# Dark Matter from Singlet Models

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The Hunt for Dark Matter
Fermilab

May 10, 2007

# Intro to Singlet Models

- SM context:

$$
\begin{aligned}
V &= \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2} H^\dagger H S + \frac{\delta_2}{2} H^\dagger H S^2 \\
&+ \left(\frac{\delta_1 m^2}{2\lambda}\right) S + \frac{\kappa_2}{2} S^2 + \frac{\kappa_3}{3} S^3 + \frac{\kappa_4}{4} S^4,
\end{aligned}
$$

- Supersymmetry context:
  - motivation: $\text{solution to the } \mu \text{ problem}$

    $\text{Additional associated } \chi_i^0, \chi_j^\pm$

- Either case can have large impact on
  - Direct and indirect DM searches
  - Higgs searches at the LHC and ILC

# SM Context

Add one scalar singlet to SM Higgs potential

- Higgs can be indistinguishable from SM
- Singlet obtains no VEV

$$
\begin{aligned}
V &= \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2} H^\dagger H S + \frac{\delta_2}{2} H^\dagger H S^2 \\
&+ \left(\frac{\delta_1 m^2}{2\lambda}\right) S + \frac{\kappa_2}{2} S^2 + \frac{\kappa_3}{3} S^3 + \frac{\kappa_4}{4} S^4,
\end{aligned}
$$

O'Connell, Ramsey-Musolf, Wise

Two cases of singlet:

- Singlet mixes with SM Higgs (O'Connell et al.)
- Reflection Symmetry $S \to -S$ (McDonald & Burgess et al.)
  - ➡ DM singlet interacts only with Higgs bosons

