Light Dark Matter and the Electroweak Phase Transition in the NMSSM

Nausheen R. Shah
FNAL PPD/Theory

In Collaboration with:
M. Carena and C. Wagner
arXiv: 1109.SOON

Outline

- NMSSM:
  - Near Peccei-Quinn (*PQ*) Limit
  - *"Dark Light Higgs"*
- Relevant Phenomenology :
  - CP-even/odd Higgs mass spectrum.
  - Lightest Neutralino mass.
  - Experimental bounds.
- Electroweak Symmetry Breaking (EWSB) at $T = 0$.
- Electroweak Phase Transition (EWPT) at Finite Temperature.
  - Strong First Order Phase Transition for Baryogenesis possible?
- Cosmological Bounds
  - Spin Independent(SI) cross-section
  - Relic density
- Simplified Model
  - Small λ + *PQ* Limit.
- Numerical Results
  - Consistent parameter space.
    - EWSB
    - EWPT with $T_c < \phi_c$ => Baryogenesis possible.
    - $\Omega h^2 \sim 0.1$
    - $\sigma_{SI} < 10^{-40}$ cm^2
- Conclusions

The NMSSM

One-loop Effective Higgs Potential

NMSSM

- Effective Higgs Potential, including singlet S: $V = V_S + V_H.$

$$\begin{aligned} V_S &= m_S^2|S|^2 - 2\lambda A_\lambda H_u H_d S + \lambda^2|S|^2\left(|H_u|^2 + |H_d|^2\right) \\ &\quad + \kappa\lambda S^2 H_u^* H_d^* + \frac{1}{3}\kappa A_\kappa S^3 + \kappa^2|S|^4 + h.c. \end{aligned}$$

$$\begin{aligned} V_H &= m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + \lambda^2|H_u H_d|^2 + \frac{(g_1^2+g_2^2)}{8}\left(H_u^2 - H_d^2\right)^2 \\ &\quad + \quad \text{loop corrections.} \end{aligned}$$

- Example loop correction: $\Delta V_{S^4} \simeq \frac{\lambda^4}{8\pi^2} S^4 \log\left(\frac{\mu^2}{m_Z^2}\tan^4\beta\right).$

- Parameter Set: $\{\lambda, A_\lambda, \kappa, A_\kappa, \tan\beta, \tilde{\lambda}\}, \ \{m_S^2, m_{H_d}^2, m_{H_u}^2\}.$
- Near-PQ Limit: $\kappa \ll \lambda \lesssim 0.2.$

Phenomenology

CP-even/odd Higgs Masses
Neutralino Mass
Experimental Bounds

CP-Even Higgs Masses

$$\lambda S_0 \simeq \mu$$

- In parameters of interest $\varepsilon \equiv \frac{\lambda\mu}{m_Z}\varepsilon', \quad \varepsilon' \equiv \frac{A_\lambda}{\mu \tan\beta} - 1$ small.
- In the small λ + near *PQ* limit, see-saw mechanism, mostly singlet lightest state ~ few GeV:

$$m_{h_1}^2 \simeq -4v^2\varepsilon^2 + \frac{4v^2\lambda^2}{\tan^2\beta} + a_\kappa S_0 + 4\kappa^2 S_0^2 + \frac{\lambda^2\mu^2}{2\pi^2}\log\left(\frac{\mu^2}{m_Z^2}\tan^4\beta\right),$$

- The SM-like Higgs:

$$m_{h_2}^2 \simeq m_Z^2 + 3\frac{m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

- Mostly down-type heaviest state ~ TeV:

$$m_{h_3}^2 \simeq m_{H_d}^2 \simeq A_\lambda^2$$

Lightest CP-Odd Higgs and Neutralino

- *a1* pseudo-Goldstone of the approximate *PQ* symmetry ~ 10 GeV

$$m_{a_1}^2 \approx -3\kappa A_\kappa \mu/\lambda$$

- $\kappa << \lambda << 1$ implies lightest neutralino, χ_1, dark matter candidate, is mostly singlino like ~ 10 GeV:

$$m_{\chi_1} \approx v^2\lambda^2 \sin 2\beta/\mu + 2\kappa\mu/\lambda$$

Experimental Bounds

P. Draper, T. Liu, C. Wagner, L. Wang and H. Zhang (arXiv: 1009.3963 [hep-ph])

- SM-like Higgs *h2* to *h1 h1* and *a1 a1*
  - Tree-level coupling of *h2* to *h1* or *a1* suppressed

$$y_{h_2 h_1 h_1} \approx -\frac{\lambda v m_Z \varepsilon}{\sqrt{2}\mu}.$$

- *Υ(ns)* decays to *γ h1* or *γ a1*
  - Effectively constrains λ_d, coupling of light states to down type fermions $\lambda_d \approx \frac{v}{\mu}\left(\lambda + \frac{2\varepsilon\mu}{m_Z}\right)$
  - Only approaches limit for $\lambda > 0.15$
- Flavor Physics
  - Constraints from *B* physics.
- Avoided in parameter region of interest

EWSB and EWPT

EWSB

- Physical vacuum at $\phi_0 = 174$ GeV must be global minimum at T=0.
  - $dV/d\phi\,|_{\phi 0} = 0$
    - Constrains the soft Higgs mass parameters.
  - $V(\phi_0\,, 0) < 0$
  - Minimum:
    - All eigenstates of the Higgs mass matrix are positive.
      - Hessian of V positive.
    - Defines range of S_0, and hence of the soft mass, $\boldsymbol{m_s^2}$, where EWSB possible.
  - Global Minimum
    - Further constrains values of S_0 (m_s^2)

