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SMR.1227 - 8

SUMMER SCHOOL ON ASTROPARTICLE PHYSICS AND COSMOLOGY

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DARK MATTER AND PARTICLE PHYSICS

Lecture III

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Please note: These are preliminary notes intended for internal distribution only.

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A. MASIERO

MINIMAL SUSY SM (MSSM)

ALL RUNNING PARAMETERS in $\mathcal{L}_{soft}$ PARAMETRIZED AT SOME CUT-OFF SCALE Λ CLOSE TO M_P by:

UNIVERSAL GAUGINO MASS $m_{1/2}$

UNIVERSAL SCALAR MASS m_0

UNIVERSAL TRILINEAR SCALAR COUPLING A_0

PARAMETERS at M_X : $m_{1/2}, m_0, A_0, B_0, \mu_0$

$\Downarrow$

they account for the masses of 31 new particles !

WHAT IS THE MSSM ?

⇓

MINIMAL (R-PARITY IS IMPOSED)

UNIVERSALITY
+
MASS AND COUPLING RELATIONS AT M_{GUT}

⇓

5 NEW INDEPENDENT PARAM.

m_0, M, μ, A, B

\+ ⇓

ELECTROWEAK RADIATIVE BREAKING

4 INDEPENDENT PARAM..

Ex: $m_0, M, \tan\beta, A$

MINIMAL NUMBER OF SUPERFIELDS TO SUPERSYMMETRI[ZE] THE SM

BUT MASSES AND COUPLINGS AT LOW ENERGY ARE CONSIDERED AS UNRELATED PARA[M]

↓

PHENOMENOLOGICA[L] APPROACH

PRESENT DIRECT LOWER LIMITS ON

SUSY MASSES

$m_A > 62.5$ GeV $m_h > 70.7$ GeV (for large m_A)

$m_{\tilde{\chi}^+} > 91$ GeV, $m_{\tilde{e}} > 76$ GeV, $m_{\tilde{\mu}} > 59$ GeV, $m_{\tilde{\tau}} > 53$ GeV

$m_{\tilde{t}} > 65$ GeV (for light χ^0, $m_{\tilde{t}} > 95$ GeV)

$m_{\tilde{q}_{1,2}} > 210$ GeV, $m_{\tilde{g}} > 173$ GeV

HOW LARGE CAN SUSY MASSES BE ?

i.e. **WHEN SHOULD ONE GIVE UP WITH SUSY ?**

relation between ELW. SCALE AND SUSY PARAM:

$$m_Z^2 = \frac{2}{tg^2\beta - 1}\left(m_{H_1}^2 - |\mu|^2 - \left(m_{H_2}^2 + |\mu|^2\right) tg^2\beta\right)$$

$\downarrow$ **RG**

$$m_Z^2 \simeq \overset{0.5}{a_{H_1}} m_{H_1}^2(M_{GUT}) + \overset{1.5}{a_{H_2}} m_{H_2}^2(M_{GUT}) + \overset{1.1}{a_{QU}}\left[(M_Q^2)_{33}(M_{GUT}) + (M_{\tilde{U}^c}^2)_{33}(M_{GUT})\right] + \underset{0.2}{a_{AA}}\left[A_U^{33}(M_{GUT})\right]^2 + \underset{0.7}{a}\, m_{1/2}^2(M_{GUT}) + \underset{10.5}{a_{AM}} A_U^{33} m_{1/2}(M_{GUT})$$

$$m_Z^2 = \frac{2}{tg^2\beta - 1}\left(m_{H_1}^2 + |\mu|^2 - \left(m_{H_2}^2 + |\mu|^2\right) tg^2\beta\right)$$

$$\Big\downarrow \textbf{RG}$$

$$m_Z^2 \simeq \overset{0.5}{a_{H_1}}\, m_{H_1}^2(M_{GUT}) + \overset{1.5}{a_{H_2}}\, m_{H_2}^2(M_{GUT})$$

$$+ \overset{1.1}{a_{QU}}\left[(M_Q^2)_{33}(M_{GUT}) + (M_{\tilde{U}^c}^2)_{33}(M_{GUT})\right]$$

$$- 2\,|\mu(M_Z)|^2 + \overset{0.2}{a_{AA}}\left[A_U^{33}(M_{GUT})\right]^2$$

$$+ \overset{-0.7}{a_{AM}}\, A_U^{33}(M_{GUT})\, m_{1/2}(M_{GUT})$$

$$+ \overset{10.8}{a_{MM}}\, m_{1/2}^2(M_{GUT})$$

Misiak, Pokorski, Rosiek

valori dei coeff. a per $m_t = 175$ GeV e $tg\beta = 2.2$

$\Rightarrow$ il fine-tuning diventa sempre più grande quanto maggiore è $m_{1/2}$ e $(M_Q^2)_{33}$

$\Rightarrow$ chargino leggero, stop leggero ?

inoltre $m_{\tilde{q}}$ prime 2 generaz. può esser gran

SUPERSYMMETRIC GRAND UNIFICATION

In non-susy SU(5) the main problems are:

- too fast p-decay
- too small predicted value of $\sin^2\theta_W(m_Z)$
- gauge hierarchy problem $\begin{cases} - v \ll M_U \\ - \text{instability of } v \ll M_U \end{cases}$

Simplest SUSY GUT: minimal SUSY SU(5) — Dimopoulos, Georgi, Sakai

ordinary SU(5) particles + partners

Higgs superfields : $H_5 \quad \bar{H}_{\bar{5}} \quad \Sigma_{24}$

$$SU(5) \xrightarrow{\langle\Sigma\rangle} SU(3)\times SU(2)\times U(1) \xrightarrow{\langle H\rangle\langle\bar{H}\rangle} SU(3)_c \times U(1)_{em}$$

problem : DOUBLET-TRIPLET SPLITTING

$$H \to H_3\,(3,1,-1/3) + H_2\,(1,2,+1/2)$$

$$\bar{H} \to \bar{H}_3\,(\bar{3},1,+1/3) + \bar{H}_2\,(1,2,-1/2)$$

$\bar{H}_3(\bar{3},1,+1/3)$: this multiplet must be heavy — p-decay

$\bar{H}_2(1,2,-1/2)$: this has to be light — $\langle H_2\rangle, \langle \bar{H}_2\rangle$ break $SU(2)\times U(1)$

In minimal SUSY SU(5) need FINE-TUNING to split doublets from triplets (however, given the presence of SUSY this fine-tuning is stable under radiative corrections)

in non-minimal SUSY GUT's it is possible to avoid this fine-tuning (however, price to pay: complicat. of the models ...)

RUNNING OF $\alpha_1, \alpha_2, \alpha_3$ including in the b_1, b_2, b_3 coeff. of the β functions the contribution of the SUSY particles (for simplicity one assumes they all have a similar mass of $O(1\,\text{TeV})$ – in any case what is relevant is that all of them have mass $M_{susy} > m_Z$)

Input : $\alpha_{em}(m_Z)$, $\alpha_3(m_Z)$

Output : α_U, M_U, $\sin^2\theta_W(m_Z)$

non-SUSY SU(5)

$$\Rightarrow \begin{cases} \alpha_U \sim 1/24 & \longrightarrow \quad 1/45 \\ M_U \sim 2\cdot 10^{16} & \longrightarrow \quad 10^{14} \\ \sin^2\theta_W(m_Z) \simeq 0.23 & \longrightarrow \quad 0.21 \end{cases}$$

- slower p-decay from dim6 op. with intermediate gauge bosons

- "correct" $\sin^2\theta_W$

↘ **the 3 curves of $\alpha_1, \alpha_2, \alpha_3$ now actually "meet" at one point**

problems with precise evaluation on $\sin^2\theta_W$ (i.e. to what degree where the curves meet is really a point)

- threshold effects at the GUT scale
  small in minimal SU(5), but there is a much more complicated structure in realistic SUSY GUTs
- threshold effects at the elw scale → if some SUSY part. at m_Z one-step approx. is insuff. → need full one-loop computation ...
- $M_{GUT} \sim 10^{16}$, $M_{string} \sim 4\cdot 10^{17}$ GeV; $M_P \sim 2\cdot 10^{18}$ GeV !

