

# Shufang Su • U. of Arizona

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**T. Han, Z. Liu and SS, to appear**

S. Su

Outline

- **Introduction/Motivation**  $\widetilde{\mathbf{y}}$
- Eight neutralino dark matter
- $A_1/H_1$  funnel region
- sbottom coannihilation
- stau coannihilation
- Direct and indirect detections  $\sum$
- <sup>\$</sup> LHC observables
- <sup>8</sup> Nearly degenerate sfermion signals at the ILC
- <sup>©</sup> Conclusion



 $\mathbb{R}^2$ 





 $\gamma$ 











S. Su

# Dark Matter





**๏ Relic density**  $M_{\rm WIMP} \lesssim$  $\sim$  $g^2$ 0*.*3 1*.*8 TeV*.* (1.1)

current days, a WIMP mass is roughly at the order

c Composition of MITMD doub motton to Tell cools now physics. **๏ Connection of WIMP dark matter to TeV scale new physics**

**๏ DM mass, coupling, relic density: model dependent**



• **Relic density** 
$$
M_{\text{WIMP}} \lesssim \frac{g^2}{0.3} 1.8 \text{ TeV}
$$

current days, a WIMP mass is roughly at the order

c Composition of MITMD doub motton to Tell cools now physics. **๏ Connection of WIMP dark matter to TeV scale new physics**

**๏ DM mass, coupling, relic density: model dependent**

**๏ How light a WIMP dark matter can be? - preserve WIMP DM properties - satisfy current experimental constraints**

Light Dark Matter

**๏ Direct detection**





## ๏ **consistent observations among all approaches**



# Complementarity

๏ **consistent observations among all approaches**





## ๏ **consistent observations among all approaches**





BBBBBB@ 0 *µ v<sup>u</sup>* ⇤ 0 *v<sup>d</sup> µ* in the gauge interaction basis of Bino *B*˜, Wino *W*˜ <sup>0</sup>, Higgsinos *H*˜ <sup>0</sup> Here *,* are the singlet-doublet mixing and the singlet cubic interaction, respectively [36], and we have adopted the convention of *v*<sup>2</sup> *<sup>u</sup>* = (174 GeV)2. The light neutralino, assumed to the LSP DM candidate, can then be expressed as *MN*˜ <sup>0</sup> = 0 BBBBBB@ *M*<sup>1</sup> 0 *g*<sup>1</sup> <sup>p</sup> *vd* <sup>2</sup> *g*<sup>1</sup> <sup>p</sup> *vu* <sup>2</sup> 0 *M*<sup>2</sup> *g*<sup>2</sup> <sup>p</sup> *vd* <sup>2</sup> *g*<sup>2</sup> <sup>p</sup> *vu* <sup>2</sup> 0 0 *µ v<sup>u</sup>* ⇤ 0 *v<sup>d</sup>* 1 CCCCCCA

$$
\tilde{\chi}_1^0 = N_{11} \tilde{B} + N_{12} \tilde{W}^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0.
$$

*d*+*v*<sup>2</sup>



$$
M_{\tilde{N}^0} = \begin{pmatrix} m_1 & 0 & -g_1 \frac{1}{\sqrt{2}} & g_1 \frac{1}{\sqrt{2}} \\ & M_2 & g_2 \frac{v_d}{\sqrt{2}} & -g_2 \frac{v_u}{\sqrt{2}} \\ & & 0 & -\mu \\ & & & 0 \end{pmatrix}
$$

$$
\tilde{\chi}_1^0 = N_{11} \tilde{B} + N_{12} \tilde{W}^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0.
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$$

*d*+*v*<sup>2</sup>

to the LSP dimensional data then be expressed as  $\sim$ 



$$
M_{\tilde N^0}=\left(\begin{array}{c}M_1\!\!{\rm l}\!0 & -g_1\frac{v_d}{\sqrt{2}} & g_1\frac{v_u}{\sqrt{2}}\\ M_2\!\!{\rm l}\!g_2\frac{v_d}{\sqrt{2}} & -g_2\frac{v_u}{\sqrt{2}}\\ * & 0\end{array}\right)
$$

$$
\tilde{\chi}_1^0 = N_{11} \tilde{B} + N_{12} \tilde{W}^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0.
$$

*d*+*v*<sup>2</sup>





- ๏ **lightest neutralino LSP in MSSM as good dark matter candidate**



S. Su  $\frac{8}{100}$ Han, Liu and Natarajan , 1303.3040



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Draper et. al. , 1009.3963 Arbey et. al. , 1205.2557,...



