

## Light dark matter in NMSSM and implications for Higgs phenomenology (postprint)

**Authors:** Cao,J, Hikasa,K, Wang,W, Yang,JM, Hikasa,K, Wang,W, Yang,JM

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### Full Text

## Light Dark Matter in NMSSM and Implications for Higgs Phenomenology

**Junjie Cao<sup>1</sup>, Ken-ichi Hikasa<sup>2</sup>, Wenyu Wang<sup>3</sup>, Jin Min Yang**

<sup>1</sup>Institute of Theoretical Physics, College of Applied Science, Beijing University of Technology, Beijing 100124, China

### Abstract

For the experimental search of neutralino dark matter, it is important to know its allowed mass and scattering cross section with nucleons. In order to determine how light a neutralino dark matter can be in low-energy supersymmetry, we scan the parameter space of the NMSSM (next-to-minimal supersymmetric model), assuming all relevant soft mass parameters to be below the TeV scale. We find that in the parameter space allowed by current experiments, the neutralino dark matter can be as light as a few GeV and its spin-independent scattering rate off nucleons can reach the sensitivity of XENON100 and CoGeNT. Consequently, a sizable portion of parameter space is excluded by current XENON100 and CoGeNT data (the plausible CoGeNT dark matter signal can also be explained). Future XENON100 data with 6000 kg-days exposure will further explore (but cannot completely cover) the remaining parameter space. Moreover, we find that in such a light dark matter scenario, a light CP-even or

CP-odd Higgs boson must be present to satisfy the measured dark matter relic density. As a result, the SM-like Higgs boson  $h_{\text{SM}}$  may decay predominantly into a pair of light Higgs bosons or a pair of neutralinos, so that conventional decays like  $\gamma\gamma$  are strongly suppressed.

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## Introduction

Experiments for the underground direct detection of cold dark matter  $\tilde{\chi}$  have recently made significant progress. While the null observation of  $\tilde{\chi}$  in CDMS and XENON100 experiments has set rather tight upper limits on the spin-independent (SI) cross section of  $\tilde{\chi}$ -nucleon scattering [?, ?], the CoGeNT experiment [?] reported an excess that cannot be explained by any known background sources but appears consistent with the signal of a light  $\tilde{\chi}$  with mass around 10 GeV and scattering rate around  $10^{-40}$  cm<sup>2</sup>. Intriguingly, this range of mass and scattering rate is compatible with a dark matter explanation for both the DAMA/LIBRA data and preliminary CRESST data [?]. So far, due to the inconsistency between the CoGeNT result and the CDMS or XENON results, it is premature to draw any definite conclusion about the existence or nonexistence of a light  $\tilde{\chi}$ . However, considering the substantial experimental effort devoted to searching for a light  $\tilde{\chi}$ , it is theoretically important to examine possible new physics predictions for a light  $\tilde{\chi}$  and investigate its related phenomenology (such as Higgs boson searches) at the LHC. In this work we focus on low-energy supersymmetry, where the lightest neutralino  $\tilde{\chi}_1^0$  serves as the dark matter candidate, and perform an intensive study of the light  $\tilde{\chi}_1^0$  scenario.

The most popular model for low-energy supersymmetry is the minimal supersymmetric standard model (MSSM). In this model, our scan reveals that the neutralino  $\tilde{\chi}_1^0$  must be heavier than about 28 GeV. The main reason for the absence of a lighter  $\tilde{\chi}_1^0$  is that its dominant annihilation channel is  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow b\bar{b}$  through s-channel exchange of the pseudoscalar Higgs boson ( $A$ ), and the measured dark matter relic density requires  $m_A \sim (90 - 100)$  GeV and  $\tan\beta \gtrsim 50$ , which conflicts with constraints from LEP and B-physics experiments [?, ?, ?]. We emphasize that for this region, the effects of the charged Higgs on  $B \rightarrow X_s\gamma$  are unacceptably large, and even with fine-tuning of contributions from stop/chargino diagrams, such large effects cannot be reduced to an acceptable level. Our MSSM results agree with [?] but differ from [?], where the considered constraints (such as invisible Z-decay and productions of neutralinos or Higgs bosons at LEP II) are weaker than in our study. Our conclusion also differs from [?] because we used more accurate formulas for calculating the process  $B \rightarrow X_s\gamma$  [?]. Since neutralino dark matter in the MSSM cannot be as light as suggested by the CoGeNT data (albeit not corroborated by XENON100 or CDMS), we do not present our MSSM results in detail.

