SUSY Dark Matter

Yudi Santoso

IPPP - Durham - UK

SUSY - phenomenology

- SUSY must be broken softly - w/ soft masses ~ 1 TeV.
- R-parity is conserved (baryon and lepton number conservation).
  $P_R = (-1)^{3(B-L)+2S}$: even for SM particles, odd for superpartners.
- Conserved R-parity $\Rightarrow$ stable LSP $\Rightarrow$ relic density.
- Astrophysical observation - need dark matter.
  - Neutral massive LSP could be the dark matter!
  - Neutralino WIMP can have thermal relic density of the ‘correct’ order!!!

The CMSSM

(Constrained Minimal Supersymmetric Standard Model)
also known as mSUGRA = minimal Supergravity Model

- Assume unification at some high energy input scale (presumably the GUT scale).
- Only five free SUSY parameters:

$$
\begin{aligned}
m_0 &= \text{universal scalar soft mass at } m_{\rm GUT} \\
m_{1/2} &= \text{universal gaugino mass at } m_{\rm GUT} \\
A_0 &= \text{universal trilinear mass at } m_{\rm GUT} \\
\tan\beta &= \text{ratio of the two Higgs doublet vev} \\
\text{sign}(\mu) & \quad (\mu = \text{ Higgs mixing parameter})
\end{aligned}
$$

- Employ RGE to get spectrum at low energy scale.

The NUHM

(Non-Universal Higgs Masses model)

- In GUT models: matter fields and Higgs fields are not in the same type of multiplets.
- Two new parameters in addition to the CMSSM's: $m_{H_1}(m_{\rm GUT}),\, m_{H_2}(m_{\rm GUT}) \neq m_0$.
- By using EWSB conditions

$$
\begin{aligned}
\mu^2(\tan^2\beta - 1) &= m_{H_1}^2 - m_{H_2}^2 \tan^2\beta + \frac{1}{2} m_Z^2 (1 - \tan^2\beta) \\
m_A^2 &= m_{H_1}^2 + m_{H_2}^2 + 2\mu^2
\end{aligned}
$$

  these can be traded with the weak mixing parameter μ and the CP-odd Higgs mass m_A, both at weak scale.
- NUHM parameters: $m_0, m_{1/2}, A_0, \tan\beta, \mu$ and m_A.

Phenomenological Aspects of SUSY

- On particle physics:
  - Loop correction:
    muon anomalous magnetic moment $(g-2)_\mu$,
    rare decay processes $b \to s\gamma$, $B_S \to \mu^+\mu^-$, etc.
  - Higgs mass. (Georg Weiglein & collaborators - `FeynHiggs`.)
  - SUSY particles searches at colliders.
- On dark matter hypothesis:
  - relic density
  - direct detection
  - indirect detection (astrophysical signals of DM)

On the Relic Density

- Observational constraint - WMAP:

$$\Omega_{DM}^{(WMAP)} h^2 = 0.1045^{+0.0073}_{-0.0128}$$

(or WMAP+SDSS: $\Omega_{DM} h^2 = 0.111^{+0.011}_{-0.015}$)

- Caveat for theoretical analysis:
  - Is there any other dark matter (multiparticle dark matter)?
  - Is there non-thermal source of the dark matter particle?

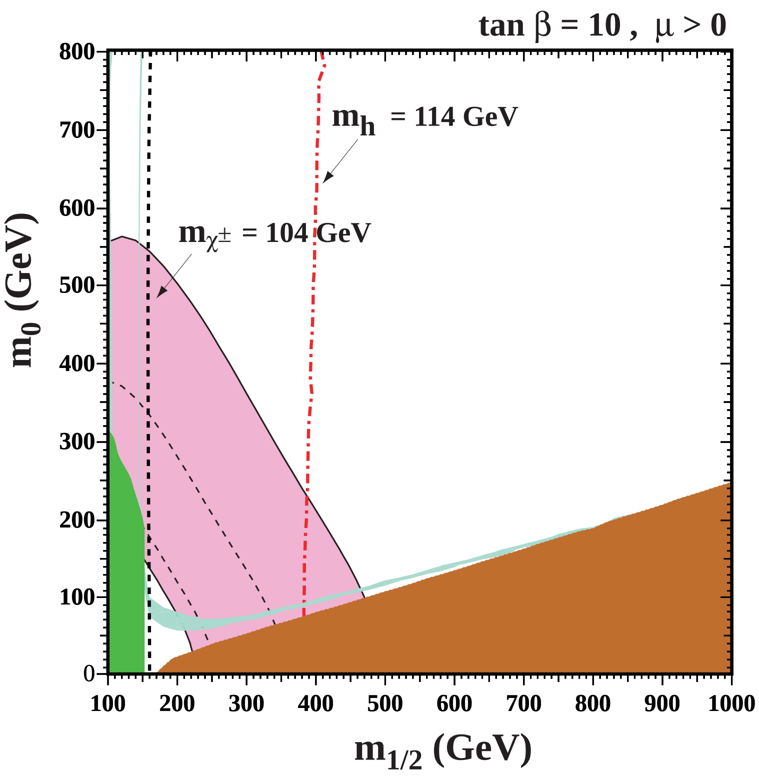
So WMAP result should be treated as an upper bound for LSP relic density.

