Dark Matter in the Universe

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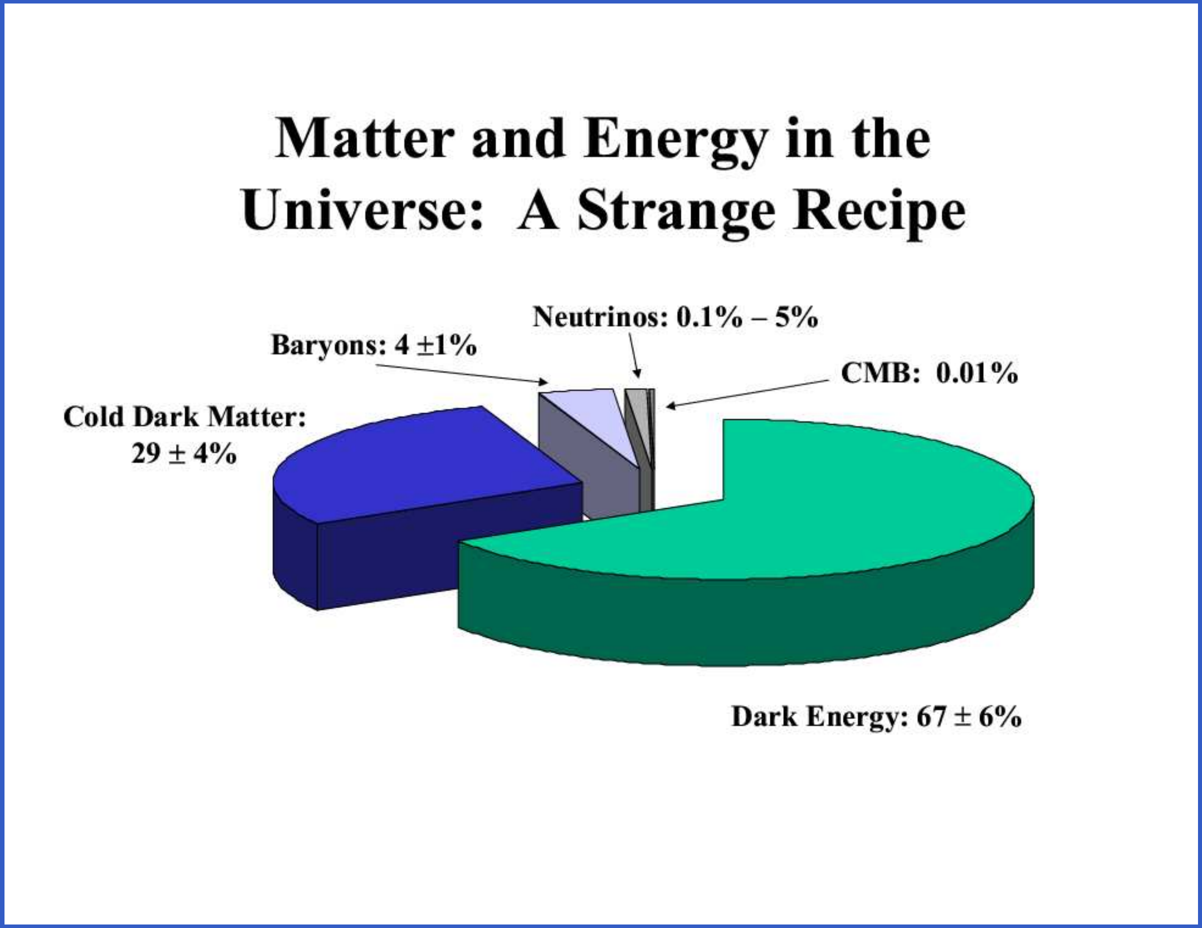
A Cosmic Pie



Freedman+Turner

What Cosmology Tells Us...

Post WMAP (Feb 03) ...+ACBAR+CBI

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- $\Omega_{\mathrm{b}} h^2 = 0.0224 \pm 0.0009$
- $h = 0.71^{+0.04}_{-0.03}$
- $\ldots$

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$\Omega = \rho/\rho_{crit}$

Hubble $H_0 = 100\, h\, \mathrm{km/\,s/\,Mpc}$

- $\Omega_{\mathrm{m}} h^2 = 0.135^{+.008}_{-.009}$
- $\Omega_{\mathrm{b}} h^2 = 0.0224 \pm 0.0009$ $\Rightarrow$ most matter non–baryonic (DM problem)
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$\Rightarrow$ cold DM

$$0.094 < \Omega_{\rm CDM} h^2 < 0.129 \quad (2\,\sigma)$$

(previously $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$)

- astrophysical limits on exotic elements

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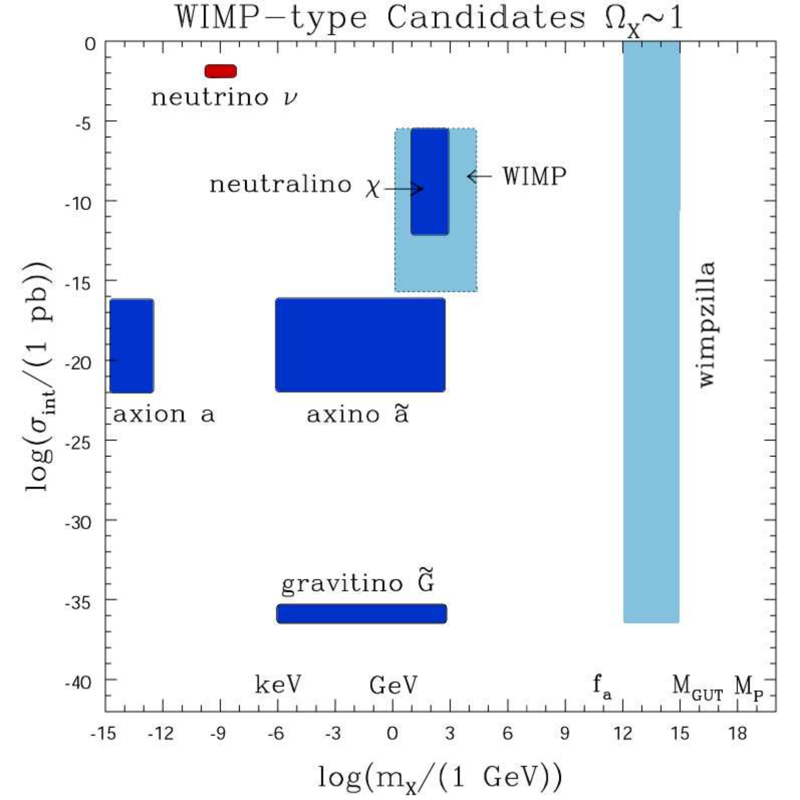
$\Rightarrow$ WIMP

weakly interacting massive particle

The Big Picture

well–motivated particle candidates s.t. $\Omega \sim 0.1$

The Big Picture



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\widetilde{a}$
- gravitino $\widetilde{G}$
- wimpzilla,. . .

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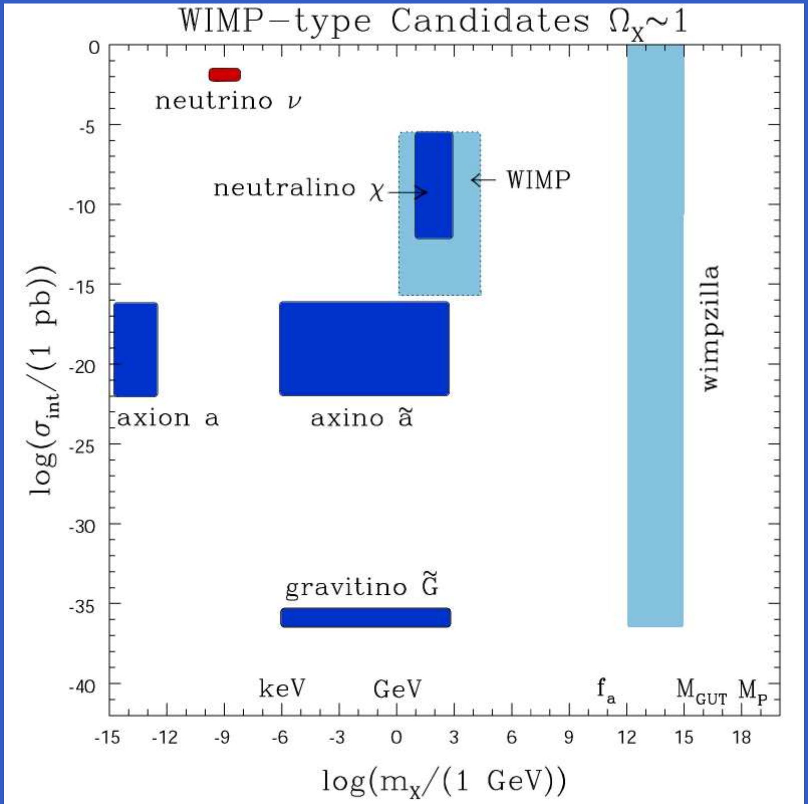

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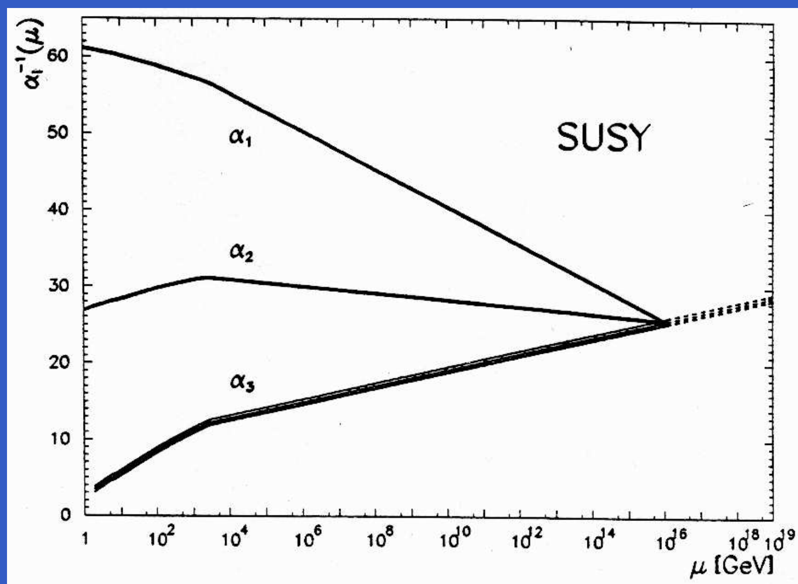
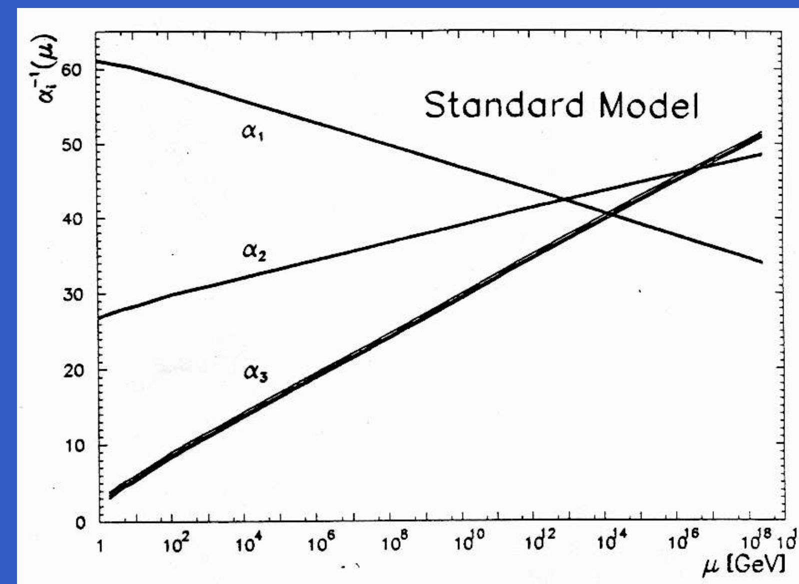
...Must go beyond SM..., SUSY (still) most promising

To SUSY or not to SUSY?





gauge couplings “run” with energy

Outline

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- which WIMP?

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specific predictions strongly model–dependent

...may be a virtue

Neutralino?

Neutralino?

Supersymmetric	Standard Model
gauginos	gauge bosons
higgsinos	Higgs bosons
sleptons	leptons
squarks	quarks
$R = -1$	$R = +1$

“neutralino” χ: lightest mass e’state of neutral gauginos and higgsinos

Majorana fermion ($\chi^c = \chi$)

stable, massive $\Rightarrow$ LSP

SUSY Models

Two basic approaches:

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- general MSSM

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  - ...

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⇐ $b \to s\gamma$:

(full LO) + ($\tan\beta$–enhanced NLO)

in MFV framework

highly unstable

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$b \longrightarrow s\gamma$ and GFM

general flavor mixing

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general flavor mixing

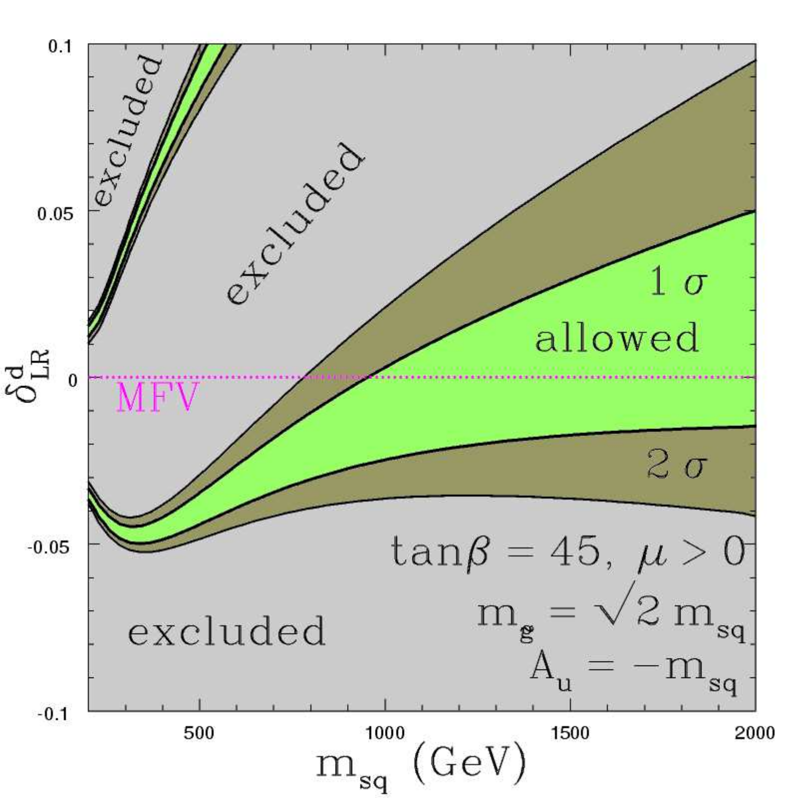
Okumura+Roszkowski, PRL'04

include dominant NLO–level contributions

enhanced at large $\tan\beta$

$$(\delta^d_{LL}) = \left(m^2_{d,LL}\right)_{23} / \sqrt{\left(m^2_{d,LL}\right)_{22}\left(m^2_{d,LL}\right)_{33}}$$

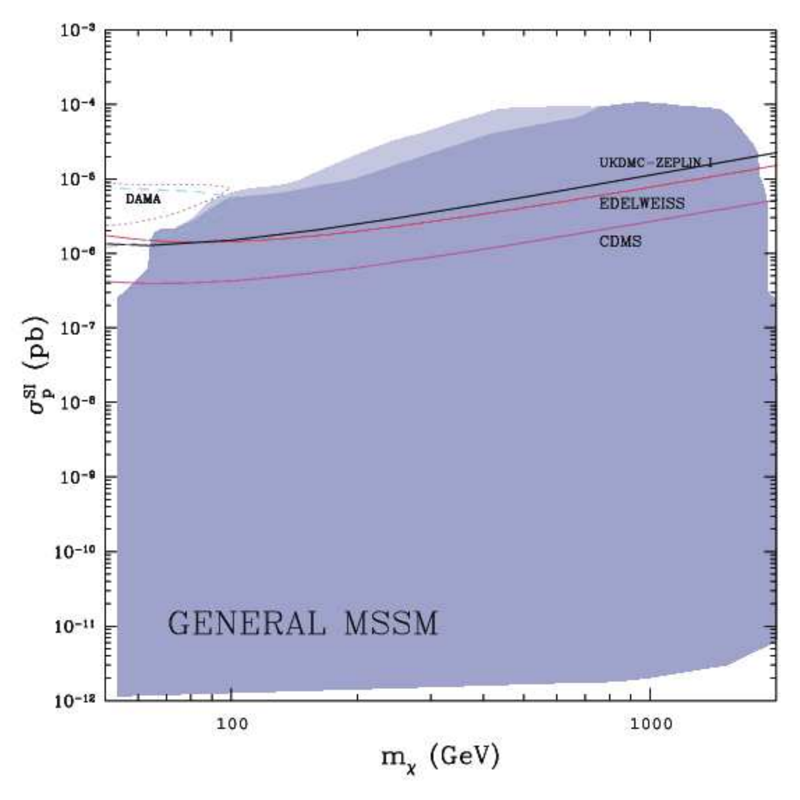
MFV: mixings among squarks identical to those among quarks $\Rightarrow \delta^d_{\cdot\cdot} = 0$



bounds highly unstable against small perturbations of MFV

MSSM: Expectations for σ_p^{SI}

$\mu > 0$



σ_p^{SI} – WIMP–proton SI elastic scatt. c.s.

(elastic c.s. for $\chi p \longrightarrow \chi p$ at zero momentum transfer)

How to Catch the WIMP?

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Since the birth of time, mankind has searched everywhere for an answer to that age old question...

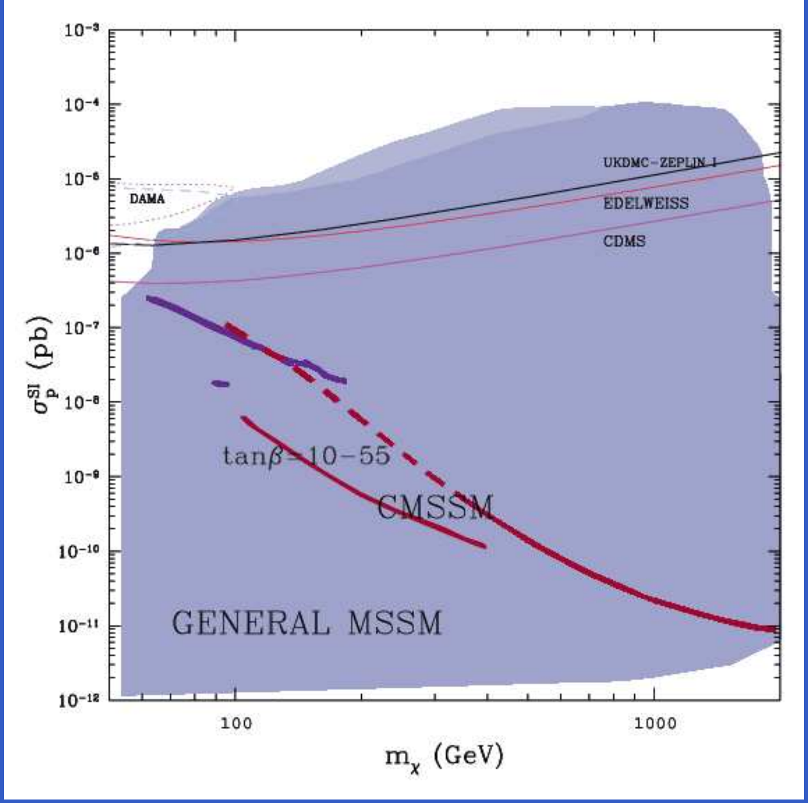
...go underground

How to Catch the WIMP?

Since the birth of time, mankind has searched everywhere for an answer to that age old question...

...grand unification!