Another popular model for low-energy supersymmetry is the next-to-minimal supersymmetric standard model (NMSSM) [?], which extends the MSSM by

adding one gauge singlet chiral superfield  $\hat{S}$ . This model is well-motivated because it provides solutions to the  $\mu$ -problem and the little hierarchy problem that afflict the MSSM. For this model we perform an intensive scan over its parameter space, assuming all relevant soft mass parameters below the TeV scale and considering various experimental constraints. We find that in this model the neutralino dark matter can be as light as a few GeV and its spin-independent scattering cross section with nucleons can reach the sensitivity of CoGeNT and XENON100.

We emphasize that our study is not restricted to explaining any particular experimental results like the CoGeNT or DAMA/LIBRA data. Instead, we aim to investigate the characteristics of a light  $\tilde{\chi}_1^0$ , such as its lower mass bound and scattering rate off nucleons, and examine the related Higgs phenomenology at the LHC.

### The NMSSM

We begin our analysis by recapitulating some basics of the NMSSM. Its superpotential and associated soft-breaking terms in the Higgs sector are given by [?]:

$$W = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3,$$

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + (\lambda A_\lambda H_u H_d S + \text{h.c.}) + \left( \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.} \right),$$

where  $H_d$ ,  $H_u$ , and  $S$  denote the scalar components of the superfields  $\hat{H}_d$ ,  $\hat{H}_u$ , and  $\hat{S}$ , respectively.

After applying the minimization conditions of the Higgs potential, this sector is described by three dimensionless parameters ( $\tan \beta$ ,  $\lambda$ ,  $\kappa$ ) and three dimensional parameters ( $\mu$ ,  $A_\lambda$ ,  $A_\kappa$ ). Due to the imposed  $Z_3$  symmetry, the superpotential does not contain dimensional parameters, and thus all dimensional parameters are generated by soft-breaking masses which, as required by electroweak symmetry breaking, should naturally be below the TeV scale [?]. Other free parameters are the same as in the MSSM: the soft masses for sfermions and gauginos, as well as the trilinear soft couplings.

Due to the presence of  $\hat{S}$ , the NMSSM predicts five neutralinos, three CP-even Higgs bosons ( $h_{1,2,3}$ ), and two CP-odd Higgs bosons ( $a_{1,2}$ ) [?]. In general, the neutralino mass eigenstates are mixtures of the MSSM neutralino fields and the singlino field (the fermion component of  $\hat{S}$ ); the CP-even (odd) Higgs mass eigenstates are similarly mixtures of the CP-even (odd) MSSM Higgs fields and the real (imaginary) part of the scalar component of  $\hat{S}$ . An important feature of the NMSSM is that one of the CP-even (odd) Higgs bosons may be singlet-like

and thus can be very light [?]. This feature is particularly useful for the light  $\tilde{\chi}_1^0$  scenario since it opens up new important annihilation channels for  $\tilde{\chi}_1^0$ , i.e., either into a pair of  $h_1$  (or  $a_1$ ) or into a pair of fermions via s-channel exchange of  $h_1$  (or  $a_1$ ) [?, ?, ?]. For the former case,  $m_{\tilde{\chi}_1^0}$  must be heavier than  $m_{h_1}$  ( $m_{a_1}$ ); while for the latter case, due to the very weak couplings of  $h_1$  ( $a_1$ ) with  $\tilde{\chi}_1^0$  and with SM fermions, resonance enhancement (i.e.,  $m_{h_1}$  or  $m_{a_1}$  must be close to  $2m_{\tilde{\chi}_1^0}$ ) is needed to accelerate the annihilation. Thus a light  $\tilde{\chi}_1^0$  should necessarily be accompanied by a light  $h_1$  or  $a_1$  to provide the required dark matter relic density.