Barger, Langacker, McCaskey, Ramsey-Musolf, GS in prep

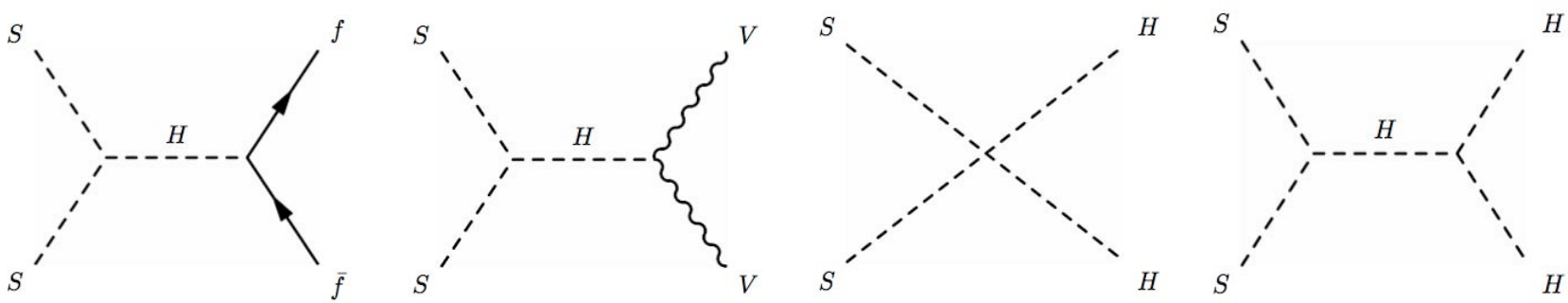
# Reflection Symmetry

- S → -S symmetry prevents S decay
  ⇒DM candidate

- DM singlet annihilates through Higgs boson

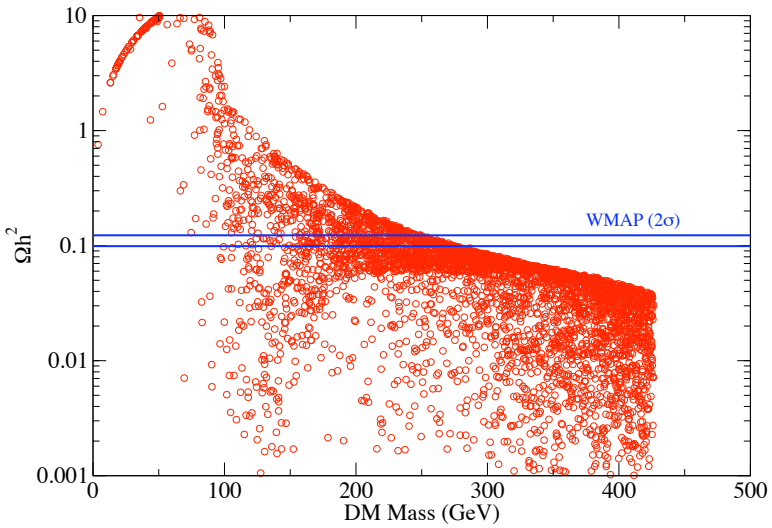
$$\frac{\delta_2}{2} H^+ H S^2$$

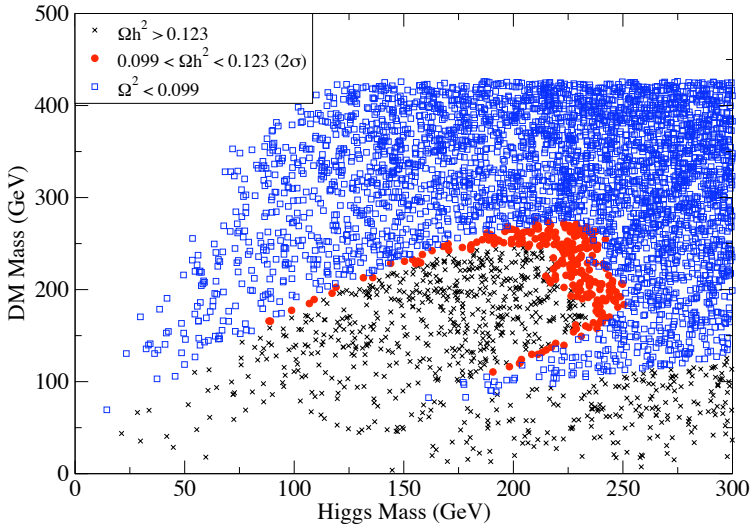
Annihilation processes:



# Relic density

- Relic density strongly dependent on DM and Higgs boson mass
- Annihilation to SM modes through Higgs boson pole and through quartic interaction
- Once SM Higgs mass known, then DM mass is predicted

