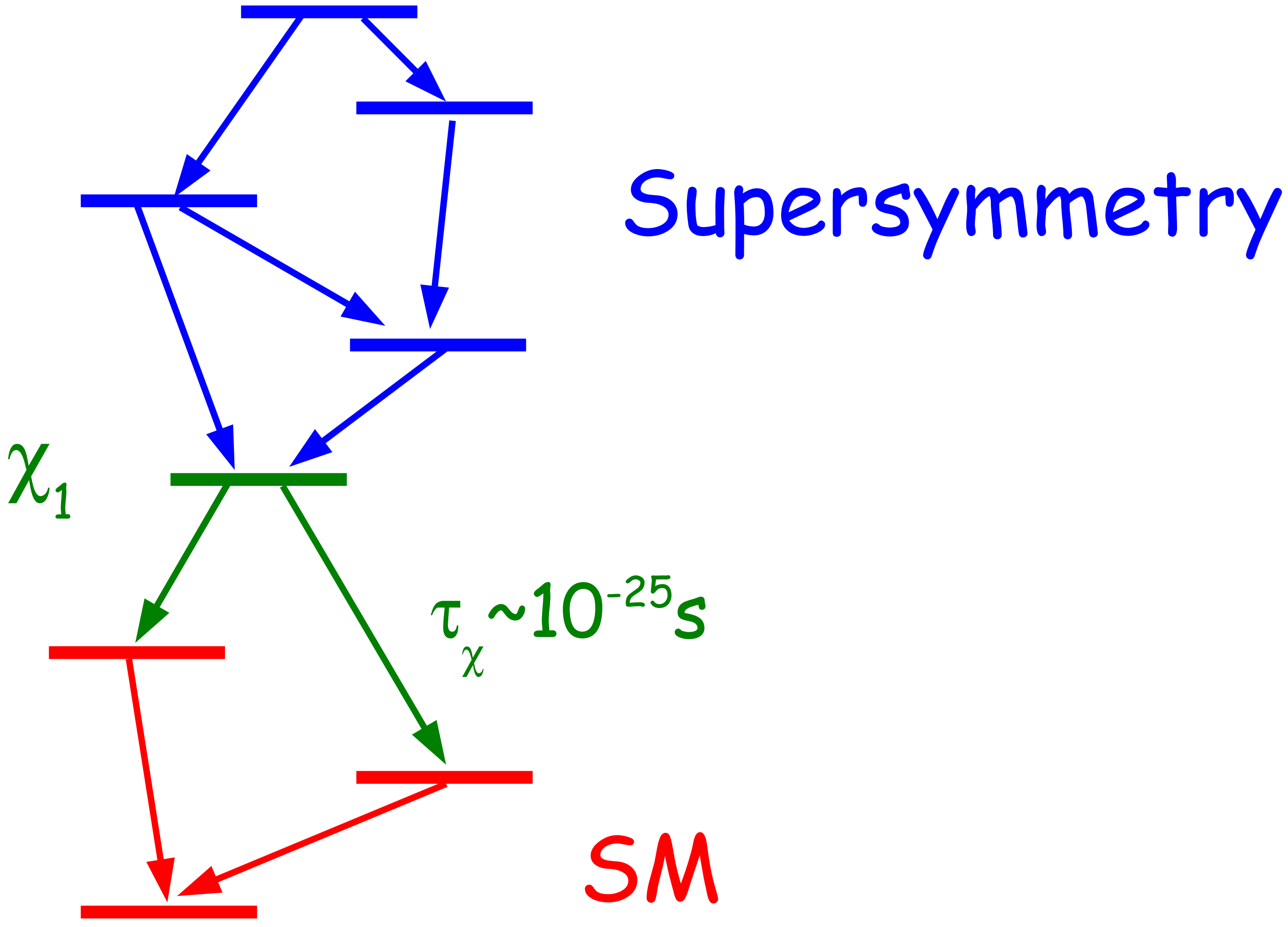

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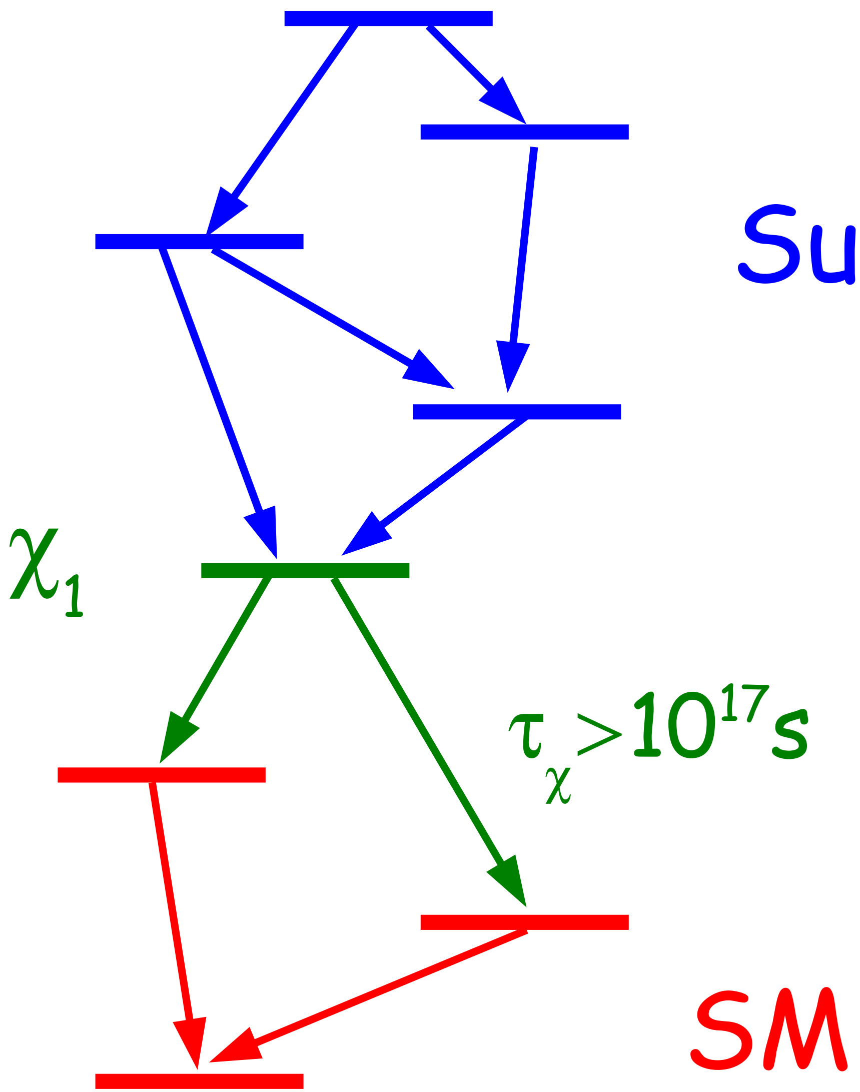
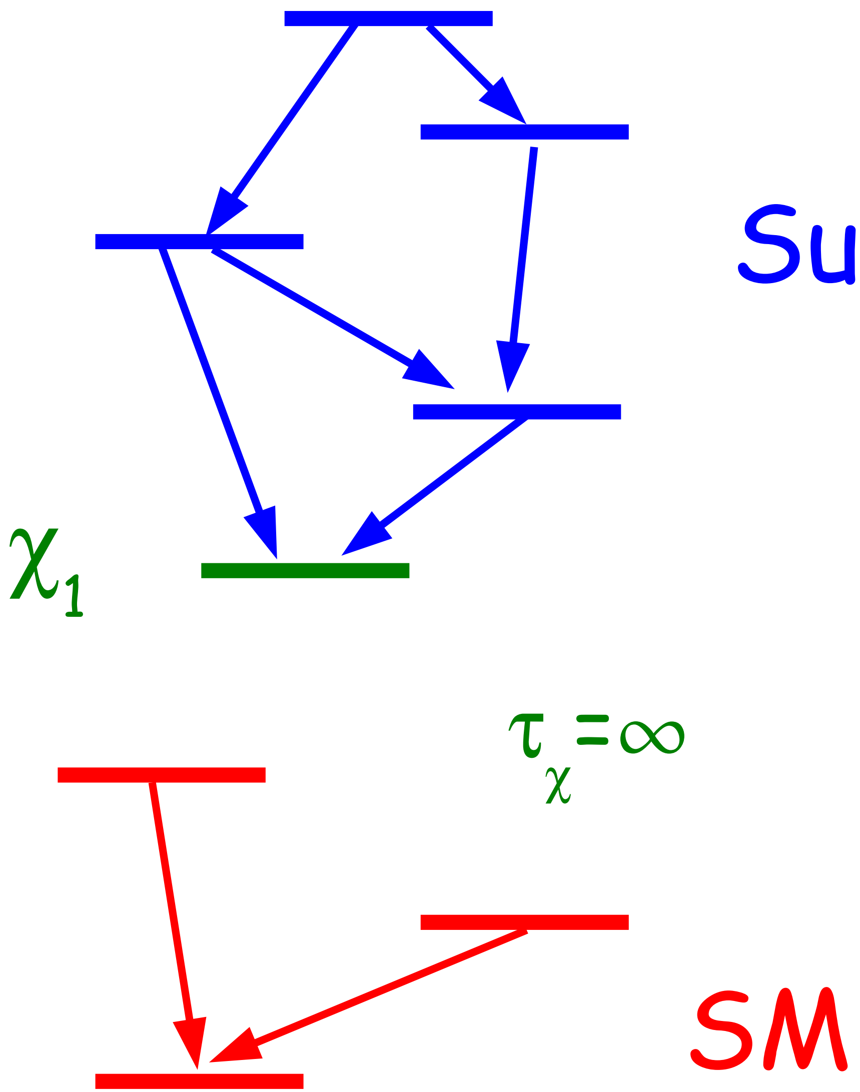


Requires a suppression of the coupling of at least 22 orders of magnitude!

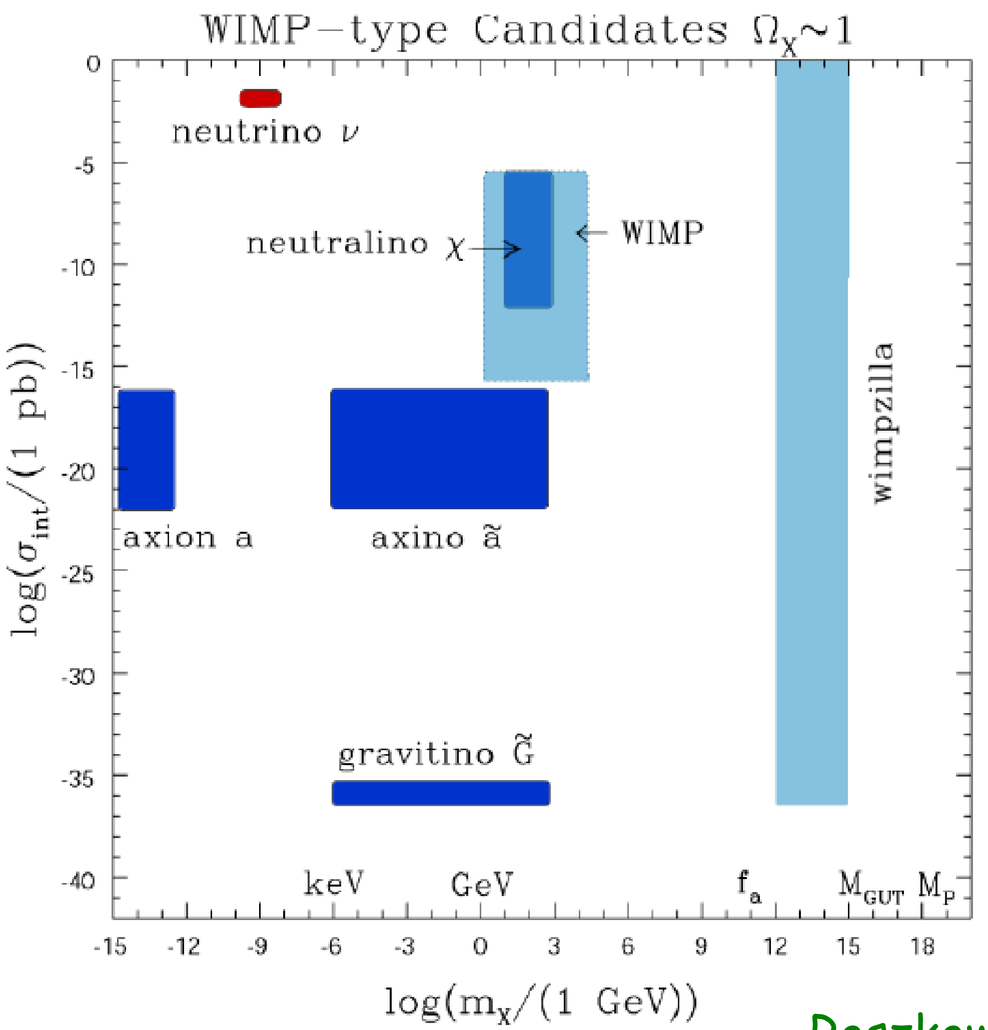
Sketch of a WIMP dark matter model:



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

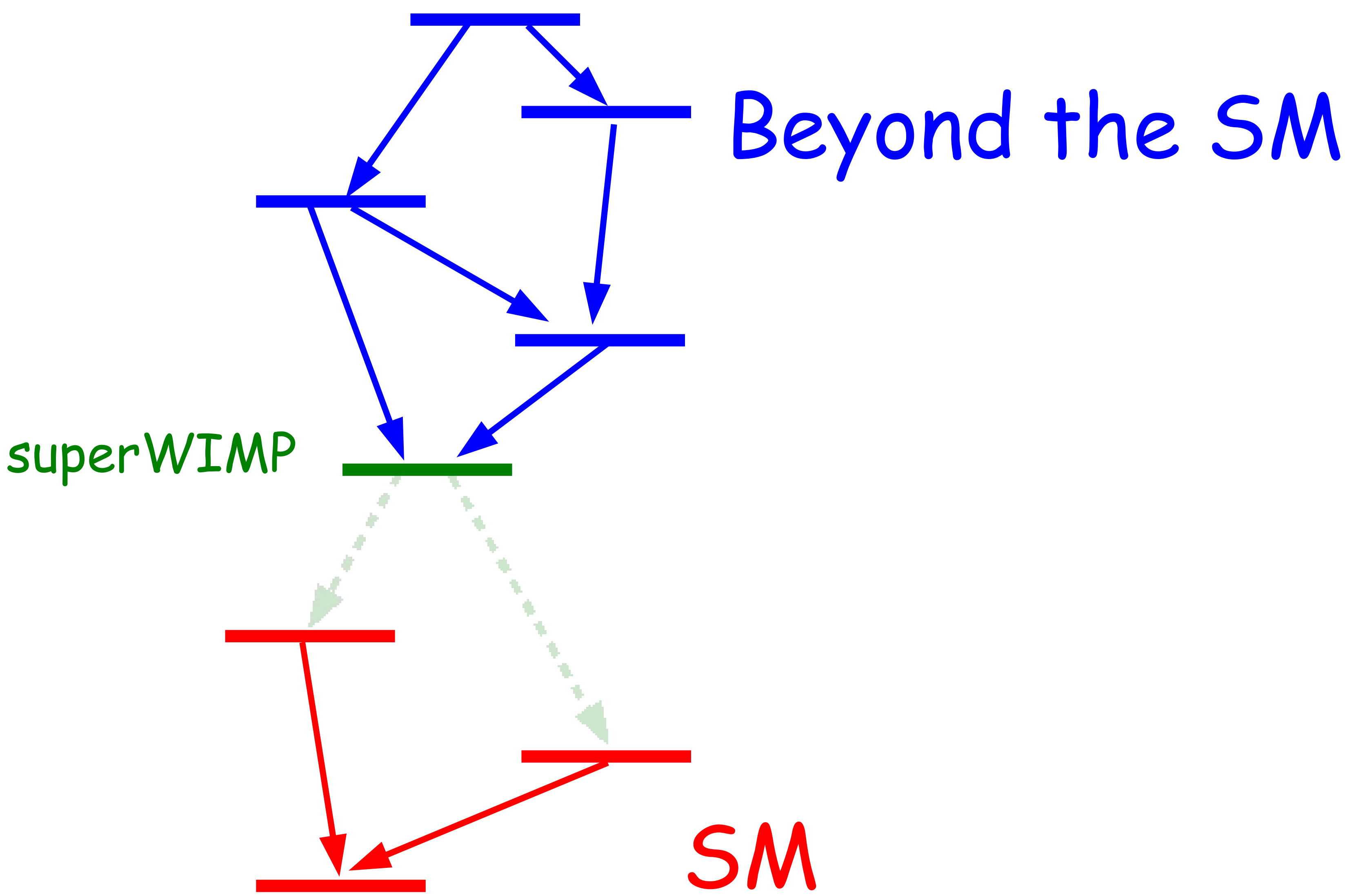
The lightest neutralino is absolutely stable

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

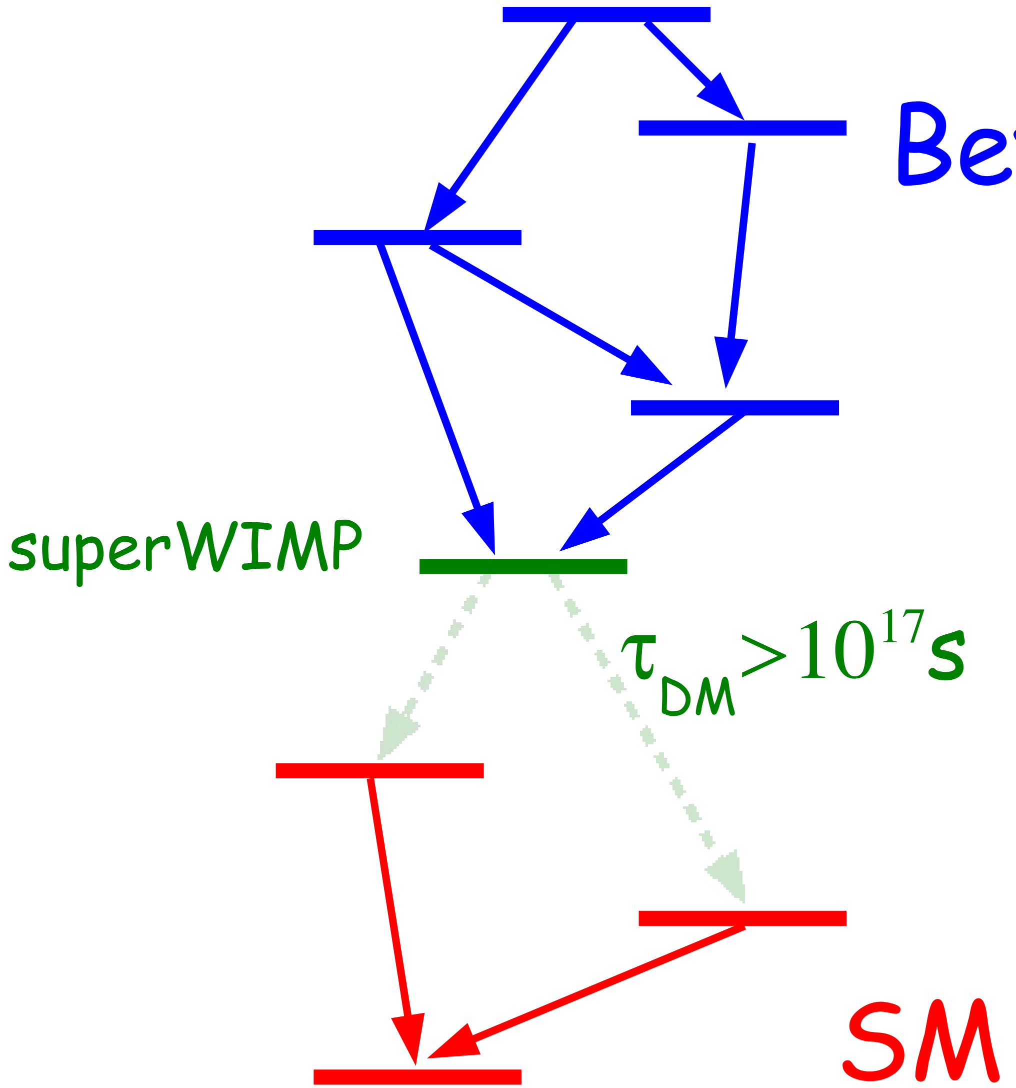


Roszkowski

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.

