Axino and decaying dark matter

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Corfu 2009, September 3, 2009

Huh and K, arXiv: 0908.0152

1. Introduction

I present the axion possibility, which is anyway needed for a strong CP solution.

Axino is accompanied with SUSY extension.

2. The simplest extension of MSSM with N

3. Decaying dark matter N

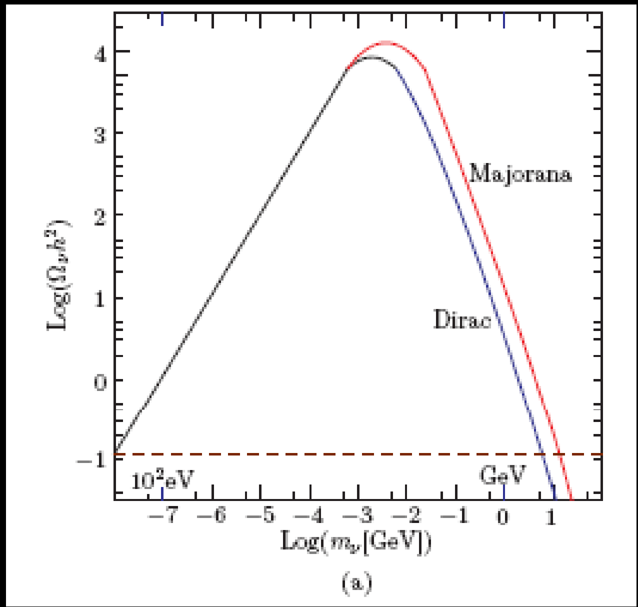
4. Fermi LAT and PAMELA data

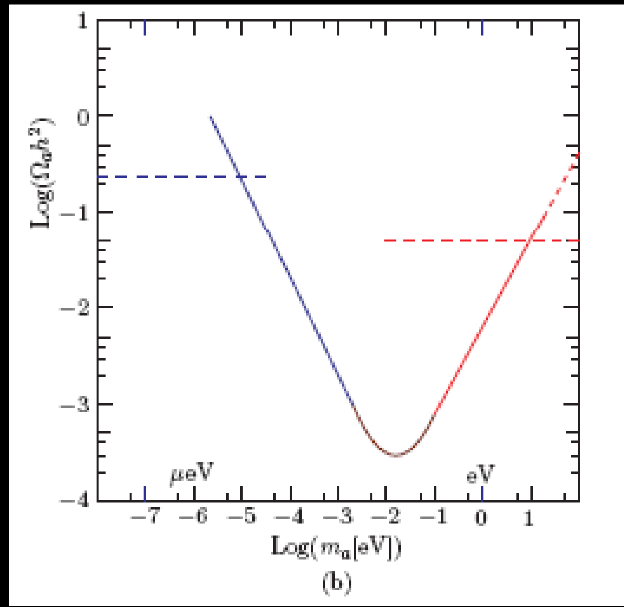
1. Introduction

The most awaited information in the universe now is what is the DM of the universe. One plausible candidate is the WIMP (eWIMP) and the other attractive candidate is a very light axion. We try to discuss these aspects from scarce experimental hints and comment on dark matter in a SUSY framework.

Axion is a Goldstone boson arising when the PQ global symmetry is spontaneously broken. The simple form dictates that its interaction is only through the anomaly term. The axion models have the spontaneous symmetry breaking scale F and the axion decay constant F_a which are related by $F=N_{DW} F_a$.

WIMP was first discussed by B. W. Lee and S. Weinberg in 1977. They considered a heavy neutrino, which implies that the usage "weak" is involved. The LSP interaction is "weak" if interaction mediators (SUSY particles) are in the 100 GeV range as the W boson. That's the reason we talk about WIMP. Now to many WIMP almost means the LSP.



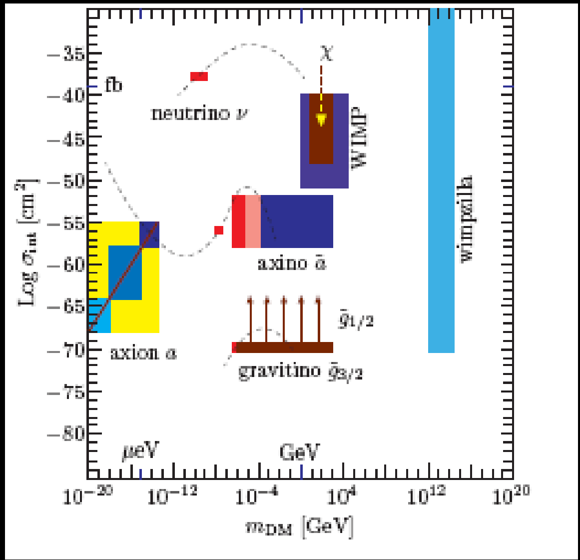


Neutrinos

Axions

Recently, taking the researches of last 20 years, it is reviewed in Kim-Carosi (RMP, 09) arXiv:0807.3125 with references.

10^9 GeV < F_a < 10^{12} GeV



A rough sketch of masses and cross sections. Bosonic DM with collective motion is always CDM.

[Roszkowski, modified]

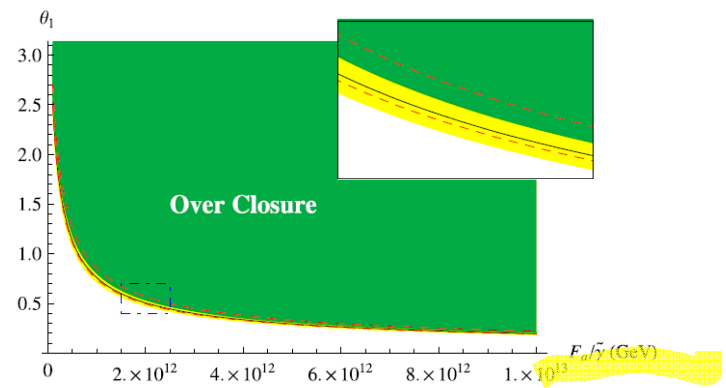


Figure 9. The bound from overclosure of the universe. The yellow band shows the error bars of Λ and two red dashed lines are the limits of the allowed current quark masses. The anharmonic effect is taken into account, including the initial correction factor of equation (15). Here, the entropy production ratio γ is absorbed into the bracket of F_a: $\tilde{\gamma} = \gamma^{(n+4)/(n+6)} \simeq \gamma^{0.84}$.

Turner (86), Grin et al (07), Giudice-Kolb-Riotto (08), Bae-Huh-K, JCAP 0809, 005 (08):

recalculated including the anharmonic term carefully with the new data on light quark masses.

It is the basis of using the anthropic argument for a large F_a.

Historically, Peccei-Quinn tried to mimick the symmetry $\theta \rightarrow \theta - 2\alpha$, by the full electroweak theory. They found such a symmetry if H_u is coupled to up-type quarks and H_d couples to down-type quarks,

$$L = \bar{q}_L u_R H_u + \bar{q}_L d_R H_d - V(H_u, H_d) + \cdots$$

[illegible]

β=α achieves the same thing as the m=0 case.

History: The Peccei-Quinn-Weinber-Wilczek axion is ruled out early in one year [Peccei, 1978]. The PQ symmetry can be incorporated by heavy quarks, using a singlet Higgs field [KSVZ axion]

$$L = \bar{Q}_L Q_R S - V(S, H_u, H_d) + \cdots$$

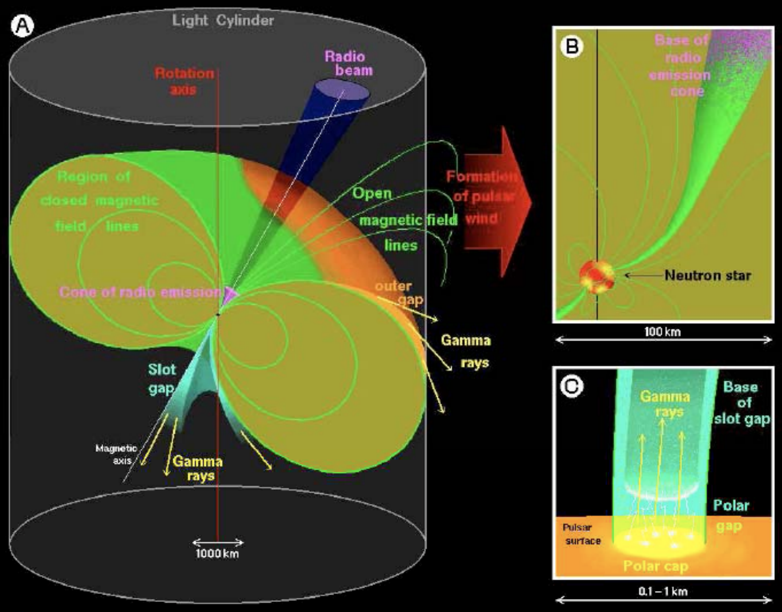
Here, Higgs doublets are neutral under PQ. If they are not neutral, then it is not necessary to introduce heavy quarks [DFSZ]. In any case, the axion is the phase of the SM singlet *S,* if the VEV of *S* is much above the electroweak scale.

