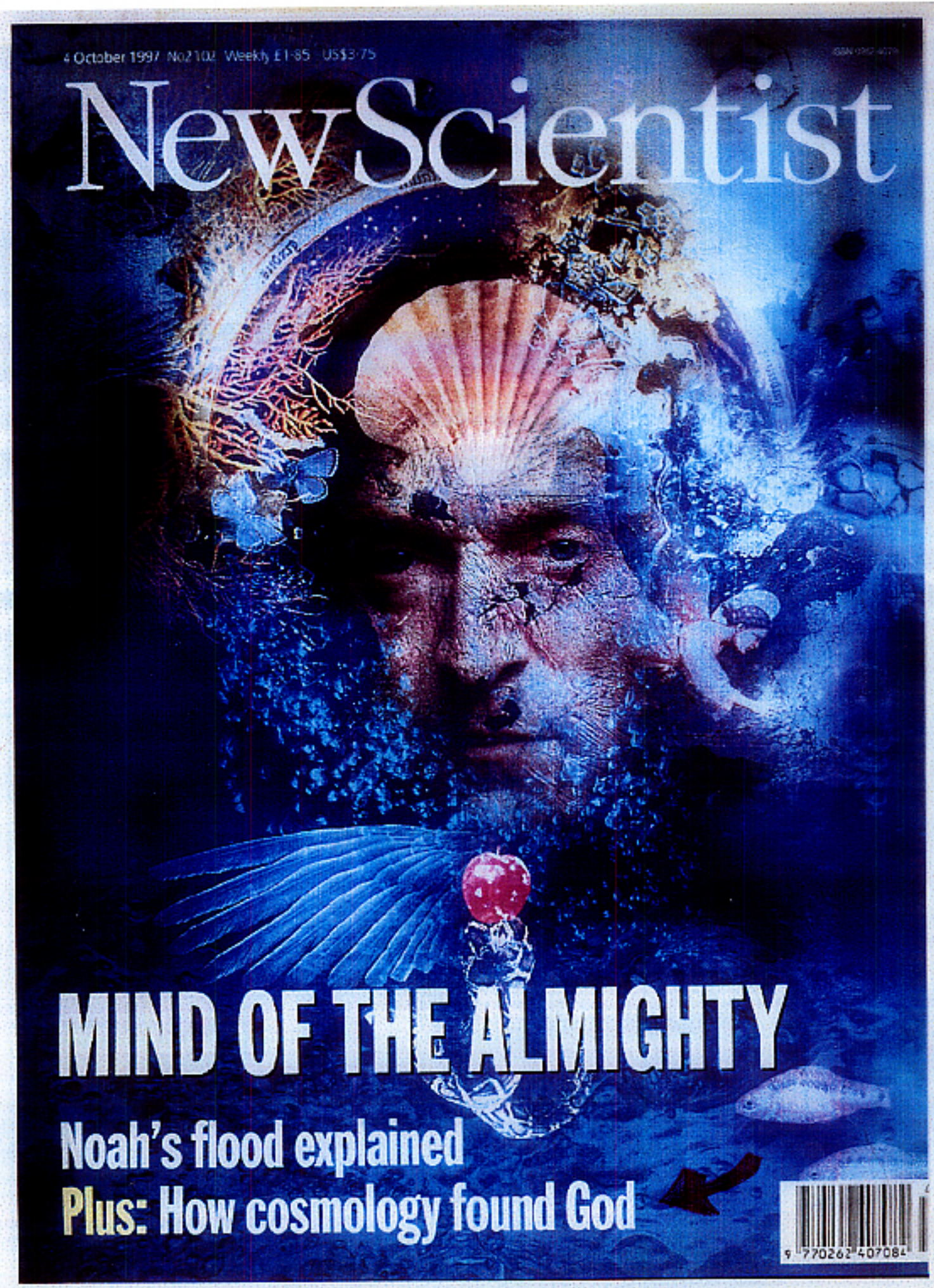
COSMO-02
(Chicago)

THE ABC OF D

L. Roszkowski

4 October 1997 No2100 Weekly £1·85 US$3·75

NewScientist



MIND OF THE ALMIGHTY

Noah's flood explained

Plus: How cosmology found God

9 770262 407084

WHAT WE KNOW

- DM PROBABLY COLD **CDM**
- $\Omega_{CDM} \approx 0.3 \pm 0.1$, $h \approx 0.7$

$\Rightarrow$ $0.1 \lesssim \Omega_{CDM} h^2 \lesssim 0.2$

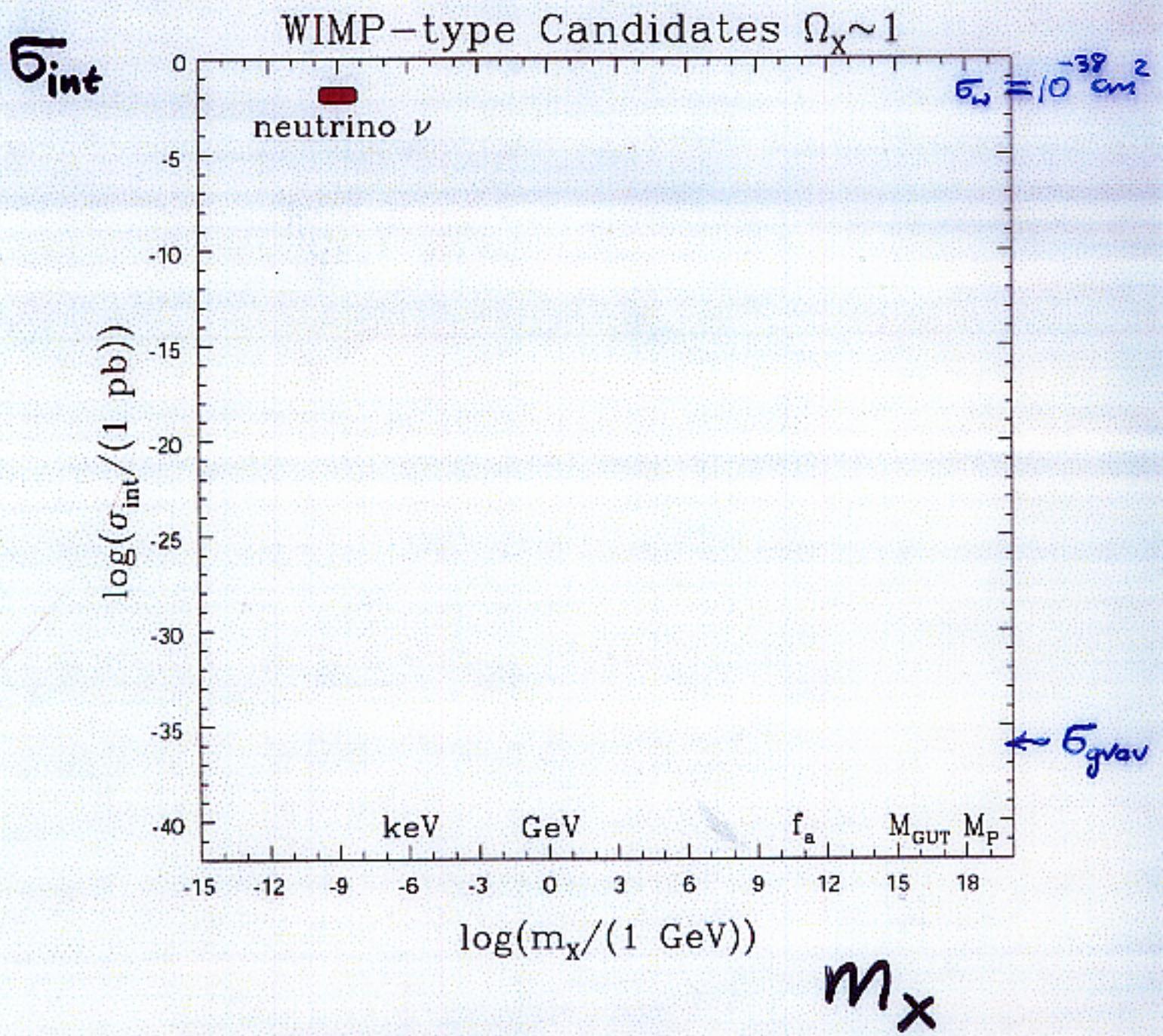
- ASTRO LIMITS ON EXOTICS
+ DM IS DARK

$\Rightarrow$ **WIMP**

WEAKLY-INTERACTING MASSIVE PARTICLE

WHAT WE DON'T KNOW

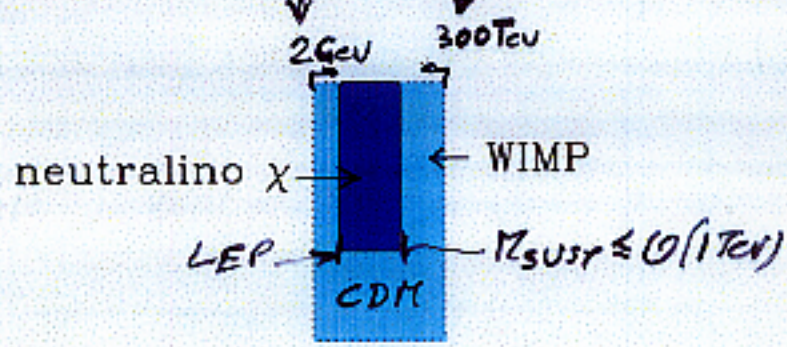
WHAT THE WIMP IS!


WIMP−type Candidates $\Omega_X \sim 1$
σ_{int}
neutrino ν
$\sigma_\nu = 10^{-38}\ cm^2$
σ_{grav}
keV
GeV
f_a
M_{GUT}
M_P
$\log(\sigma_{int}/(1\ pb))$
$\log(m_X/(1\ GeV))$
m_X

Lee-Weinberg-Hut...

(talk by A. Dolgov)

UNITARITY (Kamionkowski + Griest)



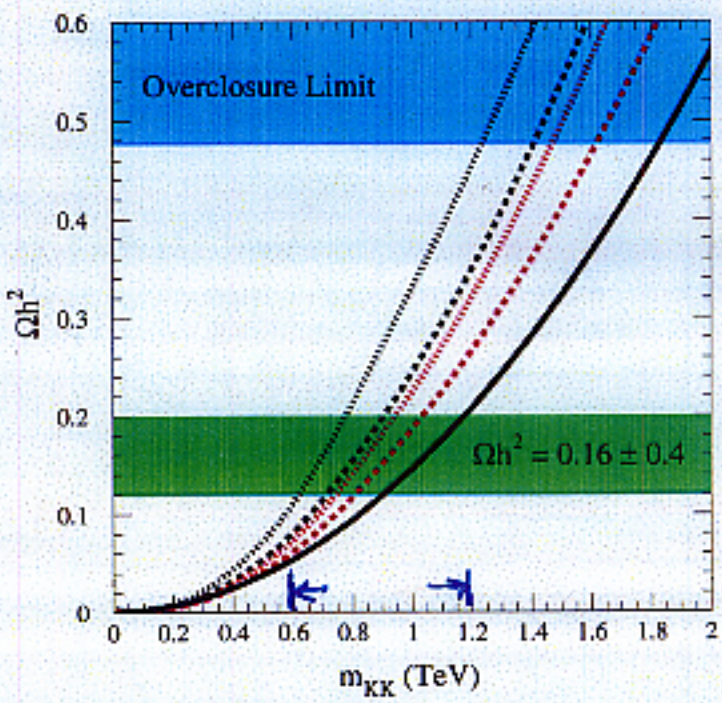
talks by

TH: Wang, Nezri, Fornengo, Coyle, Tasitsiomi, ...