Expectations for σ_p^{SI} with unification



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blue: general MSSM

red: Constrained MSSM

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...aka mSUGRA

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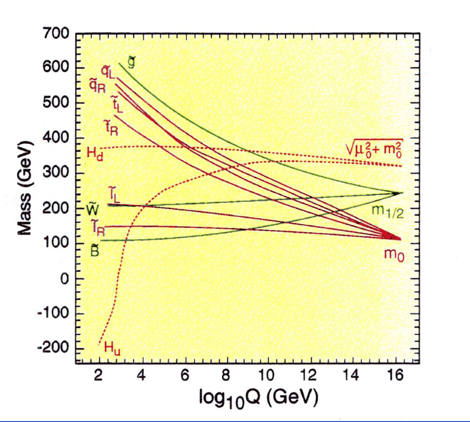

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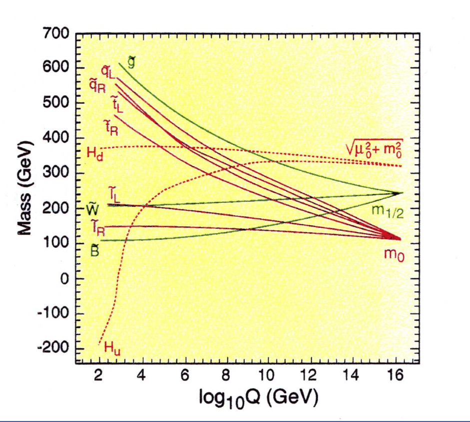

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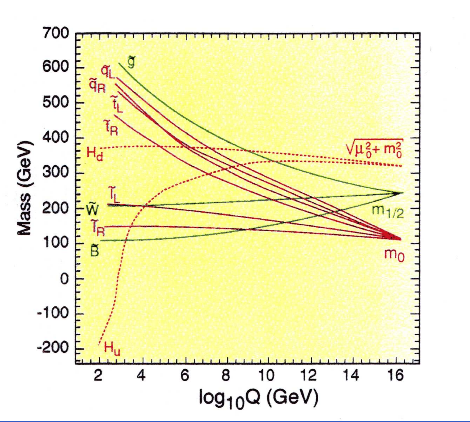

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$$\mu^2 = \frac{\left(m^2_{H_b}+\Sigma_b^{(1)}\right)-\left(m^2_{H_t}+\Sigma_t^{(1)}\right)\tan^2\beta}{\tan^2\beta-1} - \frac{m_Z^2}{2}$$

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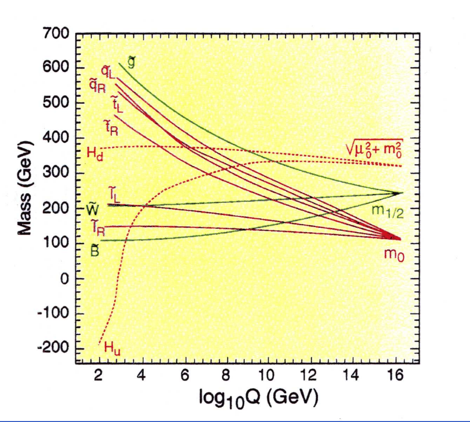

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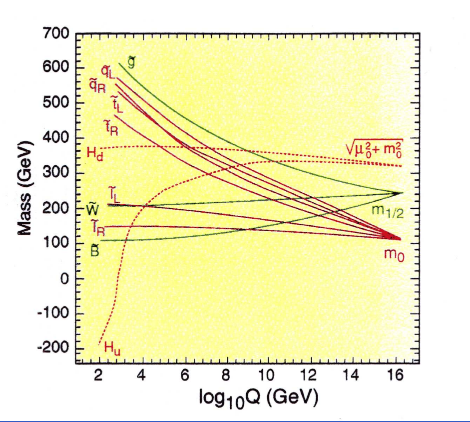

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- five independent parameters: $\tan\beta,\ m_{1/2},\ m_0,\ A_0,\ \mathrm{sgn}(\mu)$
- mass spectra at m_Z:
  run RGEs, 2–loop for g.c. and Y.c, 1-loop for masses
- some important quantities $(\mu, m_A, \ldots)$ very sensitive to procedure of computing EWSB & minimizing V_H

we use Suspect

Constrained MSSM

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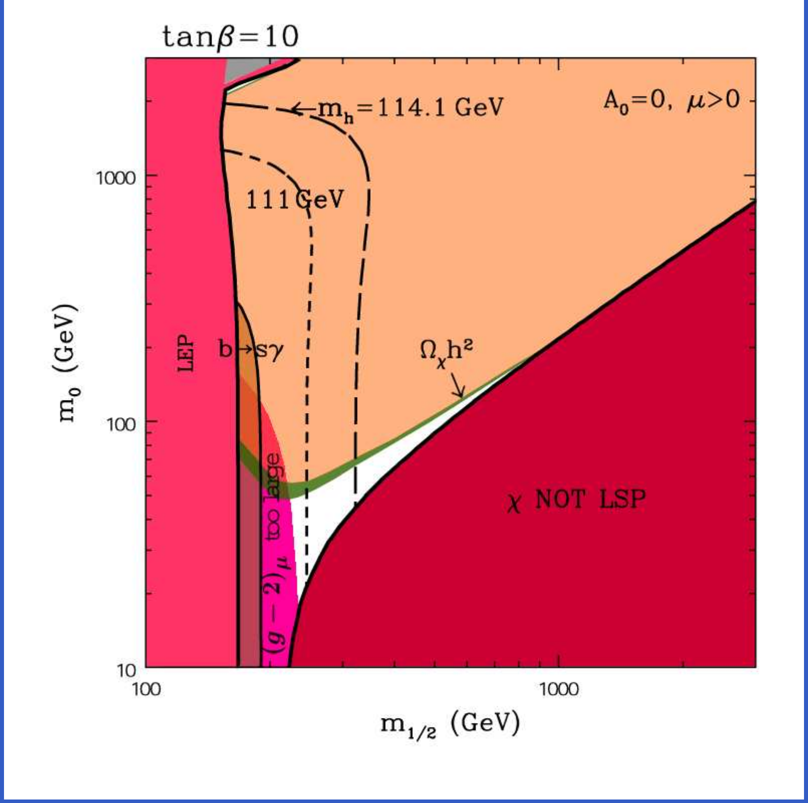
$\tan\beta \lesssim 45$



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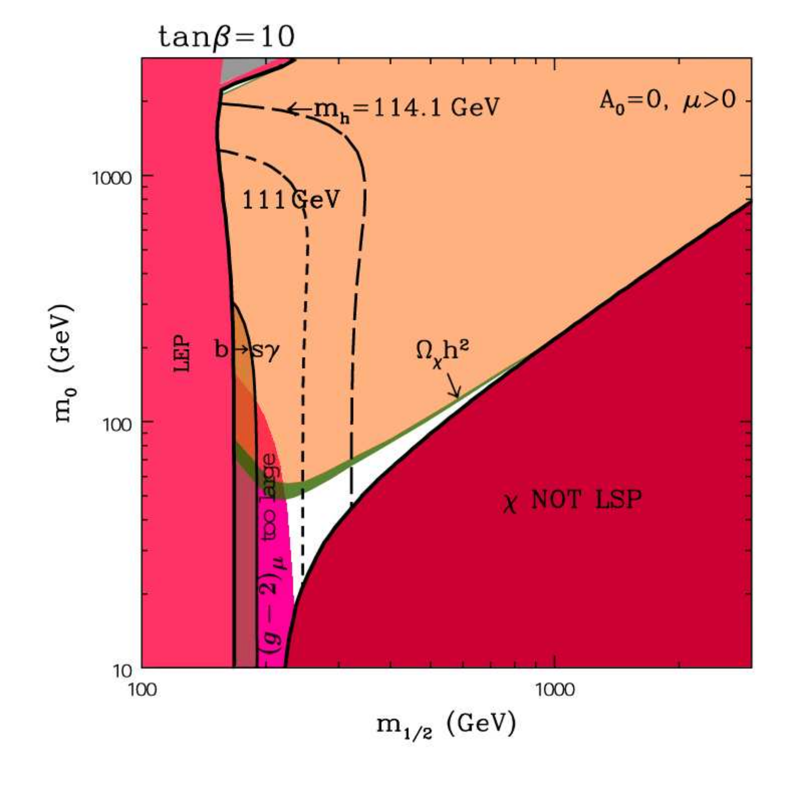
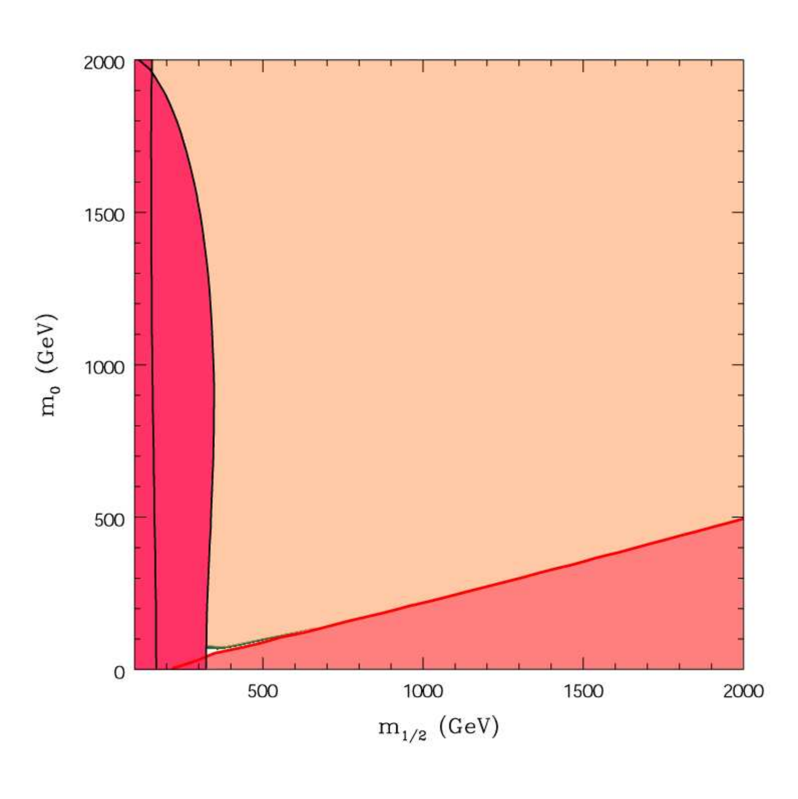


$\tan\beta \lesssim 45$, linear



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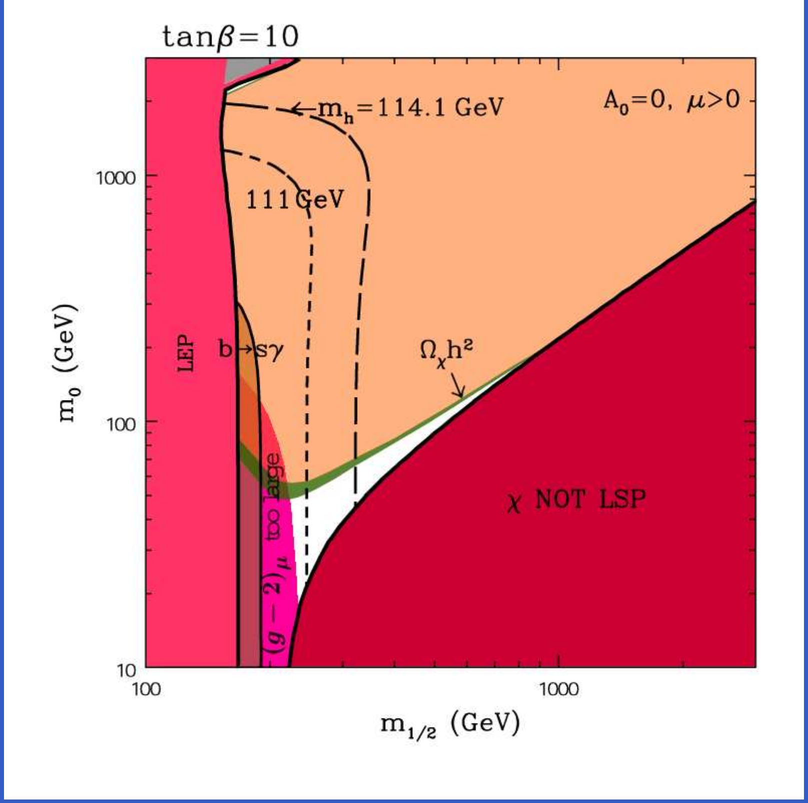
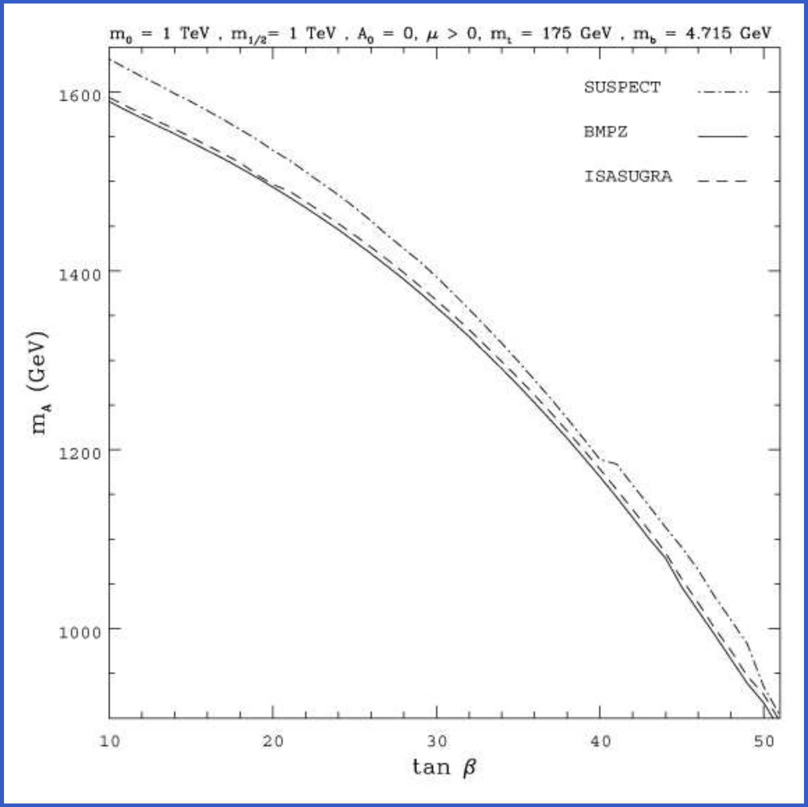


m_A vs.. $\tan\beta$



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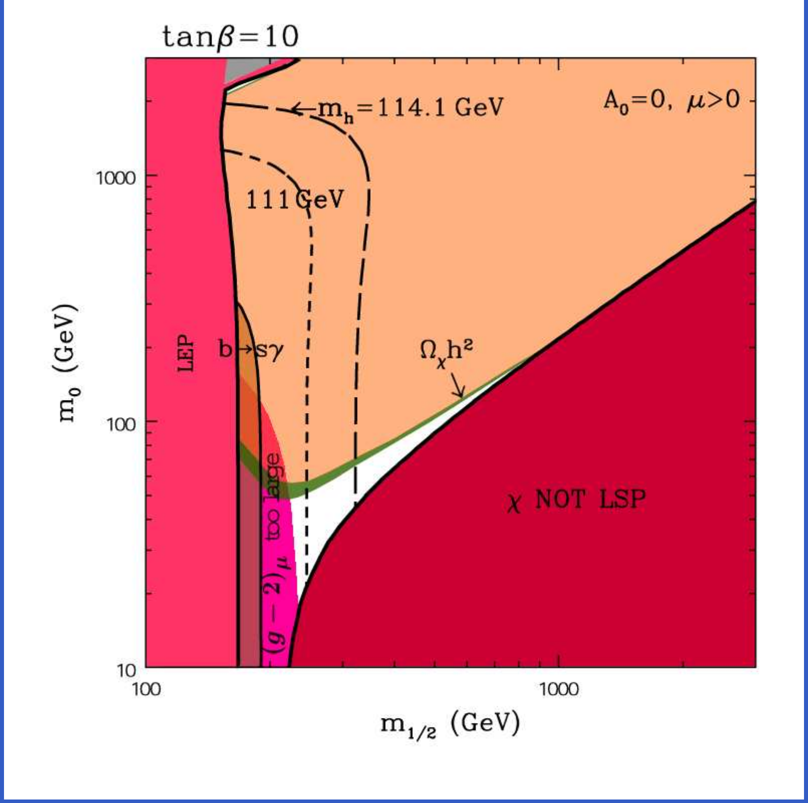

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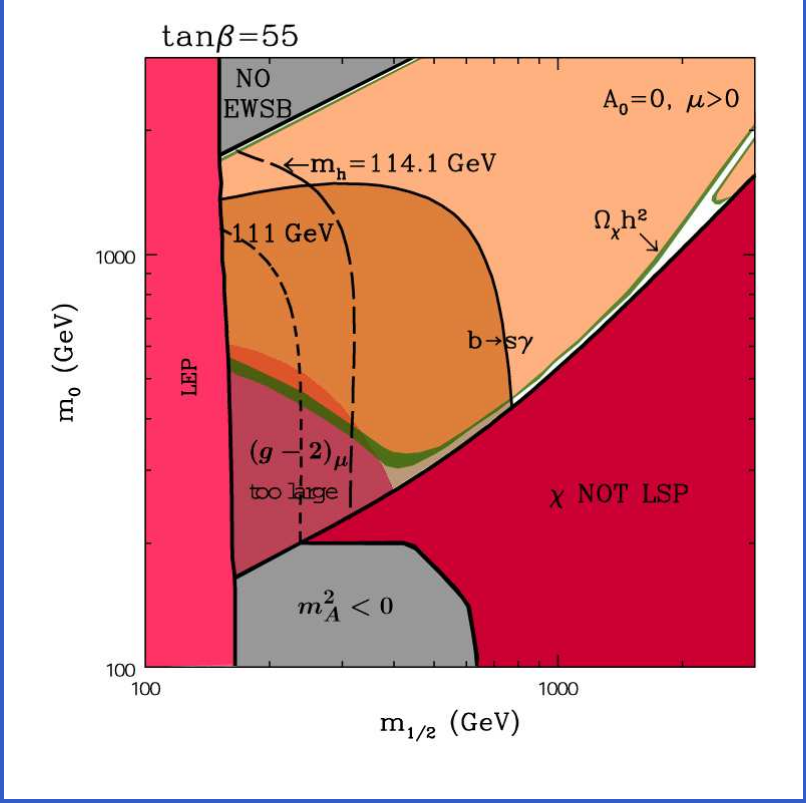

. . .left allowed

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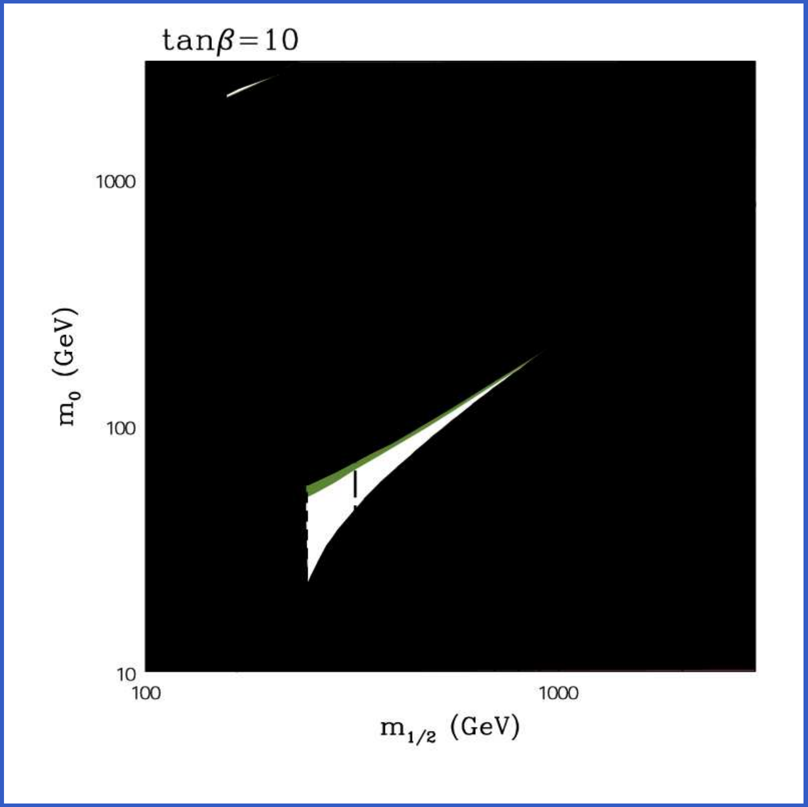

