INT. SCHOOL ON
ASTROP. AND ν PHYSICS
Varenna, June 2002

DARK MATTER

A. Masiero
Padova Univ. and INFN, Padova

DM ⟷ PARTICLE PHYSICS

↓ (from DM): Dark Matter, Dark Energy

NEW PHYSICS: Beyond the elw. SM

↓

CDM candidate ⟷ LOW ENERGY SUSY?

STATUS OF THE STANDARD MODEL

- **THEORETICALLY:**

  SPONT. BROKEN GAUGE THEORY

  → **RENORMALIZABLE GAUGE THEORY**

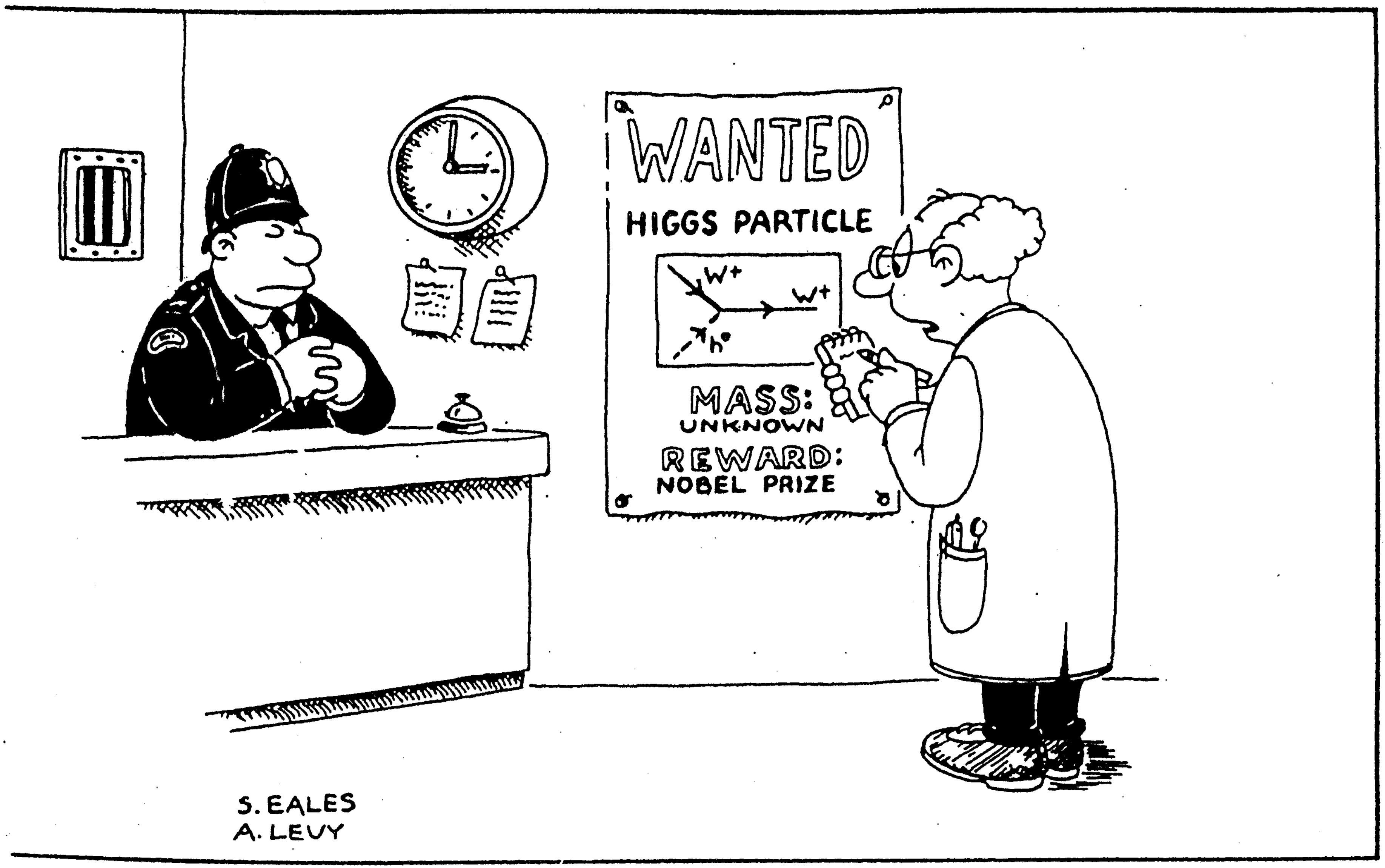
  (no theor. inconsistencies like in the Fermi theory)

- **EXPERIMENTALLY:**

  AMAZING AGREEMENT WITH ALL EXP. DATA → **ELW. TESTS*** (LEP physics) ‰ accuracy for some observables

  FCNC, CP ≠* $(b \to s\gamma, \begin{cases} \varepsilon \\ B_d - \bar{B}_d \\ V_{ub} \\ + a_{J/\psi K_S} \end{cases}, \mu \to e\gamma, \dots)$

clouds: A_{FB}^{b}, $(g-2)_\mu$, ...


WANTED
HIGGS PARTICLE
W+
W+
h°
MASS:
UNKNOWN
REWARD:
NOBEL PRIZE
S. EALES
A. LEVY

WHY TO GO BEYOND THE SM

THEOR.
- UNIFICATION PROBLEM
- FLAVOR PROBLEM
- HIERARCHY PROBLEM

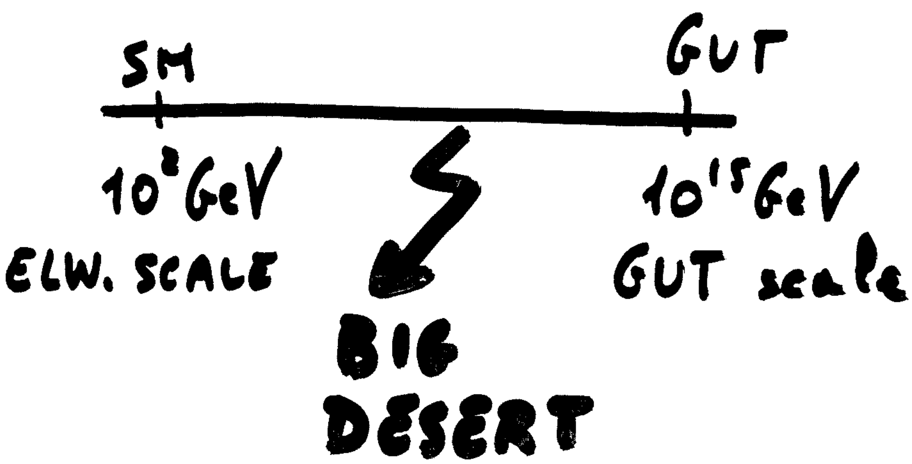
EXP.
- NO INDICATION OF NEW PHYSICS FROM ACCELERATOR PARTICLE PHYS.
- HINTS FOR NEW PHYSICS FROM ASTROPARTICLE PHYSICS

- LACK OF UNIFICATION IN THE SM

$G_F, e \rightarrow g_1, g_2 \qquad g_3 > g_1, g_2$

→ "running" gauge couplings

⇒ **GUT**



RGE $\begin{cases} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{cases}$ 3 eqs. $\begin{cases} \alpha_{GUT} \\ M_{GUT} \\ \sin^2\theta_W \end{cases}$

α_{GUT}, M_{GUT} ← physics at the GUT scale

$\sin^2\theta_W$ ← testable prediction

predicted $\sin^2\theta_W$ in the right ballpark
but after LEP precision physics
⇒ $\sin^2\theta_{W\,GUT}$ with "Big Desert" differs significantly from measured $\sin^2\theta_W$

→ need for NEW PARTICLES in the desert?

→ ex. LOW ENERGY SUSY

FLAVOR PROBLEM

- FERMION MASSES AND MIXINGS *
  → arbitrary param. in the SM
  no prediction at all

- CP ≠ SM predicts that CP is violated (CKM matrix possesses one phase) but no prediction on its size

* ν masses and mixings

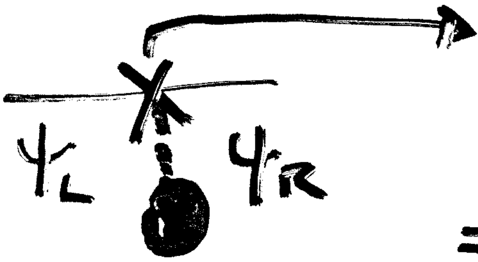
exp. novelties in flavor physics
- ν osc. → **NEW PHYS.**
- ε' (direct CP≠ in K physics)
- $a_{J/\psi K_S}$ (CP≠ in B physics)

$\Gamma(B \to J/\psi K_S) \neq \Gamma(\bar{B} \to J/\psi K_S)$

theor. → GUT $q \leftrightarrow \ell$
successful mass relation $m_b = m_\tau |_{GU}$
$m_b \sim 3 m_\tau$ at low en.
open probl. → origin of mass pattern (family symm.?

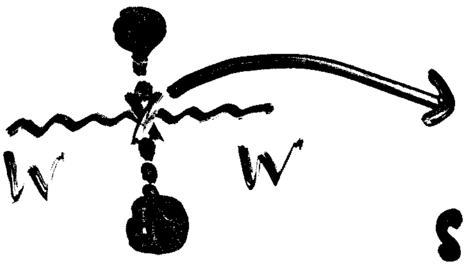
- GAUGE HIERARCHY PROBLEM

FERMION / **GAUGE BOSON** MASSES > **SYMM. PROTECTION**



mass arises ONLY when $SU(2)\times U(1)$ is broken

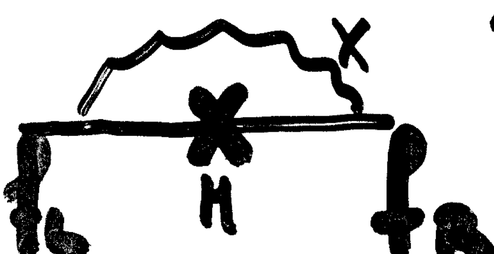
$\Rightarrow m_\psi <$ ELW. breaking scale



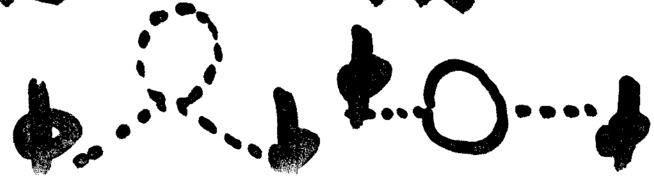
W mass $\Rightarrow$ only when ELW. symm. is broken

$\mu^2 \phi\phi^+$ **NO SYMM. PROTECTION FOR SCALAR MASSES**

μ^2 can be arbitrarily large



$$\int^\Lambda d^4k \frac{M}{(k^2-M^2)(k^2-M_X^2)} \propto \ln\Lambda$$



$$\int^\Lambda \frac{d^4k}{k^2} \propto \Lambda^2 \text{ quadr. div.}$$

SOLUTIONS FOR THE GAUGE HIERARCHY PROBLEM

NO FUNDAM. SCALARS

⇓

DYNAM. SYMM. BREAKING

$\langle F\bar{F}\rangle \neq 0$

↙

F condensates
"composite" scalars
(pion-like objects)

⇓

"Technicolor" theories

⇒ no viable model so far

NO LARGE SCALE M_X

$M_X \gg M_W$

M_P not too far from M_W

⇓

EXTRA DIM.