Now we discuss how to obtain a light  $h_1$  or  $a_1$  in the NMSSM. A light  $a_1$  can be easily obtained when the theory approaches the  $U(1)_R$  or  $U(1)_{PQ}$  symmetry limit, which can be realized by setting the product  $\kappa A_\kappa$  to be negatively small [?]. In contrast, a light  $h_1$  cannot be obtained so easily, but as shown below, it can still be achieved through somewhat subtle cancellation by tuning the value of  $A_\kappa$ . We note that for any theory with multiple Higgs fields, the existence of a massless Higgs boson implies the vanishing of the determinant of its squared mass matrix and vice versa. For the NMSSM, at tree level the parameter  $A_\kappa$  only enters the mass term of the singlet Higgs bosons, and thus the determinant ( $\text{Det } \mathcal{M}^2$ ) of the mass matrix for the CP-even Higgs bosons depends linearly on  $A_\kappa$  [?]. When other relevant parameters are fixed, one can obtain a light  $h_1$  by varying  $A_\kappa$  around the value  $\tilde{A}_\kappa$  which is the solution to the equation  $\text{Det } \mathcal{M}^2 = 0$ . In practice, one must include important radiative corrections to the Higgs mass matrix, which complicate the dependence on  $A_\kappa$ . However, we verified that the linear dependence is approximately maintained by choosing other relevant parameters at the SUSY scale, and one can solve the equation iteratively to obtain the solution  $\tilde{A}_\kappa$ .

## Numerical Scan and Results

To study the light  $\tilde{\chi}_1^0$  scenario in the NMSSM, we randomly scan over parameters in the neutralino and Higgs sectors by requiring  $m_{\tilde{\chi}_1^0} \leq 100$  GeV. The ranges of  $\lambda$ ,  $\kappa$ , and  $\tan\beta$  are  $0 < \lambda, \kappa \leq 0.7$  and  $1 \leq \tan\beta \leq 60$ , determined by perturbativity of the theory [?]. The ranges of  $\mu$  and  $A_\lambda$  are  $0 \leq \mu, A_\lambda, M_2 \leq 1$  TeV, suggested by electroweak symmetry breaking, and the narrow range of bino mass  $M_1$  is chosen to facilitate a light  $\tilde{\chi}_1^0$ . Since the gluino mass and soft parameters in the squark sector affect the properties of  $\tilde{\chi}_1^0$  little, we set all of them to 1 TeV. As for the soft slepton parameters, since they influence the muon anomalous magnetic moment  $a_\mu$  which in turn can constrain the important parameter  $\tan\beta$ , we assign them a common scale  $m_{\tilde{l}}$  and vary it below the TeV scale.

Since a light  $\tilde{\chi}_1^0$  is very likely to be accompanied by a light  $h_1$  or  $a_1$ , we perform two independent scans aiming at a light  $h_1$  and a light  $a_1$  respectively. For the light  $h_1$  case, we vary  $A_\kappa$  around  $\tilde{A}_\kappa$  obtained by solving the equation  $\text{Det } \mathcal{M}^2 = 0$ ; while for the light  $a_1$  case, we simply vary  $A_\kappa$  in the range  $[-200, 0]$

GeV.

In our scans, we require all dimensionful parameters in the Higgs potential like  $m_{H_u}$  and  $m_{H_d}$  to be below the TeV scale and keep parameter points which yield  $m_{\tilde{\chi}_1^0} \leq 20$  GeV. The constraints considered in our scan are the following [?]:

1. We require  $\tilde{\chi}_1^0$  to account for the dark matter relic density  $0.105 < \Omega h^2 < 0.119$ ;
2. We require the NMSSM contribution to explain the deviation of the muon  $a_\mu$ , i.e.,  $\Delta a_\mu^{\text{exp}} = (25.5 \pm 8.0) \times 10^{-10}$ , at the  $2\sigma$  level;
3. The LEP-I bound on invisible Z-decay,  $\Gamma(Z \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0) < 1.76$  MeV, and the LEP-II upper bound on  $\sigma(e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ , which is  $5 \times 10^{-2}$  pb for  $i > 1$ , as well as lower mass bounds on sparticles from direct searches at LEP and the Tevatron;
4. Constraints from direct searches for Higgs bosons at LEP-II, including decay modes  $h \rightarrow h_1 h_1$ ,  $a_1 a_1$ , which limit all possible production channels for Higgs bosons;
5. Constraints from B-physics observables such as  $B \rightarrow X_s \gamma$ ,  $B_s \rightarrow \mu^+ \mu^-$ ,  $B_d \rightarrow X_s \mu^+ \mu^-$ ,  $B^+ \rightarrow \tau^+ \nu$ ,  $B \rightarrow X_s \gamma a_1$ ,  $a_1$ - $\eta_b$  mixing, and mass differences  $\Delta M_d$  and  $\Delta M_s$ ;
6. Constraints from precision electroweak observables such as  $\rho_{\text{lept}}$ ,  $\sin^2 \theta_{\text{lept}}^{\text{eff}}$ ,  $m_W$ , and  $R_b$ ;
7. Constraints from the decay  $\Upsilon(nS) \rightarrow \gamma h_1$  (with  $h_1 \rightarrow \pi^+ \pi^-$ ,  $K^+ K^-$ ,  $\mu^+ \mu^-$ ),  $B_d \rightarrow X_s \mu^+ \mu^- \gamma h_1$ , and Tevatron searches for a light Higgs boson via  $4\mu$  and  $2\mu 2\tau$  signals [?].

Constraints (1-5) have been encoded in the package NMSSMTools [?]. We use this package in our calculations and extend it by adding constraints (6, 7). As pointed out in [?], constraint (7) is important for a light Higgs boson.

In Fig. 1 [Figure 1: see original paper] we display the surviving parameter samples, simultaneously projected on the  $\sigma_{\text{SI}}-m_\chi$  plane in the left frame and the  $\sigma_{\text{SI}}-m_{h_1}$  or  $\sigma_{\text{SI}}-m_{a_1}$  plane in the right frame. In our calculation we use the formula in [?] for the scattering rate and choose  $f_{T_u}^{(p)} = 0.019$ ,  $f_{T_d}^{(p)} = 0.041$ ,  $f_{T_s}^{(p)} = 0.020$ ,  $f_{T_u}^{(n)} = 0.023$ ,  $f_{T_d}^{(n)} = 0.034$ ,  $f_{T_s}^{(n)} = 0.023$ . Motivated by recent lattice simulations [?], we take a very small value of  $f_{T_s}$  and consequently our estimation of the rate is rather conservative.

The left frame of Fig. 1 clearly shows that in the NMSSM the neutralino dark matter can be as light as several GeV, while the right frame shows that such a light neutralino is accompanied by either a light  $h_1$  or a light  $a_1$ . The surviving samples are therefore classified into two sets, characterized respectively by a light  $h_1$  and a light  $a_1$ . In both the light- $h_1$  case and the light- $a_1$  case, the surviving samples give a bino-dominant  $\tilde{\chi}_1^0$  and correspondingly a small  $M_1$  ( $< 30$  GeV). The allowed regions for other parameters are listed in Table I. We see that the value of  $\mu$  is not so large (below 300 GeV in the light- $h_1$  case and 350 GeV in the light- $a_1$  case) because a low  $\mu$  can enhance the coupling of  $\tilde{\chi}_1^0$

to  $h_1$  and  $a_1$  to obtain the correct relic density. We also see a moderately loose bound on  $m_{a_1}$  (we checked that among the surviving samples about 2% have  $m_{a_1} \geq 60$  GeV). This is due to a possibly large  $\tan\beta$ , which can enhance the couplings of  $a_1$  to SM fermions so that  $m_{a_1}$  may deviate from  $2m_{\tilde{\chi}_1^0}$  significantly. In the light- $h_1$  case, about 75% of the surviving samples satisfy  $m_{h_1} \leq m_{\tilde{\chi}_1^0}$ , in which the annihilation mode  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow h_1h_1$  plays a crucial role in obtaining the required dark matter relic density. In contrast, in the light- $a_1$  case most surviving samples satisfy  $m_{a_1} \geq 2m_{\tilde{\chi}_1^0}$ , in which the dominant annihilation channel is  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow f\bar{f}$  via  $a_1$  exchange.