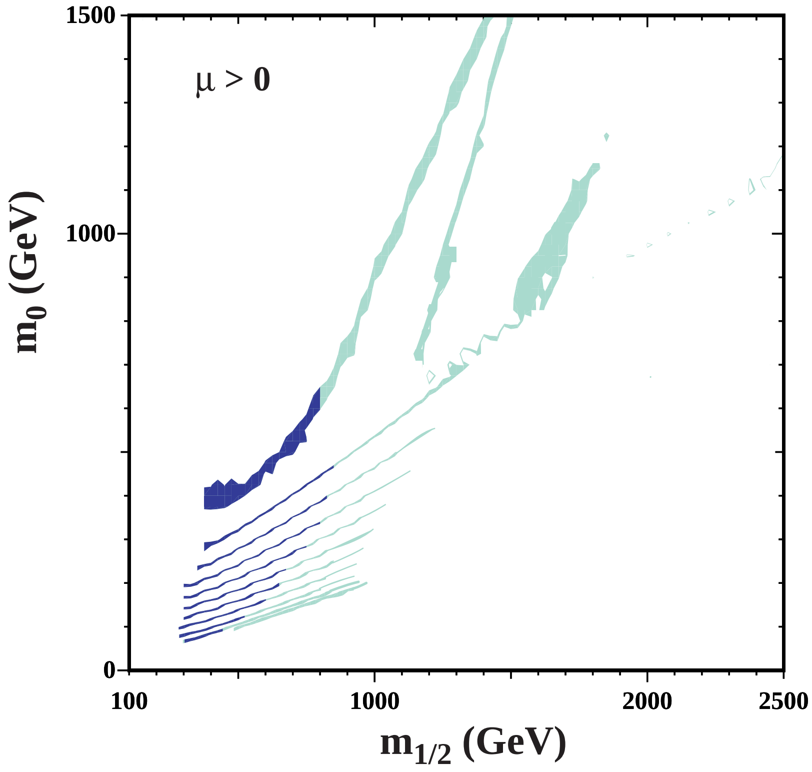
Less than WIMP

Order of magnitude analysis is not enough. Simple neutralino pair annihilation generally yields *too much* relic density. Some ways to suppress relic density further:

- Annihilation near pole (resonance)
- Focus point region (coupling enhanced by larger Higgsino content)
- Coannihilation with the next lightest supersymmetric particle (NLSP): stau, stop, ...

