IX ν Telescopes
Venice, 6-9/3, 2001

# DARK MATTER and PARTICLE PHYSICS

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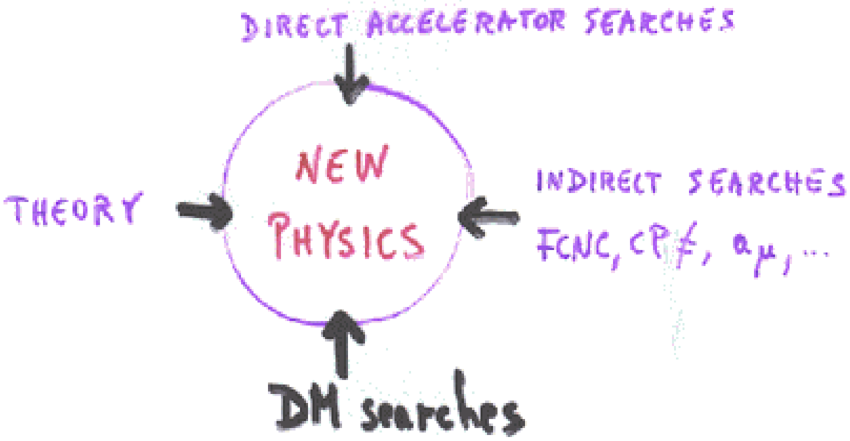



- DM ⇒ new physics
- CDM and SUSY
- complementarity of DM searches with the direct and indirect searches at accelerators for new physics

# ASTROPARTICLE HINTS OF PHYSICS BEYOND THE SM

COSMOLOGY (SM of the BIG BANG) → GWS SM → ASTROPHYSICS (SM of the SUN) ...

MANY EXAMPLES OF MUTUAL SUPPORT

(ex. # neutrino species from nucleosynthesis and LEP)

BUT ALSO CLASHES POINTING (hopefully) TO NEW PHYSICS BEYOND THE GWS SM

COSMOLOGY ↓ GWS ↓ ASTROPHYSICS

clashes

BARYOGENESIS
DARK MATTER
INFLATION

SOLAR $\nu$ ANOMALY
ATMOSPHERIC $\nu$ ANOMALY

# DM ⇄ NEW PHYSICS
(beyond SM)

Why DM ⟶ NEW PHYSICS

• NEED FOR **NON-BARYONIC DM**

$$\Omega_{Matter} = 0.35 \pm 0.10 \gg \Omega_{Baryon} = 0.045 \pm 0.005$$

(ratio of baryons to total mass in clusters $f = (0.075 \pm 0.002)\, h^{-3/2}$; if clusters provide a fair sample of matter $f = \frac{\Omega_B}{\Omega_M} \Rightarrow \Omega_M = 0.35 \pm 0.10$)

(mainly primeval abundance of deuterium $\Omega_B = (0.019 \pm 0.001)\, h^{-2}$)

+ separate evidence of NON-BARYONIC DM from
  - evolution of the abundance of clusters with redshift
  - measurement of the power spectrum of large-scale structures

+ need of $\Omega_M > \Omega_B$ for explaining the evolution of the observed structure in the Universe from density inhomogeneities of the size detected by COBE

- Already some **exp. evidence for non-baryon. DM** $\Rightarrow$ SuperK $\Delta m_\nu^2 \sim 3 \times 10^{-3} eV^2$

  $\Rightarrow$ at least one of the $\nu$'s has $m_\nu > 5 \times 10^{-2} eV$

  $\Rightarrow$ $\Omega_\nu \sim 0.2\%$ (almost $\Omega_{star}$)

- STRONG CASE IN FAVOR THAT THE BULK OF THE **NON-BARYONIC DM** IS **COLD DM**

  - success of the CDM scenario for the formation of structure in the Universe
  - failure of the pure HDM to account for it

- THE CASE FOR "VACUUM ENERGY" (COSM. CONST. ?)

  $\Rightarrow$ COSMIC COINCIDENCE
  - $\Omega_M$ from baryon fraction in clusters
  - CBR 1st peak
  - SN

$\Lambda$CDM $\rightarrow$ $\Omega_m \sim 0.4$ $\Omega_\Lambda \sim 0.6$

# STANDARD MODEL AND DARK MATTER

SM: ONLY RELICS FROM THE EARLY UNIVERSE

$\gamma \rightarrow$ CBR $\quad T_\gamma \sim 2.7$ K

$\nu \rightarrow$ CB$\nu$ $\quad$ slightly less than $\gamma$ CBR – a bit colder than $\gamma$

$m_\nu = 0$

BARYONS $\rightarrow \Omega_B < 10\%$

➡ IN SM NO EXPLANATION FOR

$\Omega_{NB} > 10\%$

$\Downarrow$

NEED MASSIVE NON-BARYONIC DM

ex: new physics may provide a mass to neutrinos

➡ ALSO IN SM NO SCALAR PARTICLE GIVING RISE TO INFLATION

→ PROBLEM FOR THE BIRTH OF INITIAL $\delta\rho/\rho$ FLUCTUAT.

NEW PHYSICS ⟶ DM

directions beyond SM suggested by

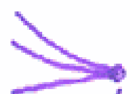
"Theoretical Shortcomings" of the SM

- LACK OF "TRUE UNIFICATION" in the SM

  $G_F, e \leftrightarrow g_1, g_2$

  $g_1, g_2, g_3$ quite far apart

  Solution: running couplings



  ↳ GUT energy scale $\sim 10^{16}$ GeV

- FLAVOR PROBLEM: SM does **not** predict fermion masses and mixings

  ⇒ no Solution (flavor symmetries ?)

- FINE-TUNING PROBLEMS
  - COSM. CONST. ⇝ $\Omega_\Lambda$
  - $\theta_{QCD}$-PROBLEM ⇝ $\Omega_{CDM}$ (axion)
  - GAUGE HIERARCHY ⇝ $\Omega_{CDM}$ (neutralino)

# "MASS PROTECTION"

for FERMIONS, VECTOR (GAUGE) and SCALAR Bosons

SYMMETRY PROTECTION
- Fermions ⇒ chiral symmetry
  $\bar{f}_L f_R$ not invariant under $SU(2) \times U(1)$
- VECTOR BOSONS ⇒ gauge symmetry

⇒ fermions and W,Z vector bosons can get a mass only when the elw. symm. is broken $m_f, m_W \leq \langle H \rangle$

**NO SYMM. PROTECTION FOR SCALAR MASSES**

⇓

# "INDUCED MASS PROTECTION"

⇒ create a symmetry (SUPERSYMMETRY) such that **FERMIONS ⟷ BOSONS**

so that the fermion mass "protection" acts also on bosons as long as SUSY is exact

⇒ **SUSY BREAKING ~ SCALE OF $O(10^2 \div 10^3\, GeV)$**

⇒ LOW ENERGY SUSY

# BARYON AND LEPTON NUMBERS IN SM and SUSY

SM ⇒ B and L are AUTOMATIC SYMMETRIES: it is IMPOSSIBLE to write a renormalizable (dim $\leq 4$) operator invariant under $SU(3) \times SU(2) \times U(1)$ which violates B or L

SUSY ⇒ B and L are NOT AUTOMATIC SYMMETRIES

$$W \supset \lambda'' u^c d^c d^c|_{\theta\theta} \Rightarrow B \neq 0$$

$$\lambda L L e^c|_{\theta\theta} \Rightarrow L \neq 0$$

$$\lambda' L Q d^c|_{\theta\theta} \Rightarrow L \neq 0$$

dim 4 operators violating either B or L

# IMPLICATIONS OF R- PARITY

SUSY PARTICLES CAN BE CREATED OR DESTROYED ONLY IN PAIRS

THE LIGHTEST SUSY PARTICLE (LSP) IS ABSOLUTELY STABLE

(relic candidate)

# LSP?

**LARGE SCALE SUSY BREAKING**

GRAVITY MEDIATED SUSY̸


$\Lambda_{SUSY} \sim 10^{11}$ GeV

$M_{SUSY} \sim \frac{\Lambda^2_{SUSY}}{M_P}$

$m_{3/2} \sim \frac{\Lambda^2_{SUSY}}{M_P}$

$M_{SUSY} \sim m_{3/2} \sim O(1\,\text{TeV})$

LSP → lightest neutralino

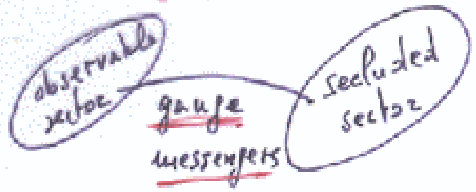
$m > 40$ GeV

CDM possibility of having $\Omega_{\chi^0} \sim 0.1-1$

→ jet + missing energy

**LOW SCALE SUSY BREAKING**

GMSB




$\Lambda_{SUSY} \sim 10^{6}$ GeV

$m_{3/2} \sim \frac{\Lambda^2_{SUSY}}{M_P} \sim 10^2 - 10^3$ eV

$M_{SUSY} \sim 100$ GeV

$\psi_{3/2}$ gravitino is LSP

WARM DM

$\tilde{\chi}^0 \to \psi_{3/2} + \gamma$

$\gamma$ in the final state

# LIGHT GRAVITINO : WARM DM CANDIDATE

WARM → for a gravitino in the (0.1 – 1) KeV range
the free-streaming mass scale ~ galaxy mass scale