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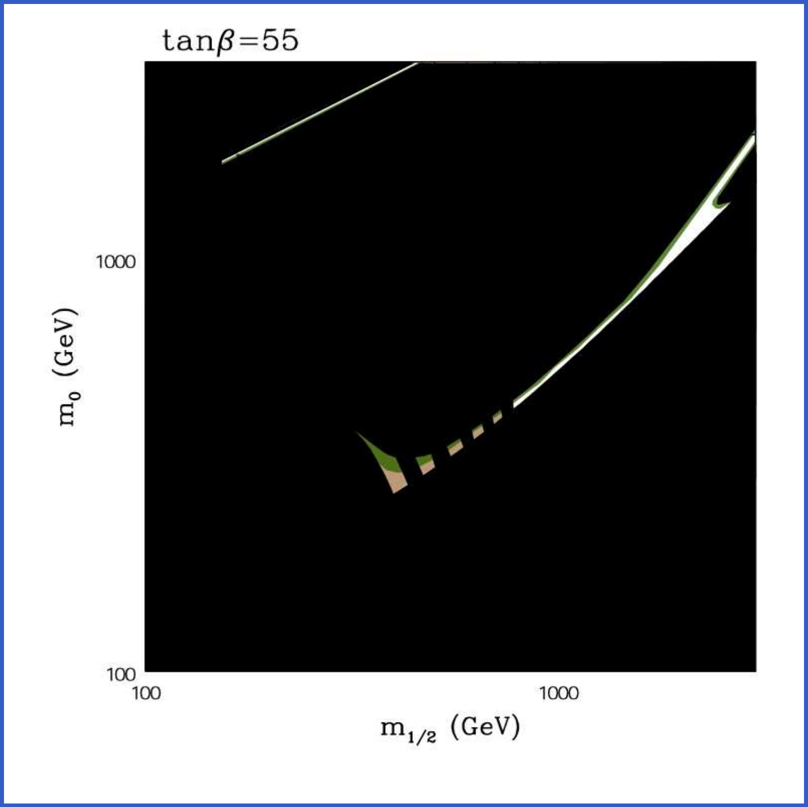

CMSSM: Implications for σ_p^{SI}

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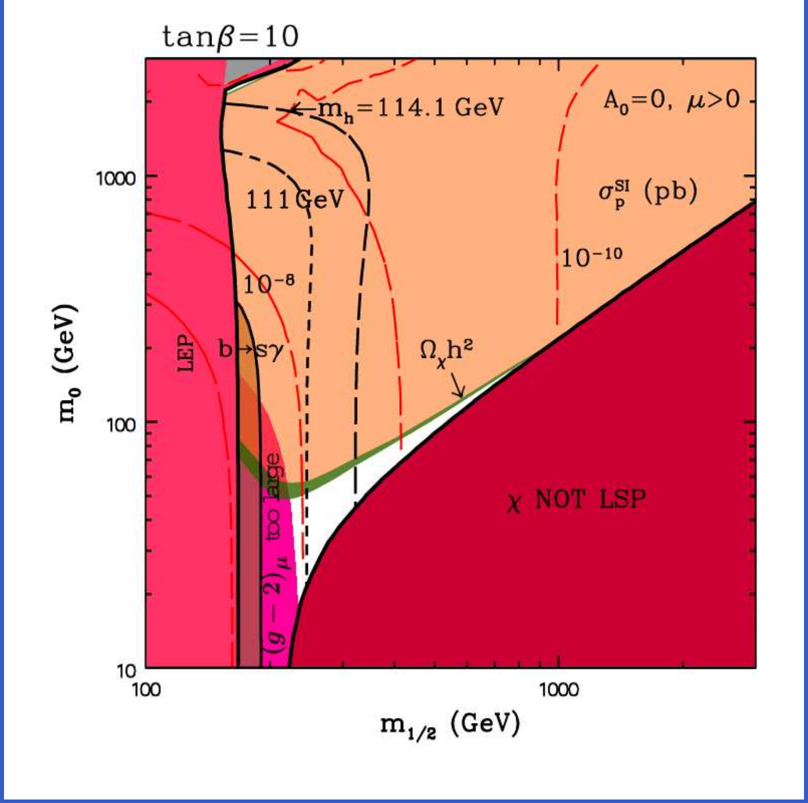

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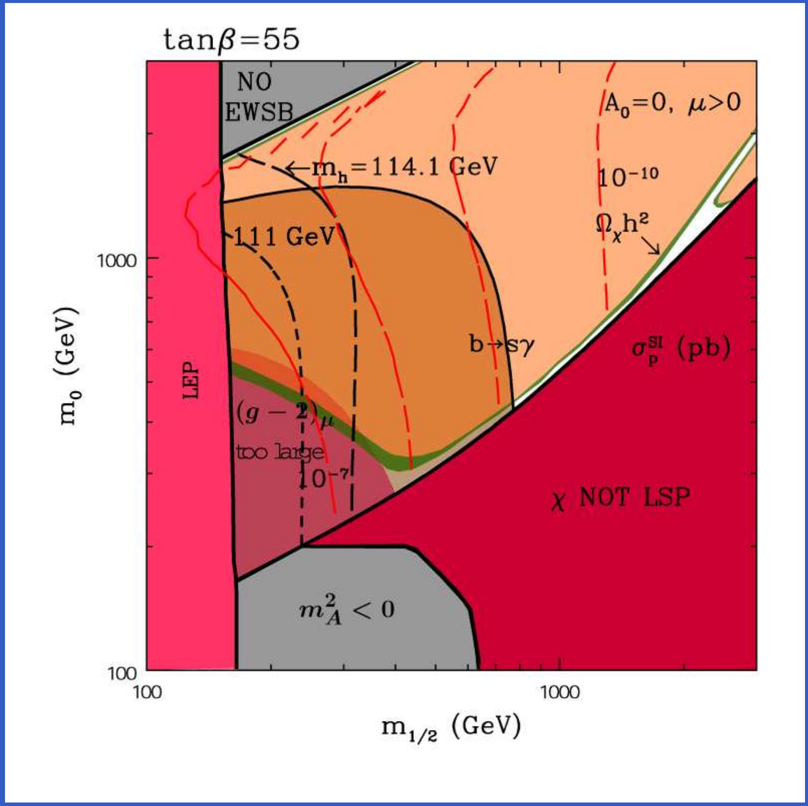
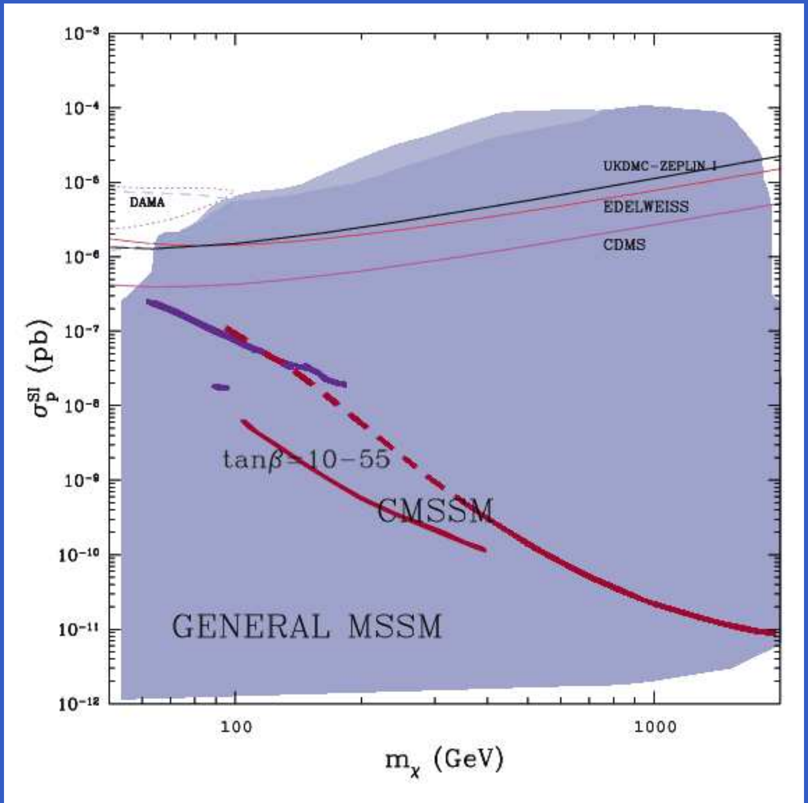


Implications for σ_p^{SI}

CMSSM, $\tan\beta = 10, 55$, $A_0 = 0$



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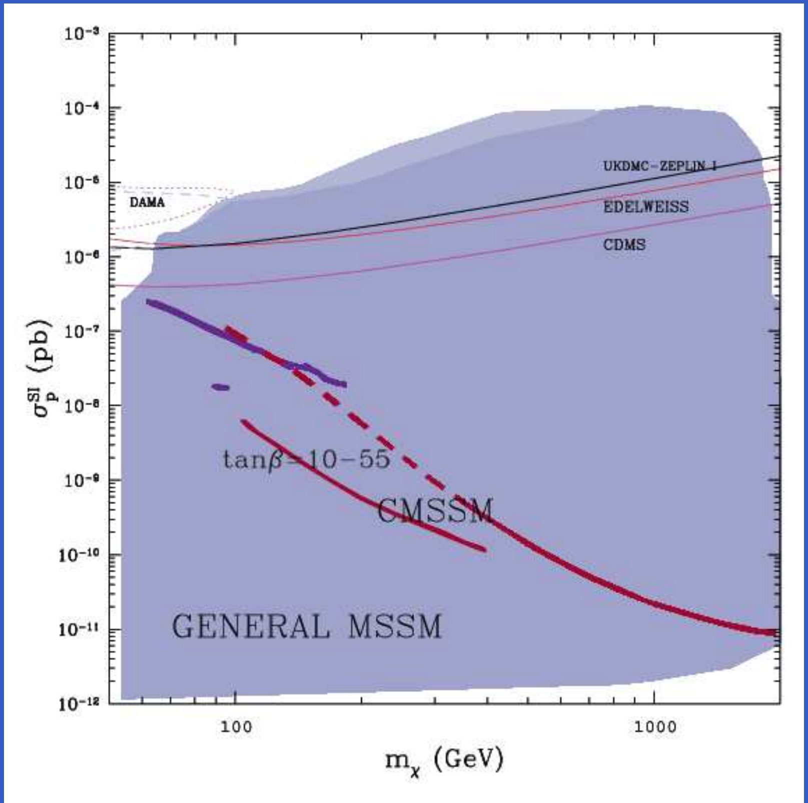
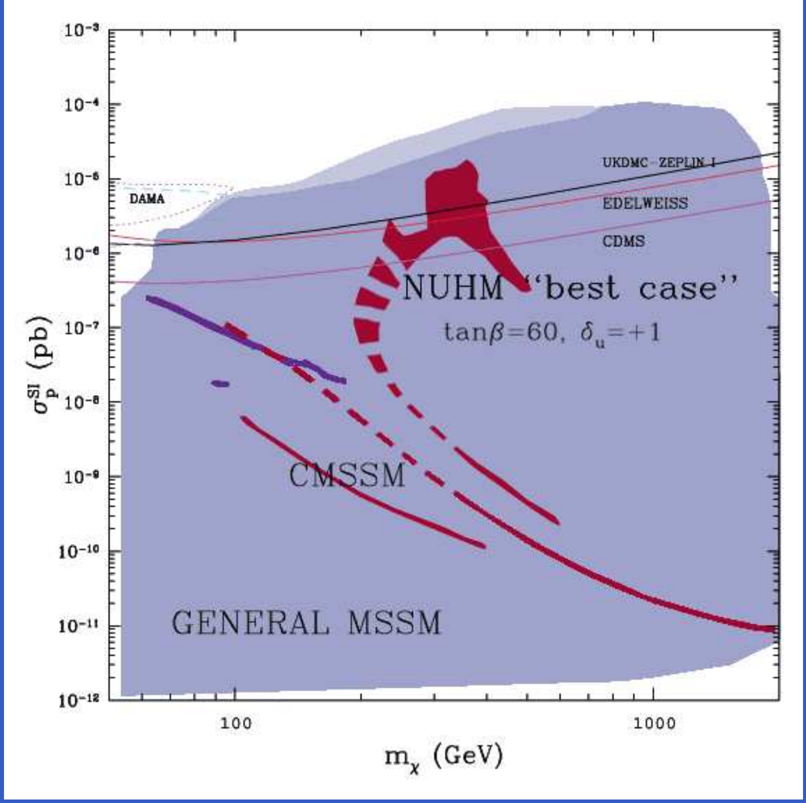


add NUHM, $\tan\beta = 60$, $\delta_u = +1$



NUHM: $m^2_{H_{u,d}} = m_0^2\,(1 + \delta_{u,d})$

σ_p^{SI} vs. $BR(B_s \to \mu^+\mu^-)$

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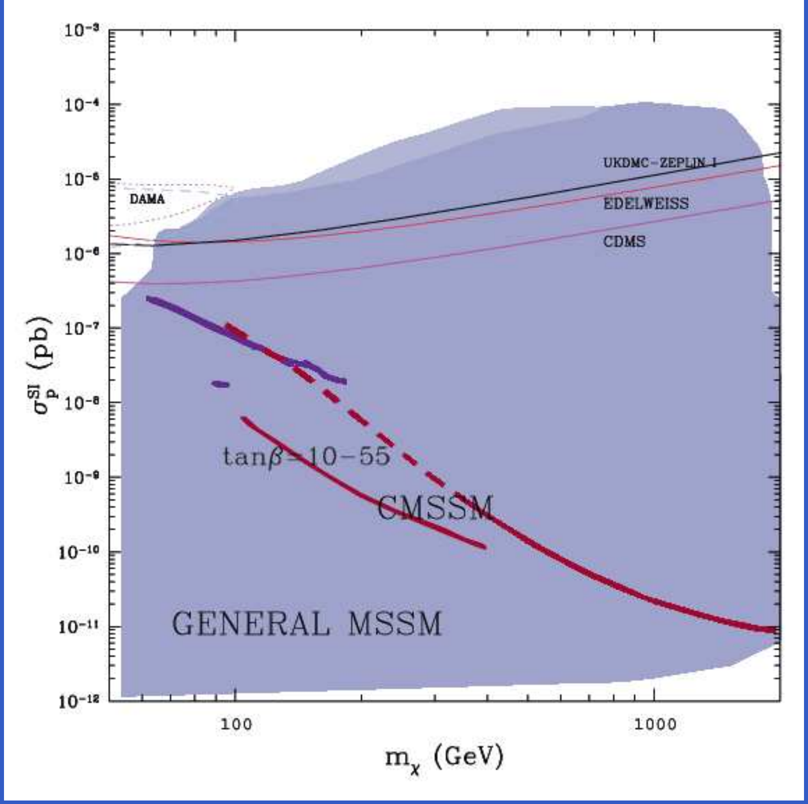
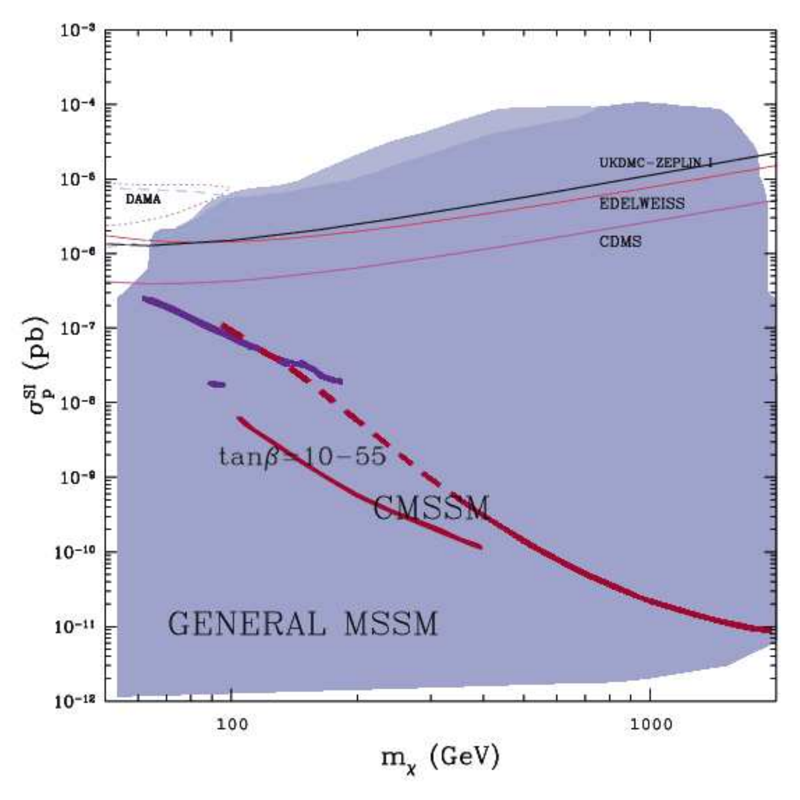
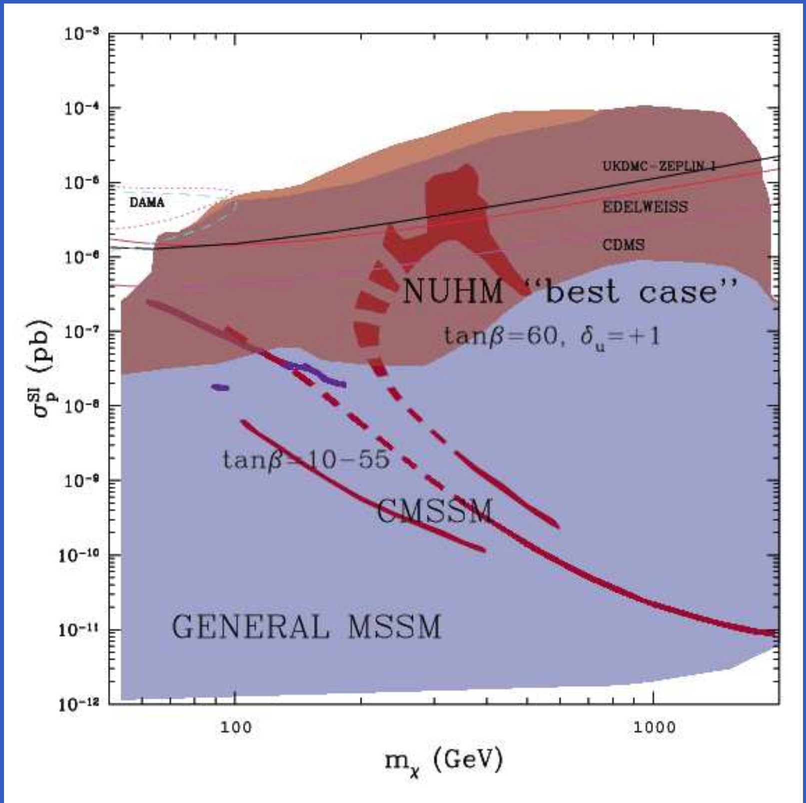