EWPT

$$V(T,m,\pm 1) = \frac{T^4}{2\pi^2}\int_0^\infty x^2 \log(1 \pm e^{-\sqrt{x^2+\frac{m^2}{T^2}}})dx$$

- *T* dependent 1-loop contribution from top, gauge bosons and Higgsinos.
  - Light Higgs Bosons and neutralinos have relatively small couplings: Finite *T* contribution small.
  - Similarly ignore gauginos.
  - Stops heavy → decouple from plasma → Only contribution at *T*=0.

$$\begin{aligned} V_T &= -8V(T,\lambda S,+1) - 12V(T,\frac{m_t}{v_u}H_u,+1) + 3V(T,\frac{m_Z}{v}\sqrt{H_u^2+H_d^2},-1) \\ &\quad + 6V(T,\frac{m_W}{v}\sqrt{H_u^2+H_d^2},-1). \end{aligned}$$

- EWPT, for Baryogenesis to be possible, needs to be **strong** and **first order**. Additionally, vacuum must be global:
  - $V(\phi_c, T_c) = 0$
  - $dV/d\phi\,|_{(\phi c\,,\,Tc)} = 0$
  - Evolve EWSB minimum with *T* and require it to remain the deepest.
- Further constrained range of S_0 (m_s^2).

Cosmological Bounds

- SI cross-section :
  - Mainly due to *h1*-mediated t-channel scattering $\chi_1 q \rightarrow \chi_1 q$

$$\sigma_{\rm SI} \approx \frac{\left(\left(\frac{\varepsilon}{0.04}\right) + 0.46\left(\frac{\lambda}{0.1}\right)\left(\frac{v}{\mu}\right)\right)^2 \left(\frac{y_{h_1\chi_1\chi_1}}{0.003}\right)^2 10^{-40}{\rm cm}^2}{\left(\frac{m_{h_1}}{1{\rm GeV}}\right)^4}.$$

$$y_{h_1\chi_1\chi_1} \approx -\sqrt{2}\kappa$$

- Relic Density:
  - Mainly controlled by *a1*-mediated s-channel process $\chi_1\chi_1 \rightarrow ff$

$$\sigma_{f\bar{f}} v_{\chi_1} \approx \frac{3|\, y_{a_1\chi_1\chi_1}\, y_{a_1 f f}|^2 (1 - m_f^2/m_{\chi_1}^2)^{1/2}}{32\pi m_{\chi_1}^2 \left(\delta^2 + \left|\frac{\Gamma_{a_1} m_{a_1}}{4m_{\chi_1}^2}\right|^2\right)}$$

$$y_{a_1\chi_1\chi_1} \approx -i\sqrt{2}\kappa \text{ and } \delta \equiv \left|\frac{1}{1-v_{\chi_1}^2/4} - \frac{m_{a_1}^2}{4m_{\chi_1}^2}\right|$$

$$\Omega h^2 \approx \frac{0.1\left(\frac{m_{a_1}}{15{\rm GeV}}\right)\left(\frac{\Gamma_{a_1}}{10^{-5}{\rm GeV}}\right)\left(\frac{\mu}{v}\right)^2\left(\frac{0.003}{y_{a_1\chi_1\chi_1}}\right)^2\left(\frac{0.1}{\lambda}\right)^2}{\text{erfc}\left(\frac{2m_{\chi_1}}{m_{a_1}}\sqrt{x_f \delta_{v_{\chi_1}\to 0}}\right)/\text{erfc}\,(2.2)}$$

Simplified Model

λ small + PQ Limit Potential

Ignore loops, except high T effects

$$V(\phi, m_s, T) = m^2(T)\phi^2 - TE\phi^3 + \tilde{\lambda}^2\phi^4 - \frac{\tilde{a}^2\phi^4}{({m_s}^2 + \lambda^2\phi^2)},$$

$$\phi = \sqrt{|H_u|^2 + |H_d|^2},\ \tilde{a} = \lambda A_\lambda \sin(\beta)\cos(\beta),\ \tilde{\lambda} \sim 0.4 \text{ and } E \sim 0.023\ .$$

EWSB $\longrightarrow$

$$m_s \begin{cases} > & \frac{\tilde{a}}{2\tilde{\lambda}}\left(1 + \sqrt{1 - \frac{4\tilde{\lambda}^2\lambda^2 v^2}{\tilde{a}^2}}\right) \\ < & \frac{\tilde{a}}{2\tilde{\lambda}}\left(1 - \sqrt{1 - \frac{4\tilde{\lambda}^2\lambda^2 v^2}{\tilde{a}^2}}\right) \end{cases}$$

EWPT

$\downarrow$

$$m_s^2 \begin{cases} < & {\lambda^2}{\phi_c}^2\left(\frac{\tilde{a}^2}{2\lambda^2{\phi_c}^2\left({\tilde{\lambda}_c}^2 - E/2\right)} - 1\right)\left(1 - \sqrt{1 - \left(\frac{\tilde{a}^2}{2\lambda^2{\phi_c}^2\left({\tilde{\lambda}_c}^2 - E/2\right)} - 1\right)^{-2}}\right) \\ > & {\lambda^2}{\phi_c}^2\left(\frac{\tilde{a}^2}{2\lambda^2{\phi_c}^2\left({\tilde{\lambda}_c}^2 - E/2\right)} - 1\right)\left(1 + \sqrt{1 - \left(\frac{\tilde{a}^2}{2\lambda^2{\phi_c}^2\left({\tilde{\lambda}_c}^2 - E/2\right)} - 1\right)^{-2}}\right) \end{cases}$$

Numerical Analysis

Parameters

- Initial sparse scan, keeping $\tilde{\lambda} = 0.4$ fixed.
- Points selected where EWSB at T=0
- Selected parameters T evolved
  - Strong first order phase transition?

