Decaying Dark Matter and the PAMELA anomaly

Alejandro Ibarra

Technische Universität München

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

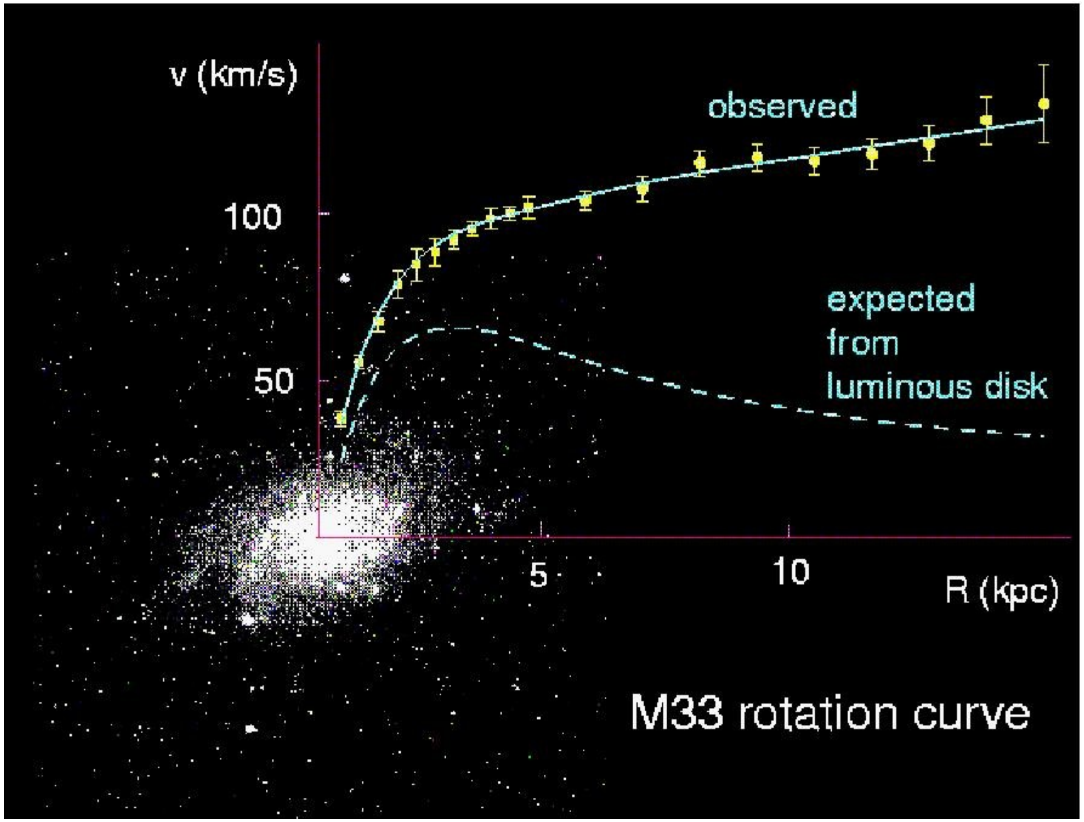
Yukawa Institute
Kyoto
6th March 2009

Outline

- Introduction.
- Anomalies in the cosmic ray fluxes.
- Astrophysical interpretation of the anomalies.
- Decaying dark matter as the origin of the cosmic ray anomalies.
- A particularly interesting candidate for decaying dark matter: decaying gravitinos.
- Conclusions.

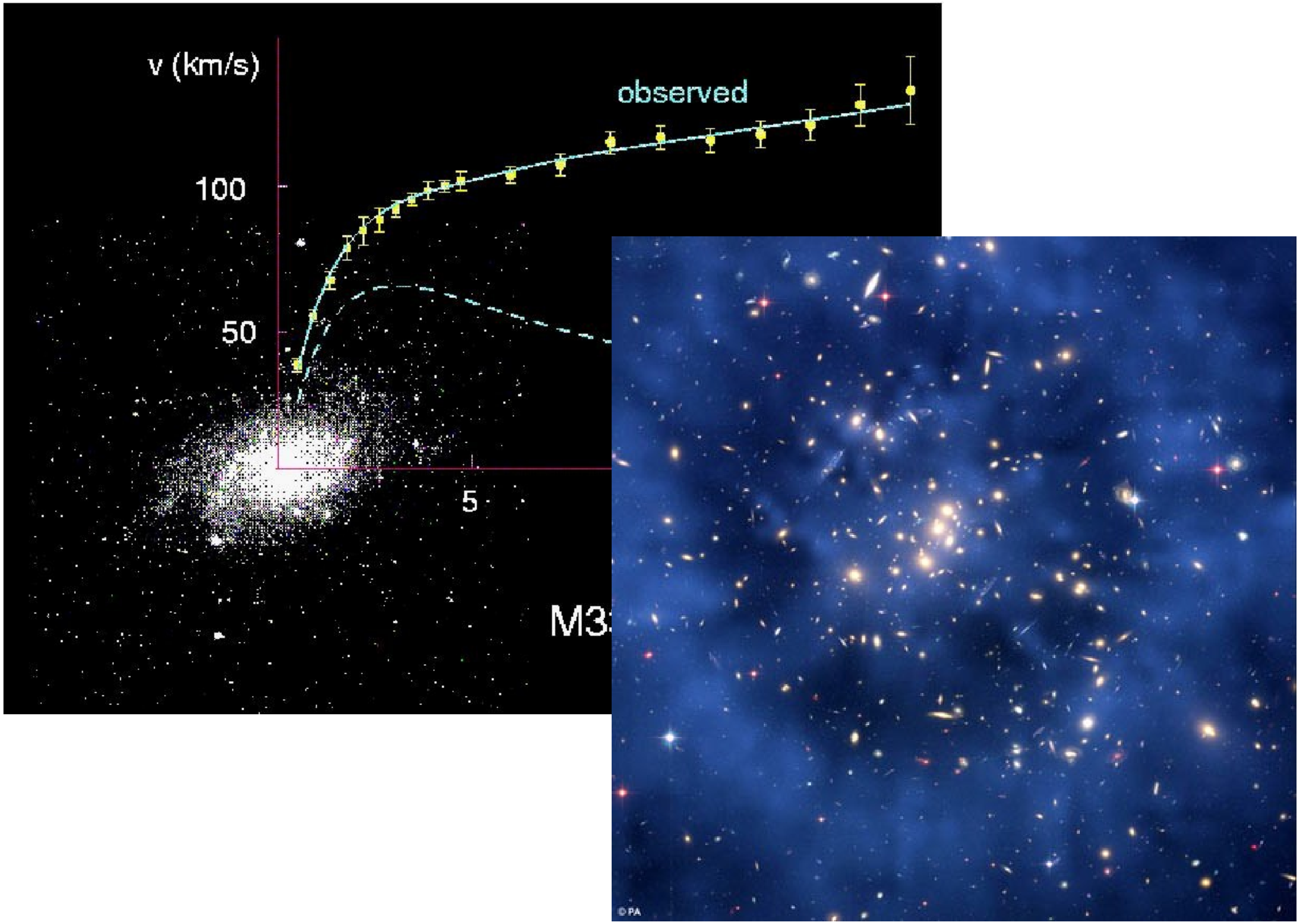
Introduction

Dark matter exist



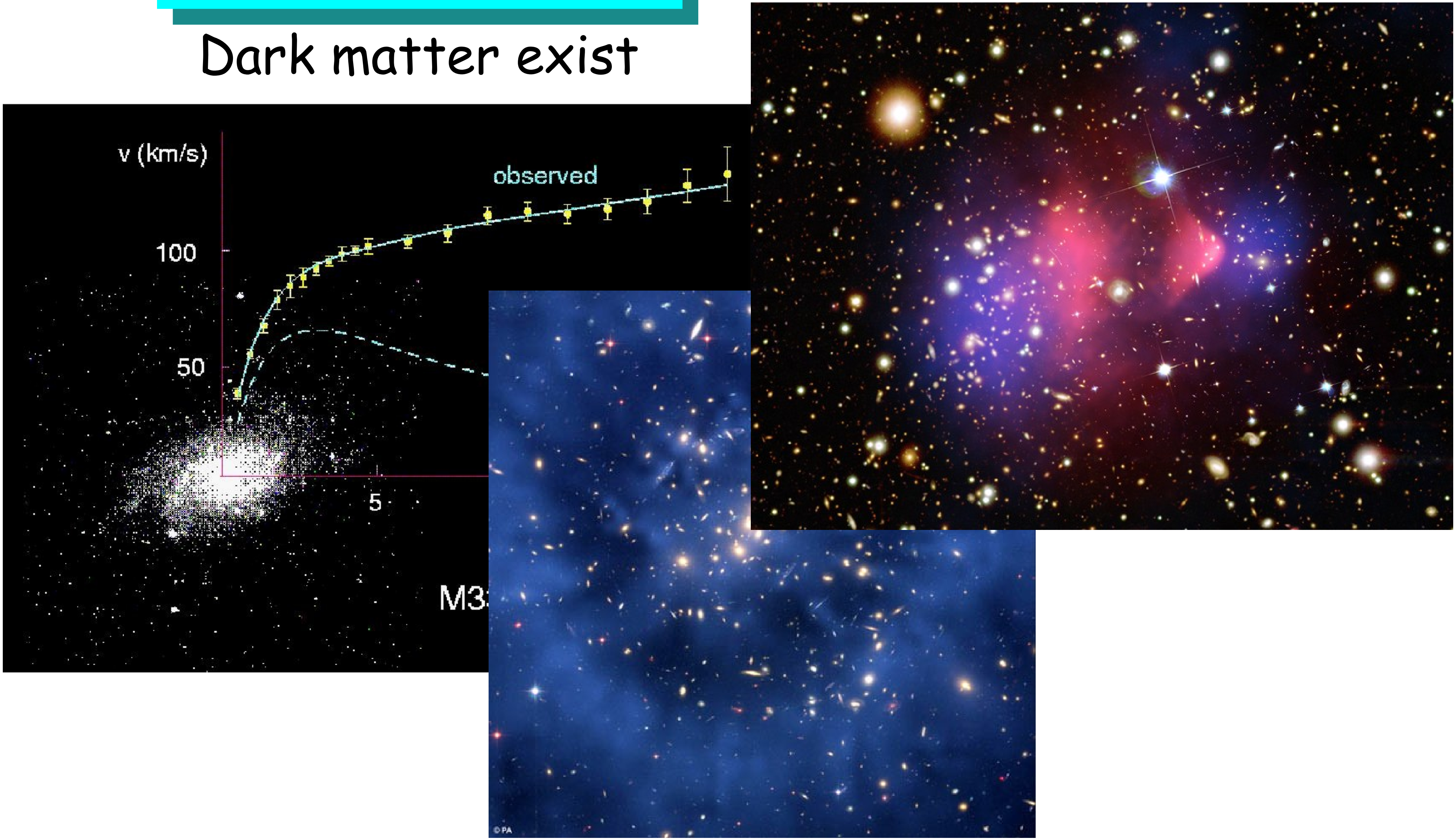
Introduction

Dark matter exist



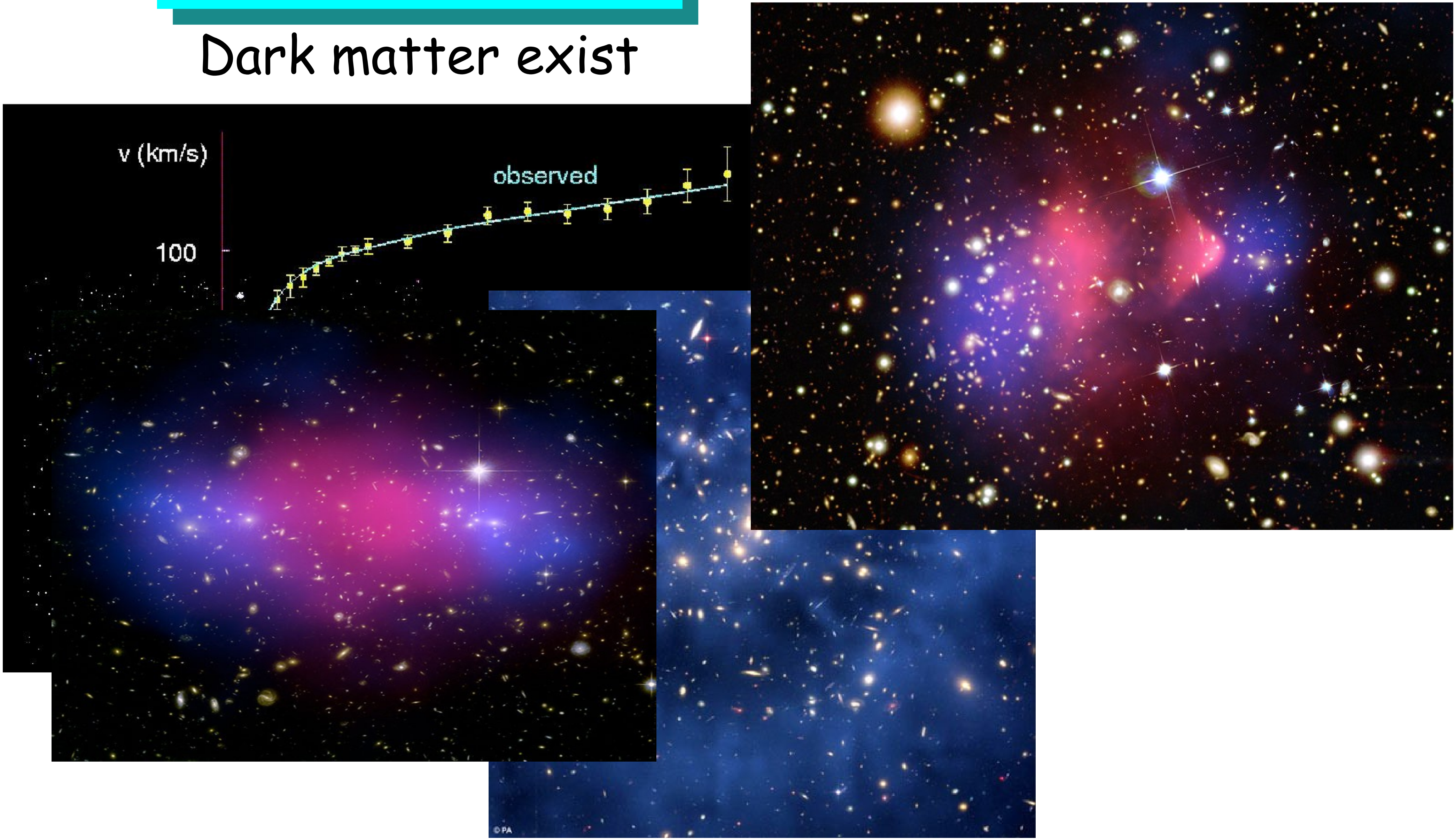
Introduction

Dark matter exist



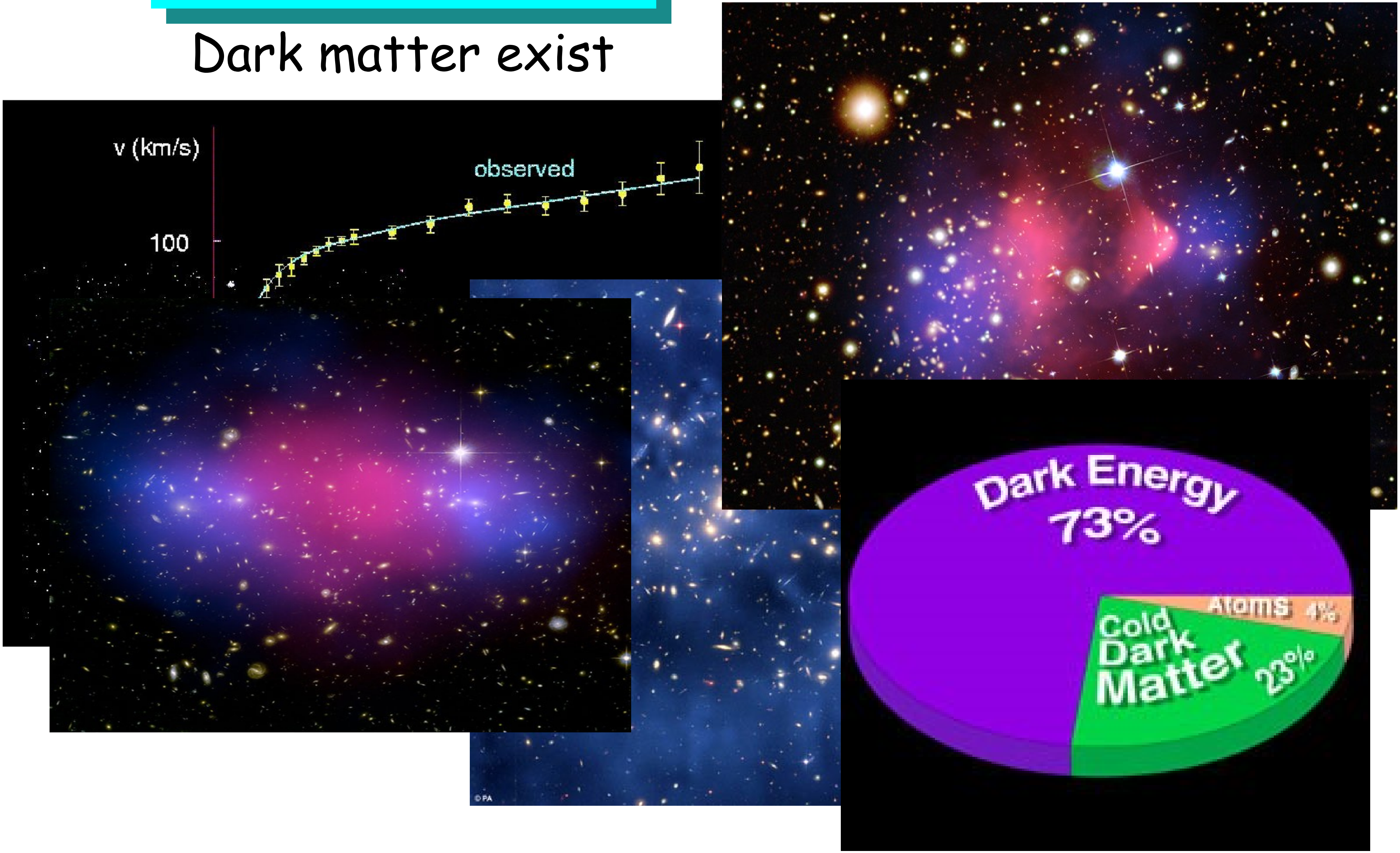
Introduction

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!)

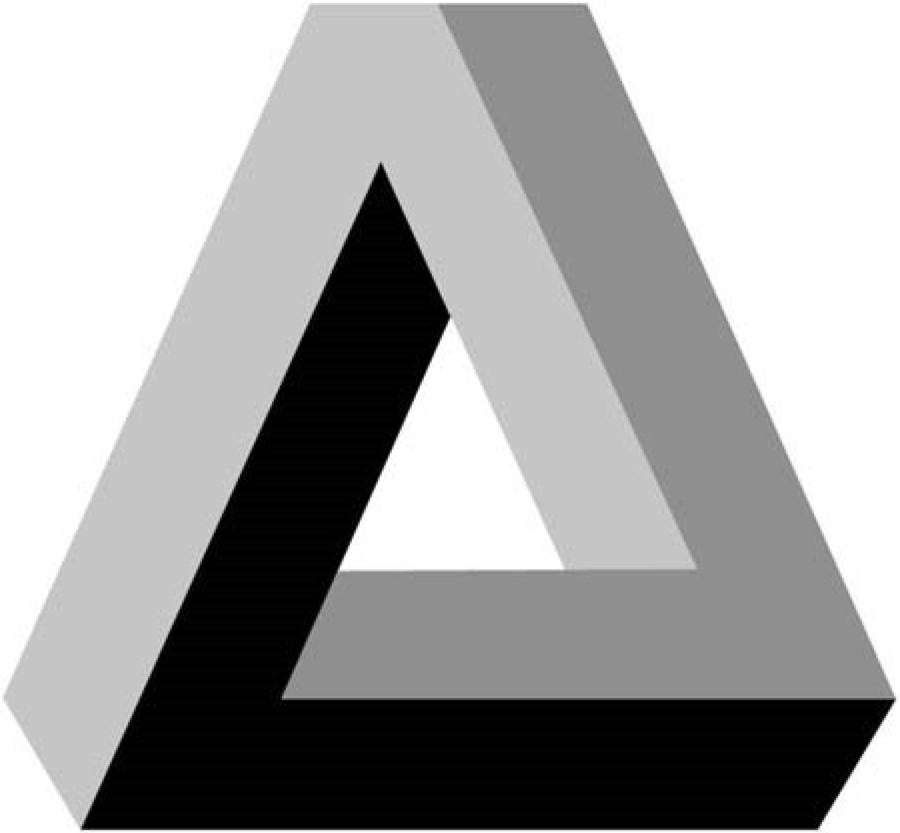
All these evidences for dark matter are of gravitational origin

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

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

Direct detection

DM nucleus → DM nucleus



Indirect detection

DM DM →γγ, e+e-... (annihilation)

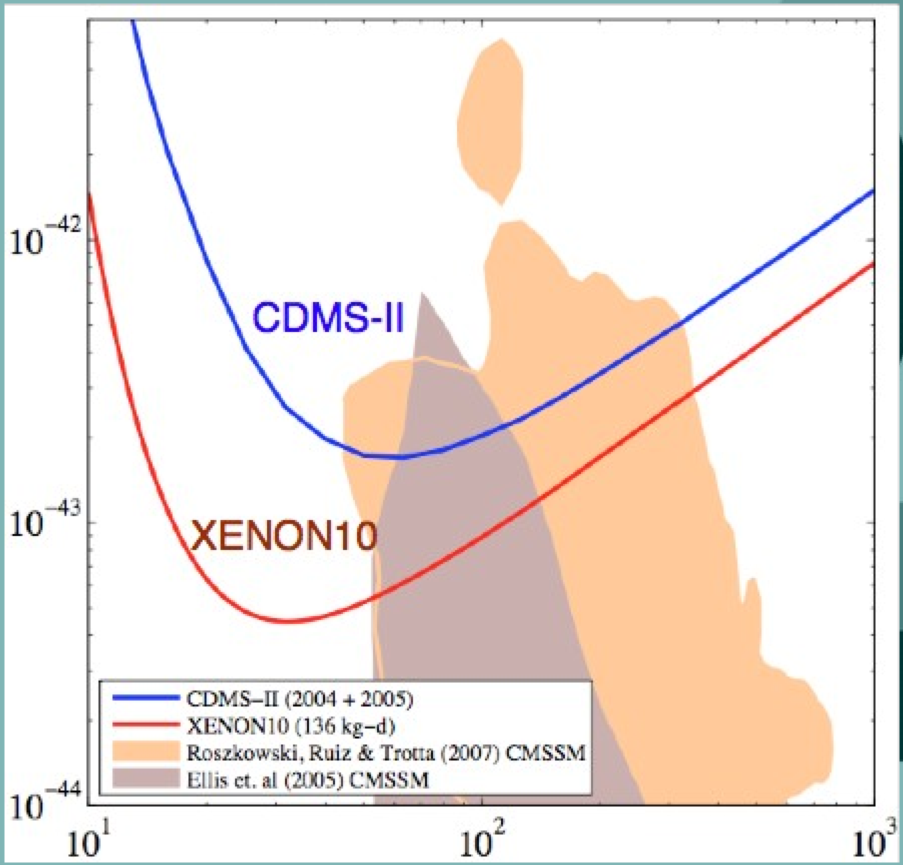
DM →γ X, e+X,... (decay)

Collider searches

pp → DM X

Direct detection

DM nucleus → DM nucleus



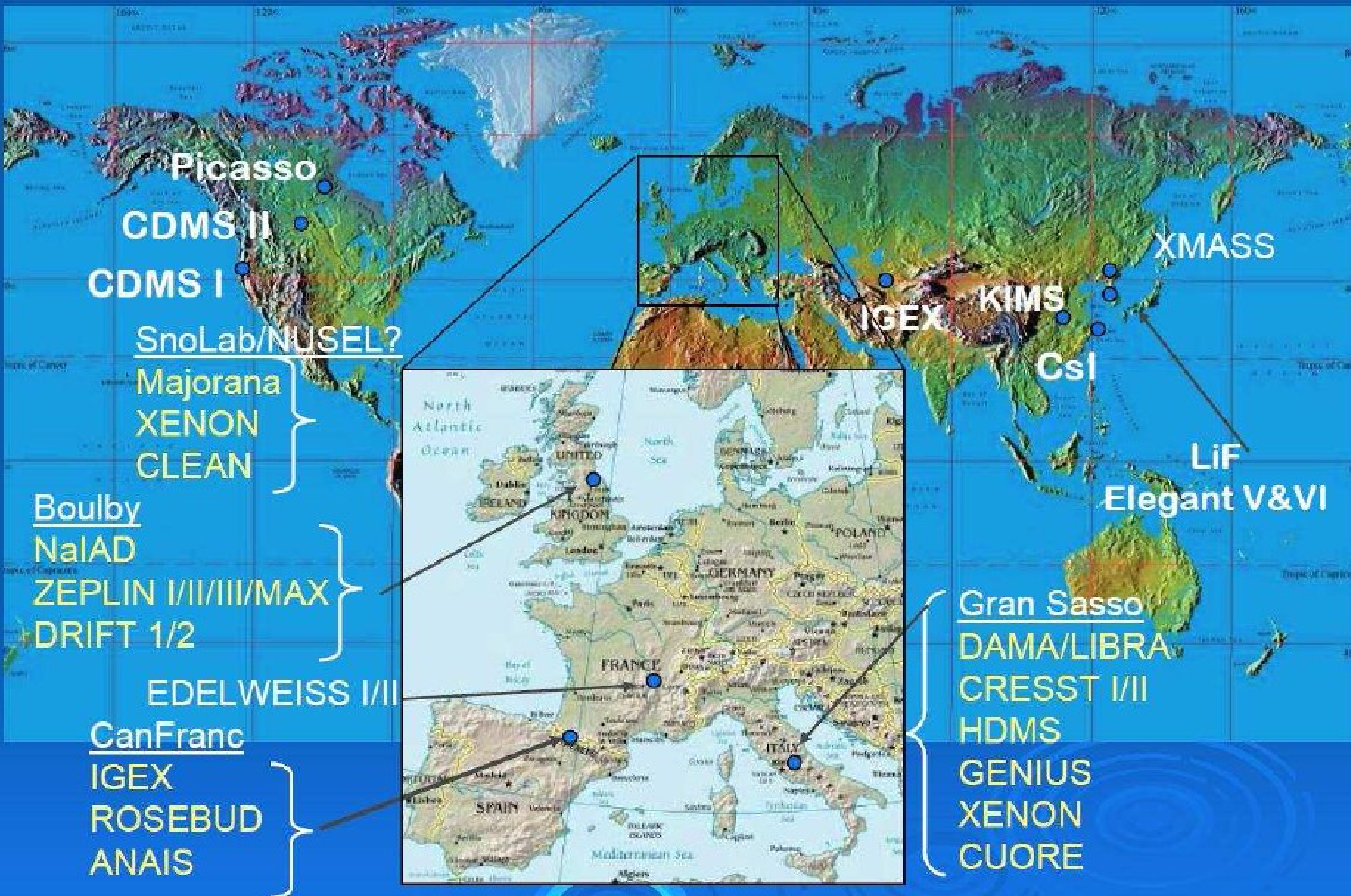
DM DM →γγ, e+e-... (annihilation)

DM →γ X, e+X,... (decay)