CMSSM after WMAP

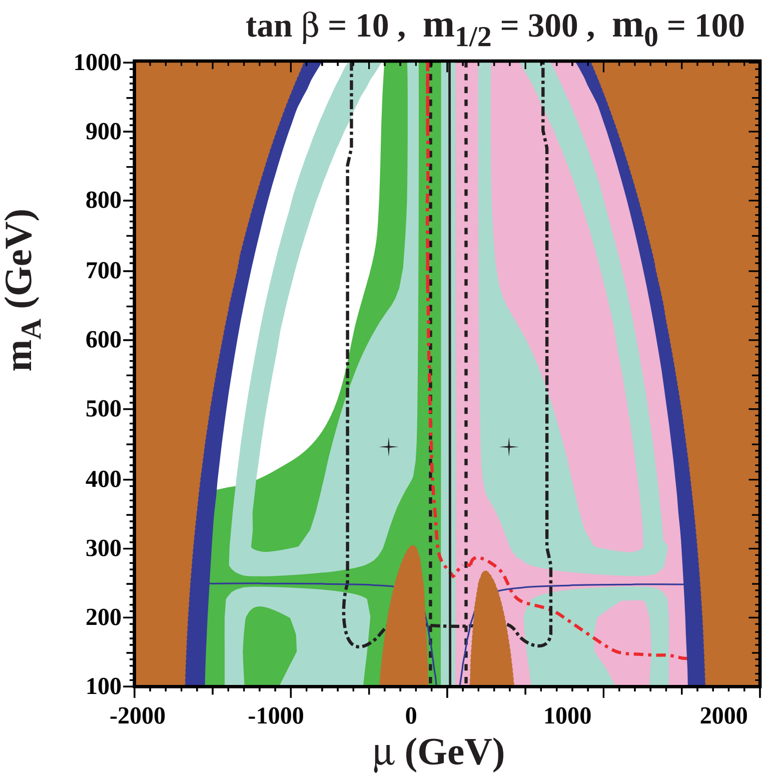




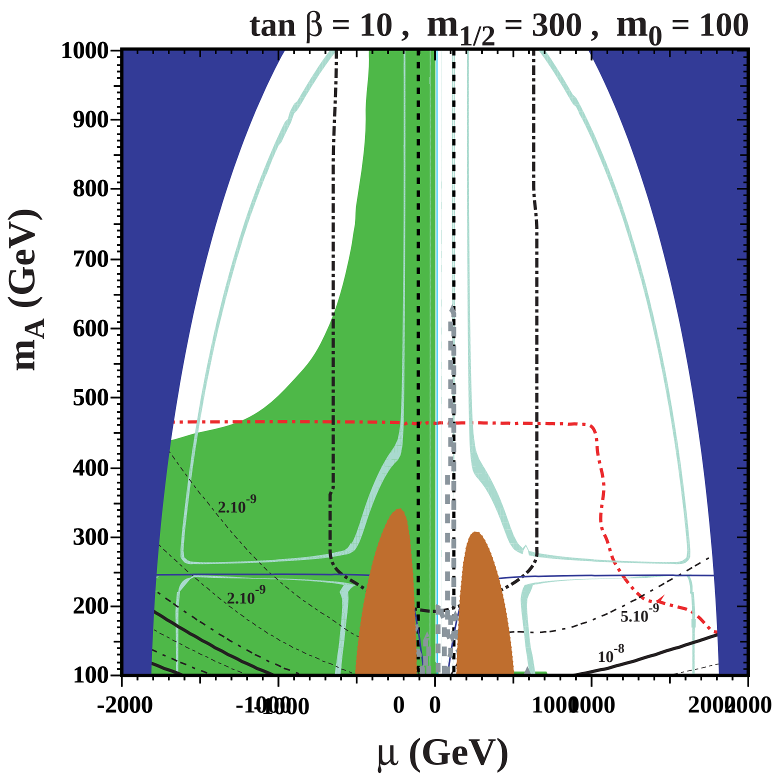
$(A_0 = 0)$

WMAP regions for various $\tan\beta$

NUHM Contour Plot



Before WMAP

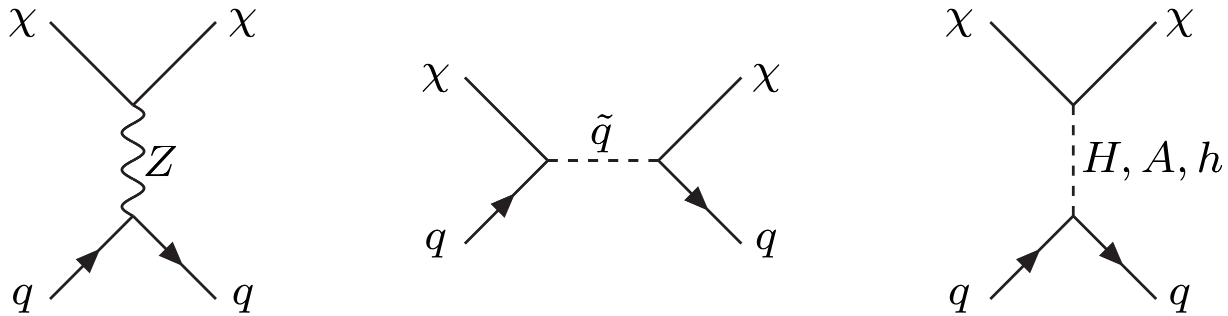


After WMAP

$(A_0 = 0)$

WIMP Direct Detection

- Three steps of detection rate calculation:
  - neutralino-quarks elastic scaterring,