EXPT: Snowden-Ifft, Cendli, Pereva, Hang, ,

WINO: Randall

Kaluza-Klein WIMP



Servant + Tait
↓
talk

ν Telescopes
PROMISING RATES
HOOPER + KRIBS
(Aug '02)

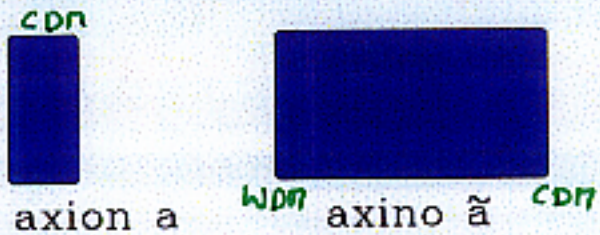
DIRECT DETECTION
BARELY ACCESSIBLE
TO FUTURE SEARCHES

Figure 3: Prediction for $\Omega_{B^{(1)}}h^2$ as in Figure 1. The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_R^{(1)}$. For each case, the black curves (upper of each pair) denote the case $\Delta = 0.01$ and the red curves (lower of each pair) $\Delta = 0.05$.

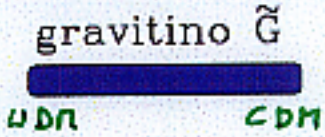
CHENG + FENG + MATCHEV (JUL '02)

The cross section $\sigma(B^{(1)}B^{(1)})$ is as derived before in Section 4. The cross section $\sigma(B^{(1)}e_R^{(1)})$ proceeds into final states with zero modes of $e\gamma$ and eZ, and in the limit in which the Z mass is neglected can be equivalently described as a single process $e_R^{(1)}B^{(1)} \to eB^{(0)}$. No νW^- final state occurs because $e_R^{(1)}$, being a weak singlet, does not couple to the SU(2) bosons, and we neglect the tiny electron Yukawa coupling which would result in a $e\Phi^0$ final state. There are also channels which convert $e_R^{(1)}\bar{e}_R^{(1)}$ into fermions and Higgs through an s-channel $B^{(0)}$ and into two $B^{(0)}$'s (or equivalently, into ZZ $\gamma\gamma$ and $Z\gamma$ final states); and channels in which $e_R^{(1)}e_R^{(1)}$ exchanges a $B^{(1)}$ to become lepton zero modes. If more than one flavor of $e_R^{(1)}$ has a mass close to $B^{(1)}$, one also has channels in which different flavors of $e_R^{(1)}$ exchange a t-channel $B^{(1)}$ and thus scatter into their corresponding zero modes. All of the needed cross sections are given in Appendix C.

Our result when including $e_R^{(1)}$ almost degenerate with $B^{(1)}$ ($\Delta = 1\%$) is a higher LKP relic density than in the case without $e_R^{(1)}$. Indeed, the self annihilation cross section



$$\sim \left(\frac{m_W}{f_a}\right)^2 \sigma_W \sim 10^{-16-22}\ \text{pb}$$



$$\sim \left(\frac{m_W}{M_p}\right)^2 \sigma_W$$

$$\sim 10^{-36}\ \text{pb}$$

(talk by G. Raffelt)

(talk by L. Covi)

Rajagopal + Turner + Wilczek '91

L. Covi + J.E. Kim + L.R '99

L.C. + J.E.K + H.B. Kim + L.R

L.C. + L.R + M. Small

(Chun + Comelli + Lyth)

Pagels + Primack 82

Buchmüller et al 98

simpzilla

(talks of
I. Albuquerque)
& P. Crotty
(also D. Hooper)

[redacted]

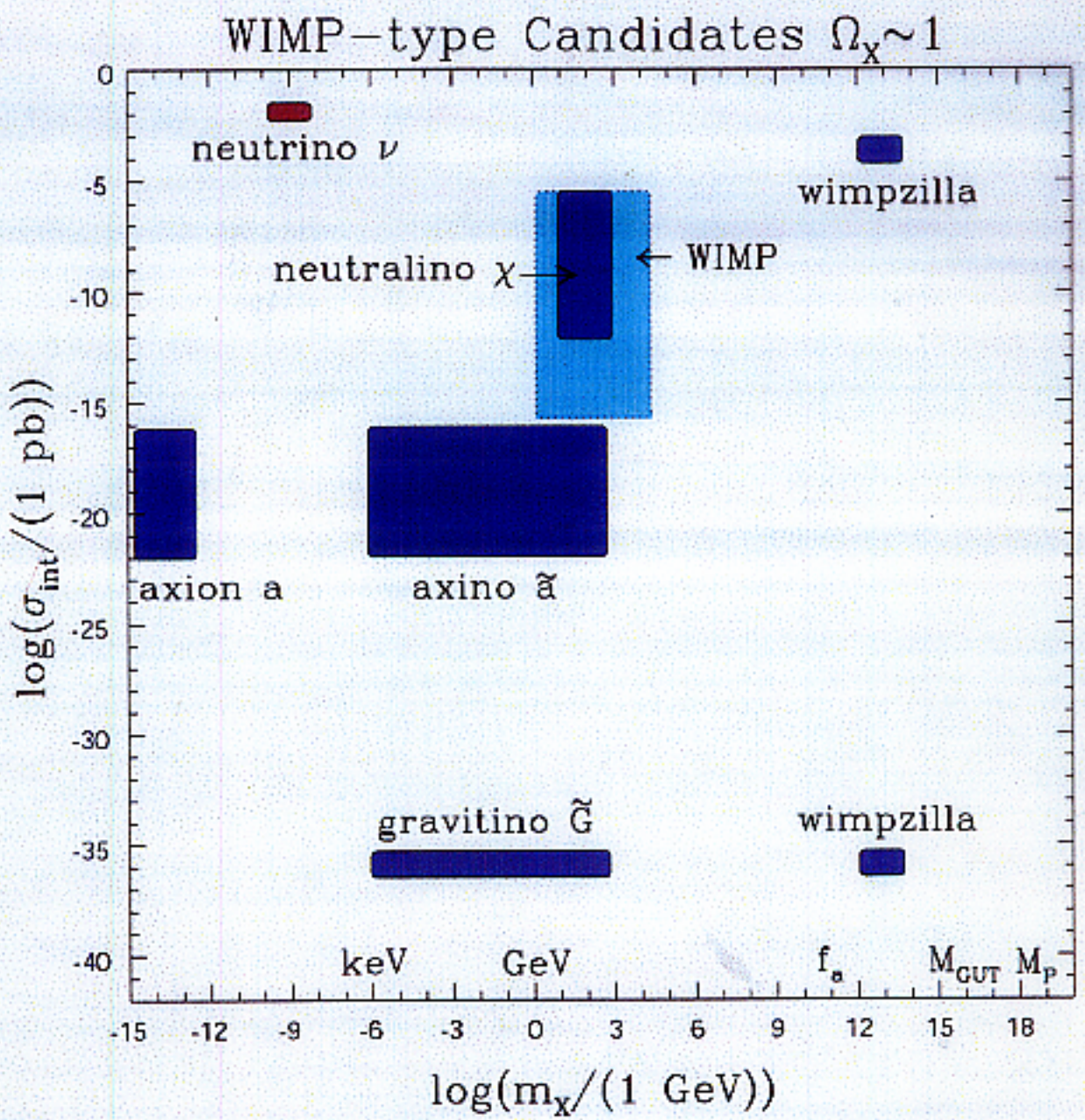
wimpzilla

Chung +
Kolb +
Riotto

Kuzmin
Tkatchev

wimpzilla

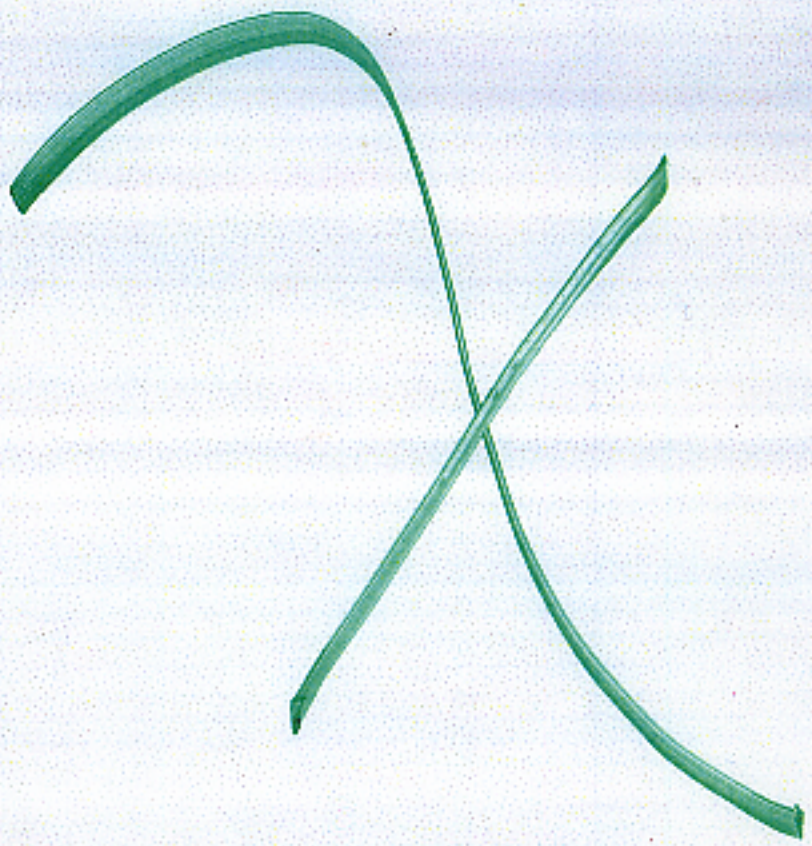
[redacted]



WIDE RANGE OF σ_{int}, ALL GIVE $\Omega_\chi \sim 1$!

USUAL ARGUMENT $\Omega \propto 1/\langle v\sigma\rangle \sim 1 \longleftrightarrow \sigma \sim \sigma_W$

APPLIES ONLY TO THERMAL RELICS



NEED

→ WIMP MASS

→ RELIC ABUNDANCE

→ INTERACTION RATES

...AND CLEVER IDEAS

SPECIFIC PREDICTIONS

STRONGLY MODEL -

- DEPENDENT

MINIMAL SUSY (MSSM) + R-PARITY

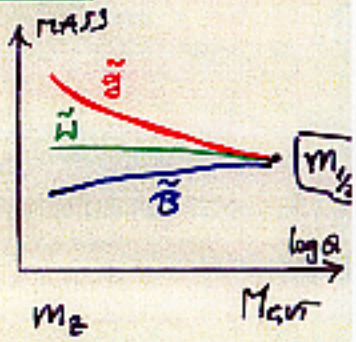
⇒ LSP STABLE

- **GAUGINOS**

$$\underbrace{M_1 \bar{\tilde{B}}\tilde{B}}_{\text{BINO}} + \underbrace{M_2 \bar{\tilde{W}}_a \tilde{W}_a}_{\text{WINO}} + m_{\tilde{g}} \bar{\tilde{g}}_b \tilde{g}_b$$

@ $Q = m_Z$ $\quad M_1 \simeq 0.5 M_2$

$M_2 \simeq \frac{1}{3} m_{\tilde{g}}$



- **HIGGSINO**

$$\mu \tilde{H}_b \tilde{H}_t + h.c.$$

- **HIGGS**

$$\mu^2 \left(H_b^2 + H_t^2\right) + \ldots$$

$$\tan\beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$$

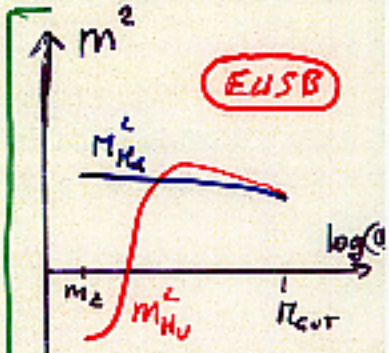
NEUTRALINOS

$$\chi_i = (\tilde{B}, \tilde{W}_3^0, \tilde{H}_b, \tilde{H}_t) \qquad i = 1 \ldots 4$$