Collider searches

pp → DM X

World Wide WIMP Search



Picasso

CDMS II

CDMS I

SnoLab/NUSEL?
- Majorana
- XENON
- CLEAN

Boulby
- NaIAD
- ZEPLIN I/II/III/MAX
- DRIFT 1/2

EDELWEISS I/II

CanFranc
- IGEX
- ROSEBUD
- ANAIS

XMASS

KIMS

IGEX

CsI

LiF

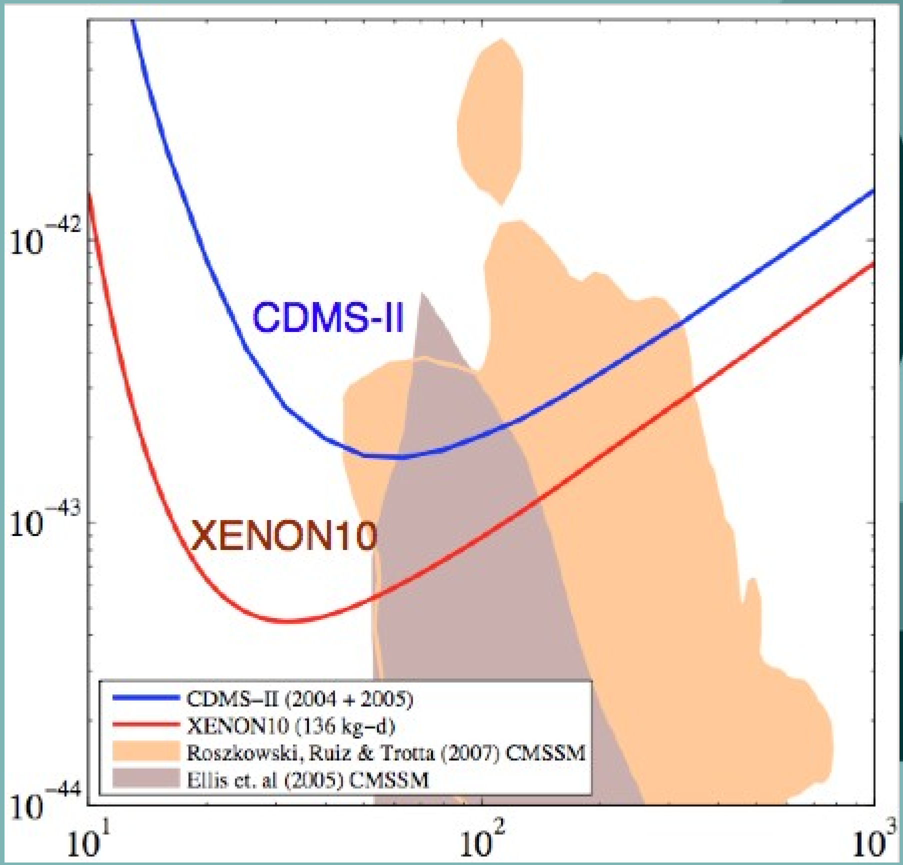
Elegant V&VI

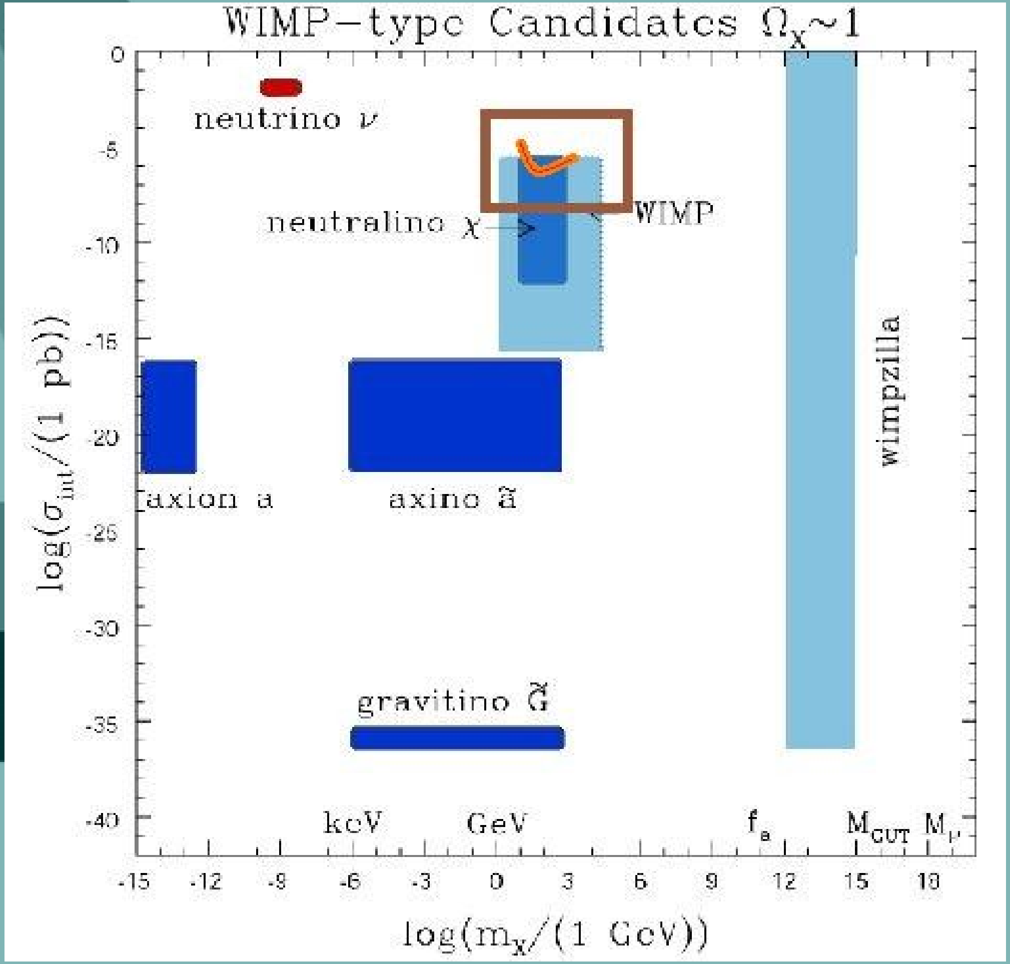
Gran Sasso
- DAMA/LIBRA
- CRESST I/II
- HDMS
- GENIUS
- XENON
- CUORE

From Laura Baudis

Direct detection

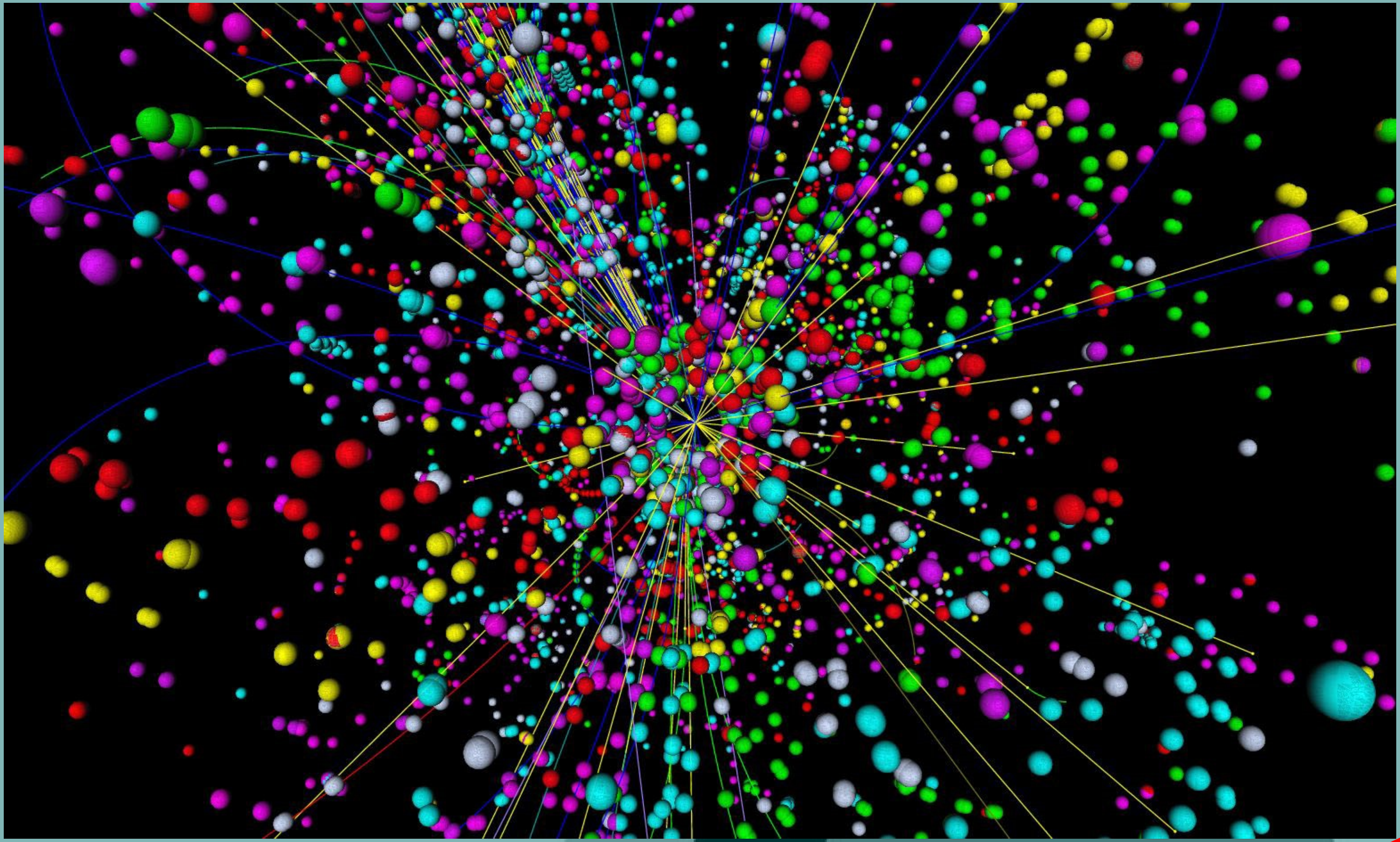
DM nucleus → DM nucleus





DM DM →γγ, e+e-... (annihilation)

DM →γ X, e+X,... (decay)



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 → DM nucleus

Indirect detection

DM DM → γγ, e+e-... (annihilation)

DM → γ X, e+X,... (decay)

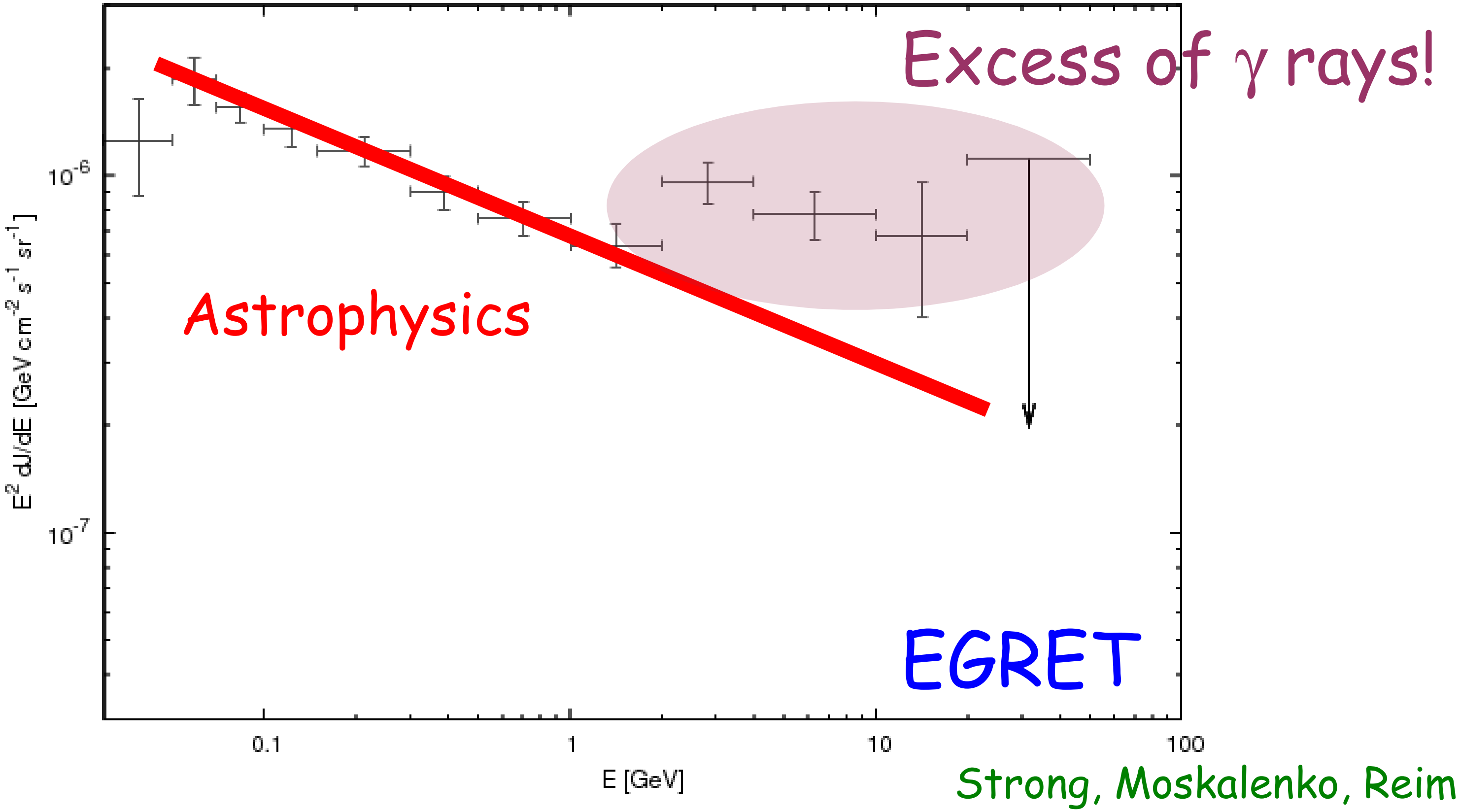
Collider searches

pp → DM X

Exciting possibility!

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

Extragalactic flux of gamma rays

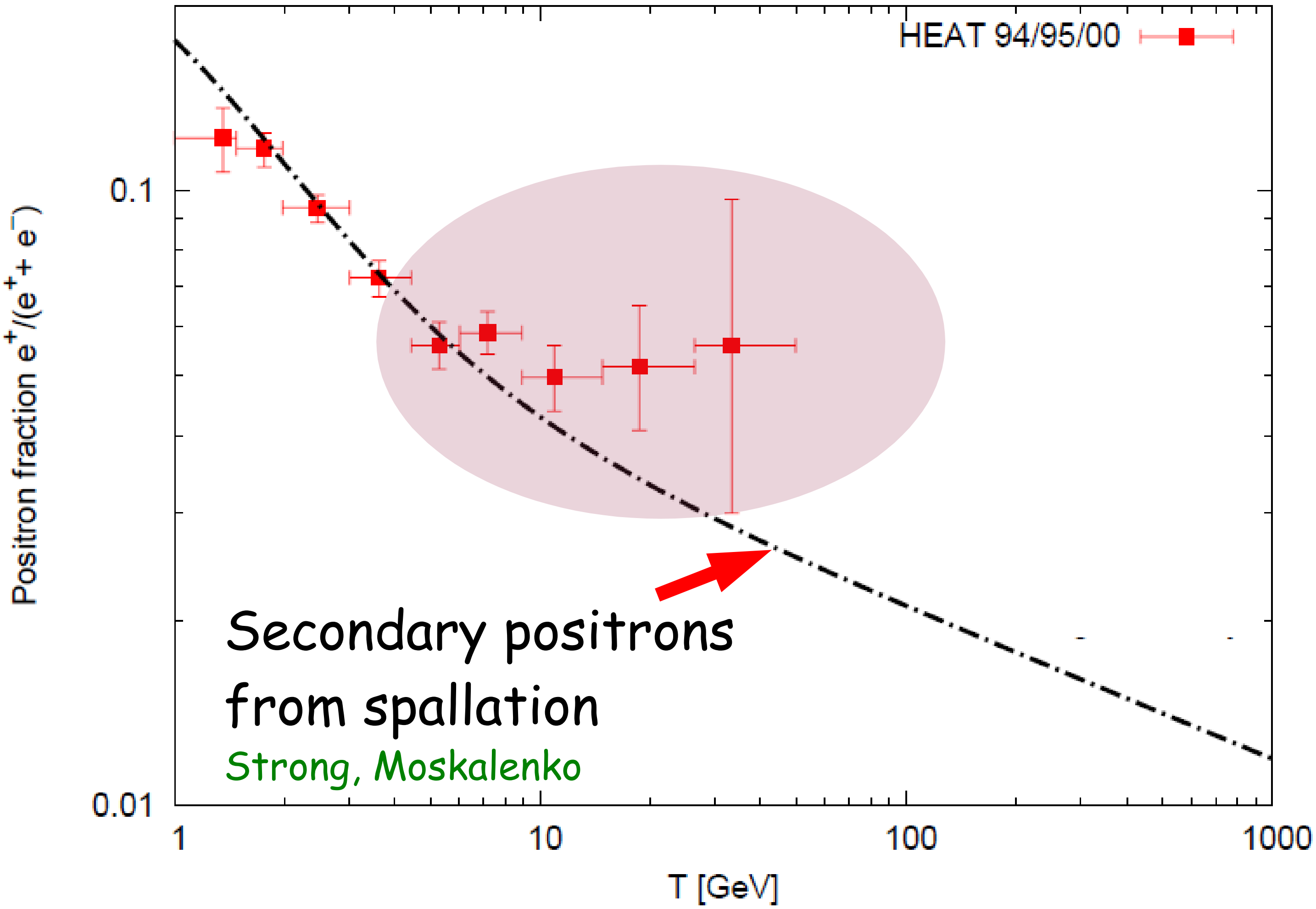


Strong, Moskalenko, Reimer

Many open questions:

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

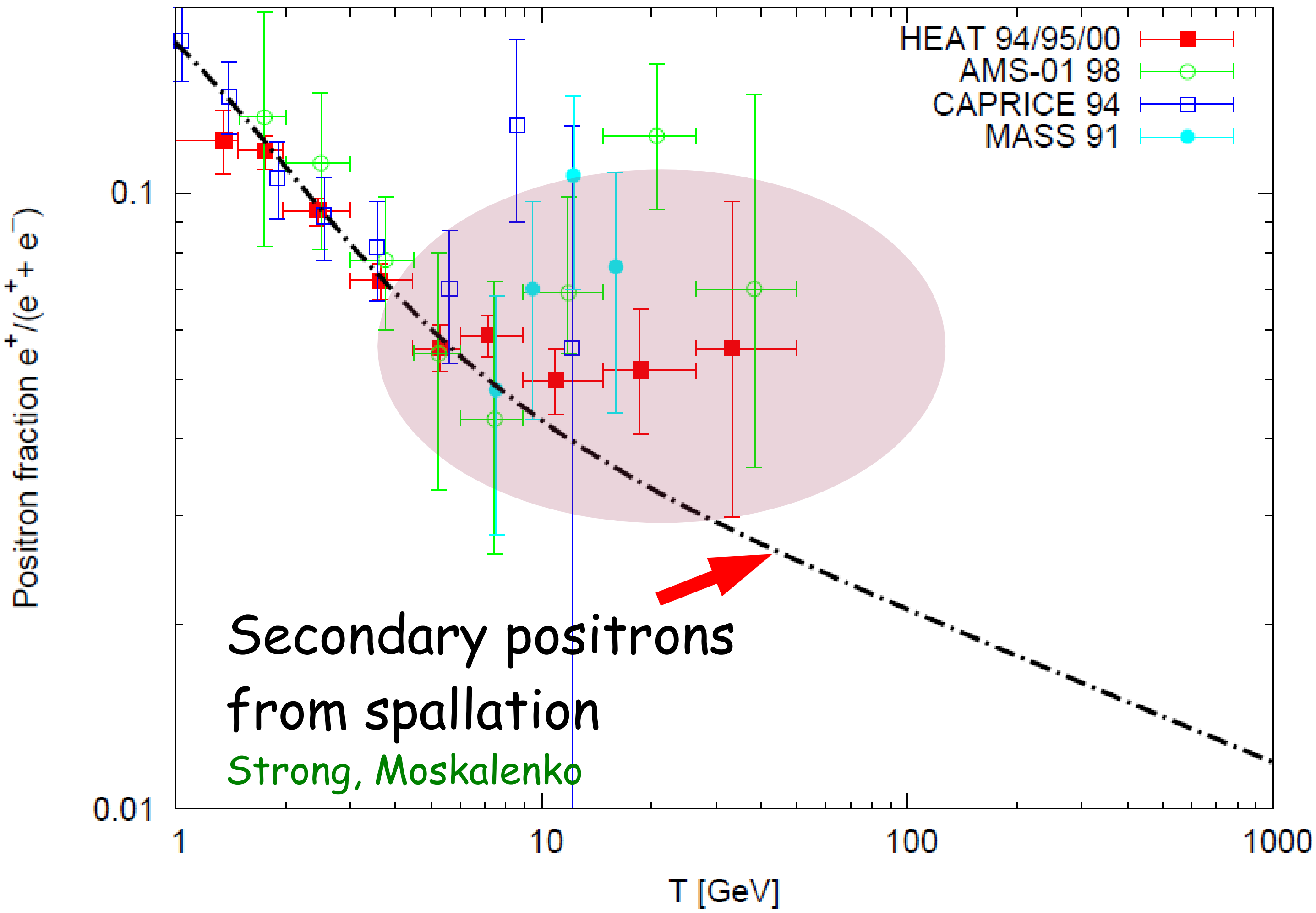
Positron Fraction



Secondary positrons from spallation

Strong, Moskalenko

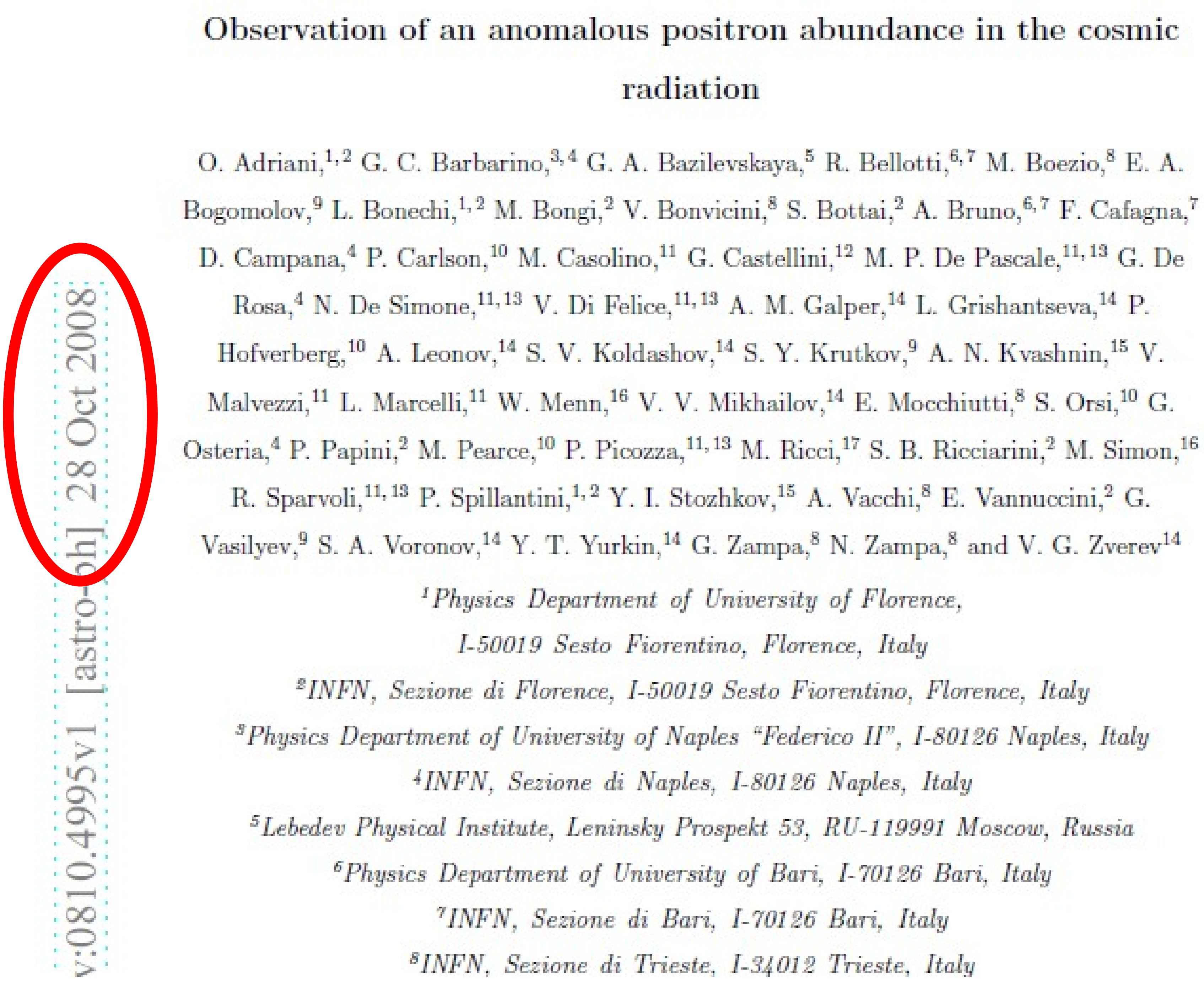
Positron Fraction



Secondary positrons from spallation

Strong, Moskalenko

Spectacular experimental progress over the last months

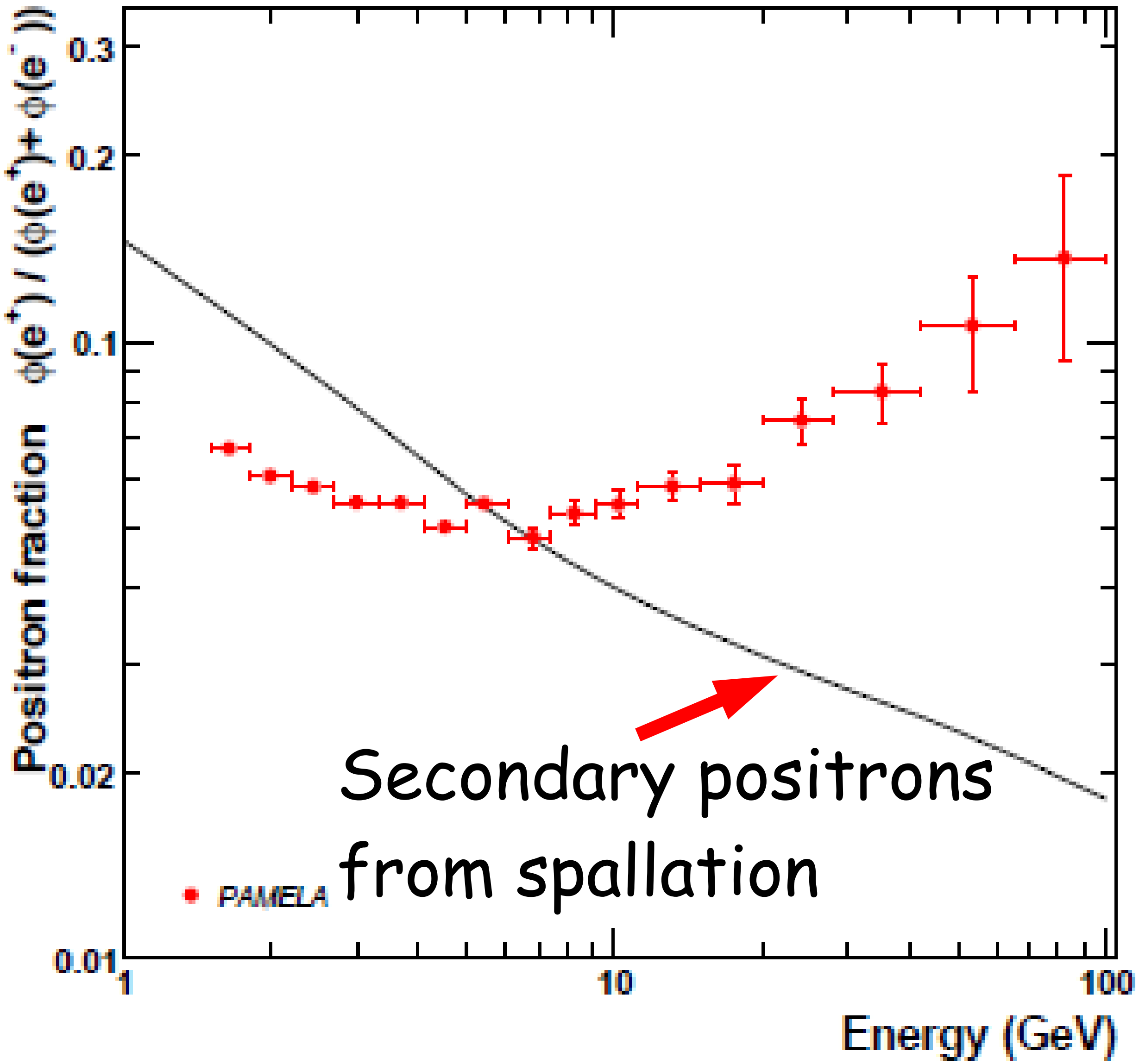


v:0810.4995v1 [astro-ph] 28 Oct 2008

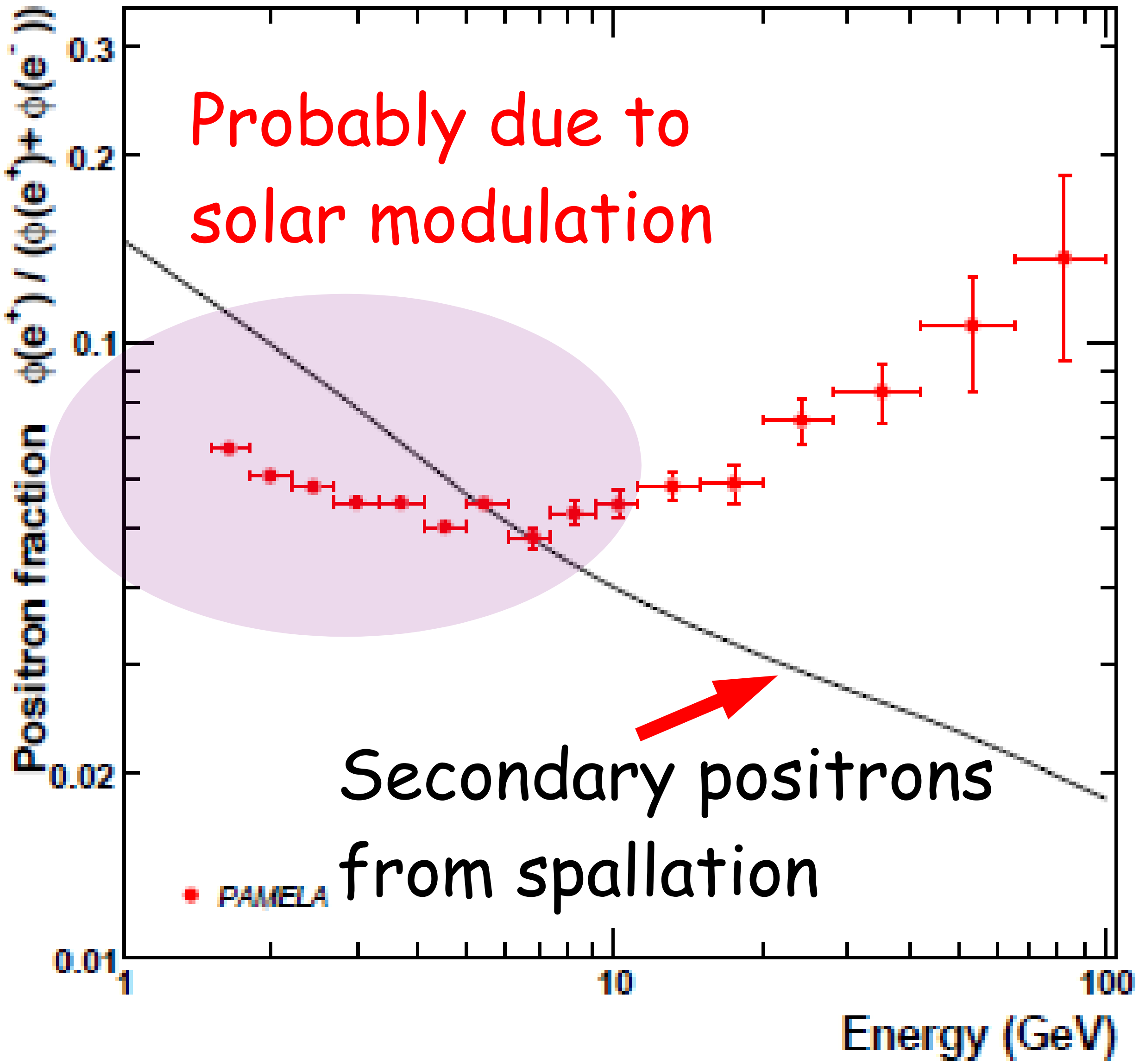
Observation of an anomalous positron abundance in the cosmic radiation