- just replacing CDM with WDM does **not** work
  (suppression of fluctuation only at the galaxy mass scale but power spectrum unaffected on the cluster mass scales where standard CDM fails)

- given the success of suitable MIXED DM and LOW-DENSITY CDM models in accounting for { low-level density fluc. ~ $10\,h^{-1}$ Mpc ; enough power at $1\,h^{-1}$ Mpc (form galaxy early enough epoch) }

⇒ **test light gravitino with { hot component ; low-density $\Omega_0 < 1$ }**

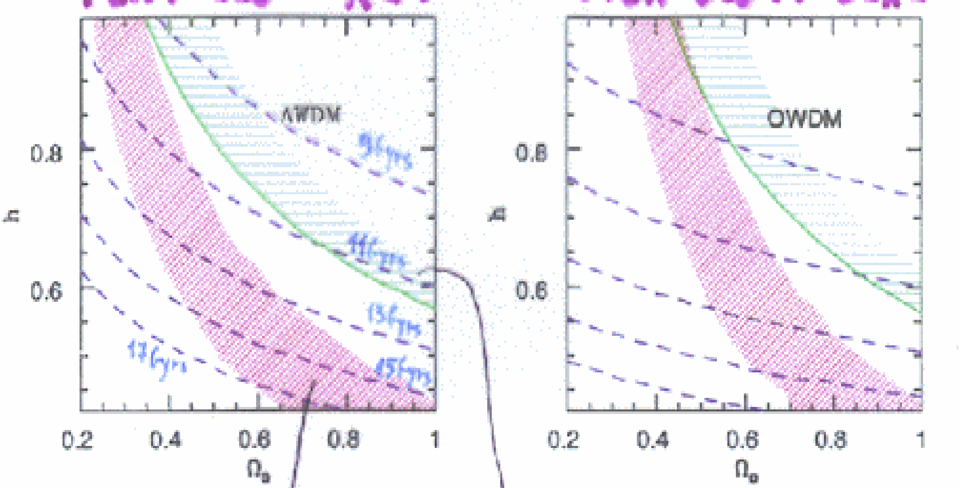
OBSERVATIONAL CONSTRAINTS { HIGH-REDSHIFT OBJECTS ; CLUSTER ABUNDANCE }

# LIGHT GRAVITINOS WITH $\Omega_{0\,matter} < 1$

$n=1$ ($n \neq 1$ does not improve the situation)

E. PIERPAOLI, S. BORGANI, A.M., M. YAMAGUCHI

**FLAT $\Omega_0 + \Omega_\Lambda = 1$** **OPEN $\Omega_0 < 1$ $\Omega_\Lambda = 0$**




$g_* = 150$

HIGH-REDSHIFT OBJECTS CONSTRAINT **

CLUSTER ABUNDANCE *

* using the relation between $\sigma_8$ (r.m.s. fluctuation value within a sphere of $8\,h^{-1}$ Mpc radius) and $\Omega_0$ from Viana and Liddle '96

** constraint from the abundance of neutral hydrogen contained within damped Ly-α system (DLAS) → value of $\Omega_{HI}$ at $z \sim 4.25$ from Storrie-Lombardi et al. '95

## BEST "THERMAL" CDM CANDIDATES ⇒ WIMPS

(weakly interacting part.)

↓ particles at one time in thermal equilibrium

(best "non-thermal" CDM candidates : axions, superheavy relic part.)

Chung, Kolb, Riotto; Ellis, Nanopoulos et al.

typically $T_{decoupl.} \sim \left(\frac{1}{20 \div 30}\right) m_\chi$

$\# \chi \sim \# \gamma$ — $m_\chi$ — $T^\chi_{decoupling}$

$\# \chi$ suppressed by $e^{-m_\chi/T}$ via $\chi$ annih.

↖ $\# \chi$ does not change any more

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

$\hookrightarrow \propto \frac{1}{\sigma_{annih}(\chi\chi \to \dots)}$

Goldberg; Ellis, Hagelin, Nanopoulos, Olive, Srednicki; Roszkowski

$$\frac{n_\chi}{T_0^3} \sim \frac{n_\chi(T_{decoupl.})}{T^3_{decoupl.}}$$

$T_{decoupl.}$ determined by : $n_\chi(T_{dec}) \langle \sigma_{ann}(\chi\chi) v_\chi \rangle \sim \frac{T^2_{decoupl.}}{M_{Planck}}$

$\Omega_\chi$ depends on particle physics ($\sigma_{annih}$) + $T_0$ + $M_{Planck}$

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\langle \sigma_{annih}(\chi\chi) v_\chi \rangle \, TeV^2}$$

$\langle \sigma_{annih}(\chi\chi) v_\chi \rangle \sim \alpha^2/M_\chi^2$

$TeV^2 \longrightarrow$ TeV from $\sqrt{T_0 \cdot M_{Planck}}$

$\Rightarrow \Omega_\chi h^2 < 1 \Rightarrow m_\chi < 1\,TeV$ $\quad$ $m_\chi \sim 10^2 - 10^3\,GeV$ $\quad$ $\Omega_\chi h^2 \sim 10^{-2} - 10$ !!!

# WIMP CANDIDATES

* HEAVY NEUTRINOS of few GeV's $\Omega_\nu h_0^2 \sim 3 \left(\frac{GeV}{m_\nu}\right)^2$

but $Z \to \nu \bar{\nu}$ if this heavy neutrino couples to Z with the usual $Z-\nu-\nu$ coupling

$\Rightarrow m_{\nu_{heavy}} > m_Z/2$ very low $\Omega$ $(\Omega_0 h_0^2 \lesssim 10^{-3})$

if the SU(2) doublet heavy $\nu$ mixes with some "sterile" $SU(2) \times U(1)$ singlet $\Rightarrow$ reduction of $Z-\nu_{heavy}$ coupling but cumbersome schemes

* Best WIMP: LIGHTEST SUSY PARTICLE IN SUSY SCHEMES WHERE A DISCRE SYMM. R-PARITY DISCRIMINATE ORDINARY FROM SUPER- PARTICLES

# NEUTRALINO

$U(1)_Y \Rightarrow B_\mu \longrightarrow \tilde{B}$ } neutral gauginos

$SU(2)_L \Rightarrow W_3 \longrightarrow \tilde{W}_3$

$H_1^0 \longrightarrow \tilde{H}_1^0$ } neutral higgsinos

$H_2^0 \longrightarrow \tilde{H}_2^0$

$$\chi = a_1 \tilde{B} + a_2 \tilde{W}_3 + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0$$

↳ lightest eigenstate is the most likely Lightest SUSY Partner (LSP)

gaugino fraction : $P = a_1^2 + a_2^2$

Cosmological range for CDM :

$$0.3 \le \Omega_{CDM} \le 0.5 \Rightarrow 0.1 < \Omega_{CDM} h^2 < 0.3$$

but, given the uncertainties, even $\Omega_{CDM}$ as low as 0.05 can still be of cosmological relevance

$\chi$ features for direct and indirect searches:

$\rho_\chi$, $\sigma^{\chi}_{nucleus}$, $\sigma_{\chi\chi}$, ...

and their **SUSY MODEL DEPENDENCE**

$$\mathcal{L}_{SUSY} = \mathcal{L}_{N=1\ SUSY} + \mathcal{L}_{SUSY\ breaking\ terms}$$

$\mathcal{L}_{N=1\ SUSY}$: extension of SM (with R parity) ← $\mu H_1 H_2$

$$\mathcal{L}_{SUSY\ breaking} \begin{cases} -\sum_i m_i |\varphi_i|^2 & \text{(sum over all scalars)} \\ -A^e_{ij} h^e_{ij} L_i H_1 E^c_j + A^d_{ij} h^d_{ij} Q_i H_1 D^c_j \\ \quad + A^u_{ij} h^u_{ij} Q_i H_2 U^c_j - B\mu H_1 H_2 \\ - M_i (\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i) \end{cases}$$

↳ gaugino masses

→ free param: $m_i$, $A^e_{ij}$, $A^d_{ij}$, $A^u_{ij}$, $M_1, M_2, M_3$ + $\mu$

⇒ 124 PARAM. !

most of this enormous param. space is already excluded by direct searches of SUSY + FCNC and CP$\not$ processes

DRASTIC REDUCTION IN SUSY PARAM.