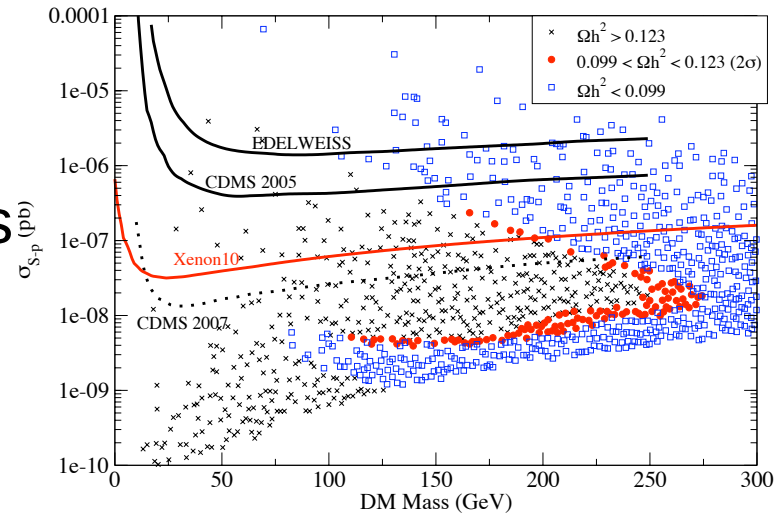


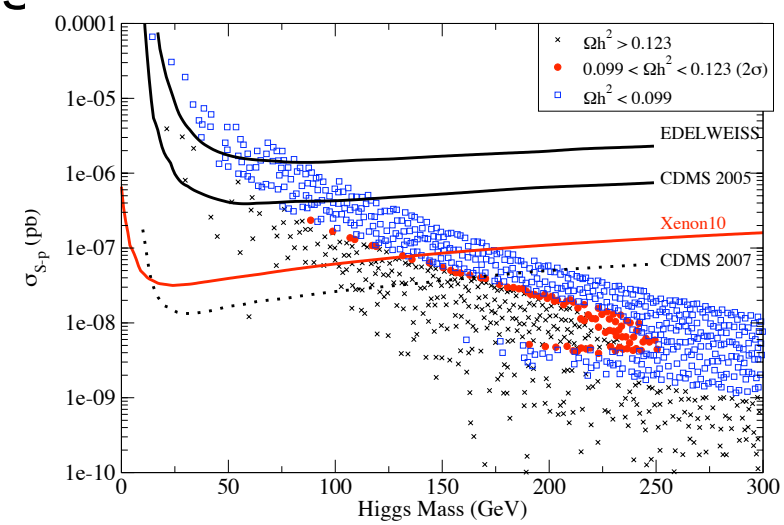



# Direct Detection

- Most of parameter space consistent with $\Omega h^2$ is below present sensitivities of recoil detection expr.

- Future experiments likely need to probe cross-sections to sub-$10^{-8}$ pb




Limits assume $\rho_{DM} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

# Supersymmetry Context

- Superpotential obeys symmetry

| Model: | MSSM | NMSSM | nMSSM | UMSSM | sMSSM |
|---|---|---|---|---|---|
| Symmetry: | – | $\mathbb{Z}_3$ | $\mathbb{Z}_5^R, \mathbb{Z}_7^R$ | $U(1)'$ | $U(1)'$ |
| Extra | – | $\frac{\kappa}{3}\hat{S}^3$ | $t_F\hat{S}$ | – | $\lambda_S S_1 S_2 S_3$ |
| superpotential term | – | (cubic) | (tadpole) | – | (trilinear secluded) |
| $\chi_i^0$ | 4 | 5 | 5 | 6 | 9 |
| $H_i^0$ | 2 | 3 | 3 | 3 | 6 |
| $A_i^0$ | 1 | 2 | 2 | 1 | 4 |

sMSSM approaches nMSSM in large $s_i$ decoupling limit

All models have spectrum similar to MSSM in large $s$ limit

Barger, Langacker, Lee, GS

# Neutralino Sector

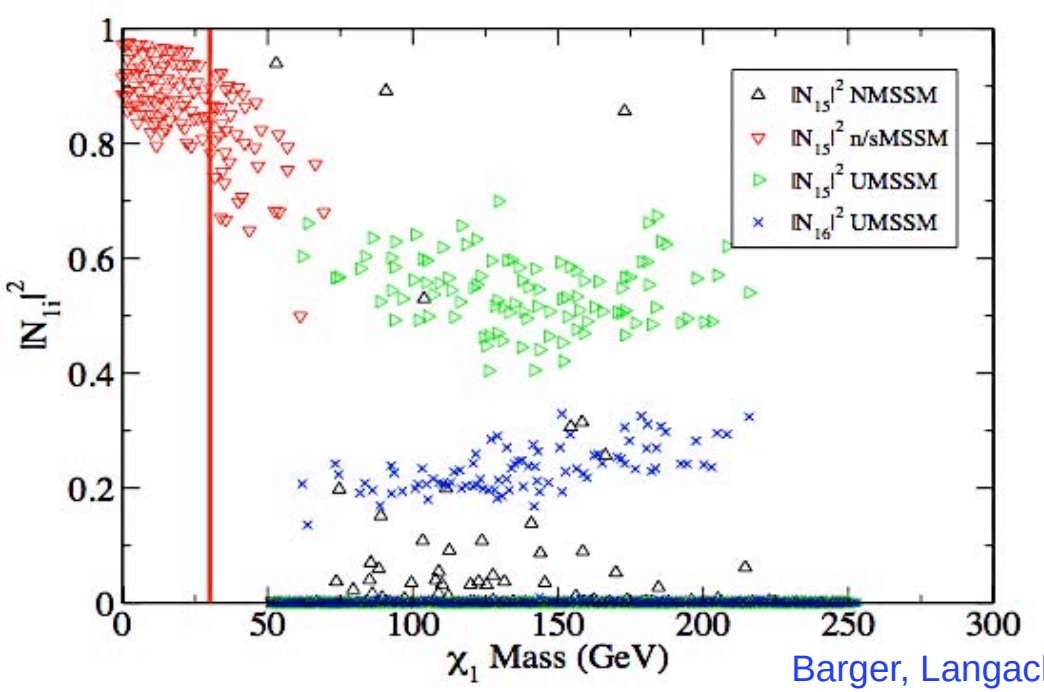
Supersymmetric partners of the singlet and Z'
increase number of neutralino states