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*

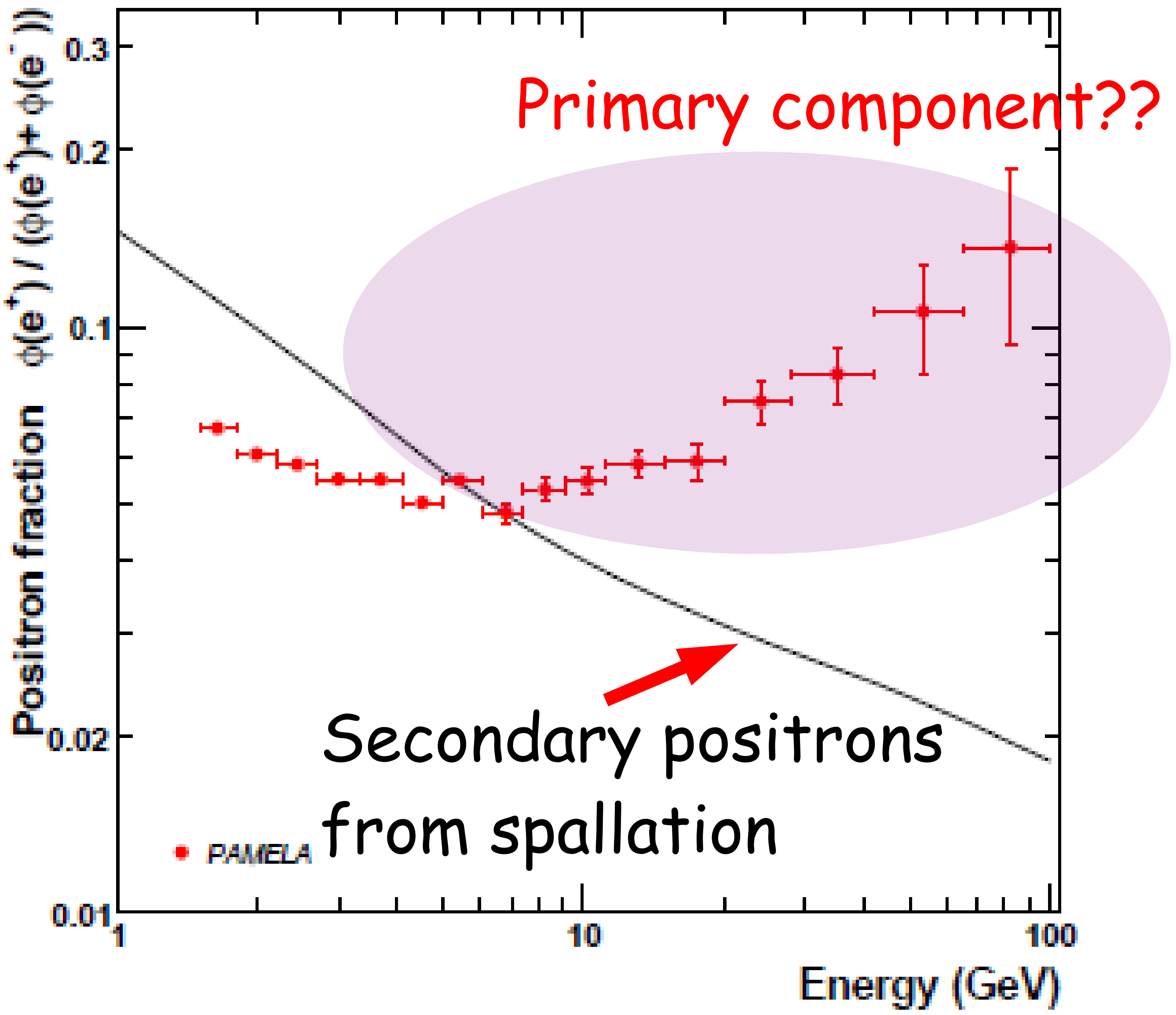


Secondary positrons from spallation



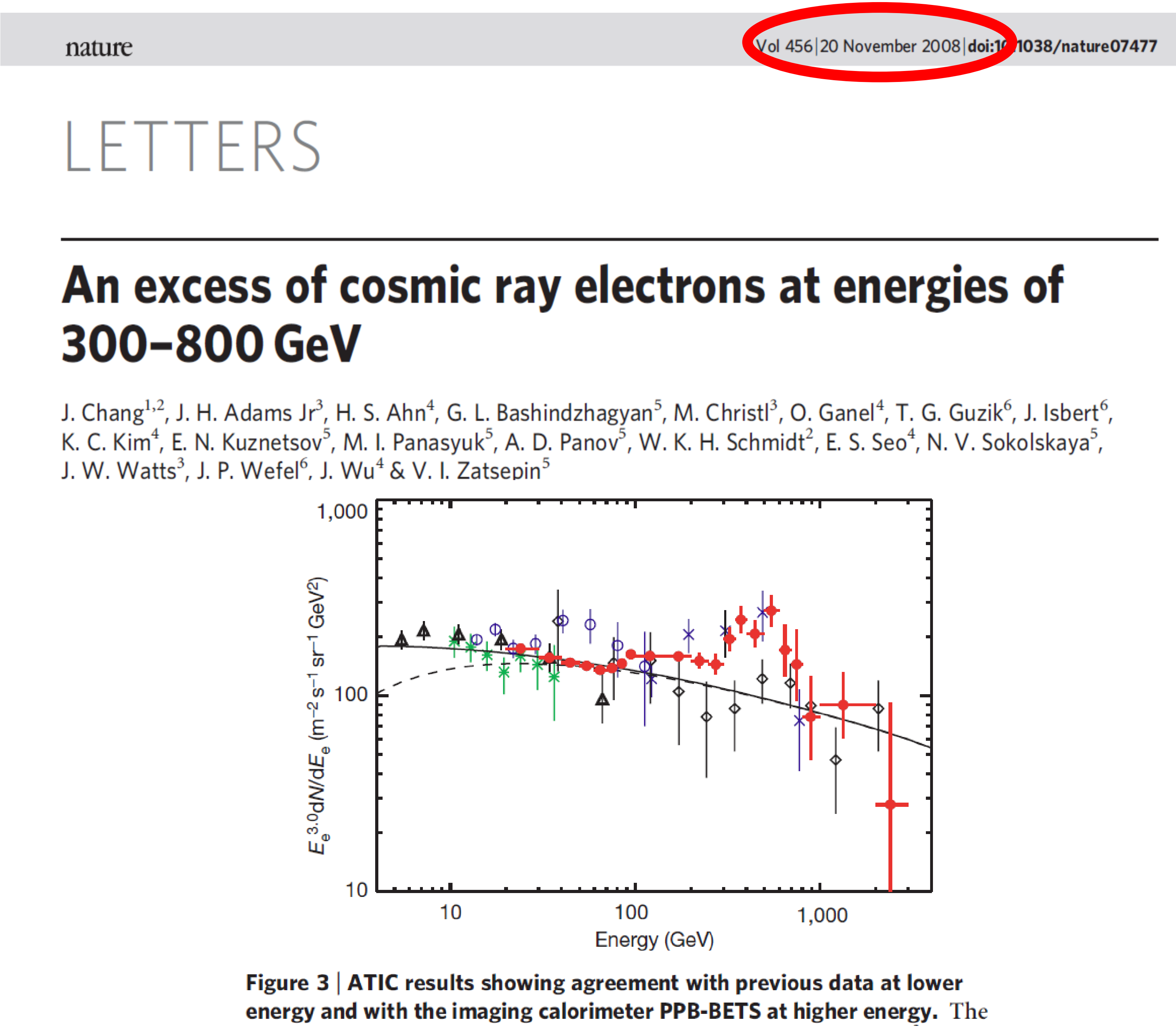
Probably due to solar modulation

Secondary positrons from spallation



Primary component??

Secondary positrons from spallation



nature

Vol 456 | 20 November 2008 | **doi:10.1038/nature07477**

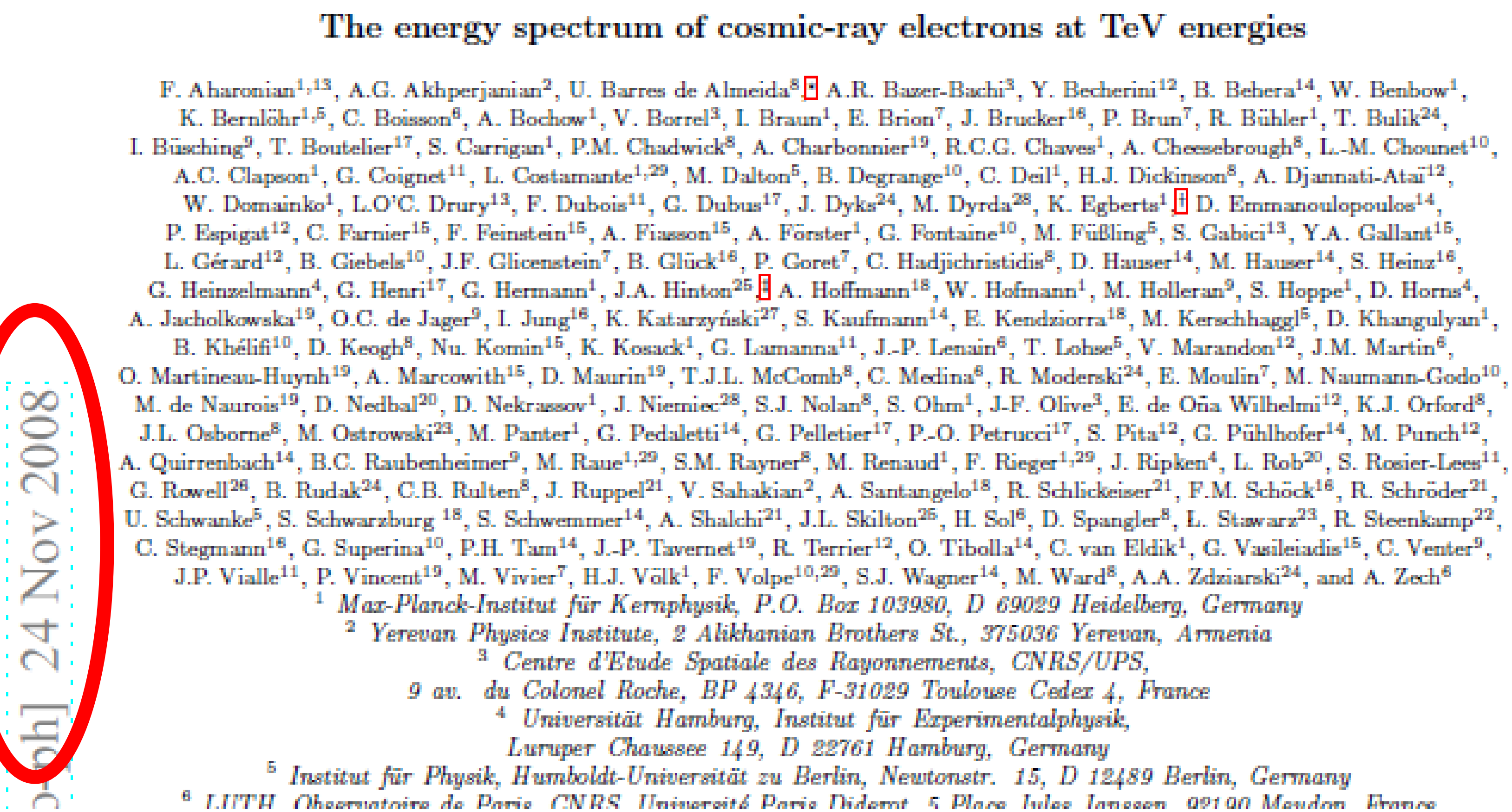
LETTERS

An excess of cosmic ray electrons at energies of 300–800 GeV

J. Chang[1,2], J. H. Adams Jr[3], H. S. Ahn[4], G. L. Bashindzhagyan[5], M. Christl[3], O. Ganel[4], T. G. Guzik[6], J. Isbert[6], K. C. Kim[4], E. N. Kuznetsov[5], M. I. Panasyuk[5], A. D. Panov[5], W. K. H. Schmidt[2], E. S. Seo[4], N. V. Sokolskaya[5], J. W. Watts[3], J. P. Wefel[6], J. Wu[4] & V. I. Zatsepin[5]

Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. The

H.E.S.S. Collaboration

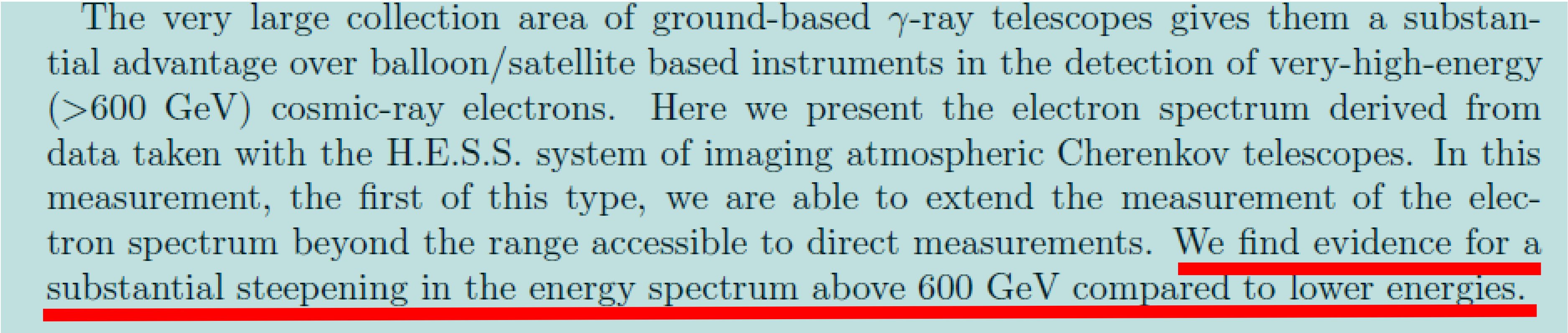


ph] 24 Nov 2008

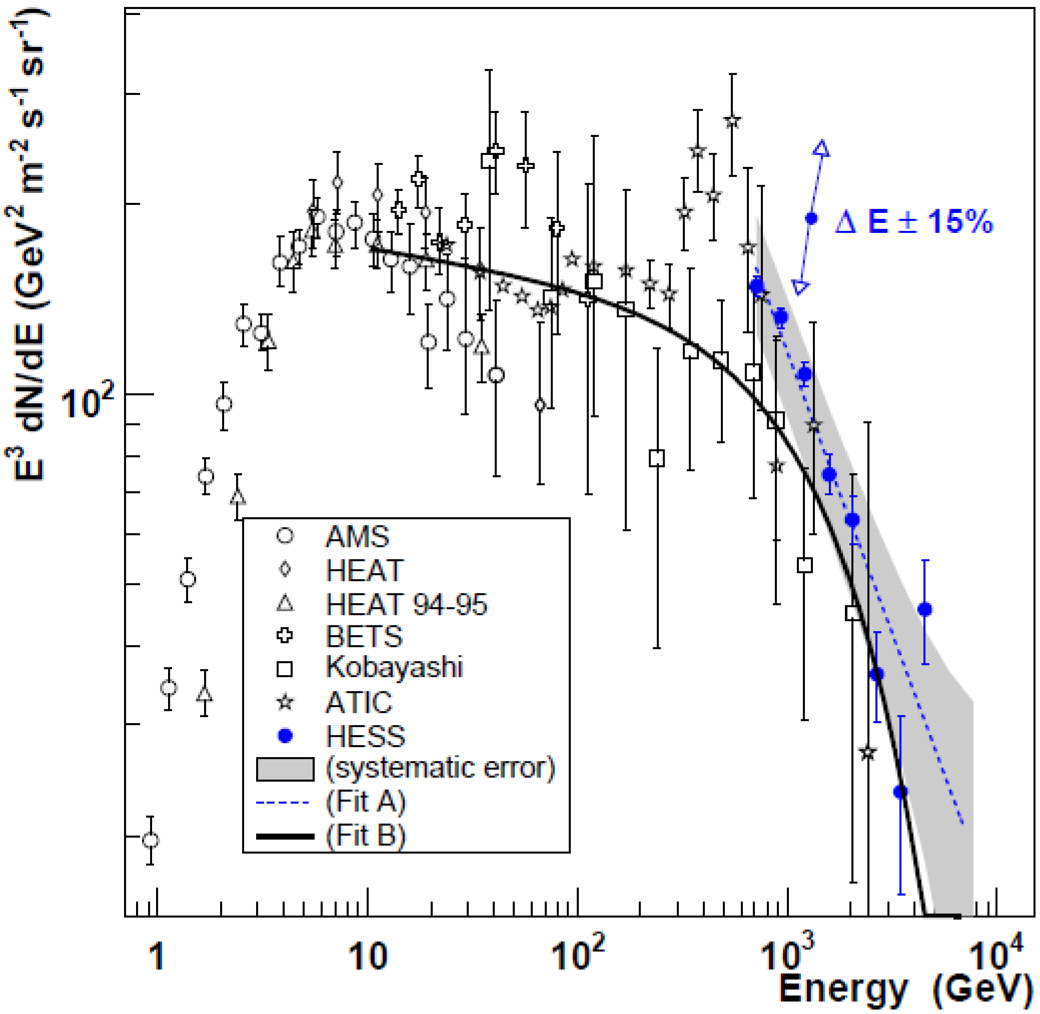
The energy spectrum of cosmic-ray electrons at TeV energies

F. Aharonian[1,13], A.G. Akhperjanian[2], U. Barres de Almeida[8,*] A.R. Bazer-Bachi[3], Y. Becherini[12], B. Behera[14], W. Benbow[1], K. Bernlöhr[1,5], C. Boisson[6], A. Bochow[1], V. Borrel[3], I. Braun[1], E. Brion[7], J. Brucker[16], P. Brun[7], R. Bühler[1], T. Bulik[24], I. Büsching[9], T. Boutelier[17], S. Carrigan[1], P.M. Chadwick[8], A. Charbonnier[19], R.C.G. Chaves[1], A. Cheesebrough[8], L.-M. Chounet[10], A.C. Clapson[1], G. Coignet[11], L. Costamante[1,29], M. Dalton[5], B. Degrange[10], C. Deil[1], H.J. Dickinson[8], A. Djannati-Ataï[12], W. Domainko[1], L.O'C. Drury[13], F. Dubois[11], G. Dubus[17], J. Dyks[24], M. Dyrda[28], K. Egberts[1,†] D. Emmanoulopoulos[14], P. Espigat[12], C. Farnier[15], F. Feinstein[15], A. Fiasson[15], A. Förster[1], G. Fontaine[10], M. Füßling[5], S. Gabici[13], Y.A. Gallant[15], L. Gérard[12], B. Giebels[10], J.F. Glicenstein[7], B. Glück[16], P. Goret[7], C. Hadjichristidis[8], D. Hauser[14], M. Hauser[14], S. Heinz[16], G. Heinzelmann[4], G. Henri[17], G. Hermann[1], J.A. Hinton[25,‡] A. Hoffmann[18], W. Hofmann[1], M. Holleran[9], S. Hoppe[1], D. Horns[4], A. Jacholkowska[19], O.C. de Jager[9], I. Jung[16], K. Katarzyński[27], S. Kaufmann[14], E. Kendziorra[18], M. Kerschhaggl[5], D. Khangulyan[1], B. Khélifi[10], D. Keogh[8], Nu. Komin[15], K. Kosack[1], G. Lamanna[11], J.-P. Lenain[6], T. Lohse[5], V. Marandon[12], J.M. Martin[6], O. Martineau-Huynh[19], A. Marcowith[15], D. Maurin[19], T.J.L. McComb[8], C. Medina[6], R. Moderski[24], E. Moulin[7], M. Naumann-Godo[10], M. de Naurois[19], D. Nedbal[20], D. Nekrassov[1], J. Niemiec[28], S.J. Nolan[8], S. Ohm[1], J-F. Olive[3], E. de Oña Wilhelmi[12], K.J. Orford[8], J.L. Osborne[8], M. Ostrowski[23], M. Panter[1], G. Pedaletti[14], G. Pelletier[17], P.-O. Petrucci[17], S. Pita[12], G. Pühlhofer[14], M. Punch[12], A. Quirrenbach[14], B.C. Raubenheimer[9], M. Raue[1,29], S.M. Rayner[8], M. Renaud[1], F. Rieger[1,29], J. Ripken[4], L. Rob[20], S. Rosier-Lees[11], G. Rowell[26], B. Rudak[24], C.B. Rulten[8], J. Ruppel[21], V. Sahakian[2], A. Santangelo[18], R. Schlickeiser[21], F.M. Schöck[16], R. Schröder[21], U. Schwanke[5], S. Schwarzburg [18], S. Schwemmer[14], A. Shalchi[21], J.L. Skilton[25], H. Sol[6], D. Spangler[8], L. Stawarz[23], R. Steenkamp[22], C. Stegmann[16], G. Superina[10], P.H. Tam[14], J.-P. Tavernet[19], R. Terrier[12], O. Tibolla[14], C. van Eldik[1], G. Vasileiadis[15], C. Venter[9], J.P. Vialle[11], P. Vincent[19], M. Vivier[7], H.J. Völk[1], F. Volpe[10,29], S.J. Wagner[14], M. Ward[8], A.A. Zdziarski[24], and A. Zech[6]

[1] *Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany*
[2] *Yerevan Physics Institute, 2 Alikhanian Brothers St., 375036 Yerevan, Armenia*
[3] *Centre d'Etude Spatiale des Rayonnements, CNRS/UPS,*
9 av. du Colonel Roche, BP 4346, F-31029 Toulouse Cedex 4, France
[4] *Universität Hamburg, Institut für Experimentalphysik,*
Luruper Chaussee 149, D 22761 Hamburg, Germany
[5] *Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany*
[6] *LUTH, Observatoire de Paris, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France*



The very large collection area of ground-based γ-ray telescopes gives them a substantial advantage over balloon/satellite based instruments in the detection of very-high-energy (>600 GeV) cosmic-ray electrons. Here we present the electron spectrum derived from data taken with the H.E.S.S. system of imaging atmospheric Cherenkov telescopes. In this measurement, the first of this type, we are able to extend the measurement of the electron spectrum beyond the range accessible to direct measurements. We find evidence for a substantial steepening in the energy spectrum above 600 GeV compared to lower energies.

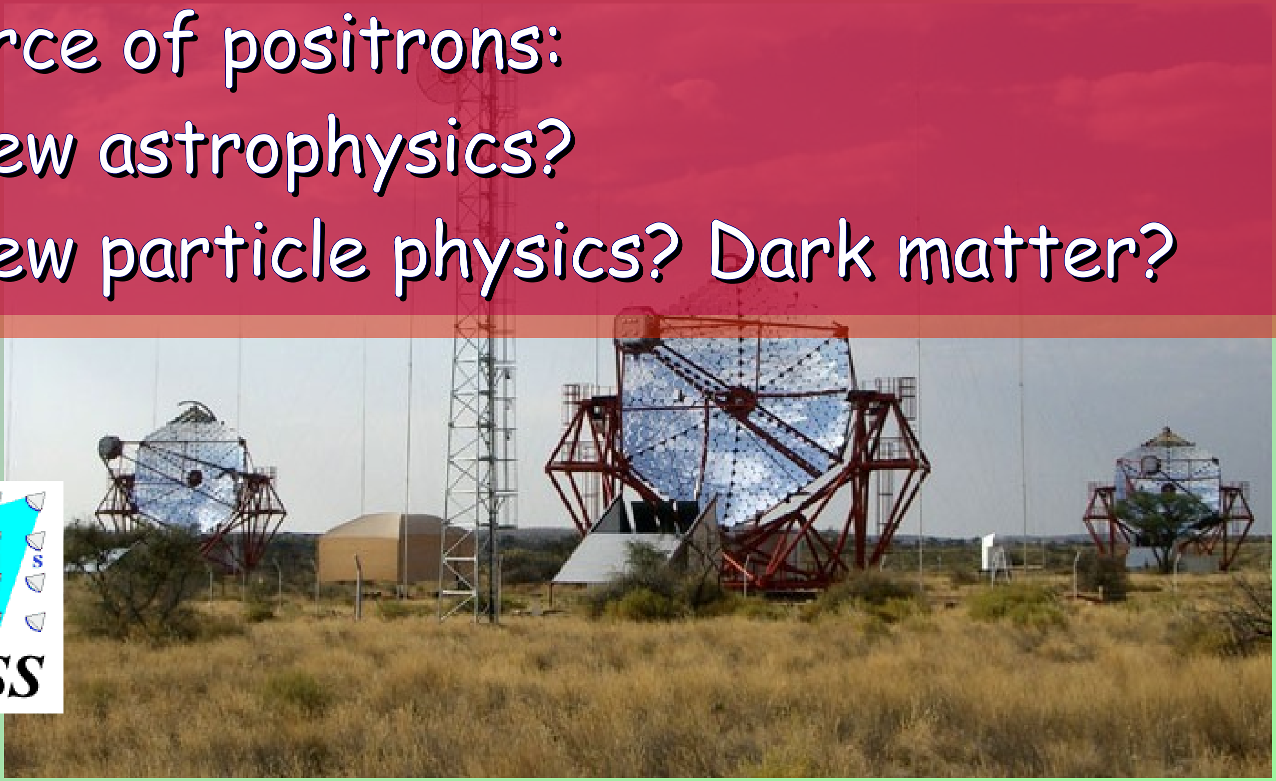

E^3 dN/dE (GeV^2 m^-2 s^-1 sr^-1)
10^2
1
10
10^2
10^3
10^4
Energy (GeV)
Δ E ± 15%
AMS
HEAT
HEAT 94-95
BETS
Kobayashi
ATIC
HESS
(systematic error)
(Fit A)
(Fit B)

PaMeLa

Advanced
Thin
Ionization
Calorimeter

Over the month of November a series of experiments have reported evidences for the existence of a primary source of positrons:

- New astrophysics?
- New particle physics? Dark matter?



HESS

Over the m ments

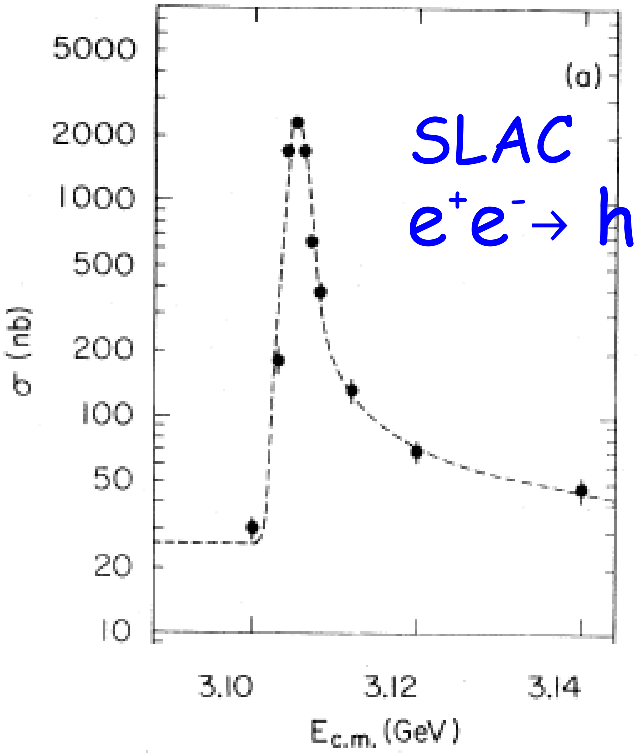
have reporte

primar

k matter?

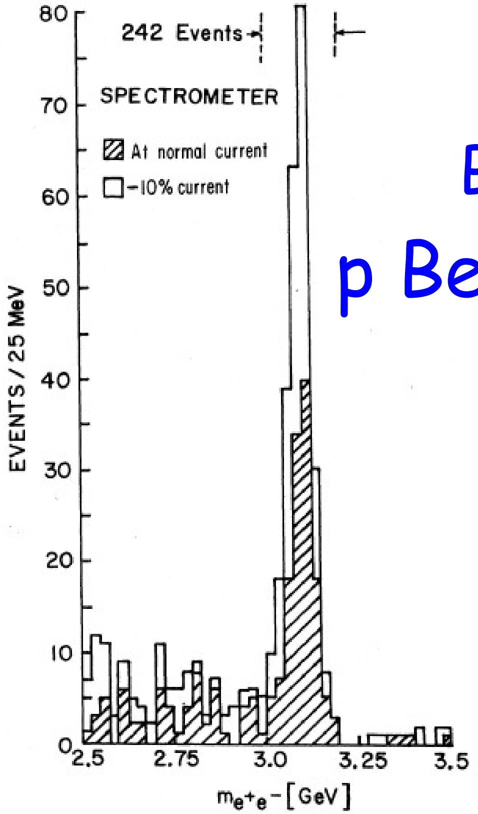
Another November revolution?