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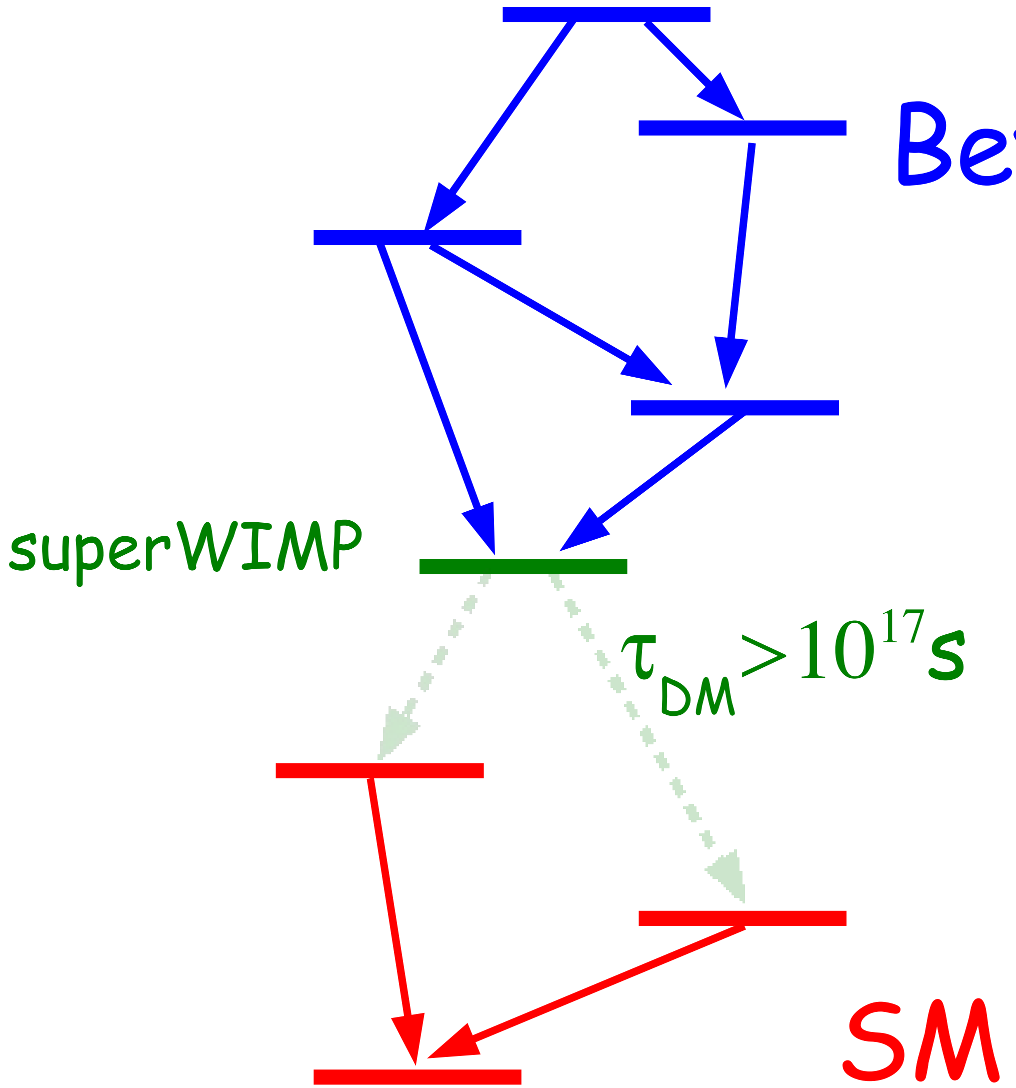


It is enough a moderate suppression of the coupling to make the superWIMP a viable dark matter candidate.

Eventually the dark matter decays!

Candidates of decaying dark matter

- Gravitinos in general SUSY models (without imposing R-parity conservation). Takayama, Yamaguchi; Buchmüller, et al.; AI, Tran; Ishiwata et al.; Choi et al.

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

- Hidden sector gauge bosons/gauginos. Chen, Takahashi, Yanagida; AI, Ringwald, Weniger;

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

- 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
AI, Tran, Weniger

fermionic DM

$\psi \to Z^0 \nu$

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

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

scalar DM

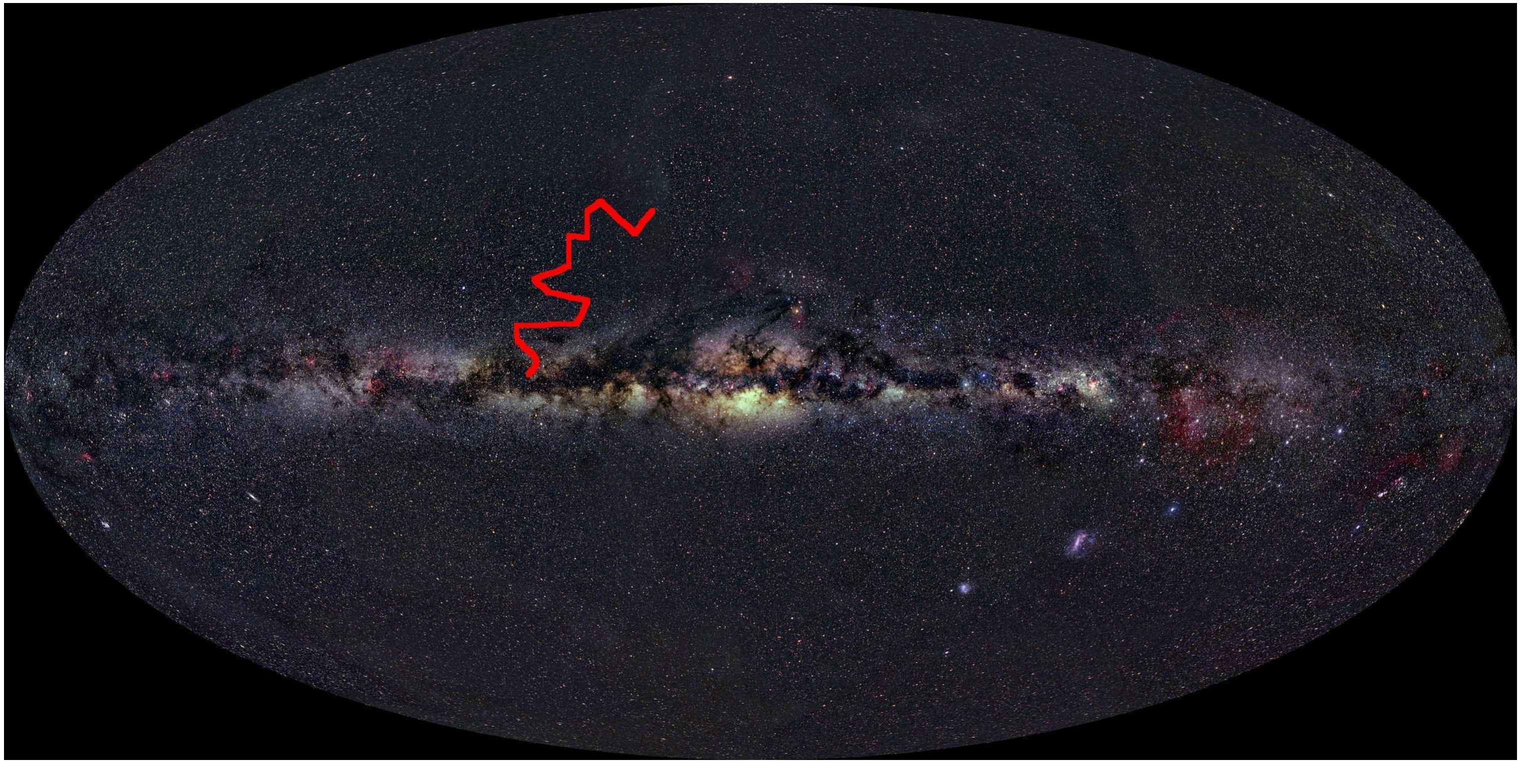
$\phi \to Z^0 Z^0$

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

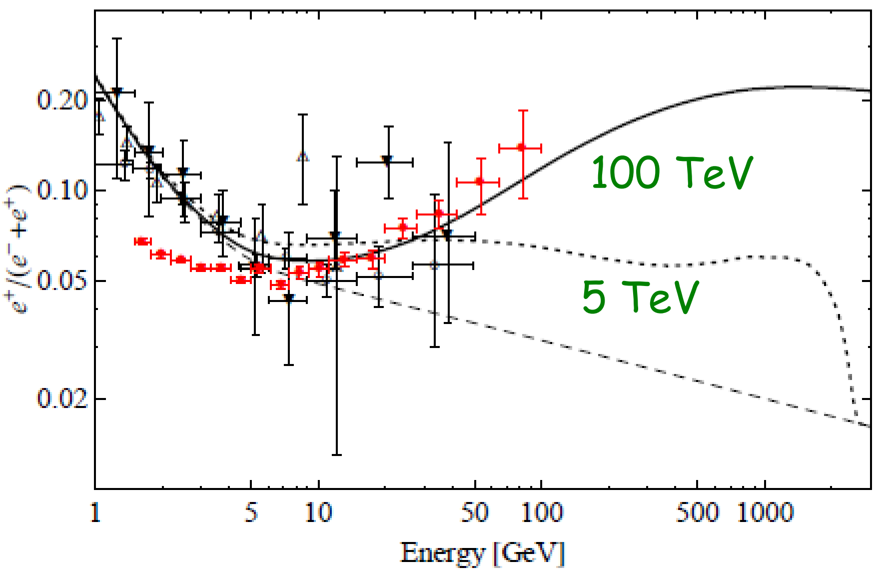
$\phi \to \ell^+ \ell^-$

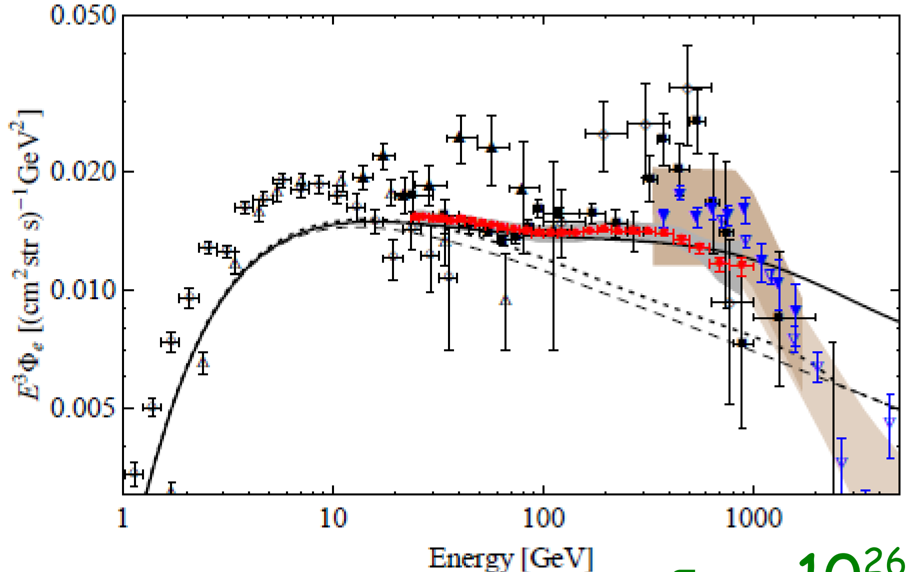
The injection spectrum of positrons depends just on two parameters: the dark matter mass and lifetime.

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



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

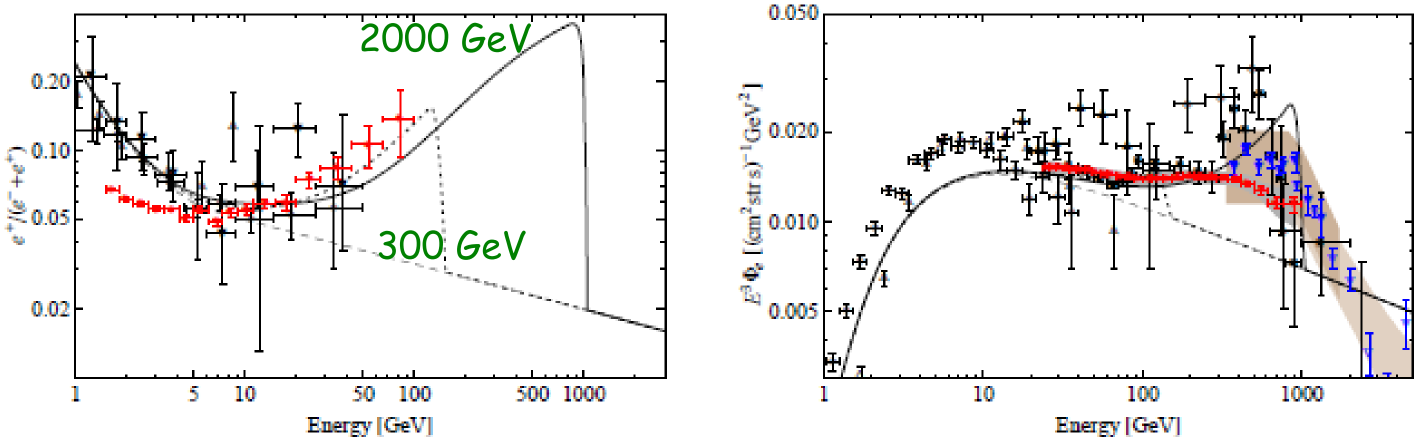




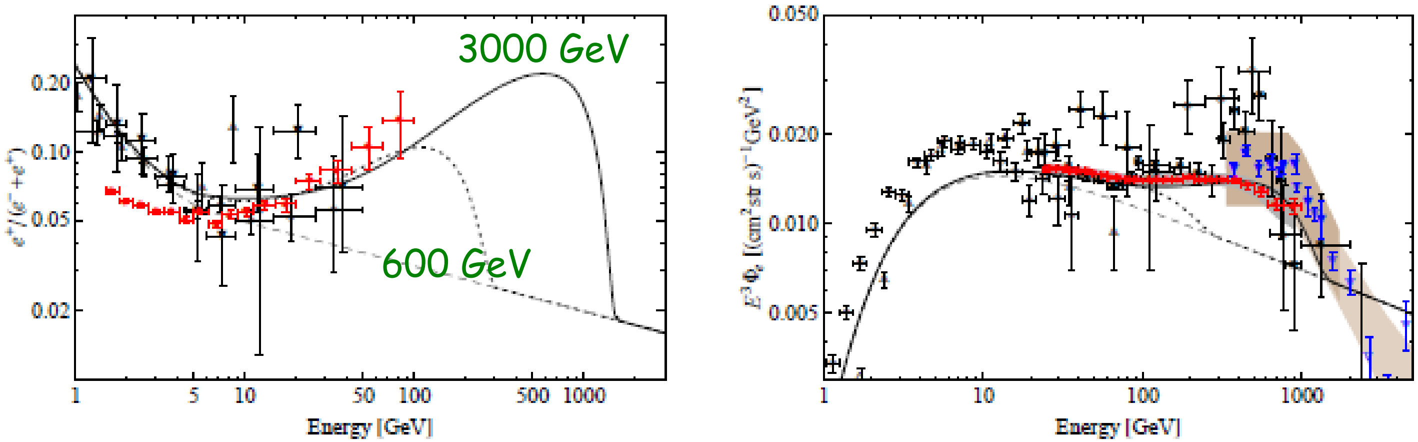
τ_{DM}~10^{26}s

For "low" DM mass: conflict with PAMELA (spectrum too flat)

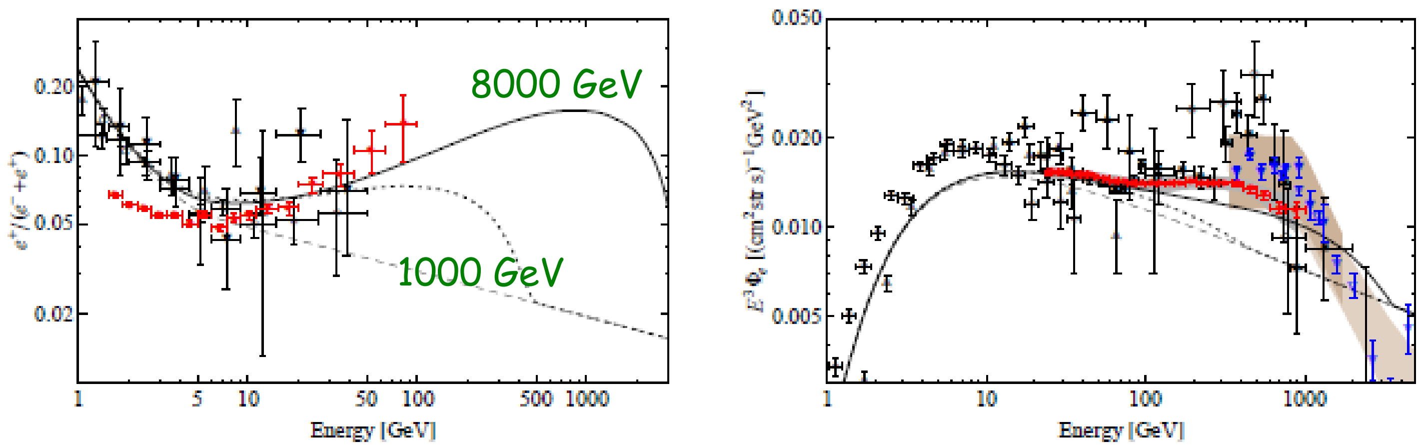
For "high" DM mass: agreement with PAMELA, but conflict with H.E.S.S.