- **SQUARKS + SLEPTONS**

$$m_{\tilde{q}_i}^2 |\tilde{q}_i|^2 + m_{\tilde{\ell}_i}^2 |\tilde{\ell}_i|^2$$

(+ 3-LINEAR SUSY-BREAKING TERMS)



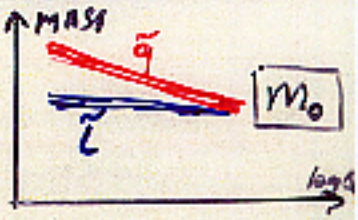
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

CONSTRAINED MSSM (CMSSM) (mSUGRA)

→ BENCHMARK MODEL FOR LHC

@ $Q = M_{GUT}$

- GAUGINOS $\quad M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- SCALARS $\quad m_{\tilde{q}} = m_{\tilde{\ell}} = m_{H_u} = m_{H_d} = m_0$
- EWSB



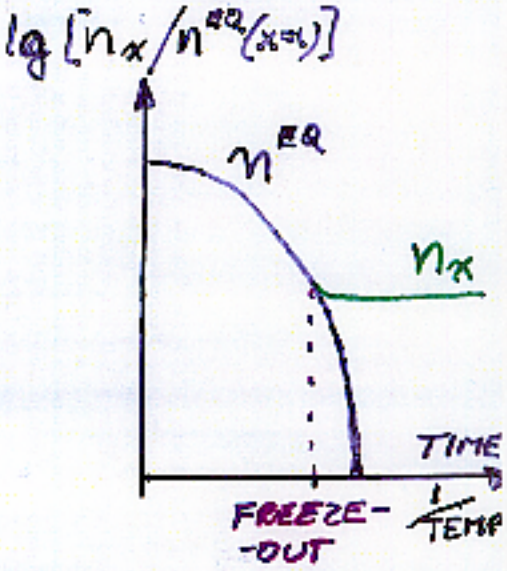
$$\tan\beta,\ m_{1/2},\ m_0,\ A_0,\ \mathrm{sgn}(\mu)$$

NEUTRALINO RELIC DENSITY

$(\nu, \chi, \tilde{G}, \tilde{a} \ldots)$

WIMPs DECOUPLE FROM THERMAL EQUILIBRIUM

FREEZE-OUT WHEN $\Gamma \lesssim H$



$x_f = \frac{T_f}{m_\chi} \approx \frac{1}{20}$

- BOLTZMANN EQ

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma_{ANN} v \rangle \left(n_\chi^2 - n_\chi^{EQ\,2}\right)$$

HUBBLE PARAMETER

$H = 100\, h \frac{km}{s \cdot Mpc}$

$h = 0.7$

n_χ - NUMBER DENSITY OF χs

n_χ^{EQ} - " IN EQUILIBRIUM

v - RELATIVE VELOCITY

$\langle \ldots \rangle$ - THERMAL AVERAGE

$$\langle \sigma v \rangle = \frac{\int dE_1 dE_2 (\sigma v) e^{-\frac{E_1}{T}} e^{-\frac{E_2}{T}}}{\int dE_1 dE_2\, e^{-E_1/T} e^{-E_2/T}}$$

RELIC ABUNDANCE

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c}$$

$\rho_\chi = m_\chi n_\chi$

ρ_c = CRITICAL DENSITY

PARTICLE PHYSICS INPUT

$\sigma_{ANN}(\chi\chi \to all)$

SOMETIMES

$+ \sigma_{COANN}(\chi\chi' \to \ldots$

$(\chi\chi^\pm \to$

$(\chi\tilde{\tau}_1 \to$

MSSM:

OVER 500 ANNIHILATION CHANNELS

MINIMAL SUSY

$\chi\chi \to 2$ BODY

Process	Exchanged particles	
	s–channel	t– and u–channel
$\chi\chi \to hh$	h, H	χ_i^0
$\chi\chi \to HH$	h, H	χ_i^0
$\chi\chi \to hH$	h, H	χ_i^0
$\chi\chi \to AA$	h, H	χ_i^0
$\chi\chi \to hA$	A, Z	χ_i^0
$\chi\chi \to HA$	h, H	χ_i^0
$\chi\chi \to H^+H^-$	h, H, Z	$\chi_k^\pm$
$\chi\chi \to W^\pm H^\mp$	h, H, A	$\chi_k^\pm$
$\chi\chi \to Zh$	A, Z	χ_i^0
$\chi\chi \to ZH$	A, Z	χ_i^0
$\chi\chi \to ZA$	h, H	χ_i^0
$\chi\chi \to W^+W^-$	h, H, Z	$\chi_k^\pm$
$\chi\chi \to ZZ$	h, H	χ_i^0
$\chi\chi \to f\bar{f}$	h, H, A, Z	f_a

Table 1: A complete set of neutralino pair-annihilation channels into tree-level two-body final states in the MSSM. The indices i, k, a run as follows: $i = 1, \ldots, 4$, $k = 1, 2$ and $a = 1, \ldots, 6$.

+ CO-ANNIHILATION

$\chi\chi^+ \to$ ALL

$\chi\chi' \to$ ALL

$\chi\tilde{\ell} \to \ldots$

$\chi\tilde{t} \to \ldots$

TECHNICALLY INVOLVED

HAS BEEN COMPLETED

ANALYTICALLY

PARTIAL WAVE EXP'N: DREES + NOJIRI

EXACT: NIKEI + LR + RUIZ

NUMERICALLY

DARKSUSY (GONDOLO et al.)

MICROMEGAS (ANNECY GP)

...

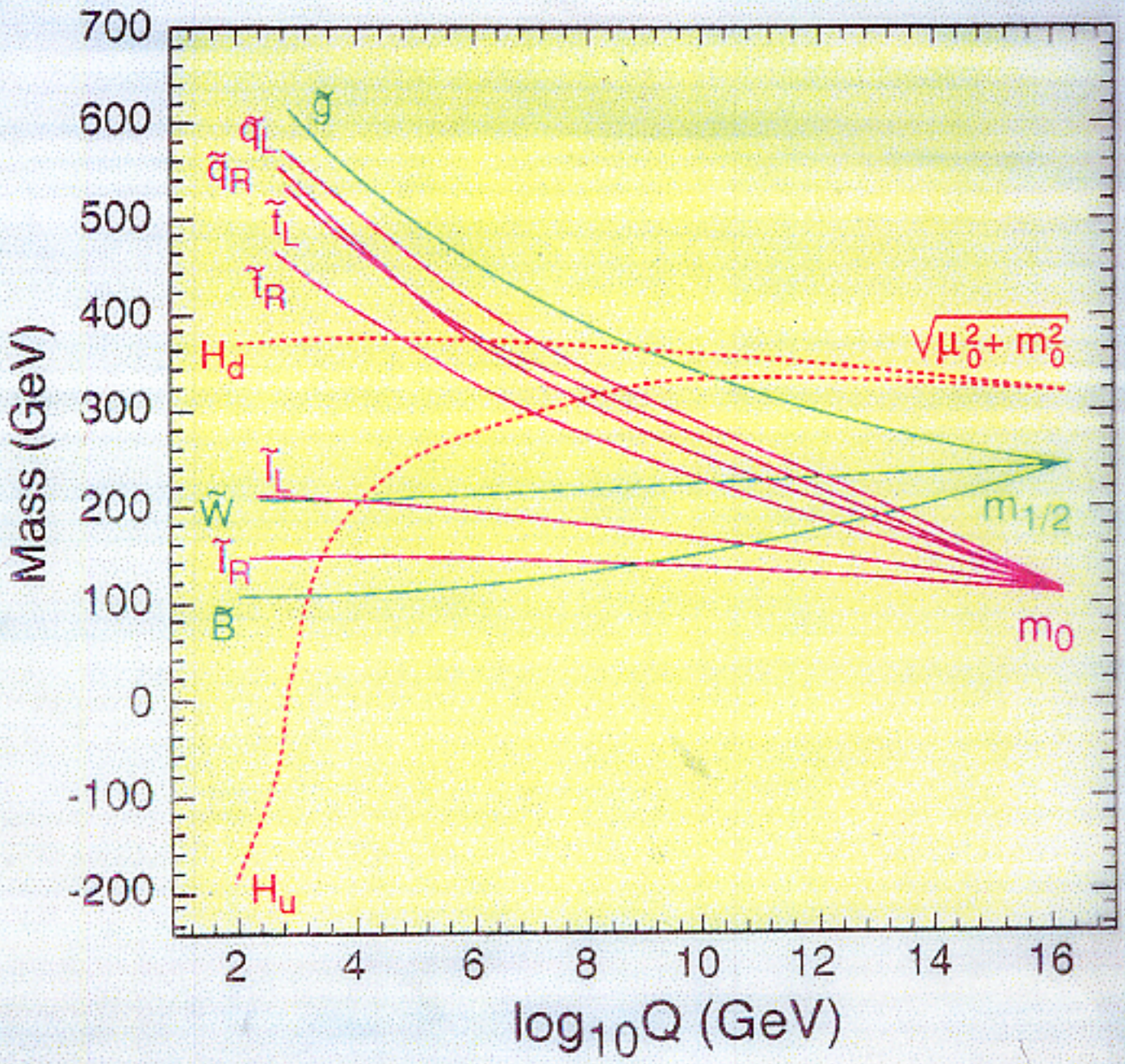
RECENT PROGRESS

$\Omega_\chi h^2$ CAN BE COMPUTED WITH HIGH ACCURACY

~FEW %

(ALSO NEAR RESONANCES, THRESHOLDS etc)

MATCH EXPTAL PRECISION


700
600
500
400
300
200
100
0
-100
-200
Mass (GeV)
2
4
6
8
10
12
14
16
$\log_{10}Q$ (GeV)
$\tilde{g}$
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{t}_L$
$\tilde{t}_R$
H_d
$\sqrt{\mu_0^2 + m_0^2}$
$\tilde{l}_L$
$\tilde{W}$
$\tilde{l}_R$
$\tilde{B}$
$m_{1/2}$
m_0
H_u