IMPOSING FLAVOR UNIVERSALITY +

GAUGE UNIFICATION

$m_i|_{M_{GUT}} \Rightarrow m_0$ $\qquad A^{\ell}_{ij} = A^{d}_{ij} = A^{u}_{ij} = A_0 m_0 \Big|_{M_{GUT}}$

$M_1(M_{GUT}) = M_2(M_{GUT}) = M_3(M_{GUT}) = m_{1/2}$

$\rightarrow m_0, A_0, m_{1/2}, B_0, \mu$

+ imposing electroweak radiative breaking

ONLY 4 NEW SUSY PARAM + one sign

$m_0, A_0, m_{1/2}, \tan\beta, \text{sign}\mu$

$\tan\beta \to v_1/v_2 \qquad v_i \equiv \langle H_i \rangle$

⇗

CMSSM or m SUGRA

Constrained Minimal SUSY SM — minimal Supergravity

# LOWER and UPPER LIMITS on $m_\chi$

CMSSM → $m_\chi \geq 95$ GeV
mSUGRA

Ellis, Ganis, Nanopoulos, Olive

\+ $\tan\beta \geq 3$

improvement from $m_\chi > 54$ GeV (in April 2000)
now $m_h$ sensitivity of the LEP exp. calculating for each CMSSM param. choice the corresponding ZZh coupling and not using the too conservative limits with the maximal mixing scenario

limits on maximum elastic scattering cross section
in CMSSM: $10^{-5}$ pb for spin-dependent
with $\tan\beta \leq 10$ $10^{-8}$ pb " spin-independent
for large $\tan\beta$ it may be one order of magnitude larger Accomando, Arnowitt, Dutta, Santoso; Bottino et al
Arnowitt, Dutta, Santoso; Lahanas, Nanopoulos, Spanos

nuSUGRA $m_\chi > 50$ GeV, $\tan\beta > 2$
(flavor universality but $m_{H_1} \neq m_{H_2}$) Ellis et al. (April 2000)

↳ to be reanalyzed with the recent LEP progress in higgs searches

UPPER BOUND: $m_\chi$ as high as 600 GeV → co-annih.

## $\chi$ COMPOSITION

CMSSM → $\chi \simeq \tilde{B}$ gaugino *

nuSUGRA → possibility of mixed
($m_{H_1}$ & $m_{H_2}$ as initial condition) gaugino - higgsino state

but LEP II searches for charginos, neutralinos and Higgs bosons together now

**EXCLUDE as DM an LSP that is more than ~ 70% higgsino**

* exception to this statement : FENG, MATCHEV, WILCZEK

"FOCUS POINT MODELS" models with unusually large squark and slepton masses (above 1 TeV) but still "natural"

Berezinsky, Bottino, Ellis, Fornengo, Mignola, Scopel

focus points in RG trajectories rendering the elw. scale largely insensitive to variations in unknown SUSY param Feng, Matchev, Moroi

# CDM in SUSY

CONSTRAINTS ON THE SUSY PARAM. SPACE

⇓

$\Omega_\chi h^2 \leq 0.3$

together with the other phenom. constraints does it lead to the

"NO LOSE THEOR." FOR LHC ?

DETECTABILITY OF THE SUSY LSP IN DIRECT AND INDIRECT SEARCHES

⇓

given the existing constraints on the SUSY param. space

can we reasonably hope to find LSP signals ?

mSUGRA



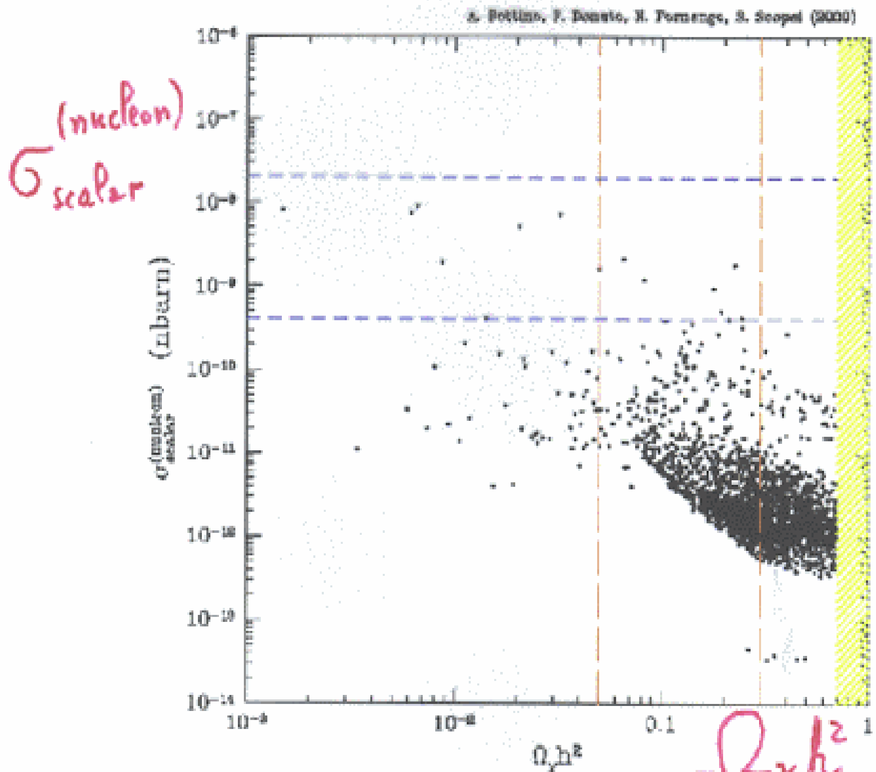



FIG. 1a. Scatter plot of $\sigma^{(nucleon)}_{scalar}$ versus $\Omega_\chi h^2$ for universal SUGRA. Set 1 for the quantities $m_q < \bar{q}q >$'s is employed. Only configurations with positive $\mu$ are shown and $m_\chi$ is taken in the range of Eq. (4). The two horizontal lines bracket the sensitivity region defined by Eq. (5). The two vertical lines denote the range $0.05 \leq \Omega_m h^2 \leq 0.3$. The region above $\Omega_\chi h^2 = 0.7$ is excluded by current limits on the age of the universe. All points of this scatter plot denote gaugino configurations.

BOTTINO, DONATO, FORNENGO, SCOPEL

effMSSM

BOTTINO et al.

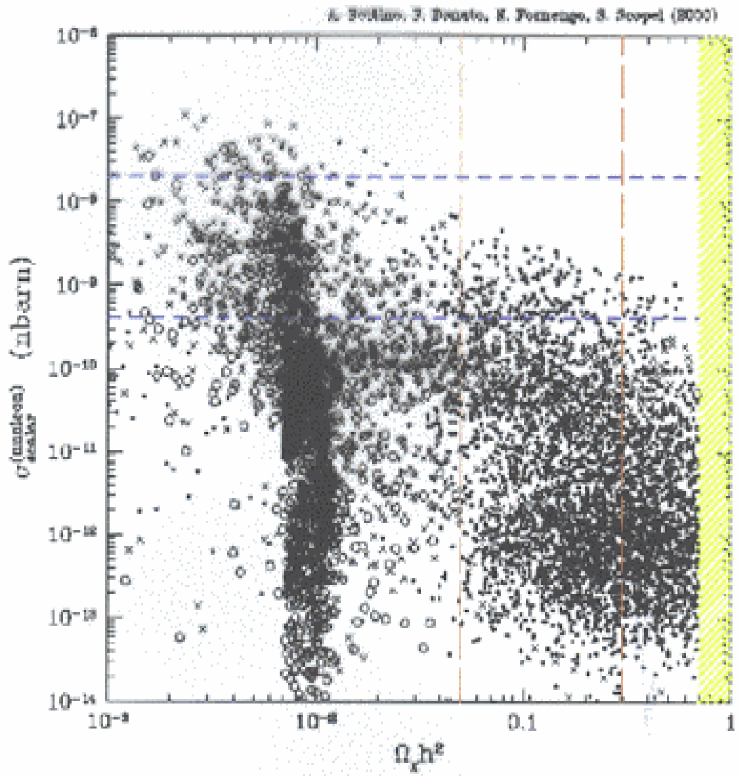
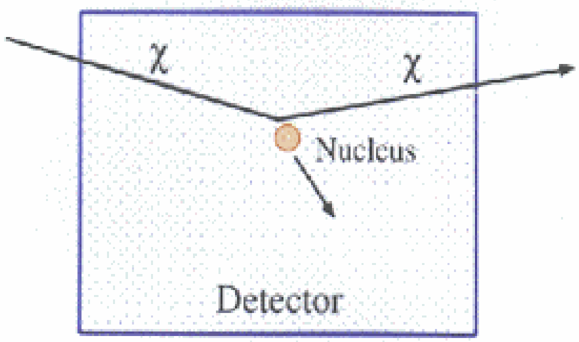


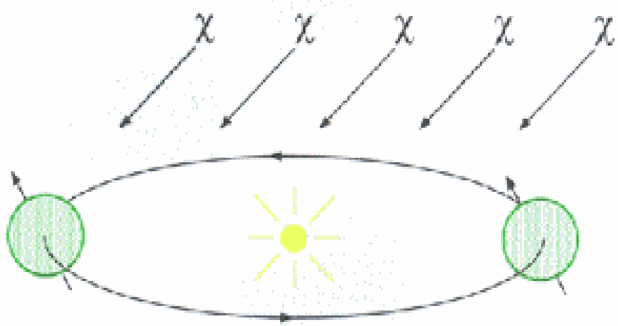

FIG. 1c. Scatter plot of $\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}}$ versus $\Omega_\chi h^2$ for effMSSM. Notations as in Fig. 1b. Both signs of $\mu$ are shown.