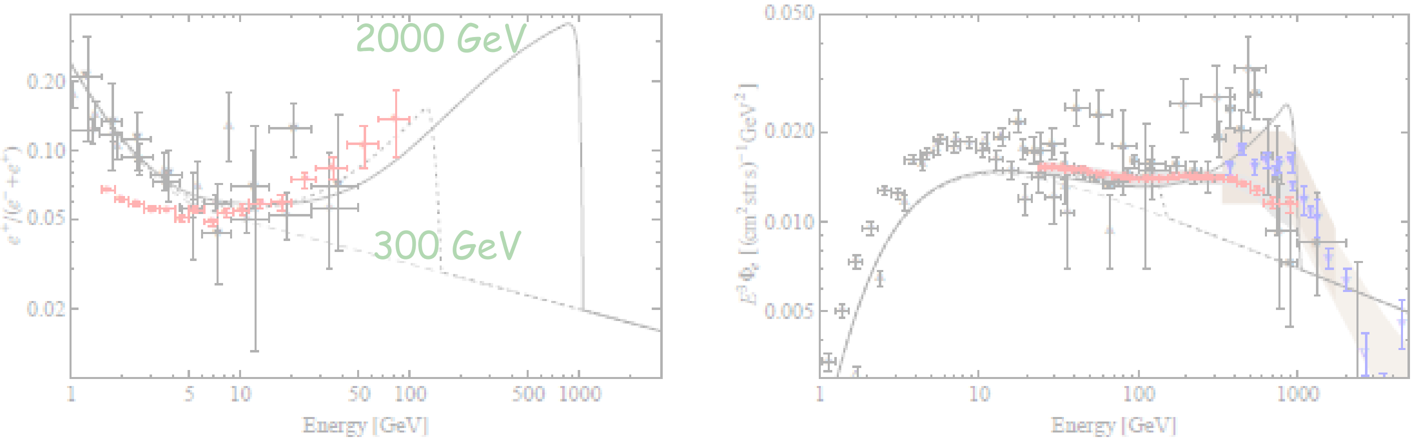
$\psi \to W^{\pm} e^{\mp}$



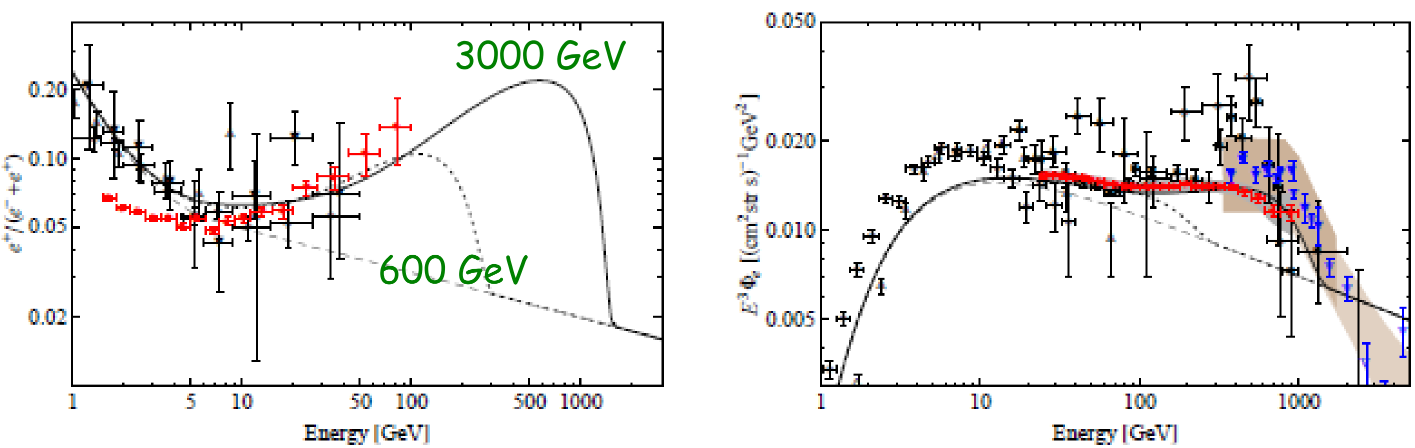
$\psi \to W^{\pm} \mu^{\mp}$



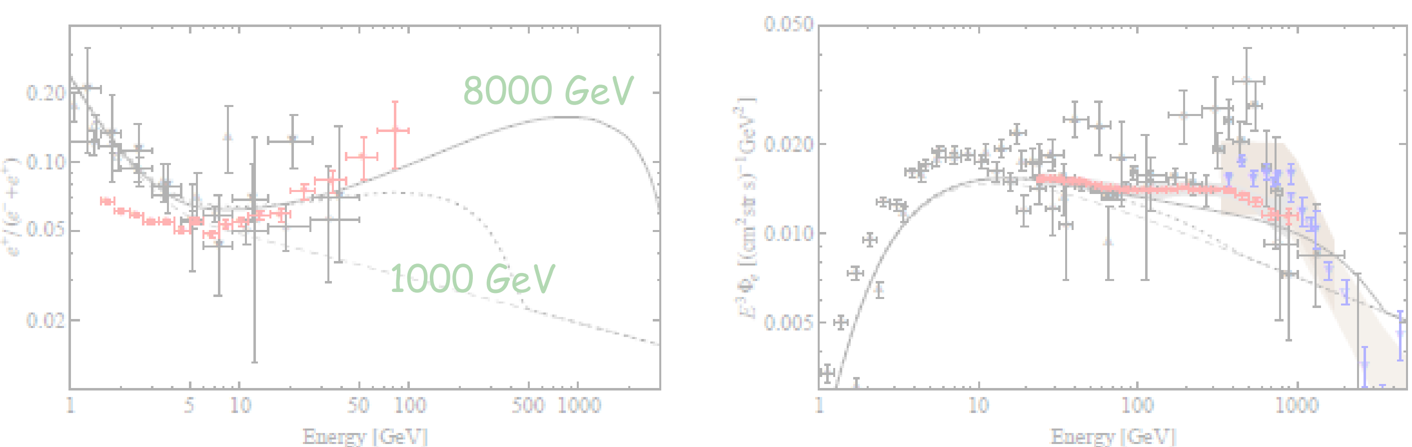
$\psi \to W^{\pm} \tau^{\mp}$



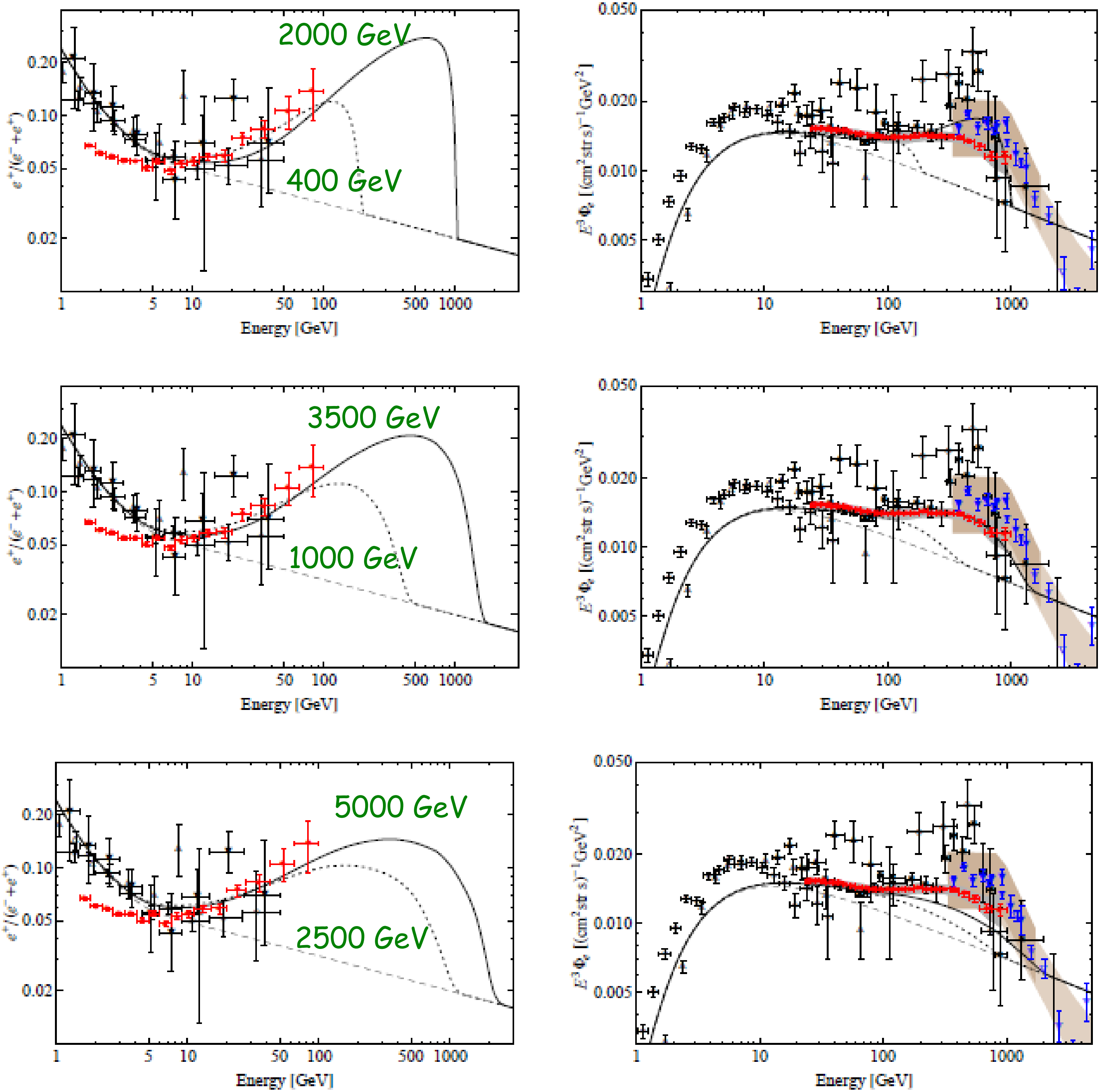
$\psi \rightarrow W^{\pm} e^{\mp}$



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



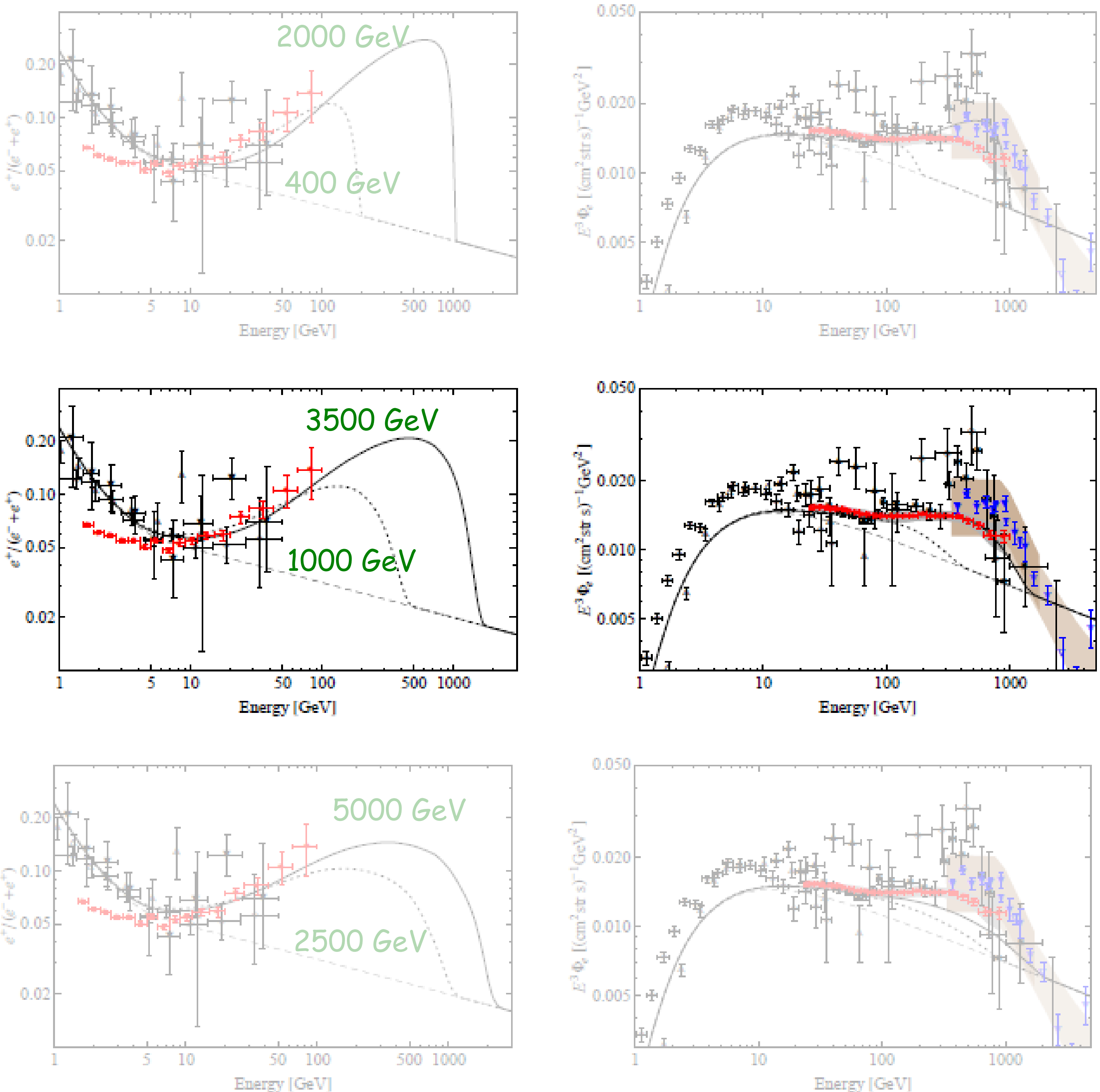
$\psi \rightarrow W^{\pm} \tau^{\mp}$



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

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

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

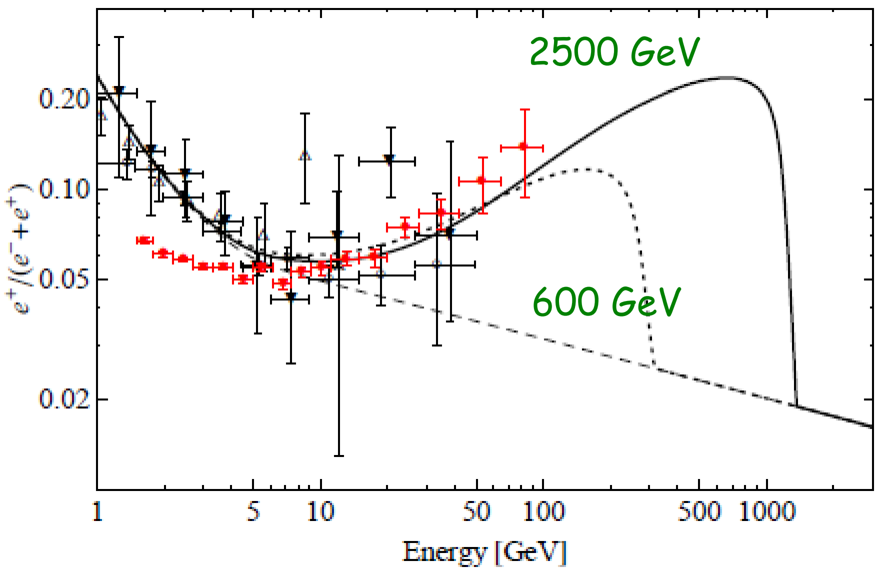


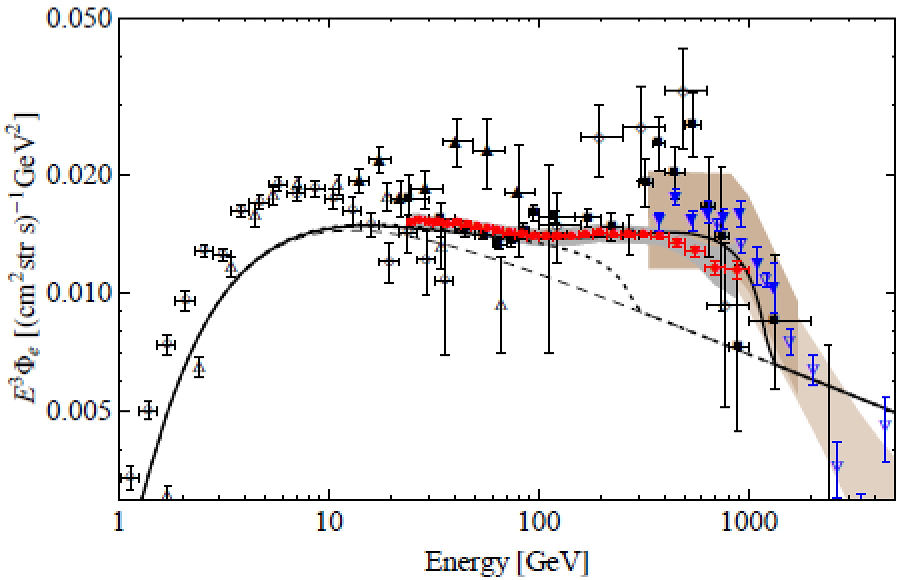
$\psi \to e^+ e^- \nu$

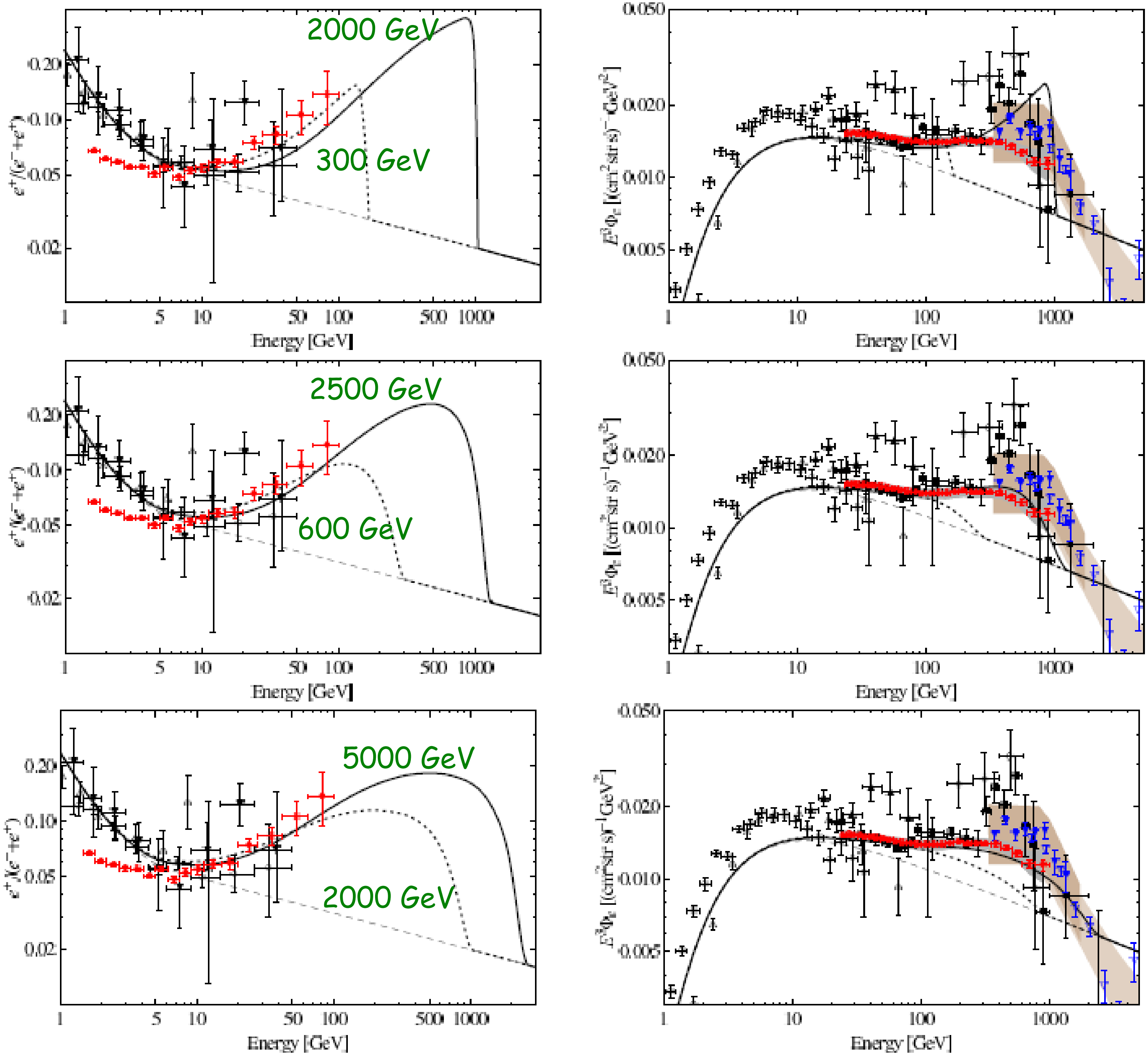
$\psi \to \mu^+ \mu^- \nu$

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

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



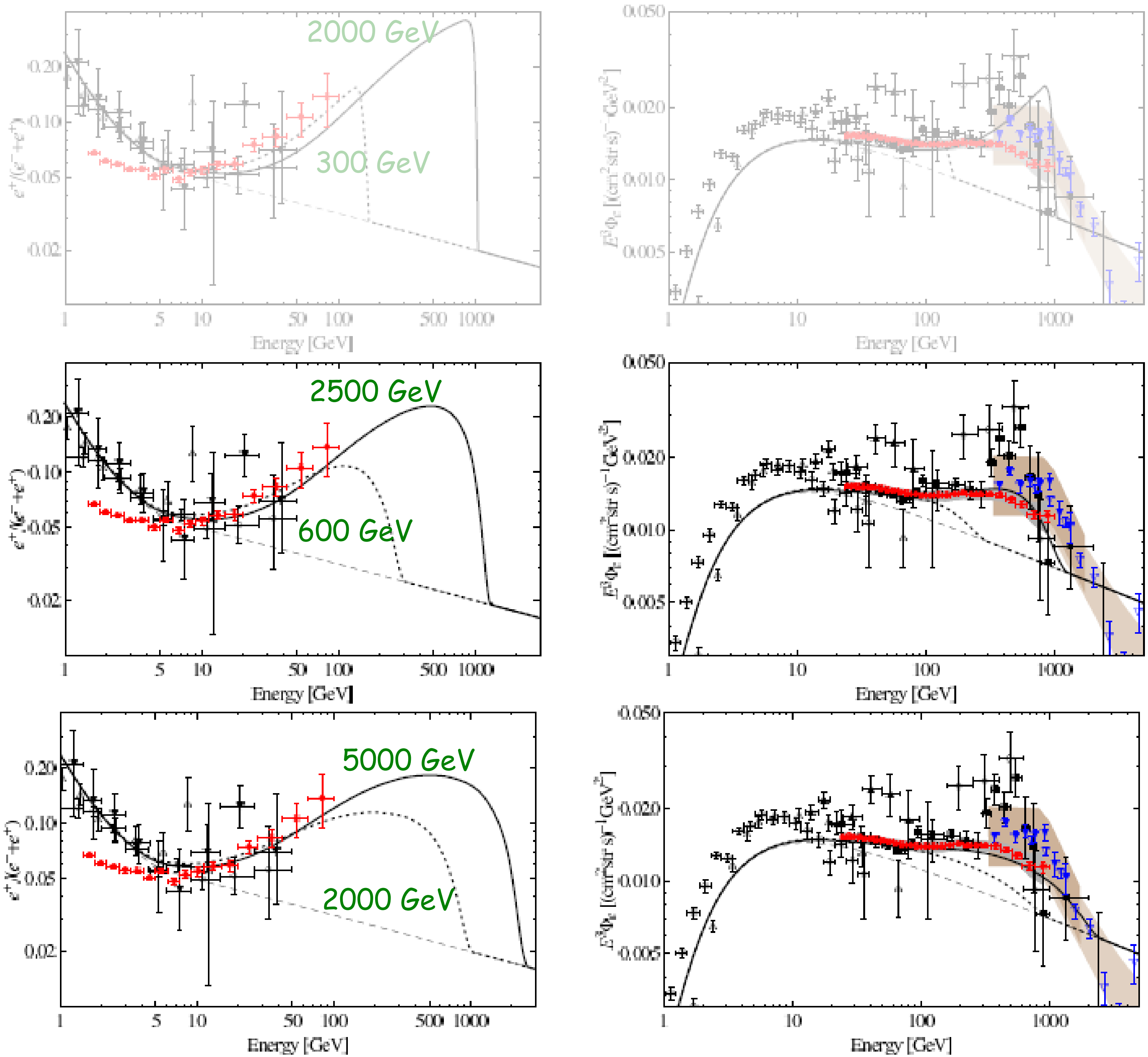




$\phi \to e^+ e^-$

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

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



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

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

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

A few decay channels can explain the PAMELA and Fermi LAT data

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

10^{26} seconds??

Eichler; Arvanitaki et al.; Nardi, Sannino, Strumia; Chen, Takahashi, Yanagida; Bae, Kyae.