Table 1. Possible solutions for light (*<* 40 GeV) neutralino DM in the MSSM and NMSSM.

- **® Study properties of those solutions**
- **O** Direct and indirect detection
	- **© Observational aspects at colliders**
- $-$  via SM-like Higgs between interesting excessive in annual modulation by the DAMA collaboration by the DAMA collaboration in the D
- **light Higgses**  $\blacksquare$  direct measurements by CoGeNT  $\blacksquare$
- $-$  light sfermion be interpreted as signals from a low mass data mass dark mass dark mass dark matter. The tantalizing events from the tantalizing events from the tantalizing events from the tantalizing events from the tantalizing events fr

## **NMSSM Higgs Sector** *W*NMSSM = *YuHuQu* + *YdHdQd* + *YeHdLe* + ⇤*SHuH<sup>d</sup>* + <sup>1</sup>

#### - ๏ **Type II Two Higgs Doublet Model plus singlet S** In the NMSSM [26, 27], a new gauge singlet chiral super field *<sup>S</sup>*<sup>ˆ</sup> is added to the MSSM **The State Sector Riggs Doublet Model plus single** in a superpotential of the form *W*NMSSM = *Yuu*ˆ*<sup>c</sup> H*ˆ*uQ*ˆ + *Y<sup>d</sup>* ˆ *dc H*ˆ*dQ*ˆ + *Yee*ˆ*<sup>c</sup> <sup>H</sup>*ˆ*dL*<sup>ˆ</sup> <sup>+</sup> ⇤*S*ˆ*H*ˆ*uH*ˆ*<sup>d</sup>* <sup>+</sup>

$$
W_{\text{NMSSM}} = Y_u \hat{u}^c \hat{H}_u \hat{Q} + Y_d \hat{d}^c \hat{H}_d \hat{Q} + Y_e \hat{e}^c \hat{H}_d \hat{L} + \lambda \hat{\mathbf{S}} \hat{H}_u \hat{H}_d + \frac{1}{8} \kappa \hat{\mathbf{S}}^3
$$
  

$$
V_{H,Soft} = m_{H_u}^2 H_u^{\dagger} H_u + m_{H_d}^2 H_d^{\dagger} H_d + M_S^2 |\mathcal{S}|^2 + (\lambda A) H_t^T \epsilon H_d |\mathcal{S} + \frac{1}{3} \kappa A_\kappa \hat{\mathbf{S}}^3 + c.c.)
$$

#### ๏ **SSB 9 SSB** After the singlet obtains a vacuum expectation value (VEV) ⇤*S*⌅ = *vs/* term is generated: *µ* = ⇤*vs/*

*Hu*

e⌧ective *b*-term *b*e = *µ*(*A*⇥ +

$$
H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \rightarrow v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \rightarrow v_d/\sqrt{2} \qquad S \rightarrow v_s/\sqrt{2} \\ (\mu = \lambda v_s/\sqrt{2}) \qquad (1 - \lambda v_s/\sqrt{2})
$$

√

$$
v_u^2 + v_d^2 = v^2 = (246 \text{GeV})^2
$$
  

$$
\tan \beta = v_u/v_d
$$
  
S. Su

**after EWSB, 7 physical Higgses**  $\frac{2}{d} = v^2 = (246 \text{GeV})^2$  **CP-even Higgses: H<sub>1</sub>, H<sub>2</sub>, H<sub>3</sub>** CP-odd Higgs: A<sub>1</sub>, A<sub>2</sub> **Charged Higgses: H±** y γ pny<br>∫  $\overline{\phantom{a}}$  $\overline{\phantom{a}}$ <mark>∟narge</mark> L  $\overline{c}$  $\overline{\blacksquare}$  $\begin{vmatrix} a & b \\ c & d \end{vmatrix}$  $\frac{1}{\sqrt{2}}$ m<sup>2</sup> *v*2 *v*2 *<sup>u</sup>* + *v*<sup>2</sup> after EVIED 7 phy  $\frac{a_1^2 + a_2^2 - a_3^2 - (246 \text{GeV})^2}{2}$  and coecients being the coefficients being the coefficients being the coefficients being the coefficients being the coefficient of  $\frac{a_1^2 + a_2^2 - a_3^2 - a_4^2}{2}$  $r_a = a$  and  $r_b = a$  and  $r_b = a$  and  $r_b = a$  and  $r_b = a$  the VEV's stated. For the VEV's stated. For the VEV's stated. For the VEV's stated. For the VISO  $r_b = a$  and  $r_b = a$ 

