# A catalogue of neutralino dark matter models with and without SUSY soft term universality

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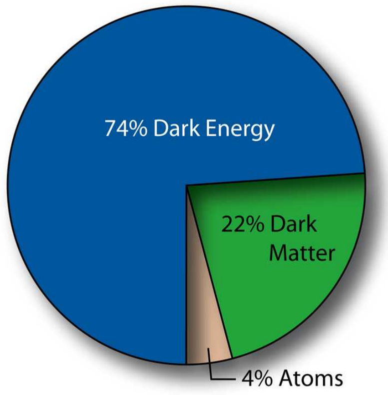
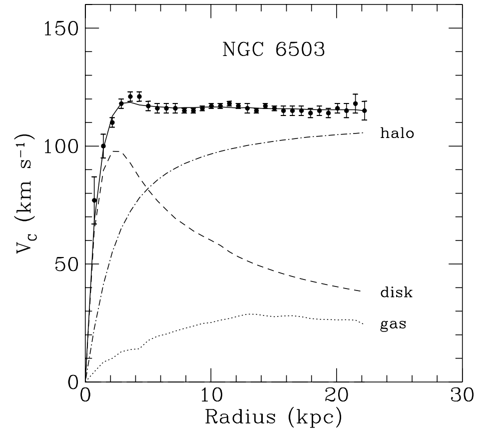
# Dark Matter

- Dominant composition of matter in our universe is not detected visibly but inferred from gravitational effects (Galactic Clustering, Rotation Curves, Gravitational Lensing, Cosmic Microwave Background ...)
- Dark Matter should be non-baryonic (no candidate in the SM), non-relativistic (cold), stable( or long-lived), weakly (or super-weakly) interacting matter
- From the WMAP results, the cold dark matter density of the universe is $\Omega_{CDM} h^2 = 0.111^{+0.011}_{-0.015}$: (upper bound is a tight constraint on SUSY models containing DM candidates : DM may consist of several components)




*http://map.gsfc.nasa.gov*

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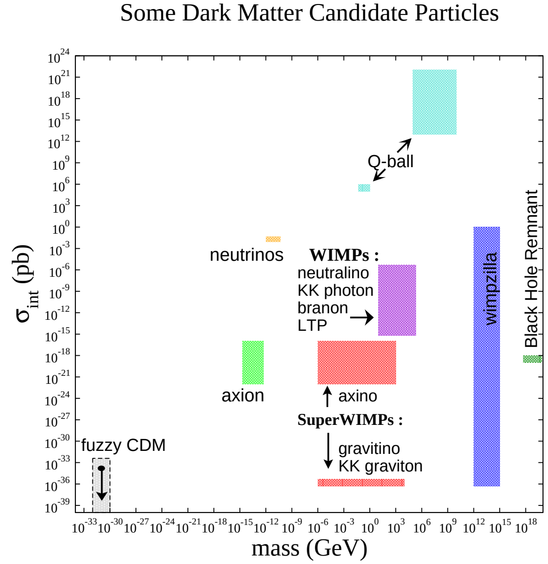
# Neutralino



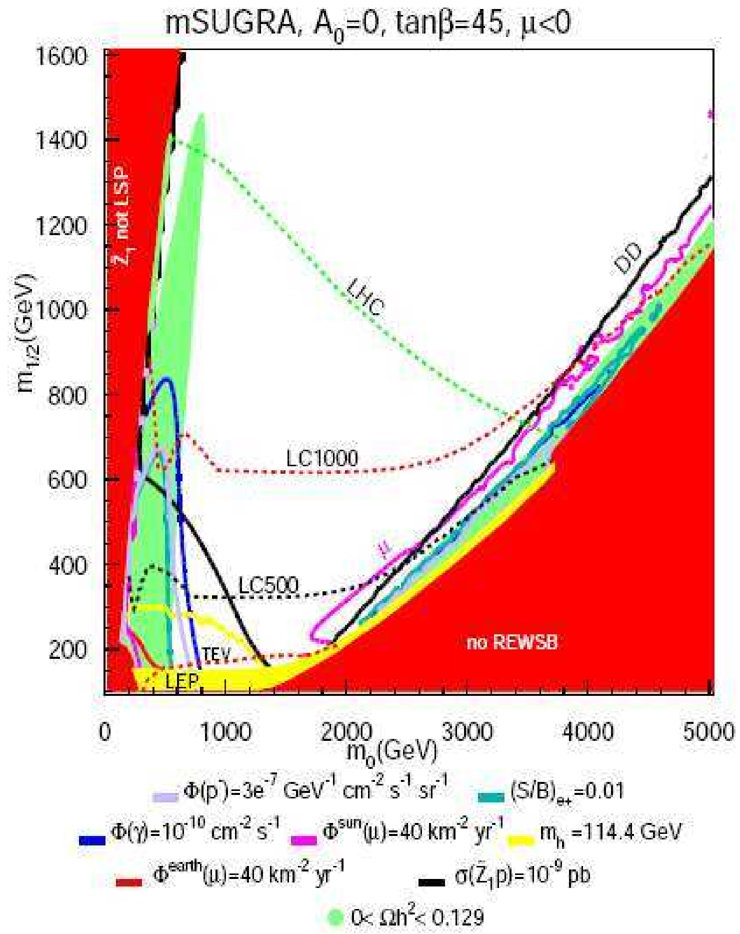

- In SUSY models with $R$-parity conservation
  $\Rightarrow$ the Lightest Supersymmetric Particle(LSP) is stable
  $\Rightarrow$ lightest neutralino $\tilde{Z}_1$ is the LSP in most of MSSM parameter space
  $\Longrightarrow$ $\tilde{Z}_1$ is good candidate for Cold Dark Matter (CDM)
  $$\tilde{z}_1 = v_1^{(1)}\psi_{h_u^0} + v_2^{(1)}\psi_{h_d^0} + v_3^{(1)}\lambda_3 + v_4^{(1)}\lambda_0$$
  Here, $R_{\tilde{w}} = |v_3^{(1)}|$, $R_{\tilde{B}} = |v_4^{(1)}|$ and $R_{\tilde{H}} = \sqrt{|v_1^{(1)}|^2 + |v_2^{(1)}|^2}$
  : $W$-ino, $B$-ino and Higgsino