σ_p^{SI} vs. $BR(B_s \to \mu^+\mu^-)$

CMSSM, $\tan\beta = 10, 55$, $A_0 = 0$



$BR(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-7}$



but $BR(B_s \to \mu^+\mu^-)$ limit is flavor model–dependent, ...assume MFV

σ_p^{SI} & Future Searches

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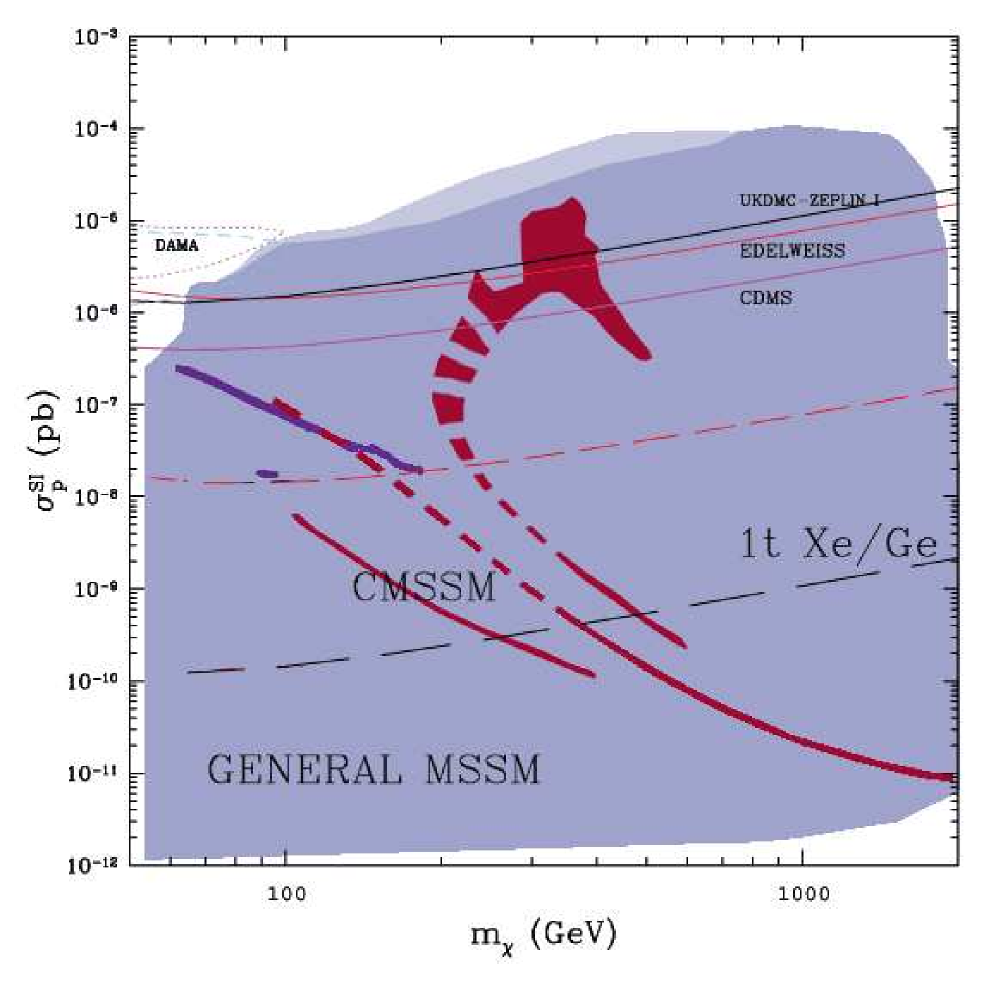
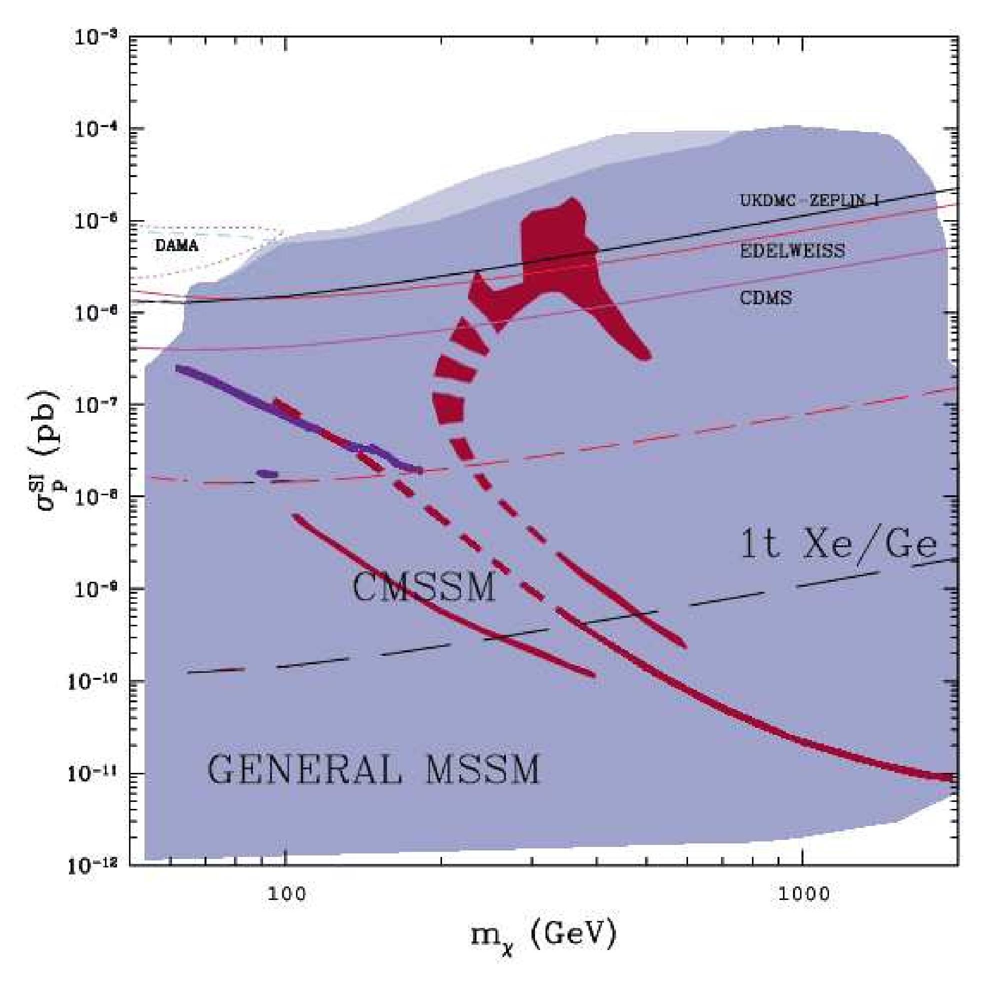


upgrades: $\sigma_p^{SI} \lesssim 10^{-8}$ pb, "1 tonne Xe/Ge": $\sigma_p^{SI} \lesssim 10^{-10}$ pb

σ_p^{SI} & Future Searches



once WIMP detected. . . . . . can discriminate among SUSY breaking scenarios?

The CMSSM & Yukawa Unification

- CMSSM universal BC's inconsistent with ***exact*** Yukawa unification

...m_b comes out too large (small) if $\mu > 0$ ($\mu < 0$)

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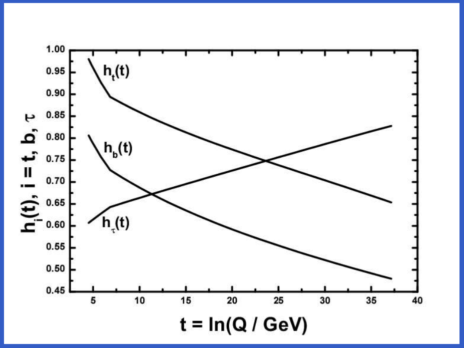
Lazarides+Pallis '04



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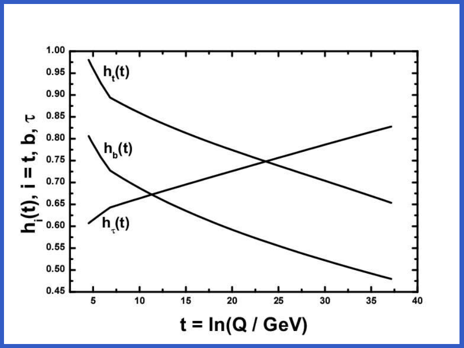
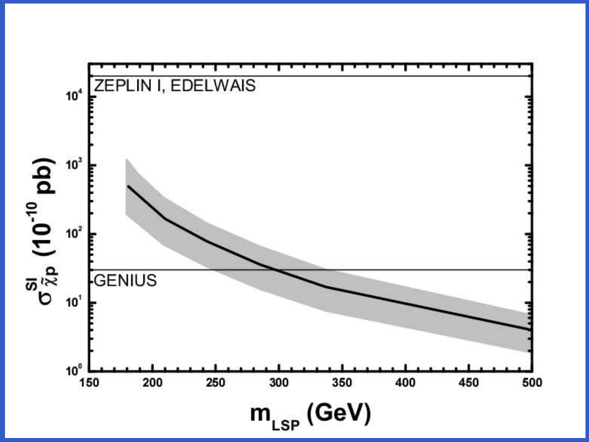
Lazarides+Pallis '04 ...and testable σ_p^{SI}





Minimal SUSY $SO(10)$ GUT Model

fully realistic GUT

Raby, et al.

- matter $\mathbf{16} \supset \mathbf{10} + \mathbf{5} + \overline{\nu}_s$
- Higgs

  $\mathbf{10}_H \supset \mathbf{5}_H + \mathbf{5} + \overline{\mathbf{5}}_H \supset H_t, H_b$
- spotential $W = \lambda \mathbf{16}\, \mathbf{10}_H\, \mathbf{16}$
- g. c. unification $\surd$

  $\epsilon_s = \frac{(\alpha_s(M_G) - \alpha_G)}{\alpha_G} \approx -4\%$
- Y. c. unification $\surd$

  large $\widetilde{g} - \chi^-$ corr's to

  $\lambda_b \Rightarrow \tan\beta \sim 50$
- realistic fermion masses $\surd$
- proton decay $\surd$

- 11 input parameters

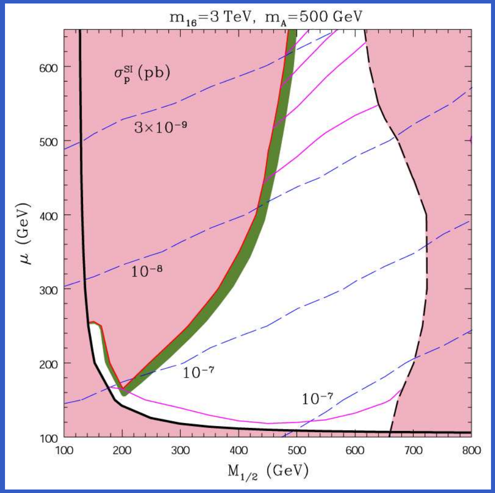
M_G, α_G,ϵ_s, λ, μ, $m_{1/2}$,A_0,$\tan\beta$,
m_{16},m_{10},$m^2_{H_{t,b}}$ $=$
$m_{10}\,(1 \mp \Delta m^2_H)$

- 2–loop RGE's for gauge and Yukawa
- full 1–loop threshold corrections at both m_Z and M_G
- 1–loop RGE's for scalars
- EWSB with 1–loop corrections
- fit 9 observables

α_{em}, G_μ,$\alpha_s(m_Z)$,m_Z,m_W,
ρ,M_τ,M_t,$m_b(m_b) = 4.20 \pm .20$ GeV

$SO(10)$: Implications for σ_p^{SI}

Dermíšek, Raby, Roszkowski, Ruiz de Austri (JHEP '03)



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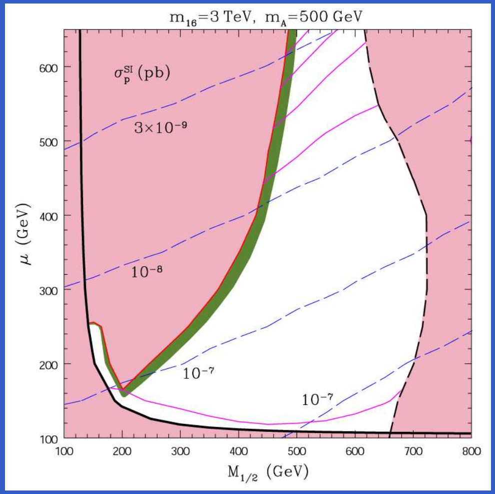
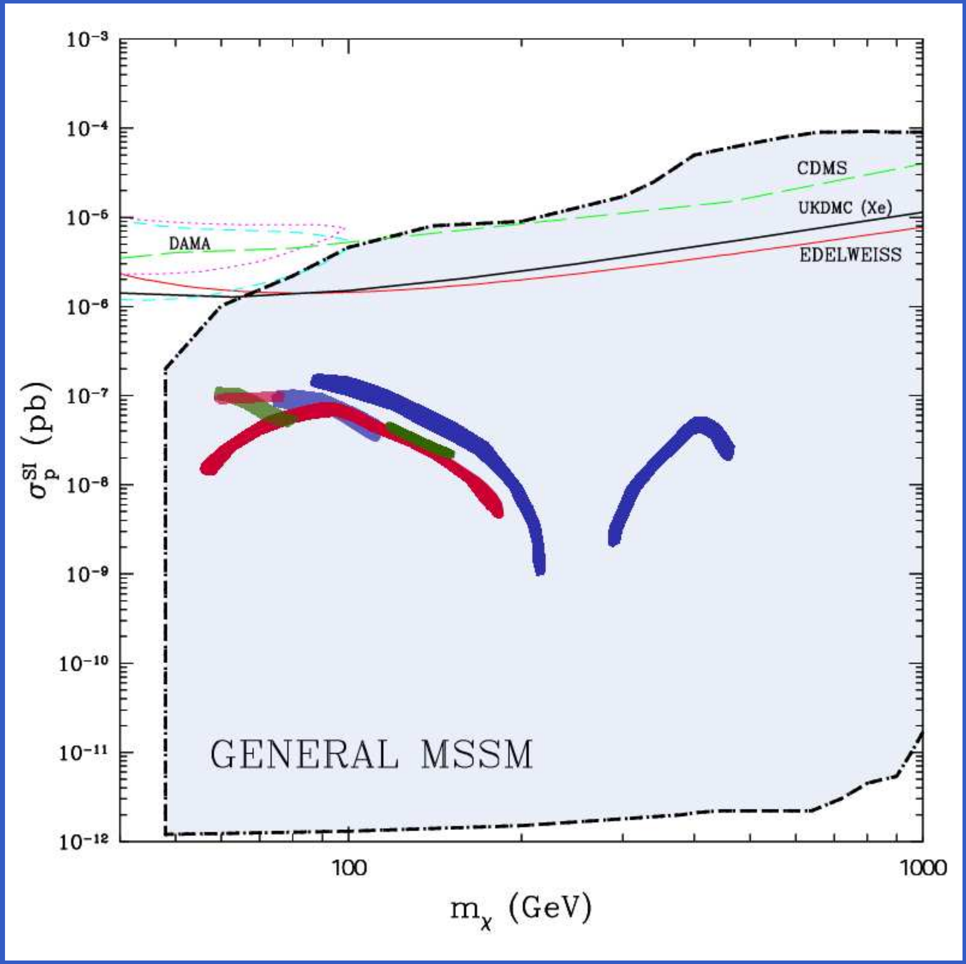




$m_{16} = 2.5$ TeV (green)

3 TeV (red)

5 TeV (blue)

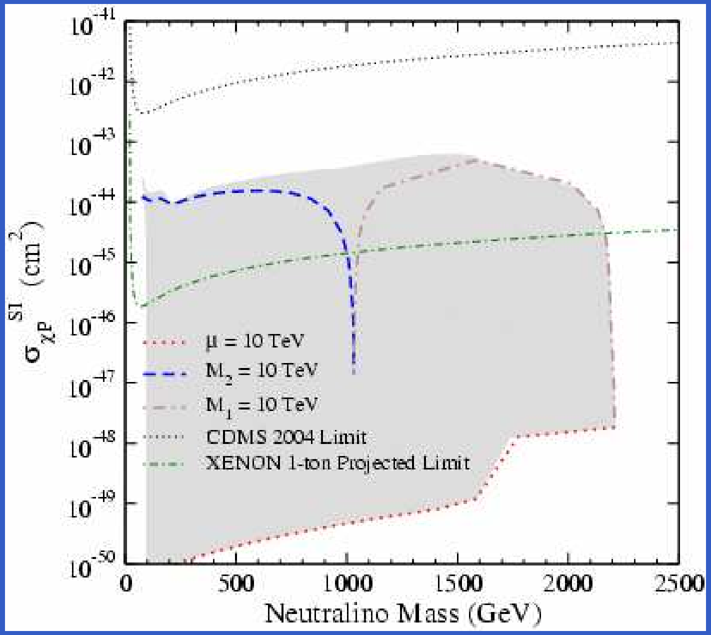
$m_A = 300$ GeV (lighter)

500 GeV (darker)

σ_p^{SI} In Split SUSY

Arkani-Hamed+Dimopoulos+Giudice+Romanino, '04: SUSY scalars VERY heavy

LSP DM: mixed gaugino–higgsino state



Masiero+Profumo+Ullio, hep-ph/0412058

testable...

A Consumption Chain...

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- observers:

cold, non–baryonic dark matter,

$$0.094 < \Omega_{\rm CDM} h^2 < 0.129 \;\; (2\,\sigma)$$

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  $$0.094 < \Omega_{\mathrm{CDM}} h^2 < 0.129 \;\; (2\,\sigma)$$

- theorists:

  (sensible) particle physics models and WIMP candidates

- experimentalists:

  take all this seriously (signal "within reach")

How to Catch the WIMP?

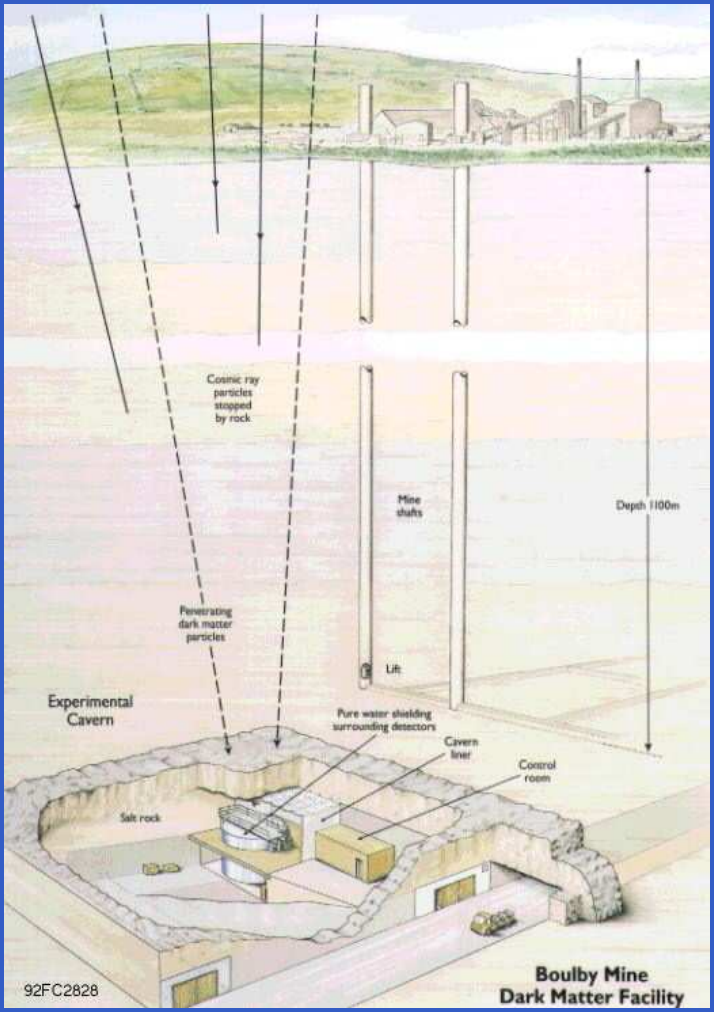
Since the birth of time, mankind has searched everywhere for an answer to that age old question...