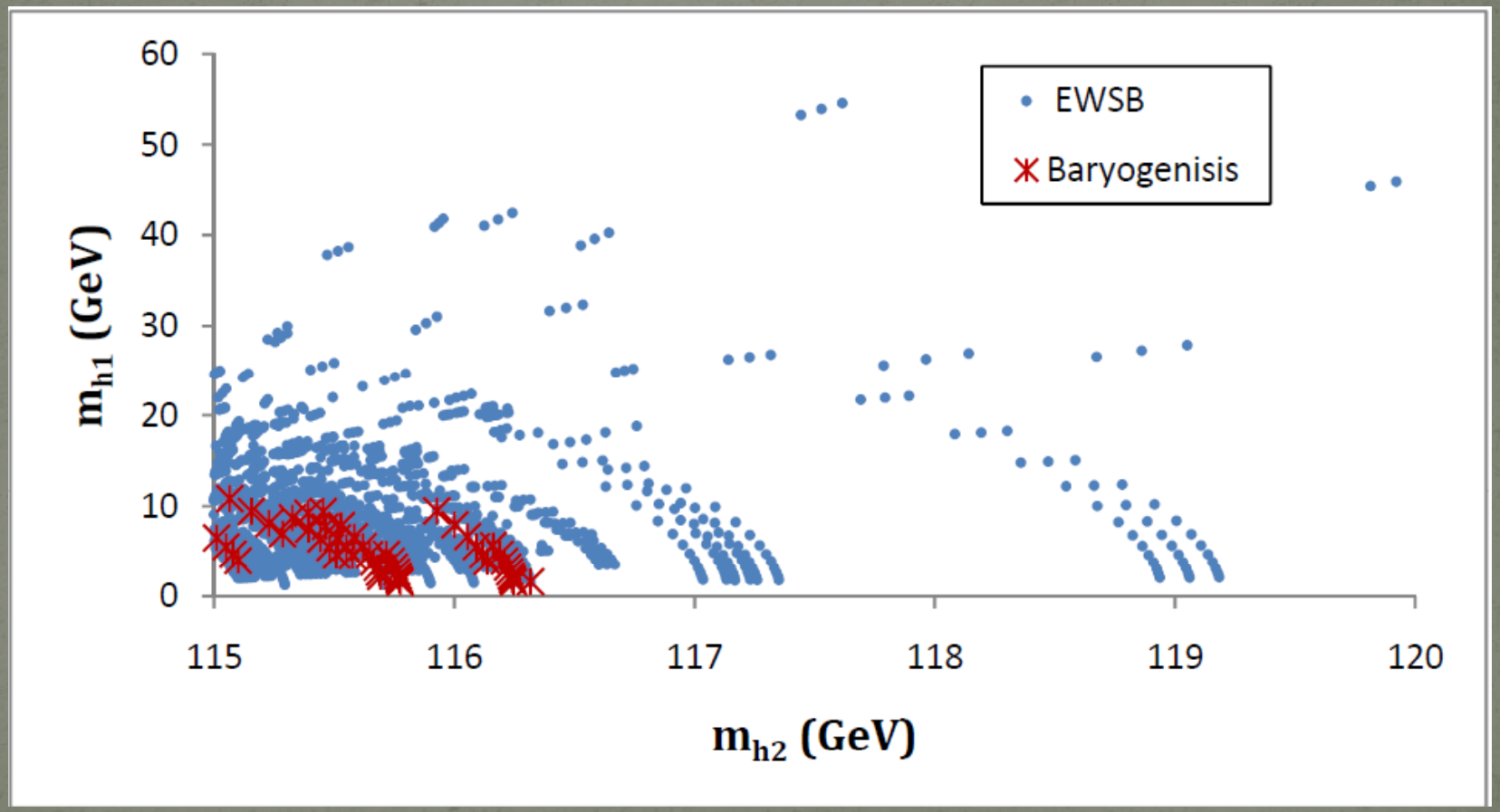
"Baryogenesis".

$$\begin{aligned} \lambda &\simeq 0.100 \text{ to } 0.130, \\ \kappa &\simeq 0.001, \text{ to } 0.007, \\ \kappa A_\kappa &\simeq -0.1 \text{ to } -0.05, \\ \lambda A_\lambda &\simeq 250 \text{ to } 450 \text{ GeV}, \\ \tan\beta &\simeq 12 \text{ to } 20, \end{aligned}$$

- Scan did not contain any points where cosmological bounds were fulfilled.
  - Varying parameters slightly we were able to find regions where all bounds may be fulfilled.