- We assume,
  - MSSM is an effective theory between the weak and GUT scale
  - $R$-parity is conserved
  - Neutralino LSP

- Number density is governed by Boltzmann equation,
  $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  $\Rightarrow$ requires evaluating many thousands Feynman diagrams
  $\Longrightarrow$ high (co-)annihilation cross section implies low relic abundance

# Review of mSUGRA

- **Parameter space : universal Soft Susy Breaking terms at $Q = M_{GUT}$**
  $m_0$, $m_{1/2}$, $A_0$, tan$\beta$, $sign(\mu)$
- **WMAP allowed Regions in $m_0$-$m_{1/2}$ space**
  *1.* $\tilde{\tau}$ co-annihilation region at low $m_0$, $m_{\tilde{\tau}_1} \sim m_{\tilde{Z}_1}$
  *2.* bulk region at low $m_0$ and $m_{1/2}$, light sleptons (LEP2 excluded)
  *3.* Higgs-funnel $H$, $A$ resonance($2m_{\tilde{Z}_1} \simeq m_{A,H}$) at large tan$\beta \sim 50$ or $h$-resonance at low $m_{1/2}$ ($2m_{\tilde{Z}_1} \simeq m_h$)
  *4.* FP/HB region at large $m_0$, low $\mu \rightarrow$ mixed higgsino dark matter (**MHDM**)
  ⋆ Region 1, 2, 3 → Bino-like LSP




H.Baer et al. JCAP0408 (2004) 005

## Motivations for SUSY models without universality in SSB terms

- **Limitation of mSUSGRA**
  - ⋆ all relic-density-consistent regions in mSUGRA are near the edges of theoretically (or LEP2 experiment) excluded regions
  - ⋆ need to examine how already drawn conclusions from the mSUGRA model are affected by relaxing the universality assumptions
  - ⋆ within $R$-parity conserved neutralino dark matter assumption, WMAP value provides a strong constraint reducing model parameter space by one unit

- **Motivation for models with non-universal SSB terms**
  - non-minimal $f_{AB}$ in SUGRA models,
    e.g. $f_{AB} \ni 1, 24, 75, 200$ in $SU(5)$ SUSY GUTs
  - various string models, e.g. KKLT model
  - extra-dim SUSY GUTs with gaugino mediated SUSY breaking,
    e.g. Dermisek-Mafi $SO(10)$ model

# Models with non-universal soft terms

- **Relic-density-consistent models** obtained by adjusting
  - composition of neutralino (WTN: Well-Tempered Neutralino*)

    *:Arkani-Hamed et al. Nucl.Phys.B741, 108, 2006
  - masses of neutralino or other sparticles
- **Non-universal scalar mass models**
  - Generation non-universality: Normal scalar mass hierarchy (NMH)
  - Non-universal Higgs mass: one extra parameter case ($\mathrm{NUHM1}_\mu$, $\mathrm{NUHM1}_A$ )
  - non-universal Higgs mass: two extra parameter case (HS-Higgs Splitting)
- **Non-universal gaugino mass models**
  - Mixed Wino Dark Matter (MWDM)
  - Bino-Wino Co-Annihilation Scenario (BWCA)
  - Low $|M_3|$ Dark Matter: Compressed SUSY (LM3DM)
  - High $|M_2|$ Dark Matter: left-right split SUSY (HM2DM)
- Some benchmark cases with mSUGRA parameter space
  $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $sign(\mu)$ = 300 GeV, 300 GeV, 0, 10, +1 and $m_t = 171.4$ GeV

# Non-universal scalar mass models

- generation non-universality: Normal scalar Mass Hierarchy (**NMH**)
  $m_0(1,2)$, $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $sign(\mu)$
  - $m_0(1,2)$: first/second generation, $m_0(3) = m_{H_u} = m_{H_d} \equiv m_0$: remaining
  - dial $m_0(1,2)$ to low enough to bulk (co-)annihilation via light sleptons
- non-universal Higgs mass: one extra parameter case (**NUHM1$_\mu$**, **NUHM1$_A$**)
  $m_0$, $\delta_\phi$, $m_{1/2}$, $A_0$, $\tan\beta$, $sign(\mu)$
  - $m_\phi = m_0(1+\delta_\phi)$, $m_{H_u}^2 = m_{H_d}^2 \equiv sign(m_\phi)|m_\phi|^2$
  - $m_\phi > m_0$: small $\mu$ and MHDM
  - $m_\phi < 0$: $m_A \sim 2m_{\tilde{Z}_1} \rightarrow$ at any $\tan\beta$
- non-universal Higgs mass: two extra parameter case (**HS**-Higgs Splitting)
  $m_0$, $m_{H_u}^2$(equivalently $\mu$), $m_{H_d}^2$(equivalently $m_A$), $m_{1/2}$, $A_0$, $\tan\beta$, $sign(\mu)$
  - $m_{H_{u,d}}^2 = m_0^2\ (1 \mp \delta_H)$
  - $\delta_H < 0$: low $\mu$ and low $m_A$
  - $\delta_H > 0$: WMAP region via $\tilde{l}_L/\tilde{\nu}$ or $\tilde{u}_R/\tilde{c}_R$ co-annihilation

# Non-universal gaugino mass models

- Mixed Wino Dark Matter (**MWDM1**, **MWDM2**):
  $m_0$, $M_1$(or $M_2$), $m_{1/2}$, $A_0$, tan$\beta$, $sign(\mu)$
  – by increasing the wino content of the LSP by reducing the ratio $M_2/M_1$
  – $M_1 \neq M_2 = M_3 = m_{1/2}$ or $M_2 \neq M_1 = M_3 = m_{1/2}$
- Bino-Wino Co-Annihilation Scenario (BWCA1, BWCA2):
  same as MWDM but $M_1$ and $M_2$ are in opposite sign
  – by allowing co-annihilation between high bino-like and wino-like states
- Low $|M_3|$ Dark Matter: Compressed SUSY (**LM3DM**):
  $m_0$, $M_3$, $m_{1/2}$, $A_0$, tan$\beta$, $sign(\mu)$
  – by increasing the higgsino content of the LSP by decreasing the gluino mass
  – $M_3 \neq M_1 = M_2 = m_{1/2}$
- High $|M_2|$ Dark Matter: left-right split SUSY (**HM2DM**):
  $m_0$, $M_2$, $m_{1/2}$, $A_0$, tan$\beta$, $sign(\mu)$
  – by allowing large $M_2$ mass
  – $M_2 >> M_1 = M_3 = m_{1/2}$

