Do astrophysical data disfavour the minimal supersymmetric standard model?

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If the minimal supersymmetric standard model (MSSM) is the only new physics around the TeV-scale, it has to account for the entire dark matter relic density, or else it will cease to be ‘minimal’.

We use this expectation to obtain the best quantitative explanation of the galactic centre γ-ray excess in GC. This becomes an important input in the analysis of γ-ray data from the galactic centre (GC) [1,3] and other celestial objects [2]. Coupled with laboratory constraints and those from direct DM search [5,9], it makes the MSSM an unfavourable fit. We show this with a comparison with the analysis of data related to the Higgs boson, where fits of indirect data preceded the direct search constraints [2,9].

Accelerator data, especially those from the Large Hadron Collider (LHC), have pushed the lower mass limits on most strongly interacting superparticles in the MSSM to about 2 TeV [9,10]. On the other hand, if the excess in GC γ-rays (principally in the range 1–10 GeV [1,2]) have to arise from DM annihilation, then the nature of the spectrum in the energy band ≈1–10 GeV suggests a relatively light (100 GeV) χ01. One of course has to satisfy all accelerator limits constraints from direct DM search [5,9], other γ-ray data from dwarf galaxies like Reticulum II [4,11,12], neighbouring galaxies such as M31 [13], and upper limits on radio synchrotron signals from galaxies and clusters [14], supposedly arising from DM annihilation.

The Planck data restrict us to Ωh2 = 0.1199 ± 0.0022 at the 1σ level [15], and any viable region in the MSSM parameter space should obey this limit. However, theoretical uncertainties, mostly due to higher order corrections, exist in the computation of the DM annihilation rate, as a result of which calculated values of the relic density somewhat beyond the above band is also given the benefit of doubt. Thus regions where the relic density estimate yields Ωh2 in the range 0.1199 ± 0.012 are taken to be consistent [16–18].

In most recent studies, however, the lower bound on Ωh2 is not taken as seriously as the upper one [19–23], and regions that predict under-abundance are taken as allowed. But that requires additional sources of DM particles, and thus stepping beyond the MSSM as the new physics scenario at low energy. The present work aims to analyse observed data in terms of MSSM in the strict sense.

Regions in the MSSM parameter space have emerged as good fits for spectra (Case 1) where all sfermions and the gluino are heavy (above 2 TeV) [19,22]. Another possibility (Case 2) [19,23] is to have one light stop mass (the ratio of the vacuum expectation values (vev) of the two Higgs doublets) [24,25], are the fittest, though with differing statistical significance, when one demands a minimum neutralino (χ01) relic density. The parameters values scanned over in the two cases are summarised in Table I.

| Case no | tan β | M1, M2 (GeV) | μ (GeV) | mA (GeV) |
|---------|-------|--------------|---------|----------|
| 1       | 2     | −1000, 1500  | [−1000, 2000] | [450, 4000] |
| 2       | 50    | −1000, 1500  | [−1000, 2000] | [850, 4000] |

TABLE I: The ranges over which the MSSM parameters have been varied in the χ2-fit for the two benchmark cases which yield the best fits to the γ-ray data. All sfermion masses are above 2 TeV, excepting the lighter stop in case 2 whose range is mentioned in the text. The parameter Am is adjusted together with ml to fix mh in the range 122–128 GeV and to retain a proper electroweak vacuum. All masses are in GeV.
The $\gamma$-ray flux from the GC is obtained as [2]:

$$\phi(E) = \frac{\langle \sigma v \rangle}{8\pi m_{\chi_1^0}^2} \frac{dN}{dE}(E) \int_{l.o.s.} \rho^2(r(s, \theta)) \, ds \, d\Omega \quad (1)$$

where $\frac{dN}{dE}$ is the photon energy distribution, and $\langle \sigma v \rangle$ is the velocity averaged total annihilation cross-section of the neutralino DM times the relative velocity of the annihilating pair. It is mostly driven by the $W^+W^-$ and $b\bar{b}$ channels in Case 1, whereas the $t\bar{t}$ channel has an important role in Case 2. The integration is over the line-of-sight variable, $l.o.s.$ ($ds$) and the solid angle ($d\Omega$) subtended at the observation point. $\rho(r)$ is the DM profile in the GC, and is related to the so-called J-factor by

$$J(\theta) = \int_{l.o.s.} \rho^2(r(s, \theta)) \, ds$$

so that the flux per unit solid angle is given by

$$\frac{d\phi}{d\Omega} = \frac{\langle \sigma v \rangle}{8\pi m_{\chi_1^0}^2} \frac{dN}{dE}(E)J_{av} \quad (3)$$

with $J_{av} = \int J(\theta) d\Omega / \int d\Omega$. Here we have used the $2\sigma$ maximum value of $J_{av}$ according to the Navarro-Frenk-White (NFW) profile [21]. This yields the most optimistic fit of the GC $\gamma$-ray excess in terms of the MSSM.