MUCH ACTIVITY IN THE FIELD

SEVERAL GROUPS
INDIVIDUALS
GUEST APPEARANCES

NIHEI + L.R + RUIZ + KIM, DREES + DJOUADI + KNEUR

ELLIS + OLIVE + ... , SREDNICKI, FARK ...
BARGER + HALZEN + KAO + HOOPER + ..
ARNOWITT + DUTTA + ..., LAMANAS + SPANOS

NATH + ... , FENG + MATCHEV + WIECZEK

BOTTINO + FORNENGO + DONATO + SCOPEL

CMSSM

BERGSTROM + EDJSO + GONDOLO, BARTZ

KAMIONKOWSKI + ULLIO + ZHANG,
+ MANY, MANY OTHERS

CMSSM

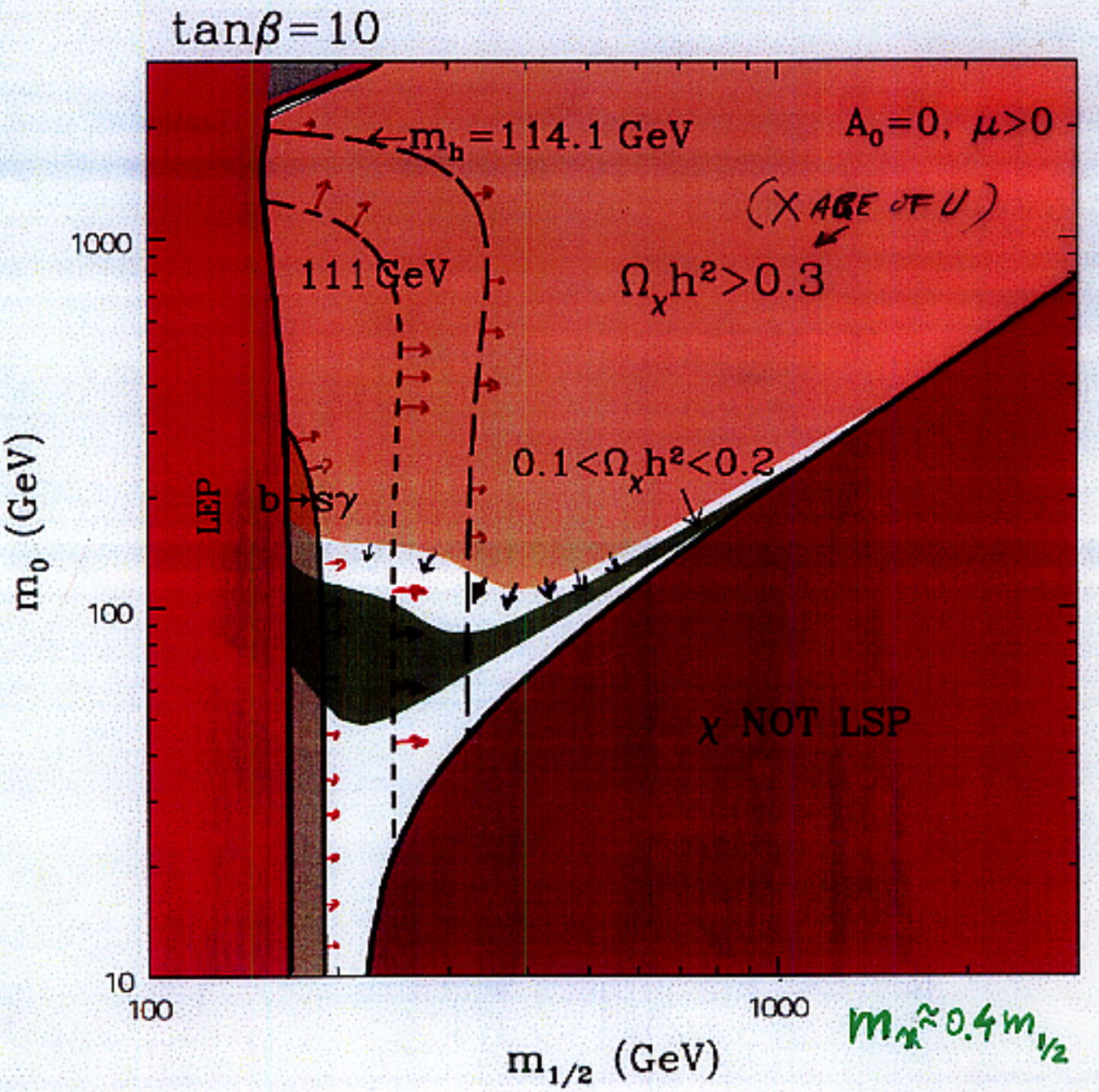
SOME DIFFERENCIES AMONG GP's

DIFFERENT CODES, APPROXIMATIONS, VARYING ACCURACY etc

SPECIFIC RESULTS LOOK DIS-SIMILAR
ESSENTIAL FEATURES SIMILAR

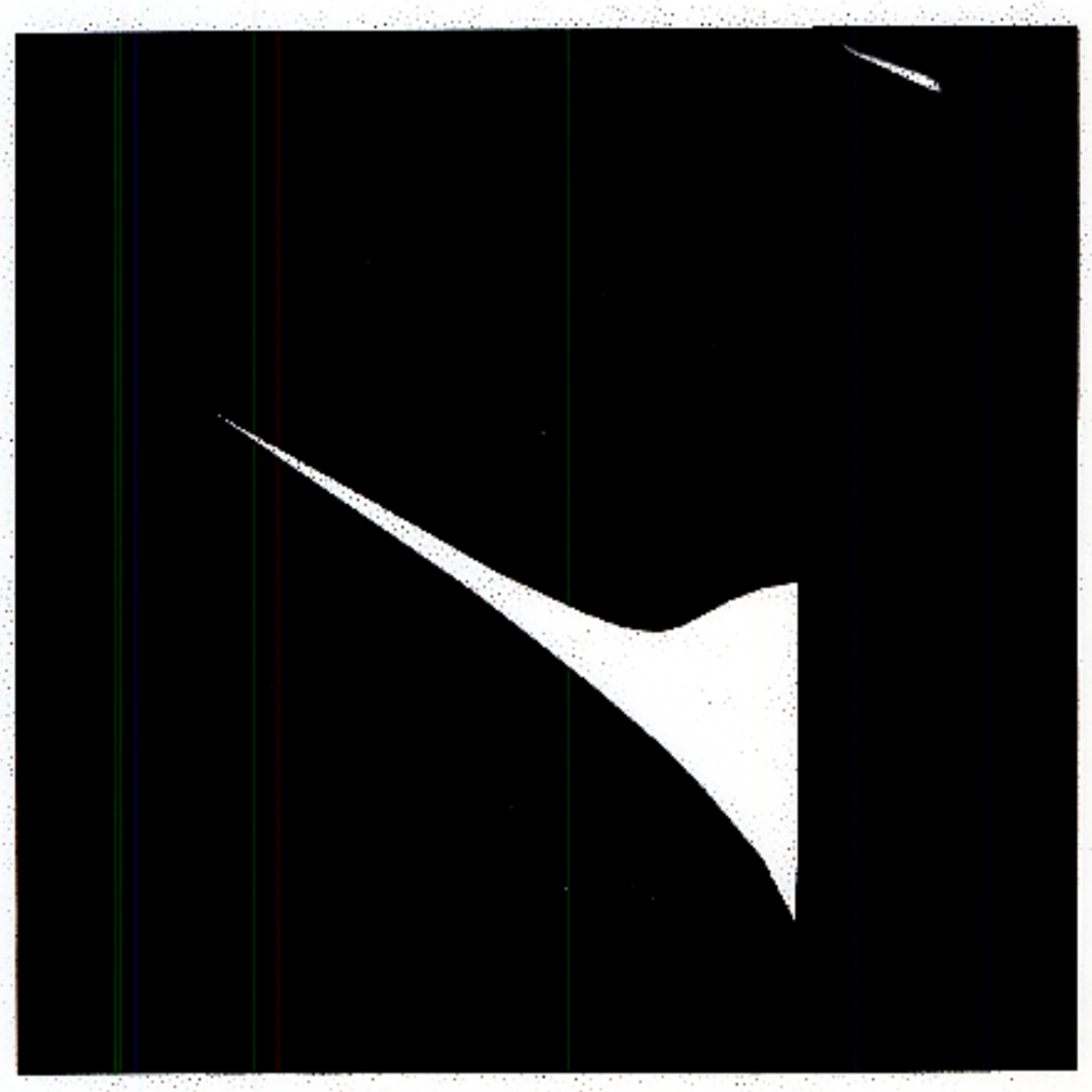
Y.G. KIM + T. NIHEI + L.R. + R. RUIZ (PREP.)

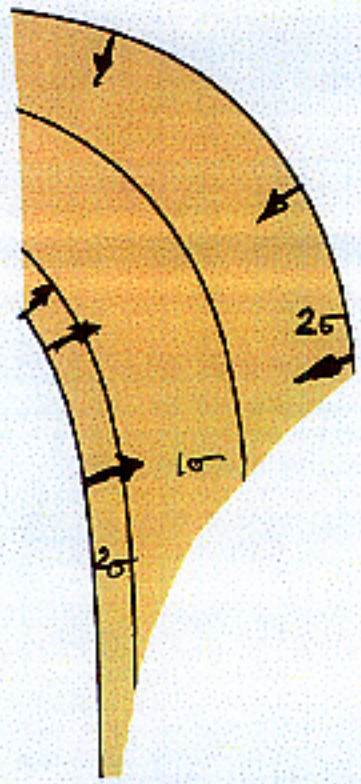
CONSTRAINED MSSM

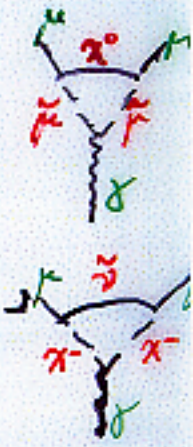


$m_\chi \approx 0.4\, m_{1/2}$

LSP=BIN







E821 (AUG '02)

$a_\mu = (g-2)_\mu/2$

$\Delta a_\mu^{SUSY} \approx \left(\frac{100\,\mathrm{GeV}}{M_{SUSY}}\right)^2 \tan\beta$ Δa_μ^{EW}

$\Delta a_\mu = a_\mu^{expt} - a_\mu^{SM} = (33.9 \pm 11.2) \times 10^{-10}$ 3σ!