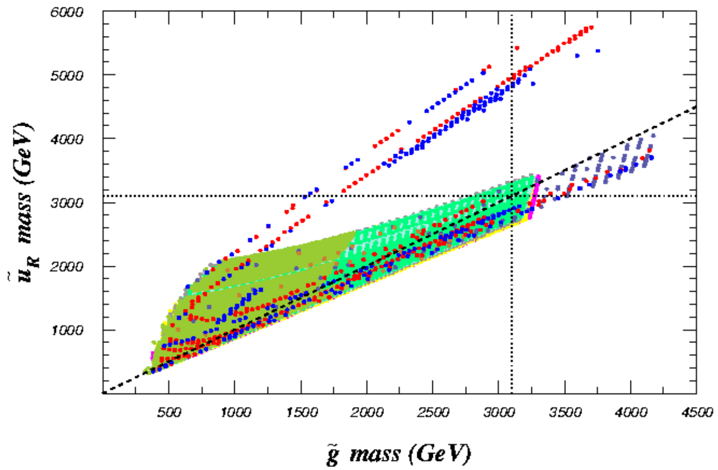
## Some Benchmark Cases: non-universal scalar mass models

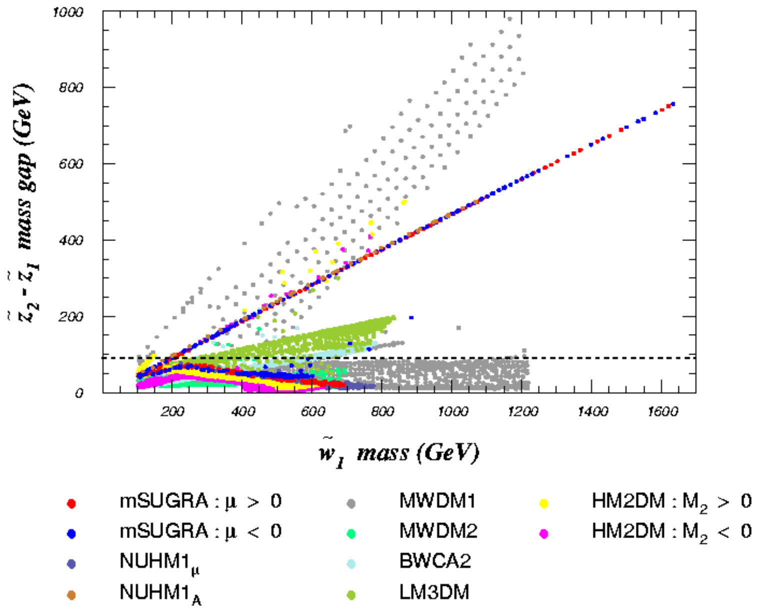
| parameter | mSUGRA | NMH | $\text{NUHM1}_\mu$ | $\text{NUHM1}_A$ | HS |
|---|---|---|---|---|---|
| special | — | $m_0(1,2)$ | $m_\phi$ | $m_\phi$ | $\delta_H$ |
| value | — | 54 | 549 | -728 | -1.36 |
| $\mu$ | 385.1 | 386.5 | 105.8 | 748.5 | 269.3 |
| $m_{\tilde{g}}$ | 729.7 | 722.1 | 731.4 | 733.4 | 728.9 |
| $m_{\tilde{u}_L}$ | 720.8 | 658.4 | 724.3 | 720.5 | 720.1 |
| $m_{\tilde{t}_1}$ | 523.4 | 526.5 | 484.1 | 624.5 | 505.8 |
| $m_{\tilde{b}_1}$ | 656.8 | 659.8 | 642.2 | 689.5 | 645.4 |
| $m_{\tilde{e}_L}$ | 364.5 | 216.2 | 364.8 | 365.8 | 373.4 |
| $m_{\tilde{e}_R}$ | 322.3 | 128.9 | 322.5 | 321.9 | 301.8 |
| $m_{\tilde{\tau}_1}$ | 317.1 | 317.6 | 317.8 | 316.4 | 299.3 |
| $m_{\widetilde{W}_2}$ | 411.7 | 412.7 | 264.7 | 754.8 | 321.1 |
| $m_{\widetilde{W}_1}$ | 220.7 | 219.5 | 91.1 | 234.9 | 196.6 |
| $m_{\widetilde{Z}_2}$ | 220.6 | 219.4 | 117.4 | 234.5 | 198.1 |
| $m_{\widetilde{Z}_1}$ | 119.2 | 118.4 | 69.0 | 121.5 | 115.4 |
| $m_A$ | 520.3 | 521.9 | 584.5 | 268.5 | 279.0 |
| $m_{H^+}$ | 529.8 | 531.4 | 593.8 | 281.6 | 292.0 |
| $m_h$ | 110.1 | 110.1 | 109.8 | 110.5 | 109.8 |
| $\Omega_{\widetilde{Z}_1}h^2$ | 1.1 | 0.10 | 0.11 | 0.11 | 0.10 |
| $\sigma_{SI}(\widetilde{Z}_1 p)$ | $2.1\times10^{-9}$ pb | $2.1\times10^{-9}$ pb | $7.8\times10^{-8}$ pb | $1.2\times10^{-9}$ pb | $2.7\times10^{-8}$ pb |
| $R_{\tilde{H}}$ | 0.15 | 0.14 | 0.84 | 0.06 | 0.26 |