↓

gravity feels new dim.

↓

$M_P \lll 10^{19}\,GeV$

"INDUCED... SYMM. PROTECTION FOR SCALARS

$\phi \leftrightarrow f$
SUPER SYMM.

$m_f \leq$ ELW scale

⇓

$m_\phi \leq$ ELW scale

if $\phi \leftrightarrow f$ good down to M_W

NEW PHYSICS HINTS FROM STANDARD MODELS CONFRONTATION

- **SM OF PARTICLE PHYSICS** GWS
- **SM OF COSMOLOGY** BIG BANG
- **SM OF THE SUN**

MUTUAL SUPPORT OF THE SM's :

ex. BBN, CMB, ...

but also some possible clashes

BIG BANG **GWS** **SOLAR MODEL**

- DM and DARK ENERGY
- BARYOGENESIS
- INFLATION

- SOLAR NEUTRINOS + ATM. ν's

THE DM PROBLEM

$\Omega = \rho/\rho_c \quad \rho_c = \frac{3H^2}{8\pi G_N} \simeq 10^{-29}\, g/cm^3;\quad H = h\, 100\ Km/s\ Mpc$

$h = 0.65 \pm 0.15$

$\Omega_{LUM} < 0.01$

$\Omega \gtrsim 0.1$ GALACTIC ROTATION CURVES

$\Omega^{matter} \sim 0.3 - 0.5$ CLUSTERIZED MATTER (in clusters and superclusters)

$\Omega_{baryons} \lesssim 0.09$ FROM NUCLEOSYNTHESIS

(confirmed by CMB peaks)

$\Omega^{TOTAL} = 1$ FROM CMB DATA

$\Omega_\Lambda \simeq 0.6 - 0.7$ SUPERNOVAE DATA ON THE ACCELERATED EXPANSION OF THE UNIVERSE

⇓

ΛCDM
$$\begin{cases} \Omega^{TOT} = 1 \\ \Omega_{CDM} \sim 0.3 - 0.4 \\ \Omega_\Lambda \sim 0.6 - 0.7 \end{cases}$$

DM $\rightleftarrows$ NEW PHYSICS (beyond SM)

Why DM ⟶ NEW PHYSICS

• NEED FOR NON-BARYONIC DM

$$\Omega_{Matter} = 0.35 \pm 0.10 \gg \Omega_{Baryon} = 0.045 \pm 0.00?$$

(ratio of baryons to total mass in clusters

$f = (0.075 \pm 0.002)\, h^{-3/27}$

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

- IN MDM models $\Omega_{MATTER} = \Omega_{CDM} + \Omega_{HDM} = 1$

but TODAY:

COSMIC CONCORDANCE

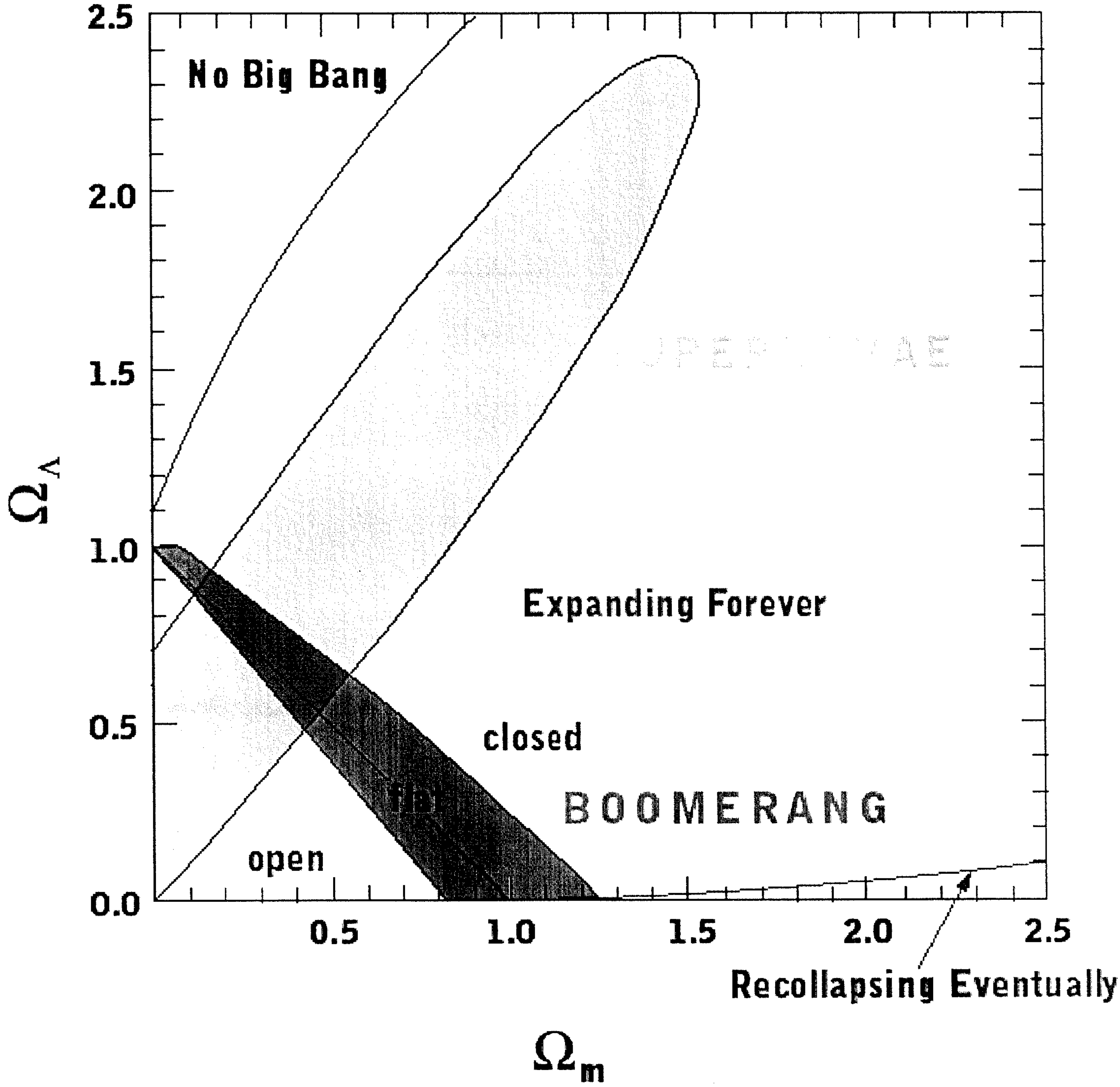
$\Omega_{MATTER} \sim 0.3-0.4$

$\Omega_{\Lambda} \sim 0.6-0.7$

- CMB $\Rightarrow \Omega_{TOTAL} = \Omega_{MATTER} + \Omega_{\Lambda} \simeq 1$
- $\Omega_{MATTER} \simeq 0.3-0.5$
- SN $\rightarrow$ UNIV. IS ACCELERATING

NEW PARADIGM $\Rightarrow$ ΛCDM

IF NOT NEED, IS THERE AT LEAST ROOM FOR ν's TO STILL PLAY THE ROLE OF A DM CONTRIBUTION?



No Big Bang
Expanding Forever
closed
BOOMERANG
open
Recollapsing Eventually
Ω_Λ
Ω_m
0.0
0.5
1.0
1.5
2.0
2.5

WHAT IS THE DM MADE OF ?

Ω — Ω_{MATTER} at least 0.3

Ω — Ω_{Λ} Λ cosm. const.

$\Omega_\gamma h^2 = 2.48 \times 10^{-5}$ with $m_\nu = 0$ $\Omega_\nu = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Omega_\gamma$

SM : relics $\gamma, \nu,$ baryons $\Omega_{SM} < 0.1$

$\Omega_B < 0.1$

⇓

NON-BARYONIC DM

CALLS FOR NEW PHYSICS

BEYOND SM

DM RELIC PARTICLES

↙ THERMAL ↘ NON-THERMAL (ex. axions)

THERMAL:

ex.: $m_\nu \sim 10\,eV$, $T_{decoupl} \sim MeV$

HOT

$m \ll T_{decoupl}$

relativistic at time structure formation starts.

COLD

ex: $m_{\chi^0} \sim 100\,GeV$, $T^{\chi^0}_{decoupl} \sim 20\,GeV$

$m \gg T_{decoupl.}$

non relativistic when galaxies start forming

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

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

  ⇒ $\Omega_\nu \sim 0.2\%$ (almost Ω_{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. ?)

  ⇒ COSMIC COINCIDENCE
  - Ω_M from baryon fraction in clusters
  - CBR 1st peak
  - SN

ΛCDM ⟶ $\Omega_M \sim 0.4$ $\Omega_\Lambda \sim 0.6$

STRUCTURE FORMATION

DM

AMOUNT AND NATURE OF THE MATERIAL IN THE UNIVERSE

$\Omega_i = \rho_i / \rho_{crit}$

COLD, HOT, WARM

SEED OF DENSITY FLUCTUATIONS

INITIAL SPECTRUM OF ρ FLUCTUATIONS

⇓

INFLATION OR TOPOLOGICAL DEFEC[T]

→ SCALE INVAR. FLUCTUATION SPECTRUM

⇓

EVOLUTION UNDER GRAVITY

→ EXP. INPUT: COBE, GALAXY DISTRIBUTIONS, PECULIAR VELOC.

→ TH. INPUT: GROWTH OF $\delta\rho/\rho$ (dependence on the nature of DM)

ν AND DM

$$\Omega_\nu \simeq \frac{\sum_i m_{\nu_i}}{(92 h^2 \text{ eV})}$$

h ↙ Hubble constant in units of 100 Km/Mpc/sec $h \simeq 0.6 - 0.8$

$\Longrightarrow \sum_i m_{\nu_i} \lesssim 90$ eV (from $\Omega h^2 < 1$ age of the Universe)

ν_i ↙ stable, light ($m_\nu < 1$ MeV) ν's

much stronger than the direct bounds on $m_{\nu_\mu}, m_{\nu_\tau}$

more recently: $\Omega_{hot} < 0.1$ (from studies of cosmological structure formation)

$\Rightarrow m_\nu < 3$ eV Tegmark, Zaldarriaga
Tegmark, Zaldarriaga, Hamilton

(from SUPER K $\Rightarrow \Omega_\nu \gtrsim 0.001$)

FROM SUPER K $\Rightarrow$ $\Omega_\nu \gtrsim 0.001$

but is it still possible to have ν's in the eV range to obtain ΛMDM scenarios (i.e. for instance $\Omega_{CDM} \sim 0.3$, $\Omega_{HDM} \sim 0.1$, $\Omega_\Lambda \sim 0.6$)?

several parameters: Ω_m, Ω_Λ, Ω_ν, N_ν, Ω_b, h, n_s

$\Rightarrow$ fit LSS observations + CMB (Boomerang + Maxima)

Novosyadlyj, Durrer, Apunevych $\Rightarrow$ with the given accuracy of the data it is not possible to conclude whether massive ν's are present at all and, if yes, what number N_ν is favoured