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!

Too large DM mass??

- The dark matter mass is a free parameter, a priori not related to any of the known mass scales.
- The electron/positron anomalies may be produced by a <u>secondary component</u> of dark matter.

The flux depends on ρ_{DM}/τ_{DM}. Therefore, the same flux can be produced by the decay of a secondary component of dark matter, provided the density and lifetime are in that same ratio $\rho/\tau=\rho_{DM}/\tau_{DM}$:

$$\rho = \alpha\, \rho_{DM}$$

$$\tau \approx \alpha\, 10^{26}\ \mathrm{s}$$

The primary component of dark matter may even be stable. New possibilities for model building!!

Example: hidden gaugino decay into DM neutralinos AI, Ringwald, Tran, Weniger

Tests of the decaying dark matter scenario as an explanation of the PAMELA/Fermi excesses

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

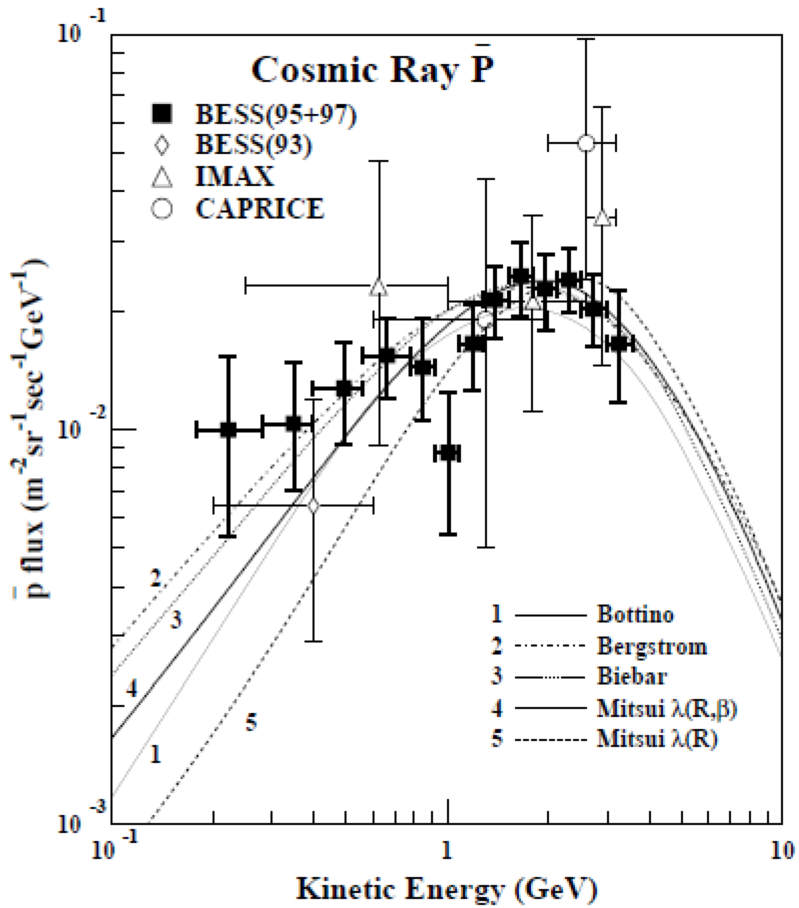
No free parameters from Particle Physics!

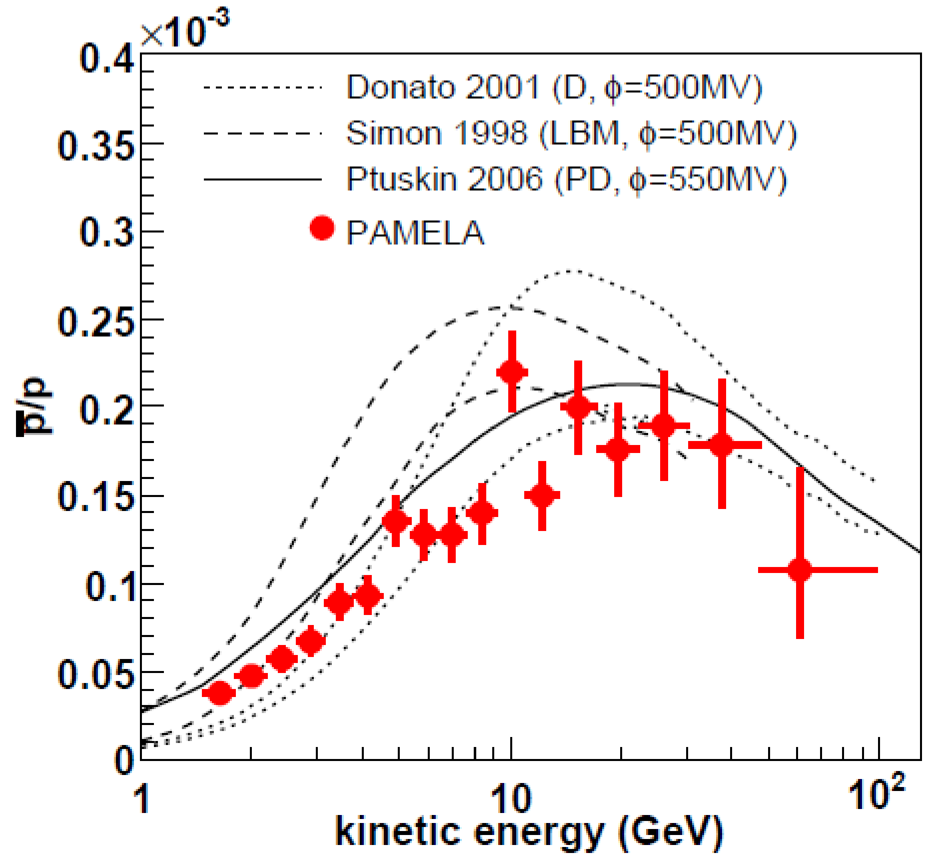
Tests of the decaying dark matter scenario as an explanation of the PAMELA/Fermi excesses

Prediction for the fluxes of:

- Antiprotons
- Gamma rays
- Neutrinos
- Antideuterons

Antiproton flux





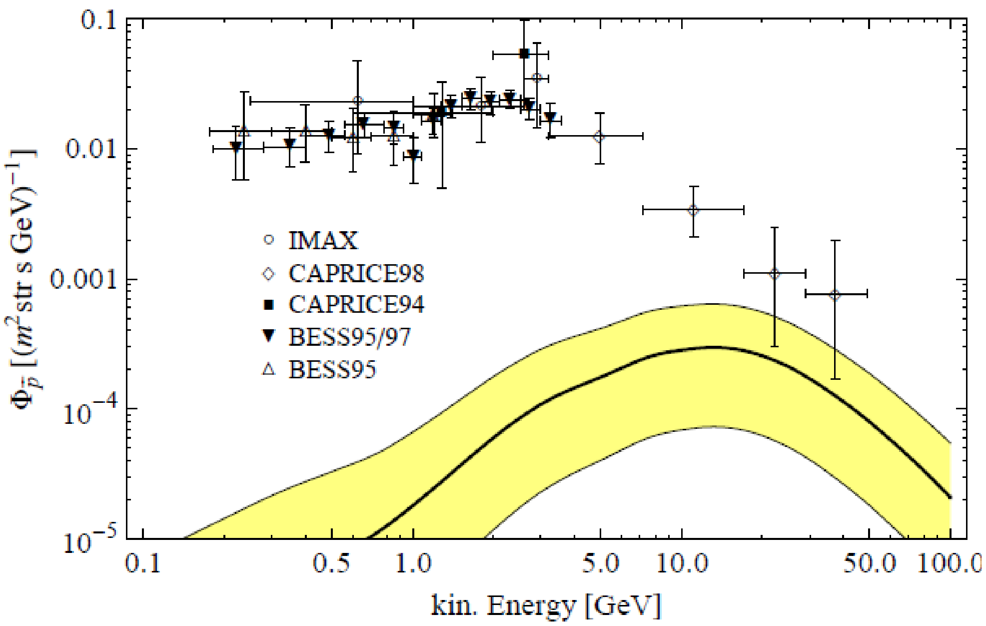
Good agreement of the theory with the experiments: no need for a sizable contribution to the primary antiproton flux. Purely leptonic decays (*e.g.* $\psi \to \mu^+\mu^-\nu$) are favoured over decays into weak gauge bosons.