We perform $\chi^2$-fits of the GC spectrum in the range $0.5 - 200$ GeV [23], assuming that all of the excess arises from annihilation of dark matter particles. We have used the package micOMEGAs 4.3.1 for $\langle \sigma v \rangle$ calculation and [23] for obtaining the GC excess data and errors. Scanning is done over $M_1$ and $M_2$ which are the U(1) and SU(2) gaugino masses, the neutral pseudoscalar mass ($m_A$) and the Higgsino mass parameter $\mu$. The remaining superparticle masses are above 2 TeV in Case 1. For Case 2, an optimally light stop mass eigenstate at 260 – 300 GeV is kept, which facilitates the $t\bar{t}$ annihilation channel. Consistency with the data from the Large Electron Positron (LEP) [34] and LHC [9, 24, 25, 27, 28], including the 125 GeV scalar [31], and all other phenomenological constraints are ensured. The most optimistic value of $\tan \beta$, the ratio of the two Higgs doublet vev’s, has been used in each case. Parameters such as the trilinear SUSY-breaking parameters $A_f$, (where $f$ stands for fermions) are adjusted to reproduce a 125 GeV neutral scalar.

The DM annihilation rate explaining the GC $\gamma$-ray excess must also be consistent with the flux from other $\gamma$-ray emitters such as dwarf galaxies. While only upper limits exist for most of these galaxies [34], some excess was claimed for Reticulum II some time ago (in the Pass 7 data) [1], to be replaced by upper limits again (the Pass 8 data) [16, 17]. It has been found [26] that the MSSM fits to the GC excess do not change appreciably whether one is using the Pass 7 excess or the Pass 8 upper limits. The results reported below are consistent with either.

Figure 1 contains the marginalised $2\sigma$ contours in various pairs of parameters, fundamental as well as derived, obtained via $\chi^2$-minimisation, using the Markov Chain Monte Carlo (MCMC) technique [35]. They include two kinds of fits: (a) Complete fits (CF), or fits where all constraints including those from direct DM search is used to restrict the parameter space used for the scan, and (b) Fit without direct search (FWDS), where $\chi^2$-minimisation is not biased by the direct search constraints which are applied only later.

It is obvious from Figure 1 that, for Case 1, the CF $2\sigma$ region falls outside the corresponding region for FWDS. In other words, the $2\sigma$ region in a completely unbiased analysis of the data gets disallowed when the latest direct search constraint [5] is imposed. This because the DM neutralino for such a spectrum has an appreciable Higgsino component in order to facilitate annihilation. This, however, faces severe restriction from direct search data, and the $2\sigma$ regions in FWDS does not survive this tug-of-war. The best fit points, barely surviving phenomenological constraints, are close to the edge of the $2\sigma$ region.

For Case 2, the direct search constraint is found to be much less restrictive. The $t\bar{t}$ annihilation channel is open here, requiring less participation of the Higgsino component in $\chi^0_1$ because of a light stop. Such a spectrum is less affected by the direct search limits. Thus there is a good overlap between the $2\sigma$ regions of FWDS and CF. However, the $t\bar{t}$ channel shifts the peak of the resulting $\gamma$-ray distribution to energies higher than what is observed. This increases the contribution to $\chi^2$ from regions of lower energies [1, 2]. Any effort to get a better fit by going to parameter regions that scale up the distribution fails, because (a) such regions require a lighter $\chi^0_1$ than what is consistent with the light stop [9, 24, 25], and (b) the annihilation rate becomes so high that the relic density drops below its lowest admissible value.