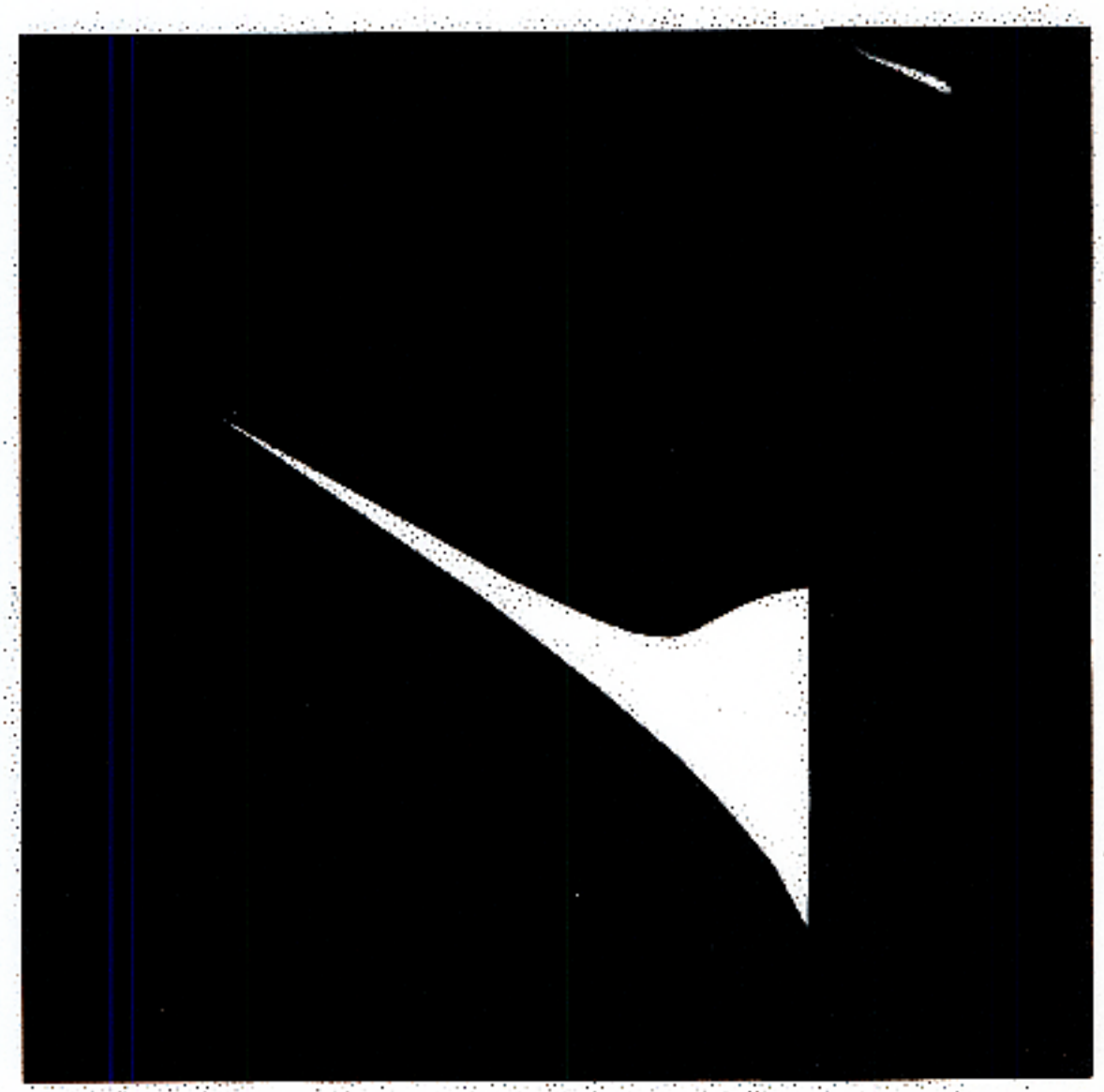
e^+e^- DATA:
FOR HADRONIC
VAC POL

LOWER & UPPER BOUND ON M_{SUSY}

ALSO $\mu > 0$

(ONLY 1.6σ W/ τ DATA

Missing Slide

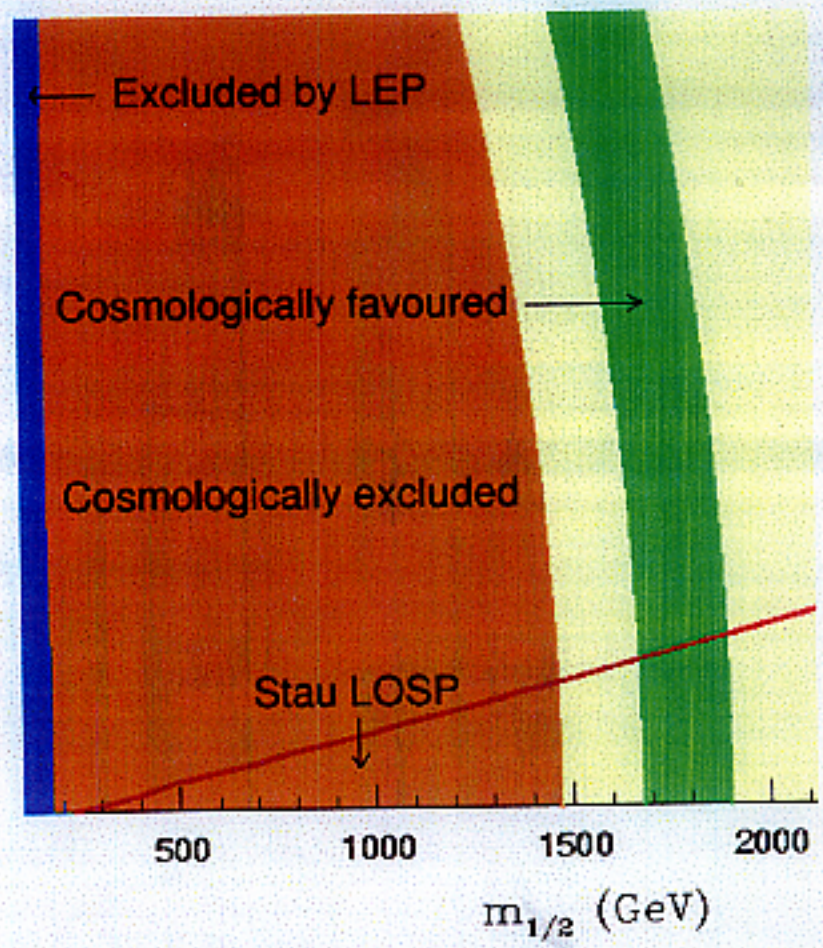


Missing Slide

$m_{\tilde{G}} = 1\,\mathrm{GeV}$

$T_R = 400\,\mathrm{GeV}$

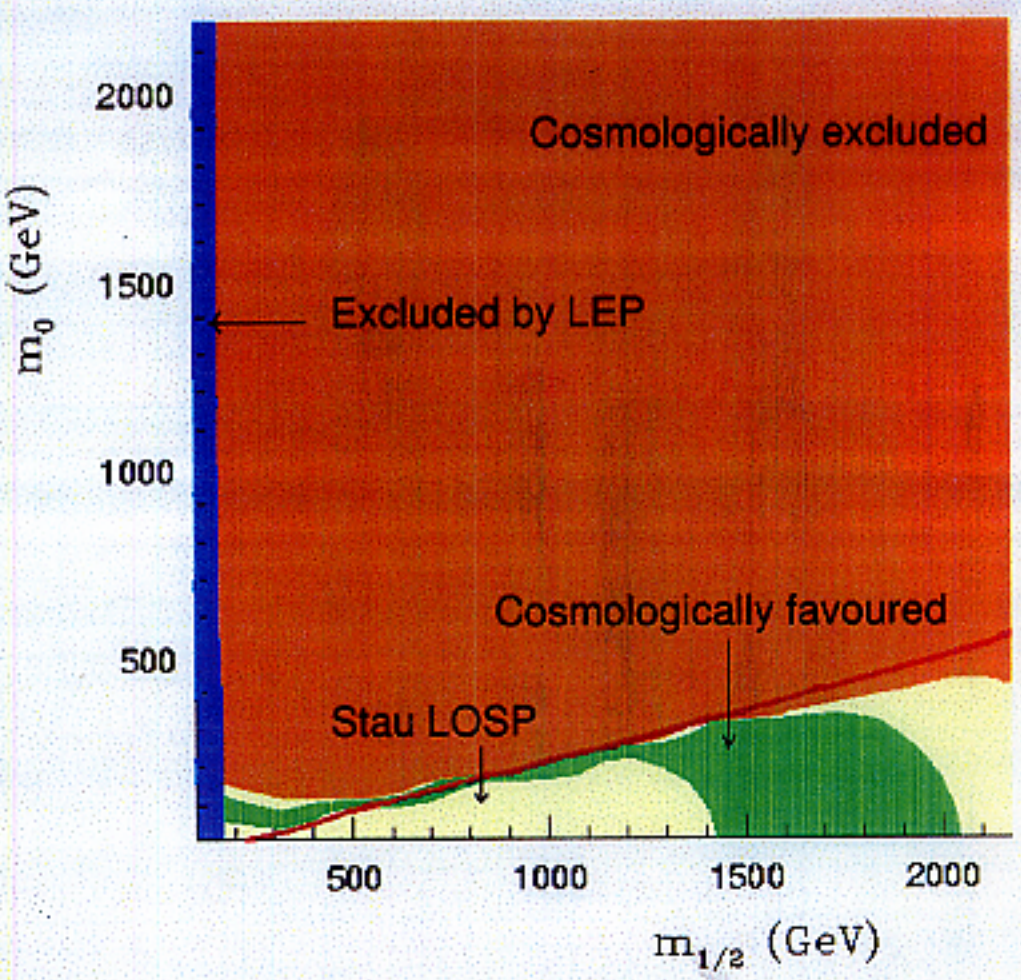
TP DOMINANT



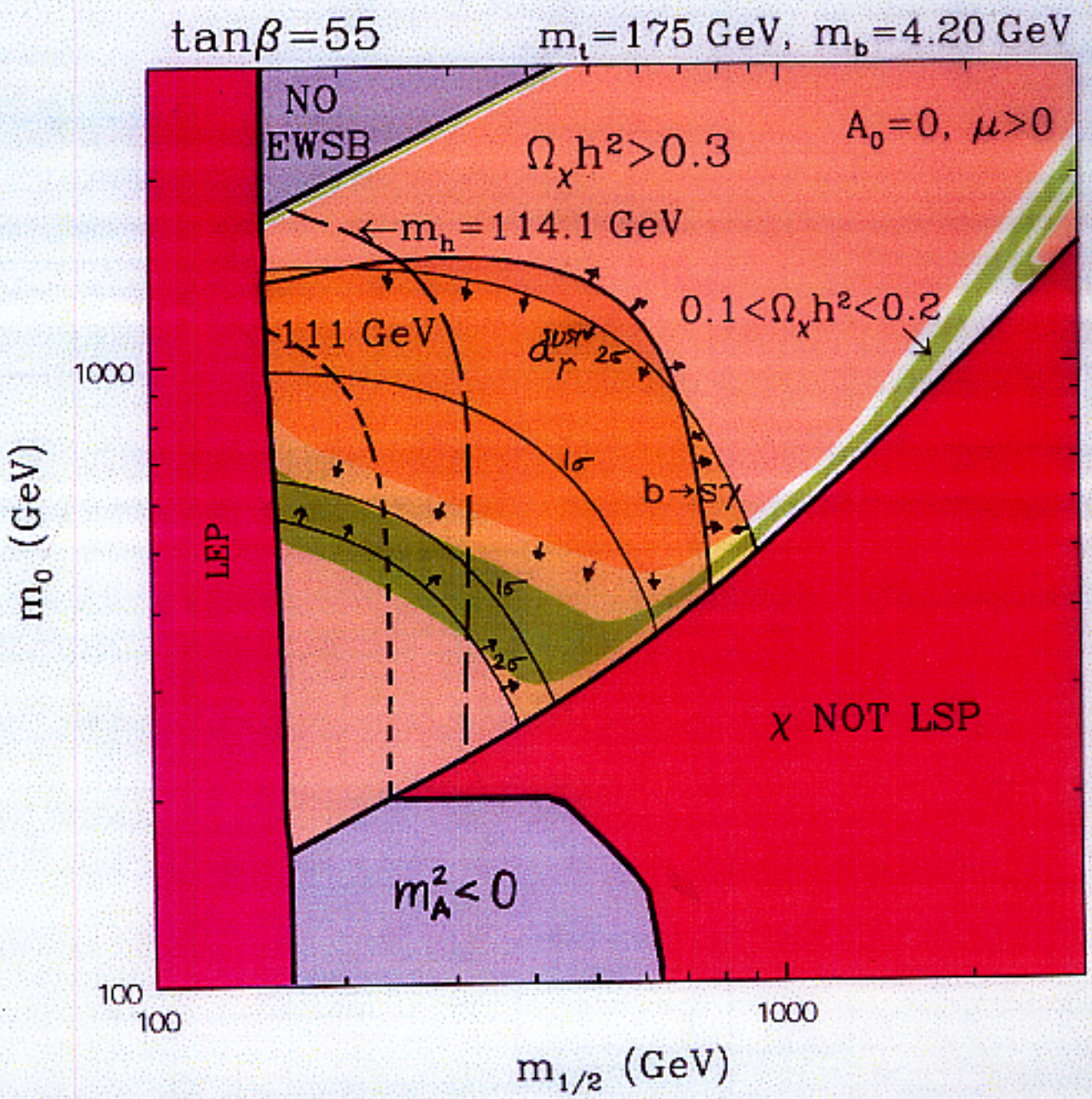
$m_{\tilde{a}} \lesssim m_{NLSP}$

$T_R = 50$ GeV

NTP DOMINANT

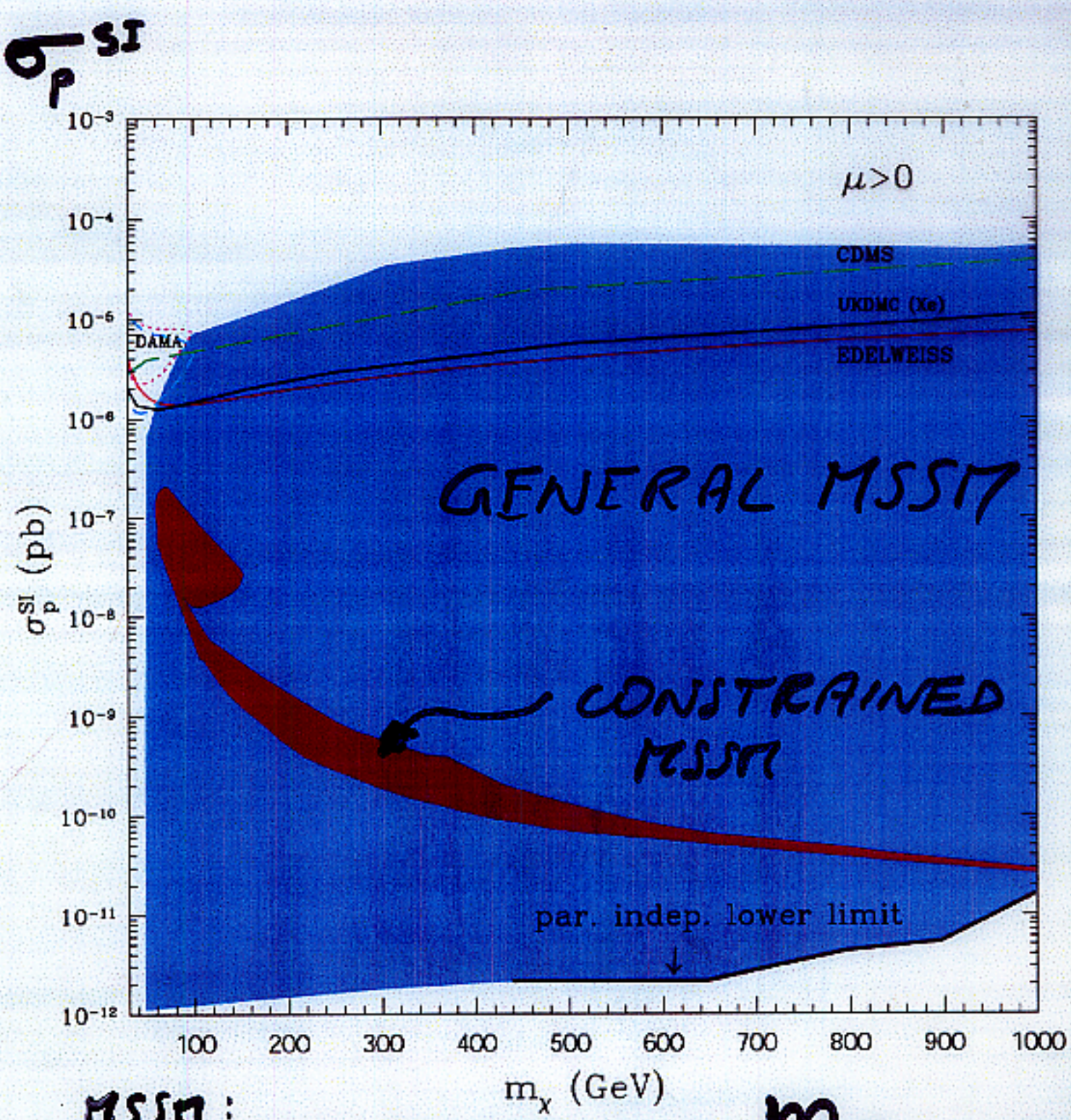


CMSSM



(IN PREP)

Y.G. KIM + T. NIHEI + L.R + R. RUIZ (HEP-PH/0208069)