N_ν	Ω_ν	m_ν (eV)	
1	0.10	3.65	
2	0.15	2.79	at 1σ C.L.
3	0.20	2.40	

A ΛCDM model (i.e. $\Omega_\nu = 0$) is within the 1σ contour of the best-fit ΛMDM model

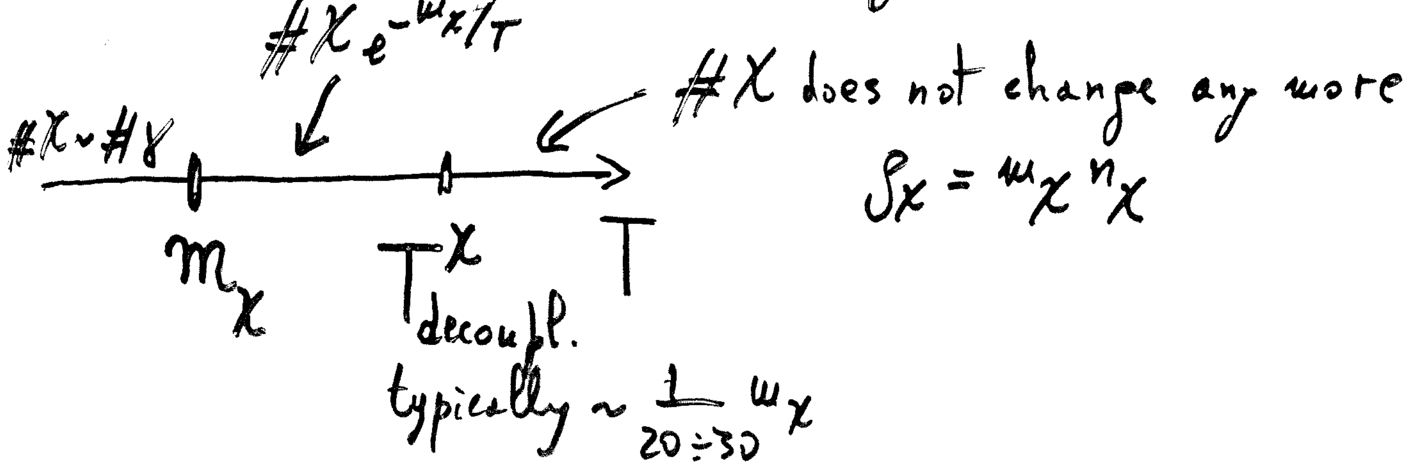
Fukugita, Liu, Sugiyama: not varying all param., they obtain the more stringent bound $m_\nu \lesssim 0.6-1.8$ eV for $\Omega_{matter} \sim 0.3-0.4$

BEST "THERMAL" CDM CANDIDATES

$\Downarrow$

WIMPS

Weakly Interacting Particles



Ω_χ depends on particle physics ($\sigma^\chi_{annih.}$) and "cosmological" quantities (H, T_0, ...)

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\underbrace{\langle \sigma_{annih.}(\chi\chi)\, v_\chi \rangle}_{\sim \alpha^2/M_\chi^2}\ \mathrm{TeV}^2}$$

$\mathrm{TeV}^2 \longrightarrow$ from $\sqrt{T^0 M_{Planck}}$

$\Omega_\chi h^2$ in the range $10^{-2} - 10$ to be cosmologically interesting (for DM)

$m_\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\Rightarrow \Omega_\chi h^2 \sim 10^{-2} - 10$!

IS A HEAVY STABLE ν OF FEW GEV's A VIABLE CANDIDATE FOR COLD DARK MATTER ?

$$\Omega_\nu h_0^2 \sim 3 \left(\frac{GeV}{m_\nu} \right)^2$$

$\Rightarrow$ m_ν of few GeV's is OK to have $\Omega_\nu \sim 0.1 - 1$

BUT (and this is a definitive "but")

LEP destroys this possibility

if ν has usual couplings to Z

$m_\nu^{DIRAC} > 44$ GeV

$\Omega_{0\nu}^{Dirac} h_0^2 < 10^{-3}$

$m_\nu^{MAJORANA} > 39$ GeV

$\Omega_{0\nu}^{Majorana} h_0^2 < 2 \cdot 10^{-3}$

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 Ω $(\Omega_0 h_0^2 \lesssim 10^{-3})$

if the SU(2) doublet heavy ν mixes with some "sterile" SU(2) x 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**

WHY SUSY SHOULD BE PRESENT AT SOME EN. SCALE IN NATURE

- most general symm. compatible with QFT
- local susy = supergravity → superstring → consistent quantization of gravity

WHY SUSY AT LOW ENERGY

i.e. at the ELW. scale (⇒ visible at (Tevatron?) – LHC)

→ **GAUGE HIERARCHY PROBLEM**

+

susy particles at the ELW. scale → new contributions in the RGE's of $\alpha_1, \alpha_2, \alpha_3$

⇒ **REMARKABLE AGREEMENT for $\sin^2\theta_W$**

+

LSP → CDM candidate

THE SUPERSYMMETRIC STANDARD M.

Particle content

VECTOR MULTIPLETS

$J=1$ → $J=1/2$

g (gluon) → $\tilde{g}$ (gluinos)

$W^\pm, W^3$ → $\tilde{W}^\pm, \tilde{W}^3$ (winos)

B → $\tilde{B}$ (bino)

CHIRAL MULTIPLETS

$J=1/2$ → $J=0$

q_L, q_R (quarks) → $\tilde{q}_L, \tilde{q}_R$ (squarks)

l_L, l_R (leptons) → $\tilde{l}_L, \tilde{l}_R$ (sleptons)

(Higgsinos) $\tilde{H}_1, \tilde{H}_2$ → H_1, H_2 (higgses)

↳ 2 higgs doublets

BARYON AND LEPTON NUMBERS IN SM and SUSY

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

SUSY $\Rightarrow$ B and L are *NOT* AUTOMATIC SYMMETRIES

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

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

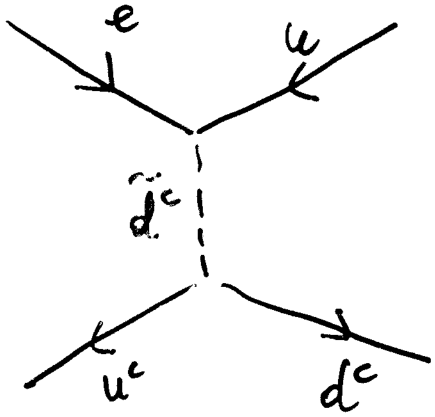
$$\lambda' \, L \, Q \, d^c|_{\theta\theta} \Rightarrow L \neq 0$$

dim 4 operators violating either B ...

if both λ'' and λ (or λ') terms are present p-decay is very fast

ex. : $LQd^c|_{\theta\theta} \Rightarrow e\,u\,\tilde{d}^c$

$u^c d^c d^c|_{\theta\theta} \Rightarrow u^c d^c \tilde{d}^c$

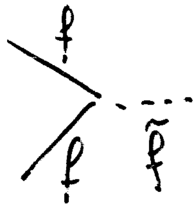


$p \to e^+ + X$

$m_{\tilde{d}^c} \le O(1\,TeV)$

$\Rightarrow$ NEED TO IMPOSE AN ADDITIONAL SYMMETRY TO FORBID EITHER $B\!\!\!/$ OR $L\!\!\!/$ OPERATORS IN W OR <u>ALL</u> B and L $\neq$ OPERATORS

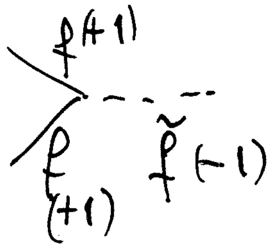
R PARITY



all $\lambda, \lambda', \lambda''$ dangerous vertices involve two (ordinary) fermions and one (supersymmetric) sfermion

impose a multiplicative discrete symm. such that R (ordinary particles) = 1

and R (susy particles) = −1

⇒ 

forbidden

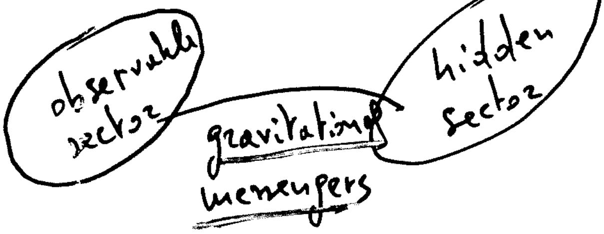
Gauge ⊗ N=1 susy ⊗ R parity ➡ W conserves B AND L.

R PARITY ➡
- superparticles can be produced or annihilated only in pairs
- the lightest susy particle (LSP) IS ABSOLUTELY STABLE

LSP?