...go underground

Go underground/–ice/–water

...as deep as one can

Go underground/–ice/–water



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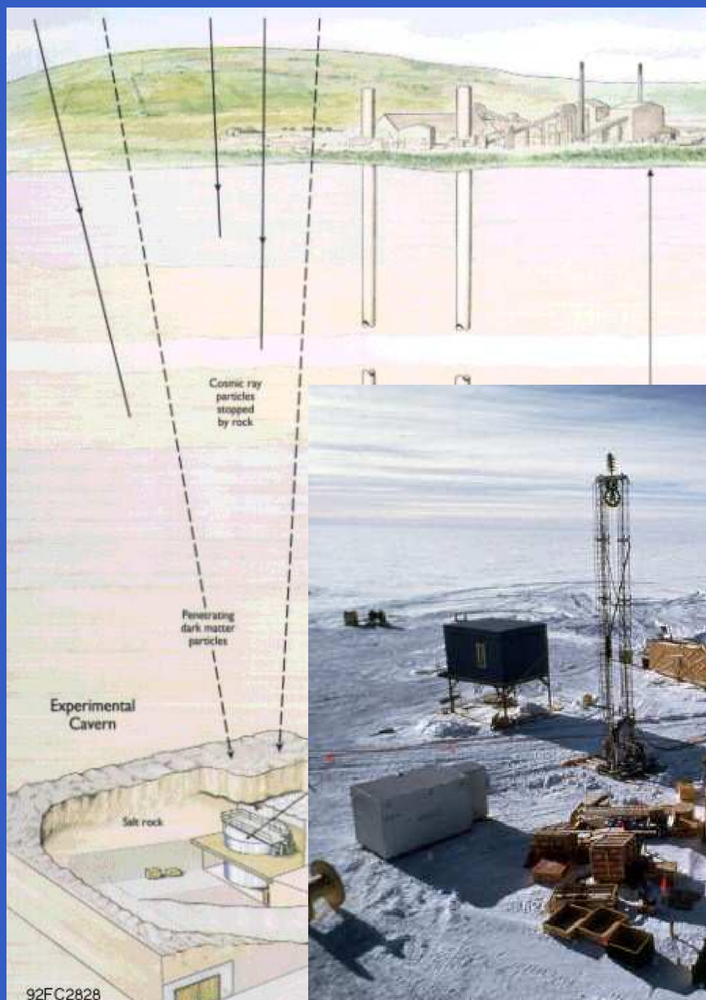

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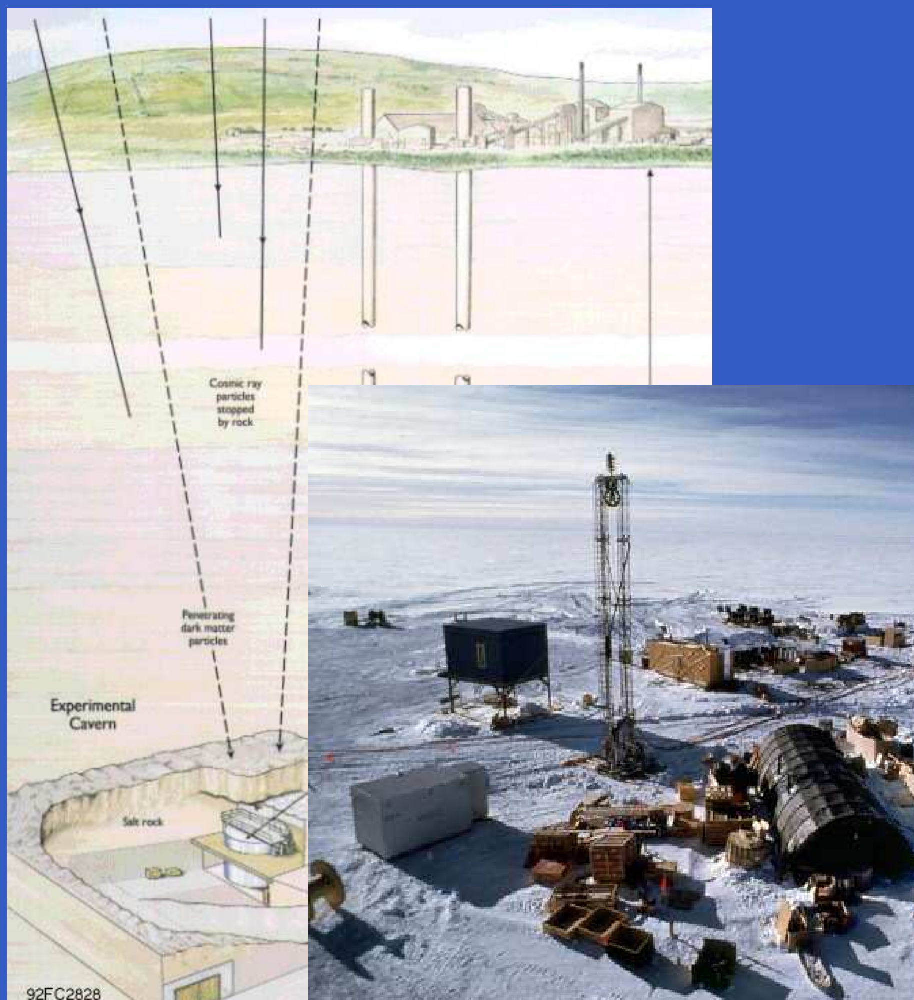

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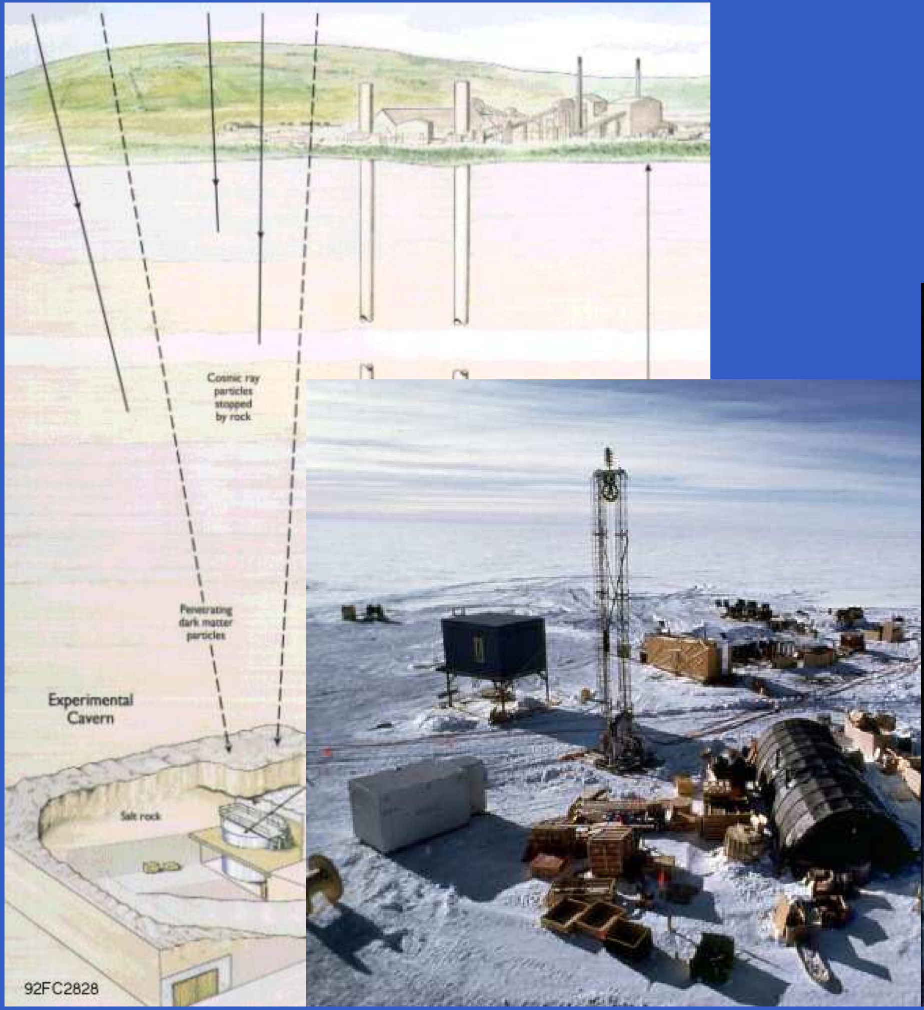

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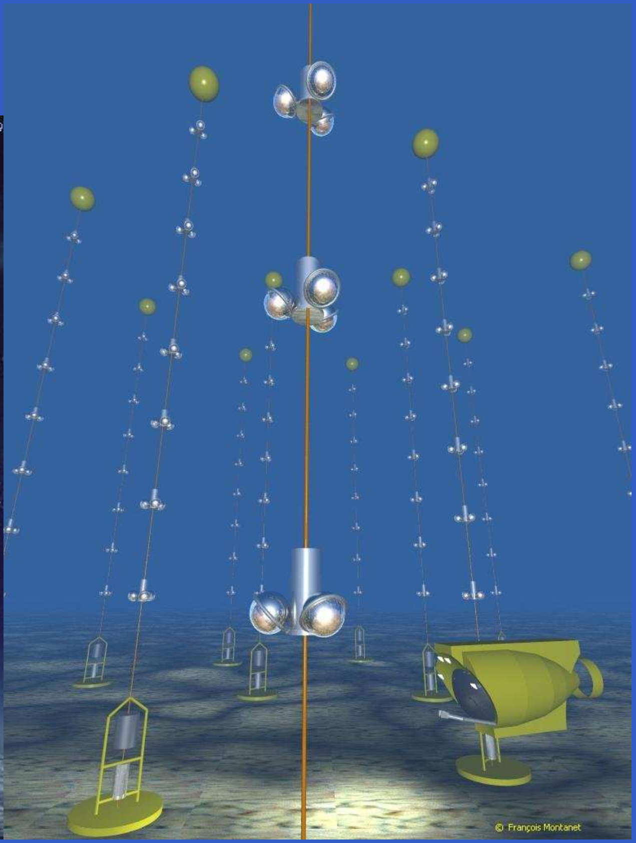
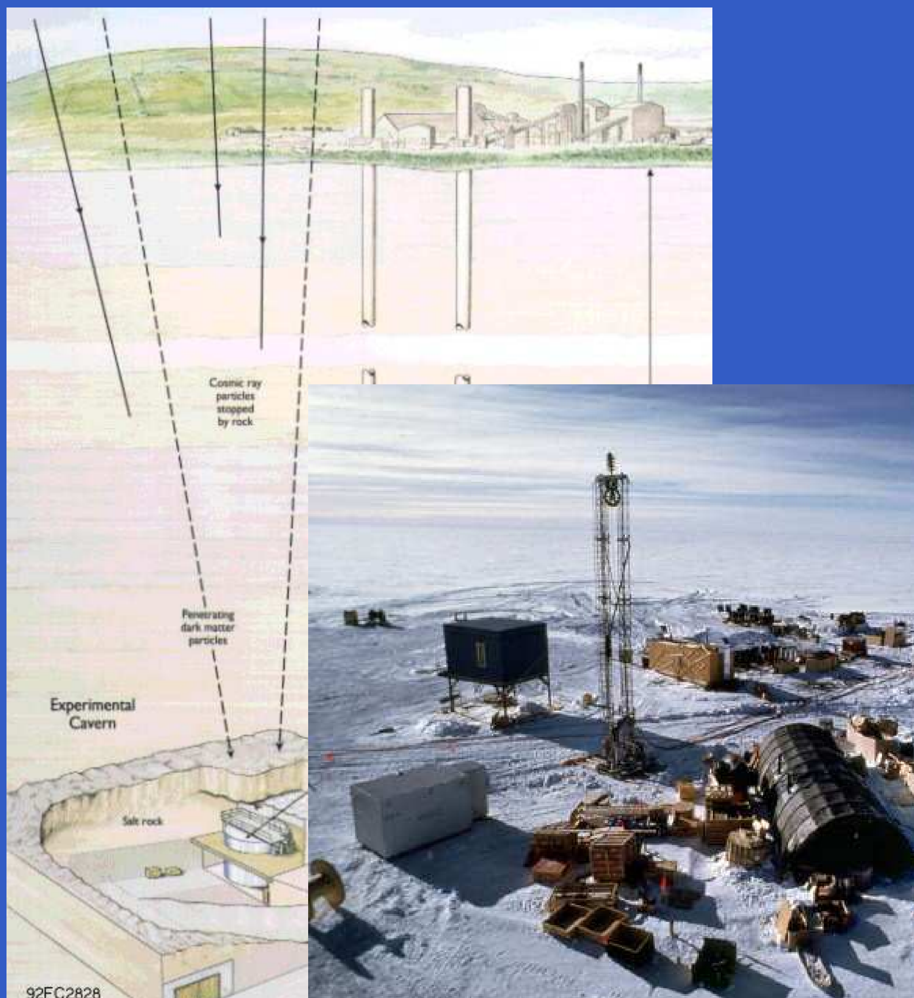
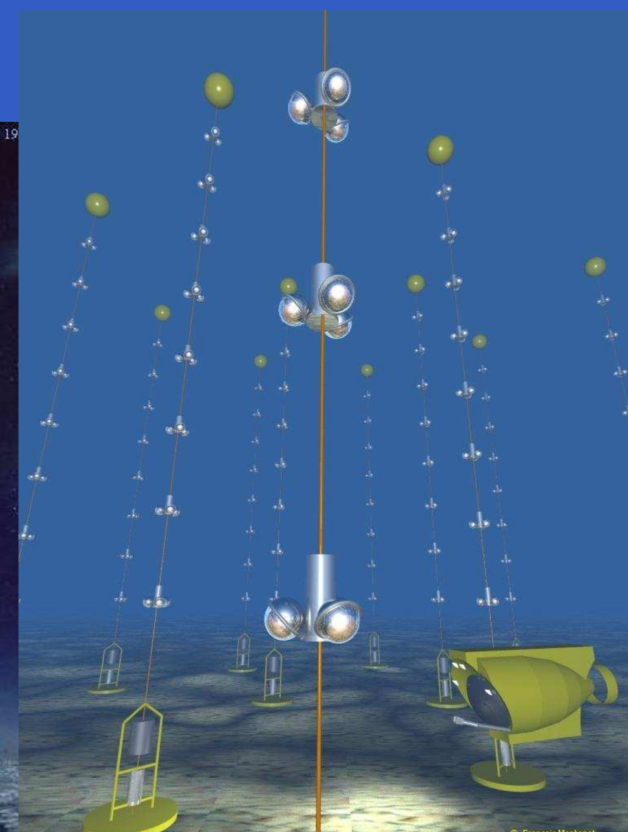