11th November 1974



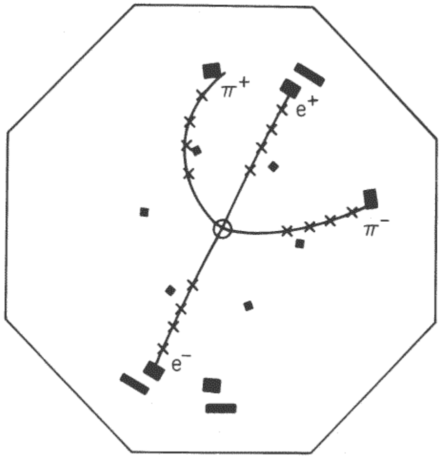
SLAC

$e^+e^- \rightarrow$ hadrons



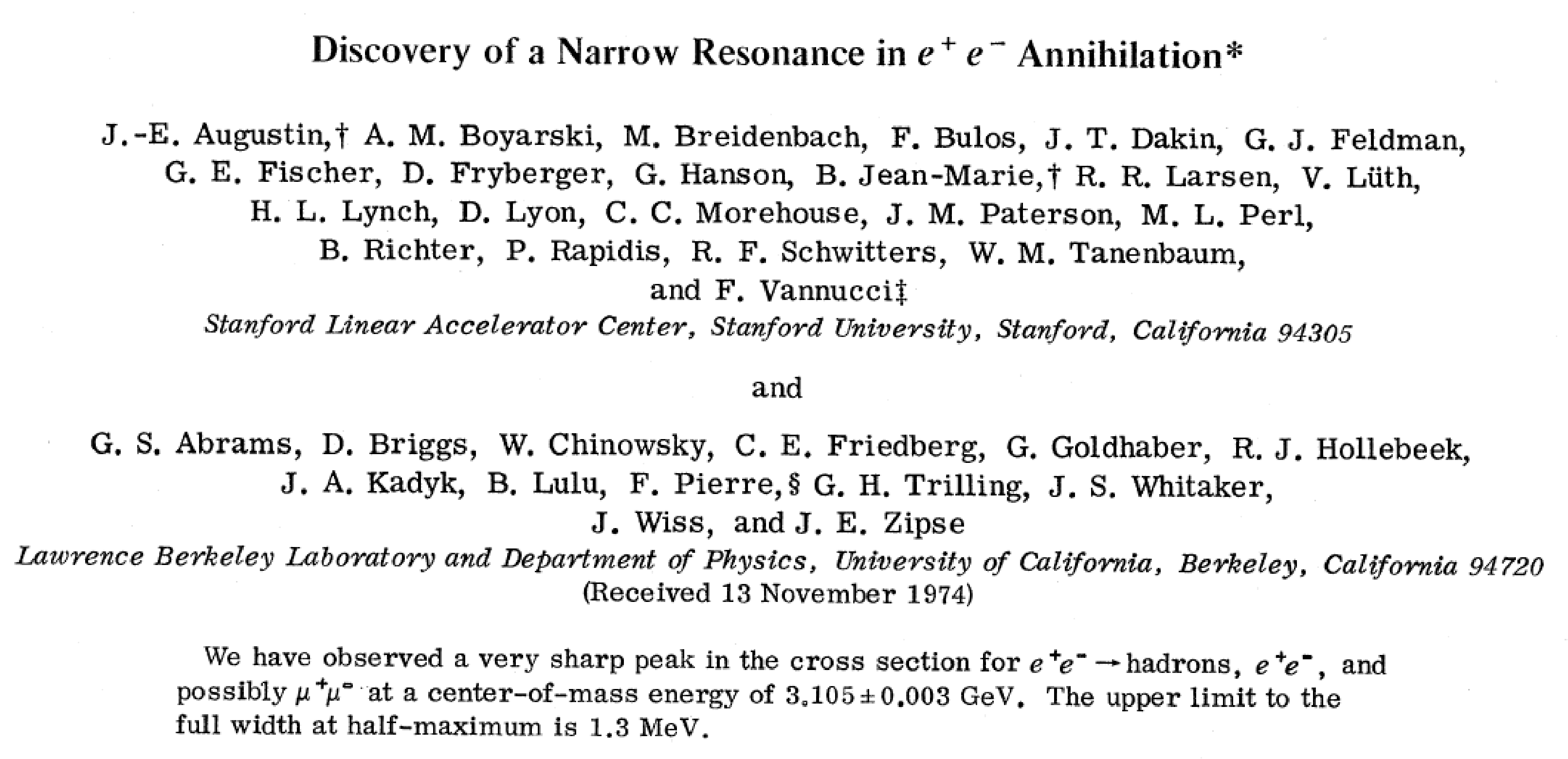
BNL

$p\,Be \rightarrow e^+e^- X$



SPEAR's Mark I detector

SLAC



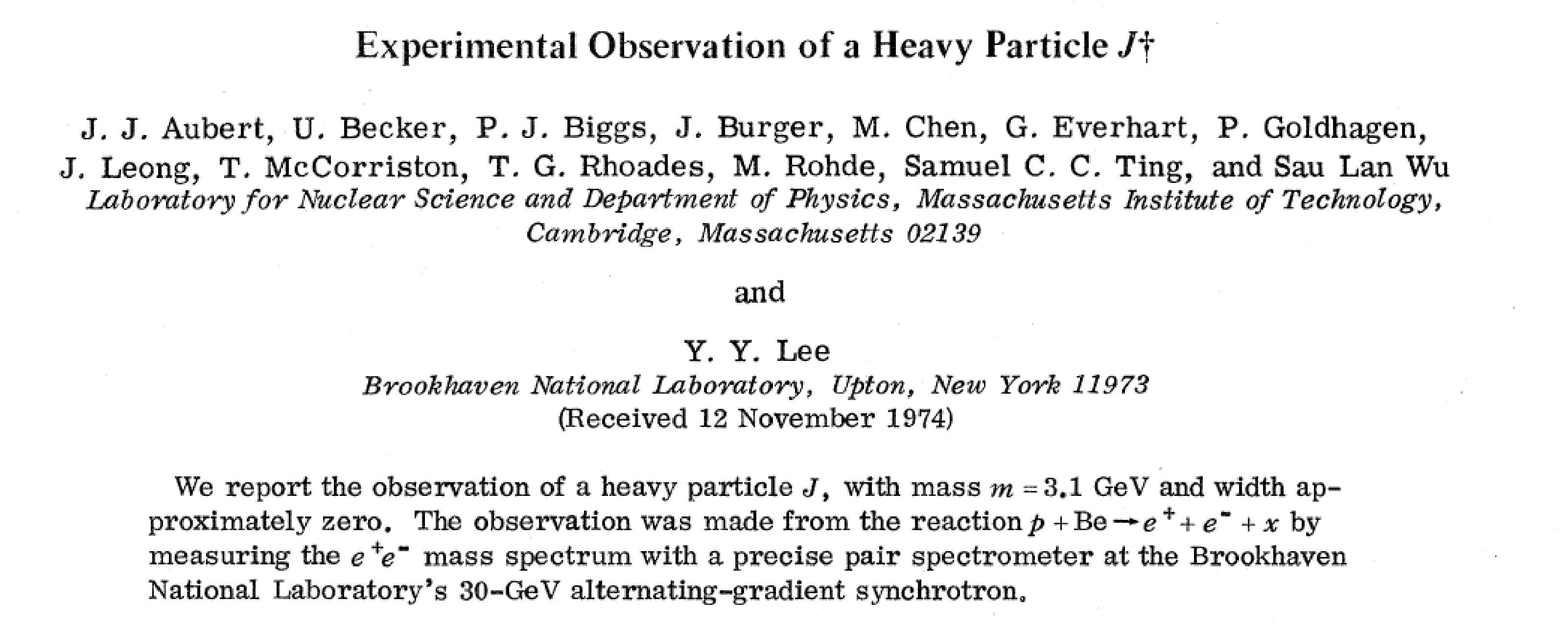
Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.



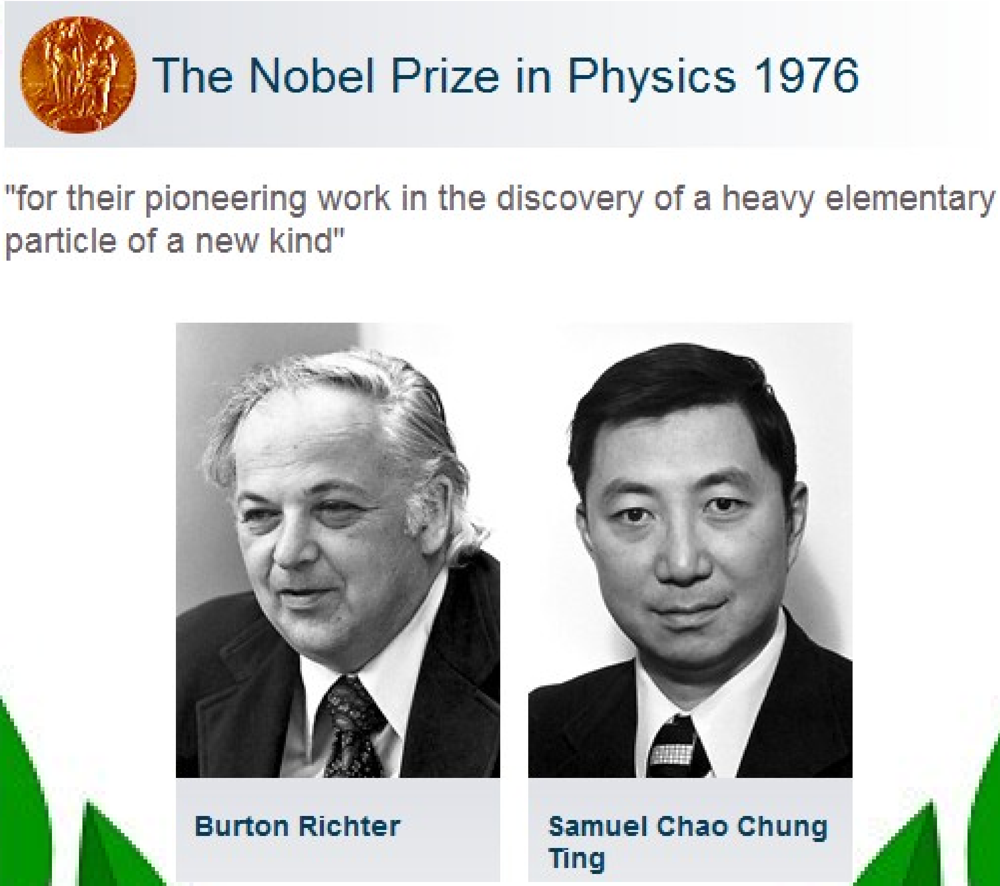
Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
*Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139*

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.



The Nobel Prize in Physics 1976

"for their pioneering work in the discovery of a heavy elementary particle of a new kind"

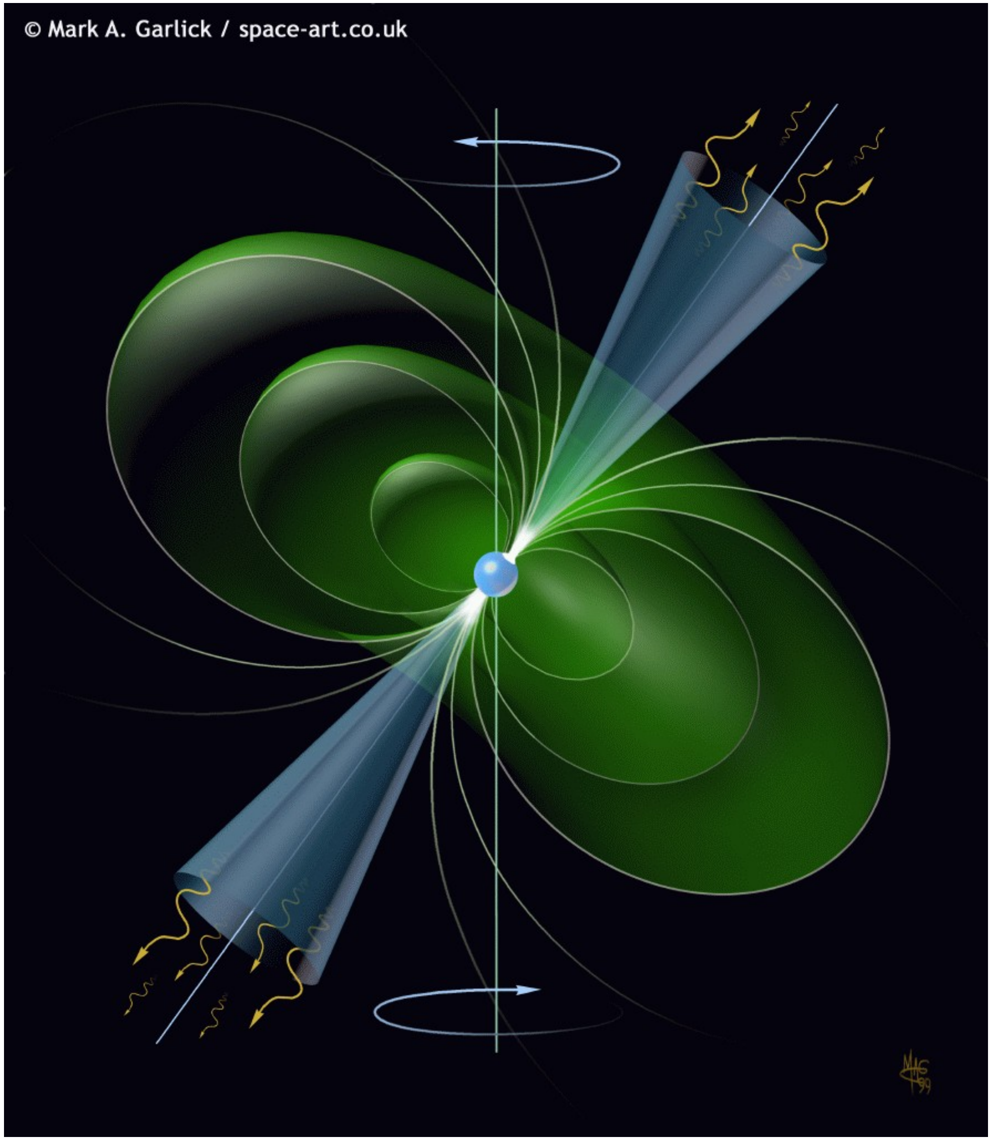
Burton Richter

Samuel Chao Chung Ting

Astrophysics?

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

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



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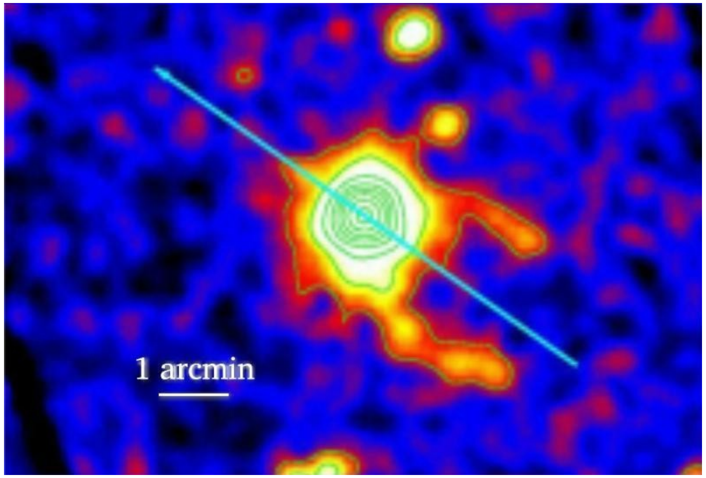
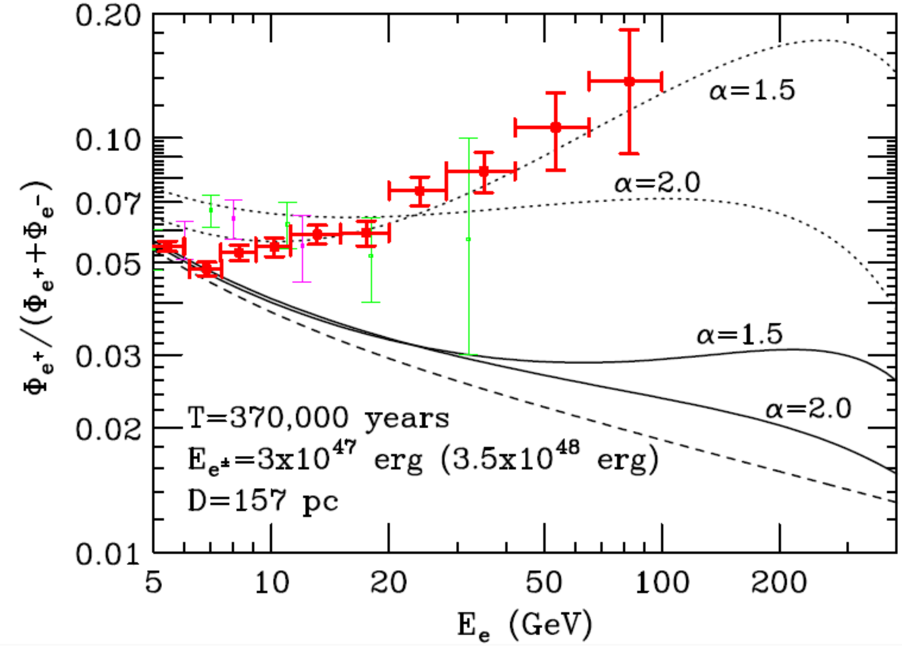
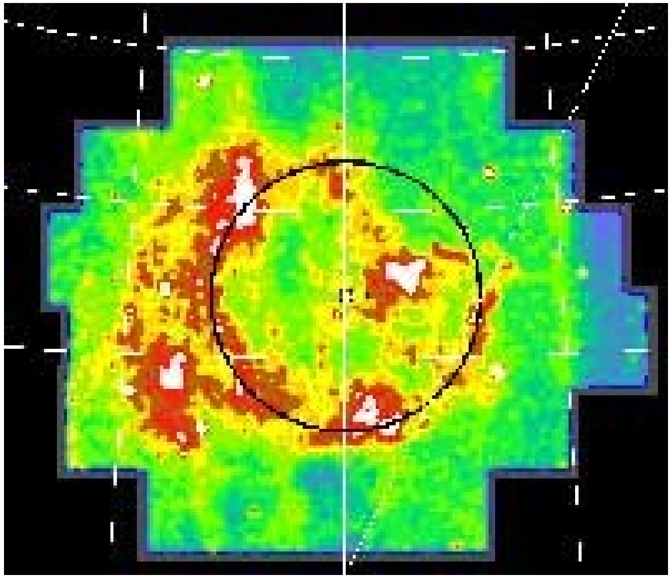
$$dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/600\text{GeV})$$

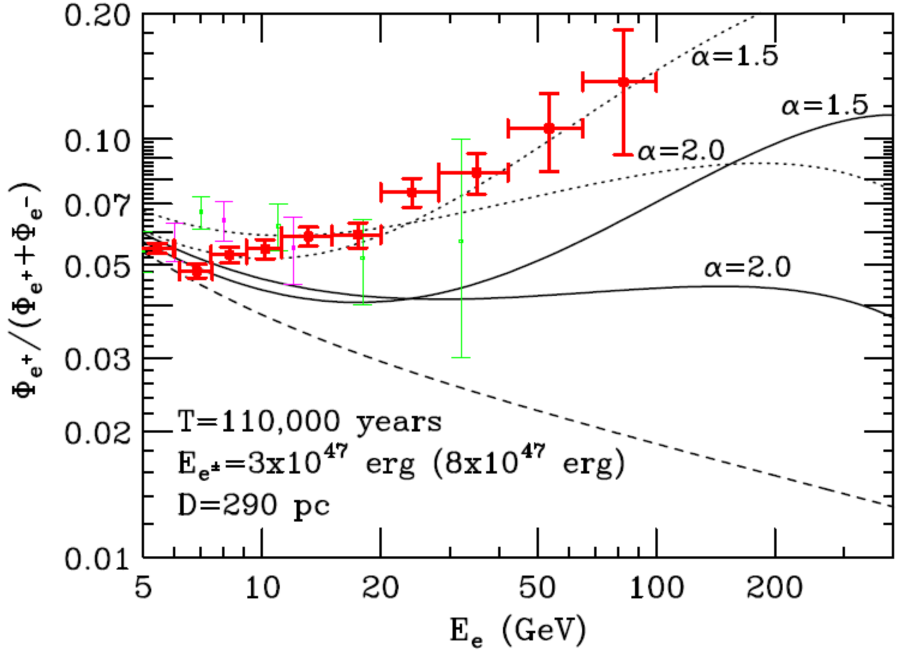
Geminga





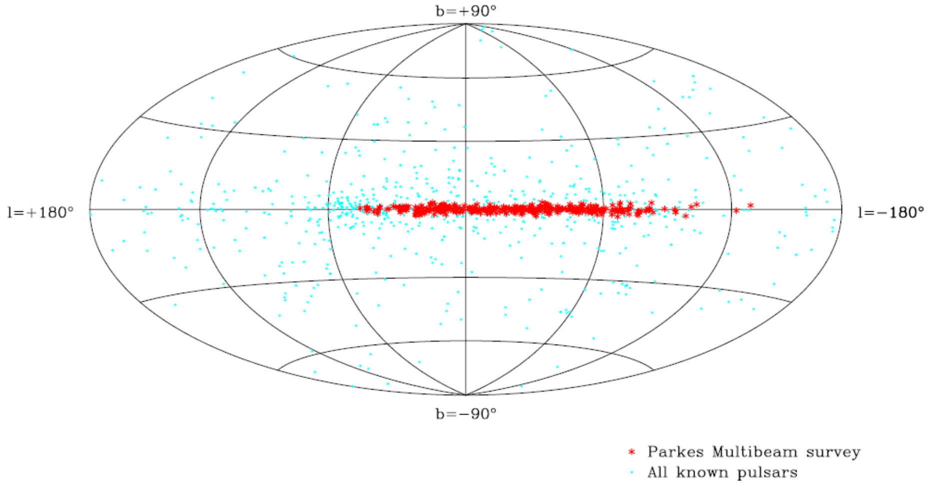


B0656+14



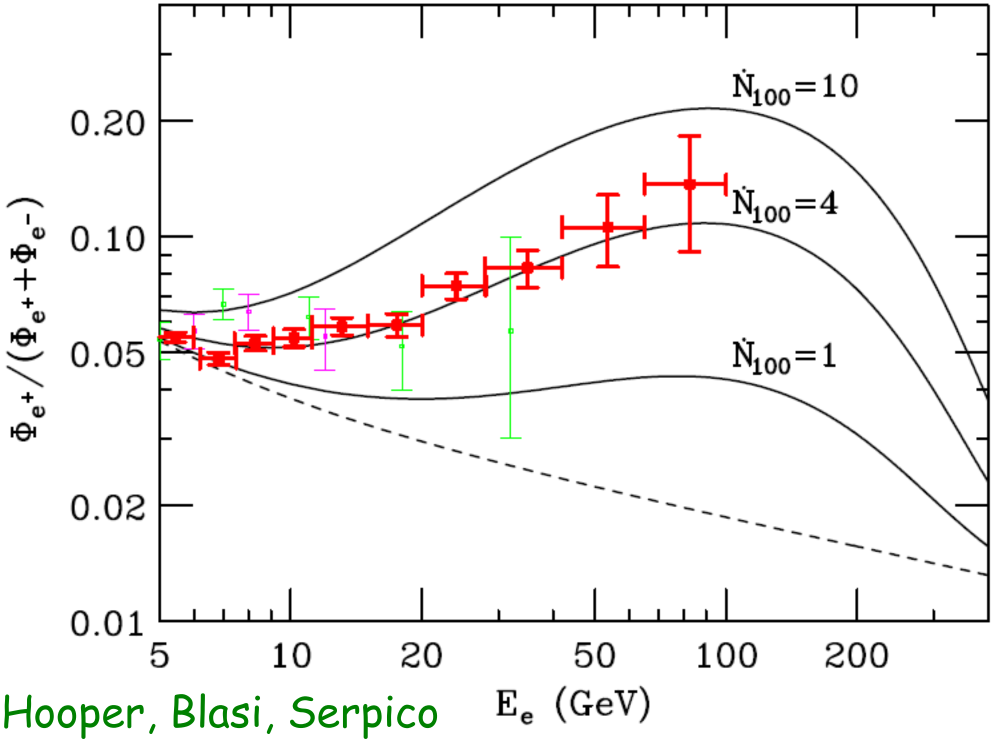
Hooper, Blasi, Serpico

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



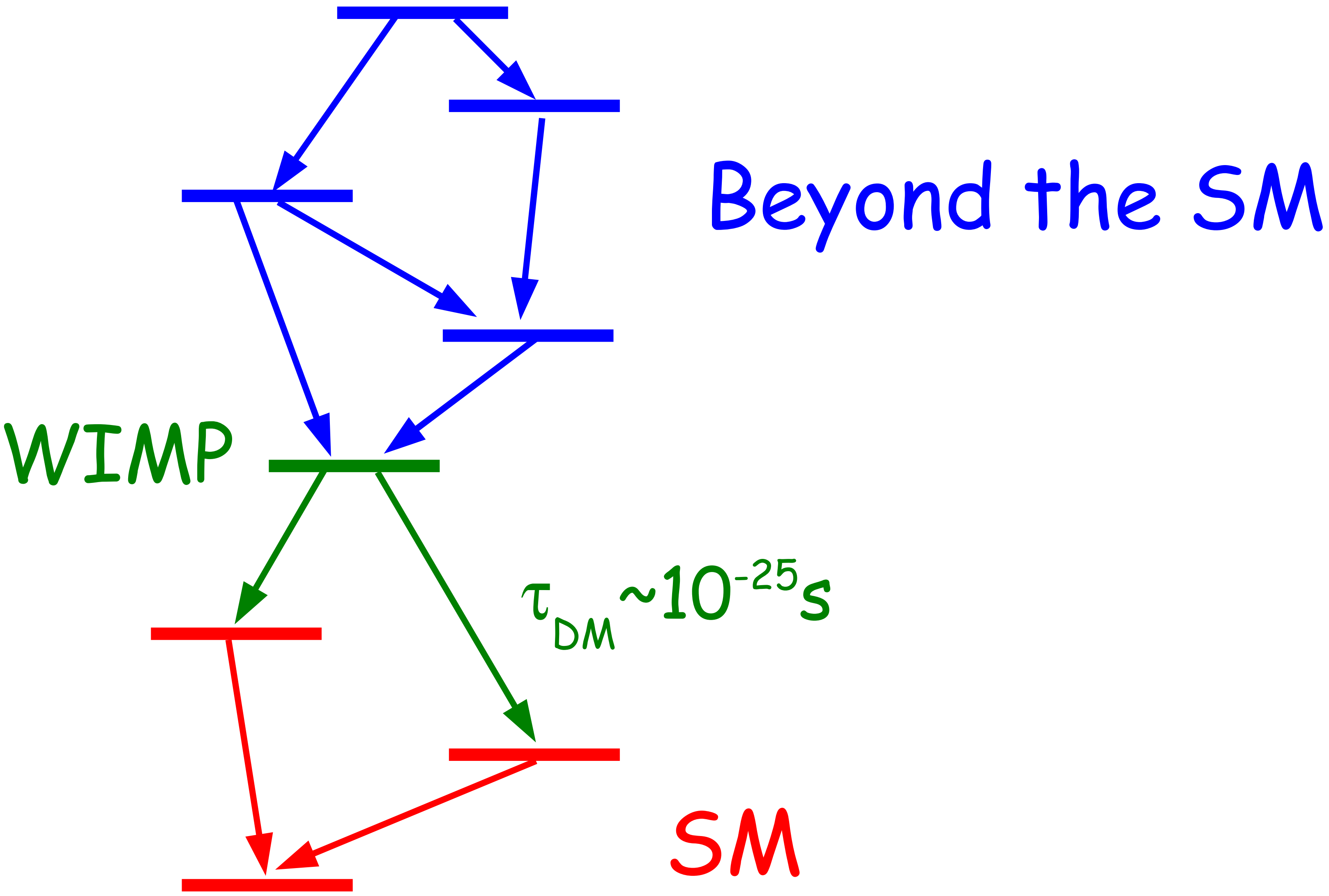
Hooper, Blasi, Serpico

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:



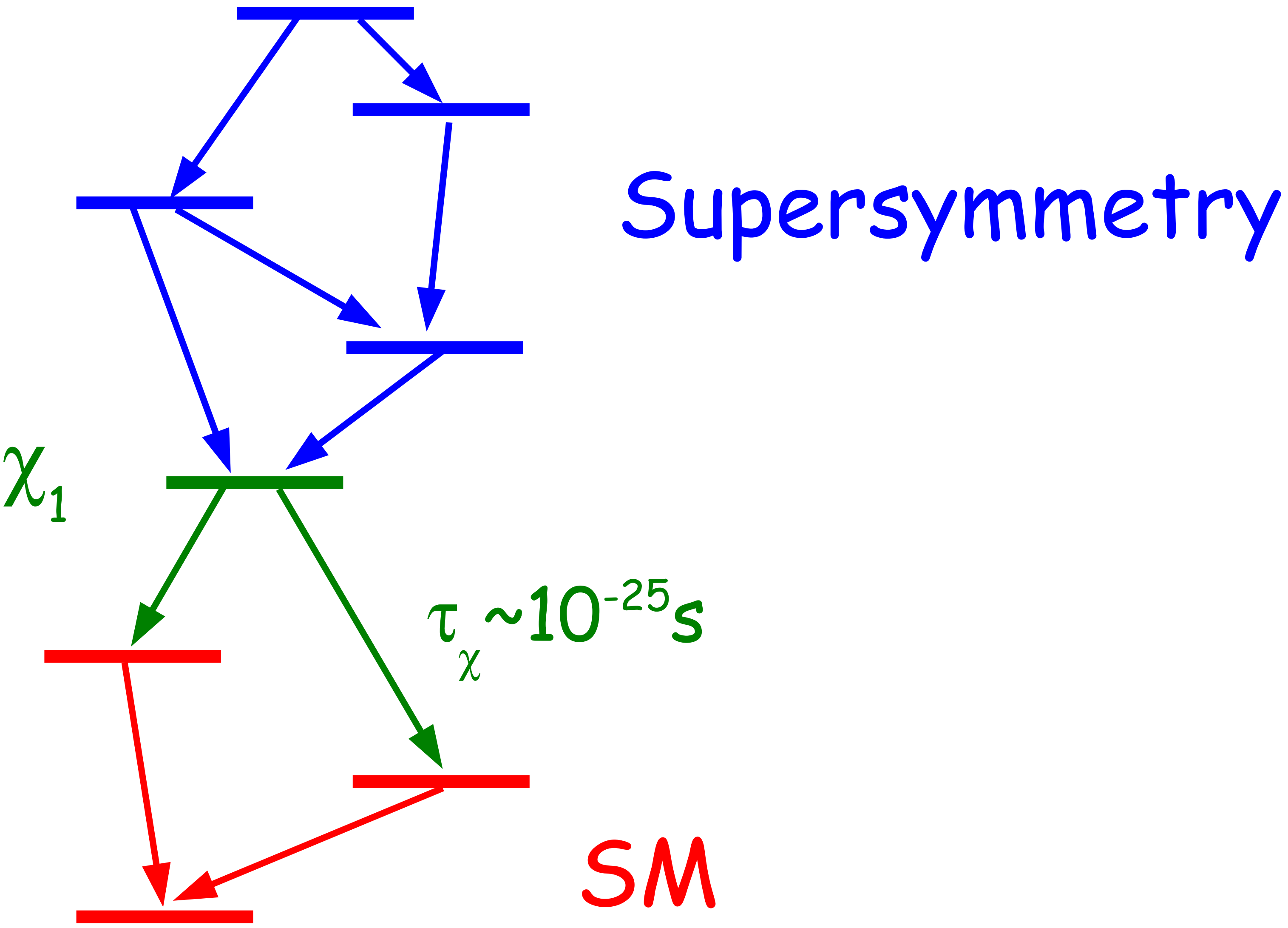
Beyond the SM

WIMP

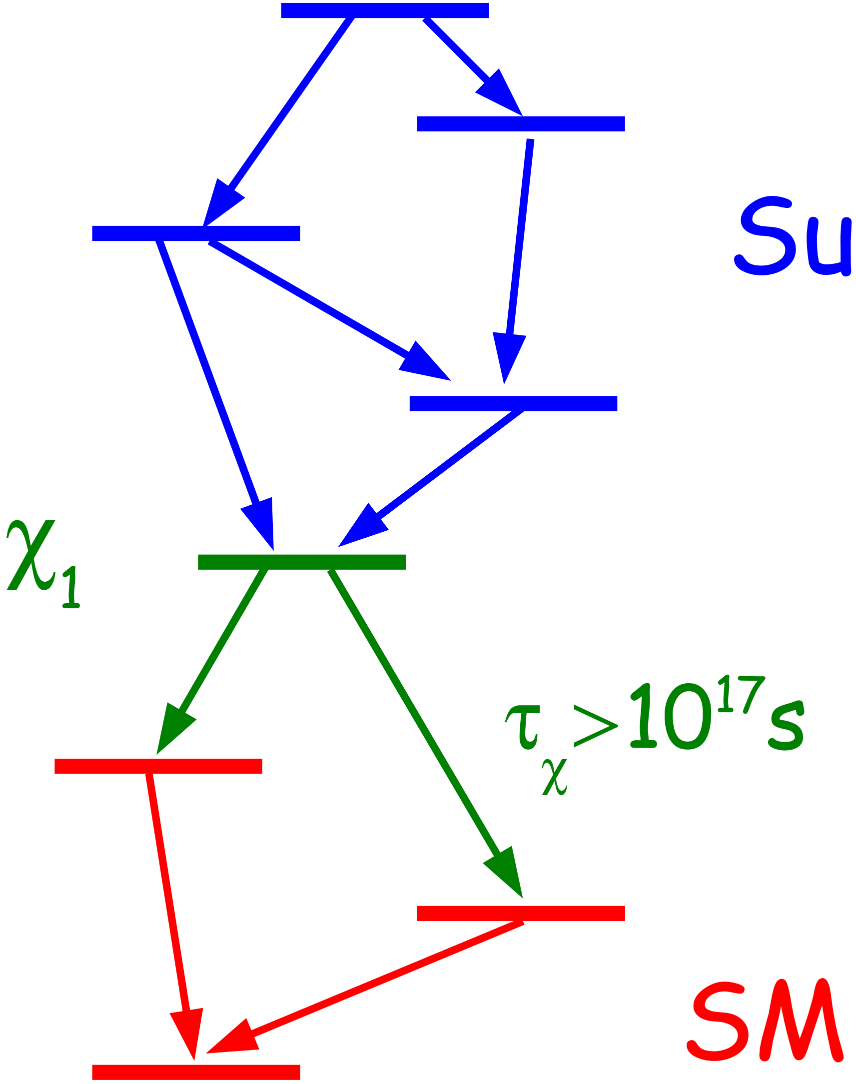
$\tau_{DM} \sim 10^{-25}$ s

SM

Sketch of a WIMP dark matter model:

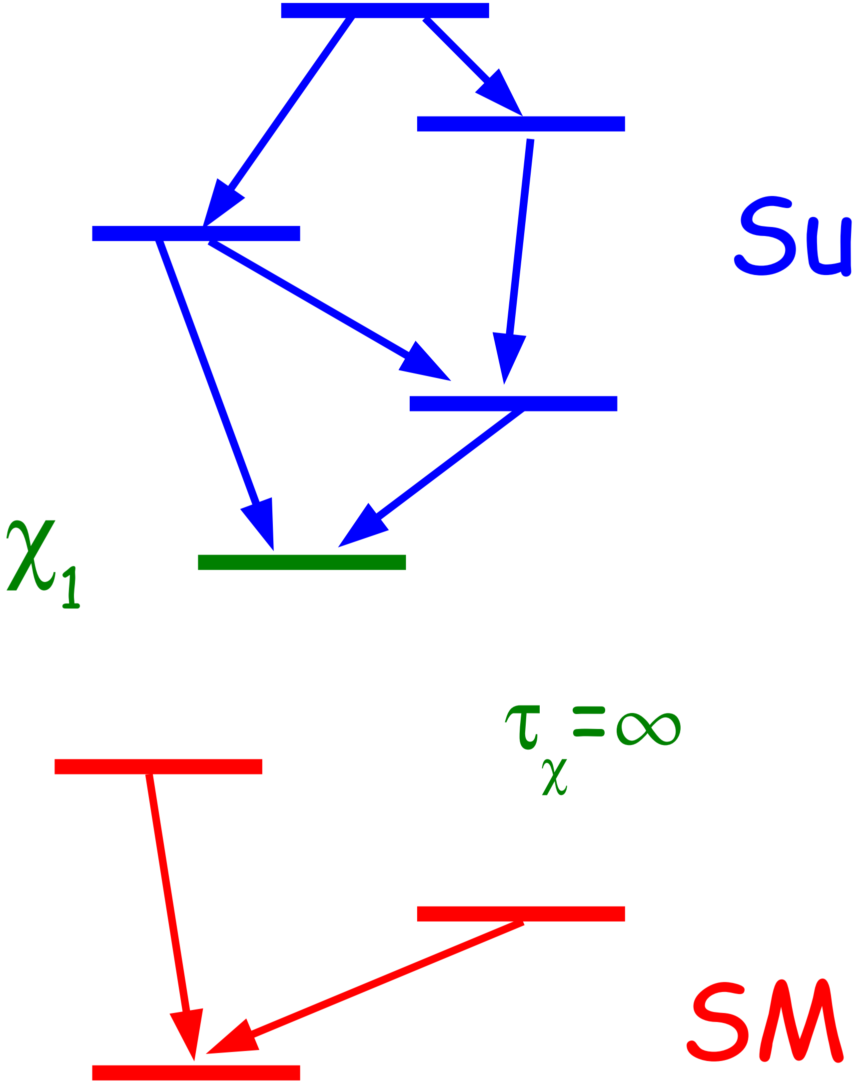


Sketch of a WIMP dark matter model:



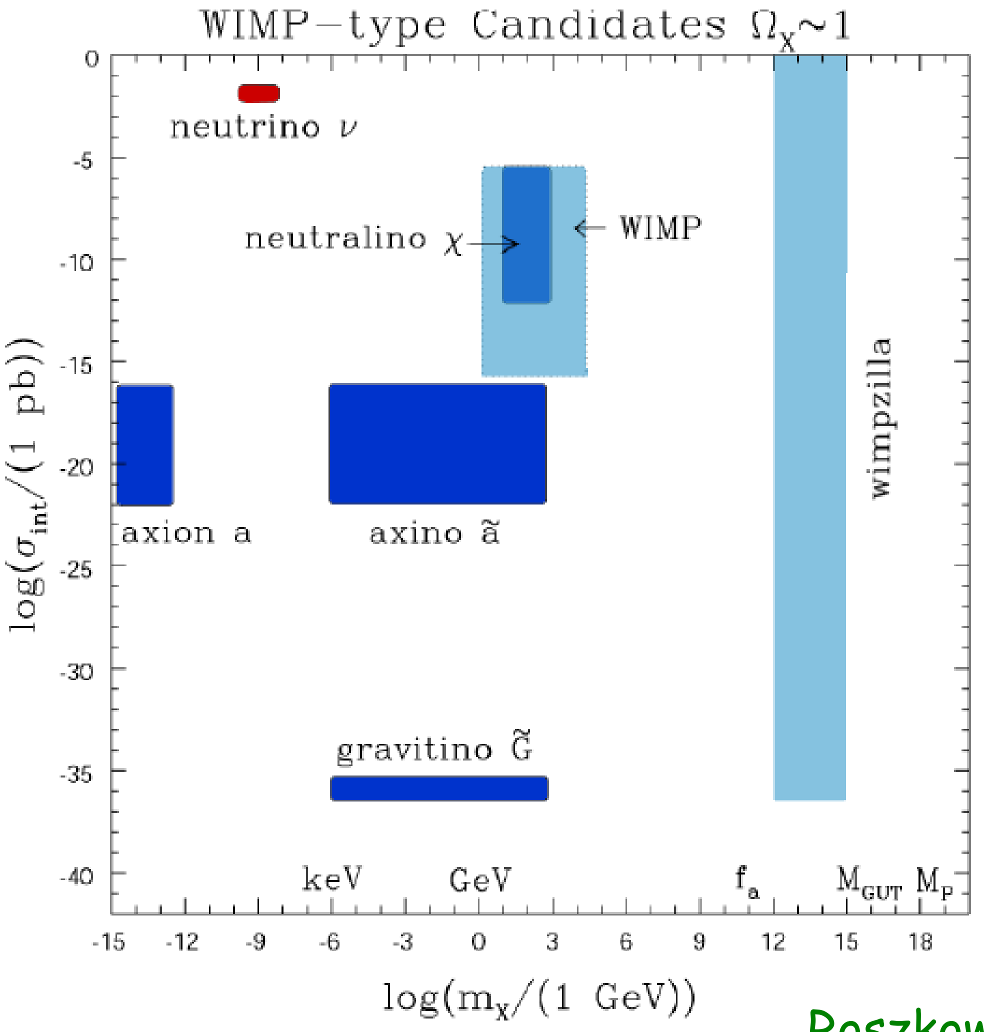
Requires a suppression of the coupling of at least 22 orders of magnitude!

Sketch of a WIMP dark matter model:



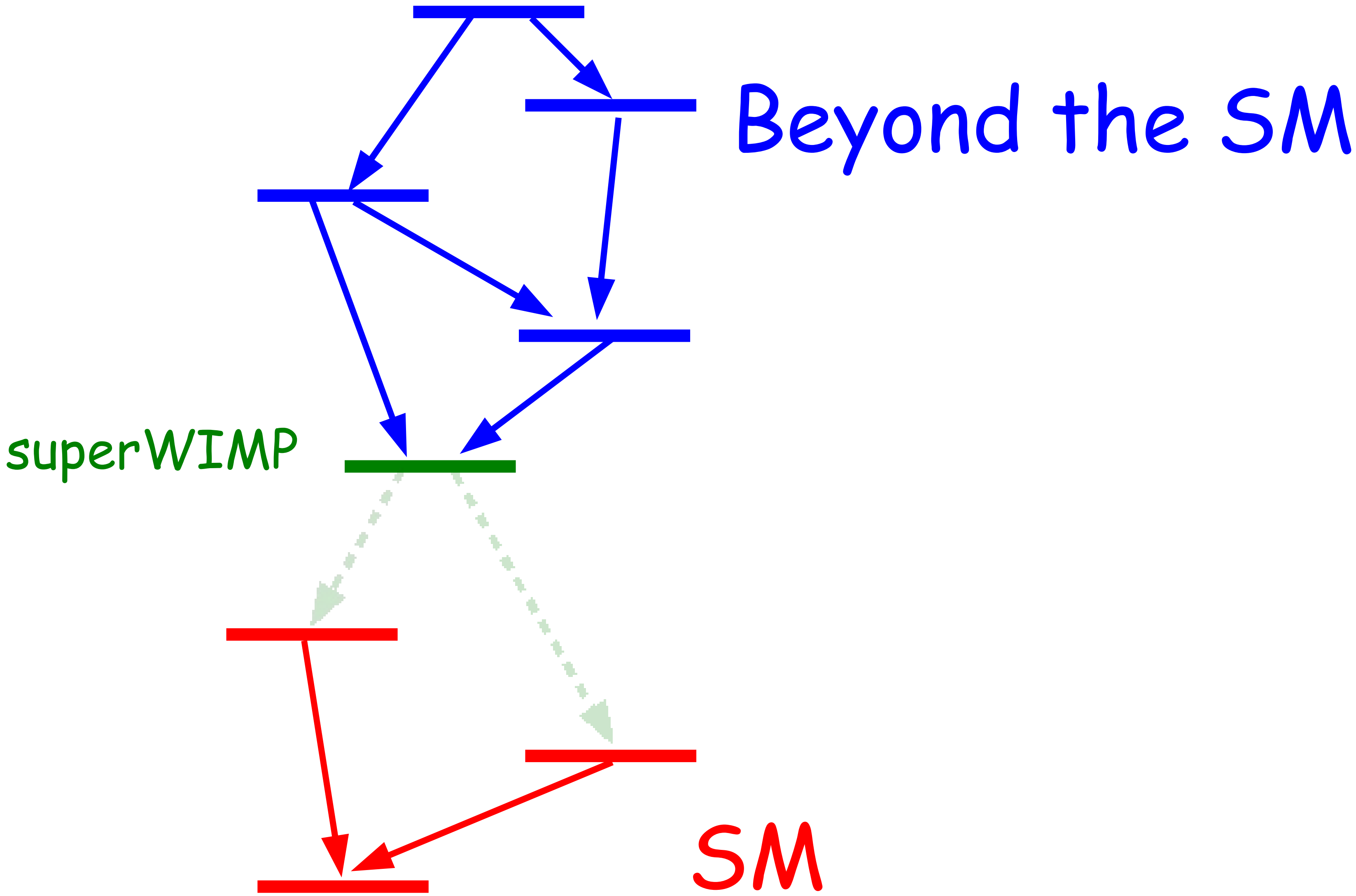
Simplest solution: forbid the dangerous couplings altogether by imposing exact R-parity conservation. **The lightest neutralino is absolutely stable**

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:

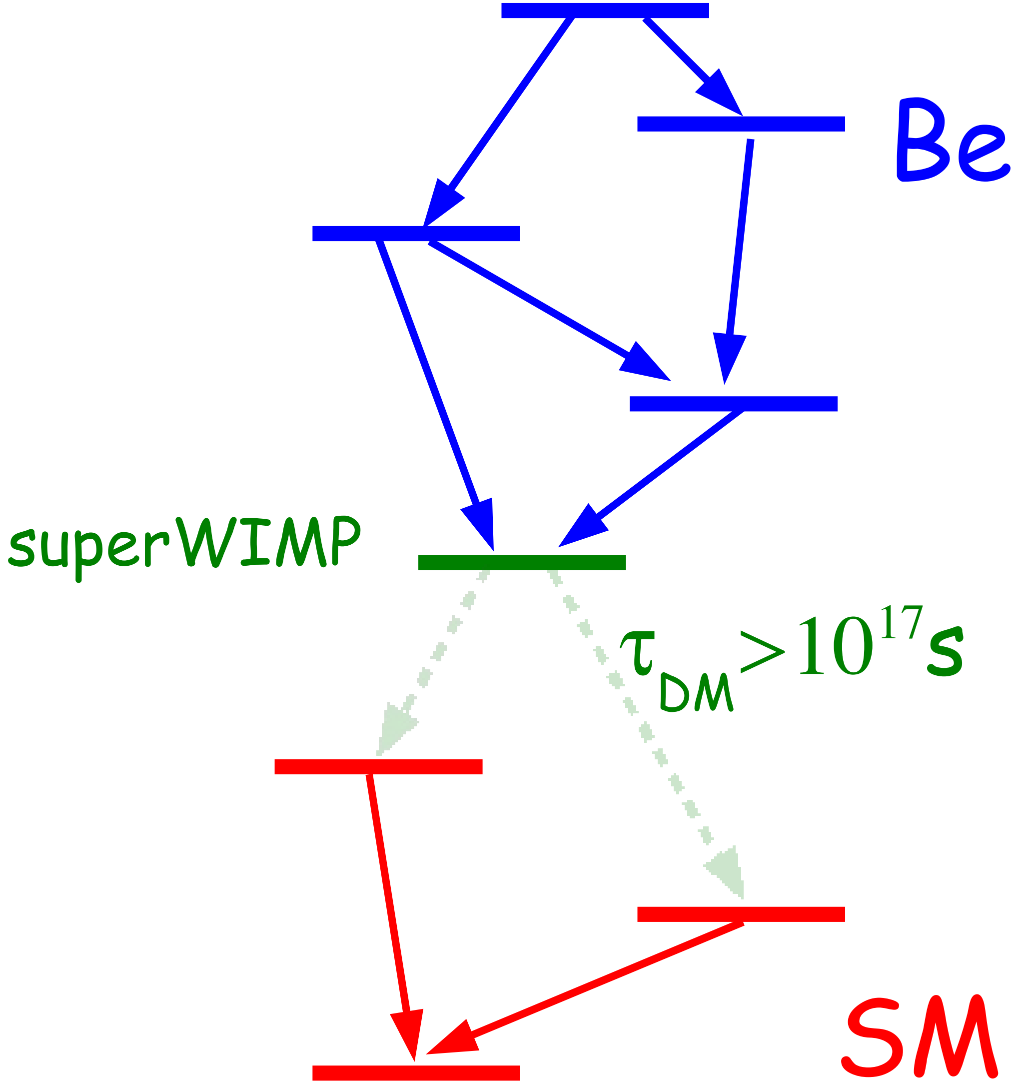


Beyond the SM

superWIMP

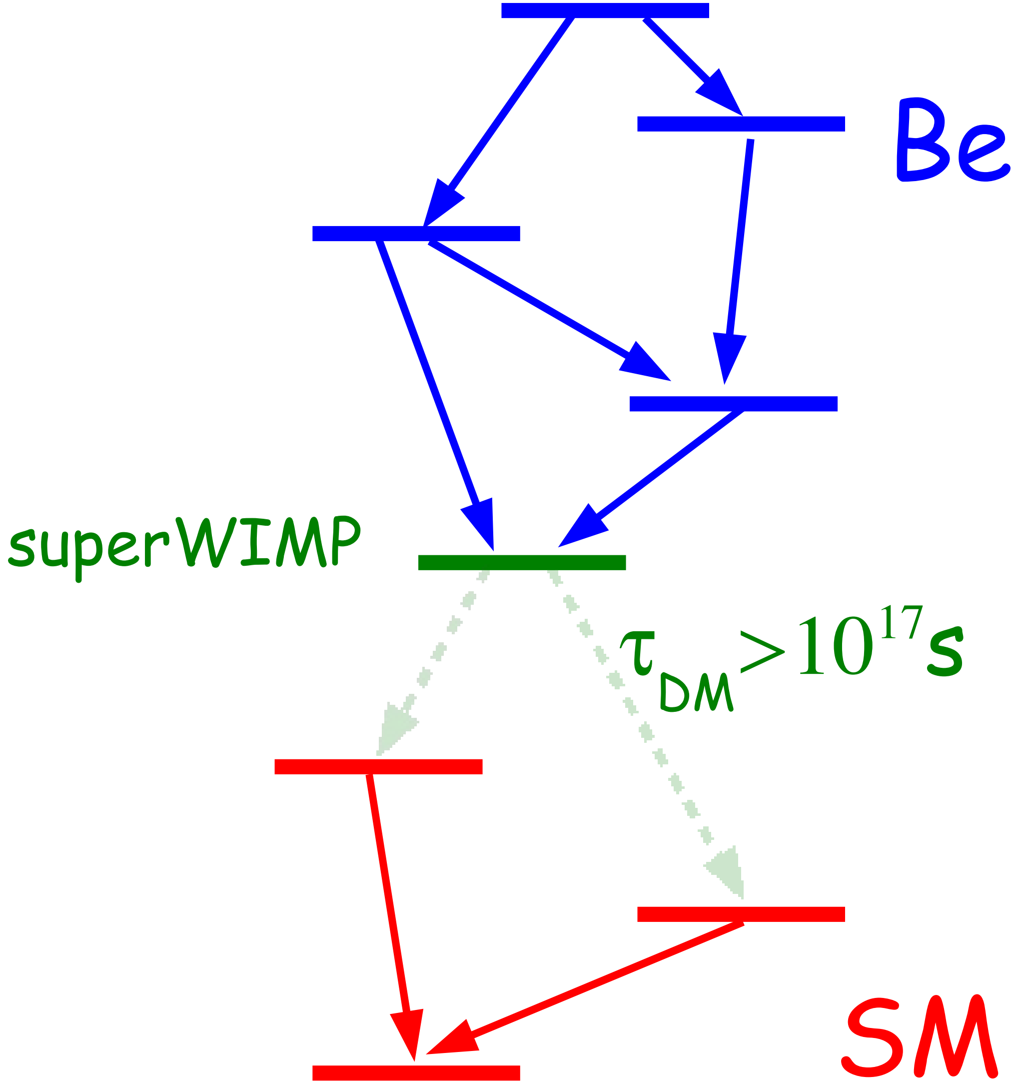
SM

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.



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.

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

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

AI, Tran

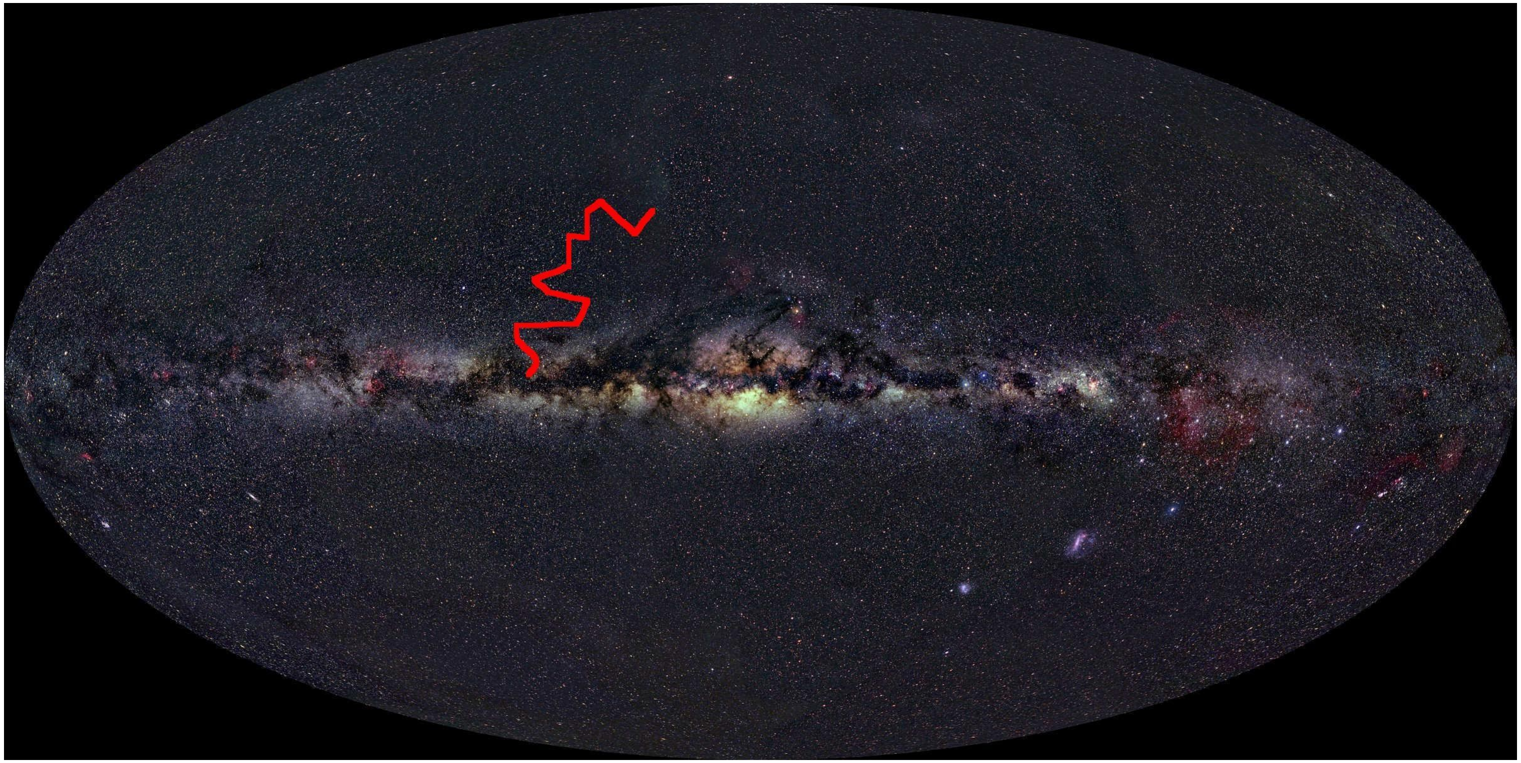
Possible decay channels

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

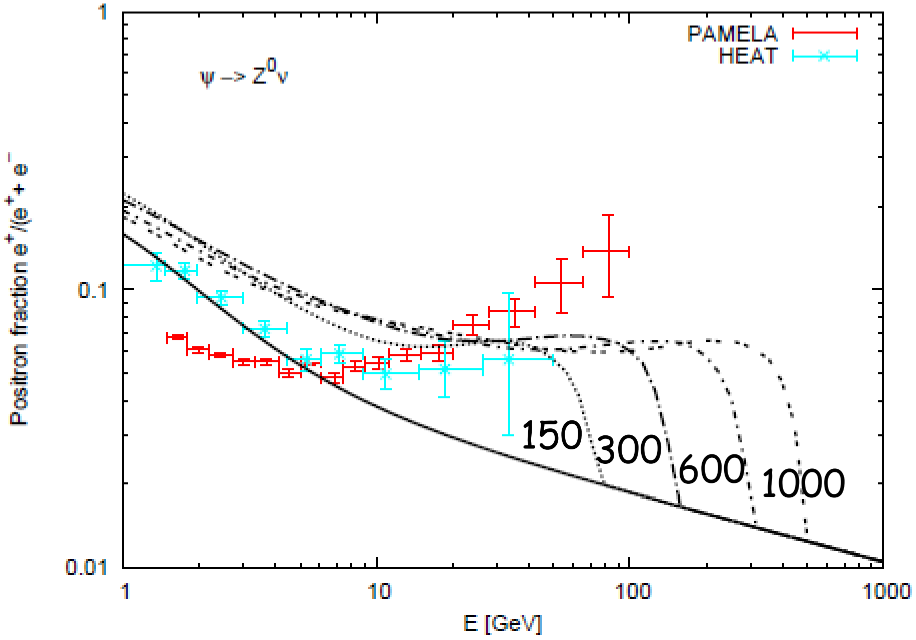
scalar DM
- $\phi \to Z^0 Z^0$
- $\phi \to W^+ W^-$
- $\phi \to \ell^+ \ell^-$

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



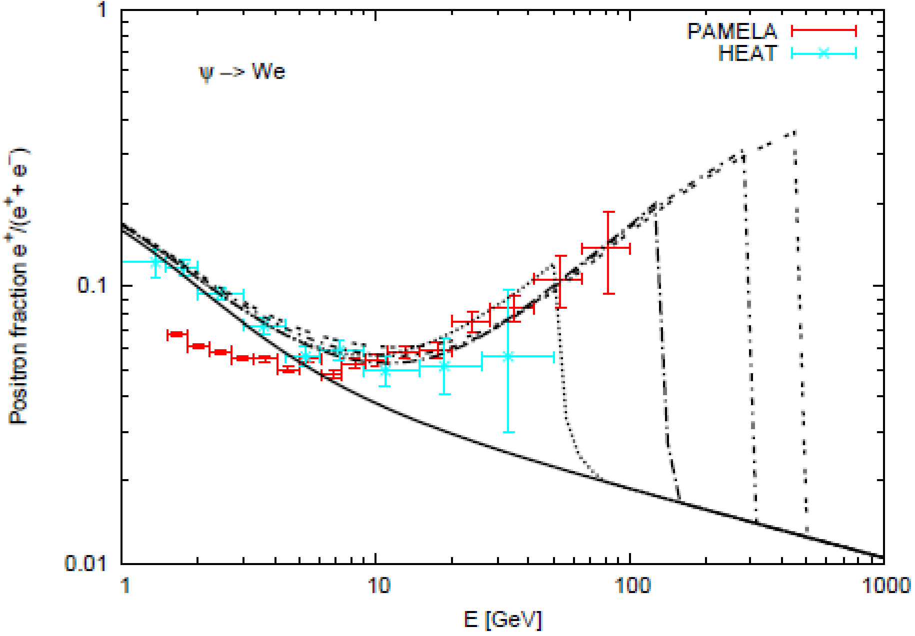
$\psi \to Z^0 \nu$



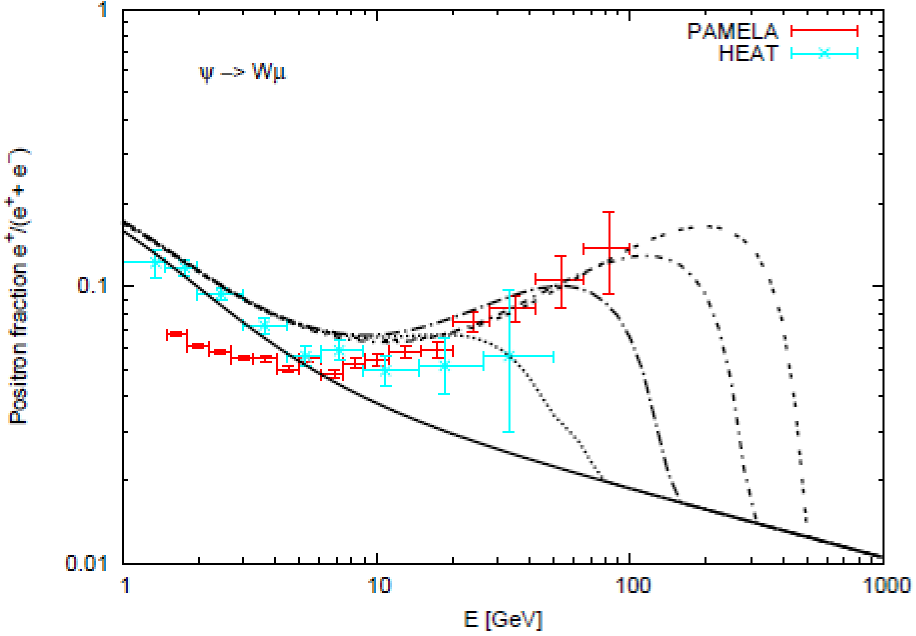
$\tau_{DM} \sim 10^{26}$s

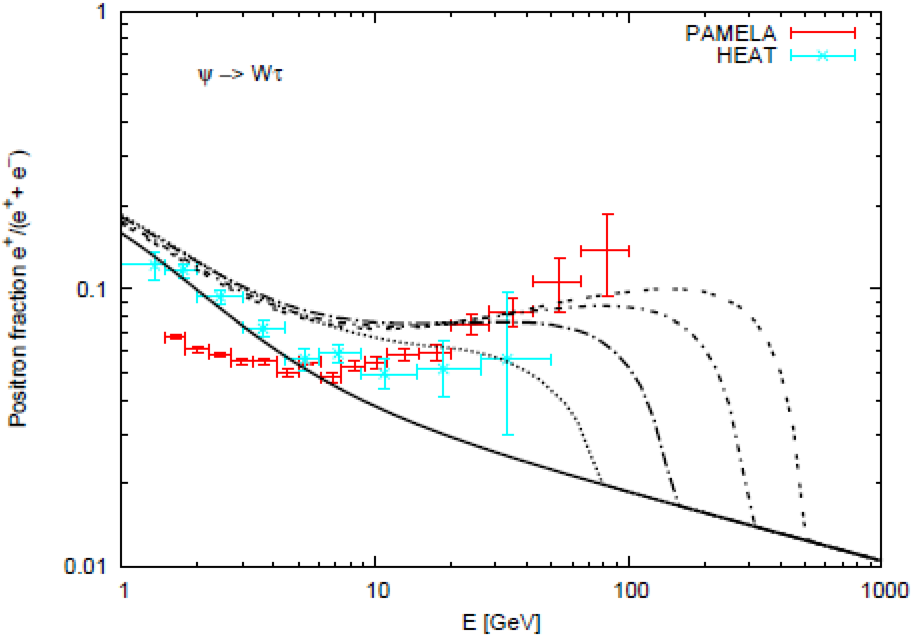
Too flat to explain the steep rise
in the spectrum observed by PAMELA