(+ IN PREP)



MSSM:

COLLIDER BOUNDS

+ $BR(B \to X_s \gamma)$

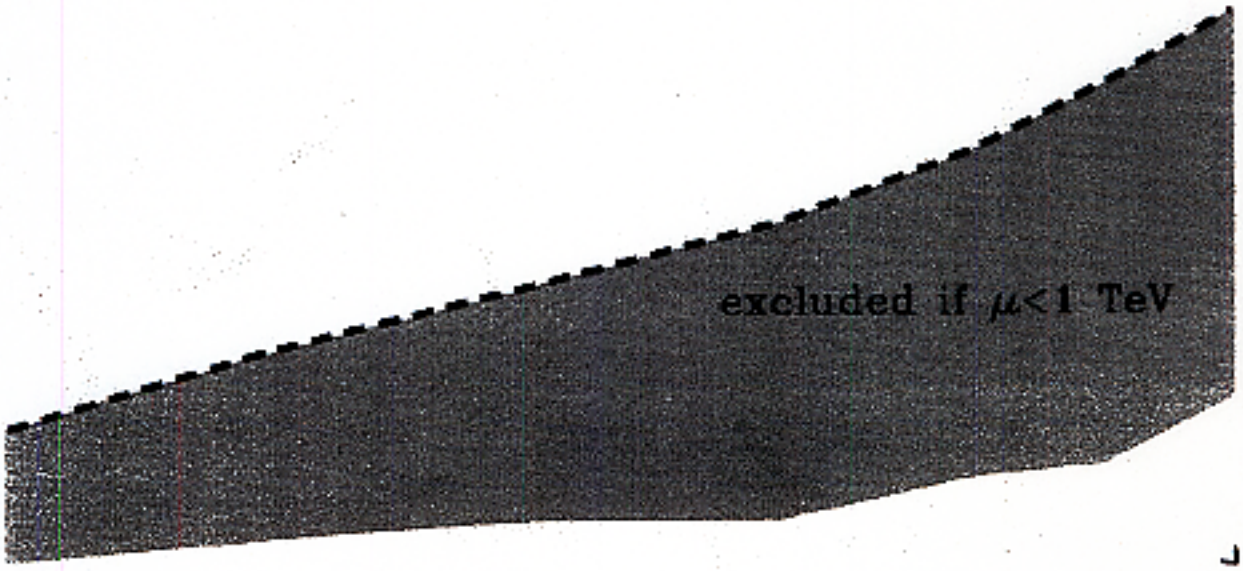
+ $0.1 < \Omega_\chi h^2 < 0.2$

NO $(g-2)_\mu$

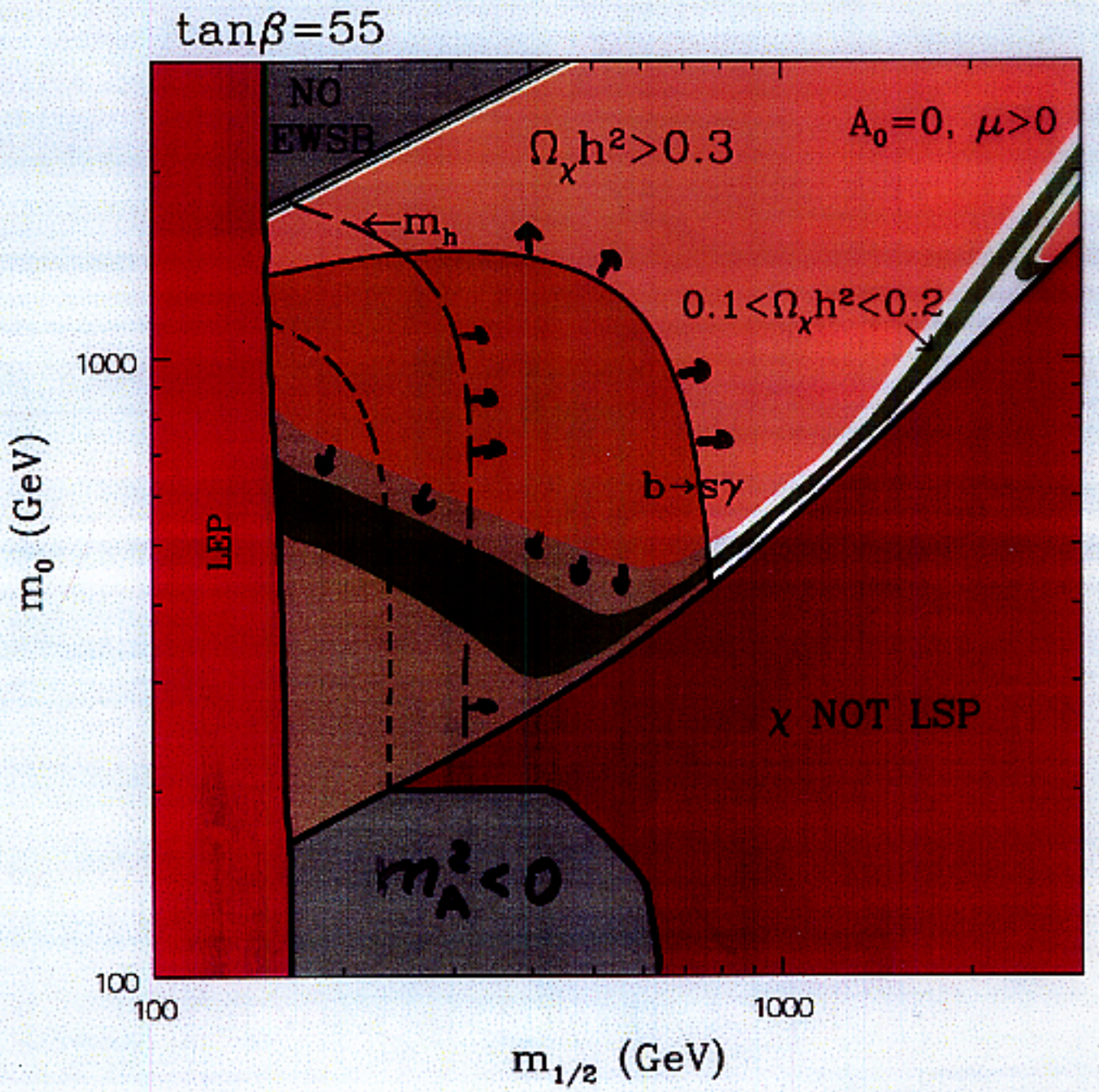
CMSSM:

NO $BR(B \to X_s \gamma)$

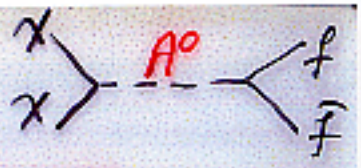
NO $(g-2)_\mu$


excluded if μ<1 TeV

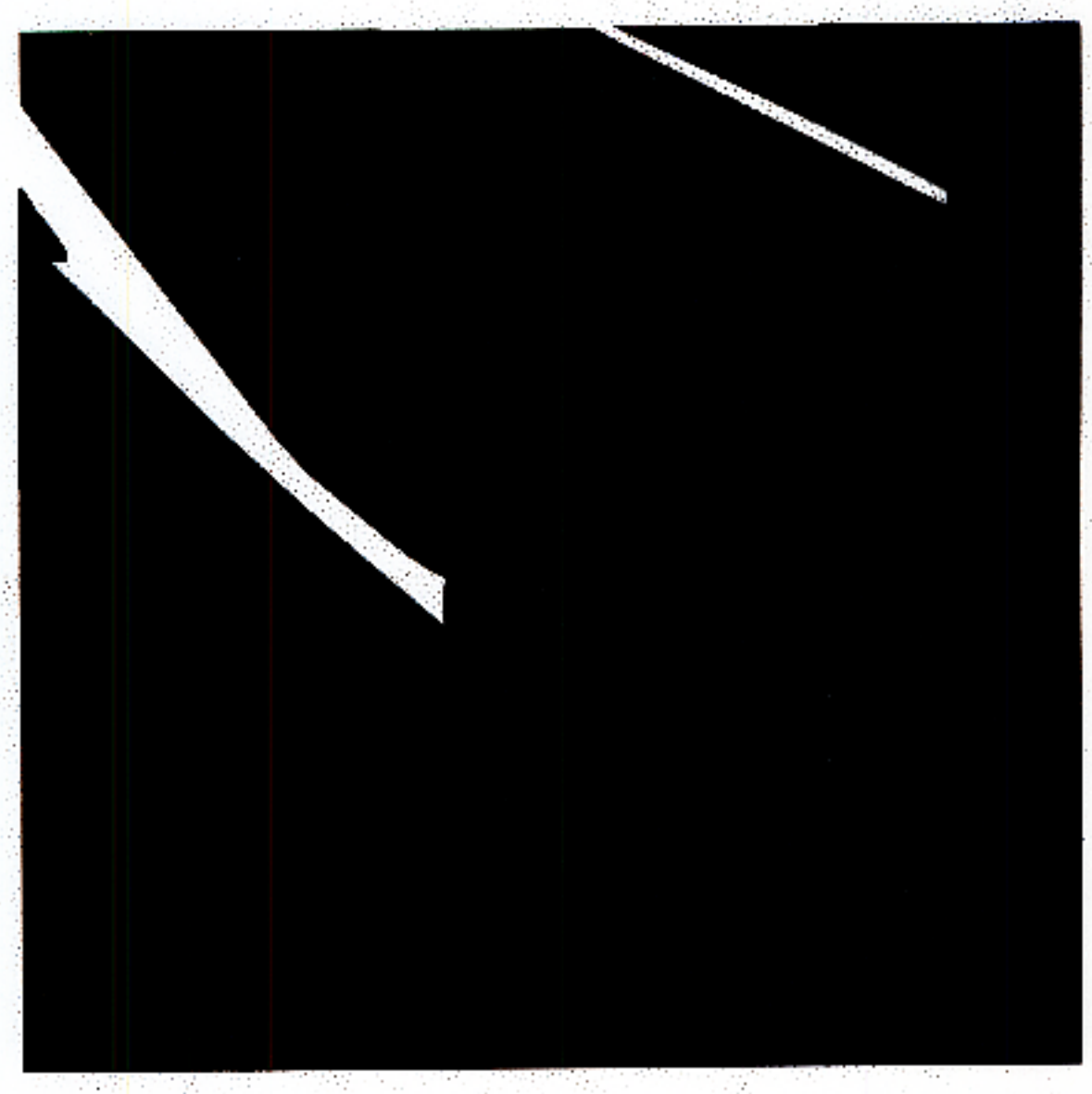
CMSSM


tanβ=55
NO EWSB
$\Omega_\chi h^2>0.3$
$A_0=0,\ \mu>0$
$\leftarrow m_h$
$0.1<\Omega_\chi h^2<0.2$
$b\to s\gamma$
LEP
χ NOT LSP
$m_A^2<0$
1000
100
100
1000
m_0 (GeV)
$m_{1/2}$ (GeV)