LARGE SCALE SUSY BREAKING

GRAVITY MEDIATED SUSY B



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

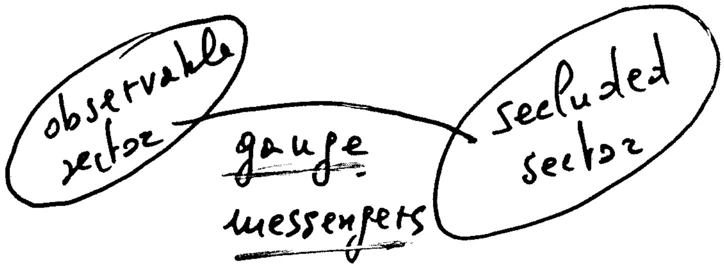
$m > 40$ GeV

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

↑

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

$M_{SUSY} \sim 100$ GeV

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

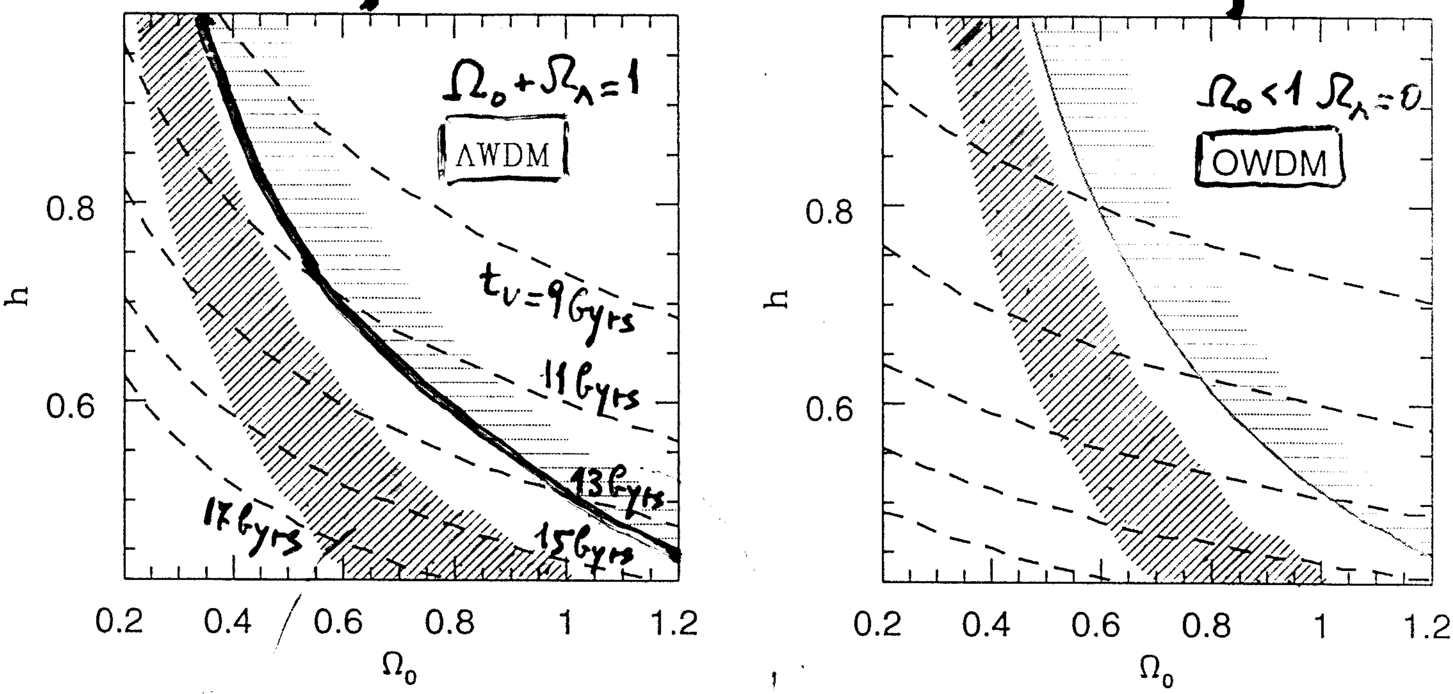
WARM DM

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

γ in the final state

Constraints on light gravitinos as WDM from structure formation

flat $\Omega_{matter} < 1$ open



high-redshift ** objects constraint

cluster * abundance

Pierpaoli, Borgani, A.M., Yamaguchi

$n = 1$ in the above figs

taking $n<1$ or $n>1$ does not improve the situation

* using relation between σ_8 (r.m.s. fluctuation value within a sphere of $8 h^{-1}$ Mpc radius) and Ω_0 from Viana and Liddle '96

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

NEUTRALINO

$U(1)_Y \Rightarrow B_\mu \longrightarrow \tilde{B}$
$SU(2)_L \Rightarrow W_3 \longrightarrow \tilde{W}_3$
} neutral gauginos

$H_1^0 \longrightarrow \tilde{H}_1^0$
$H_2^0 \longrightarrow \tilde{H}_2^0$
} neutral higgsinos

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

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

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

Cosmological range for CDM :

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

but, given the uncertainties, even Ω_{CDM} as low as 0.05 can still be of cosmological relevanc

χ COMPOSITION

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

nu SUGRA $\rightarrow$ possibility of mixed
($m_{H_1} \neq m_{H_2}$ 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

LOWER and UPPER LIMITS on m_χ

CMSSM $\longrightarrow$ $m_\chi \geq 95$ 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 $\tan\beta \leq 10$ $\quad 10^{-8}$ 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

nu SUGRA $\quad$ $m_\chi > 50$ 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_χ as high as 600 GeV → co-annih.

χ features for direct and indirect searches:

Ω_χ, $\sigma^\chi_{nucleus}$, $\sigma_{\chi\chi}$, ...

and their **SUSY MODEL DEPENDENCE**

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

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

$\mathcal{L}_{SUSY\ breaking}$: SUSY breaking terms

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

$M_i(\lambda_i \lambda_i + \bar\lambda_i \bar\lambda_i)$ → gaugino masses

→ free param: m_i, A^l_{ij}, A^d_{ij}, A^u_{ij}, M_1, M_2, M_3 + μ

⇒ 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

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

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

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

+ imposing electroweak radiative breaking

ONLY 4 NEW SUSY PARAM + one sign

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

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

⇗

CMSSM or mSUGRA

constrained Minimal SUSY SM — minimal supergravity

CDM in SUSY

CONSTRAINTS ON THE SUSY PARAM. SPACE

$\Downarrow$

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

together with the other phenom. constraints does it lead to the "NO LOSE THEOR." FOR LHC ?

YES if one calls for SUSY to explain the a_μ discrepancy

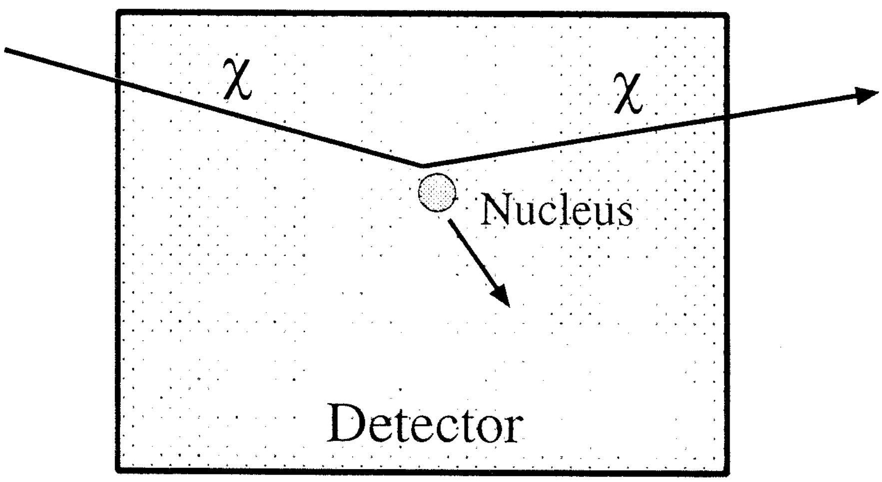
DETECTABILITY OF THE SUSY LSP IN DIRECT AND INDIRECT SEARCHES

$\Downarrow$

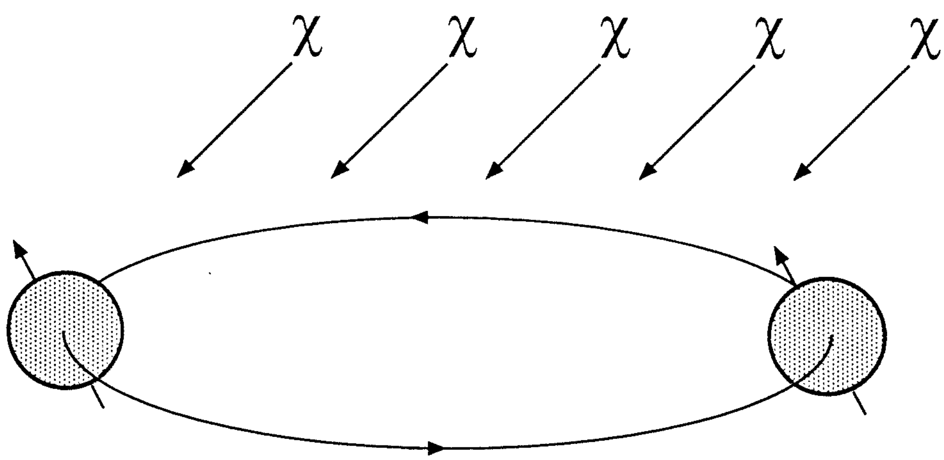
given the existing constraints on the SUSY param. space can we reasonably hope to find LSP signals ?