⌃2, which solves the so-called *<sup>µ</sup>*-problem of the MSSM. An

1

*<sup>u</sup>* + *v*<sup>2</sup>

⌃2, an e⌧ective *<sup>µ</sup>*

⇥*S*ˆ<sup>3</sup> (2.1)

#### Neutralinos @ NMSSM 2.1 New York 1980, the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS  $\blacksquare$ In the neutralino DM candidate is the neutralino  $\blacksquare$

$$
M_{\tilde{N}^0} = \begin{pmatrix} M_1 & 0 & -g_1 \frac{v_d}{\sqrt{2}} & g_1 \frac{v_u}{\sqrt{2}} \\ & M_2 & g_2 \frac{v_d}{\sqrt{2}} & -g_2 \frac{v_u}{\sqrt{2}} \\ & & 0 & -\mu \\ & & & 0 \end{pmatrix}
$$

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$$

#### Neutralinos @ NMSSM 2.1 New York 1980, the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS  $\blacksquare$ In the neutralino DM candidate is the neutralino  $\blacksquare$ tralinos @ NMS: *M*<sup>2</sup> *g*<sup>2</sup> <sup>p</sup> *vd vu* <sup>2</sup> *g*<sup>2</sup> <sup>p</sup> <sup>2</sup> 0  $\overline{\phantom{0}}$

$$
M_{\tilde N^0}=\begin{pmatrix} M_1 & 0 & -g_1\frac{v_d}{\sqrt{2}} & g_1\frac{v_u}{\sqrt{2}} & 0 \\ & M_2 & g_2\frac{v_d}{\sqrt{2}} & -g_2\frac{v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\frac{\kappa}{\lambda}\mu \end{pmatrix}
$$

-

$$
\tilde{\chi}^0_1=N_{11}\tilde{B}+N_{12}\tilde{W}^0+N_{13}\tilde{H}_d^0+N_{14}\tilde{H}_u^0+N_{15}\tilde{S}
$$

*d*+*v*<sup>2</sup>

and we have adopted the convention of *v*<sup>2</sup>

*<sup>u</sup>* = (174 GeV)2. The light neutralino, assumed

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$$
M_{\tilde N^0}=\begin{pmatrix} M_1 \t\end{pmatrix} \begin{matrix} 0 & -g_1 \frac{v_d}{\sqrt{2}} & g_1 \frac{v_u}{\sqrt{2}} & 0 \\ M_2 & g_2 \frac{v_d}{\sqrt{2}} & -g_2 \frac{v_u}{\sqrt{2}} & 0 \\ 0 & -\mu & -\lambda v_u \\ * & 0 & -\lambda v_d \\ & & 2 \frac{\kappa}{\lambda} \mu \end{matrix}
$$

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#### Neutralinos @ NMSSM 2.1 New York 1980, the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS  $\blacksquare$ In the neutralino DM candidate is the neutralino  $\blacksquare$  $r$ **d** *d* **<b>***w w w d d n mussiv*



#### Neutralinos @ NMSSM 2.1 New York 1980, the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS  $\blacksquare$ In the neutralino DM candidate is the neutralino  $\blacksquare$ **Neutralinos @ NMSSM**  $\overline{\mathsf{S}}$ <sup>2</sup>, are typically of the order of *<sup>O</sup>*(*g*1*vu,d/µ*) and *Deutralinos @ NM*  $\mathbf{U}$



$$
\begin{aligned}\n&\textcirc \text{ Bino-like LSP} \\
N_{11} &\approx 1, \quad N_{15} \approx 0, \\
N_{13} &\approx \frac{m_Z s_W}{\mu} s_\beta, \quad N_{14} \approx -\frac{m_Z s_W}{\mu} c_\beta.\n\end{aligned}
$$

|
|
|

#### Neutralinos @ NMSSM 2.1 New York 1980, the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS Microsoft in the NMSS  $\blacksquare$ In the neutralino DM candidate is the neutralino  $\blacksquare$ **Neutralinos @ NMSSM**  $\overline{\mathsf{S}}$ <sup>2</sup>, are typically of the order of *<sup>O</sup>*(*g*1*vu,d/µ*) and  $N$ eutralinos @ NMSSM  $\mathbf{U}$ where  $\mathbf{r}$  are the mixing matrix  $\mathbf{r}$  are the Higgs fields with the Higgs fields w *H<sup>i</sup>* = ⇠*h<sup>v</sup> <sup>i</sup> <sup>h</sup><sup>v</sup>* <sup>+</sup> ⇠*H<sup>v</sup> <sup>i</sup> <sup>H</sup><sup>v</sup>* <sup>+</sup> ⇠*<sup>S</sup> <sup>i</sup> S, A<sup>i</sup>* = ⇠*<sup>A</sup>*