$$
\mathcal{M}_{\chi^0} = \begin{array}{c}
\begin{array}{cccccc} \widetilde{B} & \widetilde{W} & \widetilde{H}_d & \widetilde{H}_u & \widetilde{S} & \widetilde{Z}' \end{array} \\
\left(\begin{array}{cccc|c|c}
M_1 & 0 & -g_1 v_d/2 & g_1 v_u/2 & 0 & 0 \\
0 & M_2 & g_2 v_d/2 & -g_2 v_u/2 & 0 & 0 \\
-g_1 v_d/2 & g_2 v_d/2 & 0 & -\mu_{\text{eff}} & -\mu_{\text{eff}} v_u/s & g_{1'} Q_{H_d} v_d \\
g_1 v_u/2 & -g_2 v_u/2 & -\mu_{\text{eff}} & 0 & -\mu_{\text{eff}} v_d/s & g_{1'} Q_{H_u} v_u \\
\hline
0 & 0 & -\mu_{\text{eff}} v_u/s & -\mu_{\text{eff}} v_d/s & \sqrt{2}\kappa s & g_{1'} Q_S s \\
\hline
0 & 0 & g_{1'} Q_{H_d} v_d & g_{1'} Q_{H_u} v_u & g_{1'} Q_S s & M_{1'}
\end{array}\right)
\end{array}
\begin{array}{c} \widetilde{B} \\ \widetilde{W} \\ \widetilde{H}_d \\ \widetilde{H}_u \\ \widetilde{S} \\ \widetilde{Z}' \end{array}
$$

The Singlino and Z' ino, mix with MSSM gauginos and higgsinos, altering the neutralino spectrum and composition

# Neutralino composition

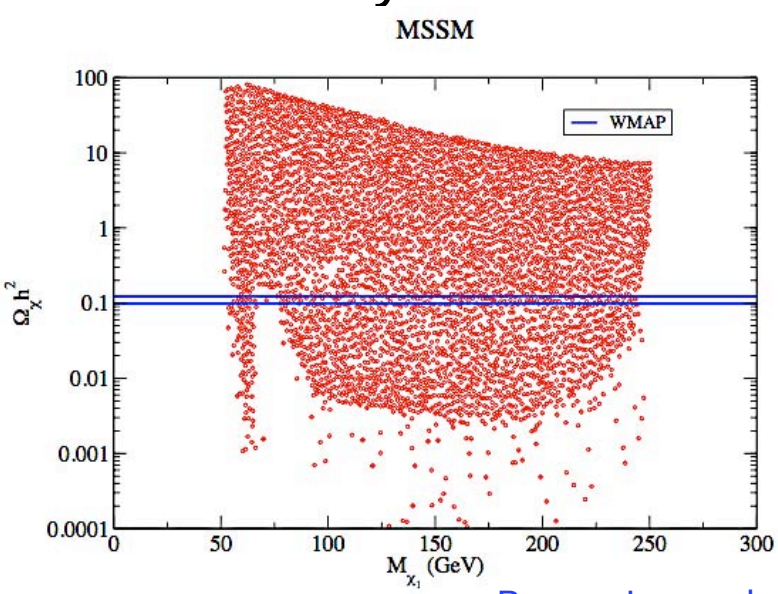
- Lightest neutralino can have large singlino mixture
  - Has large impact on relic density and direct detection prospects
  - Natural in tadpole model