Direct detection - basic principles

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

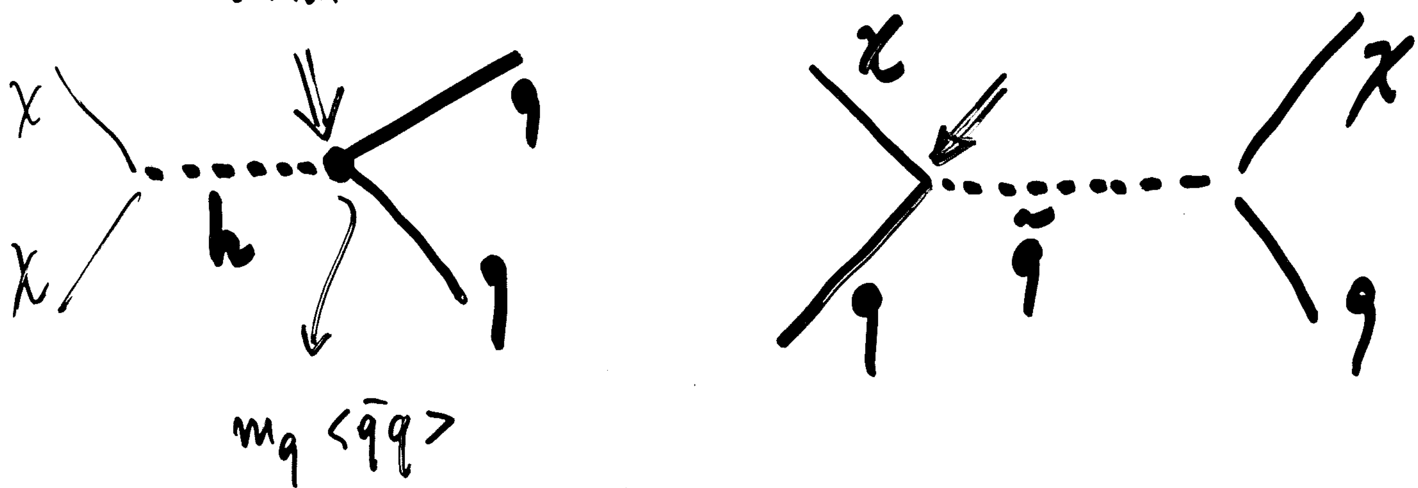


- Search for an annual modulation



FOR DIRECT SEARCHES ⇒ important UNCERTAINTIES

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



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

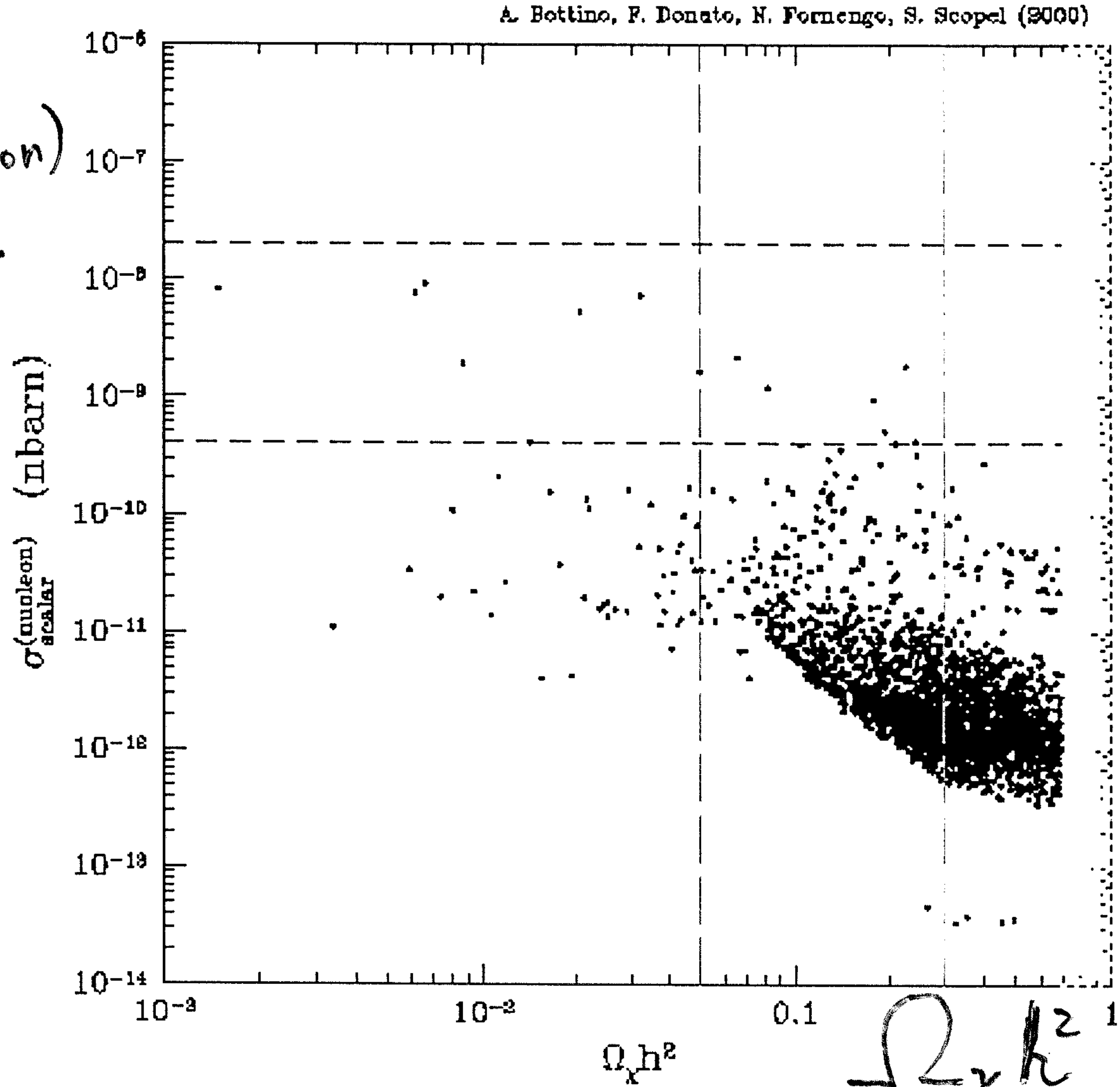


FIG. 1a. Scatter plot of $\sigma^{(\text{nucleon})}_{\text{scalar}}$ versus $\Omega_\chi h^2$ for universal SUGRA. Set 1 for the quantities $m_q < \bar{q}q >$'s is employed. Only configurations with positive μ are shown and m_χ is taken in the range of Eq. (4). The two horizontal lines bracket the sensitivity 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

nuSUGRA

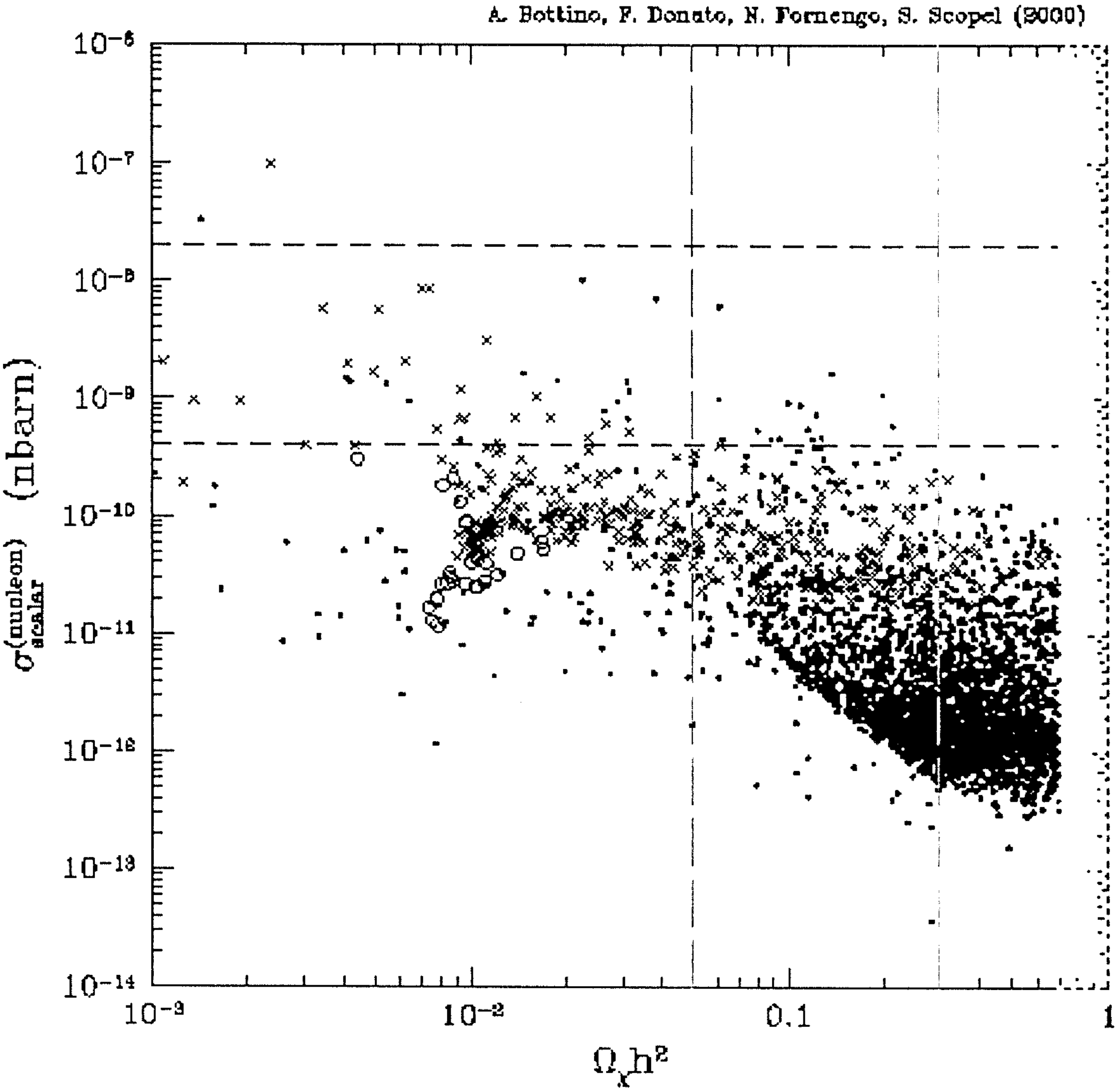


FIG. 1b. Scatter plot of $\sigma^{(\text{nucleon})}_{\text{scalar}}$ versus $\Omega_\chi h^2$ for nuSUGRA. Notations as in Fig. 1a, except that here the scatter plot contains neutralinos of various configurations: dots denote gauginos, circles denote higgsinos and crosses denote mixed configurations.

• gauginos
o higgsinos
x mixed gaugino-higgsino

effMSSM

BOTTINO et al.

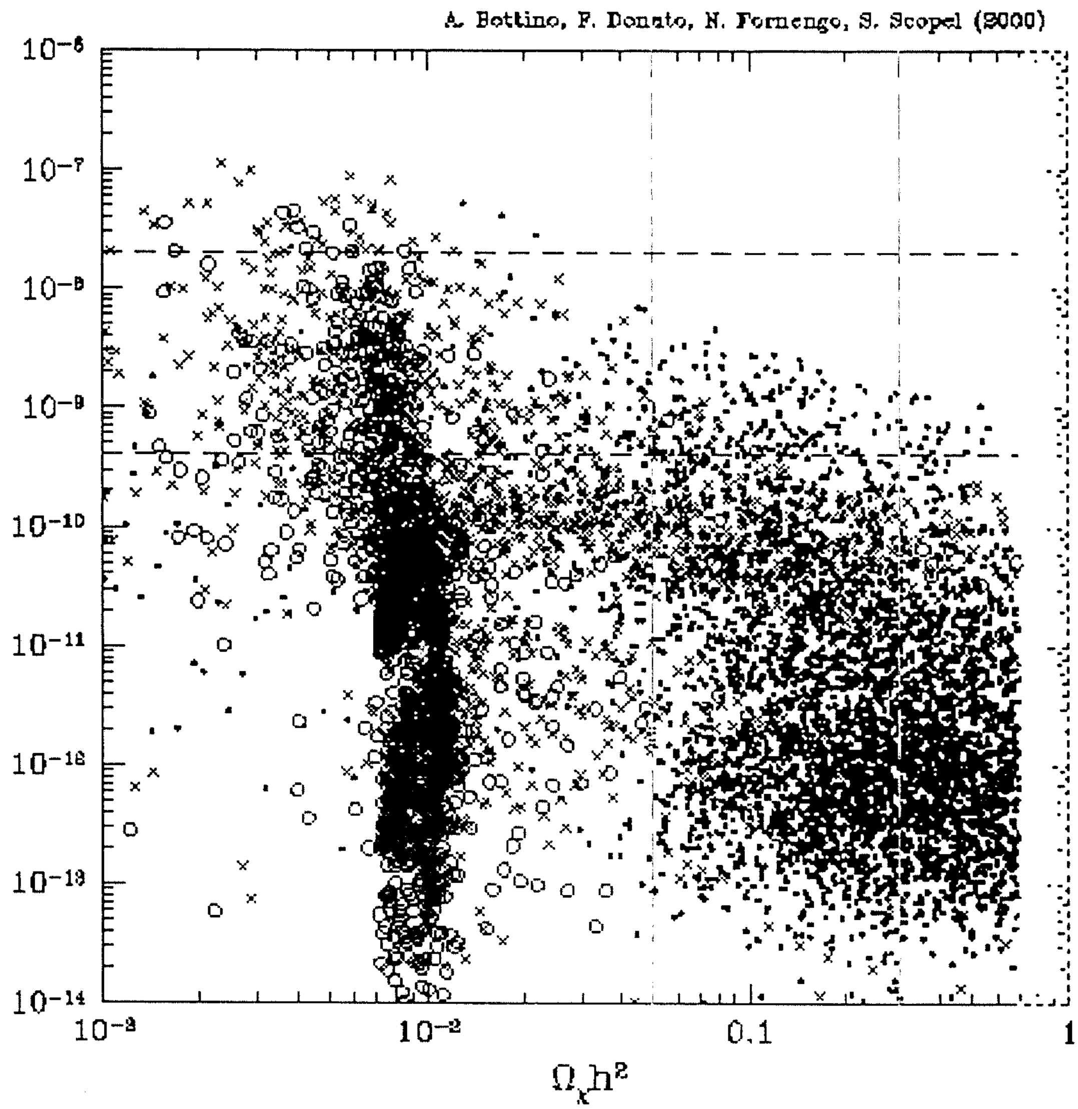


FIG. 1c. Scatter plot of $\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}}$ versus $\Omega_\chi h^2$ for effMSSM. Notations as in Fig. 1b. Both signs of μ are shown.