## Direct detection - basic principles

- WIMP + nucleus → WIMP + nucleus
- Nuclear recoil energy measured

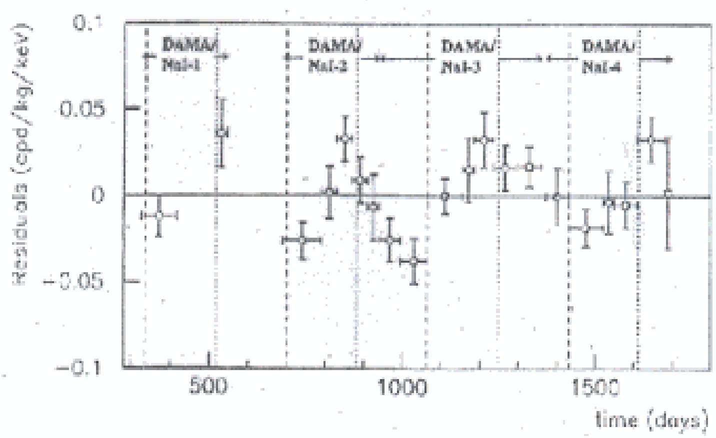



- Search for an annual modulation

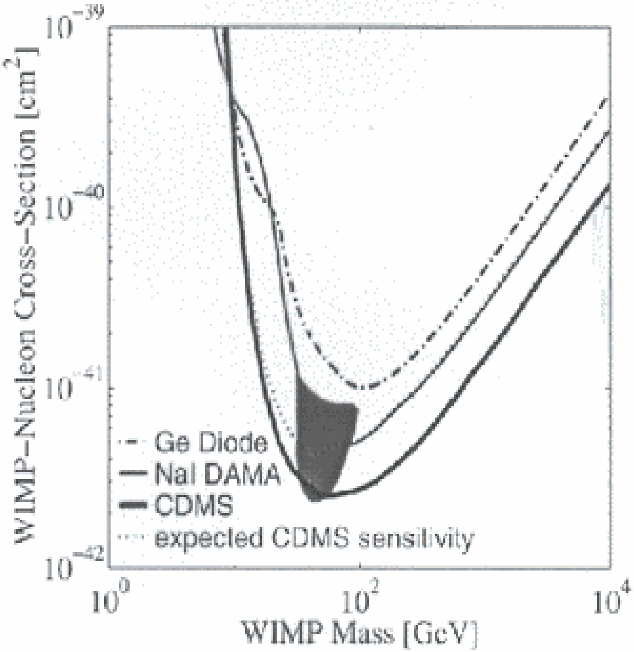


# DAMA:

RAW DATA $E_{ee} \in (2-6)$ keV



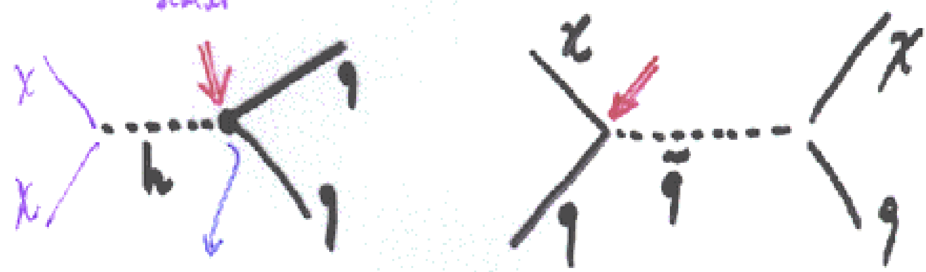

Phys. Lett. B 480 (2000) 23



$10^{-39}$
$10^{-40}$
$10^{-41}$
$10^{-42}$
WIMP–Nucleon Cross–Section [cm$^2$]
Ge Diode
NaI DAMA
CDMS
expecled CDMS sensitivity
$10^0$
$10^2$
$10^4$
WIMP Mass [GeV]

FOR DIRECT SEARCHES $\Rightarrow$ important UNCERTAINTIES

in $\sigma^{(nucleon)}_{scalar}$ due to uncertainties in




$m_q \langle \bar{q} q \rangle$

s-quark content

+

uncertainties in astrophysical quantities

($\vec{v}$, $f(\vec{v})$ WIMP velocity and velocity distribution function in the Earth frame

local value of the non-baryonic DM, ...)

# mSUGRA

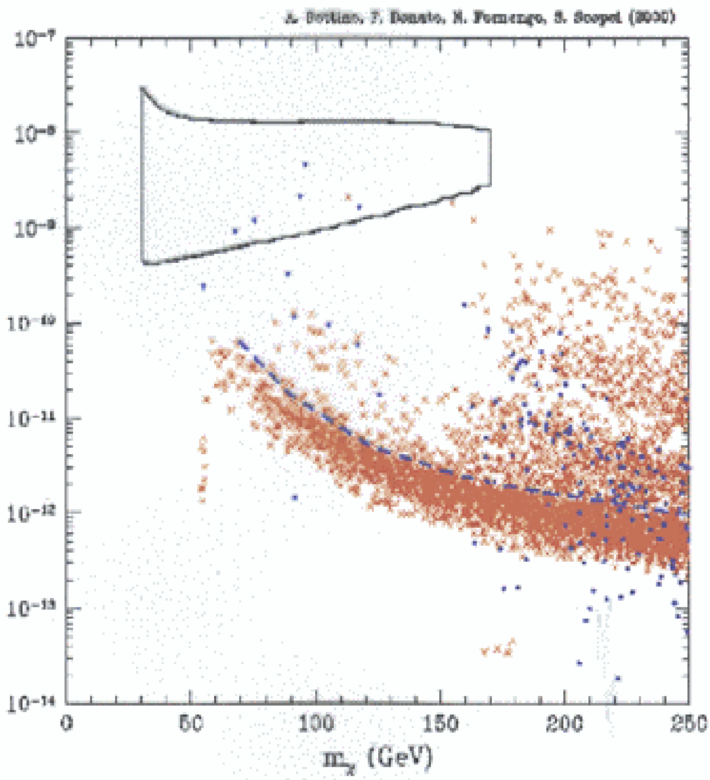



FIG. 5a. Scatter plot of $\xi\sigma^{(nucleon)}_{scalar}$ versus $m_\chi$ in case of universal SUGRA. Set 1 for the quantities $m_q < \bar{q}q >$'s is employed. Crosses (dots) denote configurations with $\Omega_\chi h^2 > 0.05$ ($\Omega_\chi h^2 < 0.05$). The dashed line delimits the upper frontier of the scatter plot, when the inputs of Ref. [11] are used. The solid contour denotes the $3\sigma$ annual modulation region of Ref. [2] (with the specifications given in the text).

× $\Omega h^2 > 0.05$ — BOTTINO, DONATO,

• $\Omega h^2 < 0.05$ — FORNENGO, SCOPEL effMSSM BOTTINO et al.