HINT FOR SUSY FROM GRAND UNIFICATION

Langacker, Amaldi et al, Ellis et al

LEPEWWG: $\alpha_s(m_Z) = 0.120 \pm 0.003$

World average PDG: $\alpha_s(m_Z) = 0.118 \pm 0.003$

use $\sin^2\theta_W$ as input ⇒ asking for GU predict $\alpha_s(m_Z)$

SM + big desert ⇒ $\alpha_s(m_Z) = 0.073 \pm 0.002$

CMSSM susy masses ≤ 1 TeV $\alpha_s(m_Z) \geq 0.126$

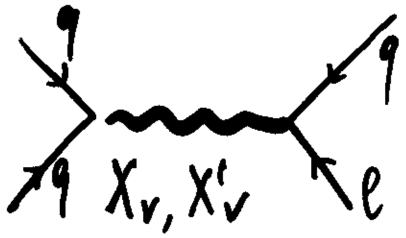
⇒ but possible corrections from GUT thresholds

ex: SU(5) with missing doublet mechanism

some SO(10) schemes

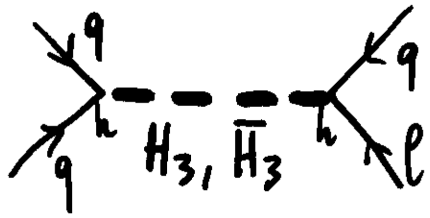
Bagger, Matchev, Pierce; Dedes, Lahanas, Rizos, Tamvakis; Lucas, Raby.

PROTON DECAY IN SUSY GUTS



since now $M_U \sim 10^{16}$ $\tau_p \to \frac{1}{M_U^4}$

$p \to e^+ \pi^0$ undetectable

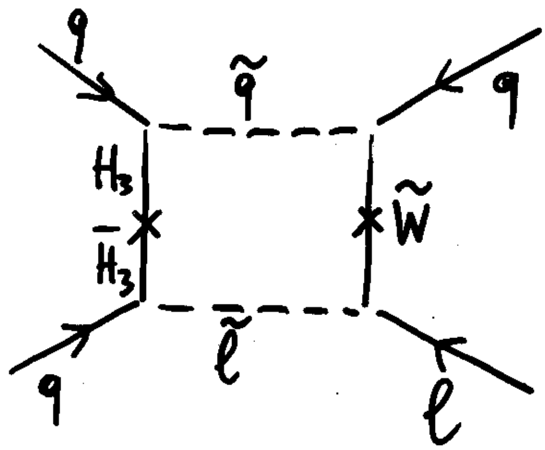


$\to \frac{h^2}{M_H^2}$ if $M_H \sim M_U$

$p \to \mu^+ K^0, \bar{\nu}_\mu K^+$ undetectable

BUT DIM=5 OP.

$\underbrace{q q \tilde{q} \tilde{l}}_{\text{dim 5}}$



$p \to K^+ \bar{\nu}_\mu$

$\Gamma \sim \left(\frac{g^2 h^2}{M_H M_{SUSY}} \right)^2$

⇒ precise prediction is quite model-dependent (in particular, for a given model, the result depends on the region of param. space which is considered – for instance important dependence on $\tan\beta$, $m_{\tilde{W}}$, ...)

⇒ IN ANY CASE DIM=5 OP. ARE DANGEROUS

possibility of getting rid of them with additional symm.

THE FATE OF LEPTON NUMBER

L VIOLATED
↓
ν Majorana ferm.

L CONSERVED
↓
ν Dirac ferm.
(dull option)

$h\,\bar{\nu}_L \Phi \nu_R \Rightarrow m_\nu = h \langle \Phi \rangle$

$m_\nu < 5\ eV \Rightarrow h < 10^{-11}$

SMALLNESS of m_ν
↓
PRESENCE OF A **NEW** PHYSICAL MASS SCALE

NEW HIGH SCALE — NEW LOW SCALE

SEE-SAW MECHAN.
↓ Gell-Mann, Ramond, Slansky, Yanagida
ENLARGEMENT OF THE FERMIONIC SPECTRUM (ν_R)

$M \nu_R \nu_R + h\,\bar{\nu}_L \Phi \nu_R$

	ν_L	ν_R
ν_L	~ 0	$h \langle \Phi \rangle$
ν_R	$h \langle \Phi \rangle$	M

LR models?

MAJORON MODELS
↓ Gelmini, Roncadelli
ENLARGEMENT OF THE HIGGS SCALAR SECTOR (Δ)

$h\, \nu_L \nu_L \Delta$

$m_\nu = h \langle \Delta \rangle$

N.B.: EXCLUDED BY LEP

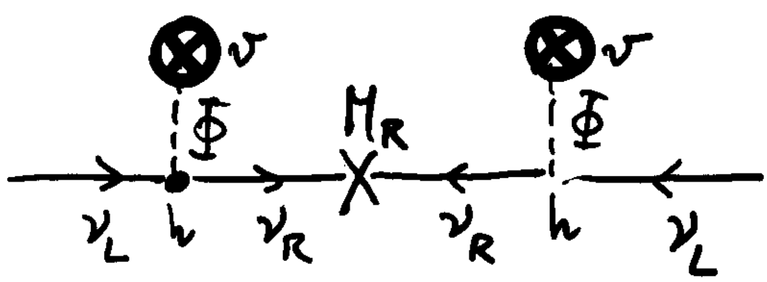
THE SEE-SAW MECHANISM

ν_L **AND** ν_R $\rightarrow$ $m_D \, \bar{\nu}_L \nu_R$ Dirac mass does not violate L

if one allows for L violation

$$\Rightarrow \begin{cases} \lambda \dfrac{\nu_L \nu_L \langle\phi\rangle\langle\phi\rangle}{M} \Rightarrow m_L \sim \dfrac{\lambda v^2}{M} & \text{Majorana } \nu_L \nu_L \\ M_R \nu_R \nu_R \Rightarrow \text{Majorana } \nu_R \nu_R & \end{cases}$$

$\Rightarrow$



$h \, \bar{\nu}_R \nu_L \Phi$

$$\begin{cases} m_D = h v \\ m_L \sim h^2 v^2 / M_R \\ m_R \sim M_R \end{cases}$$

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & h^2 v^2 / M_R & h v \\ \nu_R & h v & M_R \end{array}$$

//

ν as HDM

- consider $m_\nu < 1$ MeV and ν stable
  $\downarrow$ it decouples when still relativistic

if $m_\nu < 10^{-4}$ eV $\rightarrow$ ν still relativistic today

if $m_\nu > 10^{-4}$ eV $\rightarrow$ $\rho_\nu = m_\nu \, n_\nu$

- n_ν determined by $T^\nu_{decoupling}$
  $\rightarrow$ weak interactions

$T^\nu_{dec} > m_e$ $\Rightarrow$ relic ν slightly colder than relic γ

$$\rightarrow n_\nu = \frac{3}{22} \, g_\nu \, n_\gamma \qquad \left(g_\nu = \begin{cases} 2 & \text{Major} \\ 4 & \text{Dirac} \end{cases} \right)$$

$\Downarrow$

$$\Omega_\nu \equiv \frac{\rho_\nu}{\rho_c} = \underline{0.01} \times m_\nu(\text{eV}) \, h_0^{-2} \left(\frac{g_\nu}{2}\right)\left(\frac{T_0}{2.7}\right)$$

$0.4 < h_0 < 0.9$

$\Omega_{LUM} \lesssim 0.01$

LIGHT ν AS HDM

$$\Omega_\nu h^2 \sim \frac{m_\nu}{90\,\mathrm{eV}}$$

→ few eV ν fine to obtain $\Omega_{DM} \sim 0.1 - 1$

PROBLEMS: a) impossible for ν to form the dark haloes of dwarf galaxies (phase space dens. of ν limited by Fermi statistics)

b) light ν are HOT: still relativistic when galaxy formation could have begun (causal horizon contained about 1 galactic mass) ⇒ hot DM has a large free-streaming length which tends to smear out primordial density perturbations until ν slow down enough

⇒ first superlarge structures form → too few old galaxies

→ cosmic strings as "seeds" of perturbations ?