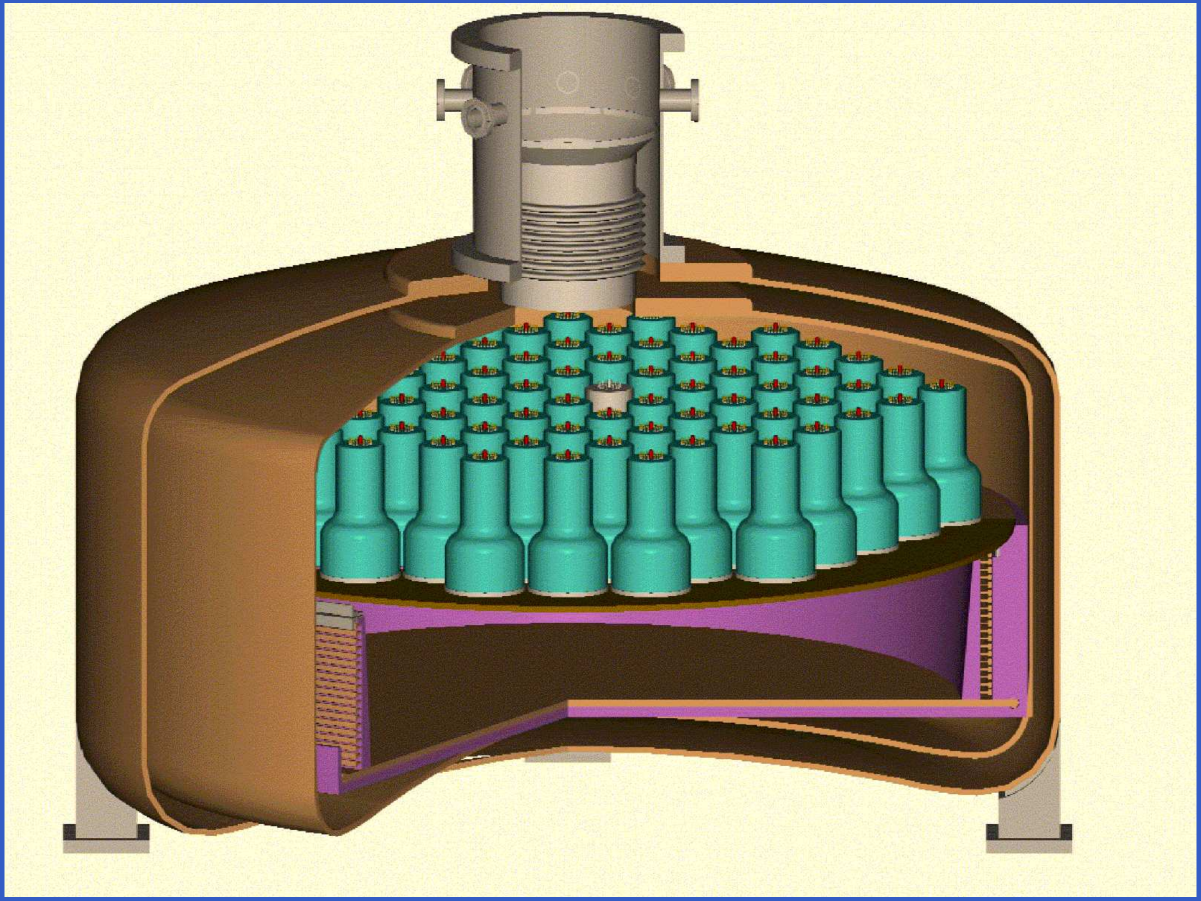
Go underground/–ice/–water

...as deep as one can
impressive experimental effort

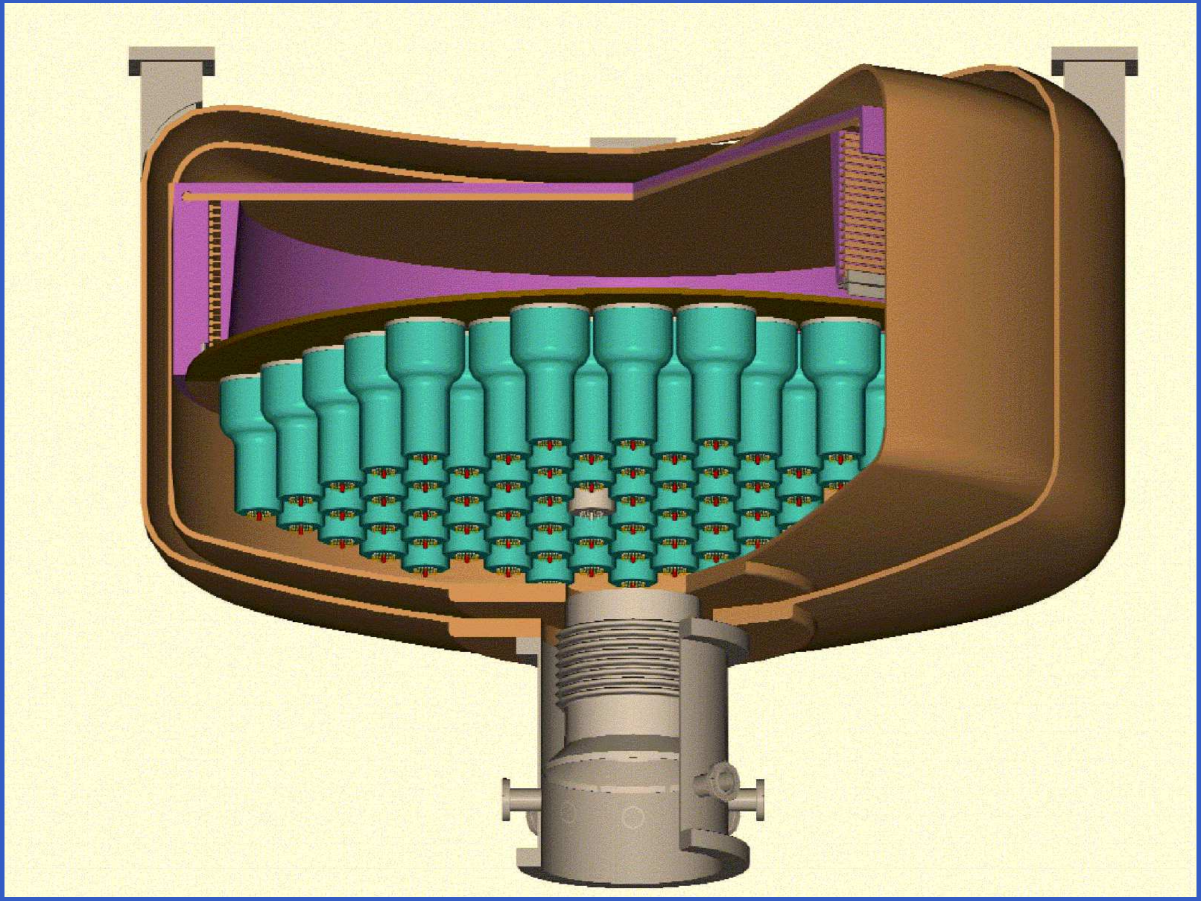




Zeplin Detector



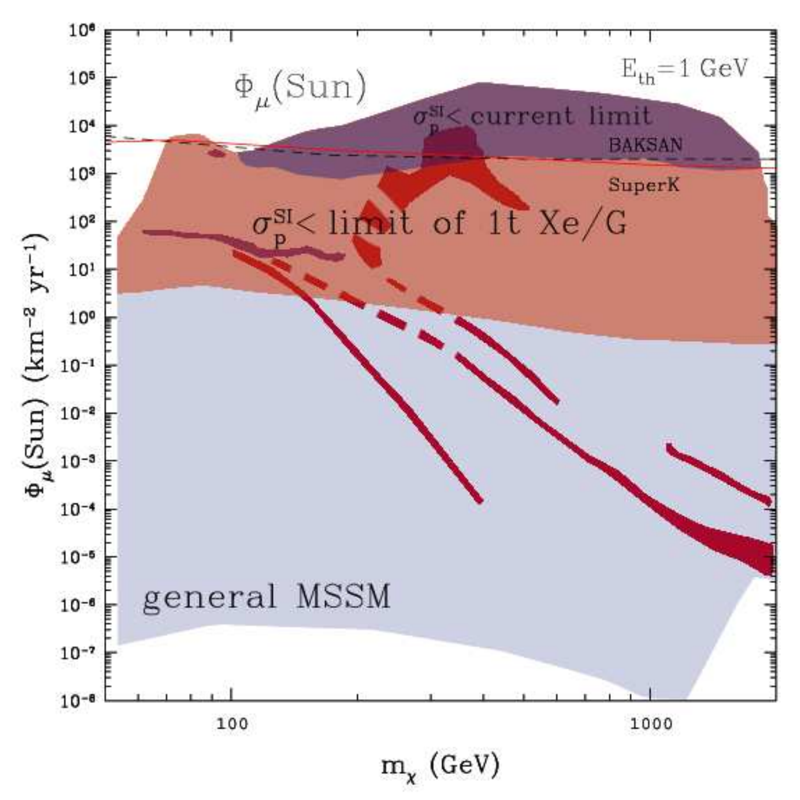
can this thing detect most mass in the Universe???



... or at least milk a cow???

Direct vs. Indirect Detection

... if $\sigma_p^{SI} \lesssim 10^{-10}$ pb



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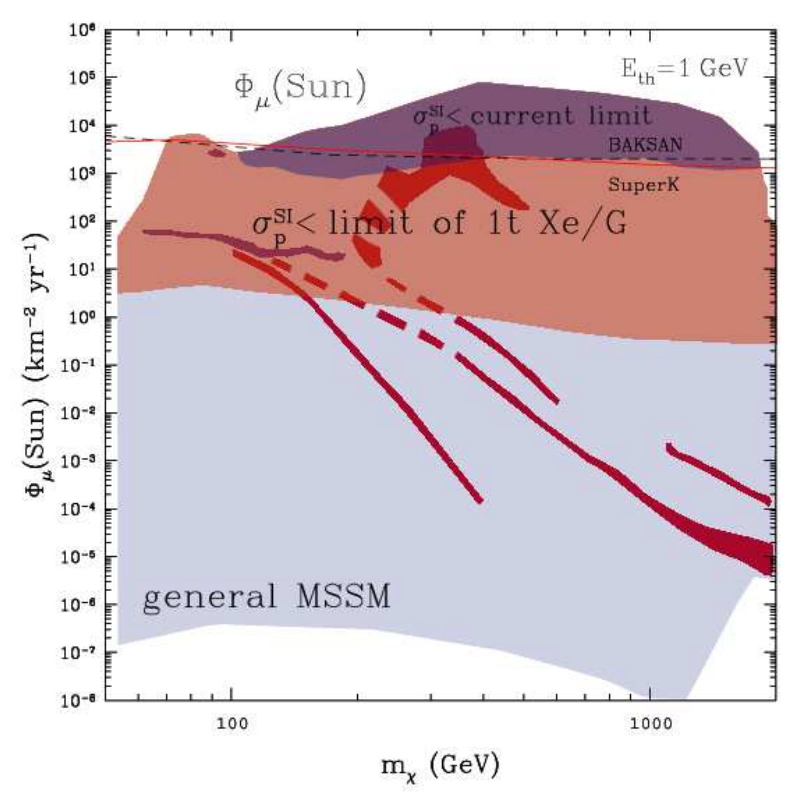
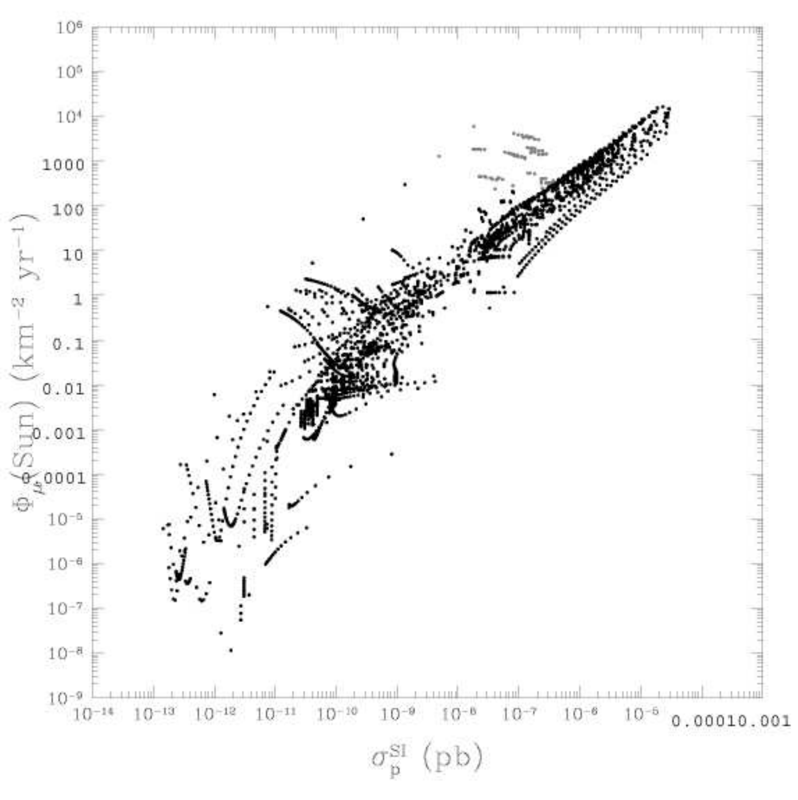


MSSM, $\tan\beta = 35$



purple: σ_p^{SI} $<$ current limits, brown: σ_p^{SI} $<$ limits from "1 tonne" detectors (Xe/Ge)

ICECUBE reach: ~ 10 events/ km^2/yr, can't do better than DD

“Exotic” SUSY WIMPs: $\widetilde{G}$ & $\widetilde{a}$

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historically first:

$\widetilde{G}$: Pagels+Primack, Weiberg ('82)

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$\widetilde{\gamma}$: Goldberg ('83)

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(assume usual gravity mediated SUSY breaking)

	axino	gravitino
spin	1/2	3/2
interaction	$\sim 1/f_a^2$	$\sim 1/M_{\rm P}^2$
mass	$\not\propto M_{\rm SUSY}$	$\propto M_{\rm SUSY}$

mass model dependent

treat it as a free parameter

$f_a \sim 10^{9-12}$ GeV – PQ scale

$M_{\rm P} = 2.4 \times 10^{18}$ GeV – reduced Planck mass

$M_{\rm SUSY} \sim 100$ GeV — 1 TeV – soft SUSY mass scale

Recent activity...

axino – work with:

- L. Covi, J.E. Kim, PRL'99 (hep-ph/9905212);
- L. Covi, H.-B. Kim, J.E. Kim, JHEP'01 (hep-ph/0101009);
- L. Covi, M. Small, JHEP'02 (hep-ph/0206119);
- L. Covi, R. Ruiz de Austri, M. Small, JHEP'04 (hep-ph/0402240)

related recent work:

- H.-B. Kim, J.E. Kim, hep-ph/0108101
- D. Hooper, L.-T. Wang, hep-ph/0402220
- A. Brandenburg, F.D. Steffen, hep-ph/0406021
- ...

gravitino – work with:

- R. Ruiz de Austri, hep-ph/0408227

related recent work:

- al et Buchmüller (BBP, '98, BBB '00)
- Feng et al, '02-'04
- Ellis et al. (EOSS), Dec 03
- ...

Axino WIMP

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L. Covi+J.E. Kim+LR, PRL'99

consider: (KSVZ model)

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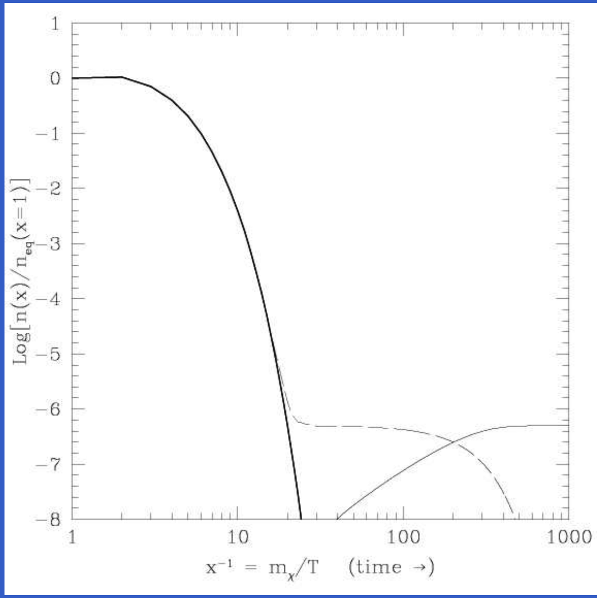

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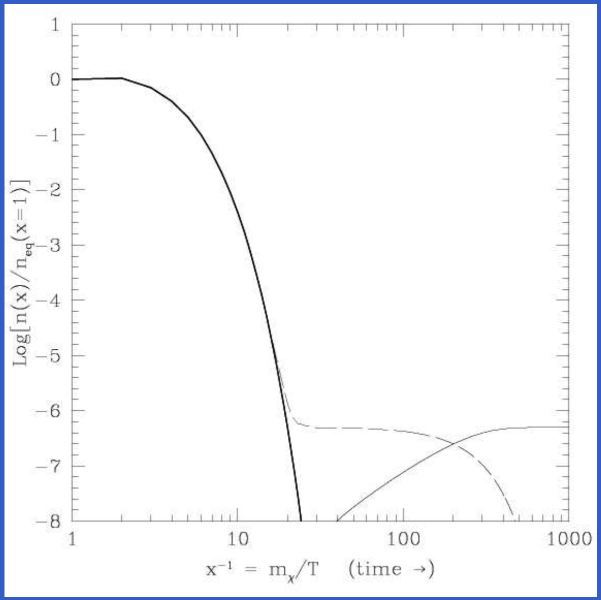

$$\tau(\chi \to \widetilde{a}\,\gamma) \simeq 0.3\,\mathrm{sec}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^3 \ldots$$

$(\chi \simeq \widetilde{B})$

...before BBN

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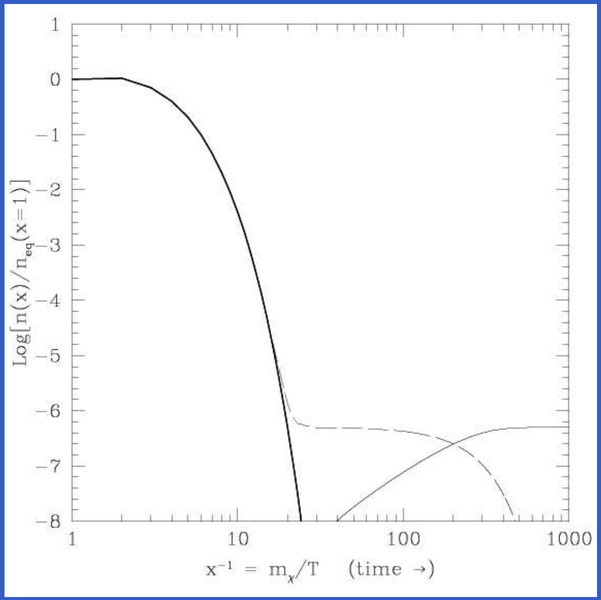

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NTP: non–thermal production

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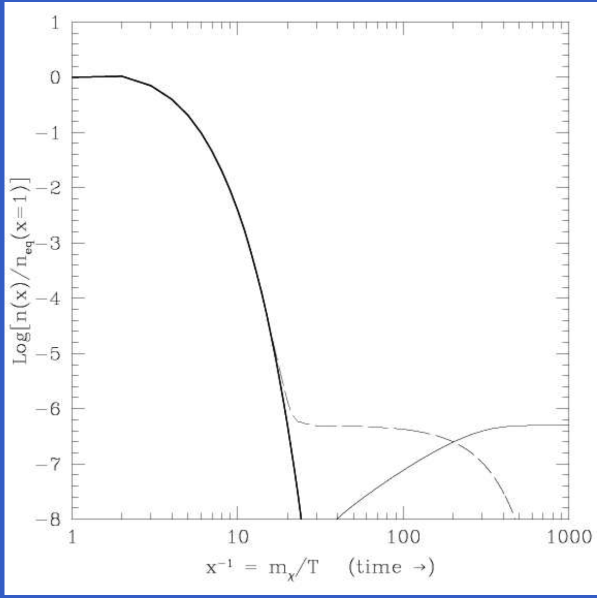

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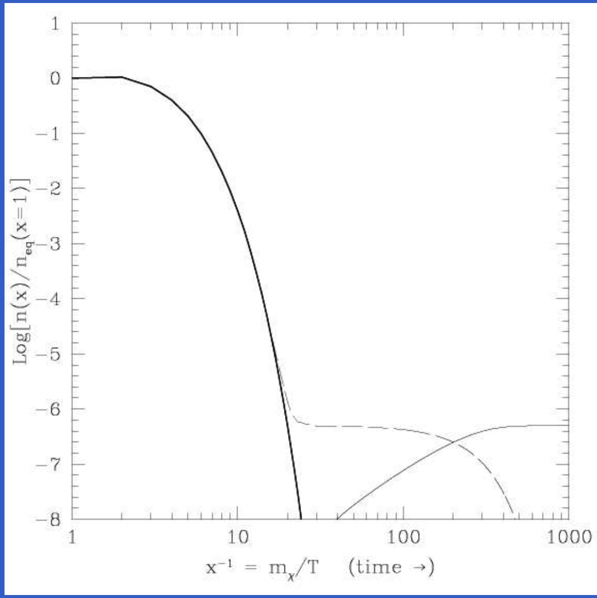

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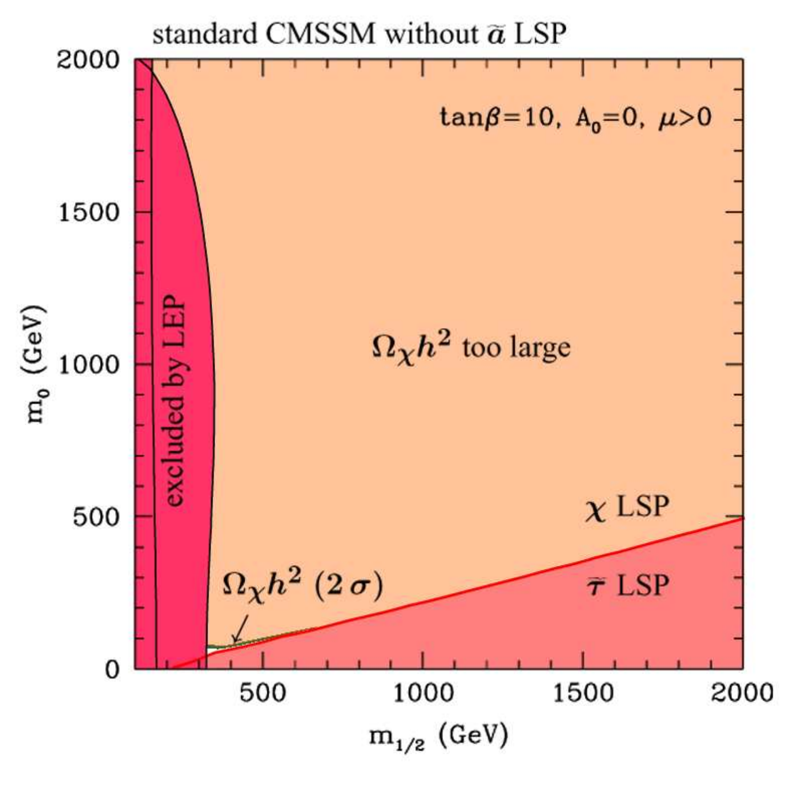
- TP: $q\,q \to \widetilde{a}\,\widetilde{g}, \quad \widetilde{q} \to \widetilde{a}\,q, \ldots$

TP: thermal production

Very different cosmological picture

Covi, LR, Ruiz de Austri, Small, JHEP'04 (hep-ph/0402240)

CMSSM, $\tan\beta = 10$, $A_0 = 0$



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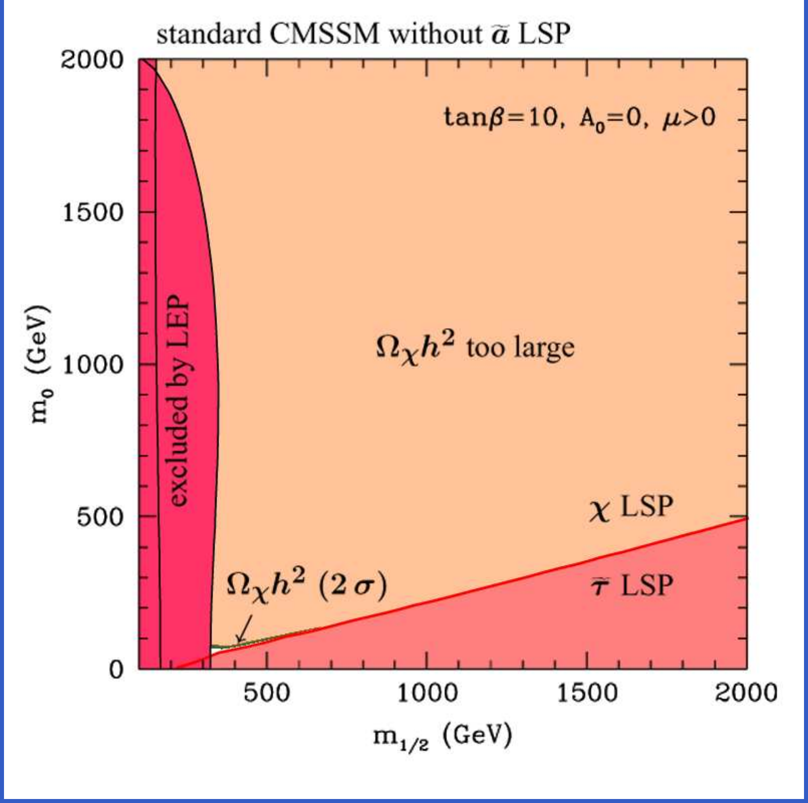
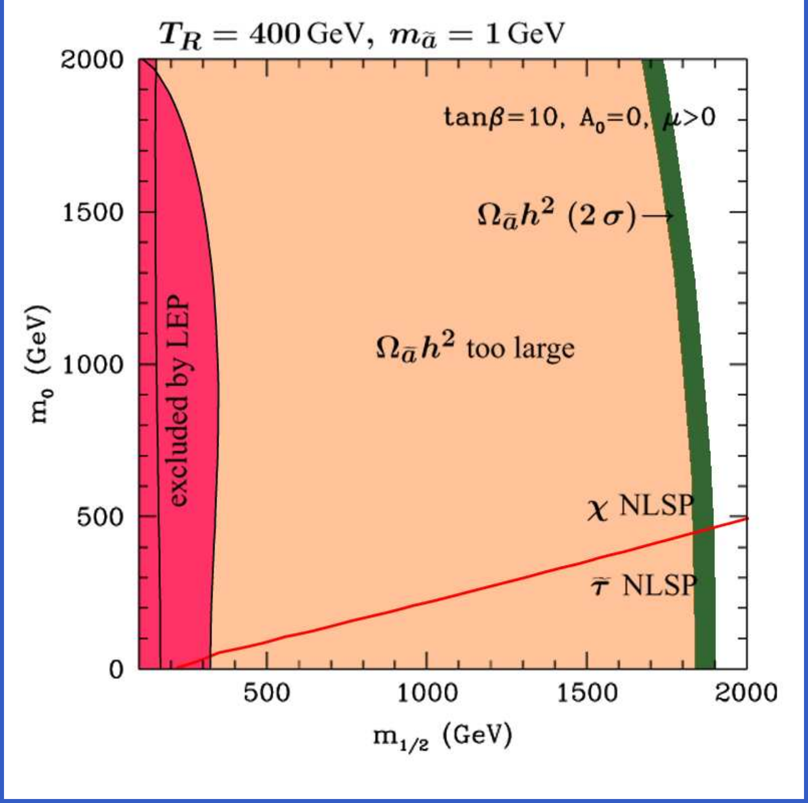


$\widetilde{a}$ LSP, $m_{\widetilde{a}} \simeq m_\chi$, $T_R = 400$ GeV, TP



SUSY could be heavy, LOSP (NLSP) could be charged, . . .