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



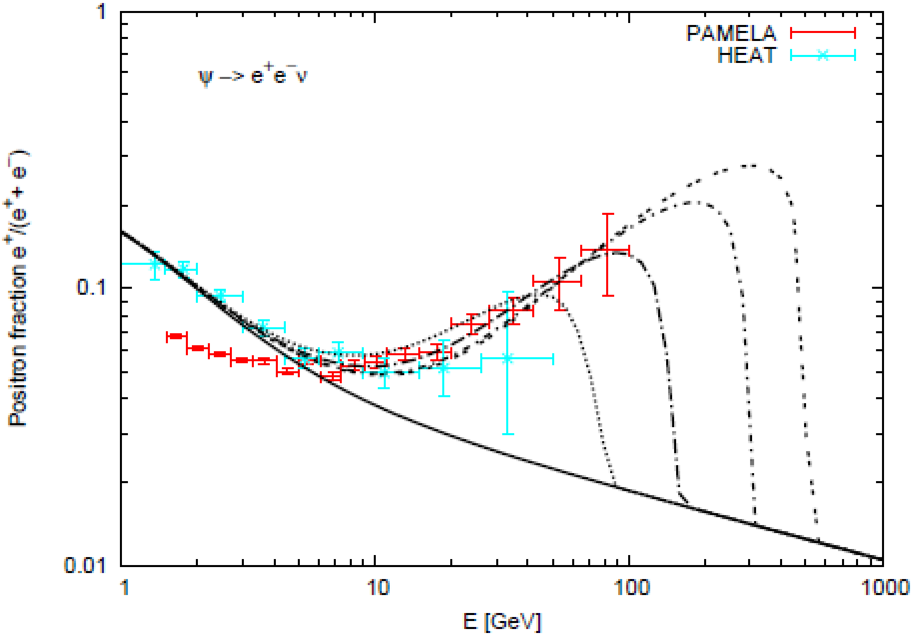
$\psi \to W^{\pm} \mu^{\mp}$



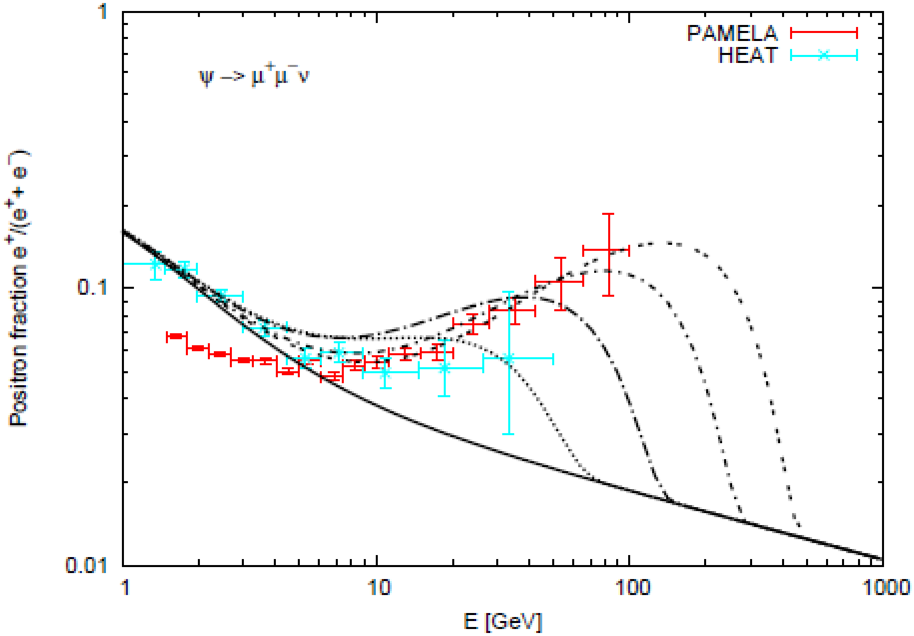


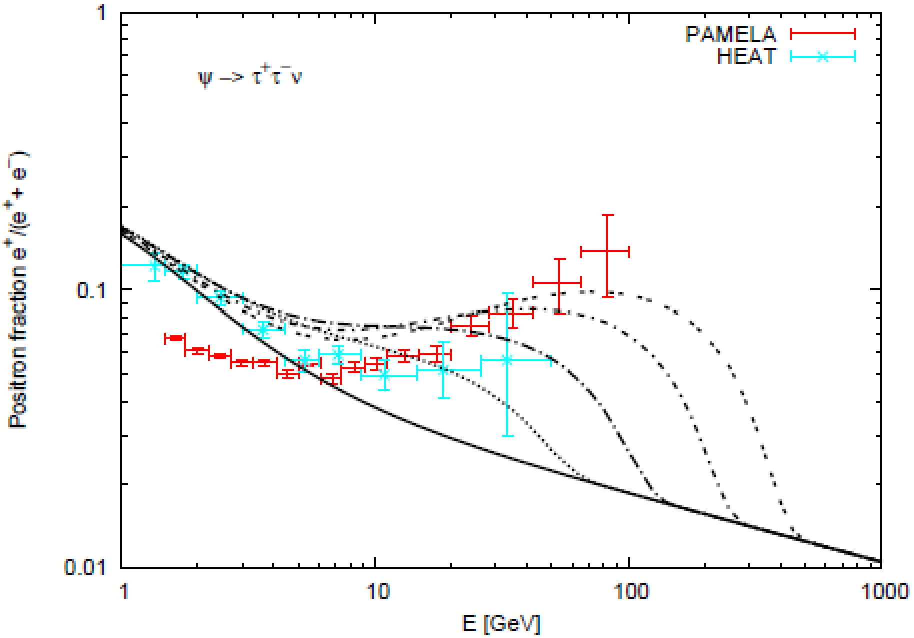
$\psi \to W^{\pm} \tau^{\mp}$

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



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





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

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

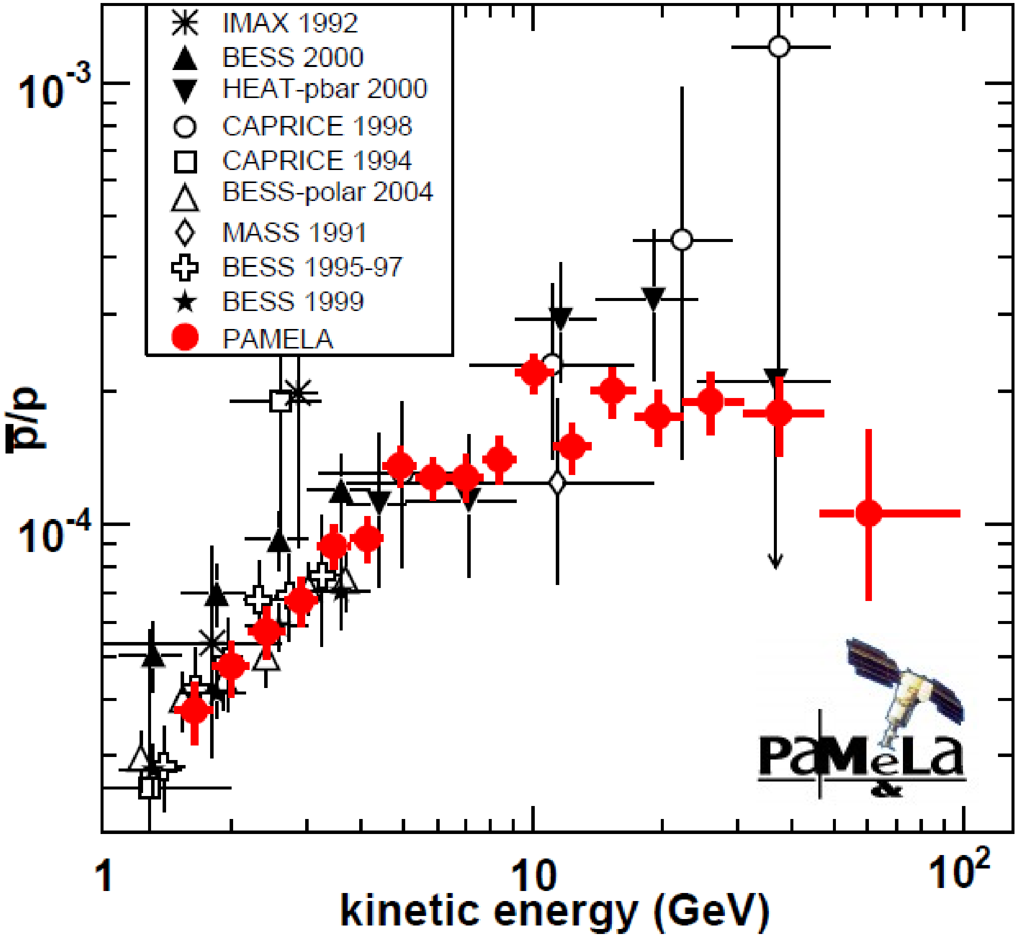
- **Has a mass larger than ~300 GeV,**
- **Has a lifetime around 10^{26} seconds,**
- **Decays preferentially into leptons of the first or second generation.**

The decay of dark matter also predicts a flux of

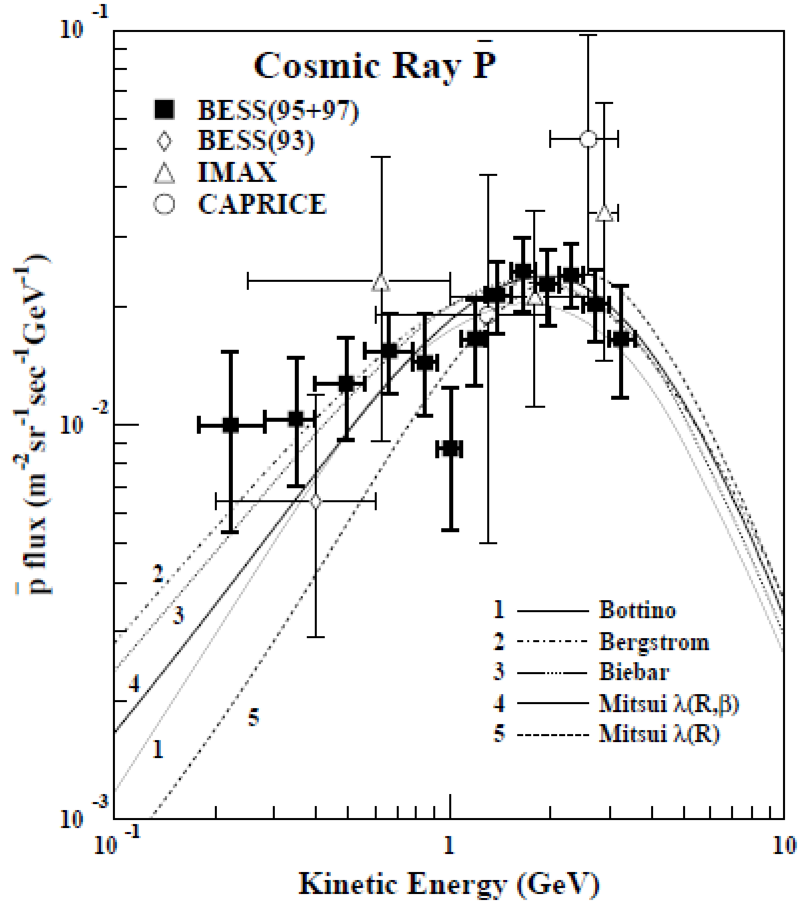
- Antiprotons
- Gamma rays
- Neutrinos

Additional constraints to the scenario!

Antiproton flux from PAMELA



Expectations from spallation

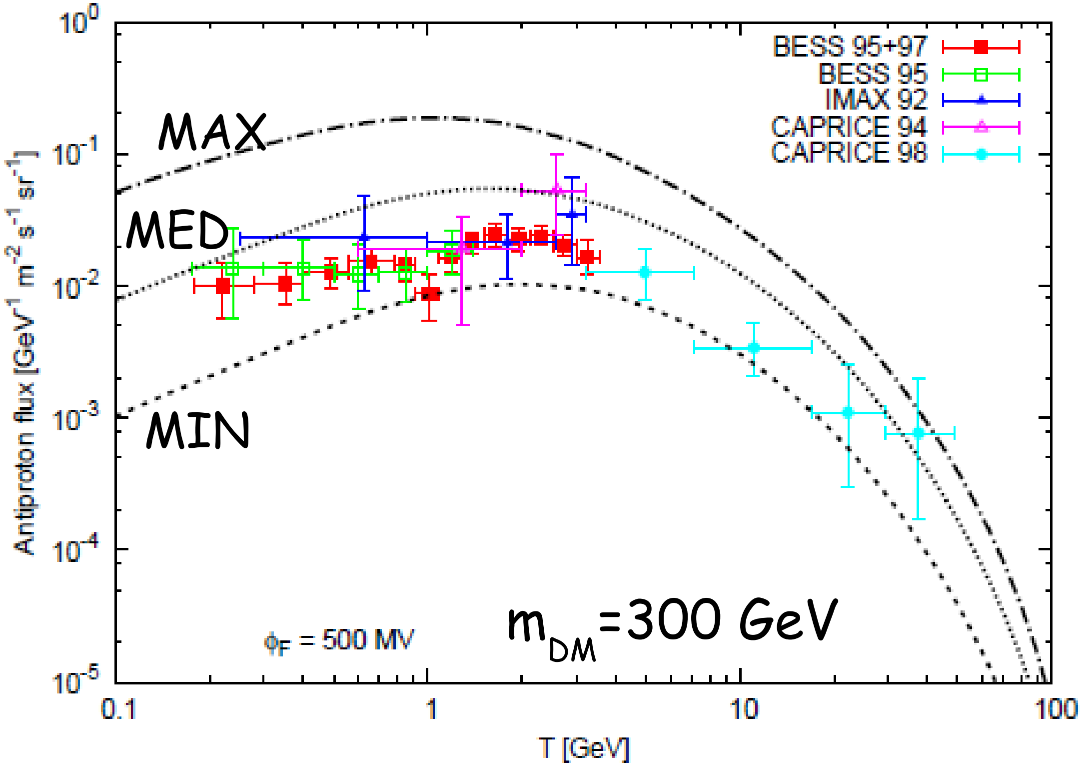


Good agreement of the theory with the experiments: no need for a sizable contribution to the primary antiproton flux. Purely leptonic decays (*e.g.* $\psi \rightarrow e^+e^-\nu$) are favoured over decays into weak gauge bosons.

Antiproton flux from dark matter decay

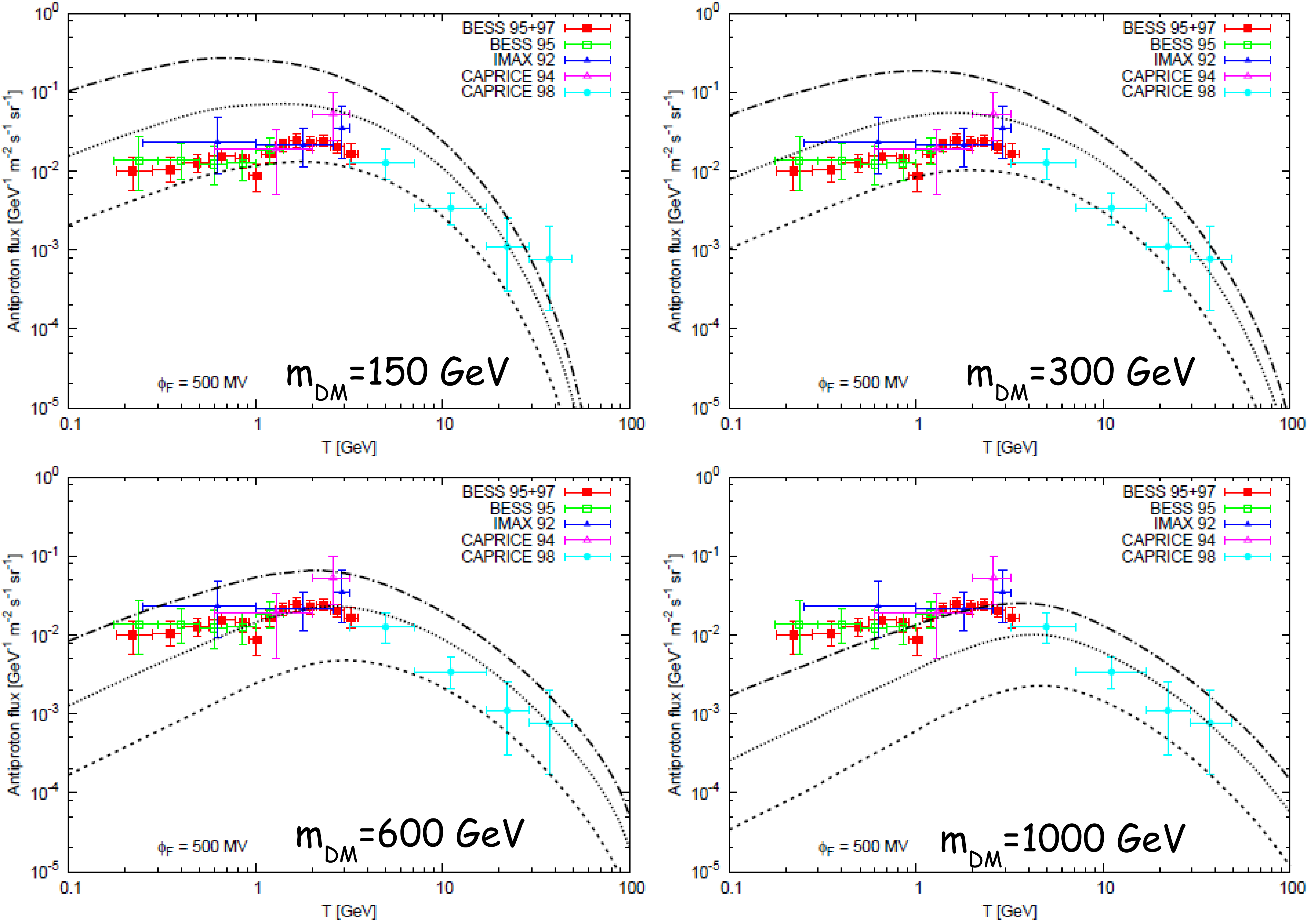
Propagation mechanism more complicated than for the positrons.
We neglect in our analysis reacceleration and tertiary contributions

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



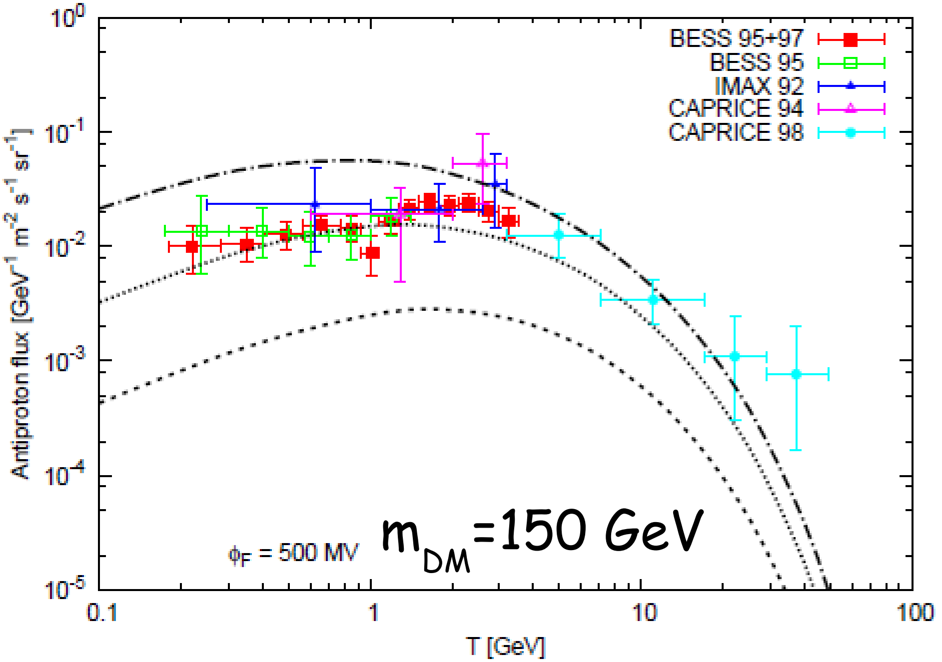
$\psi \rightarrow Z^0\, \nu$

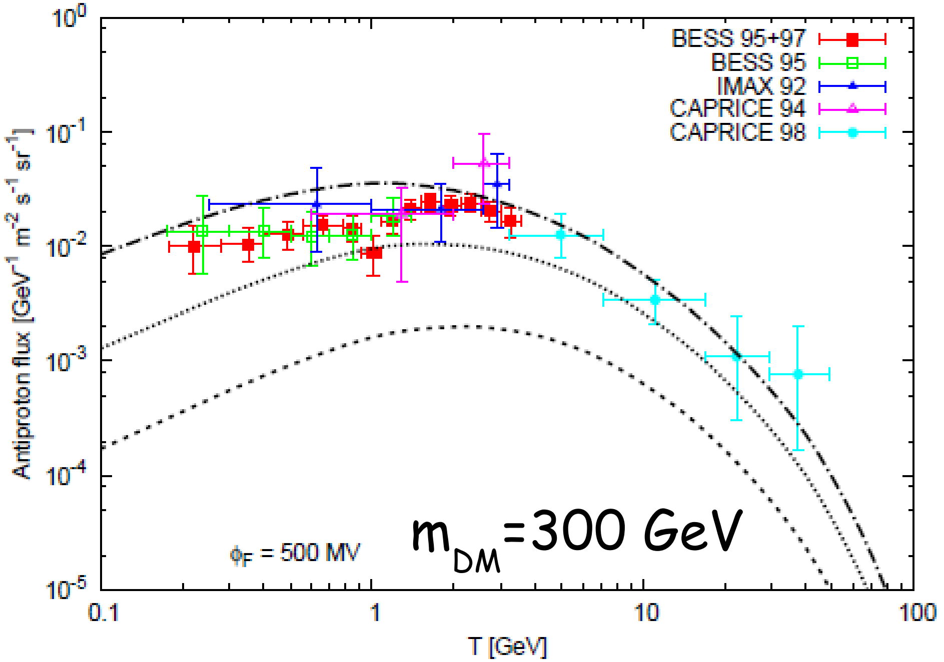
$\psi \to Z^0 \nu$

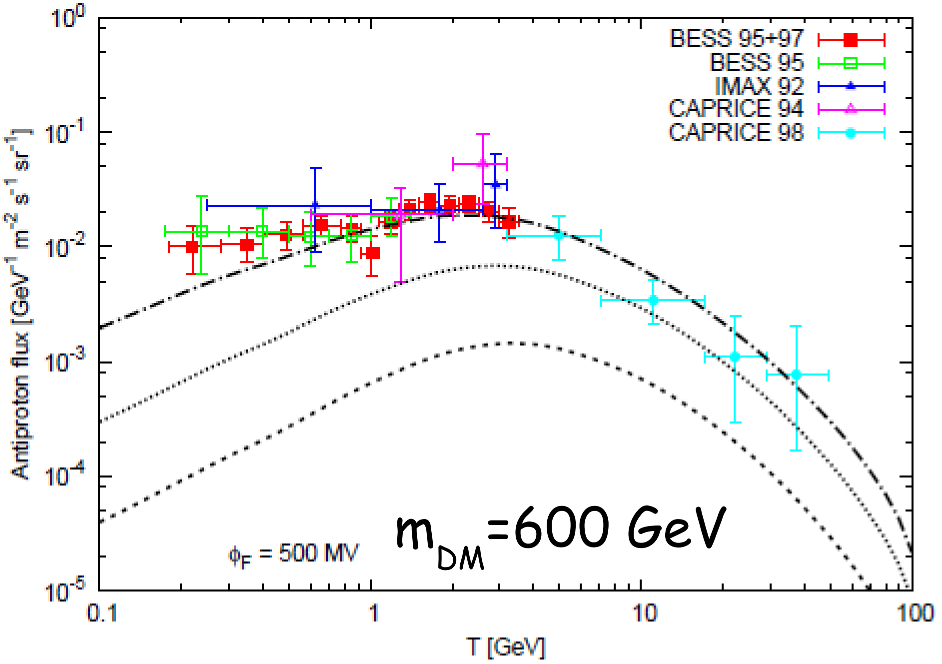


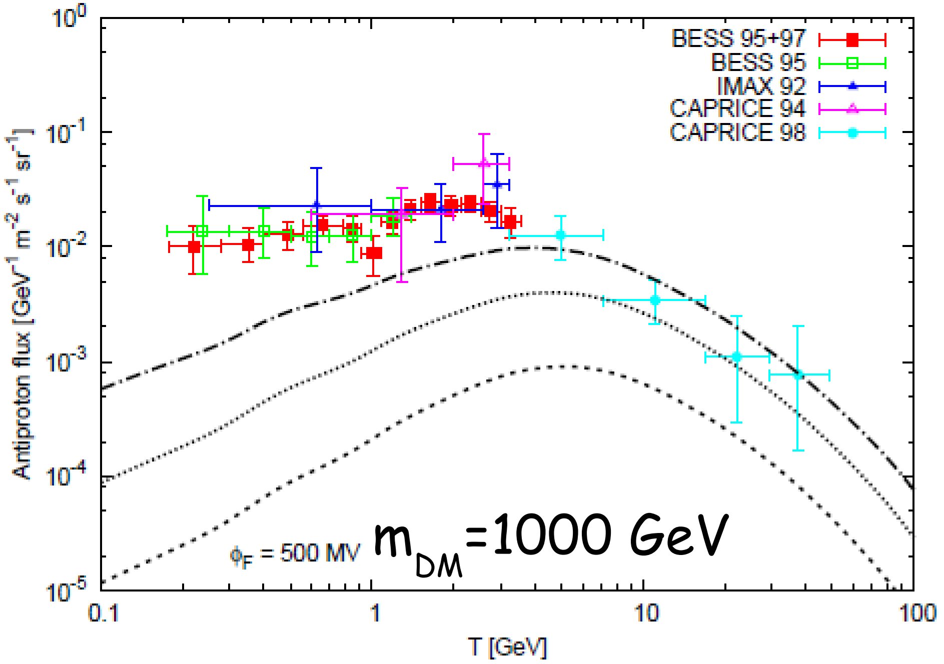
BESS 95+97
BESS 95
IMAX 92
CAPRICE 94
CAPRICE 98
Antiproton flux [GeV^{-1} m^{-2} s^{-1} sr^{-1}]
T [GeV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.1
1
10
100
ϕ_F = 500 MV
m_{DM}=150 GeV
m_{DM}=300 GeV
m_{DM}=600 GeV
m_{DM}=1000 GeV