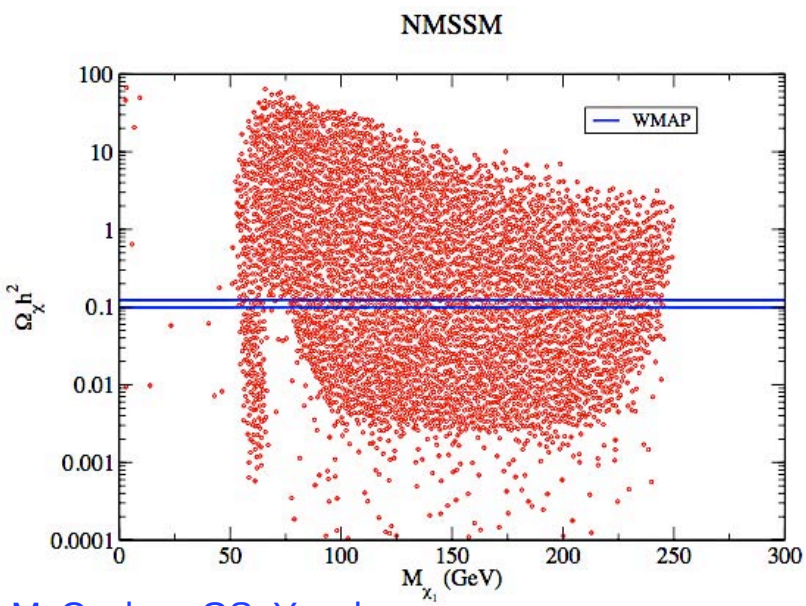



Barger, Langacker, GS

# Relic density in xMSSM

- Low energy spectrum of NMSSM and UMSSM usually similar to MSSM
  - Relic density similar to that of MSSM
- Most points in MSSM, NMSSM and UMSSM sit in Focus Point region (mixed Higgsino-Bino DM + decoupled scalars)
- Annihilation via Higgs pole can yield observed relic density




Barger, Langacker, Lewis, McCaskey, GS, Yencho

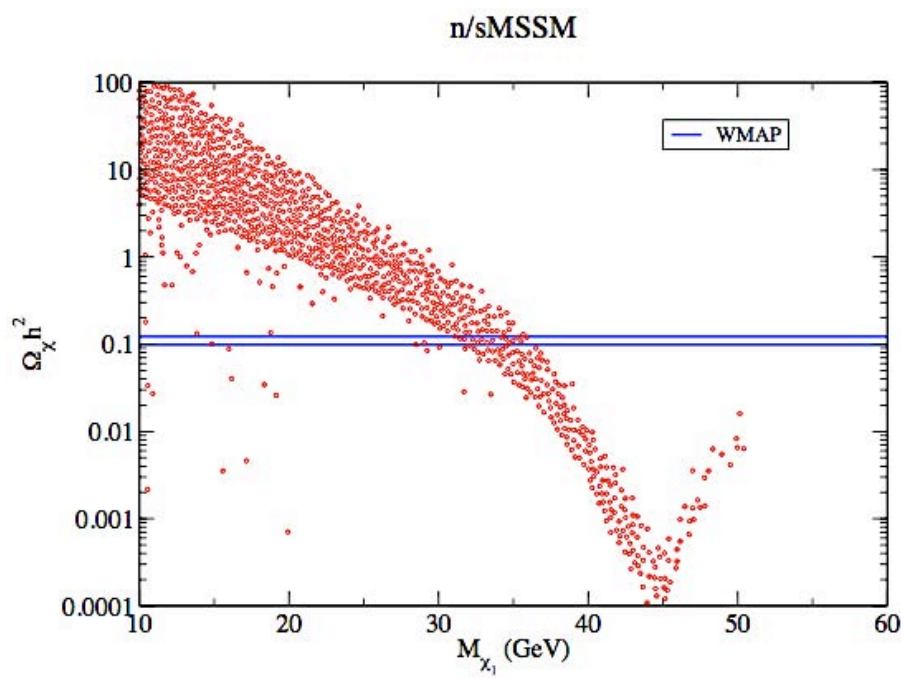
# Relic density in tadpole model (nMSSM)