Gravitino WIMP in the CMSSM

Gravitino WIMP in the CMSSM

(analogous to $\widetilde{a}$ LSP)

LR+Ruiz de Austri,
hep-ph/0408227

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...long after BBN

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$\Rightarrow$ NTP:

NTP: non–thermal production

$$\Omega_{\widetilde{G}}^{\mathbf{NTP}} = \frac{m_{\widetilde{G}}}{m_{\mathbf{NLSP}}}\,\Omega_{\mathbf{NLSP}}$$

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Feng, et al. (FST 02-04), MSSM

Ellis, et al. (EOSS 03), CMSSM

Gravitino WIMP in the CMSSM

(analogous to $\widetilde{a}$ LSP)

LR+Ruiz de Austri, hep-ph/0408227

- $\widetilde{G} =$ LSP
- NLSP (χ or $\widetilde{\tau}_1$) first freezes out, then decays

$$\tau(\text{NLSP} \rightarrow \widetilde{G} + \gamma/\tau) \sim 10^8\,\mathbf{sec}\left(\frac{\mathbf{100\,GeV}}{m_{\mathbf{NLSP}}}\right)^5 \left(\frac{m_{\widetilde{G}}}{\mathbf{100\,GeV}}\right)^2 \ldots$$

$(\mathbf{NLSP} = \chi(\simeq \widetilde{B}), \widetilde{\tau}_1)$

...long after BBN

$\Rightarrow$ NTP:

NTP: non–thermal production

$$\Omega_{\widetilde{G}}^{\mathbf{NTP}} = \frac{m_{\widetilde{G}}}{m_{\mathbf{NLSP}}}\,\Omega_{\mathbf{NLSP}}$$

$\Rightarrow$ TP: $q\,q \rightarrow \widetilde{G}\,\widetilde{g},\quad \widetilde{q} \rightarrow \widetilde{G}\,q, \ldots$

TP: thermal production

$$\Omega_{\widetilde{G}}^{\mathbf{TP}} \simeq 0.2\left(\frac{T_R}{10^{10}\,\mathbf{GeV}}\right)\left(\frac{\mathbf{100\,GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\widetilde{g}}(\mu)}{\mathbf{1\,TeV}}\right)^2$$

Bolz+Brandenburg+Buchmüller ('00)

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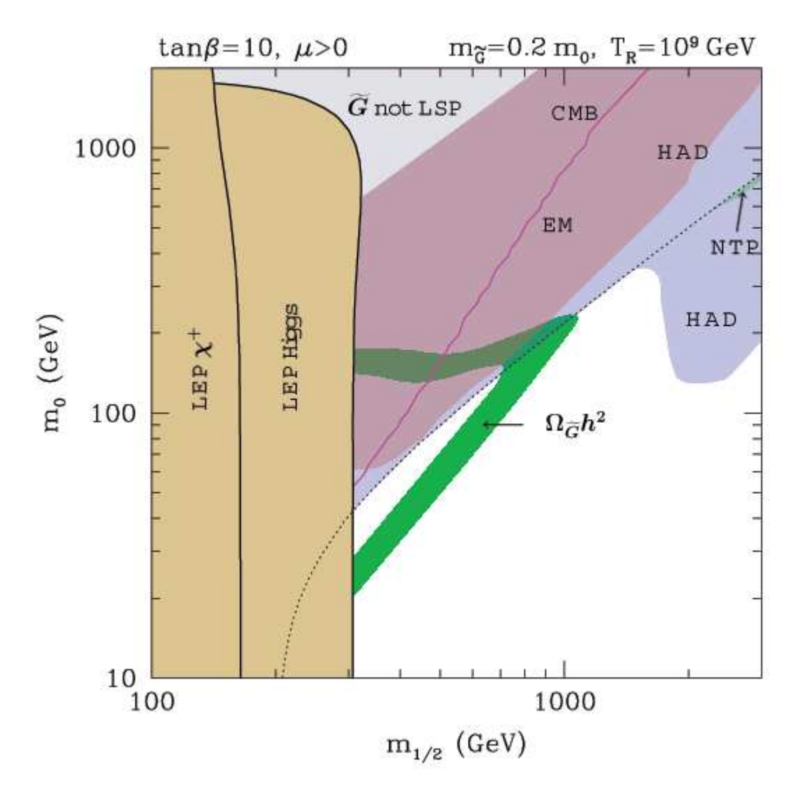
At high $T_R \gtrsim 10^9$ GeV TP is important

Results, $m_{\widetilde{G}} = 0.2m_0$

LR+Ruiz de Austri, hep-ph/0408227



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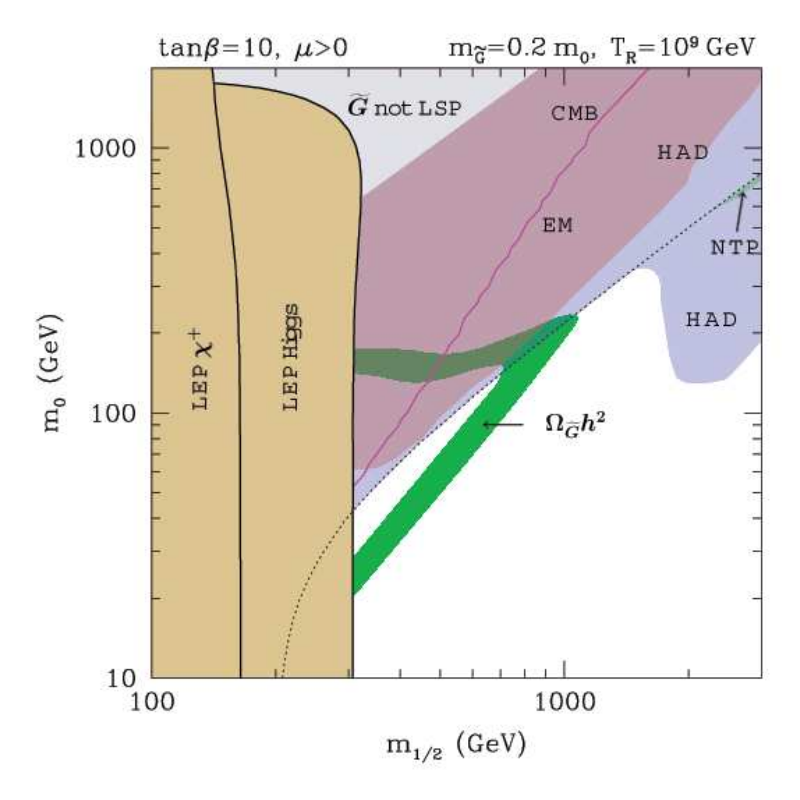

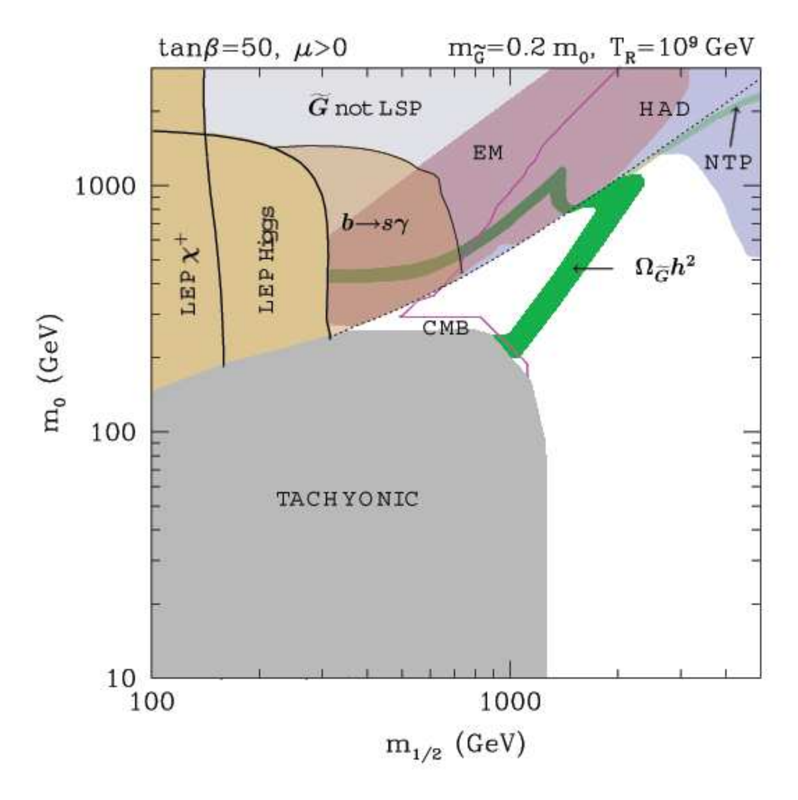

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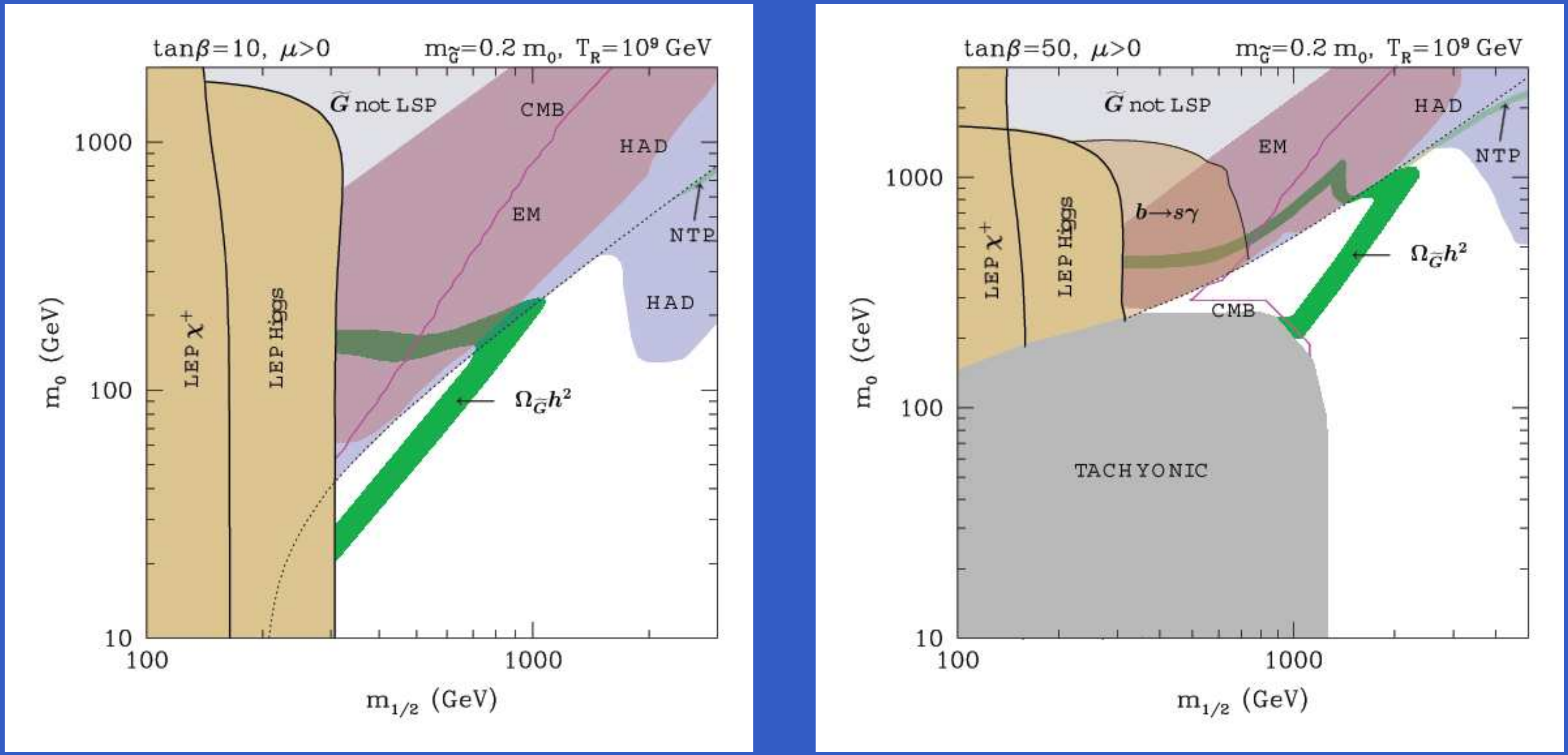

$$m_\chi \simeq 0.4 m_{1/2}, \;\; m_{\tilde{\tau}_1} \simeq \sqrt{0.15 m_{1/2}^2 + m_0^2}, \;\; m_{\tilde{g}} \simeq 2.7 m_{1/2}$$

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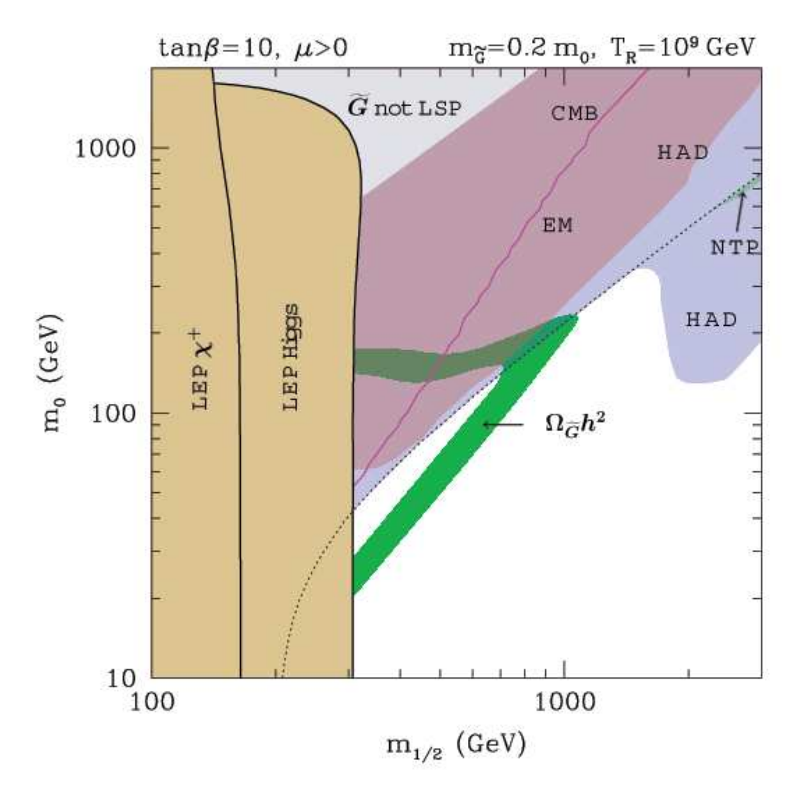
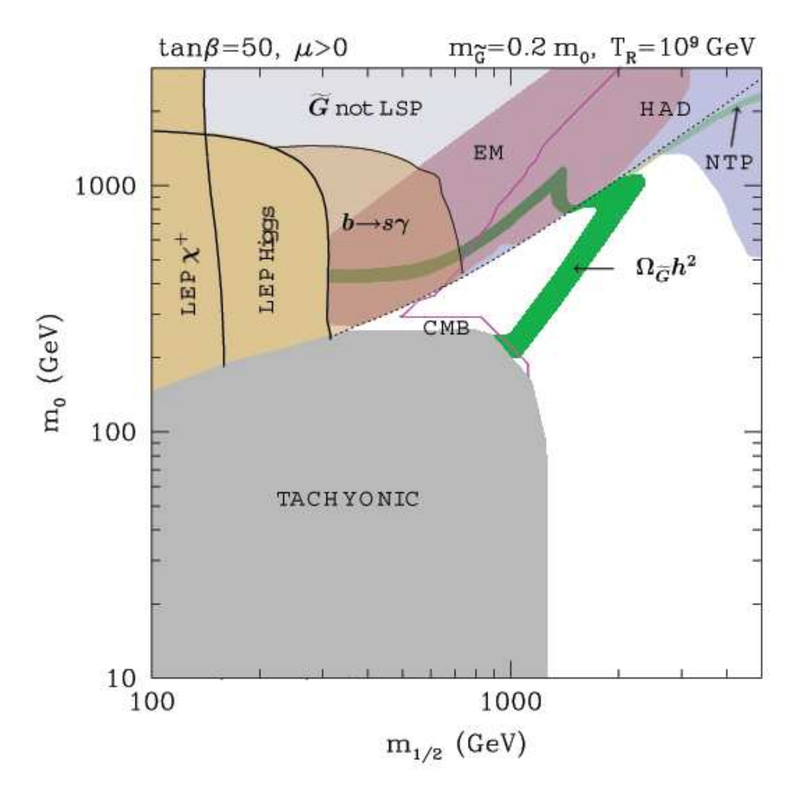