 $\mu$  are elements of  $\mu$  that diagonalize neutralino matrix  $\mu$ <sup>n</sup>

*,* (2.6)

*µ*

i

*<sup>i</sup> c*2

*mZs<sup>W</sup>*

Given the current constraints of  $\mu$  denotes the either Bino-SUSY DM candidate could be either Bino-SUSY DM candidate constraints of  $\mu$ 

*v* h

<u>μ</u>

 $\beta$ 

2*N*<sup>15</sup>

i

h

*mZs<sup>W</sup>*

|
|
|

*µ*

 $\frac{\partial}{\partial \mu} - \frac{\partial}{\partial \mu} S_{\beta}$ 

*µ*

 $\lambda v$ 

:

*v*

*µ*

 $s_{\beta}$ 

*<sup>i</sup> <sup>s</sup>*2 <sup>+</sup> ⇠*H<sup>v</sup>*

# Parameter Scan

-

#### **NMSSMTools4**





#### **NMSSMTools4**





#### **NMSSMTools4**





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#### **NMSSMTools4**



#### Experimental Constraints Focusing on the light DM solutions motivated in Table. 1, and guided by the collider  $\mathcal{L}$ t discussed above, we are following the following the following the following the following the following the f for the rest of the studies:

- Theoretical constraints such as Vacuum stability.
- *•* Collider Higgs search limits from the LEP, the Tevatron and the LHC.
- *•* LEP, Tevatron and LHC constrains on searches of supersymmetric particles, such as charignos, leptons and squarks;
- 2 $\sigma$  window of the SM-like Higgs boson mass:  $122.7 128.7$  GeV (including linearly added estimated theoretical uncertainties of *±*2 GeV).
- 2 $\sigma$  window of the SM-like Higgs bosons cross sections for  $\gamma\gamma$ , ZZ,  $W^+W^-$ ,  $\tau^+\tau^$ and  $b\bar{b}$  different production modes.
- *• Z* boson invisible width and hadronic width as in Eq. (2.11) and Eq. (2.12).
- B-physics constrains, including  $b \to s\gamma$ ,  $B_s \to \mu^+\mu^-$ ,  $B \to \chi_s\mu^+\mu^-$  and  $B^+ \to \tau^+\nu_{\tau}$ , as well as  $\Delta m_s$ ,  $\Delta m_d$ ,  $m_{\eta_b(1S)}$  and  $\Upsilon(1S) \rightarrow a\gamma$ ,  $h\gamma$ .

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#### Constraints for Low Mass Precision measurements of *Z*-boson's invisible width put strong constraint on the light *Constraints for Low Mass* tan = 1. It could also be small when the LSP is "decoupled" from Higgsinos, *e. g.* for a

neutralino LSP. The 95% C.L. upper limit on *Z* boson invisible width is [40]

 $\Delta\Gamma_{\rm inv} < 2.0$  MeV

 $\overline{\phantom{a}}$ 

๏ **Light neutralino LSP: invisible Z decay with** inv *<* 2*.*0 MeV*.* (2.11) Bino-like LSP *|µ| |M*1*|, g*1*vu,d* or a Singlino-like LSP *|µ|* 2*|/µ|, ||vu,d*.  $\odot$  Light neutralino LSP: invisible Z decay with  $\rm \odot\,_{inv} < 2.0~MeV$   $\rm \odot\,$ 

tan = 1. It could also be small when the LSP is "decoupled" from Higgsinos, *e. g.* for a

value is near 0.1. The increasing in the allowed range for larger *m*˜<sup>0</sup>

neutralino LSP. The 95% C.L. upper limit on *Z* boson invisible width is [49]

$$
Z\tilde{\chi}_1^0\tilde{\chi}_1^0 \text{ coupling}, \quad N_{14}^2 - N_{13}^2
$$

- Bino LSP:  $\mu$  > 140 GeV
	-



#### Constraints for Low Mass sneutrino. Only sbottom and stau could co-annihilate with the neutralino LSP. Conctrointe for Low M CONSITUINIS TOT LOW MIUSS