Tadpole model: $m_{\chi_1^0} \lesssim 50$ GeV

$\rightarrow$ Annihilation to $Z$-boson is typically most relevant

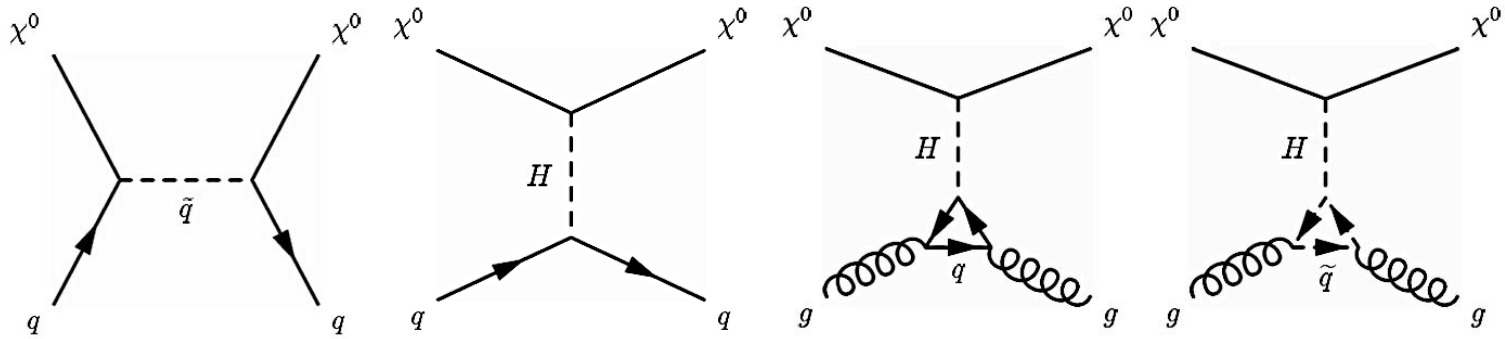
If $\Omega_{DM} < 0.123(2\sigma)$, then $m_{\chi_1^0} \gtrsim 30$ GeV

Very light neutralinos with observed relic density allowed by very light Higgs resonance