mSUGRA

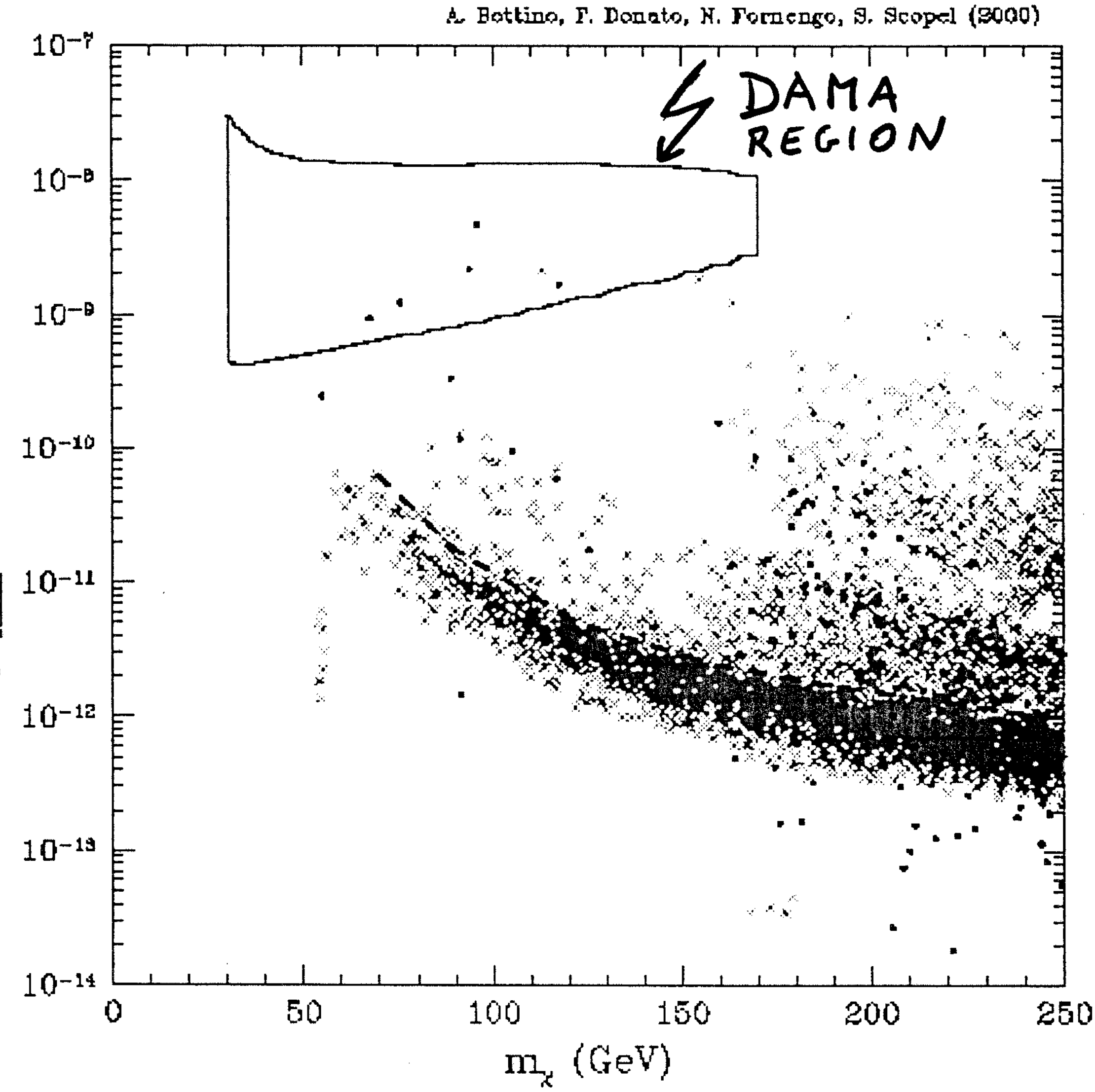


FIG. 5a. Scatter plot of $\xi\sigma_{\rm scalar}^{\rm (nucleon)}$ versus m_χ in case of universal SUGRA. Set 1 for the quantities $m_q < \bar{q}q >$'s is employed. Crosses (dots) denote configurations with $\Omega_\chi h^2 > 0.05$ ($\Omega_\chi h^2 < 0.05$). The dashed line delimits the upper frontier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

× $\Omega h^2 > 0.05$

• $\Omega h^2 < 0.05$

BOTTINO, DONATO, FORNENGO, SCOPEL

effMSSM BOTTINO et al.

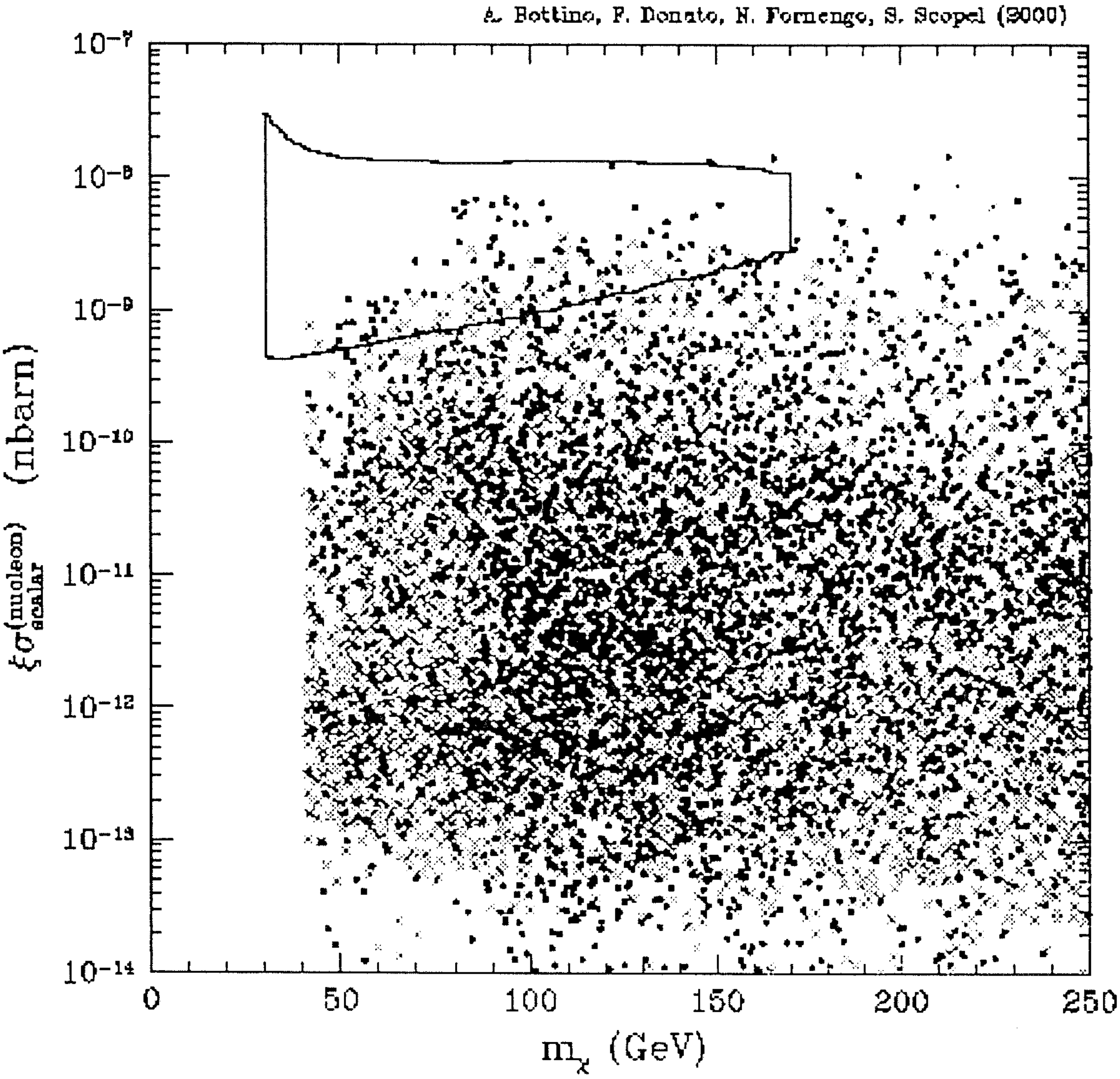
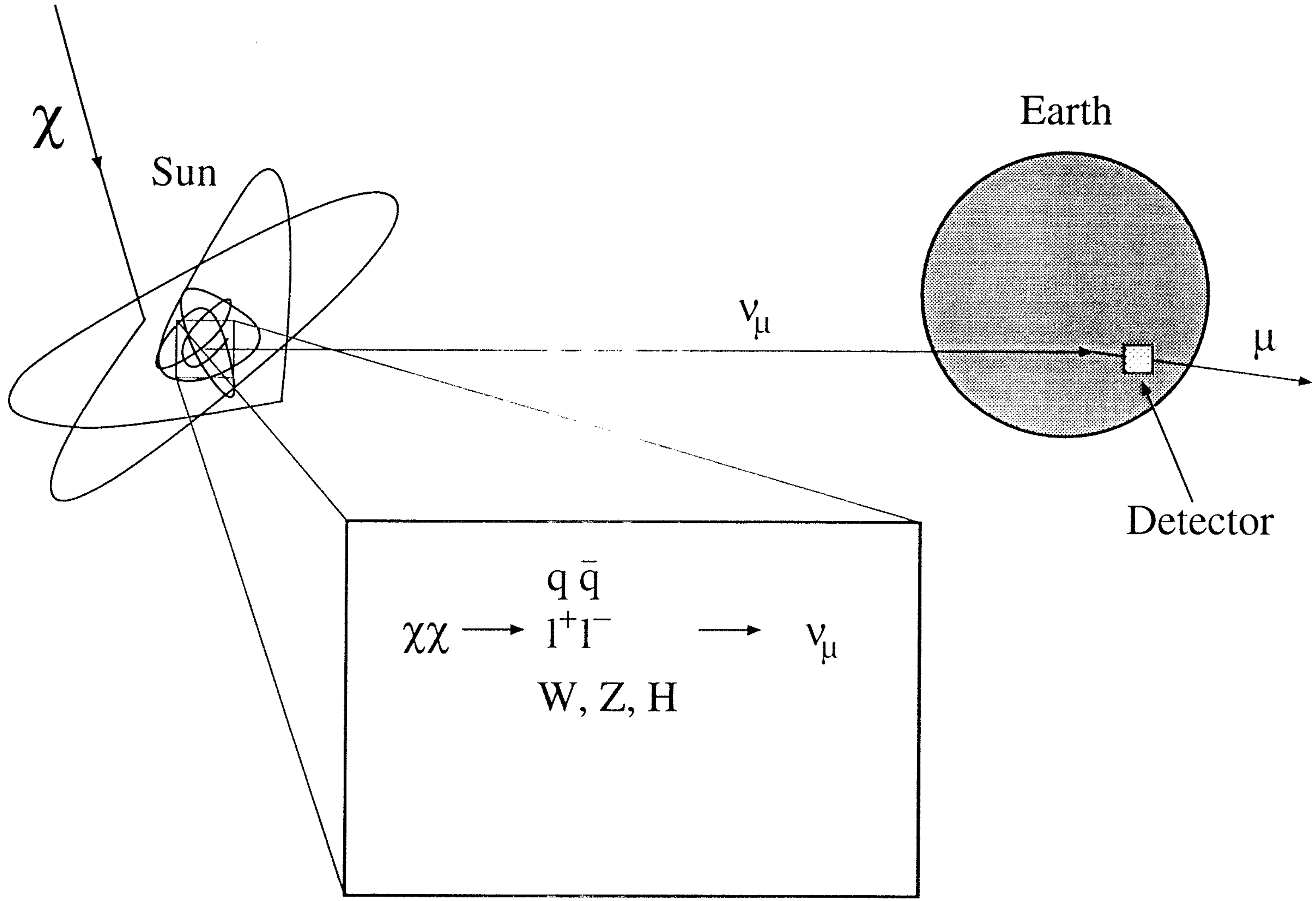


FIG. 5c. Same as in Fig. 5a in case of effMSSM.