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

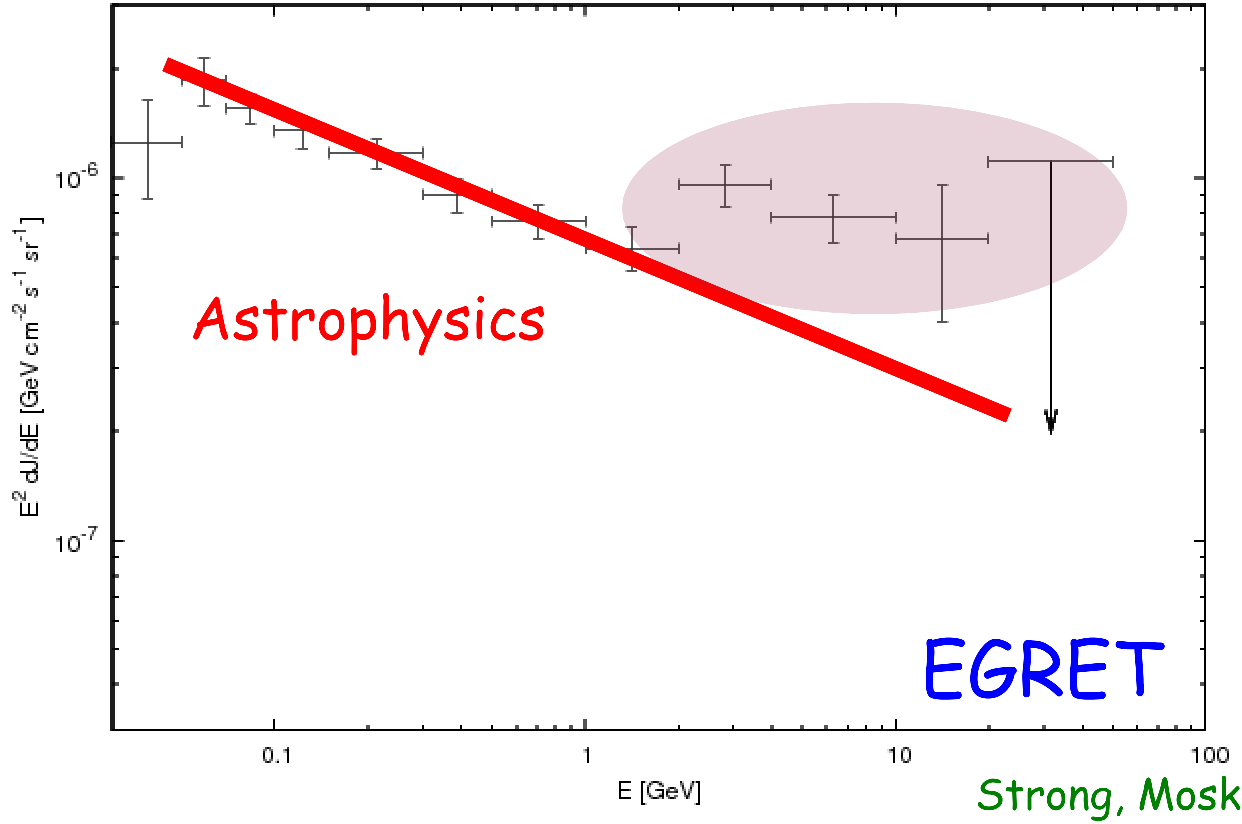








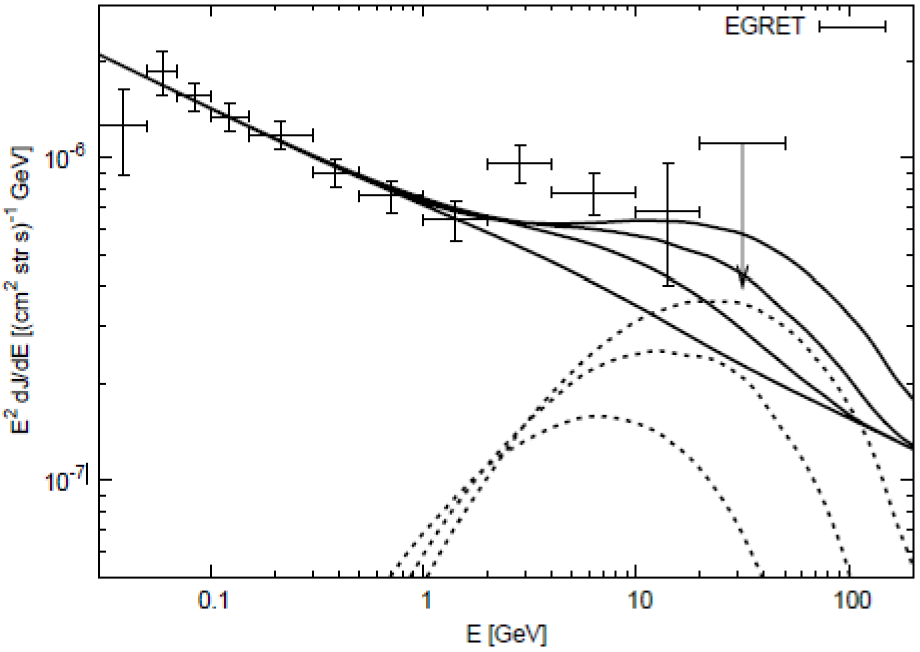
Extragalactic gamma ray flux from EGRET



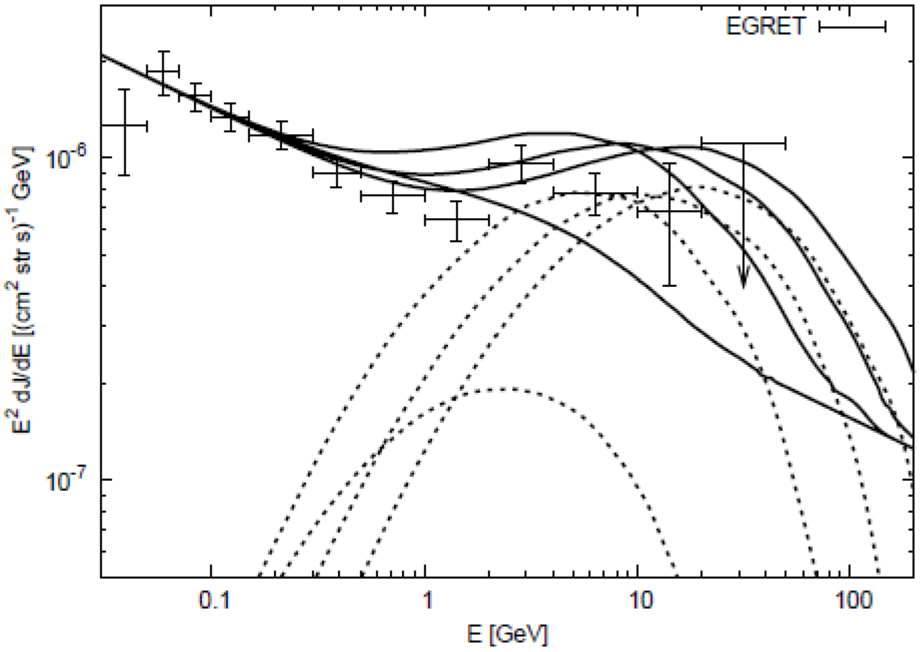
Strong, Moskalenko, Reimer

Hint for an exotic contribution in the extragalactic gamma ray flux

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

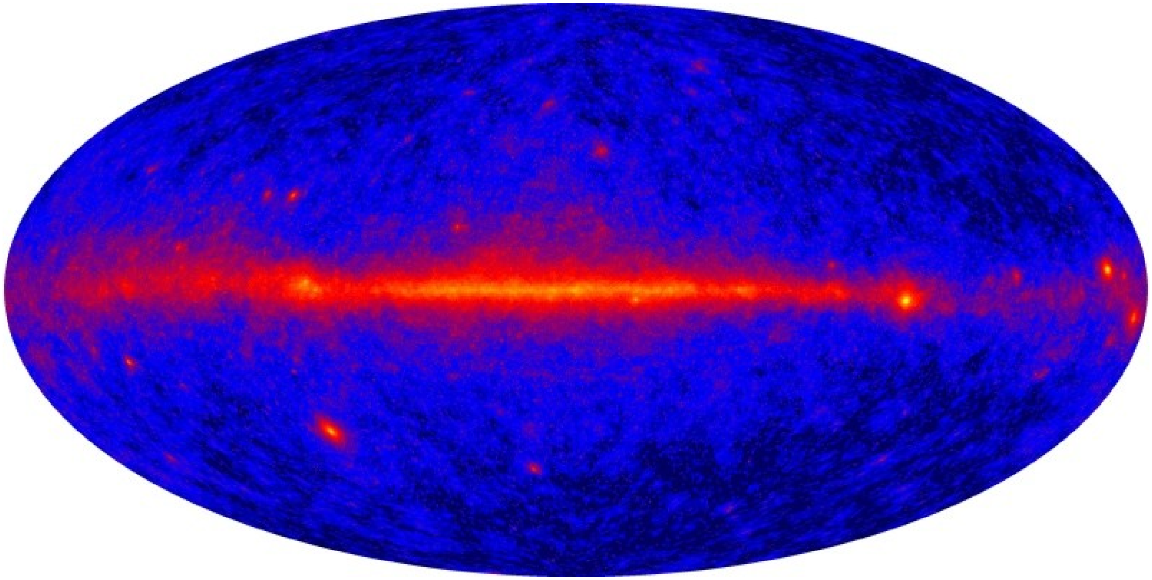


$\psi \to Z^0\, \nu$



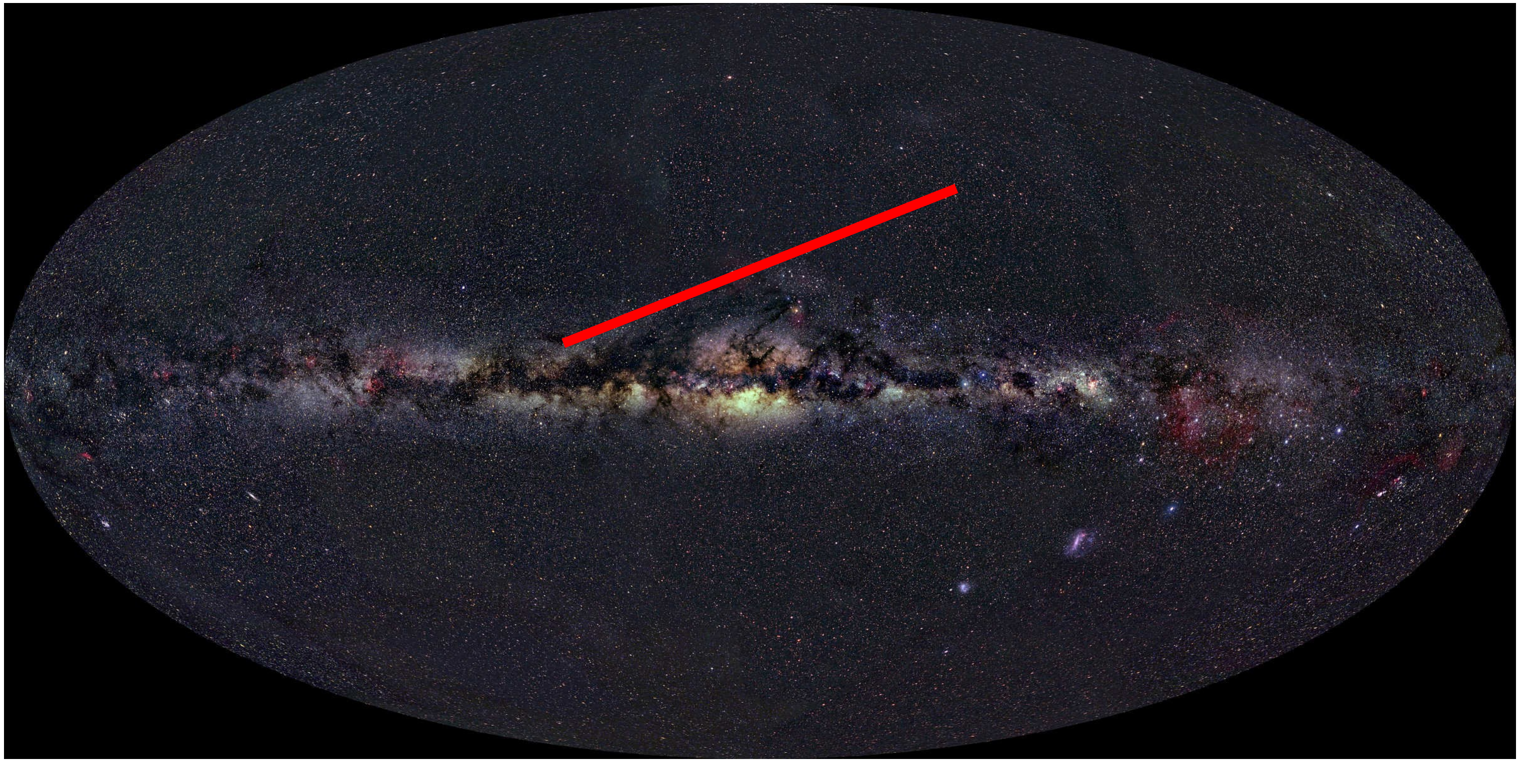
Better measurements will be available soon

Fermi
Gamma-ray
Space Telescope



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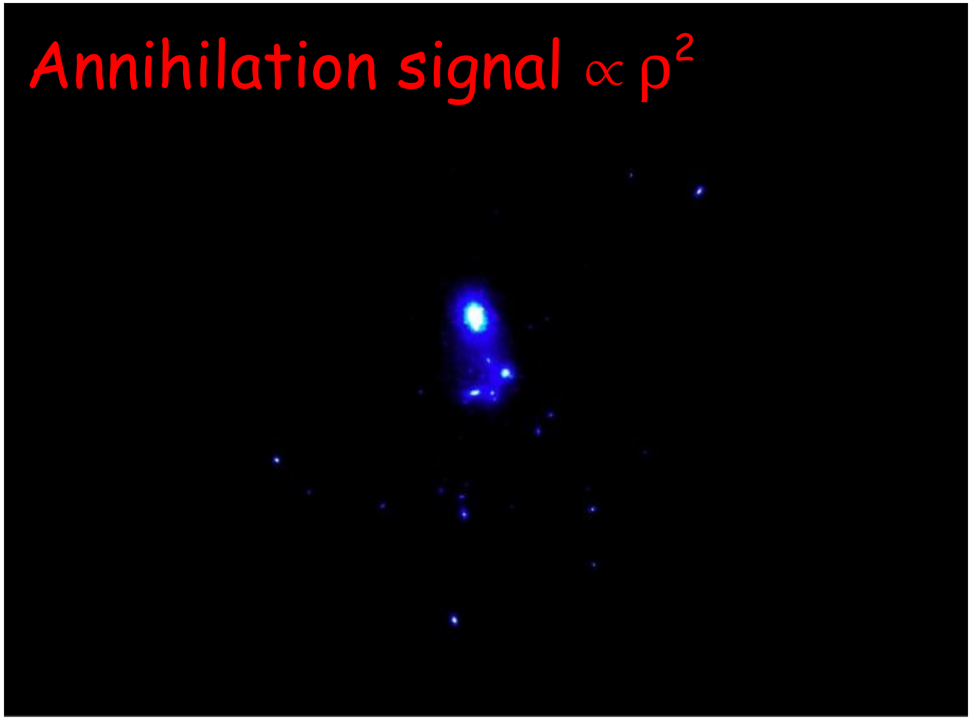
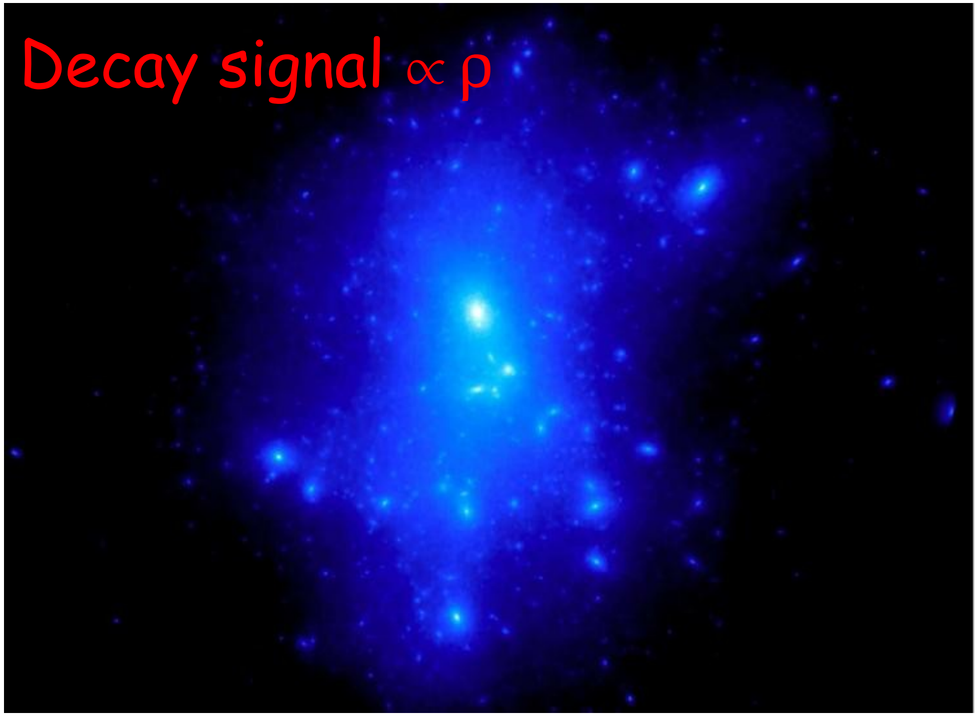
Gamma rays do not diffuse and point directly to the source!

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



Annihilation signal $\propto \rho^2$



Decay signal $\propto \rho$

From B. Moore

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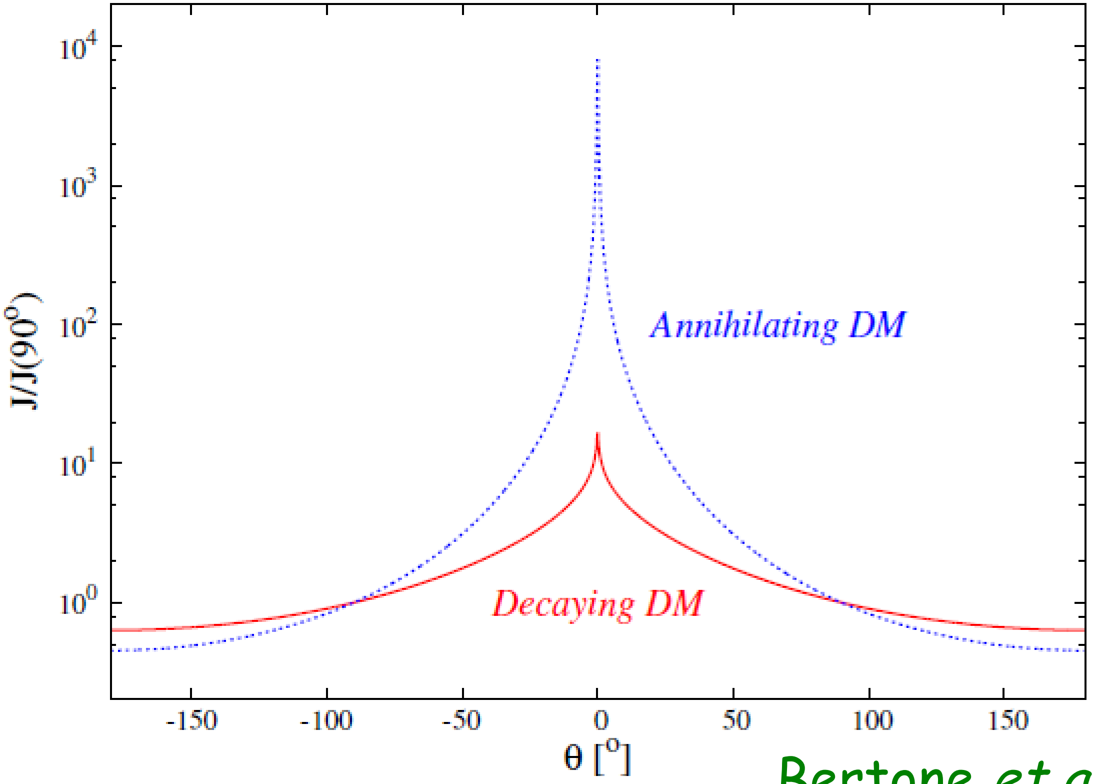
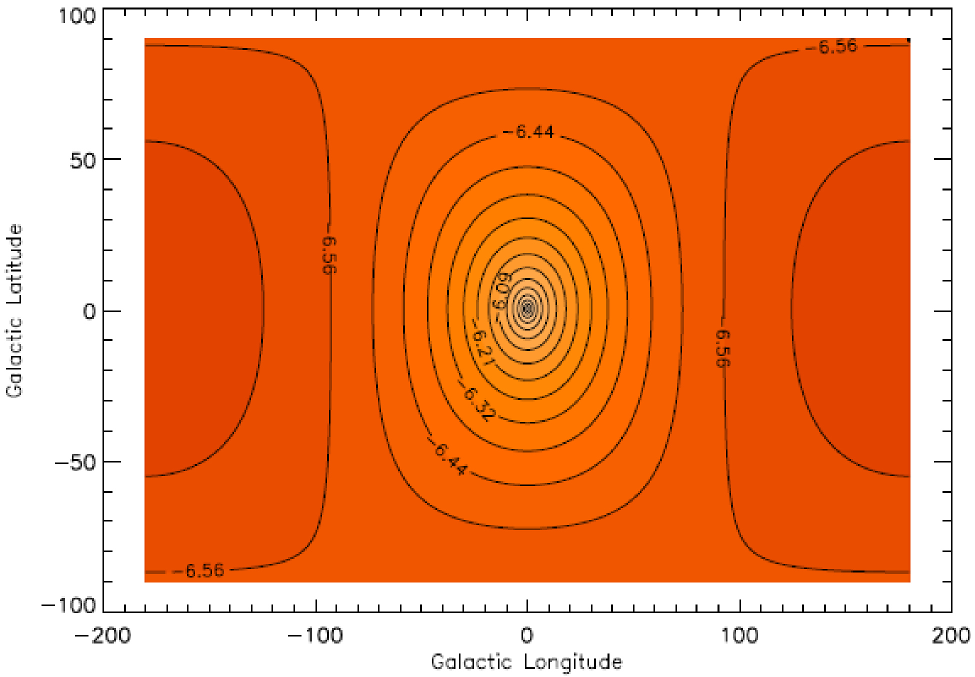


Bertone *et al.*

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

signal



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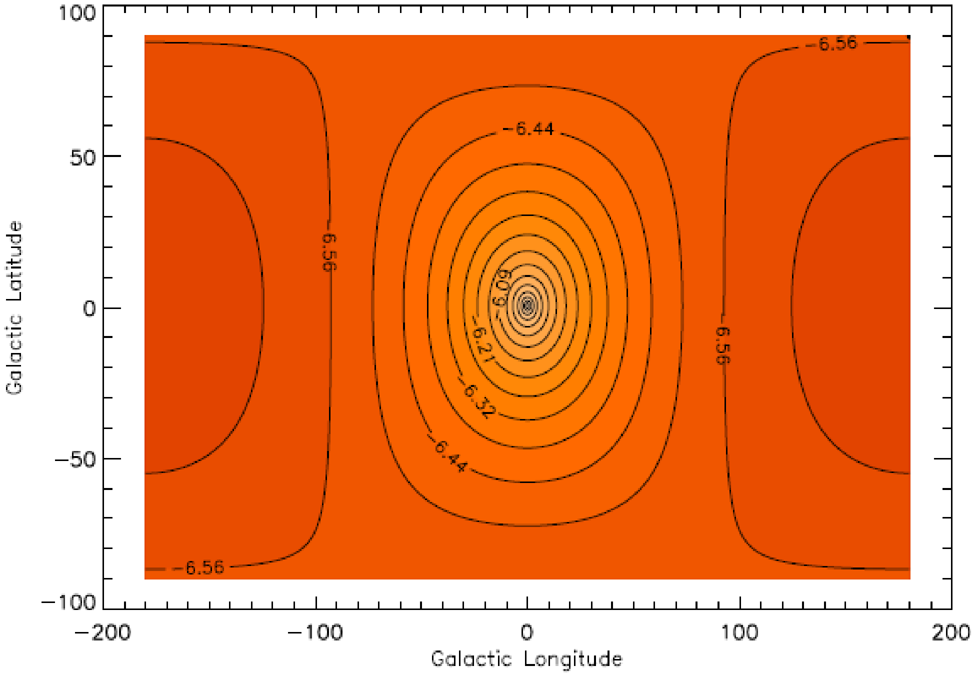
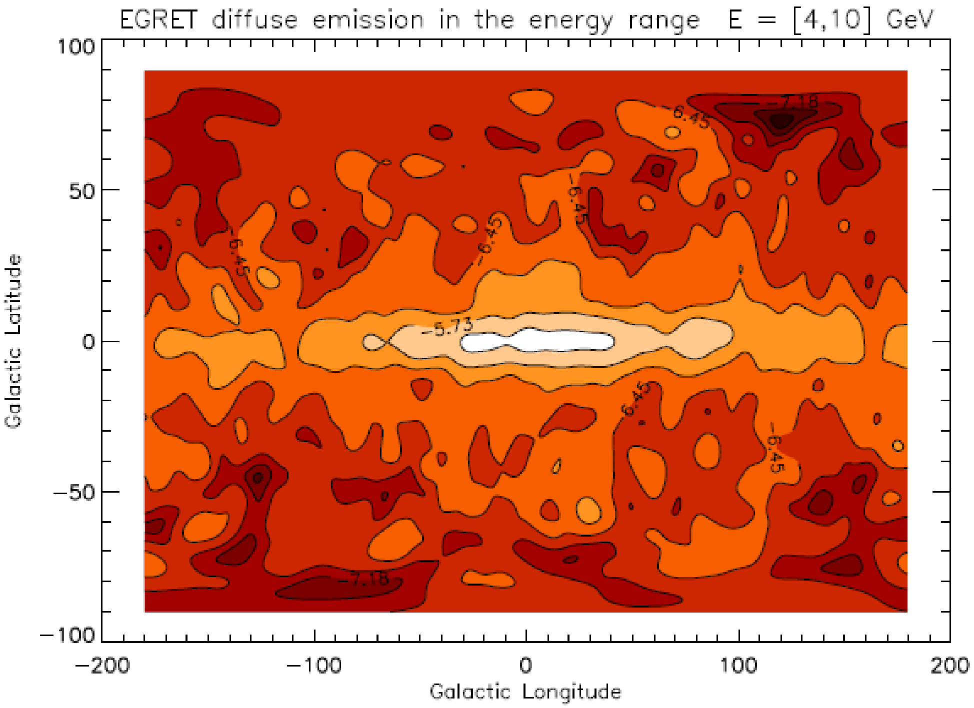


signal+background


EGRET diffuse emission in the energy range E = [4,10] GeV

Bertone *et al.*

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.

Decaying gravitinos as dark matter candidate

Very well motivated scenario for decaying dark matter.
Interesting with independence of the cosmic ray anomalies.
(in fact, it was proposed before the results from PAMELA appeared)

The gravitino is present in any theory with local SUSY. When the gravitino is the lightest supersymmetric particle, it constitutes a very interesting (and promising!) candidate for the dark matter of the Universe.

The relic abundance is calculable in terms of few parameters:

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2$$

Bolz, Brandenburg, Buchmüller
Pradler, Steffen

NICELY COMPATIBLE WITH LEPTOGENESIS!
(T_R >10^9 GeV)

The ultimate goal is to construct a consistent thermal history of the Universe.

With strict R-parity conservation, there seems to be a conflict between these three paradigms:

- Supersymmetric dark matter
- Big Bang Nucleosynthesis
- Leptogenesis ($T_R > 10^9$ GeV)

The extremely weak interactions of the gravitino can be very problematic in the early Universe.

If R-parity is conserved, the NLSP can only decay into gravitino and Standard Model particles, with a decay rate strongly suppressed by M_P.

$$\Gamma_{\mathrm{NLSP}} \simeq \frac{m^5_{\mathrm{NLSP}}}{48\pi m^2_{3/2} M^2_P} \longrightarrow \text{Very long lifetimes}$$

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$$\Gamma_{\mathrm{NLSP}} \simeq \frac{m_{\mathrm{NLSP}}^5}{48\pi m_{3/2}^2 M_P^2} \quad \longrightarrow \text{Very long lifetimes}$$

The leptogenesis constraint ($T_R > 10^9$ GeV) requires for gravitino dark matter $m_{3/2} > 5$ GeV . Then

$$\tau_{\mathrm{NLSP}} \simeq 2 \text{ days} \left(\frac{m_{3/2}}{5 \text{ GeV}}\right)^2 \left(\frac{150 \mathrm{GeV}}{m_{\mathrm{NLSP}}}\right)^5$$

The NLSP is present during and after BBN. The successful predictions of the Standard BBN scenario could be jeopardized.

This is in fact the case for the most probable candidates for the NLSP!

- Neutralino: hadro-dissociation of primordial elements.
- Stau: formation of bound states with ^{4}He, catalyzing the production of ^{7}Li.

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A simple solution to the problem: accept a small amount of R-parity violation. The NLSP decays into SM particles before the onset of BBN.

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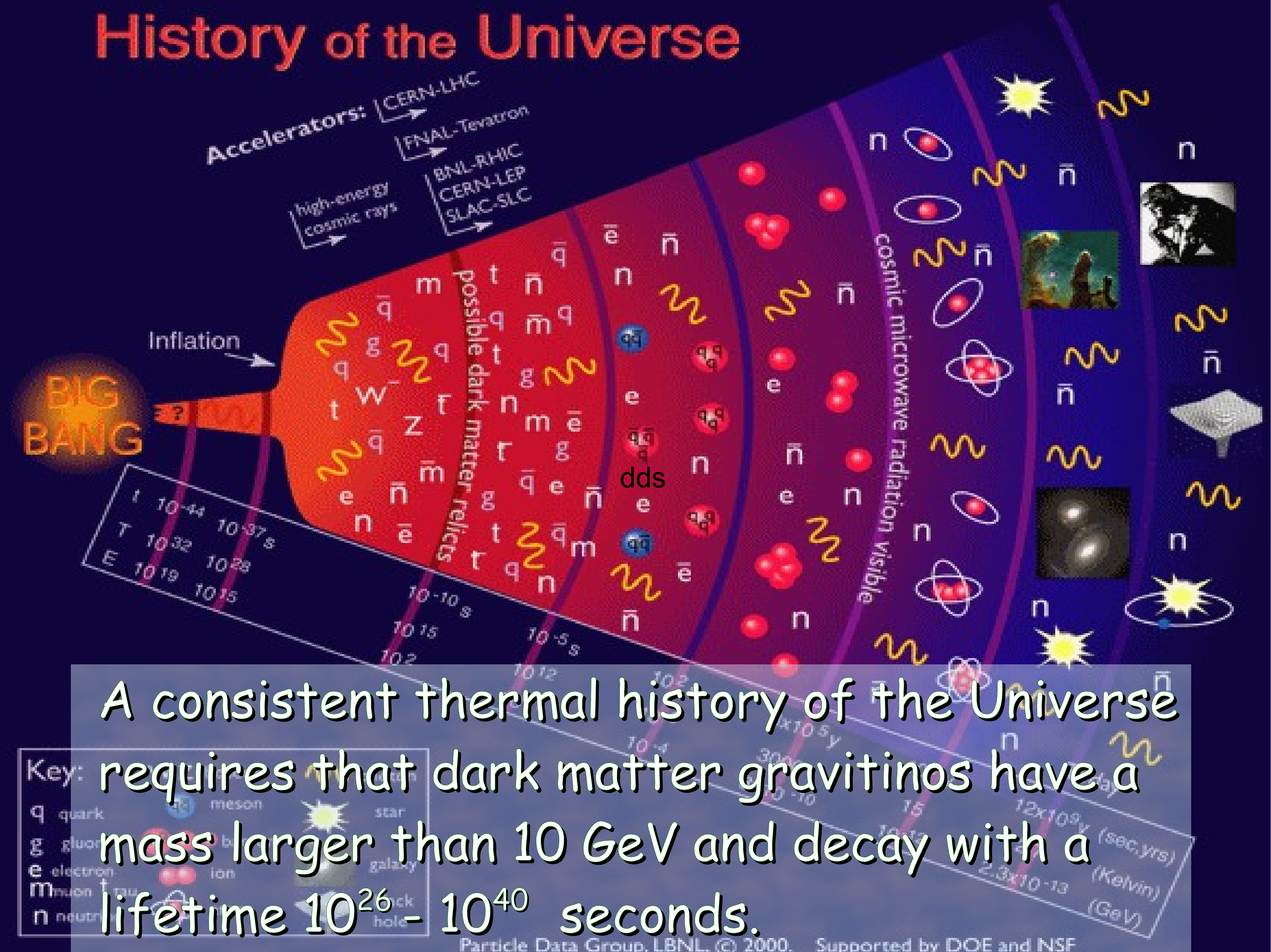
A simple solution to the problem: accept a small amount of R-parity violation. The NLSP decays into SM particles before the onset of BBN.