˜ + *g<sup>R</sup>*

*f sin2 ∪<sub>f</sub> sin2 ∪<sub>f</sub>* 

 $\odot$  Light sfermion: total Z decay width  $\gtrsim \Delta\Gamma_{\rm tot} < 4.7\,\text{ MeV}$  $\mathbf{r} \cdot \mathbf{r} = \mathbf{r} \cdot \math$  $\bullet$  Light stermion: total Z decay widtl

 $\Delta\Gamma_{\rm tot} < 4.7$  MeV ˜ ˜*f<sup>L</sup>* +

mental precision on *Z* boson decay width is 2*.*4952 *±* 0*.*0023 GeV [40], leading to

, (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (<br>, (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13), (2.13),

$$
Z\tilde{f}_1\tilde{f}_1:g_f^L\cos^2\theta_{\tilde{f}}+g_f^R\sin^2\theta_{\tilde{f}} \quad \tan^2\theta_{\tilde{f}}^{min}=-g_f^L/g_f^R.
$$

-

*f* cos<sup>2</sup> ∕*f* cos<sup>2</sup>

The coupling of the *Z* to the sermons depends on the mixing angle of the sermons, - sbottom: mostly right-handed - **sbottom: mostly right-handed**

*Z* ˜*f*<sup>1</sup> ˜*f*<sup>1</sup> : *g<sup>L</sup>*

which originated from the left-right mixing in the series in the series  $\mathcal{M}$  in the mixing in the mixing

which income the left-right mass of the series of the series of the series of the series of the mixing in the mixing in the mixing in the mixing of the mixing in the mixing in the mixing of the mixing in the mixing in the the fermion term is the *fermion terminial of left and right-handed* - **stau: even mixture of left and right-handed** 



## Dark Matter Properties e.g., Die der die ties the time time time the time the time the time the time the time the time that the time t

 $0.0947 \, (0.001) < \Omega_{\tilde{\chi}_{1}^{0}} h^2 < 0.142,$ 

-



**funnel**

**sb-coann**

S. Su 16 **stau-coann**





























# **Indirect Detection**



# Indirect Detection



# Indirect Detection





๏ **Observation of a SM-like Higgs poses strong constraints** S Observation of a SM like Higgs passe strong constraints required to the total properties to the SM Higgs boson. As a result, and SM Higgs boson. As a result, and  $\alpha$ 

- mixture from other Higgses
- new decay modes open:  $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ ,  $A_1 A_1$ ,  $H_1 H_1$ ,  $\tilde{\tau}_1^+ \tilde{\tau}_1^-$  and  $\tilde{b}_1 \tilde{b}_1^*$
- light sbottom/stau appears in **Hgg, Hγγ**



# **SM Higgs**



# **SM Higgs**





## . Dark matter production via Higgs portal



## $H \rightarrow XX$



## **© Coupling and Decay: singlet like**





## • Production: < 10% SM rate



## ggH bbH ttH **VBF VH**



**๏ Light sbottom with compressed spectrum: small Δm**

- **-** <sup>Δ</sup>**m > mb: prompt sbottom decay**
- **-** <sup>Δ</sup>**m < mb: prompt, displaced vertex, R-hadron, ... depend on the flavor structure**

## **๏ LEP limits**



## **๏ ATLAS limits: 2b+MET,bbj+MET**





## ๏ **recast ATLAS sbottom search results for light sbottom**  $m_{sb}$ =20 GeV, mx=14 GeV, prompt decay





๏ **recast ATLAS sbottom search results for light sbottom**  $m_{sb}$ =20 GeV, mx=14 GeV, prompt decay





#### **๏ LEP limit** <sup>76</sup> DELPHI [50] ˜*<sup>b</sup>* ! ˜0*b*, all ✓˜*b*, *m >* 7 GeV **∂** LEP IIMIT



- **© LHC limit with stau from neutralino/chargino decay not applicable with large MT2 cut of 90-110 GeV** *for applicable with large witz cut of su-fill GeV*
- **◎ ττ(j) + MET** search difficult with WW(j)+MET background. accommodated with *m*⌧˜<sup>1</sup> & 32 GeV, especially for large *m*⌧˜<sup>1</sup> when there is extra kinematic

#### suppression in phase space. These are a direct results of collider constrains and tuning. For  $\rho$  light stau difficult at <code>LHC</code> as well.



### **◎ bby+MET, ттү+MET**



S. Su



## **light neutralino dark matter (2 - 40 GeV)**