In 2008, PAMELA reported the excess positrons but no excess antiprotons in CR spectrum at 10-80 GeV. In the MSSM, it is difficult to explain this. The binolike LSP χ is its own antiparticle, and $\chi + \chi$ annihilation is forbidden at the same point due to the Pauli exclusion principle. The additional DM component is needed.

Huh-K-Kyae [arXiv:0809.2601] introduced N at 100 GeV order. But the ATIC data raised the DM Scale to the TeV region. This affair introduced the decaying DM at the TeV scale. Now, we reformulate the N theory for DDM. This is the simplest extension of the MSSM.

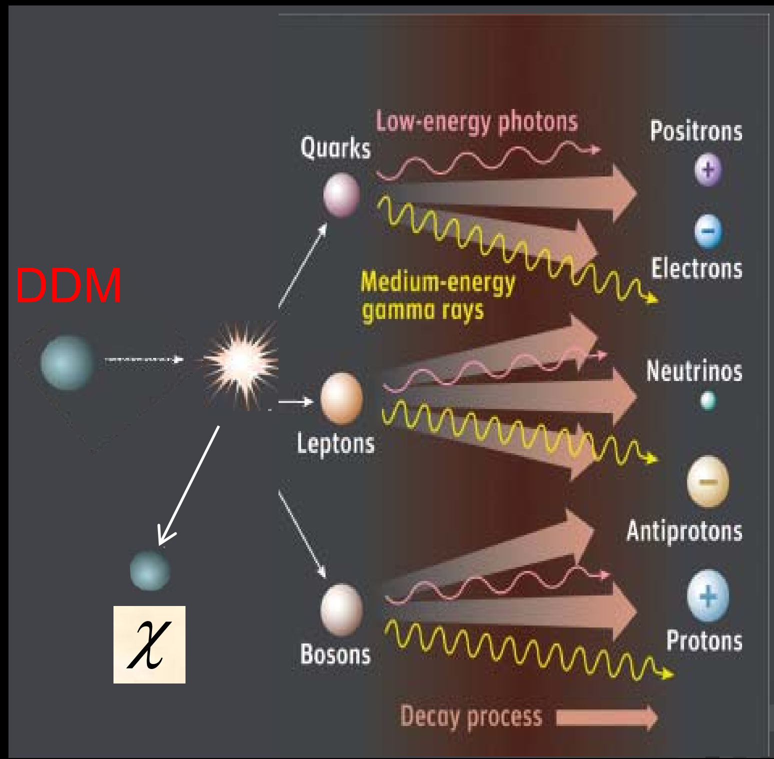
Profumo(SUSY 09): Fermi LAT measurement of a hard ($\sim E^{-3}$) CR $e^{\pm}$ implies

"Additional positron source(s) are needed with **PAMELA's** e^{+} excess.**"**



Pulsars

Image Credit: F. Paige / Fermilab Webpage



Dark Matter

We look for this possibility

What is needed for DDM?

(1) It must be at a TeV scale.

(2) The lifetime is of order 10^{27} s.

(3) Its interaction is suppressed by M_{GUT}^2.

Even if it is suppressed by the Planck mass, the one power suppression gives the lifetime at 1 s, and the two power suppression gives the lifetime at 10^{40} s. So, the two power GUT scale suppression is compelling.

Therefore, for N decay it is of utmost importance to forbid dimension-5 operators. One expects with the symmetries of MSSM, the superpotential of the form,

$$W = N W_{MSSM}$$

where W_{MSSM} is the MSSM superpotential. But this leads to dimension-5 N decay interactions and must be forbidden. Additional symmetries are needed.

So, we introduce the PQ symmetry and axino.

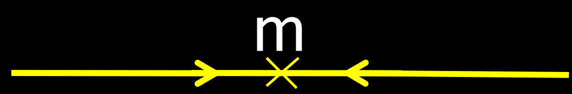
Given SUSY and other symmetries, we have rules to estimate the suppression factor. For the propagator,

(1) The one direction arrow is

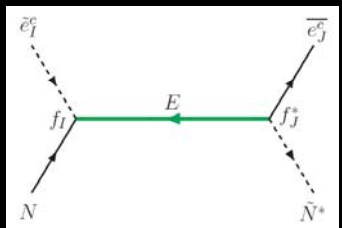
$$\frac{ik_\mu\gamma^\mu}{k^2-m^2}$$

(2) The colliding arrow is

$$\frac{im}{k^2-m^2}$$

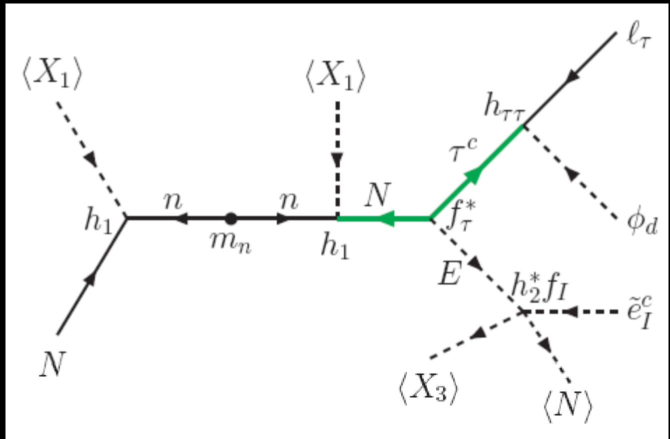


The case (2) is the familiar Majorana mass suppression with the violation of a global symmetry. The following is 4 external lines but suppressed by M^2.



$$\frac{\tilde{N}^*}{M^2}(\overline{e_J^c}\partial_\mu\gamma^\mu)N\tilde{e}_I^c, \qquad M^2=\frac{m_E^2}{f_I f_J^*}$$

One exercise is



$$
\begin{aligned}
\frac{\mathrm{TeV}}{M^2} &\sim \frac{h_1^2 |h_2|^2 f_\tau^* f_I h_{\tau\tau} (i m_n i \not{k}_N i \not{k}_\tau i) \langle X_1 \rangle^2 \langle X_3^* \rangle \langle N^* \rangle}{(k_n^2 - m_n^2)(k_N^2 - m_N^2)(k_\tau^2 - m_\tau^2)(k_{\tilde{E}}^2 - m_{\tilde{E}}^2)} \\
&\sim \frac{F_a^2 V^* \langle X_3^* \rangle}{M_{\mathrm{comb}}^3} \frac{h_1^2 |h_2|^2 f_\tau^* f_I h_{\tau\tau}}{M_{\mathrm{comb}}^2} \\
&\sim 2.5 \times 10^{-3} \frac{\langle X_3^* \rangle h_1^2 |h_2|^2 f_\tau^* f_I h_{\tau\tau}}{(10^{13}\mathrm{GeV})^2} \\
&\sim 25 h_1^2 |h_2|^2 f_\tau^* f_I h_{\tau\tau} \frac{\langle X_3^* \rangle}{(10^{15}\mathrm{GeV})^2}.
\end{aligned}
$$

It describes the decay of N:

$$N \to \ell_\tau + \tilde{e}_I^c + \phi_d$$

And id expressible in terms of a superpotential,

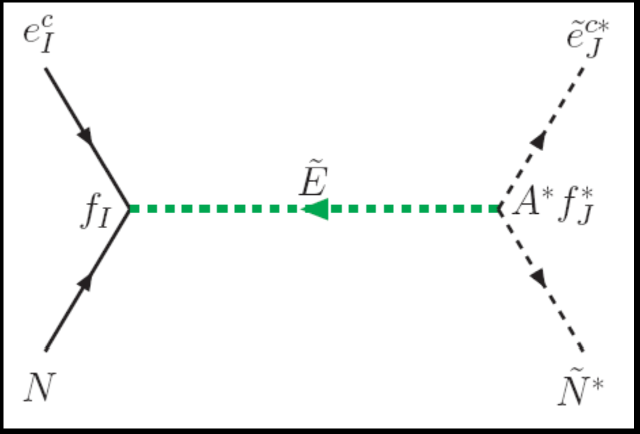
$$W = N \ell_\tau e_I^c \phi_d$$

But, one cannot express any interaction in terms of a superpotential.