Albrecht and Stebbins

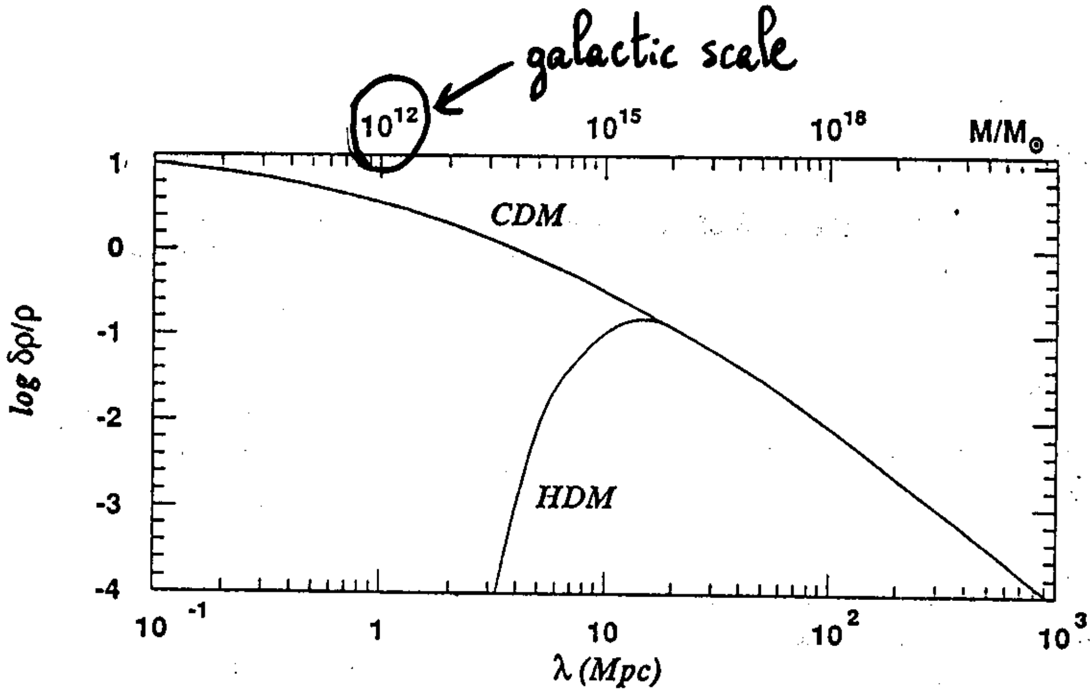


Fig.2

The spectrum of perturbations at the present epoch $t = t_0$ normalized according to COBE data. The HDM curve is for Hot Dark Matter (neutrino) and CDM is for Cold Dark Matter. Note that the maximum amplitude for HDM is ~ 0.1, which is smaller than needed for the beginning of the nonlinear stage of evolution. For CDM the amplitude for the galactic scale $M \sim 10^{12} M_\odot$ is larger than one.

THE STANDARD COLD DARK MATTER (CDM) MODEL

$\Omega = 1$; $\Omega_{CDM} \sim 90-95\%$

$\Omega_B \sim 5-10\%$; $\Omega_{\gamma,\nu} < 1\%$

seed fluctuations are generated during inflation and with a scale-invariant spectrum

$\lambda_{EQ} \simeq 30\,(\Omega h^2)^{-1}$ Mpc

↳ scale at which $\rho_{matter} = \rho_{radiation}$

PROBLEM: with the normalization fixed at COBE data

⇒ THE STANDARD CDM MODEL PREDICTS MORE POWER AT SMALL SCALES THAN OBSERVED (see fig.)

(λ_{EQ} relatively small)

Albrecht + Stebbins

16.

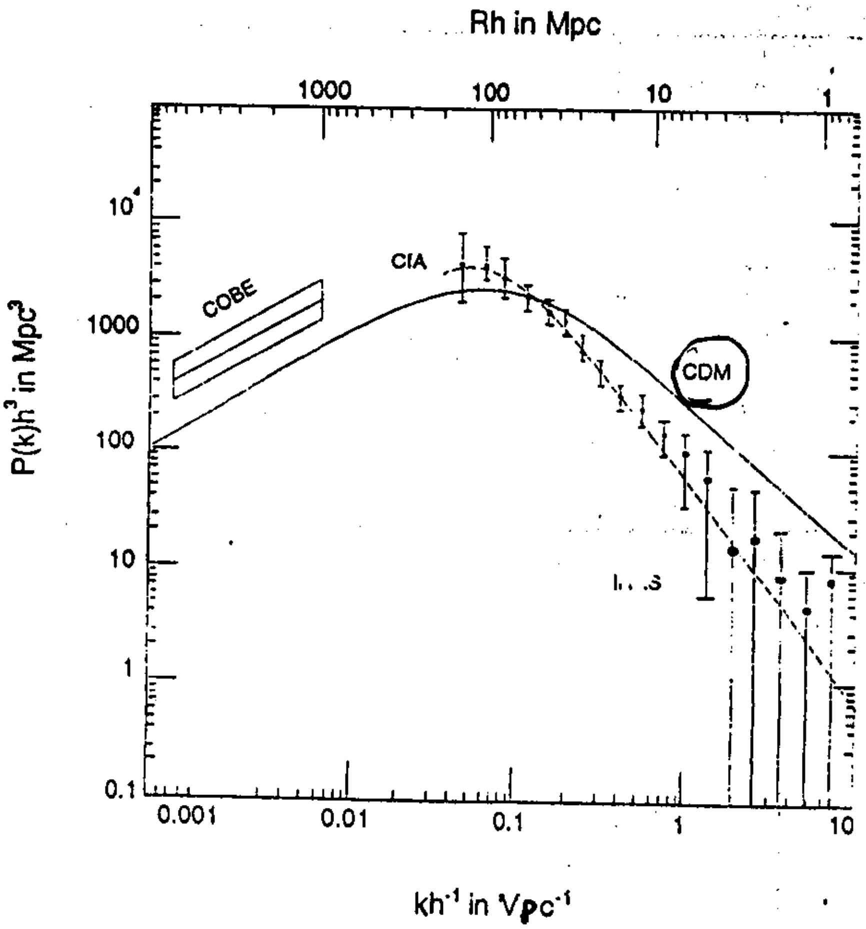


Fig.5

The simulated CDM spectrum of perturbations (solid curve) in comparison with observational data (COBE, IRAS and CfA - the dashed curve)[19]. By changing the normalization of CDM spectrum it is impossible to avoid the conflict with COBE or IRAS + CfA data.