## Some Benchmark Cases: non-universal gaugino mass models

| parameter | mSUGRA | MWDM | BWCA | LM3DM | HM2DM |
|---|---|---|---|---|---|
| special | — | $M_1(M_{GUT})$ | $M_1(M_{GUT})$ | $M_3(M_{GUT})$ | $M_2(M_{GUT})$ |
| value | — | 490 | -480 | 160 | 900 |
| $\mu$ | 385.1 | 385.9 | 376.6 | 185.3 | 134.8 |
| $m_{\tilde{g}}$ | 729.7 | 729.9 | 731.7 | 420.2 | 736.4 |
| $m_{\tilde{u}_L}$ | 720.8 | 721.2 | 722.0 | 496.9 | 901.8 |
| $m_{\tilde{u}_R}$ | 702.7 | 708.9 | 709.9 | 467.0 | 696.3 |
| $m_{\tilde{t}_1}$ | 523.4 | 526.5 | 536.3 | 312.2 | 394.3 |
| $m_{\tilde{b}_1}$ | 656.8 | 656.0 | 658.9 | 443.2 | 686.4 |
| $m_{\tilde{e}_L}$ | 364.5 | 371.5 | 371.4 | 366.1 | 669.3 |
| $m_{\tilde{e}_R}$ | 322.3 | 353.3 | 352.2 | 322.6 | 321.3 |
| $m_{\widetilde{W}_2}$ | 411.7 | 412.4 | 404.5 | 282.9 | 719.7 |
| $m_{\widetilde{W}_1}$ | 220.7 | 220.8 | 220.0 | 152.5 | 136.5 |
| $m_{\widetilde{Z}_2}$ | 220.6 | 223.2 | 219.2 | 163.6 | 142.3 |
| $m_{\widetilde{Z}_1}$ | 119.2 | 194.6 | 201.7 | 105.5 | 94.8 |
| $m_A$ | 520.3 | 525.9 | 518.6 | 398.3 | 670.7 |
| $m_{H+}$ | 529.8 | 535.3 | 528.1 | 408.7 | 679.8 |
| $m_h$ | 110.1 | 110.2 | 109.8 | 106.0 | 111.9 |
| $\Omega_{\widetilde{Z}_1} h^2$ | 1.1 | 0.10 | 0.10 | 0.10 | 0.10 |
| $\sigma_{SI}(\widetilde{Z}_1 p)$ | $2.1 \times 10^{-9}$ pb | $1.5 \times 10^{-8}$ pb | $3.1 \times 10^{-11}$ pb | $7.2 \times 10^{-8}$ pb | $3.4 \times 10^{-8}$ pb |
| $R_{\tilde{H}}$ | 0.15 | 0.25 | 0.16 | 0.50 | 0.67 |