All of the above features, especially the effect of direct search limits, are seen in Figure 2. The $2\sigma$ region in Case 1 for FWDS is thus disallowed whereas that for Case 2 are relatively unaffected. Figure 1 shows the result of imposing a lower bound on the MSSM contribution to the relic density. One finds on comparing the lowest row in Figure 1 with the topmost one that this condition plays a role even before doing FWDS. The disallowed regions correspond to low $m_{\chi_1^0}$ and high $\langle \sigma v \rangle$. The whole range of the data gets disallowed. Figure 1 shows the result of imposing a lower bound on the MSSM contribution to the relic density. One finds on comparing the lowest row in Figure 1 with the topmost one that this condition plays a role even before doing FWDS. The disallowed regions correspond to low $m_{\chi_1^0}$ and high $\langle \sigma v \rangle$.
FIG. 1: $1\sigma$ (inner region) and $2\sigma$ (outer) joint constraints on $M_1 - M_2$ (left) and $m_{\chi^0} - \langle \sigma v \rangle$ (right) along with their best-fit values (solid gray lines) for various scenarios mentioned in the text. From top to bottom - 1st panel: 1(CF); 2nd panel: 1(FWDS); 3rd panel: 2(CF); 4th panel: 2(FWDS); and 5th panel: 1(FWDS without relic lower limit).
On the whole, while Case 1 suffers from the lower limit on the relic density as well as the direct search constraint, Case 2, less affected by both, has an intrinsic disadvantage due to the shape of the energy distribution of GC γ-rays coming from the t⁻t channel.

| Case no | $\chi^2_{\text{min}}$/DOF | p-value |
|---------|----------------|---------|
| 1 (FWDS without relic lower limit) | 44.2/29 | $4 \times 10^{-2}$ |
| 1 (FWDS) | 45.1/29 | $3 \times 10^{-2}$ |
| 1 (CF) | 56.2/29 | $2 \times 10^{-3}$ |
| 2 (FWDS) | 66.1/29 | $1 \times 10^{-4}$ |
| 2 (CF) | 66.2/29 | $1 \times 10^{-4}$ |

TABLE II: Comparison of the quality of fitting between different types of analysis for Cases 1 and 2. DOF stands for degrees of freedom whose value is 29 when the Reticulum II excess bins are counted.

We have already said that our benchmarks for Cases 1 and 2 represent rather faithfully the MSSM spectra that yield the best possible fits. The other important candidate scenario is one with a light stau close (within 4%) to $\tilde{\chi}_1^0$, where co-annihilation causes freeze-out of the latter. It however leads to a fit worse than the two cases reported above [26]. This is because the optimum region for this in the MSSM parameter space corresponds to a somewhat heavier $\tilde{\chi}_1^0-\tilde{\tau}_1$ pair, which again shifts the GC γ-ray distribution peak to unacceptably high values. The situation with both the $\tilde{\tau}_1$ and the $\tilde{t}_1$ light is also worse off for similar reasons.

Finally, we contrast this with a comparable situation in the context of Higgs boson search. Before the LHC data came up with anything decisive, there was a lower bound on the Higgs boson mass of about 114 GeV from LEP [7, 8]. Similarly, the Tevatron data strongly disfavoured the mass range 158 GeV < $m_h$ < 172 GeV [7]. On the other hand, the best fit value of $m_h$ from indirect data including those from precision electroweak measurements was less than 100 GeV, ruled out by direct searches. However, the 2σ region in $\chi^2$ extended up to $m_h \approx 160 - 170$ GeV. Though the LEP and Tevatron limits removed regions with the 2σ range of such a ‘standard fit’, it left out the value 125 GeV at the edge of the 1σ band, and that is where the particle was finally discovered at the LHC. When instead a ‘complete fit’ was performed in July, 2012, assigning large values to $\chi^2$ in the bands disallowed (disfavoured) by LEP (Tevatron), and duly weighing in the LHC data analysed till then, the best fit point was close to 120 GeV. Also, $\chi^2_{\text{min}}$/DOF converged from 16.6/13 in the ‘standard fit’ to 17.8/14 in the ‘complete fit’ [7, 8]. The p-value, too, increased convergently from 0.21 to 0.23. This showed that the successive imposition of constraints was improving the search, taking one closer to actual discovery. Thus it became clear that the Glashow-Salam-Weinberg theory is a good fit for Higgs-related data. In contrast, the above analysis on GC γ-ray data, whose results are adumbrated in Table II and Figures 1 and 2, indicate that the MSSM is not a good fit the available astrophysical observations. The requirement that the entire relic density must be explained by the MSSM (without which it is not strictly ‘minimal’), as also direct search constraints, has a role in this conclusion. This suggestion loses ground only if (a) the γ-ray excess from GC is due to some yet unknown astrophysical effect, or (b) a large body evidence from alternative astronomical observations render the GC excess insignificant.

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