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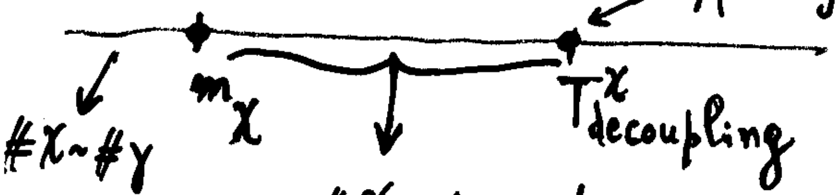
BEST "THERMAL" CDM CANDIDATES ⇒ WIMPS (weakly interacting part.)

↓ particles at one time in thermal equilibrium

(best "non-thermal" CDM candidates : axions, superheavy relic part.)
Chung, Kolb, Riotto ; Ellis, Nanopoulos et al.

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



$\#\chi$ does not change any mor

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

$\rho_\chi = m_\chi n_\chi$
↳ $\propto \frac{1}{\sigma_{annih}(\chi\chi \to ...}$

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

Ω_χ depends on particle physics (σ_{annih}) + T_0 + M_{Planck}

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

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

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

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

WIMPs AS CDM

WIMPs ↓ weakly interacting massive particles

$$\Omega_{WIMP} h^2 \simeq \frac{0.1\,\text{pb} \cdot c}{\langle \sigma_A v \rangle} \quad *$$

σ_A = total annihilation cross section of a pair of wimps into SM particles

v = relative velocity between the two WIMPs in their cms system

$\langle\ \rangle$ thermal average

* from: $\Gamma = n_{WIMP} \langle \sigma_A v \rangle$ compared to H

$T_{decoupl} \sim m_{WIMP}/20$

WIMP
- direct searches : scattering off nuclei in a detector; en. deposition (tens of) keV *
- indirect searches : WIMP capture in celestial bodies; annihilation → emission of neutrinos

* annual modulation signature (DAMA hint)

WIMP CANDIDATES

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

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

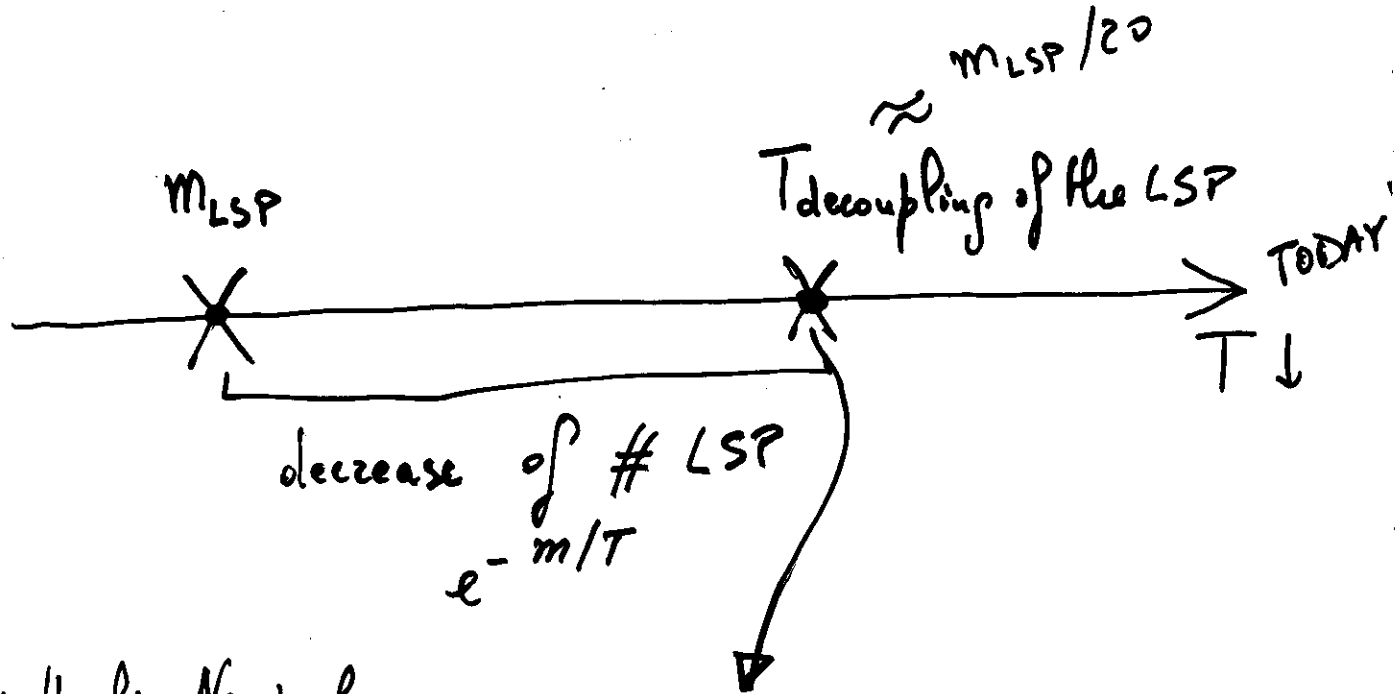
if the SU(2) doublet heavy ν mixes with some "sterile" $SU(2) \times U(1)$ singlet $\Rightarrow$ reduction of $Z-\nu_{heavy}$ coupling but cumbersome schemes

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

THE IMPORTANCE OF BEING THE LSP (Lightest Susy Particle)

or

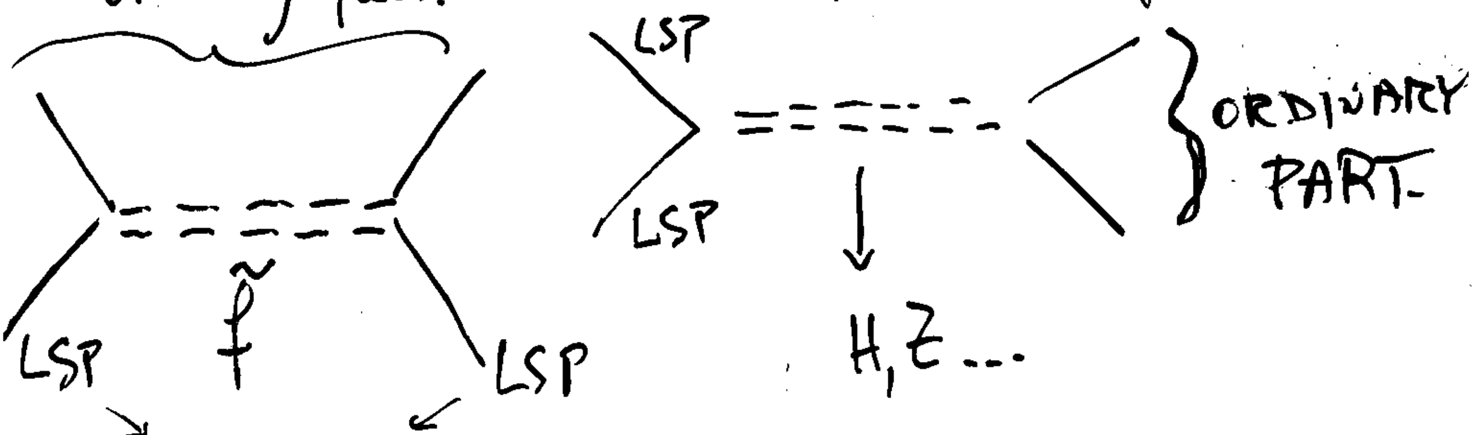
SHORT STORY OF THE LSP's



Ellis, Hagelin, Nanopoulos, Olive, Srednicki

to determine $T_{decoupl.}$

computation of annihi. rate



particularly important for LSP gaugino

MSSM minimal supersymm. standard model) where ... R is imposed

NEUTRALINO

or

the most promising CDM candidate

NEUTRALINOS → EIGENVECTORS OF THE

$\tilde{W}_3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0$ MASS MATRIX

LSP → Lightest Neutralino χ

$\tilde{W}_3 \tilde{W}_3 M_2$ $\quad \tilde{B}\tilde{B} M_1$ $\quad \tilde{H}_1^0 \tilde{H}_2^0 \mu$