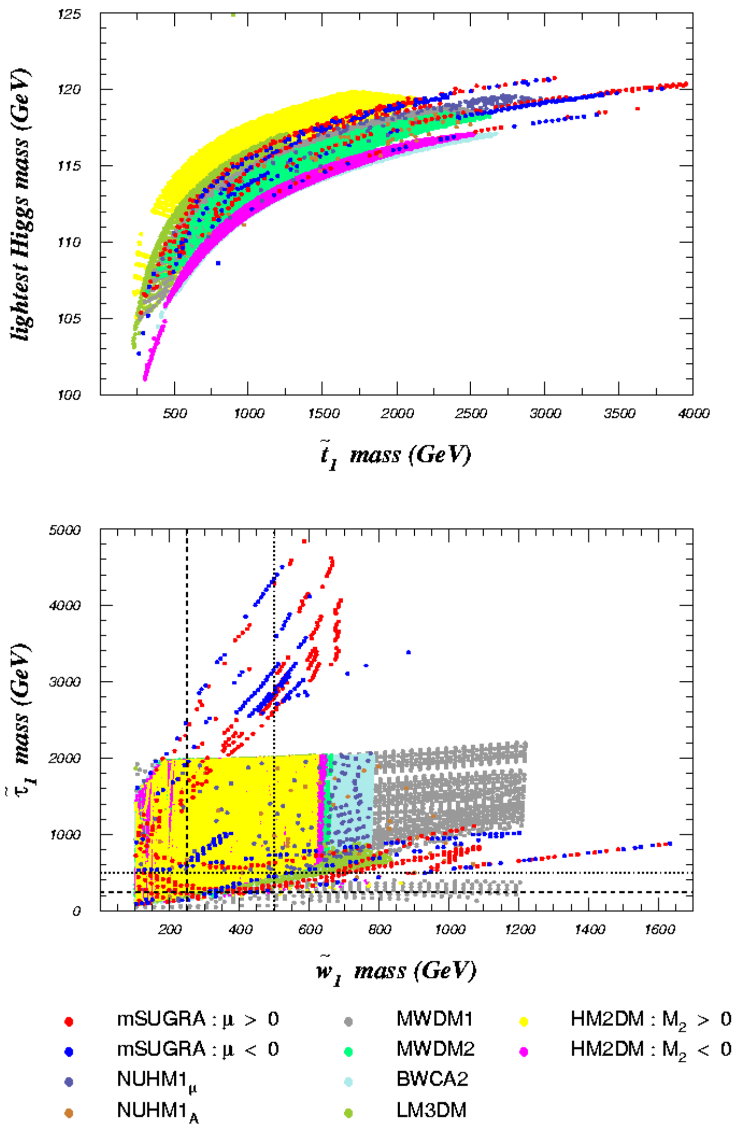
# Implications for collider searches 1



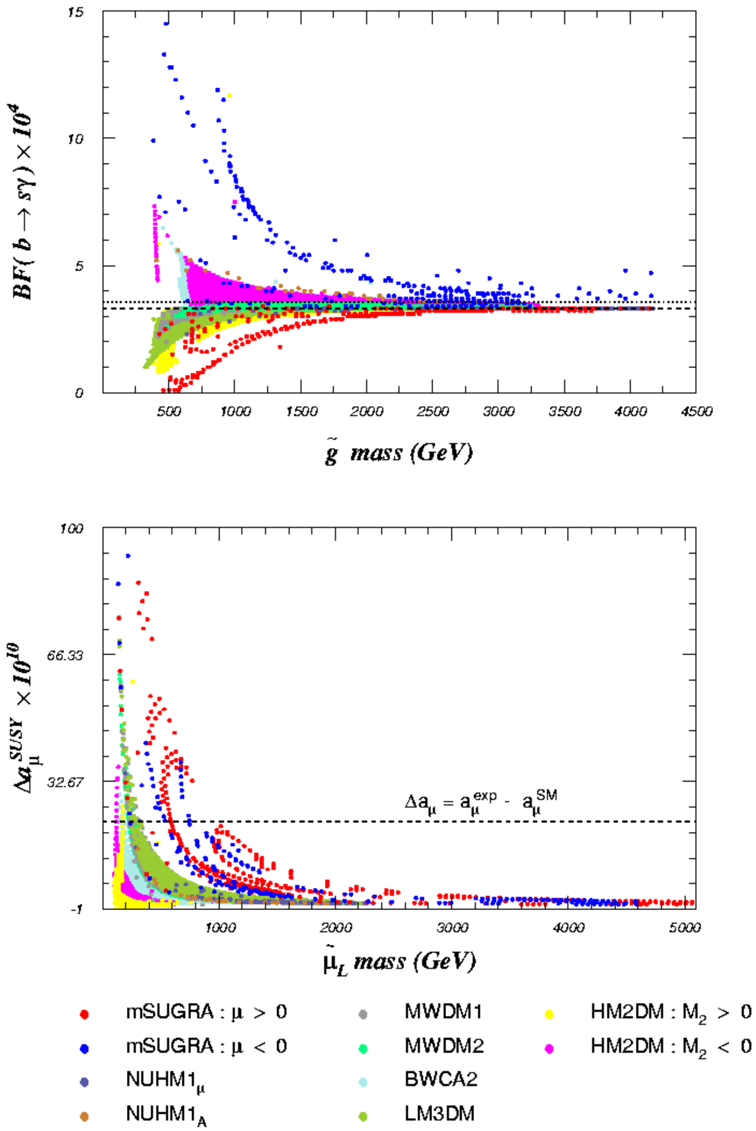

- – with $A_0 = 0$, $m_t = 171.4$ GeV, $\tan\beta = 10$ (except for the mSUGRA model: $\tan\beta = 10$, 30, 45, 50, 52 and 55)
  – non-universal mass dialed to yield $\Omega_{\widetilde{Z}_1} h^2 \simeq 0.11$
- $m_{\tilde{g}}$ *vs.* $m_{\tilde{u}_R}$
  – dotted lines: 100 fb$^{-1}$ reach of CERN LHC
  – dashed line: $m_{\tilde{u}_R} = m_{\tilde{g}}$
  – most of models within reach of LHC except HB/FP region of mSUGRA
- $m_{\widetilde{W}_1}$ *vs.* $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$
  – dashed line: $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} = M_Z$
  – below the line, 3-body decay like $\tilde{Z}_2 \to \tilde{Z}_1 l\bar{l}$ open
  – in most models, $m(l\bar{l})$ mass edge visible at LHC

# Implications for collider searches 2




- $m_h$ *vs.* $m_{\tilde{t}_1}$
  - heavier $\tilde{t}_1$ squarks are correlated with larger values of $m_h$ (due to top-Yukawa radiative corrections to $m_h$)
  - in many models with $m_A \gg M_Z$, then $h \simeq H_{\rm SM}$: the LEP2 lower bound of 114.1 GeV applicable
- $m_{\widetilde{W}_1}$ *vs.* $m_{\tilde{\tau}_1}$
  - dashed lines: reach of ILC500 ($\sqrt{s} = 500$ GeV)
  - dotted lines: reach of ILC1000 ($\sqrt{s} = 1000$ GeV)

# Implications for $BF(b \to s\gamma)$ and $(g-2)_\mu$




- $BF(b \to s\gamma)$
  - dotted line: combined experimental measurement (CLEO, Belle, BABAR)
    $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$
  - dashed line: SM prediction
    $BF(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$
- $(g-2)_\mu$
  - *positive* deviation in $a_\mu \equiv \frac{(g-2)_\mu}{2}$
    $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 22(10) \times 10^{-10}$
  - $\Delta a_\mu^{\mathrm{SUSY}} \propto \tan\beta$