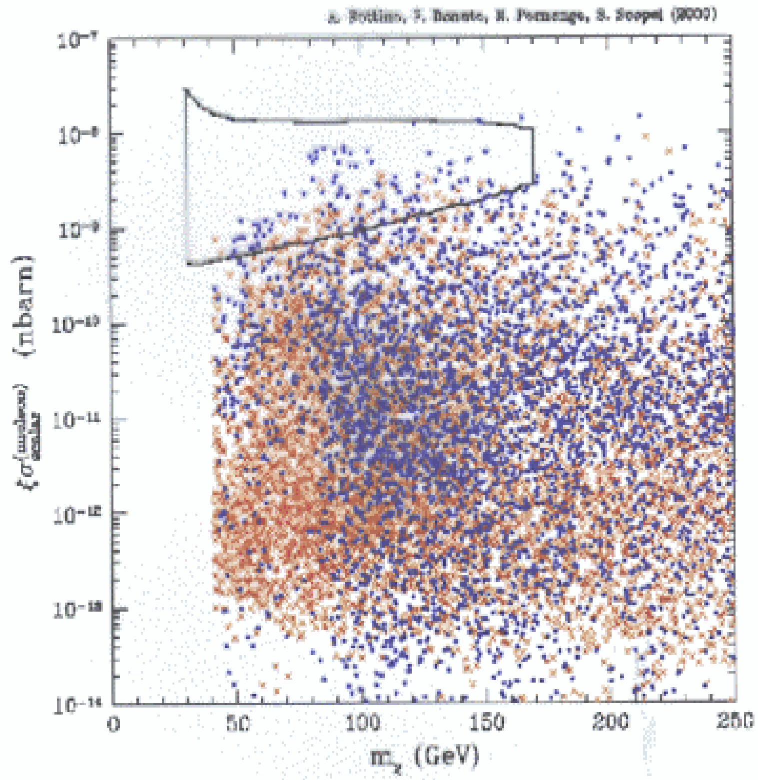
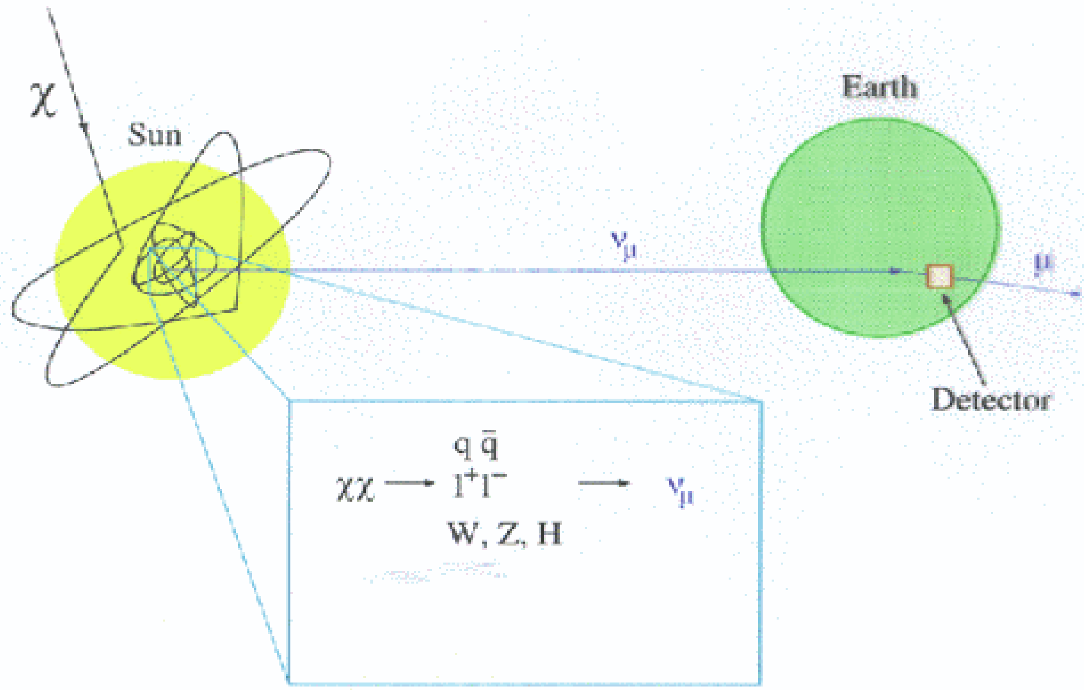



FIG. 5c. Same as in Fig. 5a in case of effMSSM.

x $\Omega h^2 > 0.05$

• $\Omega h^2 < 0.05$

# $\nu$ telescopes - basics



# INDIRECT SEARCHES

NEUTRINOS: when $\chi$ pass through astrophysical objects, they may be slowed below escape velocity by elastic scattering

$\Rightarrow$ once captured $\chi$ settle to the center where their densities and annihilation rates are greatly enhanced

$\chi\chi$ annihilation $\Rightarrow$ $\nu$'s are not absorbed

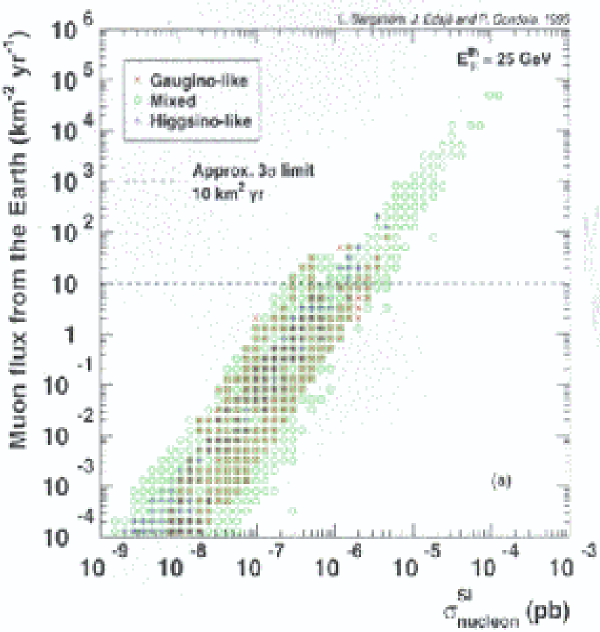
$$\text{typical } E_\nu \sim \left(\tfrac{1}{2} \div \tfrac{1}{3}\right) m_\chi$$

$\rightarrow$ upward-going $\nu_\mu$ converting to $\mu$ producing through-going $\mu$'s in detectors

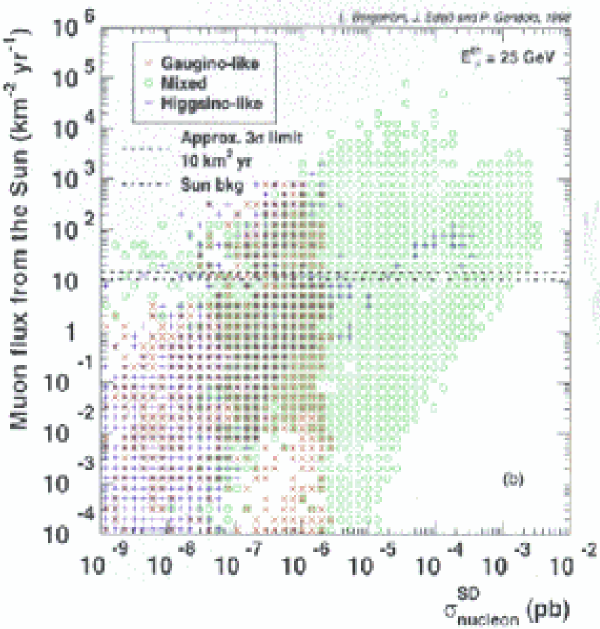
in the next few years $\phi_\mu \sim 10\text{-}100\ km^{-2} yr^{-1}$ may be within reach

$\Rightarrow$ such sensitivities are typically **NOT** sufficient to discover $\tilde{B}$-like LSP unless they are light and $\tan\beta$ is large – but it is a good opportunity to detect $\chi$ in the MIXED GAUGINO-HIGGSINO DM scenario Feng et al

BERGSTRÖM, EDSJO, GONDOLO



BERGSTROM, EDSJO, GONDOLO



**PHOTONS**: high-energy $\gamma$'s provide a unique signal of DM annihilation: they point back to their sources and their energy distribution is directly measurable → given sufficient angular and energy resolution in $\gamma$-ray detectors a variety of signals may be considered

**$\gamma$ signal from**
- galactic center Berezinski et al
- galactic halo Bergstrom et al
- extra-galactic sources Bultz et al

most promising: galactic center where large enhancements in DM density are possible

**$\gamma$ energy distribution**: line and continuum

line ↓ loop processes $\chi\chi \to \gamma\gamma$, $\chi\chi \to \gamma Z$

detection difficult unless large higgsino component and cuspy halo profile
Bergstrom, Ullio, Buckley

continuum ↓ from cascade decays of other primary annihilation products

ANTI-MATTER: excess of cosmic anti-particles and anti-matter from DM annihilation

$e^+$ signal is perhaps the most promising

DM signal is most promising at high energies where the background is relatively small and well understood

$\chi\chi \to WW, ZZ$ followed by the direct decay of gauge bosons to $e^+$

$e^+$ signal is typically too small for $\tilde{B}$-like LSP's (in mSUGRA); excess of few percent possible for gaugino-higgsino DM (however the region of detectable $e^+$ signals may be extended if, for example, the halo is clumpy or if the local density is larger than 0.3 GeV/cm$^3$

CONSTRAINTS ON SUSY models
with EXPS. LIKELY TO REACH
THESE SENSITIVITIES BEFORE 2006

| | | |
|---|---|---|
| $\tilde{\chi}^{+}\tilde{\chi}^{-}$ | $m_{\tilde{\chi}^{\pm}} > 100$ GeV | LEP II |
| $\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ | $m_{\tilde{\chi}^{\pm}} > 150-170$ GeV | Tevatron |
| $B \to X_s \gamma$ | $\lvert \Delta B(B \to X_s \gamma) \rvert < 1.2 \times 10^{-4}$ | Babar, Belle |
| $\mu$ MDM | $\lvert a_{\mu}^{SUSY} \rvert < 8 \times 10^{-10}$ | Brookhaven E821 |
| Direct DM | | CDMS (Soudan), Cresst, Dama, ... |
| $\nu$ from Earth | $\phi_{\mu}^{\oplus} < 100\ km^{-2} yr^{-1}$ | Amanda, Antares |
| $\nu$ from Sun | $\phi_{\mu}^{\odot} < 100\ km^{-2} yr^{-1}$ | " , " |
| $\gamma$ (gal. center) | $\phi_{\gamma}(1) < 1.5 \times 10^{-10}\ cm^{-2} s^{-1}$ | GLAST |
| $\gamma$ (gal. center) | $\phi_{\gamma}(50) < 3 \times 10^{-12}\ cm^{-2} s^{-1}$ | Magic, Hess, Cangaroo III |
| $e^{+}$ cosmic rays | $(S/B)_{max} < 0.01$ | AMS-02 |