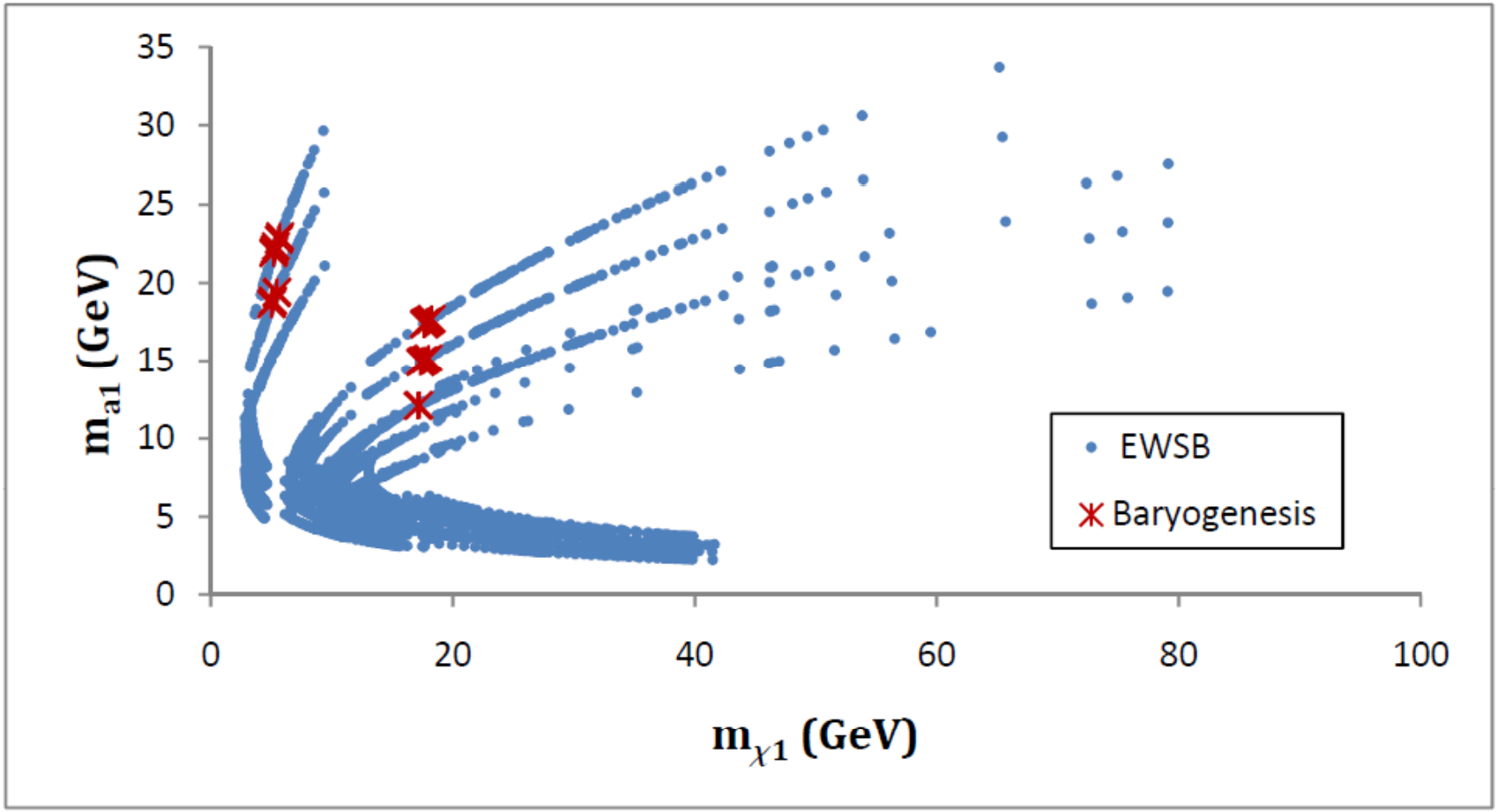
λ: 0.1-0.5, κ: 0.00125-0.0125, λA_λ: 250–450, κA_κ: –0.04– –0.08, tan β: 12–20