BROAD RESONANCE



(DEPLETES $\Omega_\chi h^2$)



TRENDS

★ COLLIDER BOUNDS ($m_{\chi^+} > 210$, $m_h > 114.1$) PUSH M_{SUSY} UP

[ALSO FLAVOR BOUNDS]

★ $b \to s\gamma$ DOES THE SAME

[ESP. AT LARGE $\tan\beta$]

★ $\Omega_\chi h^2$ PUSHES M_{SUSY} DOWN

[EXCEPT FOR "SPECIAL" CASES]

★ $(g-2)_\mu$ SUGGESTS

$M_{SUSY} = O(\text{FEW } 100 \text{ GeV})$

[STILL CONTROVERSIAL]

[IN CONFLICT WITH $b \to s\gamma$ AT LARGE $\tan\beta$]

WHEN THINGS GET TIGHT,

RE-EXAMINE...

[?]

CONTOURS OF $BR(B \to X_s \gamma)$

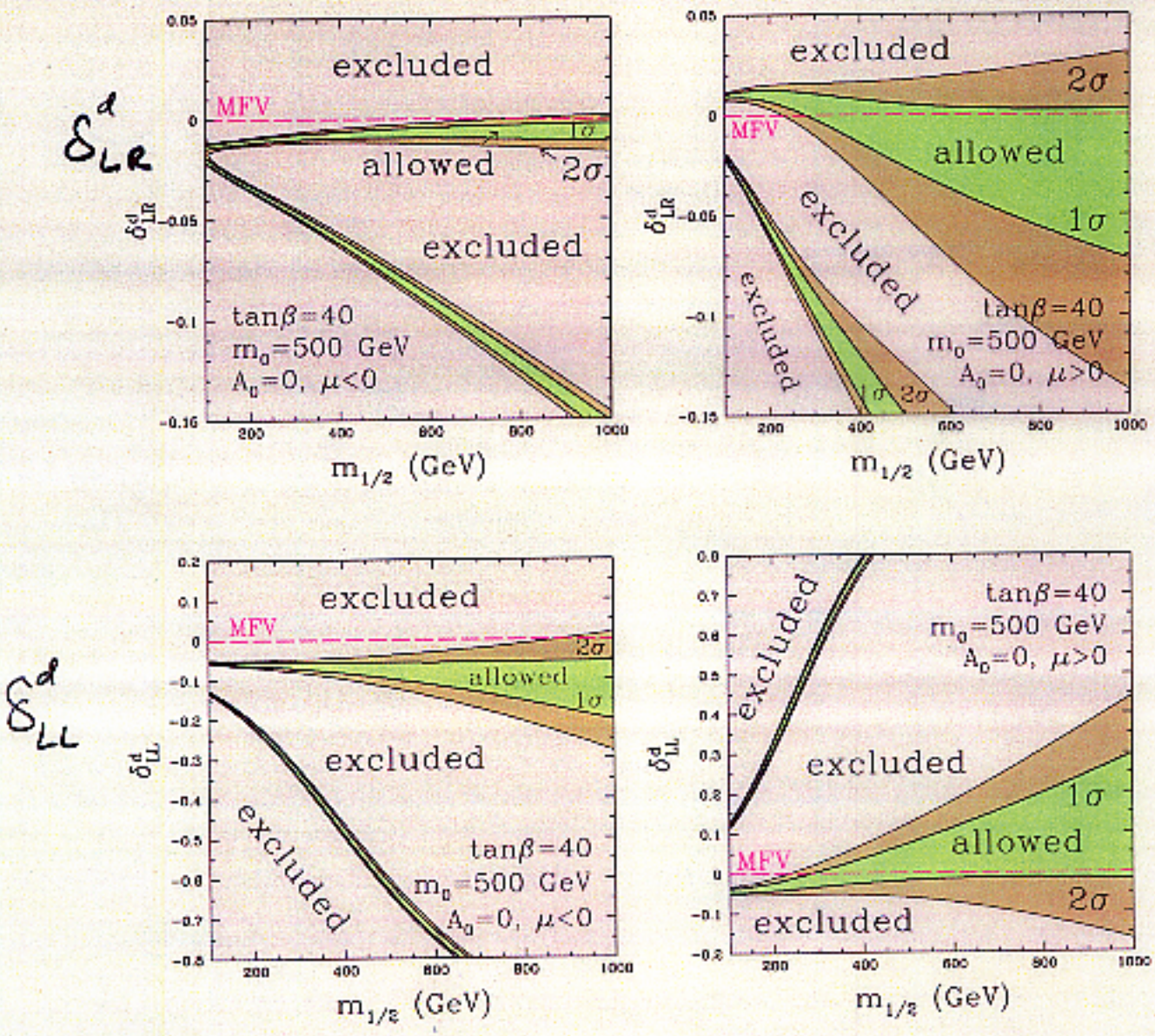


FIG. 2. We plot contours of $BR(B \to X_s\gamma)$ vs. $m_{1/2}$ and δ^d_{LR} (upper windows) and δ^d_{LL} (lower windows) for $\mu < 0$ (left side) and $\mu > 0$ (right side) in the Constrained MSSM. Regions (in grey) beyond the 1σ (green) and 2σ CL (dark yellow) agreement with experiment (Eq. (1)) are marked "excluded".

K. OKUMURA + L. R
(AUG '02)

N. FORNENGO + A. RIOTTO + S. SCOPEL
(HEP-PH/0208072)

EFFECT OF LOW T_R ON $\Omega_\chi h^2$

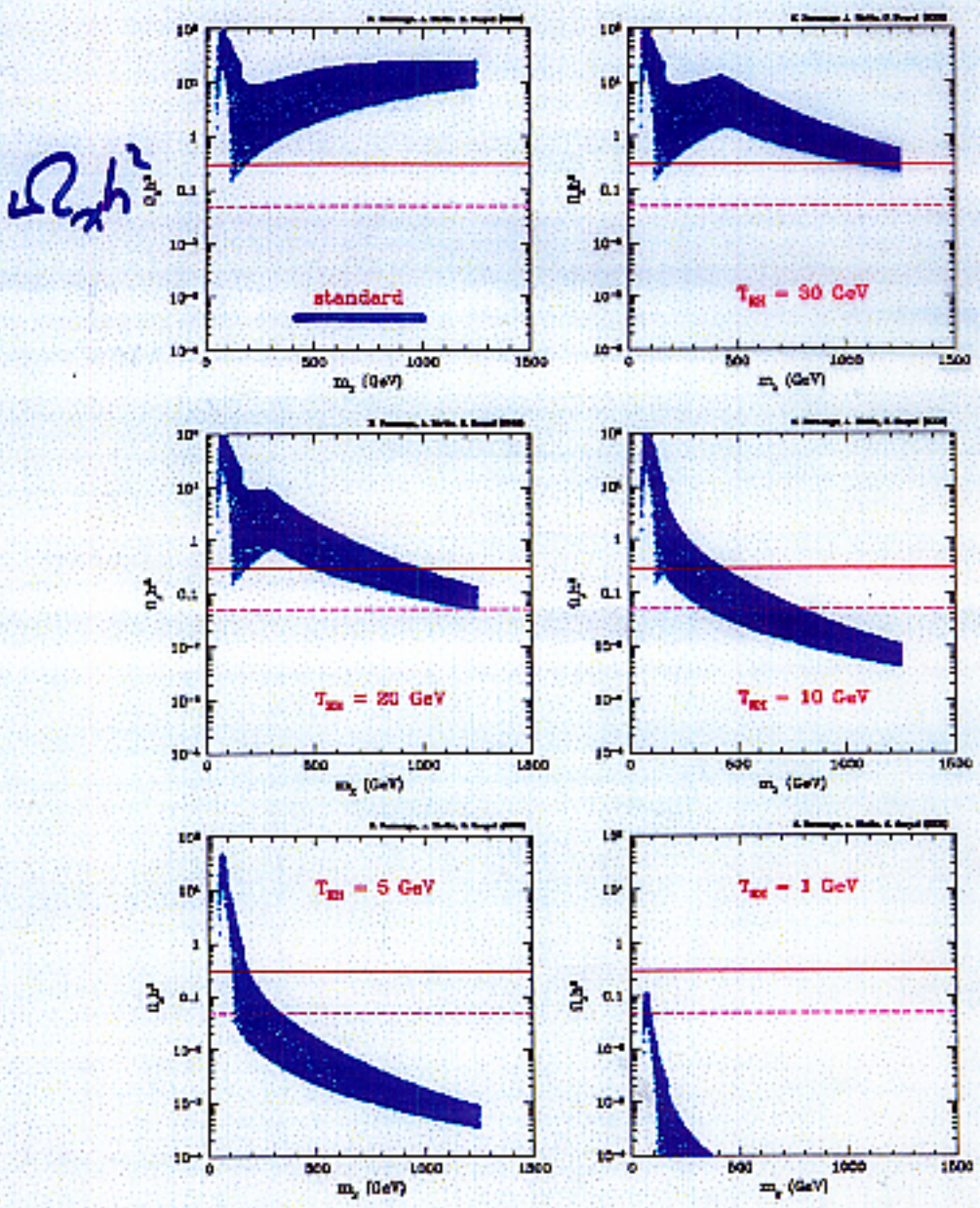


FIG. 2: Neutralino relic density $\Omega_\chi h^2$ as a function of the neutralino mass m_χ in universal SUGRA, for $\tan\beta = 30$ and $A_0 = 0$. The parameters m_0 and $m_{1/2}$ are varied according to the intervals of Eq. (18). The values of $m_t^{\rm pole}$, m_b and α_s are fixed at their central values: $m_t^{\rm pole} = 175$ GeV, $m_b(M_Z) = 3.02$ GeV and $\alpha_s(M_Z) = 0.118$. The upper-left panel shows results for standard cosmology. The other panels refer to different values of the reheating temperature $T_{\rm RH}$. The horizontal solid and dashed lines delimit the interval for the amount of non-baryonic dark matter in the Universe, given in Eq. (2).