Feng, Matchev, Wilczek

FENG, MATCHEV, WILCZEK

mSUGRA

tanβ=10

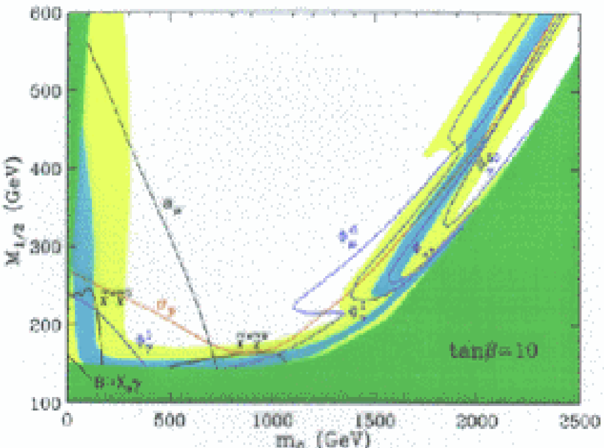



FIG. 18. Estimated reaches of various high-energy collider and low-energy precision searches (black), direct dark matter searches (red), and indirect dark matter searches (blue) before the LHC begins operation, for $\tan\beta = 10$. The projected sensitivities used are given in Table IV. (The LEP chargino mass bound will marginally extend the bottom and right excluded regions and is omitted.) The shaded regions are as in Fig. 1. The regions probed extend the curves toward the forbidden, green regions. The dark matter reaches are not modulated by the thermal relic density. Bounds from photons from the galactic center are highly halo model-dependent; we assume a moderate halo profile parameter $\bar{J} = 500$. (See text.)

tanβ=50

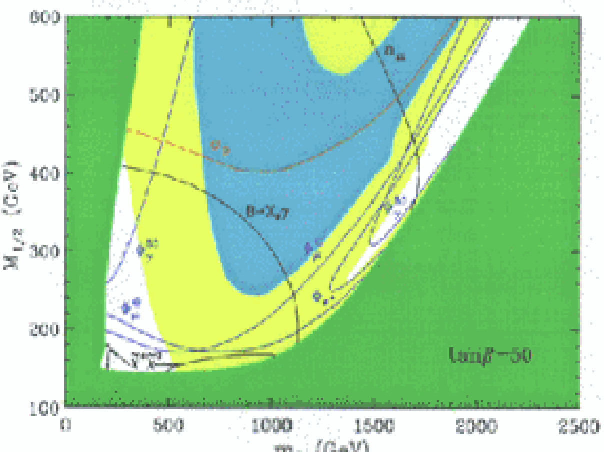



FIG. 19. As in Fig. 18, but for $\tan\beta = 50$. Here the $\Phi^1_\gamma$ probe is sensitive to all of the parameter space shown and so its limit contour does not appear.

SINCE LAST SUMMER WE GOT

**TWO NEW EXPT. INPUTS**

**HIGGS**
- $m_h > 113.5$ GeV
- "possible signal" corresponding to $m_h = 115^{+1.3}_{-0.7}$ GeV (2.9σ significance)

$a_\mu \equiv \frac{g_\mu - 2}{2}$ BNL E821

$\delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} \simeq (43 \pm 16) \times 10^{-10}$

↳ 2.6σ discrepancy

CONSTRAINING SUSY

PUTTING TOGETHER
- Tevatron + LEP information (in particular $m_h$)
- FCNC, CP̸ (in particular $b \to s + \gamma$)
- $a_\mu$
- **DM** (in particular $\Omega_\chi h^2 < 0.3$)

# SUSY "NO LOSE THEOREM" for LHC?

before the E821 result on $a_\mu$:

in mSUGRA for $\tan\beta \leq 20$ ⇒ in particular

the DM constraint $\Omega_\chi h^2 < 0.3$ limits

$m_0, m_{1/2}$ guaranteeing SUSY VISIBILITY at LHC

for $\tan\beta > 20$ ⇒ possibilities of $\chi$

CO-ANNIHILATIONS ⟶ NO "GUARANTEE"

OF DISCOVERY OF SUSY PARTICLES

AT LHC ELLIS, FALK, GANIS, OLIVE, SREDNICKI

ARNOWITT, DUTTA, HU, SANTOSO

but even with $2\sigma$ downward fluctuation

in the the E821 discrepancy with SM still

the upper bounds on $m_0$, $m_{1/2}$

⇓

guarantee in mSUGRA SUSY

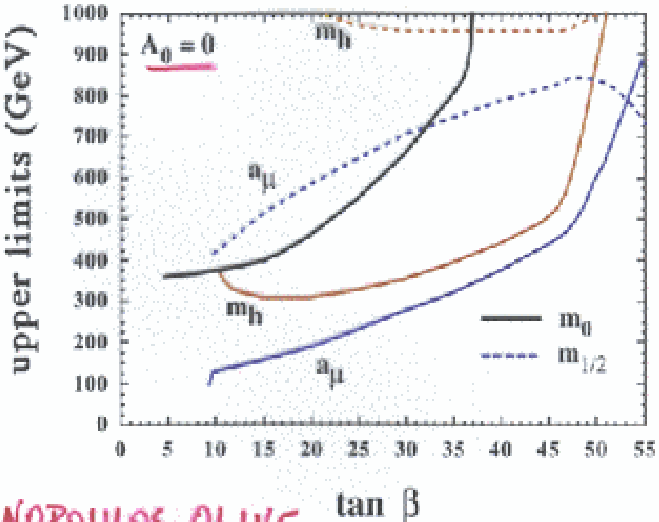
visibility at LHC ELLIS, NANOPOULOS, OLIVE

(but no guarantee for linear collider with $E_{CM} < 1.2$ TeV)

COMBINING $a_\mu$ and other constraints on Susy

- Everett, Kane, Rigolin, Wang hep-ph/0102145
- Feng, Matchev hep-ph 0102146
- Baltz, Gondolo hep-ph 0102147
- Chattopadhyay, Nath hep-ph 0102157
- Komine, Moroi, Yamaguchi hep-ph 0102204
- Hisano, Tobe hep-ph 0102315
- Ellis, Nanopoulos, Olive hep-ph 0102331
- Arnowitt, Dutta, Hu, Santoso hep-ph 0102344

ON SUSY "VISIBILITY" $\mu > 0$




ELLIS, NANOPOULOS, OLIVE

Figure 2: *Upper limits on $m_{1/2}$ and $m_0$ obtained as functions of $\tan\beta$ for $\mu > 0$, assuming $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$, $m_t = 175$ GeV and $A_0 = 0$. We show the upper limits on $m_{1/2}$ obtained by combining cosmology with the LEP Higgs 'signal' and the E821 lower limit on $\delta a_\mu$, and the upper limits on $m_0$ imposed by cosmology alone and in association with either $a_\mu$ or the LEP Higgs 'signal'.*

'funnel' moves to lower $m_{1/2}$ as $m_b$ increases, reducing the combined upper limit on $m_{1/2}$ when $m_b(m_b)^{\overline{MS}}_{SM} = 4.5$ GeV, and increasing the upper limit on $m_0$. However, our overall conclusions on the observability of the CMSSM at different colliders are unchanged. As seen in panels (c) and (d), the main effects of varying $m_t$ are to move the $m_h$ contours and the allowed cosmological region [6]. As a result, the lower bound on $\tan\beta$ is relaxed for $m_t = 180$ GeV. However, the effects on the bounds on $m_{1/2}$ and $m_0$ in Fig. 2 are again relatively minor. We do not display the effects of varying $-2 \times m_{1/2} \leq A_0 \leq 2 \times m_{1/2}$: the main changes are in the allowed cosmological region, whose sensitivity to input assumptions were commented on previously [28], but the effects on the bounds on $m_{1/2}$ and $m_0$ in Fig. 2

[6] Note also the black region in panel (c) of Fig. 3, which is where we find no consistent electroweak vacuum. There are similar but smaller regions for larger $m_t$, that are not shown. The size of this forbidden region is quite sensitive to the treatment of $m_t$, a topic we leave for another occasion.