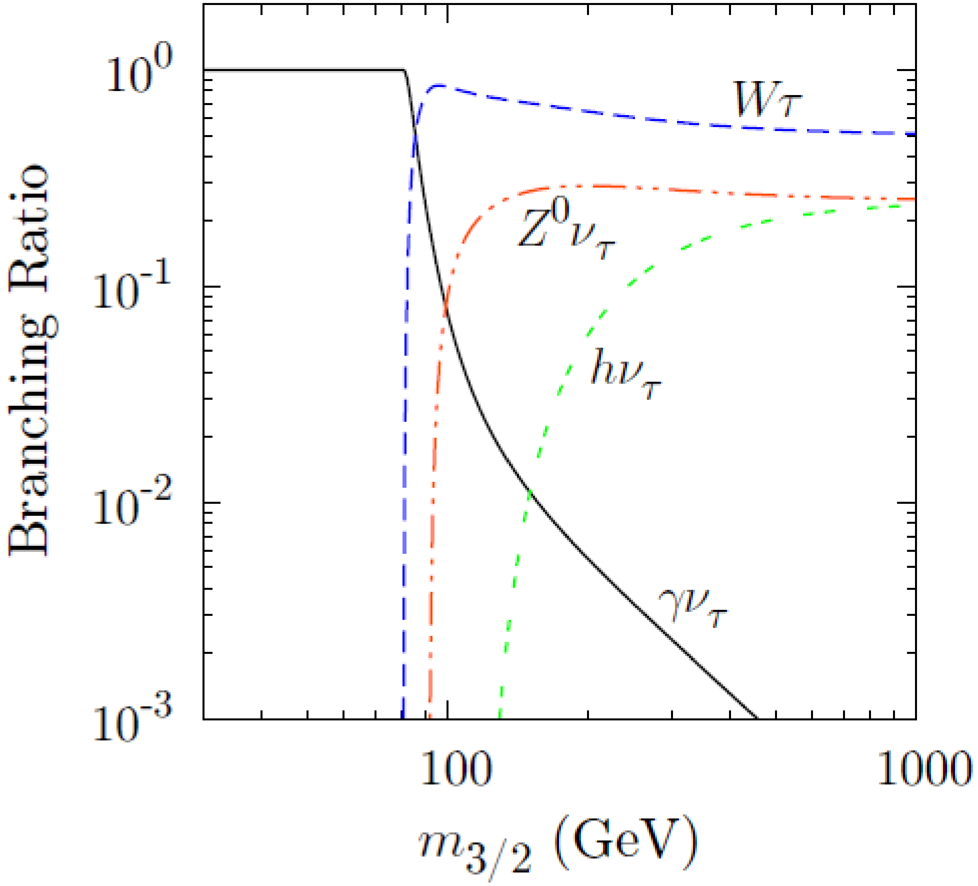
With R-parity violation, the gravitino is no longer stable (*e.g.* $\psi_{3/2} \to \nu\, \gamma$) but still long lived. Takayama, Yamaguchi

Moreover, the requirement of successful baryogenesis *implies* that the gravitino is long lived enough to be the dark matter. Buchmüller, Covi, Hamaguchi, AI, Yanagida



A consistent thermal history of the Universe requires that dark matter gravitinos have a mass larger than 10 GeV and decay with a lifetime 10^{26} - 10^{40} seconds.

The energy spectrum of electrons and positrons from gravitino dark matter decay depends mainly on the gravitino mass and lifetime (with a milder dependence on other SUSY parameters)

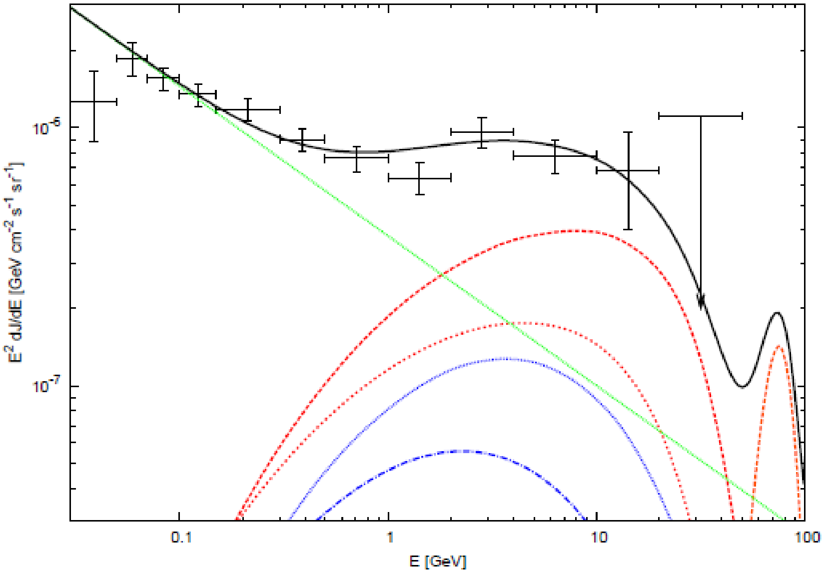


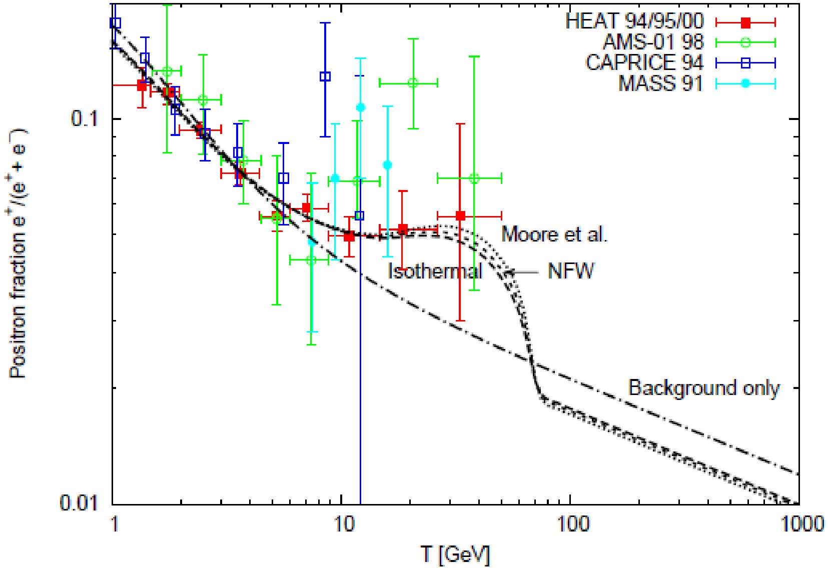
Covi, Grefe, AI, Tran

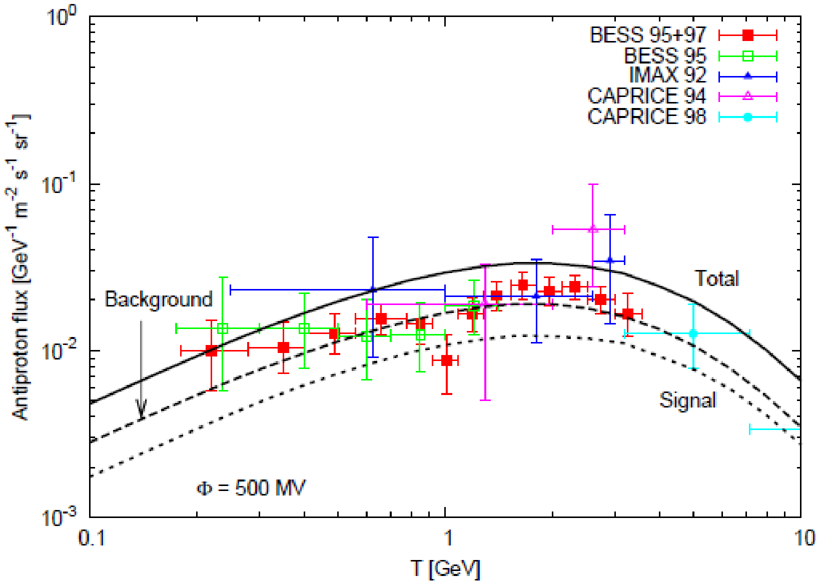
Status before PAMELA

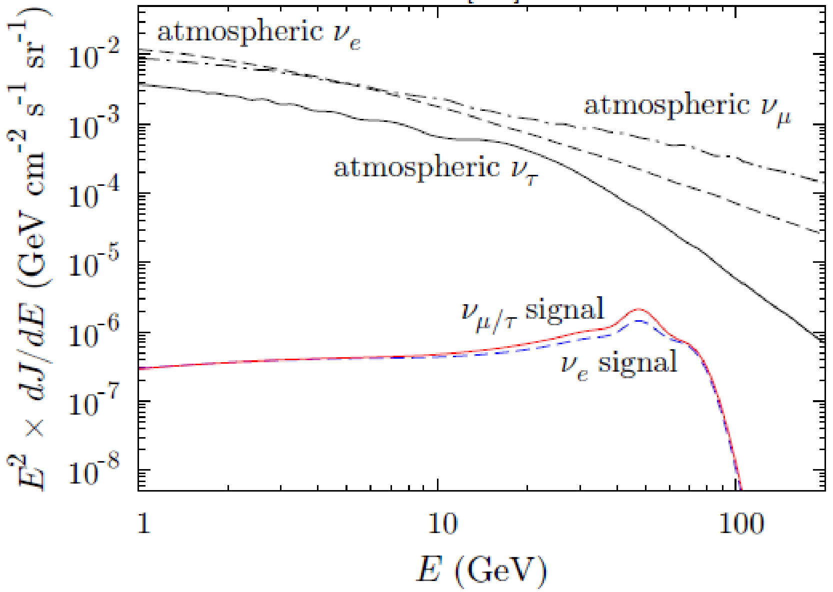
AI, Tran, arXiv:0709.4593, 0804.4596
Covi, Grefe, AI, Tran, arXiv:0809.5030

$$m_{3/2} \sim 150\ \text{GeV},\ \tau_{3/2} \sim 10^{26}\,\text{s}$$





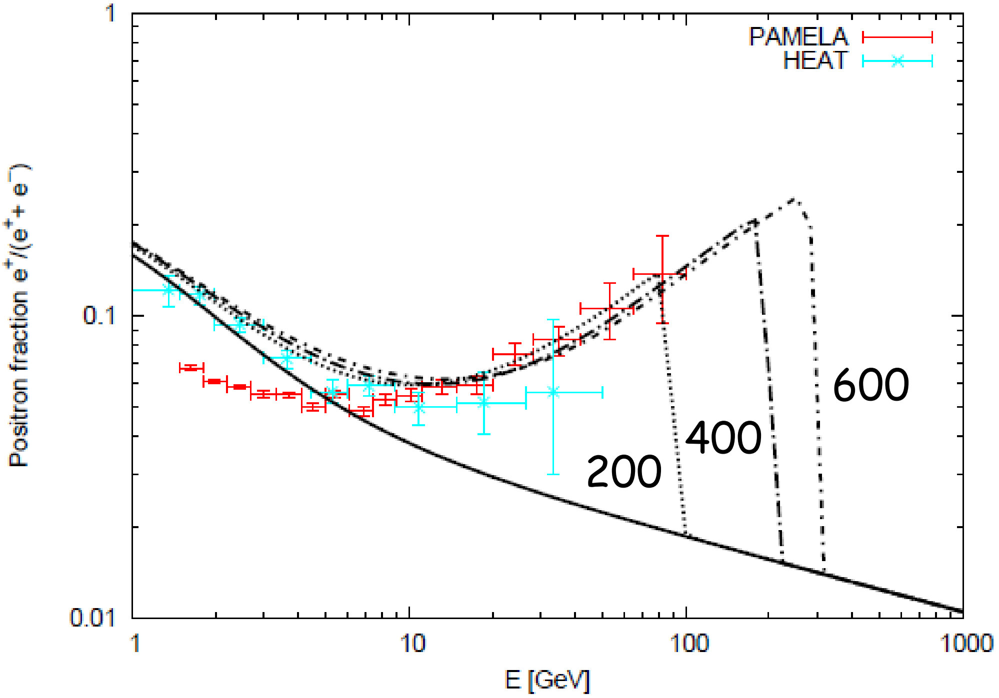




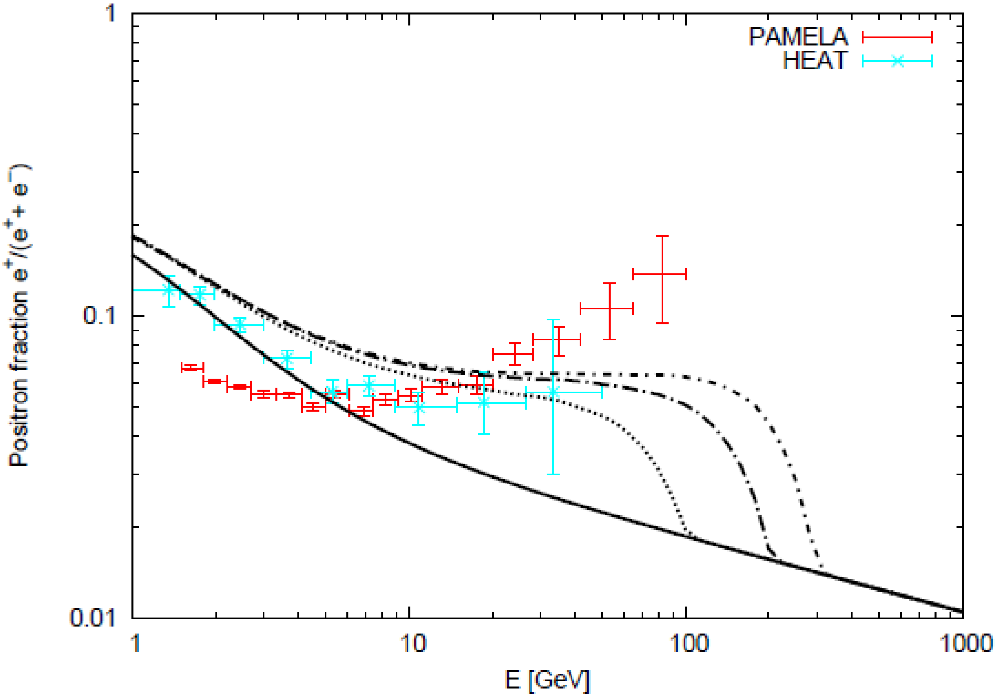
Status after PAMELA

Buchmüller, AI, Shindou, Takayama, Tran '09

Positron fraction from gravitino decay

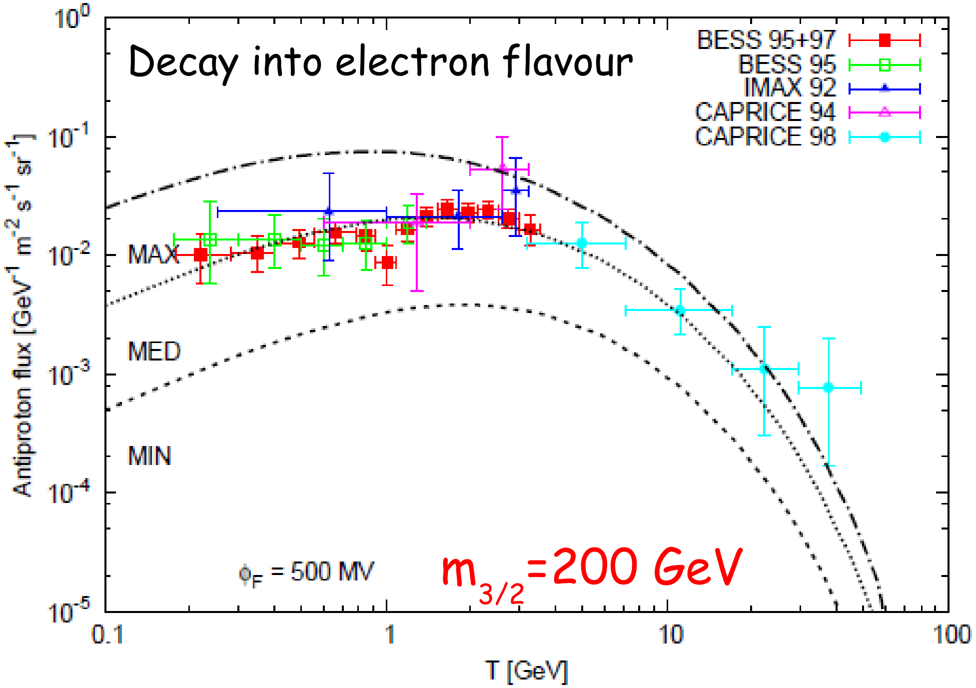


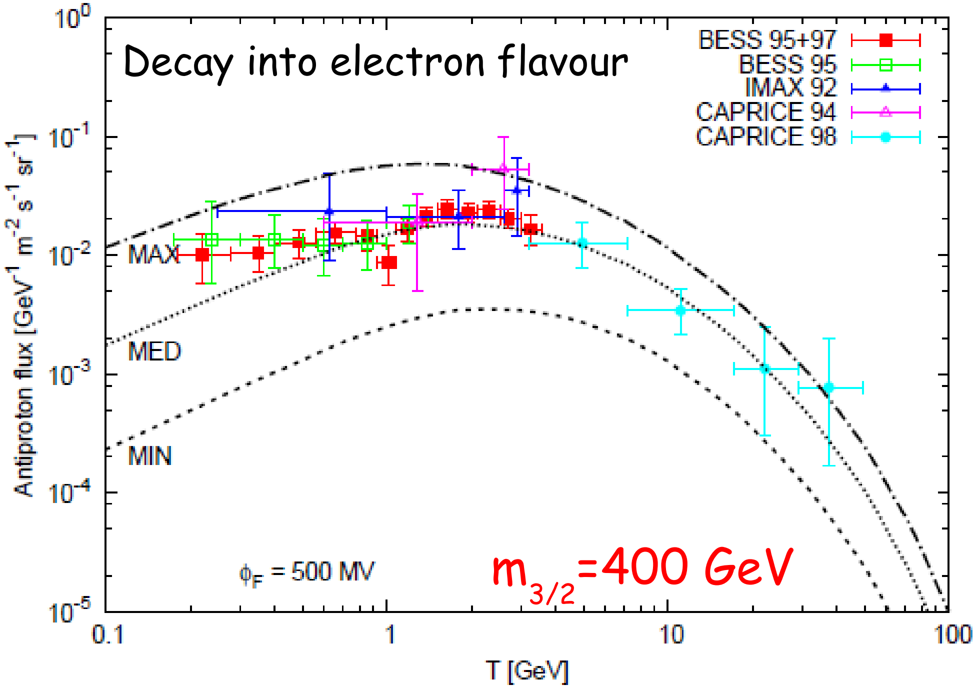
Decay into electron flavour

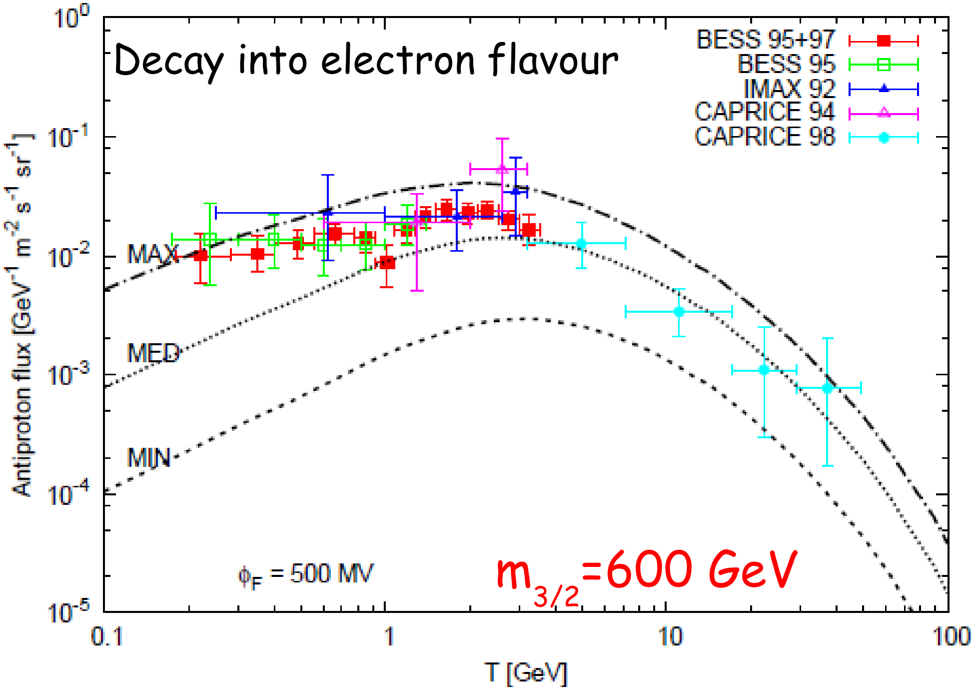


Decay into tau flavour

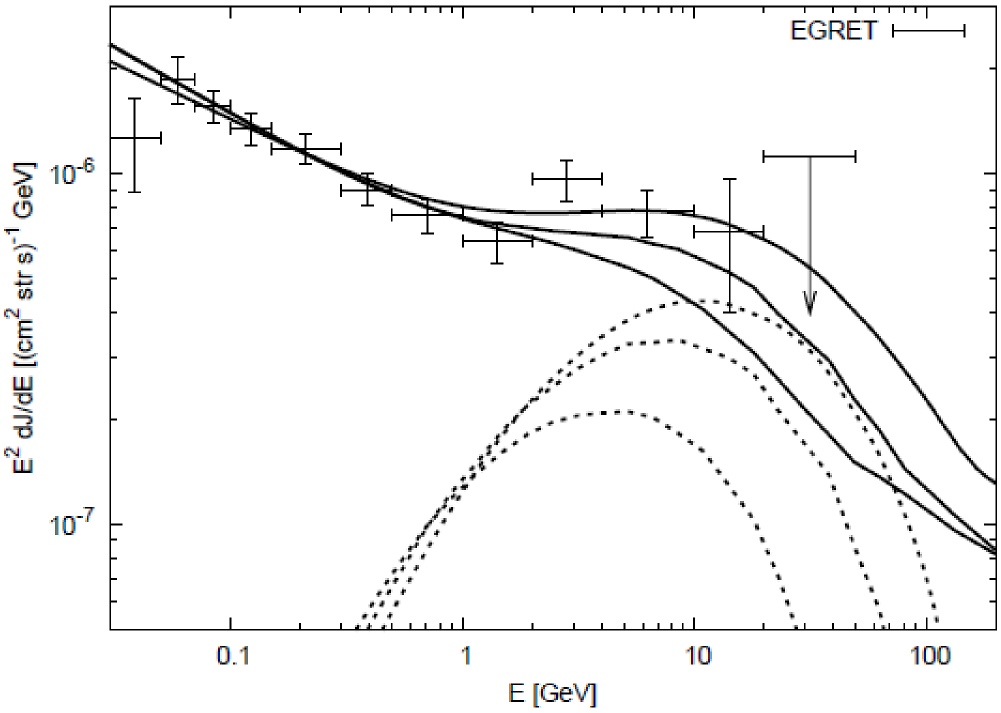
Antiproton flux from gravitino decay



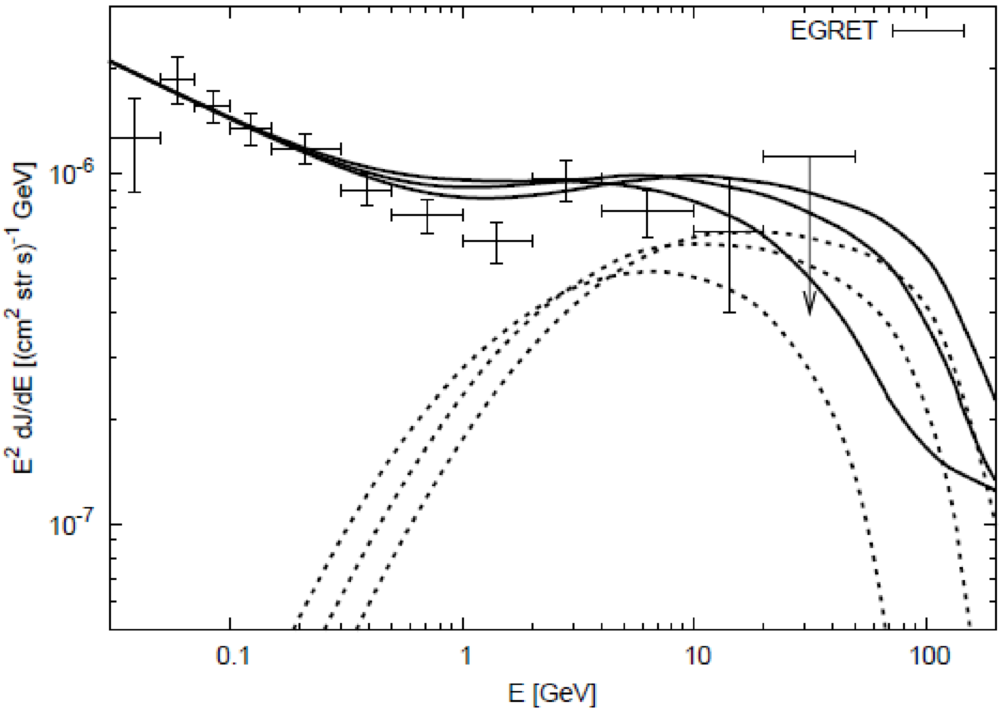




Diffuse gamma ray flux from gravitino decay



Decay into electron flavour



Decay into tau flavour

Signatures at the LHC

In this scenario the next-to-lightest supersymmetric particle decays is predicted to have a lifetime larger than a nanosecond (short in cosmological scales, but long at collider).

If the stau is the NLSP, it decays $\tilde{\tau} \to \mu\, \nu_\tau,\ \tau\, \nu_\mu$ with identical branching ratios.

$$c\tau_{\tilde{\tau}}^{\mathrm{lep}} \sim 15\ \mathrm{cm} \left(\frac{m_{\tilde{\tau}}}{400\mathrm{GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2}$$

Long heavily ionizing charged track, followed by a muon track or a jet. A very spectacular signal at colliders.

The gravitino lifetime is correlated to the stau mass and lifetime.

$$\tau_{3/2} \sim 10^{26}\mathrm{s} \left(\frac{m_{3/2}}{150\mathrm{GeV}}\right)^{-3} \left(\frac{m_{\tilde{\tau}}}{400\mathrm{GeV}}\right) \left(\frac{\tau_{\tilde{\tau}}}{10^{-8}\mathrm{s}}\right)$$

The measurement of the stau parameters will provide independent information about the gravitino properties.

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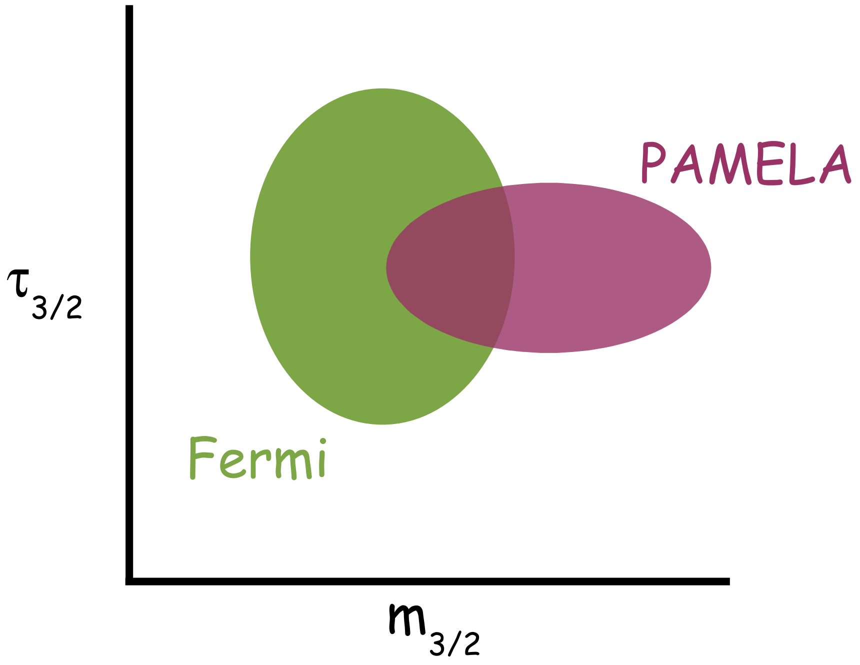

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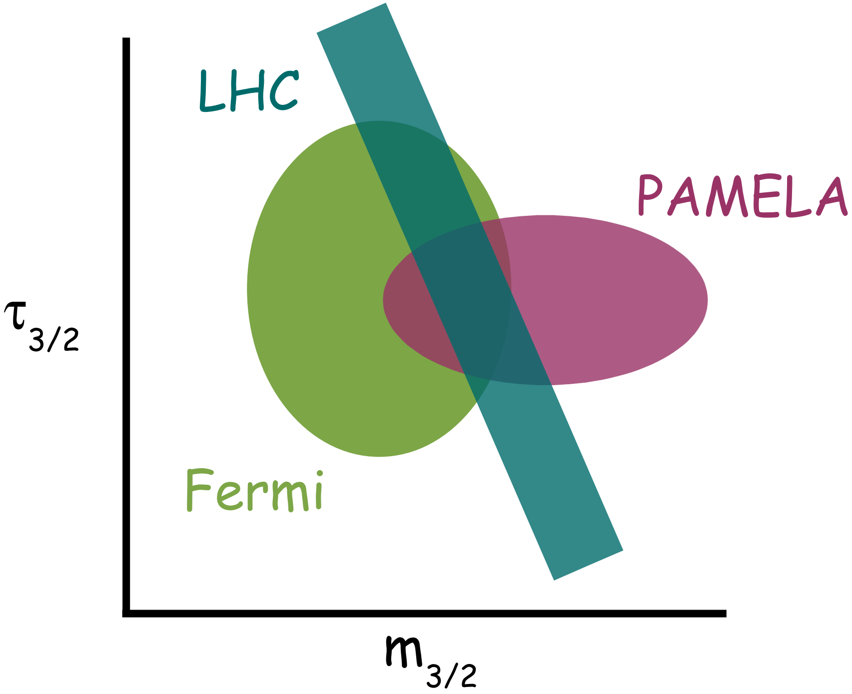

Conclusions

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

- Decaying gravitinos as dark matter are a particularly interesting possibility. They provide a consistent thermal history of the Universe and can explain the PAMELA anomaly.