$\tilde{W}_3 \tilde{H}_1^0 m_Z \cos\theta_W \cos\beta$ $\quad \tilde{W}_3 \tilde{H}_2^0 m_Z \cos\theta_W \sin\beta$

$\tilde{B} \tilde{H}_1^0 m_Z \sin\theta_W \cos\beta$ $\quad \tilde{B} \tilde{H}_2^0 m_Z \sin\theta_W \sin\beta$

$tg\beta \equiv \frac{v_2}{v_1}$

$m_t = h_t v_2$

IF one assumes $M_1 = M_2 = M_3$ at GUT scale

$\Rightarrow M_1 \simeq M_2/2 \qquad M_2 \simeq m_{\tilde{g}}/3$

+ UNIVERSALITY + ELW. RADIATIVE BREAKING

$\Rightarrow tg\beta, \mu, M_2$

exp: $\boxed{m_\chi > 40 \text{ GeV}}$ (in particular relevant constraint from $M_{\chi^\pm} > 91$ GeV)

$$\left(\tilde{W}_3 \tilde{W}_3 M_2\right) \quad \left(\tilde{B}\tilde{B} M_1\right) \quad \left(\tilde{H}^\circ_1 \tilde{H}^\circ_2 \mu\right)$$

$\tilde{W}_3 \tilde{H}^\circ_1 \; m_Z \cos\theta_W \; \underline{\underline{\cos\beta}}$ $\qquad$ $\tilde{W}_3 \tilde{H}^\circ_2 \; m_Z \cos\theta \; \underline{\underline{\sin\beta}}$

$\tilde{B} \tilde{H}^\circ_1 \; m_Z \sin\theta_W \; \underline{\underline{\cos\beta}}$ $\qquad$ $\tilde{B} \tilde{H}^\circ_2 \; m_Z \sin\theta \; \underline{\underline{\sin\beta}}$

$$\boxed{tg\,\beta \equiv \frac{v_2}{v_1}}$$

$v_2 \to m_t = h_t v_2$

$v_1 \to m_b = h_b v_1$

M_1 and M_2 are two independent parameters, but **IF** one assumes there is a GUT and at the GUT scale $M_1 = M_2 = M_3$, then at M_W.

$$\boxed{M_1 = \frac{5}{3} tg^2\theta_W M_2 \simeq \frac{M_2}{2}} \; ; \quad \boxed{M_2 = \frac{g_2^2}{g_3^2} m_{\tilde{g}} \simeq \frac{m_{\tilde{g}}}{3}}$$

$$\tilde{B}^0 \quad \tilde{W}_3 \qquad \tilde{H}_1^0 \quad \tilde{H}_2^0$$

neutral gauginos — M_1, M_2 — neutral higgsinos — μ

A) $|\mu| > M_1, M_2$ — χ^0 (lightest neutralino) $\sim$ gaugino

if $M_1 > M_2 \rightarrow \chi^0 \sim \tilde{B}$ bino

$Z - \chi^0 - \chi^0 \propto$ square of small higgsino component

$H - \chi^0 - \chi^0 \propto$ linear in the " " "

$\chi^0 - f - \tilde{f} \propto$ full $U(1)_Y$ gauge strength

unless $m_{\chi^0} \sim \frac{m_Z}{2}$ or $m_{\chi^0} \sim \frac{m_H}{2}$ $\Rightarrow$ annihilation through $\tilde{f}$ exchange

$\tilde{l}_R$ " dominates

$$\Omega_{\chi} h^2 \simeq \frac{\left(m_{\chi^0}^2 + m_{\tilde{l}_R}^2\right)^2}{(1\,\mathrm{TeV})^2\, m_{\chi^0}^2} \; \frac{1}{\left(1 - \frac{m_{\chi^0}^2}{m_{\chi^0}^2 + m_{\tilde{l}_R}^2}\right)^2 + \frac{m_{\chi^0}^4}{\left(m_{\chi^0}^2 + m_{\tilde{l}_R}^2\right)^2}}$$

$\hookrightarrow \sim O(1)$ **for reasonable SUSY param.!**

if $M_1^2, M_2^2 \gg \mu^2 \Rightarrow$ LSP HIGGSINO

$$\chi_1^0 \simeq \frac{1}{\sqrt{2}}\left(\tilde{h}_1^0 - \text{sign}(\mu)\,\tilde{h}_2^0\right) \qquad (M_1, M_2 \to \infty)$$

$\rightarrow$ { Higgs - χ_1^0 - χ_1^0 coupling $\to 0$
Z - χ_1^0 - χ_1^0 coupling $\to 0$
$\chi_1^0 - f - \tilde{f}$ coupling $\to$ Yukawa coupl.

but for $M_2^2 \gg \mu^2 \Rightarrow$ MSSM has 3 light higgsino-like st
(one light chargino + 2 neutral higgsinos

$\rightarrow$ CO-ANNIHILATION

$\chi_1^0 \chi_2^0 \to f\bar{f}$, $\chi_1^0 \chi_1^\pm \to f\bar{f}'$

important $\Rightarrow$ light χ_1^0 relic density $\downarrow$

$\rightarrow$ rad. corrections may induce a mass splitting drastically reducing the co-annihilation

if χ_1^0 is heavier than W : $\chi_1^0\chi_1^0 \to W^+W^-, ZZ$
$\Rightarrow m_{\chi_1^0} > 250$ (600) GeV to form galactic (all cold) DM

EXPERIMENTAL SEARCHES OF WIMPS

SCATTERING OF WIMPS ON NUCLEI

↓

measure recoil energy

- DAMA, CDMS {present exps}
- ↳ exploits annual modulation of the signal

WIMPS ACCUMULATED IN CELESTIAL BODIES (EARTH, SUN)

⇒ equil. when capture rate ~ annih. rate

⇒ in their annih neutrinos are produced

⇒ ν telescopes (AMANDA)

\+

WIMP ANNIHILATION IN OUR GALAXY

Direct and indirect detection rates (for ν's from the center of the earth) of CDM predicted by SUSY

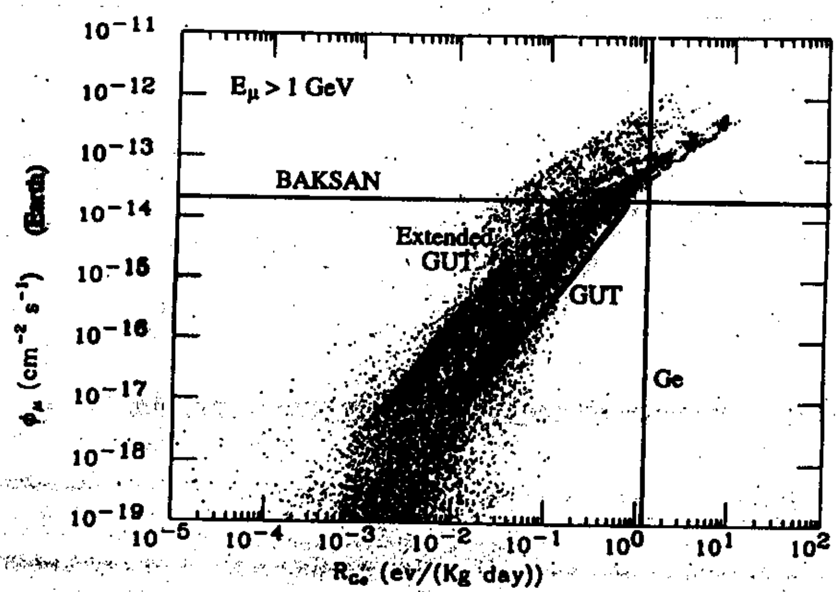


Figure 1: Direct and indirect detection rates (for neutrinos from the center of the earth in the figure shown) of cold dark matter particles predicted by supersymmetric theory. Grand unified theories favor the parameter space indicated. Part of it is already excluded by present experiments as indicated by the horizontal and vertical lines.