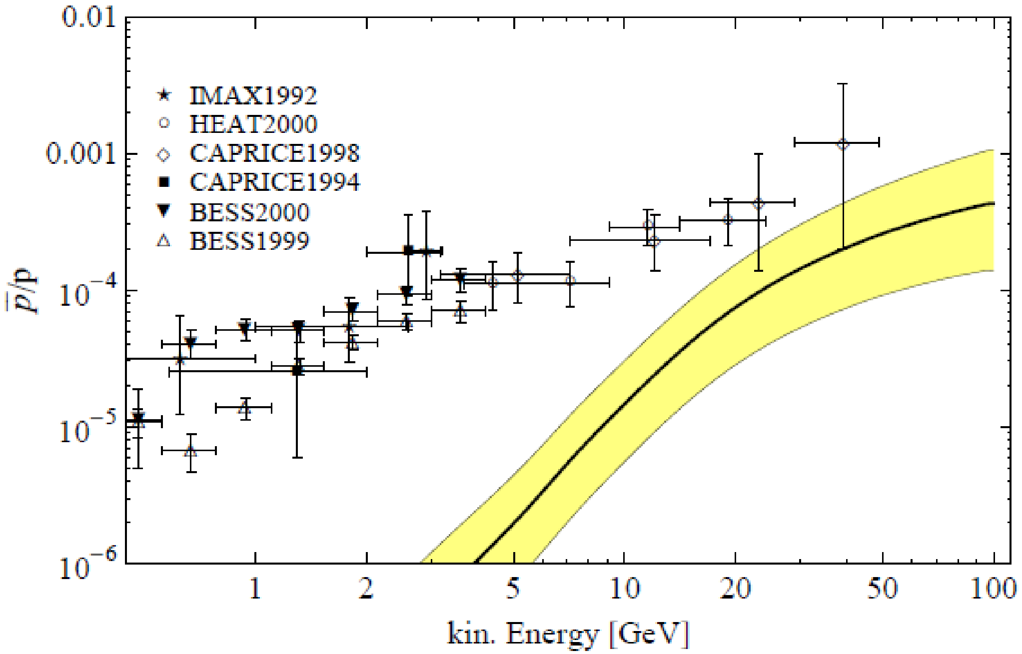
Antiproton flux from dark matter decay

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

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





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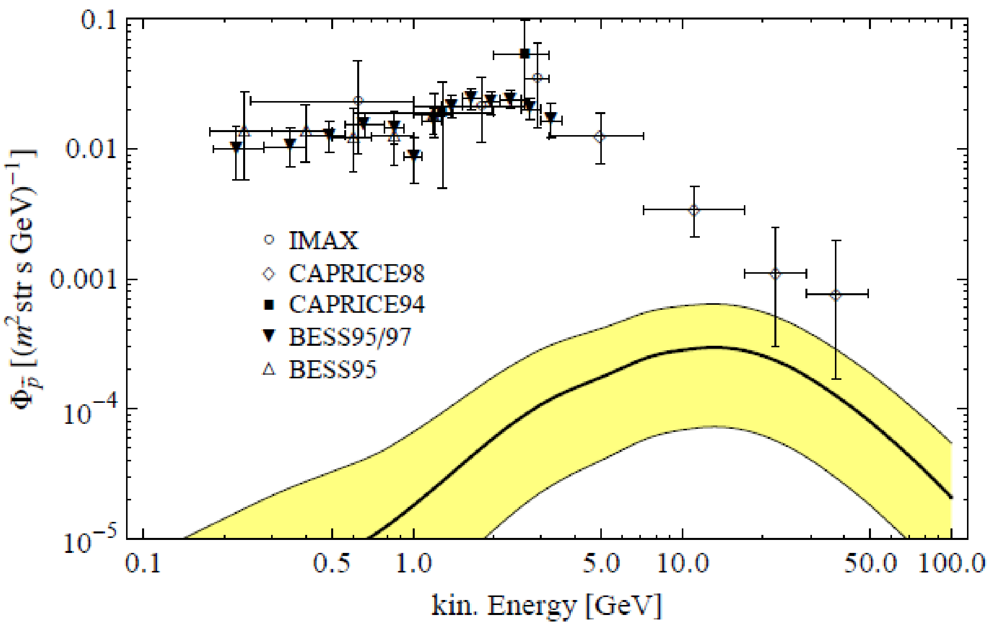
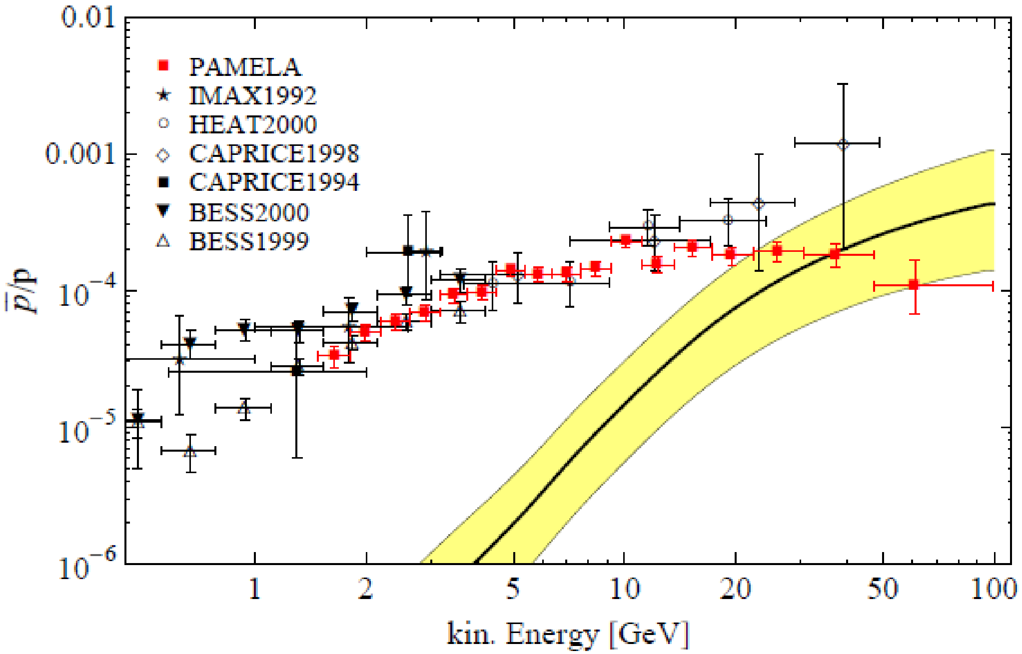
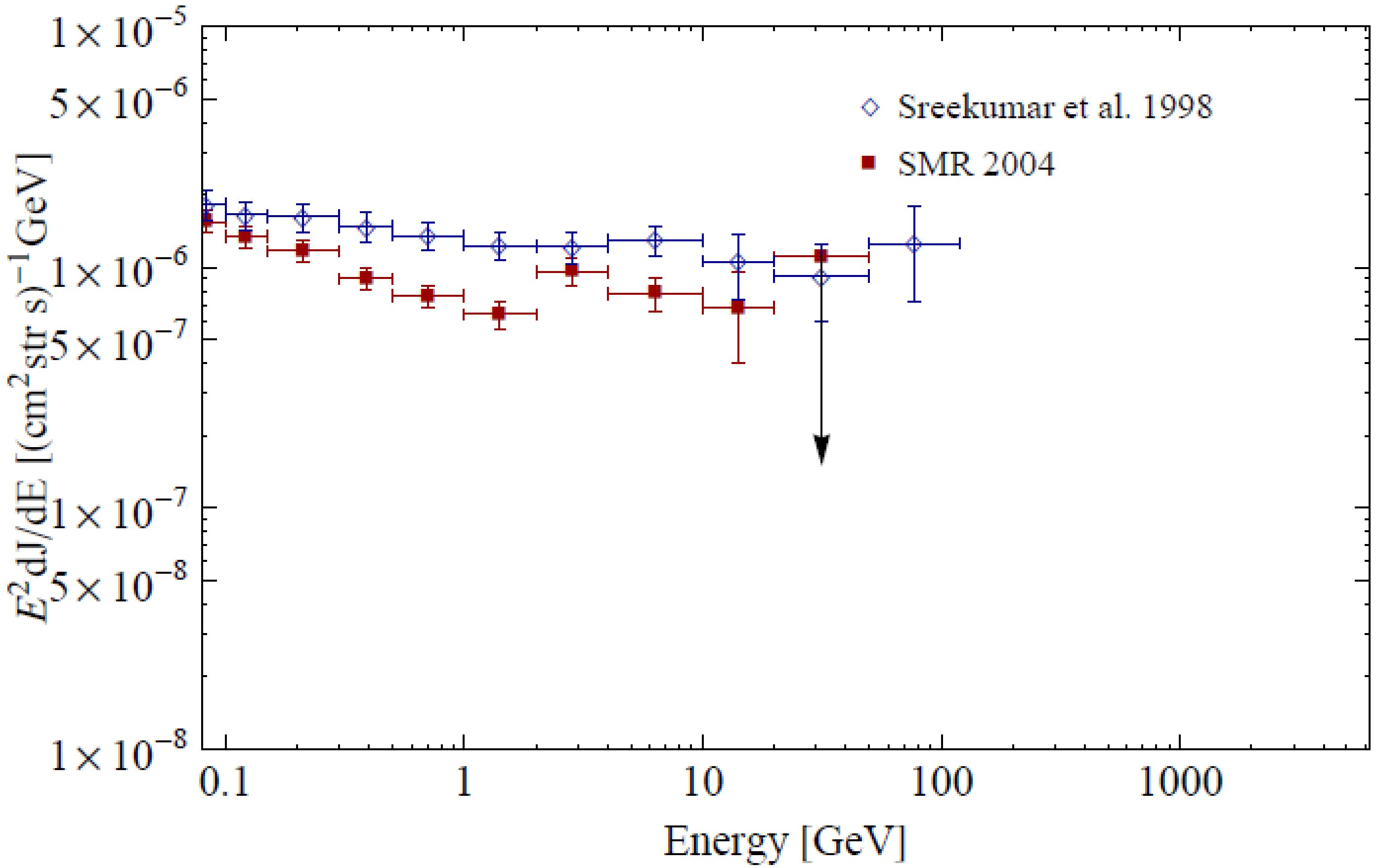
The predicted flux suffers from huge uncertainties due to degeneracies in the determination of the propagation parameters

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



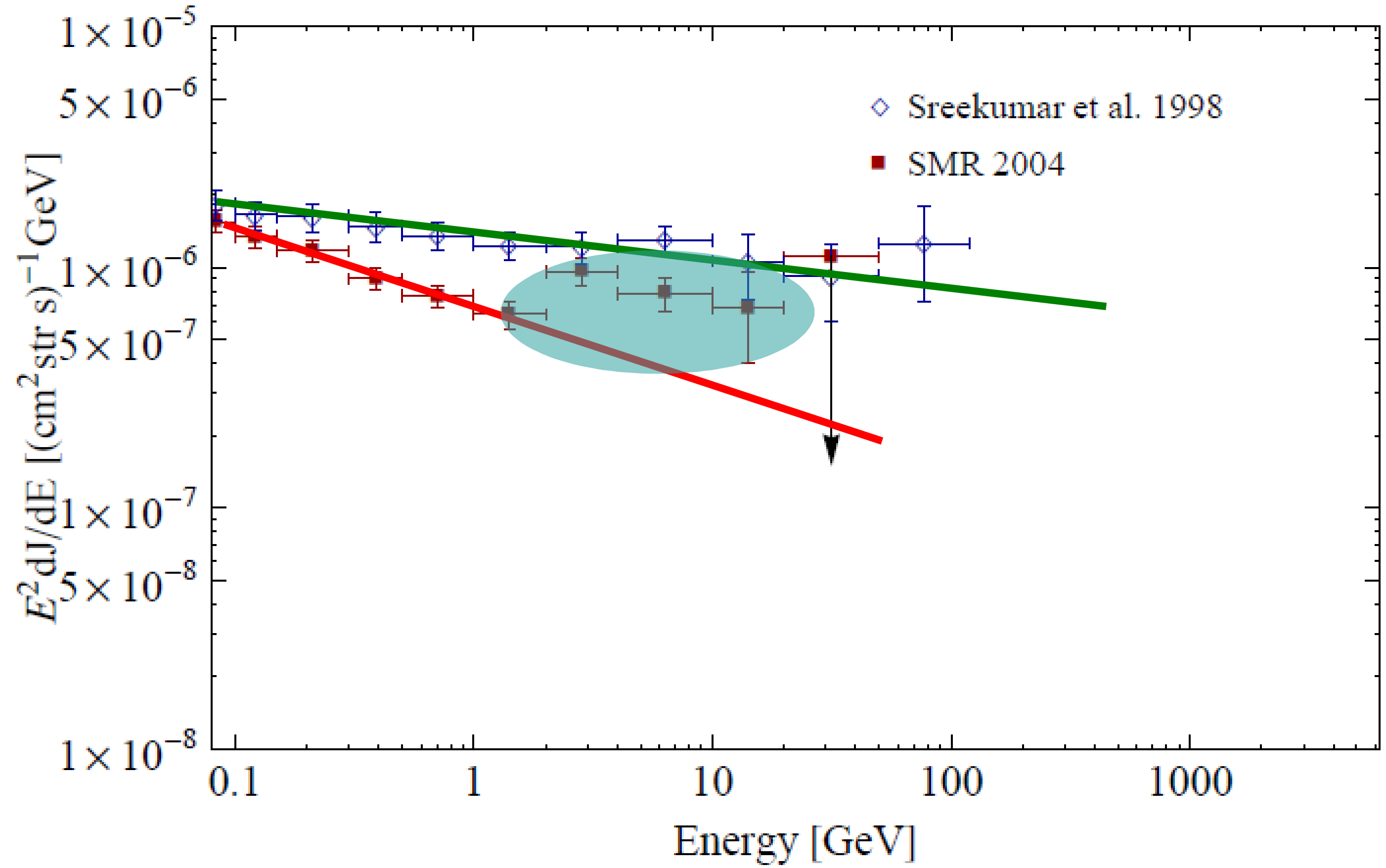


Extragalactic diffuse gamma ray flux from EGRET



Two extractions of the EG gamma ray flux.

Extragalactic diffuse gamma ray flux from EGRET



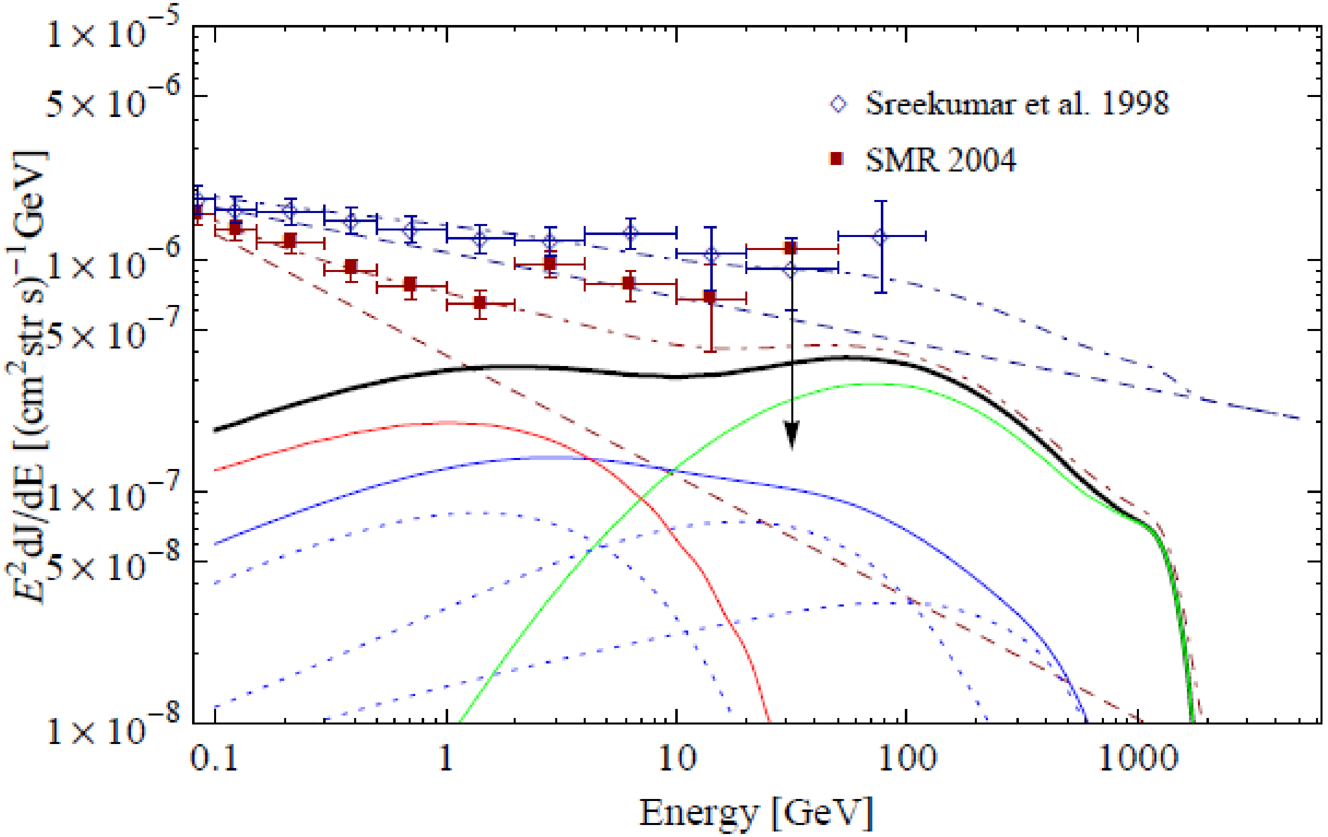
Two extractions of the EG gamma ray flux.

Need for new data and better understanding of the galactic foreground.

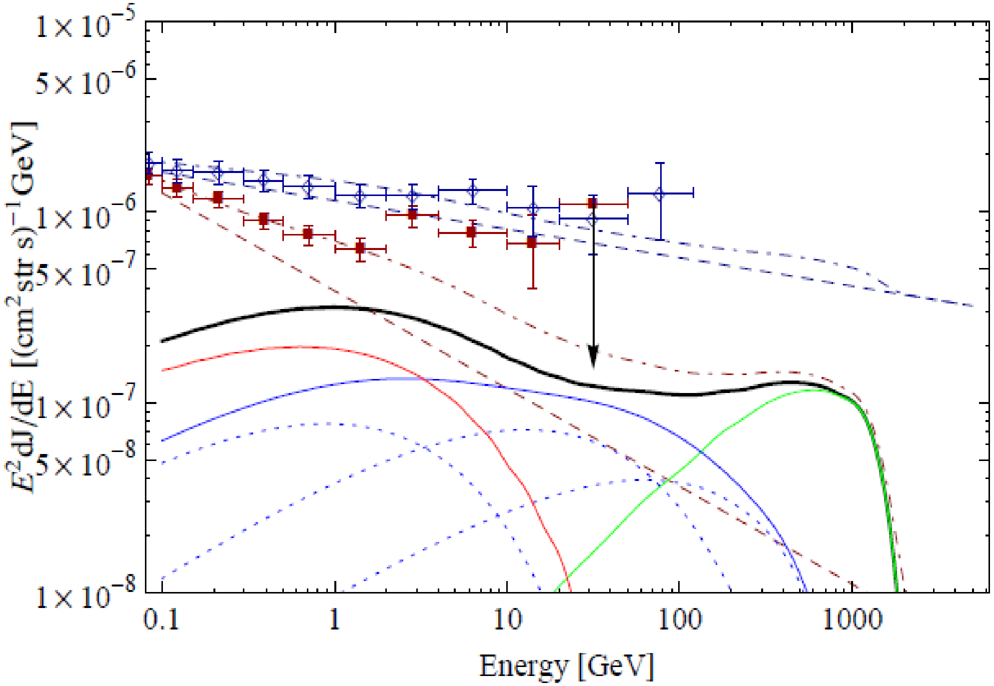
"Predictions" for the extragalactic diffuse gamma ray flux

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

m_{DM}=3000 GeV,
τ_{DM}=2.1× 10^{26} s



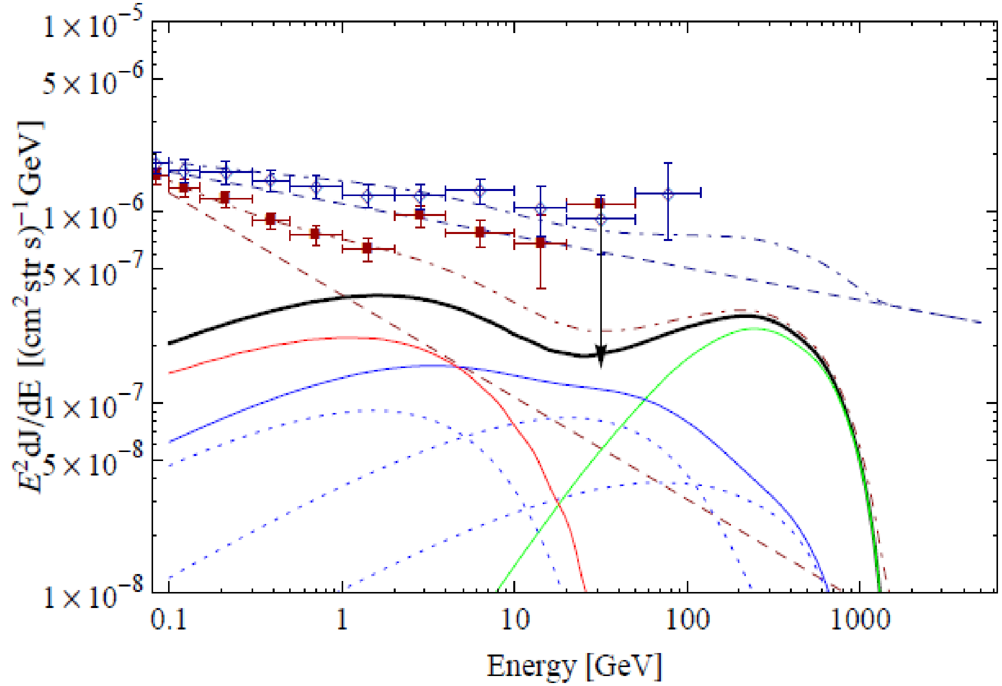
$\psi \to \mu^+ \mu^- \nu$



m_{DM}=3500 GeV,

$\tau_{DM}=1.1\times10^{26}$ s

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



m_{DM}=2500 GeV,

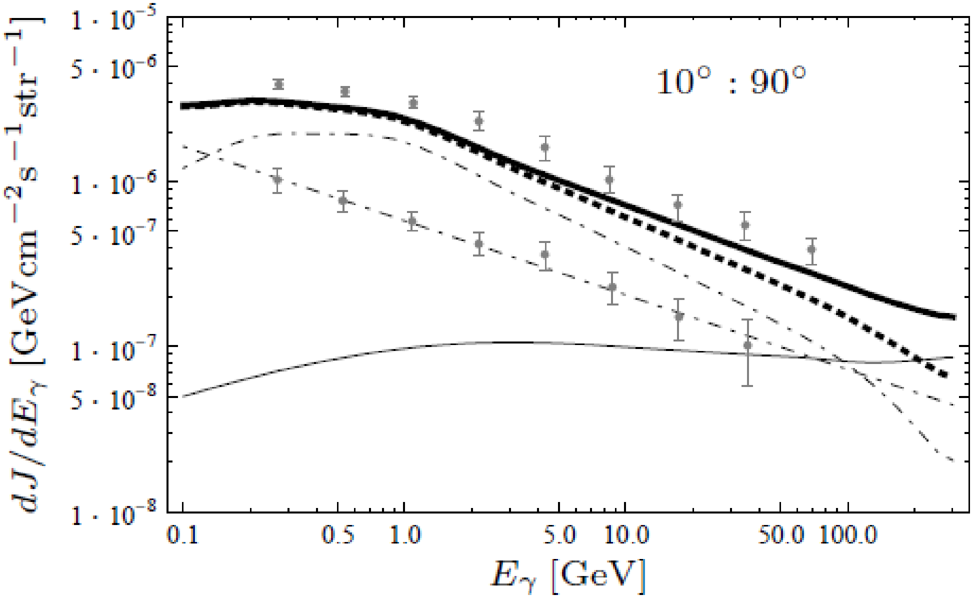
$\tau_{DM}=1.5\times10^{26}$ s

In some scenarios it is expected a prominent bump in the diffuse extragalactic gamma ray spectrum.