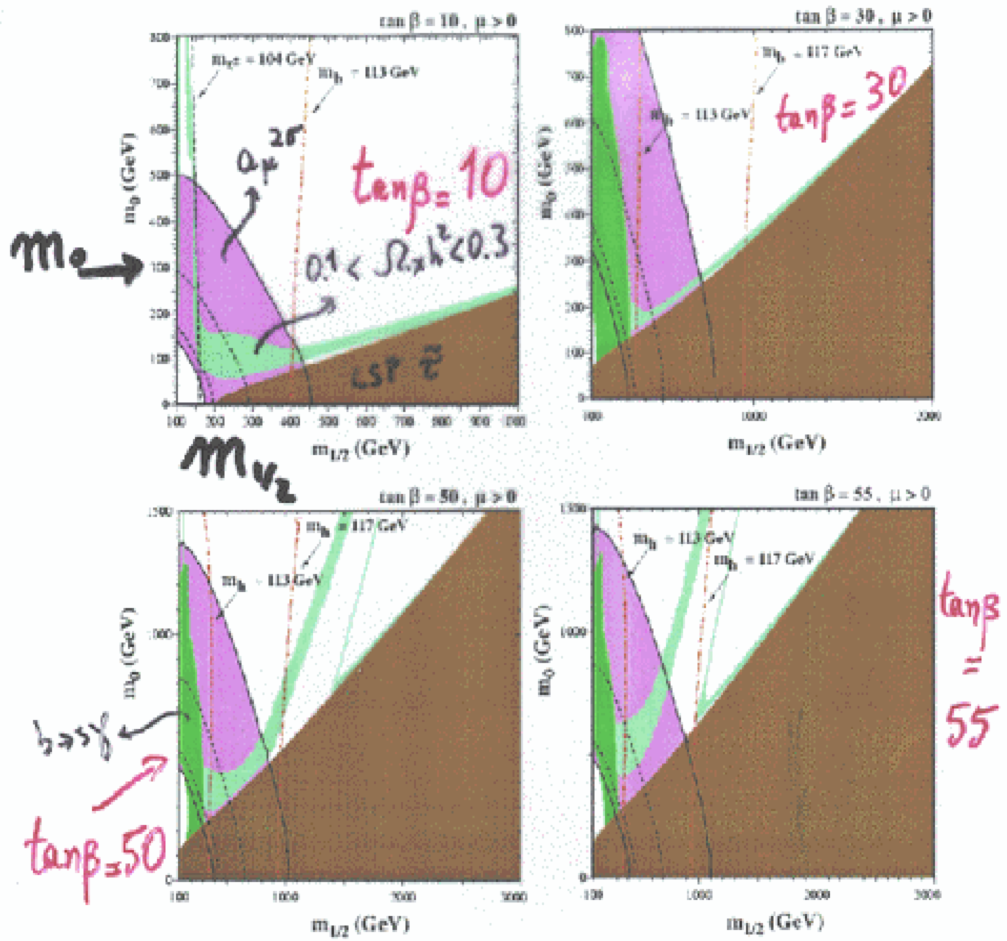



Figure 1: *The $(m_{1/2}, m_0)$ planes for $\mu > 0$ and $\tan\beta =$ (a) 10, (b) 30, (c) 50 and (d) 55, found assuming $A_0 = 0, m_t = 175$ GeV and $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ GeV. The near-vertical (red) dot-dashed lines are the contours $m_h = 113, 117$ GeV, and the near-vertical (black) dashed line in panel (a) is the contour $m_{\chi^\pm} = 104$ GeV. The medium (dark green) shaded regions are excluded by $b \to s\gamma$. The light (turquoise) shaded areas are the cosmologically preferred regions with $0.1 \le \Omega_\chi h^2 \le 0.3$. In the dark (brick red) shaded regions, the LSP is the charged $\tilde{\tau}_1$, so this region is excluded. The regions allowed by the E821 measurement of $a_\mu$ at the 2-σ level are shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-σ ranges.*

$\mu > 0$

ELLIS, NANOPOULOS, OLIVE

BOTTINO, FORNENGO, SCOPEL

# mSUGRA

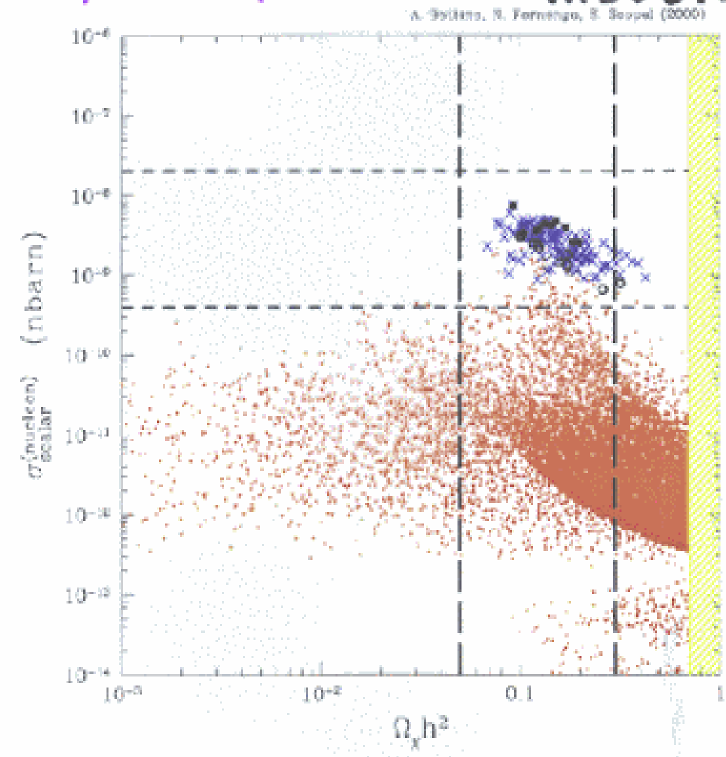



FIG.2b - Scatter plot of the neutralino-nucleon scalar cross section $\sigma_{\rm scalar}^{\rm (nucleon)}$ versus the neutralino relic abundance $\Omega_\chi h^2$ for universal SUGRA. Notations and definitions as in Fig.2a.

• points referring to $e^+e^- \to Z + h \to (q,\bar{q}) + (b,\bar{b})$ (h → 115 GeV)

× crosses referring to $e^+e^- \to Z + H \to (q,\bar{q}) + (b,\bar{b})$ (H → 115 GeV)

# effMSSM

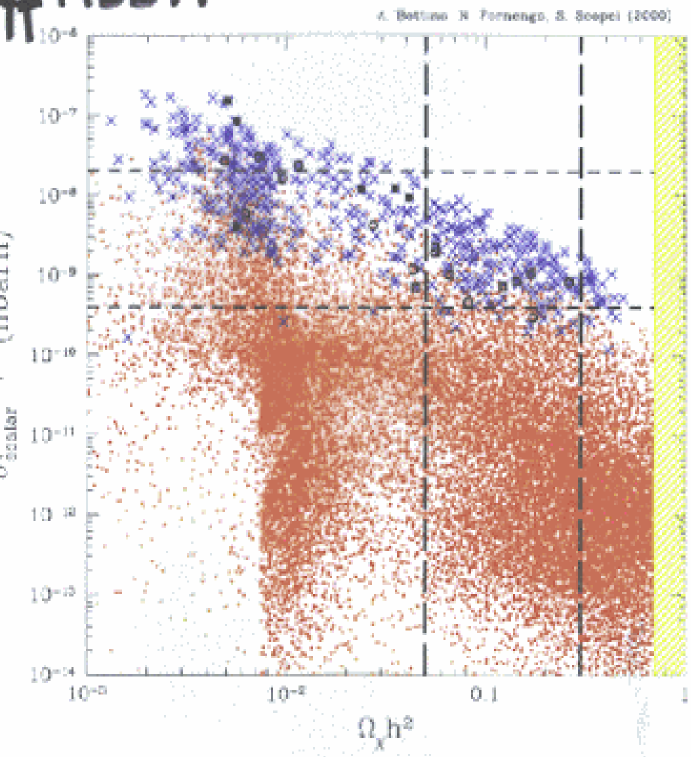



FIG.2a - Scatter plot of the neutralino–nucleon scalar cross section $\sigma_{scalar}^{(nucleon)}$ versus the neutralino relic abundance $\Omega_\chi h^2$ for the effMSSM. Set 1 for the quantities $m_q < \bar{q}q >$'s is employed in the calculation of $\sigma_{scalar}^{(nucleon)}$. The two horizontal lines bracket the sensitivity region defined by Eq. (1). The two vertical lines denote the range $0.05 \le \Omega_\chi h^2 \le 0.3$. The region where $\Omega_\chi h^2 > 0.7$ is excluded by current limits on the age of the Universe. Different points (notations as in Fig.1a) refer to different categories of events able to reproduce the relevant LEP Higgs events.

Bottino, Fornengo, Scopel

# mSUGRA

Bottino et al.