We will study

$$\frac{A}{M_{IJ}^2}\tilde{N}^*\overline{e_J^c}N\tilde{e}_I^c + h.c.$$

It can arise by the A term if SUSY is broken.



But, not all interactions are expressible in terms of a superpotential.

2. The simplest extension of MSSM with N

GUT motivation: 15 chiral fields SU(5) : No N available
16 chiral fields SO(10) : There are but at high energy scale

So we need more GUT singlets N beyond 15 or 16.
It is decoupled at the MSSM level, but couples to the MSSM particles with a suppressed mass M.

At the minimum level, we need $E^{\pm}$ to couple N to MSSM.

$E^{\pm}$ is possible in the flipped SU(5):

$SU(5) \times U(1)_X$

10 (X=1) 5* (X=-3) 1 (X=5)

X=±5 singlets are Q=±1 singlets

If there is only one Majorana fermion DM (here called LNX), the Fermi-Dirac statistics implies that s-wave amplitude needs anti-parallel helicities of two incoming LNX, i.e. J=0. Since we have v is of order 10^{-3}, J=0 initially.

If the final state is f f-bar, where f is much lighter than LNX, it must have J=0. If electron-positron pair is directly produced (not by decays of heavy particles), it is suppressed. One may consider the unsuppressed diagram (a), but it is Yukawa suppressed, or (b) at higher order of the e.m. coupling.

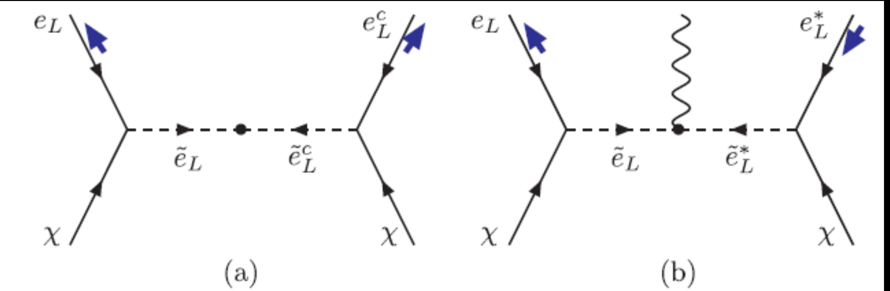
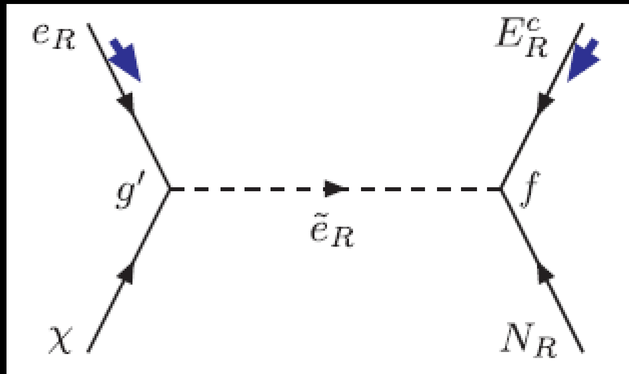


FIG. 1 (color online). The binolike neutralino annihilation. (a) The bullet carries an $SU(2)_W$ quantum number. (b) Here, the bullet can carry angular momentum 1. The helicities of electrons and positrons are shown by thick arrow lines.

So we need at least two components for WIMP DMs.

Now our simplest extension of the MSSM will be
- (i) Keep the most features of the MSSM.
- (ii) Add one more two component neutral DM N.
- (iii) Include extra particles such that N-LNX does not have the Fermi-Dirac suppression for e^+e^- production. One must include additional particles such that the needed interaction is present.

The simplest extension is, Introducing N(neutral)and E(charged). The production diagram is



e^c is an SU(5) singlet. We can introduce heavy E and E^c just below the GUT scale in flipped SU(5).

And DM N

Now, these singlets can have the interaction

$$f\, N\, E\, e^c$$

For O(100 GeV) E has been studied in view of the PAMELA data has been considered by

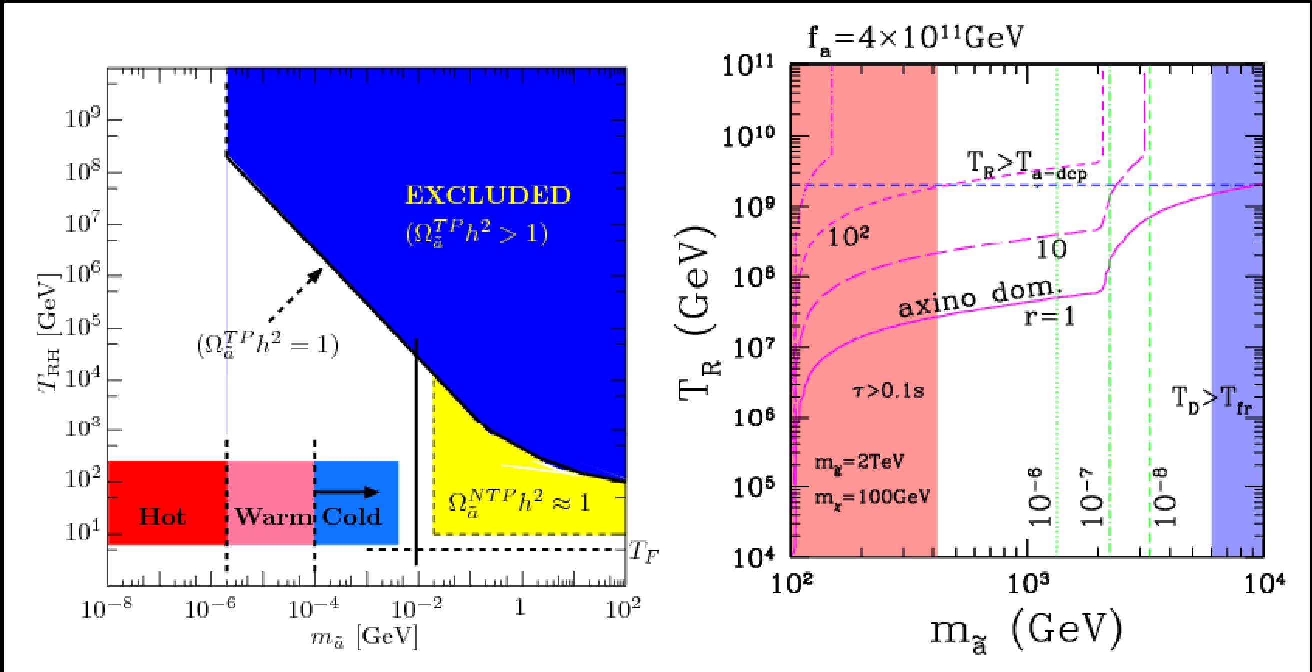
Huh-K-Kyae, PRD79, 063529 (2009), arXiv: 0809.2601
Bae-Huh-K-Kyae-Viollier, NPB817, 58, arXiv: 0812.3511

Then, ATIC raised the scale to TeV and Fermi LAT has been reported.

Note 1: For DM, N at a TeV scale is needed
Note 2: E may not be at the TeV scale.
Note 3: In most DDM models, its number density is not calculated.