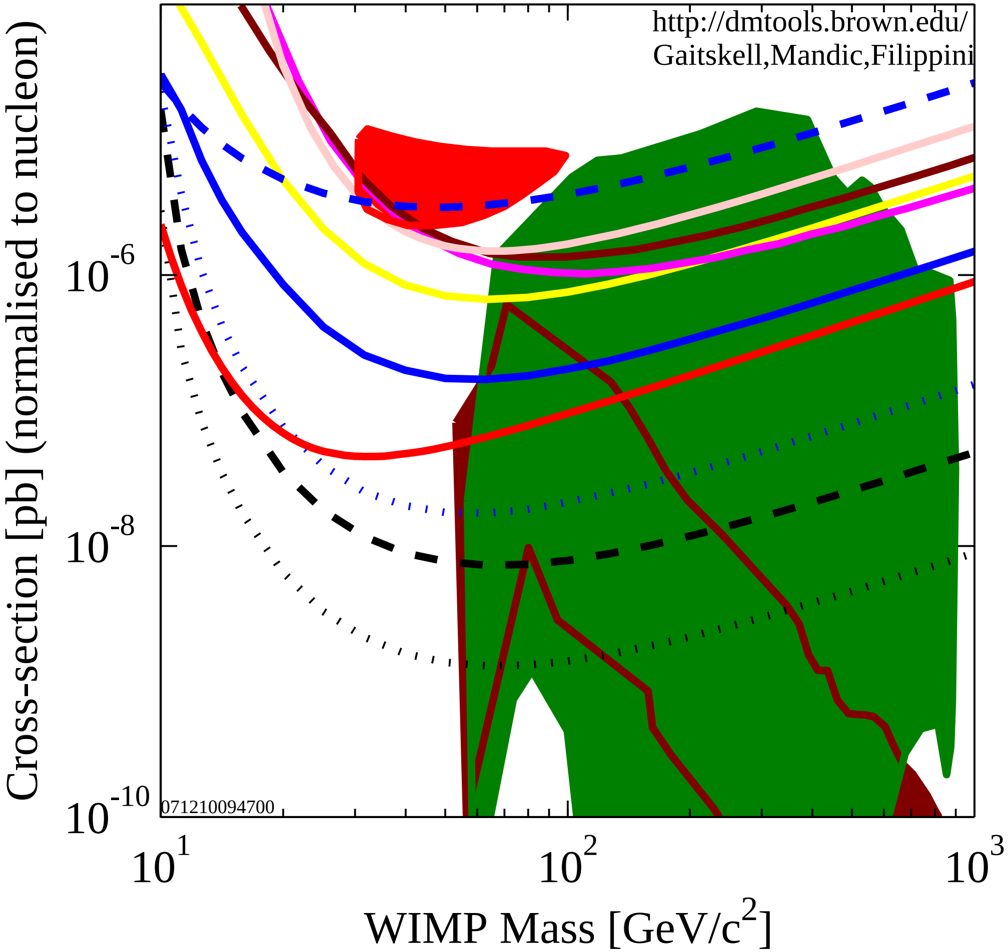
  - interaction with nucleons,
  - interaction with nucleus.

To compare various experimental results, we usually presented the results in term of neutralino-proton cross section.

$\chi - p$ Scalar Cross Section

Experimental Collaborations on DM (WIMP) detection:

- DAMA
- CRESST
- EDELWEISS
- WARP
- ZEPLIN II
- CDMS (Soudan)
- XENON 10
- etc.



(Th. from Ellis, Olive, YS, Spanos)

Other SUSY DM candidate?

- As long as it is weakly interacting, stable and massive it can qualify as 'candidate' for dark matter.
- Within SUSY, neutralino is not the only dark matter candidate. Other SUSY candidates are sneutrino and gravitino.
- Left-handed sneutrino dark matter is excluded by direct detection.
- Gravitino is still a good candidate for dark matter.

Gravitino Dark Matter Scenario

- Gravitino interacts very weakly, its coupling $\propto 1/M_{Pl}$.
- The Next Lightest Supersymmetric Particle (NLSP) could be long lived.
- It would be very difficult to detect gravitino directly. Signatures come from the NLSP.
- There are many possibilities for the NLSP: stau, neutralino, stop, selectron, sneutrino, (sup/scharm) ...