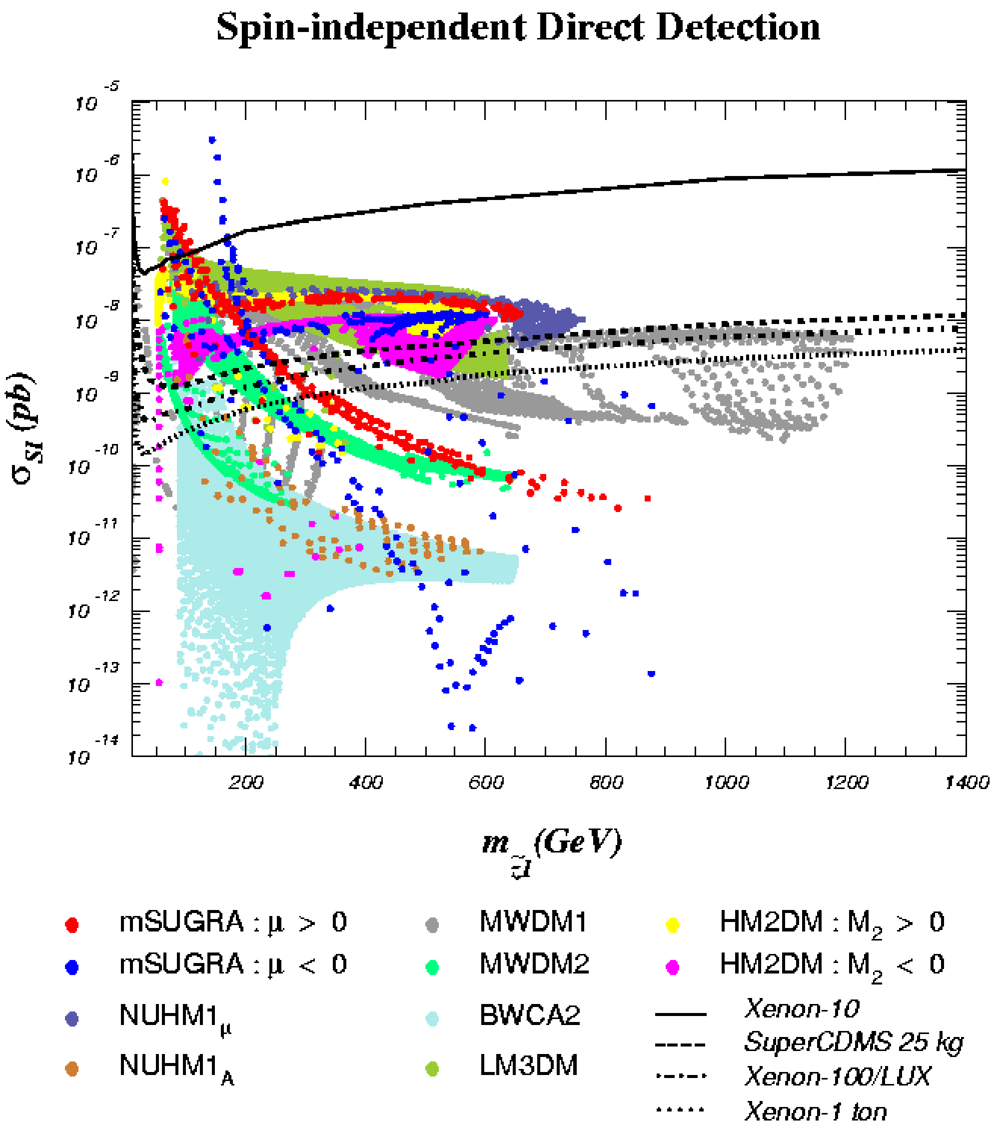
⋆ We assume,

  - (near)degeneracy of first and second generation of SSB sfermions → FCNC suppressed
  - CP-violating phases in SSB suppressed → CP contribution of SUSY is small

# Direct and Indirect Dark Matter Detection

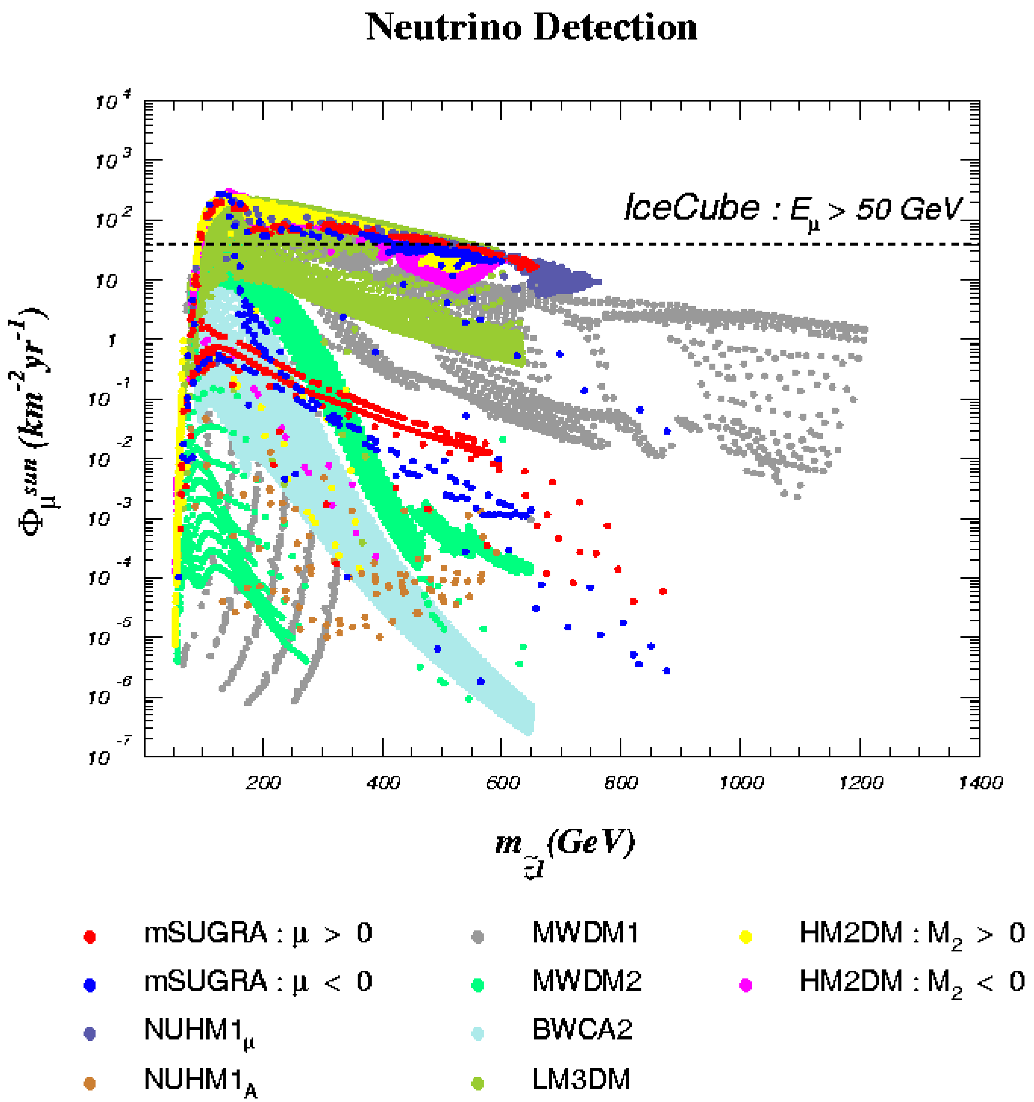
- Direct Detection: Spin independent Neutralino-Proton scattering Cross section (with current experimental sensitivities:Xenon-10(100, 1000), SuperCDMS, LUX)
- Indirect Detection
  - Detection of $\mu$ : Neutrinos from the Sun - IceCube
    $\tilde{Z}_1\tilde{Z}_1 \rightarrow W^+W^-, q\bar{q}, \ldots \rightarrow \pi^-(\pi^+) \rightarrow \bar{\nu_\mu}(\nu_\mu) \rightarrow \mu^-(\mu^+)$
  - Detection of antiparticles : $\tilde{Z}_1\tilde{Z}_1 \rightarrow W^+W^-, q\bar{q}, ZZ, \ldots \rightarrow jets$
    Antiprotons ($jets \ni \bar{p}$) : PAMELA, Positrons ($jets \ni e^+$) : PAMELA,
    Antideuterons ($jets \ni \bar{D}$) : GAPS
  - Detection of Gamma Rays from the galactic center - GLAST
- IsaRES code and DarkSUSY