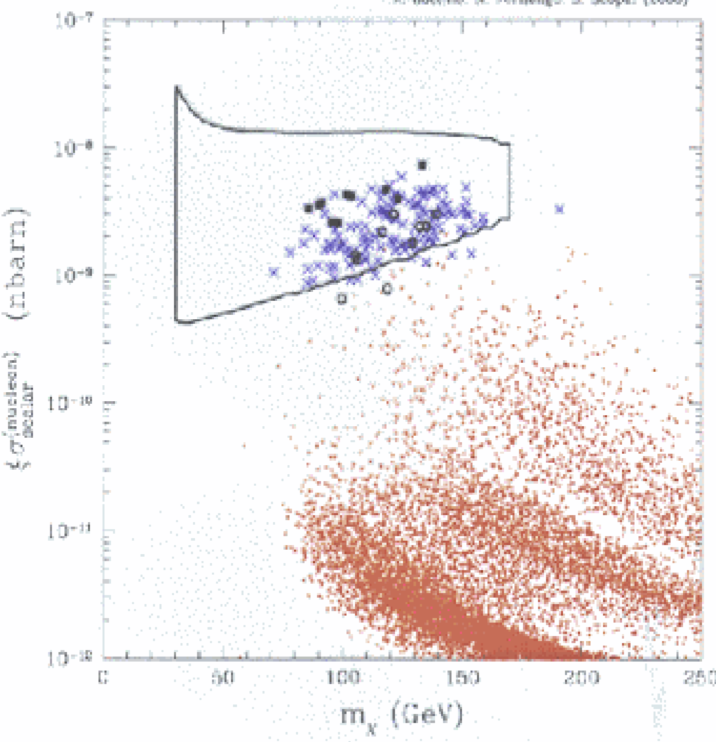



FIG.3b - Scatter plot of $\xi\sigma_{scalar}^{(nucleon)}$ versus the neutralino mass $m_\chi$ for universal SUGRA. Notations and definitions as in Fig.3a.

effMSSM

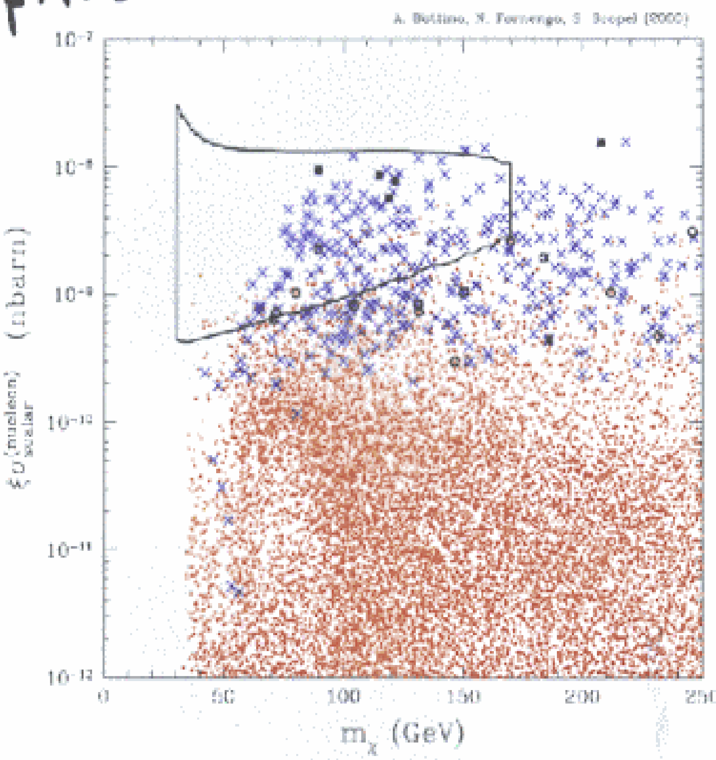



FIG.3a - Scatter plot of $\xi\sigma^{(nucleon)}_{scalar}$ versus the neutralino mass $m_\chi$ for the effMSSM. Set 1 for the quantities $m_q < \bar{q}q >$'s is employed in the calculation of $\sigma^{(nucleon)}_{scalar}$. Different points (notations as in Fig.1a) refer to different categories of events able to reproduce the relevant LEP Higgs events. The solid contour denotes the $3\sigma$ annual-modulation region of Ref. [5] when taking into account the uncertainties in the local dark matter density and in the dispersion velocity of the velocity distribution function of WIMPs in the galactic halo.

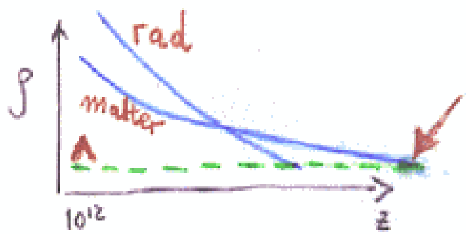
BOTTINO et al

# $\Omega_\Lambda \neq 0$

only a nightmare for
a particle physicist?

i) FIRST CANDIDATE: COSMOLOGICAL CONSTANT

$p = -\rho$ $\quad w = -1$ $\quad (p = w\rho)$




TODAY

- why $\Lambda$ so small?*
- why today?

* en. of the vacuum $\sim (0.003\,\text{eV})^4$

ii) SECOND POSSIBILITY:

DYNAMICAL TIME-DEPENDENT AND SPATIALLY INHOM.
COMPONENT WITH $\boxed{p = w\rho}$ $\rightarrow -1 < w < 0$

present data seem to favor $w \sim -0.6$ or so

HOW TO MAKE VACUUM ENERGY DYNAMICAL ?

Simplest case: EVOLVING SCALAR FIELD which has not reached its state of minimum energy

⇒ the energy of the true vacuum is zero but not all fields have evolved to their state of minimum energy: field classically unstable rolling towards its lowest energy state

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \quad ; \quad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

eq. of motion: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

$$w = \left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) / \left(\frac{1}{2}\dot{\phi}^2 - V(\phi)\right)$$

↳ can take any value from +1 to −1

w can vary with time

Bronstein 1933 "decaying cosmological constant"
Freese et al. 87 ; Ozer-Taha 87 ; Ratra-Peebles 88 ;
Frieman et al 95 ; Coble et al. 96 ; Turner-White 97 and ...

R. Caldwell, Dave and Steinhardt PRL '98

↳ name for this rolling scalar :

QUINTESSENCE

Candidates : pseudo-Goldstone bosons
Frieman, Hill, Stebbins, Waga
axions J.E. Kim, K. Choi
scalar fields with a scalar potential
decreasing to zero for infinite field
values Caldwell et al; Turner and White;
Spergel and Pen ; Zlatev, Wang, Steinhardt

↓

IDEA : such a behaviour occurs
naturally in models of
BINETRUY;
A.M., Pietroni, Rosati DYNAMICAL SUSY BREAKING

Scalar potential of susy models has many flat
directions (directions in field space where the potential vanishes)

after dynamical susy breaking ⇒ degeneracy of flat
directions is lifted but flat directions restored at
infinite values of the scalar fields !

⇒ potential smoothly decreasing to zero at infinity

GLOBAL SUSY ⇒ VANISHING GROUND STATE ENERGY

(hope for solution of the cosm. const. problem Zumino)

$V(\phi) \to 0$ at infinity

(in some case $\phi \to 1/g$ → coupl. const. associated with the dynamics responsible for SUSY breaking

$\phi \to \infty$ $g \to 0$ → restoration of SUSY $V=0$)

ex: dilaton $\phi$ not appearing in $V$

$\phi F^{\mu\nu} F_{\mu\nu}$ → G gauge symm.

when G interaction strong $\Lambda = M_P \, e^{-\phi/2b_0}$

$\Rightarrow \langle \bar\lambda \lambda \rangle = \Lambda^3 = M_P^3 \, e^{-3\phi/2b_0}$

$V \to e^{-\phi/b_0}$

$w_\phi$ starts at 1 then $w_\phi$ decreases to $w_\phi = 0$ for $\phi \to \infty$

but $w$ positive !

# QUINTESSENCE MODELS FROM THE PARTICLE PHYSICS POINT OF VIEW

## 2 CLASSES OF PROBLEMS

construction of "realistic" field theory models with the required scalar potentials

ex: inverse law scalar potentials appear in SUSY QCD theories with $N_c$ colors and $N_{flavours} < N_c$

(BINETRUY)

interaction of the quintessence field with the rest of the fields of the SM

$\Downarrow$

the quintessence field today has typically a mass of order $H_0 \sim 10^{-33}$ eV

$\Rightarrow$ it would mediate long range interactions of gravitational strength

CARROLL

Bartolo, Pietroni

# OUTLOOK

DIRECT ACCELERATOR SEARCHES

⇓

THEORY ⇒ NEW PHYSICS ⇐ FCNC, CP̸, $a_\mu$

⇑

DM (direct and indirect) SEARCHES

- certain amount of **CDM** in excess of the allowed amount of baryonic DM is needes
  $\Omega_{CDM} \sim 0.3-0.5$
- best thermal CDM candidates **WIMPS**
- "**natural**" WIMP candidate: SUSY LIGHTEST PART.
  ⇒ lightest NEUTRALINO
- complementarity of the direct and indirect DM searches
- **DM searches** ⇒ SUSY hints in the pre-LHC era ?