Bergström, Edsjo, Gondolo

FURTHER POSSIBILITY OF INDIRECT DETECTION : χ^0 annihilation in the galactic halo

↓

products of the annihilation ⇒ ANTIPROTONS

γ rays

* antiprotons: upcoming space experiments **(AMS, PAMELA)** needed to disentangle a low-energy signal from the smooth cosmic-ray induced background
→ antiprotons from χ^0 annihilation populate also the sub-100 MeV energy band Bottino et al

* γ rays from loop-induced annihilations

$\chi\chi \to \gamma\gamma$, $\chi\chi \to Z\gamma$

monoenergetic γ with $E_\gamma = m_\chi$ or $E_\gamma = m_\chi \left(1 - \frac{m_Z^2}{4m_\chi^2}\right)$

→ detection probability of a γ line signal depends on the very poorly known density profile of the DM halo

Bergström, Gondolo, Ullio, Bergm, Gondolo,

COSMIC-RAY $\bar{p}$ FLUX AT THE TOP OF THE ATMOSPHERE MEASURED BY THE BALLOON-BORNE BESS SPECTROMETER IN ITS 1995 FLIGHT

→ AT $T_{\bar{p}} < 1$ GeV the interstellar secondary $\bar{p}$ spect is expected to drop-off markedly while exotic $\bar{p}$ (annih. of relic part., BH evaporation, cosmic strings) have a milder fall off