Both N and χ are produced by the decay of a heavy particle. This particle dominates the mass density of the universe. This possibility is studied in terms of axino. Anyway, the strong CP must be solved and axion and hence axino also are needed.

Covi-H.B.Kim-K-Roszkowski, JHEP0105, 033 (2001)
Choi-K-Lee-Seto, PRD77, 123501 [arXiv: 0801.0491]



With $F_a=10^{12}$ GeV, the purple region is outside.

Axino can decay by the Lagrangian

$$\int d^2\vartheta \left(\frac{1}{4M'} NNXX - \frac{c_g \alpha_g}{4\sqrt{2}\pi} \vartheta_g W_g W_g \right), \qquad c_3 \vartheta_3 = \frac{X}{F_a} \qquad \text{(A)}$$

For a sufficiently large F_a, > 4x10^{11} GeV, the axino decay time is after the temperature is below the LSP decoupling temperature. By that time, axino could have dominated the mass density of the universe if the reheating temperature is high enough. Then, the ratio of mass densities of N and χ is

$$\frac{Number \quad of \quad N}{Number \quad of \quad \chi} = 2\frac{32\pi^2}{\alpha_3^2}\left(\frac{\langle X \rangle}{M'}\right)^2 \to 10^{-1} - 10^{-2}$$

M' at M_{GUT} is possible.

Model to suppress all N decay operators up to dim-5:

	N	n	X_1	X_2	Σ	E	E^c	ℓ_I	e_I^c	ϕ_u	ϕ_d
R	$+$	$+$	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$+$	$+$
Y	0	0	0	0	0	-1	$+1$	$-\frac{1}{2}$	$+1$	$+\frac{1}{2}$	$-\frac{1}{2}$
Γ	$+1$	0	-1	$+1$	$+2$	0	0	$0,-1,-1$	$1,1,1$	$+2$	0
P	$-$	$-$	$+$	$+$	$+$	$-$	$-$	$+,+,+$	$+,+,+$	$+$	$+$

with the following interaction,

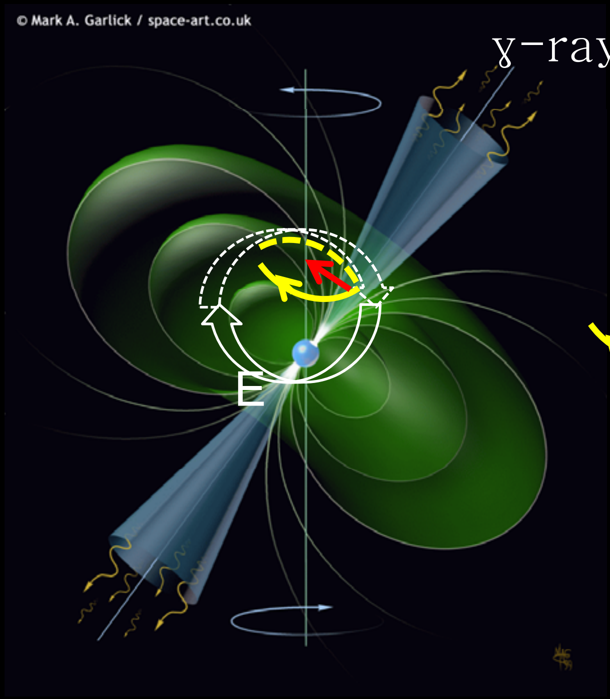
$$W = f_{I\alpha} N e_I E_\alpha^c + m_E^\alpha E_\alpha E_\alpha^c + \frac{1}{2} m_n n^2 + \lambda X_1^2 \Sigma$$

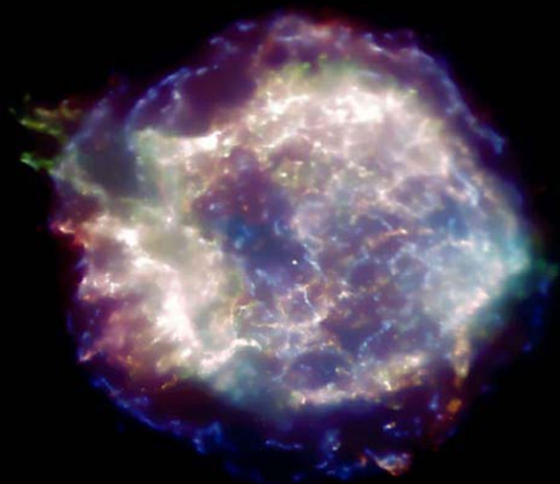
E is separated from the TeV scale, but by the f coupling the TeV sector feels the presence of GUT scale E, through the couplings suppressed by M^2. We investigate the consequence.

Profumo (SUSY 2009):

Pulsars can seed e+e- direct pair production with the rotating strong magnetosphere.

Strong rotationally induced **electric fields** in the magnetoshpere accelerate and extract **e-** from stellar surface, which radiate **gamma rays**; gammas cascade produce **e+e- pairs**, escaping the magnetosphere from the polar cap regions)

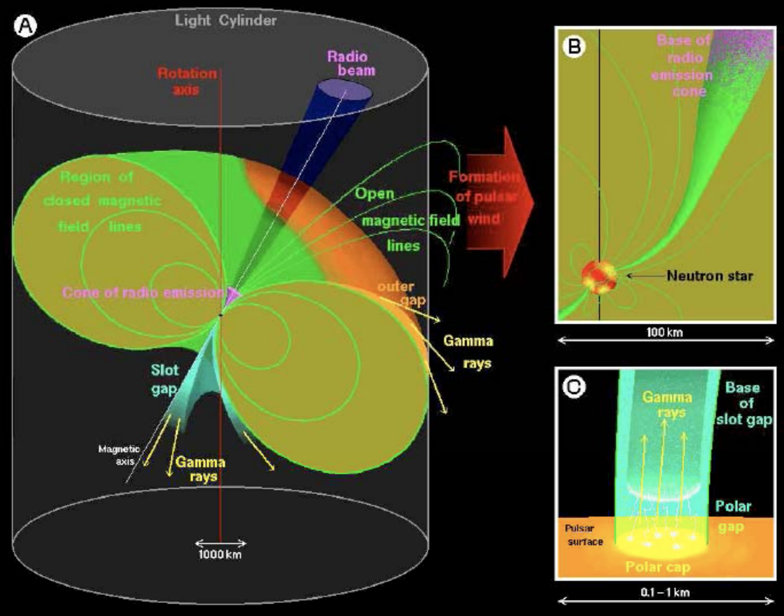




SN remnant & pulsar wind nebulae
shock acceleration

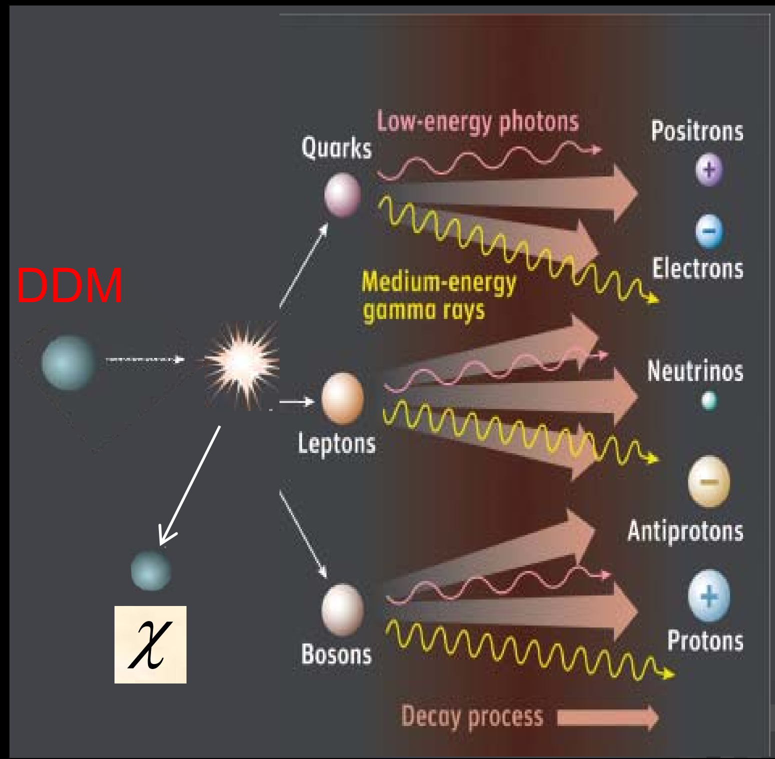
Profumo(SUSY 09): **Fermi** LAT measurement of a hard (~E^{-3}) CR $e^{\pm}$ implies

"Additional positron source(s) are needed with **PAMELA's** e^{+} excess."