× $\Omega h^2 > 0.05$

• $\Omega h^2 < 0.05$

ν telescopes - basics



SEARCH FOR EXOTIC COSMIC RAYS

IN THE HALO

$\chi\chi \longrightarrow$ **SM** PARTICLES

↓ HADRONIZATION AND/OR DECAY

COSMIC RAY SOURCES

LOOK AT: γs, $\bar{p}$, e^+, ν

I.E. SPECIES WITH LOW AND/OR WELL-KNOWN BACKGROUD.

SEARCH FOR ANTIMATTER IN SPACE: AMS, PAMELA

SEARCH FOR γ IN SPACE: AGILE, GLAST

ON SURFACE: MAGIC, HESS, CANGUROO III

SEARCH FOR ν (ice, water): AMANDA, NESTOR ANTARES, NEMO

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

$\bar{p}$, 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

PHOTONS: high-energy γ'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 γ-ray detectors a variety of signals may be considered

γ signal from
- galactic center Berezinski et al.
- galactic halo Bergstrom et
- extra-galactic sources Baltz et al

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

γ 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

INDIRECT SEARCHES

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

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

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

$$\downarrow$$

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

$\rightarrow$ upward-going ν_μ converting to μ producing through-going μ's in detectors

in the next few years $\phi_\mu \sim 10-100\ Km^{-2} yr^{-1}$ 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 χ in the**

MIXED GAUGINO-HIGGSINO DM scenario

Feng et a

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
μ MDM	$\lvert a_\mu^{SUSY}\rvert < 8 \times 10^{-10}$	Brookhaven E821
Direct DM		CDMS (Soudan), Cresst, Dama, ...
ν from Earth	$\Phi_\mu^{\oplus} < 100$ $km^{-2} yr^{-1}$	Amanda, Antares
ν from Sun	$\Phi_\mu^{\odot} < 100$ $km^{-2} yr^{-1}$	" , "
γ (gal. center)	$\Phi_\gamma(1) < 1.5 \times 10^{-10}$ $cm^{-2} s^{-1}$	GLAST
γ (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

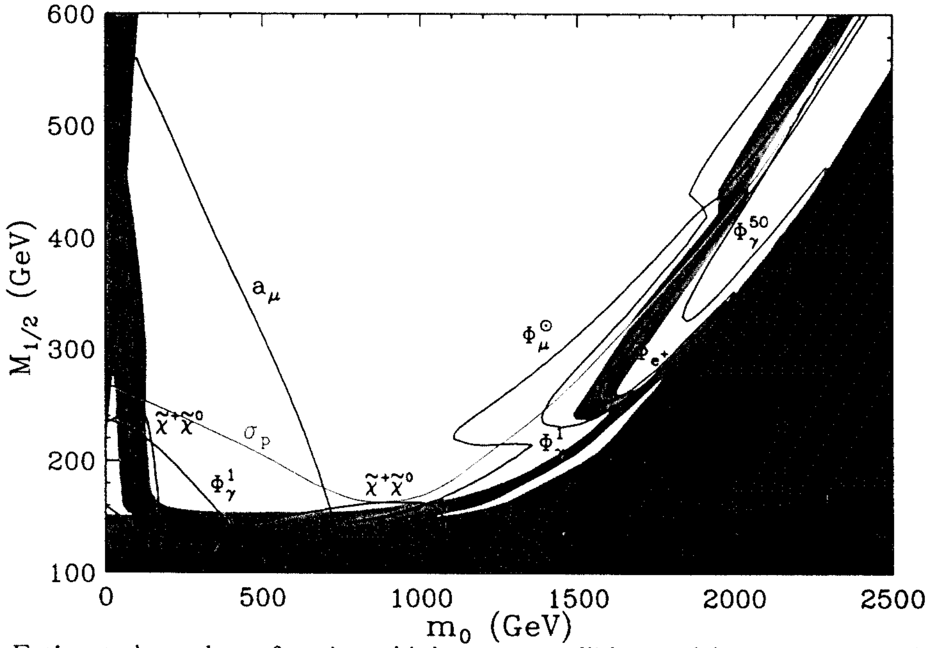


FIG. 18. Estimated reaches of various high-energy collider and low-energy precision searches (black), direct dark matter searches (red), and indirect dark matter searches (blue) before the LHC begins operation, for $\tan\beta = 10$. The projected sensitivities used are given in Table IV. (The LEP chargino 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

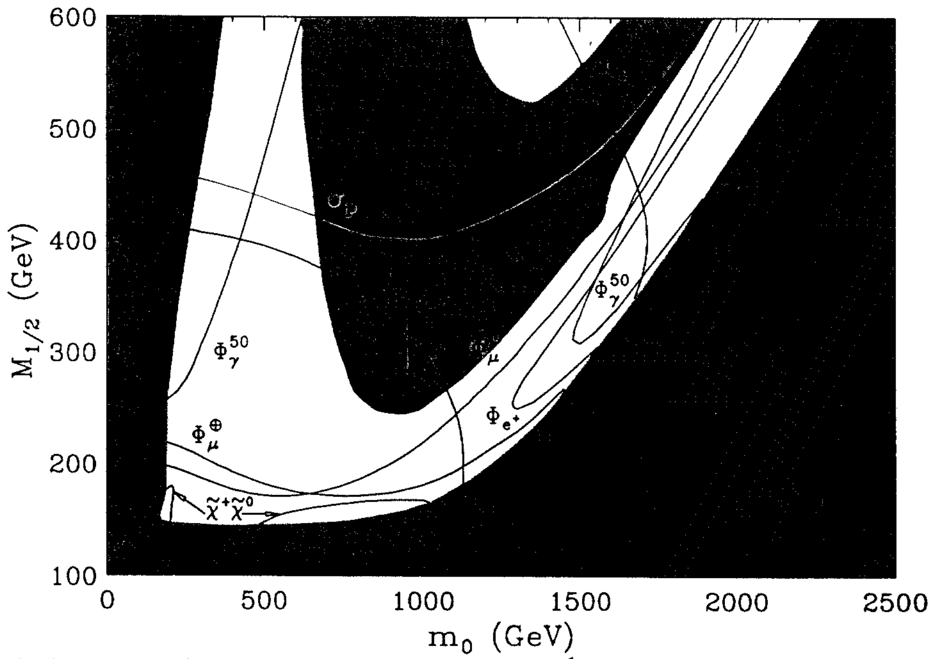


FIG. 19. As in Fig. 18, but for $\tan\beta = 50$. Here the Φ^1_γ probe is sensitive to all of the parameter space shown and so its limit contour does not appear.

THE PROBLEM OF THE COSM. CONST.

Einstein eq.: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G_N T_{\mu\nu} + \lambda g_{\mu\nu}$

$[\lambda] = L^{-2}$

Constraint on λ:

$$\frac{\dot{a}(t)^2}{a(t)^2} = -\frac{k}{a^2} + \frac{1}{3}\left(8\pi G_N \rho + \lambda\right)$$

$\frac{\dot{a}(t)^2}{a(t)^2} \to H^2$

$\frac{k}{a^2} \to$ not a dominant contrib. presently

$\rho \to$ en. density presently $\sim \frac{3 H_0^2}{8\pi G_N}$

$$H_{presently} = H_0 = h_0 \times 100 \text{ Km } s^{-1} \text{ Mpc}^{-1}$$
$$\simeq h_0 \times 10^{-26} \text{ m}^{-1}$$

$|\lambda| \lesssim H_0^2$ $\qquad \frac{1}{|\lambda|^{1/2}} \gtrsim \frac{1}{H_0} = \frac{1}{h_0} \times 10^{26} \text{ m}$

$\Downarrow$

not a problem at the classical level

Quantum level: gravitation + quantum theory

$8\pi G_N \rightarrow$ mass scale $\quad m_P = \sqrt{\frac{\hbar c}{8\pi G_N}} = 2.4 \times 10^{18}\,\mathrm{GeV}$

$$\downarrow$$

$$l_P = \frac{\hbar}{m_P c} = 8 \times 10^{-34}\,\mathrm{m.}$$

$$\Rightarrow \quad \frac{1}{|\lambda|^{1/2}} \gtrsim \frac{1}{H_0} \sim 10^{60}\, l_P$$

$\downarrow$ obvious solution $\rightarrow \lambda = 0$

VACUUM ENERGY PROBLEM

If the vacuum (i.e. ground state) energy is nonzero

$$\langle T_{\mu\nu} \rangle = - \langle \rho \rangle g_{\mu\nu}$$

$$\Rightarrow \quad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = - 8\pi G T_{\mu\nu} + \underbrace{8\pi G_N \langle \rho \rangle g_{\mu\nu}}_{= \lambda_{eff} \equiv \frac{\Lambda^4}{m_P^2}}$$

$$\frac{1}{|\lambda_{eff}|^{1/2}} = \frac{m_P}{\Lambda^2} \gtrsim \frac{1}{H_0} = 10^{60}\, l_P = 10^{60} \frac{1}{m_P} \Longrightarrow$$

$$\Lambda \lesssim 10^{-30} m_P \sim \text{a few } 10^{-3} eV$$

SUSY (global)

$\Rightarrow$ unbroken SUSY

$$\{Q_r, Q_{\bar{s}}\} = 2\gamma^\mu P_\mu \delta_{rs}$$

$$H = \frac{1}{4}\sum_r Q_r^2 \quad ; \quad \langle H \rangle = \frac{1}{4}\sum_r \langle Q_r^2 \rangle = 0$$

$\Rightarrow$ broken SUSY $\quad m_B - m_F \geq O(100\ GeV) = M_{SB}$

$$\Lambda \sim M_{SB} \gtrsim 100\ GeV$$

Local SUSY (supergravity)

$g_{\mu\nu} \longleftrightarrow \psi_\mu$

graviton $\qquad$ gravitino

$m_{3/2} \neq 0 \Rightarrow$ cancellation in the contrib. of the scalar potential

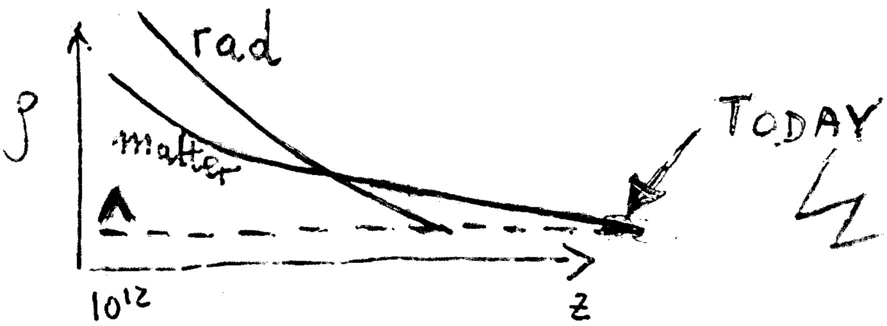
Λ fine-tuned to zero

$\Omega_\Lambda \neq 0$

only a nightmare for
a particle physicist?

i) FIRST CANDIDATE: COSMOLOGICAL CONSTANT

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



why Λ so small*?
why today?