Gravitino Dark Matter Scenario 2

- The gravitino relic comes from two sources:
  - thermal production by reheating (depends on T_R),
  - decays of the NLSP,

$$\Omega_{\widetilde{G}}^{\mathrm{NT}} = \frac{m_G}{m_{\mathrm{NLSP}}} \Omega_{\mathrm{NLSP}}$$

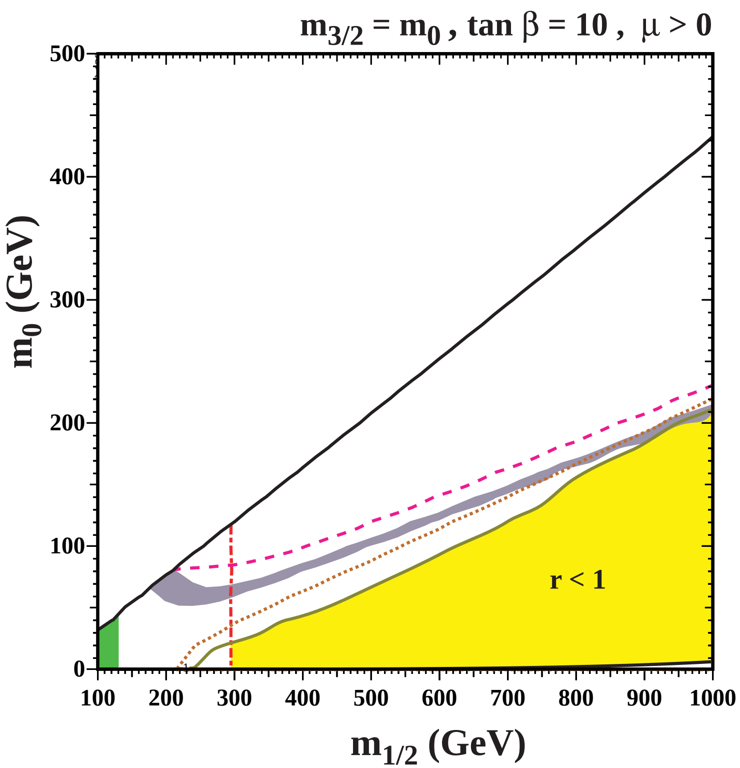
We do not know the value of T_R, so

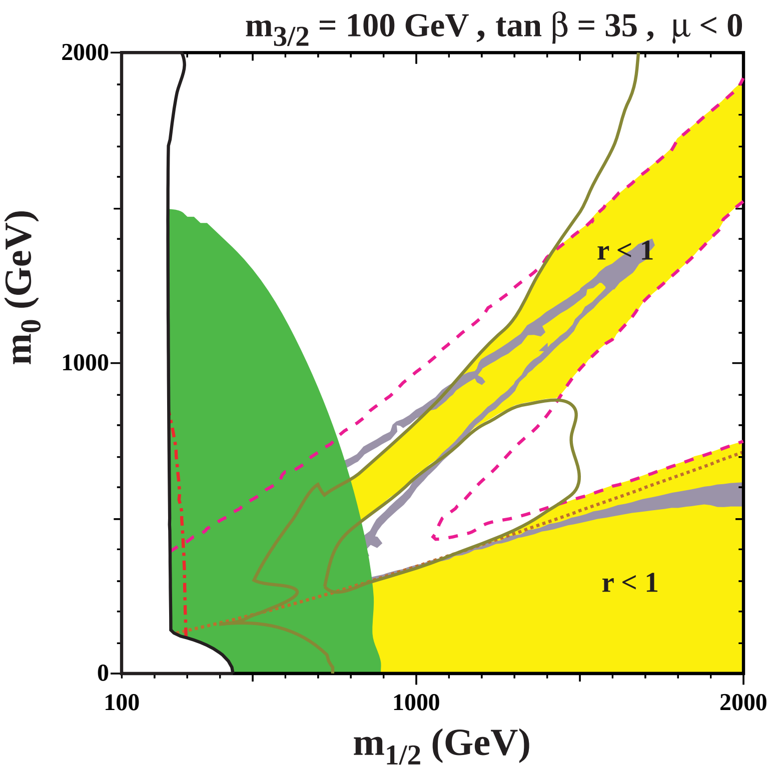
$$\Omega_{\widetilde{G}}^{\mathrm{NT}} < \Omega_{\mathrm{DM}}^{\mathrm{WMAP}}$$

Gravitino Dark Matter Scenario 3

- The metastable NLSP typical lifetime is $\gtrsim O(1\,\mathrm{s})$ (for $m_{\mathrm{NLSP}} \lesssim 1$ TeV, $m_{\widetilde{G}} \gtrsim 1$ GeV) $\Rightarrow$ direct effect on Big Bang Nucleosynthesis (BBN):
  - photodissociation
  - hadrodissociation
  - change of n/p ratio
  - catalytic effect (for negatively charged NLSP)

CMSSM with GDM





Concluding Remarks

- From phenomenological point of view supersymmetric models are very interesting.
- The dark matter puzzle might be solved through particle physics.
- Many ideas. Nevertheless we need some data to guide us.
- We hope that the LHC will open a new chapter in our quest beyond the Standard Model.