Pulsars

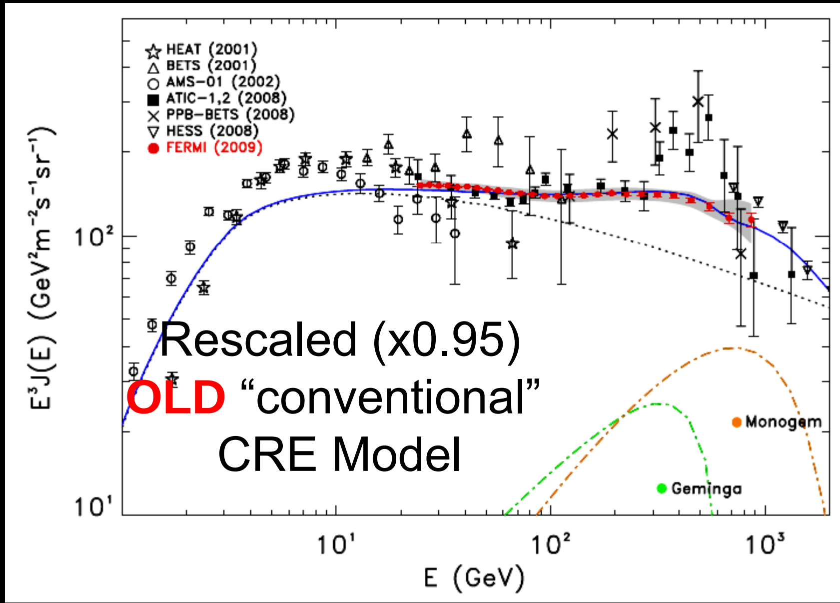
Image Credit: F. Paige / Fermilab Webpage

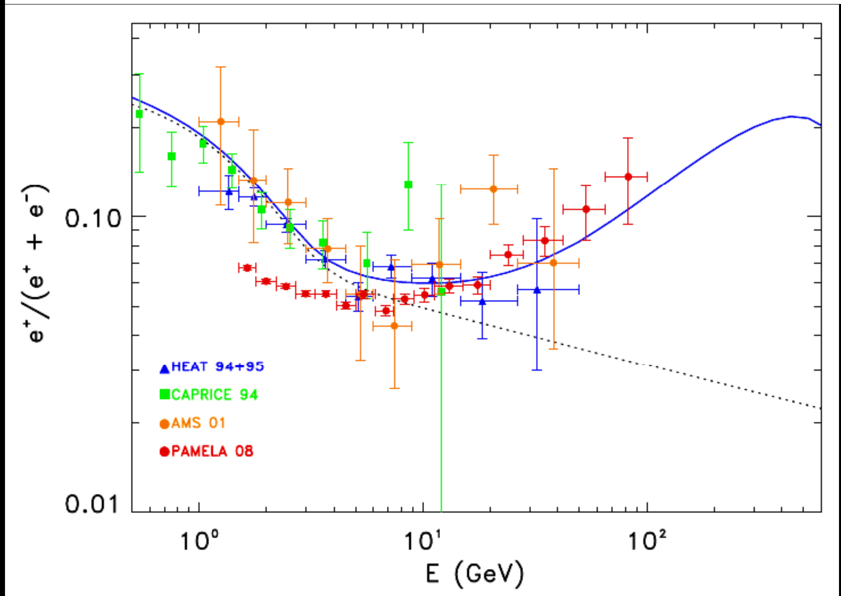


Dark Matter

We look for this possibility

Grasso, Profumo, Strong et al., 0905.0636





Example of fit to both **Fermi LAT** and **PAMELA** data with known (**ATNF** catalogue) nearby, mature pulsars, and with a single, nominal choice for the **e+/e- injection** parameters.

For the **PAMELA** data, two narby pulsars with the parameters,

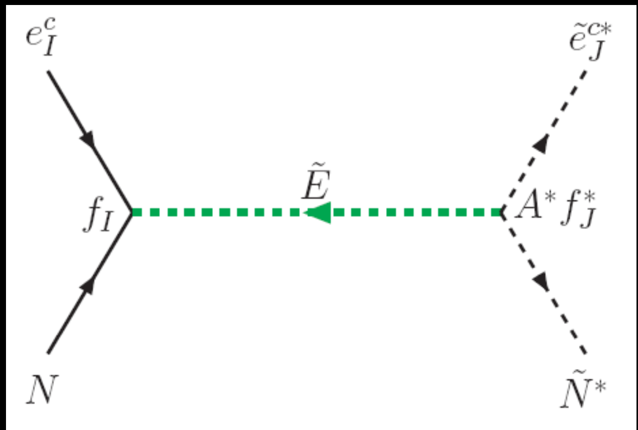
$$\Gamma = 1.7 \qquad E_{\rm cut} = 1100\ {\rm GeV}, \qquad \eta_{e\pm} = 40\% \qquad \Delta t = 6 \times 10^4\ {\rm yr}.$$

3. Decaying dark matter N

DDM must dominate the mass density: It is achieved by the heavy axino domination.

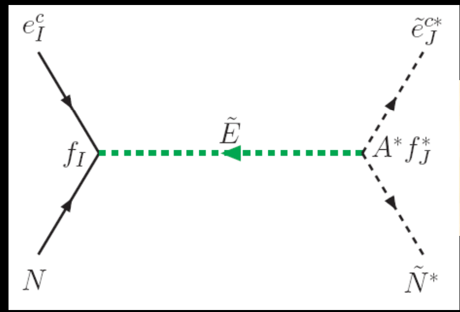
DDM N must decay with the lifetime of O(10^{27} s).

From the previous coupling, we study the following diagram:



$$\frac{A}{M_{IJ}^2}\tilde{N}^*\overline{e_J^c}N\tilde{e}_I^c + h.c.$$

There are other diagrams in addition to

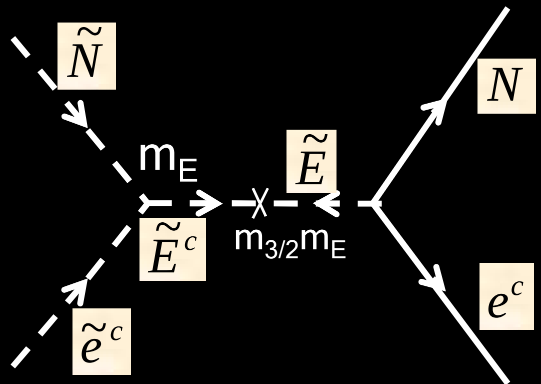


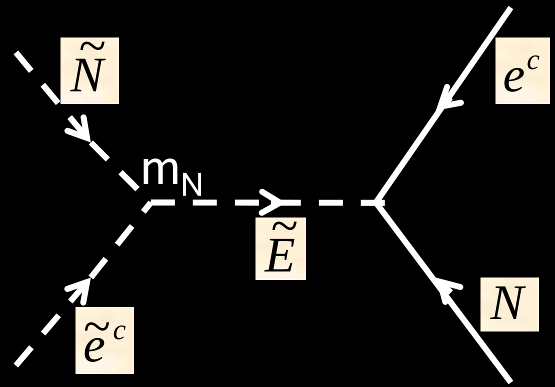
$$\frac{A}{M^2}$$

$$W = Ne^c E + \frac{m_N}{2} N^2 + m_E E E^c$$

$$\frac{\partial W}{\partial E} = Ne^c + m_E E^c : \qquad m_E \tilde{N} \tilde{e}^c \tilde{E}^{c*}$$

$$\frac{\partial W}{\partial N} = Ee^c + m_N N : \qquad m_N N \tilde{e}^{c*} \tilde{E}^*$$





$$\frac{m_E m_{3/2} m_E}{m_E^2 m_E^2} = \frac{m_{3/2}}{m_E^2}$$

$$\frac{m_N}{m_E^2}$$

Let us study the implication of the interaction: $\frac{A}{M_{IJ}^2}\tilde{N}^* \overline{e_J^c} N \tilde{e}_I^c + h.c.$