See also
Barger, Kao, Langacker, Lee

# Direct detection prospects

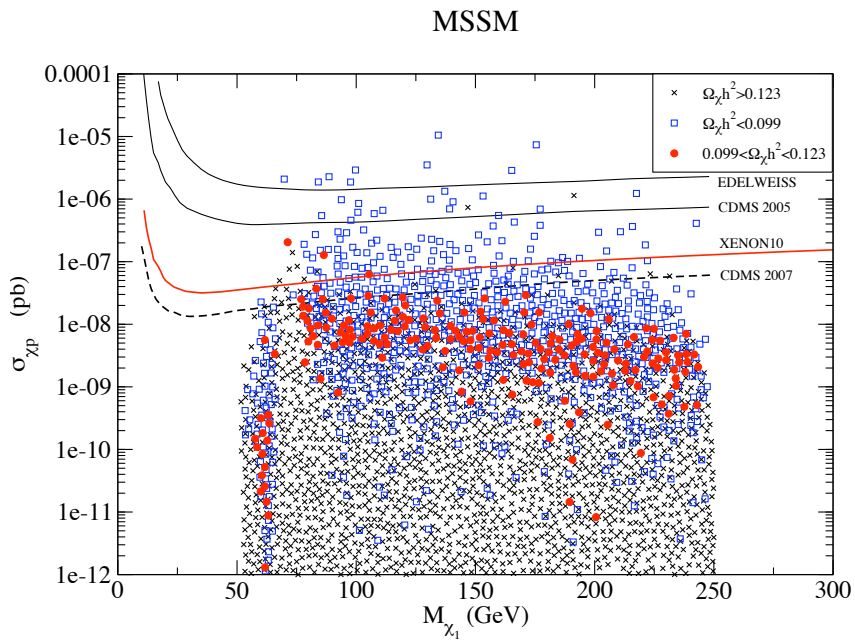


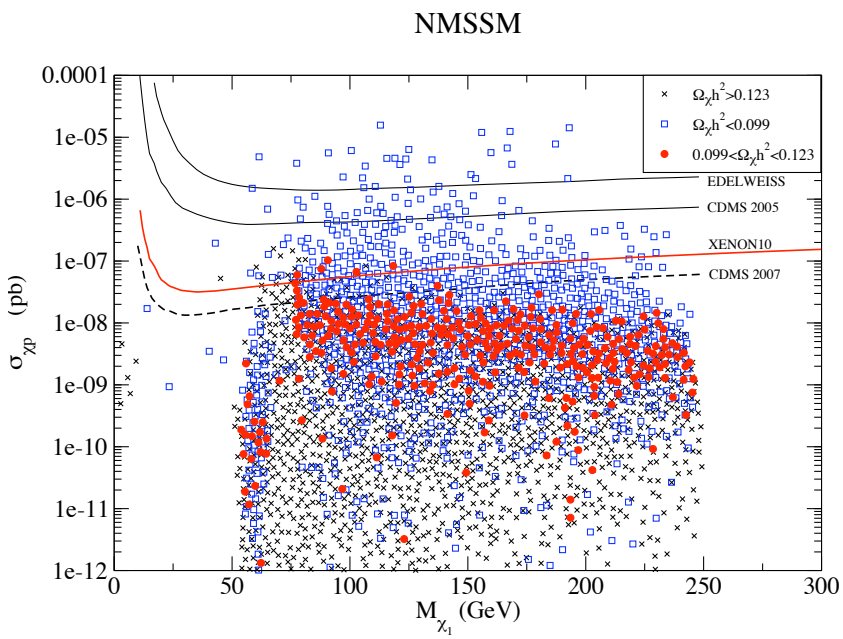

- Spin-independent scattering dominated by Higgs exchange (we take decoupled squarks)

- $h\chi_1^0\chi_1^0$ coupling important
  - Singlet-singlino-singlino interactions can be large