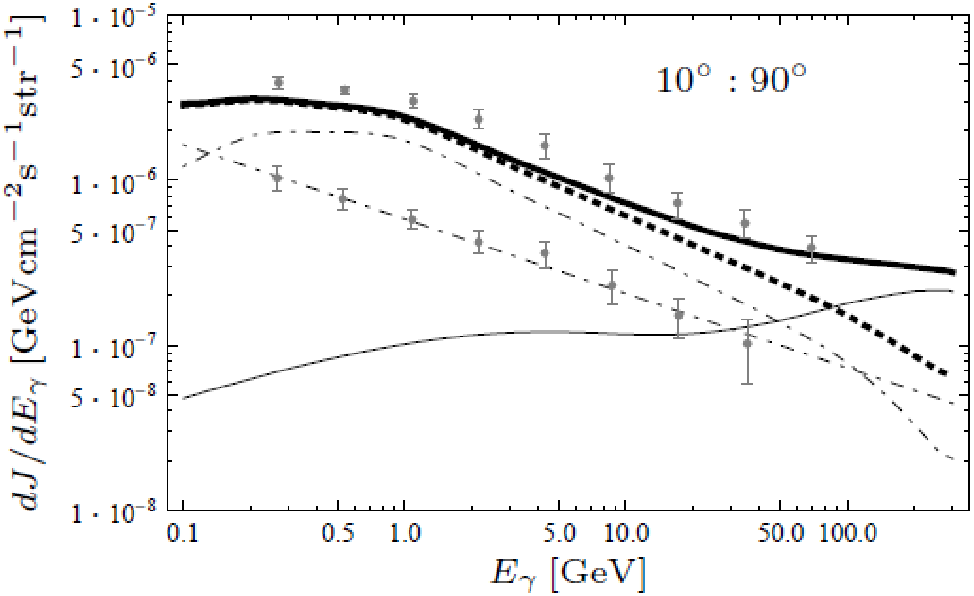
Impact of the preliminary Fermi data.

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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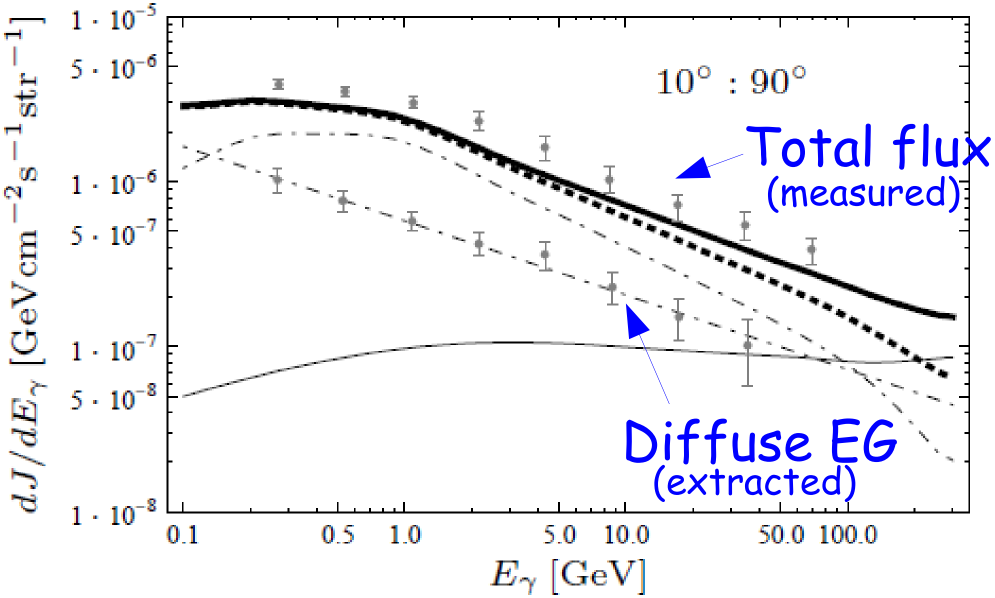
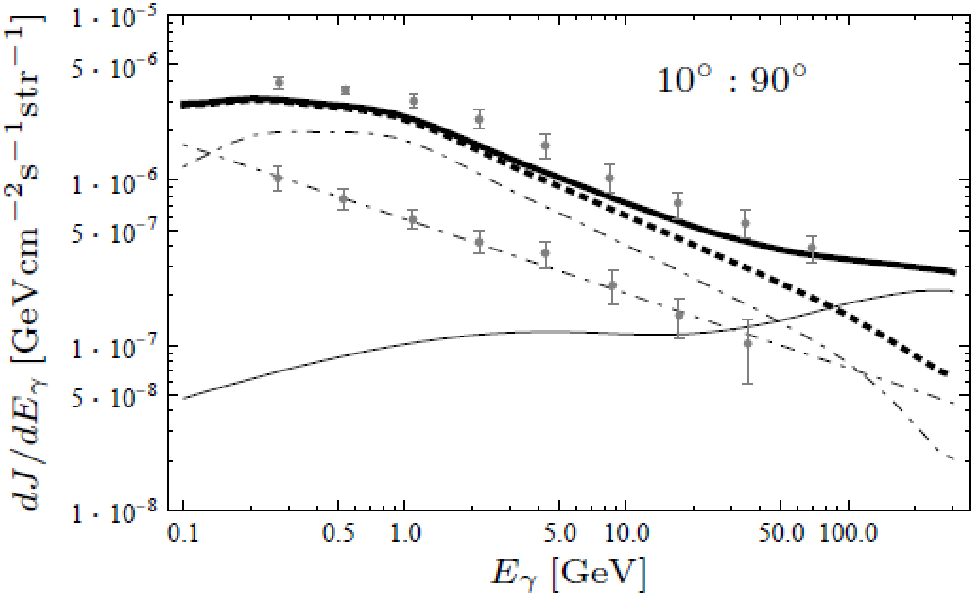


$\psi\to\mu^+\mu^-\nu$



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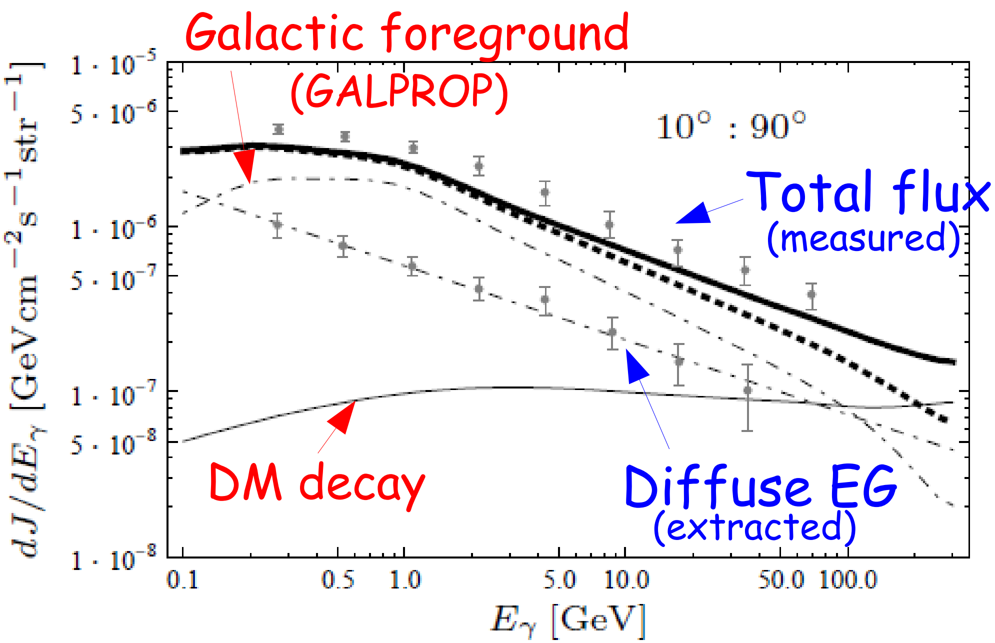
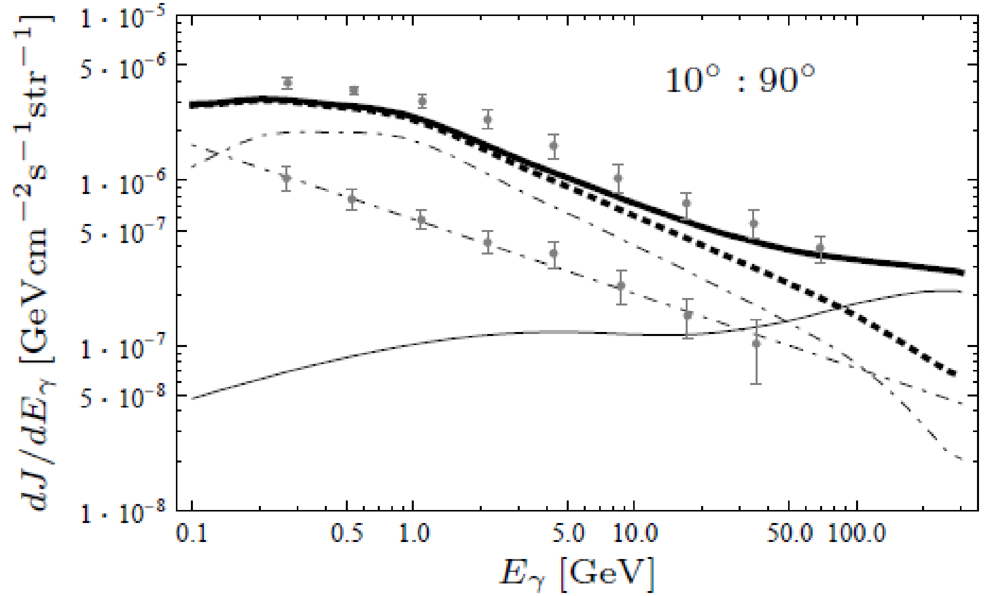


$\psi \to \mu^+\mu^-\nu$



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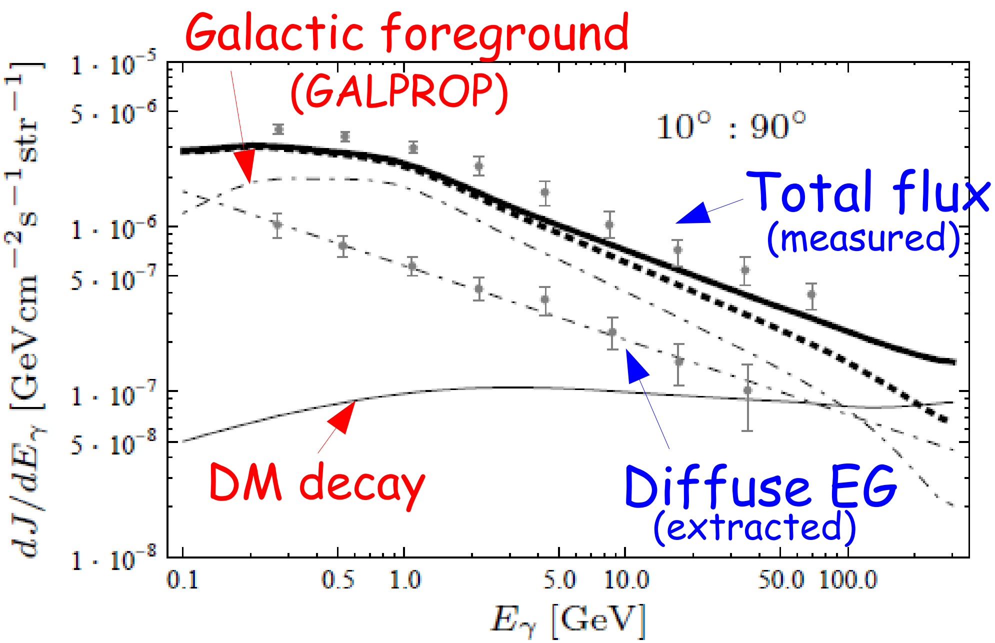

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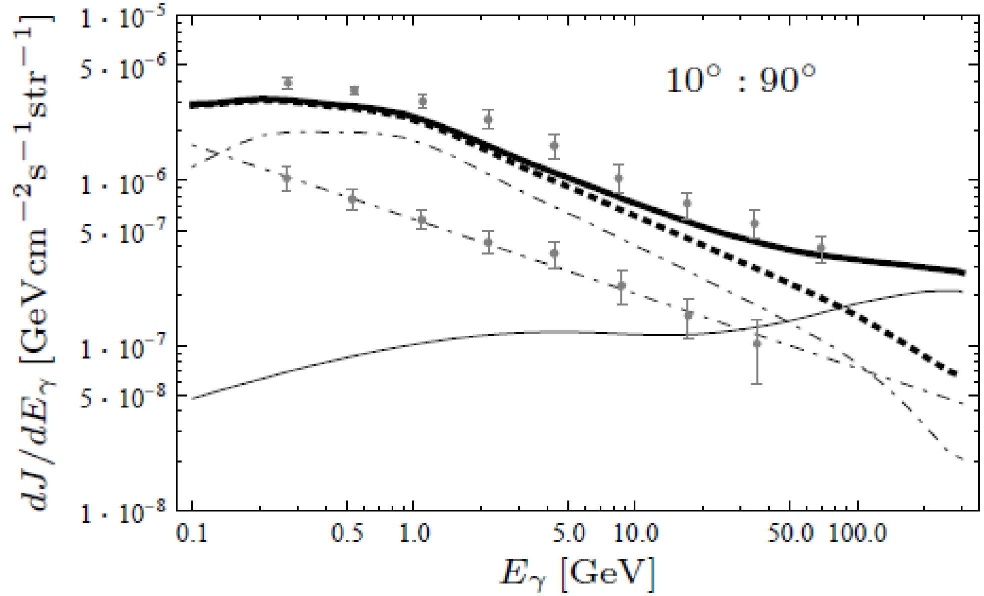

$\psi \to \ell^+\ell^-\nu$

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

Impact of the preliminary Fermi data.

AI, Tran, Weniger
arXiv: 0909.3514

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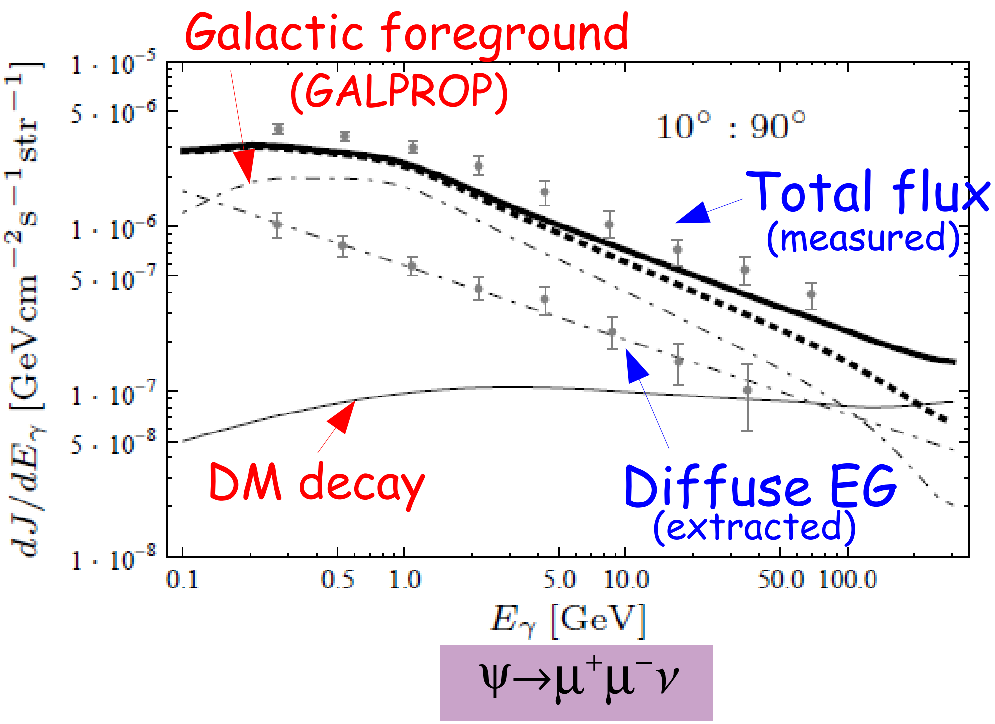

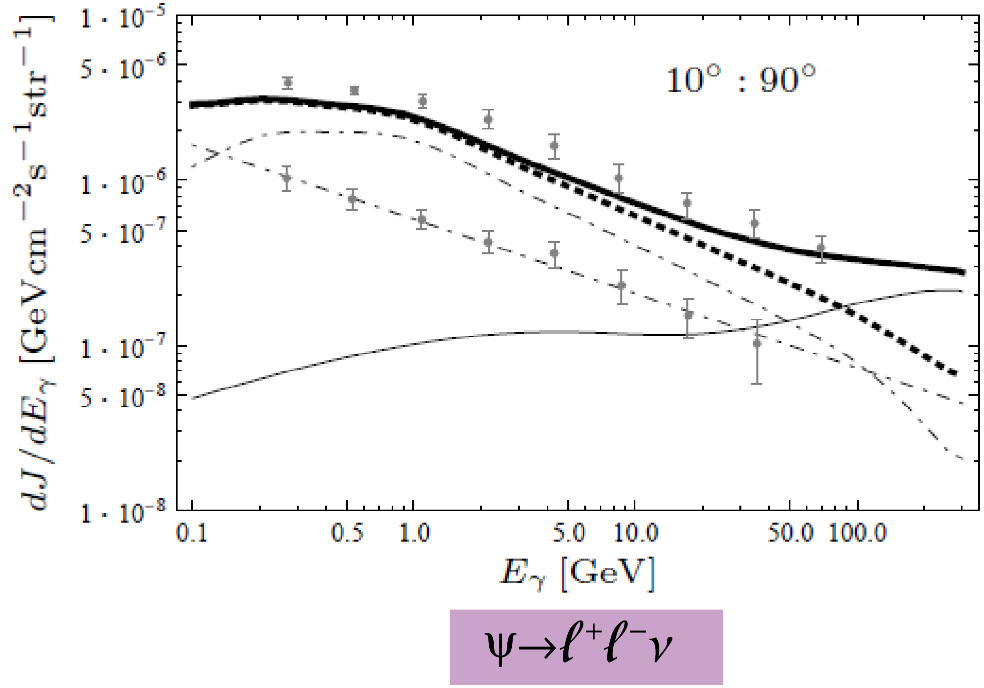

- Crucial test: the contribution from DM decay to the total flux does not exceed the measured one.
- In some channels, there starts to be a deviation from the power law in the diffuse EG flux at higher energies.