(1) Decay $N \to \tilde{N}^* \overline{e_J^c} e_I^c + cc \qquad for \quad m_N > m_{\tilde{N}}, V = 0$

$$\Gamma = \frac{A^2 m_N^3}{2^6 \pi^3 M^4} \int_{\sqrt{y}}^{\xi_{\max}} d\xi \frac{(1-x+y-2\xi)^2 (1-\xi)\sqrt{\xi^2 - y}}{(1+y-2\xi)^2}$$

$$x = m_{\tilde{N}}^2 / m_N^2, \; y = m_{\tilde{e}_J}^2 / m_N^2, \qquad \xi_{\max} = (1/2)(1-x+y)$$

(2) Decay $\tilde{N} \to N e_I^c \tilde{e}_J^* \qquad for \quad m_{\tilde{N}} > m_N, V = 0$

$$\Gamma = \frac{A^2 m_{\tilde{N}}^3}{2^6 \pi^3 M^4} \int_{\sqrt{\tilde{x}}}^{\eta_{\max}} d\eta \frac{(1+\tilde{x}-\tilde{y}-2\eta)^2 (\eta - \tilde{x})\sqrt{\eta^2 - \tilde{x}}}{(1+\tilde{x}-2\eta)^2}$$

$$\tilde{x} = m_N^2 / m_{\tilde{N}}^2, \; \tilde{y} = m_{\tilde{e}_J}^2 / m_{\tilde{N}}^2, \qquad \eta_{\max} = (1/2)(1+\tilde{x}-\tilde{y})$$

(3) Decay $N^c(=N) \to e_I^c + \tilde{e}_J^{c*} \quad for \quad m_{\tilde{N}} > m_N, V \neq 0$

$$\Gamma \cong \frac{V^2 A^2 m_N}{16\pi M^4}\left(1 - \frac{m_{\tilde{e}_J}^2}{m_N^2}\right)^2$$

For massless final states, the total decay rates are for m_χ=100 GeV

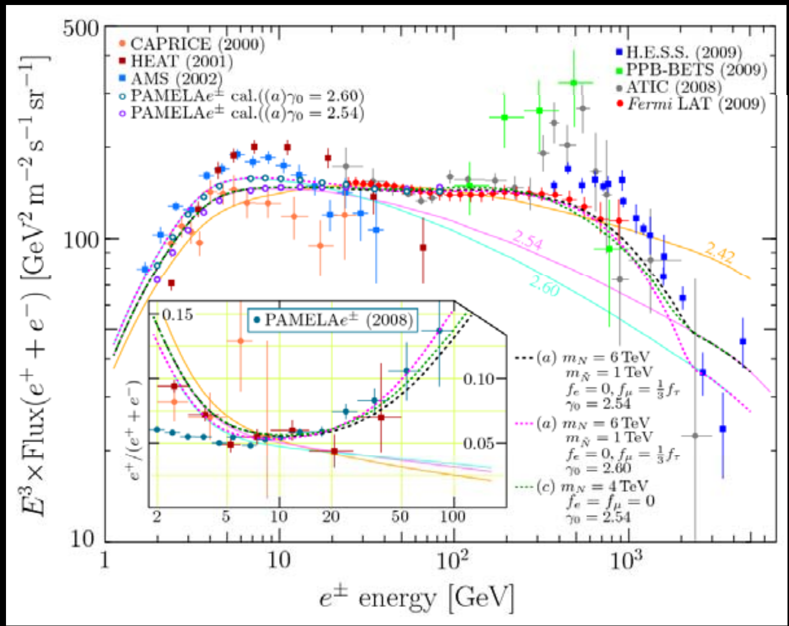
(1) $$\Gamma = \frac{A^2 m_N^3}{768\pi^3 M^4}, \qquad M \approx 2.8\times 10^{15}(m_N/TeV) \quad GeV$$

(2) $$\Gamma = \frac{A^2 m_N^3}{1536\pi^3 M^4}, \qquad M \approx 2.8\times 10^{15}(m_N/TeV) \quad GeV$$

(3) $$\Gamma = 3\times 10^{-23} s^{-1}\left(\frac{10^{15}GeV}{M}\right)^4\left(\frac{V}{100GeV}\right)^2\left(\frac{A}{10TeV}\right)^2\left(\frac{m_N}{TeV}\right),$$
$$M \approx 7.4\times 10^{15}(m_N V/TeV^2)^{1/2} GeV$$

All these mass scales, together with the axino decay case, fall in the GUT scale. But the scales we obtain are not necessarily the scale of the GUT gauge bosons.

4. Fermi LAT and PAMELA data



Injection spectrum γ_0 from supernovae may fit just the low energy or the high energy spectrum, but not both. PAMELA's positrons are hard to be fitted together with Fermi LAT.

Two possibilities:

(1) Astrophysical origin: pulsars

(2) Dark matter origin—Here we study this case.

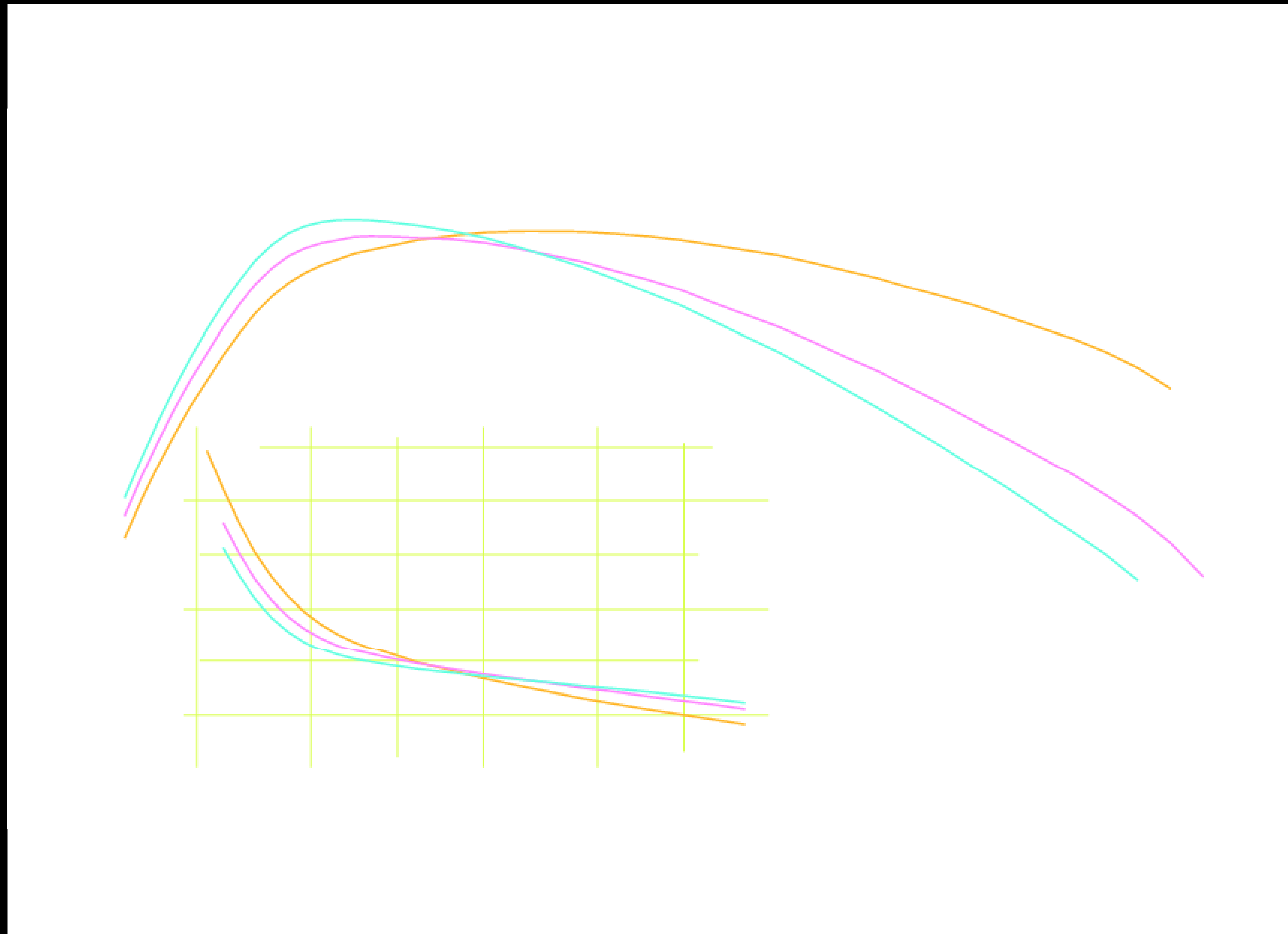
There have been numerous supernova explosions$\longrightarrow$
Injection of electrons and positrons in the galaxy $\longrightarrow$
Homogeneous background of $e^{\pm}$ $\longrightarrow$
Injection spectrum γ_0 from supernovae needed