# Implications for direct dark matter detection



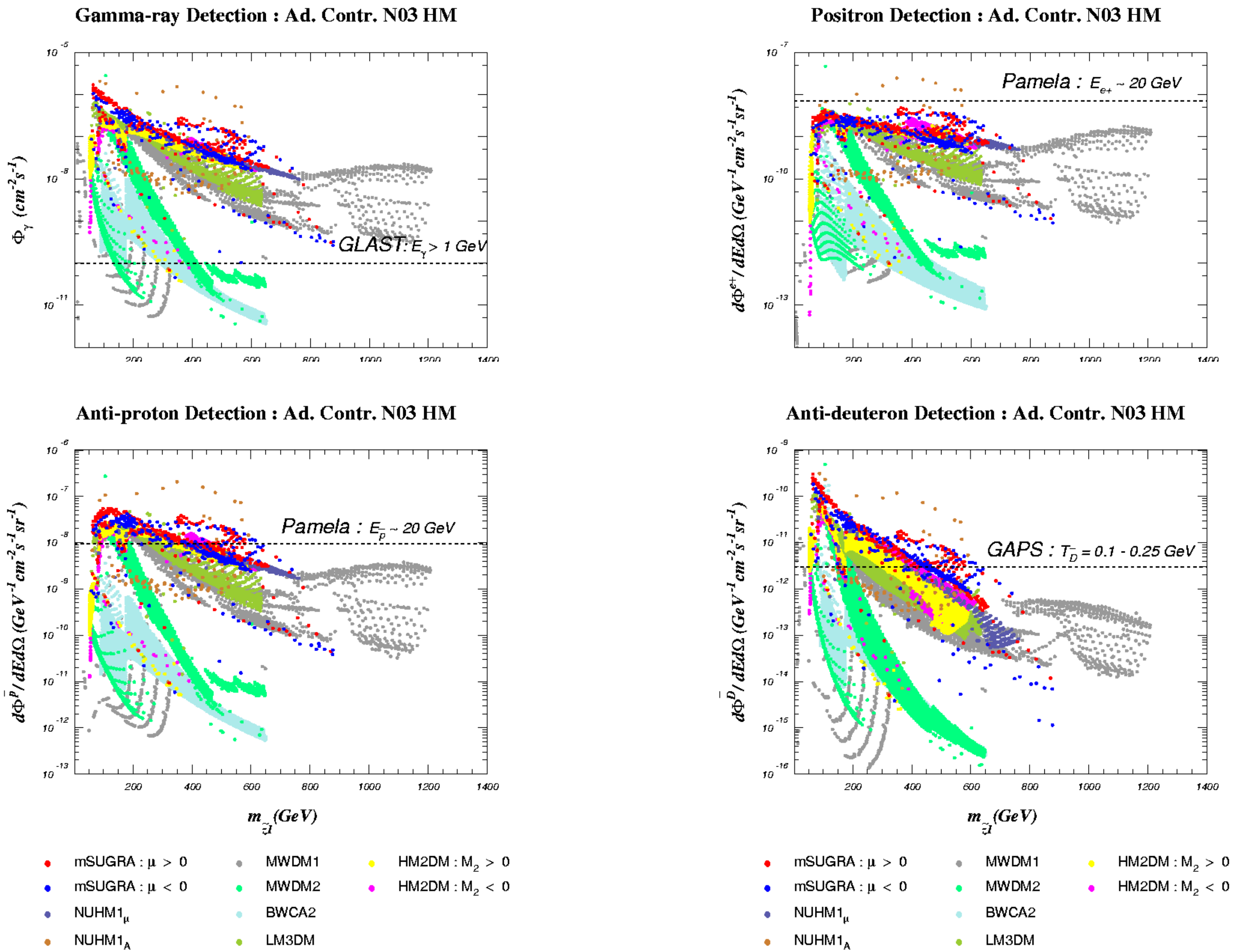

- models with WTN within reach of next generation of detectors
- models adjusted masses to get WMAP value below sensitivities of detectors