Impact of the preliminary Fermi data.

AI, Tran, Weniger
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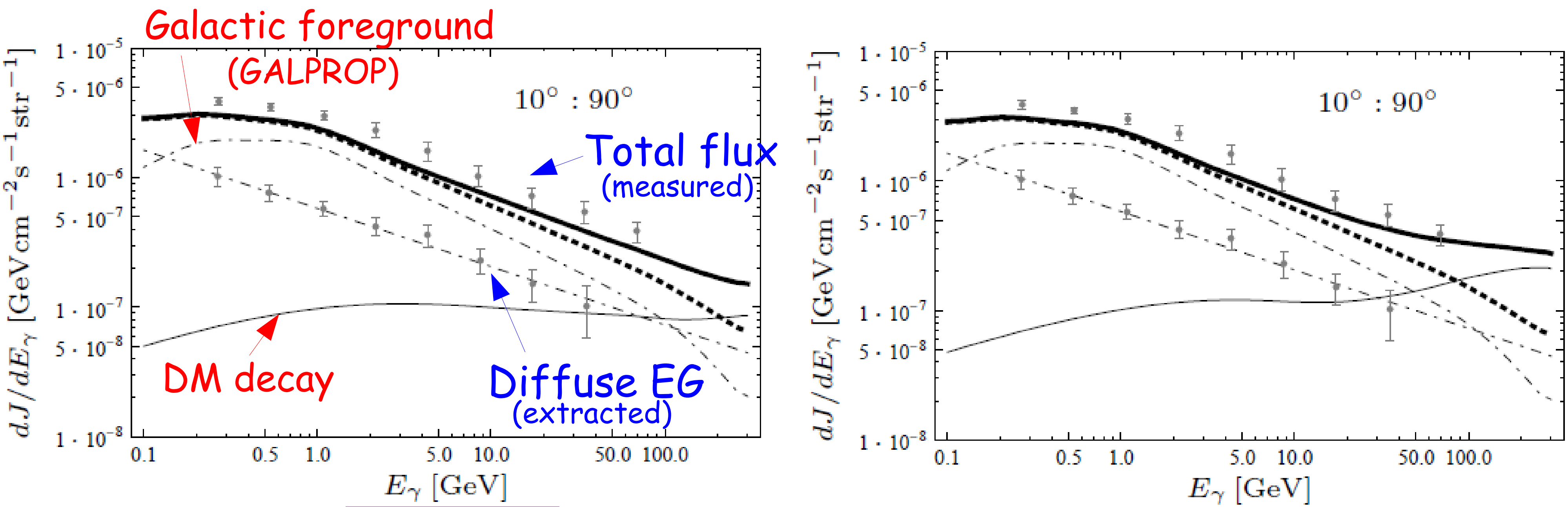


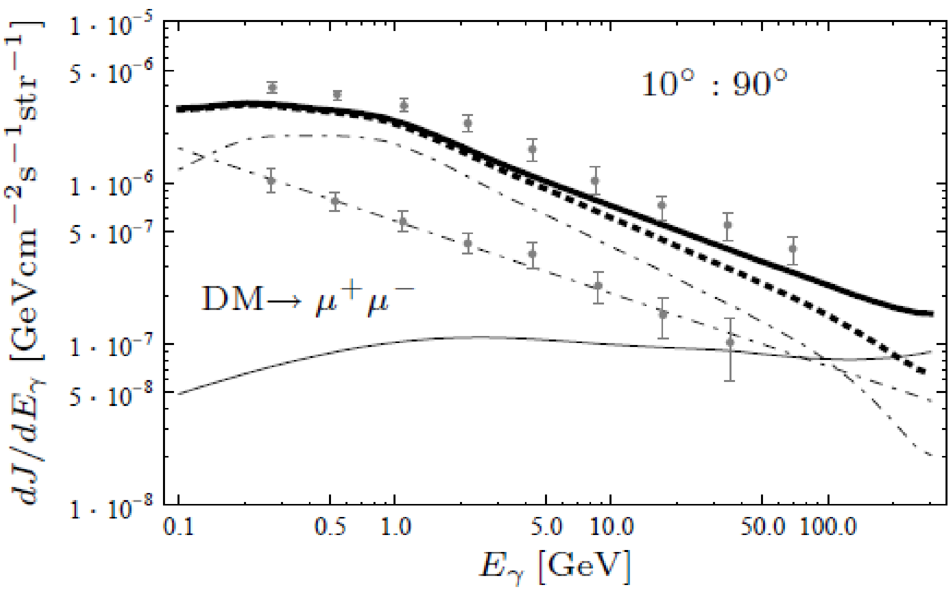
$\psi \to \mu^+ \mu^- \nu$ $\psi \to \ell^+ \ell^- \nu$

- Crucial test: the contribution from DM decay to the total flux does 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.
- **Warning**, the total flux predicted by the theory does not match the observations, even at low energies.

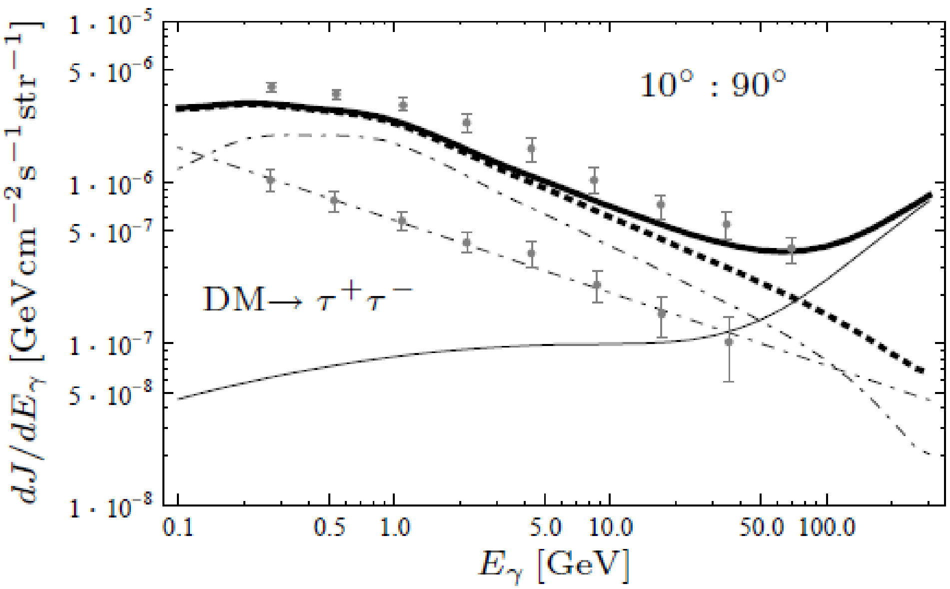
Impact of the preliminary Fermi data.

AI, Tran, Weniger
arXiv: 0909.3514

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



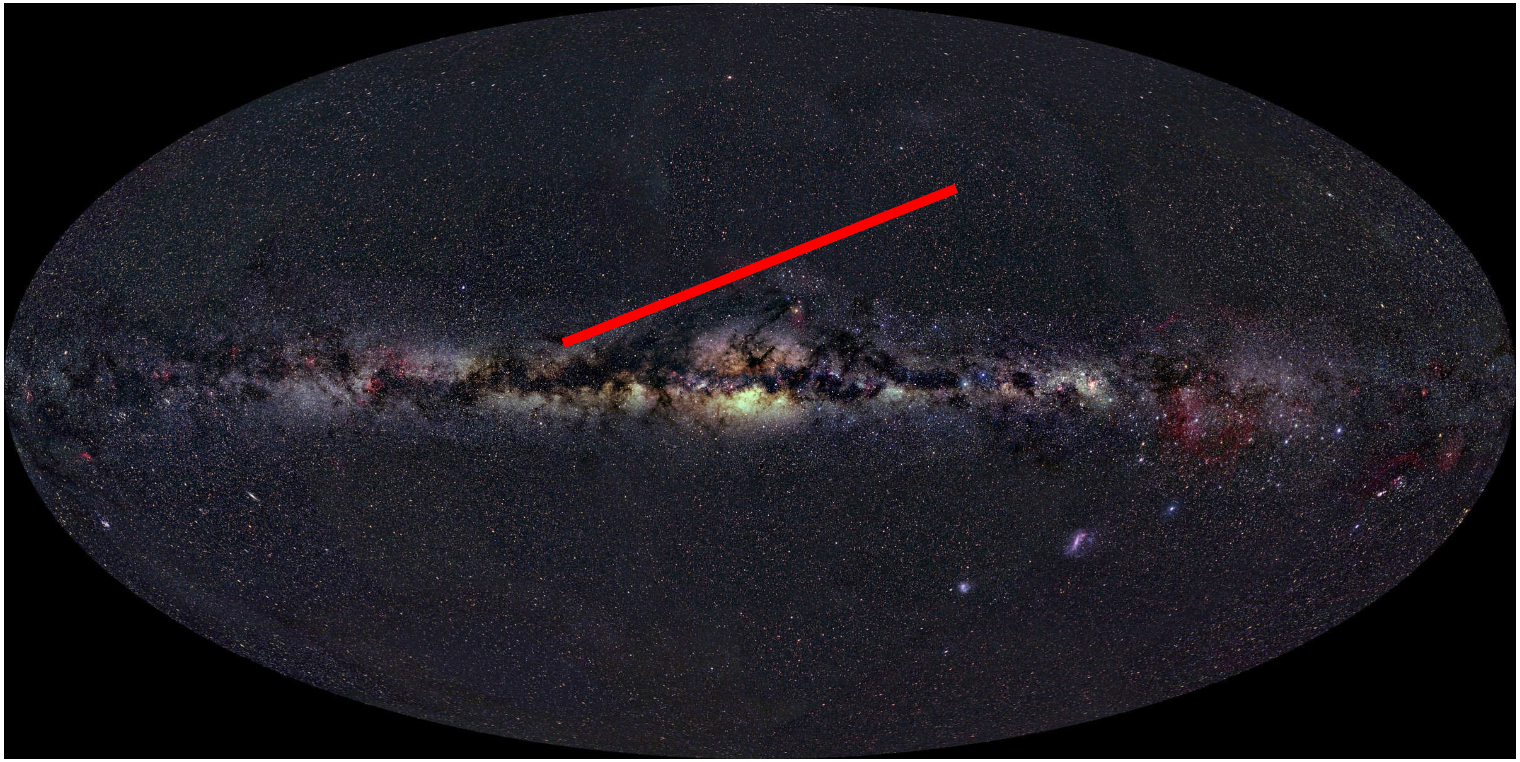
$\phi \to \mu^+\mu^-$



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

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

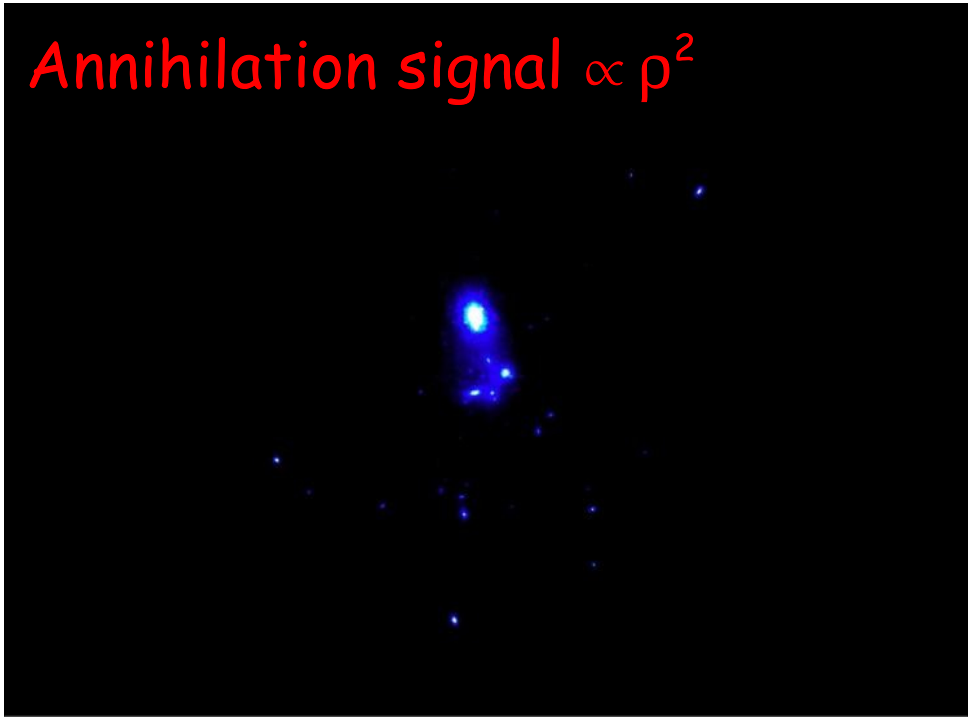
Gamma rays do not diffuse and point directly to the source!

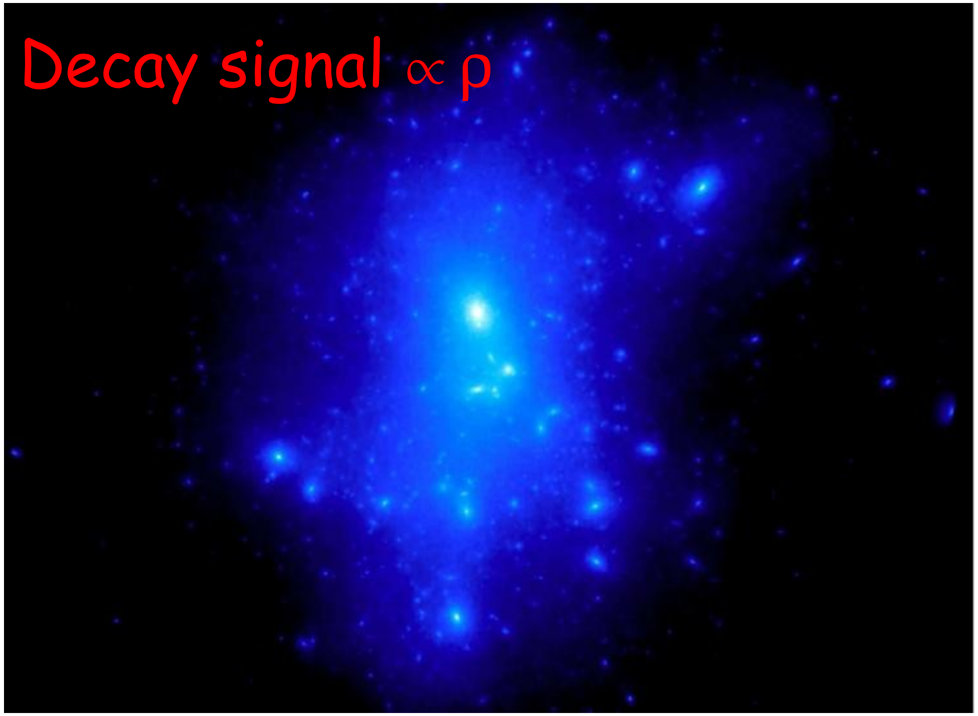


More indications for or against the decaying dark matter scenario arise from the angular distribution of gamma-rays.

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

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





From B. Moore

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

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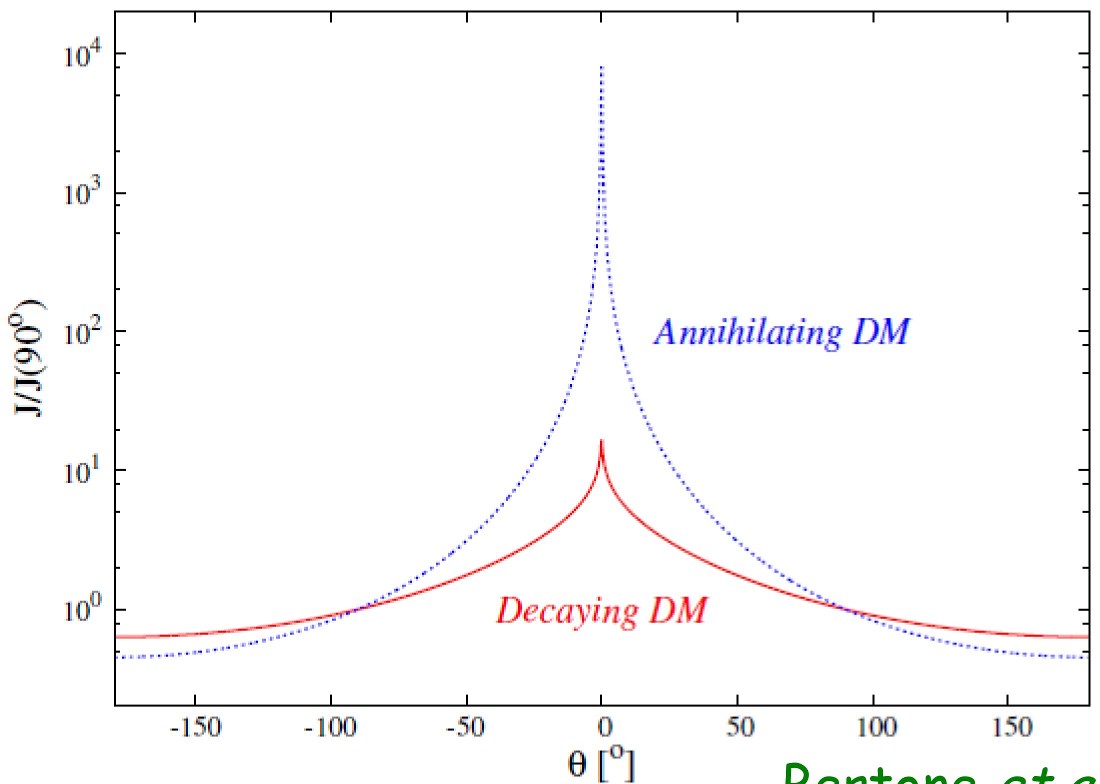
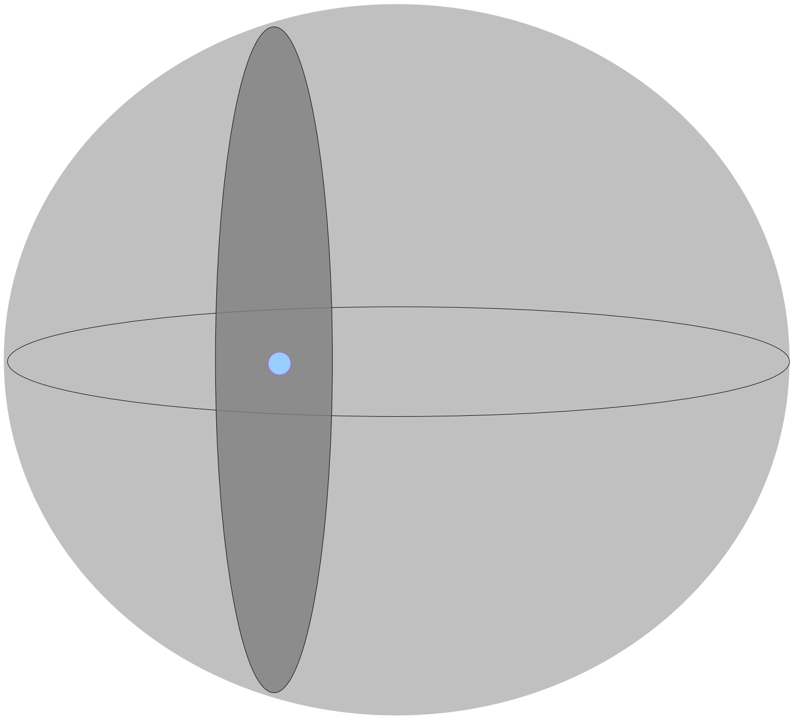


Bertone *et al.*

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.