# Direct Detection

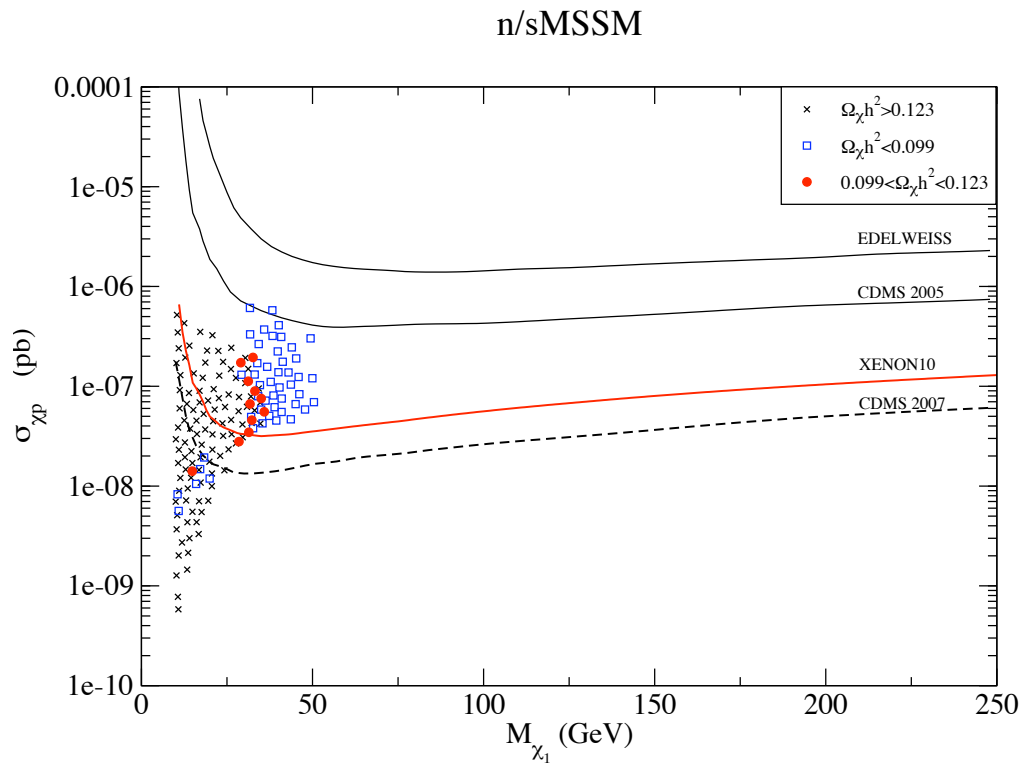
- Elastic scattering cross sections similar between MSSM, and the cubic and U(1) models
- Annihilation through Higgs allows $h\chi_1^0\chi_1^0$ to be small
  - Scattering cross sections in this region very small
  - More likely in extended models (5 Higgs states)



# Tadpole model very constrained

- New results from XENON limit Tadpole model
  - Most parameter points consistent with $\Omega_{DM}$ ruled out




- Annihilation through s-channel Higgs still possible
- Rates decrease if scalar quarks are light

# Summary

SM Higgs + 1 scalar singlet:

- Singlet is DM candidate
- Relic density in observed range for much of parameter space
- SI cross section below $10^{-8}$ pb for most of parameter space
  - Future experiments needed to probe this level

SUSY + 1 scalar singlet:

- Relic density and direct detection limits from XENON eliminate nearly all the parameter space in the nMSSM
- Higgs resonance from one of many states may suppress direct detection rates below future limits

# Backup Slides

# The models

- MSSM - Minimal Supersymmetric SM
  gaugino unification but general $\mu$
- NMSSM Next-to-Minimal Supersymmetric SM
  May have domain wall problems
- nMSSM nearly-Minimal Supersymmetric SM
  Avoids domain wall; tadpole operator from higher order loops
  Often very light Neutralino and Higgs boson
- UMSSM $U(1)'$-extended Supersymmetric SM
  Constraints due to precision electroweak on extra $Z'$
  $\Rightarrow$ similar low mass spectra to MSSM
- sMSSM Secluded $U(1)'$ extended Supersymmetric SM

(reduces to nMSSM in $S_i$ decoupling limit)

  Constraints of UMSSM evaded by additional secluded singlet sector

# Parameter Scan Range

Case A:

| Min | | Max |
|---|---|---|
| 0 | $\lambda$ | 3 |
| 0 | $\lambda_S = \delta_2 + \kappa_2 / v^2$ | 3 |
| -200 GeV | $\delta_1$ | 200 GeV |
| -1 TeV | $\kappa_3$ | 1 TeV |

Case B:

| Min | | Max |
|---|---|---|
| 0 | $\lambda$ | 3 |
| $-200$ GeV | $\delta_1$ | 200 GeV |
| $-3$ | $\delta_2$ | 3 |
| -(200 GeV)$^2$ | $\kappa_2$ | -(200 GeV)$^2$ |
| $-1$ TeV | $\kappa_3$ | 1 TeV |