$\tilde{\lambda} = 0.4$



λ: 0.1-0.5, κ: 0.00125-0.0125, λA_λ: 250–450, κA_κ: –0.04– –0.08, tan β: 12–20

$\tilde{\lambda} = 0.4$

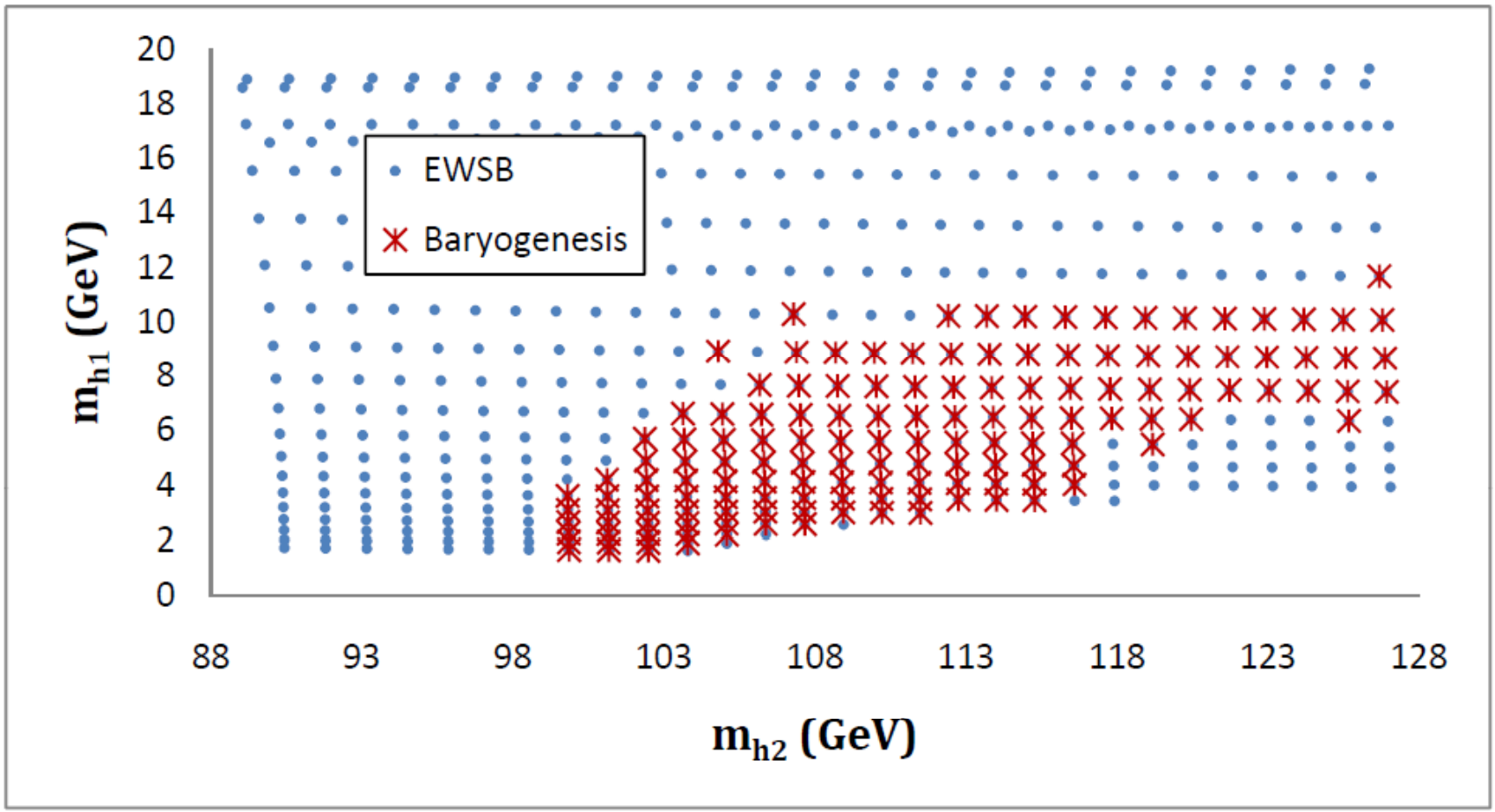


$\lambda = 0.125,\ \kappa = 0.00225,\ \lambda A_\lambda = 350,$

$\kappa A_\kappa = -0.06,\ \tan\beta = 13,$

$\tilde{\lambda}$: 0.34–0.43

$m_{\chi 1}$: 6.5–9.5 GeV m_{a1}: 16–19 GeV

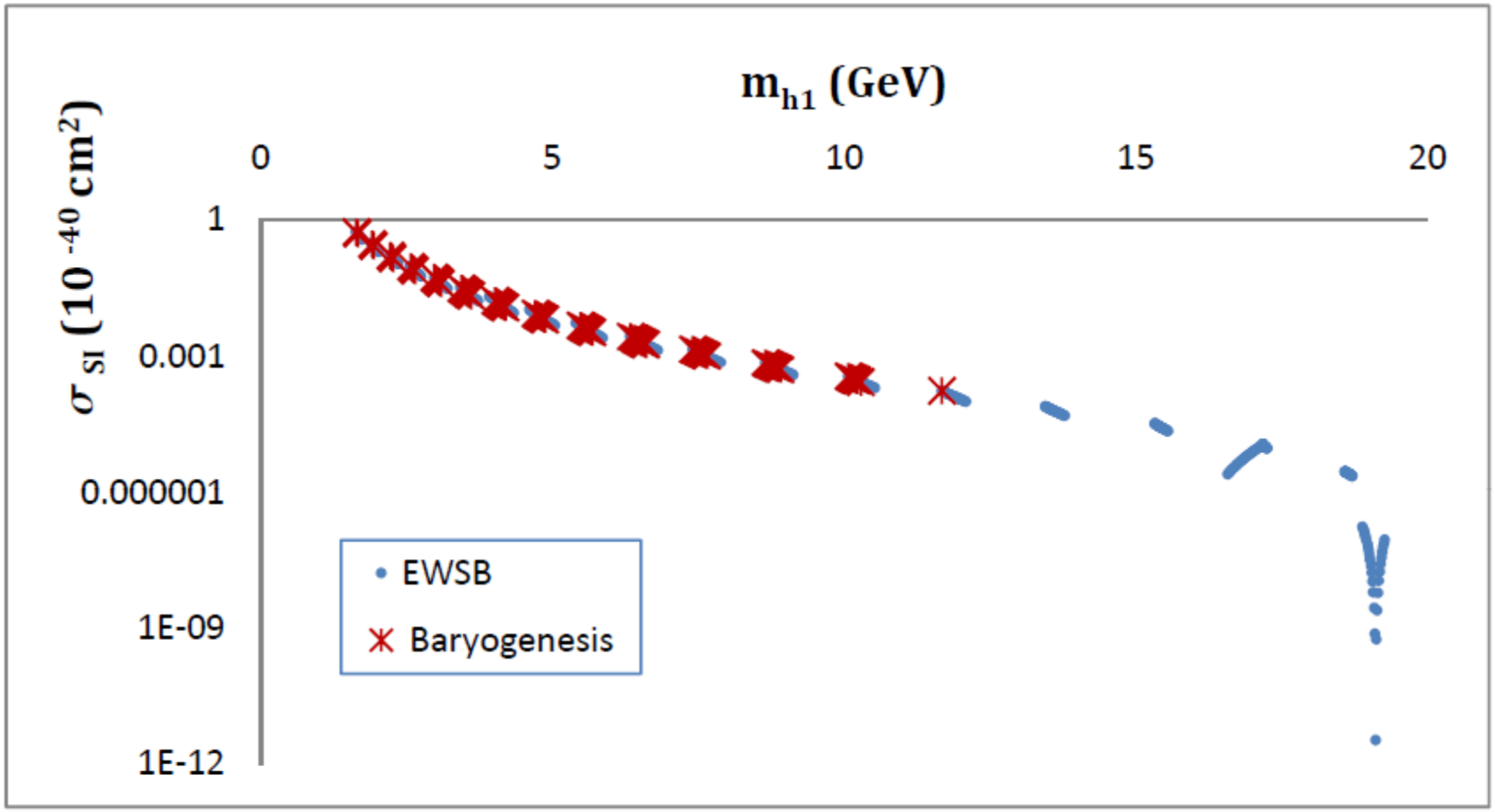


$\lambda = 0.125,\ \kappa = 0.00225,\ \lambda A_\lambda = 350,$

$\kappa A_\kappa = -0.06,\ \tan\beta = 13,$

$\tilde{\lambda}$:0.34–0.43

$m_{\chi 1}$: 6.5–9.5 GeV m_{a1}: 16–19 GeV

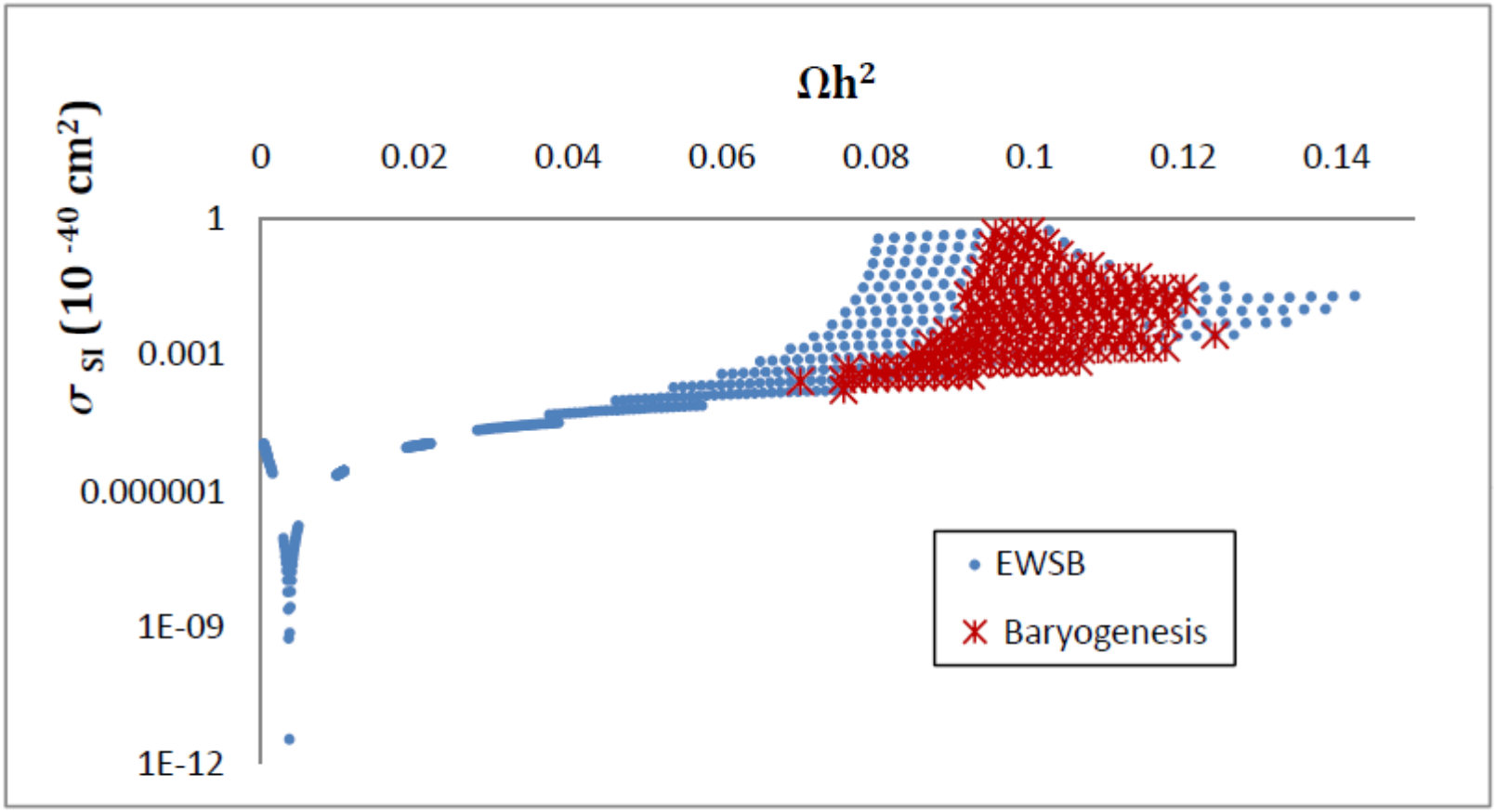


$\lambda = 0.125,\ \kappa = 0.00225,\ \lambda A_\lambda = 350,$