# Implications for indirect DM detection - Neutrino Detection

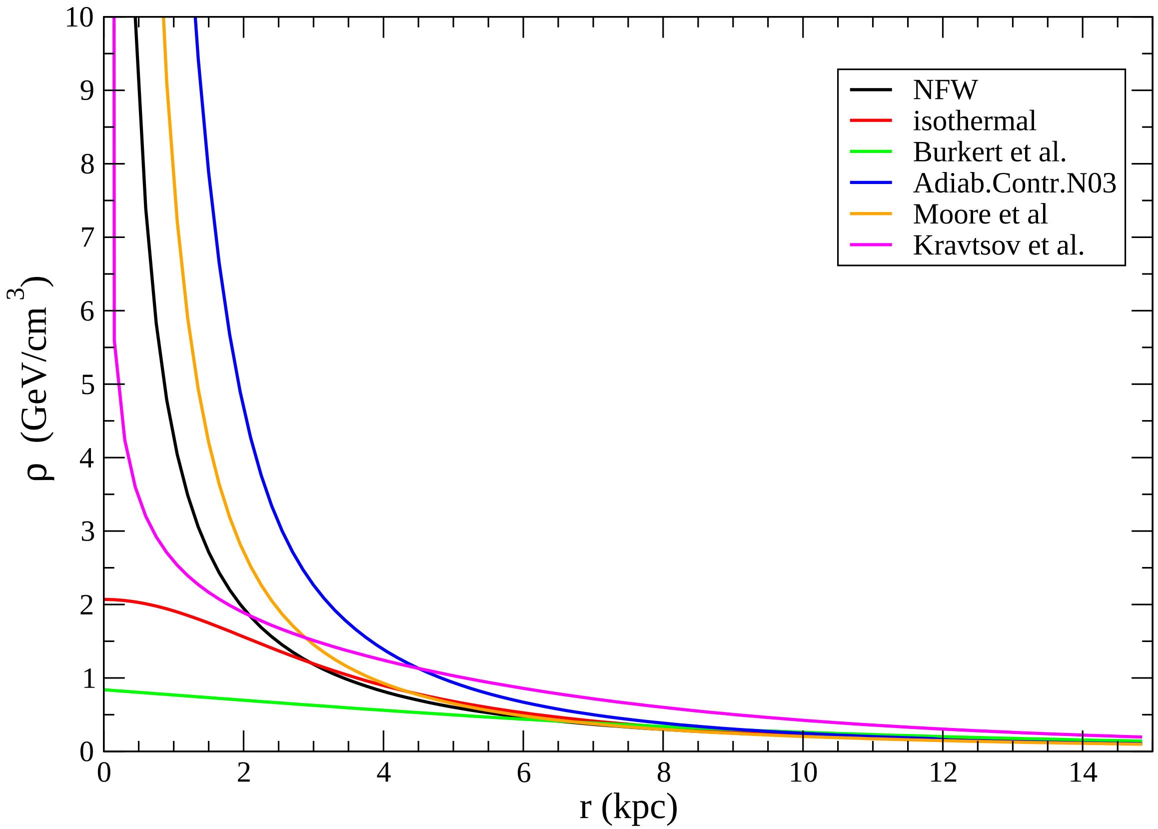



- muon fluxes from neutralino annihilation in the solar core to $\nu_\mu$ states
- main contribution comes from $Z$-exchange ← enhanced if neutralino has high higgsino content

# Implications for indirect($\gamma$-ray, antiparticle) DM detection



# Halo Density Profile



# Conclusions

1. ⋆ WTN occurs *only* in FP/HB region in mSUGRA (MHDM: $m_{\tilde{q}} >> m_{\tilde{Z}_1, \tilde{W}_1, \tilde{g}}$).
   But, in relic-density-consistent models, easily get WTN with $m_{\tilde{q}} \sim m_{\tilde{g}}$
   ⋆ Higgs funnel enhancement is *only* for very large tan$\beta$ values in mSUGRA.
   But, in non-universal Higgs mass models, we have Higgs funnel for any tan$\beta$ value

2. In many relic-density-consistent models, $\tilde{Z}_2 - \tilde{Z}_1$ mass gap $< M_Z$
   → 2-body decay modes kinematically closed
   → 3-body decay modes open ⇒ at least one dilepton mass edge detectable at LHC
   → location of dilepton mass edge is clean signature of SUSY models

3. ⋆ $m_{\tilde{q}} = m_{\tilde{g}}$, $m_{\tilde{q},\tilde{g}}$ <3100 GeV for most relic-density-consistent models
   → implies SUSY signals at LHC
   ⋆ $m_{\tilde{\tau}}$ <500 GeV for LM3DM
   → accessible at ILC with $\sqrt{s}$=1 TeV

4. In WTN models,
   ⋆enhanced annihilation rates enhance direct DM detection rates
   ⋆in many cases, muon neutrino signals accessible at IceCube
   ⋆indirect DM searches in galactic halo into gamma rays and anti-matter elevated; large uncertainties associated with unknown galactic DM density profile

# MSSM RGEs

$$\frac{dm^2_{H_u}}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$\frac{dm^2_{H_d}}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + 3f_b^2X_b + f_\tau^2X_\tau\right)$$

$$\frac{dm^2_{Q_3}}{dt} = \frac{2}{16\pi^2}\left(-\frac{1}{15}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{10}g_1^2S + f_t^2X_t + f_b^2X_b\right)$$

$$\frac{dm^2_{\tilde{t}_R}}{dt} = \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 - \frac{2}{5}g_1^2S + 2f_t^2X_t\right)$$

$$\frac{dm^2_{\tilde{b}_R}}{dt} = \frac{2}{16\pi^2}\left(-\frac{4}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{5}g_1^2S + 2f_b^2X_b\right)$$

$$\frac{dm^2_{L_3}}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + f_\tau^2X_\tau\right)$$

$$\frac{dm^2_{\tilde{\tau}_R}}{dt} = \frac{2}{16\pi^2}\left(-\frac{12}{5}g_1^2M_1^2 + \frac{3}{5}g_1^2S + 2f_\tau^2X_\tau\right)$$

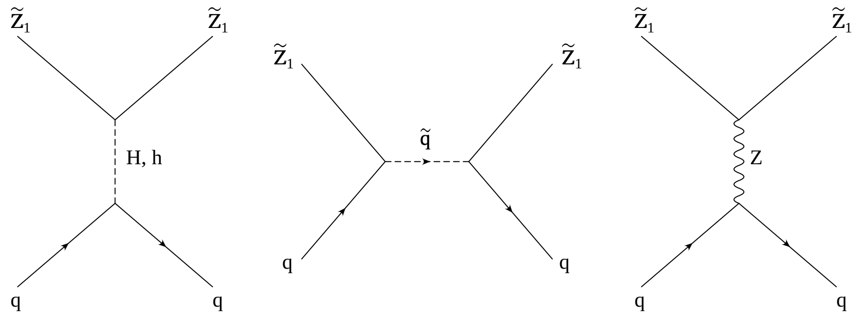
$$S = m^2_{H_u} - m^2_{H_d} + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$$

where $t = \log(Q)$, $f_{t,b,\tau}$ are the $t$, $b$ and $\tau$ Yukawa couplings, and

$$\begin{aligned} X_t &= m^2_{Q_3} + m^2_{\tilde{t}_R} + m^2_{H_u} + A^2_t \\ X_b &= m^2_{Q_3} + m^2_{\tilde{b}_R} + m^2_{H_d} + A^2_b \\ X_\tau &= m^2_{L_3} + m^2_{\tilde{\tau}_R} + m^2_{H_d} + A^2_\tau \end{aligned}$$

# Feynman Diagrams Contributing to Neutralino DM Detection

- Direct Detection




- Indirect Detection