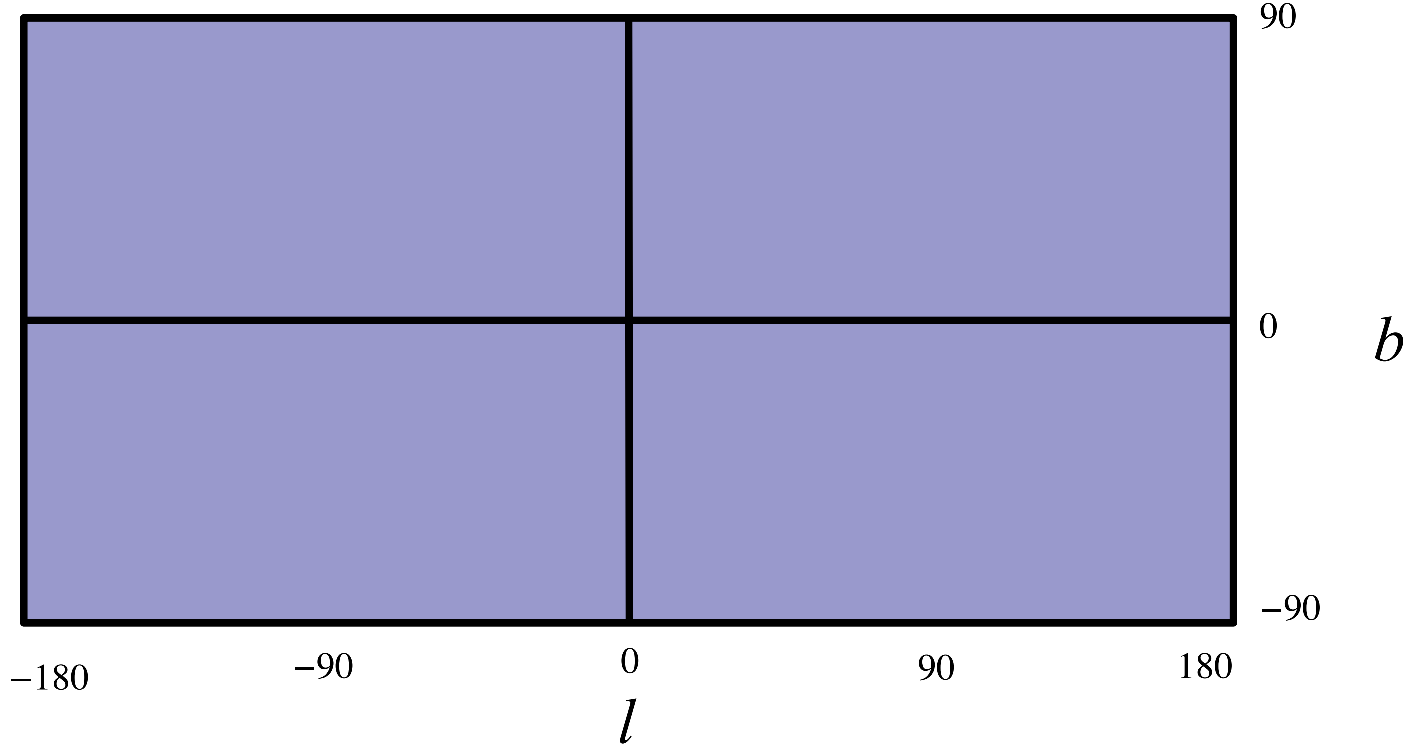
Bertone *et al.*
AI, Tran, Weniger



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.

Bertone *et al.*
AI, Tran, Weniger

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.

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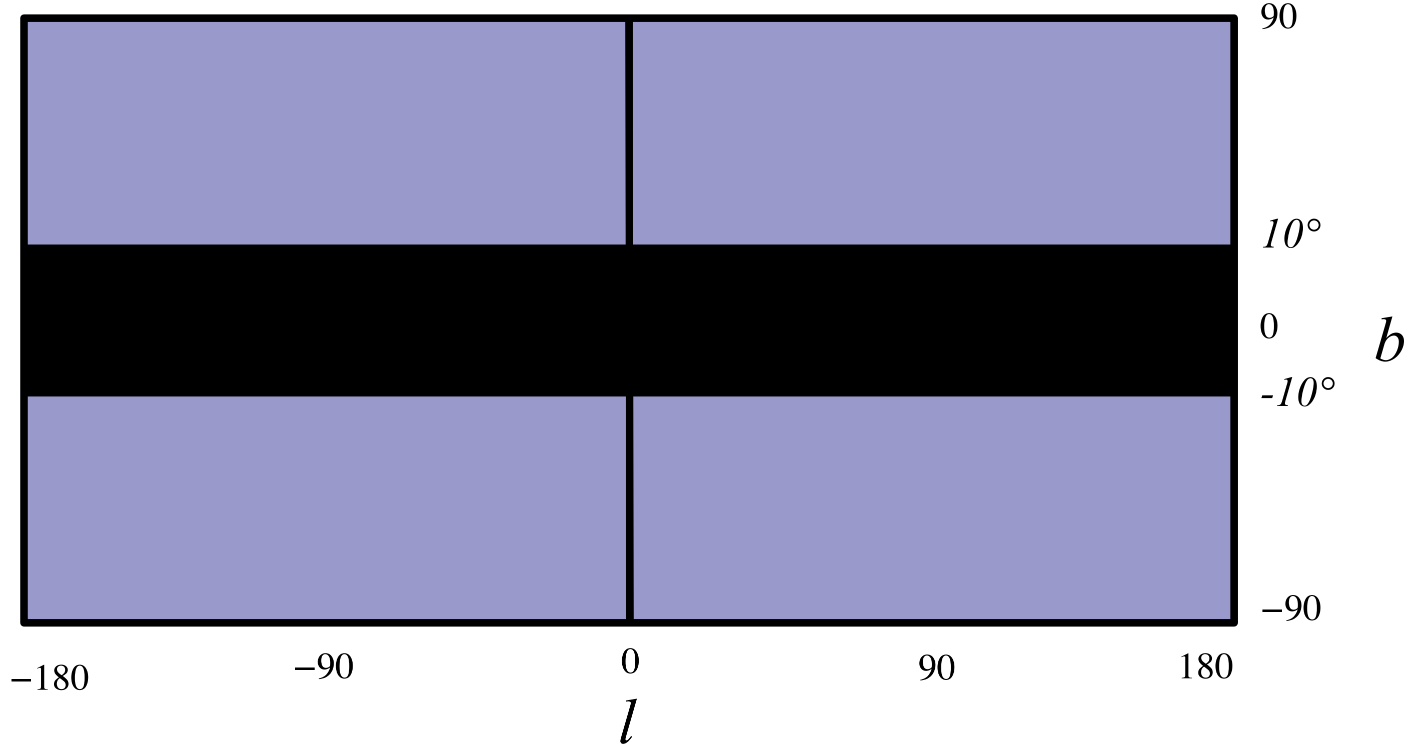
Strategy: 2) Remove the galactic disk



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.

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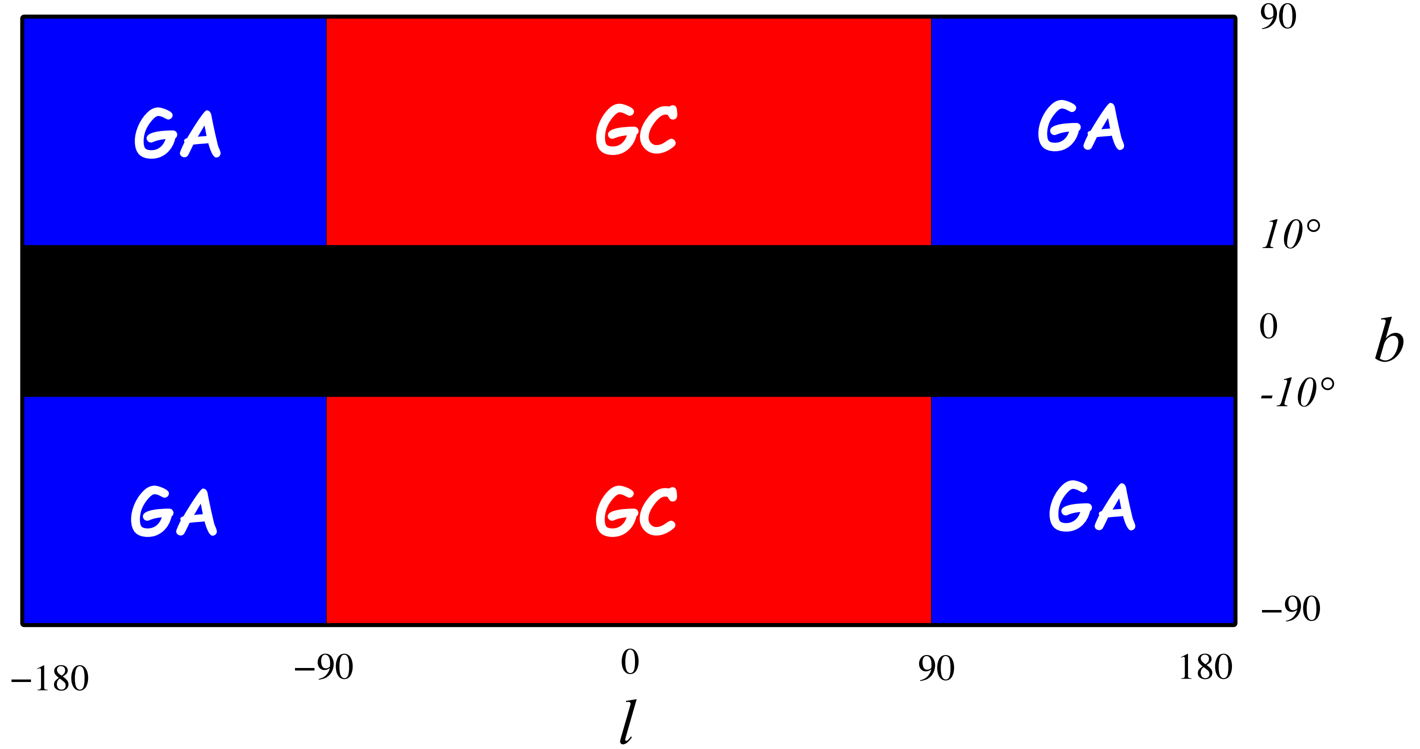
Strategy: 3) Take the total fluxes coming from the direction of the galactic center (J_{GC}) and the galactic anticenter (J_{AC}).



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.

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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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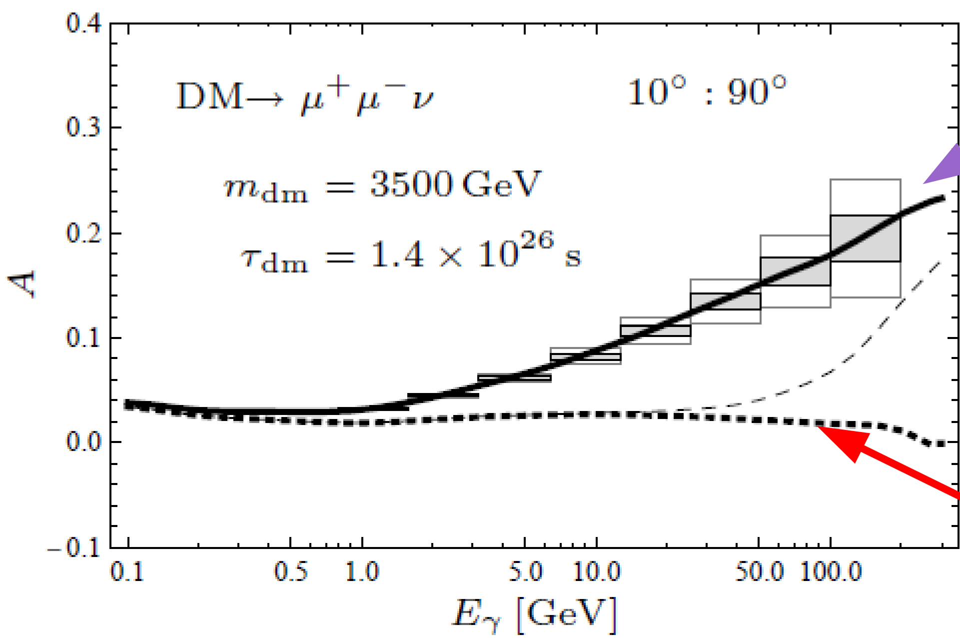
Strategy: 4) Calculate the anisotropy, defined as:

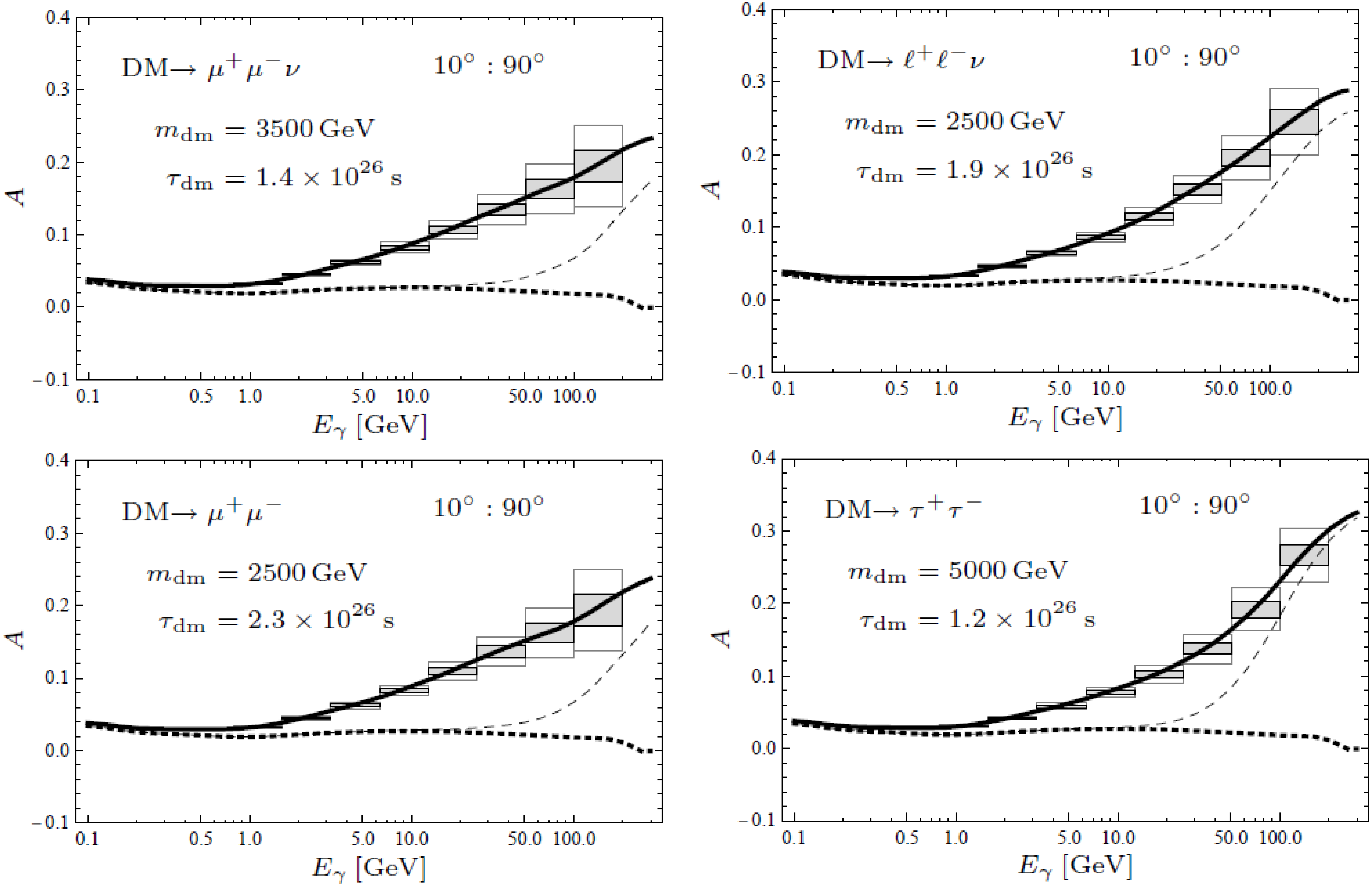
$$A(E) = \frac{J_{GC} - J_{GA}}{J_{GC} + J_{GA}}$$



DM decay prediction: 20% at high energies!

GALPROP prediction

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



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?

• 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.

• Decaying dark matter could explain the electron/positron excesses observed by PAMELA and Fermi. Furthermore, these scenarios make predictions for gamma-ray observations, namely a diffuse gamma-ray flux which is anisotropic and an energy spectrum which departs from a simple power law.