$\kappa A_\kappa = -0.06,\ \tan\beta = 13,$

$\tilde{\lambda}: 0.34\text{–}0.43$

$m_{\chi 1}: 6.5\text{–}9.5\ \text{GeV} \quad m_{a1}: 16\text{–}19\ \text{GeV}$



Conclusions and Outlook

- We investigate EW structure of the NMSSM near the *PQ* limit.
- Using a simplified model, we argue that there exists a region of small m_s^2, consistent with both EWSB and first order strong EWPT.
- In near *PQ* limit of the NMSSM, we find *new* parameter space of small m_s^2 :
  - Electroweak Symmetry Breaking realized
  - Strong First Order Phase Transition realized
  - Can be consistent with all cosmological constraints
  - Light DM, candidate for CoGeNT + DAMA/LIBRA?
- Would like to understand better the dependence of the phase transition on the parameters of the model.
- Much larger parameter space, if we allow for 2-step phase transition and/or metastable vacuum.
  - Would need to study lifetimes and tunneling for such vacua.

Backup Slides

	$\tan\beta$	λ	λA_λ	κ	κA_κ
Set 1	13	0.10375	250	0.006875	-0.06
Set 2	13	0.10375	250	0.006875	-0.08
Set 3	13	0.10375	350	0.00125	-0.06
Set 4	13	0.10375	350	0.00125	-0.08
Set 5	18	0.10375	350	0.006875	-0.06
Set 6	18	0.10375	350	0.006875	-0.08
Set 7	18	0.10375	450	0.00125	-0.06
Set 8	18	0.10375	450	0.00125	-0.08

	$\tan\beta$	λ	λA_λ	κ	κA_κ
Set a	13	0.125	350	0.00225	-0.06
Set b	13	0.0105	350	0.00225	-0.08