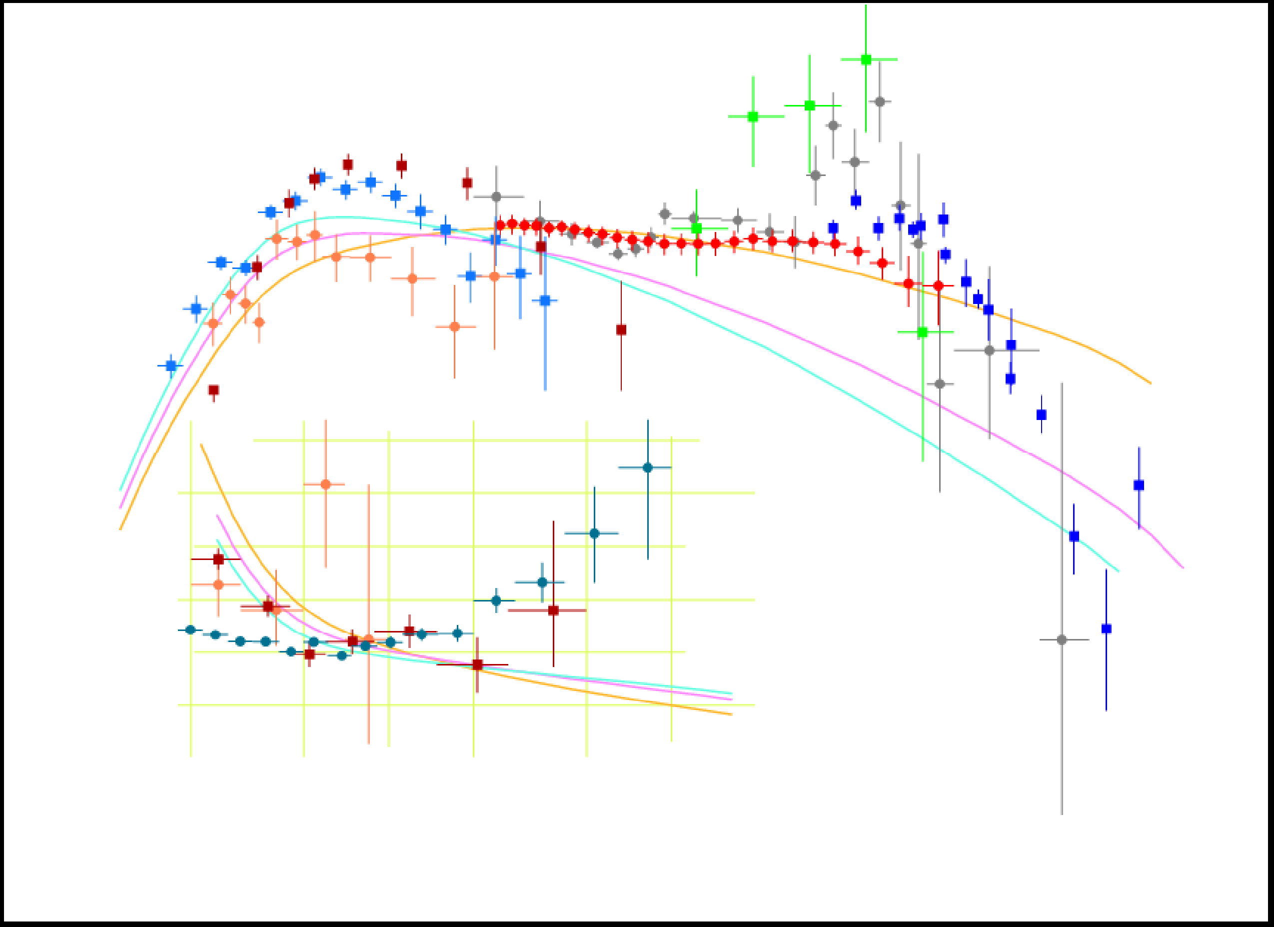
This background is coded in the GALPROP package.
Moskalenko-Strong, Adv. Space Res. 27, 767 (2001)
http://galprop.stanford.edu

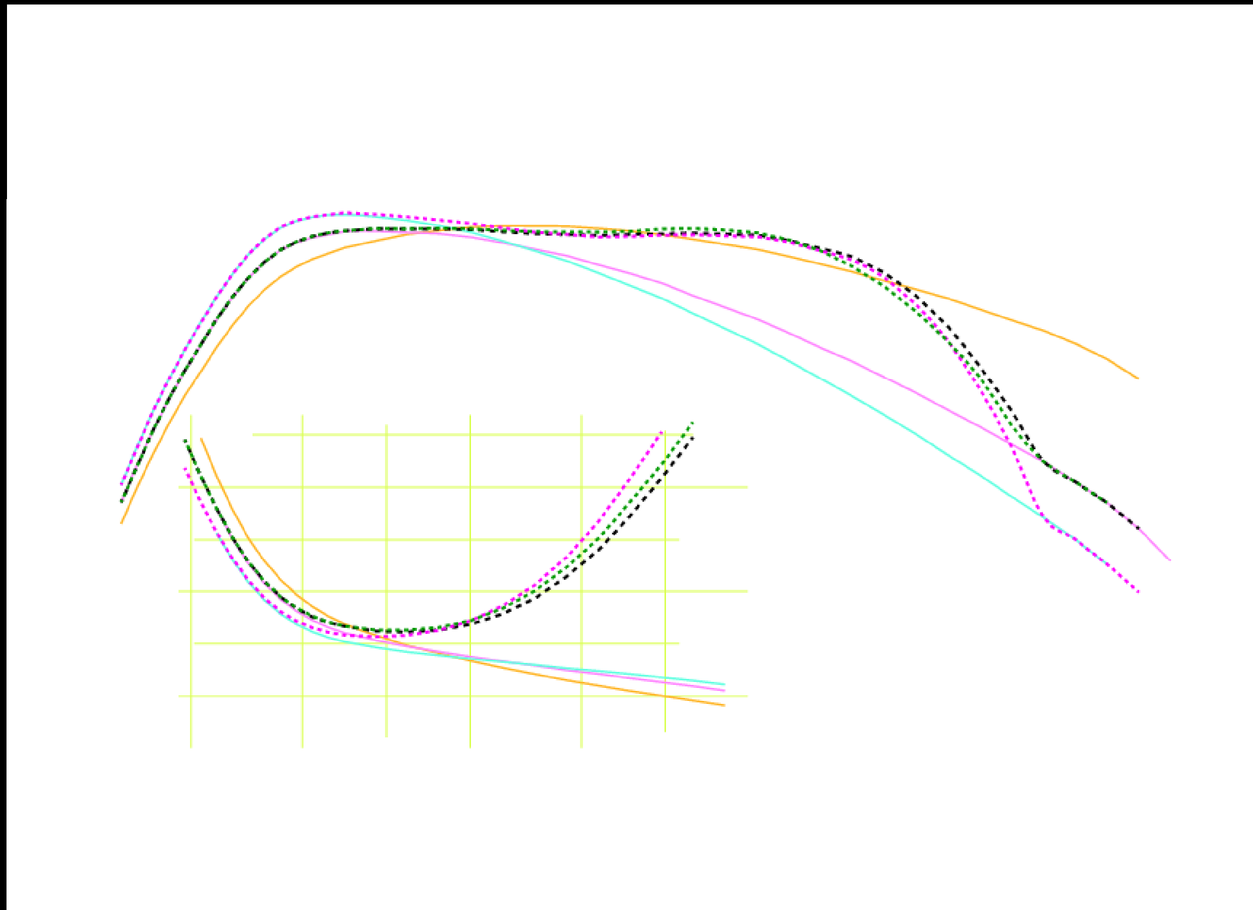
In principle, different SNs can have different injection spectra, but we study using the same injection spectrum γ_0.