* en. of the vacuum $\sim (0.003\ eV)^4$

ii. SECOND POSSIBILITY:

DYNAMICAL TIME-DEPENDENT AND SPATIALLY INHOM

COMPONENT WITH $\boxed{p = w\rho}$ → $-1 < w < 0$

present data seem to favor $w \sim -0.7$ 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: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

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

↳ 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 BREAKI...

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 ϕ not appearing in V

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

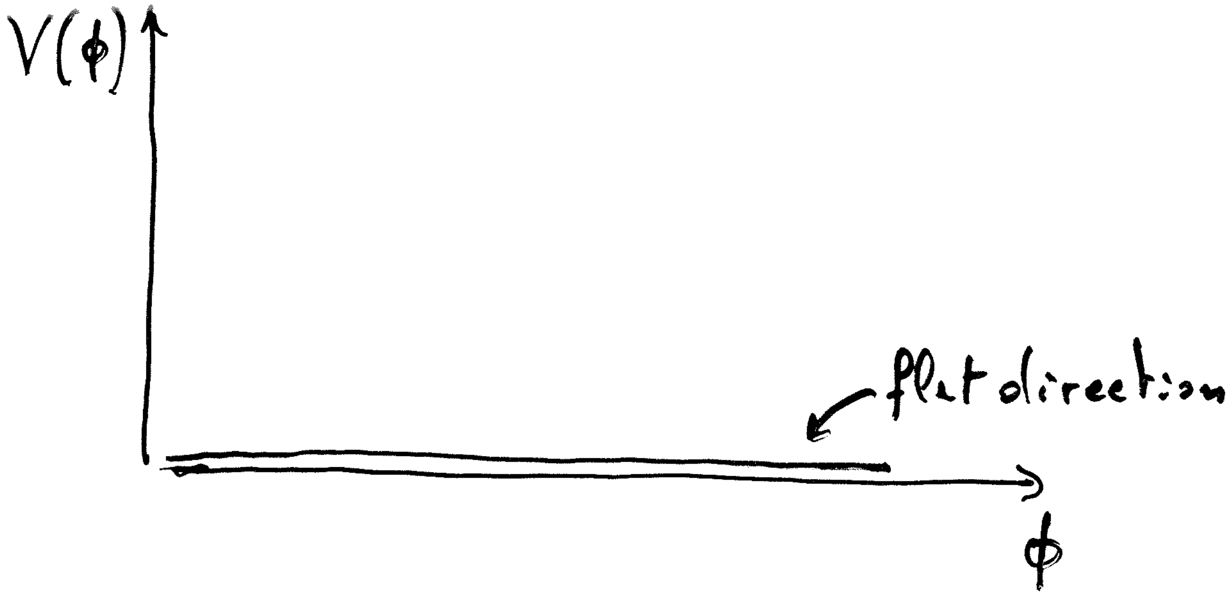
when G interaction strong $\Lambda = M_P \, e^{-\phi/2b_0}$

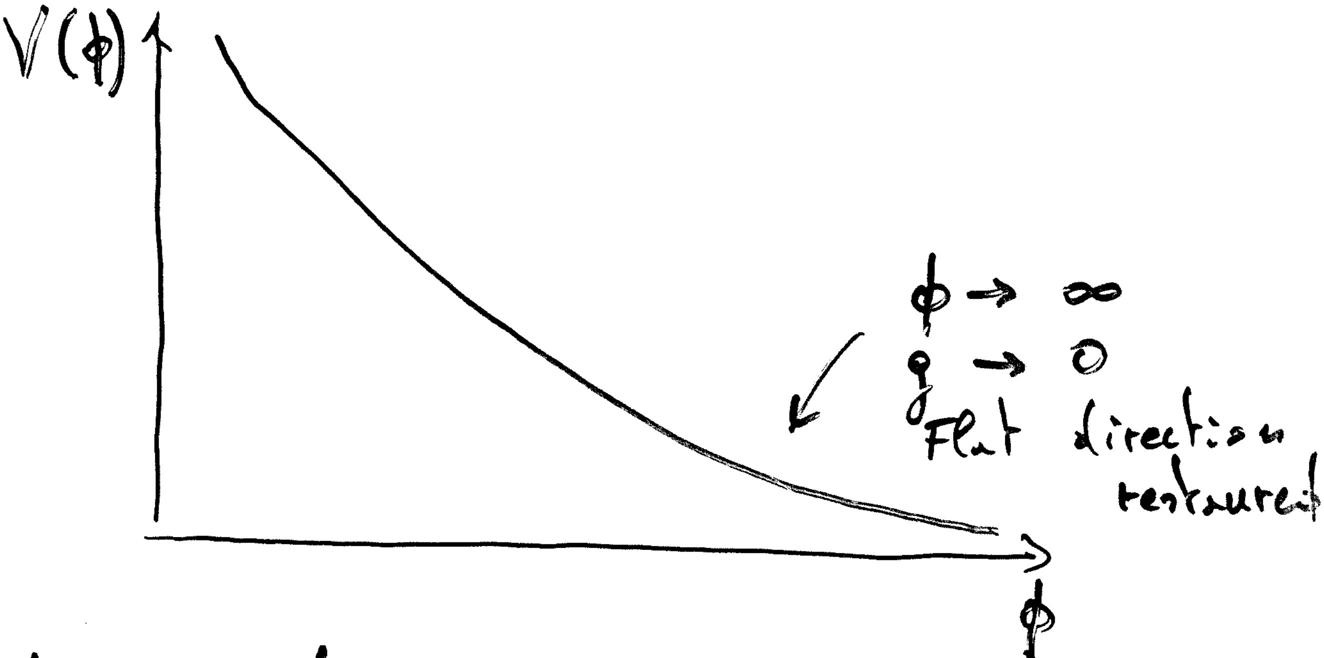
$\Rightarrow \langle \bar\lambda \lambda \rangle = \Lambda^3 = M_P^3 \, e^{-3\phi/2b_0}$

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

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

but w positive !





$$\langle\phi\rangle \sim \frac{1}{\text{coupling}}$$

dynamical breaking of SUSY ⇒ large scale hierarchies

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

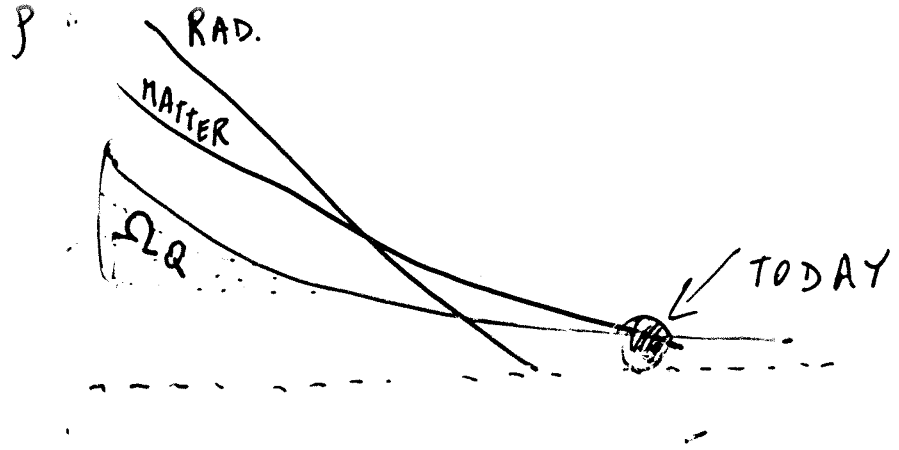
⇓

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

⇒ it would mediate long range interactions of gravitational strength

CARROLL

Bartolo, Pietroni



IF ATTRACTOR SOLUTION

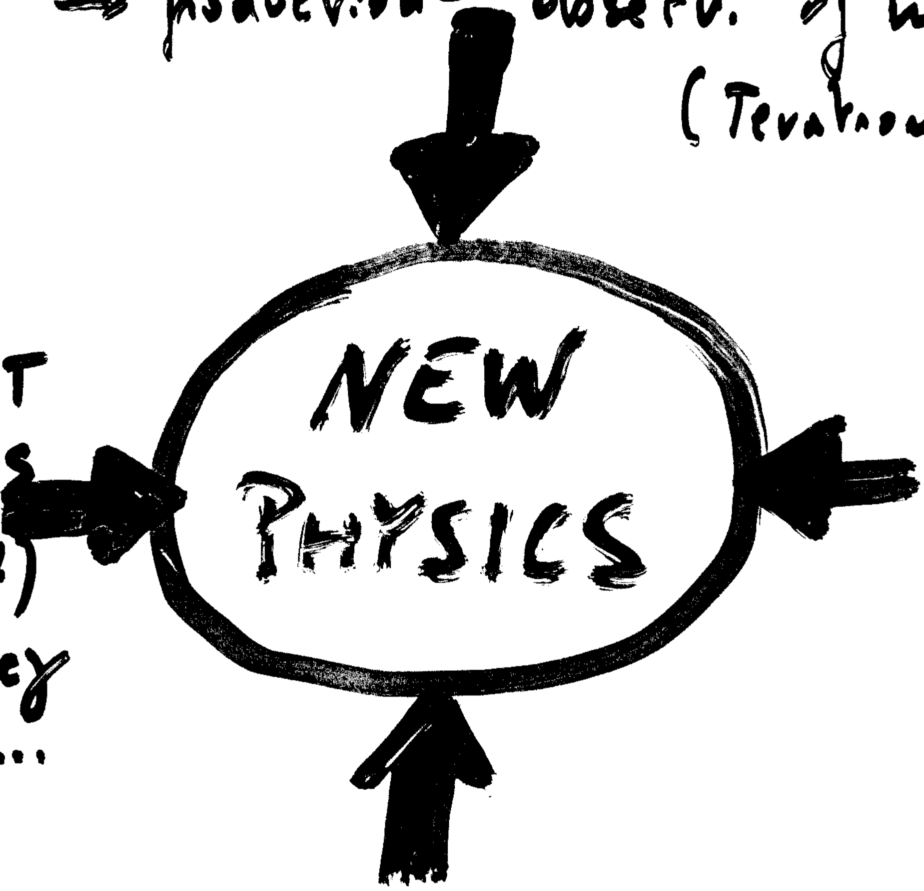
⇒ Q TRACKER FIELD

the field Q is alway "attracted"
to the "right" track leading
to $\Omega_M \sim \Omega_Q$ today

"partial" solution to the
why today problem
still smallness of Λ is an open problem

DIRECT SEARCHES

→ production - observ. of new particles
(Tevatron II - LHC)



INDIRECT SEARCHES
(FCNC, CP̸)
LFV → $\mu \to e\gamma$
d_n^e, d_e^e, ...
B physics

THEOR. PROGRESS
(supergr.
↓
superstrings
M-theory)

ASTROPARTICLE PHYSICS

ν physis

DM direct - indirect searches

cosmic rays

γ - astronomy

→ NEW PHYSICS SIGNALS FROM THE "SKY" BEFORE LHC ?

→ THIS DECADE TO SOLVE "THE ELW. SYMM. BREAKING PUZZLE"