P. Draper, T. Liu, C. Wagner, L. Wang and H. Zhang (arXiv: 1009.3963 [hep-ph])

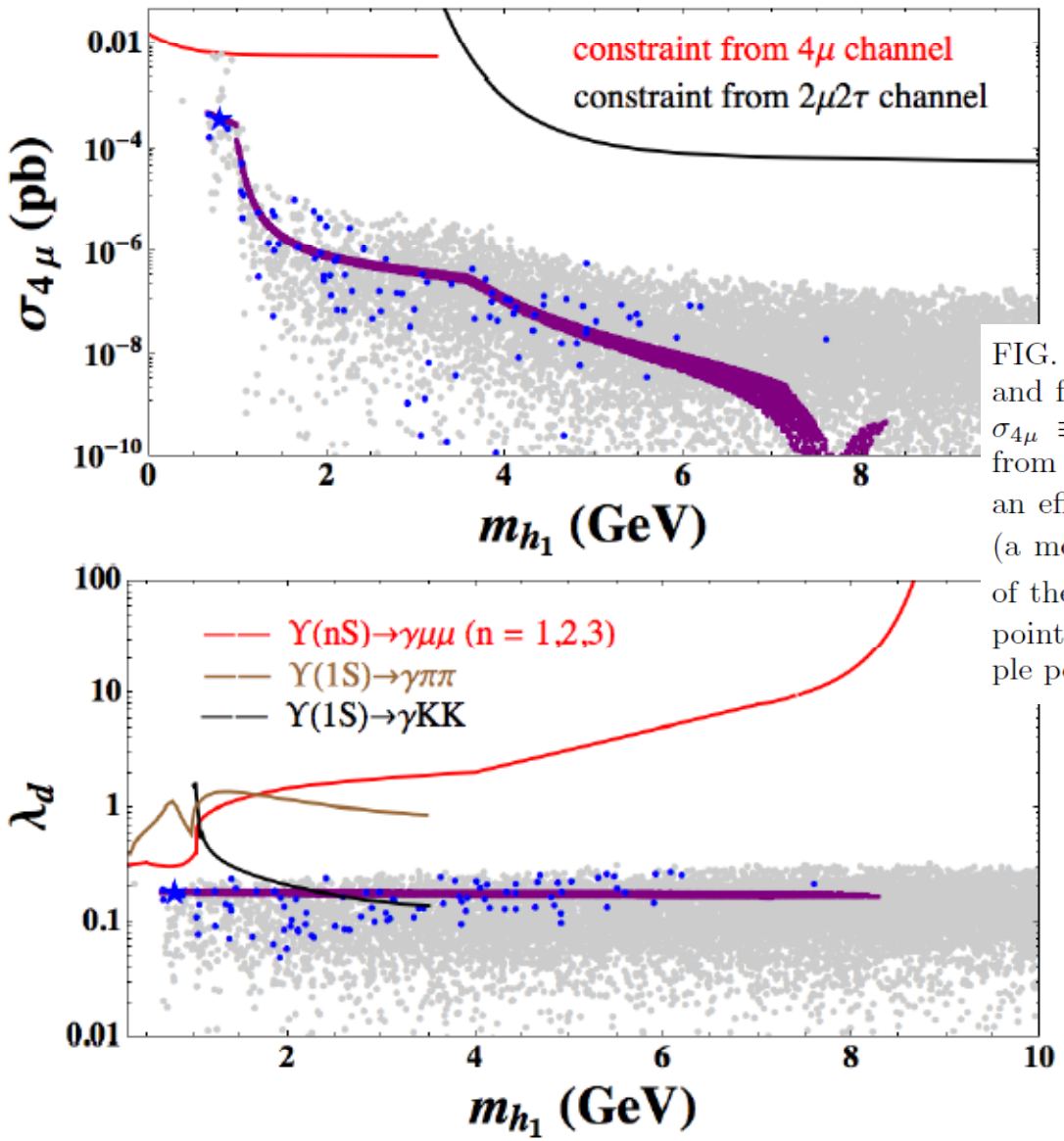
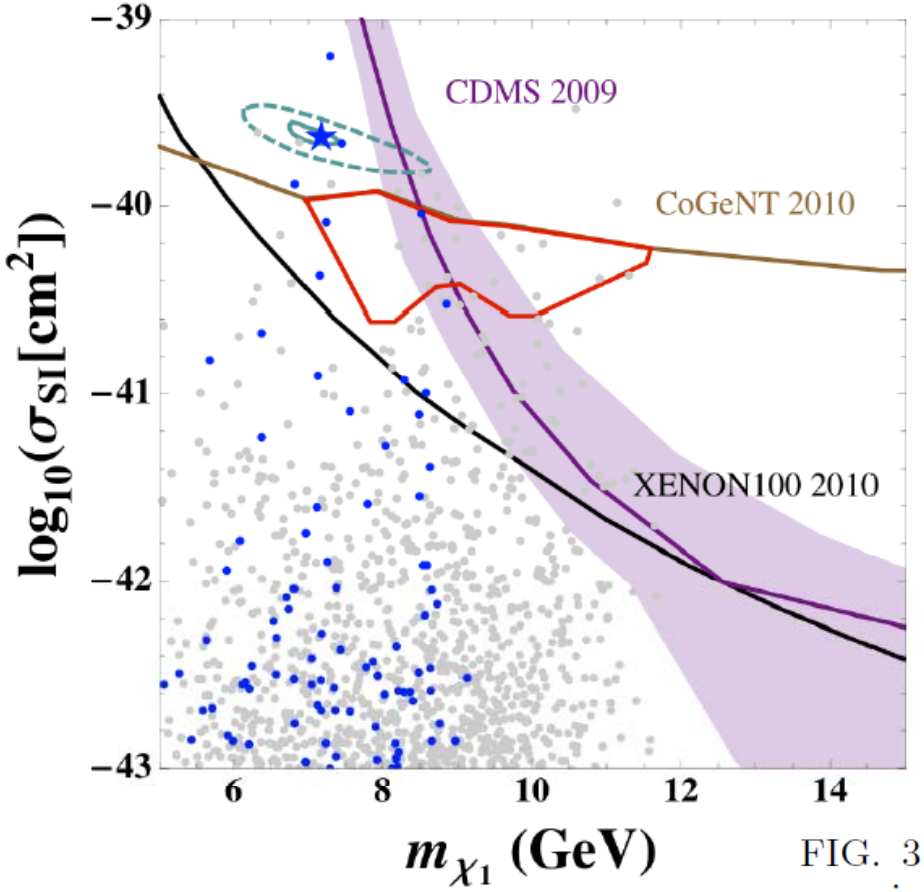


FIG. 2: Constraints from the decays $h_2 \to h_1 h_1 \to 4f$ (*top*) and from the decays $\Upsilon \to \gamma h_1 (h_1 \to \mu\mu, \pi\pi, KK)$ (*bottom*). $\sigma_{4\mu} \equiv \sigma_{h_2} \mathrm{Br}(h_2 \to h_1 h_1 \to 4\mu)$. To show the constraint from the $2\mu 2\tau$ channel on the same plot we convert it into an effective constraint on 4μ by rescaling it with $\frac{\mathrm{Br}(h_1 \to \mu\mu)}{\mathrm{Br}(h_1 \to \tau\tau)}$ (a model-independent quantity). λ_d is a tree-level coupling of the down-type interaction $-\frac{\lambda_d m_{f_d}}{\sqrt{2}v} h_1 \bar{f}_d f_d$. Gray and blue points correspond to the gray and blue points in FIG. 3. Purple points correspond to the points in the scan of FIG. 4.



P. Draper, T. Liu, C. Wagner, L. Wang and H. Zhang
(arXiv: 1009.3963 [hep-ph])

FIG. 3: Cross section of SI direct detection for χ_1. The scan is over all parameters, in the ranges $0.05 \leq \lambda \leq 0.15$, $0.001 \leq \kappa \leq 0.005$, $|\varepsilon'| \leq 0.25$, $-30 \leq A_\kappa \leq -15$ GeV, $5 \leq \tan\beta \leq 50$ and $100 \leq \mu \leq 250$ GeV. The dark blue (dark) points have a relic density $0.09 \leq \Omega h^2 \leq 0.13$. The red contour is the CoGeNT favored region presented in [12] and the two blue circles above the red one are the most recent interpretations of fitting CoGeNT + DAMA/LIBRA [13]. Note that all contours assume a local density which may be sensitive to the relic density. The purple, brown, and black lines are the limits from CDMS [17], CoGeNT [12], and XENON100 [18], respectively.