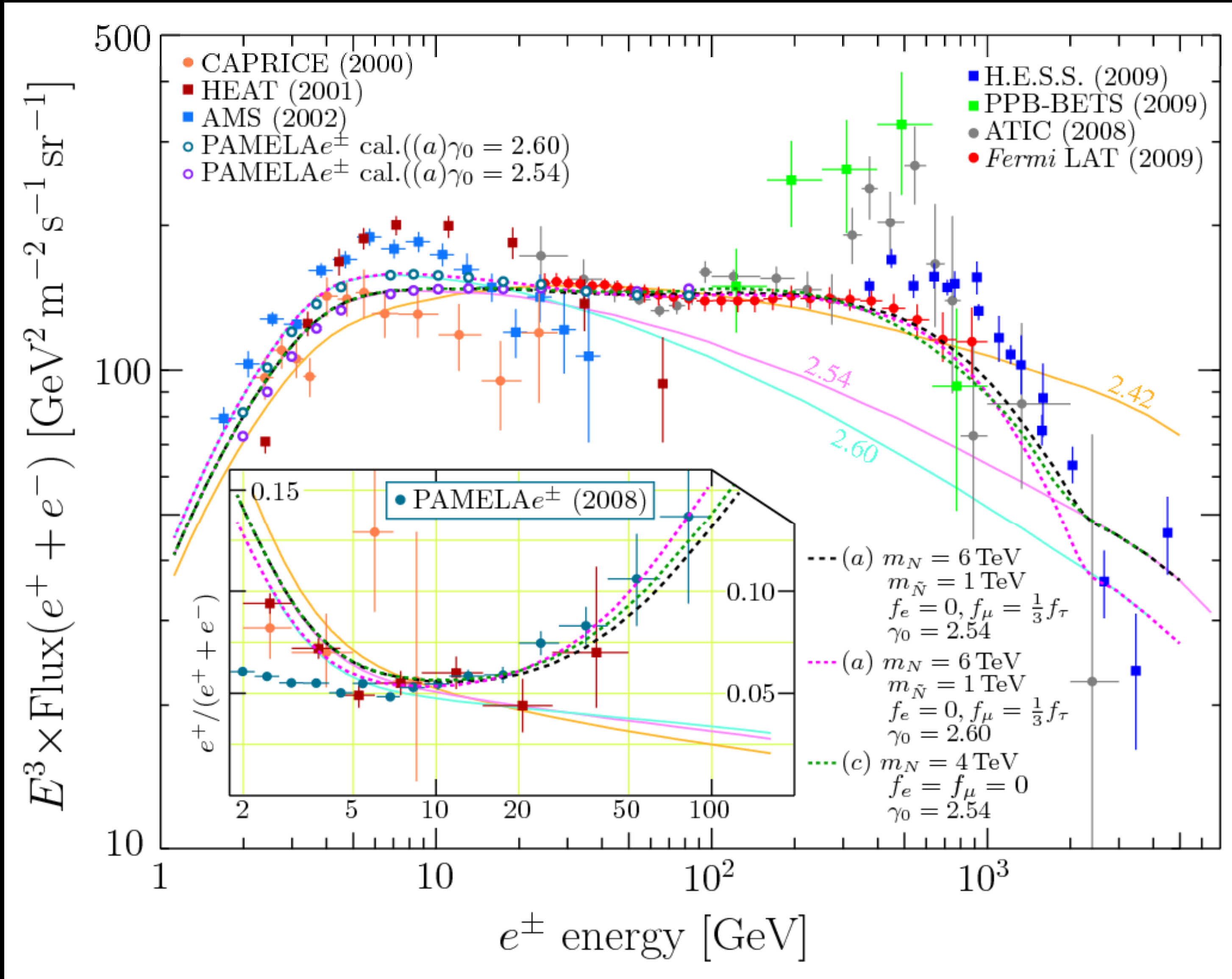
Then, we add $e^{\pm}$ obtained from the decay of N whose density given by the DM profiles of isothermal, NFW, Via Lactea II simulations. The decay of N produces $e^{\pm}$.

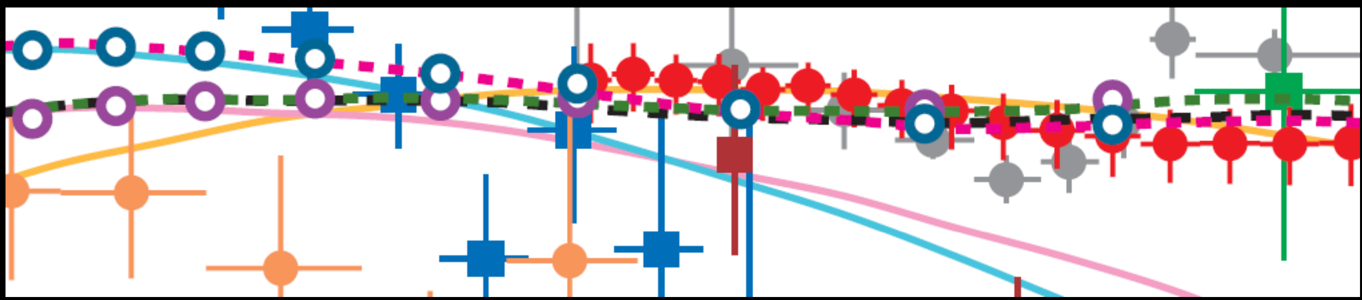
PYTHIA calculation of cascading down to $e^{\pm}$ is used.








CAPRICE (2000)
HEAT (2001)
AMS (2002)
PAMELA$e^{\pm}$ cal.((a)$\gamma_0 = 2.60$)
PAMELA$e^{\pm}$ cal.((a)$\gamma_0 = 2.54$)
H.E.S.S. (2009)
PPB-BETS (2009)
ATIC (2008)
Fermi LAT (2009)
PAMELA$e^{\pm}$ (2008)
$e^+/(e^+ + e^-)$
(a) $m_N = 6$ TeV $m_{\tilde N} = 1$ TeV $f_e = 0, f_\mu = \frac{1}{3} f_\tau$ $\gamma_0 = 2.54$
(a) $m_N = 6$ TeV $m_{\tilde N} = 1$ TeV $f_e = 0, f_\mu = \frac{1}{3} f_\tau$ $\gamma_0 = 2.60$
(c) $m_N = 4$ TeV $f_e = f_\mu = 0$ $\gamma_0 = 2.54$
2.54
2.60
2.42
$E^3 \times \mathrm{Flux}(e^+ + e^-)$ [GeV^2 m^{-2} s^{-1} sr^{-1}]
$e^{\pm}$ energy [GeV]



Comments:

1. Astrophysical sources may explain the PAMELA $e^{\pm}$.
   The pulsar parameters can be determined in principle.
   The pulsar point-like sources can show directions since the needed pulsars must be nearby.
2. DDM sources of $e^{\pm}$ is homogeneous.

$\longrightarrow$ Measurement of the directionality of high energy gamma rays and $e^{\pm}$ can distinguish the point-like and homogeneous sources, and will give a hint for or against the heavy DDM.

5. Conclusion

We studied the possibility of DDM in view of the PAMELA and Fermi LAT data.

1. We introduced the DDM minimally, above the MSSM scales. N is a two-component Majorana spinor.
2. We discussed the suppression factor M^2. It must fall in the GUT scale region.
3. The GUT scale is provided by the heavy E and E^c and the coupling, Ne E^c. This simplest extension is possible in the flipped SU(5).
4. The heavy axino decay can produce the needed DMs.
5. Indeed, it is possible to fit both the PAMELA and Fermi LAT data with the DDM N with a few TeV mass.

END