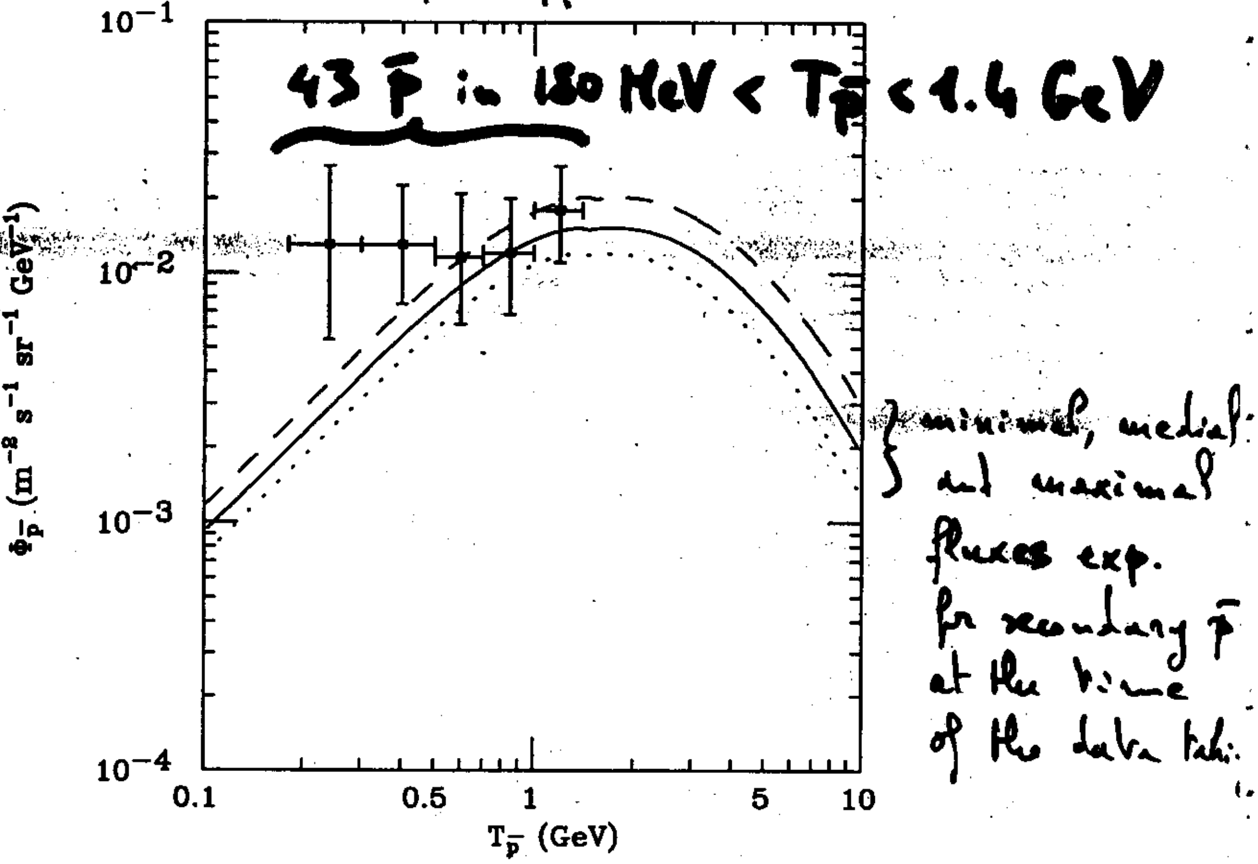


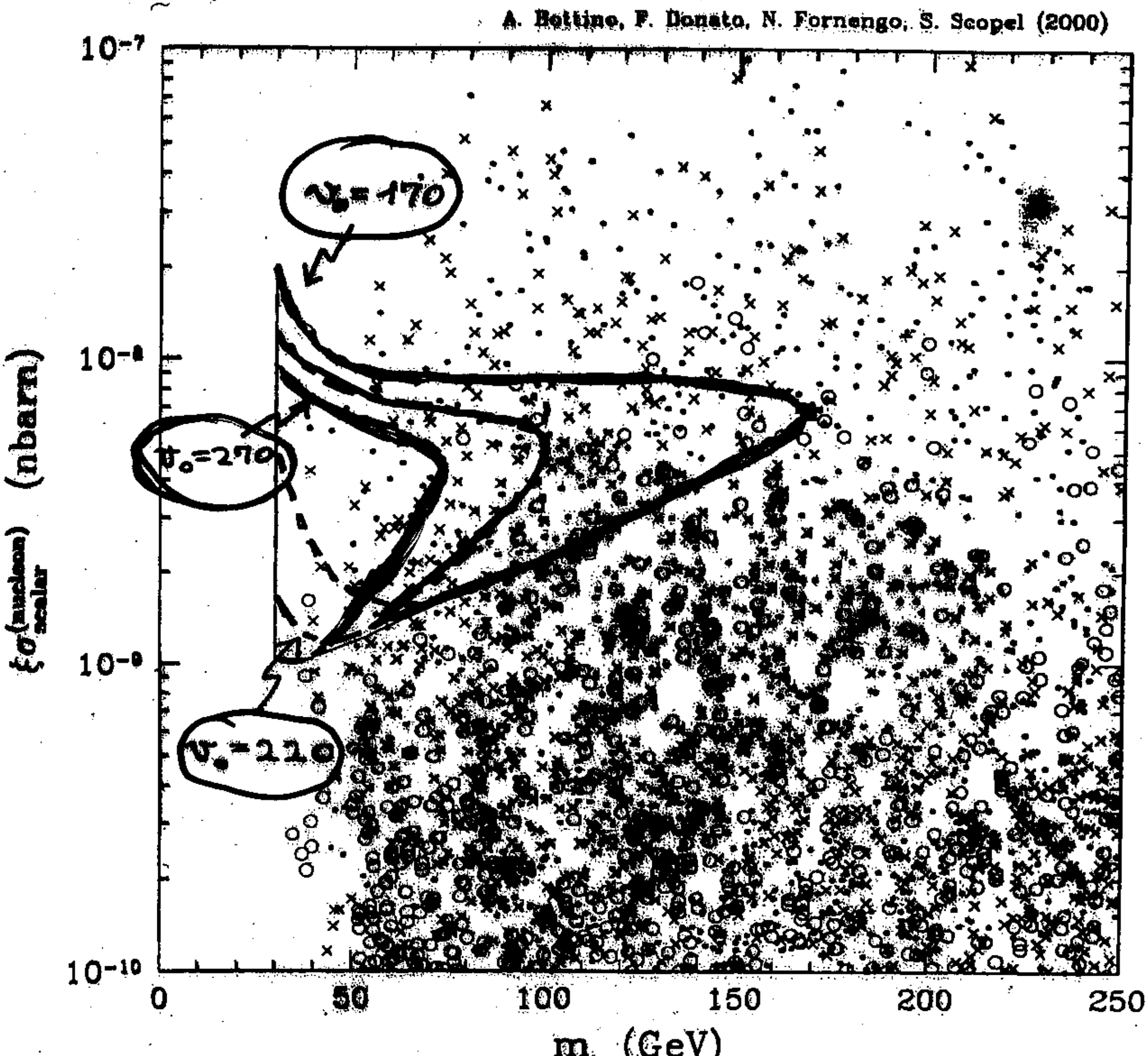
Figure 1

DAMA 3σ C.L. annual-modulation region

(exposure : 57986 kg · day)

Bernabei et al., Phys. Lett. B480 (2000) 23
preprint INFN/AE-00/01 (www.lngs.infn.it)

$\rho_l = 0.3$ GeV · cm^{-3} , v_0 in km · sec^{-1}



BOTTINO et al.

generic scatter plot

∘ $\Omega_\chi h^2 > 0.1$

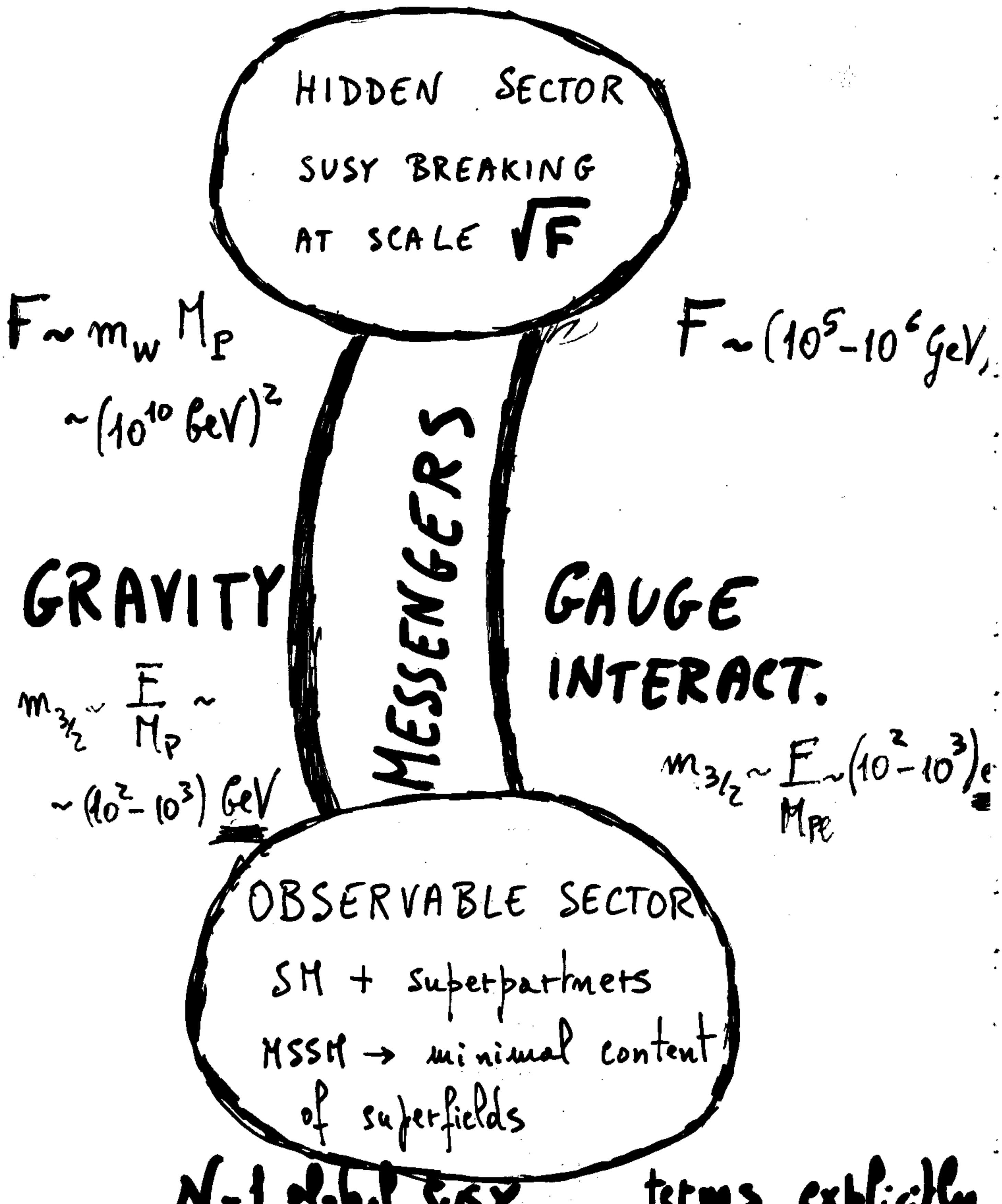
× $0.01 < \Omega_\chi h^2 < 0.1$

• $\Omega_\chi h^2 < 0.01$

$$\xi = \min\left\{1, \frac{\Omega_\chi h^2}{(\Omega h^2)_{min}}\right\}$$

$$(\Omega h^2)_{min} = 0.01$$

WHICH SUSY



N=1 global SUSY version of SM + terms explicitly (softly) breaking SUSY

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-DENSIT CDM models in accounting for { low-level density fluc. $\sim 10 h^{-1}$ M; enough power at $1 h^{-1}$ Mpc (form galaxy early enough epoch) }