N. FORNENGO + A. RIOTTO + S. SCOPEL
(HEP-PH/0208072)

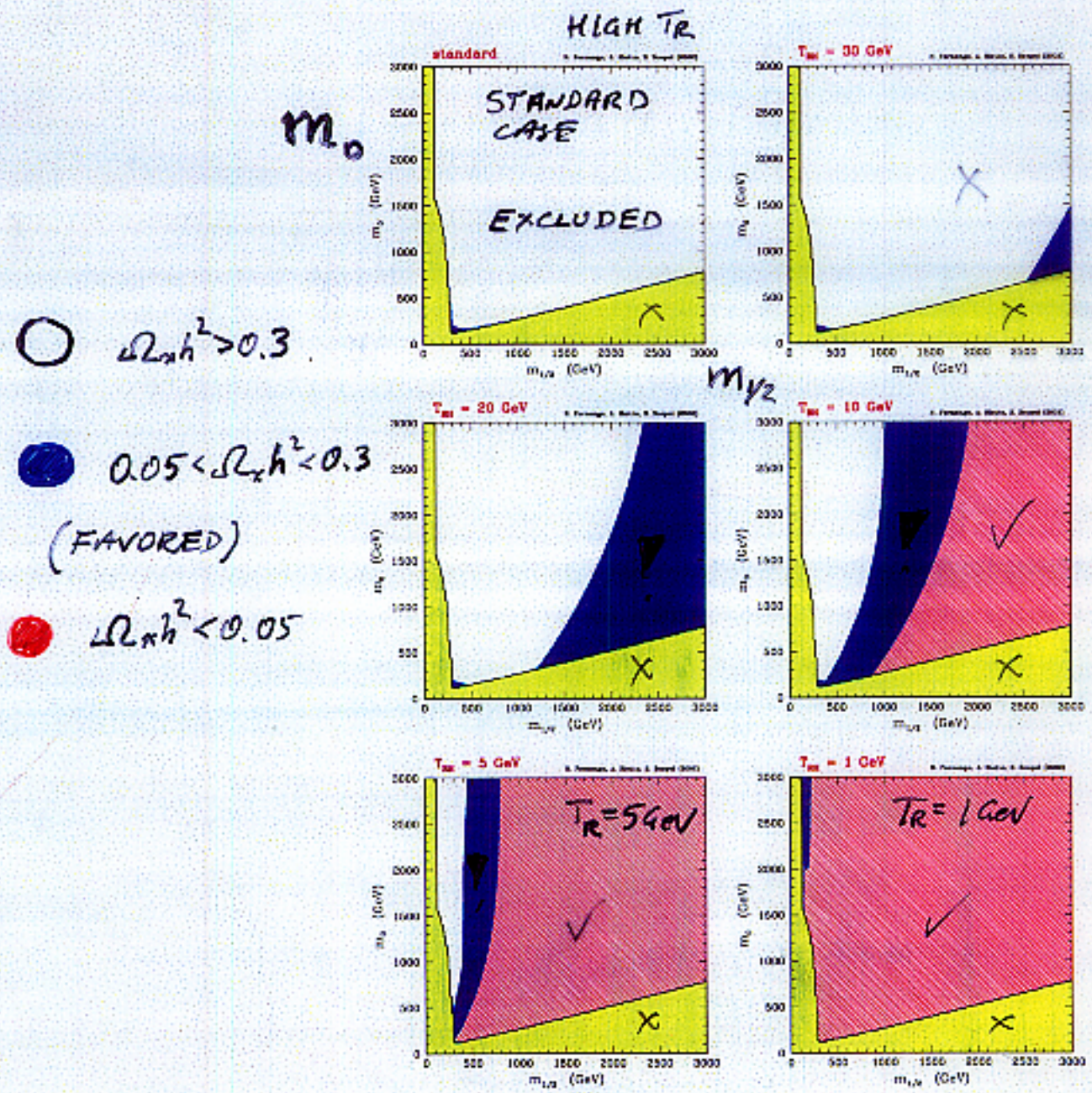


FIG. 4: Cosmologically favoured regions in the plane $m_{1/2}$–m_0 in universal SUGRA for $\tan\beta = 30$ and $A_0 = 0$. The values of $m_t^{\rm pole}$, m_b and α_s are fixed at their central values: $m_t^{\rm pole} = 175$ GeV, $m_b(M_Z) = 3.02$ GeV and $\alpha_s(M_Z) = 0.118$. The upper–left panel shows results for standard cosmology. The other panels refer to different values of the reheating temperature T_{RH}. The dark–shaded (blue) areas correspond to configurations where $0.05 \leq \Omega_\chi h^2 \leq 0.3$. Hatched (red) areas denote configurations where $\Omega_\chi h^2 < 0.05$. Light–shaded (yellow) regions are excluded either by experimental constraints or by theoretical arguments.

THE

AXINO - BINO CONCORDAT OF DARK MATTER

$\tilde{a}$ - TRUE WIMP → DM

χ - PHENOMENOLOGICAL WIMP (PIMP?)

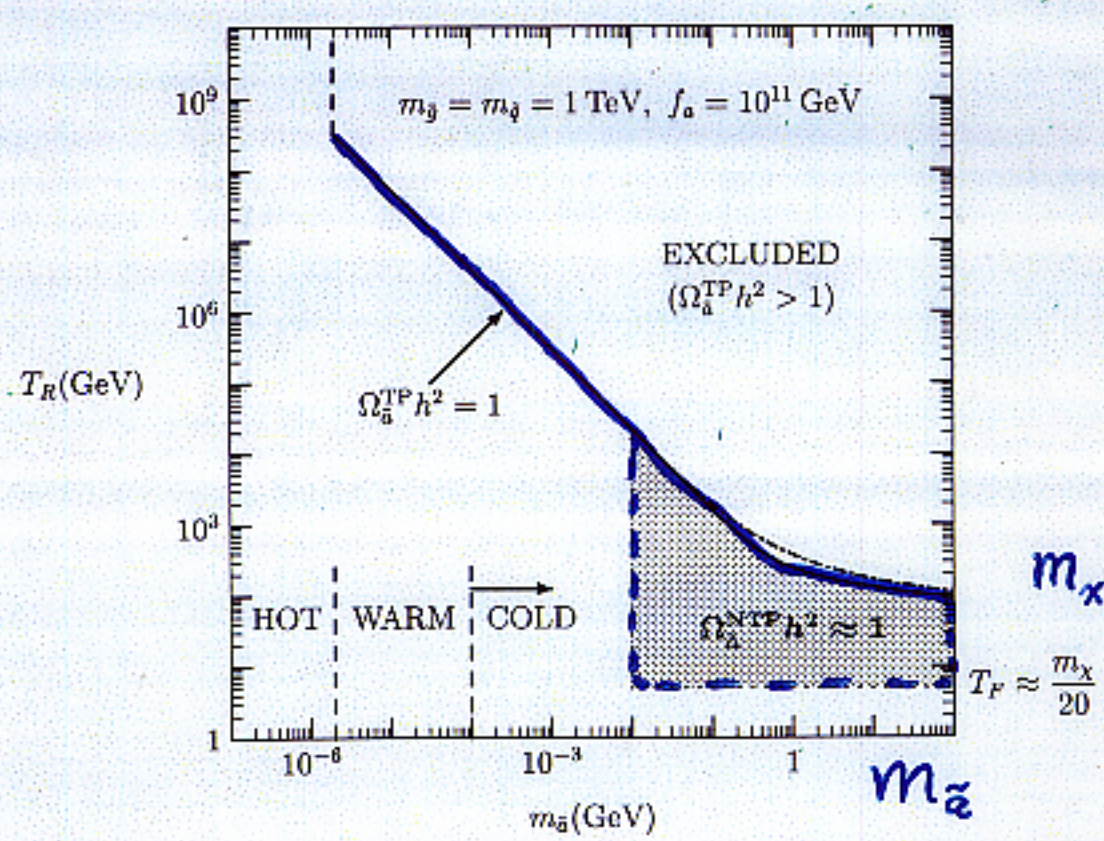
STABLE IN

NEUTRAL FERMION
MAJORANA ($\tilde{a}^c = \tilde{a}$)
LSP

AXINO DM

KSVZ AXION
+ SUSY

$\tilde{a}$ CDM : $T_R \lesssim 10^6$ GeV



OUT-OF-EQUILIBRIUM RELIC

THERMAL PROD'N

eg.

$$g + \tilde{g} \to \tilde{a} + g$$

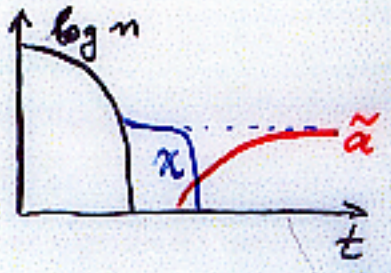
DIM-5 OP

$$+ \quad \tilde{q} \to \tilde{a} + q \quad \text{etc}$$

DIM-4 OP

NON-THERMAL PROD'N

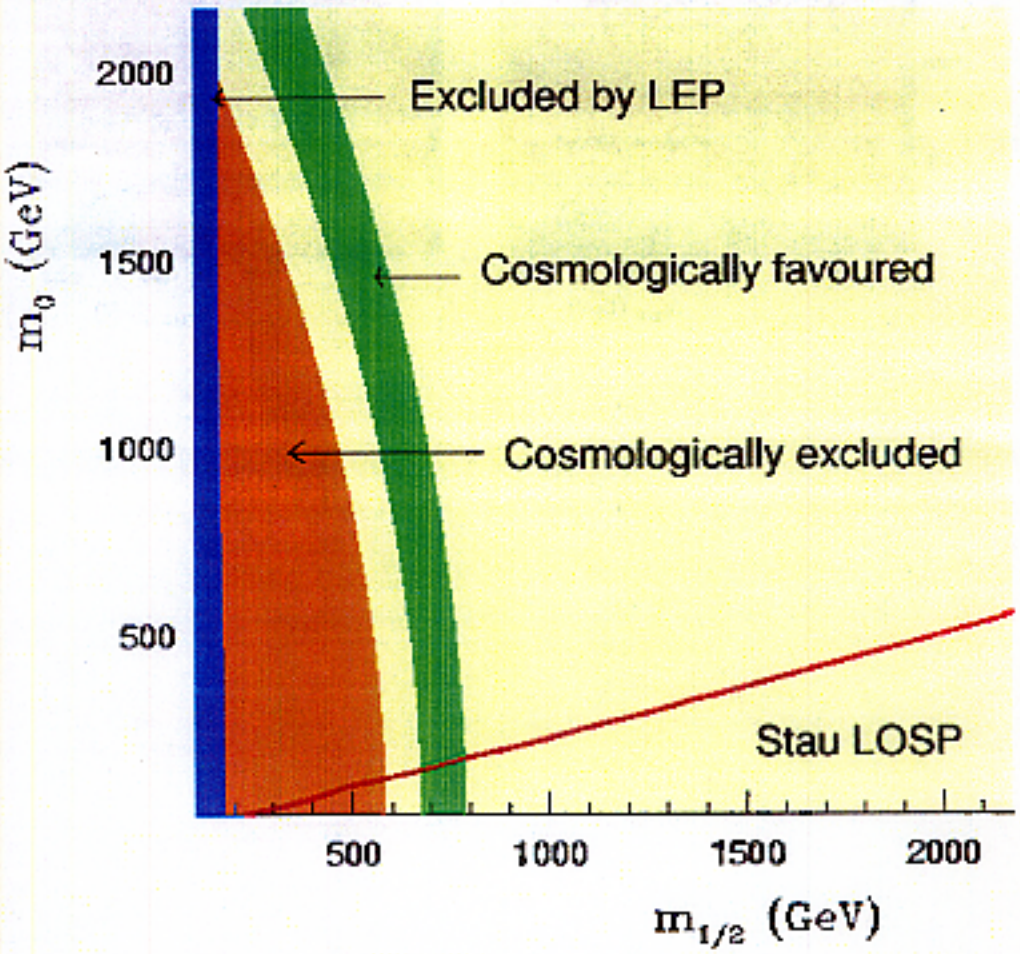
$$\chi \to \tilde{a} + \gamma$$



$$\tau \approx (0.3\ \text{sec}) \times \left(\frac{10^{11}\ \text{GeV}}{f_a}\right)^2 \left(\frac{100\ \text{GeV}}{m_\chi}\right)^3$$

COVI + L.R + RUIZ + STAEL
(IN PREP)

$m_{\tilde{a}} = 1$ GeV

$T_R = 200$ GeV

TP DOMINANT