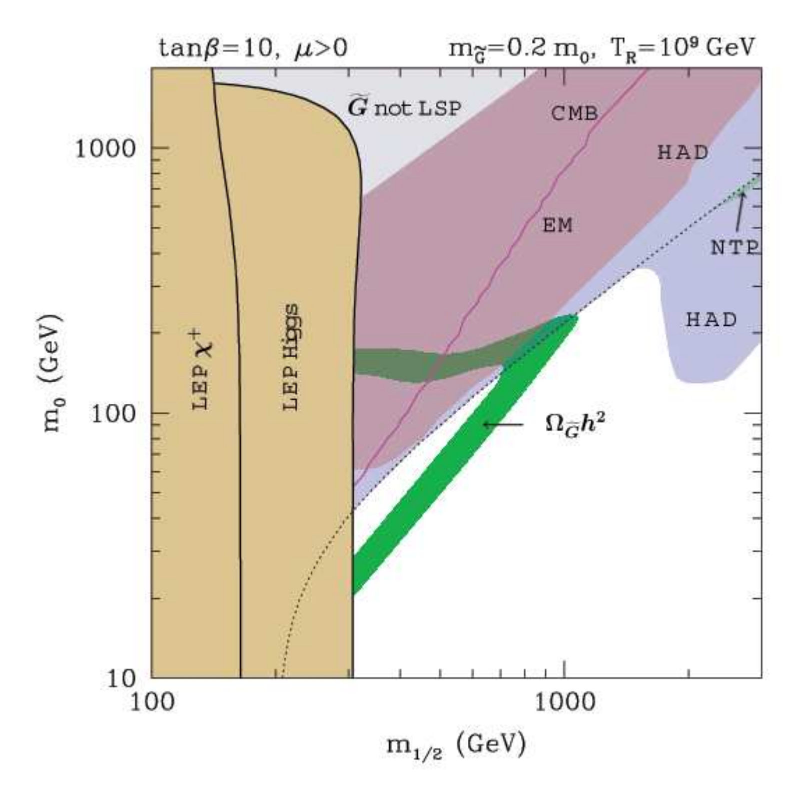


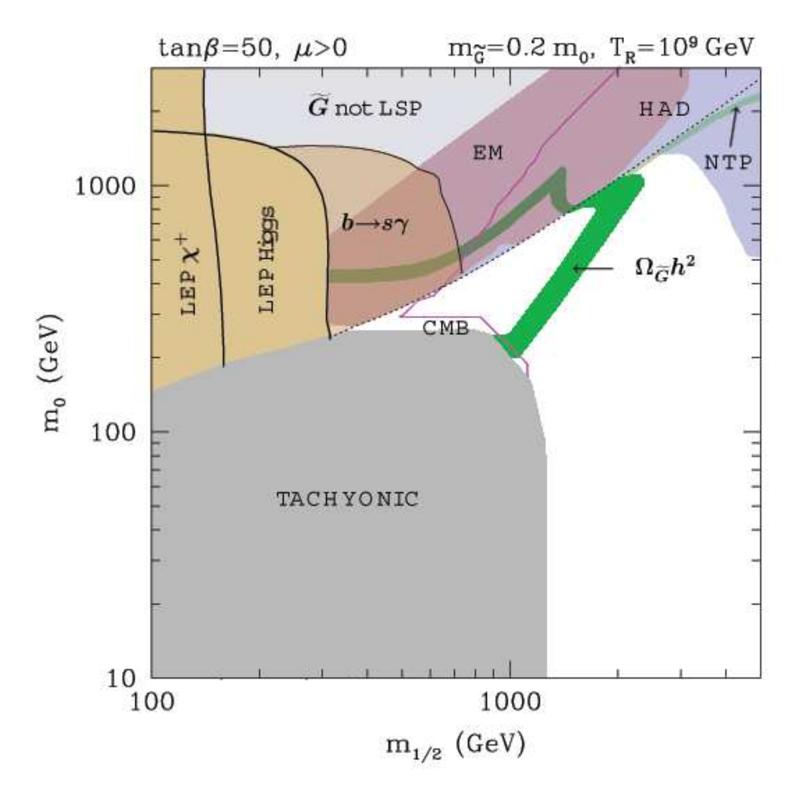
LHC: charged “stable” NLSP ($\widetilde{\tau}_1$)

LHC will reach ~ 1 TeV $\Rightarrow m_{1/2} \lesssim 2.5$ TeV (?)

Results, $m_{\widetilde{G}} = 0.2m_0$

LR+Ruiz de Austri, hep-ph/0408227



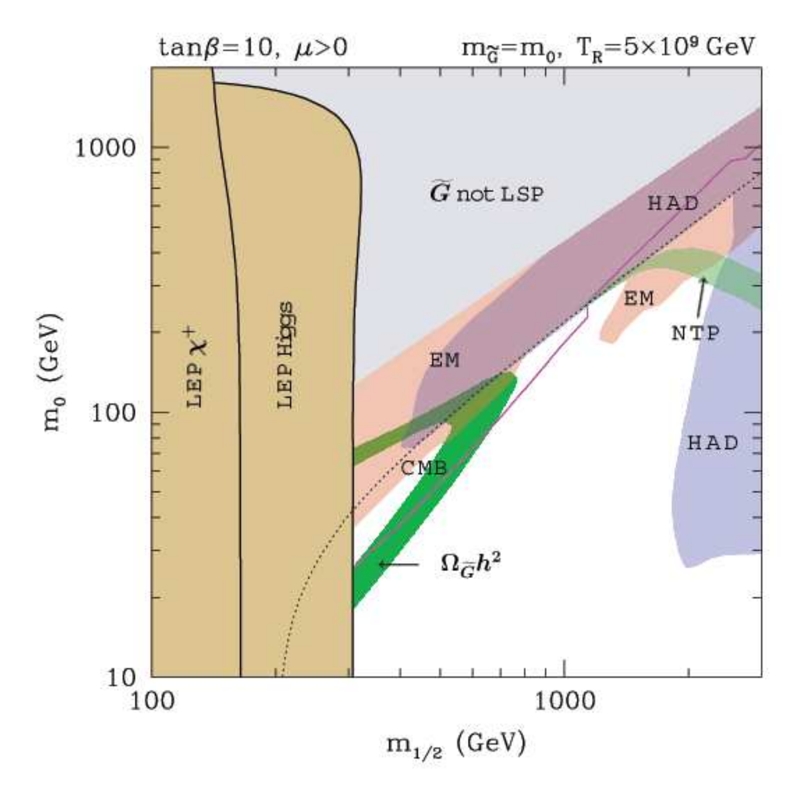


LHC will probe $m_{1/2} \lesssim 1$ TeV ($m_{\widetilde{g}} \lesssim 2.7$ TeV in $\widetilde{g}$ searches), $\widetilde{q}$'s lighter than the $\widetilde{g}$

Bound $T_R \lesssim 5 \times 10^9$ GeV

LR+Ruiz de Austri, hep-ph/0408227

$m_{\widetilde{G}} = 0.2 m_0$, $T_R = 5 \times 10^9$ GeV



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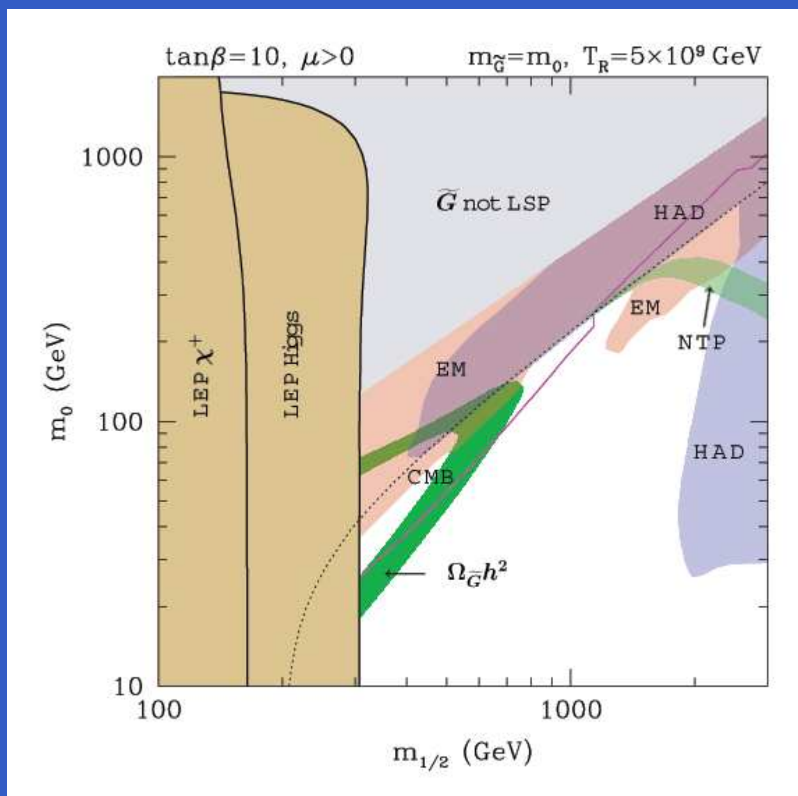

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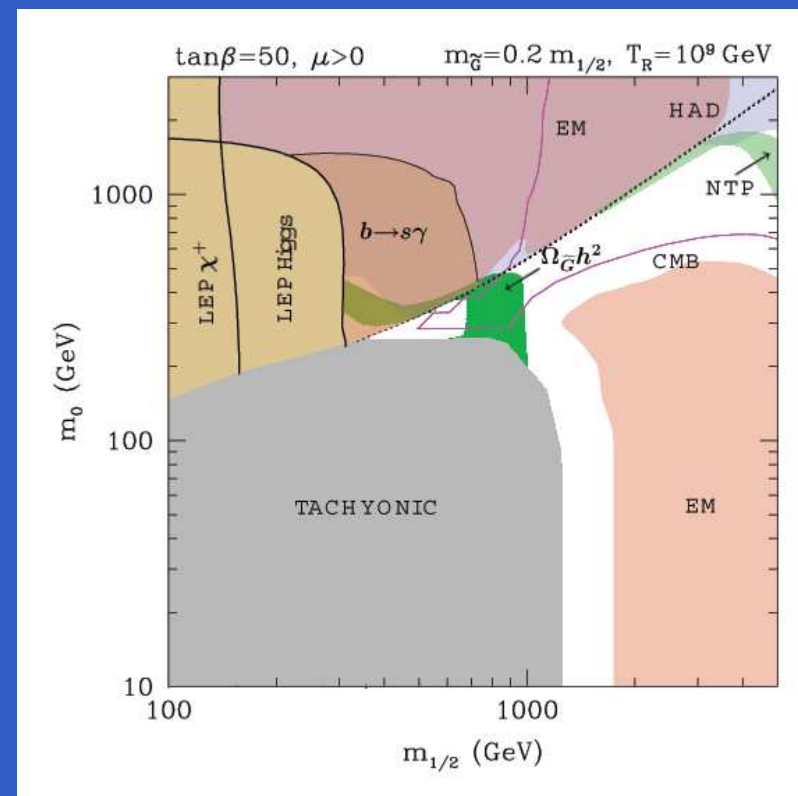
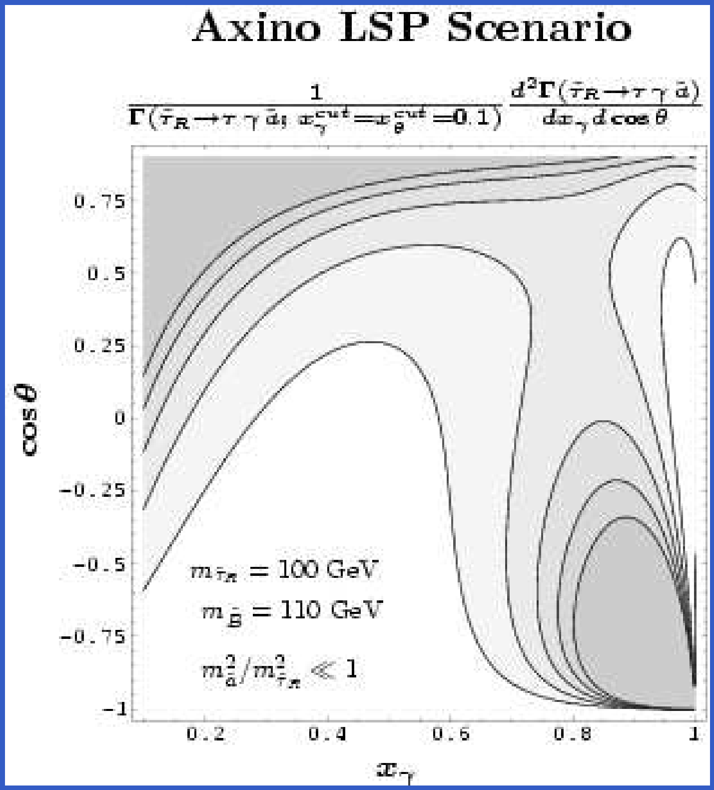


thermal leptogenesis of Fukugida–Yanagida: $T_R \gtrsim 2 - 5 \times 10^9$ GeV

$\tilde{a}$?, $\tilde{G}$?, Will we ever know?

LHC?

Brandenburg+Covi+Hamaguchi+L.R.+Steffen, hep-ph/0501287



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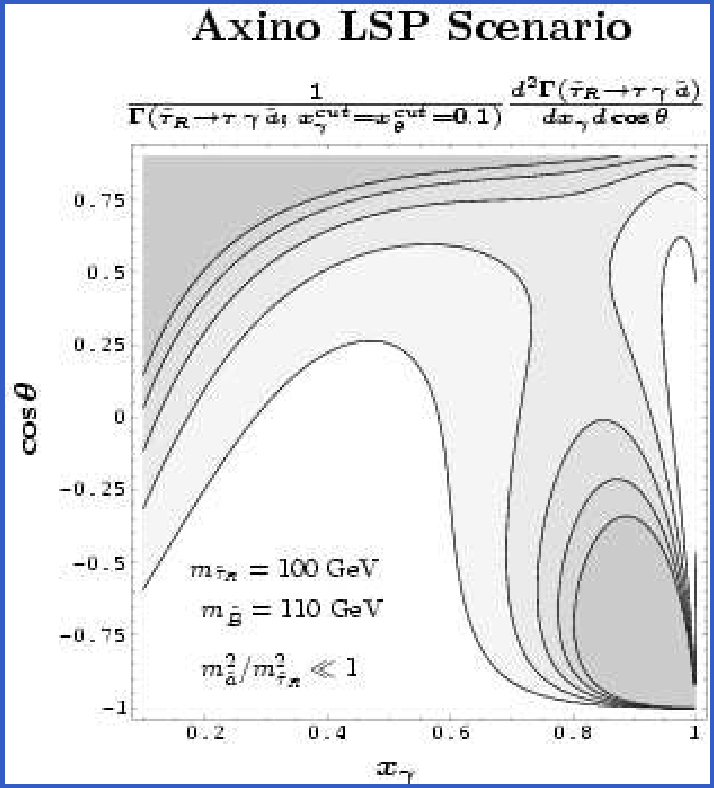
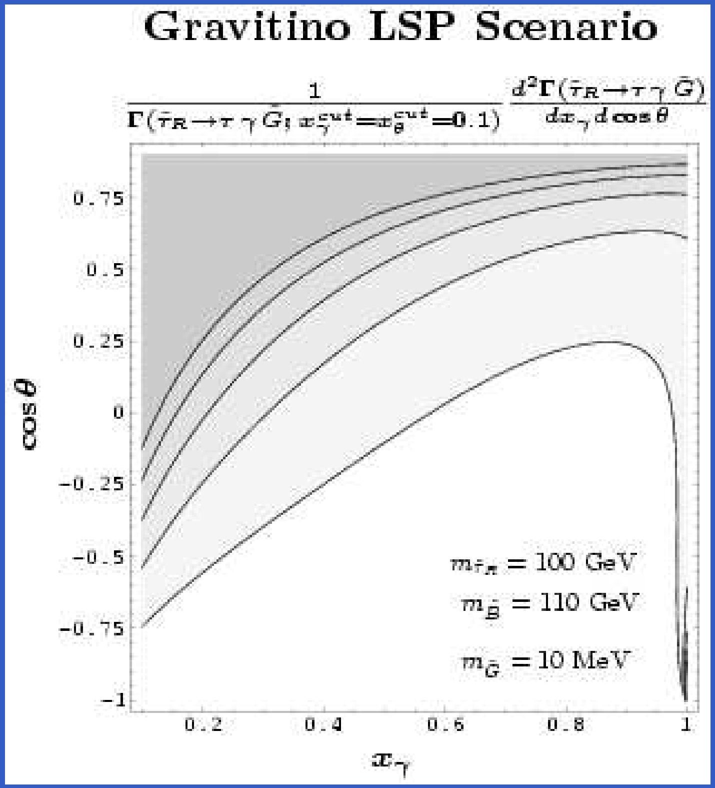
Brandenburg+Covi+Hamaguchi+L.R.+Steffen, hep-ph/0501287





testable... ...different event distributions

Conclusions

many possible candidates
few well–motivated

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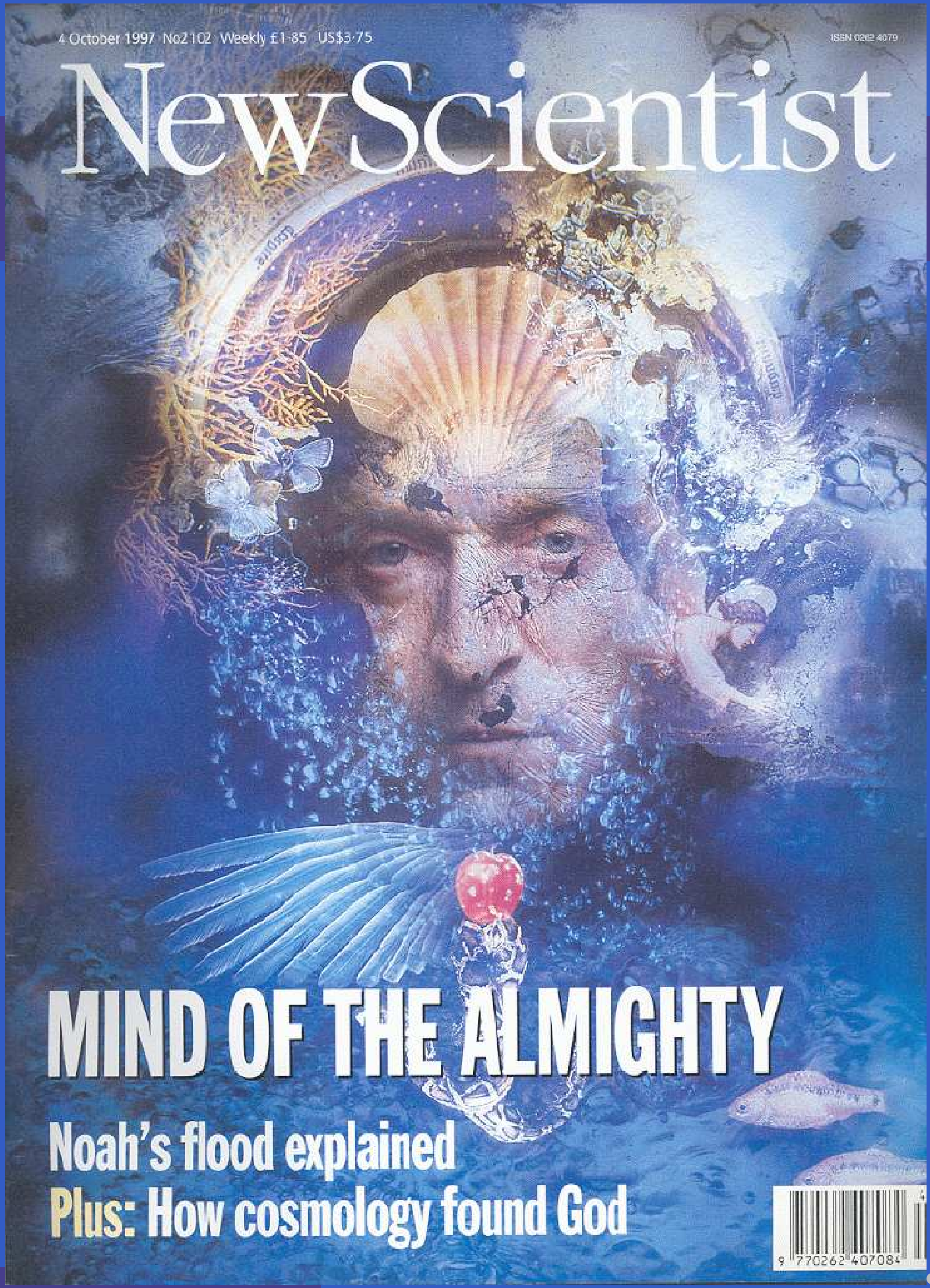
. . . whether the favourite neutralino WIMP or alternatives

expect a wealth of data from DD, Tevatron & the LHC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