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

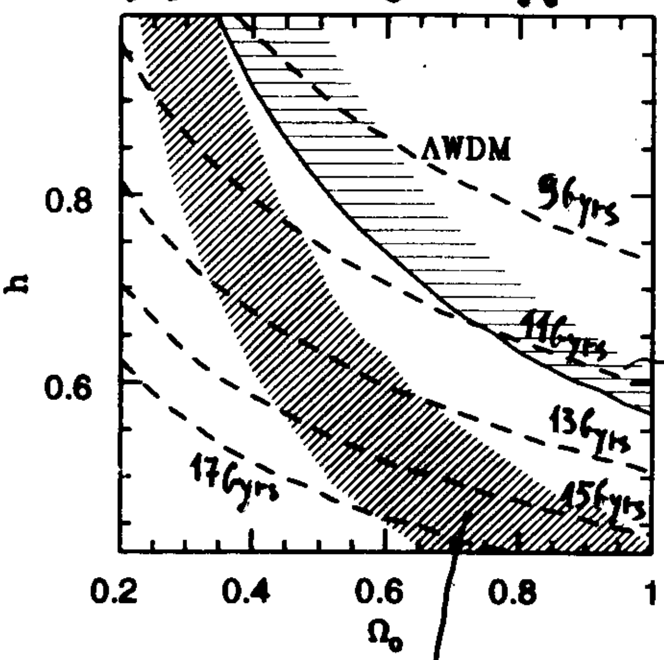
OBSERVATIONAL CONSTRAINTS { HIGH-REDSHIFT OBJECTS ; CLUSTER ABUNDANCE }

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

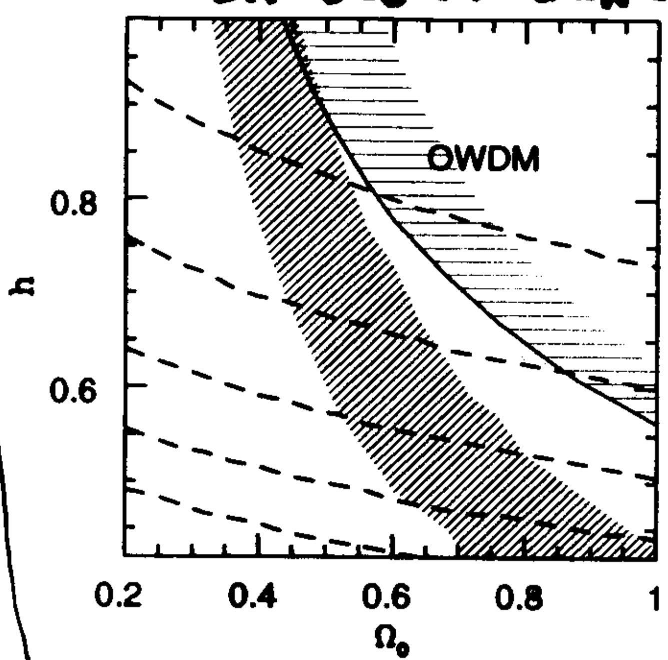
$n=1$ ($n \neq 1$ does not improve the situation)

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

FLAT $\Omega_0 + \Omega_\Lambda = 1$



OPEN $\Omega_0 < 1$ $\Omega_\Lambda = ($



$g_* = 150$

CLUSTER ABUNDANCE *

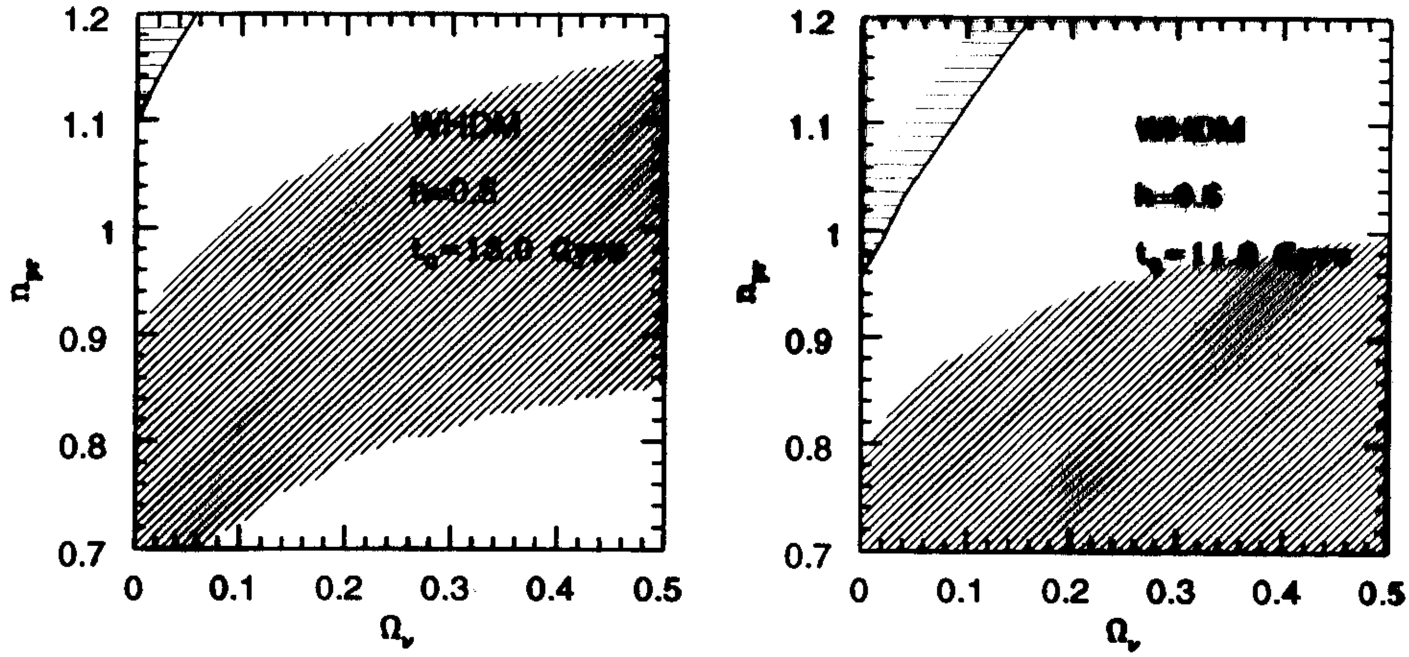
HIGH-REDSHIFT OBJECTS CONSTRAINT **

* using the 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 system (DLAS) → value of Ω_{HI} at $z \sim 4.25$ from Storrie-Lombardi et al '95

WARM + HOT DM $\Omega_0 = 1$

$(g_* = 150)$ E. PIERPAOLI, S. BORGANI, A.M., M. YAMAGUCHI



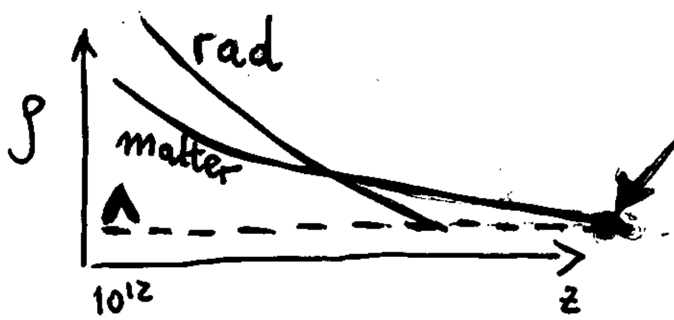
COMBINED FREE STREAMING OF ν and $\psi_{3/2}$ $\Rightarrow$ STRONG SUPPRESSION OF FLUCTUATIONS AT $\sim 1\, h^{-1}$ Mpc $\Rightarrow$ DIFFICULT TO FORM $z \sim 4$ PROTOGALACTIC OBJECTS (while matching low-z cluster abundance)

$\Omega_\Lambda \neq 0$

only a nightmare for
a particle physicist ?

i) FIRST CANDIDATE : COSMOLOGICAL CONSTANT

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



TODAY → { why Λ so small* ; why today ? }

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

ii) SECOND POSSIBILITY :

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

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

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

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

CARROLL

Bartolo, Pietroni

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 ...

⇒ 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 !

R. Caldwell, Dave and Steinhardt PRL '98

↳ name for this rolling scalar:

QUINTESSENCE

Candidates: pseudo-Goldstone bosons
Frieman, Hill, Stabbins, 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, Steinhar

↓

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!