From Fig. 1 we see that the scattering rate of light dark matter can reach the sensitivity of XENON100 and, consequently, a sizable parameter space is excluded by XENON100 (2011) data [?]. The future XENON100 experiment (6000 kg-days exposure) [?] can further explore (but cannot completely cover) the remaining parameter space. Note that in the light- $h_1$  case the scattering rate can be large enough to reach the CoGeNT sensitivity and can cover the CoGeNT-favored region. The underlying reason is that  $\chi$ -nucleon scattering can proceed through t-channel exchange of CP-even Higgs bosons, which can be enhanced by a factor  $1/m_{h_1}^4$  for a light  $h_1$  [?]; while a light  $a_1$  cannot give such enhancement because CP-odd Higgs bosons do not contribute in this way. We note that studies in [?, ?] claimed that the NMSSM cannot explain the CoGeNT data because they did not consider the light- $h_1$  case.

The light- $h_1$  samples are separated into three regions of  $m_{h_1}$ , as shown in the right frame of Fig. 1. This is due to combined constraints from the dark matter relic density and the processes  $\Upsilon(1S) \rightarrow \gamma h_1$  (with  $h_1 \rightarrow \pi^+\pi^-, K^+K^-, \mu^+\mu^-$ ),  $B_d \rightarrow X_s\mu^+\mu^-\gamma h_1$ , and  $p\bar{p} \rightarrow 4\mu$  (or  $2\mu 2\tau$ ) at the Tevatron, which tightly limit the couplings and mass of  $h_1$ . For example, since in this case  $h_1$  mainly acts as the product of dark matter annihilation, its coupling to  $\tilde{\chi}_1^0$  must be moderately large to obtain the correct relic density, while its couplings to SM fermions and  $h_{\text{SM}}$  must be small to suppress the rates of the processes mentioned above [?]. The situation differs for the light- $a_1$  case, where the relic density and LEP Higgs searches require  $m_{a_1} > 8$  GeV. For such a “heavy”  $a_1$ , the aforementioned low-energy processes give no stringent constraints, and thus the light- $a_1$  samples are not separated into different regions of  $m_{a_1}$ , as shown in the right frame of Fig. 1.

### Implications for Higgs Physics

In the NMSSM, the light  $\tilde{\chi}_1^0$  scenario may predict rather peculiar Higgs phenomenology due to the presence of light particles. Among the predicted Higgs bosons, the SM-like Higgs boson  $h_{\text{SM}}$ , defined as the CP-even Higgs boson with the largest couplings to  $Z^0$  pairs, will be the most important one to search for at the LHC since it is primarily responsible for electroweak symmetry breaking. We therefore focus on  $h_{\text{SM}}$  in our discussion.

In the light  $\tilde{\chi}_1^0$  scenario,  $h_{\text{SM}}$  may decay exotically into  $\tilde{\chi}_i^0\tilde{\chi}_j^0$ ,  $h_1h_1$ , or  $a_1a_1$ , and

consequently the conventional decays are reduced. This feature is illustrated in Fig. 2 [Figure 2: see original paper], which shows that the sum of exotic decay branching ratios may exceed 50% and traditional decays  $h_{\text{SM}} \rightarrow b\bar{b}, \tau\bar{\tau}, WW^*, \gamma\gamma$  can be severely suppressed. Numerically, we find that the branching ratio of  $h_{\text{SM}} \rightarrow b\bar{b}$  is suppressed below 30% for all surviving samples in the light- $h_1$  case and for about 96% of surviving samples in the light- $a_1$  case. For the remaining 4% of samples in the light- $a_1$  case, due to kinematic forbiddance of the decay  $h_{\text{SM}} \rightarrow a_1 a_1$  by  $m_{a_1} > 58$  GeV and  $m_{a_2} \geq 350$  GeV with  $\tan\beta \gtrsim 8$ , the ratio of  $h_{\text{SM}} \rightarrow b\bar{b}$  usually exceeds 30% and may even approach its SM value (up to 70%). Samples with this ratio exceeding 65% are characterized by  $m_{a_1} \geq 58$  GeV,  $m_{a_2} \geq 350$  GeV, and  $\tan\beta \gtrsim 8$ .

Another interesting feature shown in Fig. 2 is that, due to the opening of exotic decays,  $h_{\text{SM}}$  may be significantly lighter than the LEP bound. This situation is favored by fits to precision electroweak data and is of great theoretical interest [?].

Since conventional decay modes of  $h_{\text{SM}}$  may be greatly suppressed, especially in the light- $h_1$  case which can give a rather large  $\chi$ -N scattering rate, LHC searches for  $h_{\text{SM}}$  via traditional channels may become difficult. Noting that  $h_{\text{SM}}$  is bounded from above by about 130 GeV and hence its most important discovery channel at the LHC is the di-photon signal, we show the di-photon rate at the LHC with  $\sqrt{s} = 14$  TeV in Fig. 3 [Figure 3: see original paper]. In calculating this rate, we used the narrow width approximation and only considered leading contributions to  $pp \rightarrow h_{\text{SM}}$  from top quark, bottom quark, and squark loops.

Fig. 3 indicates that, compared with the SM prediction, the NMSSM rate in the light  $\tilde{\chi}_1^0$  scenario is suppressed to less than 20 fb for the light- $h_1$  case, and for the light- $a_1$  case most samples (about 96%) give the same conclusion. Since in the light- $h_1$  case the  $\chi$ -N scattering rate can reach CoGeNT sensitivity, this means that in the framework of the NMSSM, the CoGeNT search for light dark matter will be correlated with the LHC search for the Higgs boson via the di-photon channel.

Note that, as shown in the left frame of Fig. 3, a few samples can give a di-photon rate comparable with or even exceeding the SM prediction. We checked that these samples predict approximately the same decay branching ratios of  $h_{\text{SM}}$  as the SM Higgs boson, so the excess is mainly due to slight suppression of the total width of  $h_{\text{SM}}$ , which enhances  $\text{Br}(h_{\text{SM}} \rightarrow \gamma\gamma)$ . We also checked that the null result from future XENON100 6000 kg-days exposure will imply a Higgs di-photon signal below 20 fb at the LHC with 99% probability.

Finally, we point out that our light- $h_1$  scenario differs from that considered in [?]. The basic ideas of [?] are: (1) Consider a special region of parameter space characterized by  $\lambda, \kappa \sim 0$  to obtain a light  $h_1$ ; (2) Consider a nearly decoupled  $\hat{S}$  so that the singlino serves as dark matter with  $\mu \sim \tan\beta$  so that  $\text{Det } \mathcal{M}^2 \sim 0$  and  $A_\lambda \sim \mu \tan\beta$ , with its annihilation and scattering with nu-

cleons proceeding mainly by exchanging a light singlet  $a_1$  and  $h_1$  respectively. Such treatment obviously suffers from an unnaturalness problem in electroweak symmetry breaking since the condition  $A_\lambda \sim \mu \tan \beta$  usually pushes the soft mass  $m_{H_d}$  up to several TeV. We note that the results of [?] also suffer from this problem. In our scenario, however, we maintain naturalness by requiring all soft masses to be below the TeV scale.

## Conclusion

We scrutinized the light neutralino dark matter scenario in the NMSSM by scanning the parameter space with all relevant soft masses below the TeV scale. We found that in parameter space allowed by current experiments, neutralino dark matter can be as light as a few GeV and its scattering rate with nucleons can reach the sensitivity of XENON100 and CoGeNT (the CoGeNT signal can be explained). Present XENON100 and CoGeNT data exclude a large portion of parameter space, and future XENON100 data with 6000 kg-days exposure can further explore (but cannot completely cover) the remaining parameter space. In such a light dark matter scenario, a light CP-even or CP-odd Higgs boson must be present to satisfy the measured dark matter relic density. Consequently, the SM-like Higgs boson  $h_{\text{SM}}$  may dominantly decay into a pair of light Higgs bosons or a pair of neutralinos, and conventional decays like the di-photon signal at the LHC will be strongly suppressed.

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